FACULTY
OF SCIENCES

DEPARTMENT < PHYSICS AND ASTRONOMY >
RESEARCH GROUP < EXPERIMENTAL PARTICLE PHYSICS >

STUDY OF TOP QUARK PRODUCTION AT FUTURE ELECTRON-POSITRON COLLIDERS

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Mentor: dr. Kirill Skovpen

Motivations for Top quark studies

Unique properties:

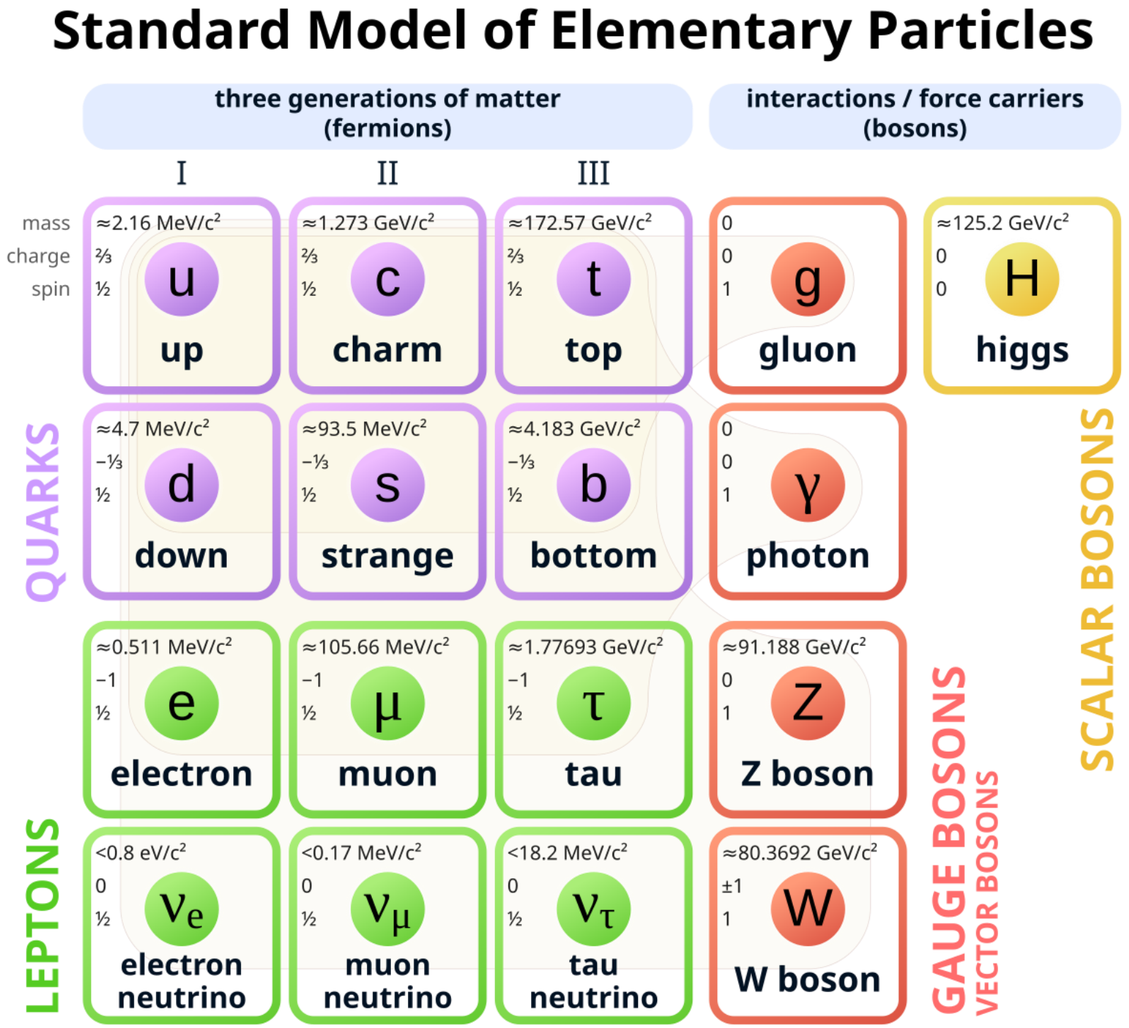
- Heaviest SM particle
- Yukawa coupling ≈ 1

Clean decay signature:

- Short lifetime $\tau \approx 5 \times 10^{-25} s$
- Decays before hadronizing
- Direct access spin properties

Probe BSM physics:

- Accurate Reconstruction needed



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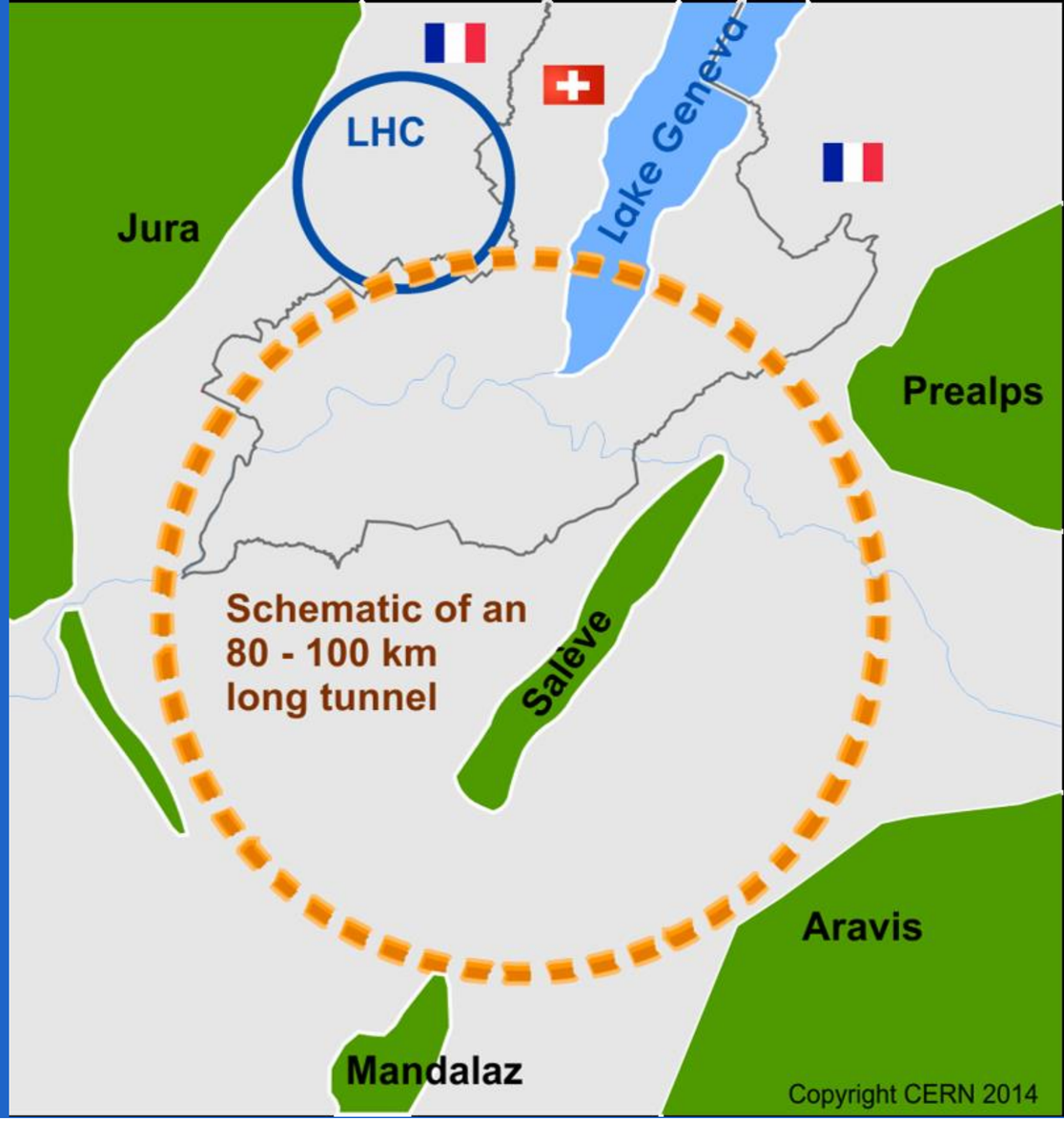
THE NEED FOR A NEW COLLIDER



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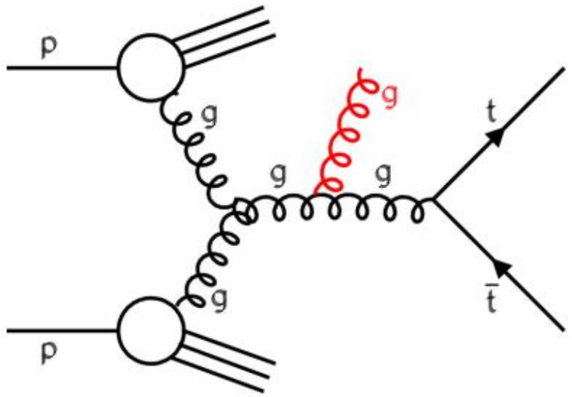
Hadron and Lepton colliders

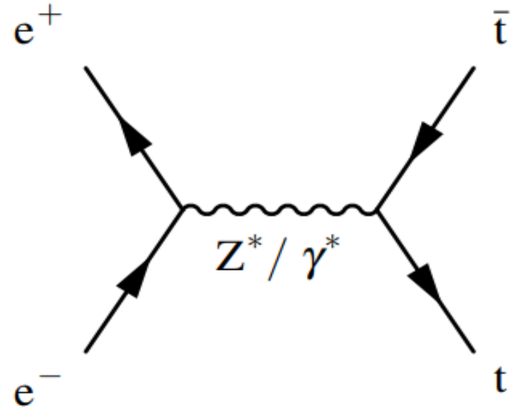


Proton is a compound object:

- Initial state unknown
- Limits in achievable precision

High Energy Circular colliders possible

High rates of QCD backgrounds



e^+e^- are pointlike

- Initial state well-defined
- High-precision measurements

High energies (> 380 GeV) require linear colliders

Clean experimental environment

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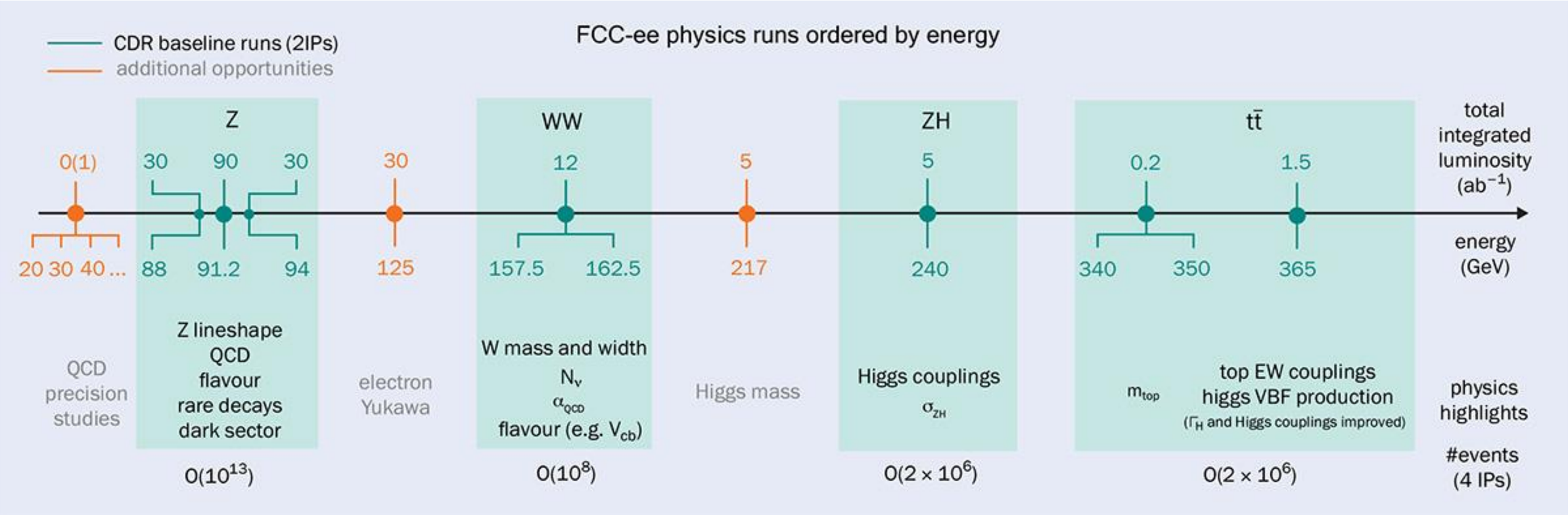
FCC-ee

- 4 Stages



FCC study (CERNCOURIER)

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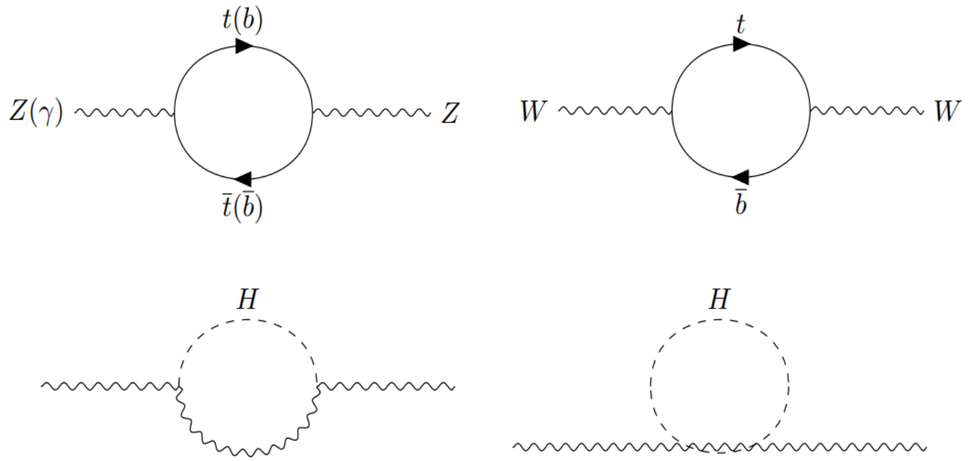
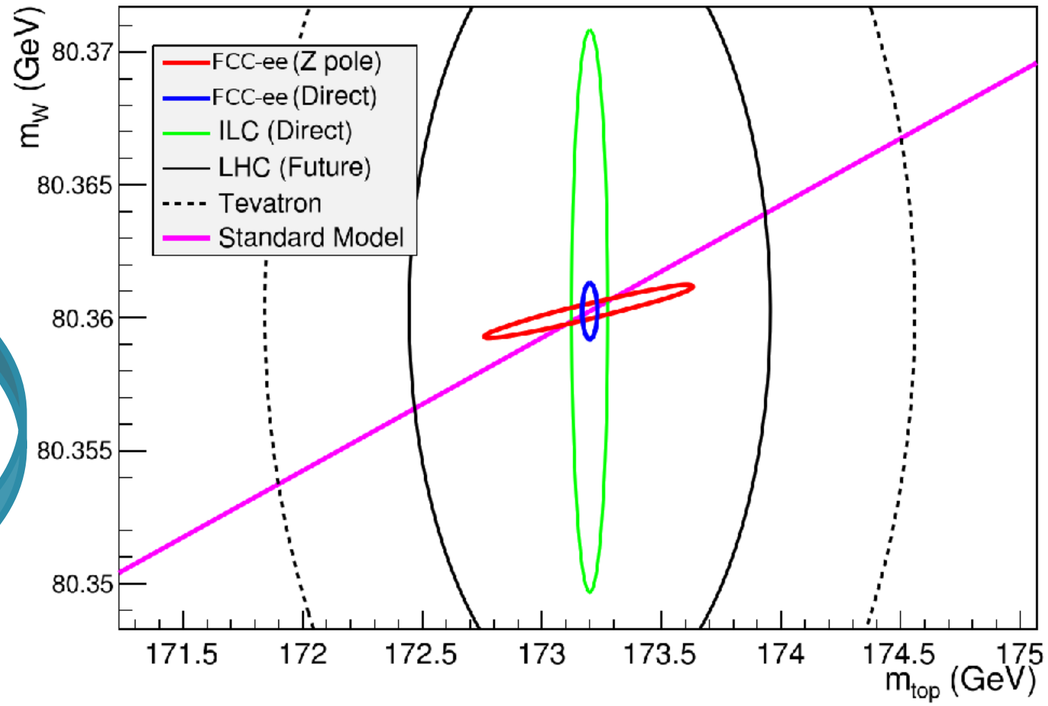
FCC-ee: Top quark studies

- Radiative corrections connect:
  - m_W, m_t, m_H, ...

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_W} \cdot \frac{1}{1-\Delta r(m_t, M_H)}$$

$$\Delta r(m_t, M_H) \simeq c_t m_t^2 + c_H \ln\left(\frac{M_H^2}{M_Z^2}\right) + \cdots$$





Looking for new physics!

