Probing the time structure of the QGP

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Jet Quenching Formalism

- Modifications imprinted by a hot and dense medium on fast traversing particle
- In pQCD, the description of such phenomena is based on a high energy approximation:

$$p_\mu = \left(p_+, p_- = \frac{p_\perp^2}{2p_+}, p_\perp\right) \qquad p_+ \gg p_\perp \gg p_-$$

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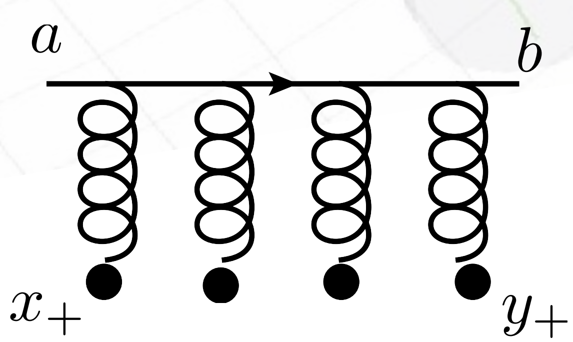

Where the medium is seen as a collection of static scattering centres…

$$A_+ = 0$$

…Not able to exchange momentum: (eikonal approximation)

$$W_{ba}(y_+, x_+, x_\perp) = \mathcal{P} \exp\left\{ig \int_{x_+}^{y_+} d\xi A_-(\xi, x_\perp)\right\}$$

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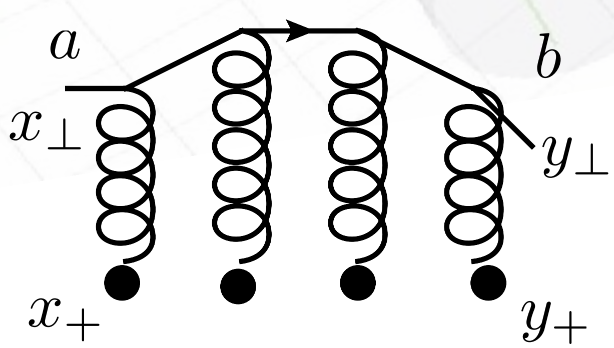

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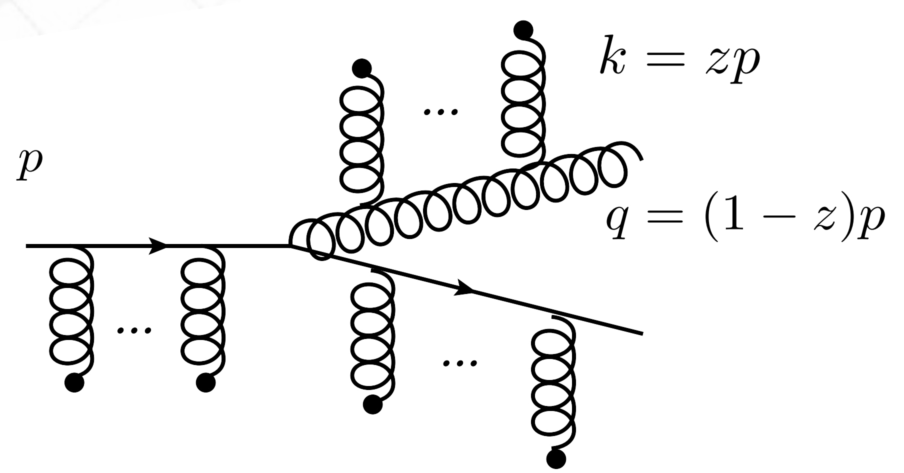
…or able to induce transverse Browninan motion (beyond eikonal approximation):

$$G_{ba}(y_+, y_\perp; x_+, x_\perp) = \int_{r(x_+)=x_\perp}^{r(y_+)=y_\perp} \mathcal{D}r(\xi) \exp \left\{ \frac{ip_+}{2} \int_{x_+}^{y_+} d\xi \left(\frac{dr}{d\xi}\right)^2 \right\}$$

Jet Quenching Effects

- Jet Quenching signatures:
  - Medium-induced energy loss and transverse momentum broadening:
    - Single gluon emission (beyond) eikonal limit



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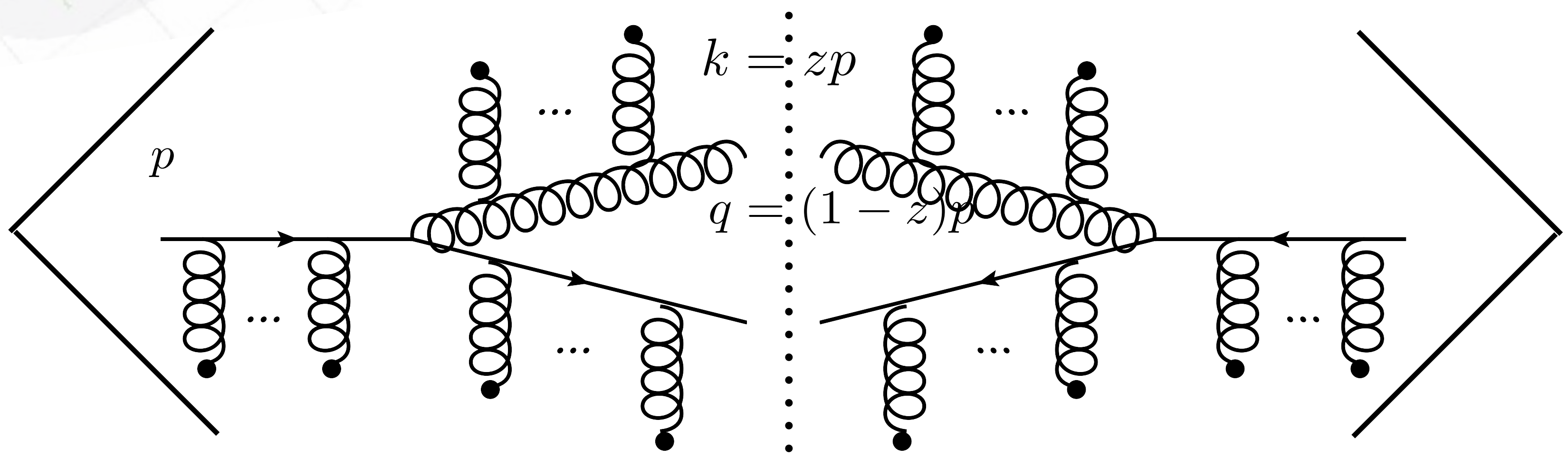
$$k_+ \frac{dI}{dk_\perp dk_+} =$$



Average over medium color configurations:
multiple soft scattering approximation

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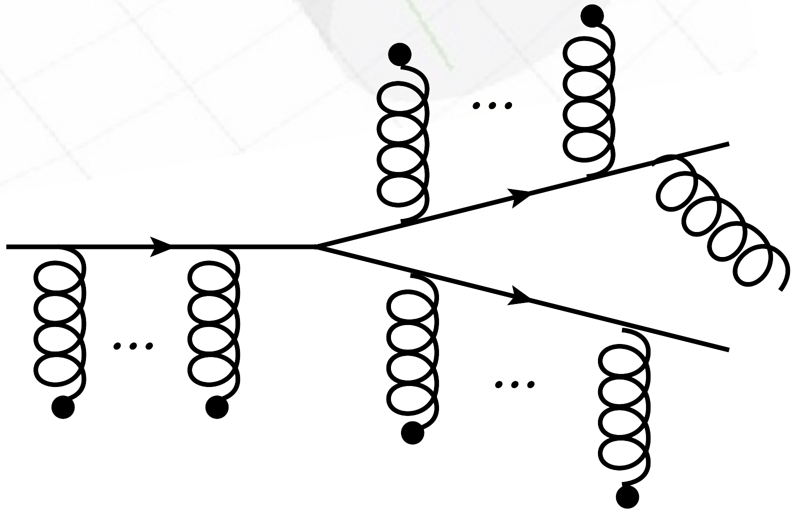

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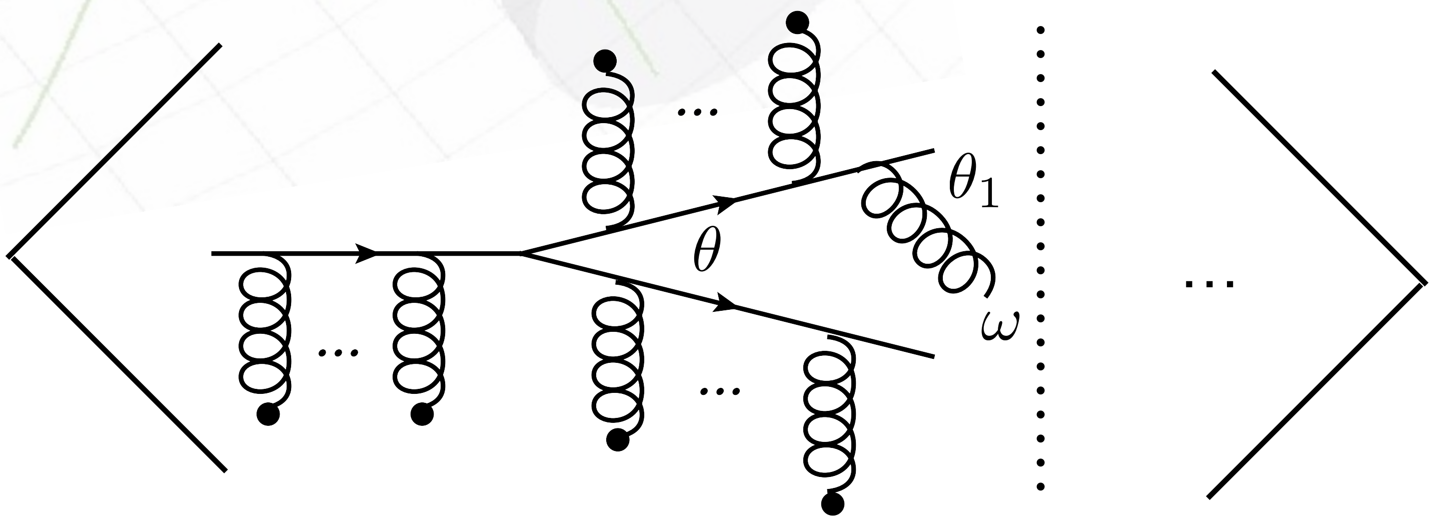

Antenna transverse resolution:
$$Q_s = \sqrt{\hat{q}L}$$

Medium transverse scale:
$$r_\perp = \theta L$$

$$\Delta_{med} \approx 1 - \mathrm{e}^{-\frac{1}{12}Q_s^2 r_\perp^2}$$

After integrating over azimuthal angle:

$$dN_q^{\omega\to 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin\theta d\theta}{1-\cos\theta} \left[\Theta(\cos\theta_1 - \cos\theta) + \Delta_{med}\Theta(\cos\theta - \cos\theta_1)\right]$$

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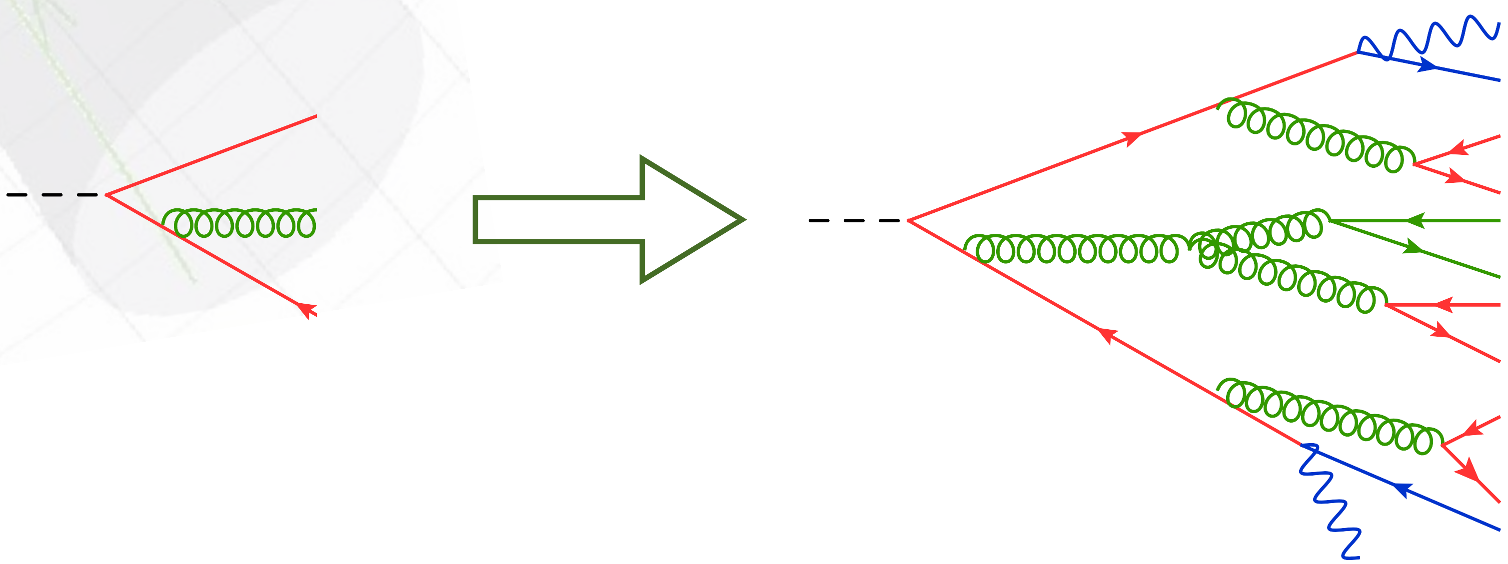
- From single particle measurements (single particle) to jets (full partonic shower) requires better theoretical description:



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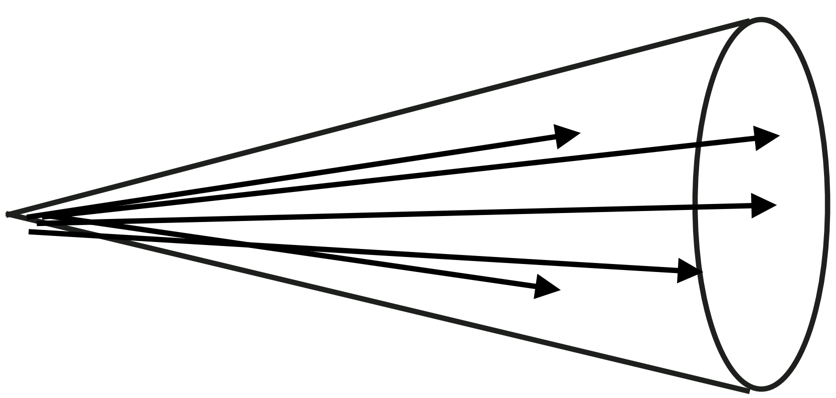
But main signatures in qualitative agreement with experimental observations!



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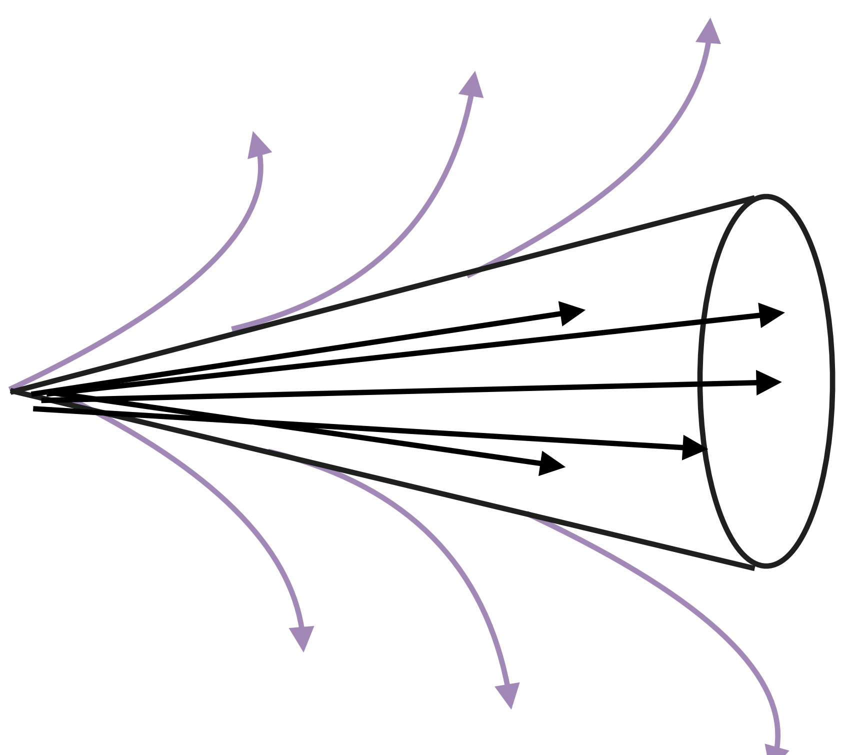

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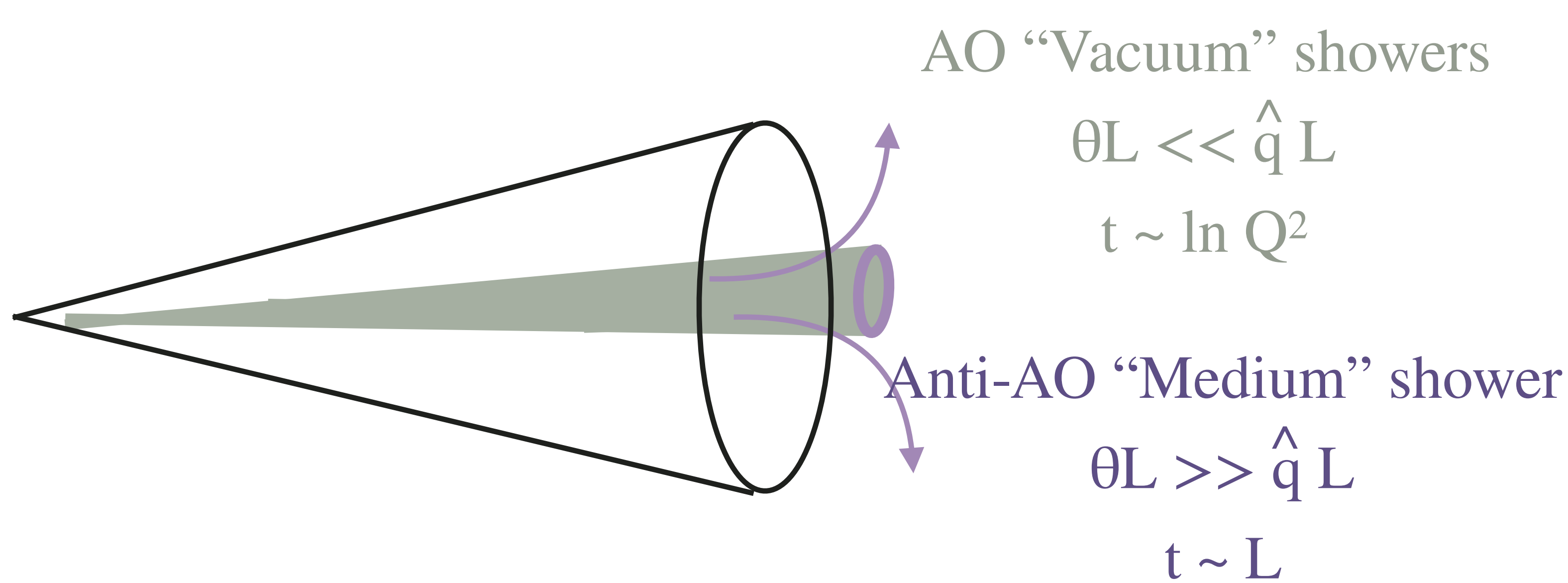
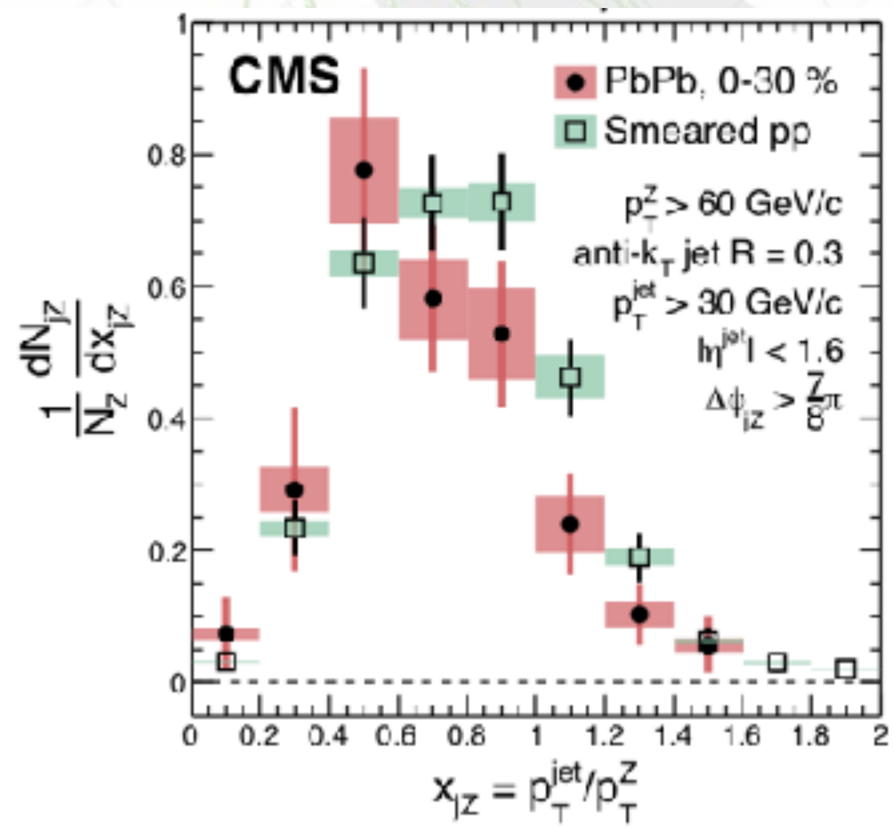


Jet Quenching Observables

Dijet/Boson+Jet Asymmetry



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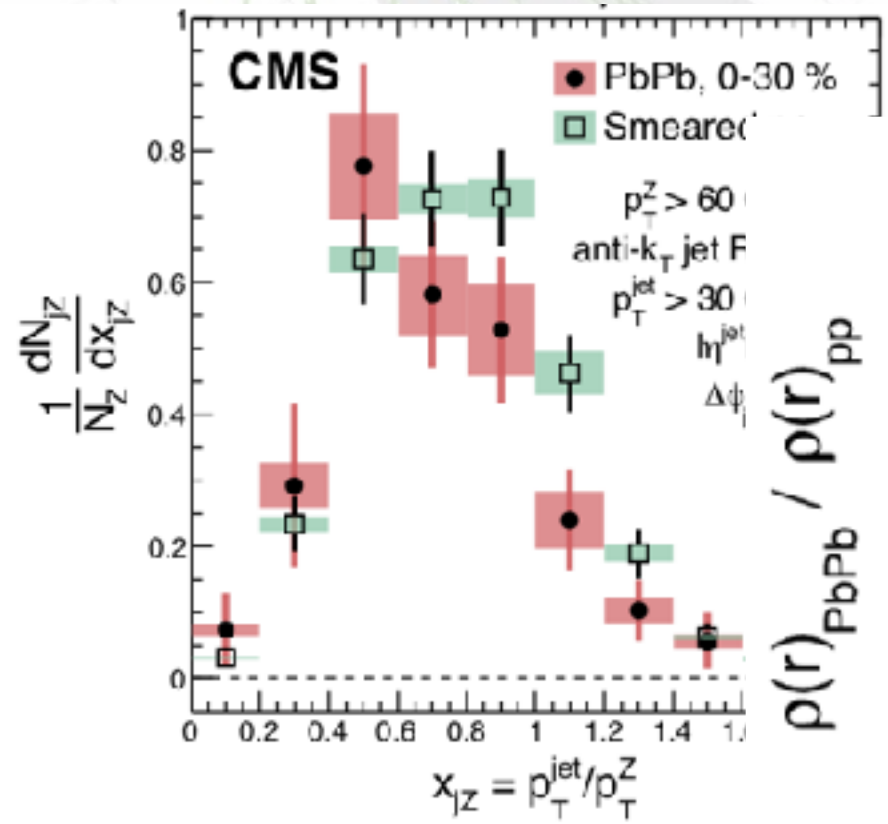
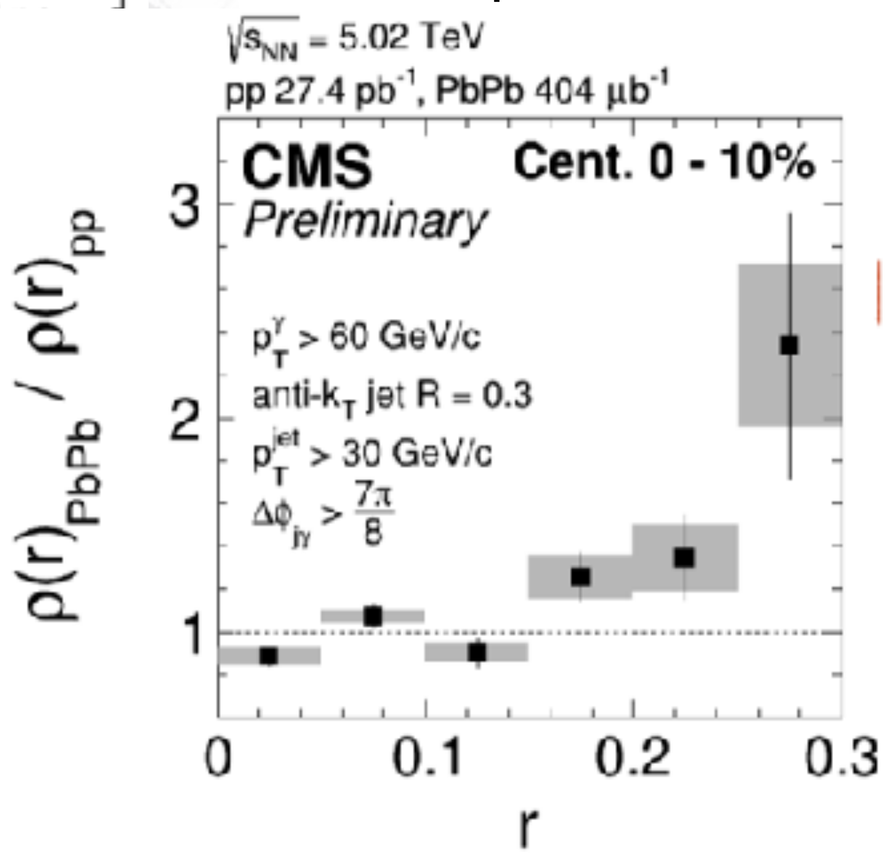
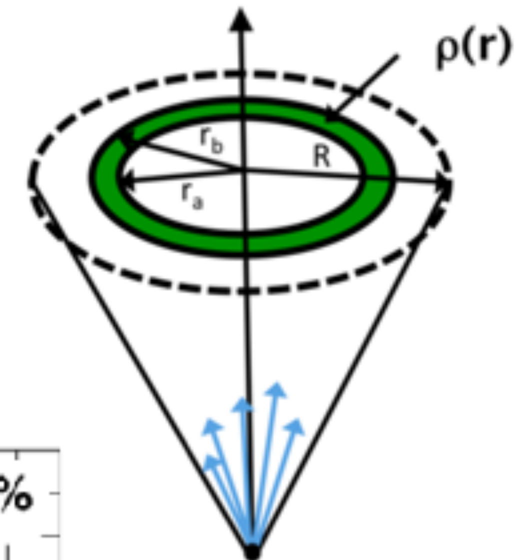


Jet Shapes





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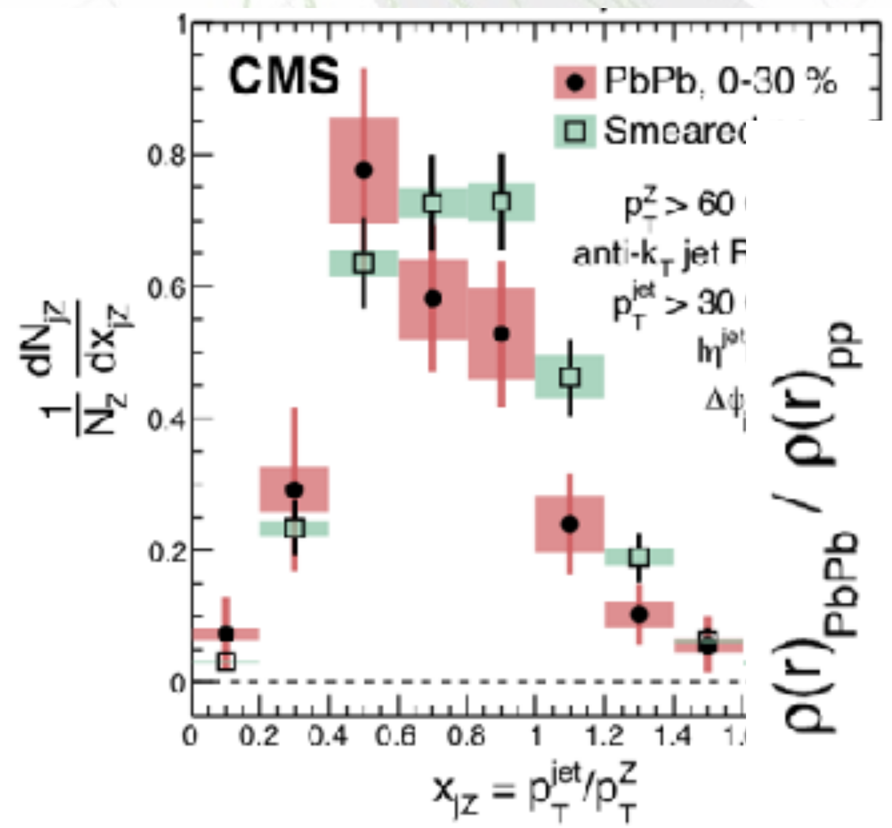

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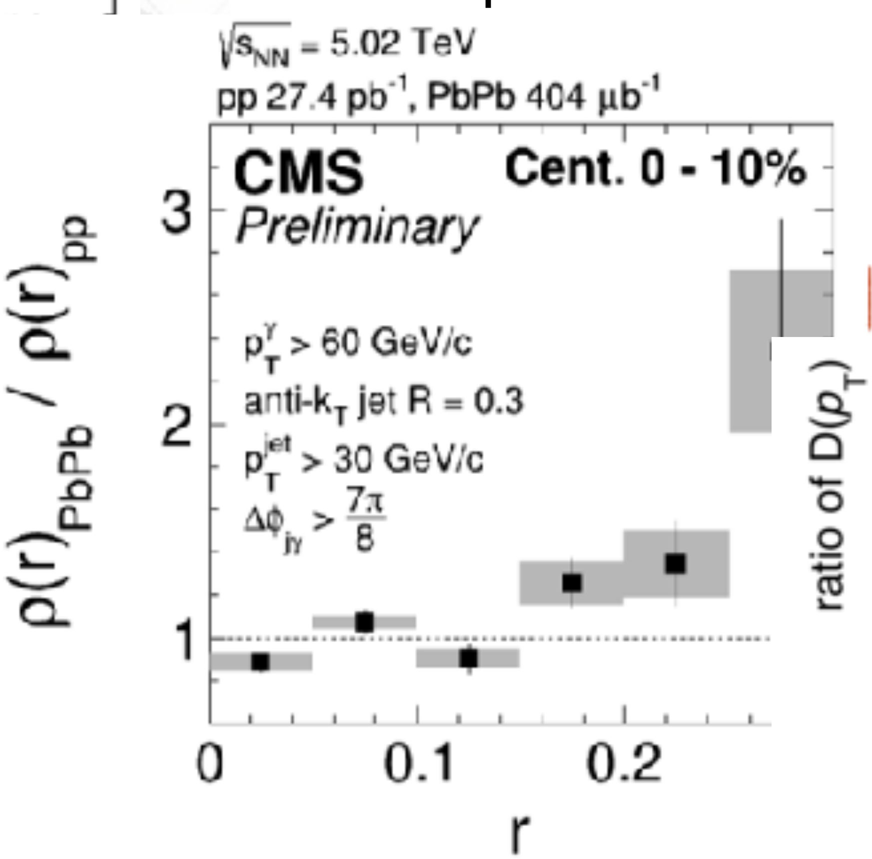
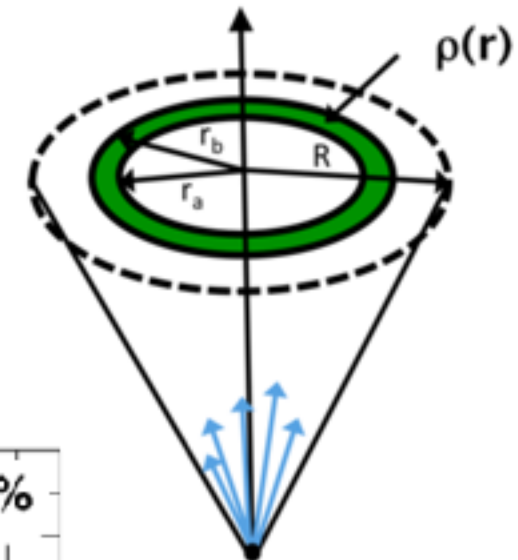
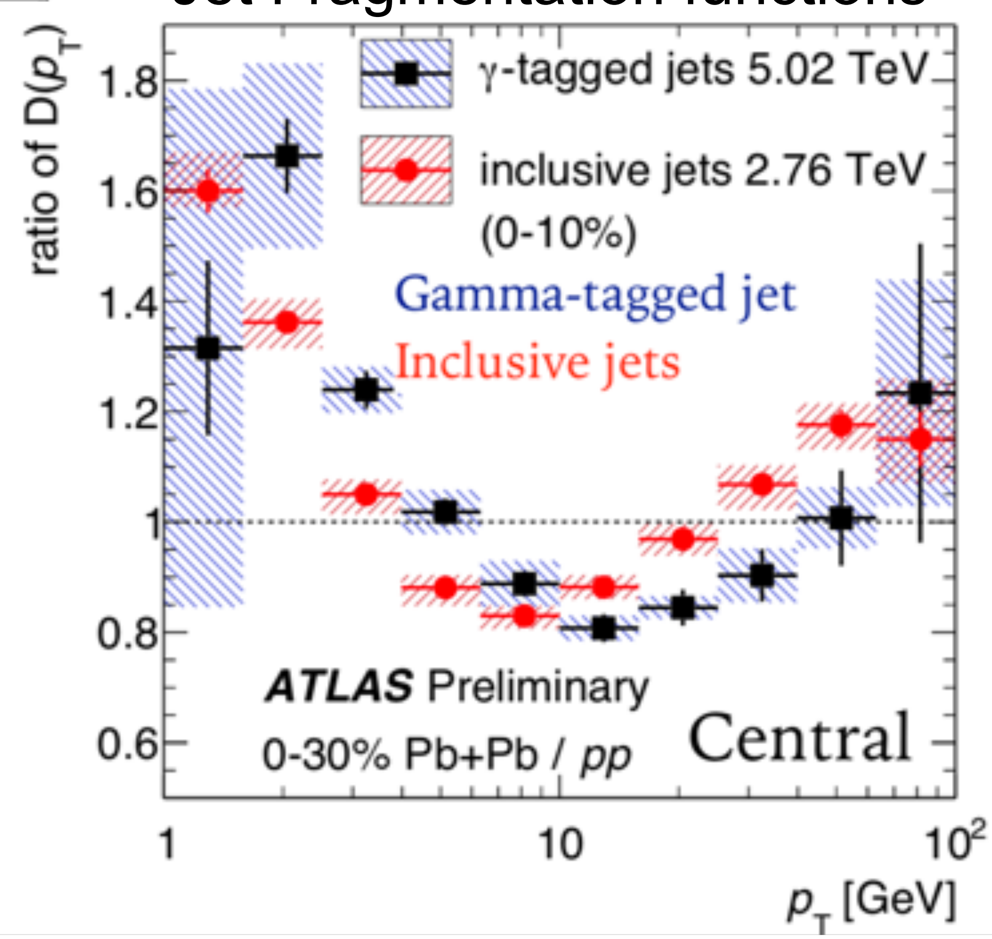




