Physics with heavy ions at FCC

Liliana Apolinário

on behalf of the FCC-hh working group

Based on:

A. Dainese et al. arXiv:1605.01389 and the chapter 16 of FCC-CDR Volume 1

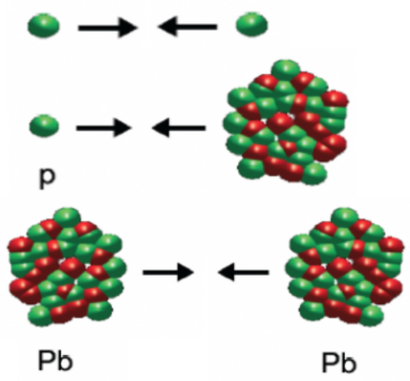
FCC-AA Motivation

- Large increase in Centre-of-mass energies:

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

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

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



- Why a heavy-Ion program?
  - Fundamental questions about nature of QCD matter at high temperature and density:

    How collective phenomena emerge from a QFT?

    How is the partonic structure of nucleons and nuclei at small-x?

- More info: https://fcc.web.cern.ch

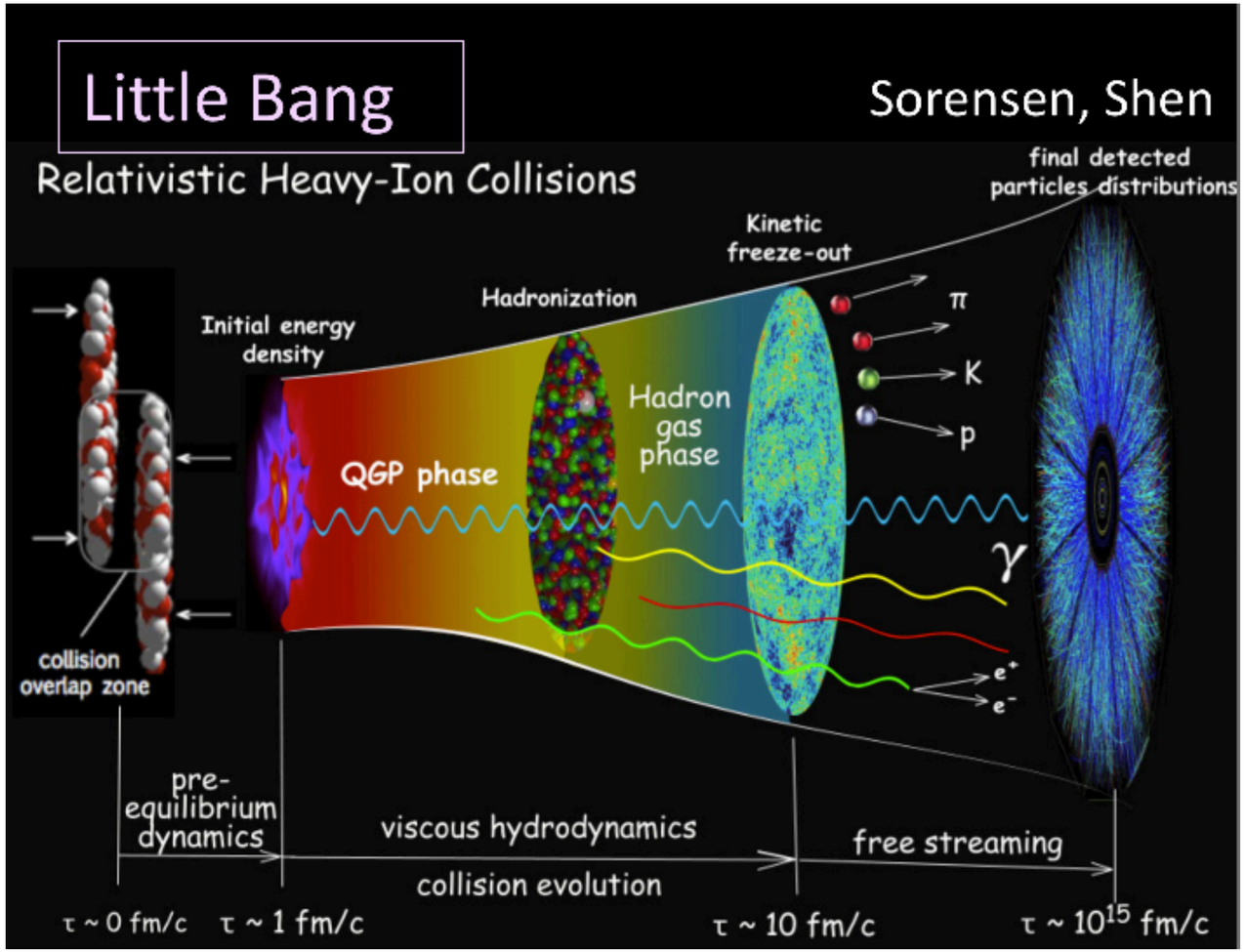
  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HeavyIons

Ch.4 of CERN YR: arXiv:1605.01389

Section editors:
N. Armesto, A. Dainese, D. d'Enterria, J. Jowett, J.P.Lansberg, G. Milhano, C. Salgado, M. Schaumann, M. van Leeuwen, U. Wiedemann

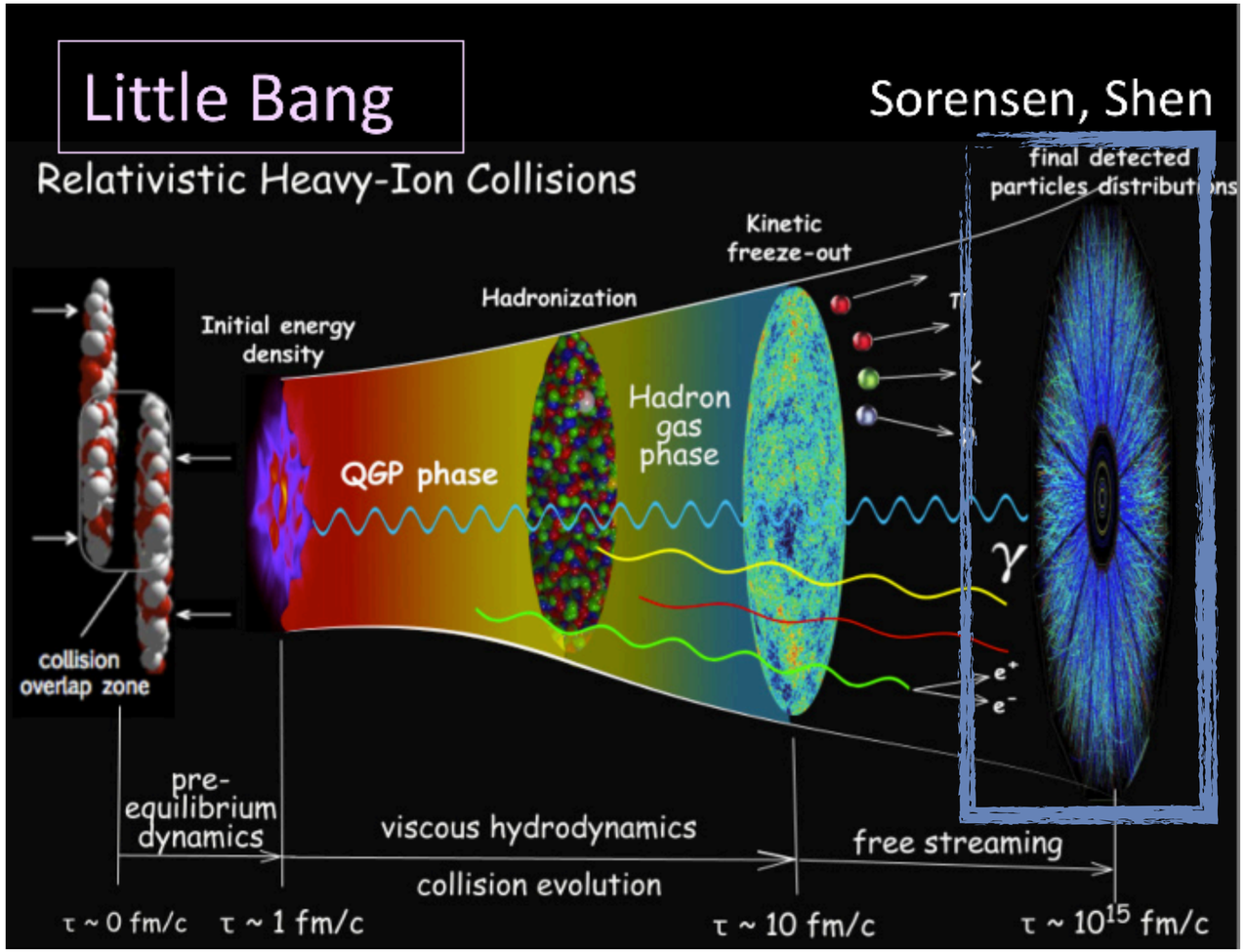
QGP Studies

- Heavy-Ion Collisions:
  - Study of nuclear matter in extreme regimes of temperature and density in a controlled environment;
    - Very short lifetime ⇒ Only indirect probing:
      - Direct decay products of its evolution (Soft Probes)
      - High momentum particles produced within the collision (Hard Probes)



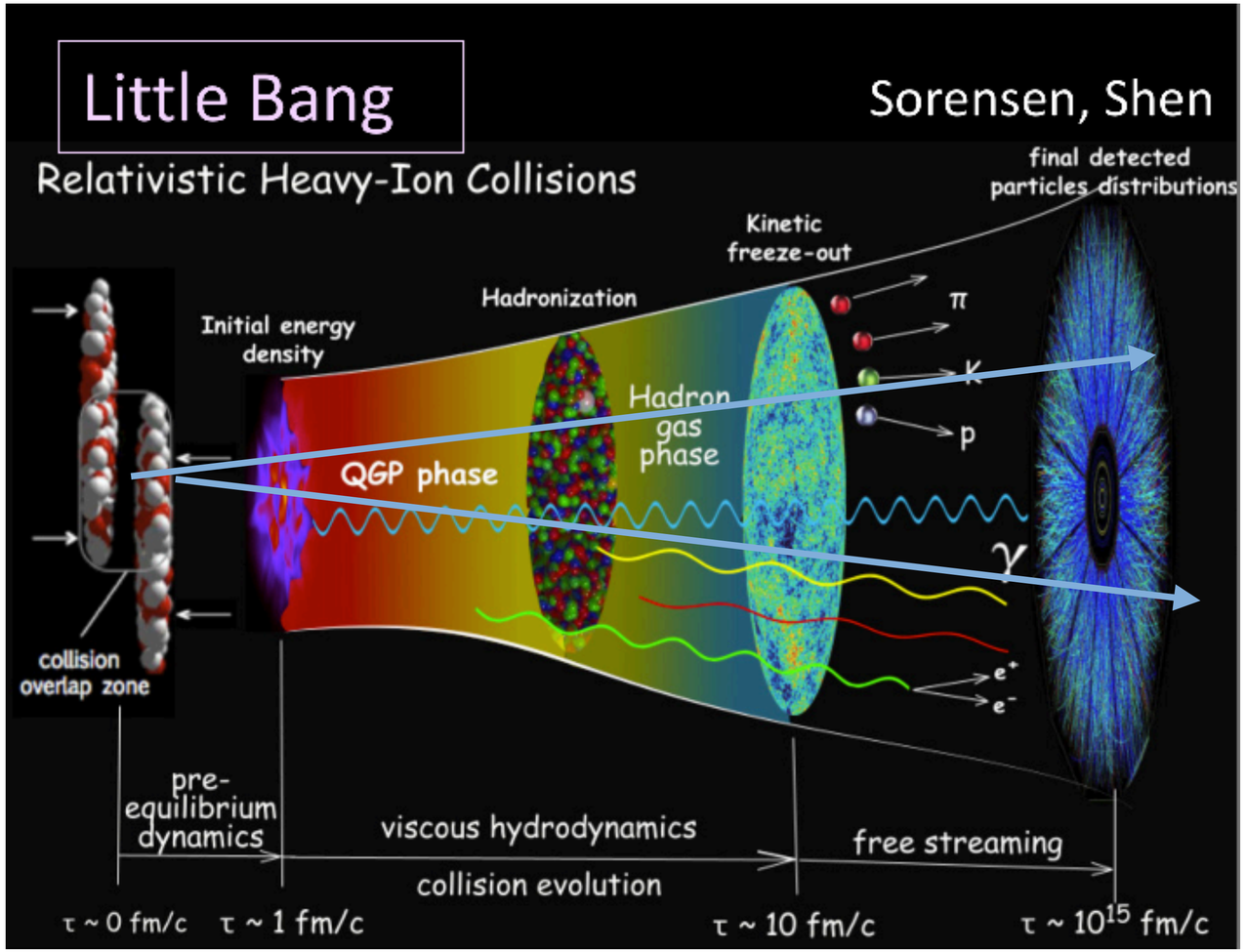
QGP Studies

- Heavy-Ion Collisions:
  - Study of nuclear matter in extreme regimes of temperature and density in a controlled environment;
    - Very short lifetime ⇒ Only indirect probing:
      - Direct decay products of its evolution (Soft Probes)
      - High momentum particles produced within the collision (Hard Probes)



QGP Studies

- Heavy-Ion Collisions:
  - Study of nuclear matter in extreme regimes of temperature and density in a controlled environment;
    - Very short lifetime ⇒ Only indirect probing:
      - Direct decay products of its evolution (Soft Probes)
      - High momentum particles produced within the collision (Hard Probes)



FCC HI Performance

See Monday talks
(D. Schulte and W. Riegler)

- 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

vs LHC: 5.5 (PbPb) and 8.8 (pPb)

	Unit	Baseline		Ultimate	
Operation mode	-	PbPb	pPb	PbPb	pPb
Number of Pb bunches	-	2760		5400	
Bunch spacing	[ns]	100		50	
Peak luminosity (1 experiment)	$[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	80	13300	320	55500
Integrated luminosity (1 experiment, 30 days)	$[\mathrm{nb}^{-1}]$	35	8000	110	29000

(ultimate scenario)
1 month ~ 10x LHC

Outline

- Focus on qualitative advances from the FCC:

QGP bulk properties	*Hard probes*	*Initial State*
Decay products of QGP ⇧ Volume and Lifetime ⇧ Temperature: charm thermal production ⇧ Multiplicity: Collectivity in small systems	Indirect probing of the QGP ⇧ Production Rate: tops, Higgs,… Boosted objects: QGP time evolution Quarkonia: QGP temperature evolution	Fix initial conditions for collectivity ⇧ Parton densities: Saturation Physics ⇧ Energy: nuclear PDFs in different kinematic range

QGP Bulk Properties

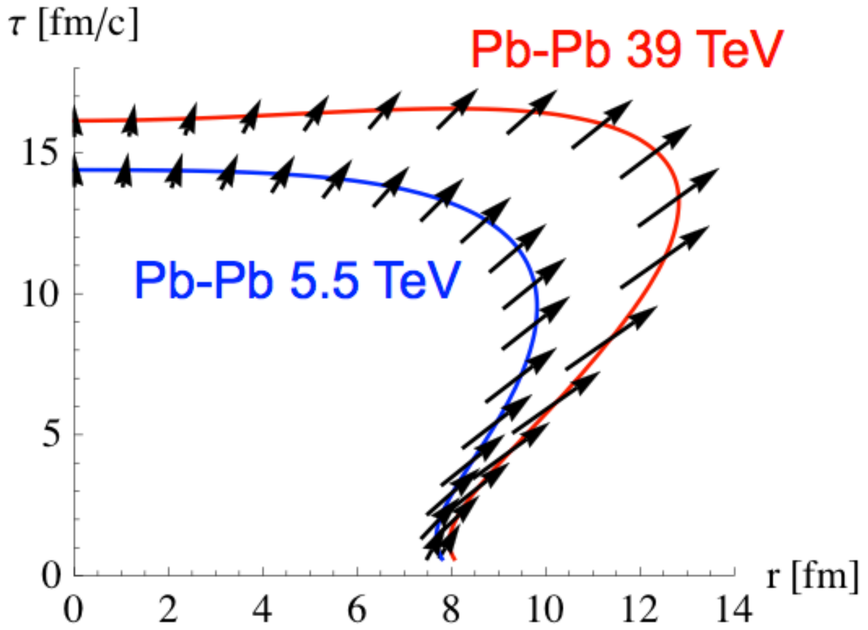
Medium Bulk Properties

- Global properties:

Quantity	Pb–Pb 5.5 TeV	Pb–Pb 10.6 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	2000	2400	3600
$dE_T/d\eta$ at $\eta = 0$	2.3–2.6 TeV	3.1–3.4 TeV	5.2–5.8 TeV
Homogeneity volume	6200 fm^3	7400 fm^3	11000 fm^3
Decoupling time	11 fm/c	11.5 fm/c	13 fm/c
ε at $\tau = 1$ fm/c	16–17 GeV/fm^3	22–24 GeV/fm^3	35–40 GeV/fm^3

~ x 1.5-2 w.r.t (HE)-LHC TeV

- Expected impact on medium bulk proprerties:
  - Denser medium ⇒ longer expansion and larger volume (before freeze-out)



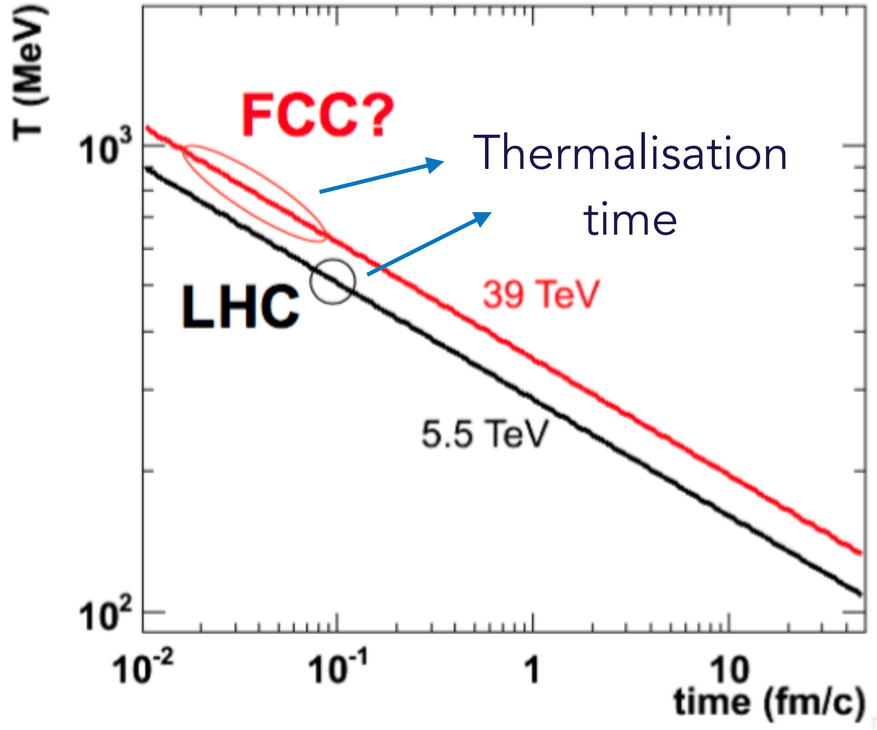
Medium Bulk Properties

- Global properties:

Quantity	Pb–Pb 5.5 TeV	Pb–Pb 10.6 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	2000	2400	3600
$dE_T/d\eta$ at $\eta = 0$	2.3–2.6 TeV	3.1–3.4 TeV	5.2–5.8 TeV
Homogeneity volume	6200 fm^3	7400 fm^3	11000 fm^3
Decoupling time	11 fm/c	11.5 fm/c	13 fm/c
ε at $\tau = 1$ fm/c	16–17 GeV/fm^3	22–24 GeV/fm^3	35–40 GeV/fm^3

~ x 1.5-2 w.r.t (HE)-LHC TeV

- Expected impact on medium bulk proprerties:
  - Denser medium ⇒ longer expansion and larger volume (before freeze-out)
  - Higher initial energy ⇒ larger temperature and smaller thermalisation time



Medium Bulk Properties

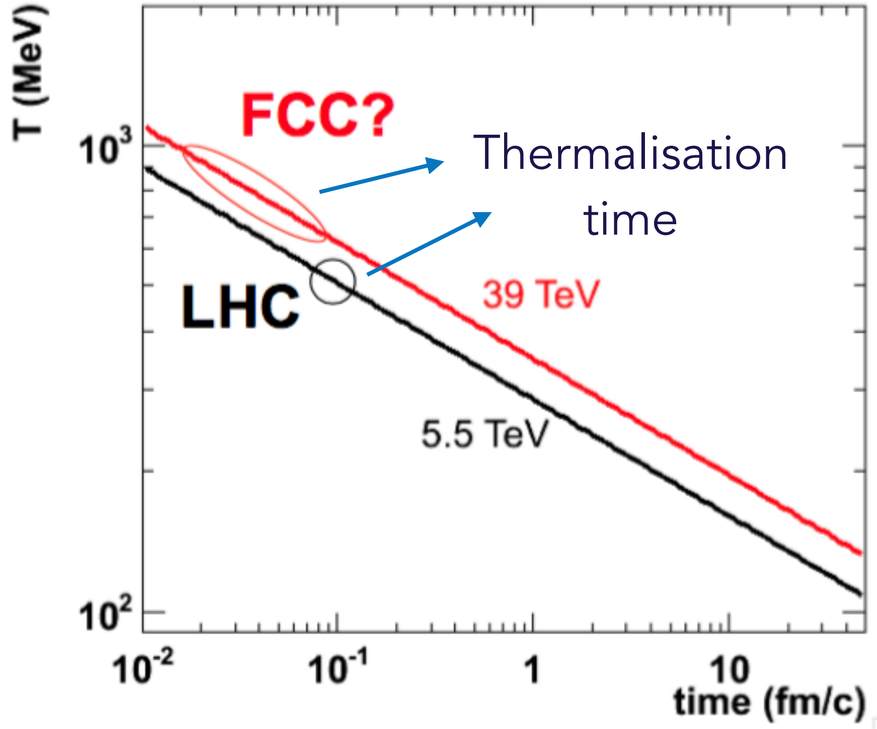
- Global properties:

Quantity	Pb–Pb 5.5 TeV	Pb–Pb 10.6 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	2000	2400	3600
$dE_T/d\eta$ at $\eta = 0$	2.3–2.6 TeV	3.1–3.4 TeV	5.2–5.8 TeV
Homogeneity volume	6200 fm^3	7400 fm^3	11000 fm^3
Decoupling time	11 fm/c	11.5 fm/c	13 fm/c
ε at $\tau = 1$ fm/c	16–17 GeV/fm^3	22–24 GeV/fm^3	35–40 GeV/fm^3

~ x 1.5-2 w.r.t (HE)-LHC TeV

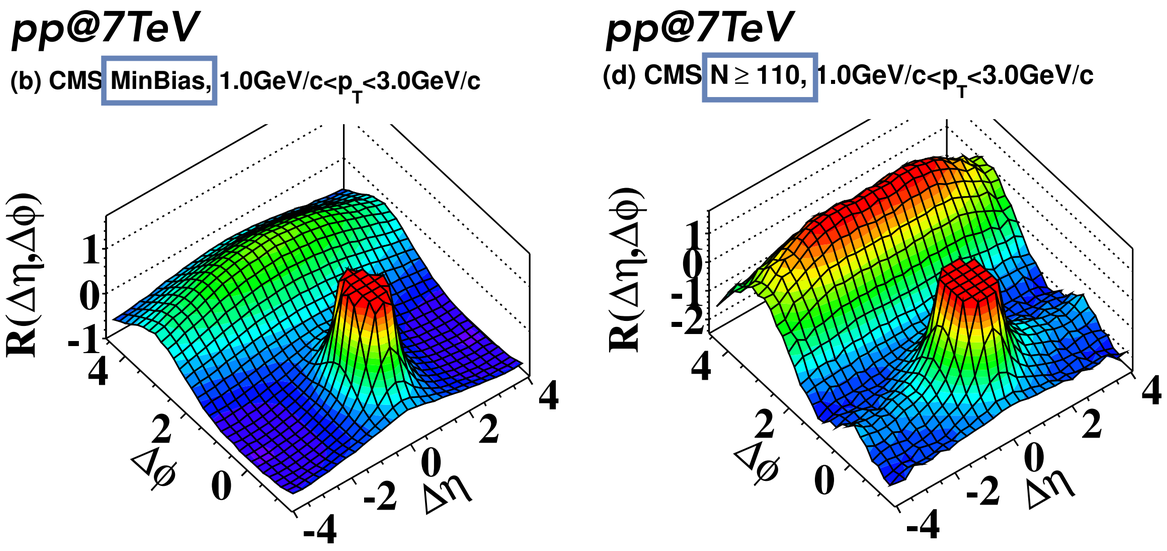
What can this larger/denser/hotter medium do for us?

