BOOSTED TOPS AND HEAVY-ION COLLISIONS
A YOCTOSECOND CHRONOMETER?

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work in progress with Liliana Apolinário,
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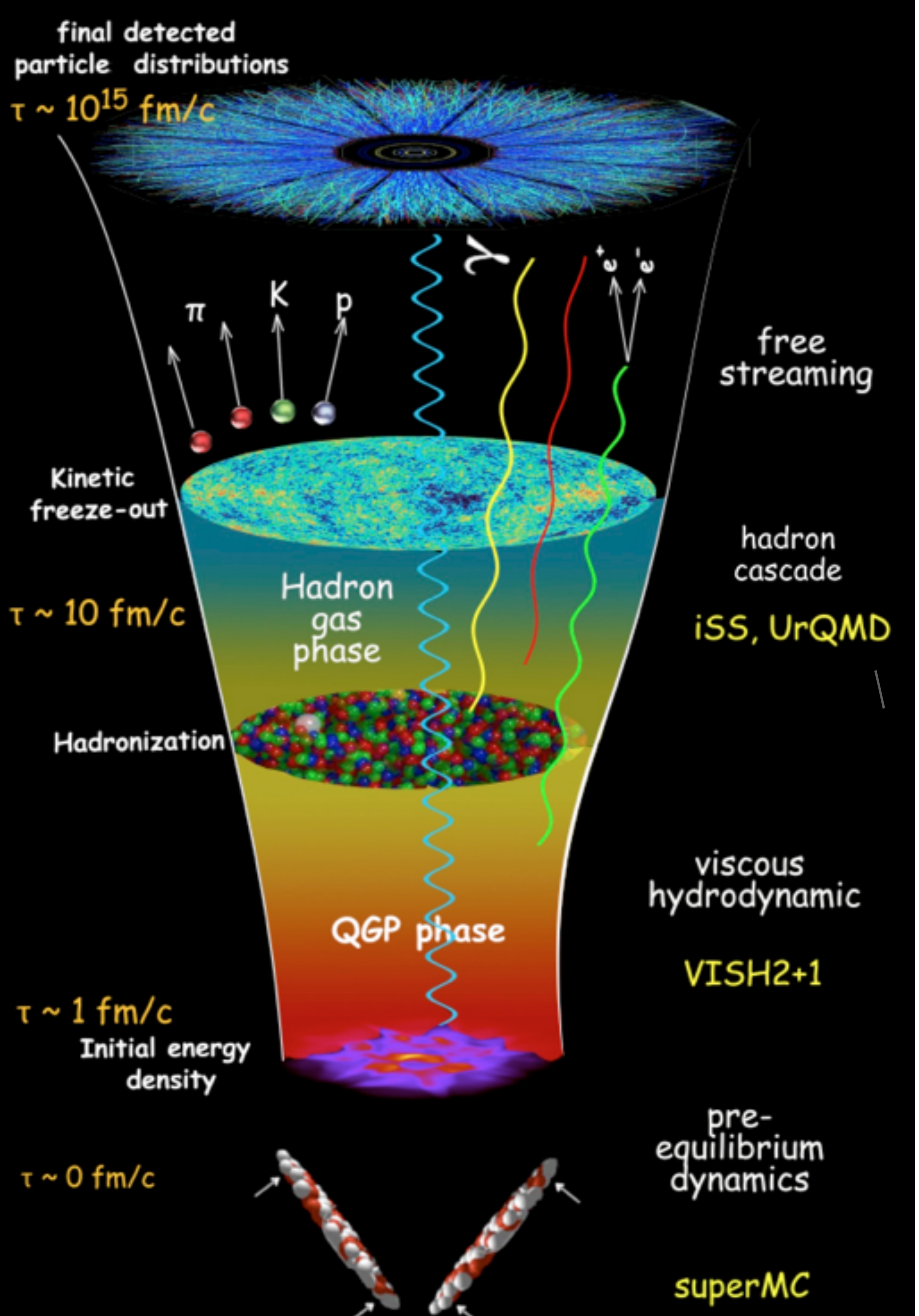
this talk is about developing methods to measure time on scale of 1fm/c ~ 10^{-24} s (1 yoctosecond)

1) one day we might discover new particle(s). Can we find new ways of measuring or constraining their lifetime?

2) in heavy-ion collisions, dynamics of the early universe takes place on timescale of 1-5fm/c.
Can we time-resolve it?



https://u.osu.edu/vishnu/physics/

QUARK-GLUON PLASMA

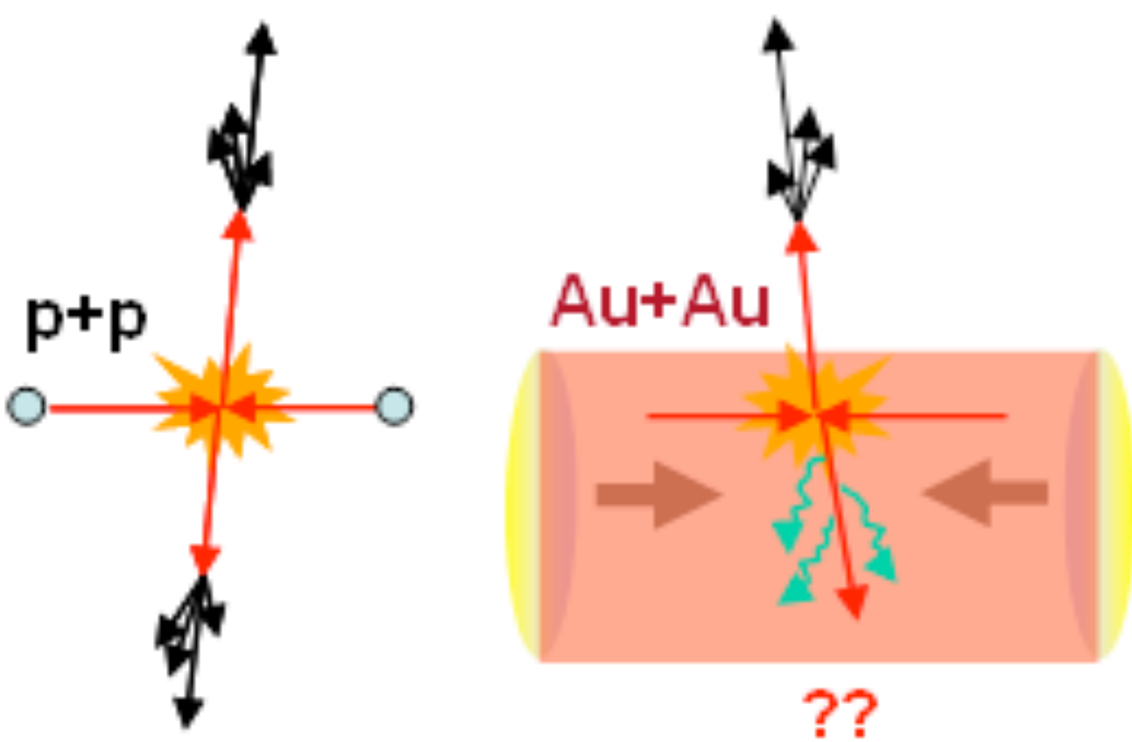
Deconfined state of quarks and gluons:

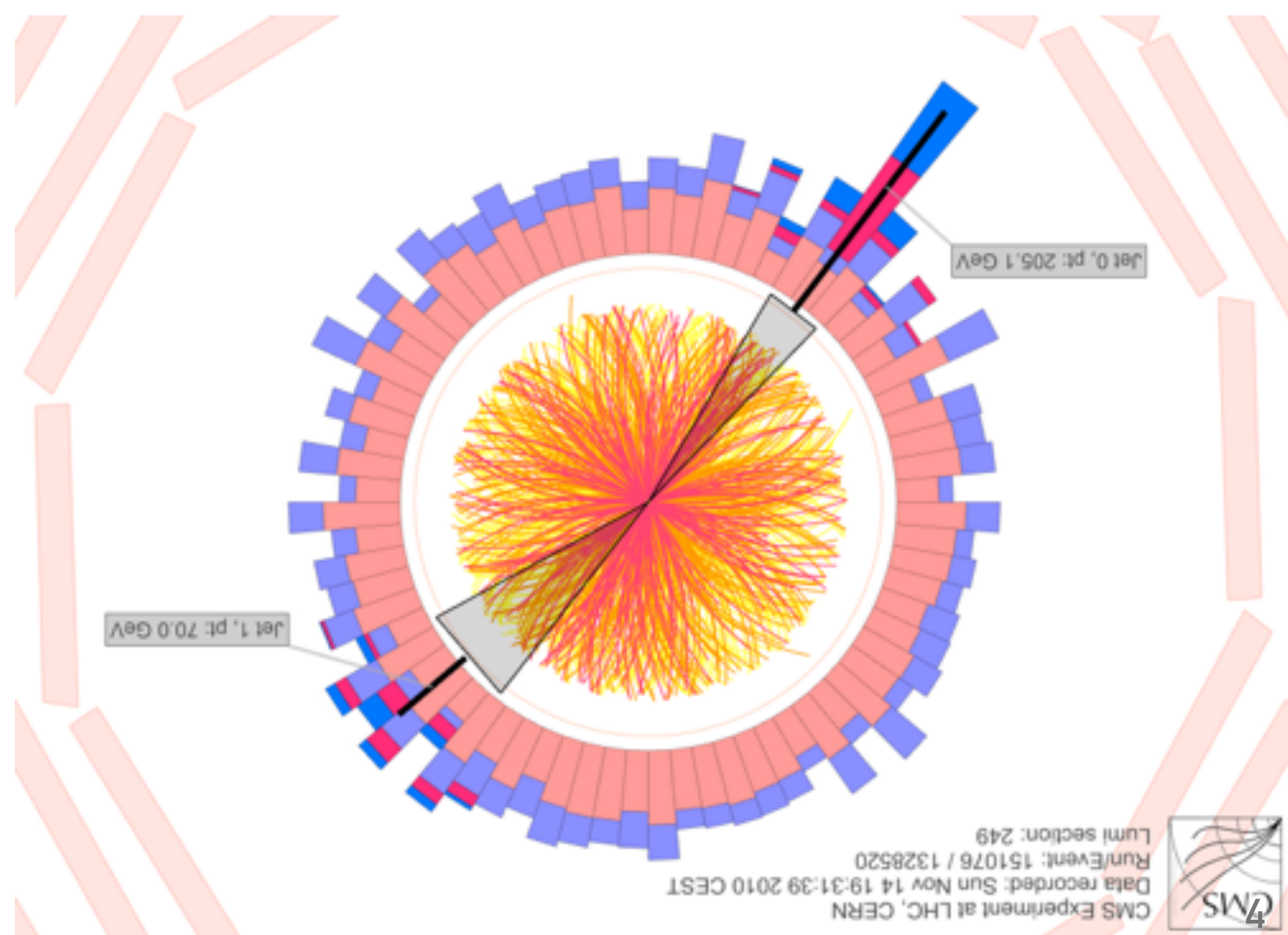
- first few μs of our universe
- first few fm/c of heavy-ion collisions