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ANALYSIS OF THE TOP QUARK

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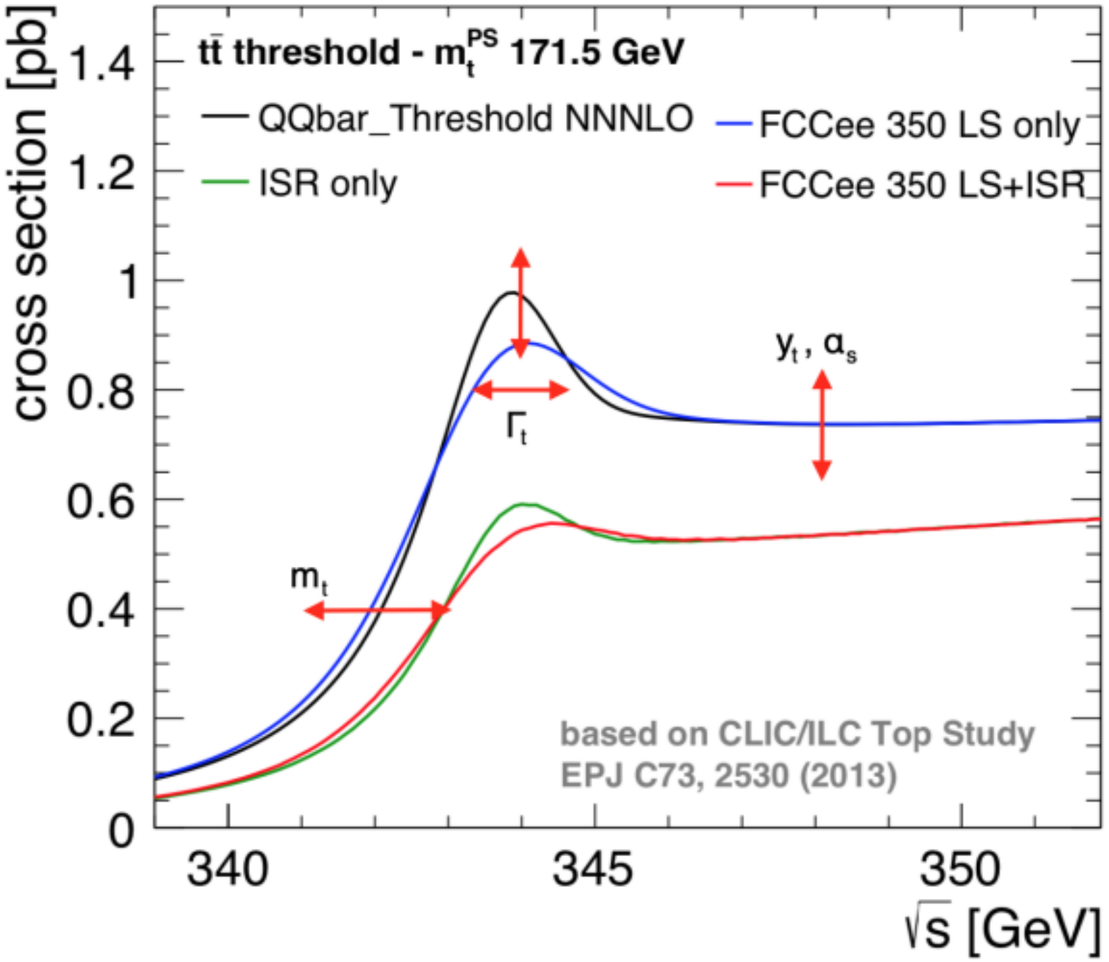
Measuring the Top quark properties

Cross section threshold scan

- $\sqrt{s} = 345 - 350\ GeV$
- Exploit resonant behavior
- Shape: y_t, α_s, Γ_t, m_t
- Fit theoretical prediction



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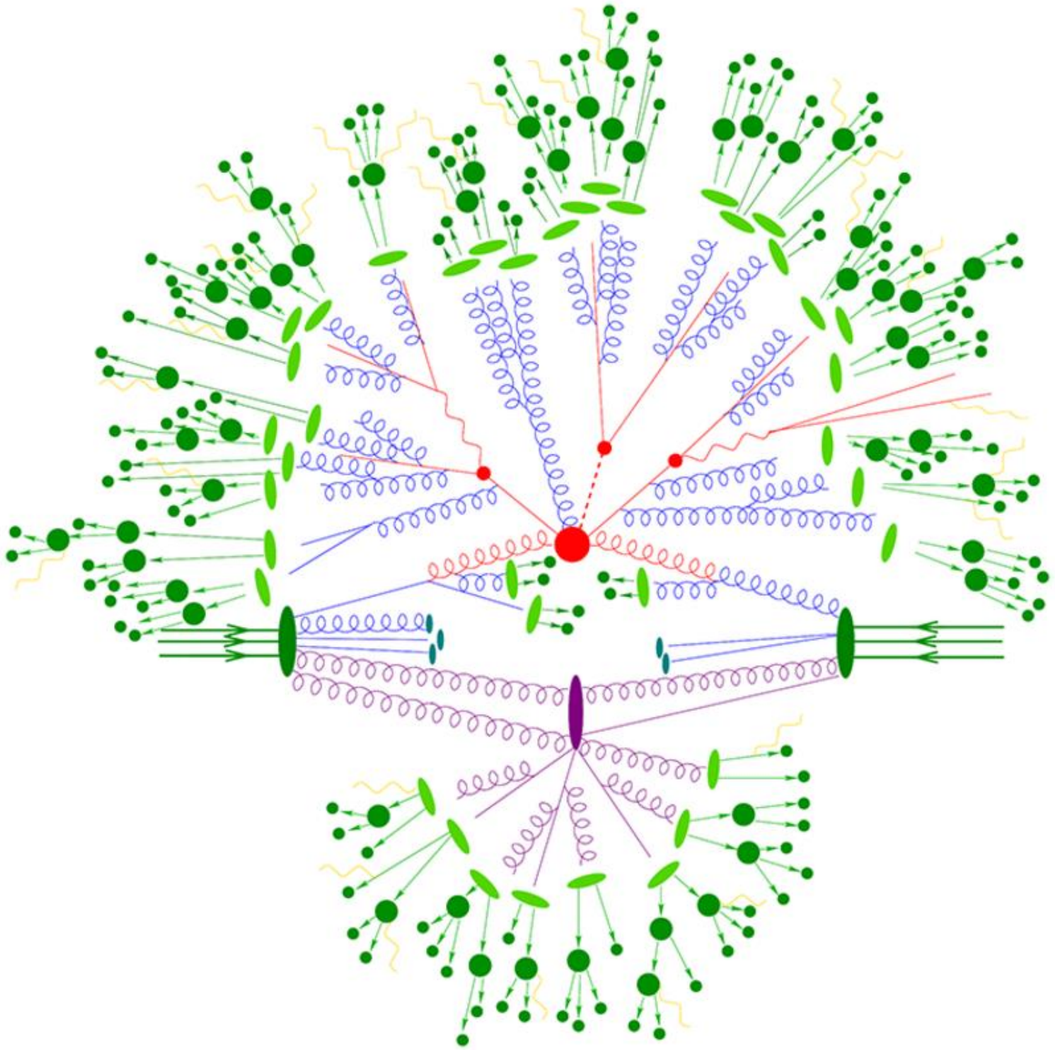
Measuring the Top quark properties

Direct reconstruction

- $\sqrt{s} = 365\ GeV$
- Exploit final state kinematics
- Compare to simulation
  - Varying m_t^{MC}



DOI: 10.1007/JHEP12(2024)156

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Analysis strategy

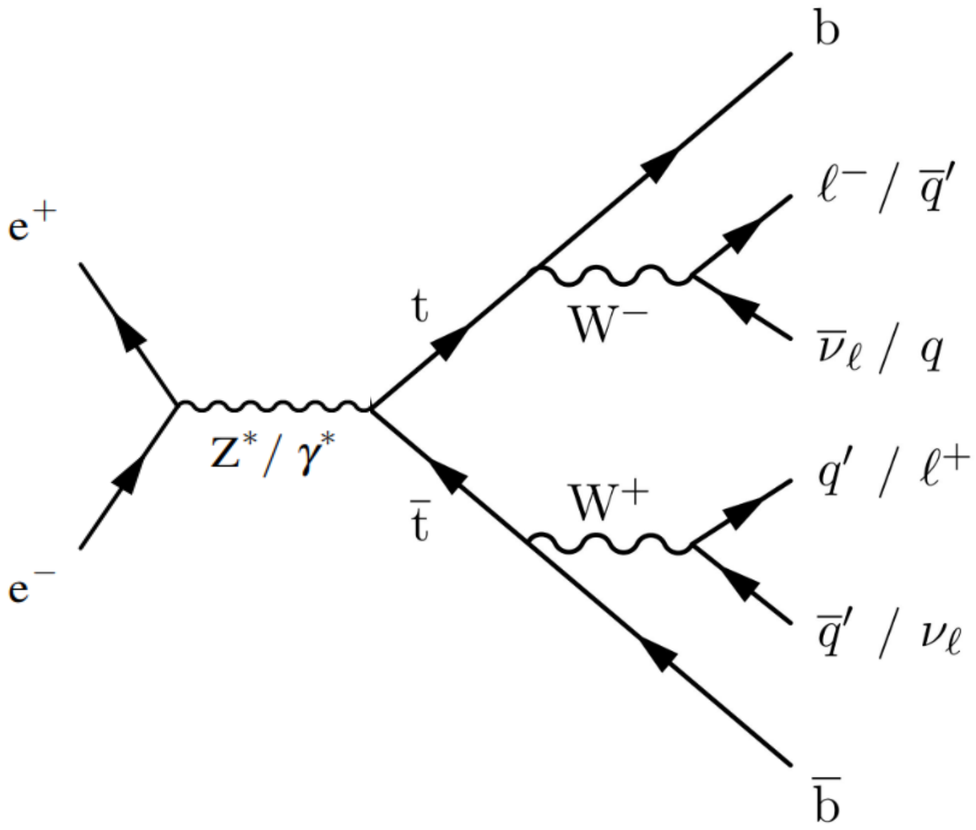
- Decay Channels:

Final state	BR [%]	Signature
Fully Hadronic	46.2	6 jets
Semi-leptonic	43.5	4 jets, 1 $l^{\pm}$, 1 ν
'Fully' Leptonic	10.3	2 jets, 2 $l^{\pm}$, 2 ν

$$t\bar{t} \rightarrow b\bar{b}W^+W^- \rightarrow b\bar{b}qq\bar{q}\bar{q}$$

$$t\bar{t} \rightarrow b\bar{b}W^+W^- \rightarrow b\bar{b}q\bar{q}l^-\bar{\nu}(l^+\nu)$$

$$t\bar{t} \rightarrow b\bar{b}W^+W^- \rightarrow b\bar{b}l^+\nu l^-\bar{\nu}$$



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Simulation framework: **Key4HEP**

Event Generation:	• Madgraph: Hard-scattering • Pythia8: Hadronization
Detector Simulation:	• Delphes (IDEA)
Data Format: EDM4HEP	• Contains full information about simulation and reconstruction
FCCAnalysis:	• Preform associations: Generator-/ Detector-level
Machine Learning	• Event Selection and Reconstruction, ...

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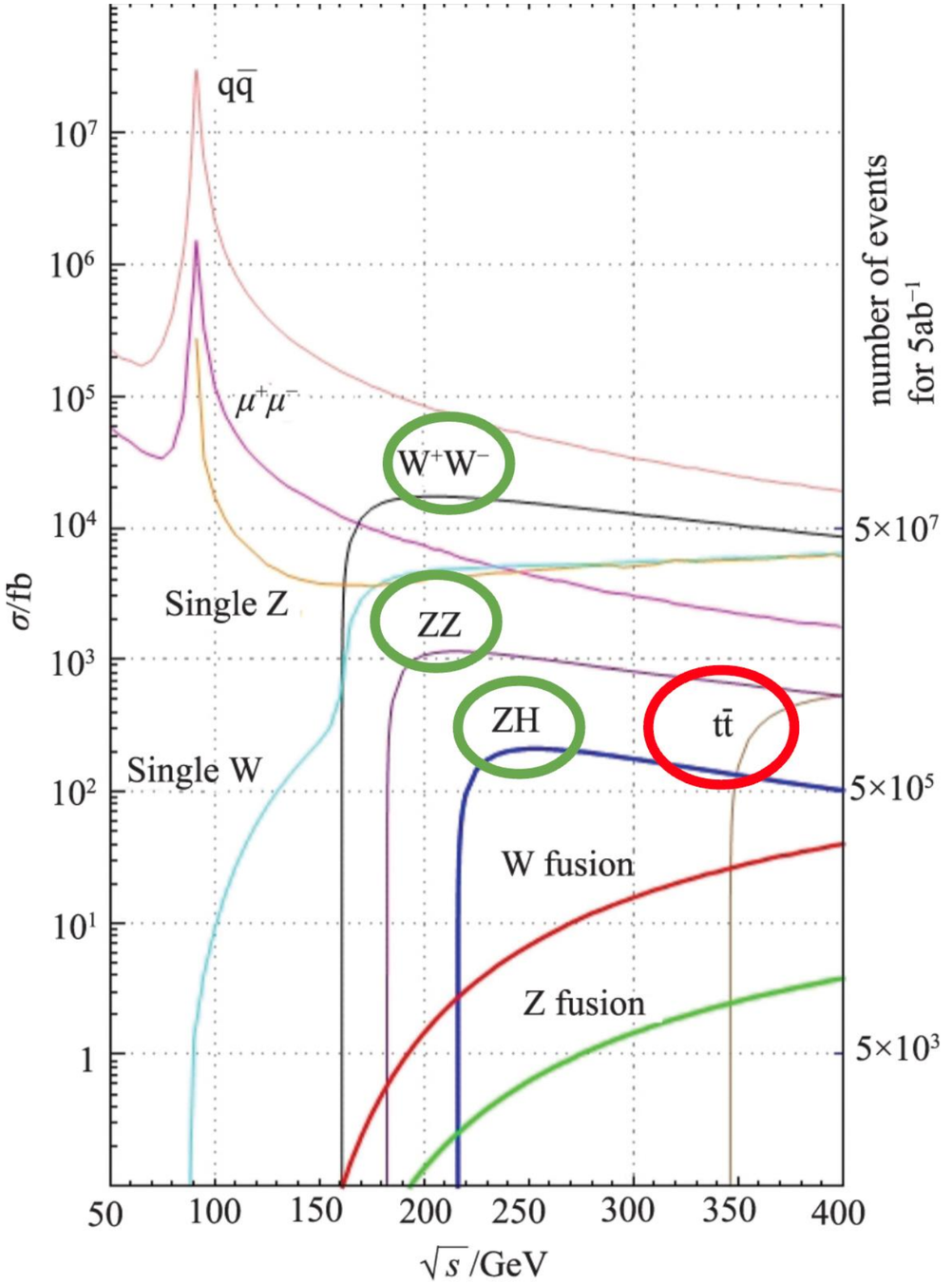
Event generation

- Jet p ≥ 5 GeV
- 10 000 events

  → $W^+W^-, ZZ, ZH, t\bar{t}$
- $\sqrt{s} = 365\ GeV$

DOI:10.1088/1674-1137/40/3/033001



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BACKGROUND SUPPRESSION

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Signal vs Background Classification

Recursive Feature Elimination (RFE)

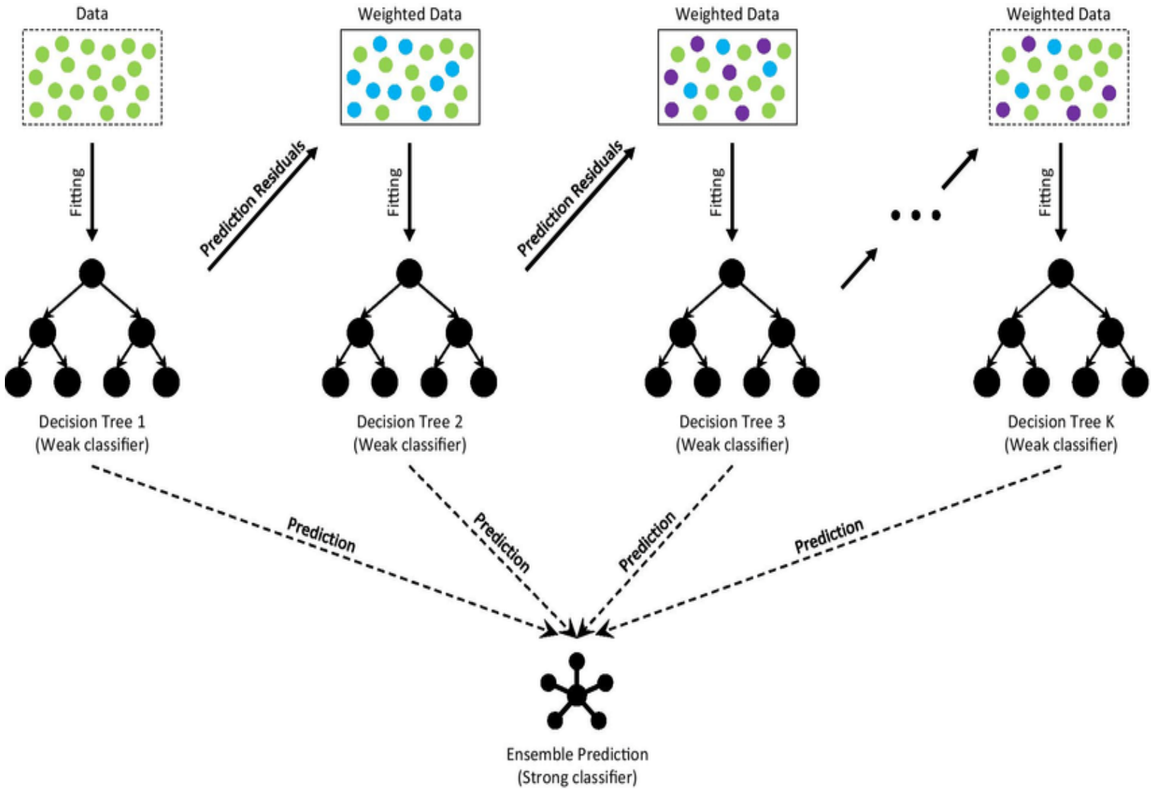
- 7 features remained

Hyperparameter Optimization

- GridSearch

Boosted Decision Tree (BDT)

- 75% train / 25% test split



DOI: 10.1186/s12911- 021- 01701- 9

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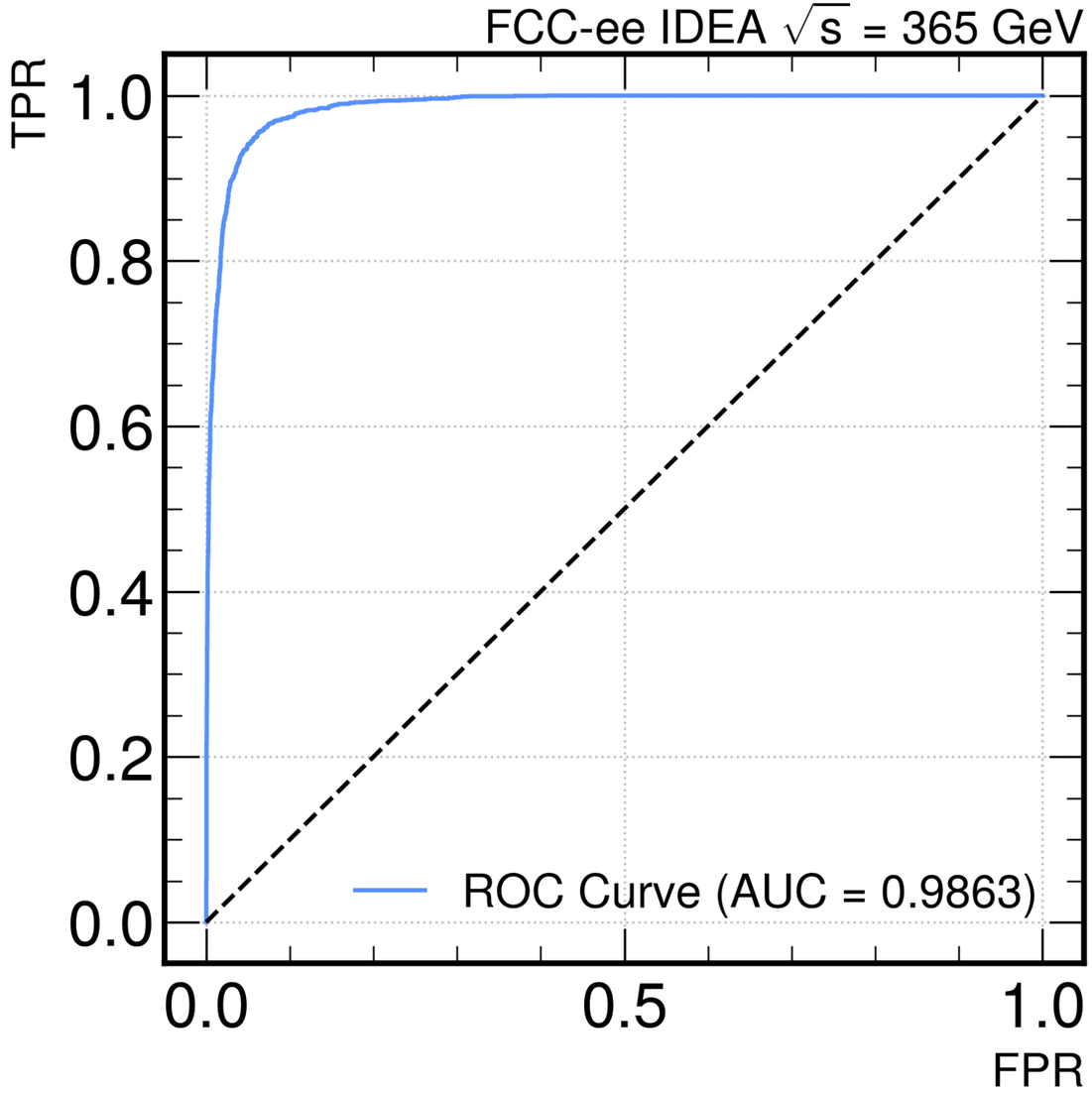
Signal vs Background Classification