- Expected impact on medium bulk proprerties:
  - Denser medium ⇒ longer expansion and larger volume (before freeze-out)
  - Higher initial energy ⇒ larger temperature and smaller thermalisation time



Collectivity in Small Systems

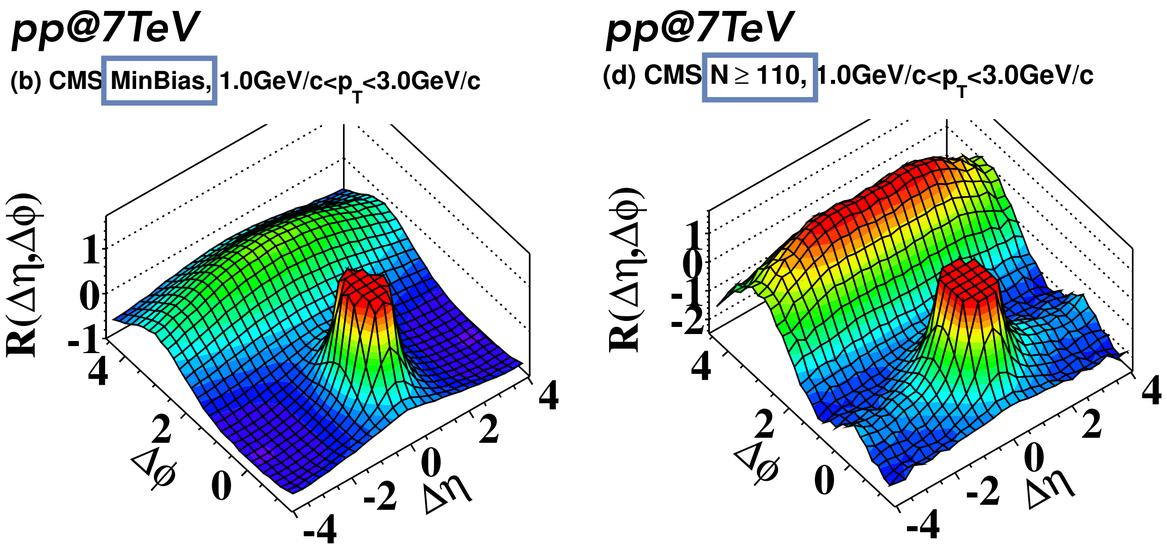
- Collectivity signs in pA and high multiplicity pp?
  - System size dependence of flow needs higher order cumulants (large multiplicities)



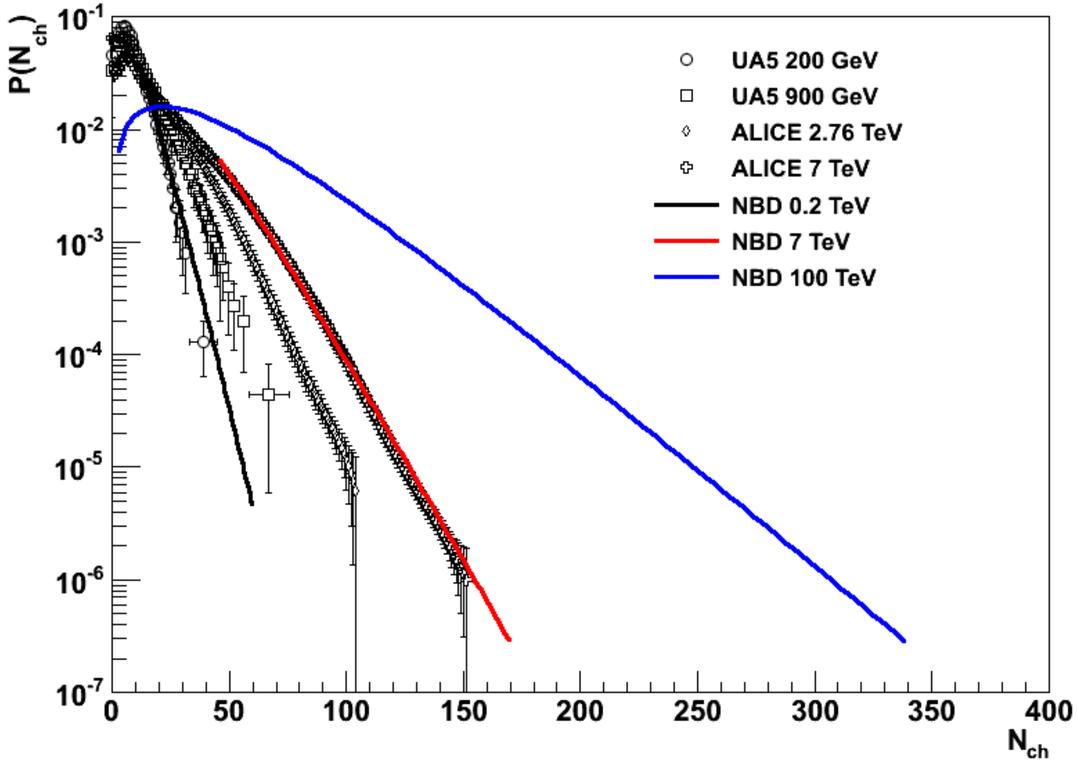
CMS [1009.4122]

Collectivity in Small Systems

- Collectivity signs in pA and high multiplicity pp?
  - System size dependence of flow needs higher order cumulants (large multiplicities)



CMS [1009.4122]

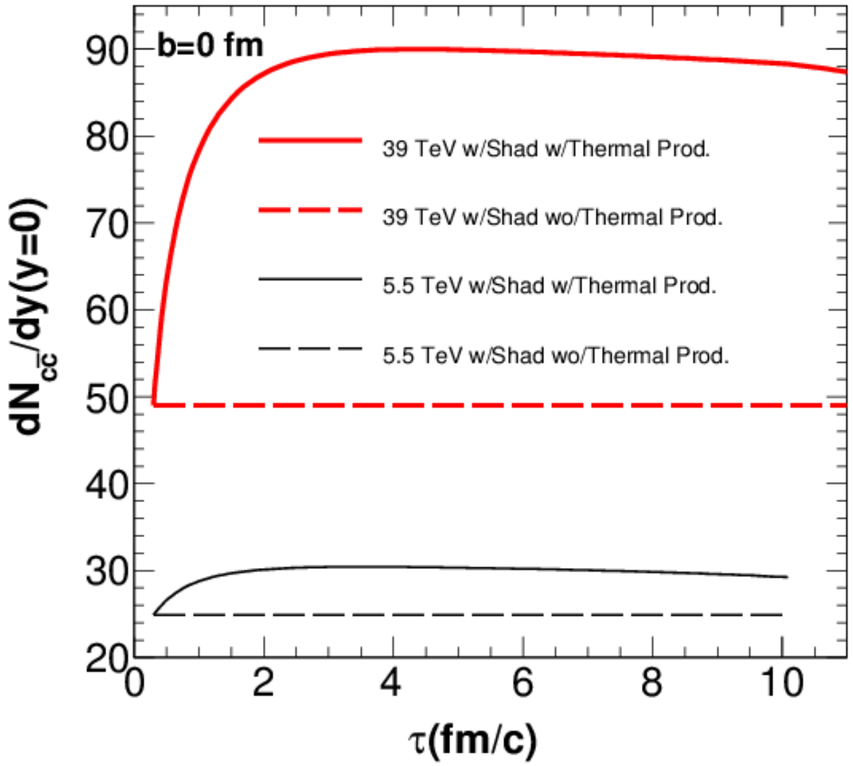


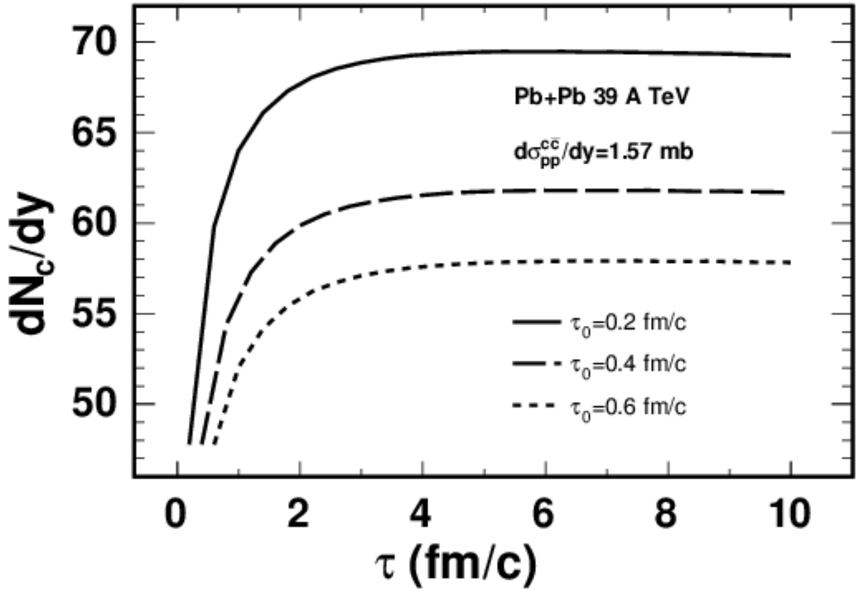
✓ Increase of multiplicity at FCC can help to answer this question!

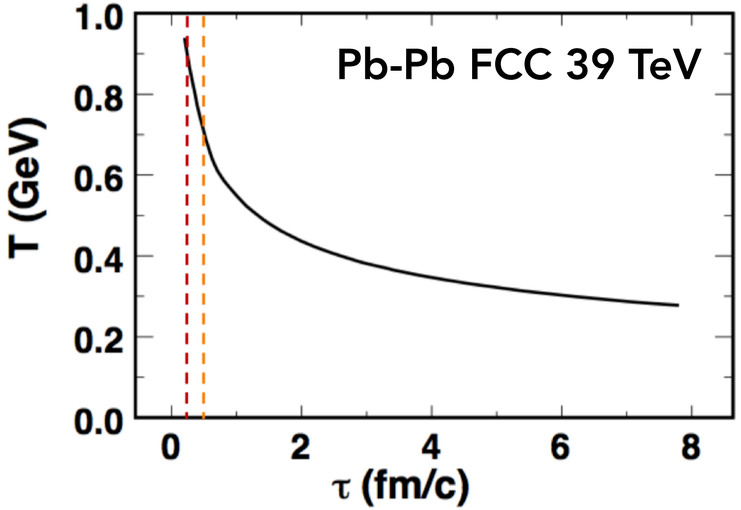
Thermal Charm Production

Zhou et al (16), Uphoff et al (10-14), Liu et al (16)

- Increase of temperature ⇒ Production of low p_T $c\bar{c}$ pairs







900 MeV at τ = 0.2 fm/c

650 MeV at τ = 0.5 fm/c

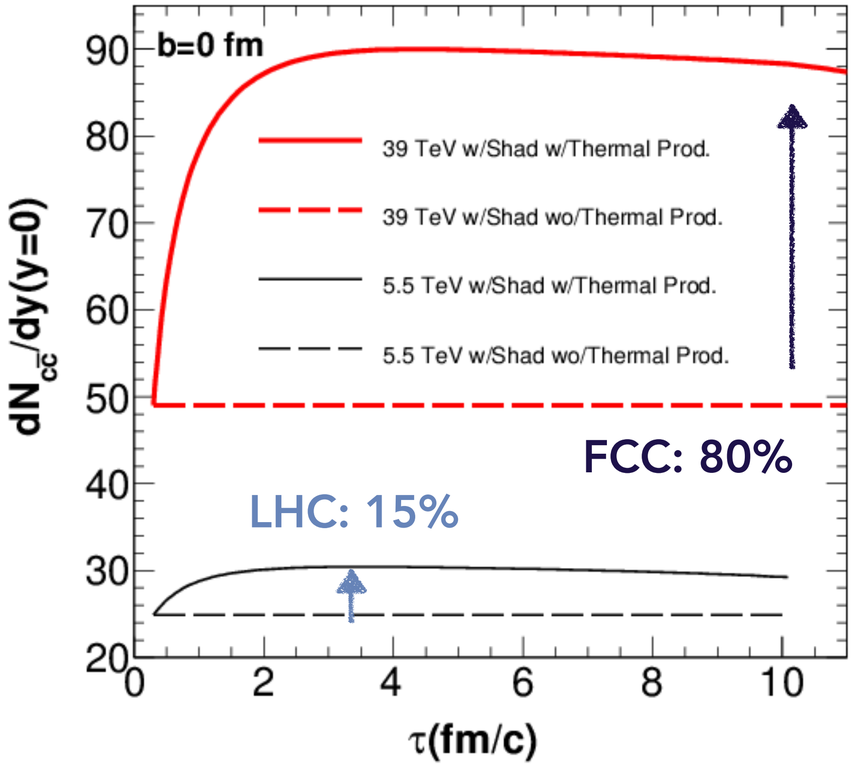
vs LHC 5.5 TeV:

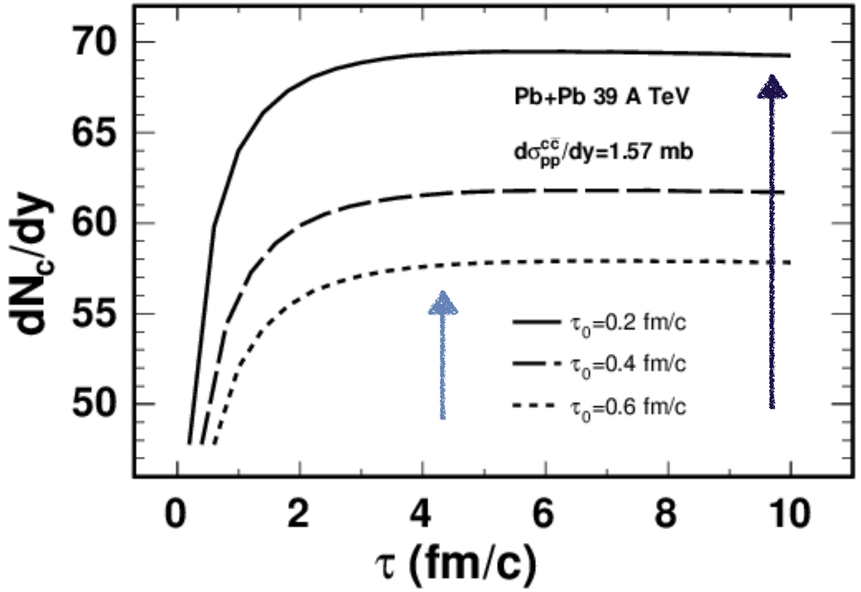
580 MeV at τ = 0.6 fm/c

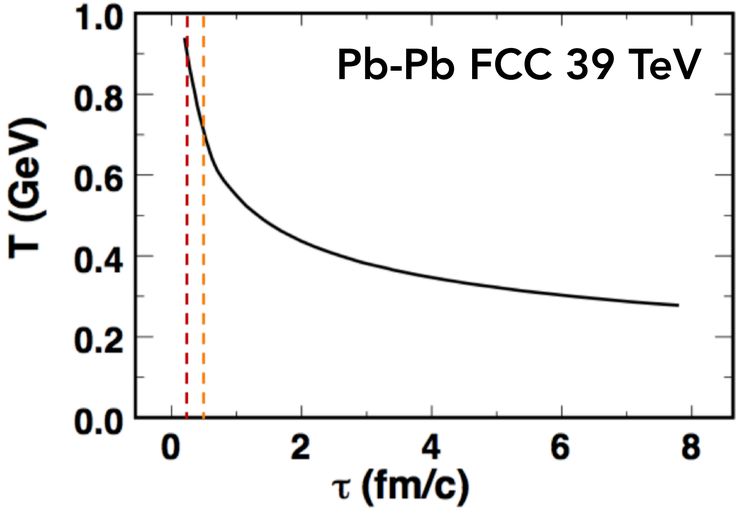
Thermal Charm Production

Zhou et al (16), Uphoff et al (10-14), Liu et al (16)

- Increase of temperature ⇒ Production of low p_T $c\bar{c}$ pairs







900 MeV at τ = 0.2 fm/c

650 MeV at τ = 0.5 fm/c

vs LHC 5.5 TeV:

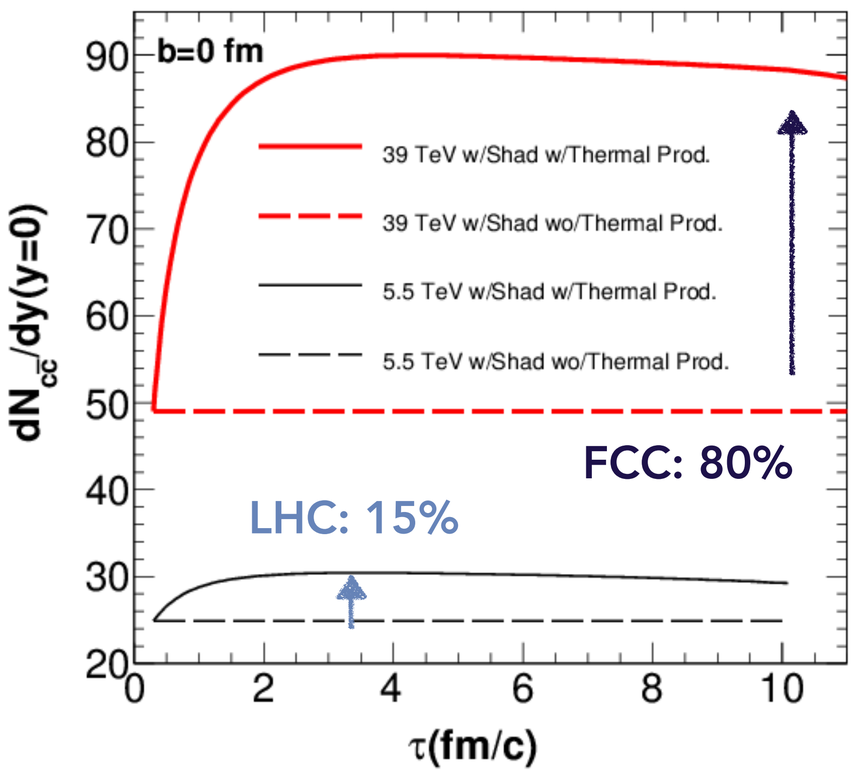
580 MeV at τ = 0.6 fm/c

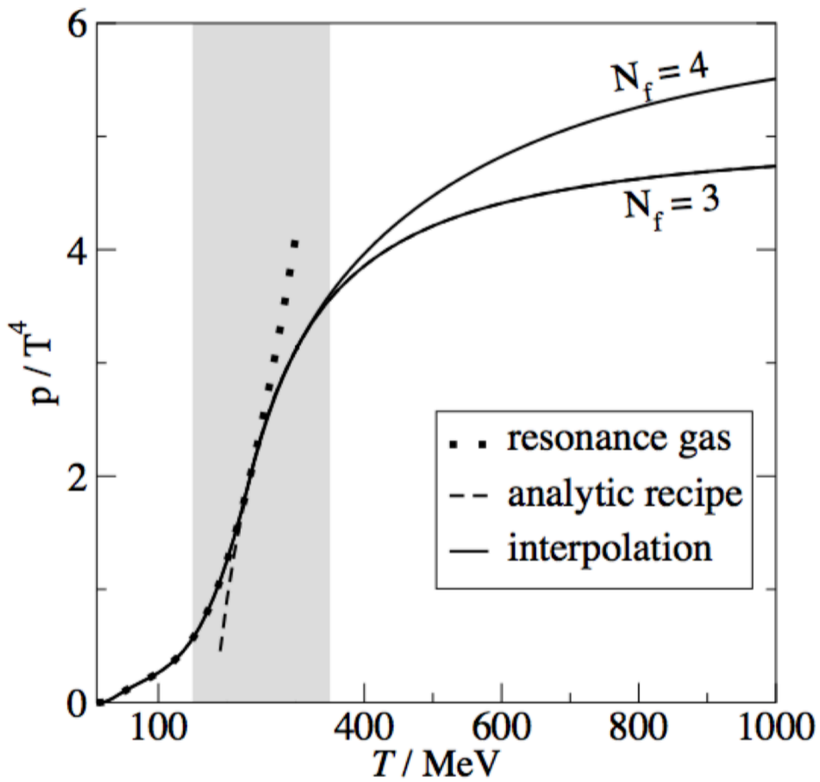
✓ FCC: handle on the QGP temperature evolution and formation time!

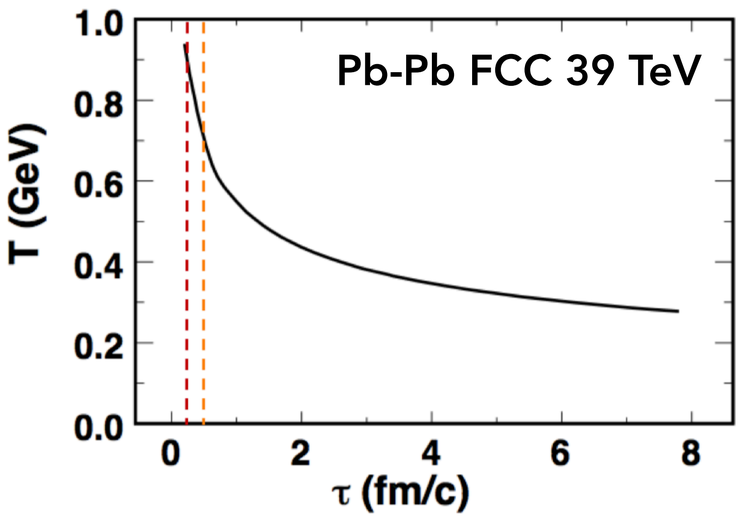
Thermal Charm Production

Zhou et al (16), Uphoff et al (10-14), Liu et al (16)

- Increase of temperature ⇒ Production of low p_T $c\bar{c}$ pairs







900 MeV at τ = 0.2 fm/c

650 MeV at τ = 0.5 fm/c

vs LHC 5.5 TeV:

580 MeV at τ = 0.6 fm/c

✓ FCC: handle on the QGP temperature evolution and formation time!

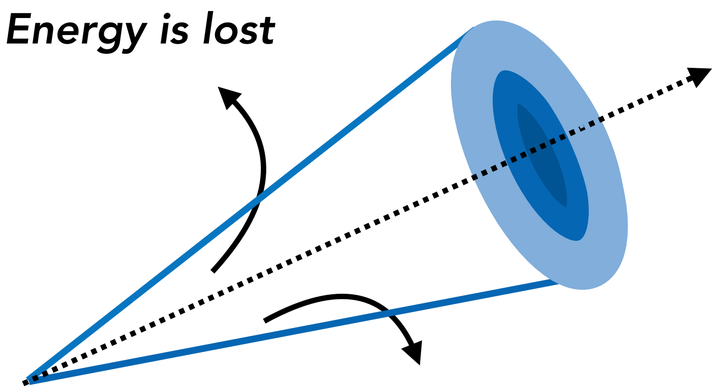
✓ FCC: charm start contribute to QCD equation of state!


Hard Probes

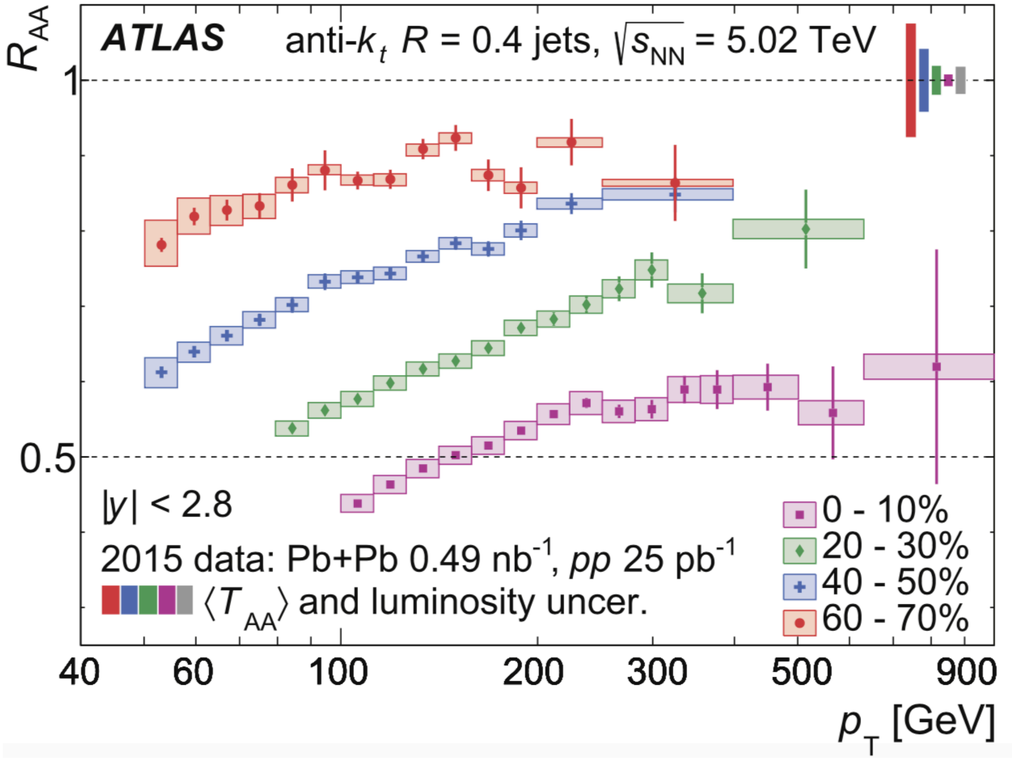
Jet Quenching

ATLAS [1805.05635]

- Current picture of a medium-modified jet:



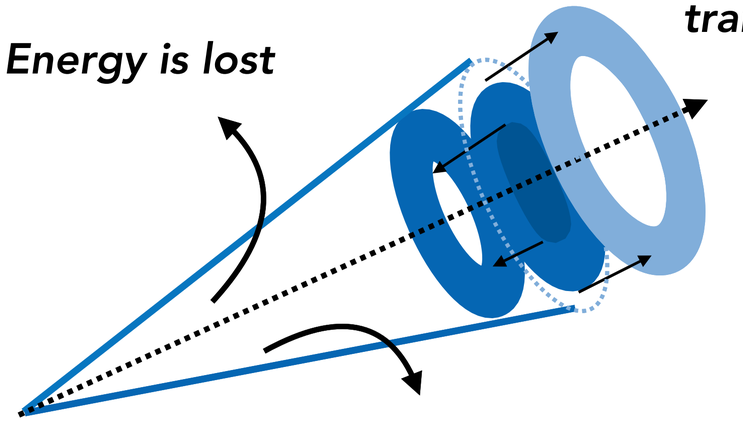
Jet Transverse momentum spectrum (pp/PbPb)



Jet Quenching

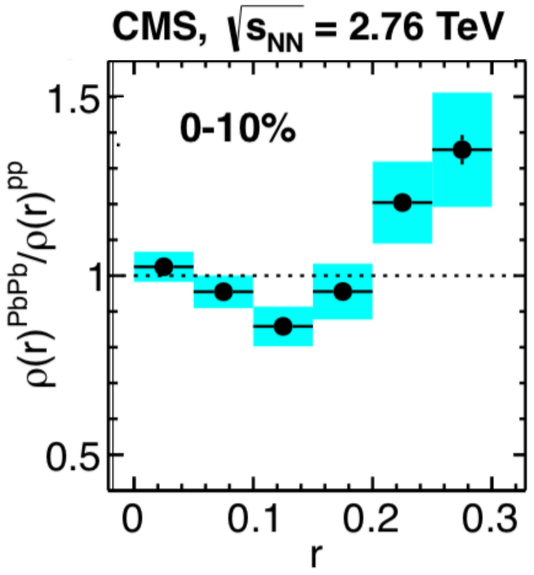
CMS [1310.0878]

- Current picture of a medium-modified jet:

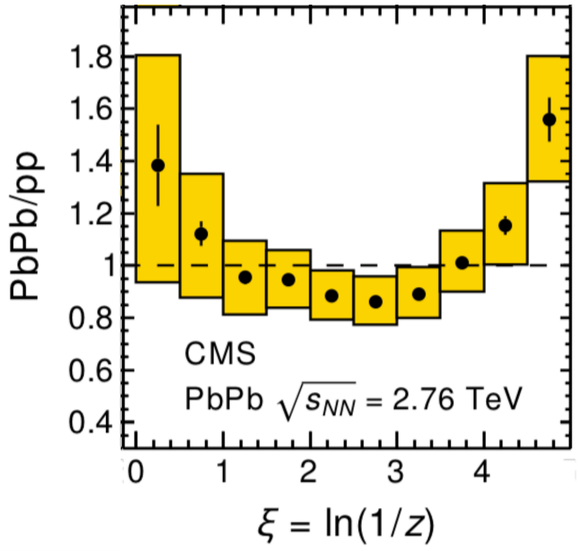


@ LHC: Jets can provide a range of scales to probe the QGP!

