FCC heavy-ion physics studies

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on behalf of the HI Working Group of FCC-hh/Physics&Exp

Outline

- Organization and physics report 2016
- Ions at the FCC: projected performance
- Quark-Gluon Plasma studies (high-density QCD in the final state of heavy-ion collisions)
- Small-x and gluon saturation (high-density QCD in the initial state)
- Contributions to other sectors of HEP and physics with injectors
- Detector considerations

Organization and Report 2016

- Ions at FCC-hh Working Group:
  - Coord: A.D., S. Masciocchi, C. Salgado, U. Wiedemann
  - Sub-group of “FCC-h Physics, Experiments, Detectors”
  - Participation of CERN Beams dep. (J. Jowett, M. Schaumann)
  - Contact with HI theory group of CEPC-SppC
  - Twiki https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HeavyIons
- 6 workshops/meetings 2013-15
  - https://indico.cern.ch/event/331669/ and links therein
- “Report2016” is ready, will go to arXiv soon
  - 40 pages, about 50 authors
  - Similar outline as this talk
  - 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

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Energies and first operation studies

- Centre-of-mass energy per nucleon-nucleon collision:

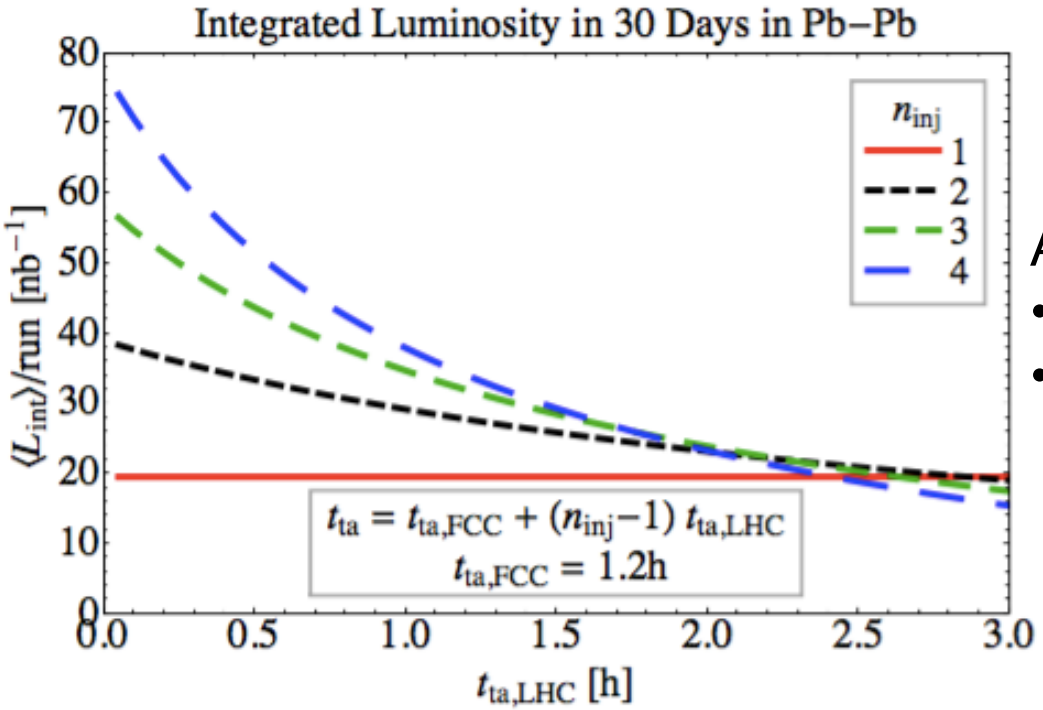
$$\sqrt{s_{NN}} = \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}\sqrt{s_{pp}} \quad \Rightarrow \quad \sqrt{s_{PbPb}} = 39\ TeV \quad \sqrt{s_{pPb}} = 63\ TeV \quad \text{for} \quad \sqrt{s_{pp}} = 100\ TeV$$

- First study on operation scenario and estimates of luminosity one year ago: M. Schaumann, Phys. Rev. ST Accel. Beams 18 (2015) 9, 091002, arXiv:1503.09107
  - Conservative scenario: LHC as injector with parameters as in p-Pb run 2013
  - Operation mode: 1 injection from LHC→1/4 of FCC ring, then ramp and collide; re-fill and ramp the LHC during FCC collisions
  - Resulted in L_{int}/month ~ 8/nb
- This scenario was now been updated in view of the 2015 Pb run performance and of recent studies on the injection

M.Schaumann, J.Jowett

Optimised scenario (2016)

- L_{int}/month can be increased by using 4 injections from LHC to FCC if the LHC turn-around time is less than ~1h



Assumptions:
- 100% efficiency
- 1 int. point

- Optimal performance for n_{inj}=4, $t_{ta,LHC}$=9min and $t_{ta,FCC}$=1.2h
- Assuming reduction of LHC cycle time as per recent studies

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Luminosity for Pb-Pb and p-Pb

- Optimised operation scheme (prev. slide) with 50% efficiency

Operation mode		Pb–Pb	p–Pb
Beam energy	[TeV]	4100	50
$\sqrt{s_{\mathrm{NN}}}$	[TeV]	39.4	62.8
No. of bunches per LHC injection	-	518	518
No. of bunches in the FCC	-	2072	2072
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
Integrated luminosity/run	$[\mathrm{nb}^{-1}]$	33	8000

- Per month: 33/nb for Pb-Pb and 8/pb for p-Pb
- E.g. in three 1-month Pb-Pb runs: 100/nb ~ 10x full LHC programme

M.Schaumann, J.Jowett

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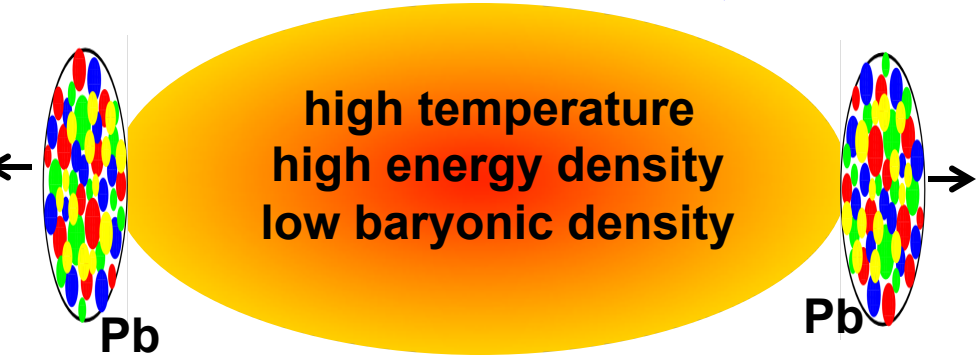
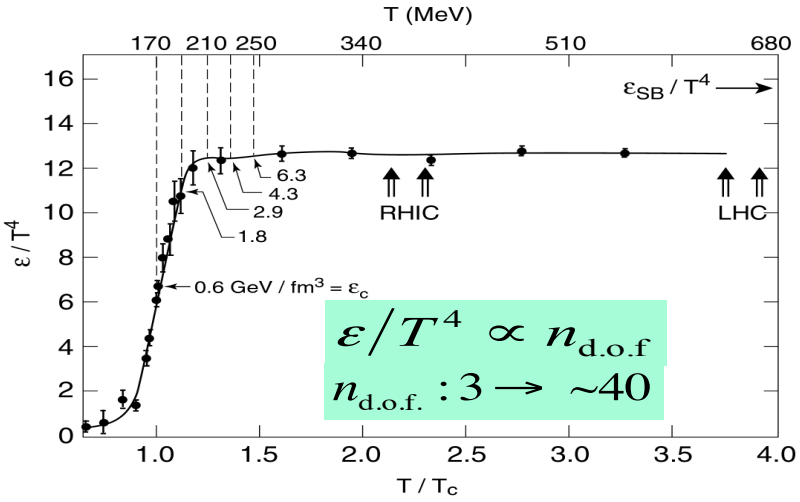
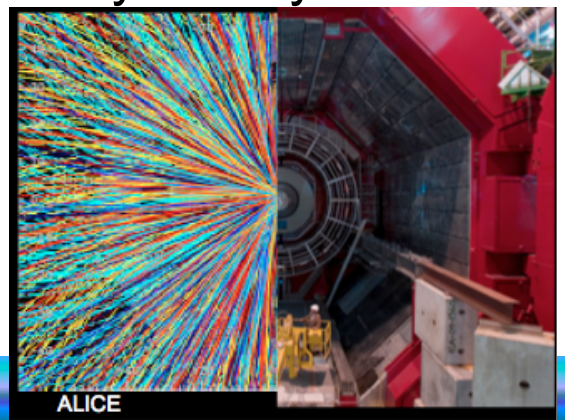
High-density QCD in the final state: the Quark Gluon Plasma

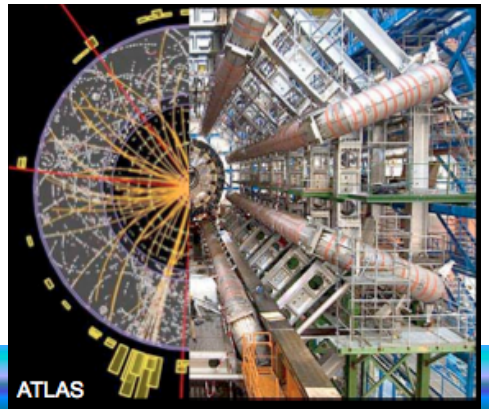


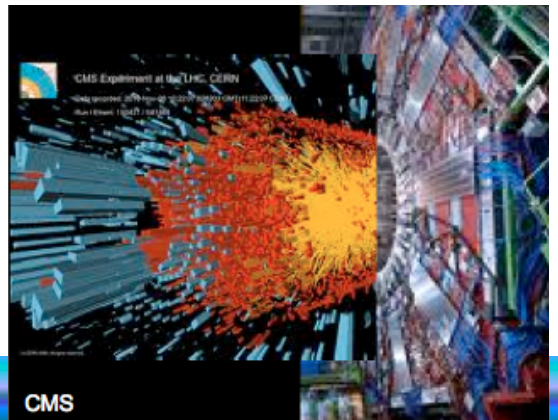


- Lattice QCD predicts phase transition at T_c~155 MeV
  - → **Quark-Gluon Plasma**
- Color deconfinement and chiral symmetry restoration

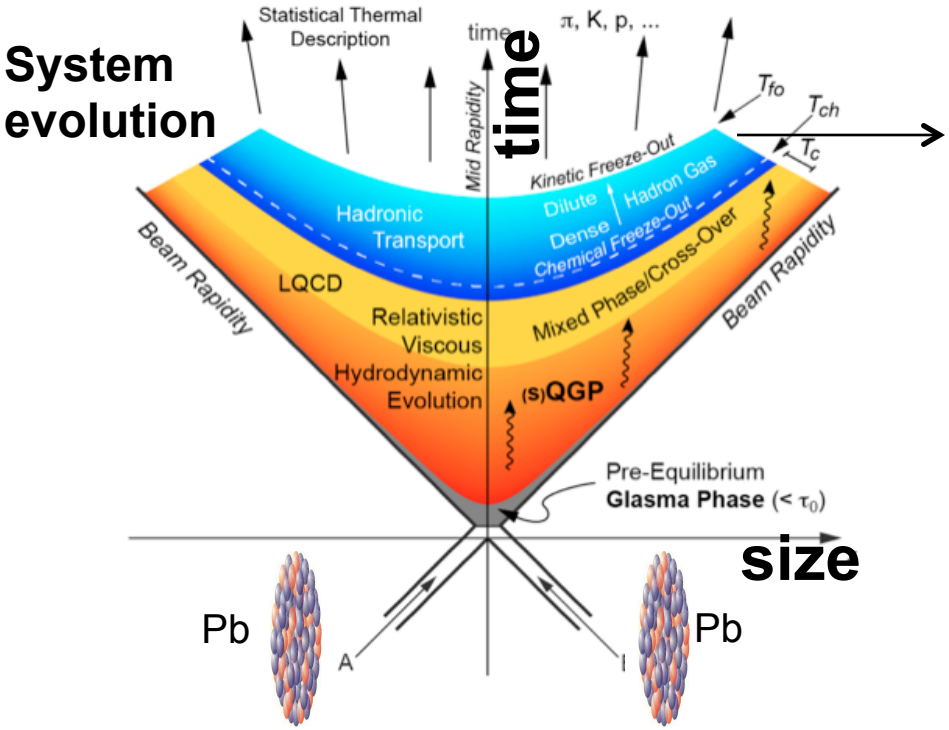
- Partonic degrees of freedom
- Unique opportunity to study in the laboratory spatially-extended multi-particle QCD system

