QGP tomography through boosted objects

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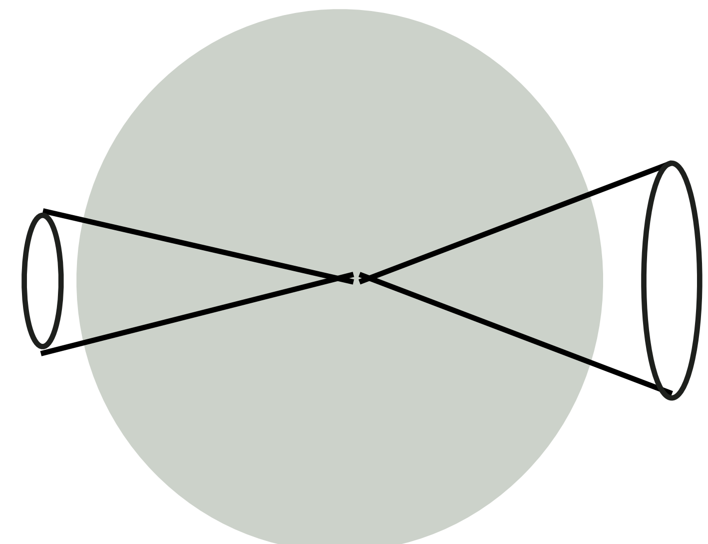
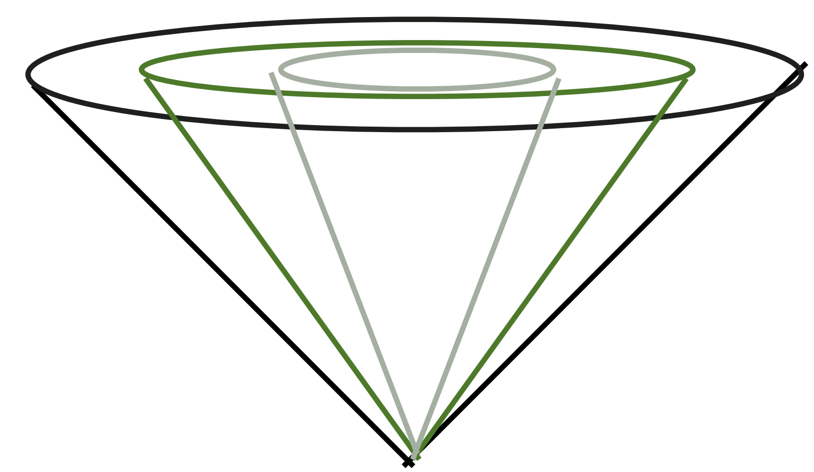
Work partially included in FCC-hh report
arXiv:1605.01389

HIC Probes: Road so far…

- What we measured so far? What properties can we assess?
  - Jet R_{AA}, Jet energy loss (dijets, Z/Jet, photon/Jet), Missing p_T, …
    - Average behaviours of in-medium showering, possible path-length dependence, amount of back-reaction (?)…
  - Intra-Jet observables (Jet Shapes, Splitting Functions)
    - Intrinsic properties of QCD in the presence of hot and dense medium





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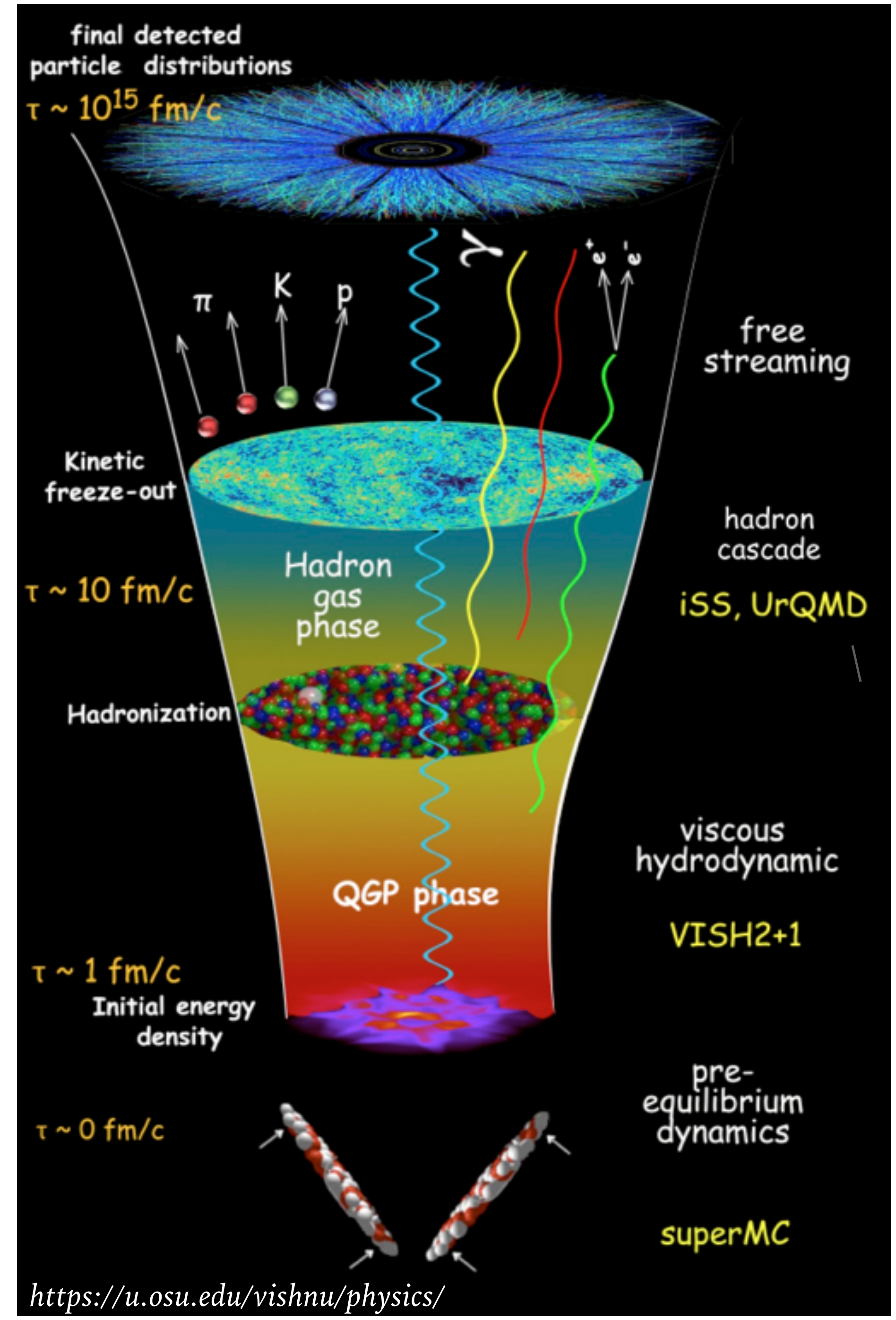
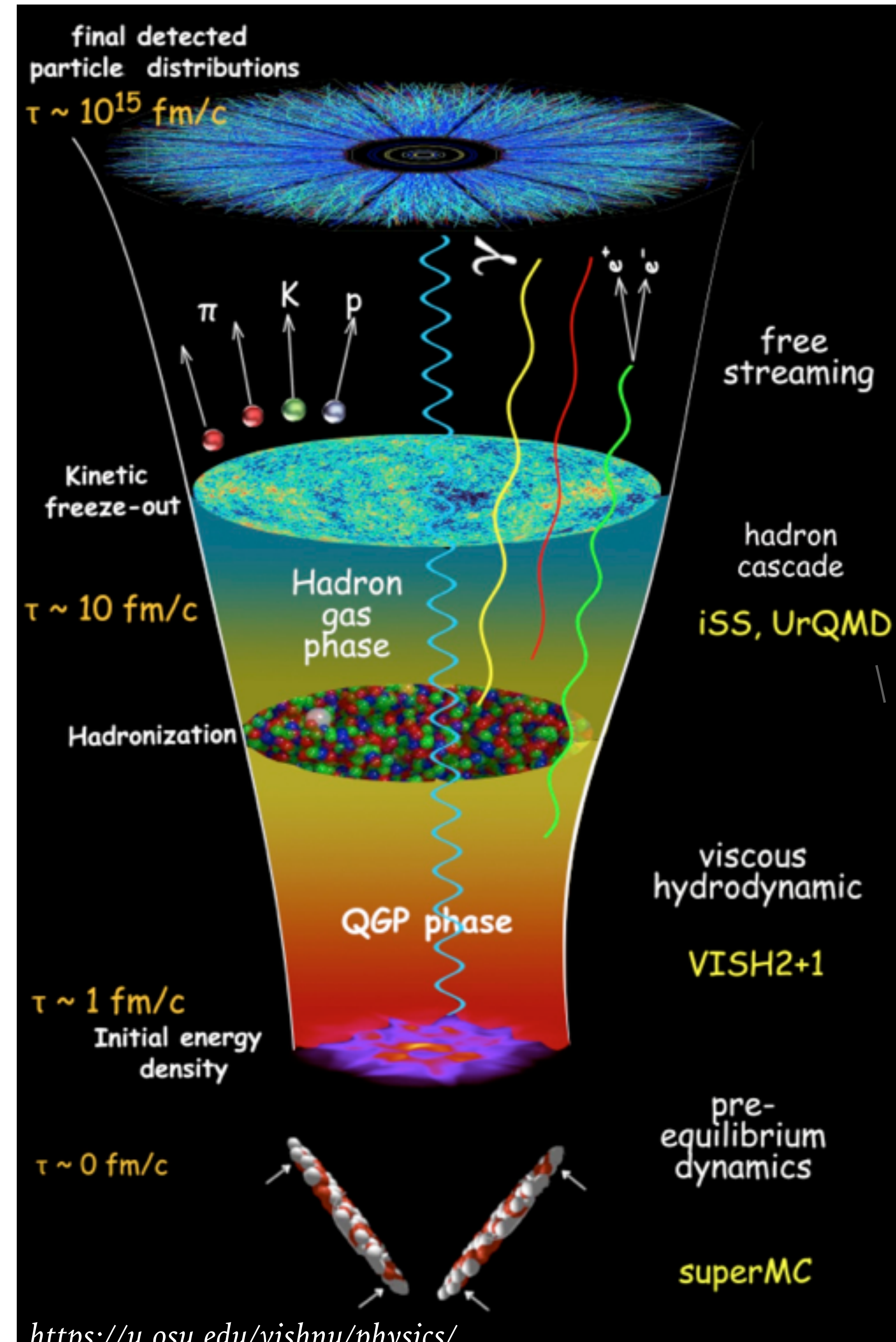


All of them are the integrated result over the whole medium evolution…

QGP Time Evolution

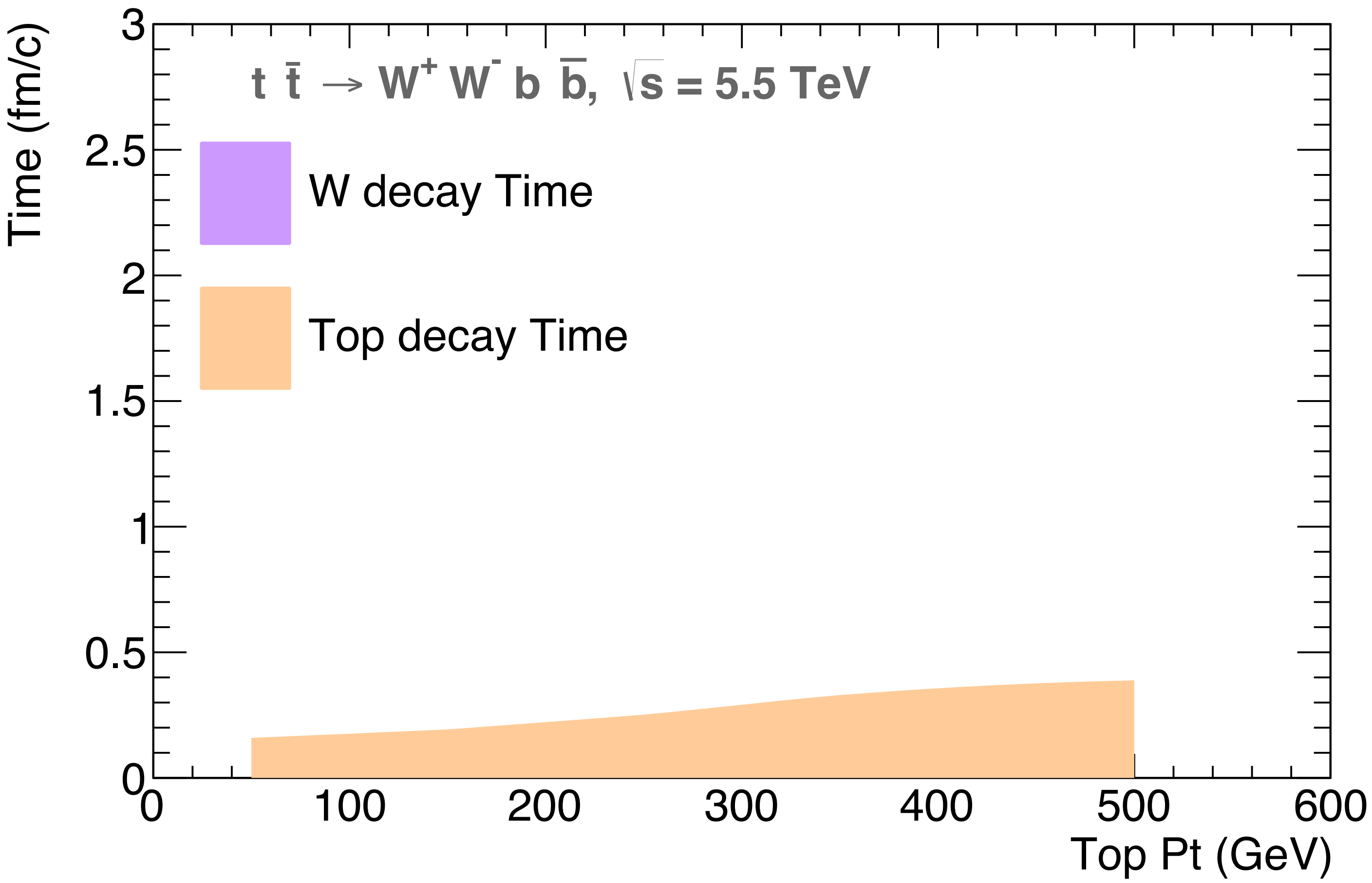
- Is it possible to assess different time intervals of the medium evolution?
  - Using sources of QCD particles that are delayed in time:
    - $t + tbar \rightarrow b + bbar + W^+ + W^- \rightarrow q + qbar + nu + mu$
      - Hadronic W boson: probe of the medium
      - Leptonic W boson: tagging
    - Top lifetime at rest: ~0.15 fm/c
    - W boson lifetime at rest: ~0.10 fm/c



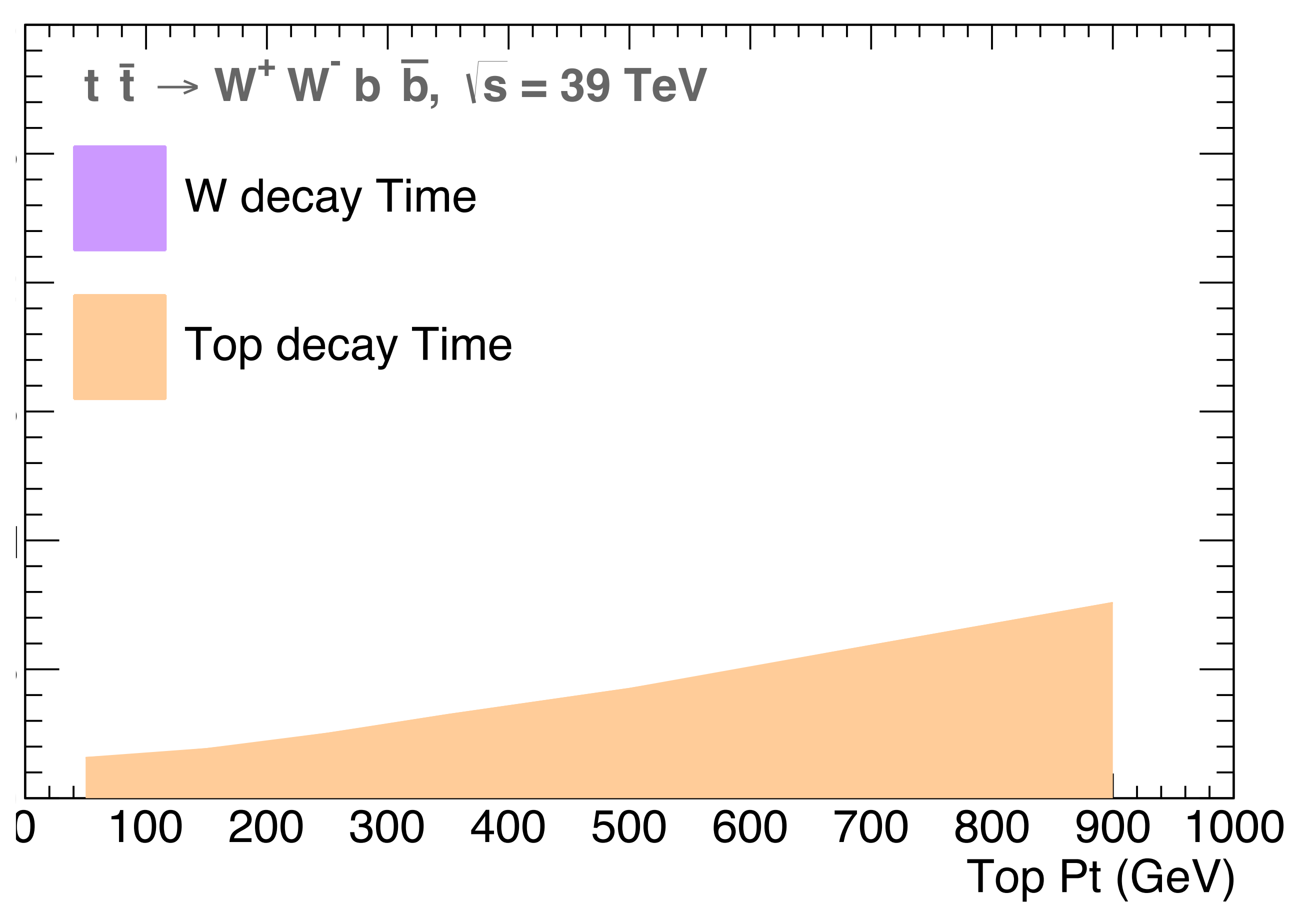
QGP Time Evolution

- LHC (5.5 TeV) and FCC (39 TeV) centre-of-mass energies large enough to probe different timescales as a function of the probe p_T:

LHC (5.5 TeV)



FCC (39 TeV)



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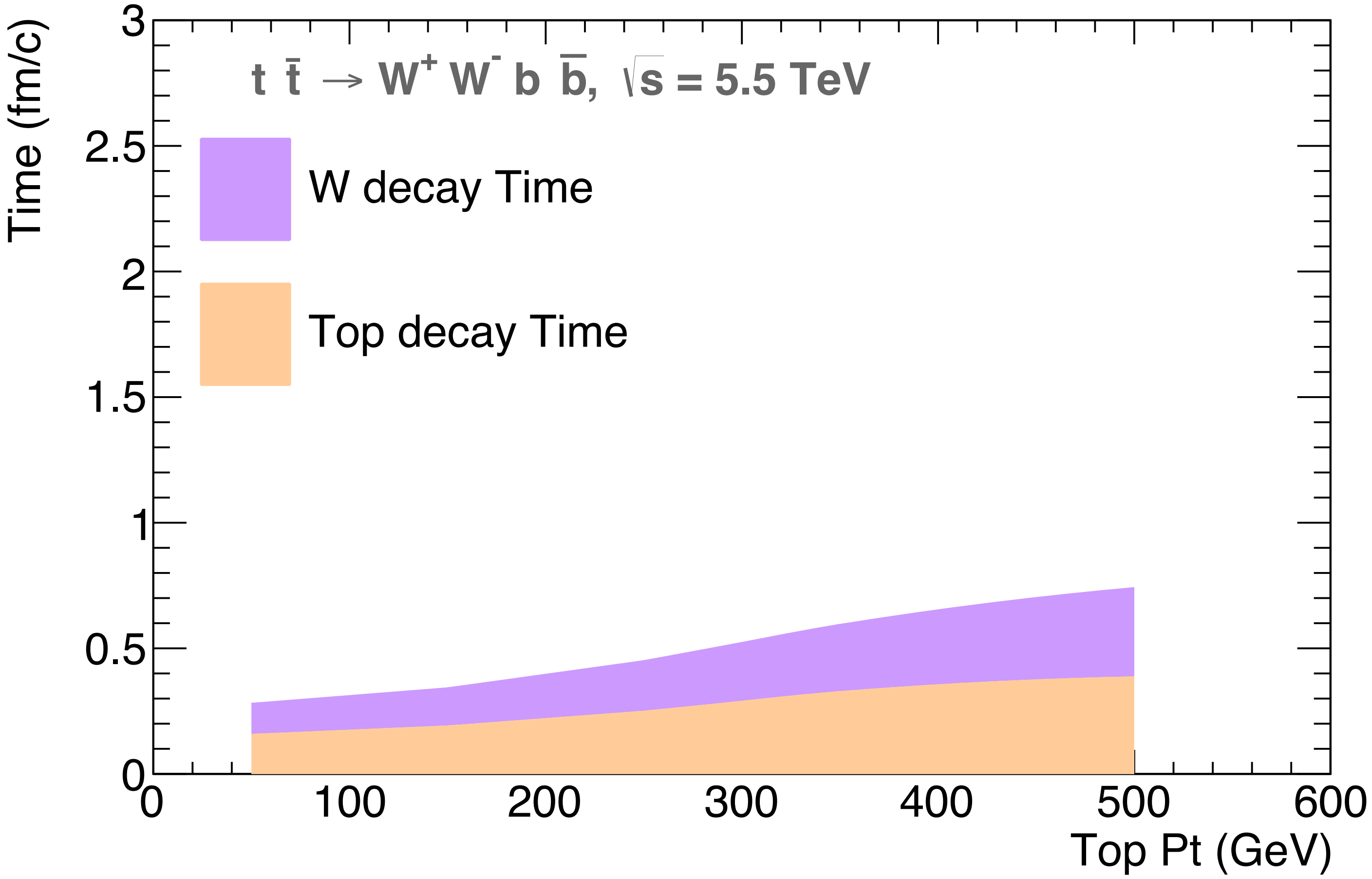
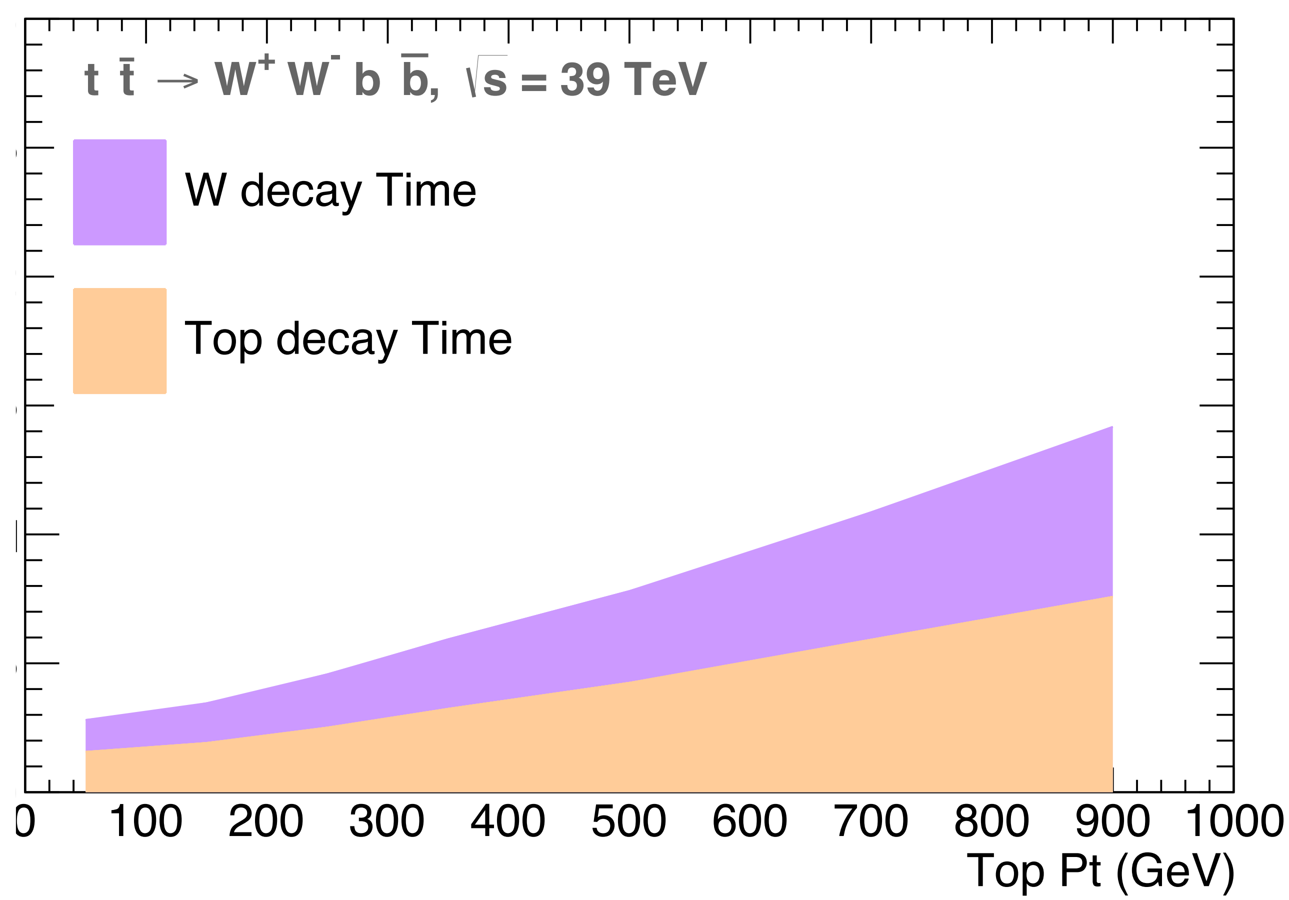
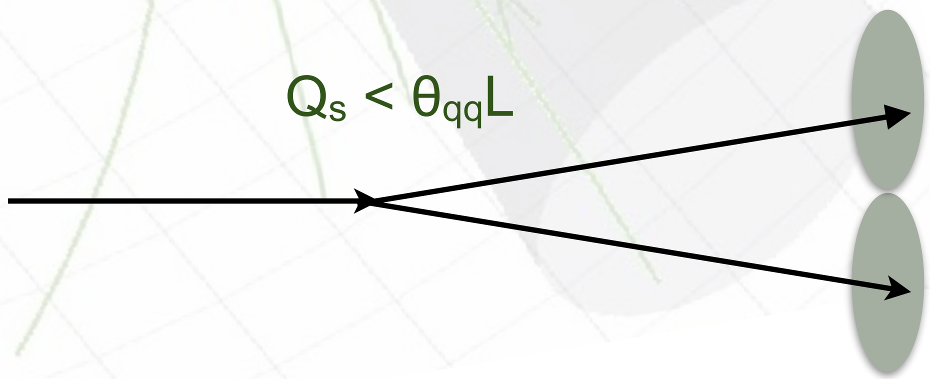
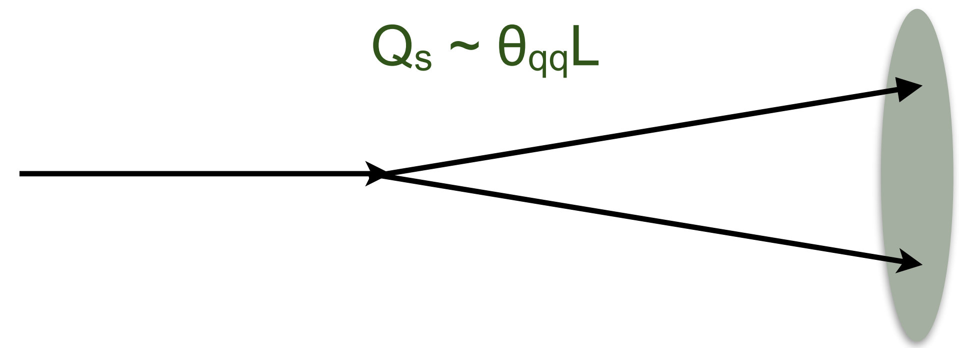
	

Jet Quenching

- Moreover, W boson hadronic decay is the natural setup to study coherence effects:



Medium able to "see" both particles
Color correlation is broken
Both particle emit independently



Medium "sees" both particles as one single emitter
Particles emit coherently

Saturation scale: $Q_s^2 = \hat{q}\,L$

Transport coefficient: $\hat{q}$

Medium length: L

Mehtar-Tani, Salgado, Tywoniuk (2010-2011)
Casalderrey-Solana, Iancu (2011)

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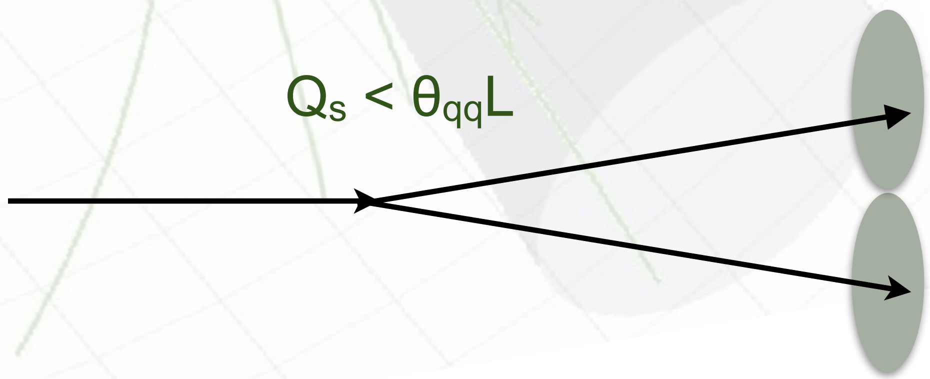

