QGP studies with FCC-Heavy Ions

Liliana Apolinário

(LIP)

on behalf of the FCC-hh heavy-ions working group

Based on:

A. Dainese et al. arXiv:1605.01389

January 2017, "1st FCC Physics Workshop", CERN

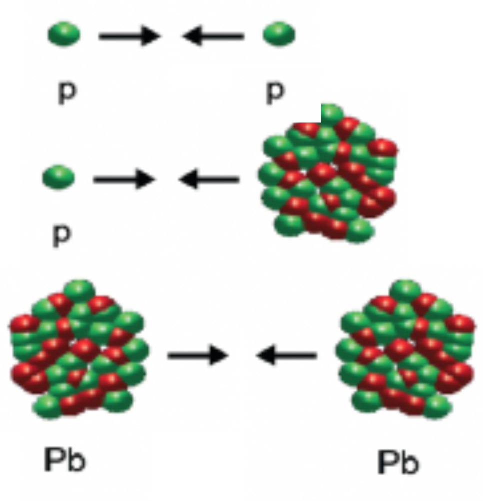
FCC-hh HI Motivation

- Centre-of-mass energies:

pp: $\sqrt{s_{NN}}$ = 100 TeV

pPb: $\sqrt{s_{NN}}$ = 63 TeV

PbPb: $\sqrt{s_{NN}}$ = 39 TeV



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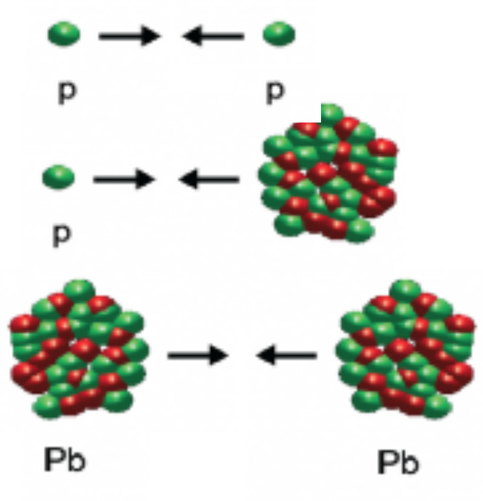

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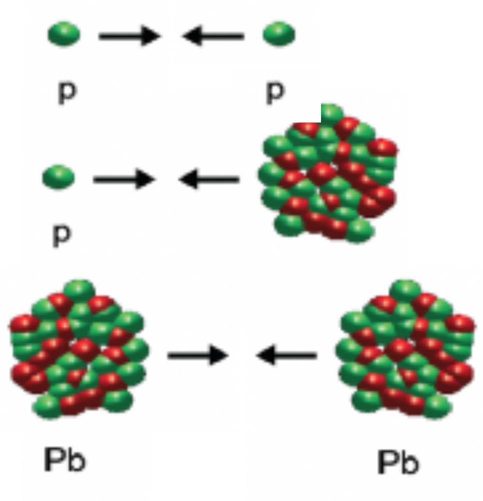

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Bulk Collision:	Hard Probes	Initial State
⇧ Volume and Lifetime ⇧ Temperature: charm thermal production ⇧ Multiplicity: Collectivity in small systems	⇧ Production Rate Boosted objects: Probe QGP time evolution Quarkonia: Probe QGP temperature evolution	⇧ Parton densities: Saturation Physics; Fix initial conditions for collectivity

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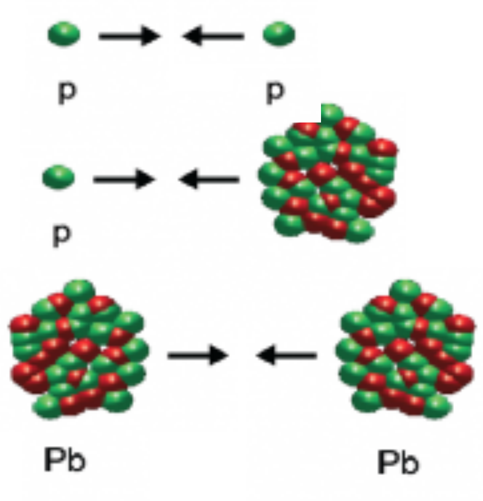

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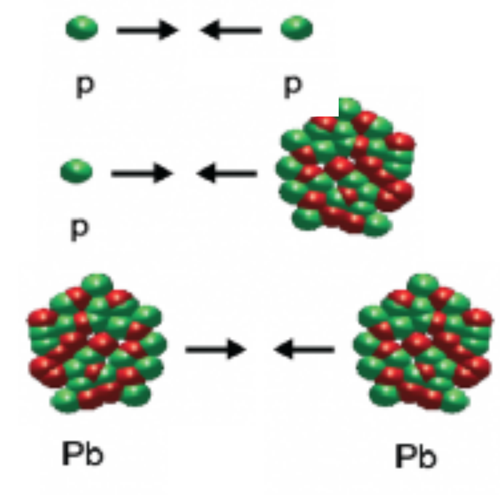

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FCC performance

- Heavy-ion performance of FCC-hh:
  - FCC parameters for PbPb and pPb collisions:

	Unit	FCC Injection	FCC Collision	
Operation mode		Pb	Pb–Pb	p–Pb
Beam energy	[TeV]	270	4100	50
$\sqrt{s_{\mathrm{NN}}}$	[TeV]	-	39.4	62.8
No. of bunches per LHC injection	-	518	518	518
No. of bunches in the FCC	-	2072	2072	2072
No. of particles per bunch	$[10^8]$	2.0	2.0	164
Transv. norm. emittance	$[\mu\mathrm{m}]$	1.5	1.5	3.75
Number of IPs in collision	-	-	1	1
Crossing-angle	$[\mu\mathrm{rad}]$	-	0	
Initial luminosity	$[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	-	24.5	2052
Peak luminosity	$[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	-	57.8	9918
Integrated luminosity per fill	$[\mu\mathrm{b}^{-1}]$	-	553	158630
Average luminosity	$[\mu\mathrm{b}^{-1}]$	-	92	20736
Time in collision	[h]	-	3	6
Assumed turnaround time	[h]	-	1.65	1.65
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vs LHC: 5.5 (PbPb) and 8.8 (pPb)

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vs LHC (total):
PbPb: ~1 (Run2); ~4 (Run3); ~4 (Run4)
pPb: 50-400 (2 weeks)

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For an update, see
J. Jowett, 2017 Chamonix
workshop

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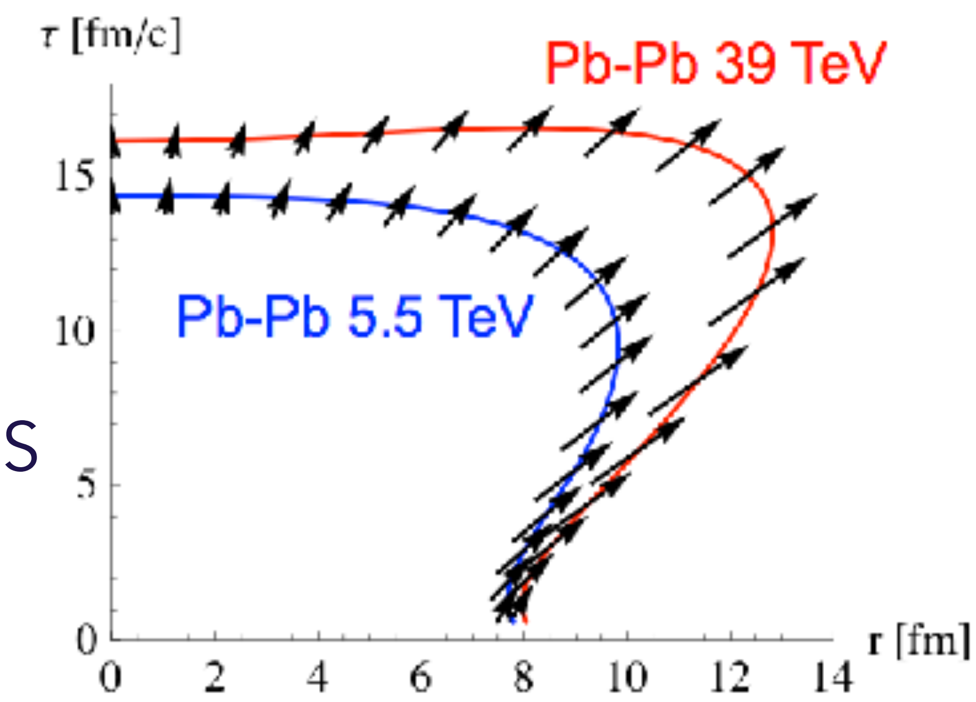
Soft Probes
Direct Signal of QGP Formation

Medium bulk properties

- Expectations:
  - Charged hadron multiplicity: $\left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0} \propto (\sqrt{s_{NN}})^{0.3} \Rightarrow$ LHC 5.5 TeV $\overset{\times 1.8}{\longmapsto}$ FCC 39 TeV
    - Can constrain the initial entropy density
  - Freeze-out hypersurfaces:
    - Initial energy density from two Wood-Saxon profiles (without energy dependence or fluctuations)
    - Parameterisation of a realistic QCD EoS ($\eta/s = 1/(4\pi)$)



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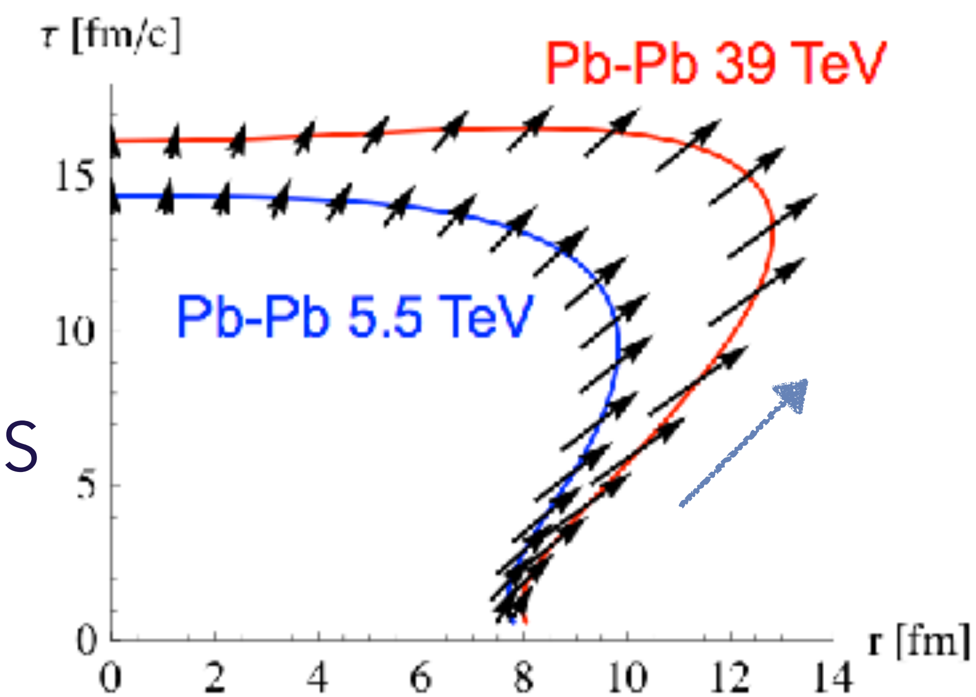

Denser regime has to expand to a larger volume and for a longer time

Freeze-out volume increase is proportional to event multiplicity

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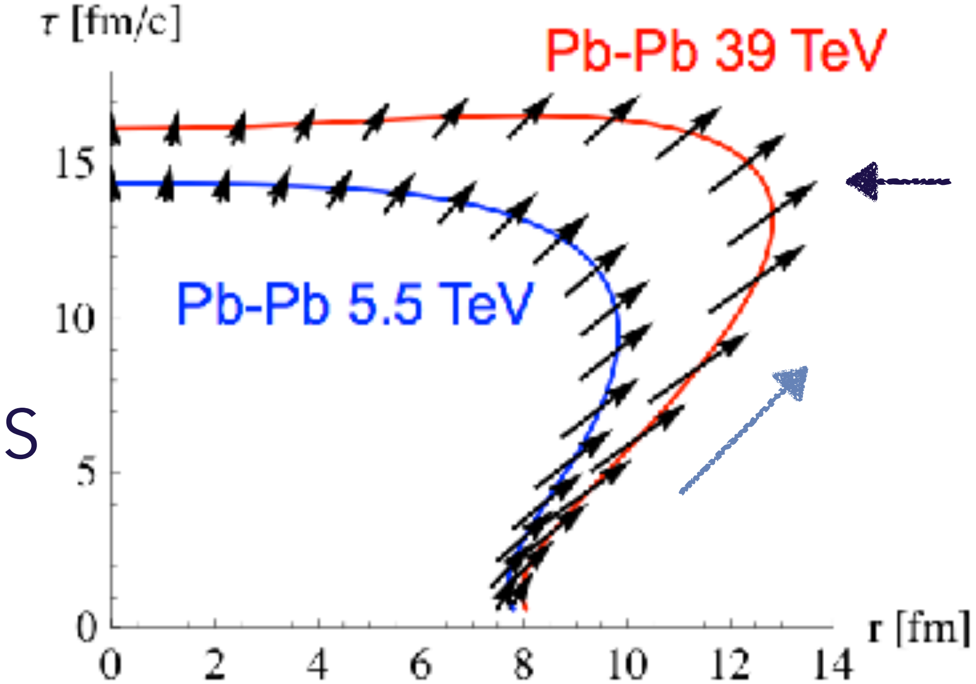

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Increase of collective flow phenomena

Medium bulk properties

- Expectations:
  - Energy density per rapidity unit: $\frac{dE_T}{d\eta}$
    - Constrains the initial energy density
    - Bjorken expansion + Free streaming

$$\epsilon(\tau) = \frac{1}{\pi R_A^2}\frac{1}{c\tau}\frac{dE_T}{d\eta} \sim \frac{1}{\tau} \Rightarrow (\tau = 1\text{fm}): \text{LHC} \xrightarrow{\times 2} \text{FCC}$$

LHC: 5.5 TeV → FCC: 39 TeV

πR_A^2: Transverse overlap area

$c\tau$: Longitudinal extent

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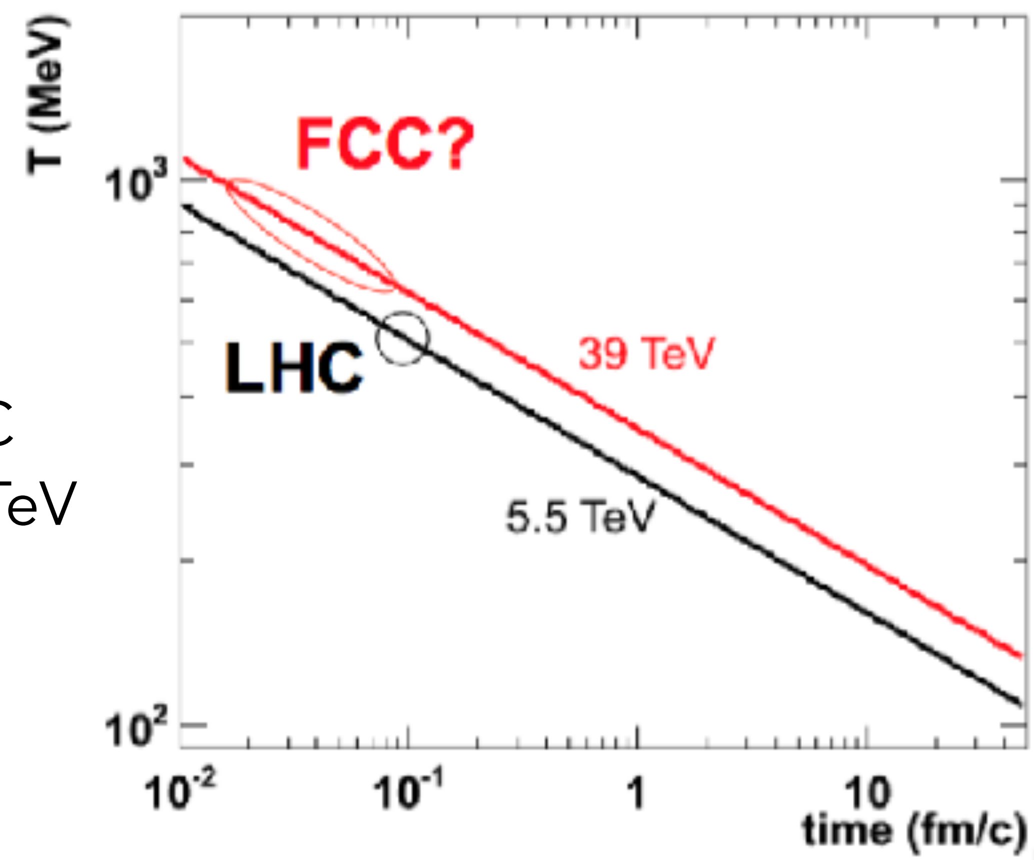
- Stefan-Boltzmann limit:

$$\Rightarrow T(\tau) = \left[\epsilon(\tau) \frac{30}{\pi^2} \frac{1}{n_{d.o.f.}}\right]^{1/4} \sim \frac{1}{\tau^{1/4}}$$

At a given time, expected increase of temperature of 30%



gluons and 3 quark flavours: $n_{d.o.f.} = 47.5$

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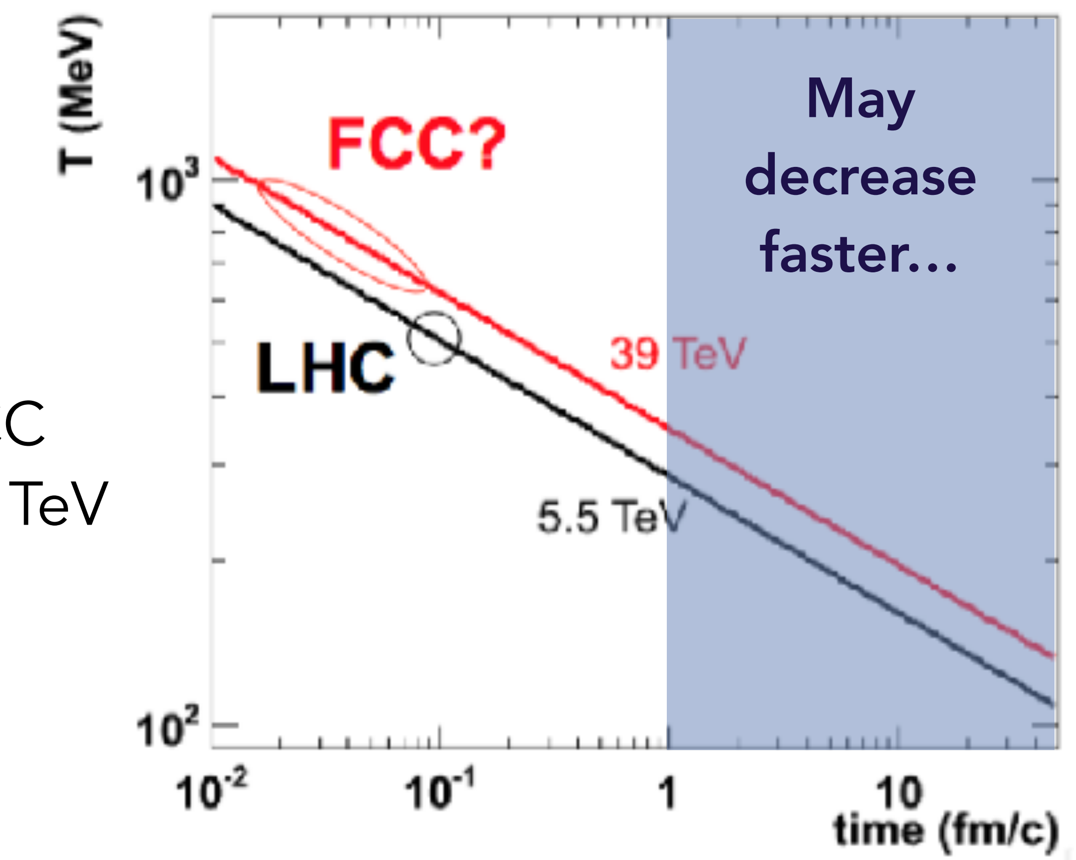

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Medium bulk properties

Thermalisation time = time at which hydro starts (good description of the system)

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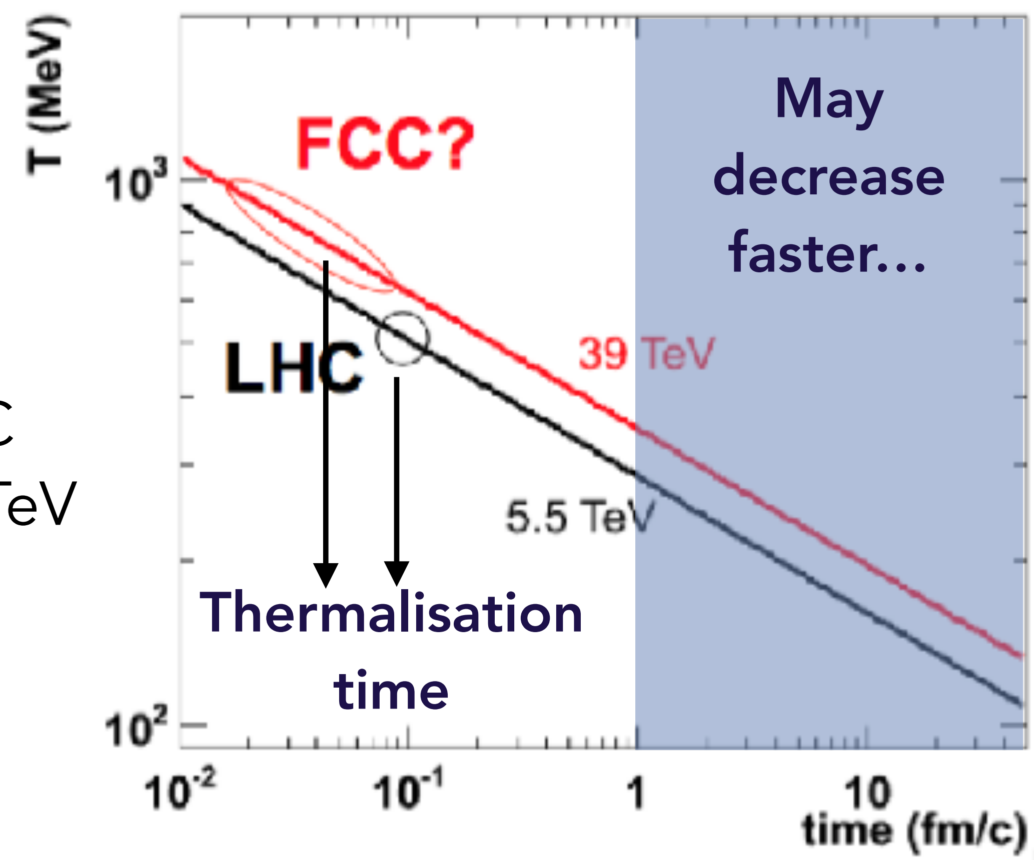

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At a given time, expected increase of temperature of 30%

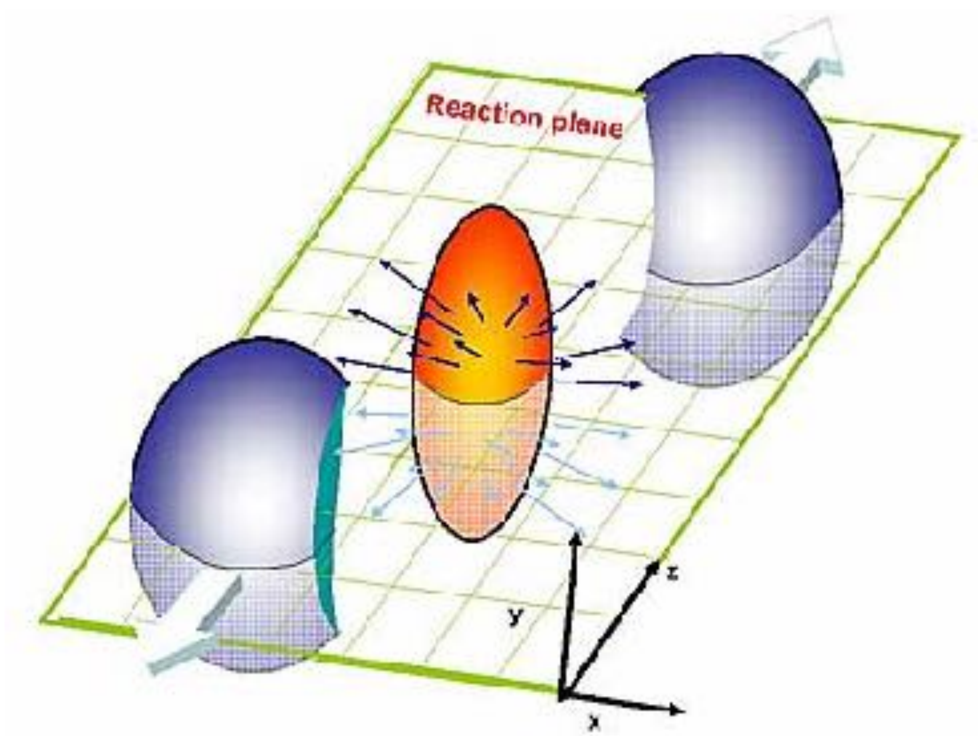
Thermalisation time expected to be significantly smaller ($T_0 \approx$ 800-1000 MeV)

Flow-like effects

- Azimuthal dependence of particle production:

$$\frac{dN_{ch}}{p_T dp_T d\eta d\phi} = \frac{1}{2\pi}\frac{dN_{ch}}{p_T dp_T d\eta}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T,\eta)\cos(n(\phi - \Psi_n))\right]$$

Ψ_n: Reaction plane for harmonic "n"