Jet Fragmentation functions



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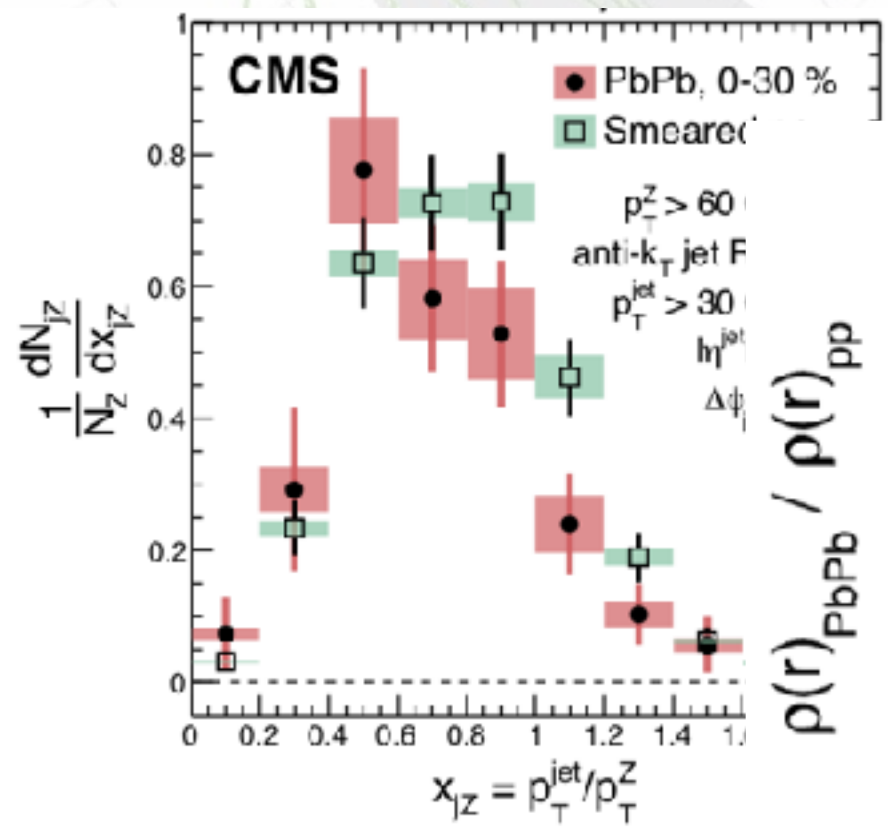

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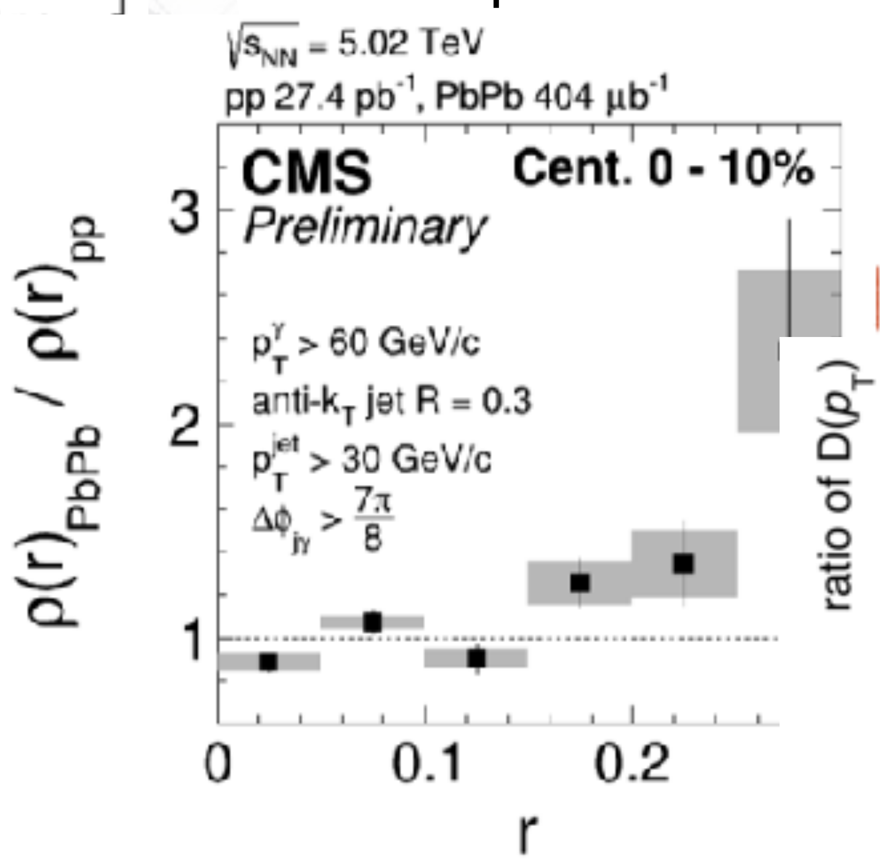

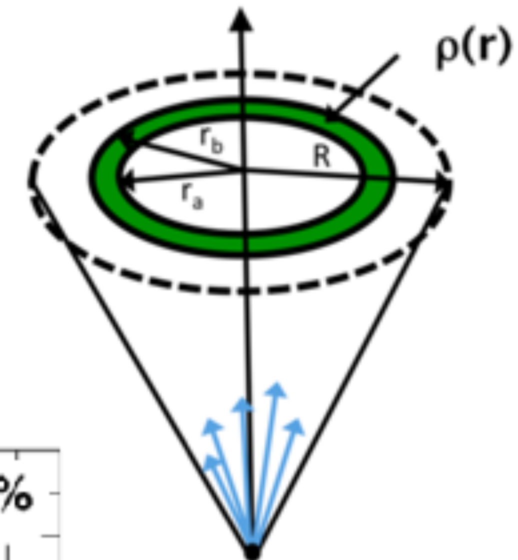

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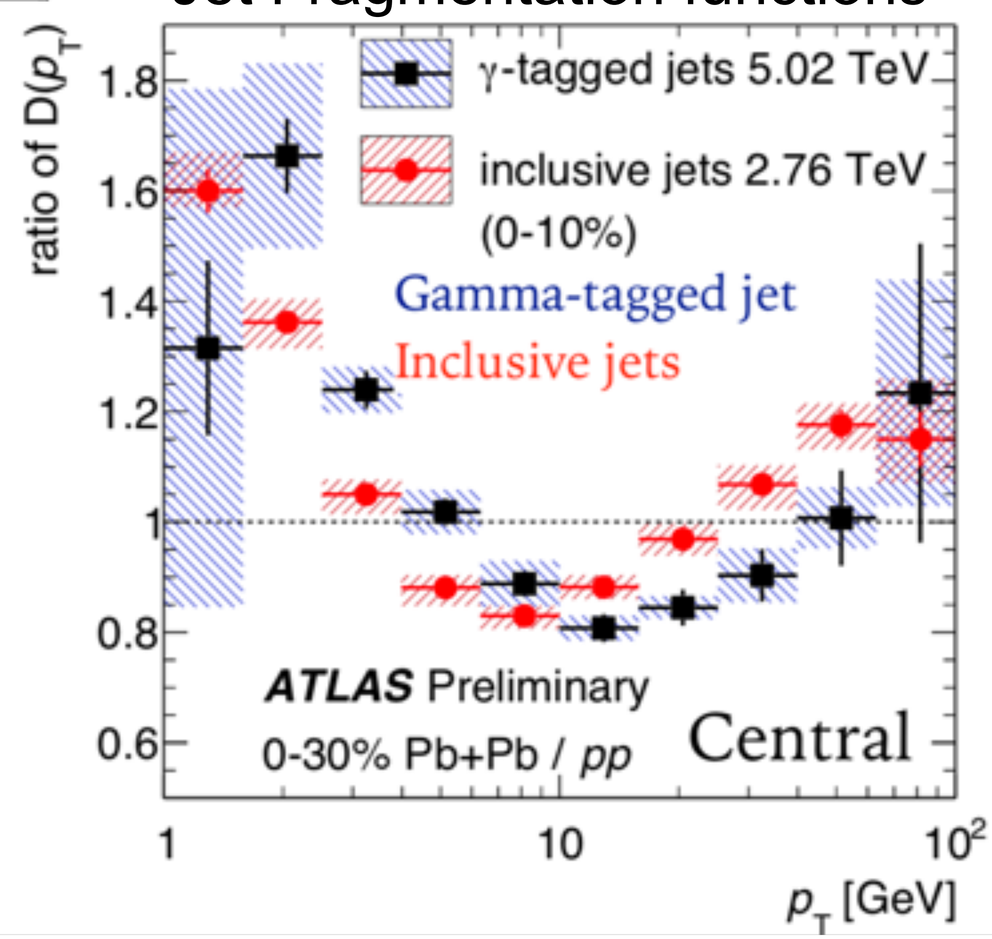

Jet Quenching can be used to assess
QGP properties!

Probing of the QGP

- Probing of the QGP in heavy-ion collisions through a range of complementary probes:
  - Jets, Quarkonia, Hydrodynamical Flow coefficients, Hadrochemistry,…
    - All of them are the integrated result over the whole medium evolution

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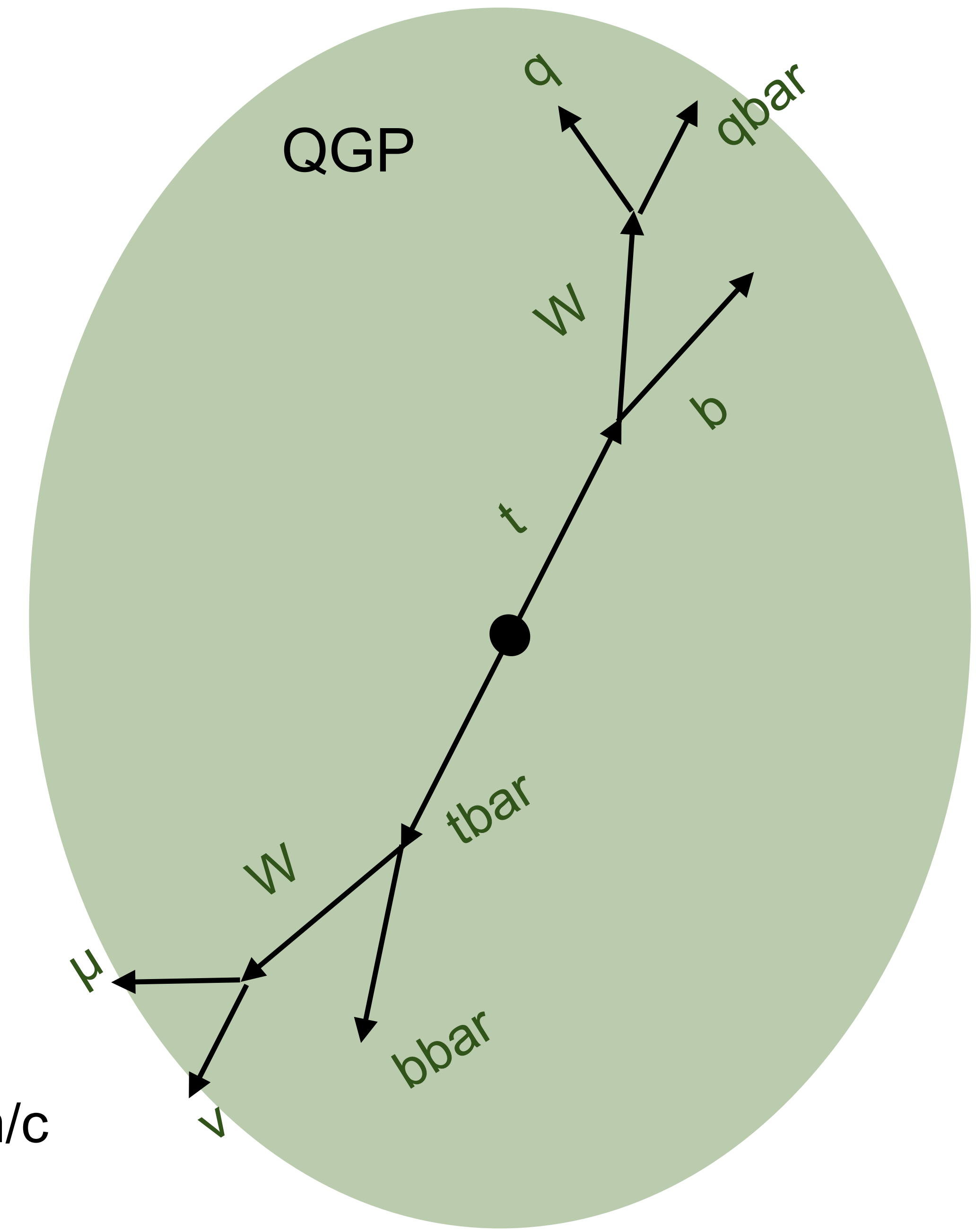
Need to devise a strategy to probe the time-structure of the QGP!

Jet Quenching

- Jet Quenching probes so far: Dijets, Z+jet, γ+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…

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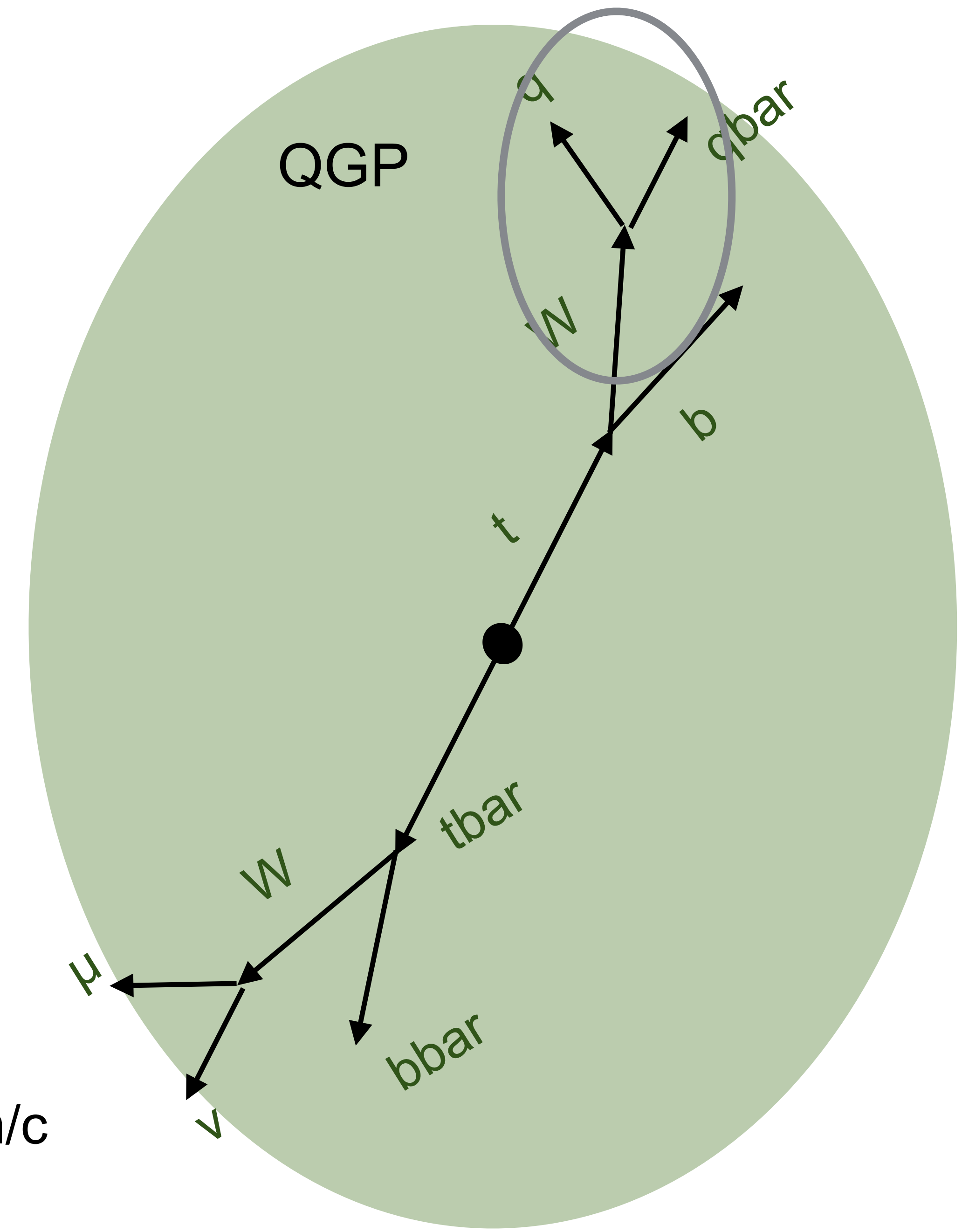
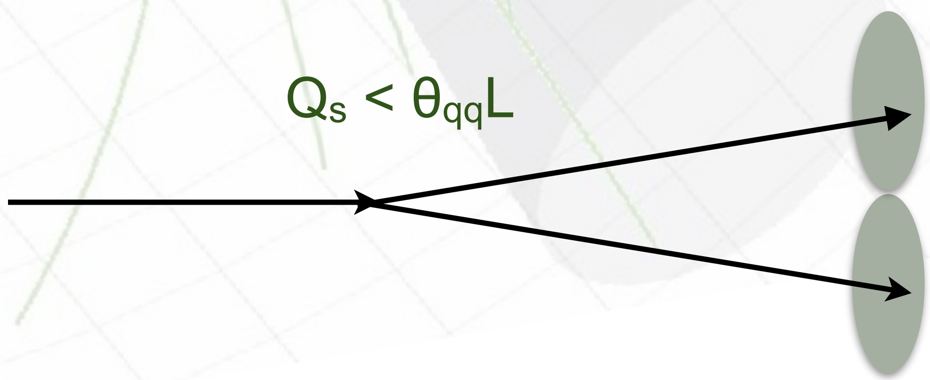
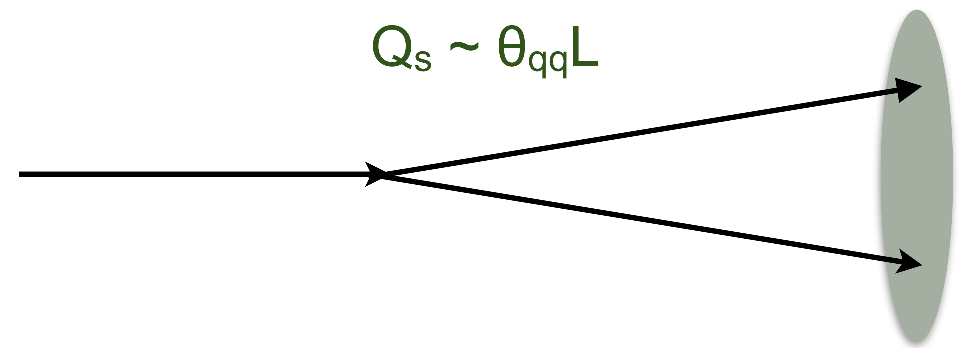


Color Coherence

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

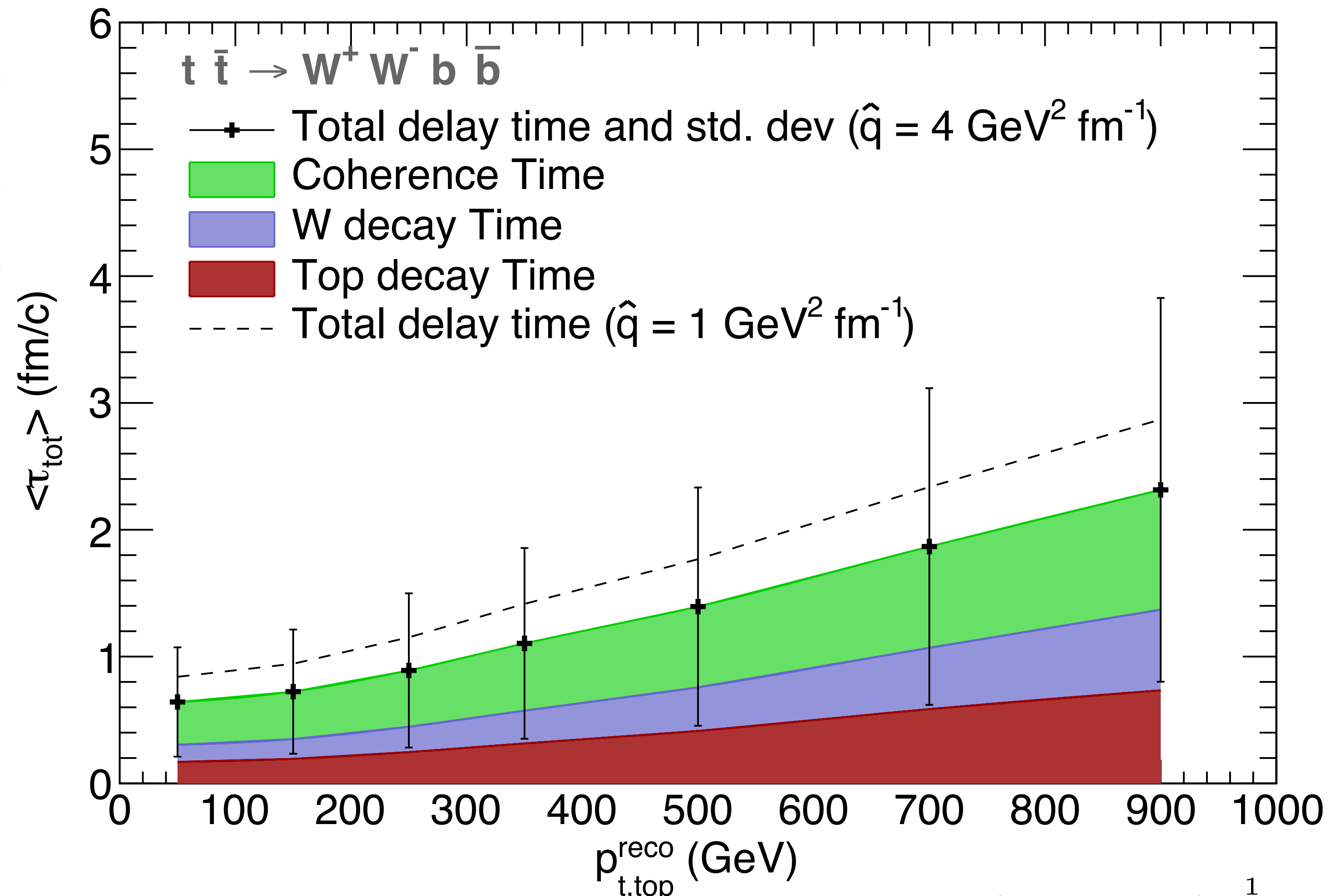
Transport coefficient: $\hat{q}$
Medium length: L

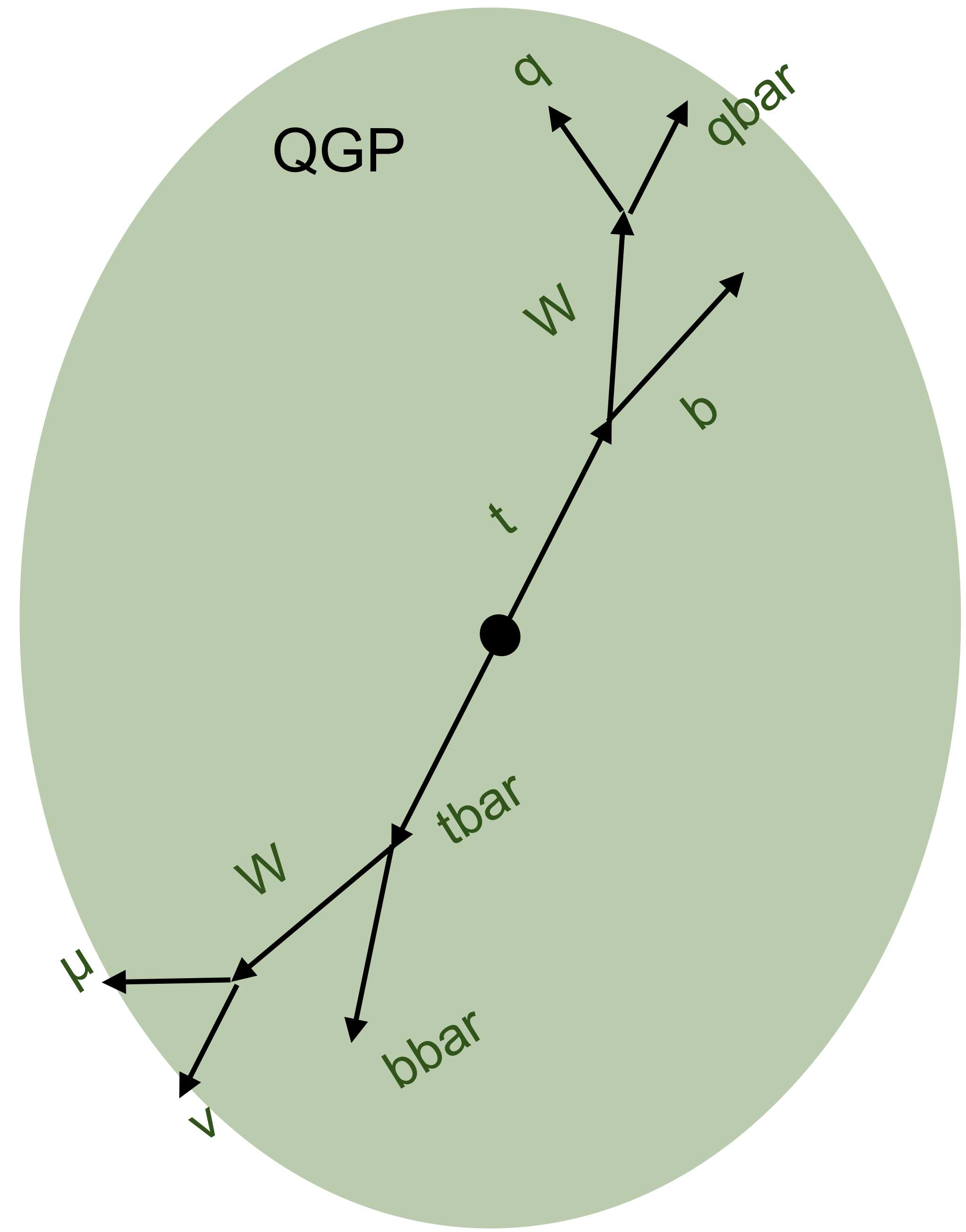
- Increases even more the time delay allowing to have a complete mapping of the QGP evolution:
  - Stay in colourless singlet state during: $t_d = \left(\frac{12}{\hat{q}\theta_{q\bar{q}}^2}\right)^{1/3}$

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

Time Delayed Probes

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





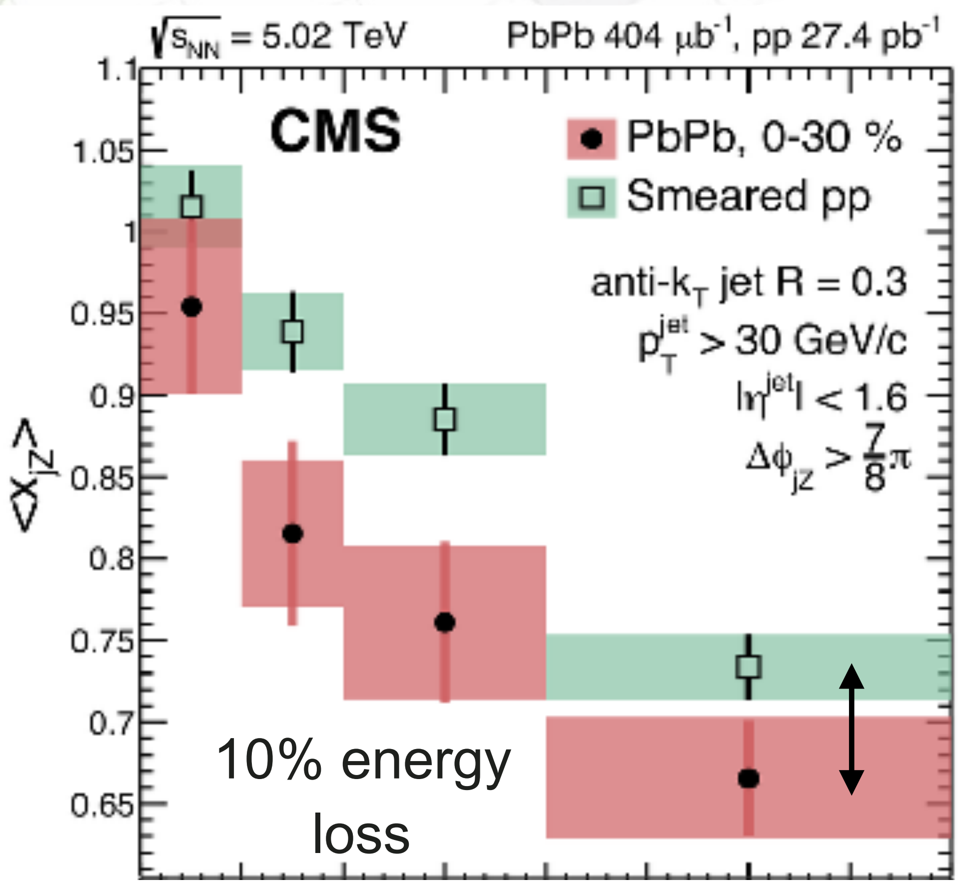
Transverse boost factor: $\gamma_{t,X} = \left(\frac{p_{t,X}^2}{m_X^2} + 1\right)^{\frac{1}{2}}$

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

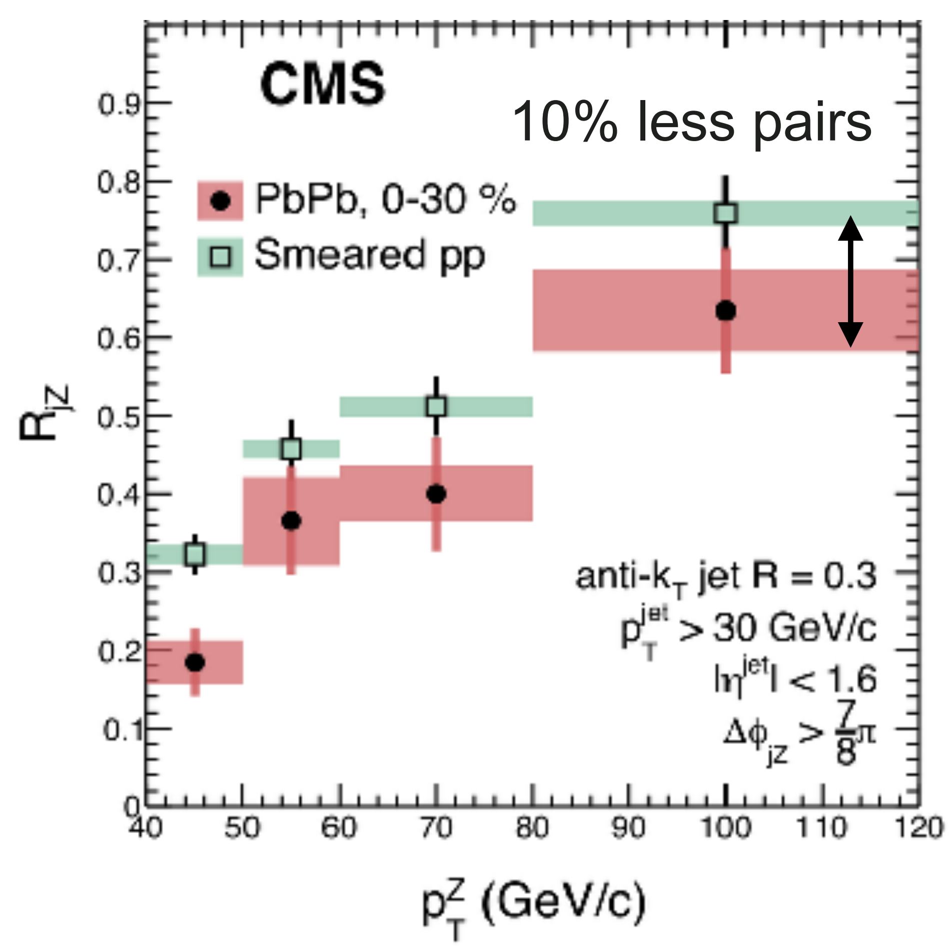
Time Dependence Toy Model

- Toy model for energy loss (current jet quenching Monte Carlo event generators without medium modifications to coherence pattern):
  - For a fixed medium length, a coloured particle loses, e.g.,15% of its energy

