FACULTY OF SCIENCES

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

STUDY OF TOP QUARK PRODUCTION AT FUTURE ELECTRON-POSITRON COLLIDERS

Stijn Verhulst

GHENT UNIVERSITY

Promotor: prof. Didar Dobur

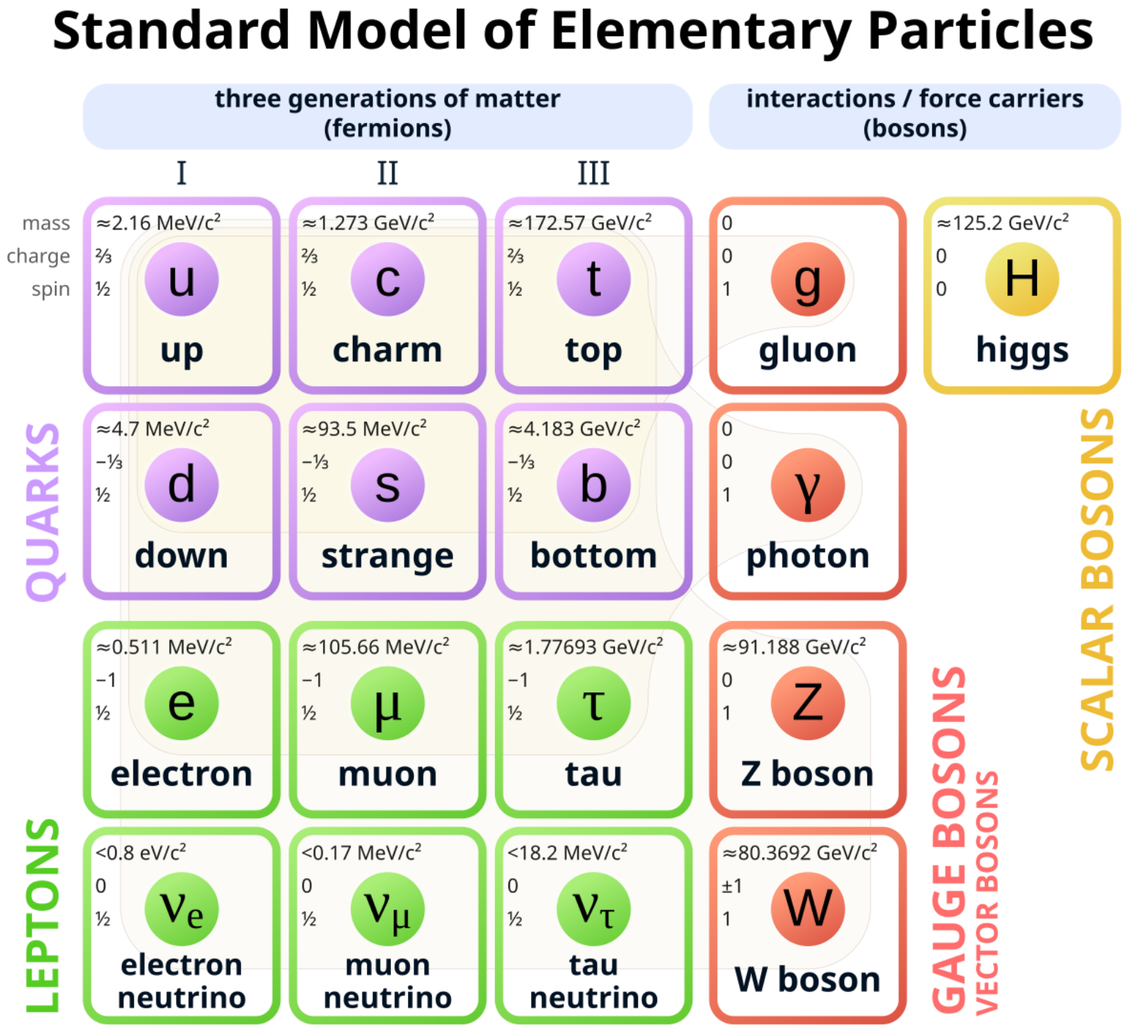
Mentor: dr. Kirill Skovpen

Why study Top quarks?

Unique properties:
- Heaviest SM particle
- Yukawa coupling ≈ 1

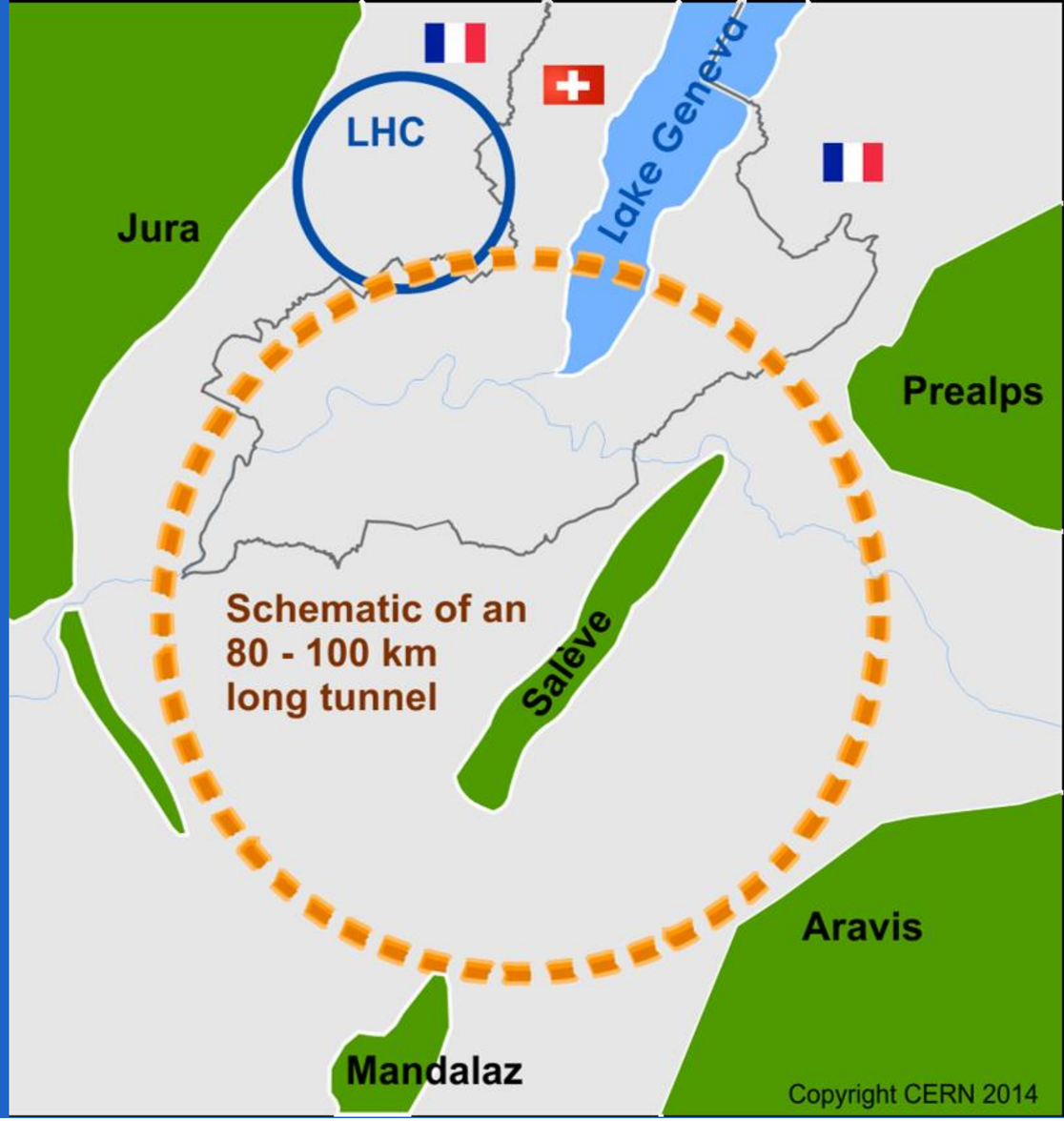
Clean decay signature:
- Decays before hadronizing

Probe BSM physics:
- Accurate Reconstruction needed



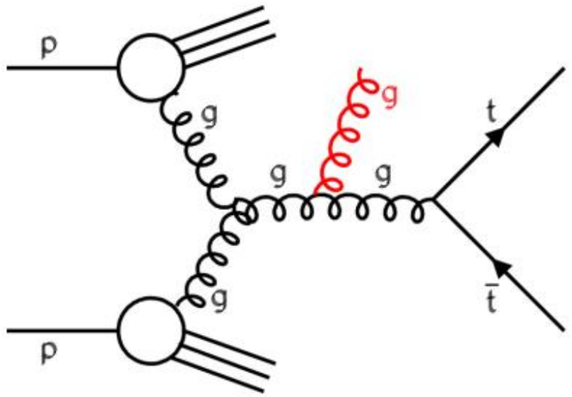
GHENT UNIVERSITY

THE NEED FOR A NEW COLLIDER



GHENT UNIVERSITY

Hadron and Lepton colliders

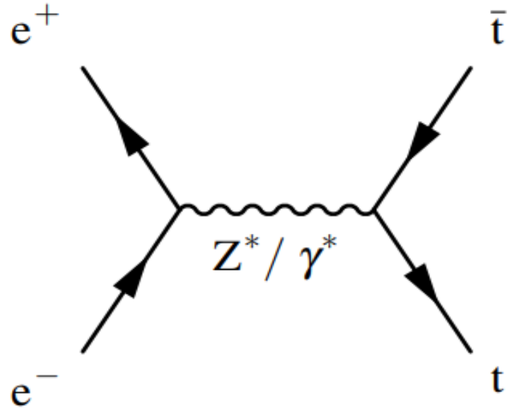


Proton is a compound object:

- 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
- Beam polarization distinguishes Z/γ
- High-precision measurements