- Greatly improves signal purity

- Better performance
- AUC score = 98.63%



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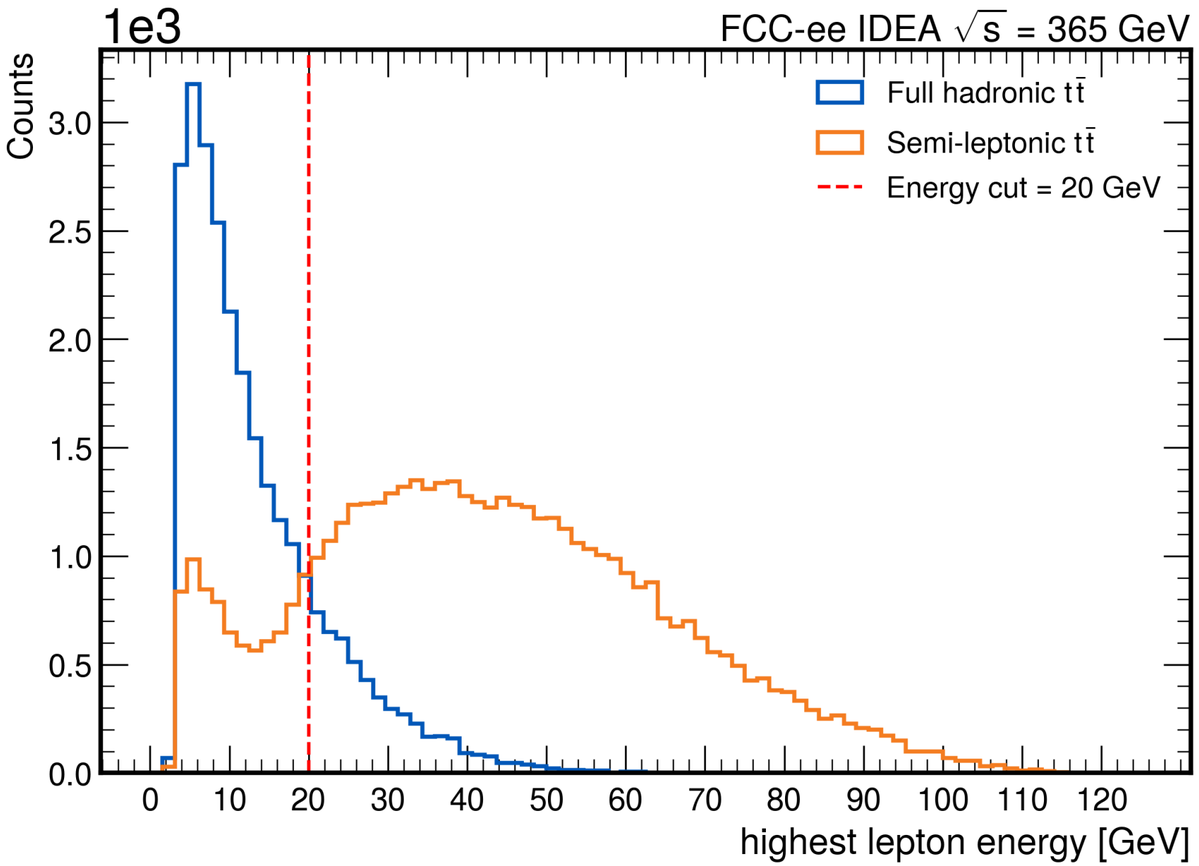
Signal classification

- Highest-energy lepton cut:
  - 20 GeV

+ no leptons → fully hadronic

- Selection efficiencies:
  - $\varepsilon_{lep} = 83.70\%$,
  - $\varepsilon_{had} = 80.15\%$



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TOP QUARK RECONSTRUCTION

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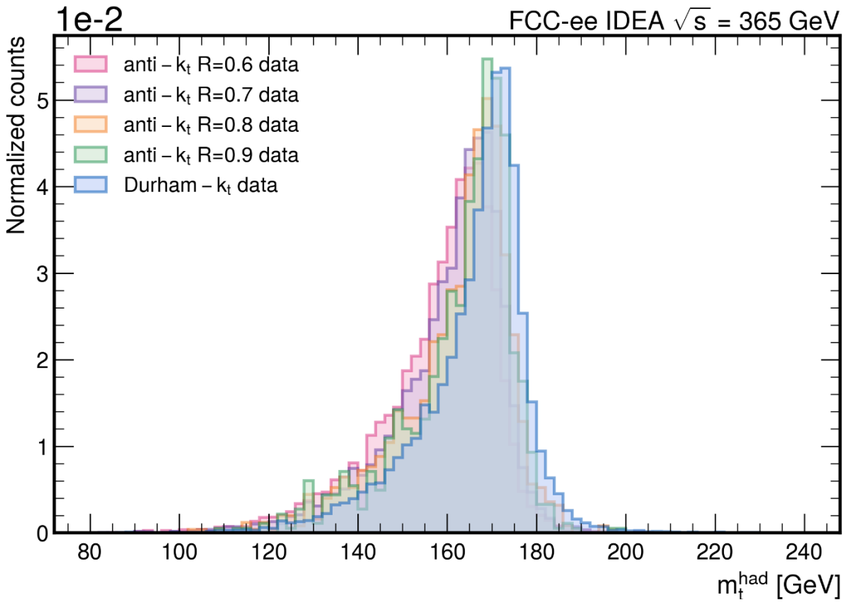
Baseline reconstruction performance

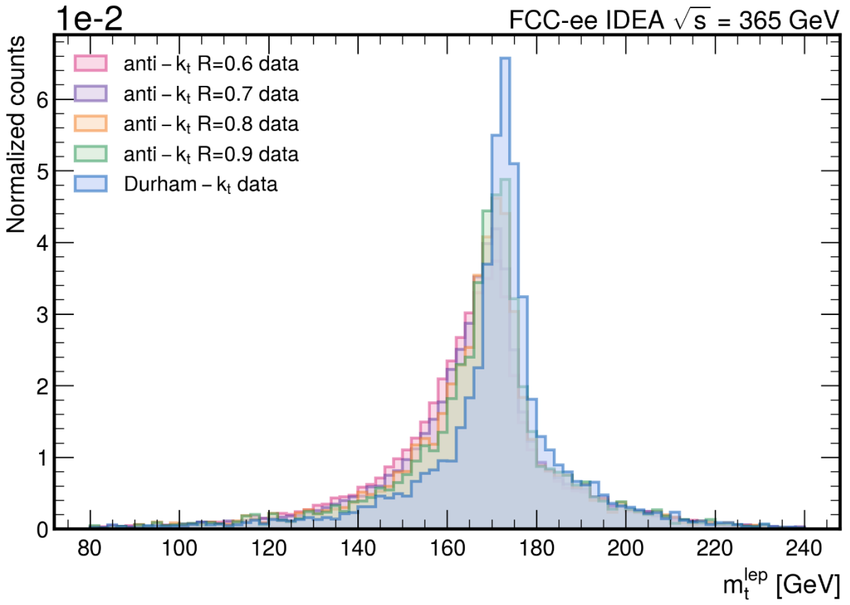
- Estimate best case reconstruction (IDEA)
- Jet-parton matching: $\Delta R < 0.15$

- Comparing Durham-k_t and anti-k_t:
  - Best results: Durham-k_t

- Crystal ball/Breit-Wigner fit results:

Channel	m_t^{base}	Γ_t^{base}	m_W^{base}	Γ_W^{base}	f_{match}
Fully hadronic	171.55	13.4	79.70	7.59	39.30%
Semi-leptonic	172.88	9.85	80.14	8.01	73.28%





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Fully hadronic reconstruction

- Kinematic fitting:

$$\chi^2_{had} = \frac{(m_{b1j1j2} - m_t\ )^2}{\sigma^2_{m_t}} + \frac{(m_{b2j3j4} - m_t\ )^2}{\sigma^2_{m_t}} + \frac{(m_{j1j2} - m_W)^2}{\sigma^2_{m_W}} + \frac{(m_{j3j4} - m_W)^2}{\sigma^2_{m_W}}$$

- Jet permutations
- 6 jets or more
- χ^2 value < 20 to be retained
- With and w/o b-tagging

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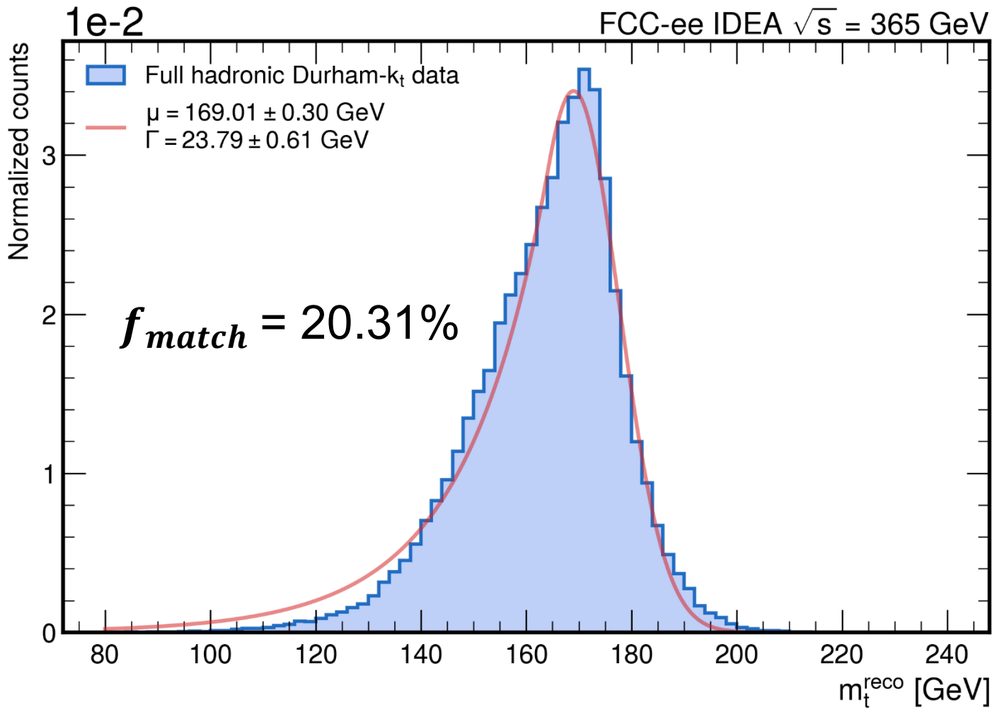
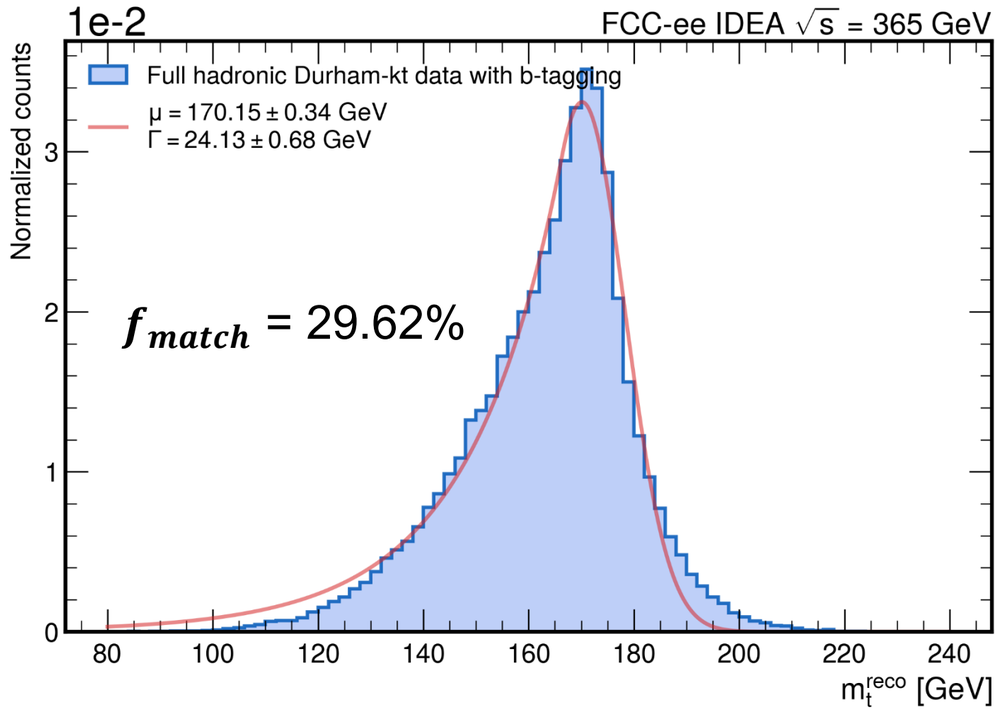
Fully hadronic kinematic reconstruction



Invariant top quark mass

Using χ^2 - fit



Invariant top quark mass

Using χ^2 - fit **with b-tagging**

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Semi-leptonic reconstruction

- Kinematic fitting:

$$\chi^2_{lep} = \frac{(m^{had}_{b1j1j2} - m_t\ )^2}{\sigma^2_{m_t}} + \frac{(m^{lep}_{b2lv} - m_t\ )^2}{\sigma^2_{m_t}} + \frac{(m^{had}_{j1j2} - m_W)^2}{\sigma^2_{m_W}} + \frac{(m^{lep}_{lv} - m_W)^2}{\sigma^2_{m_W}}$$

- Jet permutations
- 4 jets or more
- χ^2 value < 20 to be retained
- With and w/o b-tagging
- One isolated lepton $p_T \geq 20$ GeV

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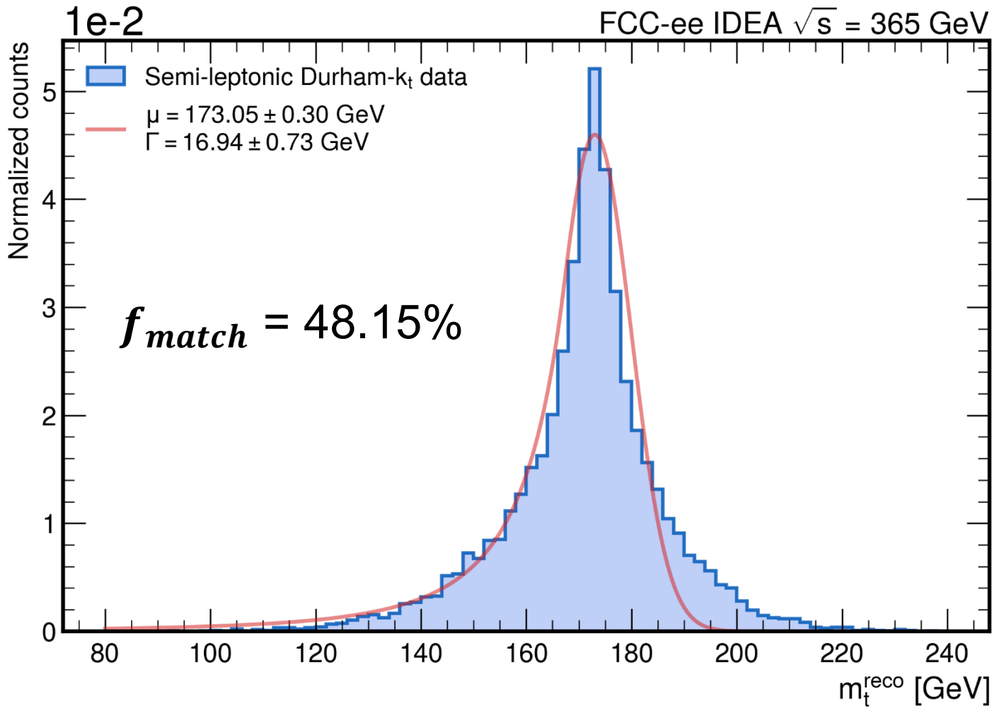
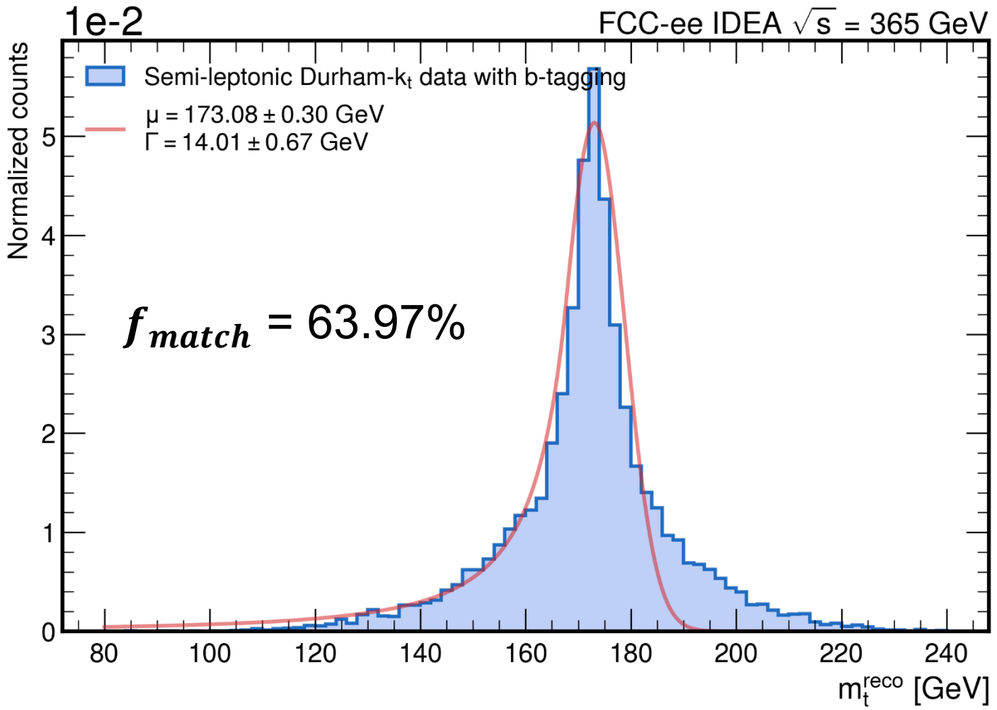
Semi-leptonic kinematic reconstruction



Invariant top quark mass

Using χ^2 - fit



Invariant top quark mass

Using χ^2 - fit **with b-tagging**

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Kinematic reconstruction: BDT approach

Both fully hadronic and semi-leptonic

Training data construction:

- All jet-parton permutations
- Labeled using $\Delta R < 0.15$
- 75% train / 25% test split

Features:

- Invariant masses & p_T of top and W candidates
- Angular separations jets and partons/leptons

Performance:

- $AUC_{had} = 96.76\%, \quad AUC_{lep} = 94.47\%$

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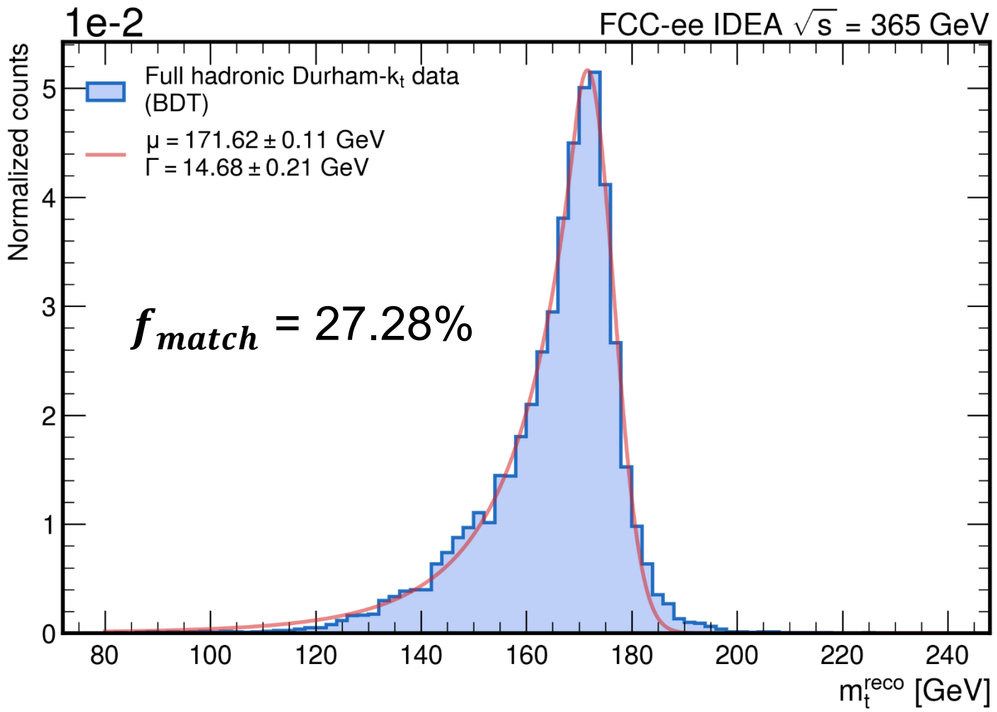
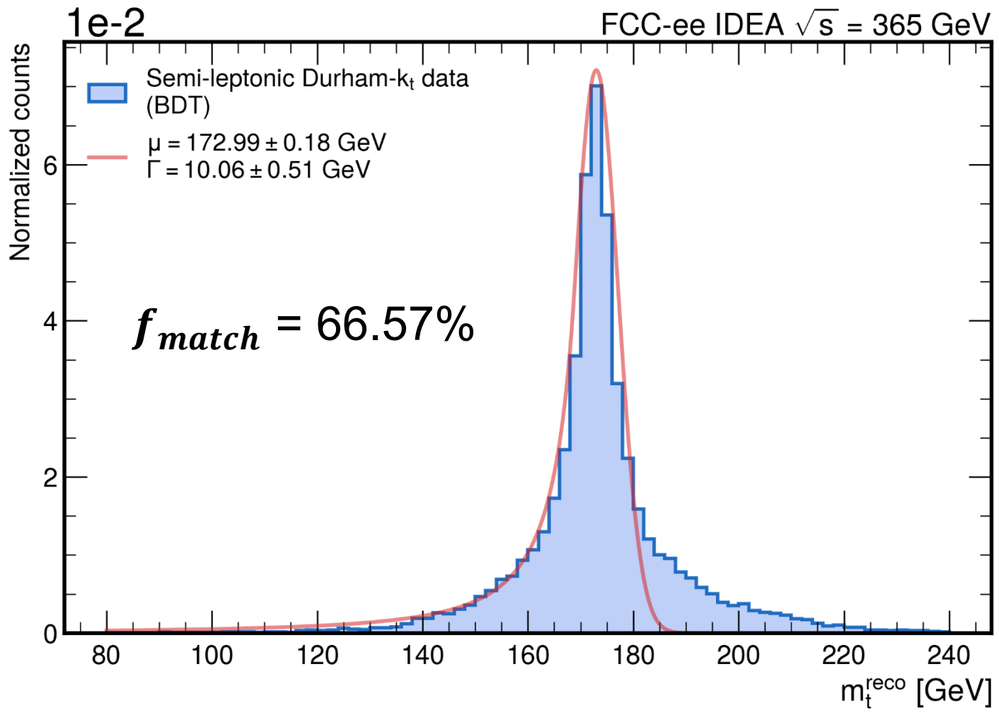
BDT reconstruction results

- Fully hadronic



- Semi-leptonic



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FORWARD-BACKWARD ASYMMETRY

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FB Asymmetry

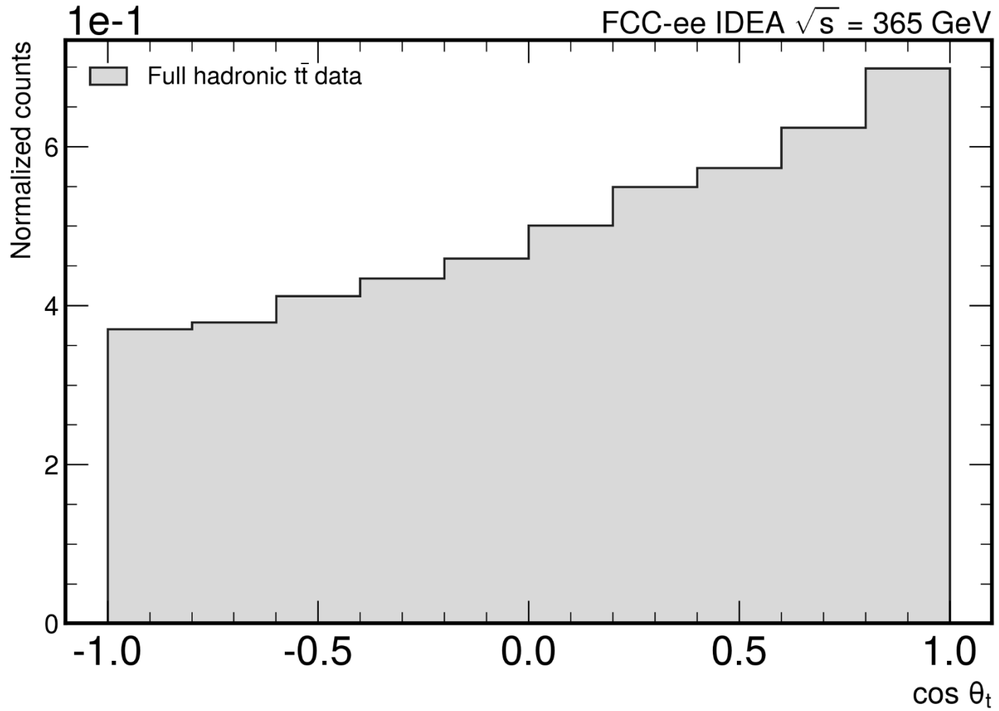
- Semi-leptonic channel

$$A_{FB}^{t} = \frac{N(cos\,\theta > 0) - N(cos\,\theta < 0)}{N(cos\,\theta > 0) + N(cos\,\theta < 0)} = \frac{N_F - N_B}{N_F + N_B}$$

- Reference using MC truth info

$$A_{FB}^{MC} = 0.1781 \pm 0.0044$$

- Compare χ^2-fit with and w/o b-tagging



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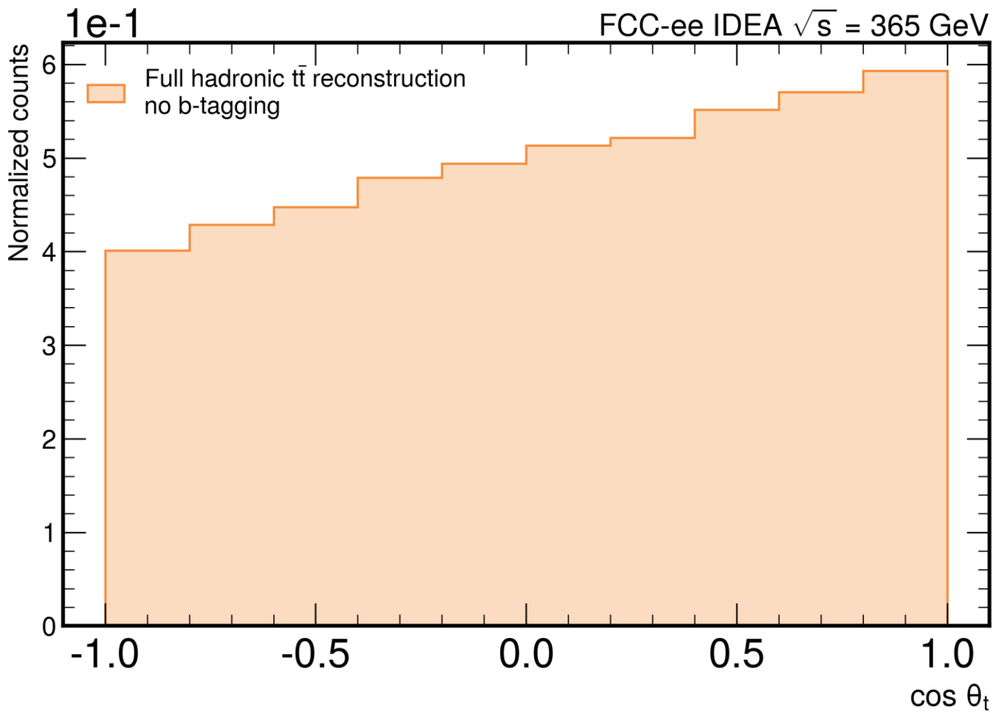
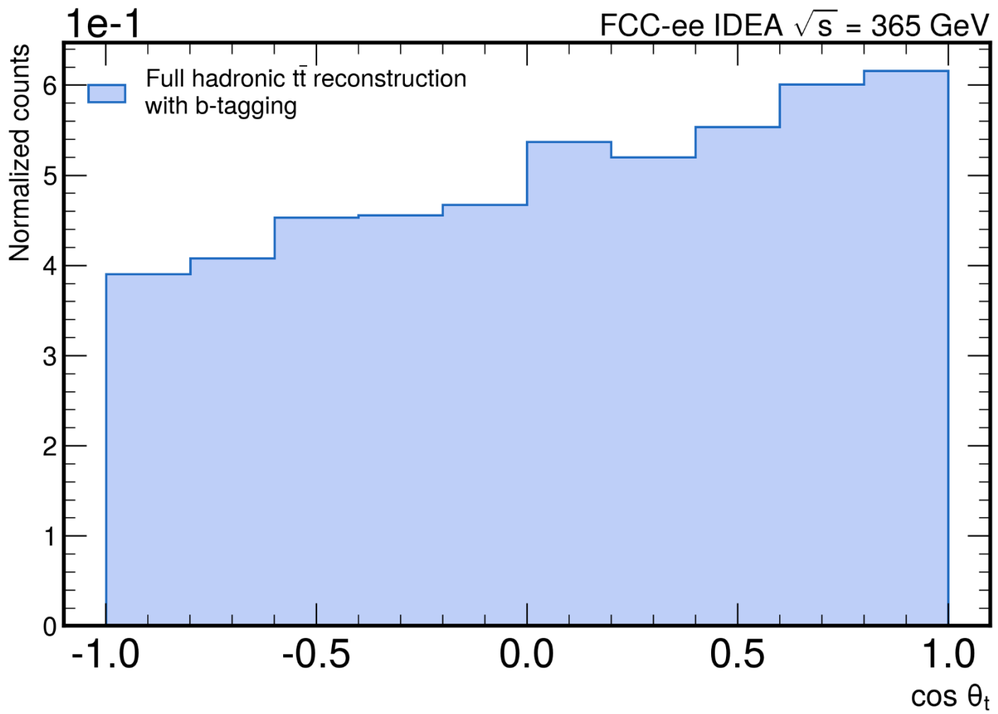
FB Asymmetry

- Results from semi-leptonic reconstruction



$$A_{FB}^{t} = 0.0999 \pm 0.0050$$



$$A_{FB}^{t} = 0.1249 \pm 0.0061$$

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Relies on reconstruction performance!

Summary

- Top quark pair production at FCC-ee
- IDEA detector at $\sqrt{s} = 365\ GeV$
- Simulated datasets with Key4HEP: fully hadronic & semi-leptonic

- Great classification of signal vs backgrounds & signal channels

- **Kinematic reconstruction:**
- χ^2 reconstruction:
  - Fast and easy to implement, b-tagging improves assignment accuracy

- BDT outperforms χ^2 −based methods
  - Better resolution and higher accuracy, Computational resources

- **FB Asymmetry:**
  - Performed a preliminary study on the measurement of FB asymmetry at FCC-ee

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NEXT STEPS

- Future directions include:
  - Refining reconstruction algorithms (additional constraints, better neutrino treatment, deep learning).
  - Extending analysis to full GEANT4 detector simulations.
  - Evaluating alternative detector concepts.
  - Investigating threshold scan scenarios.

QUESTIONS?

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BACKUP

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Summary of reconstruction methods

- Reconstruction fully hadronic & semi-leptonic
- IDEA detector at $\sqrt{s} = 365\ GeV$

- χ^2 reconstruction:
  - Fast and easy to implement
  - B-tagging improves assignment accuracy

- BDT outperforms χ^2 –based methods

  + Better resolution and higher accuracy

  - Computational resources

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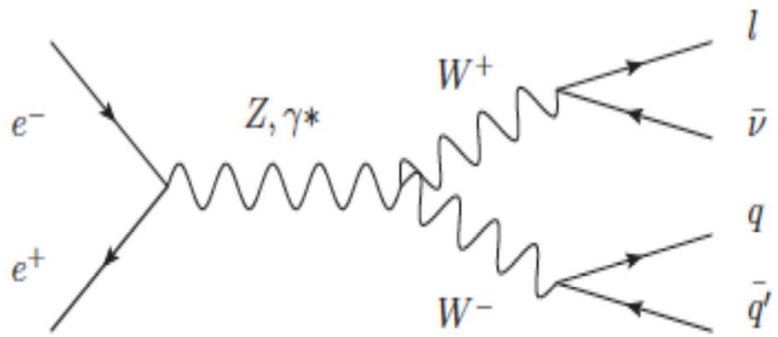
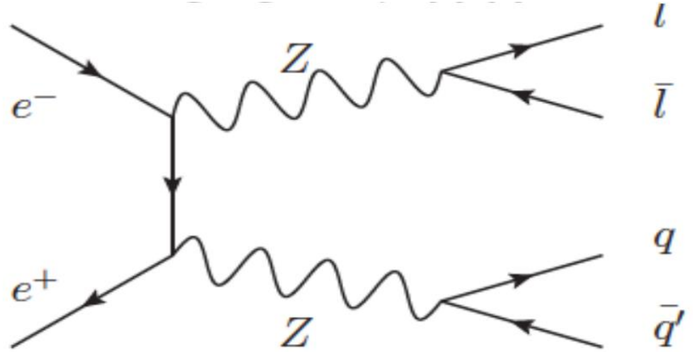
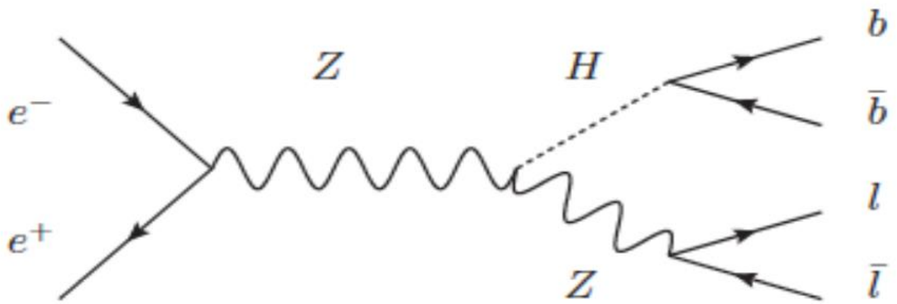
Background processes topologies







