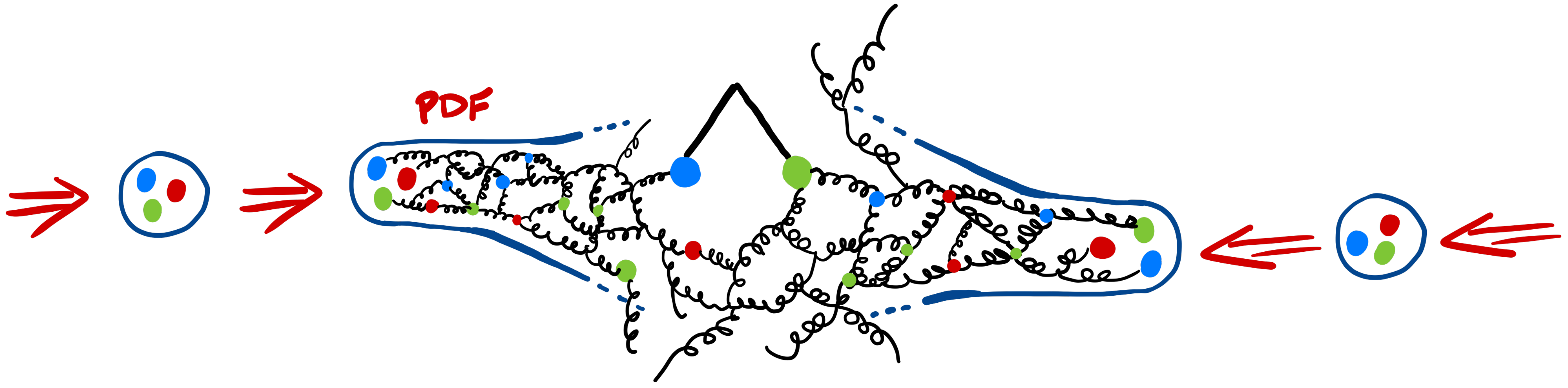
SCALE VARIATIONS AS THEORETICAL UNCERTAINTIES

Simone Devoto

GHENT UNIVERSITY

FACULTY OF SCIENCES

THEORETICAL INGREDIENTS



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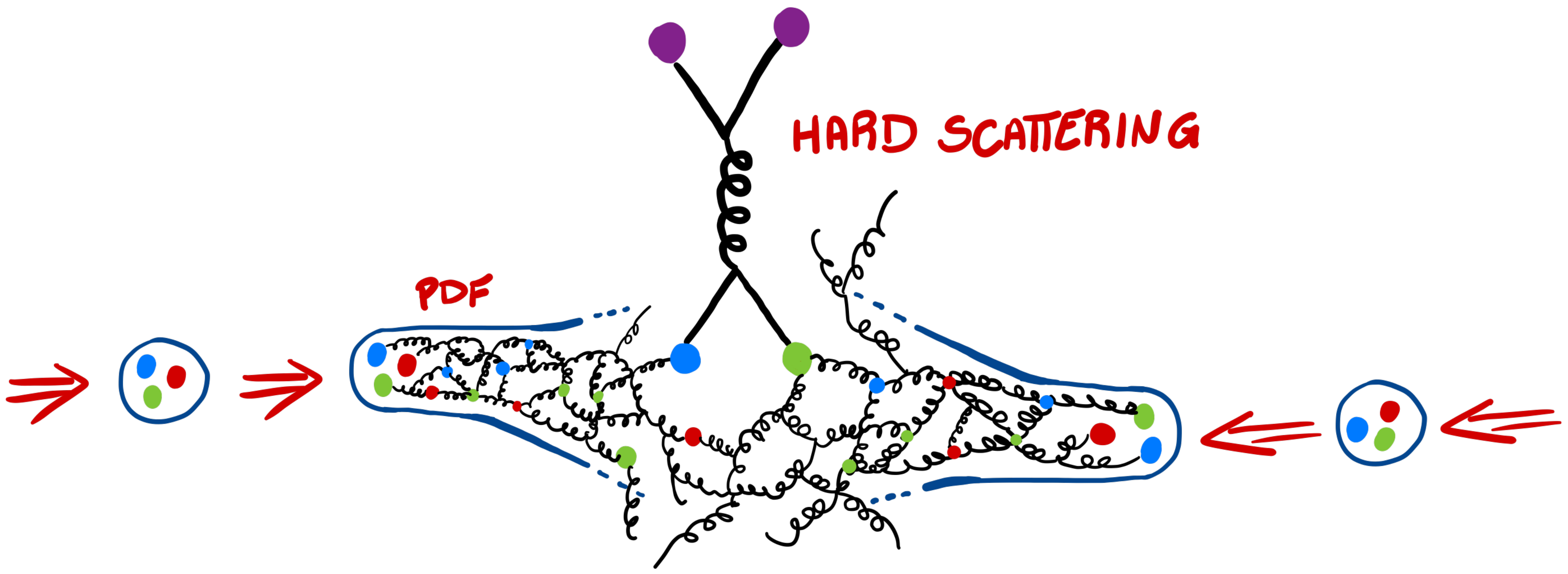

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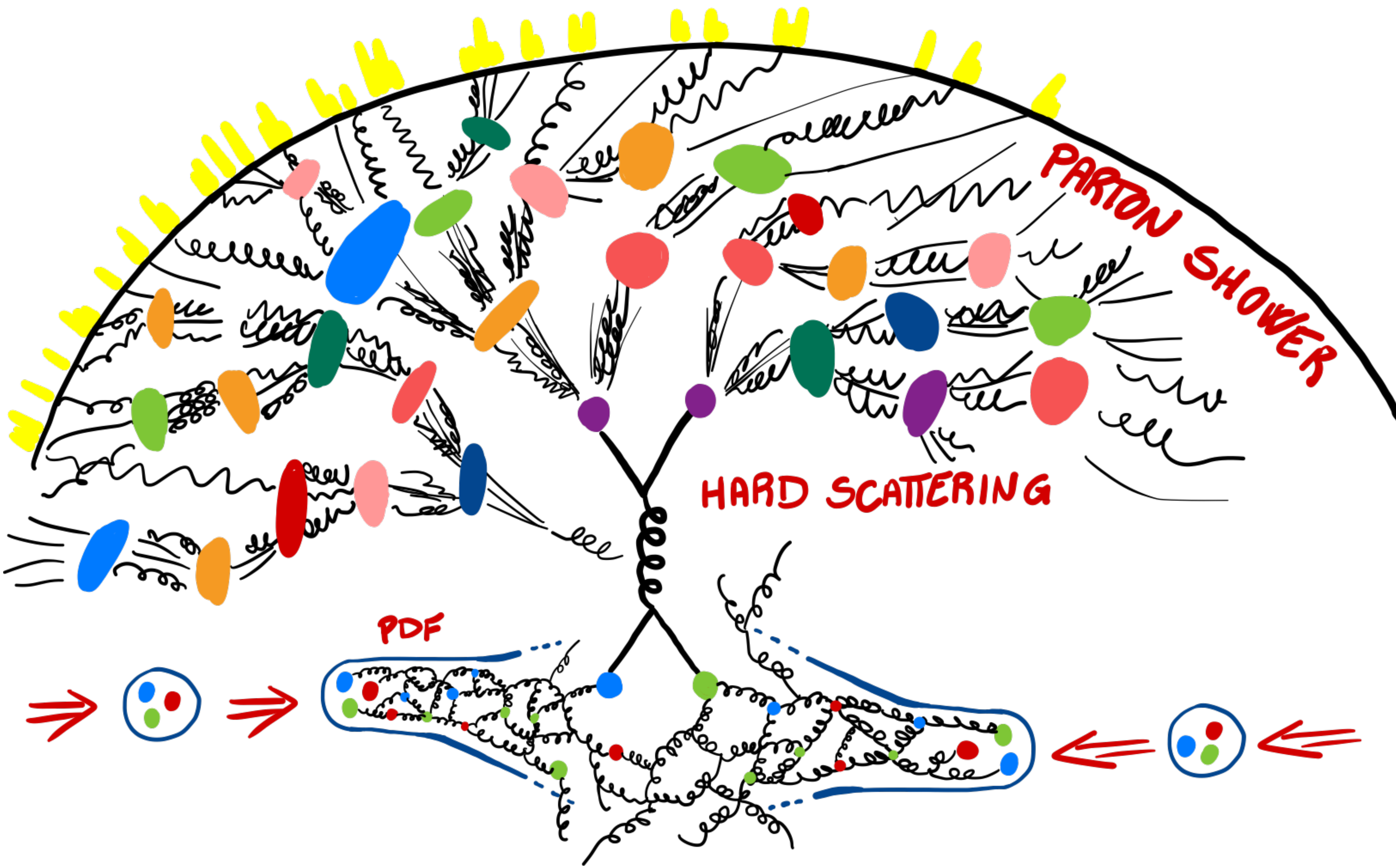