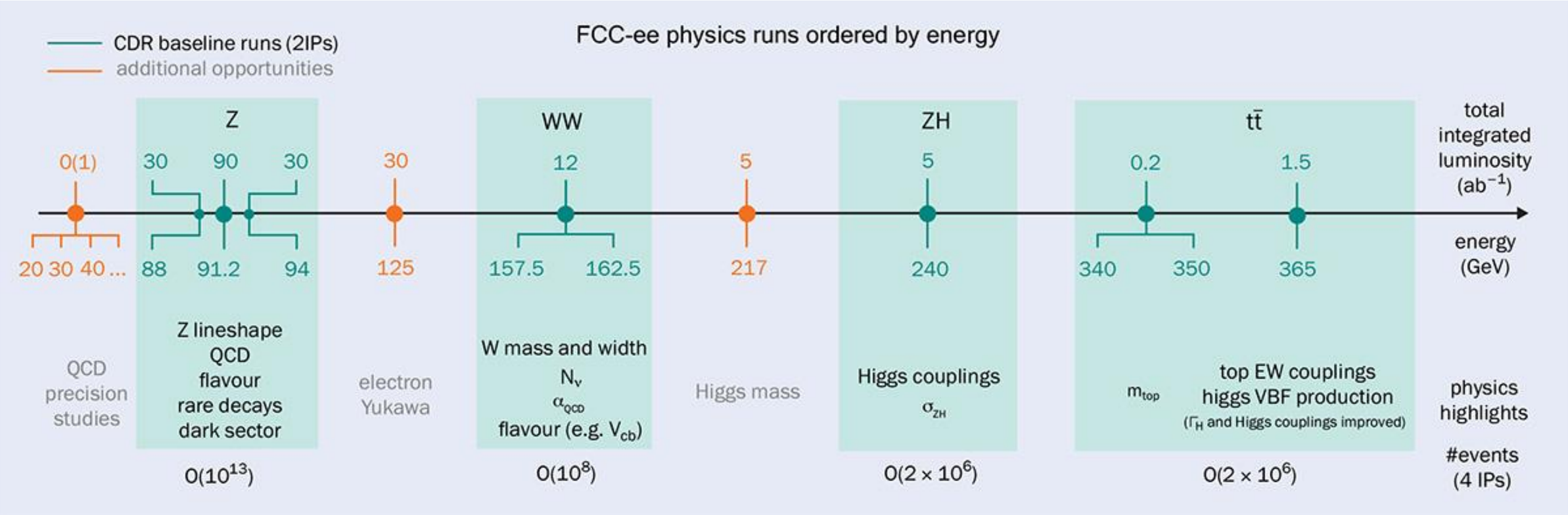
High energies (> 380 GeV) require linear colliders

Clean experimental environment

GHENT UNIVERSITY

FCC-ee

- 4 Stages



FCC study (CERNCOURIER)

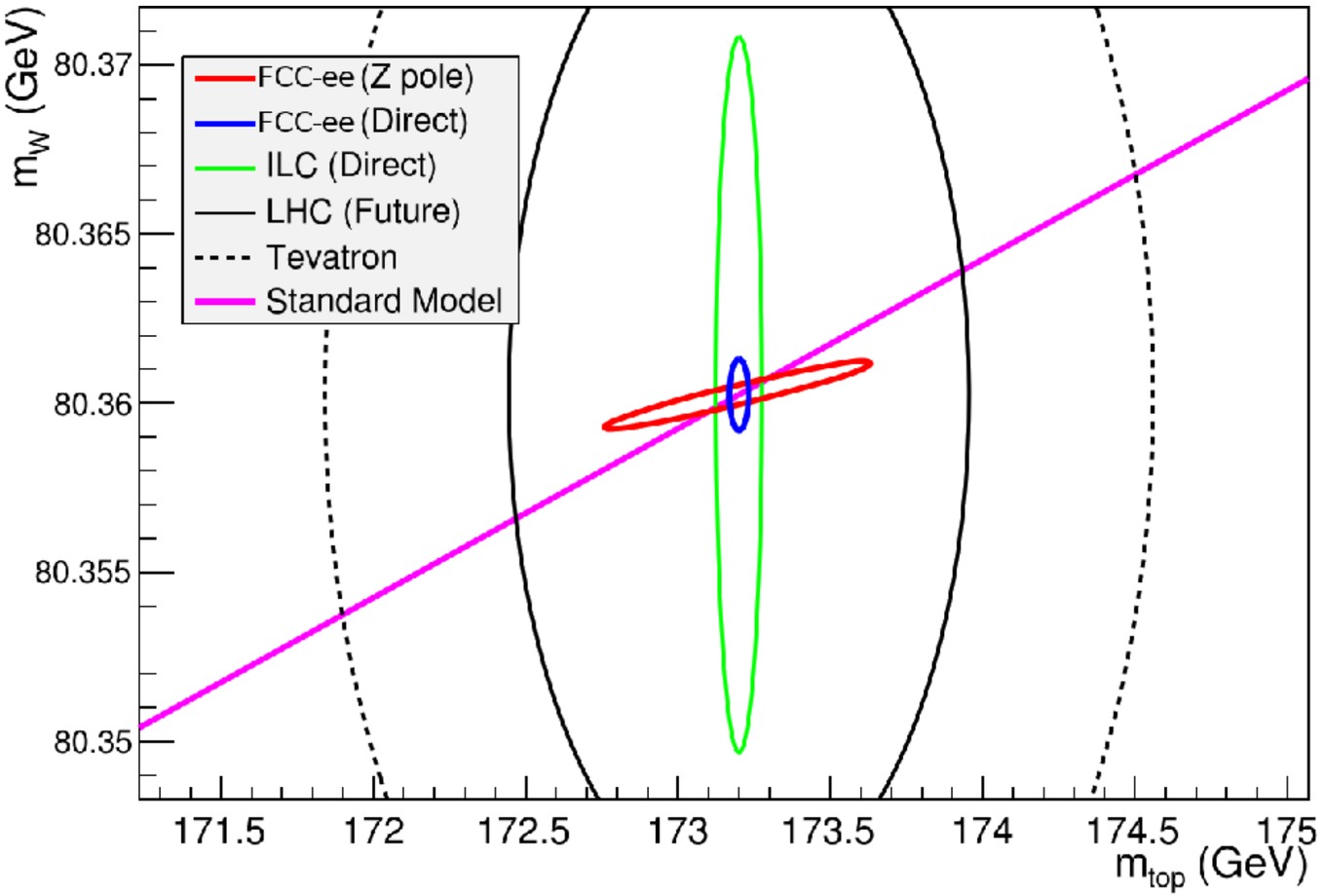
GHENT UNIVERSITY

FCC-ee Improvements

- Improve precision in: electroweak observables

- Look for new physics effects through this high precision

d'Enterria, David (CERN)



GHENT UNIVERSITY

ANALYSIS OF THE TOP QUARK

GHENT UNIVERSITY

Strategy

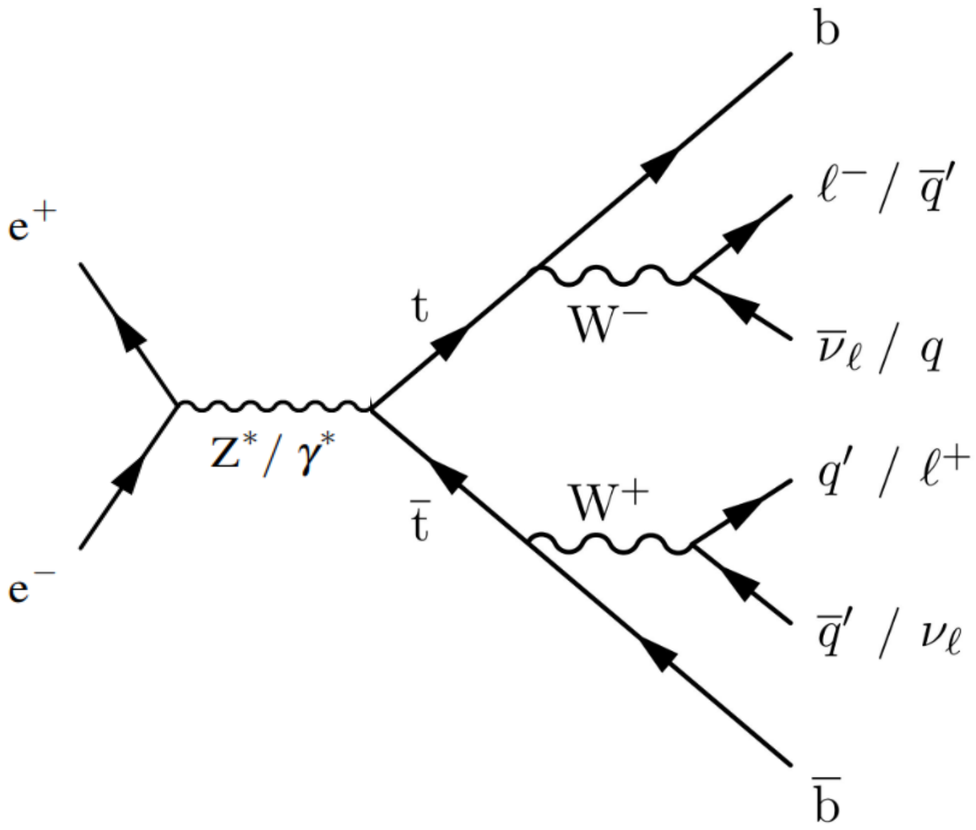
- Decay Channels:

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

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

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

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



GHENT UNIVERSITY

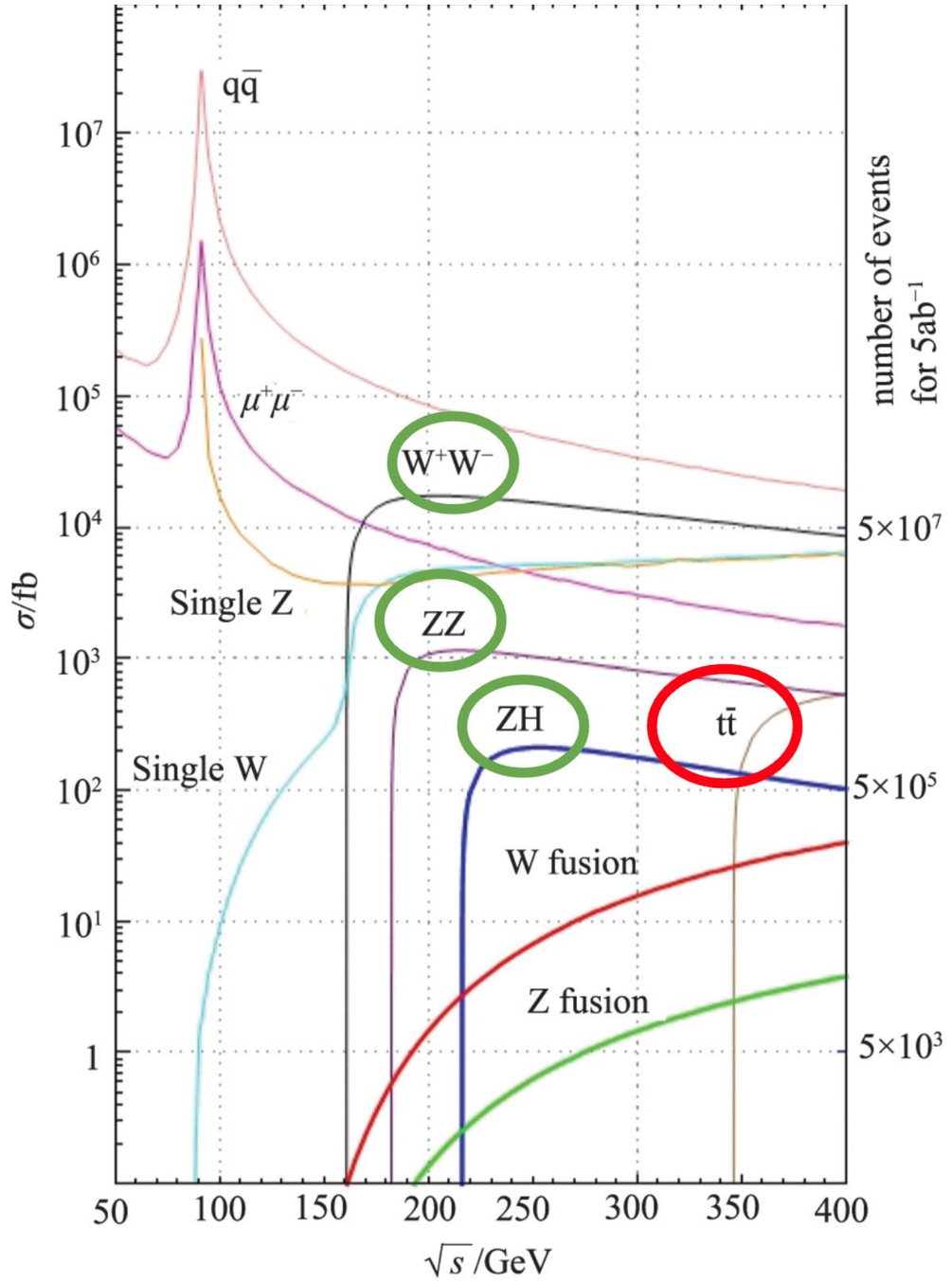
Simulation framework: **Key4HEP**

Event Generation:	• Madgraph + Pythia8
Detector Simulation:	• Delphes
Data Format: EDM4HEP	• Contains full information about simulation and reconstruction
FCCAnalysis:	• preform associations
Machine Learning	• Event Selection and Reconstruction