Jet radial profile (pp/PbPb)



Fraction of energy of jet fragments (pp/PbPb)



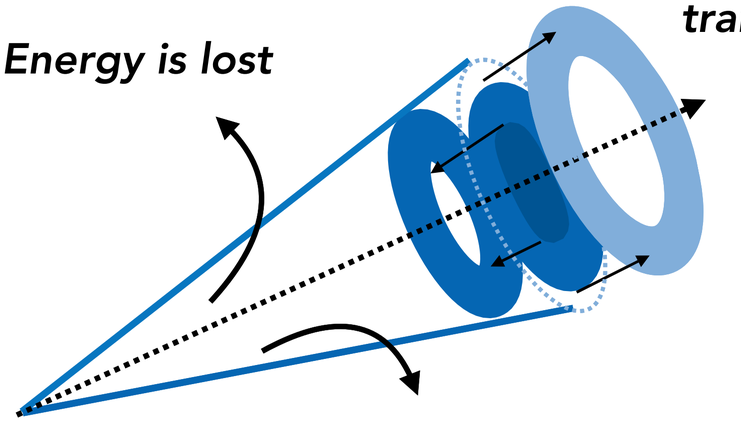
Jet Quenching

CMS [1310.0878]

- Current picture of a medium-modified jet:

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

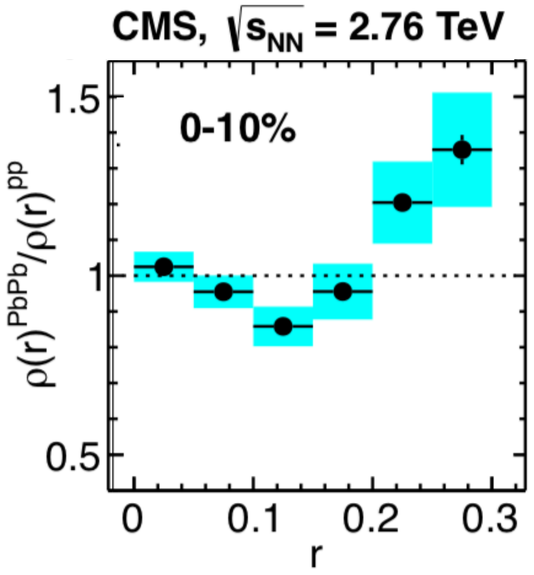
Energy is lost



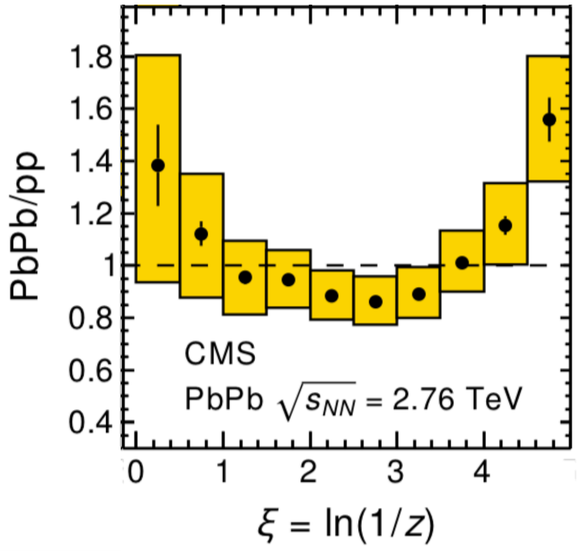
Core of the jet transverse profile/hard fragments unmodified

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

Jet radial profile (pp/PbPb)



Fraction of energy of jet fragments (pp/PbPb)



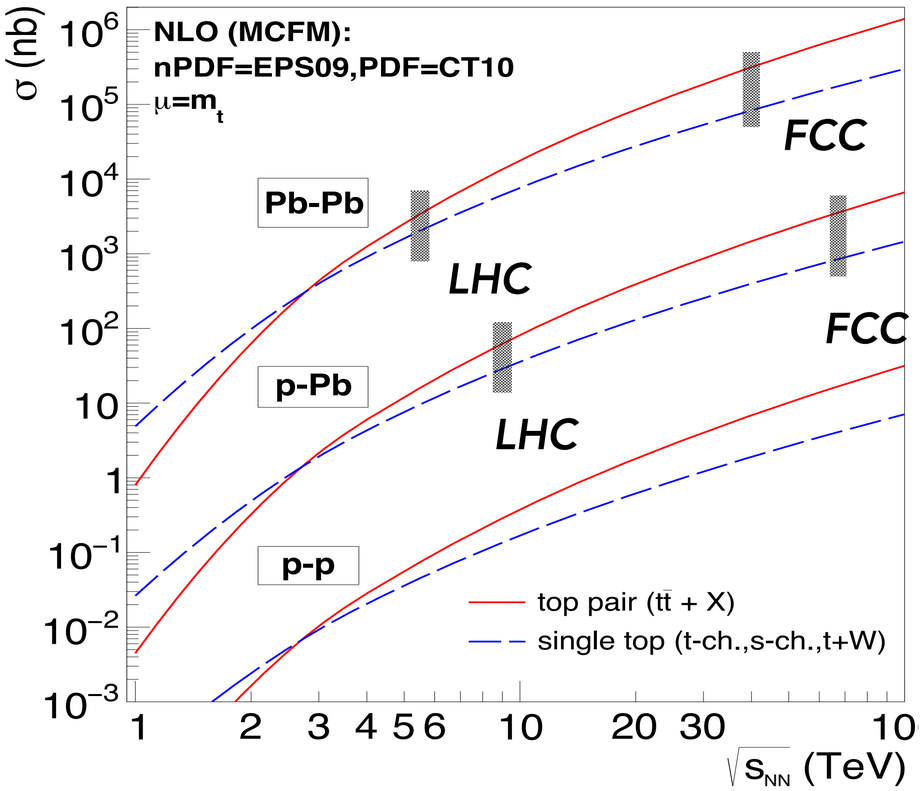
@ LHC: Jets can provide a range of scales to probe the QGP!

@ FCC: What can it bring of new?

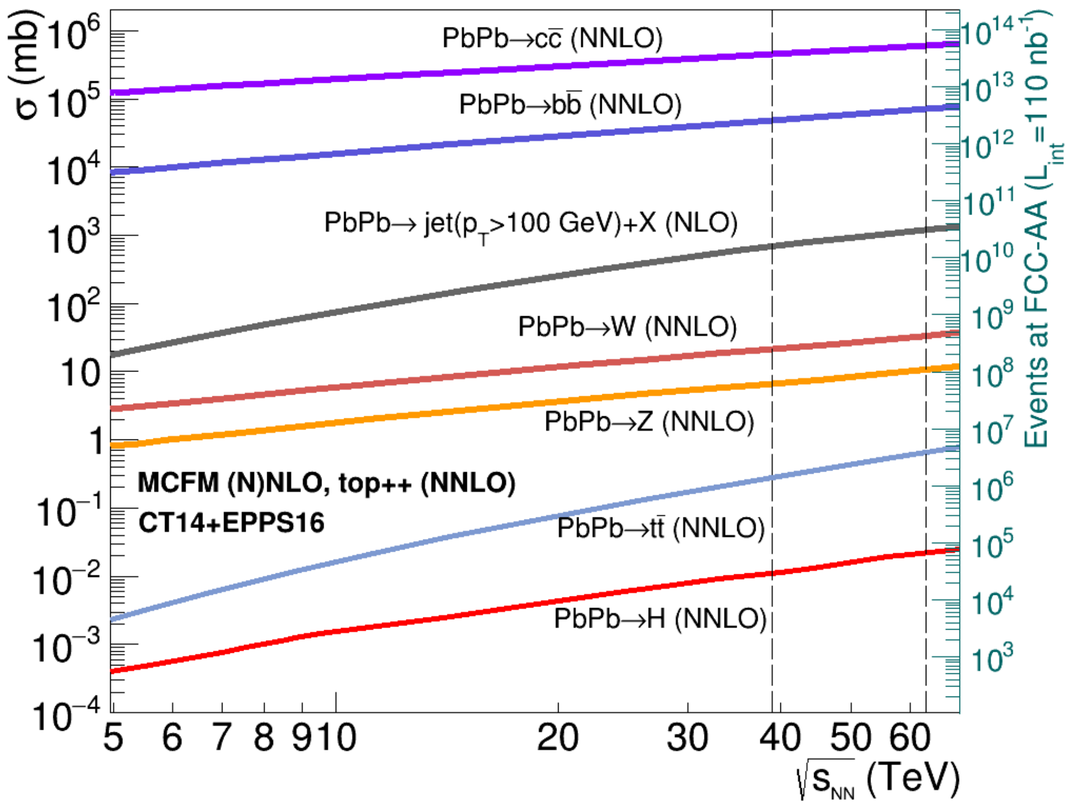
Tops (and much more)

d'Enterria et al (15)

- Top cross section increases by x80 from 5.5 TeV to 39 TeV



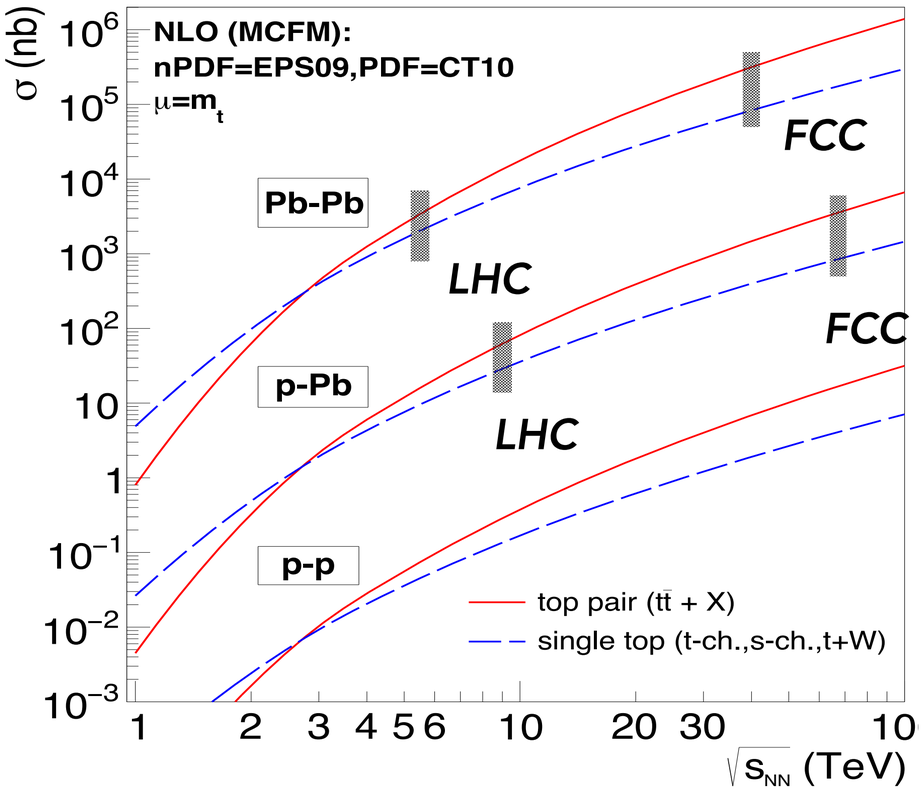
- Boson-Jet cross-section increases by x20
- Bottom cross-section increases by x6



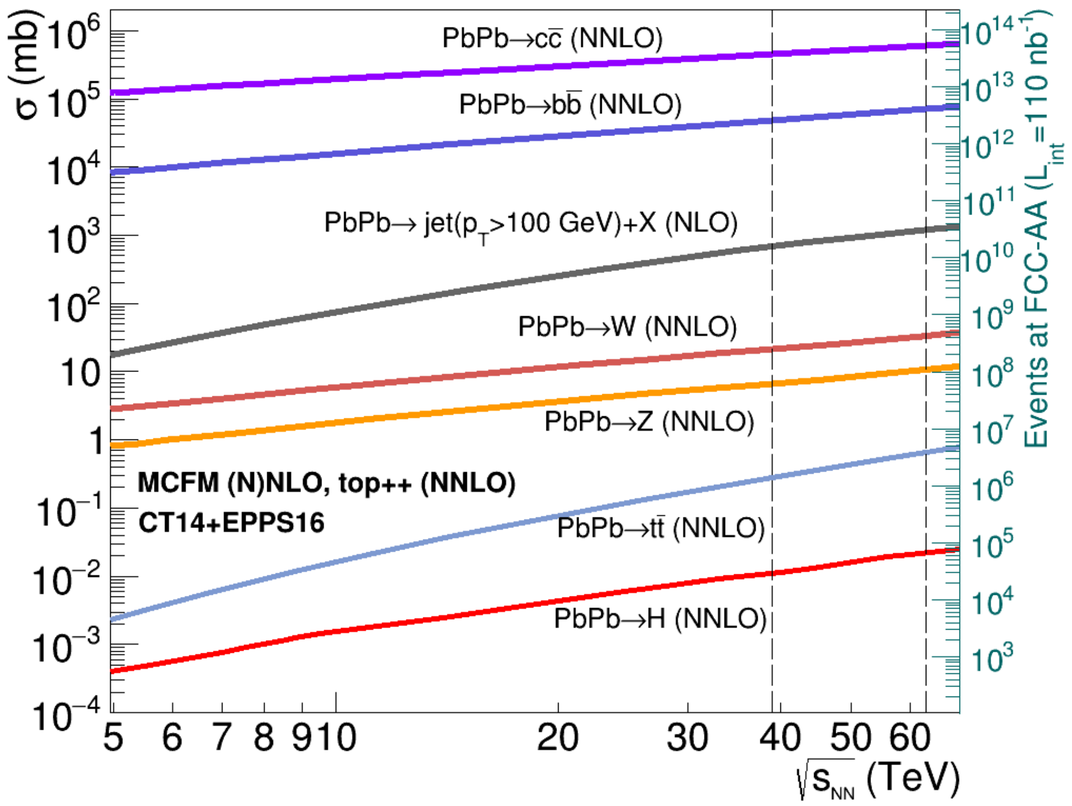
Tops (and much more)

d'Enterria et al (15)

- Top cross section increases by x80 from 5.5 TeV to 39 TeV



- Boson-Jet cross-section increases by x20
- Bottom cross-section increases by x6

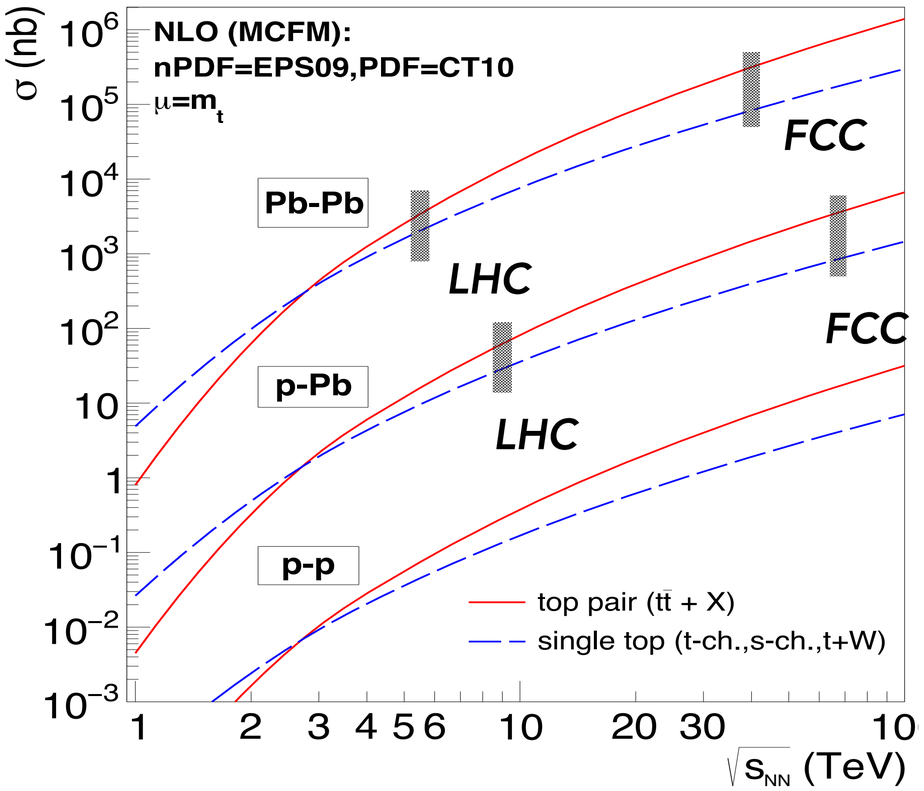


✓ Accurate Jet quenching studies

Tops (and much more)

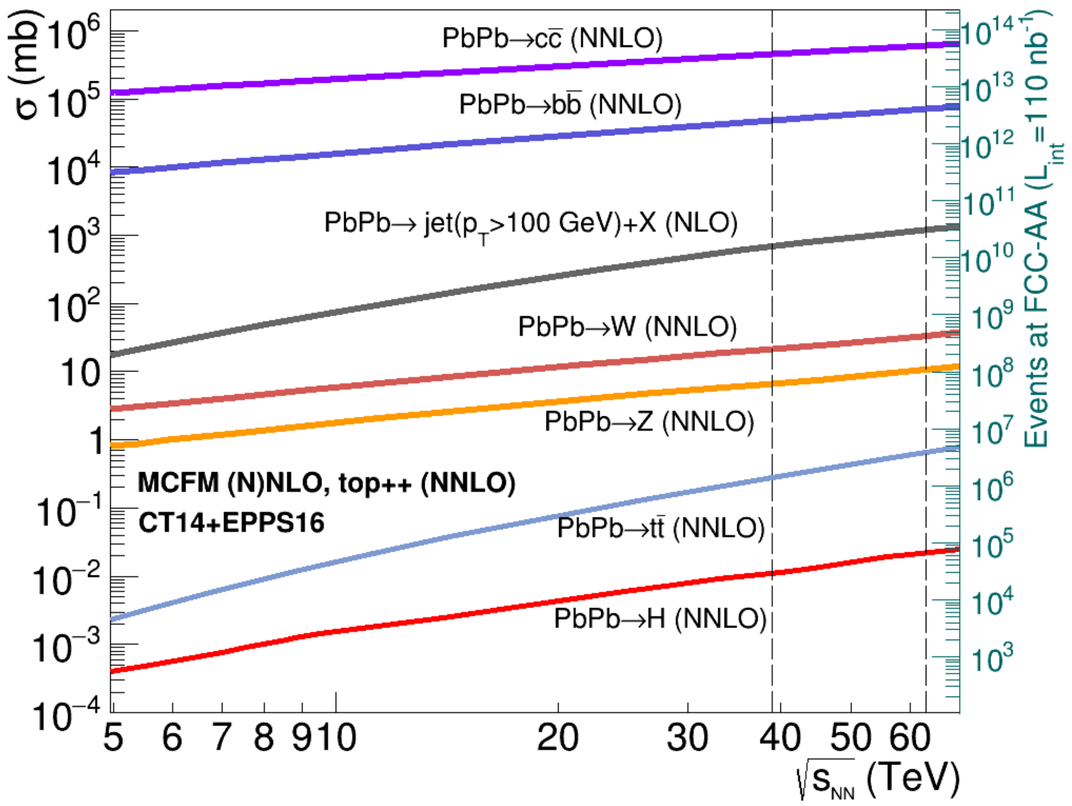
d'Enterria et al (15)

- Top cross section increases by x80 from 5.5 TeV to 39 TeV



✓ Boosted objects

- Boson-Jet cross-section increases by x20
- Bottom cross-section increases by x6

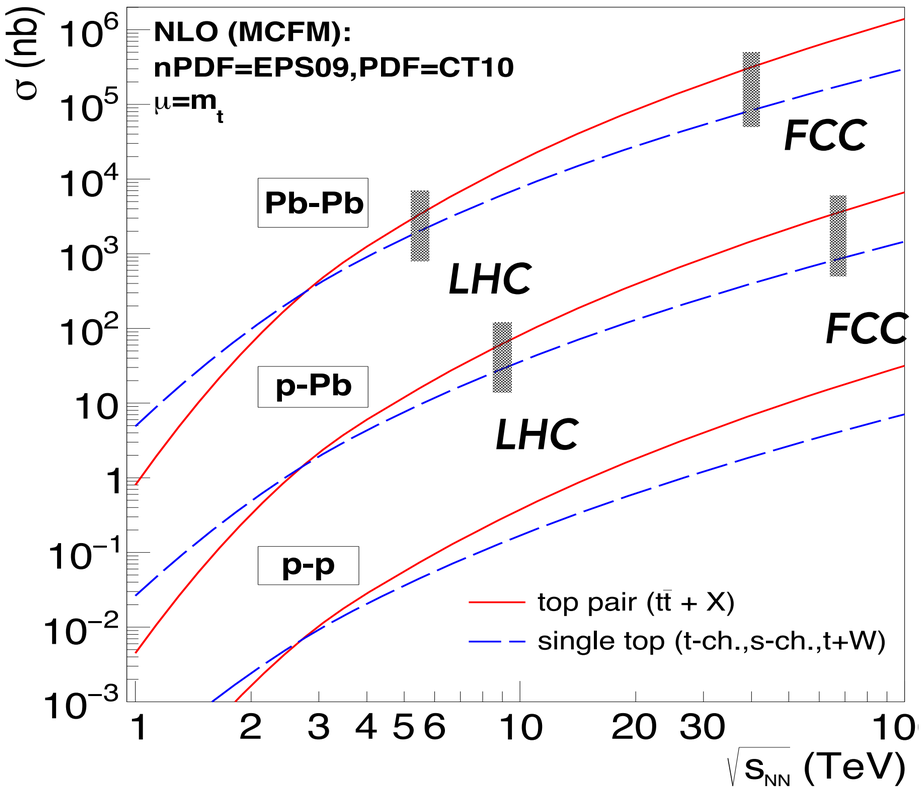


✓ Accurate Jet quenching studies

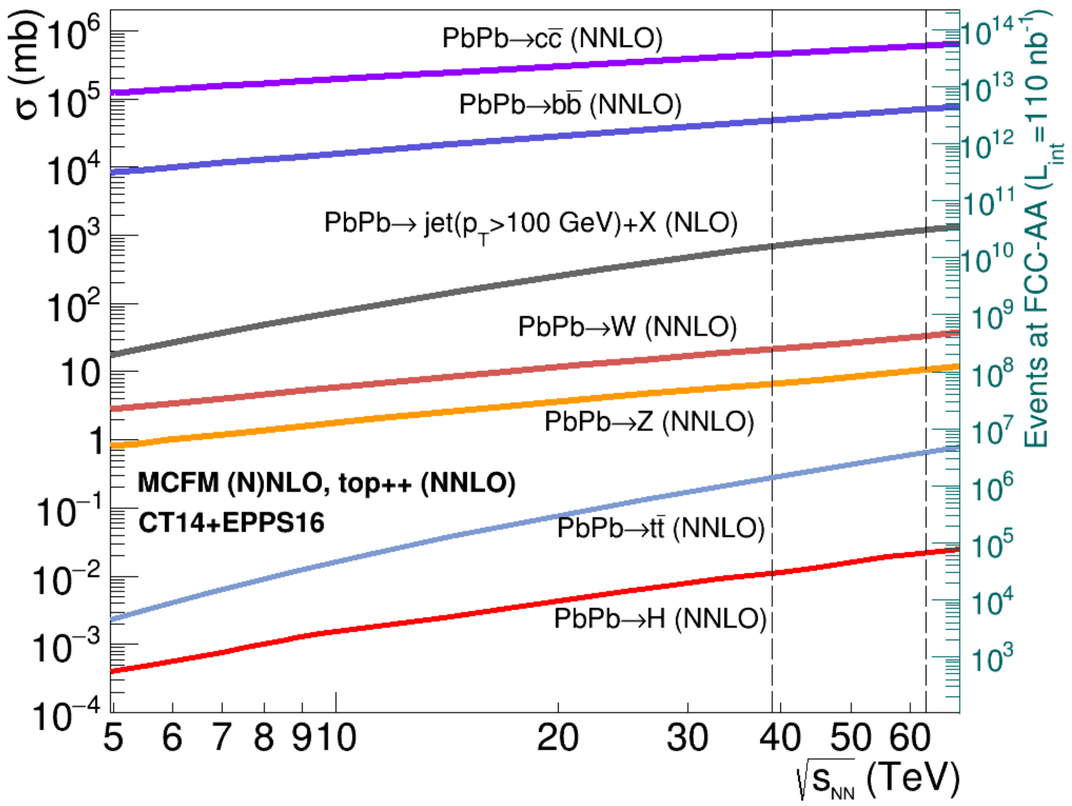
Tops (and much more)

d'Enterria et al (15)