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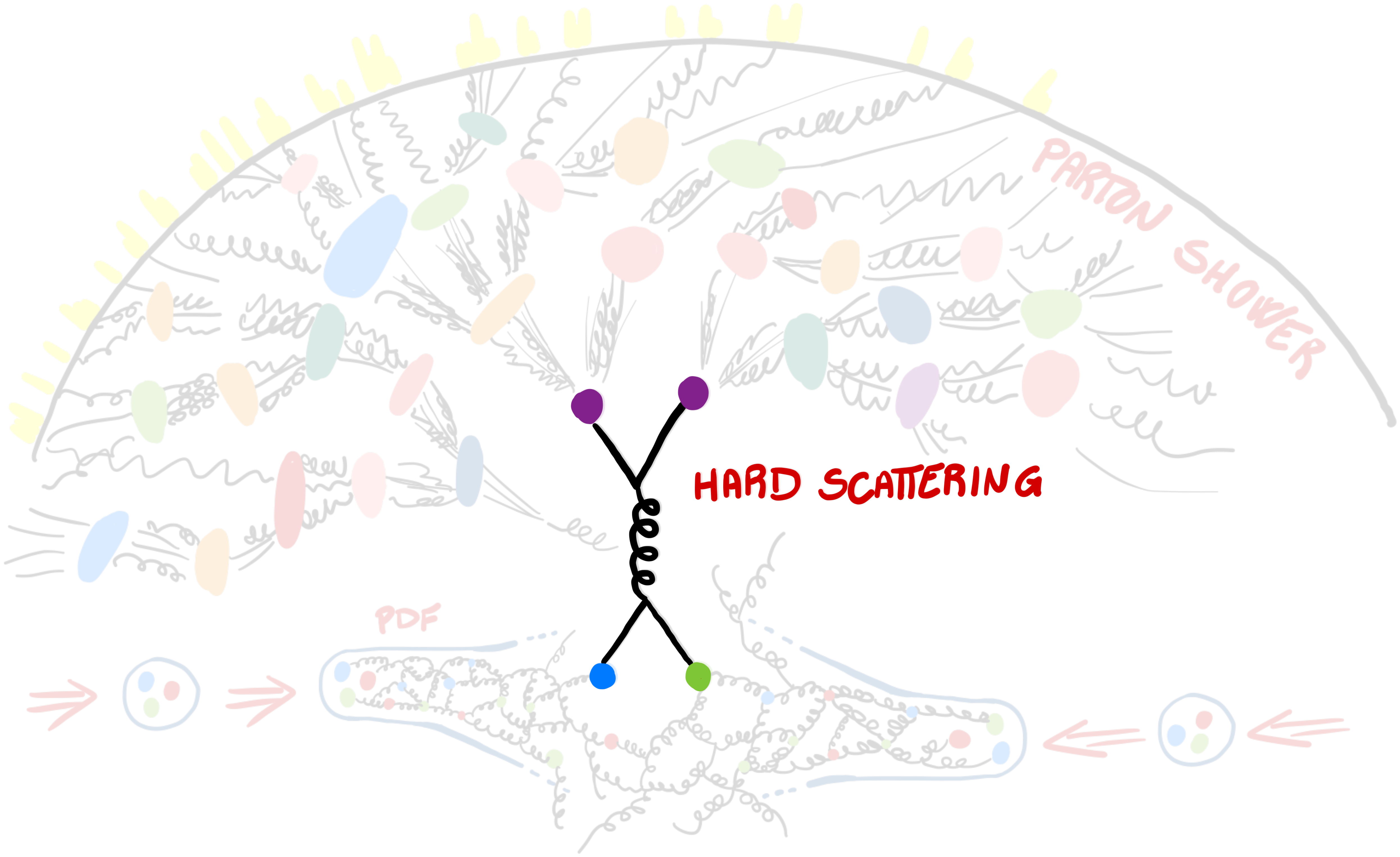
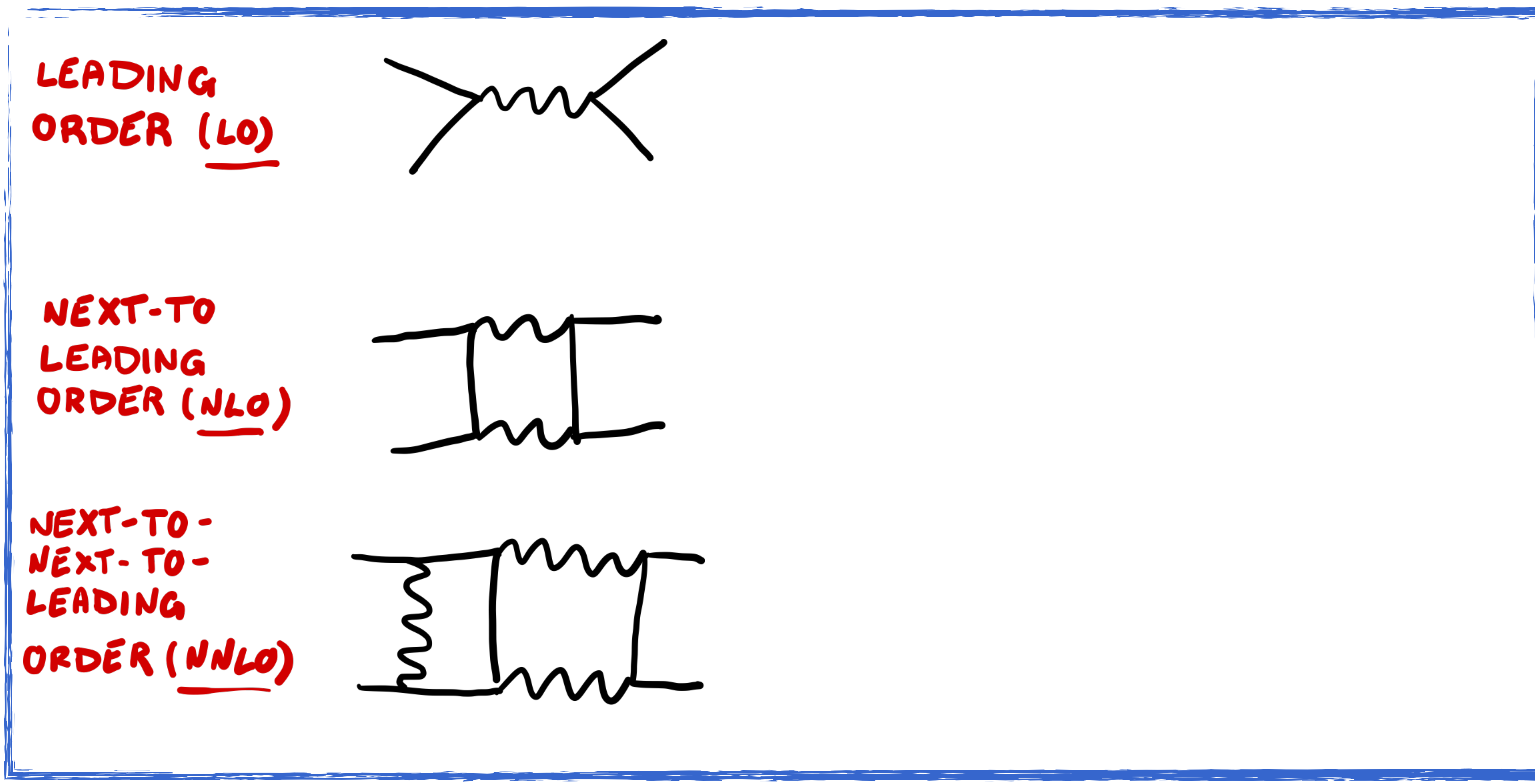


PRECISION TESTS OF THE STANDARD MODEL

- High precision in the theoretical prediction requires the computation of **higher order corrections**.



