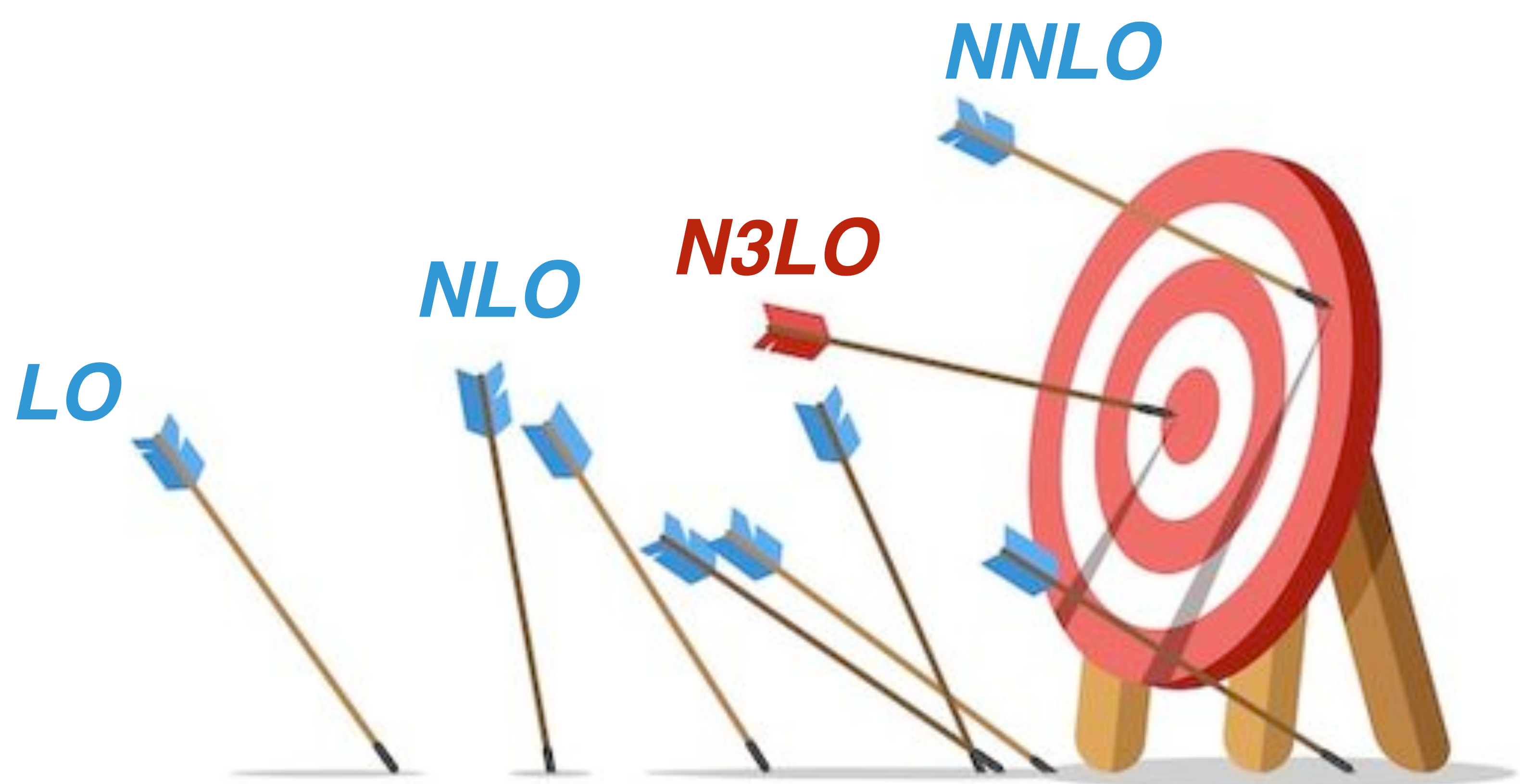
QCD and Monte Carlo event generators (Lecture 3 — Resummation & MCs)

Marius Wiesemann

Max-Planck-Institut für Physik



BND summer school 2024

Blankenberge (Belgium), September 2-12th, 2024

Recap of Lecture 1

★ LHC Master Formula is based on factorizing long-distance form short-distance physics

$$\sigma_{\rm had} = \sum_{ij} \int \mathrm{d}x_1\, \mathrm{d}x_2\, f_i(x_1, \mu_{\rm F})\, f_j(x_2, \mu_{\rm F}) \times \sigma_{ij}(x_1 P_1, x_2 P_2, \mu_F) + \mathcal{O}(\Lambda/Q)$$

★ Perturbative (higher-order) QCD calculations vital for partonic (hard) cross section

- LO just gives a rough order-of-magnitude estimate
- NLO is largely automated by now and the minimum requirement for a reliable description of the physical cross sections at the LHC
- NNLO has been substantially advanced in the past years and is required for precision data/theory comparisons & to reduce theory uncertainties at the LHC (current bottleneck: mostly 2-loop amplitudes)

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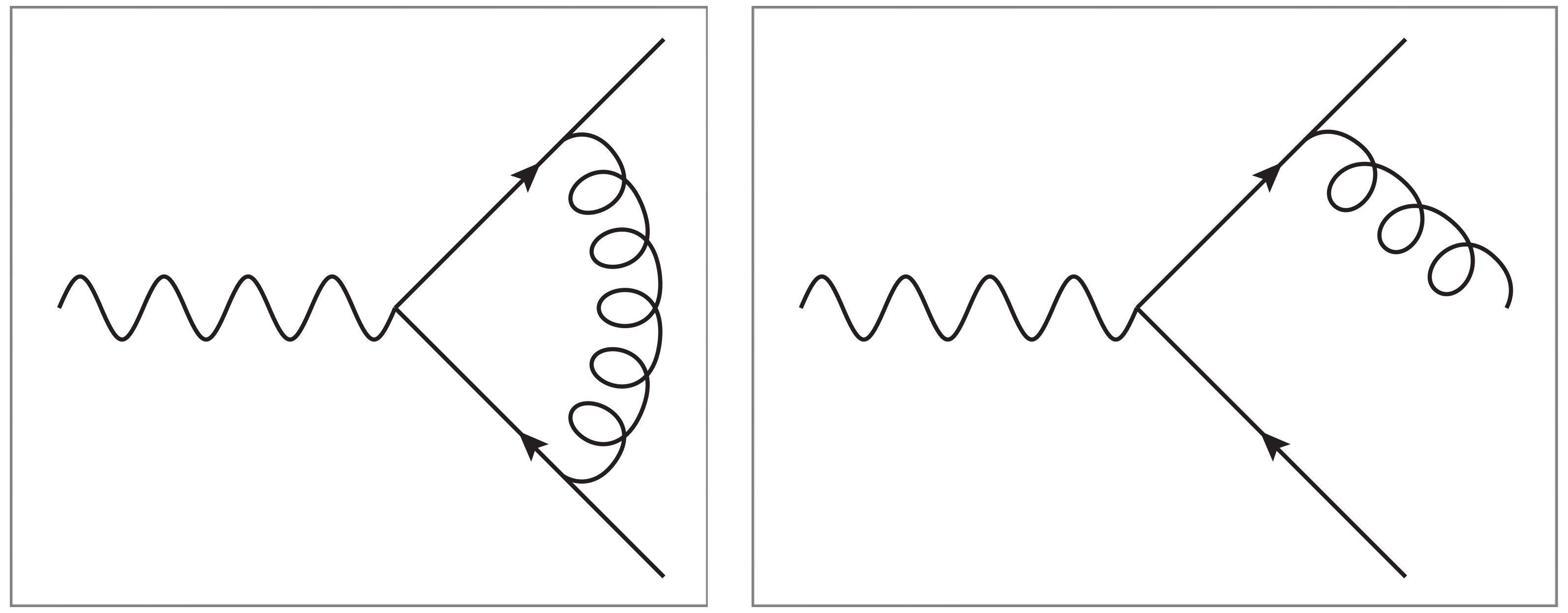
★ EW corrections?

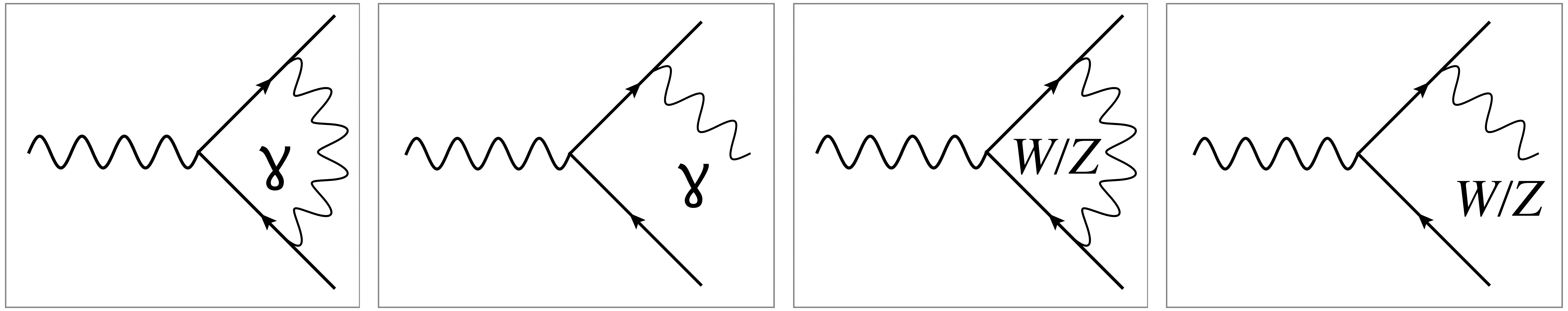
EW corrections

★ EW corrections just like (abelian version of) QCD corrections, and yet different…

NLO QCD



NLO EW



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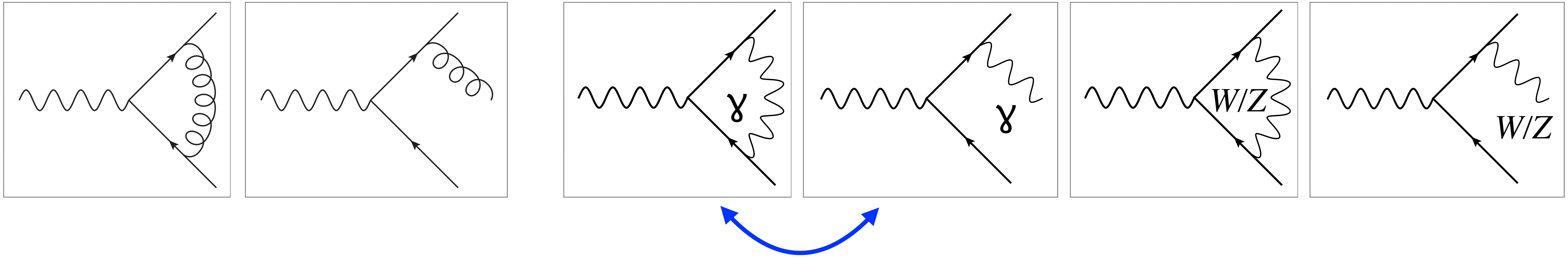

cancellation of IR singularities

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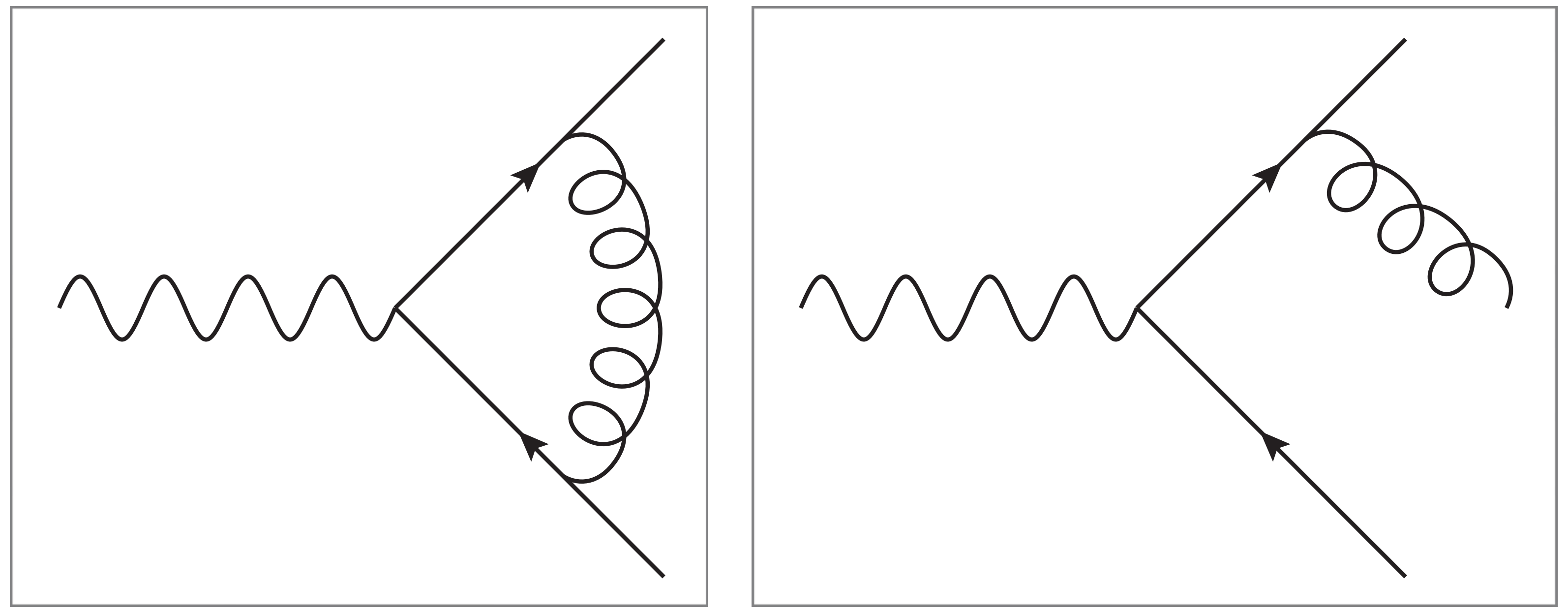
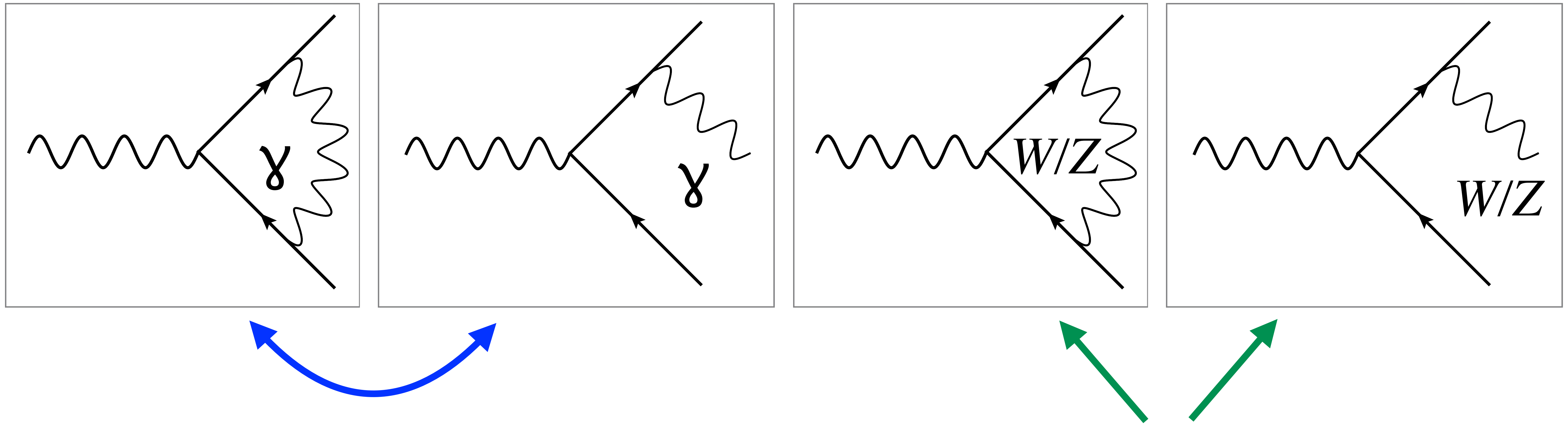
NLO QCD



NLO EW



cancellation of IR singularities

IR singularities regulated by $m_{Z/W}$

→ separately finite

→ real Z's/W's can be measured

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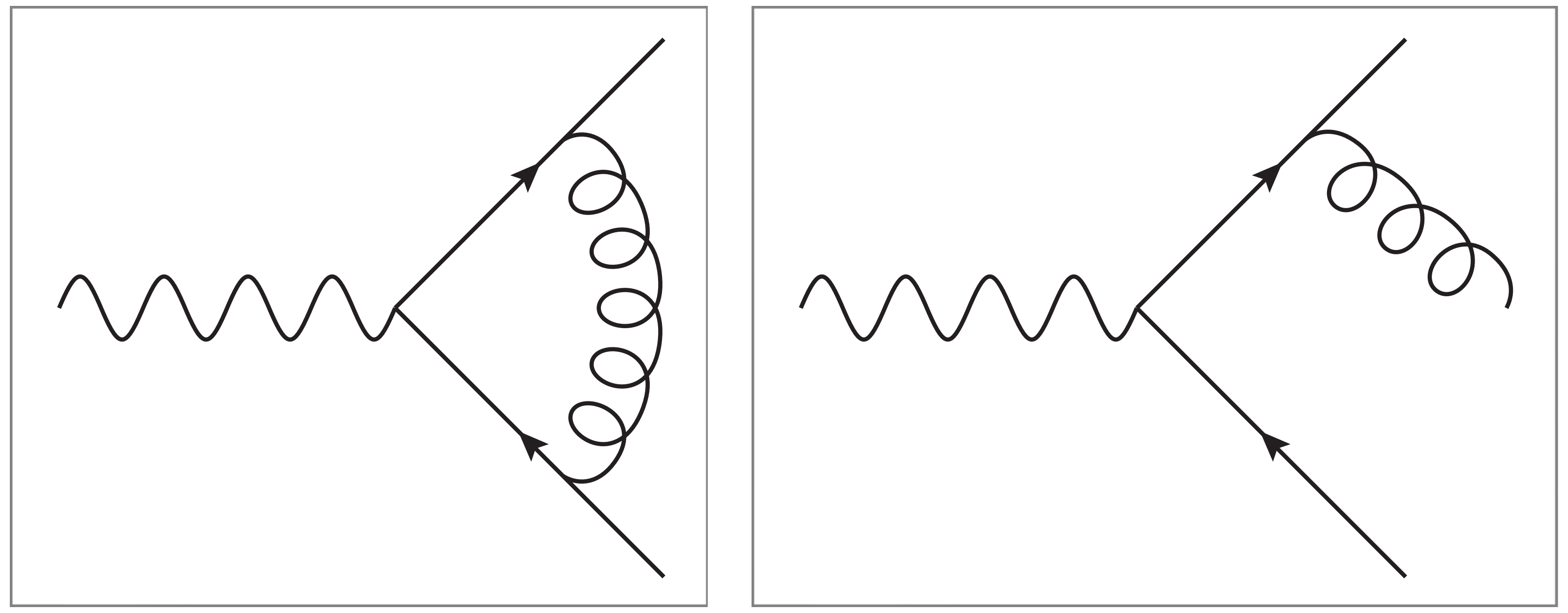
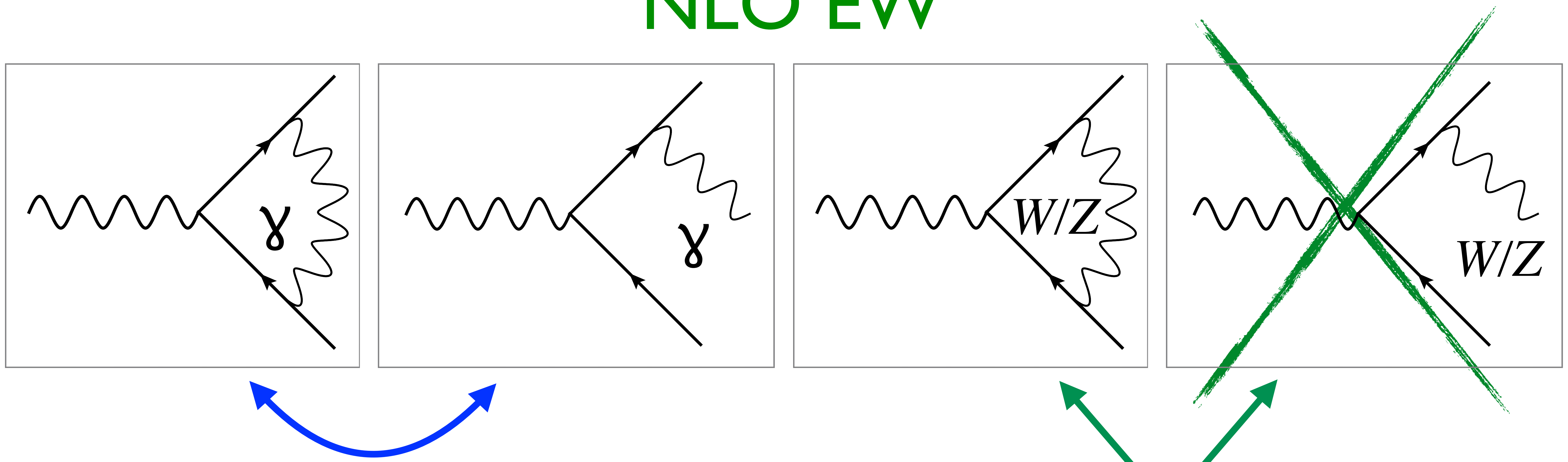
NLO QCD



NLO EW



cancellation of IR singularities

IR singularities regulated by $m_{Z/W}$

→ separately finite

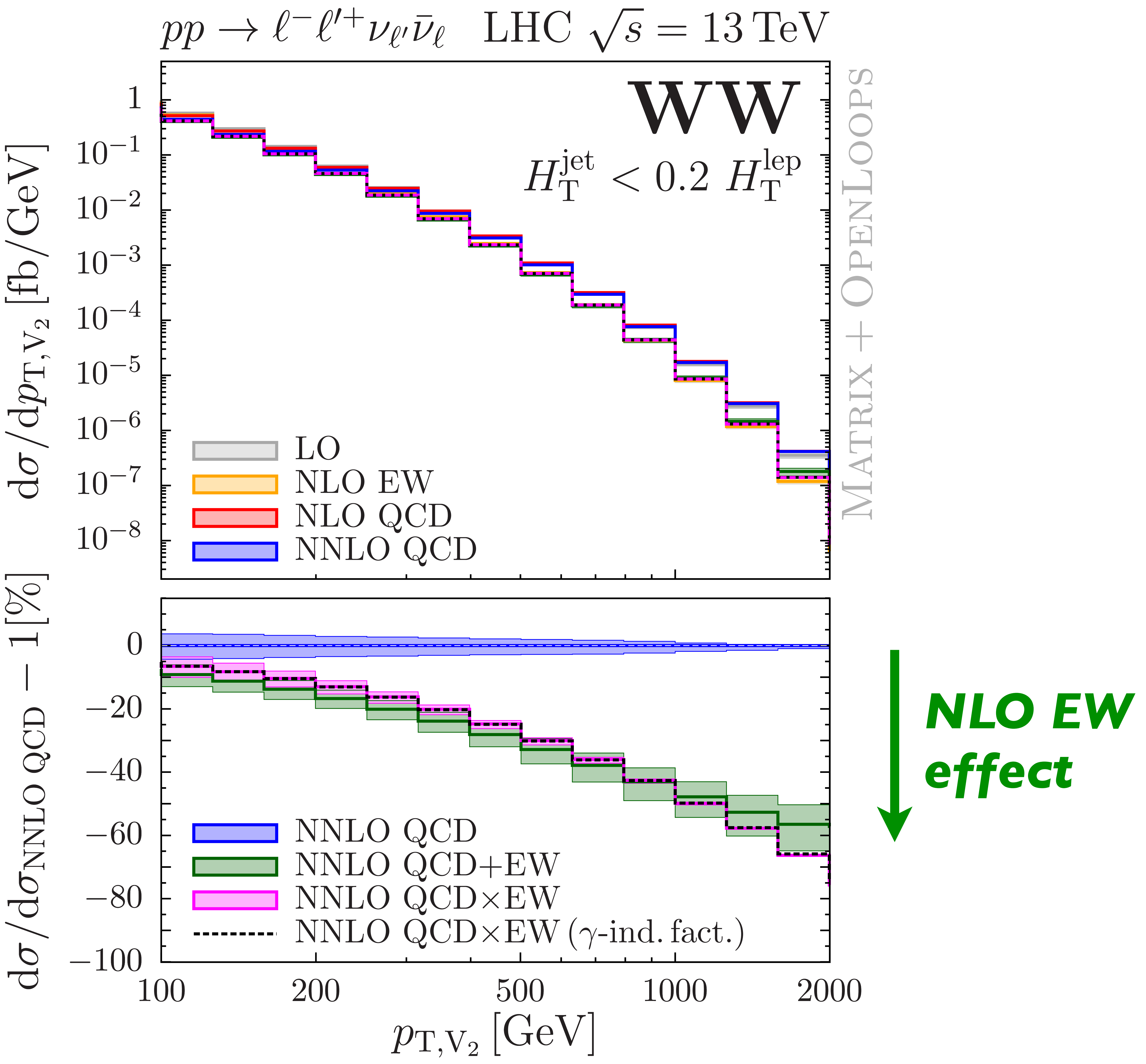
→ real Z's/W's can be measured

→ large EW Sudakov logs:

$$\alpha^n \log^k \left(s / m_{Z/W}^2 \right), \quad k \leq 2n$$

EW corrections

[Grazzini, Kallweit, Lindert, Pozzorini, MW '19]



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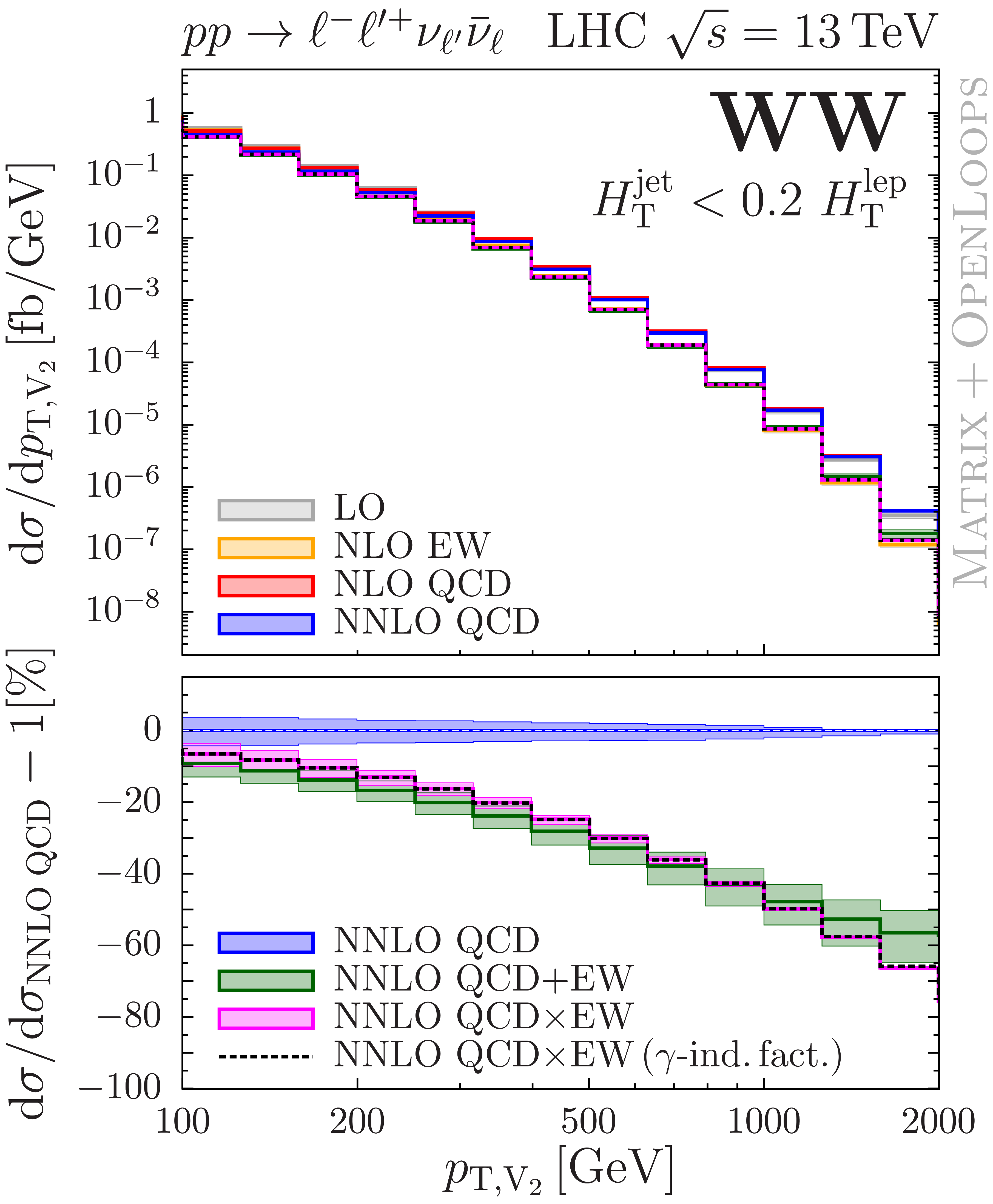
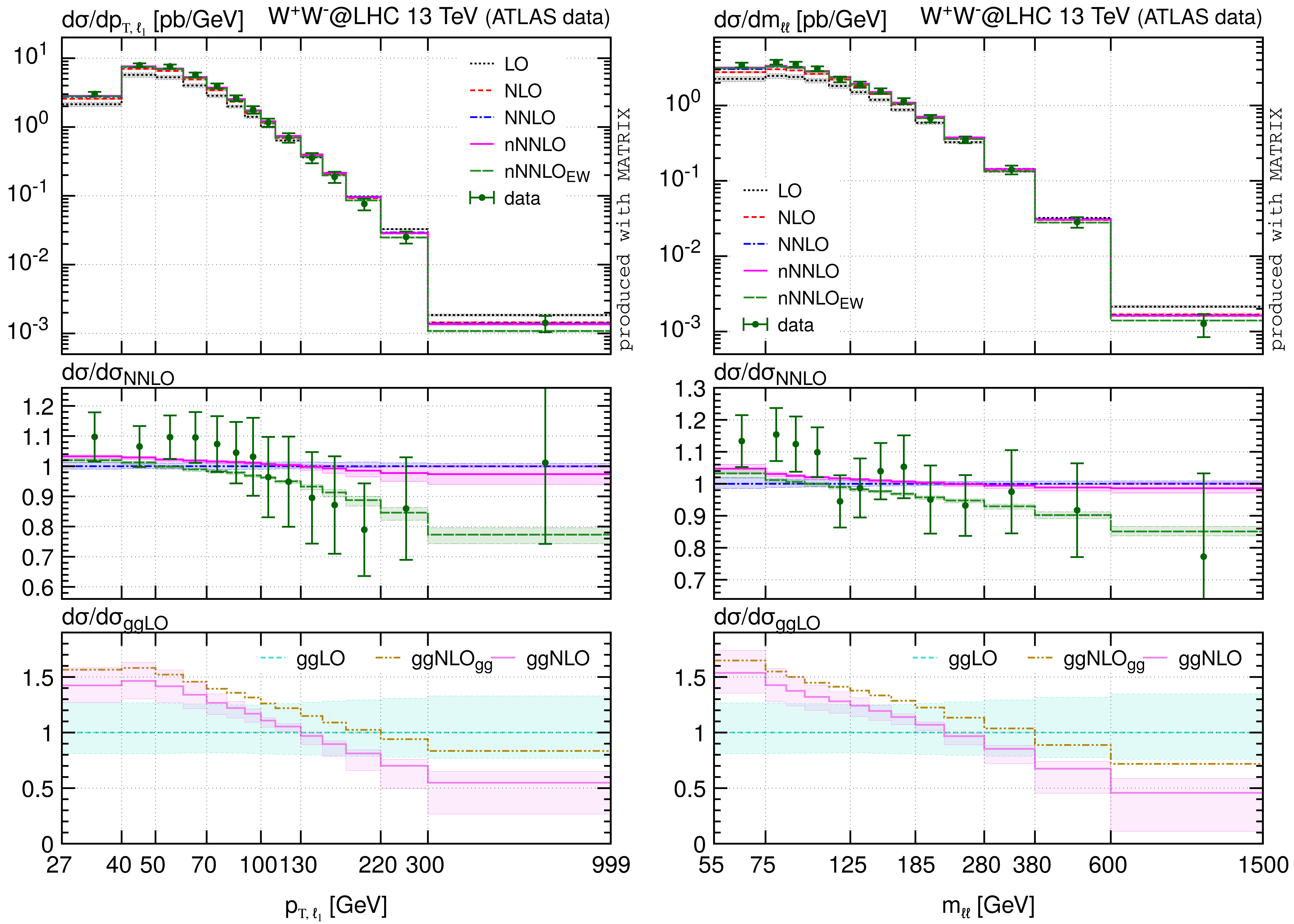


[Grazzini, Kallweit, MW, Yook '20], [Grazzini, Kallweit, Linder, Pozzorini '19]



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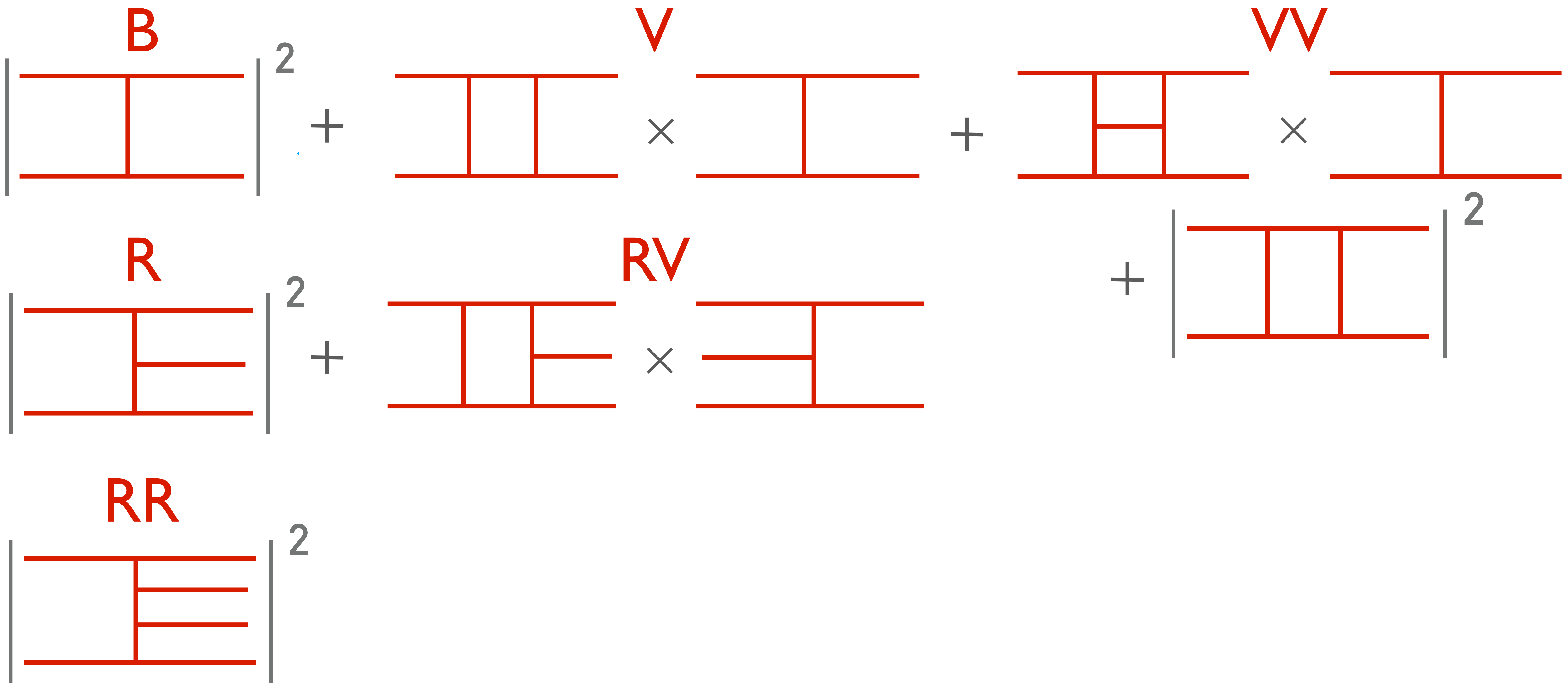
- N^3LO frontier passed for $2 \to 1$ processes (Higgs & Drell-Yan)

★ EW corrections important due to photon radiation & EW Sudakov logarithms (in tails)

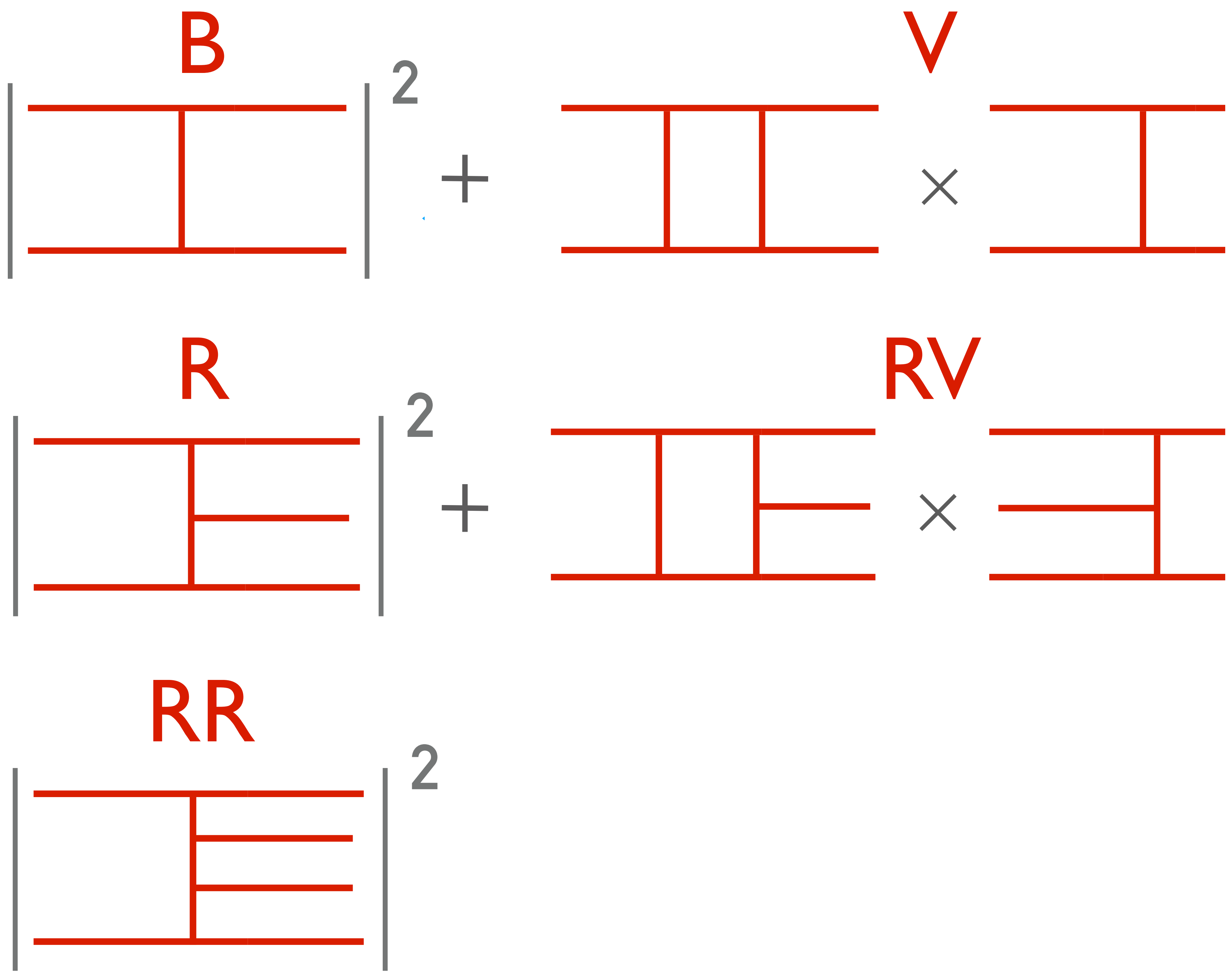
$$\sigma_{\rm NNLO} = \int d\Phi_{\rm B}\, \left(\sigma_{\rm B} + \sigma_{\rm V} + \sigma_{\rm VV}\right) + \int d\Phi_{\rm R}\, \left(\sigma_{\rm R} + \sigma_{\rm RV}\right) + \int d\Phi_{\rm RR}\, \sigma_{\rm RR}$$



main problems to solve:

1. phase-space integration -- easy/understood if finite, using MC methods
2. evaluation of (loop) amplitudes -- tree/1-loop understood, 2-loop bottleneck
3. combination of different (singular) ingredients -- several methods at NNLO

$$\sigma_{\rm NNLO} = \int d\Phi_B \, (\sigma_B + \sigma_V + \sigma_{VV}) + \int d\Phi_R \, (\sigma_R + \sigma_{RV}) + \int d\Phi_{RR} \, \sigma_{RR}$$



Local subtraction

- ***Antenna*** [Gehrmann-De Ridder, Gehrmann, Glover '05]
- ***STRIPPER*** [Czakon '10]
- ***nested soft.-coll.*** [Caola, Melnikov, Röntsch '17]
- ***CoLorFul*** [Del Duca, Somogyi, Troscanyi '05]
- ***Projection-to-Born*** [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]

non-local/slicing

- ***q_T-subtraction*** [Catani, Grazzini '07, MATRIX]
- ***N-jettiness*** [Gaunt, Stahlhofen Tackmann, Walsh '15] [Boughezal, Focke, Lui, Petriello '15, MCFM]

main problems to solve:

1. phase-space integration -- easy/understoo
2. evaluation of (loop) amplitudes -- tree/1-l
3. NNLO methods

‹

Outline

Lecture 1

★ Fixed-order calculations

- QCD basics (Lagrangian, Feynman rules, strong coupling)
- LHC Factorization/Master Formula (PDFs, partonic cross section)
- NLO QCD (methods, slicing vs. subtraction vs. analytic)
- NNLO QCD (methods, timeline)
- EW corrections (NLO, Sudakov logarithms, mixed QCD-EW corrections?)

Lecture 2: Hands-on session on MATRIX

Lecture 3

★ Monte Carlo Event Generation & Resummation

- Resummation
- Parton Shower Generators (formalism, hadronization, MPI)
- NLO+PS Matching (MC@NLO, Powheg, merging)
- NNLO+PS Matching (MiNNLO, Geneva)

Resummation

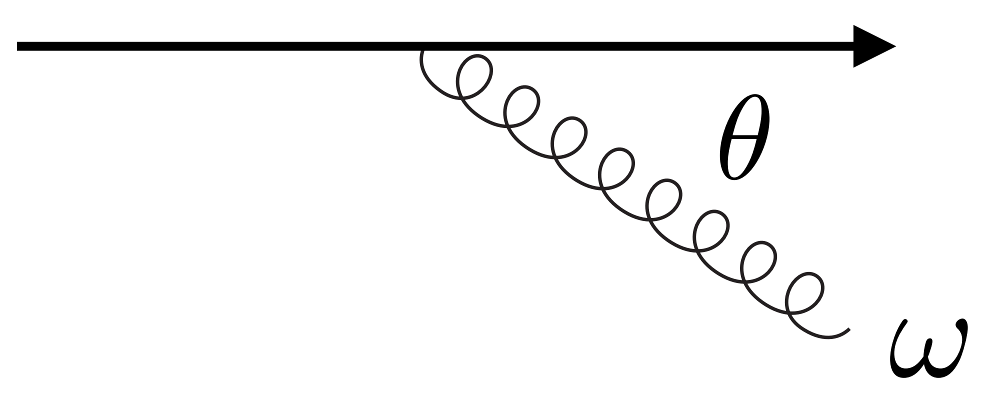
★ By KLN theorem IR (soft/collinear) singularities cancel for IR-safe observables

The cancellation of real & virtual singularities can be spoiled in certain regions of phase space

★ This is the case, when observables become sensitive to soft/collinear (QCD) radiation.

→ large logarithmic terms invalidate the perturbative expansion of the cross section

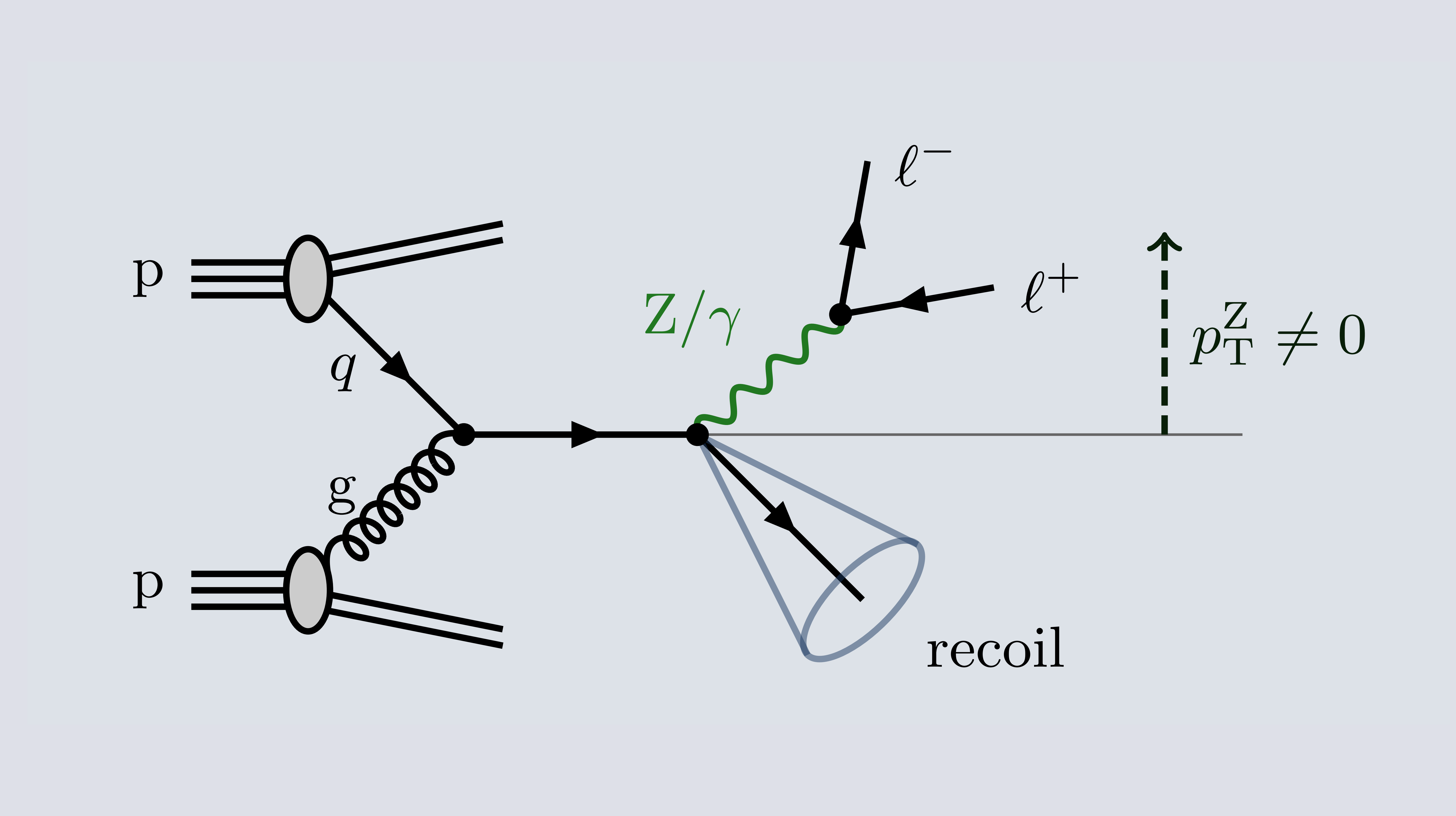
★ Gluon radiation produces a double-log behaviour (one collinear and one soft logarithm)



$$\sim \frac{\alpha_S}{\pi} \frac{d\theta^2}{\theta^2} \frac{d\omega}{\omega}$$

Resummation

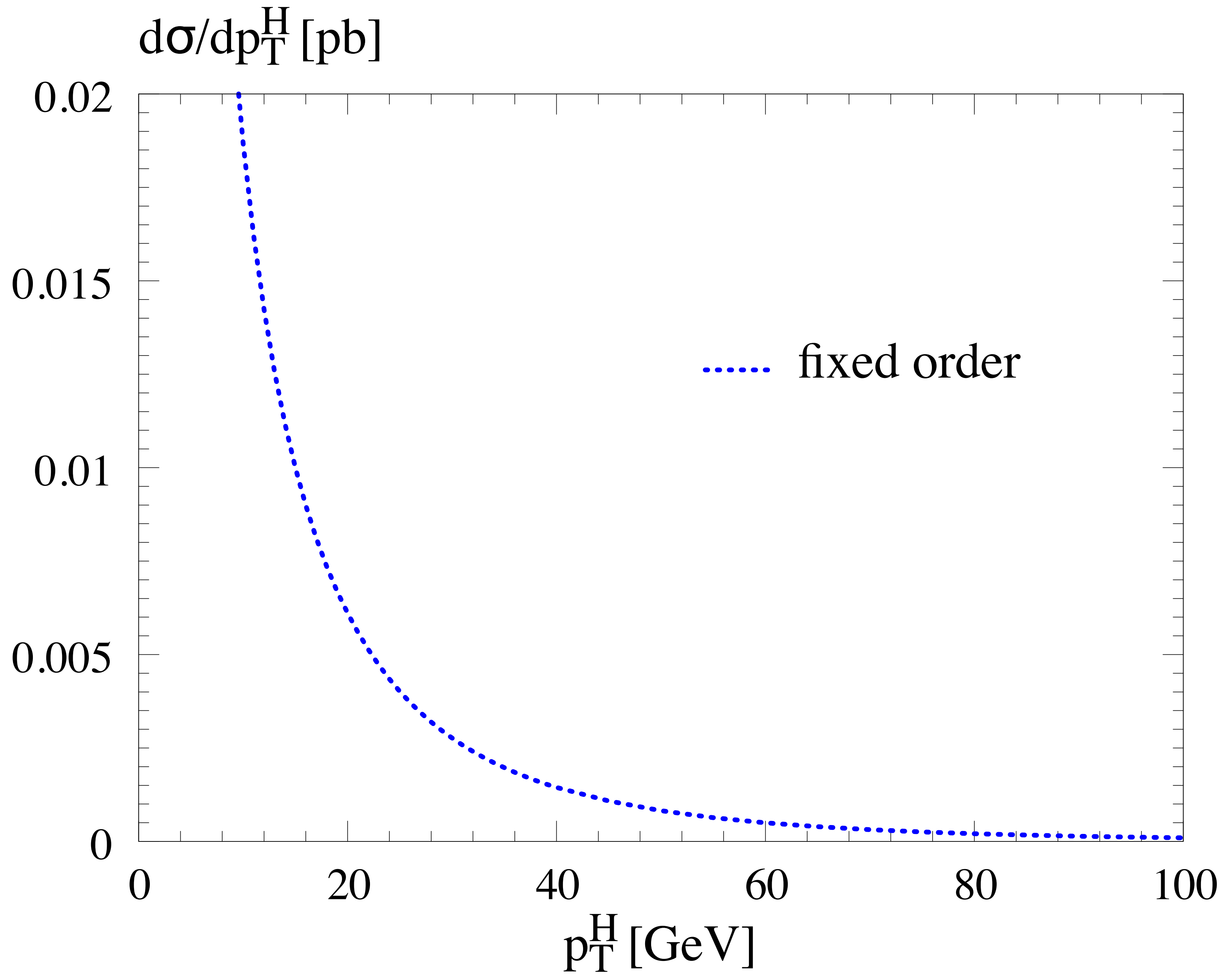
- production of colorless particles (system $\mathcal{F}$, invariant mass M)



Resumming

- production of colorless particles (system $\mathcal{F}$, invariant mass M)
- problem: p_T distribution of $\mathcal{F}$ diverges at $p_T \to 0$
- reason: large logs $\ln p_T^2/M^2$ for $p_T \ll M$

$$\alpha_s: \quad \ln(p_T^2/M^2),\ \ln^2(p_T^2/M^2)$$
$$\alpha_s^2: \quad \ln(p_T^2/M^2),\ \ln^2(p_T^2/M^2),\ \ln^3(p_T^2/M^2),\ \ln^4(p_T^2/M^2)$$
$$\ldots$$



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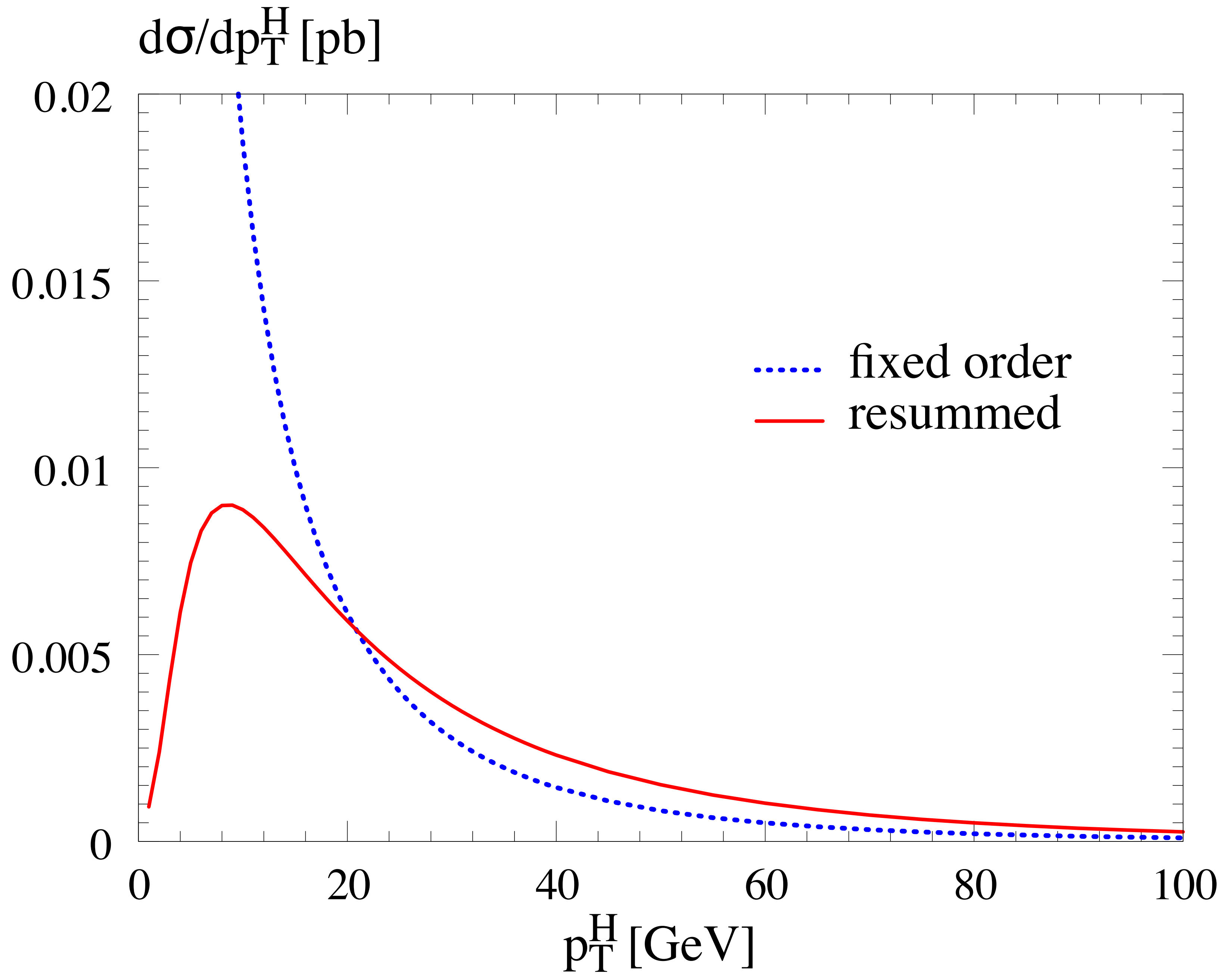
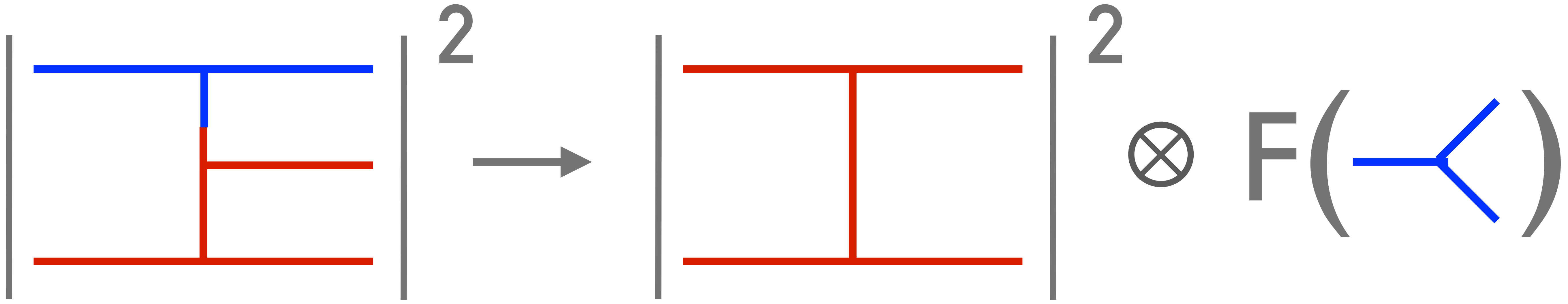
$$\dots$$

- solution: all order resummation



Transverse-momentum resummation

★ Factorization of soft and collinear radiation in matrix elements allows for resummation



universal

→ eikonal factor $\boldsymbol{J^a}$ (soft) or splitting function $\boldsymbol{P_{ij}}$ (collinear)

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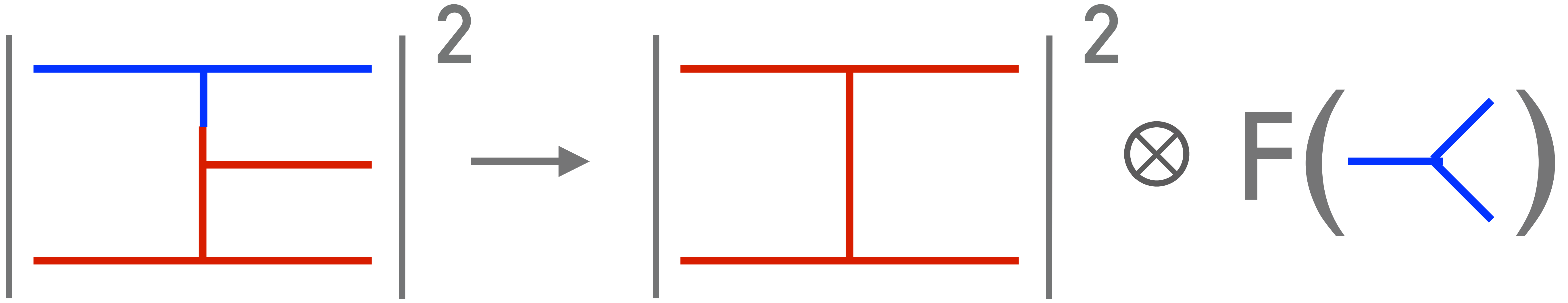

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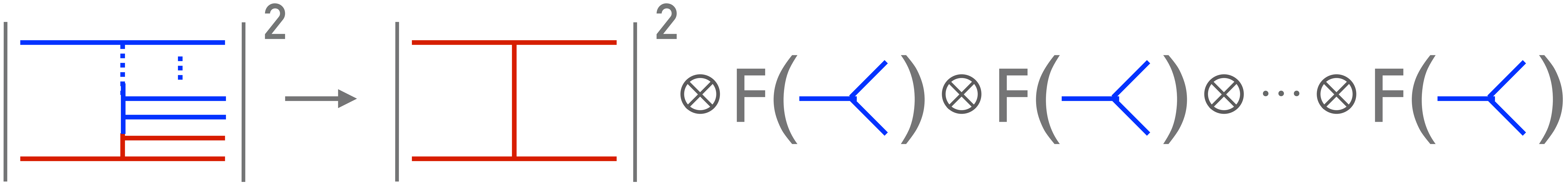
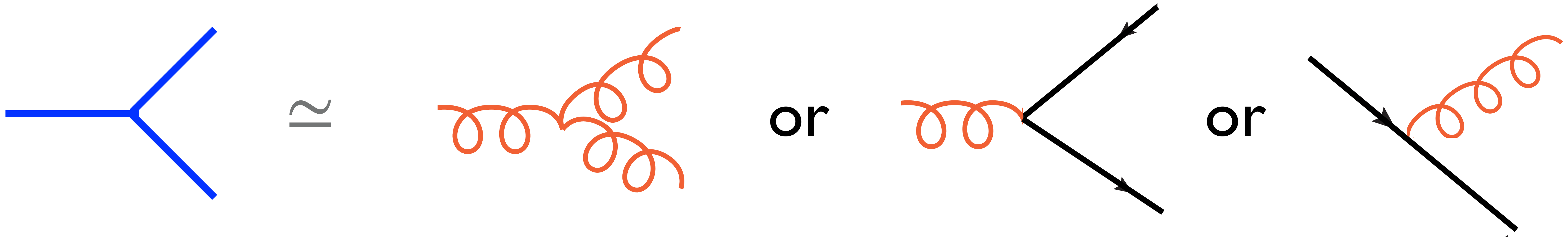
→ Multiple emissions of soft/collinear QCD radiation fulfills factorization



possible splittings:



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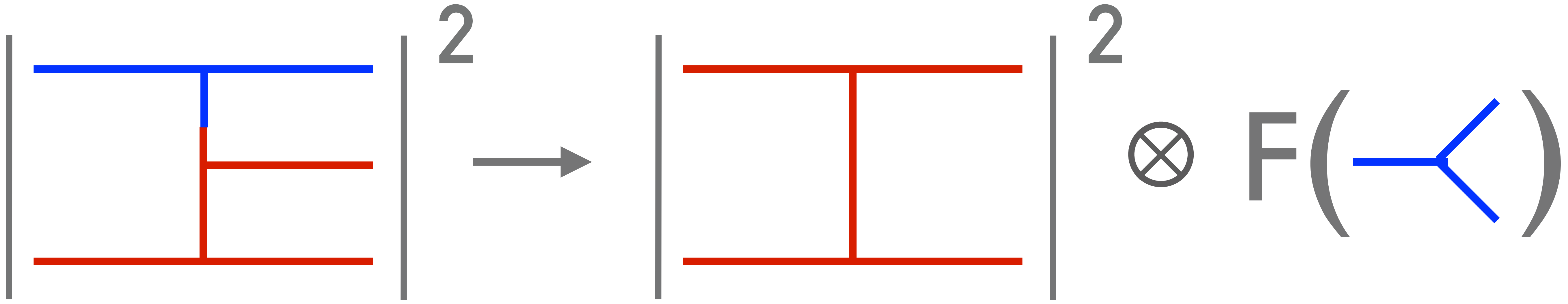