- Top cross section increases by x80 from 5.5 TeV to 39 TeV



- Boson-Jet cross-section increases by x20
- Bottom cross-section increases by x6



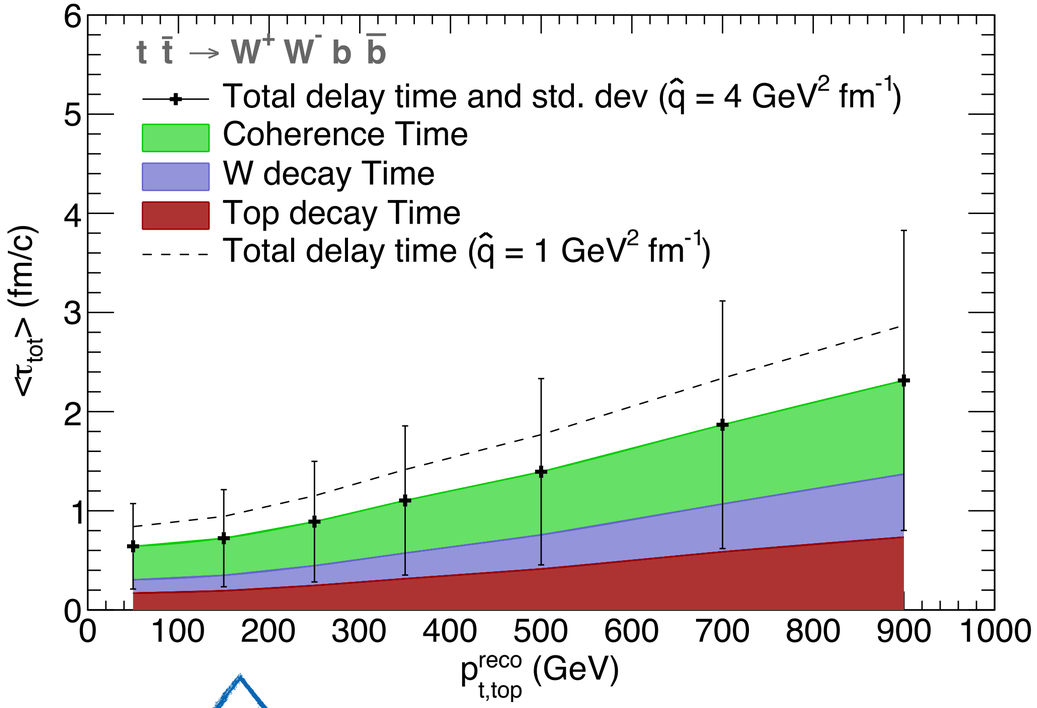
✓ Boosted objects ⬅ ***What can we do with these?***

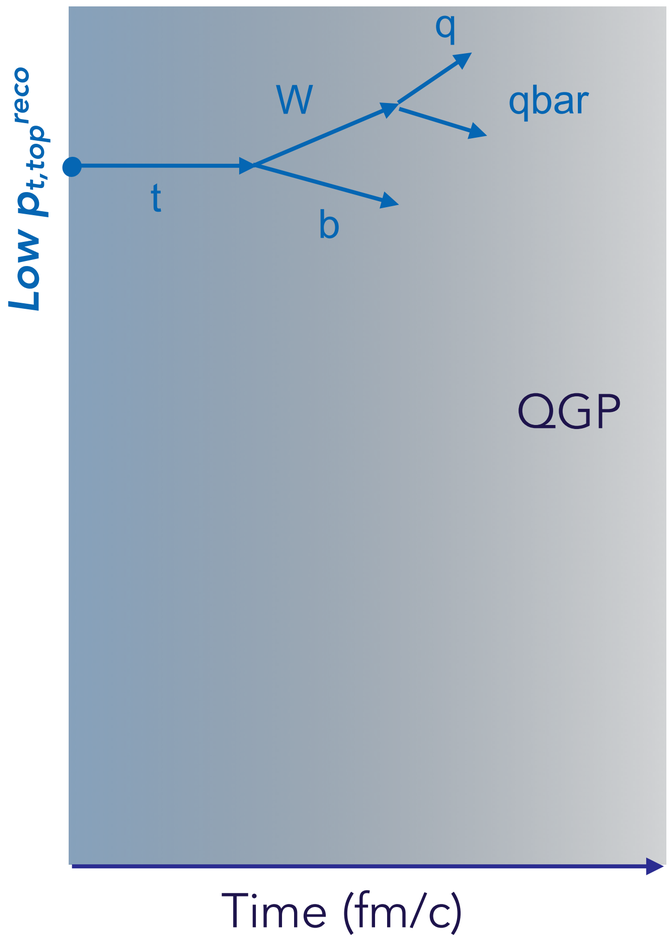
✓ Accurate Jet quenching studies

Boosted Tops: QGP Tomography

Apolinário et al (18)

- Semi-leptonic decay of tt events produce jets that start interacting with the QGP only at later times

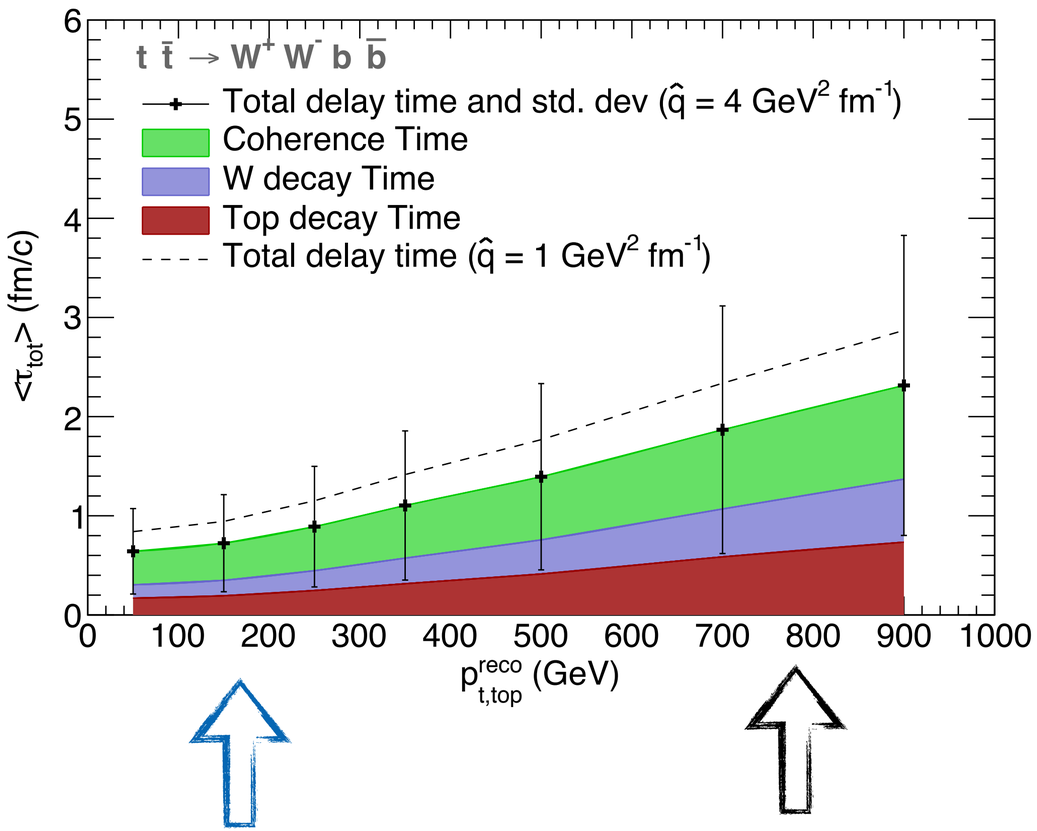


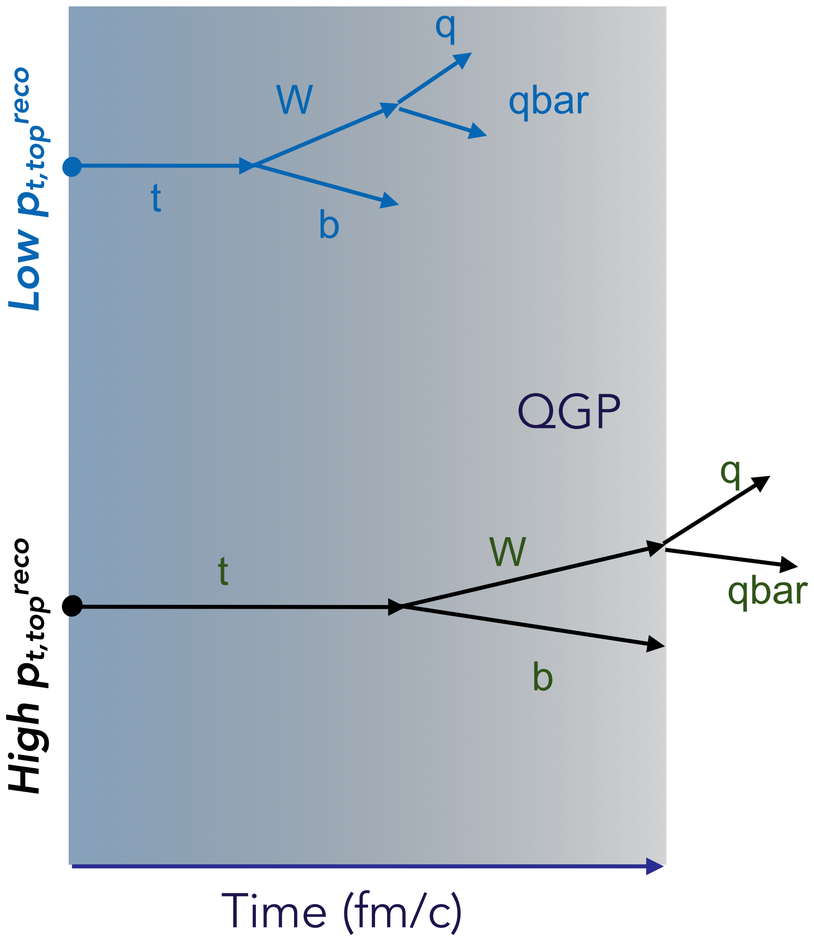


Boosted Tops: QGP Tomography

Apolinário et al (18)

- Semi-leptonic decay of tt events produce jets that start interacting with the QGP only at later times

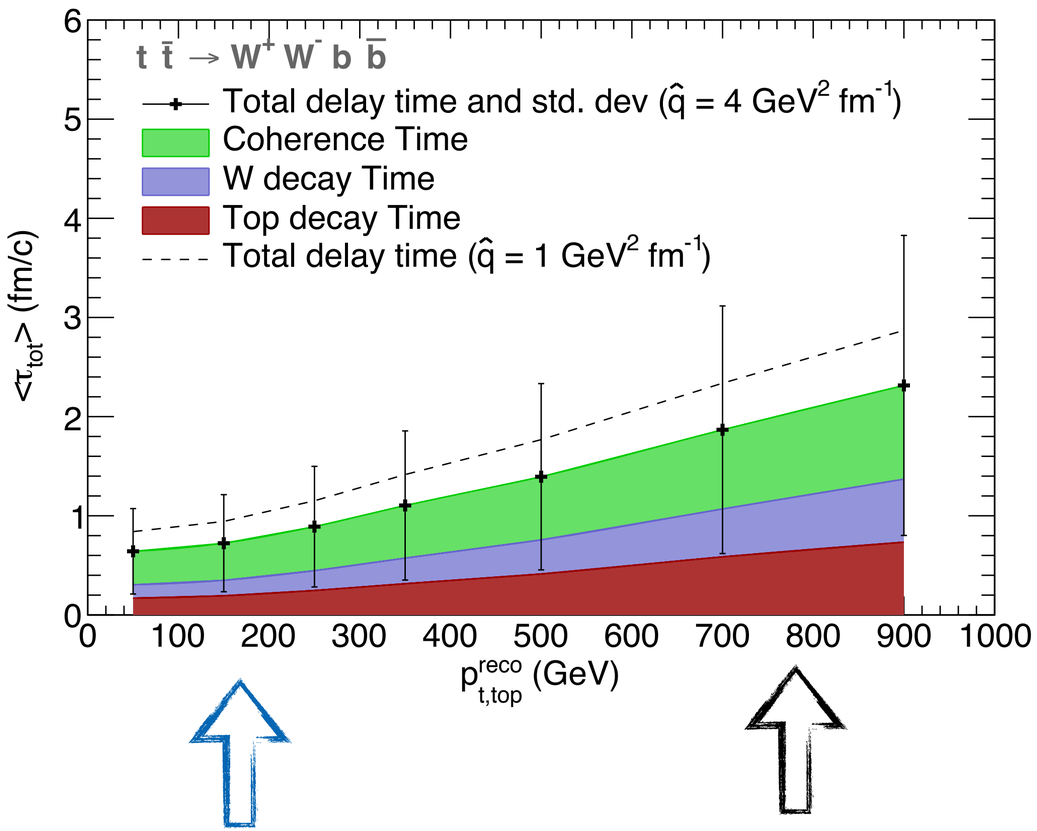


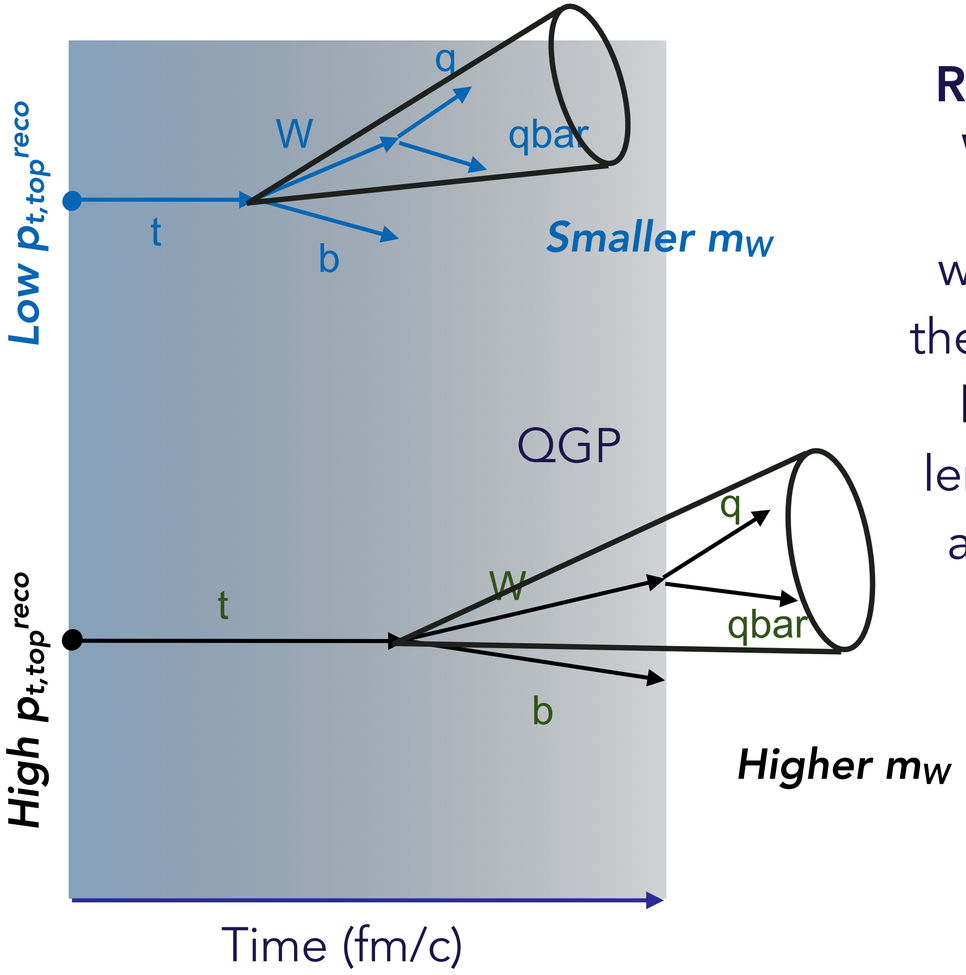


Boosted Tops: QGP Tomography

Apolinário et al (18)

- Semi-leptonic decay of tt events produce jets that start interacting with the QGP only at later times





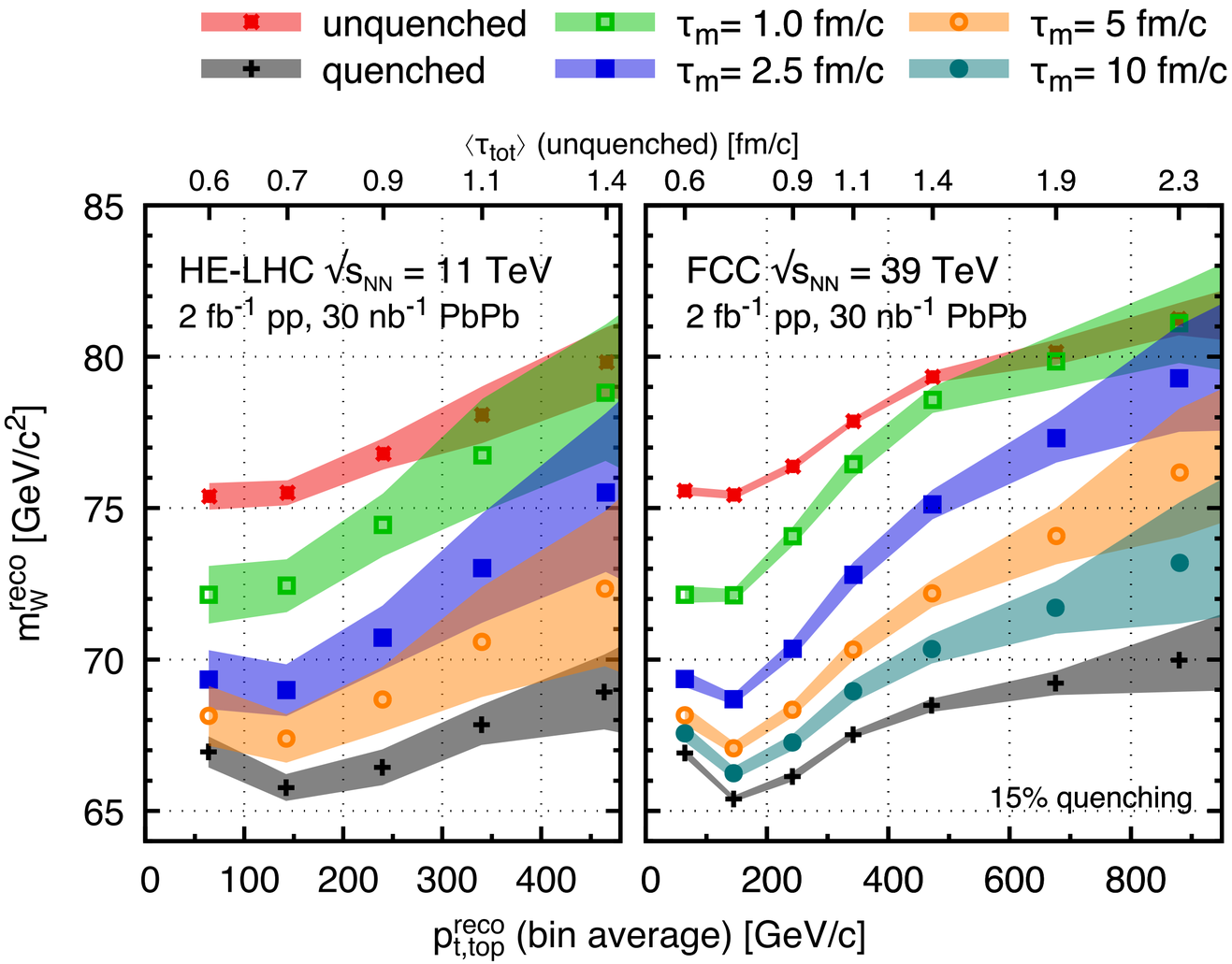
Reconstructed W mass: m_W

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

Boosted Tops: QGP Tomography

Apolinário et al (18)

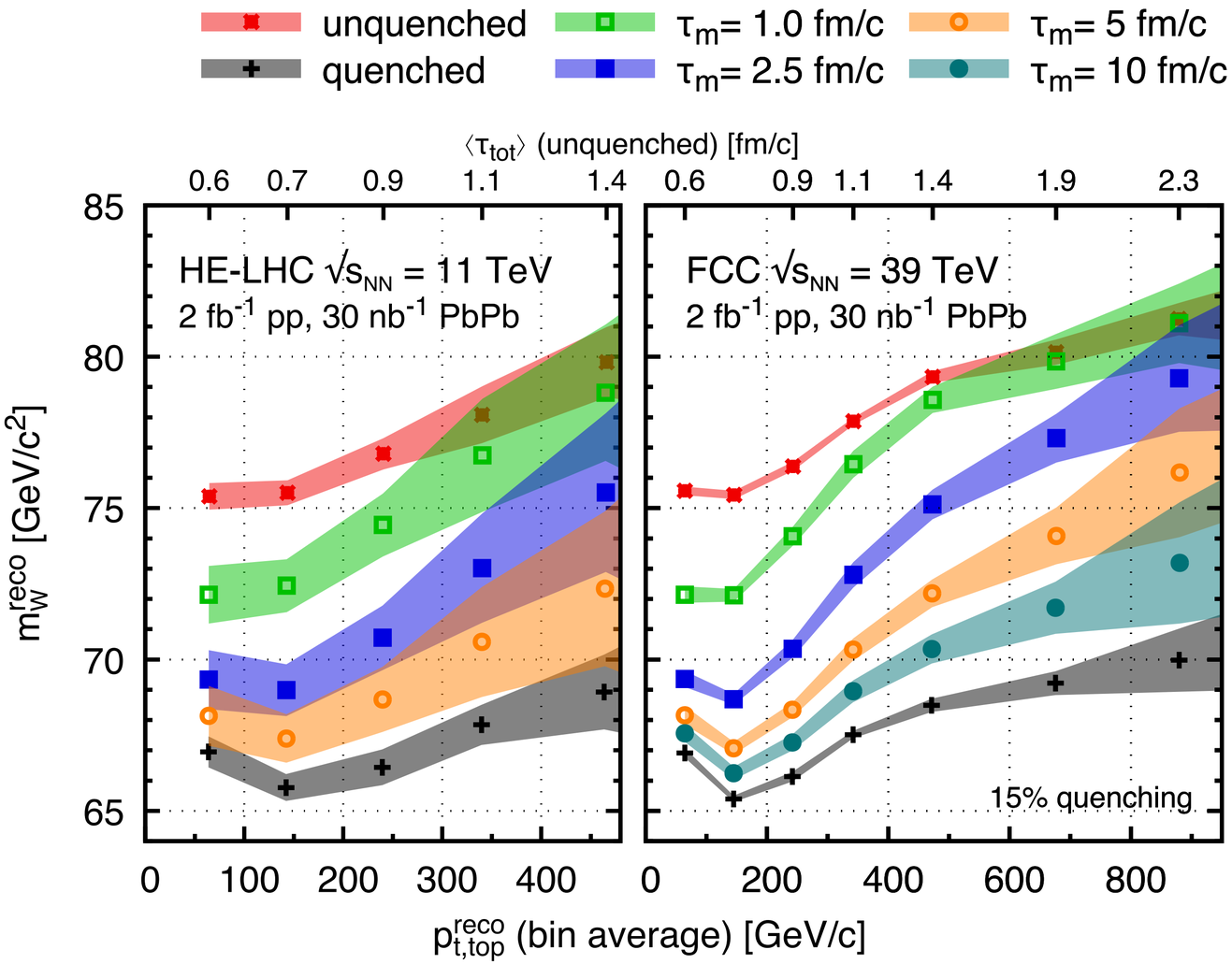
- Reconstructed W Mass as a function of the top p_T:
  - Useful probe of the QGP density evolution



Boosted Tops: QGP Tomography

Apolinário et al (18)

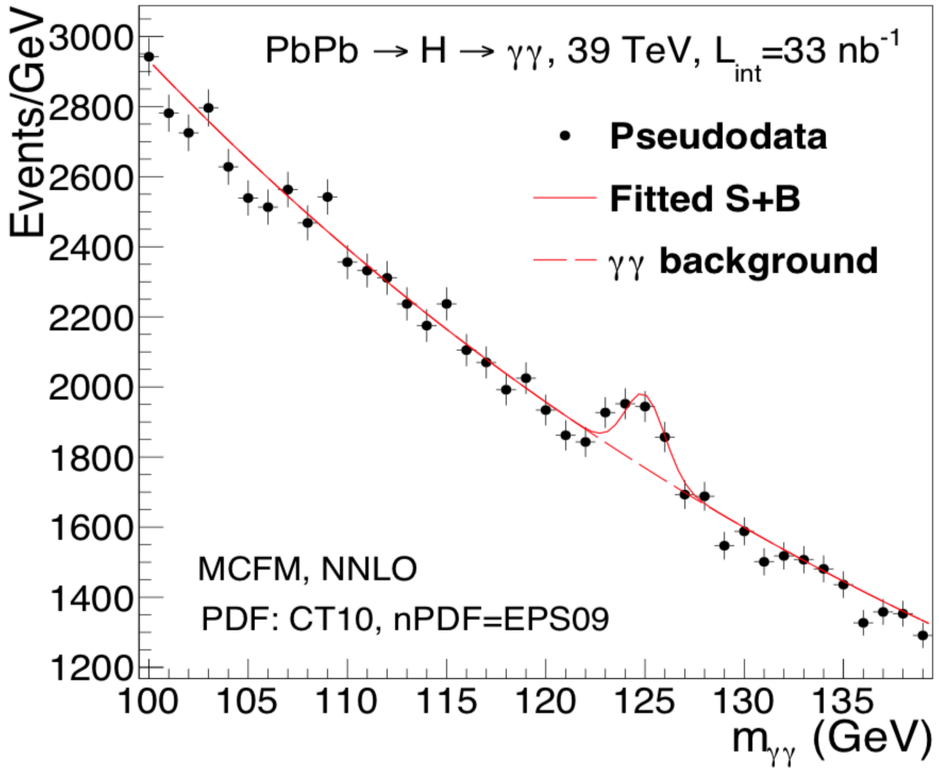
- Reconstructed W Mass as a function of the top p_T:
  - Useful probe of the QGP density evolution
- QGP tomography:
  - HE-LHC: Some discrimination between short vs long lived medium
  - ✓ FCC: able to scan entire QGP lifetime!



