Time structure of QGP using top quarks in PbPb collisions

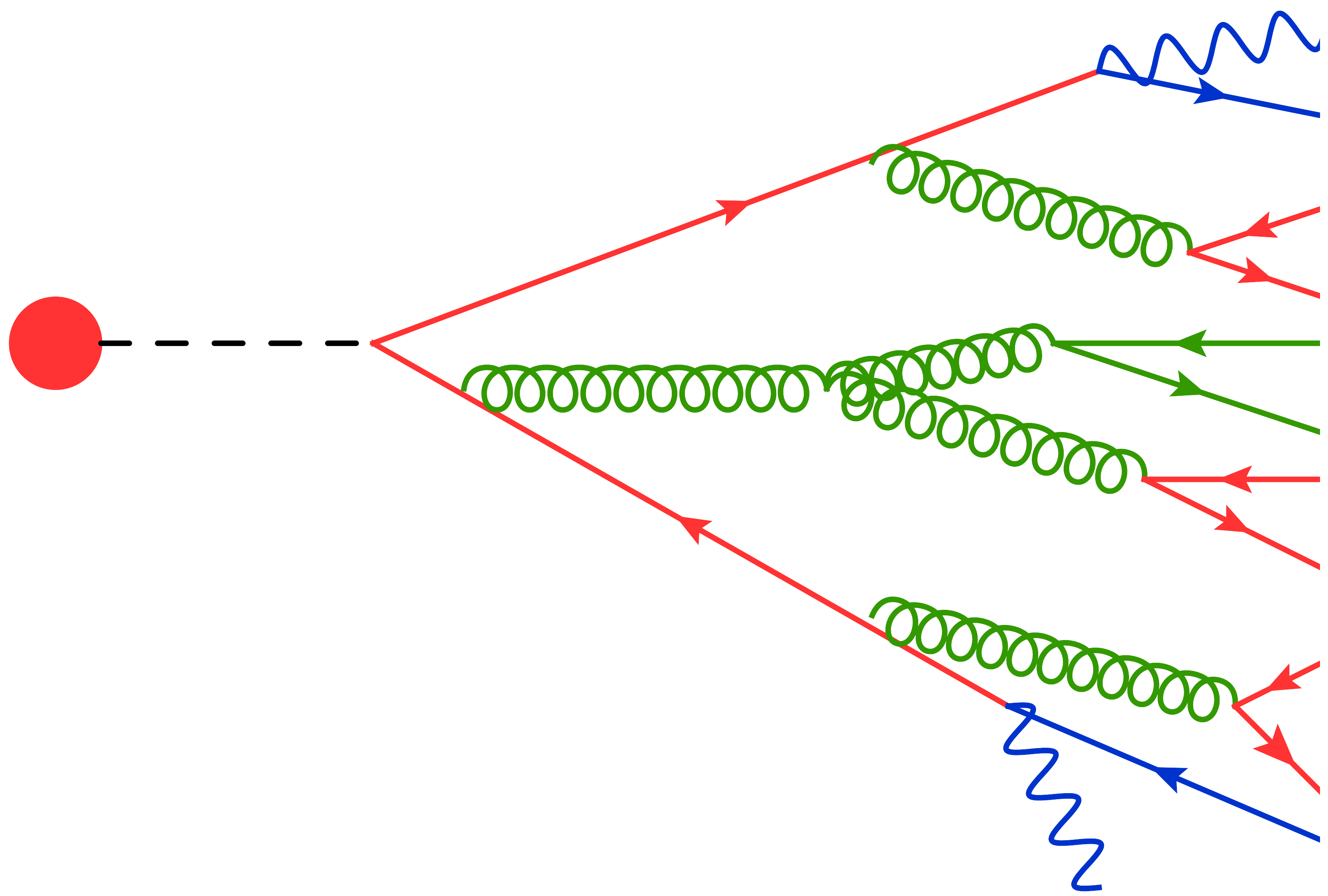
Liliana Apolinário

February 2020

IPN Orsay, France

Hard Probes in the QGP

- What happens when a high momentum particle travels through the QGP?



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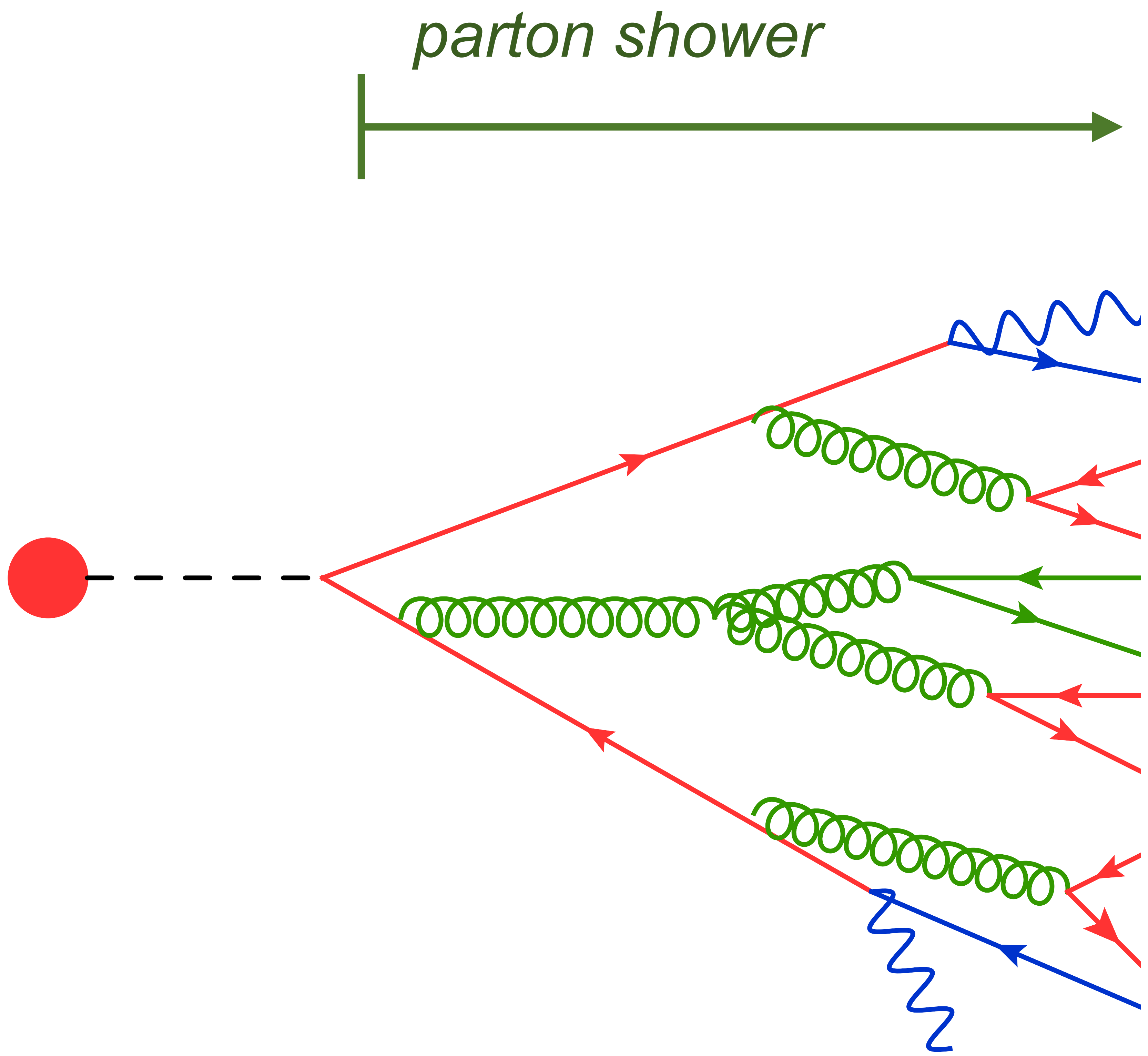

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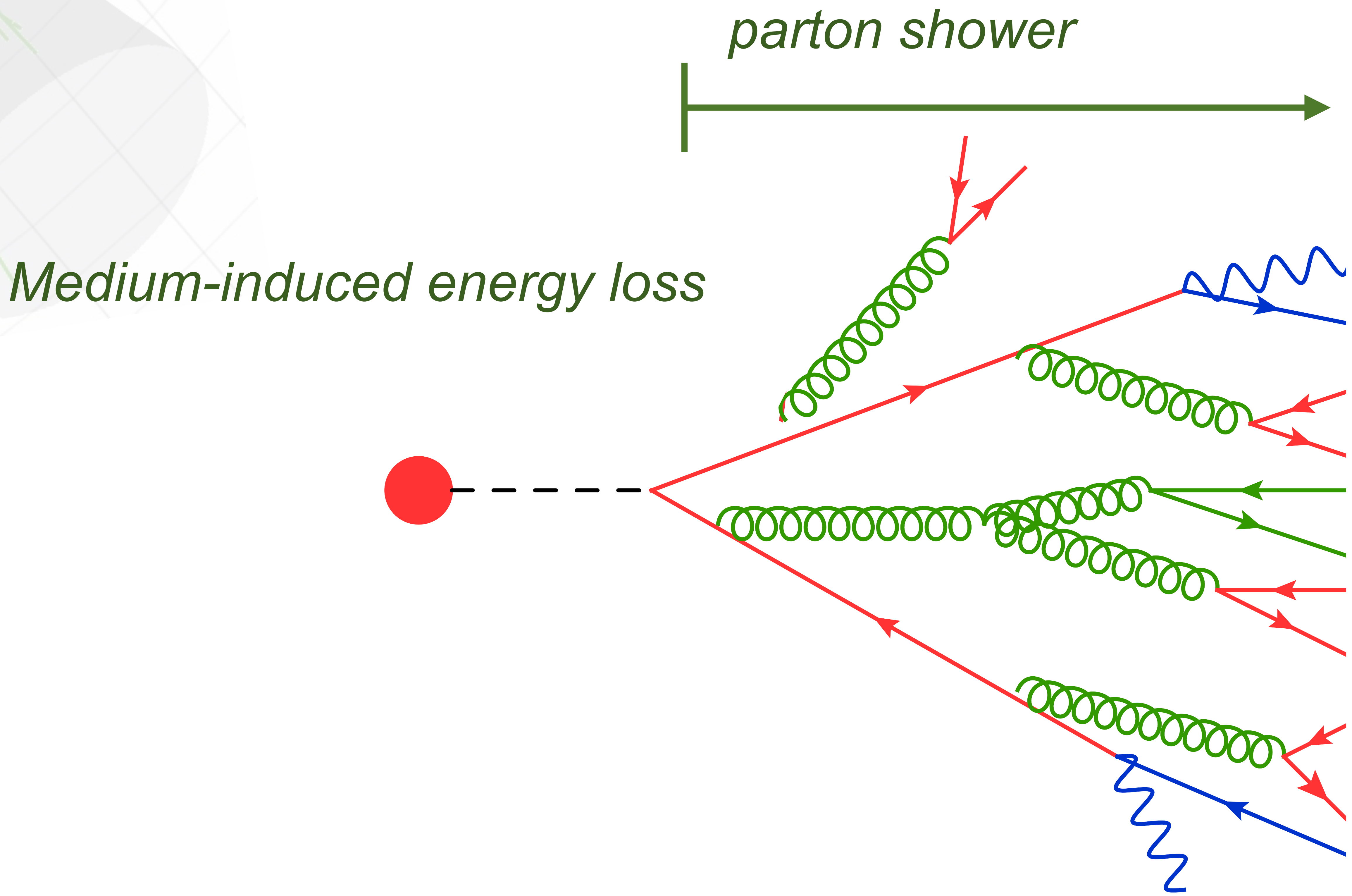

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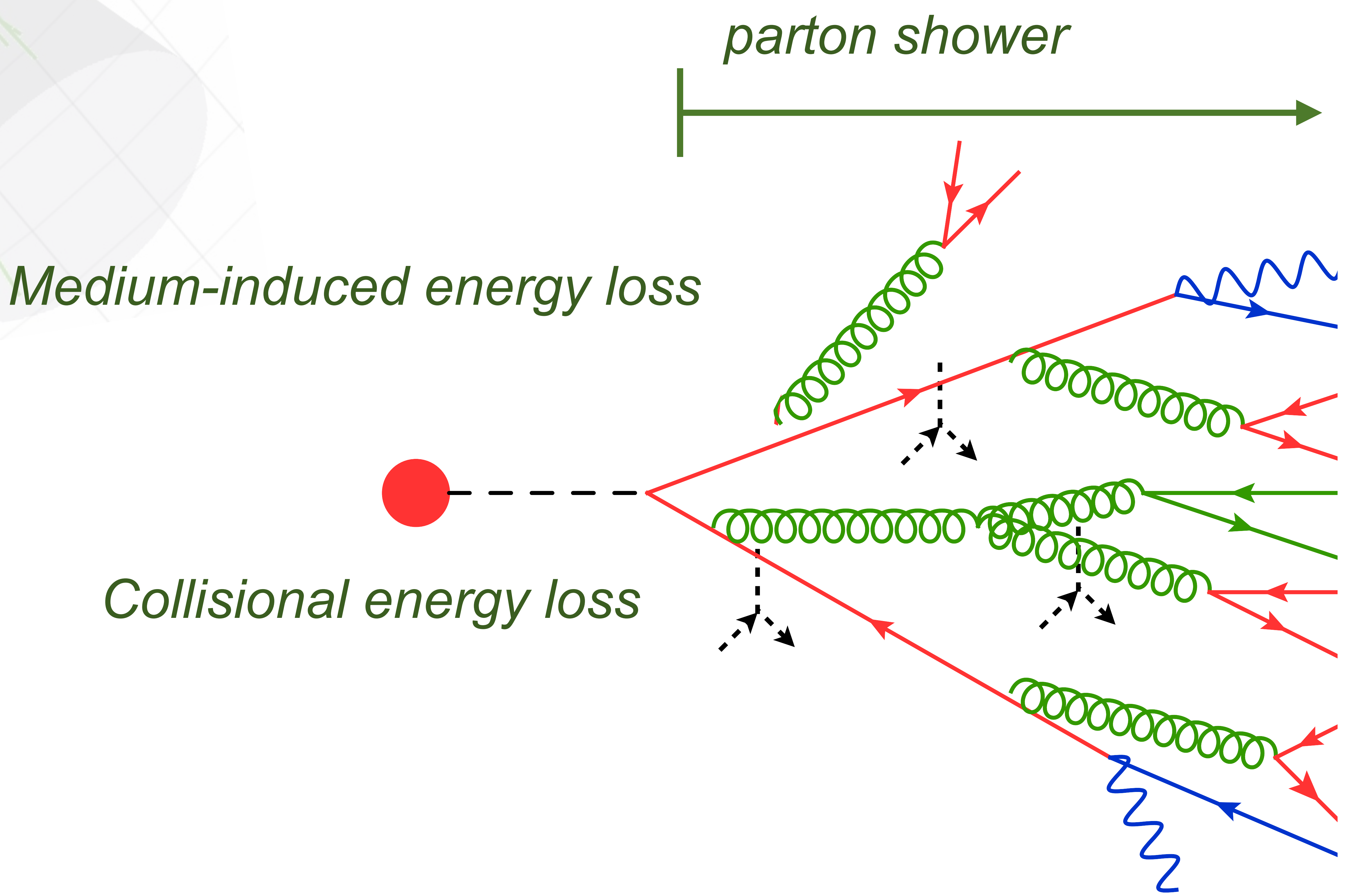

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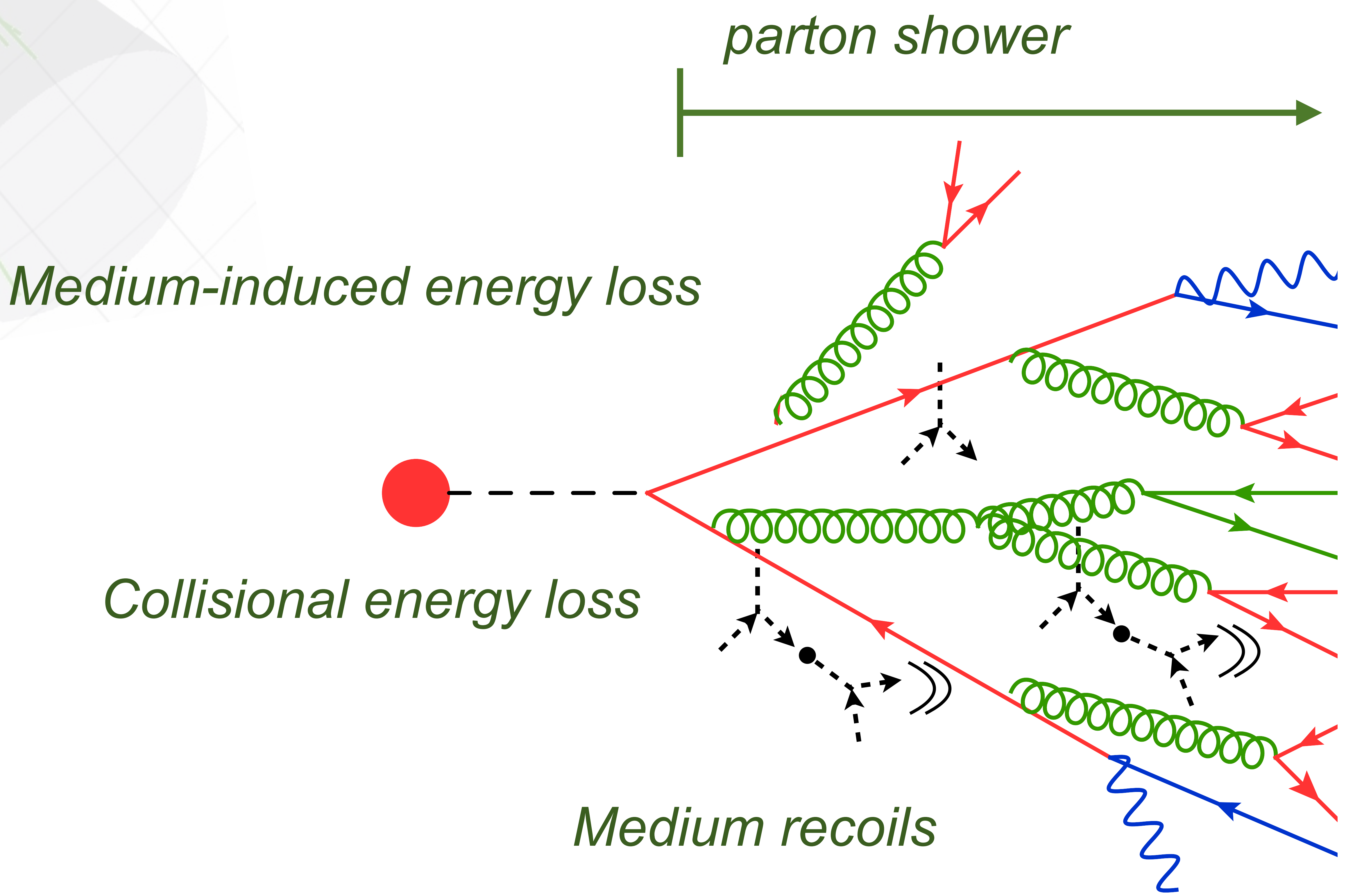

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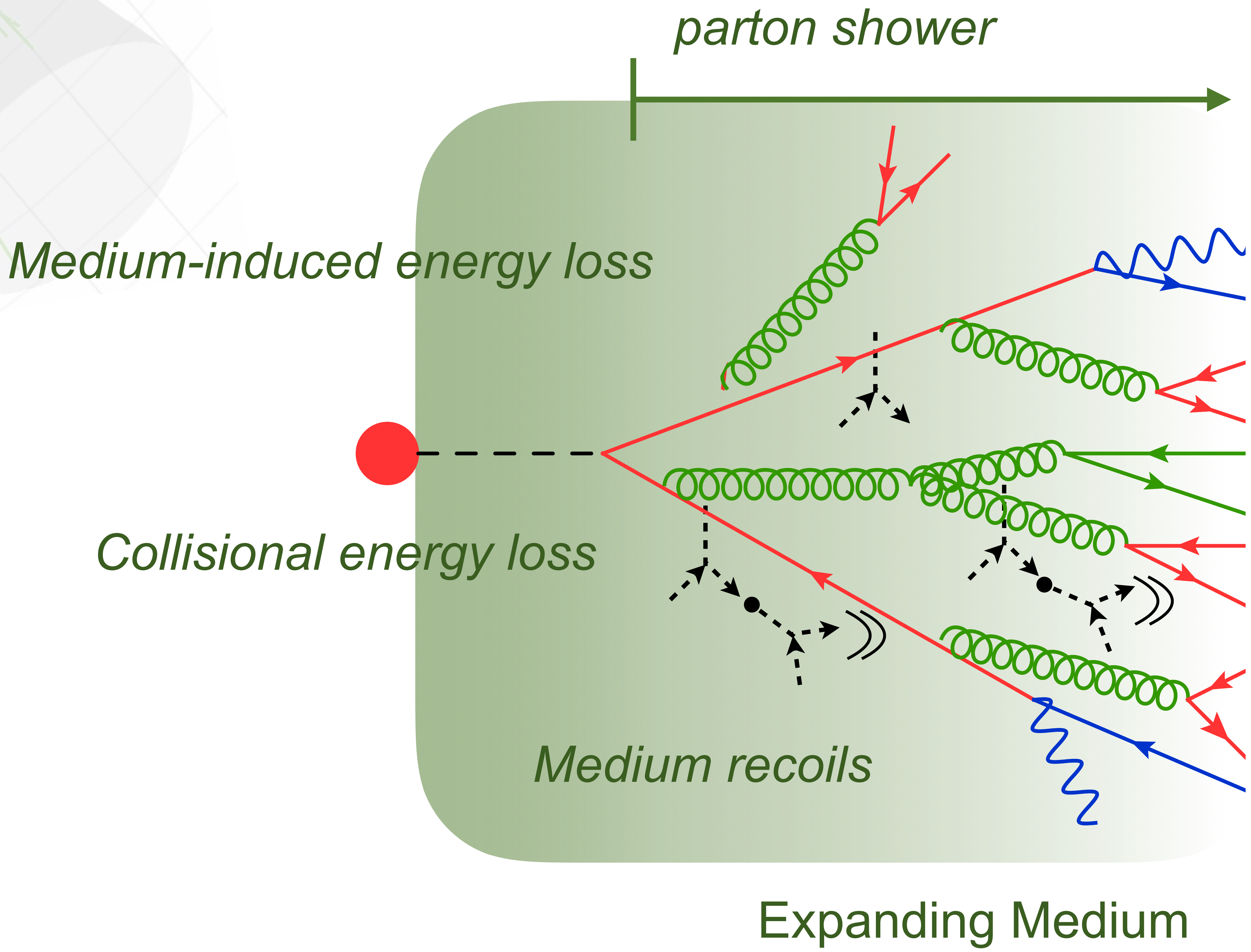

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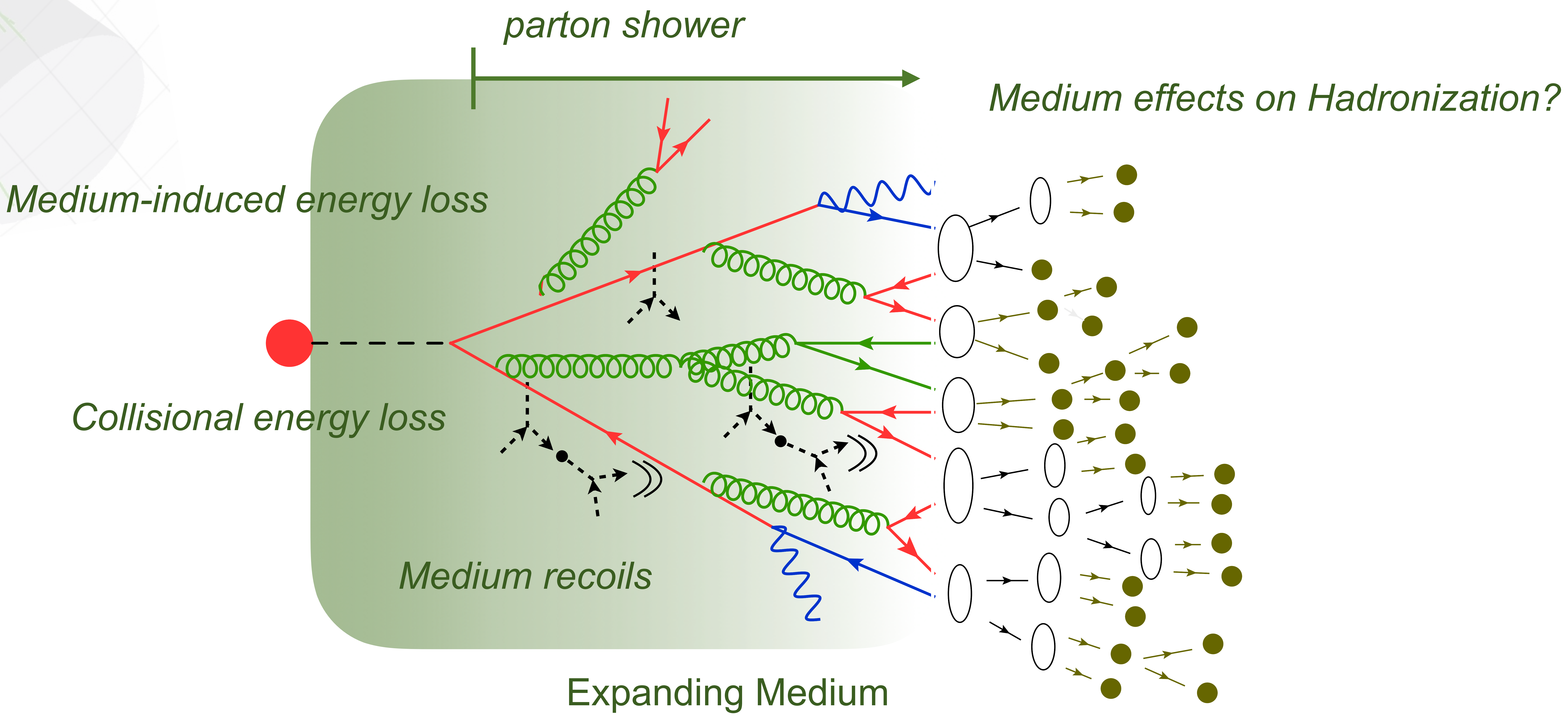

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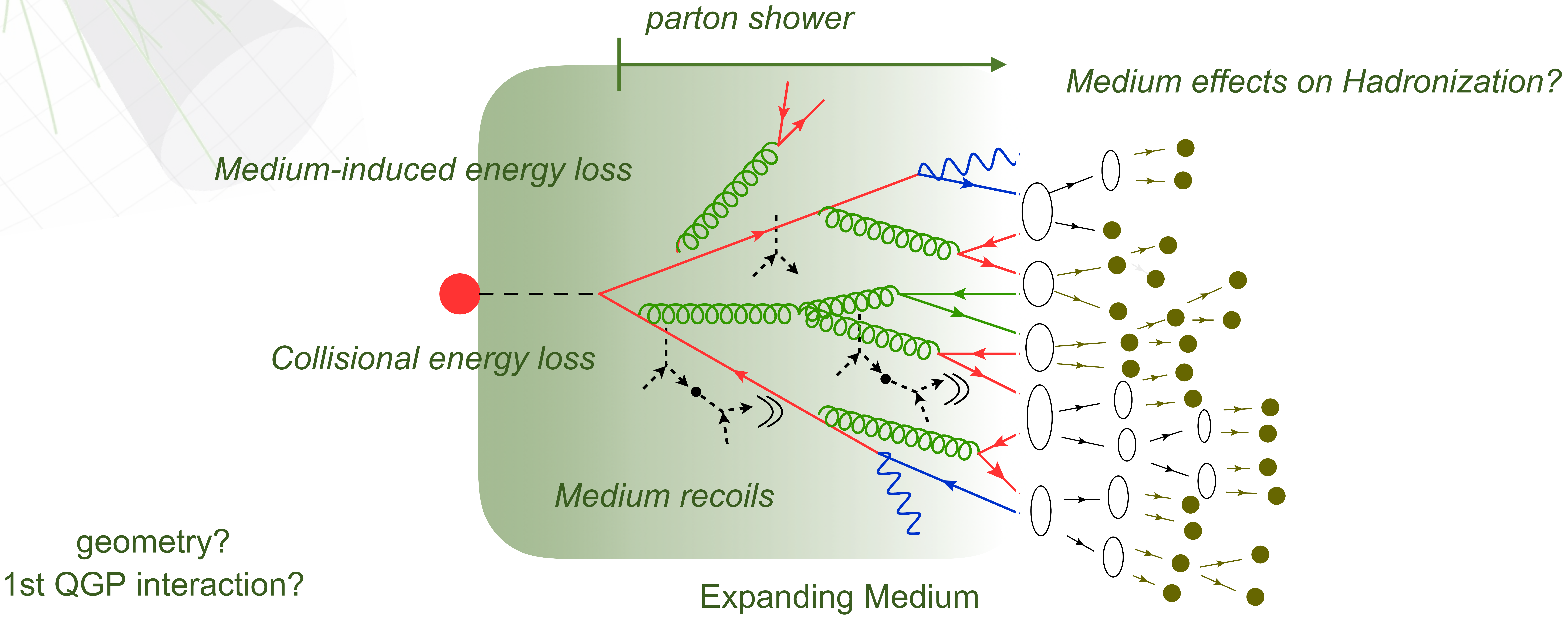

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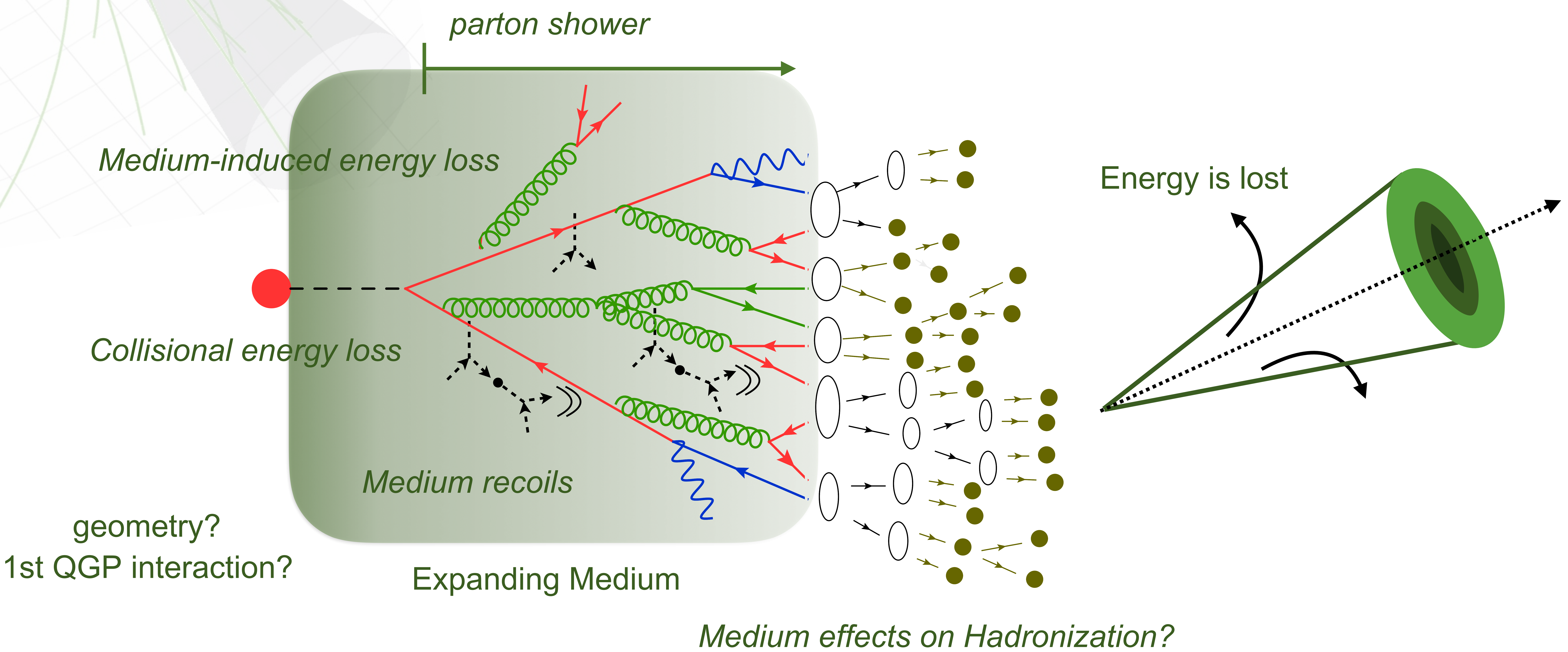

Hard Probes in the QGP

Increase of outer region of the jet transverse profile/soft fragments

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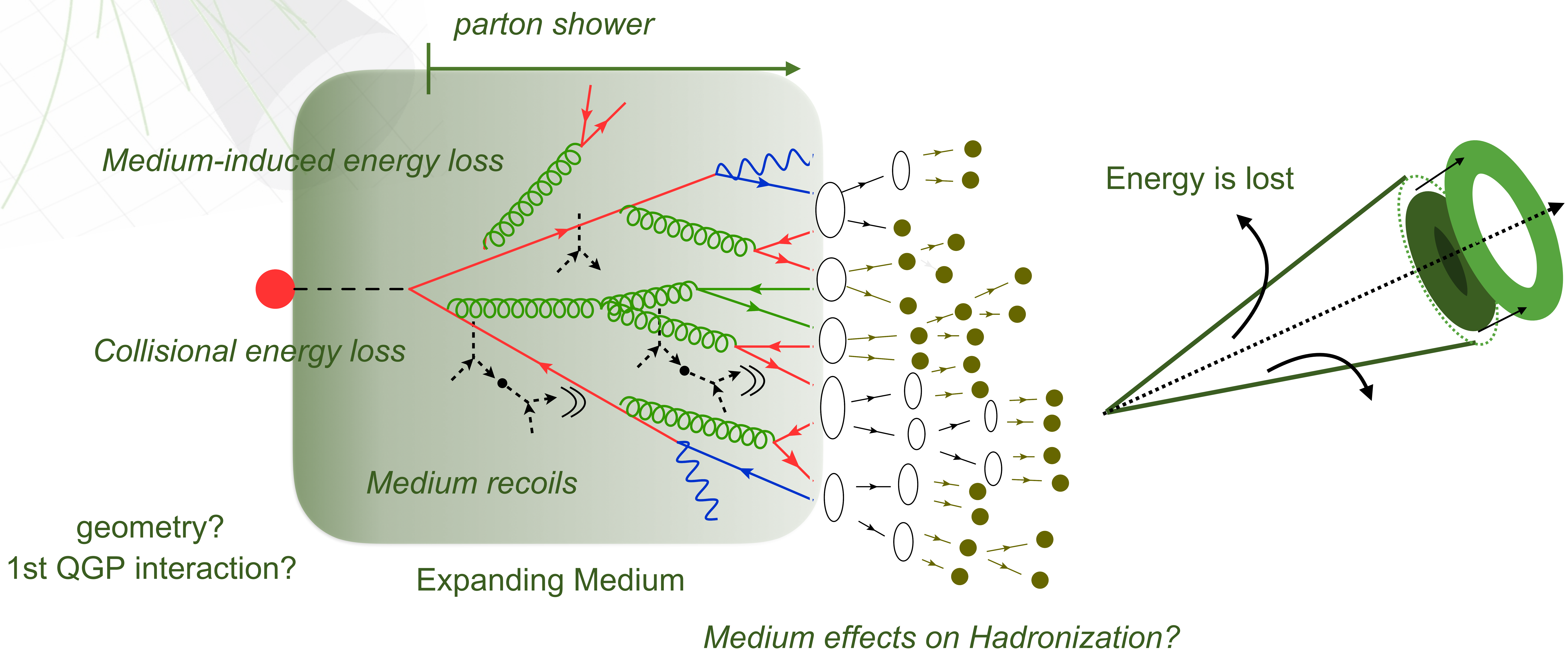

CMS (2014)
ATLAS (2014)

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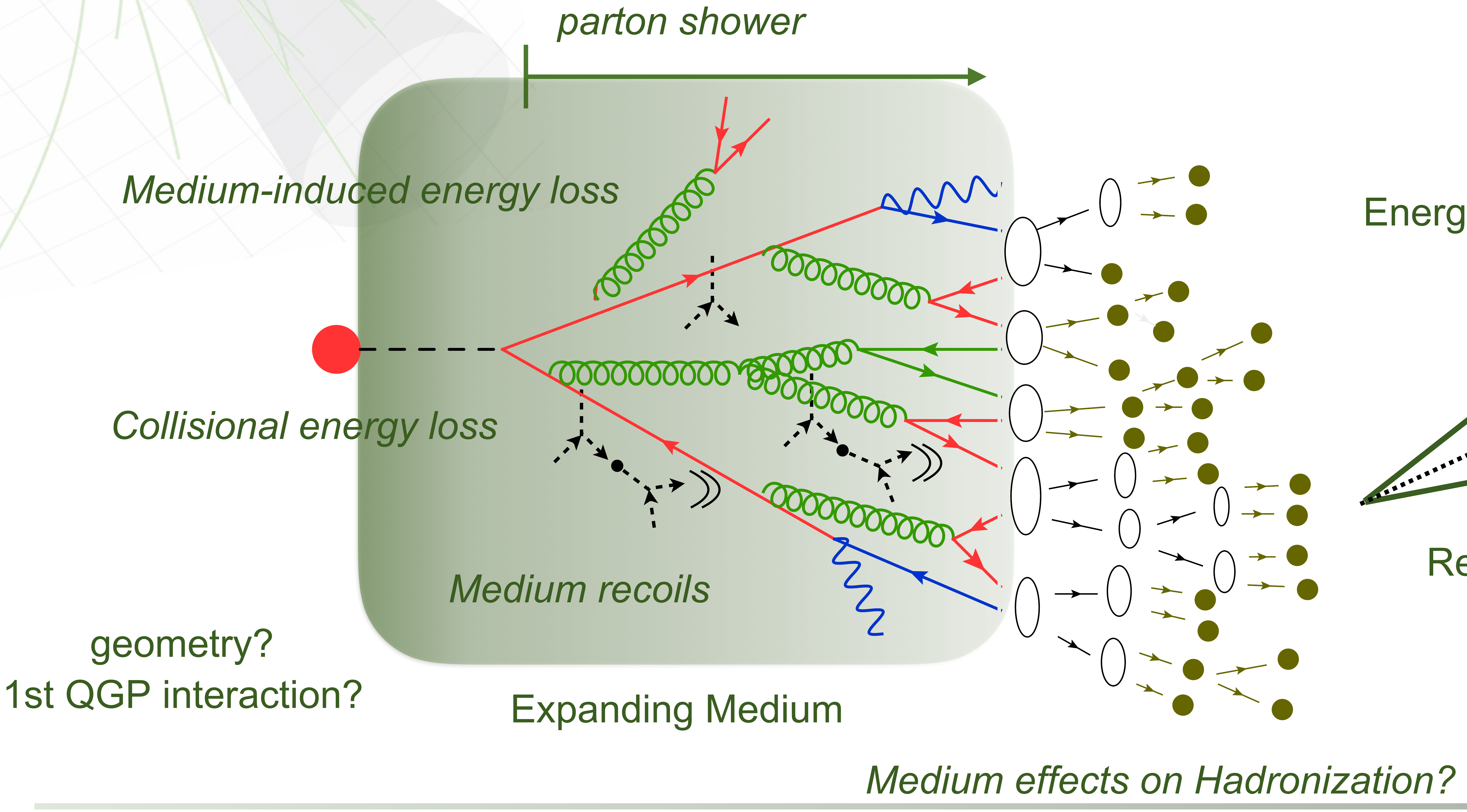