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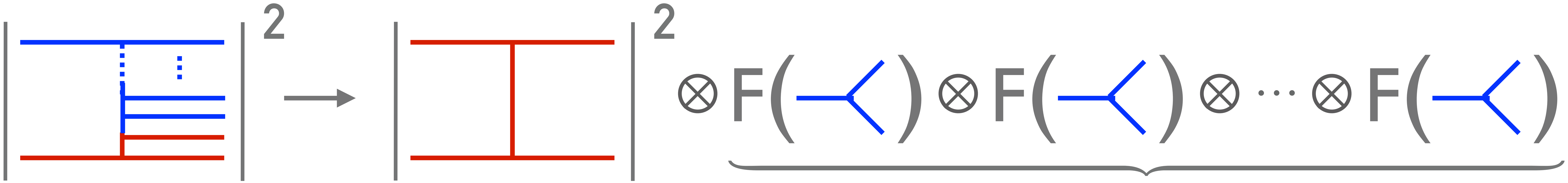

$$= \exp(-S)$$

Sudakov form factor

Transverse-momentum resummation

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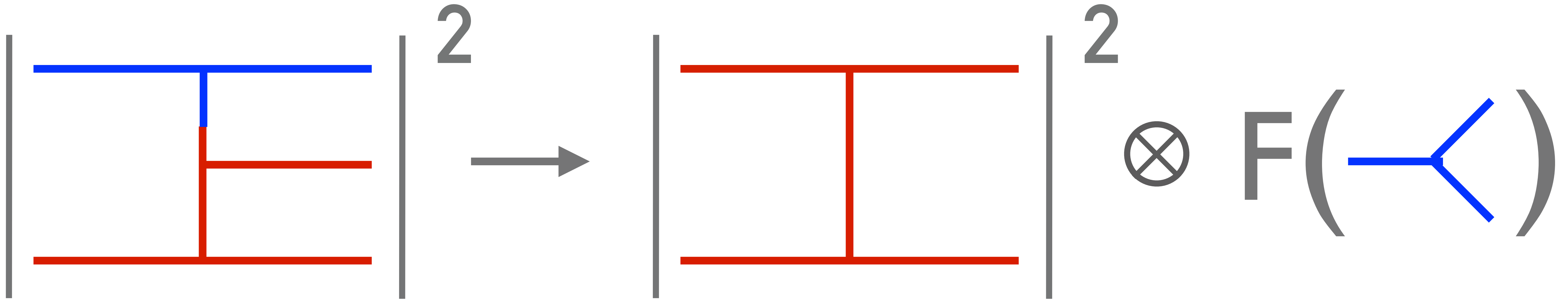

universal

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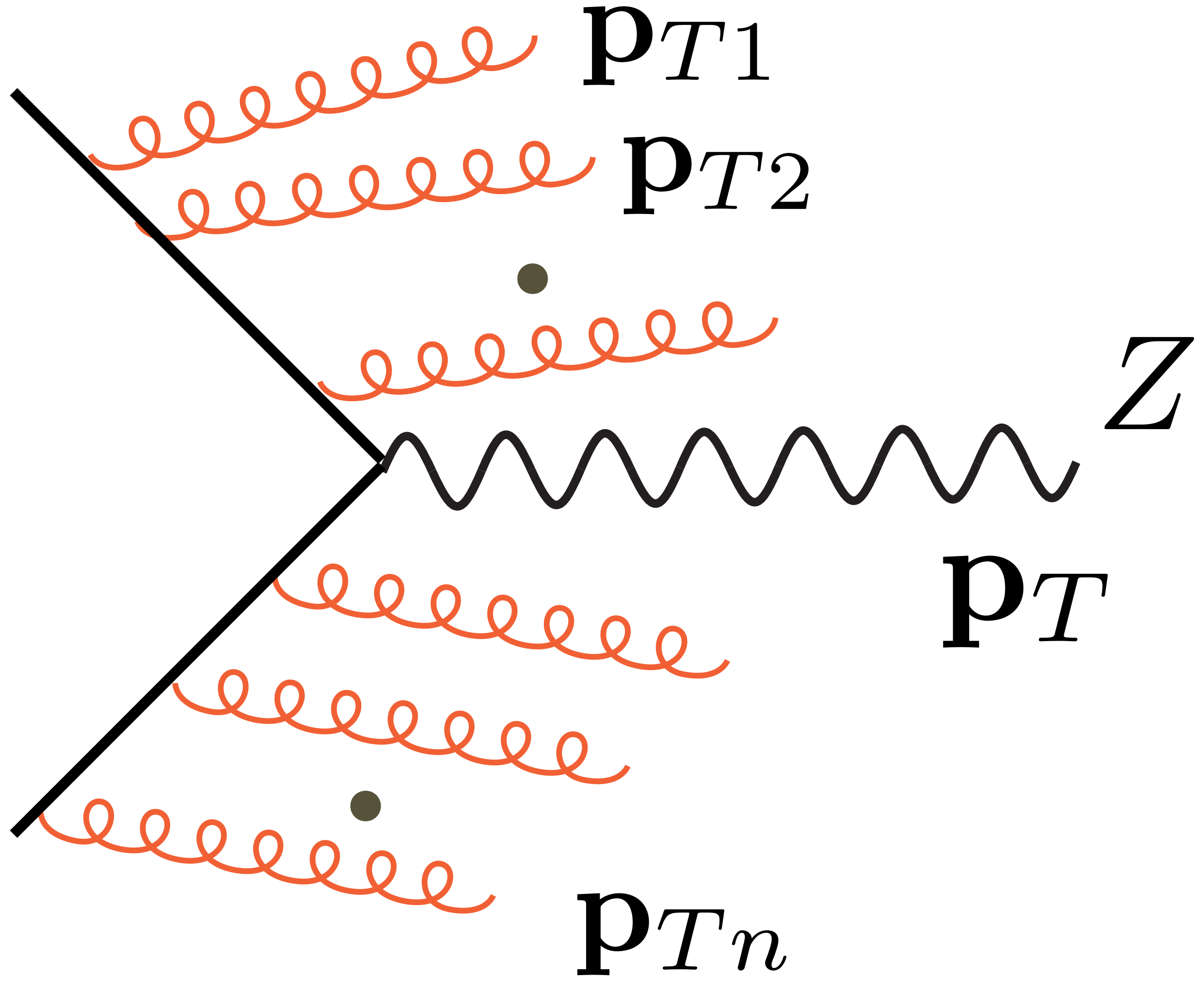
→ Multiple emissions of soft/collinear QCD radiation fulfills factorization

★ However, also the phase space needs to be factorized

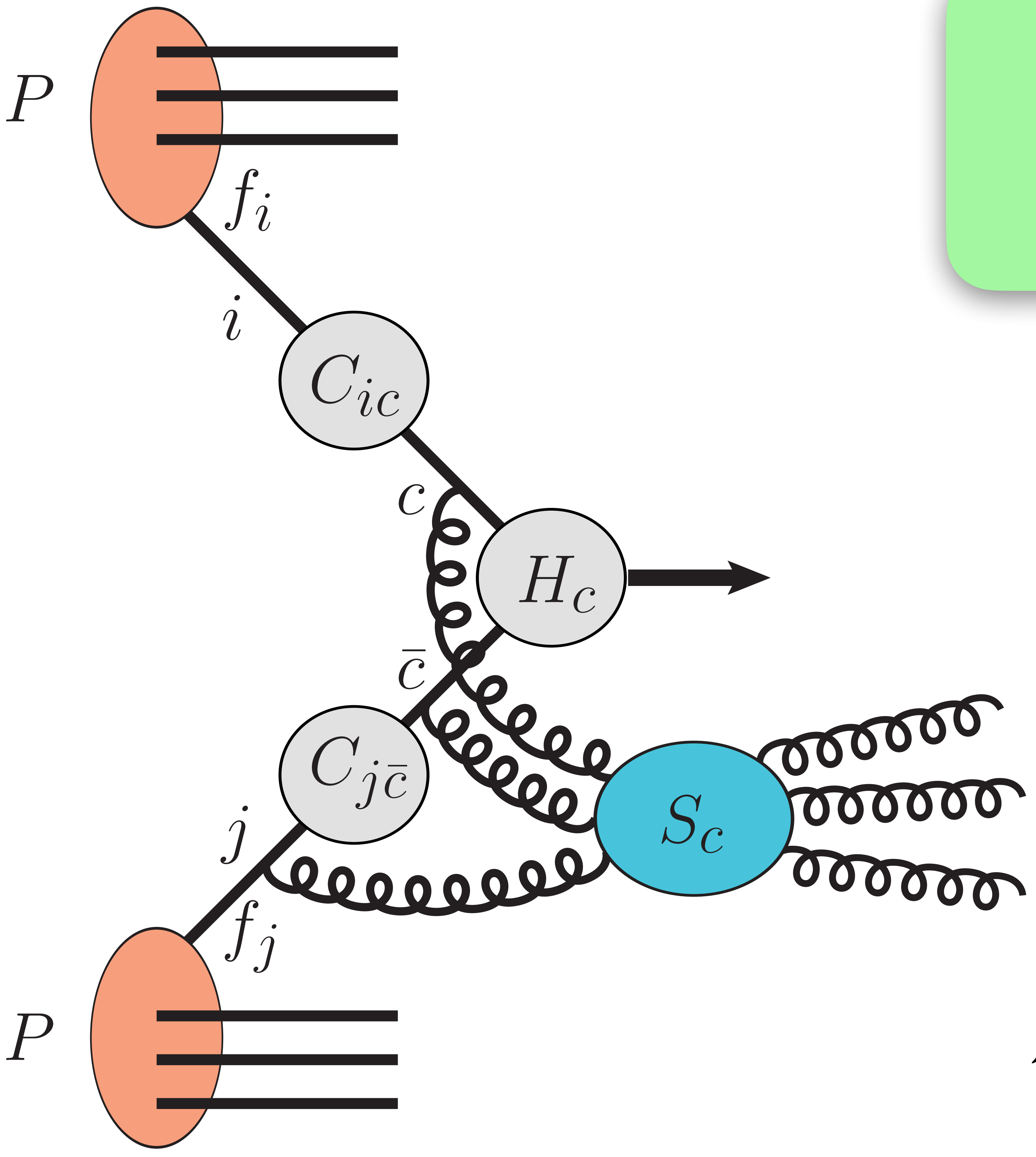
→ go to impact-parameter space (in case of p_T), where radiation factorizes, to implement momentum conservation

$$\delta^{(2)}(\mathbf{p}_T - \mathbf{p}_{T1} - \ldots\ldots\mathbf{p}_{Tn}) \quad \Rightarrow \quad e^{i\mathbf{b}\cdot\mathbf{p}_T}\prod_{i=1}^{n} e^{-i\mathbf{b}\cdot\mathbf{p}_{Ti}}$$



Transverse-momentum resummation

[Collins, Soper, Sterman '85]



$$\frac{\mathrm{d}\sigma(p_\mathrm{T})}{\mathrm{d}\Phi_\mathrm{F}} = p_\mathrm{T} \int_0^\infty db J_1(b\, p_\mathrm{T})\, e^{-S(b_0/b)} \mathcal{L}_b(Qb/b_0)$$

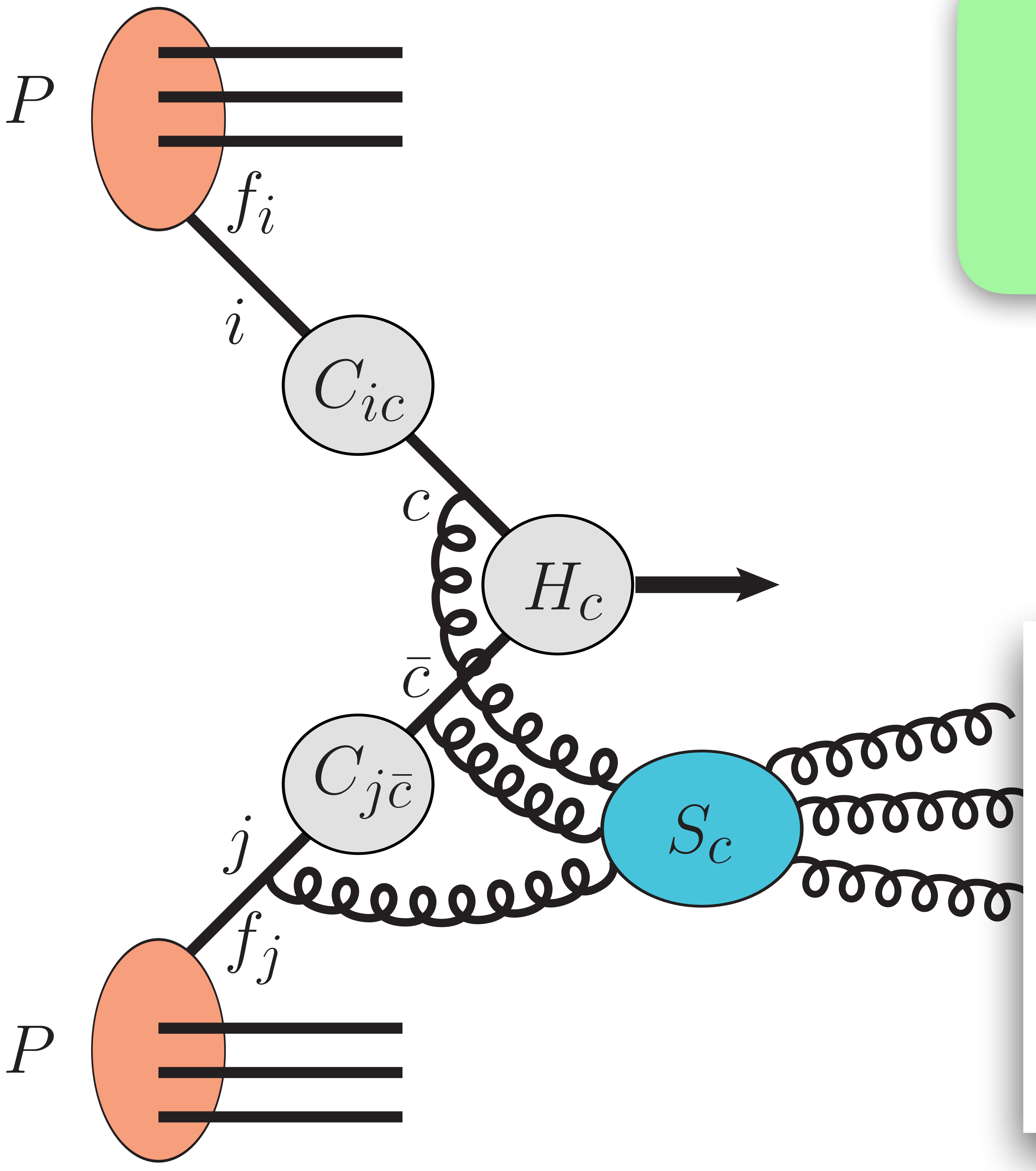
$$S(p_\mathrm{T}) = 2\int_{p_\mathrm{T}}^{Q} \frac{\mathrm{d}q}{q} \left(A(\alpha_s(q)) \ln \frac{Q^2}{q^2} + B(\alpha_s(q)) \right),$$

$$A(\alpha_s) = \sum_{k=1}^{2} \left(\frac{\alpha_s}{2\pi}\right)^k A^{(k)}, \qquad B(\alpha_s) = \sum_{k=1}^{2} \left(\frac{\alpha_s}{2\pi}\right)^k B^{(k)}$$

$$\mathcal{L}_b(Qb/b_0) = \sum_{c,c'} \frac{\mathrm{d}|M^\mathrm{F}|^2_{cc'}}{\mathrm{d}\Phi_\mathrm{F}} \sum_{i,j} \left\{ \left(C^{[a]}_{ci} \otimes f^{[a]}_i\right) \bar{H}(Qb/b_0) \left(C^{[b]}_{c'j} \otimes f^{[b]}_j\right) \right\}$$

Transverse-momentum resummation

[Collins, Soper, Sterman '85]



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$$S_c(A,B) = \exp\Big\{\underbrace{\underbrace{\underbrace{L\,g^{(1)}(\alpha_s L)}_{LL} + g^{(2)}(\alpha_s L)}_{NLL} + \alpha_s g^{(3)}(\alpha_s L)}_{NNLL} + \alpha_s^2\cdots\Big\}$$

Transverse-momentum resummation

★ developed already 40 years ago
[Parisi, Petronzio ’79], [Dokshitzer, Diakonov, Troian ’80], [Curci, Greco, Srivastava ’79], [Bassetto, Ciafaloni, Marchesini ’80], [Kodaira, Trentadue ’82], [Collins, Soper, Sterman ’85]

★ newer formulations and advancement up to NNLL
[Catani, de Florian, Grazzini ’01], [Bozzi, Catani, de Florian, Grazzini ’06 ’07]

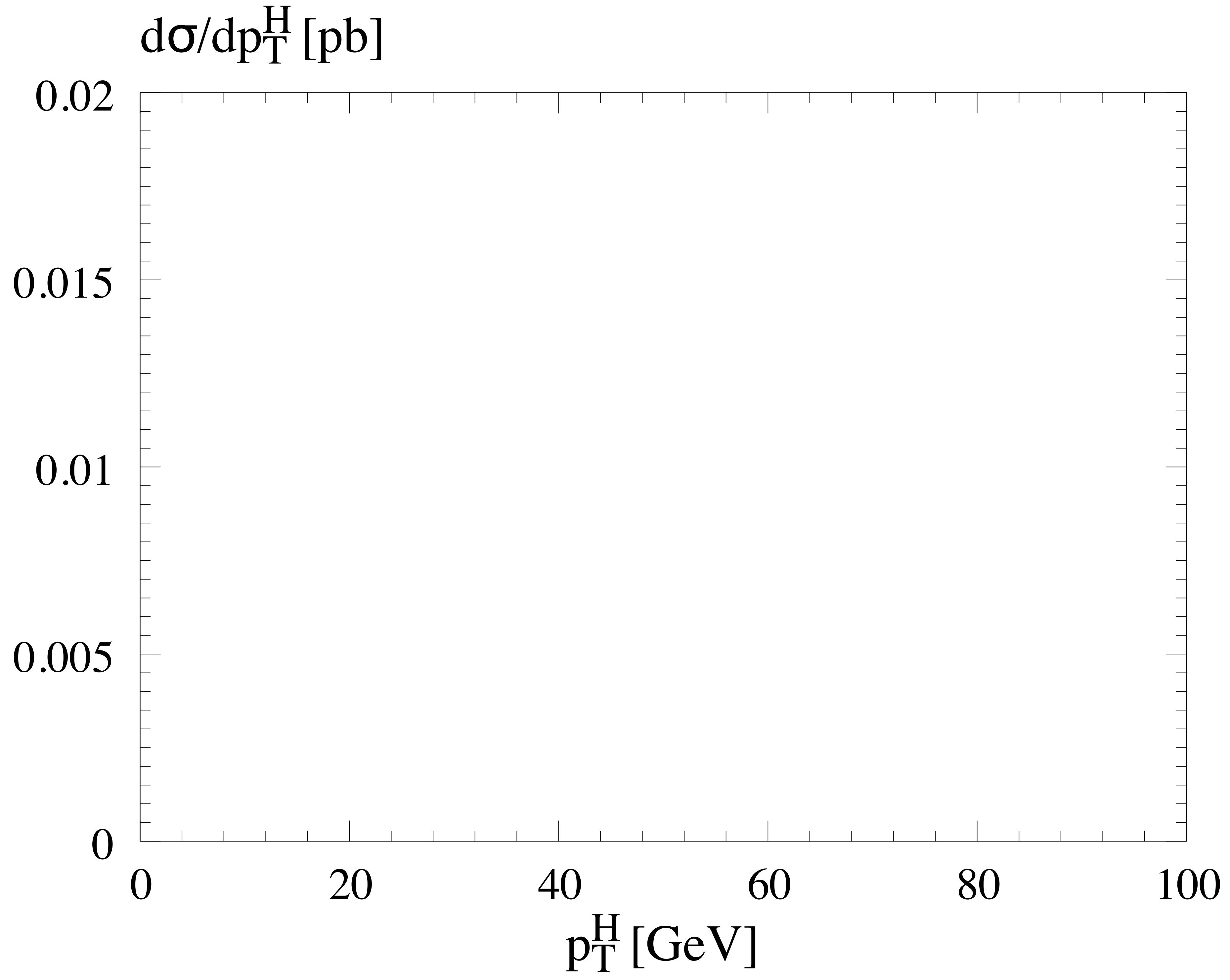
★ recent reformulation in direct space, conserving momentum & keeping relevant subleading terms in p_T [Monni, Re, Torrielli '16], [Ebert, Tackmann '17]

★ Current state-of-the-art: N3LL & partial N4LL
[Matrix+RadISH: Kallweit, Re, Rottoli, MW; CuTe+MCFM: Becher, Campbell, Neumann, et al.; RadISH: Monni, Re, Rottoli, Torrielli; NangaParbat: Bacchetta, Bertone, Bozzi, et al.; Artemide: Scimemi, Vladimirov; DYTurbo: Catani, Grazzini, Ferrera, Cieri, Camarda, et al.; SCETlib: Billis, Ebert, Michel, Tackmann, et al.; reSolve: Coradeschi, Cridge; Resbos: Isaacson, Yuan, et al.;]

(several seminal works in SCET not discussed here)

Matching of resummation & fixed-order

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} =$$



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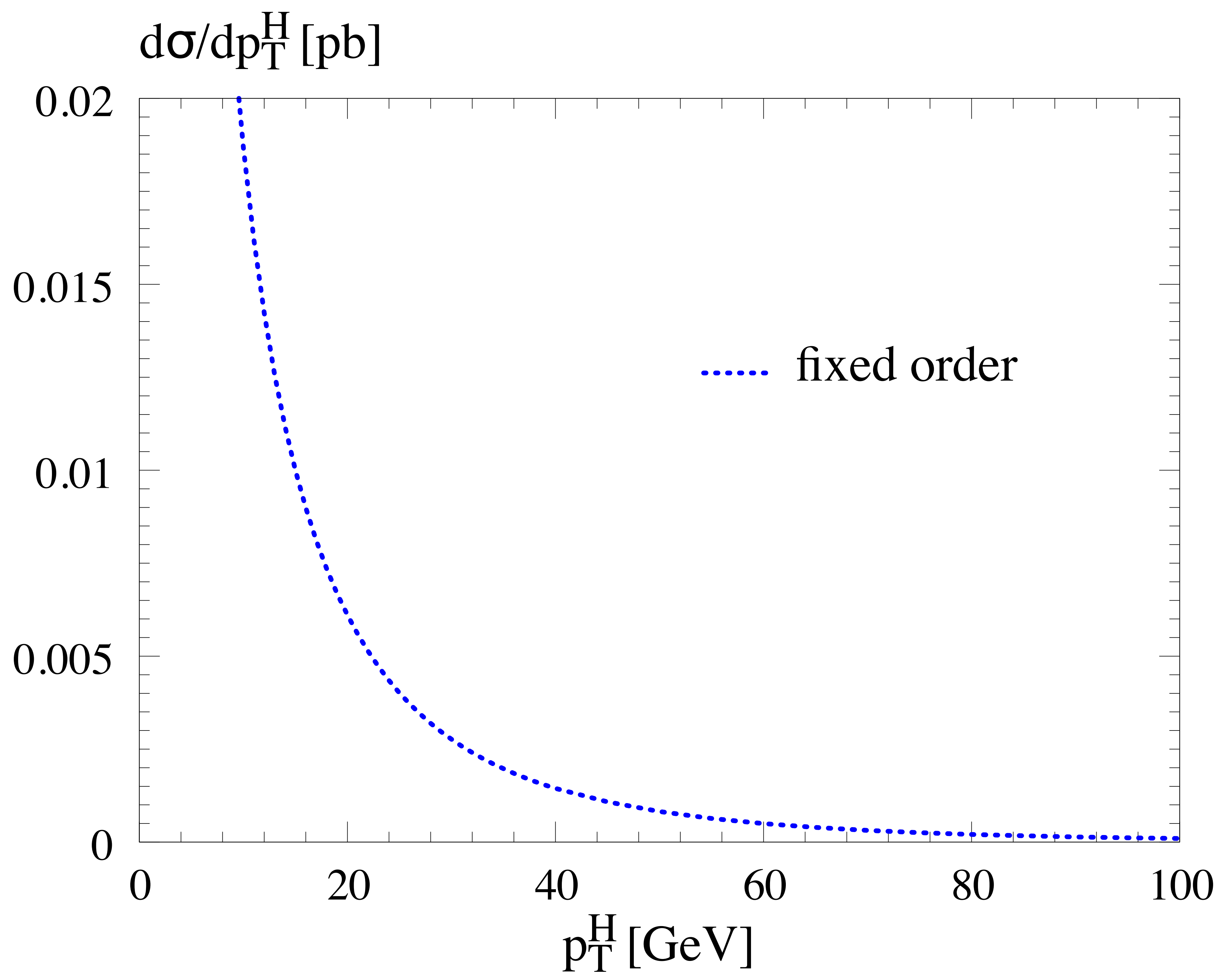

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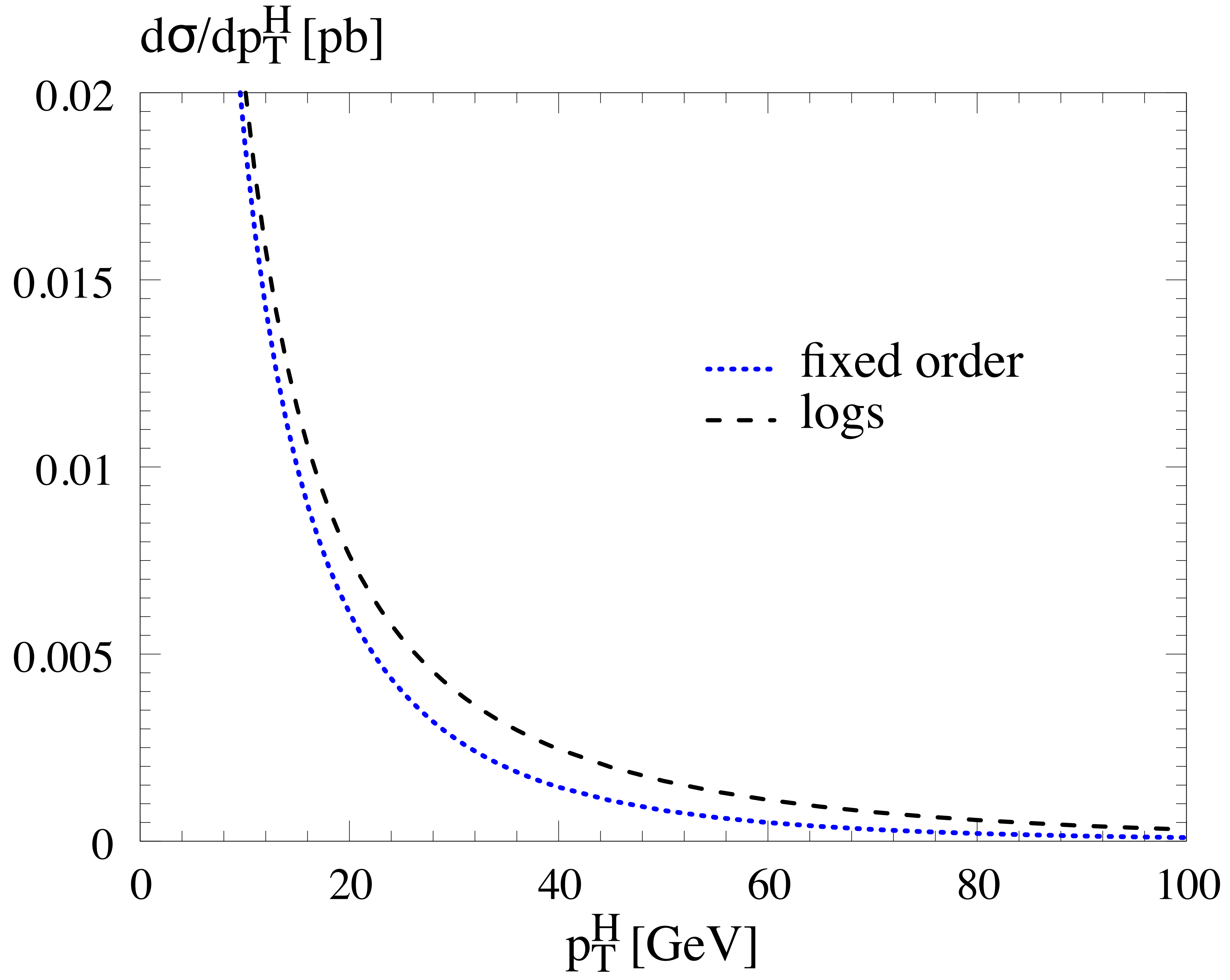

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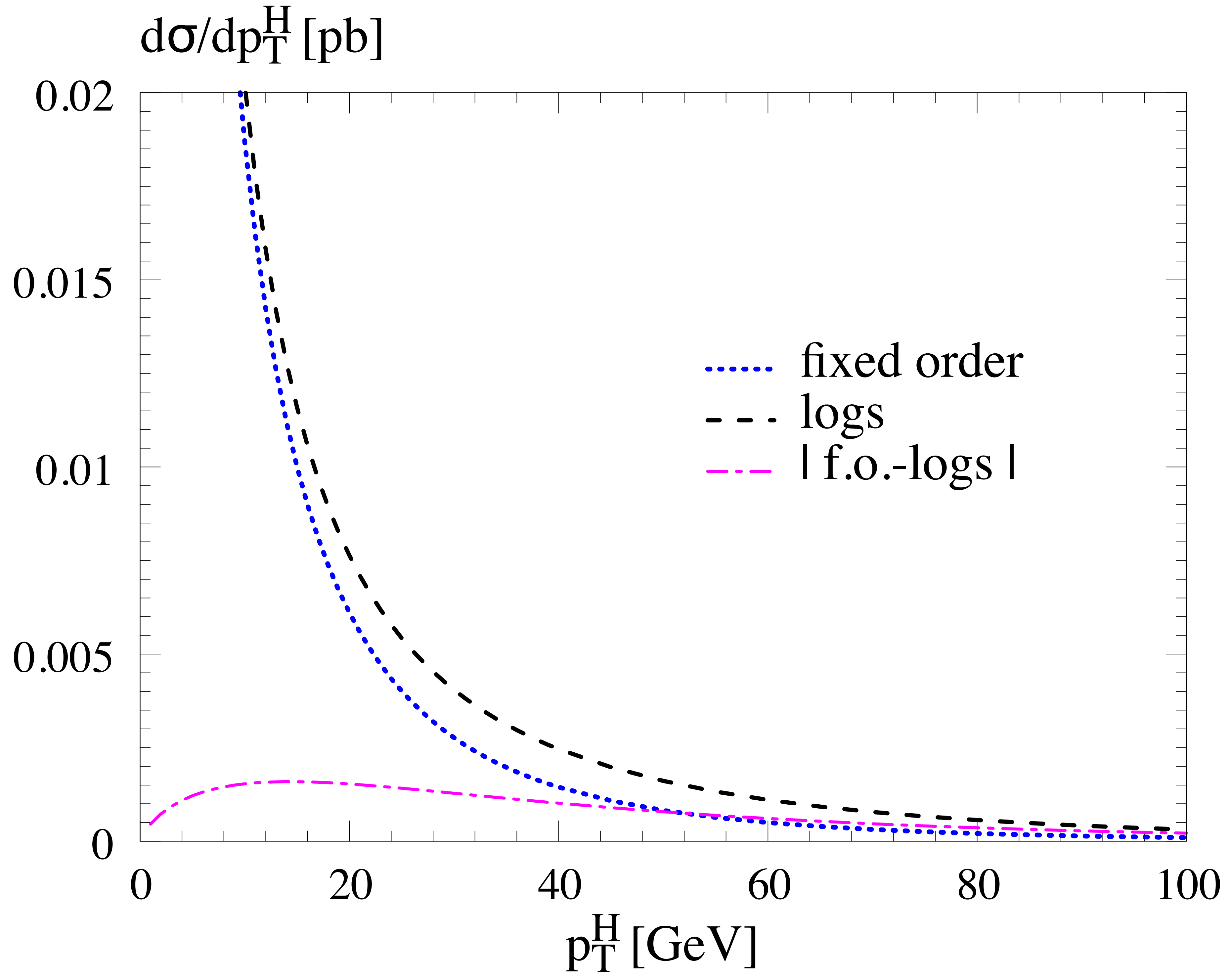
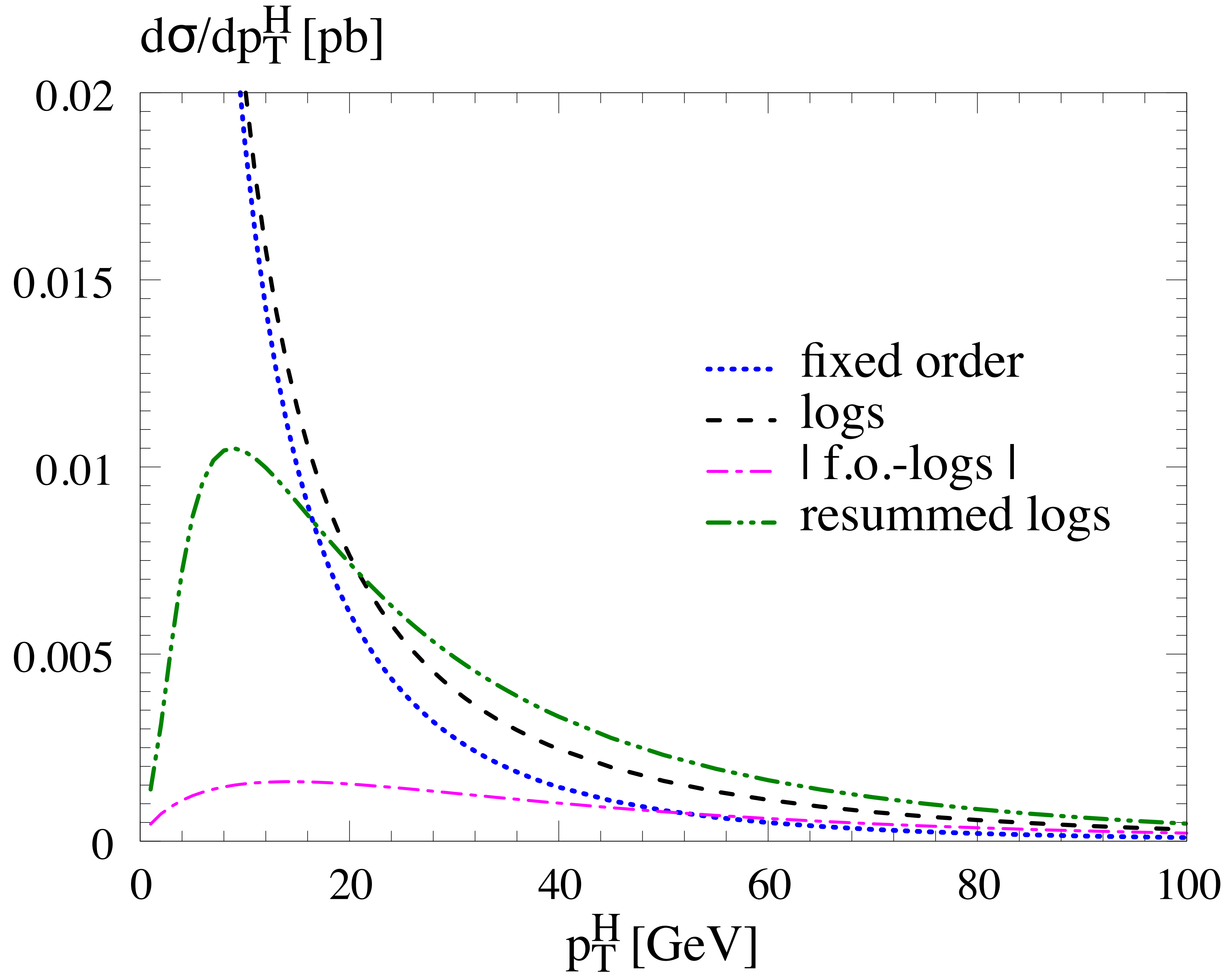


Matching of resummation & fixed-order

$$\left[\frac{d\sigma}{dp_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{d\sigma}{dp_T^2}\right]_{\text{f.o.}} - \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{f.o.}} + \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{l.a.}}$$



Matching of resummation & fixed-order

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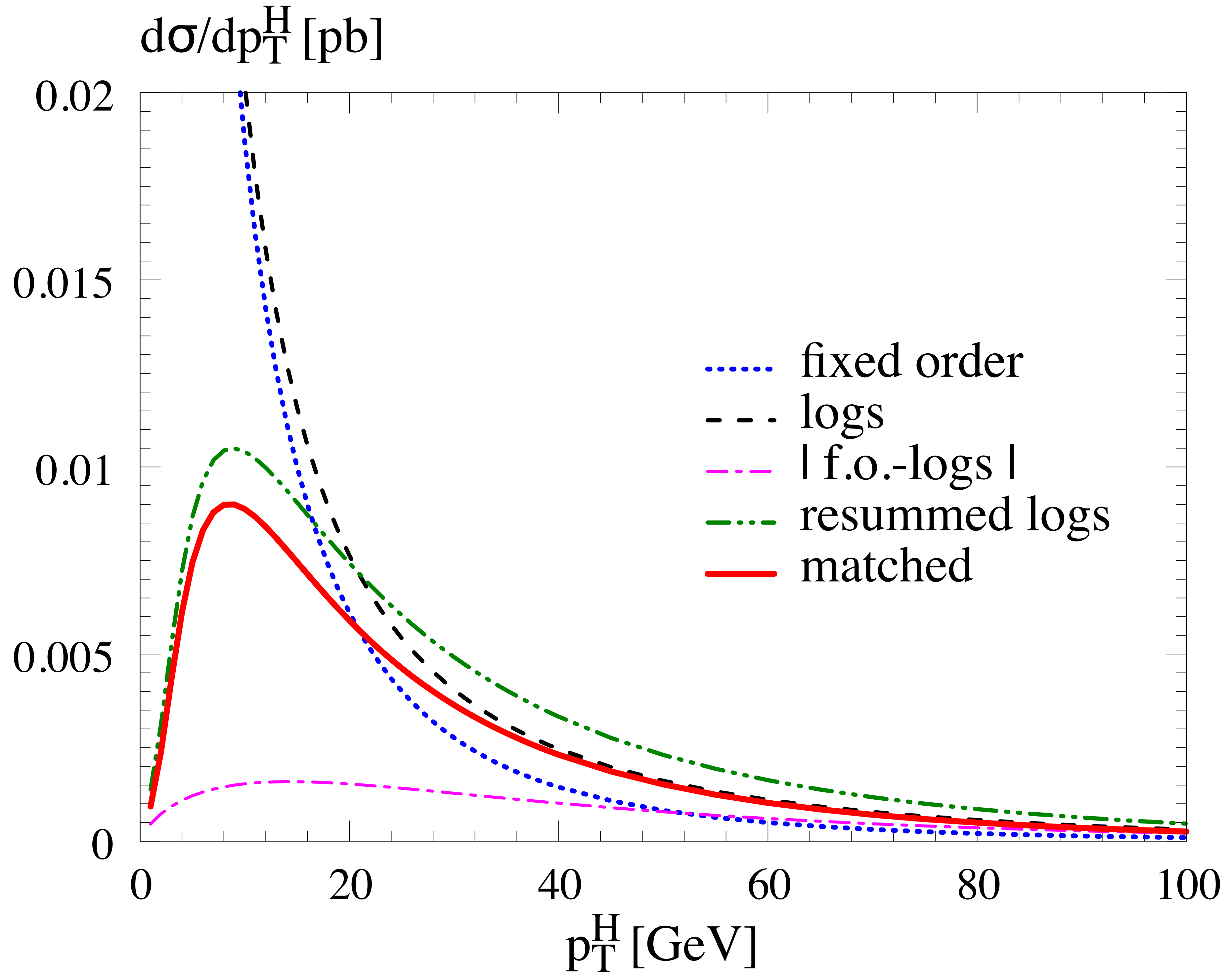
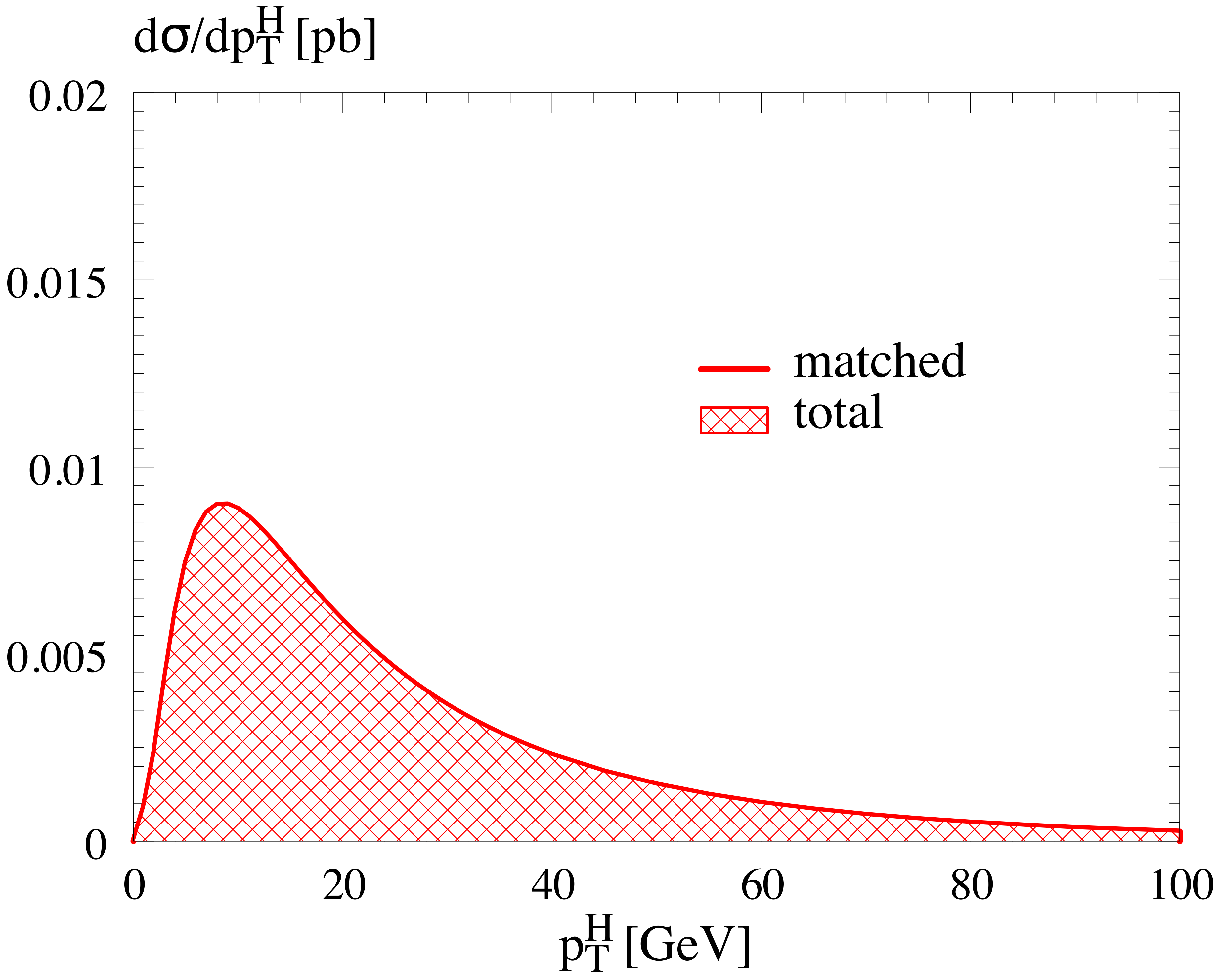


Matching of resummation & fixed-order

$$\int \mathrm{d}p_T^2 \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} \equiv \left[\sigma^{(\text{tot})}\right]_{\text{f.o.}} .$$



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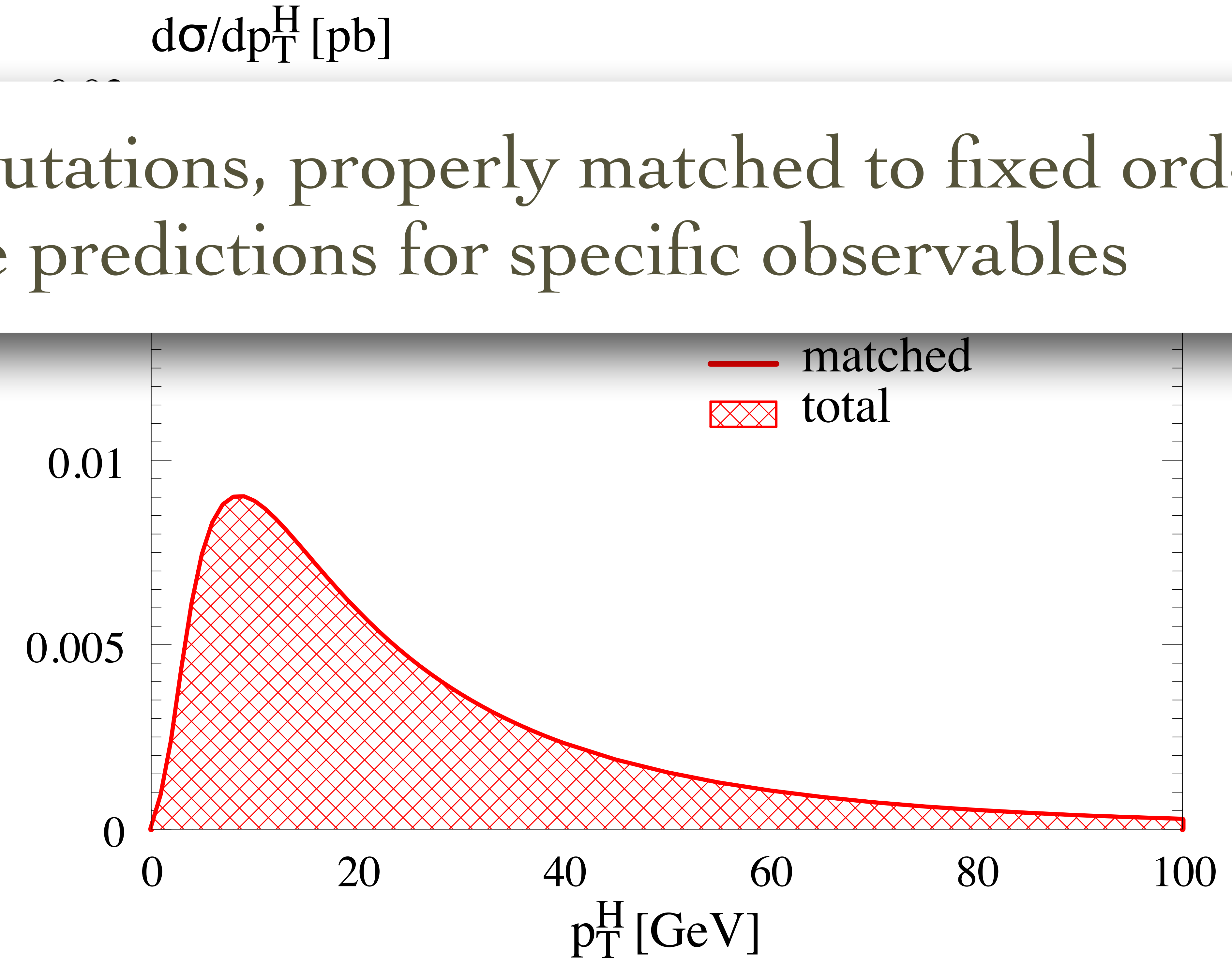
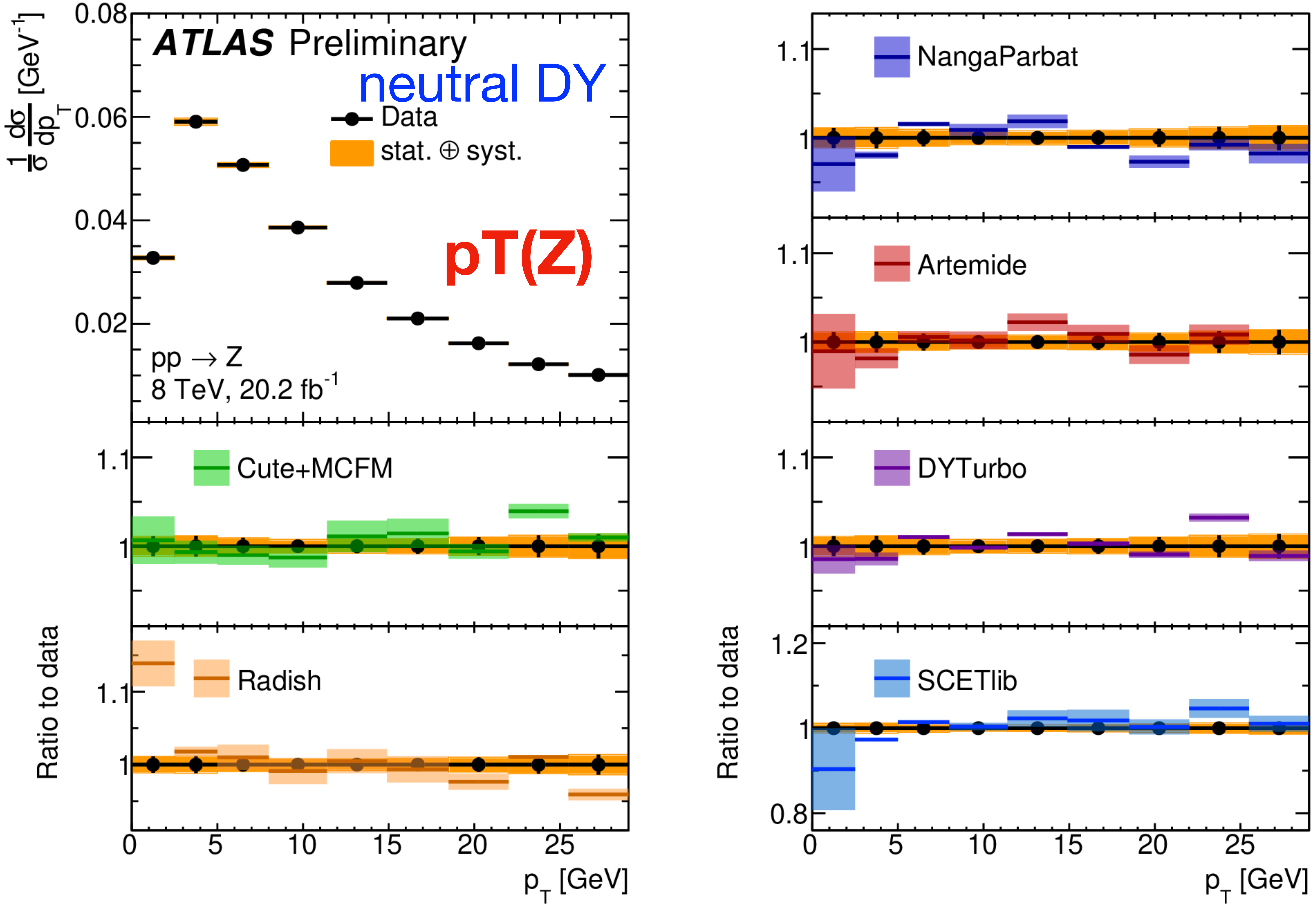


Resummed computations, properly matched to fixed order, are able to provide the most accurate predictions for specific observables

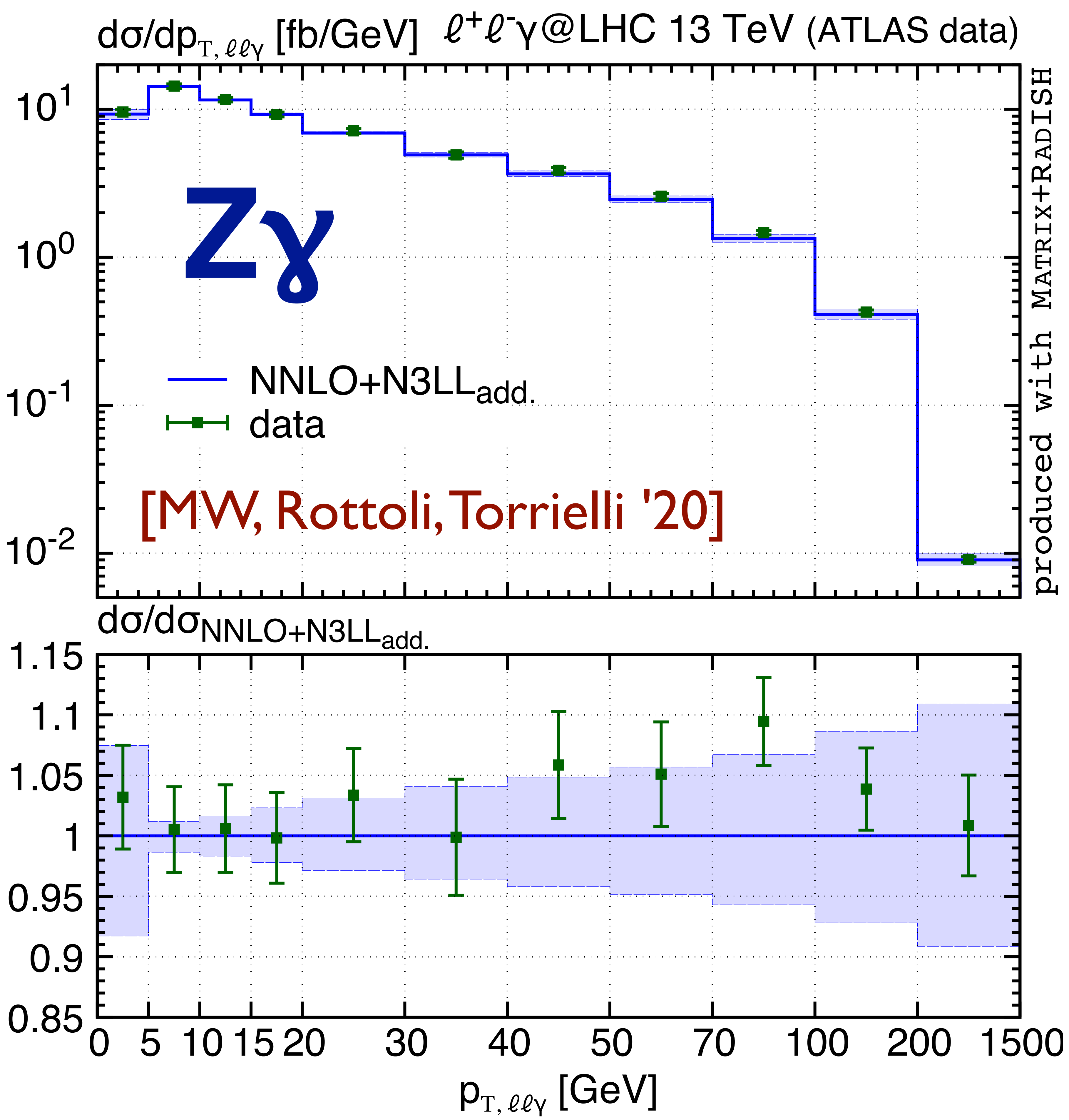
Resummation: Example #1

[ATLAS-CONF-2023-013]

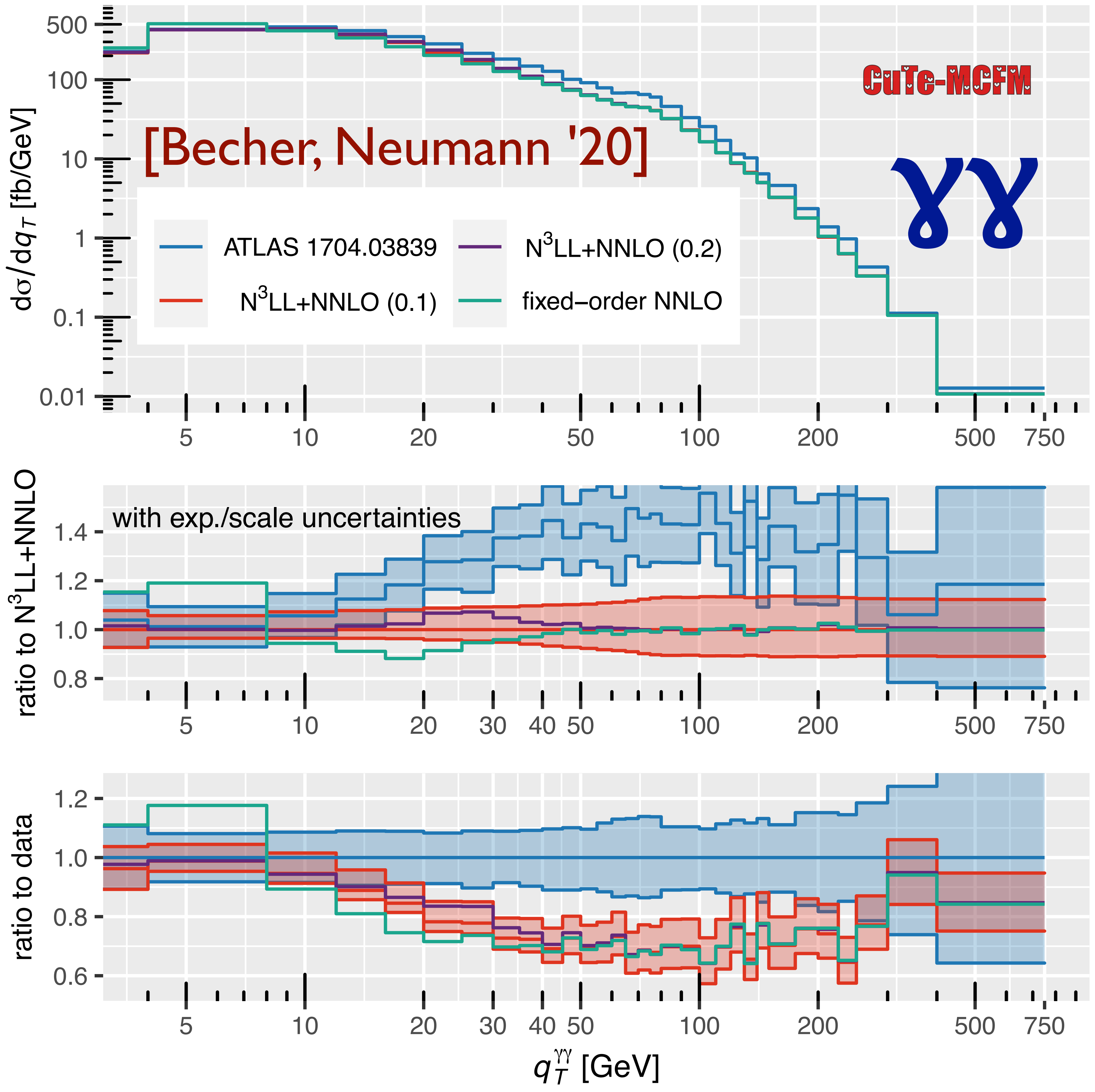


Resummation: Example #2

MATRIX+RADISH

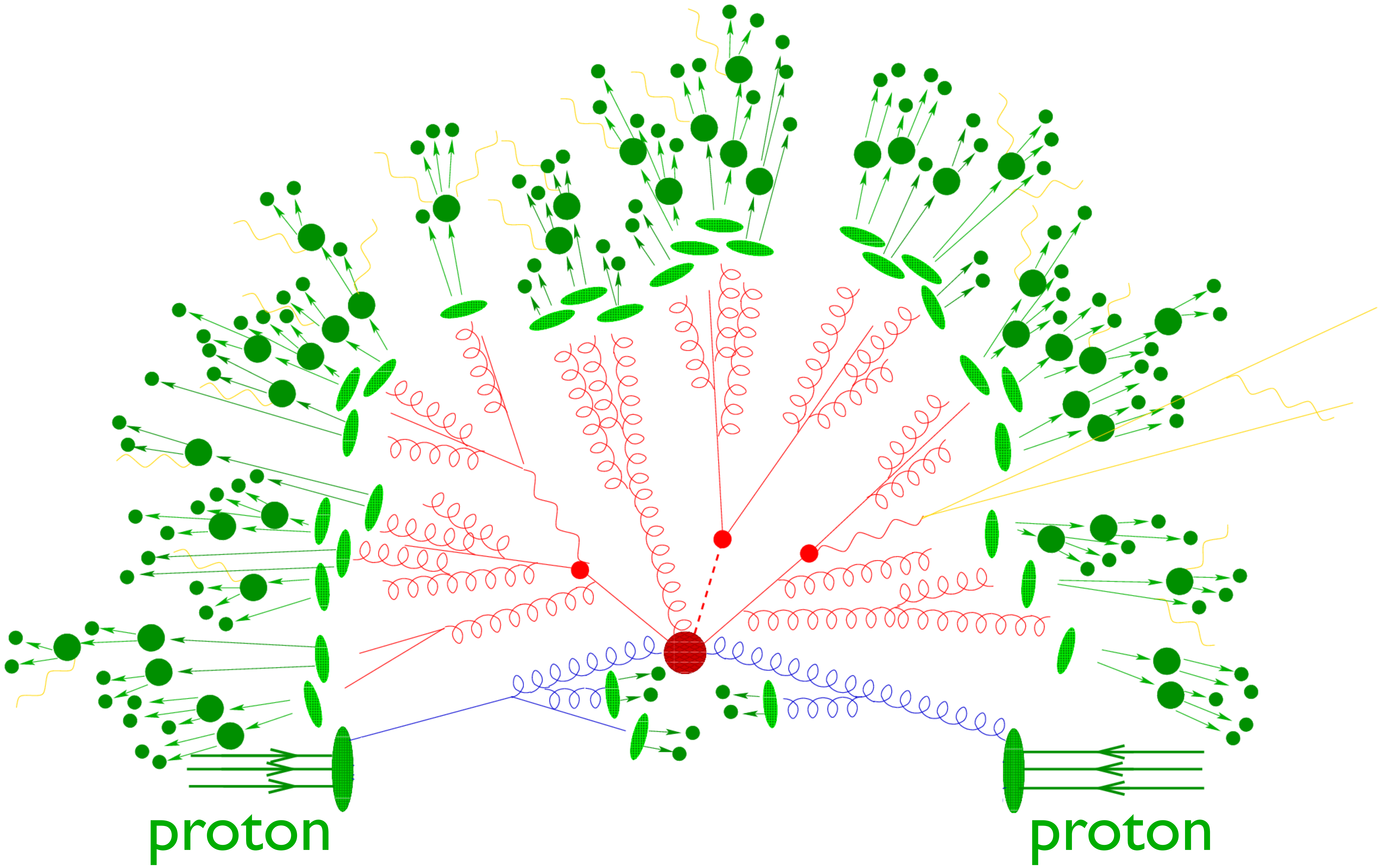


CuTe-MCFM

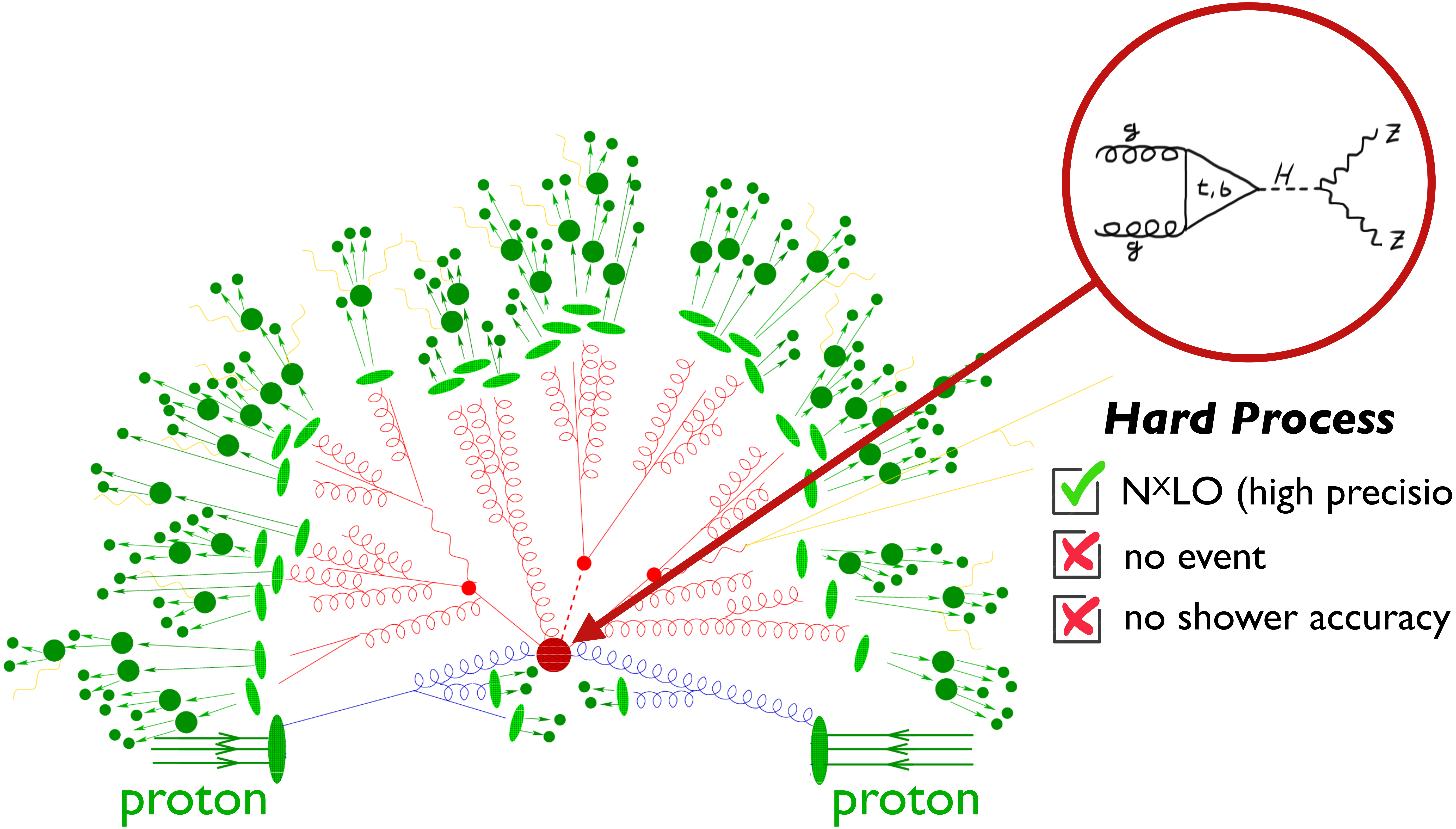


Questions?