New Hard Probe: Higgs

d'Enterria et al (18), Ghiglieri et al (19)

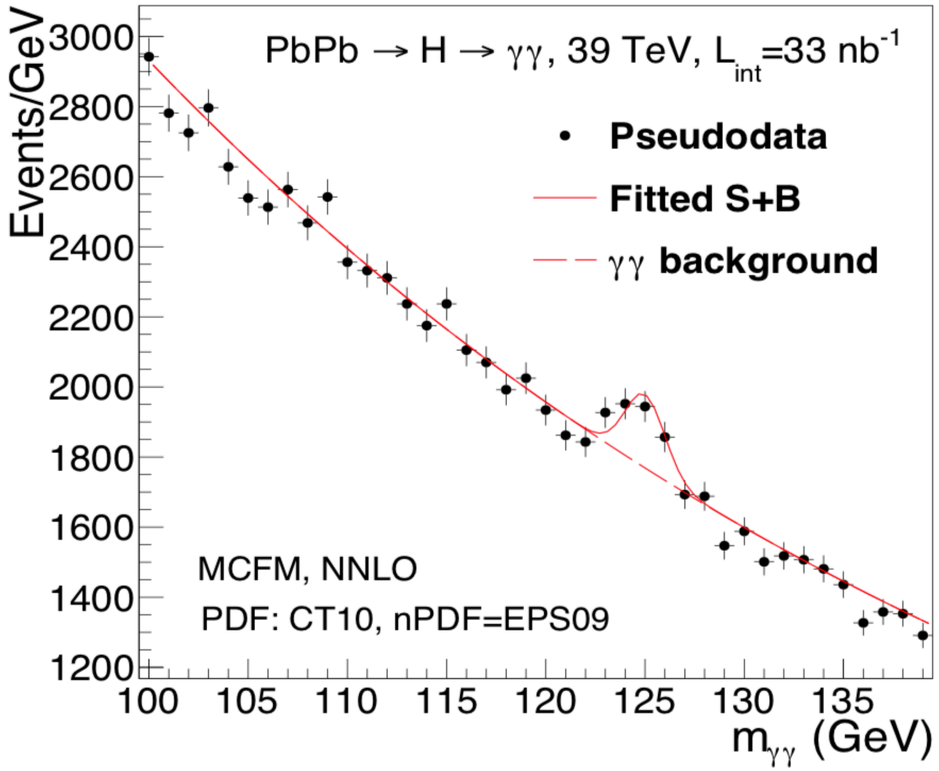
- Possible to measure Higgs→γγ with 5.5σ in one Pb-Pb month with baseline L_{int}



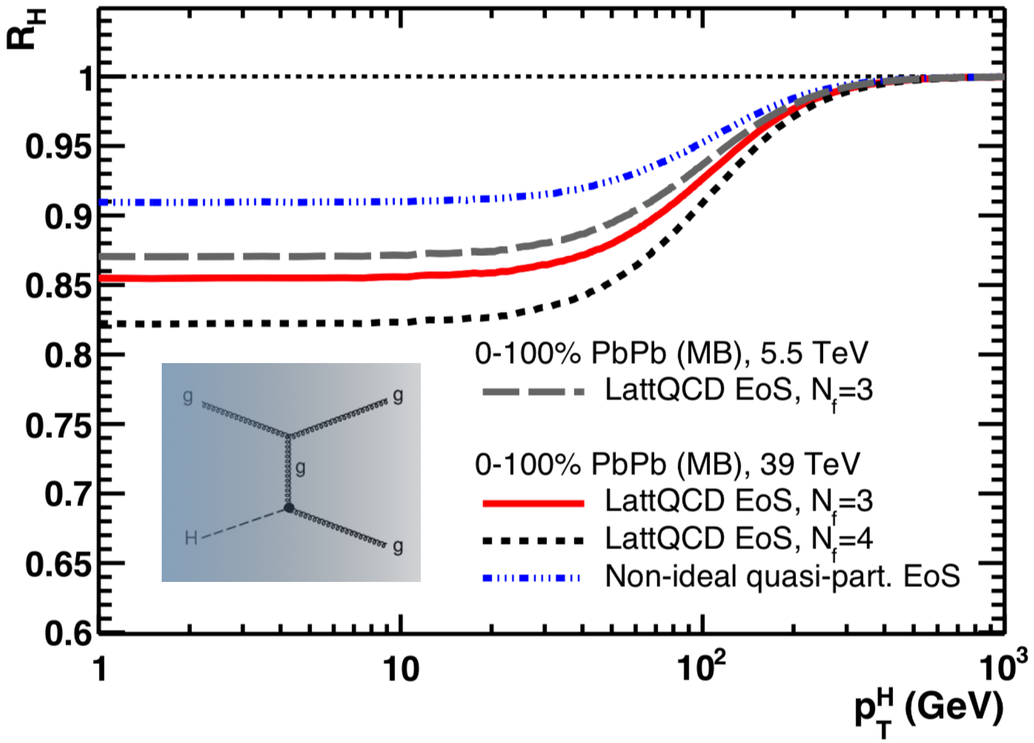
New Hard Probe: Higgs

d'Enterria et al (18), Ghiglieri et al (19)

- Possible to measure Higgs→γγ with 5.5σ in one Pb-Pb month with baseline L_{int}



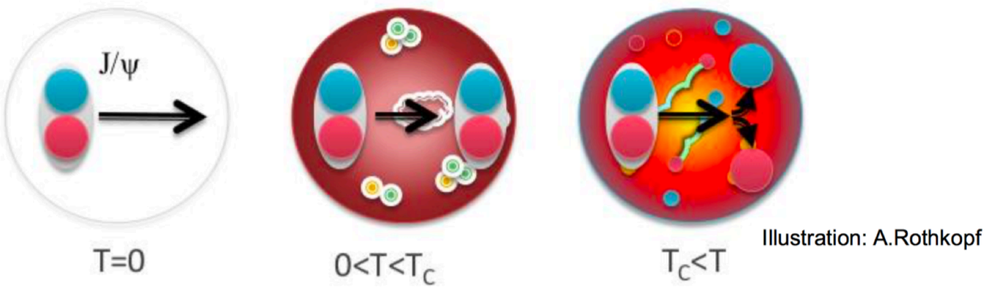
- Interaction with QGP will induce a decay to gg (reducing other boson decays) ⇒ Suppression of the Higgs yield

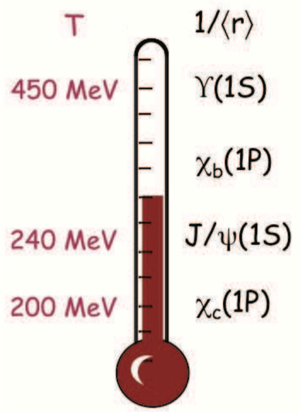


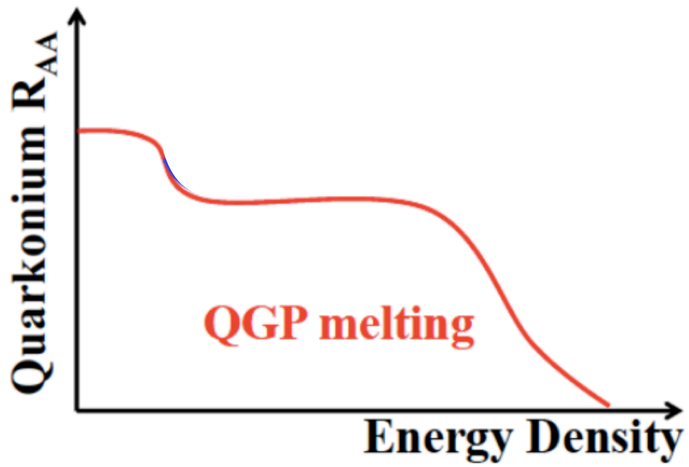
FCC: Higgs Suppression depends on EoS (but virtual corrections lead to a null impact in the Higgs hadronic width)

Quarkonia

- Quarkonia production in the presence of a medium:
  - Sequential melting can be used as a thermometer of the QGP!

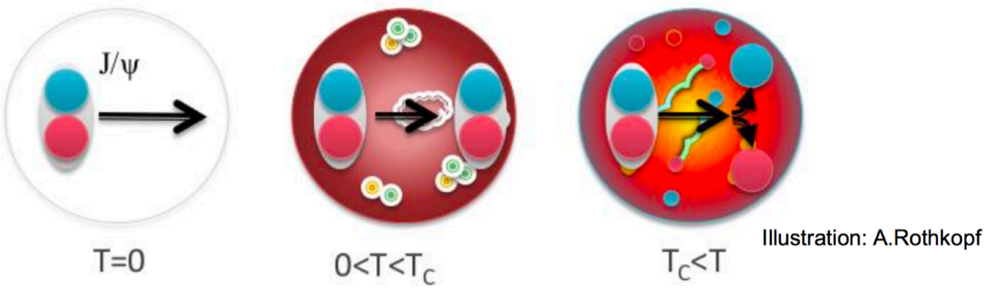


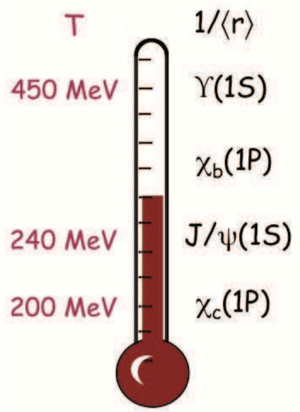




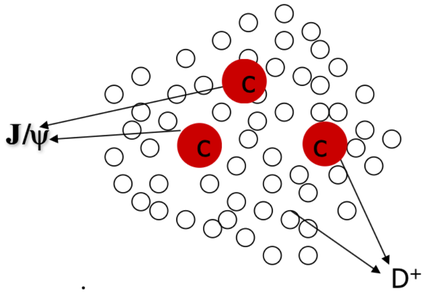
Quarkonia

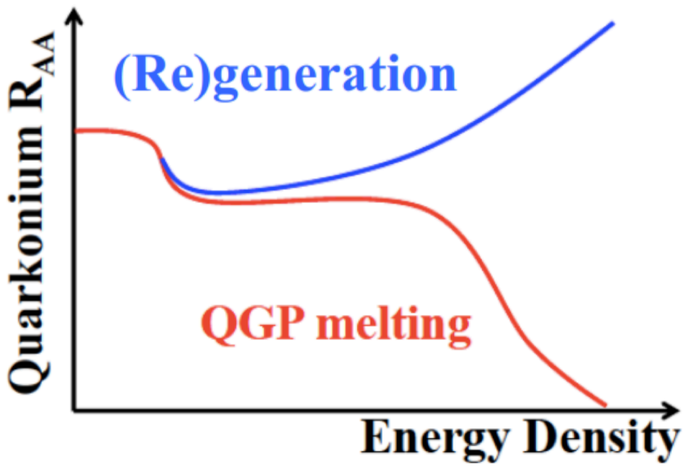
- Quarkonia production in the presence of a medium:
  - Sequential melting can be used as a thermometer of the QGP!





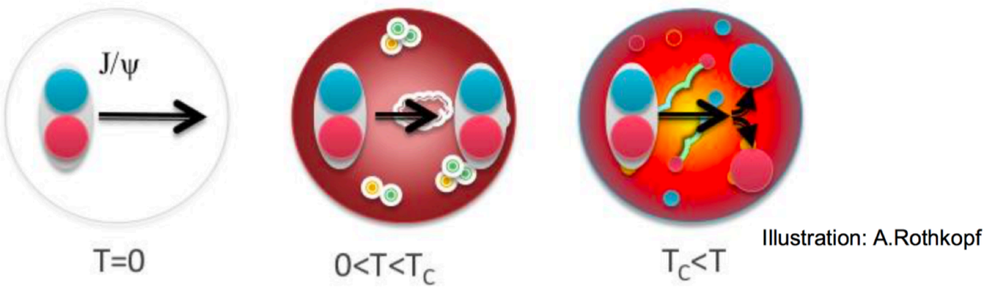
  - Final yield is a competition between QGP melting and regeneration with QGP thermal quarks

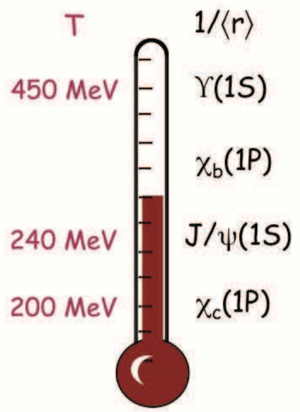




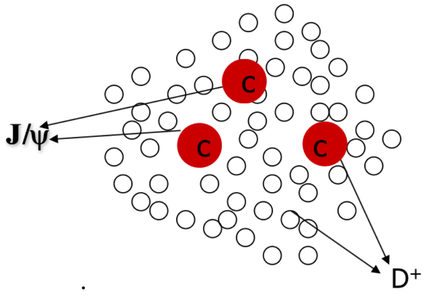
Quarkonia

- Quarkonia production in the presence of a medium:
  - Sequential melting can be used as a thermometer of the QGP!

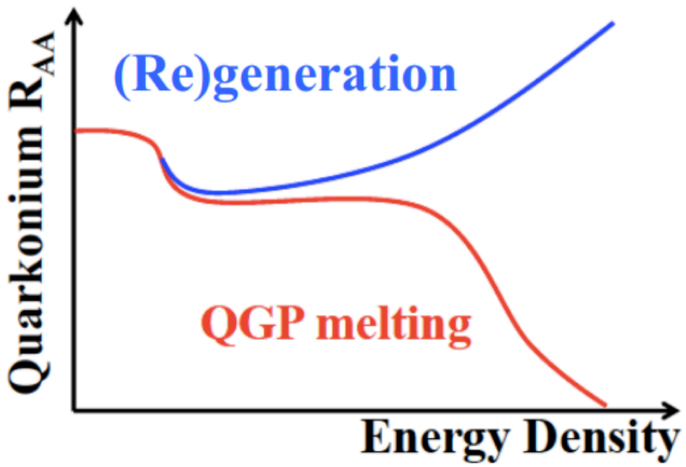




  - Final yield is a competition between QGP melting and regeneration with QGP thermal quarks



Expected changes at the FCC?

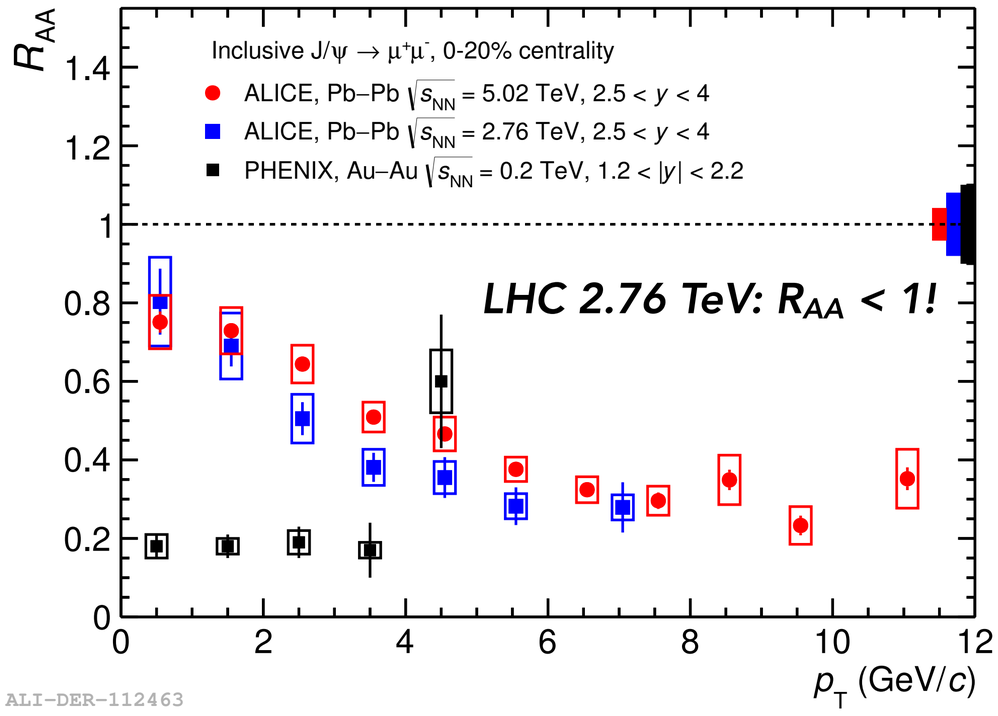


Quarkonia

Liu et al (09), Zhao et al (11), Andronic et al, 11

- J/ψ regeneration depends
  - QGP thermal cc production
  - Larger hard cross-section

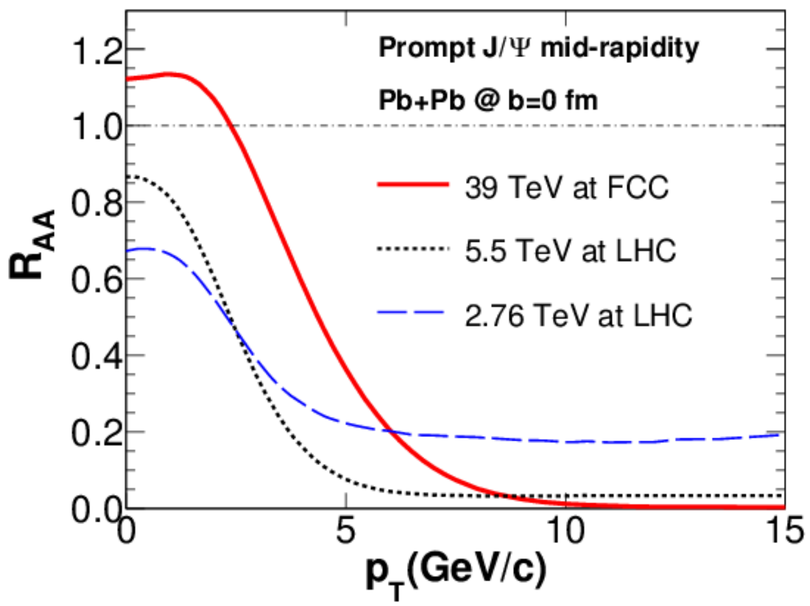
ALICE [1311.0214]



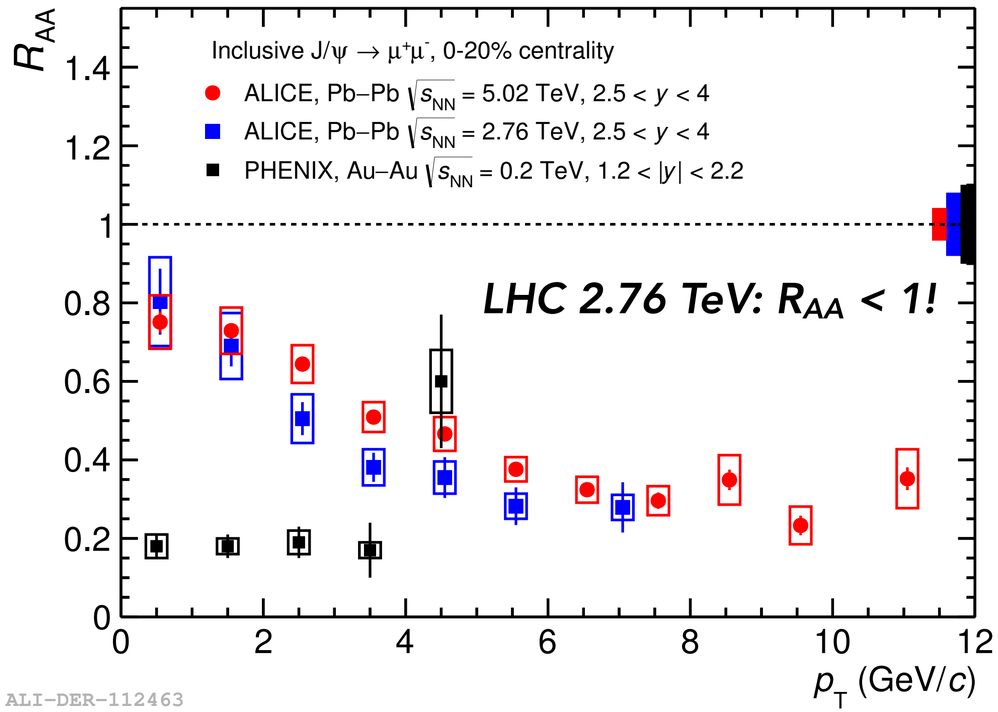
Quarkonia

Liu et al (09), Zhao et al (11), Andronic et al, 11

- J/ψ regeneration depends ***FCC***
  - QGP thermal cc production ***x1.5 w.r.t LHC***
  - Larger hard cross-section ***x2-2.5 w.r.t LHC***



ALICE [1311.0214]

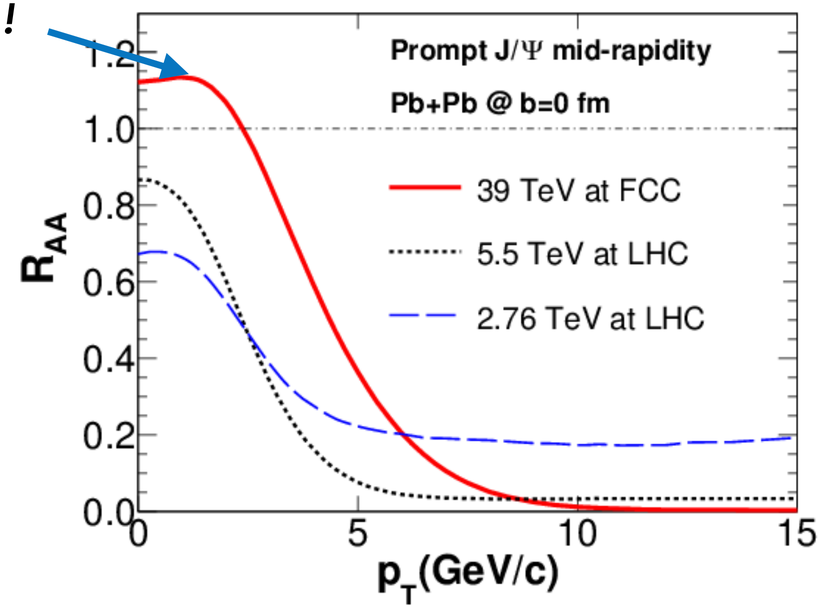


Quarkonia

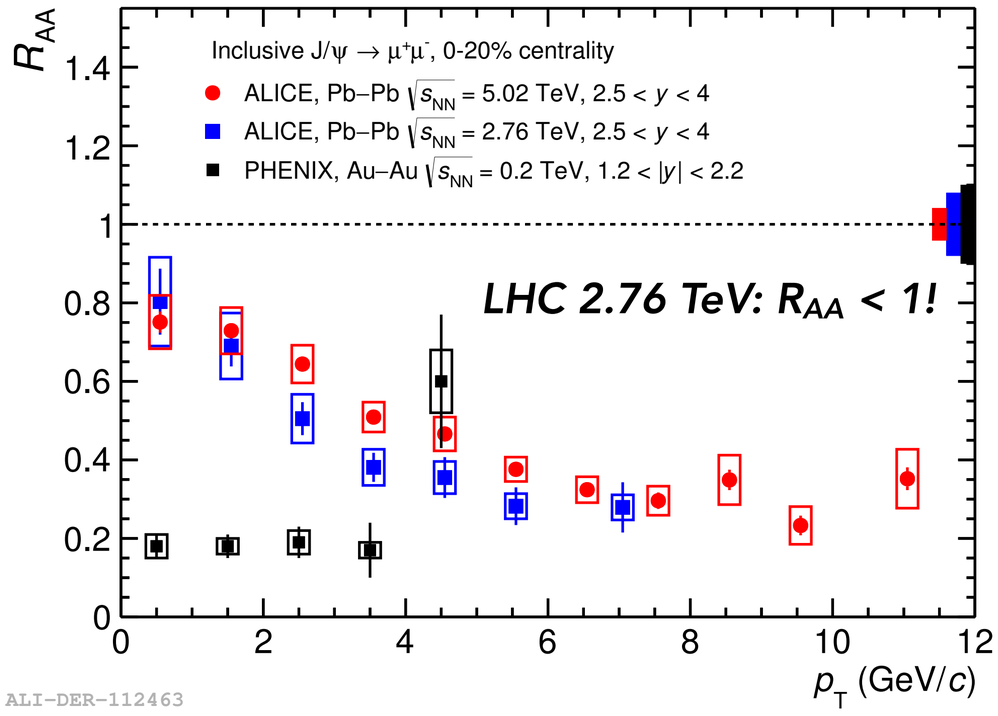
Liu et al (09), Zhao et al (11), Andronic et al, 11

- J/ψ regeneration depends ***FCC***
  - QGP thermal cc production ***x1.5 w.r.t LHC***
  - Larger hard cross-section ***x2-2.5 w.r.t LHC***

R_{AA} > 1!