GHENT UNIVERSITY

Event generation

- Jet p and pt 20 GeV cuts
- 10 000 events for each dataset
- $\sqrt{s} = 365\ GeV$



GHENT UNIVERSITY

BACKGROUND SUPPRESSION

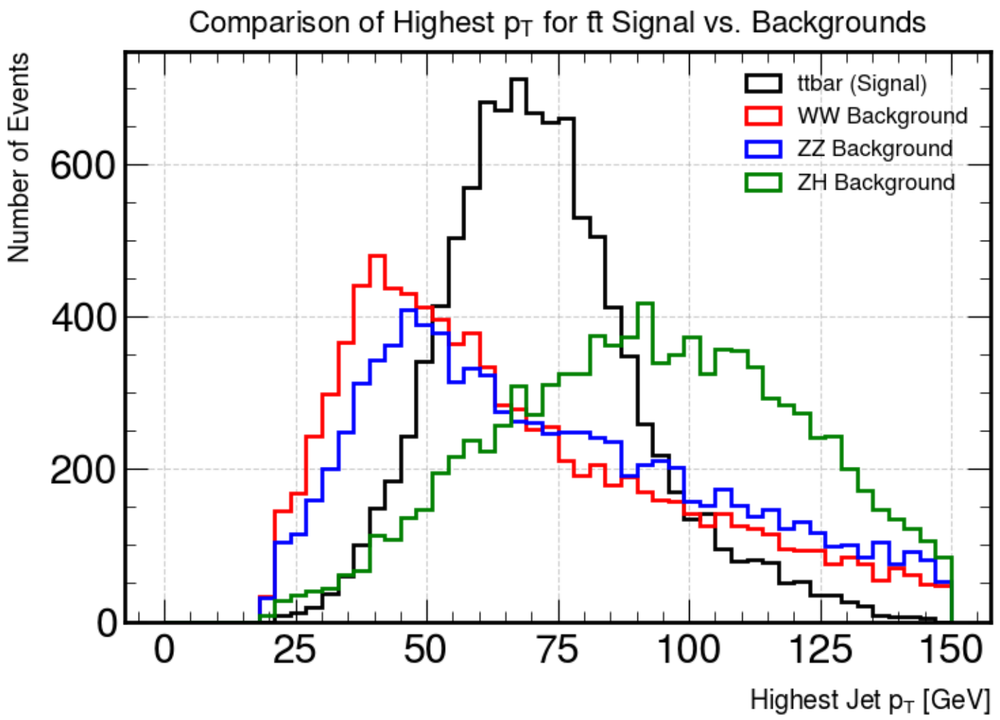
GHENT UNIVERSITY

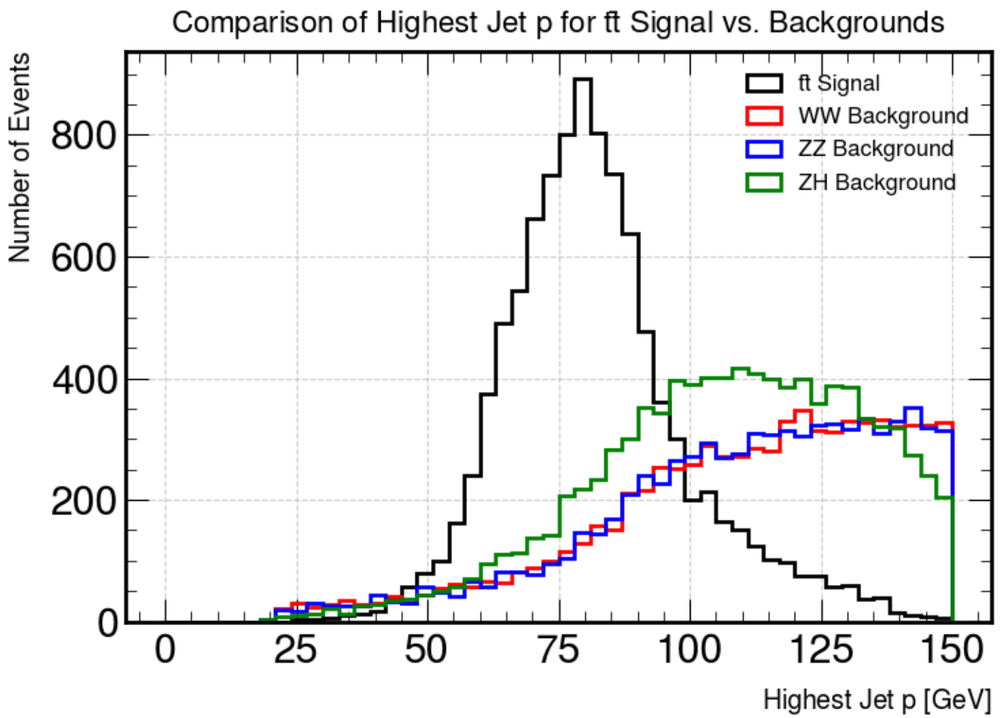
Signal vs Background Classification

- Recursive Feature Elimination (RFE)
  - 7 features remained
- Hyperparameter Optimization
  - GridSearch
- Boosted Decision Tree (BDT)
  - Train 75%, Test 25% splits

