Heavy ions at the FCC

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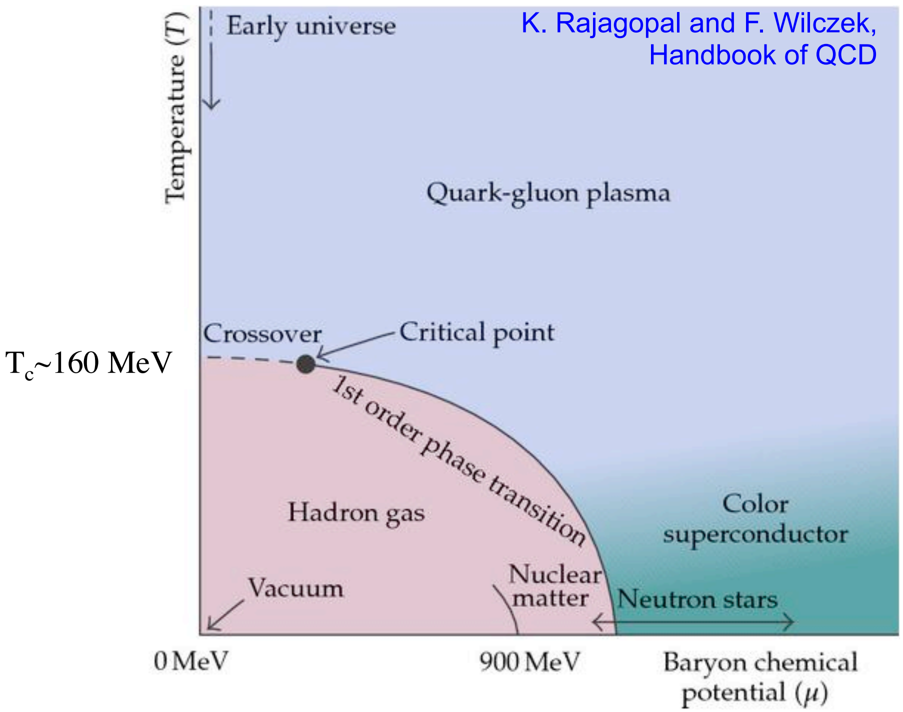
Outline

- Introduction
- Future heavy ion runs at the LHC
- Organization of FCC HI studies
- FCC with ions: machine parameters
- Quark-Gluon Plasma at FCC
- Gluon Saturation at FCC

Exploring the phase diagram of strongly-interacting matter



[~ Density of baryons – anti-baryons]

- At high energy density ε → phase transition to the QGP
  - Colour confinement removed
  - Chiral symmetry approx. restored
- Lattice QCD: $\varepsilon_c \sim 1$ GeV/fm^3
  - Transition is a crossover at low μ_B

High-energy heavy-ion collisions:

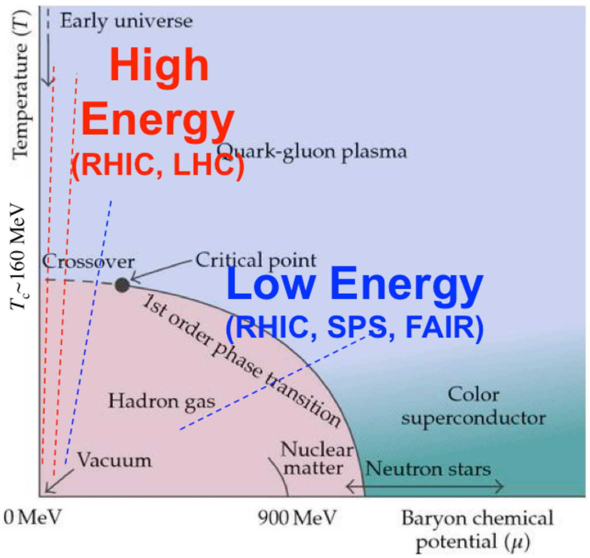
→ **Unique opportunity** to verify the basic predictions of **QCD** and characterize it as a many-body theory in the **non-perturbative** regime

Current status:

The QGP as seen at RHIC/LHC:

- Energy density > 10 GeV/fm^3
- Colour charge deconfined
- Strong energy loss for hard partons
- Expands hydro-dynamically like a very-low viscosity liquid
- Hadronizes as in thermal equilibrium

Future directions:



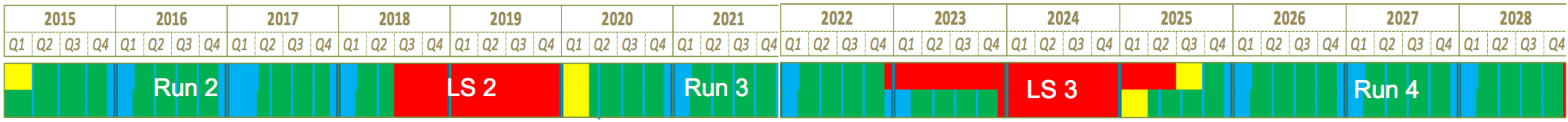
High Energy collisions (RHIC,LHC, FCC):

- Quantify properties of QGP fluid

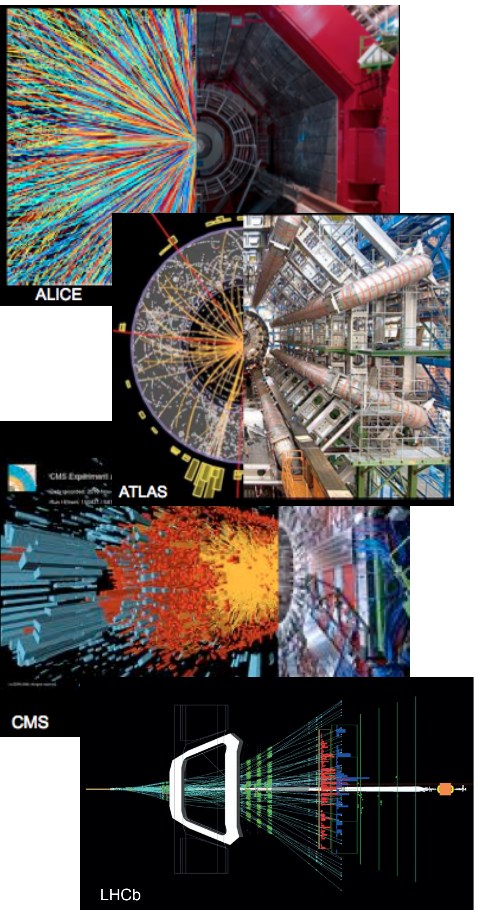
Low Energy collisions (RHIC,SPS,FAIR):