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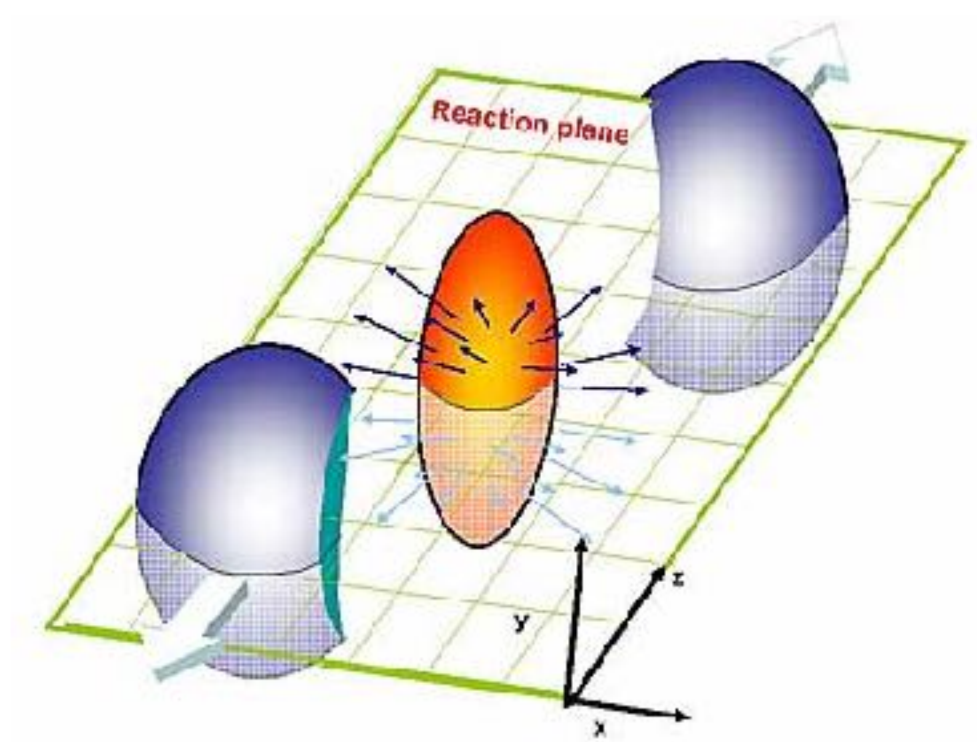


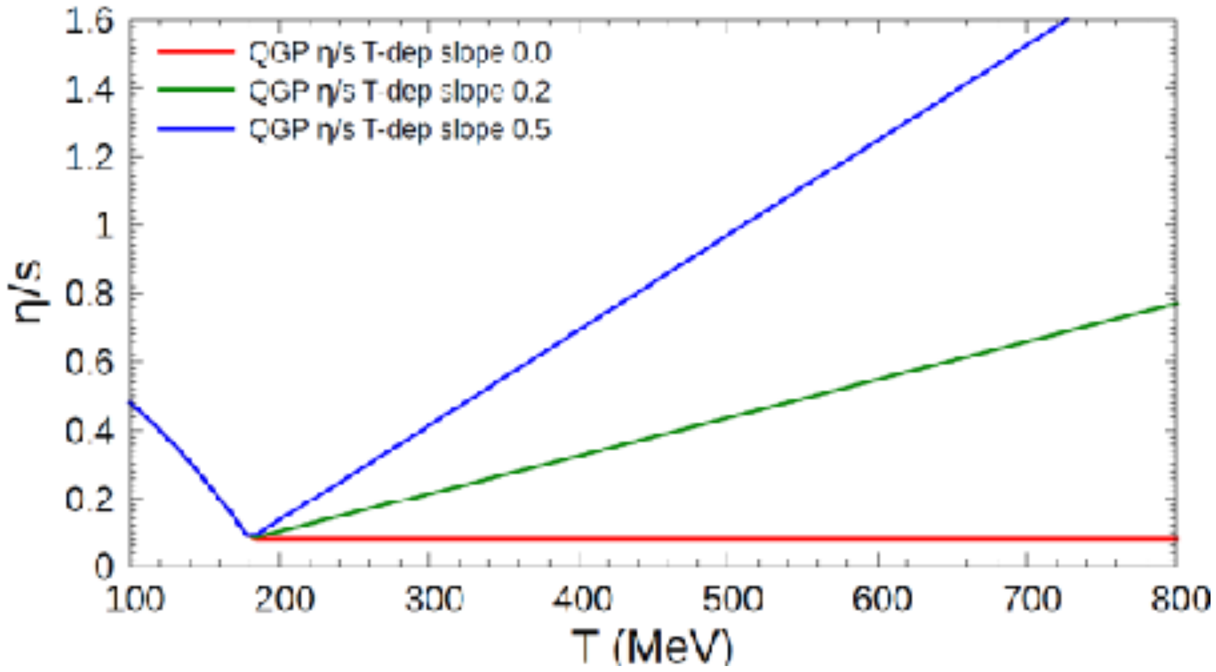
Disentangle from same data set using multi-particle azimuthal correlations

Ollitrault et al, 09
Voloshin et al, 09
Bilandzic et al, 14

Flow-like effects

- ⇧ Multiplicity at FCC:
  - Measurement on an event-by-event basis;
  - Sensitivity to further dependences of transport coefficients ($v_n \sim \eta/s$ (T))

Gale et al, 12
Niemi et al, 14
Denial et al 14



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(Still under theoretical development…)

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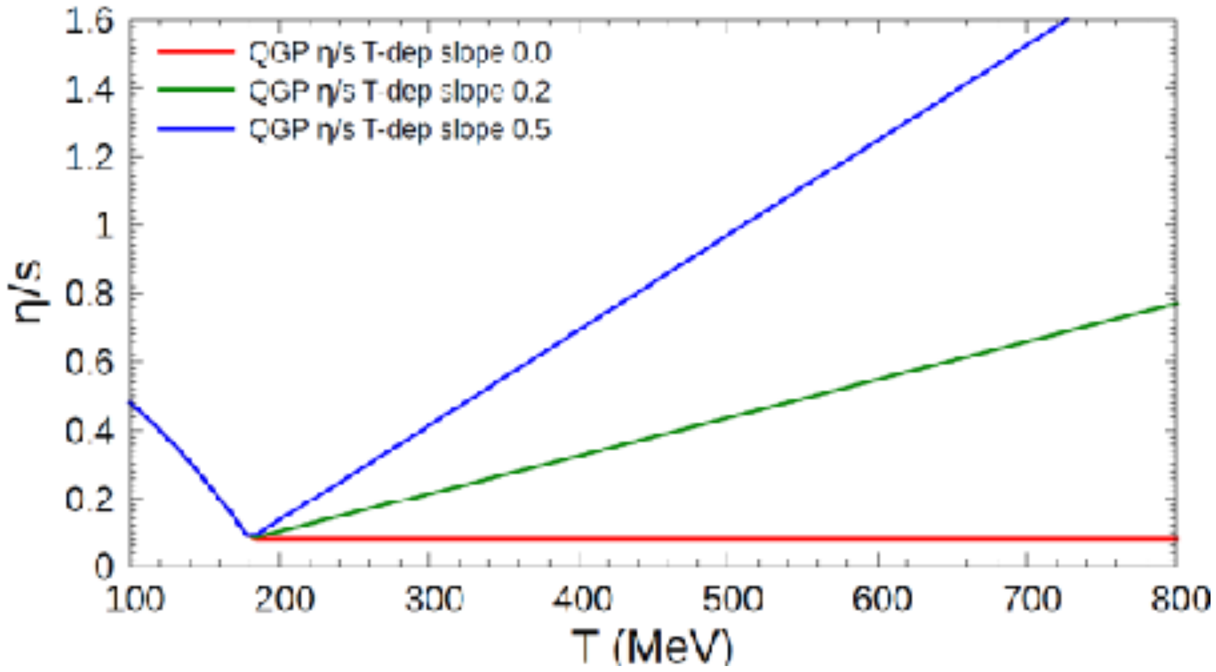

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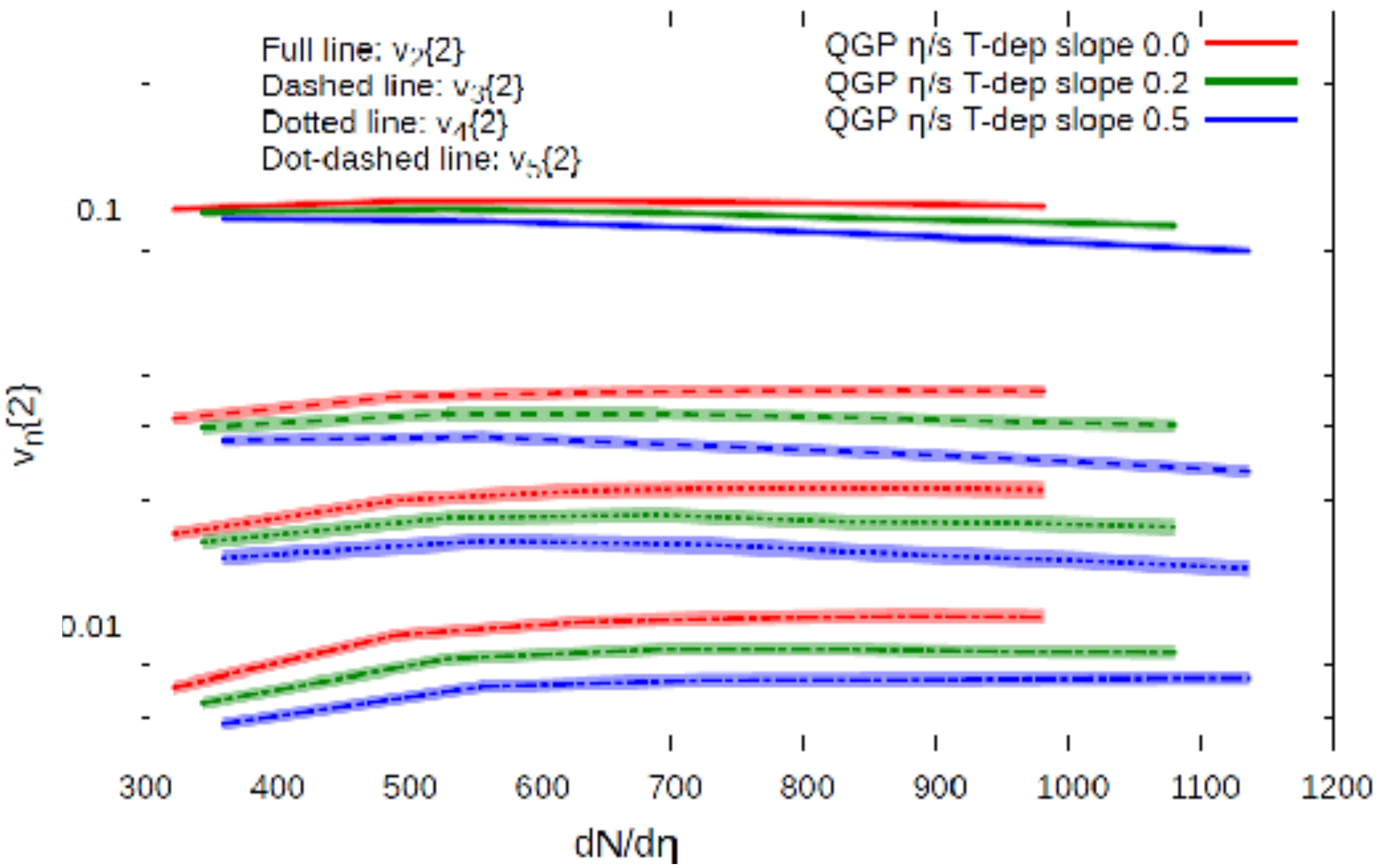

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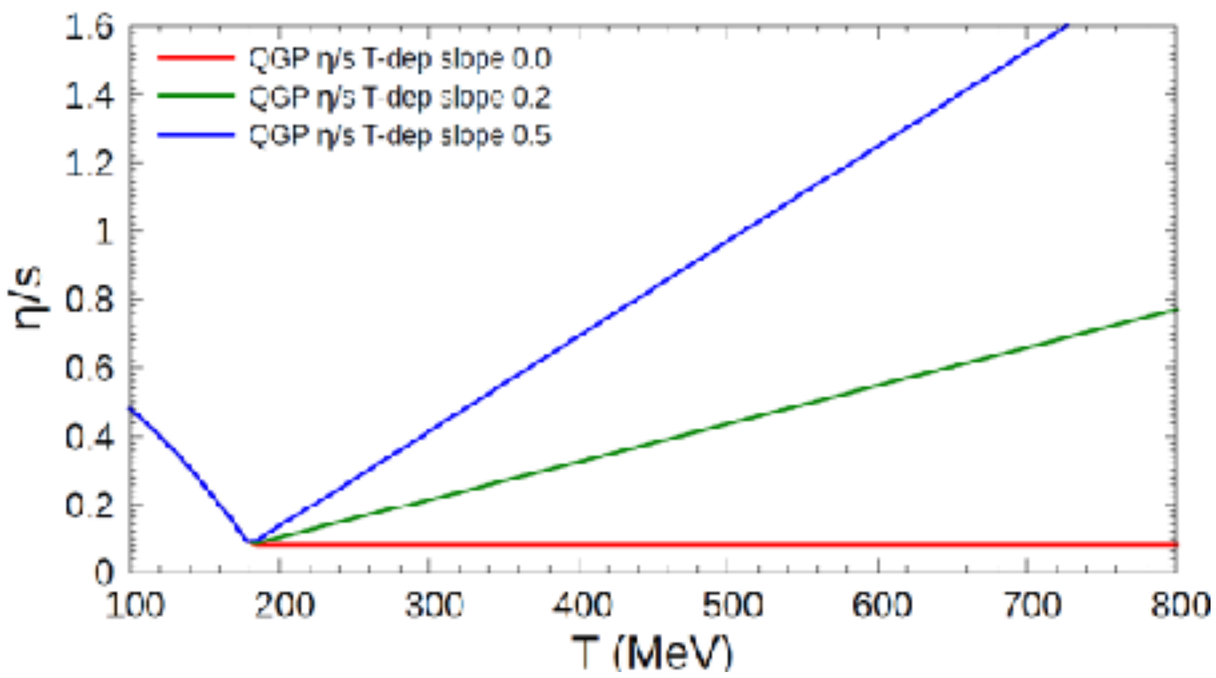

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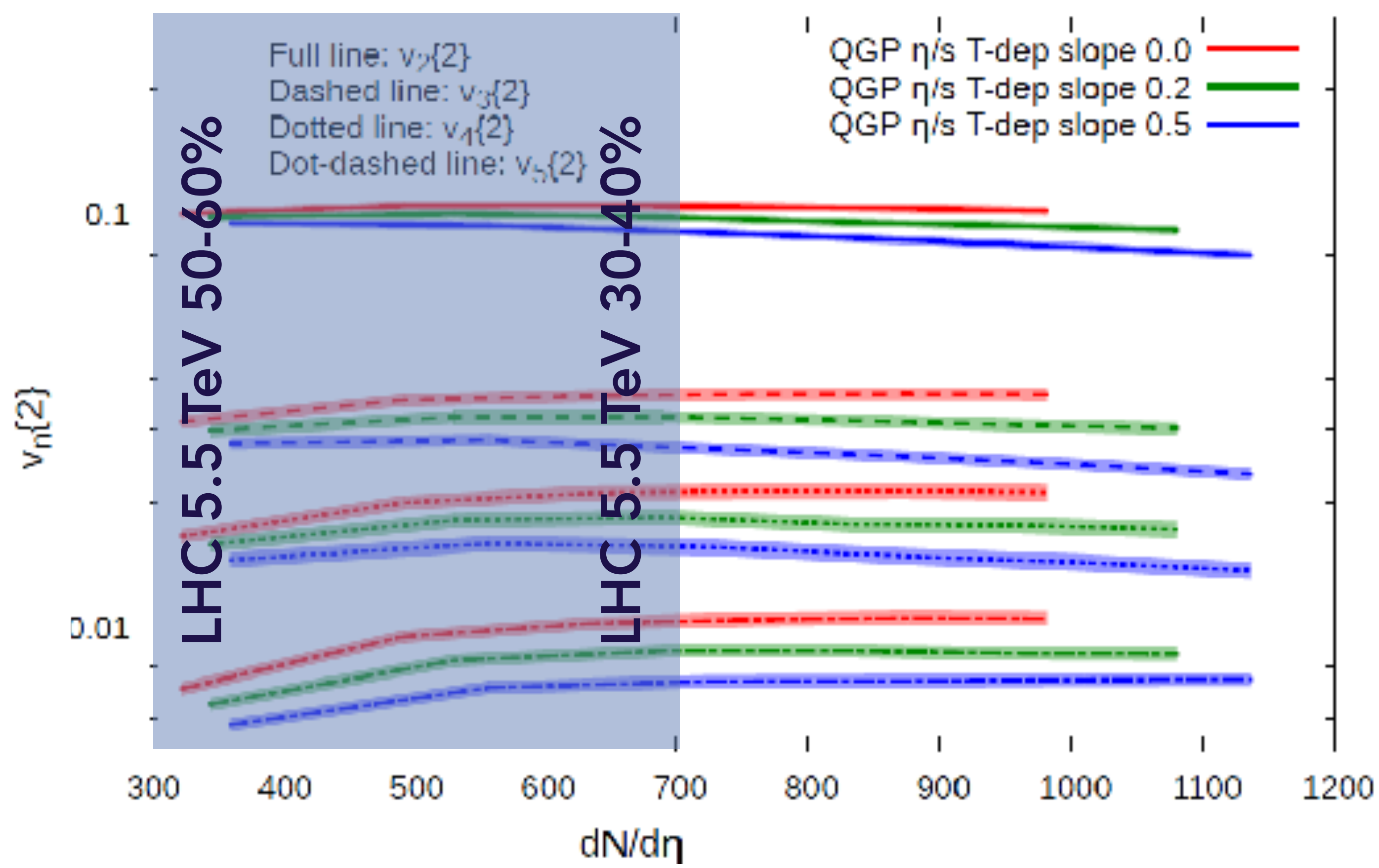

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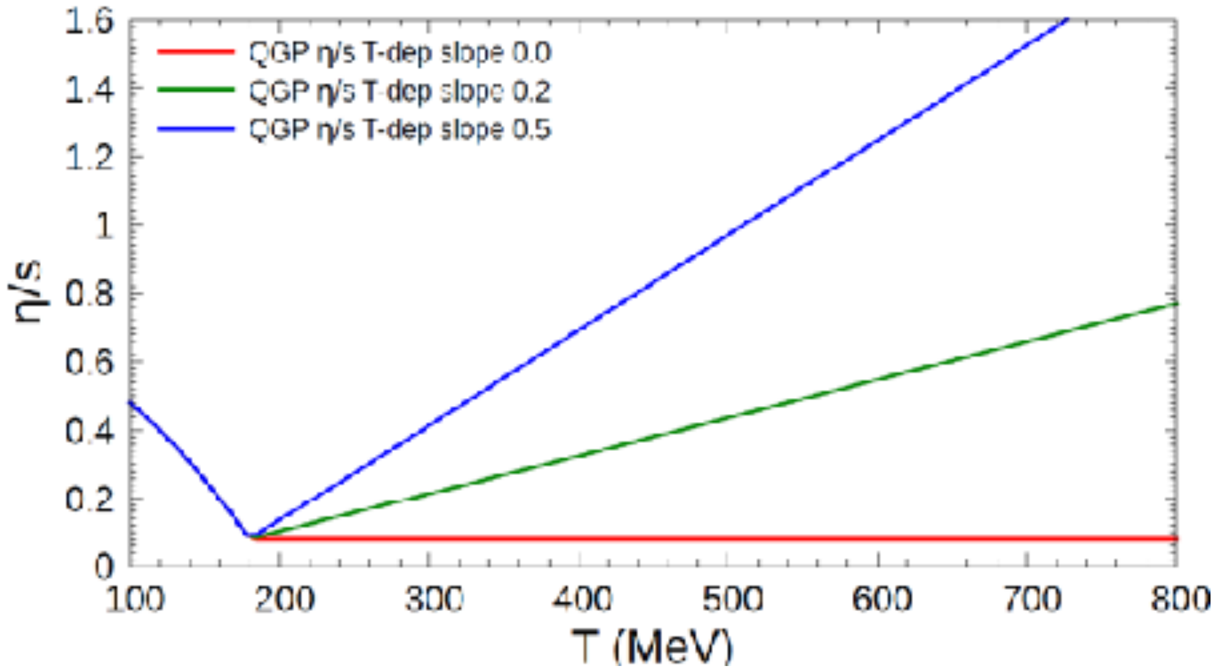

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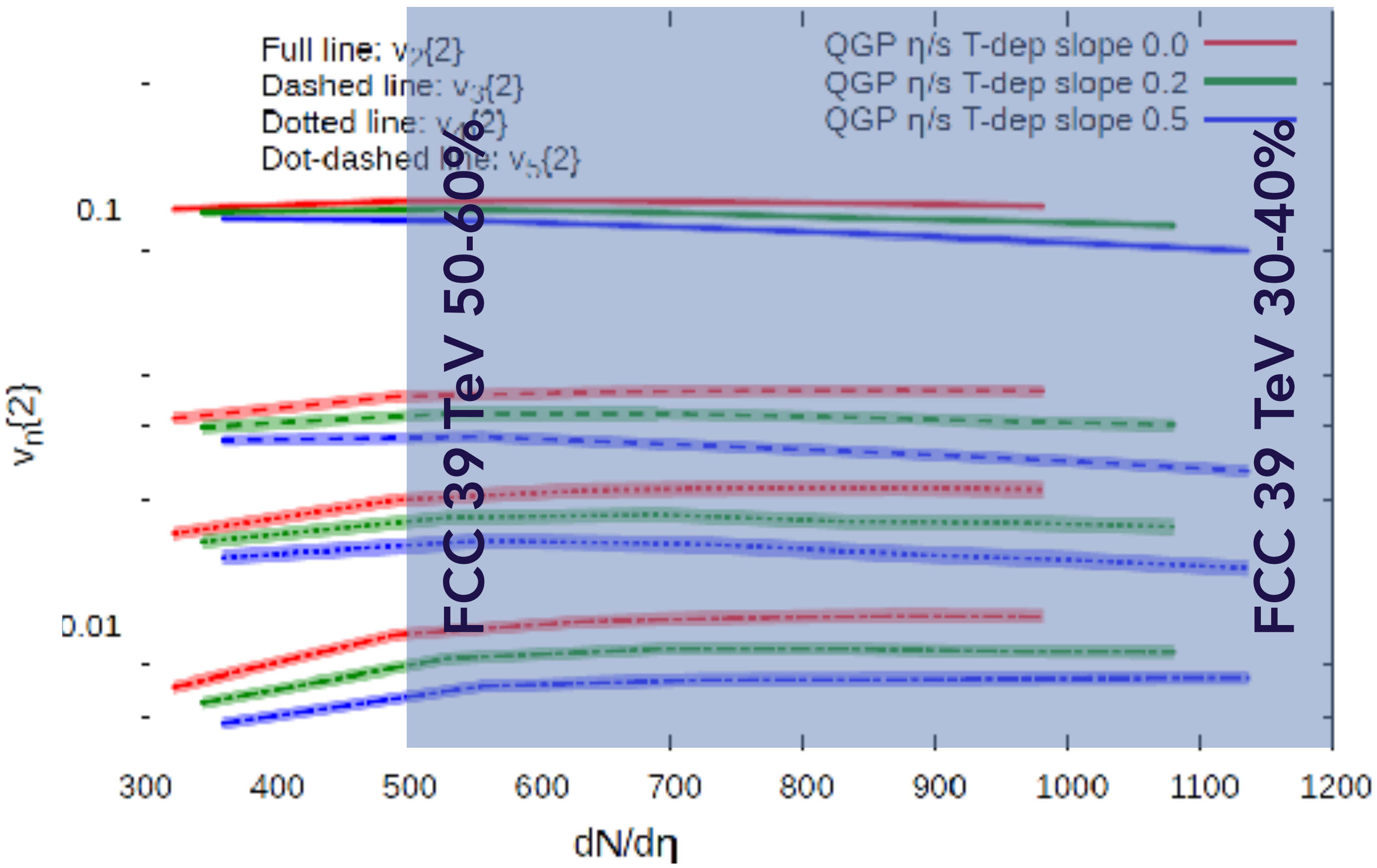

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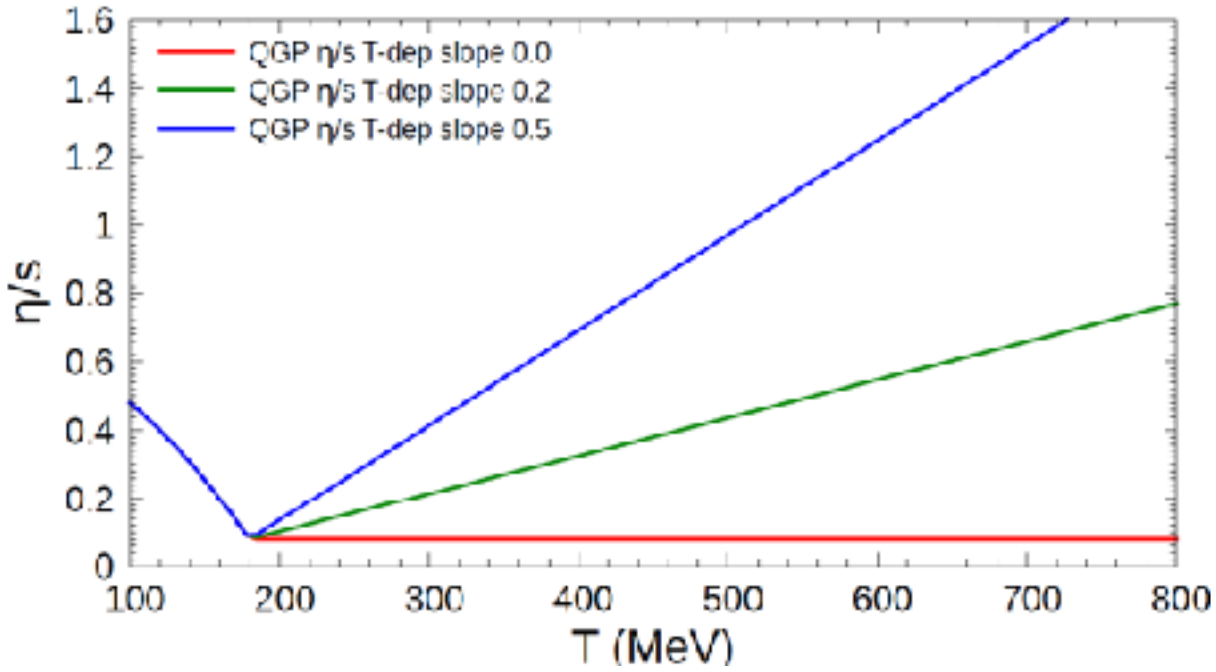