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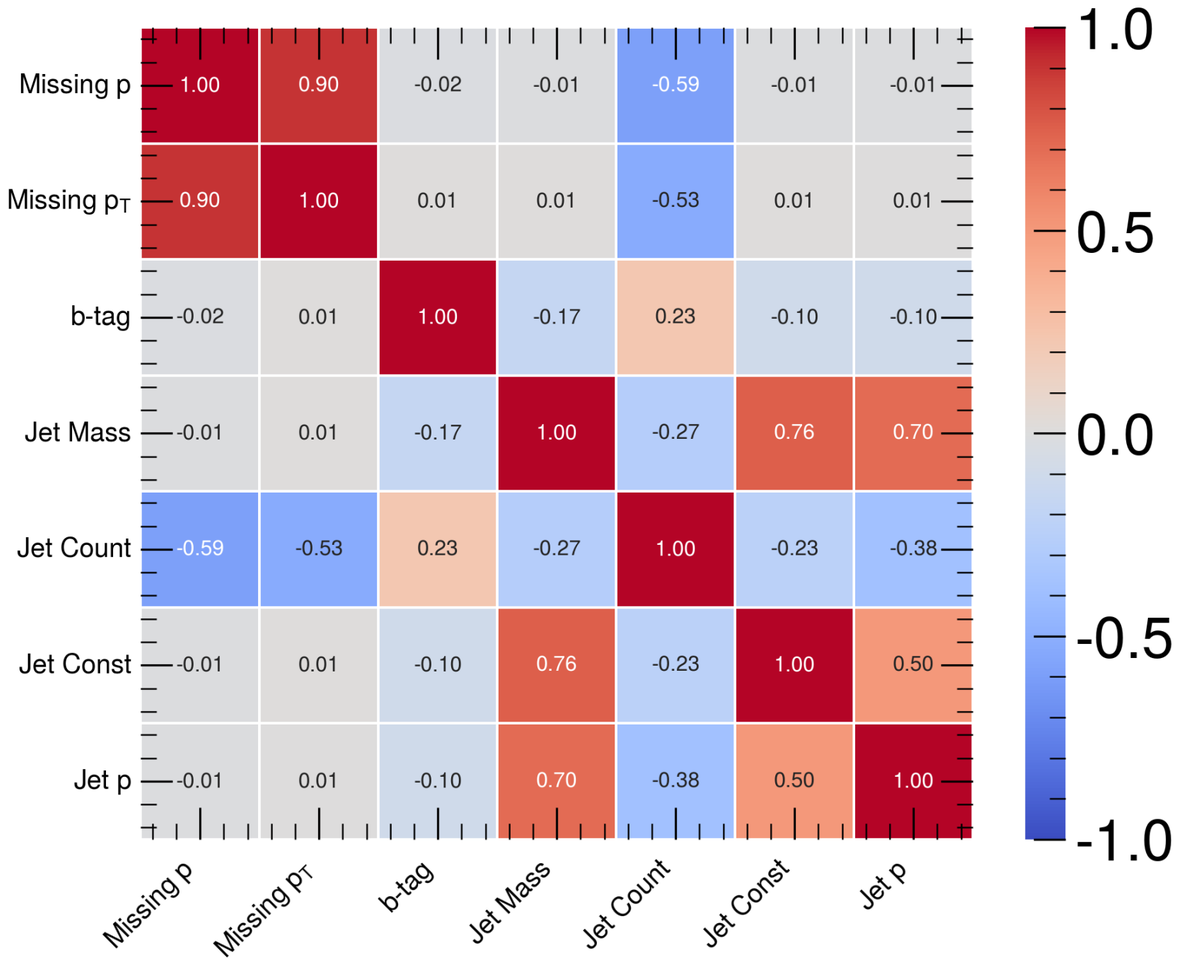
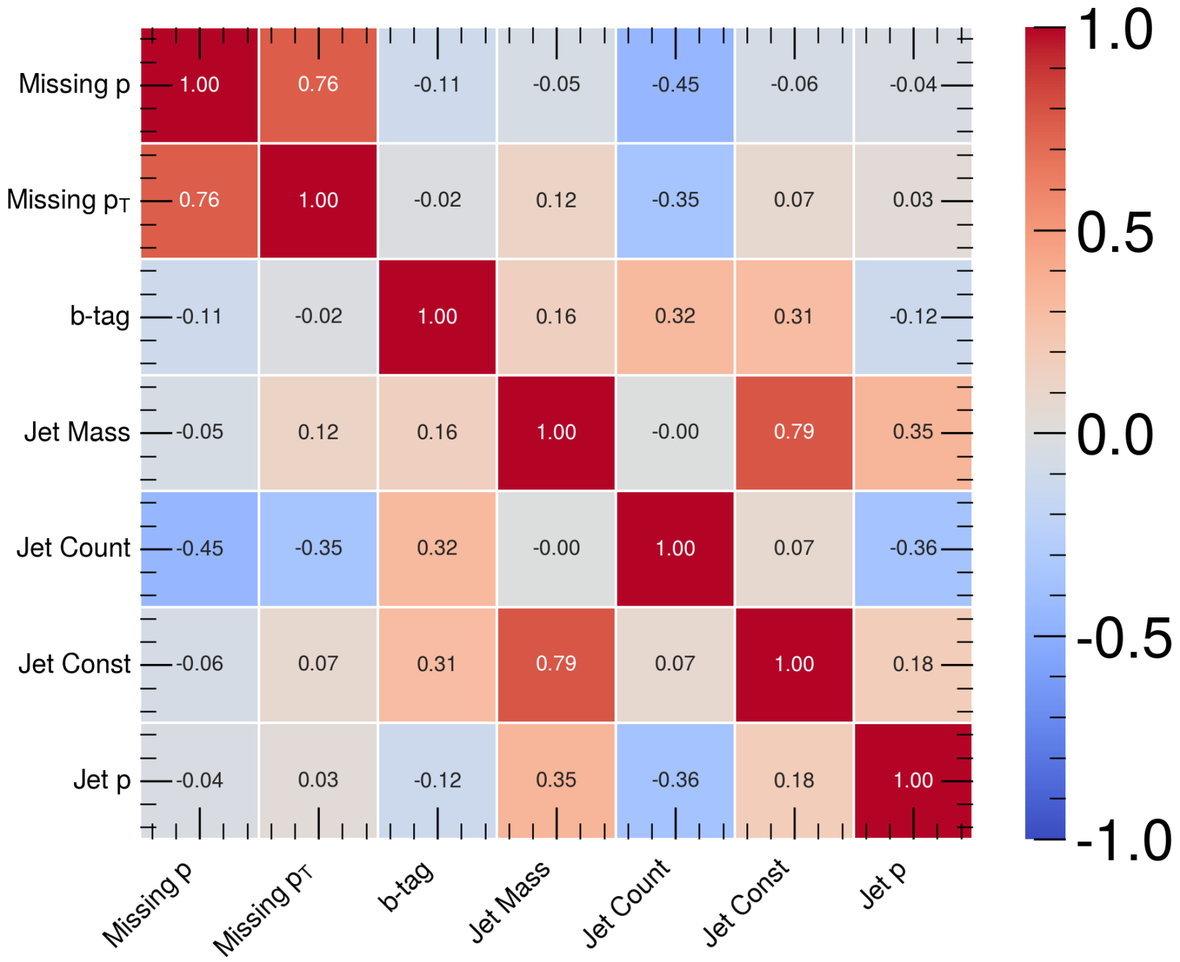
Feature Correlation





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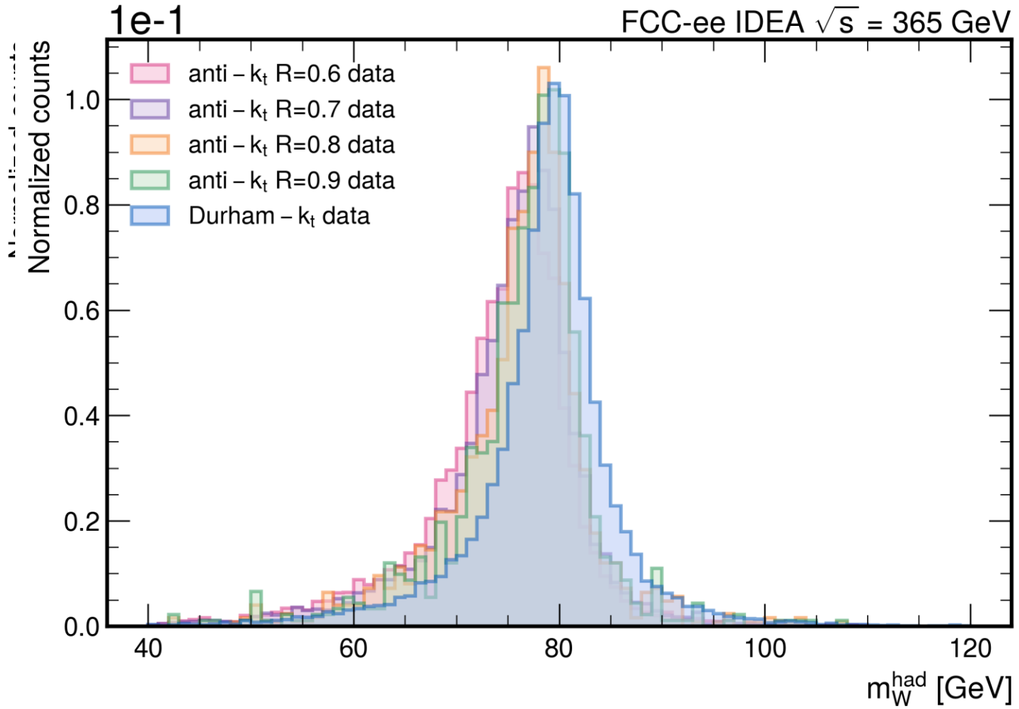
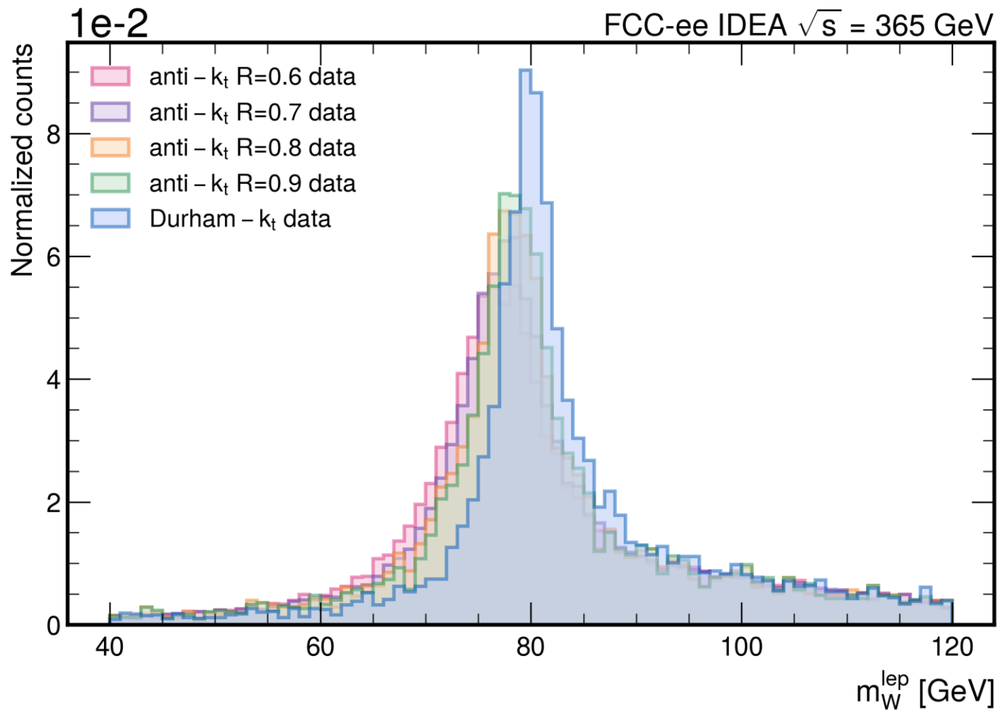
Baseline W boson reconstruction performance



Invariant W boson mass

Using MC truth information

→ **Fully hadronic**



Invariant W boson mass

Using MC truth information

→ **Semi-leptonic**

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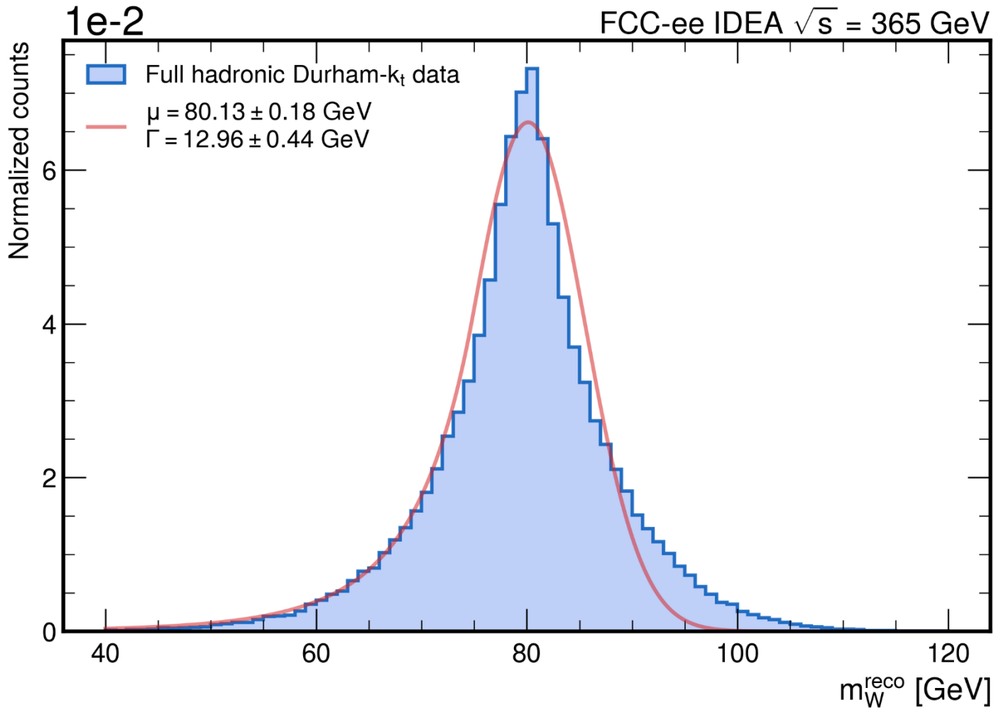
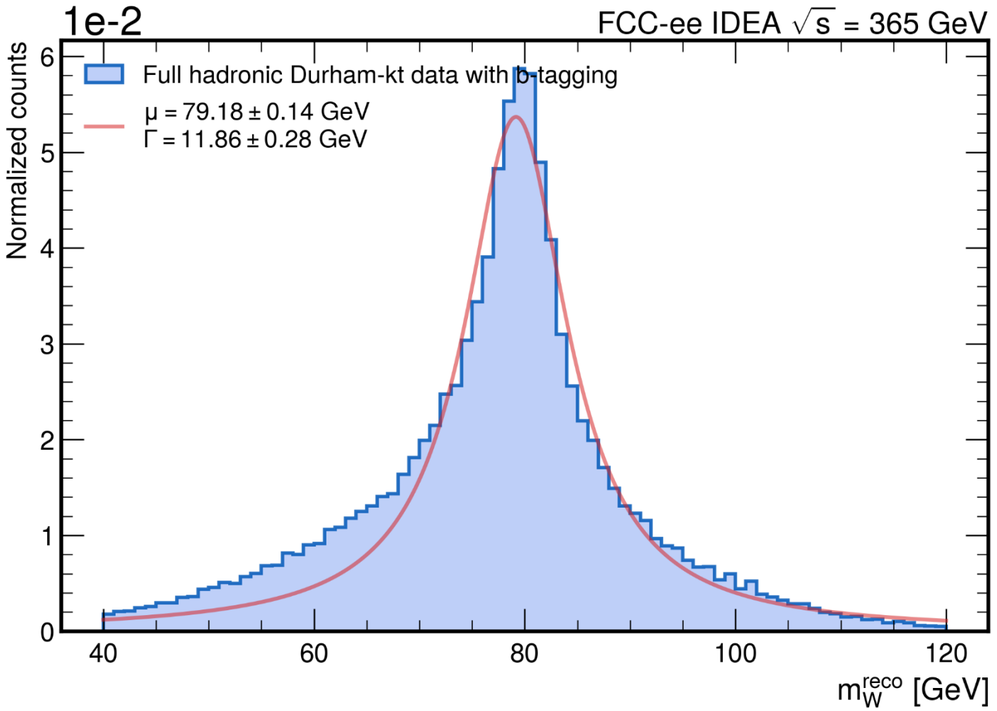
Fully hadronic W boson kinematic reconstruction



Invariant W boson mass

Using χ^2 - fit



Invariant W boson mass

Using χ^2 - fit **with b-tagging**

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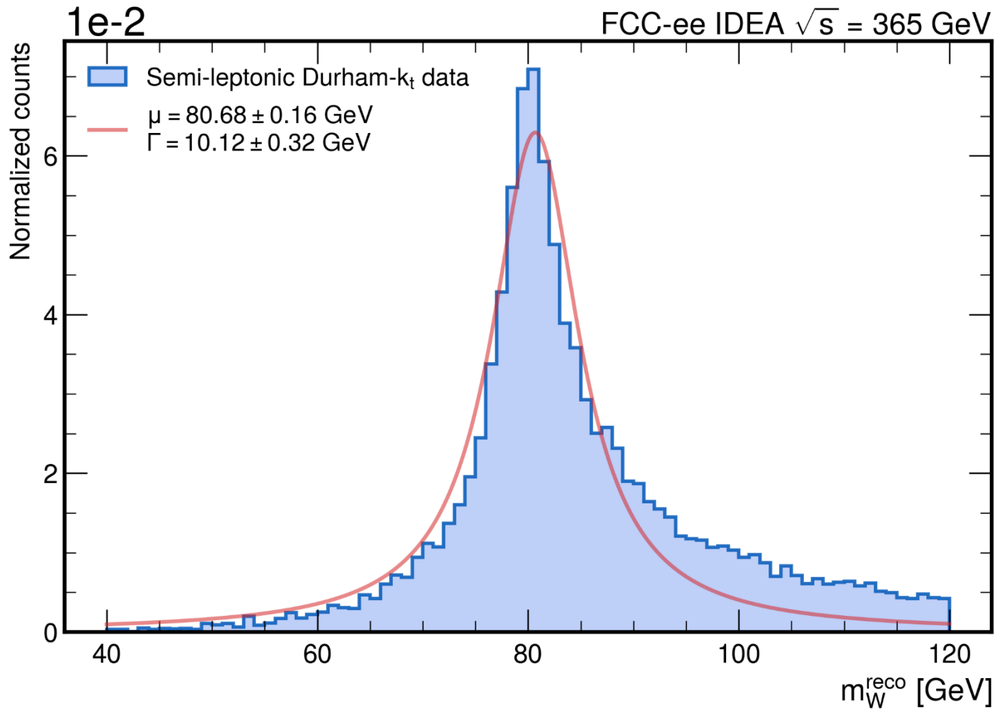
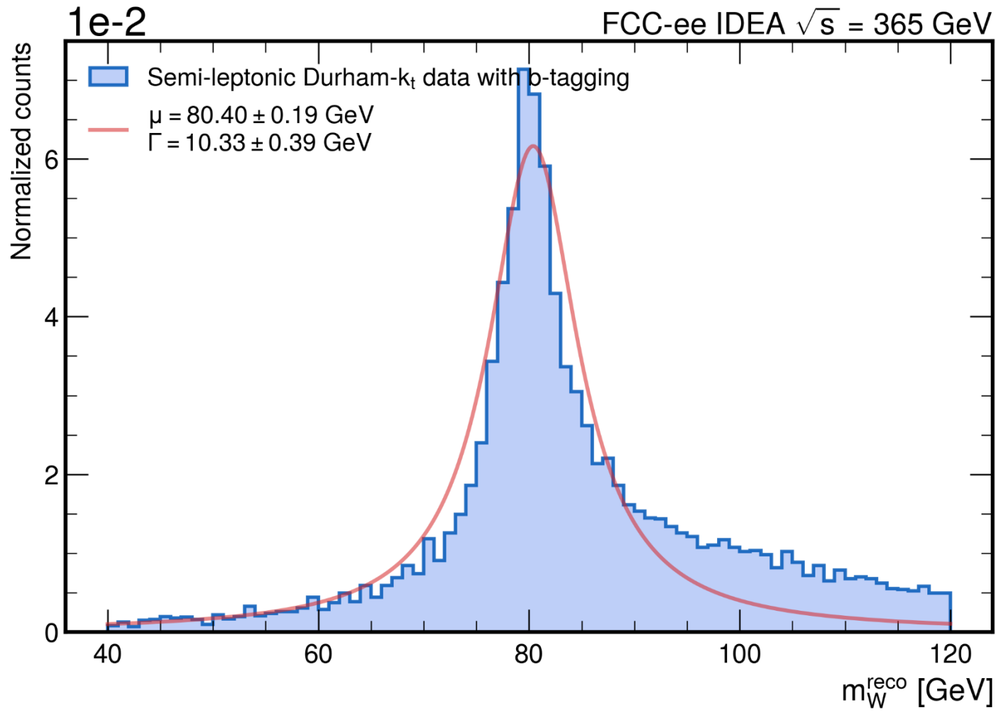
Semi-leptonic W boson kinematic reconstruction