A KEY PROBE OF THE MEDIUM: JET QUENCHING

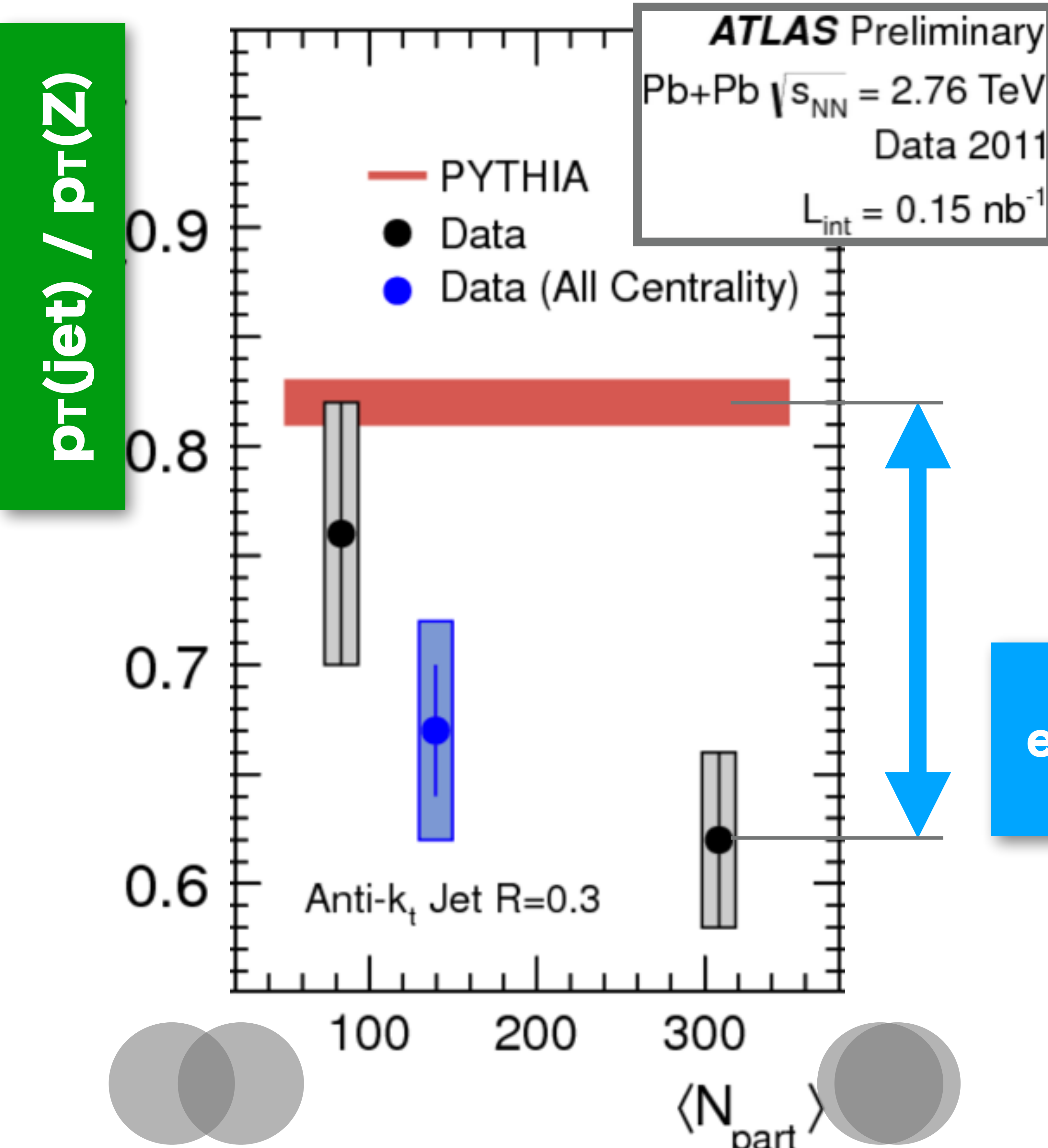
As a parton goes through the quark-gluon plasma, it loses energy.

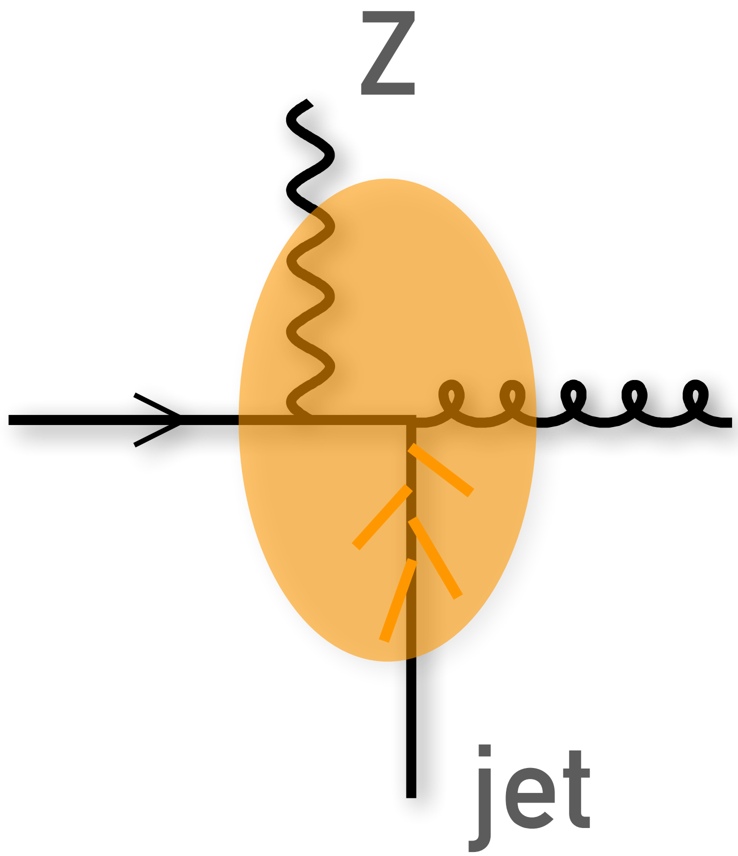
Amount (and pattern) of energy loss tells you about the medium. Interpretation of existing data is still an open topic.





magnitude of effects? Look at Z – jet p_T balance

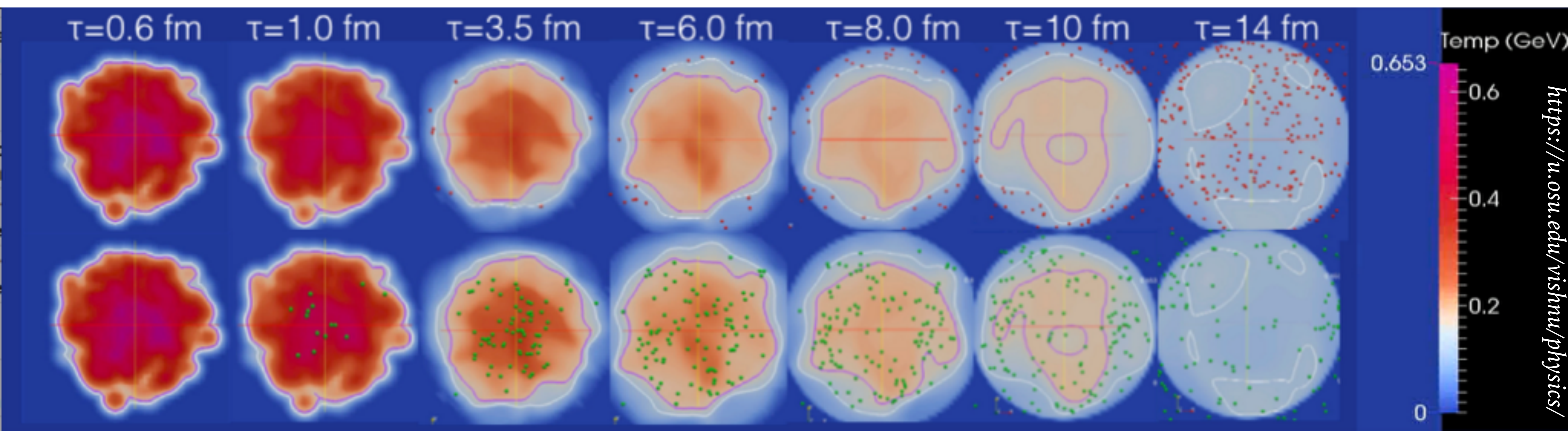




Jet loses 10–20% of its energy through interactions with the medium

TIME DEPENDENCE

- Most probes of the HI medium involve an integral over time (e.g. jet quenching, thermal photons), or come from freezeout (hadrons)
- Can we find probes where we can control the time when they interact with the medium?



top quarks and W's have finite lifetime *(and decay to jets)*

top quark @ rest	~0.15 fm/c
W boson @ rest	~0.10 fm/c

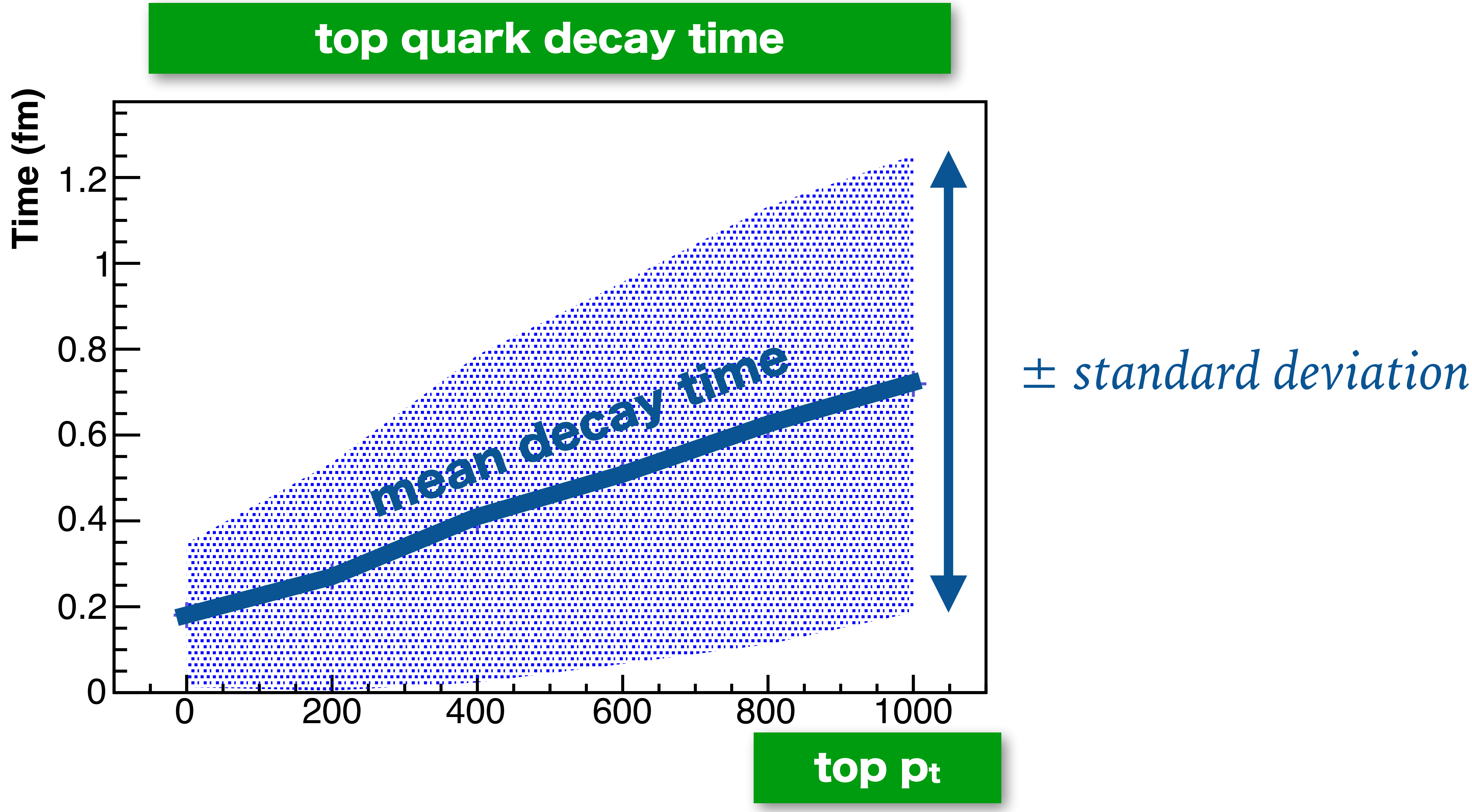
- you can control the lifetime by selecting the p_T of the top (or W) and exploiting time dilation
- colour singlet qqbar from W doesn't start interacting with medium right away — the q and qbar need to **decohere**