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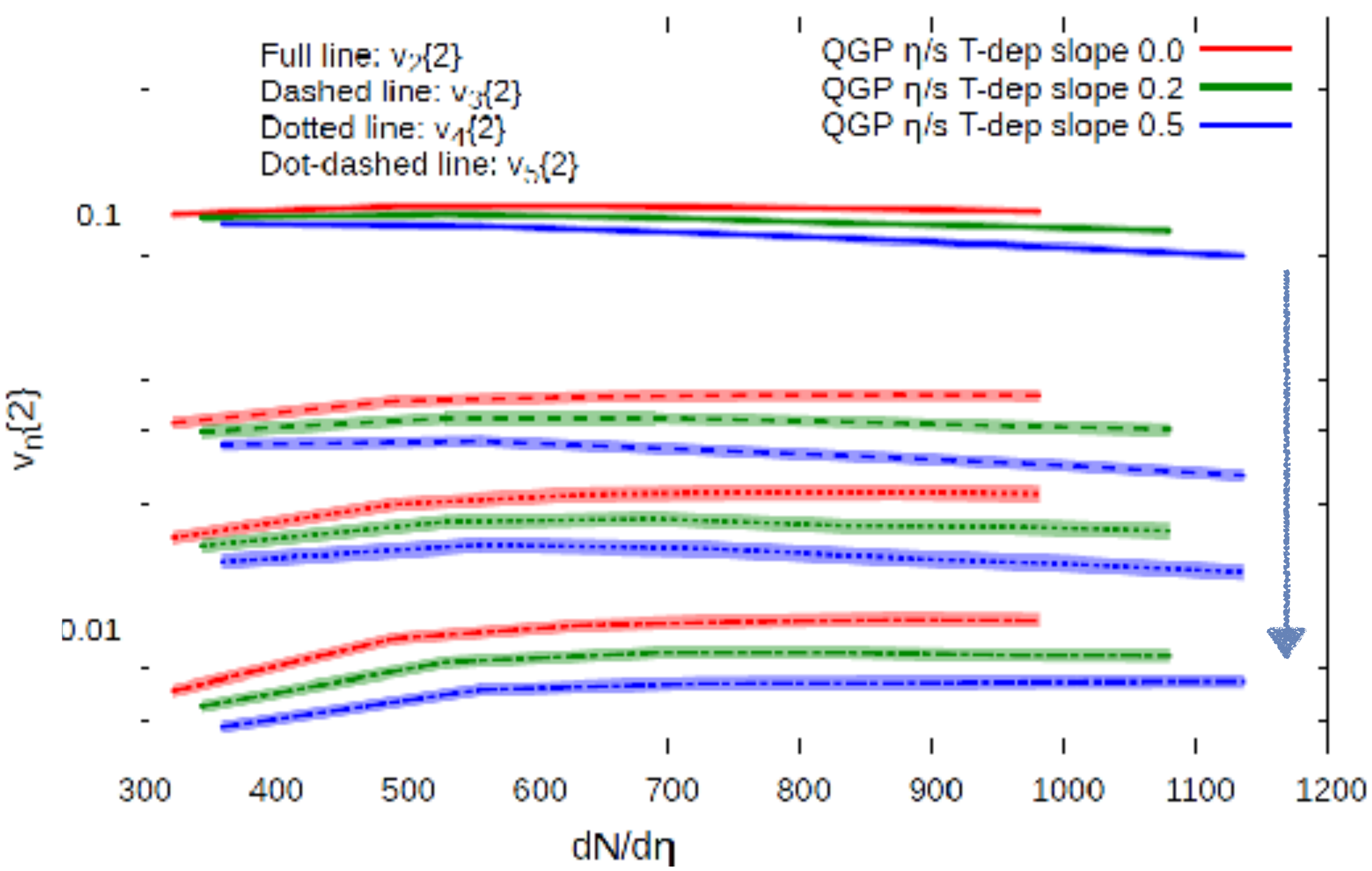
Sensitivity to η/s (T) increases with multiplicity



Flow in small systems

- Collective behaviour in:
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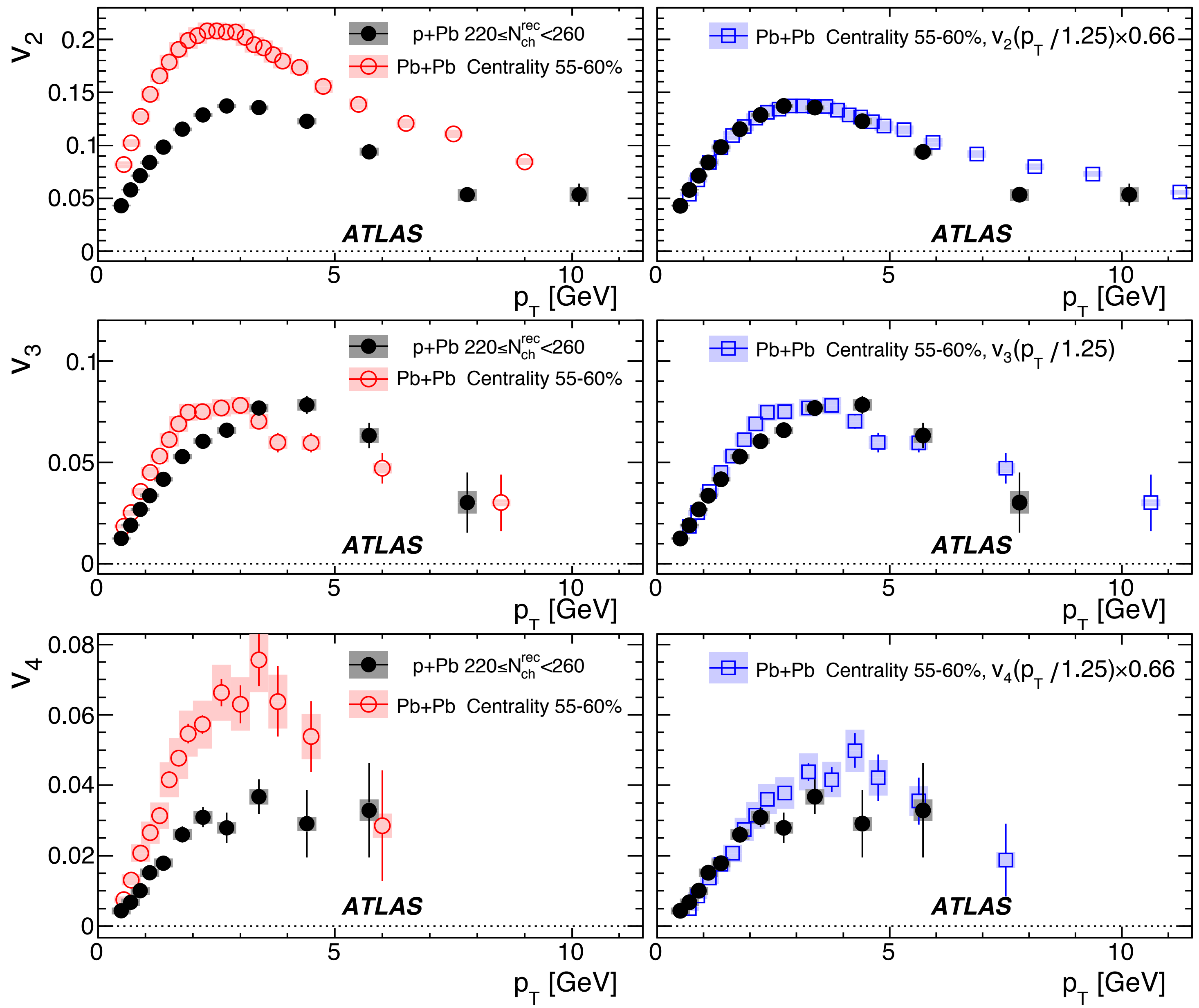

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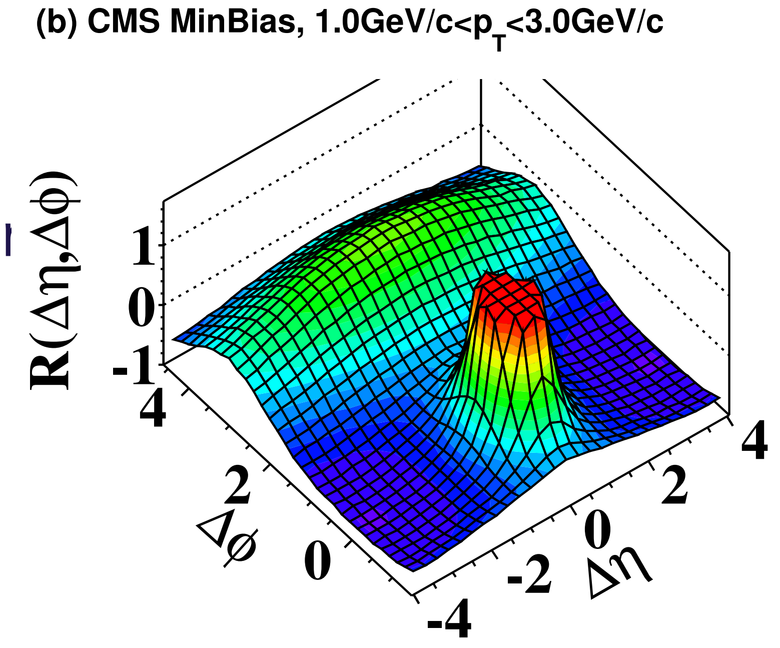

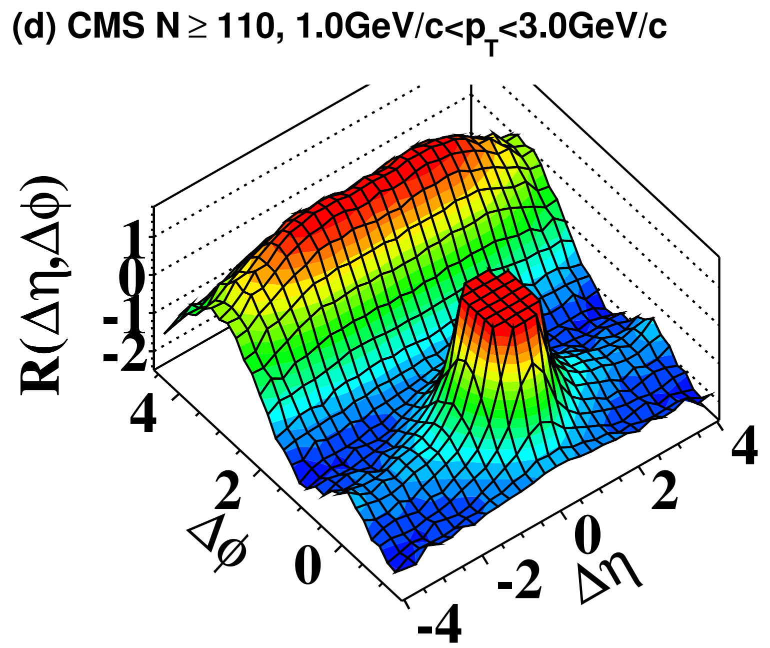

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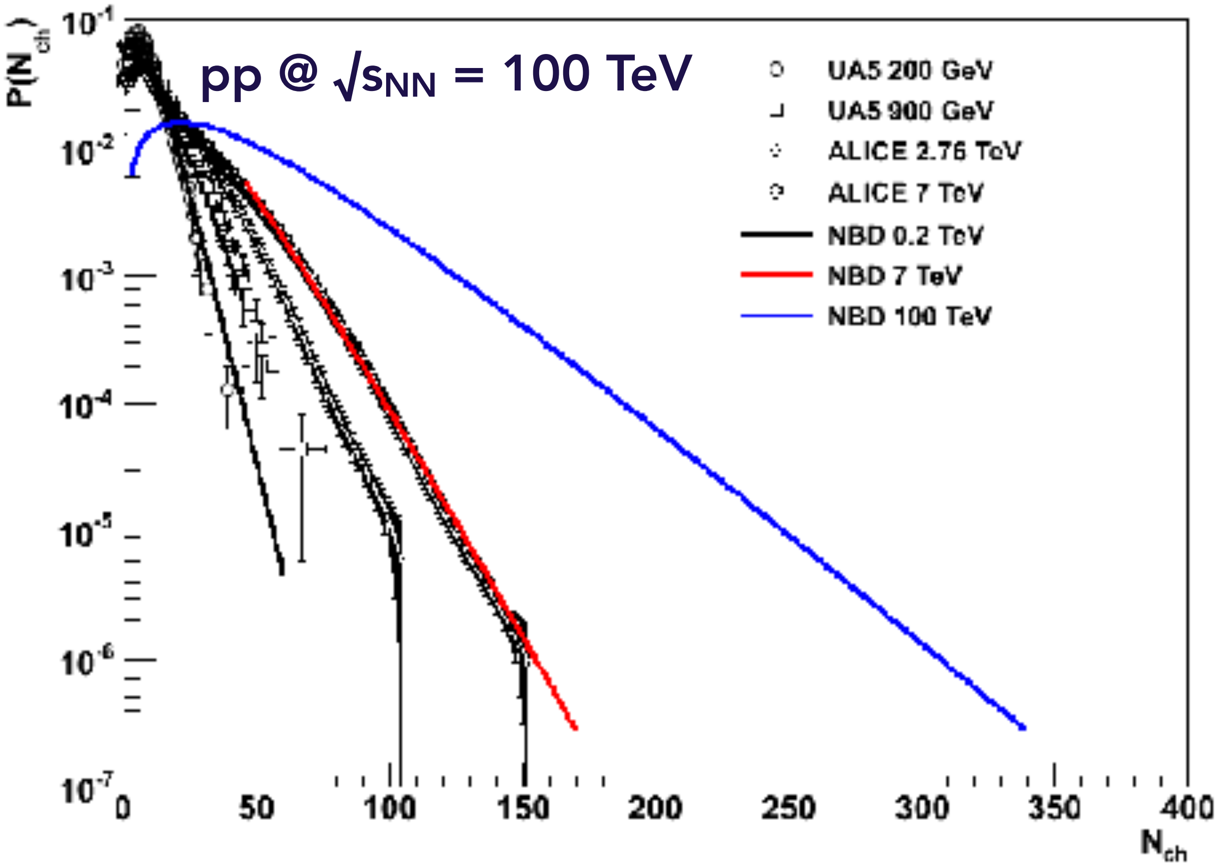

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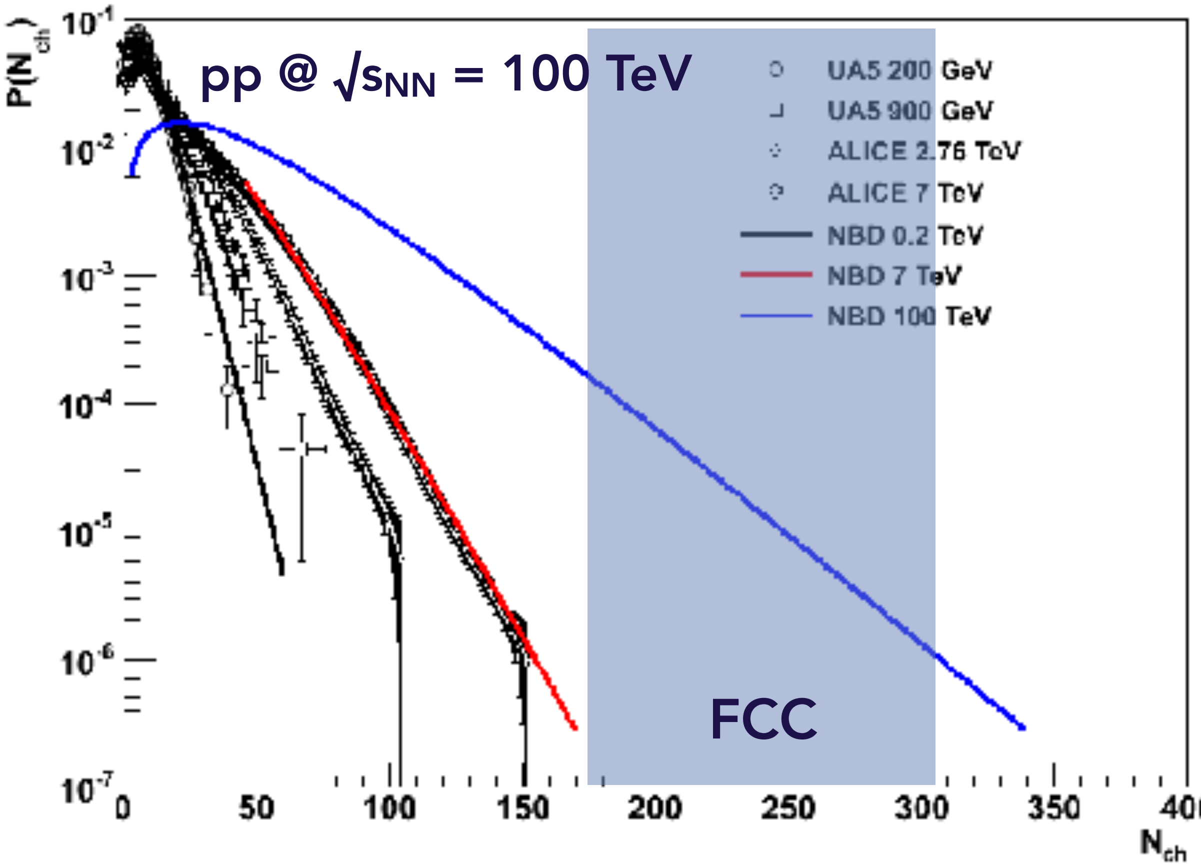
Identification of flow-like phenomena, in small systems, with statistically demanding analysis



Hadrochemistry

- Relative abundance of hadronic species well described by the grand canonical partition function:
  - 2 free parameters: T and μ_B at decoupling
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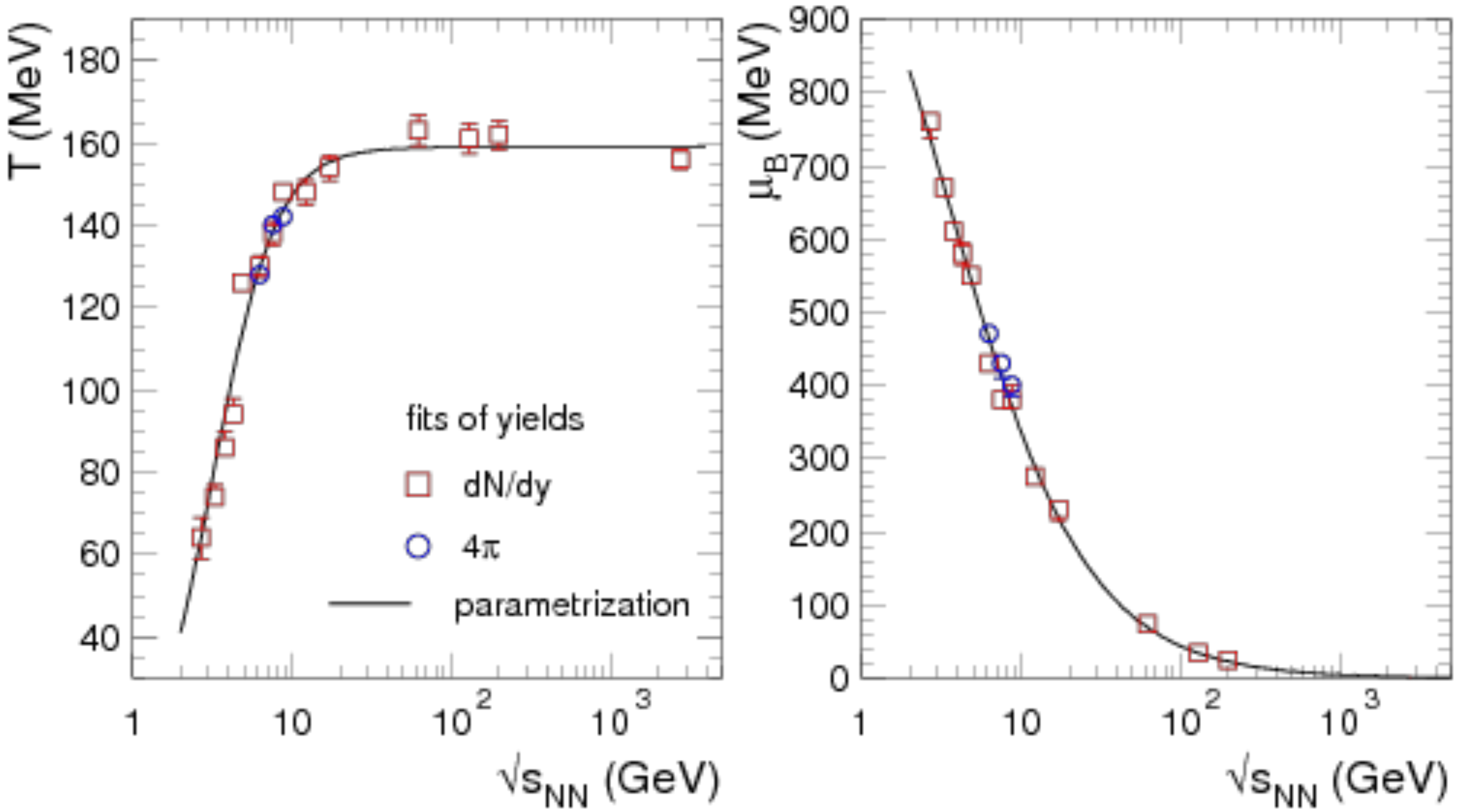

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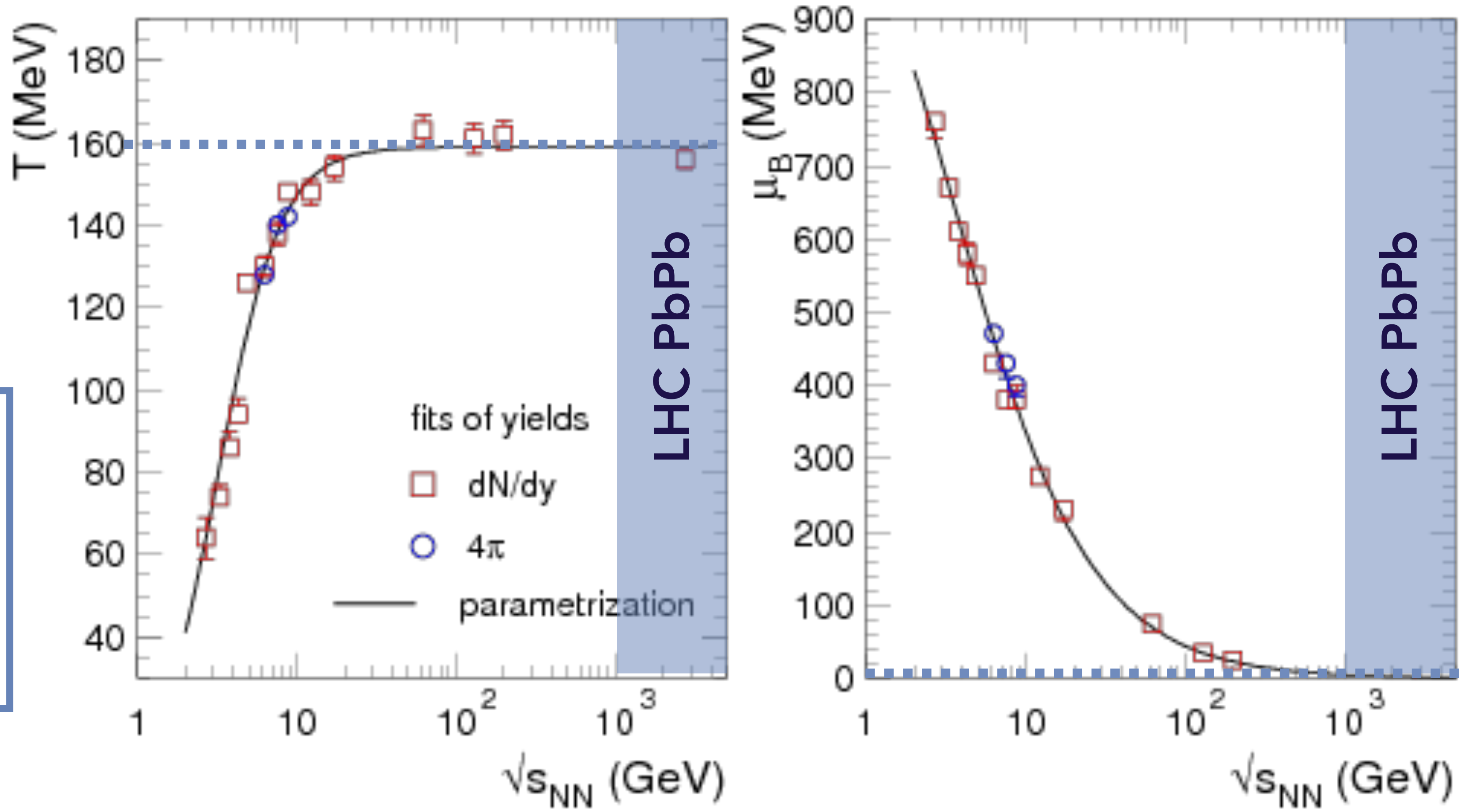

All ratios of thermal hadronic abundance are expected to remain unchanged from FCC to LHC


Hard Probes
Results from the interaction with the QGP

Heavy-Quarks

- In-medium production of heavy quarks sensitive to:
  - Formation and Temperature of the deconfined plasma
    - Quarkonia production depends on the balance between colour-charge screening mechanism and possible recombination
  - Interaction mechanisms of heavy-quarks with plasma constituents and transport properties
    - Information on the energy loss/gain mechanisms

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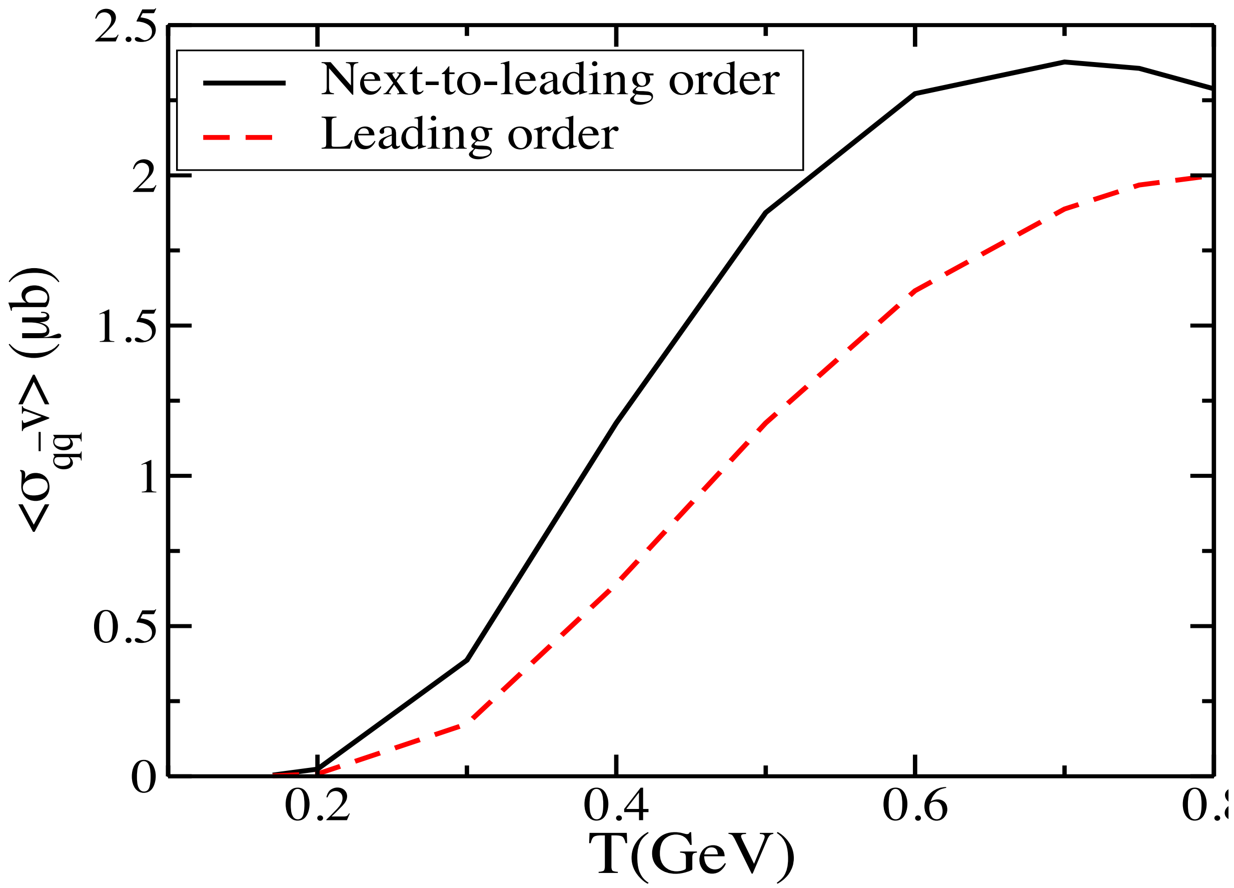
  - Interaction mechanisms of heavy-quarks with plasma constituents and transport properties
    - Information on the energy loss/gain mechanisms
- Expected increase of temperature will result in:
  - Increase of thermal charm production;
  - Charmonium enhancement;
  - Bottomonium (re)generation;