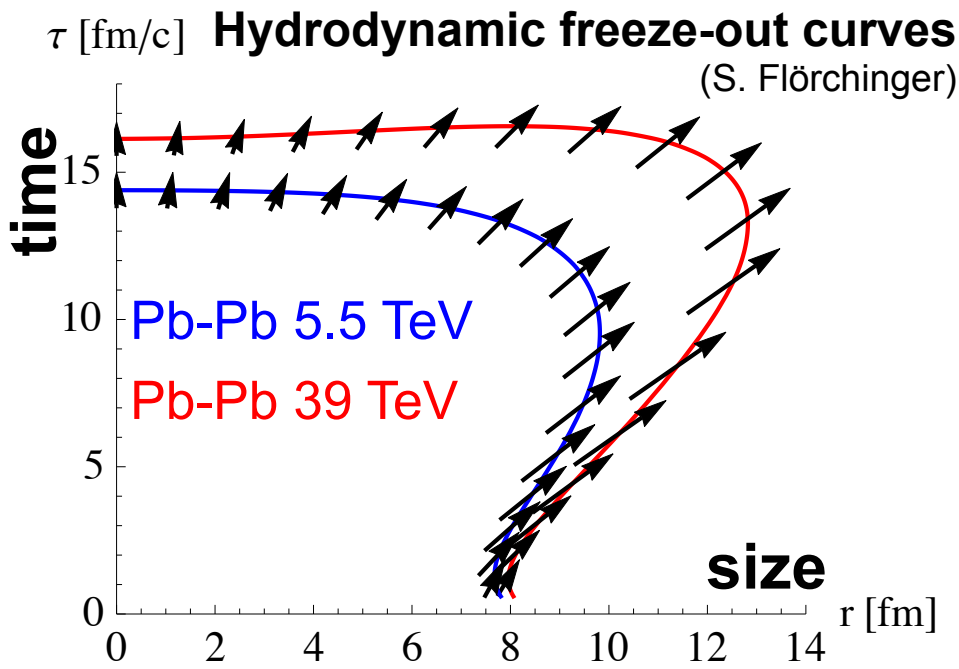






Quark-Gluon Plasma studies at FCC





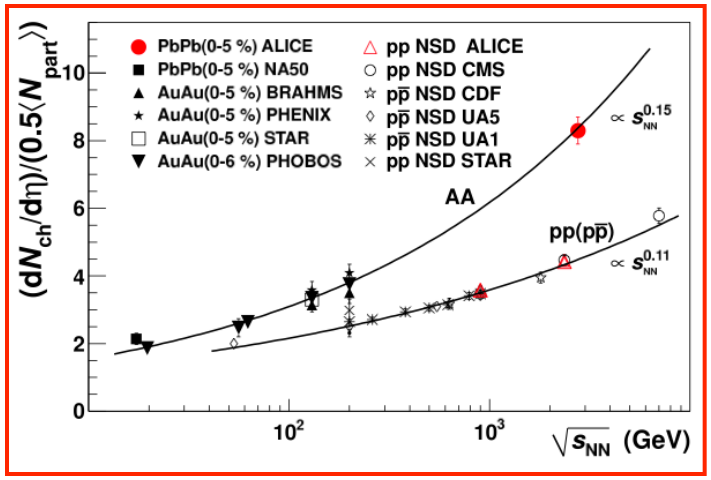
Properties of QGP:

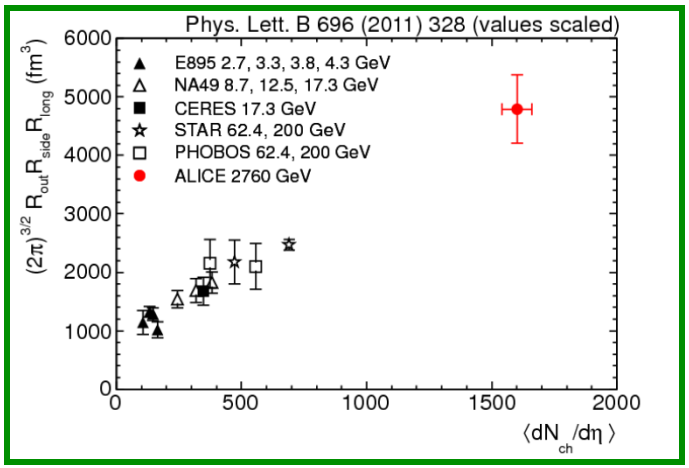
- QGP volume increases strongly
- QGP lifetime increases
- Initial temperature higher
- Equilibration times reduced

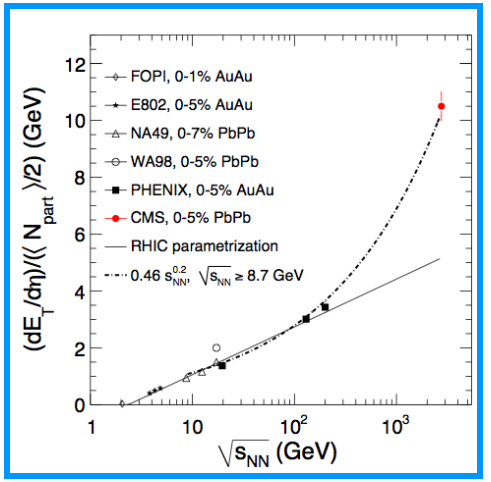
QGP "fireball": global properties

- Extrapolation to 39 TeV: increase wrt LHC 5.5 TeV

$dN_{ch}/d\eta$ x 1.8 **Volume x1.8** **$dE_T/d\eta$ (& ε) x2.2**



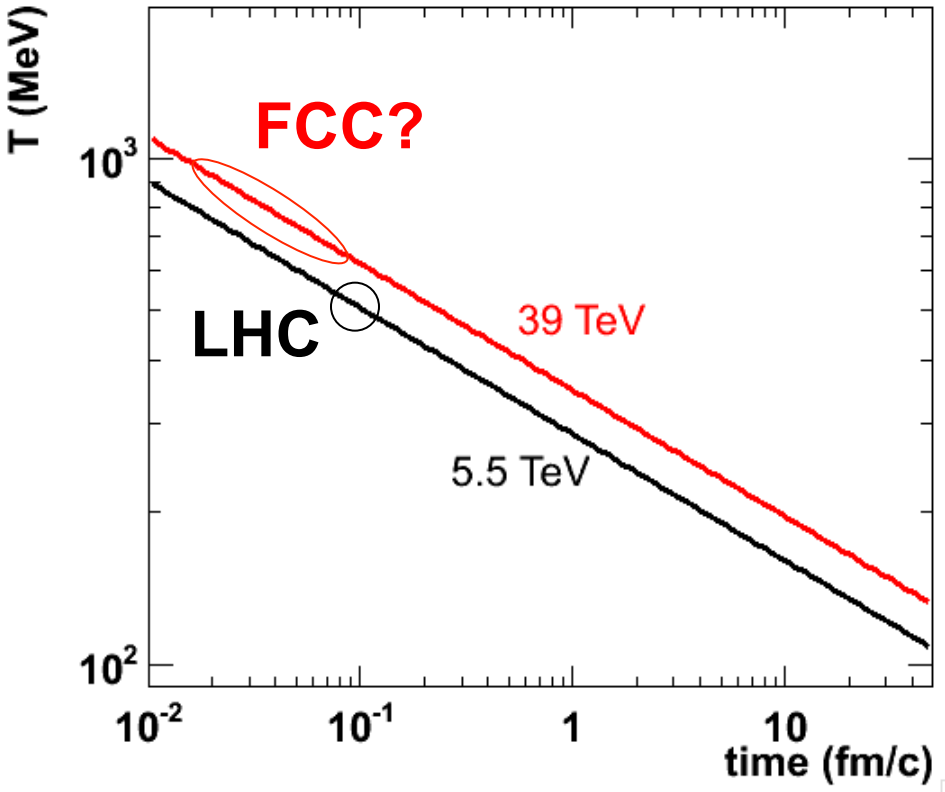




Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	1.8–2.0 TeV	2.3–2.6 TeV	5.2–5.8 TeV
Homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
Decoupling time	10 fm/c	11 fm/c	13 fm/c
ε at $\tau = 1$ fm/c	12–13 GeV/fm^3	16–17 GeV/fm^3	35–40 GeV/fm^3

Higher QGP temperature

- Larger c.m.s. energy → larger fireball temperature
- Simple estimate (from Bjorken + Stefan-Boltzmann):

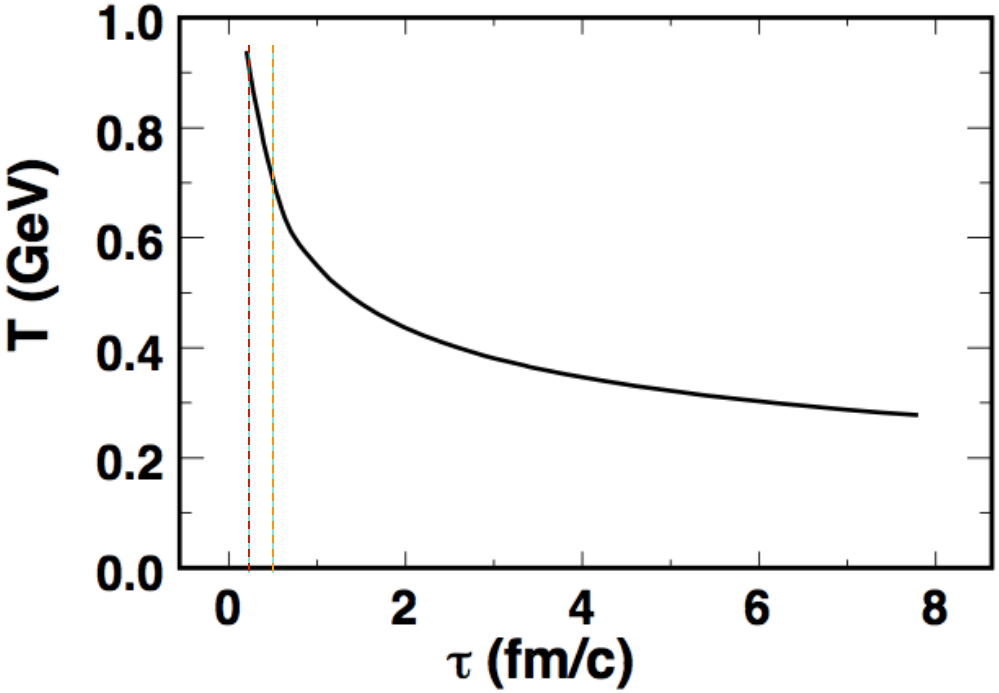


$$T(\tau) = \left(\varepsilon(\tau) \frac{30}{\pi^2 n_{d.o.f.}} \right)^{\frac{1}{4}}$$

- 20% larger for the same time
  - e.g. 360 MeV at 1 fm/c
- Initial time (QGP formation time)?
  - Usually ~0.1 fm/c for LHC
  - Could be smaller at FCC
- Significantly larger initial temperature? Could reach close to 1 GeV?

Higher QGP temperature

- Larger c.m.s. energy → larger fireball temperature
- From hydrodynamic simulation:



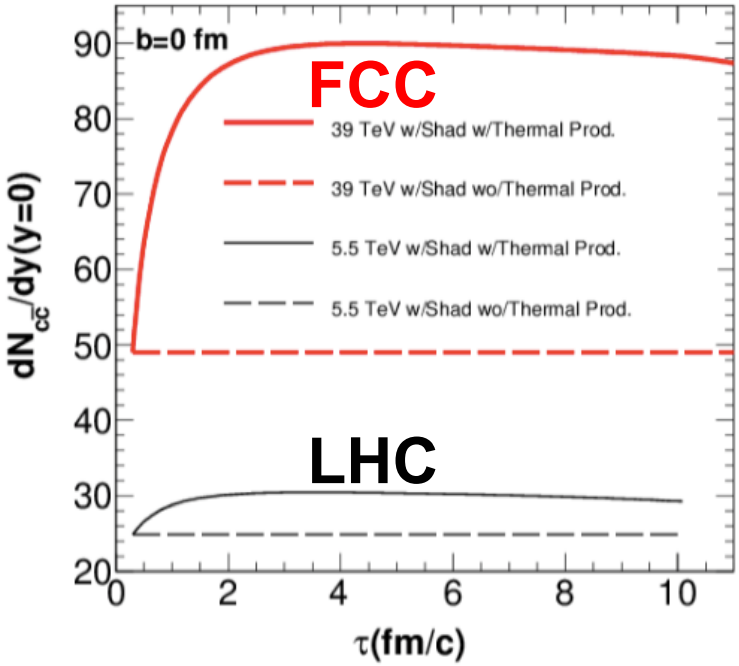
- 900 MeV at τ = 0.2 fm/c
- 650 MeV at τ = 0.5 fm/c

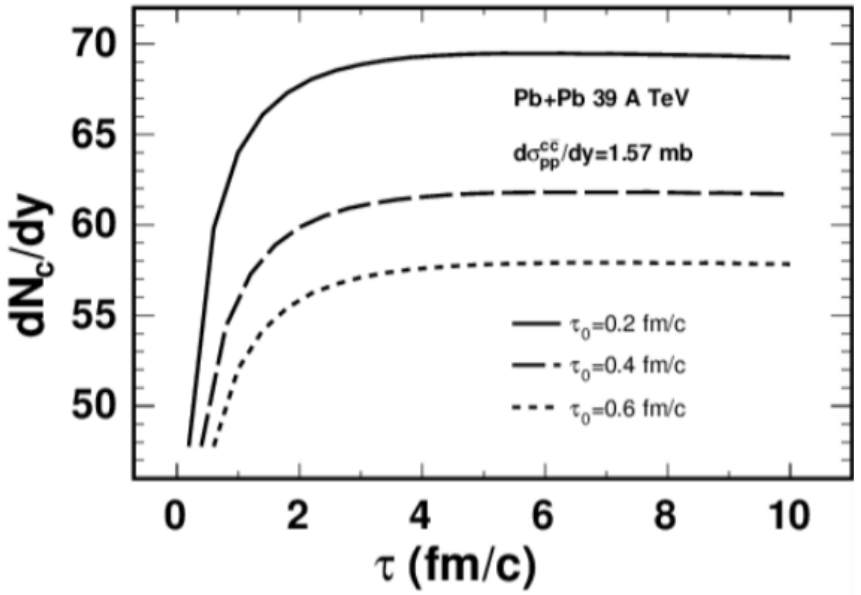
Note that a QGP with temperature T ~ 1 GeV has energy density ε ~ 2 TeV/fm^3 !

C.M. Ko, Y. Liu, arXiv:1604.01207

Thermal charm production?