GHENT UNIVERSITY

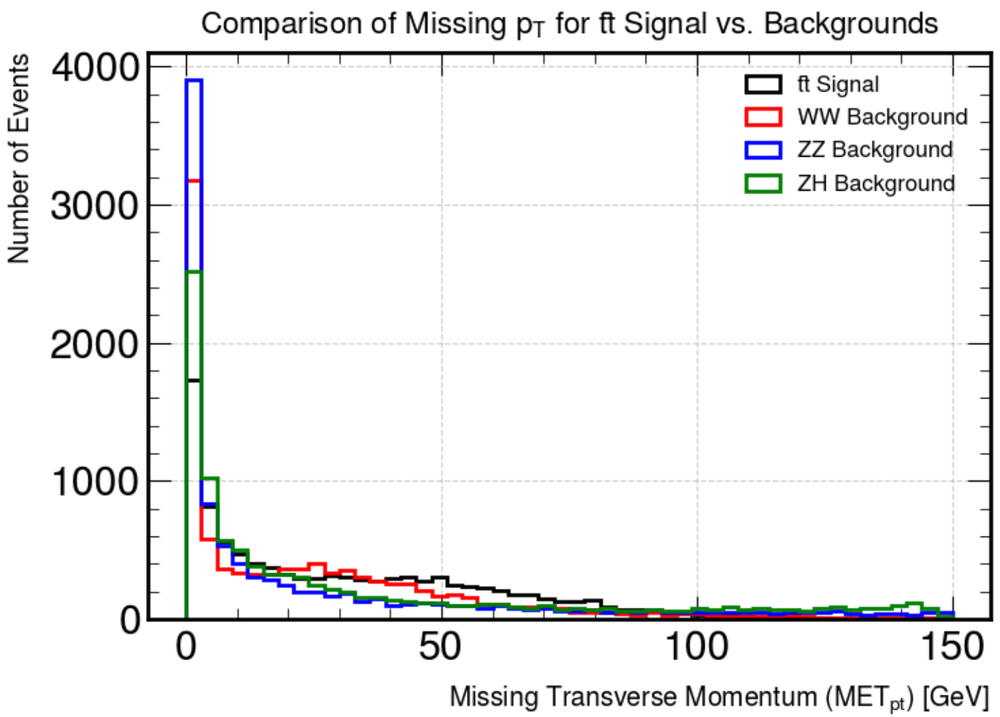
Signal vs Background Classification

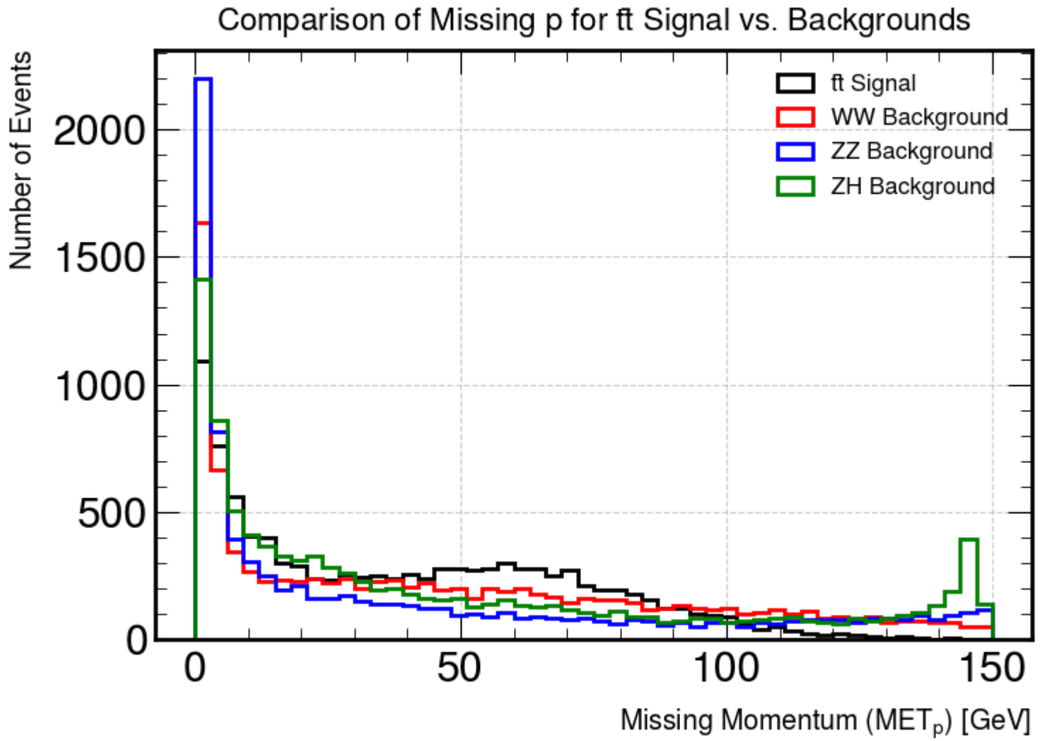




GHENT UNIVERSITY

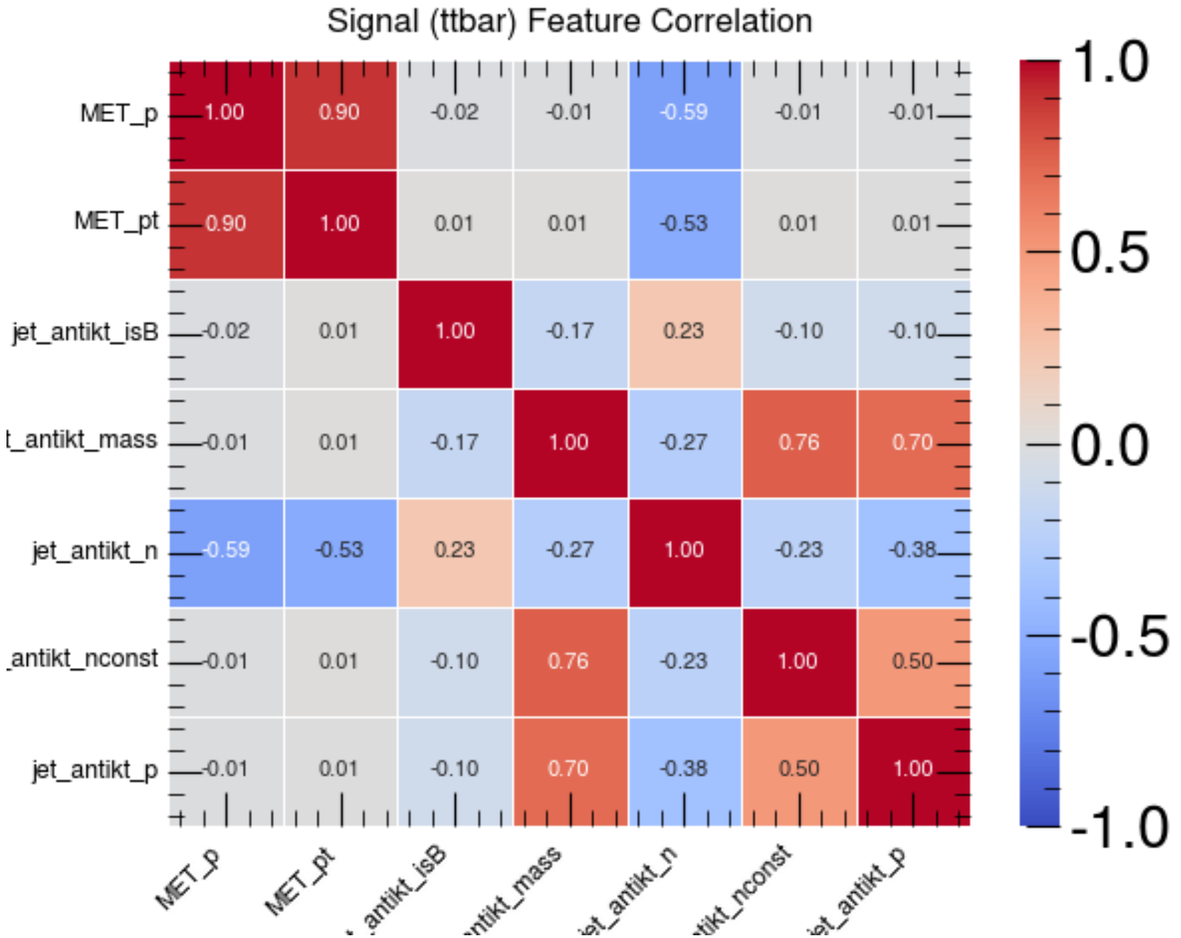
Signal vs Background Classification

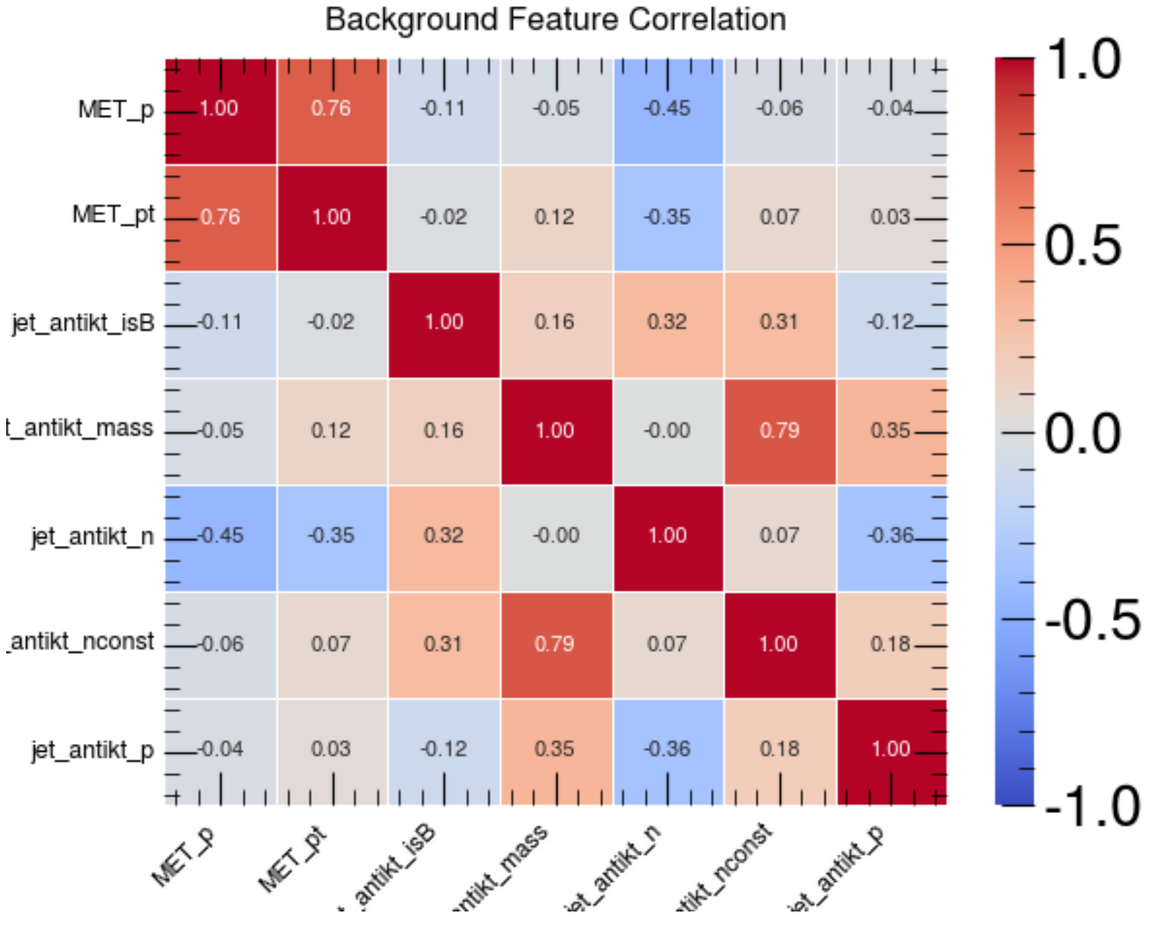




GHENT UNIVERSITY

Feature Correlation



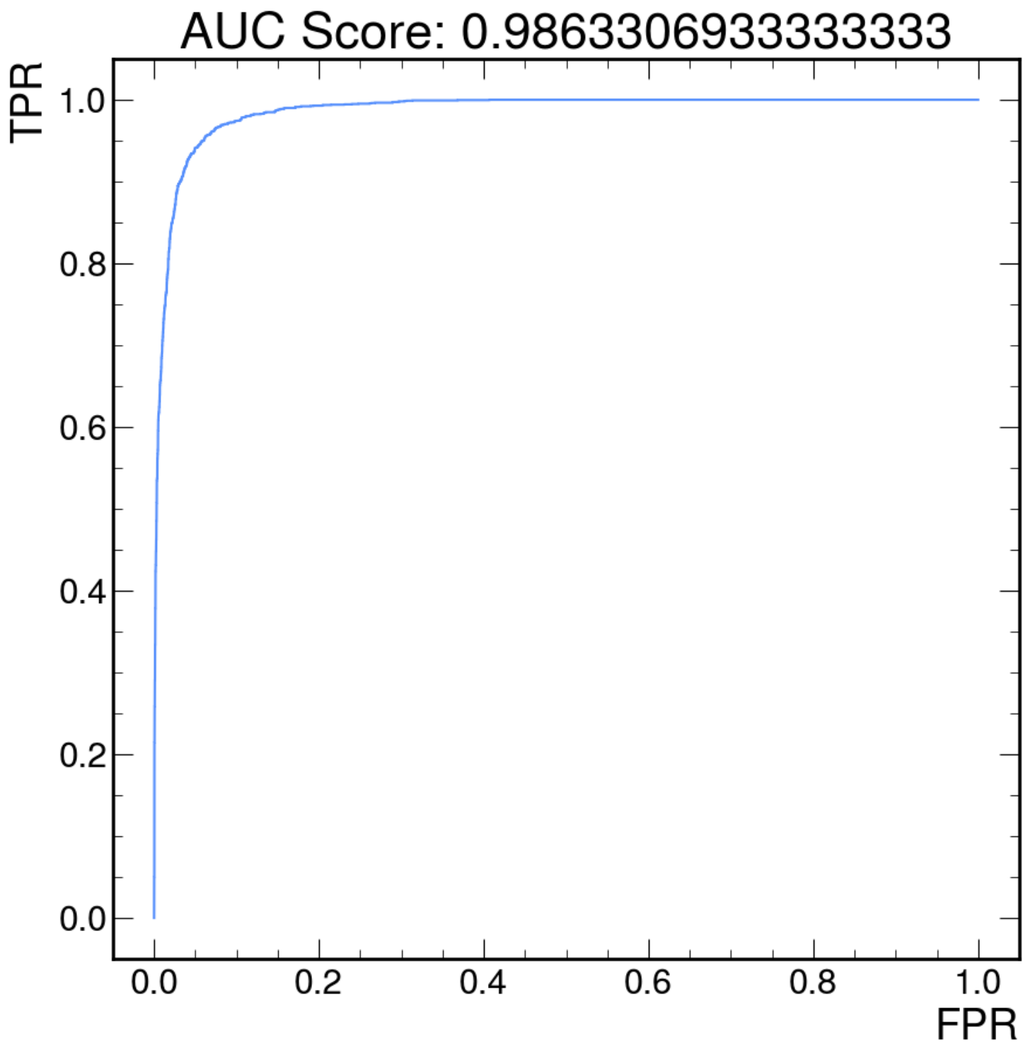


GHENT UNIVERSITY

Signal vs Background Classification

- Greatly improves sample purity

- Better performance



GHENT UNIVERSITY

TOP QUARK RECONSTRUCTION

GHENT UNIVERSITY

Reconstruction

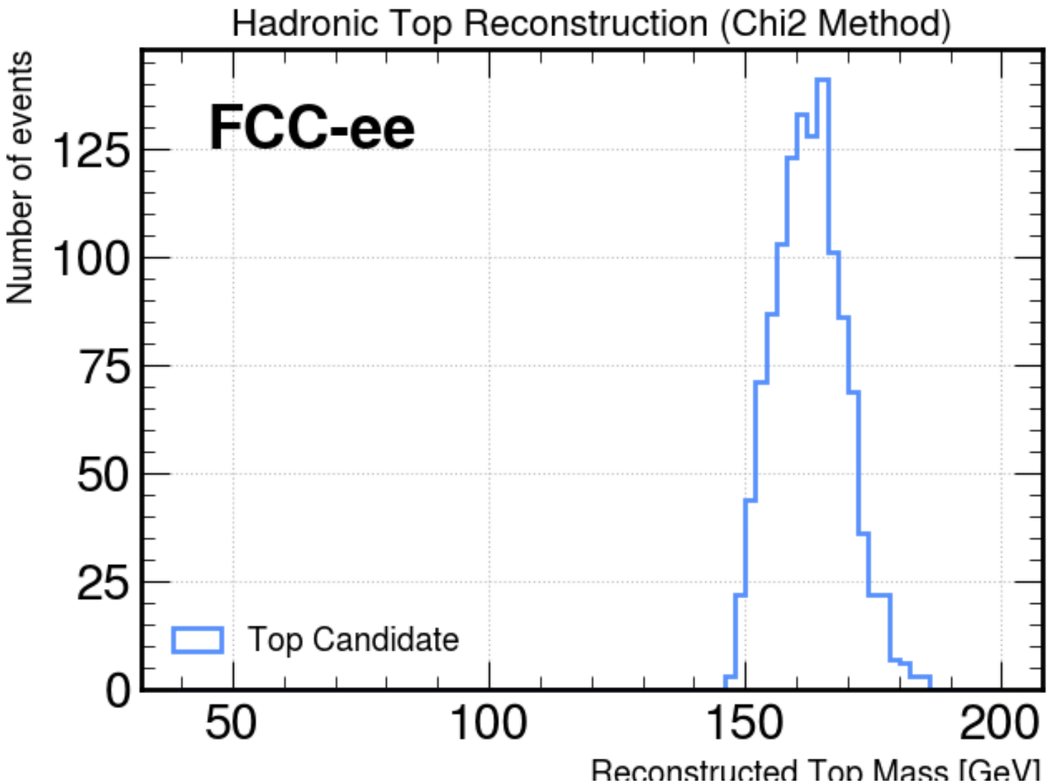
- Kinematic fitting:

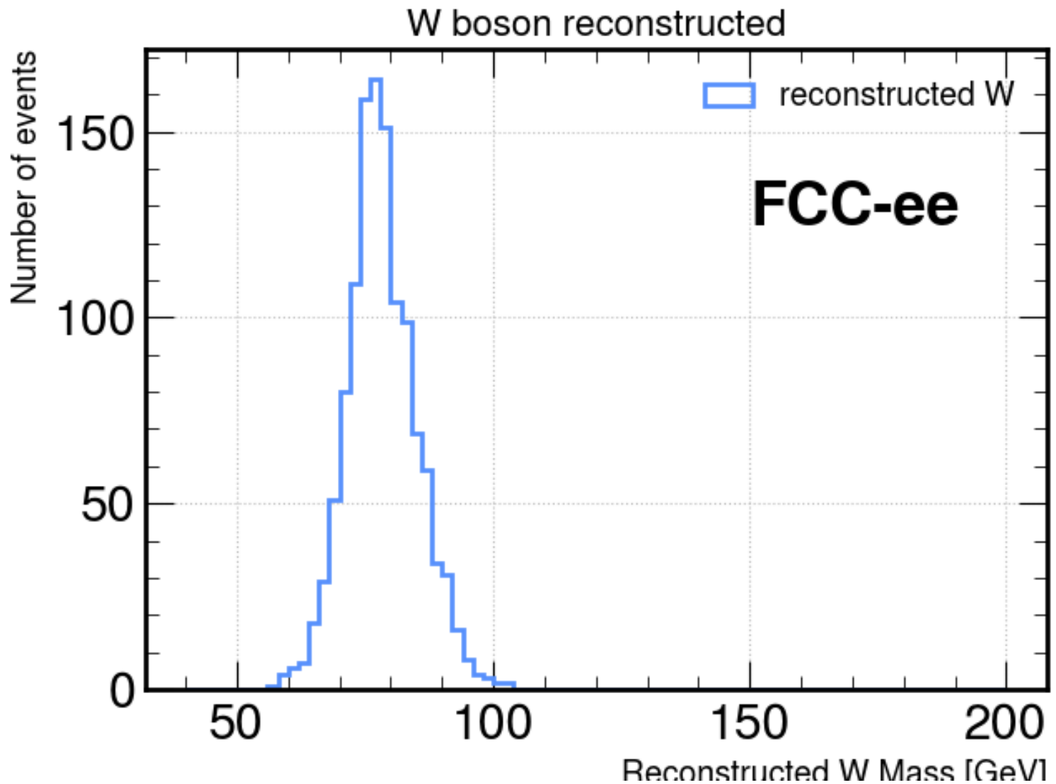