Thermal charm production

Zhang et al, 08

- Charmonium production when $\sqrt{s_{cm}} \sim 2\ m_c \sim 3$ GeV
- Thermalised medium: energy of constituents ~ T (thermal-like exponential distribution)
  - FCC: $T_{QGP} > 500$ MeV

Average σ for charm production:



Dynamical kinetic equations with an evolving medium and charm production with gain (production) and loss (annihilation) terms

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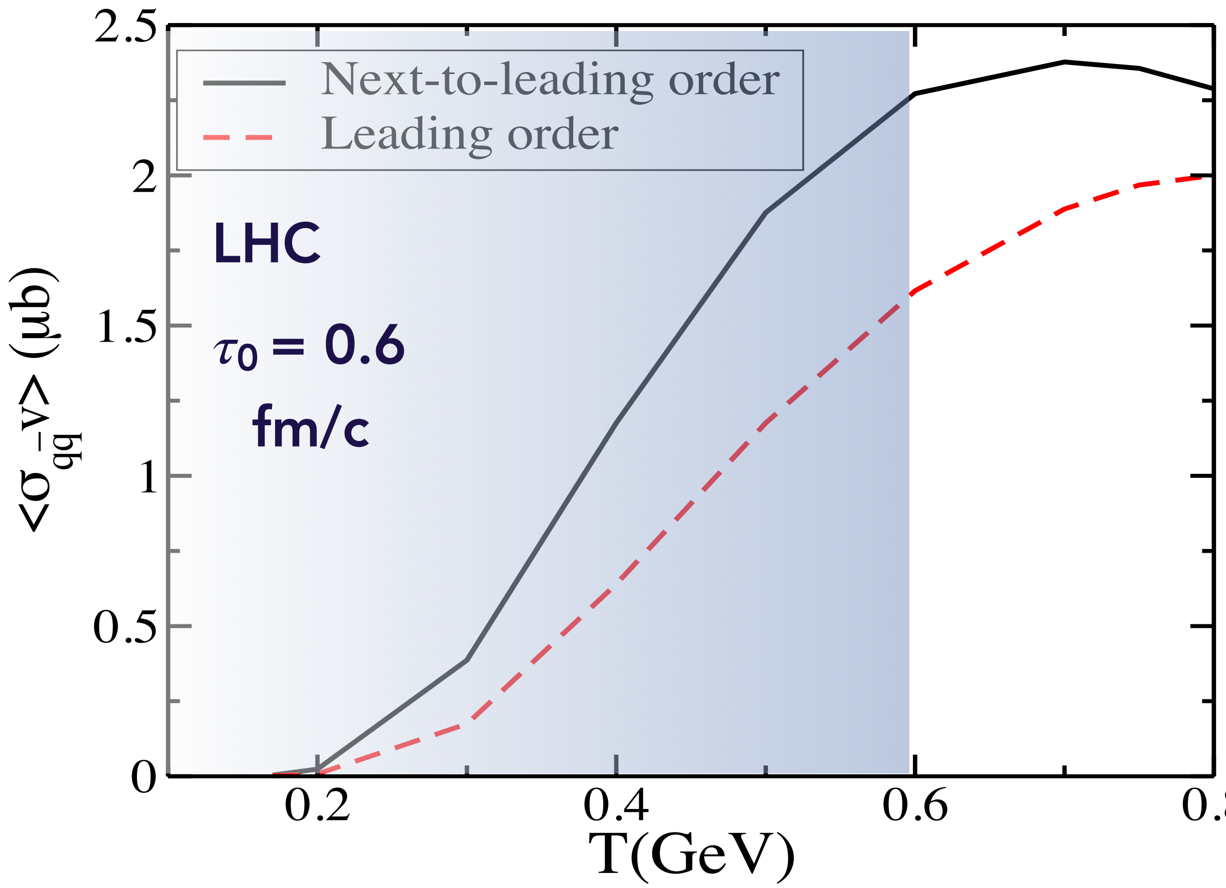

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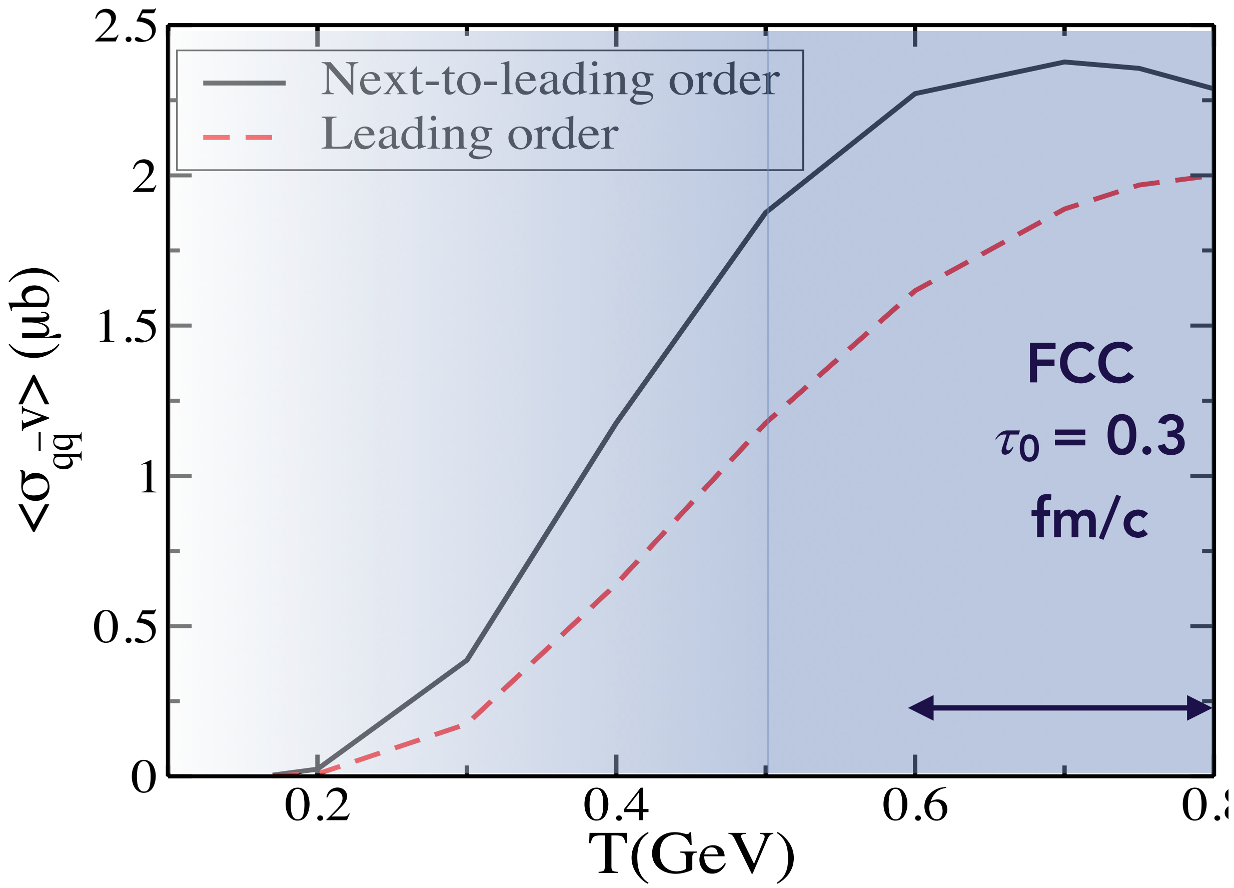

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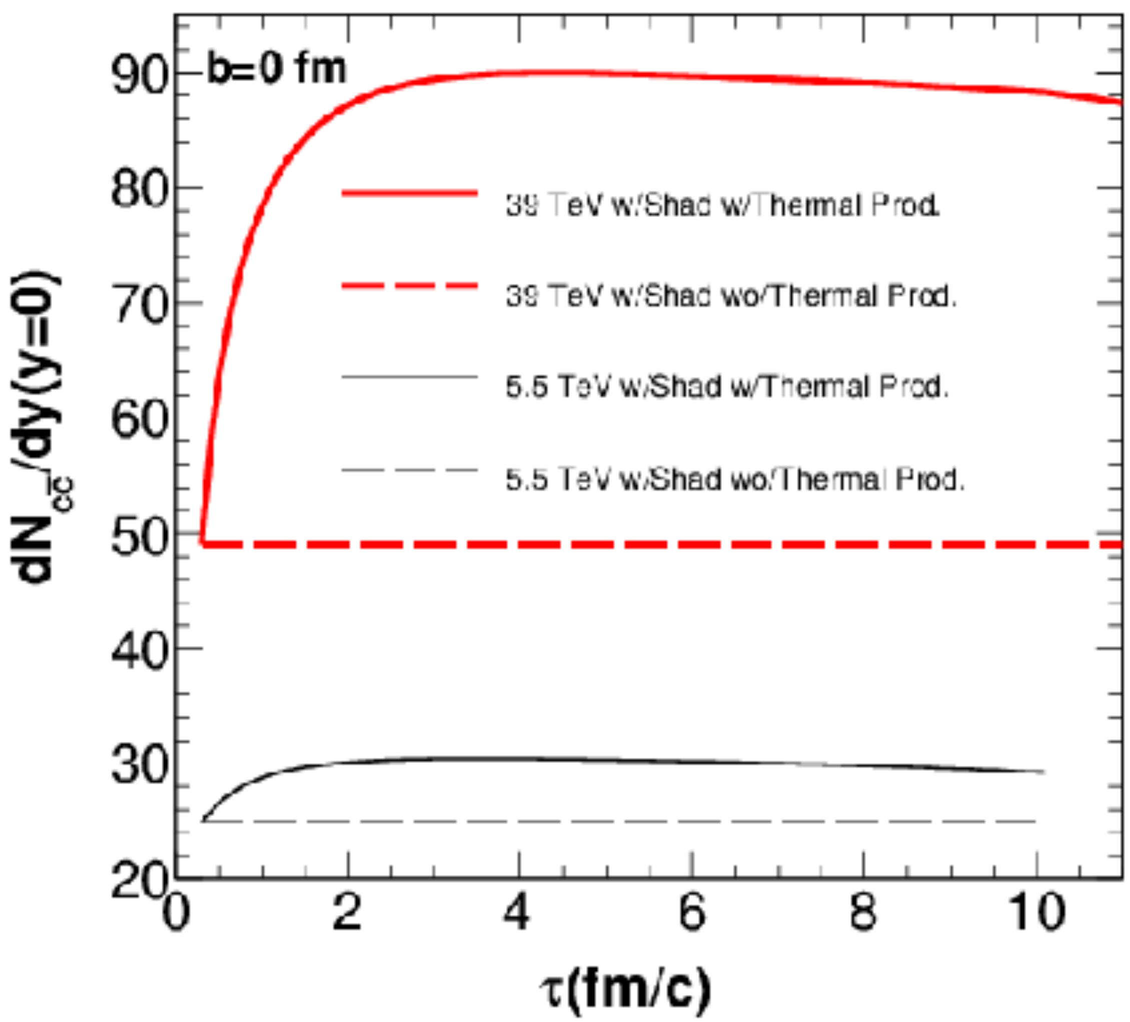

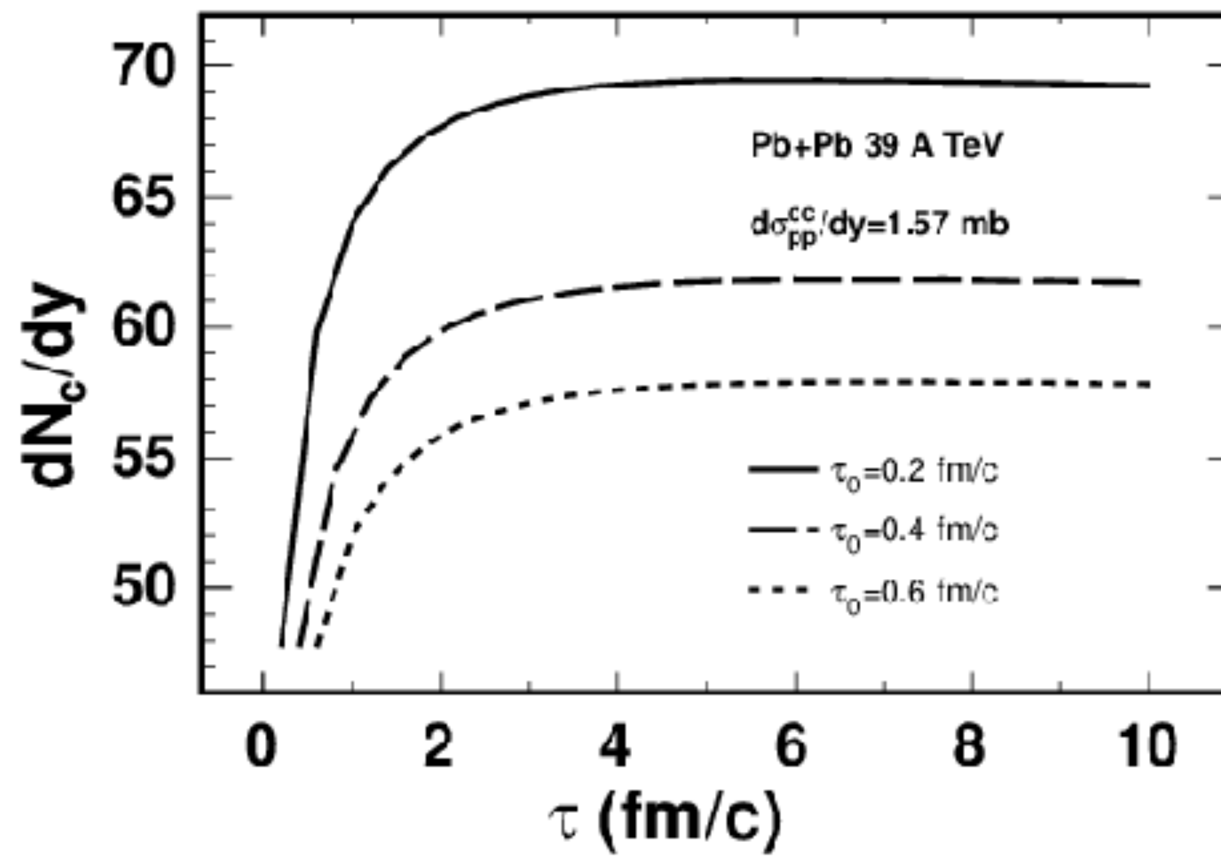

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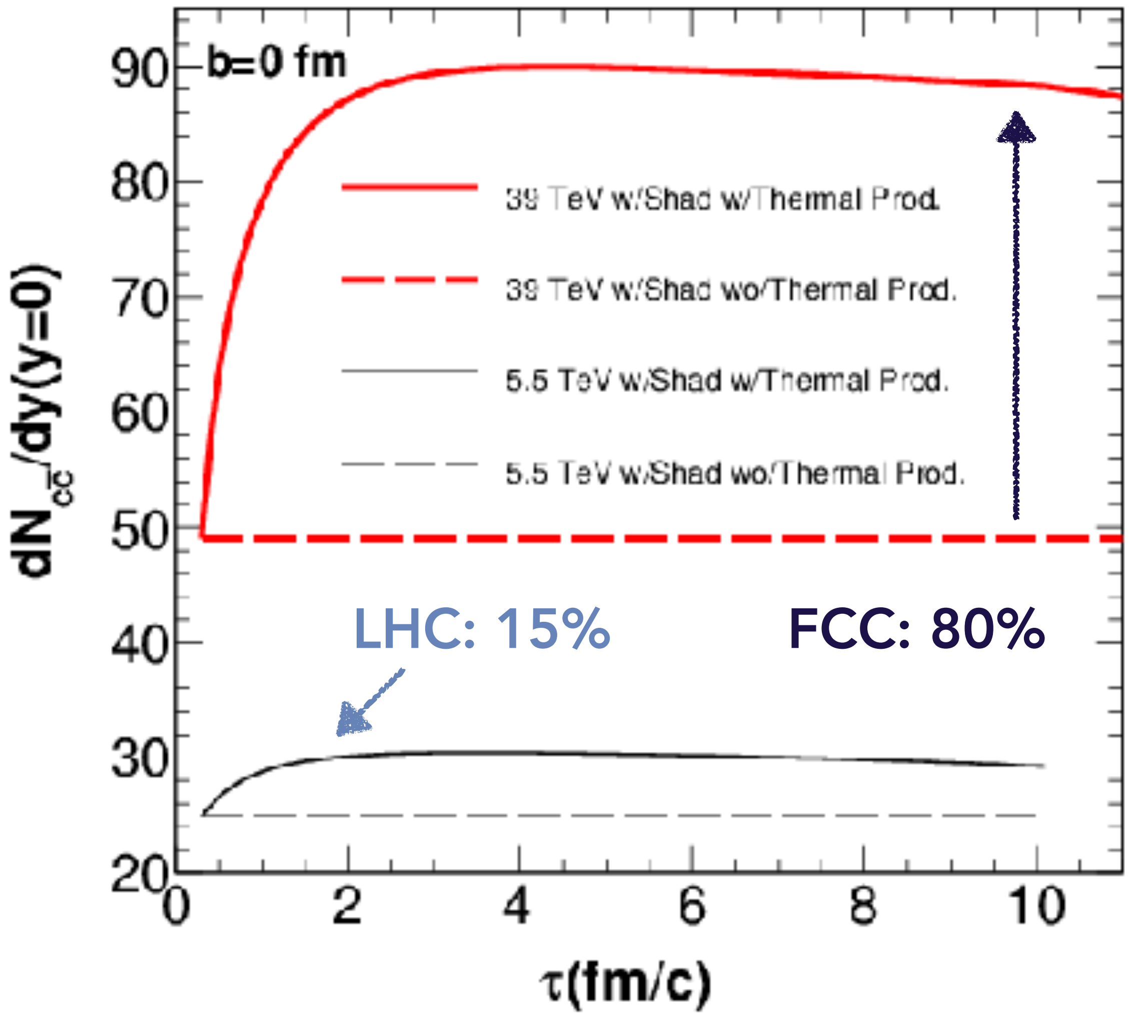

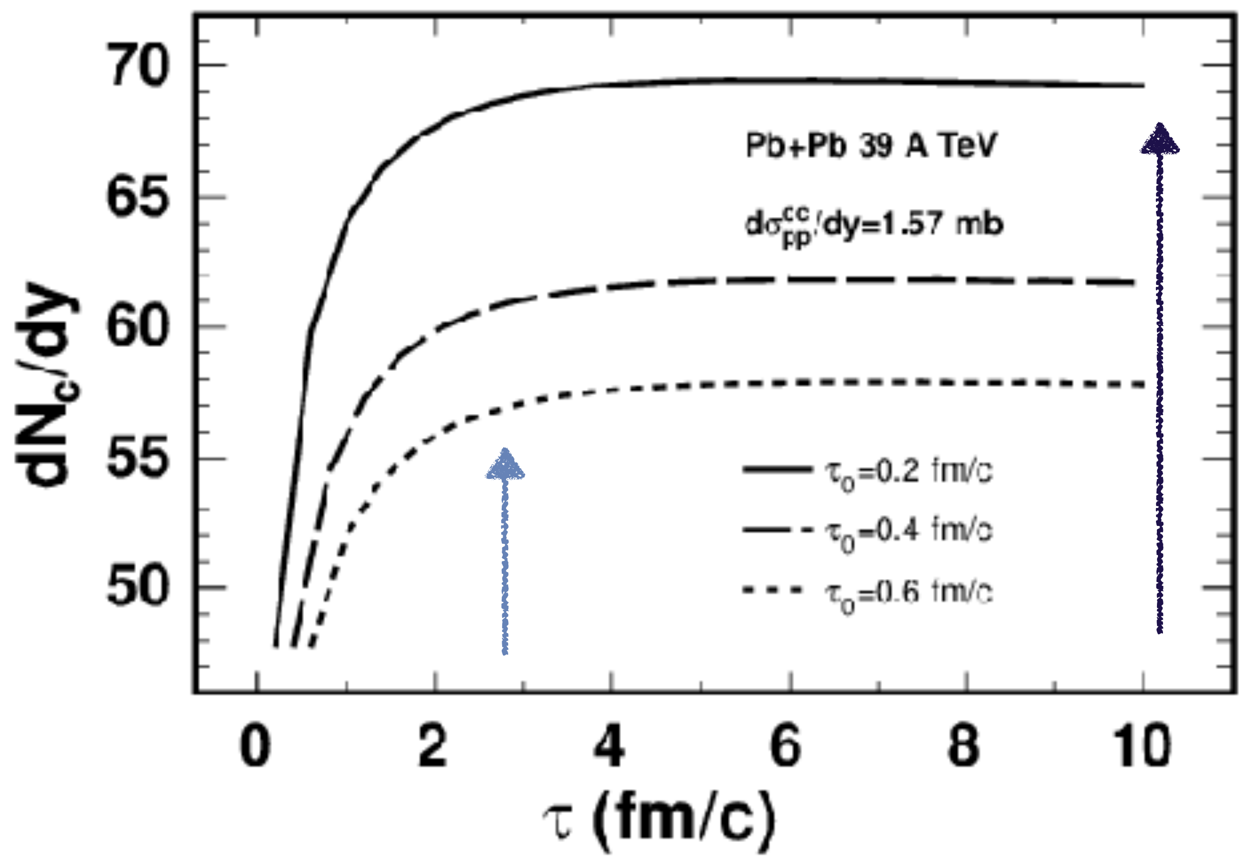

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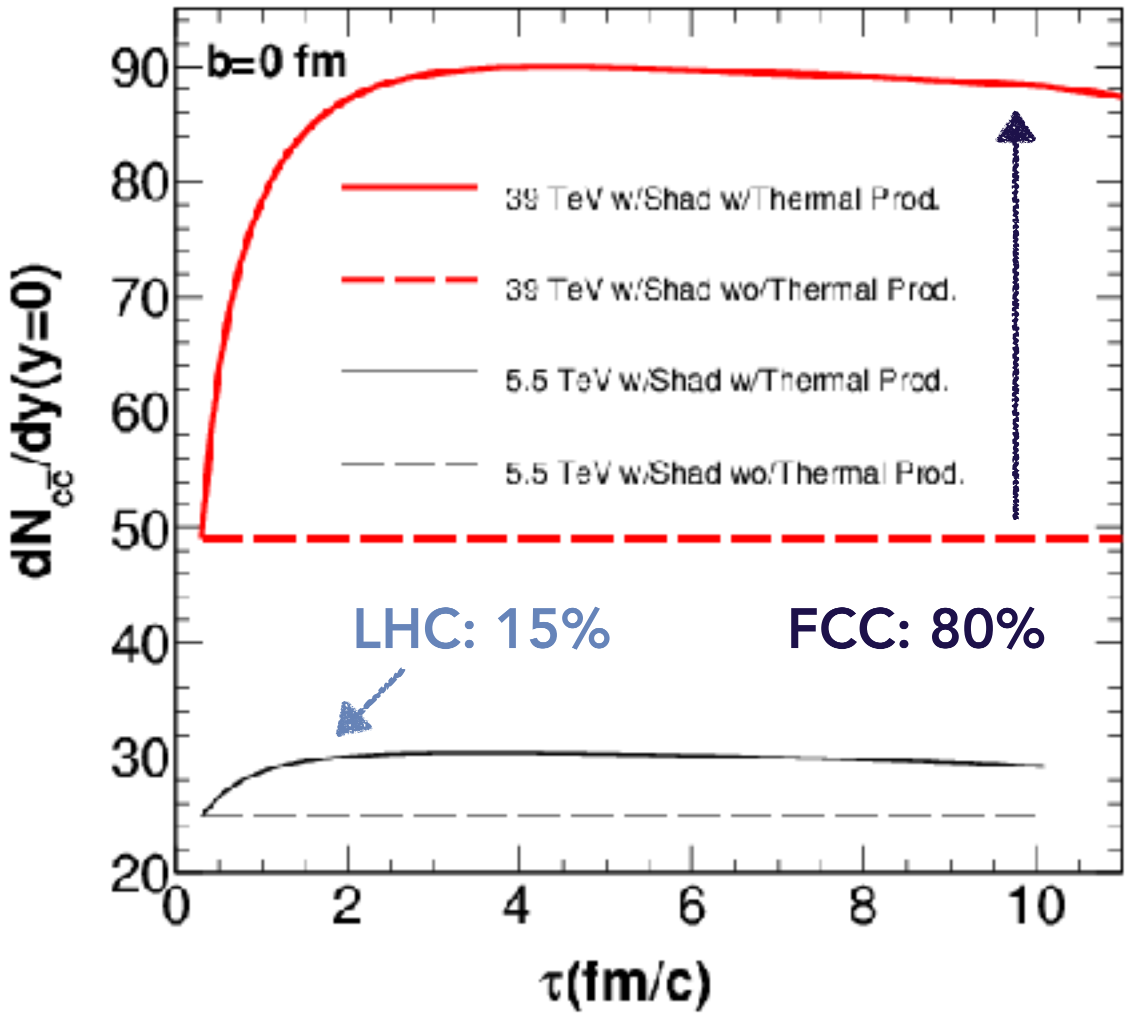

