FCC heavy-ion physics studies

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

Outline

- Organization and documents (Physics YR and CDR)
- 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)

Organization and documents

- Ions at FCC-hh Working Group:
  - Sub-group of "FCC-h Physics, Experiments, Detectors"
  - Machine studies: J. Jowett, M. Schaumann, E. Logothetis Agaliotis
  - Twiki https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HeavyIons
- A few workshops/meetings 2013-17
  - https://indico.cern.ch/event/331669/ and links therein
- In FCC-hh Physics YR 3, 635–692, arXiv:1605.01389
  - 40 pages, about 50 authors
  - 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
- In preparation for FCC CDR:
  - Vol. 1 (FCC Physics): red. version of YR + updates (~15 pages)
  - Vol. 2 (FCC-hh): executive summary (2 pages)

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Energies and luminosity studies

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

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

- Operation scenarios and luminosity projections
  - 2015 - first study on operation scenario and estimates of luminosity: L_{int}/month ~ 8/nb for Pb-Pb, with 1 injection from LHC
    - M. Schaumann, Phys. Rev. ST Accel. Beams 18 (2015) 9, 091002, arXiv:1503.09107
  - 2016 - optimised with **4 injections** and Run-2 LHC parameters: x9 in L_{int} **(Baseline scenario)**
  - 2017 - optimised filling scheme, bunch spacing, turn-around: x3 in L_{int} (**Ultimate scenario)**, introduced also scenario with 2 IPs
    - M. Schaumann, talk at FCC Week 2017
  - Ongoing: ions lighter than Pb (e.g. Ar, Kr) could allow for further increase of “equivalent” L_{int}

Luminosity for Pb-Pb and p-Pb

→ Talk by J. Jowett, https://indico.cern.ch/event/656491/contributions/2939104/

- Ultimate vs. baseline scenarios: reduced bunch spacing (50 ns) and β* (0.3 m)

	Unit	Baseline		Ultimate	
Operation mode	-	Pb-Pb	p-Pb[a]	Pb-Pb	p-Pb[a]
Centre-of-mass energy per nucleon	[TeV]	39.4	62.8	39.4	62.8
No. of bunches	-	2760		5400	
Bunch spacing	[ns]	100		50	
No. of particles per bunch	$[10^8]$	2	164	2	164
Transv. norm. emittance	[μm.rad]	1.5	3.75	1.5	3.75
β-function at the IP	[m]	1.1		0.3	
Number of IPs in collision	-	1 or 2		1 or 2	
Initial luminosity	$[10^{27}\text{cm}^{-2}\text{s}^{-1}]$	34	2800	248	20400
Peak luminosity (1 experiment)	$[10^{27}\text{cm}^{-2}\text{s}^{-1}]$	80	13300	320	55500
Integrated luminosity (1 experiment)	$[\text{nb}^{-1}/\text{run}]$	35	8000	110	29000
Integrated luminosity (2 experiments)	$[\text{nb}^{-1}/\text{run/exp.}]$	23	6000	65	18000

Includes 50% operation efficiency

- >100/nb in a 1-month Pb-Pb in ultimate scenario: ~ 10x full LHC programme
- 15 1-month HI runs in tentative FCC-hh schedule

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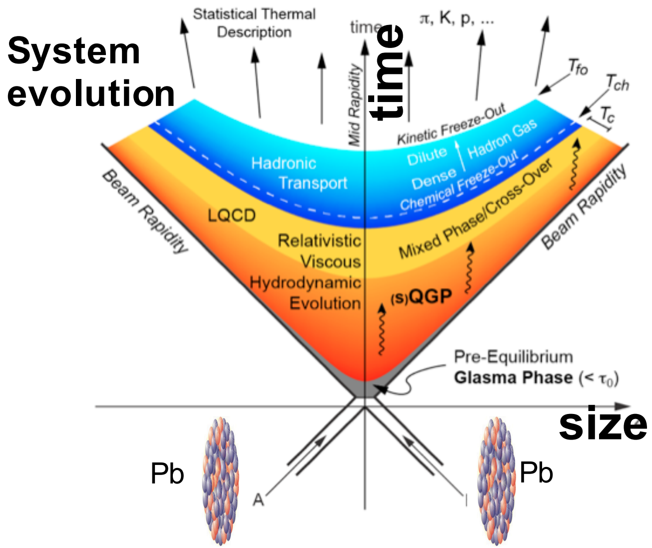
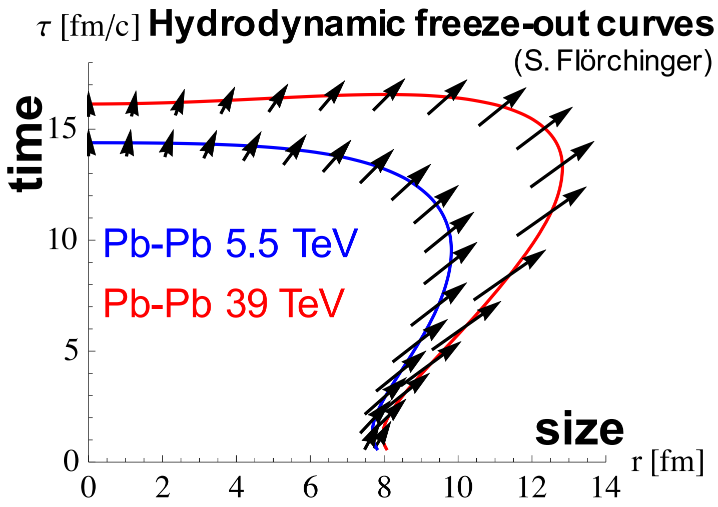
  - Global properties and collective effects
  - Hard probes and jet quenching
- Small-x and gluon saturation (high-density QCD in the initial state)

Quark-Gluon Plasma studies at FCC





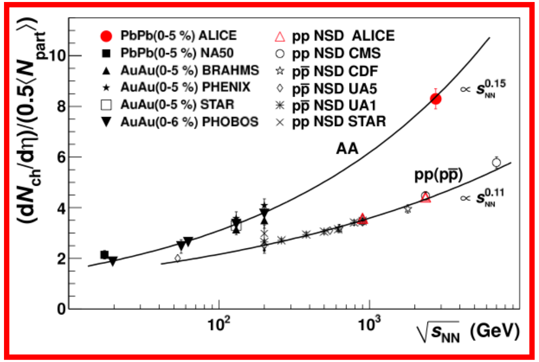
Properties of QGP:

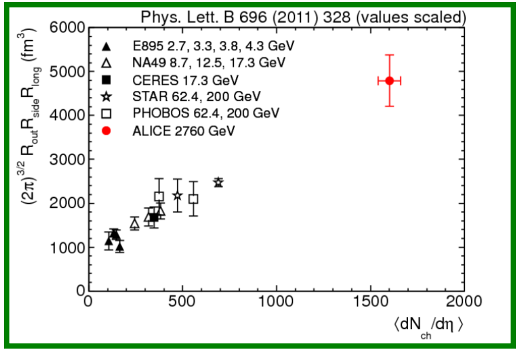
- QGP volume increases strongly
- QGP lifetime increases
- Initial temperature higher
- Equilibration times reduced