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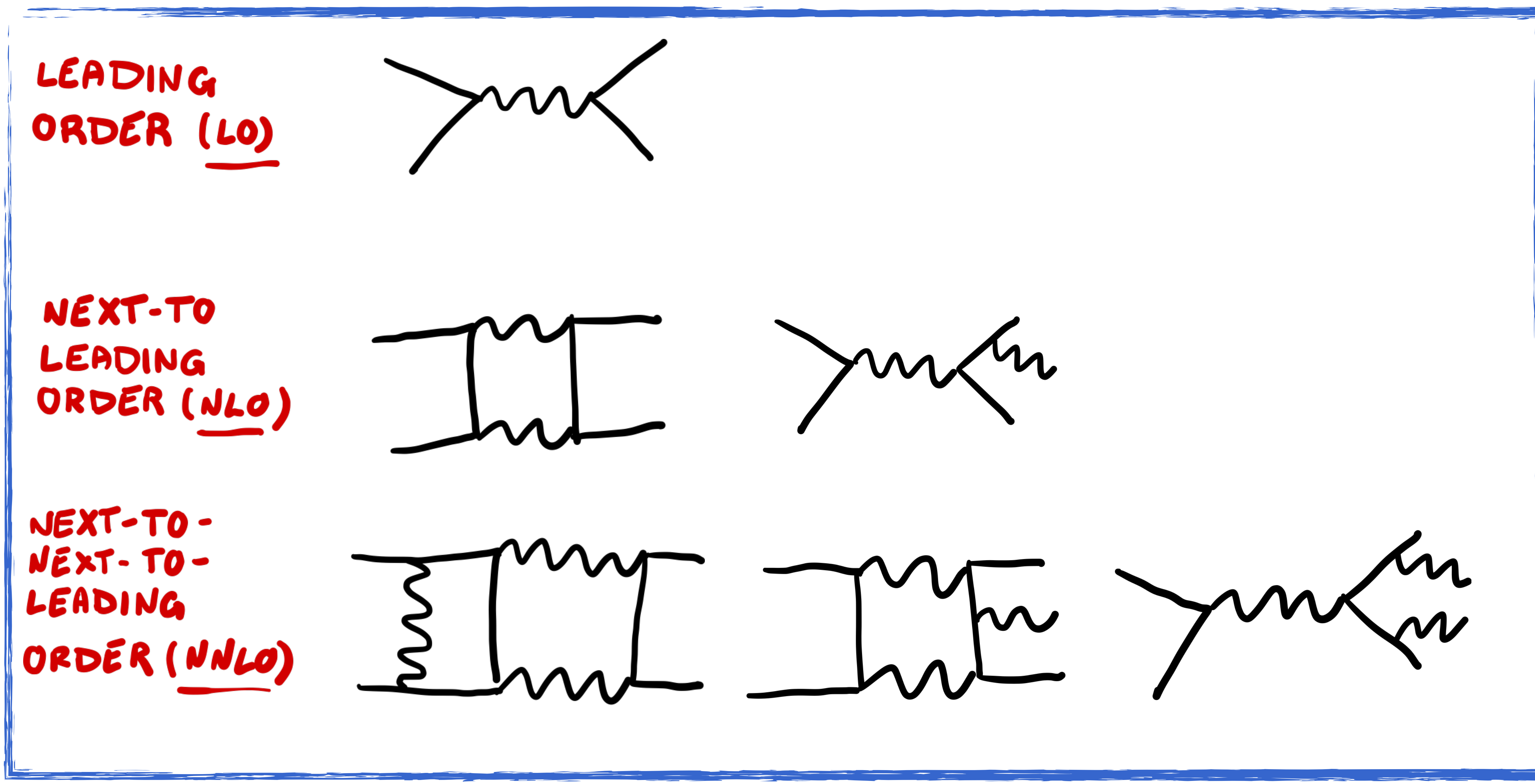
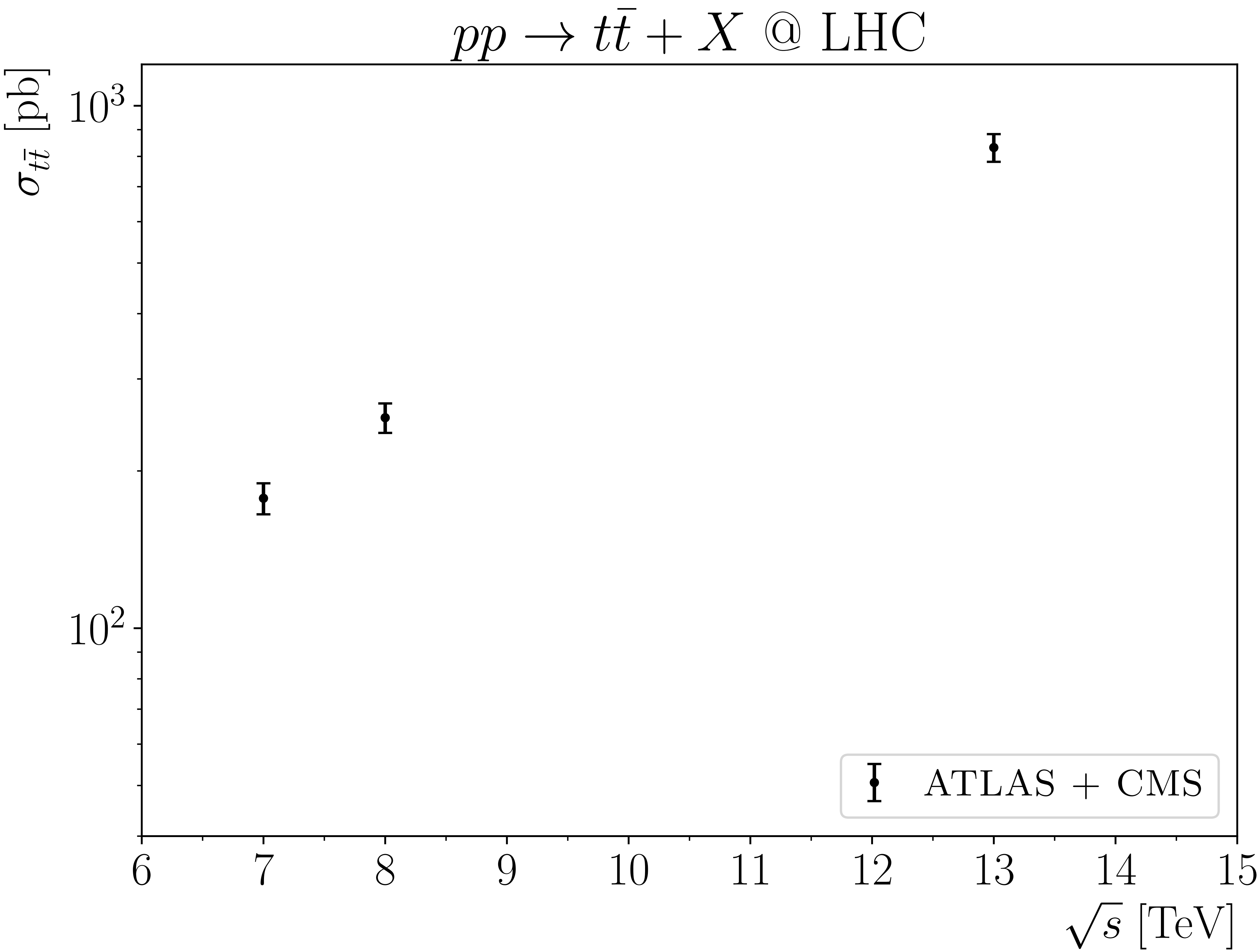