- Onset of deconfinement
- Search for the critical point

Timeline of HI programme at the LHC



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



- HI programme till 2028 with all 4 experiments (LHCb pA only)
- After LS2 (from 2020):
  - Upgraded ALICE aims at collecting x100 larger minimum-bias sample than in Run 2
  - CMS and ATLAS x10 larger triggered sample than in Run 2

→ Focus on <u>precision measurements of rare probes</u>, study their coupling with QGP medium

Organization of FCC HI studies

- A discussion group on "Ions at the FCC" started
  - Coordinated by A.D., S. Masciocchi (GSI), C. Salgado (Santiago, th), U. Wiedemann (CERN, th)
  - Sub-group of "FCC-hh Physics, Experiments, Detectors"
  - Participation from ALICE, ATLAS, CMS, theory, CERN-BE
  - Mailing list fcc-ions@cern.ch (250 people)
- 4 small workshops up now
  - https://indico.cern.ch/event/331669/ and links therein
- First ideas: arXiv:1407.7649

Ions at FCC: machine parameters

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

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

- First (conservative) estimates of luminosity (in comparison with LHC): >8 larger L_{int} per month of running

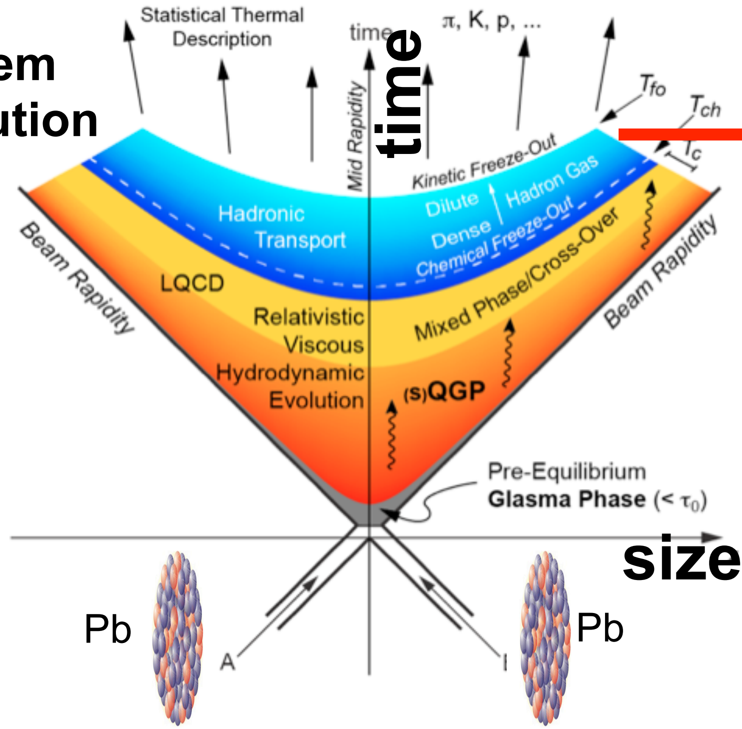
	LHC Run 2 [1]	LHC after LS2 [1]	FHC [2]
Pb–Pb peak $\mathcal{L}$ ($cm^{-2}s^{-1}$)	10^{27}	5×10^{27}	13×10^{27}
Pb–Pb L_{int} / month (nb^{-1})	0.8	1	**>8**
p–Pb peak $\mathcal{L}$ ($cm^{-2}s^{-1}$)	10^{29}	t.b.d.	3.5×10^{30}
p–Pb L_{int} (nb^{-1})	80	t.b.d.	**>1800**

- Could aim for programme of 100/nb (LHC x10)

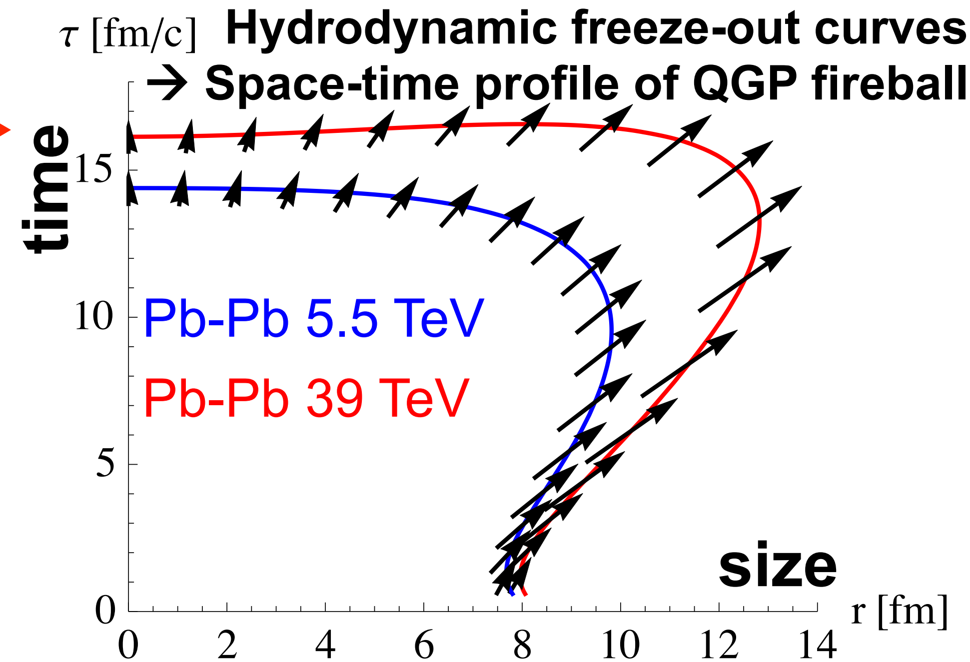
7 times larger energy, 10 times larger luminosity