Average momentum imbalance Z + Jet



Average number of Z + Jet pairs



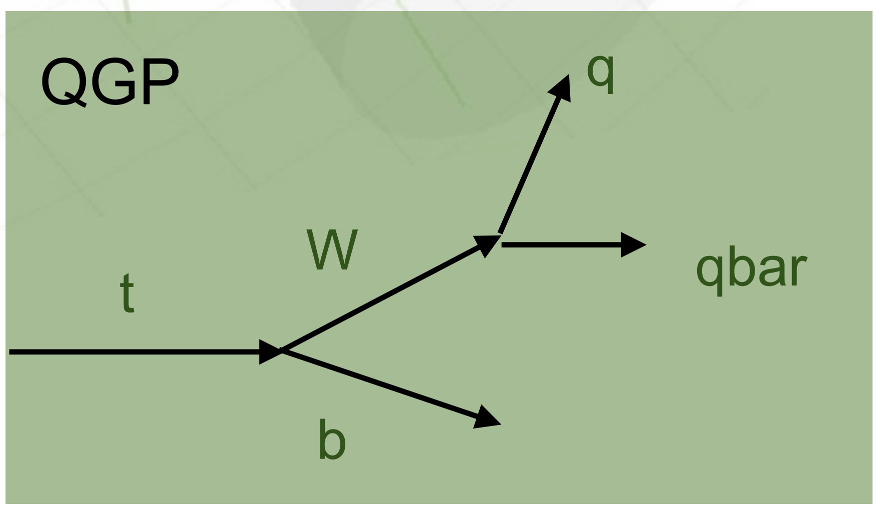
CMS PRL 2017

Time Dependence Toy Model

- W decay particles will lose energy proportionally to the distance that they travel:
  - Particles emitted from the qqbar "antenna", will lose:

$$\mathcal{Q}(\tau_{\rm tot}) = 1 + (\mathcal{Q}_0 - 1)\frac{\tau_m - \tau_{\rm tot}}{\tau_m}\Theta(\tau_m - \tau_{\rm tot})$$

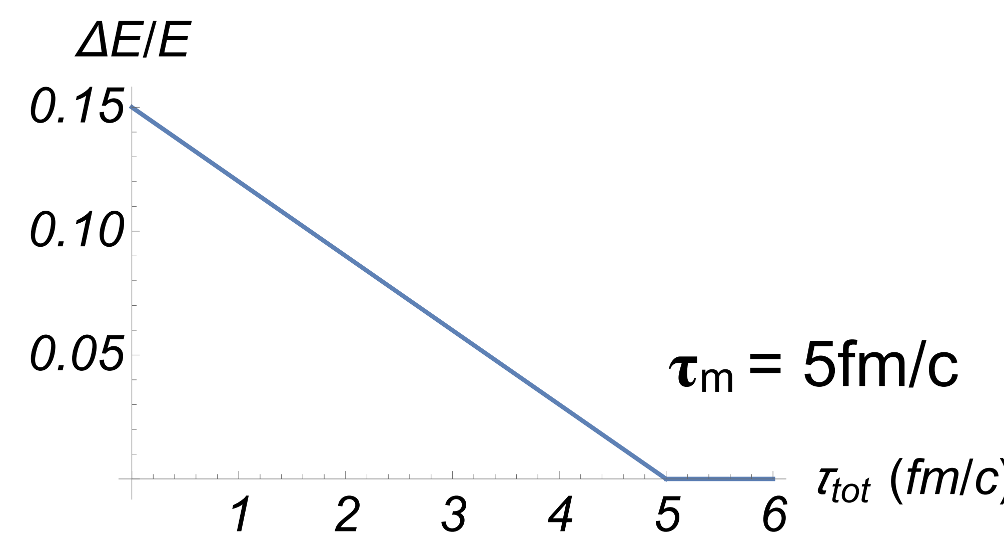
$$\mathcal{Q}_0 = 0.85$$



τ_m = medium lifetime

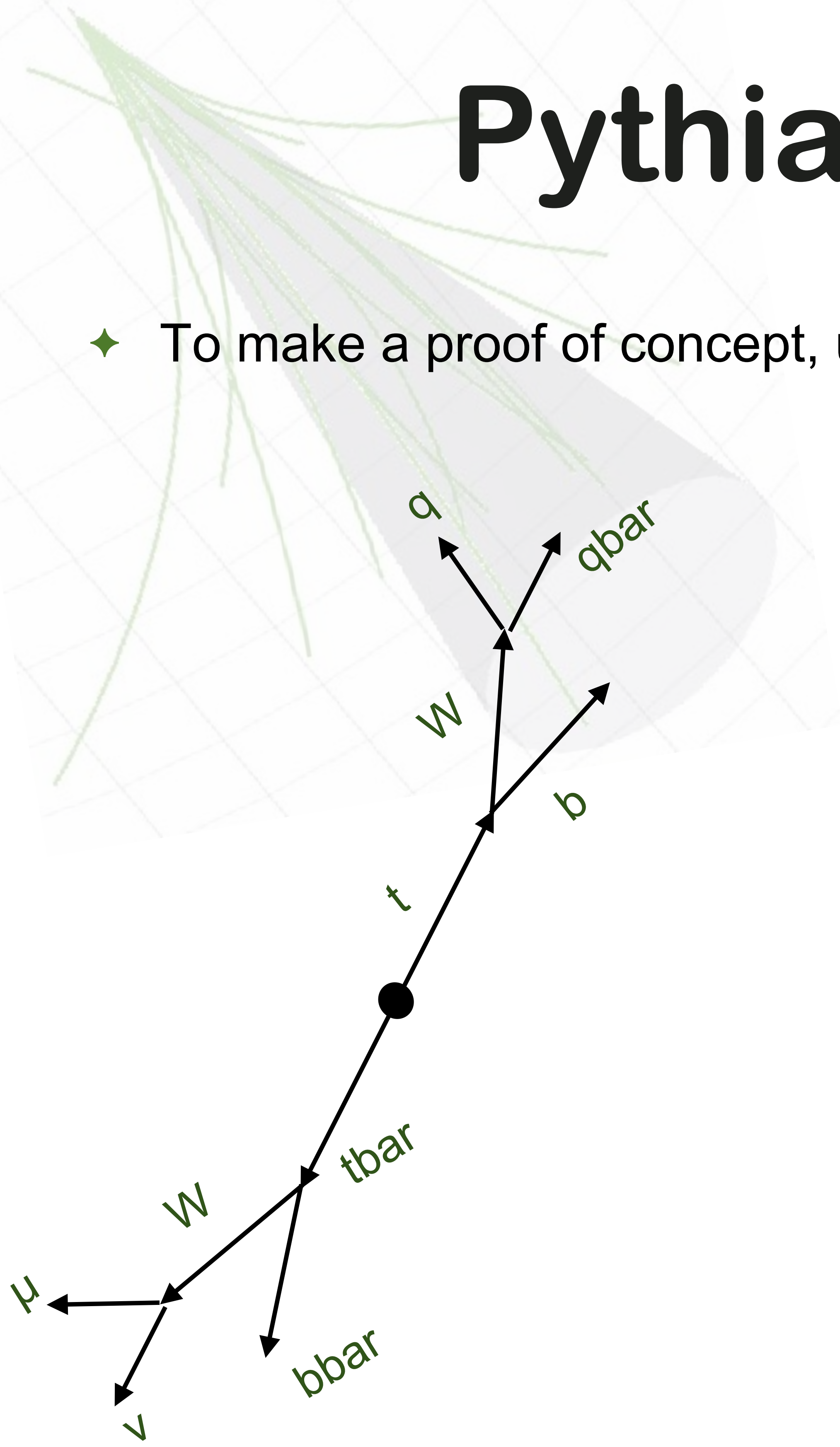
τ_{tot} = total delay time ($t_{top} + t_W + t_d$)

(time at which the antenna decoheres)

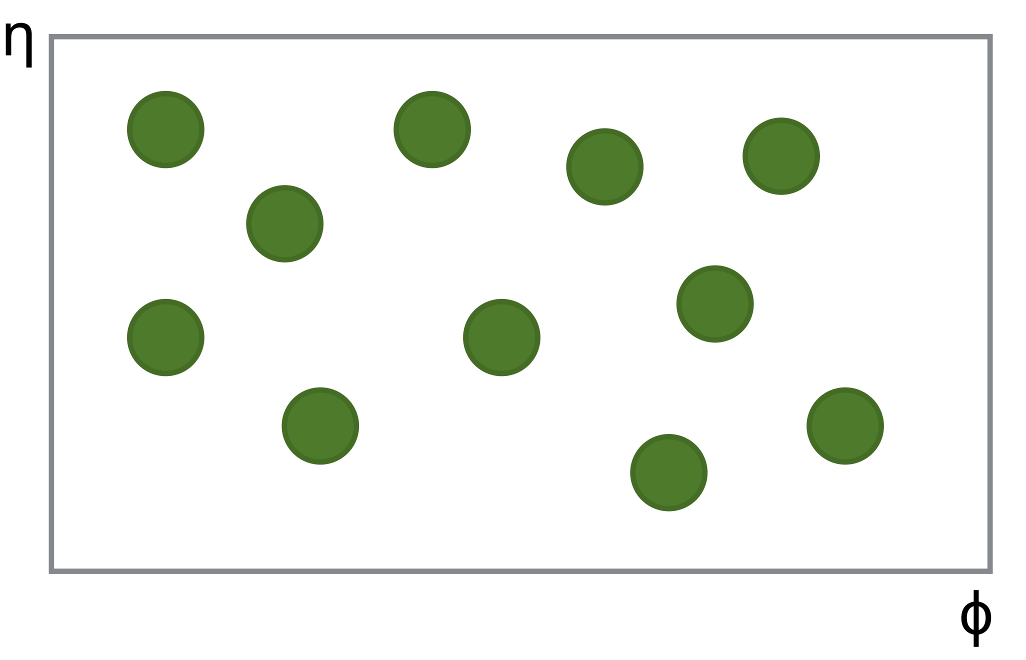


Pythia + Toy Model

- To make a proof of concept, used Pythia 8 proton-proton event:



colouring = p_T



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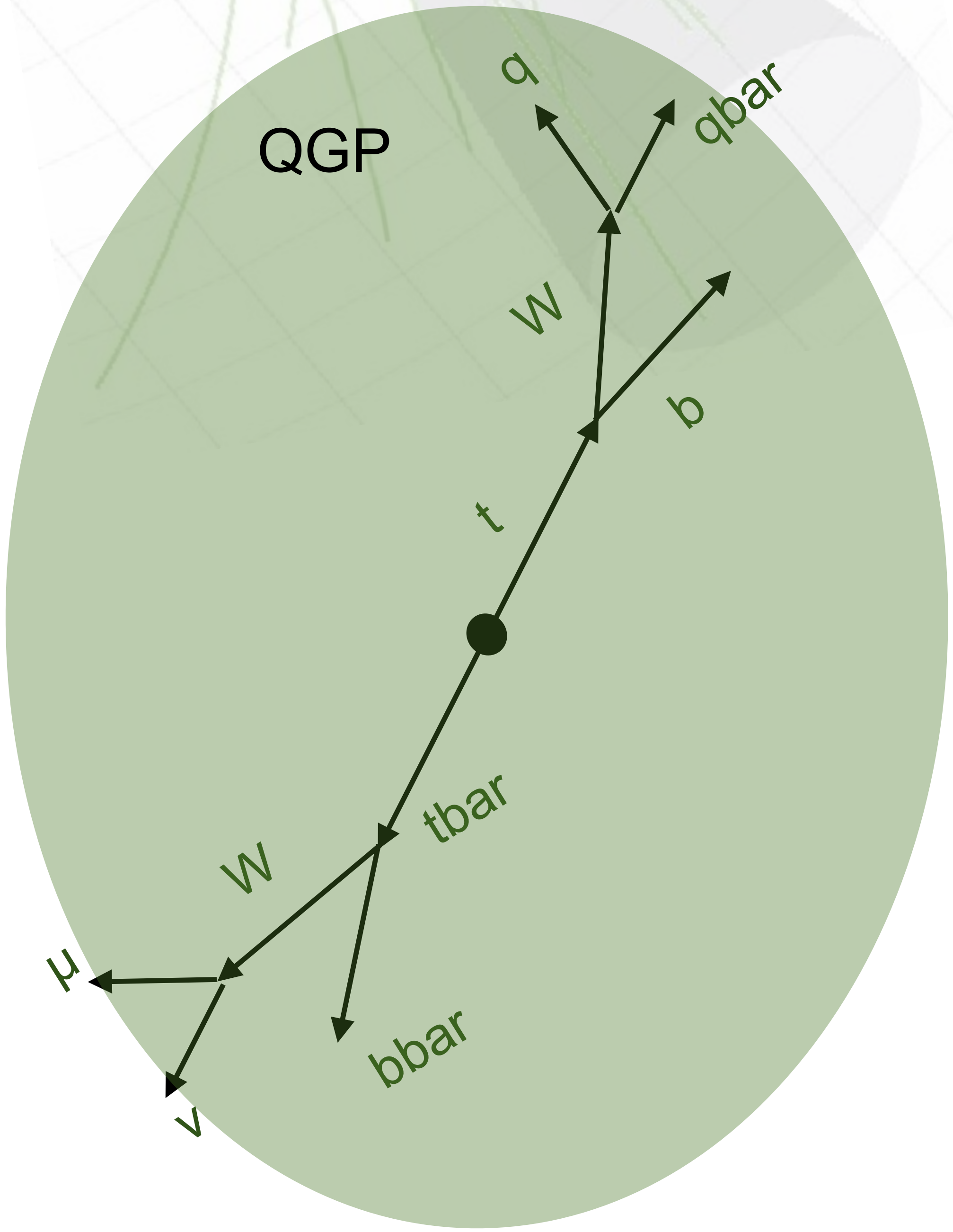

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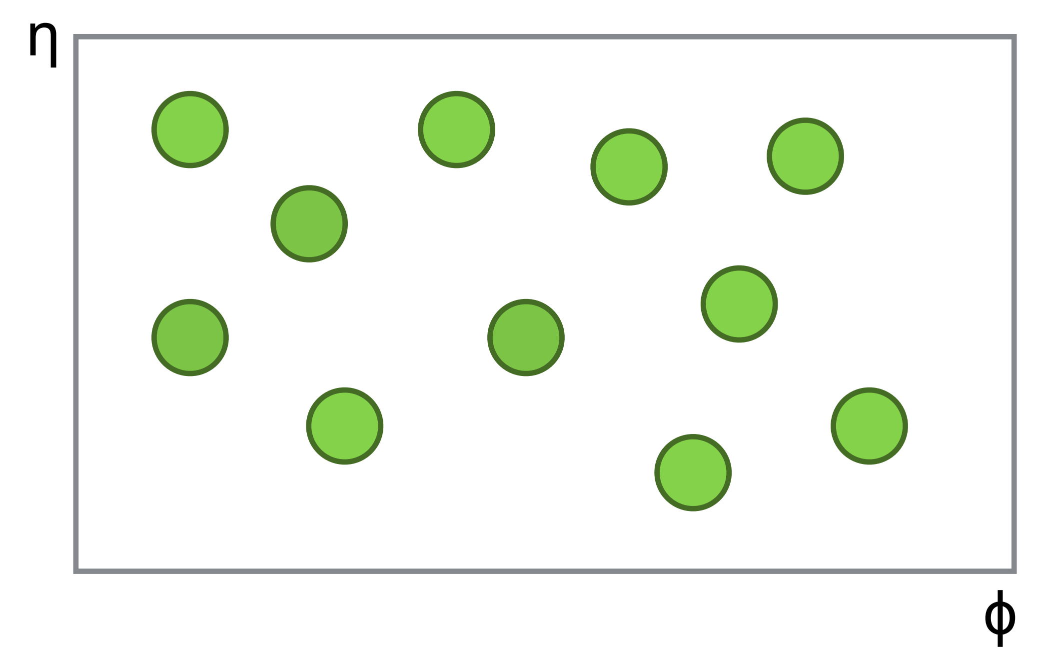

Rescaled energy momentum of the particles to mimic energy loss

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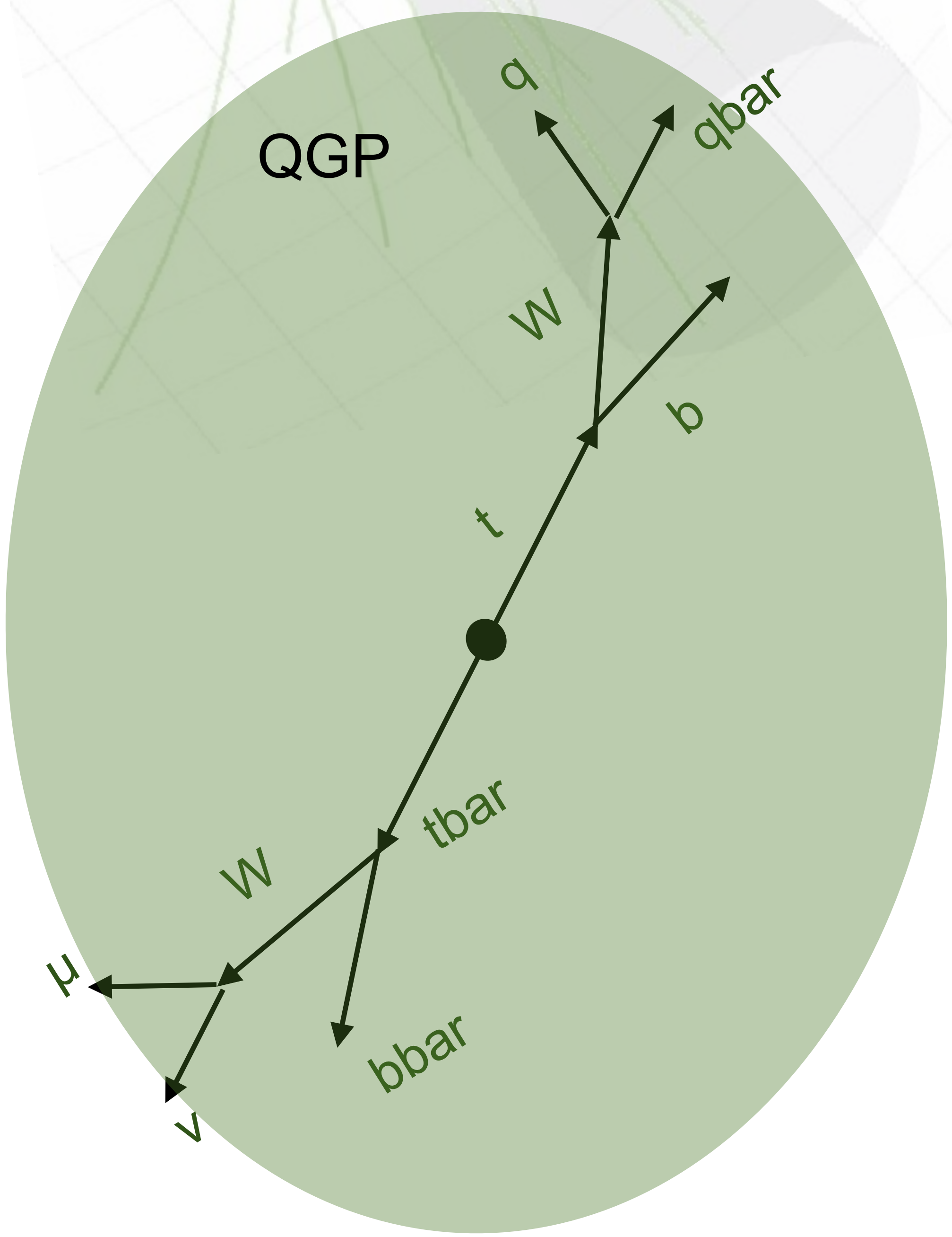

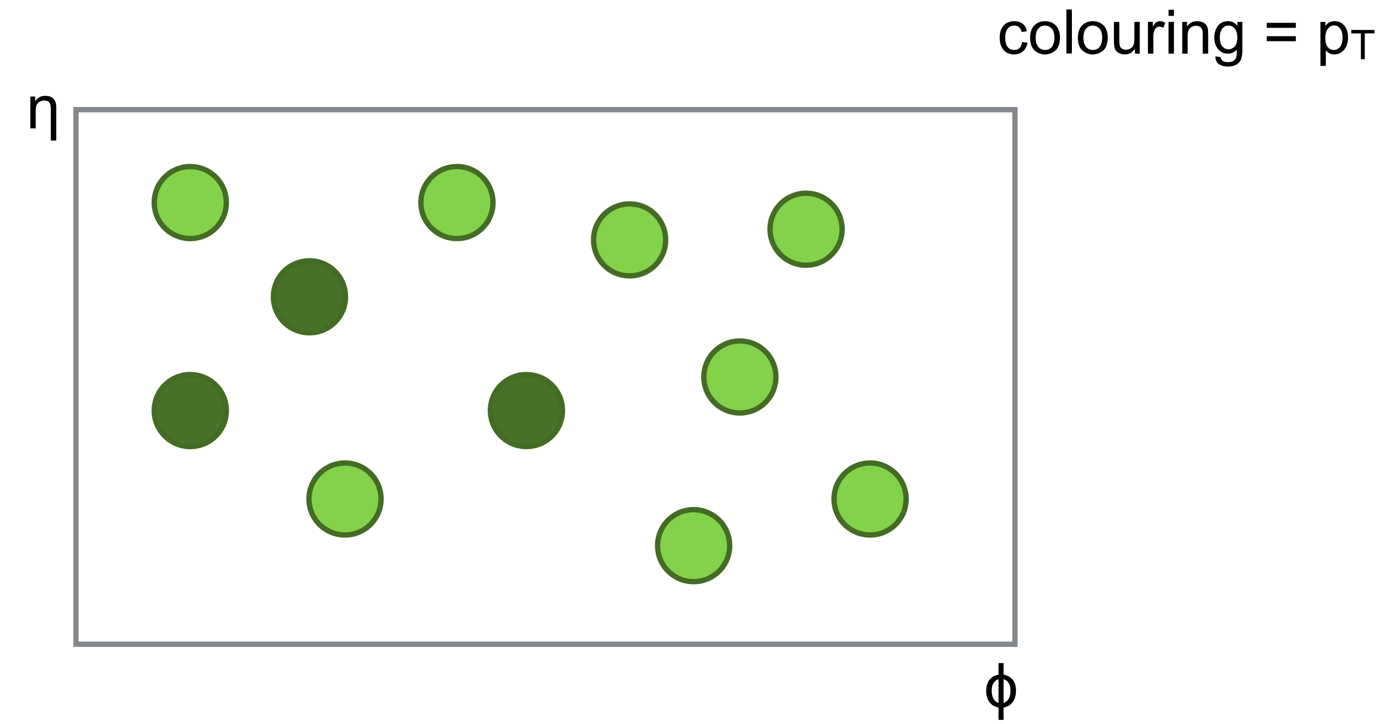

Rescale W decay particles independently to account for coherence effects

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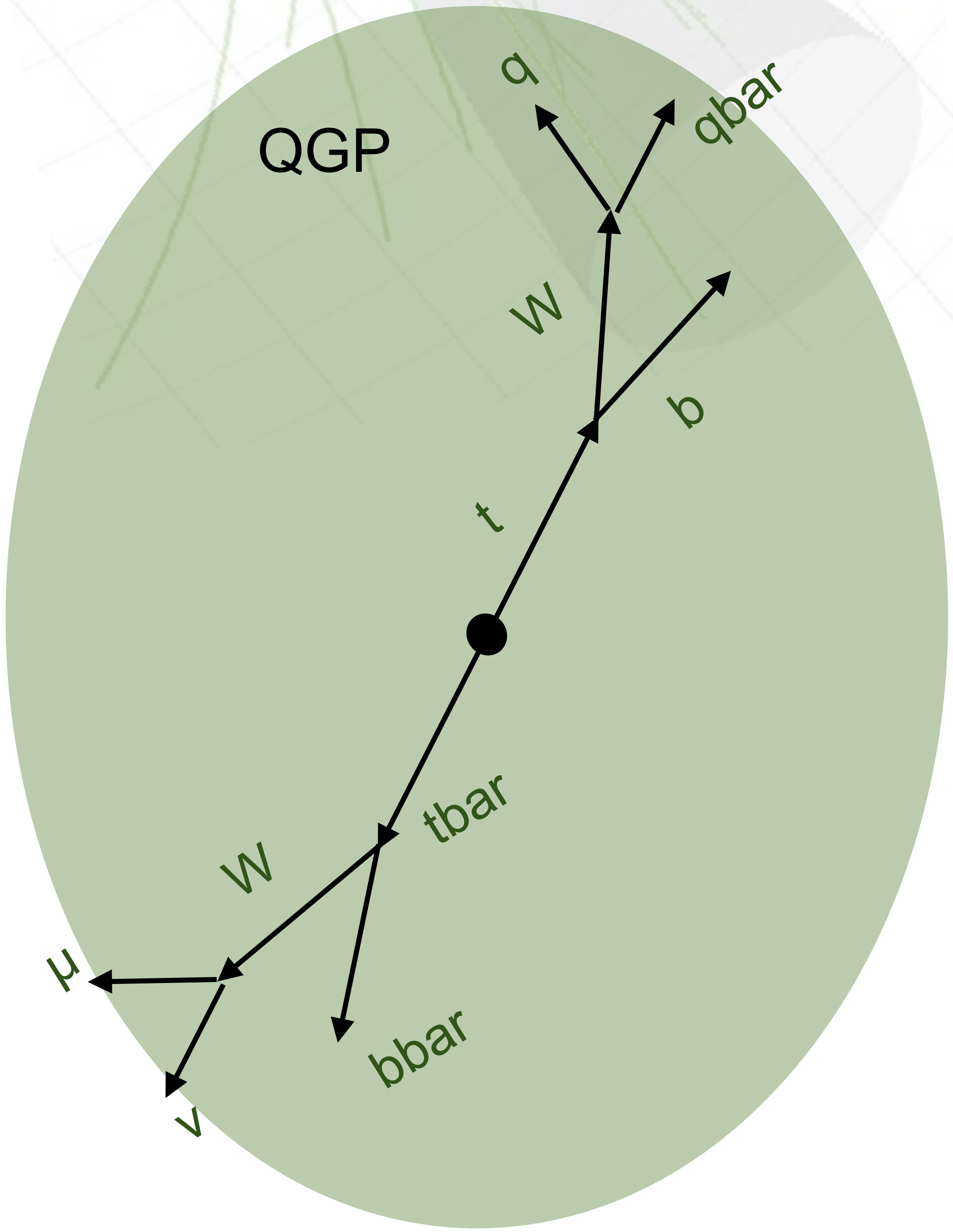

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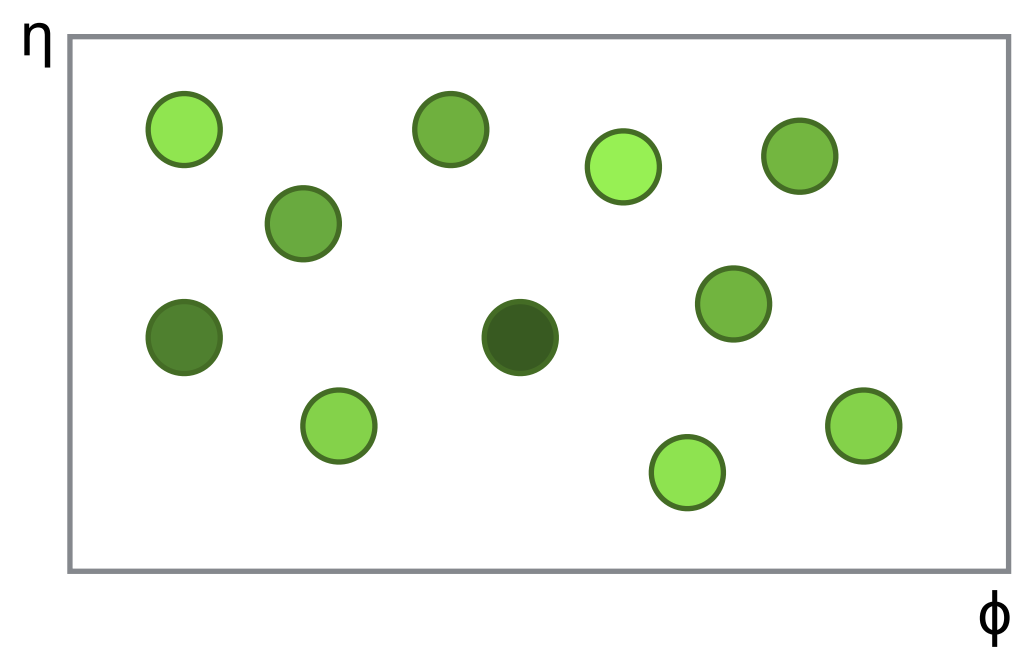

True rescaling account for energy loss fluctuations!

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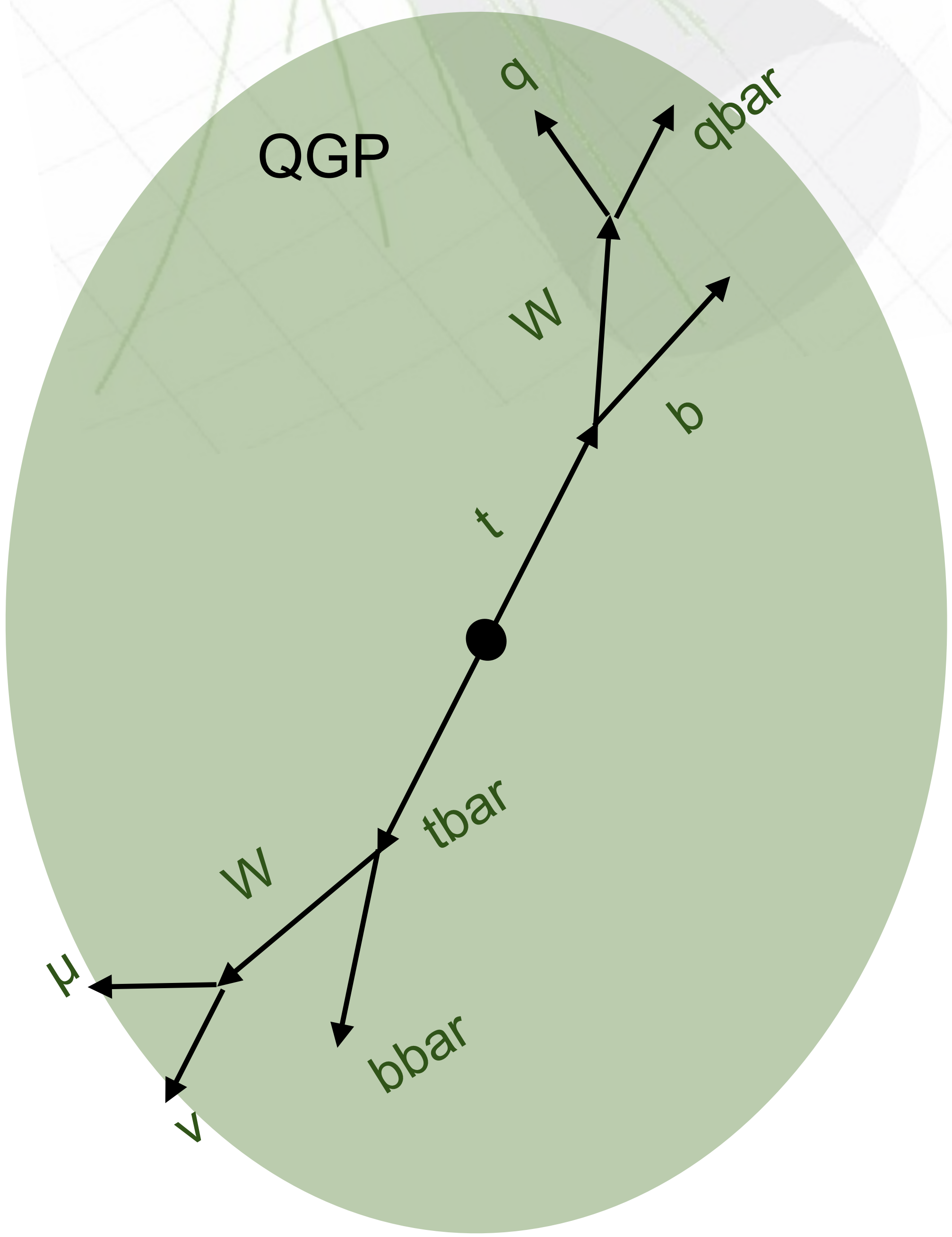

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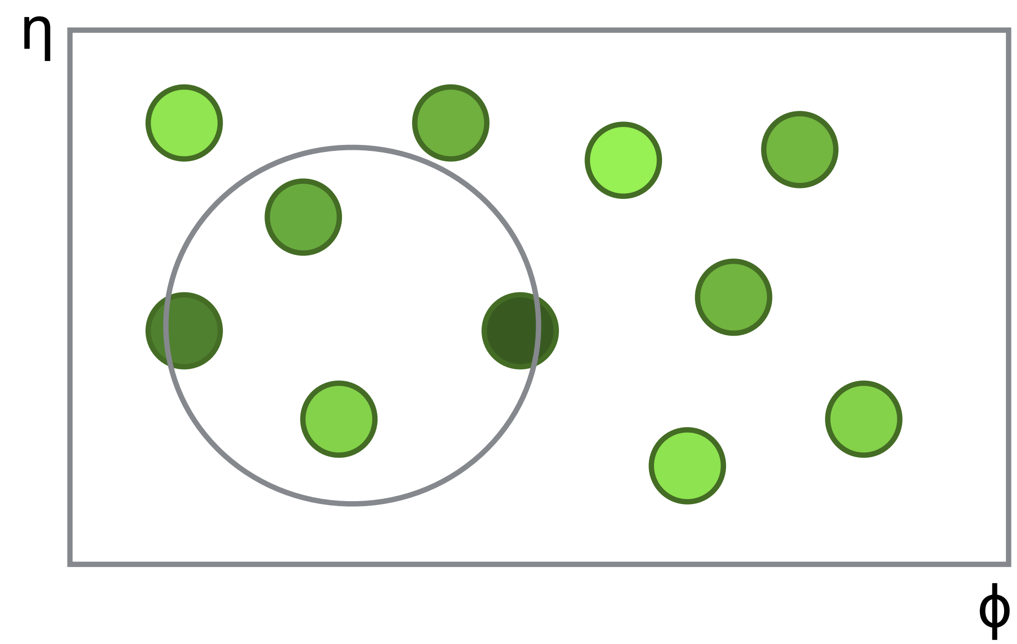


True rescaling account for energy loss fluctuations!