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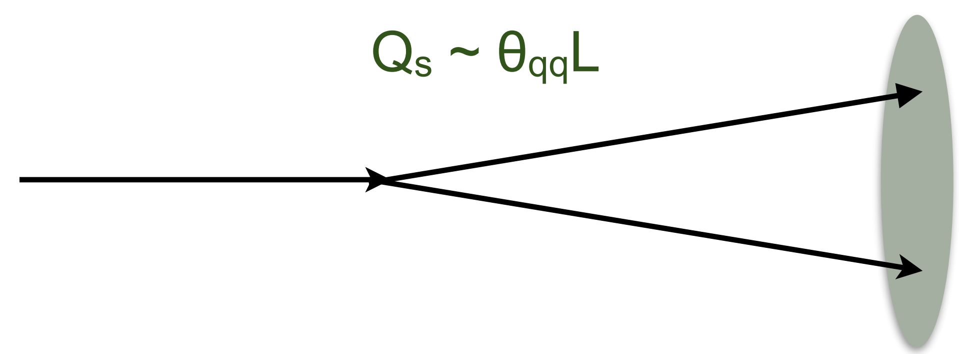

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Transport coefficient: $\hat{q}$
Medium length: L

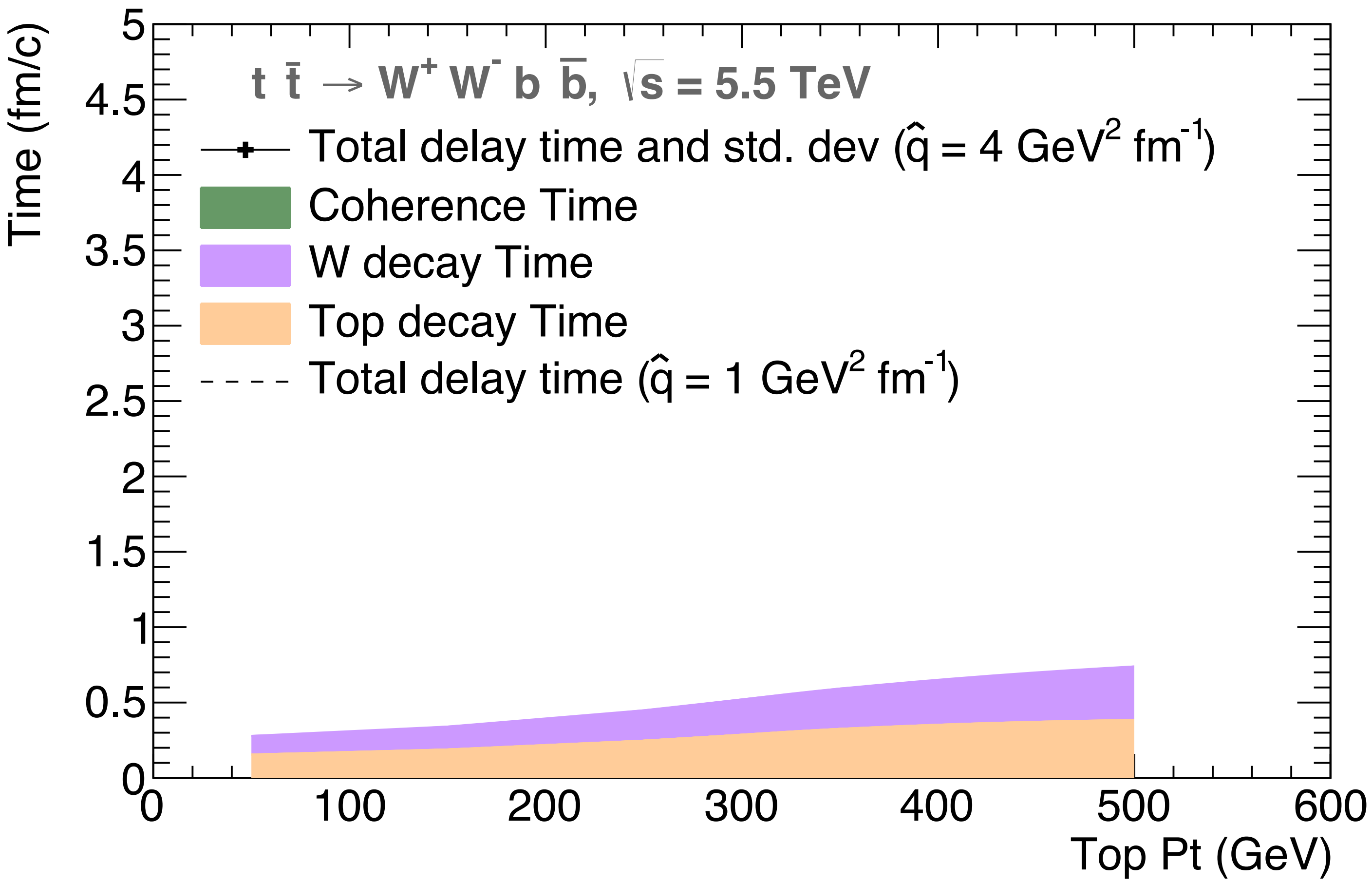
- Increase even more the time delay allowing to have a complete mapping of the QGP evolution:
  - Stay in colourless singlet state during: $t_d = \left(\frac{12}{\hat{q}\theta^2_{q\bar{q}}} \right)^{1/3}$

Mehtar-Tani, Salgado, Tywoniuk (2010-2011)
Casalderrey-Solana, Iancu (2011)

Available Time Scales

- Total delay time:
  - Boosted top lifetime + Boosted W lifetime + Decoherence Time

LHC (5.5 TeV)



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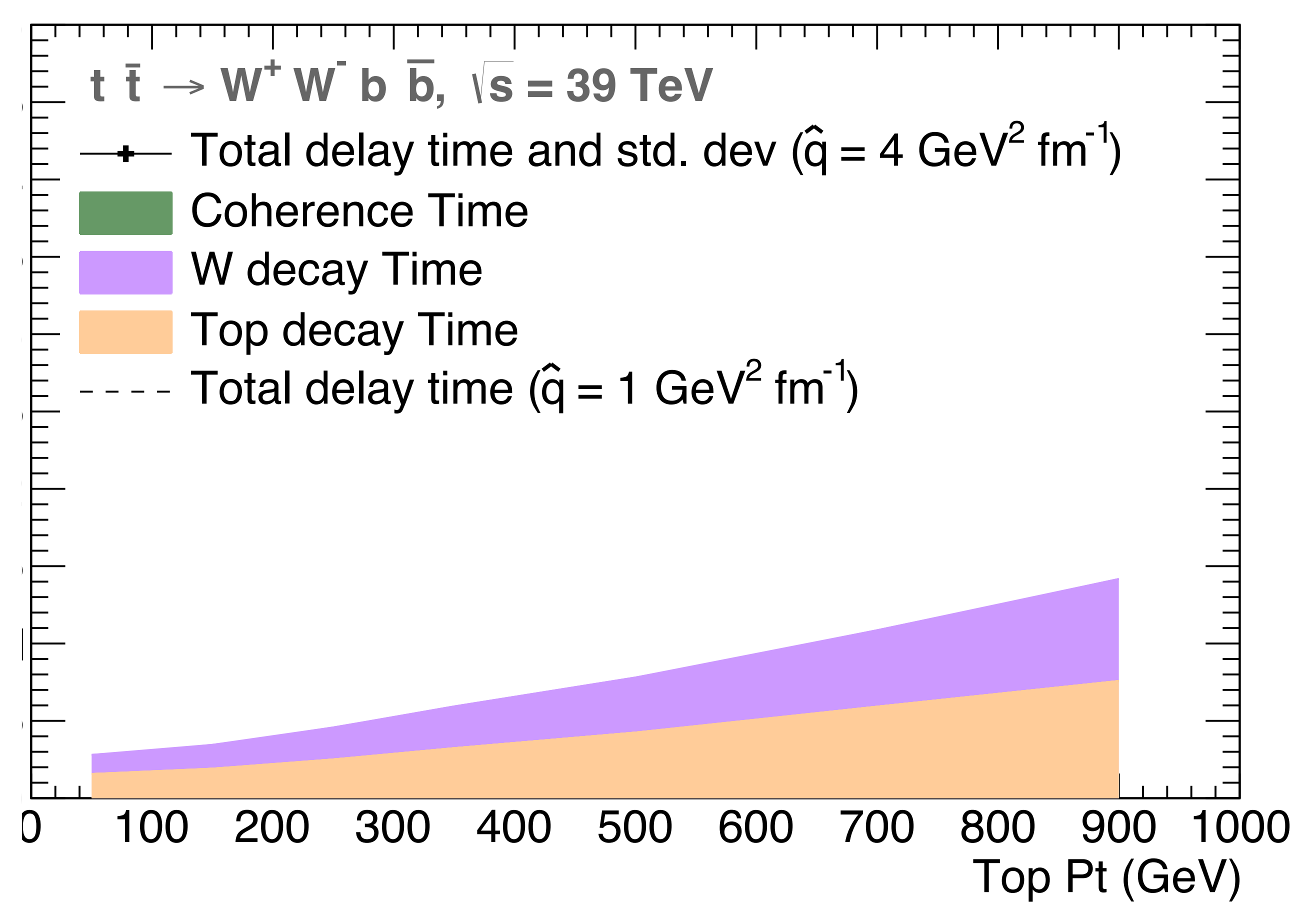

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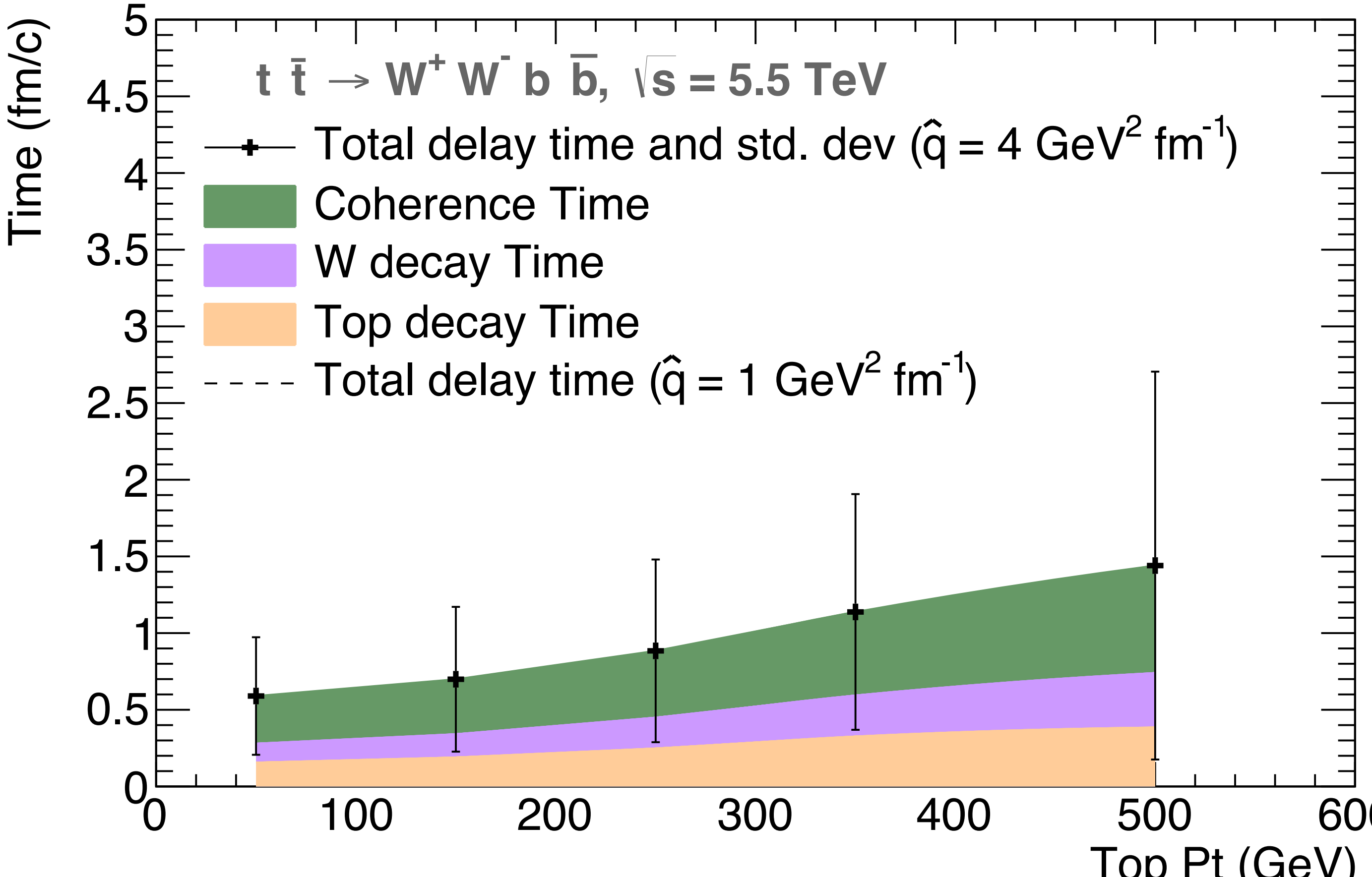
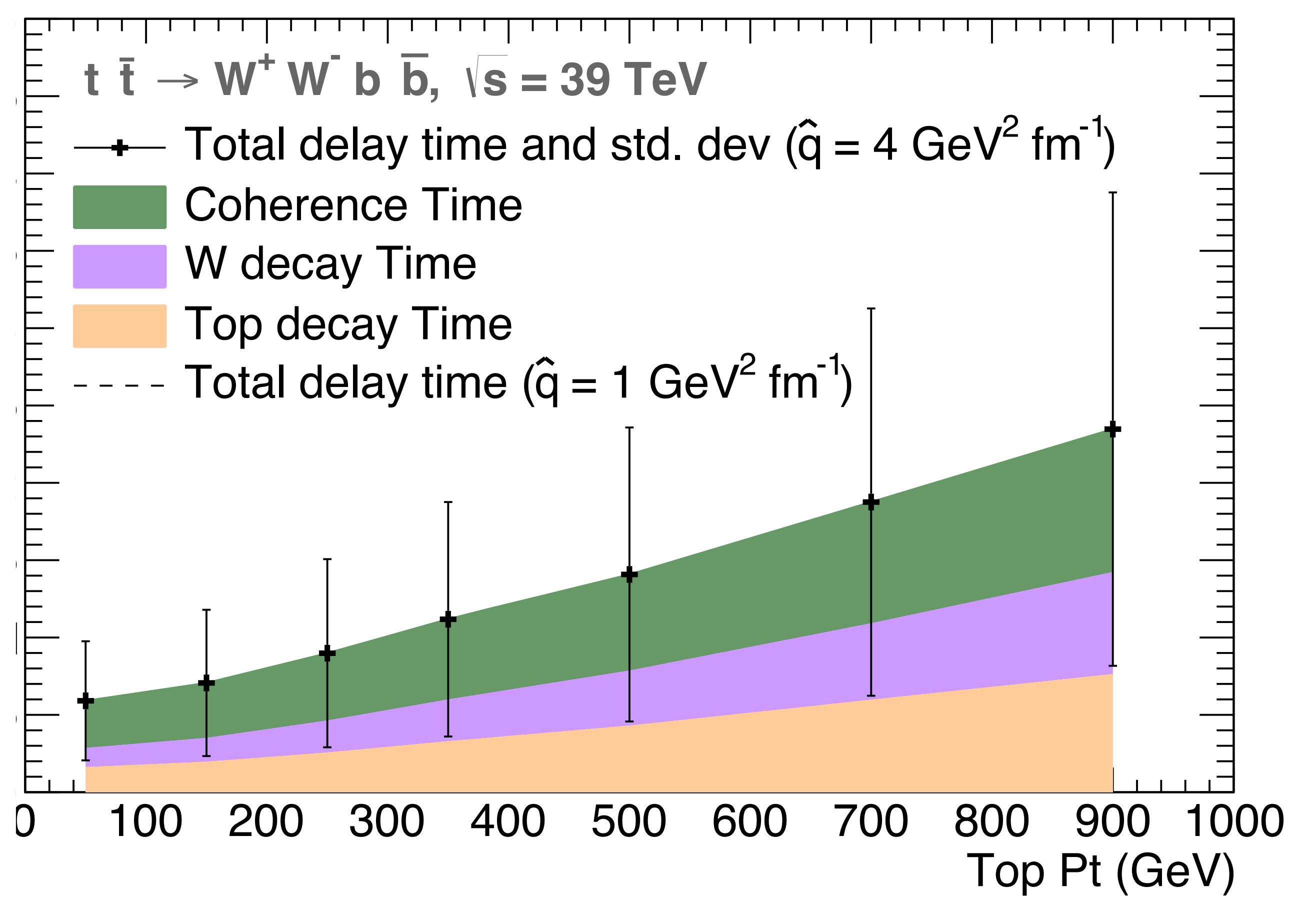


Not enough statistics…

FCC (39 TeV)



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Probe [0.5; 2.5] fm

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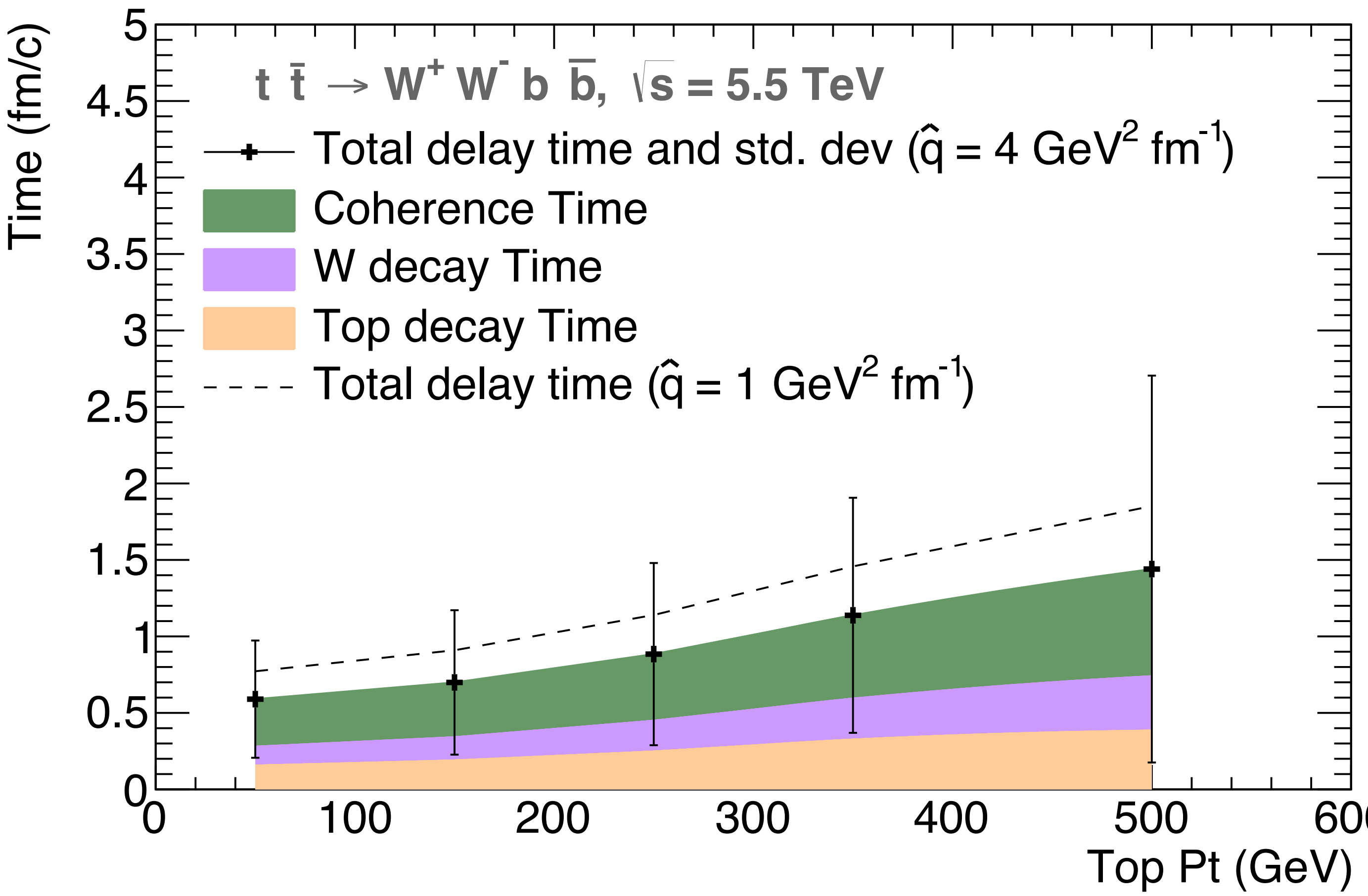
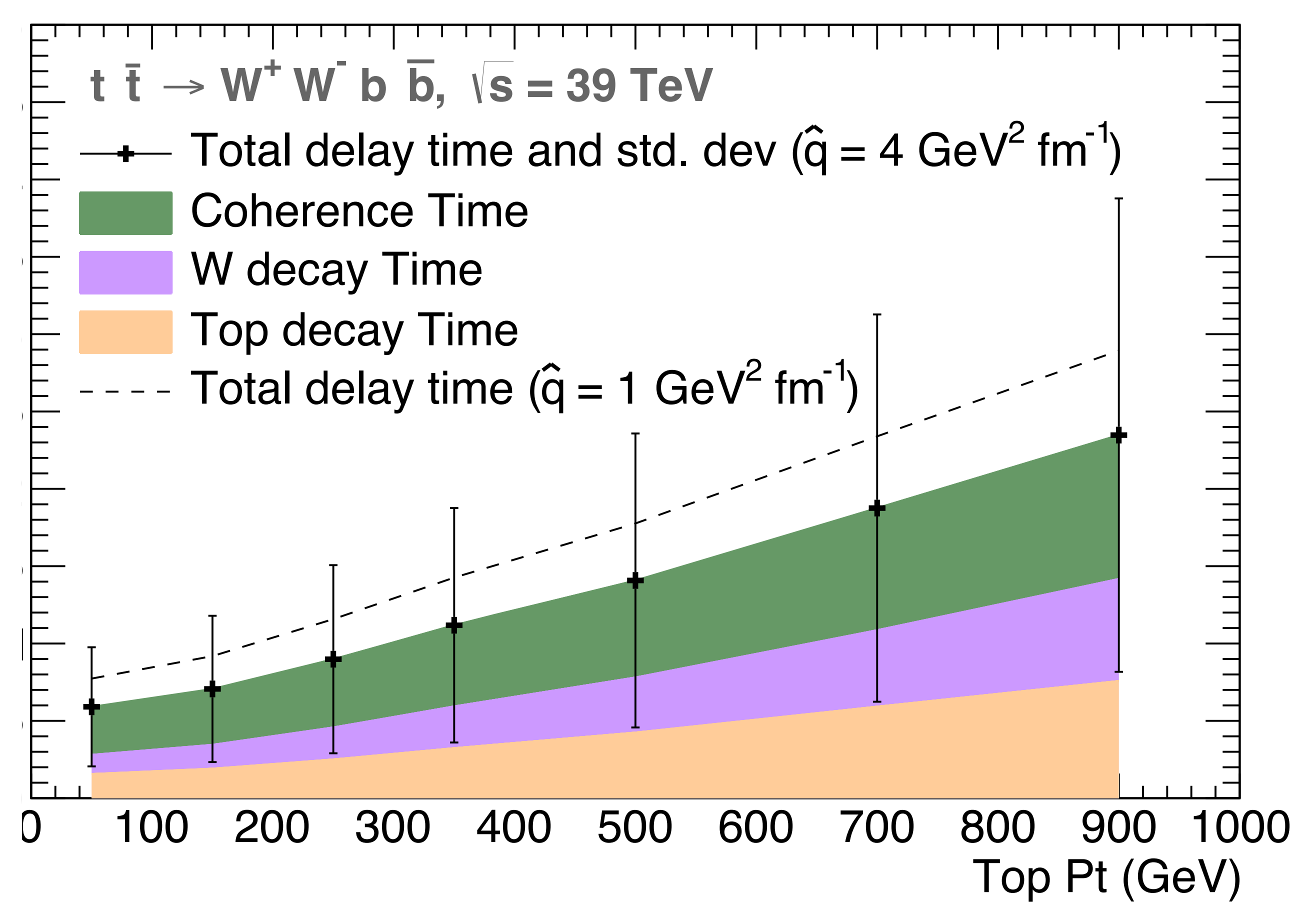
LHC (5.5 TeV)	FCC (39 TeV)





Coherence time ~ $q^{-1/3}$

⇒ Density medium increases by a factor 2, the total decay time decreases by 20%

Simple analysis to make a proof of principle

Simulation Parameters

- POWHEG (hard event) + PYTHIA 8 (parton shower)

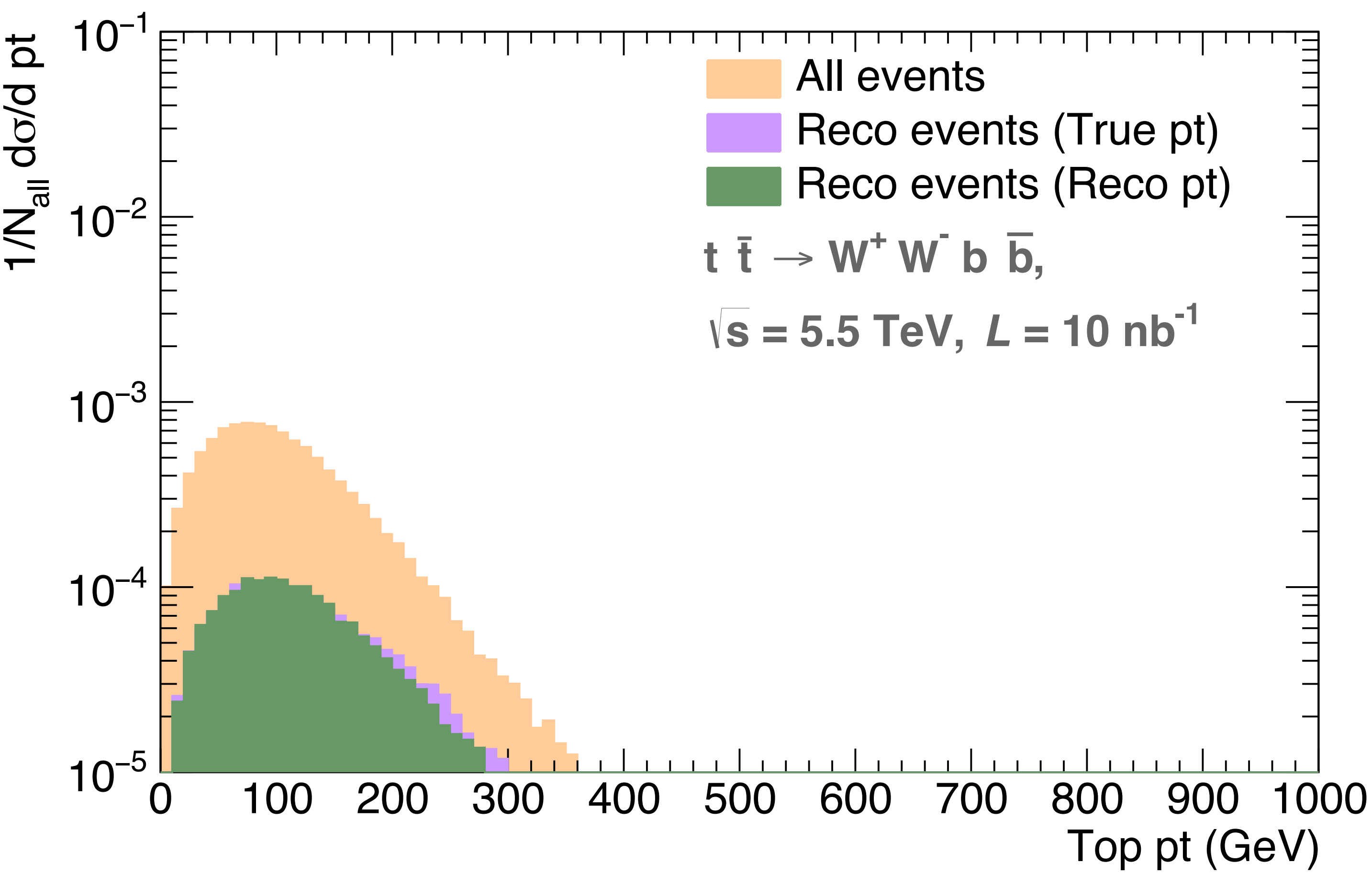
LHC - HL	FCC
5.5 TeV/nucleon	39 TeV/nucleon
L_{int} = 10 nb^{-1}	L_{int} = 30 nb^{-1}
A = 208 (Pb)	A = 208 (Pb)
0-10% centrality class (~42% of ttbar events)	0-10% centrality class (~42% of ttbar events)

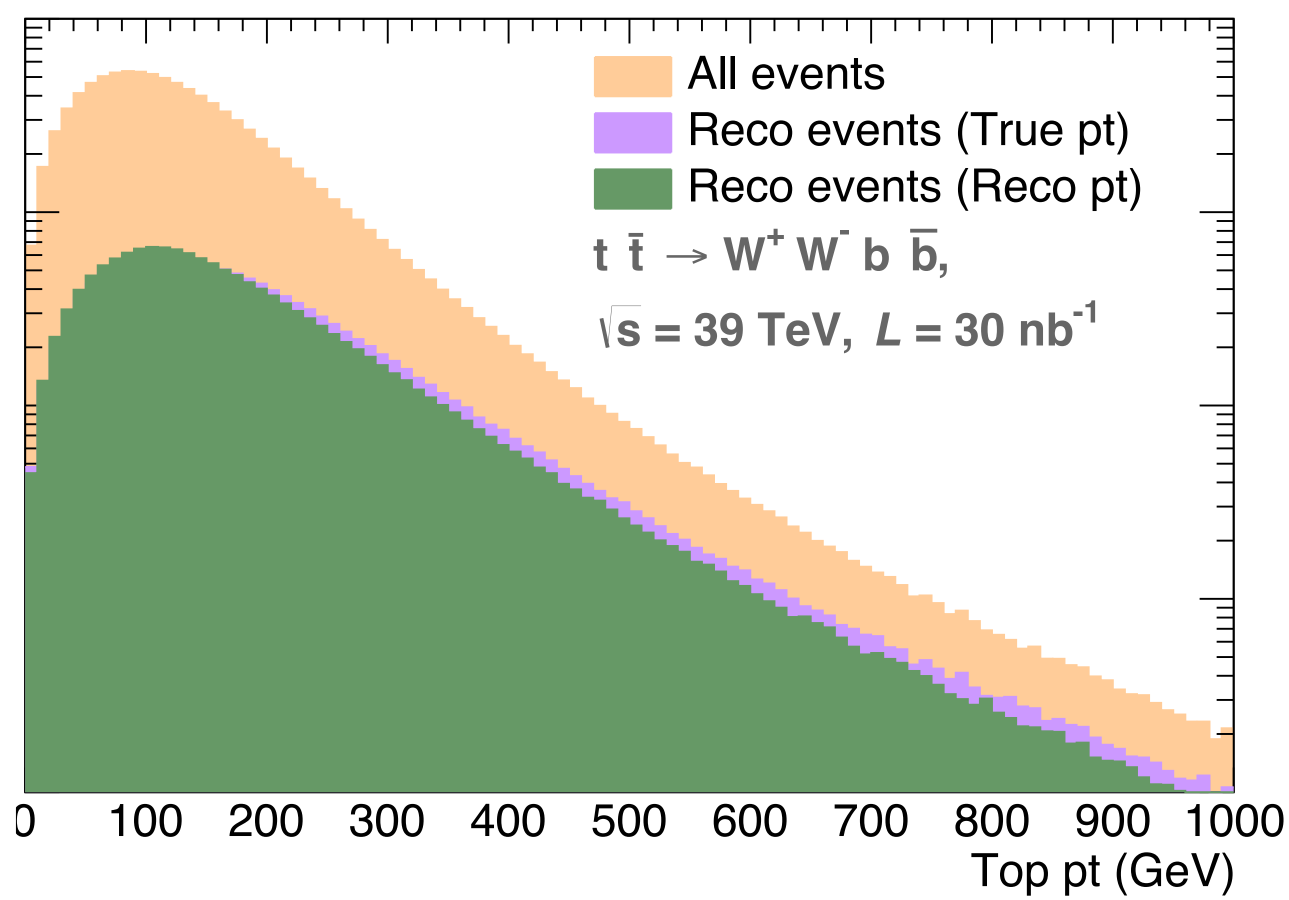
No HI background.
No detector effects.