LHC event



LHC event



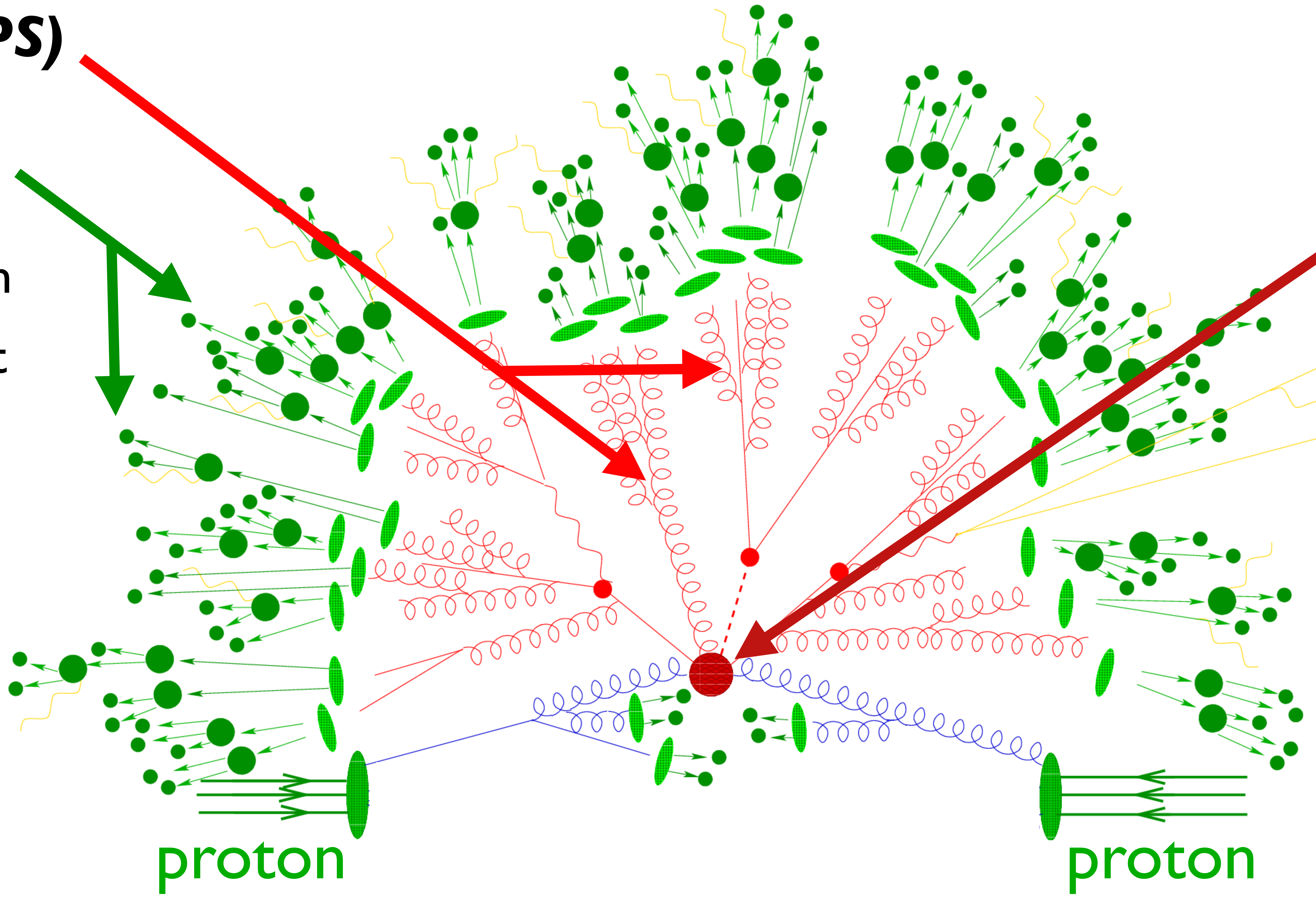
Hard Process

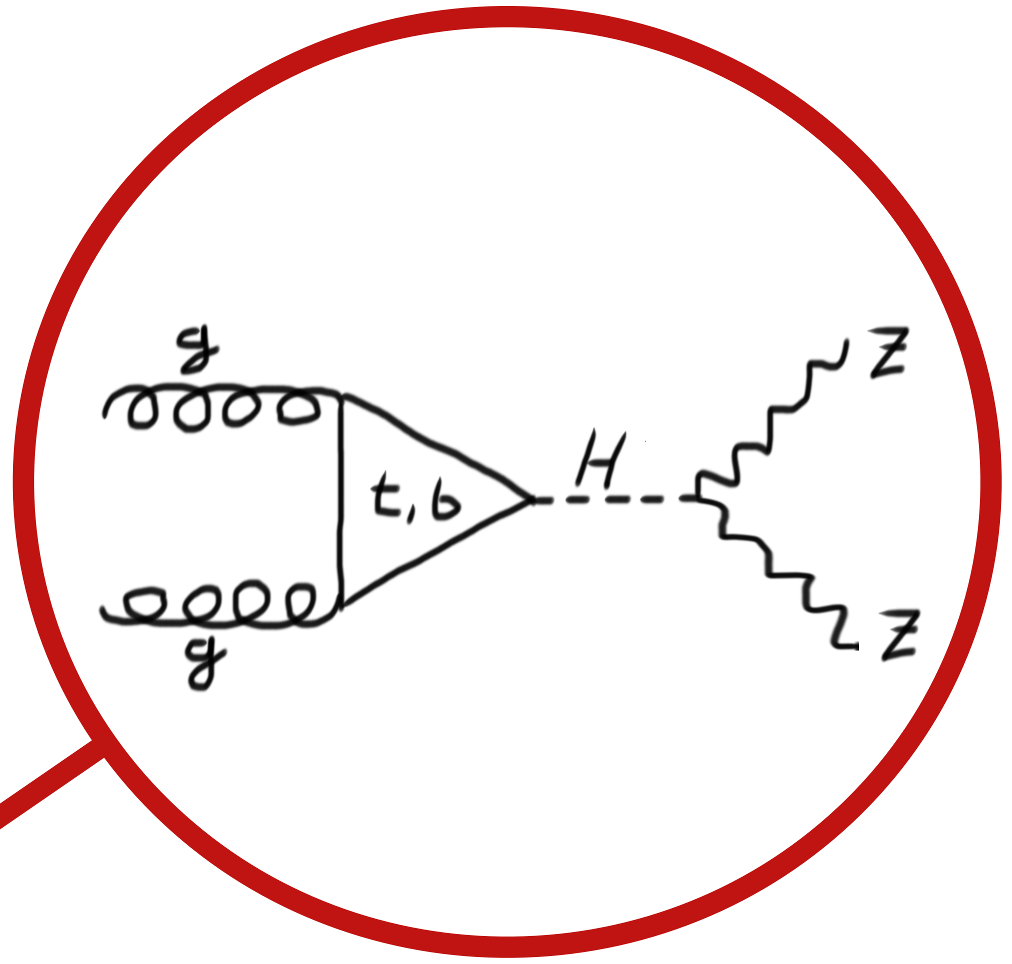
- ✓ N^xLO (high precision)
- ✗ no event
- ✗ no shower accuracy

LHC event

Parton Shower (PS)
+
Hadronization

- ☒ no $N^{X}LO$ precision
- ☑ realistic LHC event
- ☑ shower accuracy (low precision)

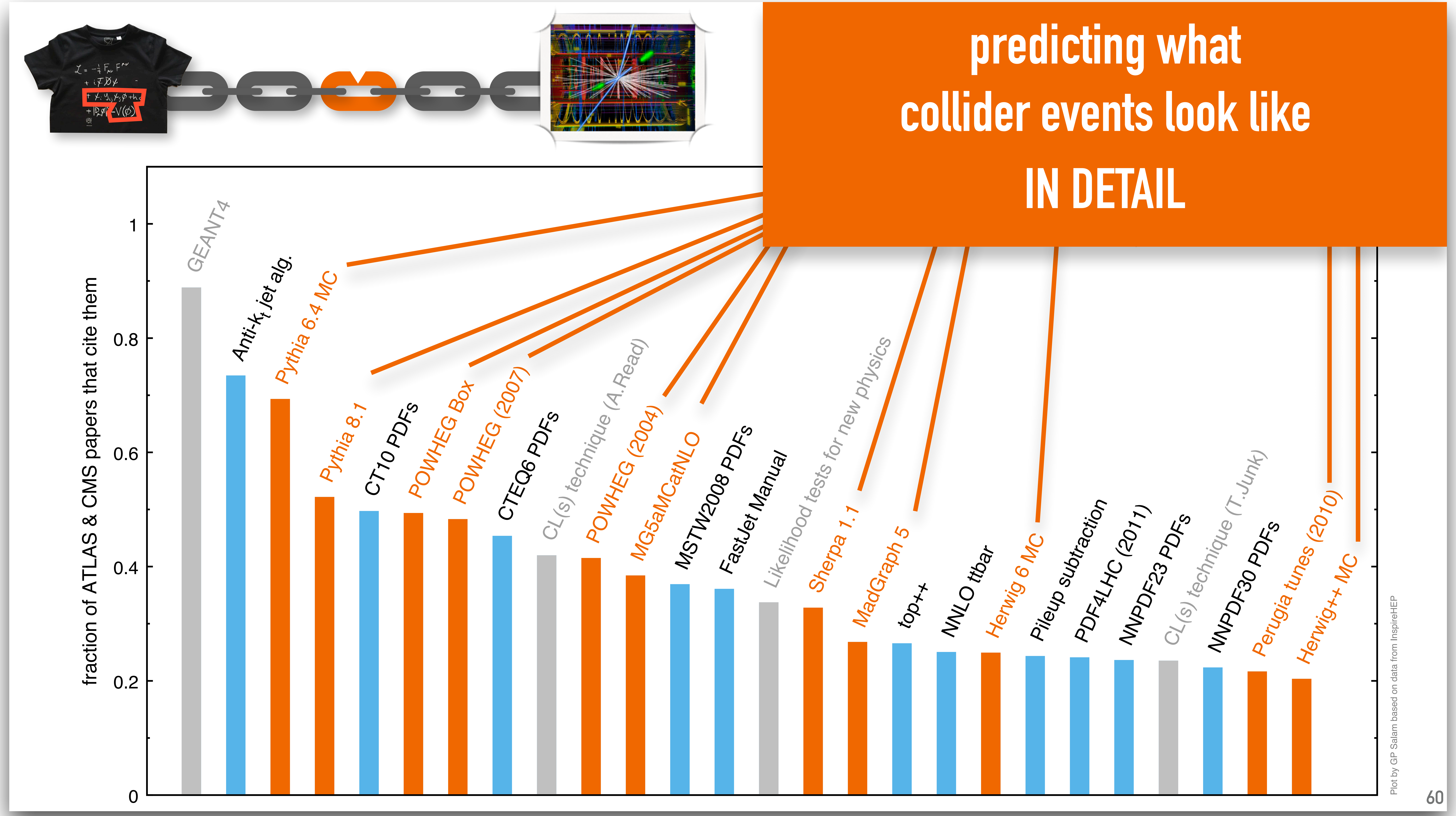




Hard Process

- ☑ $N^{X}LO$ (high precision)
- ☒ no event
- ☒ no shower accuracy

Parton Shower Event Generators

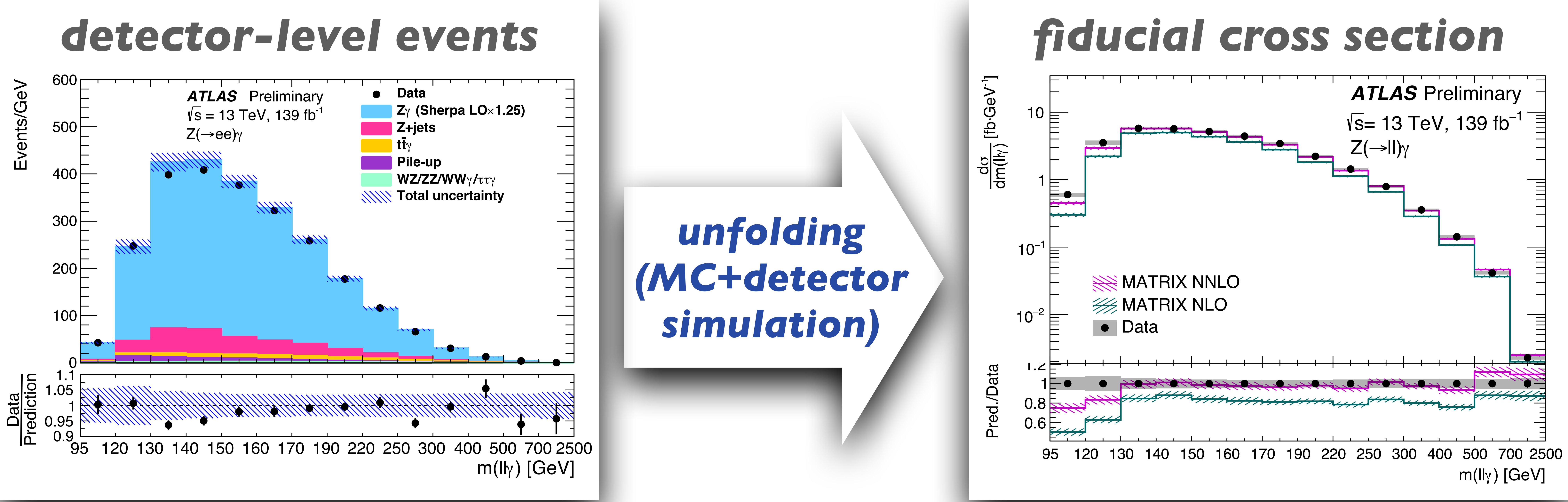


...slide borrowed from Gavin Salam

Parton Shower Event Generators

★ Parton shower event generators build the foundation of theoretical tools in experimental analyses to connect measurements & predictions

★ Used to unfold from detector-level events to fiducial cross sections.



Parton Shower Event Generators

★ Parton shower event generators build the foundation of theoretical tools in experimental analyses to connect measurements & predictions

★ Used to unfold from detector-level events to fiducial cross sections.

★ Parton showers build the core of the event simulation, combined with hadronization and multi-parton-interaction (MPI) models.

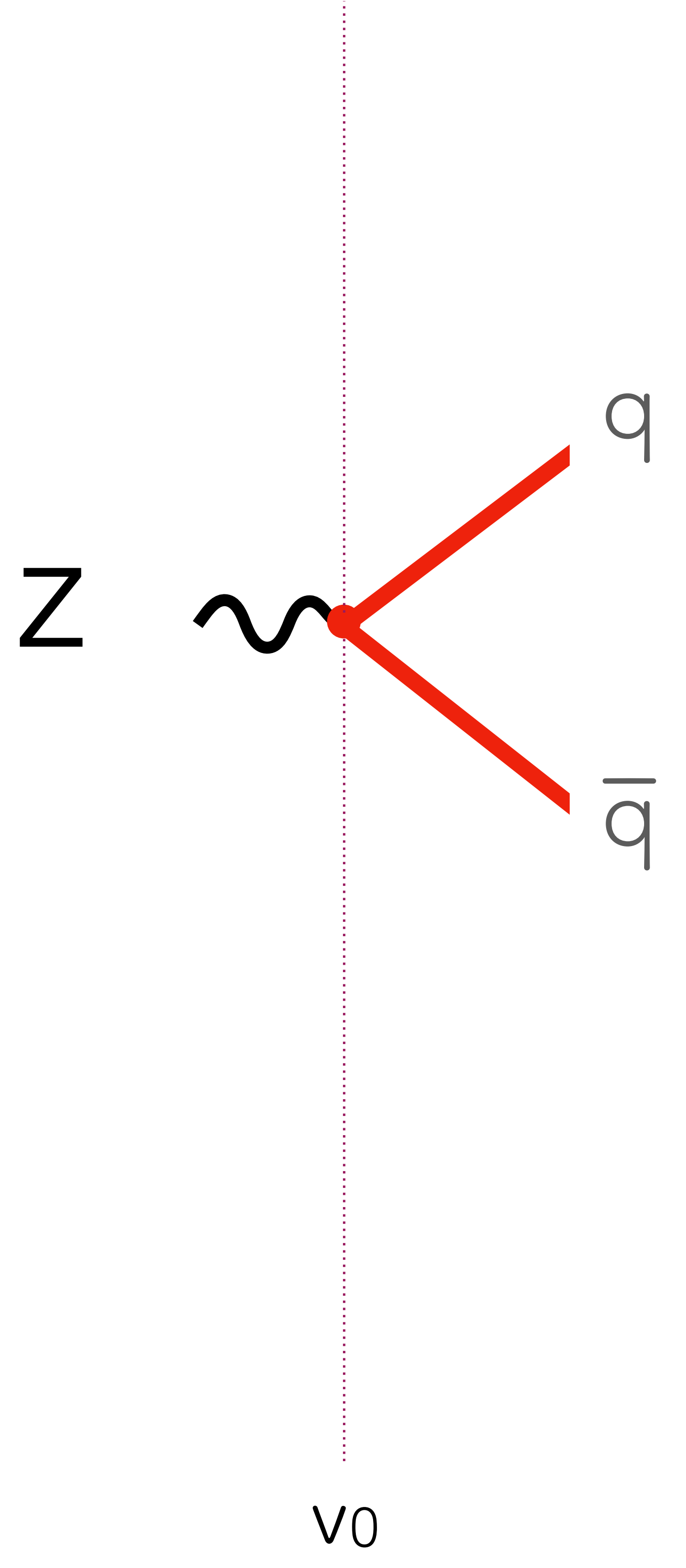
★ Parton showers provide the most flexible predictions, applicable, in principle, simultaneously to all IR-safe observables. However, unlike observable-specific resummation approaches they are limited to a lower logarithmic accuacy (so far)

★ new approaches evolving to improve logarithmic accuracy of parton showers: [Forshaw, Holguin, Plätzer '20] [Nagy, Soper '19] [Dasgupta, et al. '20; Hamilton, et al. '20; Karlberg, et al. '21, …], [Höche et al. '22 '24]

Parton Showers in a nutshell

Dipole showers [Gustafson, Pettersson, '88] are the most used shower paradigm

Start with $q\bar{q}$ state produced at a **hard scale** v_0.
(typically the invariant mass $v_0 \sim Q_{q\bar{q}}$)



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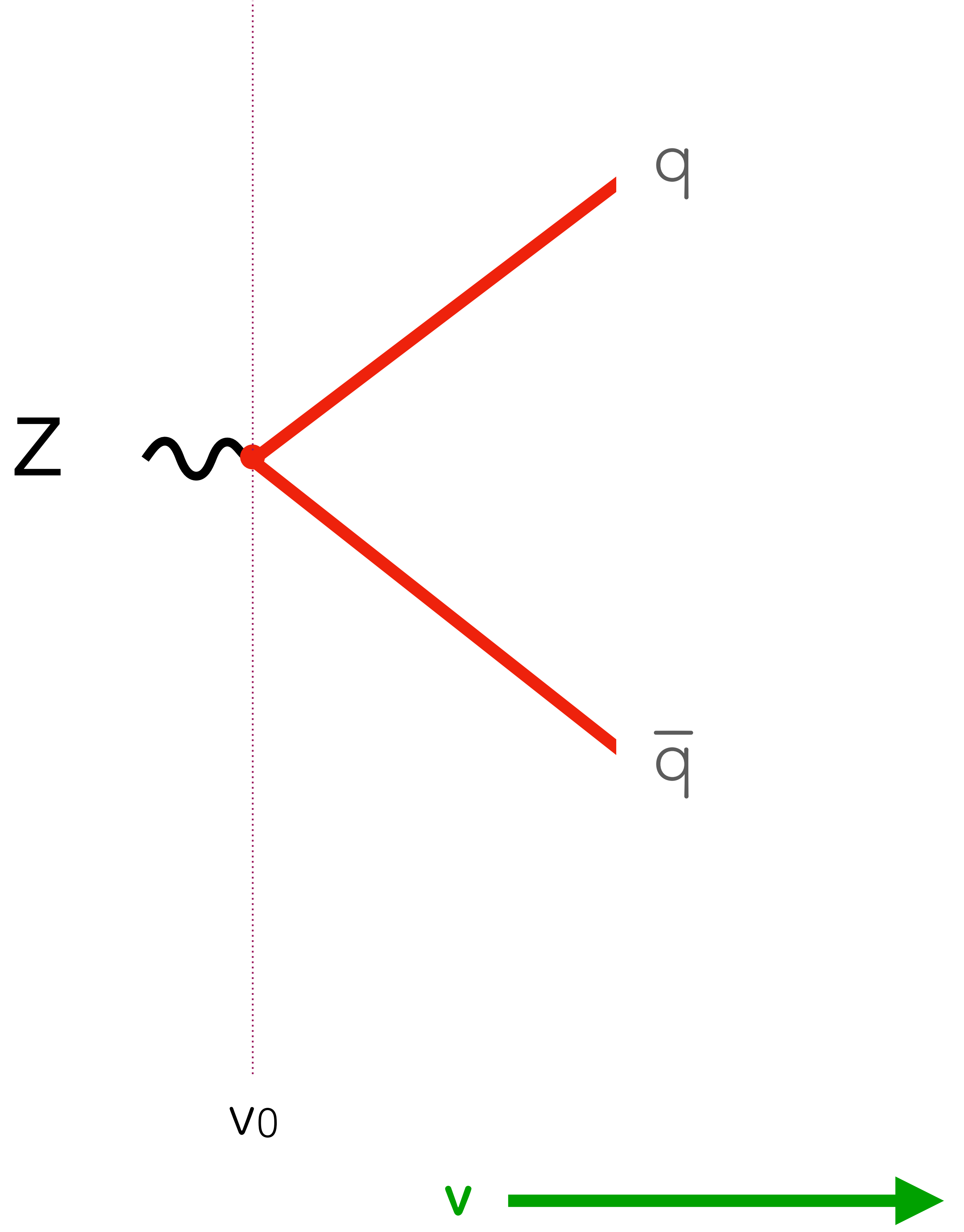

Start with $q\bar{q}$ state produced at a hard scale v_0.

Throw a random number to determine down to what scale state persists unchanged

$$\Delta(v_0, v) = \exp\left(-\int_v^{v_0} dP_{q\bar{q}}(\Phi)\right)$$

no-emission probability between the v_0 and v

Solve for scale v_1: $\Delta(v_0, v_1) \equiv n_{\mathrm{random}}$

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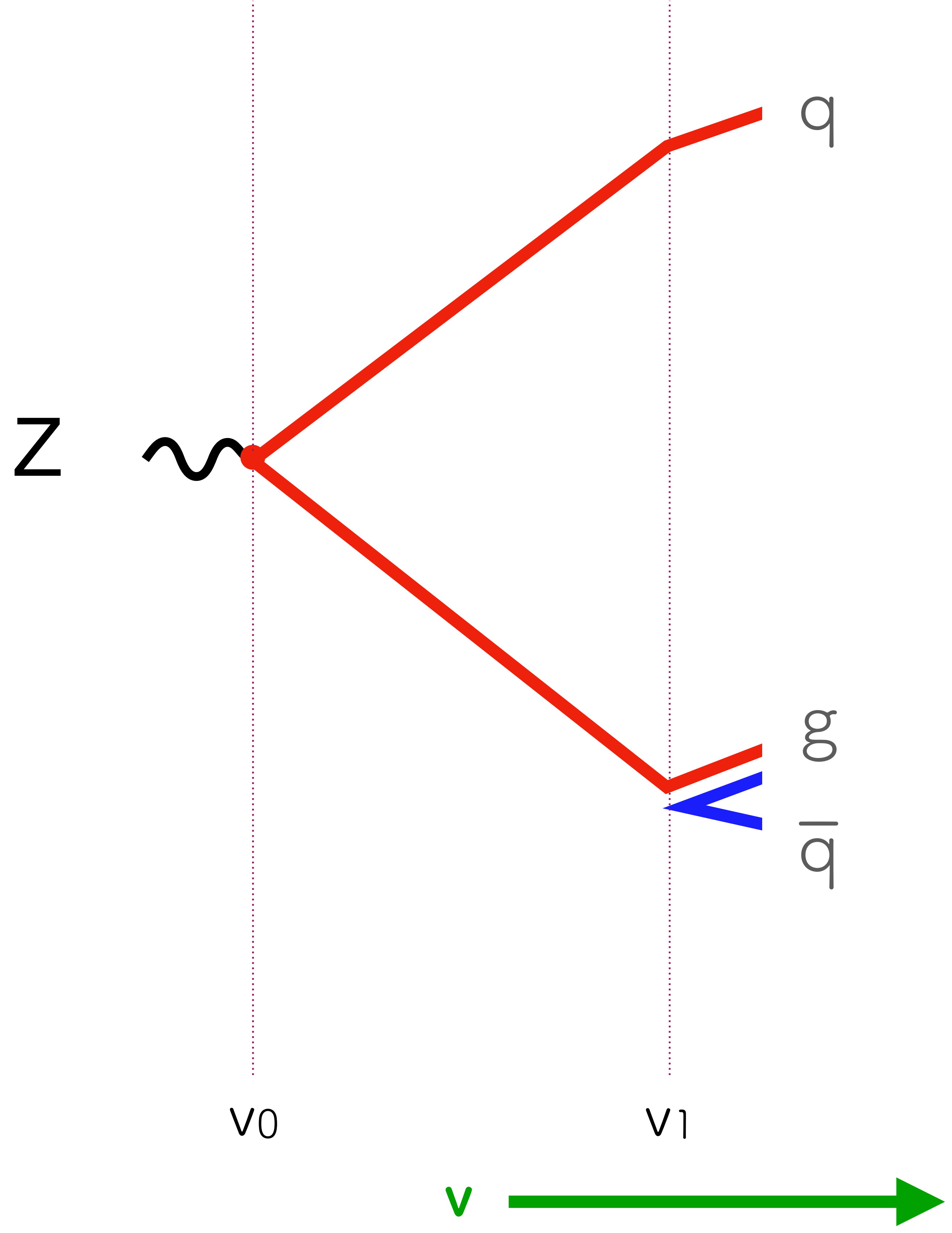
Parton Showers in a nutshell

Dipole showers [Gustafson, Pettersson, '88] are the most used shower paradigm



Start with $q\bar{q}$ state produced at a **hard scale** v_0.

Throw a random number to determine down to what **scale** state persists unchanged

At some point, **state splits** (2→3, i.e. emits gluon) at a scale $v_1 < v_0$. The kinematic (rapidity and azimuth) of the gluon is chosen according to

$$dP_{q\bar{q}}(\Phi(v_1)) \qquad \Phi = \{v, \eta, \varphi\}$$

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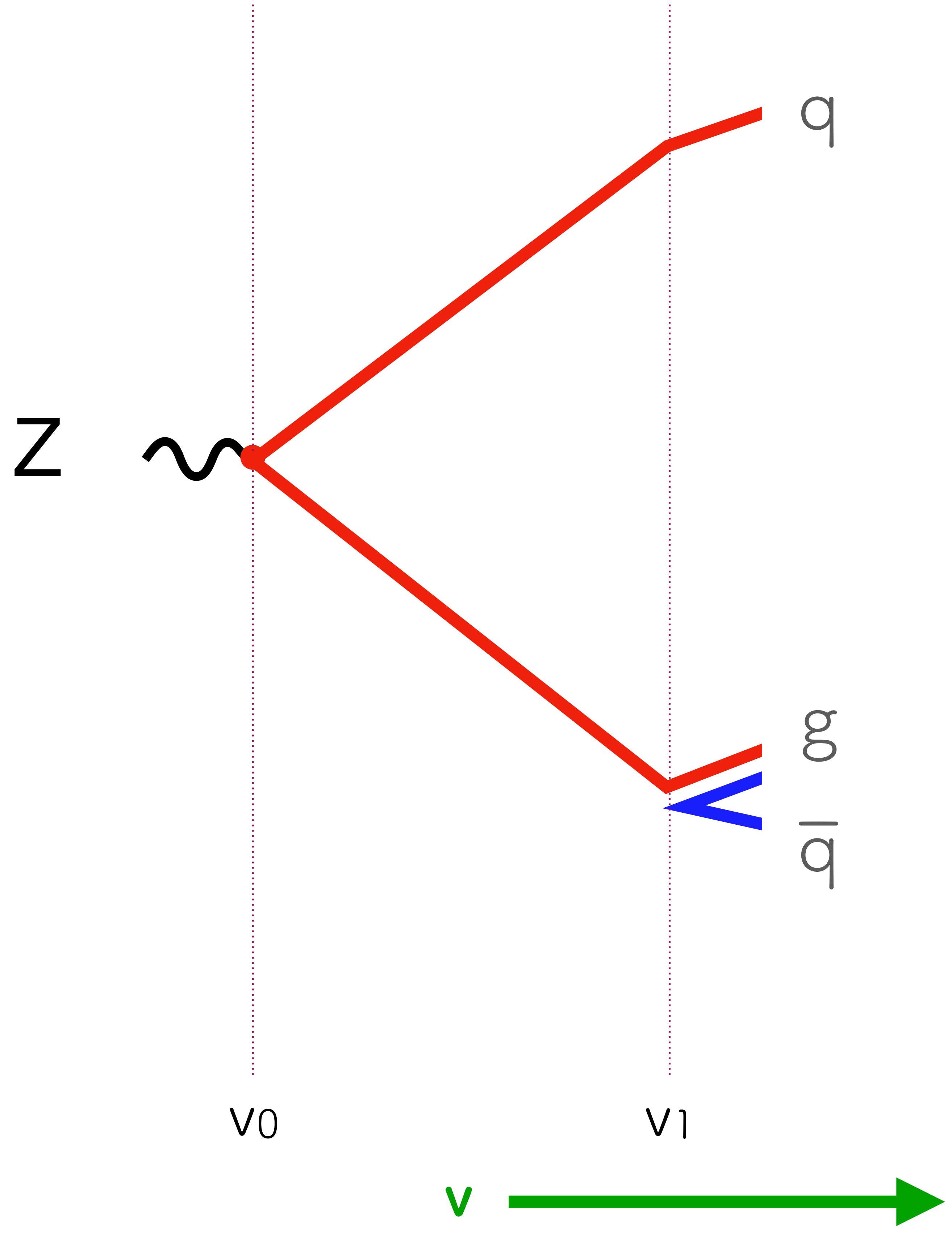
Parton Showers in a nutshell

Dipole showers [Gustafson, Pettersson, ’88] are the most used shower paradigm



Start with $q\bar{q}$ state produced at a hard scale v_0.

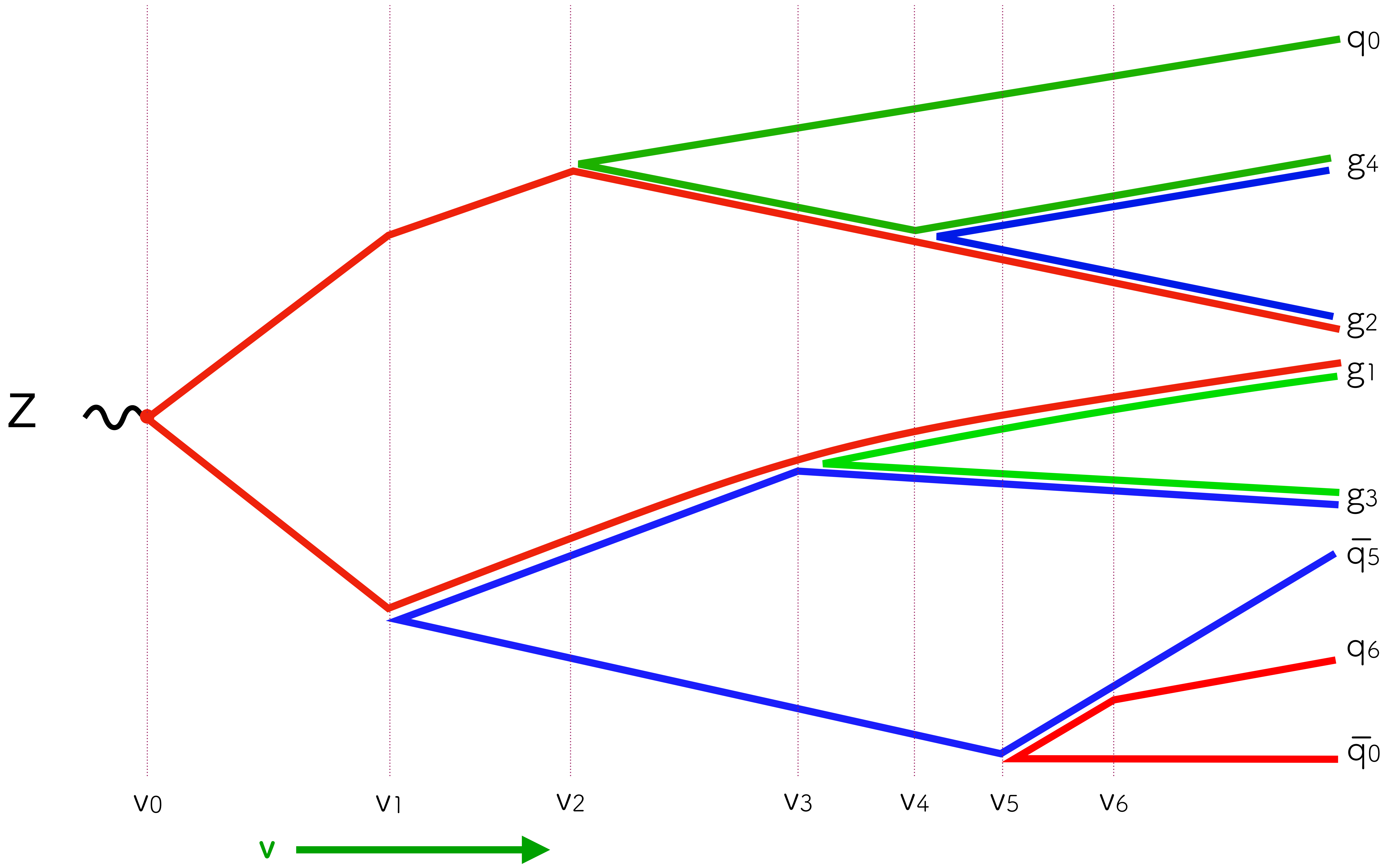
Throw a random number to determine down to what **scale** state persists unchanged

At some point, **state splits** (2→3, i.e. emits gluon) at a scale $v_1 < v_0$.

The gluon is part of two dipoles (qg), $(g\bar{q})$.

Iterate the above procedure for both dipoles independently, using v_1 as starting scale.

Parton Showers in a nutshell



self-similar evolution continues until it reaches a non-perturbative scale

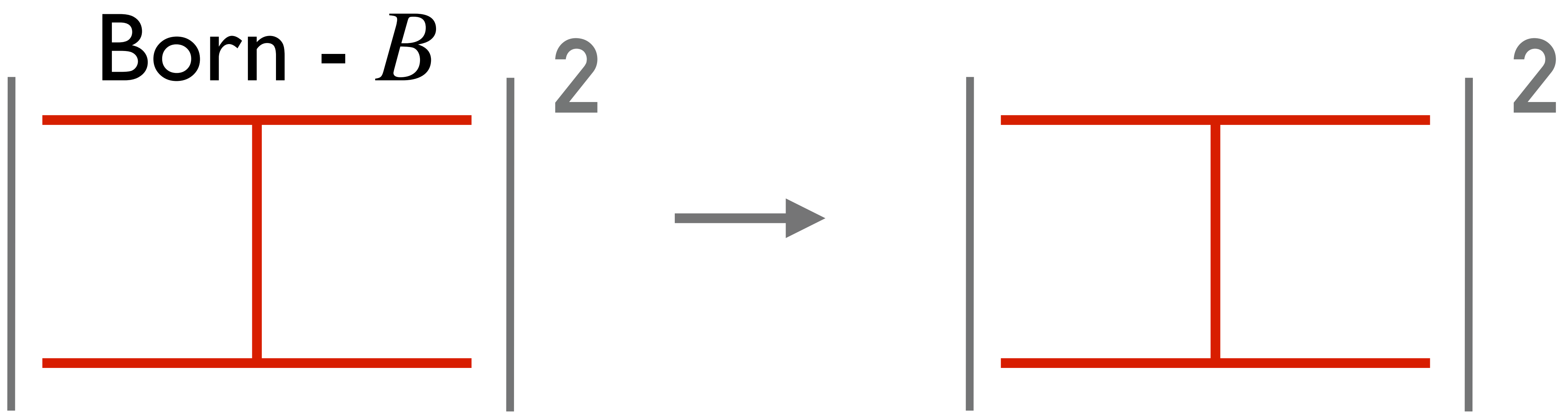
Parton Shower

$$\mathrm{d}\sigma_{\mathrm{PS}} = \mathrm{d}\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + \mathrm{d}\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}$$

Parton Shower

$$d\sigma_{\mathrm{PS}} = d\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + d\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}$$

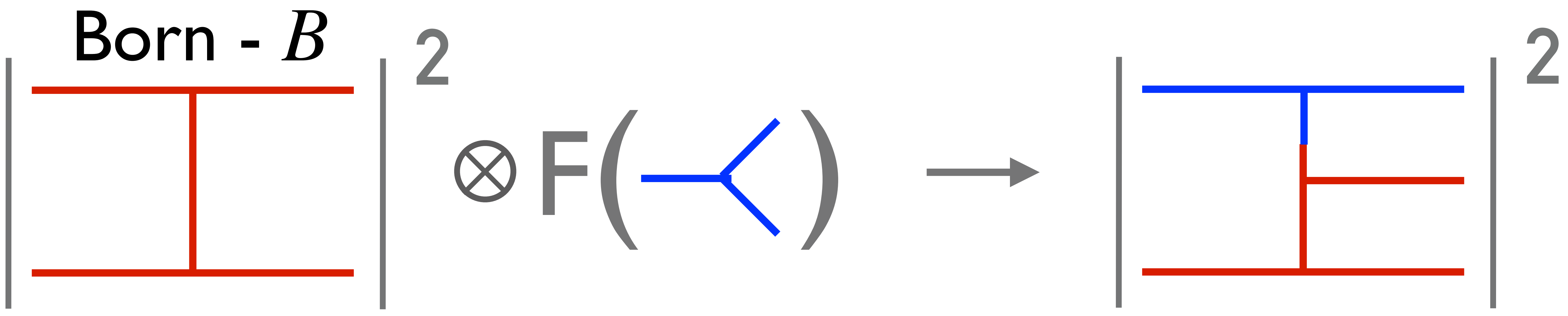
no-emission



Parton Shower

$$d\sigma_{\rm PS} = d\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + d\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}$$

no-emission first emission

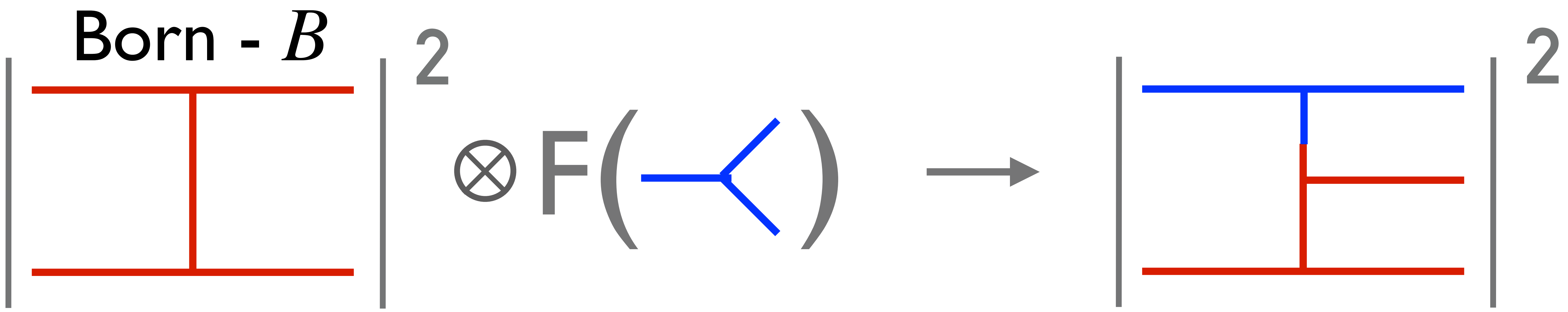


Parton Shower

$$d\sigma_{\mathrm{PS}} = d\Phi_B\, B \times \underbrace{\left\{ \Delta(\nu_0, \Lambda) + d\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}}$$

integrates to unity ➙ "unitarity" of parton shower

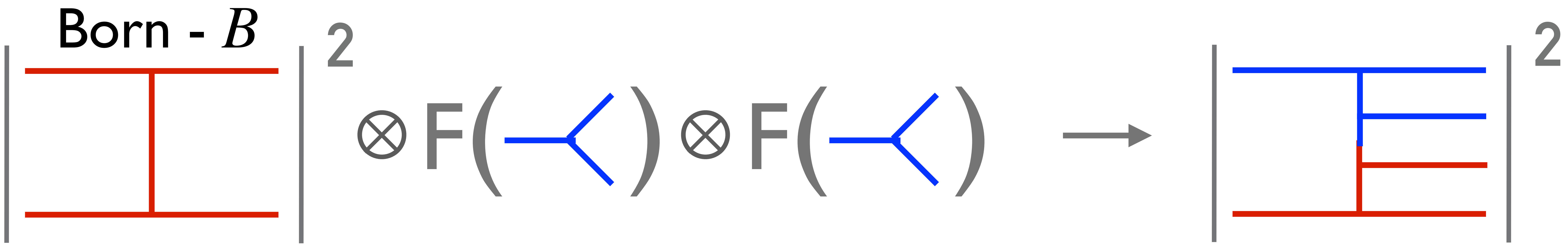
(parton shower affects kinematics, not inclusive cross section)



Parton Shower

$$d\sigma_{\text{PS}} = d\Phi_B B \times \left\{ \Delta(\nu_0, \Lambda) + d\Phi_1 \Delta(\nu_0, \nu_1) \mathscr{P}(d\Phi_1) \right\}$$

$$d\sigma_{\text{PS}} = d\Phi_B B \times \left\{ \Delta(\nu_0, \Lambda) + d\Phi_1 \Delta(\nu_0, \nu_1) \mathscr{P}(d\Phi_1) \times \left\{ \Delta(\nu_1, \Lambda) + d\Phi_2 \Delta(\nu_1, \nu_2) \mathscr{P}(d\Phi_2) \right\} \right\}$$

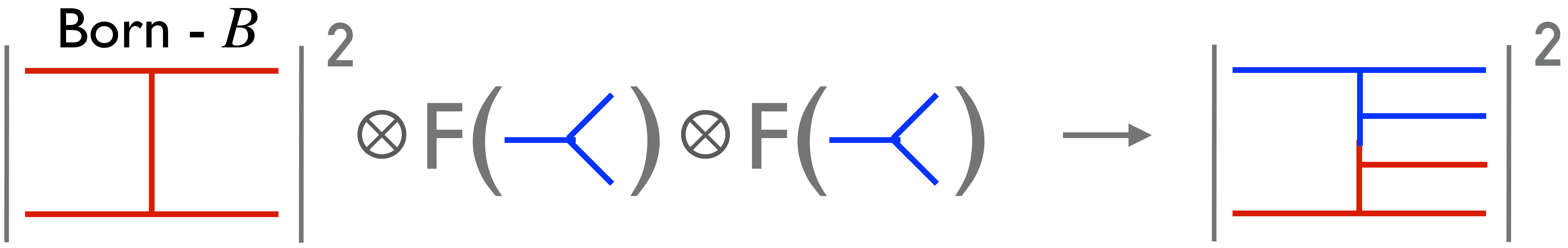


Parton Shower

$$d\sigma_{PS} = d\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + d\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}$$

$$d\sigma_{PS} = d\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + d\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \times \left\{ \Delta(\nu_1, \Lambda) + d\Phi_2 \Delta(\nu_1, \nu_2)\, \mathscr{P}(d\Phi_2) \right\} \right\}$$

no-emission — one emission — second emission



Parton Shower

$$\mathrm{d}\sigma_{\mathrm{PS}} = \mathrm{d}\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + \mathrm{d}\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}$$

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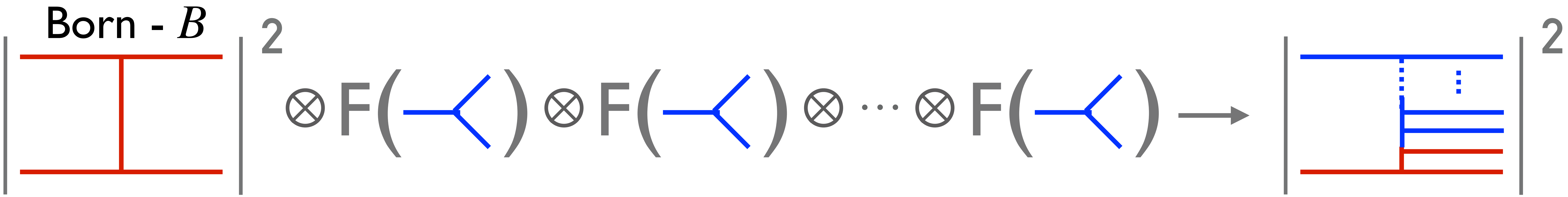
$$\mathrm{d}\sigma_{\mathrm{PS}} = \mathrm{d}\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + \mathrm{d}\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \times \left\{ \Delta(\nu_1, \Lambda) + \mathrm{d}\Phi_2 \Delta(\nu_1, \nu_2)\, \mathscr{P}(d\Phi_2) \times \right.\right.$$
$$\left.\left. \times \left\{ \Delta(\nu_2, \Lambda) + \mathrm{d}\Phi_3 \Delta(\nu_2, \nu_3)\, \mathscr{P}(d\Phi_3) \right\} \right\} \right\}$$

$\vdots$

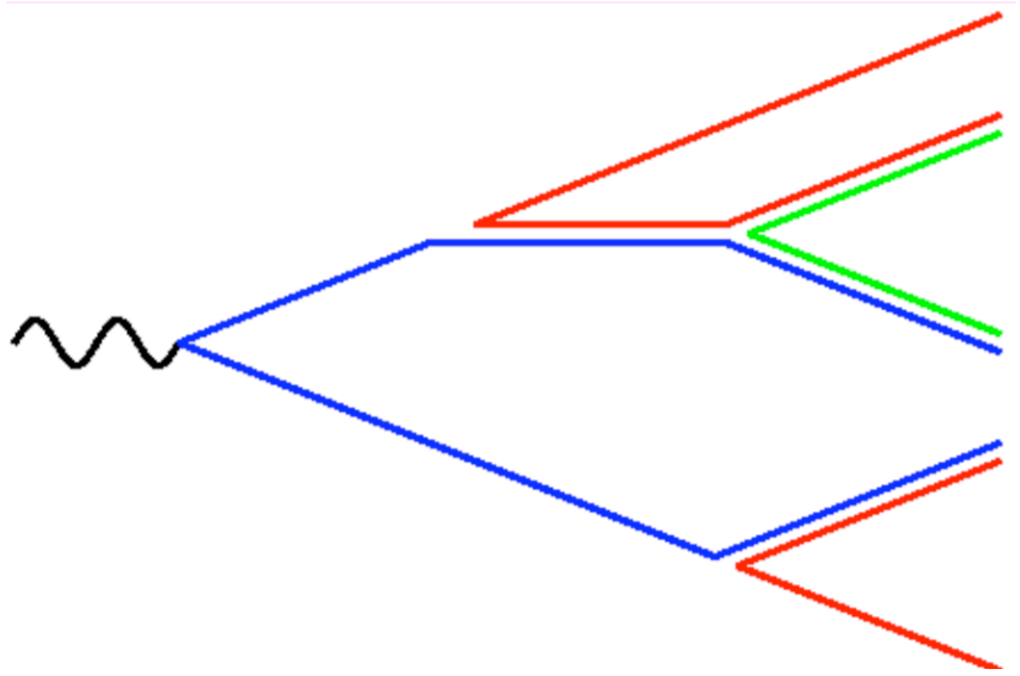


Hadronization & underlying event

★ besides perturbative showering procedure, event generators include non-perturbative models to simulate hadronization & underlying event/multi-parton interactions (MPI)

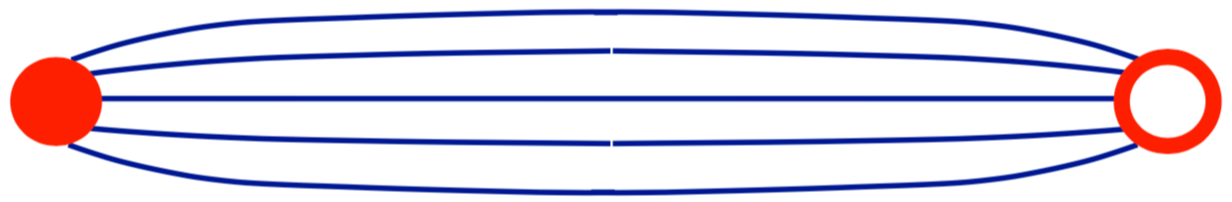
hadronization

- parton shower stops at a cutoff $\Lambda_{\text{QCD}} \sim 0.2\,\text{GeV}$ and hadronization starts
- preconfinement: colour naturally arranged ➙ colour singlets close



- phenomenological models:

string model

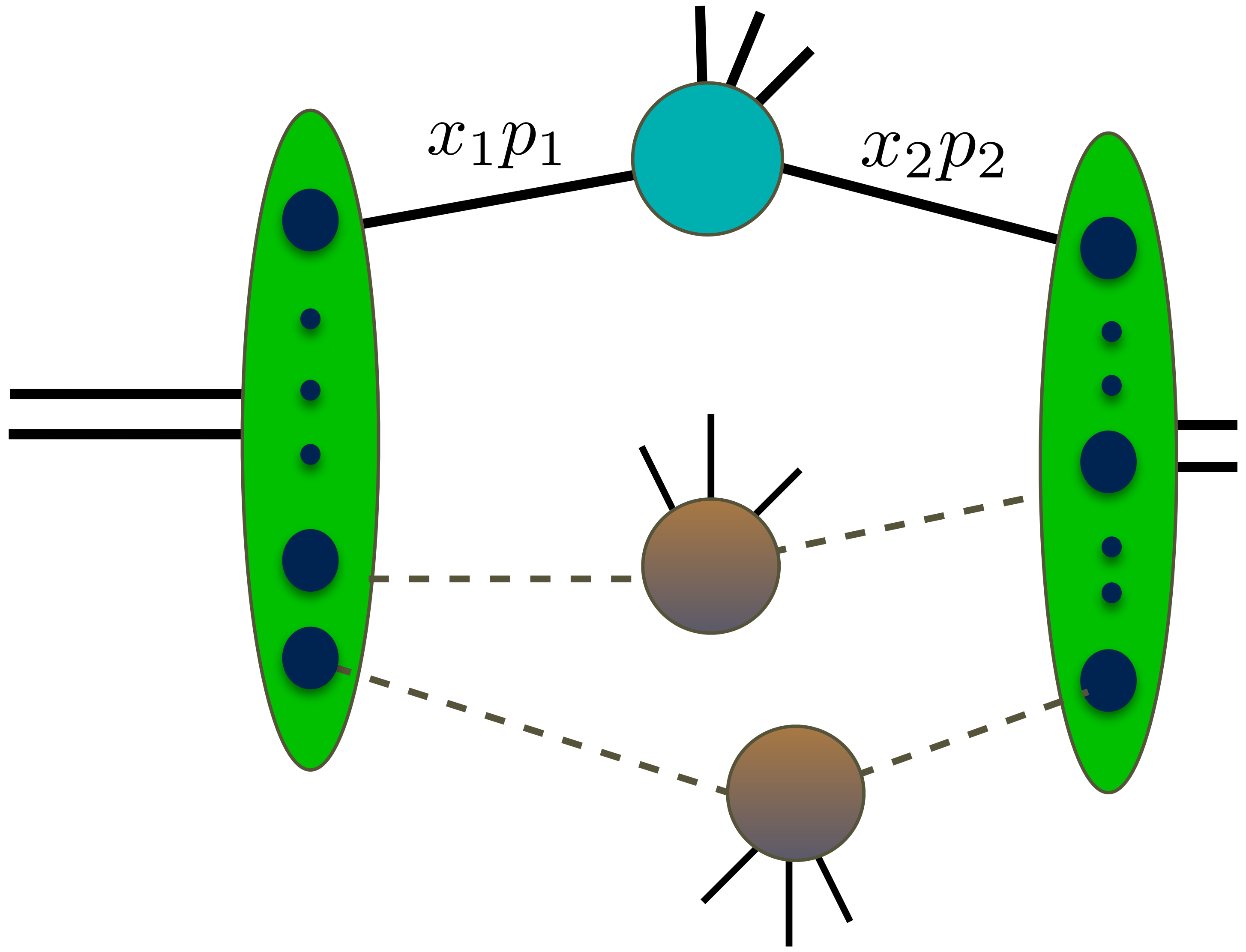


cluster model

split all gluons into quarks and recombine to colour singlets

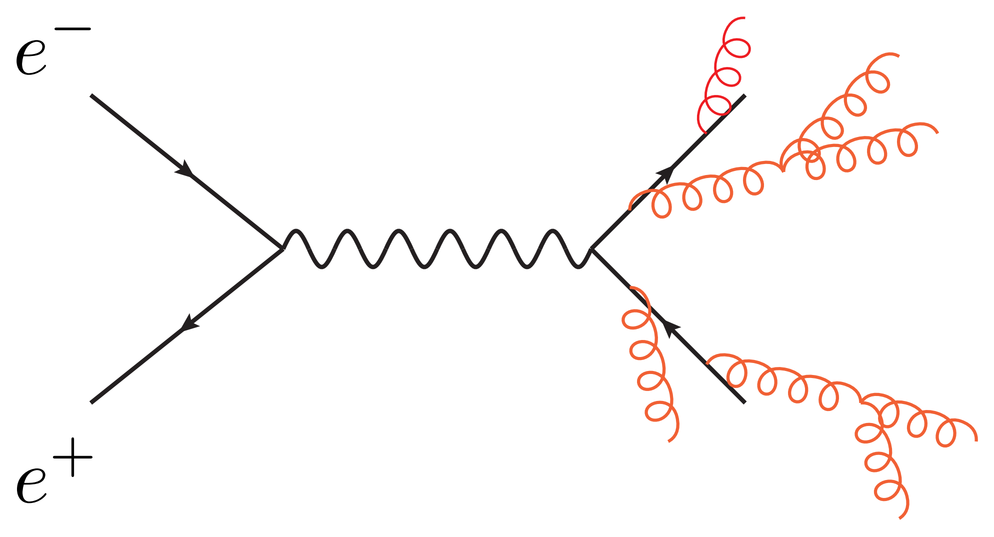
MPI

- apart from primary hard scattering (several) secondary secondary collisions from other partons inside the proton may occur

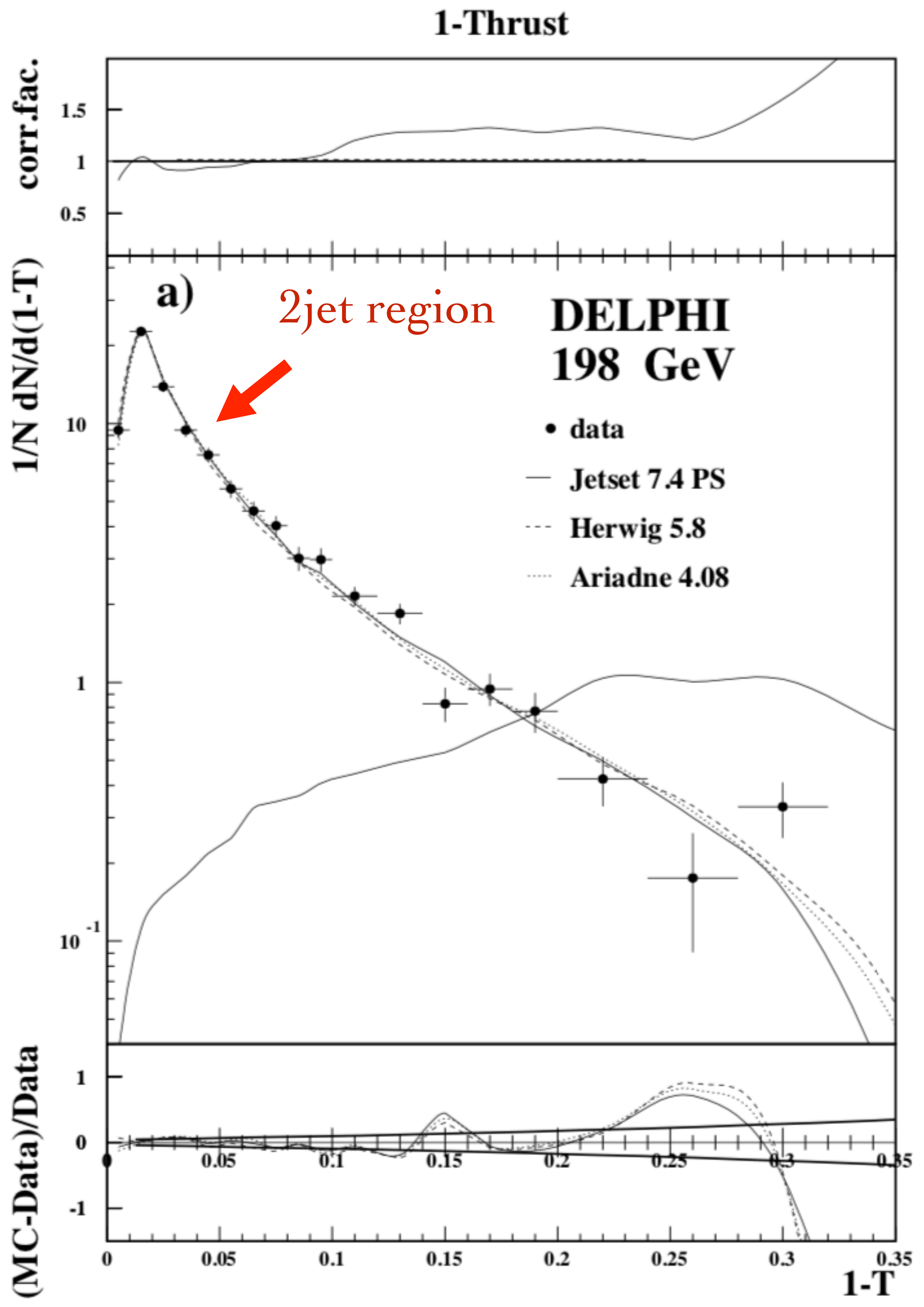


Parton showers at work

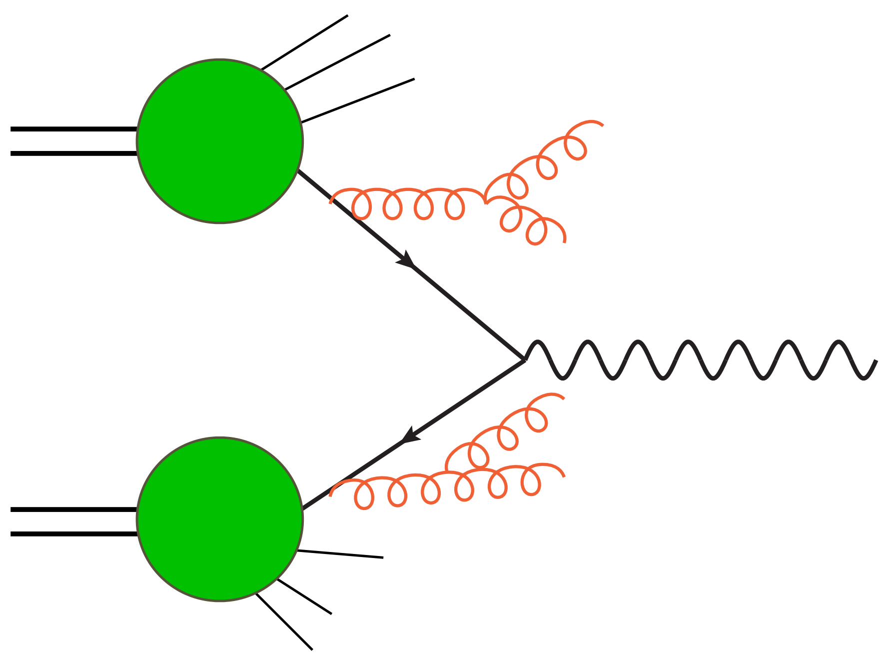
Example #1



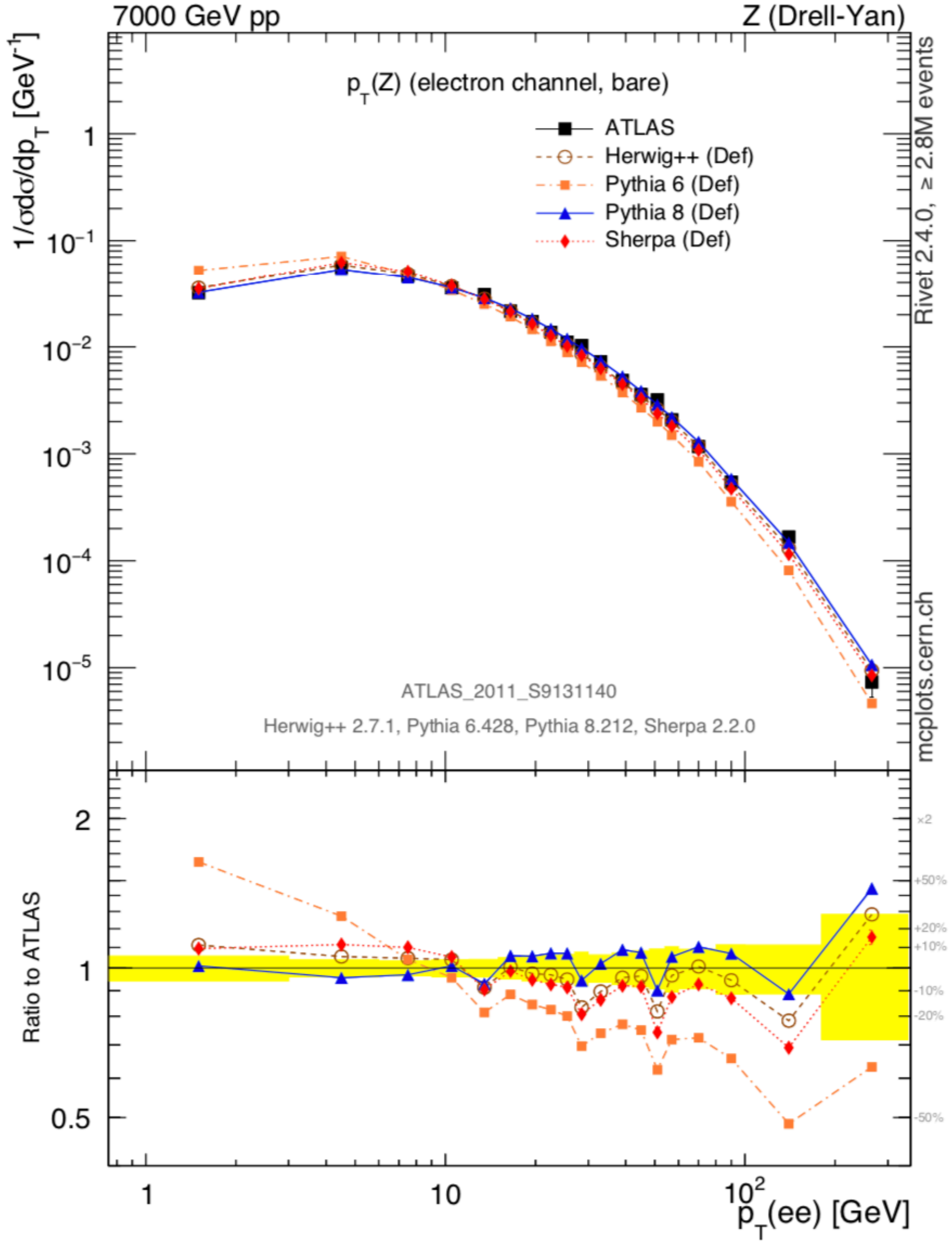
good description of dijet events in lepton collisions