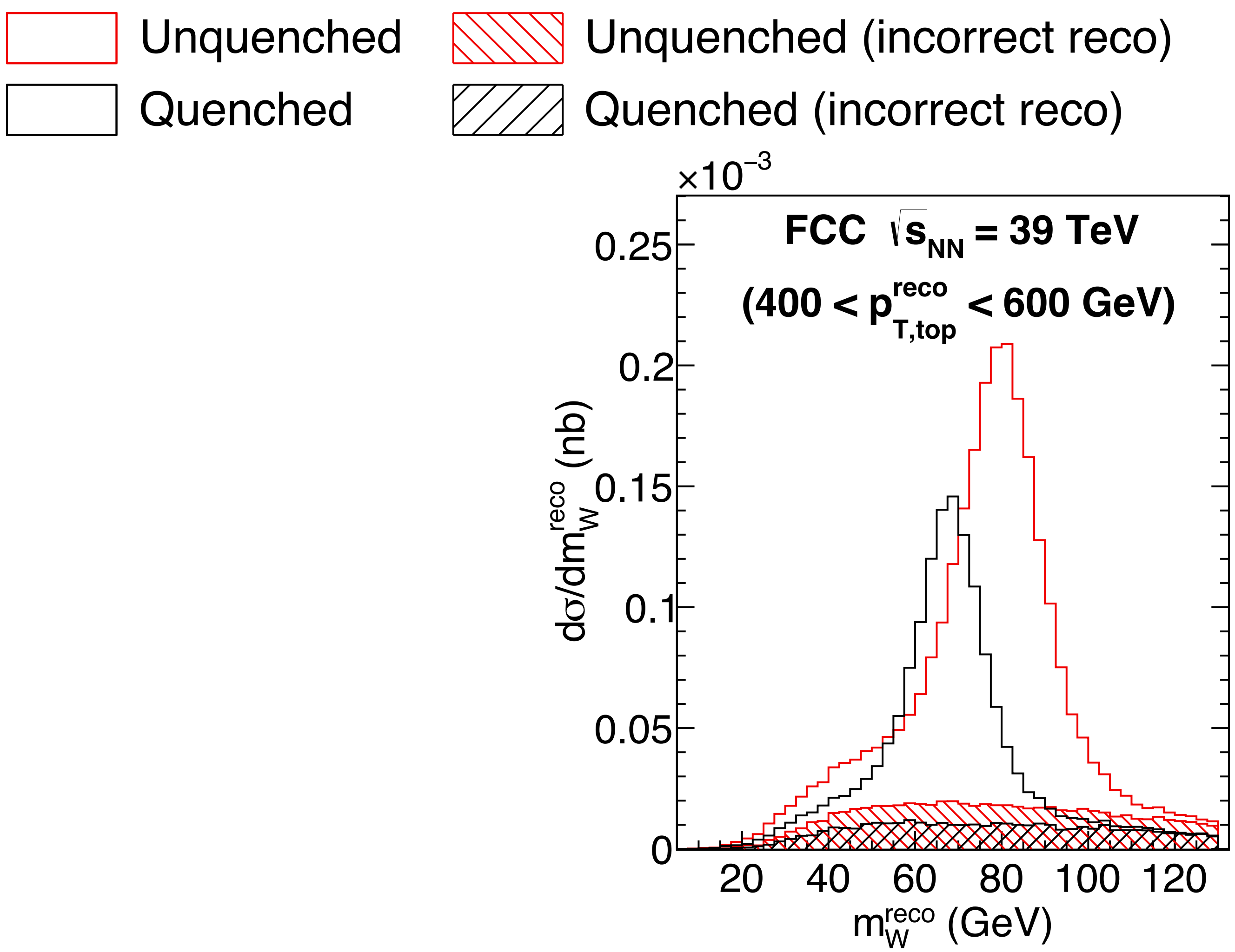
Jet energy loss ⇒ change in reconstructed W mass

Reconstructed W Mass

- Expected reconstructed W Mass:
  - At Future Circular Collider (FCC) energies ($\sqrt{s_{NN}}$ = 39 TeV):
    - $\sigma_{ttbar\rightarrow qqbar+\mu\nu}$ ~ 1 nb

pp event scaled by quenching factor (embedded in PbPb)

pp event (embedded in PbPb)



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pp event scaled by quenching factor (embedded in PbPb)

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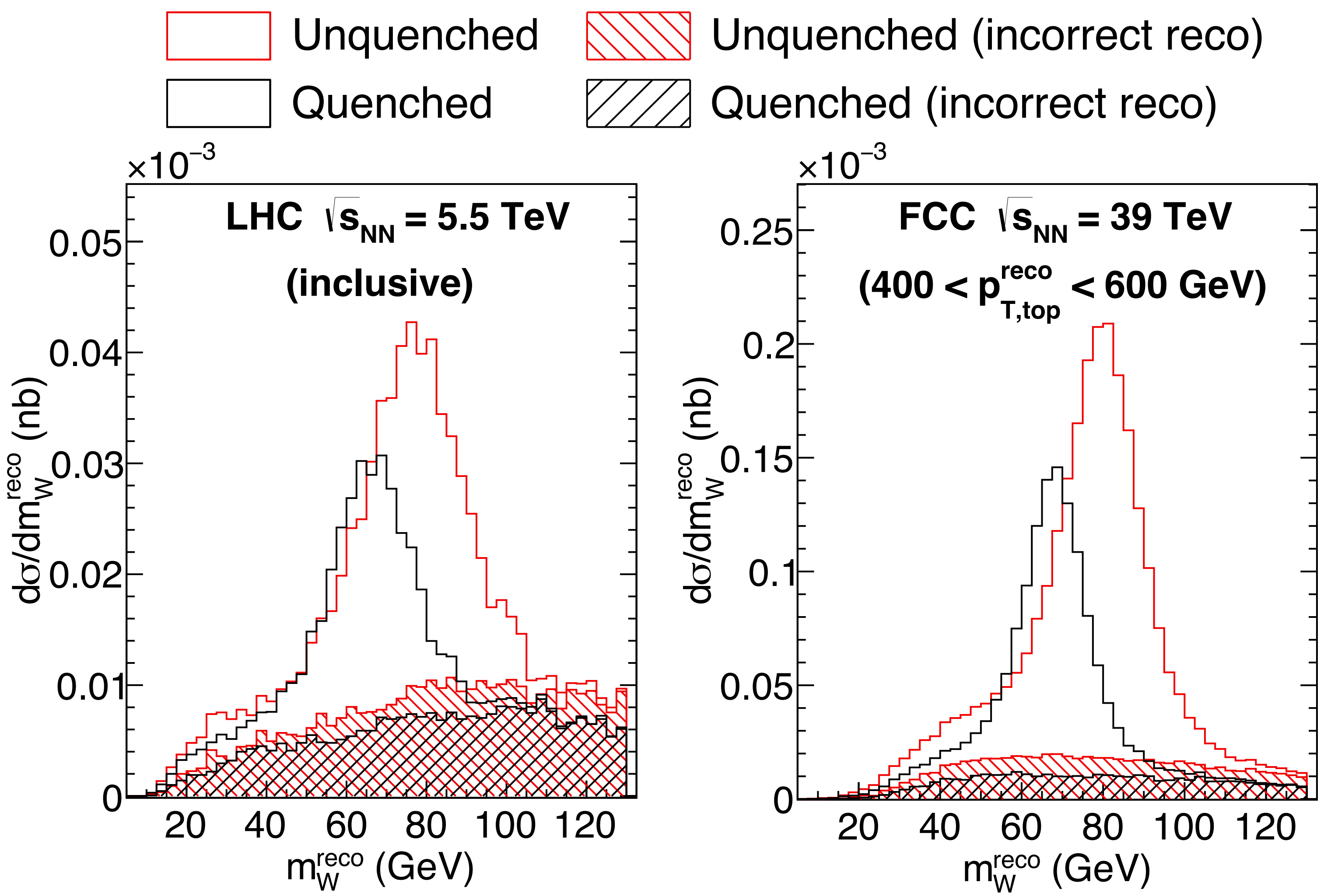

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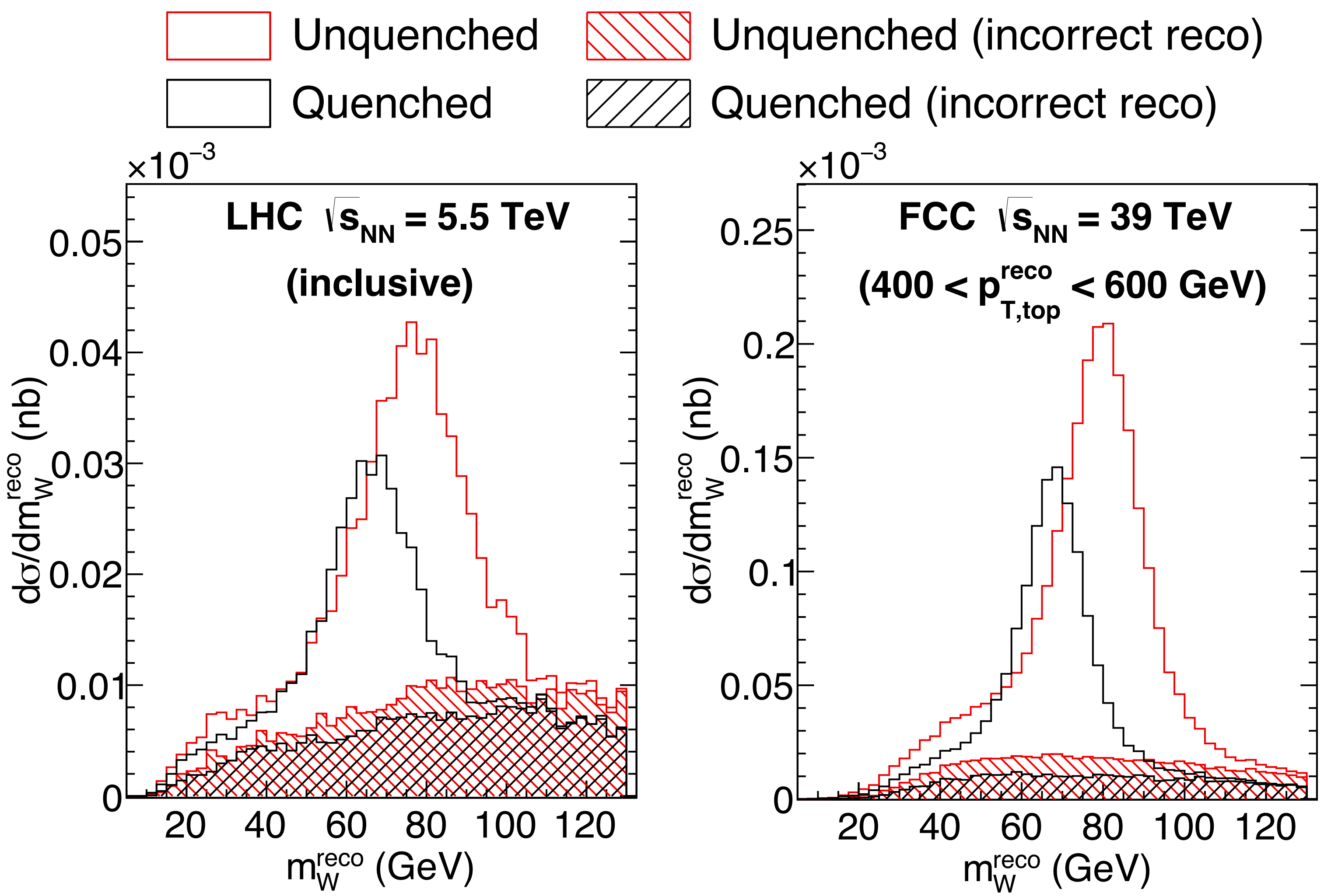

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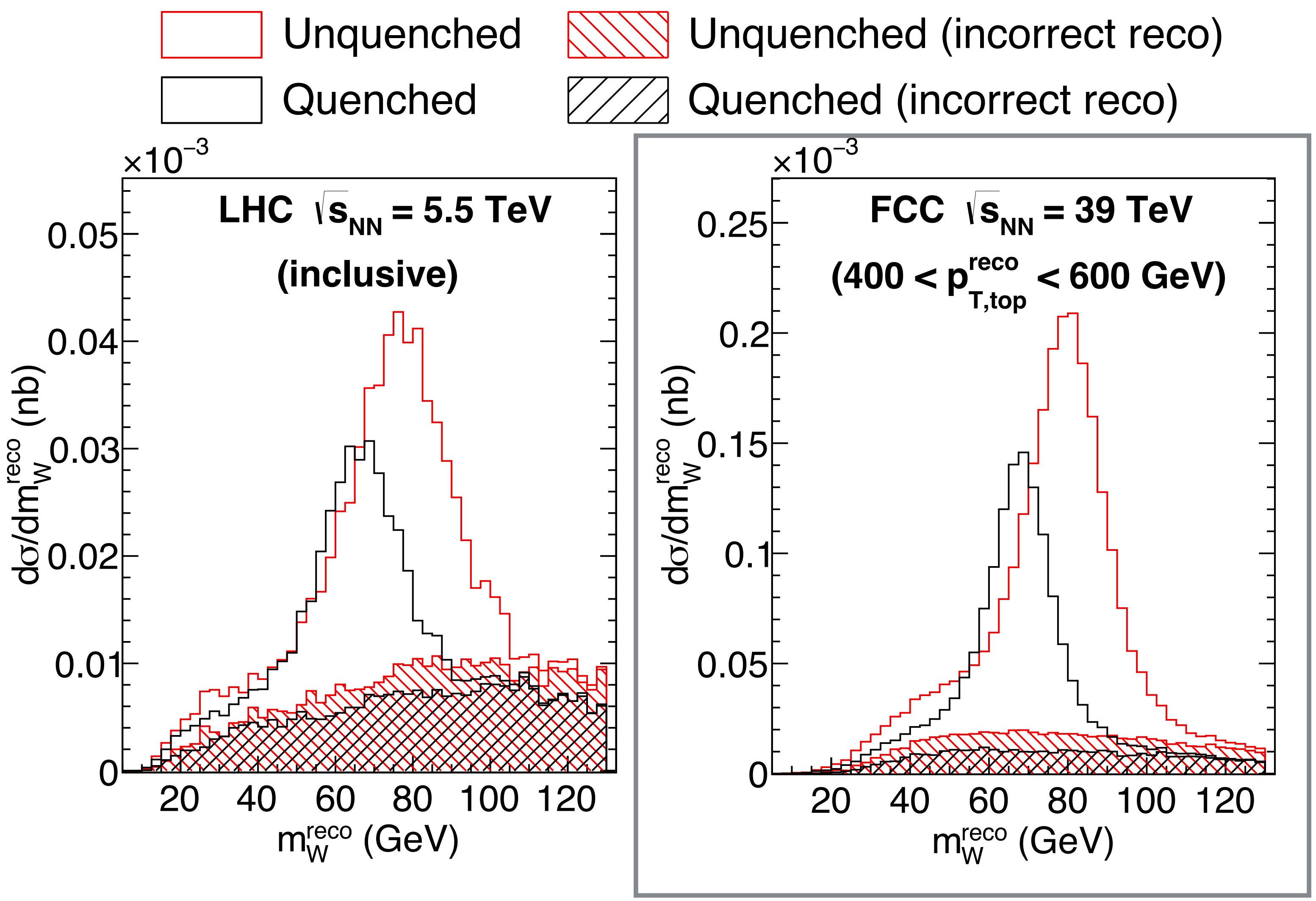

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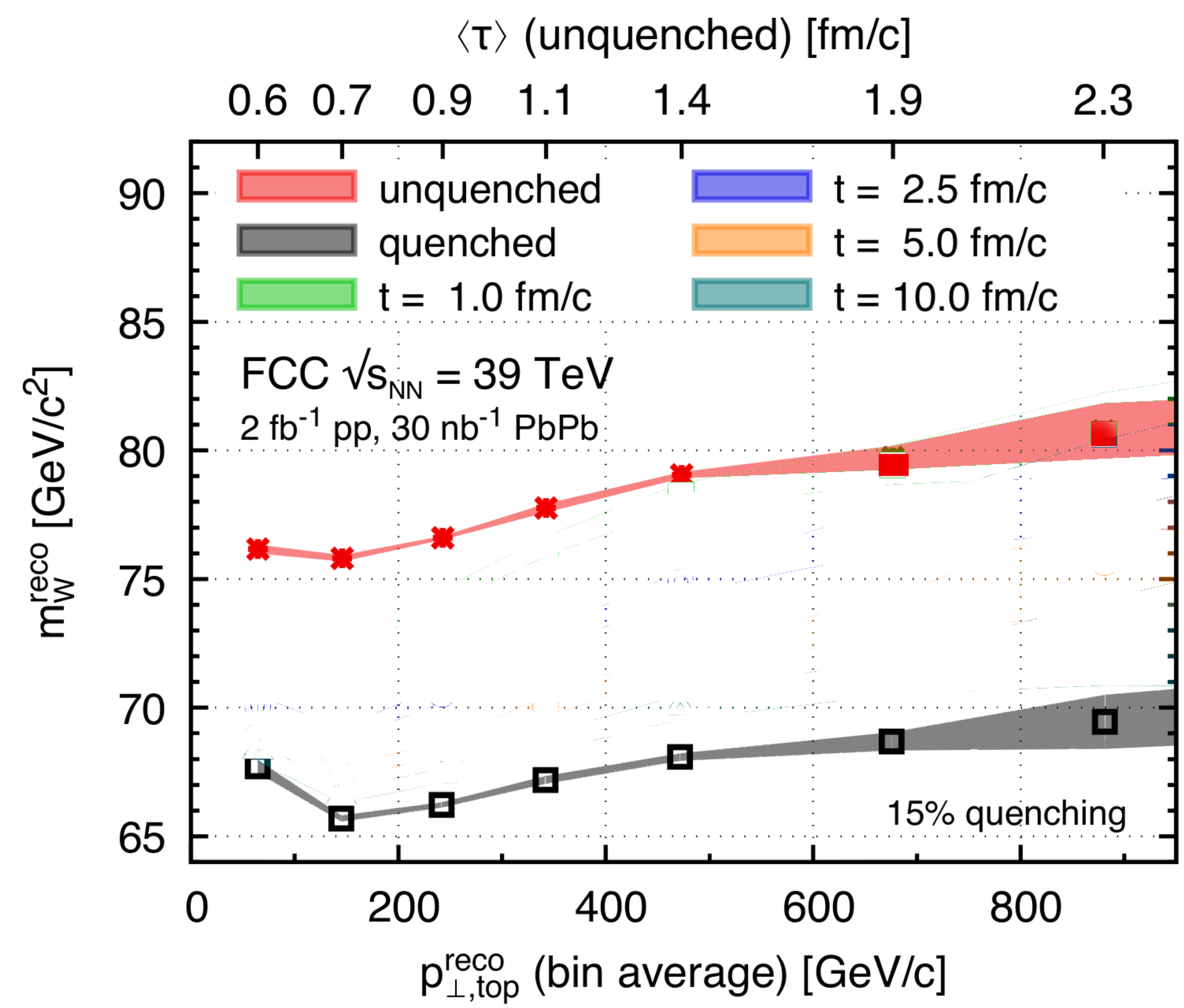
- Reconstructed W Mass as a function of the top p_T:

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

unquenched
quenched

Unquenched = pp reference
Quenched = scaled pp reference



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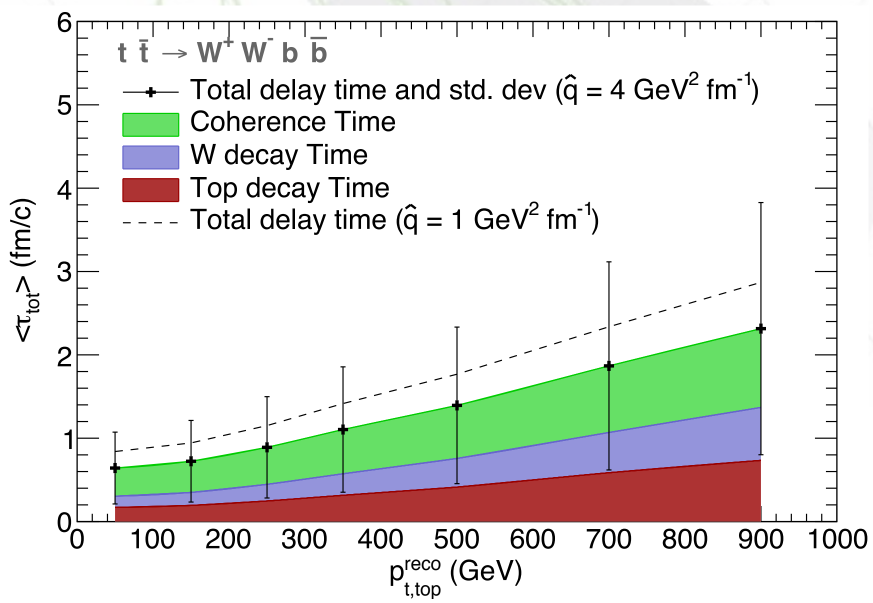

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$m_{W,jet}(p_{T,top})$: link to the time at which antenna particles start to interact

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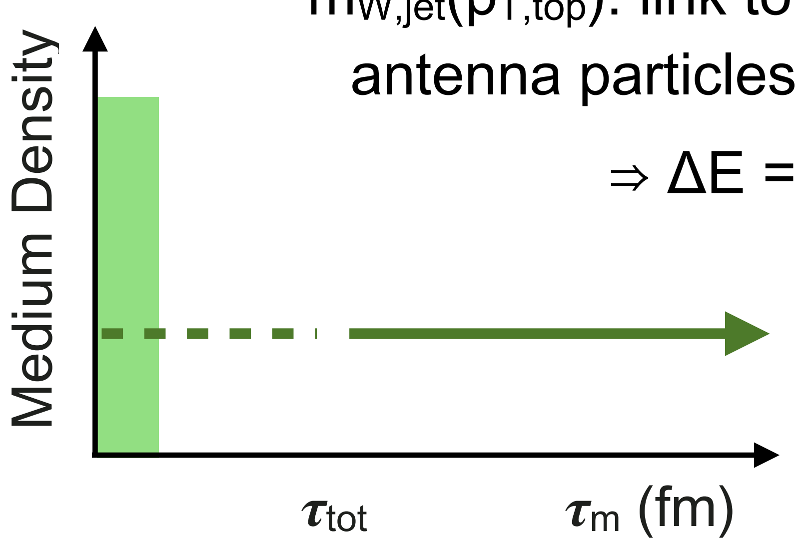

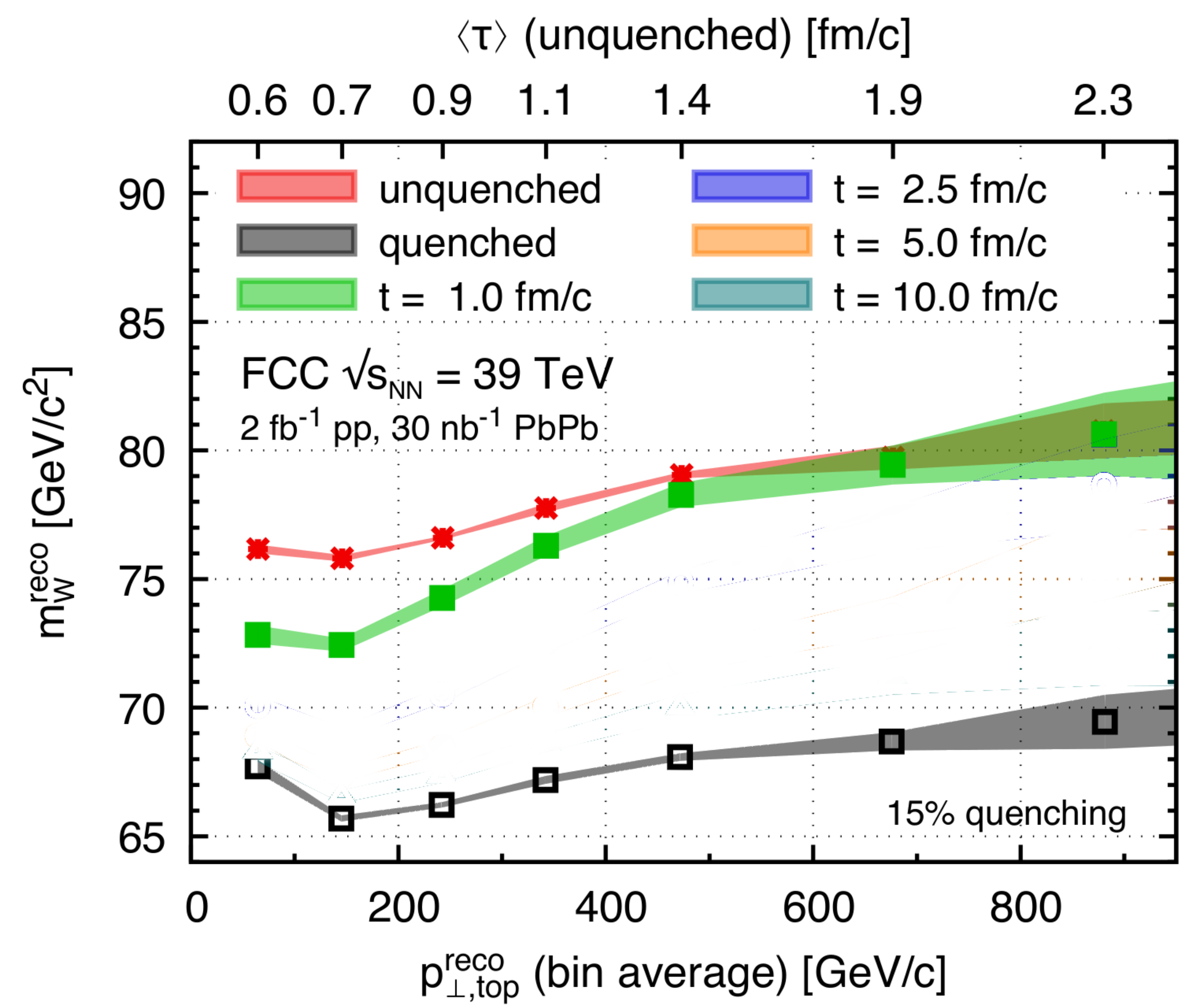

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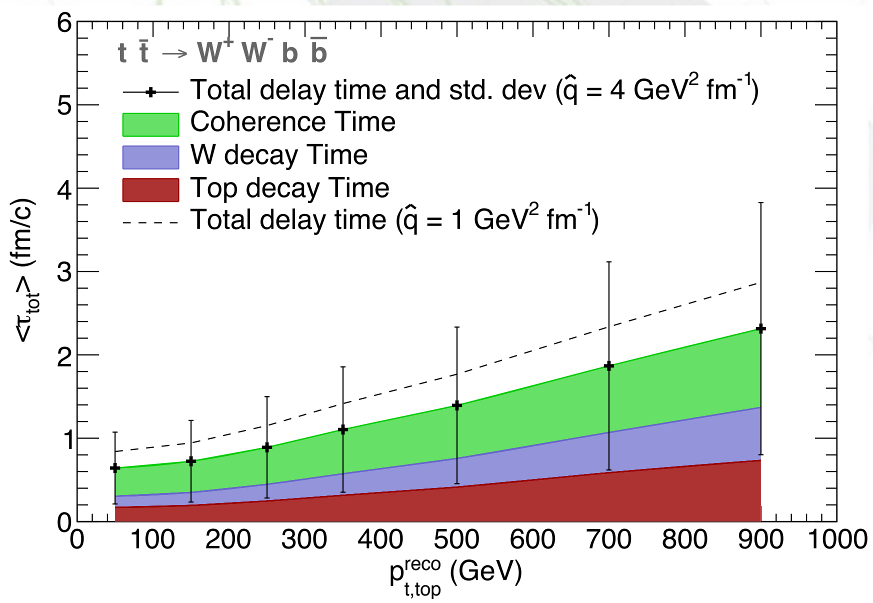

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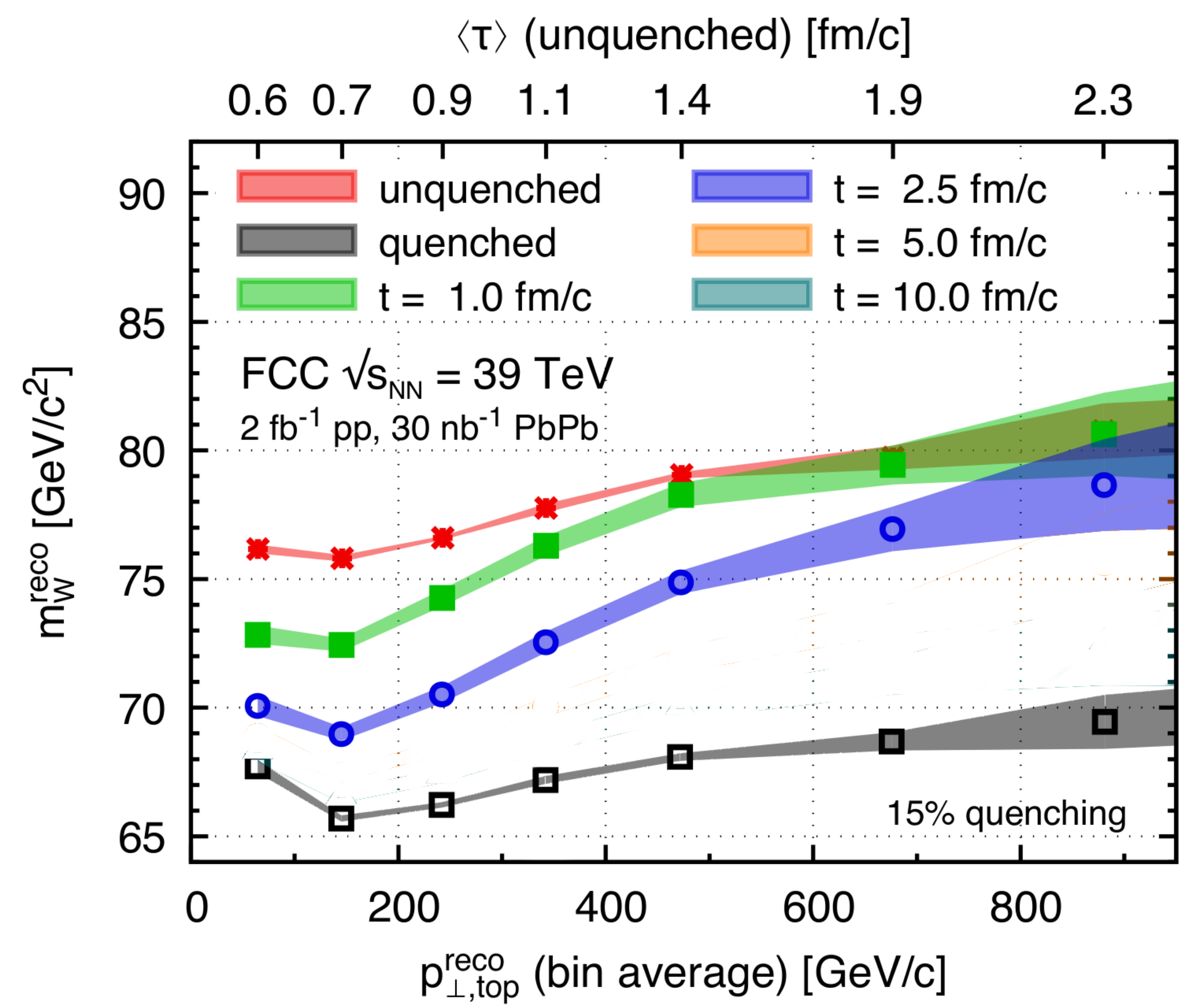

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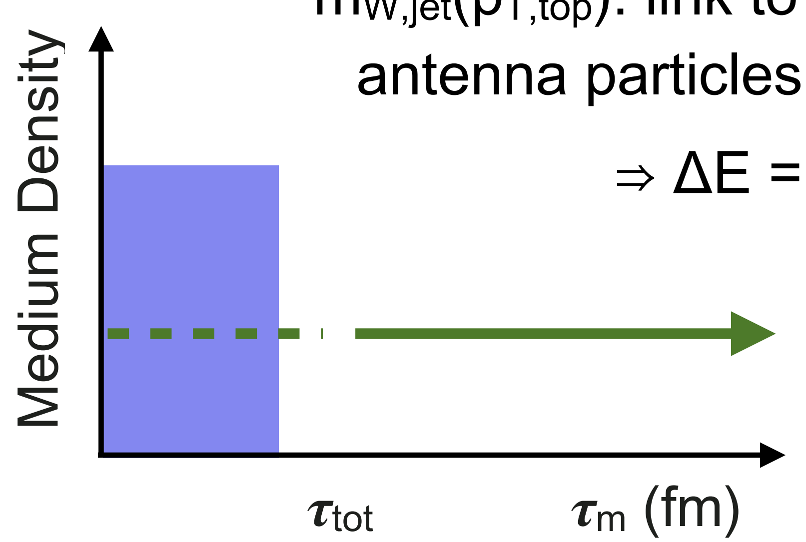