Cross-section

- Total cross-sections compatible with NLO CT14 calculations:
  - $\sigma_{ttbar \to qqbar + \mu\nu}$ ~ 10 pb (LHC) and 1 nb (FCC)

LHC (5.5 TeV)	FCC (39 TeV)





No significant distortion of the top pt spectrum from the jet reconstruction procedure

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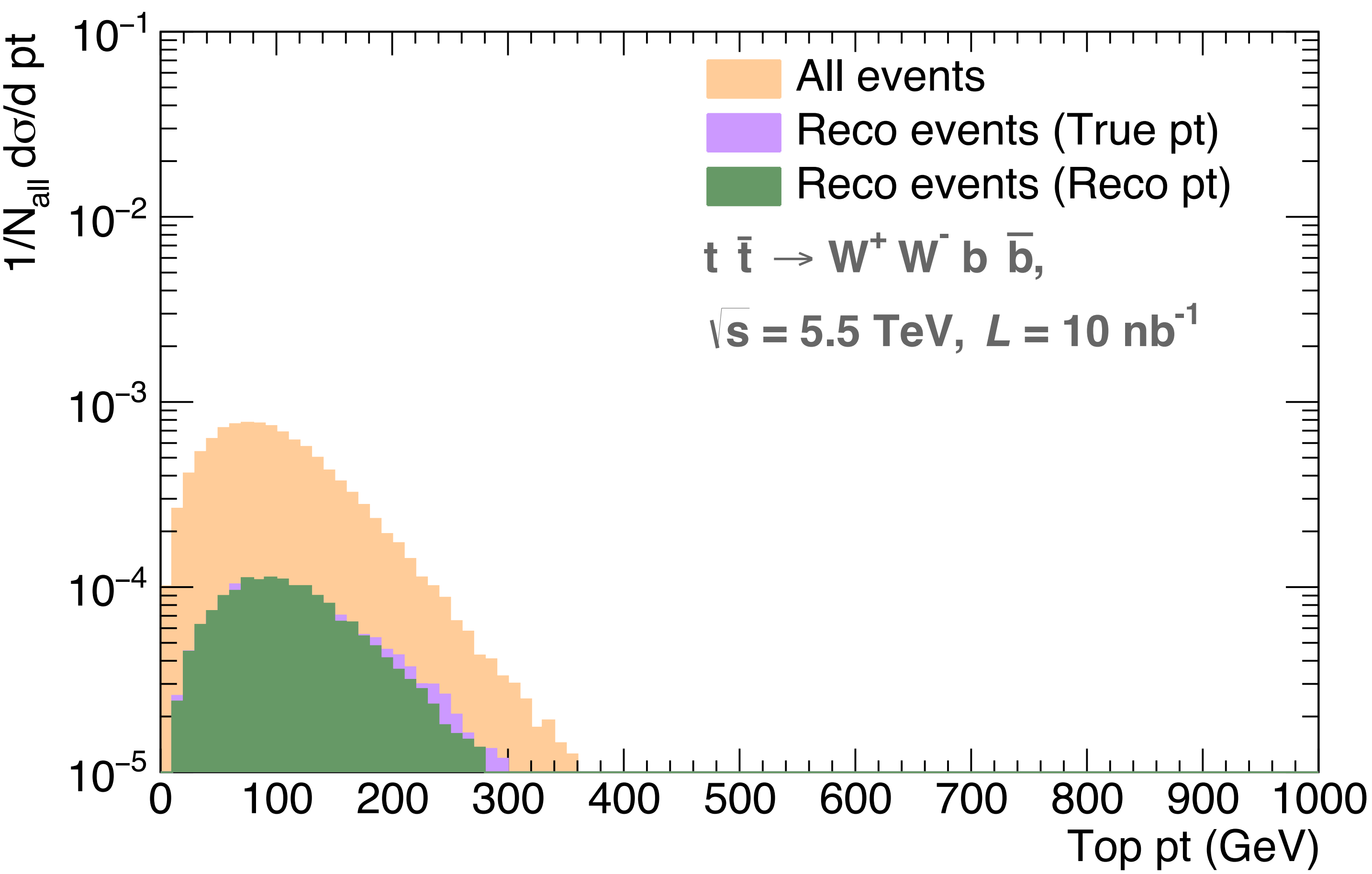

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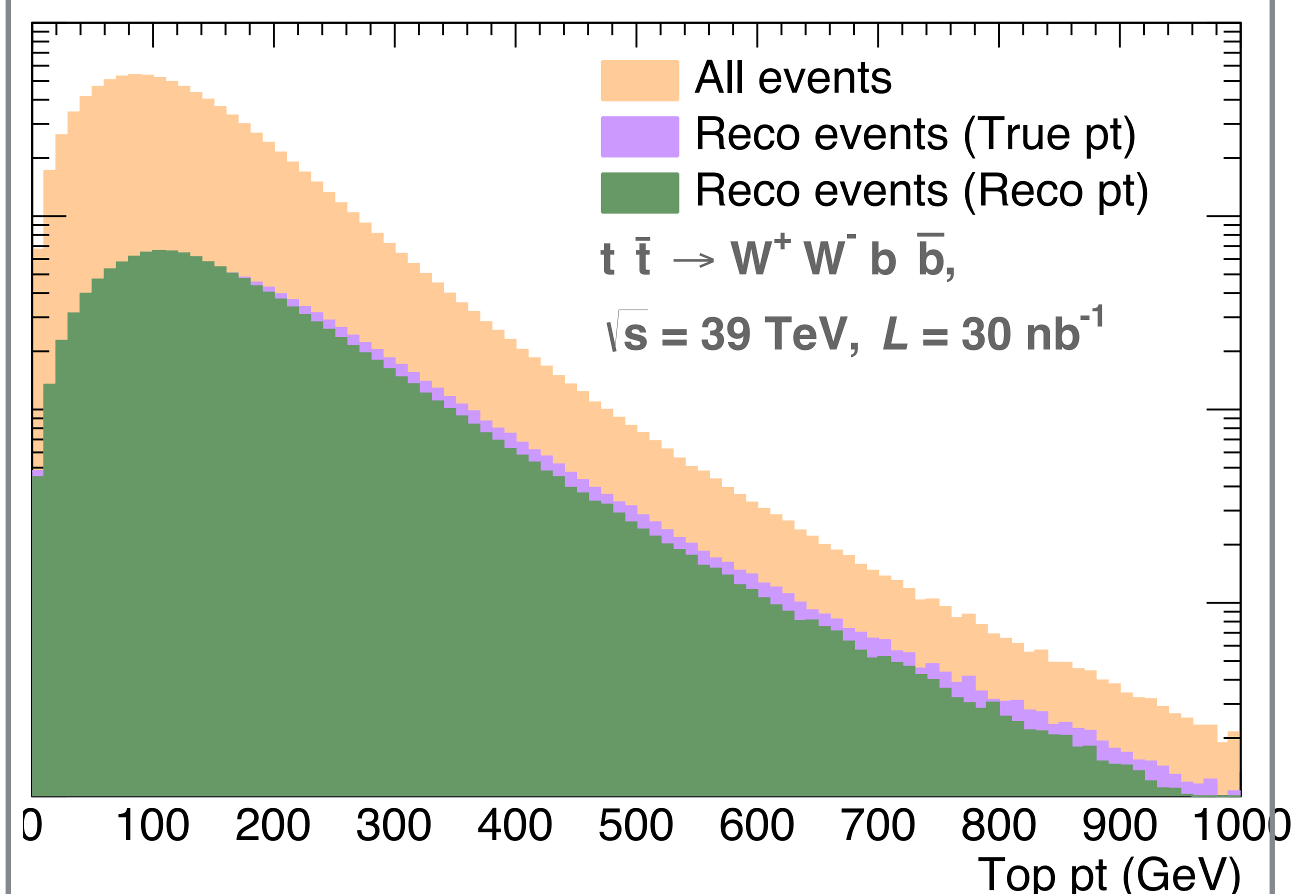

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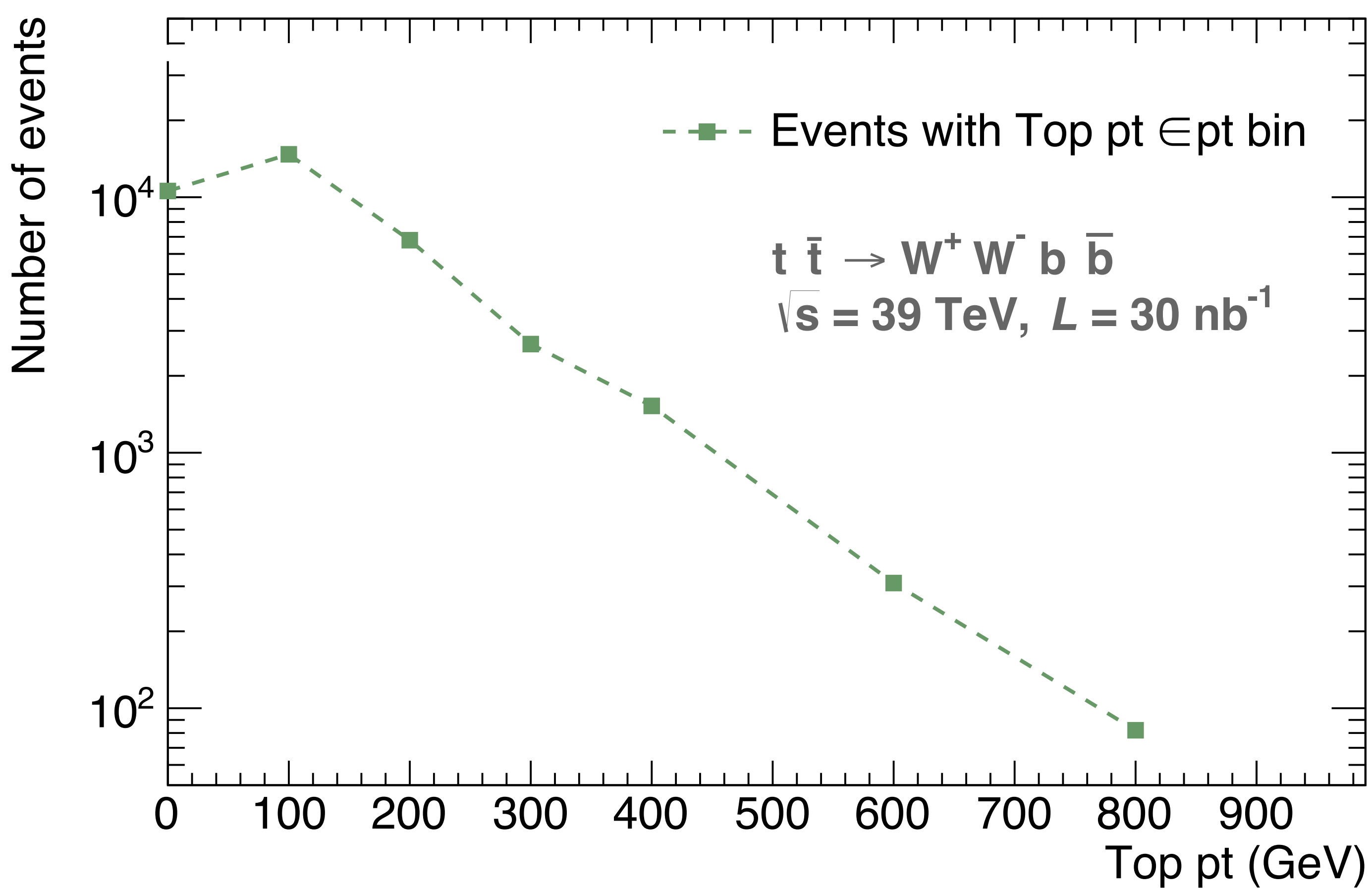
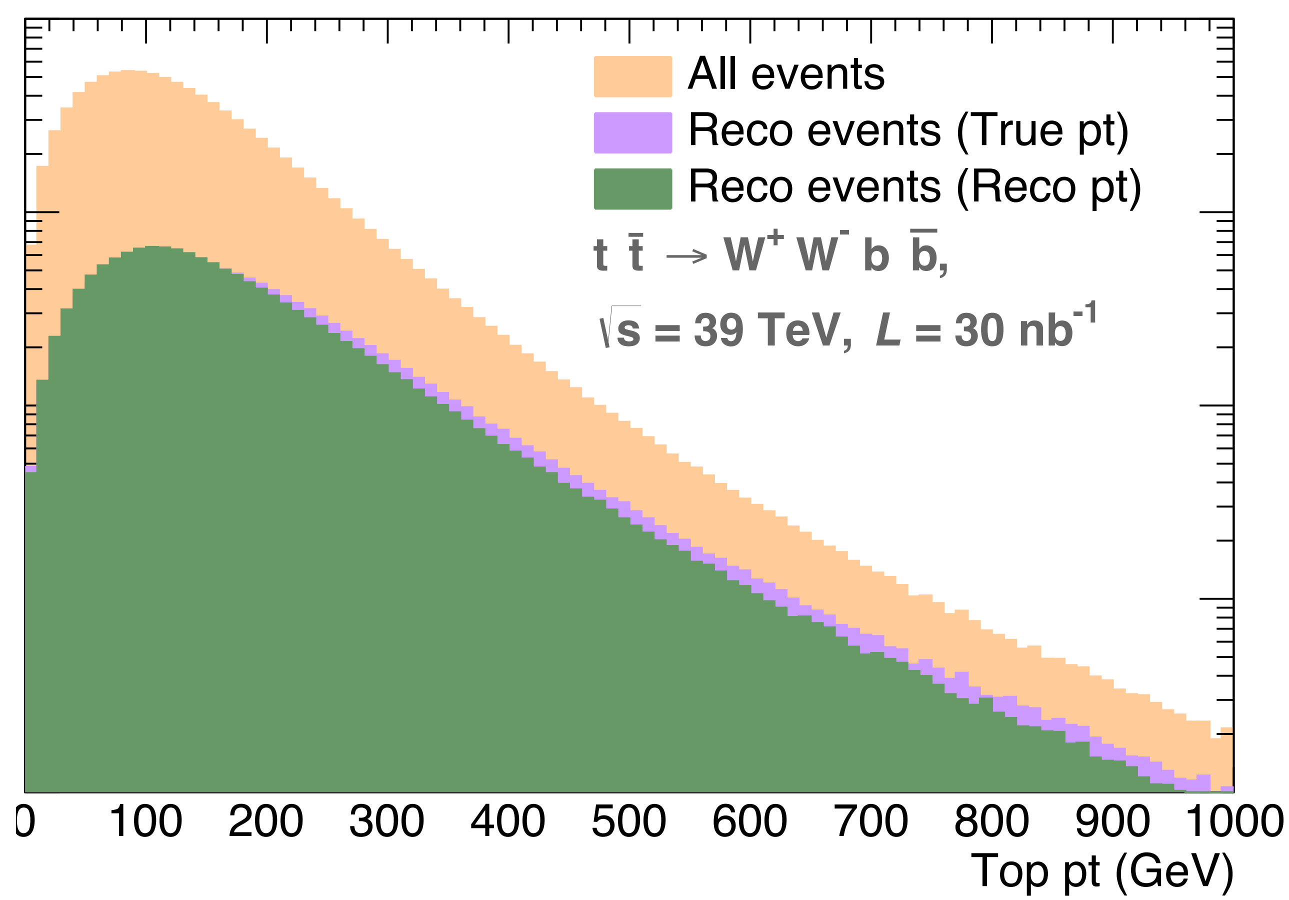
Number of expected reconstructed events	Cross-section

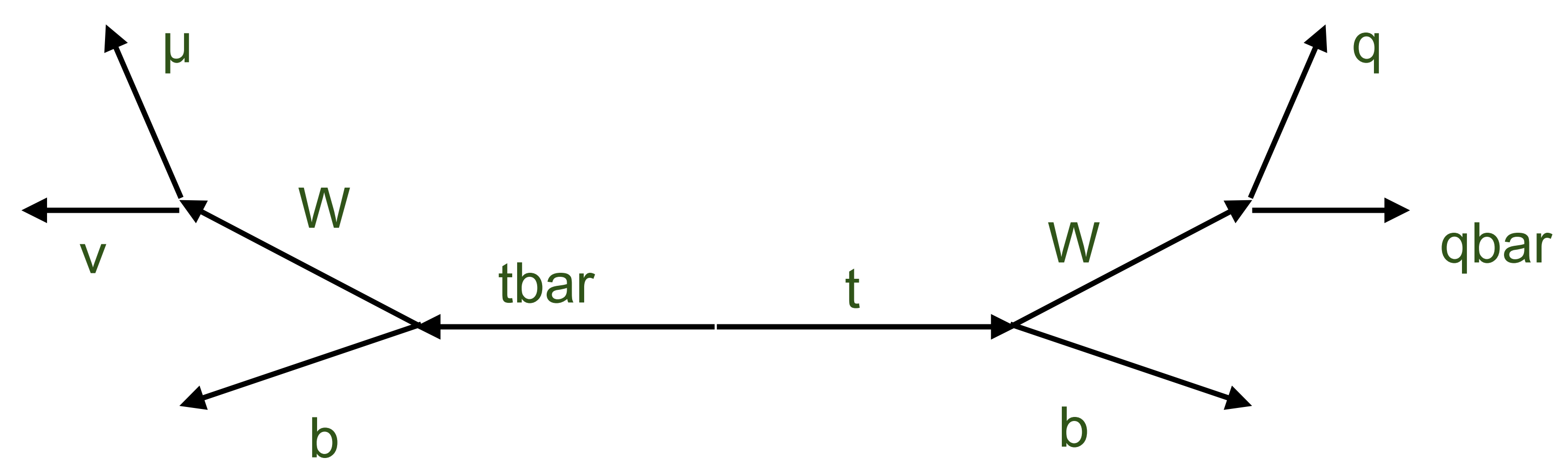




Enough statistics up to Top pt = [700-900] GeV

Jet Reconstruction

- Event with at least:
  - 1 (isolated) muon, p_T > 25 GeV, $|\eta|$ < 2.5.
  - 2 b jets (assumed 70% efficiency each)
  - >= 2 non-b jets



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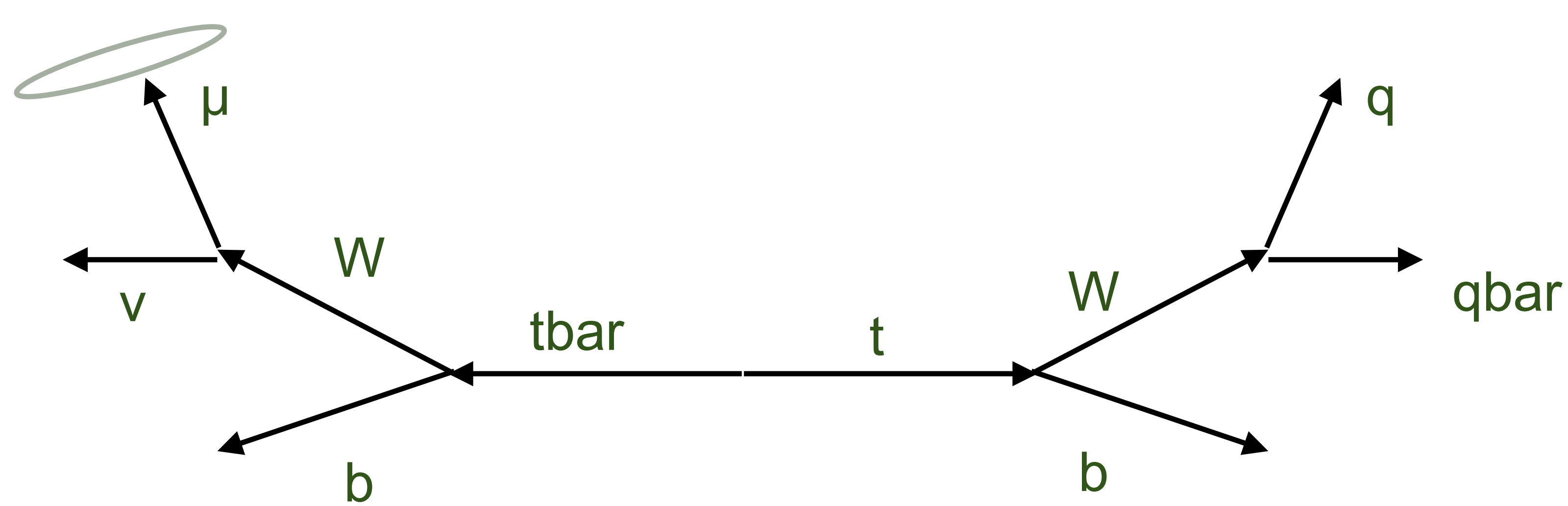

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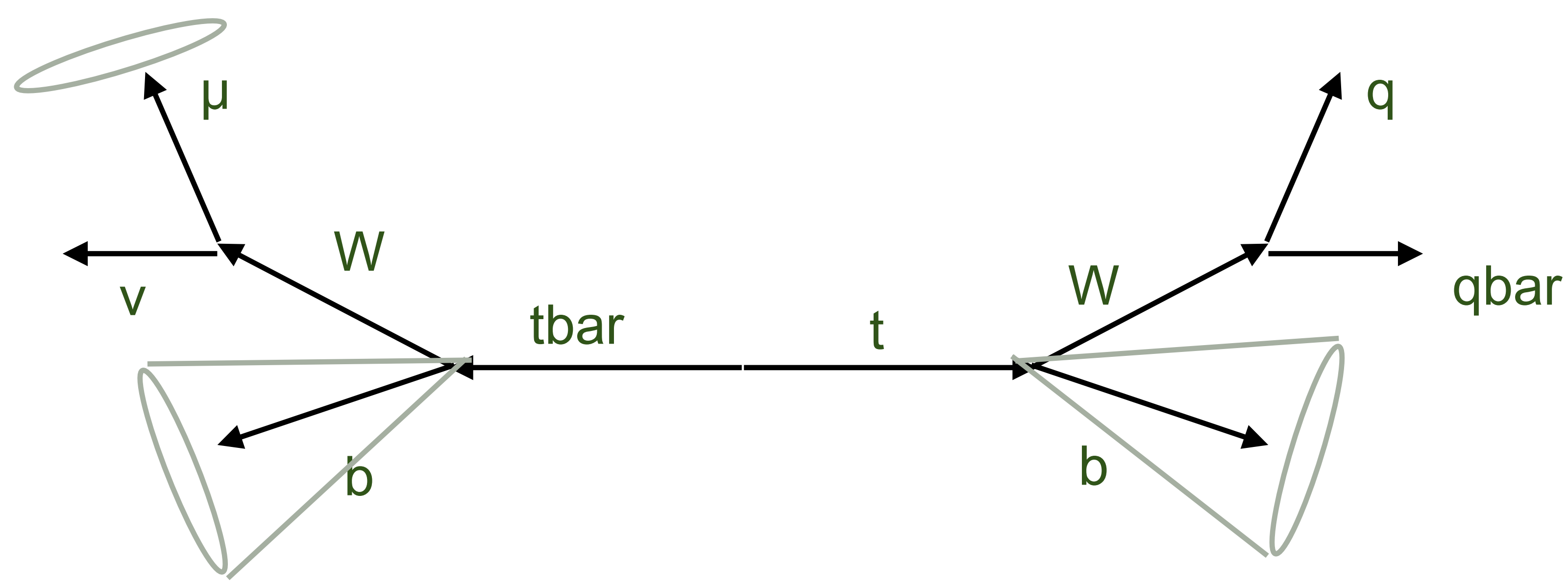

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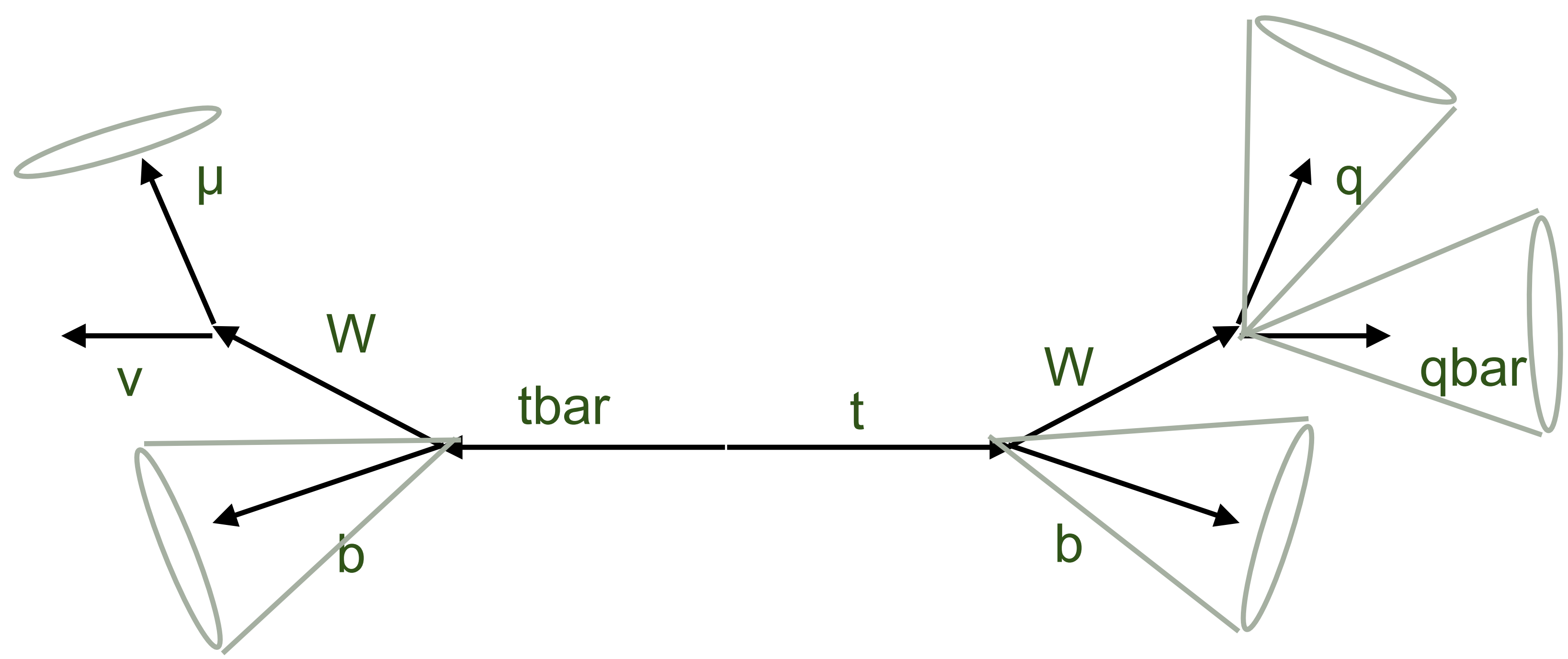