THE IMPORTANCE OF PRECISION



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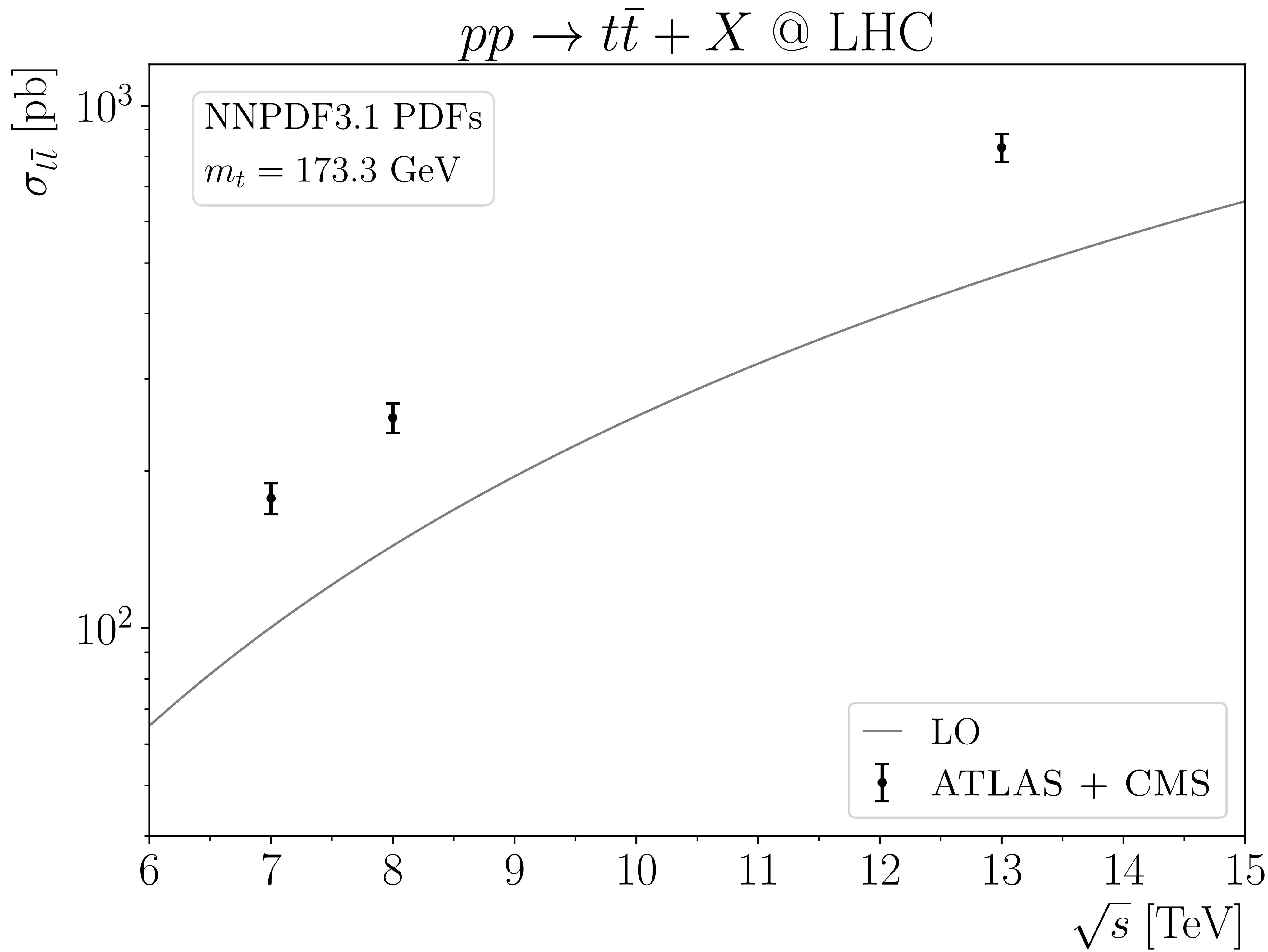

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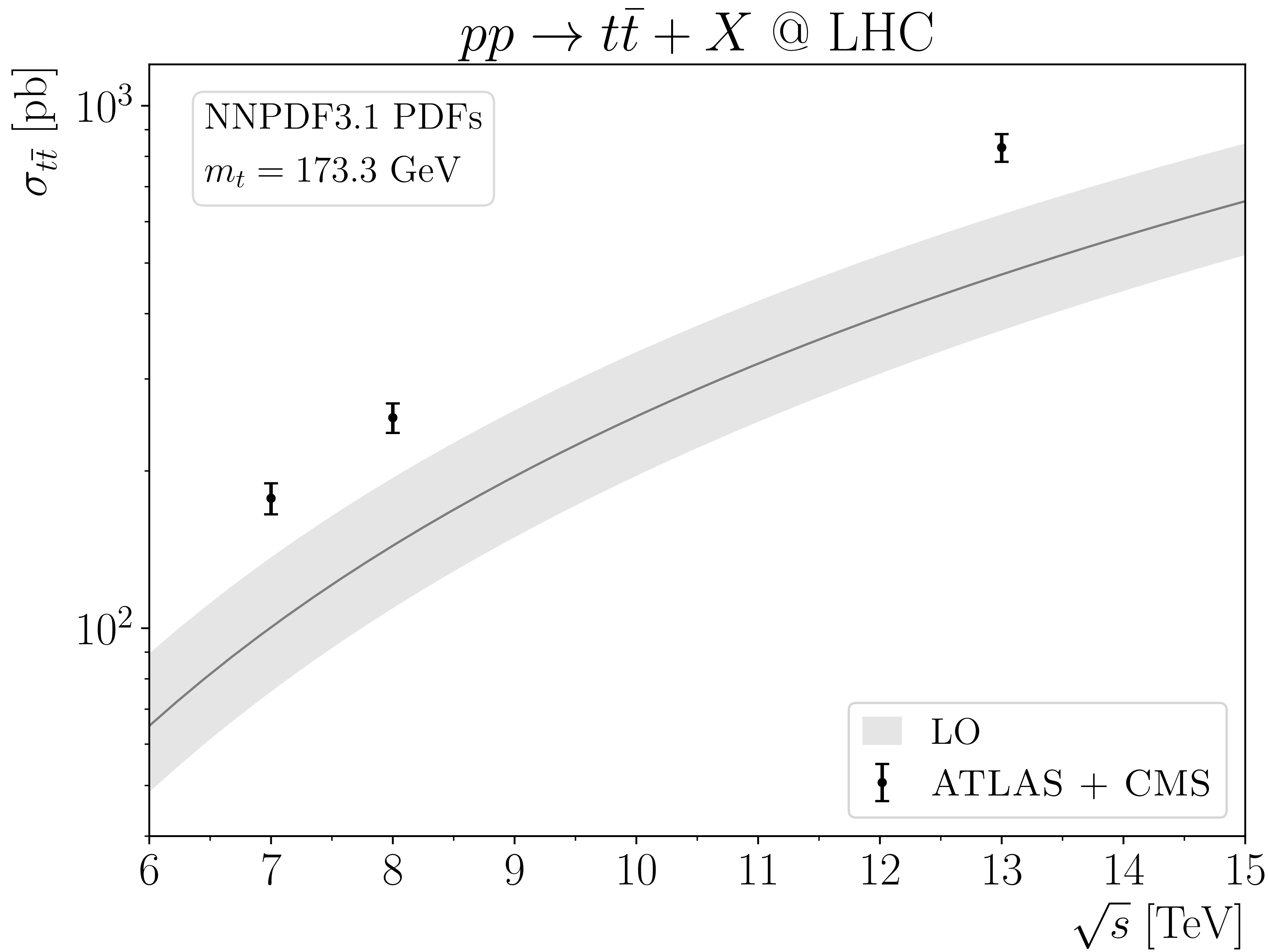