- Expect abundant secondary production of $c\bar{c}$ pairs in the medium from $gg \rightarrow c\bar{c}$, $q\bar{q} \rightarrow c\bar{c}$ + NLO …





- Up to 50-100% “enhancement” wrt primary charm
- Sensitive to QGP properties: T vs τ, and τ_0

K. Zhou et al., arXiv:1602.01667

C.M. Ko, Y. Liu, arXiv:1604.01207

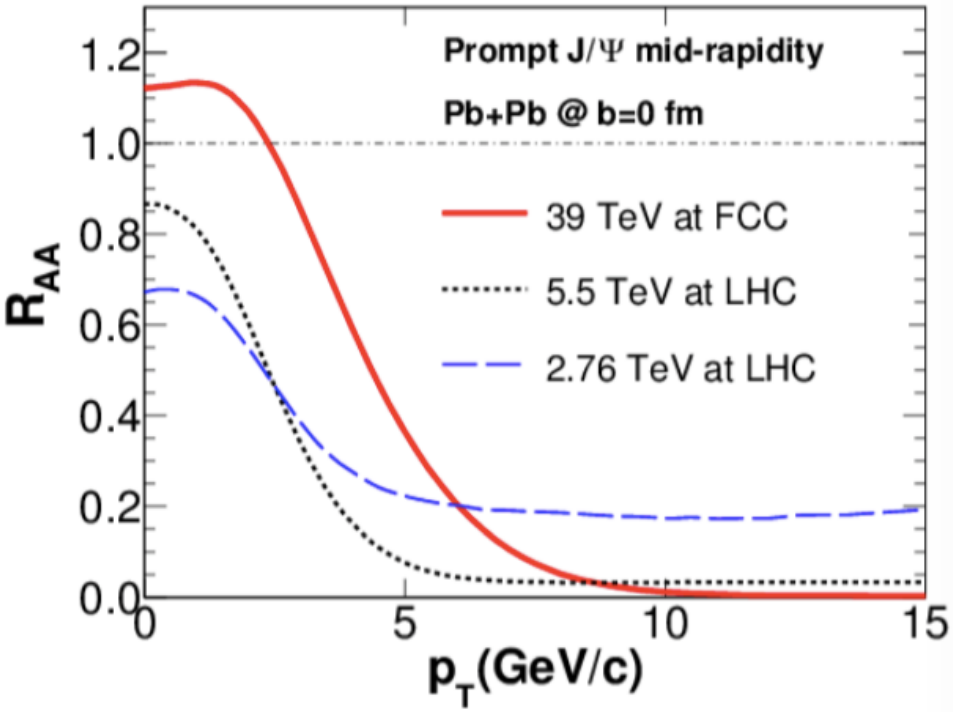
J/ψ: from suppression to enhancement?

- Quarkonium suppression in AA wrt pp(xN_{coll}) observed at SPS, RHIC and LHC is attributed to color-screening of the $Q\bar{Q}$ potential in QGP

$$R_{AA} = AA/(pp \times N_{coll}) < 1$$

- At LHC, smaller J/ψ suppression wrt RHIC suggests novel effect: "regeneration" from deconfined *c* and $\bar{c}$ quarks in the QGP

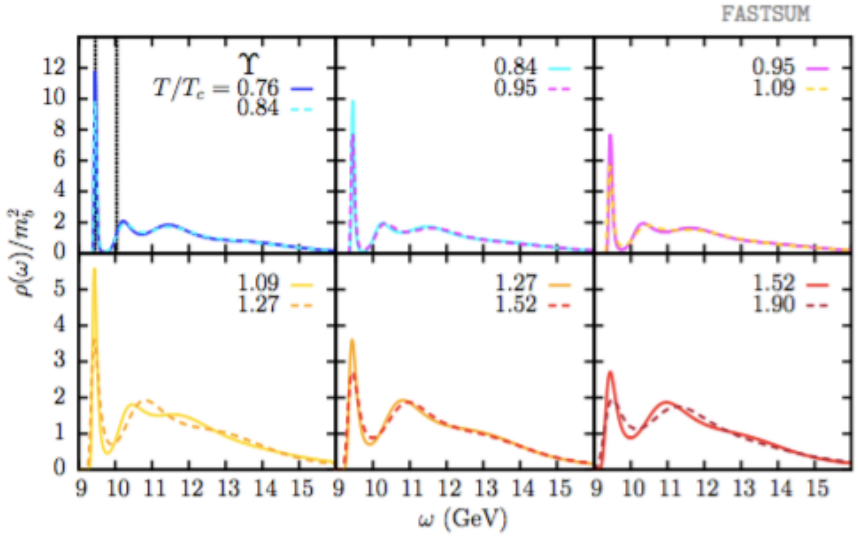
- At FCC, the large charm yield from hard scattering + thermal production may lead to a J/ψ enhancement (R_{AA}>1)
  - J/ψ yield could be sensitive to secondary/thermal charm production

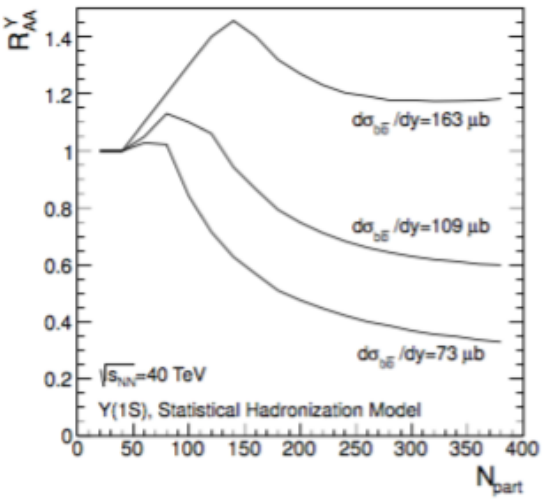


K. Zhou et al., arXiv:1602.01667

Y: full suppression or enhancement?

- Color-screening suppression reduced for tightly-bound states
- Y(1S) R_{AA}~0.5 at LHC: consistent with suppression of higher states only (2S and 3S, that feed-down to the 1S)
- Y(1S) would melt when T > 350 MeV, may be reached only at FCC
- However, the large $b\bar{b}$ yields could lead to a first observation of regeneration in the bottomonium sector (Y R_{AA}>1)





G. Aarts et al, JHEP 07 (2014) 097

A.Andronic, et al., based on JPG38 (2011) 124081

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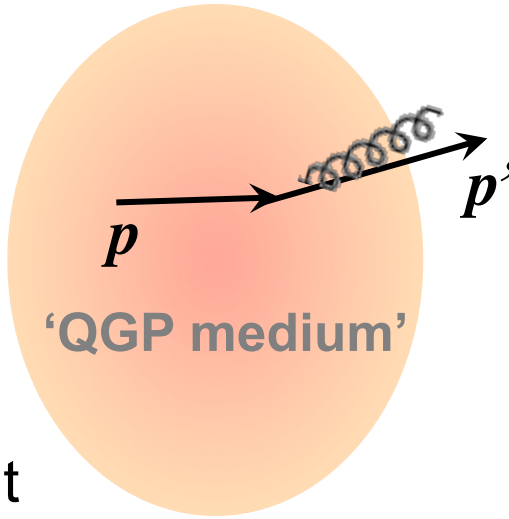
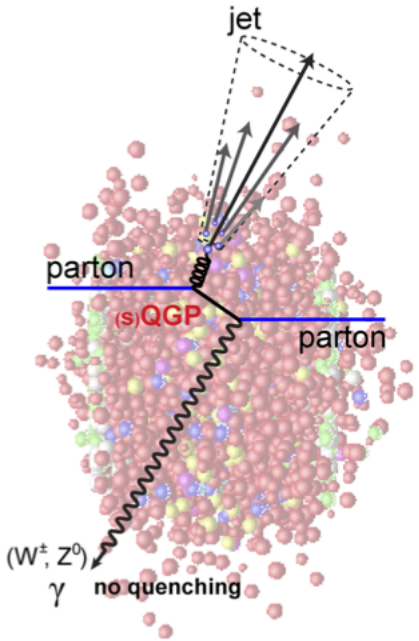
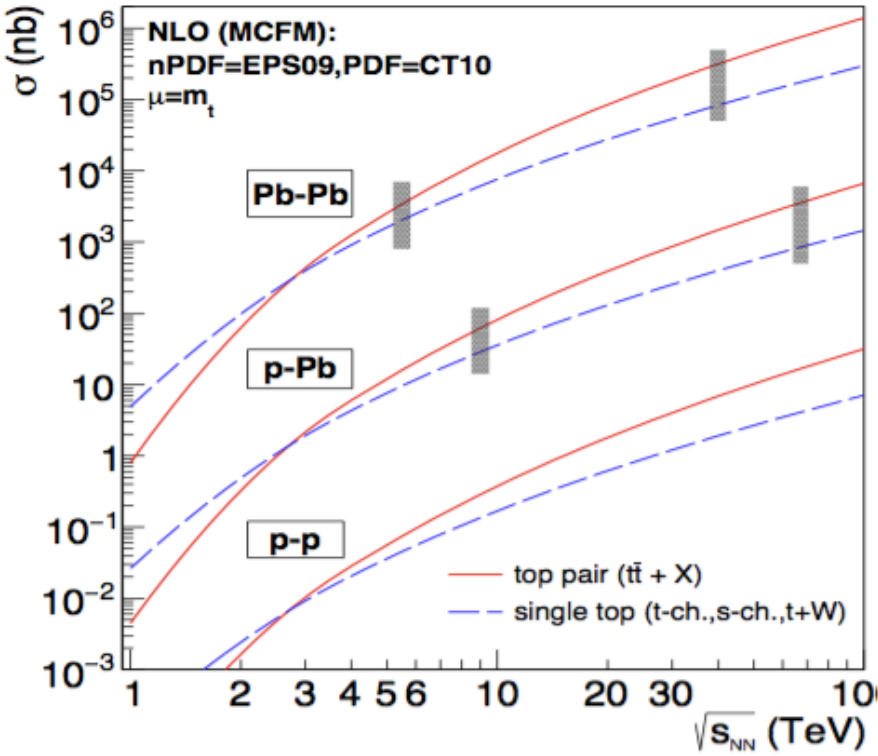
Parton energy loss in the QGP

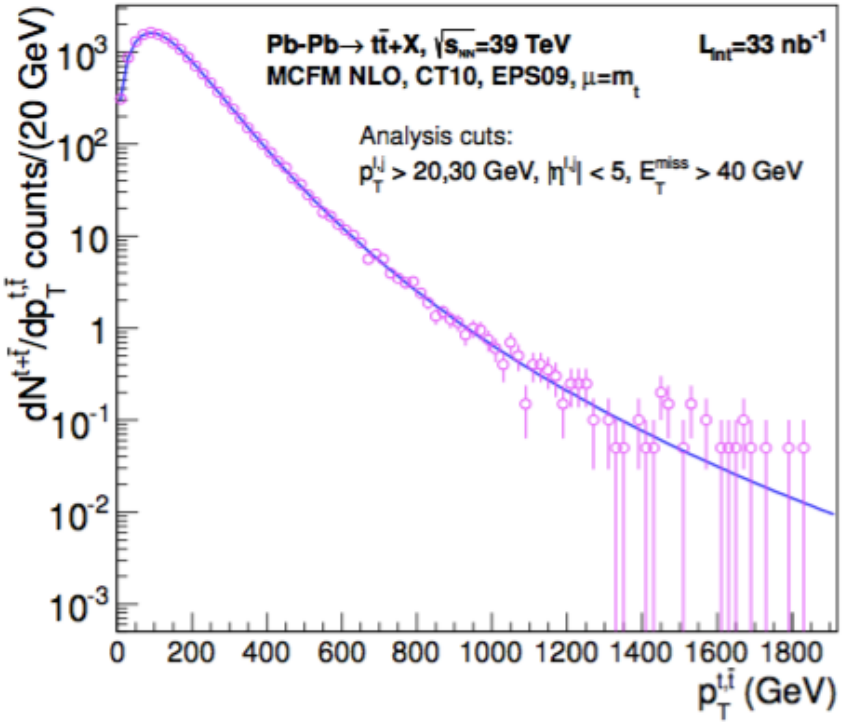
- High-energy partons from hard scattering lose energy while crossing the QGP, mainly via radiation of gluons
  - Observed as reduction of hadron and jet yields and modification of jet structure (FF softening and "out-of-cone" radiation)
- Parton energy loss is a unique tool to learn about the QGP "opacity" and the properties of the QCD interaction in an extended medium
- At the LHC, the focus is progressively shifting towards flavour-tagging and correlations (di-jets and boson-jet)
  - E.g. γ(Z)-jet provides a measurement of the initial hard parton energy
- Increase of energy and lumi by ~ x10 at FCC will make available completely novel ways to probe the QGP, e.g. top events





Top production at FCC energy



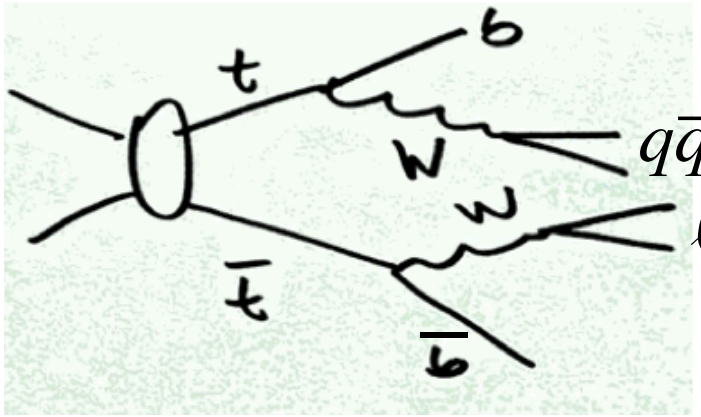


- Top cross section increases by x80 from 5.5 TeV to 39 TeV
- Kinematic simulation study: 3x10^5 $t\bar{t} \to b\bar{b}\,\ell\ell\,\nu\nu$ per run (33/nb)
- Top p_T distribution up to ~1.2 TeV/c

D. d'Enterria, et al. Phys. Lett. B746 (2015) 64–72, arXiv:1501.05879 [hep-ph]

An interesting physics case for top: boosted color singlets in the QGP

- Boosted (i.e. high p_T) top events: $t\bar{t} \rightarrow b\bar{b} + q\bar{q} + \ell + \nu$



This $q\bar{q}$ is produced as a color singlet and it "sees" the QGP with a time delay given by the boost of the t and of the W