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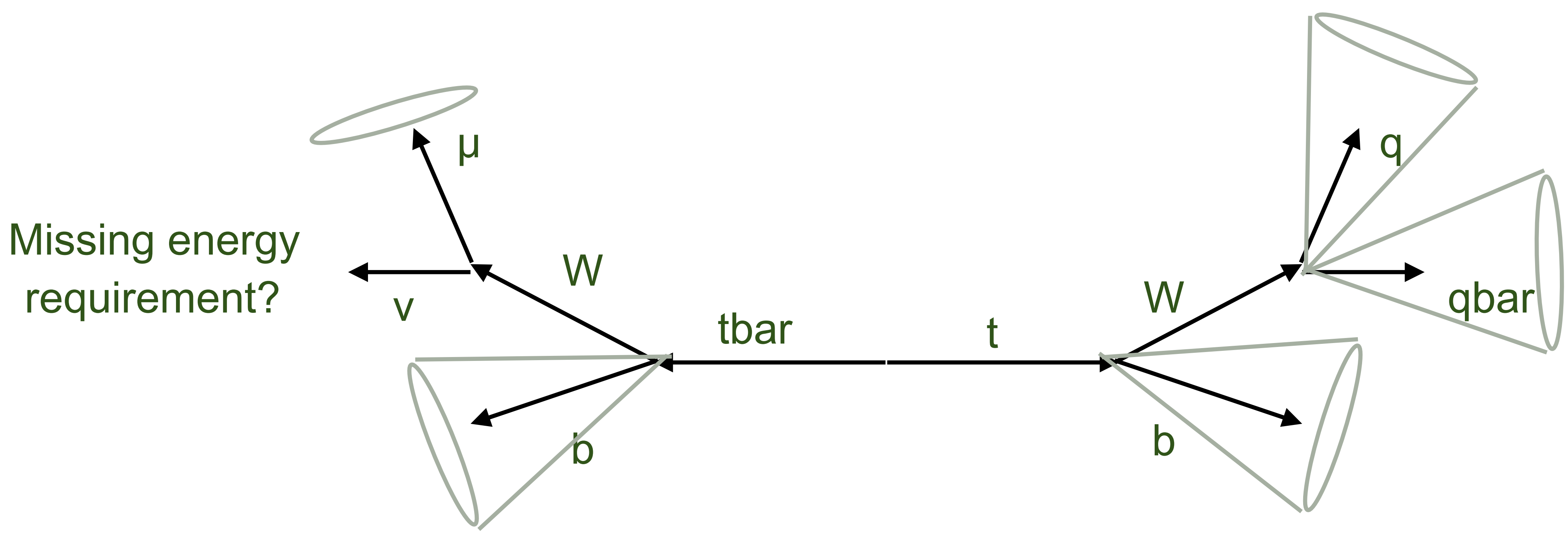
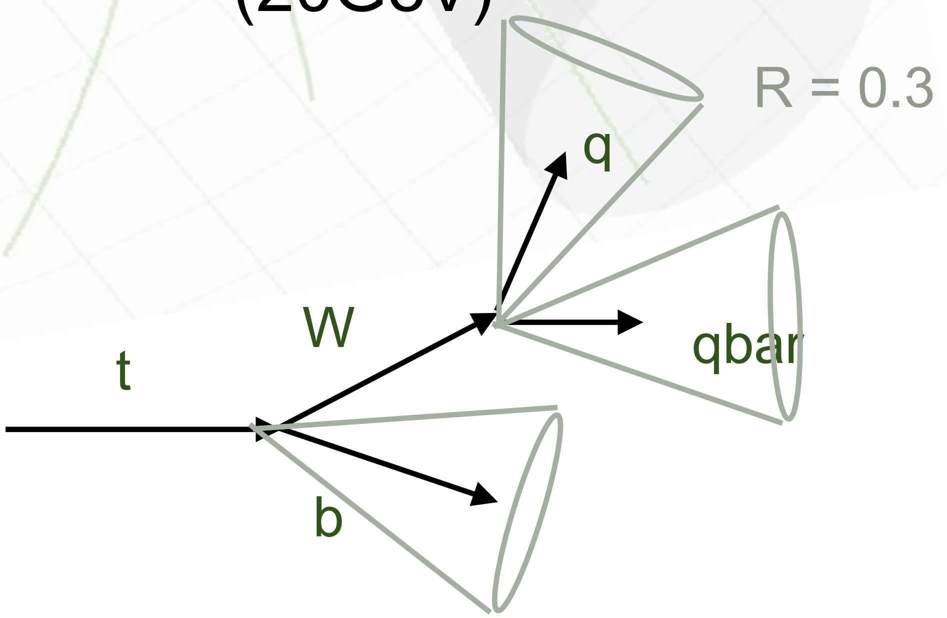


Jet Reconstruction

- Anti-k_T jets with R = 0.3, p_T > 30 GeV, $|\eta|$ < 2.5.
  - Recluster with k_T algorithm, R = 1.0 and decluster with dcut = $(20GeV)^2$



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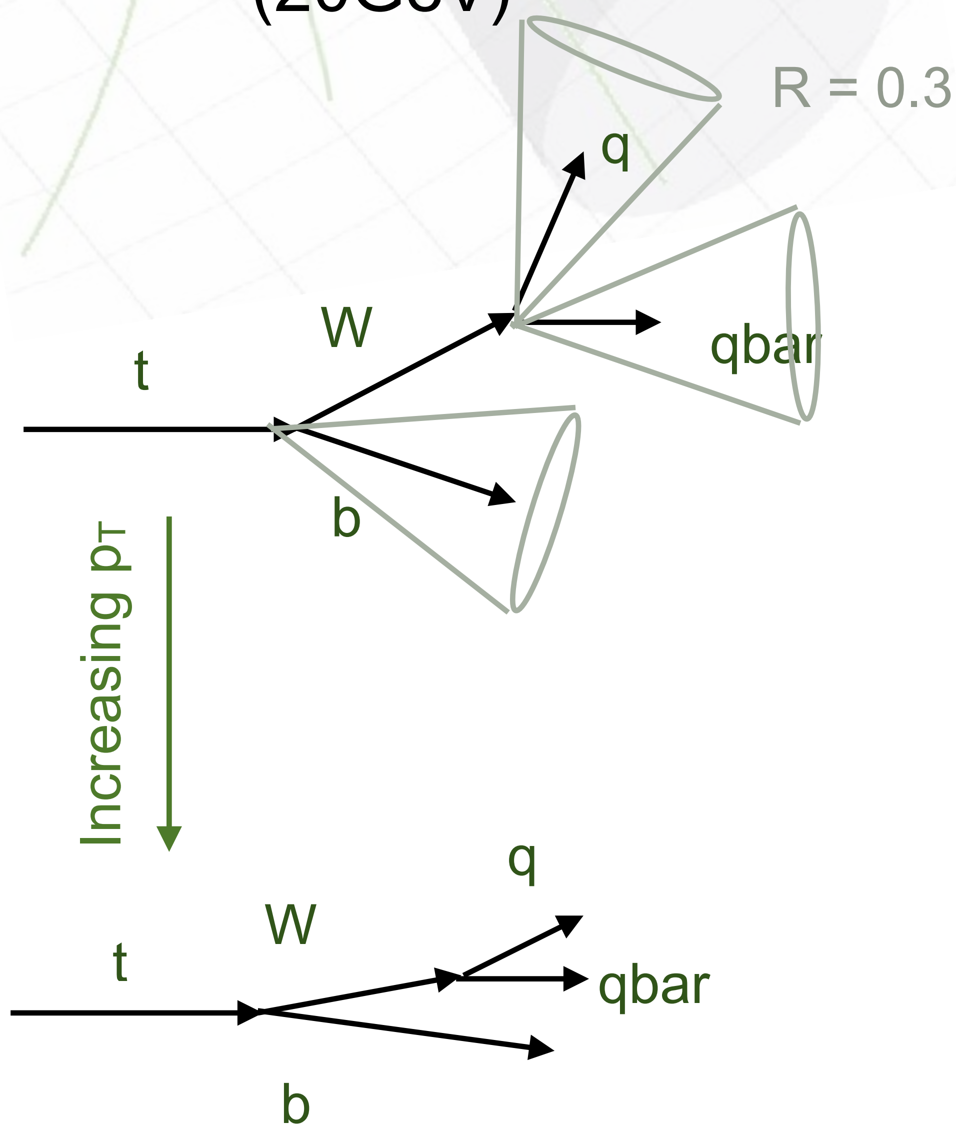

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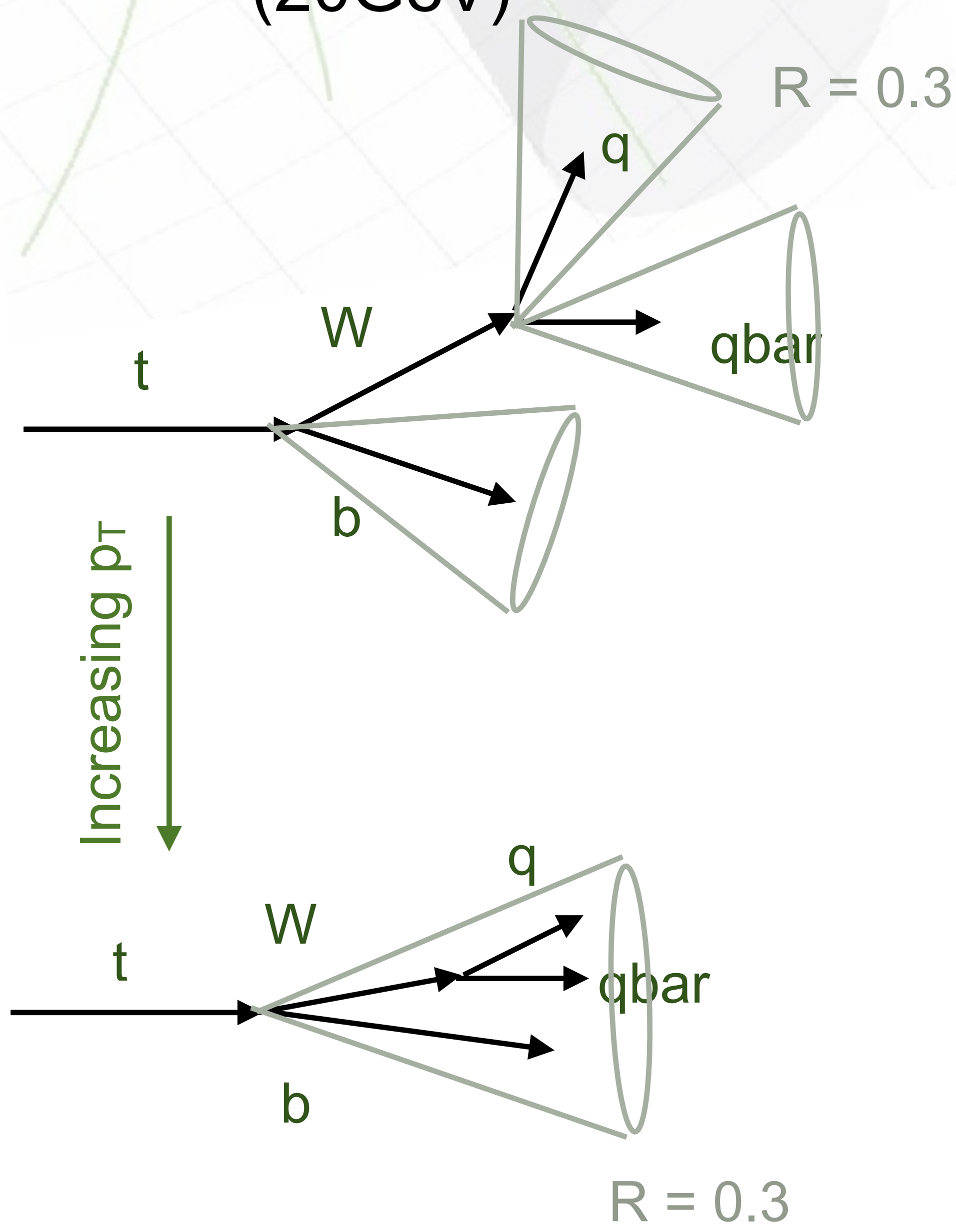

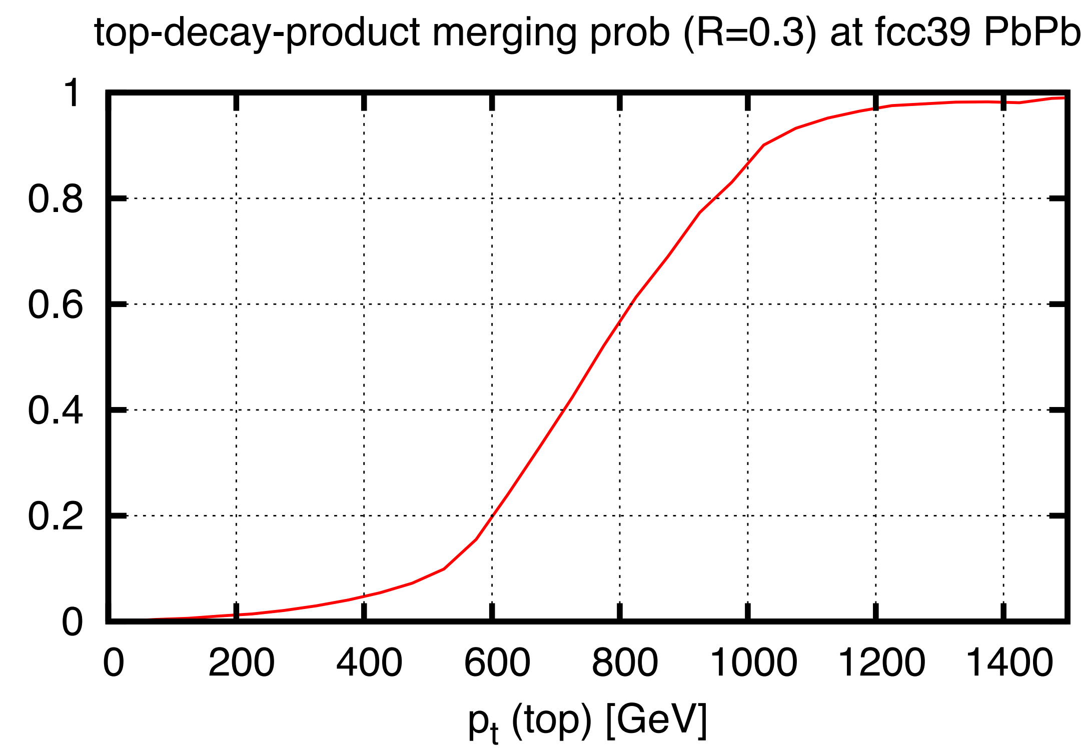

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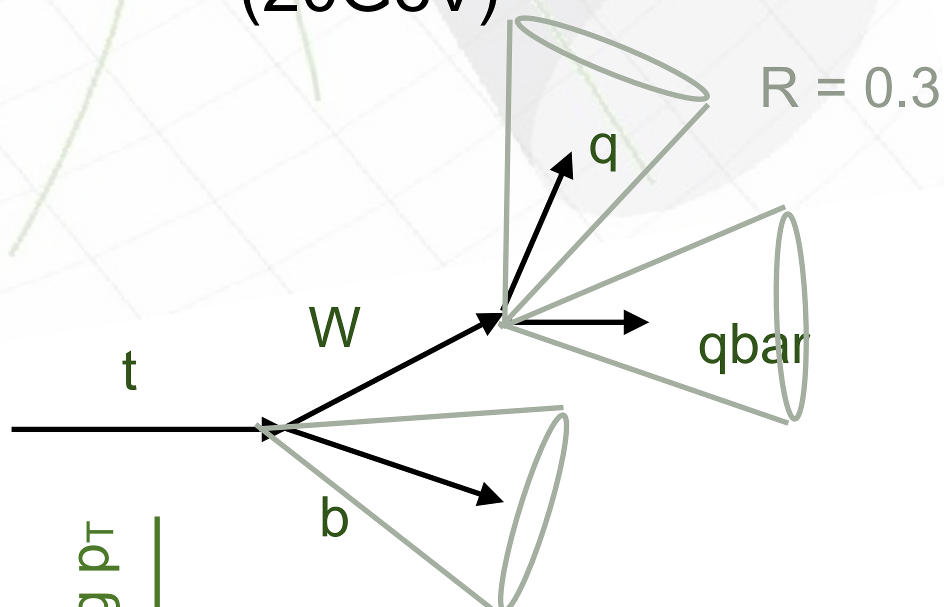

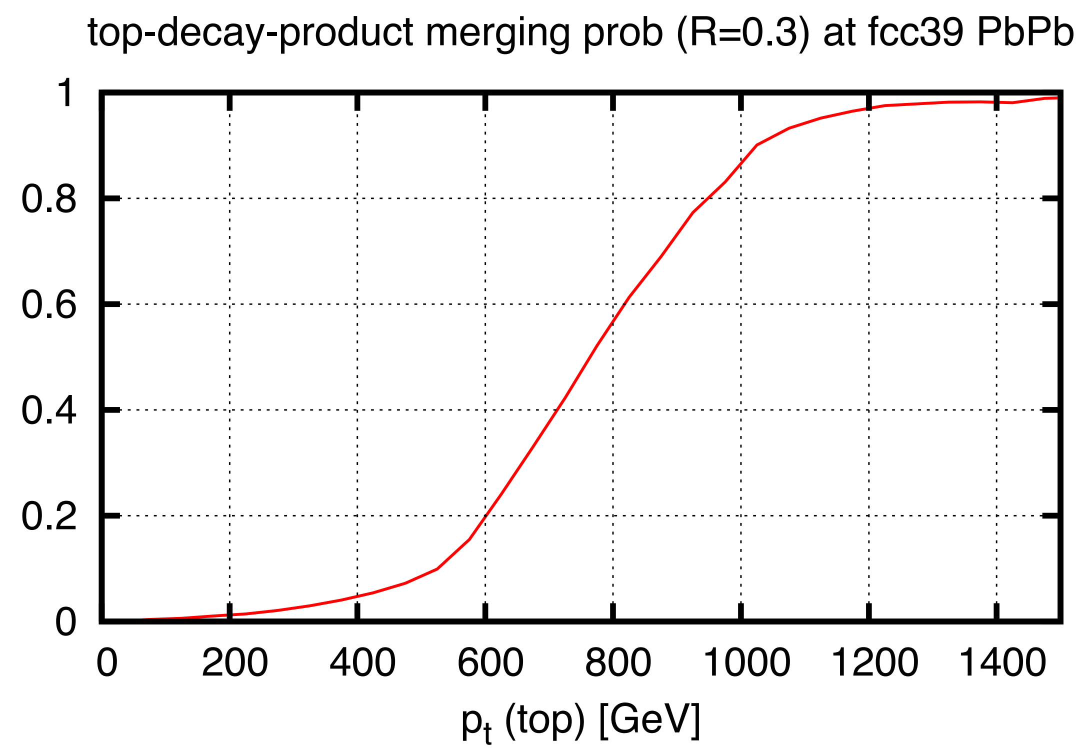

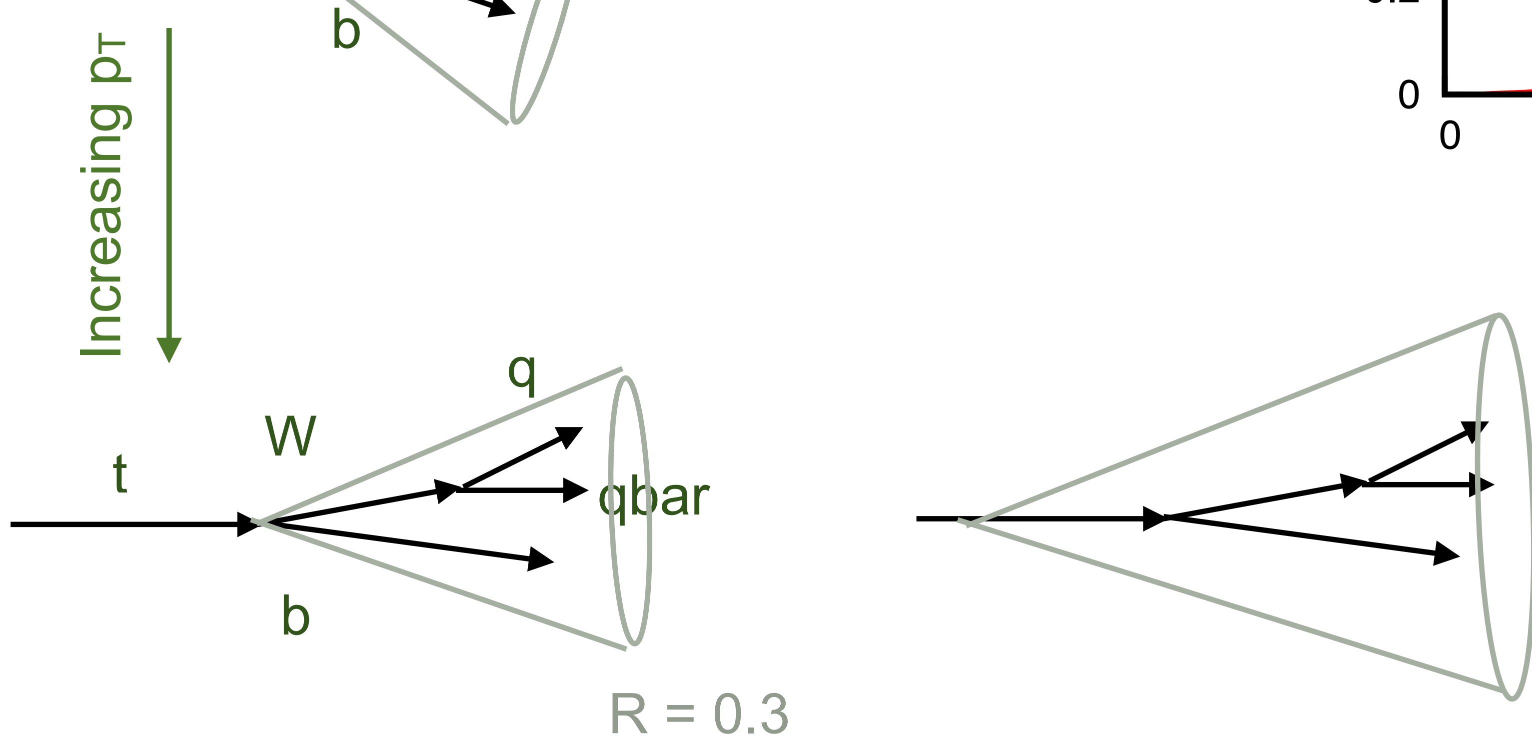

Reclusters with larger R and find sub-jets with $p_{T,rel}$ > $\sqrt{(d_{cut})}$

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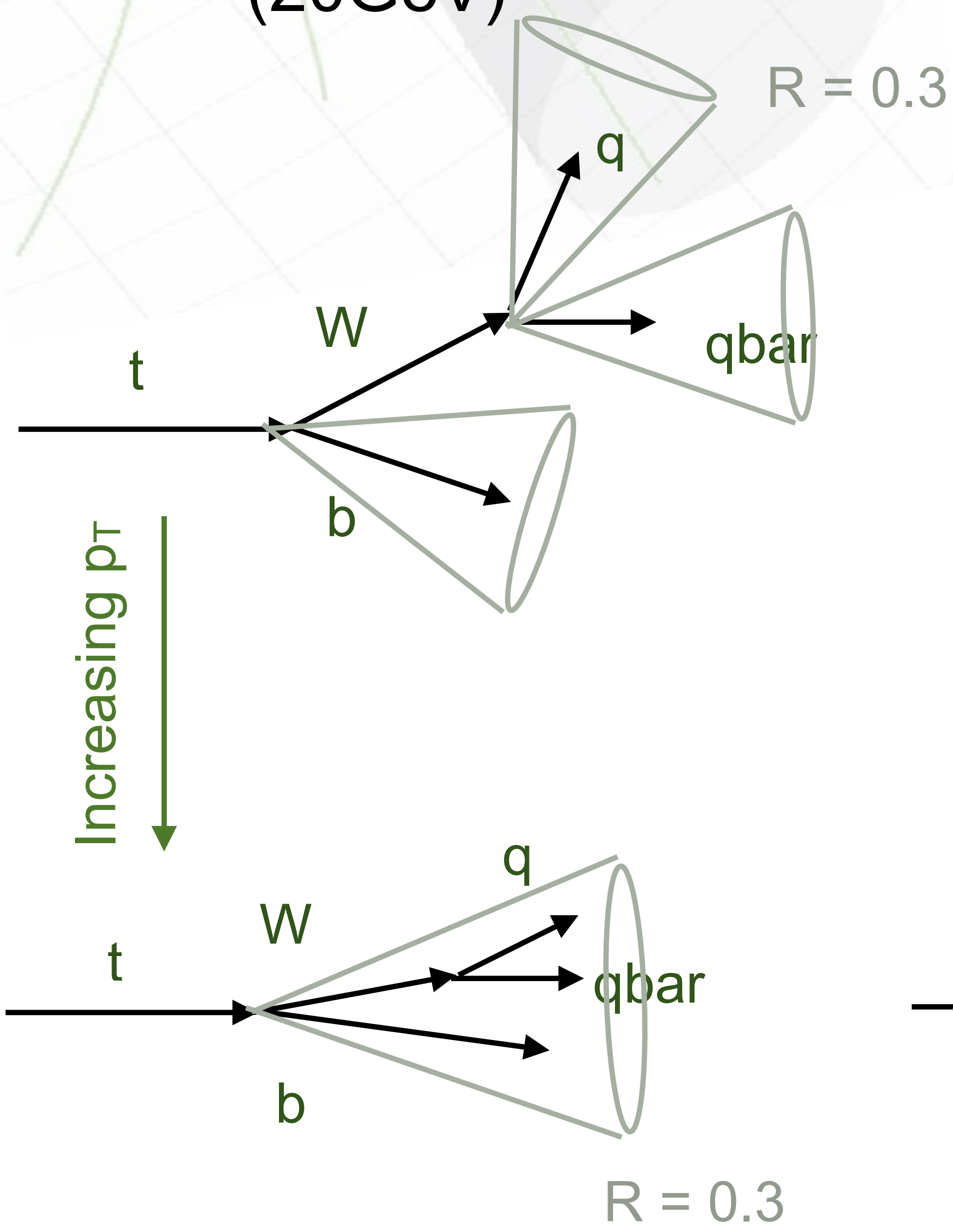

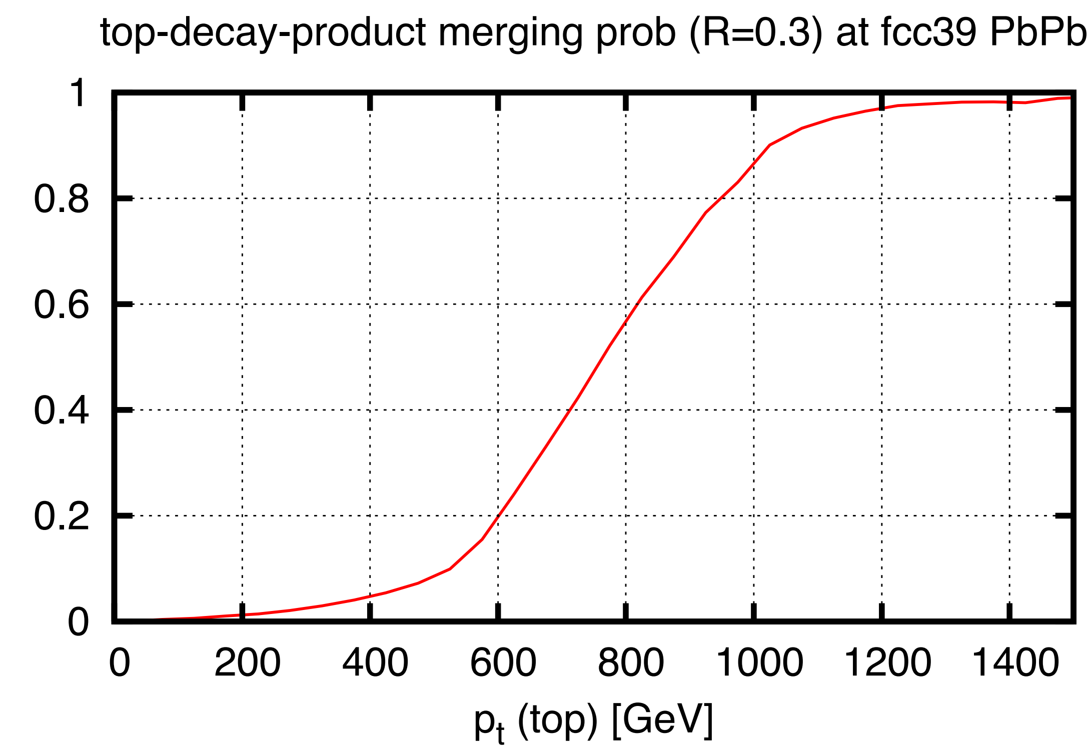

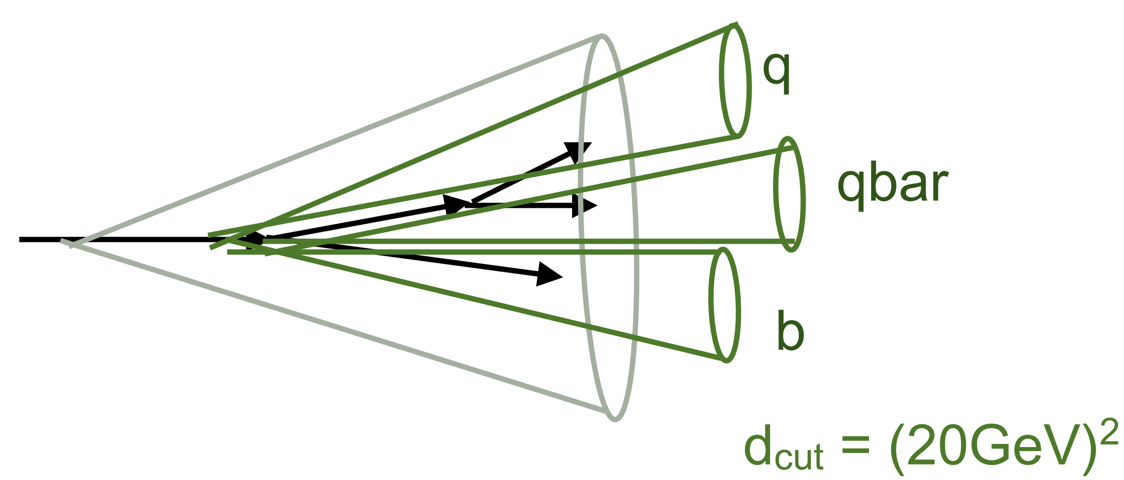

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- The W jet is taken to be the 2 non-b jets with the highest scalar p_t sum; reconstructed W Mass < 130 GeV;
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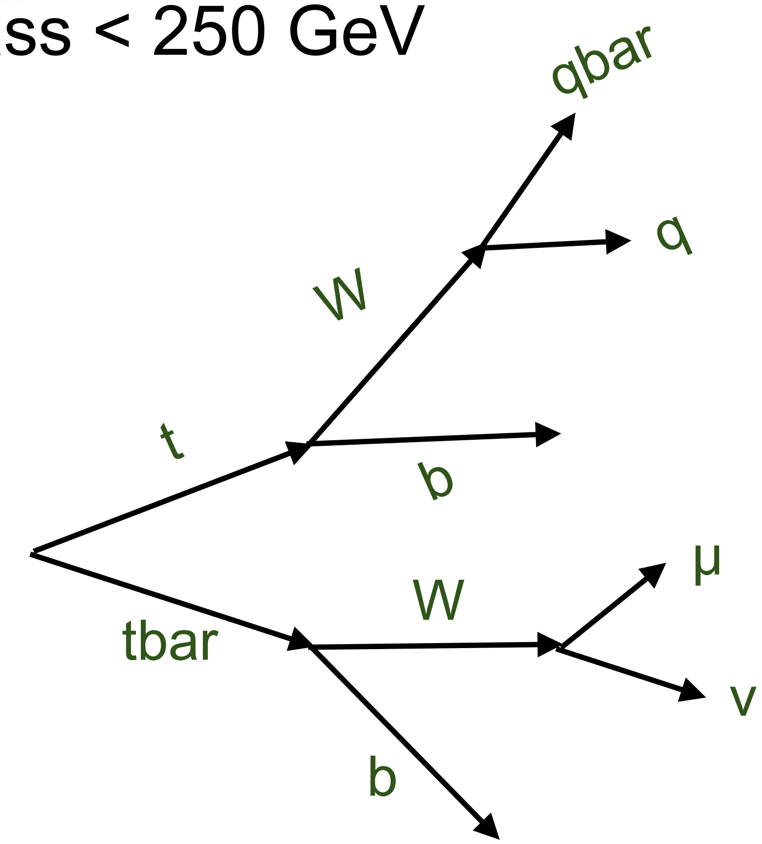
- "Hadronic" Top Mass < 250 GeV