ALICE [1311.0214]



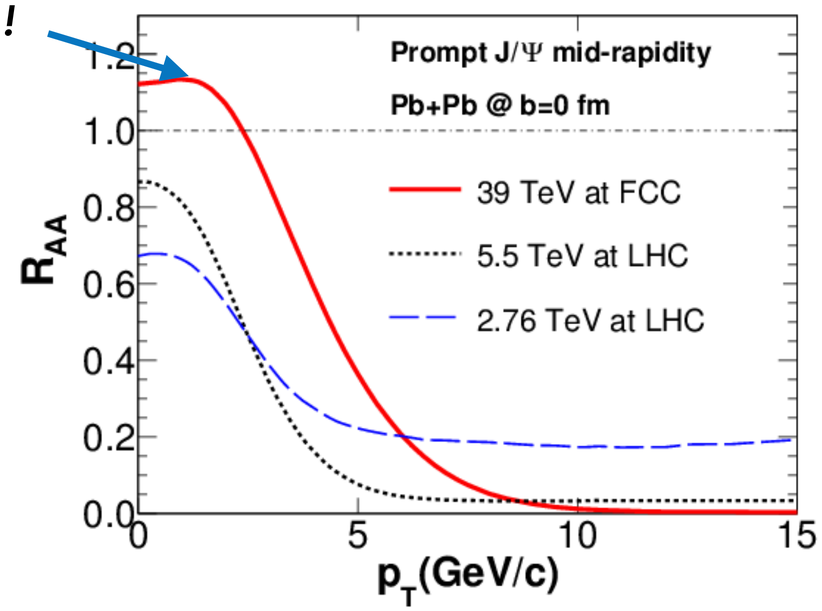
✓ FCC: Striking evidence of cc recombination

Quarkonia

Liu et al (09), Zhao et al (11), Andronic et al, 11

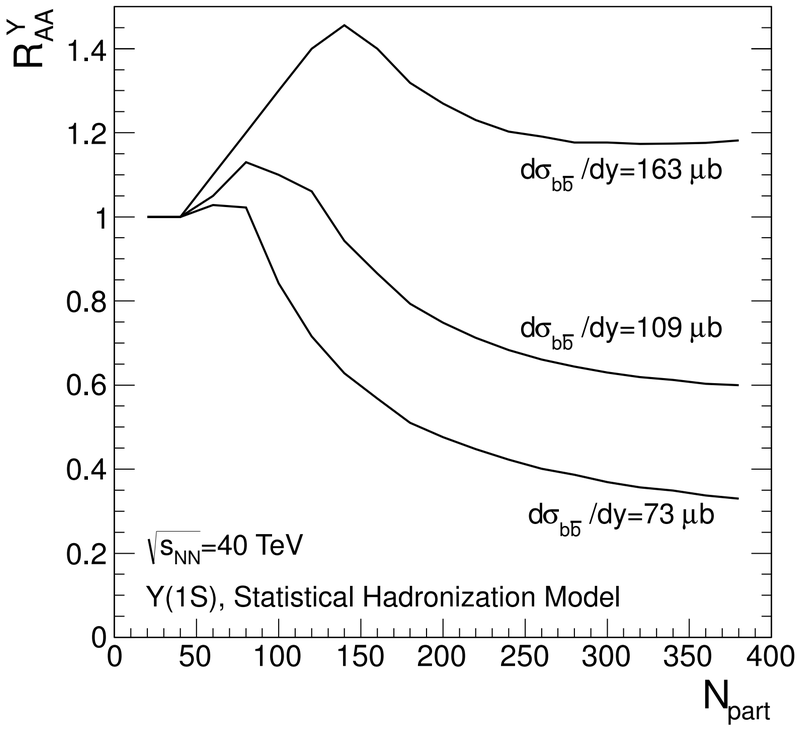
- J/ψ regeneration depends ***FCC***
  - QGP thermal cc production ***x1.5 w.r.t LHC***
  - Larger hard cross-section ***x2-2.5 w.r.t LHC***

R_{AA} > 1!



✓ FCC: Striking evidence of cc recombination

- ϒ(2S) ϒ(3S): partial/total suppression at LHC
- ϒ(1S): interplay between regeneration and melting provide a range of possibilities

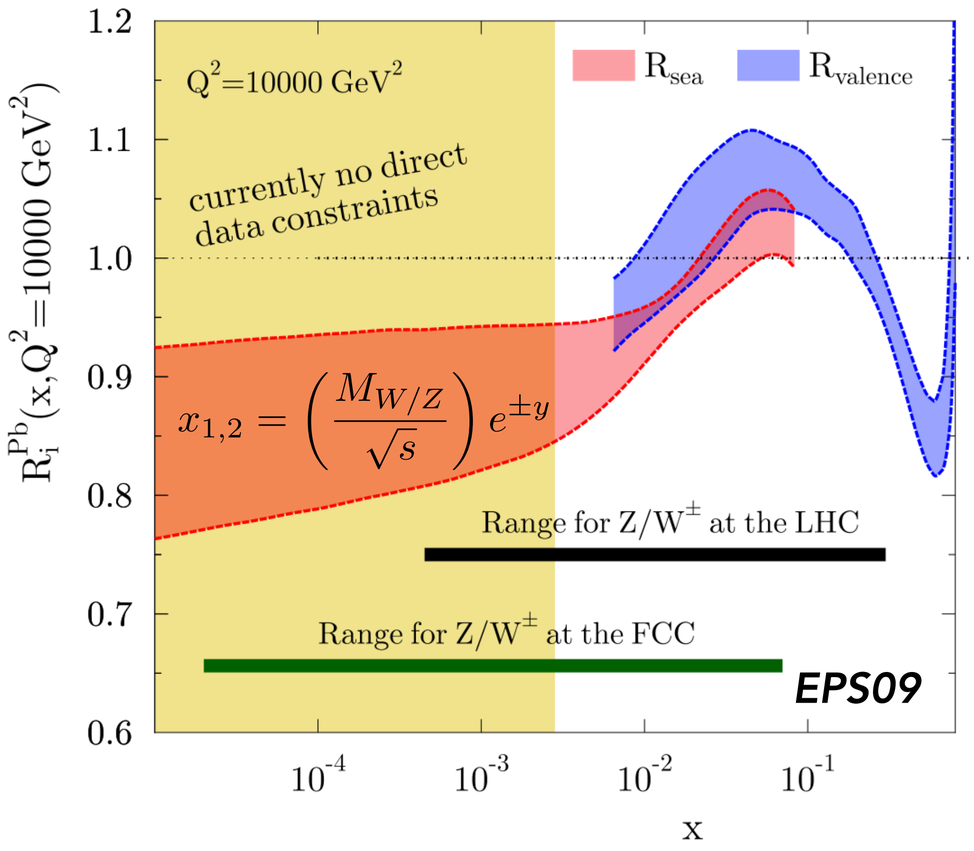



Initial State

Constraining Initial Conditions

d'Enterria et al (15)

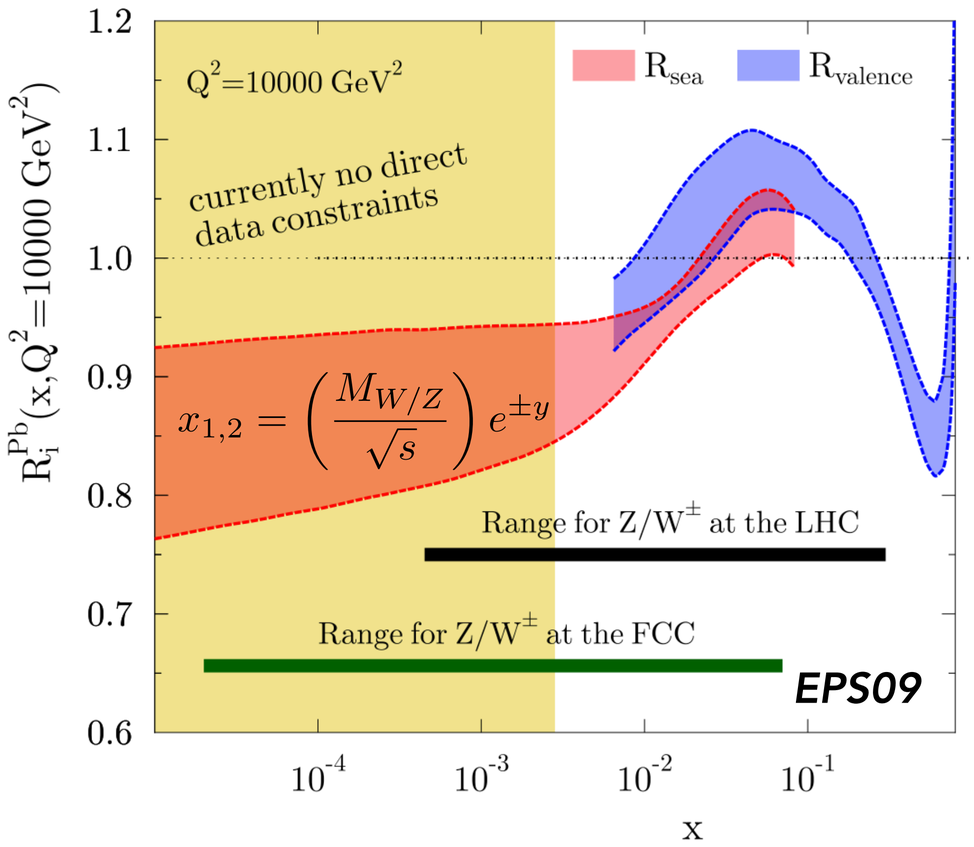
- Extraction of QGP properties highly dependent on initial conditions
  - Need a precise determination of nuclear PDFs!



Constraining Initial Conditions

d'Enterria et al (15)

- Extraction of QGP properties highly dependent on initial conditions
  - Need a precise determination of nuclear PDFs!

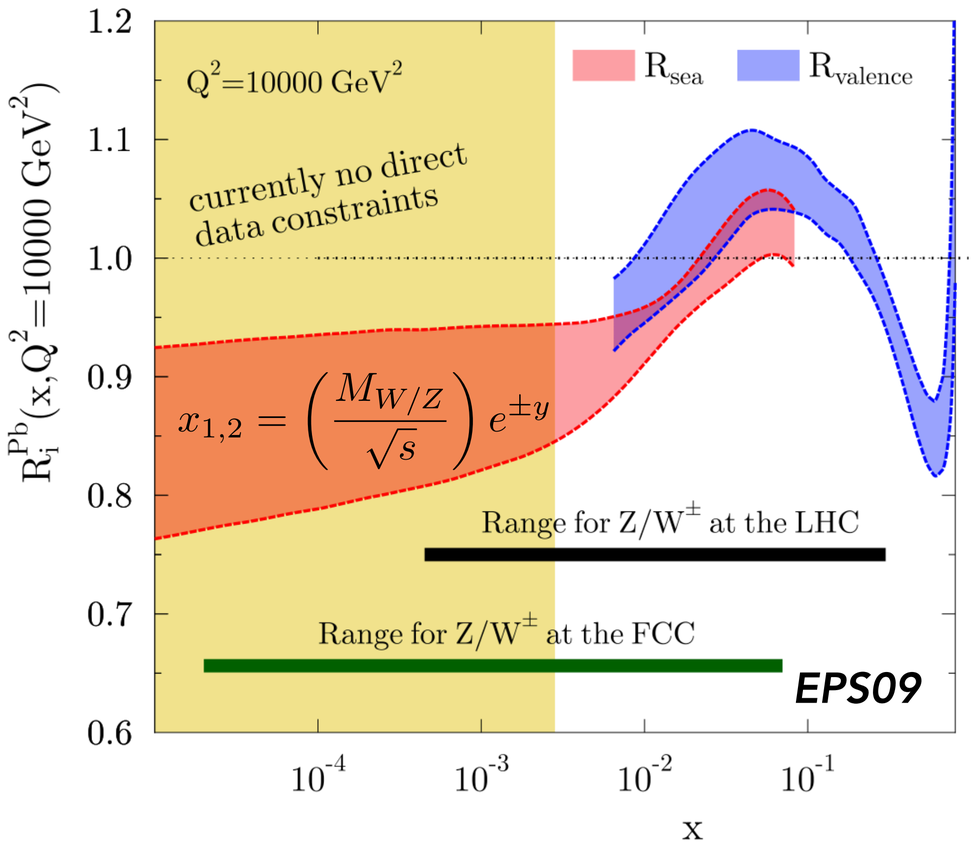


✓ FCC: Small-x reach 10x larger than LHC with bosons

Constraining Initial Conditions

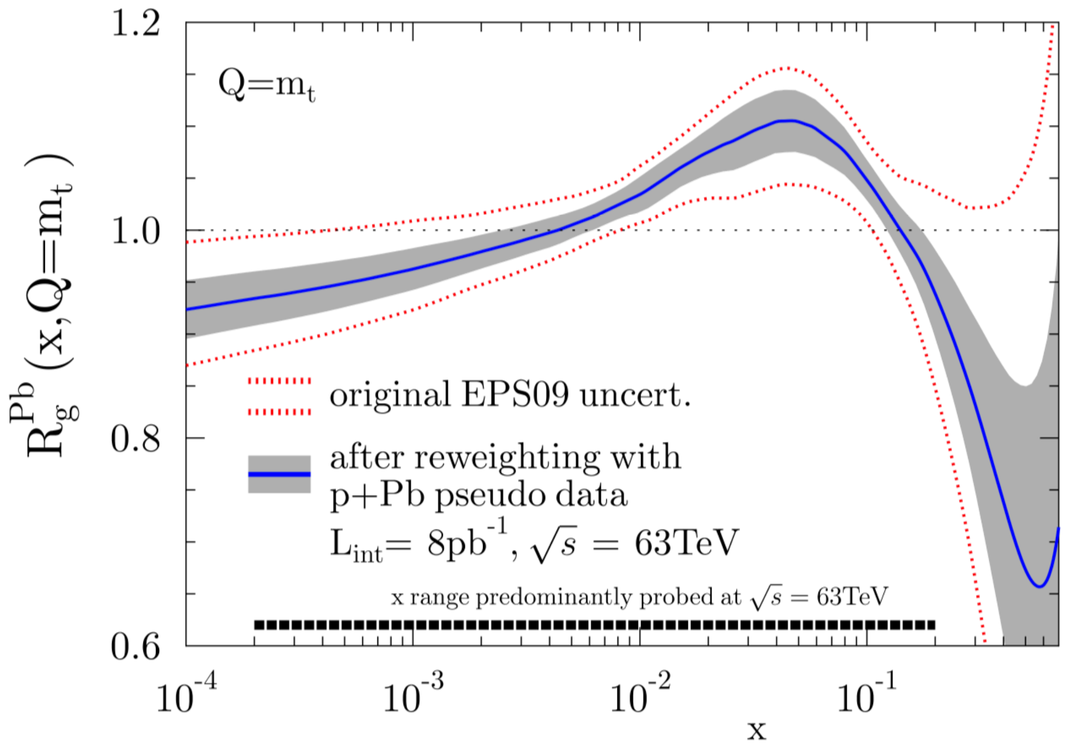
d'Enterria et al (15)

- Extraction of QGP properties highly dependent on initial conditions
  - Need a precise determination of nuclear PDFs!

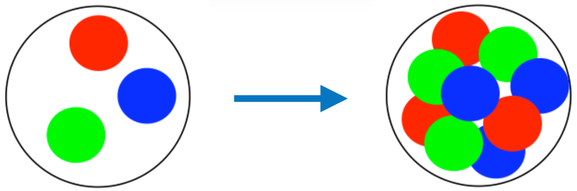


✓ FCC: Small-x reach 10x larger than LHC with bosons

✓ FCC: As in pp, top quarks can be used to reduce nPDF uncertainties (x2)



Small-x & Saturation



- Non-linear phenomena to tame the growth of parton densities
  - Onset of saturation:

Transverse area — *Number of gluons*

$$\pi R_A^2 \sim \frac{Axg(x, Q_s^2)}{Q_s^2} \Rightarrow Q_s^2 \sim A^{1/3}(\sqrt{s_{NN}})^{0.3} e^{0.3y}$$

gluon size ~ 1/Q_s^2

Increase √s, y and/or A

- Collinear factorization: non-linear effects absorbed by nuclear PDFs

$$d\sigma_{(\mathrm{med})}^{AA\to h+\mathrm{rest}} = \sum_{ijk} f_{i/A}(x_1, Q^2) \otimes f_{j/A}(x_2, Q^2) \otimes \hat{\sigma}_{ij\to f+k} \otimes D_{f\to h}^{(\mathrm{med})}(z, \mu_F^2)\,.$$

Expected to break if gluon phase space becomes saturated

Small-x & Saturation

- Non-linear phenomena to tame the growth of parton densities
  - Onset of saturation:

Transverse area — *Number of gluons*

$$\pi R_A^2 \sim \frac{Axg(x,Q_s^2)}{Q_s^2} \Rightarrow Q_s^2 \sim A^{1/3}(\sqrt{s_{NN}})^{0.3}e^{0.3y}$$

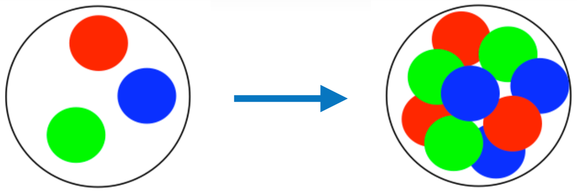
gluon size ~ 1/Q_s^2

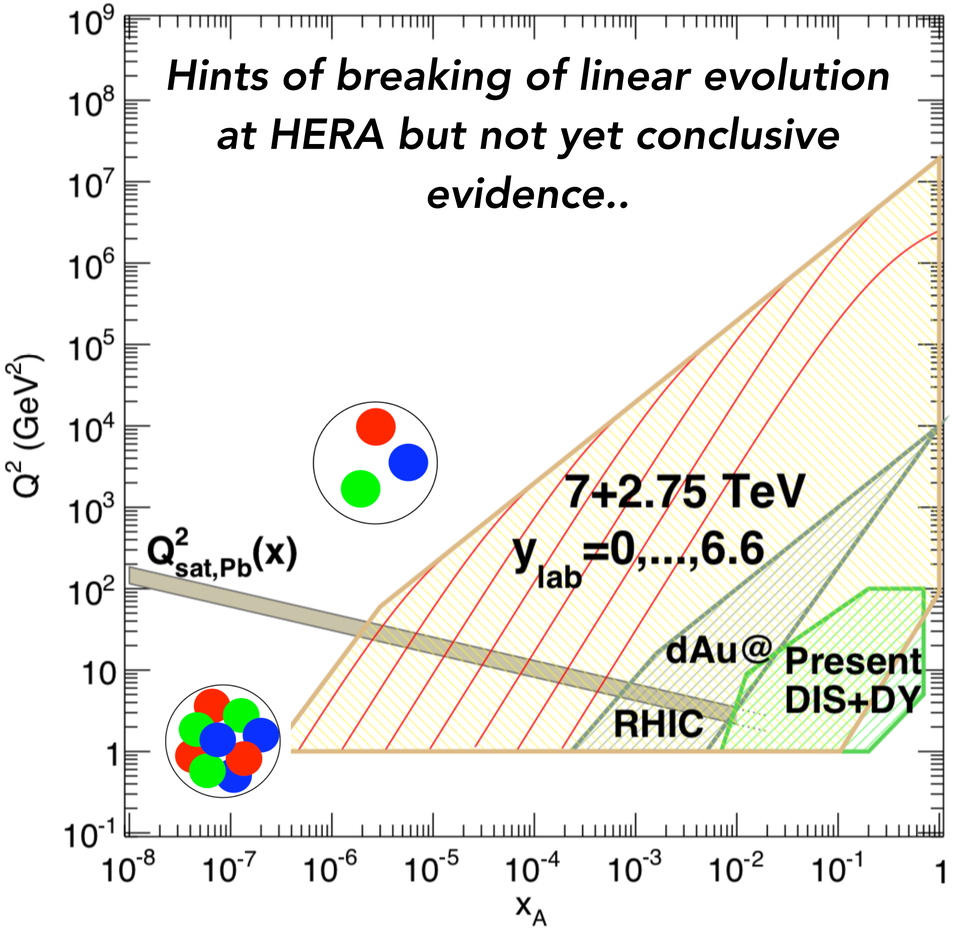
Increase √s, y and/or A

- Collinear factorization: non-linear effects absorbed by nuclear PDFs

$$d\sigma_{(\mathrm{med})}^{AA\to h+\mathrm{rest}} = \sum_{ijk} f_{i/A}(x_1,Q^2)\otimes f_{j/A}(x_2,Q^2)\otimes \hat{\sigma}_{ij\to f+k}\otimes D_{f\to h}^{(\mathrm{med})}(z,\mu_F^2)\,.$$

Expected to break if gluon phase space becomes saturated





Small-x & Saturation

- Non-linear phenomena to tame the growth of parton densities
  - Onset of saturation:

Transverse area — *Number of gluons*

$$\pi R_A^2 \sim \frac{Axg(x,Q_s^2)}{Q_s^2} \Rightarrow Q_s^2 \sim A^{1/3}(\sqrt{s_{NN}})^{0.3}e^{0.3y}$$

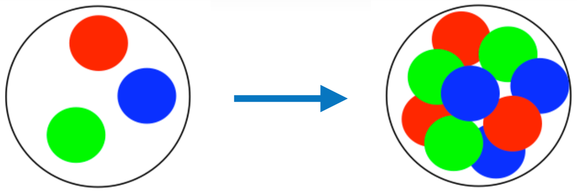
gluon size ~ 1/Q_s^2

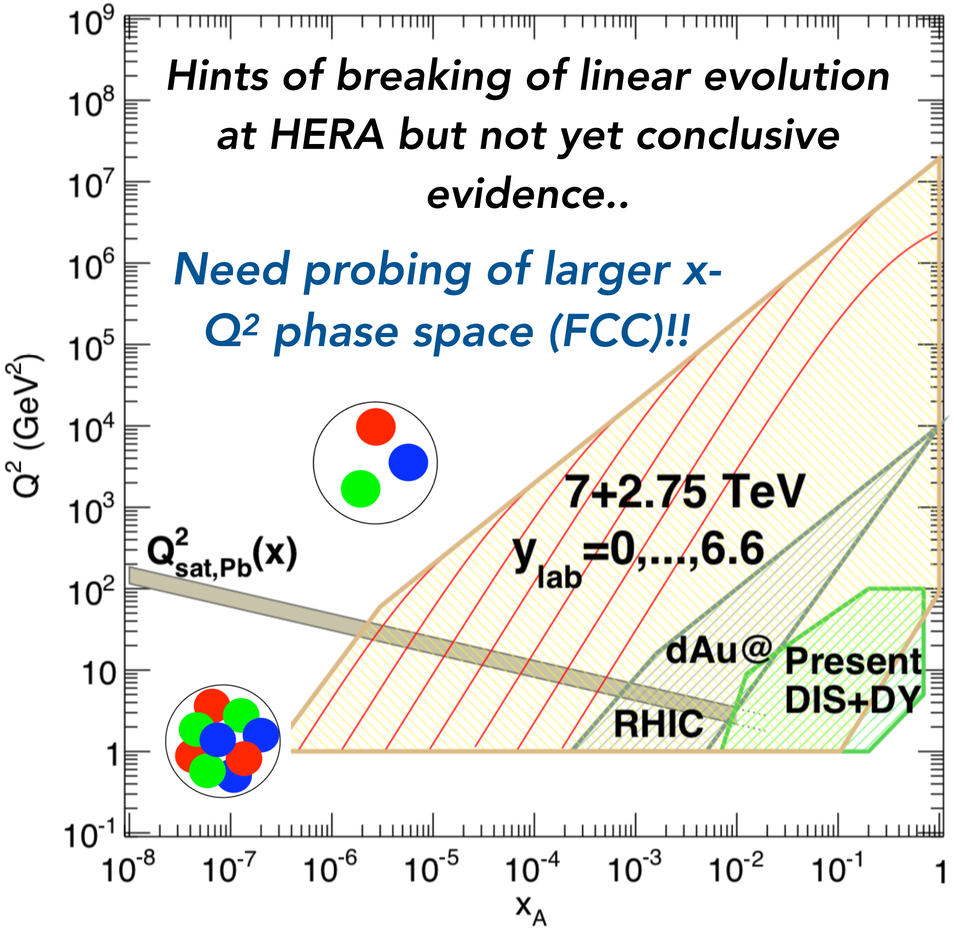
Increase √s, y and/or A

- Collinear factorization: non-linear effects absorbed by nuclear PDFs

$$d\sigma^{AA\to h+\mathrm{rest}}_{(\mathrm{med})} = \sum_{ijk} f_{i/A}(x_1,Q^2)\otimes f_{j/A}(x_2,Q^2)\otimes \hat{\sigma}_{ij\to f+k}\otimes D^{(\mathrm{med})}_{f\to h}(z,\mu_F^2)\,.$$