The rest of the final state

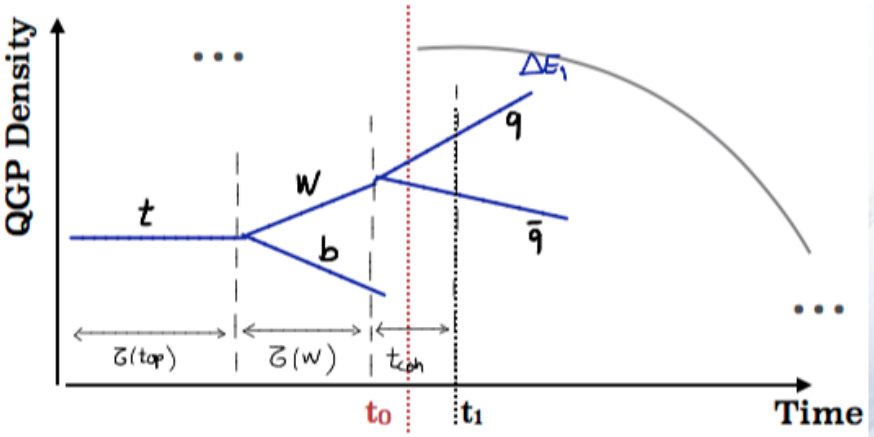
$$2\ b-jets + \ell + \not{E}_T$$

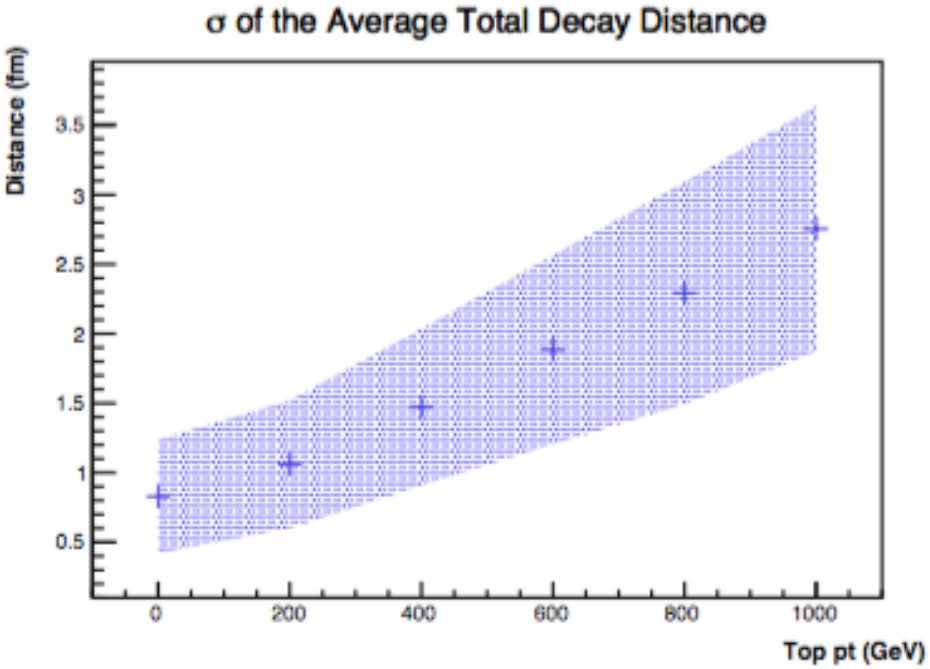
is used to tag the event topology

- Boosted-top events can therefore be used to address two novel studies in the sector of parton energy loss:
  1. Time-evolution of QGP opacity, because of the boost
  2. Role of color coherence in parton energy loss, because the pair is initially a color singlet

An interesting physics case for top: boosted color singlets in the QGP

1) Testing the time evolution of the QGP density

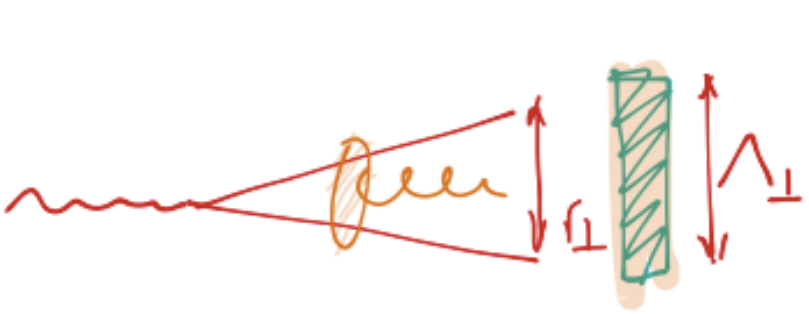




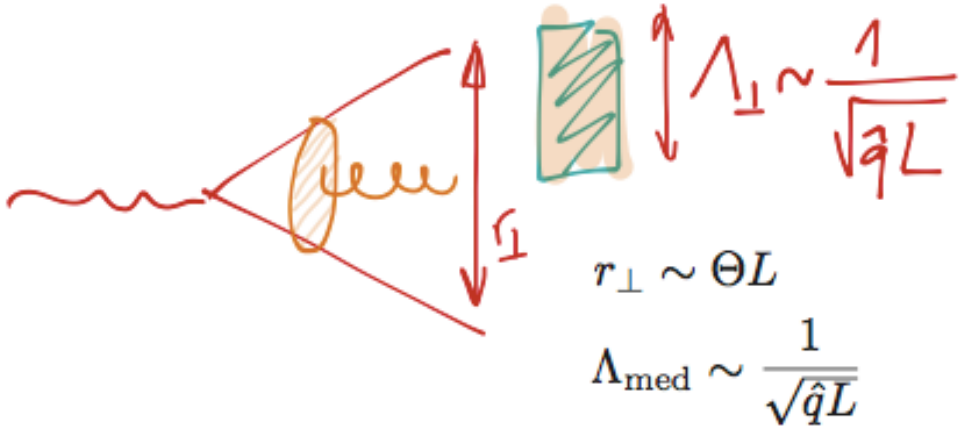
Estimate of the "start time" of energy loss: reaches 2-3 fm/c for top p_T~0.5-1 TeV/c

An interesting physics case for top: boosted color singlets in the QGP

2) Testing the role of color coherence



q-qbar with small opening angle; seen as color-singlet by the medium, **no interaction expected**



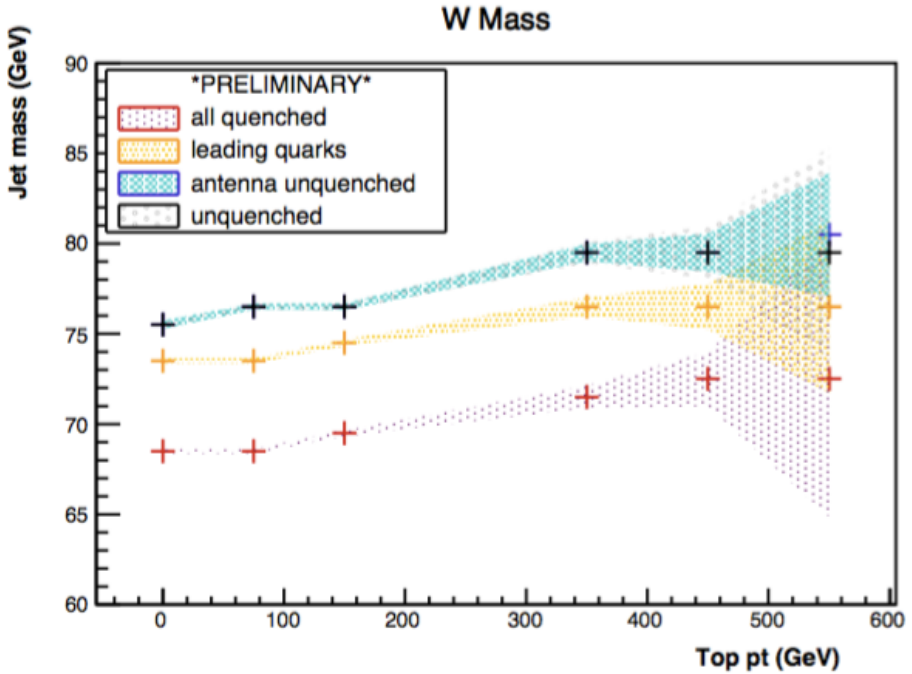
Medium induces decoherence, opening angle increases → **energy loss of color-octet's in the medium**

Armesto, Casalderrey, Iancu, Ma, Mehtar-Tani, Salgado, Tywoniuk 2010-2014

An interesting physics case for top: boosted color singlets in the QGP

- Energy loss of the $q\bar{q}$ pair results in a shift of the W mass reconstructed from the $q\bar{q}$ jet(s)
- Observables:
  1. The shift of the W mass discriminates scenarios on the role of color coherence (small shift in case coherence plays a role)
  2. The shift vs top p_T probes the time-evolution of the QGP density

Kinematic simulation study with Pb-Pb 39 TeV (10/nb)



Apolinario, Milhano, Salam, Salgado

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  - With hadronic heavy-ion collisions
  - With photon-induced collisions
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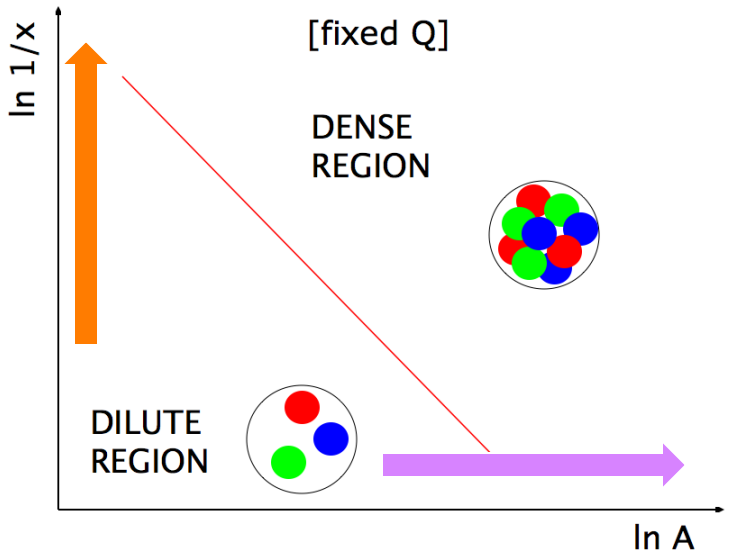
High-density QCD in the initial state: Saturation at low *x*

- Explore new unknown regime of QCD: when gluons are numerous enough (low-*x*) & extended enough (low-Q^2) to overlap → *Saturation, Non-linear PDF evolution*

Enhanced in nuclei: more gluons per unit transverse area

Saturation scale:

$$Q_S^2 \sim \frac{A g(x,Q_S^2)}{\pi A^{2/3}} \sim A^{1/3} g(x,Q_S^2) \sim A^{1/3} \frac{1}{x^{\lambda}} \sim A^{1/3} \left(\sqrt{s}\, e^{y}\right)^{\lambda} \quad (\lambda \sim 0.3)$$



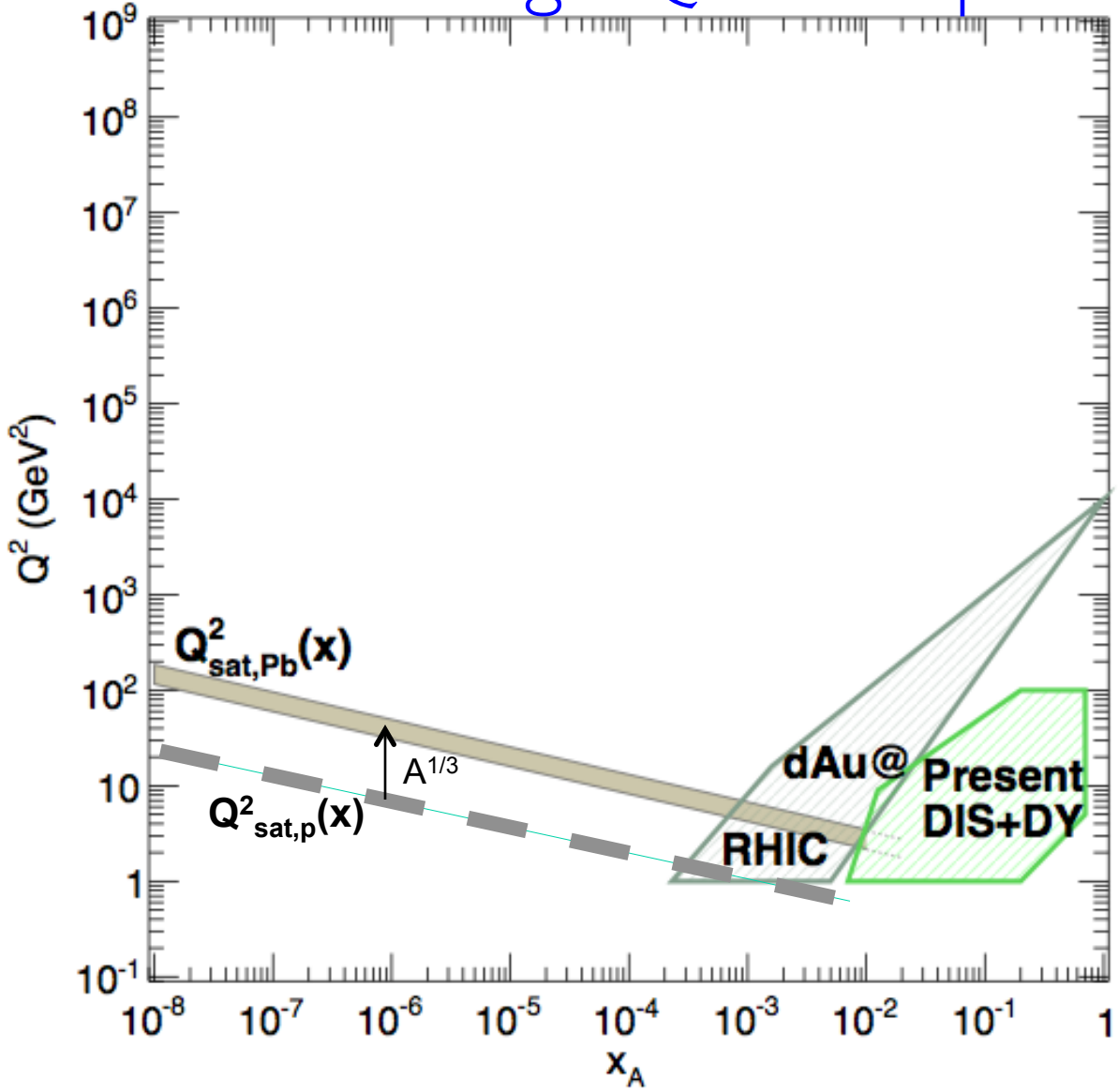
Saturation affects process with $Q^2 < Q_S^2$

Explore saturation region:

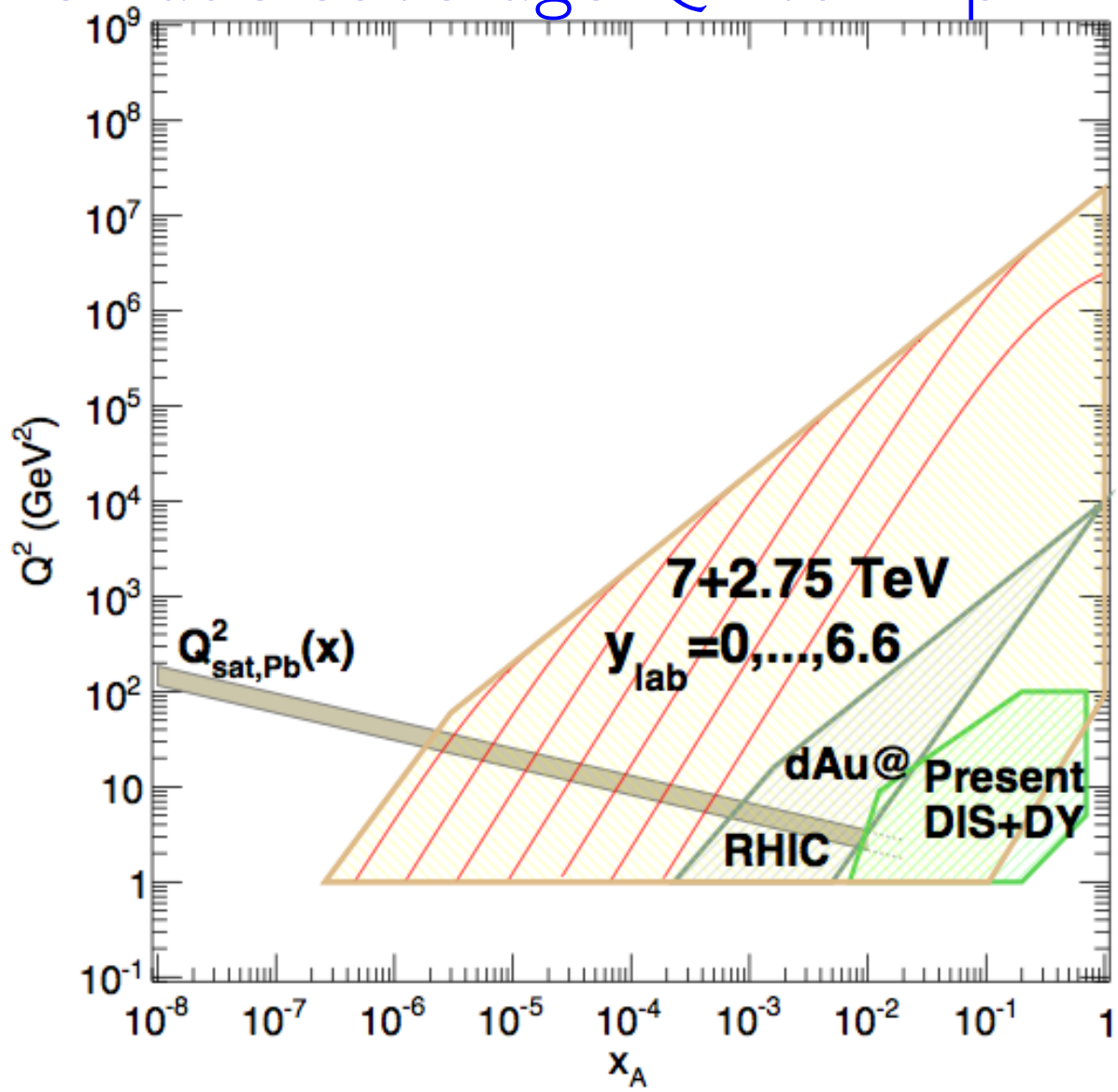
→ **decrease *x* (larger √s, larger *y*)**

→ **increase A**

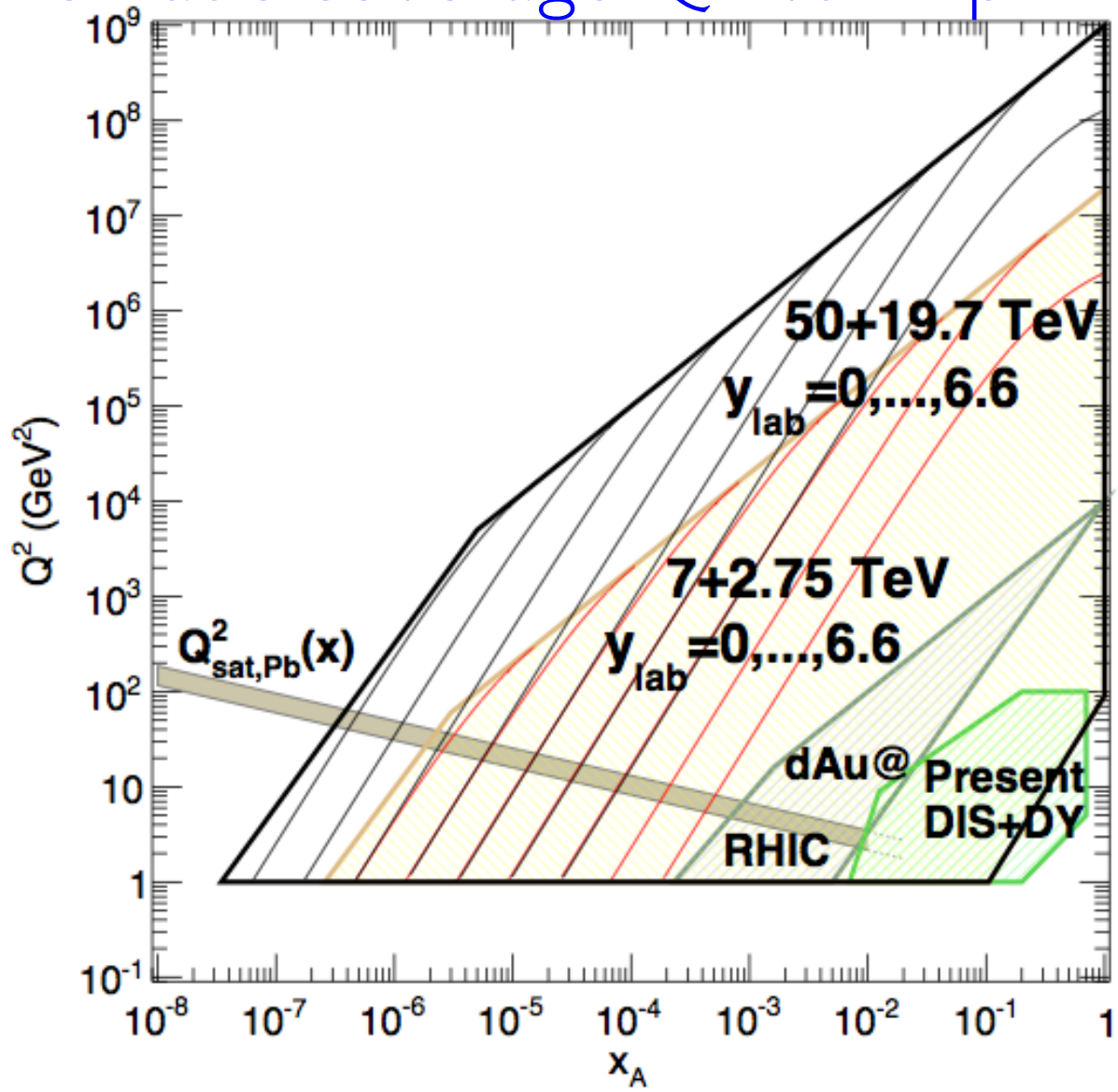
Kinematic coverage Q^2 vs. x: pre-LHC



Kinematic coverage Q^2 vs. x: pA LHC



Kinematic coverage Q^2 vs. x: pA FCC

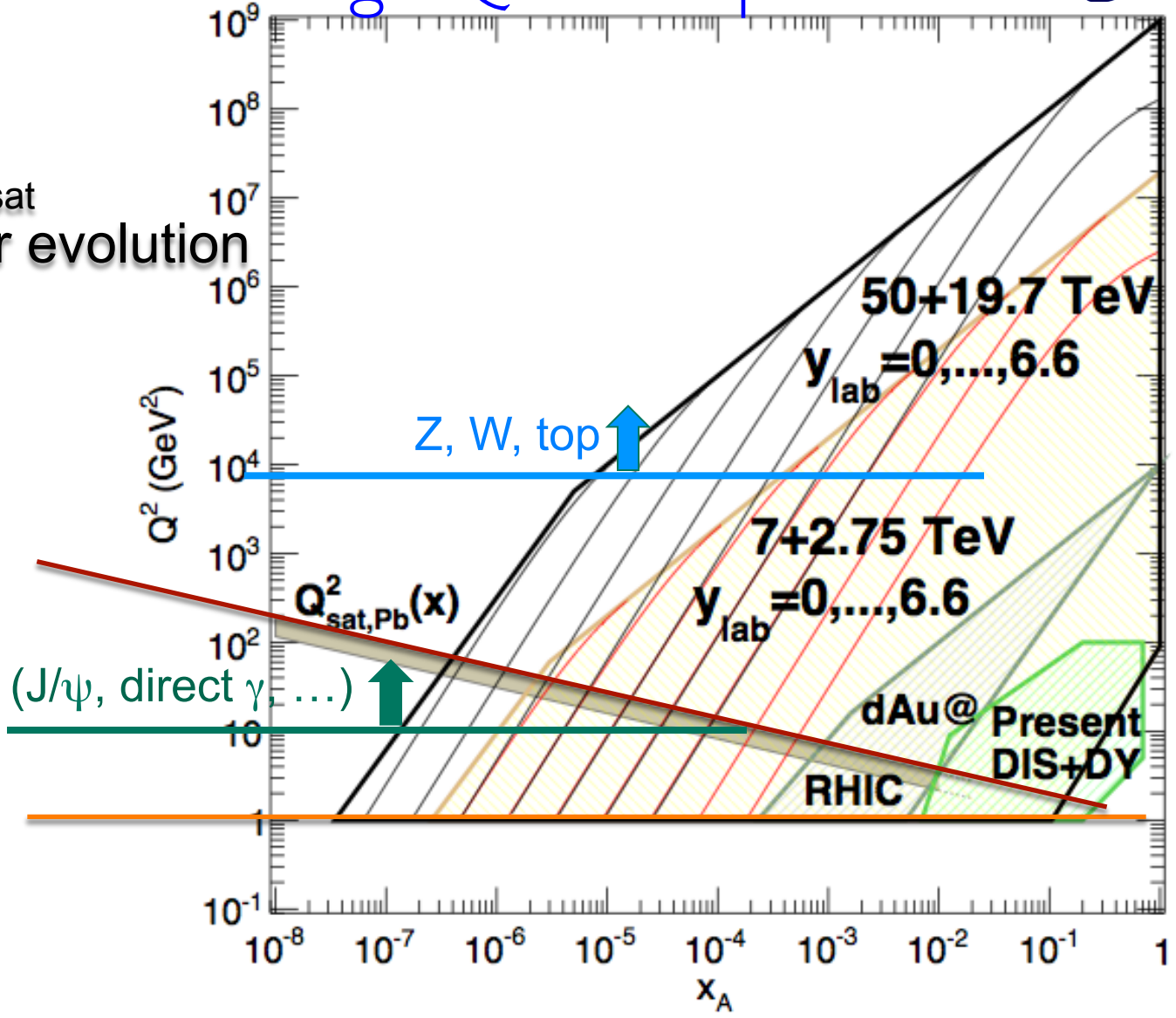


Kinematic coverage Q^2 vs. x: pA FCC

Goals:

- determine Q^2_{sat}
- test non-linear evolution

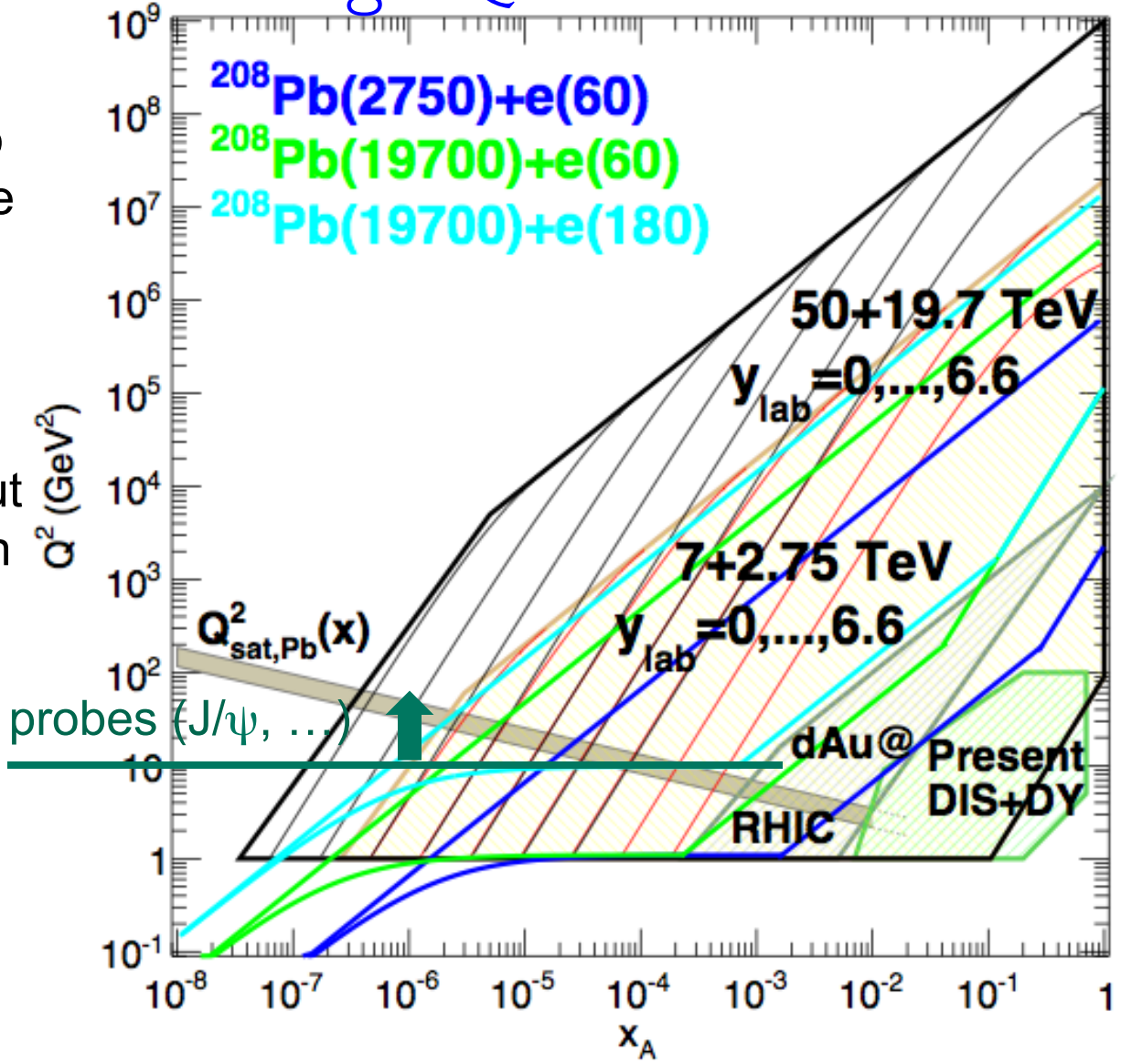
Perturbative probes (J/ψ, direct γ, …)