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

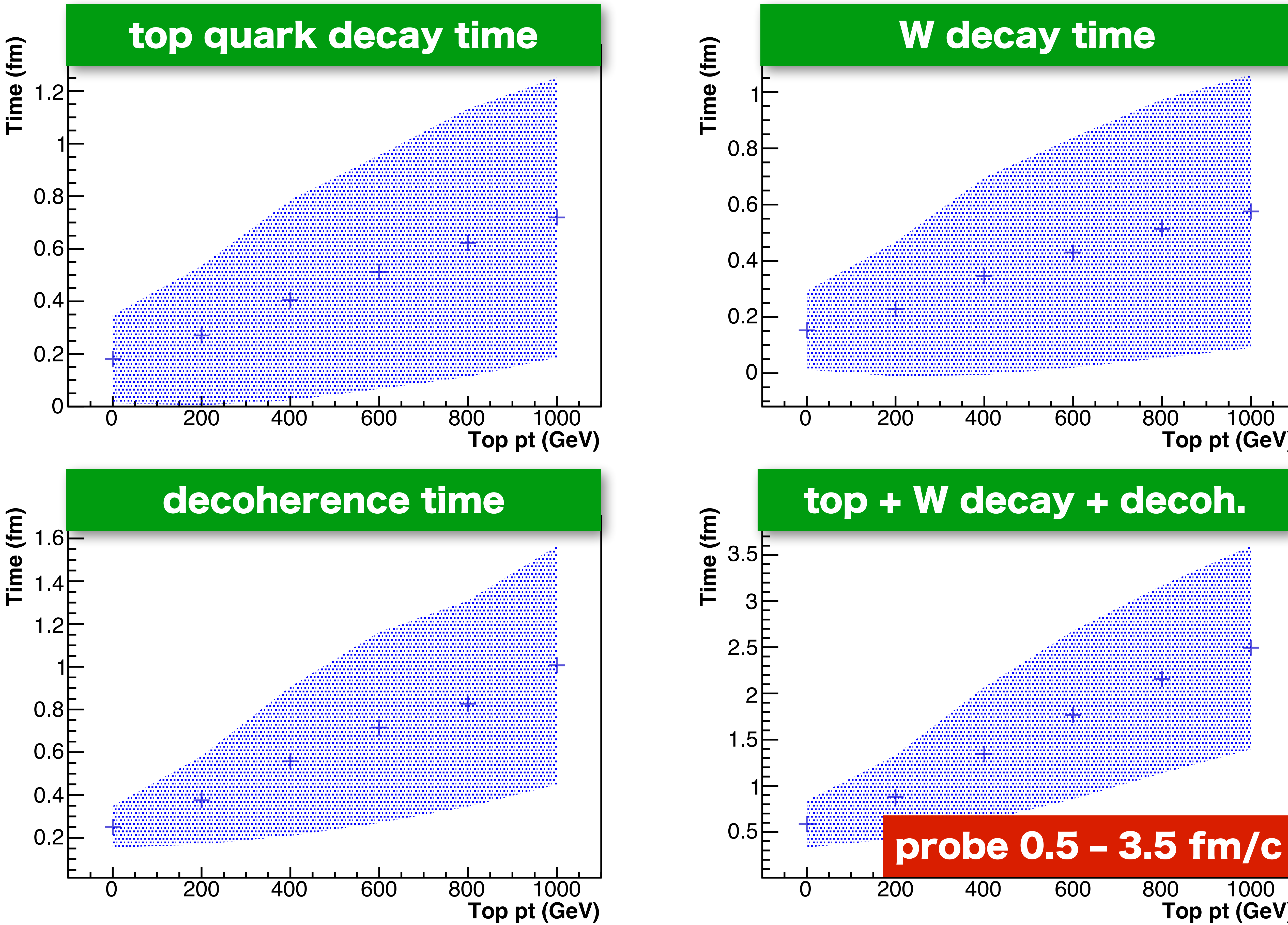
$\hat{q}$ is parameter of medium $\sim 4\,\mathrm{GeV}^2/\mathrm{fm}$

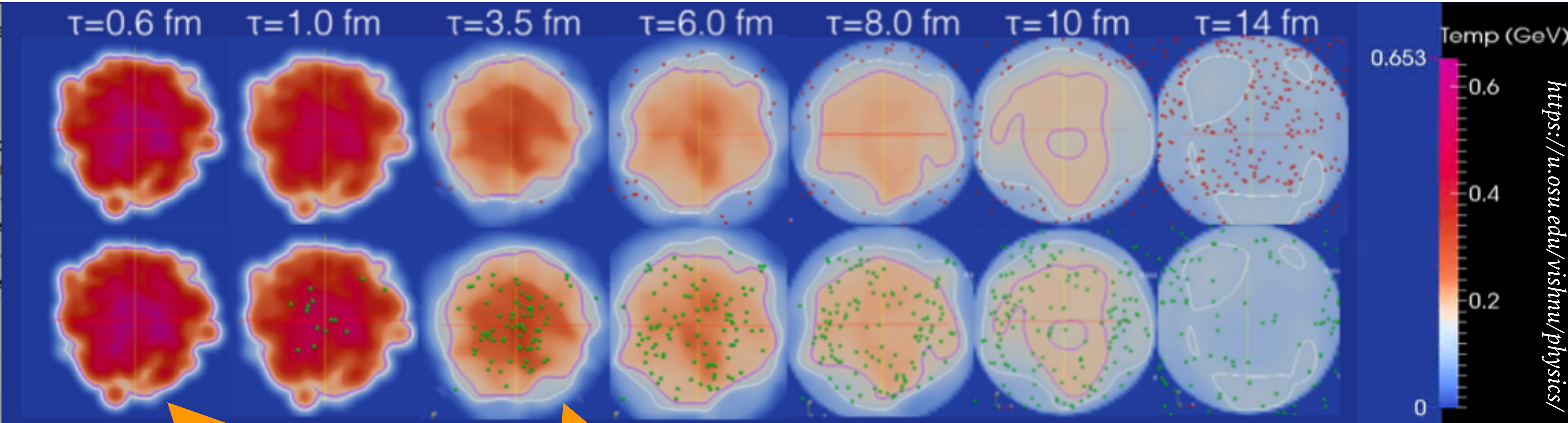
$\theta_{q\bar{q}}$ is quark-antiquark opening angle

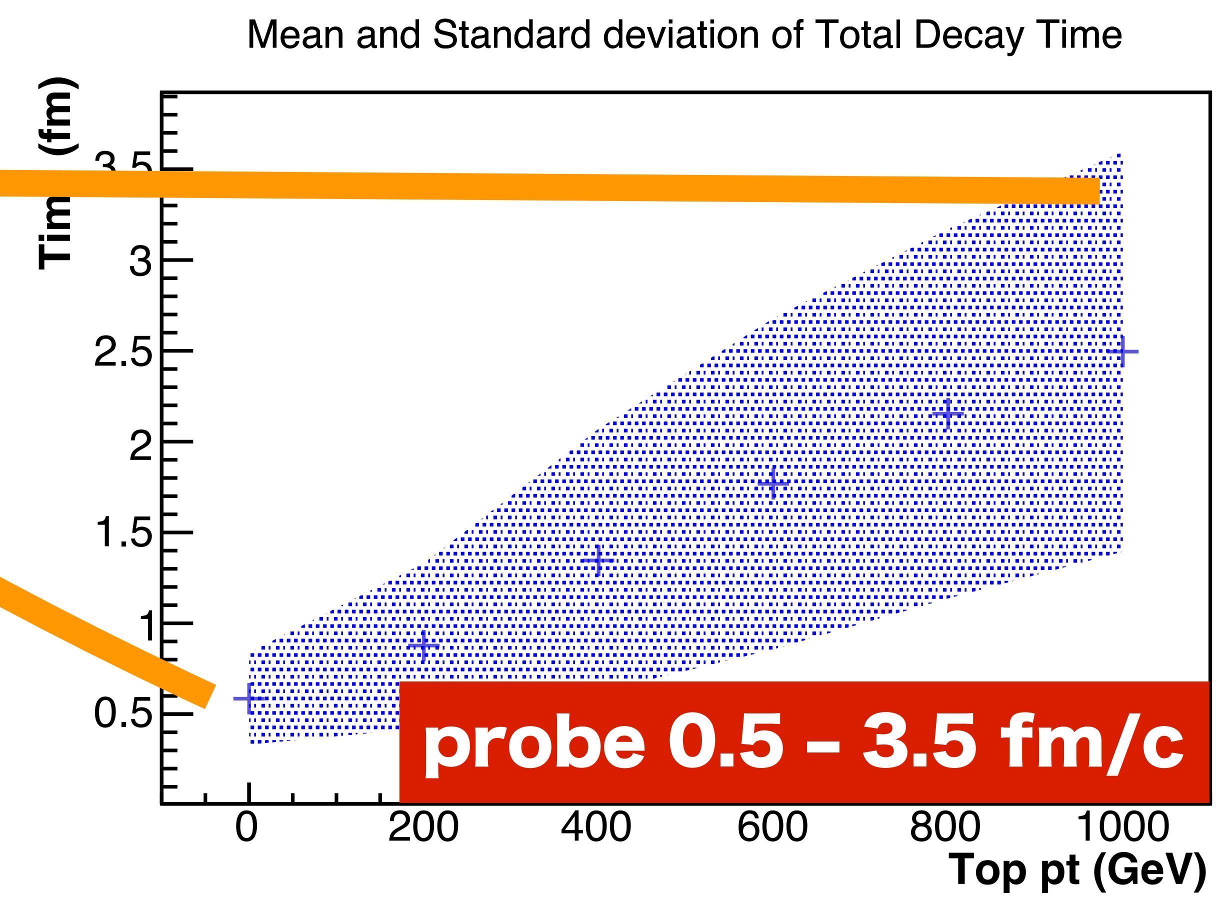
Mehtar-Tani, Salgado & Tywoniuk, 1205.5739



top quark decay time
Time (fm)
1.2
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
mean decay time
top pt
± standard deviation


top quark decay time
W decay time
decoherence time
top + W decay + decoh.
Time (fm)
Top pt (GeV)
probe 0.5 – 3.5 fm/c





top + W decay + decoh.

probe 0.5 – 3.5 fm/c

MACHINE & EVENT PARAMETERS

HL-LHC

- 5.5 TeV/nucleon
- 10 nb^{-1}
- A = 208 (Pb)
- 0–10% centrality
  (~42% of ttbar events)

FCC-hh

- 39 TeV/nucleon
- 30 nb^{-1}
- A = 208 (Pb)
- 0–10% centrality
  (~42% of ttbar events)

For this talk, we're concentrating on FCC-hh
Plan to see later if anything is possible at LHC

simulation: POWHEG + Pythia 8;
no HI background; no physics backgrounds

EVENT SELECTION & RECONSTRUCTION

Basic event selection & object def^{n}

- require 1 muon with p_T > 25 GeV, $|\eta| < 2.5$
  (in real world, require MET?)
- anti-k_T jets, R=0.3, p_T > 30 GeV, $|y| < 2.5$
  (in real world, HI background would need to be subtracted)