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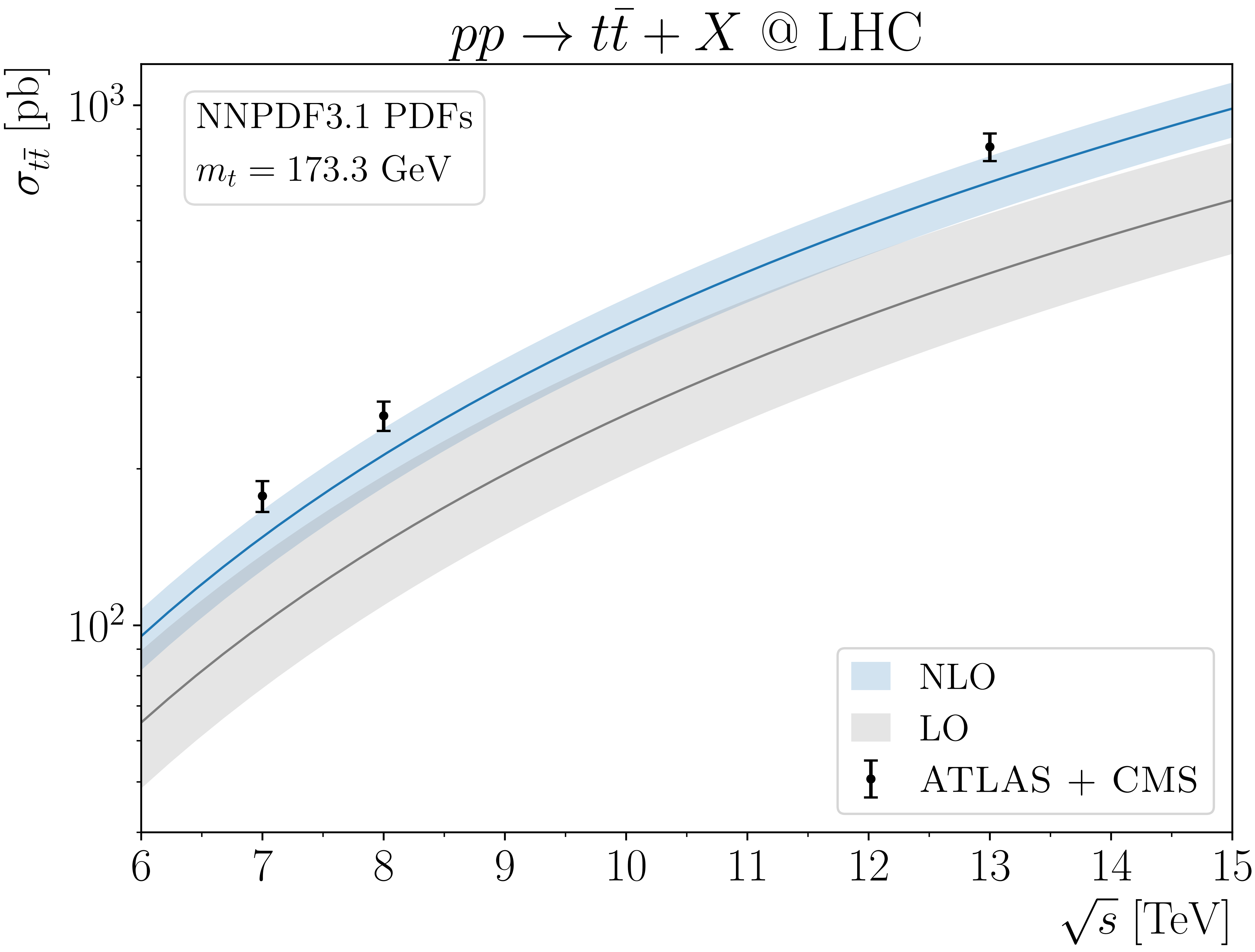

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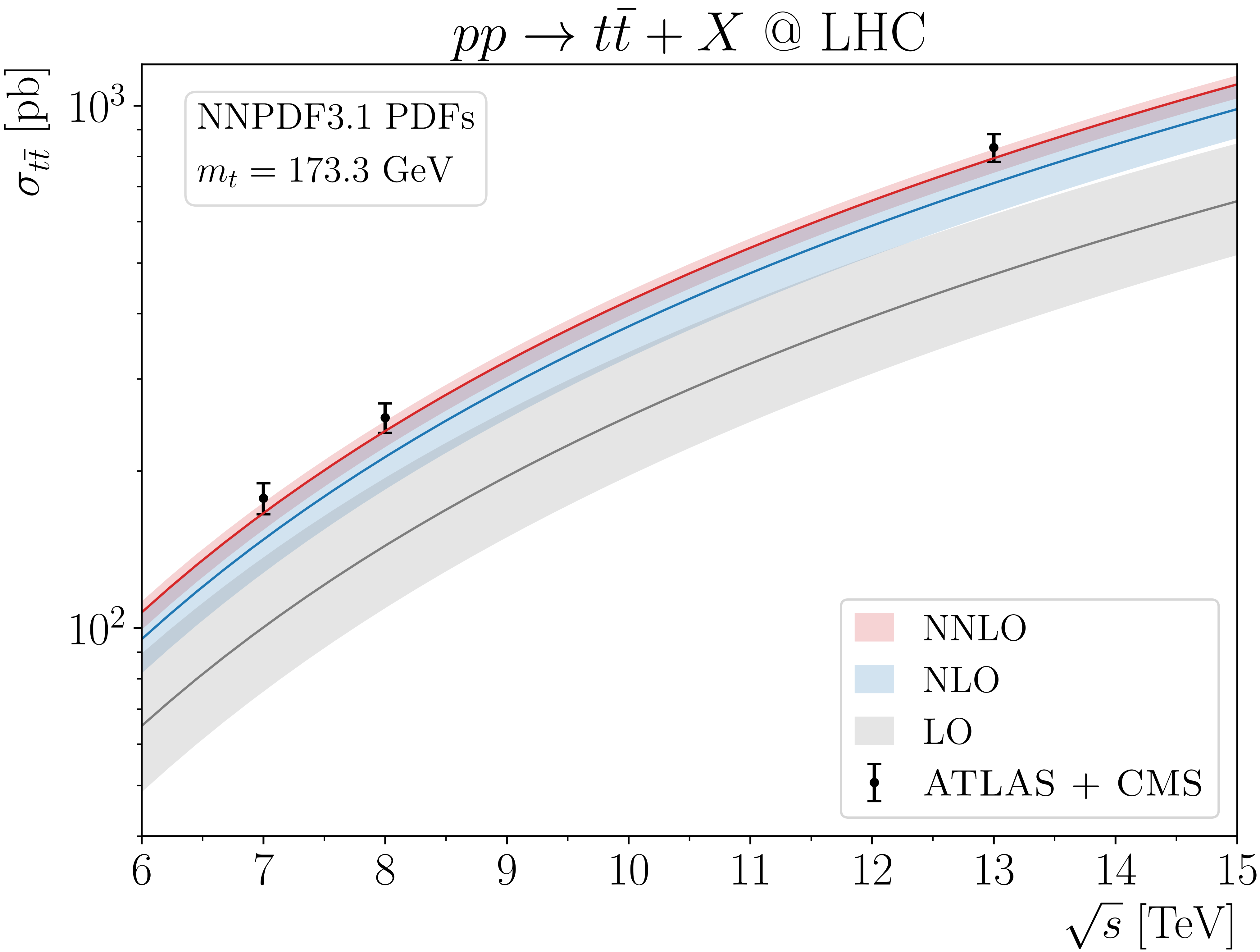
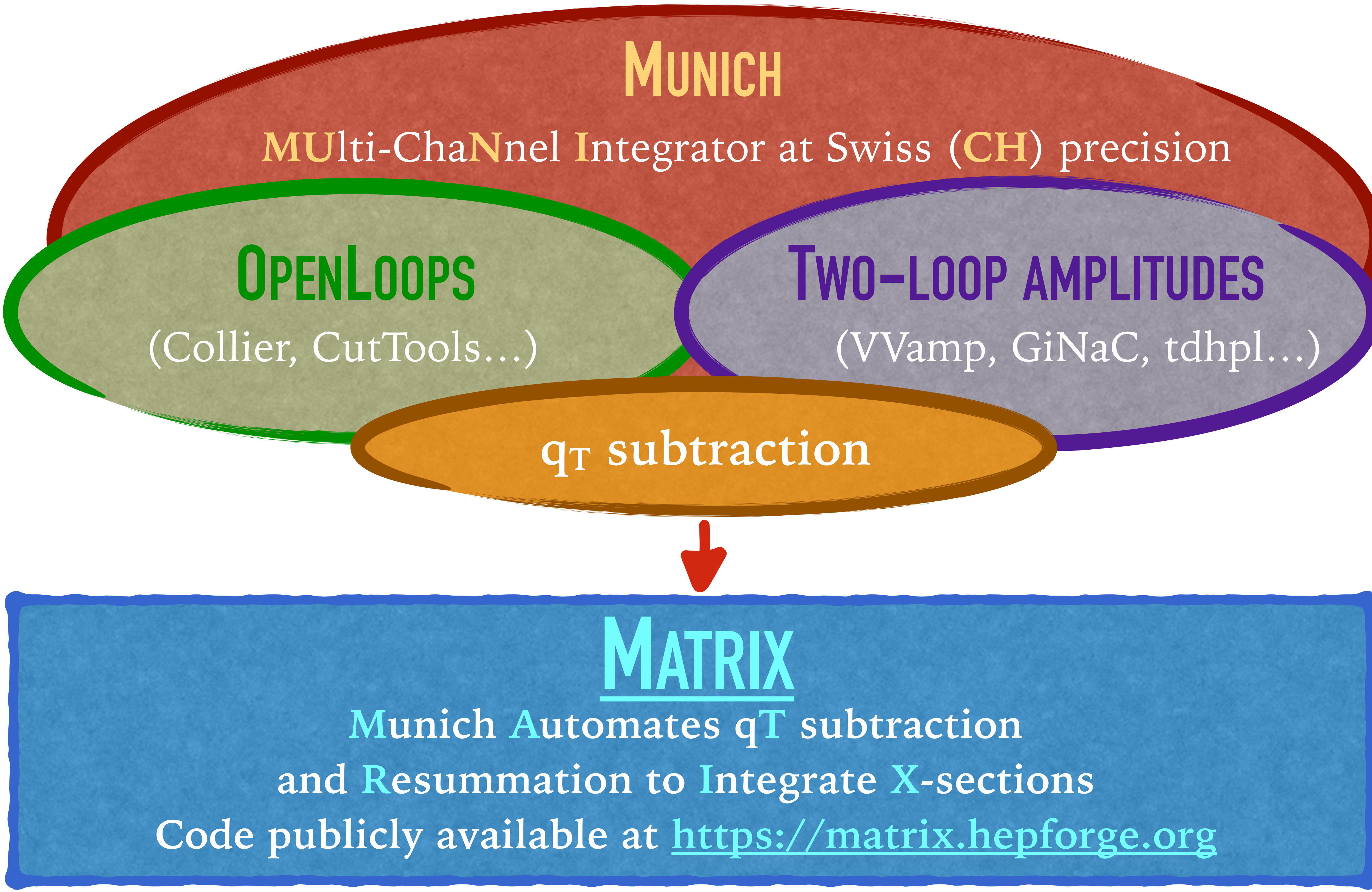