Kinematic coverage Q^2 vs. x: eA FCC

pA at FCC:
unique access down to $x<10^{-6}$ with perturbative probes

eA at FCC:
down to $x<10^{-5}$ with perturbative probes, but fully constrained parton kinematics

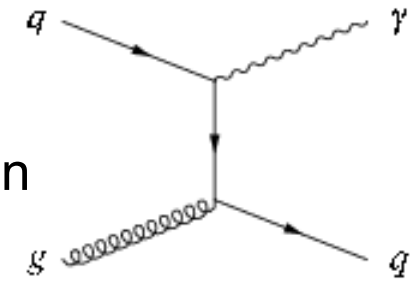


Perturbative probes (J/ψ, …)

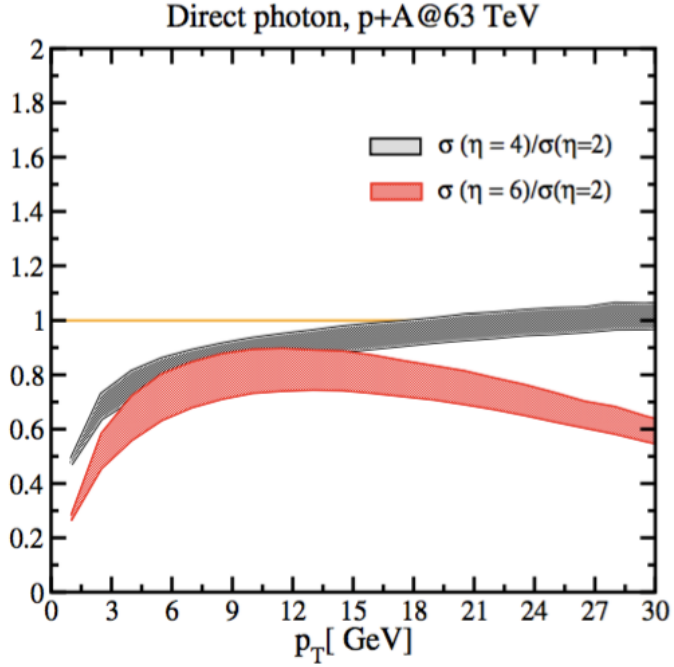
→ **N.Armesto**

Searching for saturation with photon measurements at large η

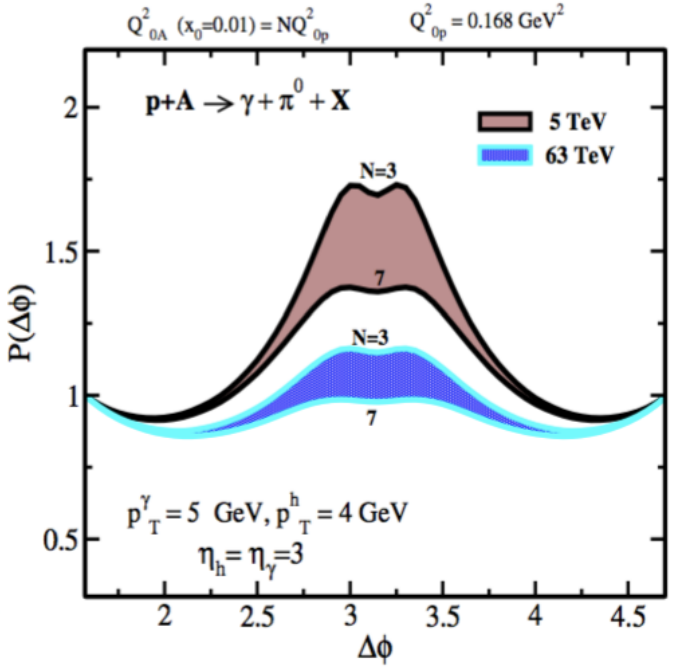
- Photon production at η~4-5 is sensitive to gluons at $x<10^{-6}$
- Photons are sensitive to the gluon density because they come dominantly from q-g scattering
- Two predictions of saturation:



γ suppression at forward η



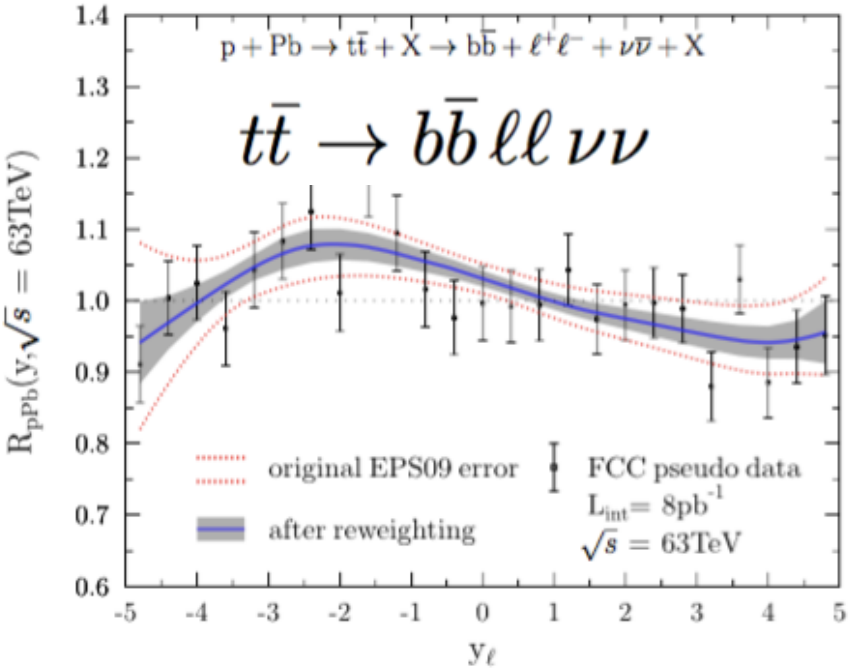
γ –π⁰ azimutal decorrelation

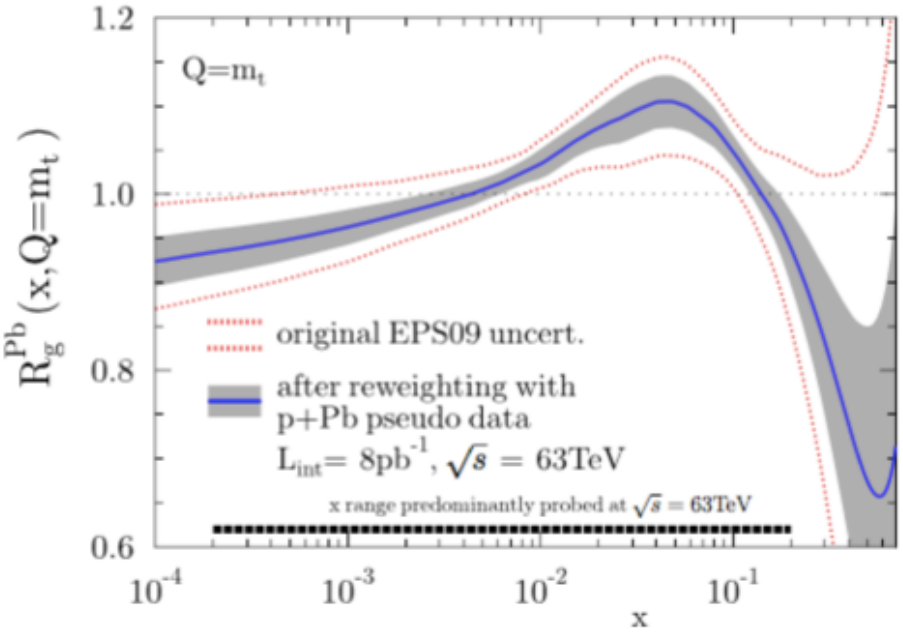


A. H. Rezaeian, *based on* PLB718 (2013) 1058–1069, arXiv:1210.2385

Constraining nuclear PDFs with top

- Within collinear factorisation, nuclear effects (including high-density effects at small-x) described using nuclear modifications to the proton PDFs:





- Top production measurements at FCC in p-Pb and in Pb-Pb can reduce by a factor ~2 the present uncertainty on the nPDFs at Q~m_{top}

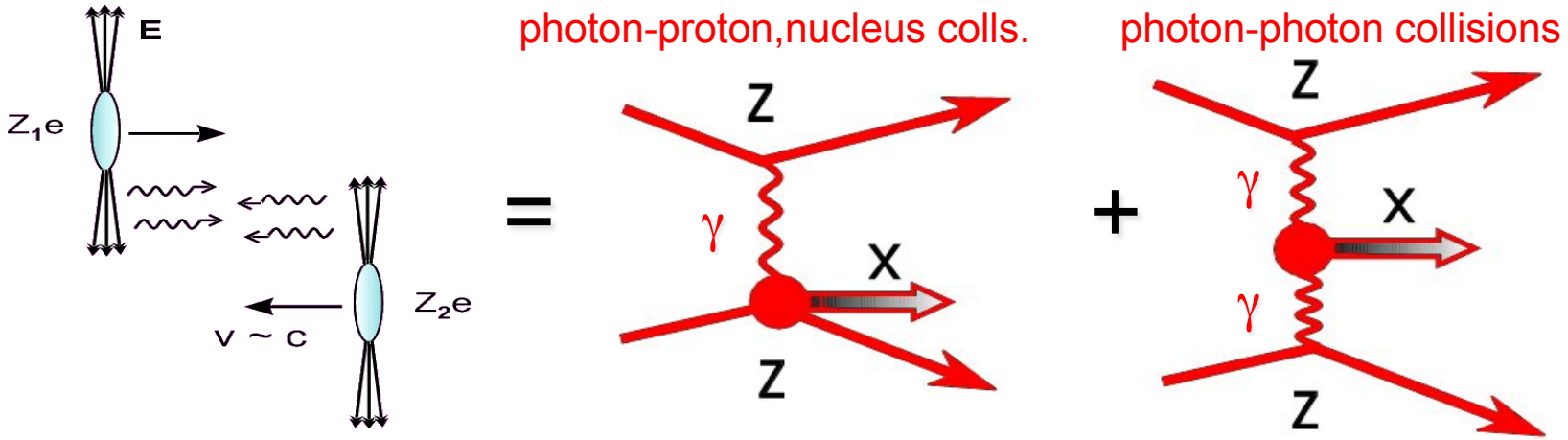
D. d'Enterria et al., PLB746 (2015) 64–72, arXiv:1501.05879

Outline

- Organization and physics report 2016
- Ions at the FCC: projected performance
- Quark-Gluon Plasma studies (high-density QCD in the final state of heavy-ion collisions)
- Small-x and gluon saturation (high-density QCD in the initial state)
- Contributions to other sectors of HEP and physics with injectors
  - Photon-photon collisions
  - Fixed target collisions with FCC or injector (LHC) beams
  - Possible New Physics searches with injectors
- Detector considerations

Photon-induced collisions

- Nuclei generate strong EM fields from coherent emission of Z=82 p's
- Photon-induced collisions can occur when two nuclei cross without interacting hadronically



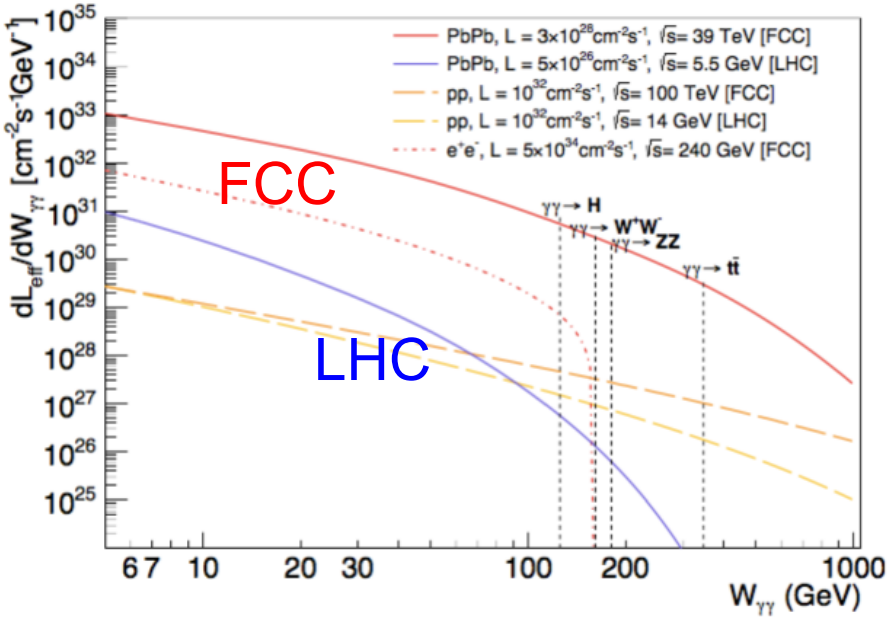
- Huge photon fluxes:
  - $\sigma(\gamma\text{-Pb}) \sim Z^2$ ($\sim 10^4$ for Pb) larger than in pp
  - $\sigma(\gamma\text{-}\gamma) \sim Z^4$ ($\sim 5 \cdot 10^7$ for Pb-Pb) larger than in pp