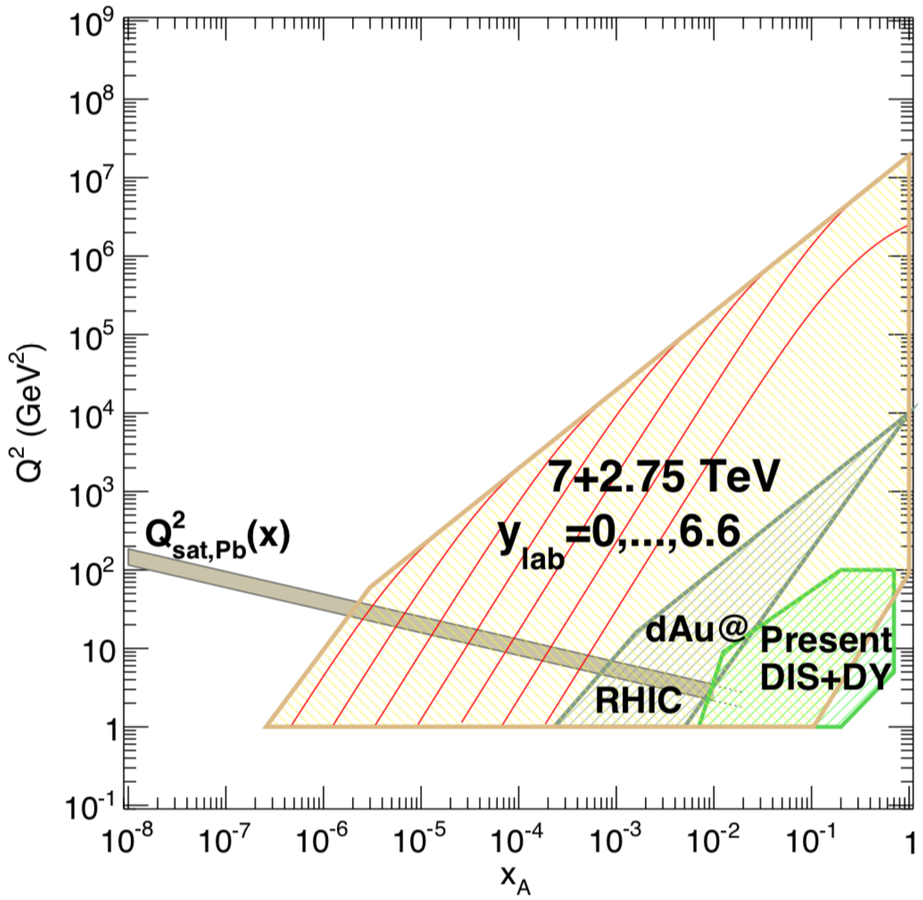
Expected to break if gluon phase space becomes saturated





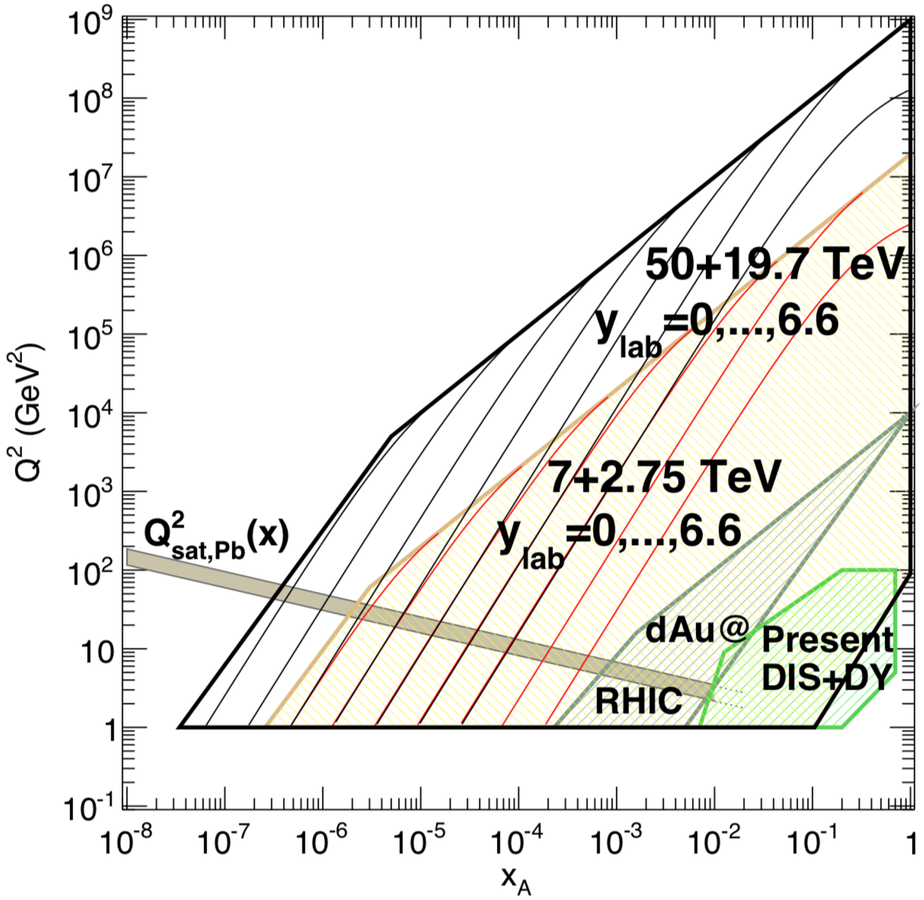
Color Glass Condensate @ FCC

- x-Q^2 phase space accessible at FCC:



Color Glass Condensate @ FCC

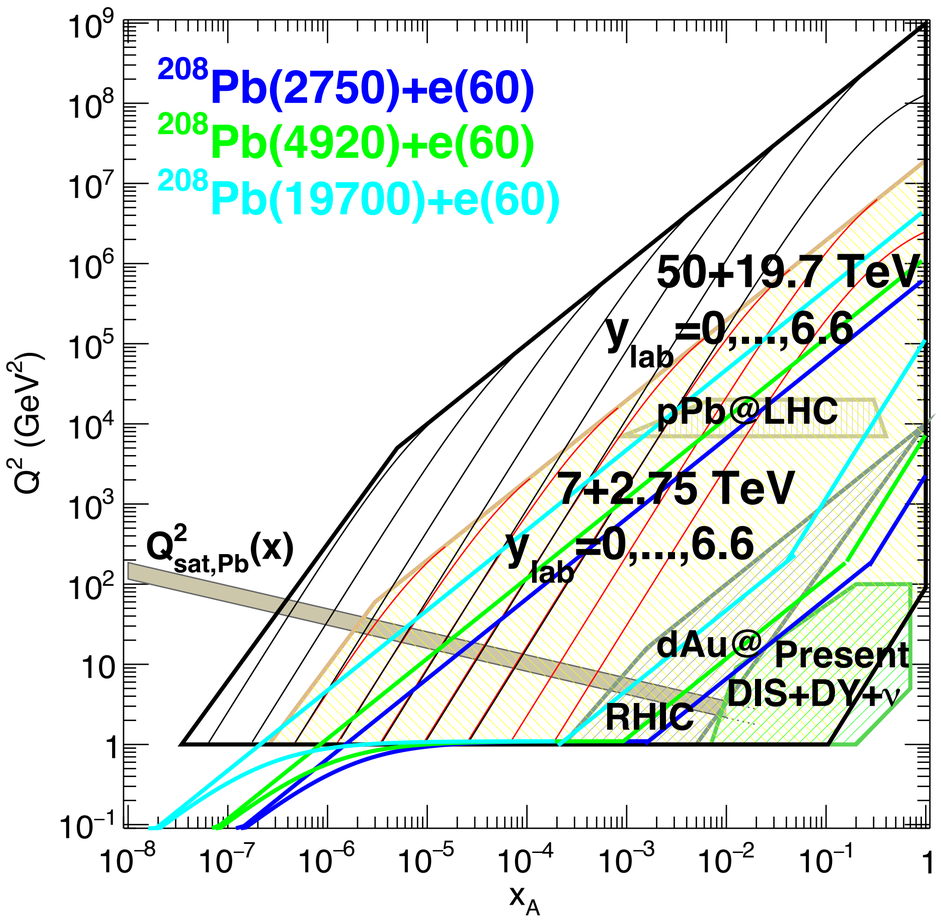
- x-Q^2 phase space accessible at FCC:



✓ FCC able to probe saturation at mid-rapidity

Color Glass Condensate @ FCC

- x-Q^2 phase space accessible at FCC:



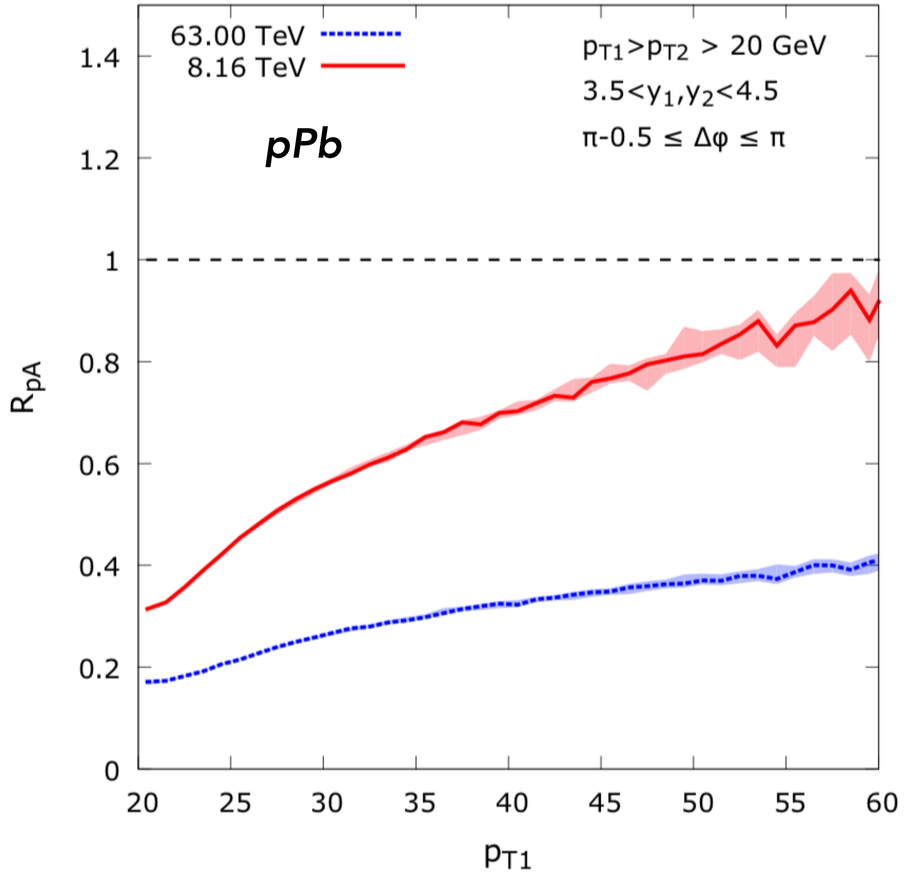
✓ FCC able to probe saturation at mid-rapidity

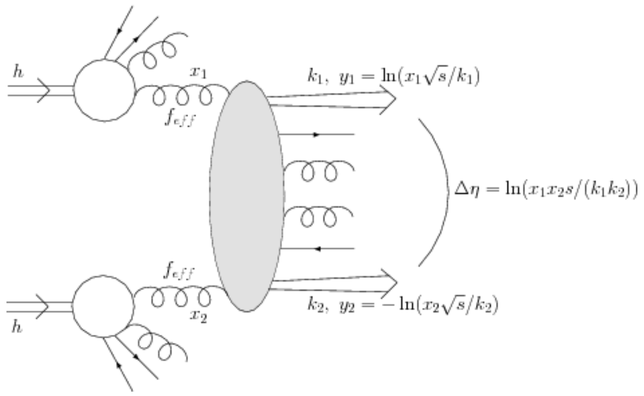
✓ Complementary eA/pA: precise knowledge on partonic structures at small-x (kinematics fully constrained)

Color Glass Condensate @ FCC

A. van Hameren et al (14), Rezaeian (12)

- Where can we see saturation phenomena?
  - Dijets at forward rapidity;

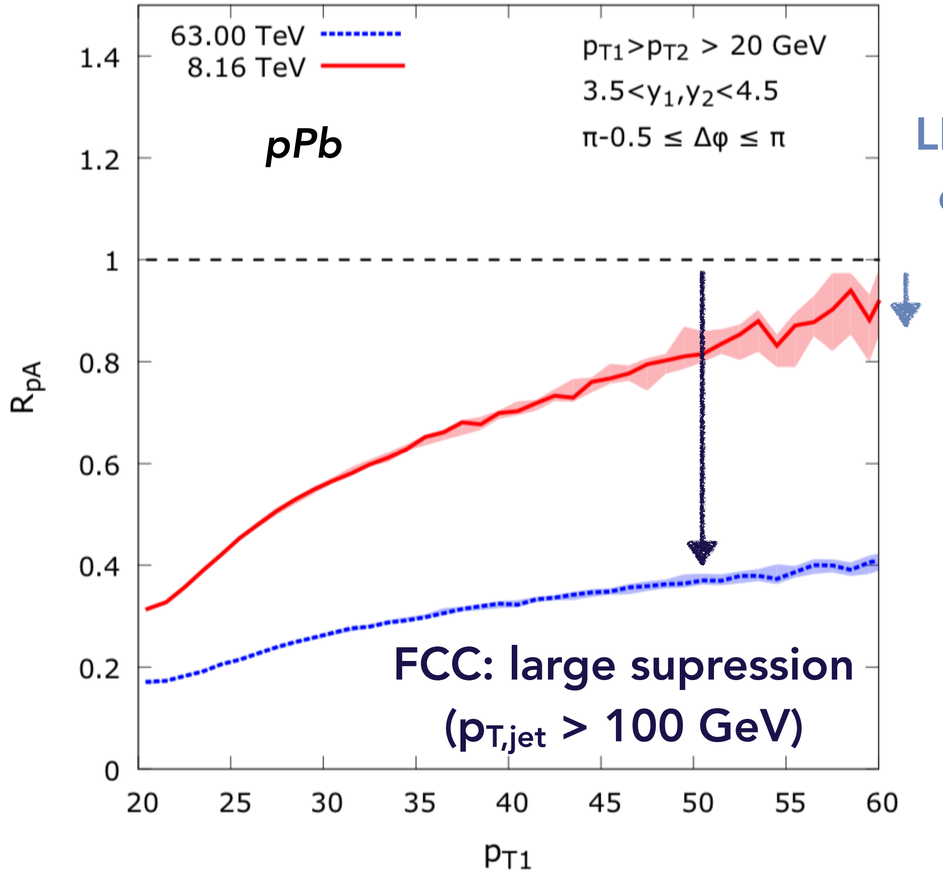




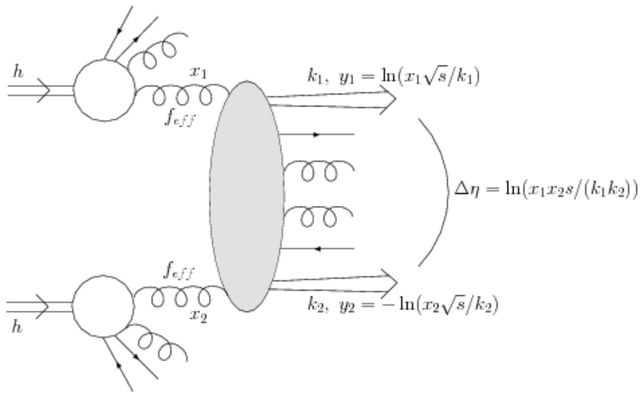
Color Glass Condensate @ FCC

A. van Hameren et al (14), Rezaeian (12)

- Where can we see saturation phenomena?
  - Dijets at forward rapidity;



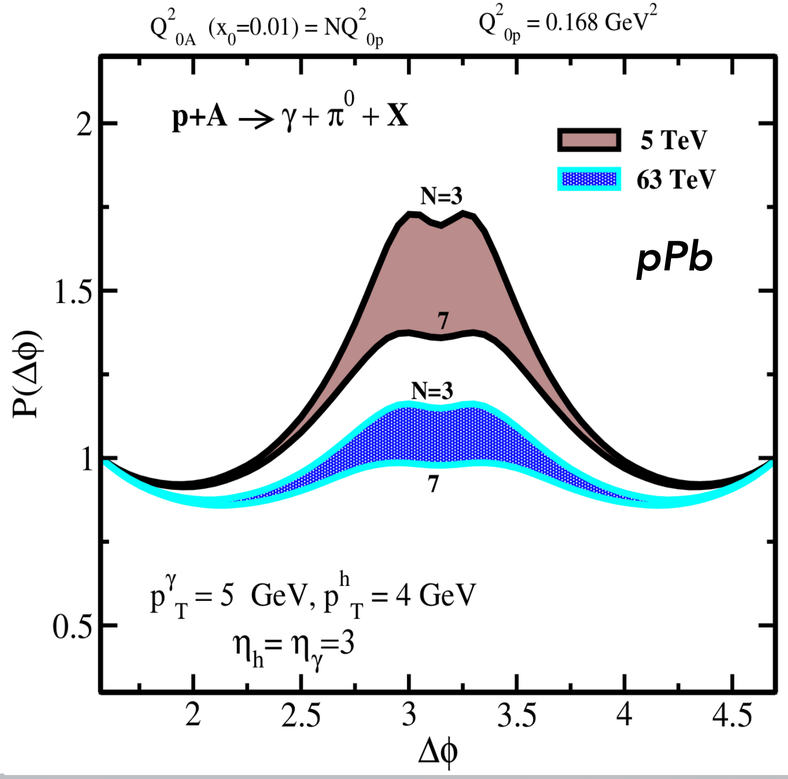
LHC: no effect

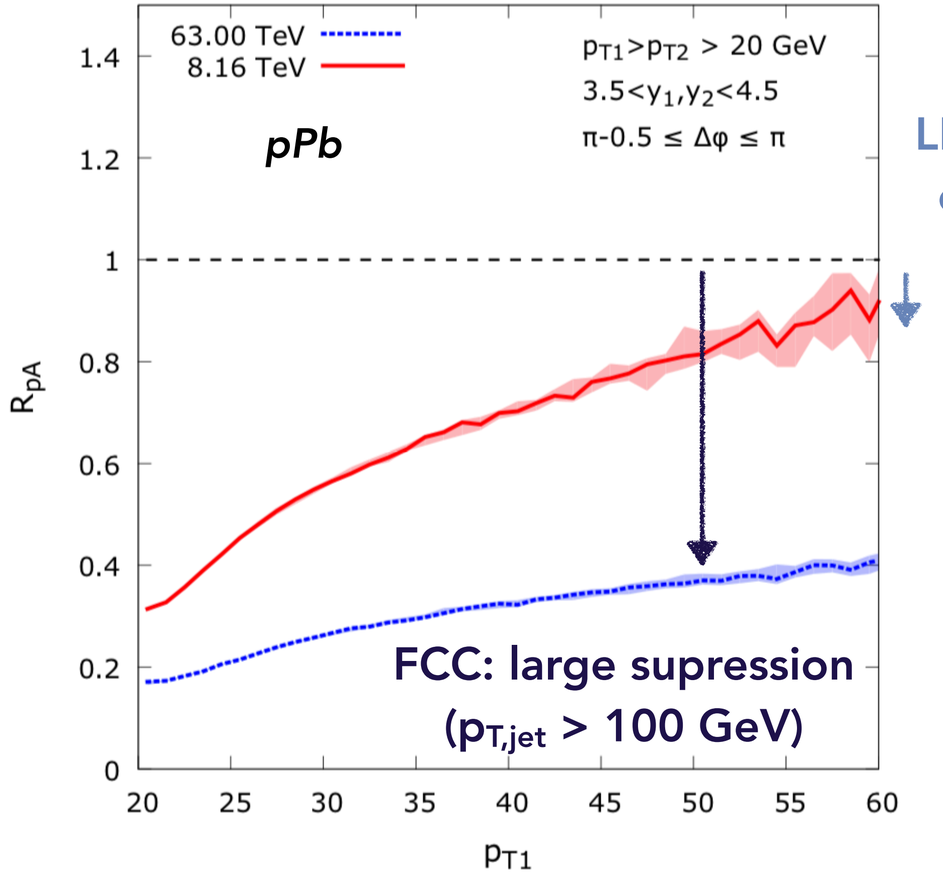


Color Glass Condensate @ FCC

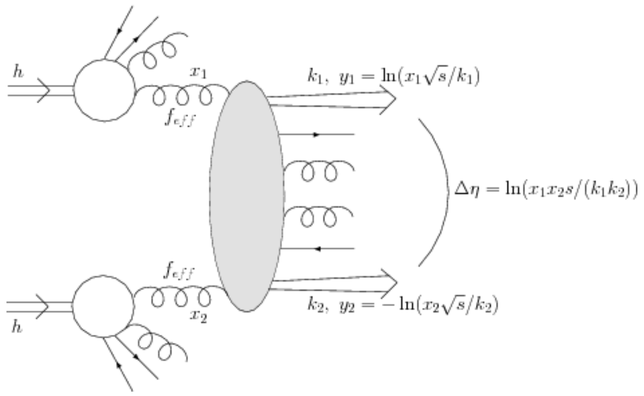
A. van Hameren et al (14), Rezaeian (12)

- Where can we see saturation phenomena?
  - Dijets at forward rapidity;
  - Recoil from direct photon;





LHC: no effect

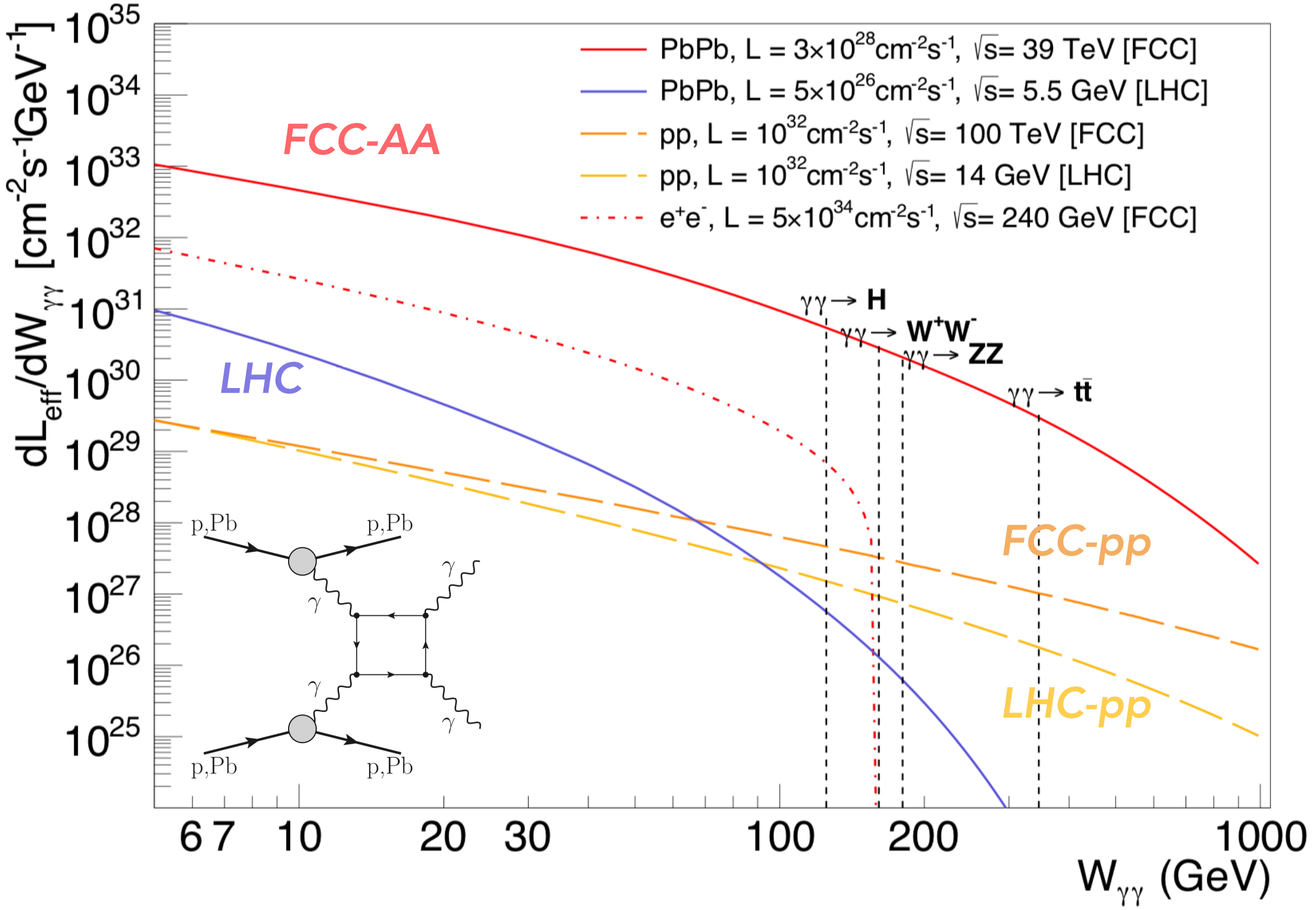


Other Sectors of High-Energy Physics

γ-γ Collisions

d'Enterria et al (17) Knapen et al (17)