THE MATRIX FRAMEWORK

[M.Grazzini, S. Kallweit, M. Wiesemann: 1711.06631]



THE MATRIX FRAMEWORK

bnd002@bnd01:/var/bnd/users/bnd002/MATRIX_v2.1.0 ⌥⌘5

```
[bnd002@bnd01 MATRIX_v2.1.0]$ ./matrix
```

THE MATRIX FRAMEWORK

bnd002@bnd01:/var/bnd/users/bnd002/MATRIX_v2.1.0

```
[bnd002@bnd01 MATRIX_v2.1.0]$ ./matrix

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           |                                                                  |
           |       Version: 2.1.0                              Mar 2023       |
           |       Reference: arXiv:1711.06631                                |
           |                                                                  |
           | Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision -- |
           | Automates qT-subtraction and Resummation to Integrate X-sections |
           |                                                                  |
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           |                                                                  |
           | M. Grazzini                            (grazzini@physik.uzh.ch) |
           | S. Kallweit                           (stefan.kallweit@cern.ch) |
           | M. Wiesemann                         (marius.wiesemann@cern.ch) |
           |------------------------------------------------------------------|
           | MATRIX is based on a number of different computations and tools  |
           | from various people and groups. Please acknowledge their efforts |
           | by citing the references in CITATIONS.bib created with every run. |
           \------------------------------------------------------------------/

<<MATRIX-MAKE>> This is the MATRIX process compilation.
<<MATRIX-READ>> Type process_id to be compiled and created. Type "list" to show
                available processes. Try pressing TAB for auto-completion. Type
                "exit" or "quit" to stop.
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THE MATRIX FRAMEWORK

bnd002@bnd01:/var/bnd/users/bnd002/MATRIX_v2.1.0 ⌥⌘5

```
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           |                                                                  |
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           |                                                                  |
           | M. Grazzini                            (grazzini@physik.uzh.ch) |
           | S. Kallweit                           (stefan.kallweit@cern.ch) |
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|============>> list
```

THE MATRIX FRAMEWORK

bnd002@bnd01:/var/bnd/users/bnd002/MATRIX_v2.1.0 ⌥⌘5

```
           | Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision -- |
           | Automates qT-subtraction and Resummation to Integrate X-sections  |
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           | /          /           /          /           /           /       |
           |                                                                   |
           | M. Grazzini                              (grazzini@physik.uzh.ch) |
           | S. Kallweit                             (stefan.kallweit@cern.ch) |
           | M. Wiesemann                           (marius.wiesemann@cern.ch) |
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|============>> list
--------------------------------------------------------------------------------------------------------
process_id    ||   process                          ||   description
--------------------------------------------------------------------------------------------------------
pph21         >>   p p --> H                        >>   on-shell Higgs production (NNLO)
ppz01         >>   p p --> Z                        >>   on-shell Z production (NNLO,NLO EW)
ppw01         >>   p p --> W^-                      >>   on-shell W- production with CKM (NNLO)
ppwx01        >>   p p --> W^+                      >>   on-shell W+ production with CKM (NNLO)
ppeex02       >>   p p --> e^- e^+                  >>   Z production with decay (NNLO,NLO EW)
ppnenex02     >>   p p --> v_e^- v_e^+              >>   Z production with decay (NNLO,NLO EW)
ppenex02      >>   p p --> e^- v_e^+                >>   W- production with decay and CKM (NNLO,NLO EW)
ppexne02      >>   p p --> e^+ v_e^-                >>   W+ production with decay and CKM (NNLO,NLO EW)
ppaa02        >>   p p --> gamma gamma              >>   gamma gamma production (NNLO)
ppeexa03      >>   p p --> e^- e^+ gamma            >>   Z gamma production with decay (NNLO)
ppnenexa03    >>   p p --> v_e^- v_e^+ gamma        >>   Z gamma production with decay (NNLO)
ppenexa03     >>   p p --> e^- v_e^+ gamma          >>   W- gamma production with decay (NNLO)
ppexnea03     >>   p p --> e^+ v_e^- gamma          >>   W+ gamma production with decay (NNLO)
ppzz02        >>   p p --> Z Z                      >>   on-shell ZZ production (NNLO)
ppwxw02       >>   p p --> W^+ W^-                  >>   on-shell WW production (NNLO)
ppemexmx04    >>   p p --> e^- mu^- e^+ mu^+        >>   ZZ production with decay (NNLO,NLO gg,NLO EW)
ppeeexex04    >>   p p --> e^- e^- e^+ e^+          >>   ZZ production with decay (NNLO,NLO gg,NLO EW)
ppeexnmnmx04  >>   p p --> e^- e^+ v_mu^- v_mu^+    >>   ZZ production with decay (NNLO,NLO gg,NLO EW)
ppemxnmnex04  >>   p p --> e^- mu^+ v_mu^- v_e^+    >>   WW production with decay (NNLO,NLO gg,NLO EW)
ppeexnenex04  >>   p p --> e^- e^+ v_e^- v_e^+      >>   ZZ/WW production with decay (NNLO,NLO gg,NLO EW)
ppemexnmx04   >>   p p --> e^- mu^- e^+ v_mu^+      >>   W-Z production with decay (NNLO,NLO EW)
ppeeexnex04   >>   p p --> e^- e^- e^+ v_e^+        >>   W-Z production with decay (NNLO,NLO EW)
ppeexmxnm04   >>   p p --> e^- e^+ mu^+ v_mu^-      >>   W+Z production with decay (NNLO,NLO EW)
ppeexexne04   >>   p p --> e^- e^+ e^+ v_e^-        >>   W+Z production with decay (NNLO,NLO EW)
ppttx20       >>   p p --> top anti-top             >>   on-shell top-pair production (NNLO)
ppaaa03       >>   p p --> gamma gamma gamma        >>   gamma gamma gamma production (NNLO)
|============>> 
```

THE MATRIX FRAMEWORK

bnd002@bnd01:/var/bnd/users/bnd002/MATRIX_v2.1.0 ⌥⌘5

