Probing the QGP time structure from large to small(er) systems with top quarks

Liliana Apolinário

LIP

Guilherme Milhano, Carlos Salgado and Gavin Salam

Based on:
arXiv:1711.03105 and arXiv: 1812.06772 (HE-LHC WG5)

Introduction

- Probing of the QGP in heavy-ion collisions through a range of complementary probes:
  - Jets, Quarkonia, Hydrodynamical Flow coefficients, Hadrochemistry,…
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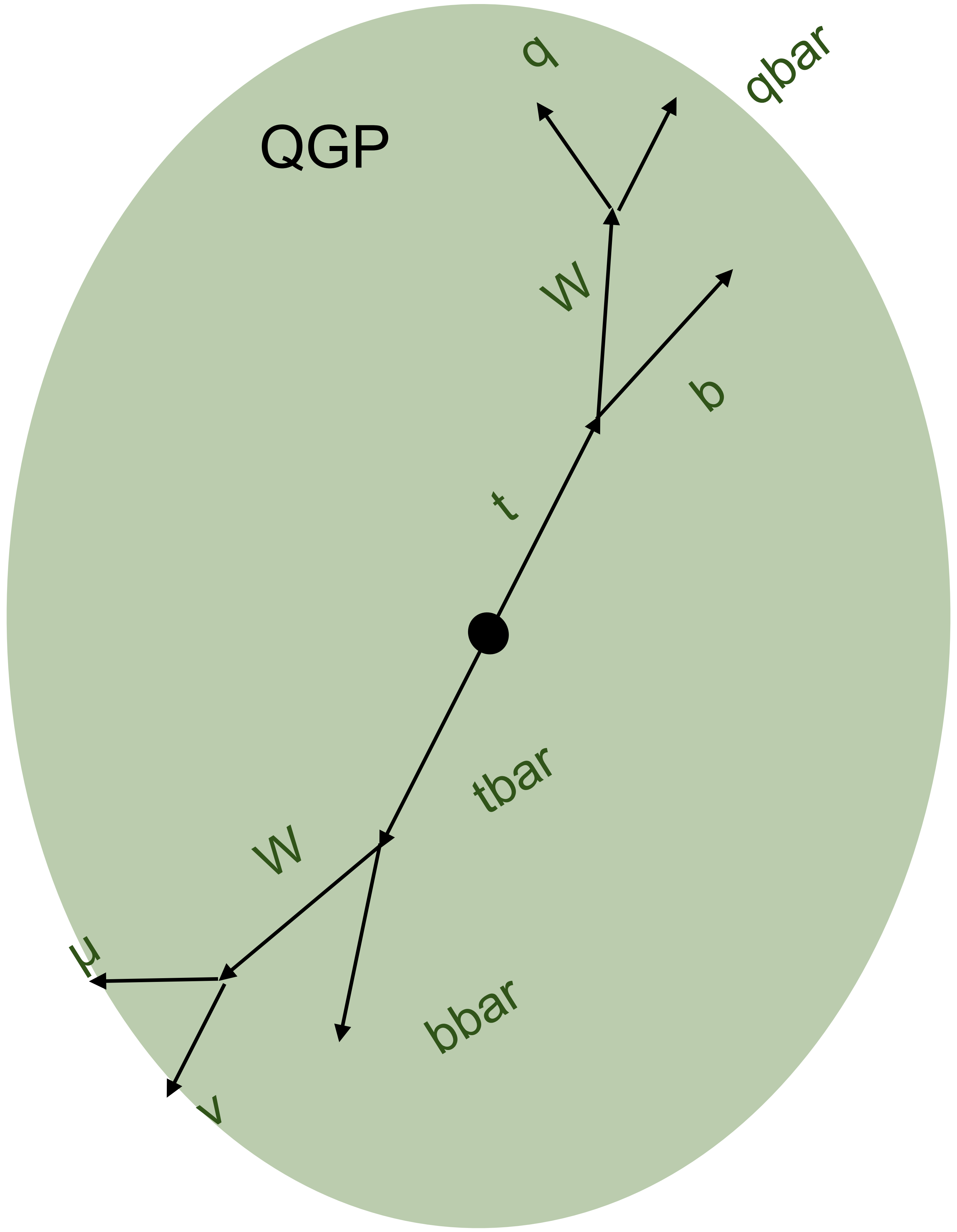
Need to devise a strategy to probe the time-structure of the QGP!

Jet Quenching

- Jet Quenching probes so far: Dijets, Z+jet, ɣ+jet, …
  - Produced simultaneously with the collision;
  - Our suggestion: t+tbar events
    - Leptonic decay: tagging;
    - Hadronic decay: probe of the medium
      - Decay chain: top + W boson
        - At rest: τ_{top} = 0.15 fm/c; τ_W = 0.10 fm/c
        - ➡ Originated jets will interact with the medium at later times



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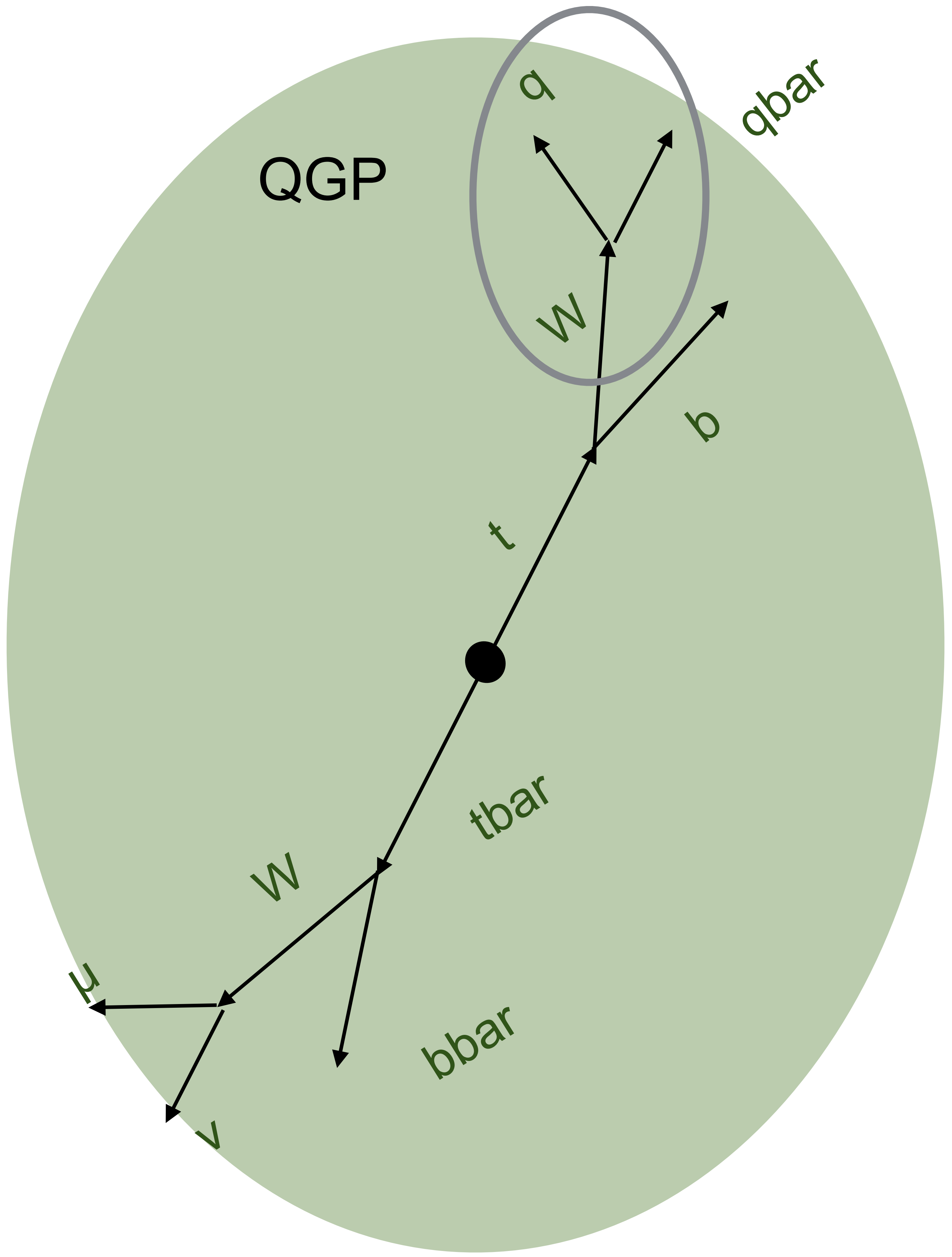
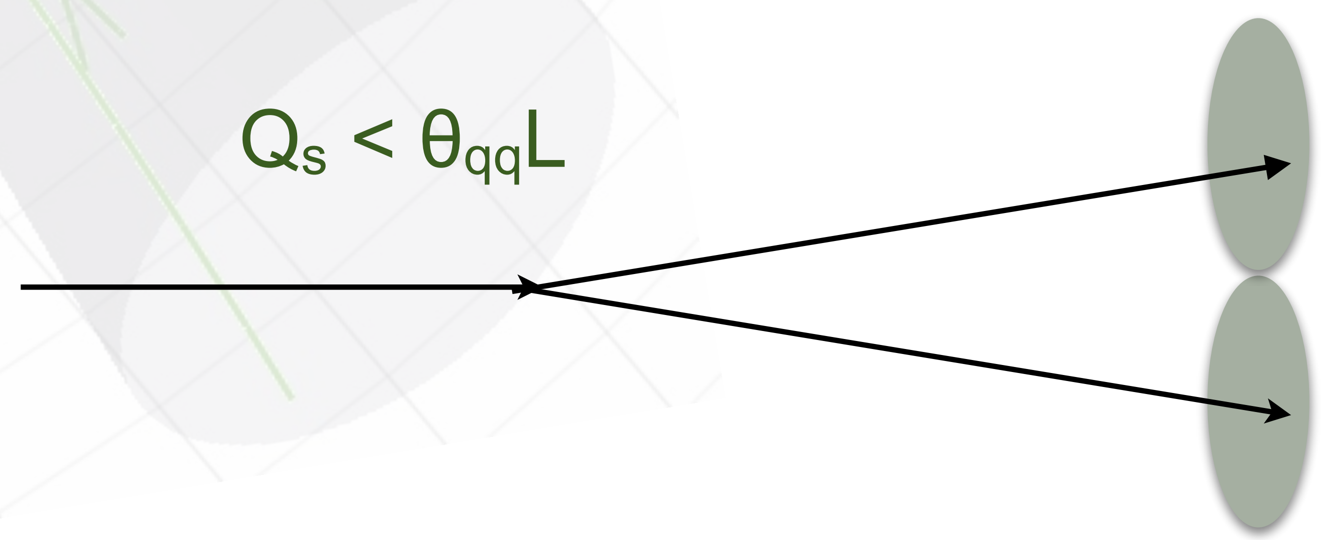
Closer look to q+qbar antenna…

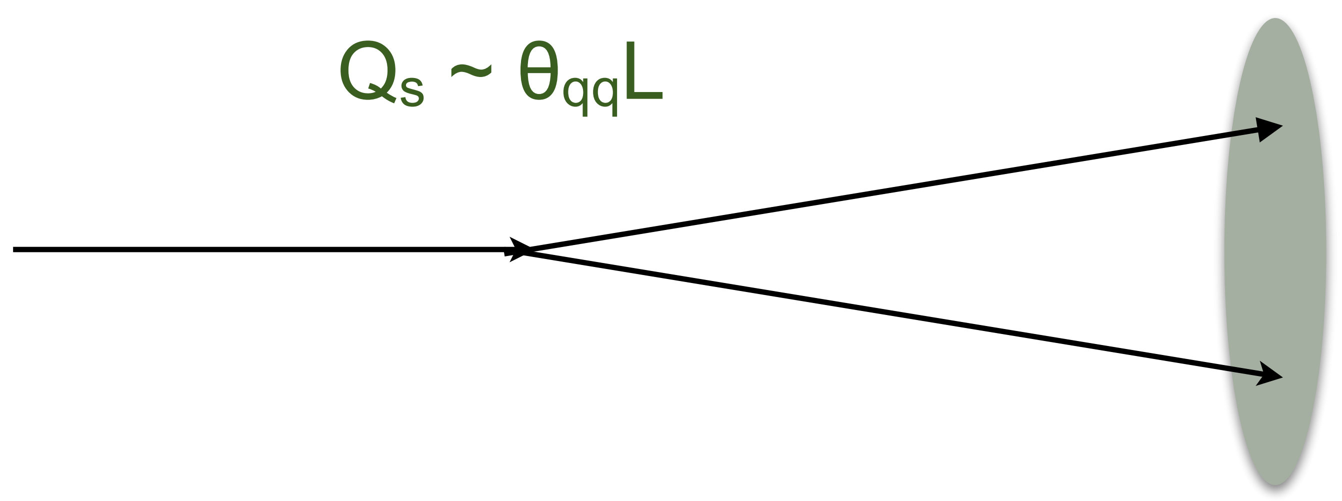


Color Coherence

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



Medium able to “see” both particles
Color correlation is broken
Both particles 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

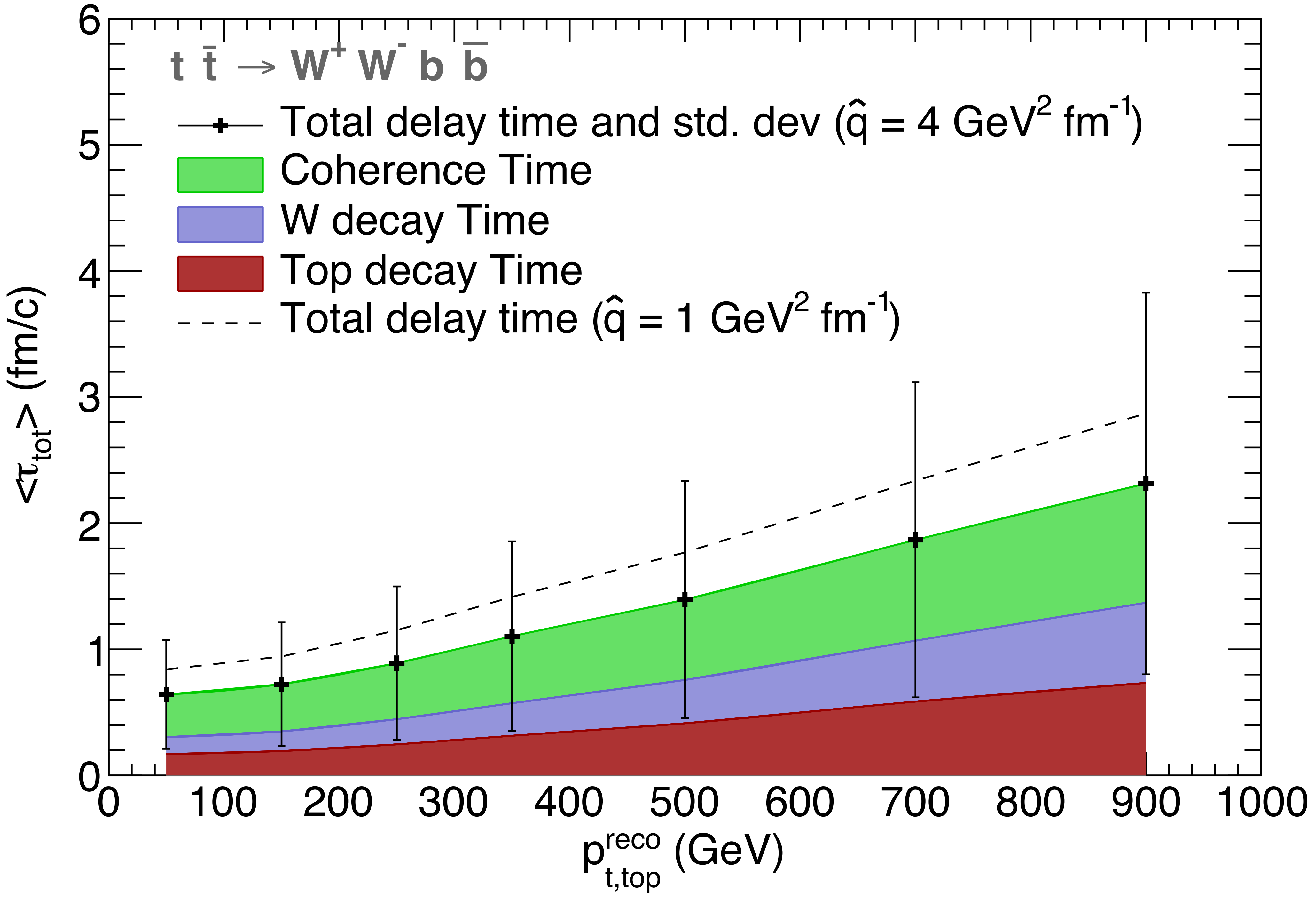
- Increases even more the time delay allowing to have a complete mapping of the QGP evolution:
  - Stay in colourless singlet state during:

$$t_d = \left(\frac{12}{\hat{q}\theta_{q\bar{q}}^2} \right)^{1/3}$$

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

Time Delayed Probes

- Total delay time as a function of the top p_T:



Transverse boost factor (top and W):

$$\gamma_{t,X} = \left(\frac{p_{t,X}^2}{m_X^2} + 1 \right)^{\frac{1}{2}}$$

Coherence time (q - qbar antenna):

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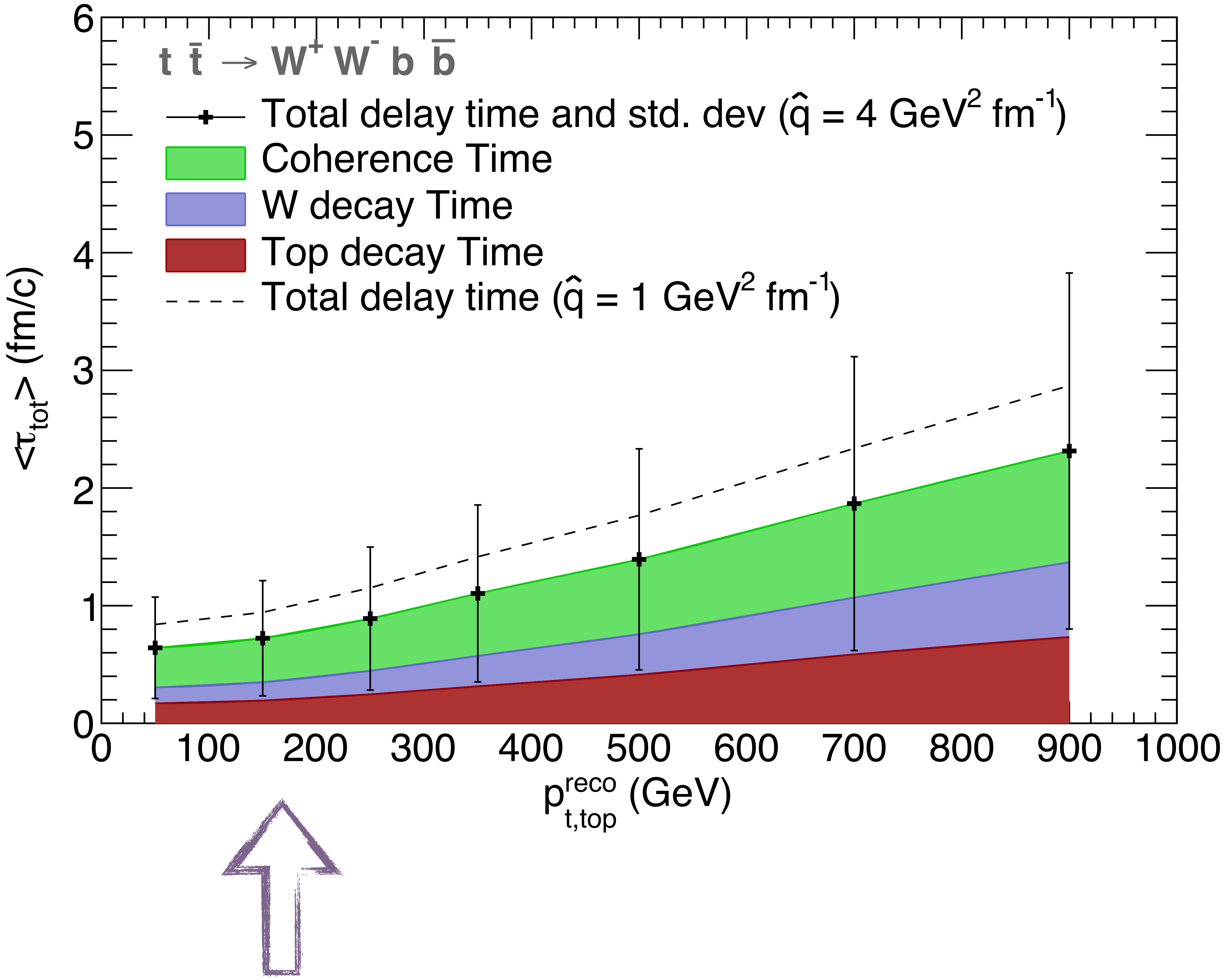

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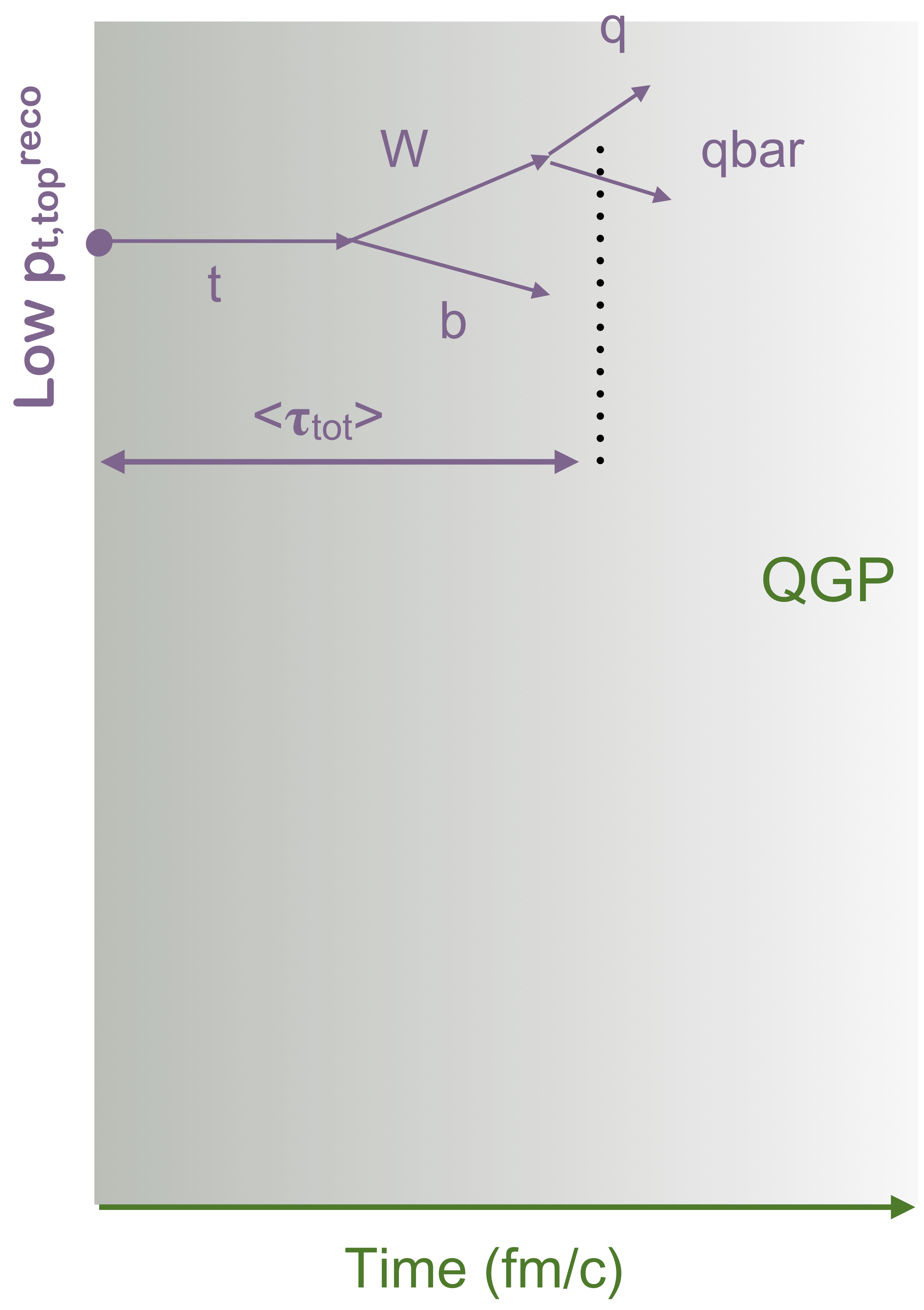

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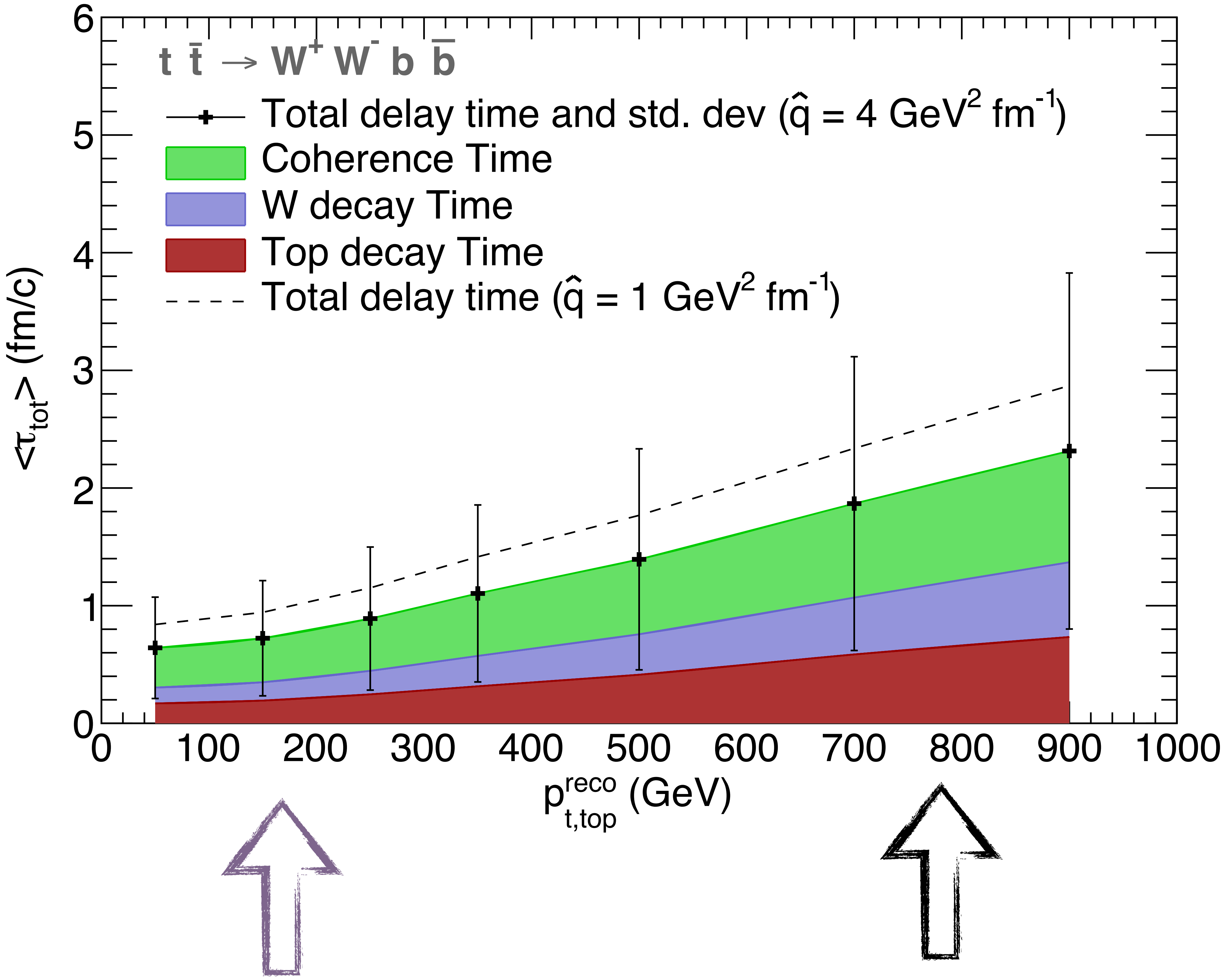