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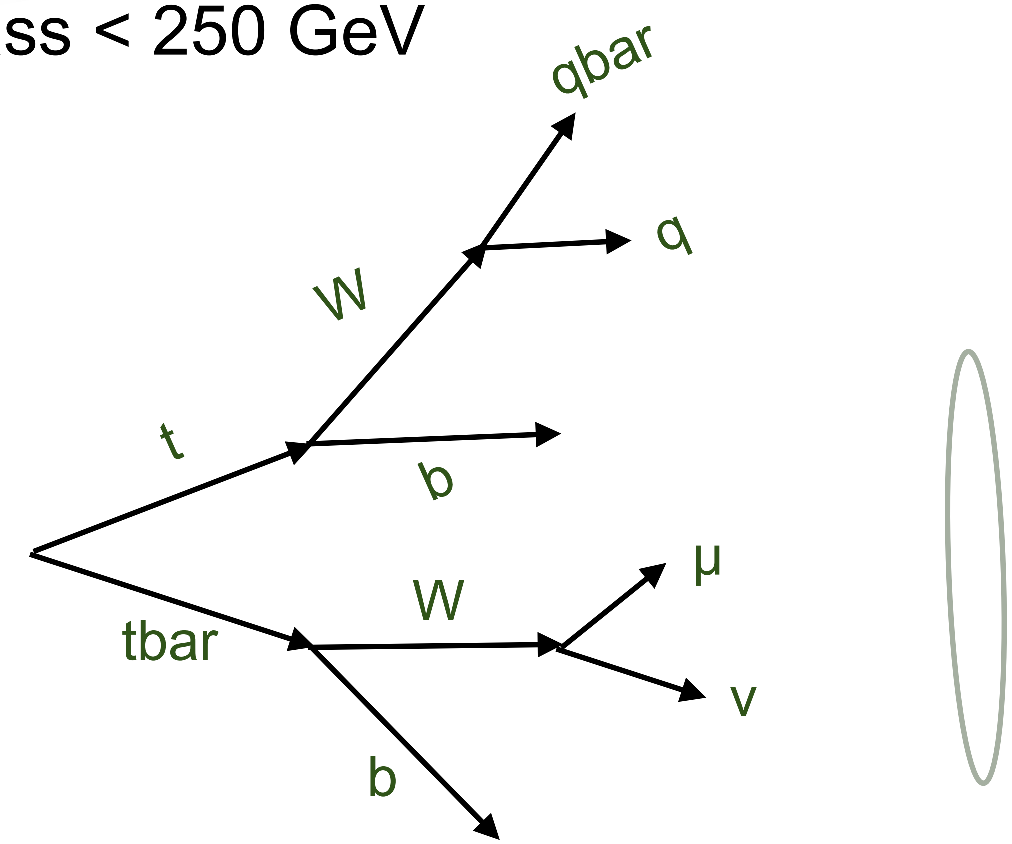

Top reconstructed with the wrong b-jet

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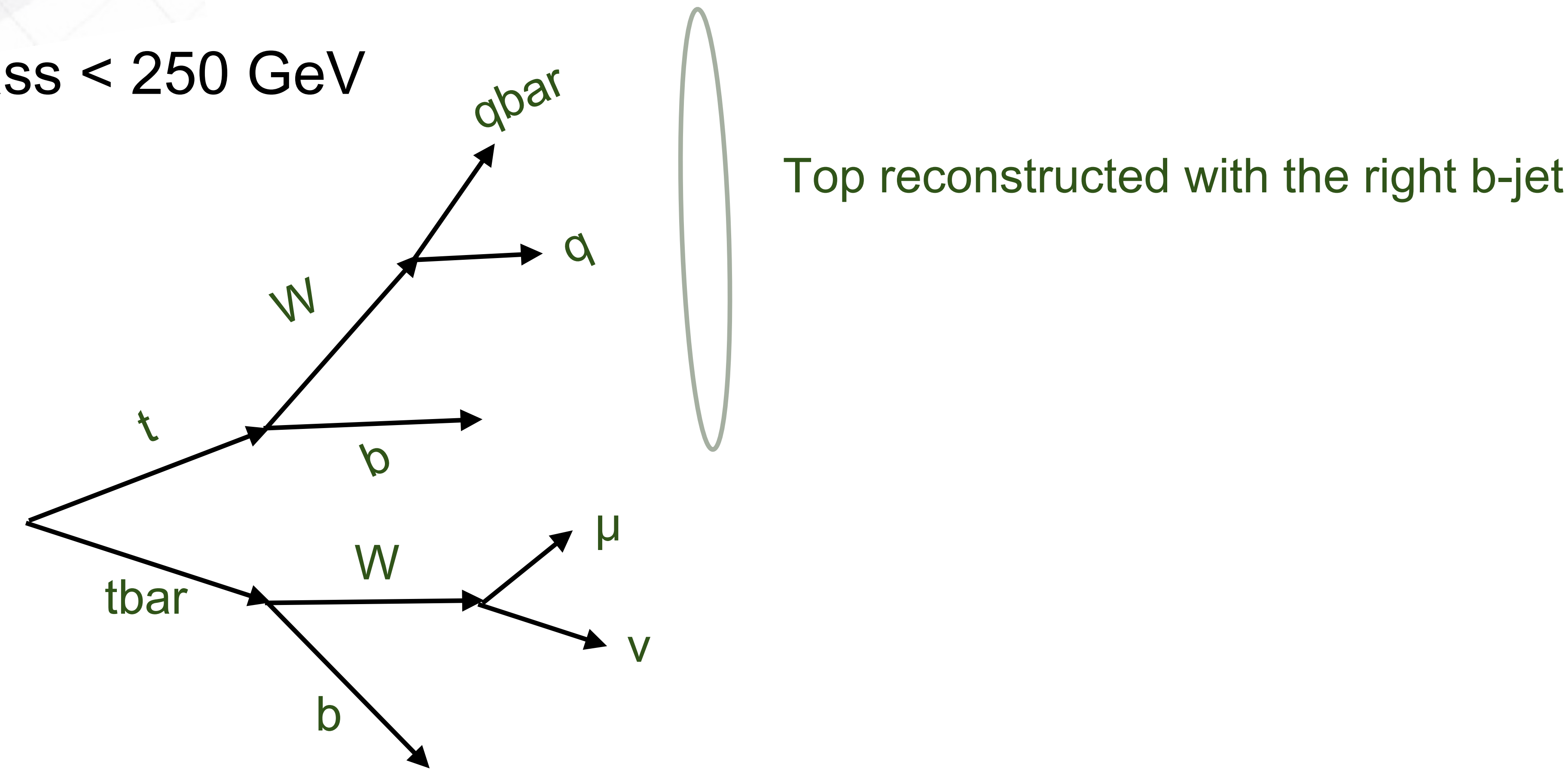
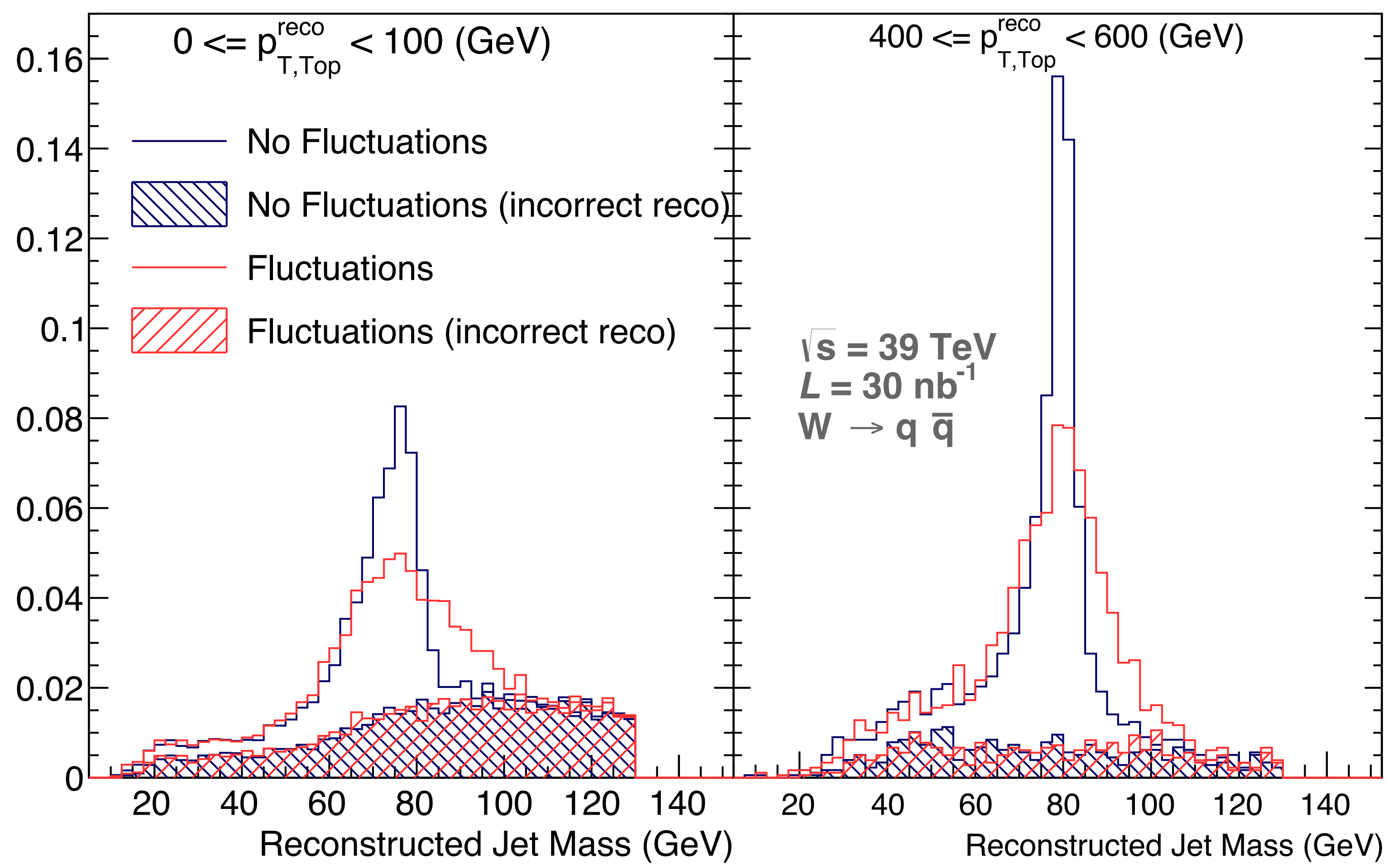


Jet Quenching Model

- Very simplistic picture of jet quenching:
  - Jet-by-jet gaussian fluctuations as 1/√pt (normalized at 100 GeV)



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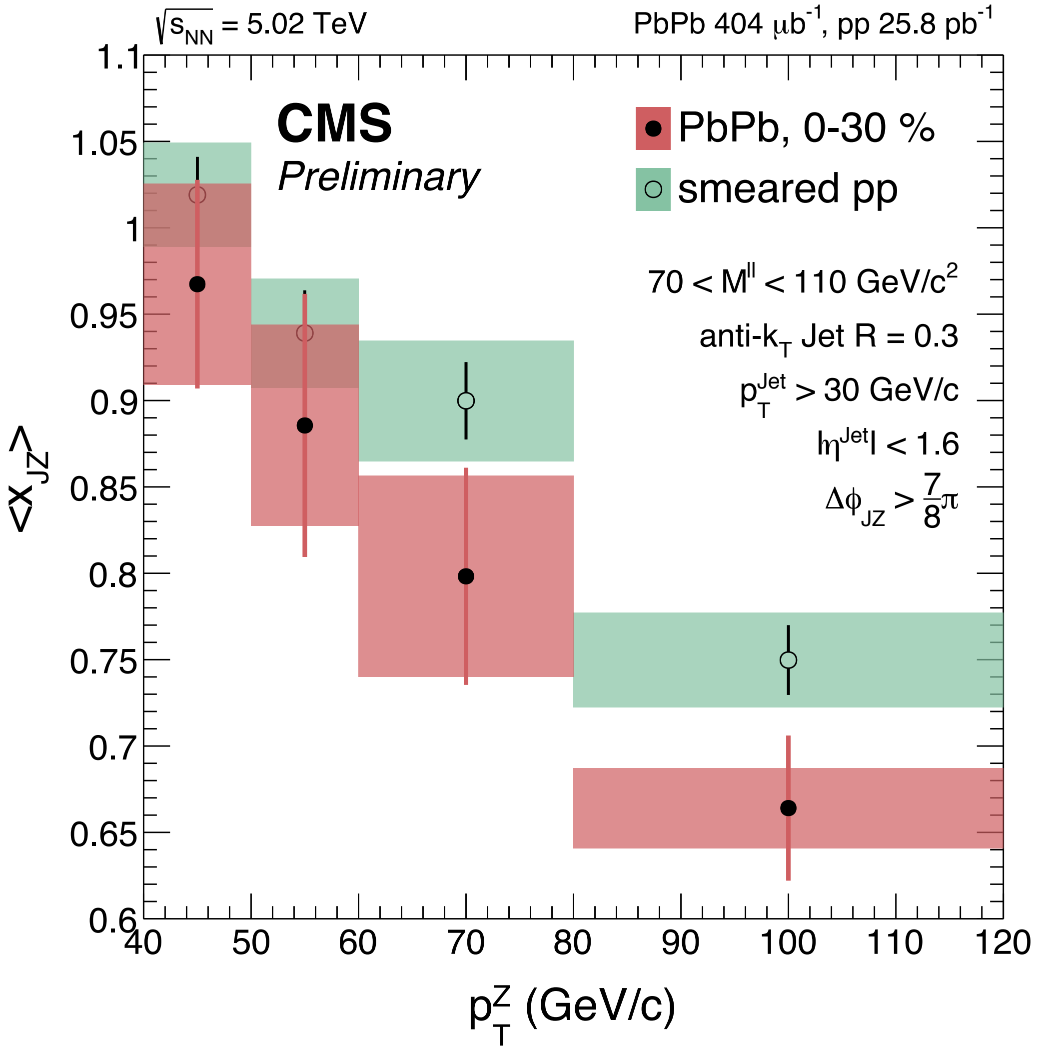
CMS-PAS-HIN-15-013
(Average momentum imbalance Z + Jet)



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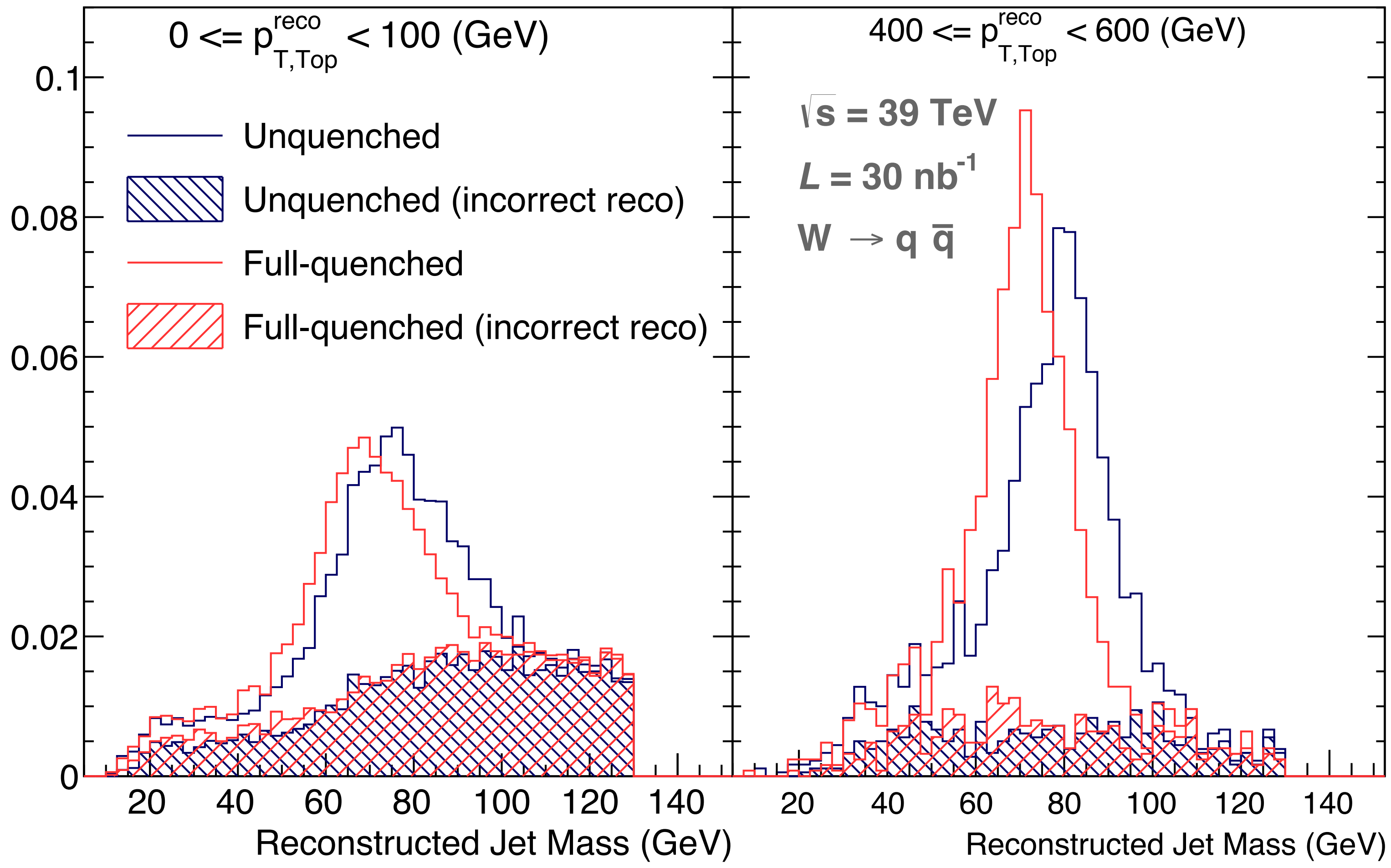
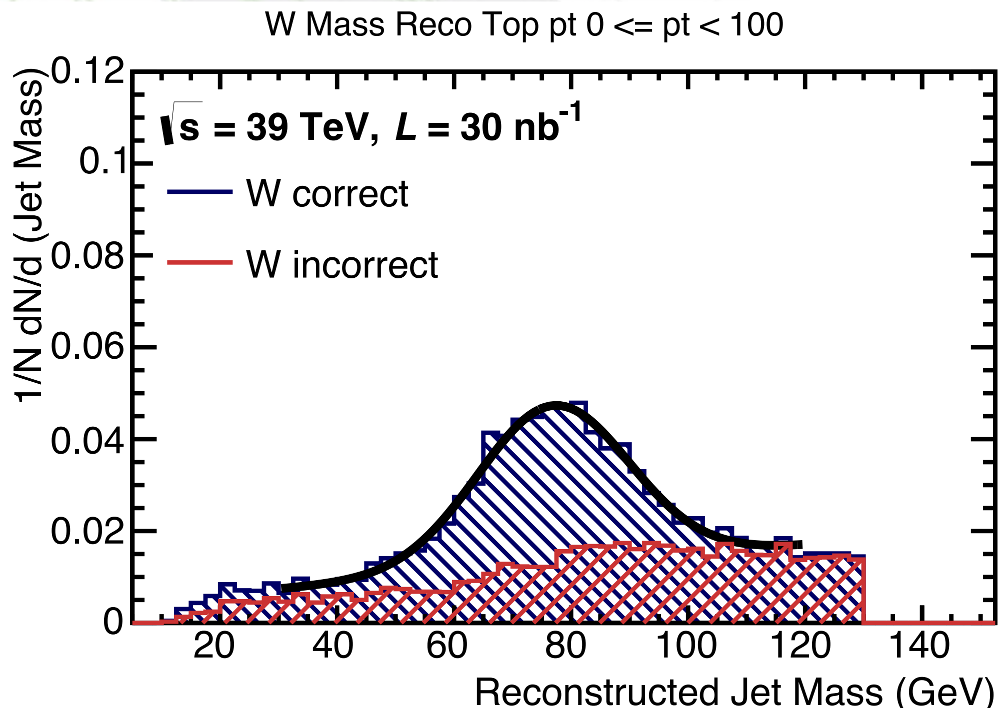
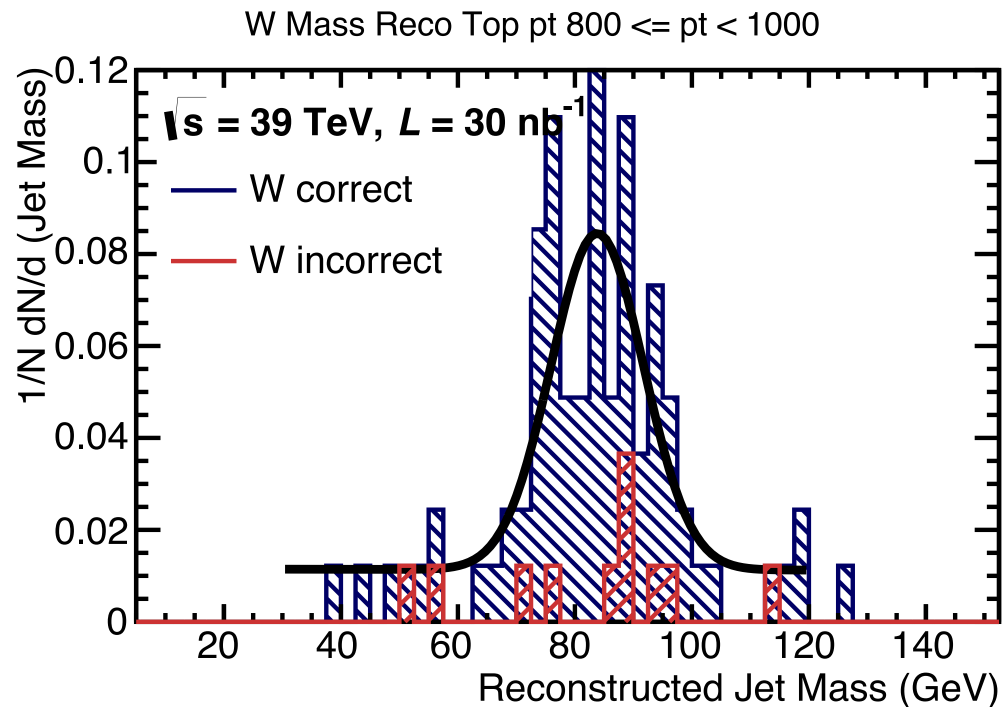
  - Z + Jet: Delta p_T in [5-10%] (low p_T) to [10-15%] (high p_T)
  - Our model: 10% of energy loss to all coloured particles