Quark-Gluon Plasma (QGP) at FCC

System evolution



Hydrodynamic freeze-out curves
→ Space-time profile of QGP fireball



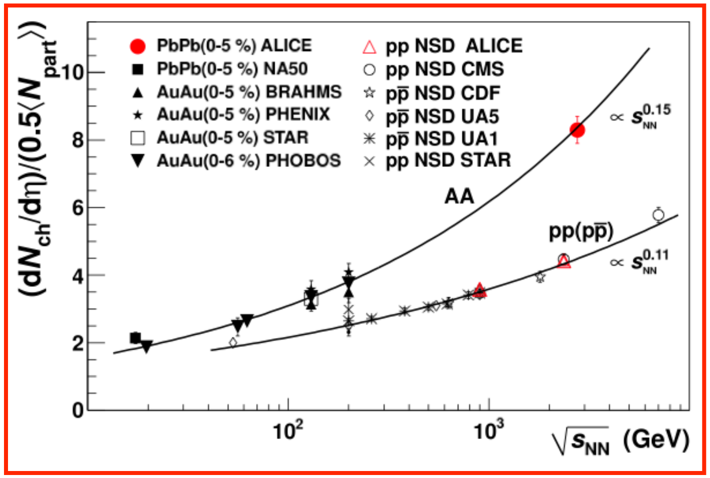
Properties of QGP at higher energy:

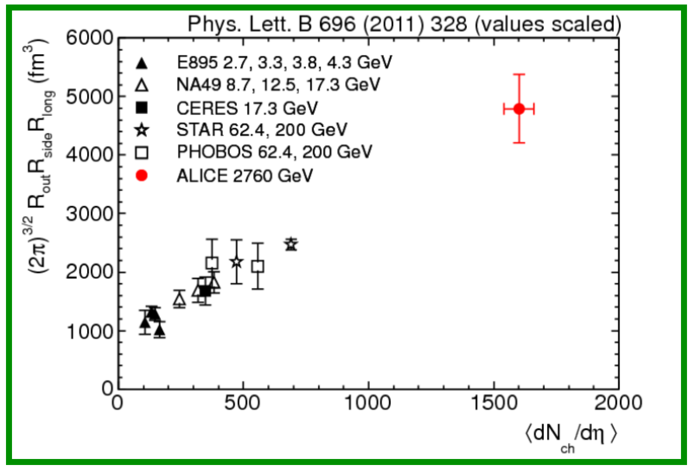
- Equilibration times reduced
- Initial temperature higher
- QGP volume increases strongly
- QGP lifetime increases

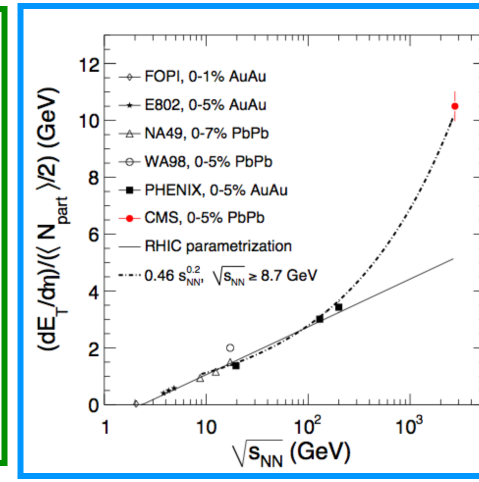
QGP at FCC: global properties

- Extrapolation to 39 TeV: increase wrt LHC 5.5 TeV

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



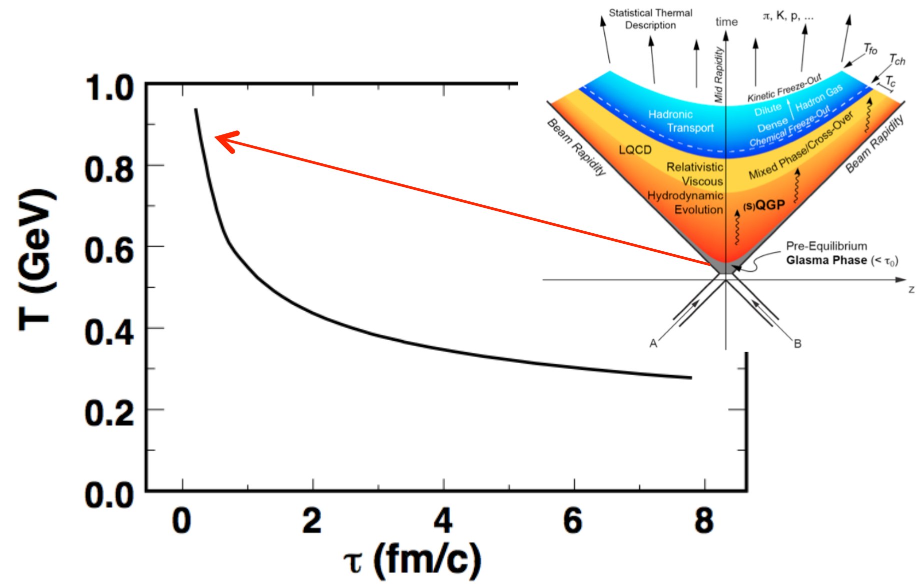


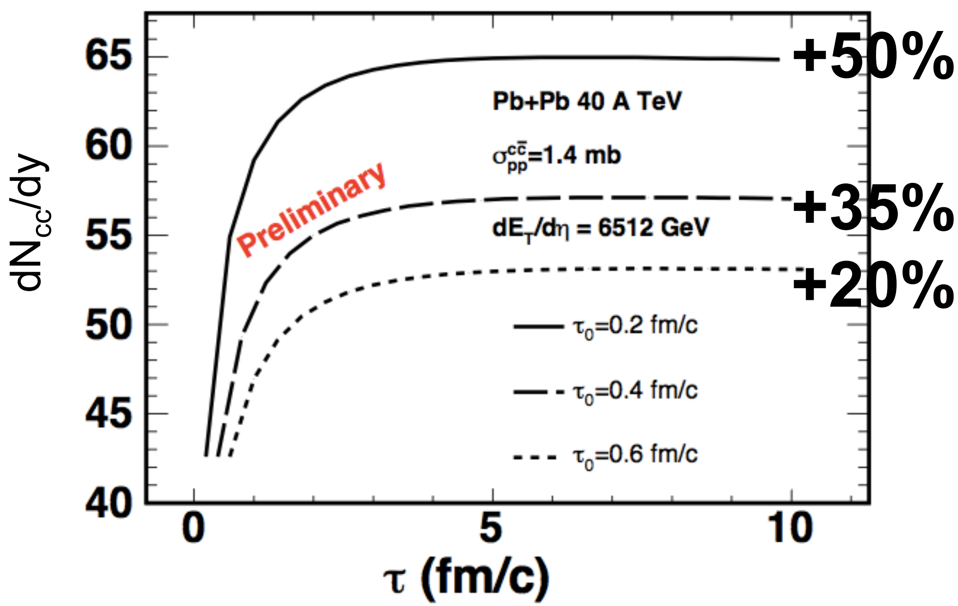


Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	2 TeV	2.6 TeV	5.8 TeV
BE homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
BE decoupling time	10 fm/c	11 fm/c	13 fm/c

FCC: thermal charm in the QGP?