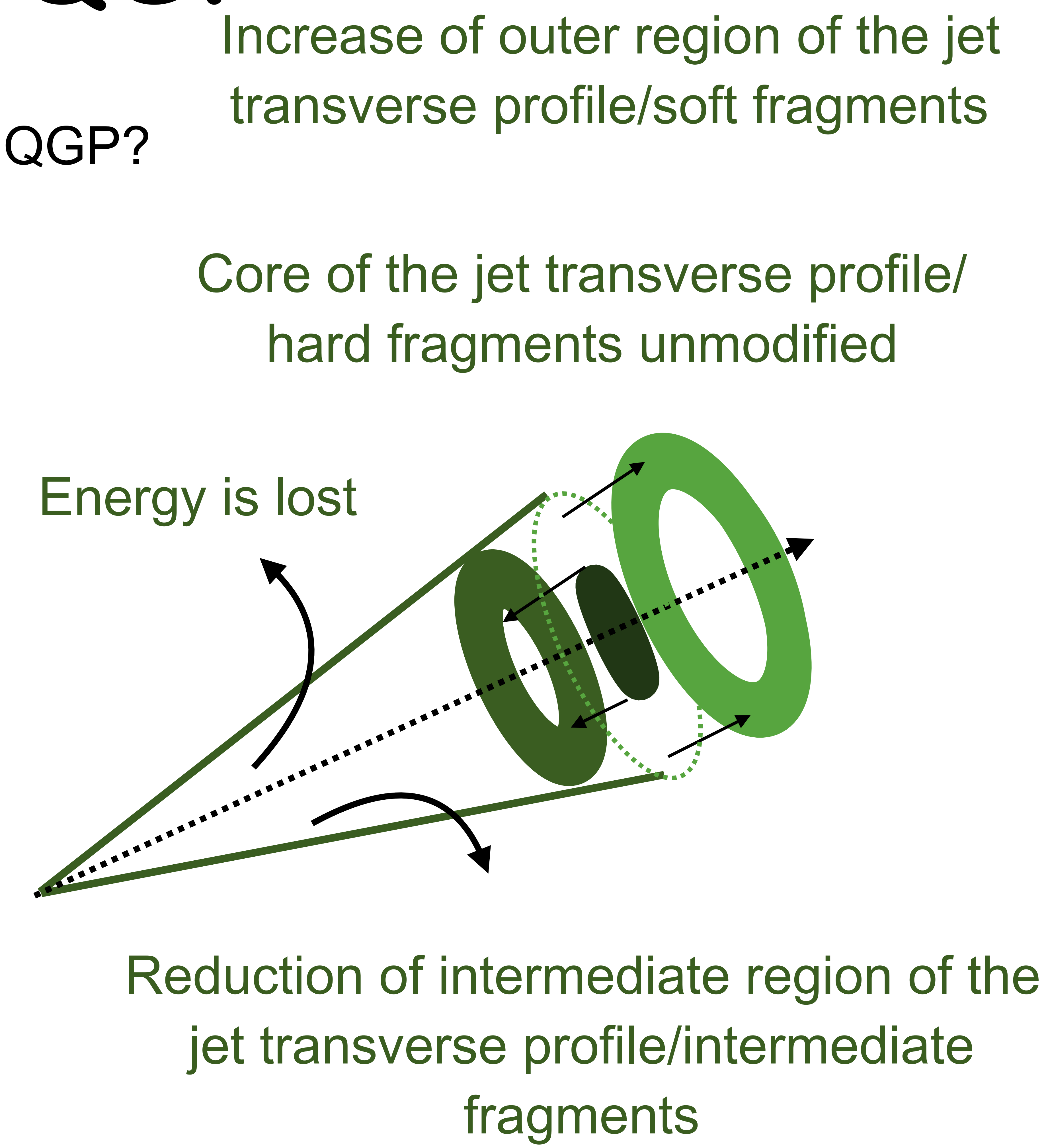

Hard Probes in the QGP

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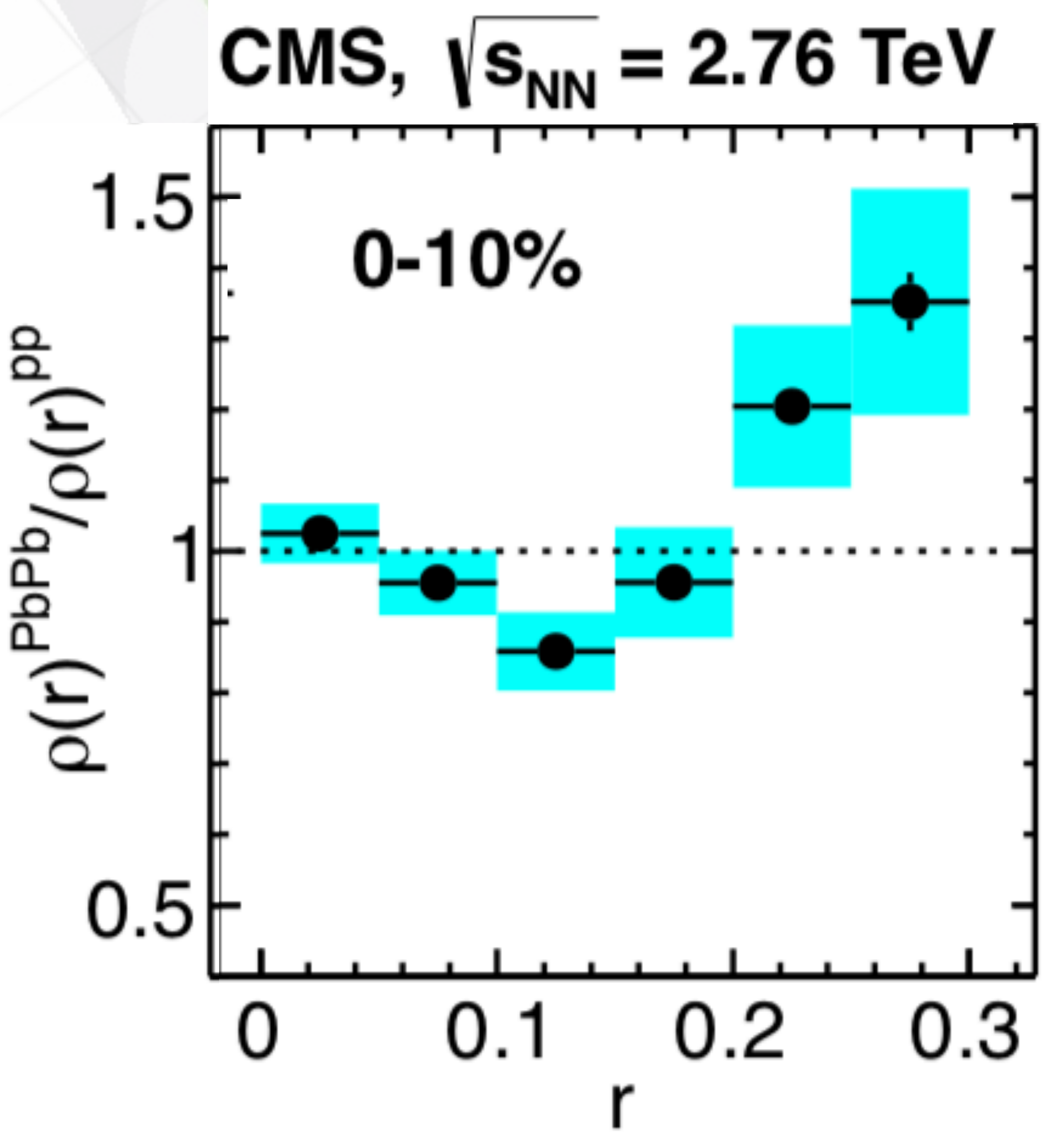
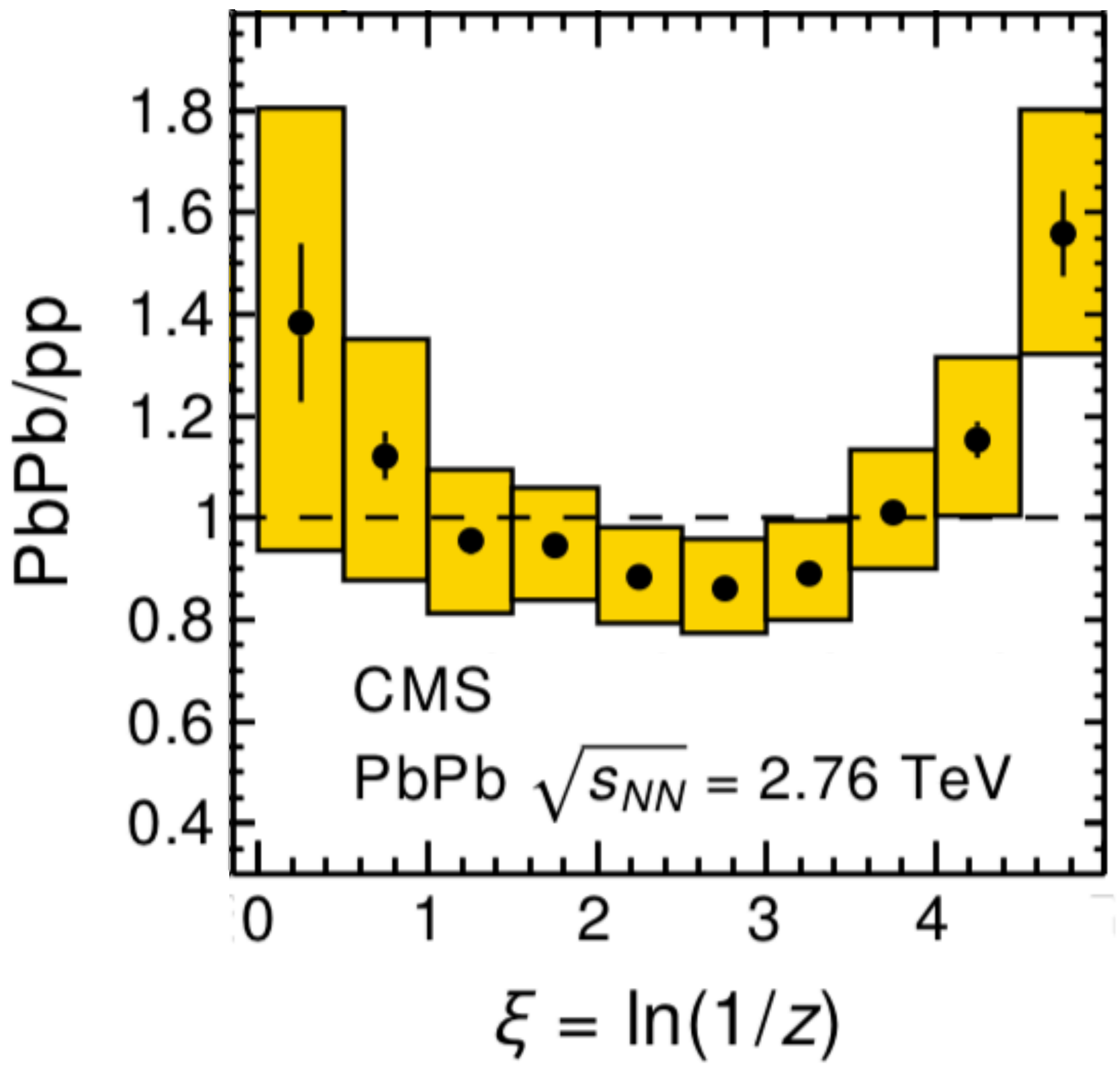
Jet radial profile (pp/PbPb)

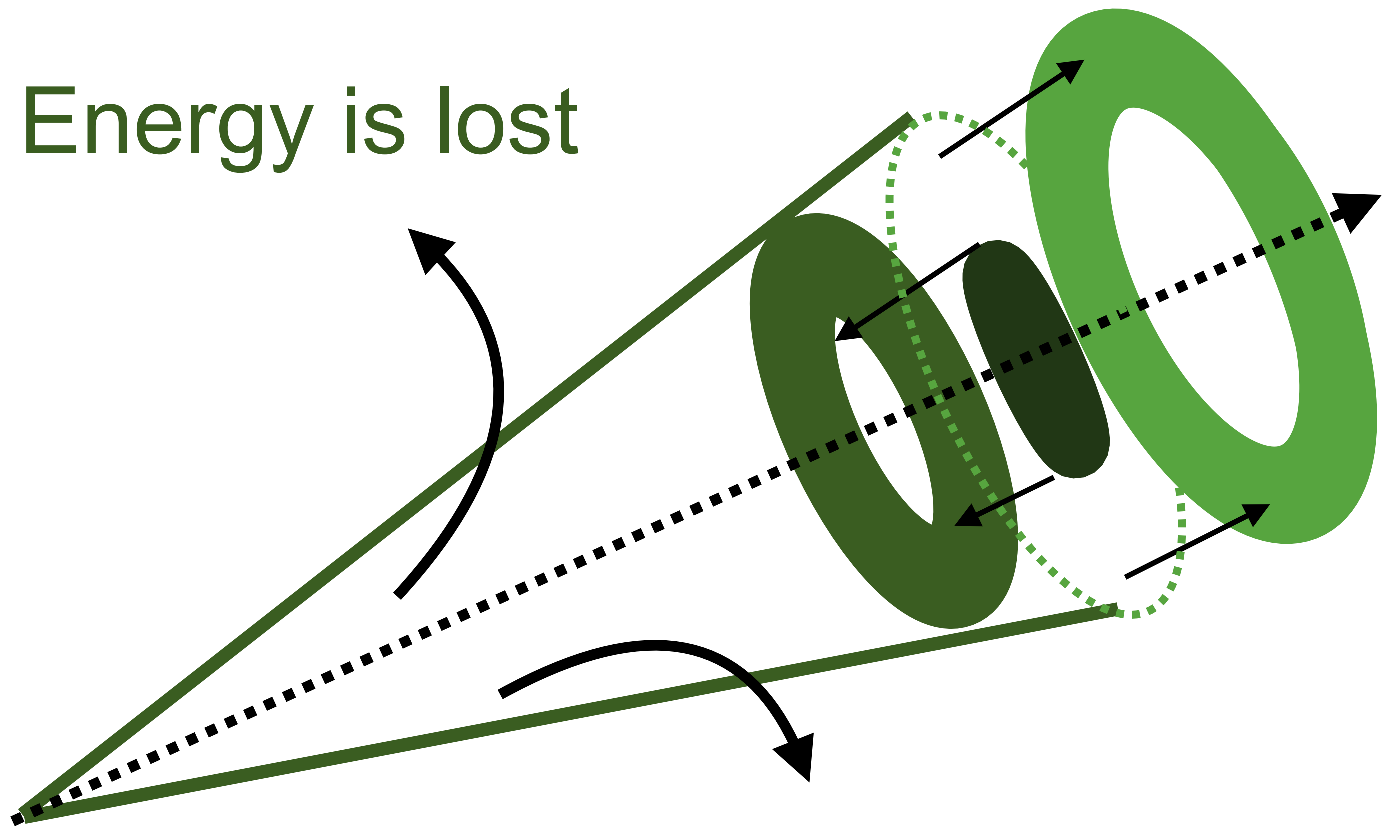


Fraction of energy of jet fragments (pp/PbPb)



Increase of outer region of the jet transverse profile/soft fragments

Core of the jet transverse profile/ hard fragments unmodified



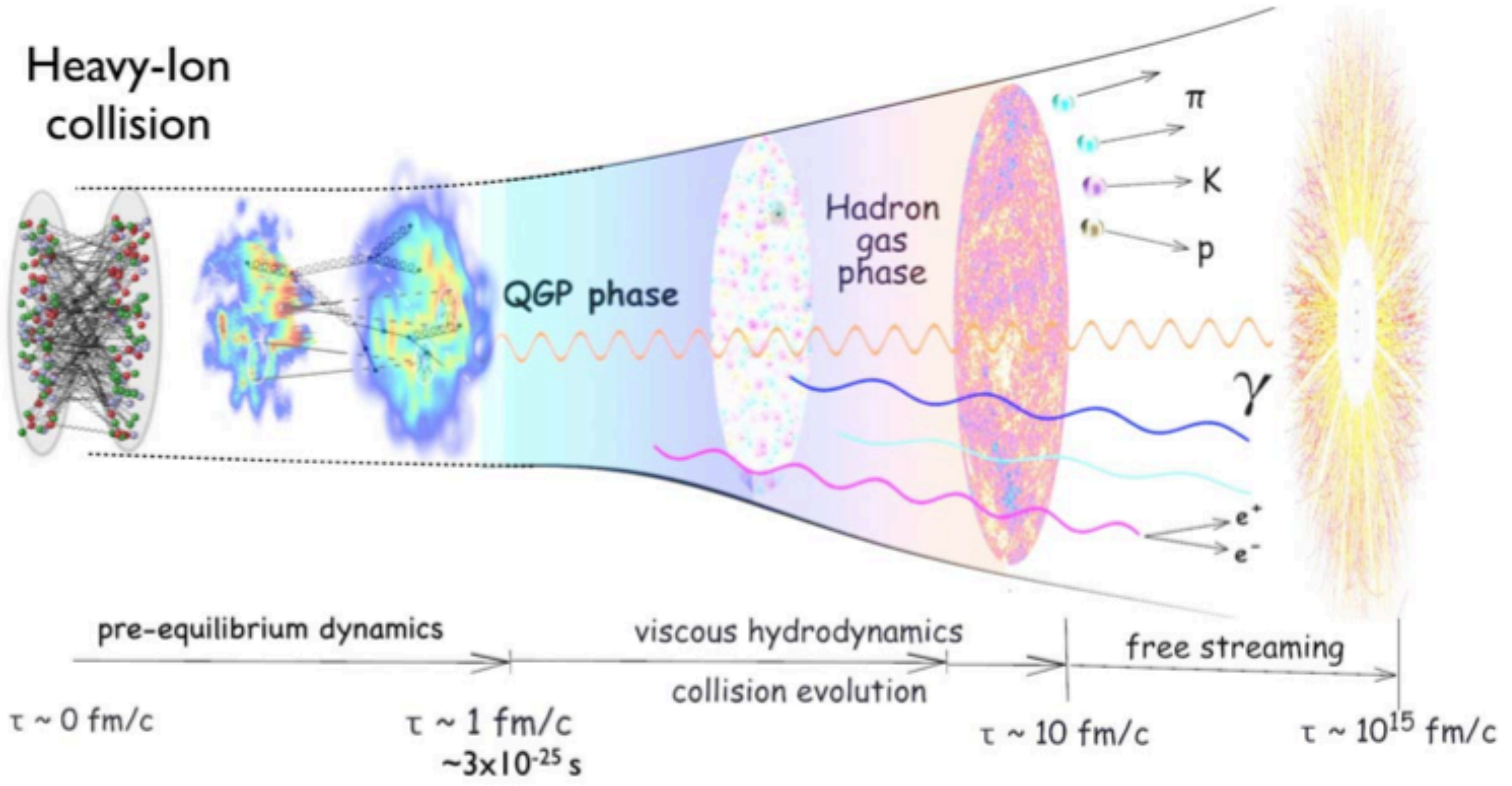
Reduction of intermediate region of the jet transverse profile/intermediate fragments

Hard Probes in the QGP

- What is the information that we get?
  - Integrated result of the whole medium (fast) evolution
    - However…

Strong time-dependence of the medium properties (expansion and cooling of the system)

Small-size systems (high-multiplicity pp and pA collisions) show signatures of collective behaviour



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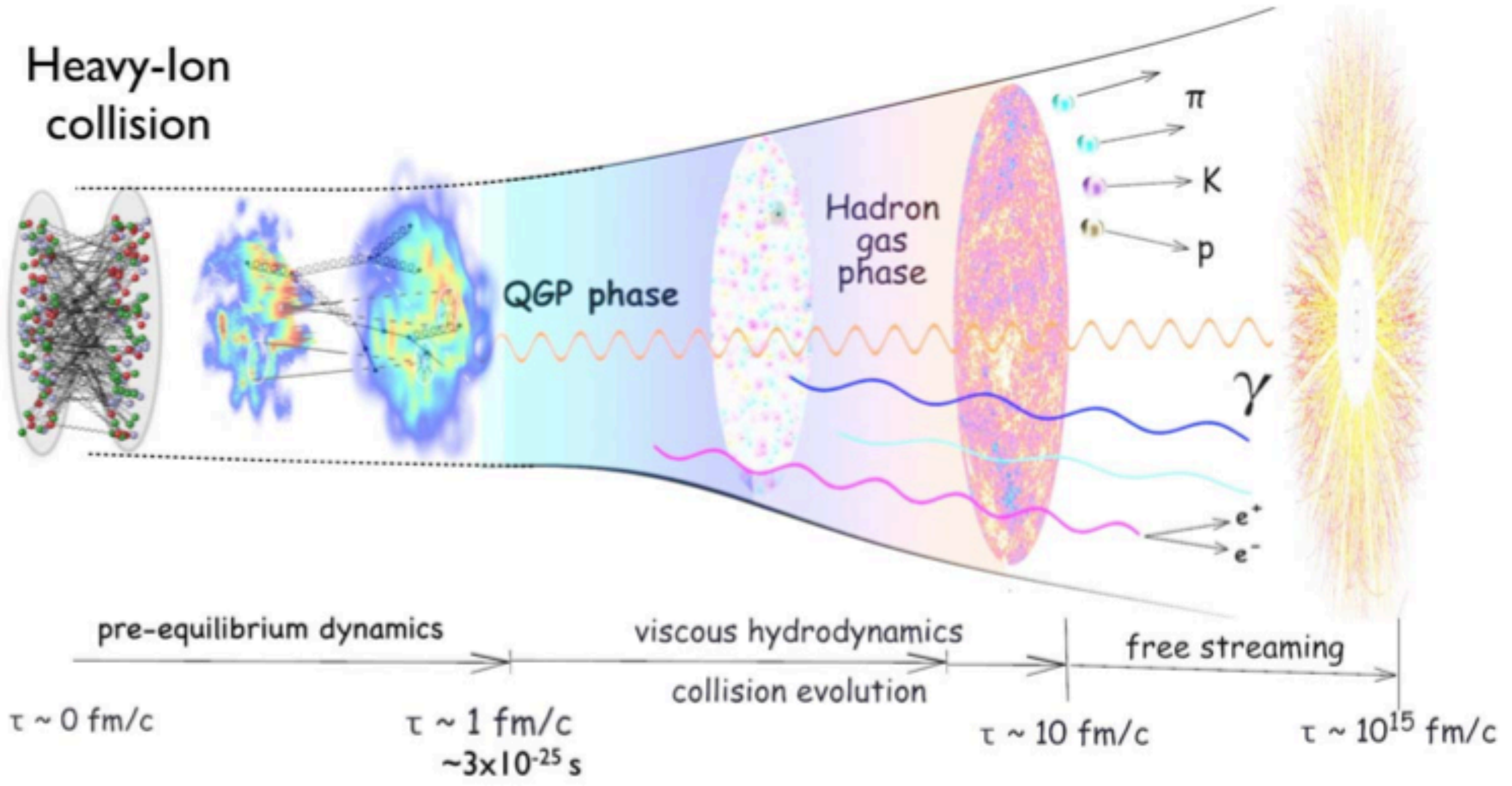
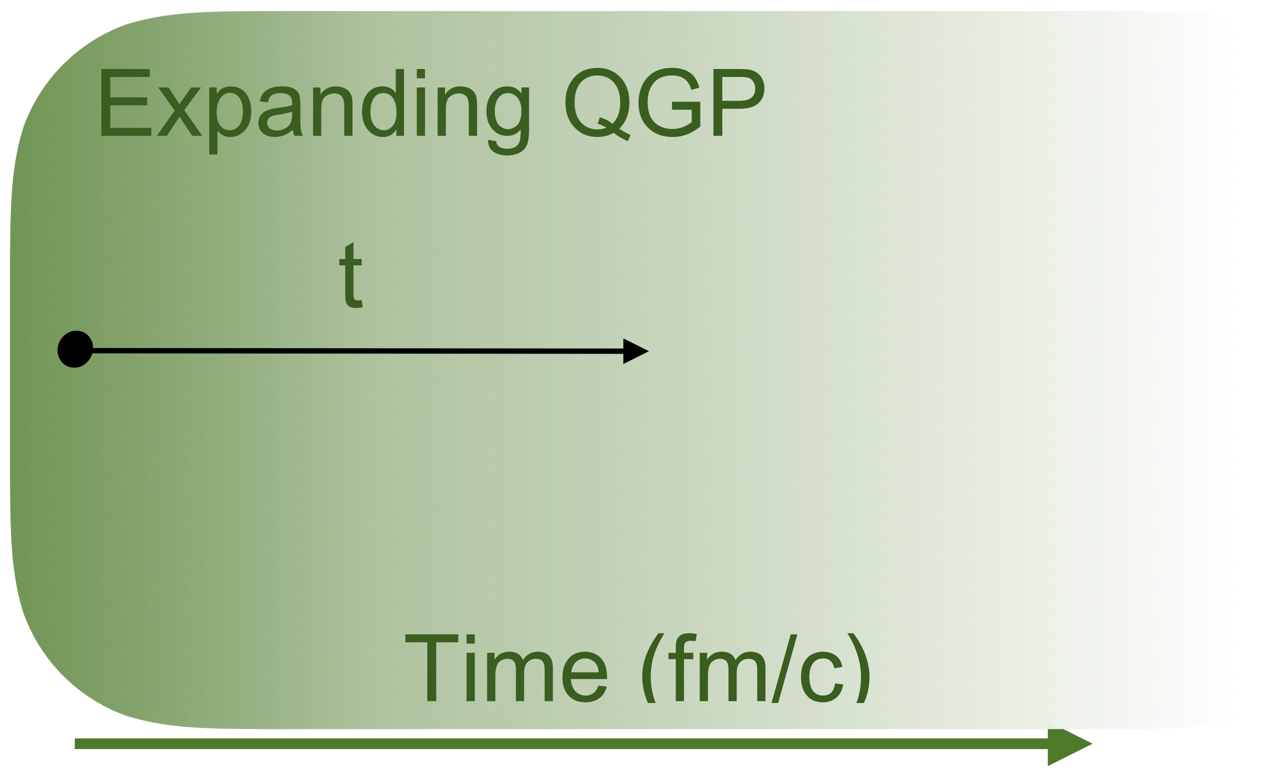


Need to devise a strategy to probe the time-structure of the QGP!

Tops in the QGP

- What is so special about tops (ttbar events) for QGP studies?
  - Small lifetime τ_{top}^{rest} = 0.15 fm/c



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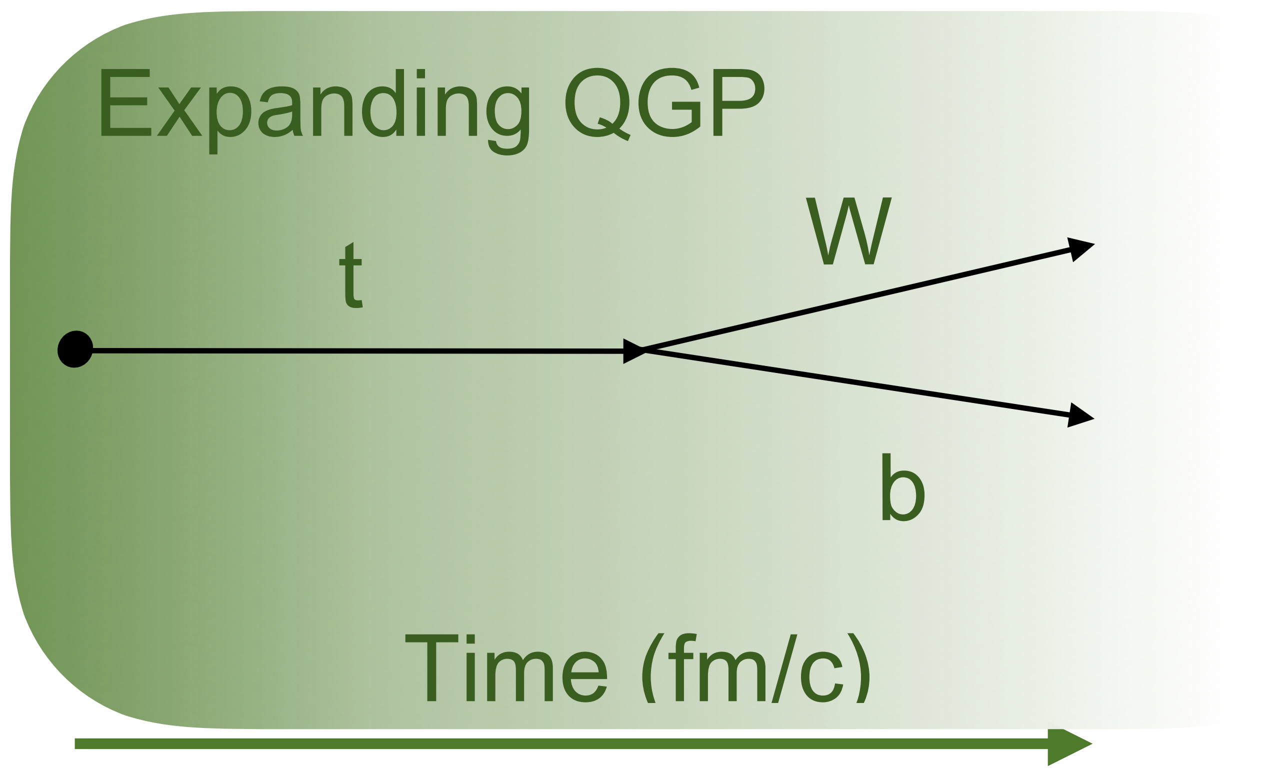

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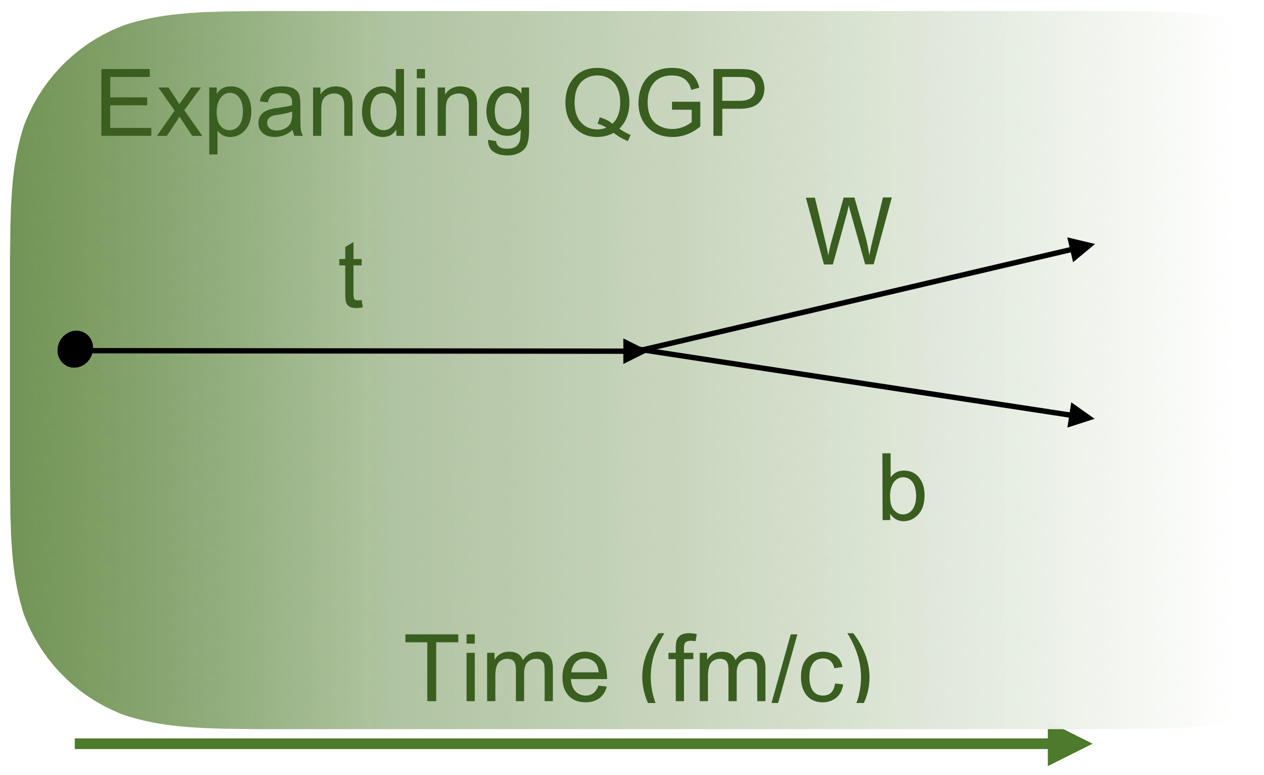

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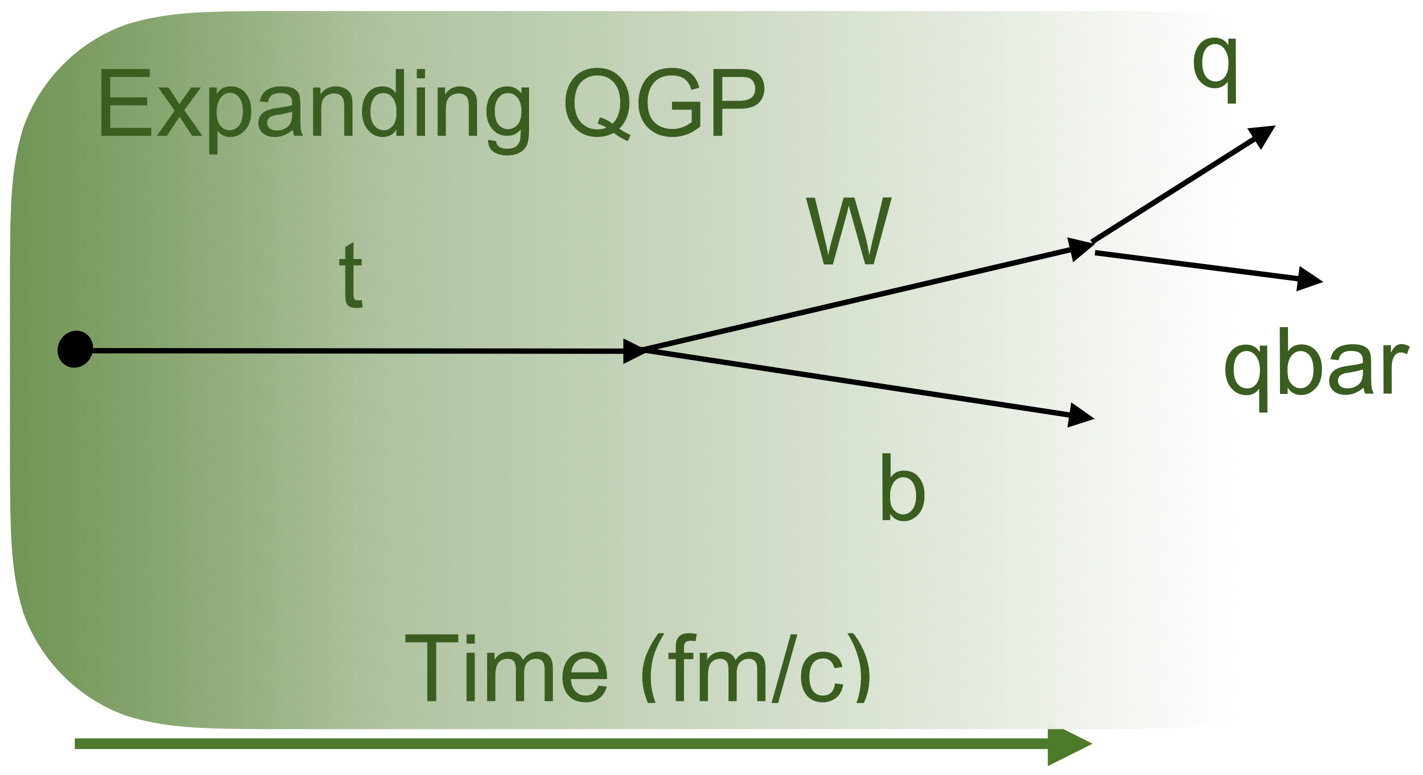

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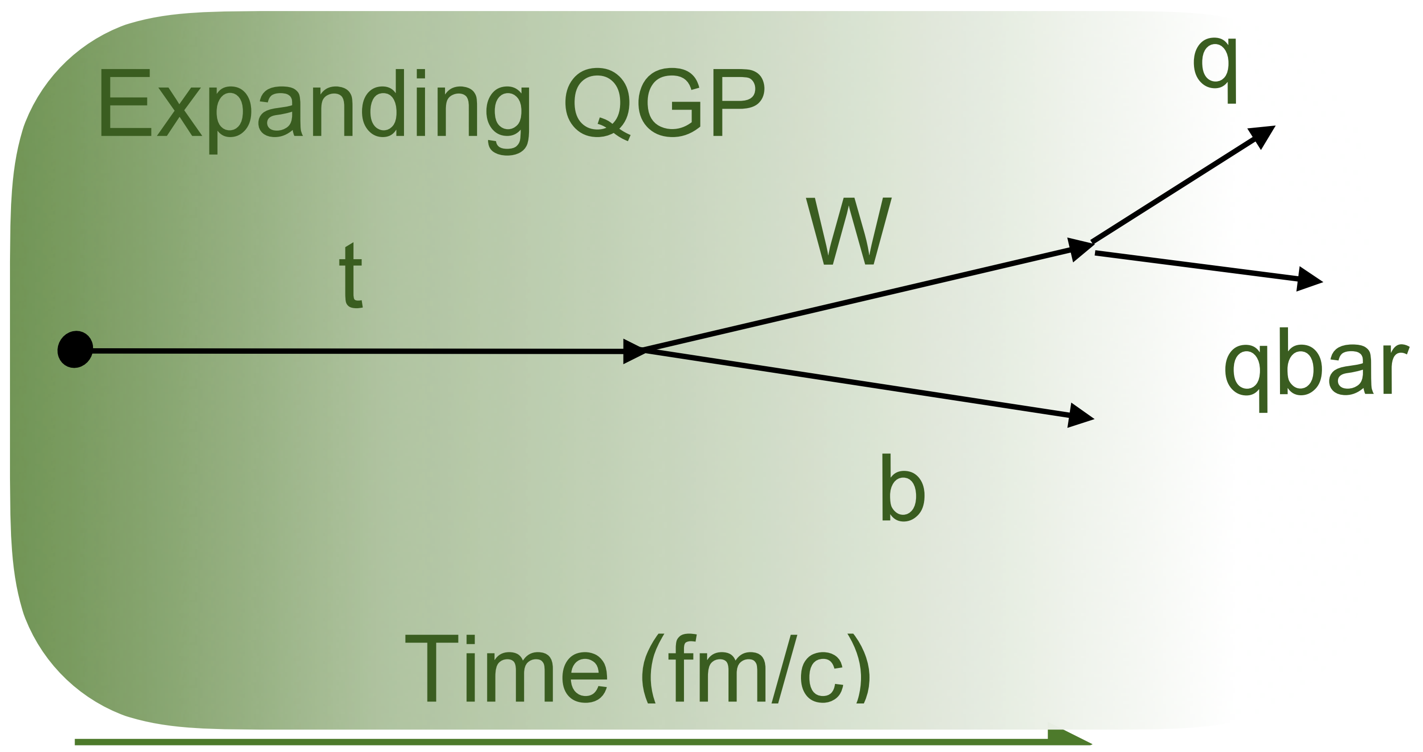
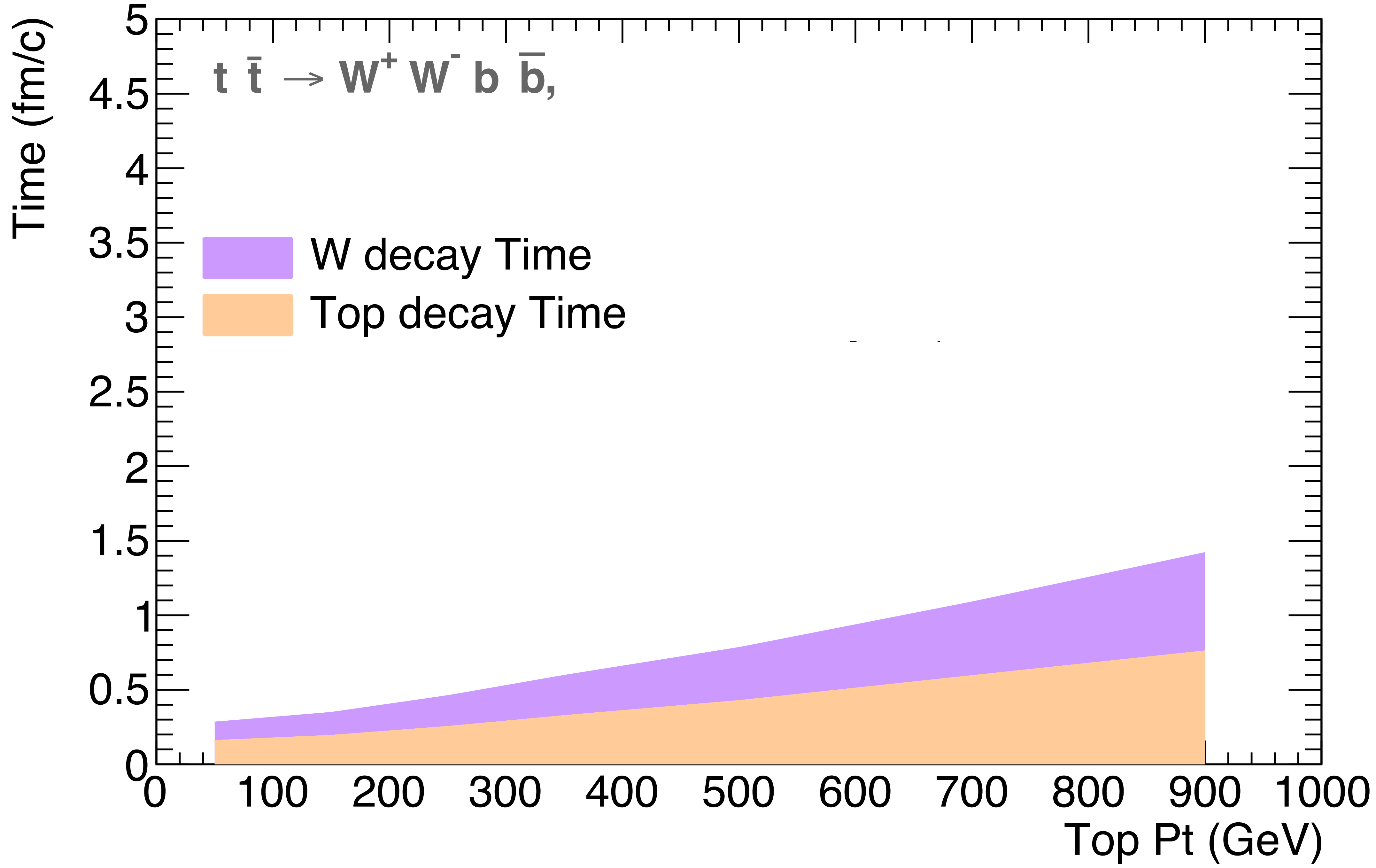