- Maximum c.m.s. energies for Pb-Pb at FCC:

$$\sqrt{s}_{\gamma\gamma} = W_{\gamma\gamma} \sim 1.2 \text{ TeV} \quad \sqrt{s}_{\gamma Pb} \sim 7 \text{ TeV}$$

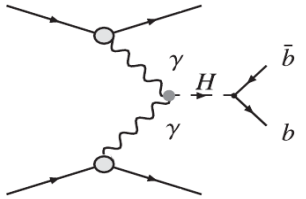
γγ physics at FCC (Pb-Pb)

- Effective lumi $dL_{eff}/dW_{\gamma\gamma}$ for γγ processes from LHC to FCC: $x10^2$ at low masses, $x10^4$ for Higgs, $x10^5$ for ZZ production
  - Unique tests for EW sectors of the SM

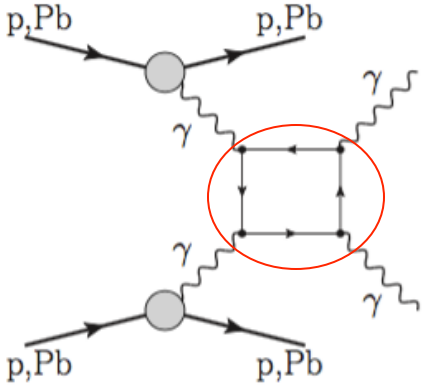


$$N_X = \int \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} W_{\gamma\gamma} \sigma_X^{\gamma\gamma}(W_{\gamma\gamma})$$

e.g. N_{higgs} >100 counts/month:



- γγ→γγ process has potential sensitivity to New Physics



P. R. Teles and D. d'Enterria, arXiv:1510.08141
D. d'Enterria and G. G. da Silveira, arXiv:1602.08088

Fixed-target collisions with FCC beams

- Fixed-target collisions with FCC (or LHC) p or Pb beams could be realized with either:
  - Beam extraction, fast (magnet) or slow (bent crystals technique)
  - Internal gas detectors, à la LHCb-SMOG

	p@LHC	Pb@LHC	p@FCC	Pb@FCC
Nucleon–Nucleon c.m.s. energy ($\sqrt{s_{\rm NN}} = \sqrt{2E_b m_N}$) [GeV]	114.6	72.0	306.6	192.5
$\Delta y^{\rm lab}_{\rm c.m.s.} = \ln(\gamma^{\rm lab}_{\rm c.m.s.} + \sqrt{(\gamma^{\rm lab}_{\rm c.m.s.})^2 - 1})$	4.80	4.33	5.79	5.32

- Luminosity and physics opportunities for LHC case are discussed in detail in the context of the AFTER@LHC proposal
- Heavy ion studies:
  - c.m.s. energy similar to RHIC energies
  - much larger luminosity and access to (very) backward rapidity region would enable unique and high-precision studies, e.g. related to quarkonium production and its cold and hot nuclear matter effects

AFTER: see e.g. S. J. Brodsky, et al., Phys. Rept. 522 (2013) 239–255, arXiv:1202.6585

New Physics searches with injectors

- Physics with (proton) extracted beams is one of the items that are discussed in the WG on "Physics with FCC-hh injectors"
  - See ch. 5 of the FCC-hh physics report (ed. B.Goddard, G.Isidori, F.Teubert)
  - Here just a short advertisement
- The following SM-precision / searches for NP beyond SM could be improved using the injectors
  1. Search for dark-sector particles using a high-intensity proton beam dump from the SPS (SHiP concept)
  2. Likewise, high precision measurement of rare kaon decays (e.g. $K_L \rightarrow \pi\nu\nu$, à la NA62)
  3. Search for flavour changing transitions through B, D, K and τ decays using a "LHCb-like" high-lumi collider experiment at the FCC-hh HEB (High Energy Booster), be it the SPS or the LHC
  4. Measurement of the proton electric-dipole moment (EDM) with sensitivity matching SM prediction ($<10^{31}$ e×cm), using polarized protons from the injectors

Back to HI: detector considerations

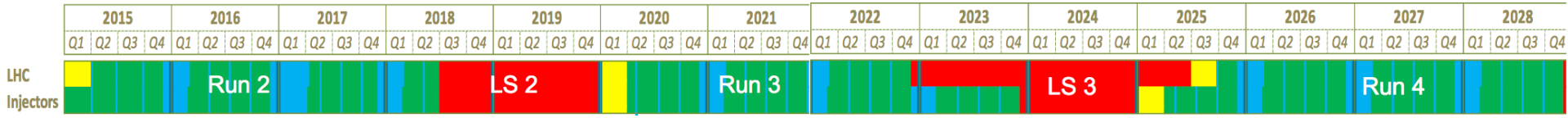
- So far we concentrated on the physics case, no studies for detector design yet
- Before considering a dedicated detector, we should consider the possibilities offered by the pp-dedicated detectors
- Possibly giving inputs for specific features
- Examples:
  - Robust tracking with $dN_{ch}/d\eta$ ~ 3500
  - Low-p_T tracking (<500 MeV) → run at lower B field (if necessary)?
  - Hadron ID → to be studied (Silicon dE/dx, TOF, RICH …)
  - Forward coverage for small-*x* studies (already foreseen for pp)
  - Jet, W/Z, top reconstruction (already foreseen for pp)

Summary

- We have a **first report** on HI projected performance and physics opportunities, with **focus on novel aspects wrt LHC**
- Pb-Pb energy: **39 TeV; L_{int} projections >10x LHC programme**
- Study of the Quark-Gluon Plasma
  - Larger temperature, volume and particle multiplicity entail potentially unique aspects, e.g. **onset of collectivity in small systems (pp, pA) and thermal production of charm**
  - Larger √s and L_{int} → **new hard observables, e.g. top, sensitive to early stages and time evolution of the medium**
- Study of gluon densities at small *x*
  - Higher energy and large nuclei → **unique access to saturation region (down to $x<10^{-6}$)** with perturbative probes, e.g. forward-*y* photons; unique access to **[small-x, large-Q^2] region with top**, W, Z
- Interesting and unique contributions to other sectors of HEP:
  - Photon-photon collisions
  - Fixed-target collisions with extracted beams
  - Input to collision models for ultra-high-energy cosmic rays

EXTRA SLIDES

Timeline of future HI running at the LHC



~0.3-1.5 nb^{-1} PbPb LS2 ~2-4 nb^{-1} PbPb LS3 ~10 nb^{-1} PbPb

Experiments request/goal:

Also corresponding pp reference

PbPb	PbPb	pPb?
5.1TeV	5.1TeV	8.2TeV

Also corresponding pp reference

ArAr pPb PbPb
5-8 TeV

PbPb pp (?)
5.5 TeV

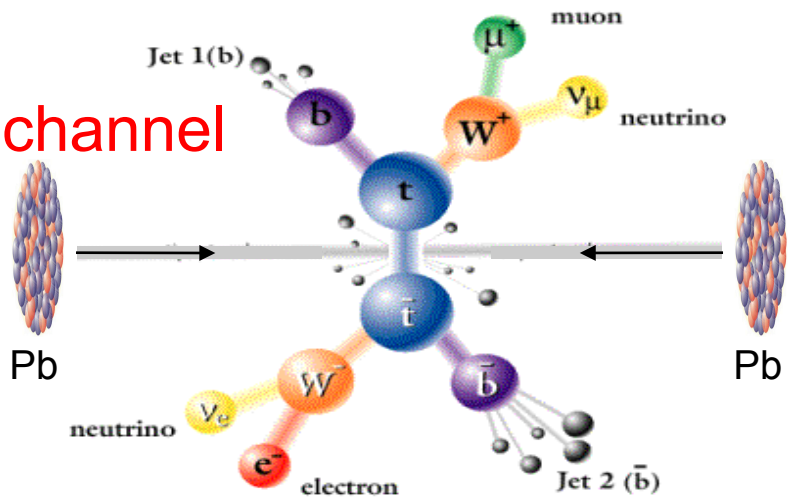
- Run 2 (LS1→LS2): Pb-Pb ~1/nb or more, at $\sqrt{s_{NN}}$ ~ 5.1 TeV
- LS2: major ALICE and LHCb upgrades, important upgrades for ATLAS and CMS, LHC collimator upgrades
- Run 3 + Run 4: Pb-Pb >10/nb, at $\sqrt{s_{NN}}$ ~ 5.5 TeV
- pp reference and p-Pb in both Runs 2 and 3-4

HI-HL-LHC Programme (not exhaustive!)

- **Jets:** characterization of energy loss mechanism both as a testing ground for the multi-particle aspects of QCD and as a probe of the medium density
  - Differential studies of jets, b-jets, di-jets, γ/Z-jet at very high p_T (focus of **ATLAS** and **CMS**)
  - Flavour-dependent in-medium fragmentation functions (focus of **ALICE**)
- **Heavy flavour:** characterization of mass dependence of energy loss, HQ in-medium thermalization and hadronization, as a probe of the medium transport properties
  - Low-p_T production and elliptic flow of several HF hadron species (focus of **ALICE**)
  - B and b-jets (focus of **ATLAS** and **CMS**)
- **Quarkonium:** precision study of quarkonium dissociation pattern and regeneration, as probes of deconfinement and of the medium temperature
  - Low-p_T charmonia and elliptic flow (focus of **ALICE**)
  - Multi-differential studies of Υ states (focus of **ATLAS** and **CMS**)
- **Low-mass di-leptons:** thermal radiation γ ($\rightarrow e^+e^-$) to map temperature during system evolution; modification of ρ meson spectral function as a probe of the chiral symmetry restoration
  - (Very) low-p_T and low-mass di-electrons and di-muons (**ALICE**)

Top quarks in Pb-Pb at HL-LHC and FCC

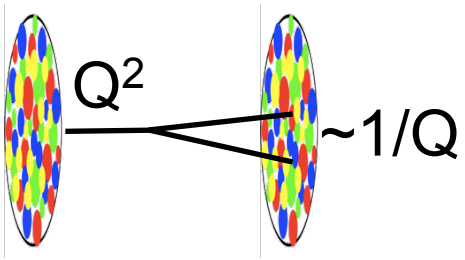
- $t\bar{t}$ decay channels:
  - 10% $b\bar{b} + \ell\ell + \not{E}_T$ observation channel
  - 44% $b\bar{b} + \ell + 2\,jets + \not{E}_T$
  - 46% $b\bar{b} + 4\,jets$



- Estimate for observation channel in CMS (CMS PAS-FTR-2013-025)
- → **~500 events for 10 nb^{-1} Pb-Pb 5.5 TeV ("HL-LHC")**
- FCC: with 100 nb^{-1}, x800 more wrt HL-LHC
- → **FCC** with CMS-like setup, **~4x10^5** for "observation channel"
  - could be 4-5x more in the other channels (but higher background)
- → few 10^3 with $p_T > 0.5$ TeV
- → few 10^2 with $p_T > 1$ TeV

Saturation scale

- Onset of non-linear QCD when gluons are numerous enough (low-x) & extended enough (low-Q^2) to overlap:

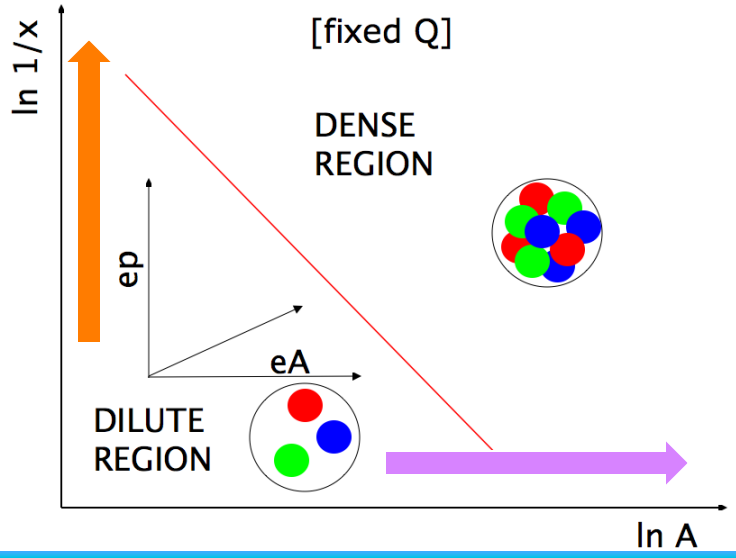


$$\frac{1}{Q^2} \cdot Ag(x,Q^2) \sim \pi R_A^2 \sim \pi A^{2/3}$$

gluon "area" — number of gluons — nuclear overlap

Saturation scale:

$$Q_S^2 \sim \frac{Ag(x,Q_S^2)}{\pi A^{2/3}} \sim A^{1/3} g(x,Q_S^2) \sim A^{1/3} \frac{1}{x^\lambda} \sim A^{1/3} \left(\sqrt{s}\, e^y\right)^\lambda \quad (\lambda \sim 0.3)$$



Saturation affects process with $Q^2 < Q_S^2$

Explore saturation region:

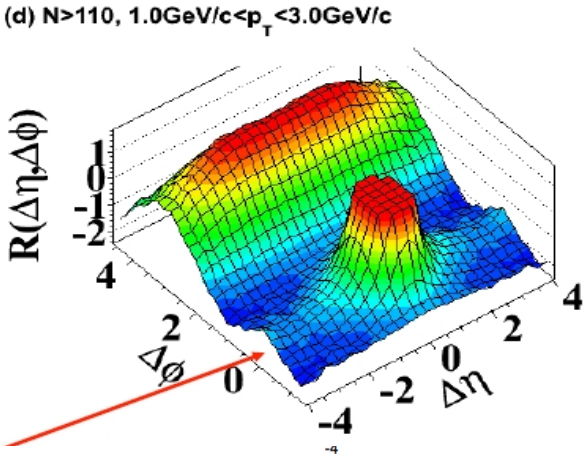
→ **decrease *x* (larger √s, larger *y*)**