- The initial temperature of the QGP could be close to 1 GeV at FCC
- Expect abundant production of charm pairs in the QGP (via $gg \rightarrow c\bar{c}$): +20-50% wrt initial hard scattering
- Secondary charm yield very sensitive to the **QGP initial temperature** and to the **temperature evolution**

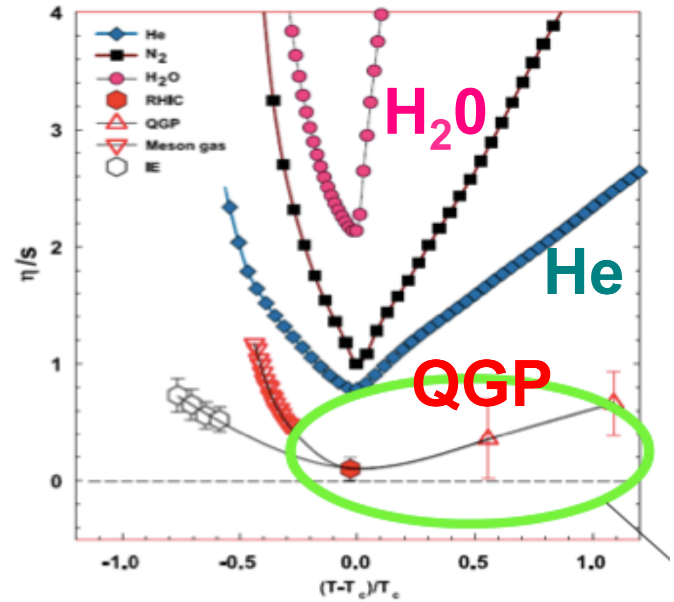




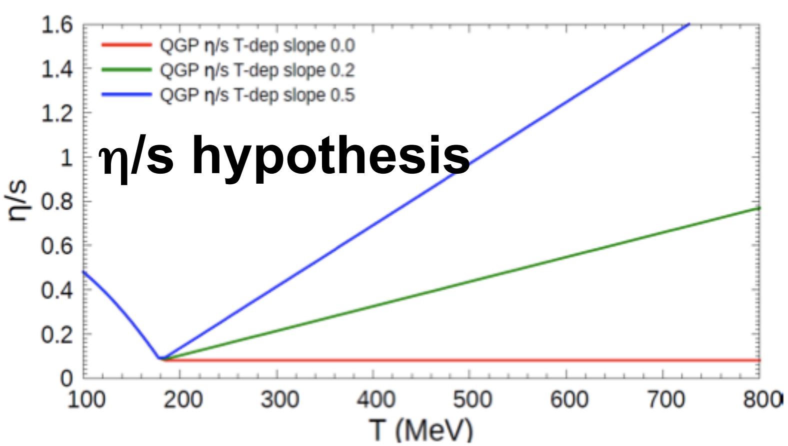
C.M. Ko, Y. Liu, private communication, based on B.-W. Zhang et al. PRC77 (2008)

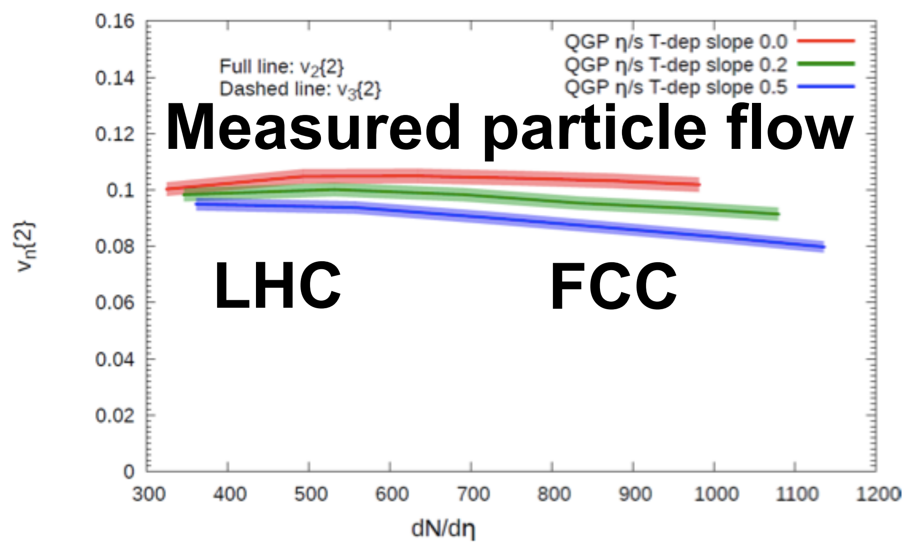
FCC: measurement of QGP properties

- The QGP observed at RHIC and LHC appears to be the fluid with lowest viscosity
- The ratio of *shear viscosity to entropy density* (η/s) is one of fundamental properties of the QGP
- At FCC energies, the temperature dependence of viscosity could become accessible for the first time via particle flow measurements