Affects the number of degrees of freedom in EoS ($\propto P/T^4$)

Enhancement of charmed hadron production at very low p_T (related to QGP temperature)

J/Ψ Enhancement

- In-medium J/Ψ production:
  - Dissociation by colour-charge screening ⇘
  - Recombination from deconfined charm and anti-charm in the QGP ⇗

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Liu et al, 09
Zhao et al, 11 Kinetic Transport Model

Statistical Hadronization Model Andronic et al, 11

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Kinetic Transport Model

Statistical Hadronization Model Andronic et al, 11

Recombination proportional to rapidity density of charm pairs in the QGP

Expected to be larger at FCC:

- ➡ Hard scattering σ_{cc} (x 2-2.5)
- ➡ Thermal production (x 1.5)

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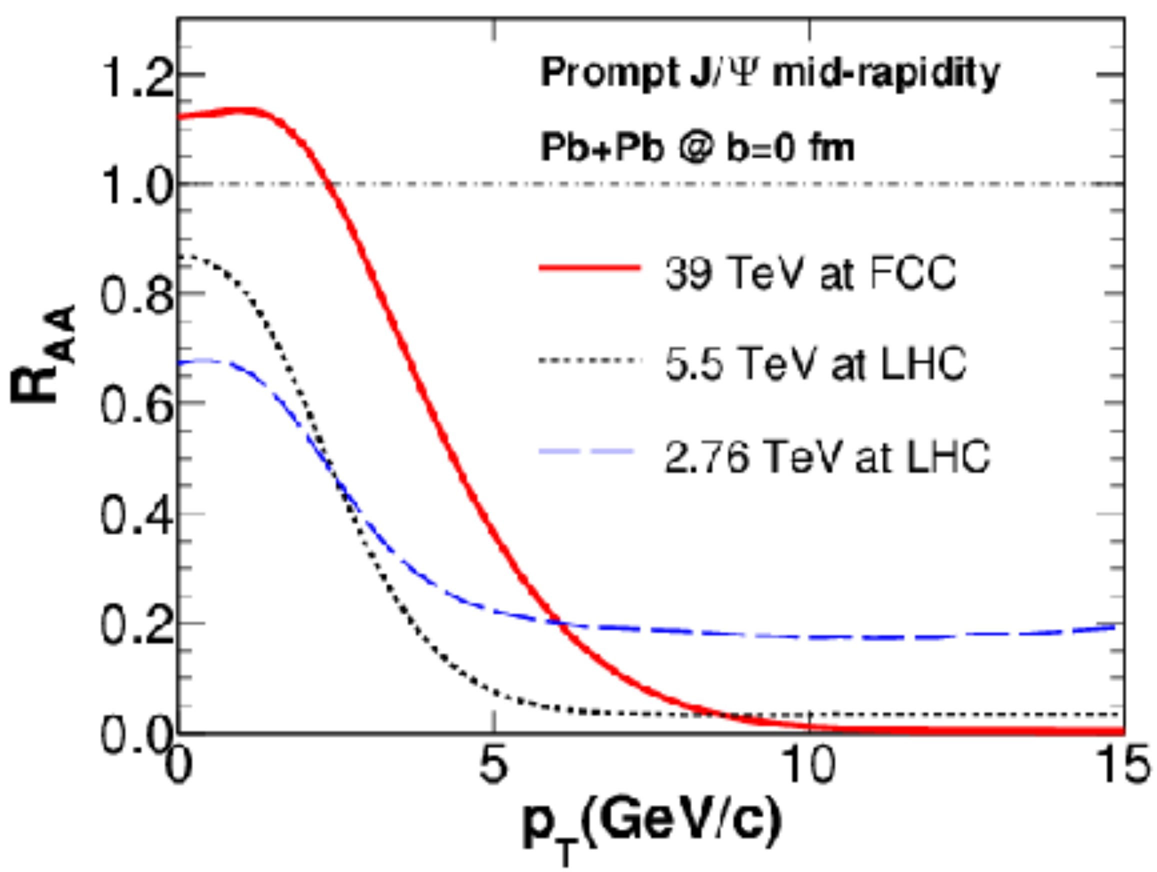

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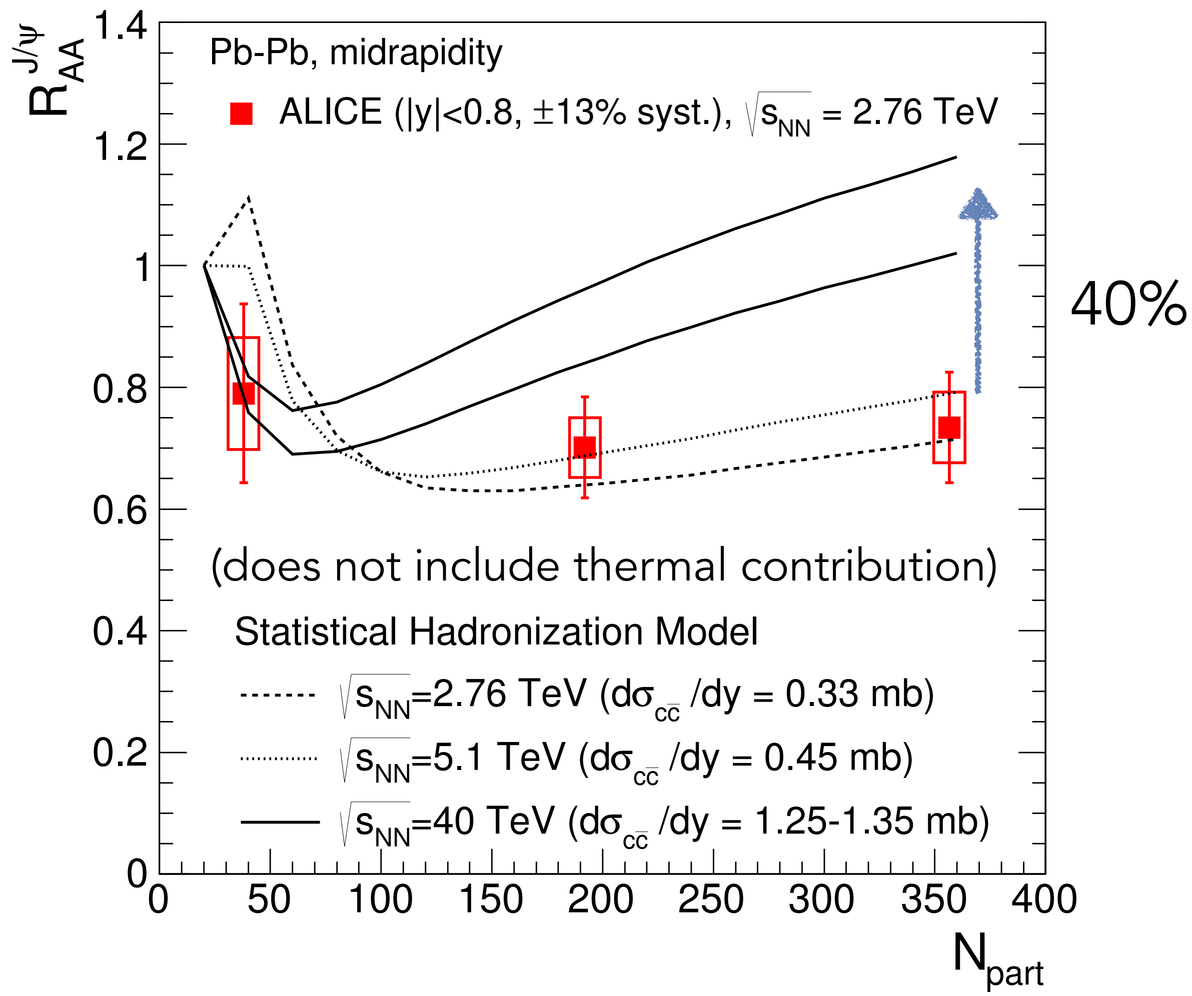
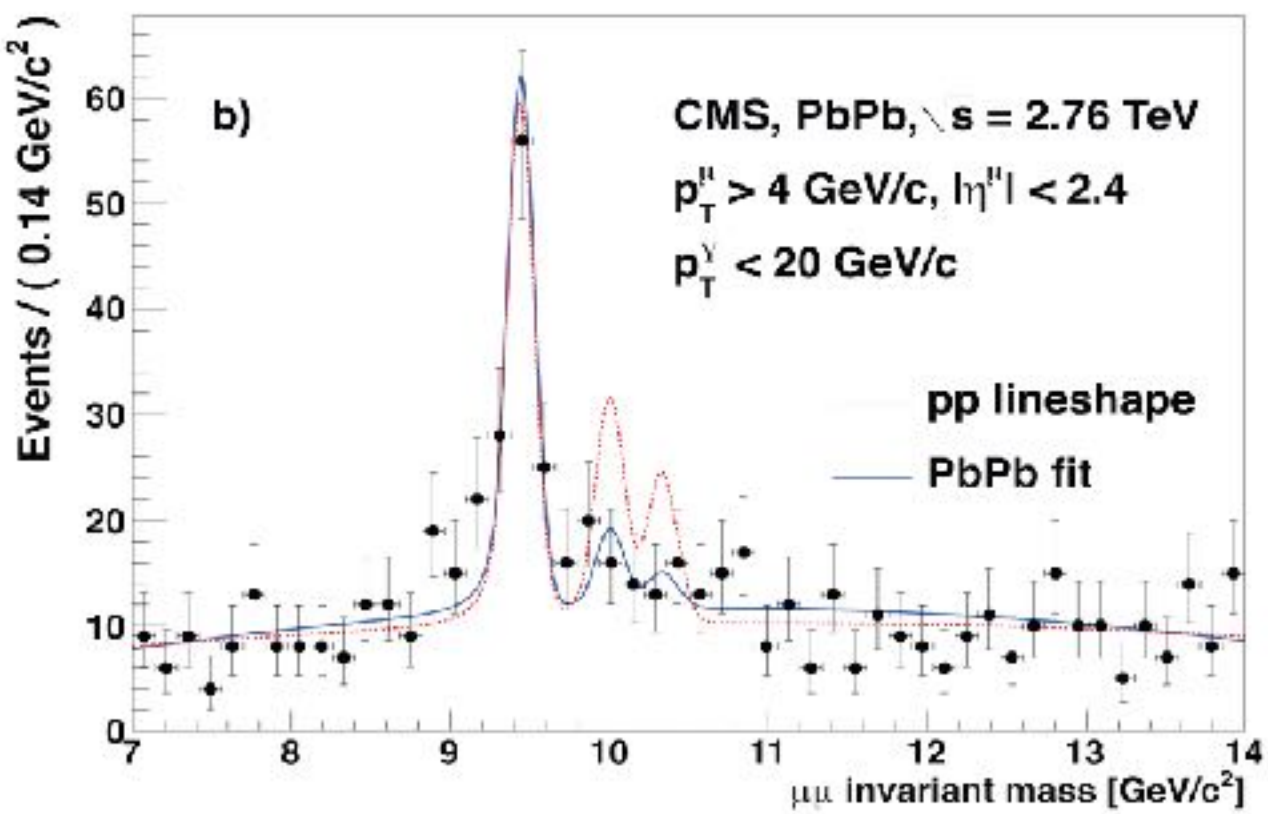
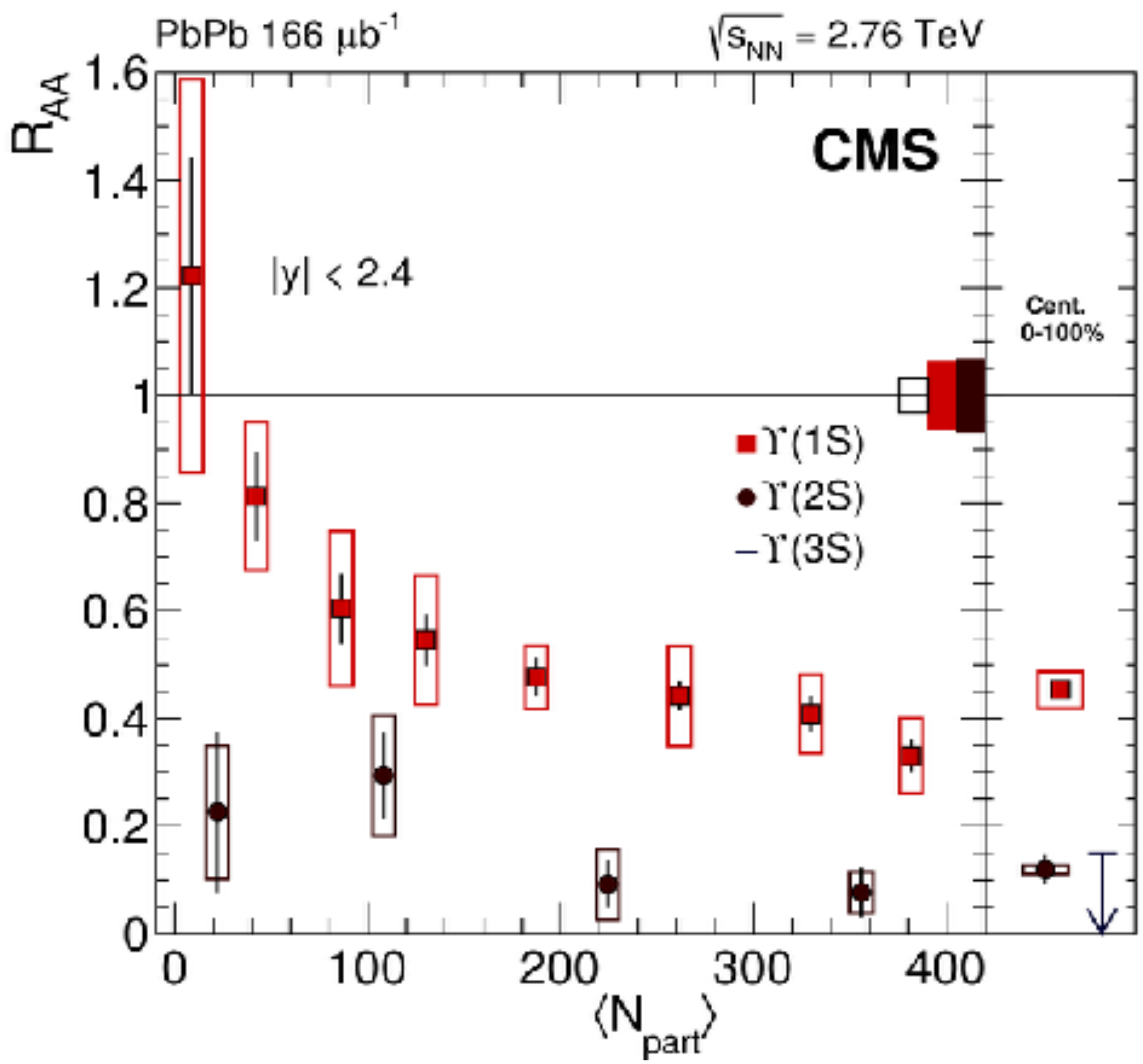


Υ(1S) color screening

- LHC: almost total suppression of 2S and 3S excited states





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Arts et al, 14

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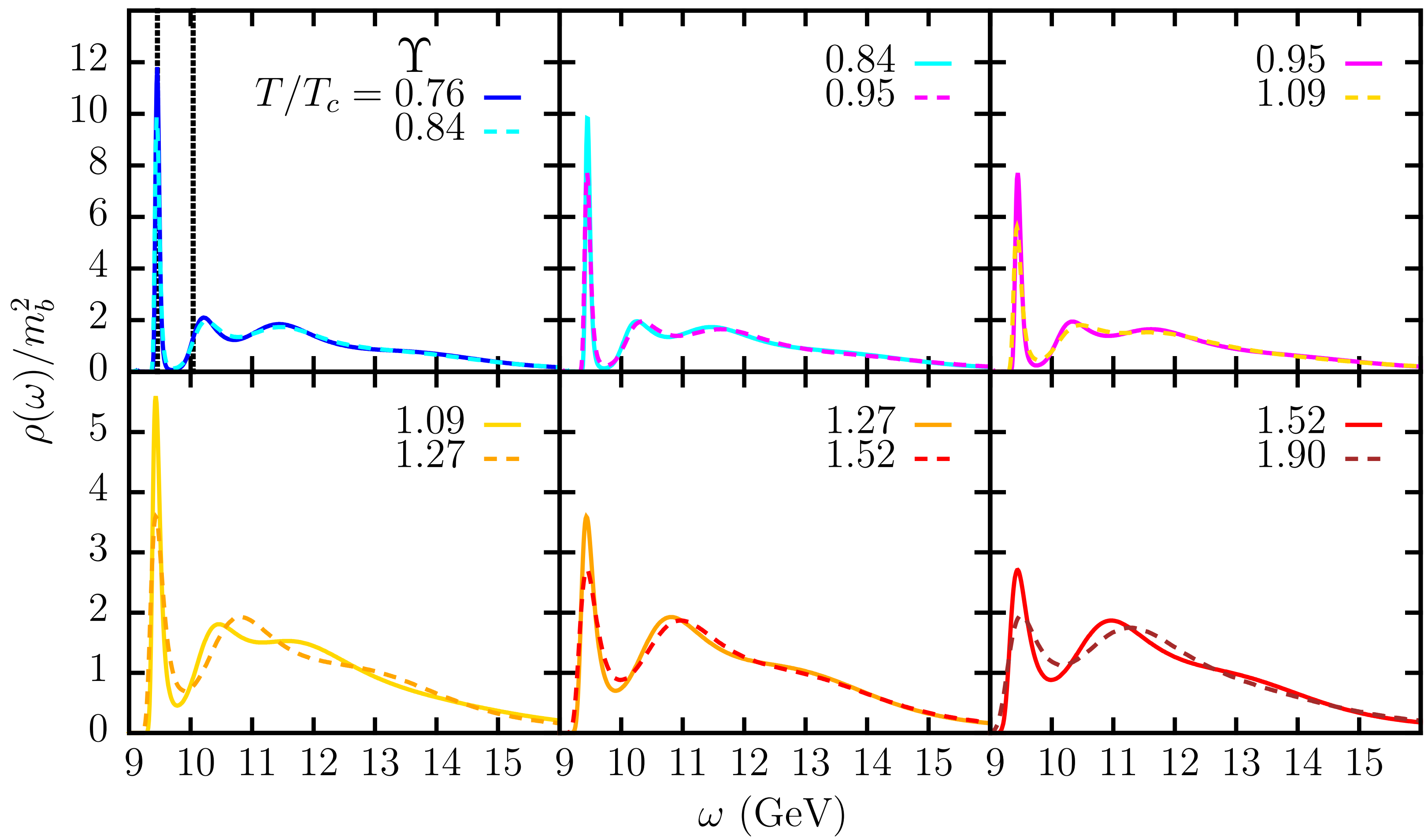


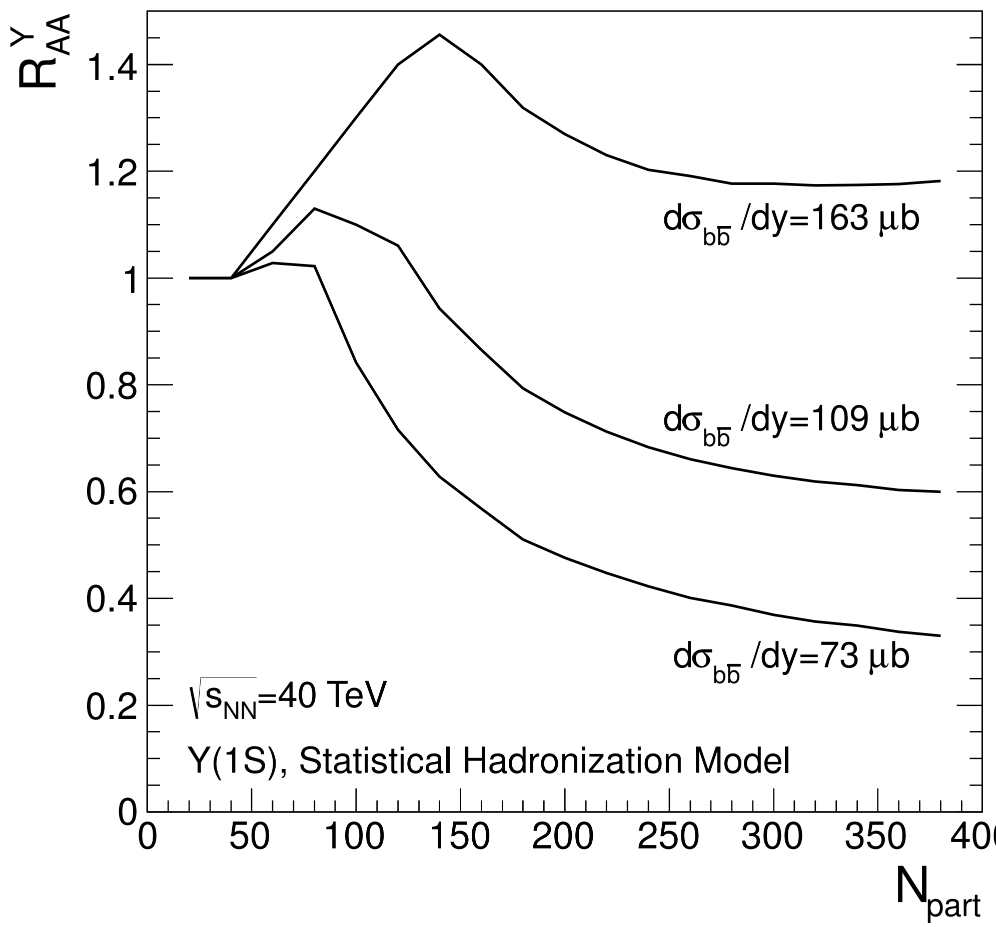
Strong suppression of Υ(1S) expected at the FCC (4-5 T_C)

Possibility to match high temperature pQCD spectral functions to lattice results

Y(1S) color screening

Arts et al, 14
Andronic et al, 11

- LHC: almost total suppression of 2S and 3S excited states
- FCC:
  - High temperature to melt even 1S
  - Density of bb pairs large enough for recombination



Expected nuclear suppression depends on the bottom cross-sections

Deconvolution from the two effects possible through precise measurement of σ_{bb} and B meson and ϒ suppression and elliptic flow

Jet quenching

- Current understanding with LHC data on overall in-medium jet evolution:
  - Jet hard structure almost unmodified by interactions with the QGP; Jet soft structure strongly affected (large broadening effects)
  - Modification of intra-jet structures depending on the in-medium transverse resolution:
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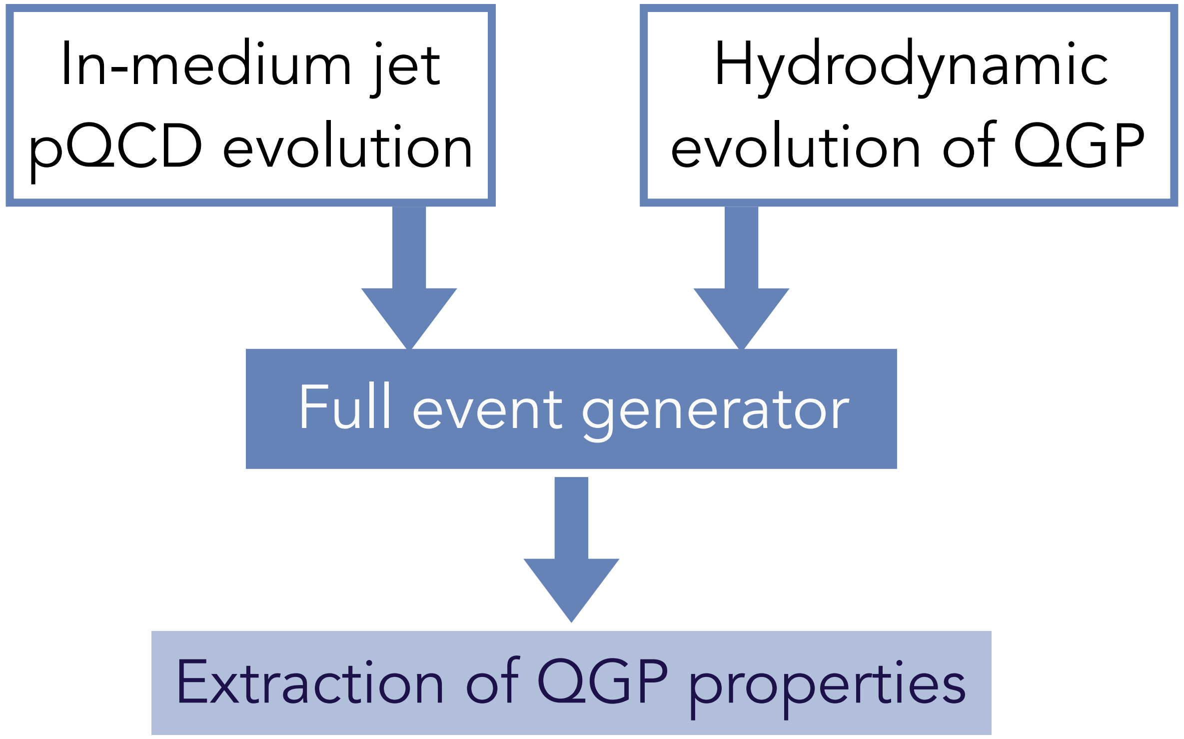