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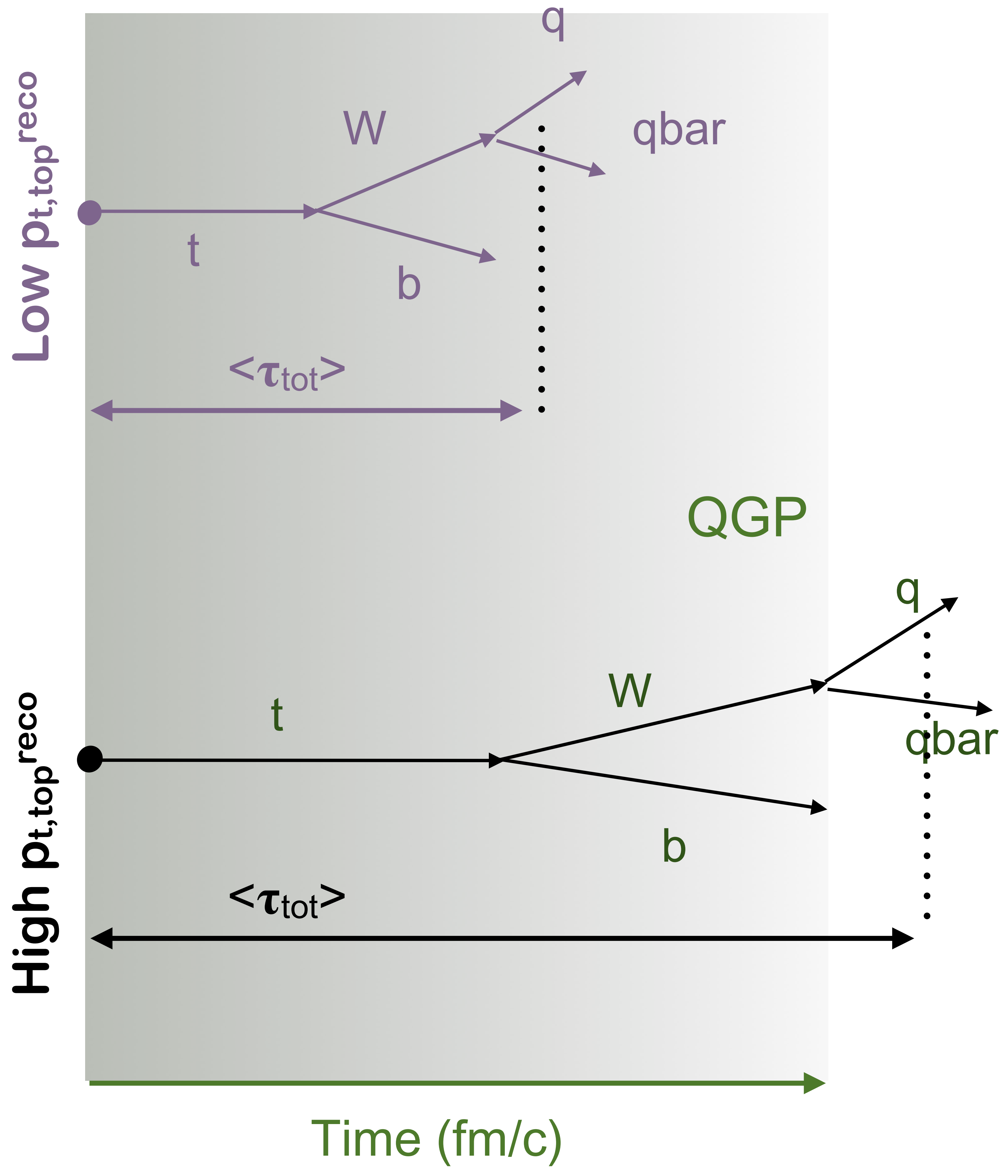
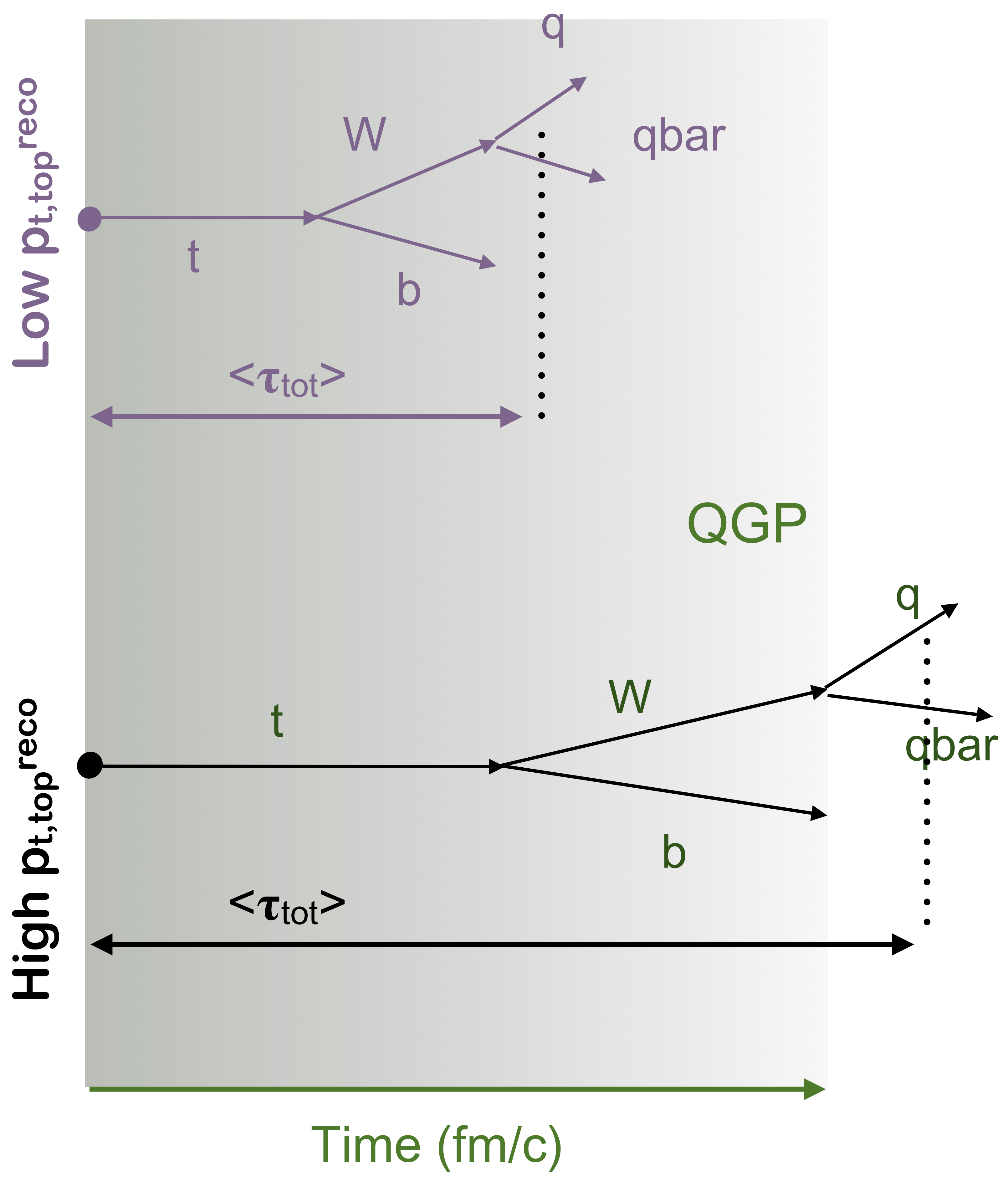


Time Dependence Toy Model

- From Z+jet measurements: $\Delta E/E \sim 15\%$ (independent of the pt)
- Particles emitted from qqbar “antenna” lose energy proportionally to the distance that they travel:
  - BDMPS (brick): $\Delta E/E \sim L^2$
  - BDMPS (expanding medium): $\Delta E/E \sim L$



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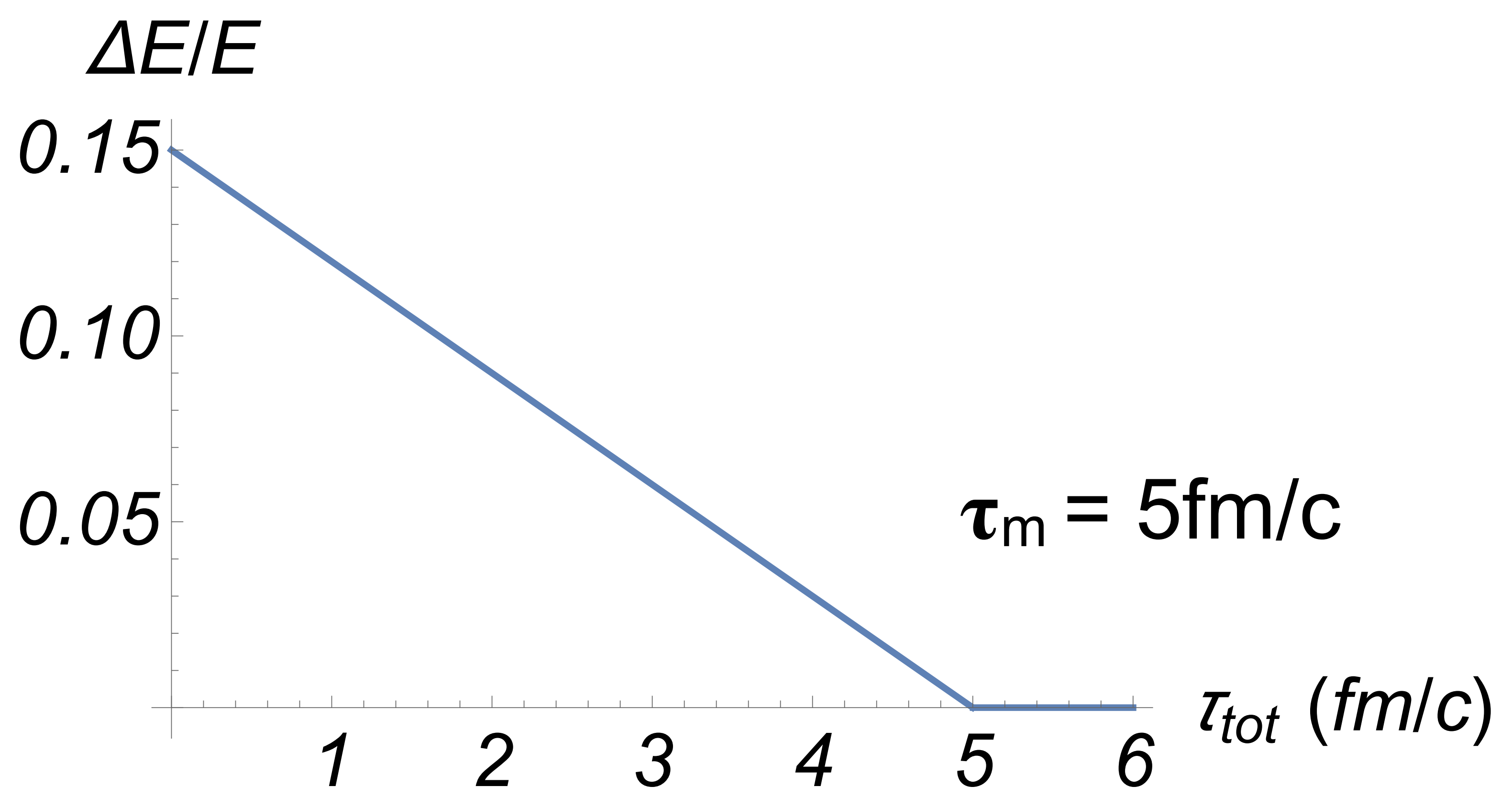
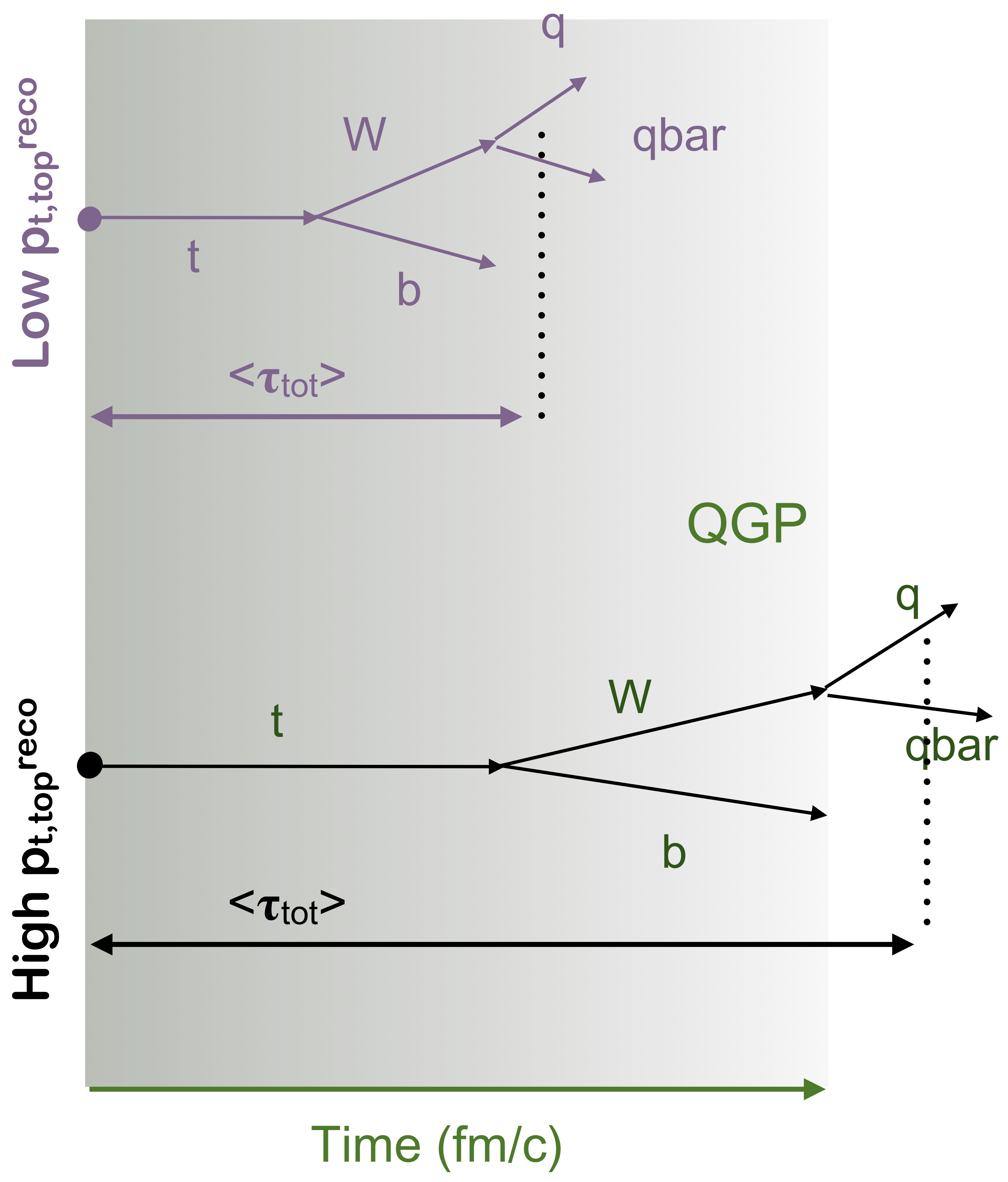


$\tau_{tot} = t_{top} + t_W + t_d$
time at which the antenna decoheres



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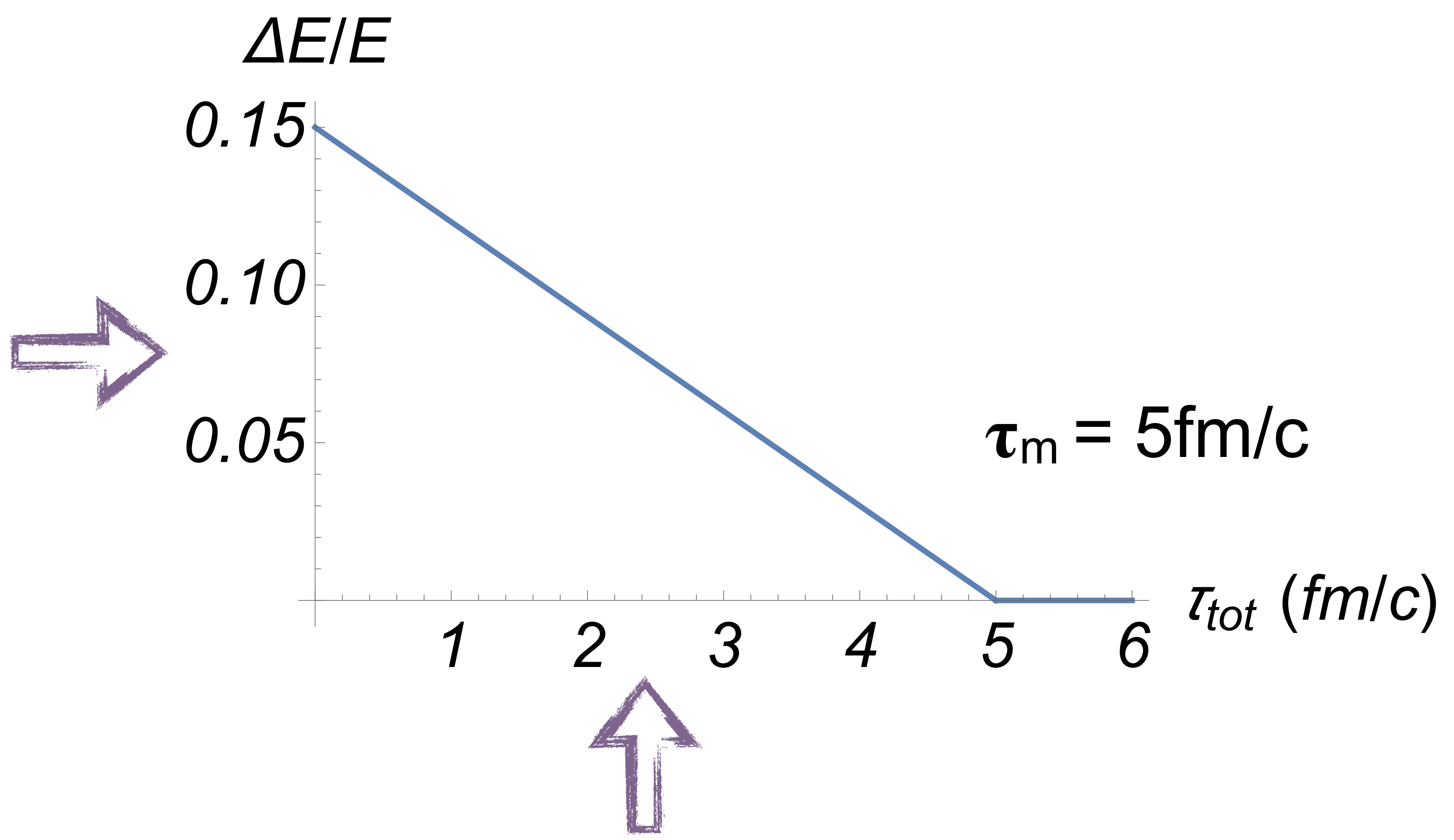

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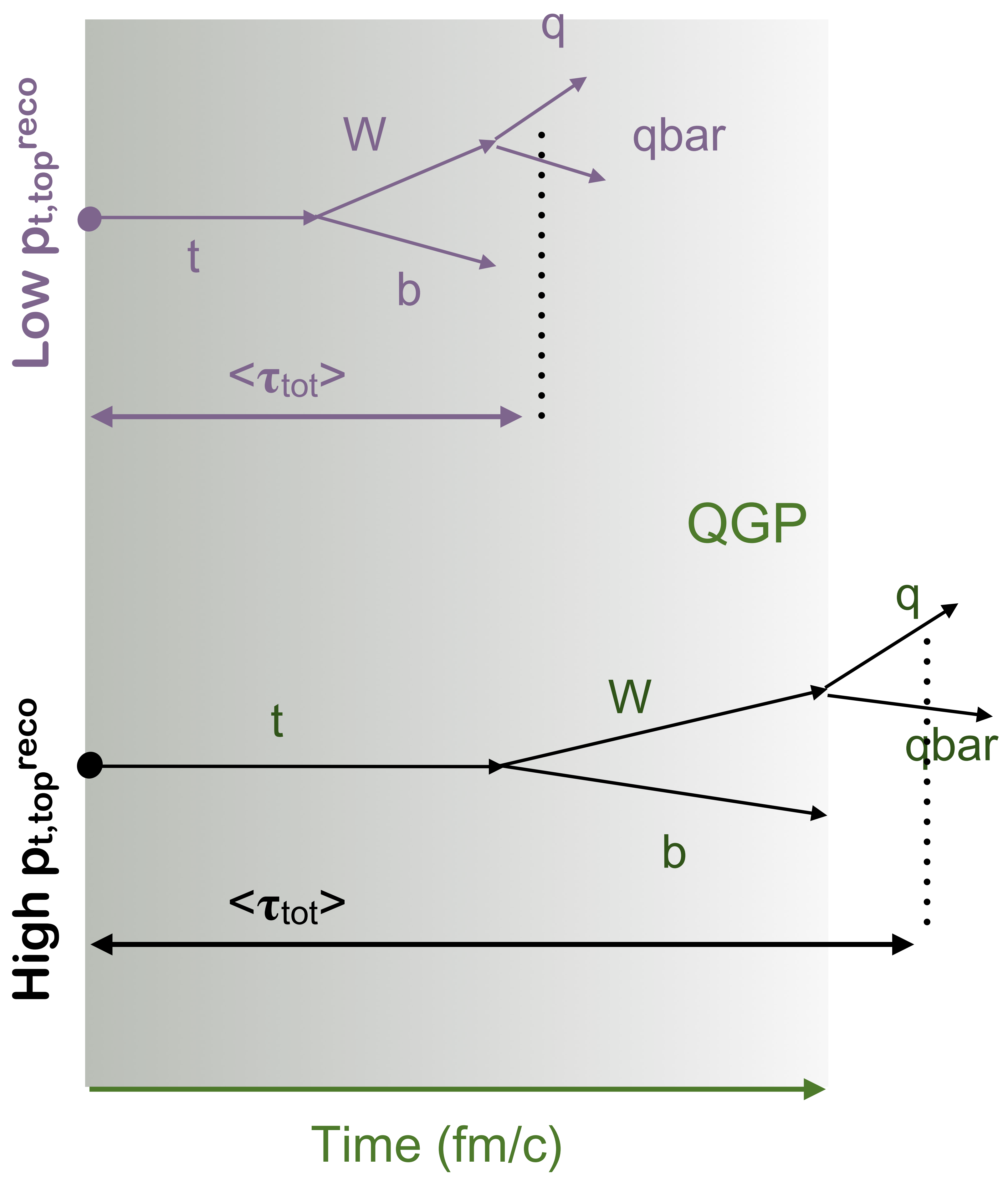

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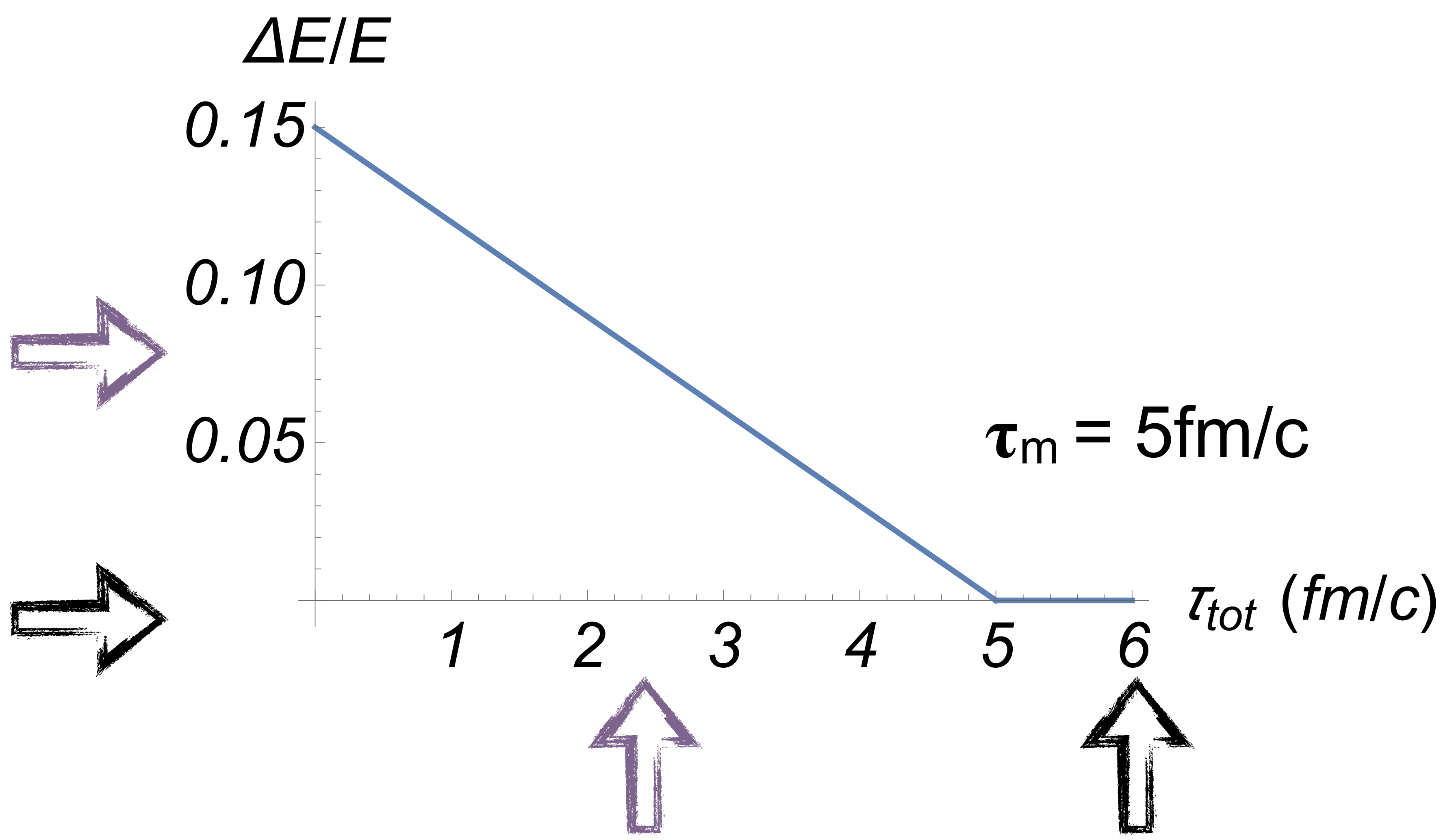