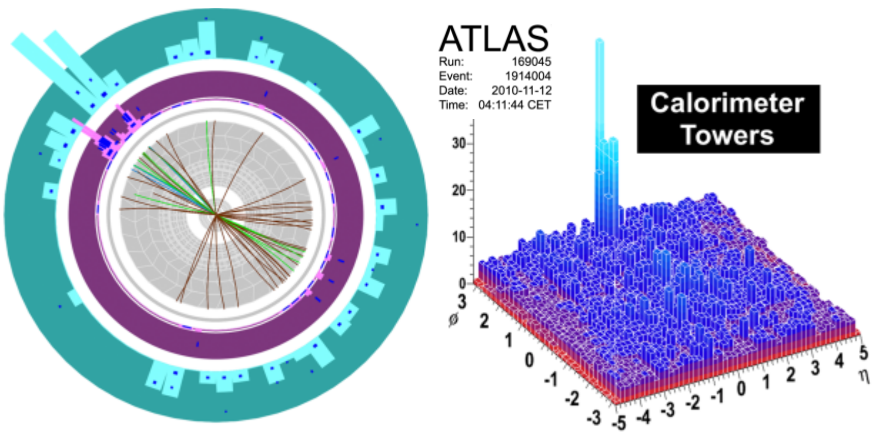
Lacey *et al*(2007)



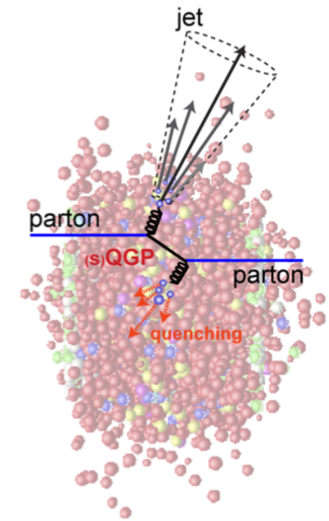


Jet quenching at LHC

- Pb-Pb events with large di-jet imbalance

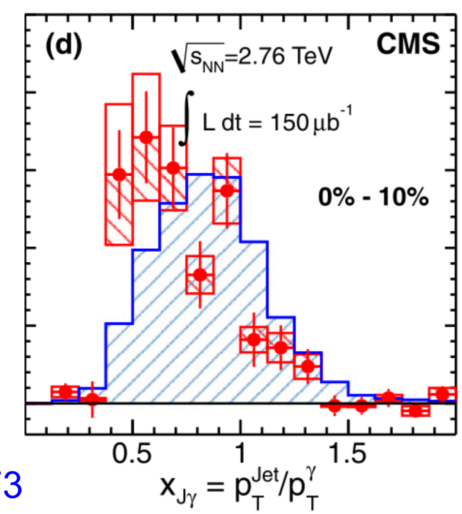


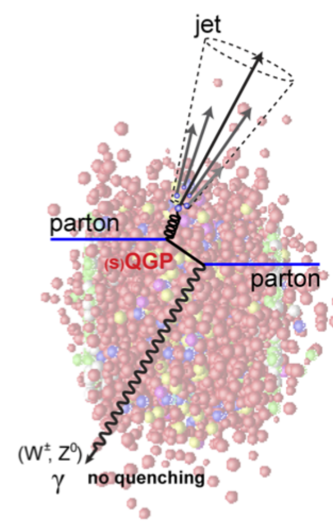
Direct observation of in-medium parton energy loss



ATLAS, PRL105 (2010) 252303
CMS, PLB712(2012) 176

- A powerful tool: γ/Z-jet correlations
  - $E^{\gamma/Z} = E^{jet}$!
  - First measurement of γ-jet p_T imbalance p_T^{Jet}/p_T^{γ}

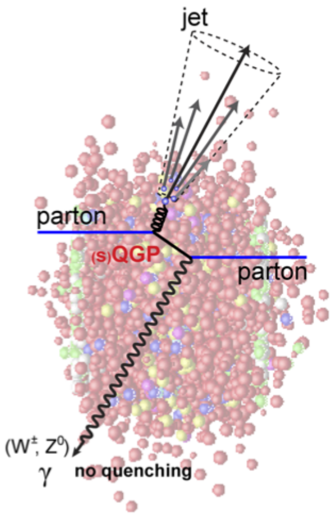




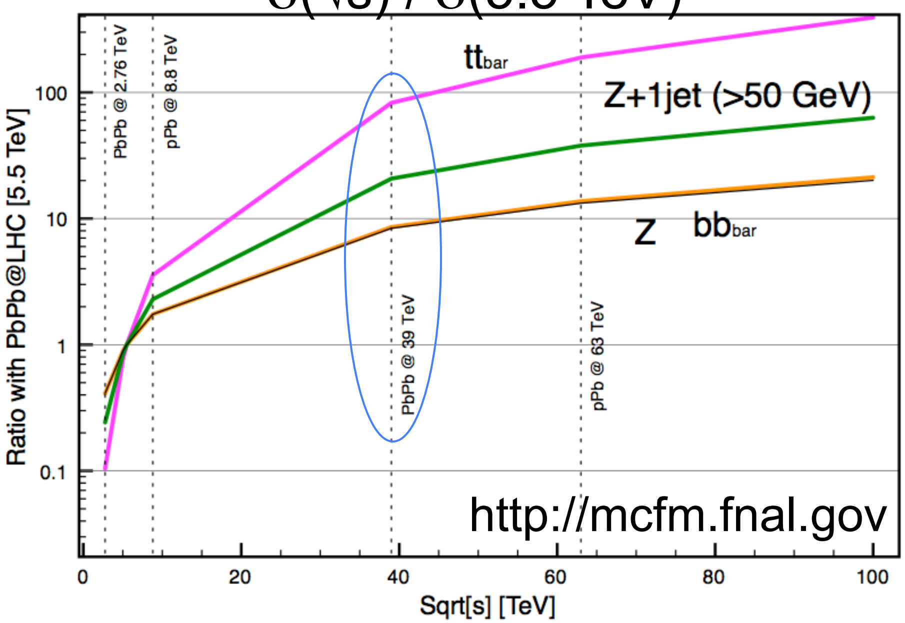
CMS, PLB718 (2013) 773

FCC: a richer set of Hard Probes

- LHC heavy-ion programme shows that it is possible to reconstruct HEP-like observables in HI collisions
  - Jets, b-jets, Z^0, W, γ-jet correlations …
- Large $\sqrt{s}$ and $\mathscr{L}$ of the FCC will make new probes abundantly available, for the study of the interaction mechanisms, of the medium density and its time evolution

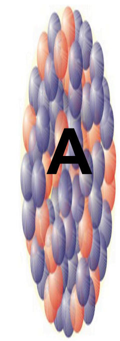


$\sigma(\sqrt{s})$ / σ(5.5 TeV)