```
            | Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision -- |
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            |                                                                   |
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ppexne02      >>   p p --> e^+ v_e^-              >>   W+ production with decay and CKM (NNLO,NLO EW)
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ppnenexa03    >>   p p --> v_e^- v_e^+ gamma      >>   Z gamma production with decay (NNLO)
ppenexa03     >>   p p --> e^- v_e^+ gamma        >>   W- gamma production with decay (NNLO)
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ppzz02        >>   p p --> Z Z                    >>   on-shell ZZ production (NNLO)
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ppemexmx04    >>   p p --> e^- mu^- e^+ mu^+      >>   ZZ production with decay (NNLO,NLO gg,NLO EW)
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ppeexnmnmx04  >>   p p --> e^- e^+ v_mu^- v_mu^+  >>   ZZ production with decay (NNLO,NLO gg,NLO EW)
ppemxnmnex04  >>   p p --> e^- mu^+ v_mu^- v_e^+  >>   WW production with decay (NNLO,NLO gg,NLO EW)
ppeexnenex04  >>   p p --> e^- e^+ v_e^- v_e^+    >>   ZZ/WW production with decay (NNLO,NLO gg,NLO EW)
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ppttx20       >>   p p --> top anti-top           >>   on-shell top-pair production (NNLO)
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|============>>
```

THE TOP QUARK

The **top quark** is the **heaviest** particle in the Standard Model: $m_t \simeq 173$ GeV.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.008																	2 He Helium 4.003
2	3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
3	11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.293
6	55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
7	87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinoids	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]

Number
Symbol
Name
Atomic Mass

57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

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THE TOP QUARK

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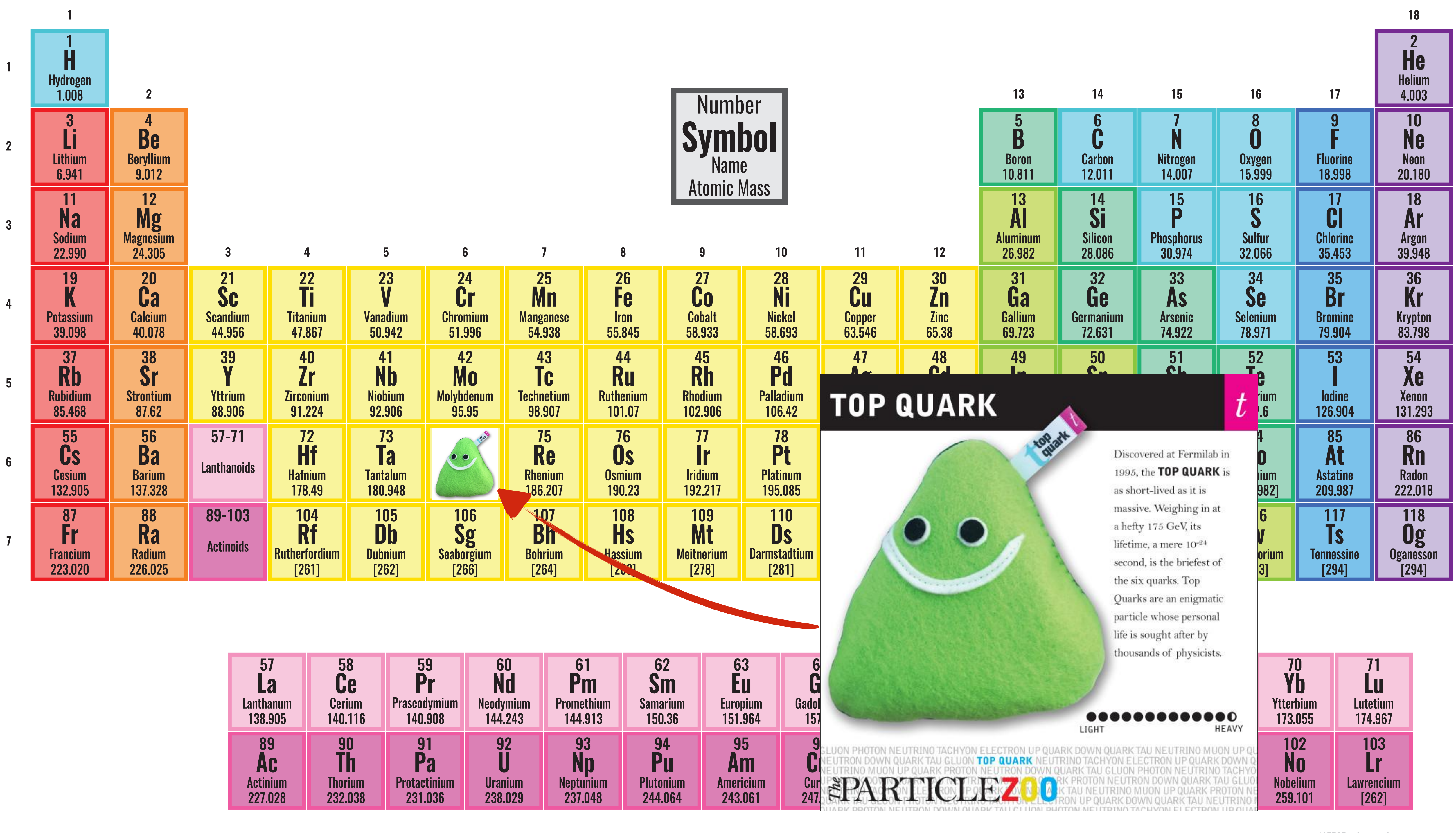
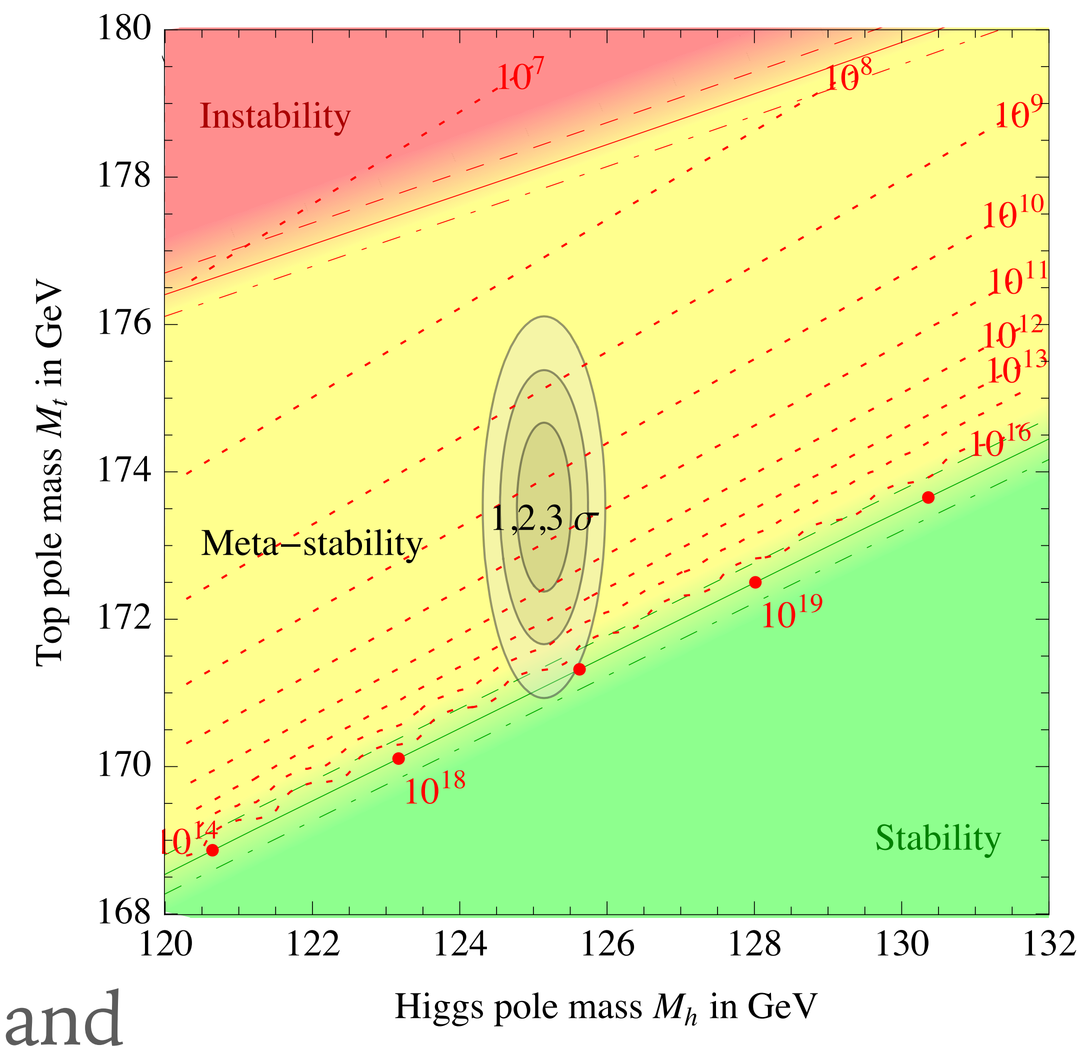


THE TOP QUARK

The Top Quark plays a major role both in Standard Model studies and Beyond the Standards Model searches!

- Has a strong coupling with the **Higgs boson**;
- The top mass is a **fundamental parameter** of the Standard Model;
- The value of the top mass plays a key role in **vacuum stability**;
- The top mass is a **standard candle** at LHC;
- possible window on **New Physics**;
- **Important background** both for SM and BSM studies.



EXPERIMENTAL MEASUREMENTS

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2018-039
2018/06/19

CMS-TOP-17-002

Measurement of differential cross sections for the production of top quark pairs and of additional jets in lepton+jets events from pp collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