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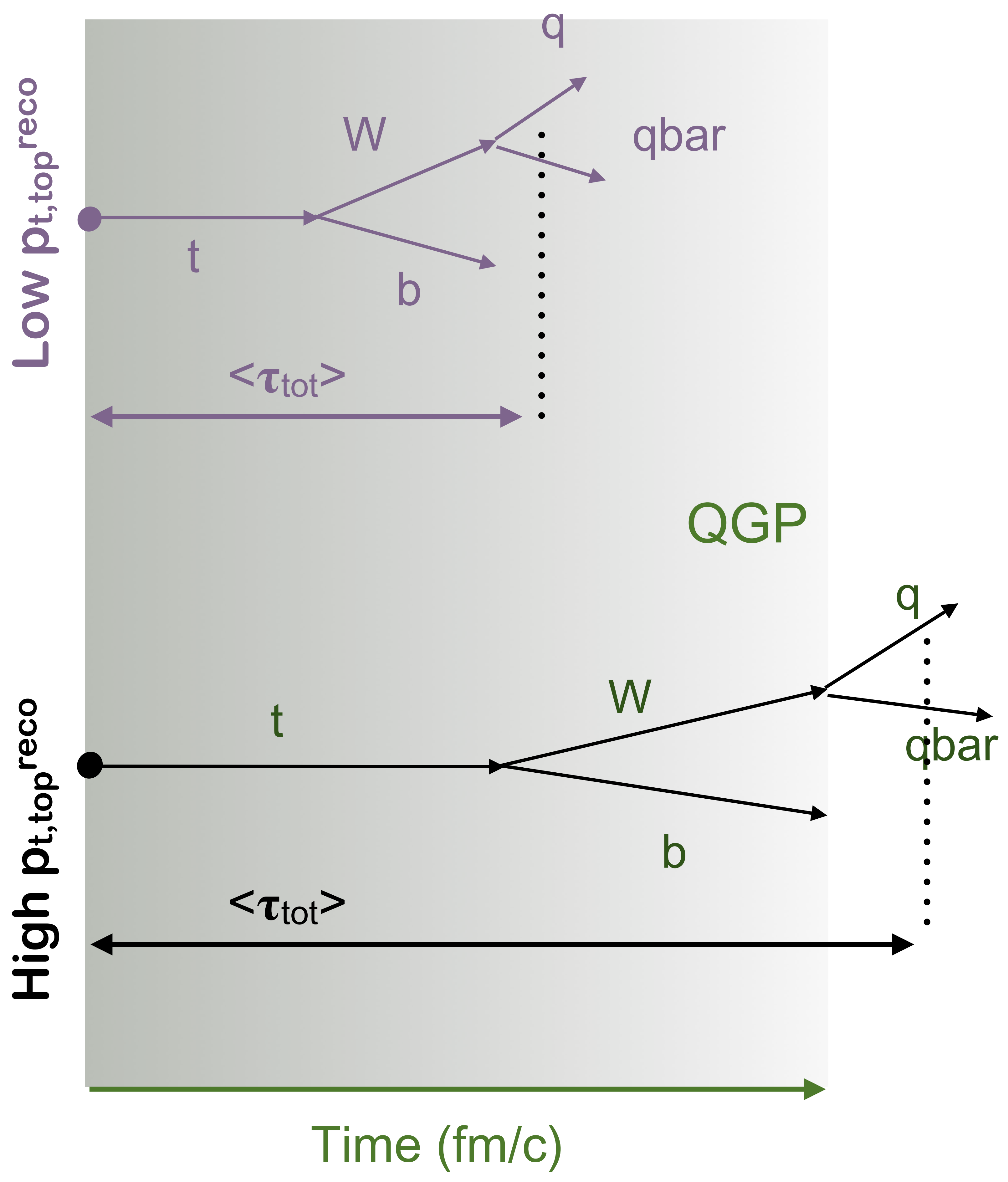
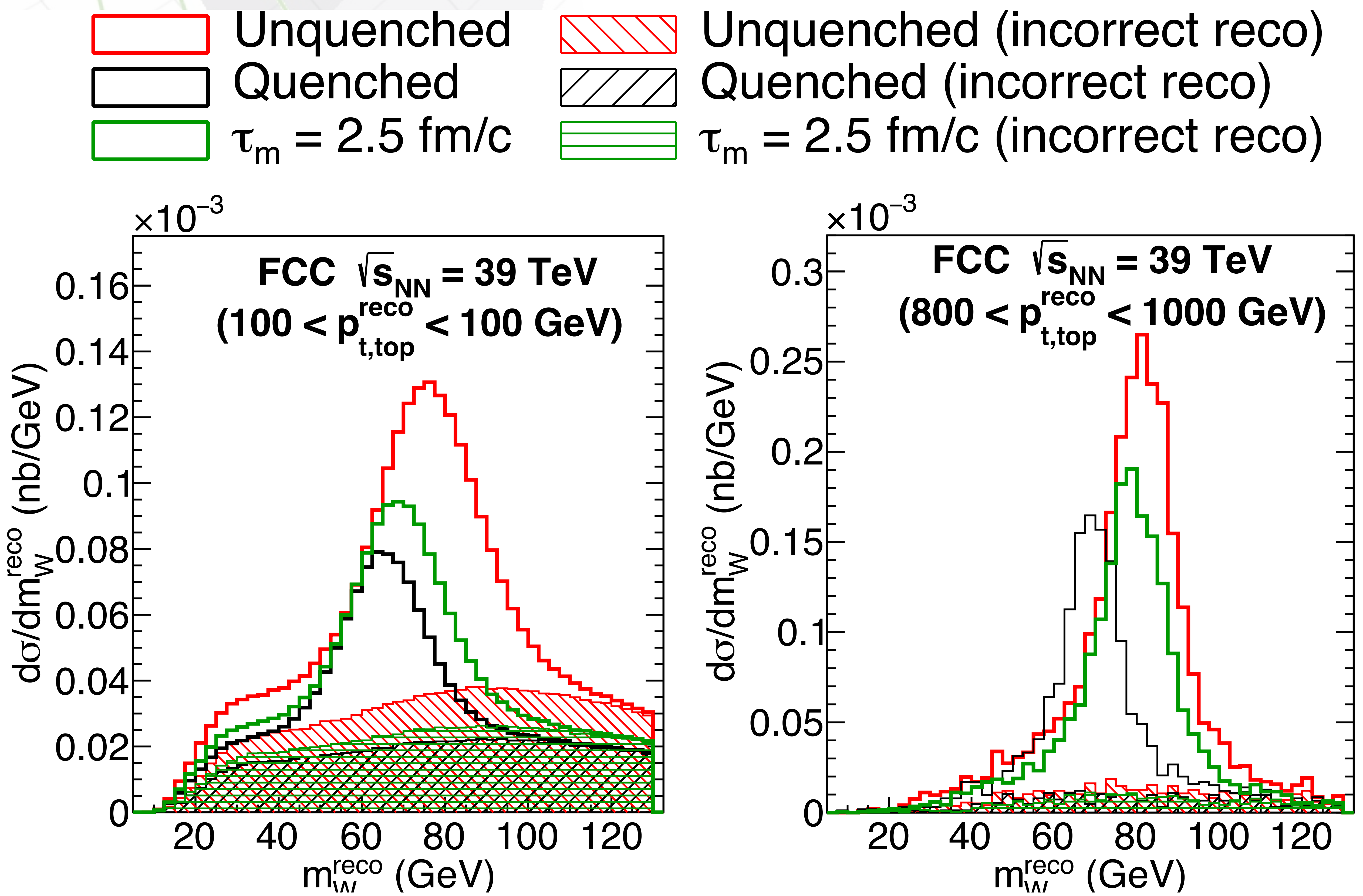
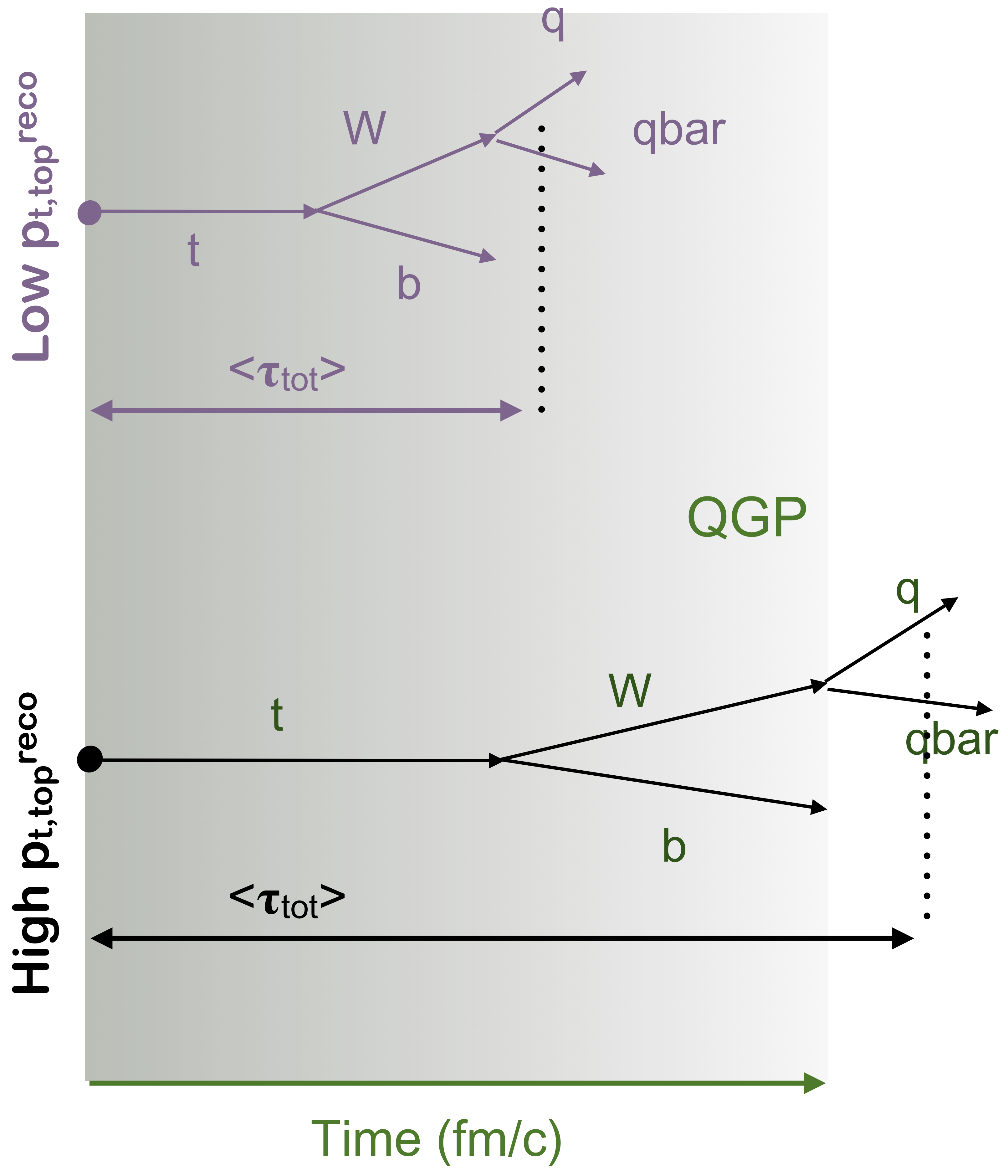


Reconstructed W Mass

- What would be the observable to measure the amount of energy loss?
  - Reconstructed W jet mass!





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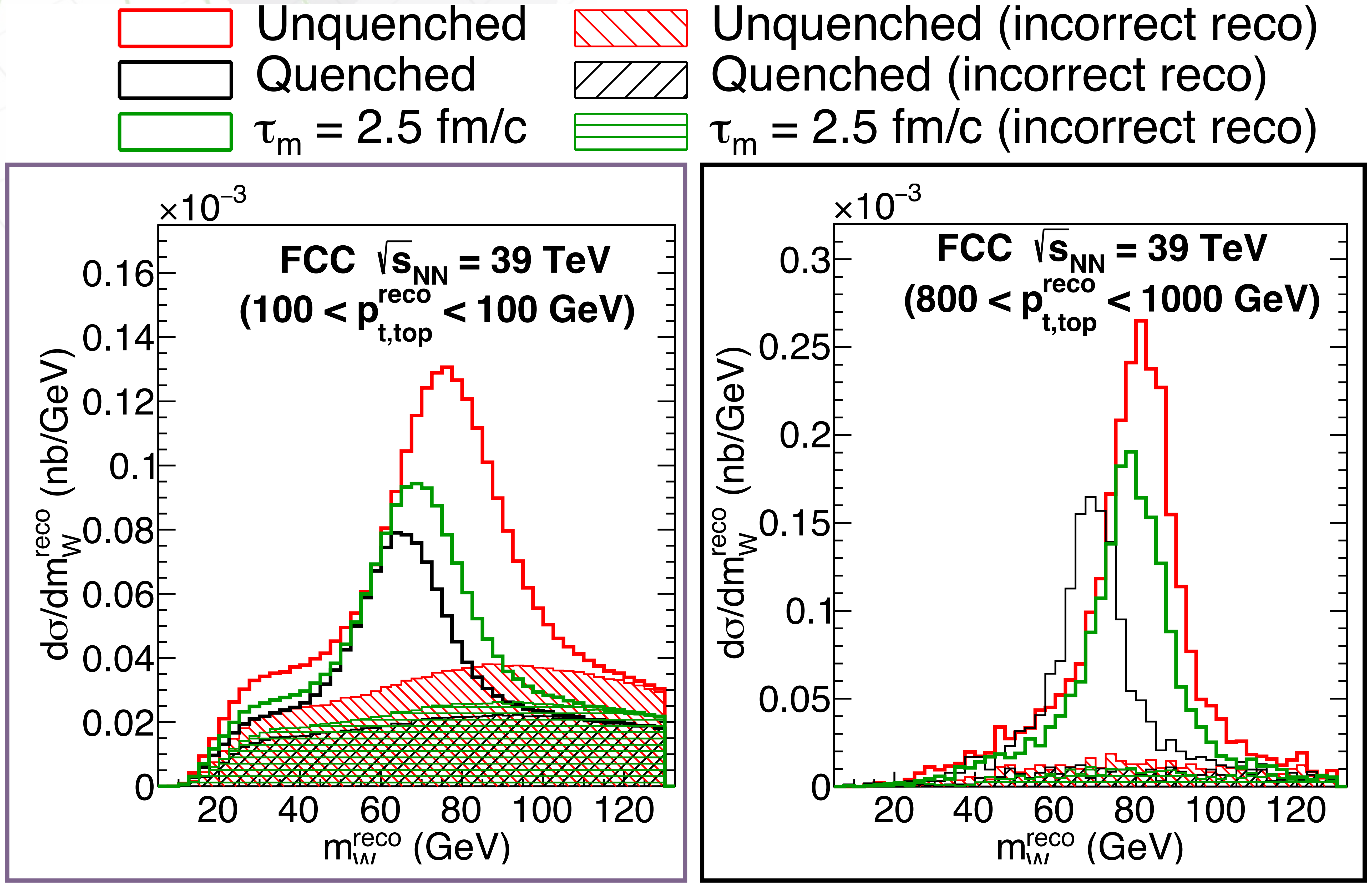

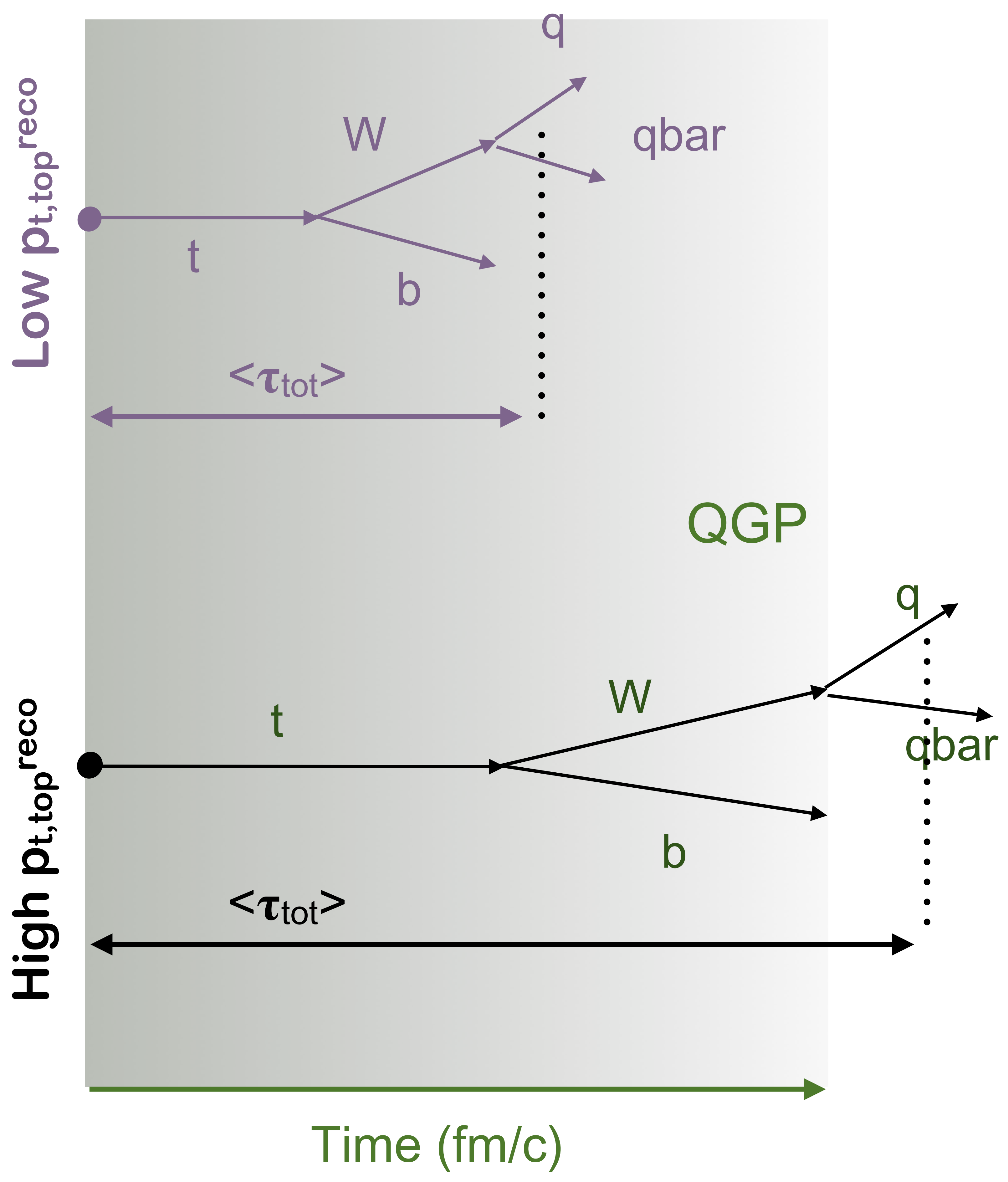

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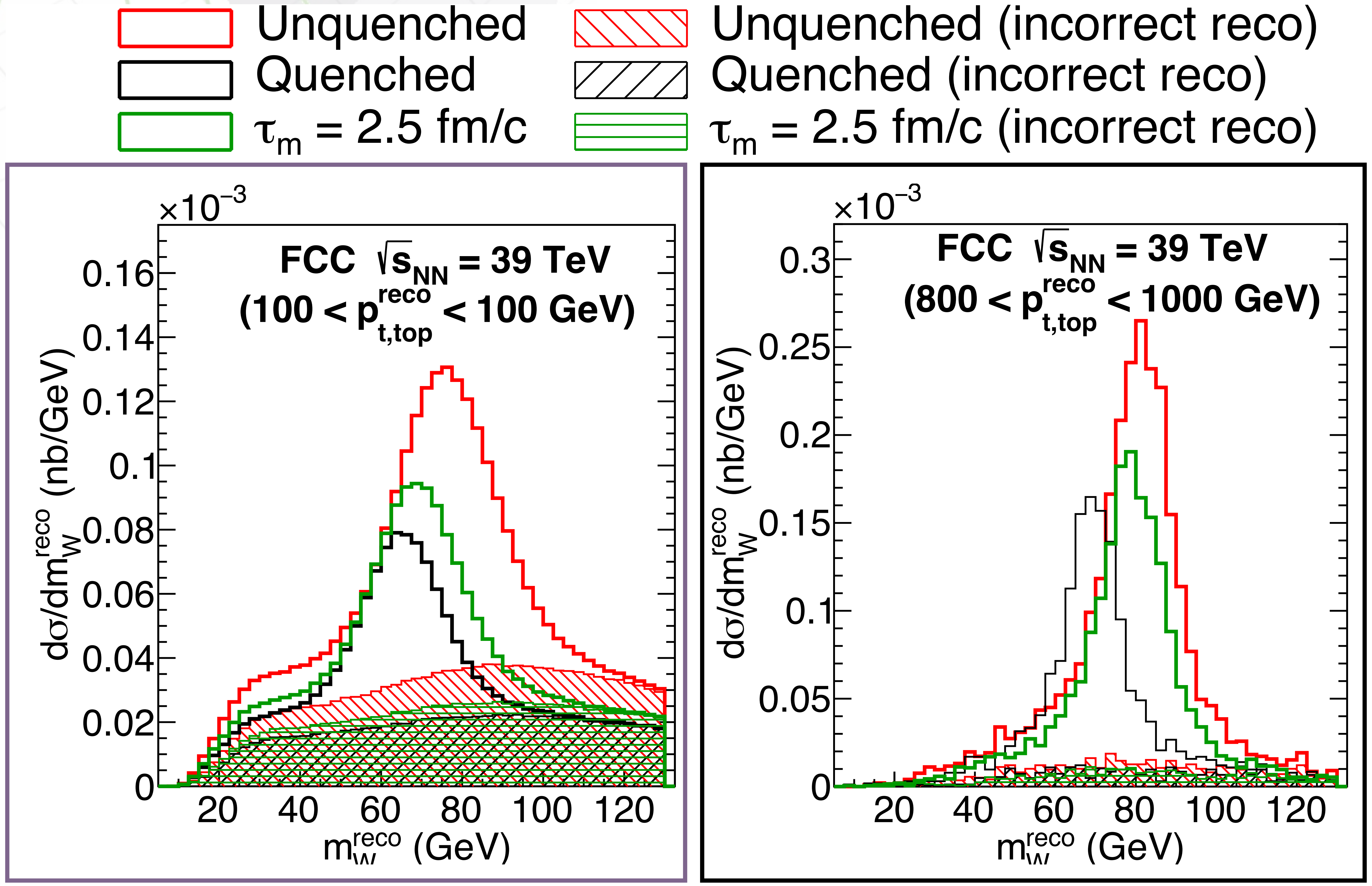


Functional form fit:

$$N(m) = a\exp\left[-\frac{(m-m_W^{fit})^2}{2\sigma^2}\right] + b + c\,m$$

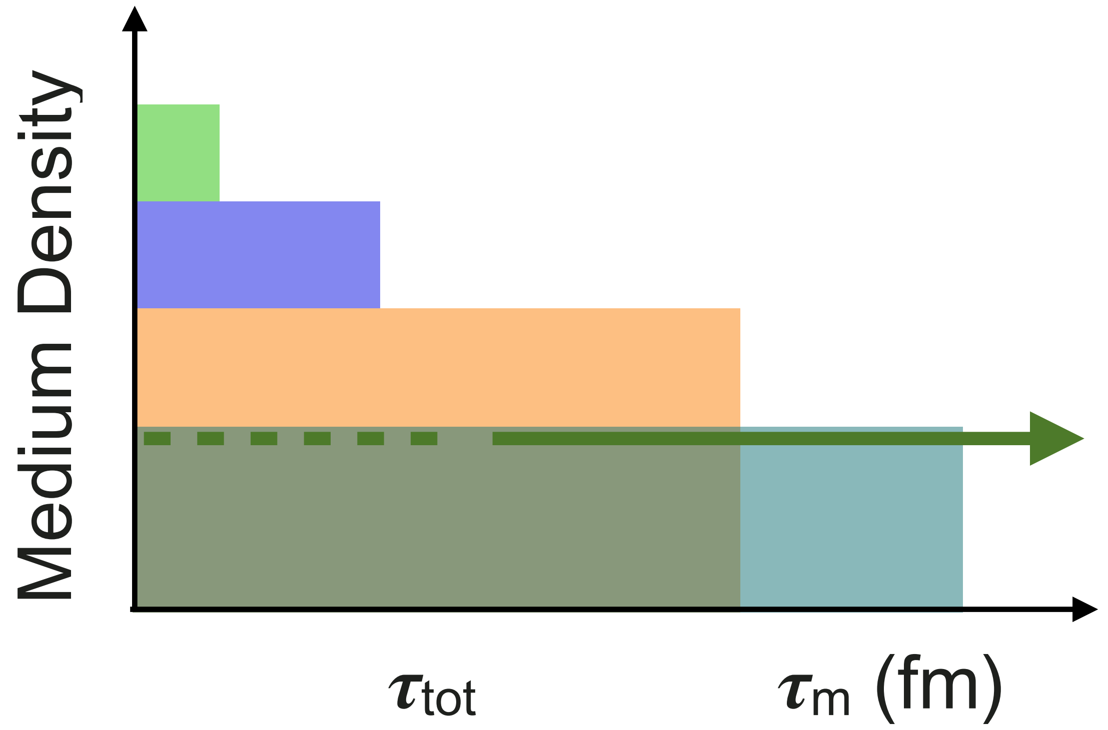
Measured shift will depend on ΔE/E

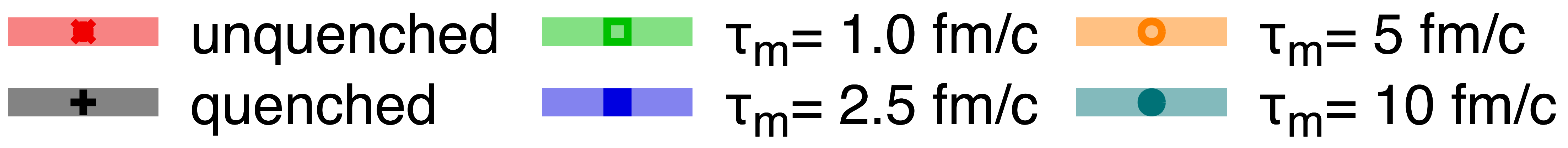
W Mass vs Top Pt

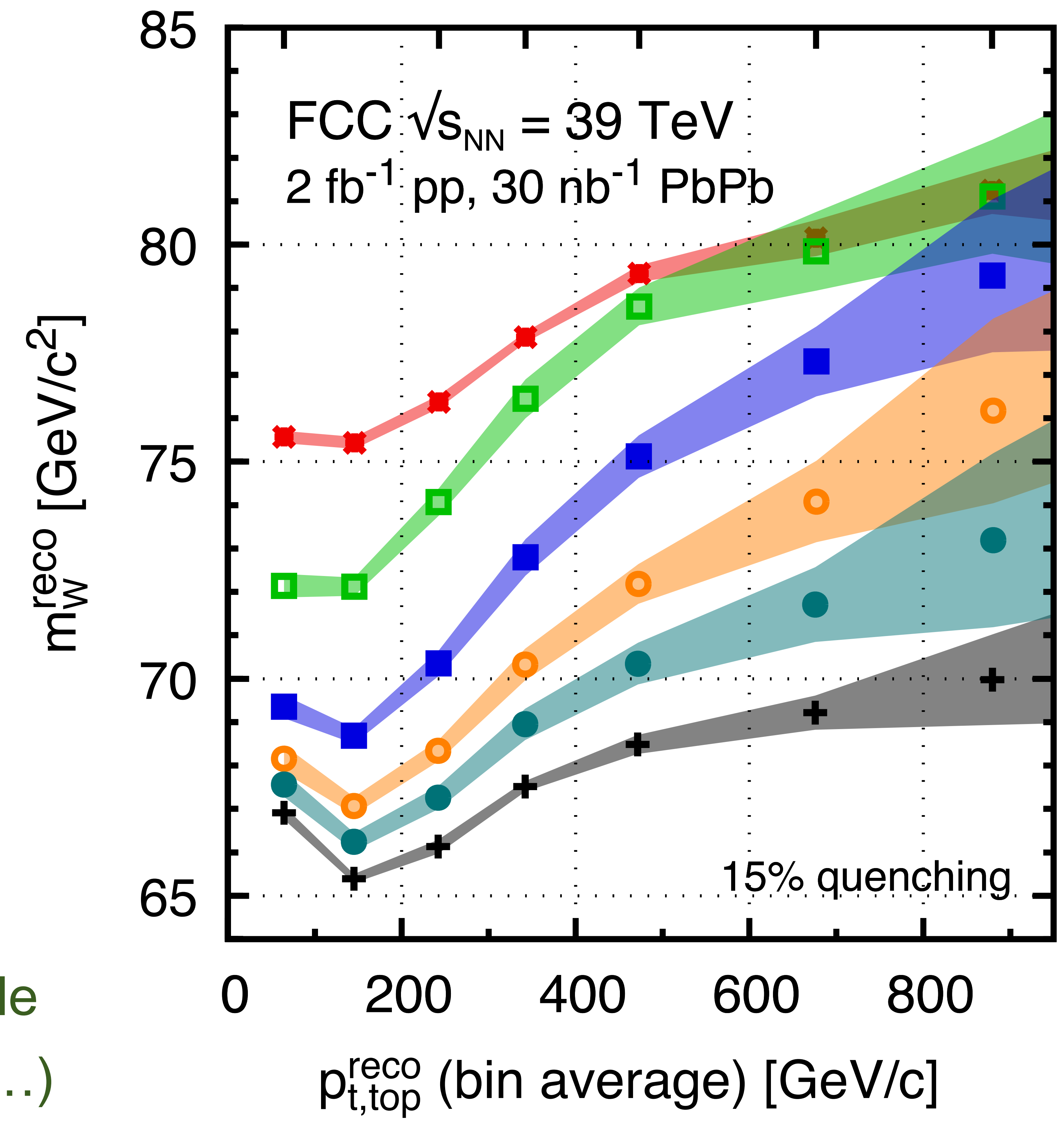
Unquenched = pp reference

Quenched = scaled pp reference

τ_m: "Antenna" inside a "brick" like medium



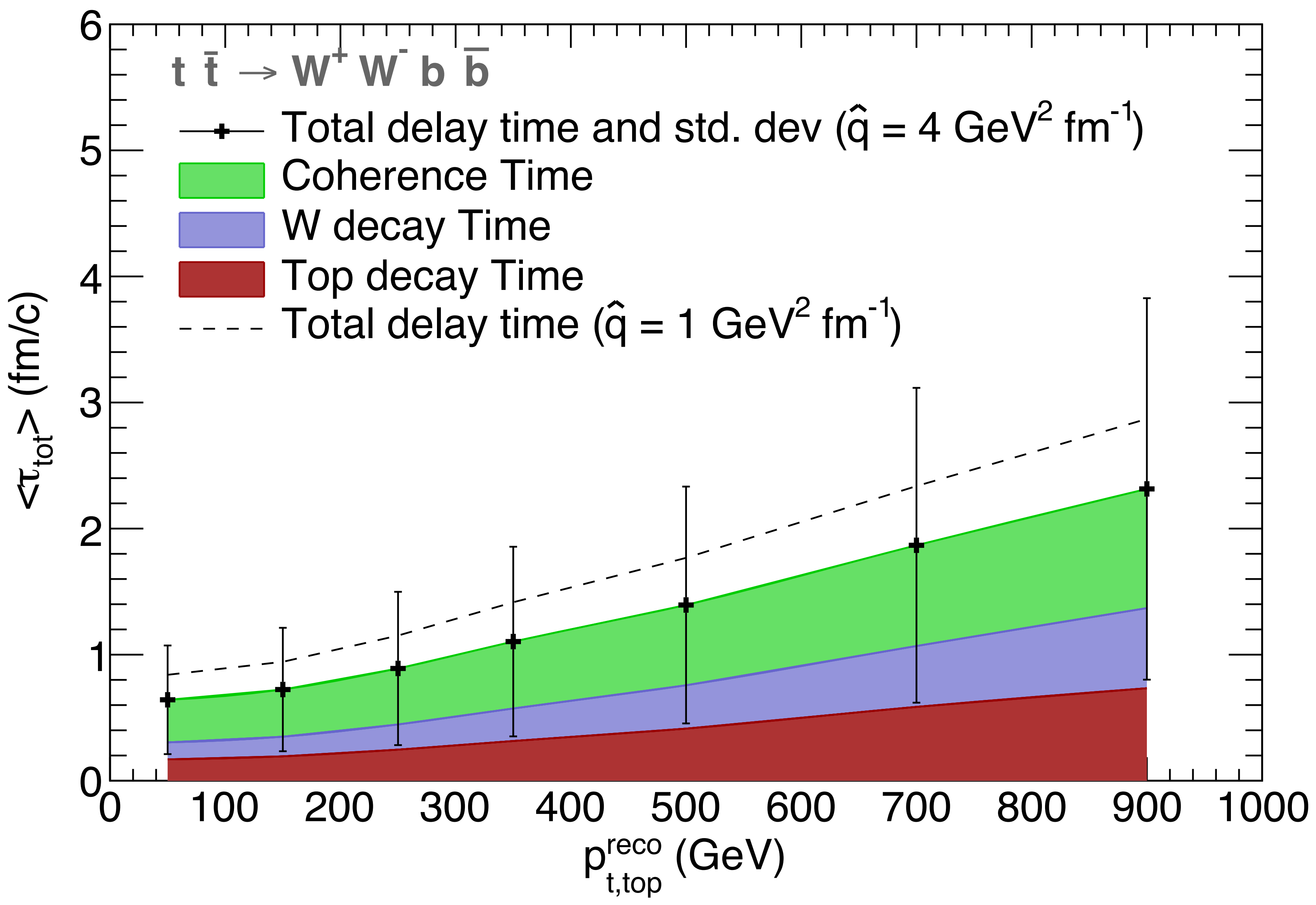




"Bands" = 1σ standard deviation from a true-sized sample (including reconstruction efficiency, b-tagging efficiency…)

W Mass vs Top Pt

- Relating the $p_{t,top}^{reco}$ to the average total delay time
  - Able extract the density evolution profile!



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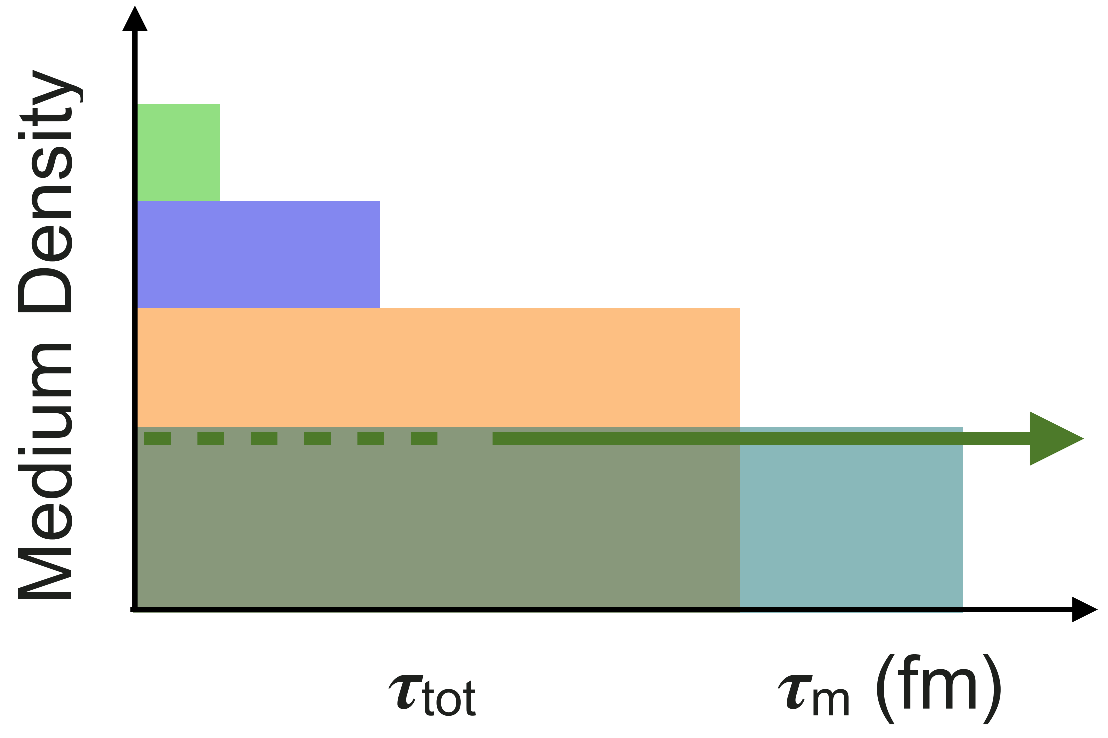

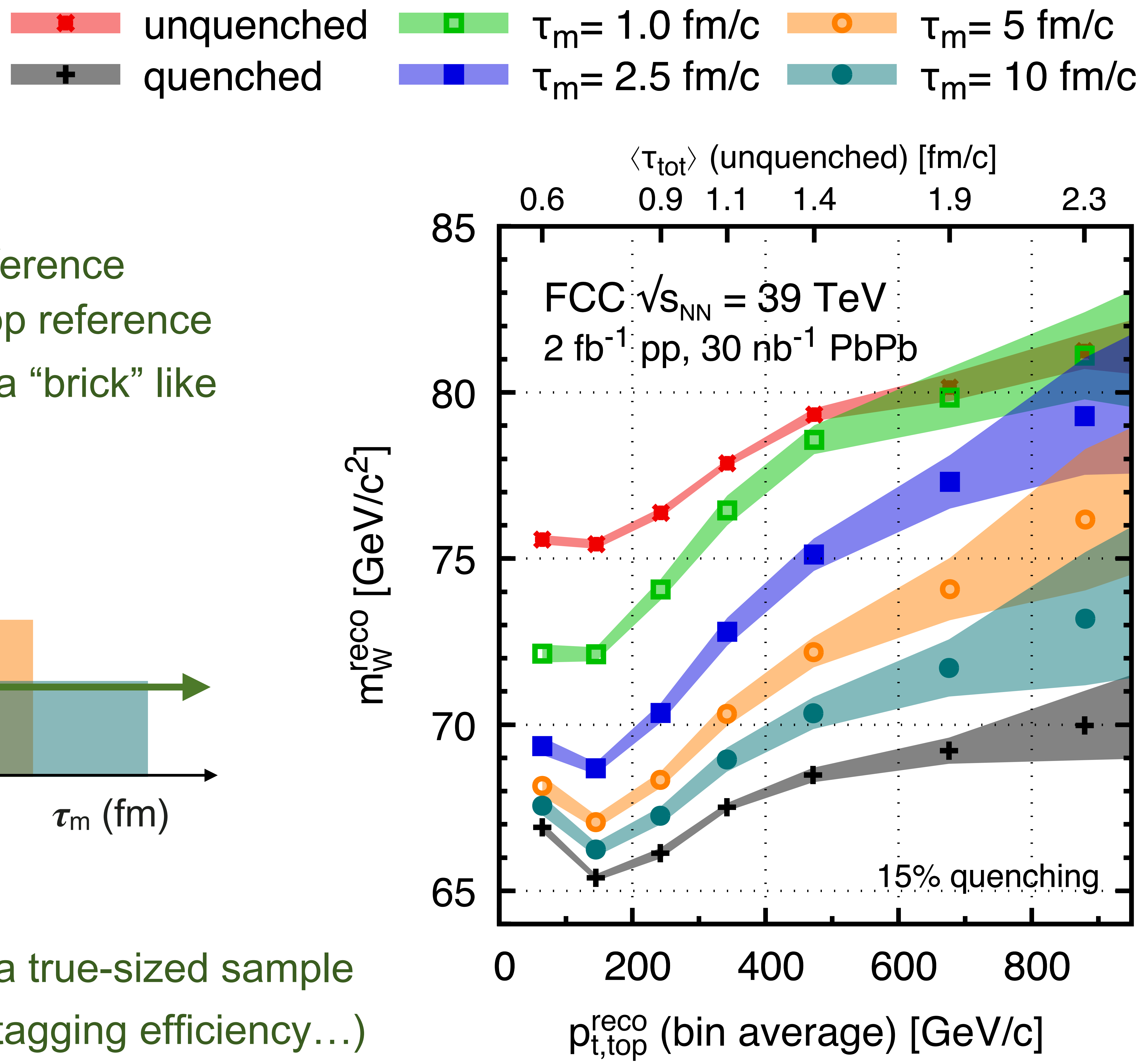

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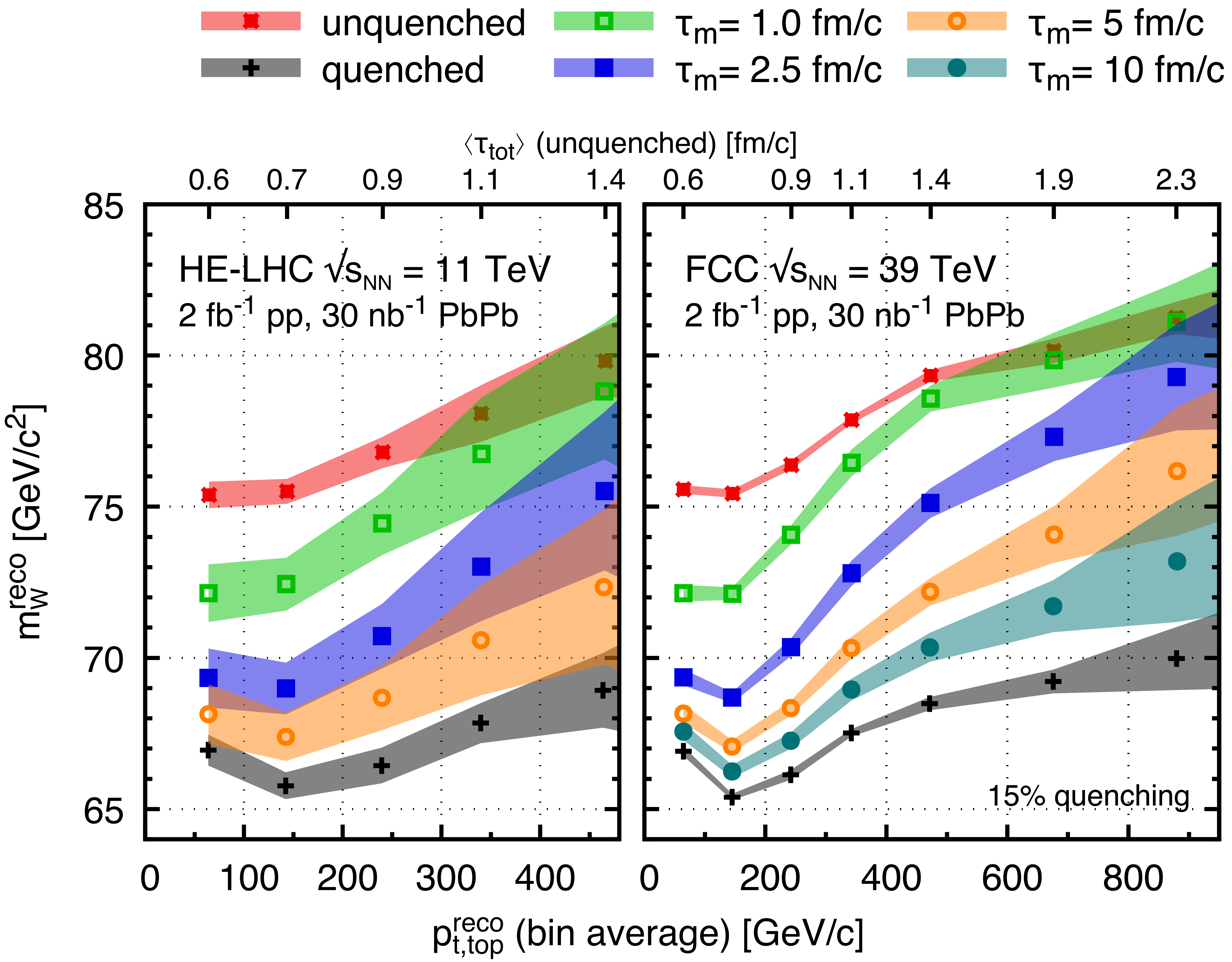
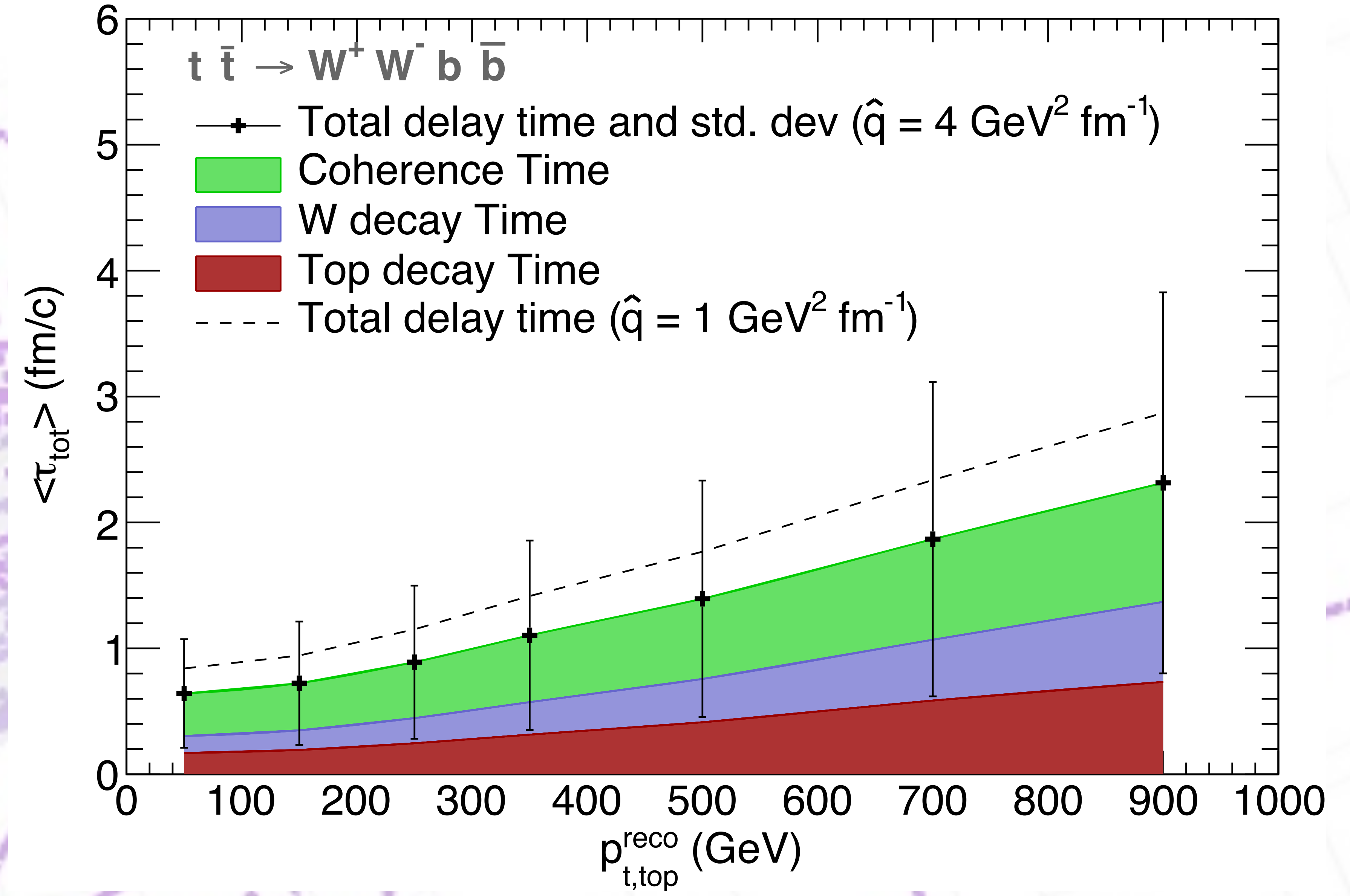
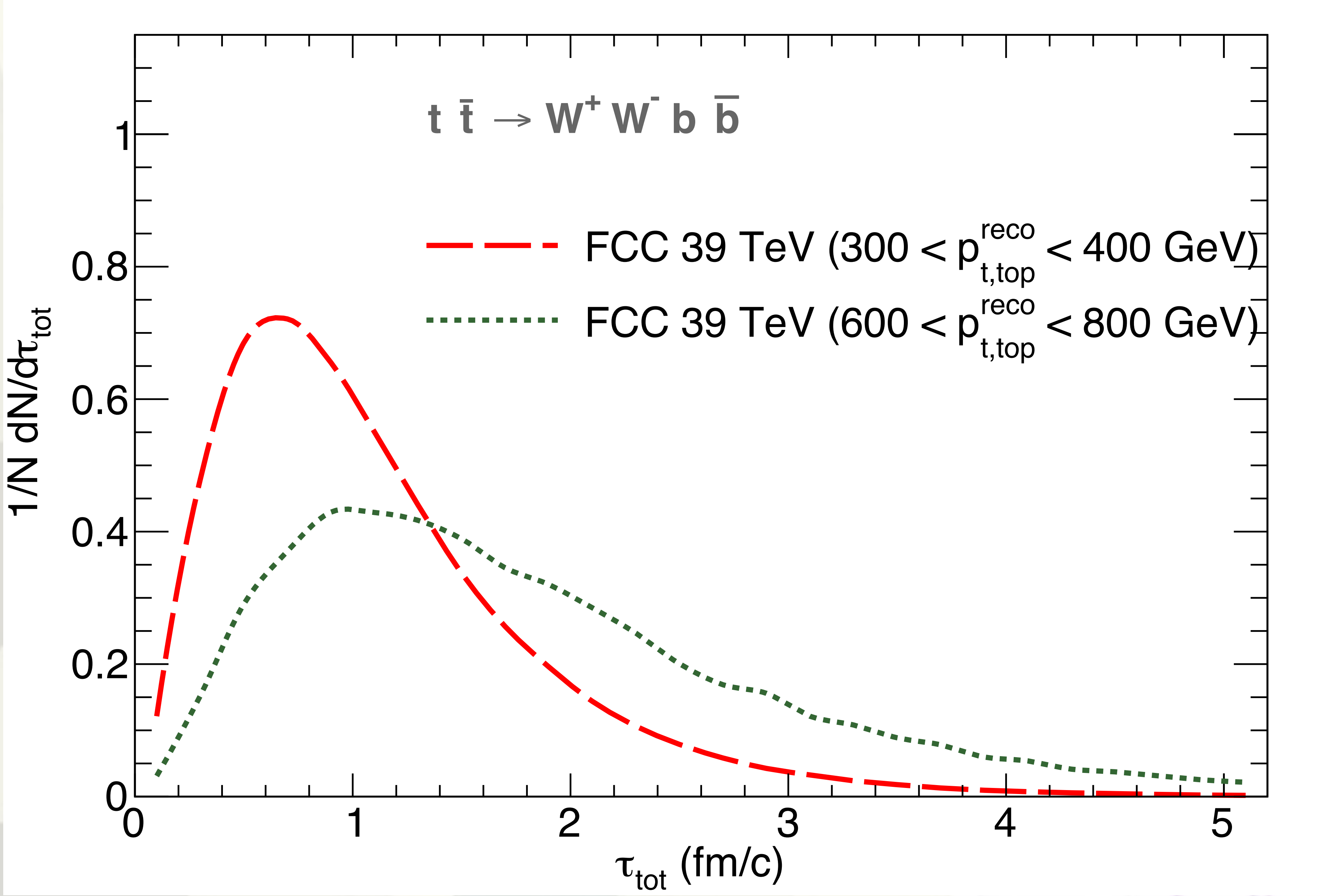
Boosted objects @ LHC

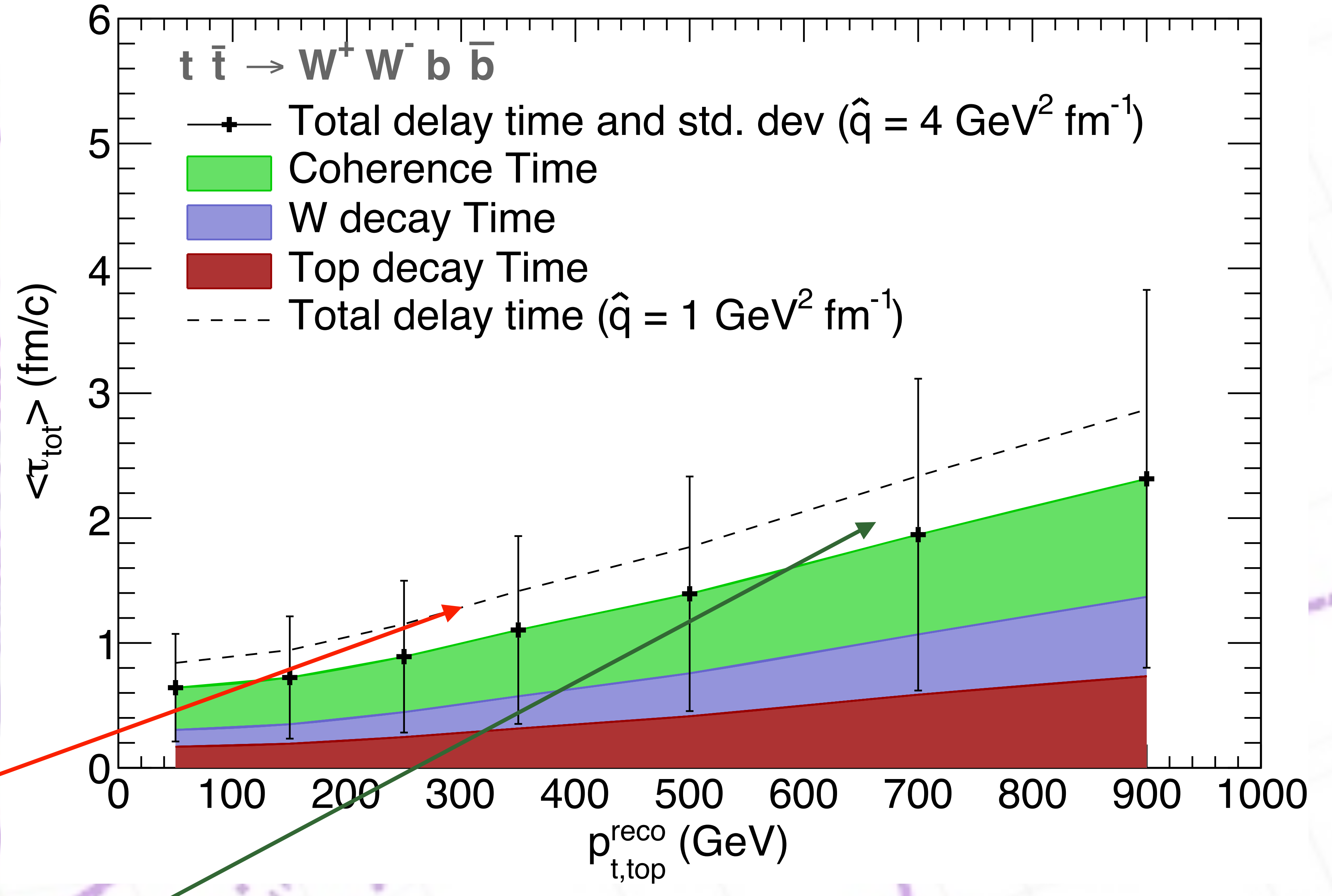
- From FCC to LHC:
  - Limited reach on the time handle at HE-LHC (11 TeV)
  - Not possible at LHC (5 TeV)
    - Cross-section rate and luminosity too limited