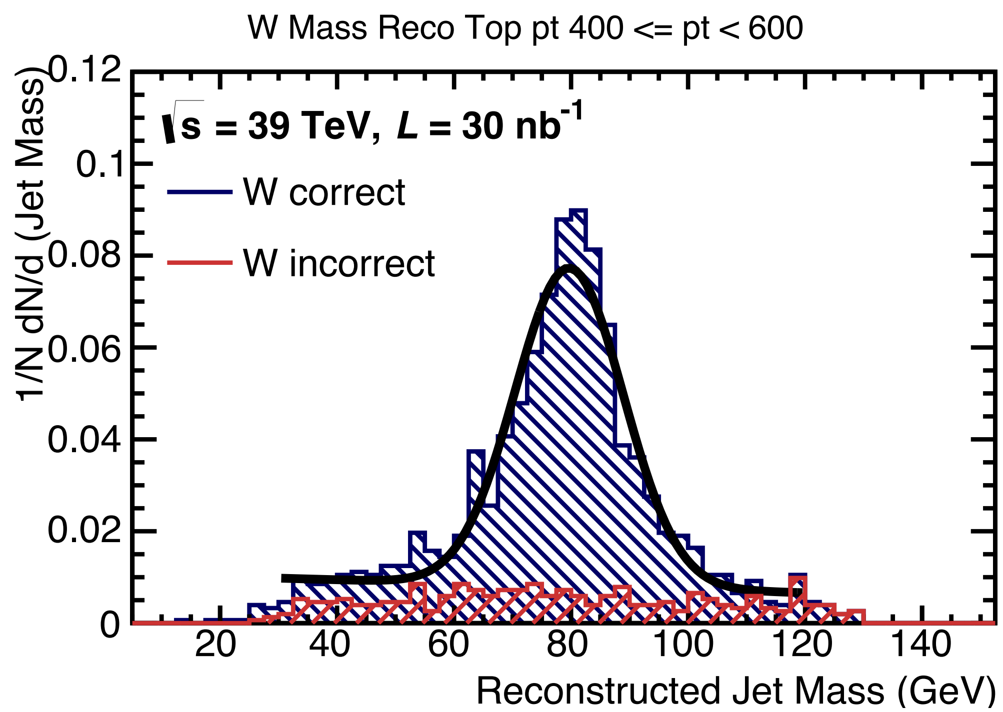


Reconstructed W Mass

- Gaussian fit + linear offset



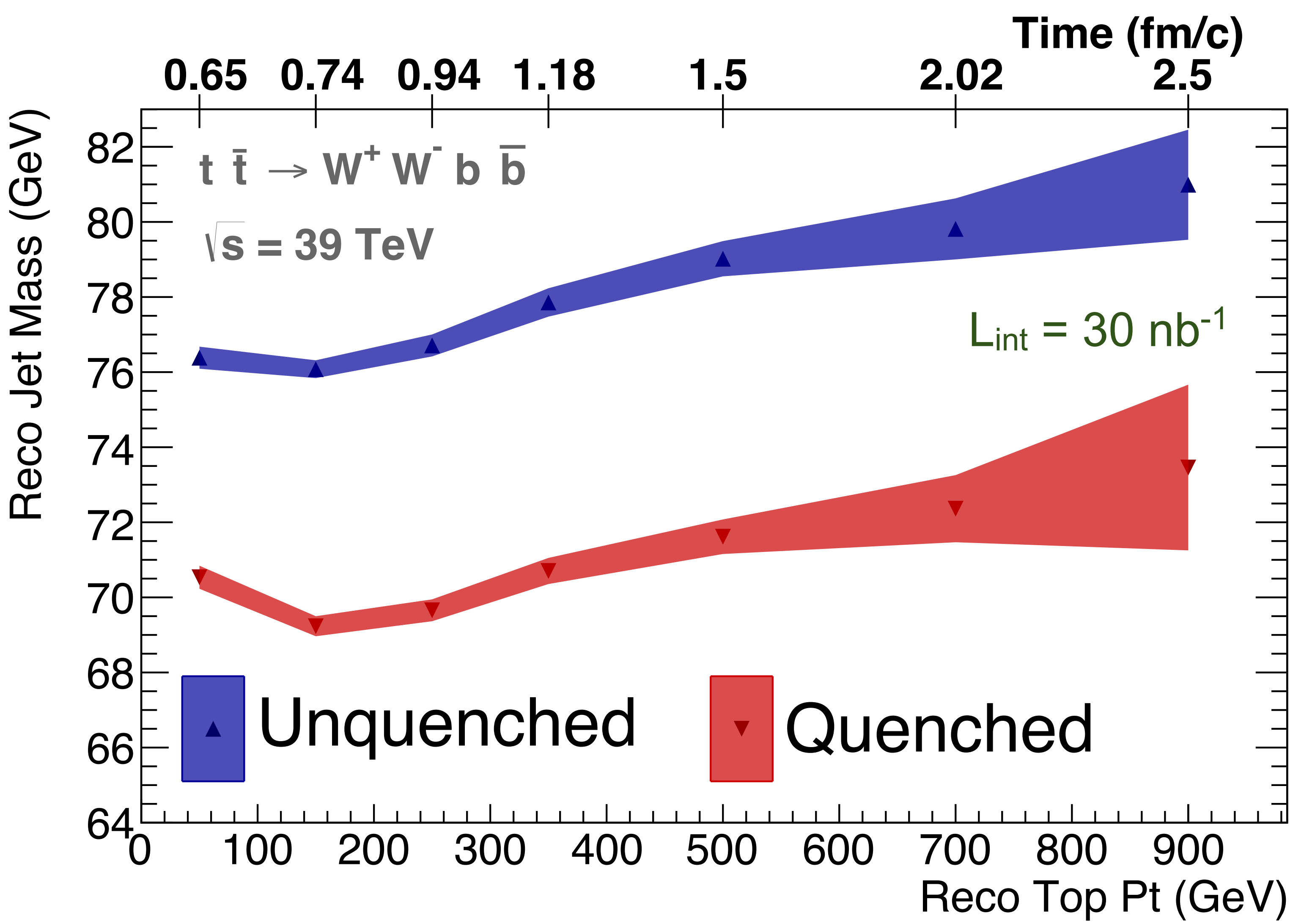




Fitting region: 30 - 120 GeV

Jet Mass with p_T

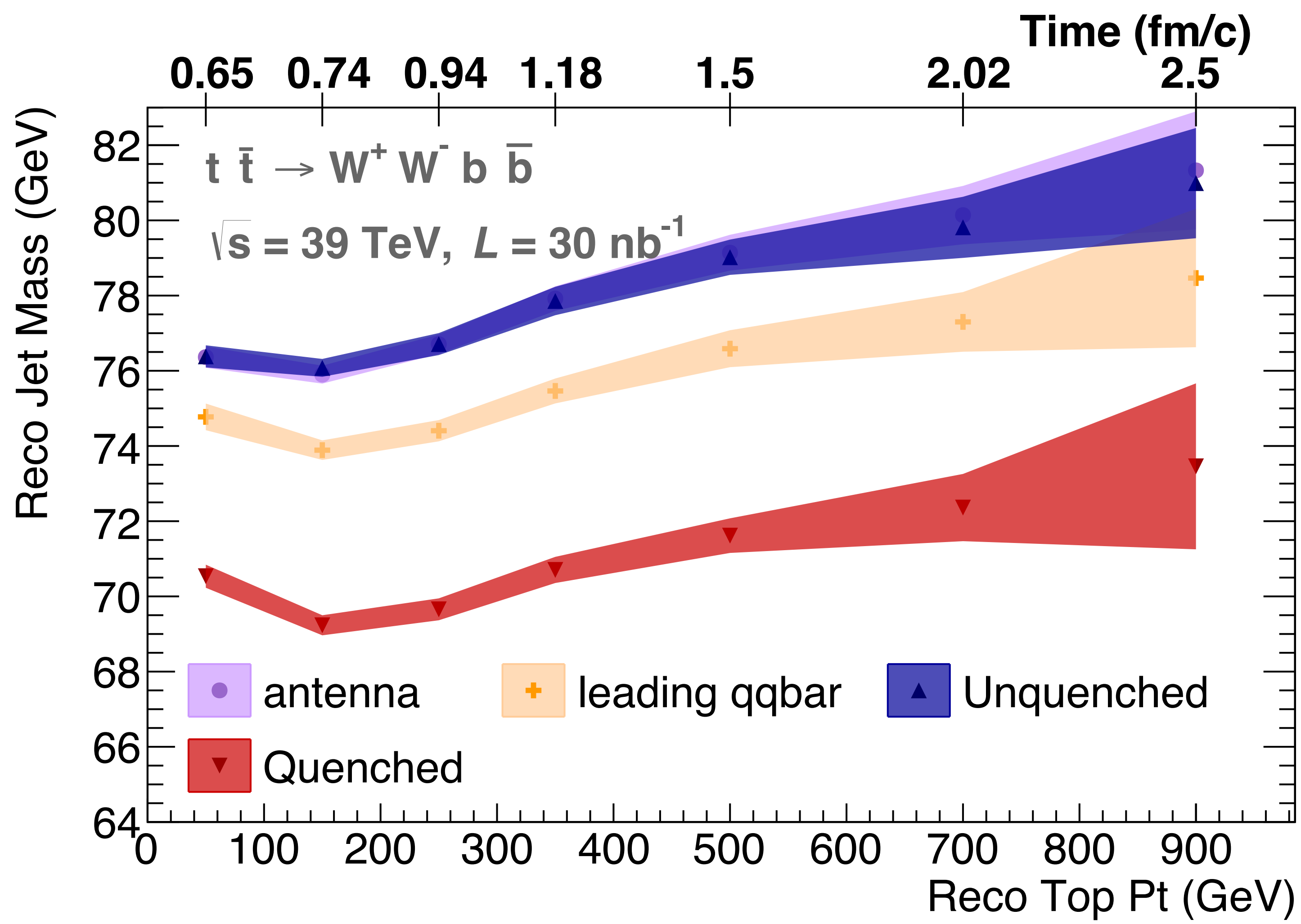
- Statistical significance using a bootstrap analysis (~60 samples)



Possible to distinguish quenched from unquenched jet masses

Jet coherence

- To study jet coherence we applied 2 simple models:
  - "antenna": energy loss applied to all colourful partons except the decay products of the hadronic W boson
  - "leading qqbar": energy loss applied to all coloured partons except the leading qqbar from the decay of the hadronic W boson



Absolute value of jet mass can give information on the "degree" of coherence of the system

- Finite lifetimes can be enhanced by boosting high-p_T particles (top and W);
- Together with a color singlet probe (W), it is possible to have an object that starts interacting with the medium in late times;

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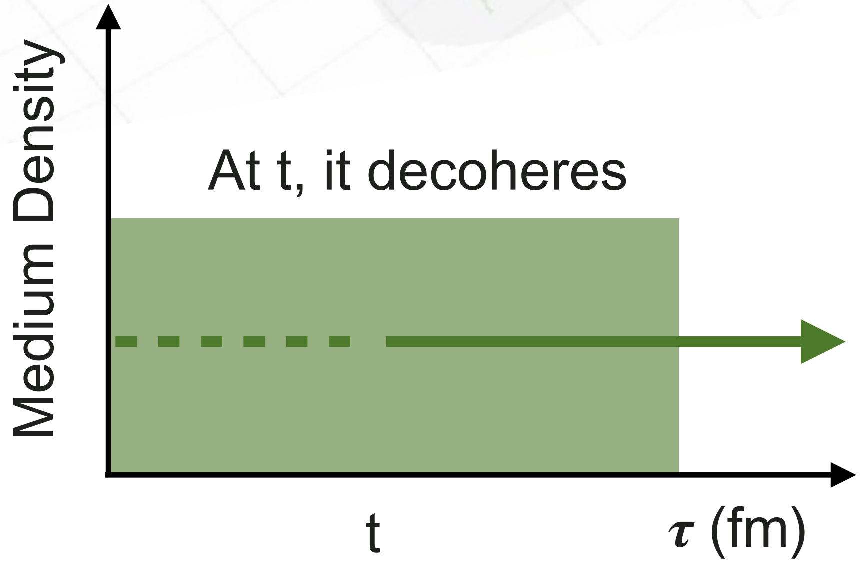
- Can we go further?
  - In theory, one can probe select timescales of the medium by using $p_T > p_{T,Cut}$

Time Dependent Energy Loss

- Very simple model: W decay products lose energy as
  - $\Delta E/E = (\tau\text{-}t)/\tau * 0.1$

τ = Total medium lifetime

t = "total" delay time (top + W + coh)



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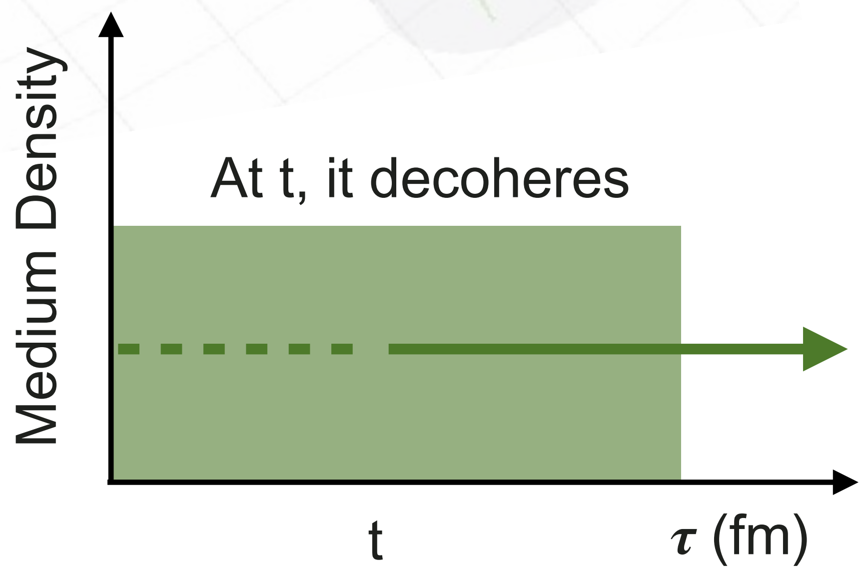

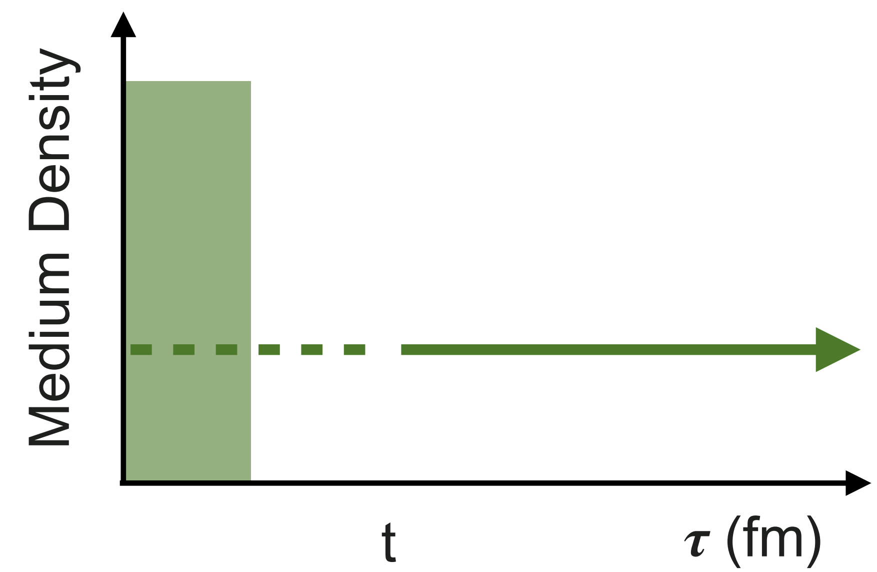

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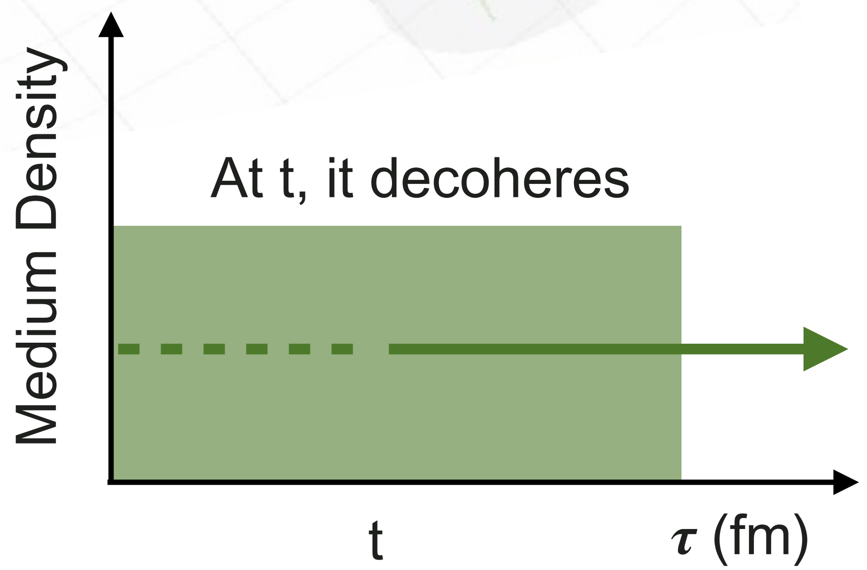

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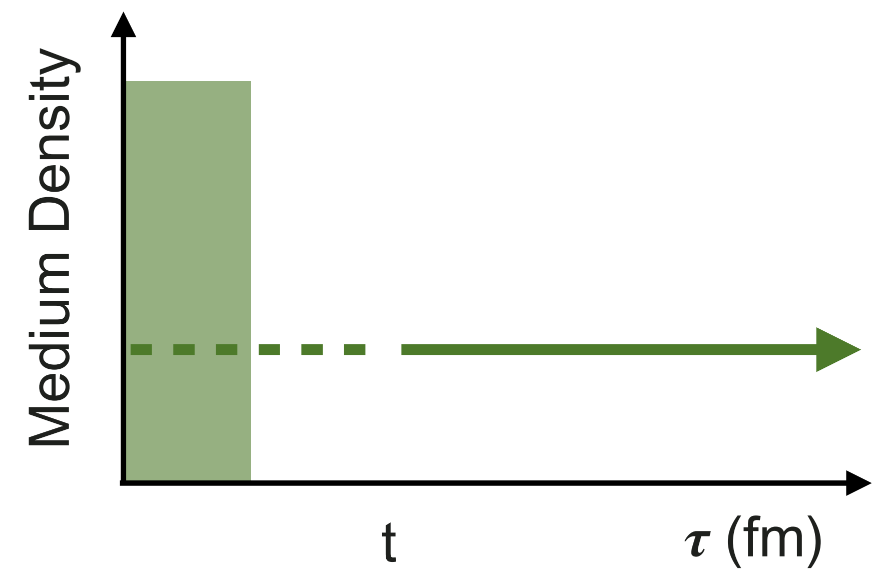

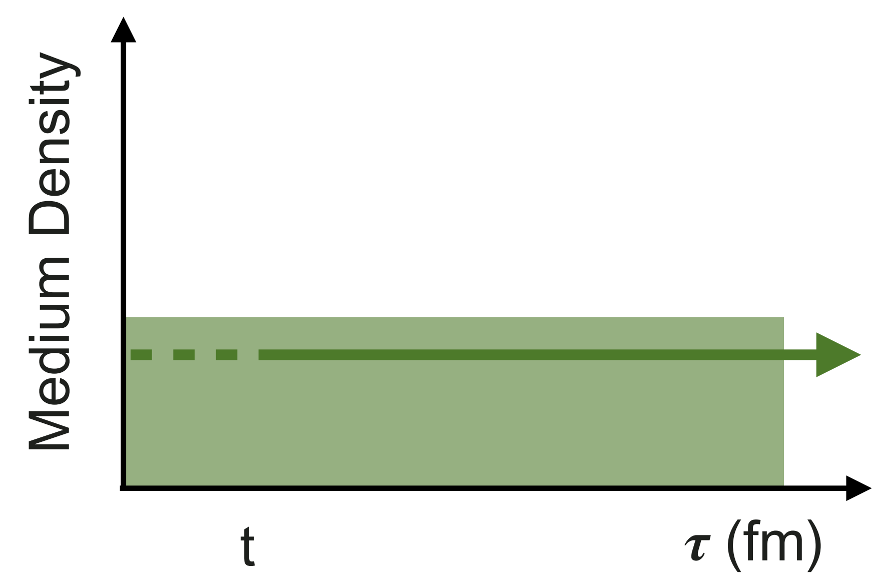

Time Dependent Energy Loss

- Reconstructed W Jet Mass:
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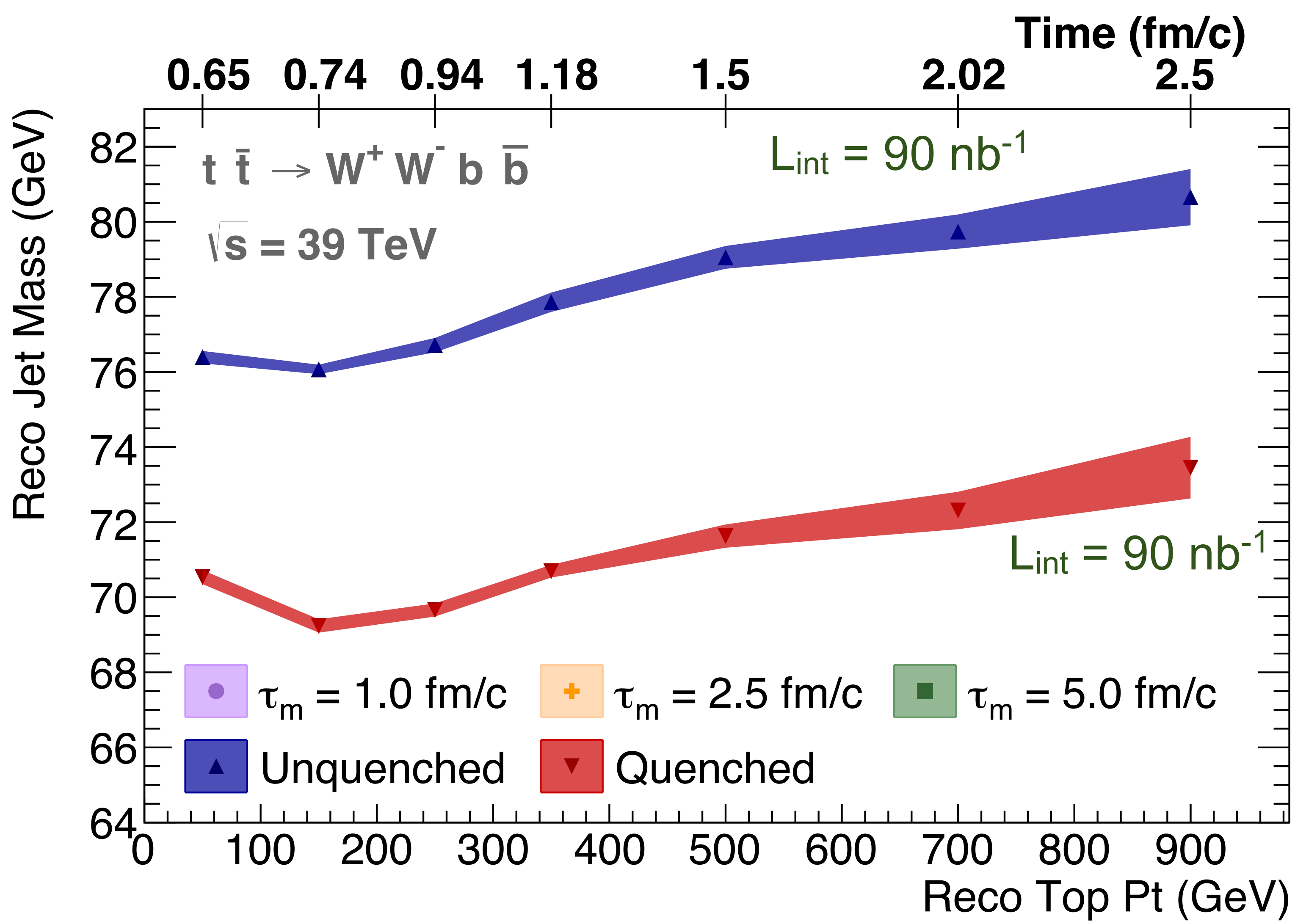
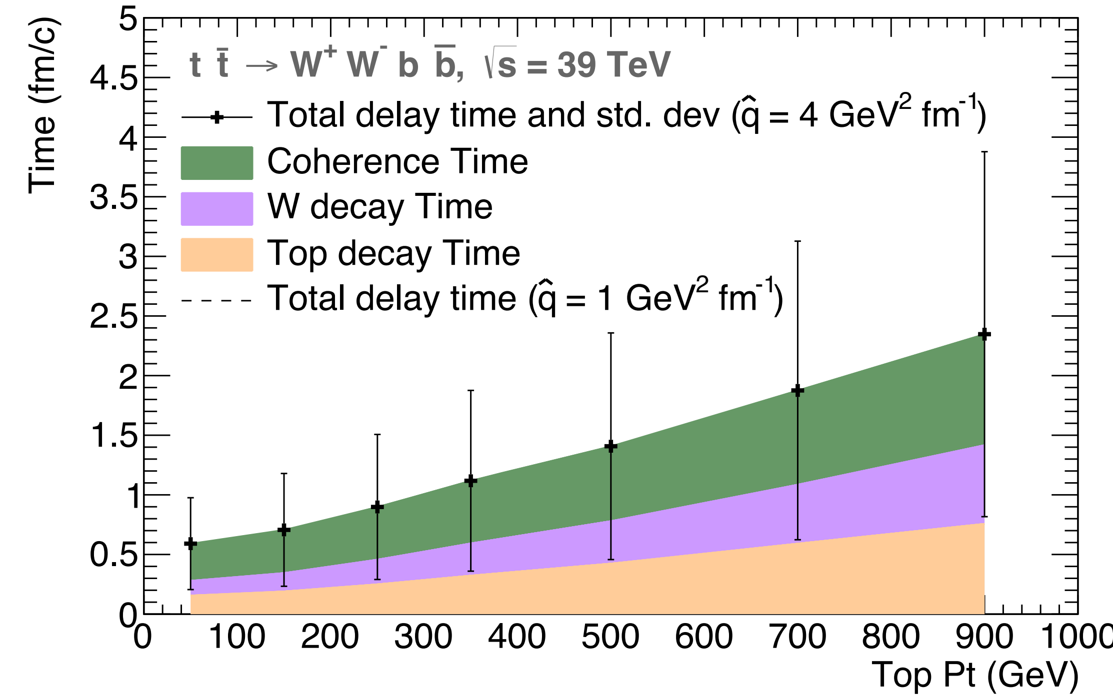
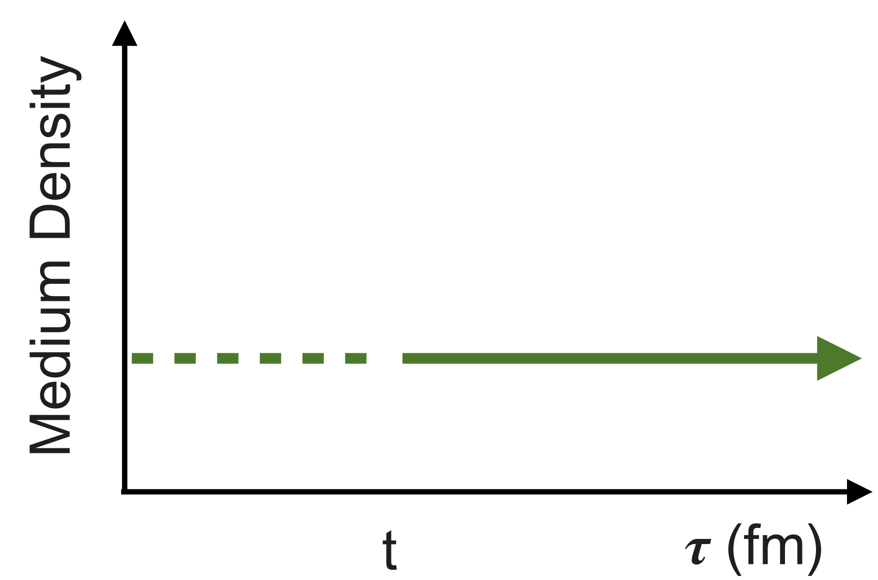


Antenna decoheres outside the medium





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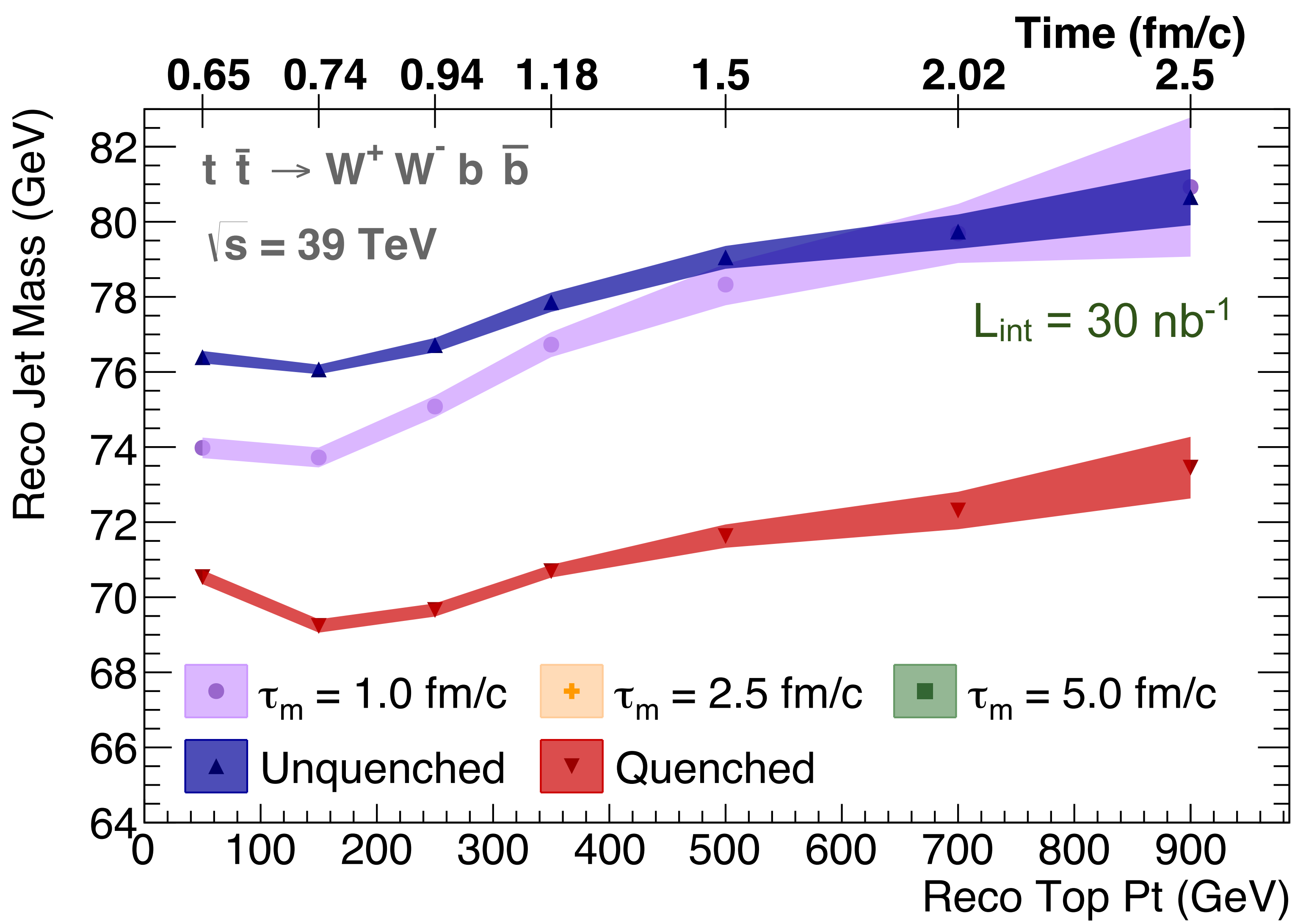