Total time delay depends on transverse boost: (X = top or W-boson)

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



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

W boson in the QGP

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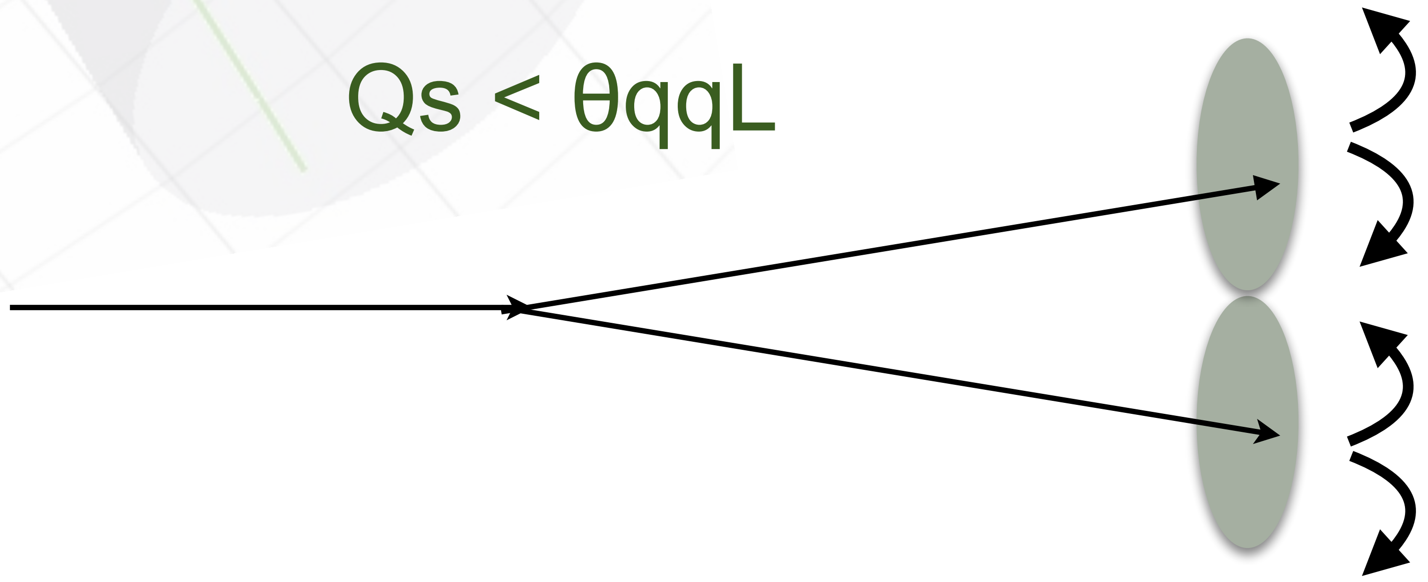
  - Depending on the transverse resolution of the decaying products:

Qs < θqqL



Medium able to “see” both particles independently

Quarks start interact with the medium independently
$\Longrightarrow$ Hadronic probe of the QGP is formed

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

Transport coefficient: $\hat{q}$

Medium length: L

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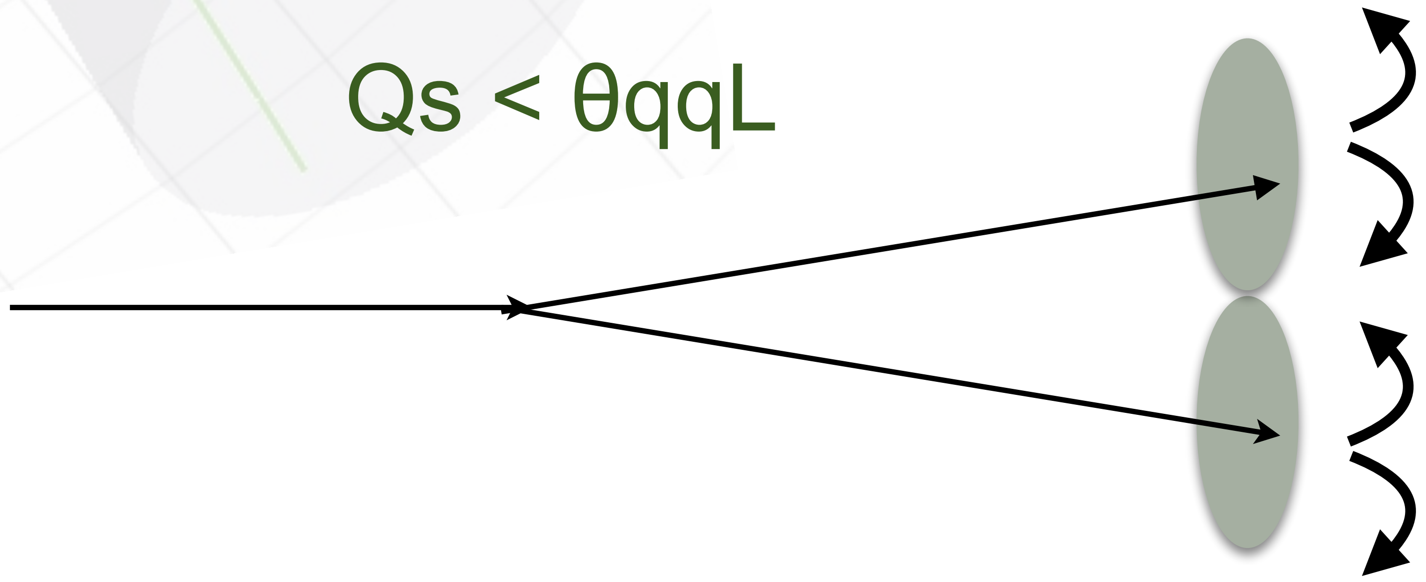

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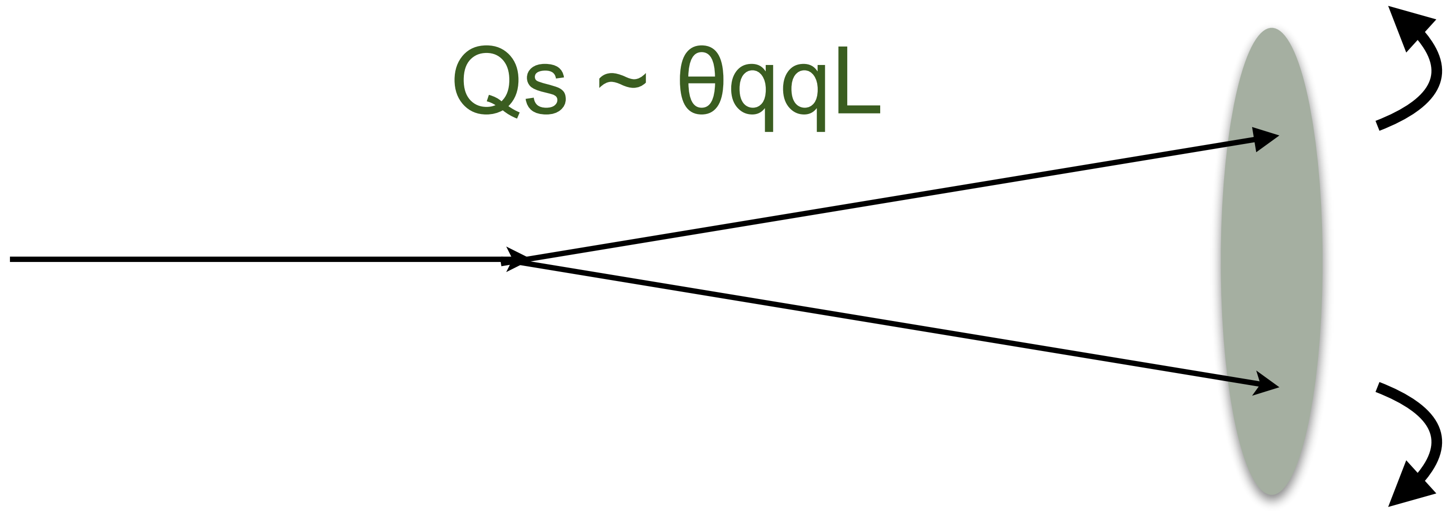

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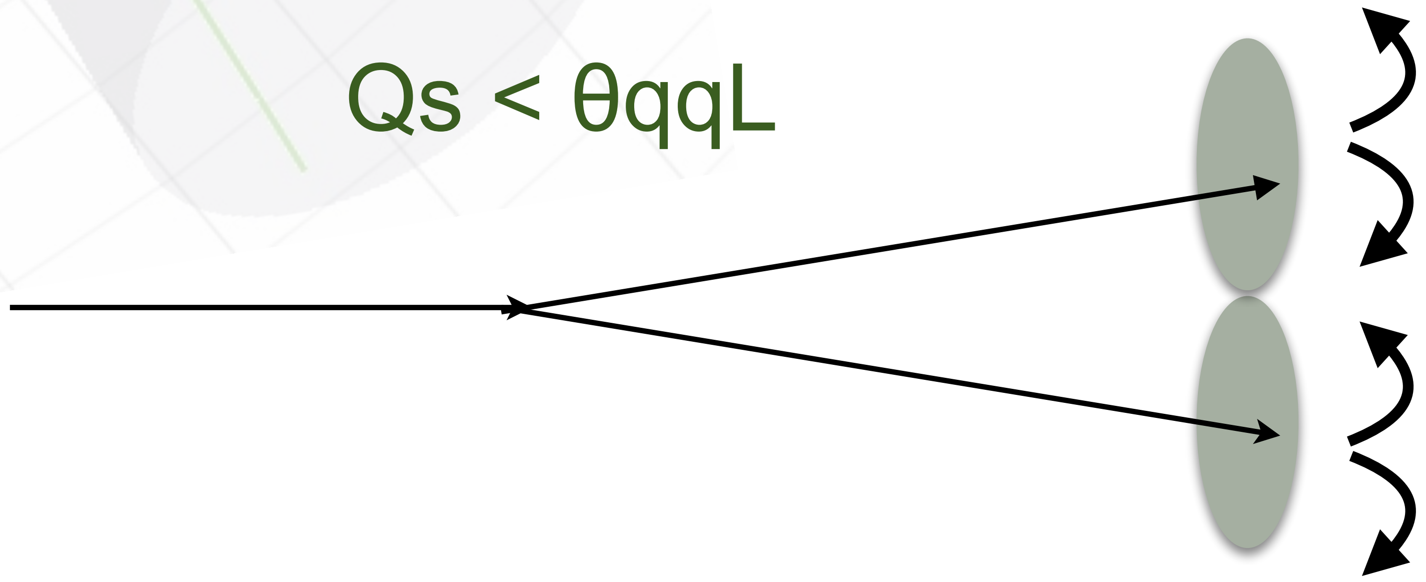

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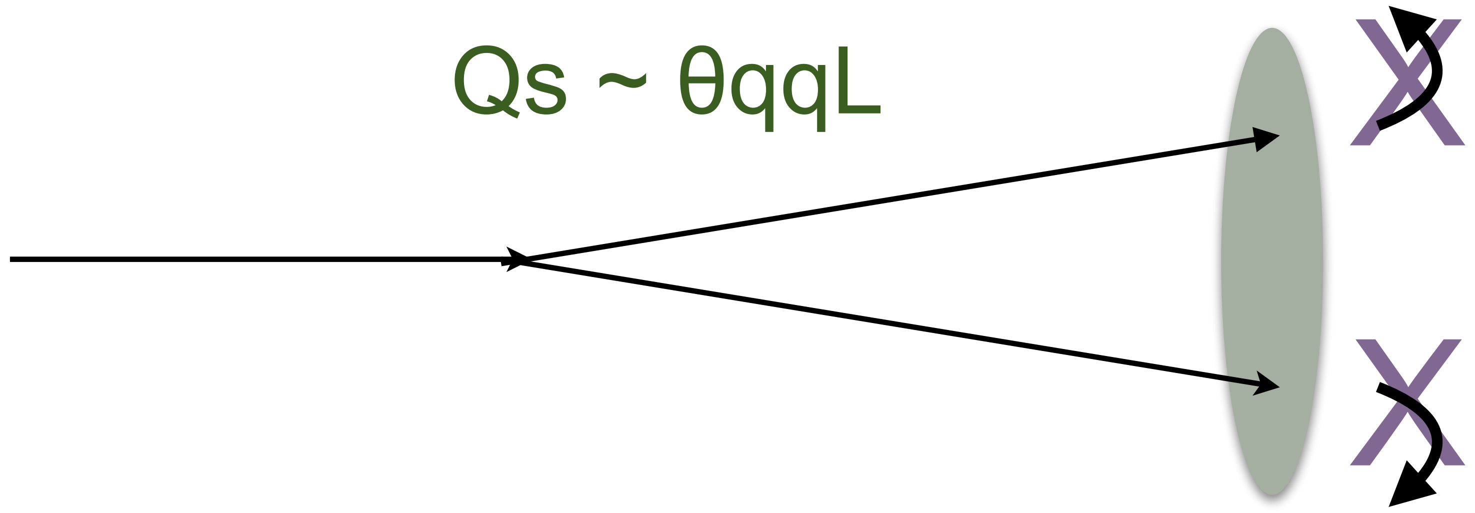

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Quarks stay in a colour neutral state during: $t_d = \left(\frac{12}{\hat{q}\theta_{q\bar{q}}^2}\right)^{1/3}$

$\Longrightarrow$ Increase delay of the Hadronic probe

Saturation scale:

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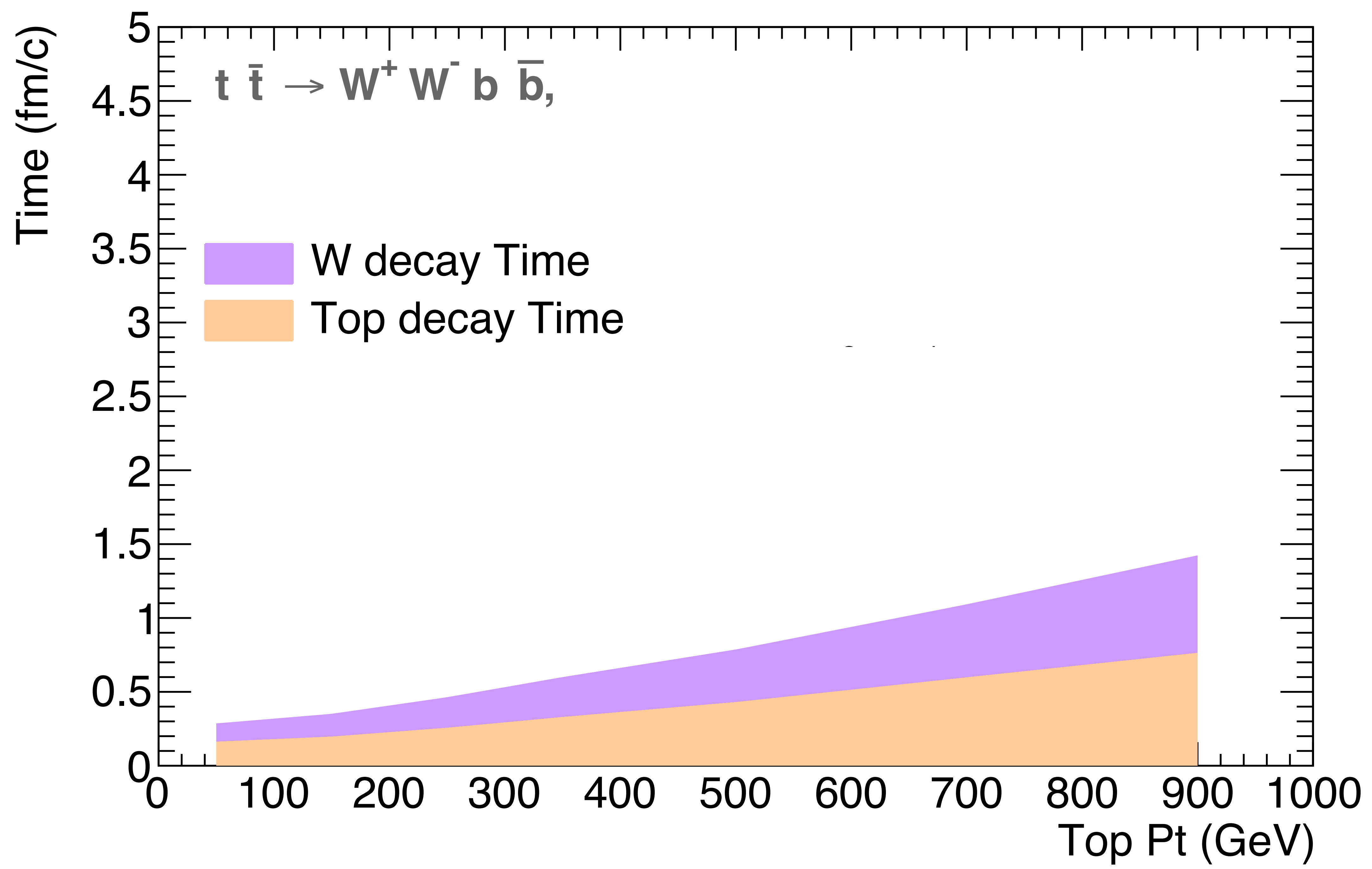
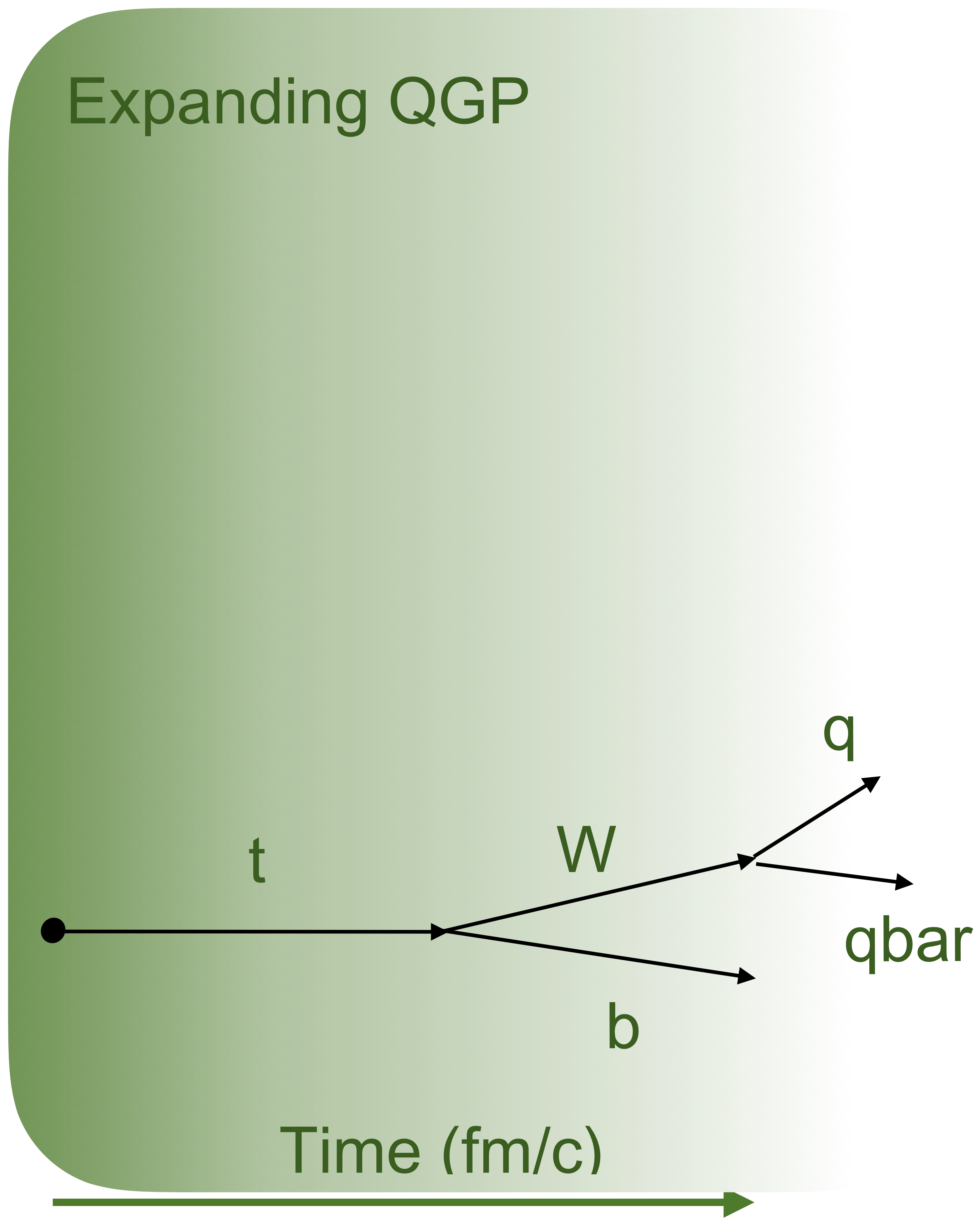
Transport coefficient: $\hat{q}$

Medium length: L

Available timescales

- What are the available timescales that we are able to probe with this system?





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LA, Milhano, Salgado, Salam (2019)

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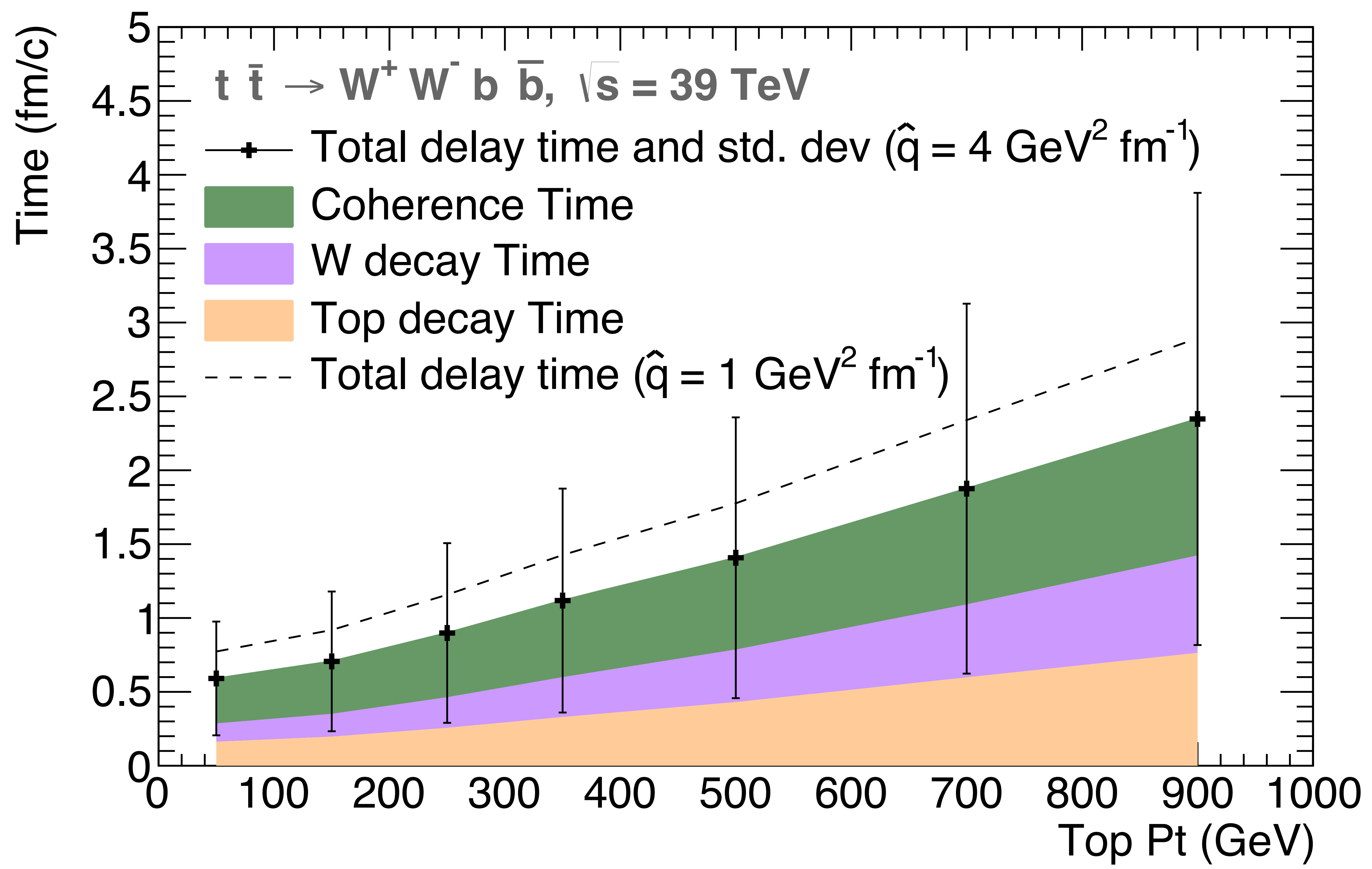

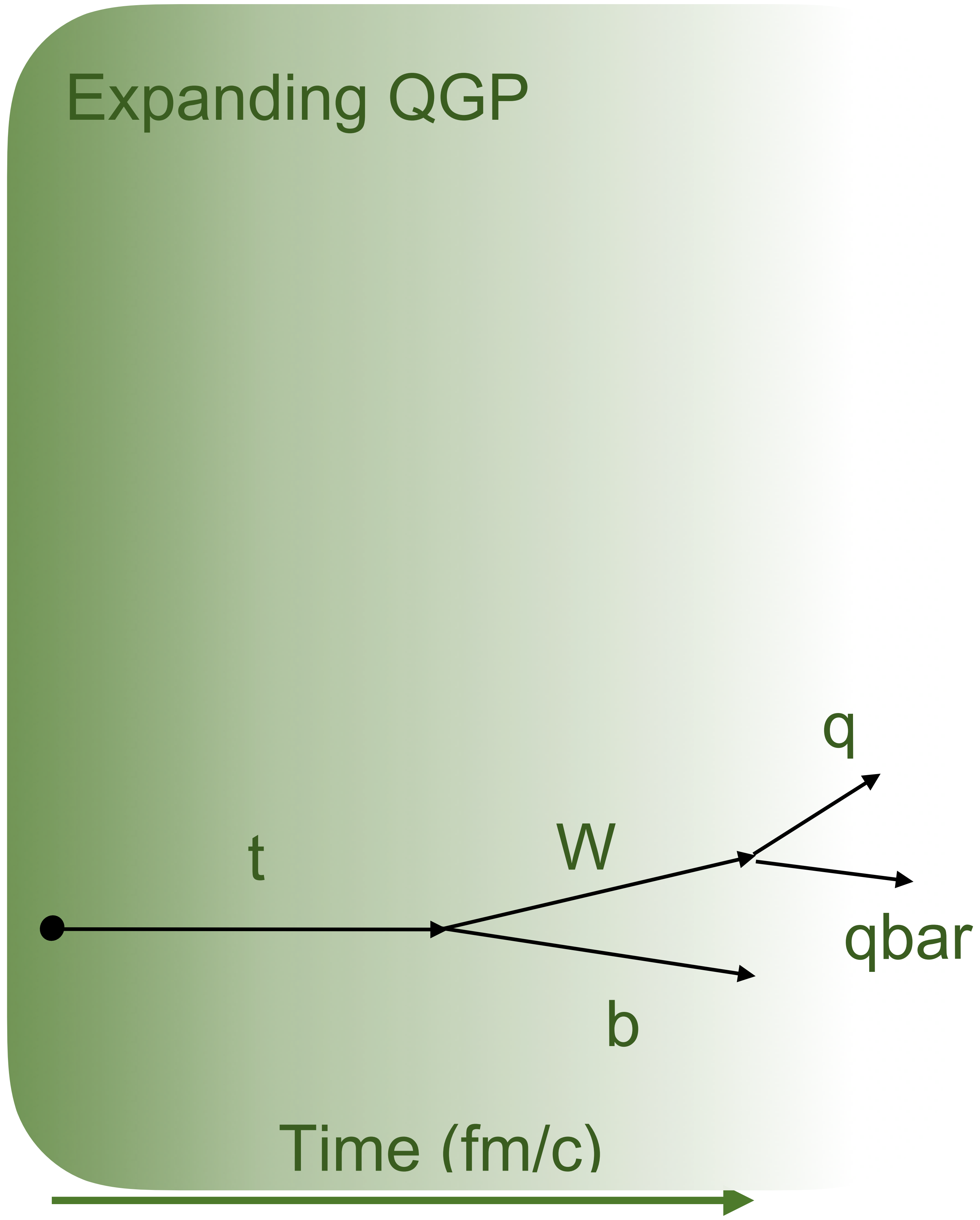

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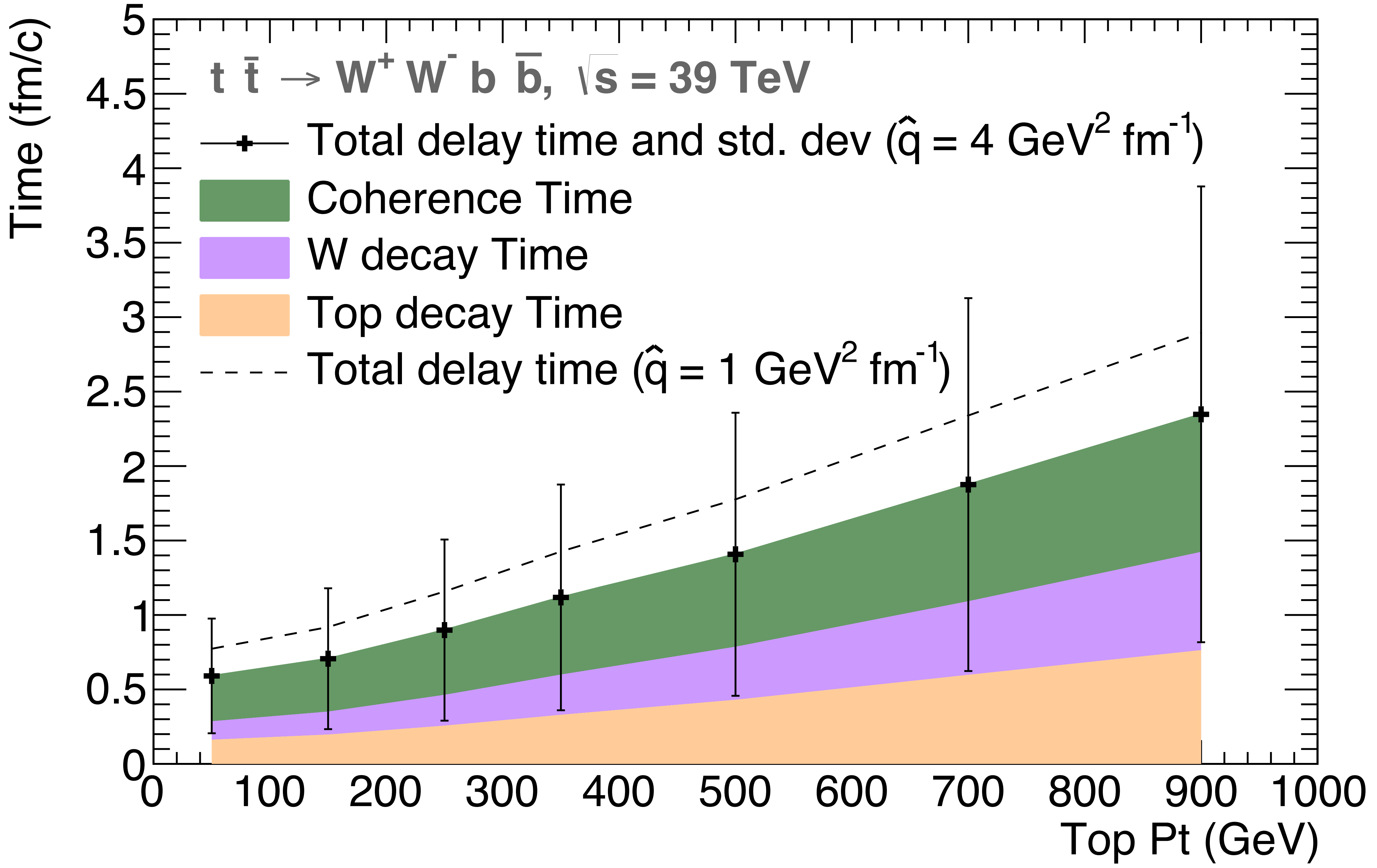