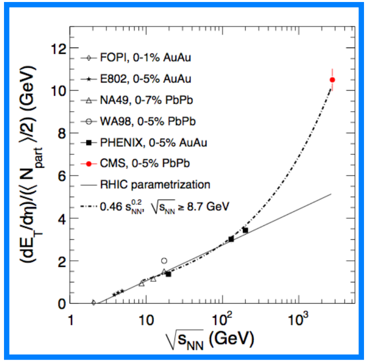
QGP "fireball": global properties

- 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**





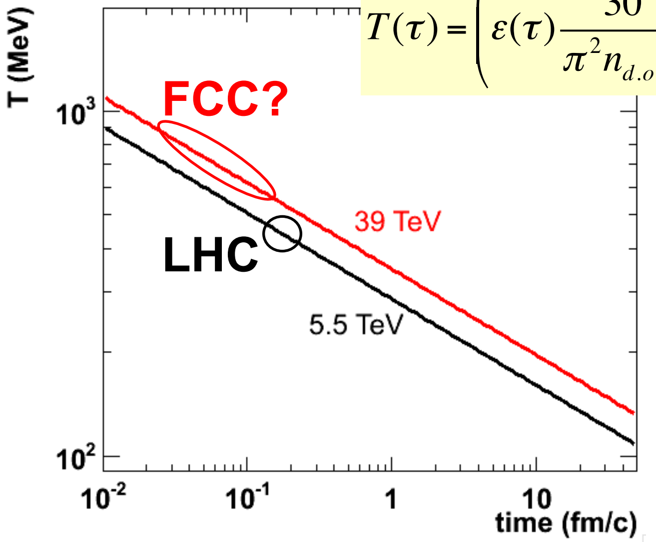


Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	1.8–2.0 TeV	2.3–2.6 TeV	5.2–5.8 TeV
Homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
Decoupling time	10 fm/c	11 fm/c	13 fm/c
ε at $\tau = 1$ fm/c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

Higher QGP temperature: thermal charm?

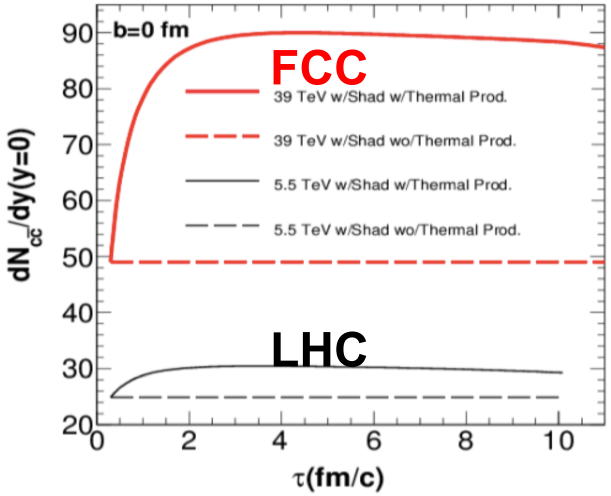
- Simple estimate (from Bjorken + Stefan-Boltzmann):

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



- 20% larger for the same time
- QGP formation time could be smaller at FCC
- Initial temperature could reach close to 1 GeV

- Expect abundant thermal production of charm in the QGP from $gg \to c\bar{c}$, $q\bar{q} \to c\bar{c}$ + NLO …



- Up to 100% increase 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

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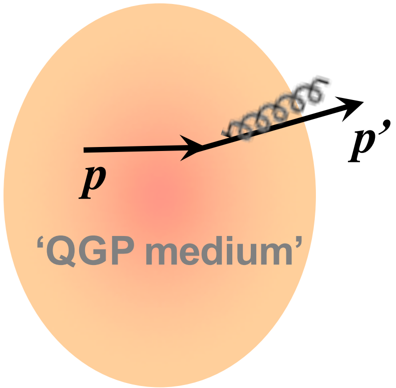
Parton energy loss in the QGP

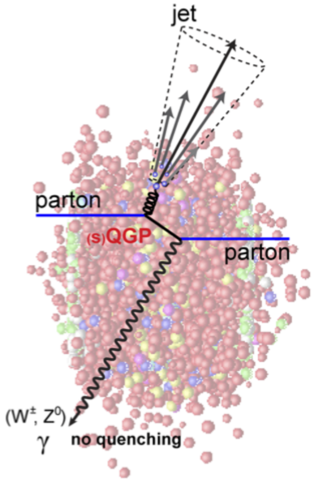
- High-energy partons from hard scattering lose energy while crossing the QGP, mainly via radiation of gluons

- Unique tool to learn about the QGP "opacity" and the properties of the QCD interaction in an extended medium

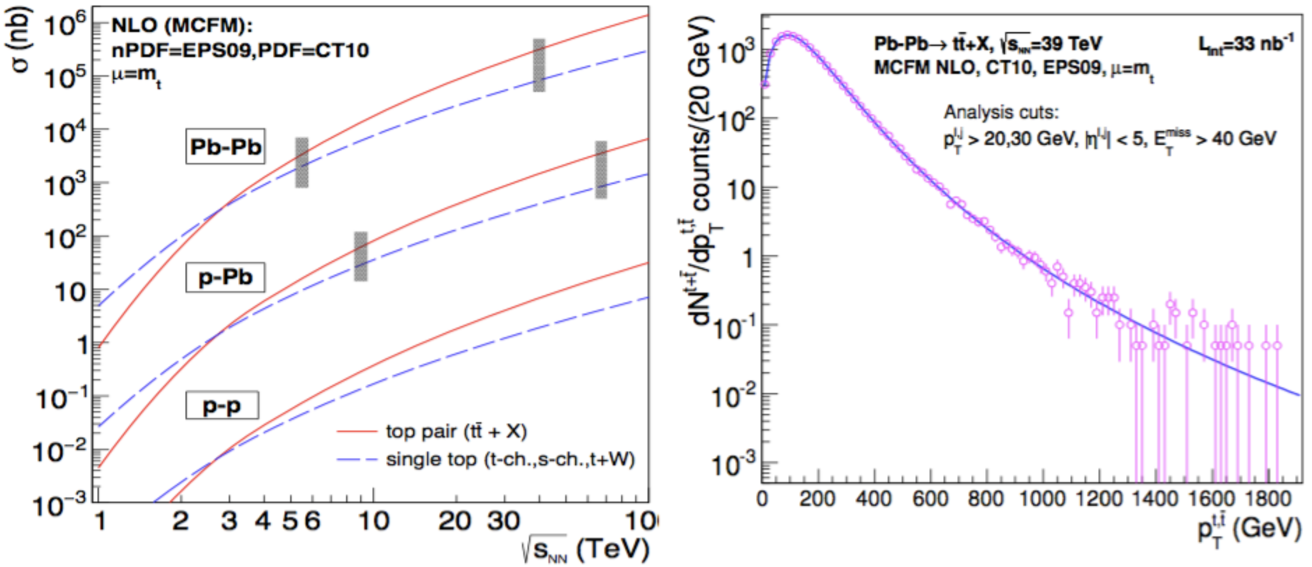
- At the LHC, the focus is progressively shifting towards flavour-tagging and correlations (di-jets and boson-jet)
  - γ(Z)-jet provides a measurement of the initial parton energy

- FCC: increase of $\sqrt{s}$ and L_{int} by ~ x10 at FCC will make available novel ways to probe the QGP, e.g. top … and Higgs