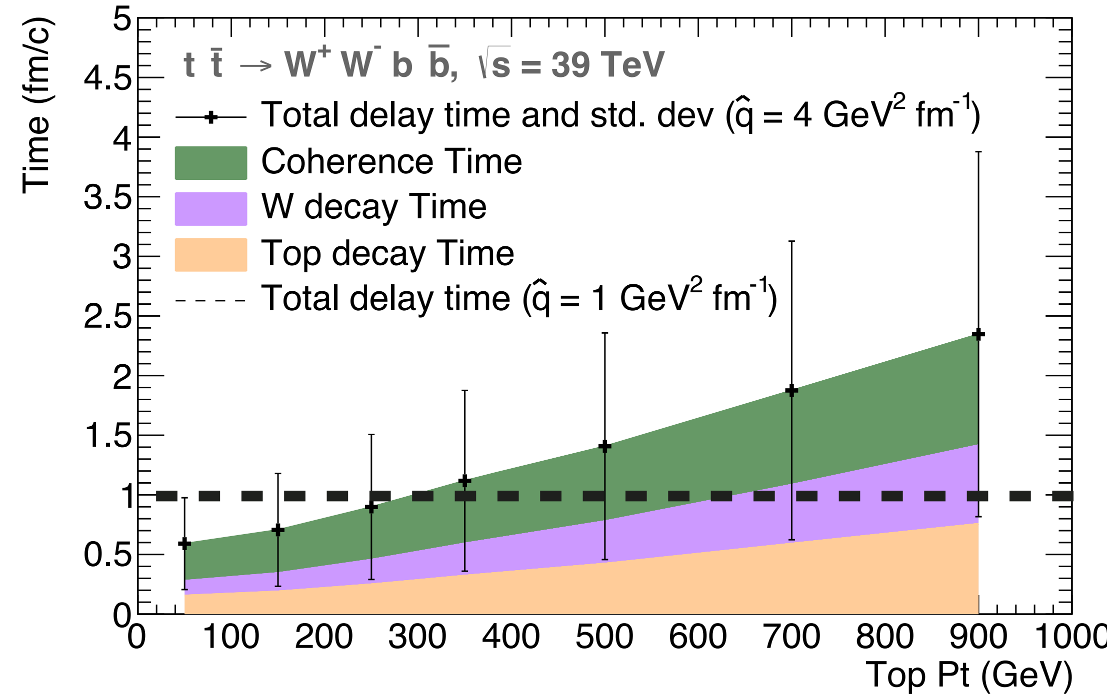

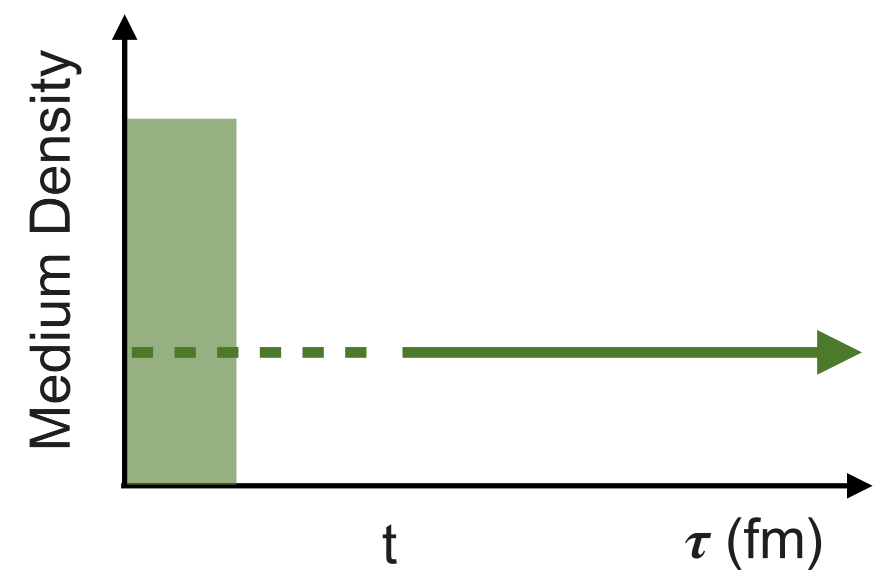

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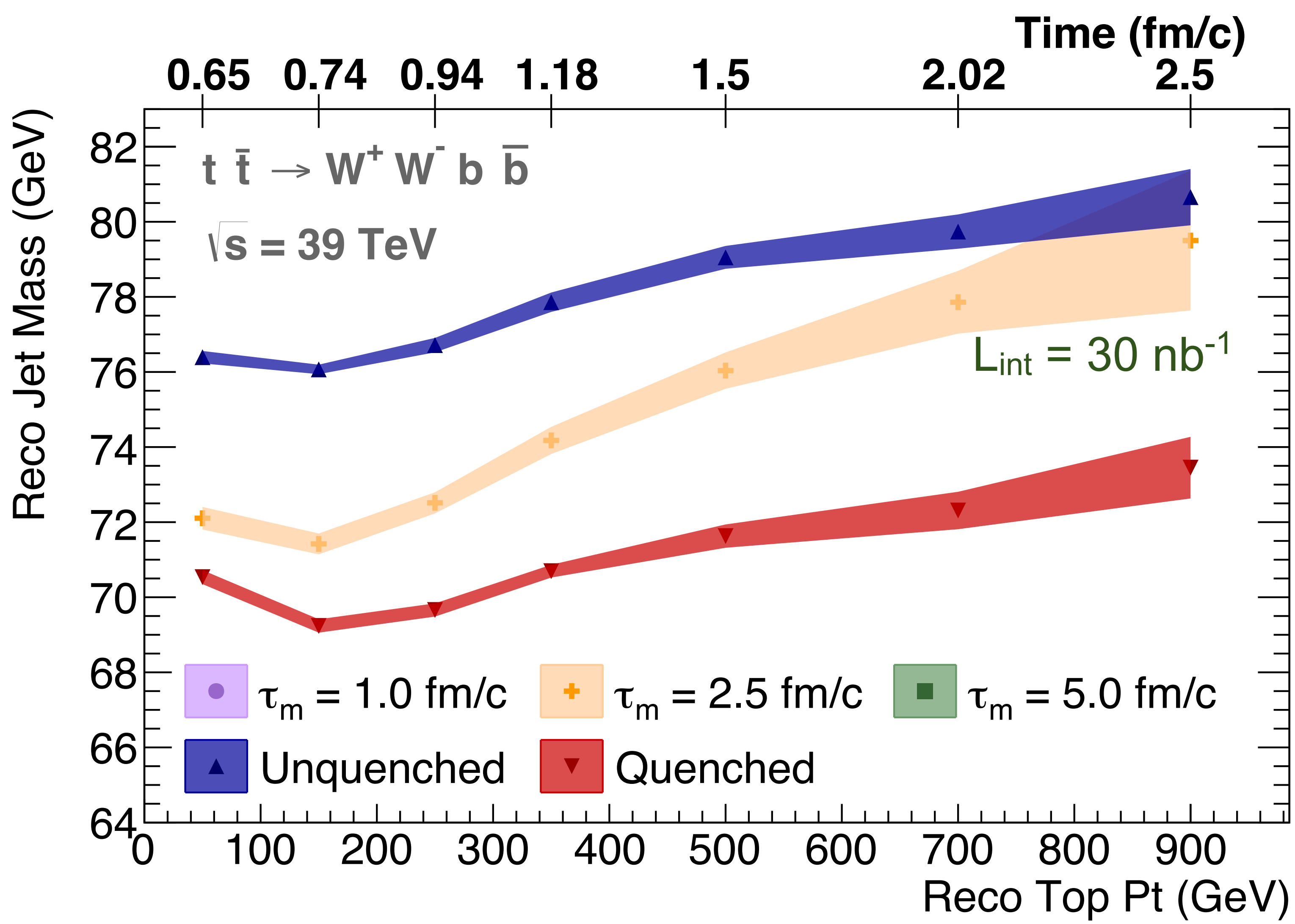

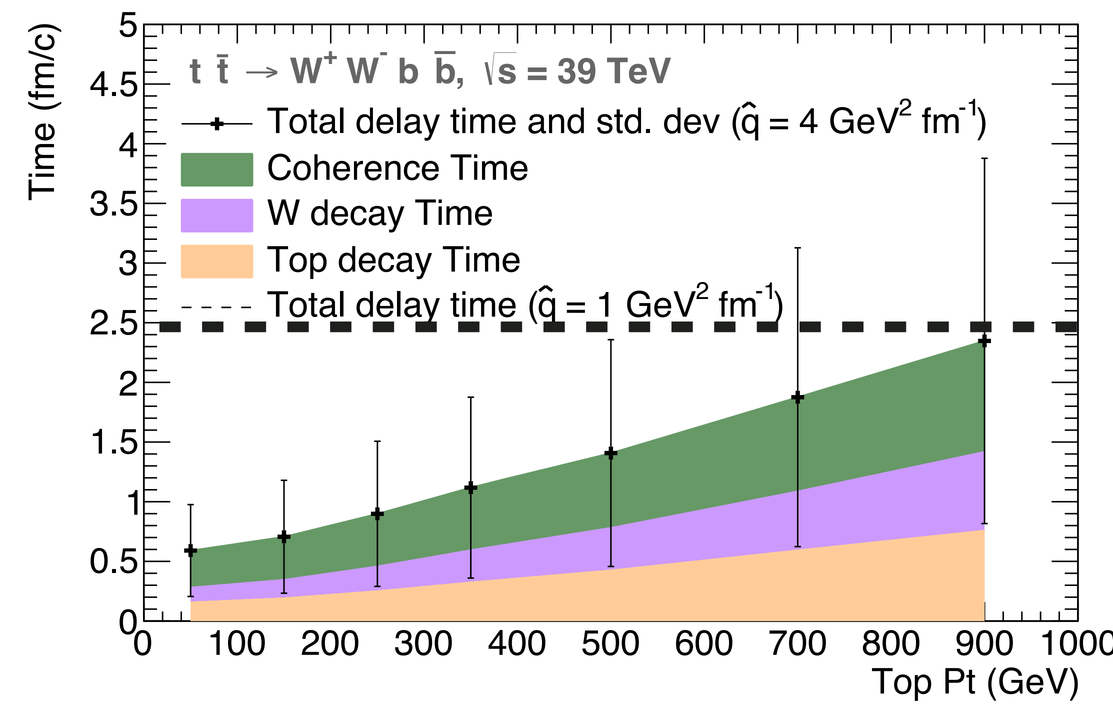

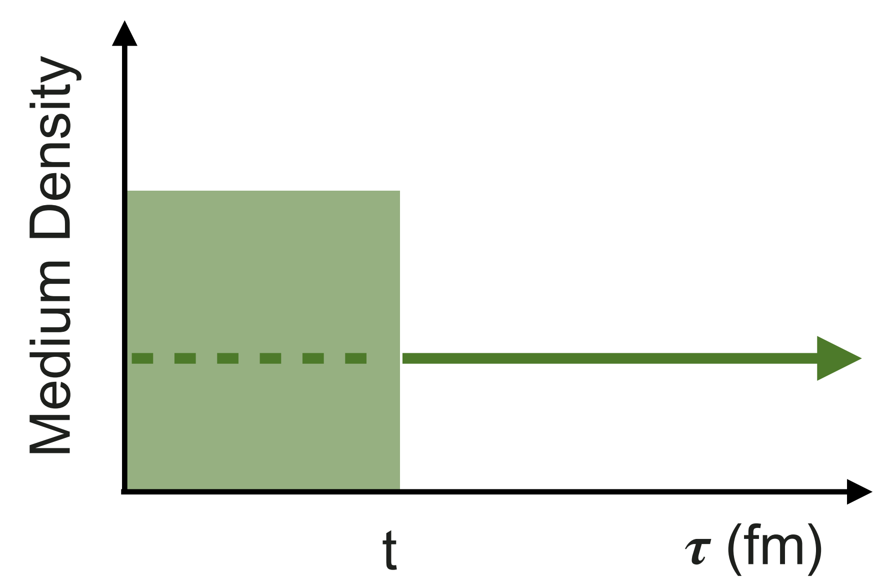

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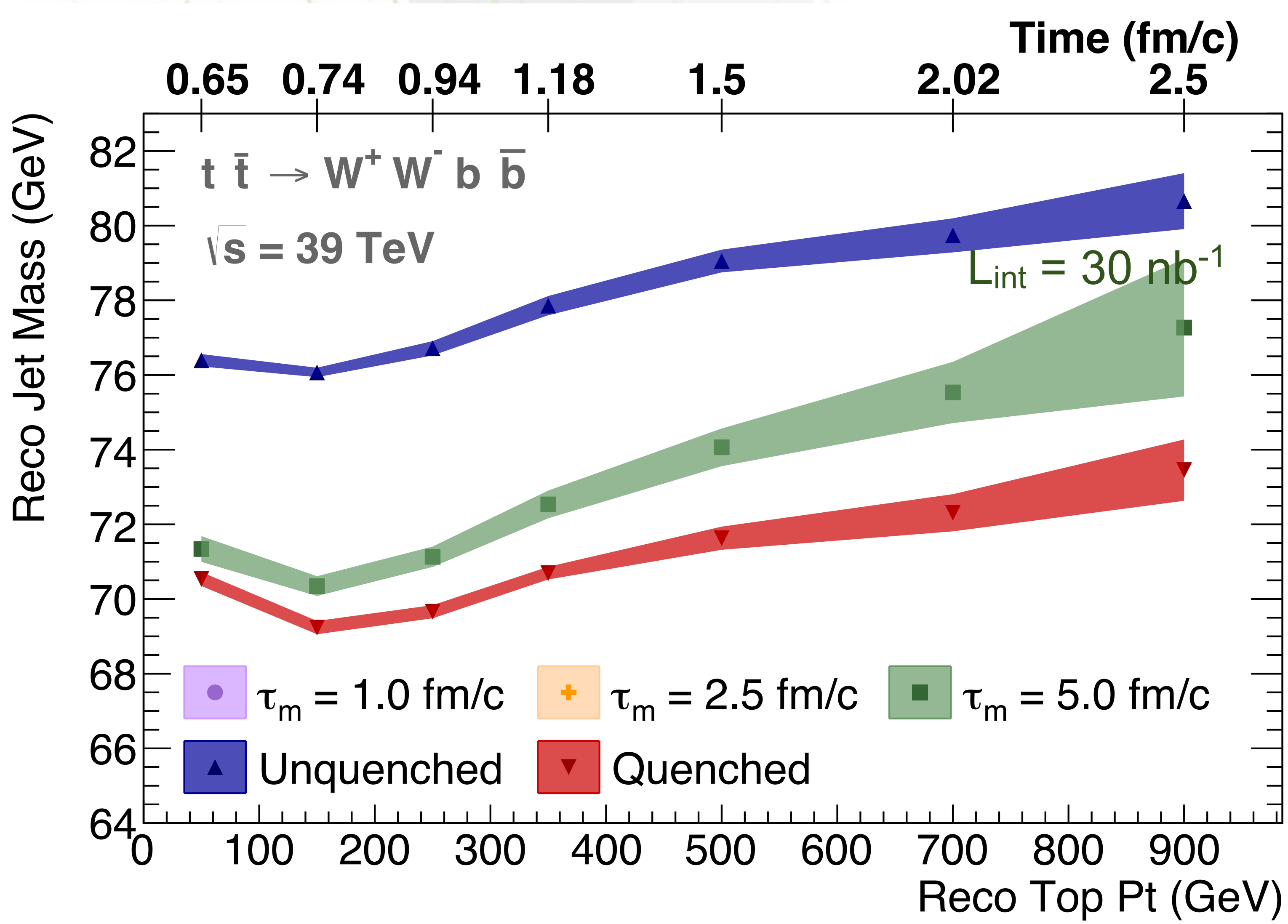

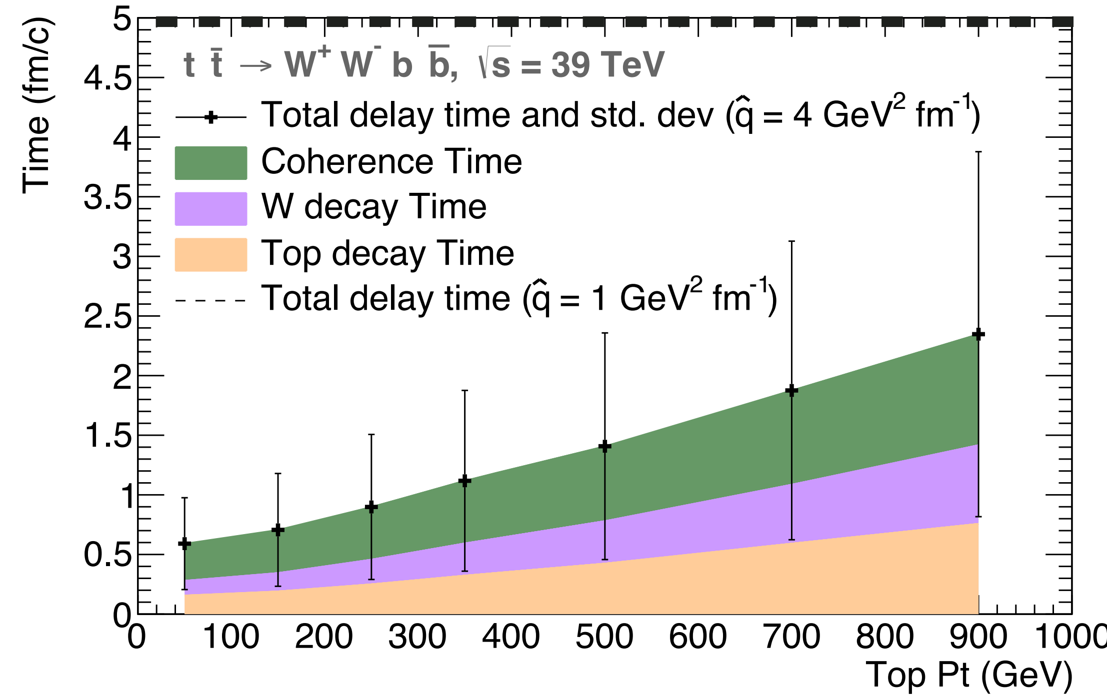

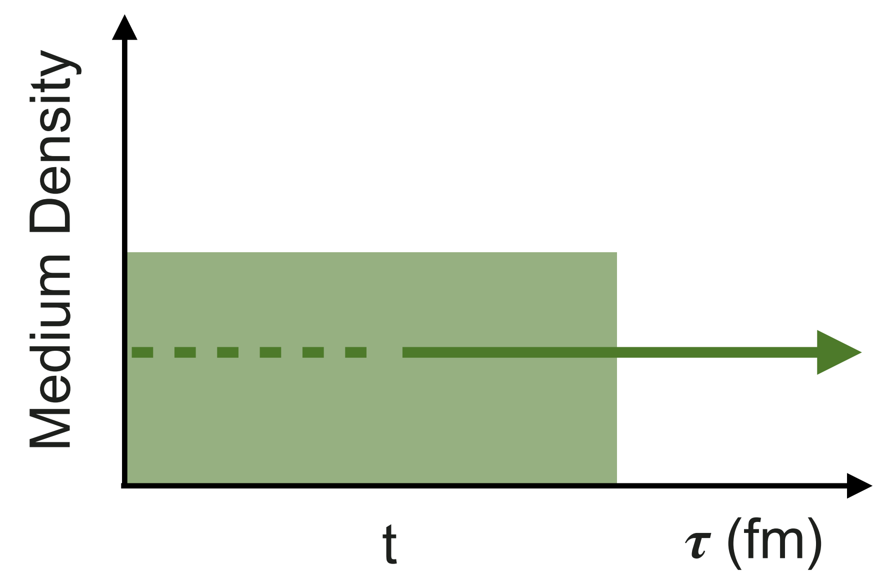

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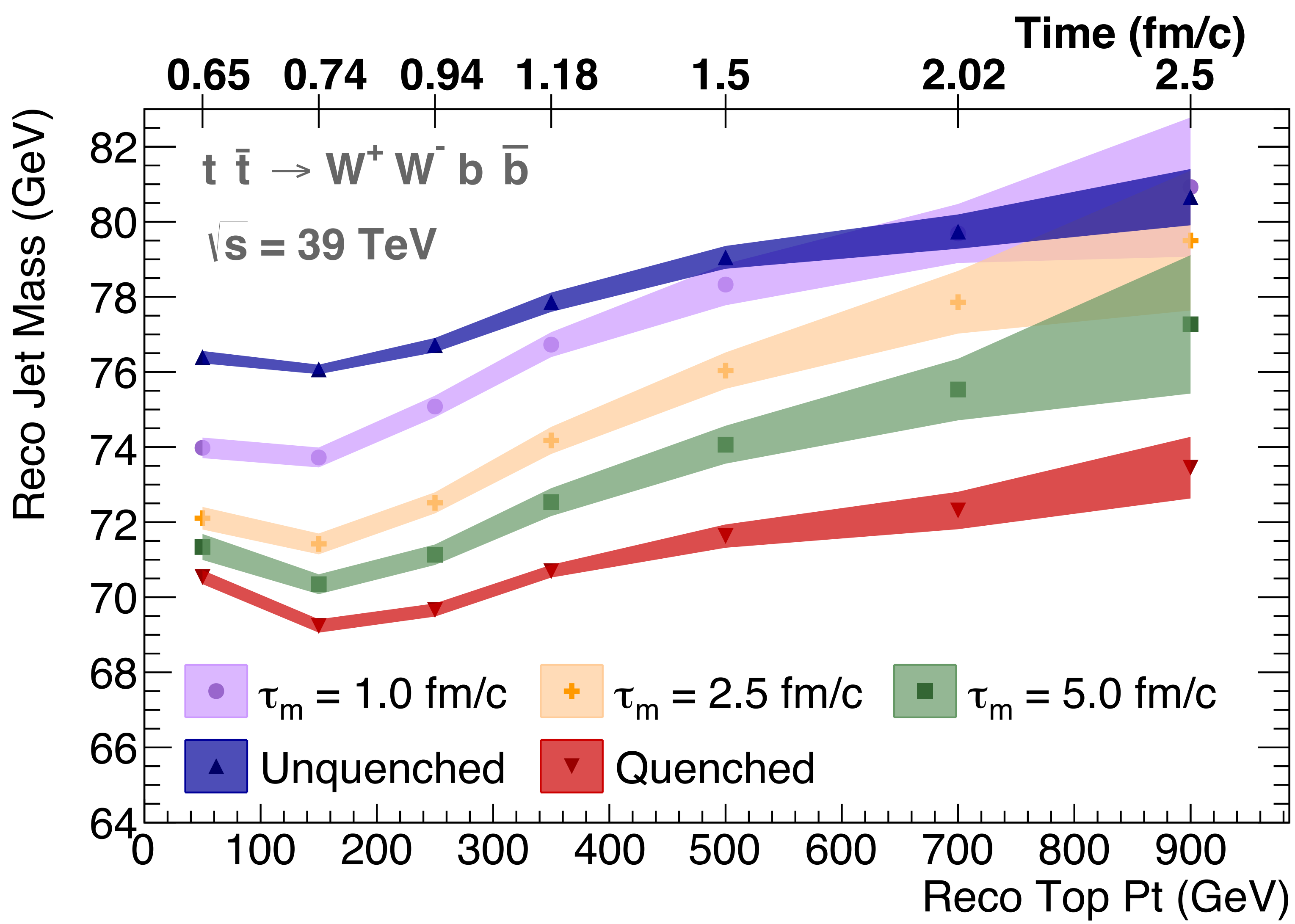

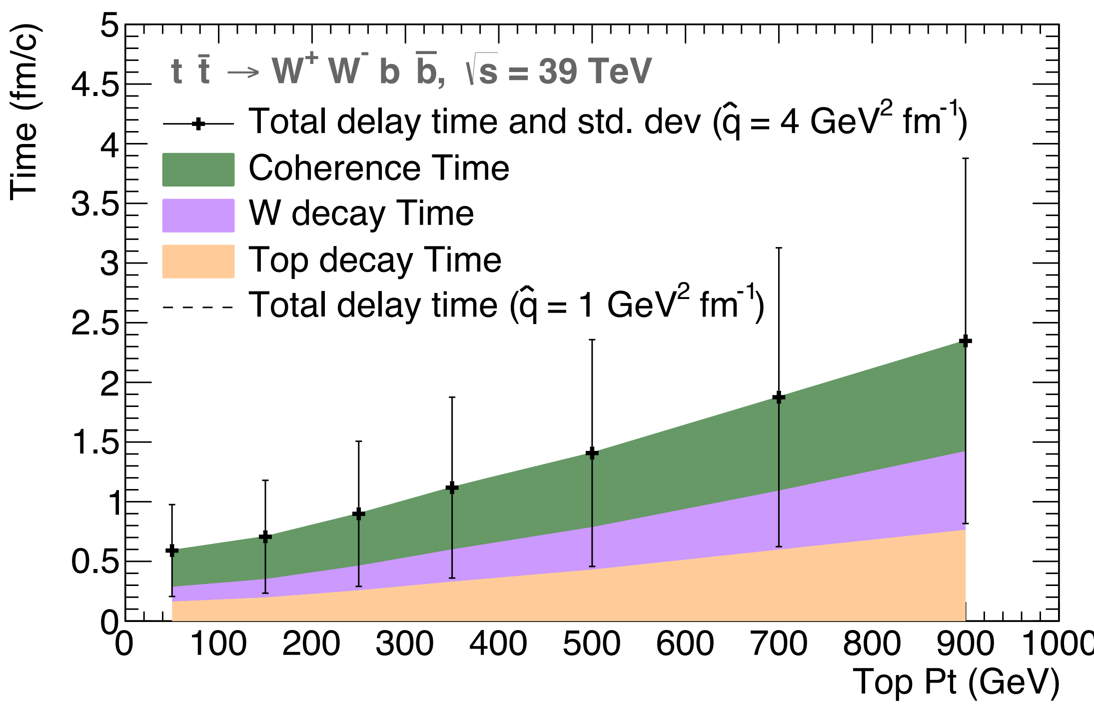

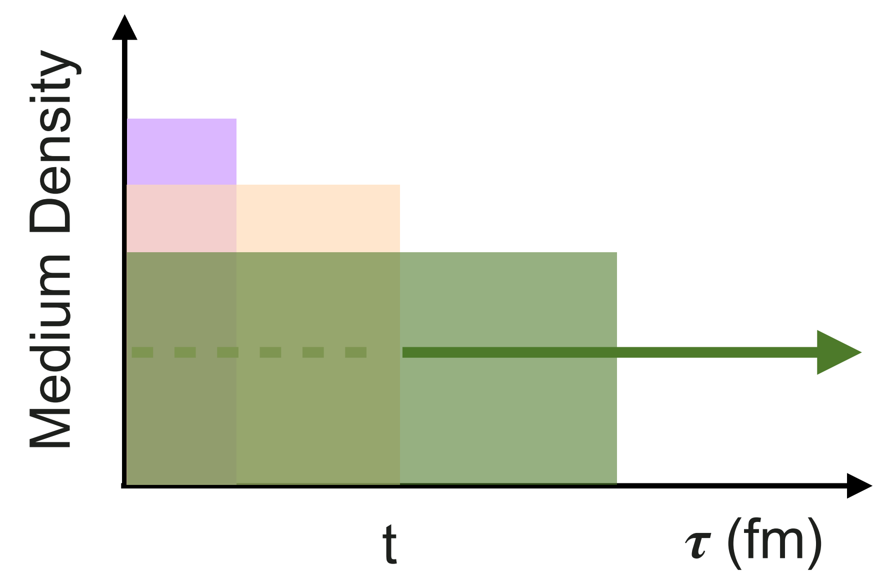

Depending on the chosen p_T, the antenna may still lose some energy.
Knowing the energy loss, it is possible to build the density evolution profile of the medium!

- Toy model to study the effect of “switching-off” the jet interaction for some time t;
  - Build up a picture of the density evolution:
    - [0.5 - 2.5] fm @ FCC
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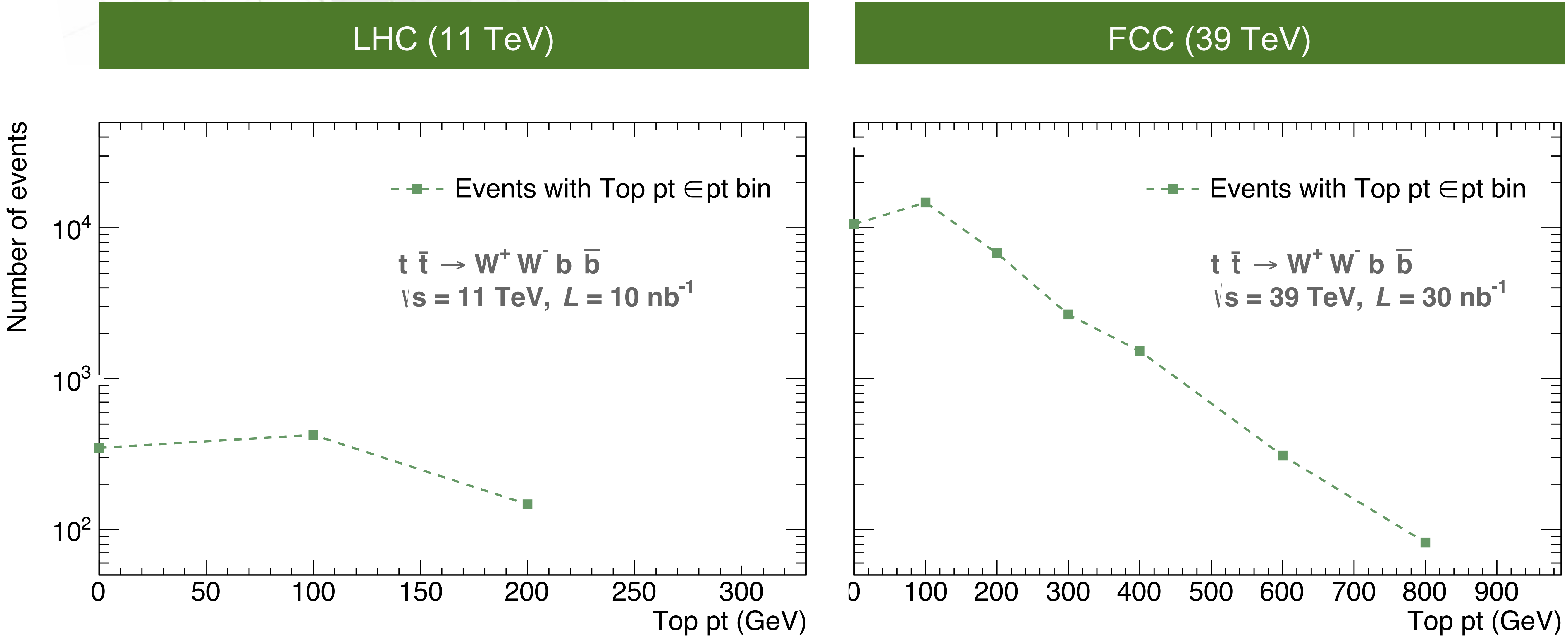
- How about at current accelerators?
  - LHC 5 TeV; LHC 11 TeV?
  - What would be the luminosity needed to probe a given time scale of the produced medium?