EVENT SELECTION & RECONSTRUCTION

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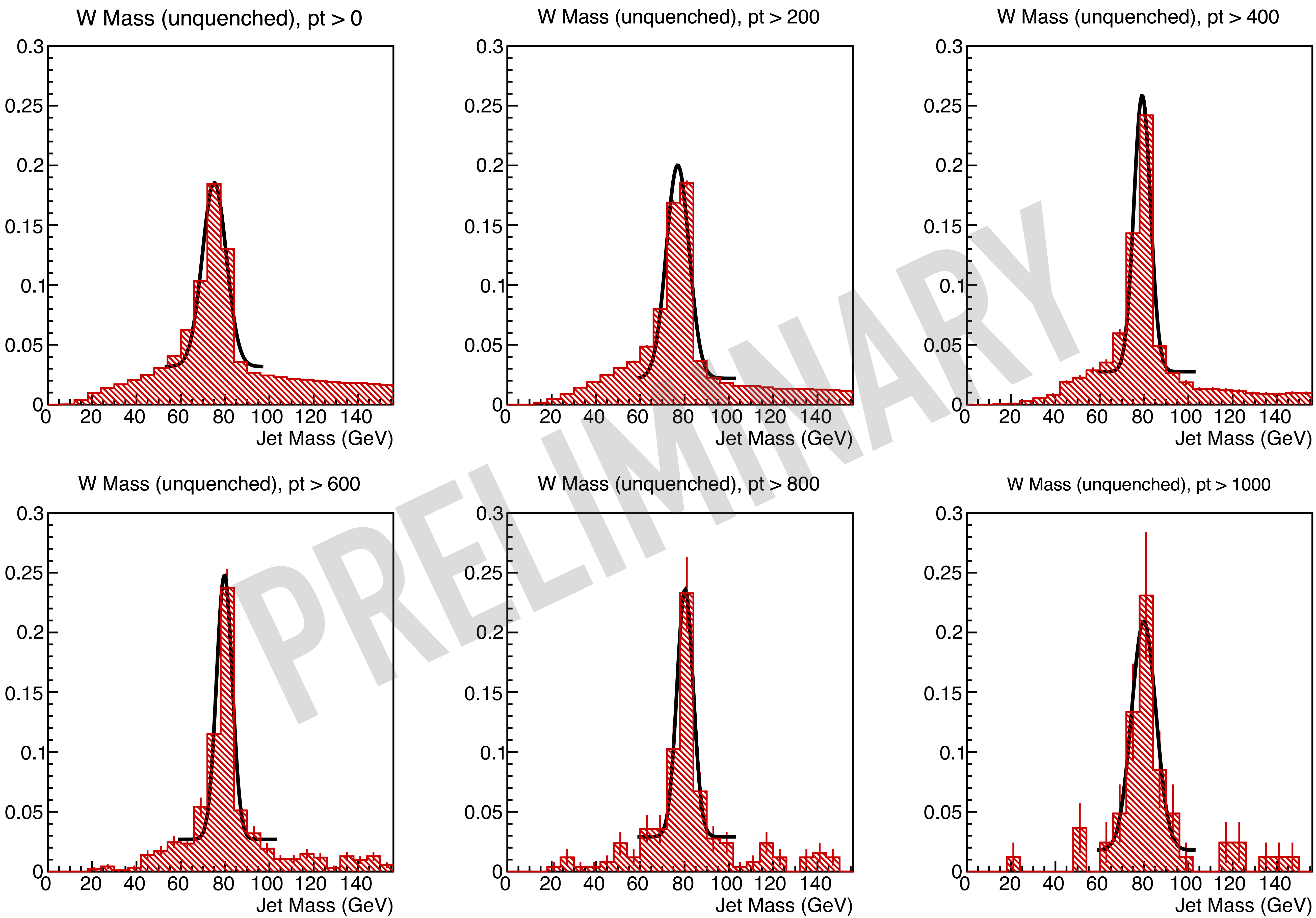
Hadronic top reconstruction

- recluster each jet with k_T, R=1, decluster with $d_{cut}=(30\ \text{GeV})^2$, replace each original jet with result of declustering
- from new list of jets, require 2 b-tagged ones (70% eff./b-tag); b-jet further from muon is candidate for b from hadronic-top
- require ≥ 2 non-b-tagged; two highest-p_T ones → hadronic W

not super-optimised, but insensitive to soft radiation and functional in boosted and non-boosted regimes

key observable: reconstructed W mass (here shown without quenching)



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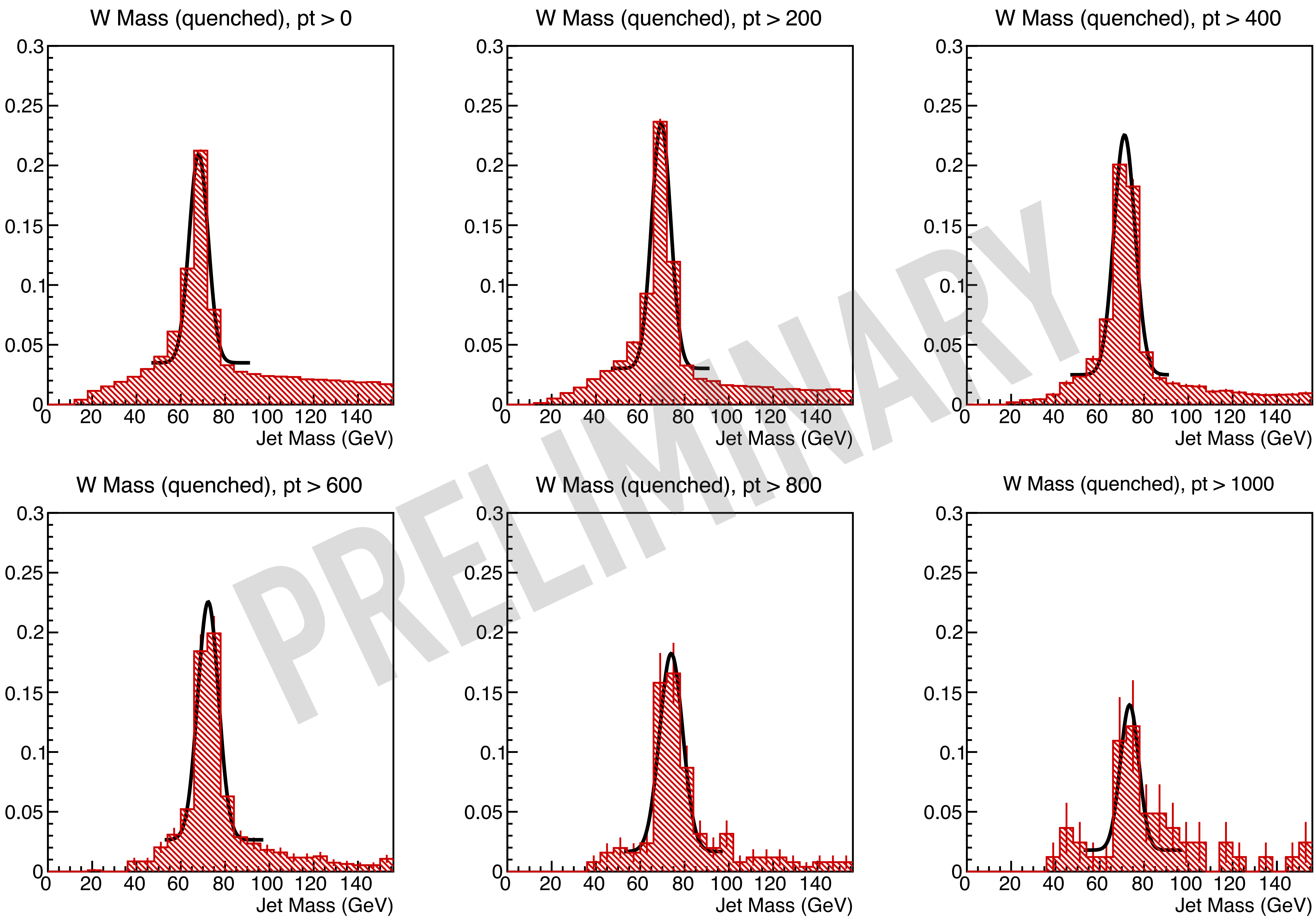
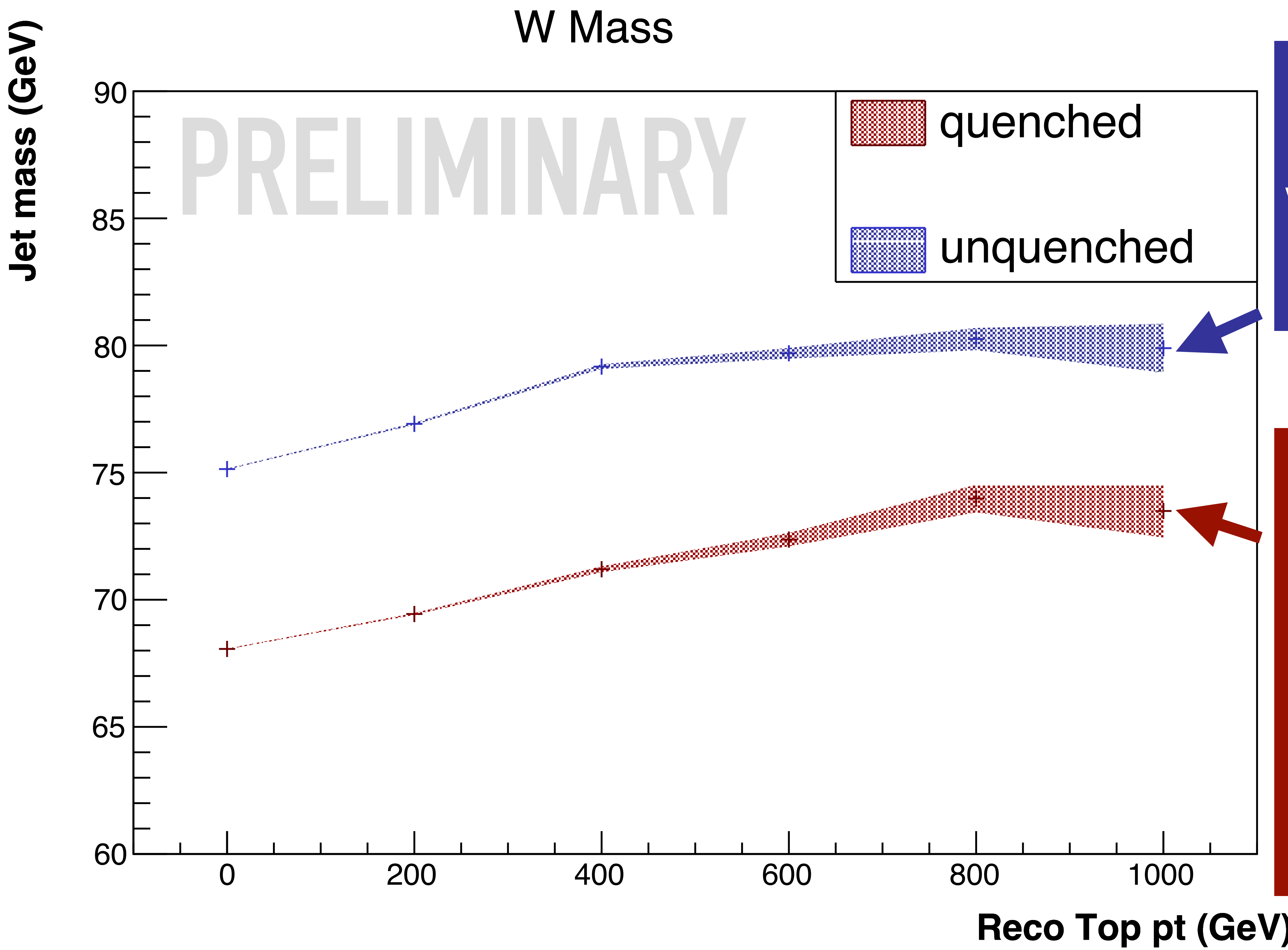