Top production at FCC energy

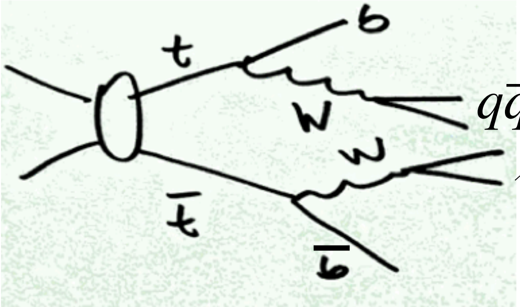


- Top cross section increases by x80 from 5.5 TeV to 39 TeV
- Kinematic simulation study: 3x10^5 $t\bar{t} \rightarrow b\bar{b}\,\ell\ell\,\nu\nu$ per run in the baseline scenario (35/nb)
- Top p_T distribution up to ~ 2 TeV/c

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

Boosted color singlets from top events

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



$q\bar{q}$

$\ell\nu$

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 top and of the W

The rest of the final state

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

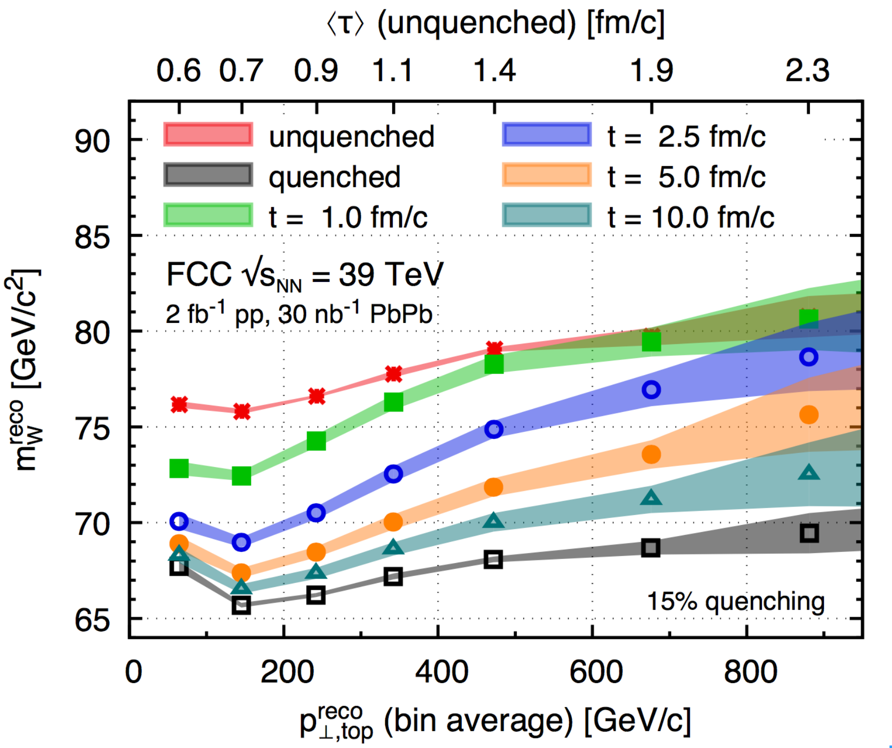
is used to tag the event topology

- 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 of the top and W
  2. Role of color coherence in parton energy loss, because the pair is initially a color singlet

Boosted color singlets from top events

- 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

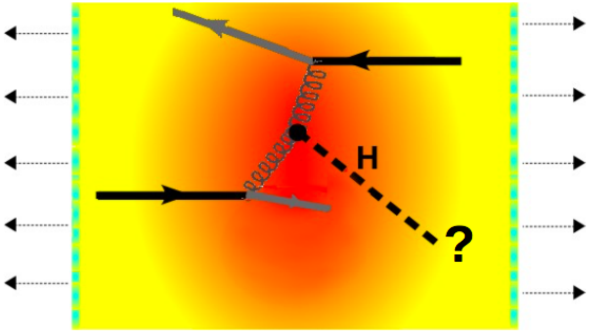
Kinematic simulation study, Pb-Pb 39 TeV (30/nb)

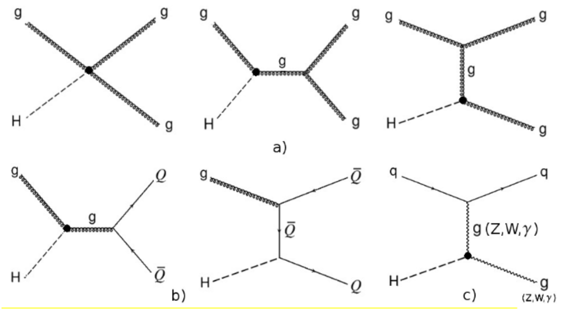


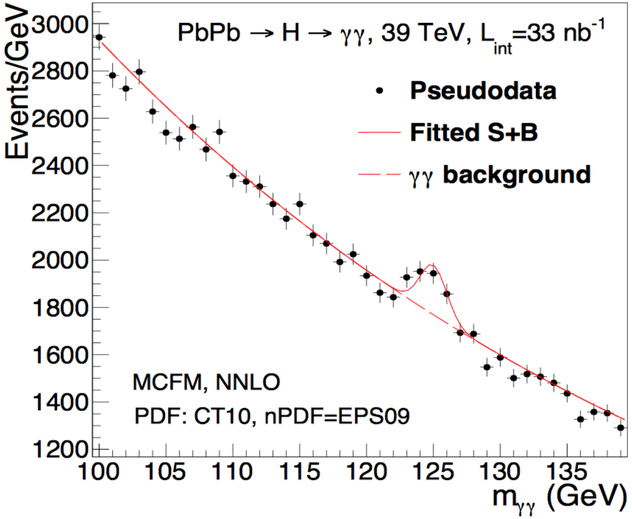
Apolinario, Milhano, Salam, Salgado, arXiv:1711.03105

Probing the QGP with Higgs bosons ?

- Higgs lifetime τ ~50 fm/c > QGP lifetime ~10 fm/c
- Strong interaction with QGP gluons induces decay to gg (g+H → gg) depleting its decay channels to $\gamma\gamma$ and ZZ*
- First estimate of absorption cross section: ~10 μb
- → gives suppression by x2 in central Pb-Pb







- First estimate of significance with FCC reference detector:
- ~ 5 (10) σ in one Pb-Pb month with baseline (ultimate) L_{int}

  → **Promising!**

D. d'Enterria, arXiv:1701.08047, D. d'Enterria, C. Loizides, in preparation

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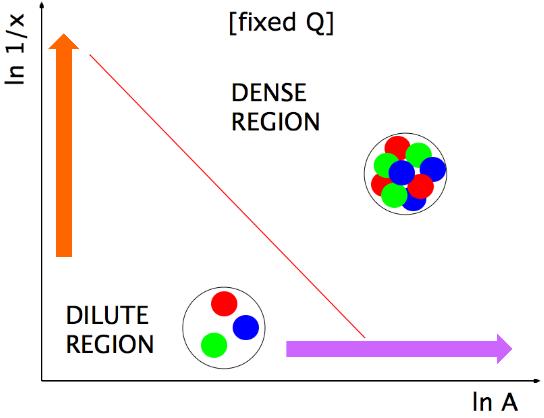
  - With hadronic heavy-ion collisions
  - With photon-induced collisions