→ **increase A**

High-multiplicity events in small systems

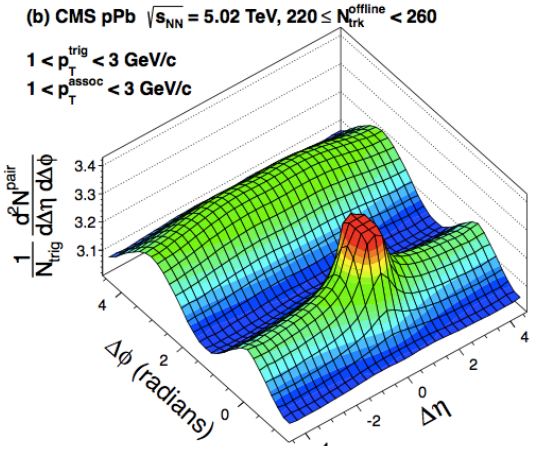
- One of the most interesting findings of the LHC HI programme: similarity of long-range correlations (ridge) in high-mult pp, pPb as in Pb-Pb collisions
- Similar mechanism? Collectivity in small high-density systems? Initial or final state collectivity?

pp, high mult



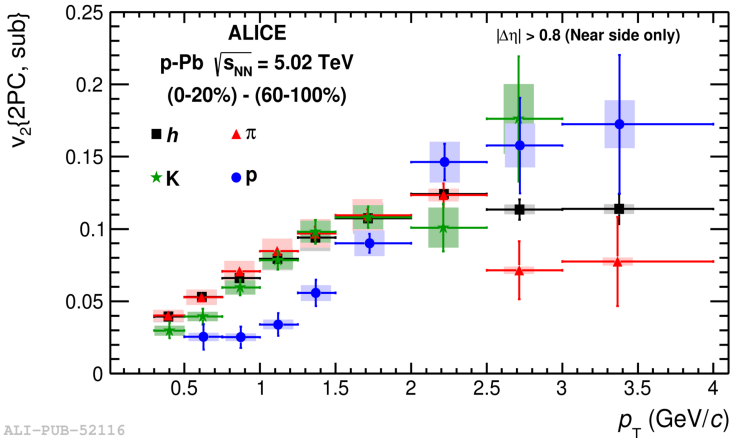
CMS, JHEP 1009 (2010) 091

pPb, high mult



CMS, PLB 724 (2013) 213

pPb, high mult



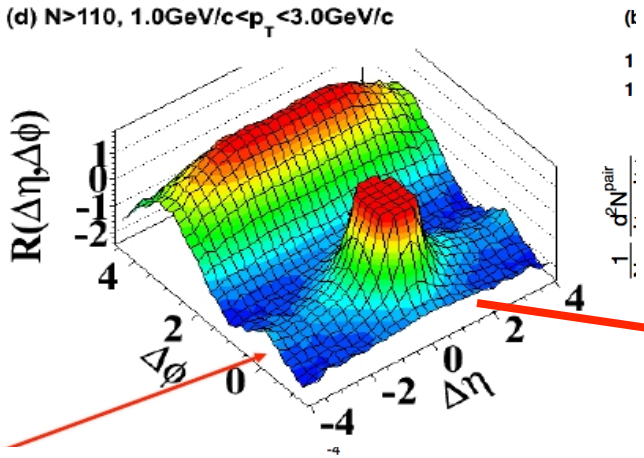
ALICE, PLB726 (2013) 164

- Increased energy and luminosity of FCC could be a unique opportunity to explore more extreme multiplicities and study QCD mechanisms that lead to thermalization/collectivity

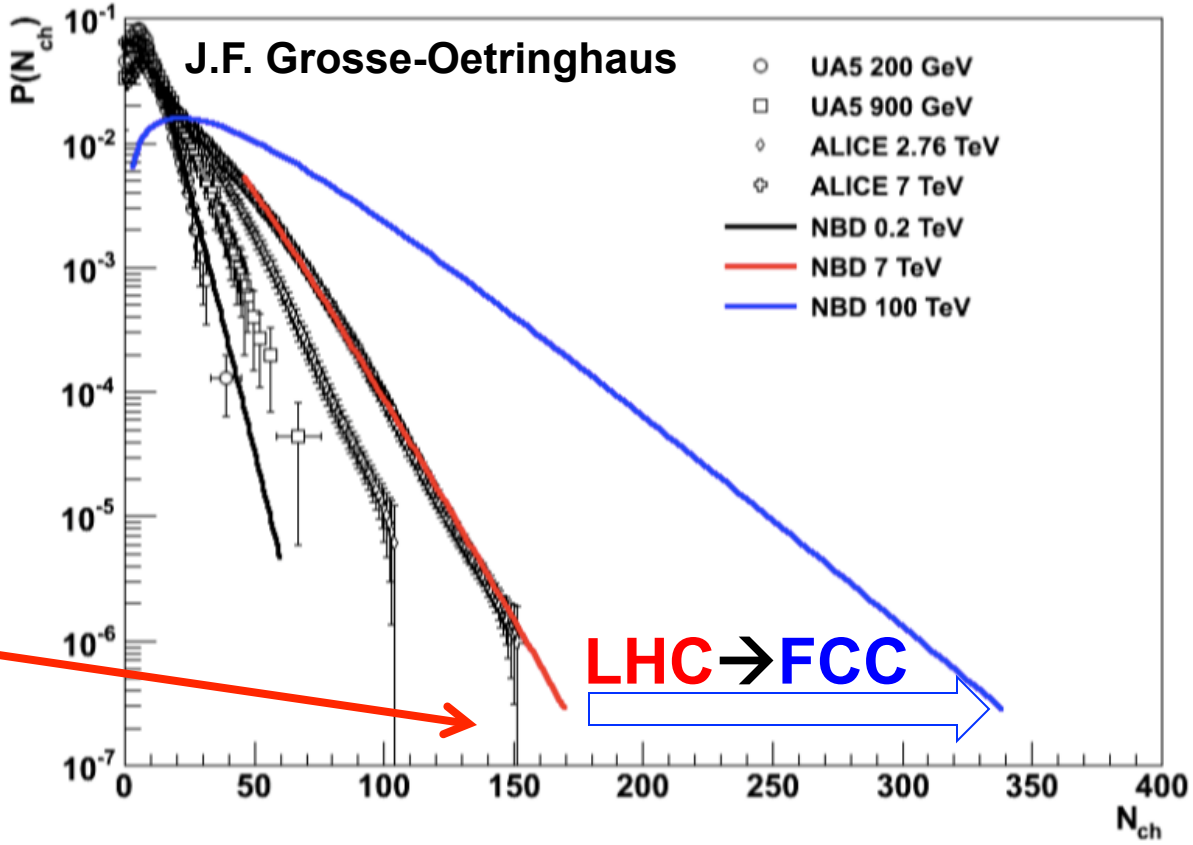
High-multiplicity events in small systems

- One of the most interes
  long-range correlations
- Similar mechanism? Cc
  final state collectivity?

pp, high mult

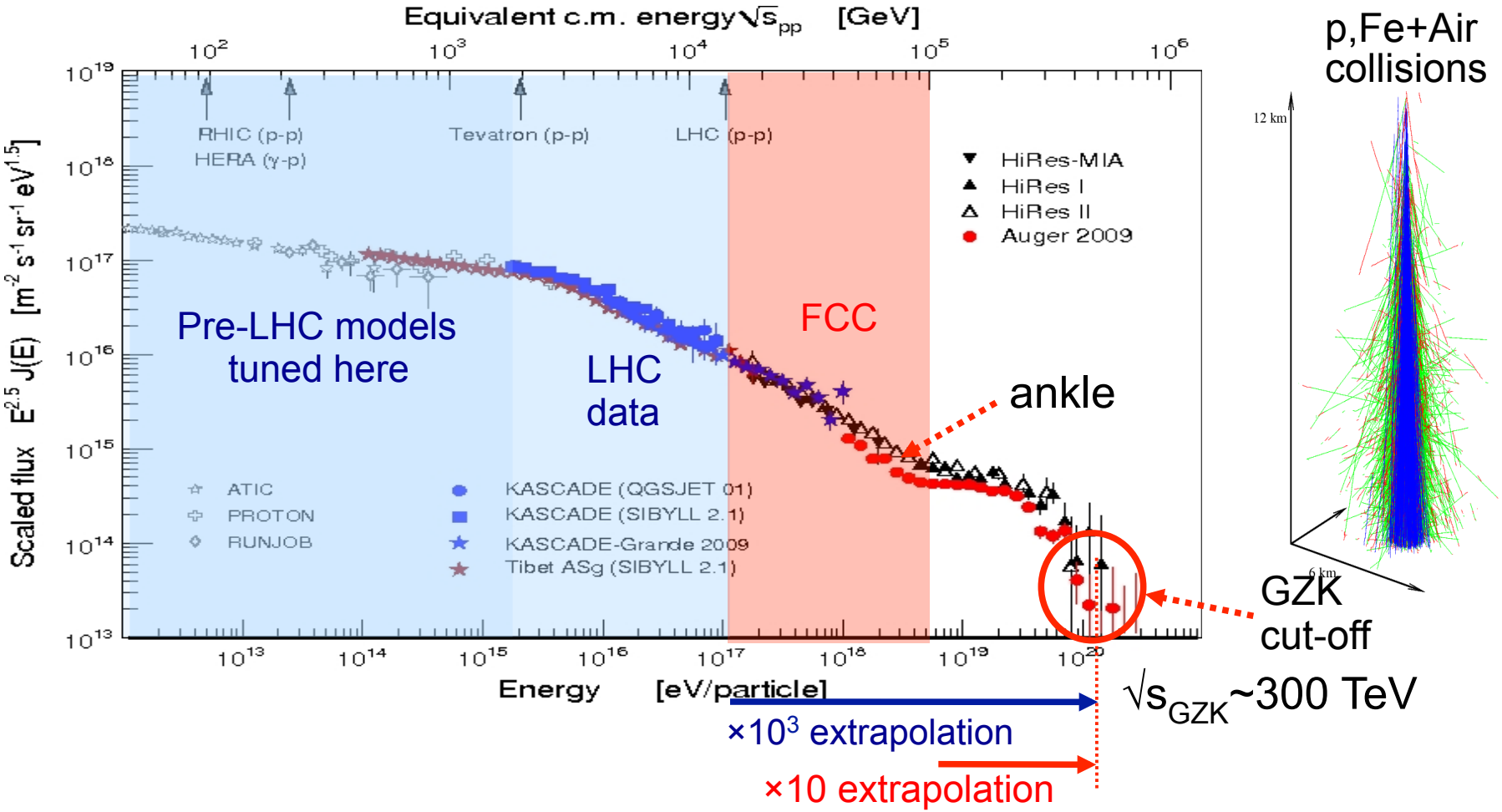


CMS, JHEP 1009 (2010) 091



- Increased energy and luminosity of FCC could be a unique opportunity to explore more extreme multiplicities and study QCD mechanisms that lead to thermalization/collectivity

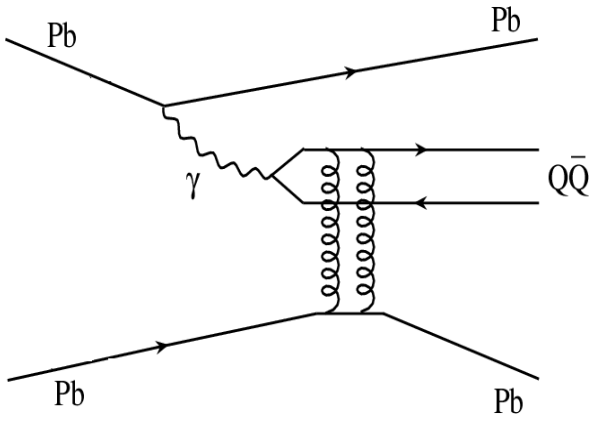
Cosmic-rays MC tuning with FCC (Pb-Pb)

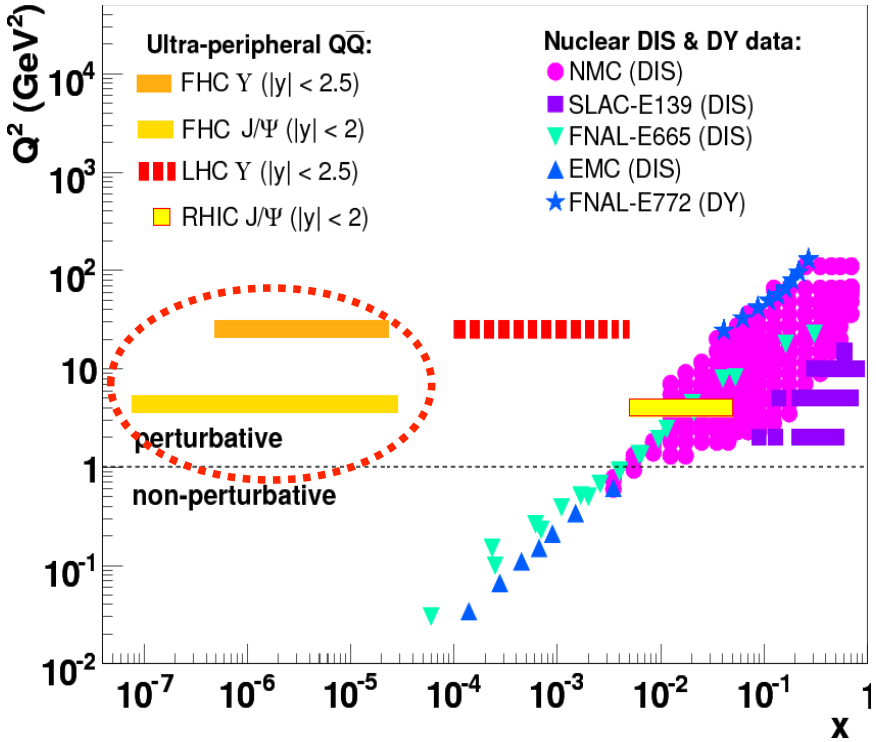


FCC pA and AA probe ankle-energy and provides strong constraints for hadronic Monte Carlos for UHECR (p,Fe+Air)

γ-Pb collisions as a tool to search for gluon saturation

- Quarkonium production in γ-Pb: sensitive to very small-*x* gluon density → powerful handle on saturation region with perturbative probes





- Exclusive Q-Qbar: $x \sim m^2_{QQ}/s_{\gamma p,\gamma Pb} \sim 10^{-7}$

~2 orders of magnitude below LHC!