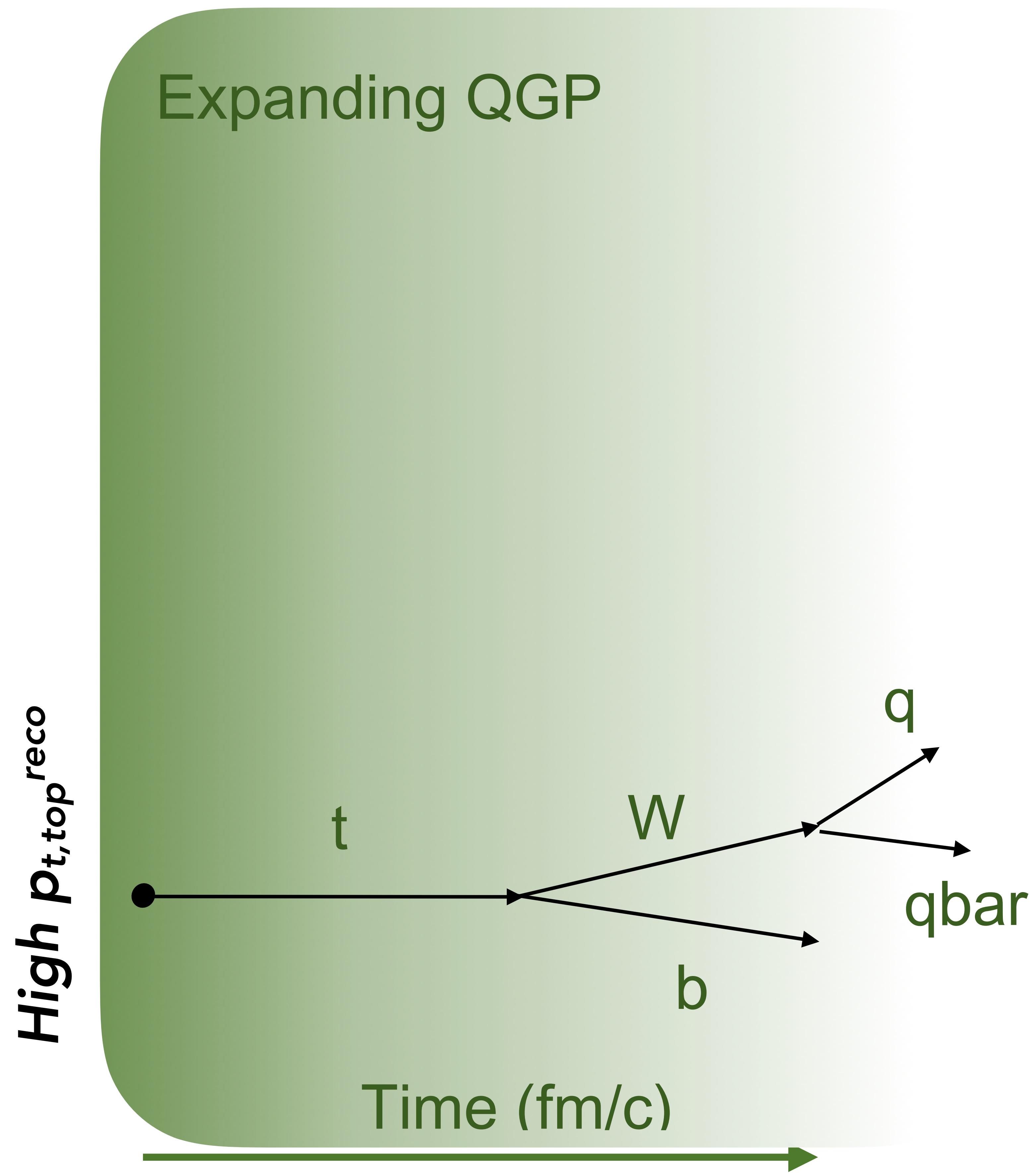

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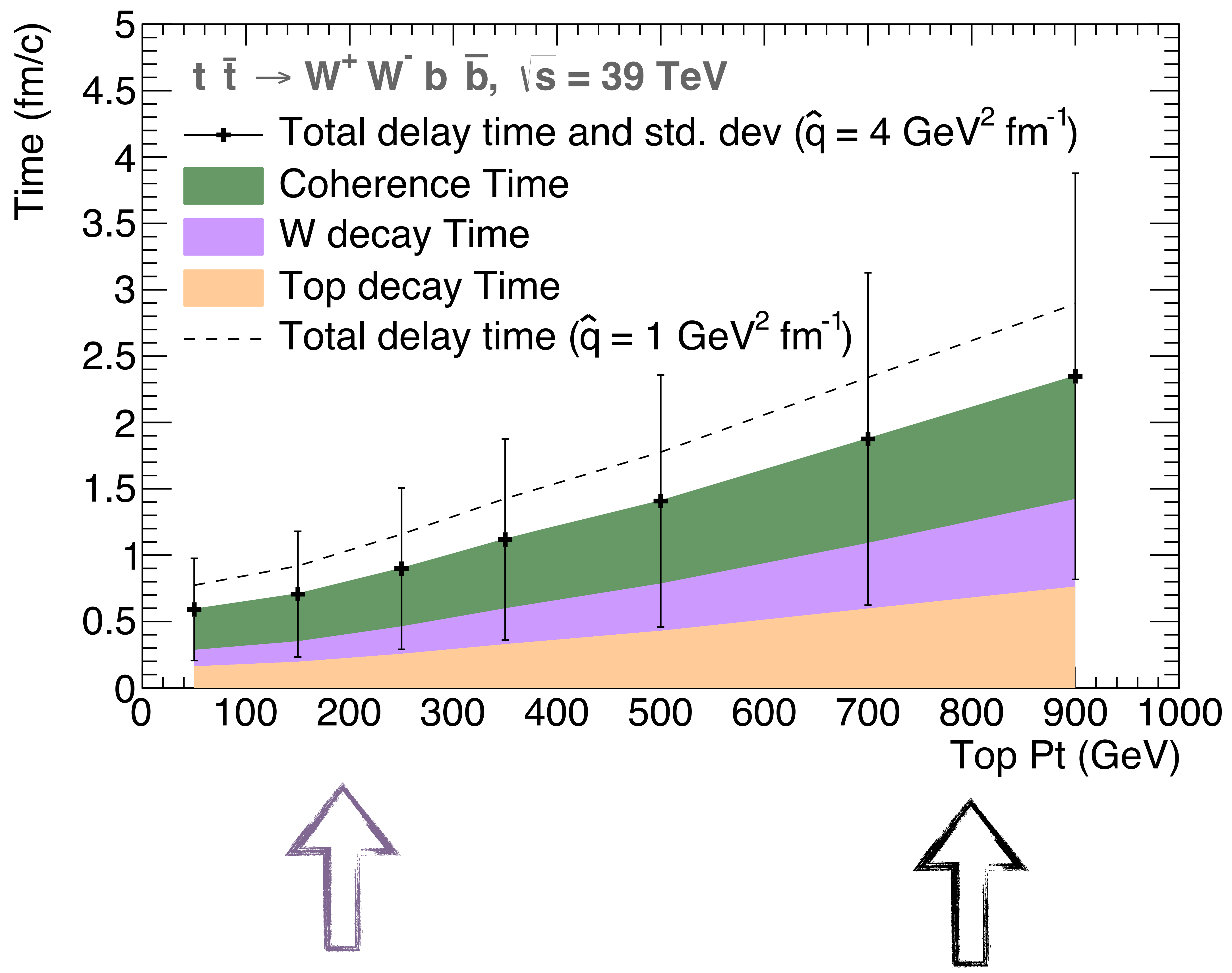
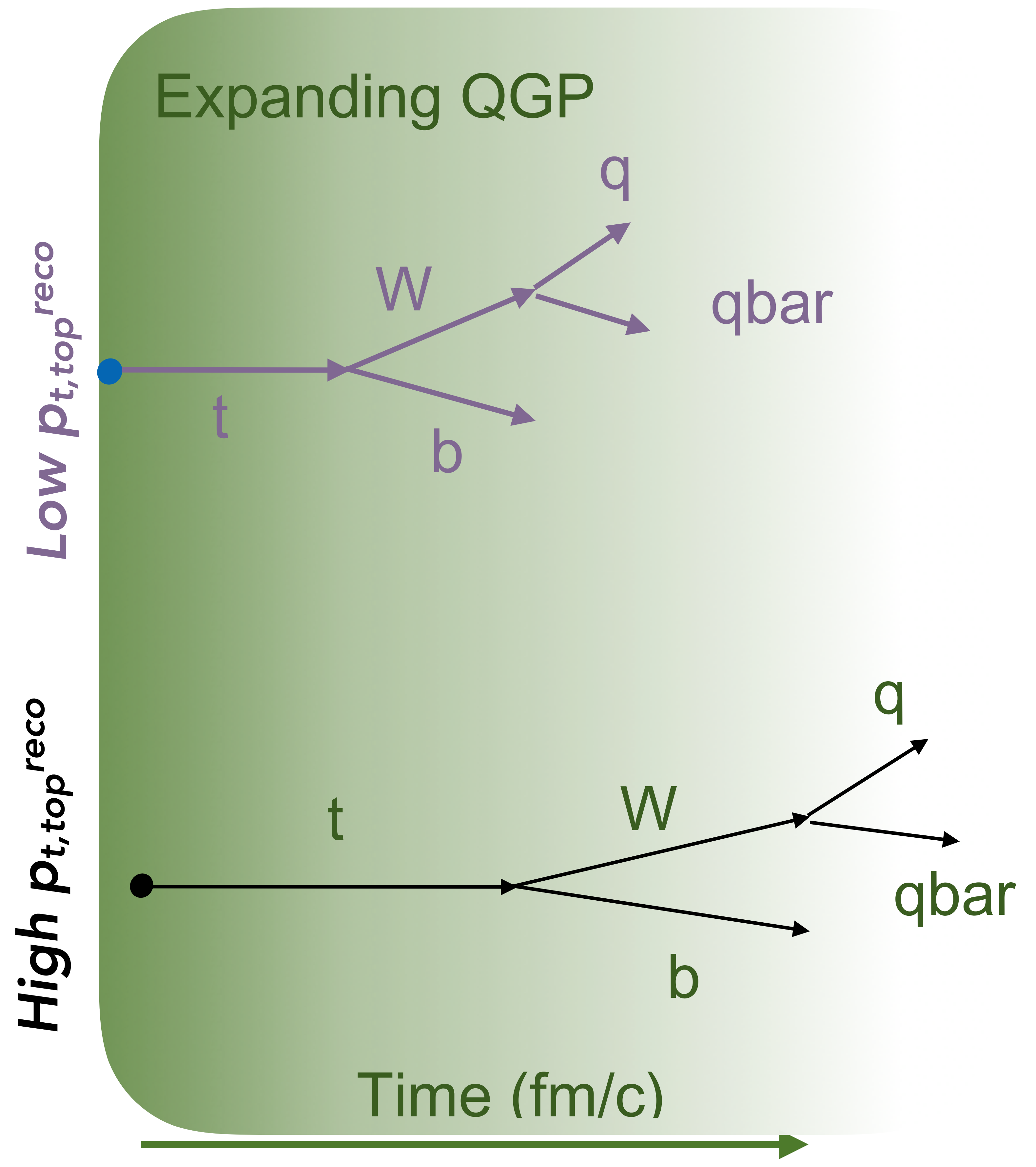
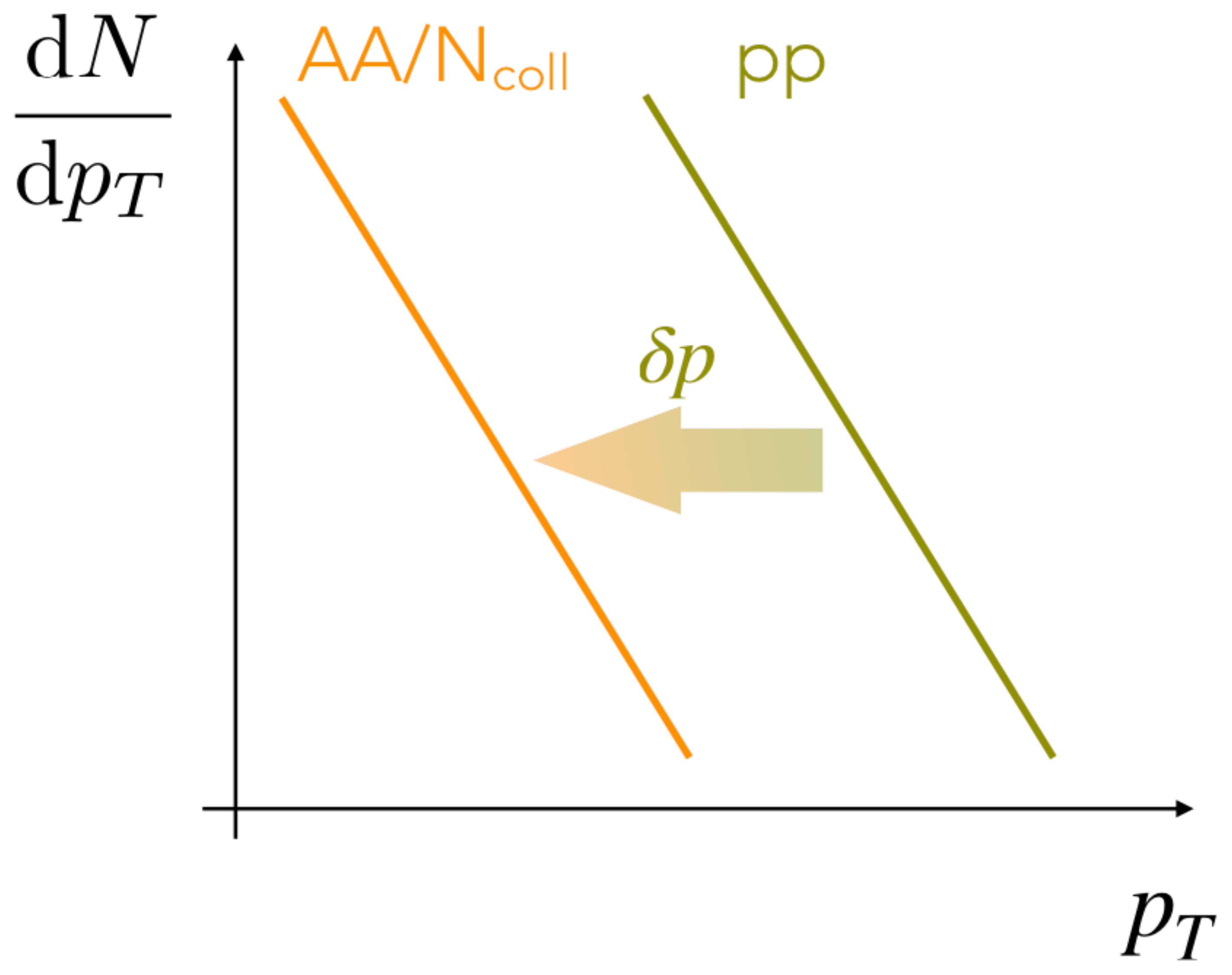




Jet Quenching: a toy model

- Pythia = pp collisions… How to include energy loss? And coherence effects?



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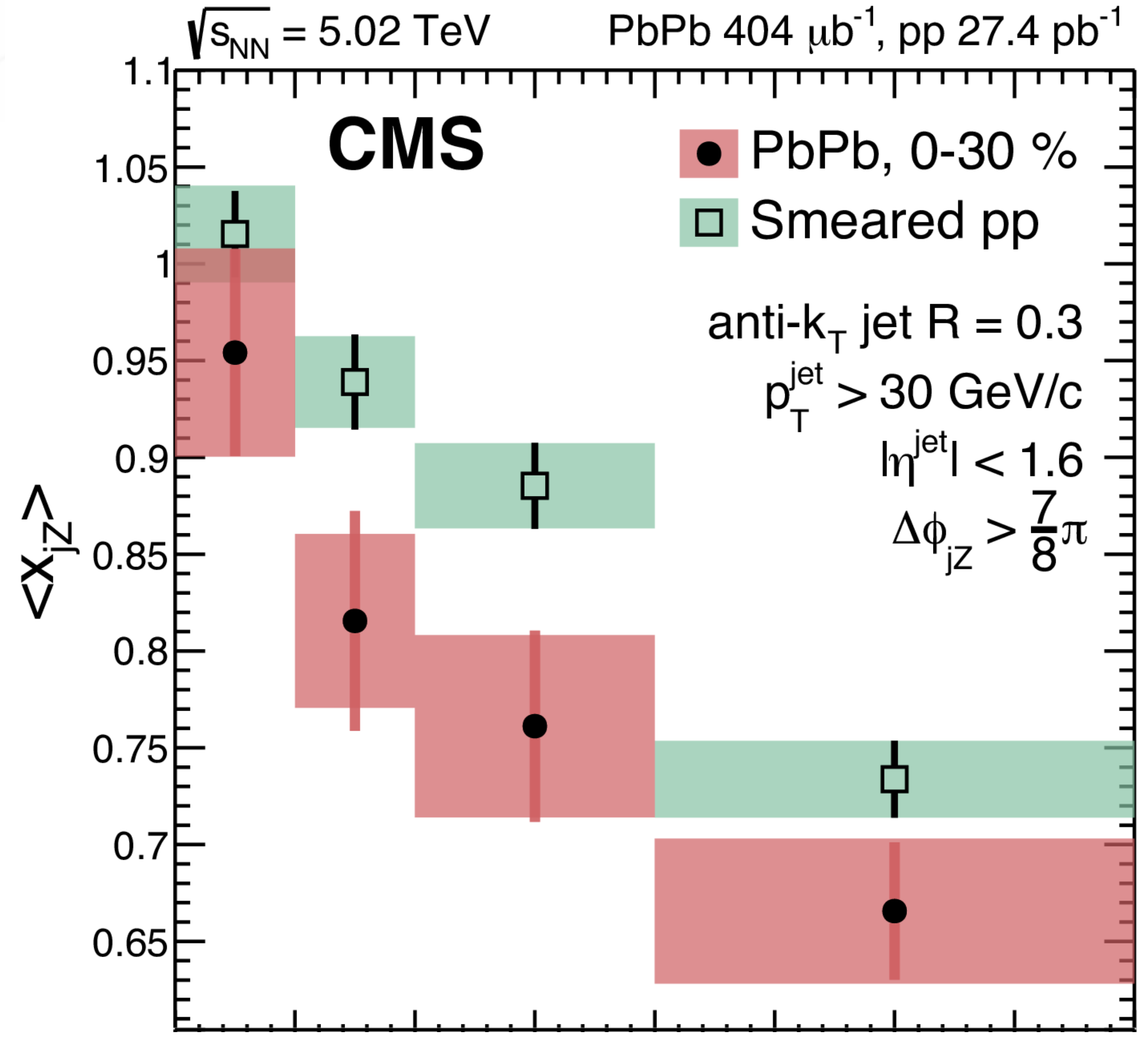
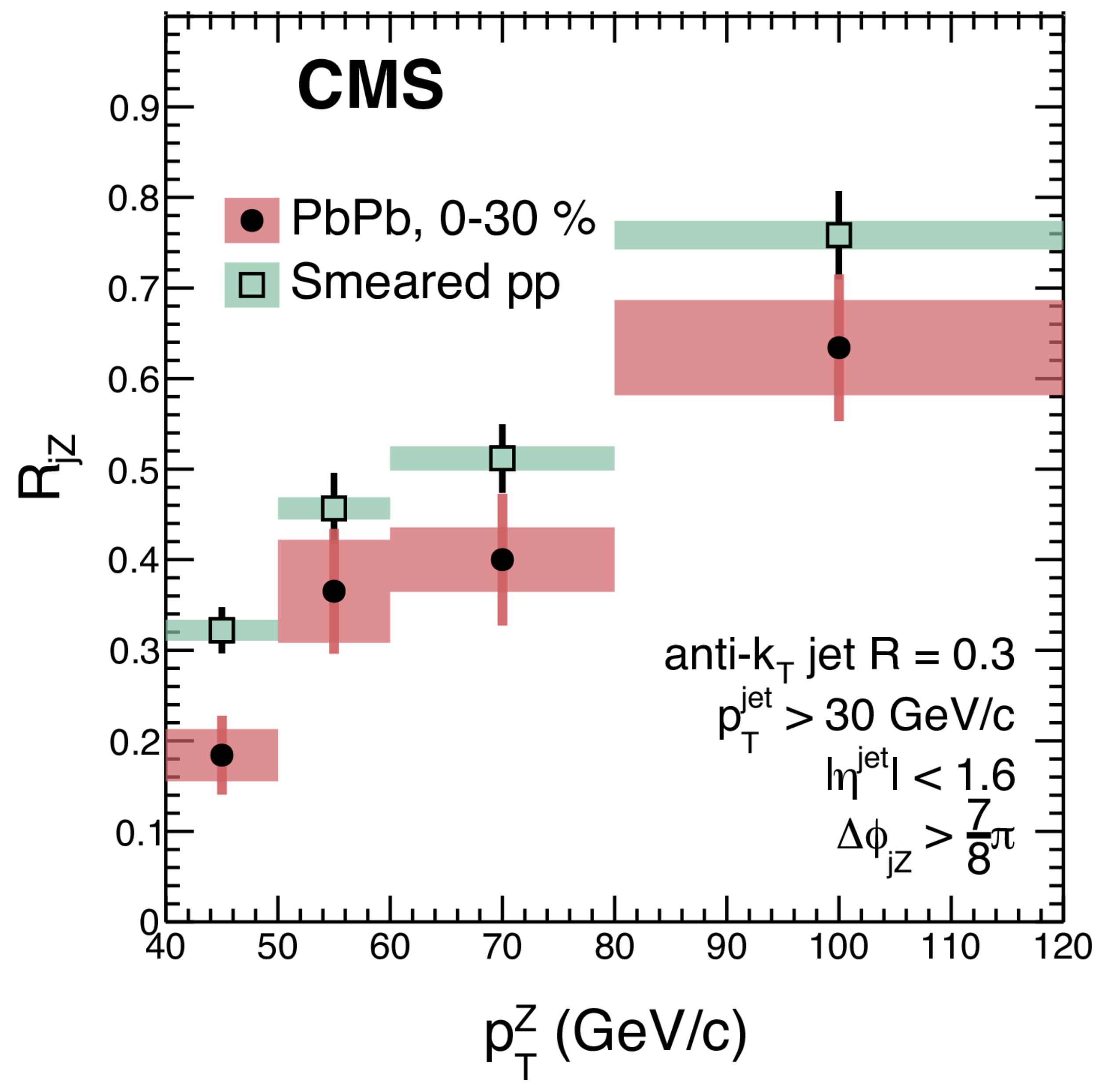
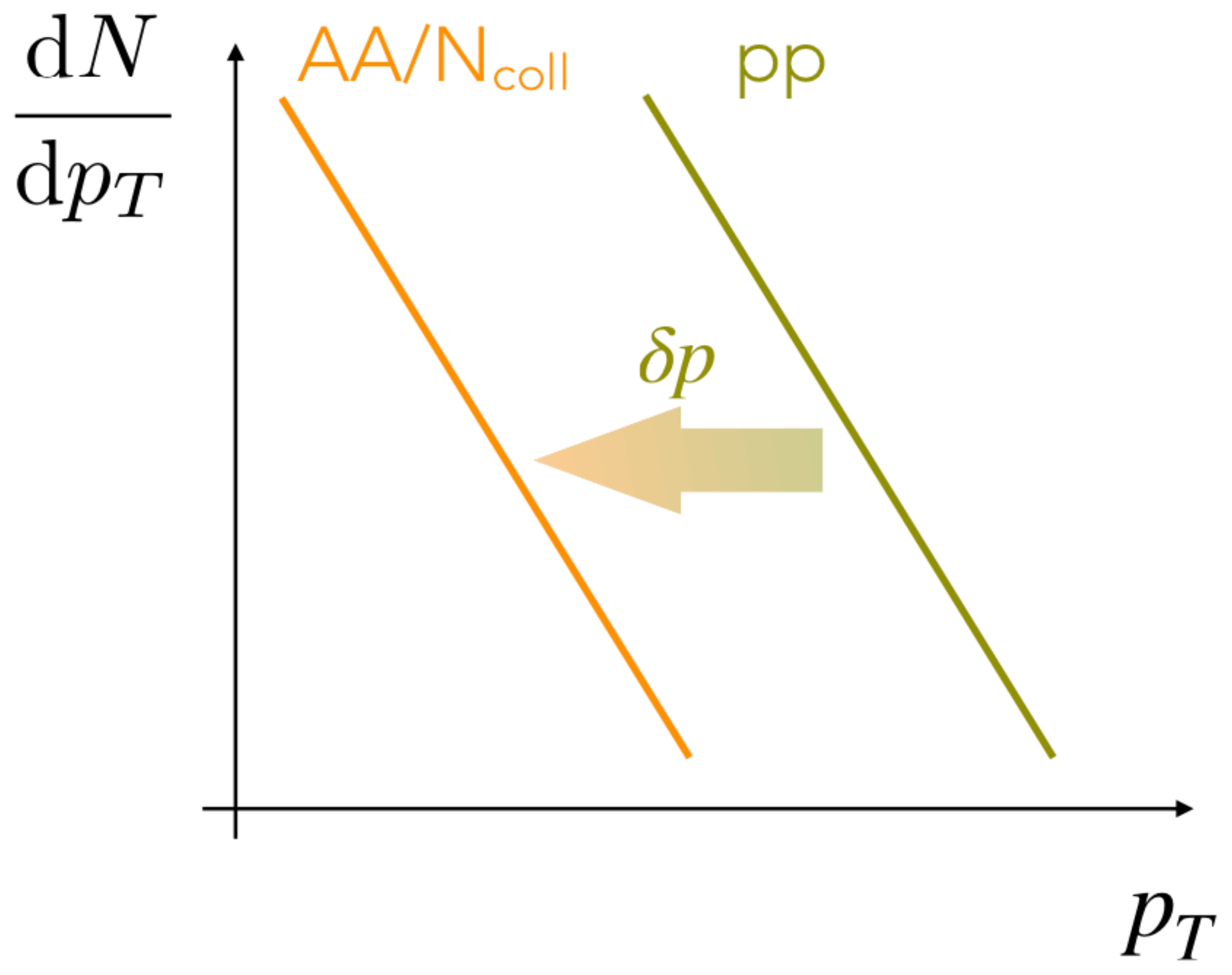
  - From Z+jet measurements: ΔE/E ~ 15% (independent of the pt)

Average momentum imbalance + Average number of lost pairs







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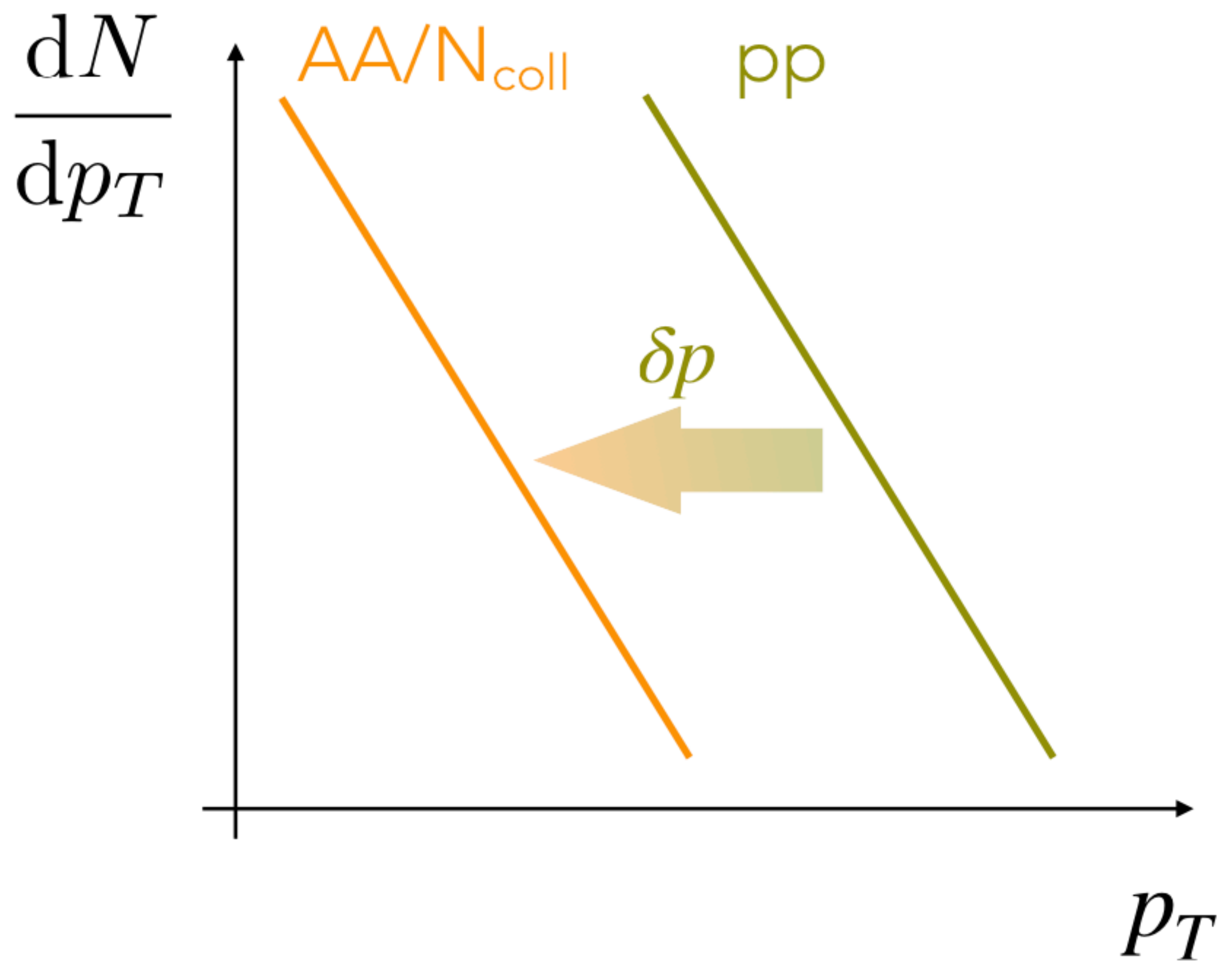
    - BDMPS (brick): ΔE/E ~ L^2
    - BDMPS (expanding medium): ΔE/E ~ L



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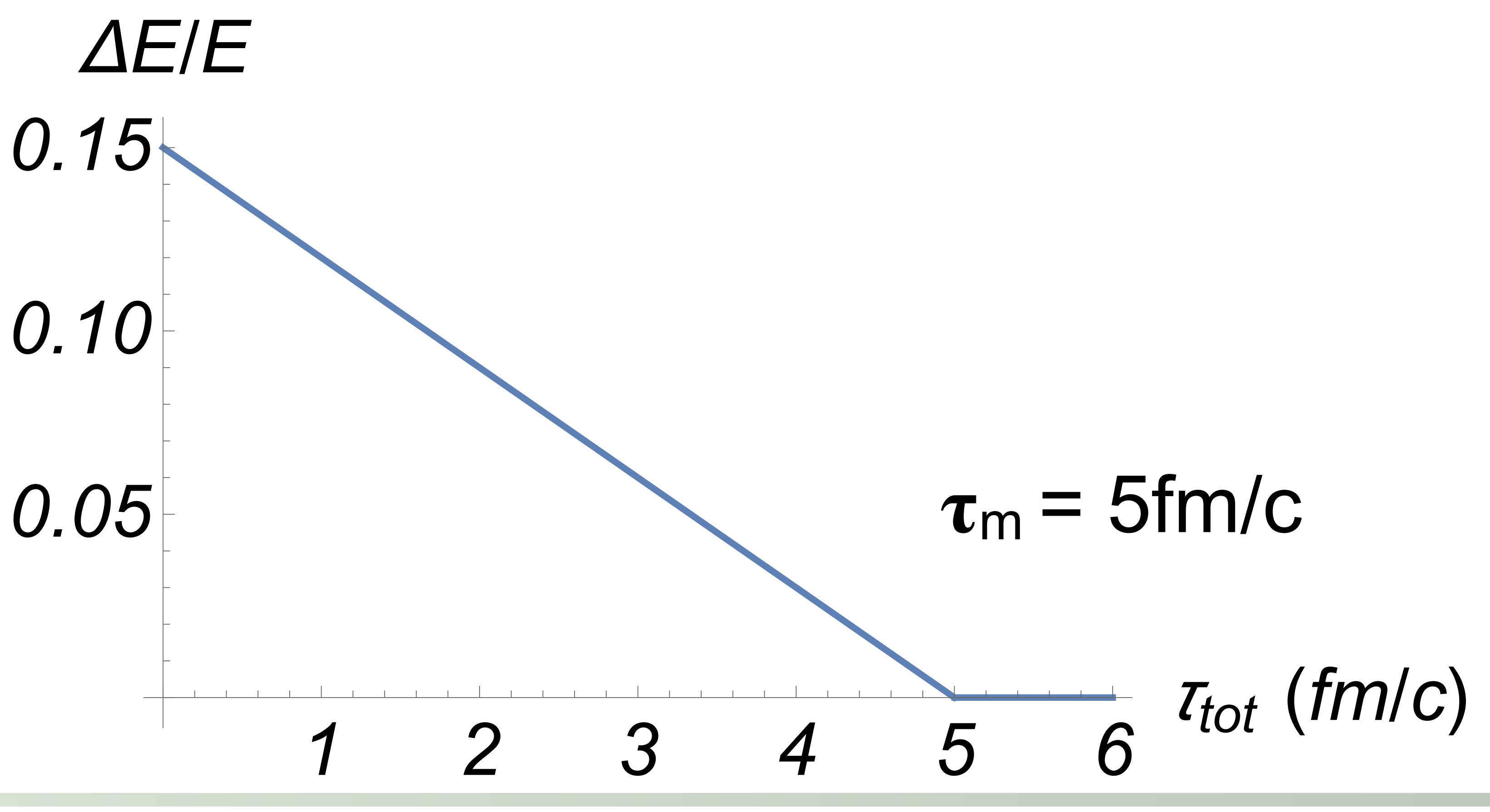
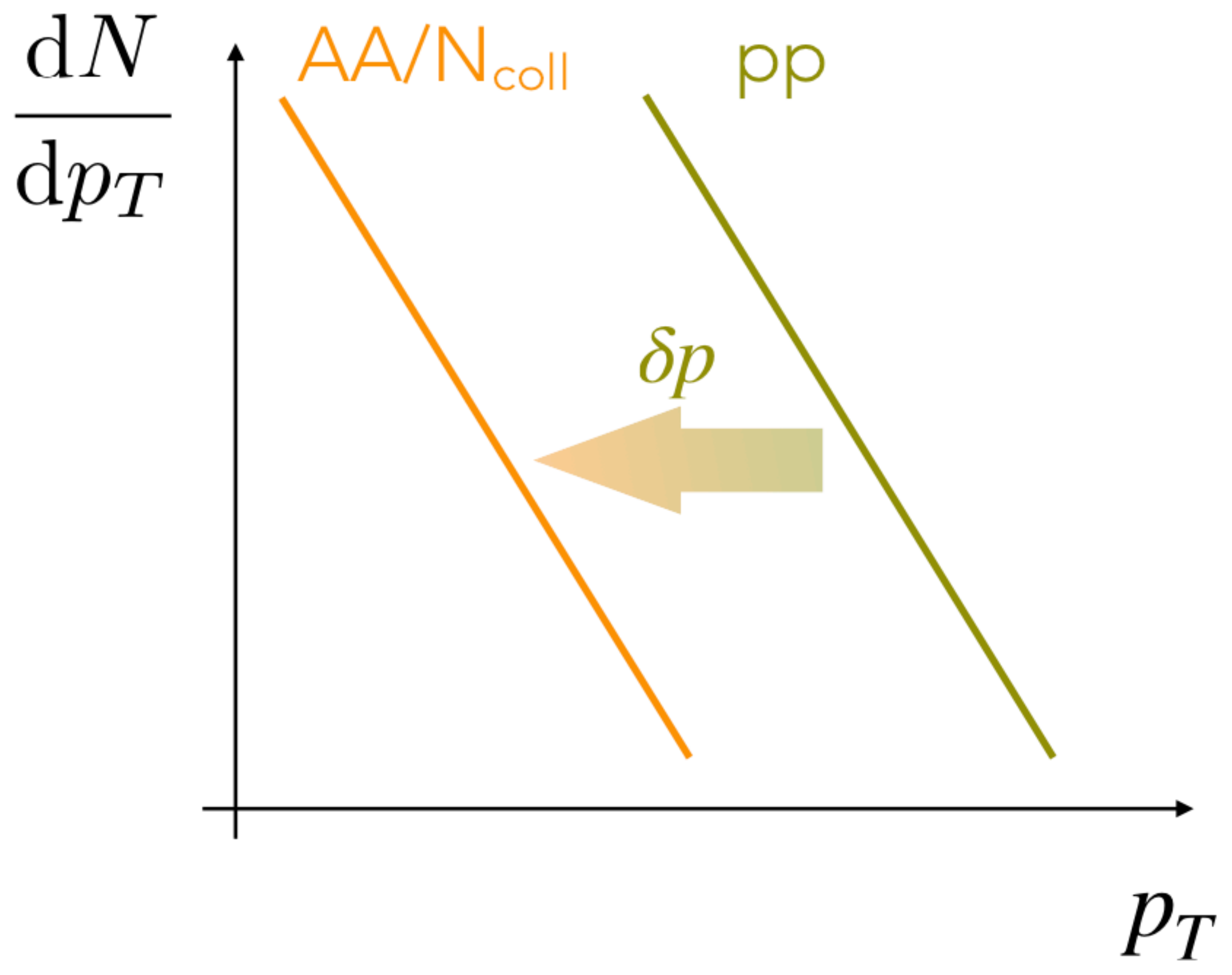


$\tau_{tot} = \tau_{top} + \tau_W + \tau_d$

Time at which the antenna decoheres



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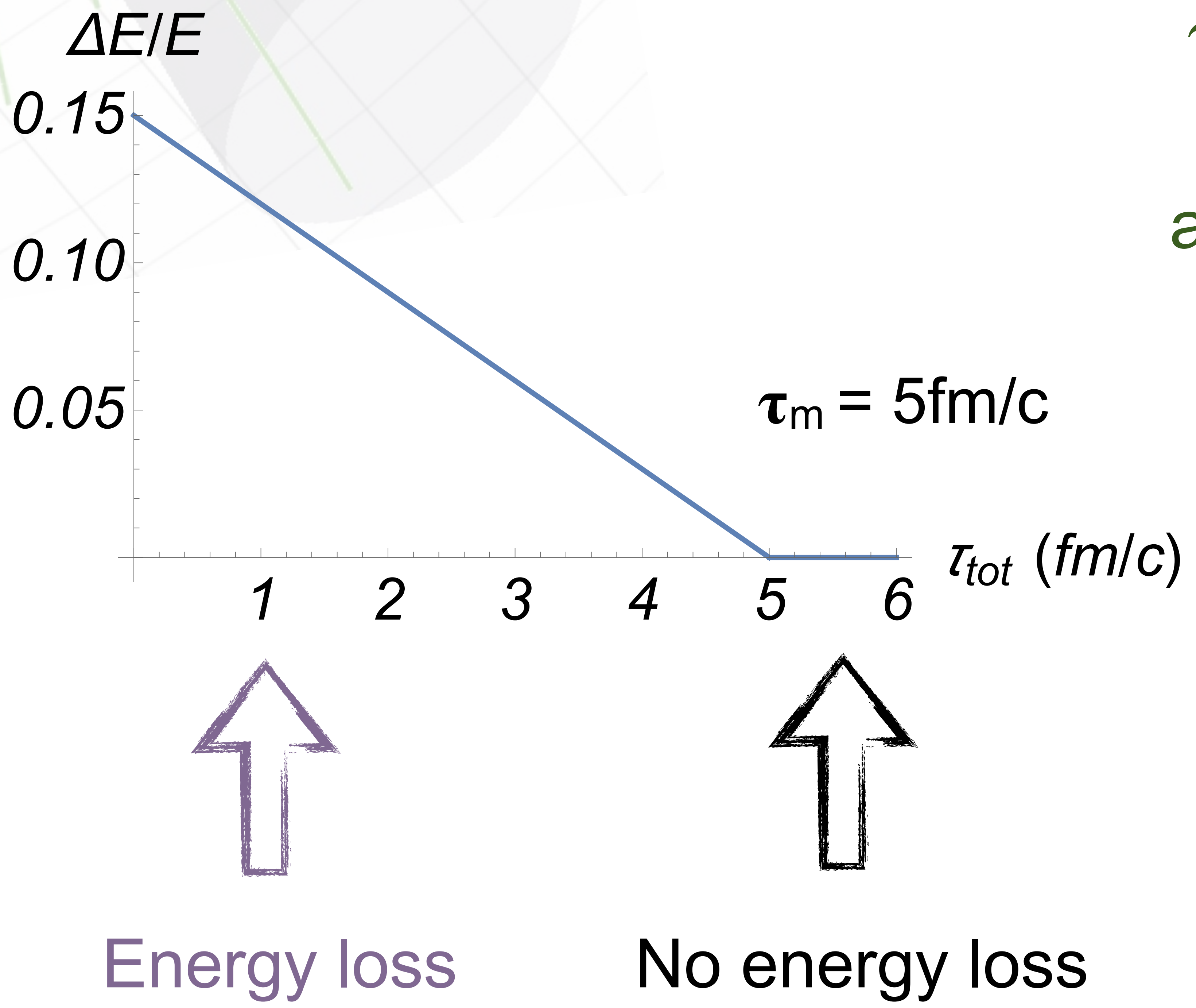

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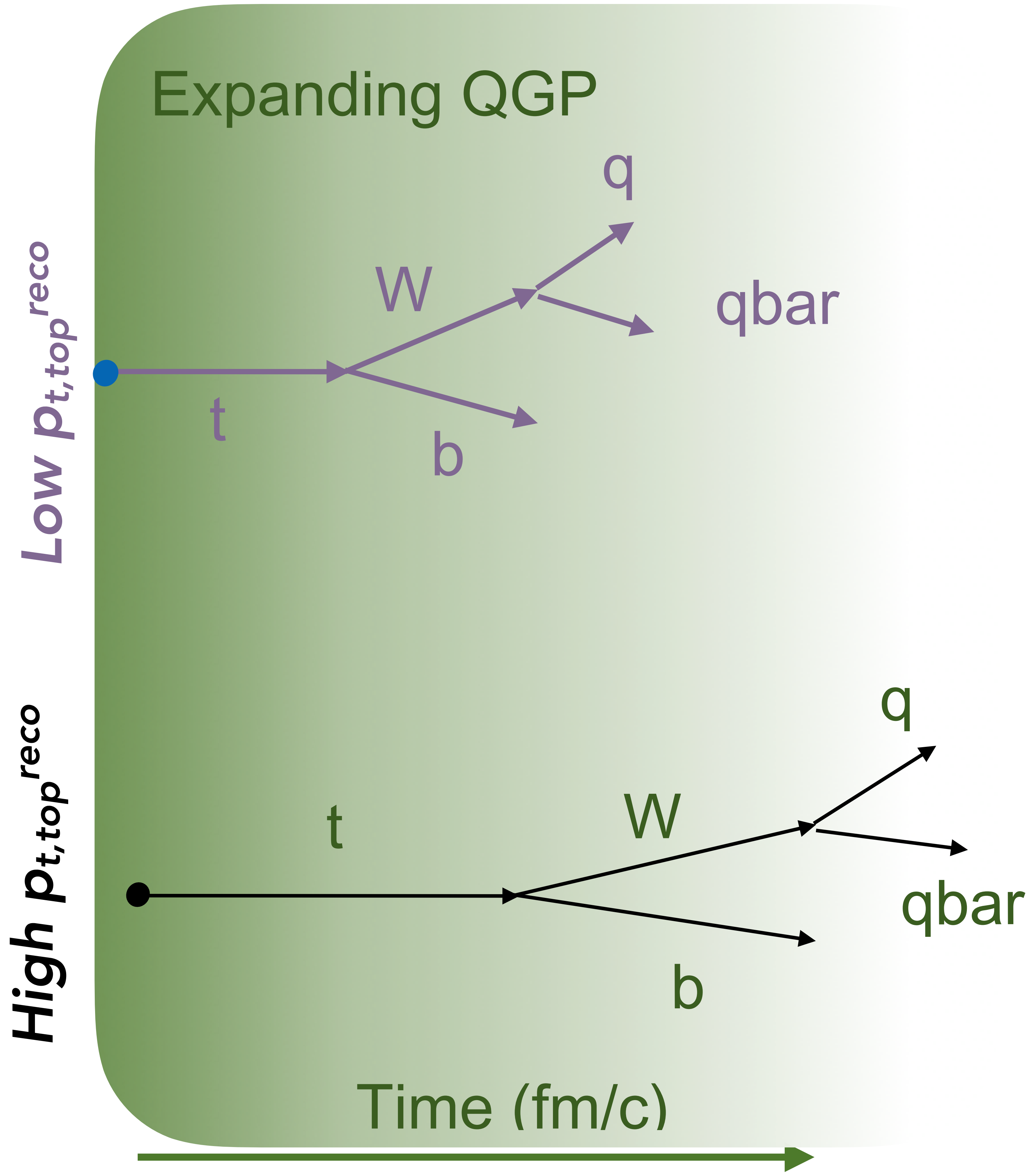