$$\chi^2 = \frac{(m_{b1j1j2} - m_t^{MC})^2}{\sigma^2_{m_t^{MC}}} + \frac{(m_{b2j3j4} - m_t^{MC})^2}{\sigma^2_{m_t^{MC}}} + \frac{(m_{j1j2} - m_W^{MC})^2}{\sigma^2_{m_W^{MC}}} + \frac{(m_{j3j4} - m_W^{MC})^2}{\sigma^2_{m_W^{MC}}}$$

- Jet permutations
- Matching reconstructed with MC truth particles
- 5 GeV cuts on jet momenta

Reconstruction Results

- Underestimates

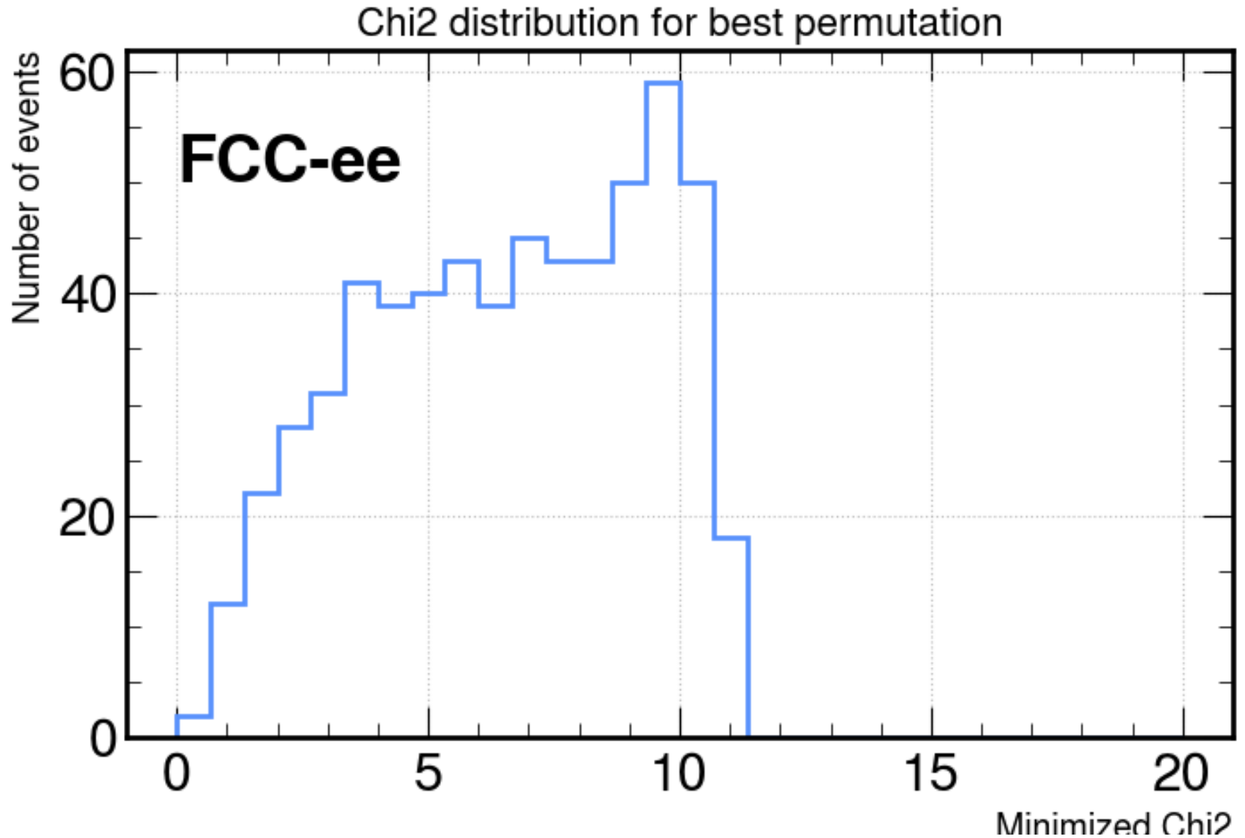




GHENT UNIVERSITY

Reconstruction: Chi² plot

- Skewed
- Need MC truth info



GHENT UNIVERSITY

NEXT STEPS

- Kinematic fit using b-tagging
- MC truth information
- ML approach for reconstruction
- Full hadronic first, now Semi-Leptonic
- Further improve Sig vs Bkg
- ....