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



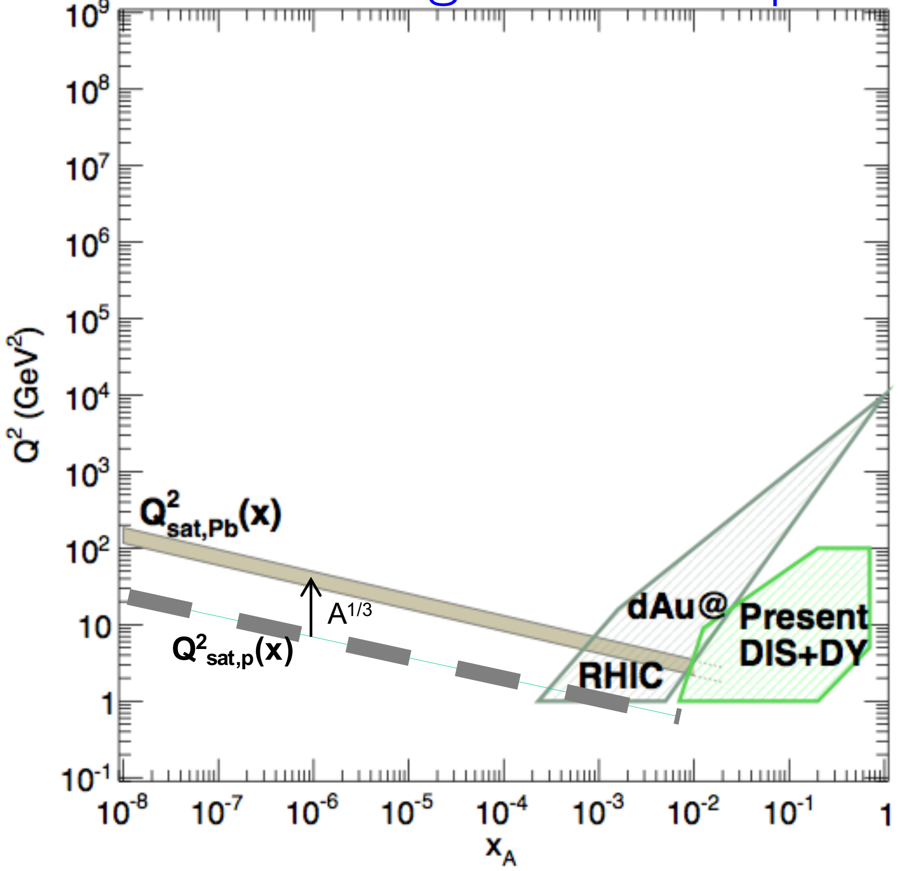
Saturation affects process with $Q^2 < Q_S^2$

Explore saturation region:

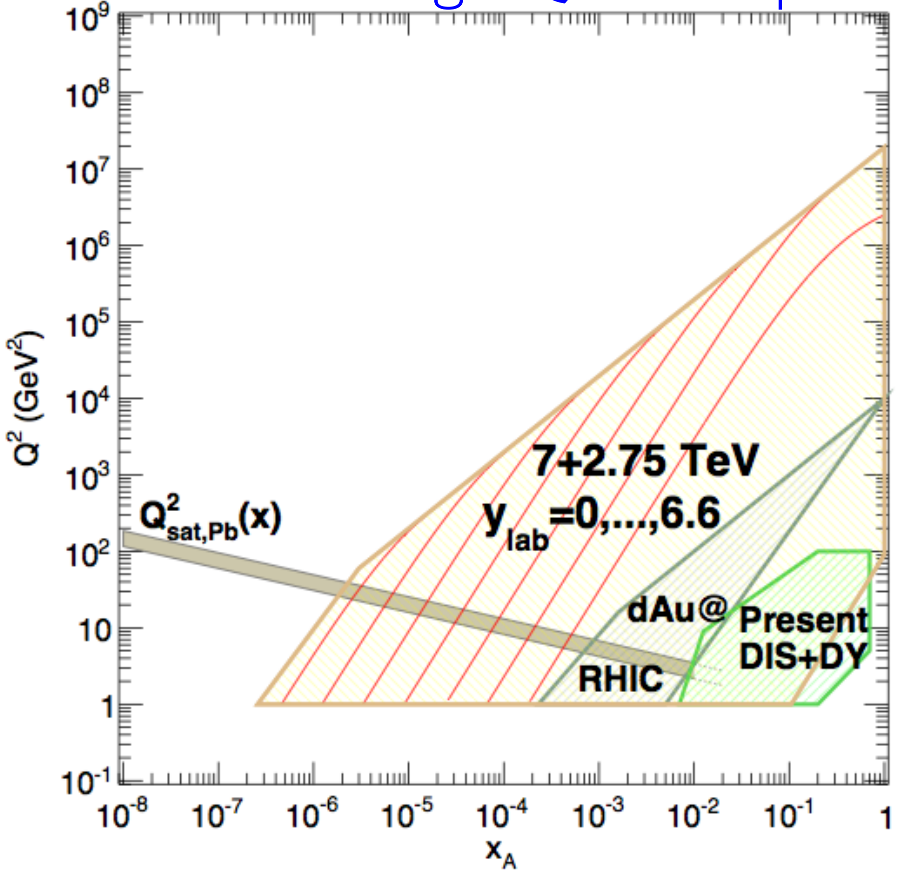
→ **decrease *x* (larger √s, larger *y*)**