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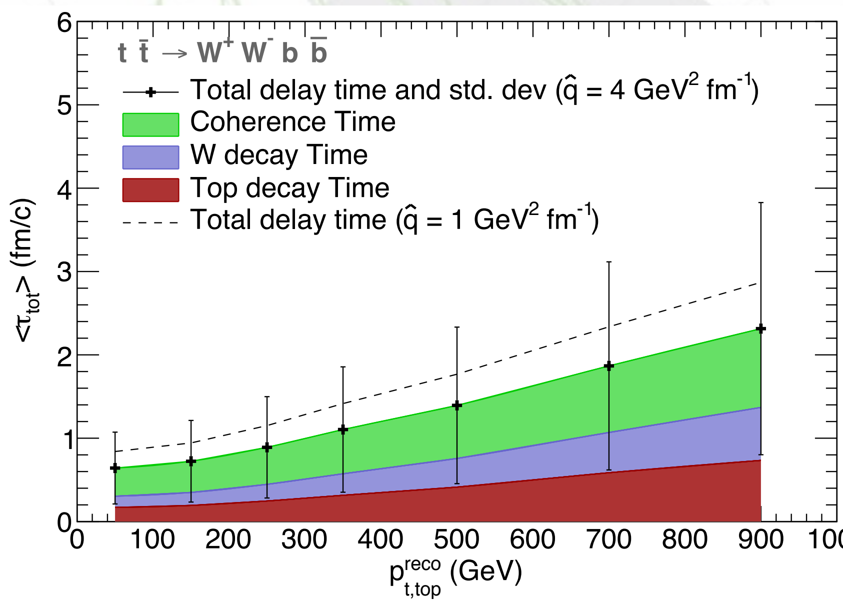

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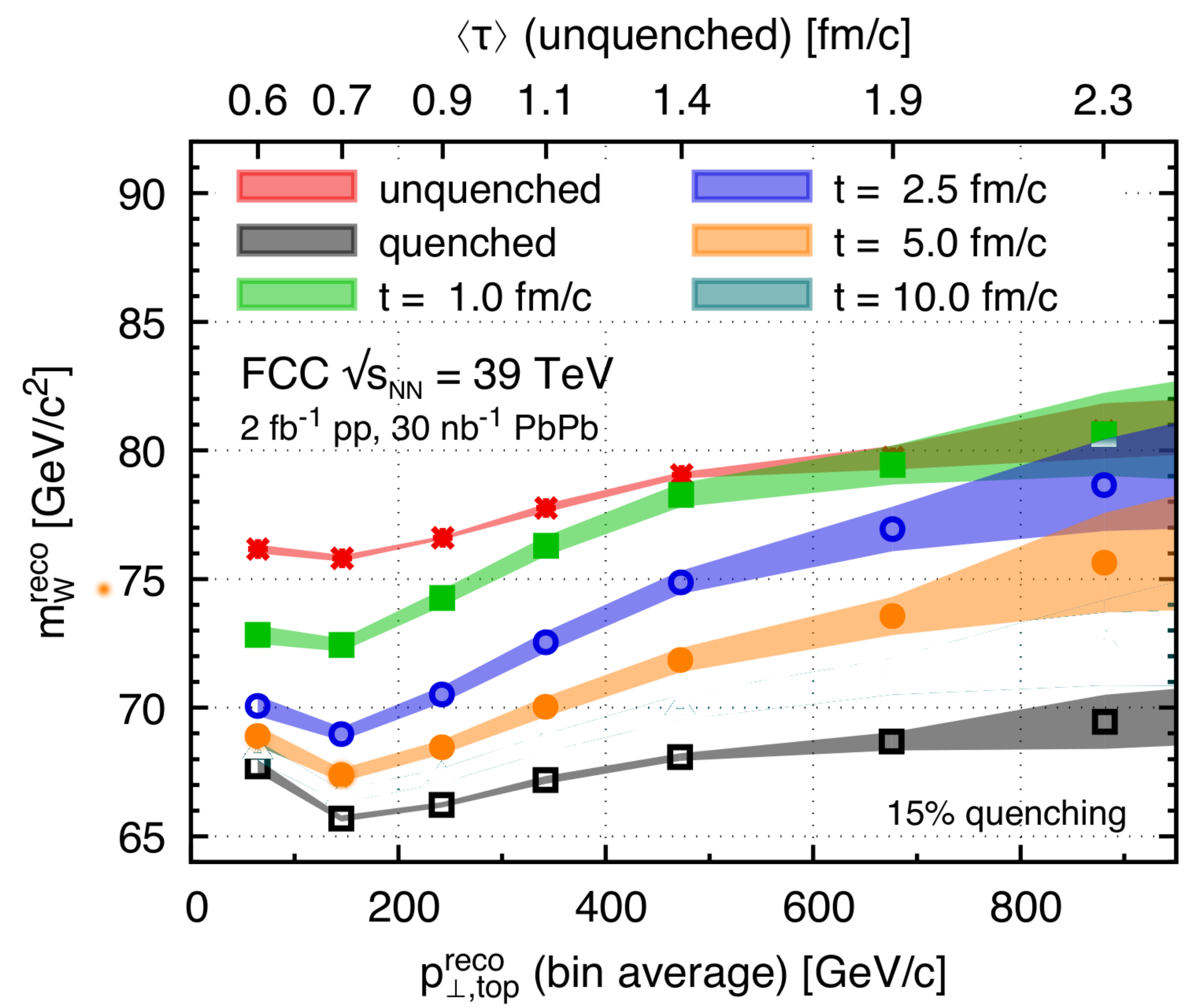
quenched | τ_m= 2.5 fm/c



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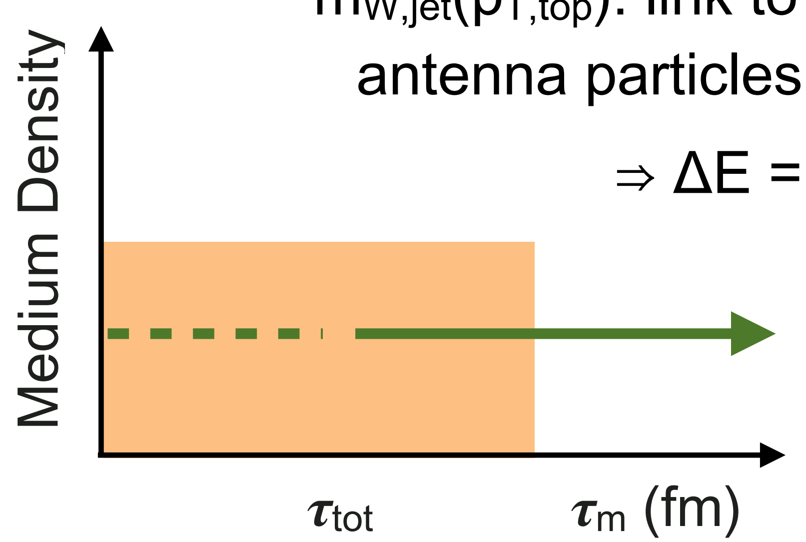

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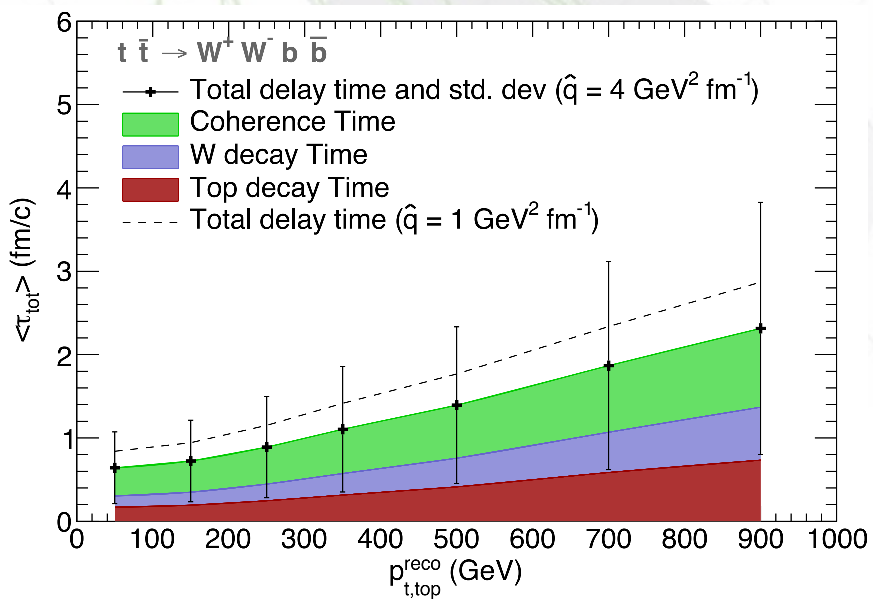

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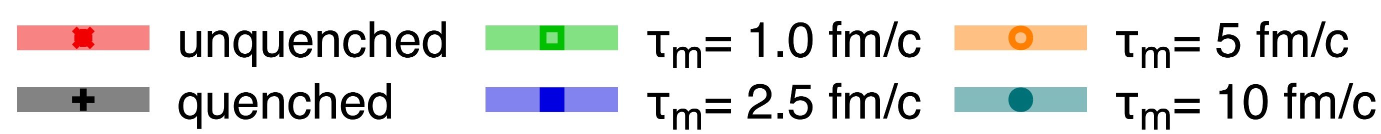

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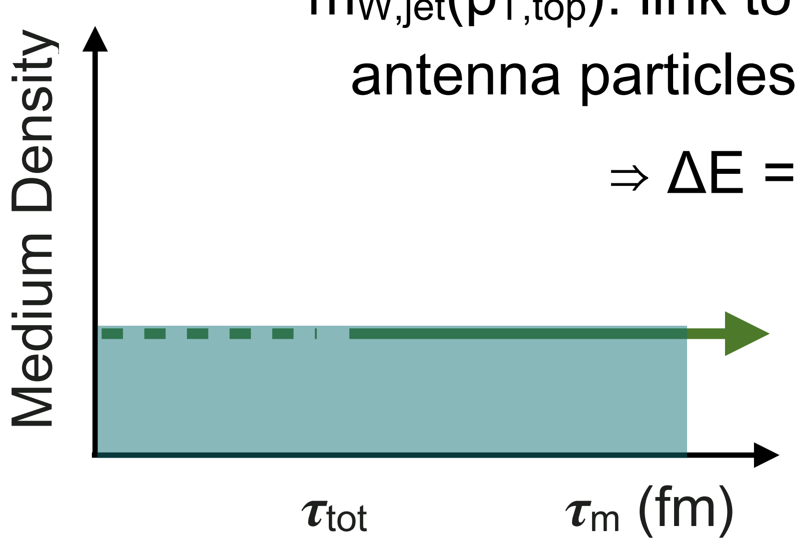

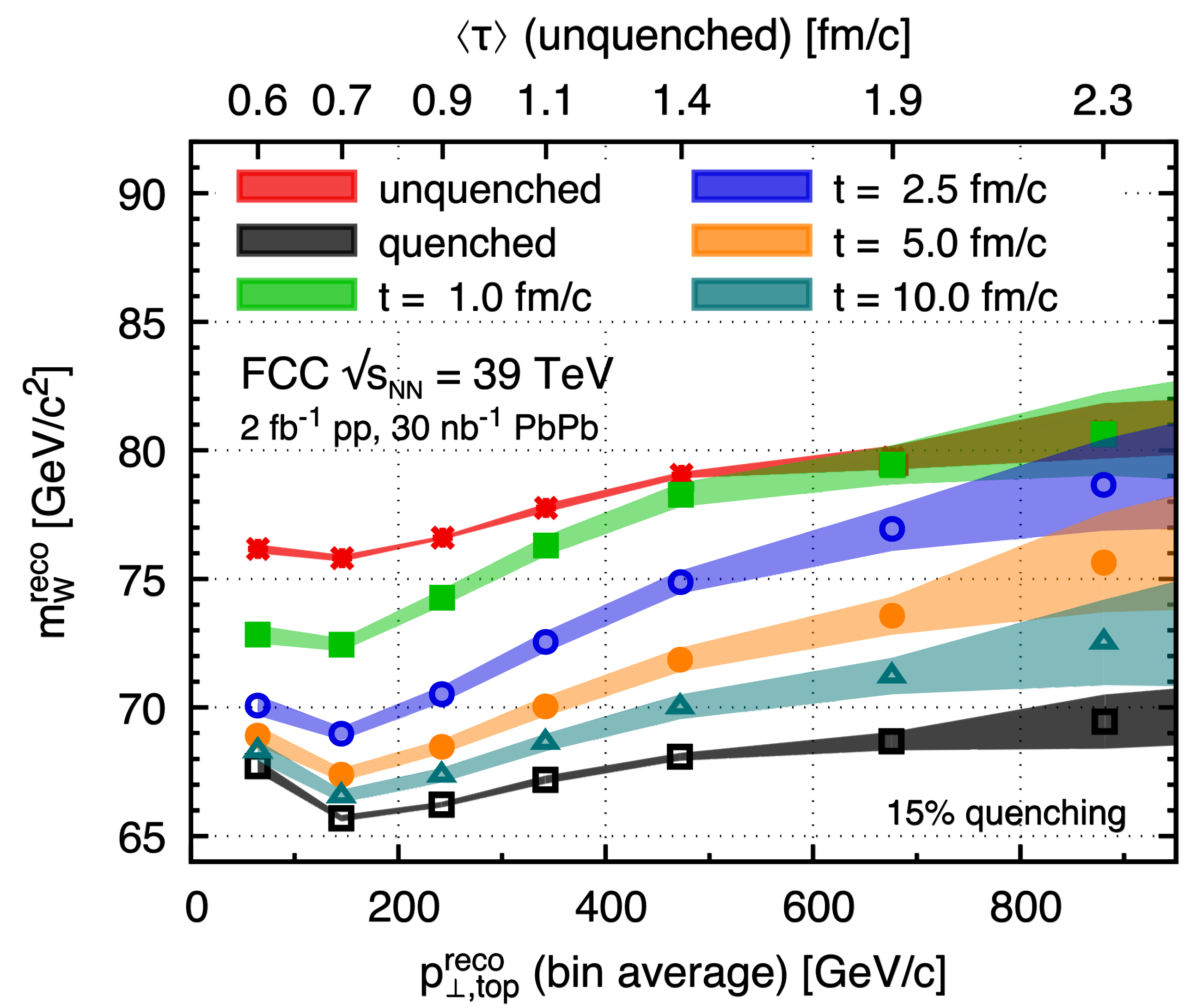

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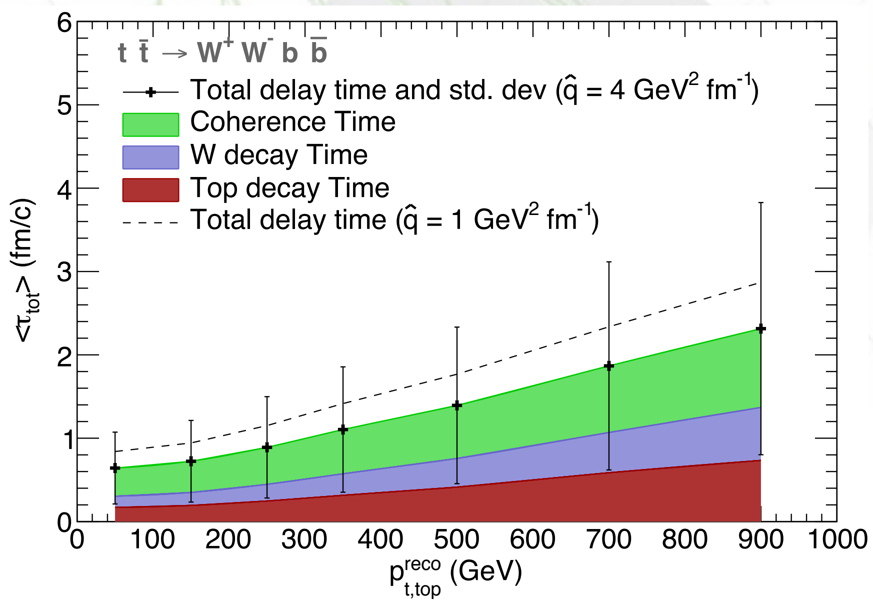

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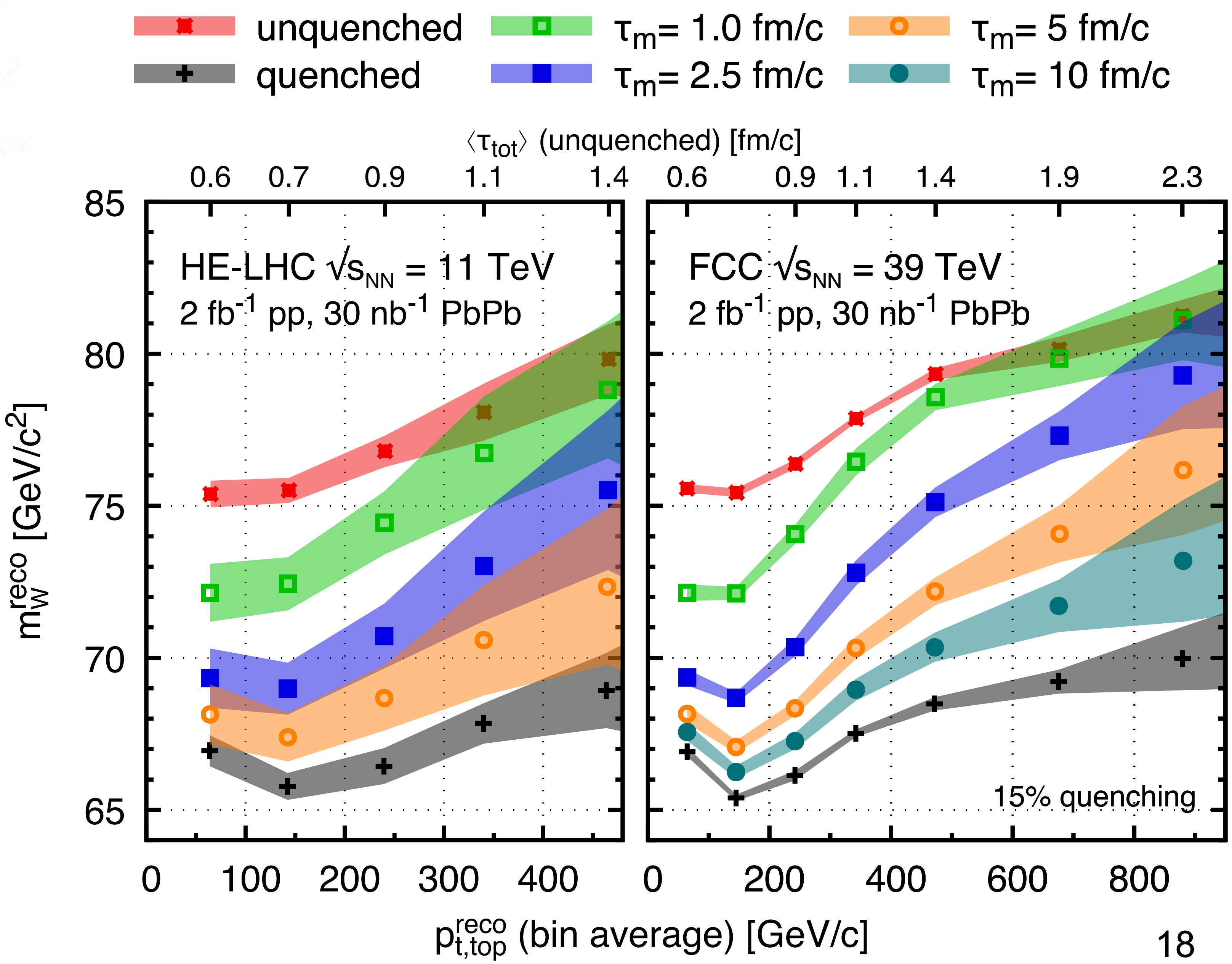

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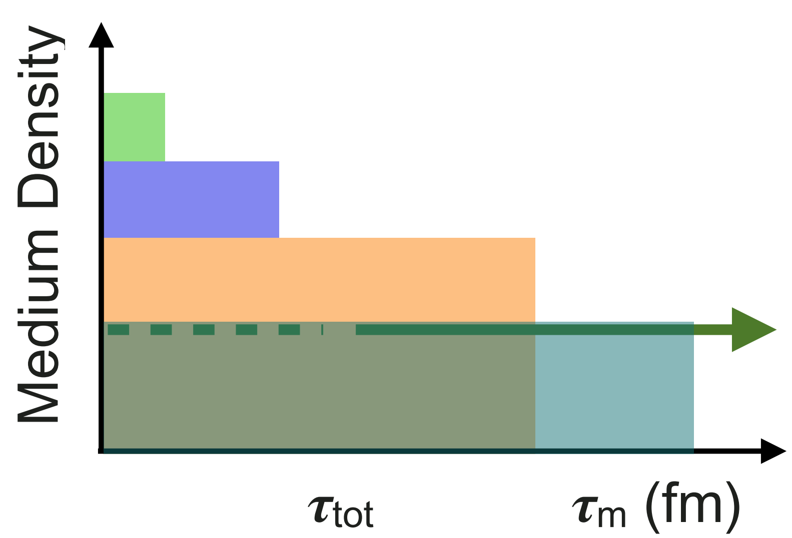

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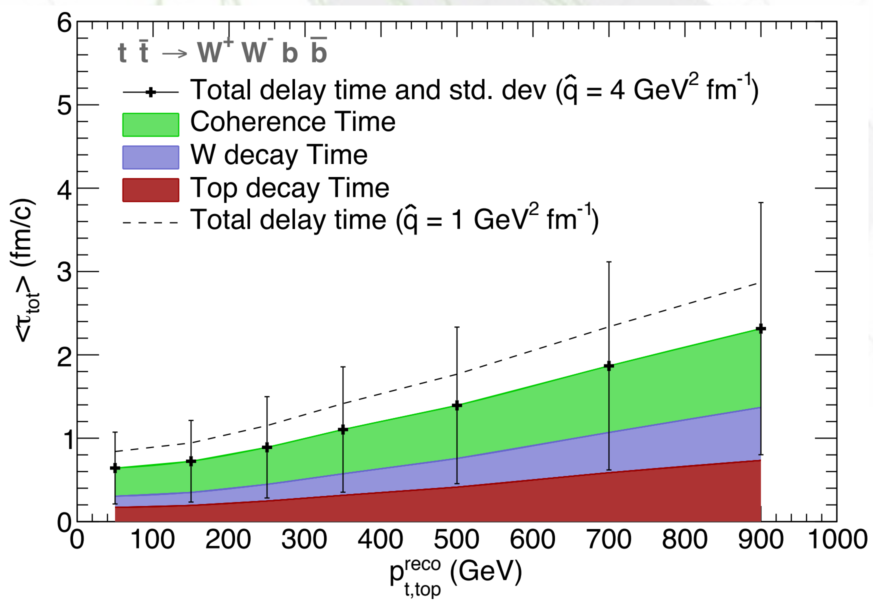
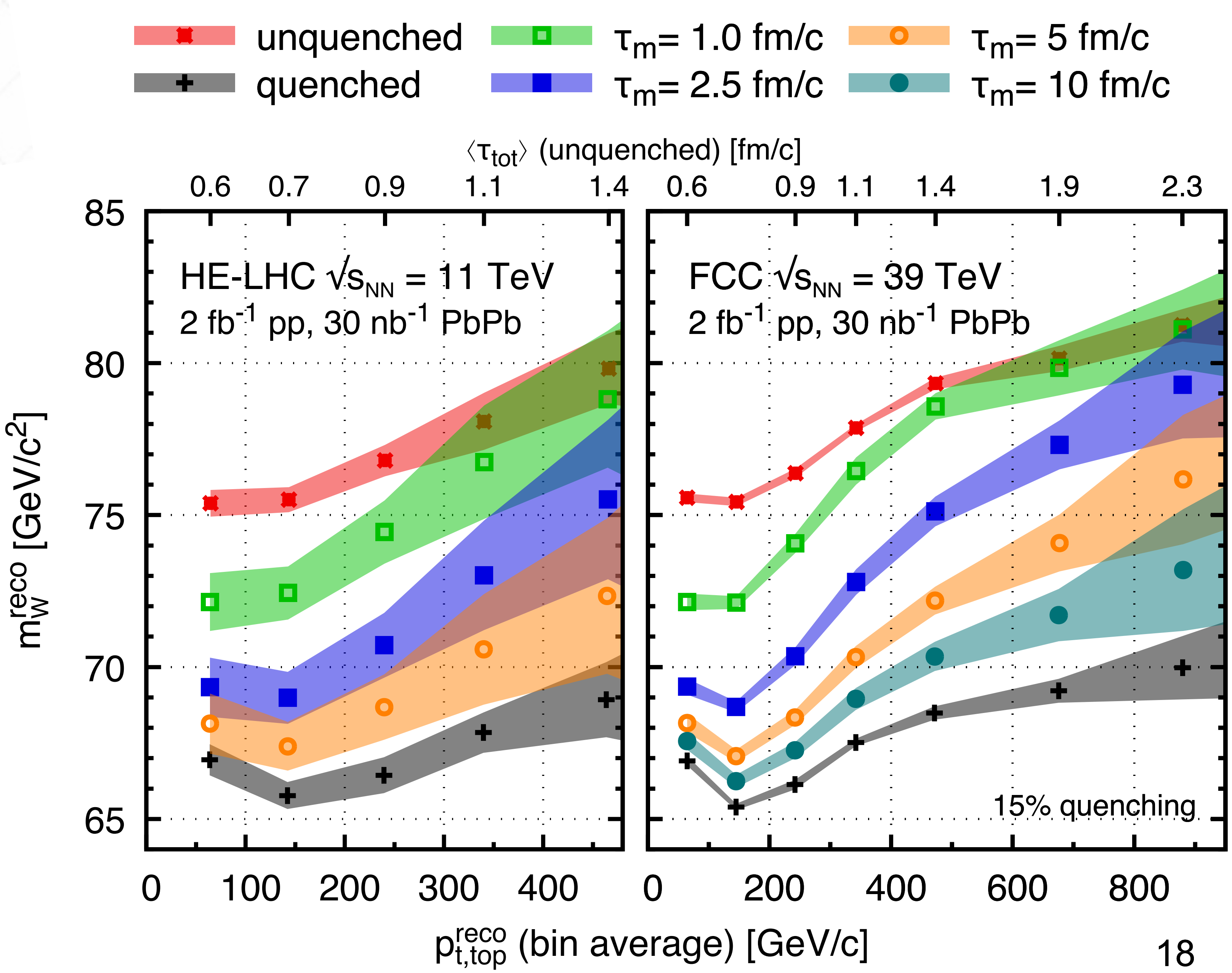


Not possible at LHC (5 TeV)…



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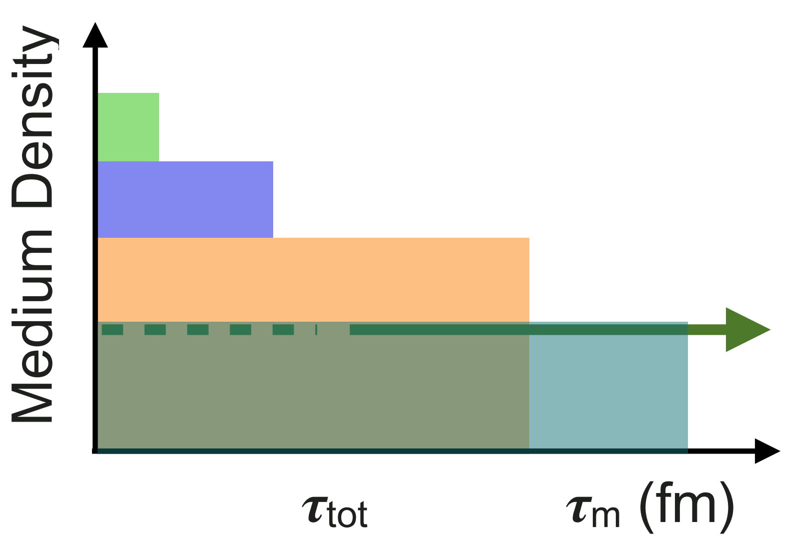
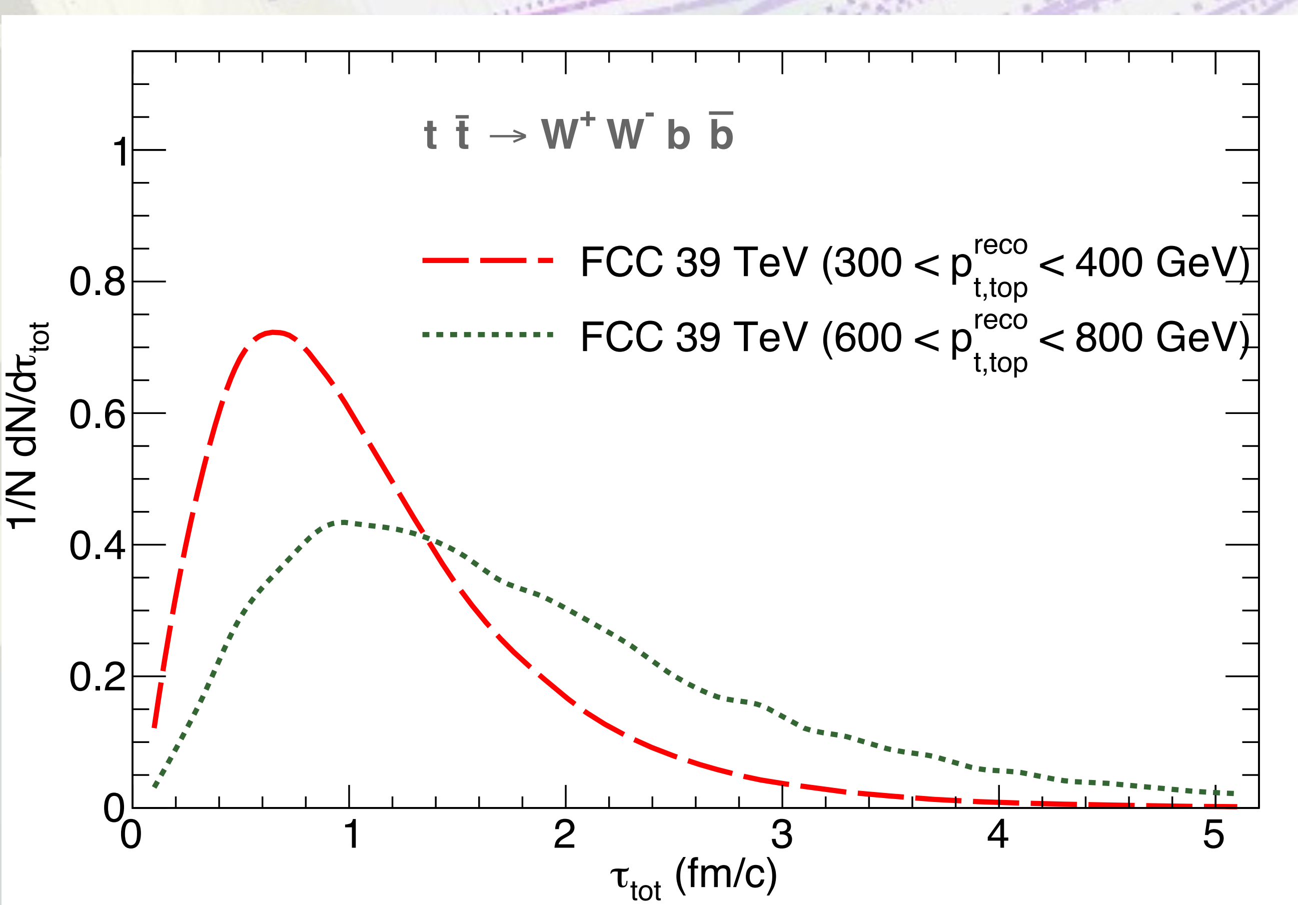
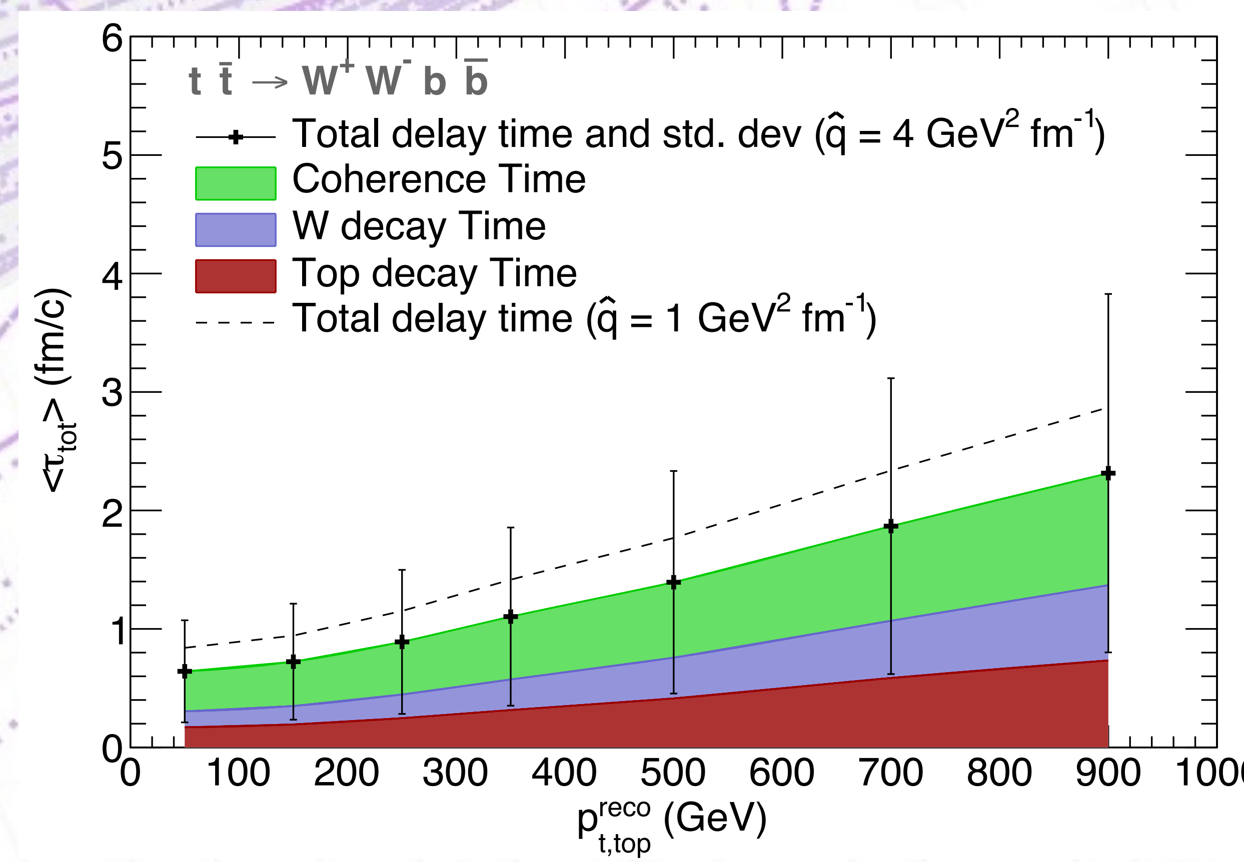


Can we say something with inclusive distributions on the top p_t?