Differential and double-differential cross sections for the production of top quark pairs in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ are measured as a function of kinematic variables of the top quarks and the top quark-antiquark ($\mathrm{t\bar{t}}$) system. In addition, kinematic variables and multiplicities of jets associated with the $\mathrm{t\bar{t}}$ production are measured. This analysis is based on data collected by the CMS experiment at the LHC in 2016 corresponding to an integrated luminosity of $35.8\,\text{fb}^{-1}$. The measurements are performed in the lepton+jets decay channels with a single muon or electron and jets in the final state. The differential cross sections are presented at the particle level, within a phase space close to the experimental acceptance, and at the parton level in the full phase space. The results are compared to several standard model predictions that use different methods and approximations. The kinematic variables of the top quarks and the $\mathrm{t\bar{t}}$ system are reasonably described in general, though none predict all the measured distributions. In particular, the transverse momentum distribution of the top quarks is more steeply falling than predicted. The kinematic distributions and multiplicities of jets are adequately modeled by certain combinations of next-to-leading-order calculations and parton shower models.

Published in Physical Review D as doi:10.1103/PhysRevD.97.112003.

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*See Appendix E for the list of collaboration members

arXiv:1803.08856v2 [hep-ex] 18 Jun 2018

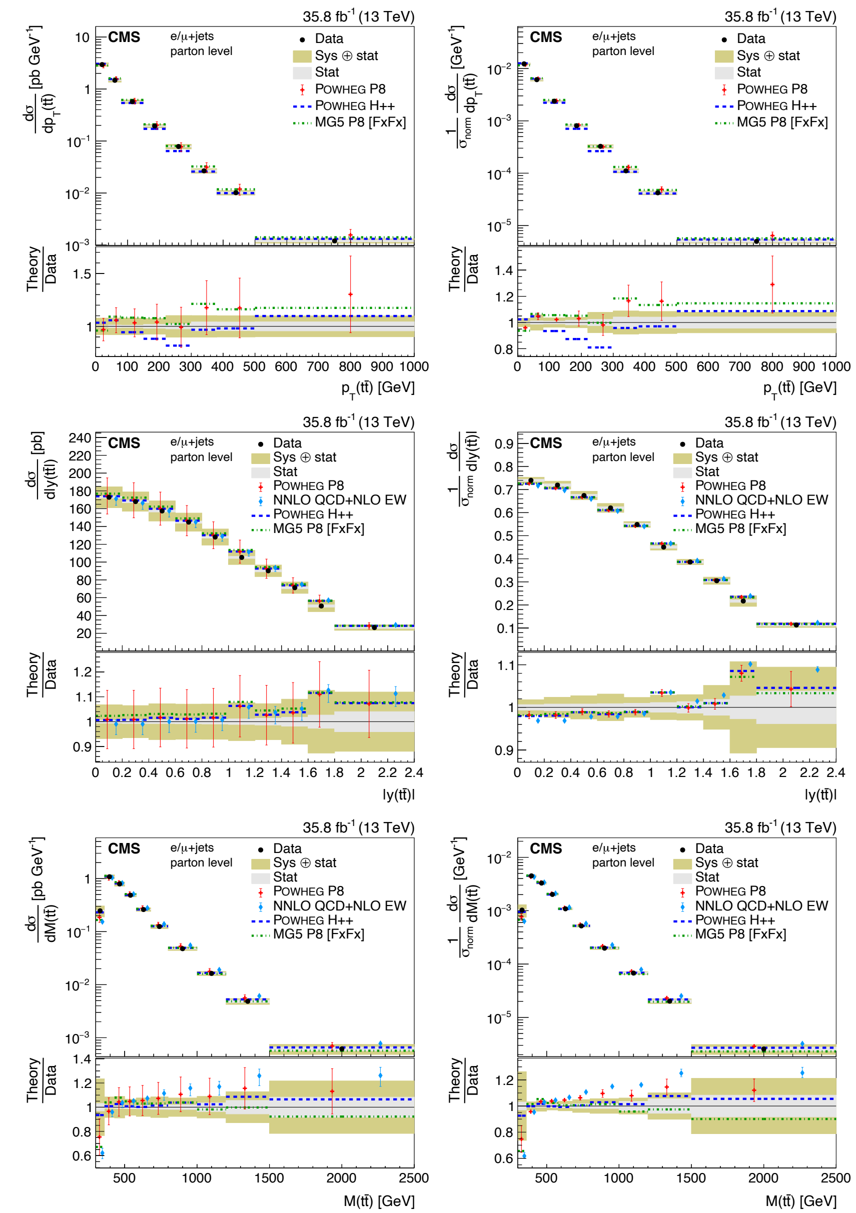

Figure 16: Absolute (left) and normalized (right) differential cross sections at the parton level as a function of $p_{\mathrm{T}}(\mathrm{t\bar{t}})$ (upper), $|y(\mathrm{t\bar{t}})|$ (middle), and $M(\mathrm{t\bar{t}})$ (lower). The data are shown as points with light (dark) bands indicating the statistical (statistical and systematic) uncertainties. The cross sections are compared to the predictions of POWHEG combined with PYTHIA8 (P8) or HERWIG++ (H++), the multiparton simulation MG5_aMC@NLO (MG5)+PYTHIA8 FxFx, and the NNLO QCD+NLO EW calculations. The ratios of the various predictions to the measured cross sections are shown at the bottom of each panel.

THE PROJECT

The CMS collaboration measured differential distributions for top pair production in the lepton+jet channel (Phys. Rev. D,97(11):112003, 2018), presenting parton level results.

- **Use MATRIX to compute NNLO theoretical predictions for the invariant mass of the $t\bar{t}$ pair, $m_{t\bar{t}}$, and the transverse momentum of the hadronically decaying top, $p_{T,t_{had}}$.** Fix the value of the top mass to $m_t = 173.3$ GeV and use the NNPDF31 set of parton distribution functions with $\alpha_S(m_Z) = 0.118$. Consider different choices for the central value μ_0 of the renormalization and factorization scale: $H_T/2$, $H_T/4$, $m_{t\bar{t}}/2$, $m_{T,t}$, $m_{T,\bar{t}}$, where $m_{T,t(\bar{t})}$ is the transverse mass of the (anti-)top quark, and H_T is defined as $H_T = m_{T,t} + m_{T,\bar{t}}$.
- **Plot the differential distributions** obtained for different central scale choices. What do you observe? Which ones exhibit a faster perturbative convergence? Which ones provide a more reliable estimate of the theoretical uncertainties?
- **Compare the theoretical predictions with experimental data**. How does the central scale choice affect the comparison? Do you observe agreement between theory and experimental measurements? If not, can you think about possible justifications?