→ **increase A**

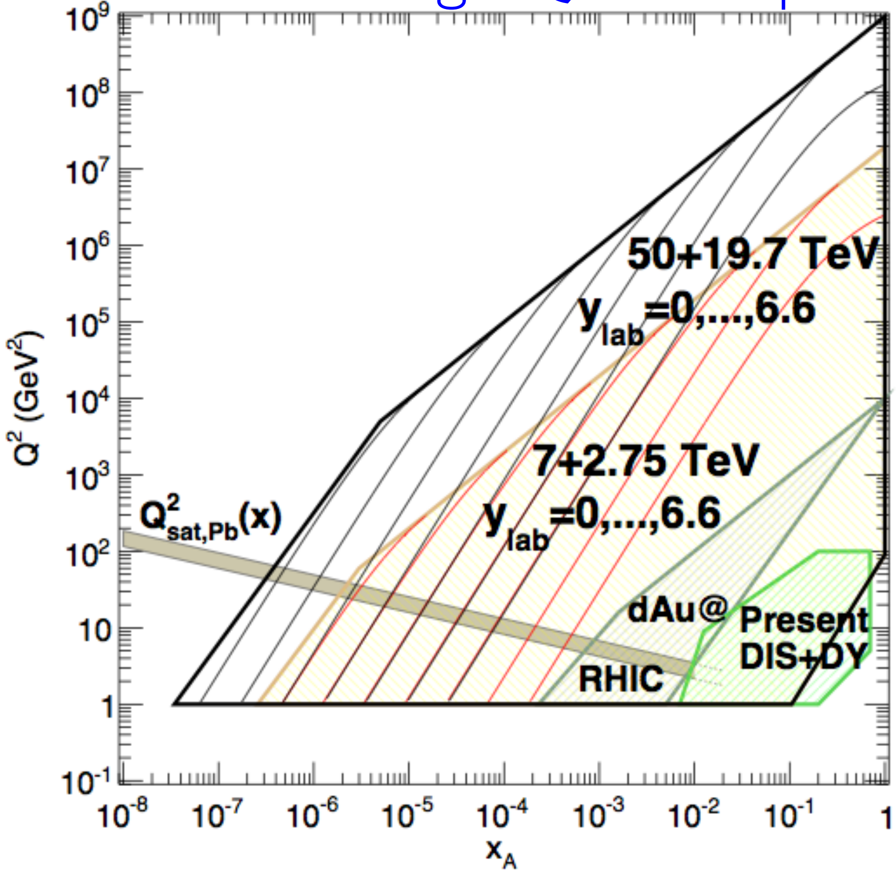
Kinematic coverage Q^2 vs. x: pre-LHC



Kinematic coverage Q^2 vs. x: pA LHC



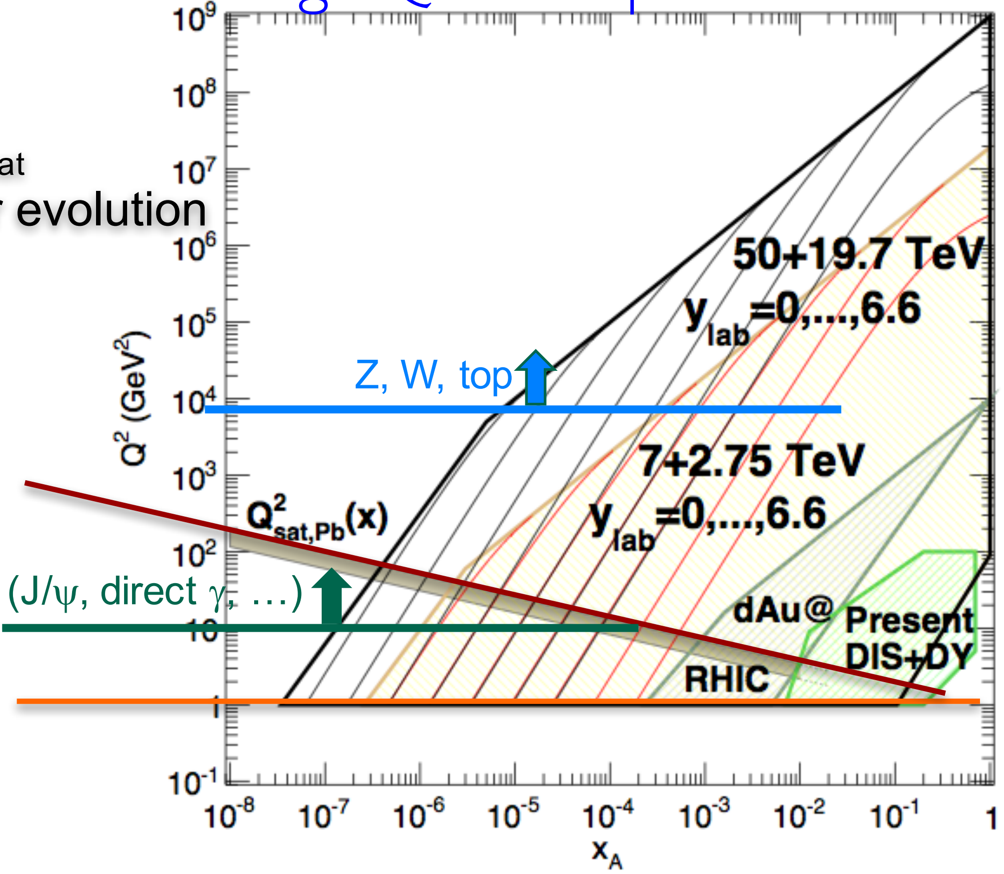
Kinematic coverage Q^2 vs. x: pA FCC



Kinematic coverage Q^2 vs. x: pA FCC

Goals:

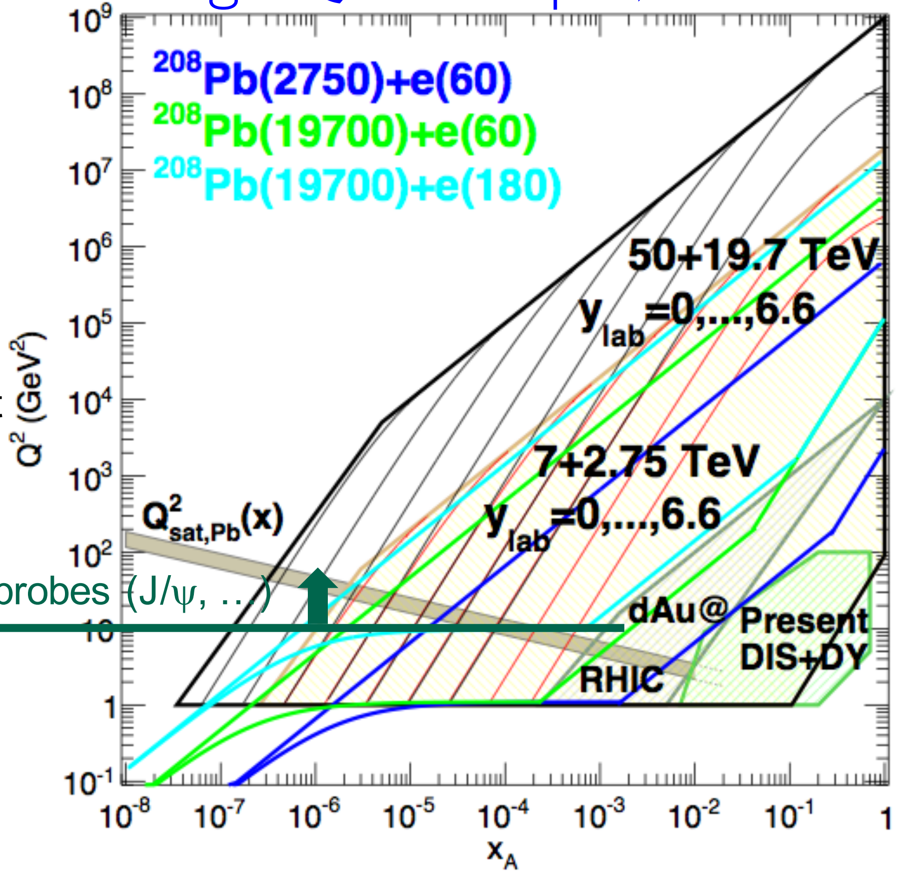
- determine Q^2_{sat}
- test non-linear evolution



Kinematic coverage Q^2 vs. x: pA, eA FCC

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

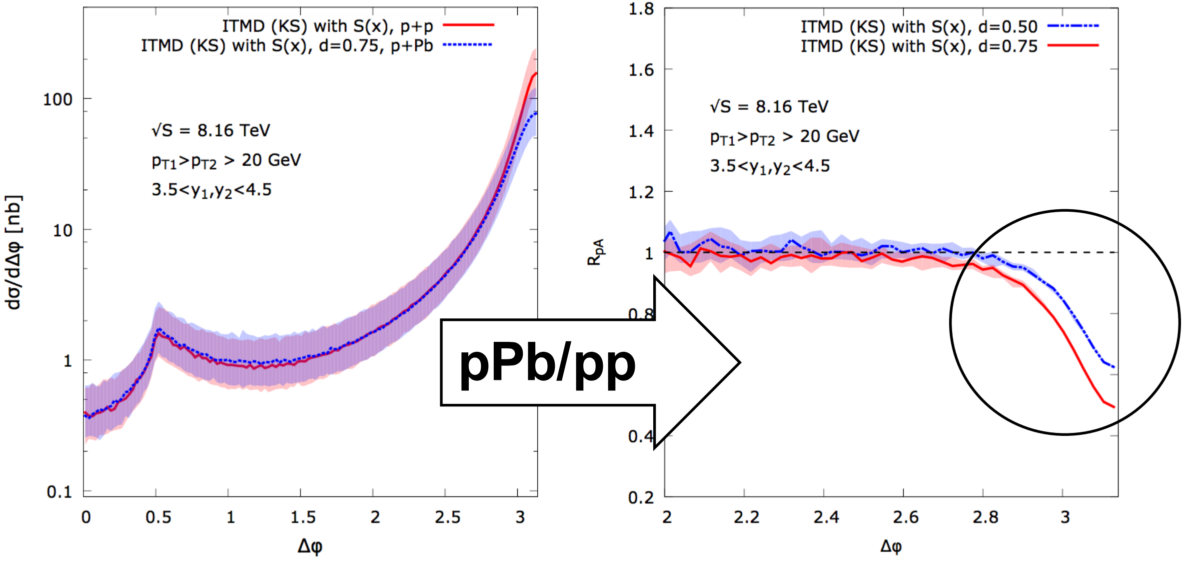
eA at FCC:
down to $x<10^{-5}$ with perturbative probes, but fully constrained parton kinematics