Example #2



correct shape at low transverse momentum of the Z-boson



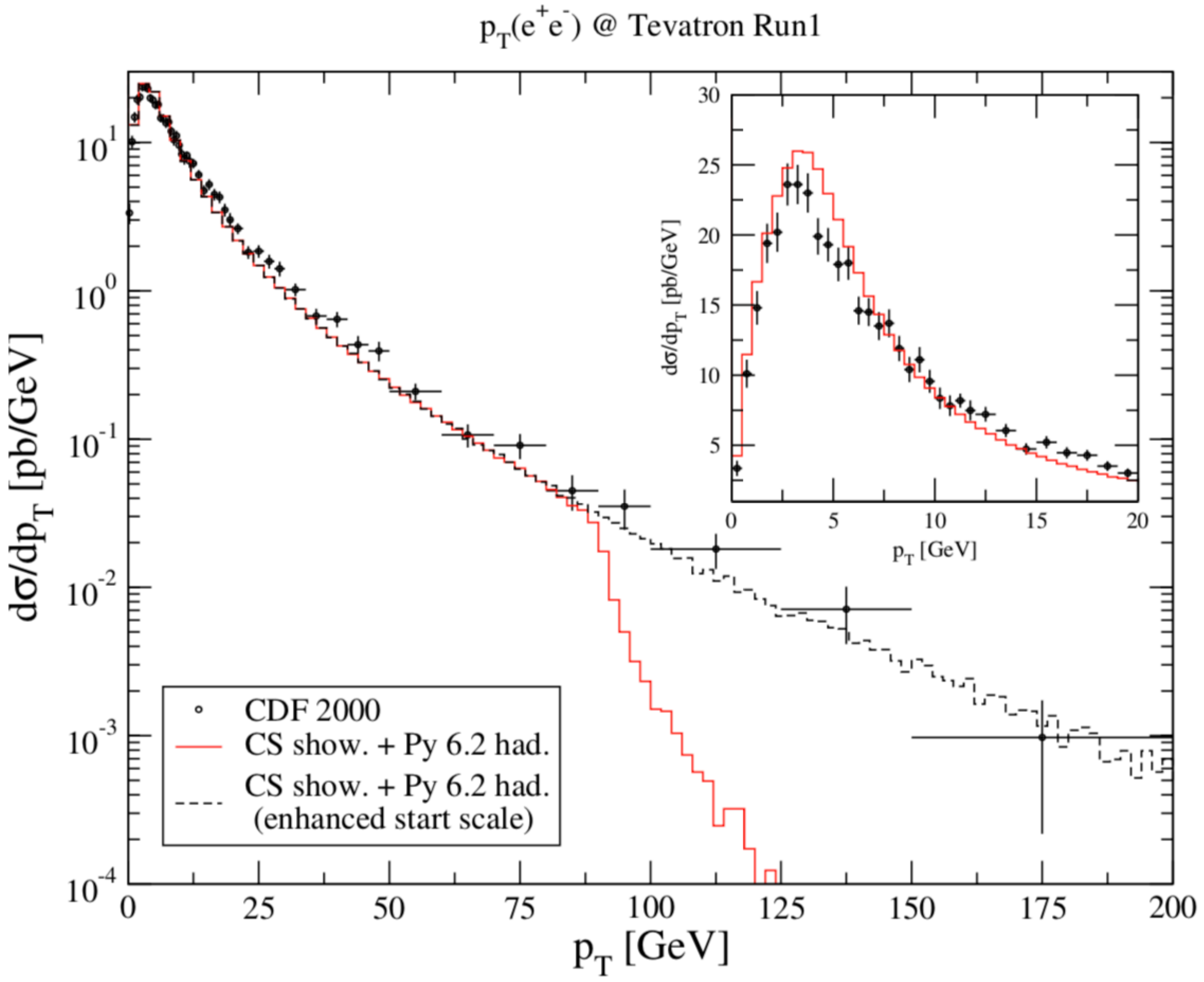
Problems of parton showers

★ parton showers rely on soft/collinear approximation for radiation (like resummation)

➞ valid only in when radiation is soft/collinear

★ in regions where hard QCD radiation is probed, such as at large p_T of a Z boson, a parton shower does not provide a physical description

★ by contrast, the shower provides a physical picture at low p_T

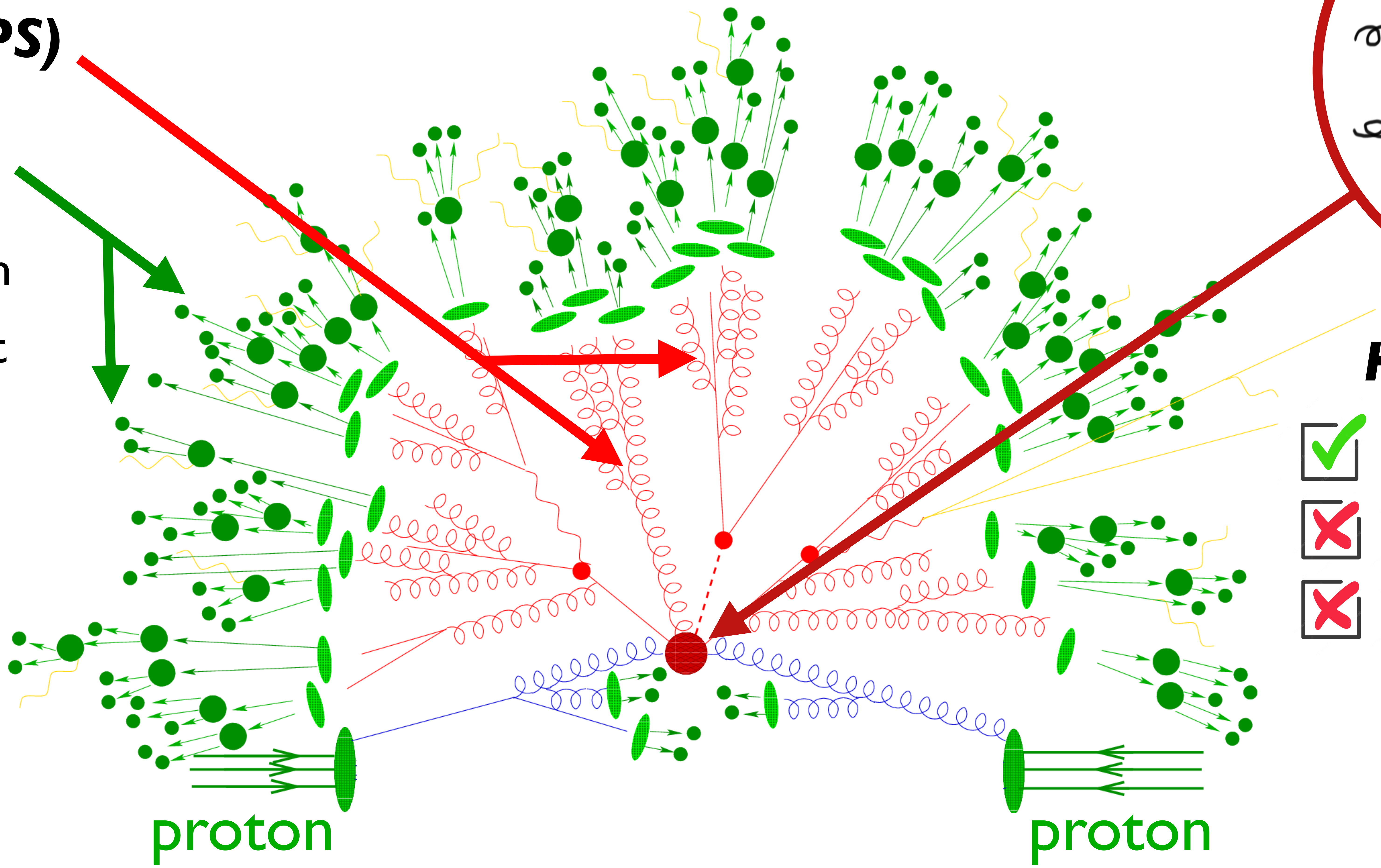


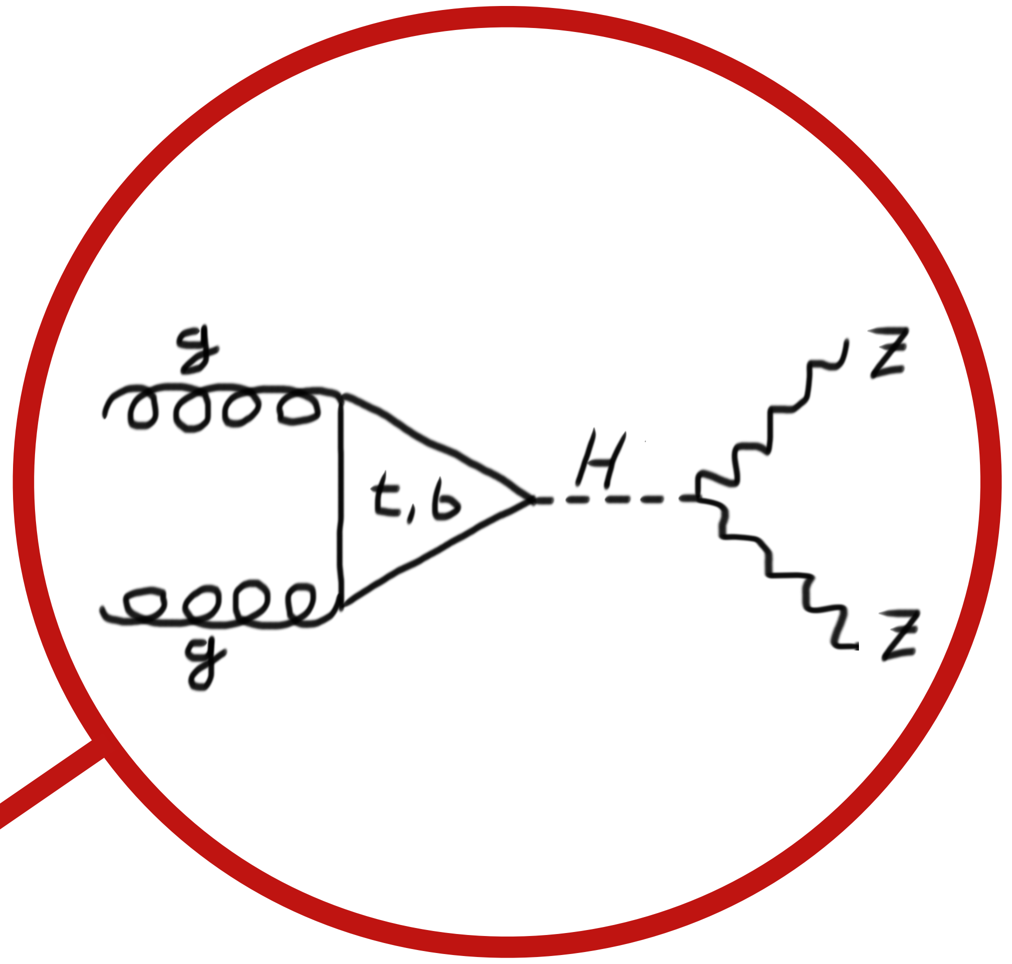
Questions?

LHC event

Parton Shower (PS)
+
Hadronization

- ✗ no N^xLO precision
- ✓ realistic LHC event
- ✓ shower accuracy (low precision)





Hard Process

- ✓ N^xLO (high precision)
- ✗ no event
- ✗ no shower accuracy

LHC event

Parton Shower (PS)

+

Hadronization

- ☒ no $\mathrm{N}^{x}\mathrm{LO}$ precision
- ☑ realistic LHC event
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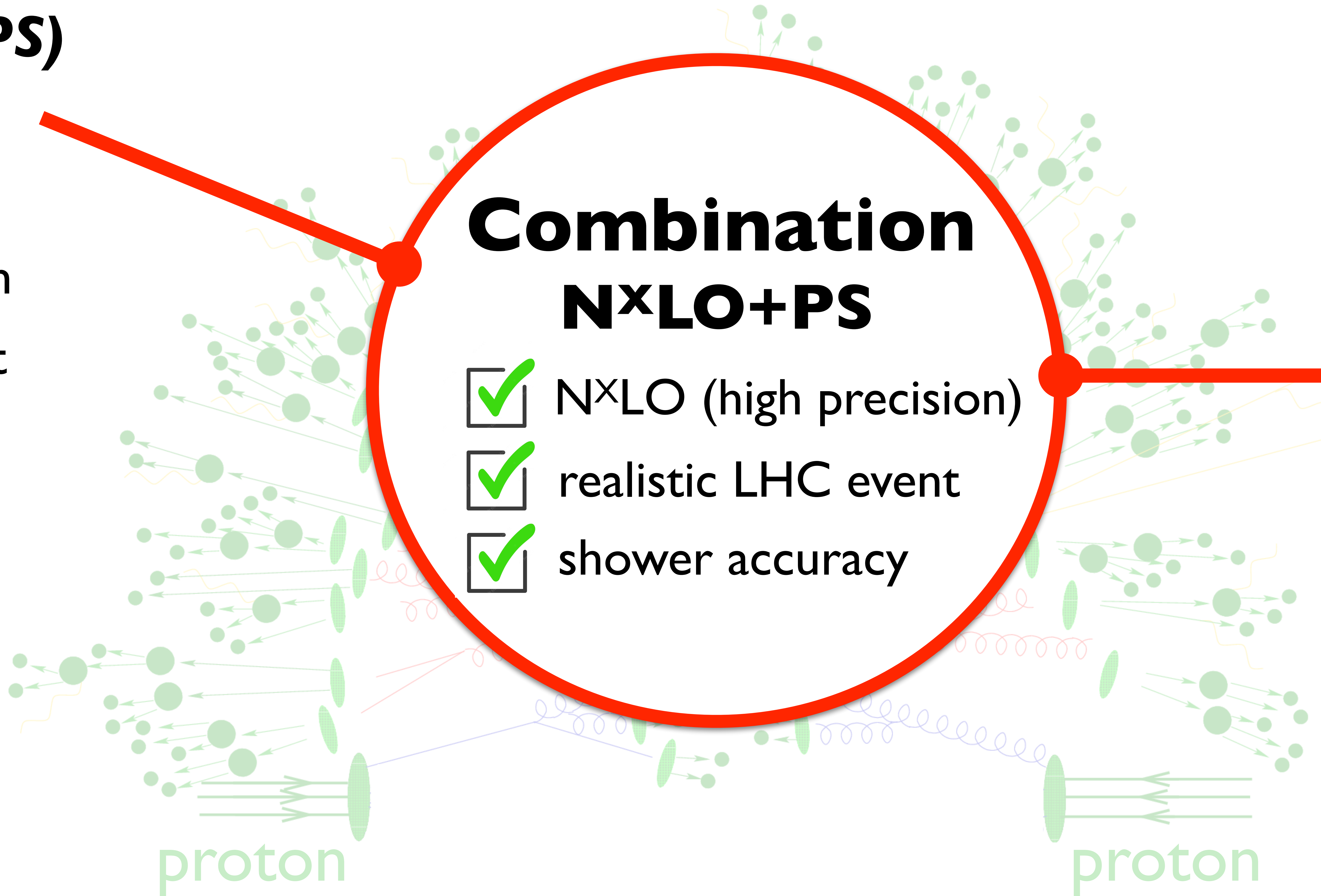


Combination

$\mathrm{N}^{x}\mathrm{LO}$+PS

- ☑ $\mathrm{N}^{x}\mathrm{LO}$ (high precision)
- ☑ realistic LHC event
- ☑ shower accuracy

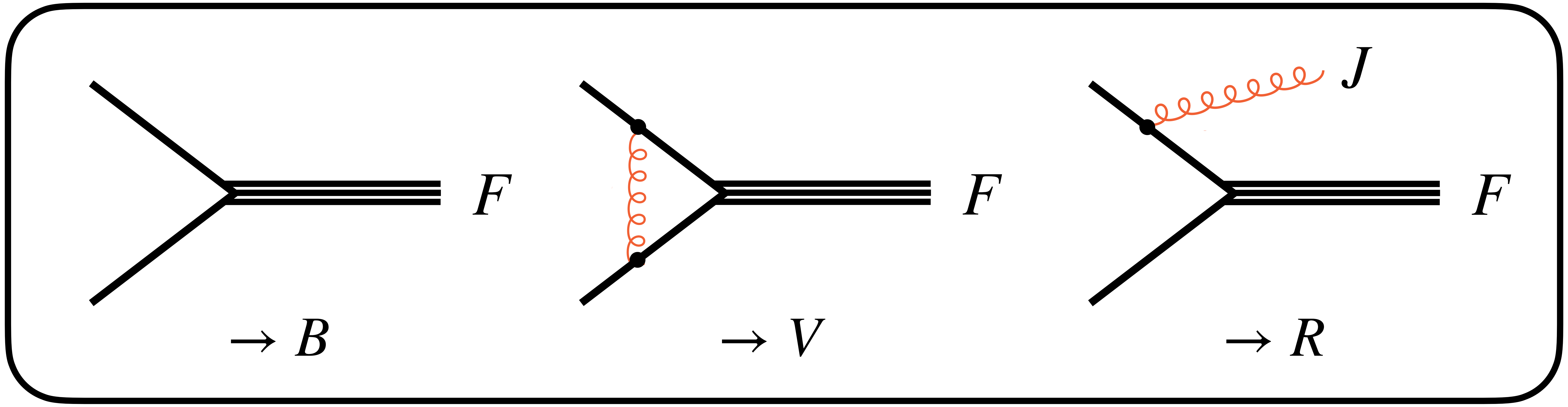
Hard Process

- ☑ $\mathrm{N}^{x}\mathrm{LO}$ (high precision)
- ☒ no event
- ☒ no shower accuracy

NLO+PS matching: MC@NLO

reminder shower formula: $$\mathrm{d}\sigma_{\mathrm{PS}} = \mathrm{d}\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + \mathrm{d}\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}$$

NLO cross section: $$\mathrm{d}\sigma_{\mathrm{NLO}} \equiv \left\{ \mathrm{d}\sigma^{(1)} + \mathrm{d}\sigma^{(2)} \right\} = \mathrm{d}\Phi_B \left(B + V + \int \mathrm{d}\Phi_{\mathrm{rad}}\, R \right)$$



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MC@NLO: additive matching (similar to analytic resummation & local subtraction):
[Frixione, Webber '02]

naive try: $\mathrm{d}\sigma^{\mathrm{naive}}_{\mathrm{MC@NLO}} = \left[\mathrm{d}\Phi_B\, (B + V) \right] \times I^{(n)}_{\mathrm{MC}} + \left[\mathrm{d}\Phi_B\, \mathrm{d}\Phi_{\mathrm{rad}}\, R \right] \times I^{(n+1)}_{\mathrm{MC}}$

$I^{(k)}_{\mathrm{MC}}$: corresponds to the shower emission propability from a k-body kinematics

NLO+PS matching: MC@NLO

reminder shower formula: $$d\sigma_{\rm PS} = d\Phi_B\, B \times \Big\{ \Delta(\nu_0,\Lambda) + d\Phi_1 \Delta(\nu_0,\nu_1)\, \mathscr{P}(d\Phi_1) \Big\}$$

NLO cross section: $$d\sigma_{\rm NLO} \equiv \Big\{ d\sigma^{(1)} + d\sigma^{(2)} \Big\} = d\Phi_B \left(B + V + \int d\Phi_{\rm rad}\, R \right)$$

MC@NLO: additive matching (similar to analytic resummation & local subtraction):
[Frixione, Webber '02]

naive try: $$d\sigma^{\rm naive}_{\rm MC@NLO} = \Big[d\Phi_B\,(B+V) \Big] \times I^{(n)}_{\rm MC} + \Big[d\Phi_B\, d\Phi_{\rm rad}\, R \Big] \times I^{(n+1)}_{\rm MC}$$

→ double counting! $\Big[\Phi_B B \times I^{(n)}_{\rm MC}\Big]$ and $\Big[d\Phi_B\, d\Phi_{\rm rad}\, R\Big]$ both include the first radiation

$I^{(k)}_{\rm MC}$: corresponds to the shower emission propability from a k-body kinematics

NLO+PS matching: MC@NLO

reminder shower formula: $$\mathrm{d}\sigma_{\mathrm{PS}} = \mathrm{d}\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + \mathrm{d}\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}$$

NLO cross section: $$\mathrm{d}\sigma_{\mathrm{NLO}} \equiv \left\{ \mathrm{d}\sigma^{(1)} + \mathrm{d}\sigma^{(2)} \right\} = \mathrm{d}\Phi_B \left(B + V + \int \mathrm{d}\Phi_{\mathrm{rad}}\, R \right)$$

MC@NLO: additive matching (similar to analytic resummation & local subtraction):

[Frixione, Webber '02]

no double counting: $$\mathrm{d}\sigma_{\mathrm{MC@NLO}} = \left[\mathrm{d}\Phi_B \left(B + V + \int \mathrm{d}\Phi_{\mathrm{rad}} MC \right) \right] \times I_{\mathrm{MC}}^{(n)} + \left[\mathrm{d}\Phi_B\, \mathrm{d}\Phi_{\mathrm{rad}}\, (R - MC) \right] \times I_{\mathrm{MC}}^{(n+1)}$$

solution: local MC counter term: $MC \simeq B \times \left[\mathrm{d}\Phi_1 / \mathrm{d}\Phi_{\mathrm{rad}}\, \mathscr{P}(d\Phi_1) \right]$ (depends on shower that you interface to)

NLO+PS matching: MC@NLO

reminder shower formula: $$\mathrm{d}\sigma_{\mathrm{PS}} = \mathrm{d}\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + \mathrm{d}\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}$$

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NLO expansion

$$= \left\{ \left(1 - \int \mathrm{d}\Phi_1\, \mathscr{P}(d\Phi_1) \right) + \mathrm{d}\Phi_1\, \mathscr{P}(d\Phi_1) \right\}$$

$$= \left\{ 1 - \int \mathrm{d}\Phi_{\mathrm{rad}} \frac{MC}{B} + \mathrm{d}\Phi_{\mathrm{rad}} \frac{MC}{B} \right\}$$

solution: local MC counter term: $MC \simeq B \times \left[\mathrm{d}\Phi_1 / \mathrm{d}\Phi_{\mathrm{rad}}\, \mathscr{P}(d\Phi_1) \right]$

NLO+PS matching: MC@NLO

reminder shower formula: $\mathrm{d}\sigma_{\mathrm{PS}} = \mathrm{d}\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + \mathrm{d}\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}$

NLO cross section: $\mathrm{d}\sigma_{\mathrm{NLO}} \equiv \left\{ \mathrm{d}\sigma^{(1)} + \mathrm{d}\sigma^{(2)} \right\} = \mathrm{d}\Phi_B \left(B + V + \int \mathrm{d}\Phi_{\mathrm{rad}}\, R \right)$

MC@NLO: additive matching (similar to analytic resummation & local subtraction):

[Frixione, Webber '02]

$$\left[\mathrm{d}\sigma_{\mathrm{MC@NLO}}\right]_{\mathrm{NLO}} = \left[\mathrm{d}\Phi_B \left(B + V + \int \mathrm{d}\Phi_{\mathrm{rad}}\, MC \right) \right] \times I_{\mathrm{MC}}^{(n)} + \left[\mathrm{d}\Phi_B\, \mathrm{d}\Phi_{\mathrm{rad}}\, (R - MC) \right] \times I_{\mathrm{MC}}^{(n+1)}$$

$$= \mathrm{d}\sigma_{\mathrm{NLO}}$$

NLO expansion

$$= \left\{ \left(1 - \int \mathrm{d}\Phi_1\, \mathscr{P}(d\Phi_1) \right) + \mathrm{d}\Phi_1\, \mathscr{P}(d\Phi_1) \right\}$$

$$= \left\{ 1 - \int \mathrm{d}\Phi_{\mathrm{rad}} \frac{MC}{B} + \mathrm{d}\Phi_{\mathrm{rad}} \frac{MC}{B} \right\}$$

solution: local MC counter term: $MC \simeq B \times \left[\mathrm{d}\Phi_1 / \mathrm{d}\Phi_{\mathrm{rad}}\, \mathscr{P}(d\Phi_1) \right]$

NLO+PS matching: MC@NLO

reminder shower formula: $\mathrm{d}\sigma_{\mathrm{PS}} = \mathrm{d}\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + \mathrm{d}\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}$

NLO cross section: $\mathrm{d}\sigma_{\mathrm{NLO}} \equiv \left\{ \mathrm{d}\sigma^{(1)} + \mathrm{d}\sigma^{(2)} \right\} = \mathrm{d}\Phi_B \left(B + V + \int \mathrm{d}\Phi_{\mathrm{rad}}\, R \right)$

MC@NLO: additive matching (similar to analytic resummation & local subtraction):

[Frixione, Webber '02]

$$\mathrm{d}\sigma_{\mathrm{MC@NLO}} = \left[\mathrm{d}\Phi_B \left(B + V + \int \mathrm{d}\Phi_{\mathrm{rad}} MC \right) \right] \times I_{\mathrm{MC}}^{(n)} + \left[\mathrm{d}\Phi_B\, \mathrm{d}\Phi_{\mathrm{rad}}\, (R - MC) \right] \times I_{\mathrm{MC}}^{(n+1)}$$

$I_{\mathrm{MC}}^{(k)}$: corresponds to the shower emission propability from a k-body kinematics

NLO+PS matching: MC@NLO

reminder shower formula: $$d\sigma_{\rm PS} = d\Phi_B\, B \times \left\{ \Delta(v_0, \Lambda) + d\Phi_1 \Delta(v_0, v_1)\, \mathscr{P}(d\Phi_1) \right\}$$

NLO cross section: $$d\sigma_{\rm NLO} \equiv \left\{ d\sigma^{(1)} + d\sigma^{(2)} \right\} = d\Phi_B \left(B + V + \int d\Phi_{\rm rad}\, R \right)$$

MC@NLO: additive matching (similar to analytic resummation & local subtraction):

[Frixione, Webber '02]

$$d\sigma_{\rm MC@NLO} = \left[d\Phi_B \left(B + V + \int d\Phi_{\rm rad} MC \right) \right] \times I_{\rm MC}^{(n)} + \left[d\Phi_B\, d\Phi_{\rm rad}\, (R - MC) \right] \times I_{\rm MC}^{(n+1)}$$

S-events H-events

only sum is positive definite for physical observables,
S- and H-events can be seperately negative

NLO+PS matching: Powheg

reminder shower formula: $$\mathrm{d}\sigma_{\mathrm{PS}} = \mathrm{d}\Phi_B \, B \times \left\{ \Delta(\nu_0, \Lambda) + \mathrm{d}\Phi_1 \Delta(\nu_0, \nu_1) \, \mathscr{P}(d\Phi_1) \right\}$$

NLO+PS matching: Powheg

reminder shower formula: $$\mathrm{d}\sigma_{\mathrm{PS}} = \mathrm{d}\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + \mathrm{d}\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}$$

Powheg: generate first emission through matrix elements:

[Nason '04], [Frixione, Nason, Oleari '07]

$$\mathrm{d}\sigma_{\mathrm{PWG}} = \mathrm{d}\Phi_B\, \tilde{B} \times \left\{ \Delta_{\mathrm{pwg}}(\Lambda_{\mathrm{pwg}}) + \mathrm{d}\Phi_{\mathrm{rad}} \Delta_{\mathrm{pwg}}(p_{T,\mathrm{rad}}) \frac{R}{B} \times I_{\mathrm{MC}}^{(n+1)} \right\}$$

NLO+PS matching: Powheg

reminder shower formula: $\mathrm{d}\sigma_{\mathrm{PS}} = \mathrm{d}\Phi_B\, B \times \left\{ \Delta(\nu_0, \Lambda) + \mathrm{d}\Phi_1 \Delta(\nu_0, \nu_1)\, \mathscr{P}(d\Phi_1) \right\}$

Powheg: generate first emission through matrix elements:

[Nason '04], [Frixione, Nason, Oleari '07]

$$\mathrm{d}\sigma_{\mathrm{PWG}} = \mathrm{d}\Phi_B\, \tilde{B} \times \left\{ \Delta_{\mathrm{pwg}}(\Lambda_{\mathrm{pwg}}) + \mathrm{d}\Phi_{\mathrm{rad}} \Delta_{\mathrm{pwg}}(p_{T,\mathrm{rad}}) \frac{R}{B} \times I_{\mathrm{MC}}^{(n+1)} \right\}$$

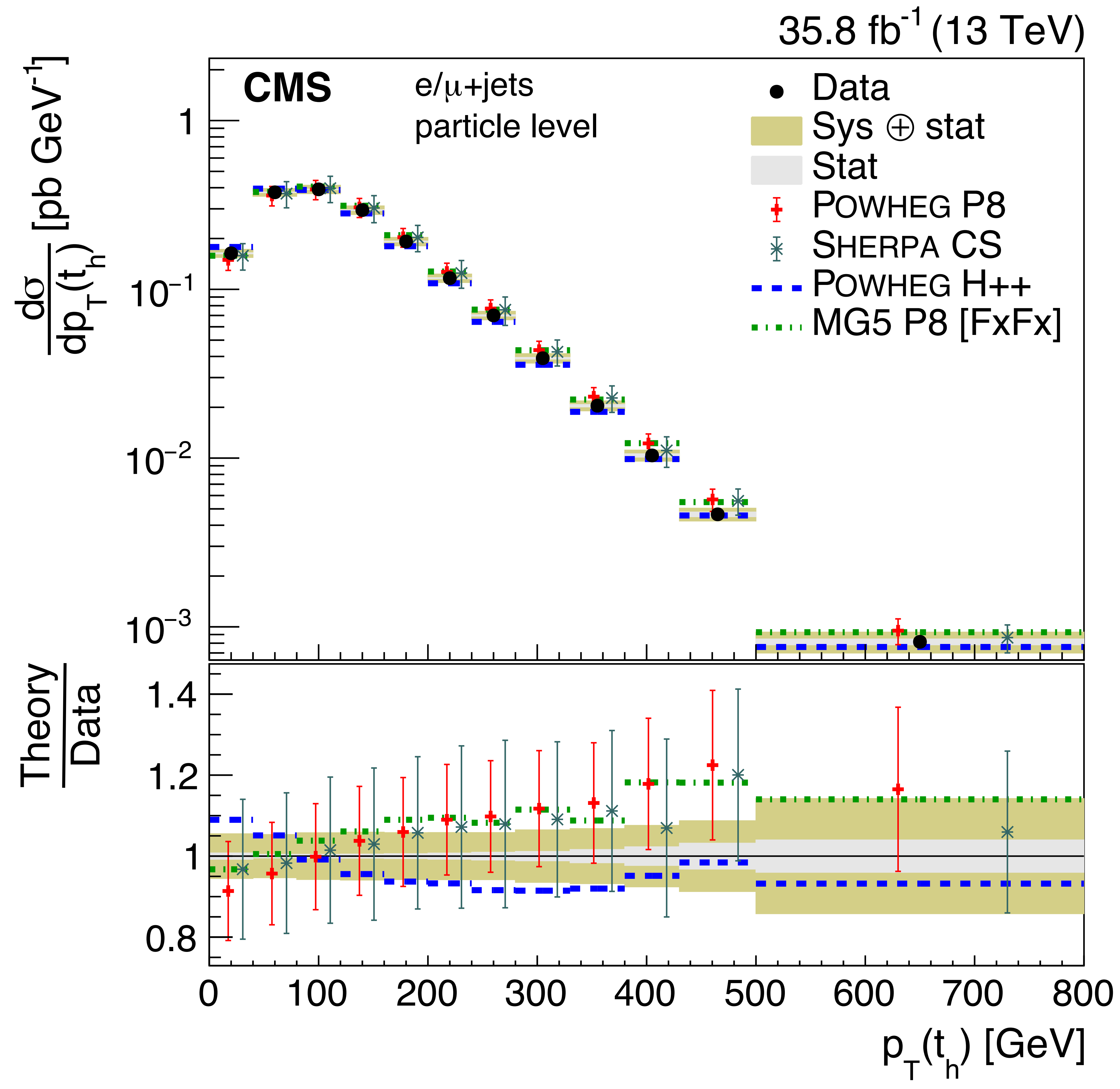
$$\tilde{B} = B + V + \int \mathrm{d}\Phi_{\mathrm{rad}}\, R$$

$$\equiv \left\{ \frac{\mathrm{d}\sigma^{(1)}}{\mathrm{d}\Phi_{\mathrm{B}}} + \frac{\mathrm{d}\sigma^{(2)}}{\mathrm{d}\Phi_{\mathrm{B}}} \right\}$$ NLO cross section, inclusive over second radiation

NLO+PS results

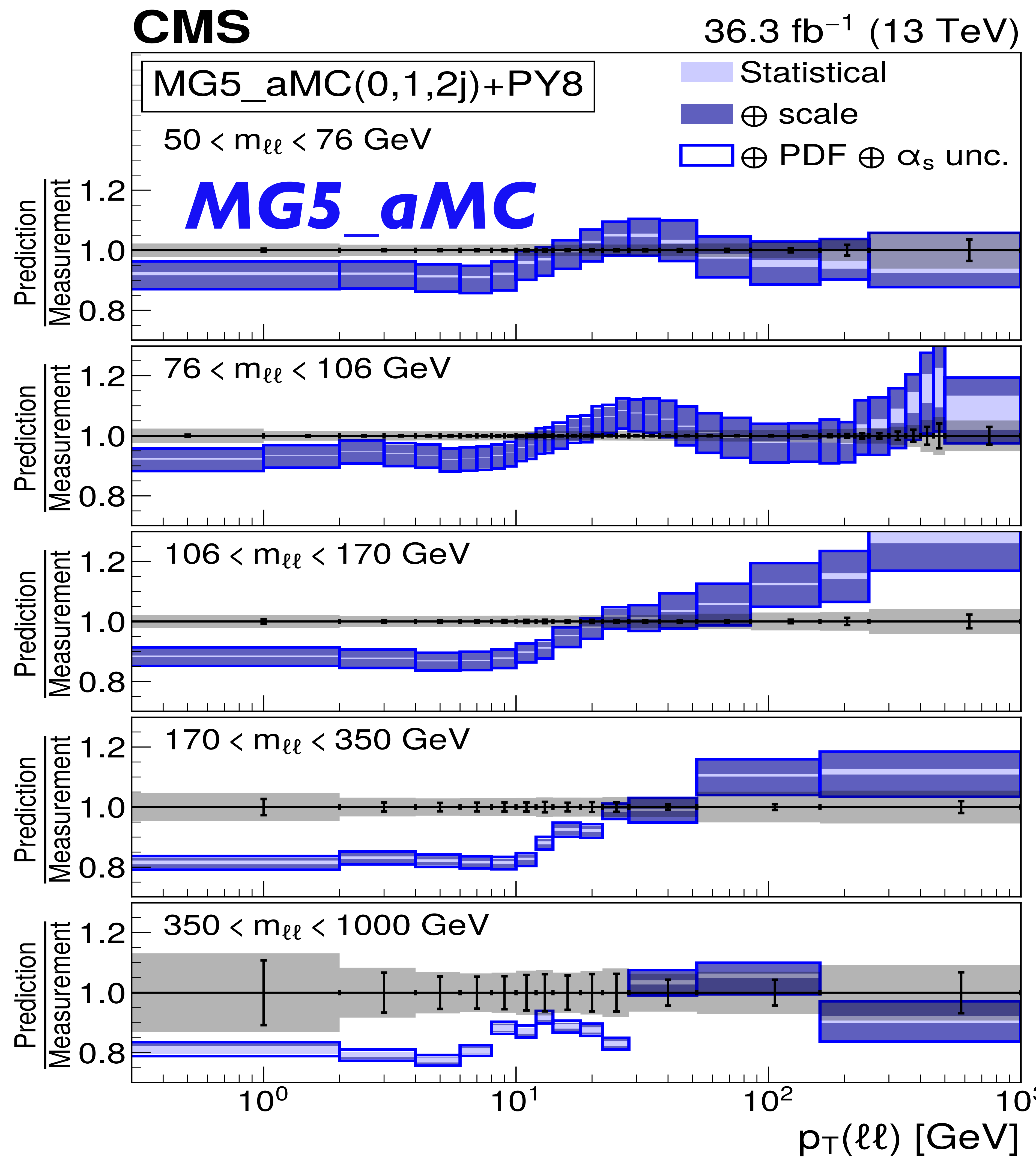
Top-quark pair production

[CMS '22 - arXiv:1803.08856]

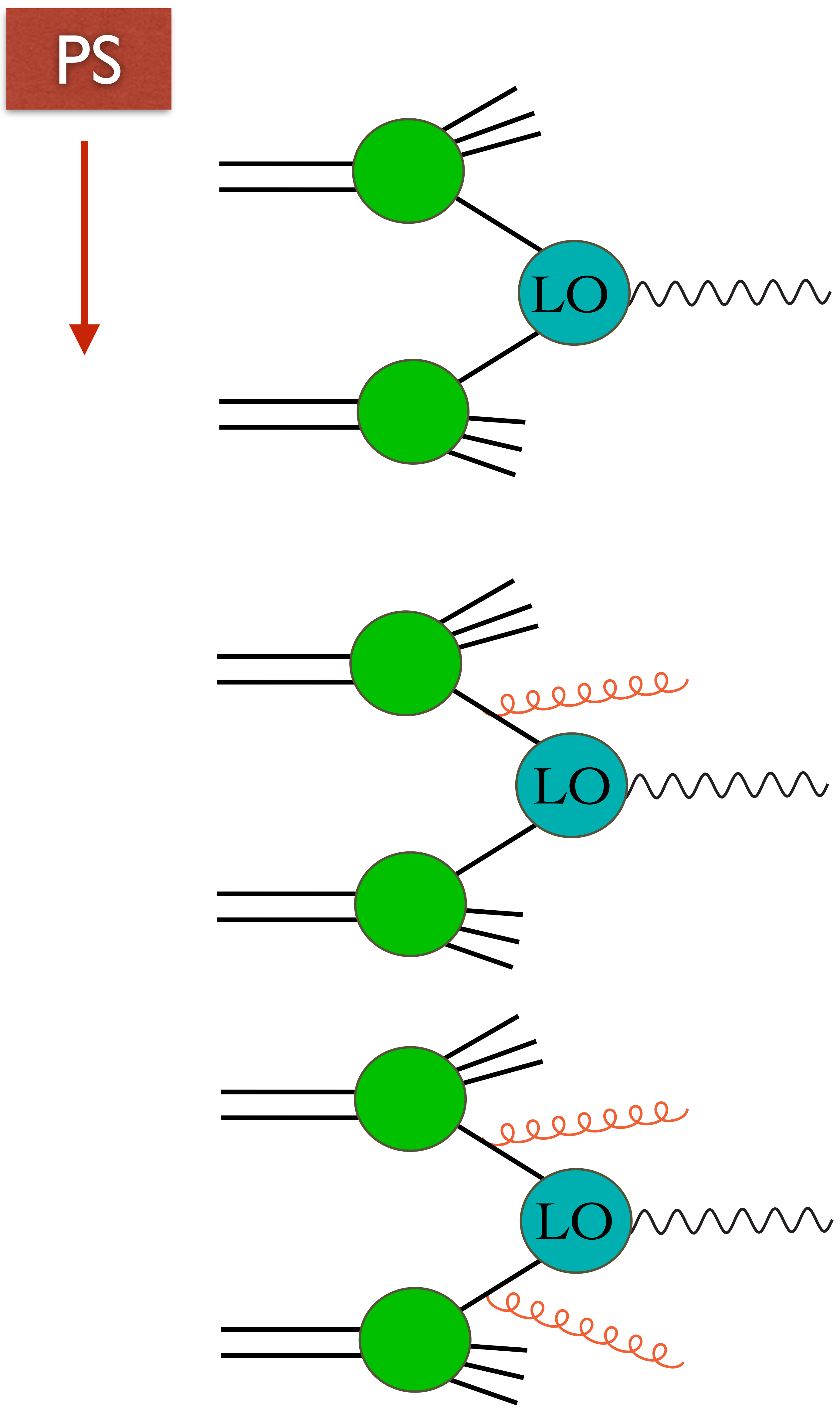


Comparison to high-precision Drell-Yan data

[CMS '22 - arXiv:2205.04897]

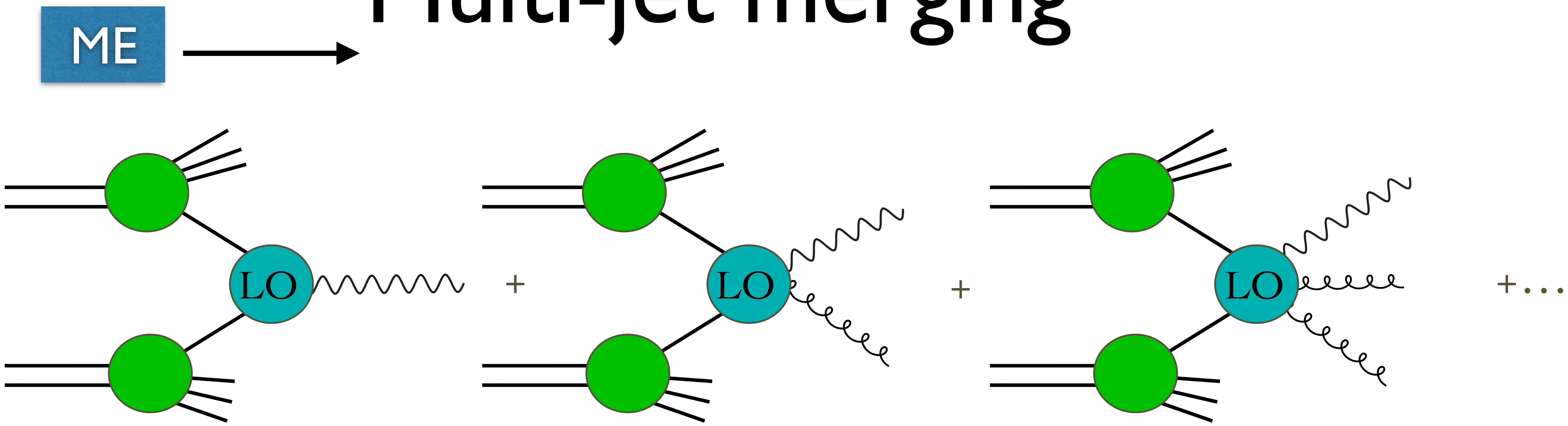


Multi-jet merging



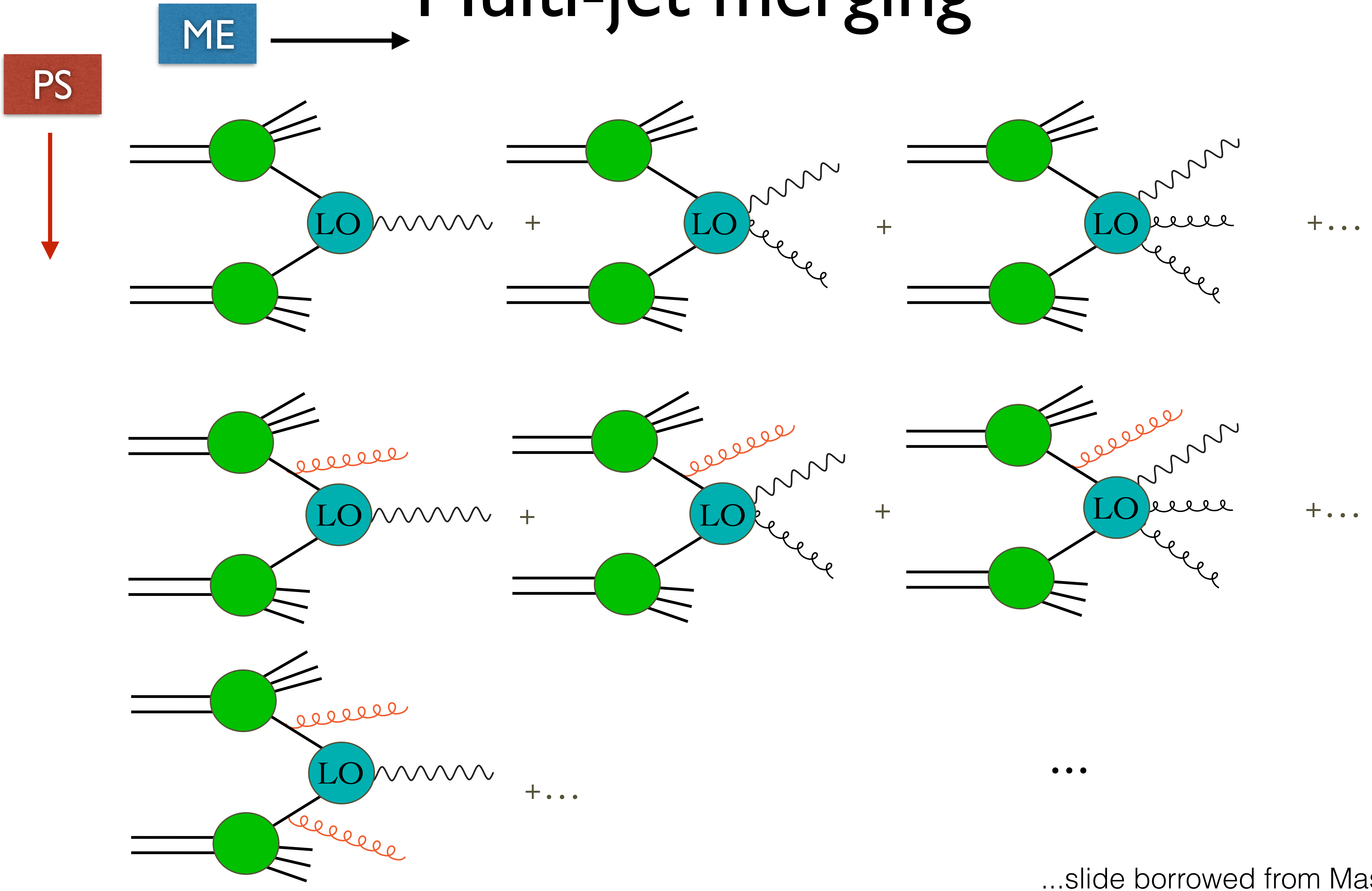
...slide borrowed from Massimilano Grazzini

Multi-jet merging



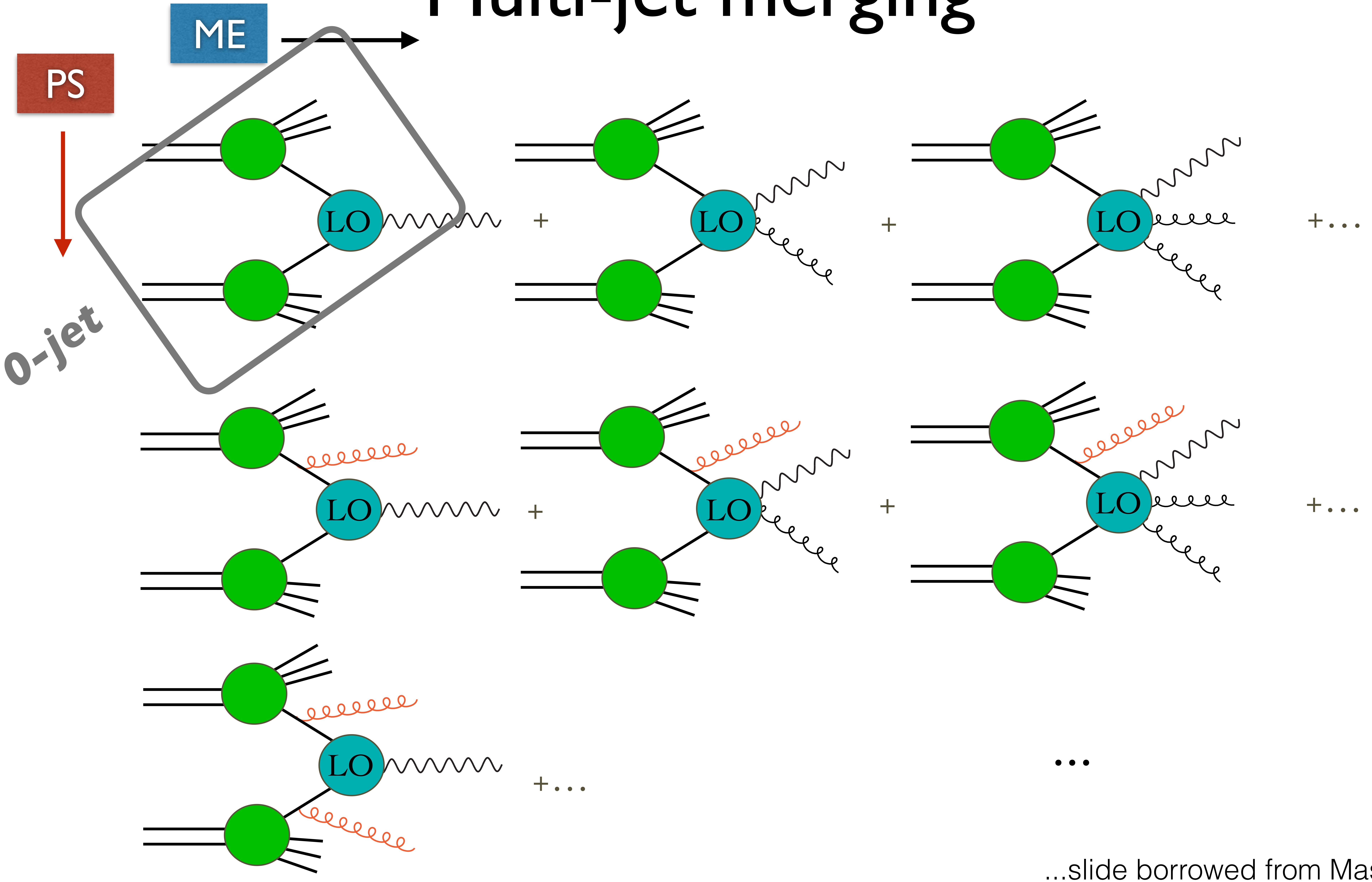
...slide borrowed from Massimilano Grazzini

Multi-jet merging



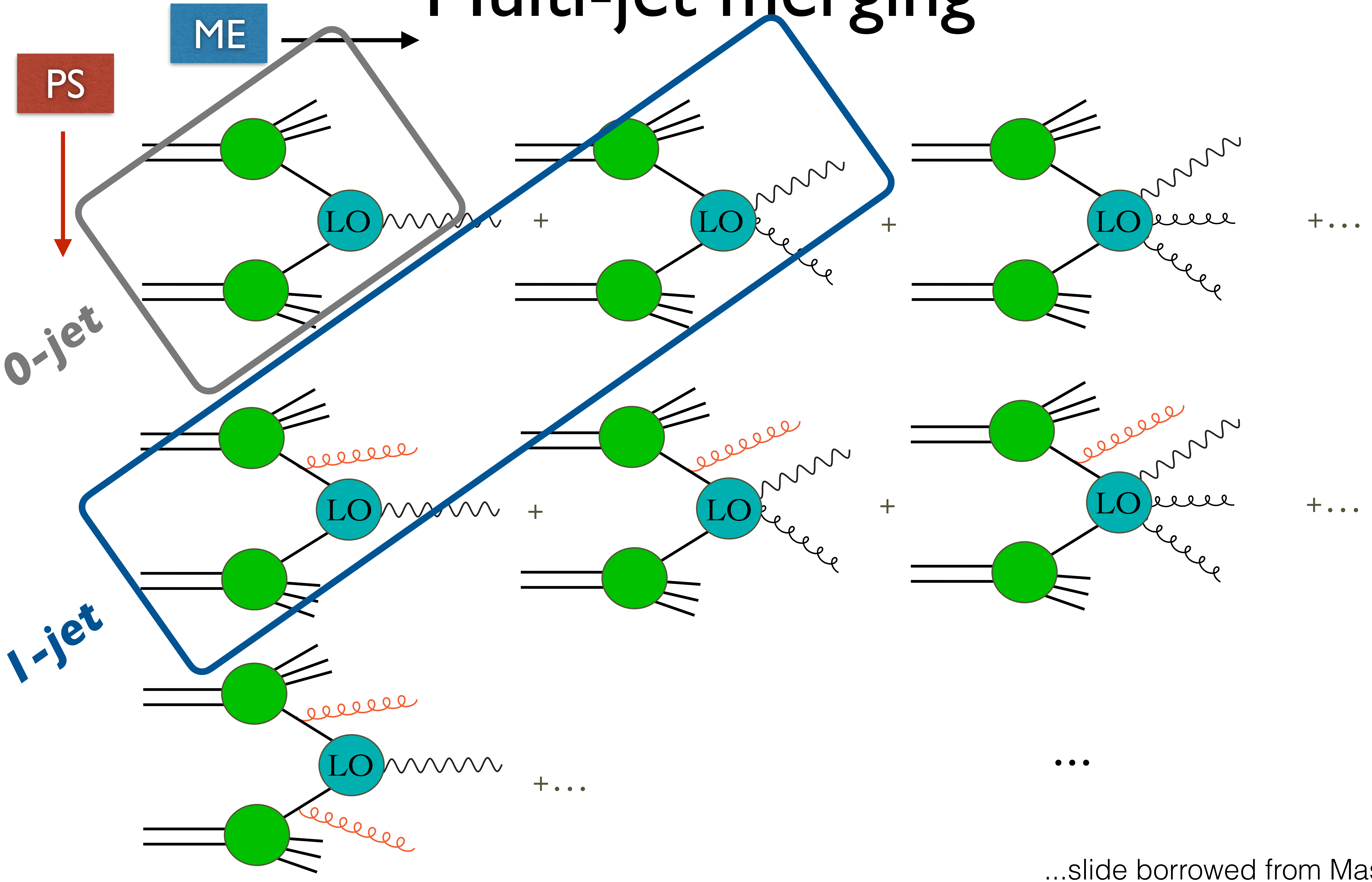
...slide borrowed from Massimilano Grazzini

Multi-jet merging



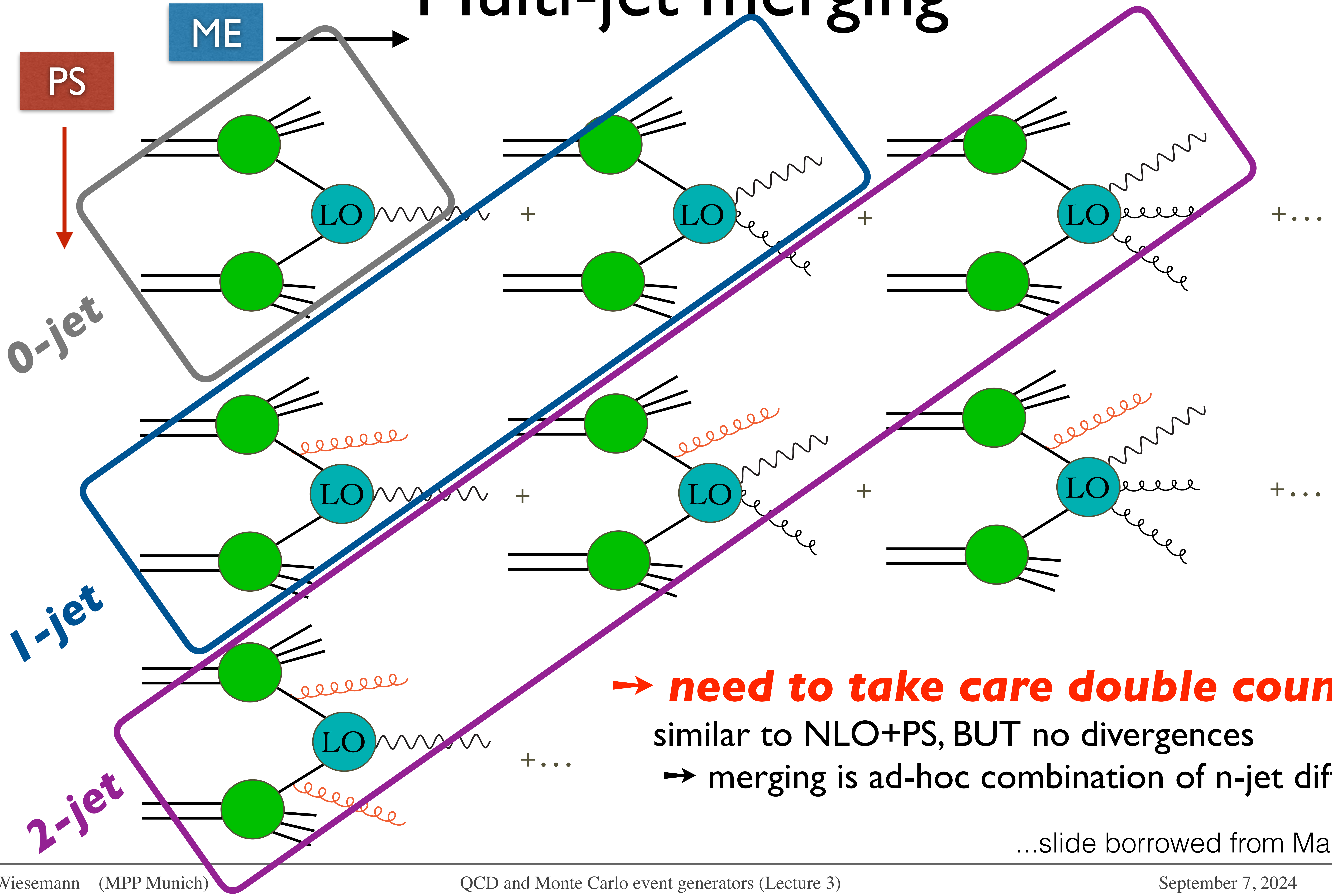
...slide borrowed from Massimilano Grazzini

Multi-jet merging



...slide borrowed from Massimilano Grazzini

Multi-jet merging

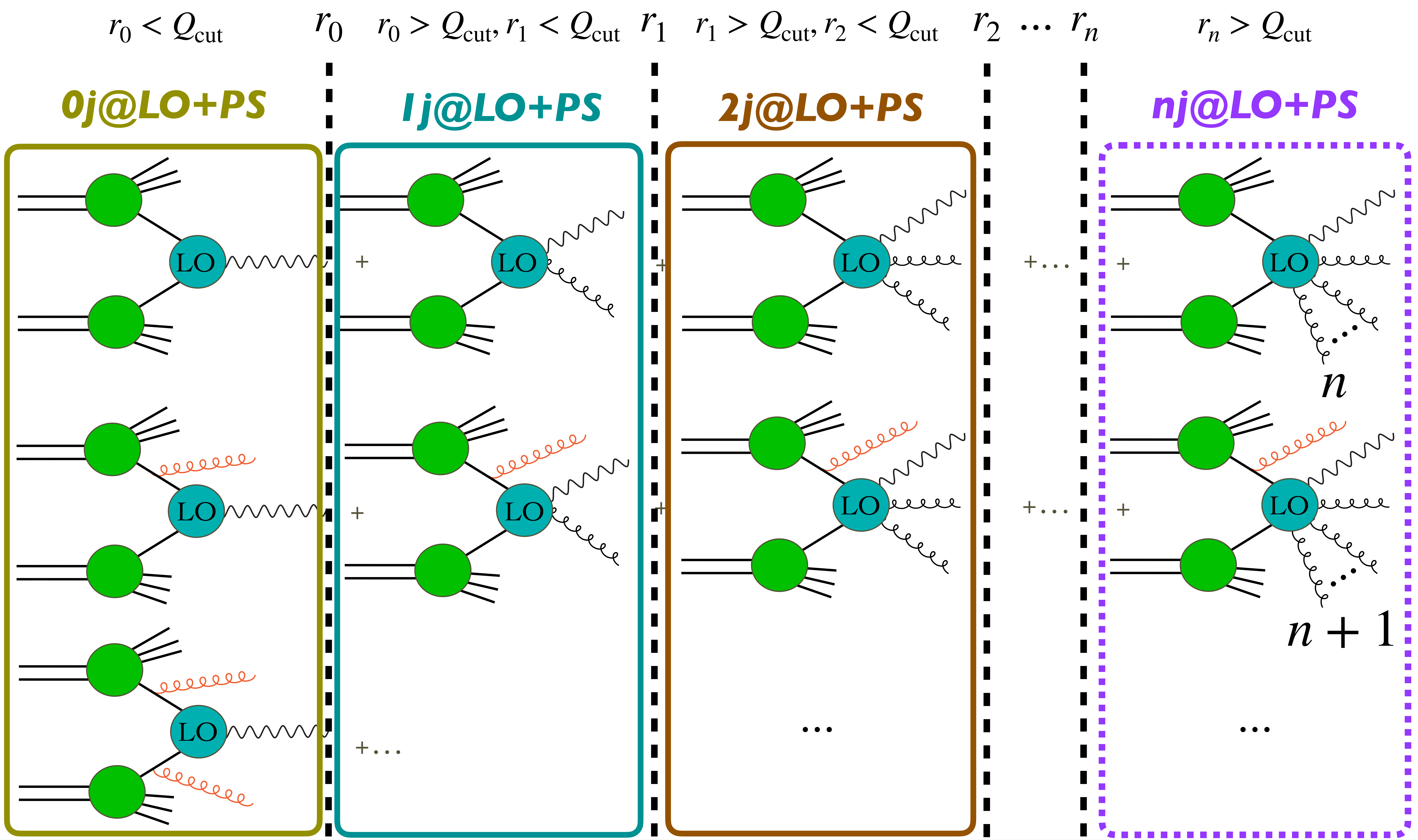


→ *need to take care double counting!*

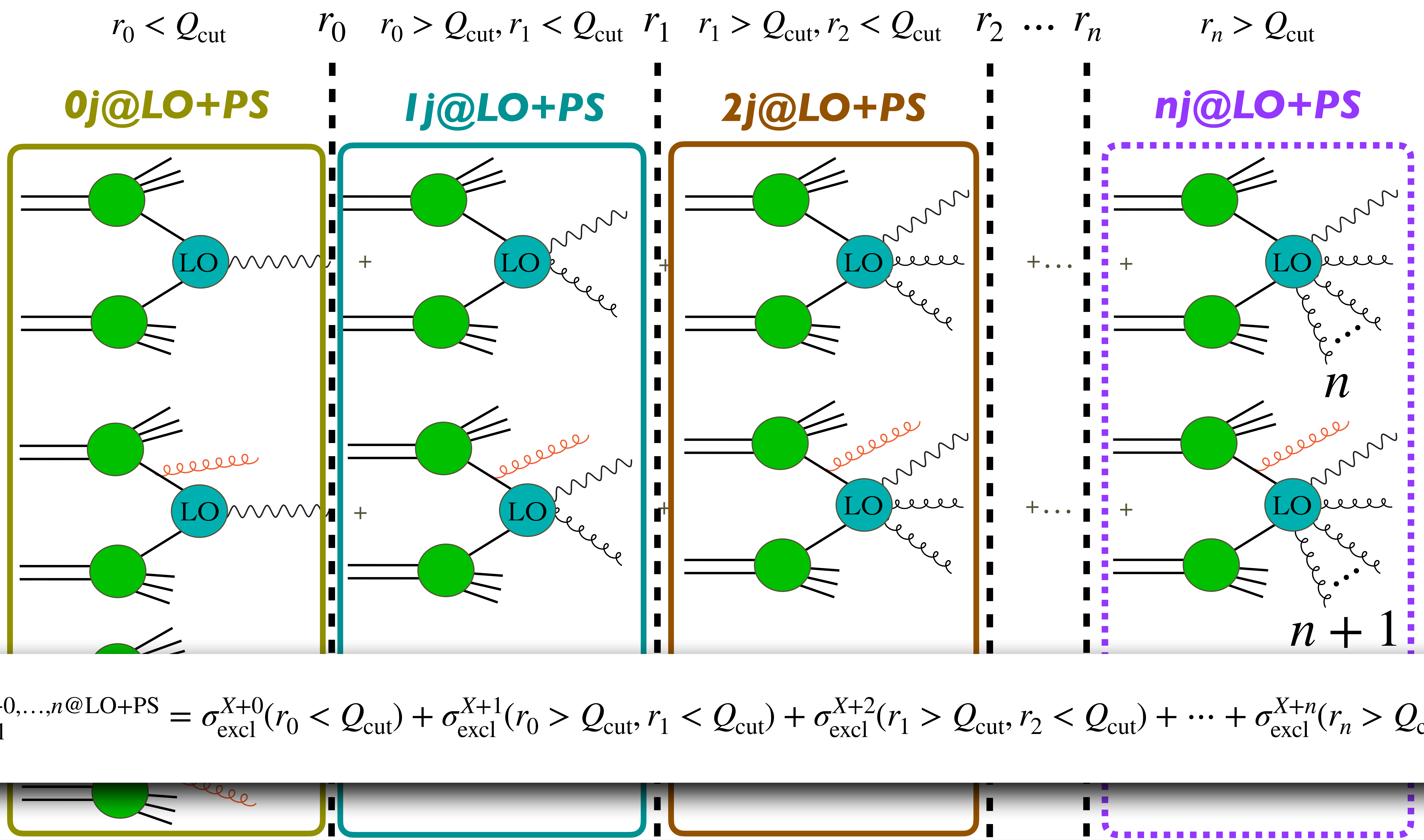
similar to NLO+PS, BUT no divergences

→ merging is ad-hoc combination of n-jet different samples

...slide borrowed from Massimilano Grazzini



$r_0 < Q_{\rm cut}$
r_0
$r_0 > Q_{\rm cut}, r_1 < Q_{\rm cut}$
r_1
$r_1 > Q_{\rm cut}, r_2 < Q_{\rm cut}$
r_2 … r_n
$r_n > Q_{\rm cut}$
0j@LO+PS
1j@LO+PS
2j@LO+PS
nj@LO+PS
LO
+
+…
n
$n+1$
…



$$\sigma_{\text{incl}}^{X+0,\ldots,n@\text{LO+PS}} = \sigma_{\text{excl}}^{X+0}(r_0 < Q_{\text{cut}}) + \sigma_{\text{excl}}^{X+1}(r_0 > Q_{\text{cut}}, r_1 < Q_{\text{cut}}) + \sigma_{\text{excl}}^{X+2}(r_1 > Q_{\text{cut}}, r_2 < Q_{\text{cut}}) + \cdots + \sigma_{\text{excl}}^{X+n}(r_n > Q_{\text{cut}})$$