reconstructed W mass v. p_T



UNQUENCHED

would be verified in pp events

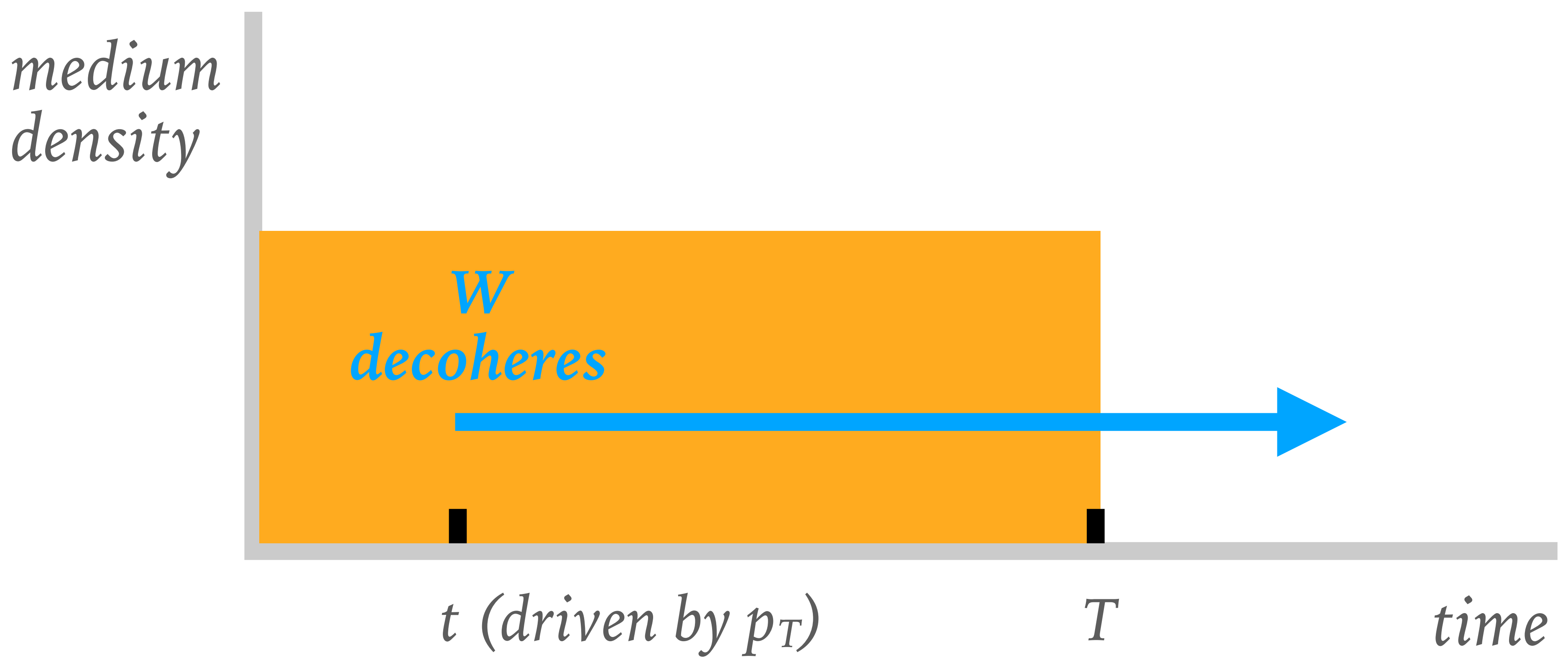
NORMALLY QUENCHED

here modeled as 10% energy loss; actual energy loss could be determined v. p_T in Z+jet events

NAIVE TIME-DEPENDENCE MODEL

- medium has constant density for time T, then vanishes
- W decoheres at time t (a function of p_t, etc.)
- energy loss is:

$$\frac{\Delta E}{E} = 10\% \cdot \frac{(T-t)}{T}$$



neglects evolution of medium density, medium expansion, L^2 proportionality of energy loss, geometry of collision v. W production, etc.

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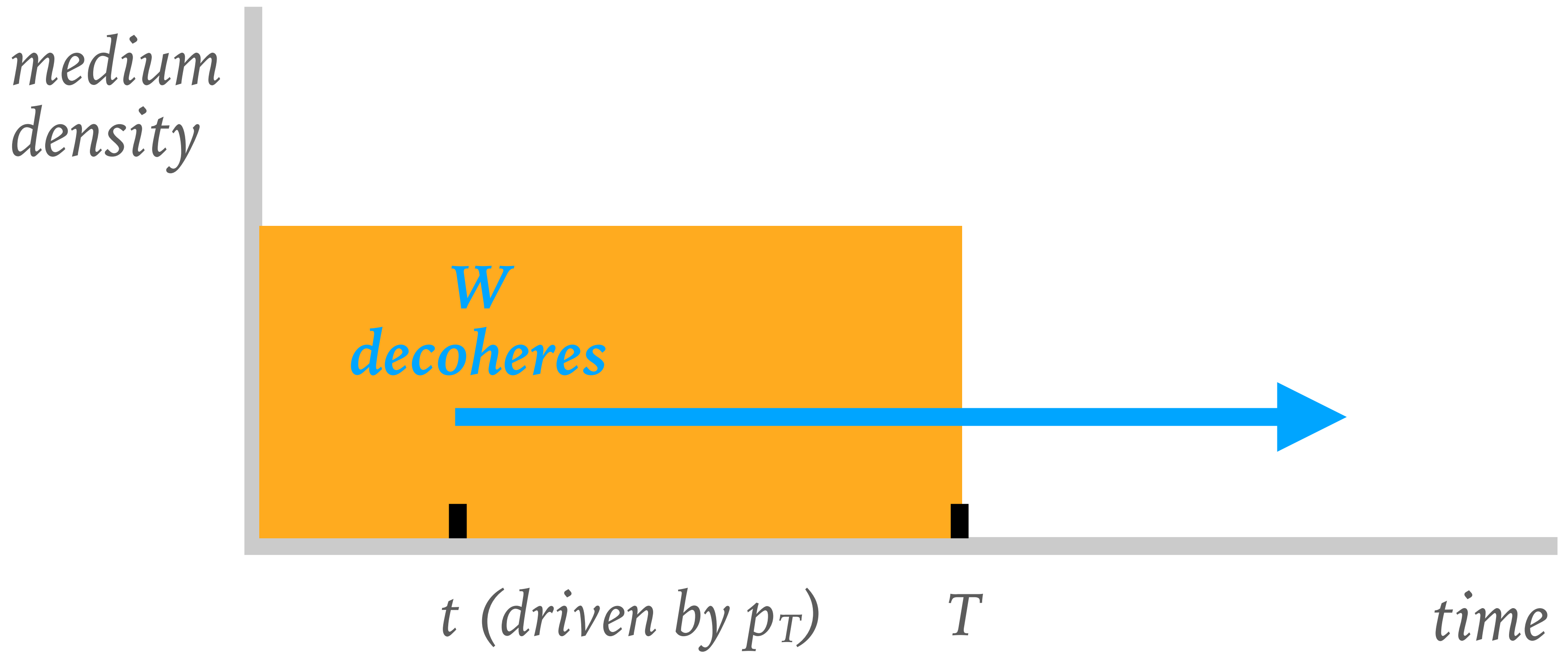

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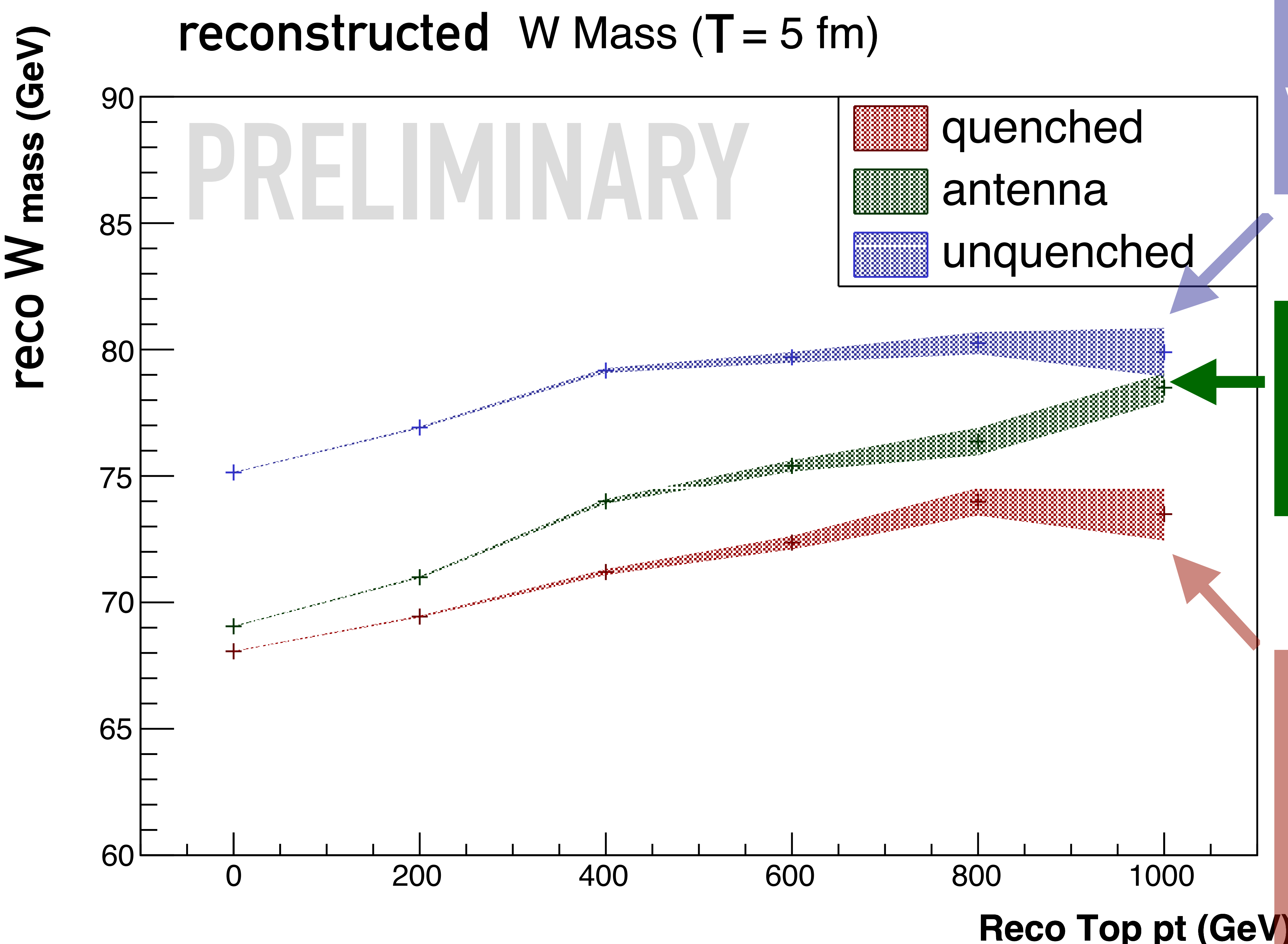