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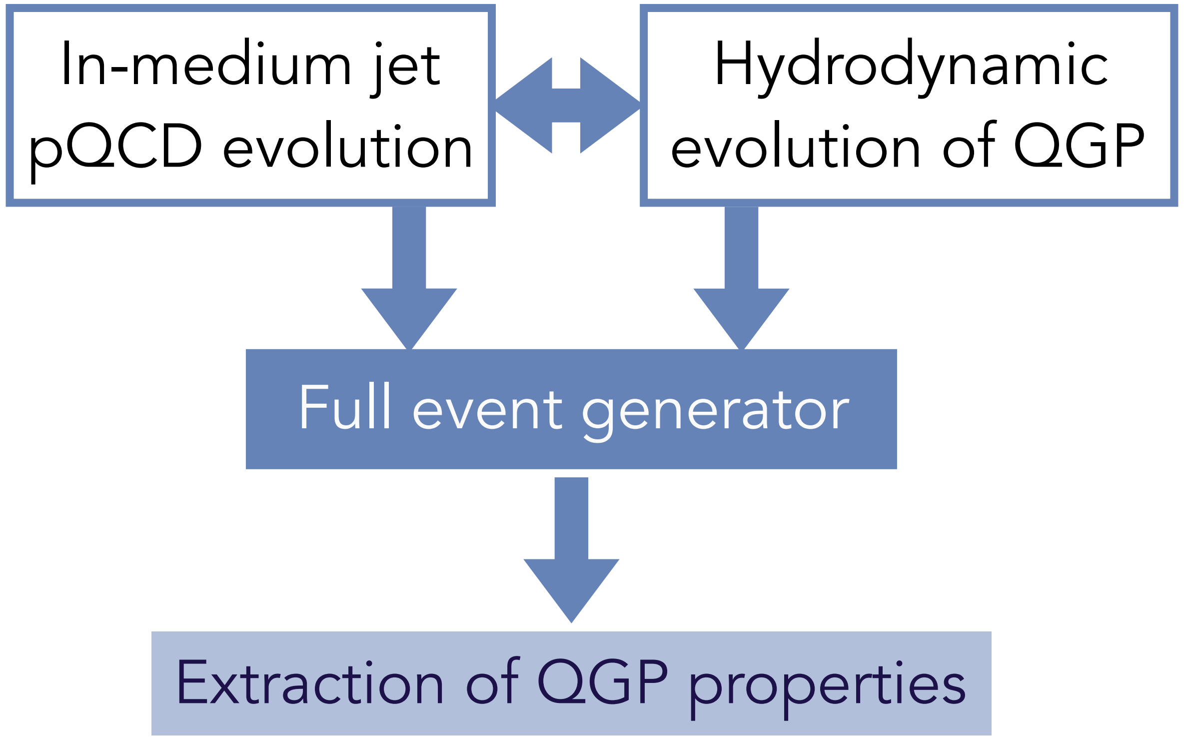

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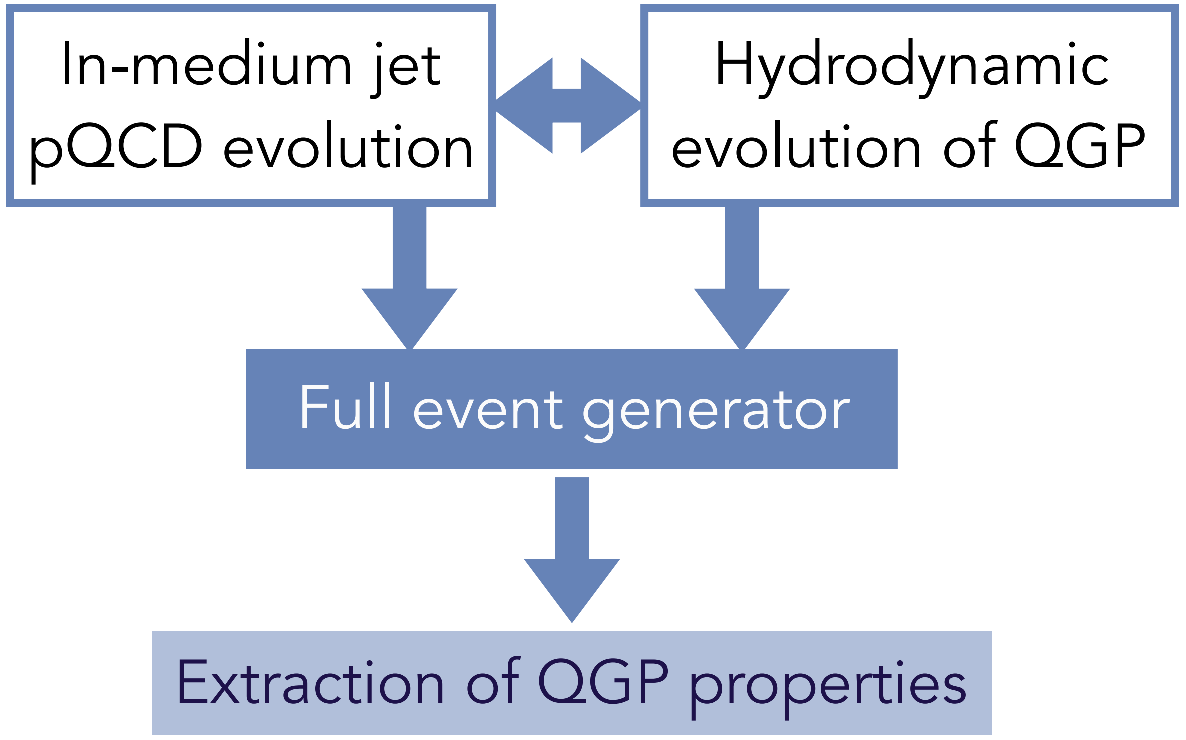


FCC-hh new possibilities:

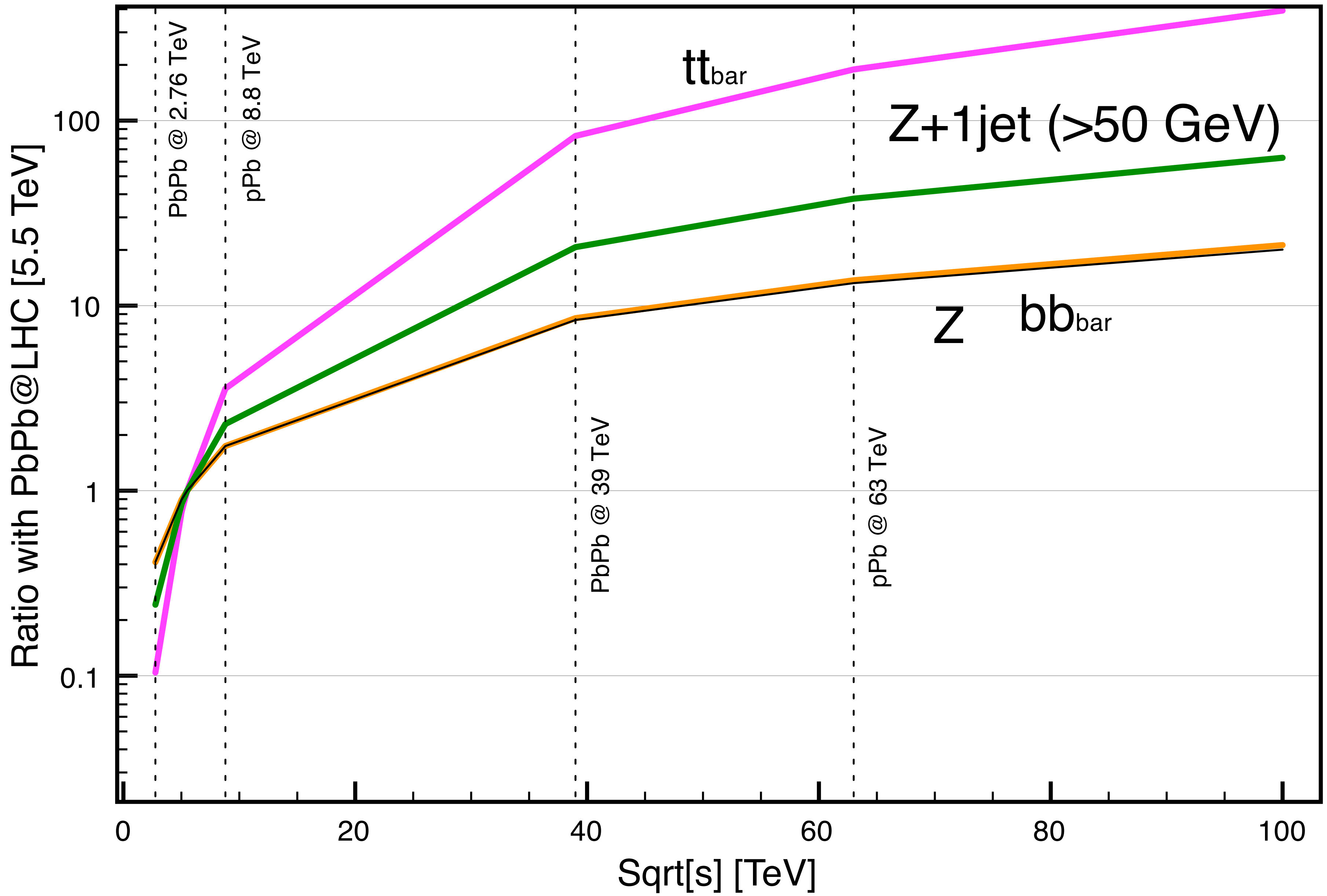
➡ More statistics in "cleaner" channels to assess jet properties more accurately (electroweak bosons + jets)

➡ Possibility to assess QGP time evolution

Hard probes cross-section

Campbell et al, 10

- LHC ($\sqrt{s_{NN}}$ = 5.5 TeV) $\longmapsto$ FCC ($\sqrt{s_{NN}}$ = 39 TeV)
  - Ratio of different processes σ:



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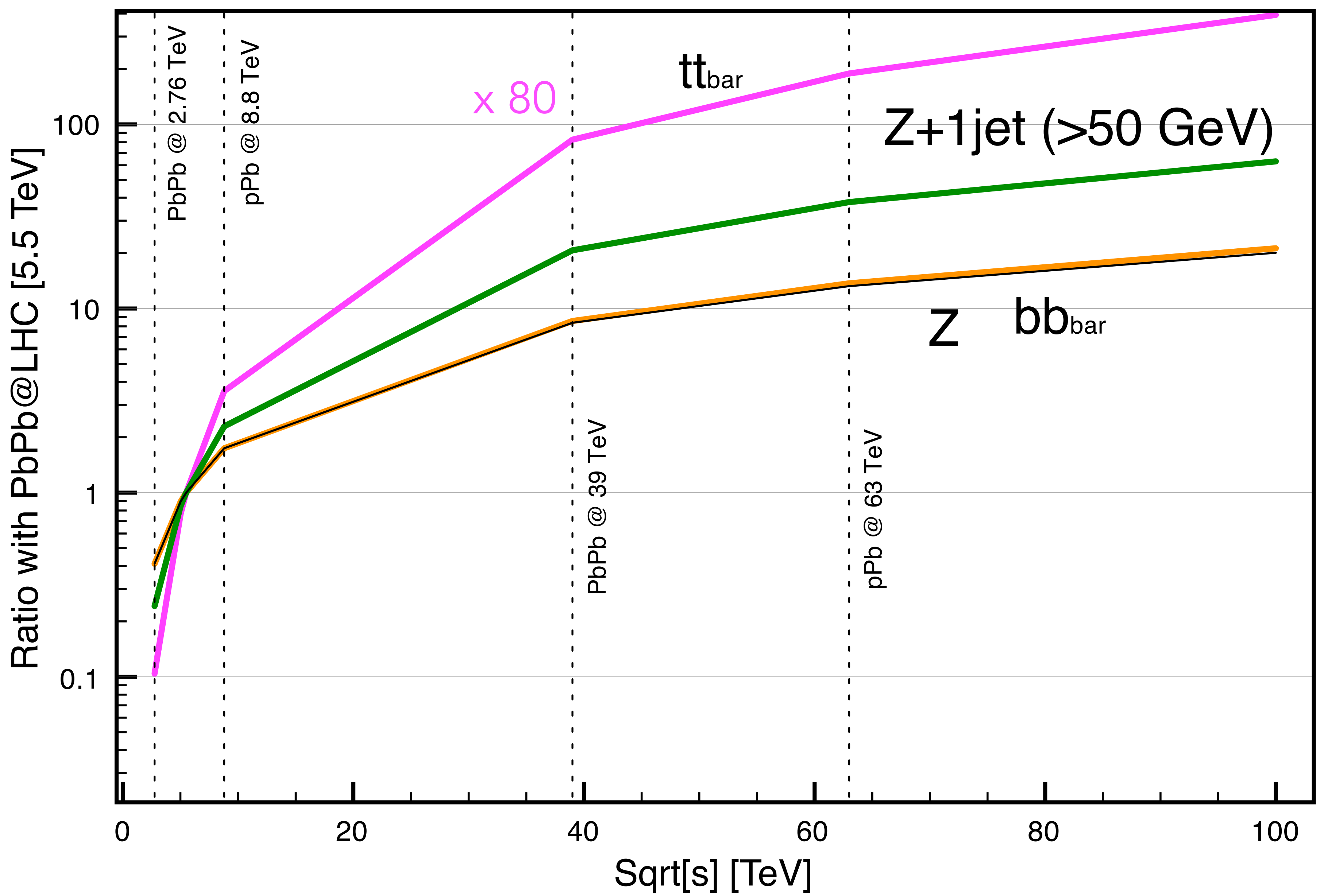

Boosted objects study

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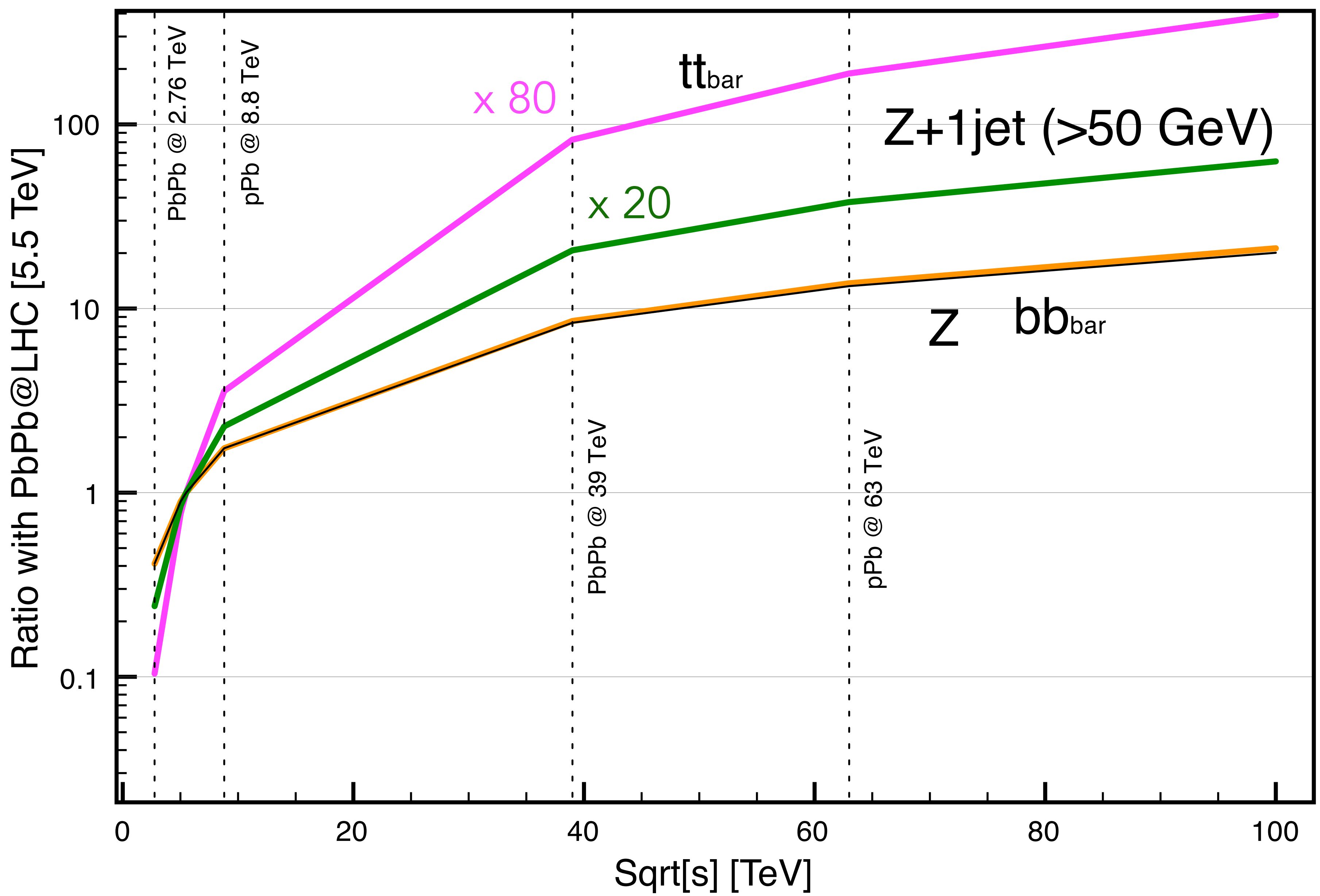

Boosted objects study

Accurate energy Loss calibration

Top production

- Motivation:
  - Probe (and constrain) nuclear PDFs in unexplored ranges so far:
    - $x \sim m_{top}/\sqrt{s} \sim 10^{-2}$; $Q \sim m \sim 173$ GeV
  - Main decay channel: W + b
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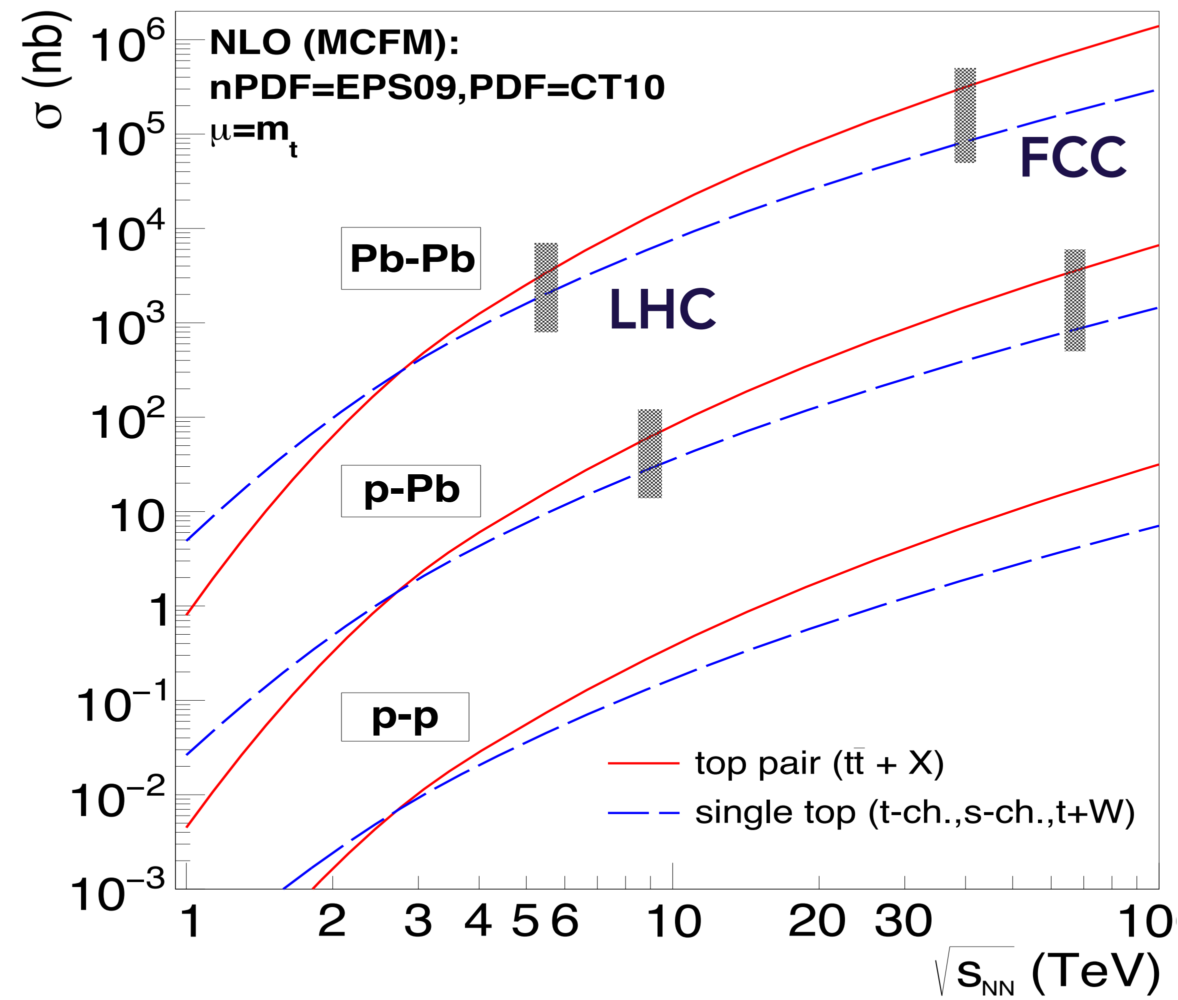
d'Enterria et al, 15



System	$\sqrt{s_{NN}}$	$\mathcal{L}_{int}$	$t\bar{t} \to b\bar{b}\,\ell\ell\,\nu\nu$	$t\,W \to b\,\ell\ell\,\nu\nu$
Pb–Pb	39 TeV	33 nb^{-1}	3.1×10^5	8.6×10^3
p–Pb	63 TeV	8 pb^{-1}	8×10^5	2.1×10^4

(b jets - 50% eff: anti-k_T, R = 0.5, p_T > 30 GeV/c, |η| < 5;
charged leptons: R_{isol} = 0.3, p_T > 20 GeV, |η| < 5;
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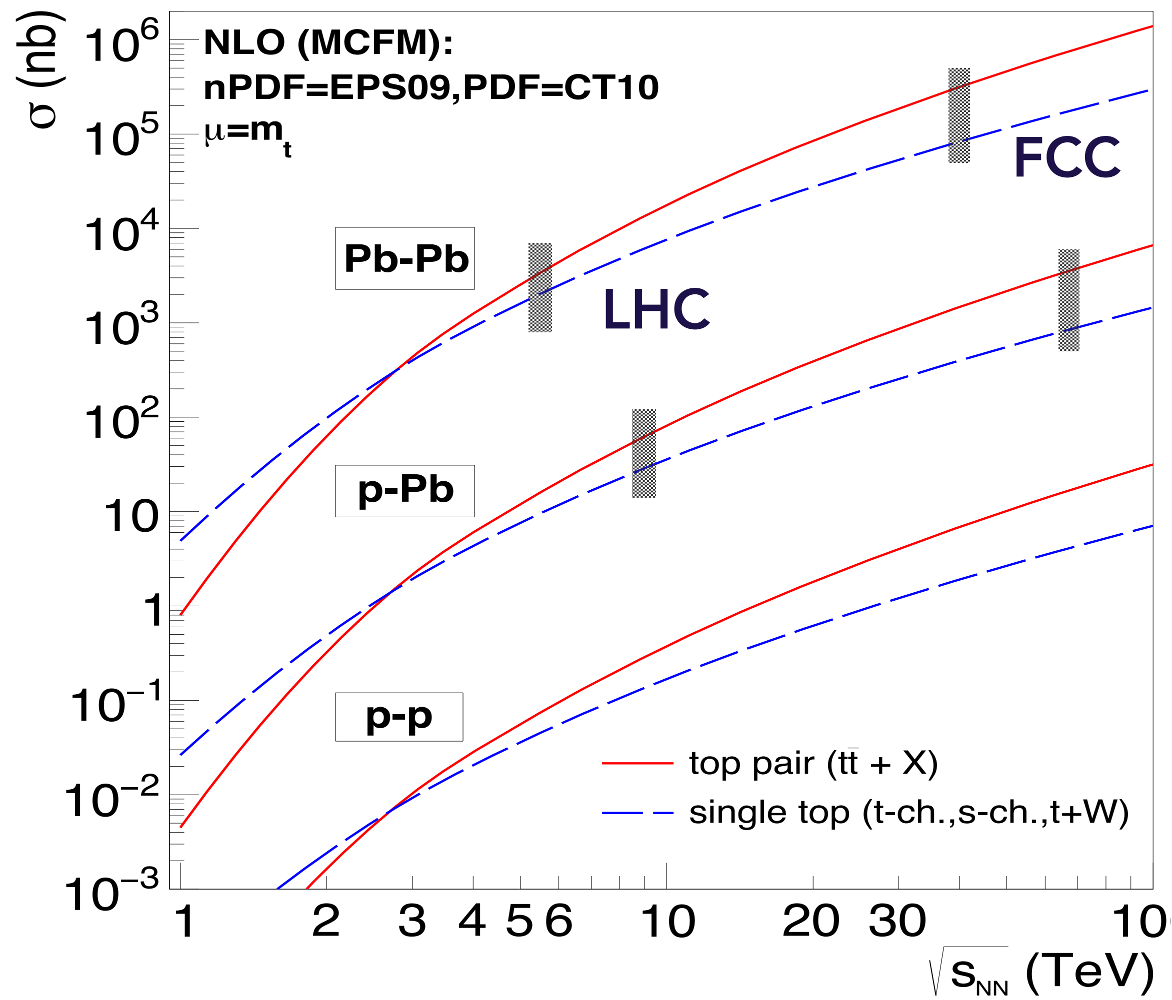

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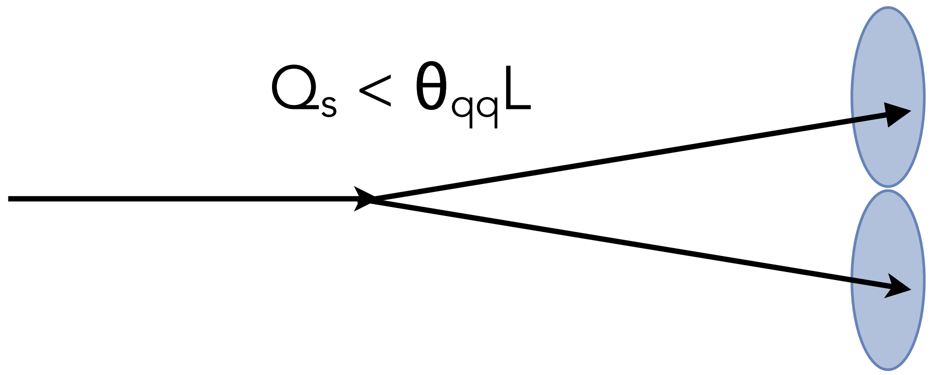
It will be possible to measure a sizeable sample of ttbar and single top events at the FCC

For Top properties and decay studies see Daniel Stolarski's talk (Th)

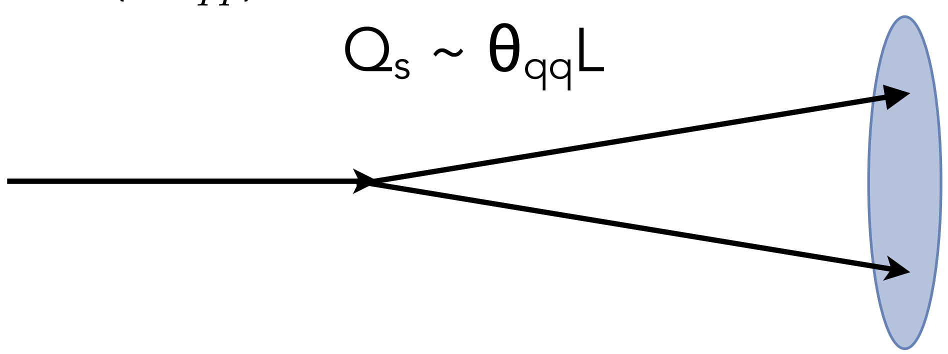
(De)Coherence

Mehtar-Tani et al, 10-11
Casalderrey-Solana et al, 11

- Motivation:
  - Decay inside the QGP, within different timescales (depending of the boost)
    - Main decay channel: W + b:
    - W hadronic decay (antenna): a colour singlet state propagating inside QGP
      - Stay in singlet state: $t_d = \left(\frac{3}{\hat{q}\theta^2_{q\bar{q}}}\right)^{1/3}$