LO+PS merging

	X	X+jet	X+2jets	X+3jets	X+nj(n>3)
X@LO	LO	—	—	—	—
X@LO+PS	LO	PS	PS	PS	PS
X+0,1j@LO+PS	LO	LO	PS	PS	PS
X+0,1,2j@LO+PS	LO	LO	LO	PS	PS
X+0,1,2,3j@LO+PS	LO	LO	LO	LO	PS

✦ main idea:

- hard emissions ($r_i > Q_{\rm cut}$) described by matrix elements, soft emissions ($r_i < Q_{\rm cut}$) by shower
- resolution variable r_i typically related to transverse momentum of the emission
- merging scale $Q_{\rm cut}$ cannot be pushed too low as large $\log(Q_{\rm cut}/Q)$ in matrix elements

✦ LO+PS merging methods: CKKW | MLM | UMEPS | MEPS@LO (Sherpa) | …

NLO+PS merging

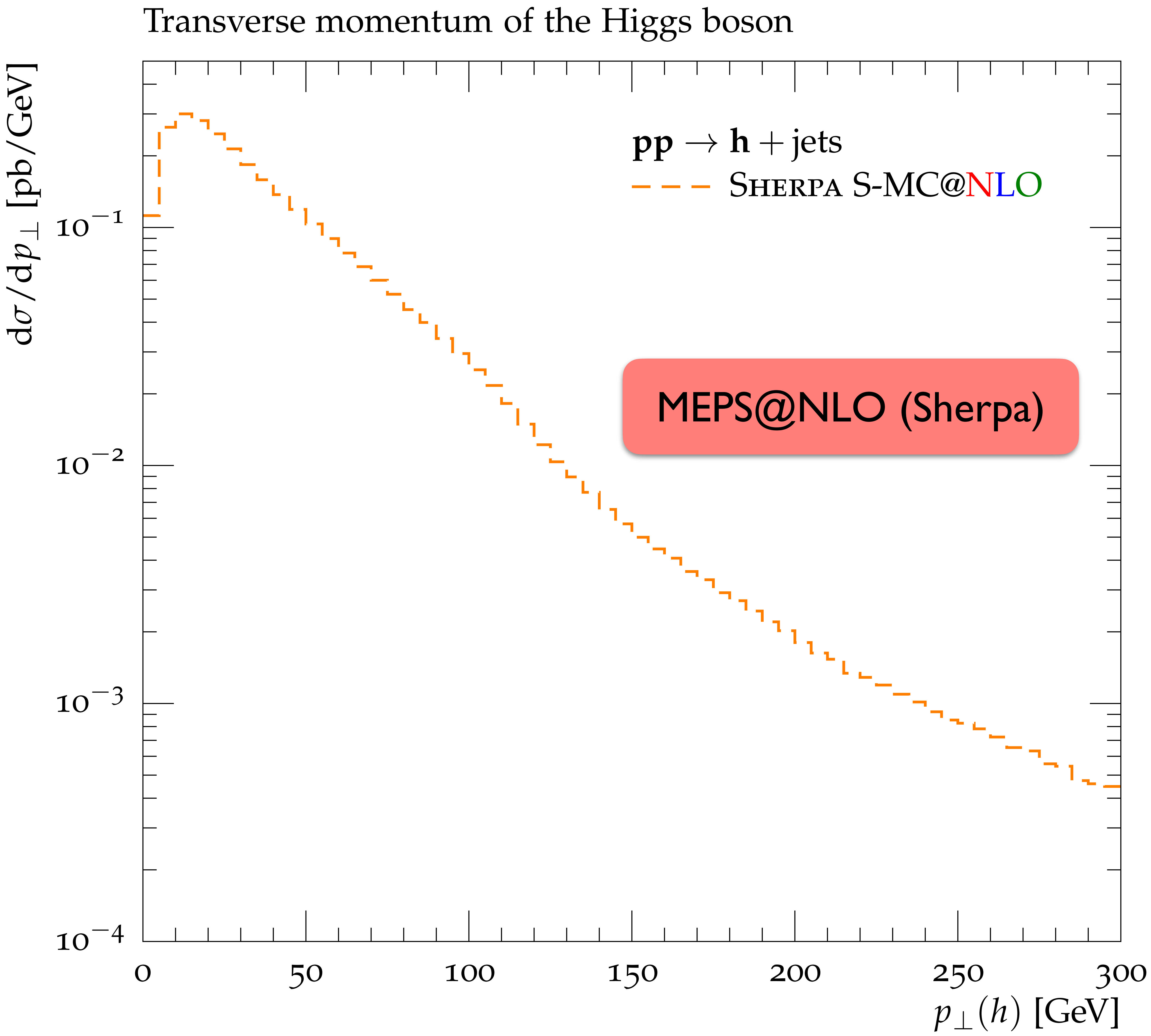
	X	X+jet	X+2jets	X+3jets	X+nj(n>3)
X@LO	LO	—	—	—	—
X@LO+PS	LO	PS	PS	PS	PS
X@NLO	NLO	LO	—	—	—
X@NLO+PS	NLO	LO	PS	PS	PS
X+0,1j@NLO+PS	NLO	NLO	LO	PS	PS
X+0,1,2j@NLO+PS	NLO	NLO	NLO	LO	PS

✦ idea very similar at NLO, but need to account for overlap in matrix elements

✦ X@NLO+PS, X+2,..,nj@LO+PS merging method: MENLOPS

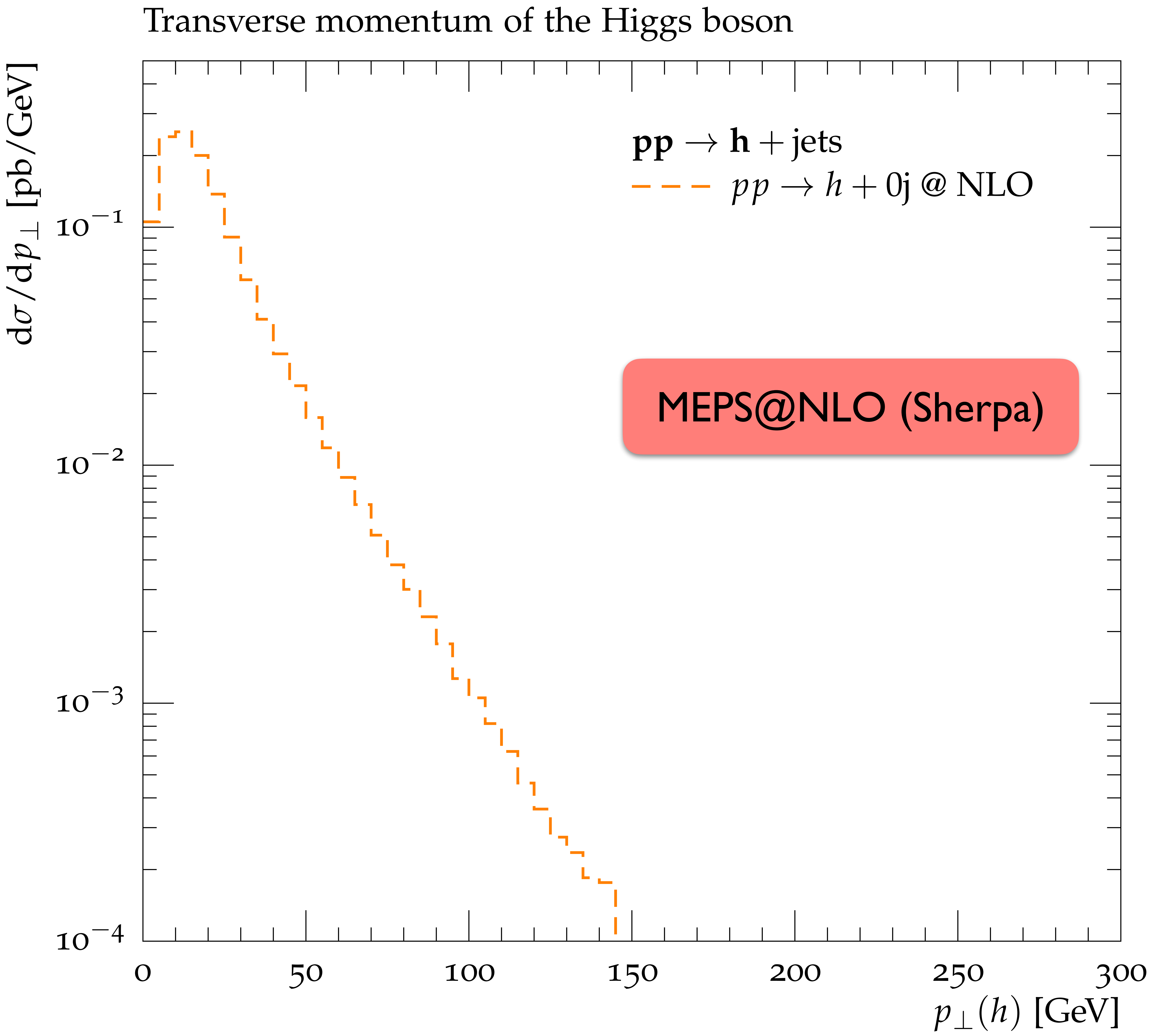
✦ X+0,…,nj@NLO+PS: MEPS@NLO (Sherpa) FxFx (MG5) MiNLO (Powheg) UNLOPS

NLO+PS merging: Example #1



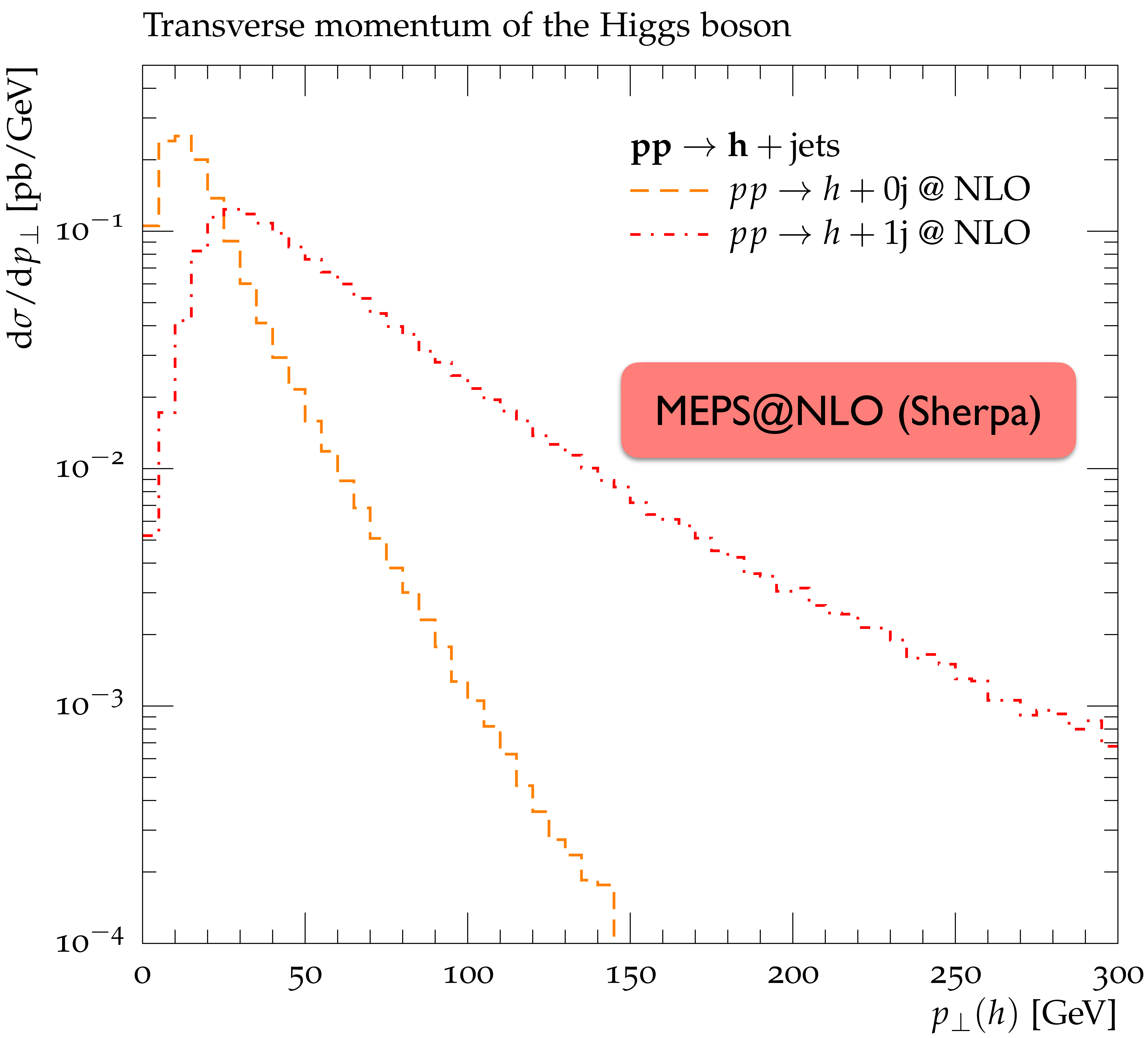
✦ start from MC@NLO for Higgs+0-jet

NLO+PS merging: Example #1



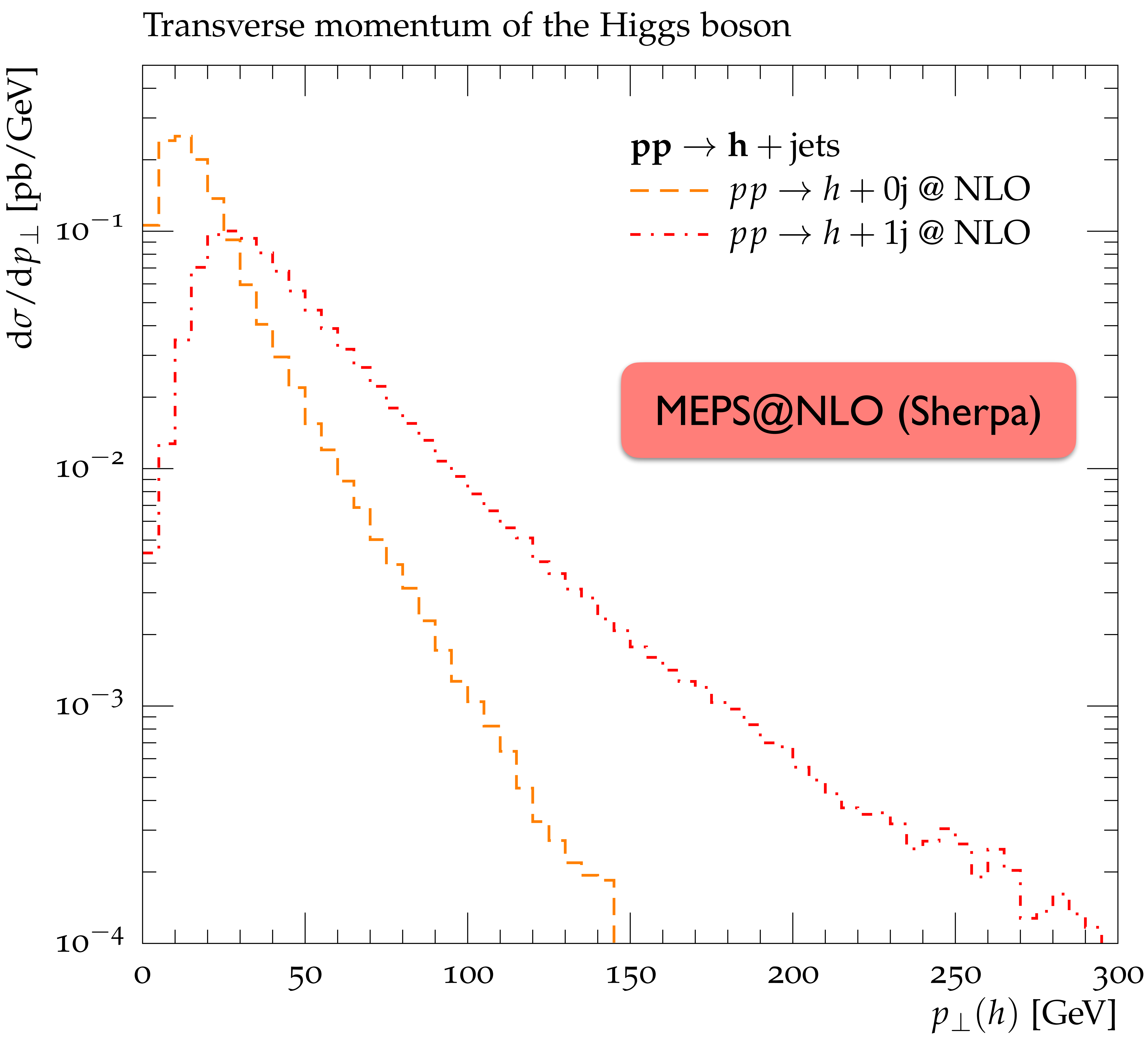
- ✦ start from MC@NLO for Higgs+0-jet
  ➙ restrict first emission $r_0 < Q_{\text{cut}}$

NLO+PS merging: Example #1



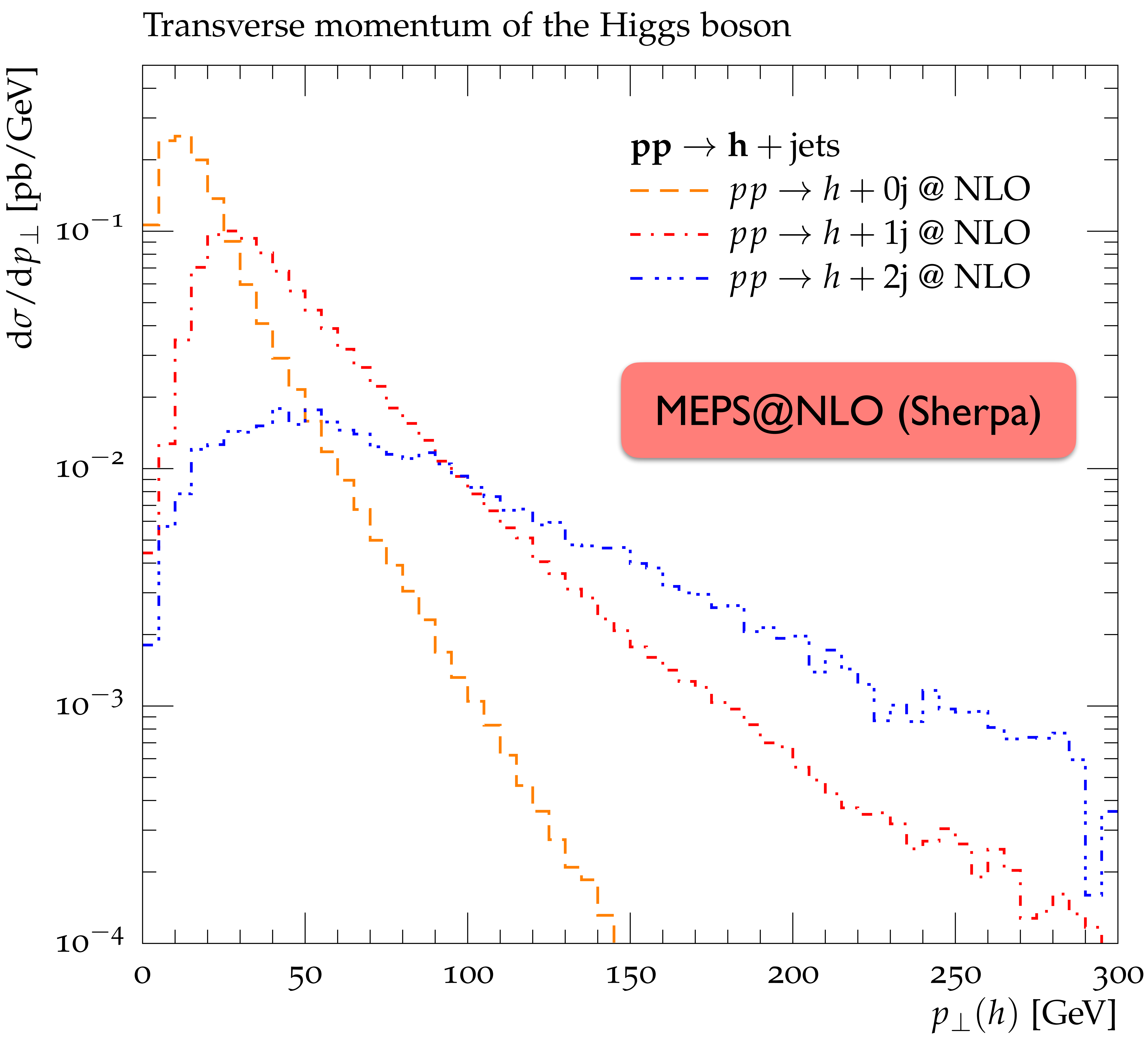
- start from MC@NLO for Higgs+0-jet
  → restrict first emission $r_0 < Q_{cut}$
- MC@NLO for Higgs+1-jet for $r_0 > Q_{cut}$

NLO+PS merging: Example #1



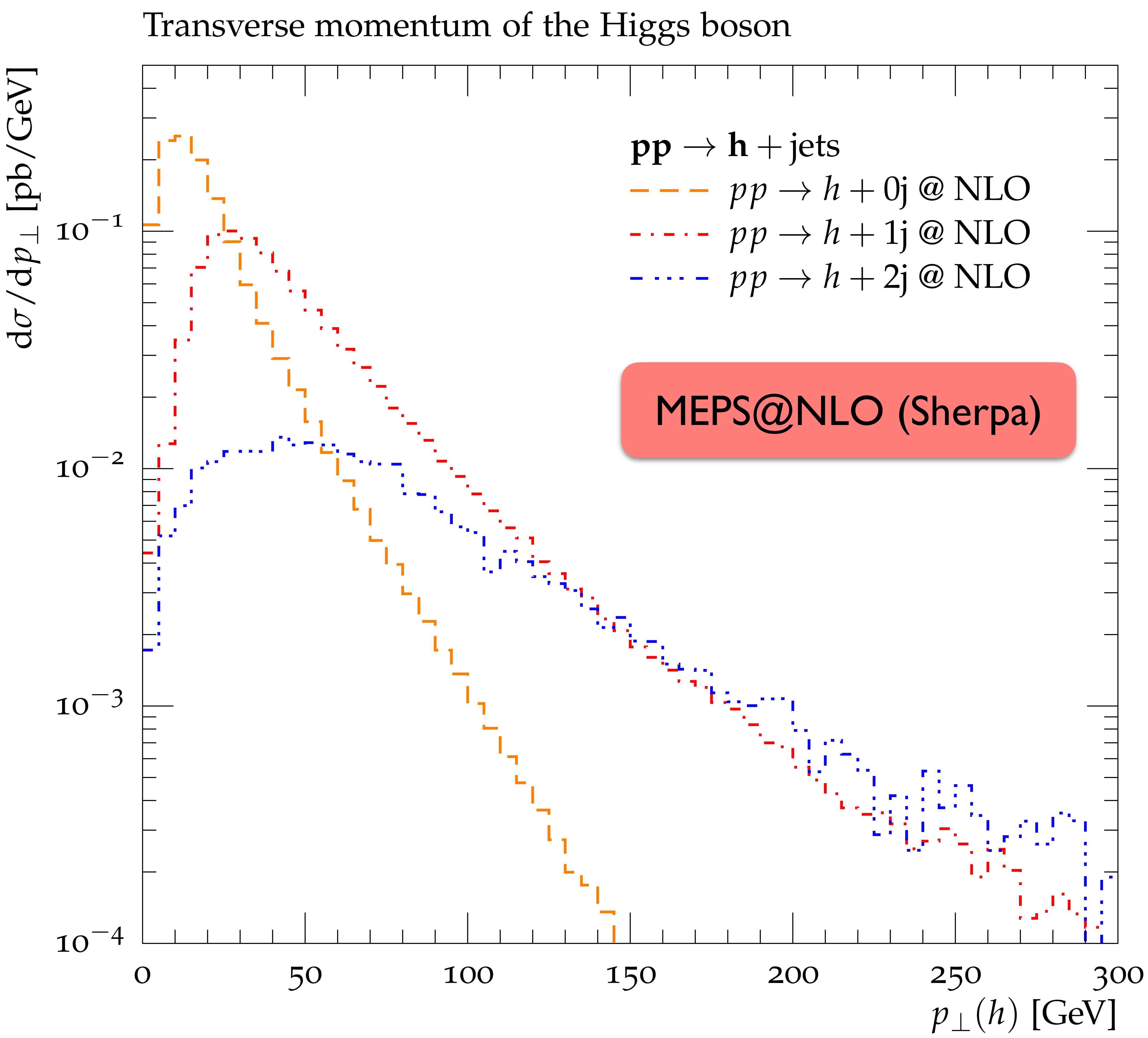
- ✦ start from MC@NLO for Higgs+0-jet
  ➞ restrict first emission $r_0 < Q_{\mathrm{cut}}$
- ✦ MC@NLO for Higgs+1-jet for $r_0 > Q_{\mathrm{cut}}$
  ➞ restrict extra emission $r_1 < Q_{\mathrm{cut}}$

NLO+PS merging: Example #1



- start from MC@NLO for Higgs+0-jet
  → restrict first emission $r_0 < Q_{\text{cut}}$
- MC@NLO for Higgs+1-jet for $r_0 > Q_{\text{cut}}$
  → restrict extra emission $r_1 < Q_{\text{cut}}$
- MC@NLO for Higgs+2-jet for $r_1 > Q_{\text{cut}}$

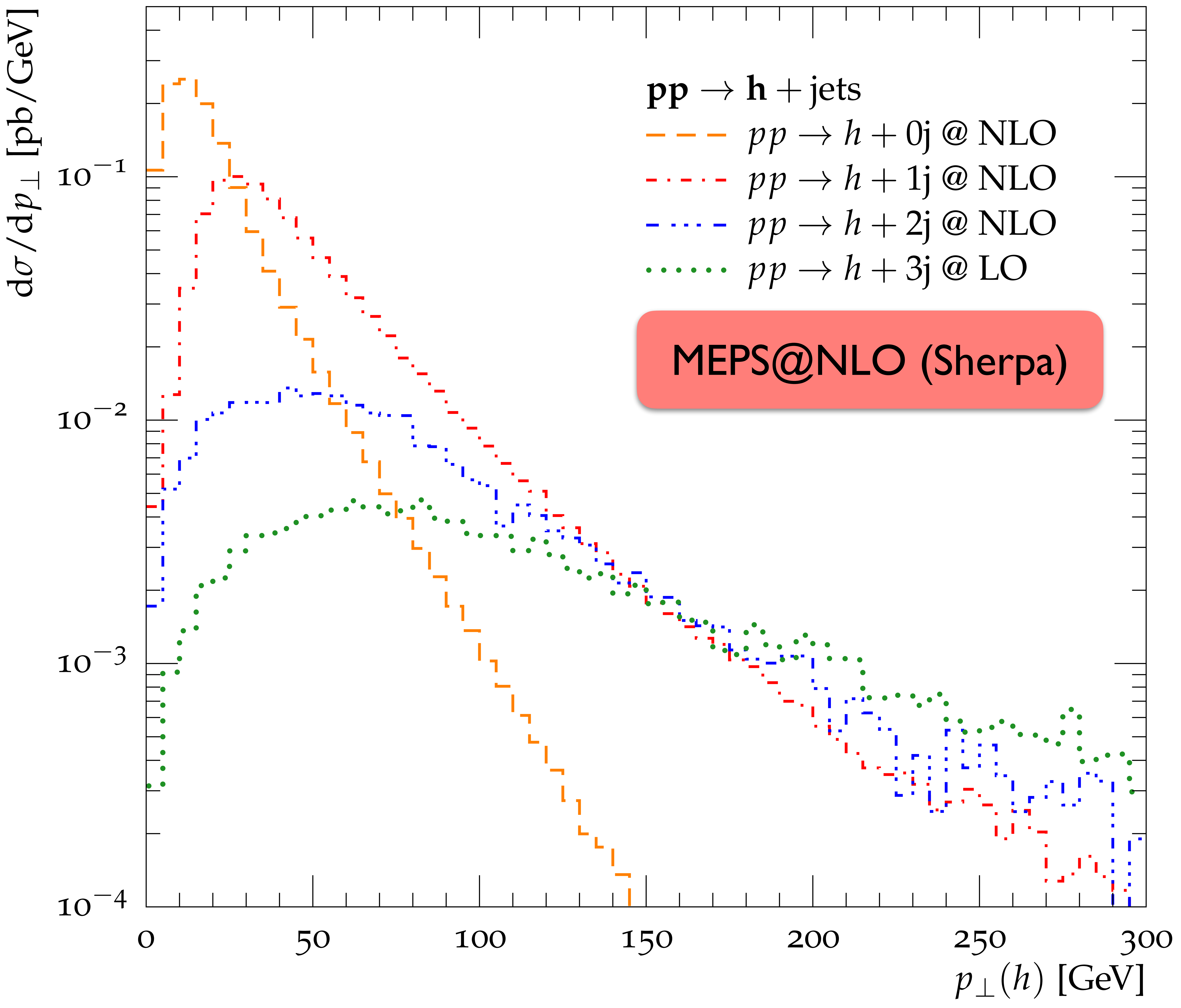
NLO+PS merging: Example #1



- ✦ start from MC@NLO for Higgs+0-jet
  ➙ restrict first emission $r_0 < Q_{\text{cut}}$
- ✦ MC@NLO for Higgs+1-jet for $r_0 > Q_{\text{cut}}$
  ➙ restrict extra emission $r_1 < Q_{\text{cut}}$
- ✦ MC@NLO for Higgs+2-jet for $r_1 > Q_{\text{cut}}$
  ➙ restrict extra emission $r_2 < Q_{\text{cut}}$

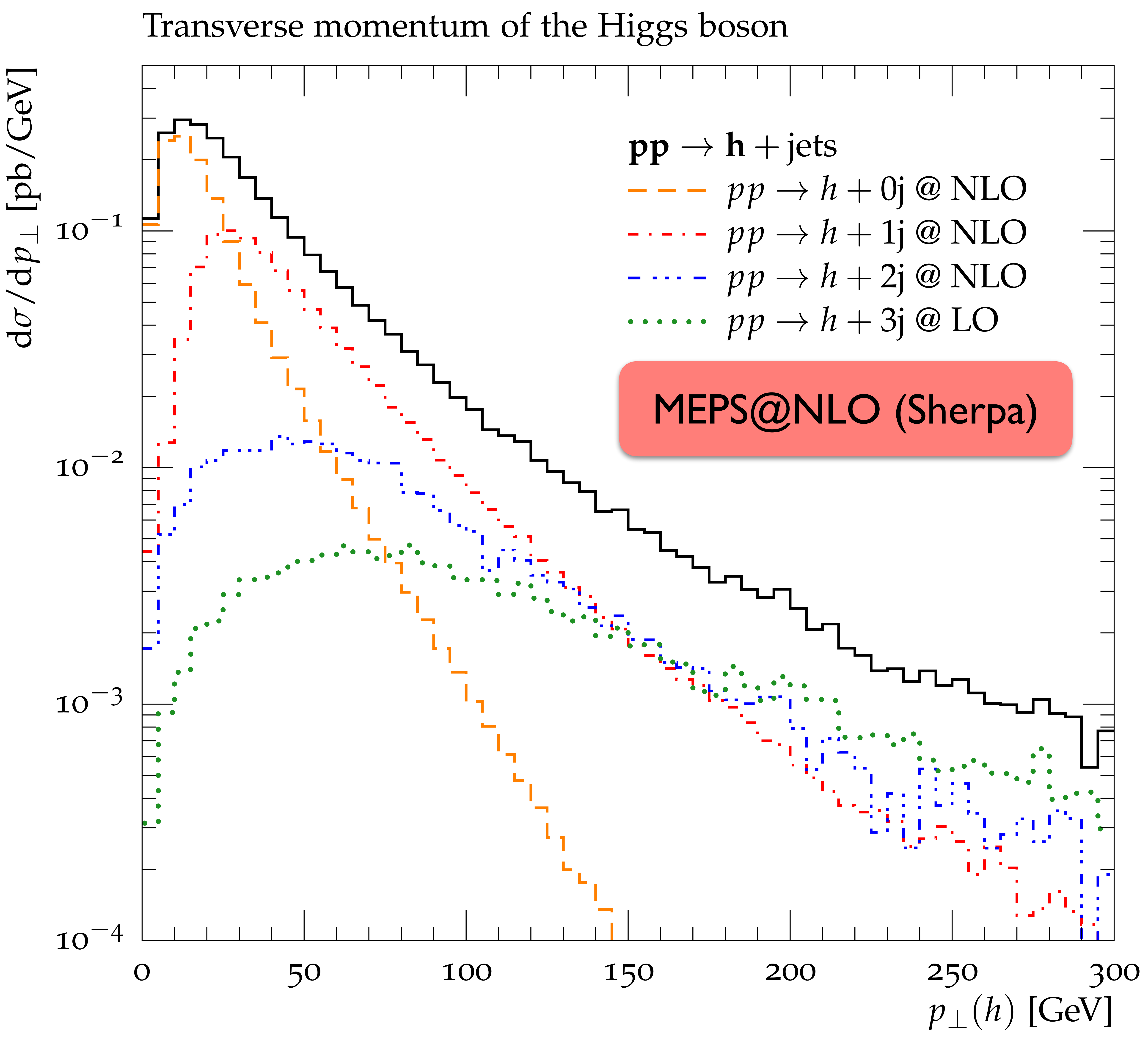
NLO+PS merging: Example #1

Transverse momentum of the Higgs boson



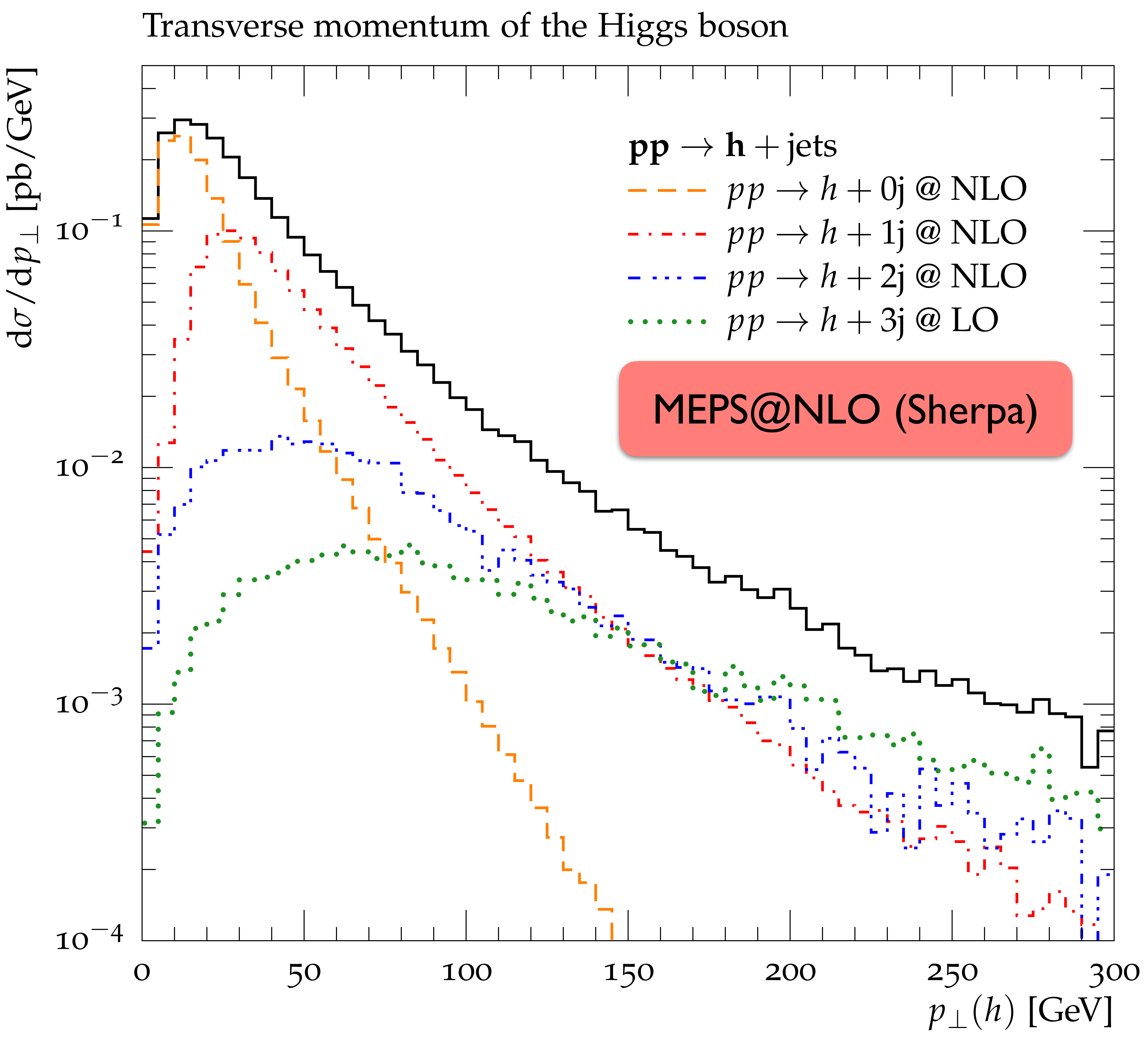
- start from MC@NLO for Higgs+0-jet
  ➙ restrict first emission $r_0 < Q_{\text{cut}}$
- MC@NLO for Higgs+1-jet for $r_0 > Q_{\text{cut}}$
  ➙ restrict extra emission $r_1 < Q_{\text{cut}}$
- MC@NLO for Higgs+2-jet for $r_1 > Q_{\text{cut}}$
  ➙ restrict extra emission $r_2 < Q_{\text{cut}}$
- LO+PS for Higgs+3-jet for $r_2 > Q_{\text{cut}}$ (MEPS@NLO/Sherpa specific)
  ➙ no restriction on further radiation (keep PS)

NLO+PS merging: Example #1



- ✦ start from MC@NLO for Higgs+0-jet
  ➙ restrict first emission $r_0 < Q_{\text{cut}}$
- ✦ MC@NLO for Higgs+1-jet for $r_0 > Q_{\text{cut}}$
  ➙ restrict extra emission $r_1 < Q_{\text{cut}}$
- ✦ MC@NLO for Higgs+2-jet for $r_1 > Q_{\text{cut}}$
  ➙ restrict extra emission $r_2 < Q_{\text{cut}}$
- ✦ LO+PS for Higgs+3-jet for $r_2 > Q_{\text{cut}}$ (MEPS@NLO/Sherpa specific)
  ➙ no restriction on further radiation (keep PS)
- ✦ sum all together ➙ Higgs+0,1,2j@NLO+PS

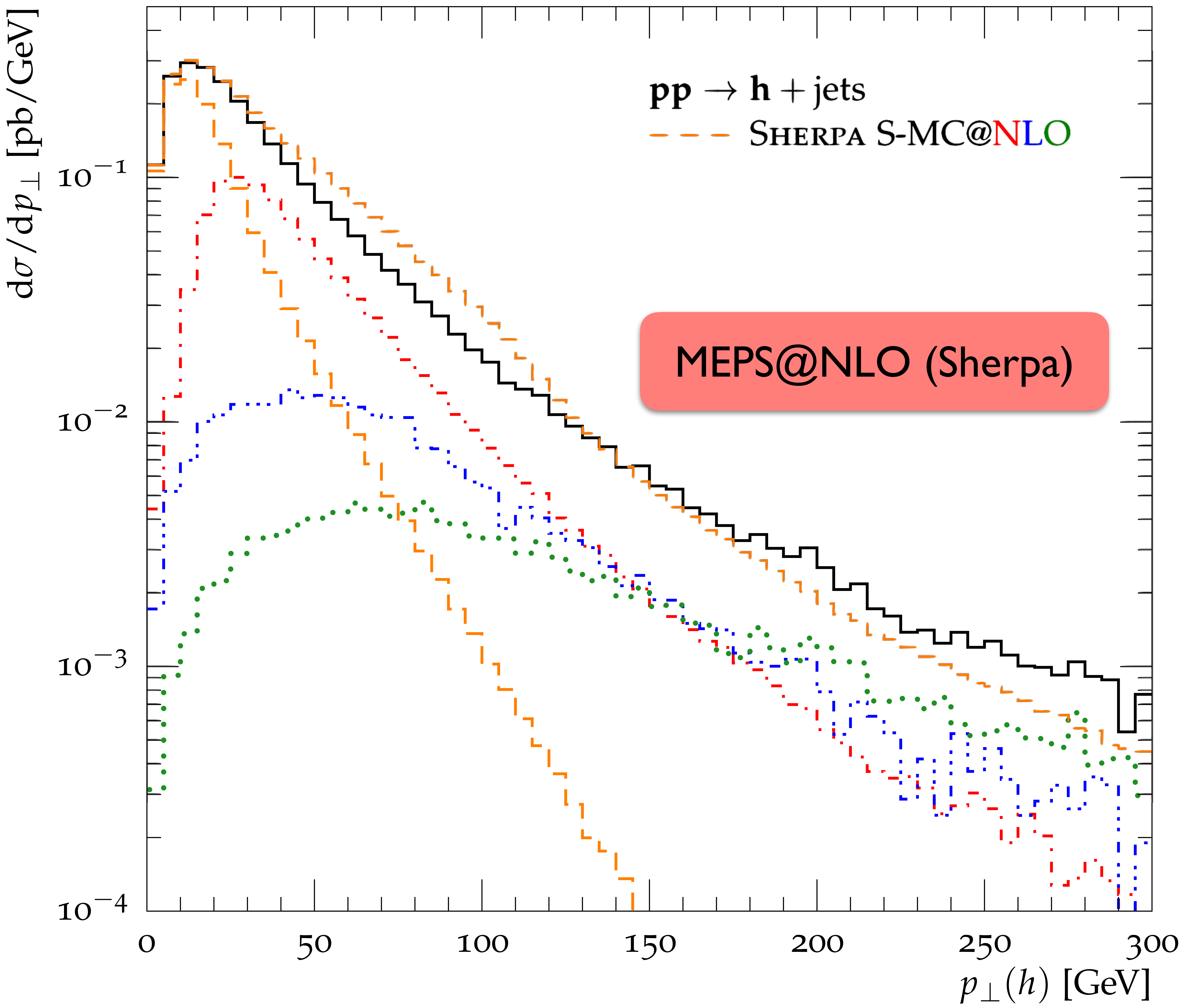
NLO+PS merging: Example #1



- start from MC@NLO for Higgs+0-jet
  ➙ restrict first emission $r_0 < Q_{\mathrm{cut}}$
- MC@NLO for Higgs+1-jet for $r_0 > Q_{\mathrm{cut}}$
  ➙ restrict extra emission $r_1 < Q_{\mathrm{cut}}$
- MC@NLO for Higgs+2-jet for $r_1 > Q_{\mathrm{cut}}$
  ➙ restrict extra emission $r_2 < Q_{\mathrm{cut}}$
- LO+PS for Higgs+3-jet for $r_2 > Q_{\mathrm{cut}}$ (MEPS@NLO/Sherpa specific)
  ➙ no restriction on further radiation (keep PS)
- sum all together ➙ Higgs+0,1,2j@NLO+PS
- high p_T receives multiple contributions

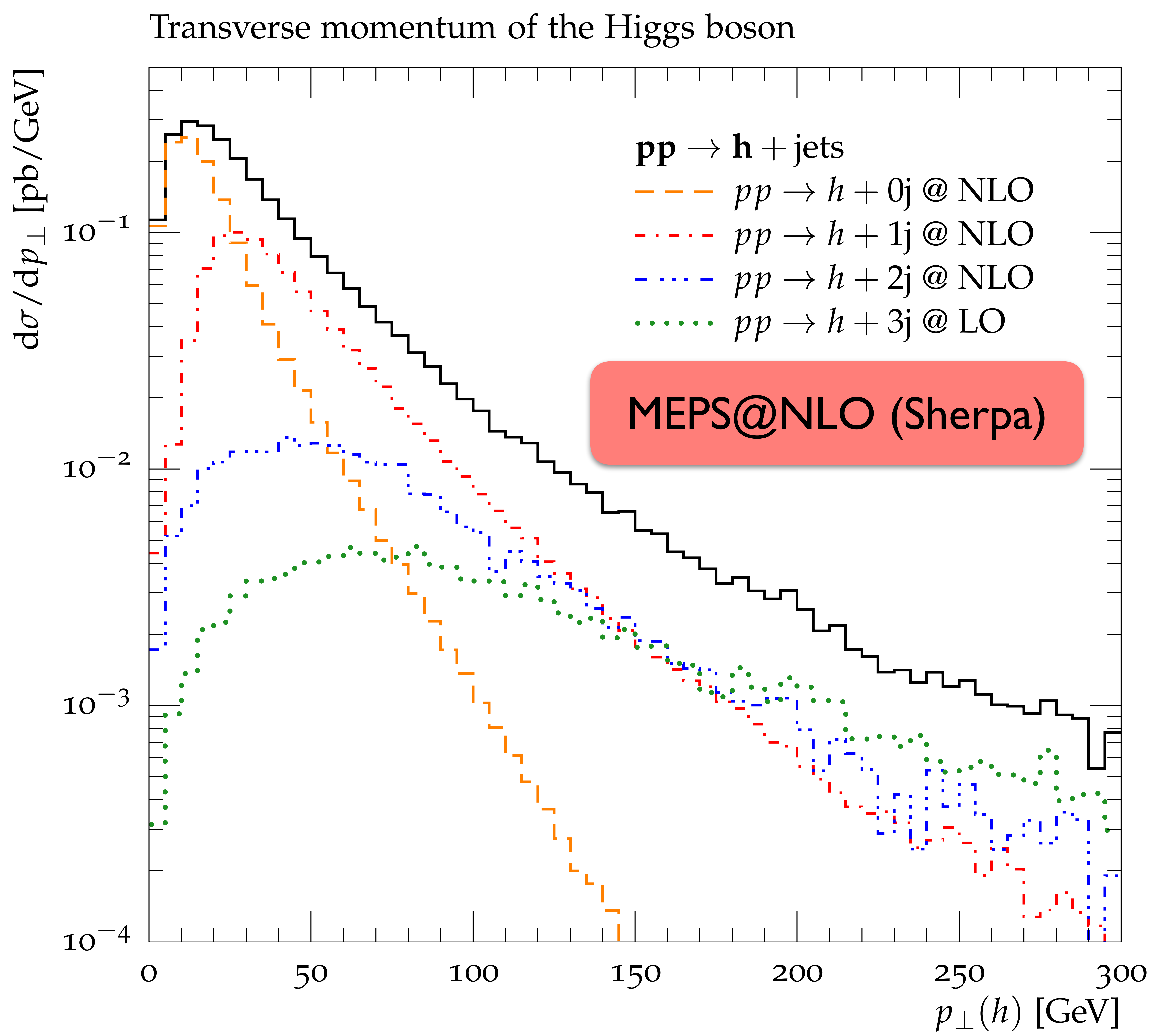
NLO+PS merging: Example #1

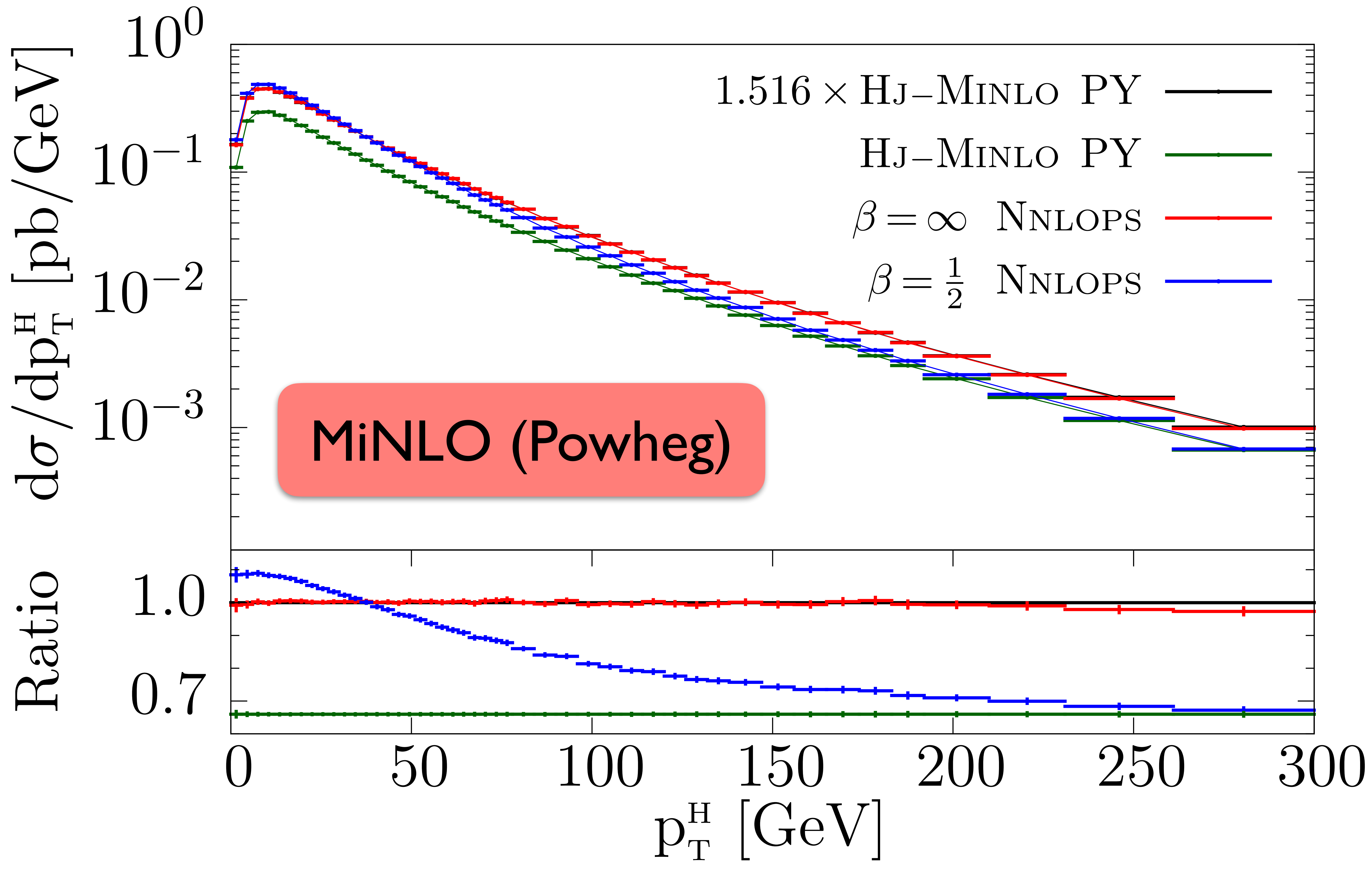
Transverse momentum of the Higgs boson



- start from MC@NLO for Higgs+0-jet
  ➙ restrict first emission $r_0 < Q_{\text{cut}}$
- MC@NLO for Higgs+1-jet for $r_0 > Q_{\text{cut}}$
  ➙ restrict extra emission $r_1 < Q_{\text{cut}}$
- MC@NLO for Higgs+2-jet for $r_1 > Q_{\text{cut}}$
  ➙ restrict extra emission $r_2 < Q_{\text{cut}}$
- LO+PS for Higgs+3-jet for $r_2 > Q_{\text{cut}}$ (MEPS@NLO/Sherpa specific)
  ➙ no restriction on further radiation (keep PS)
- sum all together ➙ Higgs+0,1,2j@NLO+PS
- high p_T receives multiple contributions
- smoother than MC@NLO for Higgs+0-jet

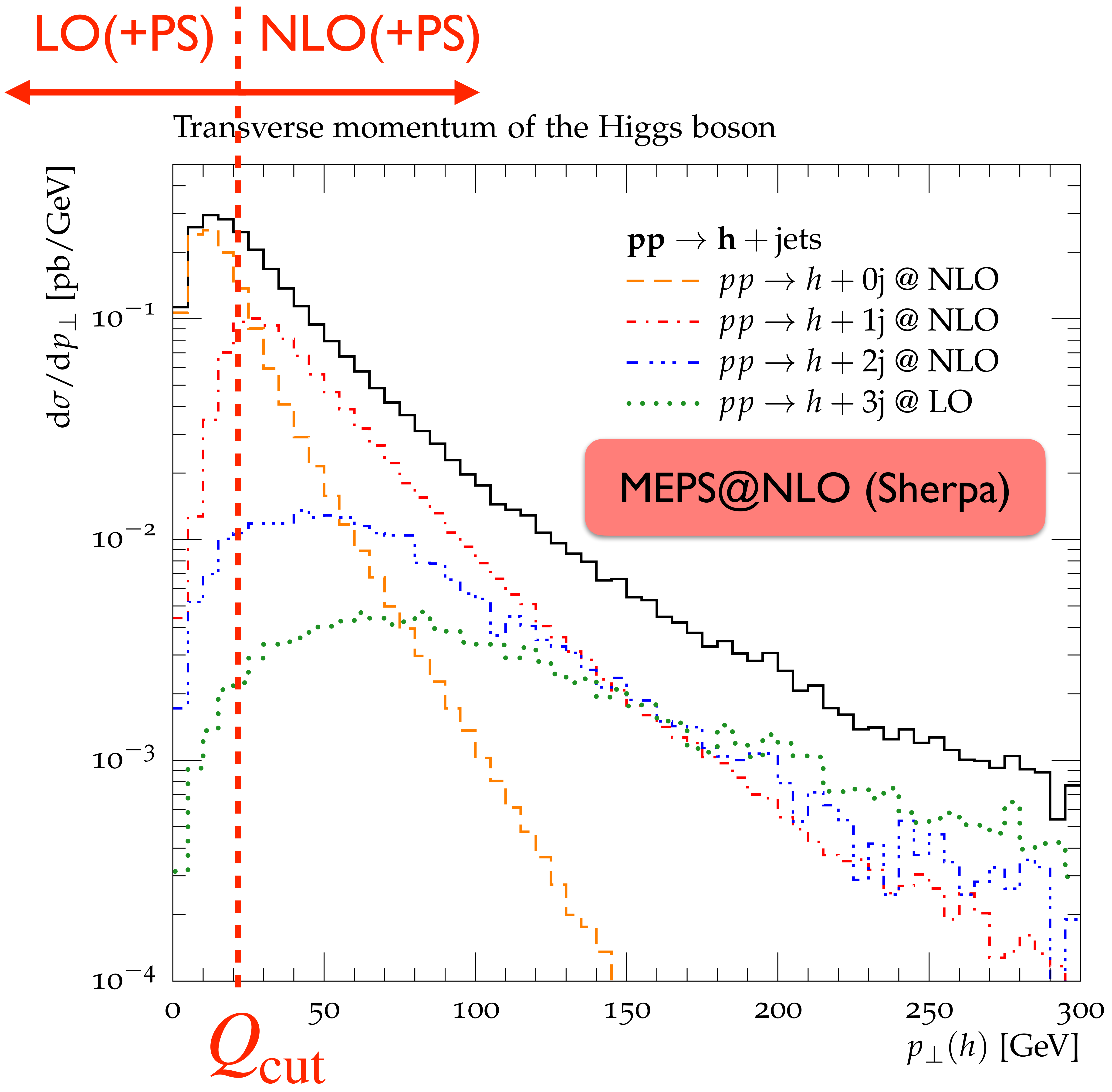
NLO+PS merging: Example #2

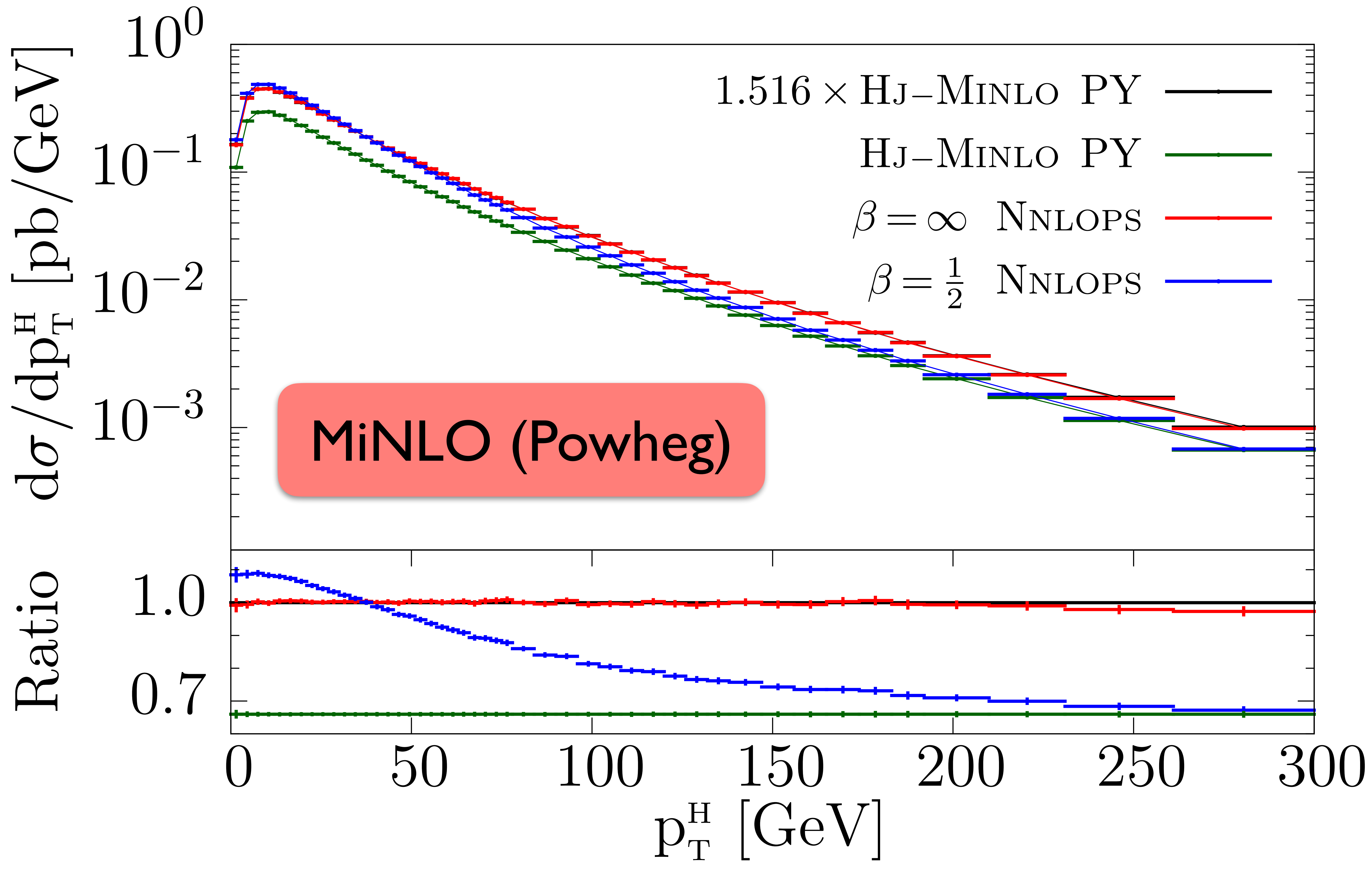




$p_\perp(h) \simeq$ H+1-jet

NLO+PS merging: Example #2

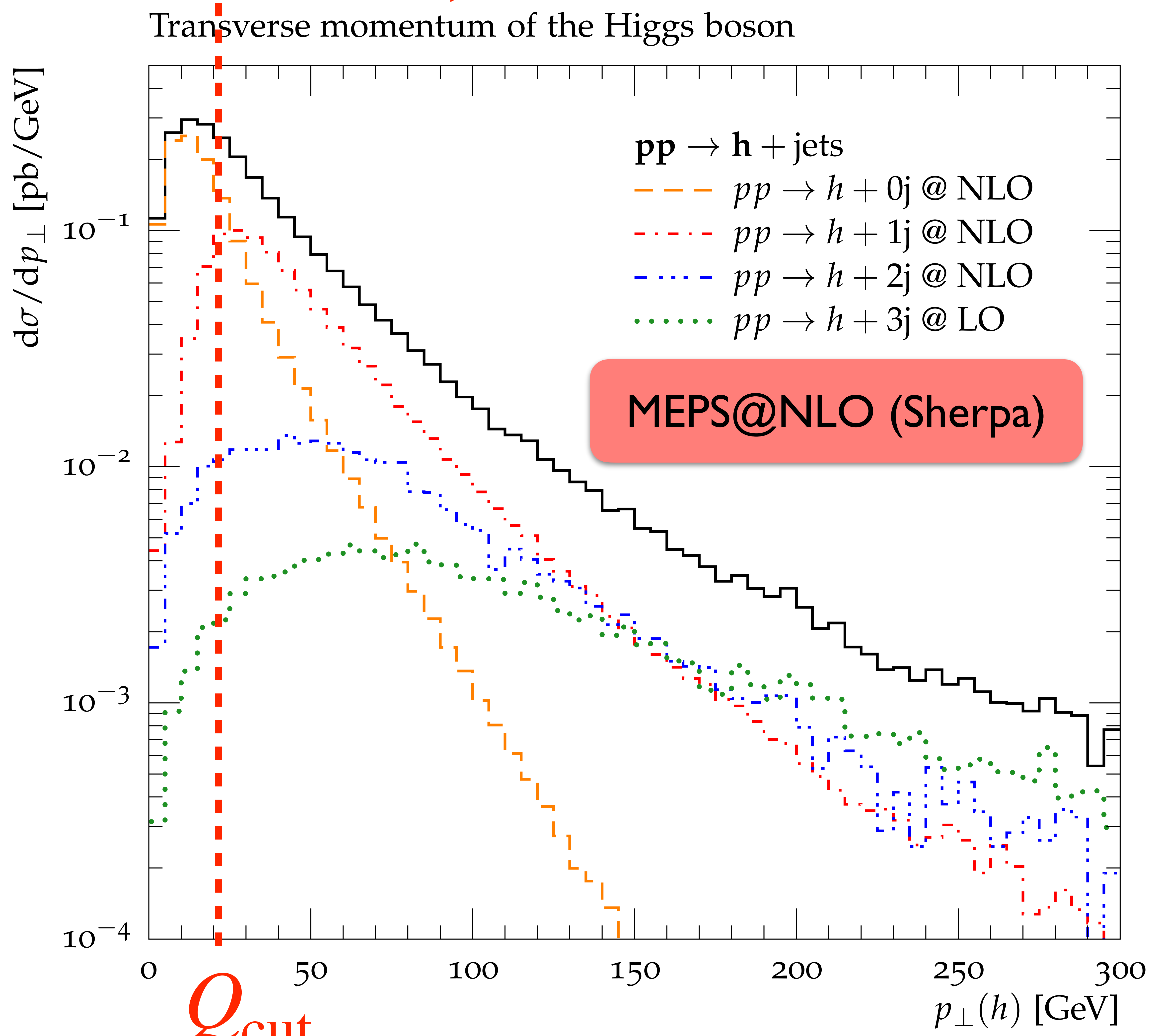




NLO+PS merging: Example #2

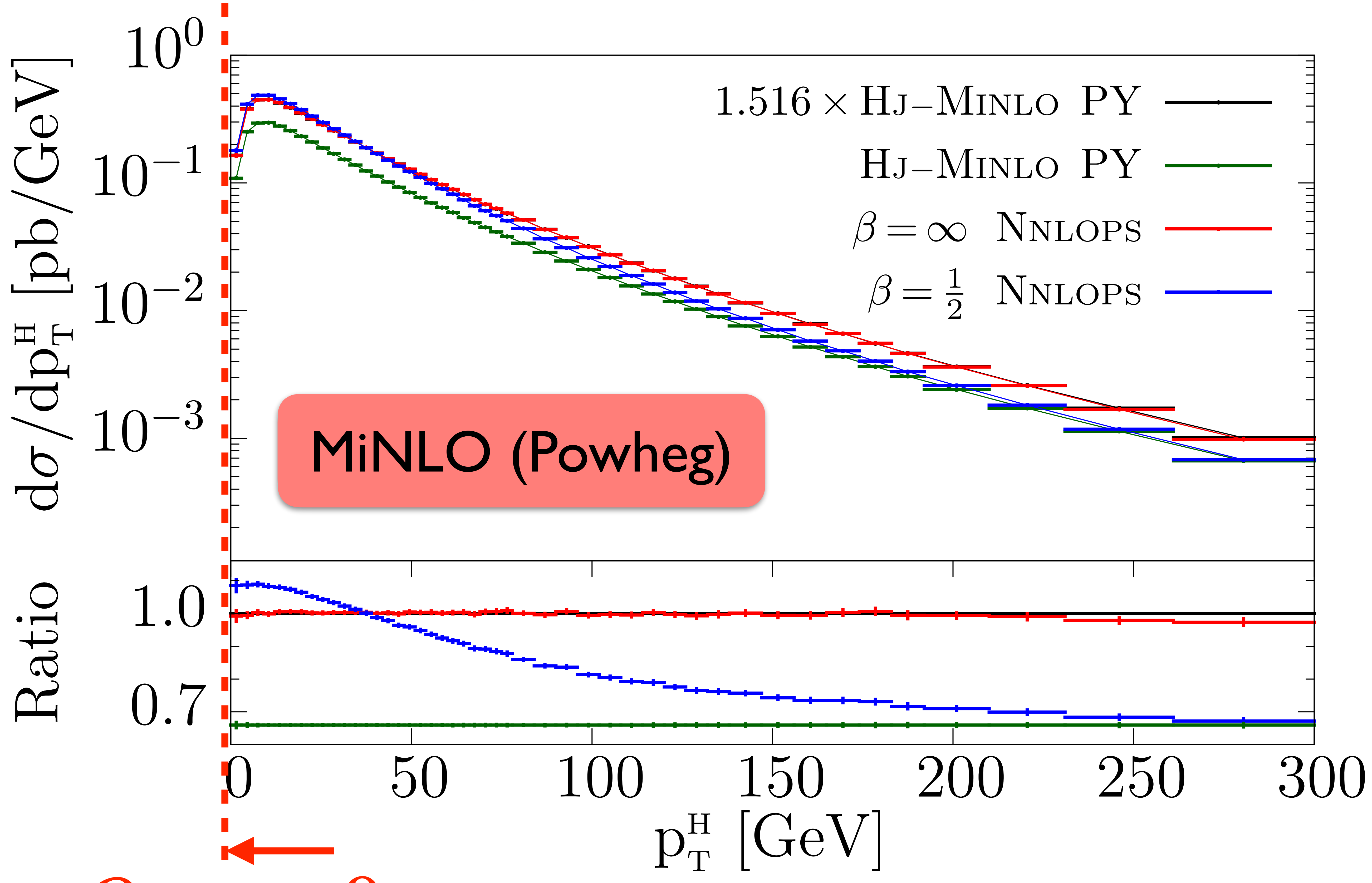
$p_\perp(h) \simeq$ H+1-jet

LO(+PS) | NLO(+PS)