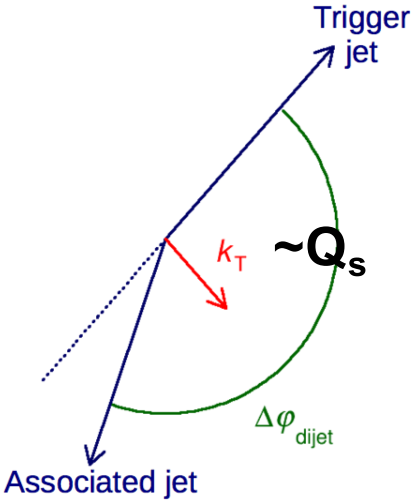


Perturbative probes (J/ψ, ...)

Searching for saturation with forward di-jet measurements in p-Pb

- Saturation effects → azimuthal decorrelation of di-jets
- Focus on di-jets with rapidity 3-5: small-x partons in the Pb
- Decorrelation k_T would be of the order of Q_s (~ few GeV)

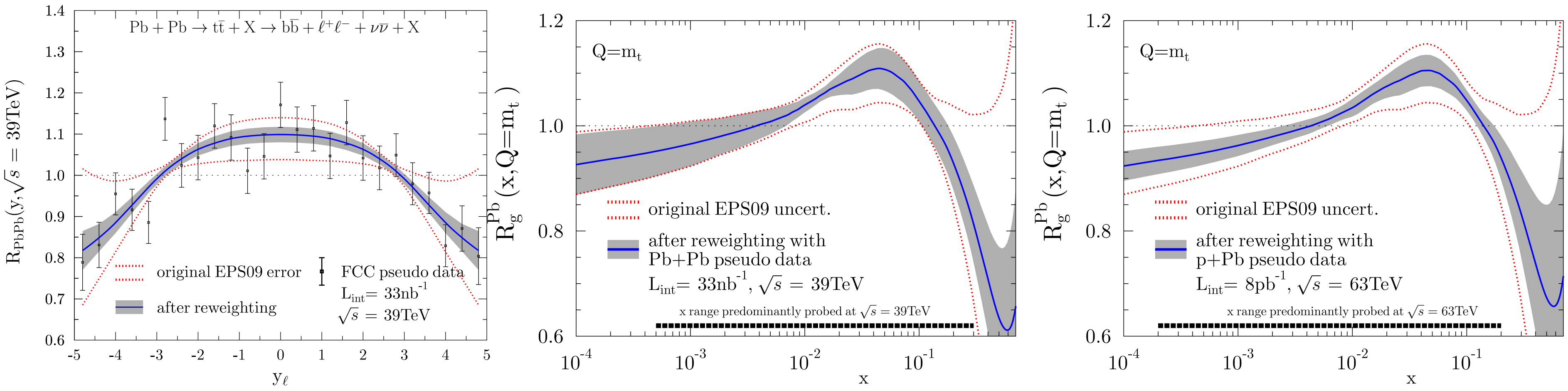




C. Marquet et al., *based on* JHEP 1612 (2016) 034

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}, in particular at x > 0.1 (EMC region)

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

Summary

- Contributions to the **FCC CDR** are being prepared, **focus on novel aspects wrt LHC**

- Pb-Pb energy: **39 TeV**; **L_{int}/month projections >10x LHC programme**

- Study of the Quark-Gluon Plasma
  - Larger temperature → **thermal production of charm**
  - Larger $\sqrt{s}$ and L_{int} → **new hard observables, e.g. top, to study jet quenching**

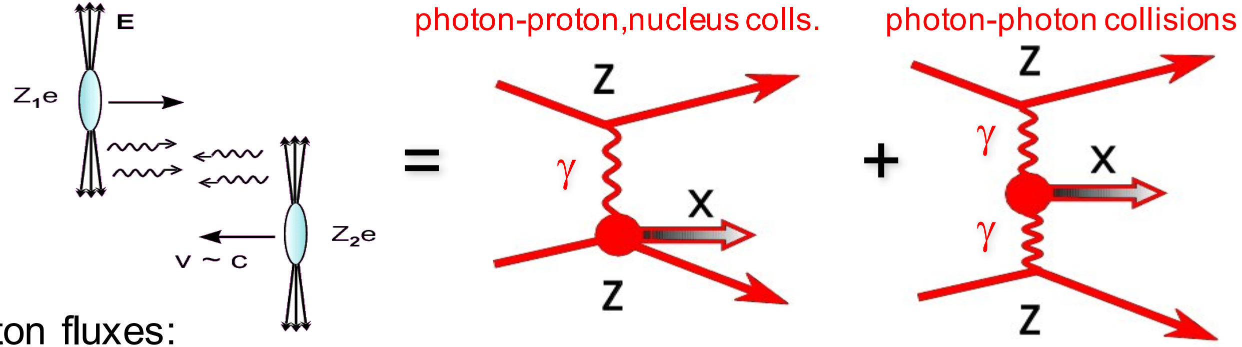
- Study of high-density initial state
  - Unique access to **saturation region (down to $x<10^{-6}$)** with perturbative probes, e.g. forward-*y* di-jets
  - Unique access to **[small-x, large-Q^2] region with top**, W, Z

- Interesting and unique contributions to other sectors of HEP (see Extra Slides)
  - Photon-photon collisions
  - Fixed-target collisions with extracted beams
  - Input to collision models for ultra-high-energy cosmic rays

EXTRA SLIDES

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



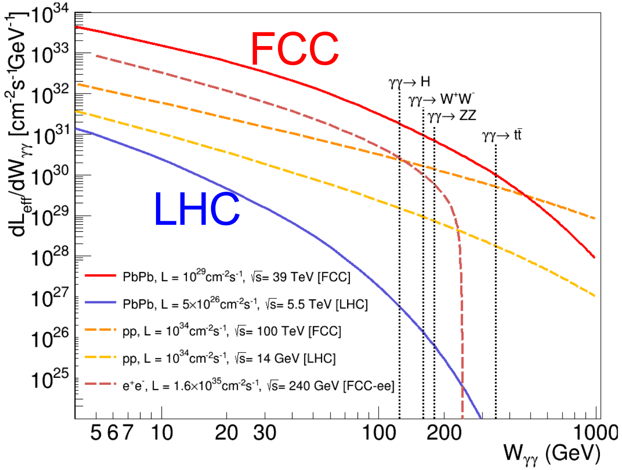
- Huge photon fluxes:
  - $\sigma(\gamma\text{-Pb}) \sim Z^2$ (~10^4 for Pb) larger than in pp
  - $\sigma(\gamma\text{-}\gamma) \sim Z^4$ (~$5 \cdot 10^7$ for Pb-Pb) larger than in pp