GHENT UNIVERSITY

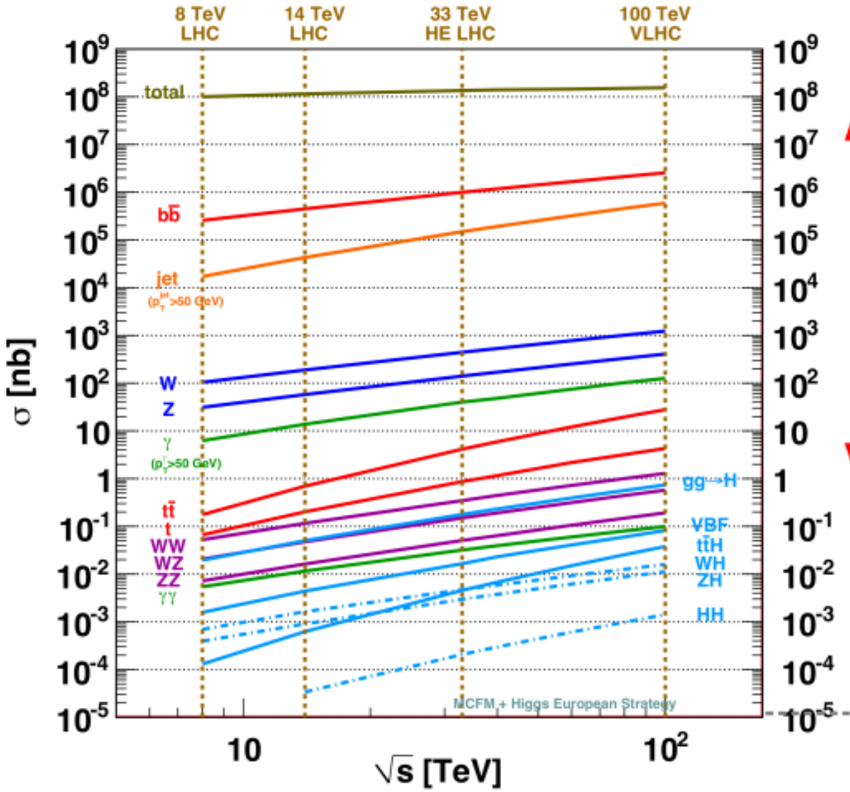
QUESTIONS?

GHENT
UNIVERSITY

BACKUP

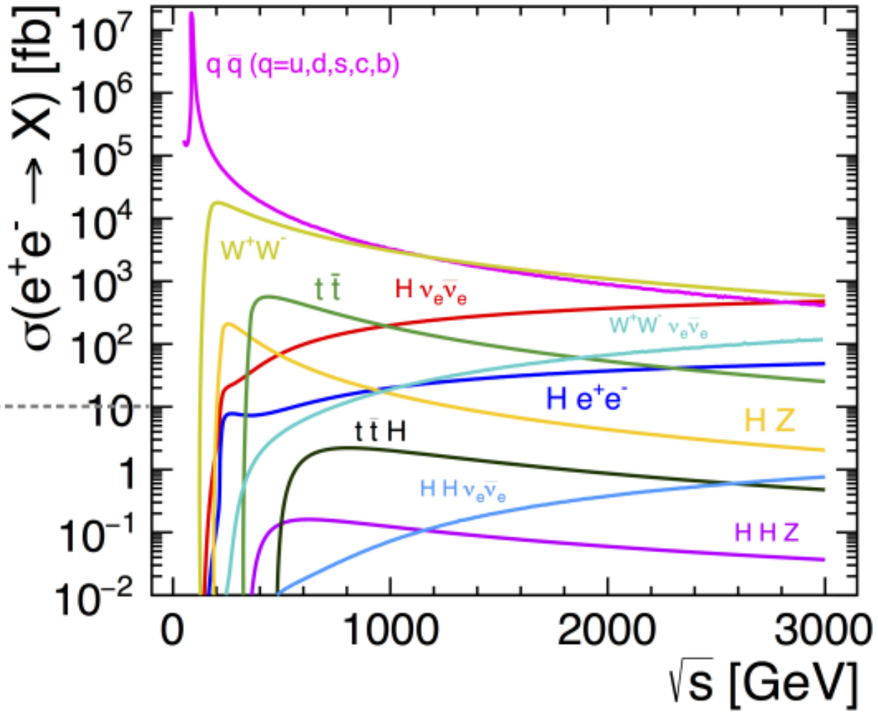
GHENT
UNIVERSITY

DISCUSSION ON BACKGROUNDS



8 orders of magnitude!

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

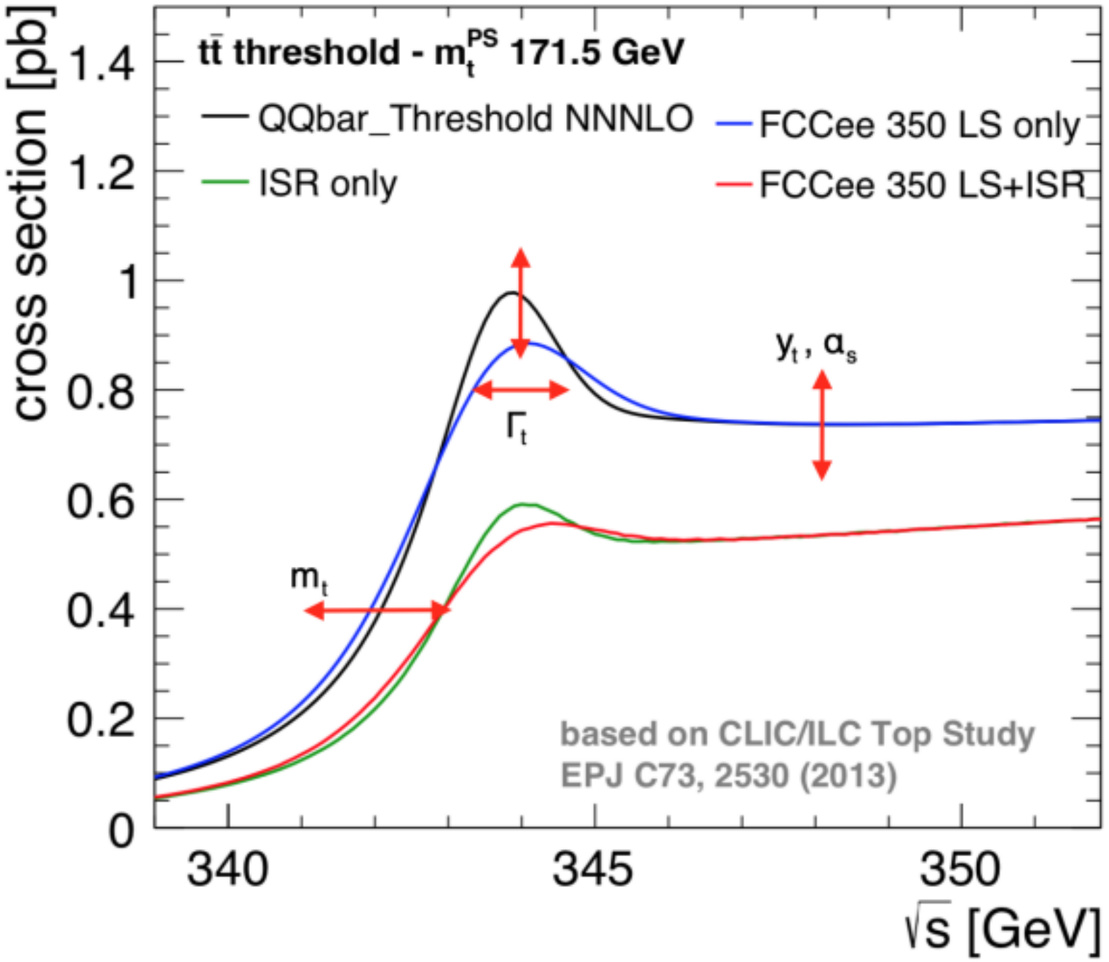


e⁺e⁻ collisions:
More "clean", all events usable

Cross section threshold scan

FCC improves precision on measurements of the top quark:

- Mass and Width
- Couplings: y_t, g_{tWb}, g_{Ztt}, $g_{\gamma tt}$
- FCNC and rare decays
- Asymmetries and other properties



GHENT UNIVERSITY

Strategy

- Decay Channels:

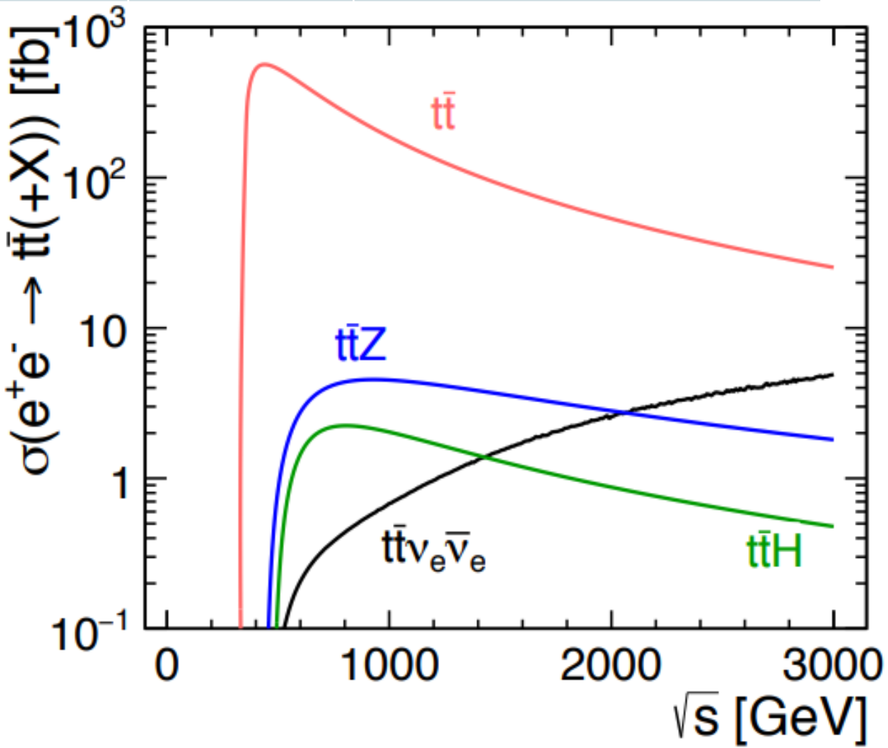
$$t\bar{t} \rightarrow b\bar{b}W^+W^- \rightarrow b\bar{b}qq\bar{q}\bar{q}$$