Available statistics at LHC and FCC

- Expected number of events:
  - LHC 11 TeV (L = 10 nb^{-1}) and FCC 39 TeV (L = 30 nb^{-1})



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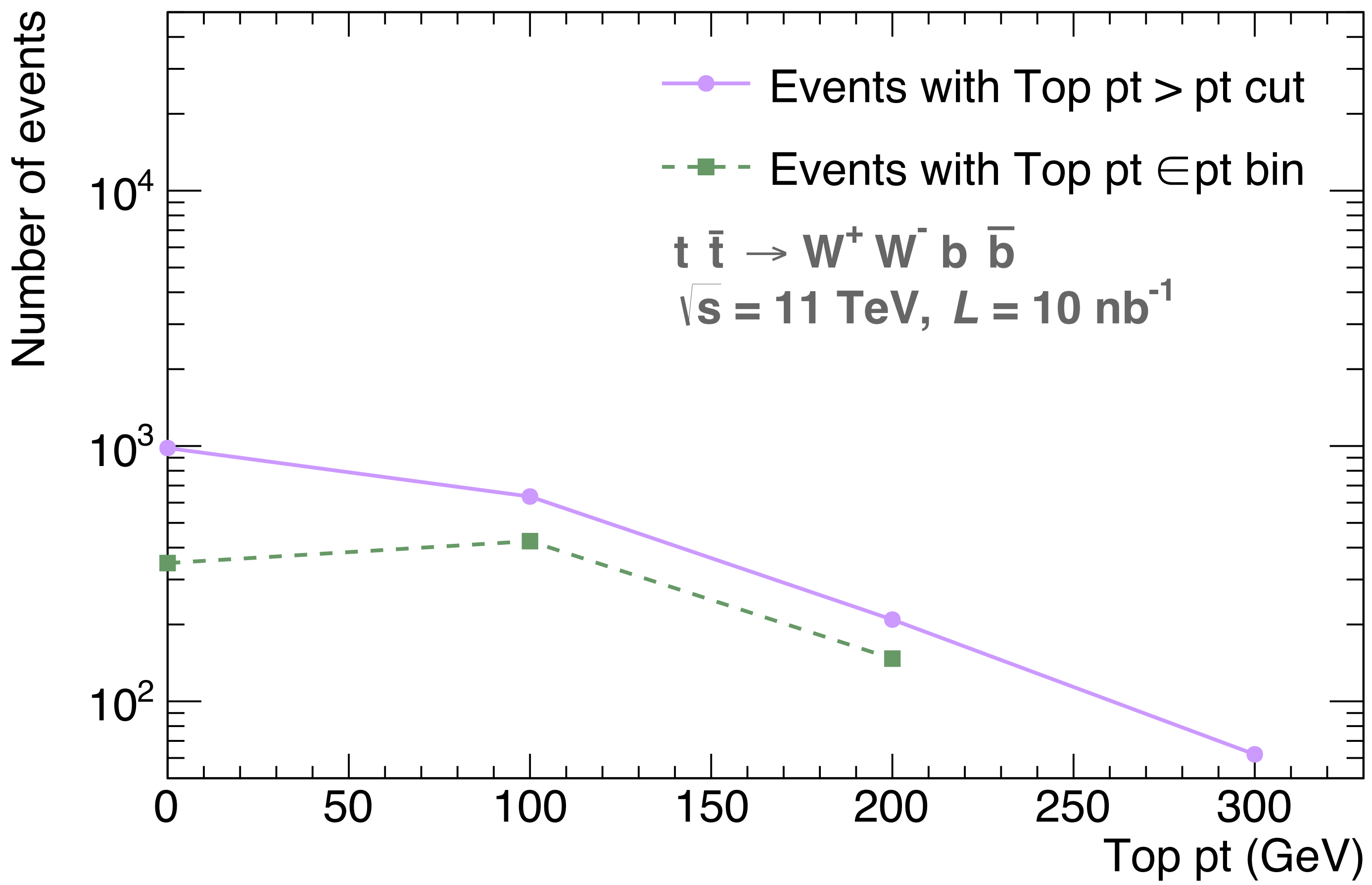
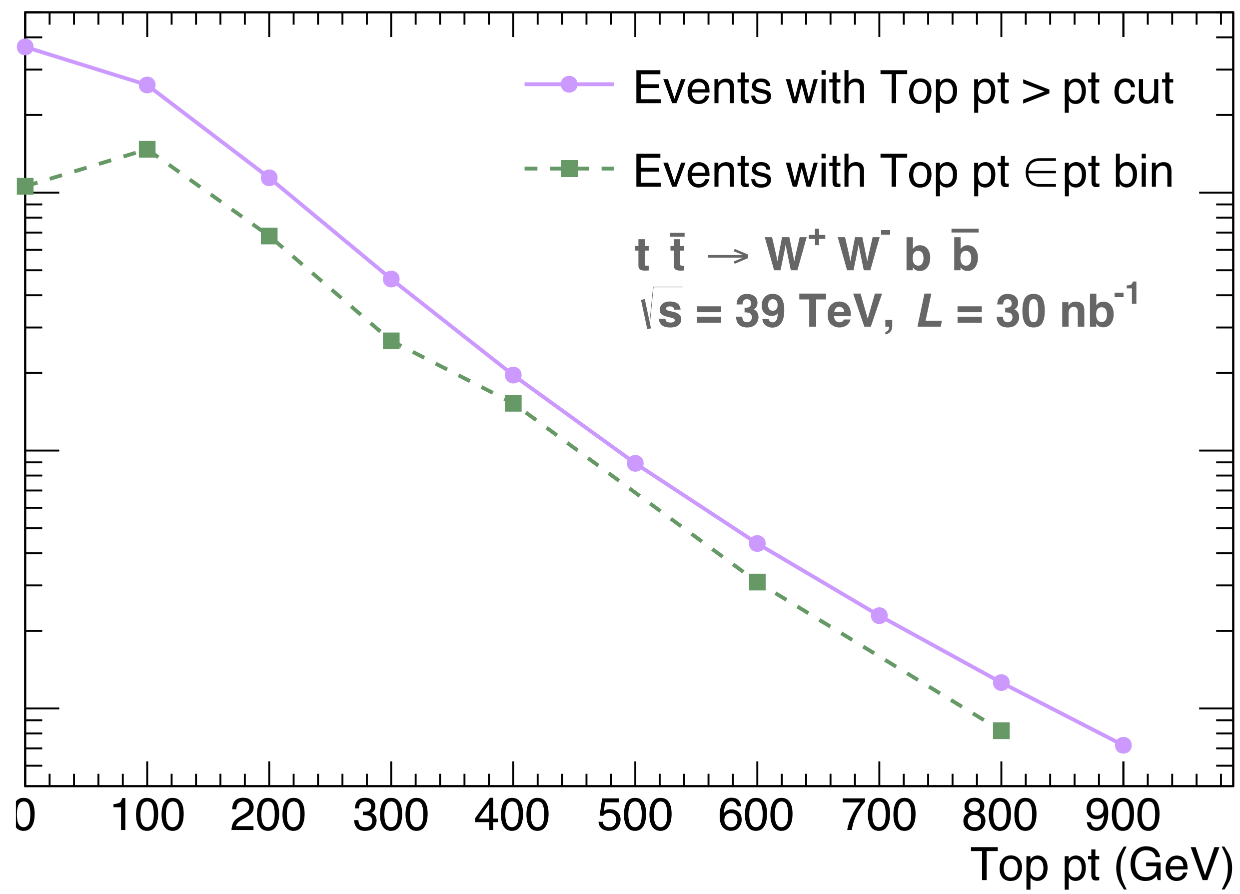
LHC (11 TeV)



FCC (39 TeV)

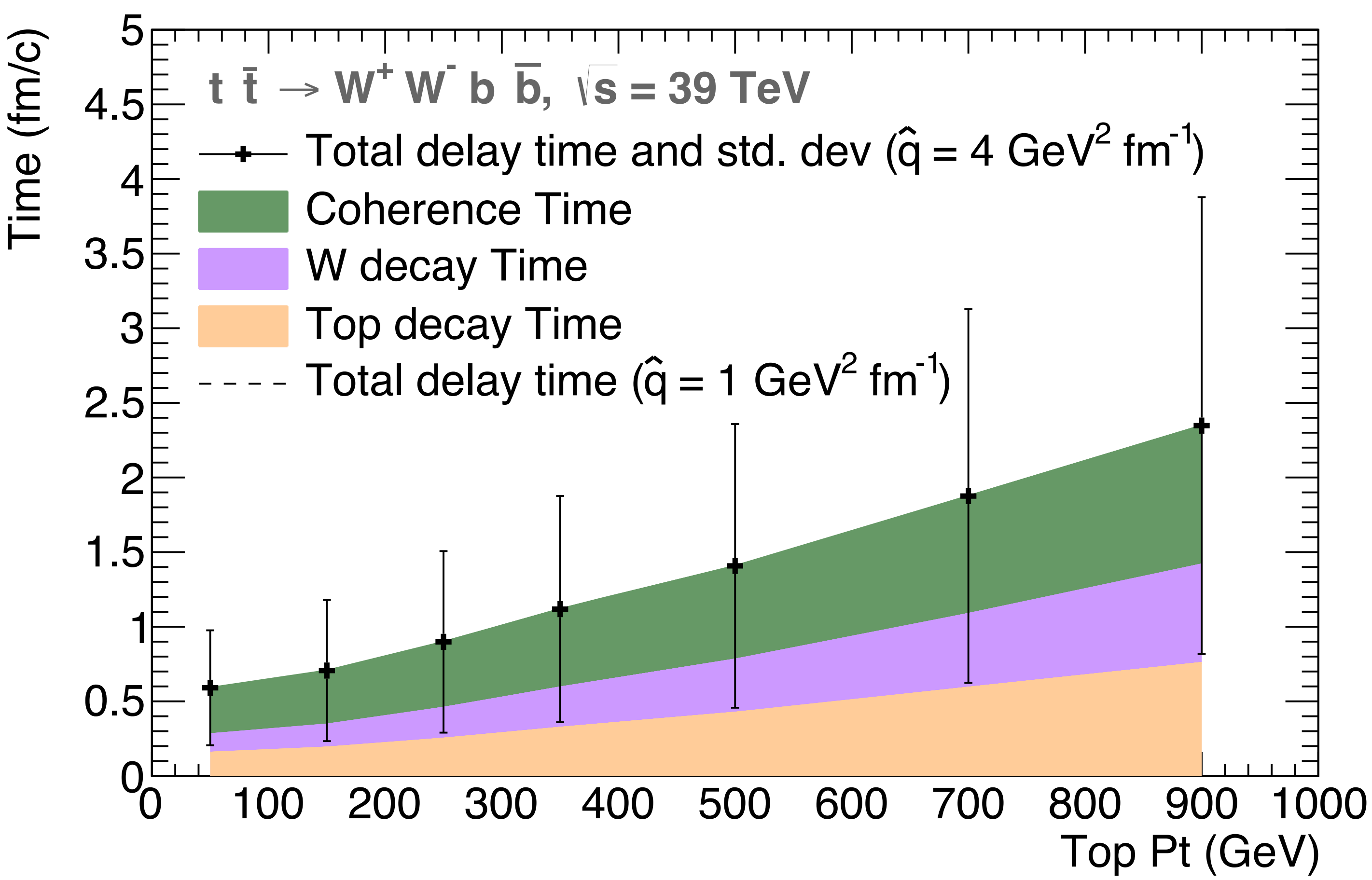


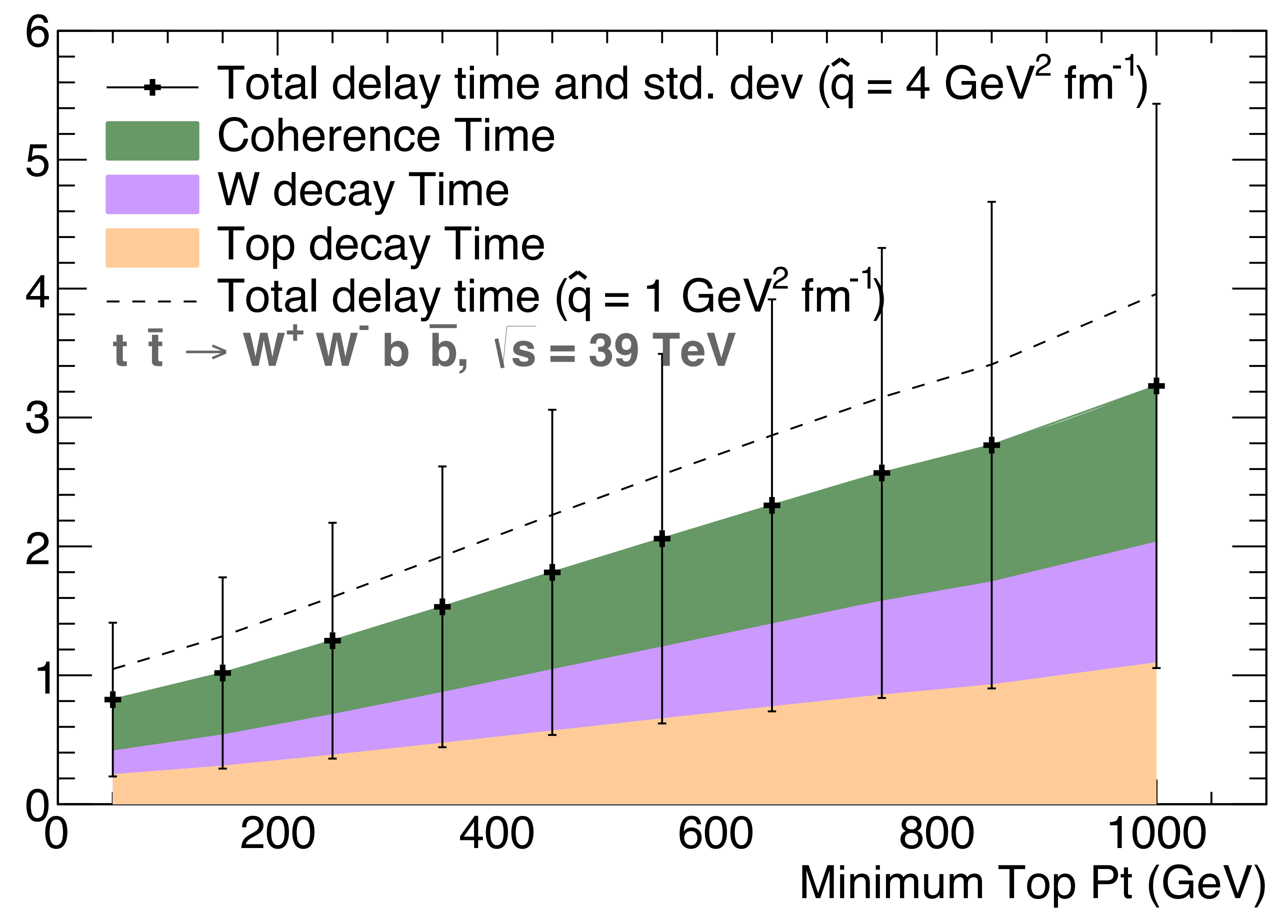
Statistics increase at least 10% when using minimum Top pt

Time scales for minimum Top pt

- Total delay time average value for Top pt vs minimum Top pt:
  - √s = 39 TeV (FCC)

Top pt bins	Minimum Top pt





Timescales vs Luminosity

- Reconstructed W jet should have at least 100 events (statistical significance ~ 1 GeV) above the estimated background

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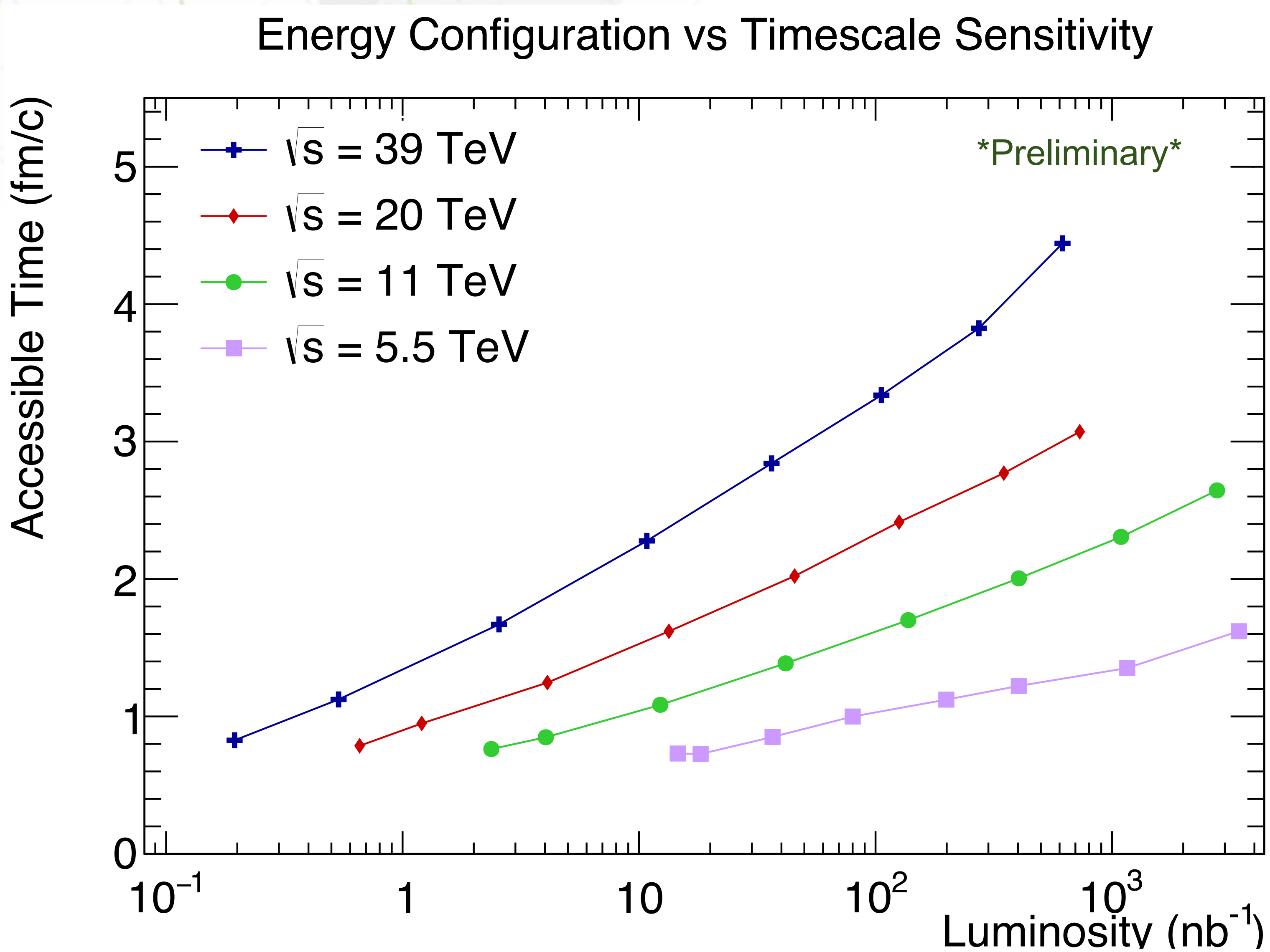

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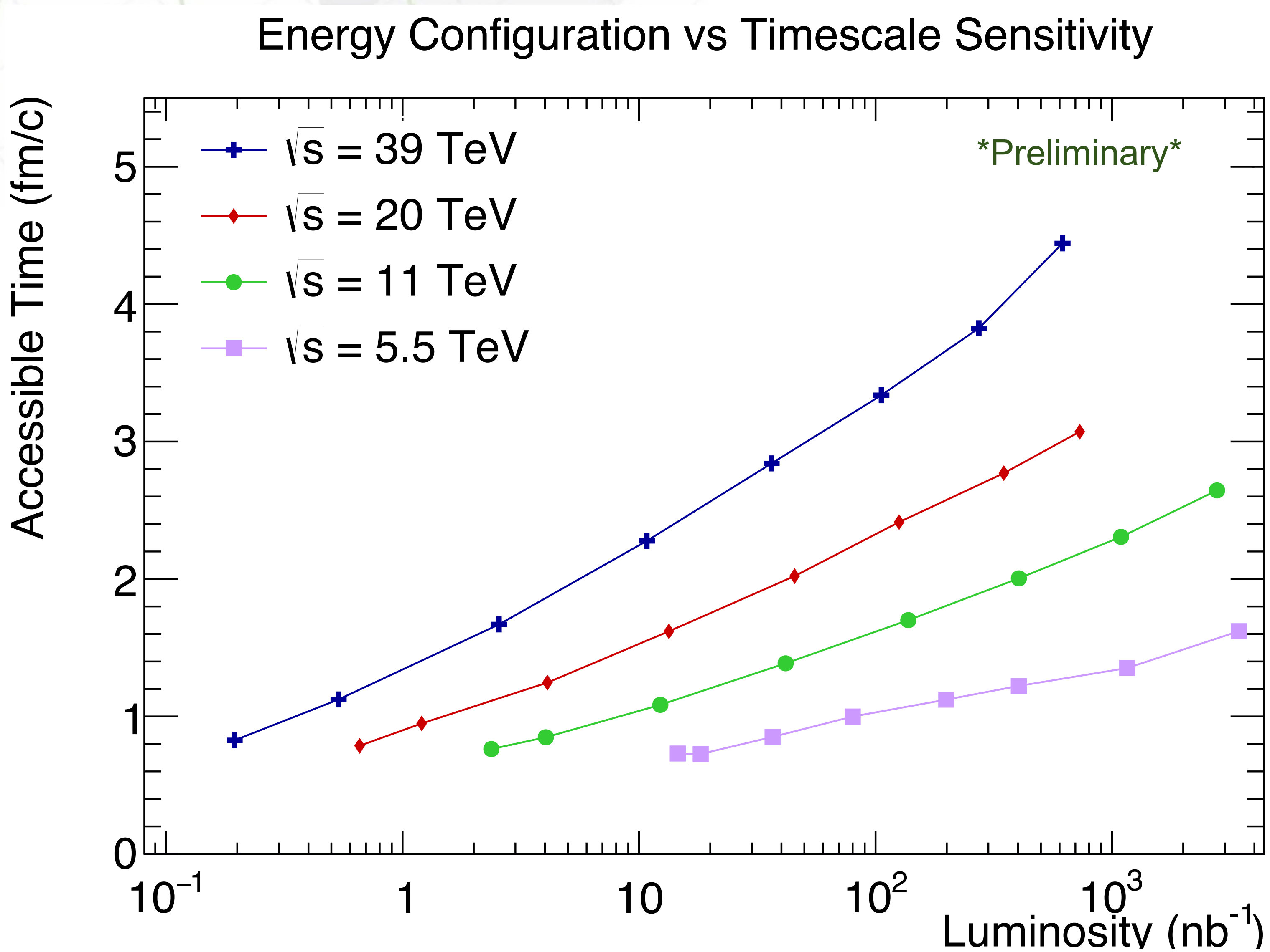

Bound free pair production ~ Z^7
L_{int} ~ A^2
Should be possible to go to a lighter nuclei

Conclusions

- First proof-of-principle analysis of boosted objects in heavy-ions;

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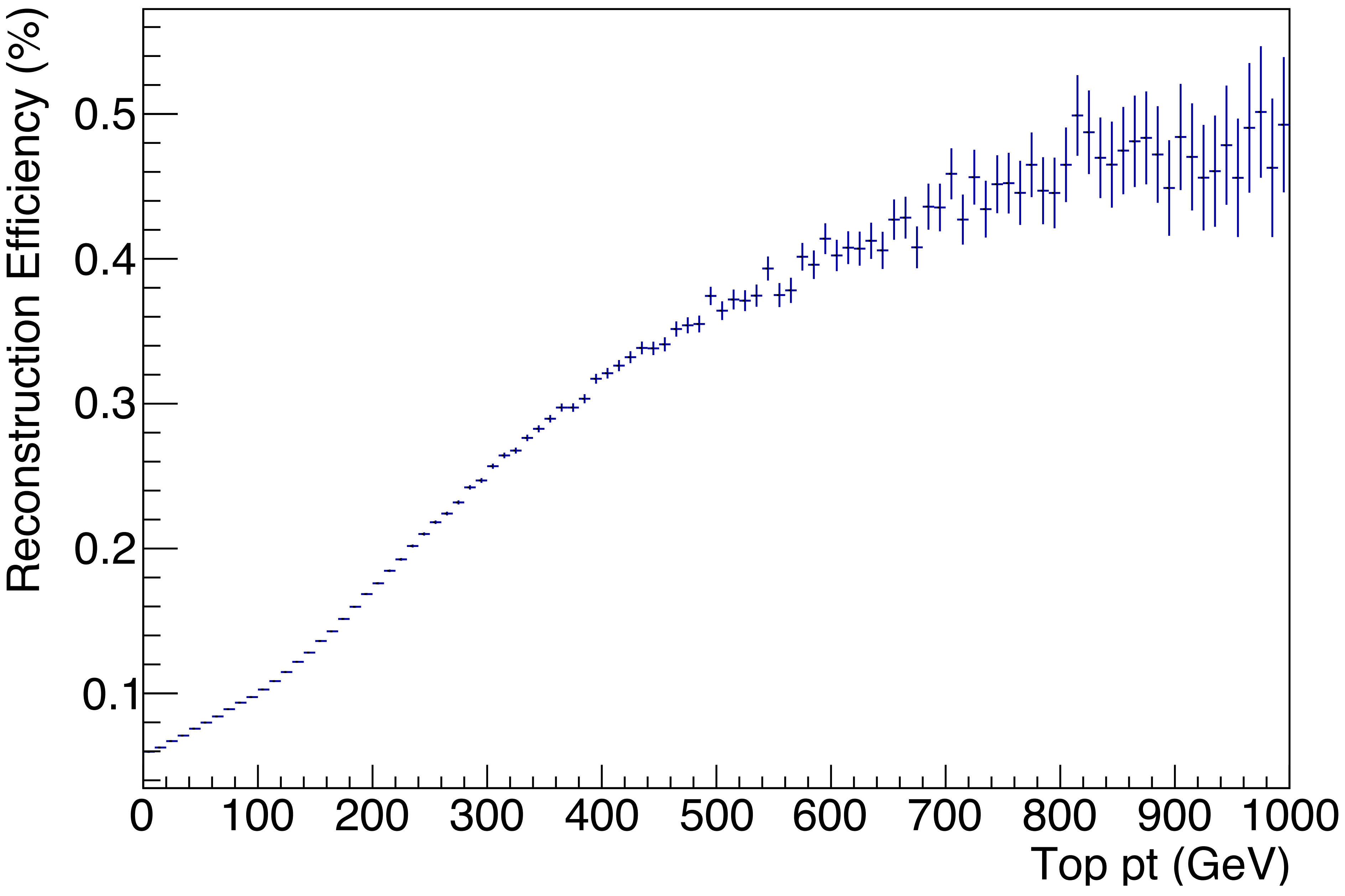
Thank you!

Backup Slides

Jet Reconstruction Efficiency

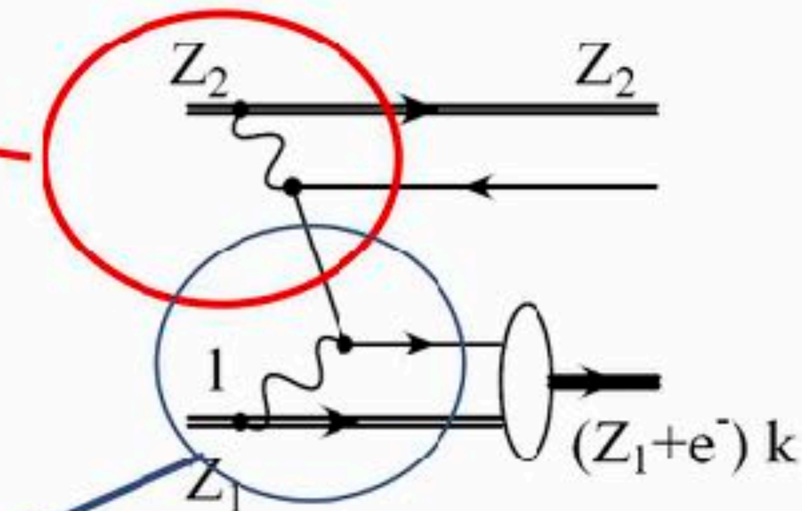


Bound Free Pair Production

J. Jowet, Initial Stages 2016

- Cross-sections for electromagnetic processes in ultra-peripheral collisions is very large:
  - Bound-free e^-e^+ pair production creates secondary beams of Pb^{81+} ions emerging from the collision point;

Pair production $\propto Z_1^2 Z_2^2$



Radial wave function of $1s_{1/2}$ state of hydrogen-like atom in its rest frame

$$R_{10}(r) = \left(\frac{Z_1}{a_0}\right)^{3/2} 2\exp\left(-\frac{Z_1 r}{a_0}\right)$$

$$\Rightarrow \quad \Psi(0) \,\square\, Z_1^{3/2} \quad \Rightarrow \quad |\Psi(0)|^2 \,\square\, Z_1^3$$

G. Baur et al, Phys. Rept. 364 (2002) 359

Cross section for Bound-Free Pair Production (BFPP) (various authors)

$$Z_1 + Z_2 \to (Z_1 + e^-)_{1s_{1/2},\ldots} + e^+ + Z_2$$

has very strong dependence on ion charges (and energy)

$$\sigma_{PP} \propto Z_1^5 Z_2^2 \left[A \log \gamma_{CM} - B\right]$$

$$\propto Z^7 \left[A \log \gamma_{CM} + B\right] \quad \text{for } Z_1 = Z_2$$

$$\approx \begin{cases} 0.2 \text{ b for Cu-Cu RHIC} \\ 114 \text{ b for Au-Au RHIC} \\ 281 \text{ b for Pb-Pb LHC} \end{cases}$$

Total cross-section □ $Z_2^2 Z_1^5$

Easy to avoid the bound by going lighter!
But lose nucleon-nucleon luminosity as A^2.