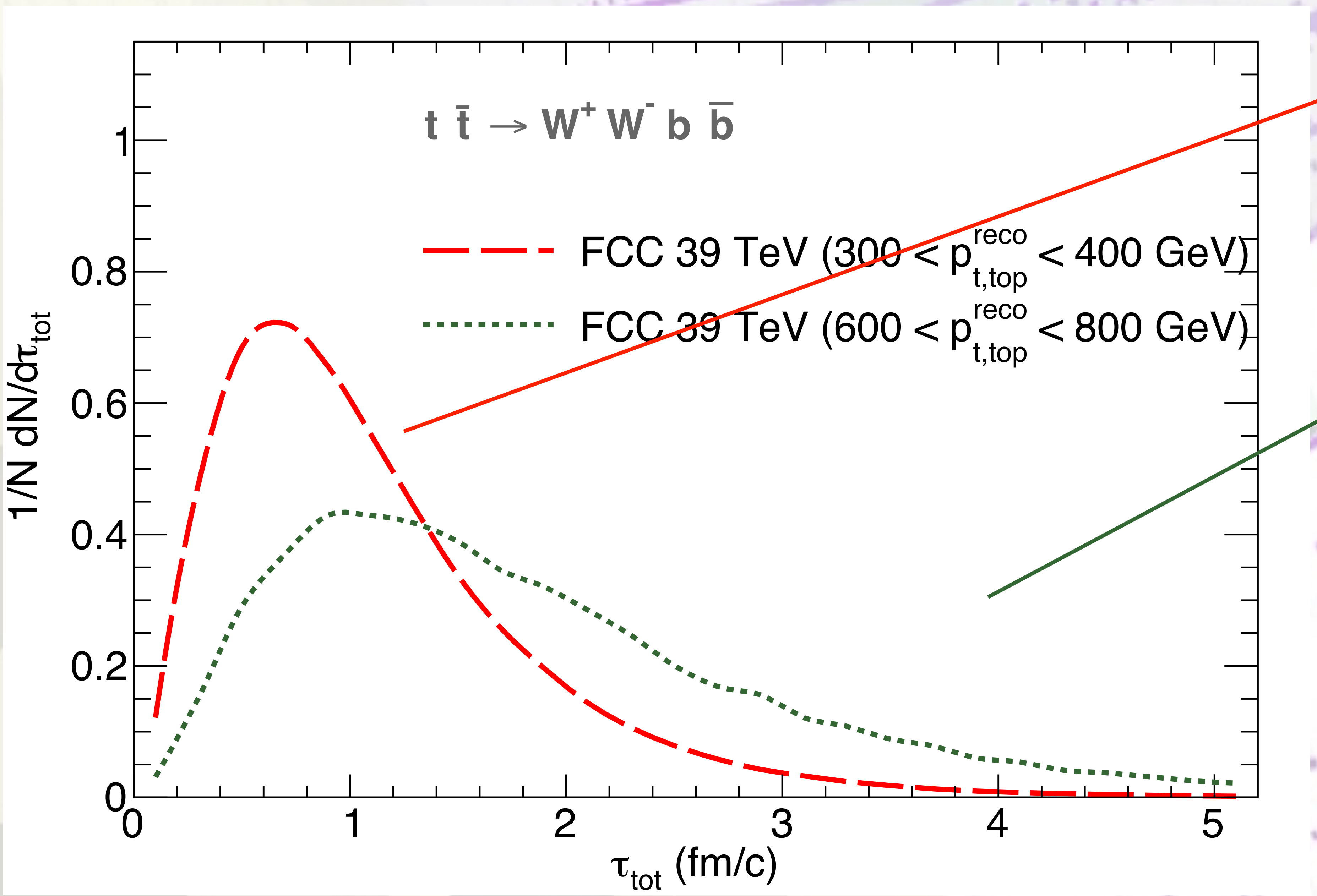






Can we say something with inclusive distributions on the top p_t?





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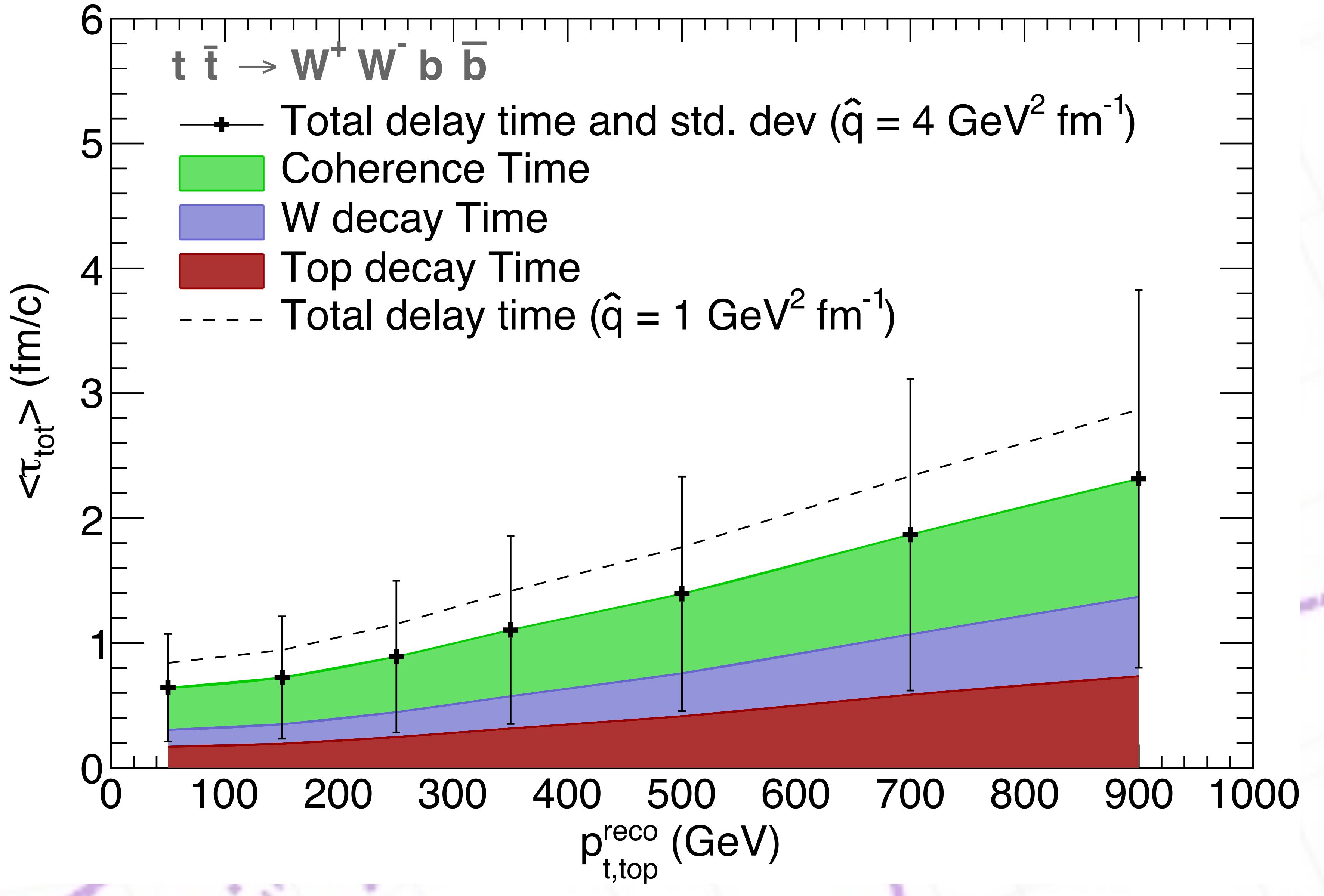
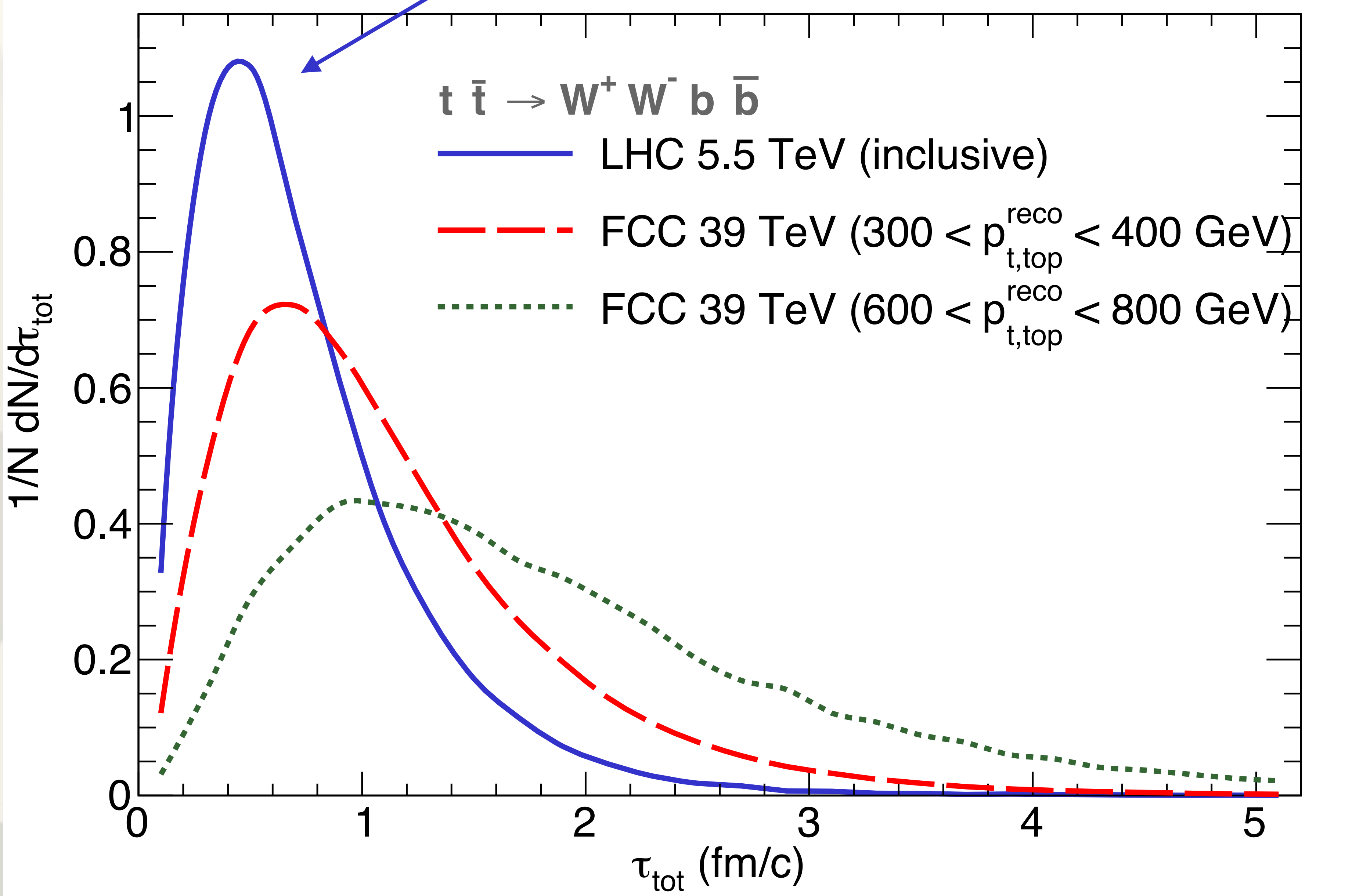


Average total delay time at the LHC is very small…



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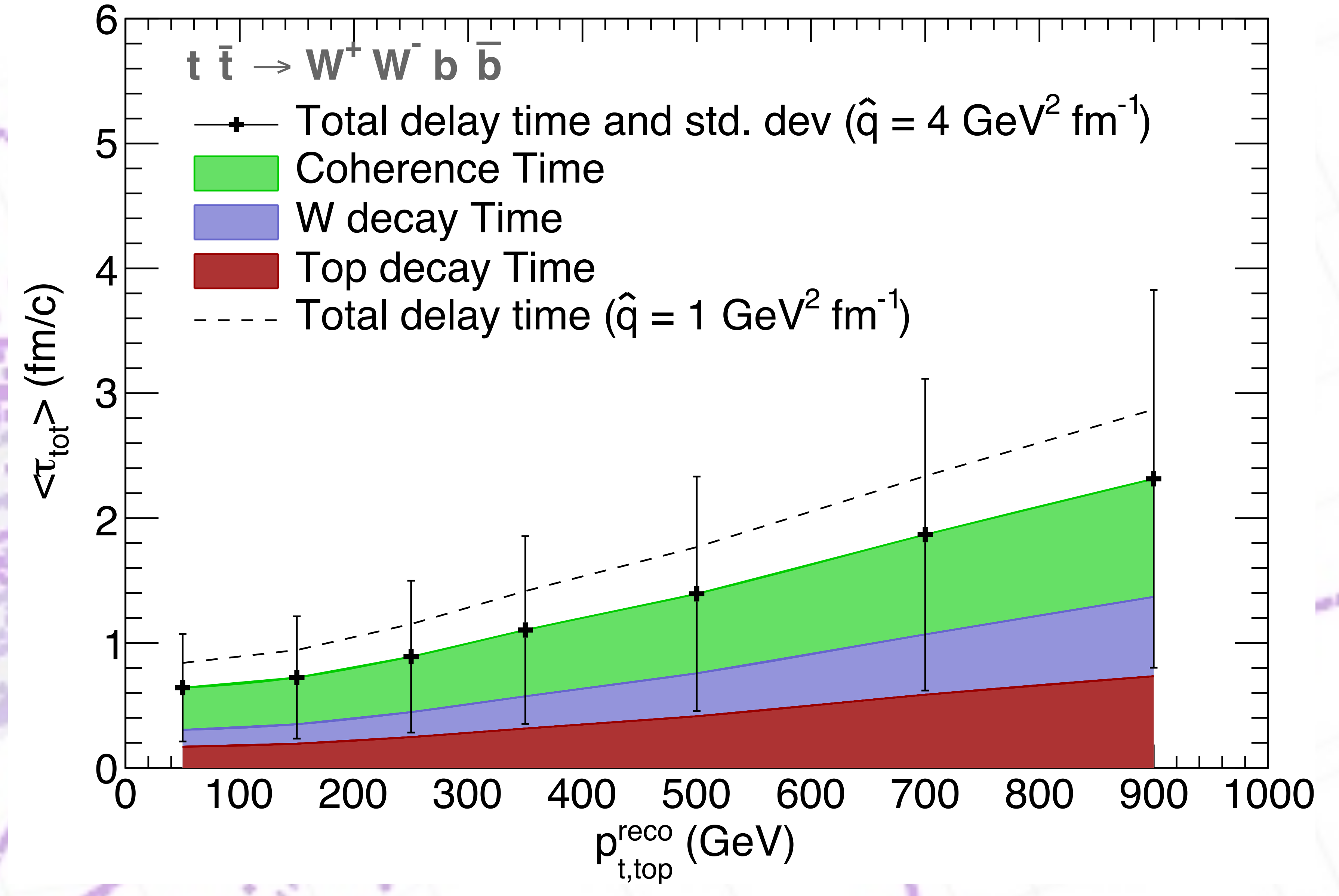
But there is a large dispersion that one can play with.



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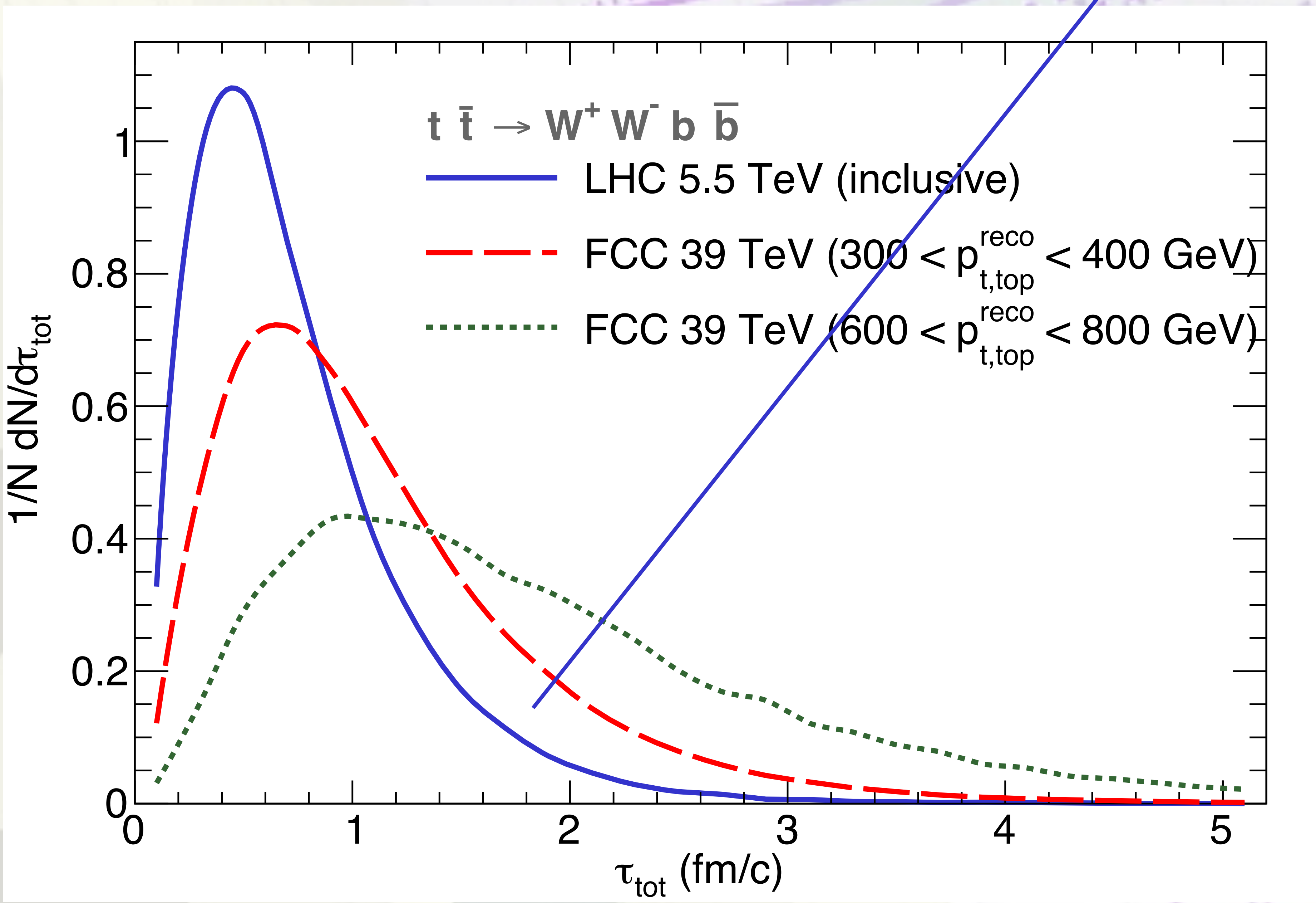

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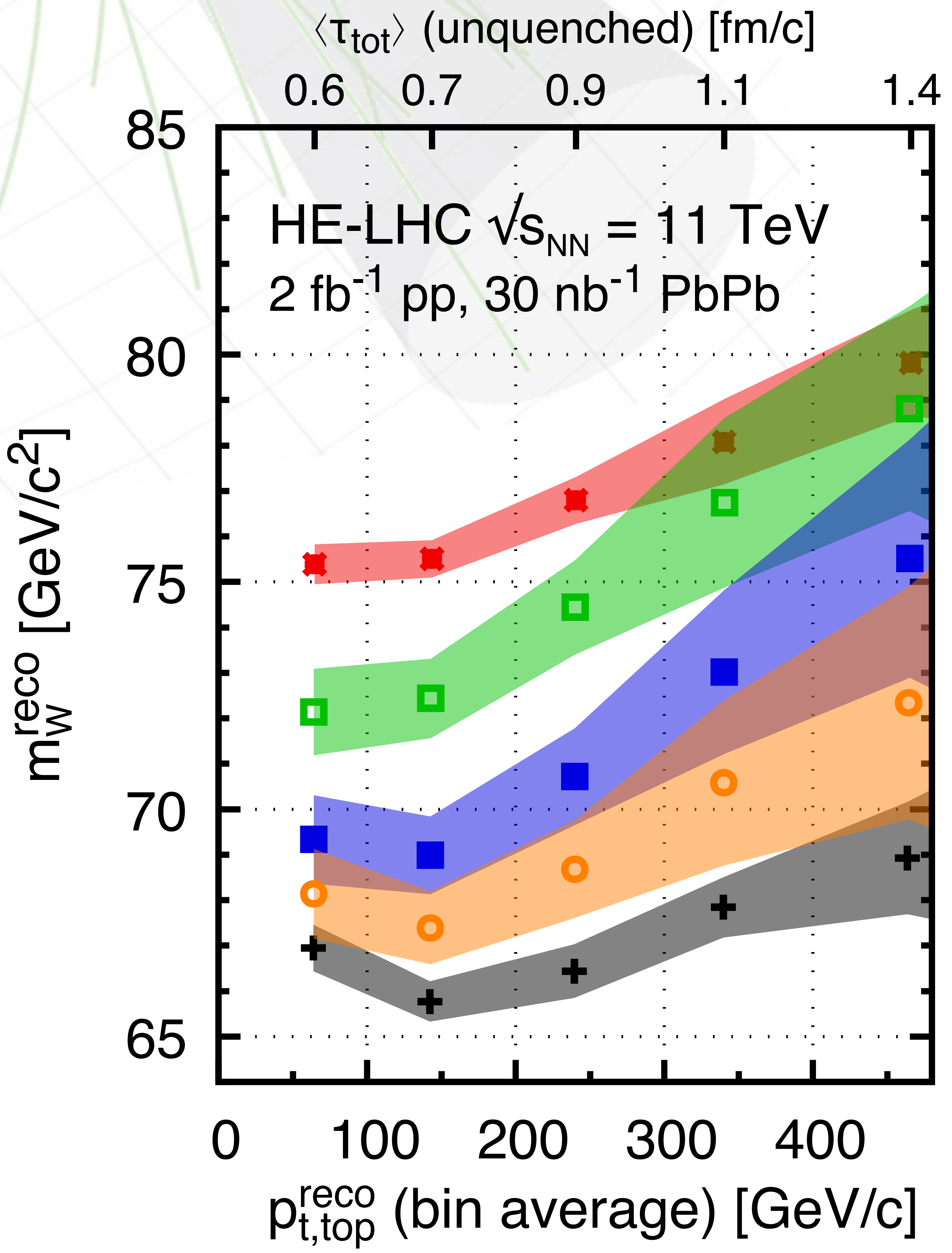
From p_T Differential to Inclusive

- Needed luminosity for LHC (PbPb) run?