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

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

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

- Threshold energy range
  - Gives less background



GHENT UNIVERSITY

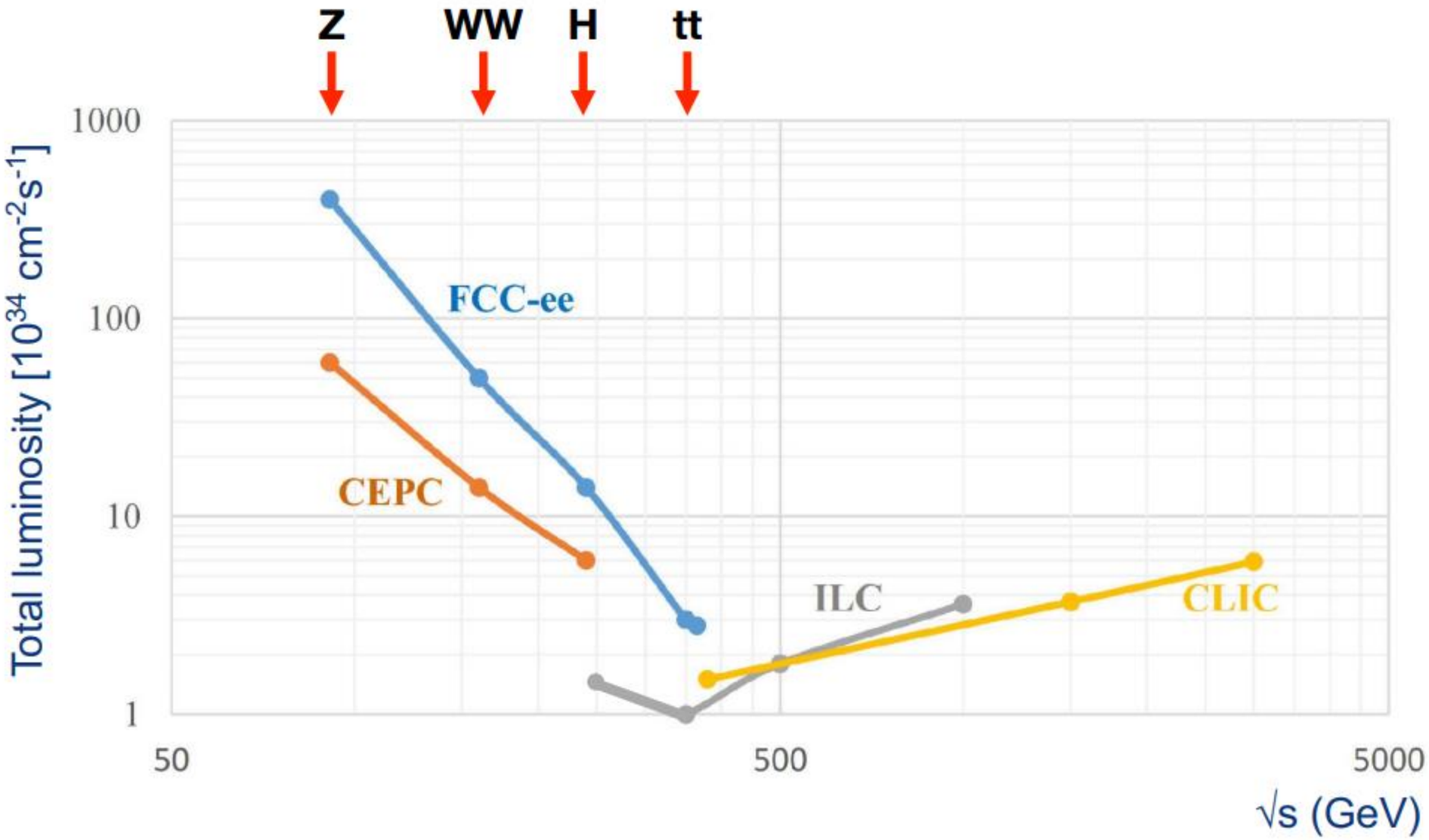
FCC TIMELINE

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

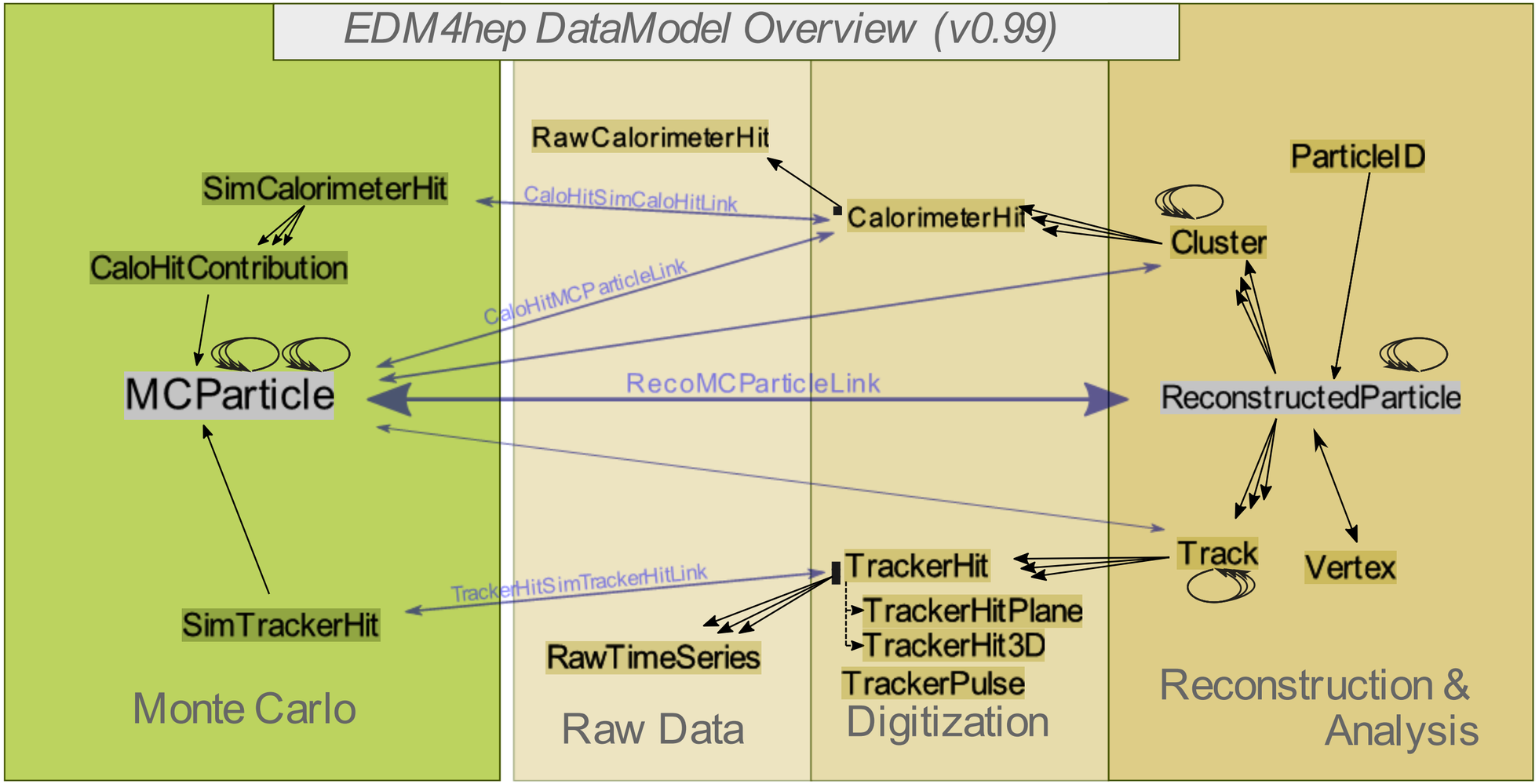
GHENT UNIVERSITY

FUTURE LEPTON COLLIDERS LUMINOSITIES



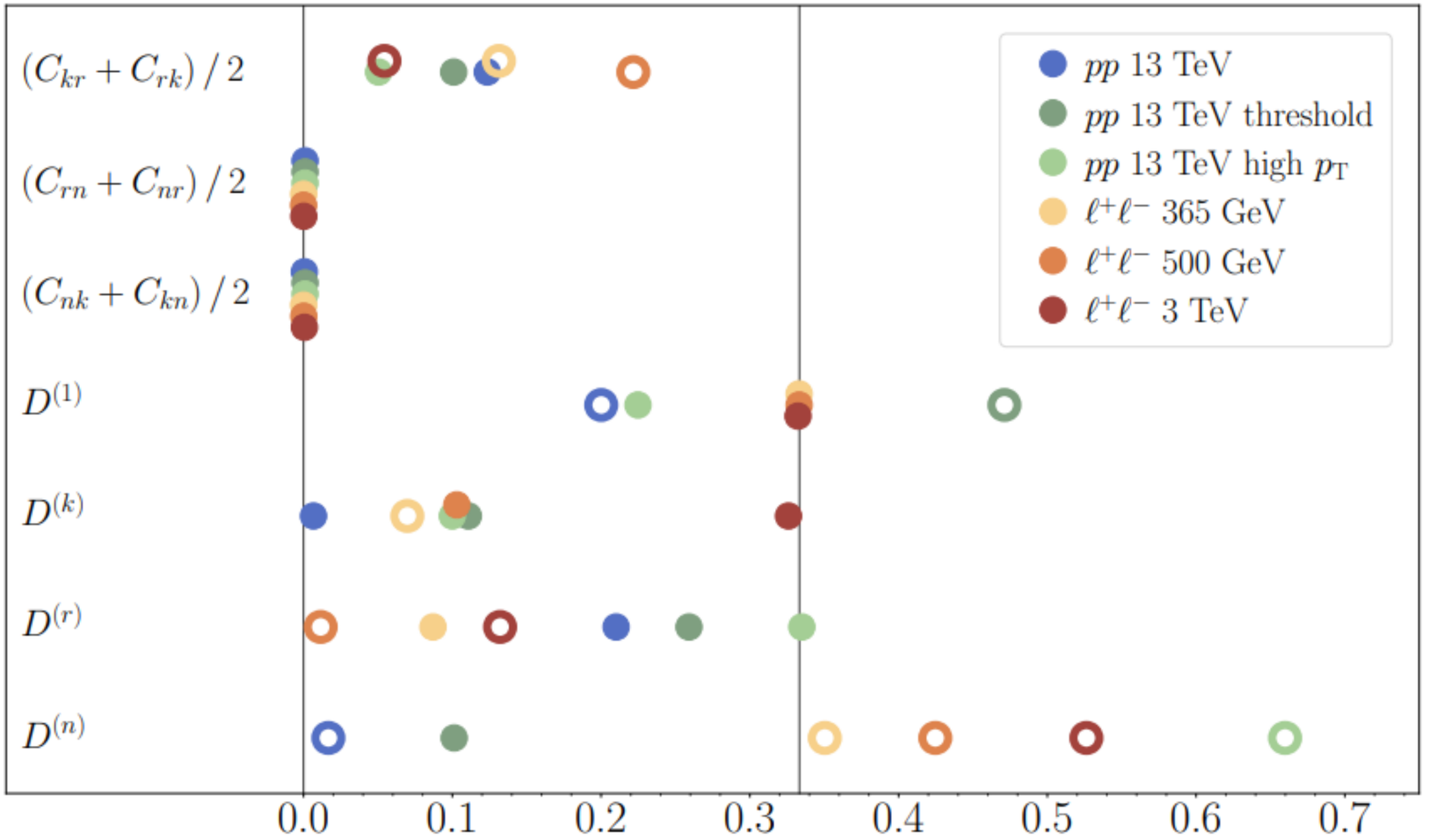
GHENT UNIVERSITY