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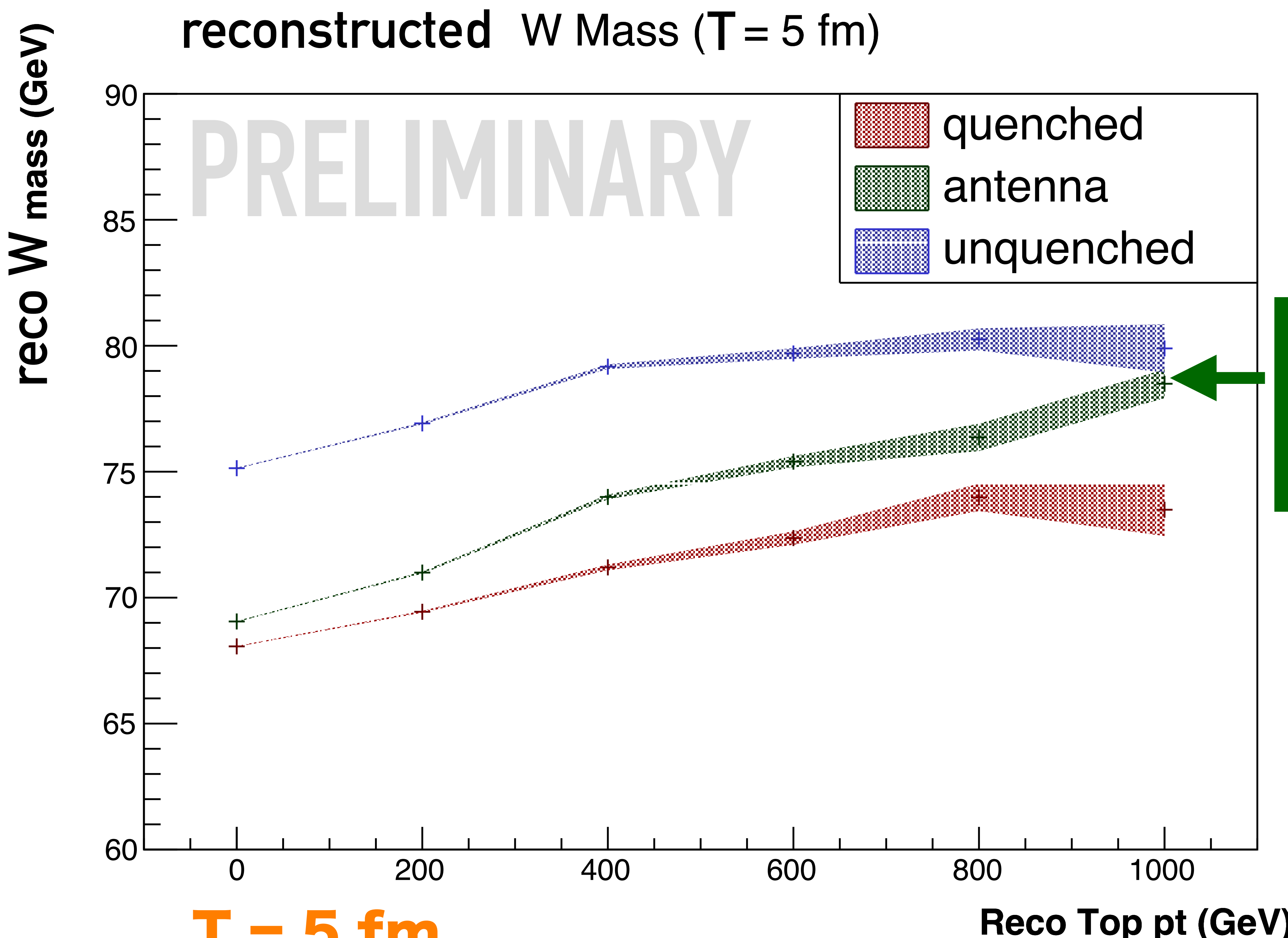