Invariant W boson mass

Using χ^2 - fit



Invariant W boson mass

Using χ^2 - fit **with b-tagging**

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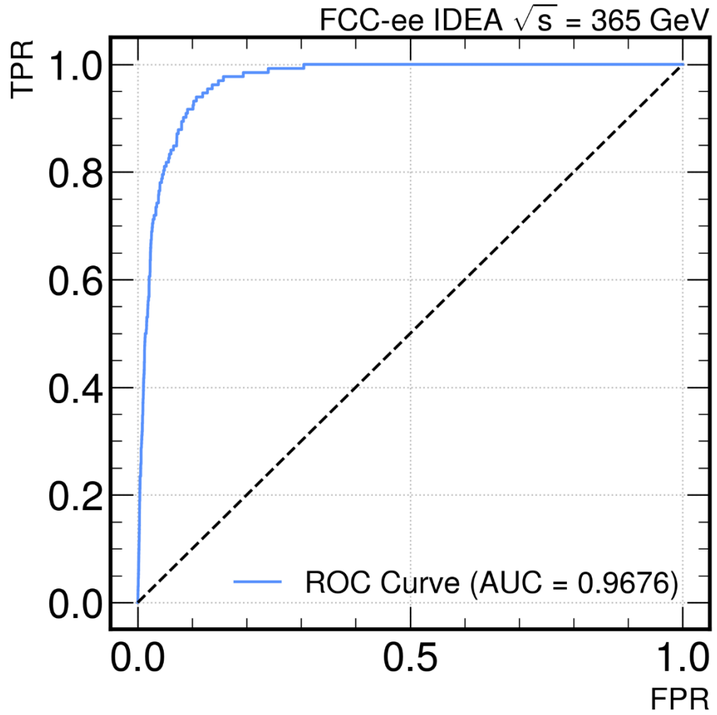
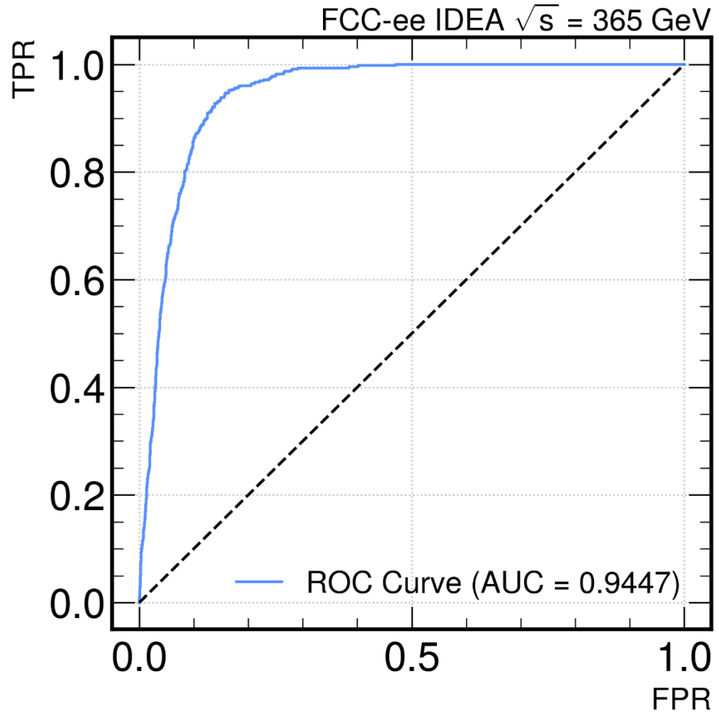
BDT reconstruction ROC curves

- (fully hadronic vs semi-leptonic)





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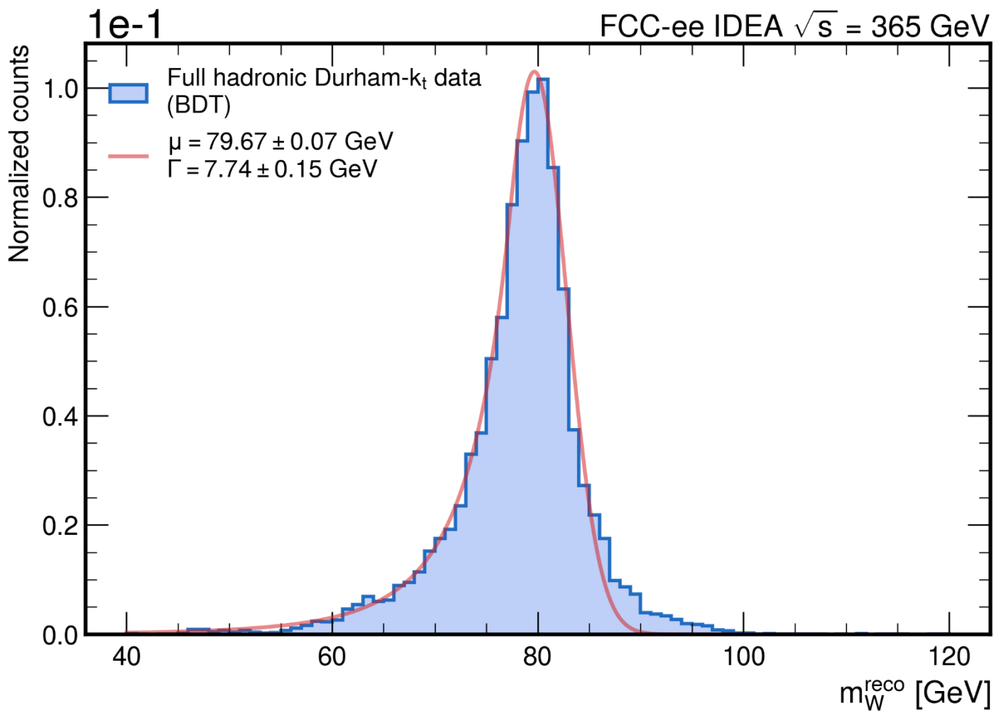
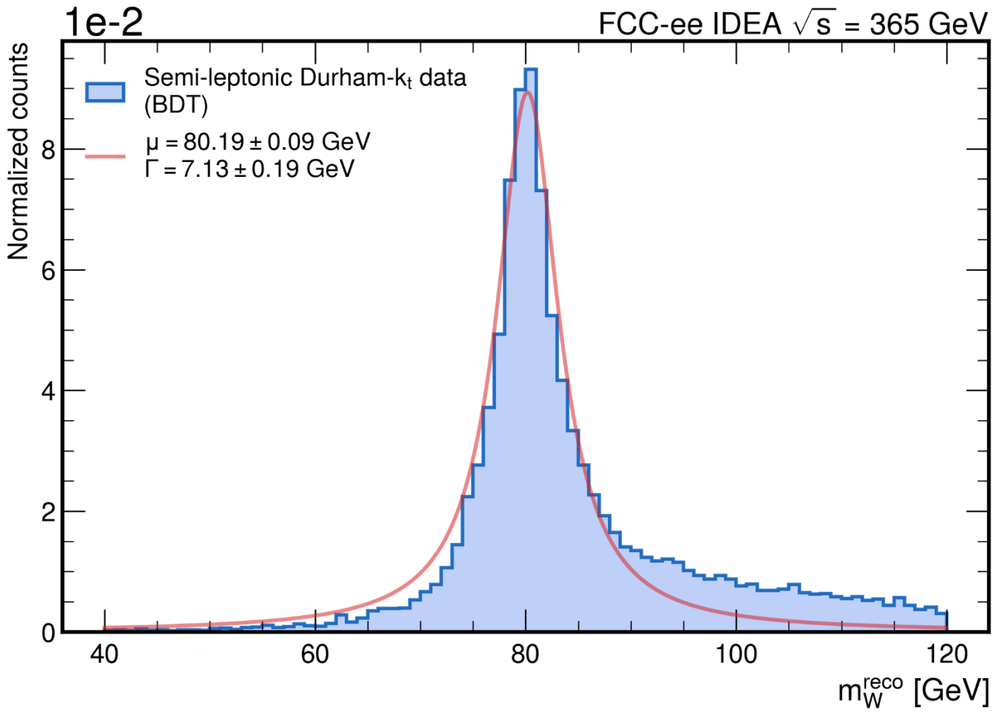
BDT W boson reconstruction



Invariant W boson mass

Using BDT approach

Fully hadronic



Invariant W boson mass

Using BDT approach

Semi-leptonic

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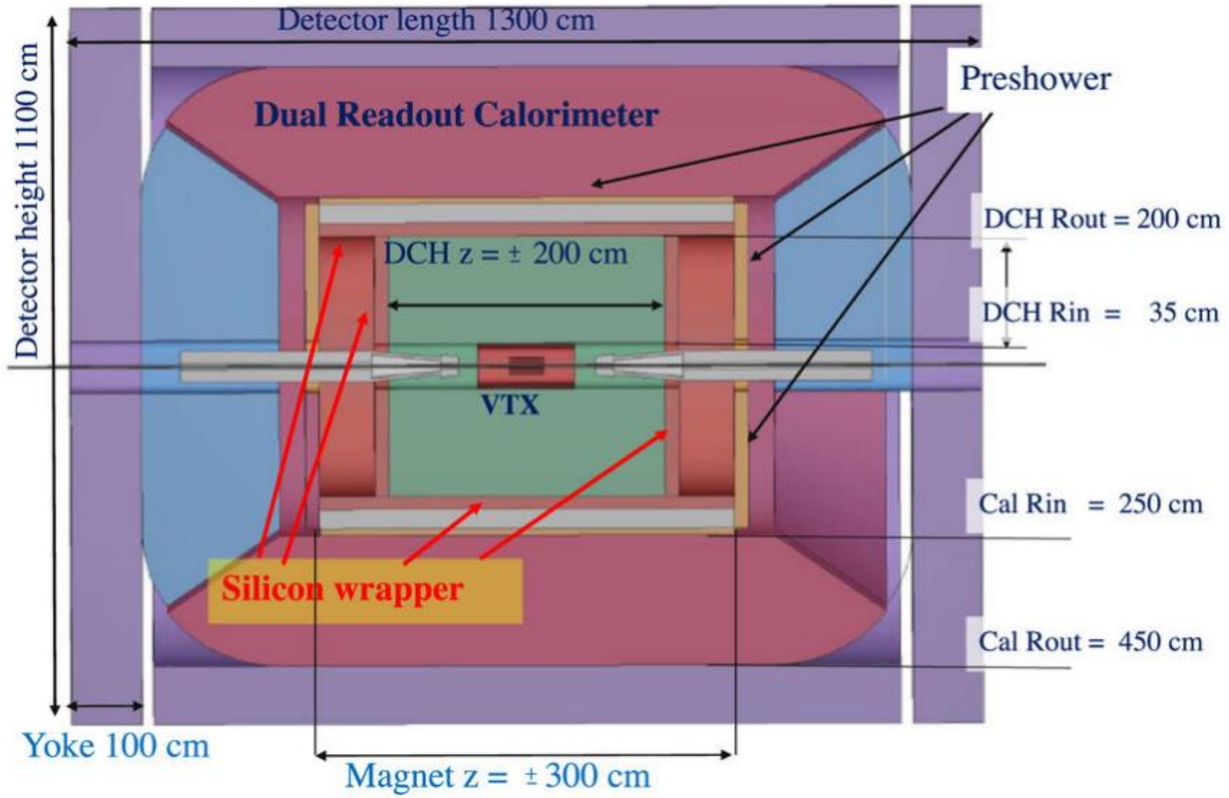
The IDEA detector

- Important features:
  - Tracking system
    - MAPS
  - Calorimeter system
    - DR crystal and fiber
  - Detector solenoid
    - 3T HTS 20 K
  - Muon system
    - MPGDs

The IDEA Study Group.



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Jet clustering algorithms

- Anti-kt:

$$d_{ij} = min(E_i^{-2}, E_j^{-2}) \frac{1 - cos\,\theta_{ij}}{1 - cos\,R}$$

- Durham-kt:

$$d_{ij} = 2min(E_i^2, E_j^2)(1 - cos\,\theta_{ij}).$$

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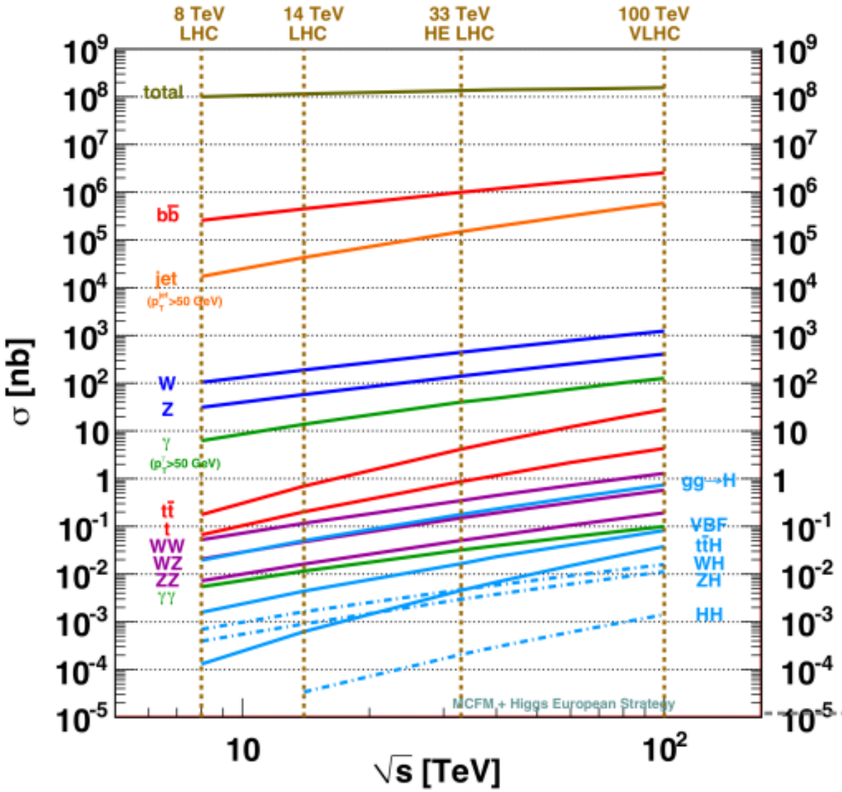
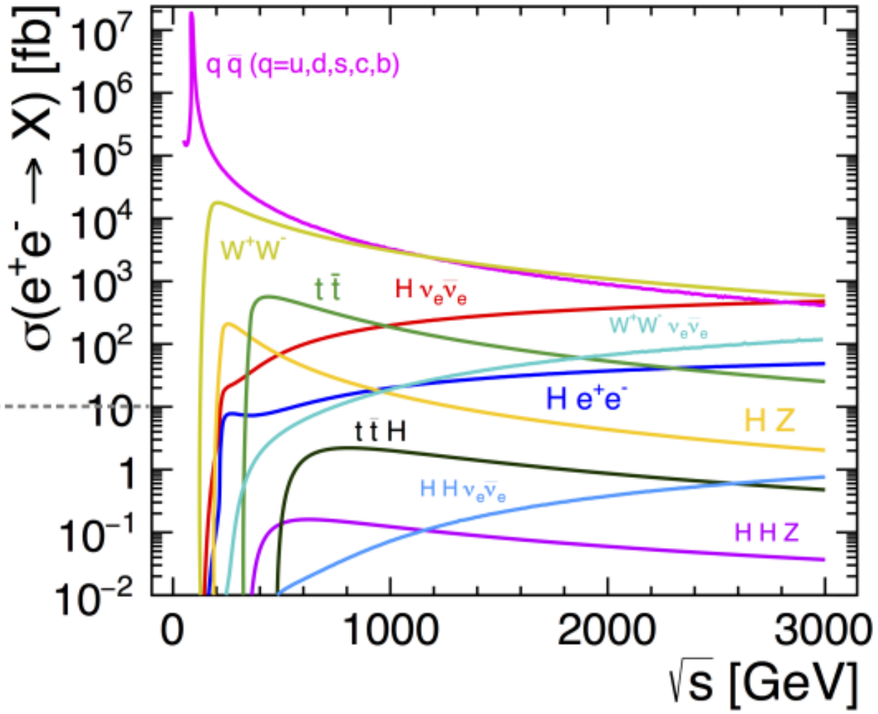
DISCUSSION ON BACKGROUNDS



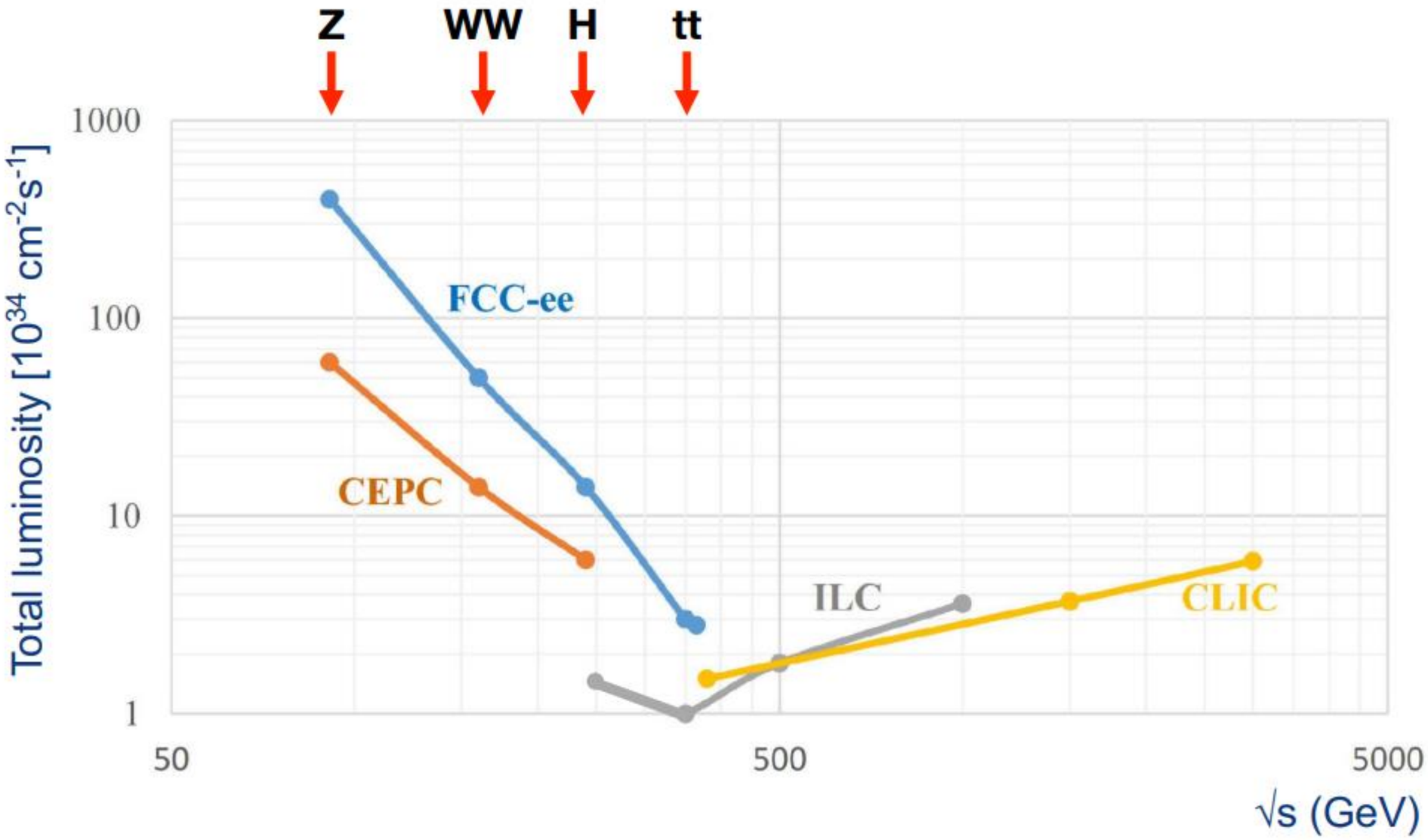
8 orders of magnitude!