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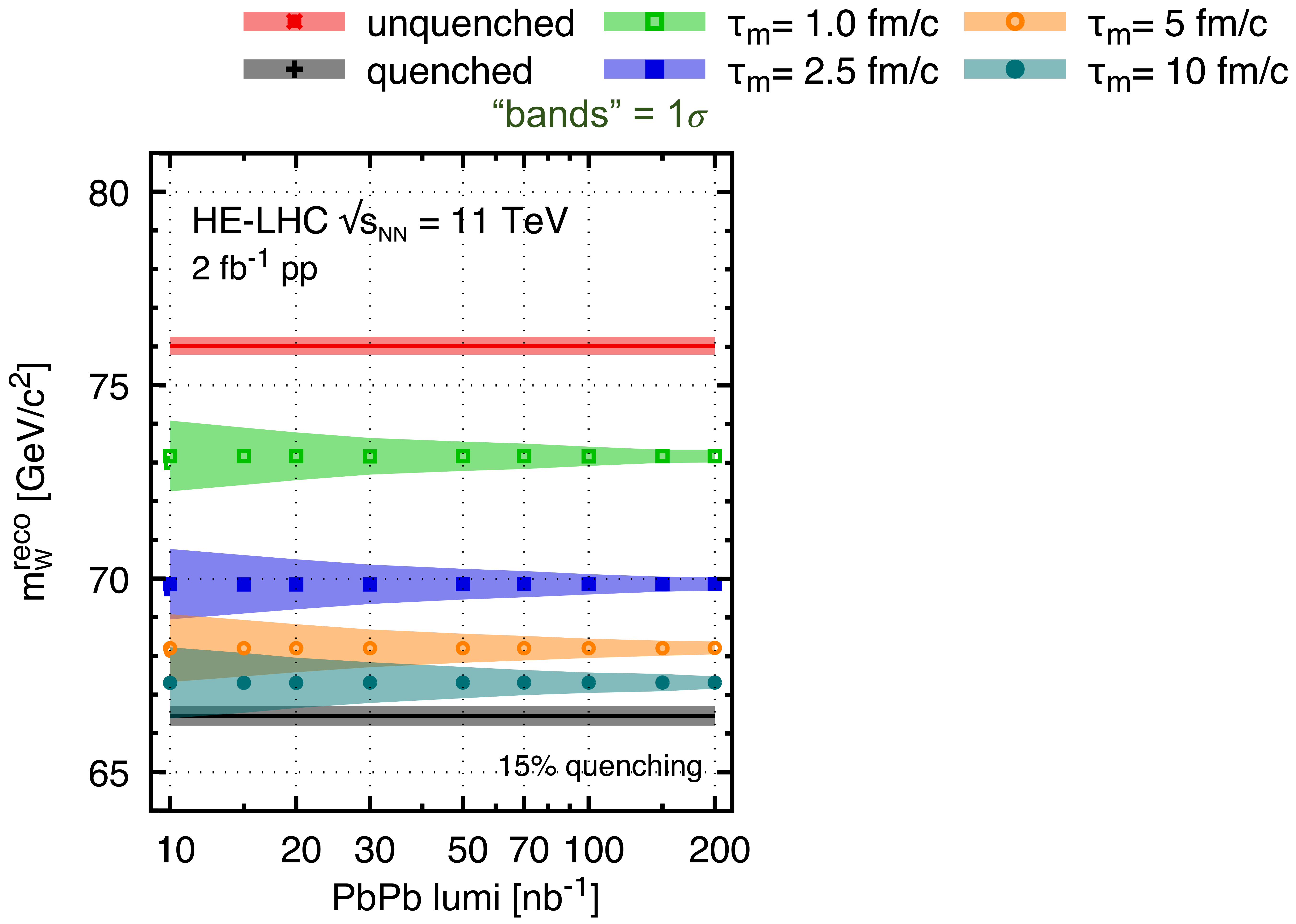

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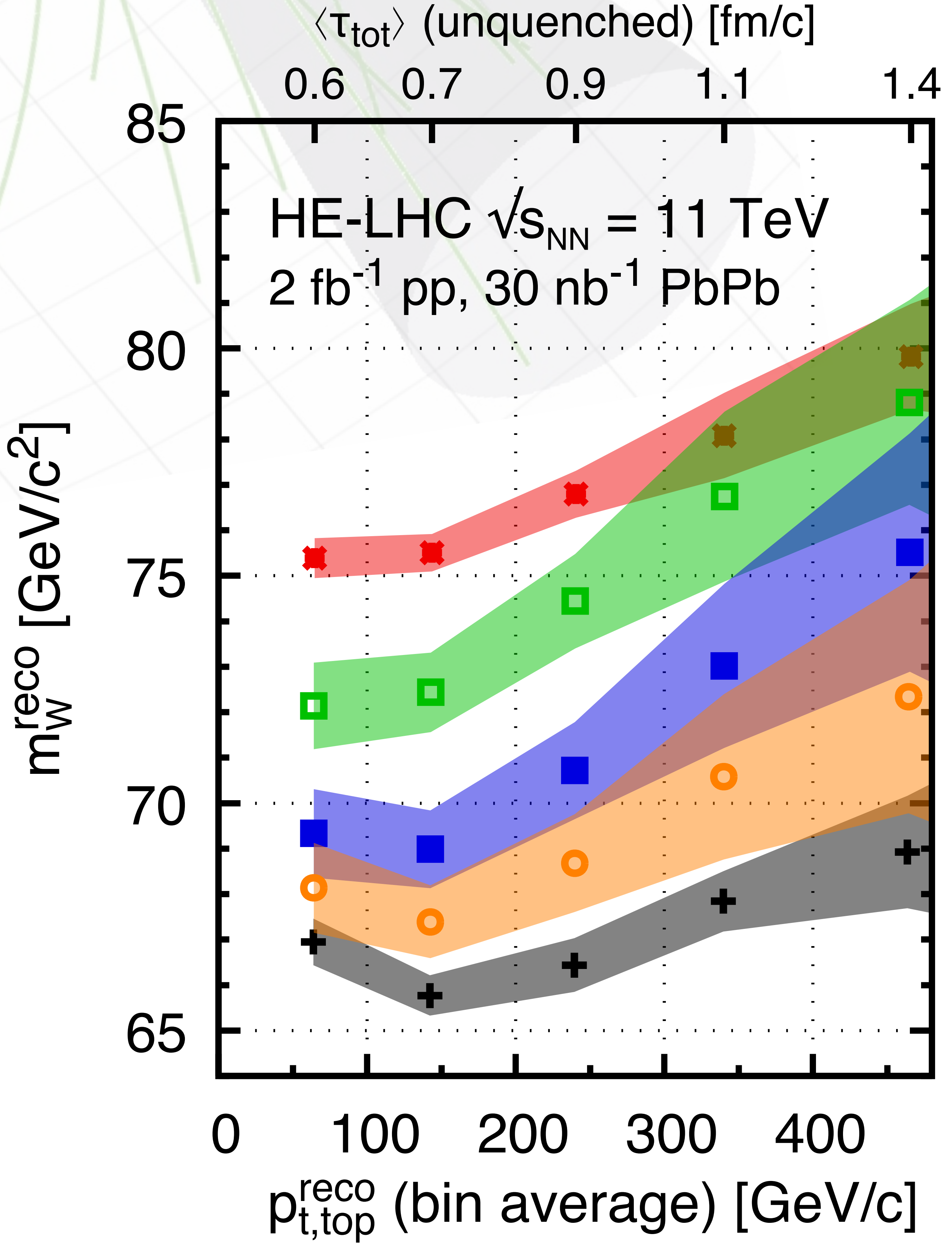

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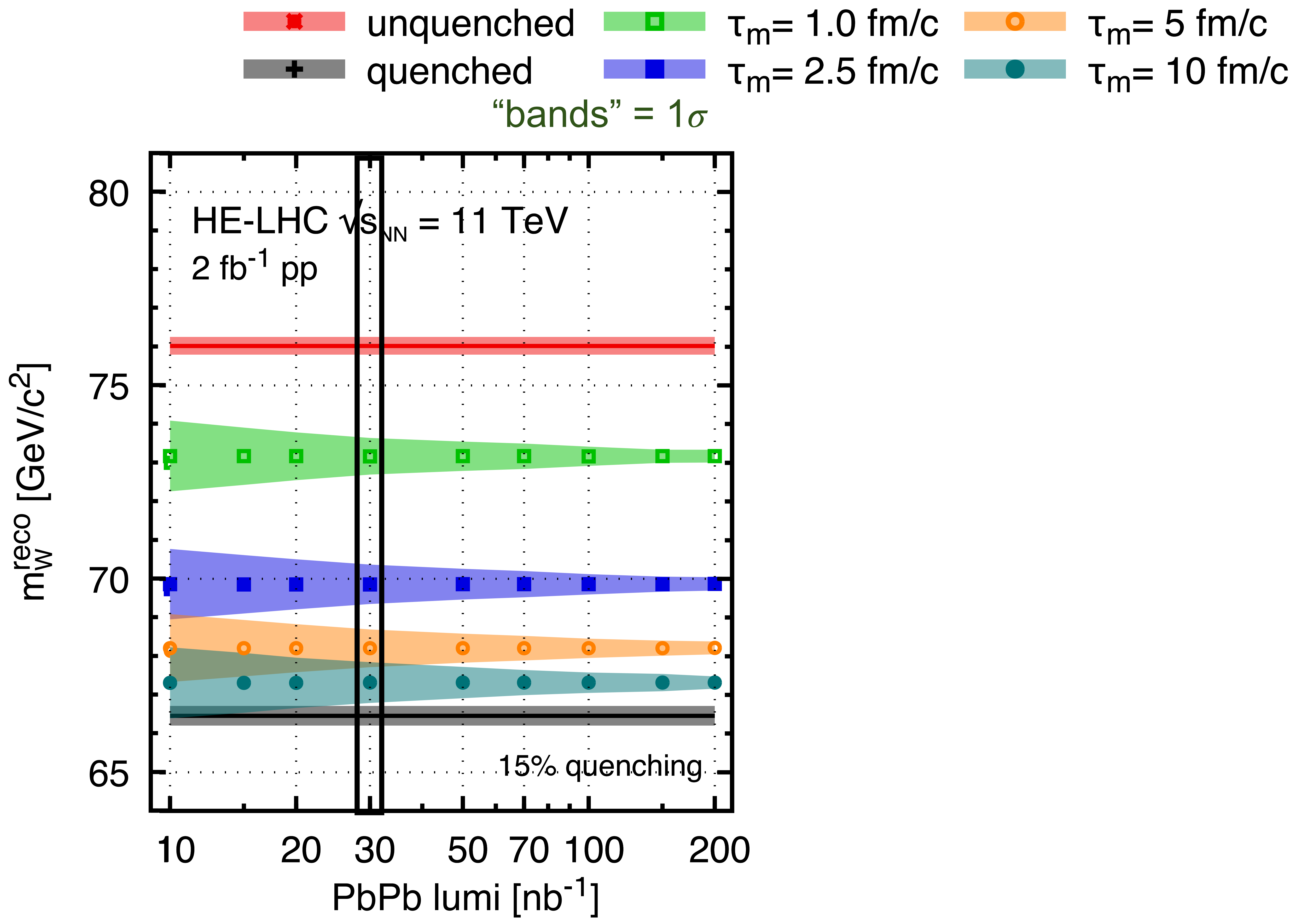

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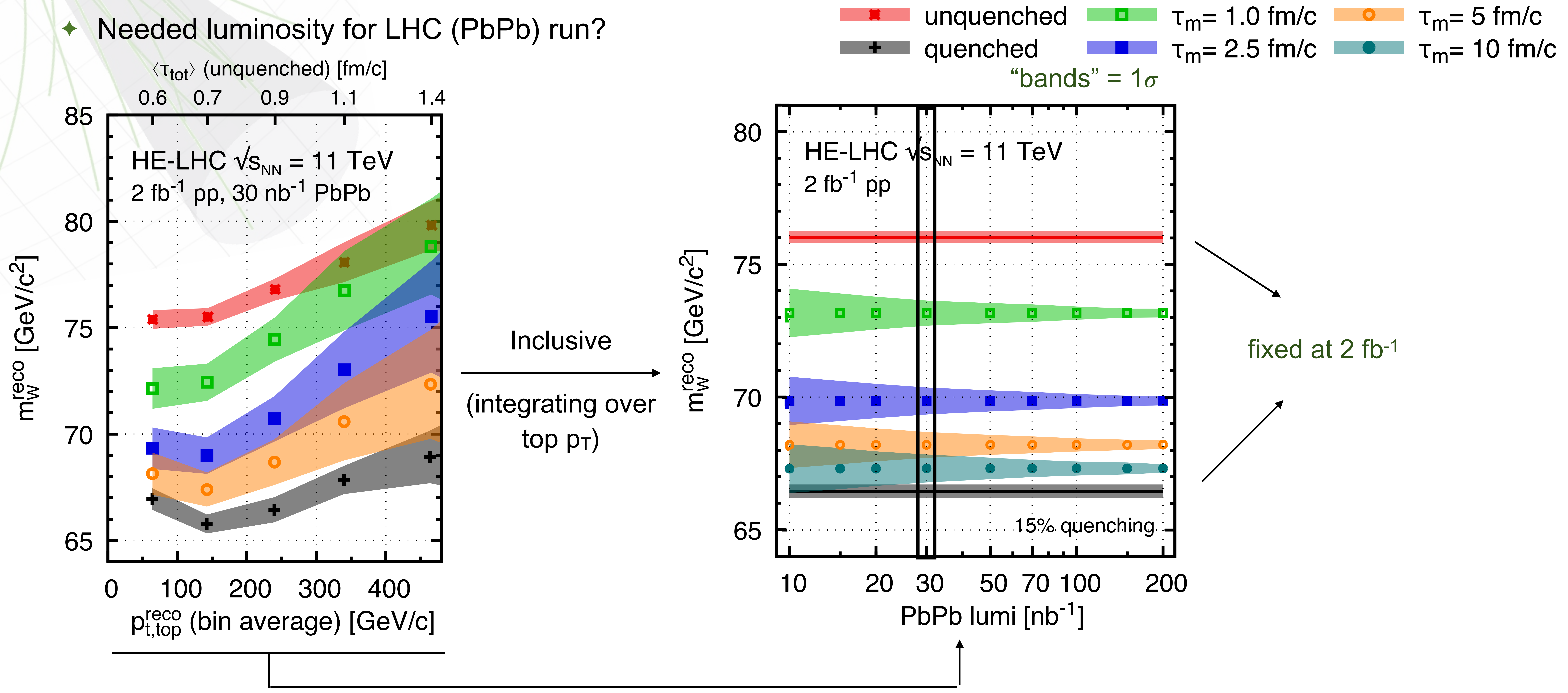

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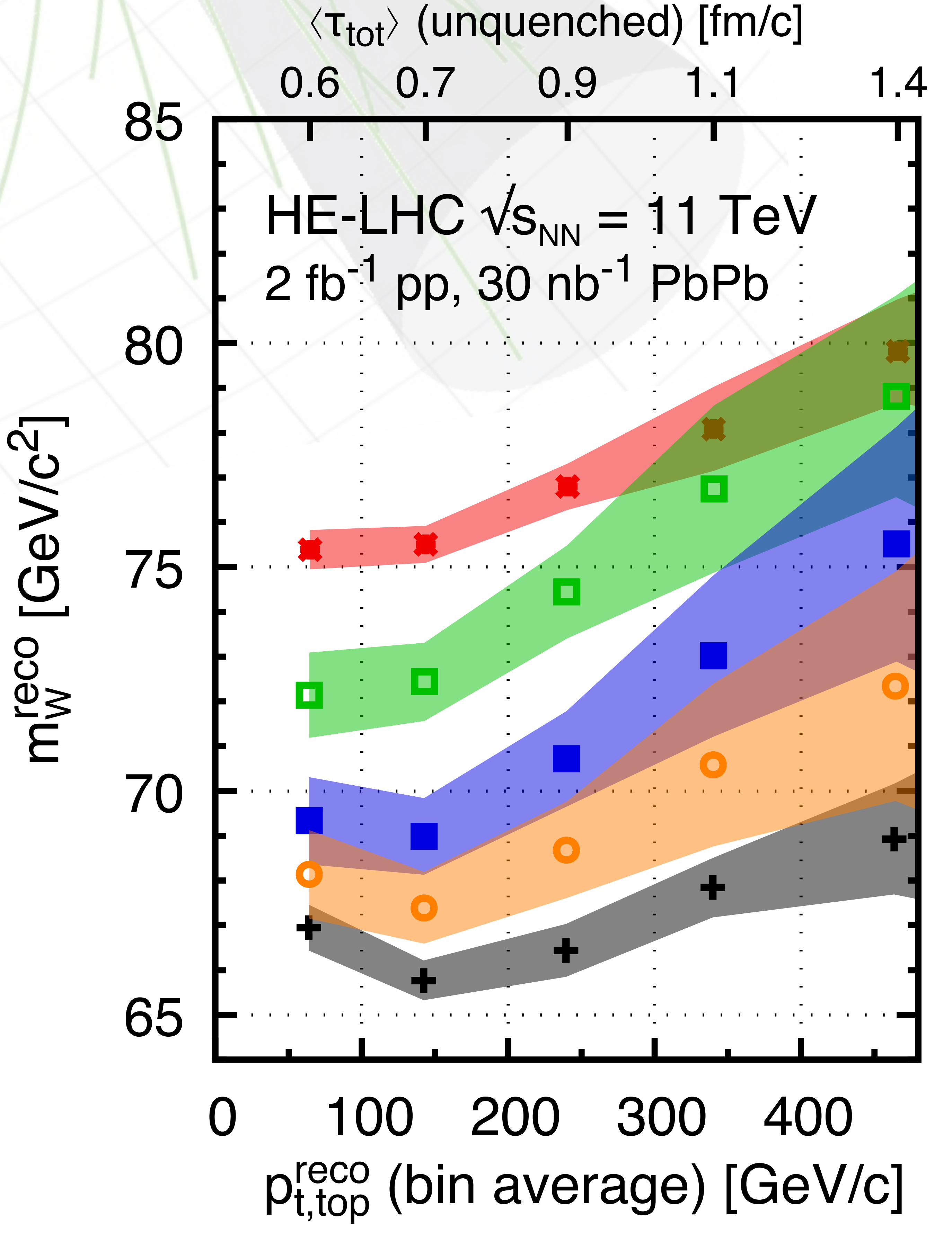

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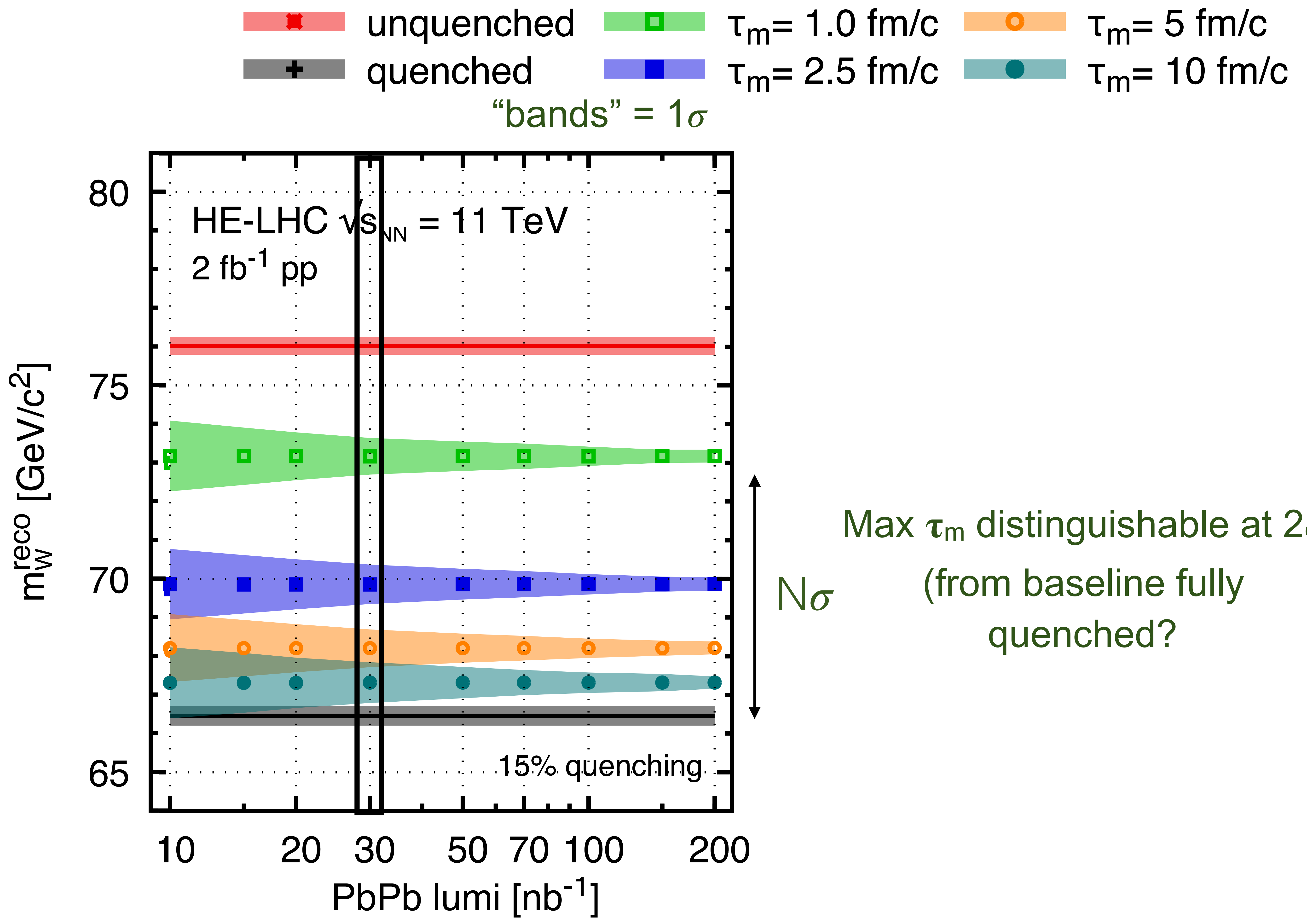
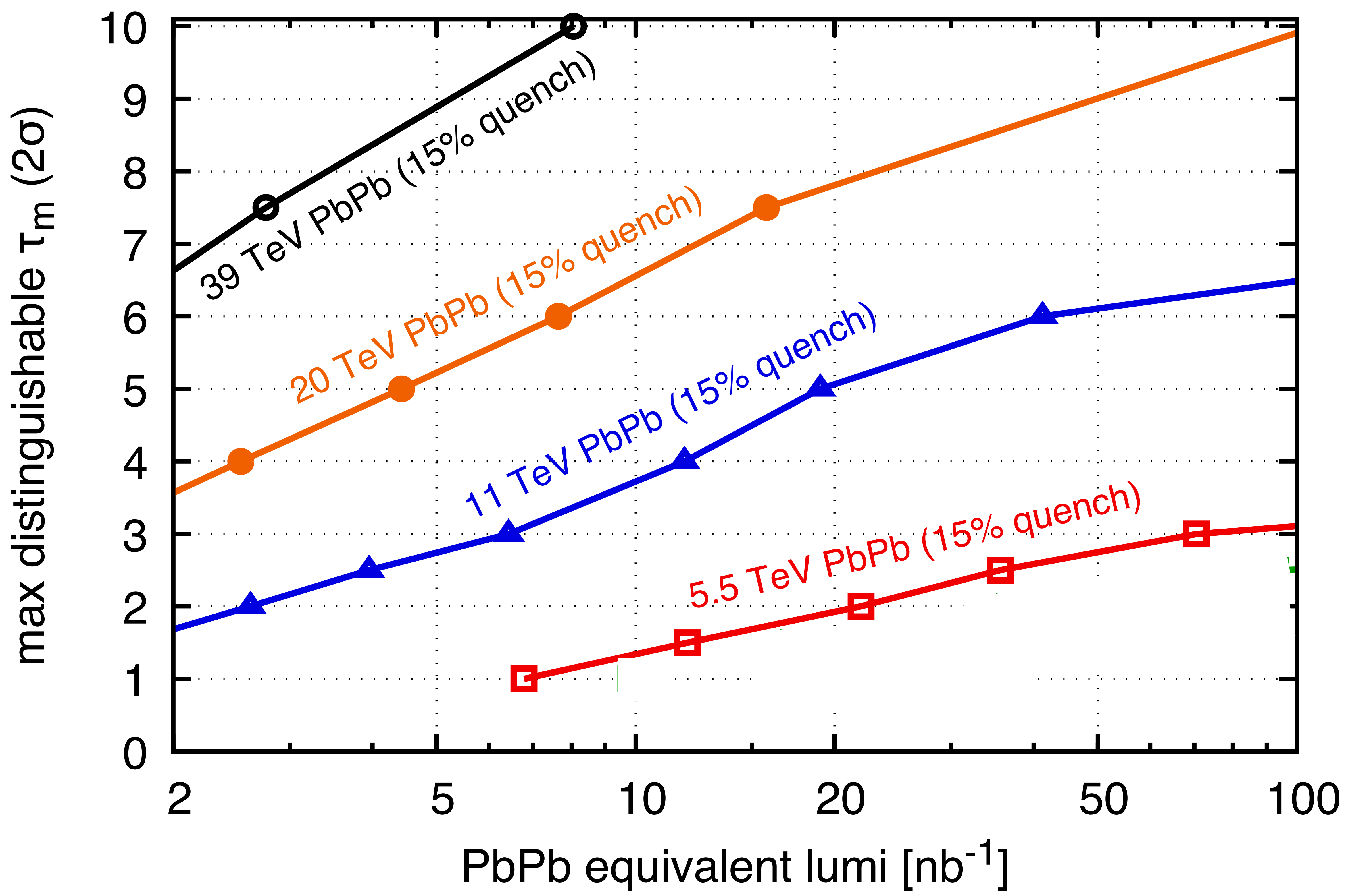


Max τ_m distinguishable at 2σ (from baseline fully quenched?

Maximum Timescales

- Translate previous results into:
  - Maximum brick time, τ_m, that can be distinguished (from full quenching) with 2σ, as a function of $\mathscr{L}_{equiv}^{PbPb}$:
    - LHC (limited by planned luminosities):
      - 10 nb^{-1}: τ_m ~ 1.3 fm/c.
      - 30 nb^{-1}: τ_m ~ 2 fm/c
    - Higher $\sqrt{s_{NN}}$ (11, 20 or 39 TeV):
      - Able to probe larger medium lifetimes

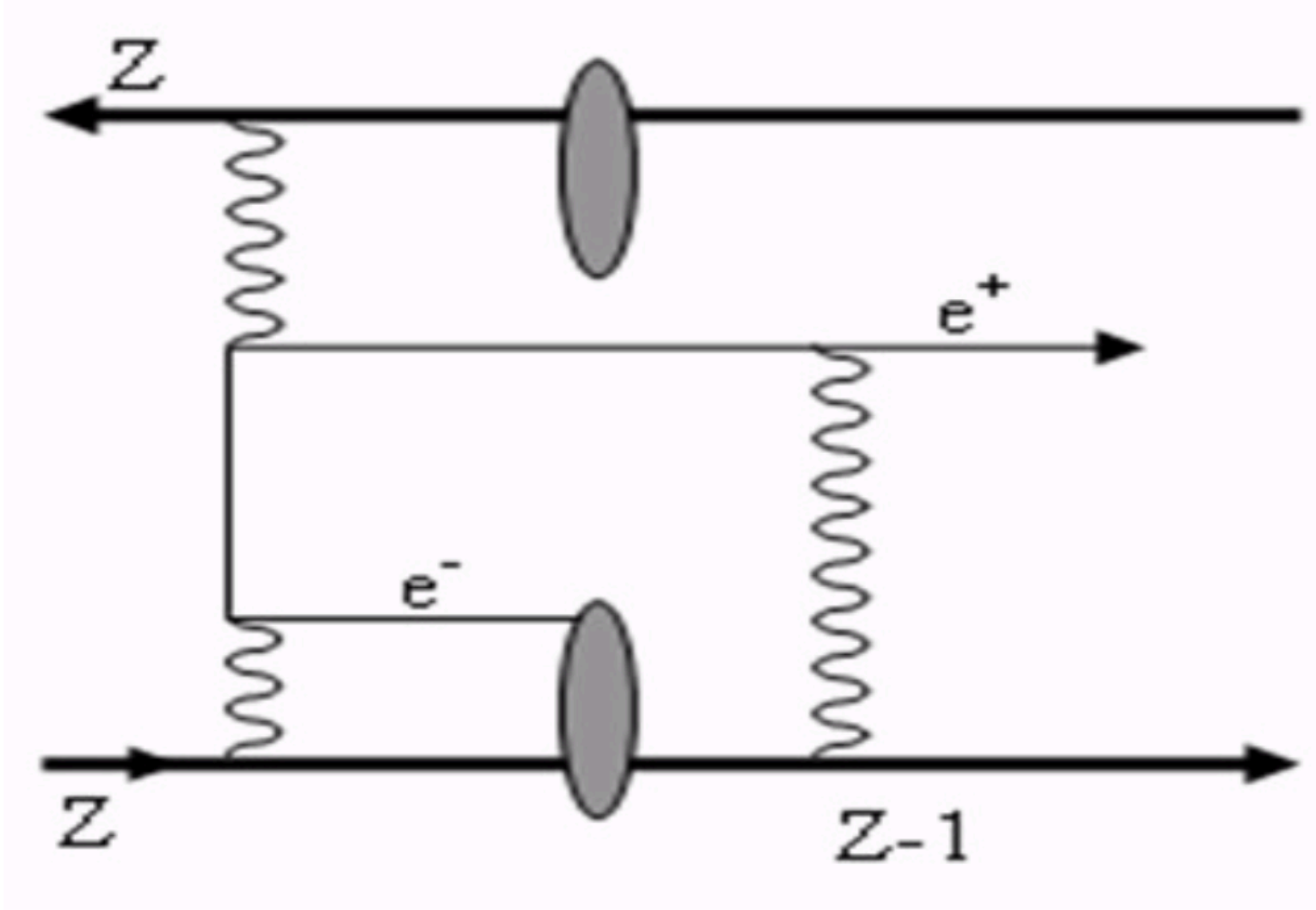


How about lighter ions? (HE/HL-LHC)