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

$\sqrt{s_{\gamma\gamma}} = W_{\gamma\gamma} \sim$ 1.2 TeV $\sqrt{s_{\gamma Pb}} \sim$ 7 TeV

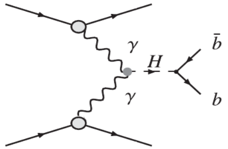
γγ physics at FCC (Pb-Pb)

- 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

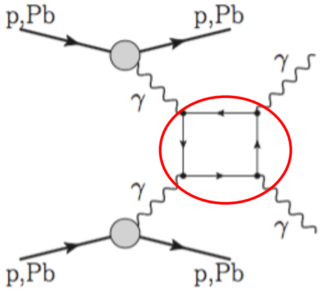


$$N_X = \int \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} W_{\gamma\gamma} \sigma_X^{\gamma\gamma}(W_{\gamma\gamma})$$

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



- γγ→γγ process has potential sensitivity to New Physics



D. d'Enterria et al., arXiv:1510.08141, arXiv:1602.08088, arXiv:1712.10104

Fixed-target collisions with FCC beams

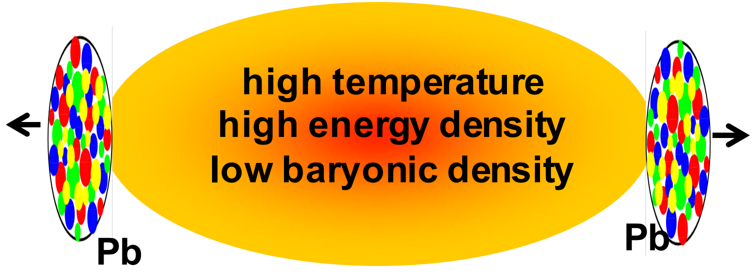
- Fixed-target collisions with FCC (or LHC) p or Pb beams could be realized with either:
  - Beam extraction, fast (magnet) or slow (bent crystals technique)
  - Internal gas detectors, à la LHCb-SMOG

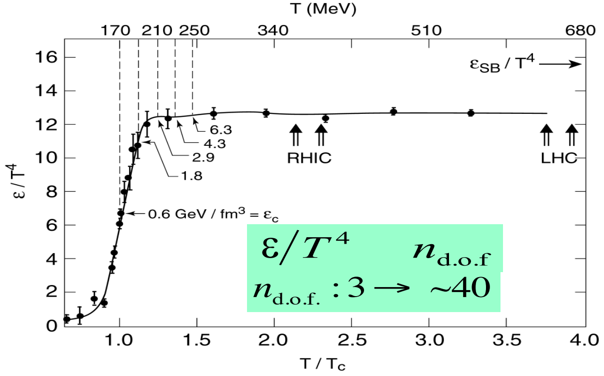
	p@LHC	Pb@LHC	p@FCC	Pb@FCC
Nucleon–Nucleon c.m.s. energy ($\sqrt{s_{NN}} = \sqrt{2E_b m_N}$) [GeV]	114.6	72.0	306.6	192.5
$\Delta y^{lab}_{c.m.s.} = \ln(\gamma^{lab}_{c.m.s.} + \sqrt{(\gamma^{lab}_{c.m.s.})^2 - 1})$	4.80	4.33	5.79	5.32

- 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

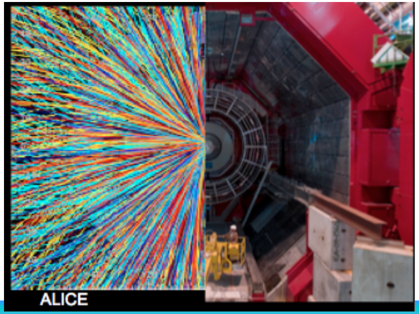
High-density QCD in the final state: the Quark Gluon Plasma

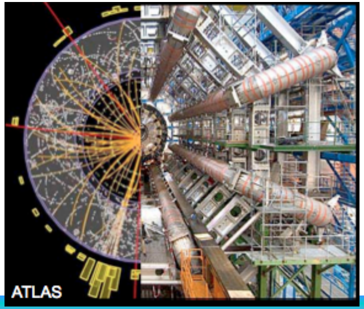


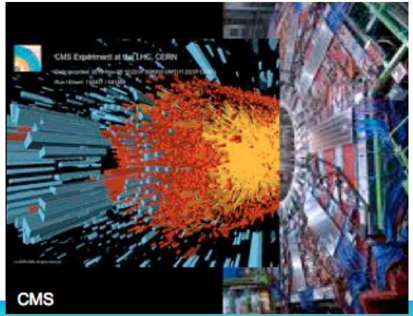


- Lattice QCD: phase transition at T_c~155 MeV
  → **Quark-Gluon Plasma**
- Color deconfinement and chiral symmetry restoration

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







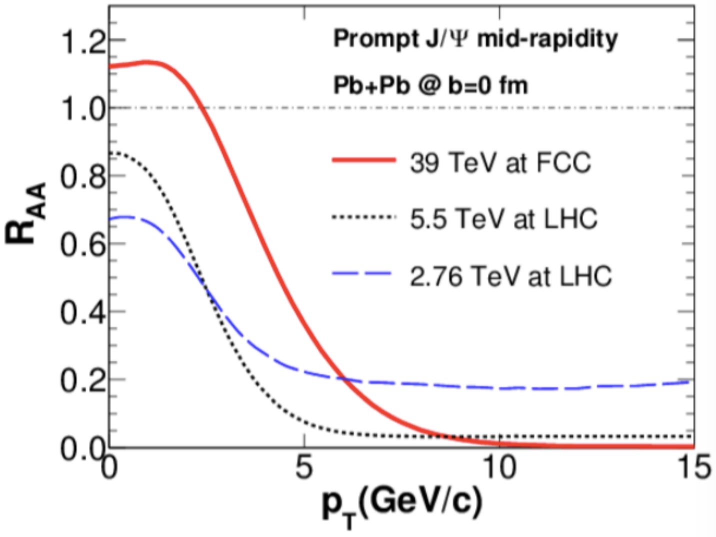
J/ψ: from suppression to enhancement?

- 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

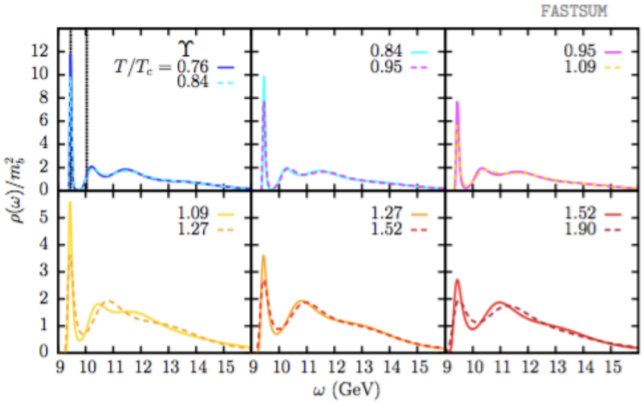
- At FCC, the large charm yield from hard scattering + thermal production may lead to a J/ψ enhancement (R_{AA}>1)
  - J/ψ yield could be sensitive to secondary/thermal charm production

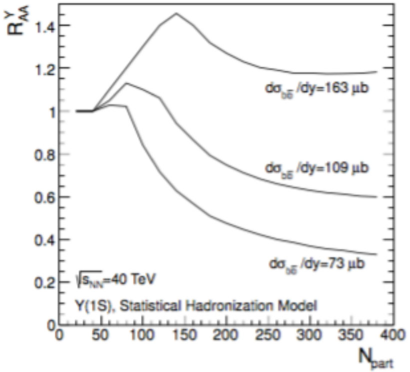


K. Zhou et al., arXiv:1602.01667

Υ: full suppression or enhancement?