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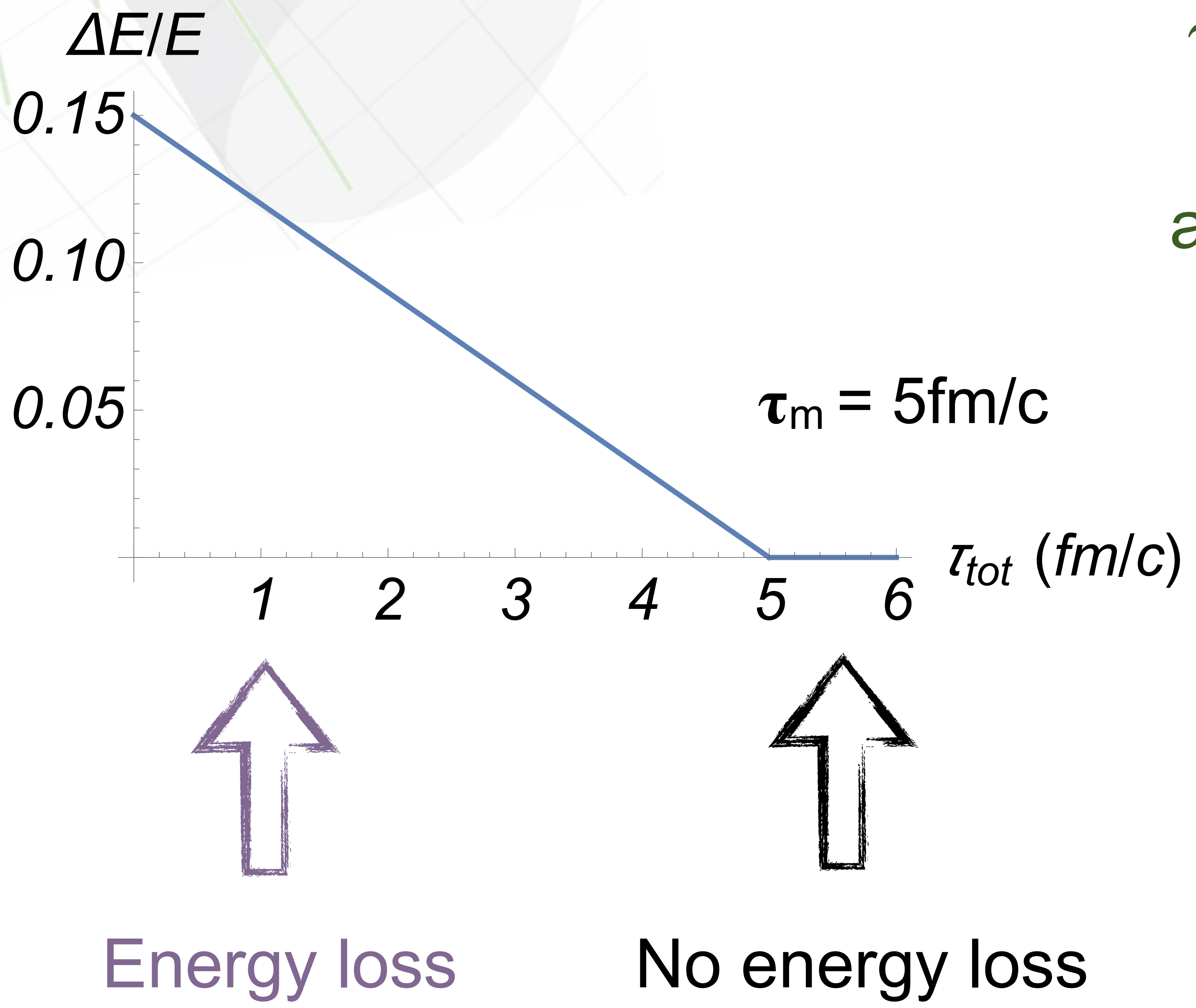

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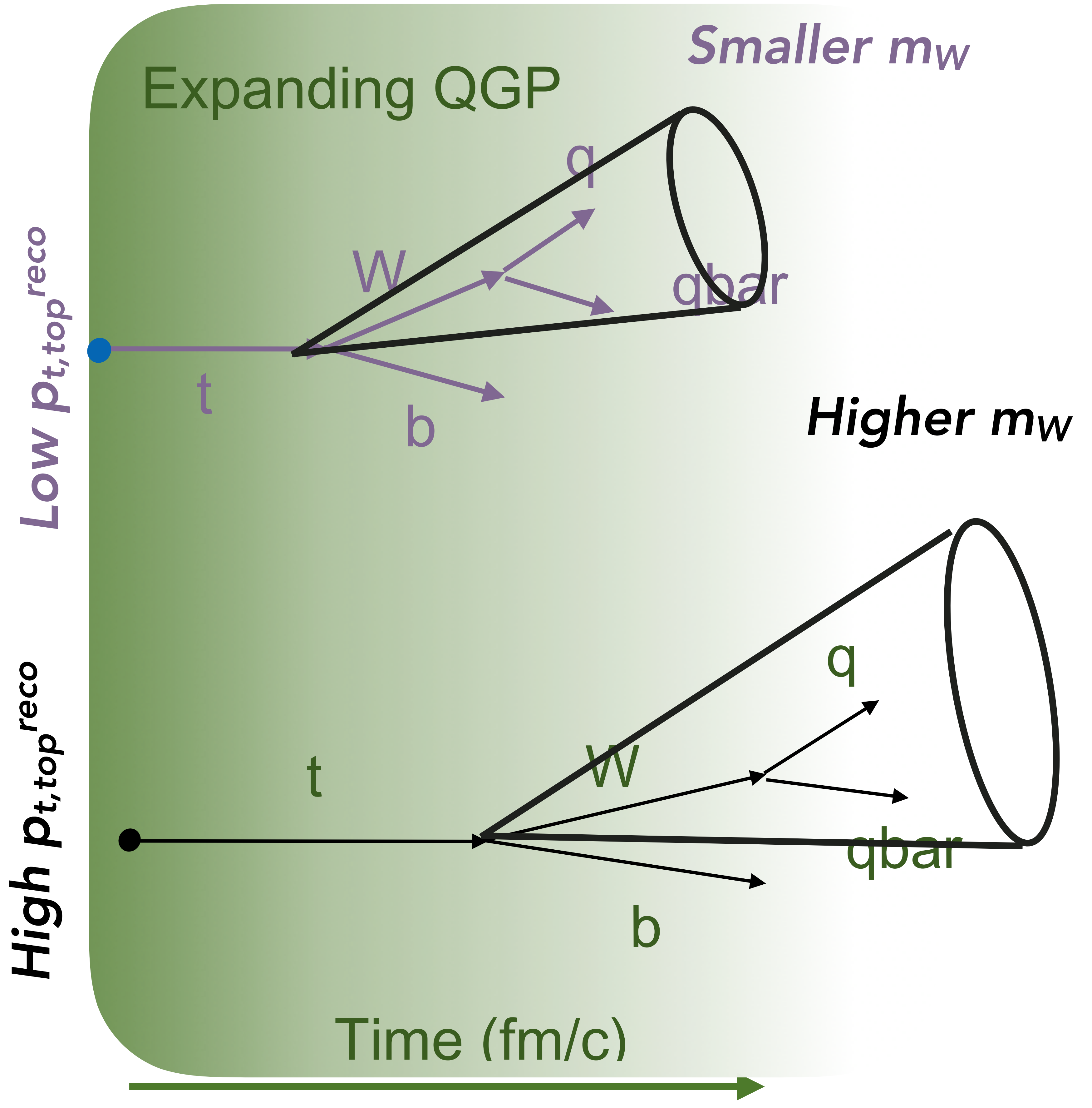
Time at which the antenna decoheres

Reconstructed W mass: m_W

will depend on the energy that is lost (medium length that jet is able to "see")



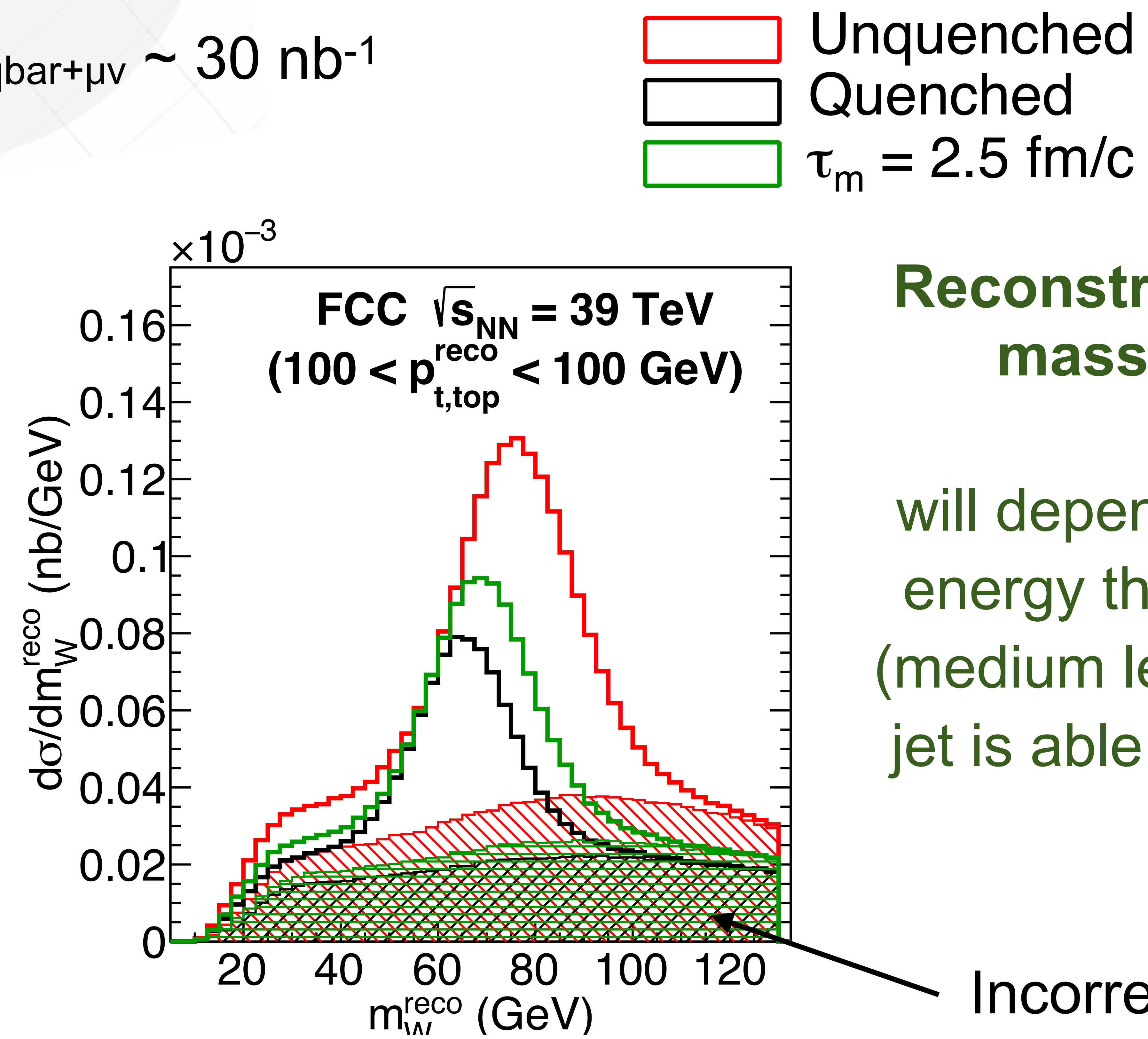
What is the observable?

- Simple observable that can be related with energy loss: reconstructed W jet mass
  - At Future Circular Collider (FCC) energies ($\sqrt{s_{NN}}$ = 39 TeV):
    - $\sigma_{t\bar{t}\rightarrow q\bar{q}+\mu\nu}$ ~ 30 nb^{-1}

pp event

pp event on top of a an expanding “brick”

pp event scaled by quenching factor (reference)



Incorrect reconstruction

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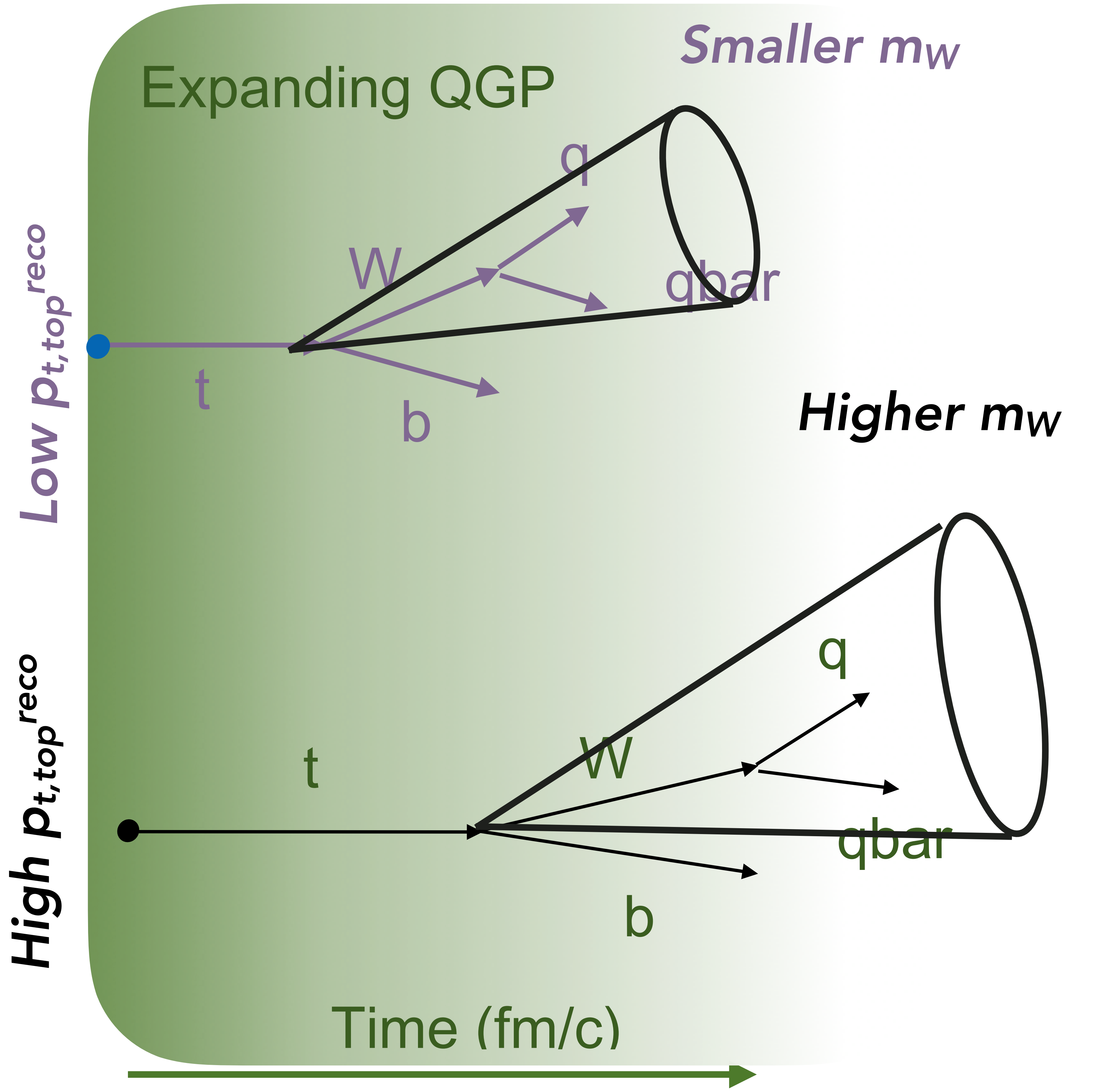
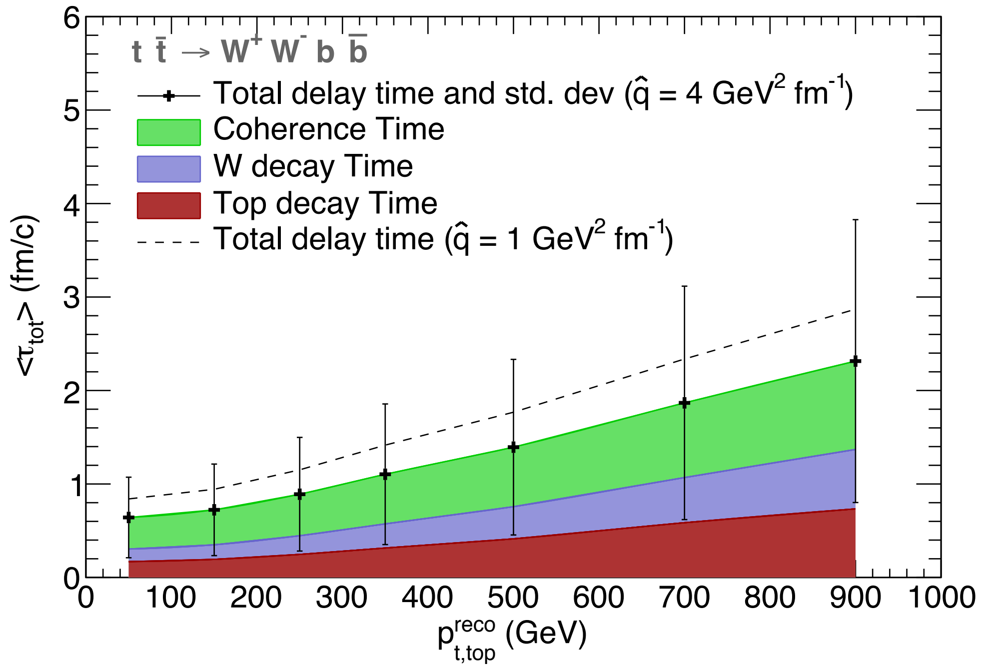
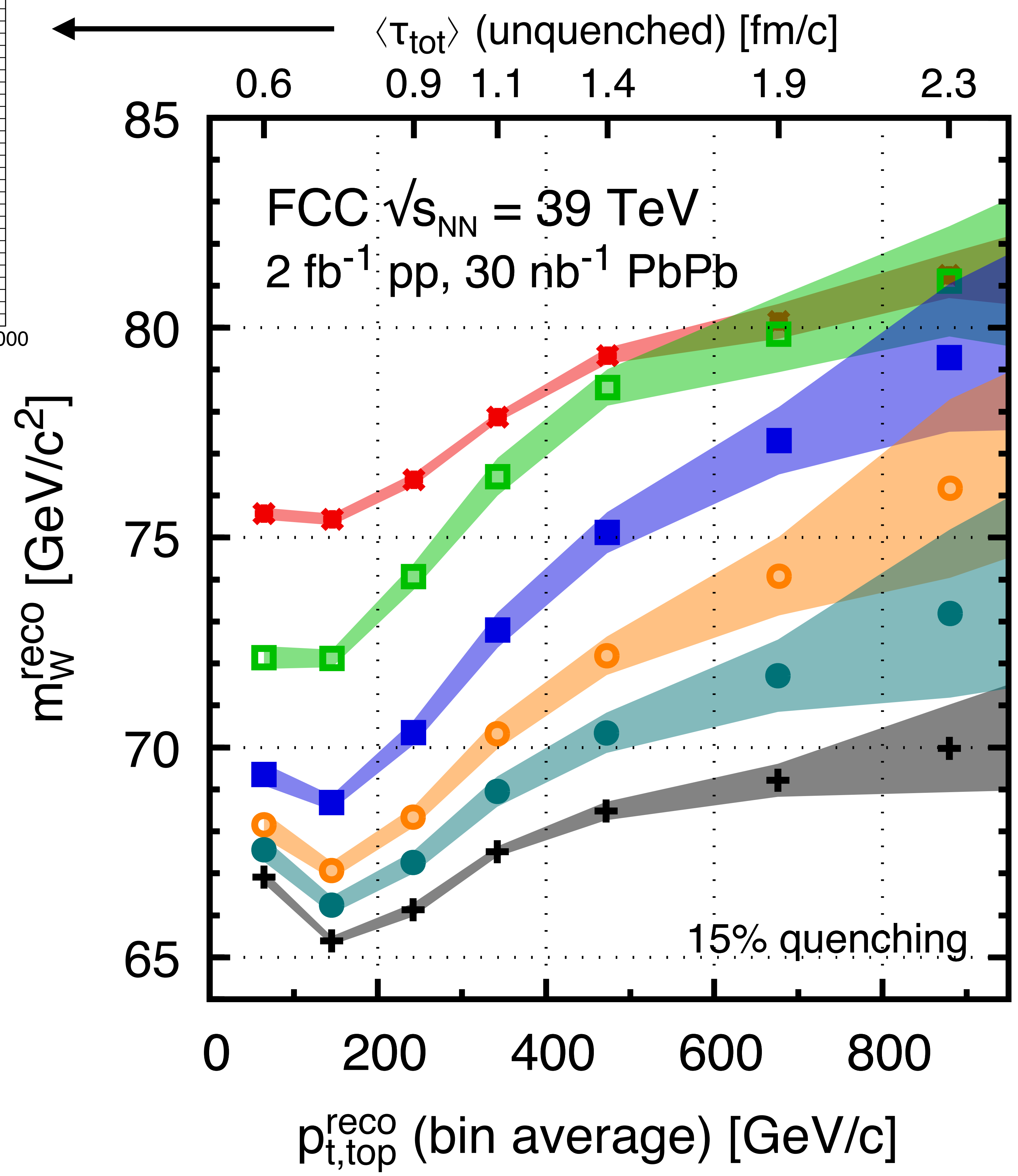


How to relate it to the timescale?

- Transverse boost (reconstructed top p_T) links to the average time at which particles start to interact with the medium
- Able to measure the density evolution profile

unquenched | τ_m= 1.0 fm/c | τ_m= 5 fm/c
quenched | τ_m= 2.5 fm/c | τ_m= 10 fm/c





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

LA, Milhano, Salgado, Salam (2019)

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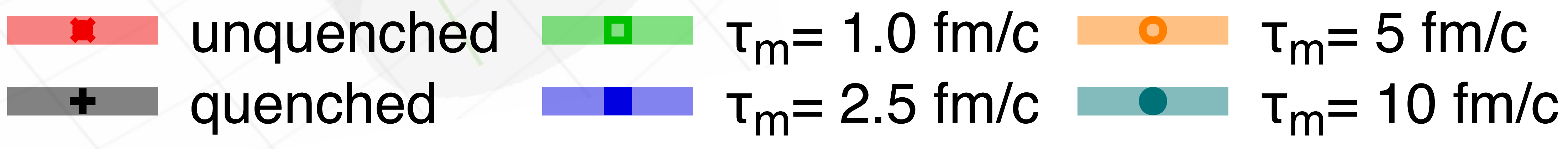
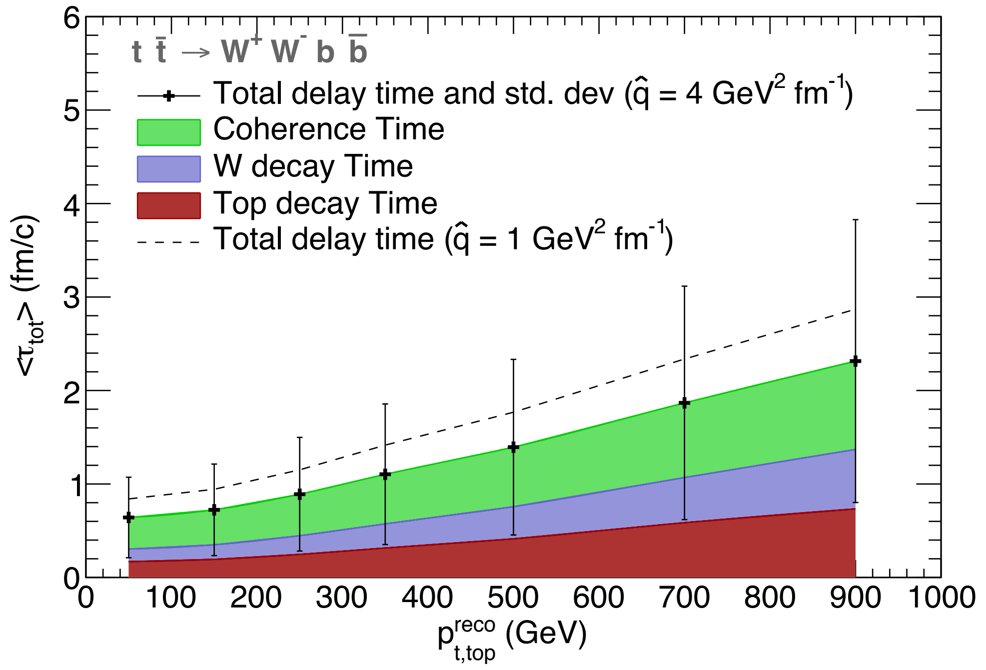
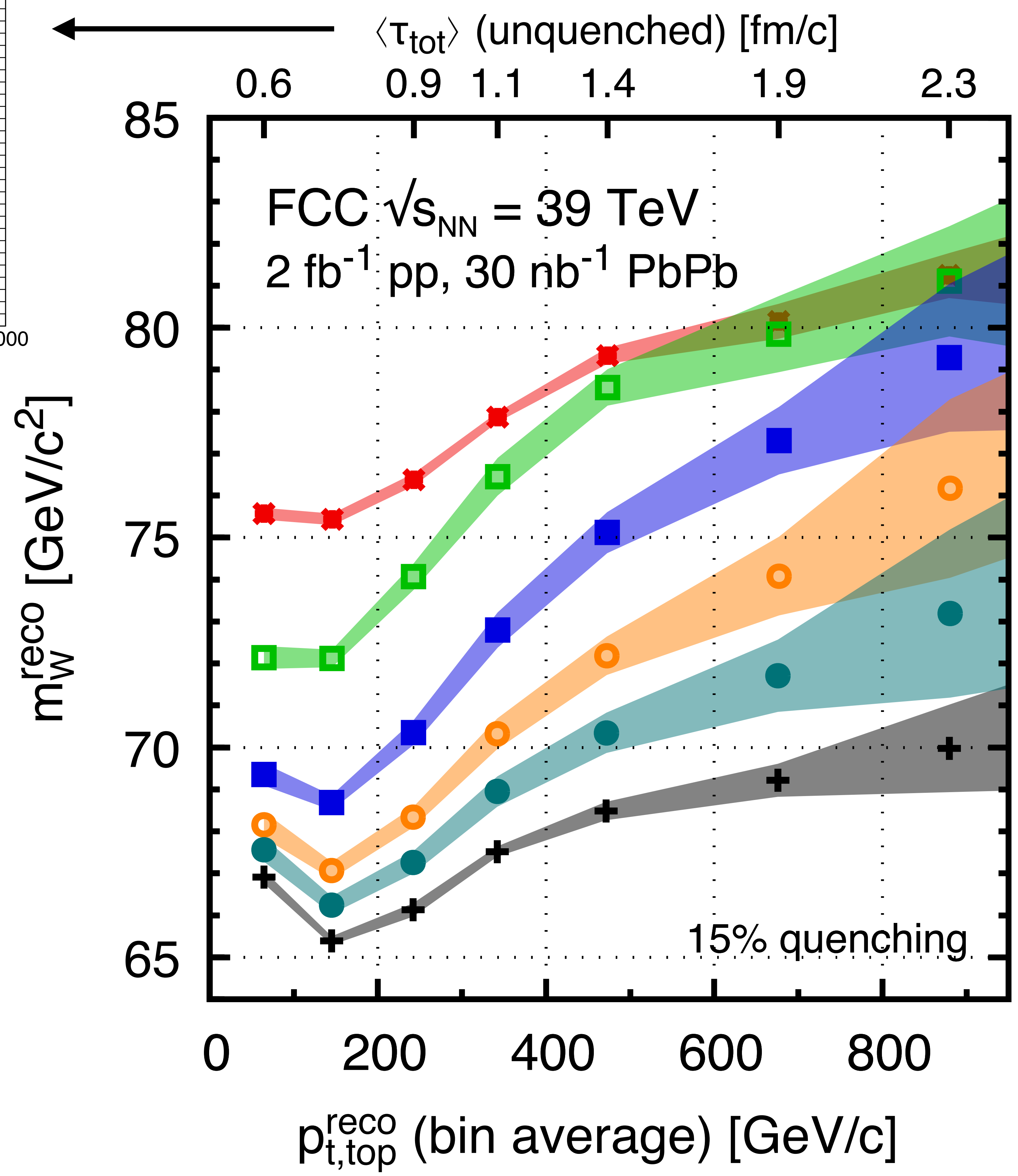
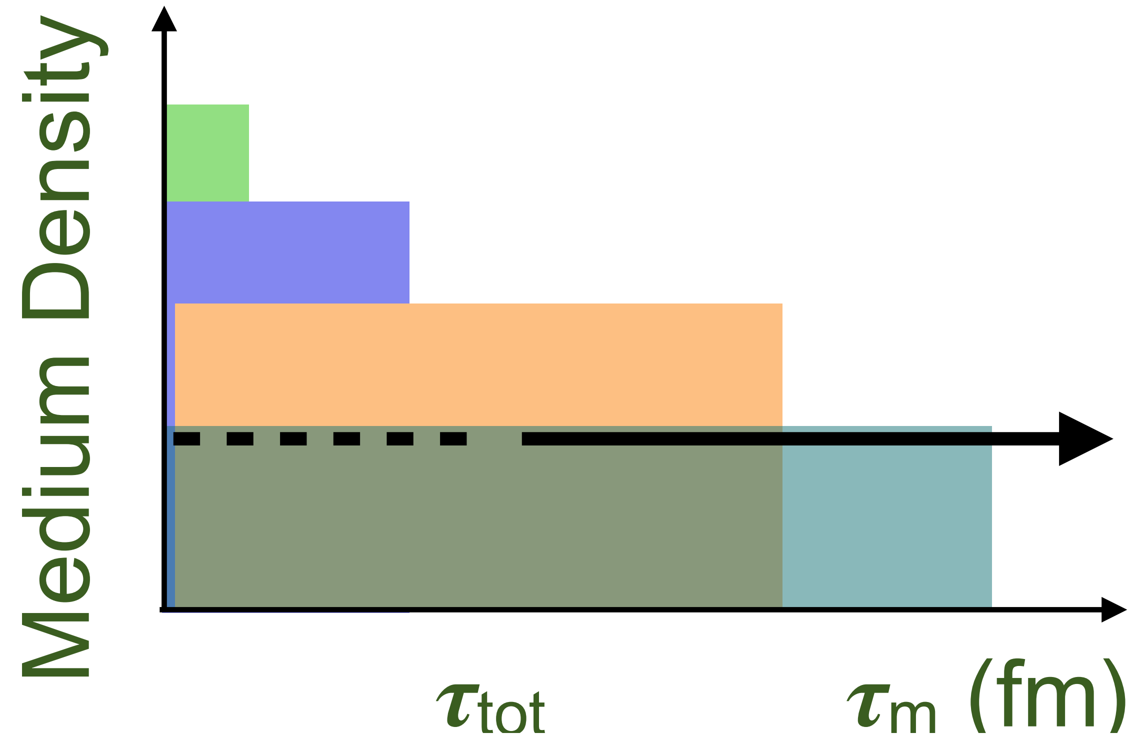






Unquenched = pp reference
Quenched = scaled pp reference

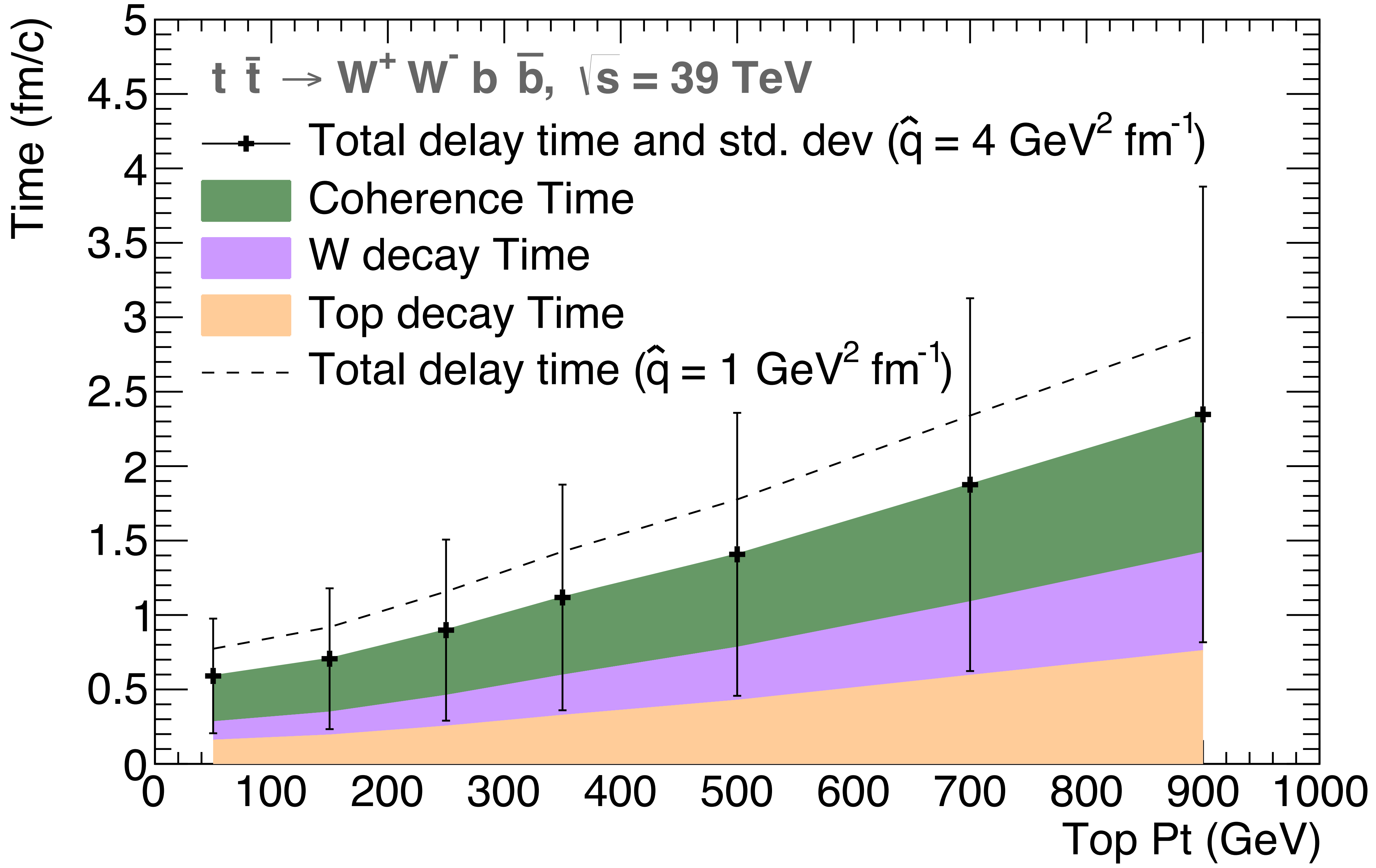
τ_m: "Antenna" inside a "brick" like medium

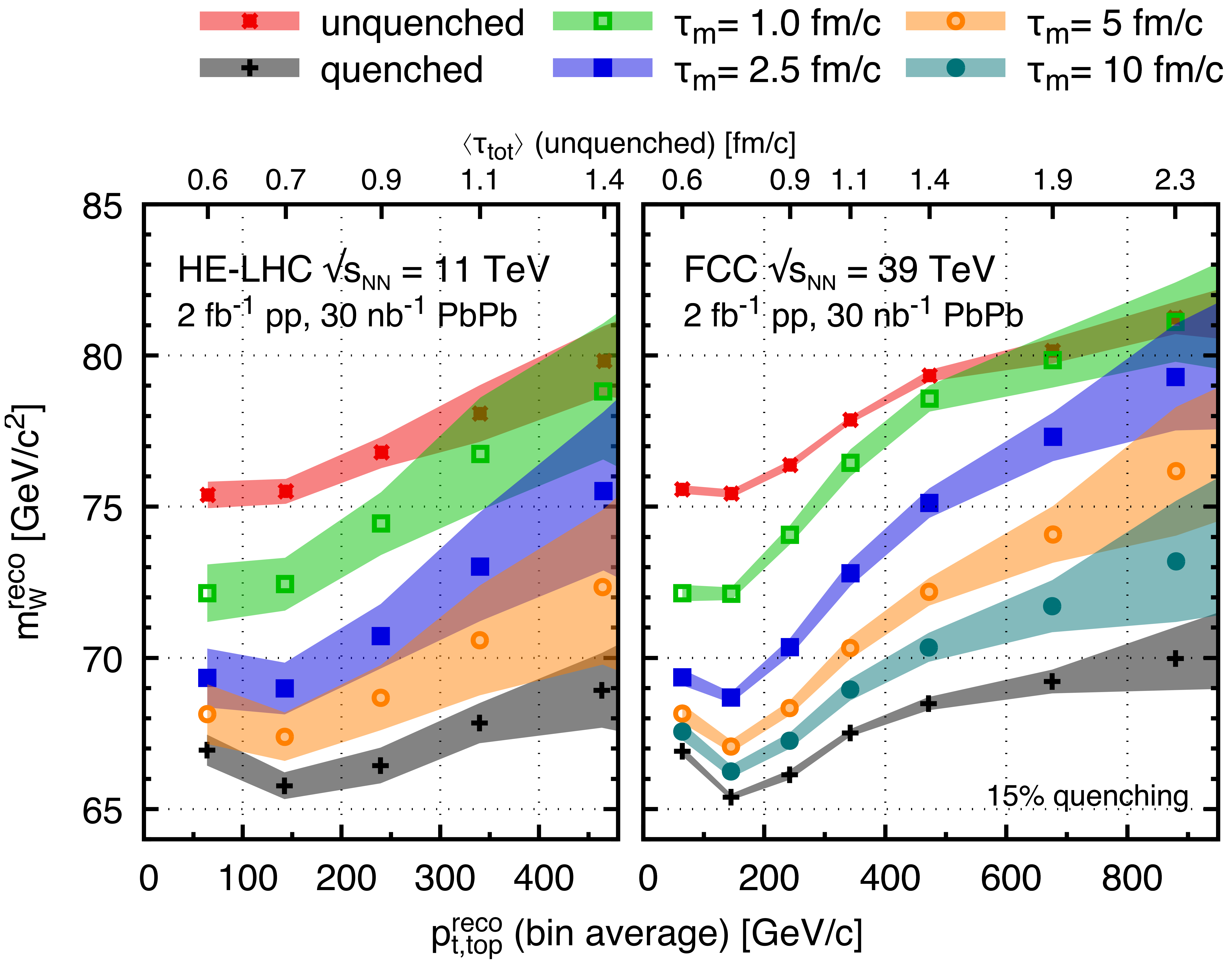


"Bands" = 1σ standard deviation from a true-sized sample (including reconstruction efficiency, b-tagging efficiency…)

QGP tomography?

- FCC: able to scan most of the QGP lifetime!
- HE-LHC: Some discrimination, but cross-section and luminosity too limited….