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



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

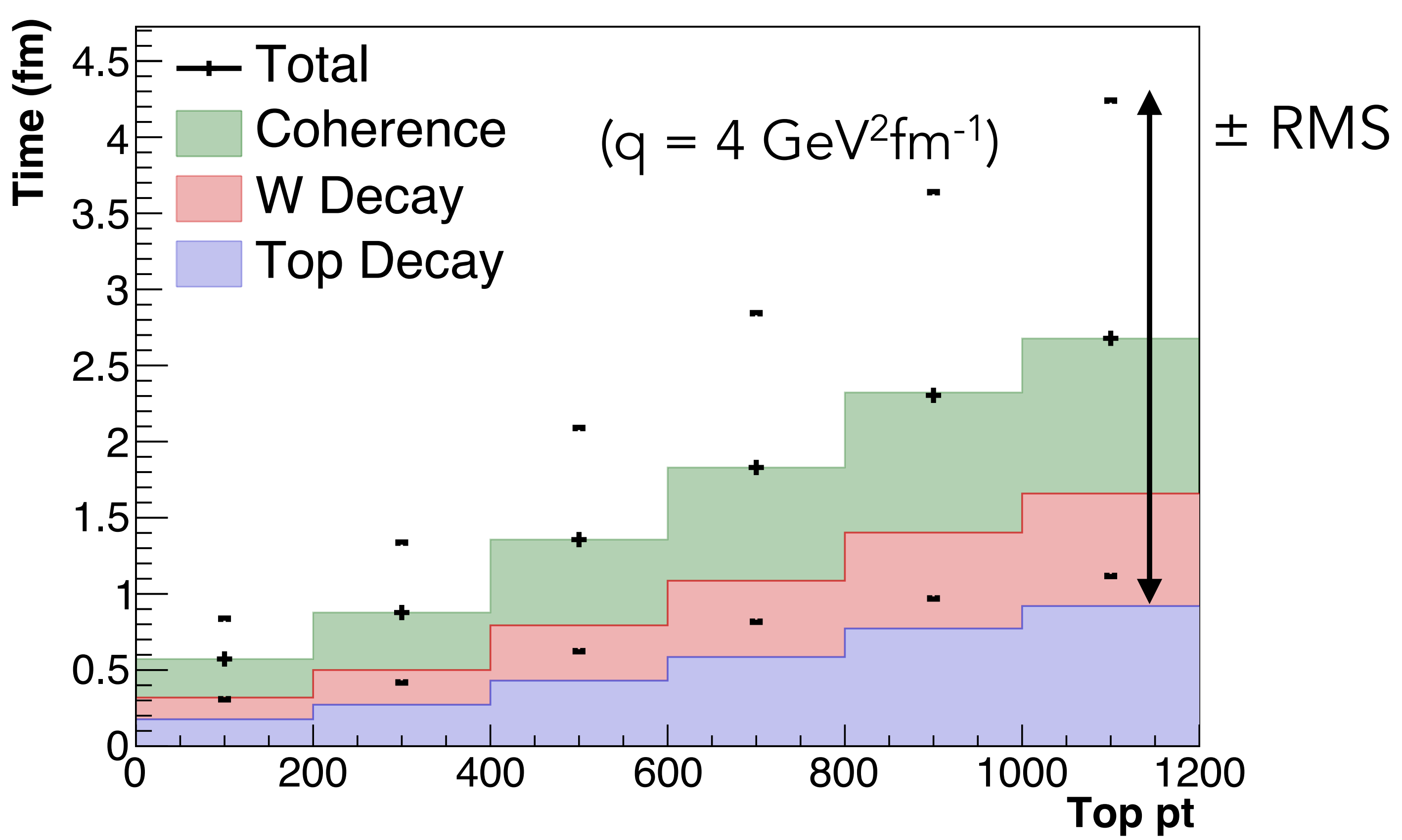
Saturation scale of the medium: $Q_s^2 = \hat{q}\,L$

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

Boosted objects

Apolinário et al, in prep.

- Timescales to probe the medium with expected cross-sections:



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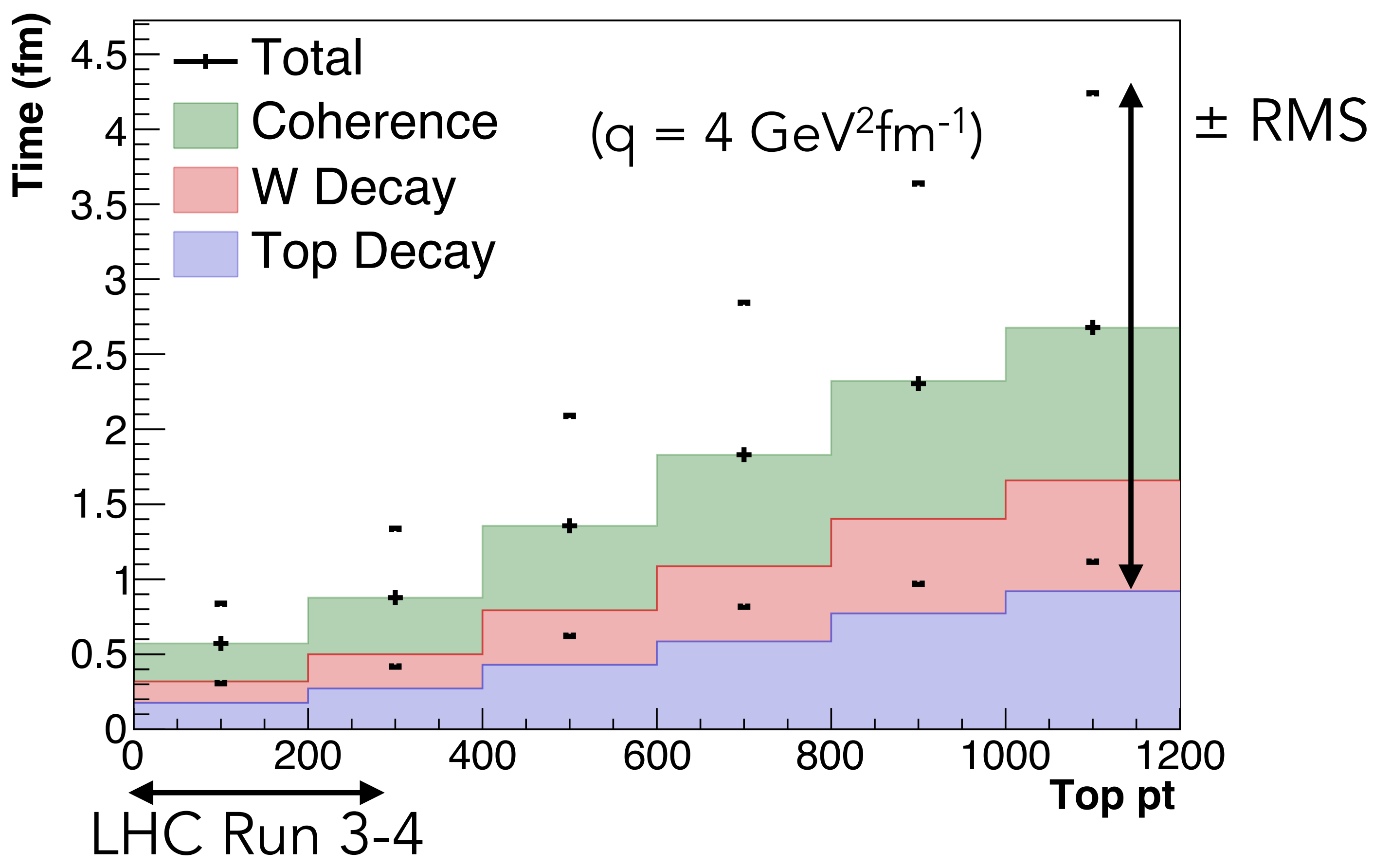

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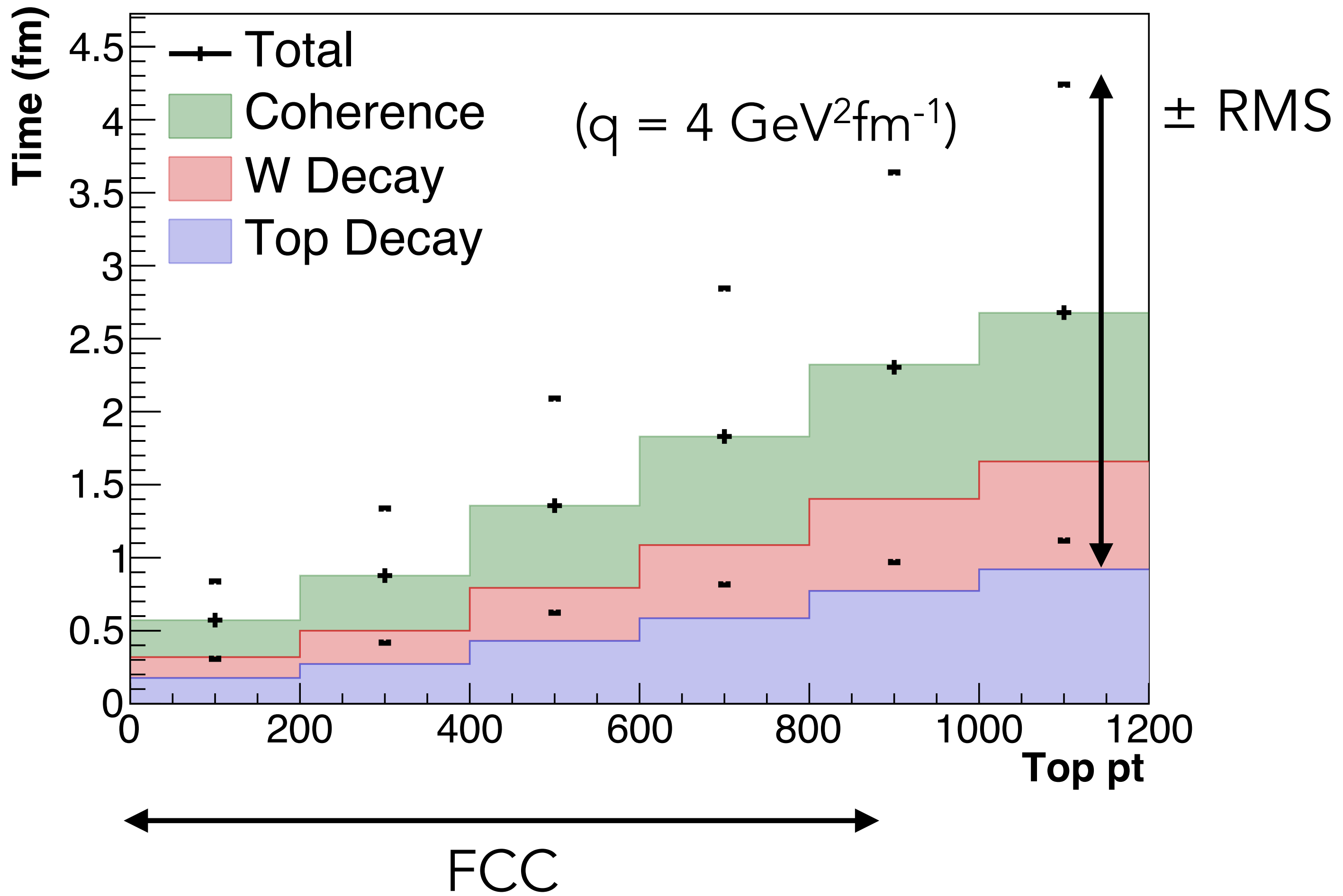

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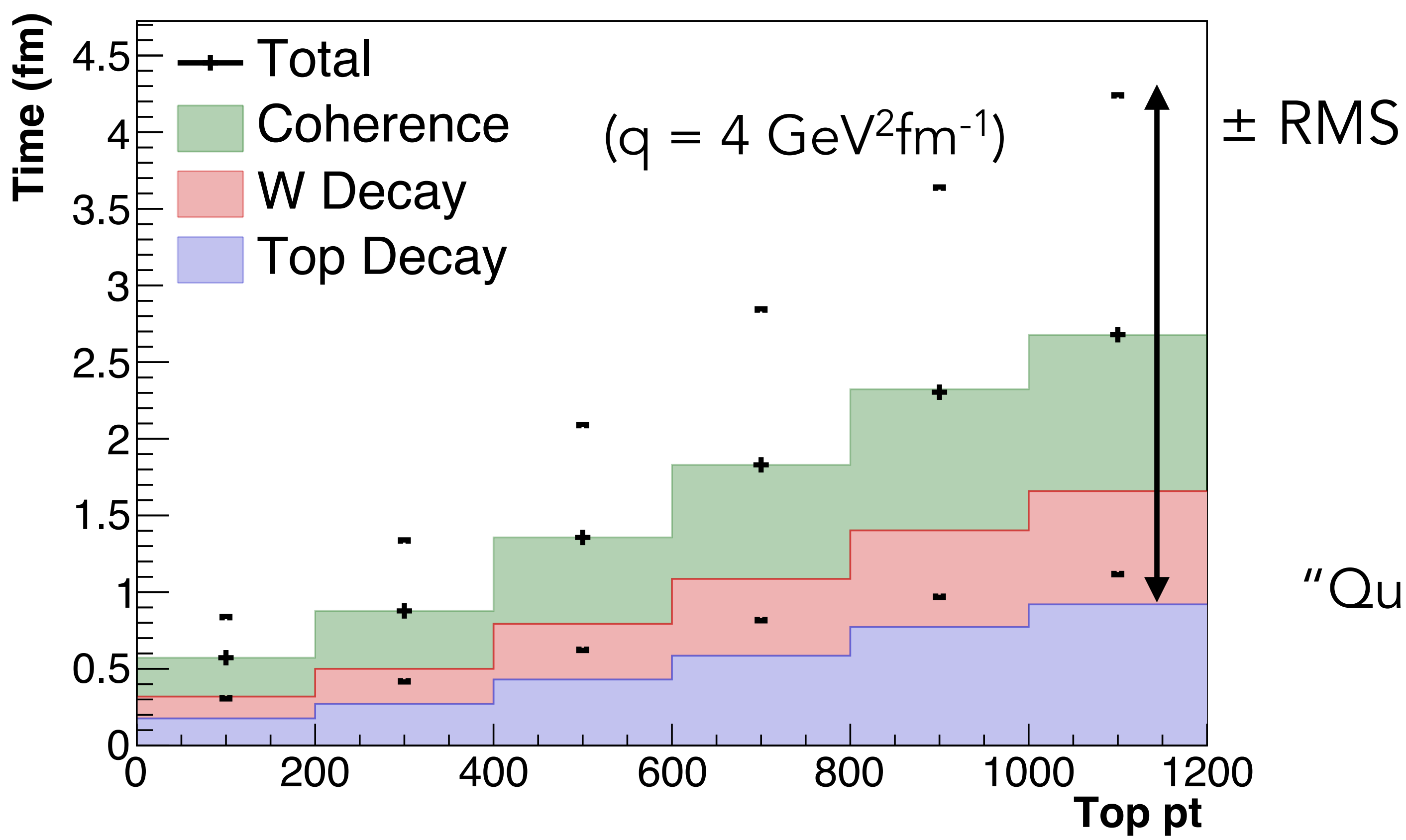
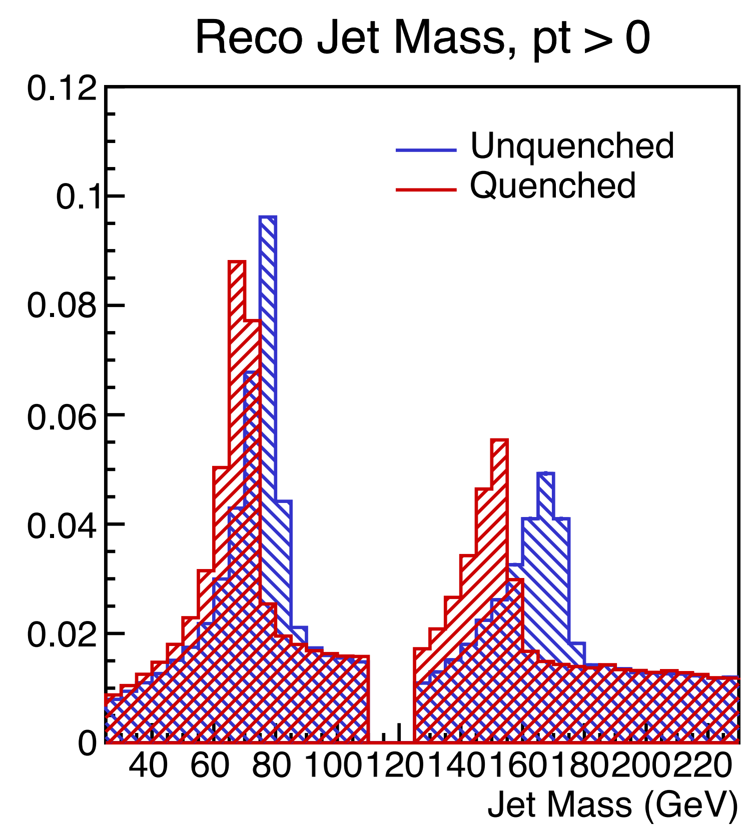


FCC



"Quenched": Hadronic particles lose 10% energy

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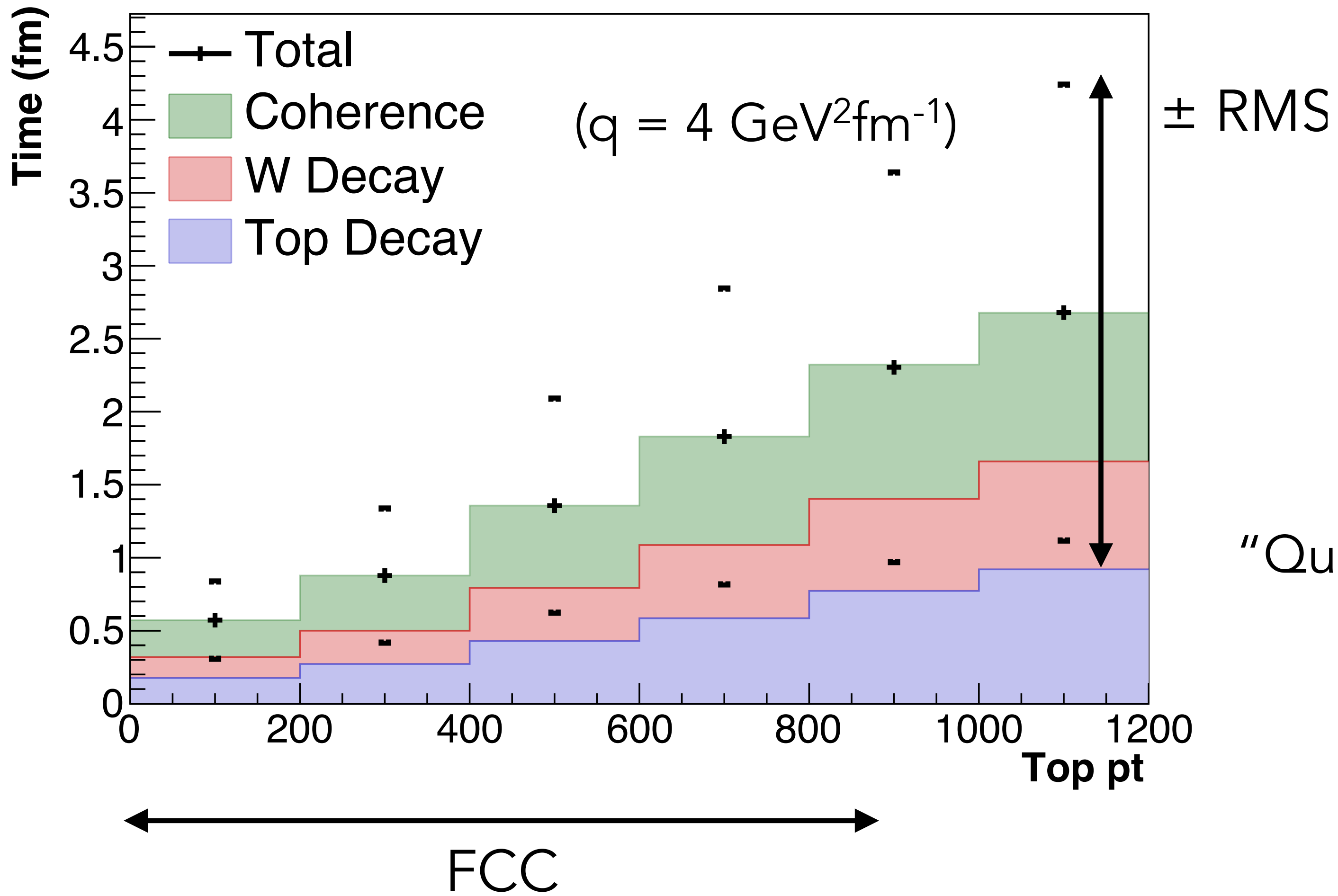

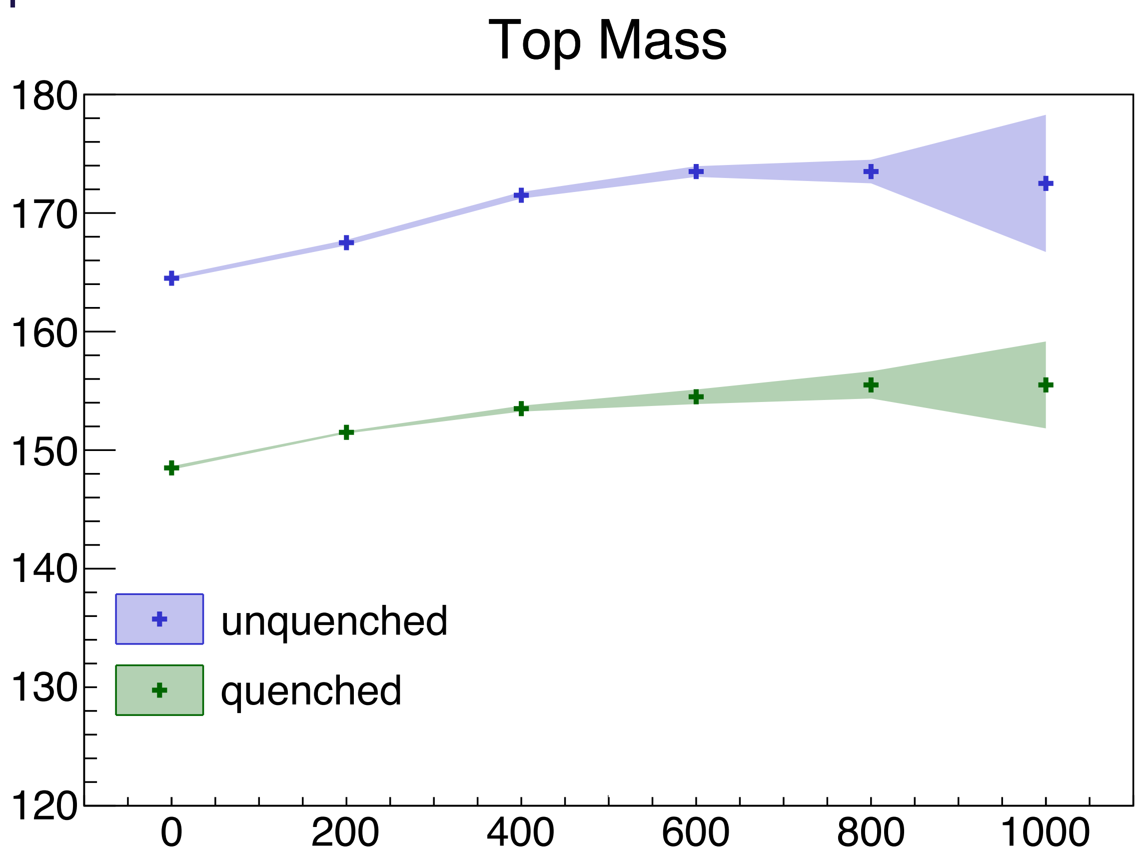

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Expected shift in the jet reconstructed mass

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Assessing QGP profile

Apolinário et al, in prep.