- Effective γγ luminosity:

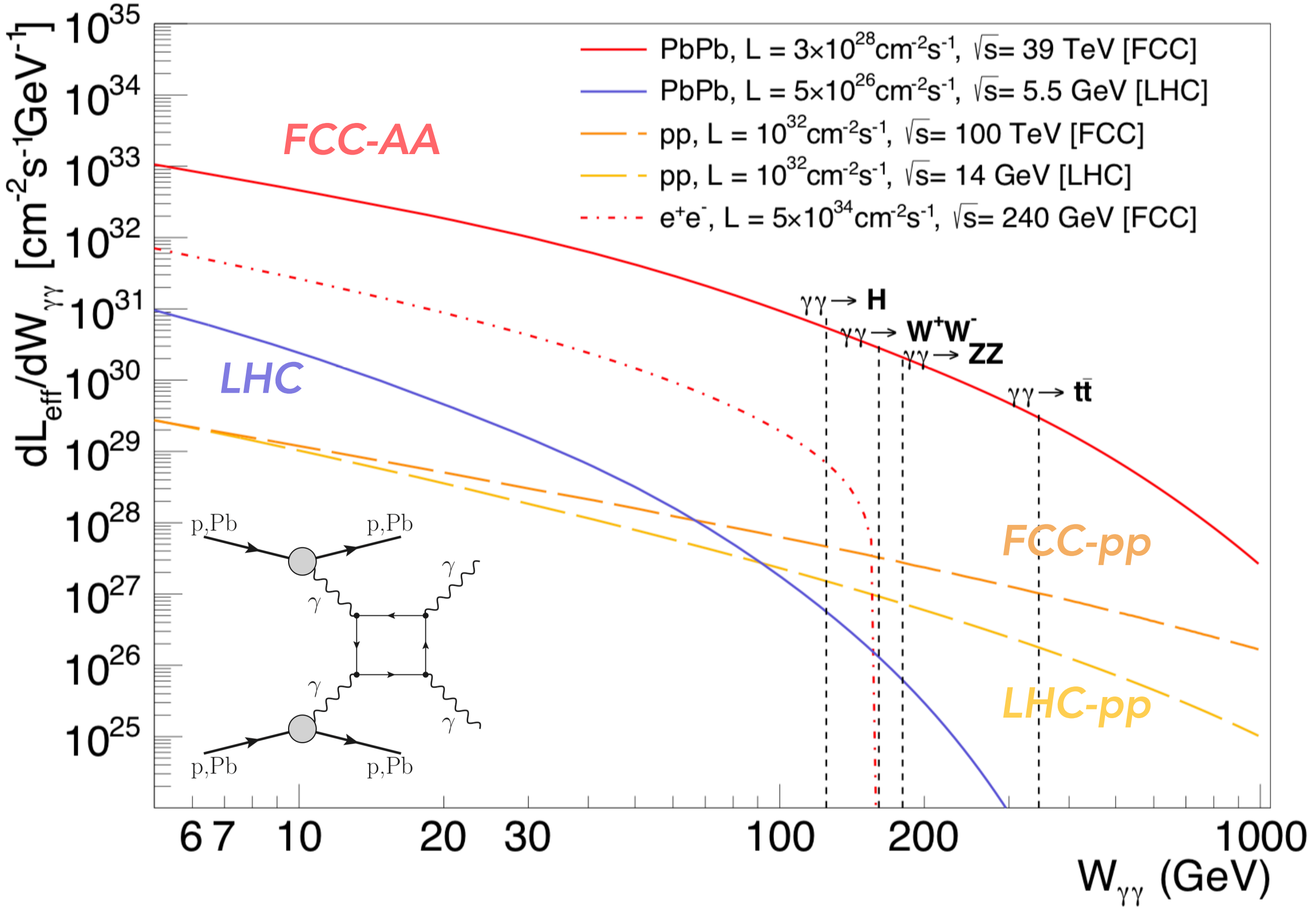


✓ FCC-AA: largest γγ luminosity!

γ-γ Collisions

d'Enterria et al (17) Knapen et al (17)

- Effective γγ luminosity:



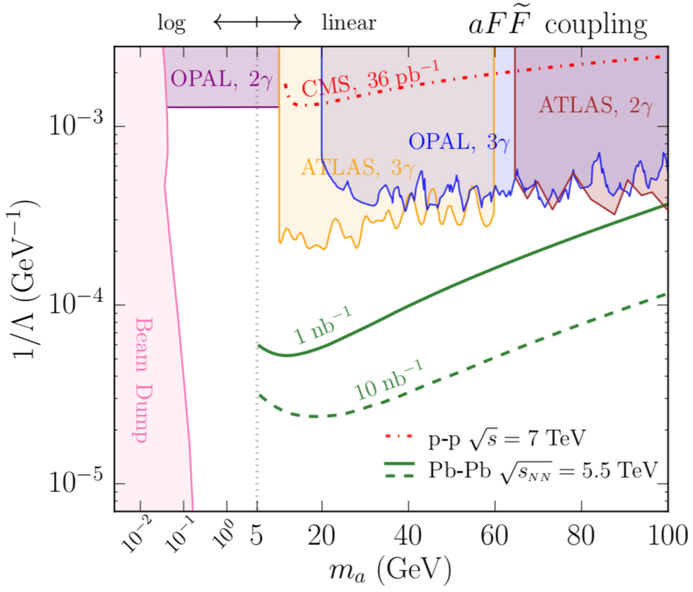
✓ FCC-AA: largest γγ luminosity!

- Light-by-light scattering measurement at FCC:

✓ Sensitivity to BSM physics (e.g: new heavy-charged SYSY particles)

✓ Axion-like particles

✓ …



Summary

Summary

- FCC-hh study aimed to assess physics potential at a:
  - $\sqrt{s}$ 7 x larger than nominal LHC energies; L_{int} projections >100 x LHC programme;
- FCC offers the possibility for an accurate determination of the QCD behaviour at large densities and temperatures:
  - Addressing current **open questions**:
    - Collectivity in small systems, Determination of saturation effects,…
  - **Unique physics opportunities**:
    - Soft probes sector: e.g: thermal charm production
    - Hard probes sector: e.g: top and Higgs to probe the QGP
    - Initial state sector: e.g: nPDFs up to a small-x reach

Summary

- FCC-hh study aimed to assess physics potential at a:
  - $\sqrt{s}$ 7 x larger than nominal LHC energies; L_{int} projections >100 x LHC programme;
- FCC offers the possibility for an accurate determination of the QCD behaviour at large densities and temperatures:
  - Addressing current **open questions**:
    - Collectivity in small systems, Determination of saturation effects,…
  - **Unique physics opportunities**:
    - Soft probes sector: e.g: thermal charm production
    - Hard probes sector: e.g: top and Higgs to probe the QGP
    - Initial state sector: e.g: nPDFs up to a small-x reach

Thank you!

Acknowledgments

REPÚBLICA PORTUGUESA

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

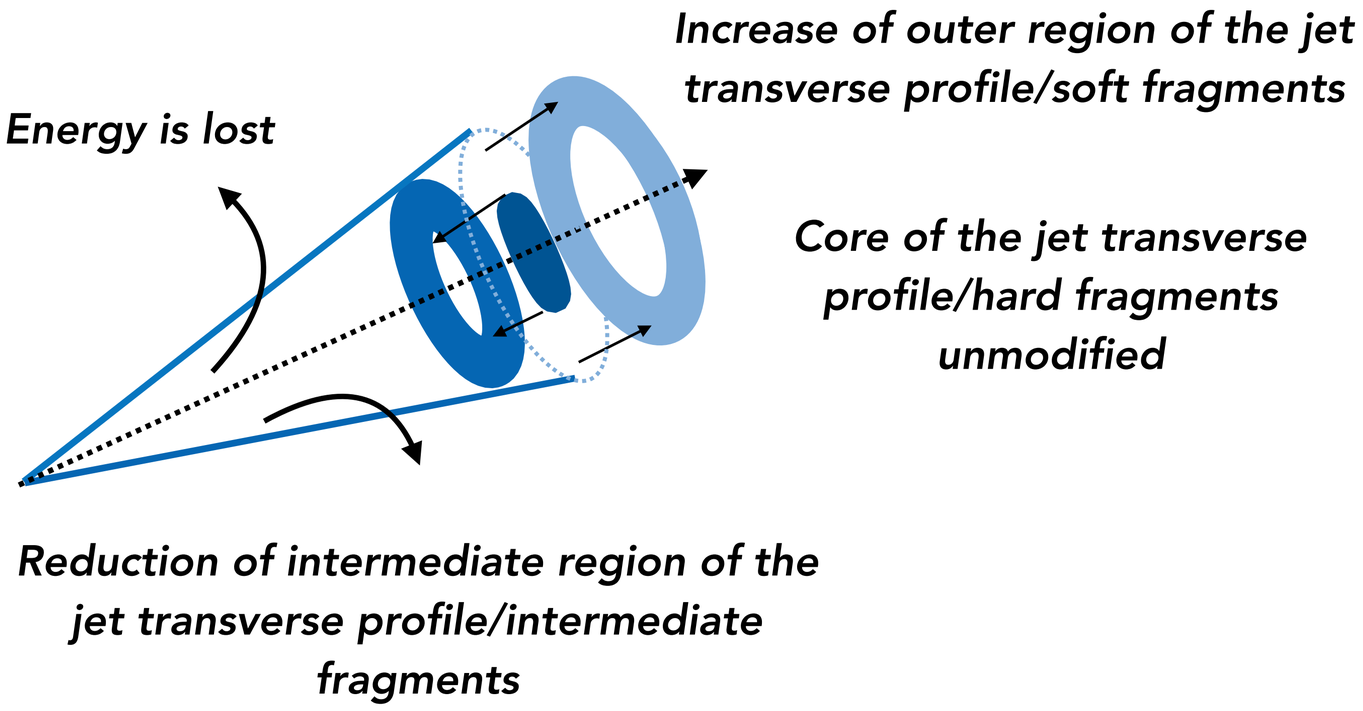
LIP

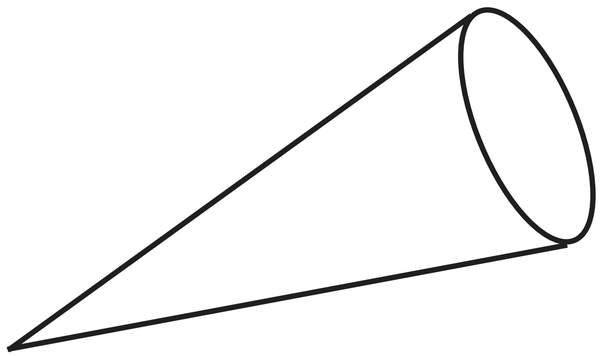
TÉCNICO LISBOA

Backup Slides

Jet Quenching

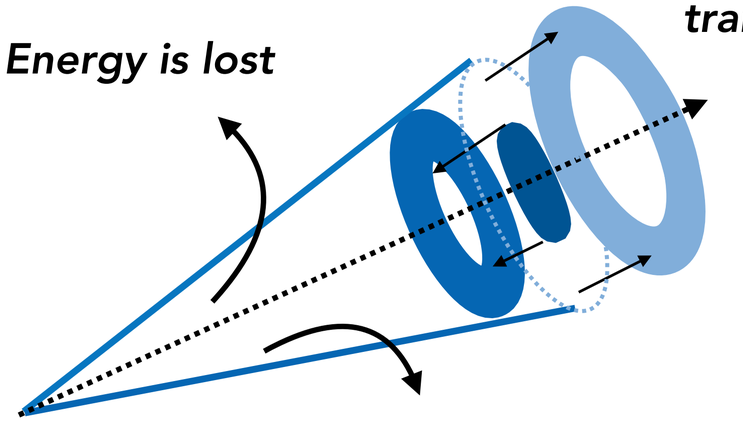
- Current picture of a medium-modified jet:





Jet Quenching

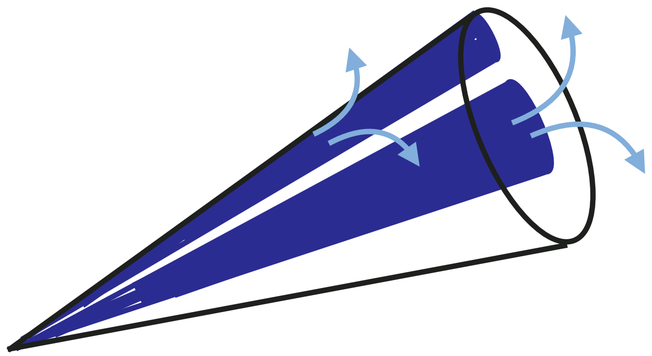
- Current picture of a medium-modified jet:



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



Finite size angular ordered structures (not resolved by the medium)

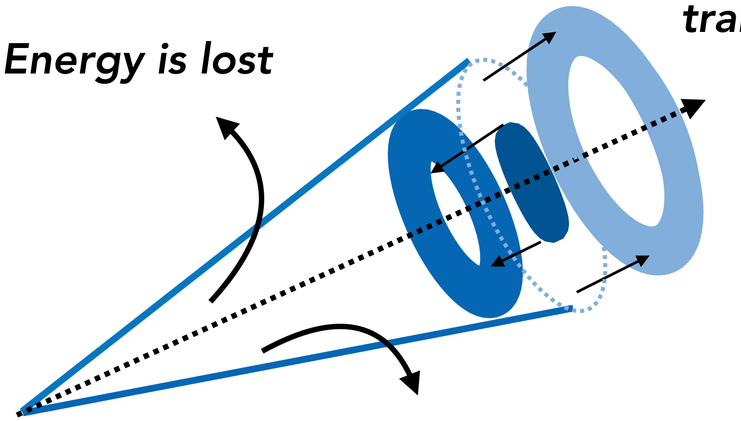
Evolve as pp-like structures (angular ordered) and radiate in-medium radiation (+anti-angular ordered)

Jet Quenching

- Current picture of a medium-modified jet:

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

Energy is lost



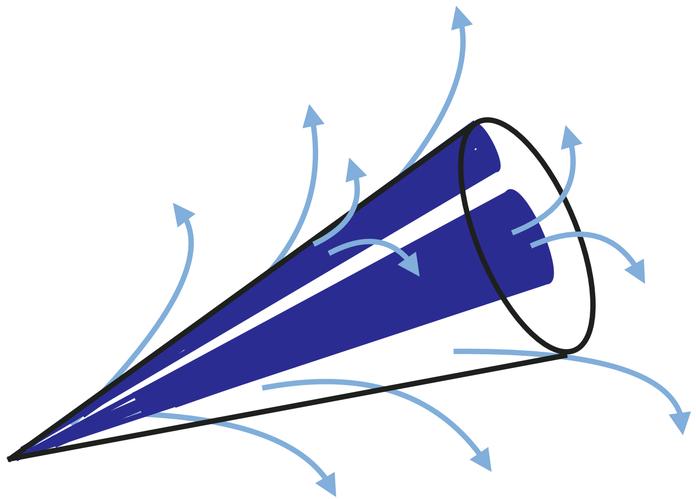
Core of the jet transverse profile/hard fragments unmodified

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

@ LHC: Jets can provide a range of scales to probe the QGP!

@ FCC: What can it bring of new?

Soft fragments: momentum broadening

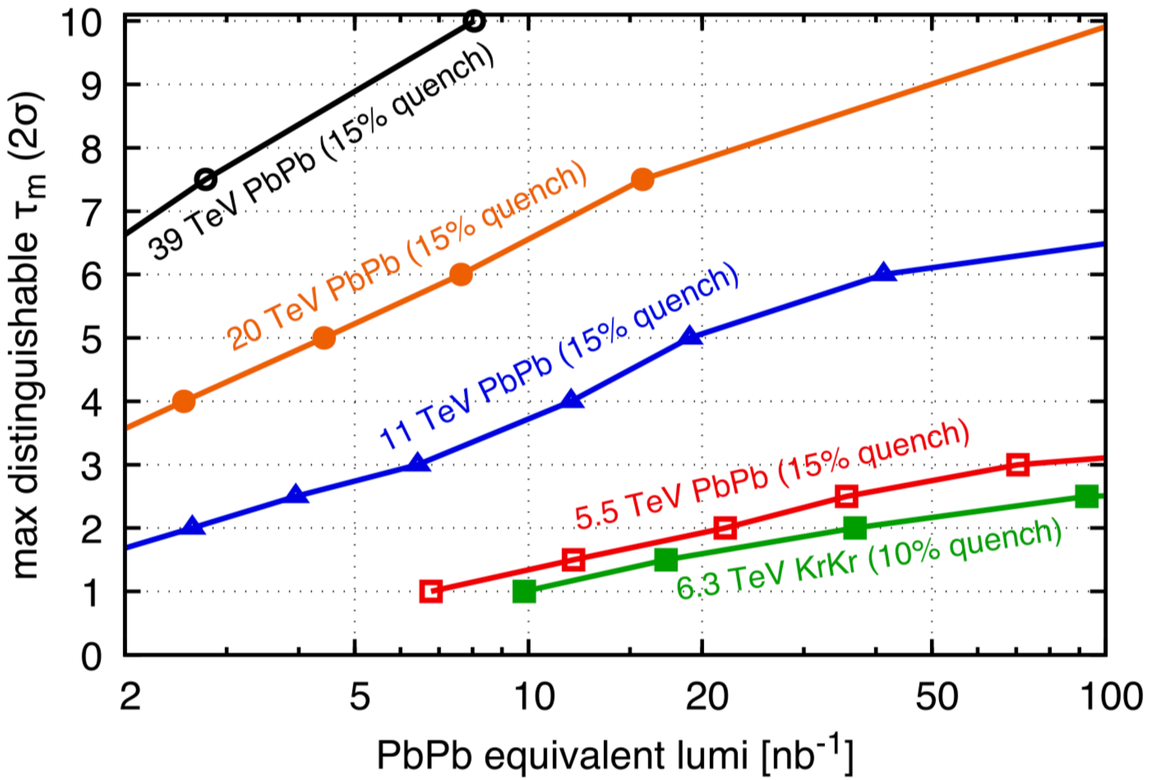


Finite size angular ordered structures (not resolved by the medium)

Evolve as pp-like structures (angular ordered) and radiate in-medium radiation (+anti-angular ordered)

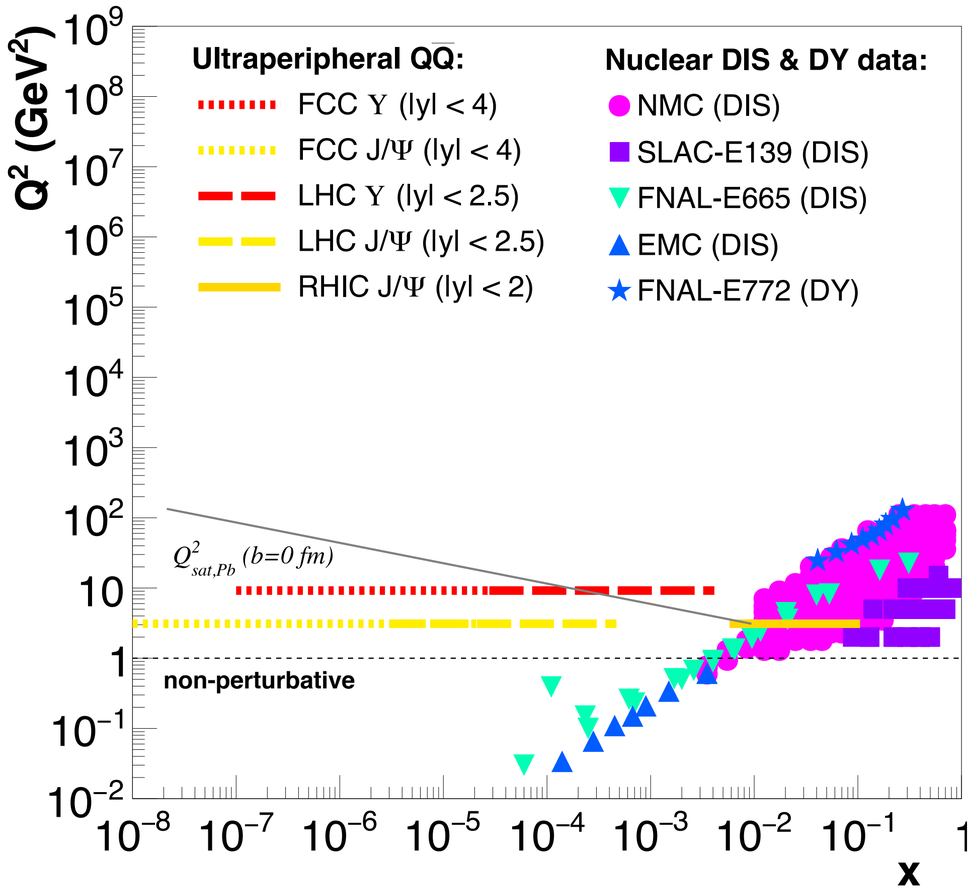
FCC: Boosted Tops

- Maximum timescales that can be distinguishable at each collider:



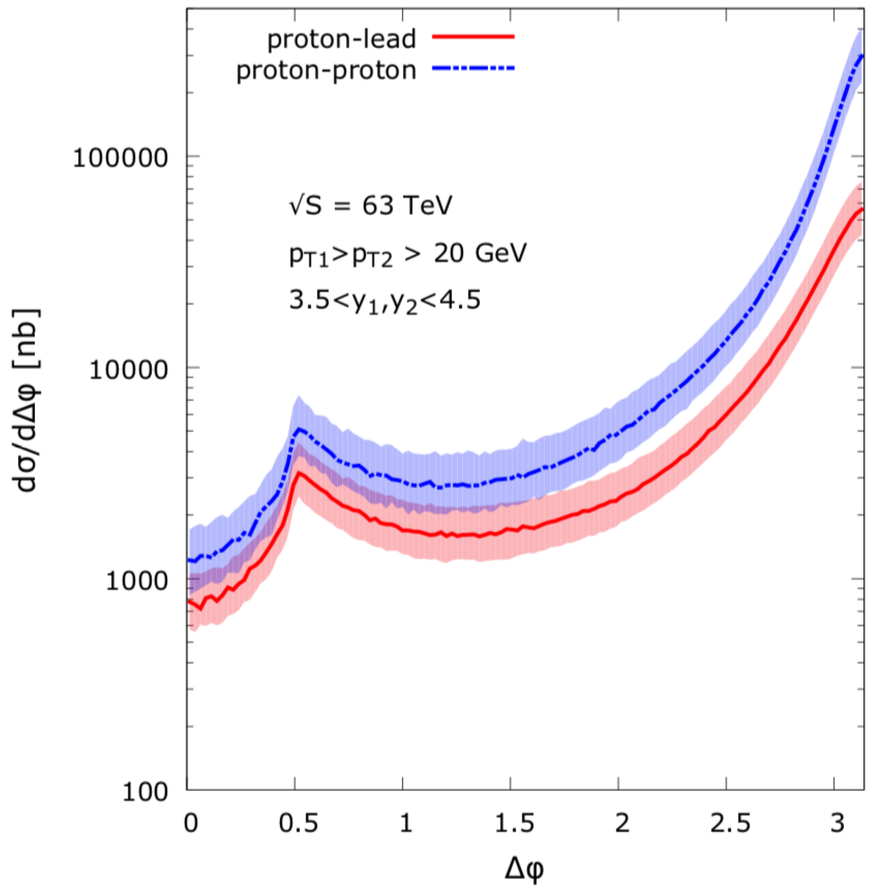
FCC: UPCs for x-Q²

- Regions of x-Q² plane covered with quarkonia in ultra peripheral ion collisions



FCC: Saturation Signals

- The recoil suppression can be also be explored using dijets at forward rapidity:
  - Expected broadening of the Δφ distribution in pPb vs pp collisions:



Detector considerations

- No detailed detector requirements so far… but:
  - Soft probes physics program require:
    - Charged-hadron identification to measure independently:
      - Low-pT charged mesons and baryons
      - Low-pT c and b mesons
    - Track reconstruction down to low pT, (starting from few MeV)

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

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 pT
      - High performance up to very large event multiplicities;