TIME-DEPENDENT QUENCHING

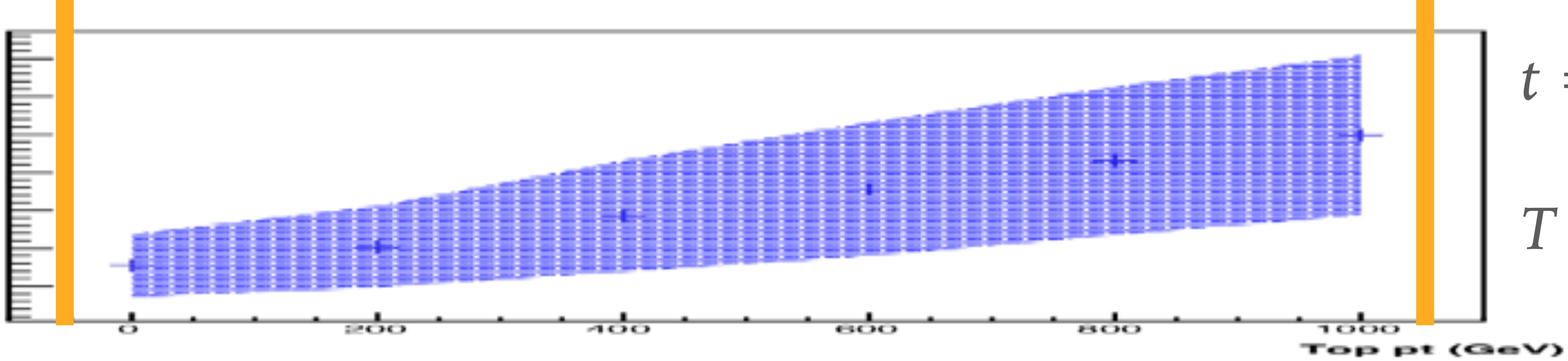
T = 5 fm

t

3 fm

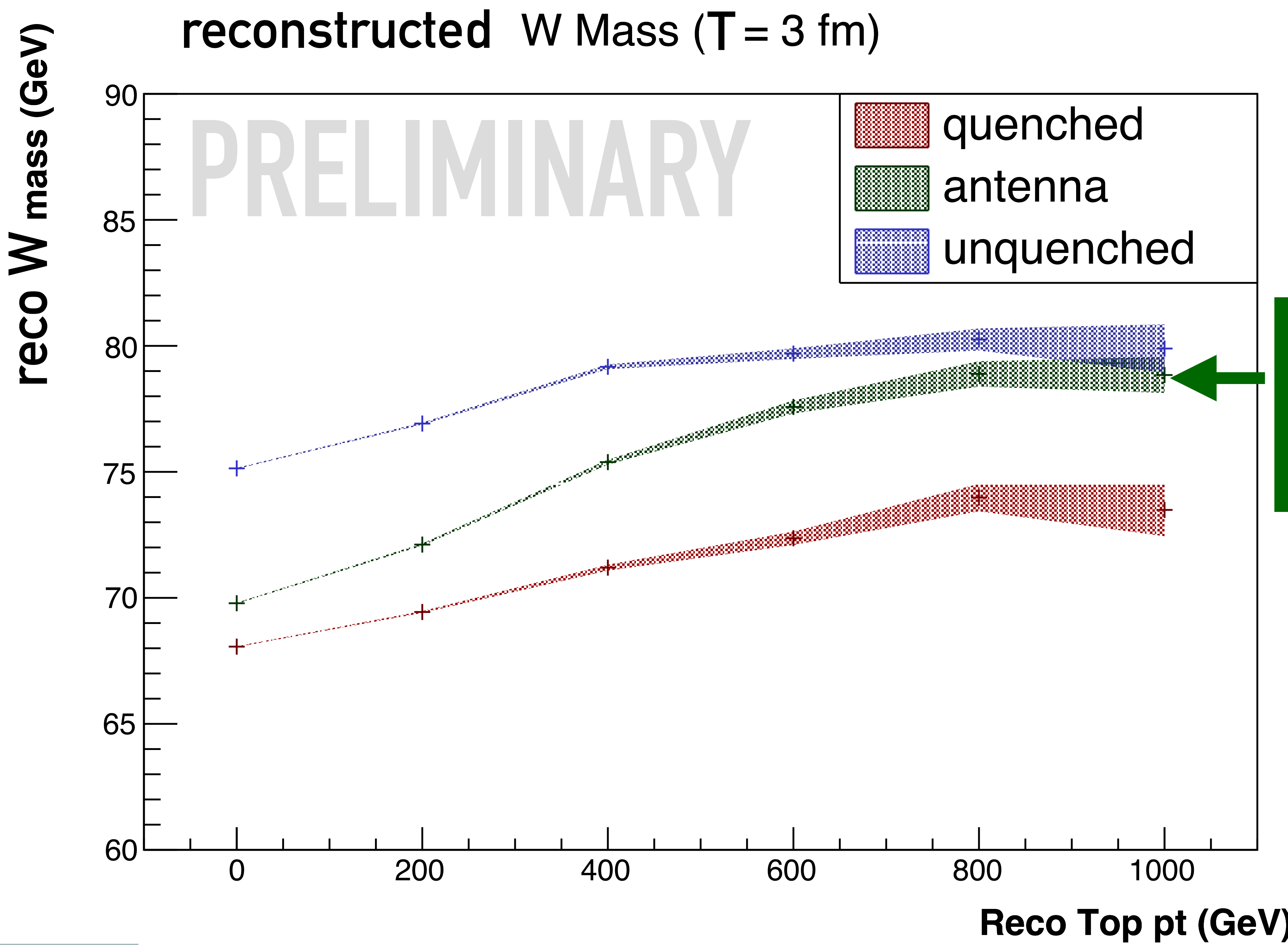
2 fm

1 fm

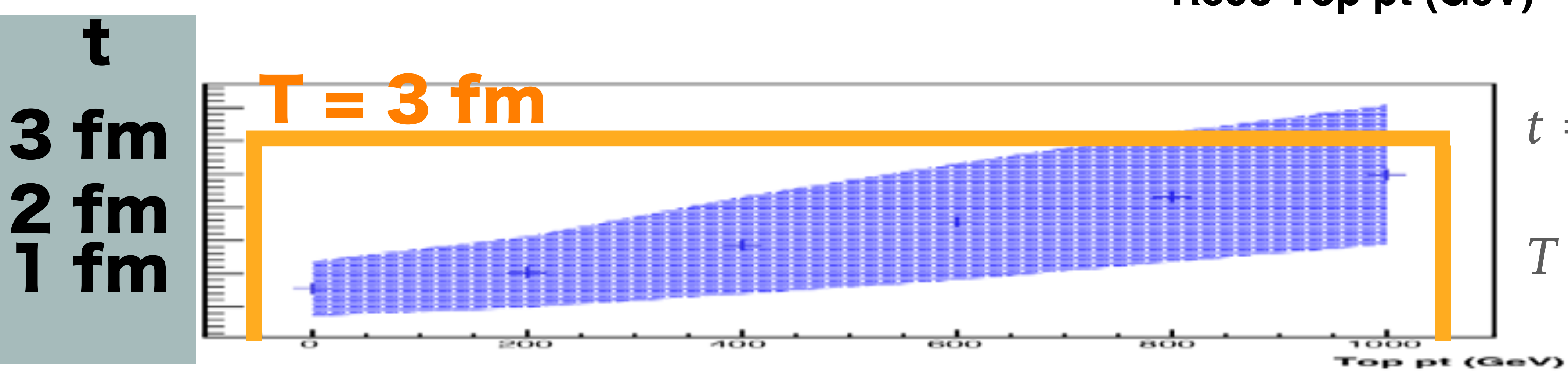


t = W decoherence time

T = medium lifetime



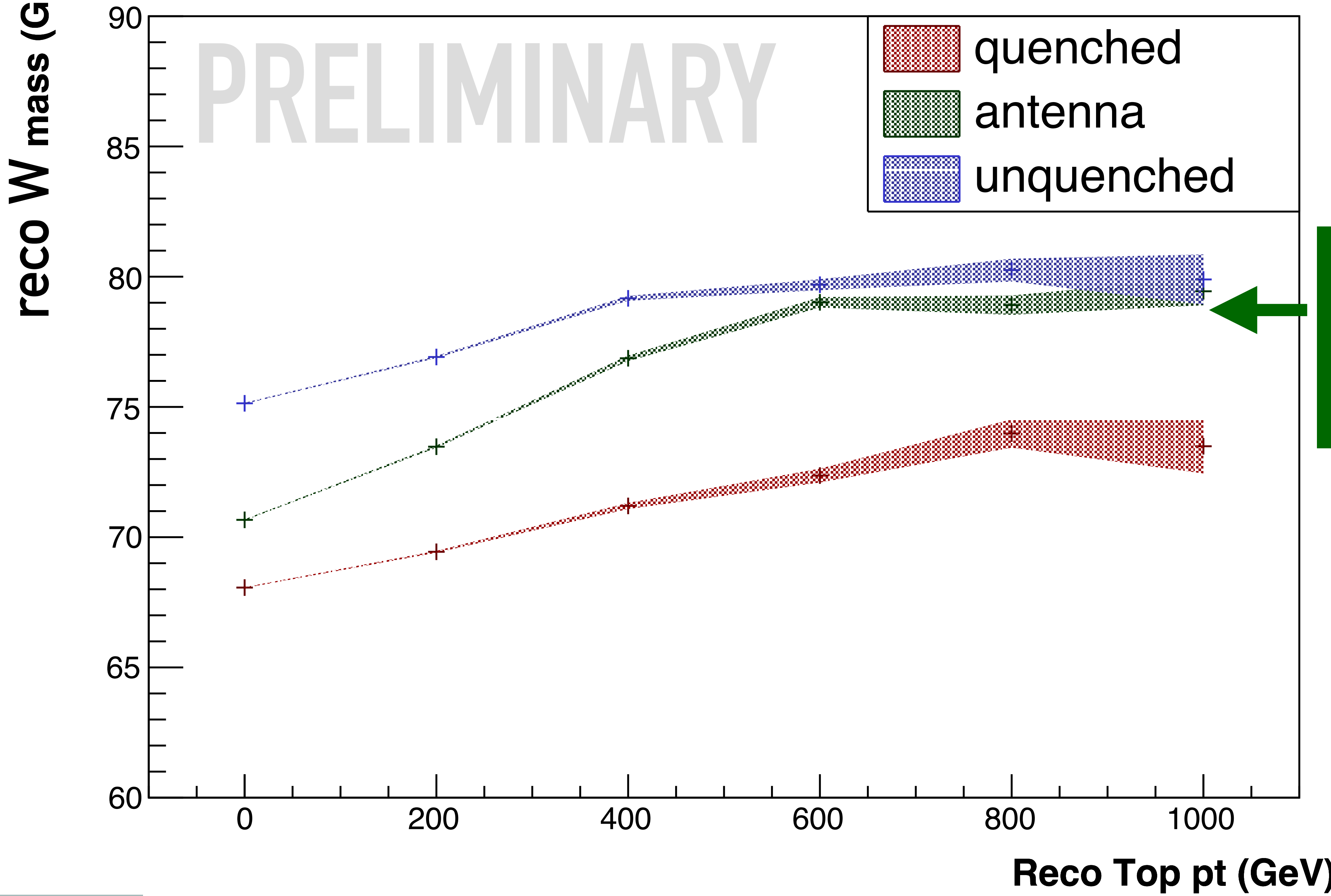
TIME-DEPENDENT QUENCHING



t = *W decoherence time*

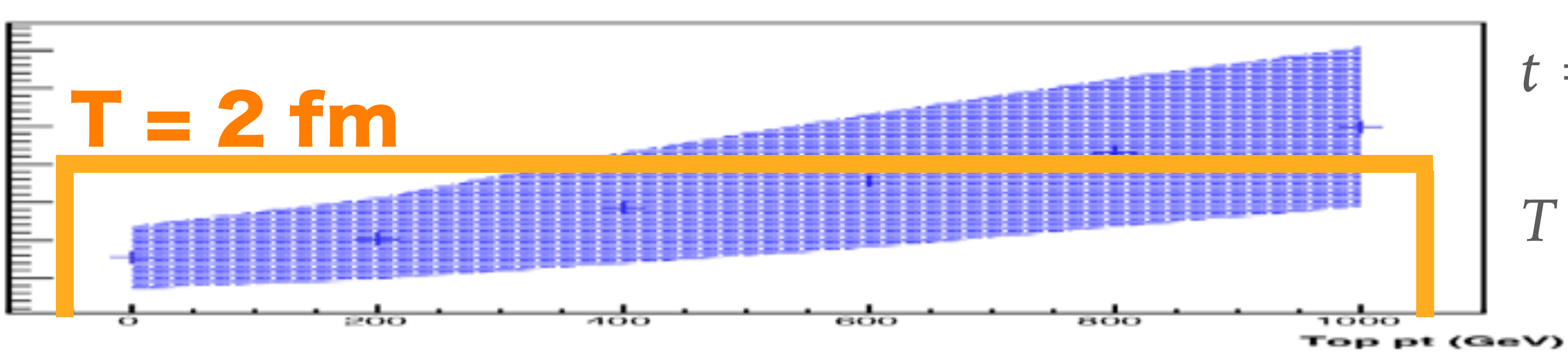
T = *medium lifetime*

reconstructed W Mass (**T** = 2 fm)



TIME-DEPENDENT QUENCHING

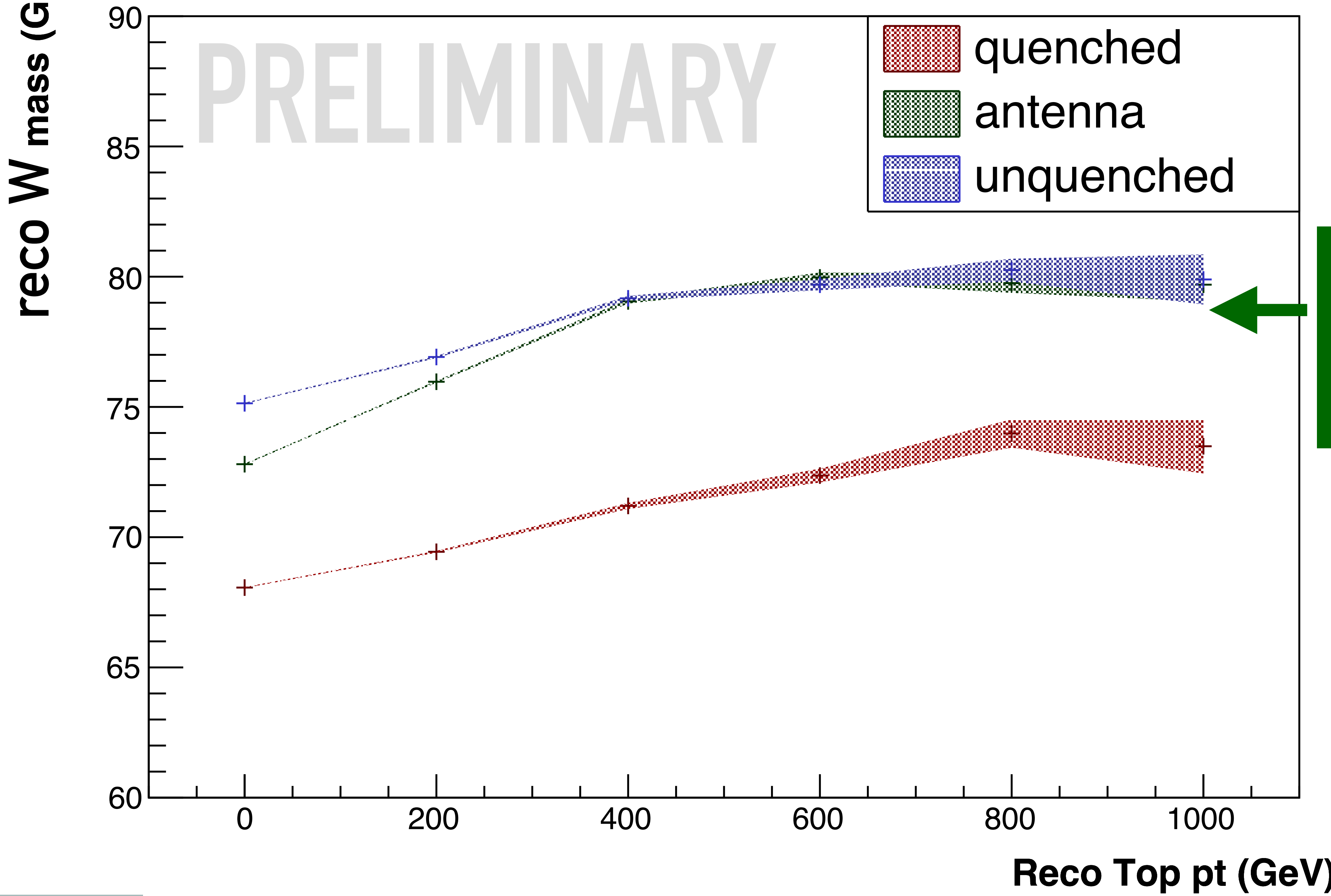
t
3 fm
2 fm
1 fm



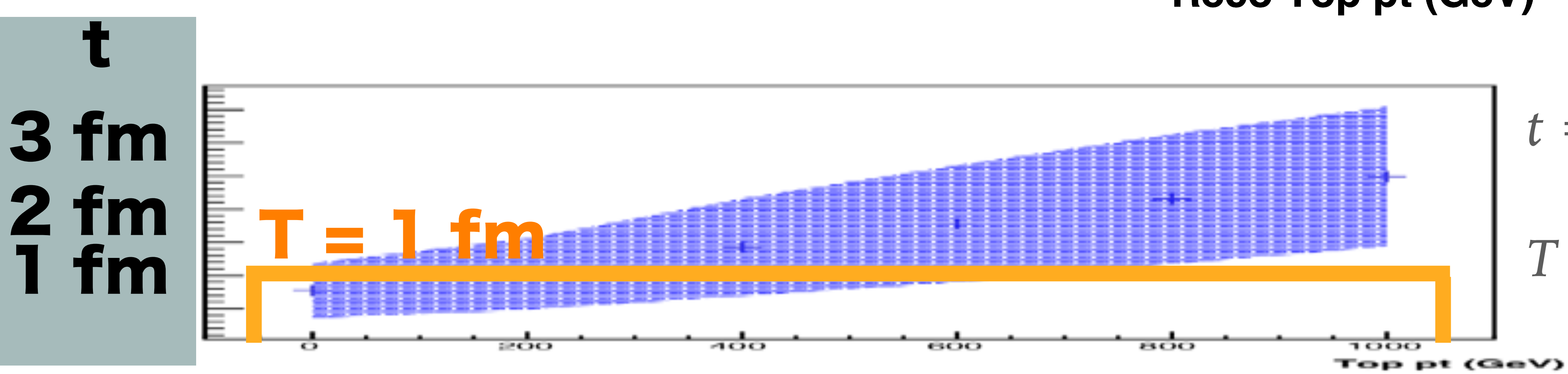
t = *W decoherence time*

T = *medium lifetime*

reconstructed W Mass (T = 1 fm)