Q_{cut}

NLO(+PS) $p_\perp(h) \simeq$ H+1-jet



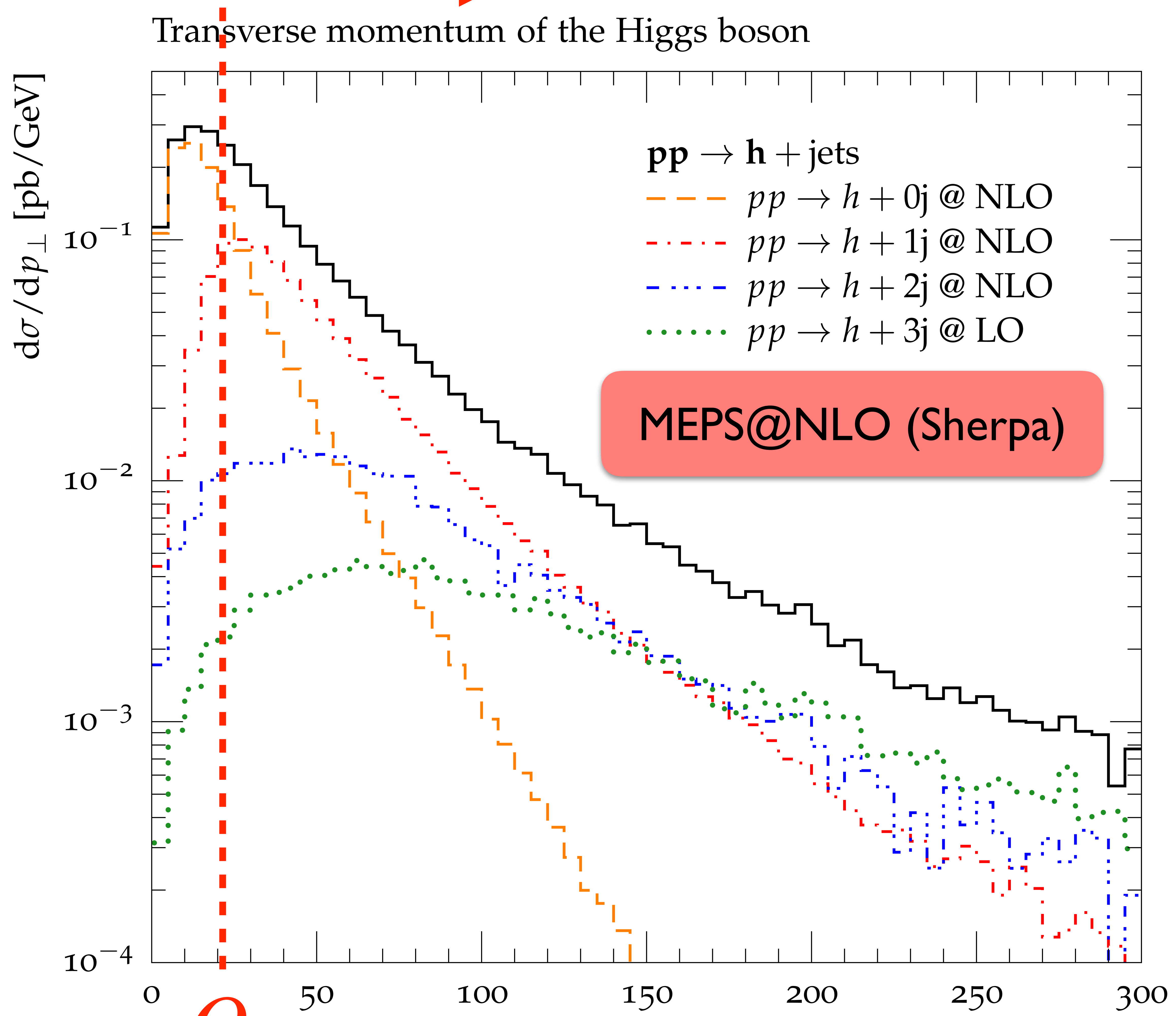
$Q_{cut} \to 0$

no merging scale!

NLO+PS merging: Example #2

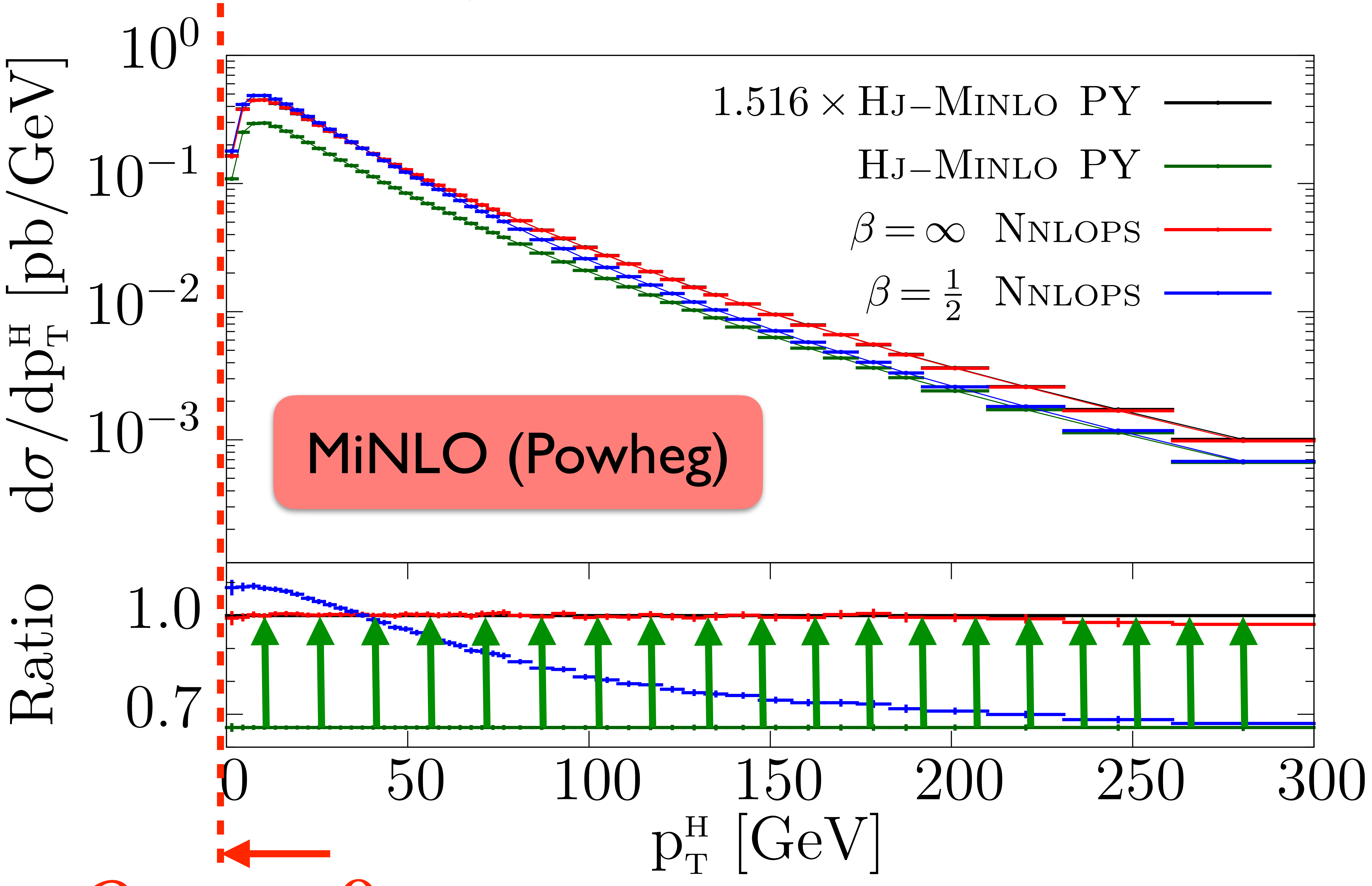
$p_\perp(h) \simeq$ H+1-jet

LO(+PS) | NLO(+PS)



$Q_{\rm cut}$

NLO(+PS) $p_\perp(h) \simeq$ H+1-jet



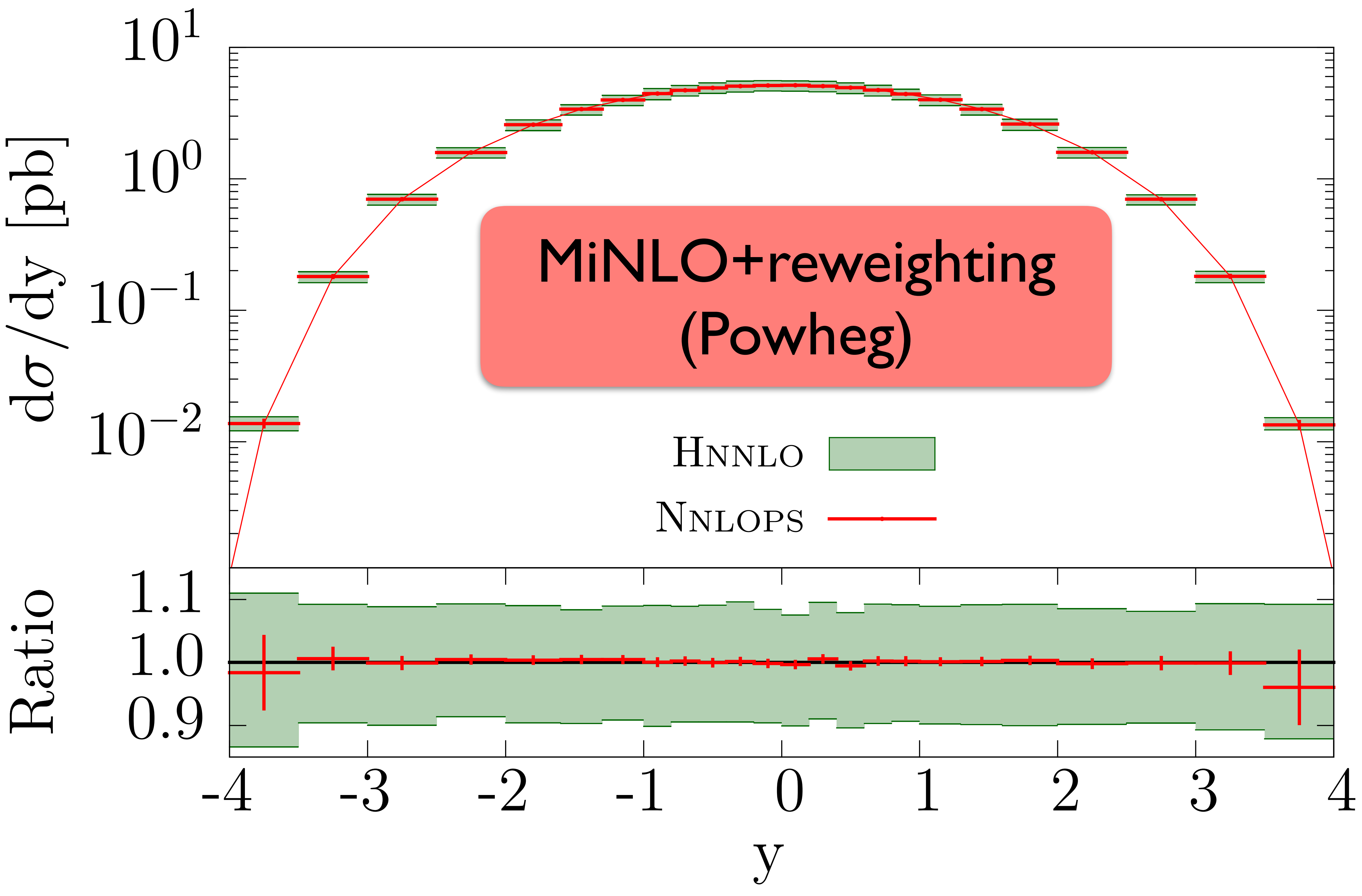
$Q_{\rm cut} \to 0$

no merging scale!

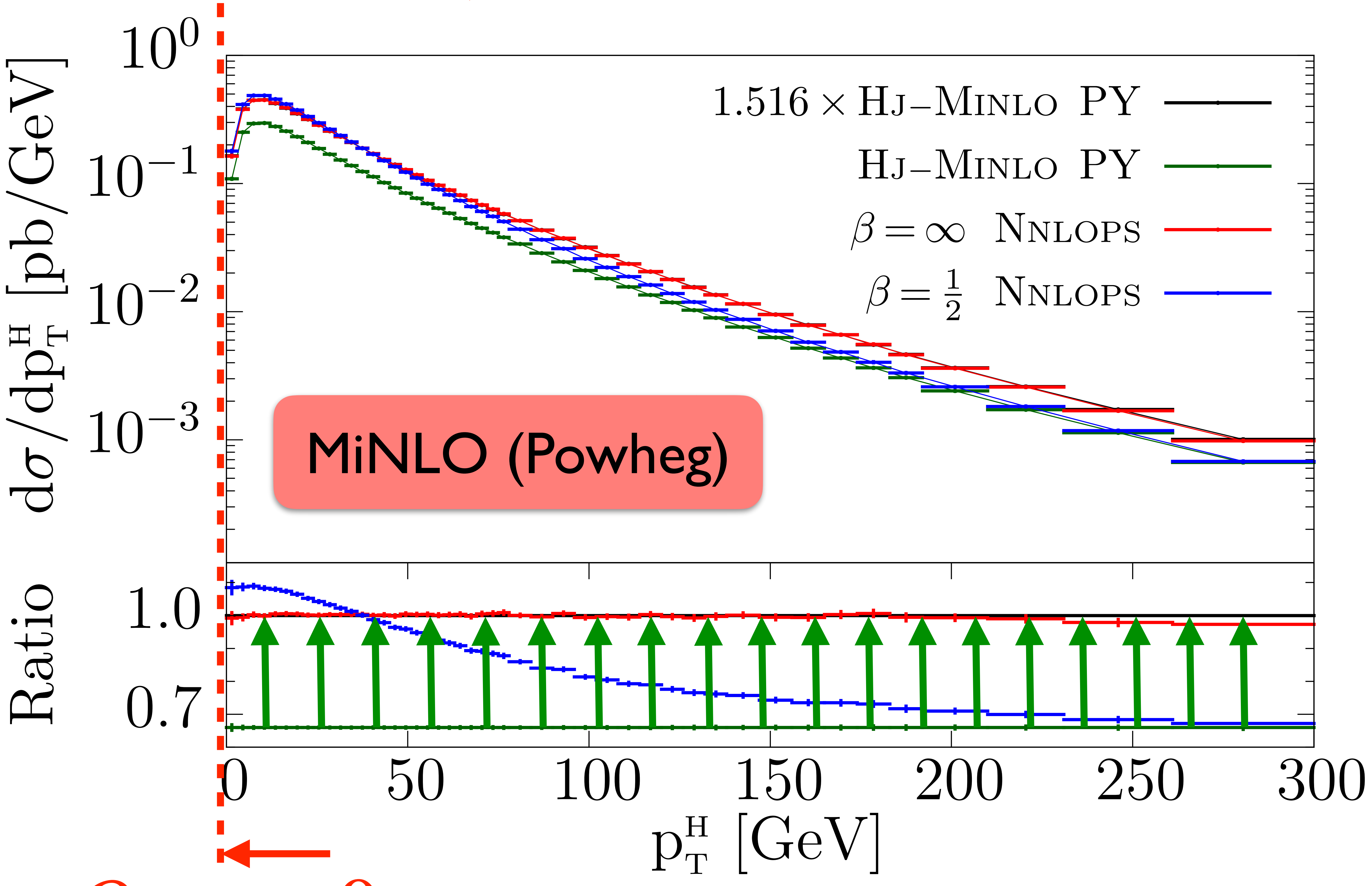
use reweighting to NNLO

(fully differential in Born)

NLO+PS merging: Example #2



NLO(+PS) $p_\perp(h) \simeq$ H+1-jet



$Q_{\text{cut}} \to 0$

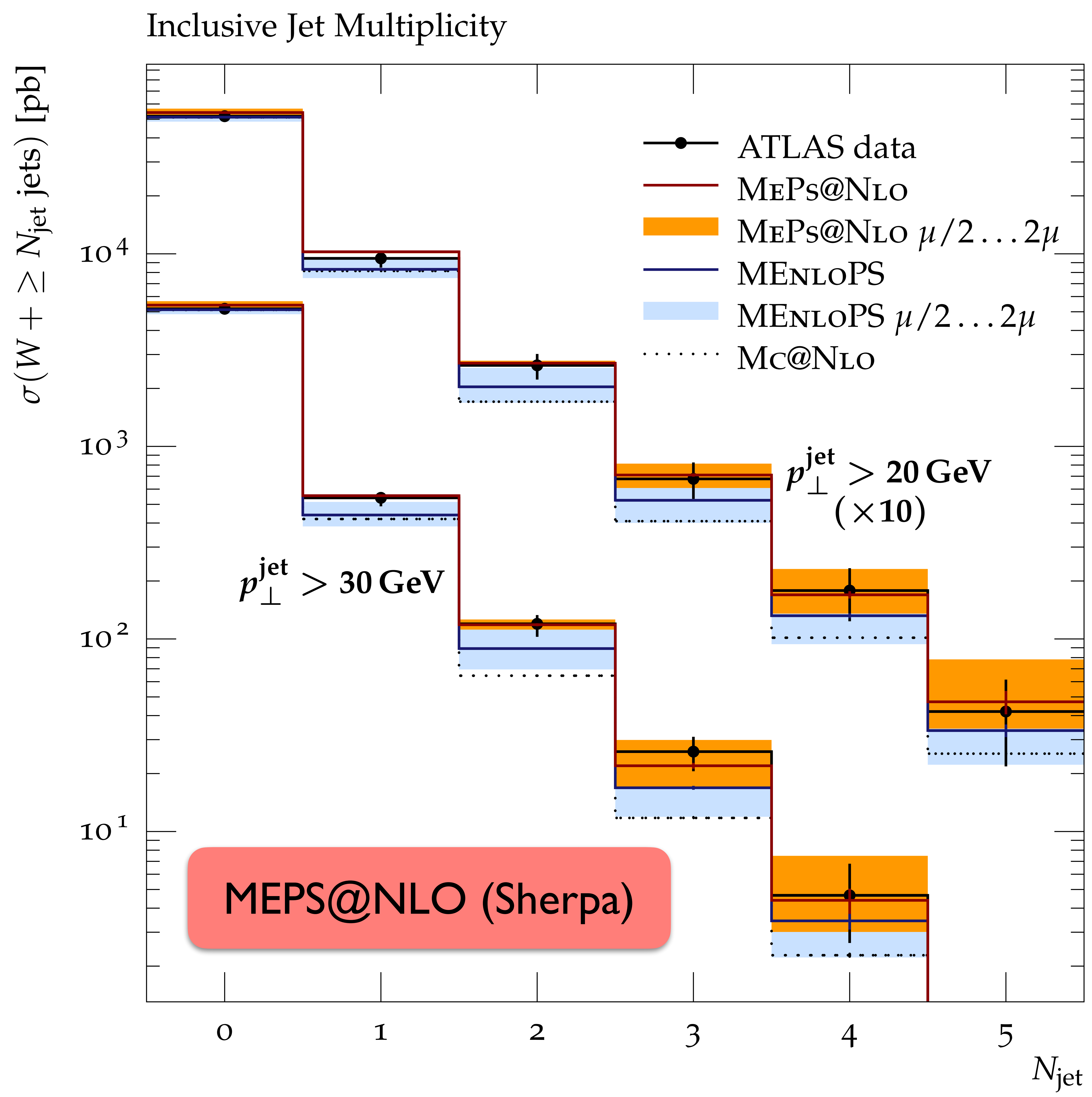
no merging scale!

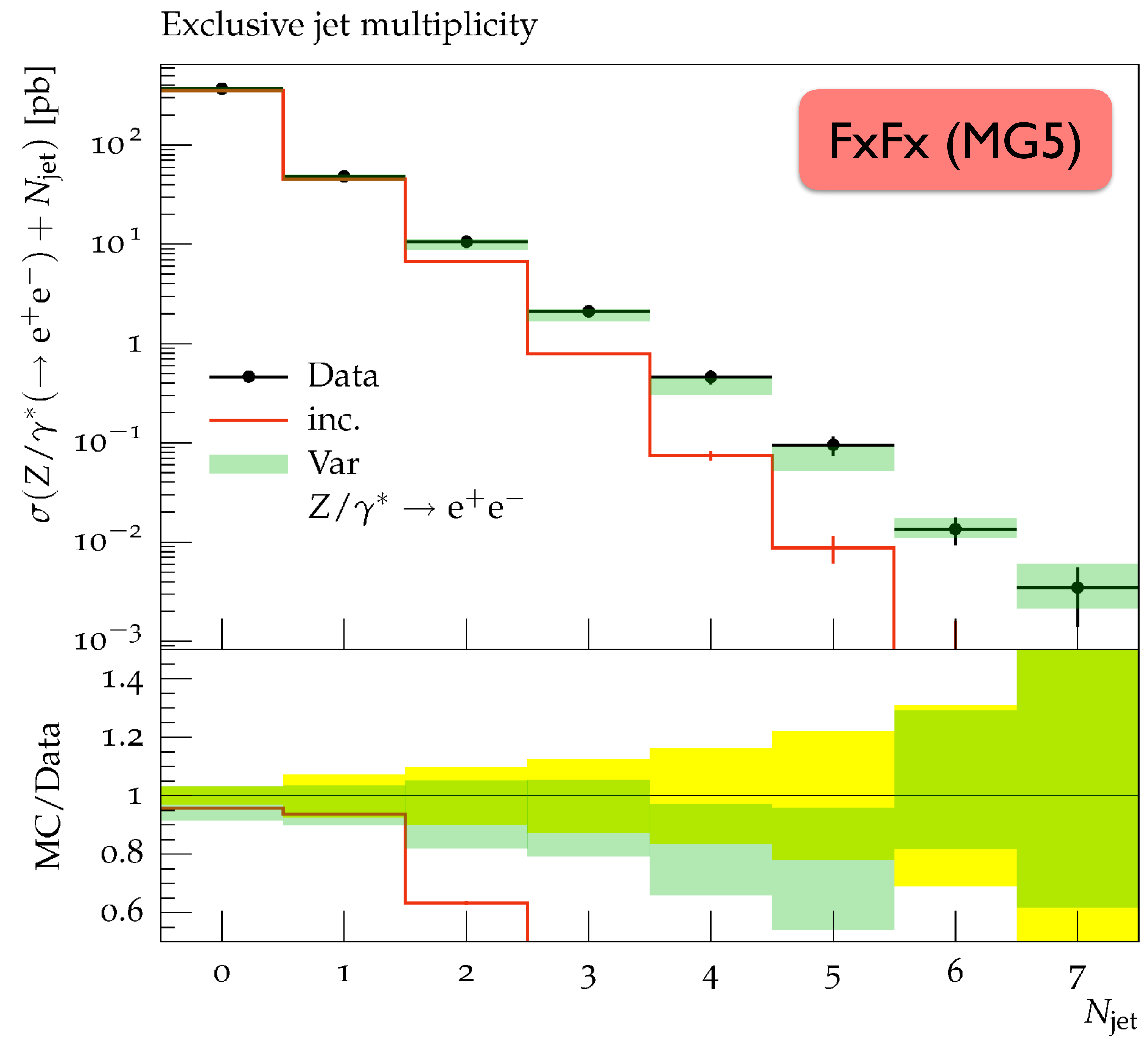
use reweighting to NNLO

(fully differential in Born)

NLO+PS merging: Example #2

NLO+PS merging: Example #3





Questions?

NNLO+PS: What do we want to achieve?

- NNLO accuracy for observables inclusive on radiation. $[d\sigma/dy_F]$
- NLO(LO) accuracy for $F+1(2)$ jet observables (in the hard region). $[d\sigma/dp_{T,j_1}]$
  - appropriate scale choice for each kinematics regime
- resummation from the Parton Shower (PS) $[\sigma(p_{T,j} < p_{T,\text{veto}})]$
- preserve the PS accuracy (leading log - LL)
- possibly, no merging scale required.

	X	X+jet	X+2jets	X+nj (n>2)
XJ (NLO)	—	NLO	LO	—
XJ-MiNLO	NLO	NLO	LO	PS
X@NNLO	NNLO	NLO	LO	—
X@NNLOPS	NNLO	NLO	LO	PS

NNLO+PS methods

NNLOPS: MiNLO+reweighting

[Hamilton, Nason, Oleari, Zanderighi '12, + Re '13], [Karlberg, Re, Zanderighi '14]

✦ LL accuracy (+ simple NLL terms) from PS
✦ no new unphysical scale (i.e. physically sound)
✦ numerically very intensive
✦ applied beyond 2→1 processes

Geneva

[Alioli, Bauer, Berggren, Tackmann, Walsh '15 + Zuberi '13]

✦ LL accuracy from PS (at most! no NNLL nonesense!)
✦ slicing cutoff (missing power corrections)
✦ numerical cancellations in slicing parameter
✦ applied beyond 2→1 processes

MiNNLO$_{PS}$

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ LL accuracy (+ simple NLL terms) from PS
✦ no new unphysical scale (i.e. physically sound)
✦ numerically efficient
✦ applied beyond 2→1 and even beyond colour singlet

UNNLOPS

[Höche, Prestel '14 '15]

✦ extension of UNLOPS merging of event samples
✦ two-loop corrections entirely in 0-jet bin
✦ only applied to 2→1 processes

there was also some recent progress on NNLO+PS for sector showers [Campbell, Höche, Li, Preuss, Slands '21]

NNLO+PS timeline

NNLO+PS timeline

Milestones:

1. First development for simple $2 \to 1$ processes

NNLO+PS timeline

Milestones:

1. First development for simple $2 \to 1$ processes
2. Extension to $2 \to 2$ processes

NNLO+PS timeline

Milestones:

1. First development for simple $2 \to 1$ processes
2. Extension to $2 \to 2$ processes
3. Extension to heavy-quark pairs

NNLO+PS timeline

Milestones:

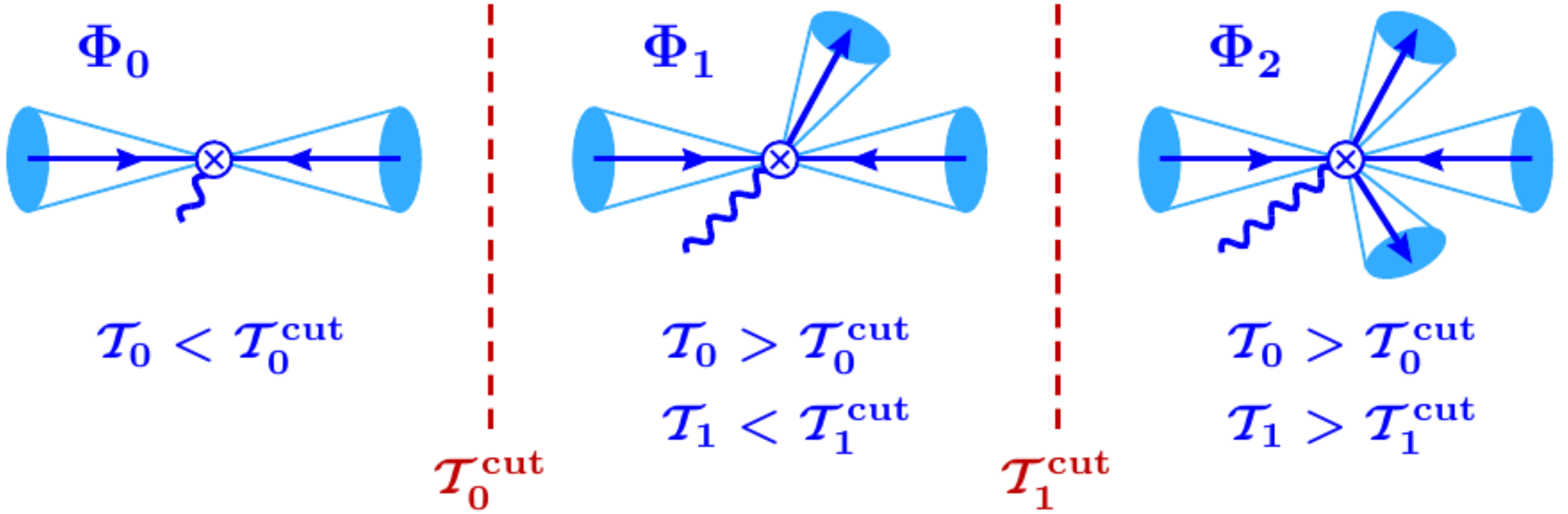
1. First development for simple $2 \to 1$ processes
2. Extension to $2 \to 2$ processes
3. Extension to heavy-quark pairs
4. Extension to heavy-quark pairs+colour singlet

NNLO+PS timeline

Milestones:

1. First development for simple $2 \to 1$ processes
2. Extension to $2 \to 2$ processes
3. Extension to heavy-quark pairs
4. Extension to heavy-quark pairs+colour singlet
5. ? next ? extension to jet processes ?

Geneva



Exclusive 0-jet bin	Exclusive 1-jet bin	Inclusive 2-jet bin
$\frac{d\sigma_0^{\text{MC}}}{d\Phi_0}(r_0^{\text{cut}})$	$\frac{d\sigma_1^{\text{MC}}}{d\Phi_1}(r_0 > r_0^{\text{cut}}; r_1^{\text{cut}})$	$\frac{d\sigma_2^{\text{MC}}}{d\Phi_2}(r_0 > r_0^{\text{cut}}, r_1 > r_1^{\text{cut}})$

$$d\sigma_F^{\text{MC}} = d\sigma_F^{\text{res}} + [d\sigma_{FJ}]_{\text{f.o.}} - [d\sigma_F^{\text{res}}]_{\text{f.o.}}$$

$$\frac{d\sigma_{FJ}^{\text{MC}}}{d\Phi_{FJ}}(r_0 > r_0^{\text{cut}}) = \frac{d\sigma^{\text{res}}}{d\Phi_F dr_0}\mathscr{P}(\Phi_{FJ}) + \frac{d\sigma^{\text{NLO}_{\text{FJ}}}}{d\Phi_{FJ}} - \left[\frac{d\sigma^{\text{res}}}{d\Phi_F dr_0}\mathscr{P}(\Phi_{FJ})\right]_{\text{NLO}}$$

✦ essentially q_T slicing, but spread by splitting function $\mathscr{P}$

MiNLO+rew / MiNNLO$_{\text{PS}}$

✦ embedded in POWHEG, startin from F+jet

$$\mathrm{d}\sigma_F^{\text{Mi(N)NLO}} = \tilde{B}^{\text{Mi(N)NLO}} \times \left\{\Delta_{\text{pwg}} + \mathrm{d}\Phi_{\text{rad}}\Delta_{\text{pwg}}\frac{R_{FJ}}{B_{FJ}}\right\}$$

✦ through modification of the $\bar{B}$ function

$$\tilde{B}^{\text{MiNLO}} \sim e^{-S}\left\{\mathrm{d}\sigma_{FJ}^{(1)}\left(1 + S^{(1)}\right) + \mathrm{d}\sigma_{FJ}^{(2)}\right\}$$

✦ inclusion of NNLO corrections:

1. multi-dim. event reweighting in Born phase space

$$W^{\text{NNLOPS}} \sim \frac{(\mathrm{d}\sigma_F^{\text{NNLO}}/d\Phi_B)}{(\mathrm{d}\sigma_F^{\text{MiNLO}}/d\Phi_B)} = \frac{c_0 + c_1\alpha_s + c_2\alpha_s^2}{c_0 + c_1\alpha_s + d_2\alpha_s^2} = 1 + \frac{c_2 - d_2}{c_0}\alpha_s^2 + \mathcal{O}(\alpha_s^3)$$

2. add relevant terms derived from resummation formula

$$\bar{B}^{\text{MiNNLO}_{\text{PS}}} \sim \bar{B}^{\text{MiNLO}} + e^{-S}\left\{\left(D - D^{(1)} - D^{(2)}\right) \times F^{\text{corr}}\right\}$$

Comparison to high-precision Drell-Yan data

[CMS '22 - arXiv:2205.04897]

MG5_aMC [Alwall et al. '14]

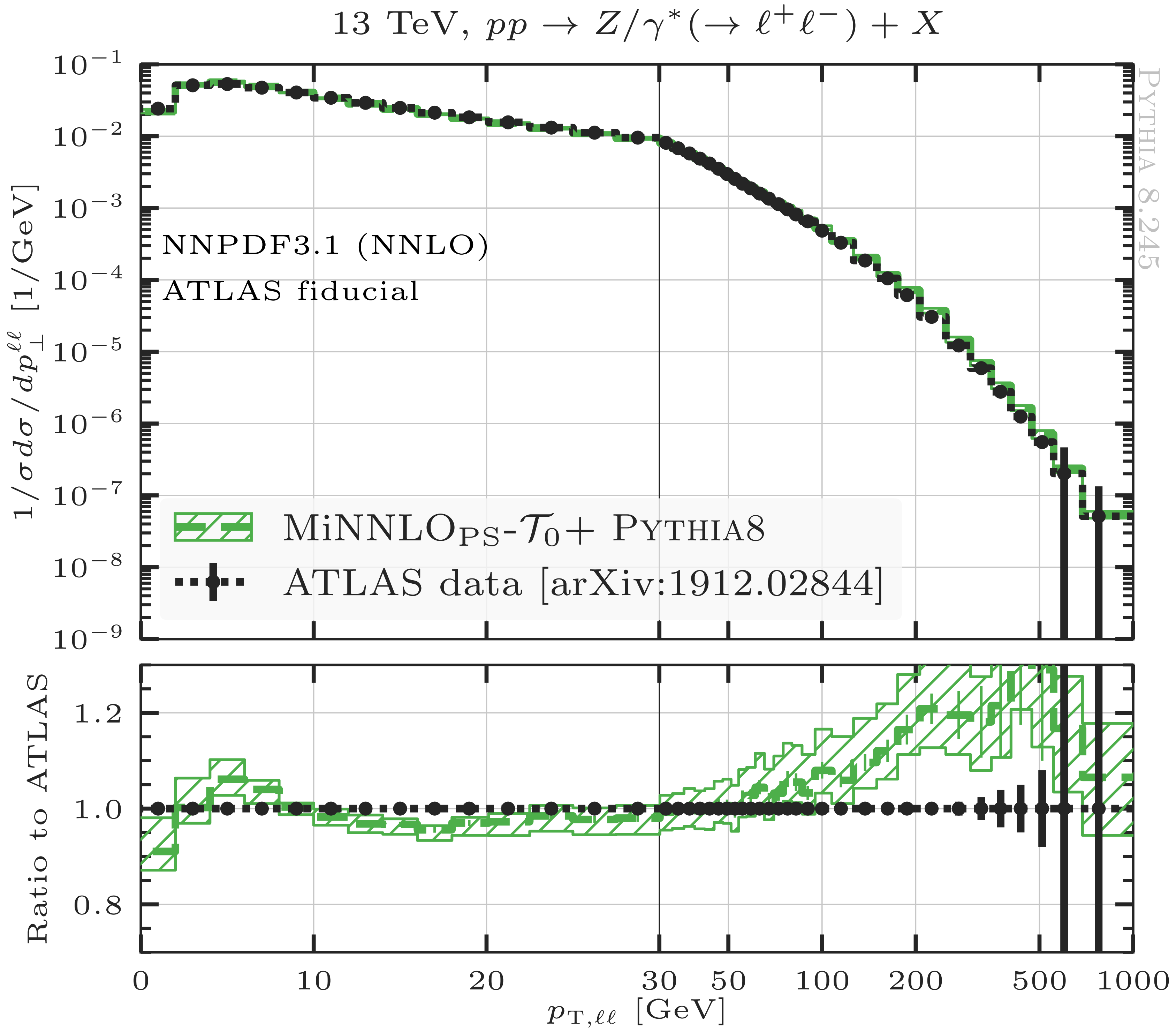
MiNNLO$_{PS}$ [Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

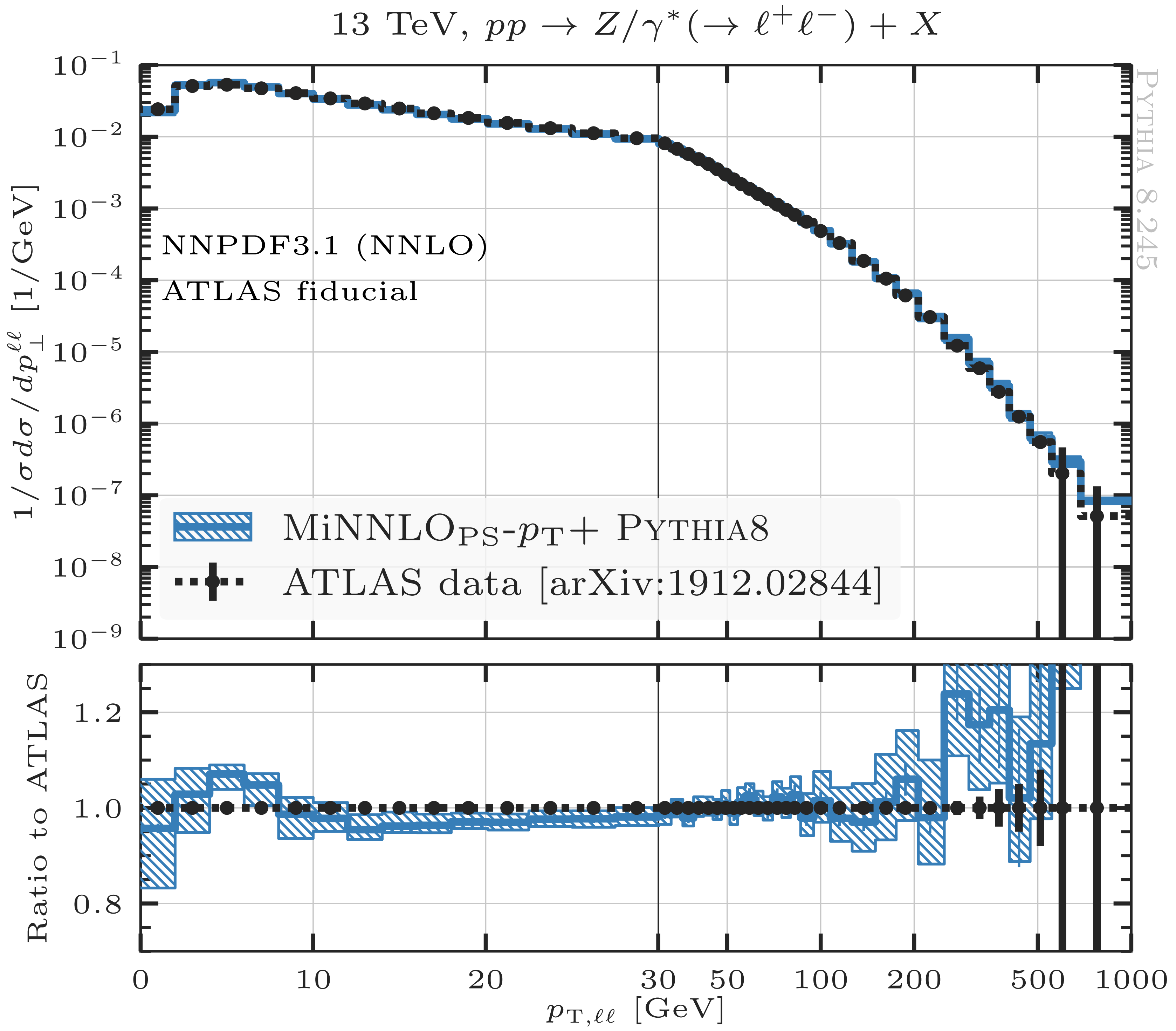
Geneva-τ_0 [Alioli et al. '13 '15]

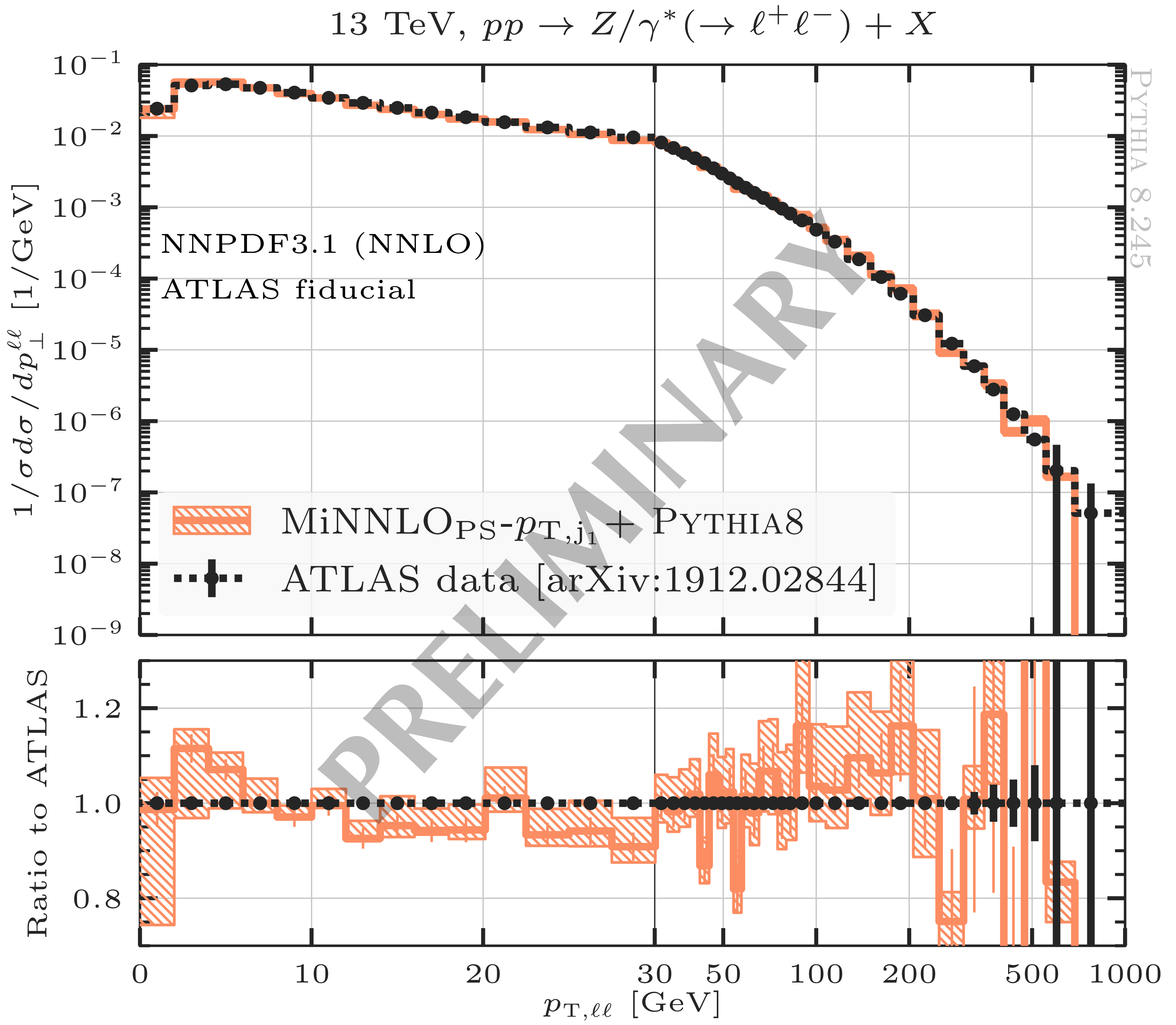
Geneva-p_T^Z [Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, Rotolli '21]

MiNNLO$_{PS}$: different matching observables

[Ebert, Rottoli, MW, Zanderighi, Zanoli '23]



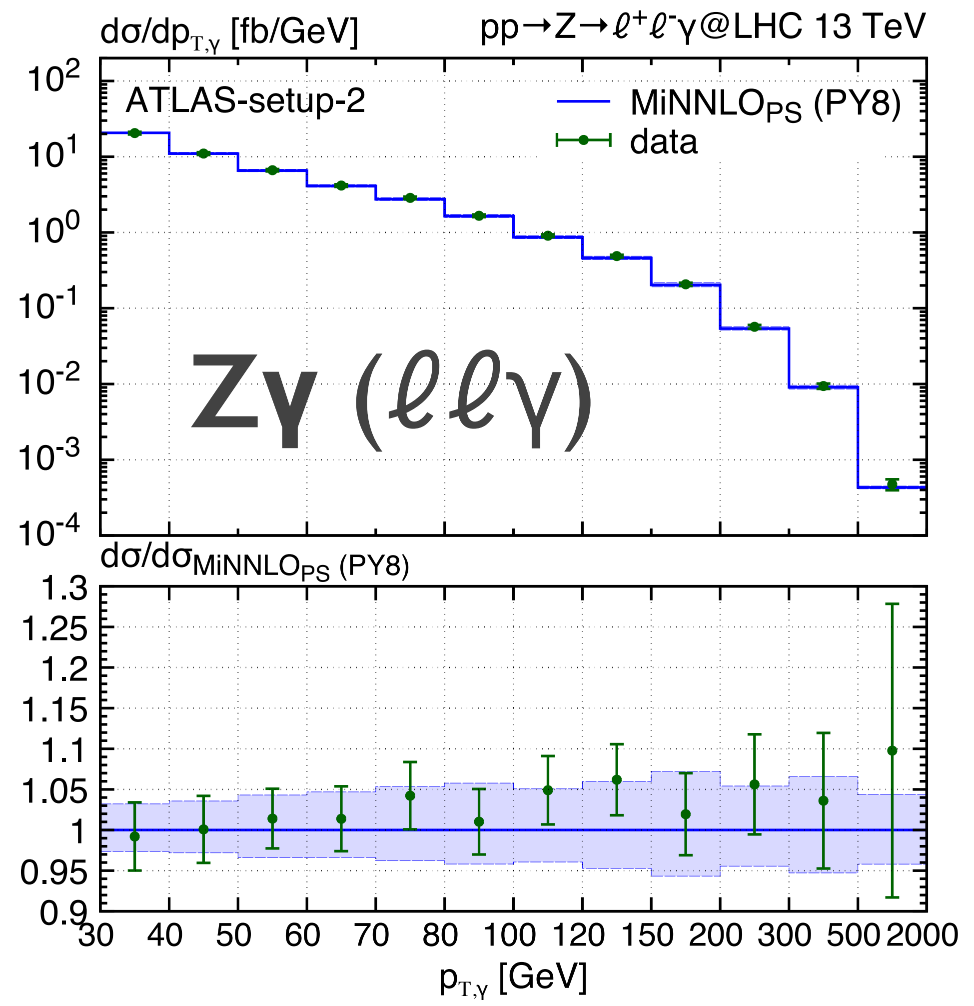




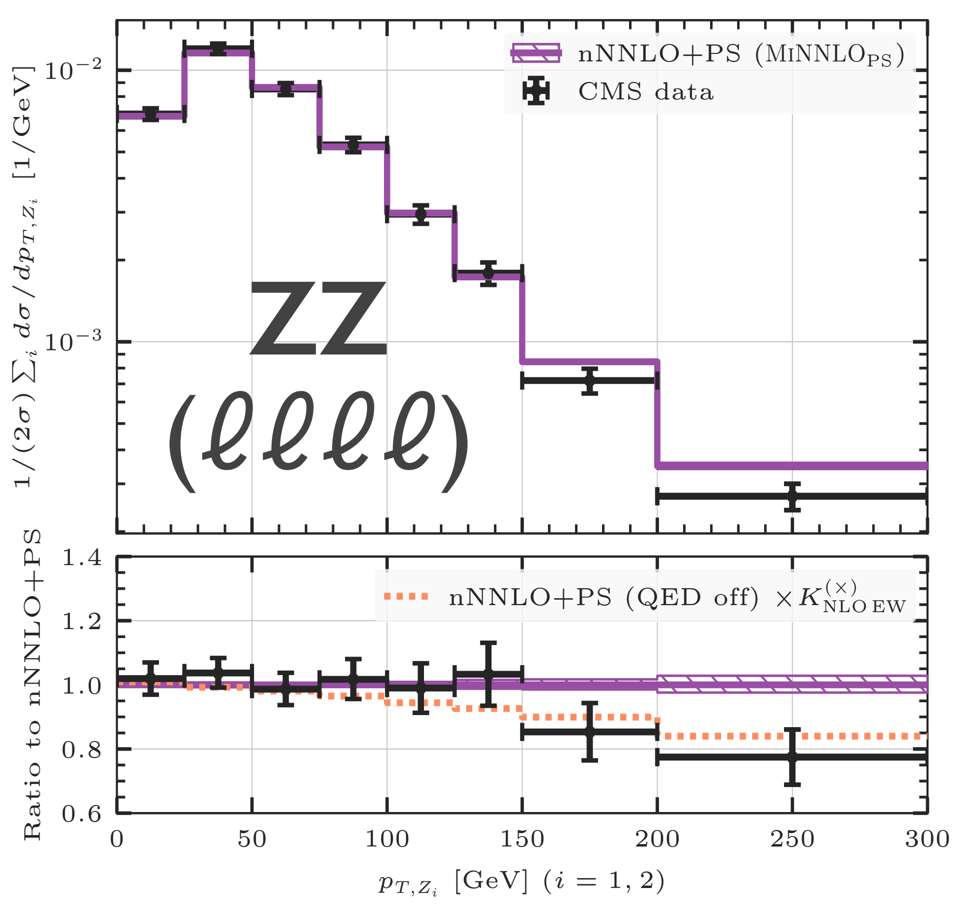
τ_0 $\qquad$ p_T $\qquad$ p_T^j

[from L. Rottoli's talk at Ringberg 2024]

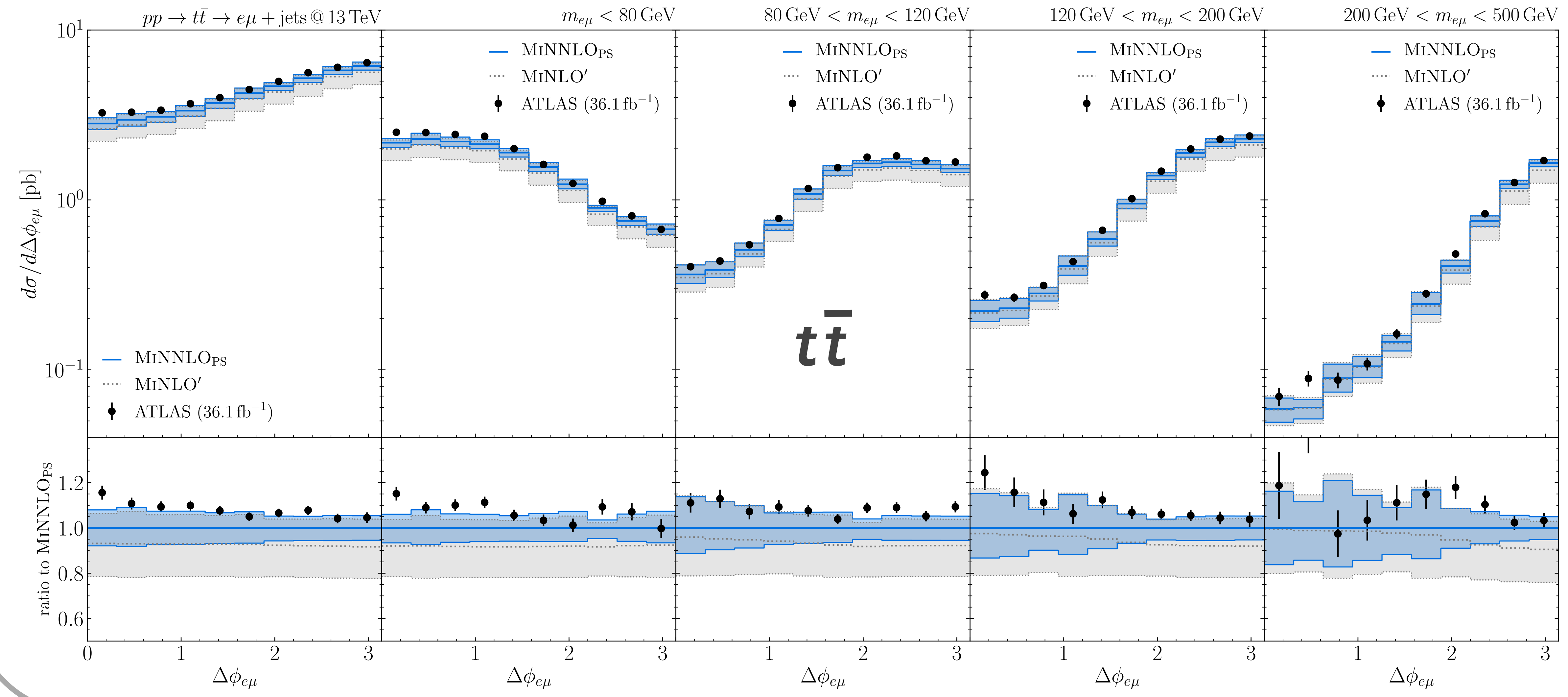
[Lombardi, MW, Zanderighi '20]



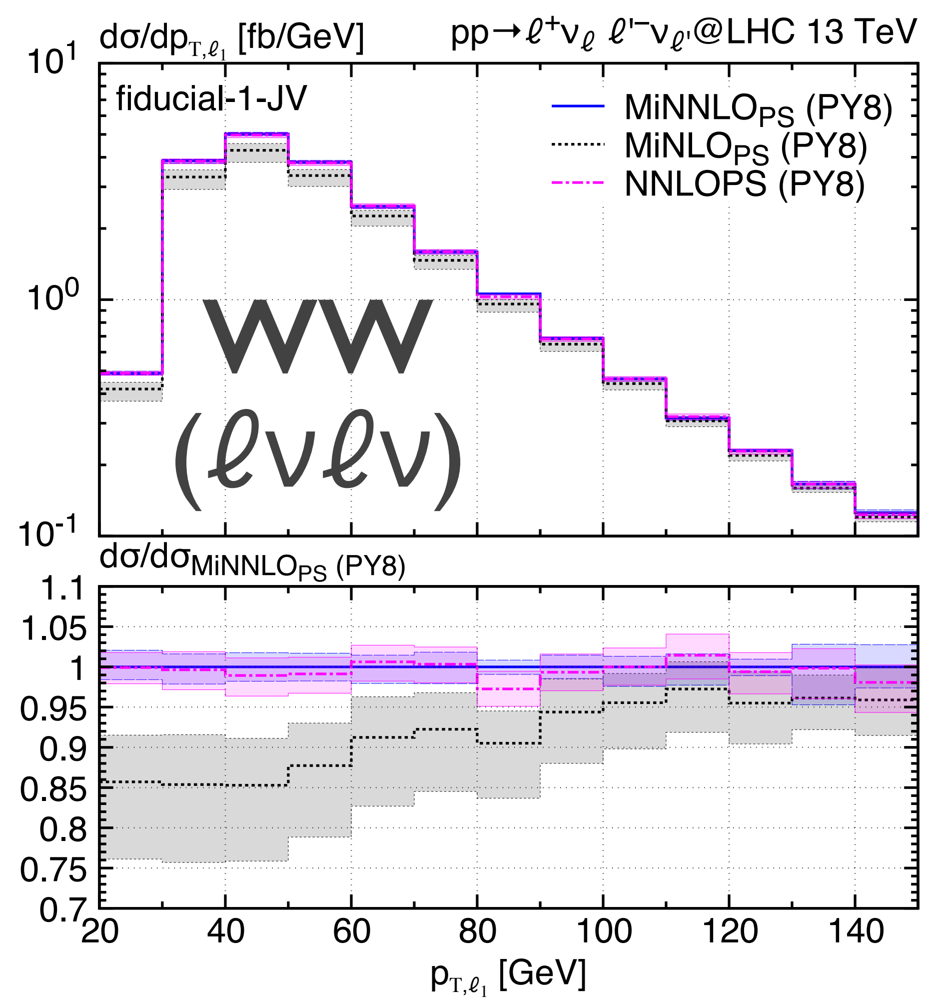
[Buonocore, Koole, Lombardi, Rottoli, MW, Zanderighi '21]