- Color-screening suppression reduced for tightly-bound states
- Υ(1S) R_{AA}~0.5 at LHC: consistent with suppression of higher states only (2S and 3S, that feed-down to the 1S)
- Υ(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 (Υ R_{AA}>1)



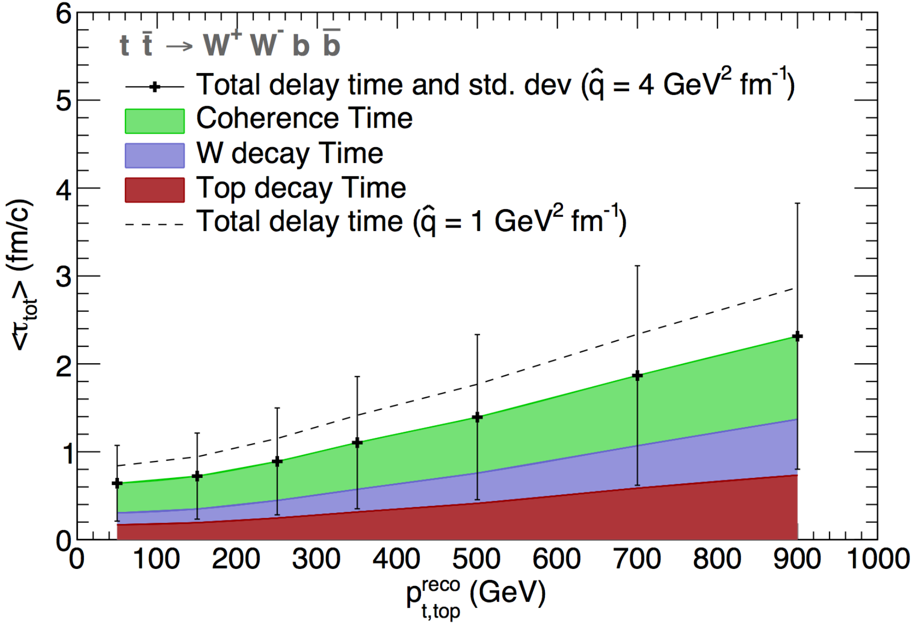


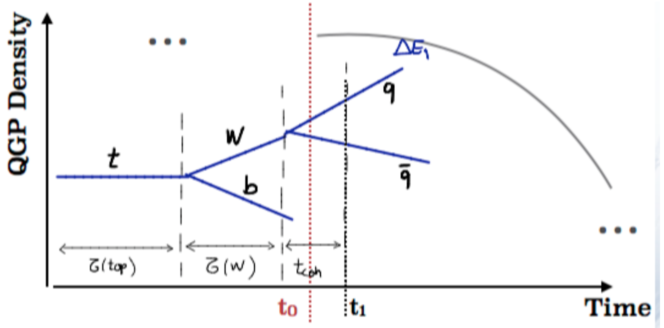
G. Aarts et al, JHEP 07 (2014) 097

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

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

1) Testing the time evolution of the QGP density



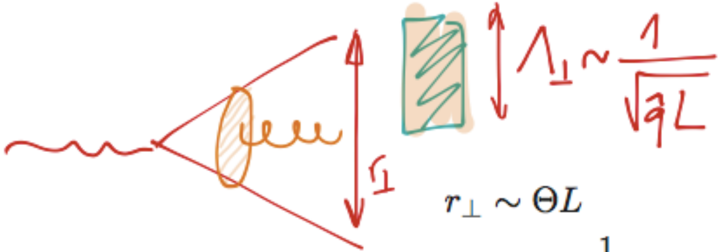


Estimate of the "start time" of energy loss: reaches 2-3 fm/c for top p_T~0.5-1 TeV/c

Apolinario, Milhano, Salam, Salgado, arXiv:1711.03105

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

2) Testing the role of color coherence



$$r_\perp \sim \Theta L$$

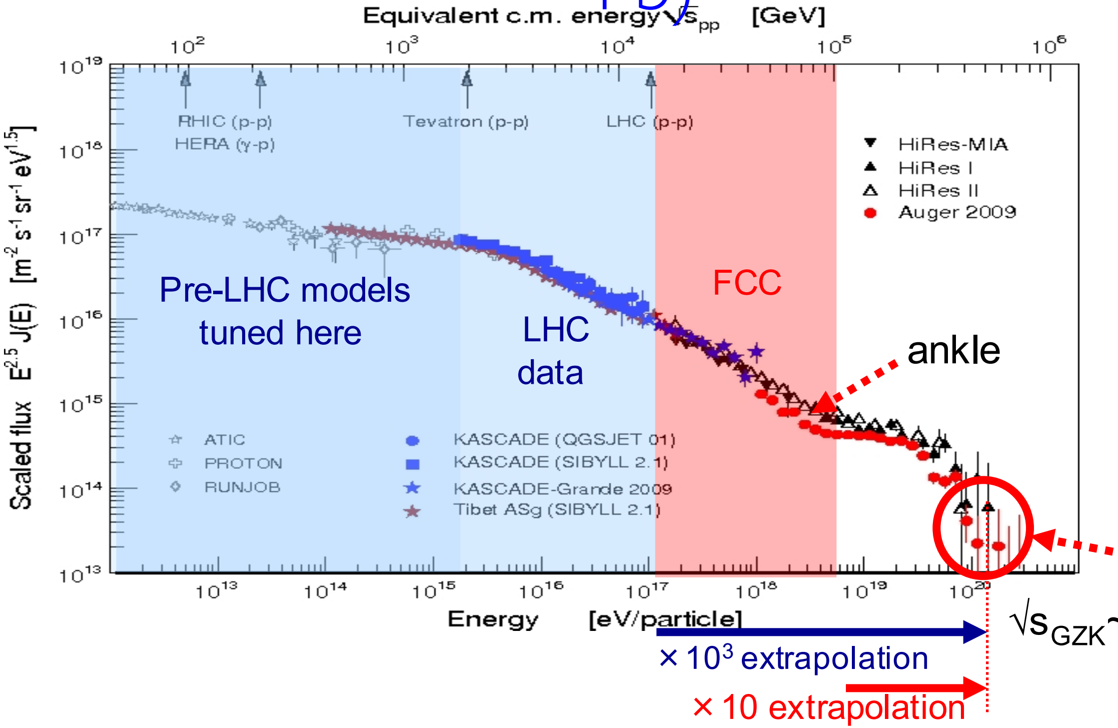
$$\Lambda_{\text{med}} \sim \frac{1}{\sqrt{\hat{q}L}}$$

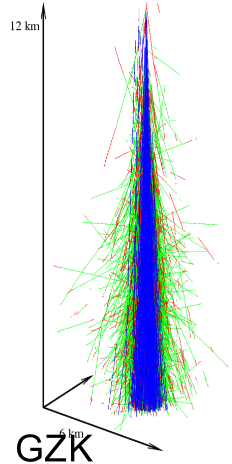
q-qbar with small opening angle; seen as color-singlet by the medium, **no interaction expected**

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

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)

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 $dN_{ch}/d\eta \sim 3500$
  - 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)