TOP QUARK RECONSTRUCTION



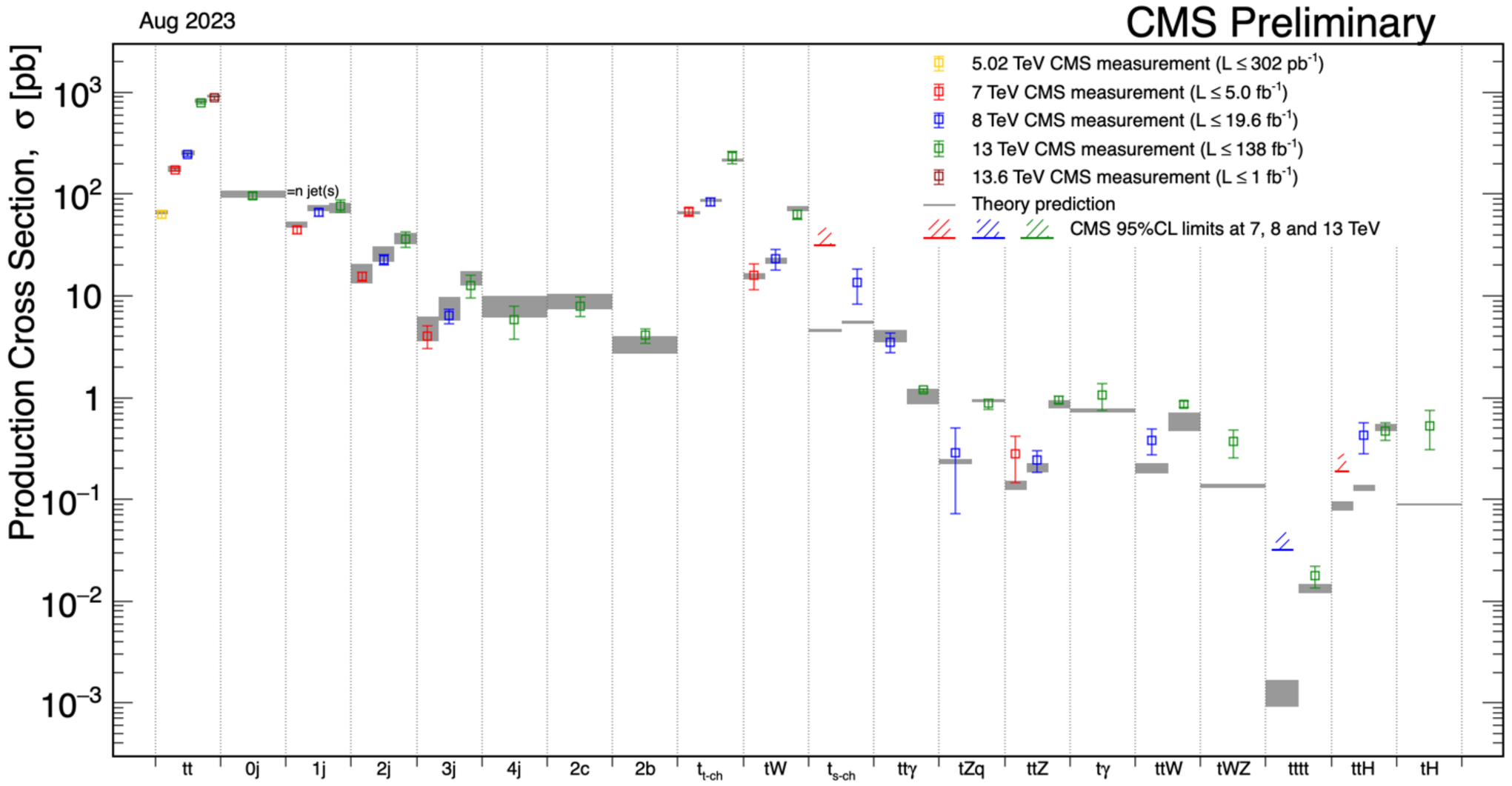
GHENT UNIVERSITY

Spin Correlation and Entanglement



arXiv:2404.08049v2 [hep-ph] 30 Aug 2024

EXTENSIVE TOP QUARK RESEARCH AT LHC



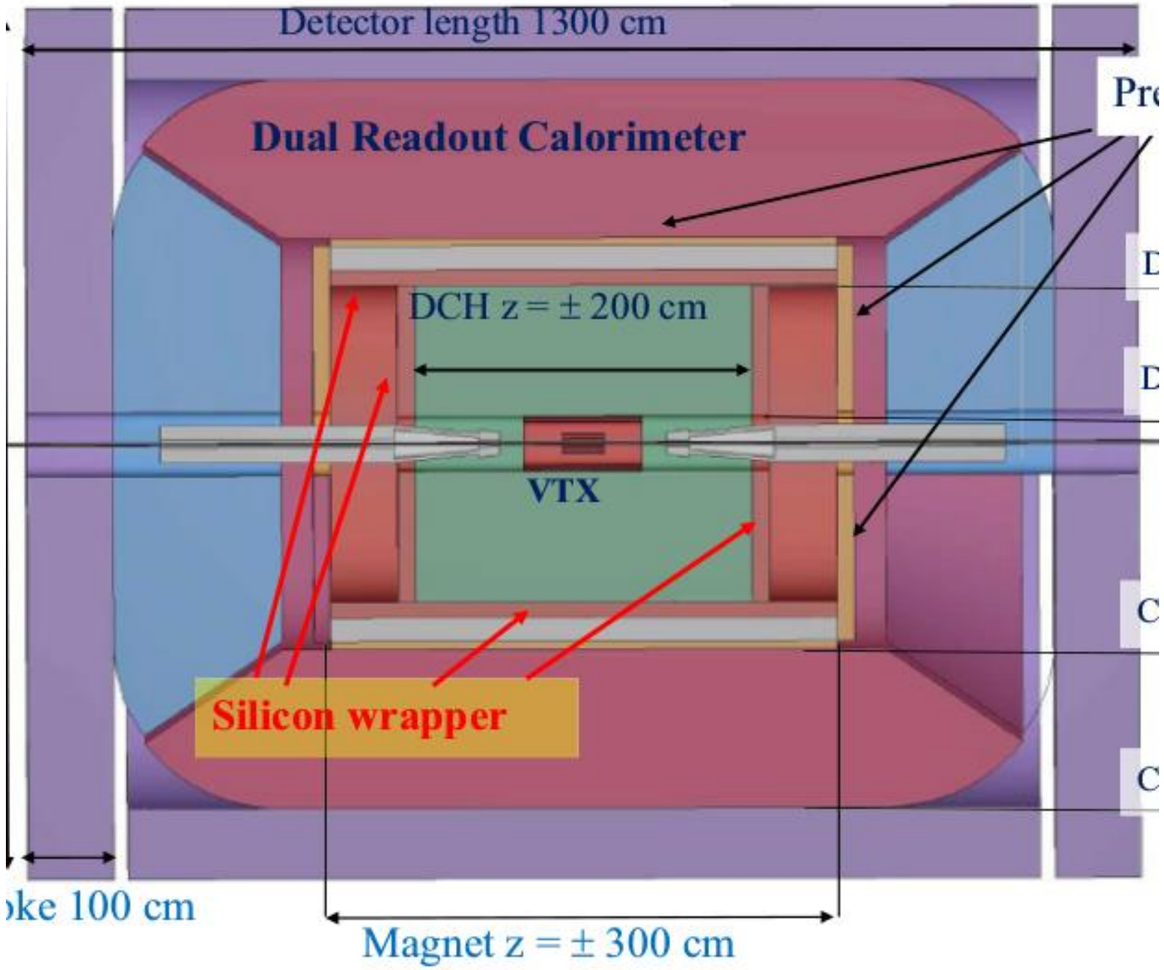
All results at: http://cern.ch/go/pNj7

GHENT UNIVERSITY

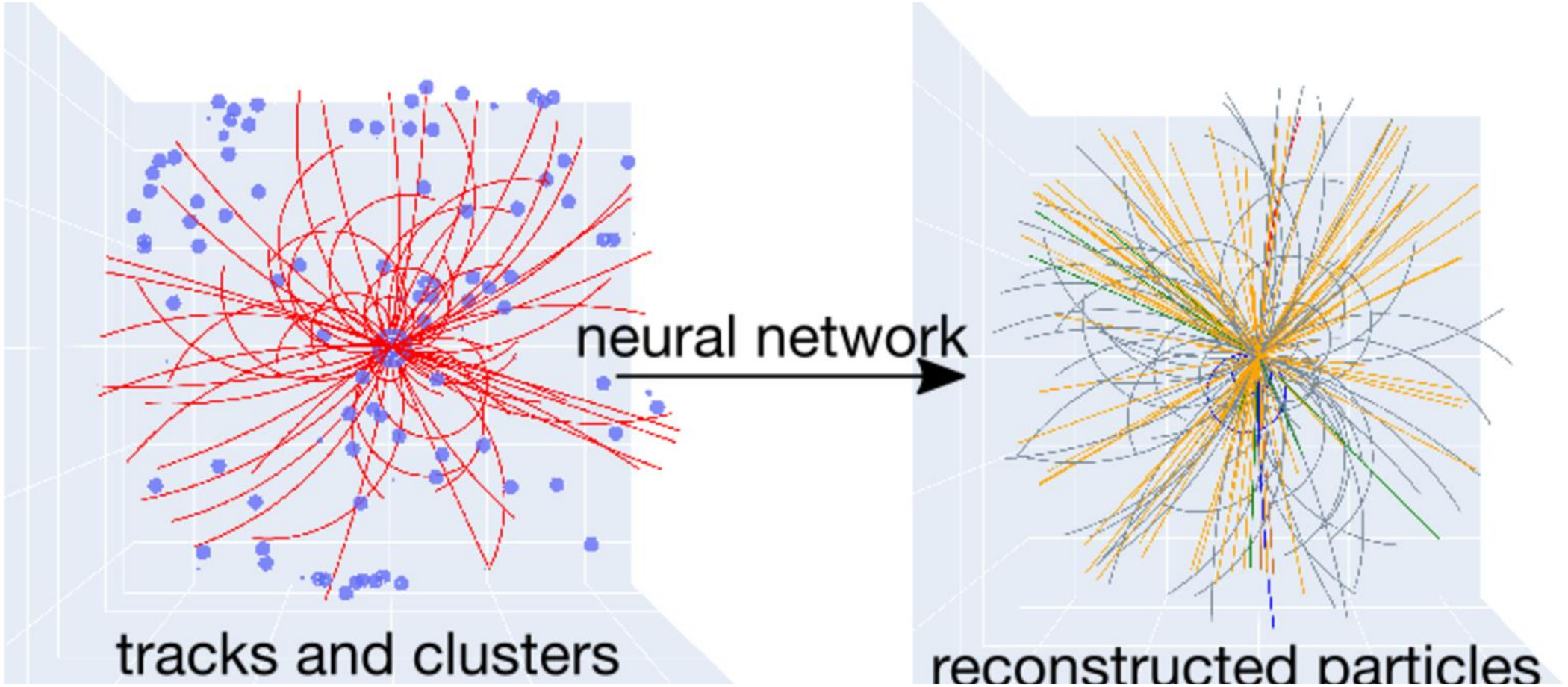
DETECTORS

- IDEA (International Detector for Electron-positron Accelerators)

- CLD (CLIC-like Detector)



GHENT UNIVERSITY



GHENT
UNIVERSITY