pp collisions:
Interesting events need to be found in huge number of collisions



e⁺e⁻ collisions:
More "clean", all events usable

FUTURE LEPTON COLLIDERS LUMINOSITIES



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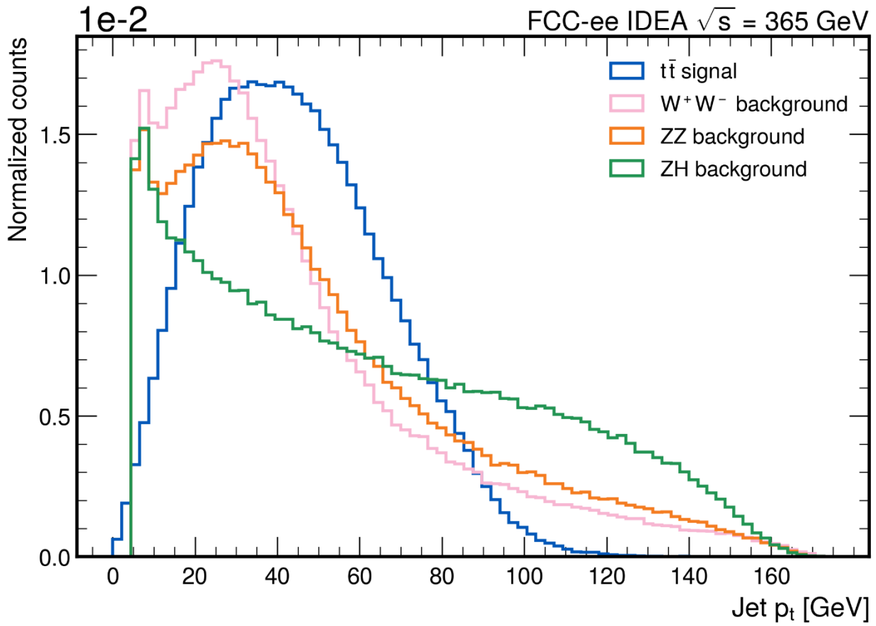
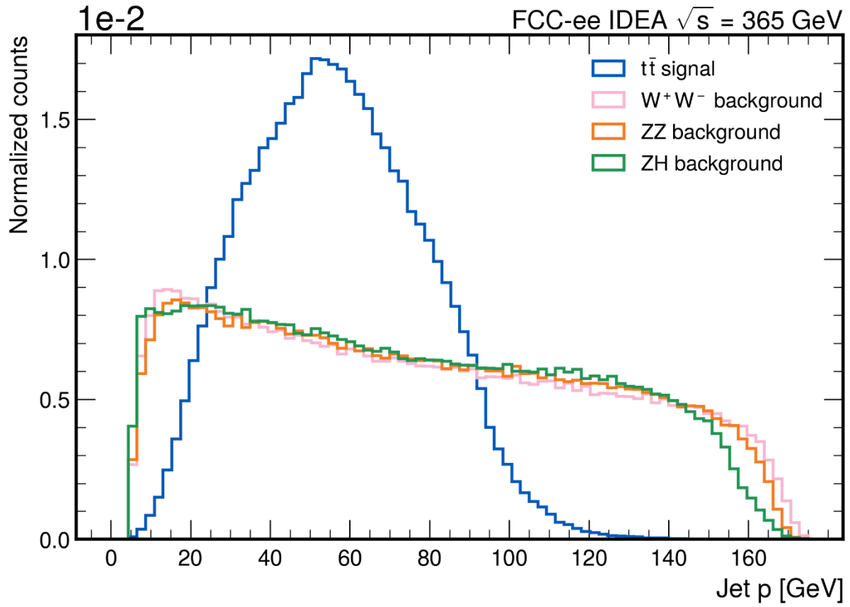
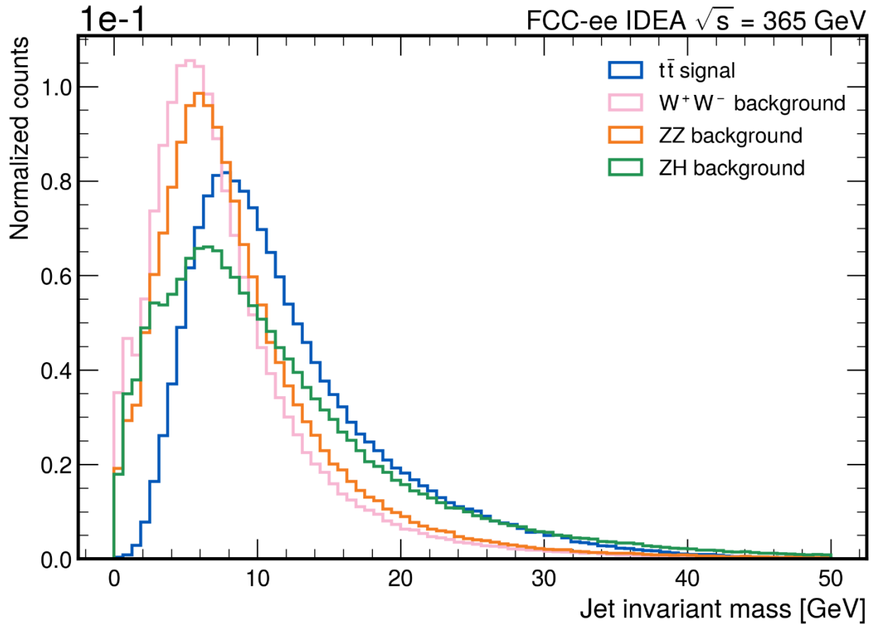
Signal vs Background Classification Extra







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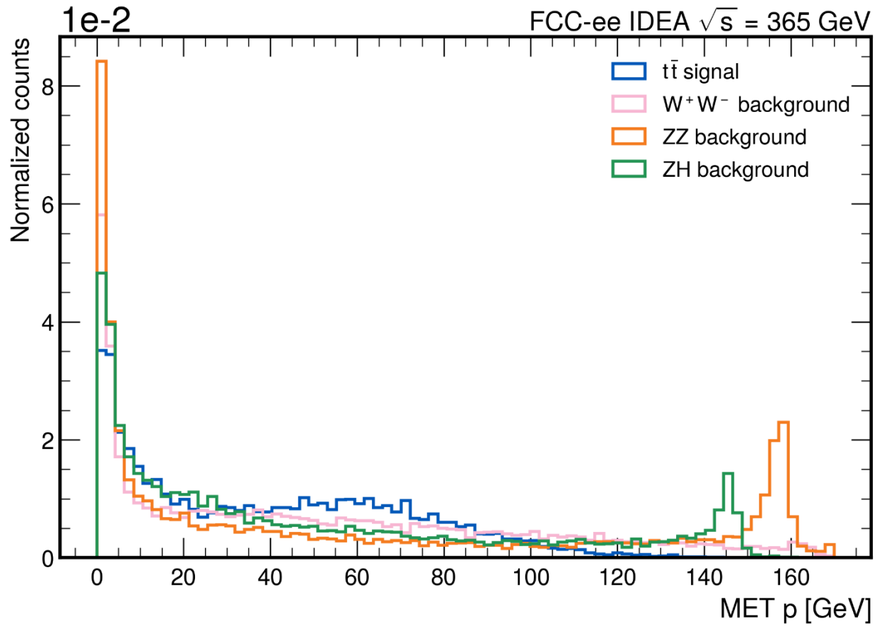
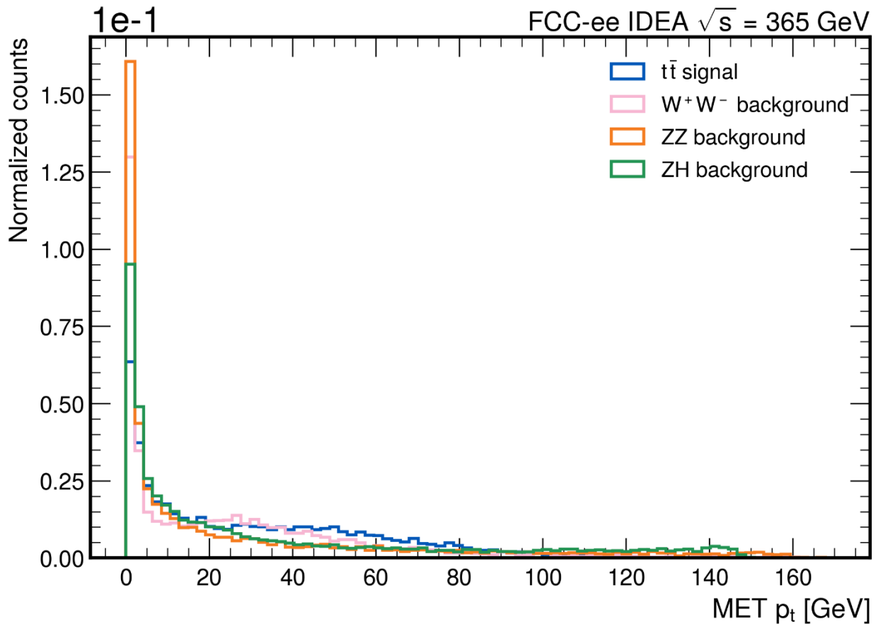
Signal vs Background Classification Extra





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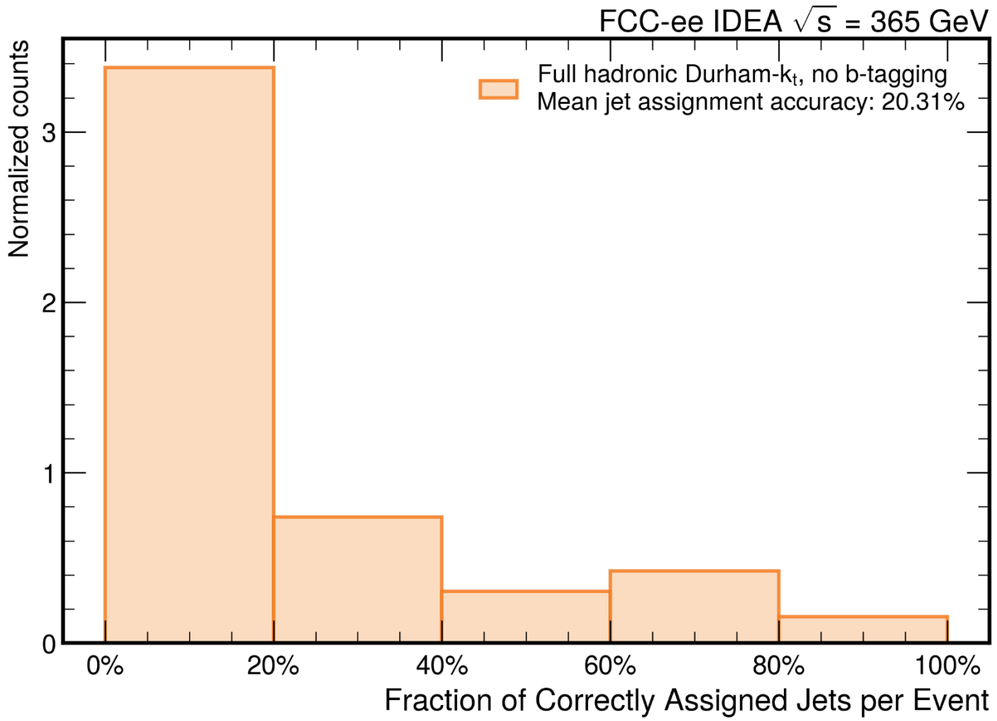
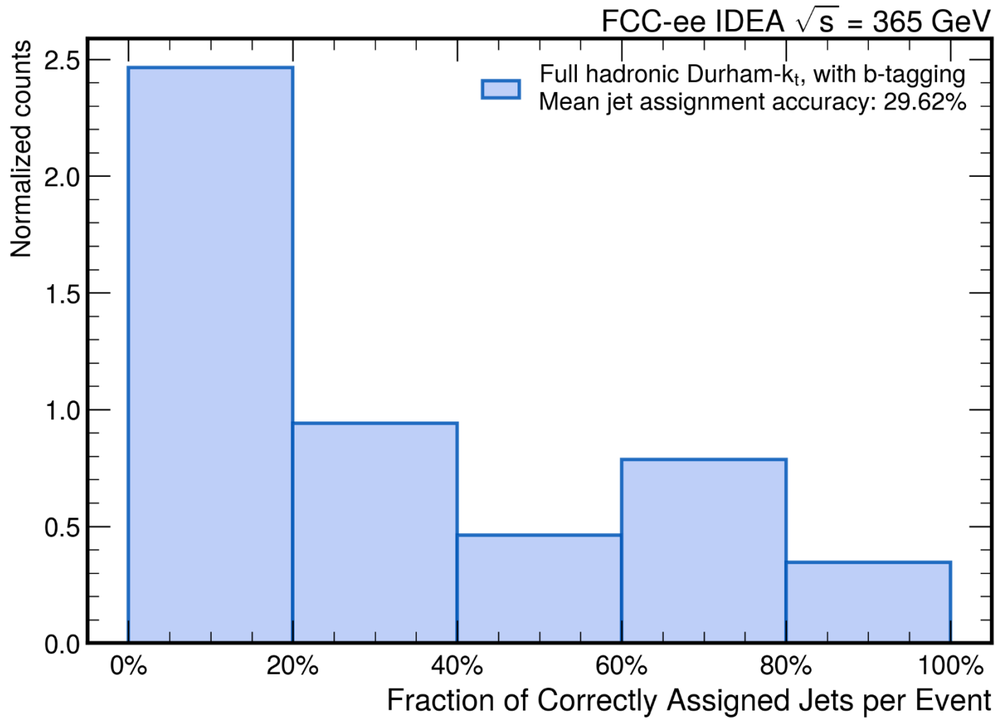
Extra reconstruction plots

- Fully hadronic kinematic reconstruction:
- (mean) Jet-parton assignment accuracy





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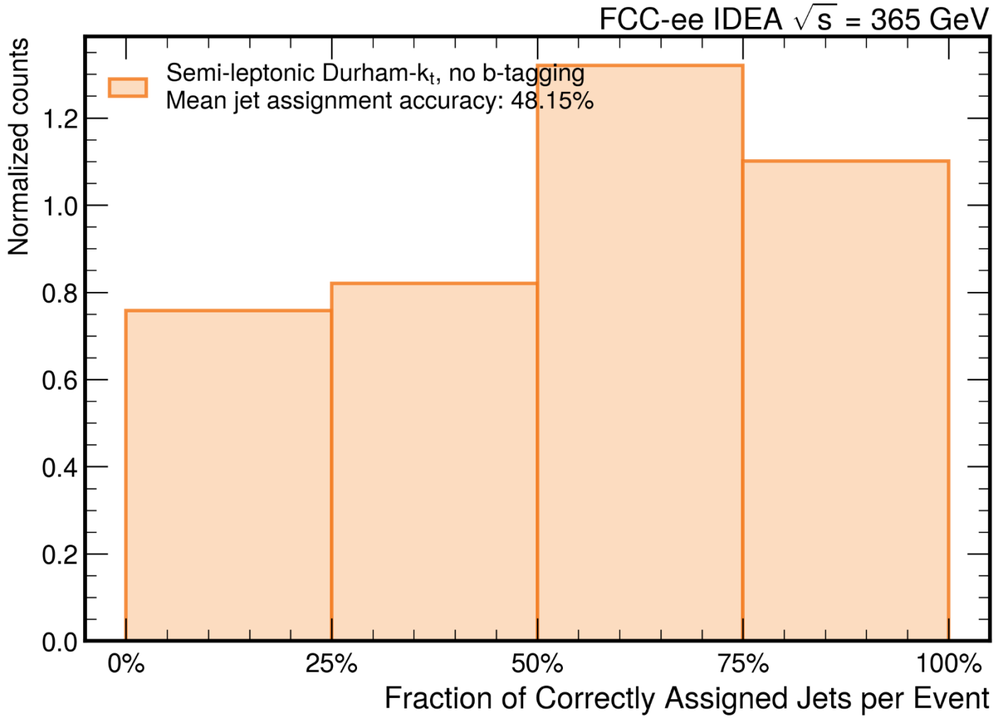
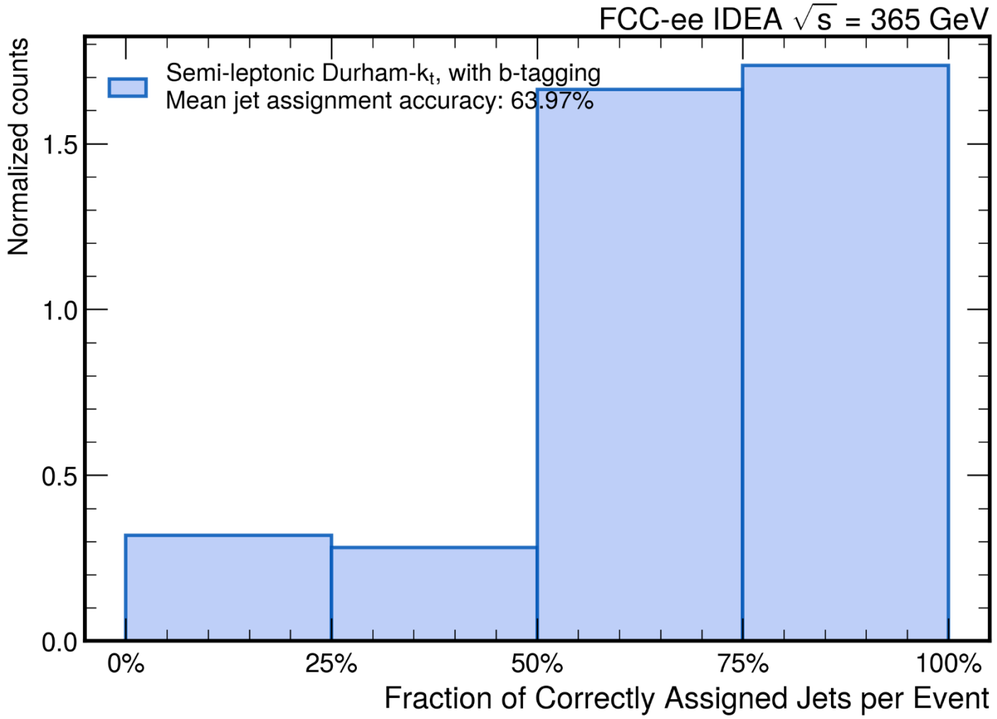
Extra reconstruction plots

- Semi-leptonic kinematic reconstruction:
- (mean) Jet-parton assignment accuracy