- Larger increases for larger masses:
  - 80x for top
  - 20x for Z^0 + 1 Jet(p_T>50 GeV)
  - 8x for bottom or Z^0

High-density QCD in the initial state: Saturation of low-x gluons



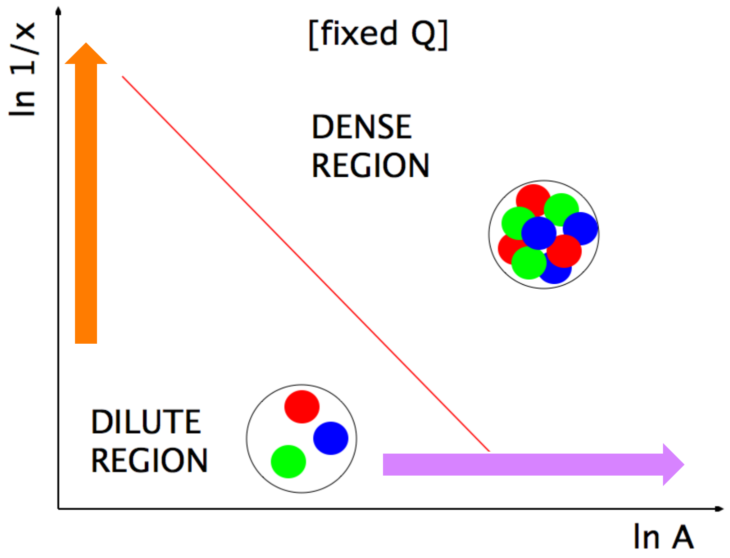
- Explore new unknown regime of QCD: when gluons are numerous enough (low-x) & extended enough (low-Q^2) to overlap → *Saturation, Non-linear PDF evolution*

Enhanced in nuclei wrt protons: more gluons per unit area

Saturation scale:

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

(λ~0.3)



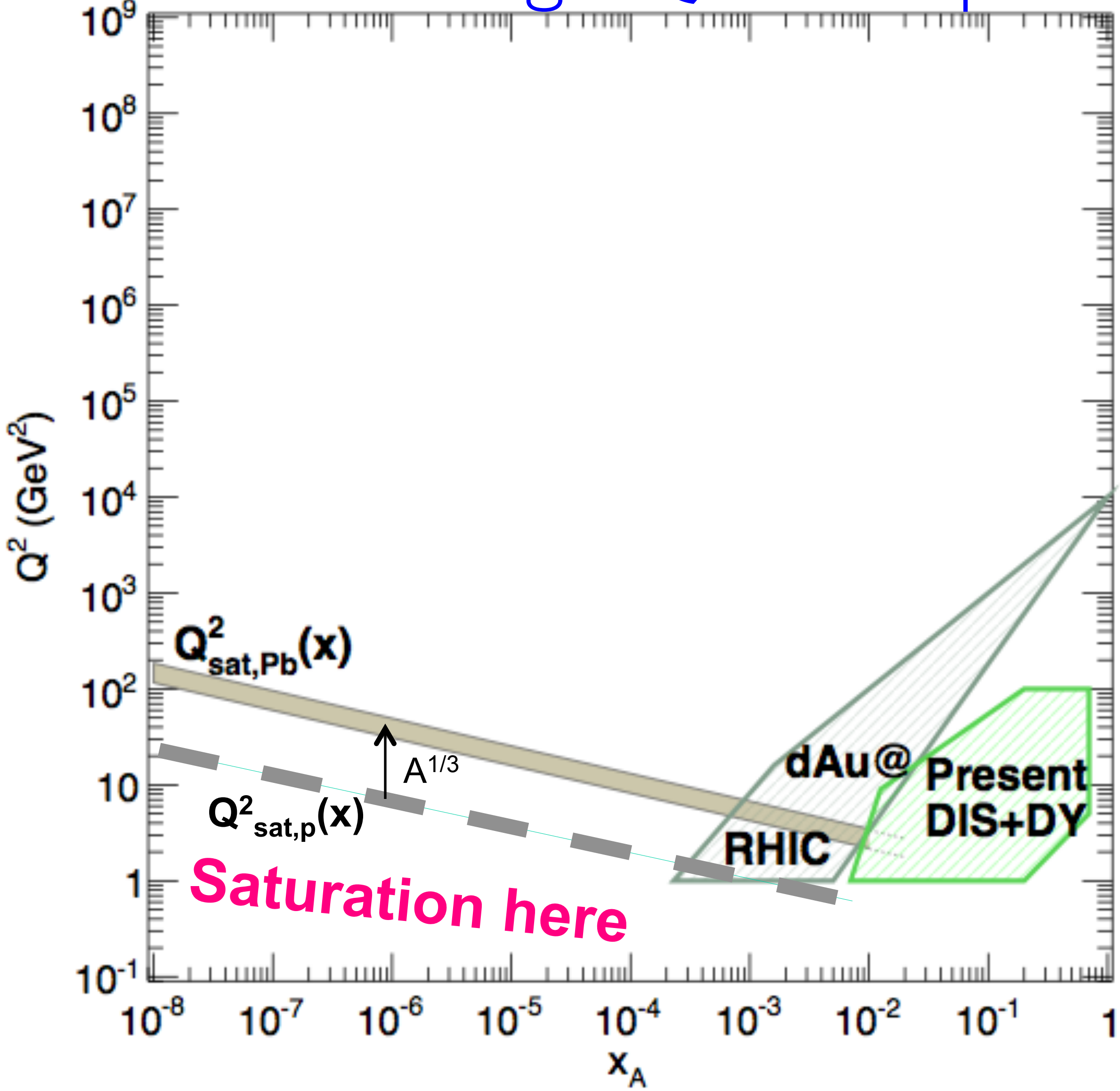
Saturation affects process with $Q^2 < Q_S^2$

Explore saturation region:

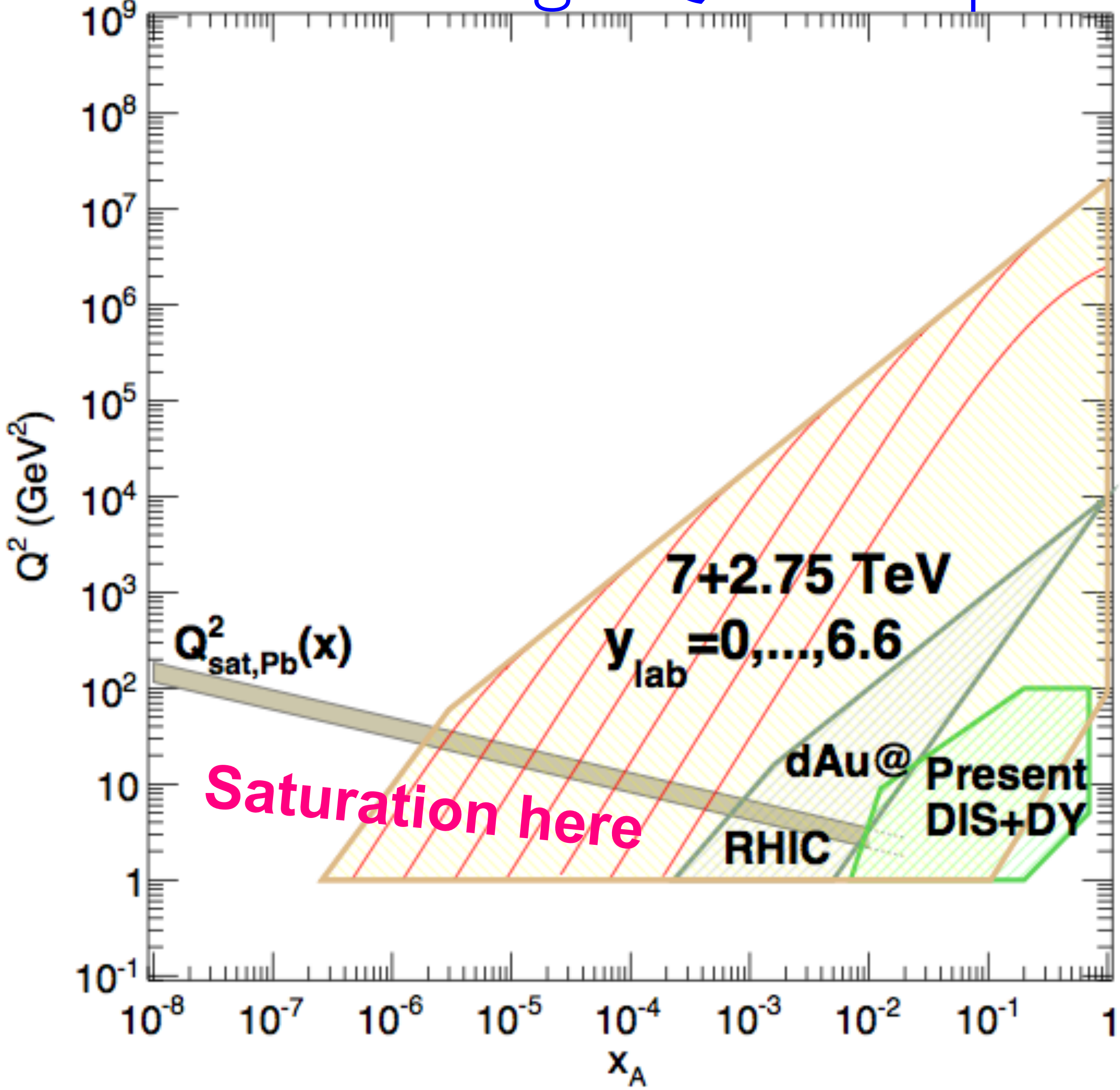
→ **decrease *x* (larger √s, larger *y*)**