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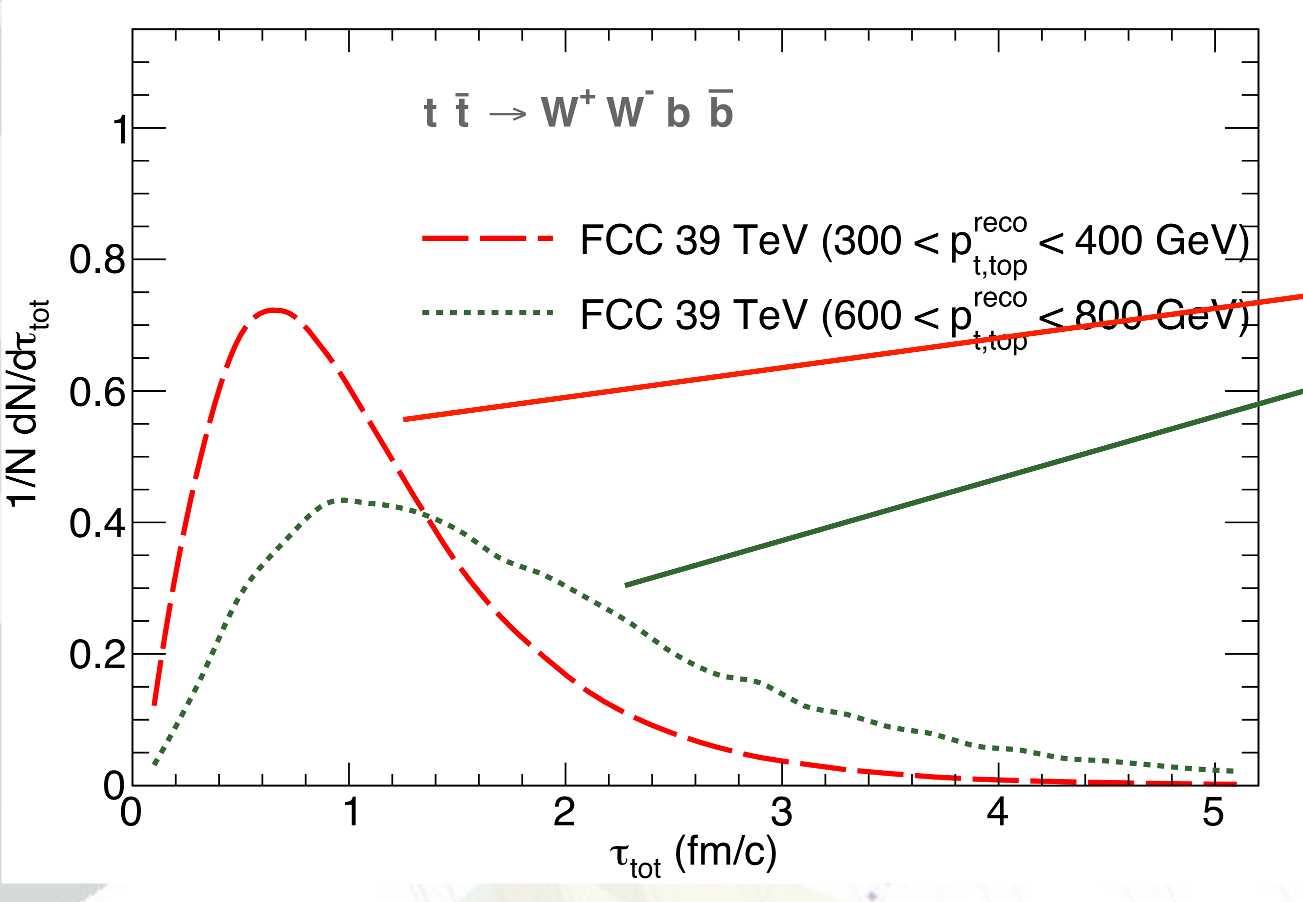

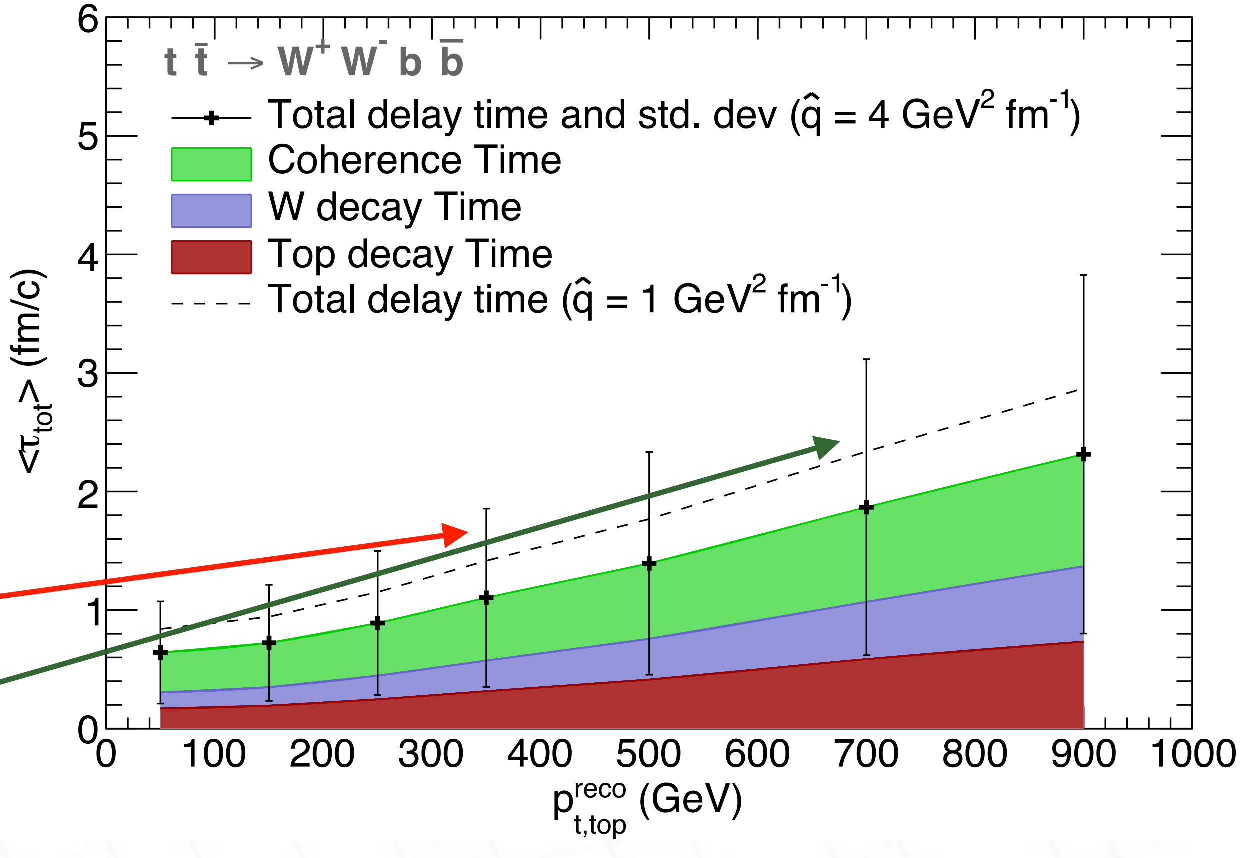

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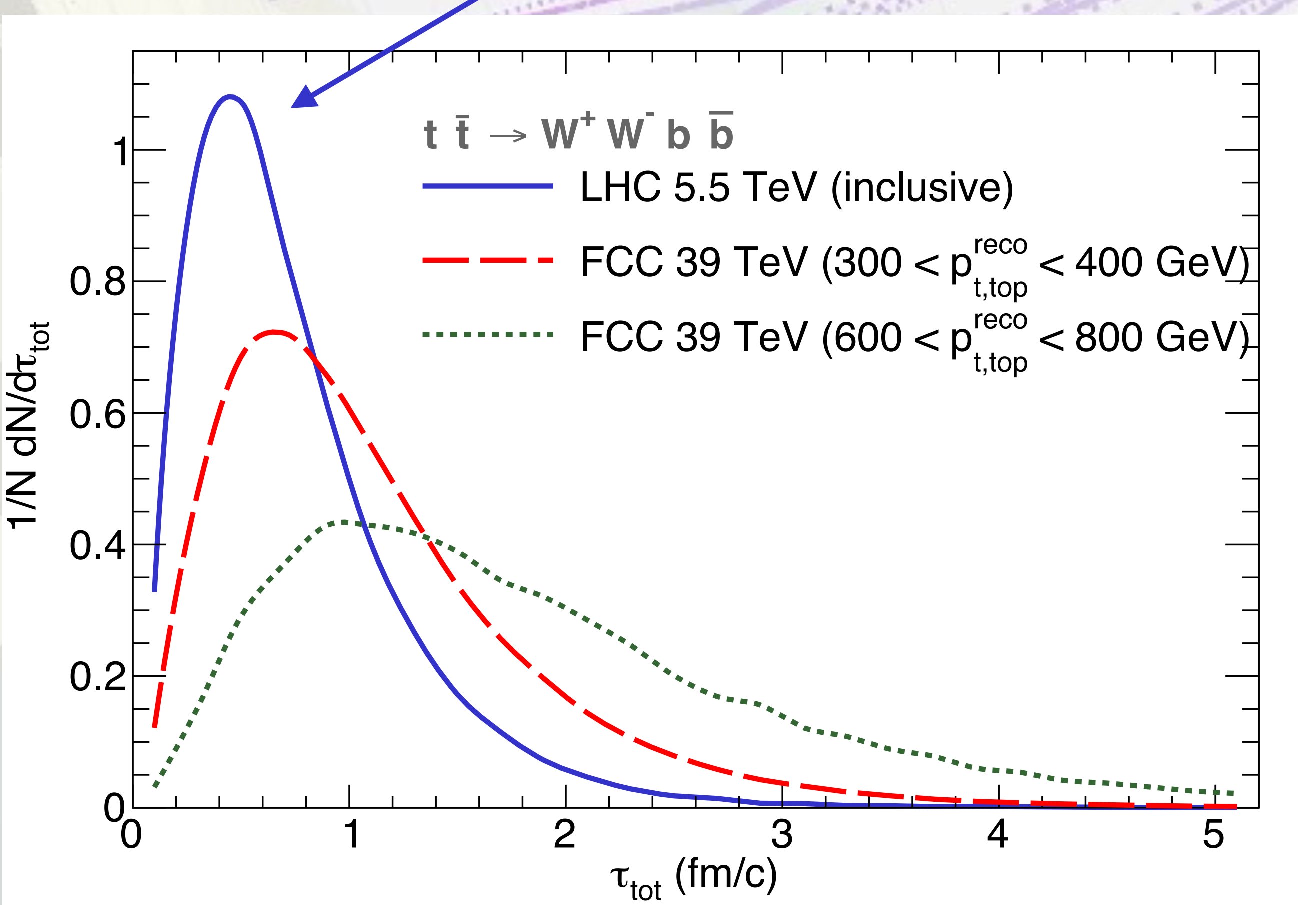

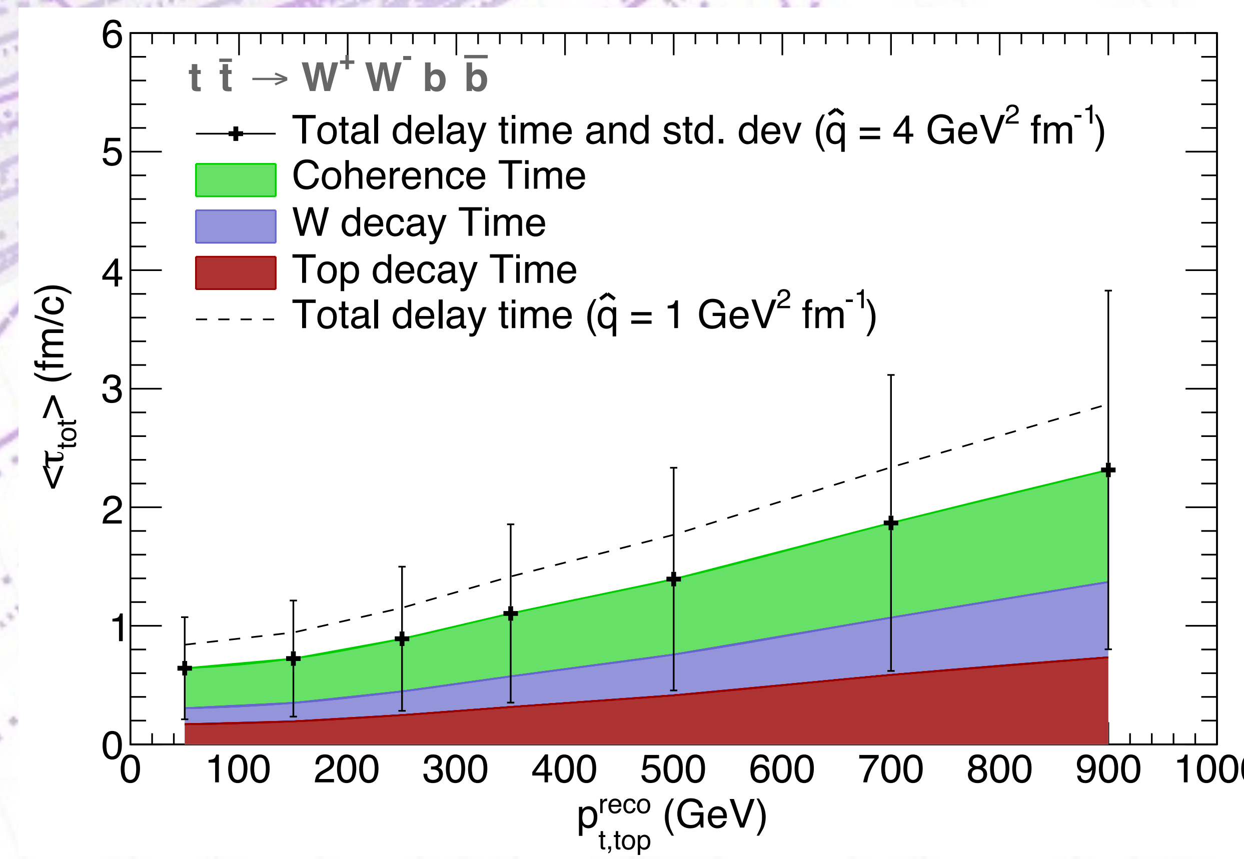

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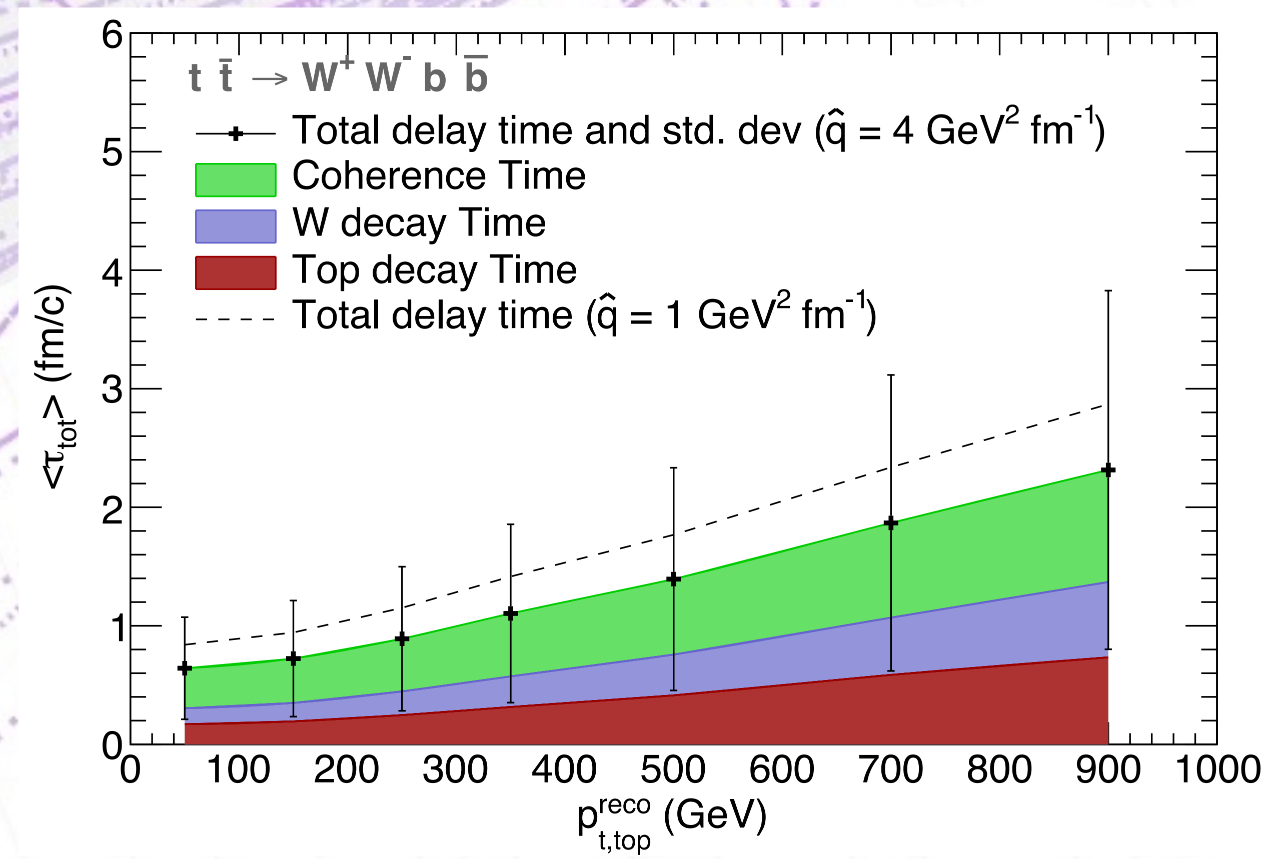
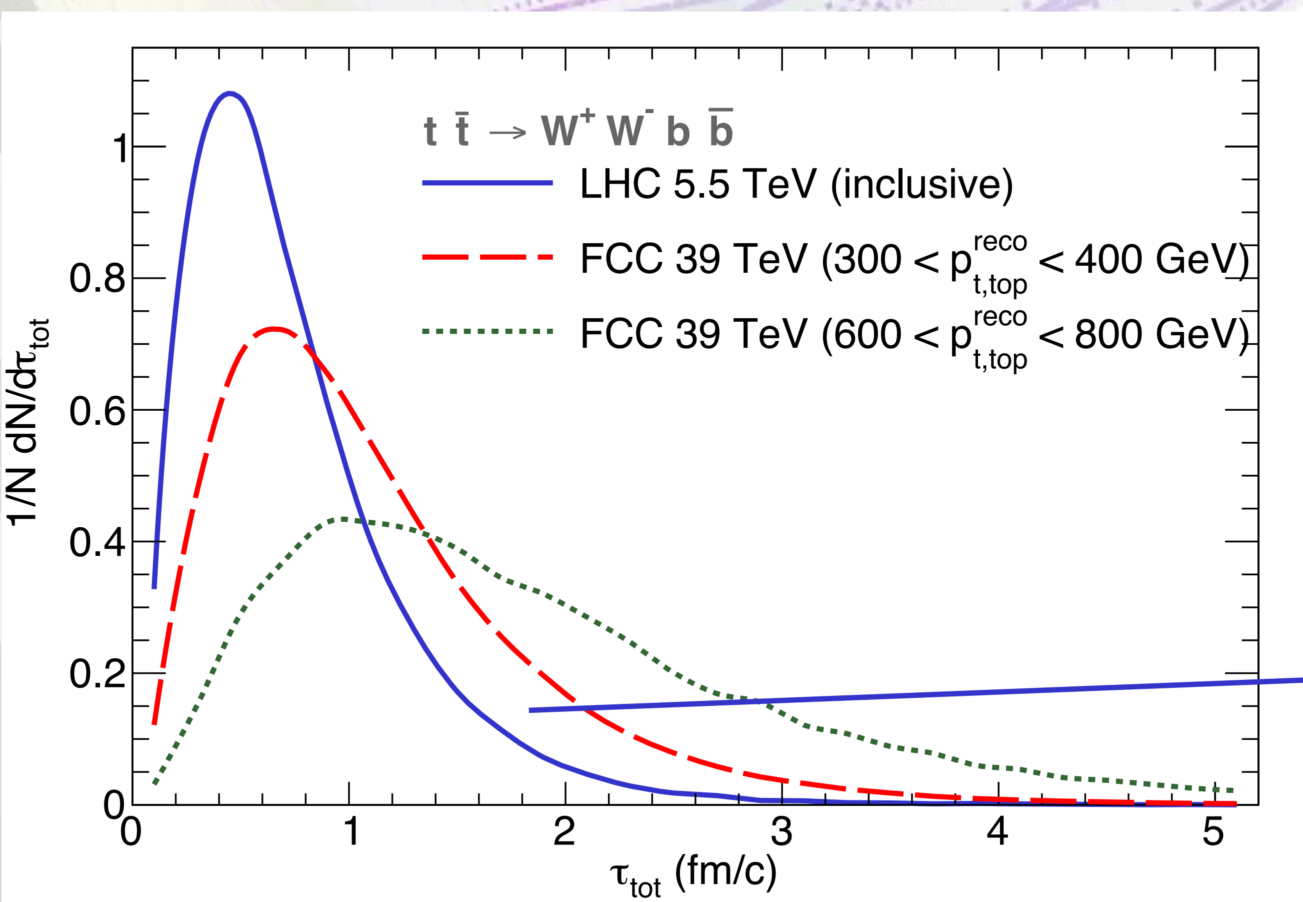
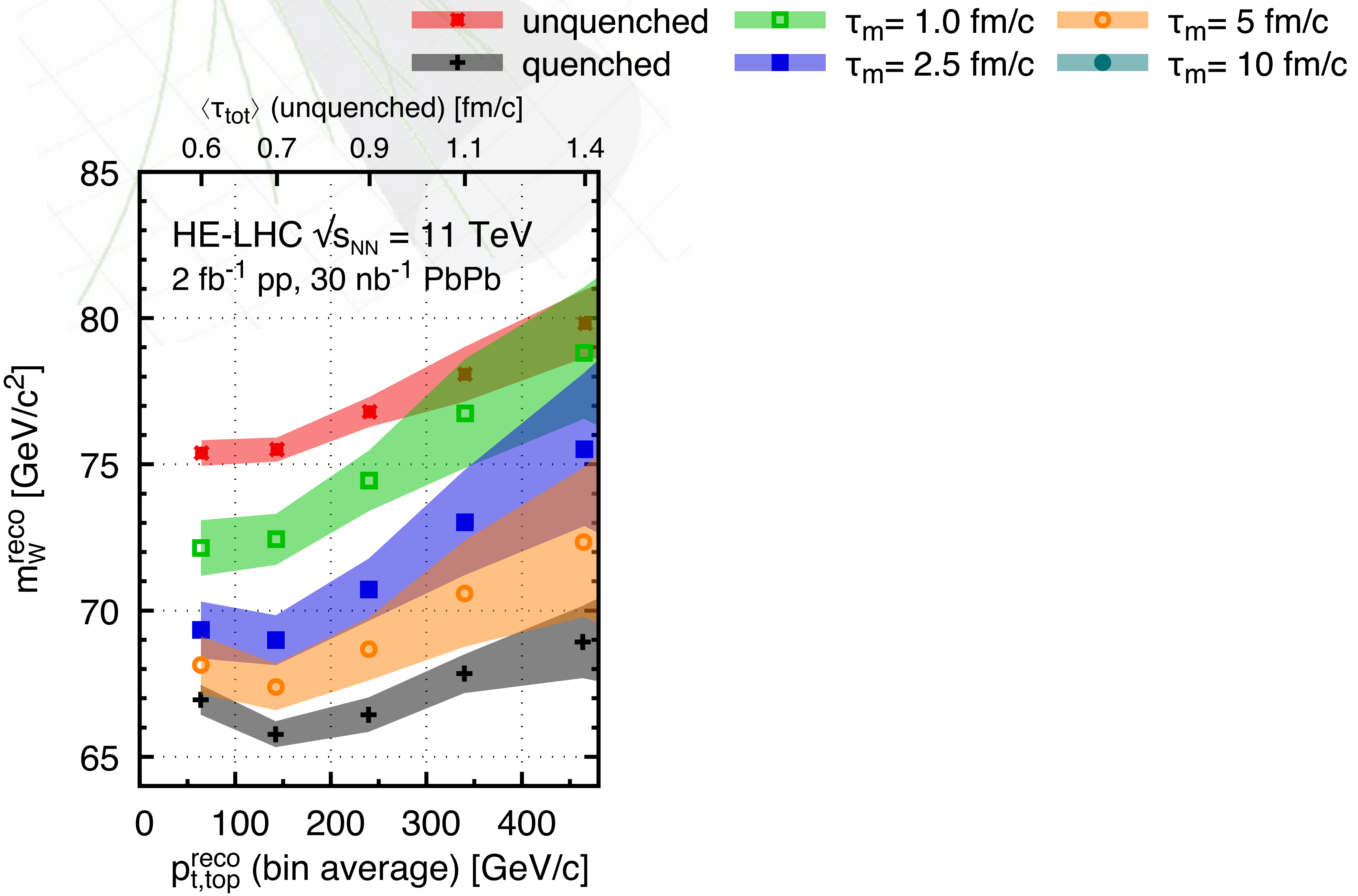




But there is a large dispersion that one can play with.

From p_T Differential to Inclusive

- Needed luminosity for LHC (PbPb) run?



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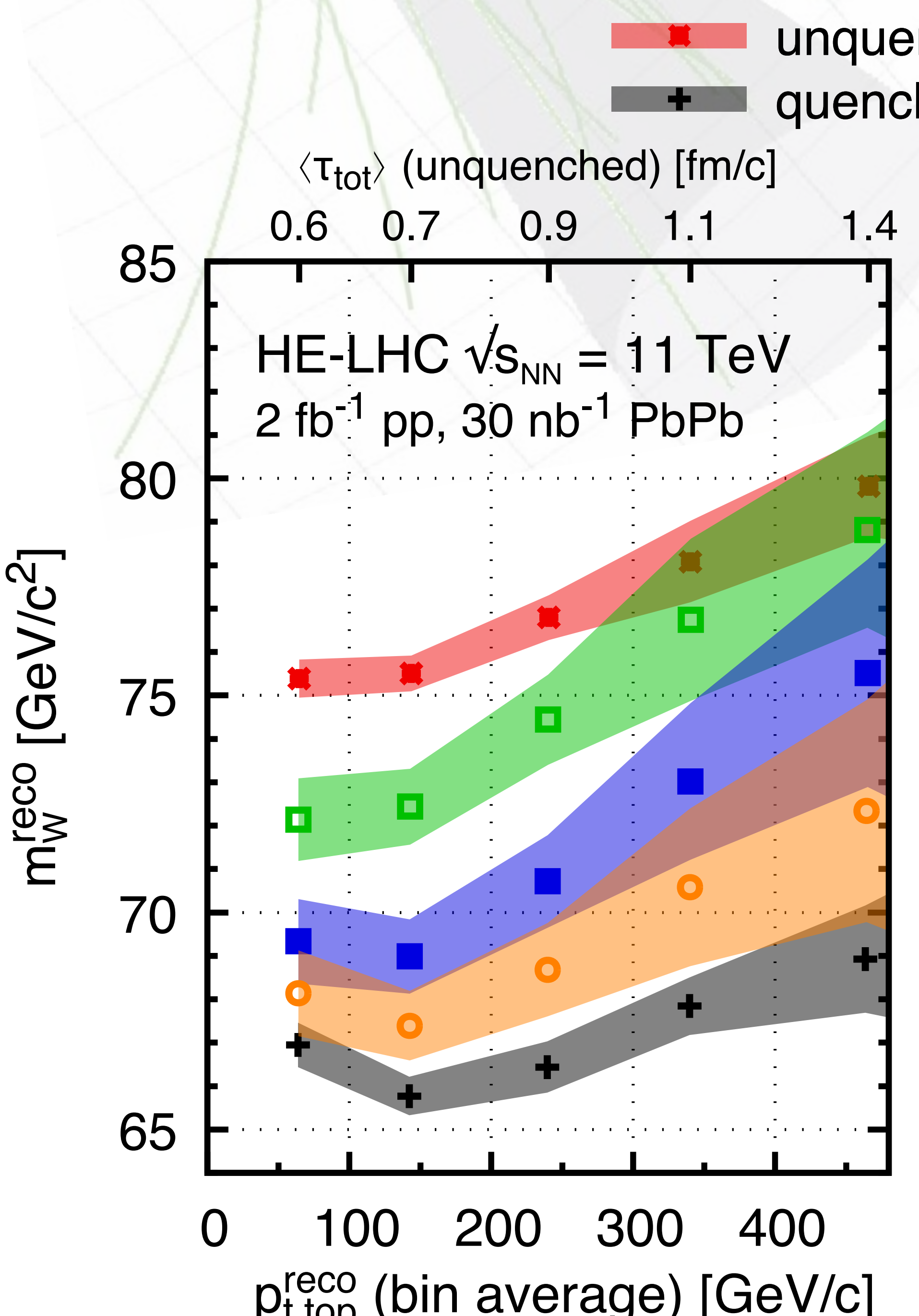
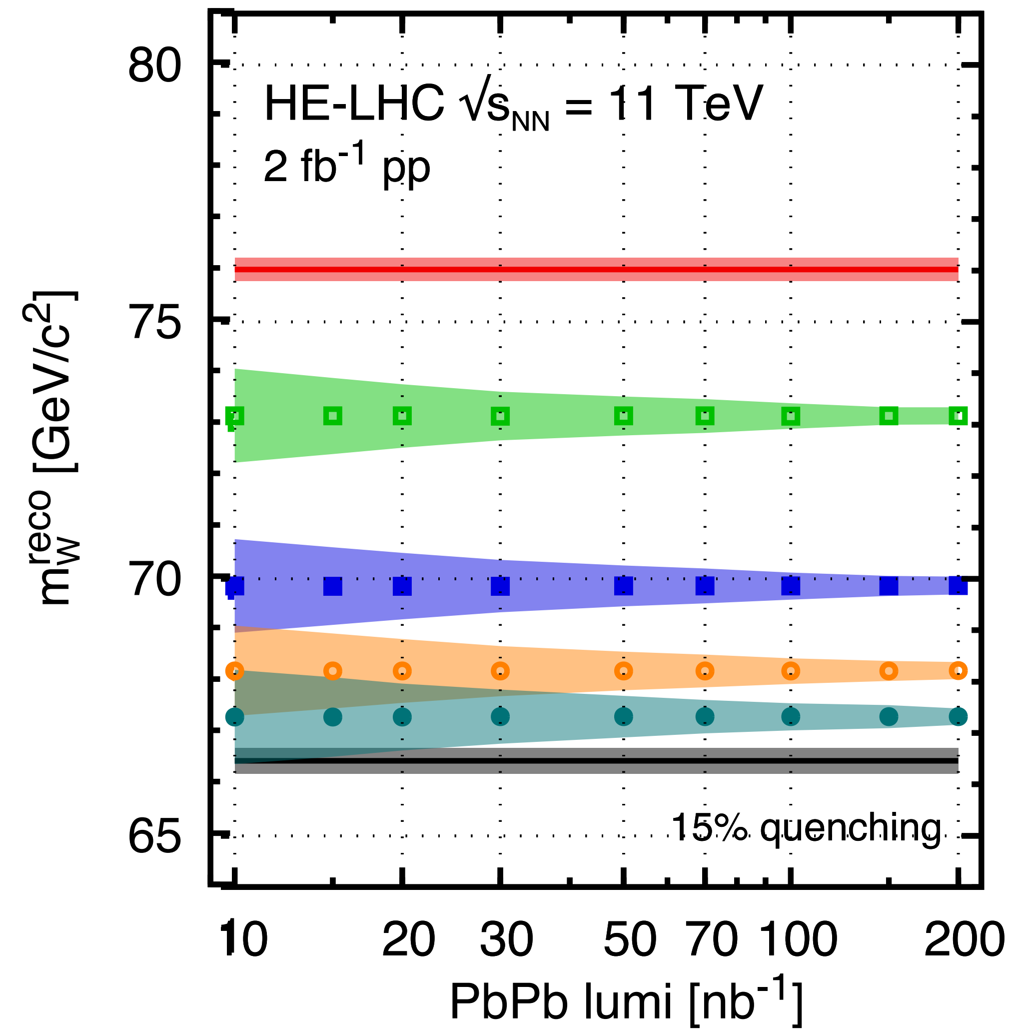


Inclusive

(integrating over top p_T)