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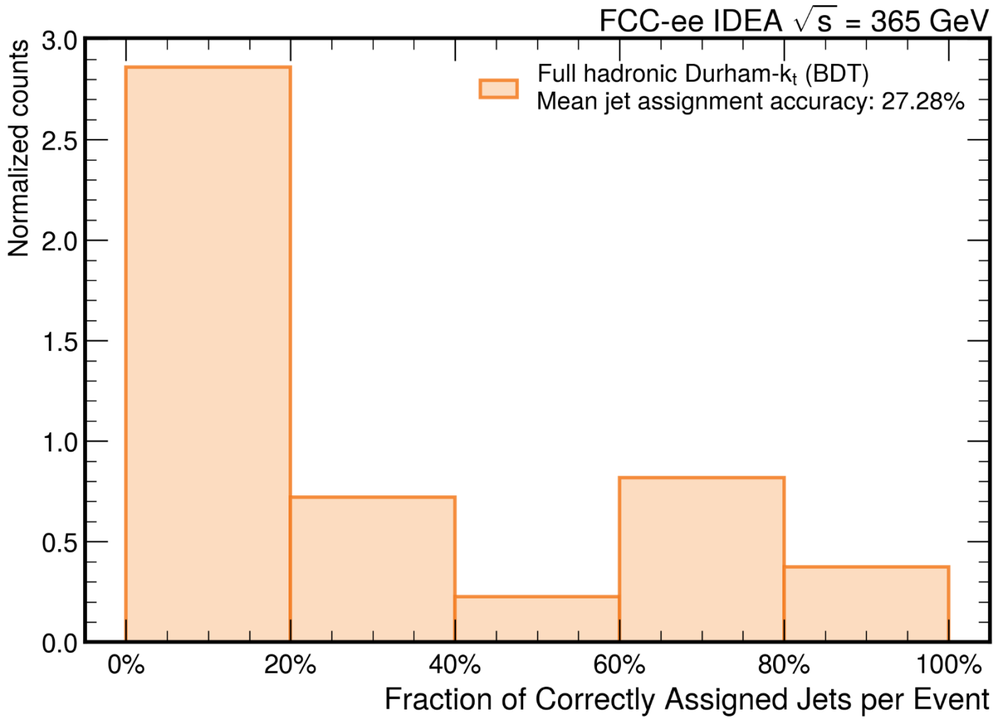
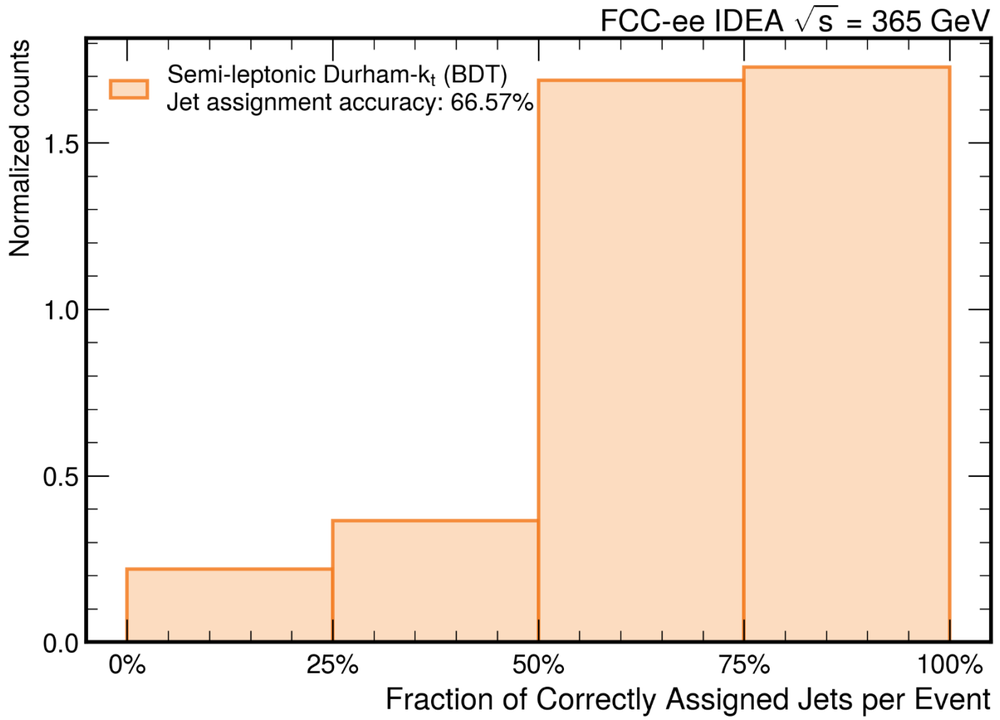
Extra reconstruction plots

- BDT reconstruction:
- (mean) Jet-parton assignment accuracy





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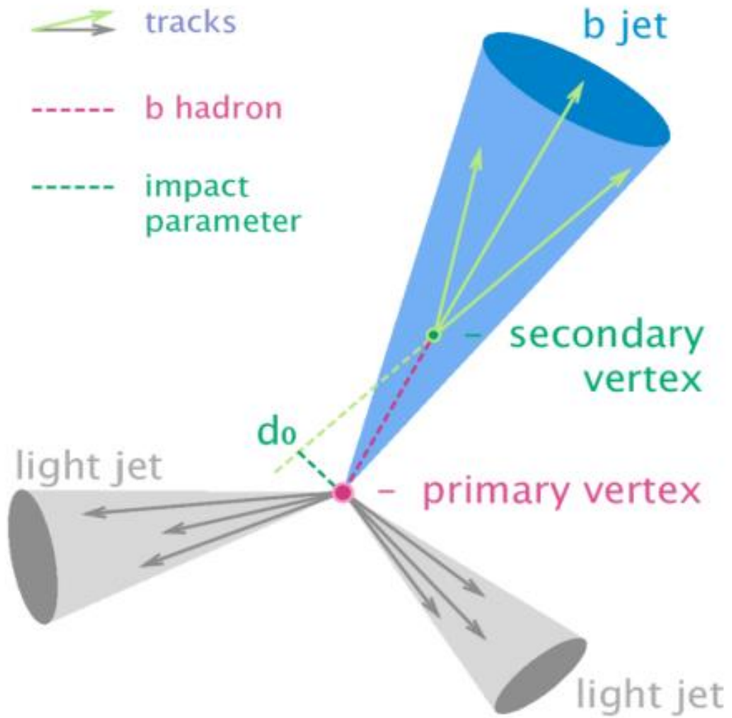
B-tagging

- Identify b-jets using Delphes
  - Cone:

$$\Delta R = \sqrt{(\eta_{jet} - \eta_b)^2 + (\phi_{jet} - \phi_b)^2}$$

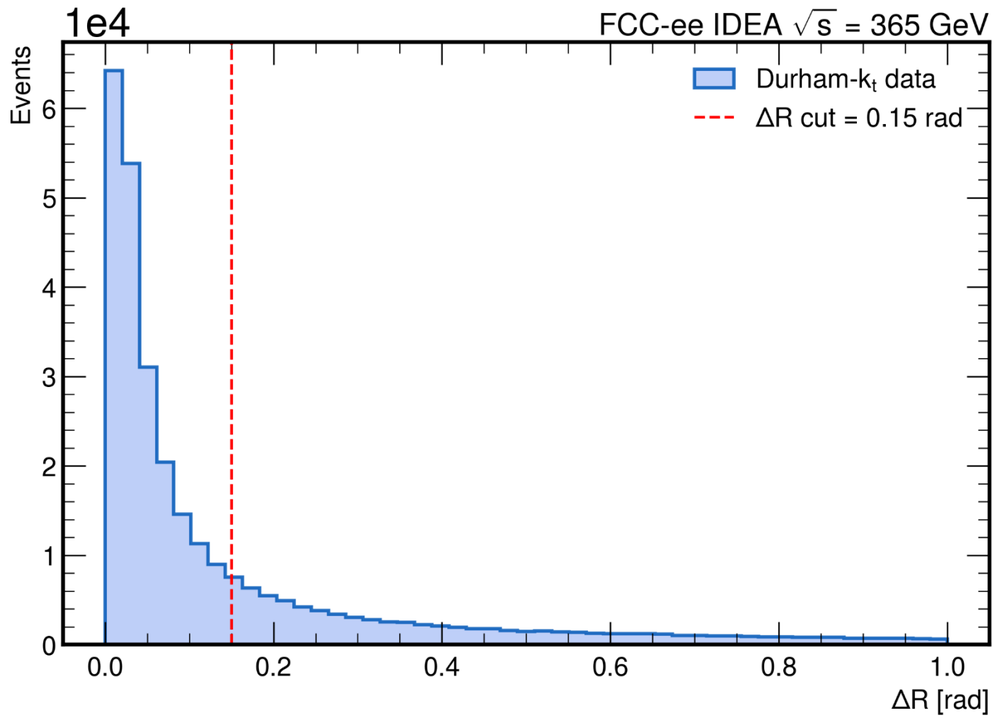
- Configure tagging-/ mis-tagging efficiencies

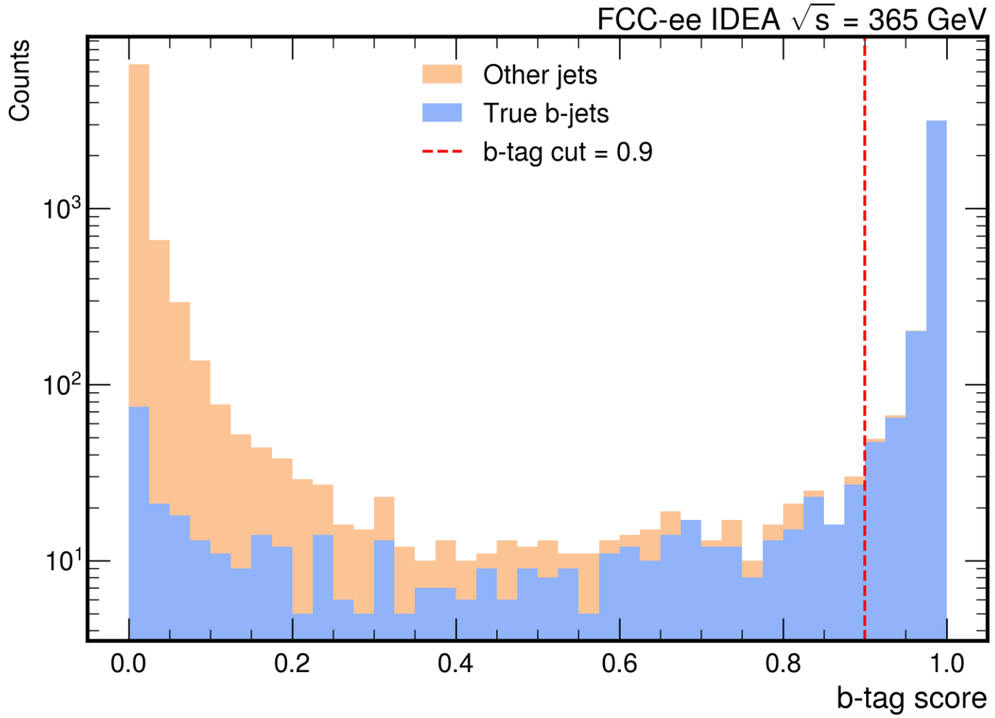


M. Stoye

Jet-parton matching and b-tagging figures

- Angular separation: $\Delta R = \sqrt{(\Delta\eta)^2+(\Delta\phi)^2} < 0.15$





$\varepsilon_{tag} = 87.91\%,$

$\varepsilon_{mis} = 0.19\%$

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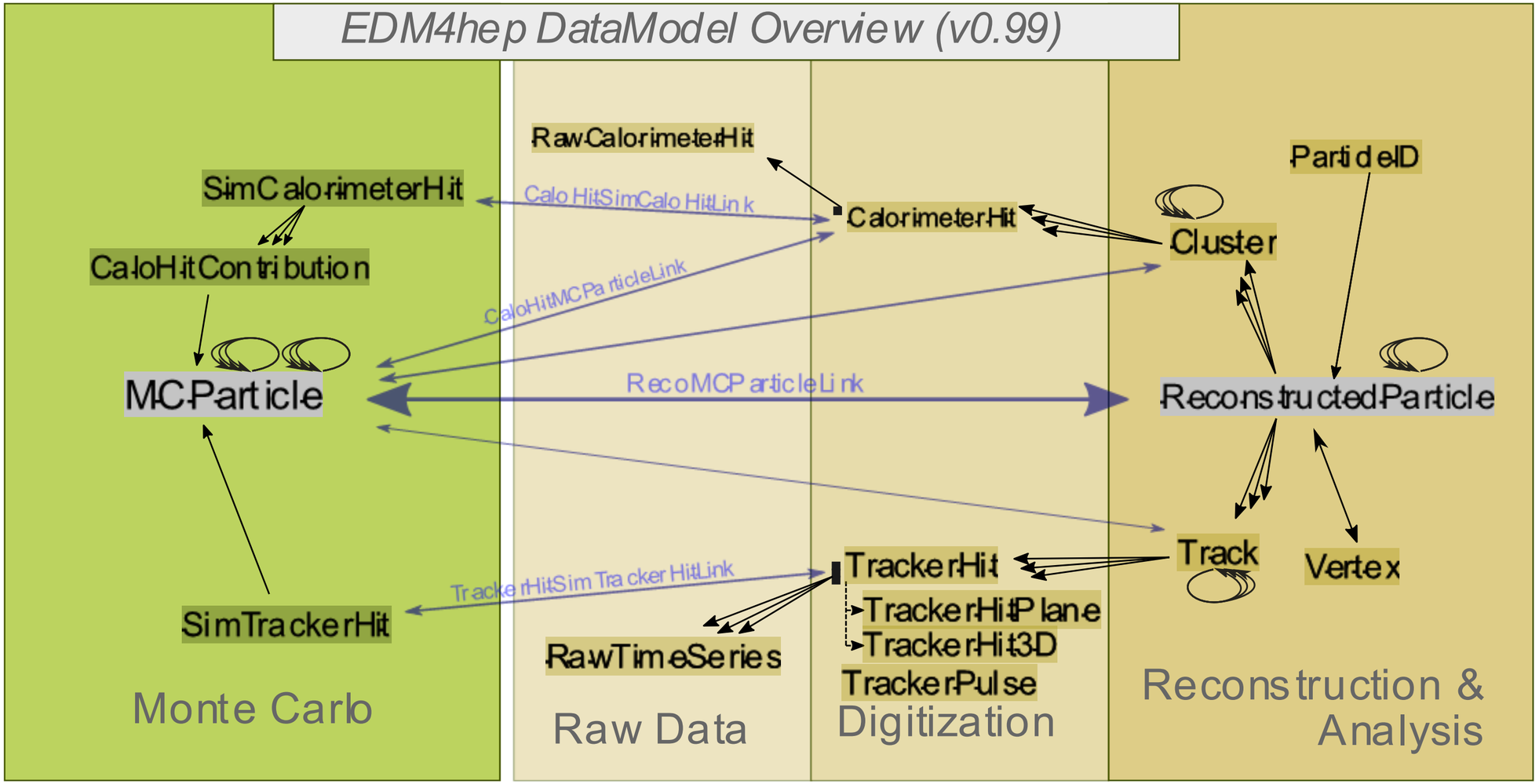
TOP QUARK RECONSTRUCTION



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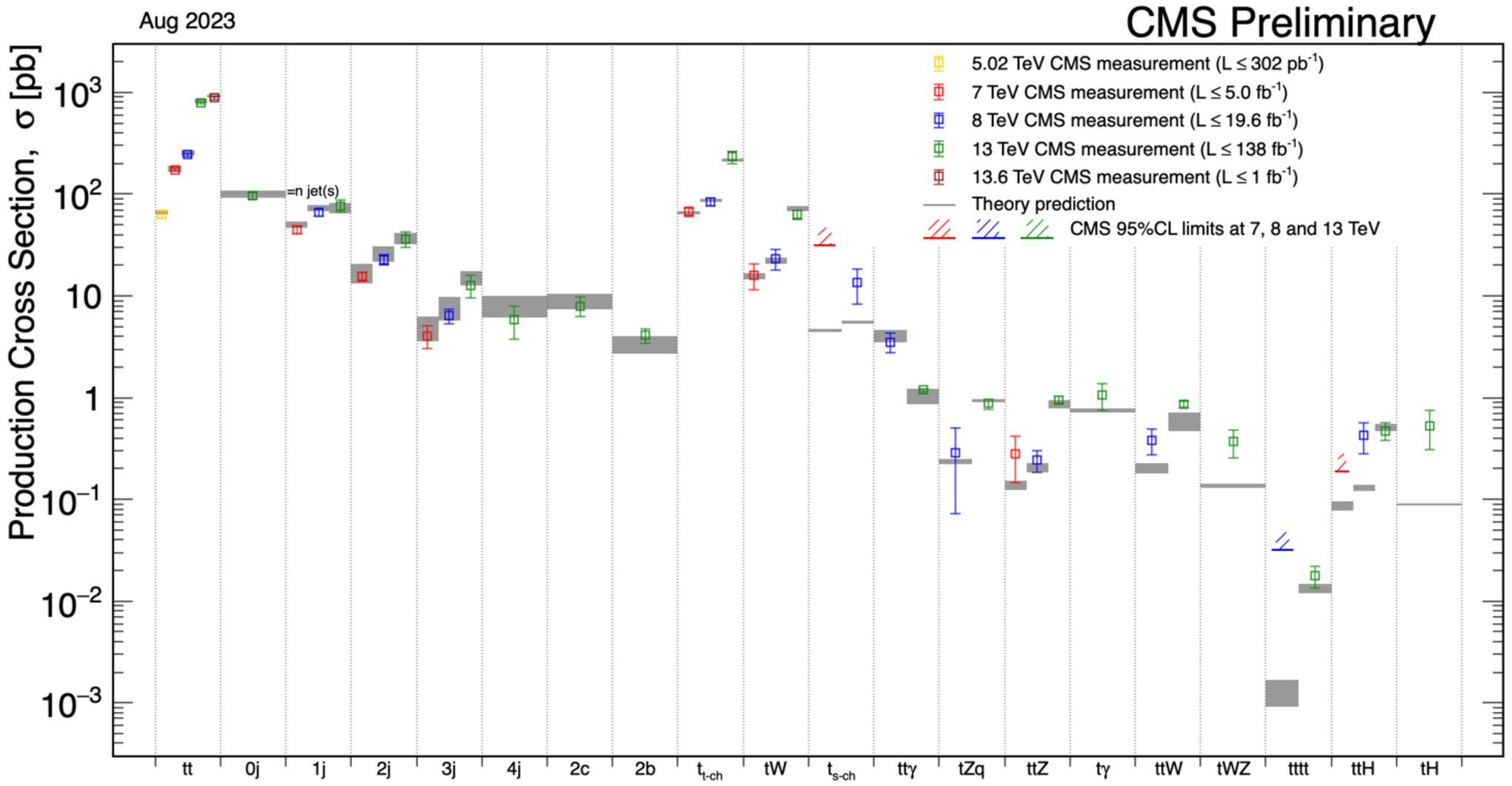
FCC TIMELINE

The tentative timeline is:

- **2025:** Completion of the FCC Feasibility Study
- **2027–2028:** Decision by the CERN Member States and international partners
- **2030s:** Start of construction
- **Mid-2040s:** FCC-ee begins operation and runs for approximately 15 years
- **2070s:** FCC-hh begins operation and runs for approximately 25 years

EXTENSIVE TOP QUARK RESEARCH AT LHC



All results at: http://cern.ch/go/pNj7

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