Lighter Ions

- Bound-free pair production cross-section: $\sigma_{pp} \propto Z^7[A \log \gamma_{cm} + B]$
  - Strong dependence on ion charges (and energy)
  - Easy to avoid the bound by going lighter!
    - Can effectively increase the luminosity with lighter ions
- Successful XeXe run at LHC!
- For QGP tomography:
  - ✓ Increase of luminosity
  - X Smaller energy loss

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



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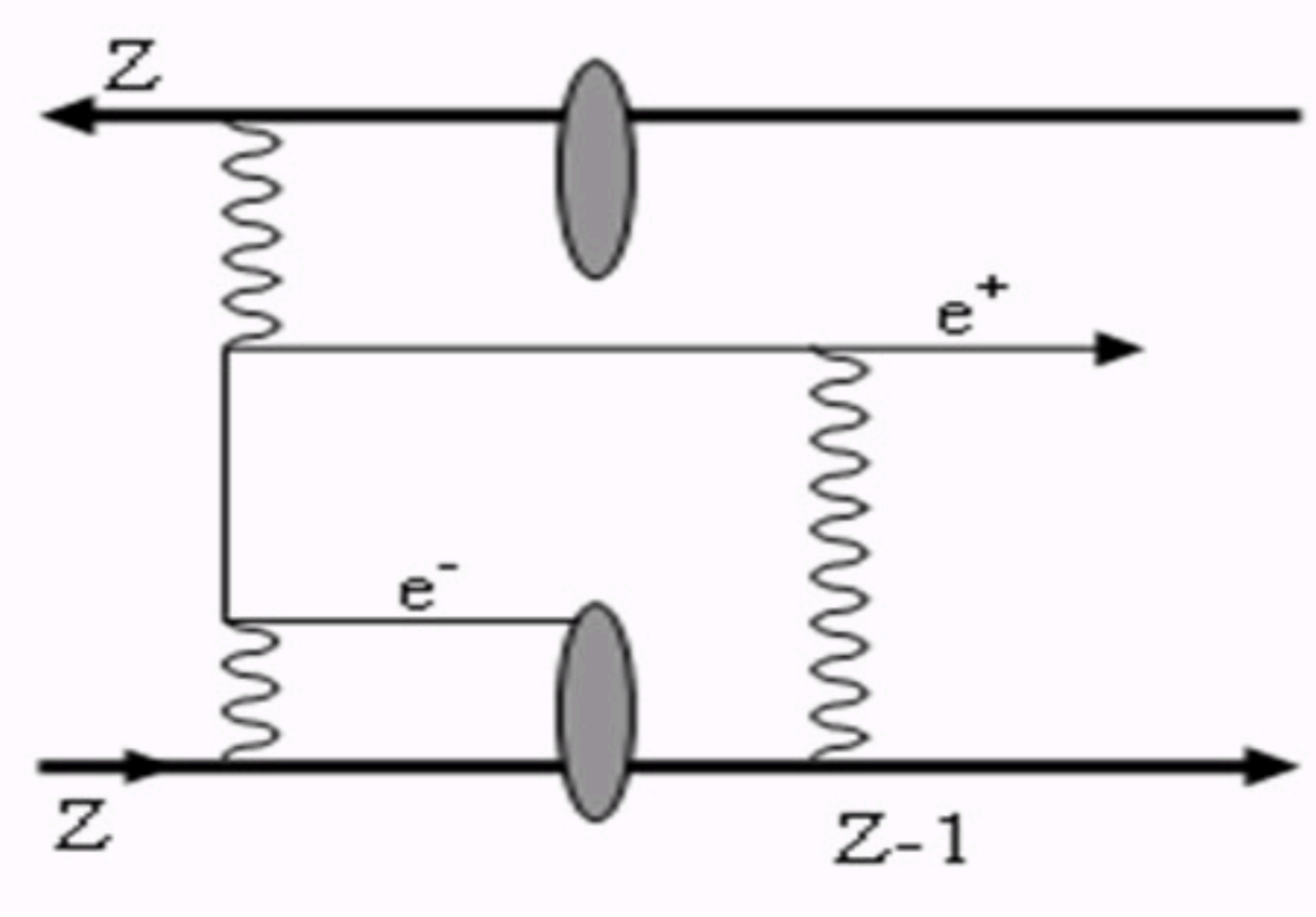

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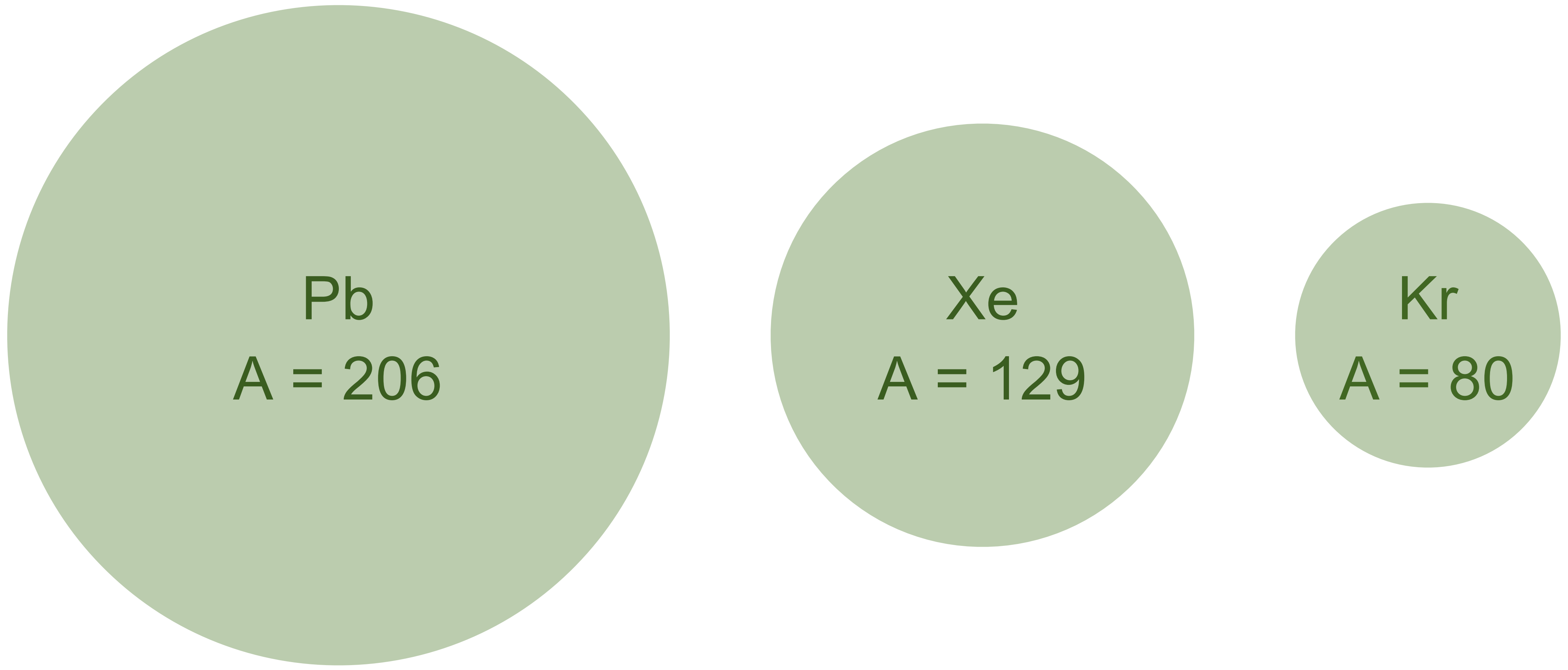
Accessible timescales (?)

Energy Loss



- Lighter ions considered: Xe and Kr
- Since $L \sim A^{1/3}$: N_p = number of participants
  - ➡ $\Delta E^{XX}/E^{XX} \sim (N_p^{XX}/N_p^{PbPb})^{1/3}\ \Delta E^{PbPb}/E^{PbPb}$

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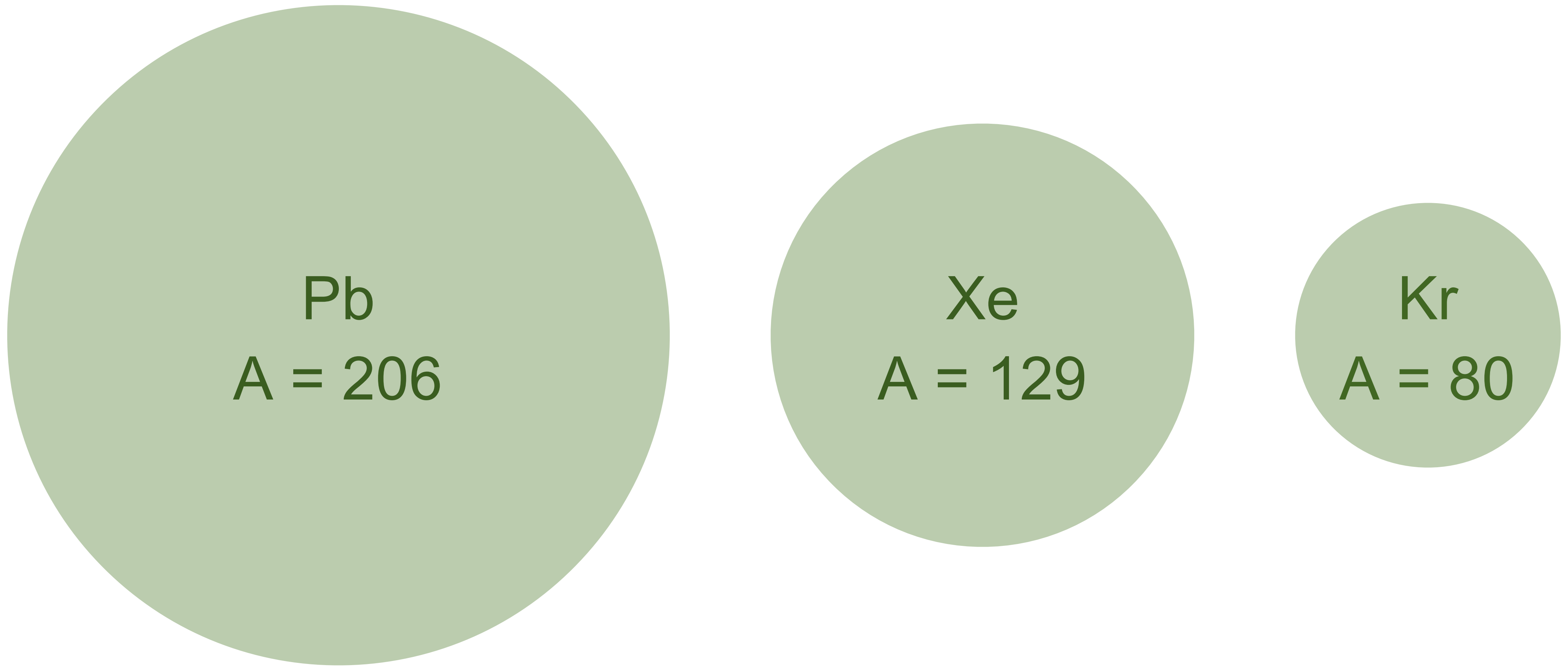
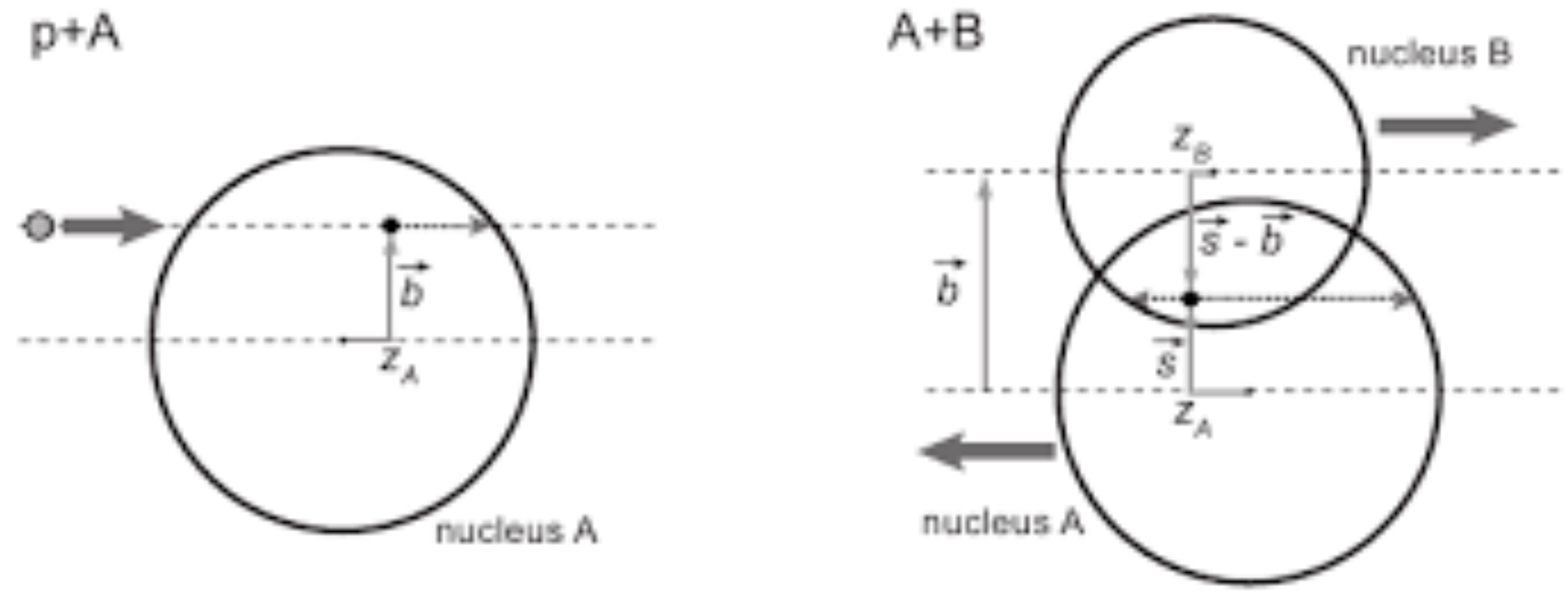
- Glauber model:
  - $N_p^{PbPb} \sim 356$ [0-10]%, $N_p^{XeXe} \sim 210$ [0-10]% and $N_p^{KrKr} \sim 110$ [0-10]%
  - ➡ $\Delta E^{XeXe}/E^{XeXe} \sim 0.13$ and $\Delta E^{KrKr}/E^{KrKr} \sim 0.1$
- Centre-of-mass energies:
  - ➡ HE-LHC: $\sqrt{s}^{XeXe}$= 11.5 TeV and $\sqrt{s}^{KrKr}$ = 10 TeV



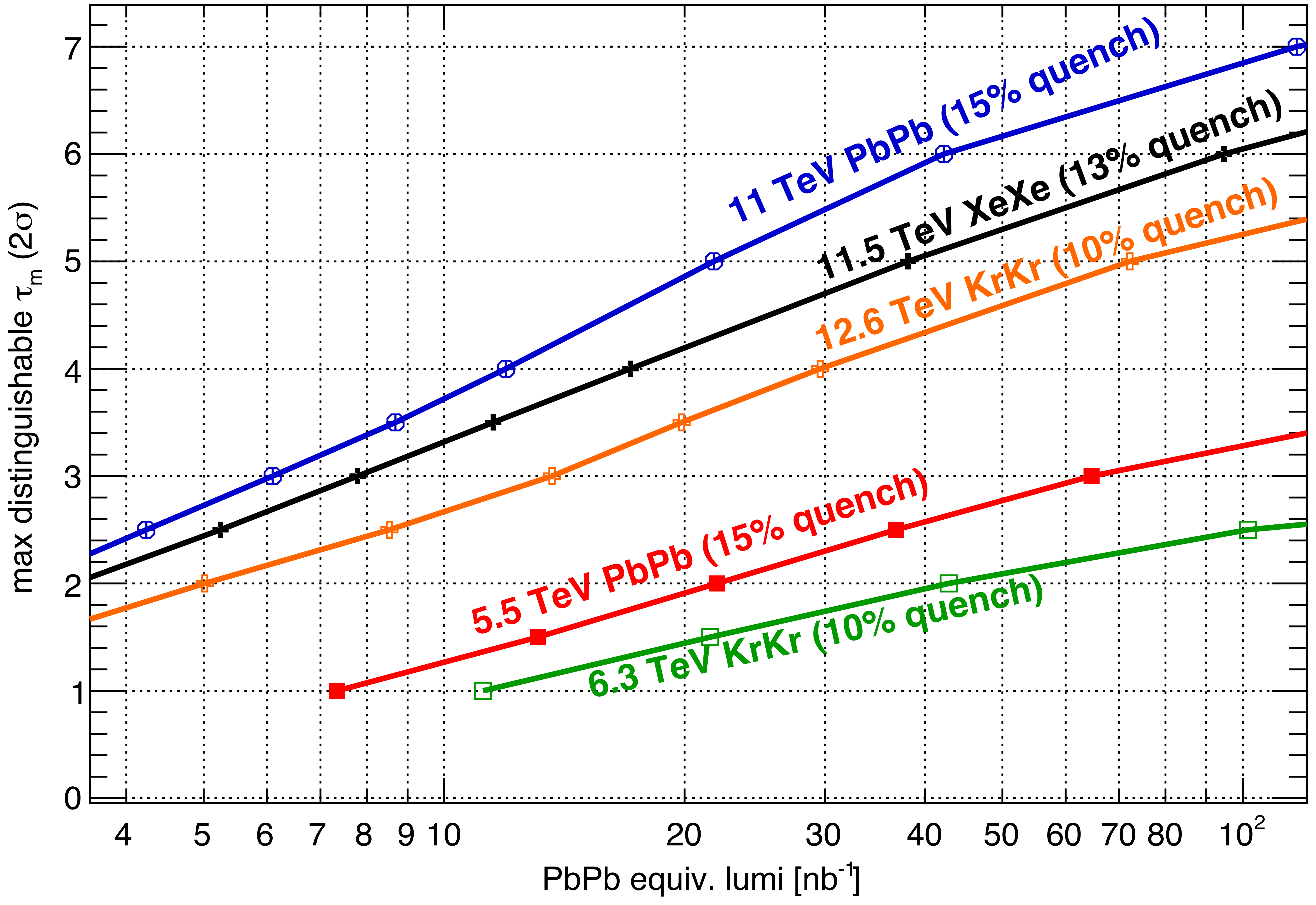


C. Loizides, J. Nagle, P. Steinberg (2014)

http://arxiv.org/abs/1408.2549

QGP Timescales @ HE-LHC

- Maximum "brick" time, τ_m, that can be distinguished (from full quenching) with 2σ, as a function of $\mathscr{L}_{equiv}^{PbPb}$:
- HL-LHC:
  - PbPb with L_{int} = 10 nb^{-1}: 1.5 fm/c
  - XeXe with L_{int} = 2-3 x L_{int} from PbPb: 1-2 fm/c
- HE-LHC:
  - PbPb with L_{int} = 30 nb^{-1} (5 months): 5.5 fm/c
  - XeXe with Lint = 2-3 L_{int} from PbPb: 5-6 fm/c



Conclusions

- Top quarks and their decays has a unique potential to resolve the time evolution of the QGP
- A first attempt along this line of research (proof of concept):
  - Energy loss fluctuations, statistical significance assessment based on a “true-sized” sample (event reconstruction efficiency, b-tagging efficiency,…), but no underlying event background or sophisticated energy loss model…

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- Promising results:
  - FCC energies: should be possible to assess the QGP density evolution (control over timescales can be done via p_T dependence);
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Thank you!

Acknowledgements

REPÚBLICA PORTUGUESA

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

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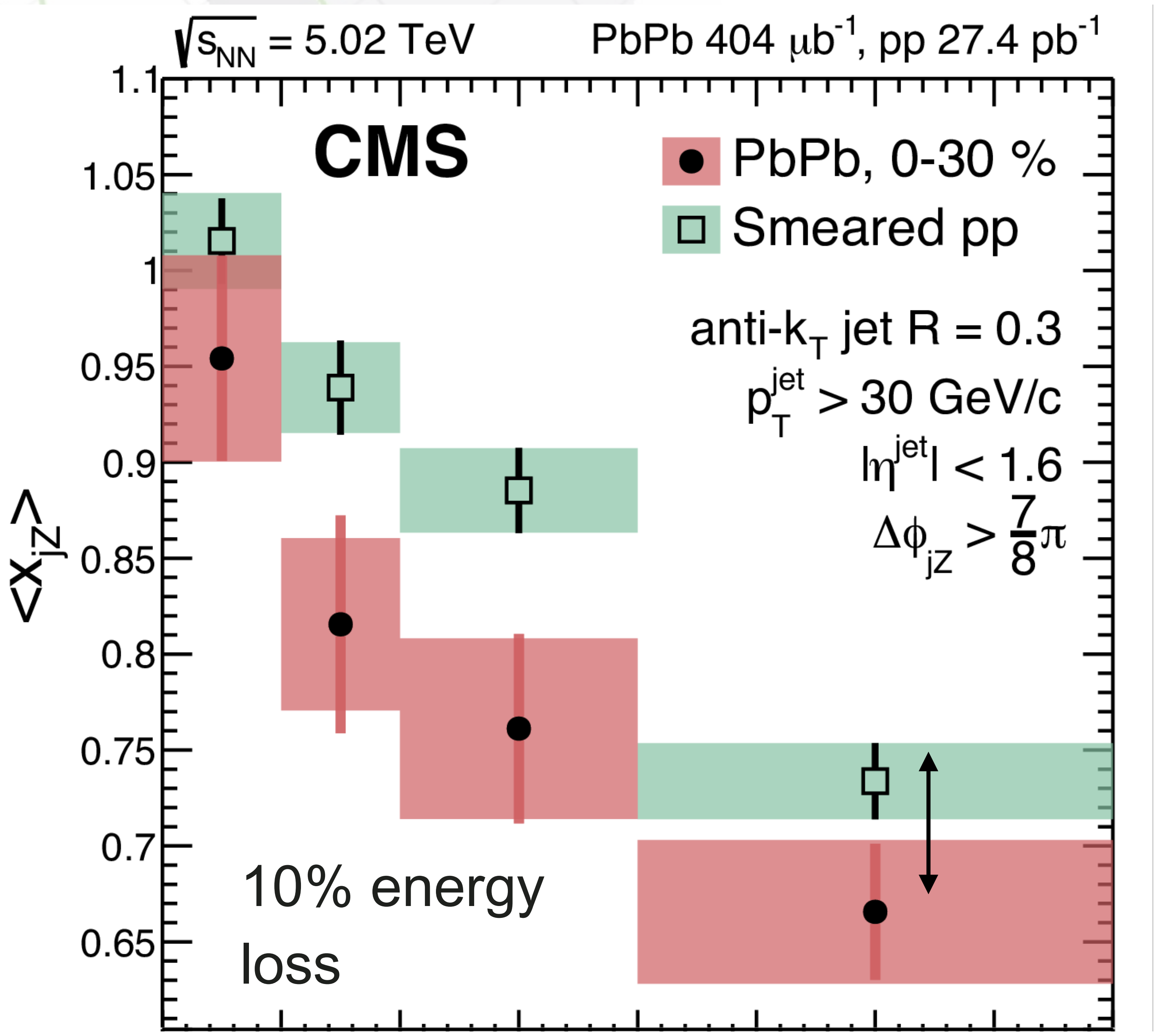
LIP

TÉCNICO LISBOA

Backup

Jet Energy Loss

- Average Jet Energy Loss:
  - Z+Jet: (CMS PRL 2017)



(Average momentum imbalance Z + Jet)

- Energy Loss Fluctuations:
  - Gaussian at particle level
  - ➡ 150%/√(pT) ≡ 15% at 100GeV

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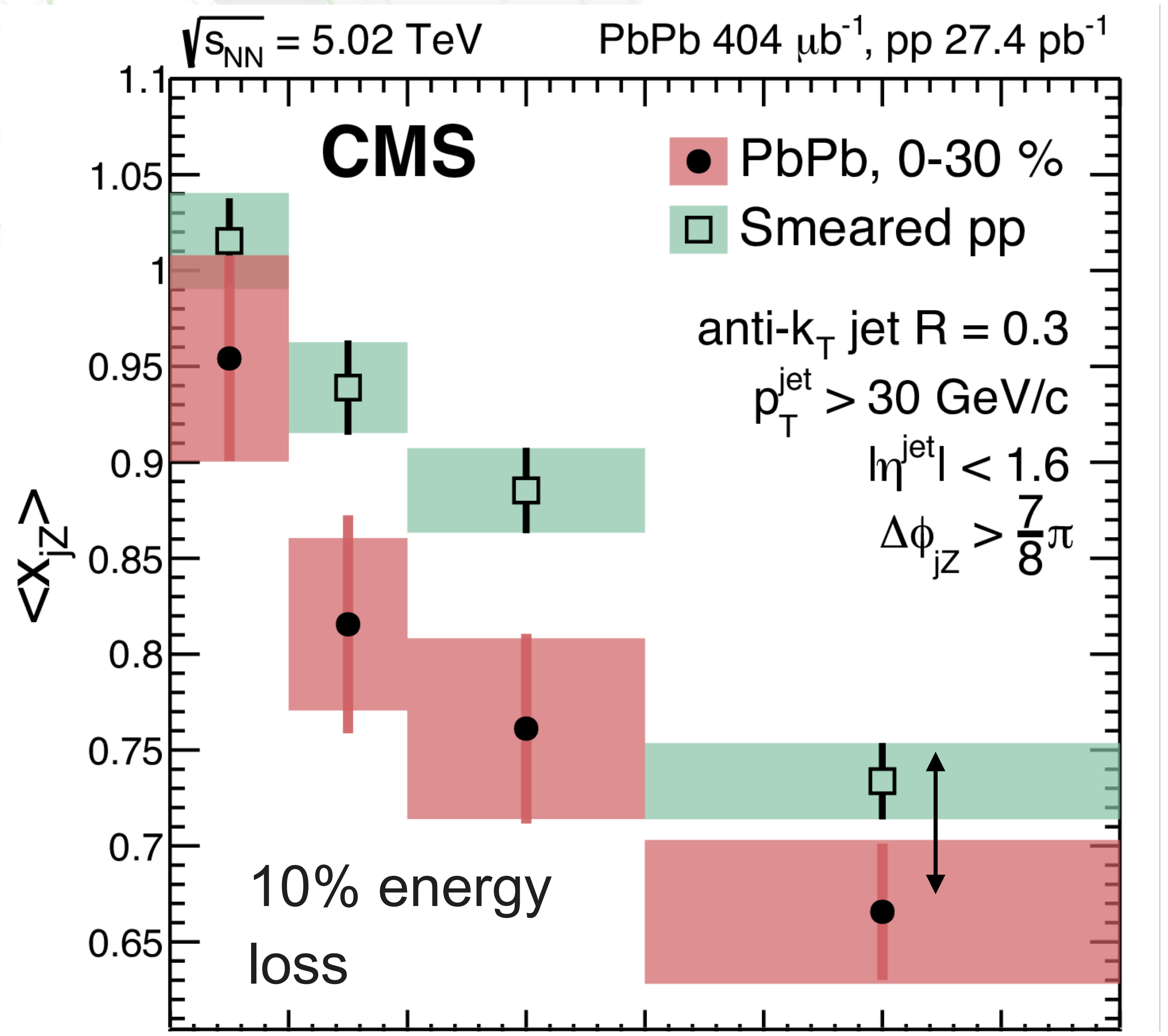
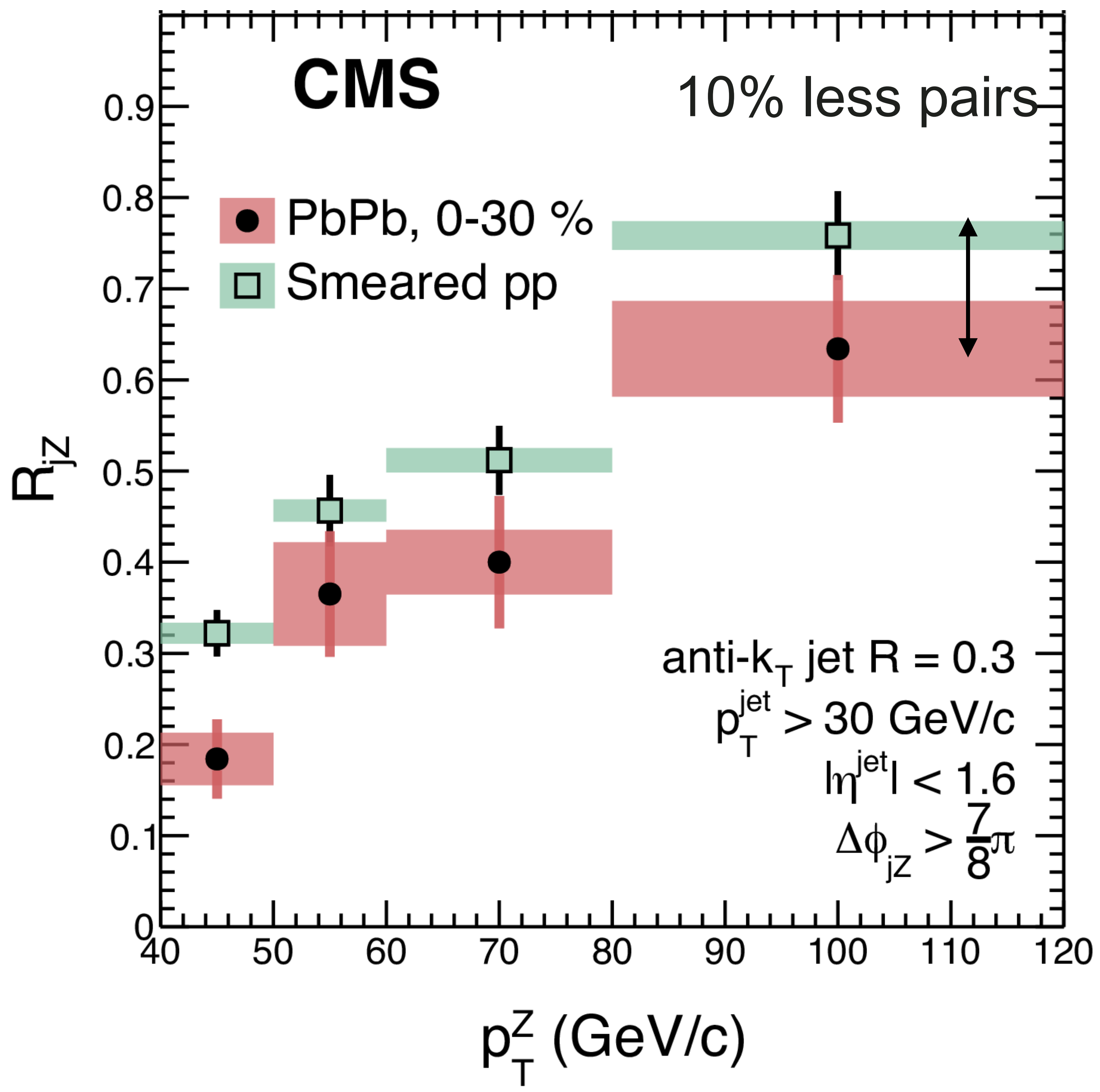