“bands” = 1σ



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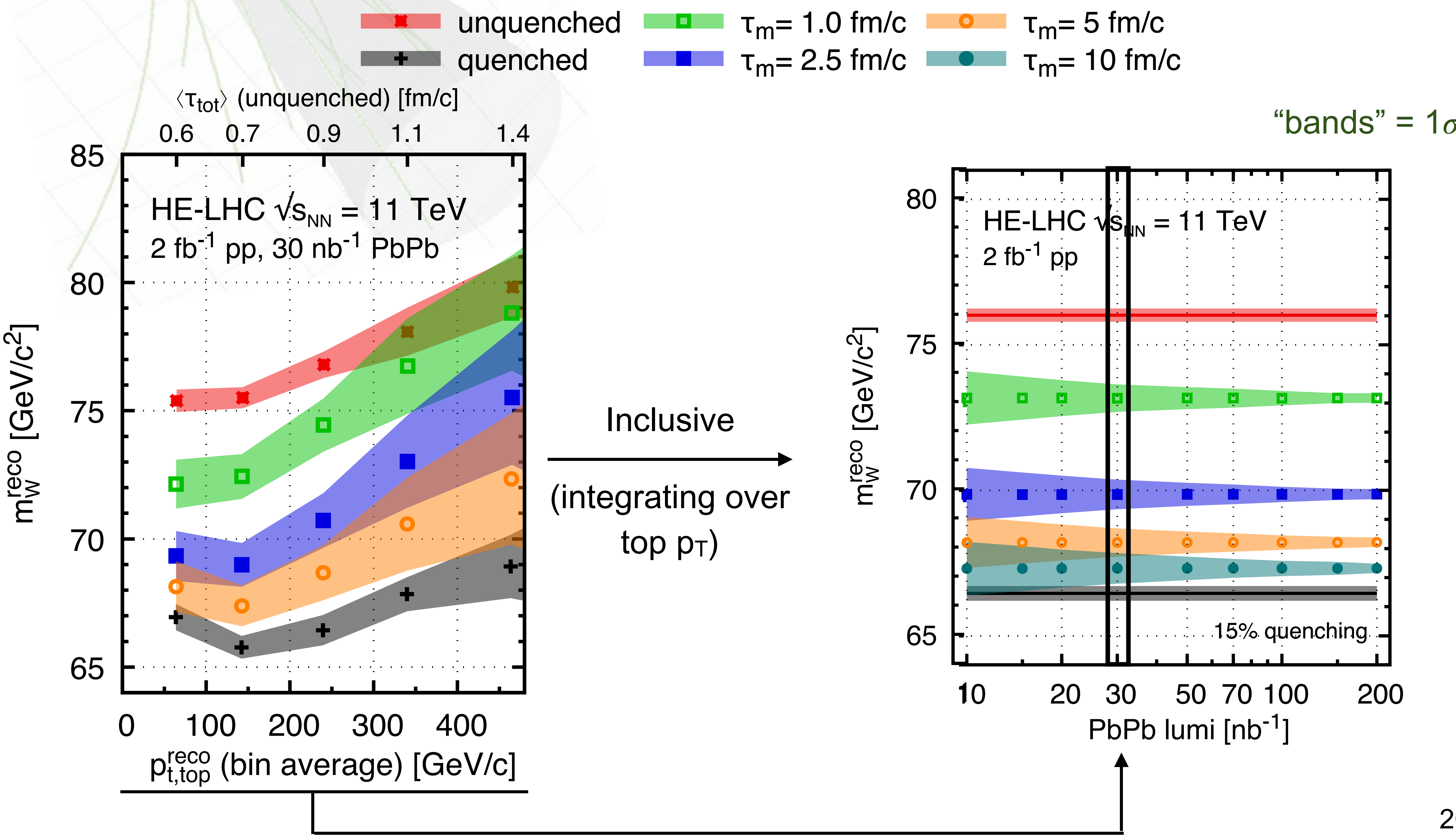

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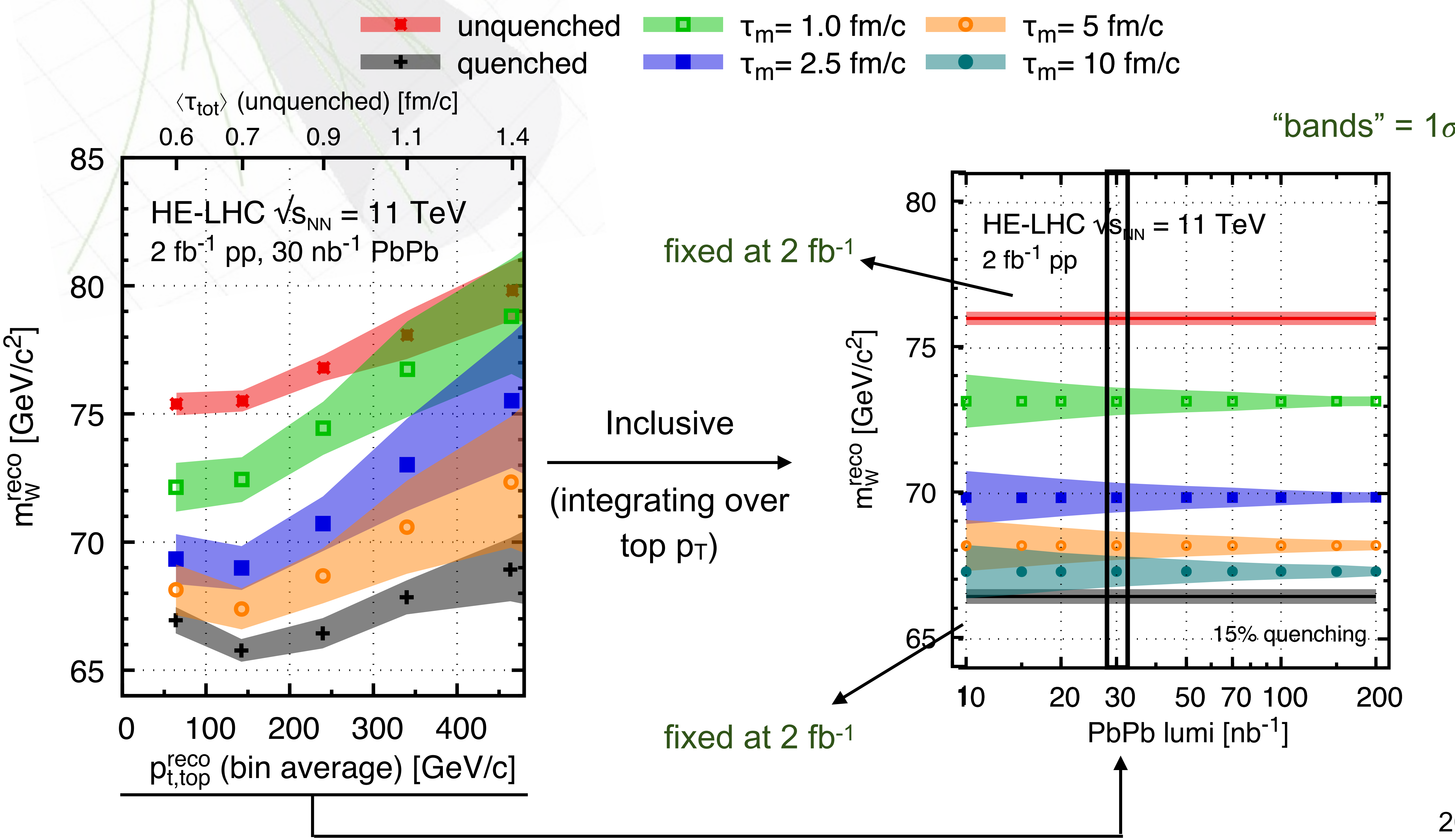

Statistical Significance:

- LHC 5.5 TeV (L_{PbPb} = 10 nb^{-1}) vs HE-LHC 11 TeV:

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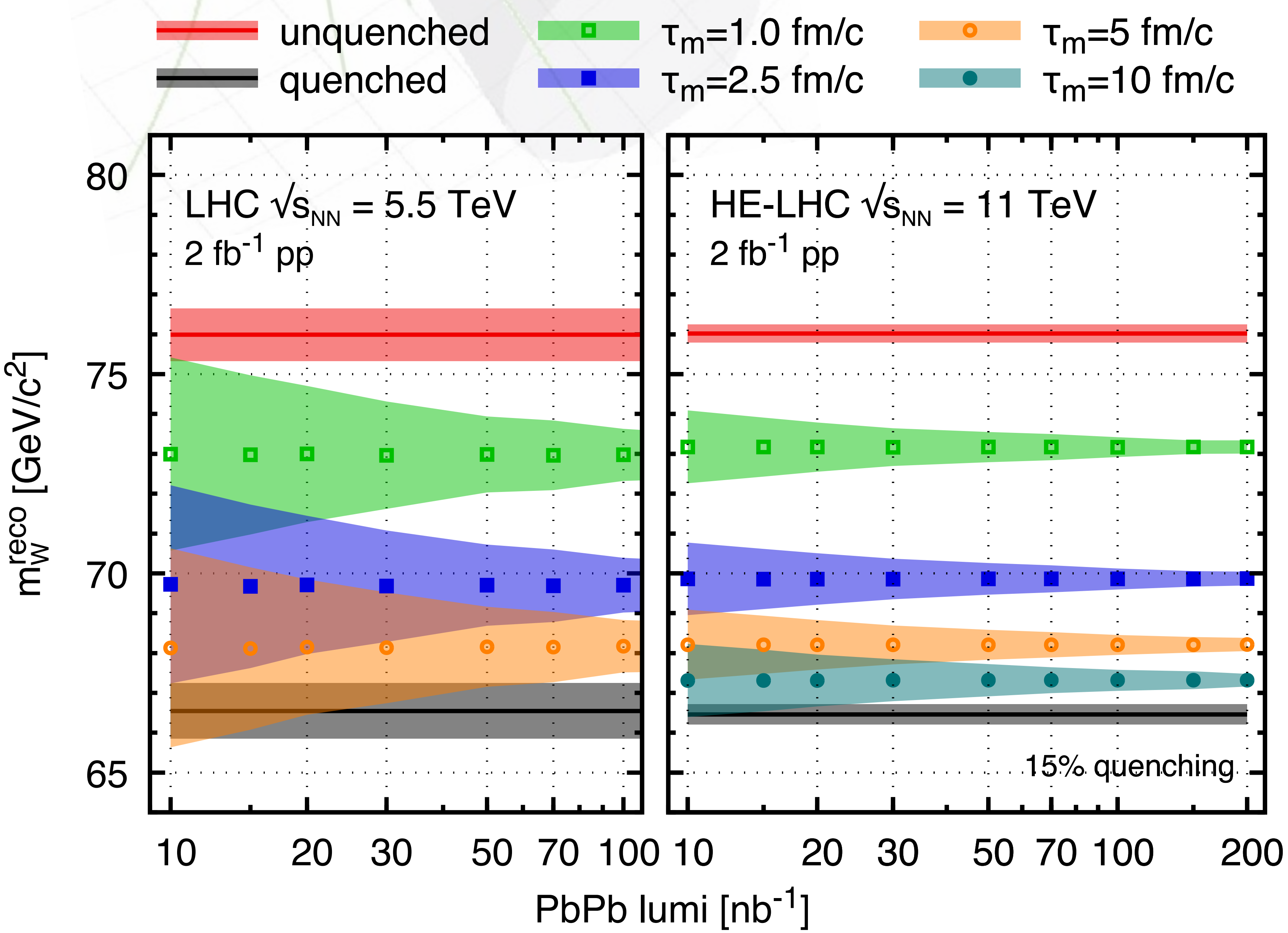
    Distinction between larger values of τ_m need higher energies (HE-LHC) and/or luminosities



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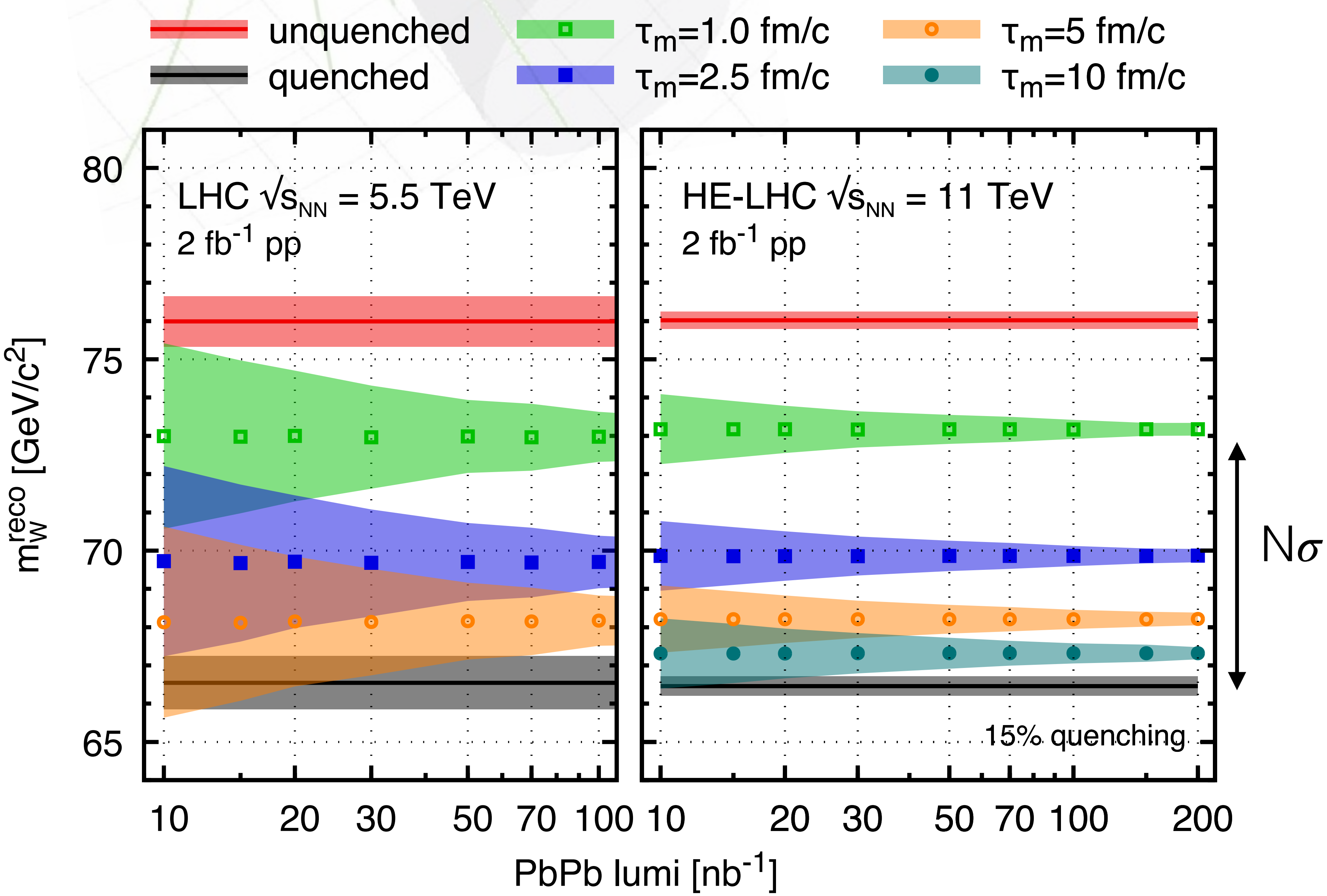


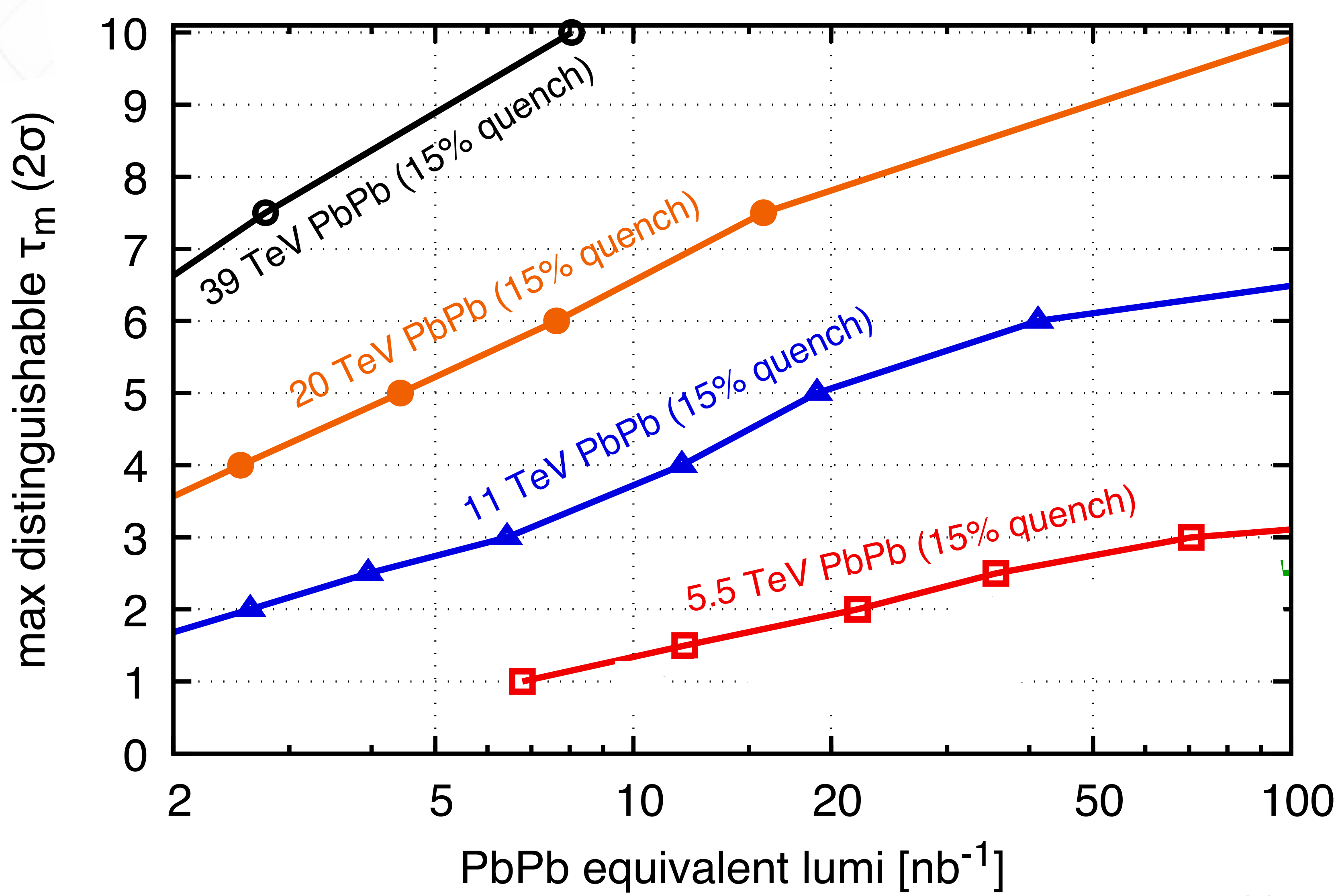
We can estimate now the maximum τ_m that can be distinguished at 2σ from the baseline full quenched result

(Include the best p_T cut that maximizes the $N\sigma$)

Maximum Timescales

- Translate previous results into:
  - Maximum brick time, $\boldsymbol{\tau}_m$, 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}: $\boldsymbol{\tau}_m$ ~ 1.3 fm/c.
  - 30 nb^{-1}: $\boldsymbol{\tau}_m$ ~ 2 fm/c
- Higher $\sqrt{s_{NN}}$ (11, 20 or 39 TeV):
  - Able to probe larger medium lifetimes



Lighter Ions: KrKr

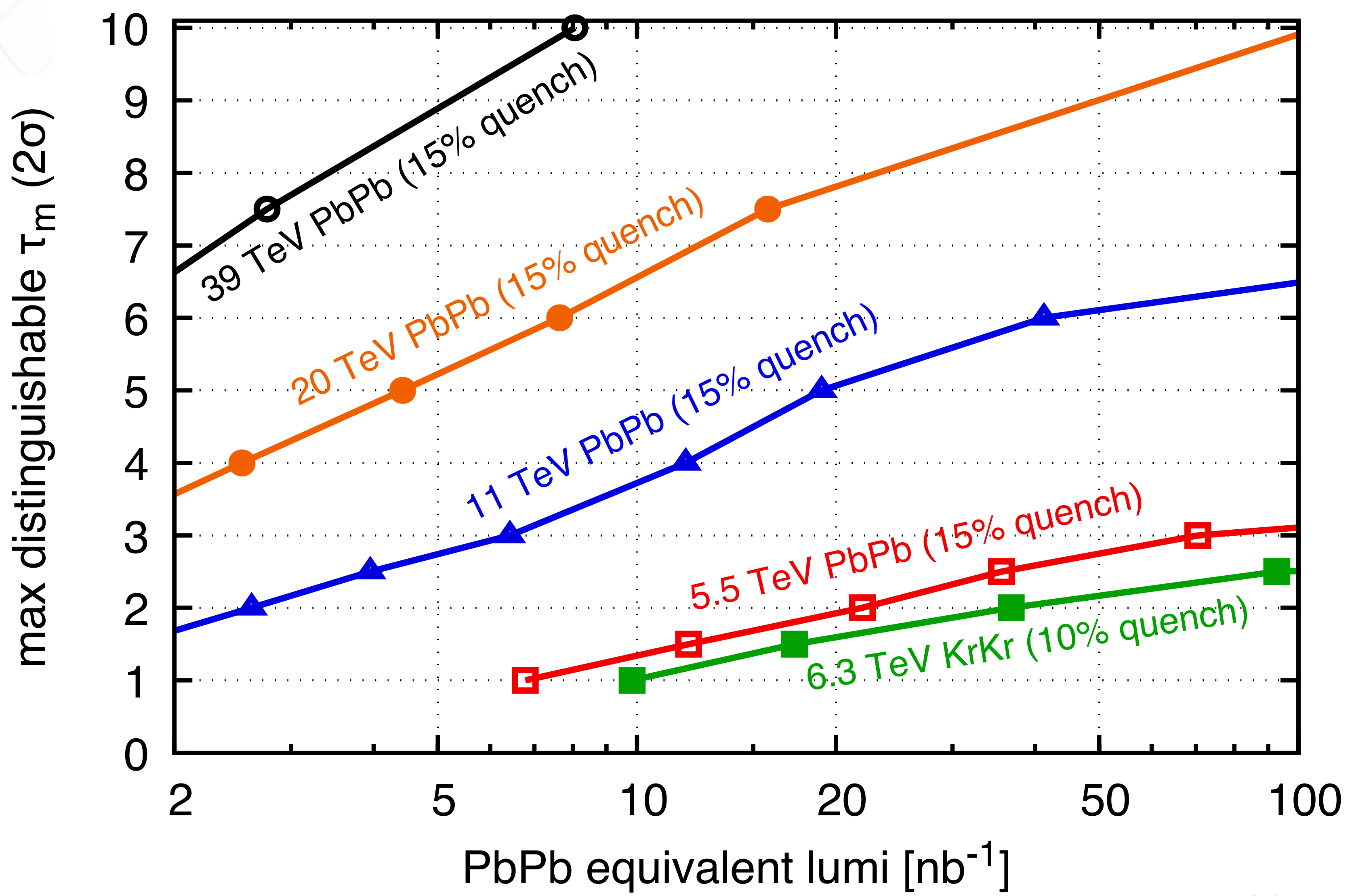
- Successful XeXe run at LHC:
  - higher nucleonic luminosity possible with lighter ions
- For QGP tomography:
  - Smaller timescales than PbPb (more accessible with top quarks);
  - Smaller energy loss

Simple estimate (based on N_{part}):

$\Delta E_{PbPb}/E_{PbPb} \sim 0.15$

$\Rightarrow \Delta E_{KrKr}/E_{KrKr} \sim 0.1$

Consistent with STAR (2010)!



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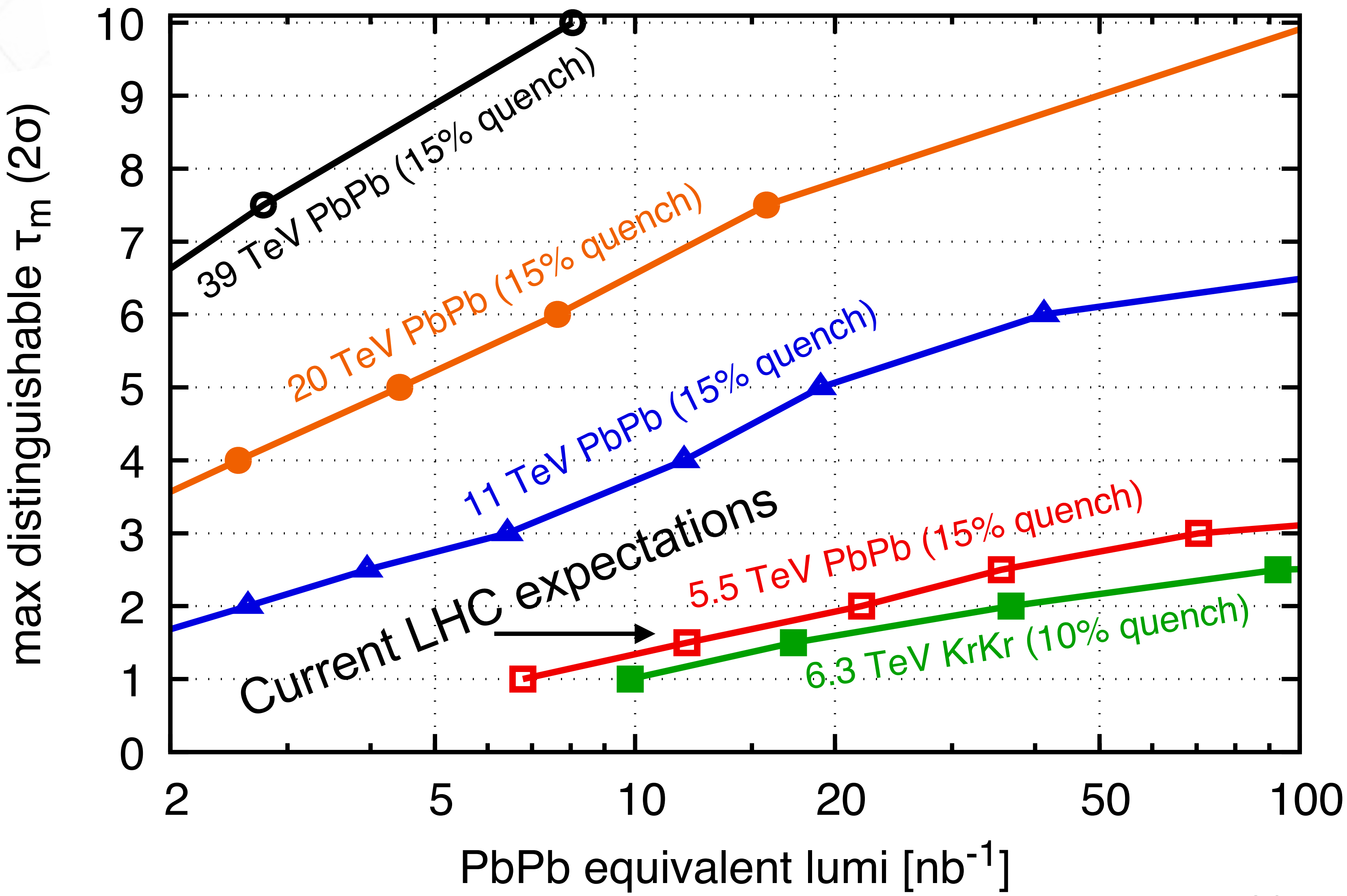

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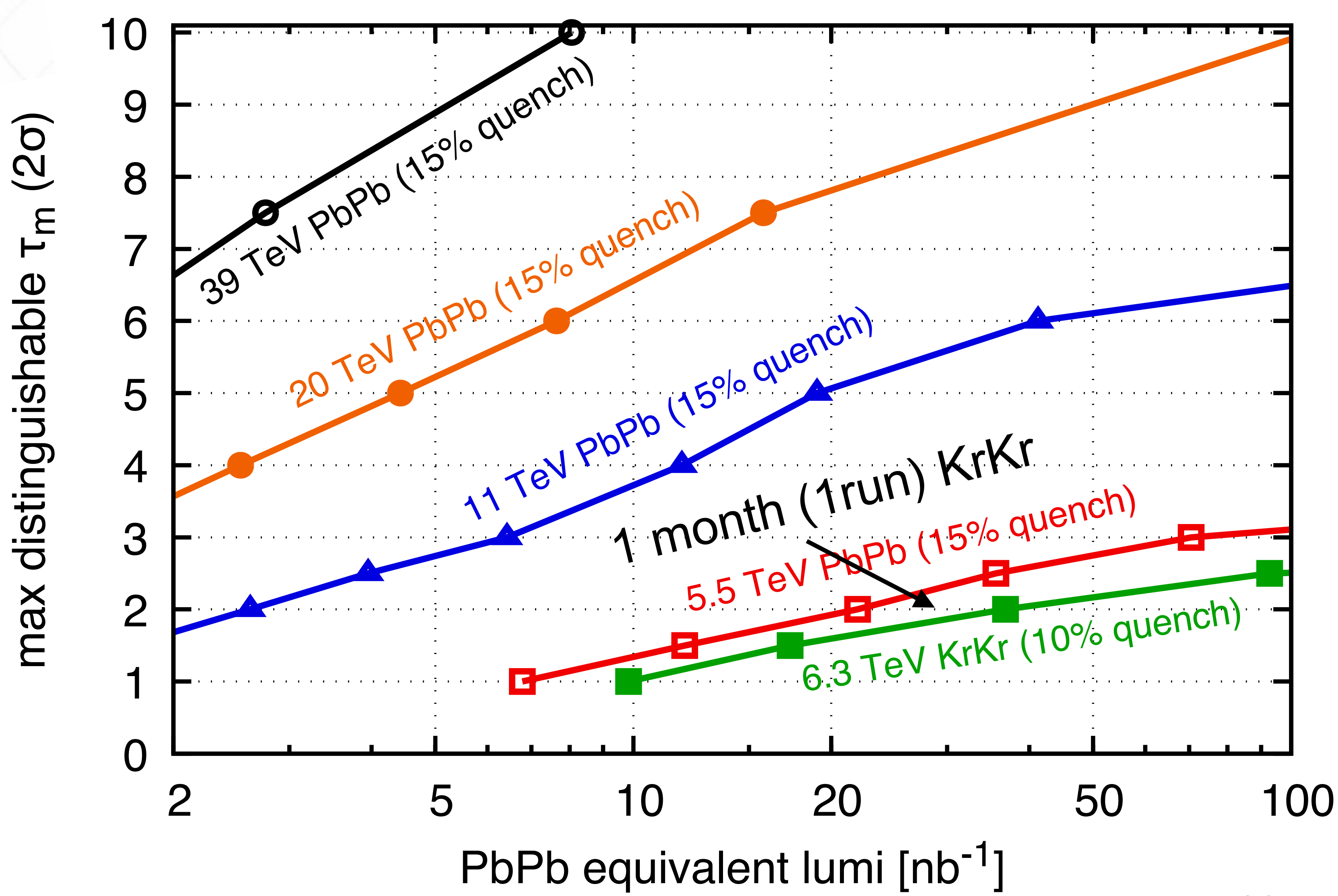

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Thank you!