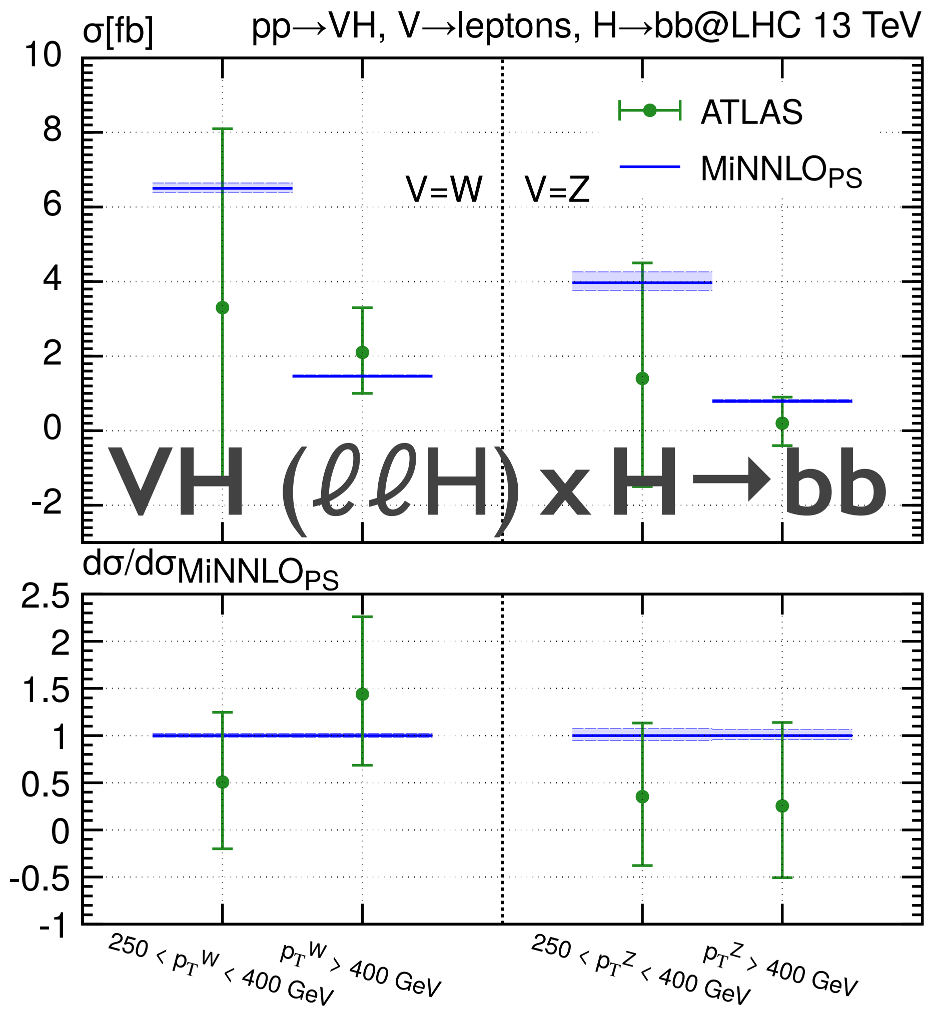
[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20 '21]



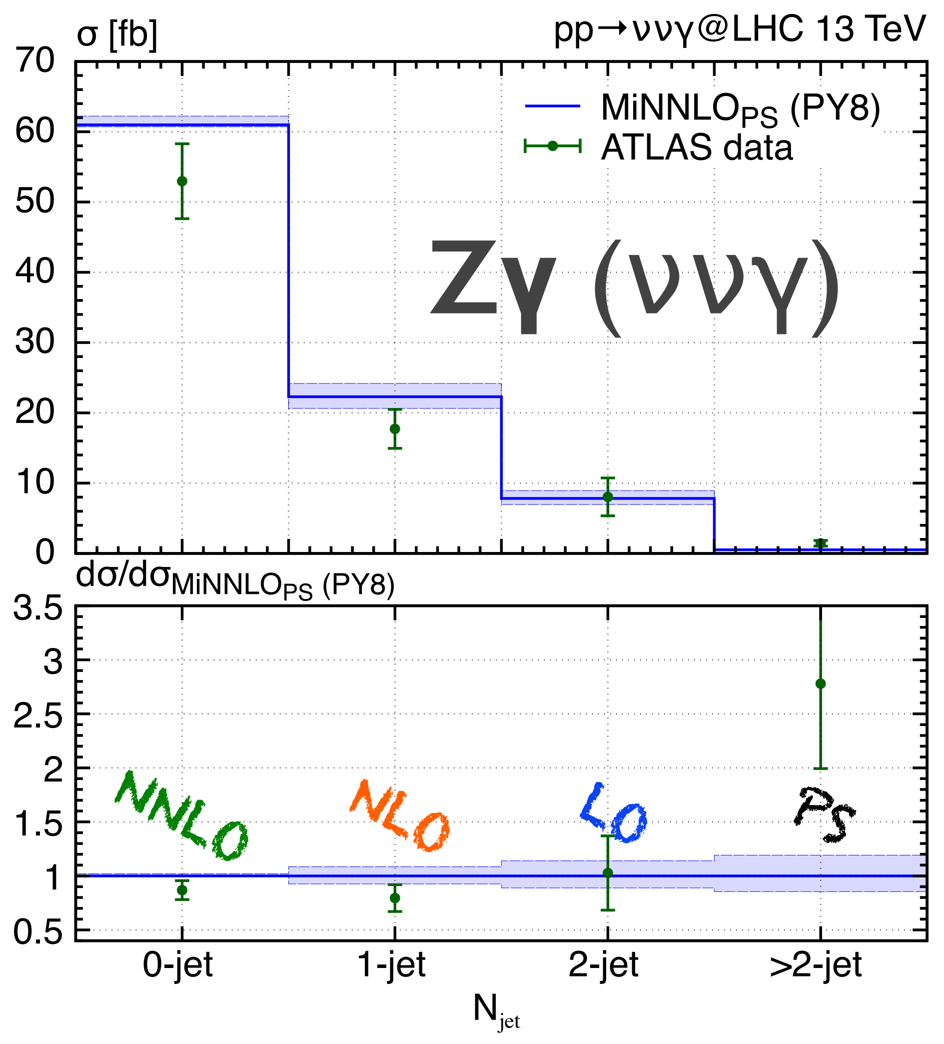
[Lombardi, MW, Zanderighi '21]



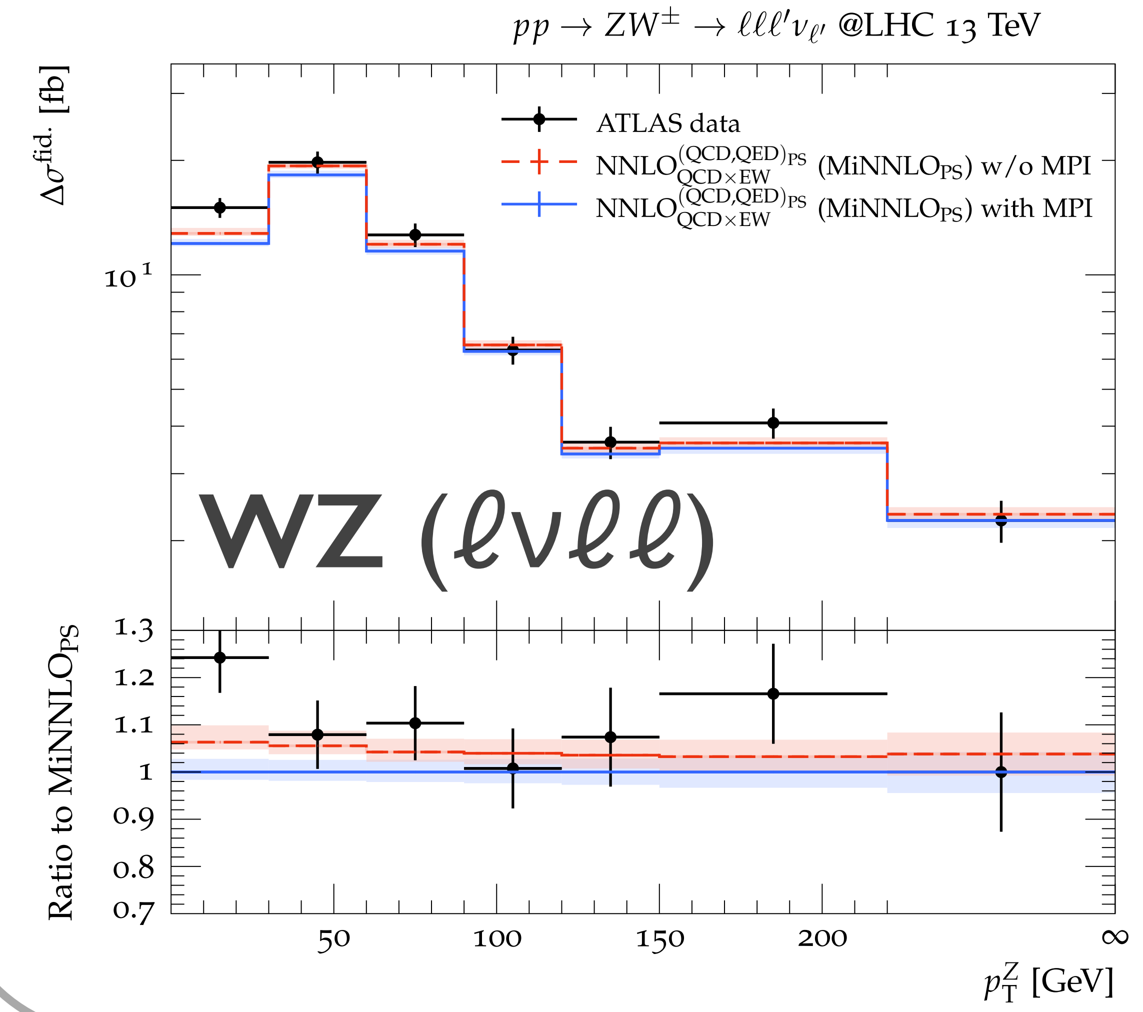
[Zanoli, Chiesa, Re, MW, Zanderighi '21]



[Lombardi, MW, Zanderighi '21]



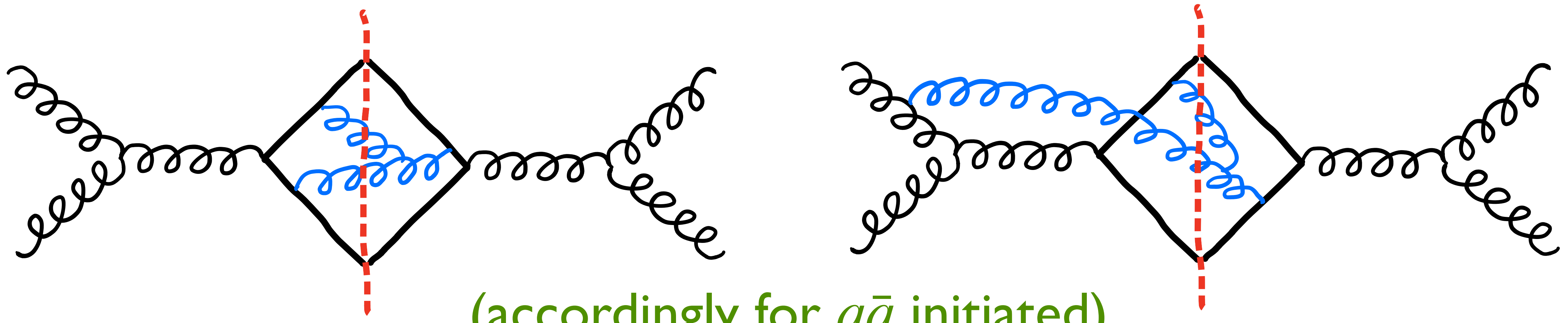
[Lindert Lombardi, MW, Zanderighi, Zanoli '22]



MiNNLO$_{PS}$: heavy quark production

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

✦ substantial complication due to final-state radiation and interferences



(accordingly for $q\bar{q}$ initiated)

✦ compare resummation formulas (very schematic):

colour singlet: $$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S} \quad H \quad (C\otimes f)(C\otimes f)\right\}$$

heavy quark pair: $$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S}\,{\rm Tr}(\mathbf{H}\boldsymbol{\Delta})\,(C\otimes f)(C\otimes f)\right\}$$

[Catani, Grazzini, Torre '14]

$\boldsymbol{\Delta}$: operator/matrix in colour space that encodes soft emissions of $t\bar{t}$ and interferences

derived to NNLO in [Catani, Devoto, Grazzini, Mazzitelli, '23]

$t\bar{t}$ production

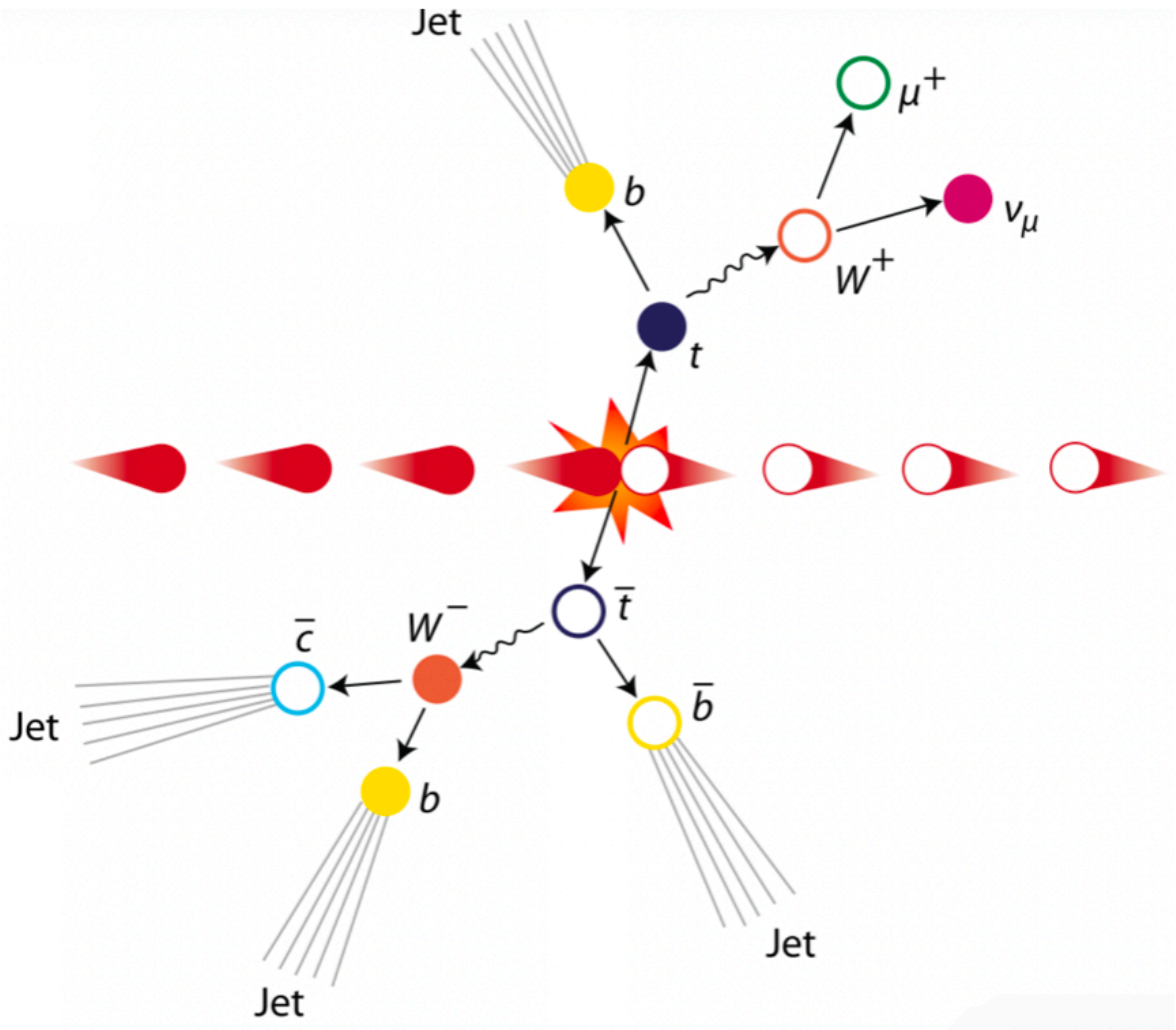
$$t\bar{t} \;\to\; b\bar{b}\,W^-W^+$$

Fully leptonic $\quad W^+W^- \;\to\; l\bar{\nu}_l\,\bar{l}\nu_l$

Semi-leptonic $\quad W^+W^- \;\to\; l\bar{\nu}_l\,q\bar{q}'$

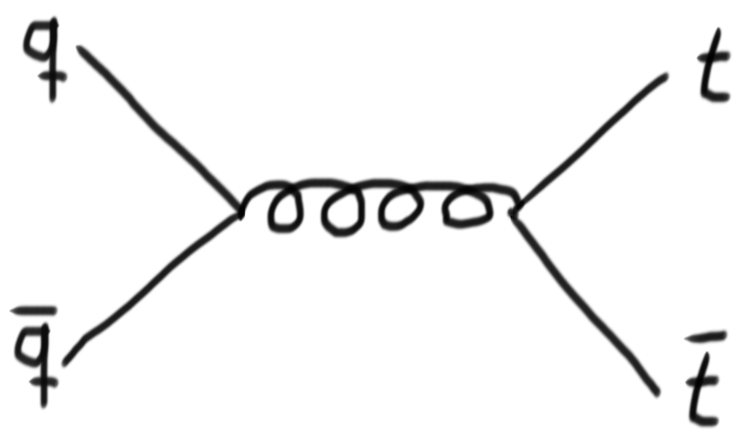
Hadronic $\quad W^+W^- \;\to\; q\bar{q}'q'\bar{q}$

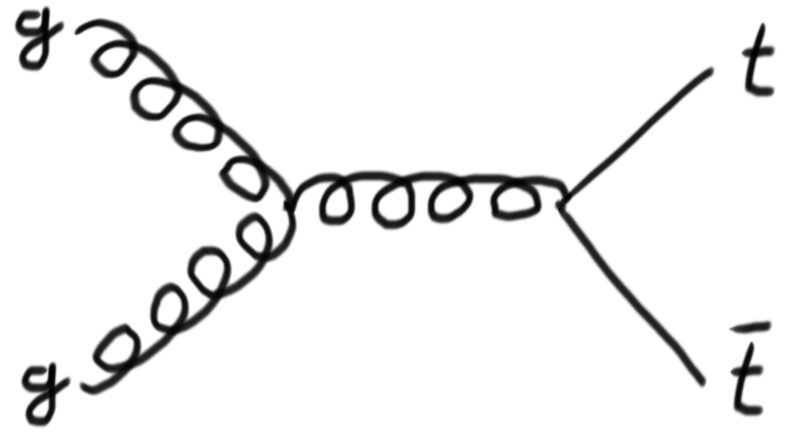
(where $q = \{u, c\}$ and $q' = \{d, s\}$)

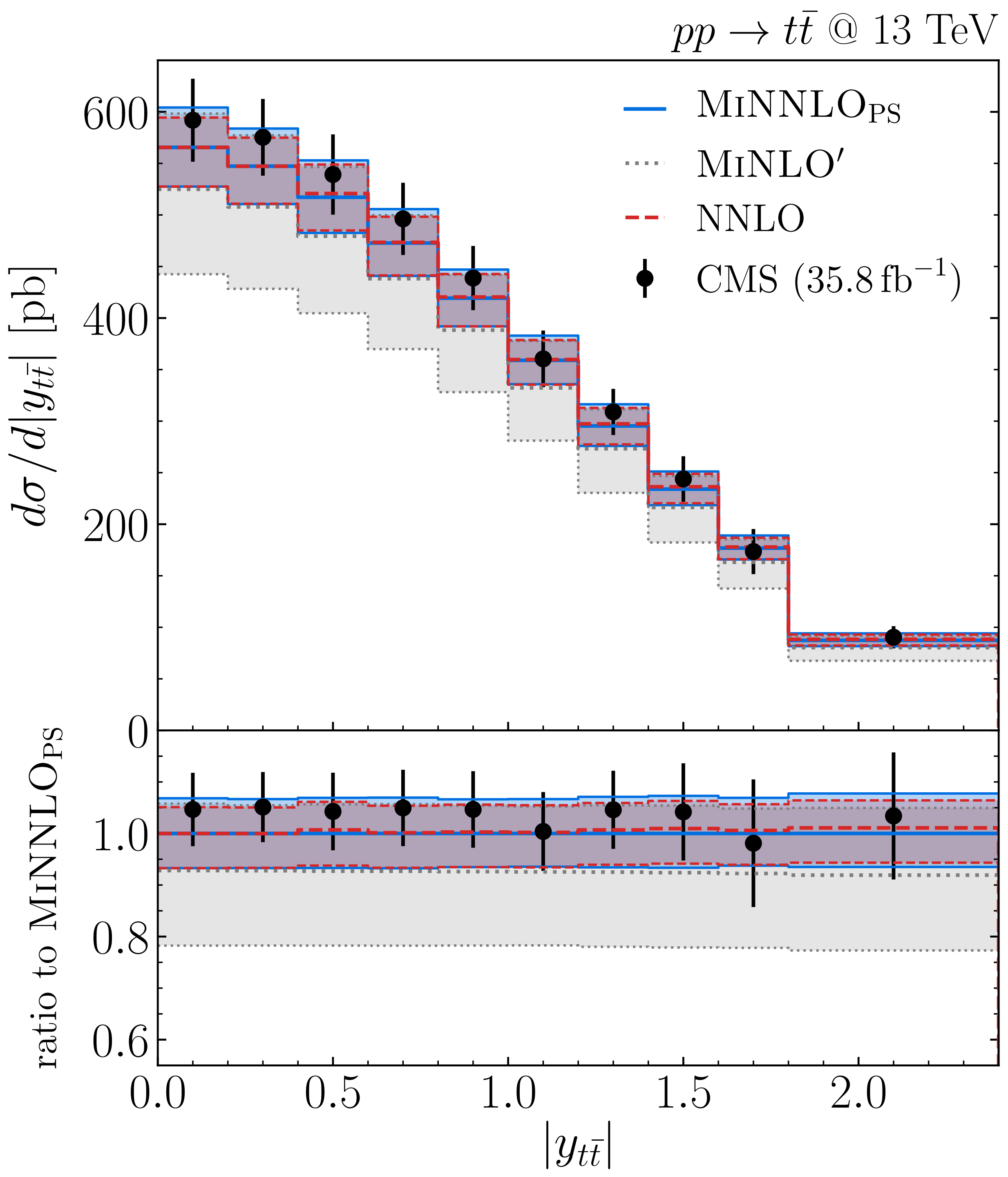


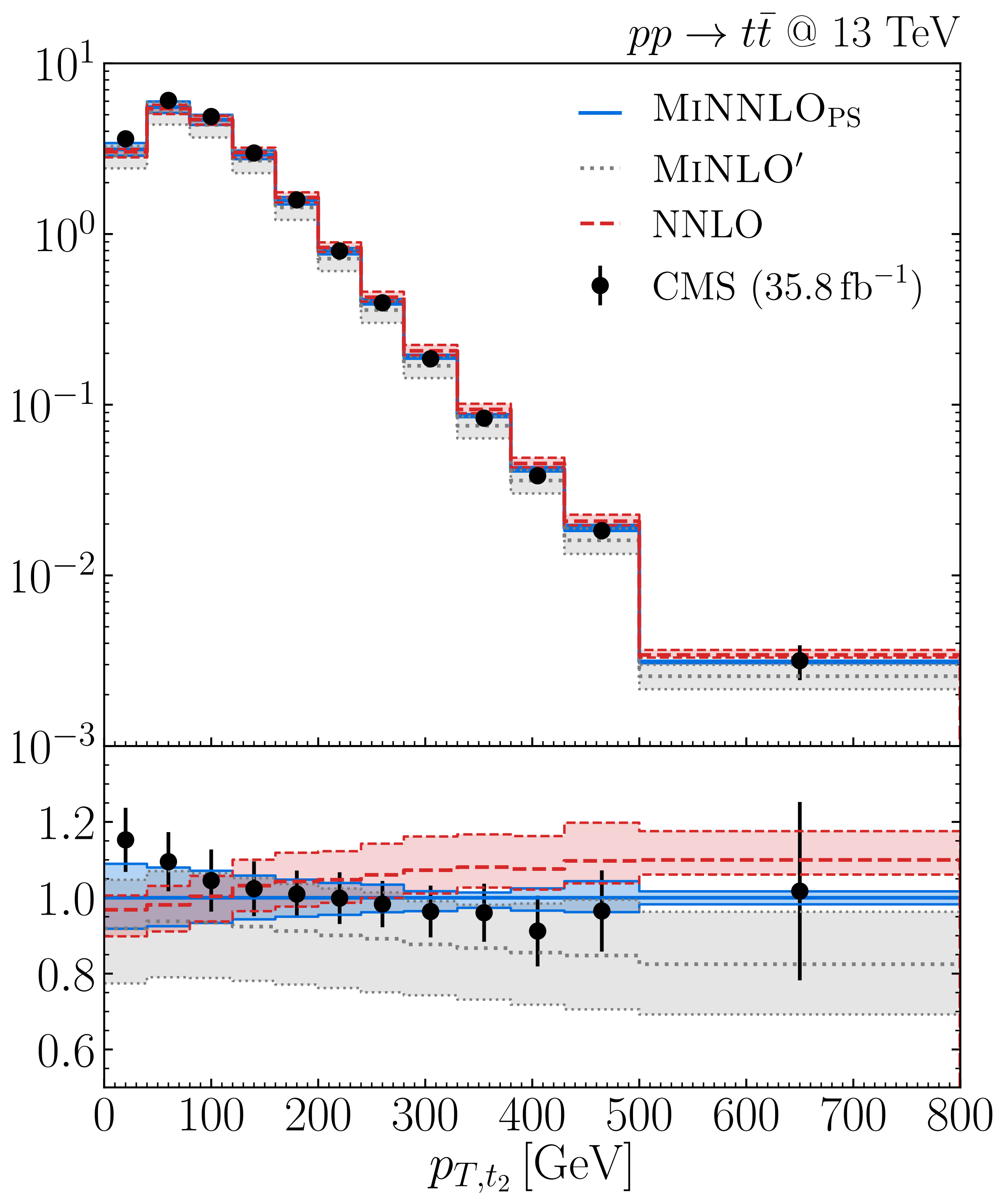
$t\bar{t}$ production

on-shell $t\bar{t}$ production





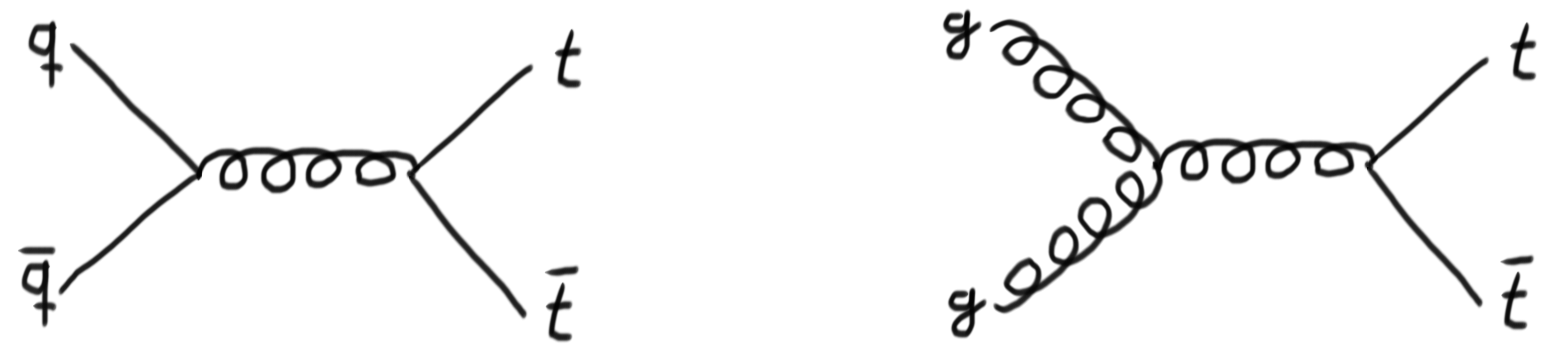


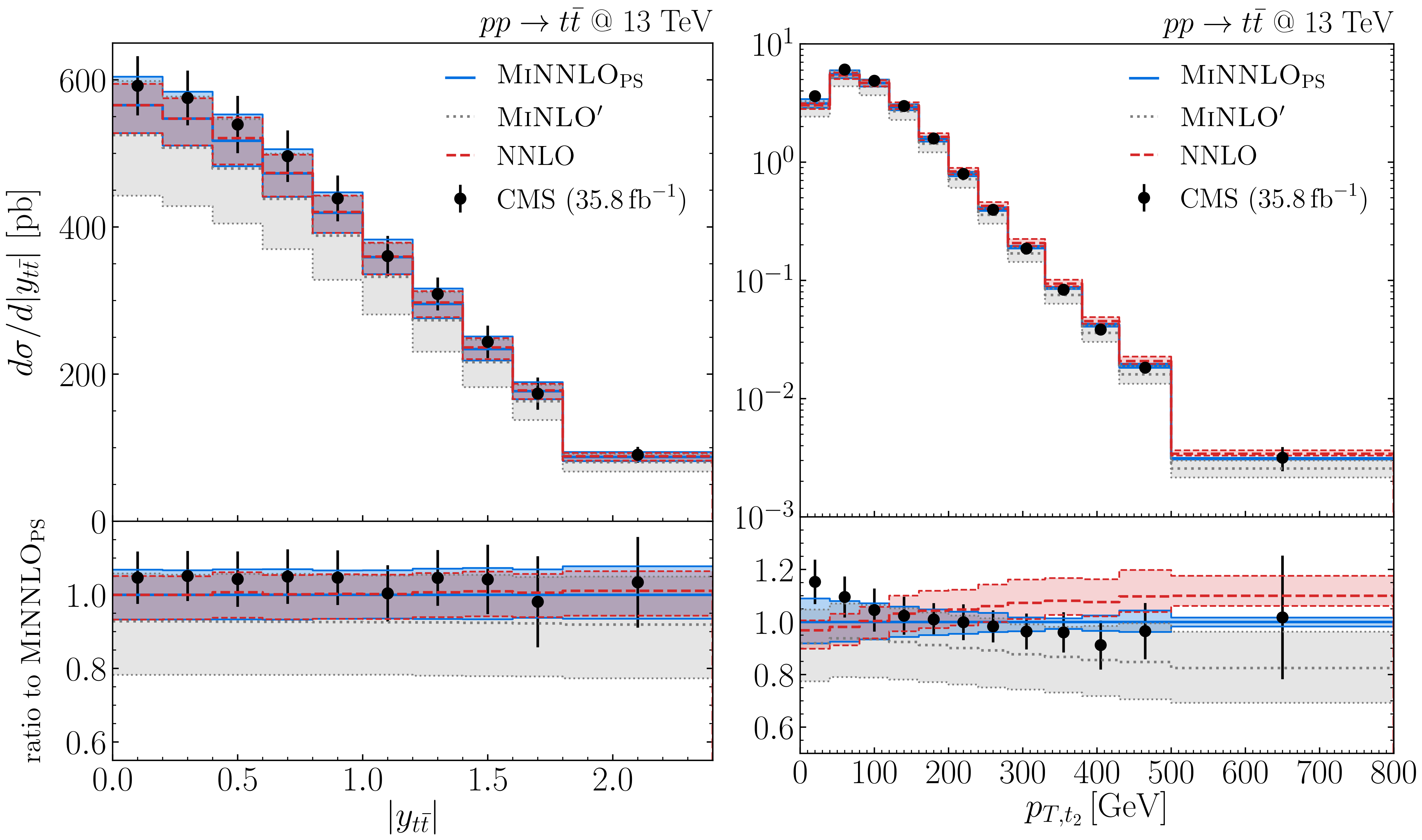


$t\bar{t}$ production

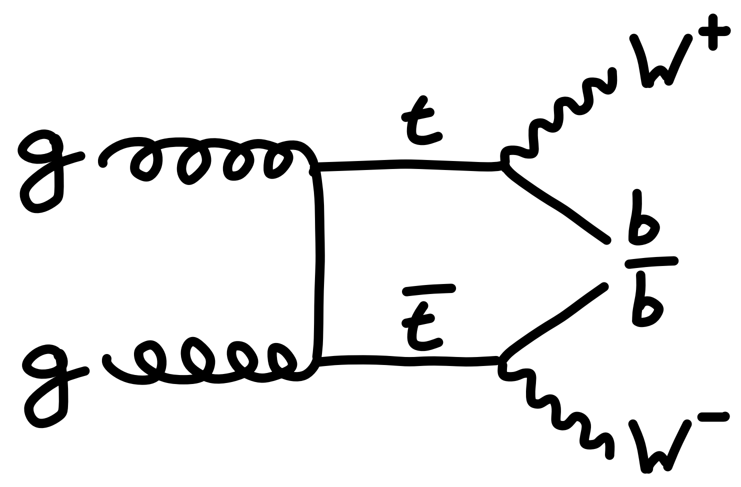
*approximated through a MadSpin-like approach using the full off-shell diagram at LO, keeping spin correlations

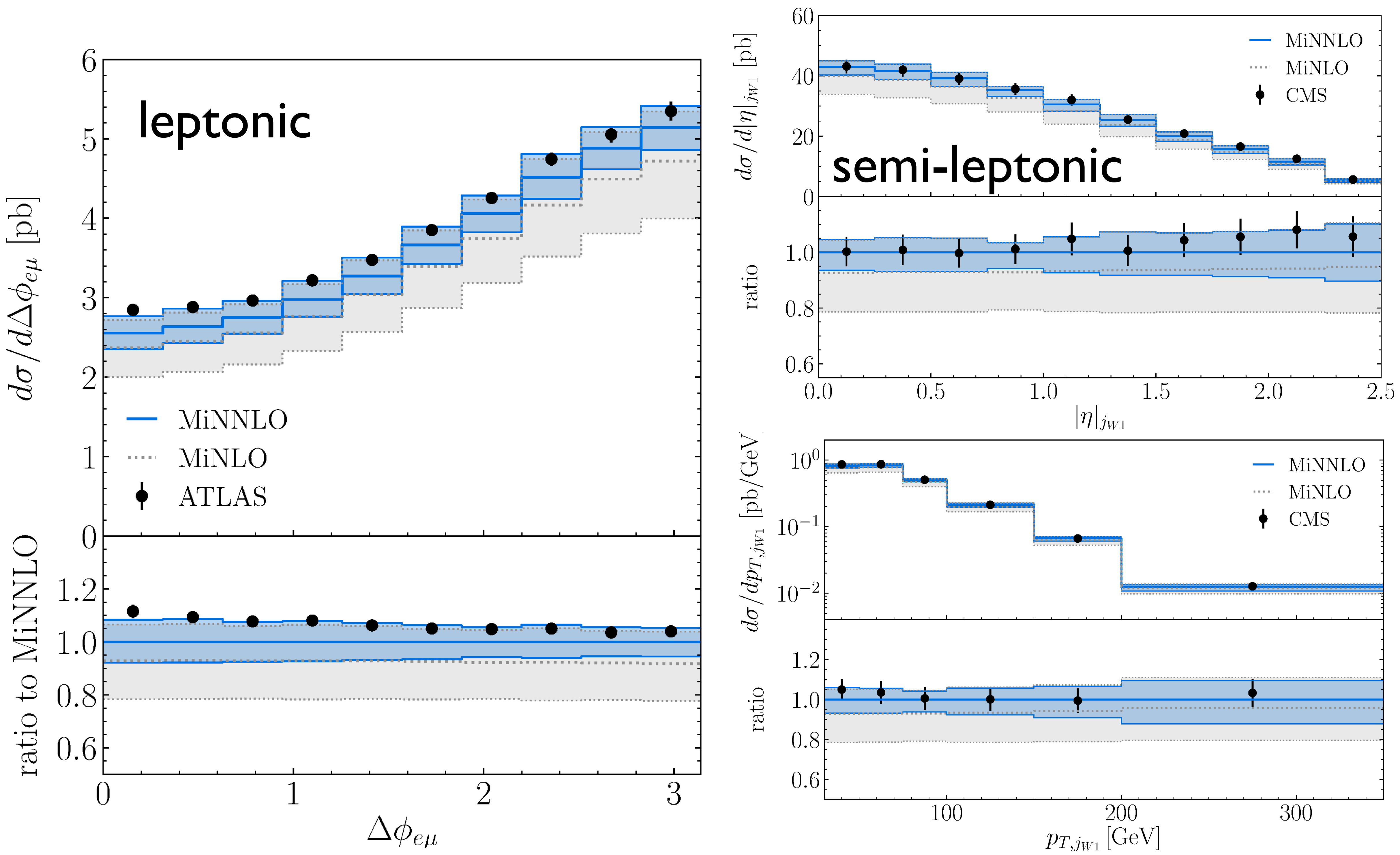
on-shell $t\bar{t}$ production



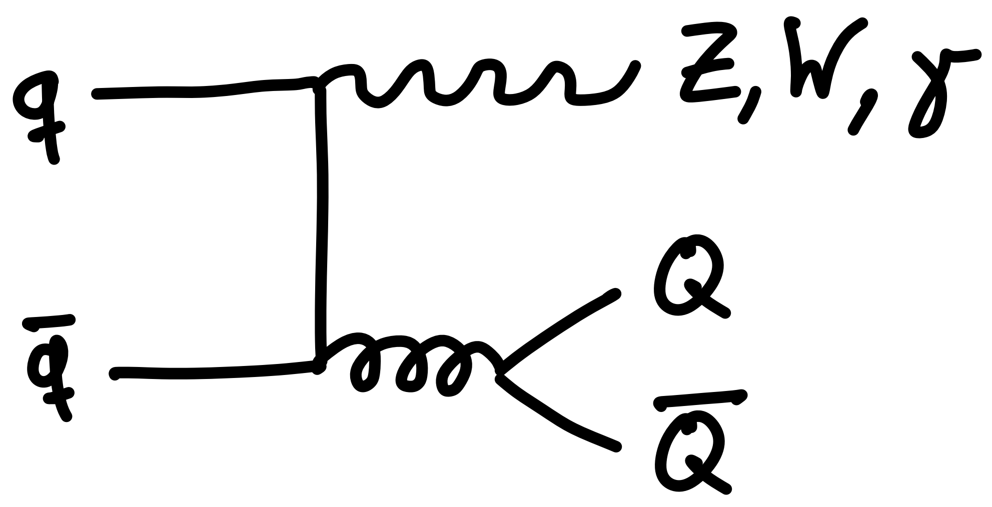


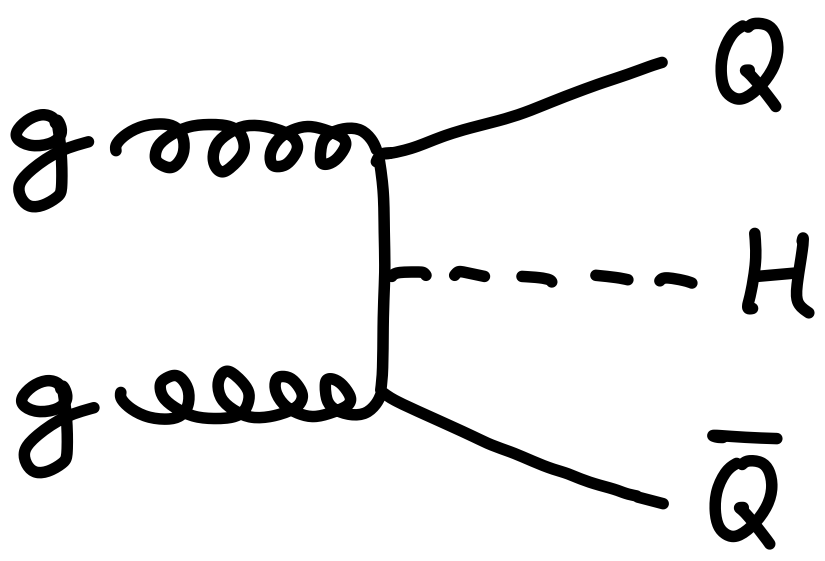
with off-shell top decays*

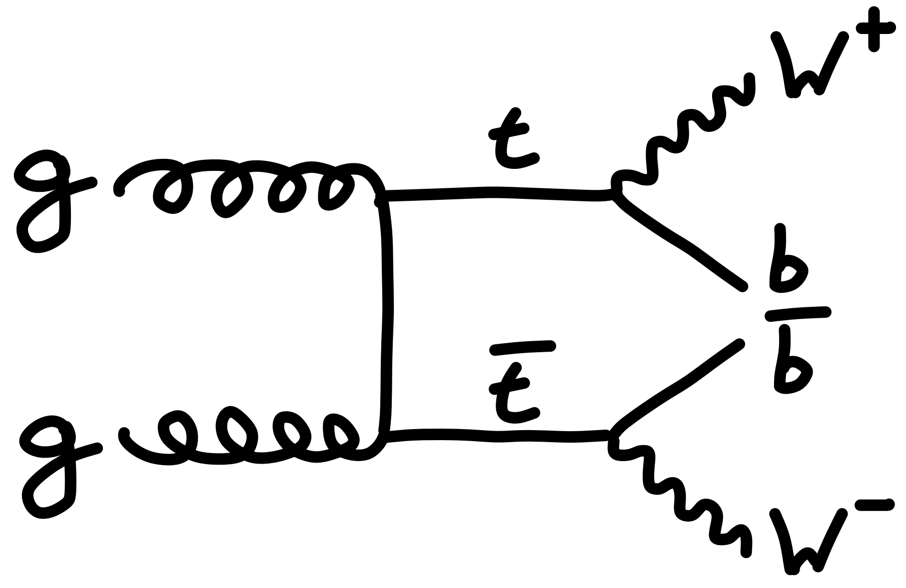




MiNNLO$_{PS}$: heavy quark + colour singlet production







[Mazzitelli, Sotnikov, Wiesemann '24]

✦ same structure of singular/resummed cross section as $Q\bar{Q}$, but need to account for recoil:

colour singlet: $$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S} \; H \; (C\otimes f)(C\otimes f)\right\}$$

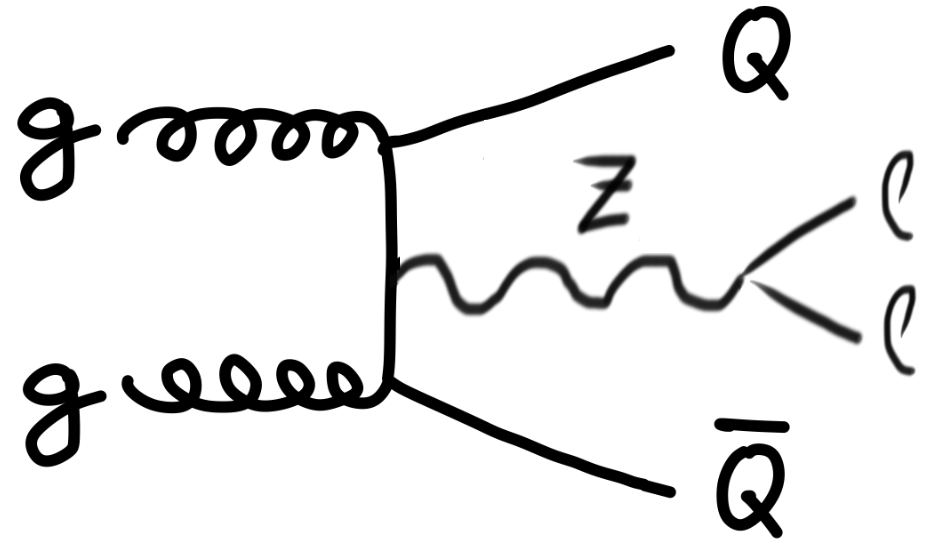
heavy quark pair: $$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S}\, \mathrm{Tr}(\mathbf{H\Delta})\,(C\otimes f)(C\otimes f)\right\}$$

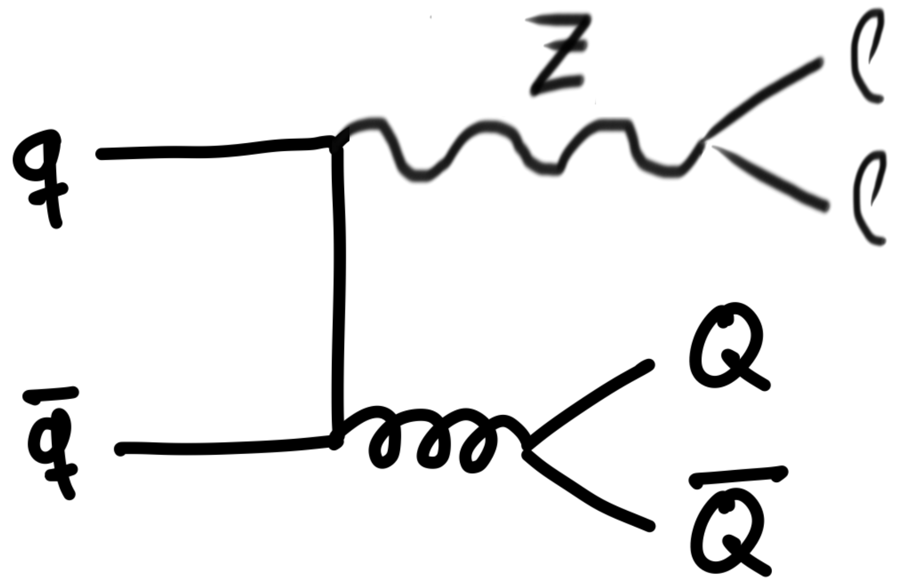
heavy quark pair + colour singlet: $$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S}\, \mathrm{Tr}(\mathbf{H\Delta})\,(C\otimes f)(C\otimes f)\right\}$$

Soft function for Heavy quark production in ARbitrary Kinematics
[Devoto, Mazzitelli 'in preparation]

$b\bar{b}Z$ production

[Mazzitelli, Sotnikov, MW '24]





★ bottom mass neither a large nor small scale: 4FS (massive bottom) and 5FS (massless bottom) viable

★ complication:
Z couples to initial-state light quarks and final-state heavy quarks & coupling depends on quark falvour

★ 2-loop amplitude: most complicated ingredient & among most complicated 2-loop computed to date

→ approximated by small-m_b expansion [Mitov, Moch '06], [Wang, Xia, Yang, Ye '23]

$$2\mathrm{Re}\langle R^{(0)} | R^{(2)} \rangle = \sum_{i=1}^{4} \kappa_i \log^i(m_b/\mu_R) + 2\mathrm{Re}\langle R_0^{(0)} | R_0^{(2)} \rangle + \mathcal{O}(m_b/\mu)$$

massive amplitude — coefficients of massification — massless amplitude [Abreu, Cordero, Ita, Klinkert, Page, Sotnikov '21] — power corrections

$b\bar{b}Z$ production

[Mazzitelli, Sotnikov, MW '24]

Z+1b-jet distributions compared to CMS data [CMS 2112.09659]

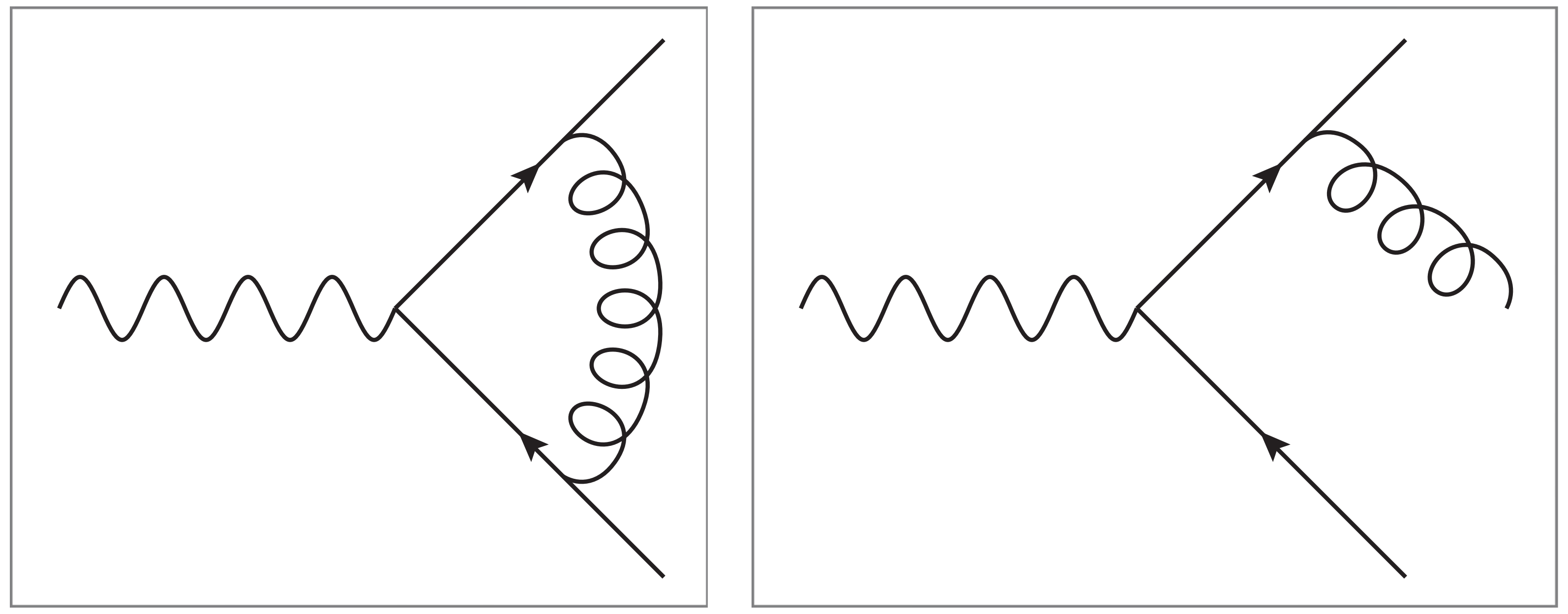
$b\bar{b}Z$ production

[Mazzitelli, Sotnikov, MW '24]

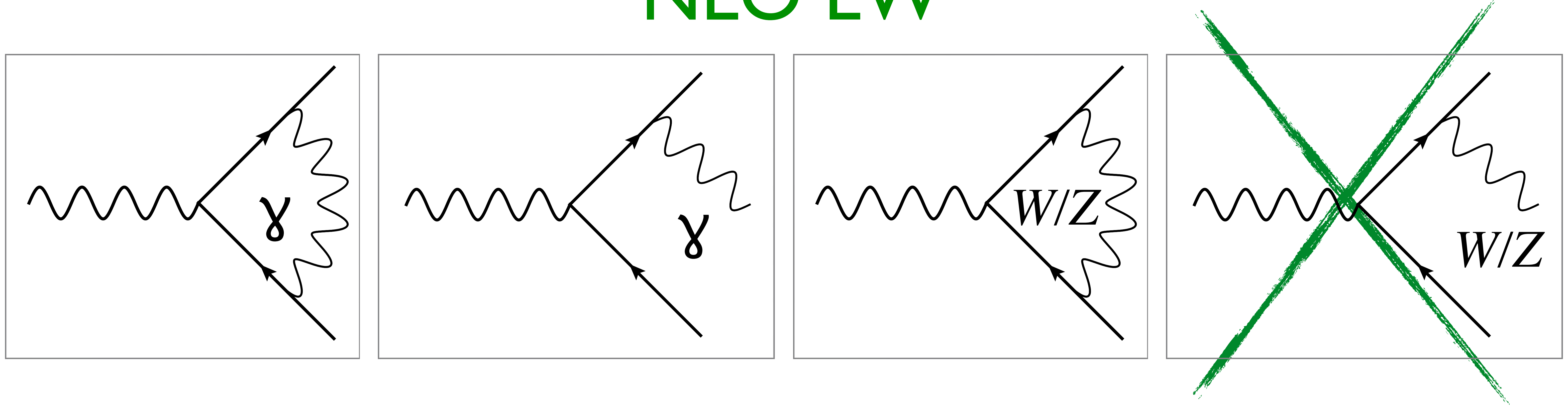
Z+2b-jet distributions compared to CMS data [CMS 2112.09659]

NLO+PS for EW corrections

NLO QCD



NLO EW



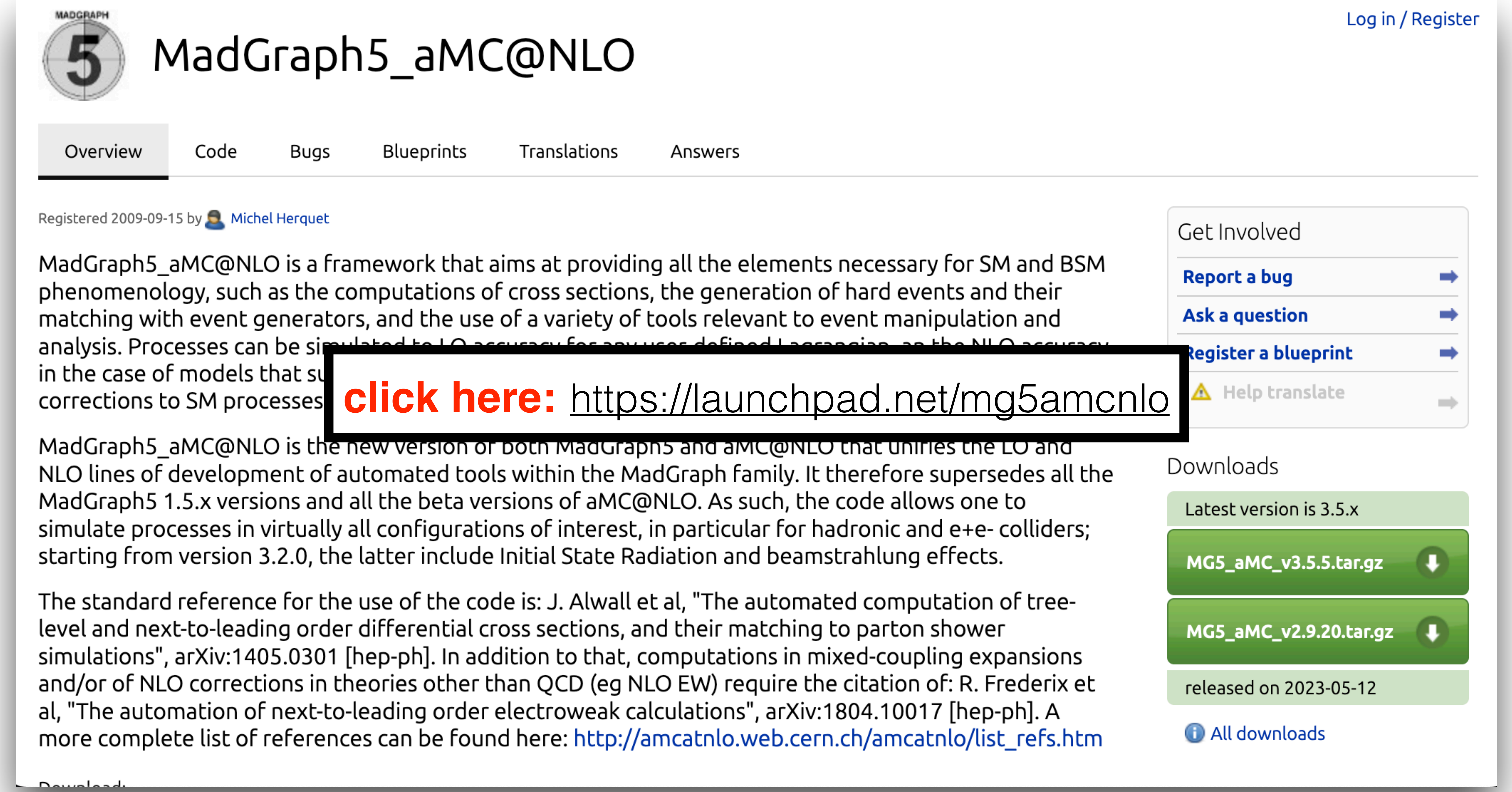
★ multiple-radiation of heavy weak bosons not relevant at LHC energies (possibly at future colliders), since emissions regulated by boson mass ➙ not included in parton showers

★ parton showers include only QED (and QCD) radiation

★ thus, NLO+PS matching done at level of QED corrections (same methods as for QCD)

★ weak-boson effect included solely in virtual matrix elements

Public (N)NLO+PS Codes


MadGraph5_aMC@NLO
Log in / Register
Overview
Code
Bugs
Blueprints
Translations
Answers
Registered 2009-09-15 by Michel Herquet
MadGraph5_aMC@NLO is a framework that aims at providing all the elements necessary for SM and BSM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis.
click here: https://launchpad.net/mg5amcnlo
NLO lines of development of automated tools within the MadGraph family. It therefore supersedes all the MadGraph5 1.5.x versions and all the beta versions of aMC@NLO. As such, the code allows one to simulate processes in virtually all configurations of interest, in particular for hadronic and e+e- colliders; starting from version 3.2.0, the latter include Initial State Radiation and beamstrahlung effects.
The standard reference for the use of the code is: J. Alwall et al, "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", arXiv:1405.0301 [hep-ph]. In addition to that, computations in mixed-coupling expansions and/or of NLO corrections in theories other than QCD (eg NLO EW) require the citation of: R. Frederix et al, "The automation of next-to-leading order electroweak calculations", arXiv:1804.10017 [hep-ph]. A more complete list of references can be found here: http://amcatnlo.web.cern.ch/amcatnlo/list_refs.htm
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Downloads
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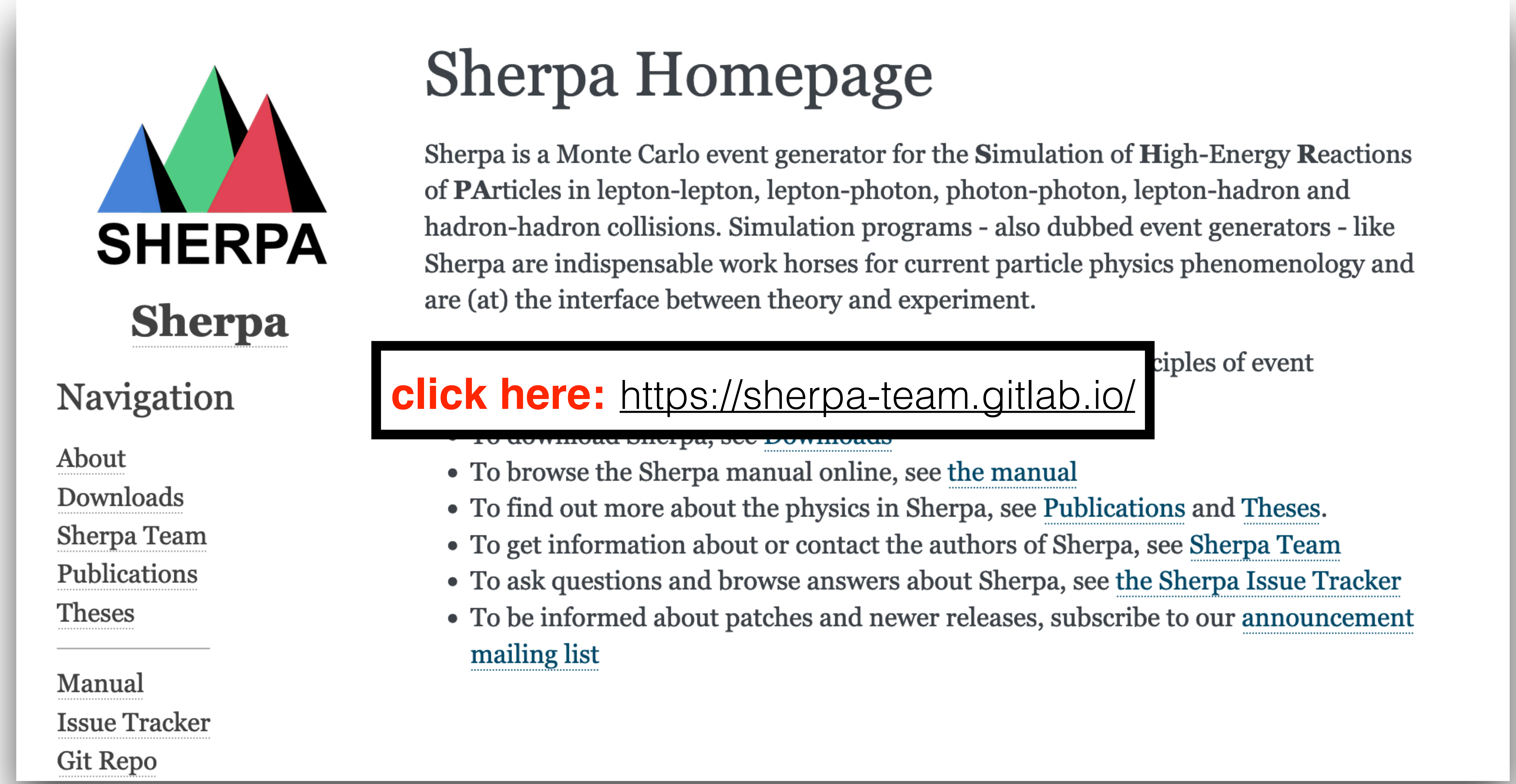
MG5_aMC_v3.5.5.tar.gz
MG5_aMC_v2.9.20.tar.gz
released on 2023-05-12
All downloads


The POWHEG BOX
Project
click here: https://powhegbox.mib.infn.it/
in shower Monte Carlo programs according to the POWHEG method. It is also a library, where previously included processes are made available to the users. It can be interfaced with all modern shower Monte Carlo programs that support the Les Houches Interface for User Generated Processes.