(Average momentum imbalance Z + Jet)

(Average number of Z + Jet pairs)



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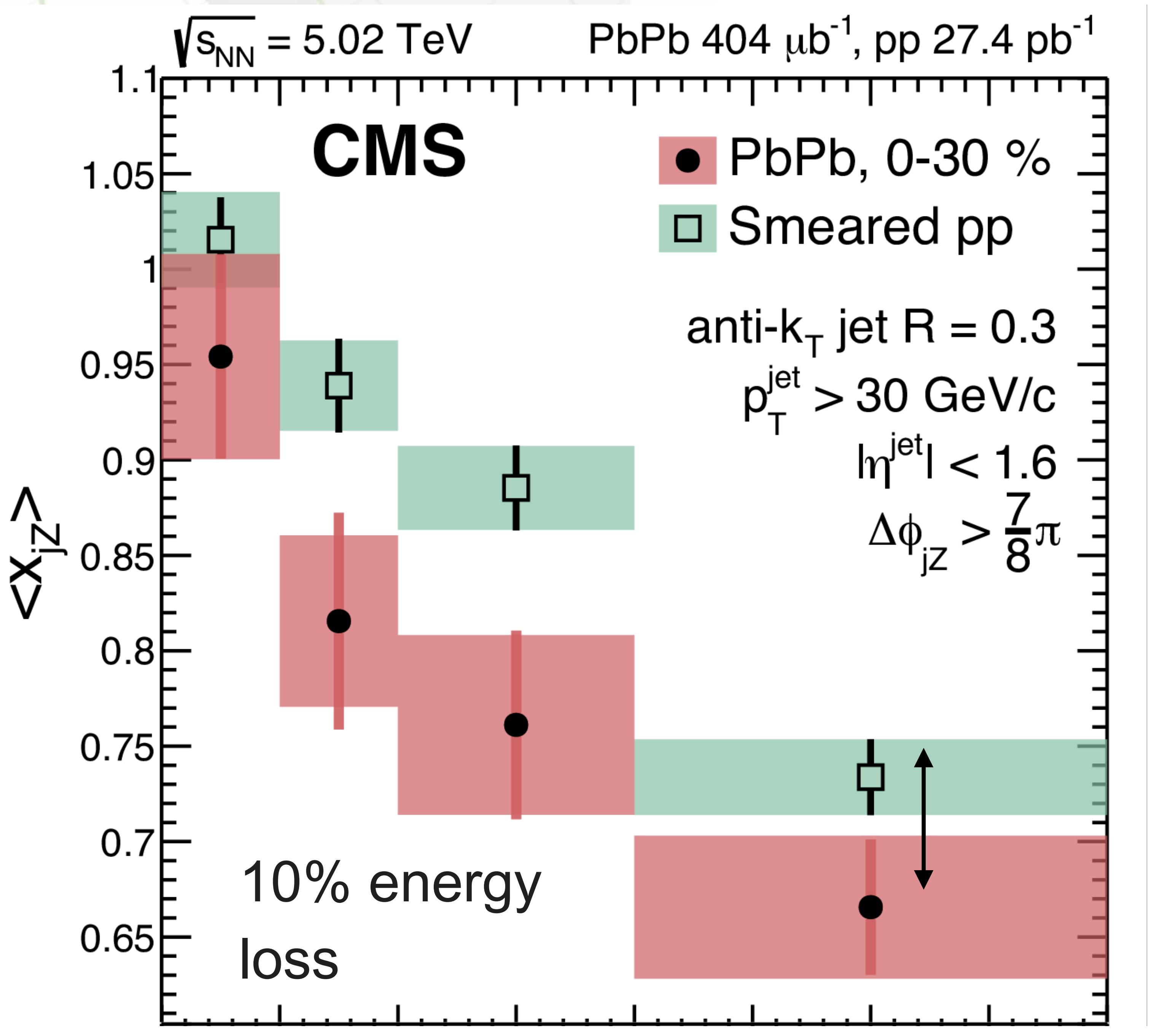

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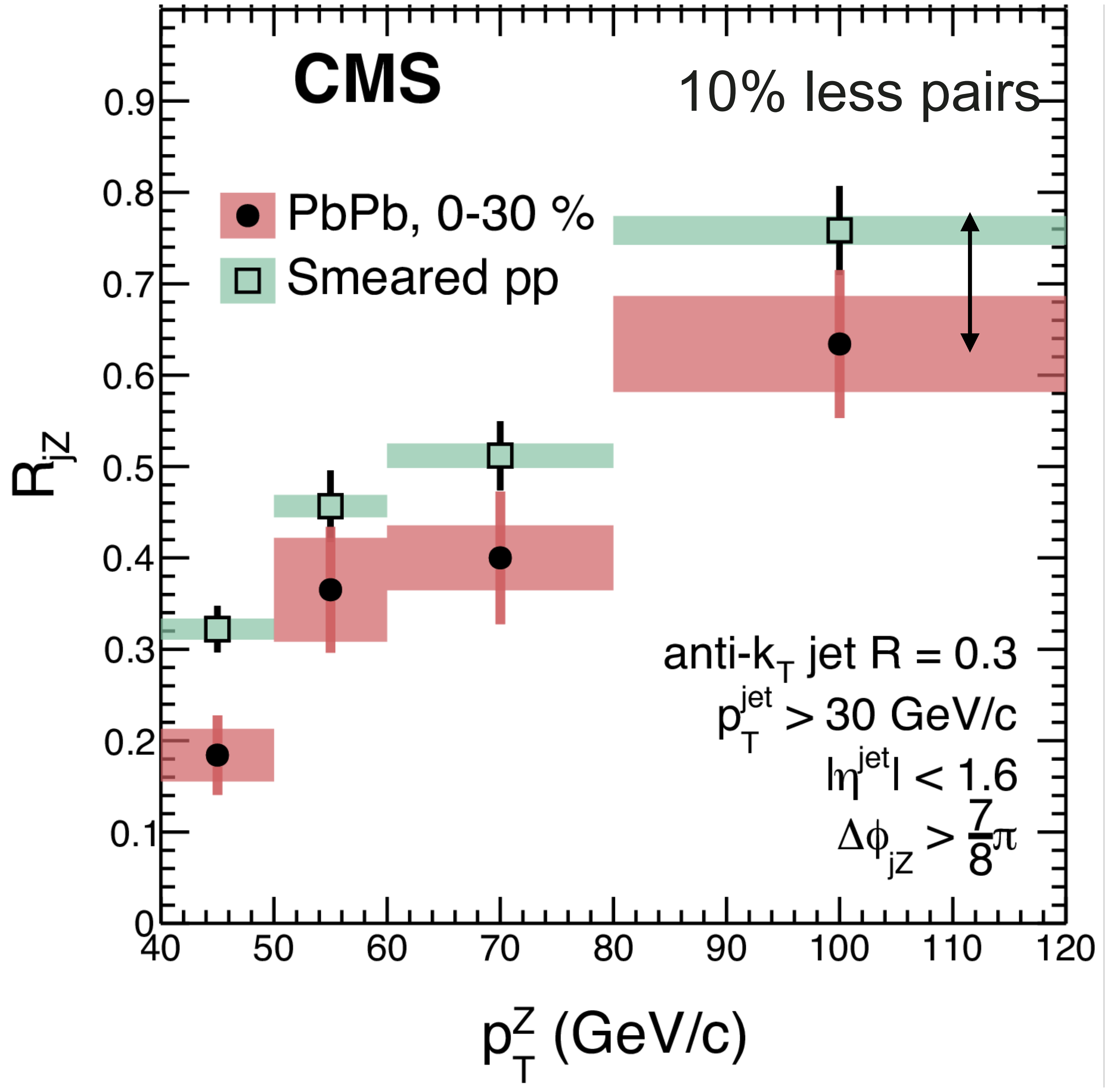

Taking into account the pairs that are lost (its pt falls below the pt cut): $\frac{\Delta E}{E} = -0.15$

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  - Gaussian at particle level
  - ➡ 150%/√(pT) ≡ 15% at 100GeV

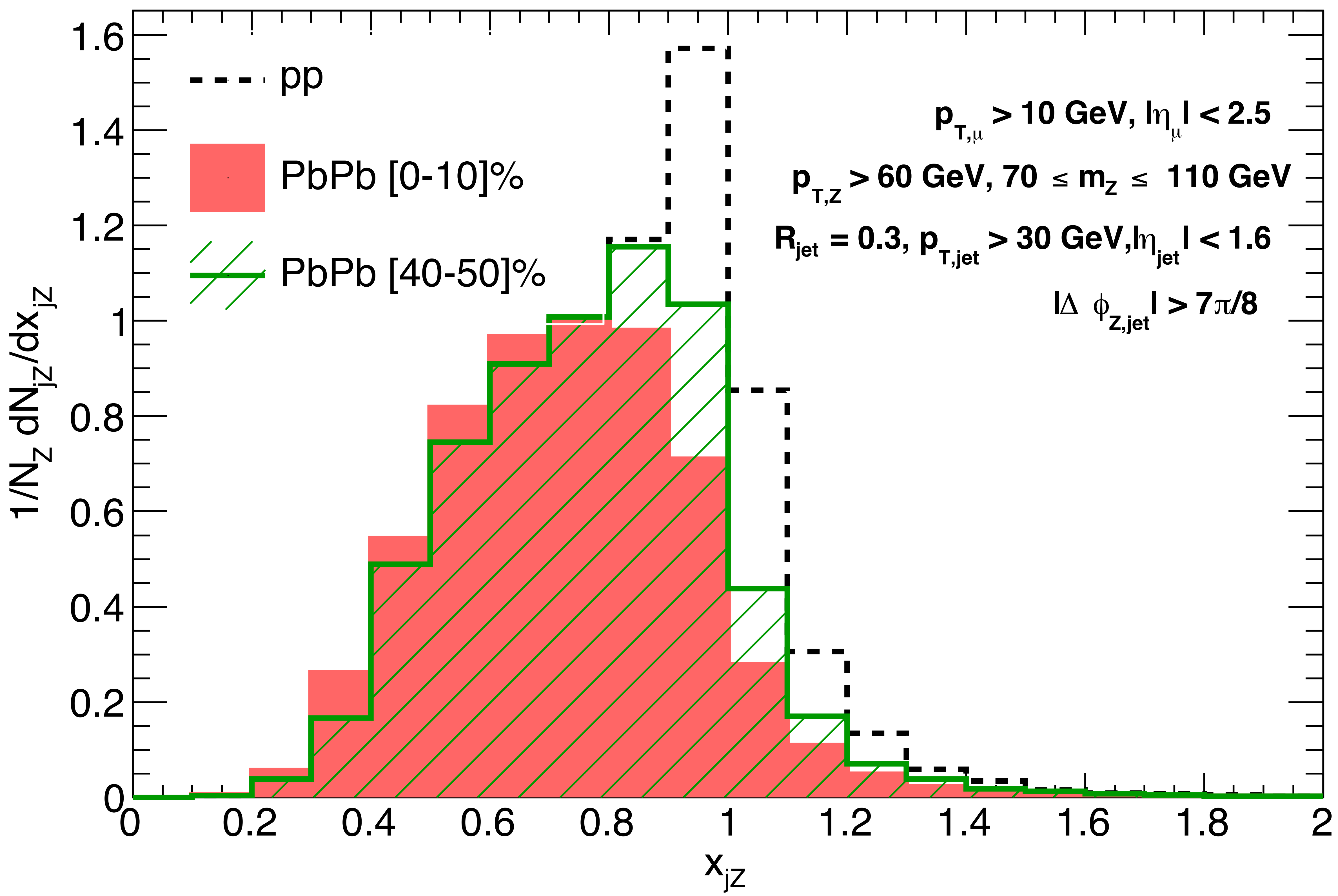
Light Systems

- Energy Loss of lighter systems (Glauber):
  - N_p^{PbPb} ~ 356 [0-10]%: $\Delta E^{KrKr}/E^{KrKr}$ ~ 0.15
  - N_p^{XeXe} ~ 210 [0-10]%: $\Delta E^{XeXe}/E^{XeXe}$ ~ 0.13
  - N_p^{KrKr} ~ 110 [0-10]%: $\Delta E^{KrKr}/E^{KrKr}$ ~ 0.1

    30% less than PbPb [0-10]%

- Energy Loss of lighter systems (γ+jet):
  - PbPb [0-10]%: $\langle x_{jz} \rangle$ ~ 0.7;
  - PbPb [40-50]%: $\langle x_{jz} \rangle$ ~ 0.8 (N_p ~ 107 [0-10]%);

    15% less than PbPb [0-10]%



Simulation

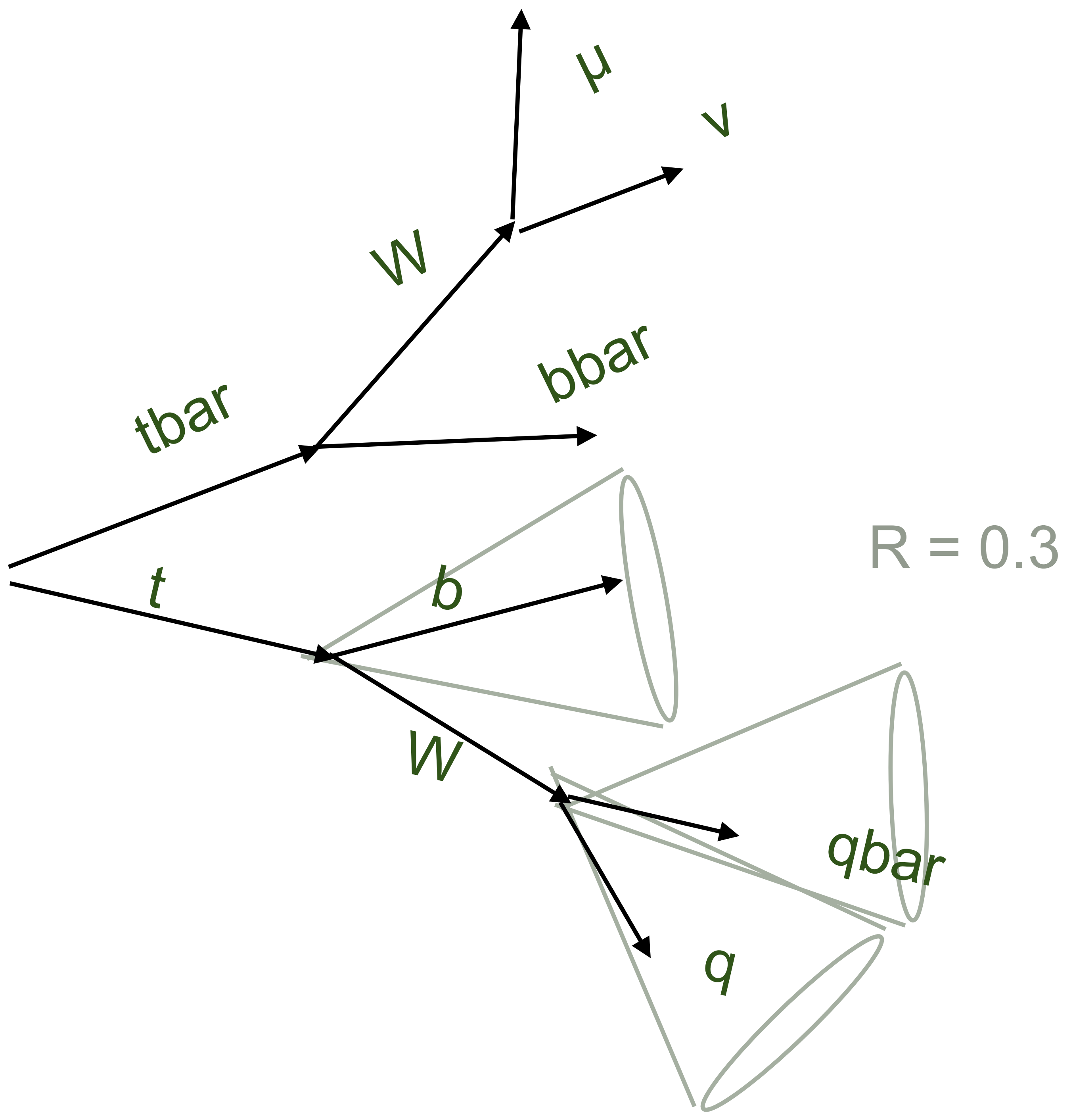
- Monte Carlo Event Generator (POWHEG NLO ttbar production + pythia 8 showering with PDF4LHC15_nlo_30_PDF):
- Rescaling at parton level with Gaussian fluctuations like:
  - $Q\,(1 + r\,\sigma_{pt} / p_{t,i} + 1\text{ GeV})^{1/2}$,
    - Q = Quenching factor (Q_0 or $Q(\tau_{tot})$)
    - r = random number from Gaussian with $\sigma = 1$
    - $\sigma_{pt} = 1.5\text{ GeV}^{1/2}$ (≡ 15% at 100GeV, arXiv:1702.01060: CMS Z+jet)

Particle Decay and Coherence Time

- To get an event-by-event estimate of the interaction start time each component has associated a randomly distributed exponential distribution with a mean and dispersion:
    - $\langle \gamma_{t,top}\, \tau_{top} \rangle \simeq 0.18$ fm/c , $\langle \gamma_{t,W}\, \tau_{W} \rangle \simeq 0.14$ fm/c , $\langle \tau_d \rangle \simeq 0.34$ fm/c
- Reconstruction of the event (at parton level)
    - 1μ with $p_T > 25$ GeV and $|\eta| < 2.5$
    - Jet reconstruction with anti-k_T R = 0.3, $p_T > 30$ GeV, $|\eta| < 2.5$. (recluster with k_T, R = 1.0 and decluster with dcut = $(20\text{GeV})^2$)
    - 2 b-jets + >= 2 non-bjets
- Quenching + energy loss fluctuations at parton level

W Mass Reconstruction

- W candidate reconstruction procedure:
  - $p_{T,\mu}$ > 25 GeV + 2 bjets + >= 2 non-bjets
  - Anti-k_T R = 0.3, p_T > 30 GeV, $|\eta|$ < 2.5. (recluster with k_T, R = 1.0 and decluster with dcut = $(20 GeV)^2$)
  - W jets = 2 highest-p_T non-b jets.
  - W candidate is reconstructed by considering all pairs of non-b jets with m_{jj} < 130 GeV; the highest scalar p_T sum pair is selected
  - b-tagging efficiency of 70% (pPb events)



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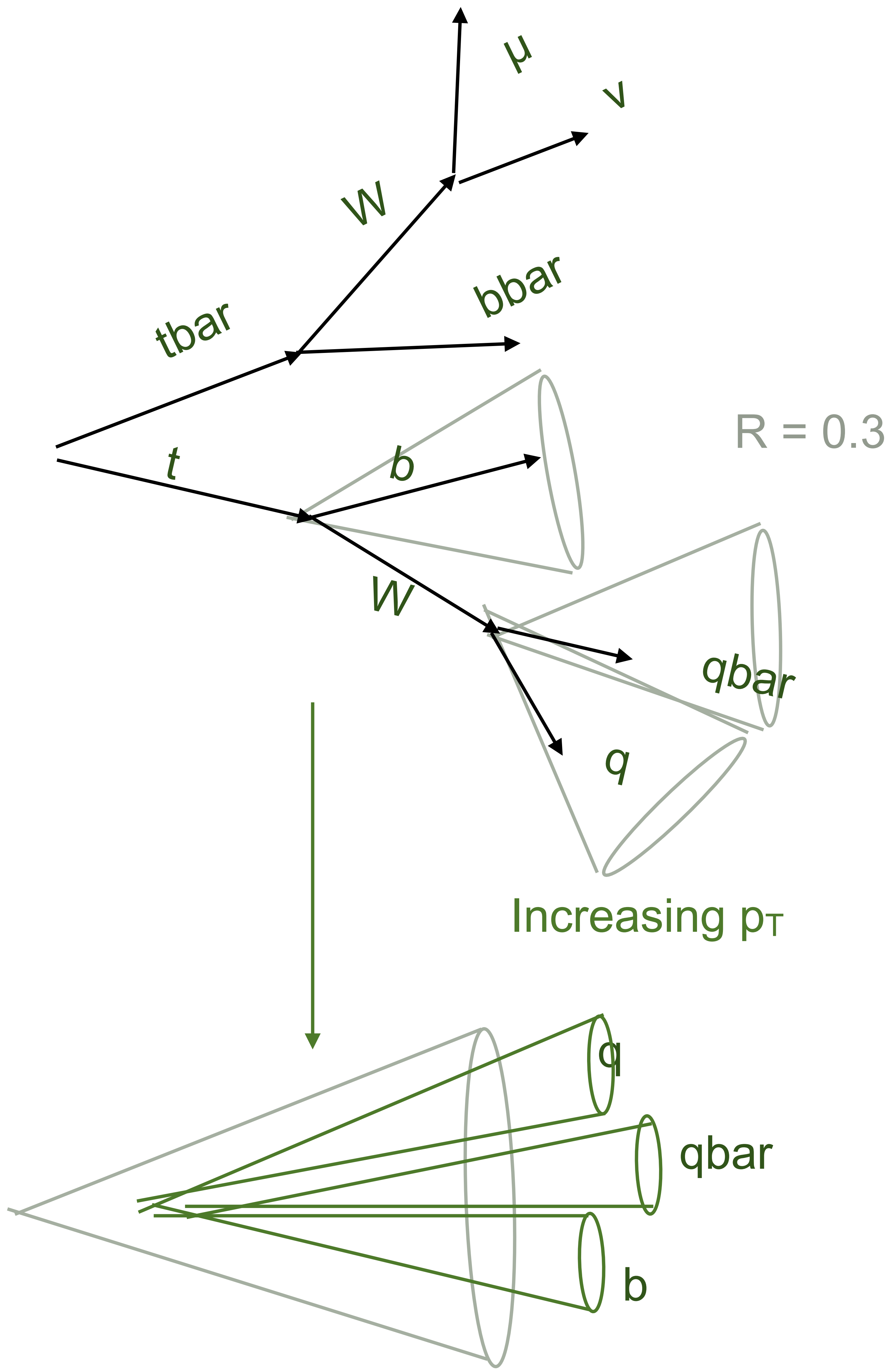

Reconstruction procedures

- Ours:
  - 1μ with $p_T > 25$ GeV and $|\eta| < 2.5$
  - Jet reconstruction with anti-k_T $R = 0.3$, $p_T > 30$ GeV, $|\eta| < 2.5$ (recluster with k_T, $R = 1.0$ and decluster with dcut = $(20\text{GeV})^2$)
  - "hadronic" W candidate is reconstructed by considering all pairs of non-b jets with $m_{jj} < 130$ GeV;
    - ➡ the highest scalar pt sum pair is selected

- CMS:
  - 1μ with with $p_T > 30$ GeV and $|\eta| < 2.1$
  - Jet reconstruction with anti-k_T $R = 0.4$, $p_T > 25$ GeV and $|\eta| < 2.5$
  - Reconstructed jets must be separated by at least $\Delta R = 0.3$ from the selected muon
  - "hadronic" W candidate is reconstructed by considering the pair with the with the smallest separation in (η,φ) plane

Reconstructed W Mass

- At Future Circular Collider (FCC) energies ($\sqrt{s_{NN}}$ = 39 TeV):
  - σttbar→qqbar+μν ~ 1 nb
- At Large Hadron Collider (LHC) energies ($\sqrt{s_{NN}}$ = 5.5 TeV):
  - σttbar→qqbar+μν ~ 10 pb
- Functional form fit:

$$N(m) = a \exp\left[-\frac{(m - m_W^{fit})^2}{2\sigma^2}\right] + b + c\,m$$

Gaussian on top of a linear background

pp event scaled by quenching factor (embedded in PbPb)

pp event (embedded in PbPb)