Acknowledgements

REPÚBLICA PORTUGUESA

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

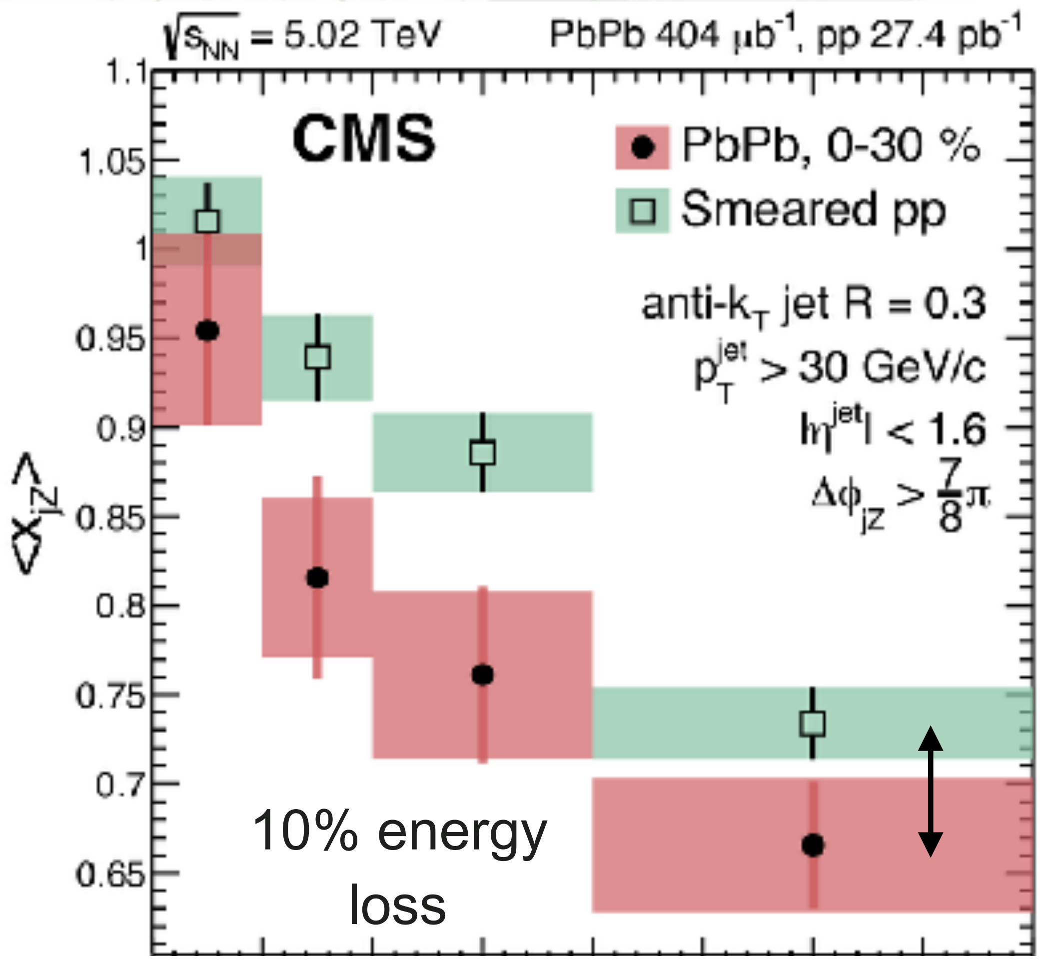
LIP

TÉCNICO LISBOA

Backup

Jet Energy Loss

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



(Average momentum imbalance Z + Jet)

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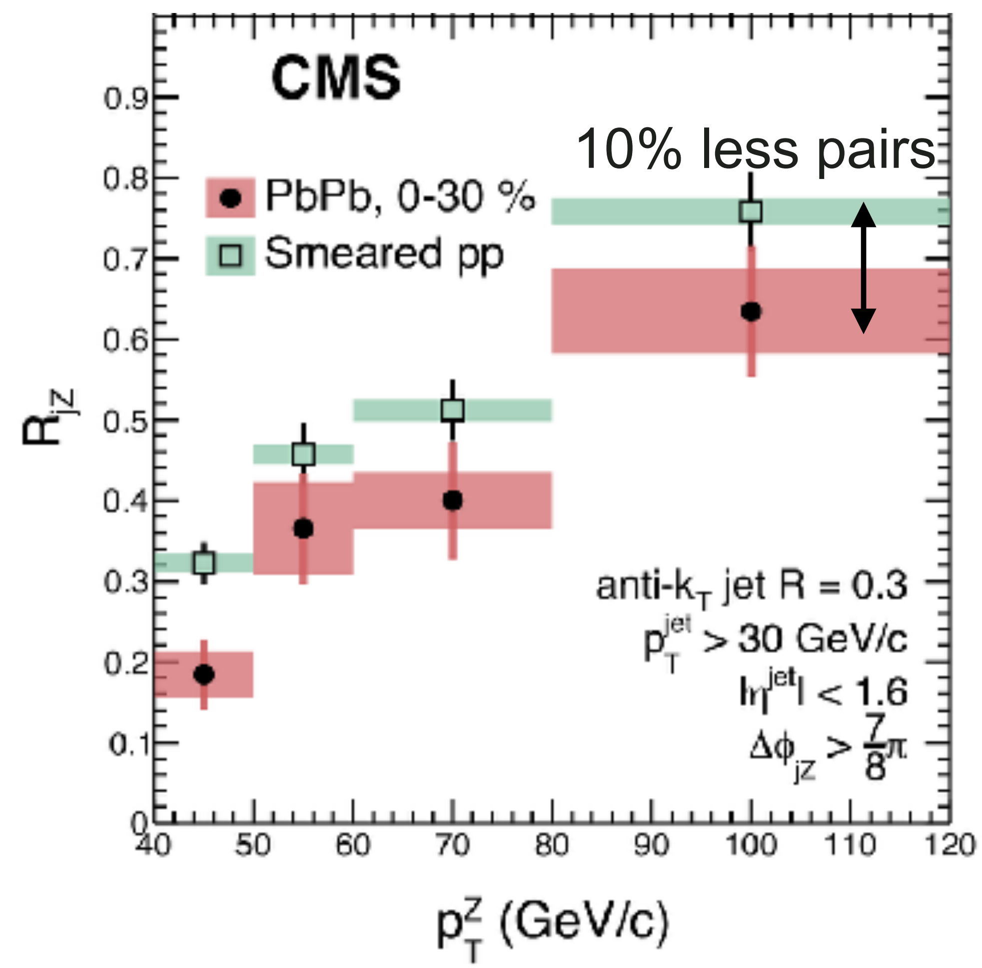
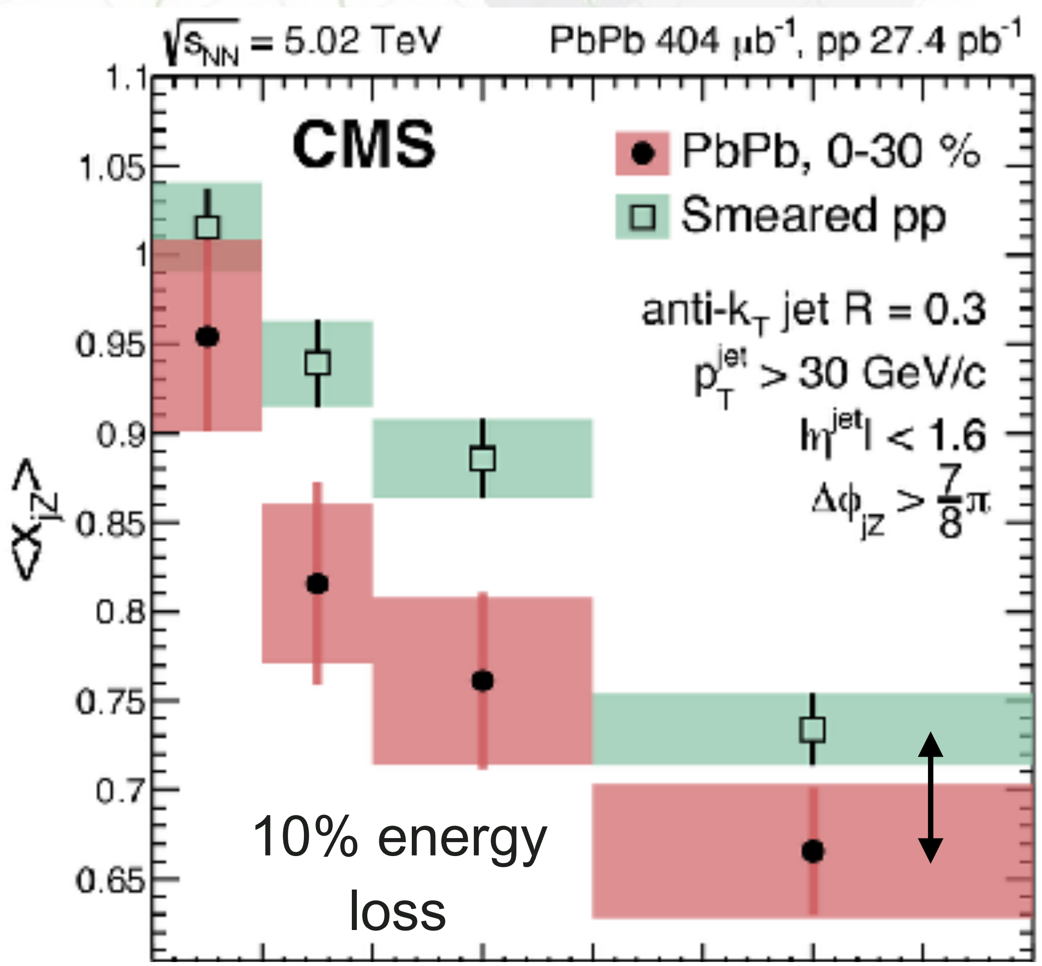
(Average number of Z + Jet pairs)





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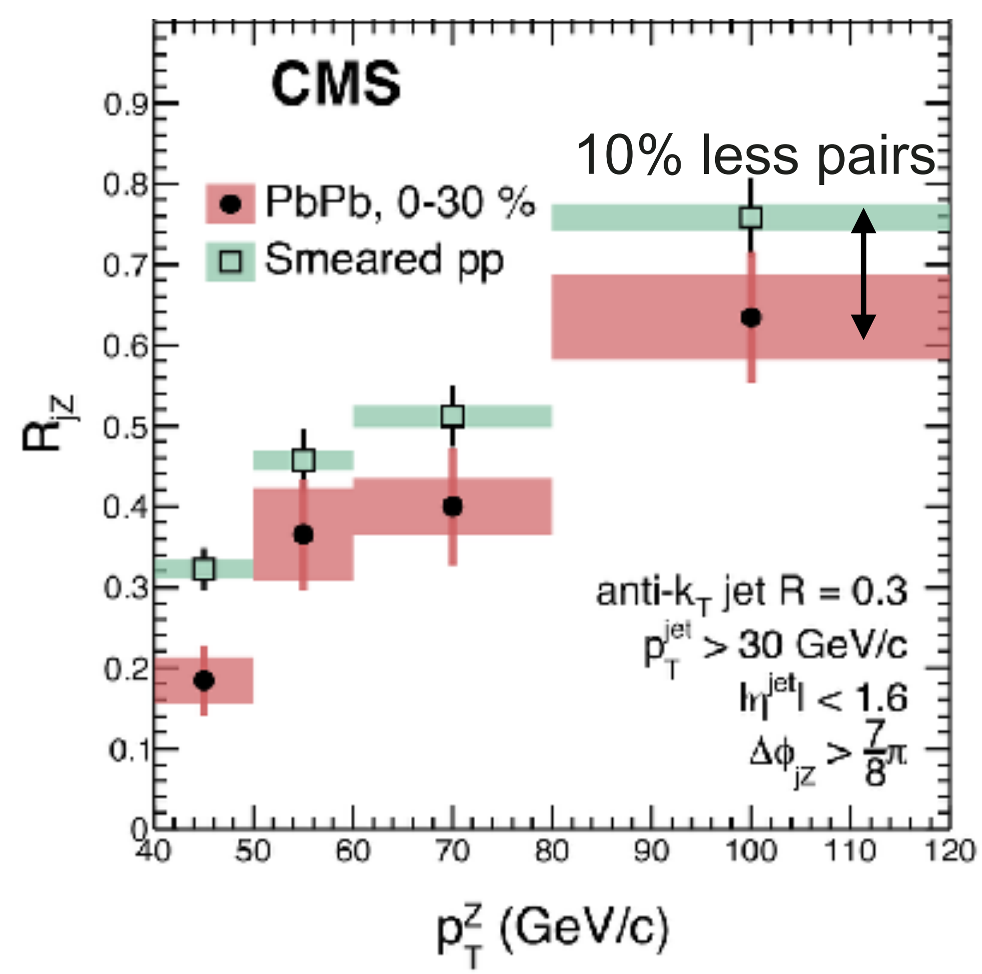
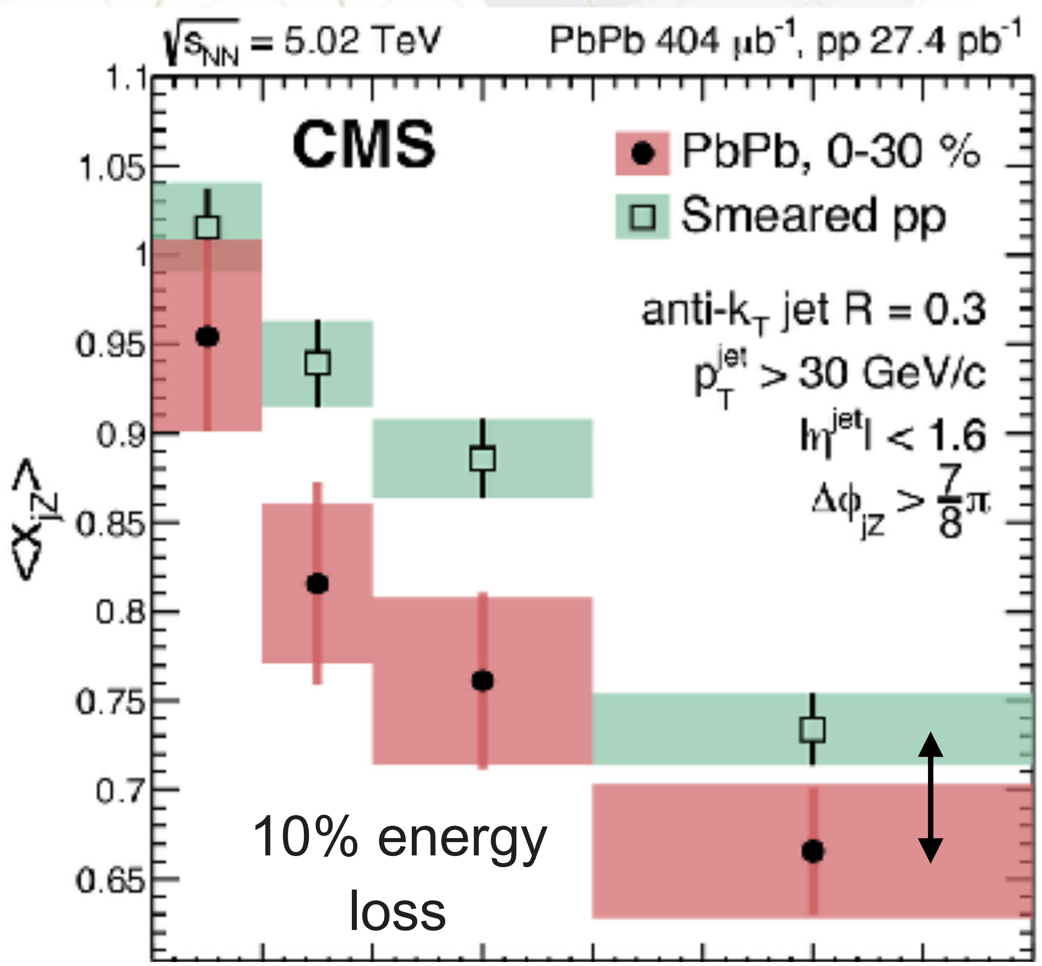




(Average momentum imbalance Z + Jet)

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) as 150%/√(pT) ≡ 15% at 100GeV

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:

  - $Q\,(1 + r\,\sigma_{pt}\,/p_{t,i} + 1\ \mathrm{GeV})^{1/2}$,

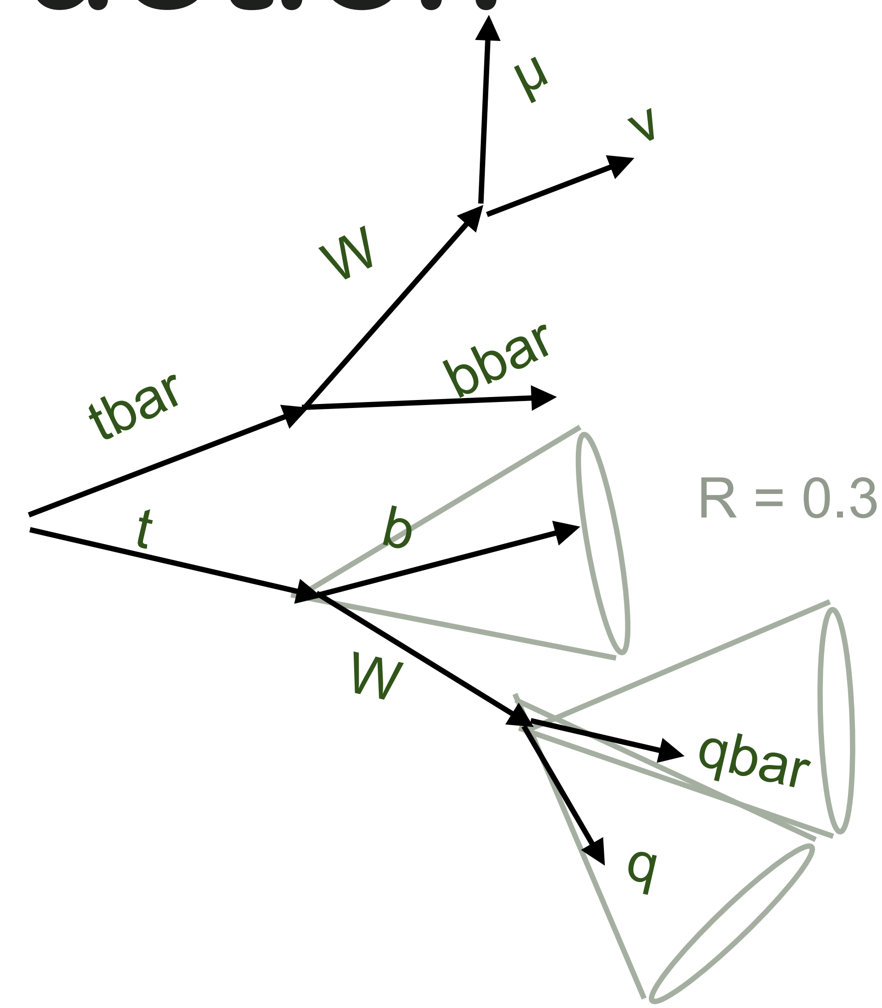
    - Q = Quenching factor (Q0 or $Q(\tau_{tot})$)

    - r = random number from Gaussian with $\sigma = 1$

    - $\sigma_{pt} = 1.5\ \mathrm{GeV}^{1/2}$ (≡ 15% at 100GeV, arXiv:1702.01060: CMS Z+jet)

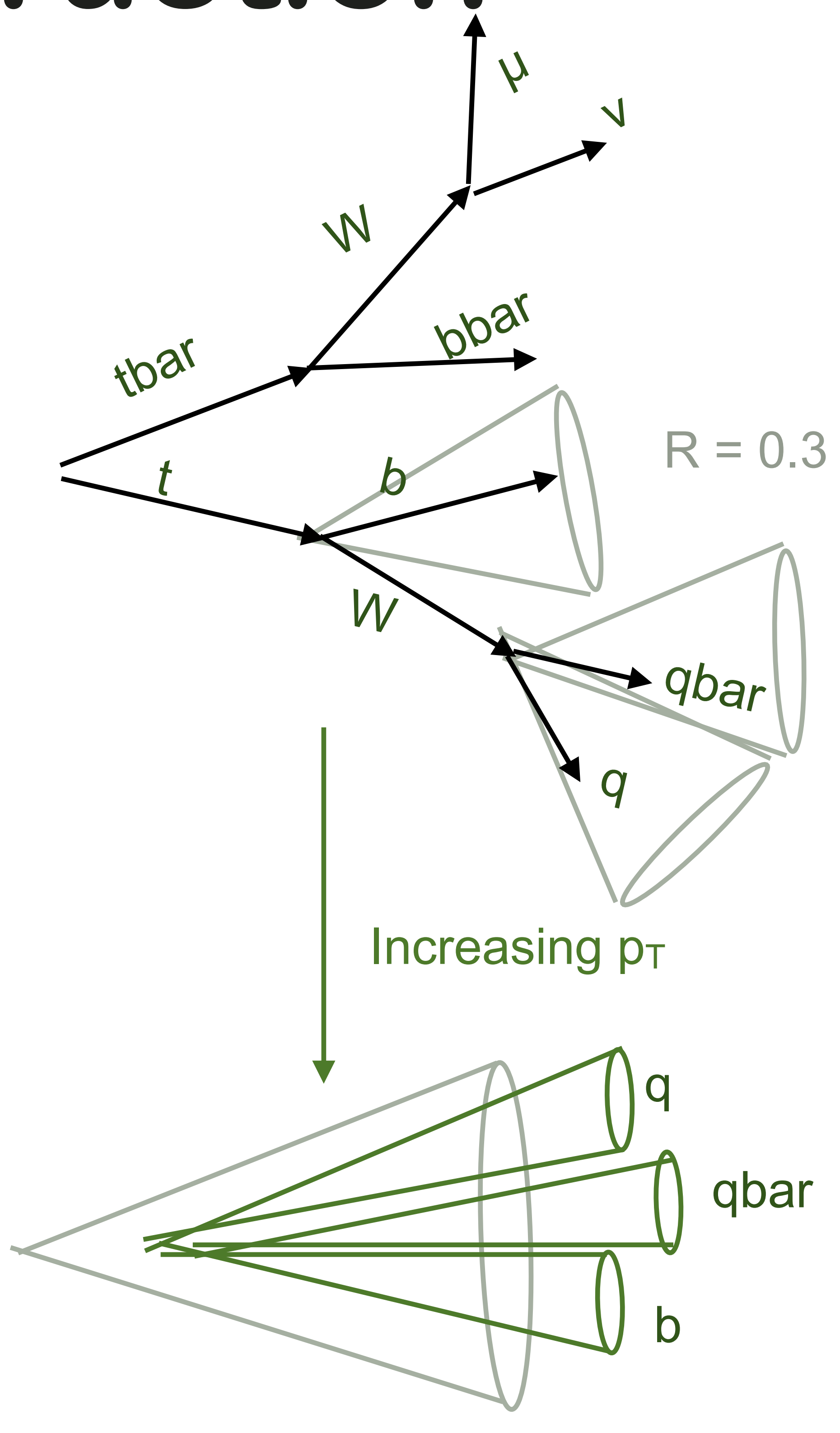
W Mass Reconstruction

- 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 = (20GeV)^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)



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 = $(20GeV)^2$)
  - 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

- Our "old"
  - 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 = $(20\text{GeV})^2$)
  - "muonic" W candidate is the one closest to the muon in Delta R (ATLAS 1502.05923)
- Our "new"
  - 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 $R = 0.4$, $pT > 25$ 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

Lighter Ions

- How about lighter nuclei?
  - Lighter nuclei can go higher in luminosity.
  - Energy loss for lighter systems? CuCu (RHIC) or KrKr (LHC)
    - Glauber model: number of participants (N_p^{KrKr} ~ 110 [0-10]%; N_p^{PbPb} ~ 356 [0-10]%)
    - BDMPS for an expanding medium ($\Delta E \sim L$)
    - Estimate: $L \sim A^{1/3} \Rightarrow \Delta E^{KrKr}/E^{KrKr} \sim (N_p^{KrKr}/N_p^{PbPb})^{1/3}\, \Delta E_{PbPb}/E_{PbPb}$
    - $\Delta E_{PbPb}/E_{PbPb} \sim 0.15 \Rightarrow \Delta E_{KrKr}/E_{KrKr} \sim 0.1$

Consistent with STAR (2010)!

Lighter Ions

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

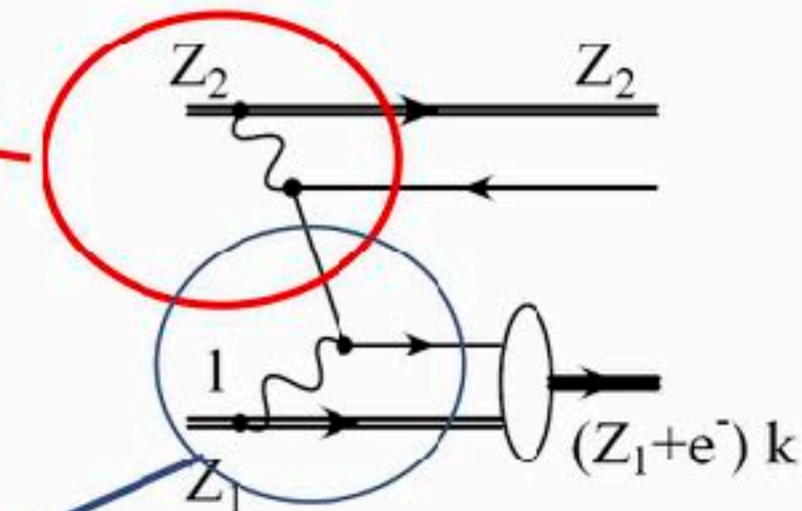
J. Jowet, Initial Stages 2016

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

Bound-free e-e+ pair production creates secondary beams of Pb^{81+} ions emerging from the collision point;

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

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



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

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

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

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

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

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

has very strong dependence on ion charges (and energy)

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

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

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

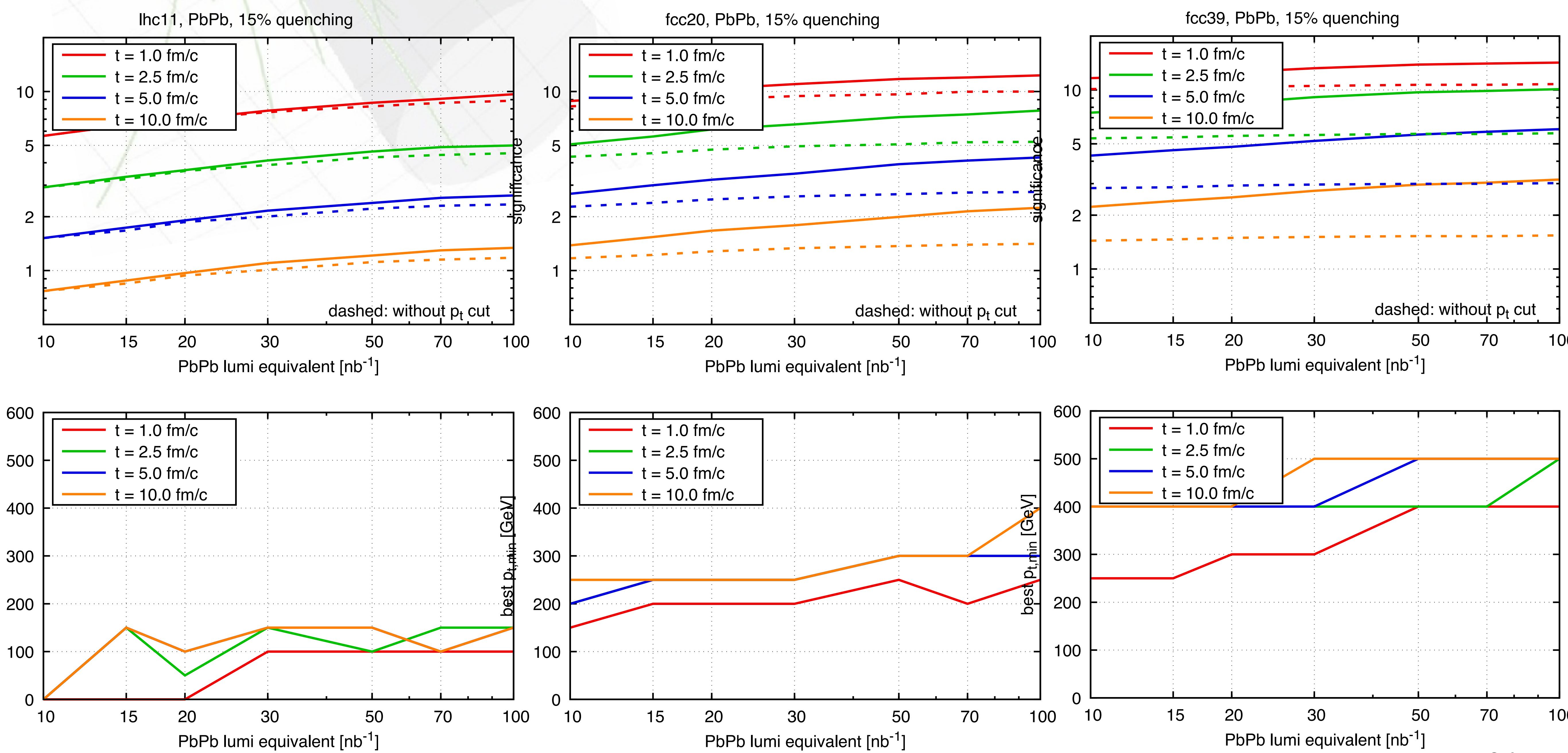
Total cross-section $\propto Z_2^2 Z_1^5$

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

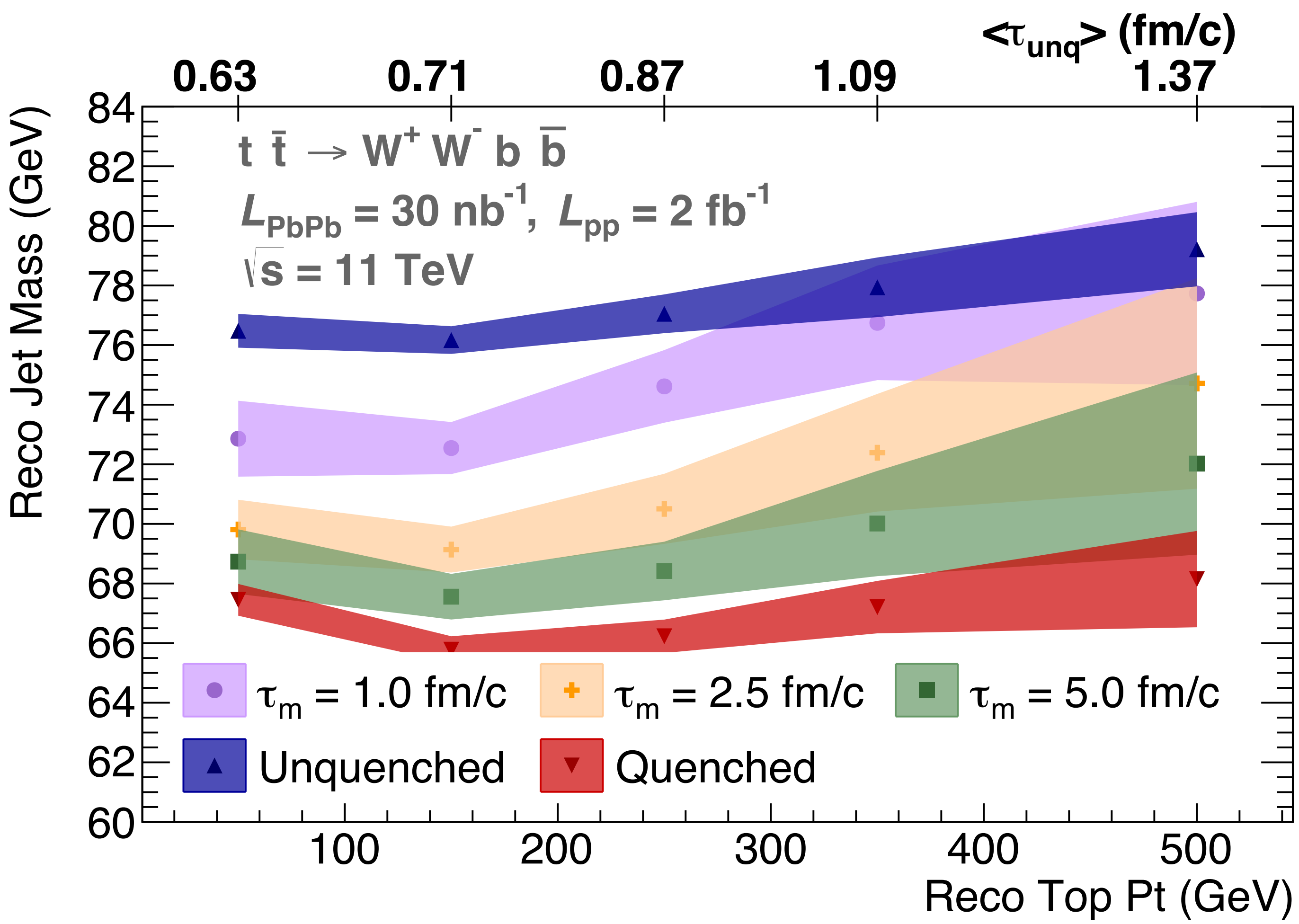
$\sqrt{s_{NN}}$ Comparisons

- $\sqrt{s_{NN}}$ = 39 TeV vs $\sqrt{s_{NN}}$ = 20 TeV vs $\sqrt{s_{NN}}$ = 11 TeV



$\sqrt{s_{NN}}$ Comparisons

- $\sqrt{s_{NN}}$ = 39 TeV vs $\sqrt{s_{NN}}$ = 20 TeV vs $\sqrt{s_{NN}}$ = 11 TeV



√sNN Comparisons

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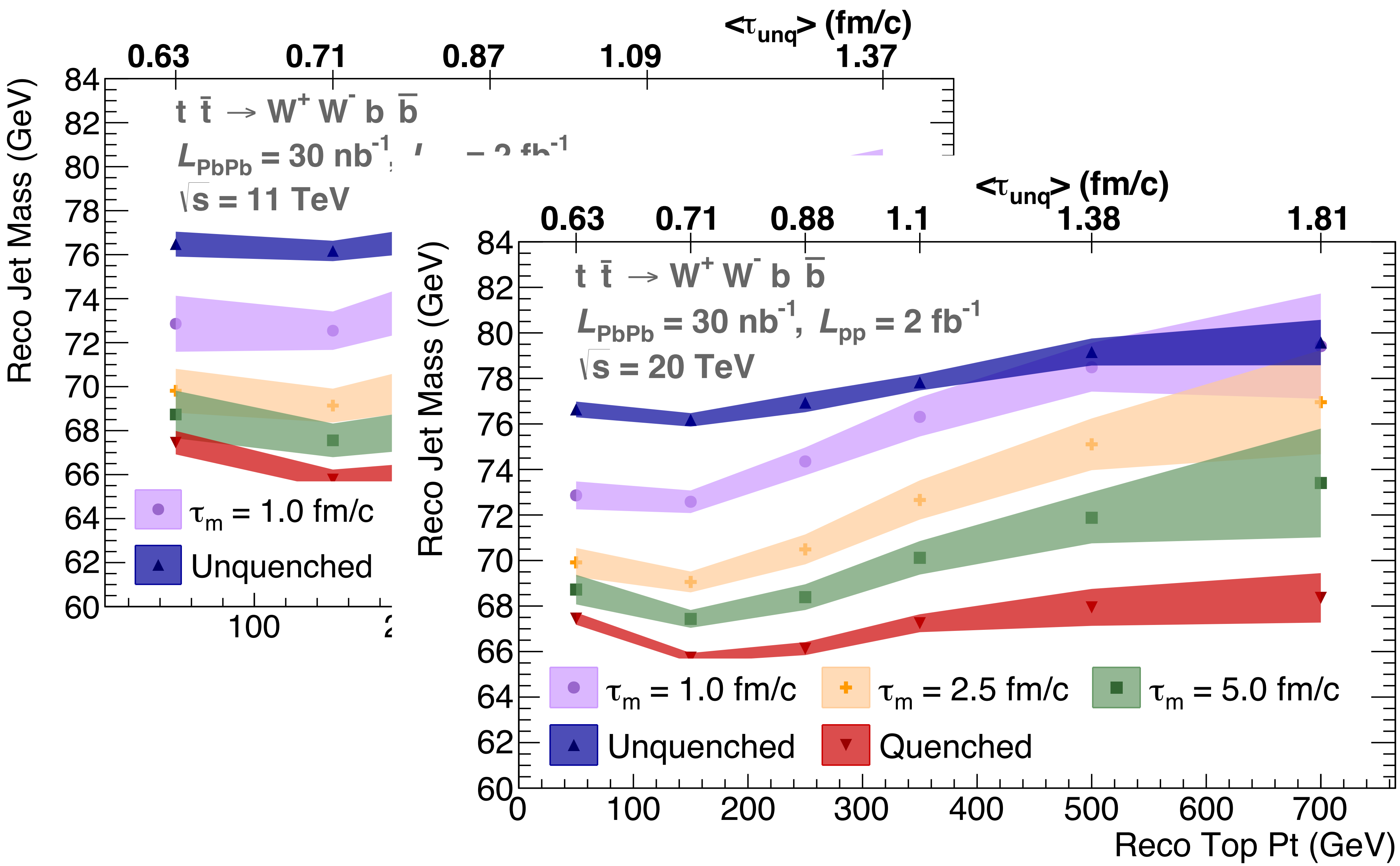

√sNN Comparisons

- $\sqrt{s_{NN}}$ = 39 TeV vs $\sqrt{s_{NN}}$ = 20 TeV vs $\sqrt{s_{NN}}$ = 11 TeV