- Very simple model: W decay products lose energy as
  - ΔE/E = (τ-t)/τ * 0.1

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t = "total" delay time

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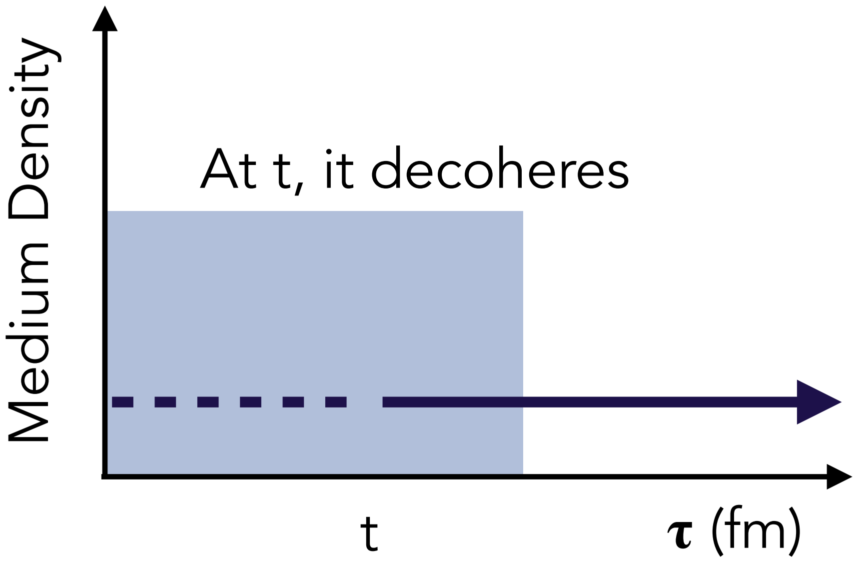

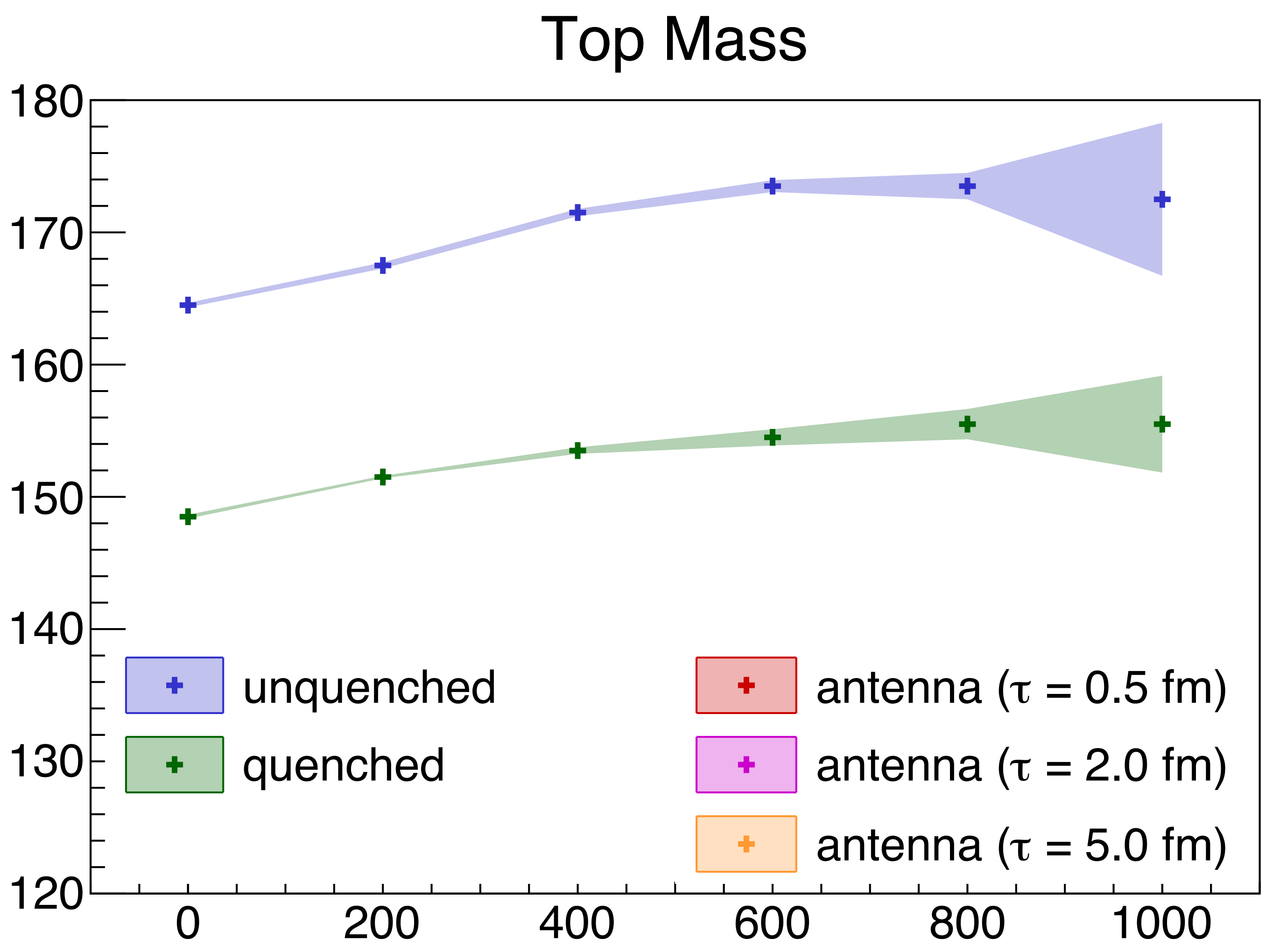

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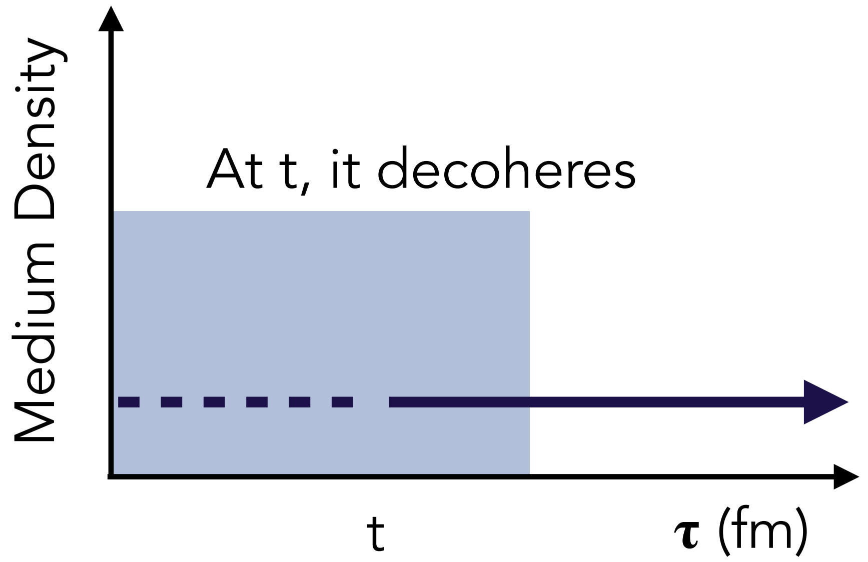

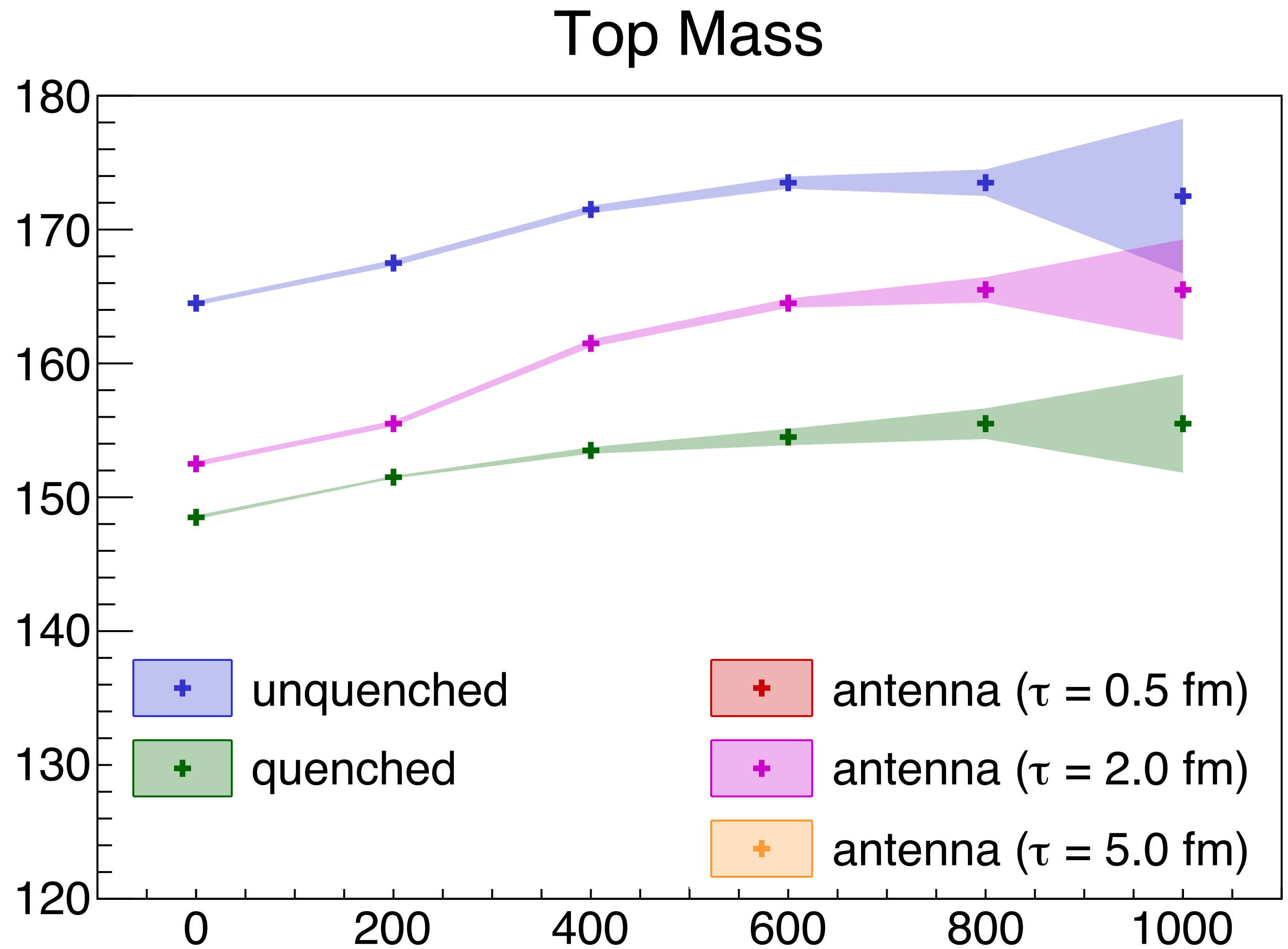

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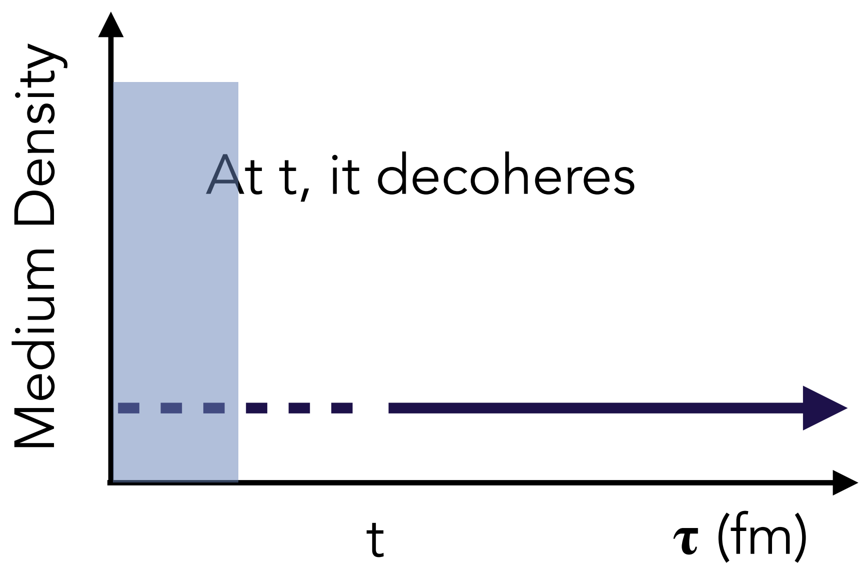

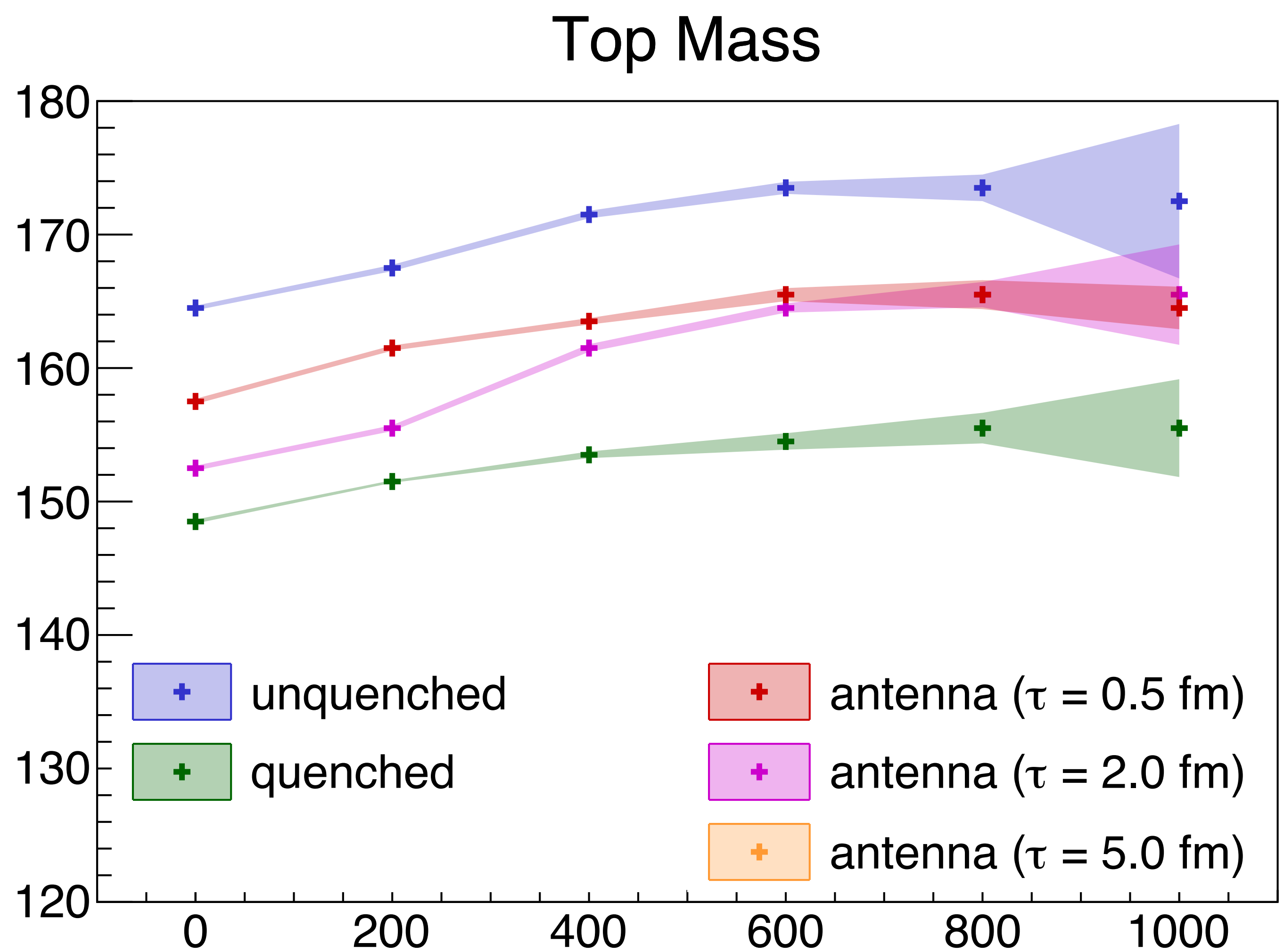

Assessing QGP profile

Apolinário et al, in prep.

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

$\boldsymbol{\tau}$ = Total medium lifetime

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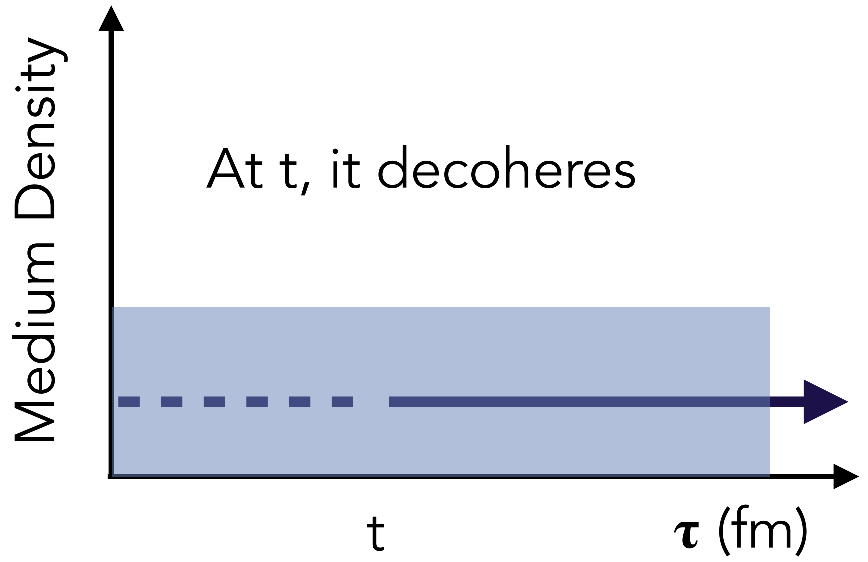

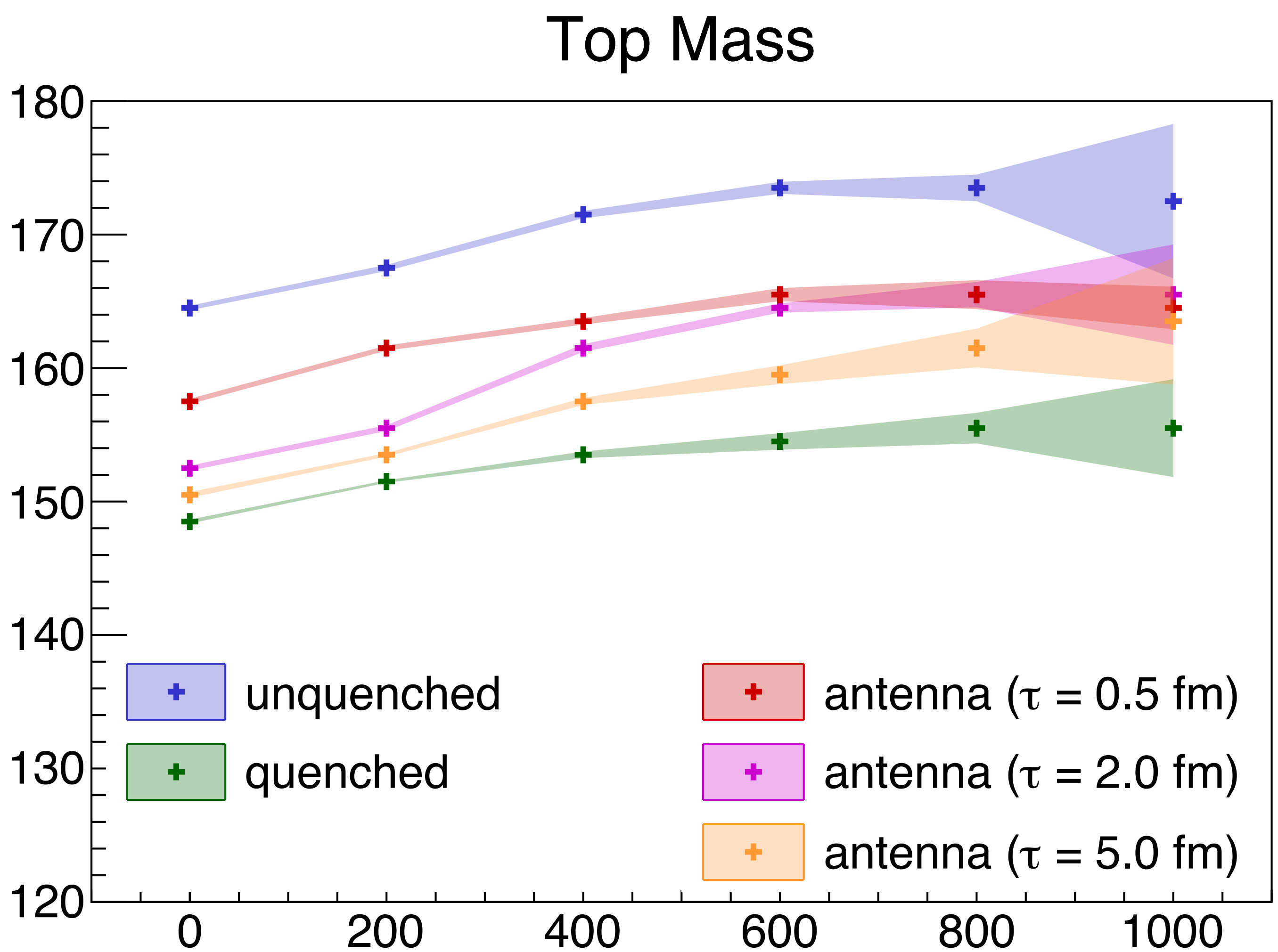

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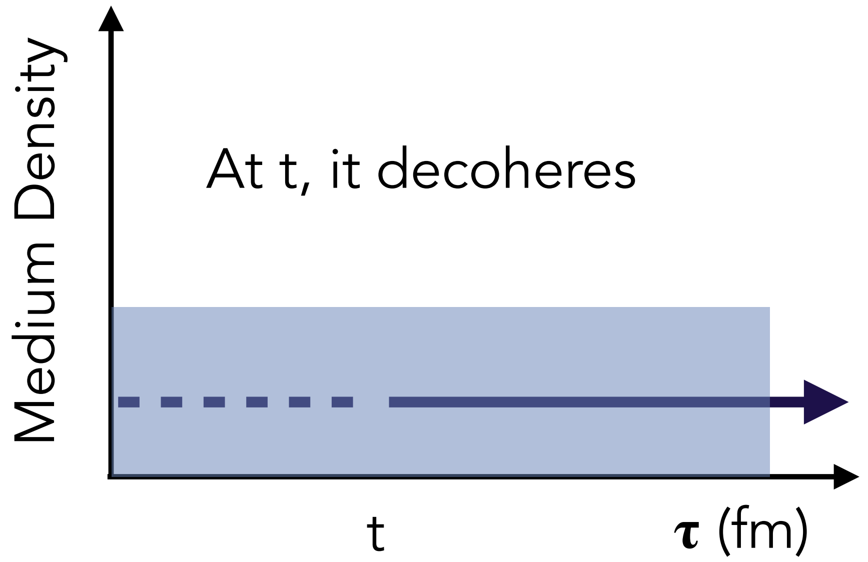
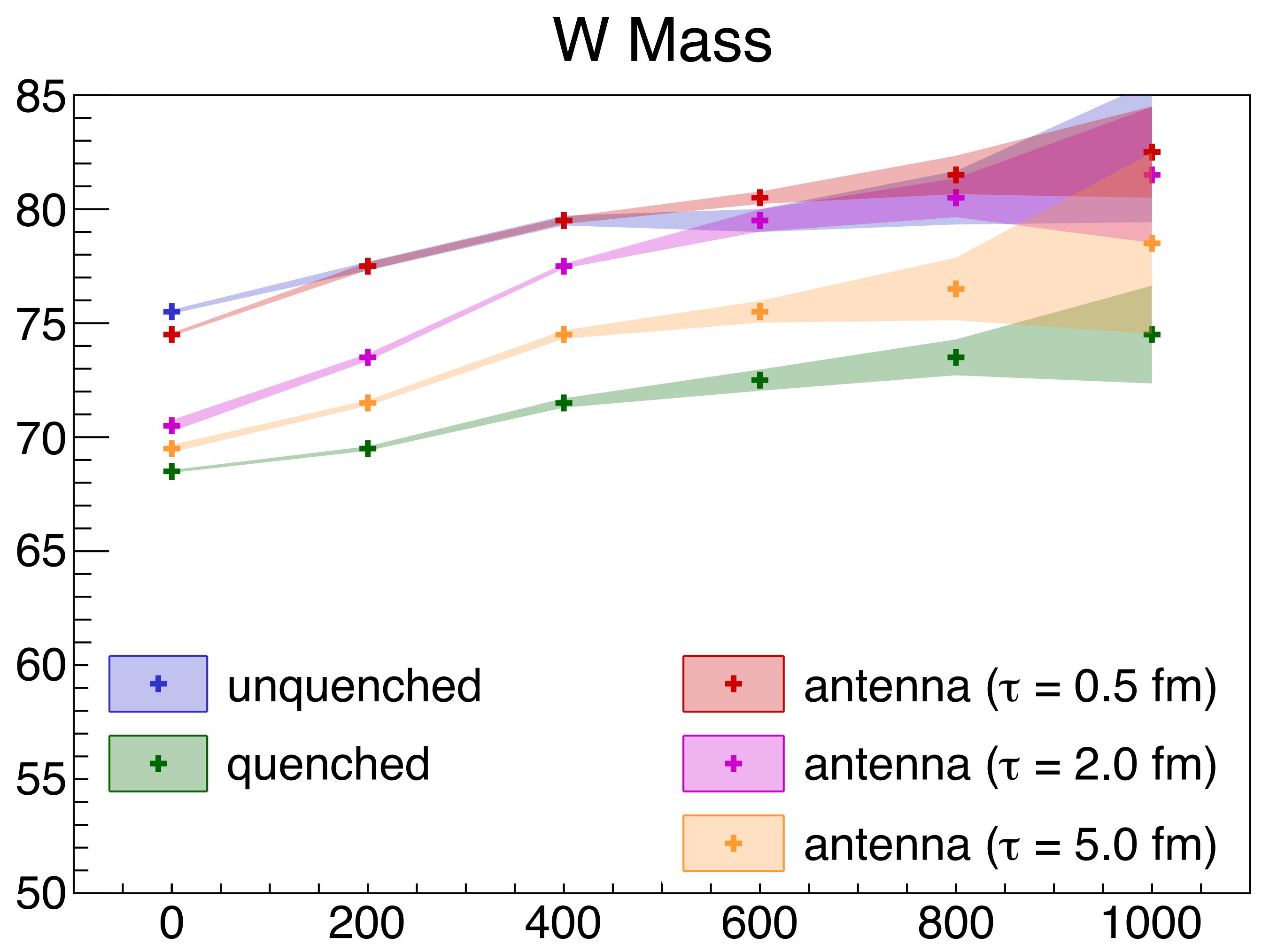


Expected shift on the jet reconstructed mass depends on the boost

Should be possible to get information on the QGP evolution profile



(Reconstruction method not optimized…)


Fixed-Target
AFTER@FCC

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- ⇧ Centre-of-mass energy (200-300 GeV, for Pb or p) and ⇧ Luminosity (1-60 fb^{-1} yr^{-1} for p and 0.002-40 nb^{-1} yr^{-1} for Pb):
  - Enough statistics for vector boson production close to threshold;
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Only some highlights…

Facility that complement measurements at RHIC and lower energies

Conclusions

- FCC-hh study aimed to assess physics potential at a centre-of-mass energy 7 times larger than the nominal LHC energies;
- This talk: First ideas on the physics opportunities to study the formed QGP:
  - Soft Probes: Larger (x 1.8), longer-lived (x 1.2-1.5), denser (x 1.8) and hotter (x 1.3) medium
    - Establish the smallest length and timescale for QCD thermalisation and its dependency with the energy density;
    - Statistical precision tests to disentangle flow effects from non-flow effects (small systems, such as pPb and pp);
    - Understand dependencies of transport coefficients;
    - Baseline to investigate the dynamical mechanisms of kinetic and chemical equilibration.

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Thank you!


Backup Slides

Detector considerations

- No detailed detector requirements so far… but:
  - Soft probes physics program require:
    - Charged-hadron identification to measure independently:
      - Low-p_T charged mesons and baryons
      - Low-p_T c and b mesons

Combination of methods that include:
- specific energy deposition in silicon trackers;
- time-of-flight;
- Cherenkov radiation,

    - Track reconstruction down to low p_T, (starting from few MeV)

Delicate interplay between material thickness of the inner tracker and strong magnetic field
- General-purpose detector operated at B ≈ 1 T (?)

Detector considerations

- No detailed detector requirements so far… but:
  - Hard probes physics program should match the same for the pp program of the FCC:
    - Hadronic and electromagnetic calorimeters with:
      - Large acceptance;
      - High energy resolution at high p_T
      - High performance up to very large event multiplicities;