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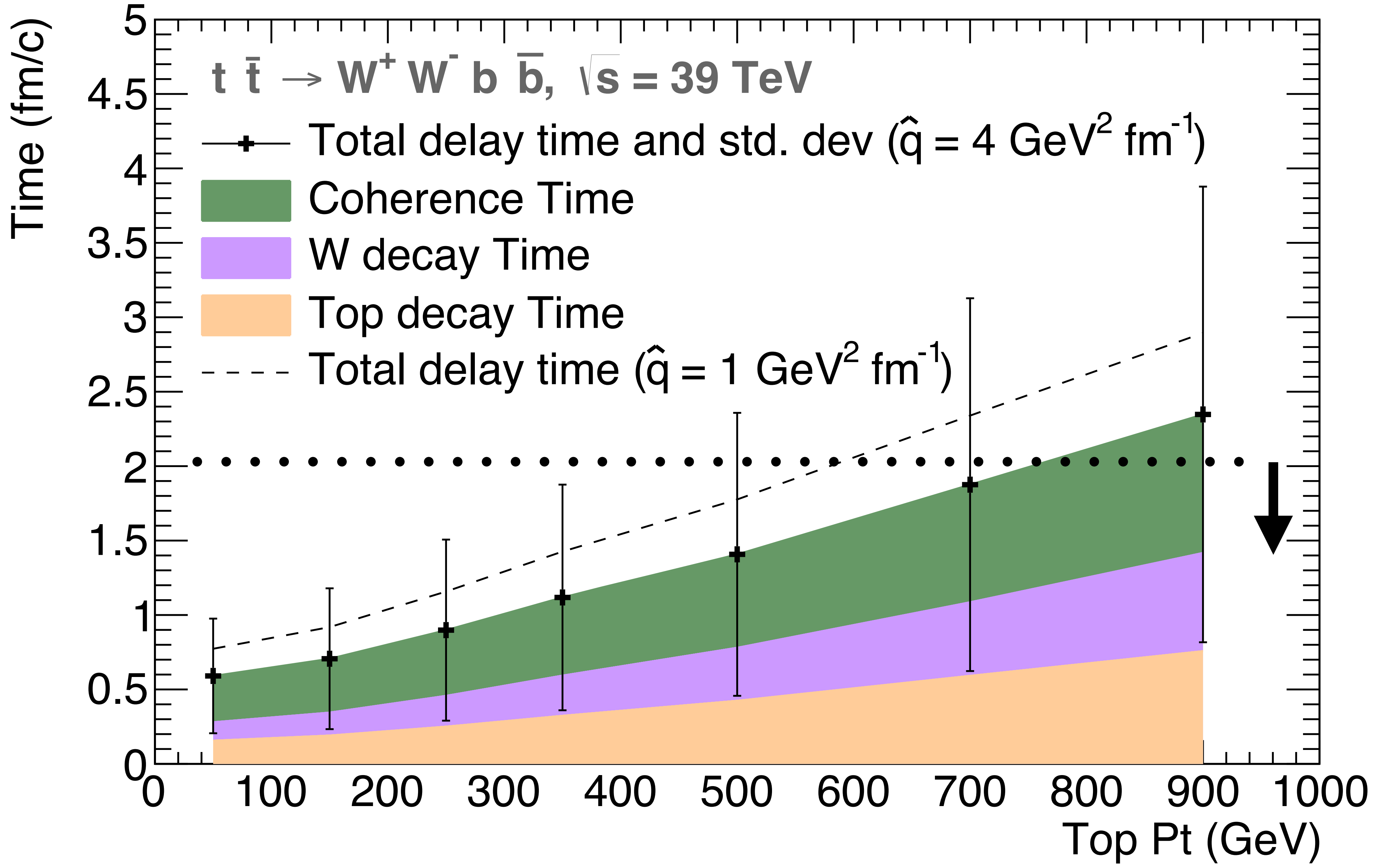
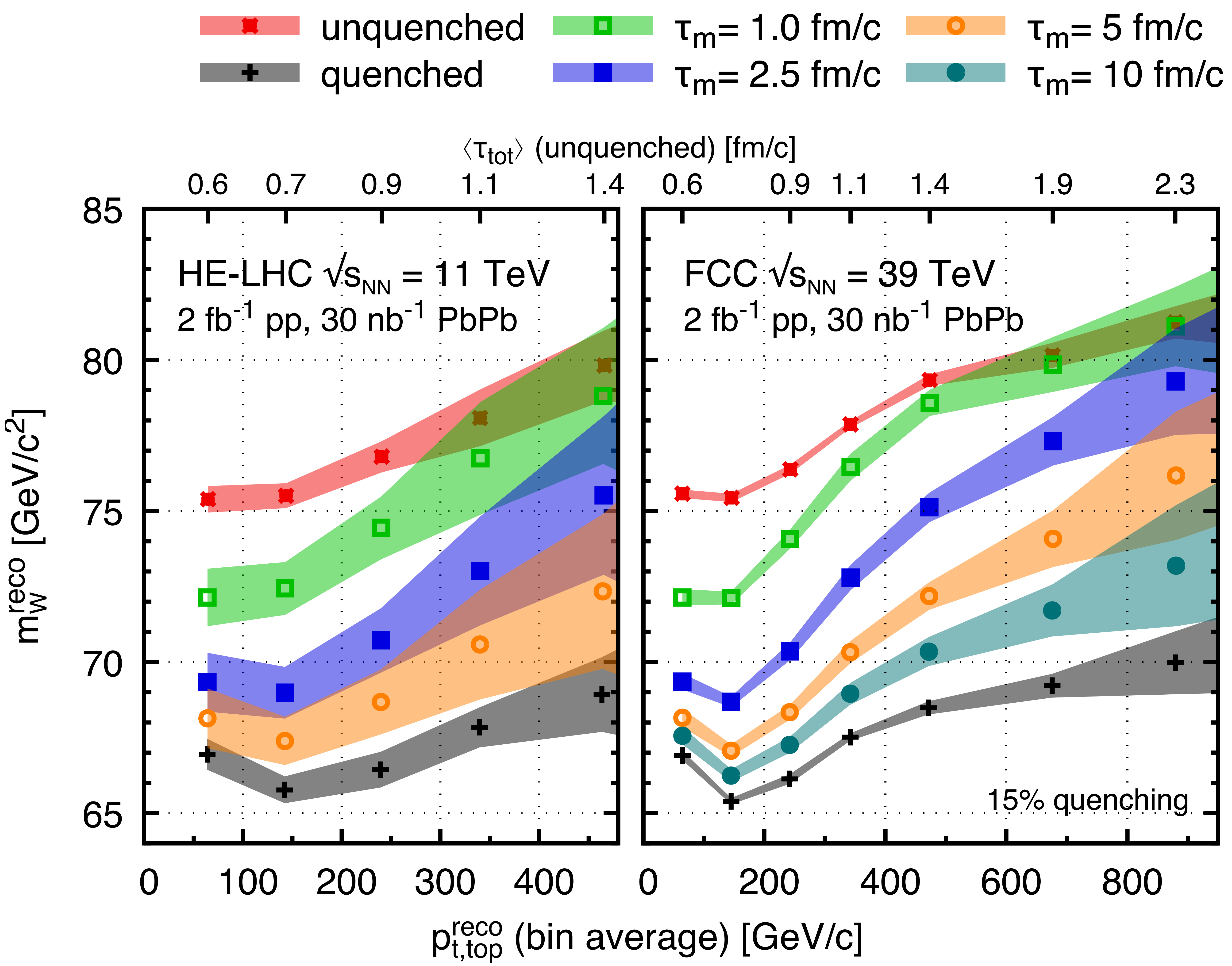
FCC





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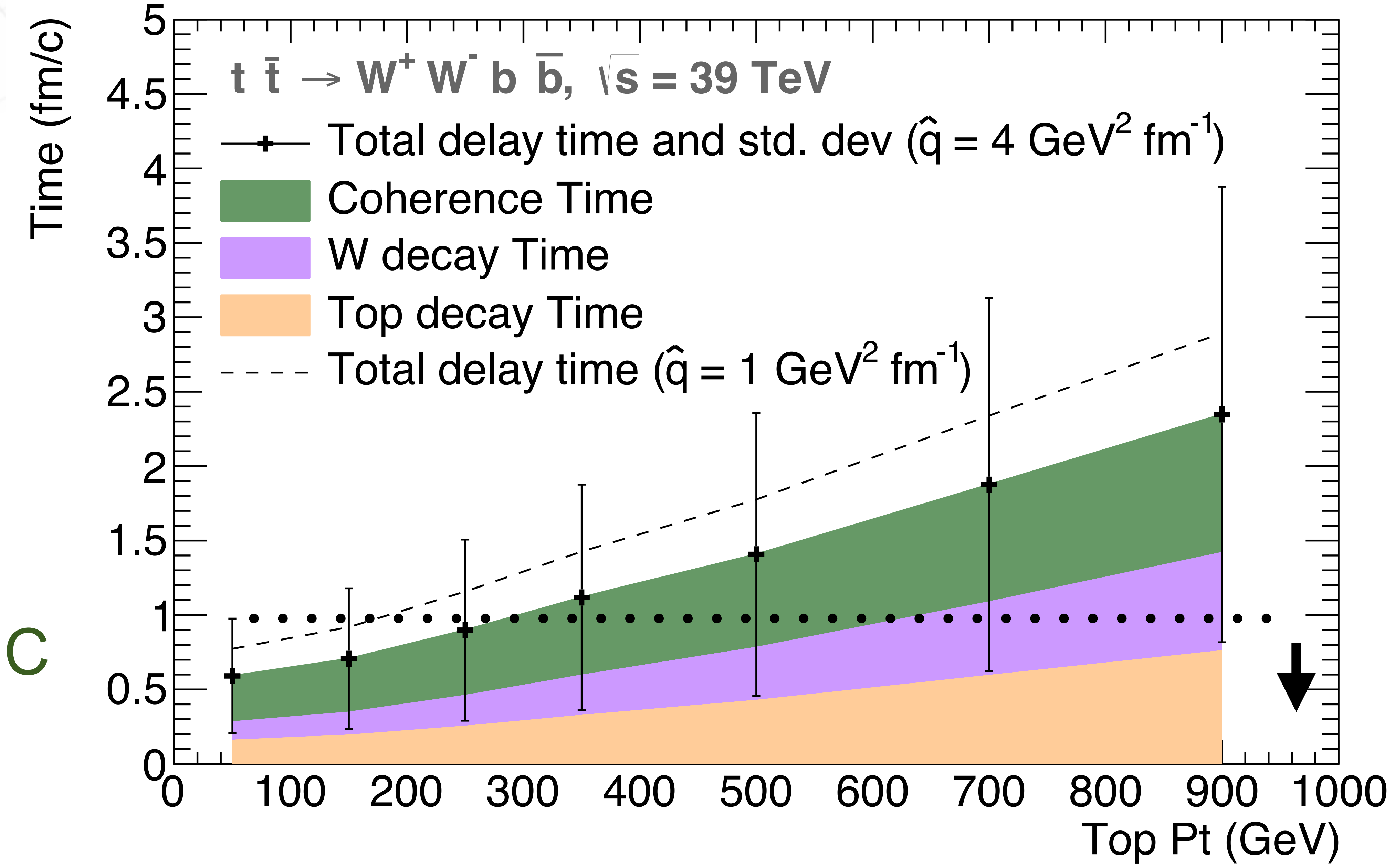
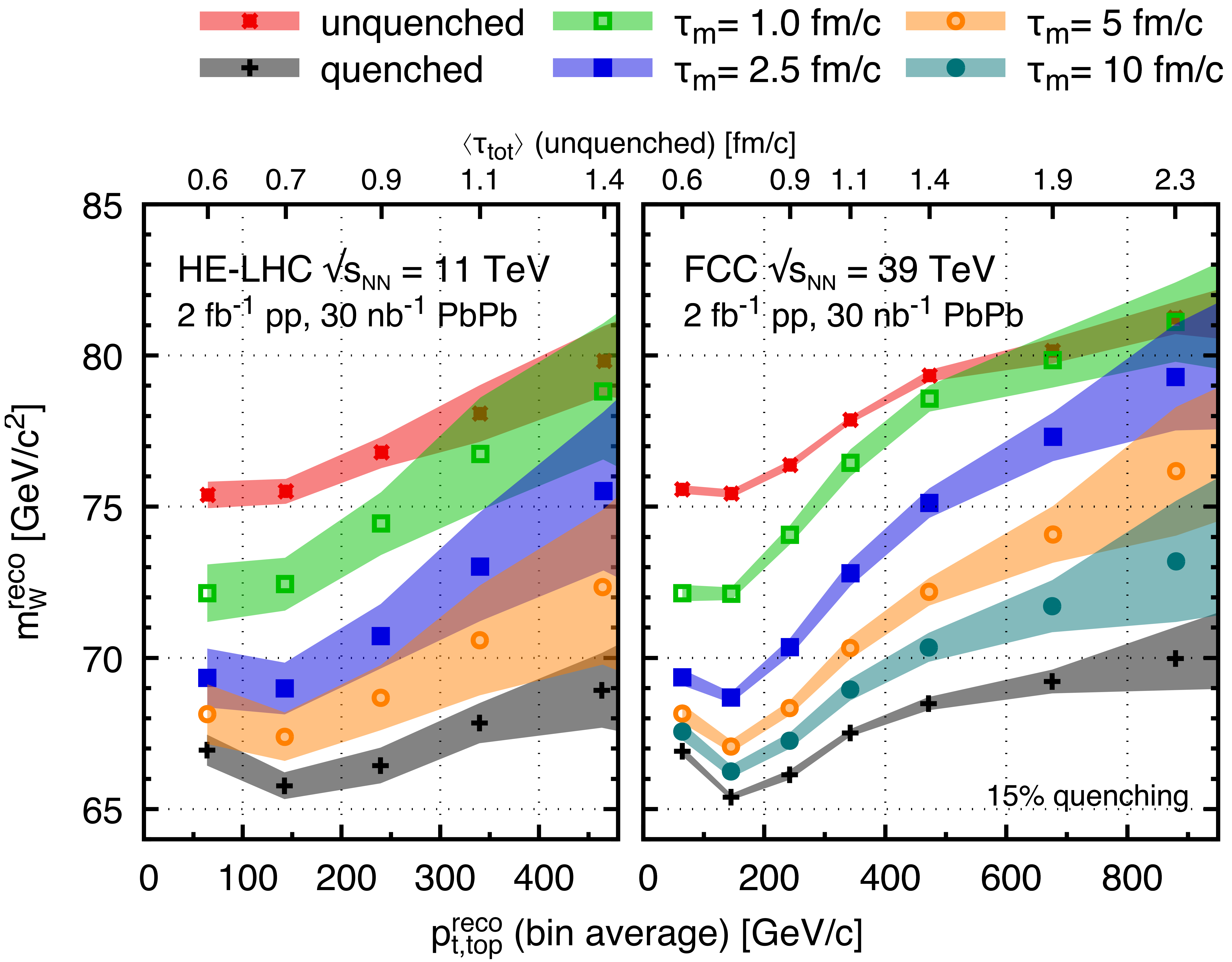


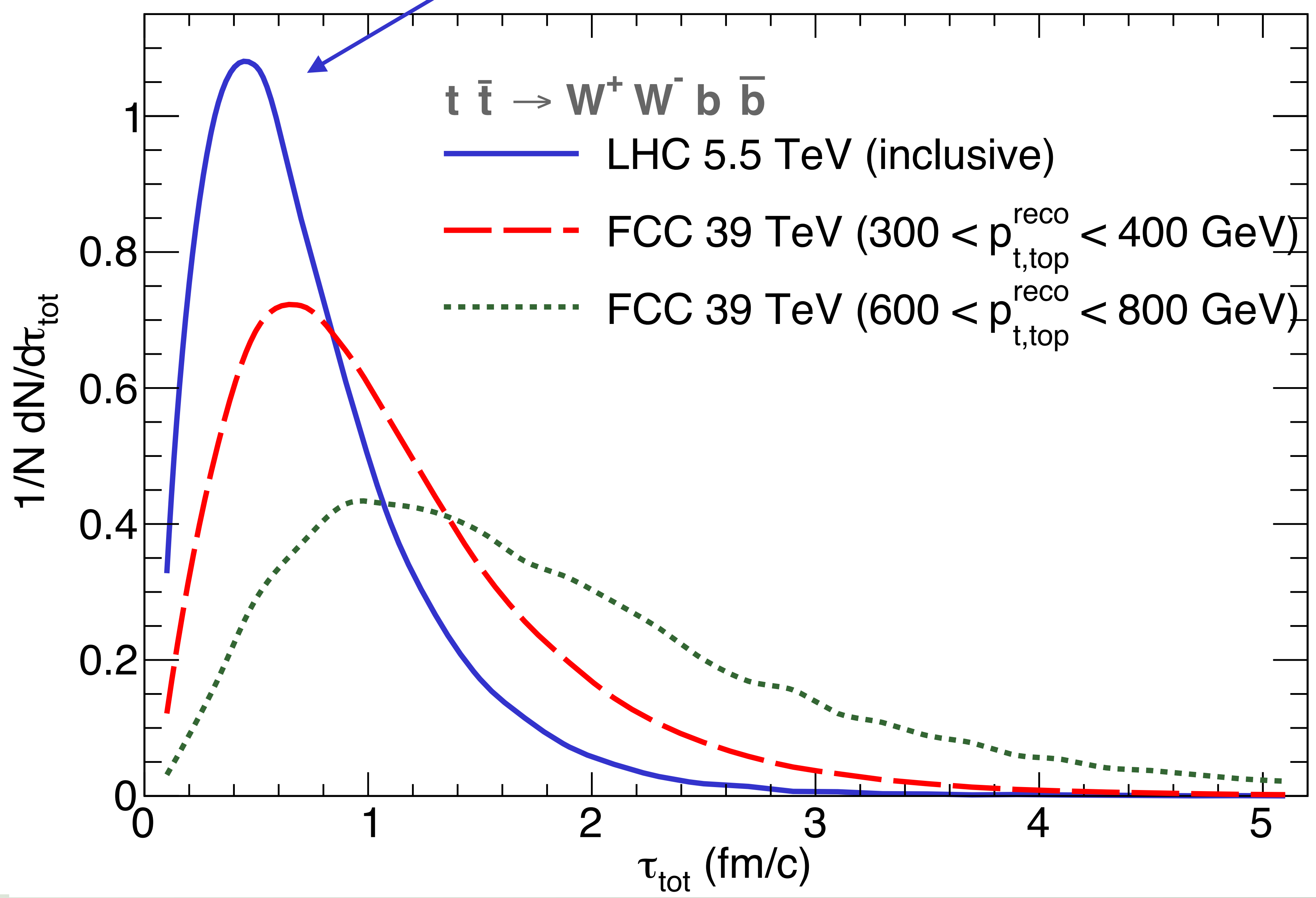
HE-LHC



Tops @ LHC

- Inclusive distribution (no pt trigger info)

Average total delay time at the LHC is very small…



Tops @ LHC

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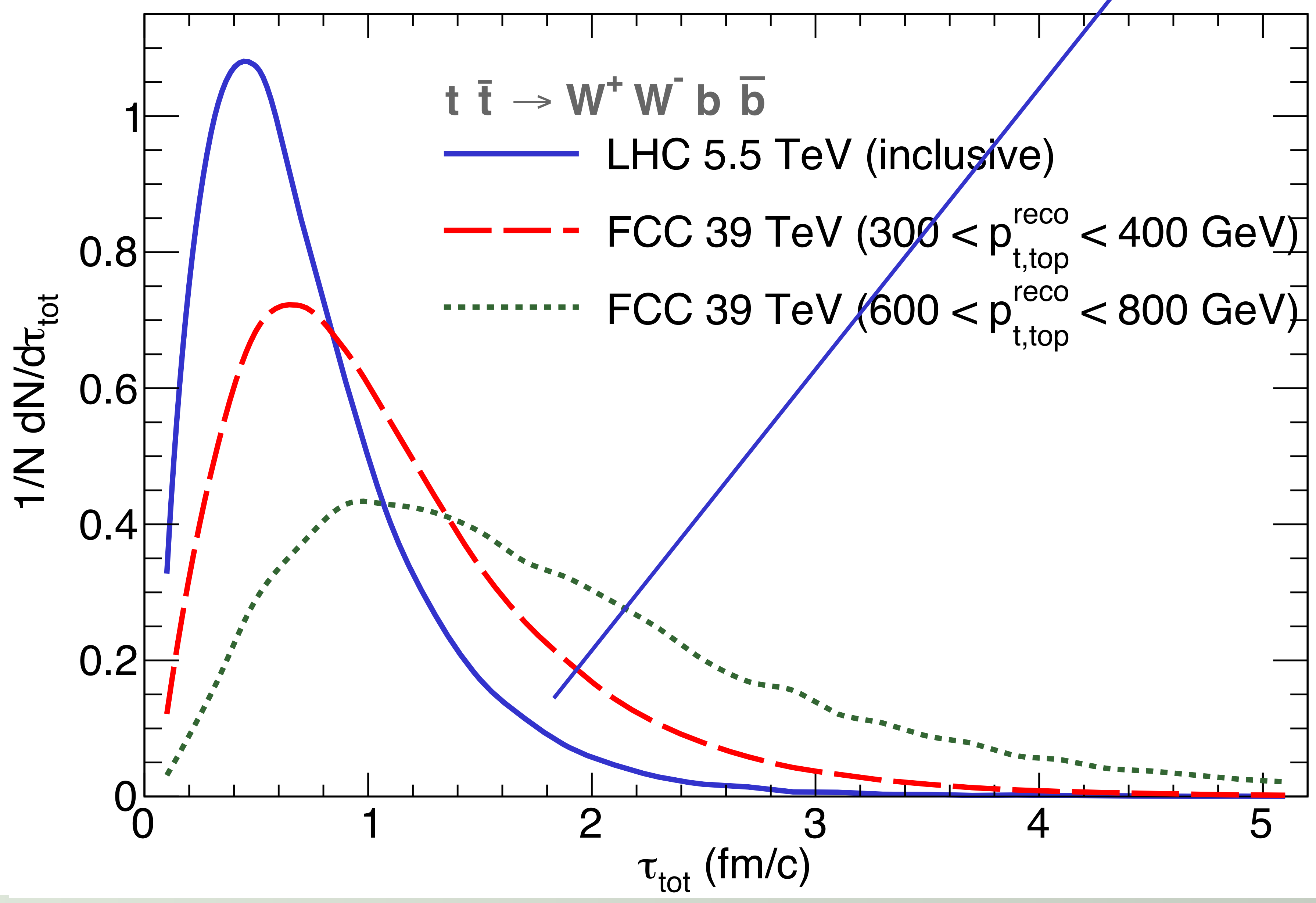
But there is a large dispersion that one can play with.

Average total delay time at the LHC is very small…



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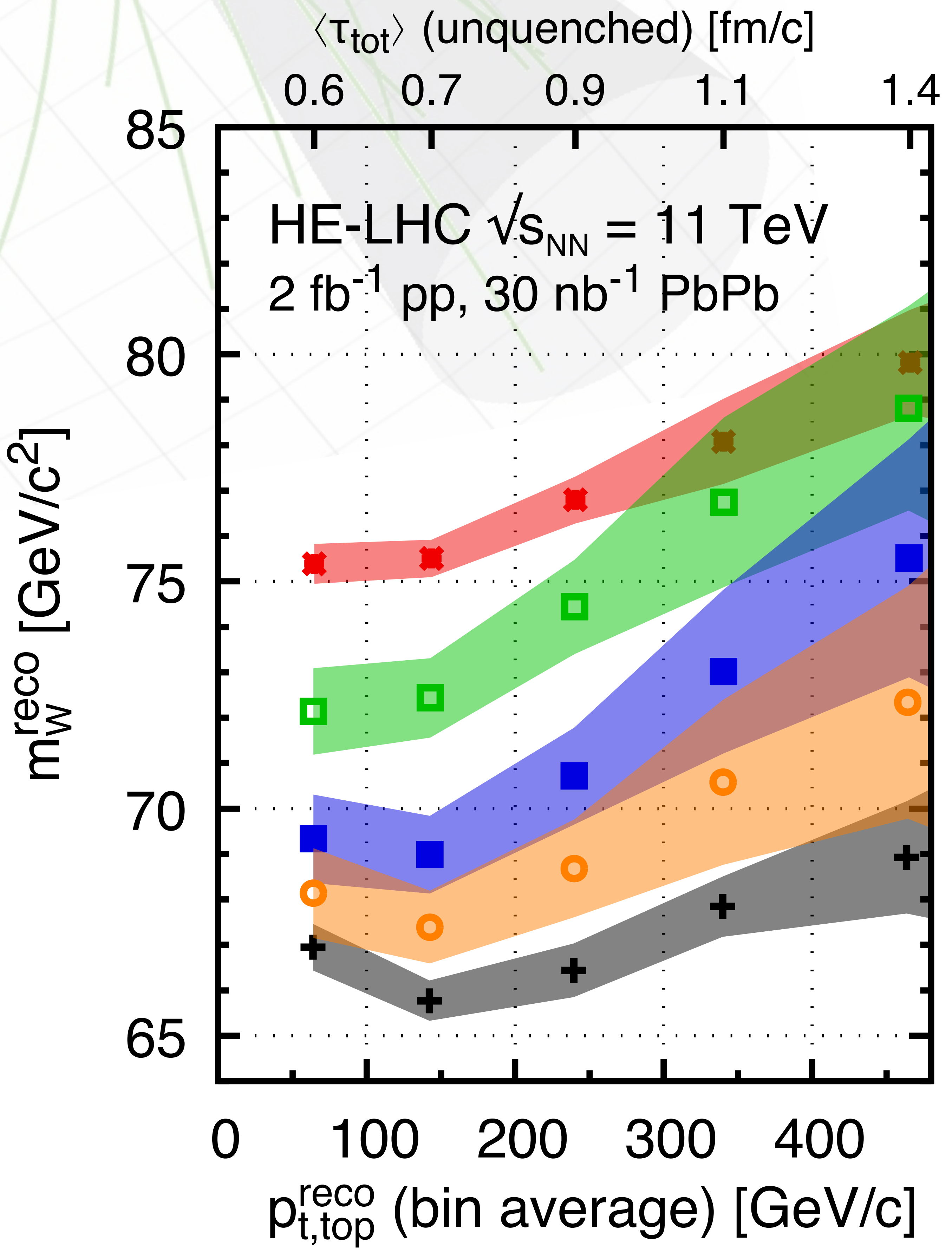

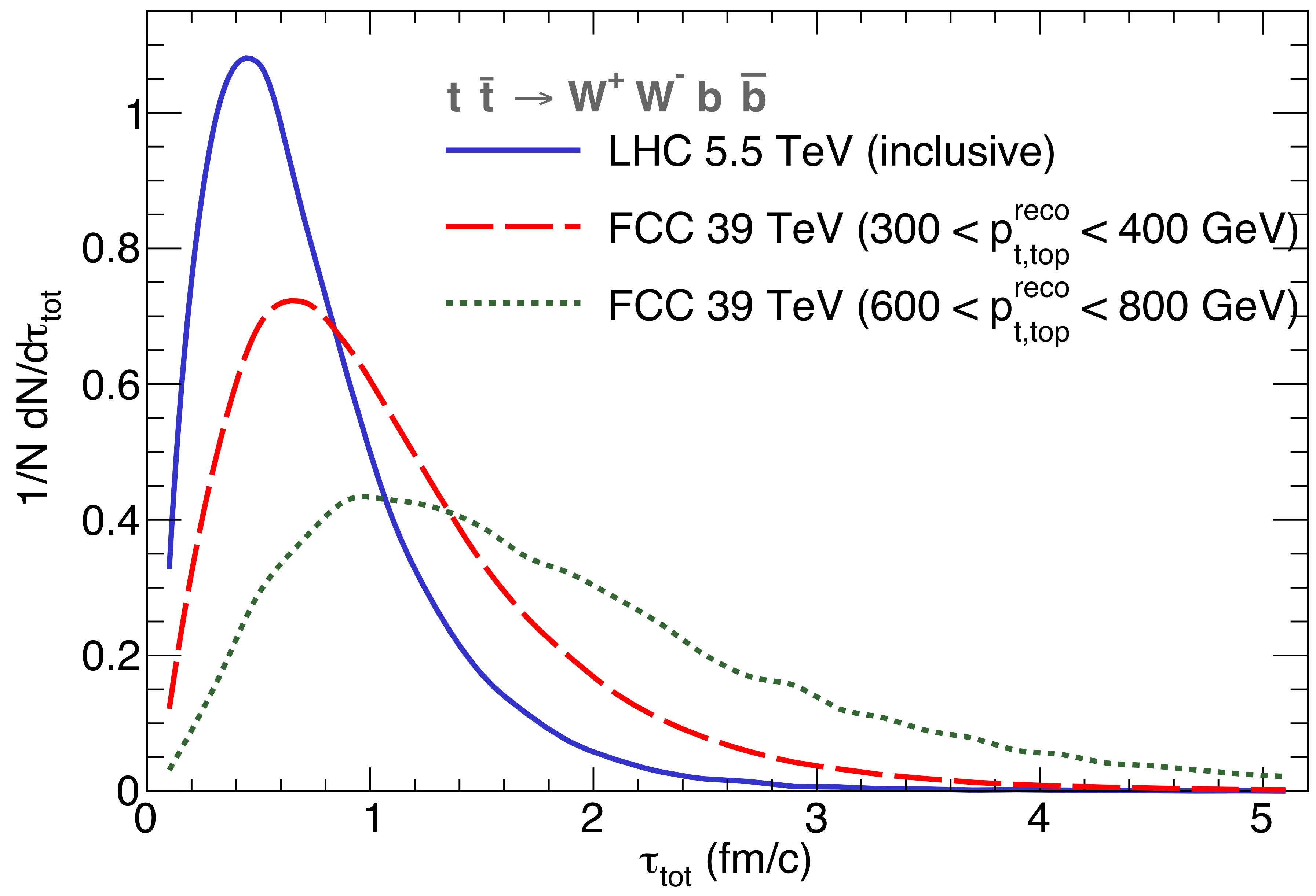

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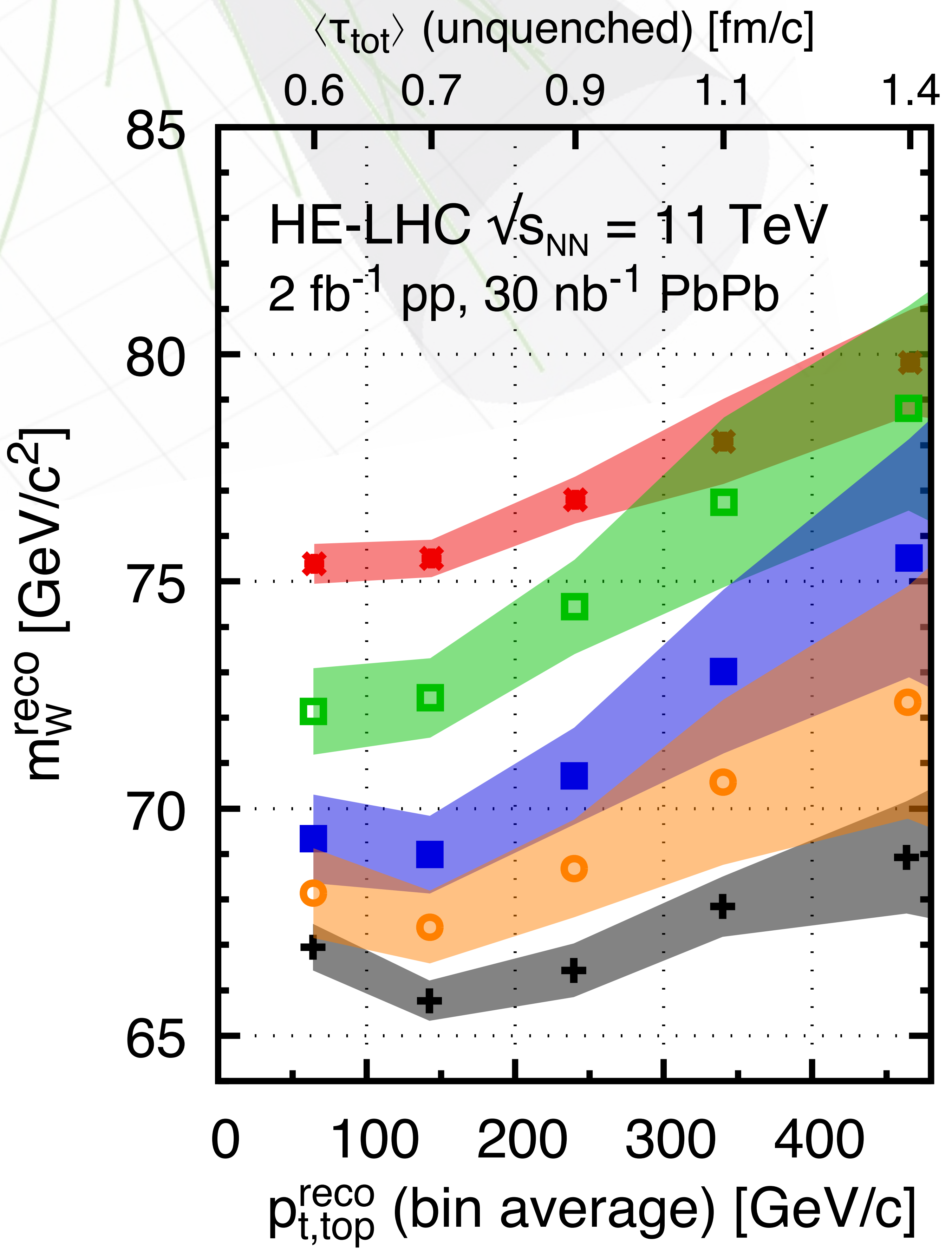
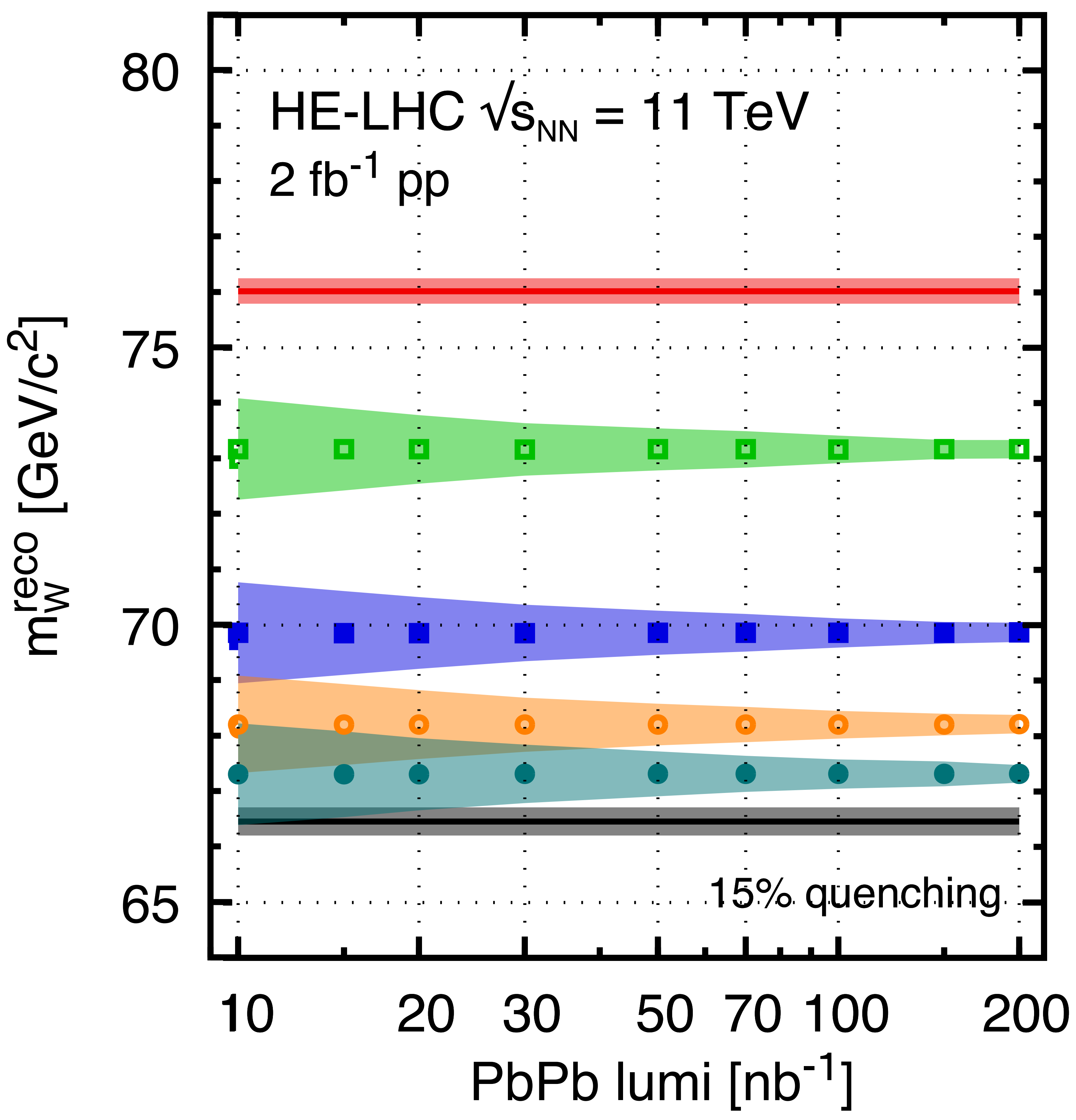


Inclusive

(integrating over top p_T)

“bands” = 1σ



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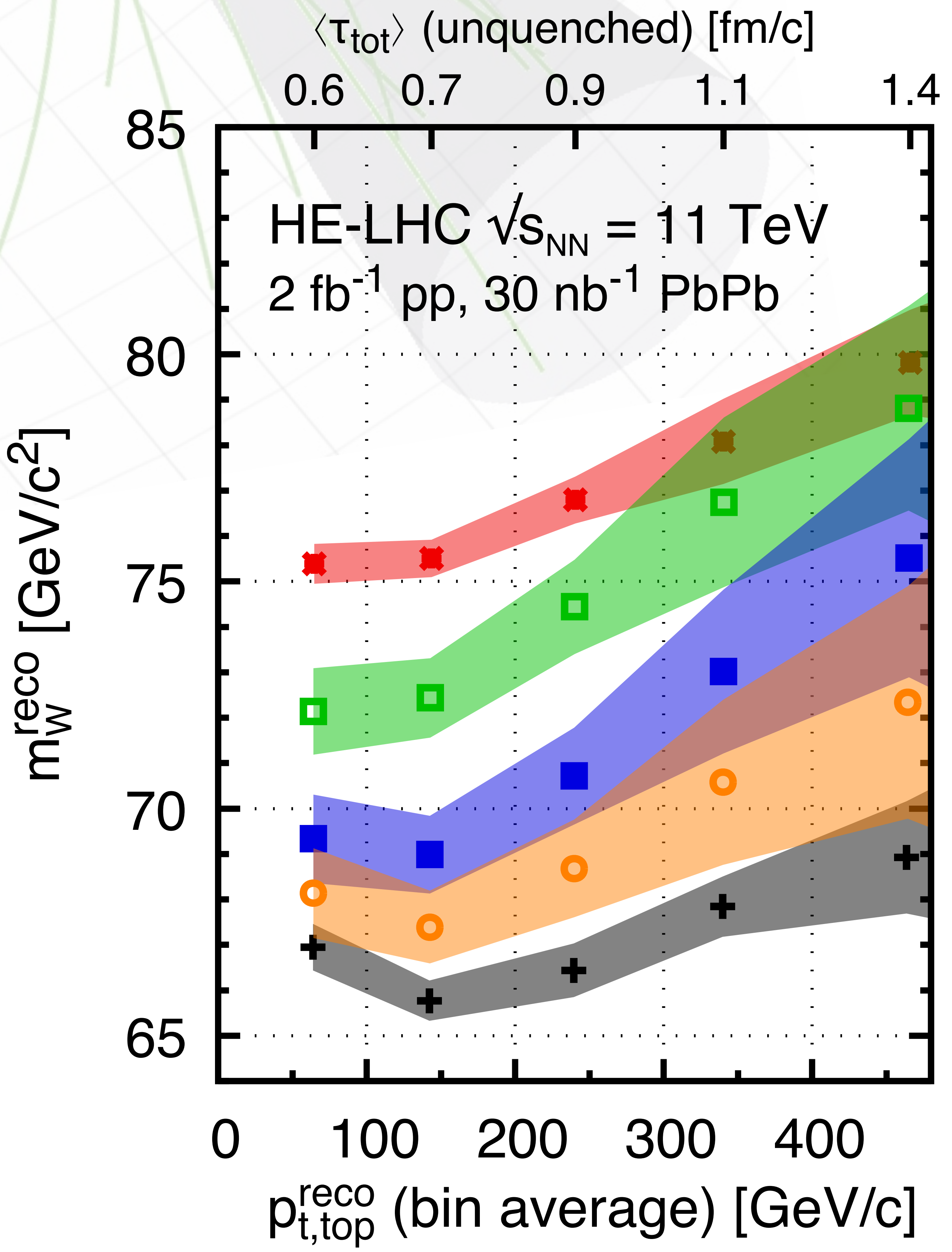