SHERPA
Sherpa
Sherpa Homepage
Sherpa is a Monte Carlo event generator for the Simulation of High-Energy Reactions of PArticles in lepton-lepton, lepton-photon, photon-photon, lepton-hadron and hadron-hadron collisions. Simulation programs - also dubbed event generators - like Sherpa are indispensable work horses for current particle physics phenomenology and are (at) the interface between theory and experiment.
click here: https://sherpa-team.gitlab.io/
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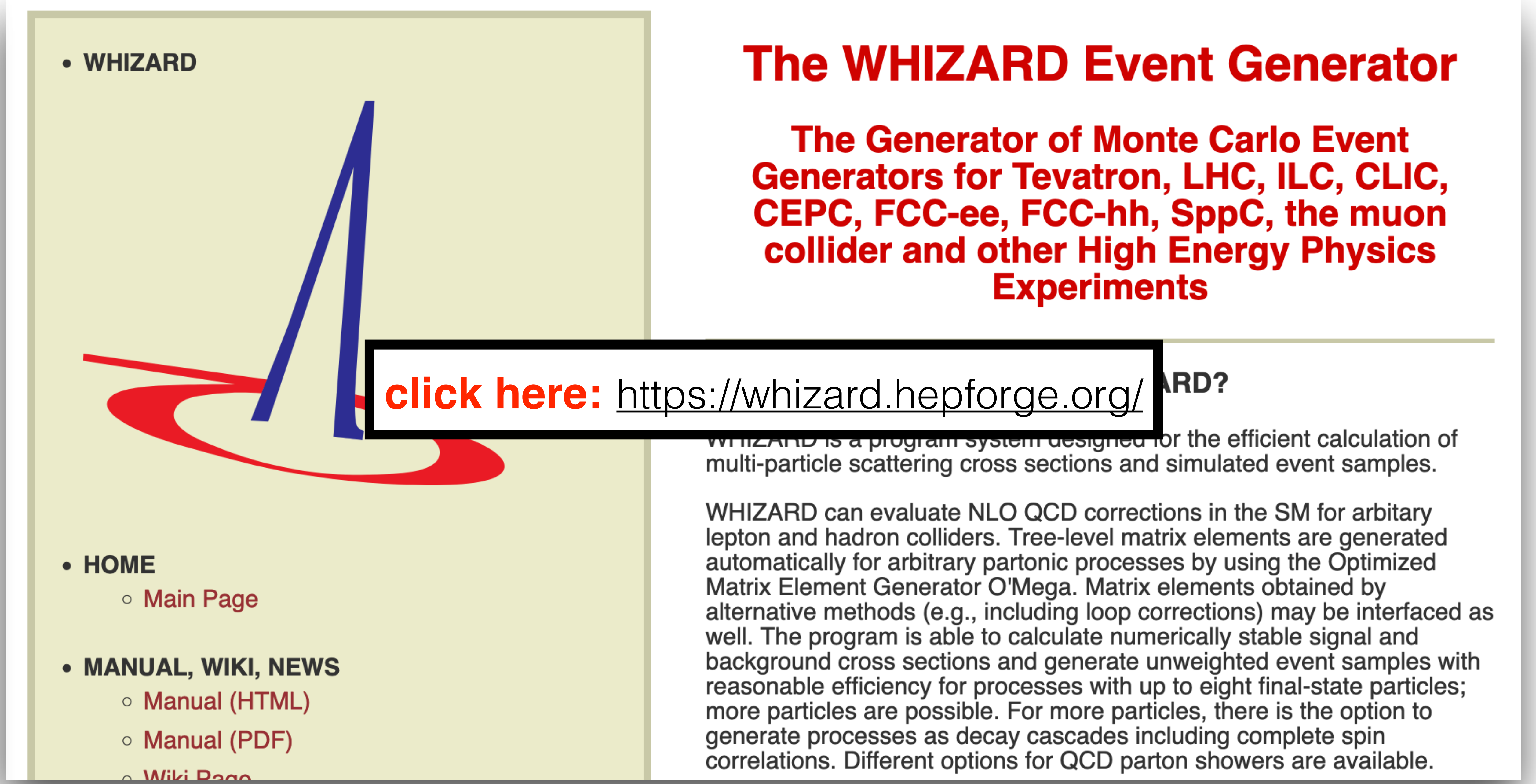
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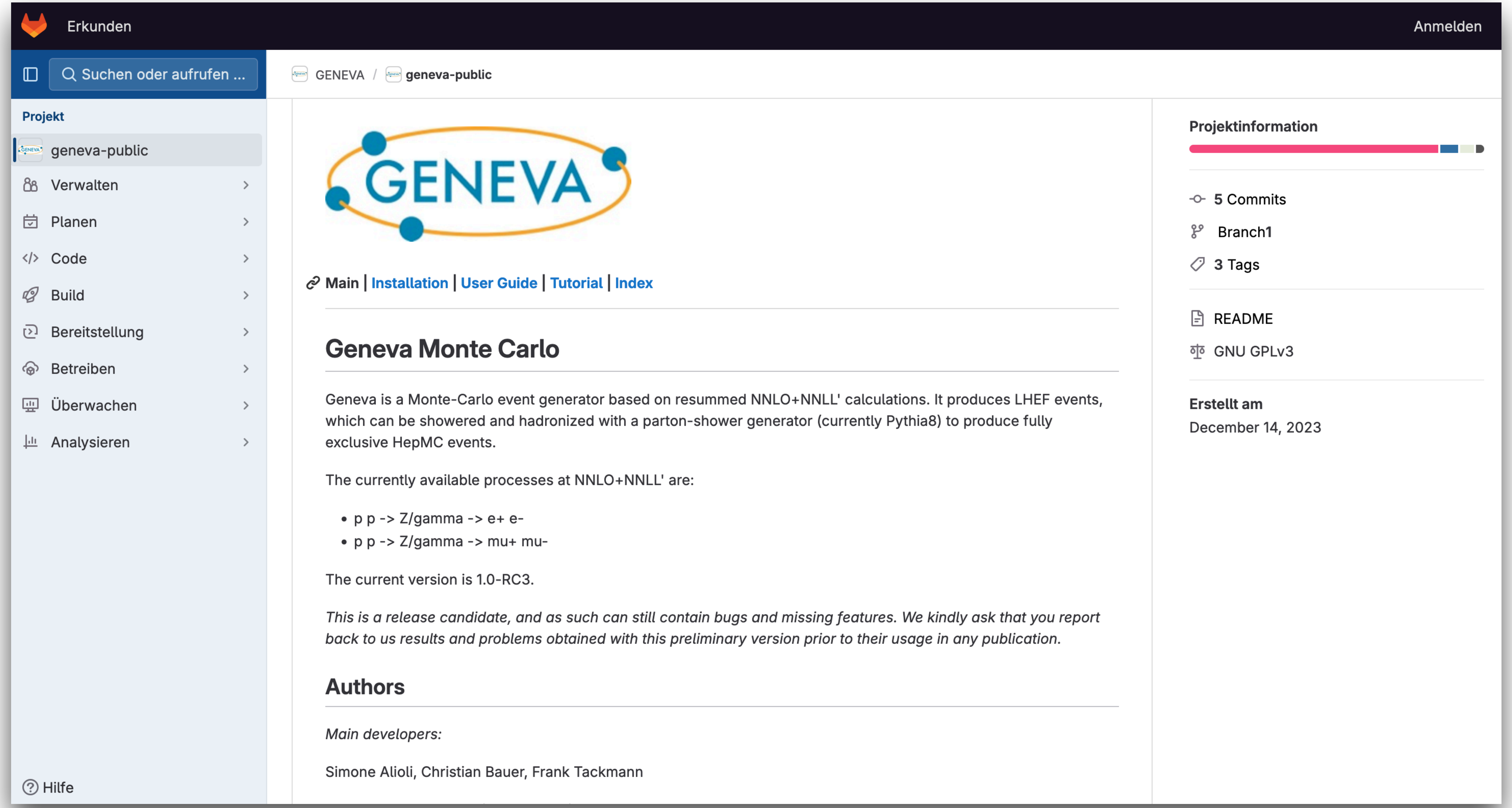
Manual (PDF)
The WHIZARD Event Generator
The Generator of Monte Carlo Event Generators for Tevatron, LHC, ILC, CLIC, CEPC, FCC-ee, FCC-hh, SppC, the muon collider and other High Energy Physics Experiments
click here: https://whizard.hepforge.org/
multi-particle scattering cross sections and simulated event samples.
WHIZARD can evaluate NLO QCD corrections in the SM for arbitary lepton and hadron colliders. Tree-level matrix elements are generated automatically for arbitrary partonic processes by using the Optimized Matrix Element Generator O'Mega. Matrix elements obtained by alternative methods (e.g., including loop corrections) may be interfaced as well. The program is able to calculate numerically stable signal and background cross sections and generate unweighted event samples with reasonable efficiency for processes with up to eight final-state particles; more particles are possible. For more particles, there is the option to generate processes as decay cascades including complete spin correlations. Different options for QCD parton showers are available.

GENEVA: release candidate since 2016



Erkunden Anmelden

Suchen oder aufrufen ...

GENEVA / geneva-public

Projekt

- geneva-public
- Verwalten
- Planen
- Code
- Build
- Bereitstellung
- Betreiben
- Überwachen
- Analysieren

Hilfe

GENEVA

Main | Installation | User Guide | Tutorial | Index

Geneva Monte Carlo

Geneva is a Monte-Carlo event generator based on resummed NNLO+NNLL' calculations. It produces LHEF events, which can be showered and hadronized with a parton-shower generator (currently Pythia8) to produce fully exclusive HepMC events.

The currently available processes at NNLO+NNLL' are:

- p p -> Z/gamma -> e+ e-
- p p -> Z/gamma -> mu+ mu-

The current version is 1.0-RC3.

This is a release candidate, and as such can still contain bugs and missing features. We kindly ask that you report back to us results and problems obtained with this preliminary version prior to their usage in any publication.

Authors

Main developers:

Simone Alioli, Christian Bauer, Frank Tackmann

Projektinformation

- 5 Commits
- Branch1
- 3 Tags
- README
- GNU GPLv3

Erstellt am

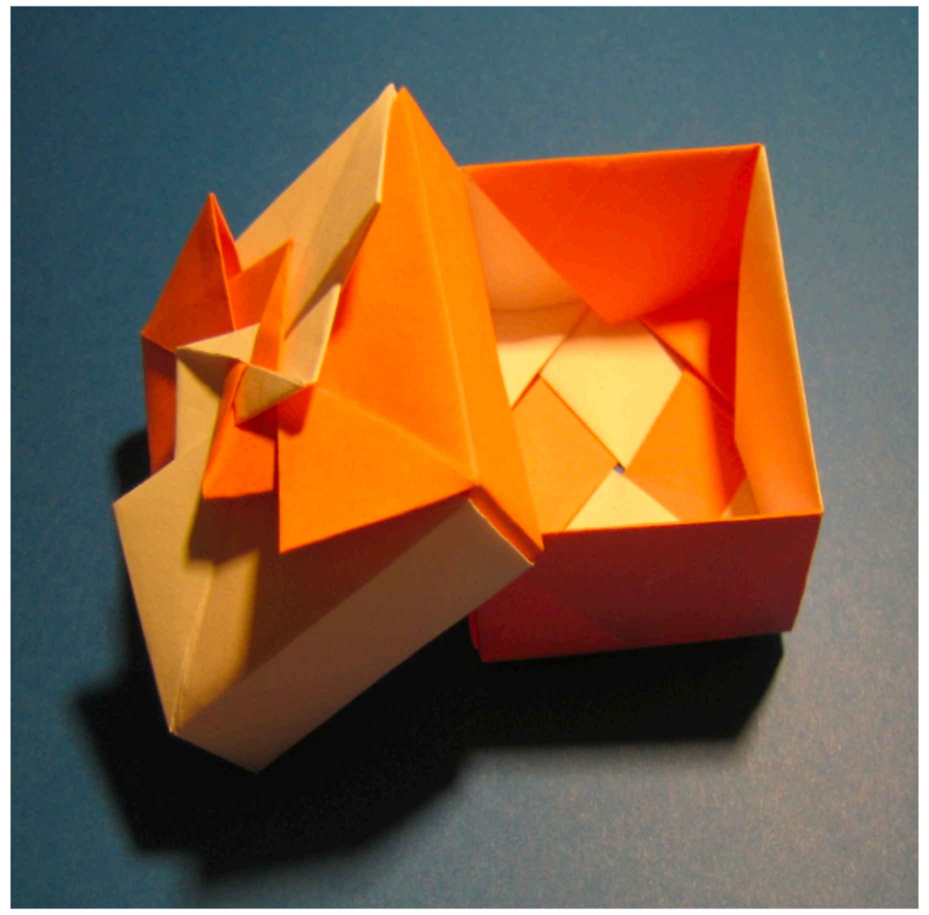
December 14, 2023

➙ release candidate (since 2016) on git repo, only process: Drell-Yan production using τ_0

click here: https://gitlab.desy.de/geneva/geneva-public

MiNNLO$_{PS}$ generators public in POWHEG BOX

The POWHEG BOX



Project

The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs according to the POWHEG method. It is also a library, where previously included processes are made available to the users. It can be interfaced with all modern shower Monte Carlo programs that support the Les Houches Interface for User Generated Processes.

Index:

- Available NLO+PS processes
- NNLOps using MiNNLOps
- Proper references
- Downloads
- Version 2
- Version RES
- Bugs
- Licence
- Contributing Authors

or click here: https://powhegbox.mib.infn.it/#MiNNLOps

MiNNLO$_{PS}$ for $2 \rightarrow 1$ processes (H, Z, W) in POWHEG-BOX-V2

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

Top-quark pair *generator*

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20 '21]

MiNNLO$_{PS}$ has been extended to $2 \rightarrow 2$ colour-singlet processes in POWHEG-BOX-RES

Zγ *generator ($Z \rightarrow \ell^+\ell^-, Z \rightarrow \nu\bar{\nu}$ + aTGC) [Lombardi, MW, Zanderighi '20, '21]*

WW *generator [Lombardi, MW, Zanderighi '21]*

ZZ *generator ($q\bar{q}$+gg) [Buonocre, Koole, Lombardi, Rottoli, MW, Zanderighi '21]*

NEW ***WZ*** *generator NNLO$_{QCD}$+PS and NLO$_{EW}$+PS*

[Lindert, Lombardi, MW, Zanderighi, Zanoli '23]

NEW ***H*** *generator with full top-mass effects @ NNLO [Niggetiedt, MW '24]*

t.b.a: ***VH*** *generator interfaced with* ***H→bb*** *decay and SMEFT effects (t.b.a.)*

[Zanoli, Chiesa, Re, MW, Zanderighi '21], [Haisch, Scott, MW, Zanderighi, Zanoli '22]

$\gamma\gamma$ *generator (t.b.a.) [Gavardi, Oleari, Re '22]*

bb *generator (t.b.a.) [Mazzitelli, Ratti, MW, Zanderighi '24]*

bbZ *generator (t.b.a.) [Mazzitelli, Sotnikov, MW '24]*

Summary

- ★ 50 years after the discovery of asymptotic freedom QCD has turned out to be a beautiful theory that allows us to provide predictions required at hadron colliders
- ★ Precision through perturbation theory: NLO, NNLO, N^{3}LO, …
- ★ Resummation for specific observables: NLL, NNLL, N^{3}LL, …
- ★ Parton Shower Event Generator bridge the gab between theory predictions and experimental measurements
- ★ Inclusion of higher-order corrections in parton showers: NLO+PS, NNLO+PS, …

→ plenty of room for improvements

(shower accuracy, shower uncertainties, non-perturbative effects, new NNLO+PS processes, …)

What I didn't have time to cover

★ Different techniques for resummation

(automation, SCET, other observables, soft resummation, …)

★ Jets in LHC collisions

(jet algorithms, infrared-safe jet flavour, jet substructure, …)

★ Details on Higgs production and decay channels

(heavy-top effective field theory, quark-mass effects, boosted Higgs analyses for VH, Higgs couplings, …)

★ Improving the accuracy of parton showers

★ …

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★ Details on Higgs production and decay channels

(heavy-top effective field theory, quark-mass effects, boosted Higgs analyses for VH, Higgs couplings, …)

★ Improving the accuracy of parton showers

Thank you very much for your attention!

Don’t be afraid ;-)

Questions?

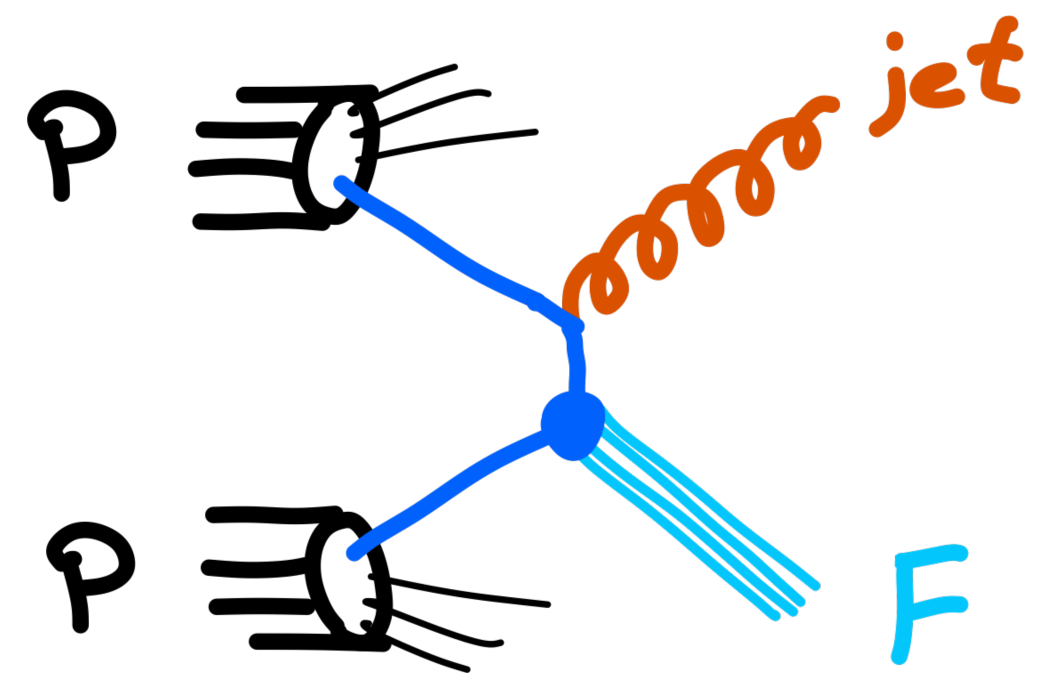
Extra Slides

MiNNLO$_{PS}$: main idea

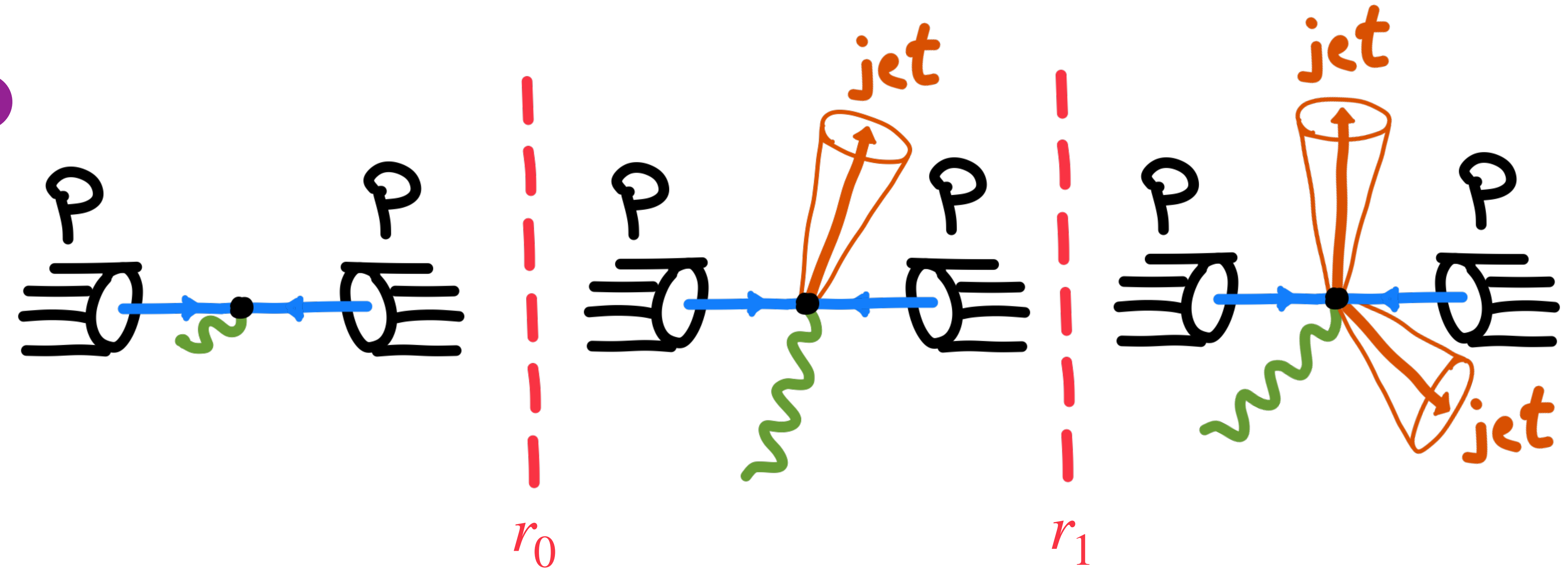
[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

N^{X}LO+Parton Shower (PS) for pp → F

N^{X-1}LO+Parton Shower (PS)
for pp → F + jet



all-order structure in
jet-resolution variable r_N



MiNNLO$_{PS}$: derivation

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ starting equation:

$$\frac{\mathrm{d}\sigma_F^{\mathrm{res}}}{\mathrm{d}p_T\,\mathrm{d}\Phi_\mathrm{B}} = \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H\,(C\otimes f)\,(C\otimes f)$$

(symbolically)

MiNNLO$_{PS}$: derivation

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ starting equation:

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$$\mathscr{L} \sim H\,(C\otimes f)\,(C\otimes f)$$

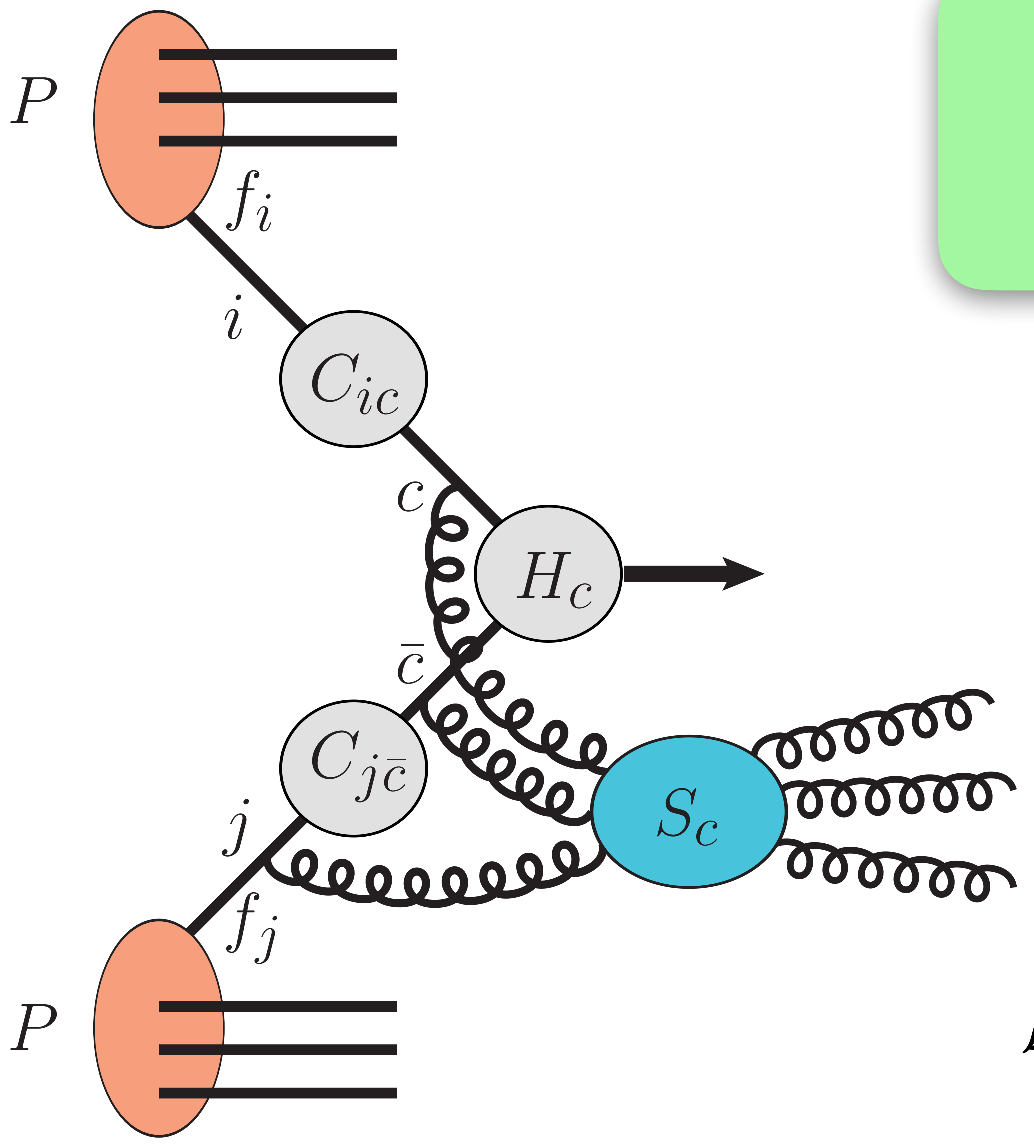
(symbolically)

integrate over b & take total derivative

reminder:

Transverse-momentum resummation

[Collins, Soper, Sterman '85]



$$\frac{\mathrm{d}\sigma(p_\mathrm{T})}{\mathrm{d}\Phi_\mathrm{F}} = p_\mathrm{T}\int_0^\infty db J_1(b\,p_\mathrm{T})\,e^{-S(b_0/b)}\mathcal{L}_b(Qb/b_0)$$

$$S(p_\mathrm{T}) = 2\int_{p_\mathrm{T}}^{Q}\frac{\mathrm{d}q}{q}\left(A(\alpha_s(q))\ln\frac{Q^2}{q^2} + B(\alpha_s(q))\right),$$

$$A(\alpha_s) = \sum_{k=1}^{2}\left(\frac{\alpha_s}{2\pi}\right)^k A^{(k)}, \quad B(\alpha_s) = \sum_{k=1}^{2}\left(\frac{\alpha_s}{2\pi}\right)^k B^{(k)}$$

$$\mathcal{L}_b(Qb/b_0) = \sum_{c,c'}\frac{\mathrm{d}|M^\mathrm{F}|^2_{cc'}}{\mathrm{d}\Phi_\mathrm{F}}\sum_{i,j}\left\{\left(C_{ci}^{[a]}\otimes f_i^{[a]}\right)\bar{H}(Qb/b_0)\left(C_{c'j}^{[b]}\otimes f_j^{[b]}\right)\right\}$$

MiNNLO$_{PS}$: derivation

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

- starting equation:

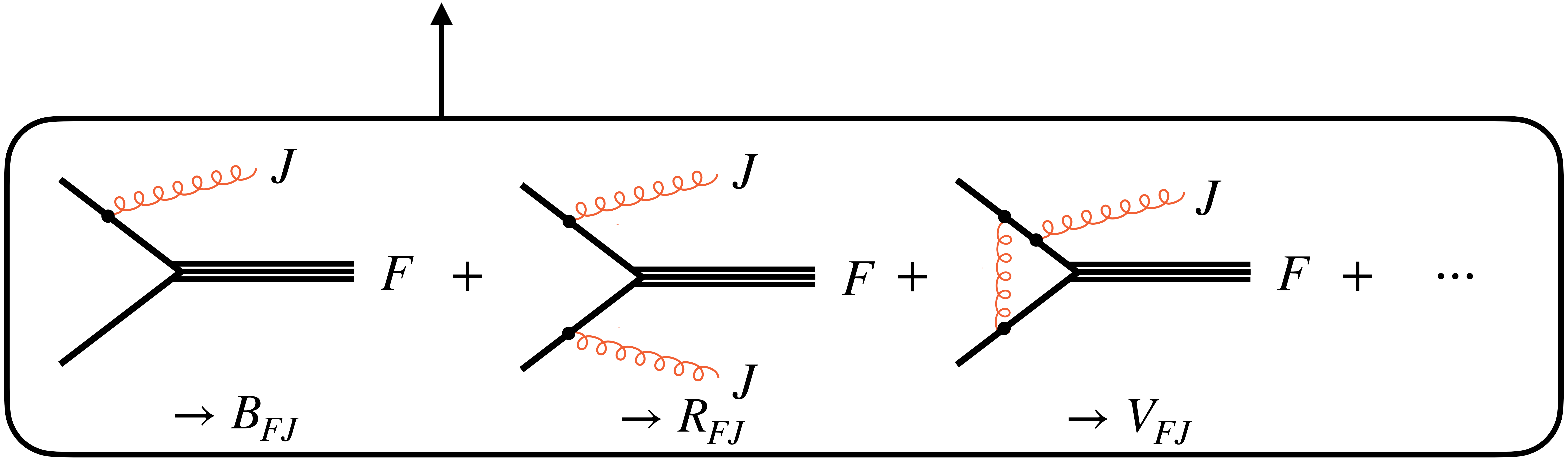
$$\frac{d\sigma_F^{\rm res}}{dp_T\, d\Phi_B} = \frac{d}{dp_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H(C\otimes f)(C\otimes f)$$

(symbolically)

- combine with F + jet fixed order $d\sigma_{FJ}$:

$$d\sigma_F = d\sigma_F^{\rm res} + [d\sigma_{FJ}]_{\rm f.o.} - [d\sigma_F^{\rm res}]_{\rm f.o.}$$



MiNNLO$_{PS}$: derivation

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ starting equation:

$$\frac{d\sigma_F^{\text{res}}}{dp_T\, d\Phi_B} = \frac{d}{dp_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H\,(C \otimes f)\,(C \otimes f)$$

(symbolically)

✦ combine with F + jet fixed order $d\sigma_{FJ}$:

$$d\sigma_F = d\sigma_F^{\text{res}} + [d\sigma_{FJ}]_{\text{f.o.}} - [d\sigma_F^{\text{res}}]_{\text{f.o.}} = e^{-S}\left\{ D + \frac{[d\sigma_{FJ}]_{\text{f.o.}}}{\underbrace{[e^{-S}]_{\text{f.o.}}}_{1-S^{(1)}\ldots}} - \underbrace{\frac{[d\sigma_F^{\text{res}}]_{\text{f.o.}}}{[e^{-S}]_{\text{f.o.}}}}_{-D^{(1)}-D^{(2)}\ldots} \right\}$$

MiNNLO$_{PS}$: derivation

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ starting equation: $$\frac{\mathrm{d}\sigma_F^{\mathrm{res}}}{\mathrm{d}p_T\,\mathrm{d}\Phi_\mathrm{B}} = \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H\,(C\otimes f)\,(C\otimes f)$$

(symbolically)

✦ combine with F + jet fixed order $\mathrm{d}\sigma_{FJ}$:

$$\mathrm{d}\sigma_F = \mathrm{d}\sigma_F^{\mathrm{res}} + [\mathrm{d}\sigma_{FJ}]_{\mathrm{f.o.}} - [\mathrm{d}\sigma_F^{\mathrm{res}}]_{\mathrm{f.o.}} = e^{-S}\left\{D + \frac{[\mathrm{d}\sigma_{FJ}]_{\mathrm{f.o.}}}{[e^{-S}]_{\mathrm{f.o.}}} - \frac{[\mathrm{d}\sigma_F^{\mathrm{res}}]_{\mathrm{f.o.}}}{[e^{-S}]_{\mathrm{f.o.}}}\right\}$$

$$= e^{-S}\left\{D + [\mathrm{d}\sigma_{FJ}]_{\mathrm{f.o.}}\left(1 - S^{(1)} - \cdots\right) - D^{(1)} - D^{(2)} - \cdots\right\}$$

MiNNLO$_{PS}$: derivation

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

- starting equation: $$\frac{d\sigma_F^{res}}{dp_T\, d\Phi_B} = \frac{d}{dp_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$\mathscr{L} \sim H\,(C \otimes f)\,(C \otimes f)$ (symbolically)

- combine with F + jet fixed order $d\sigma_{FJ}$:

$$d\sigma_F = d\sigma_F^{res} + [d\sigma_{FJ}]_{f.o.} - [d\sigma_F^{res}]_{f.o.} = e^{-S}\left\{D + \frac{[d\sigma_{FJ}]_{f.o.}}{[e^{-S}]_{f.o.}} - \frac{[d\sigma_F^{res}]_{f.o.}}{[e^{-S}]_{f.o.}}\right\}$$
$$= e^{-S}\left\{D + [d\sigma_{FJ}]_{f.o.}\left(1 - S^{(1)} - \cdots\right) - D^{(1)} - D^{(2)} - \cdots\right\}$$

- expand in $\alpha_s(p_T)$ & rearrange:

$$d\sigma_F^{MiNNLO} = e^{-S}\left\{\underbrace{d\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)}\left(1 + S^{(1)}\right) + \underbrace{d\sigma_{FJ}^{(2)}}_{\sim\alpha_s^2(p_T)} + \underbrace{\left(D - D^{(1)} - D^{(2)}\right)}_{\geq\alpha_s^3(p_T)} + \text{regular}\right\}$$

$\geq\alpha_s^3(p_T) \rightarrow D^{(3)} + \mathcal{O}(\alpha_s^4)$

MiNNLO$_{PS}$: derivation

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ starting equation:

$$\frac{\mathrm{d}\sigma_F^{\mathrm{res}}}{\mathrm{d}p_T\,\mathrm{d}\Phi_{\mathrm{B}}} = \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H\,(C\otimes f)\,(C\otimes f)$$

(symbolically)

✦ combine with F + jet fixed order $\mathrm{d}\sigma_{FJ}$:

$$\mathrm{d}\sigma_F = \mathrm{d}\sigma_F^{\mathrm{res}} + [\mathrm{d}\sigma_{FJ}]_{\mathrm{f.o.}} - [\mathrm{d}\sigma_F^{\mathrm{res}}]_{\mathrm{f.o.}} = e^{-S}\left\{D + \frac{[\mathrm{d}\sigma_{FJ}]_{\mathrm{f.o.}}}{[e^{-S}]_{\mathrm{f.o.}}} - \frac{[\mathrm{d}\sigma_F^{\mathrm{res}}]_{\mathrm{f.o.}}}{[e^{-S}]_{\mathrm{f.o.}}}\right\}$$

$$= e^{-S}\left\{D + [\mathrm{d}\sigma_{FJ}]_{\mathrm{f.o.}}\left(1 - S^{(1)} - \cdots\right) - D^{(1)} - D^{(2)} - \cdots\right\}$$

✦ expand in $\alpha_s(p_T)$ & rearrange:

MiNLO

$$\mathrm{d}\sigma_F^{\mathrm{MiNNLO}} = \boxed{e^{-S}\left\{\underbrace{\mathrm{d}\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)}\left(1 + S^{(1)}\right) + \underbrace{\mathrm{d}\sigma_{FJ}^{(2)}}_{\sim\alpha_s^2(p_T)}\right.} + \underbrace{\left(D - D^{(1)} - D^{(2)}\right)}_{\geq\alpha_s^3(p_T)} + \mathrm{regular}\Big\}$$

MiNNLO$_{PS}$: derivation

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

- starting equation: $$\frac{\mathrm{d}\sigma_F^{\mathrm{res}}}{\mathrm{d}p_T\,\mathrm{d}\Phi_\mathrm{B}} = \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L}+\mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H\,(C\otimes f)\,(C\otimes f)$$

(symbolically)

- combine with F + jet fixed order $\mathrm{d}\sigma_{FJ}$:

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$$= e^{-S}\left\{D + [\mathrm{d}\sigma_{FJ}]_{\mathrm{f.o.}}\left(1 - S^{(1)} - \cdots\right) - D^{(1)} - D^{(2)} - \cdots\right\}$$

- expand in $\alpha_s(p_T)$ & rearrange:

MiNLO | NNLO correction

$$\mathrm{d}\sigma_F^{\mathrm{MiNNLO}} = e^{-S}\left\{\underbrace{\mathrm{d}\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)}\left(1+S^{(1)}\right) + \underbrace{\mathrm{d}\sigma_{FJ}^{(2)}}_{\sim\alpha_s^2(p_T)} + \underbrace{\left(D - D^{(1)} - D^{(2)}\right)}_{\geq\alpha_s^3(p_T)} + \text{regular}\right\}$$

beyond accuracy

MiNNLO$_{PS}$: master formula

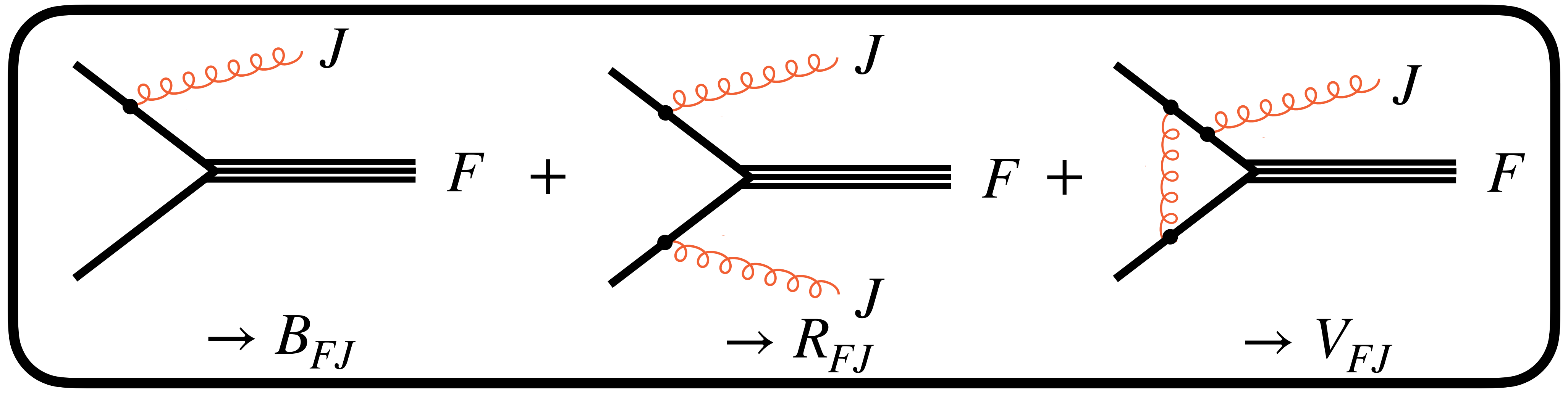
[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ apply idea to POWHEG FJ calculation

$$d\sigma_{FJ} = d\Phi_{FJ}\,\tilde{B}^{FJ} \times \left\{ \Delta_{\rm pwg}(\Lambda_{\rm pwg}) + d\Phi_{\rm rad}\Delta_{\rm pwg}(p_{T,\rm rad})\frac{R_{FJ}}{B_{FJ}} \right\}$$

$$\tilde{B}^{FJ} = B_{FJ} + V_{FJ} + \int d\Phi_{\rm rad}\, R_{FJ}$$

$$\equiv \left\{ \frac{d\sigma_{FJ}^{(1)}}{d\Phi_{\rm B}} + \frac{d\sigma_{FJ}^{(2)}}{d\Phi_{\rm B}} \right\}$$



MiNNLO$_{PS}$: master formula

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ NNLO+PS by turning POWHEG weight ($\tilde{B}$ function) NNLO accurate:

$$d\sigma_F^{\mathrm{MiNNLO_{PS}}} = d\Phi_{FJ}\, \tilde{B}^{\mathrm{MiNNLO_{PS}}} \times \left\{ \Delta_{\mathrm{pwg}}(\Lambda_{\mathrm{pwg}}) + d\Phi_{\mathrm{rad}} \Delta_{\mathrm{pwg}}(p_{T,\mathrm{rad}}) \frac{R_{FJ}}{B_{FJ}} \right\}$$

$$\tilde{B}^{\mathrm{MiNNLO_{PS}}} = e^{-S} \left\{ B_{FJ} \left(1 + S^{(1)}\right) + V_{FJ} + \int d\Phi_{\mathrm{rad}}\, R_{FJ} + \left(D - D^{(1)} - D^{(2)}\right) \times F^{\mathrm{corr.}} \right\}$$

→ *spreads NNLO corrections in the F + jet phase space*

☐ NNLO acuracy ☐ no merging/slicing cut ☐ shower accuracy (at least LL)

MiNNLO$_{PS}$: master formula

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ NNLO+PS by turning POWHEG weight ($\tilde{B}$ function) NNLO accurate:

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$$\tilde{B}^{\,\mathrm{MiNNLO_{PS}}} = e^{-S} \left\{ B_{FJ}\left(1 + S^{(1)}\right) + V_{FJ} + \int d\Phi_{\mathrm{rad}}\, R_{FJ} + \left(D - D^{(1)} - D^{(2)}\right) \times F^{\mathrm{corr.}} \right\}$$

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$$\tilde{B}^{\mathrm{MiNNLO_{PS}}} = e^{-S}\left\{ B_{FJ}\left(1 + S^{(1)}\right) + V_{FJ} + \int d\Phi_{\mathrm{rad}}\,R_{FJ} + \left(D - D^{(1)} - D^{(2)}\right) \times F^{\mathrm{corr.}} \right\}$$

☑ NNLO acuracy

☑ no merging/slicing cut

☐ shower accuracy (at least LL)

MiNNLO$_{PS}$: master formula

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

reminder 2 shower emissions: $d\sigma_{\rm PS} = d\Phi_B\, B \times \left\{ \Delta(\nu_0,\Lambda) + d\Phi_1 \Delta(\nu_0,\nu_1)\,\mathscr{P}(d\Phi_1) \times \left\{ \Delta(\nu_1,\Lambda) + d\Phi_2 \Delta(\nu_1,\nu_2)\,\mathscr{P}(d\Phi_2) \right\}\right\}$

$$d\sigma_F^{\rm MiNNLO_{PS}} = d\Phi_{FJ}\, \tilde{B}^{\,\rm MiNNLO_{PS}} \times \left\{ \Delta_{\rm pwg}(\Lambda_{\rm pwg}) + d\Phi_{\rm rad} \Delta_{\rm pwg}(p_{T,\rm rad}) \frac{R_{FJ}}{B_{FJ}} \right\}$$

$$\tilde{B}^{\,\rm MiNNLO_{PS}} = e^{-S} \left\{ B_{FJ} \left(1 + S^{(1)}\right) + V_{FJ} + \int d\Phi_{\rm rad}\, R_{FJ} + \left(D - D^{(1)} - D^{(2)}\right) \times F^{\rm corr.} \right\}$$

$$\simeq B \times \left\{ \Delta(\nu_0,\Lambda) + d\Phi_1 \Delta(\nu_0,\nu_1)\,\mathscr{P}(d\Phi_1) \right\}$$

- ☑ NNLO acuracy
- ☑ no merging/slicing cut
- ☑ shower accuracy (at least LL)

MiNNLO$_{PS}$: towards jet production

[Ebert, Rottoli, MW, Zanderighi, Zanoli '23]

✦ MiNNLO$_{PS}$ viable for any N-jet resolution variable (in principle), e.g. N-jettiness:

$$p_T \to \tau_N$$

$$\tilde{B}^{\,\mathrm{MiNNLO_{PS}}} \sim e^{-S(\tau_N)} \left\{ \mathrm{d}\sigma^{(1)}_{FJ} \big(1 + S^{(1)}(\tau_N)\big) + \mathrm{d}\sigma^{(2)}_{FJ} + \big(D(\tau_N) - D^{(1)}(\tau_N) - D^{(2)(\tau_N)}\big) \times F^{\mathrm{corr}} \right\}$$

MiNNLO$_{PS}$: towards jet production

[Ebert, Rottoli, MW, Zanderighi, Zanoli '23]

✦ MiNNLO$_{PS}$ viable for any N-jet resolution variable (in principle), e.g. N-jettiness: $p_T \to \tau_N$

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✦ Differences in singular cross section (SCETI vs SCETII) leads to a richer logarithmic structure for τ_N :

$$\mathrm{d}\sigma^{\mathrm{res}}_F(\tau_N) = e^{-S(\tau_N)}\Big[\mathscr{L}(\tau_N)\Big(1 - \frac{\zeta_2}{2}[(S')^2 - S''] - \zeta_3 S'S'' + \frac{3\zeta_4}{16}(S'')^2 + \frac{\zeta_3}{3}S'''\Big) + \mathscr{L}'(\tau_N)\big(\zeta_2 S' + \zeta_3 S''\big)$$
$$+\mathscr{L}'(\tau_N)\big(\zeta_2 S' + \zeta_3 S''\big) - \frac{\zeta_2}{2}\mathscr{L}''(\tau_N) + \mathcal{O}(\alpha_s^3)\Big]$$

[Ebert, Rottoli, MW, Zanderighi, Zanoli '23]

to be compared with:

$$\mathrm{d}\sigma^{\mathrm{res}}_F(p_T) = e^{-S(p_T)}\Big[\mathscr{L}(p_T)\Big(1 - \frac{\zeta_3}{4}S'S'' + \frac{\zeta_3}{12}\mathcal{S}'''\Big) - \frac{\zeta_3}{4}\frac{\alpha_s(p_T)}{\pi}S''\hat{P}\otimes\mathscr{L}(p_T) + \mathcal{O}(\alpha_s^3)\Big]$$

[Monni, Nason, Re, MW, Zanderighi '19]

MiNNLO$_{PS}$: towards jet production

[Ebert, Rottoli, MW, Zanderighi, Zanoli '23]

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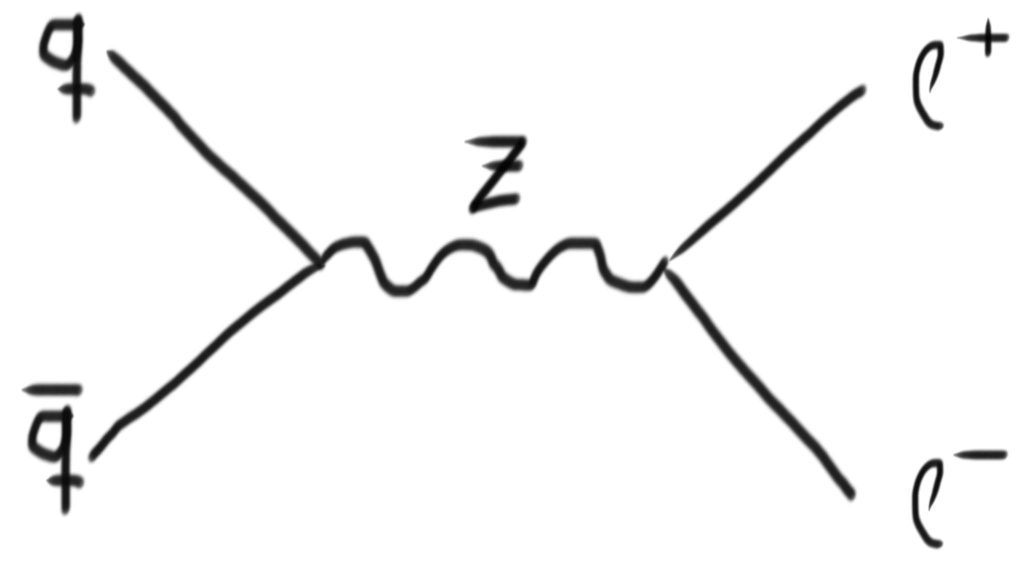
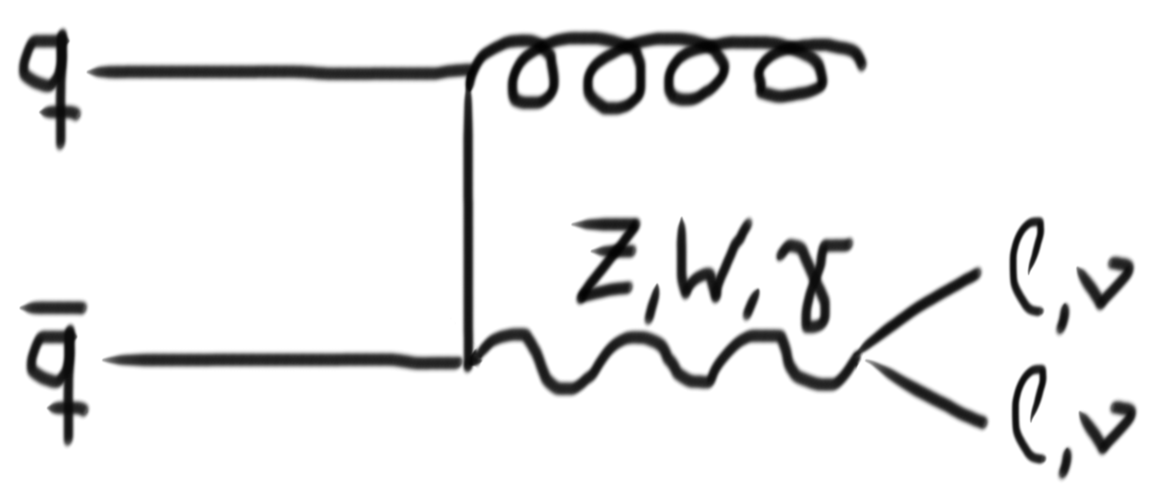
$$p_T \to \tau_N$$

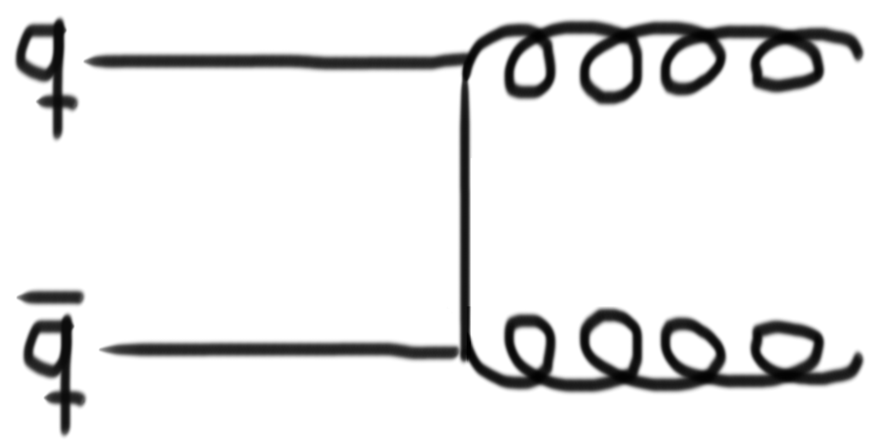
$$\tilde{B}^{\text{MiNNLO}_{\text{PS}}} \sim e^{-S(\tau_N)} \left\{ \mathrm{d}\sigma_{FJ}^{(1)} \left(1 + S^{(1)}(\tau_N)\right) + \mathrm{d}\sigma_{FJ}^{(2)} + \left(D(\tau_N) - D^{(1)}(\tau_N) - D^{(2)(\tau_N)}\right) \times F^{\text{corr}} \right\}$$



τ_0



τ_1



τ_2

see also Matthew's talk for recent developments in Geneva

[Alioli et al. '23]

MiNNLO$_{PS}$: towards jet production

[Ebert, Rottoli, MW, Zanderighi, Zanoli '23]

✦ MiNNLO$_{PS}$ viable for any N-jet resolution variable (in principle), e.g. N-jettiness:

$$p_T \to \tau_N$$

$$\tilde{B}^{\,\mathrm{MiNNLO_{PS}}} \sim e^{-S(\tau_N)} \left\{ \mathrm{d}\sigma^{(1)}_{FJ}\big(1 + S^{(1)}(\tau_N)\big) + \mathrm{d}\sigma^{(2)}_{FJ} + \big(D(\tau_N) - D^{(1)}(\tau_N) - D^{(2)(\tau_N)}\big) \times F^{\mathrm{corr}} \right\}$$

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$$\mathrm{d}\sigma^{\mathrm{res}}_F(\tau_N) = e^{-S(\tau_N)} \Big[\mathscr{L}(\tau_N) \Big(1 - \frac{\zeta_2}{2}[(S')^2 - S''] - \zeta_3 S' S'' + \frac{3\zeta_4}{16}(S'')^2 + \frac{\zeta_3}{3} S''' \Big) + \mathscr{L}'(\tau_N)\big(\zeta_2 S' + \zeta_3 S''\big)$$
$$+ \mathscr{L}'(\tau_N)\big(\zeta_2 S' + \zeta_3 S''\big) - \frac{\zeta_2}{2} \mathscr{L}''(\tau_N) + \mathcal{O}(\alpha_s^3) \Big]$$

[Ebert, Rottoli, MW, Zanderighi, Zanoli '23]

to be compared with:

$$\mathrm{d}\sigma^{\mathrm{res}}_F(p_T) = e^{-S(p_T)} \Big[\mathscr{L}(p_T) \Big(1 - \frac{\zeta_3}{4} S' S'' + \frac{\zeta_3}{12} \mathcal{S}''' \Big) - \frac{\zeta_3}{4} \frac{\alpha_s(p_T)}{\pi} S'' \hat{P} \otimes \mathscr{L}(p_T) + \mathcal{O}(\alpha_s^3) \Big]$$

[Monni, Nason, Re, MW, Zanderighi '19]

MiNNLO$_{PS}$: towards jet production

[Ebert, Rottoli, MW, Zanderighi, Zanoli '23]

τ_0 p_T p_T^j

[from L. Rottoli's talk at Ringberg 2024]

MiNNLO$_{PS}$: heavy quark production

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20 '21]

$$\mathrm{d}\sigma^F_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T} \left\{ e^{-S} \, \mathrm{Tr}(\mathbf{H\Delta}) \, (C \otimes f) \, (C \otimes f) \right\}$$

$$S = -\int \frac{\mathrm{d}q^2}{q^2} \left[\frac{\alpha_s(q)}{2\pi} \left(A^{(1)} \log(M/q) + B^{(1)}\right) + \frac{\alpha_s^2(q)}{(2\pi)^2} \left(A^{(2)} \log(M/q) + B^{(2)}\right) + \ldots \right]$$

$$\mathrm{Tr}(\mathbf{H\Delta}) = \langle M | \mathbf{\Delta} | M \rangle, \quad \mathbf{\Delta} = \mathbf{V}^\dagger \, \mathbf{D} \, \mathbf{V}, \quad \mathbf{V} = \exp\left\{ -\int \frac{\mathrm{d}q^2}{q^2} \left[\frac{\alpha_s(q)}{2\pi} \mathbf{\Gamma}^{(1)}_{\mathbf{t}} + \frac{\alpha_s^2(q)}{(2\pi)^2} \mathbf{\Gamma}^{(2)}_{\mathbf{t}} \right] \right\}$$

matrix in colour space

MiNNLO$_{PS}$: heavy quark production

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'B-type' correction to Sudakov

$$\mathrm{Tr}(\mathbf{H\Delta}) = \langle M|\,\mathbf{\Delta}\,|M\rangle, \quad \mathbf{\Delta} = \mathbf{V}^\dagger\,\mathbf{D}\,\mathbf{V}, \quad \mathbf{V} = \exp\left\{-\int\frac{dq^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\mathbf{\Gamma}_t^{(1)}+\frac{\alpha_s^2(q)}{(2\pi)^2}\mathbf{\Gamma}_t^{(2)}\right]\right\}$$

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- ✦ approximations keeping NNLO and (N)LL
  - ❖ azimuthal average with $\left[\mathbf{D}\right]_\phi = 1$ ➙ modifies $H \to \overline{H}$ and $(C\otimes f) \to \overline{(C\otimes f)}$ at α_s^2

see [Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Sargsyan '19]

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  - $\langle M|\boldsymbol{\Delta}|M\rangle \approx \underbrace{\langle M|M\rangle}_{=H}\,\frac{\langle M^{(0)}|\boldsymbol{\Delta}|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle}$

absorb mistake at NNLO in $B^{(2)}$

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- ❖ $\langle M|\boldsymbol{\Delta}|M\rangle \approx \underbrace{\langle M|M\rangle}_{=H}\,\dfrac{\langle M^{(0)}|\boldsymbol{\Delta}|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle}$
- ❖ expand $\mathbf{V} = \underbrace{\exp\left\{-\int\frac{\mathrm{d}q^2}{q^2}\frac{\alpha_s(q)}{2\pi}\boldsymbol{\Gamma}^{(1)}_{\mathbf{t}}\right\}}_{\equiv \mathbf{V}_{\mathrm{NLL}}}\times\left(1-\int\frac{\mathrm{d}q^2}{q^2}\frac{\alpha_s^2(q)}{(2\pi)^2}\boldsymbol{\Gamma}^{(2)}_{\mathbf{t}}\right)+\mathcal{O}(\mathrm{N^3LL})$

absorb in $B^{(2)}$ coefficient

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✦ using those approximations (exact up to NNLO & (N)LL) we have:

$$\tilde{B}^{(2)} = B^{(2)} + \frac{\langle M^{(0)}|\,\boldsymbol{\Gamma}^{(2)\dagger}+\boldsymbol{\Gamma}^{(2)}\,|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle} + \frac{2\,\mathrm{Re}\left\{\langle M^{(1)}|\,\boldsymbol{\Gamma}^{(1)\dagger}+\boldsymbol{\Gamma}^{(1)}\,|M^{(0)}\rangle\right\}}{\langle M^{(0)}|M^{(0)}\rangle} - \frac{2\,\langle M^{(0)}|\,\boldsymbol{\Gamma}^{(1)\dagger}+\boldsymbol{\Gamma}^{(1)}\,|M^{(0)}\rangle\,\mathrm{Re}\left\{\langle M^{(1)}|M^{(0)}\rangle\right\}}{\langle M^{(0)}|M^{(0)}\rangle^2}$$

and $$e^{-S}\langle M|\,\boldsymbol{\Delta}\,|M\rangle = e^{-\tilde{S}}\,\frac{\langle M^{(0)}|\,\mathbf{V}^\dagger_{\rm NLL}\mathbf{V}_{\rm NLL}\,|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle}\,H + \mathcal{O}(\alpha_s^5)$$

(reminder: $\mathbf{V}_{\rm NLL} \equiv \exp\left\{-\int\frac{dq^2}{q^2}\frac{\alpha_s(q)}{2\pi}\boldsymbol{\Gamma}^{(1)}_{\rm t}\right\}$)

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use basis $|M^{(0)}\rangle$ where $\boldsymbol{\Gamma}^{(1)}$ diagonal

$$\bar{B}^{(1)} = B^{(1)} + \gamma_i$$

eigenvalues of $\mathbf{V}^\dagger_{\rm NLL}\mathbf{V}_{\rm NLL}$ exponent

(reminder: $\mathbf{V}_{\rm NLL} \equiv \exp\left\{-\int\frac{dq^2}{q^2}\frac{\alpha_s(q)}{2\pi}\boldsymbol{\Gamma}^{(1)}_{\mathbf{t}}\right\}$)

MiNNLOPS: heavy quark production

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20 '21]

$$\mathrm{d}\sigma^F_{\rm res} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\,\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta})\,(C\otimes f)\,(C\otimes f)\right\}$$

$$\ldots^{2)} \log(M/q) + B^{(2)}\Big) + \ldots \Big]$$

MiNNLOPS for colour singlets

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ starting equation:

$$\frac{\mathrm{d}\sigma_F^{\rm res}}{\mathrm{d}p_T\,\mathrm{d}\Phi_{\rm B}} = \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$\mathscr{L} \sim H\,(C\otimes f)\,(C\otimes f)$

...LL) we have:

$$\ldots \boldsymbol{\Gamma}^{(1)\dagger} + \boldsymbol{\Gamma}^{(1)}\,|M^{(0)}\rangle\,\mathrm{Re}\left\{\langle M^{(1)}|M^{(0)}\rangle\right\} \over \langle M^{(0)}|M^{(0)}\rangle^2$$

and $$e^{-S}\langle M|\boldsymbol{\Delta}|M\rangle = e^{-\tilde{S}}\underbrace{\frac{\langle M^{(0)}|\mathbf{V}^\dagger_{\rm NLL}\mathbf{V}_{\rm NLL}|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle}}\,H + \mathcal{O}(\alpha_s^5)$$

$$= \sum_i c_i\,\underbrace{e^{-\tilde{S}+S_i}}_{\equiv e^{\bar{S}_i}}$$

simplified to sum of terms with same structure as starting formula for colour singlet case

$$\Rightarrow\ \mathrm{d}\sigma^F_{\rm res} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{\sum_i e^{-\bar{S}_i}\,\underbrace{c_i\,\overline{H}\,\overline{(C\otimes f)}\,\overline{(C\otimes f)}}_{\equiv\overline{\mathscr{L}}_i}\right\} + \text{terms beyond NNLO \& (N)LL}$$

MiNNLO$_{PS}$: $b\bar{b}Z$ production

[Mazzitelli, Sotnikov, MW '24]

Two-loop amplitude

★ complete calculation (five-point functions with massive b's) out of reach

★ we exploit small-mass expansion in m_b (massification procedure)

$1/\varepsilon$ poles in 5FS ⟷ $\log(m_b)$ in 4FS

$$2\mathrm{Re}\langle R^{(0)} | R^{(2)} \rangle = \sum_{i=1}^{4} \kappa_i \log^i(m_b/\mu_R) + 2\mathrm{Re}\langle R_0^{(0)} | R_0^{(2)} \rangle + \mathcal{O}(m_b/\mu)$$

massive amplitude — coefficients of massification (κ_i) — massless amplitude — power corrections

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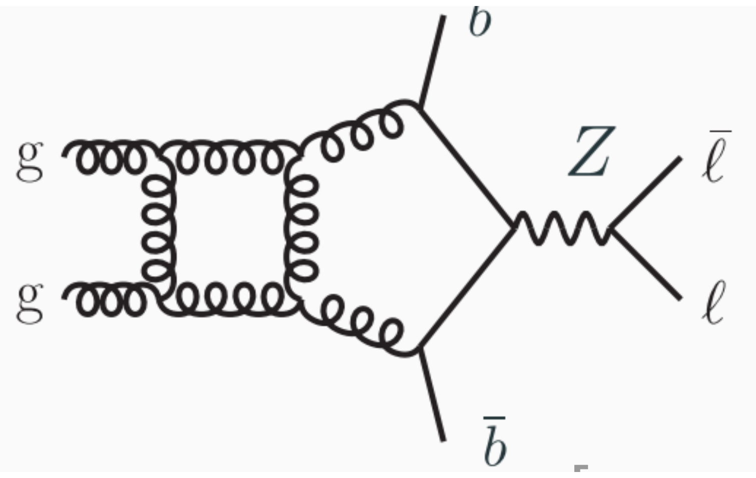
massive amplitude; coefficients of massification (κ_i); massless amplitude; power corrections

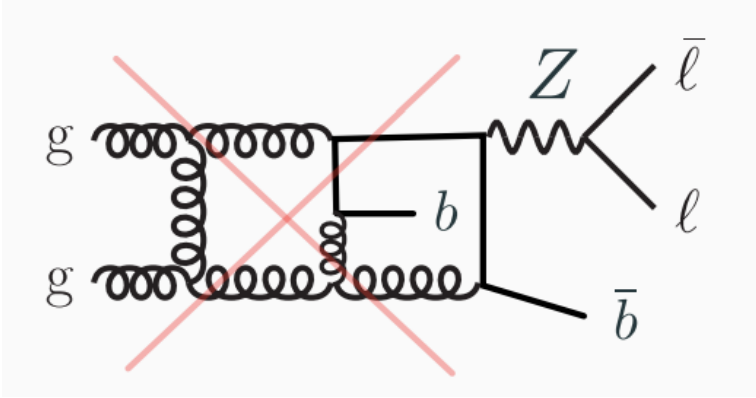
★ logarithmic terms exact (massless loops: [Mitov, Moch '06], massive loops: [Wang, Xia, Yang, Ye '23])

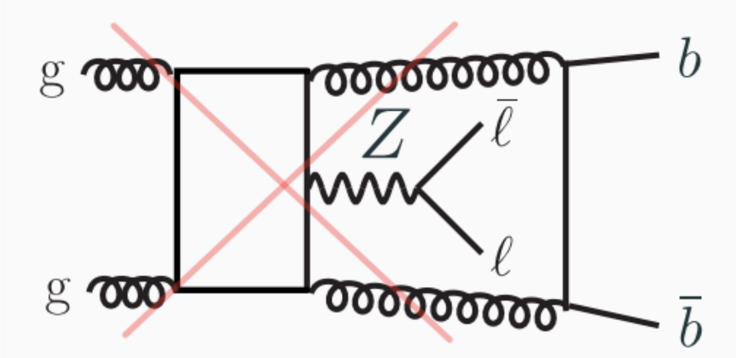
★ infra-red safe mapping required from massive to massless momenta

★ massless two-loop in LC approx. & dropping Z coupling to closed quark loops (small at NLO)

(based on [Chicherin, Sotnikov, Zoia '2110.07541], [Abreu, Cordero, Ita, Klinkert, Page, Sotnikov '2110.07541])







MiNNLO$_{PS}$: $b\bar{b}Z$ production

[Mazzitelli, Sotnikov, MW '24]

total cross section: $66\,\text{GeV} \leq m_{\ell^+\ell^-} \leq 116\,\text{GeV}$

	σ_{total} [pb]	ratio to NLO
NLO+PS ($m_{b\bar{b}\ell\ell}$)	$31.86(1)^{+16.3\%}_{-13.3\%}$	1.000
MiNLO′ ($m_{b\bar{b}\ell\ell}$)	$22.33(1)^{+28.2\%}_{-17.9\%}$	0.701
MiNNLO$_{PS}$ ($m_{b\bar{b}\ell\ell}$)	$50.58(4)^{+16.8\%}_{-12.2\%}$	1.587
NLO+PS ($H_T/2$)	$41.42(1)^{+19.2\%}_{-15.4\%}$	1.000
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→ MiNLO/multi-jet merging not suitable due to incomplete α_s^2 correction and large $\log(m_b)$ contribution in 2-loop (leading to miscancellation with $\log(m_b)$ from reals)
(only a problem for bottom quarks and processes with $Q \gg m_b$)

MiNNLO$_{PS}$: $b\bar{b}Z$ production

[Mazzitelli, Sotnikov, MW '24]

Comparison to CMS Z+b-jet analysis [CMS 2112.09659]

Object	Selection
Dressed leptons	p_T(leading) > 35 GeV, p_T(subleading) > 25 GeV, $\|\eta\| < 2.4$
Z boson	$71 < m_{\ell\ell} < 111$ GeV
Generator-level b jet	b hadron jet, $p_T > 30$ GeV, $\|\eta\| < 2.4$

5FS MG5_aMC from CMS paper

σ_{fiducial} [pb]	$Z+\geq 1$ b-jet	$Z+\geq 2$ b-jets
NLO+PS (5FS)	7.03 ± 0.47	0.77 ± 0.07
NLO+PS (4FS)	4.08 ± 0.66	0.44 ± 0.08
MiNNLO$_{PS}$ (4FS)	6.59 ± 0.86	0.77 ± 0.10
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huge difference between 4FS and 5FS calculation

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huge discrepancy of 4FS calculation with data

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NNLO corrections make 4FS and 5FS compatible

MiNNLO$_{PS}$: $b\bar{b}Z$ production

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NNLO corrections lift tension of 4FS with data