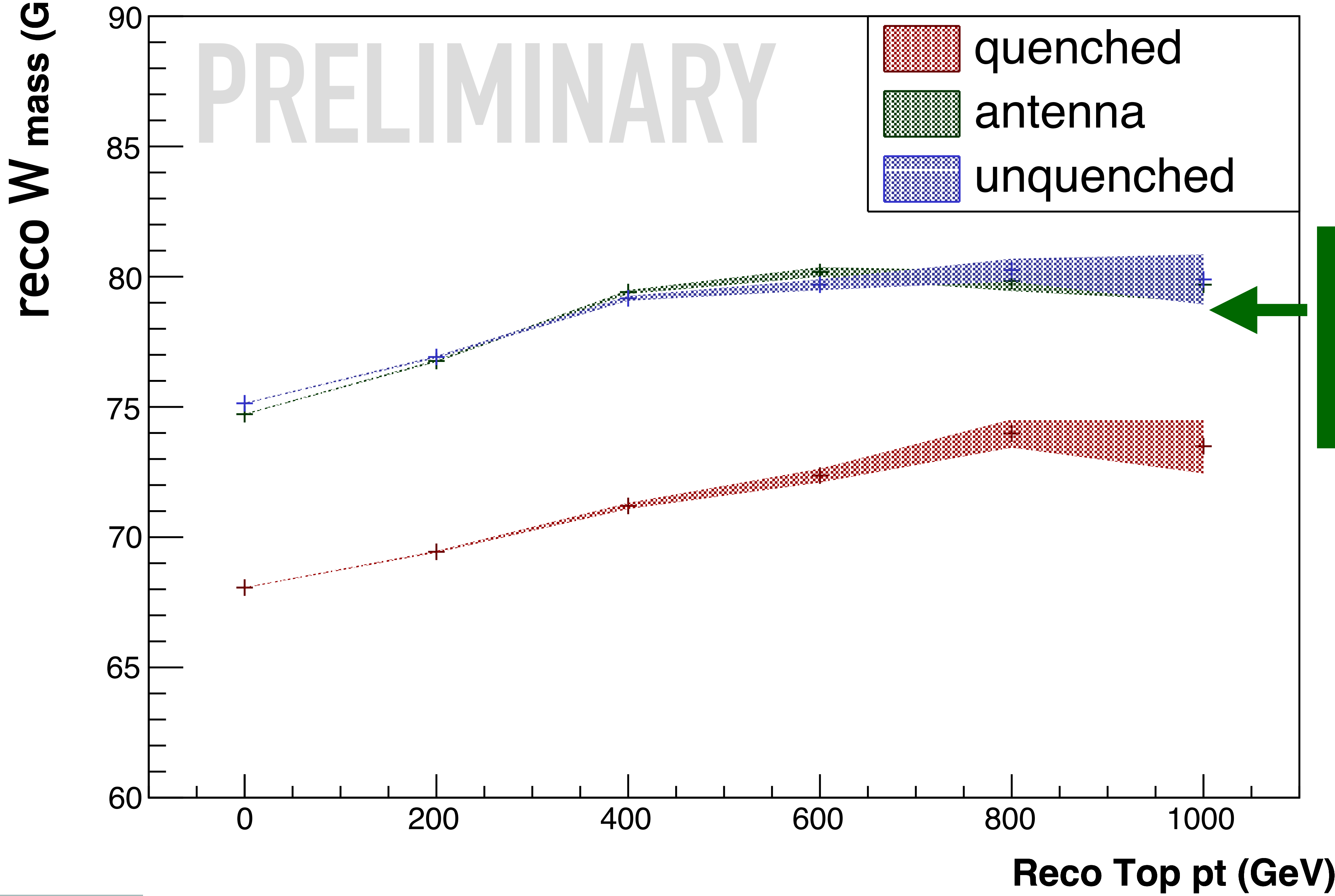
TIME-DEPENDENT QUENCHING



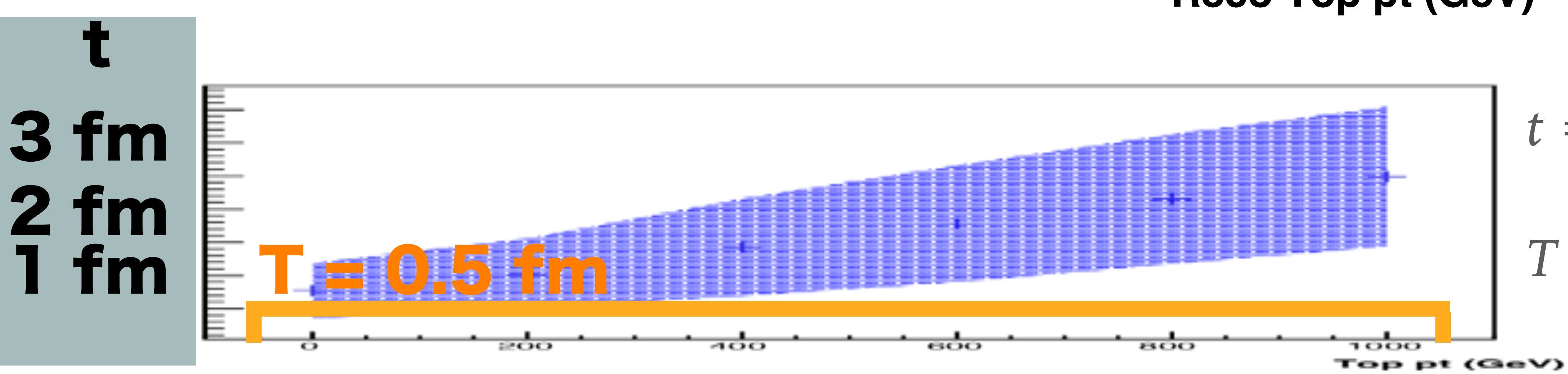
t = *W decoherence time*

T = *medium lifetime*

reconstructed W Mass (T = 0.5 fm)



TIME-DEPENDENT QUENCHING



t = W decoherence time

T = medium lifetime

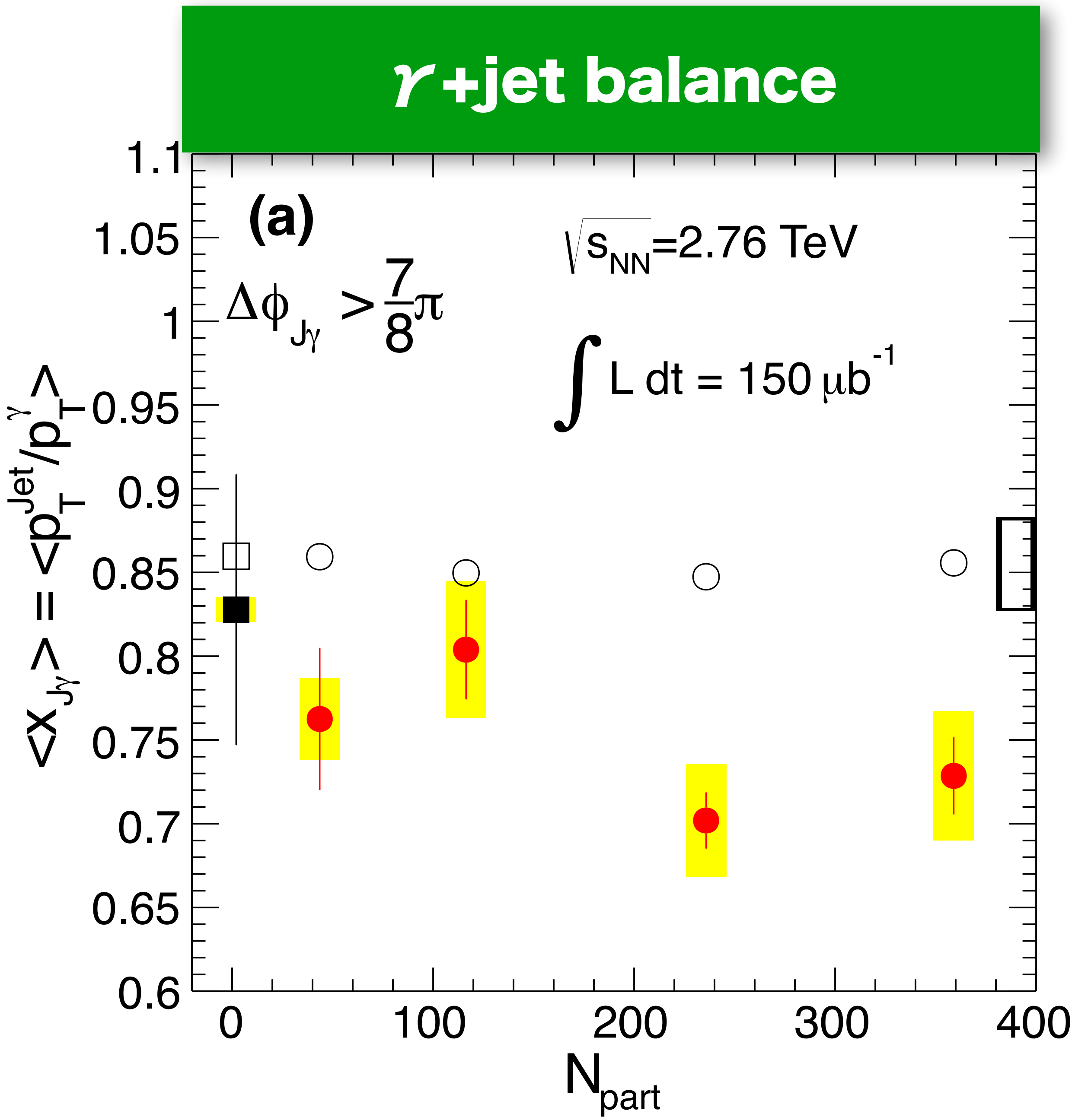
CONCLUSIONS

- Top & W finite lifetimes (+qqbar decoherence time) mean top $\to$ W $\to$jets may quench differently from normal hadronic jets
- By controlling boost of top quark, you can control time when jets interact with the heavy-ion medium. Unique means to learn about medium's time structure.
- Gives information in range 0.5fm/c – 5 fm/c with p_T < 1 TeV
- Some info maybe even accessible at HL-LHC (p_T < 200 GeV)

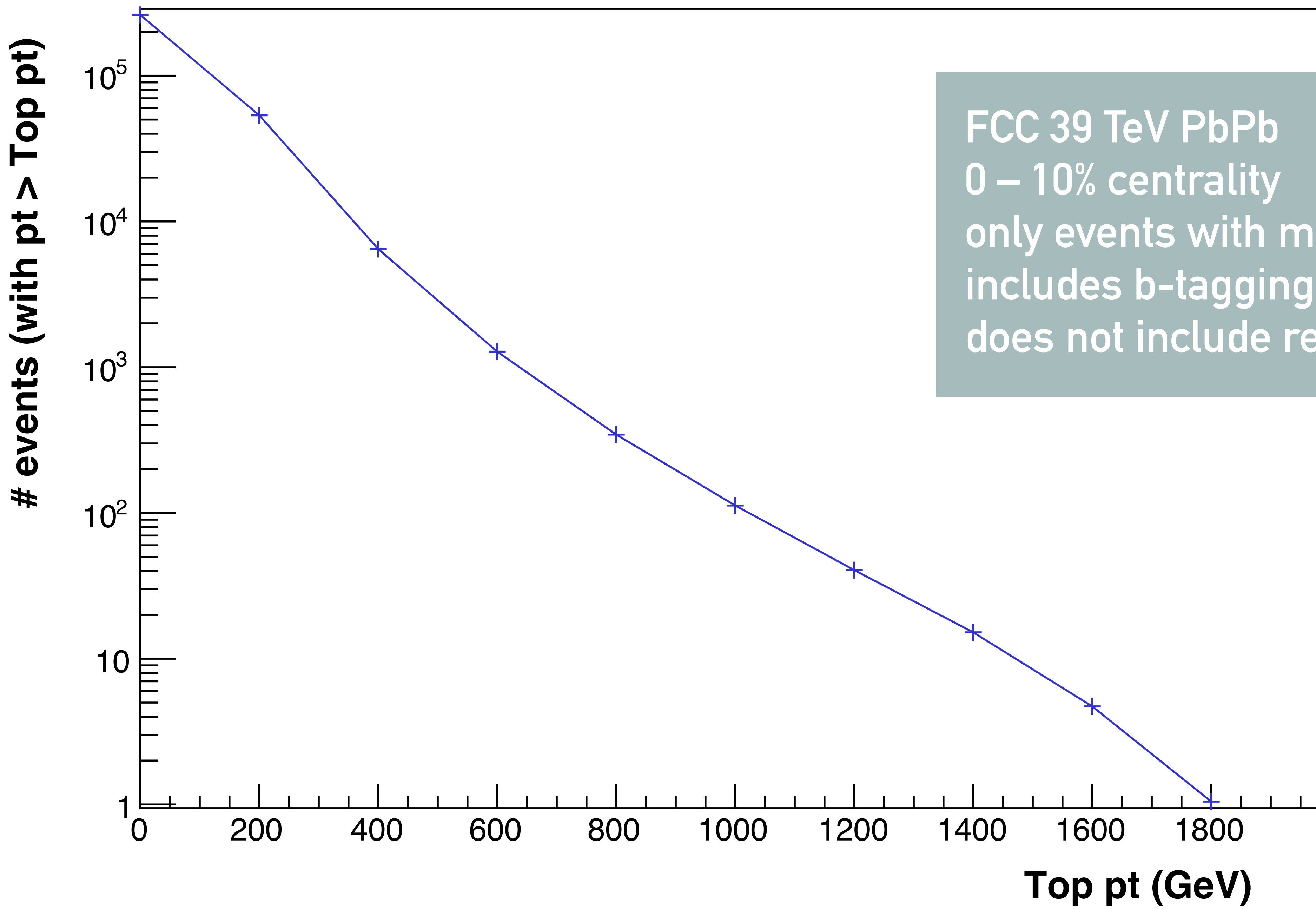
- *[if a new particle decays hadronically, and is produced with a big cross section, quenching of its decay jets could tell you about its lifetime]*

BACKUP

JET QUENCHING IN GAMMA + JET BALANCE



NUMBER OF HADRONIC TOPS WITH P_T ABOVE SOME THRESHOLD



FCC 39 TeV PbPb
0 – 10% centrality
only events with muon
includes b-tagging efficiency ($70\%^2$)
does not include reconstruction efficiency

DISTRIBUTIONS OF DECAY + DECOHERENCE TIME FOR W V. TOP P_T