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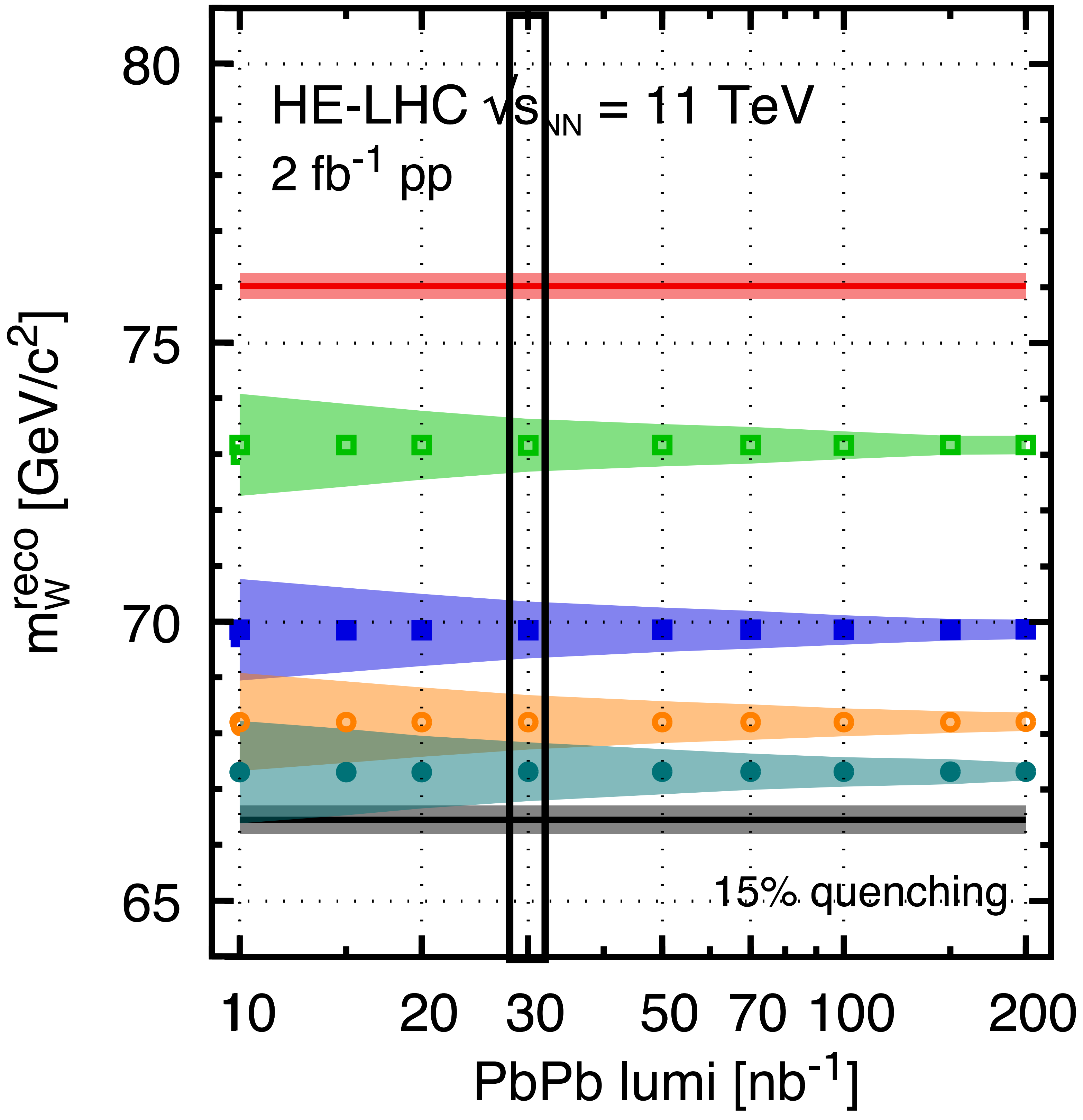

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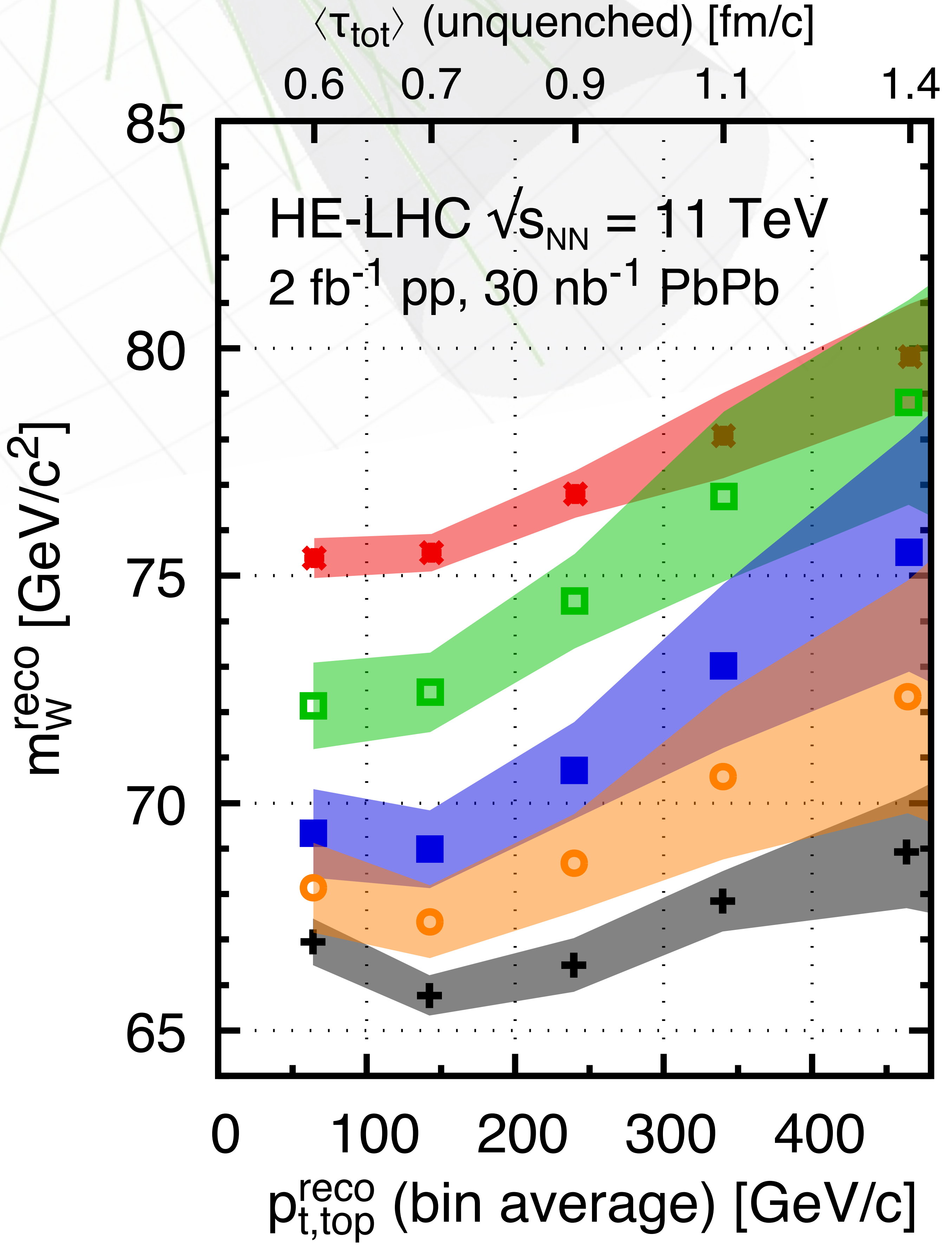

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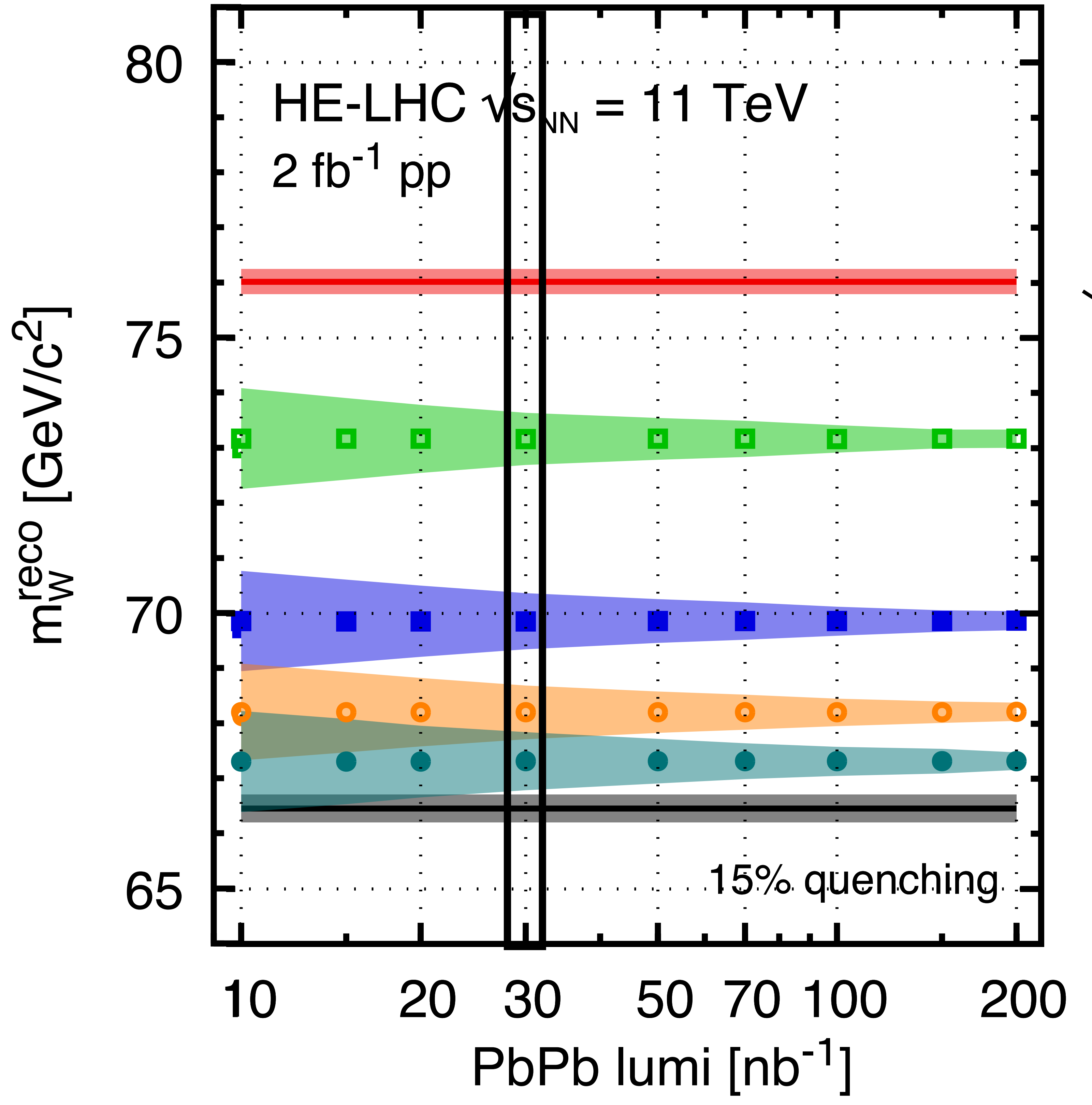

fixed at 2 fb-1

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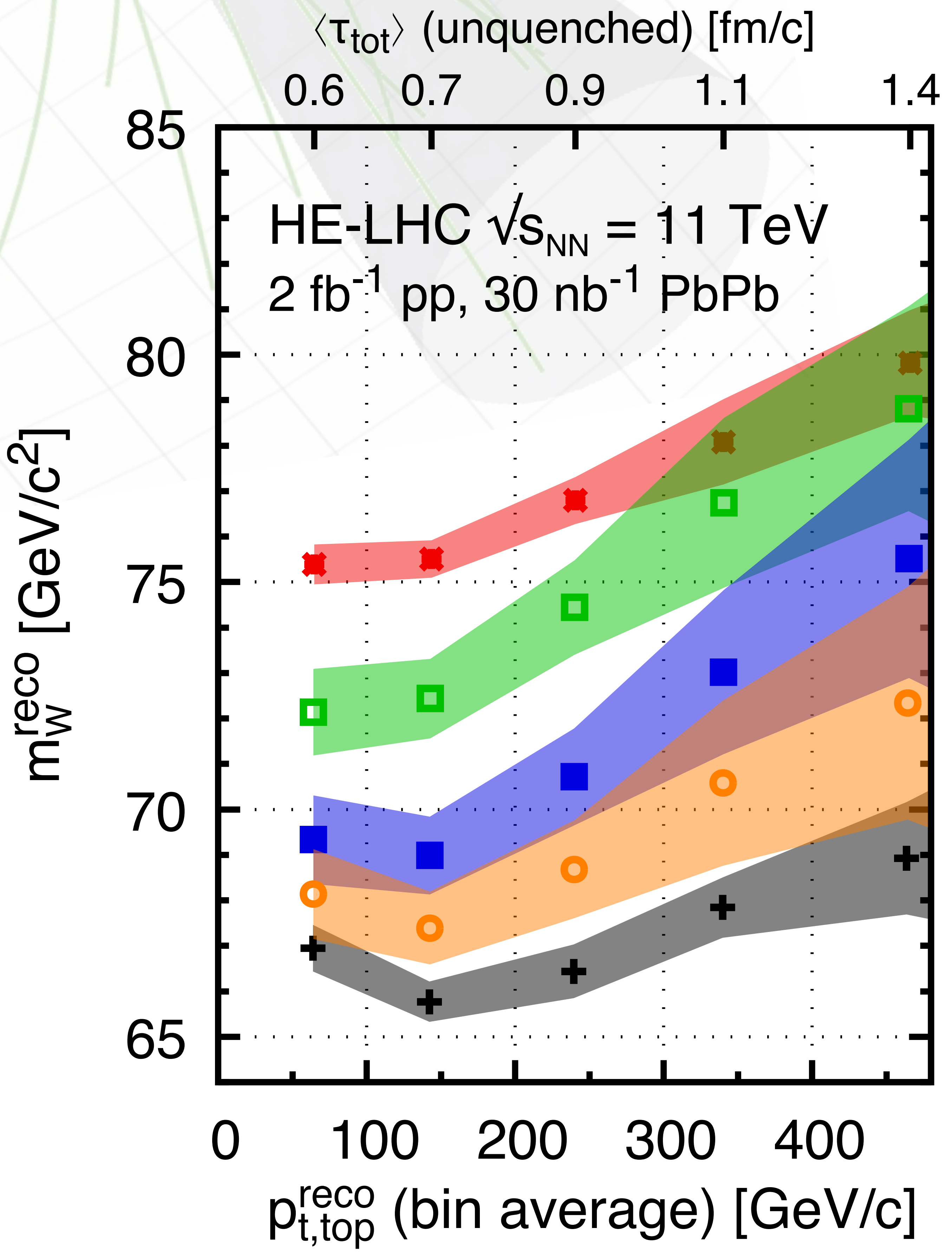

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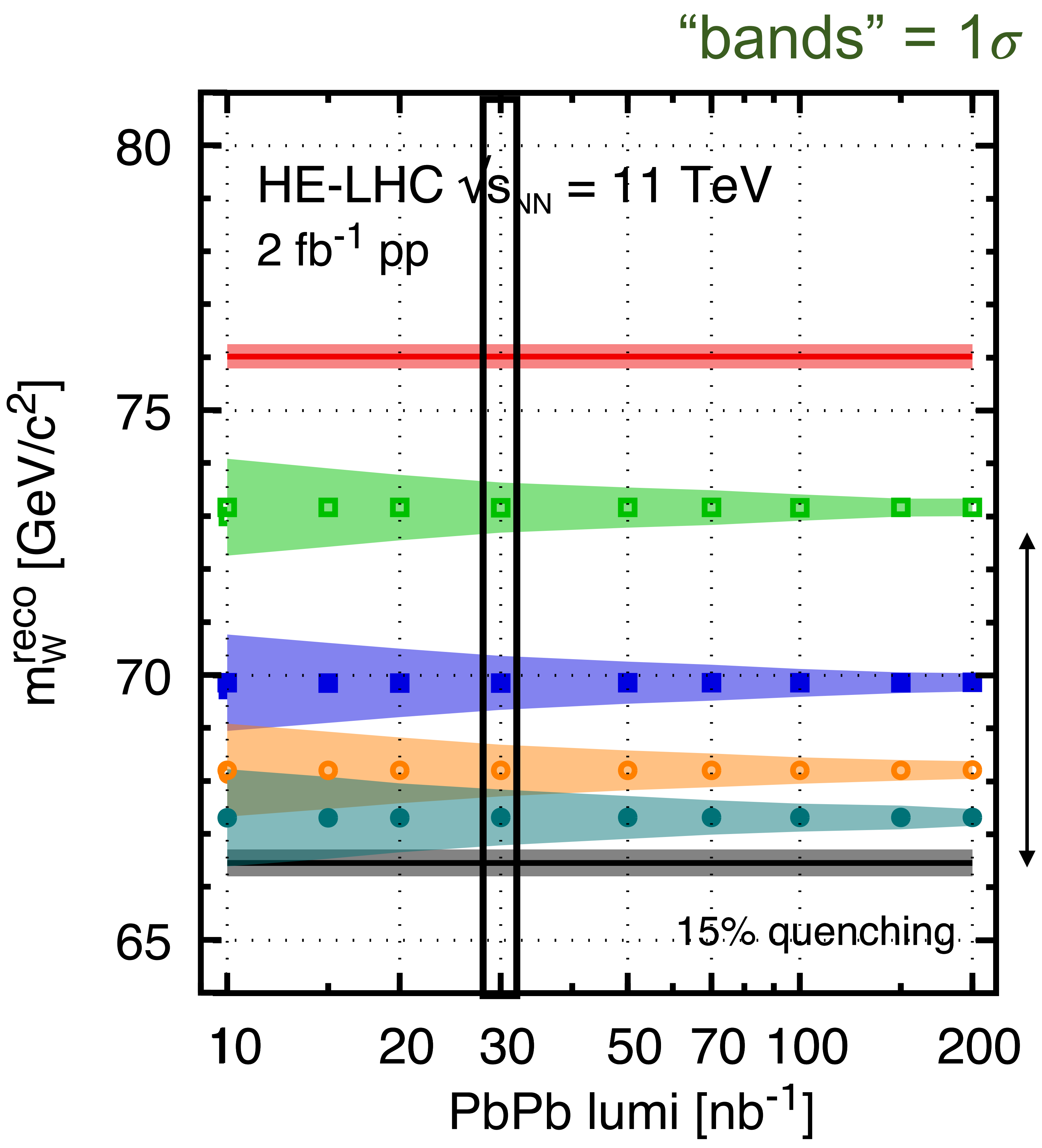


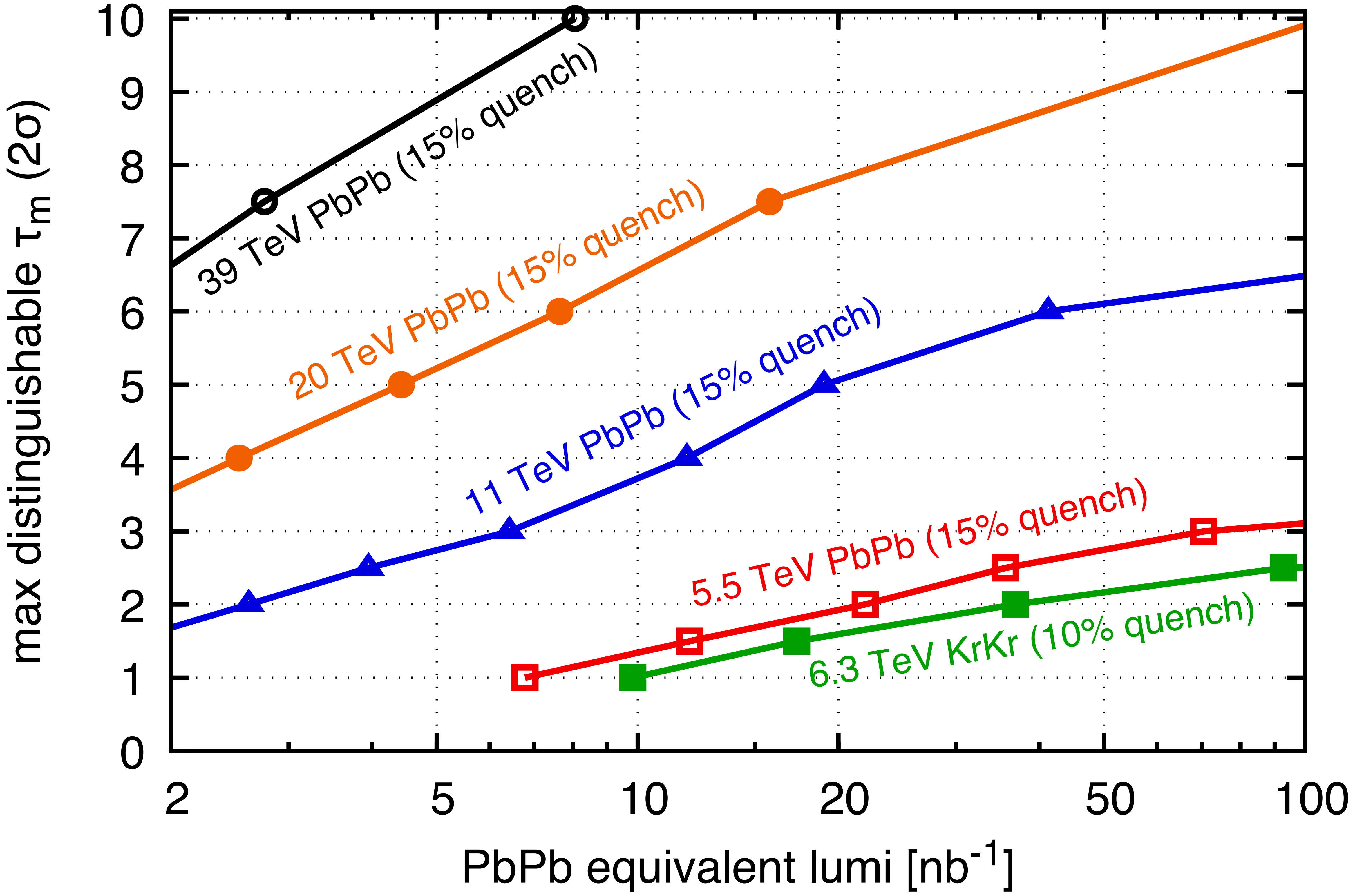
Max τ_m distinguishable at 2σ (from baseline fully quenched?

Short vs Long lived medium

- Maximum brick time, τ_m, that can be distinguished (from full quenching) with 2σ, as a function of $\mathscr{L}_{equiv}^{PbPb}$:

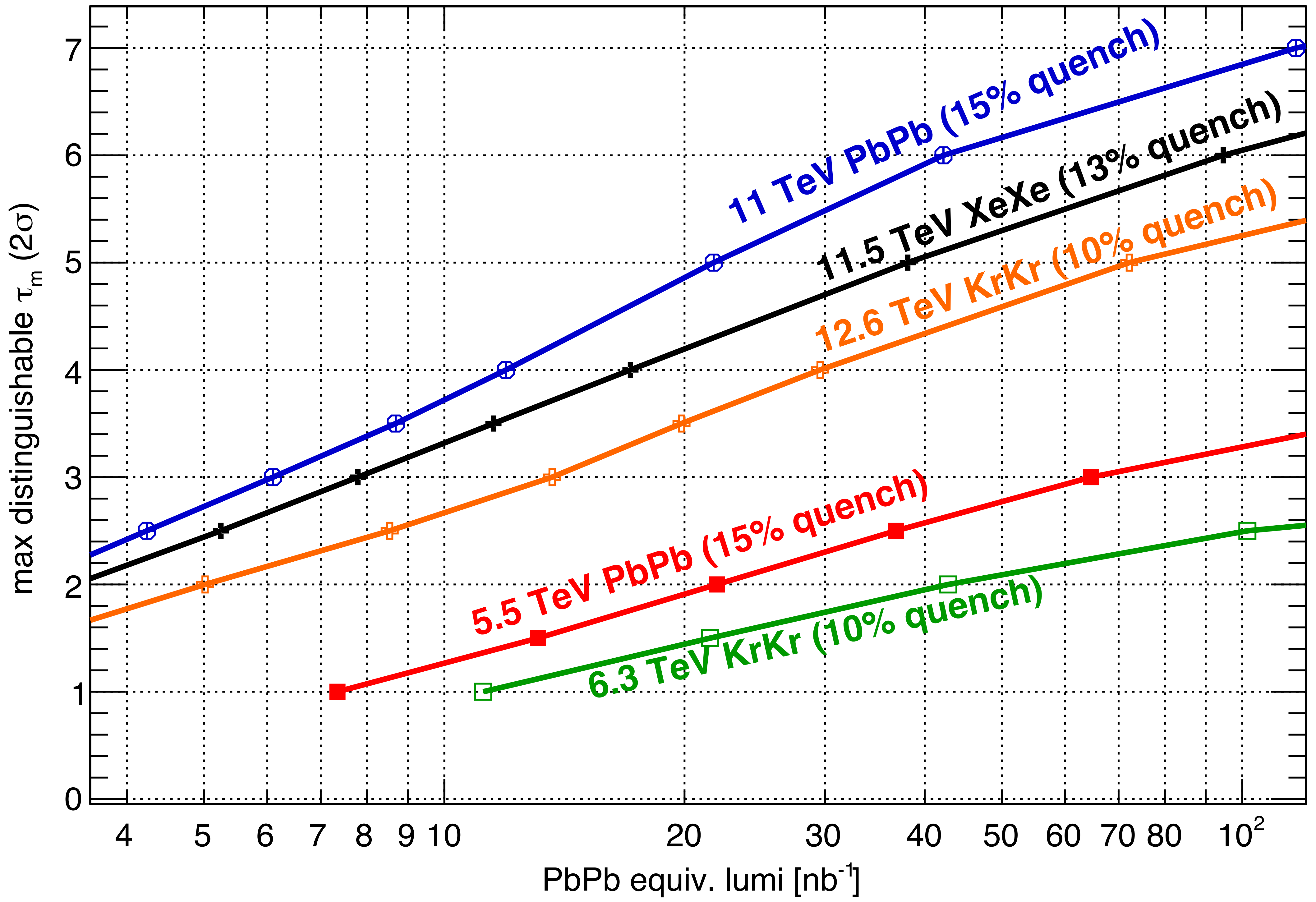
  - Distinction between different timescales still possible at the LHC:

    - 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



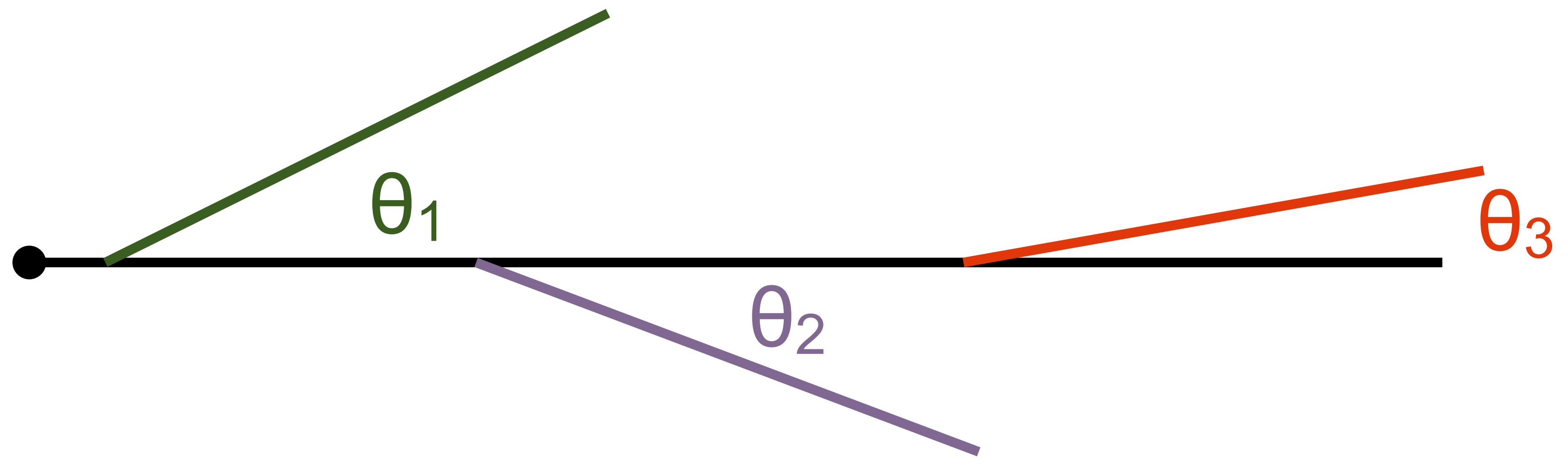
Lighter Ions

- Higher luminosity, but smaller energy loss…
  - Might bring some advantages on the achieved timescales
    - 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



Can other probes do QGP tomography?

- Jets can provide a range of scales to probe the QGP!
  - In pp: jets develop in momentum/virtuality/… scale



$\theta_1 >> \theta_2 >> \theta_3$ … : angular-ordering

$\left(\tau_{form} = \frac{1}{z(1-z)E\theta^2} \right)$ $\tau_1 \lesssim \tau_2 \lesssim \tau_3$ …

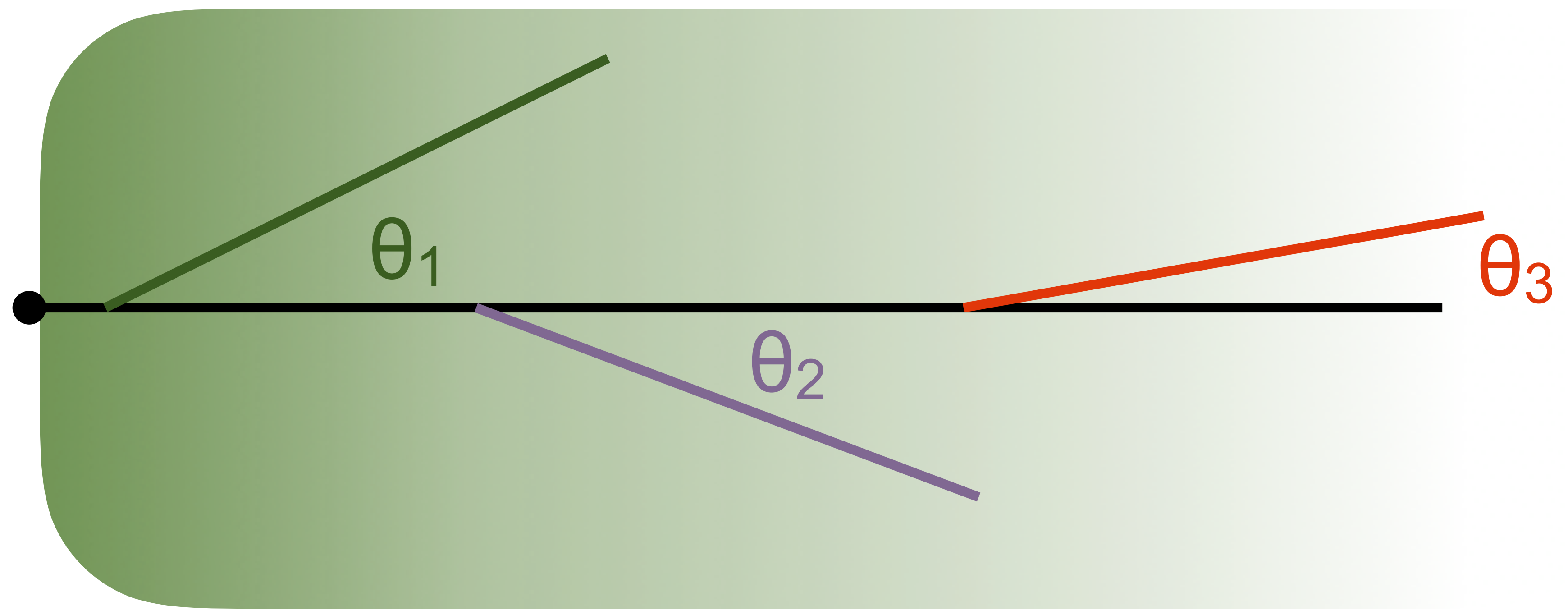
Experimentally accessible through unclustering with C/A (p = 0)

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{t,i}^{2p}$$

If θ_1 takes place place at τ_1 or not does not affect the final result

Can other probes do QGP tomography?

- Jets can provide a range of scales to probe the QGP!
  - In pp: jets develop in momentum/virtuality/… scale
  - In PbPb: jets propagate through a spatially extended medium. Jets will have a space-time picture!



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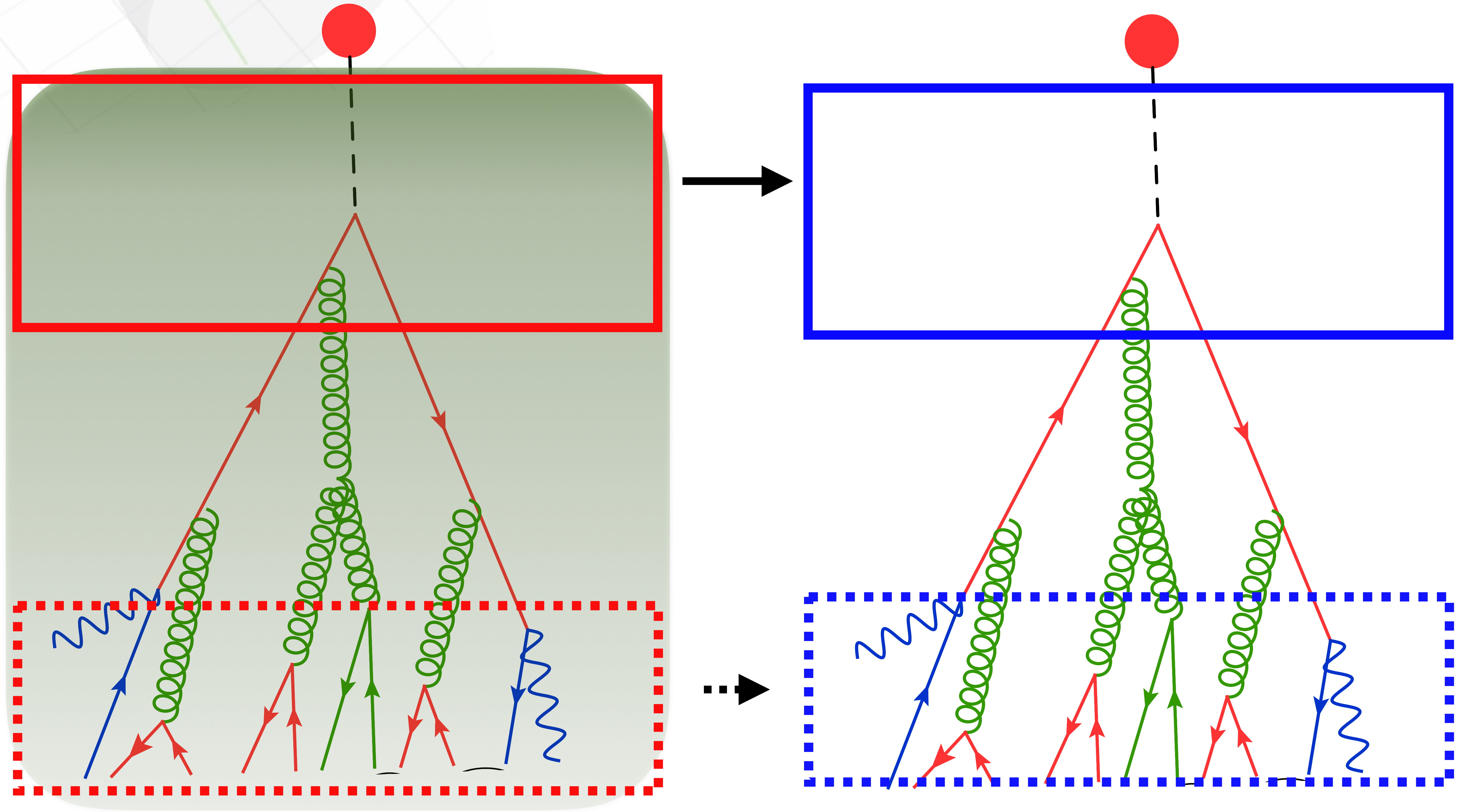
If θ_1 takes place place at $\boldsymbol{\tau_1}$ will induce a different fragmentation pattern

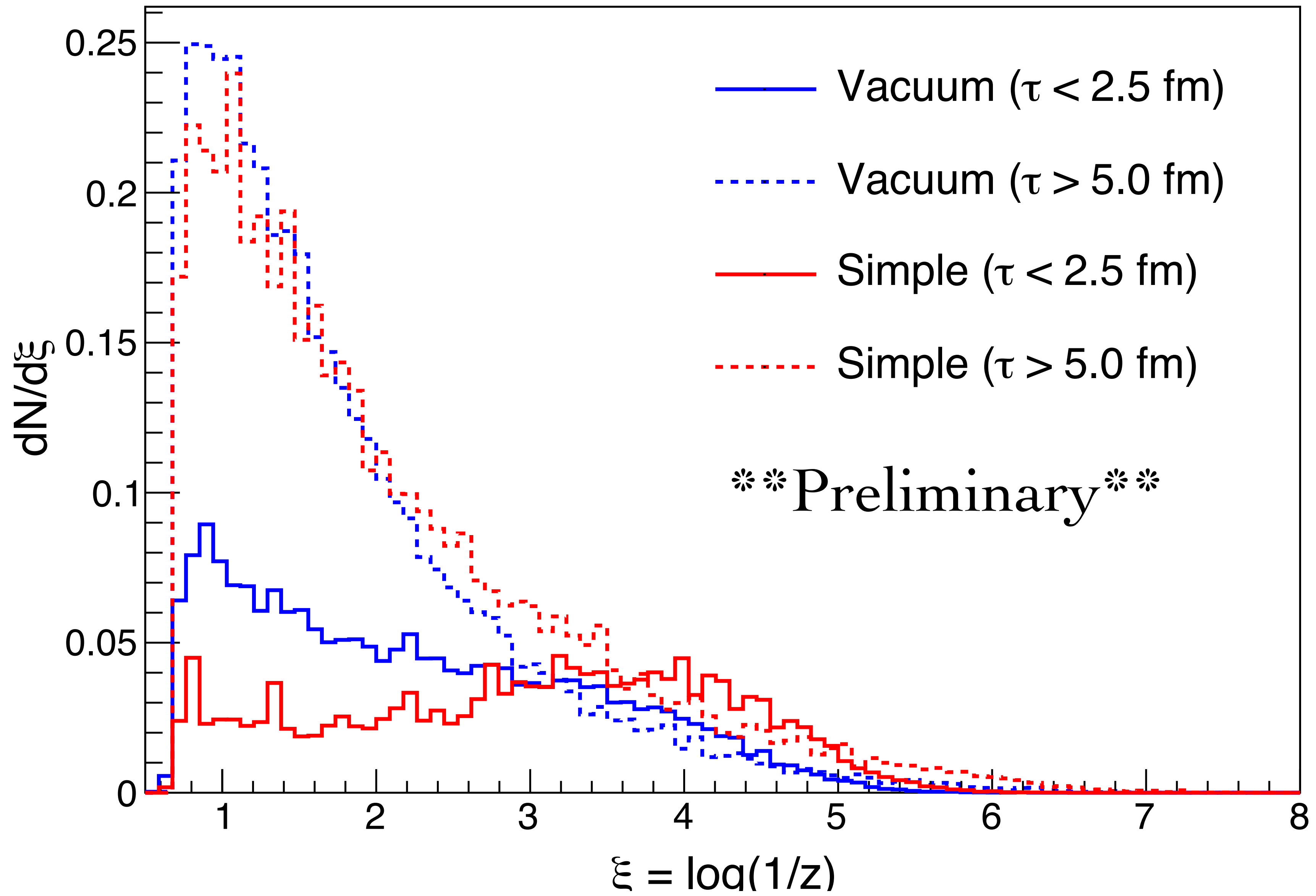
p = 0.5: $d_{ij} \sim p_{T,i}\frac{\Delta R_{ij}^2}{R^2} \sim p_T\theta^2 \sim \frac{1}{\tau_{form}}$

Time structure with jets

- Unclustering jet and selecting different τ_{form}:
  - Is the energy fraction changed with respect to a vacuum parton shower?



JEWEL 5.02 TeV w/o recoils

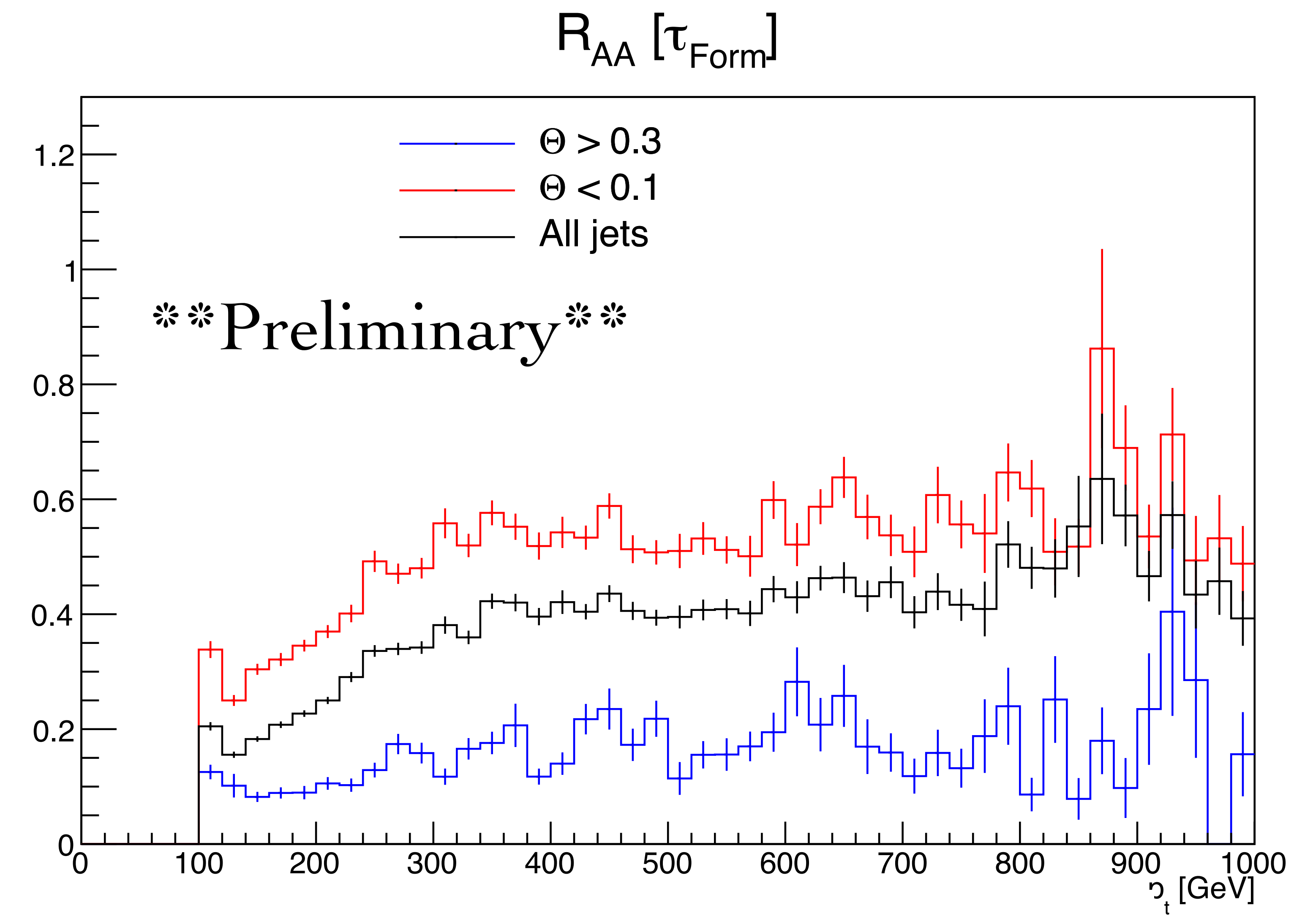


LA, et al (in preparation)

Time structure with jets

- Unclustering jet and selecting different τ_{form}:
  - Can we select jets that do not experienced energy loss?

Collinear jets lose less energy (coherent emissions)



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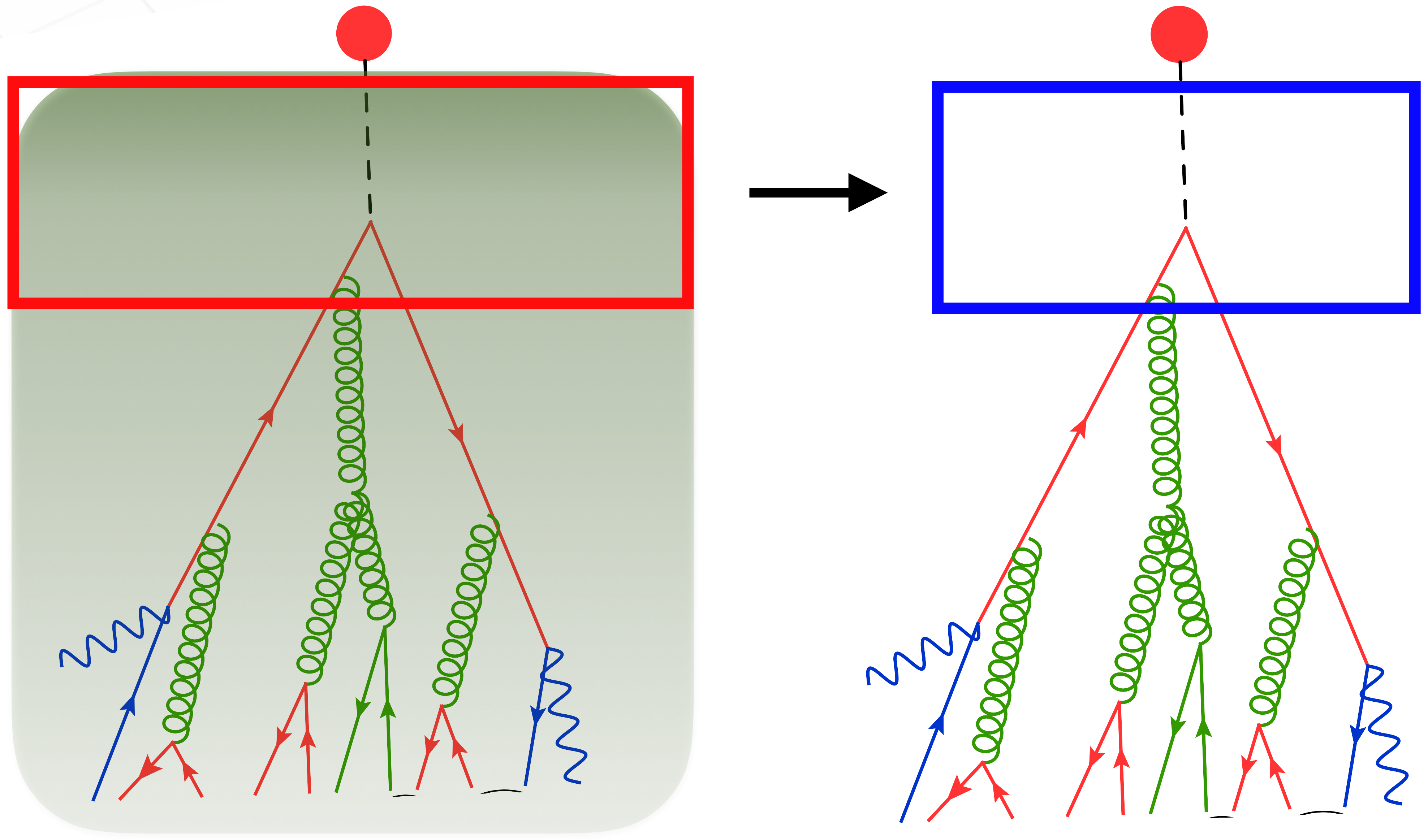

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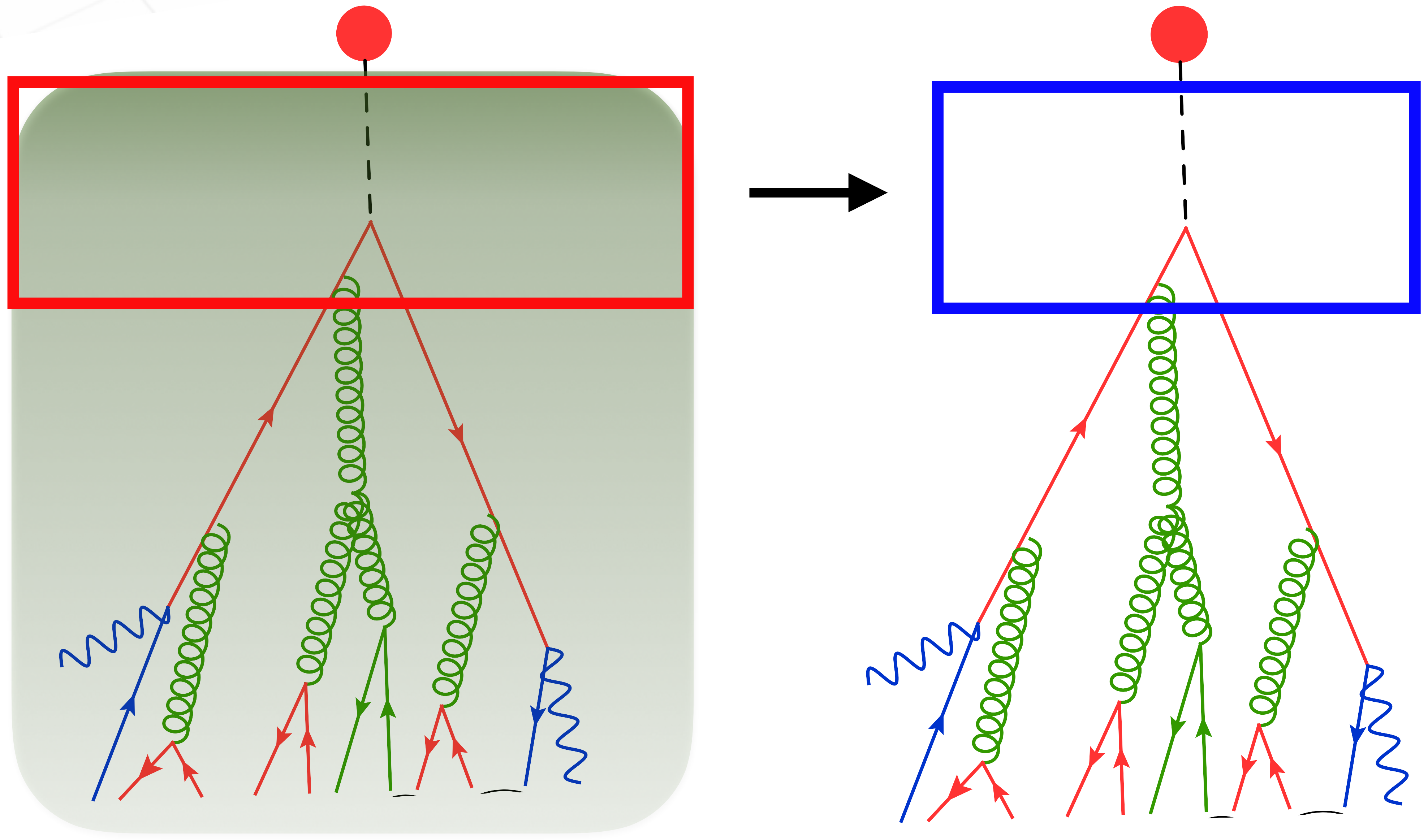
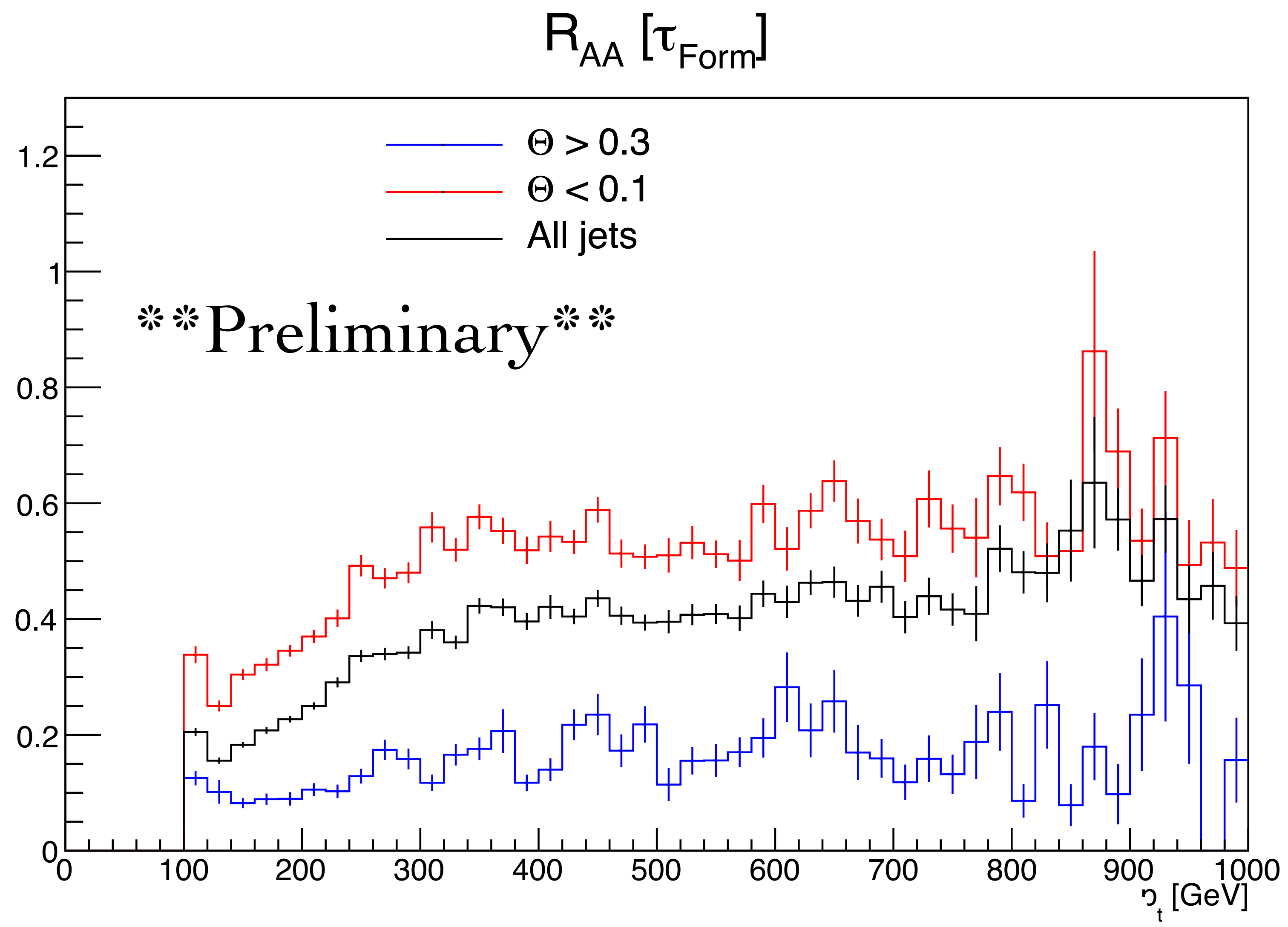


Jets with a first splitting with τ_{form} ~ L, will be more like vacuum-like jets



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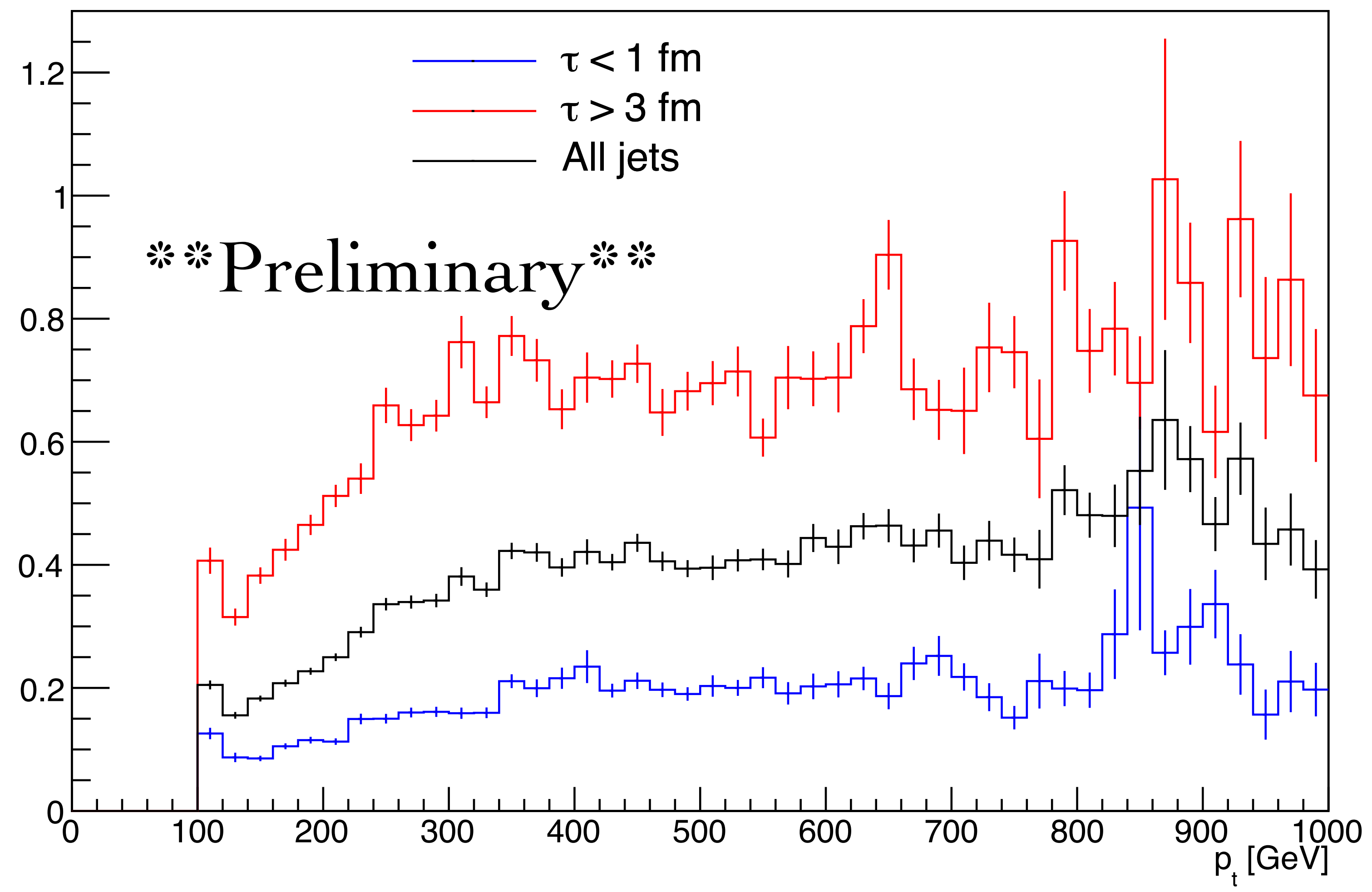

Summary

- 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…

  - Promising results: **I. Kucher's talk!!**

    - HL/HE-LHC: still able to distinguish broad range of medium-duration scenarios/quenching dominated regions from the inclusive top sample;

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Thank you!

Acknowledgements

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

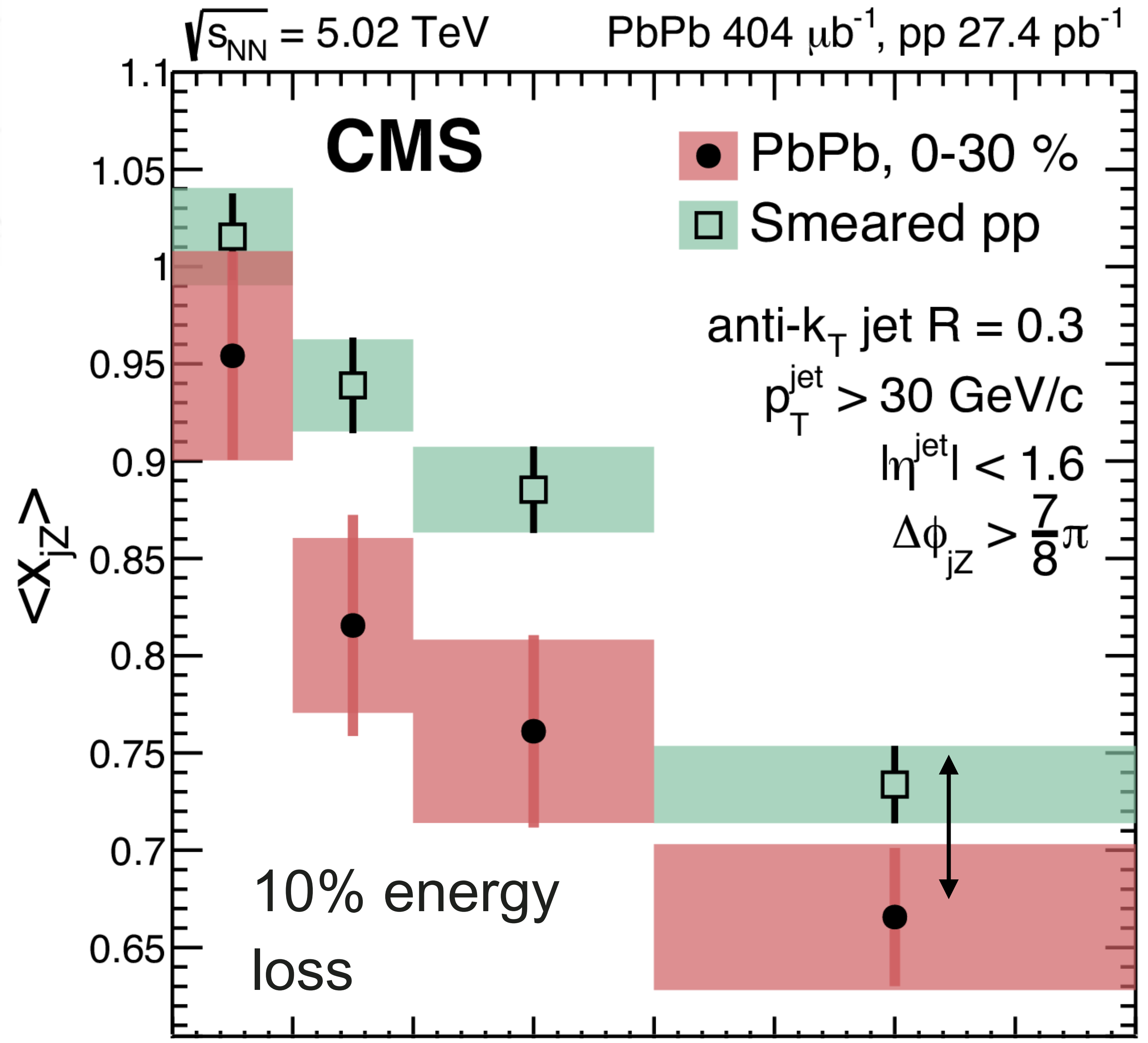
LIP

TÉCNICO LISBOA

Backup Slides

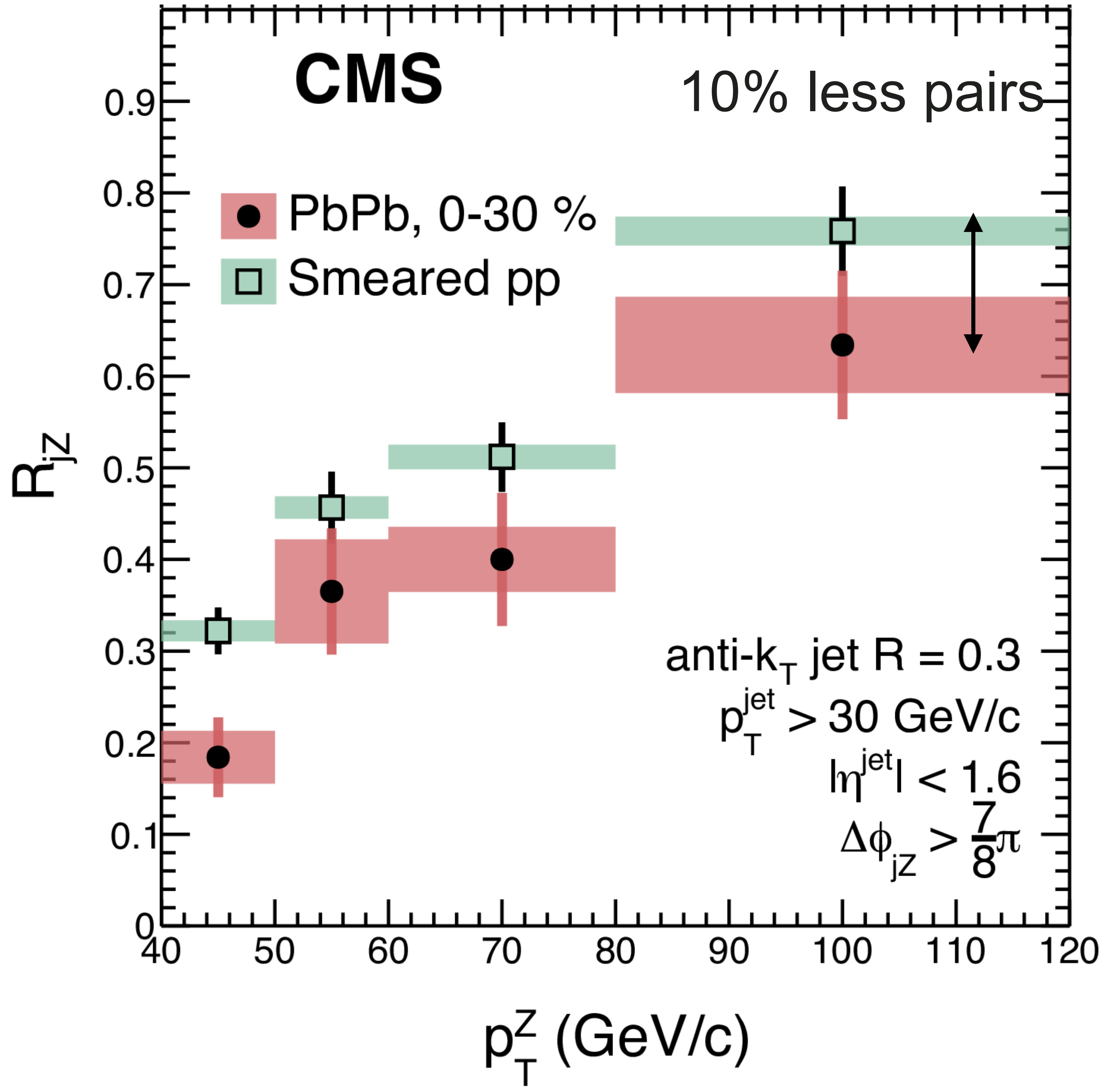
Jet Energy Loss

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



(Average momentum imbalance Z + Jet)

(Average number of Z + Jet pairs)



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

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

Lighter Ions

J. Jowet, Initial Stages 2016

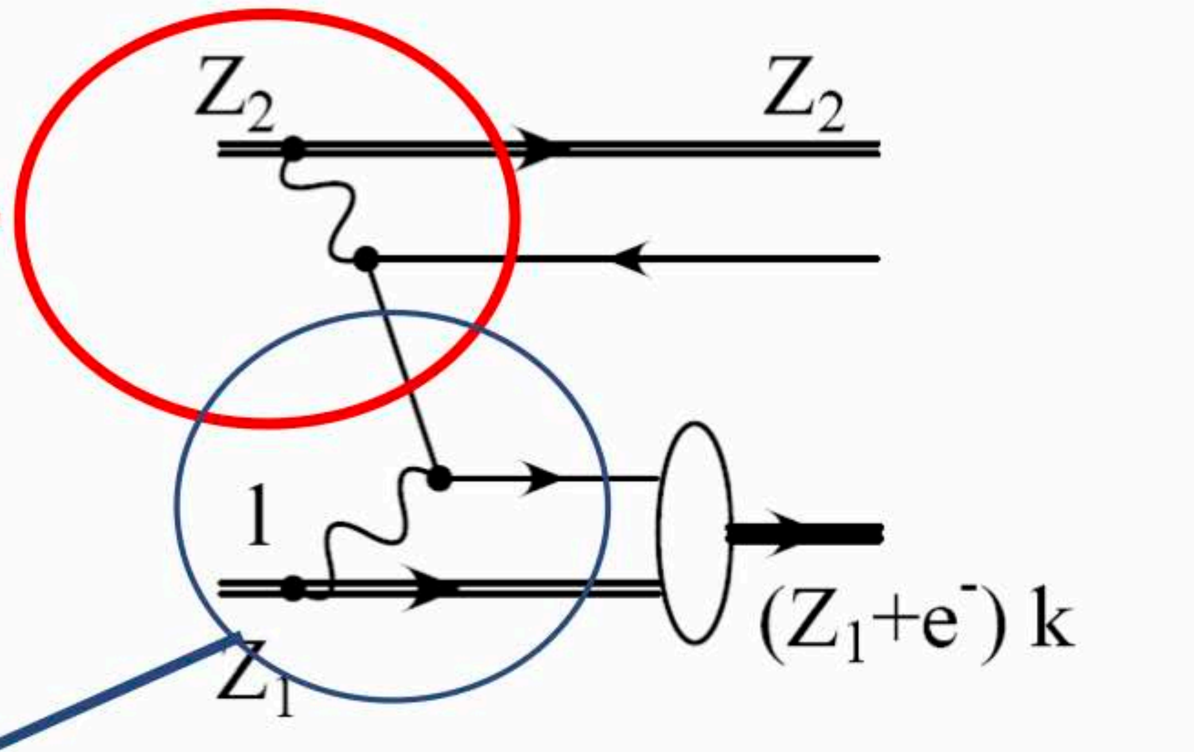
- How about lighter nuclei?
  - Lighter nuclei can go higher in luminosity.

Large cross-sections for electromagnetic processes in ultra-peripheral collisions:

Bound-free e-e+ pair production creates secondary beams of Pb81+ ions emerging from the collision point;

Easy to avoid the bound by going lighter!
But lose nucleon-nucleon luminosity as A2.

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

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

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

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)

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

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

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

Total cross-section $\sim Z_2^2 Z_1^5$

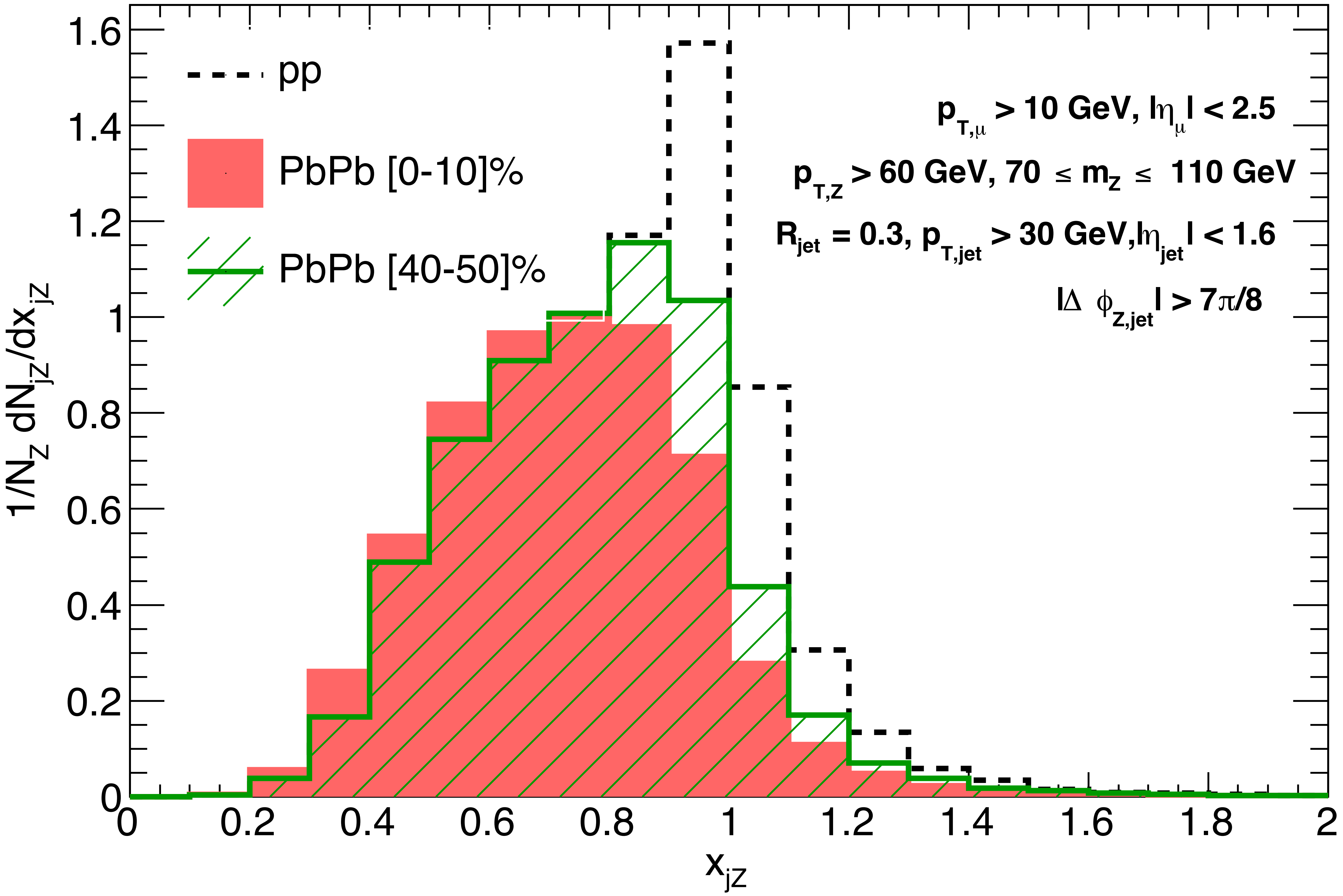
Light Systems

- 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

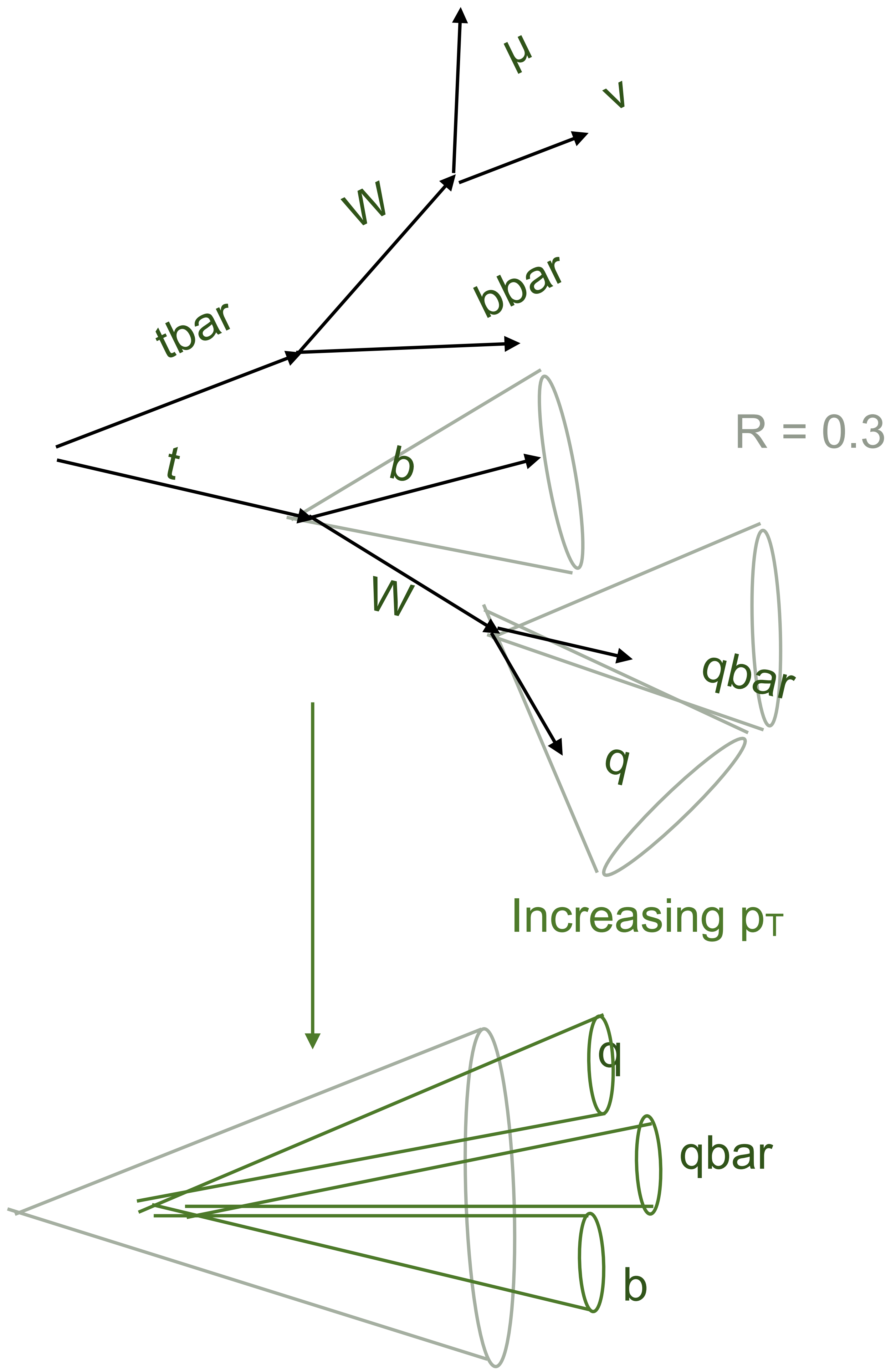
- Monte Carlo Event Generator (POWHEG NLO ttbar production + pythia 8 showering with PDF4LHC15_nlo_30_PDF):
- Rescaling at parton level with Gaussian fluctuations like:
  - $Q\,(1 + r\,\sigma_{pt}\,/p_{t,i} + 1\text{ GeV})^{1/2}$,
    - Q = Quenching factor (Q_0 or $Q(\boldsymbol{\tau}_{tot})$)
    - 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 = $(20\text{GeV})^2$)
  - 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)



Reconstruction procedures

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- “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

Reconstructed W Mass

- At Future Circular Collider (FCC) energies ($\sqrt{s_{NN}}$ = 39 TeV):
  - $\sigma_{ttbar \to qqbar+\mu\nu}$ ~ 1 nb
- At Large Hadron Collider (LHC) energies ($\sqrt{s_{NN}}$ = 5.5 TeV):
  - $\sigma_{ttbar \to qqbar+\mu\nu}$ ~ 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)