→ **increase A**

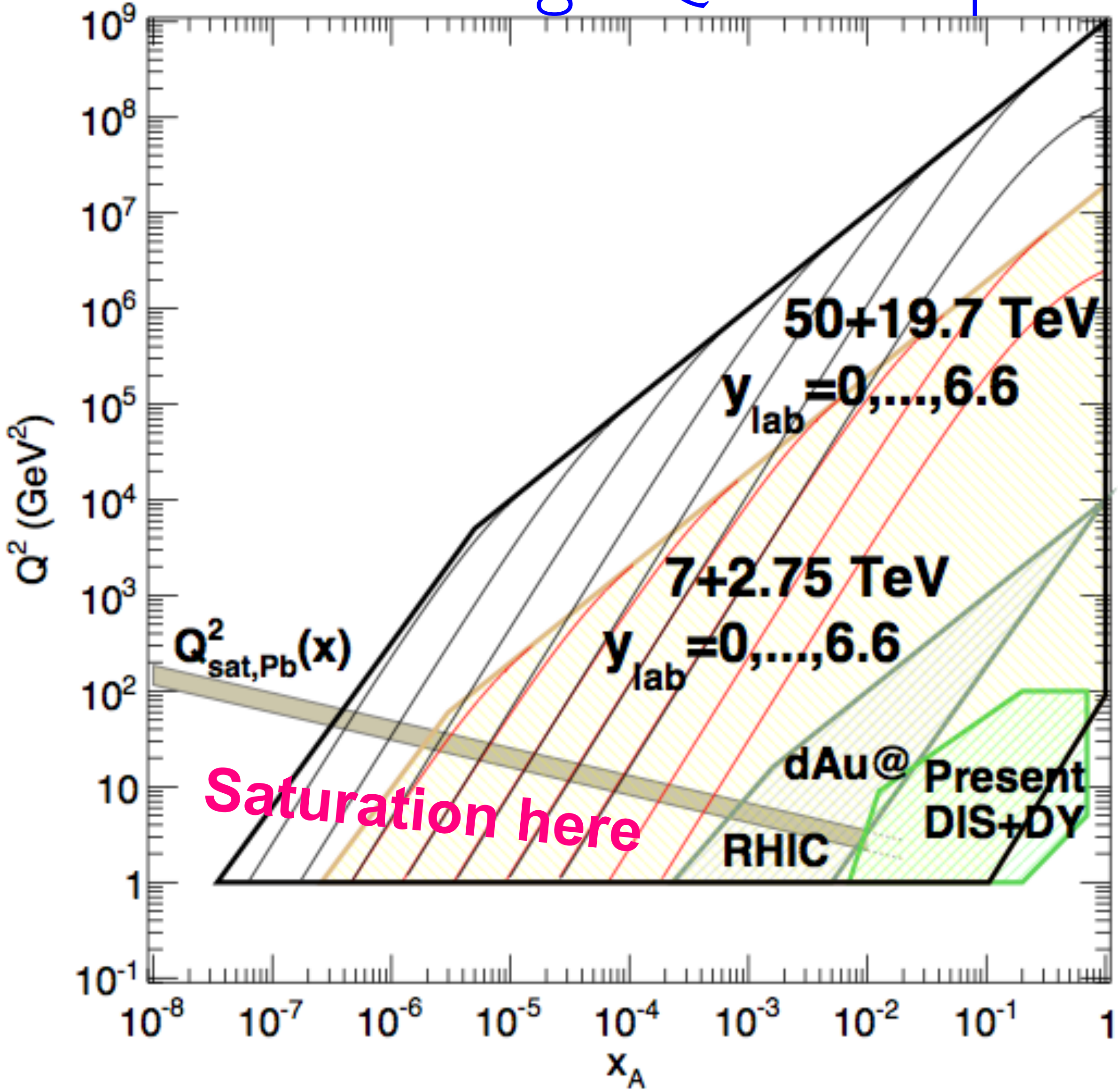
Kinematic coverage Q^2 vs. x: pre-LHC



Kinematic coverage Q^2 vs. x: pA LHC

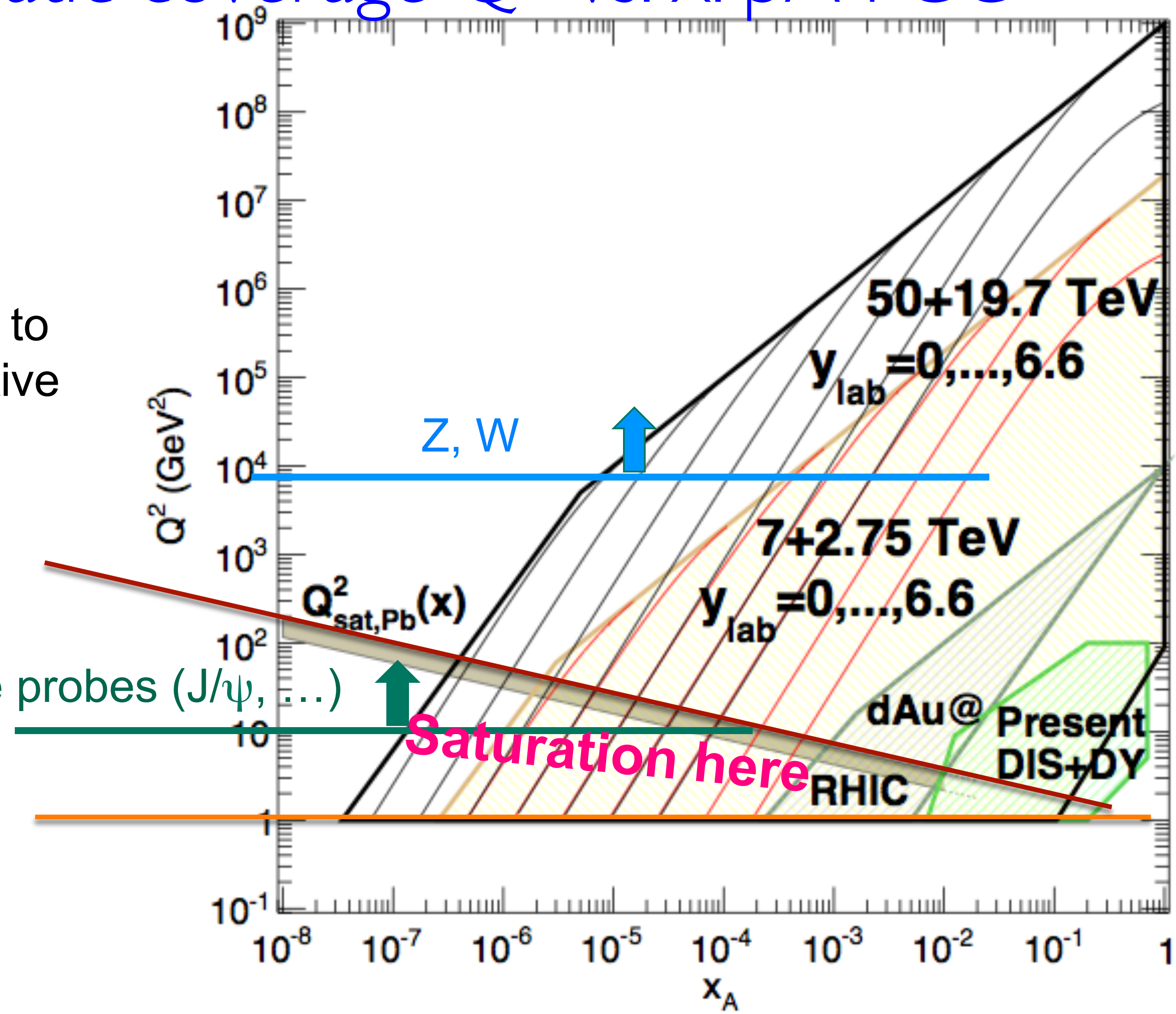


Kinematic coverage Q^2 vs. x: pA FCC



Kinematic coverage Q^2 vs. x: pA FCC

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



Considerations on experiment design

- Probably not necessary to have a dedicated HI experiment
- HI community could provide inputs on HI-specific requirements for general purpose detectors
- Examples:
  - Possibility to reduce magnetic field for low-p_T tracking
  - Hadron identification (measure spectra and flow of bulk multiplicity)
  - Forward coverage for low-x studies (ideally to η~6)
  - …

Summary

- Discussions started on opportunities with heavy ions, within the FCC Study
- QGP physics
  - Larger initial temperature and volume entail potentially unique aspects, e.g. thermal production of charm
  - Larger $\sqrt{s}$ and L_{int} → new hard observables, possibly sensitive to early stages and time evolution of the medium
- Saturation physics in pA (but also eA and γA)
  - Higher energy and large nuclei → unique access to saturation region (down to $x<10^{-6}$) with perturbative probes

EXTRA SLIDES

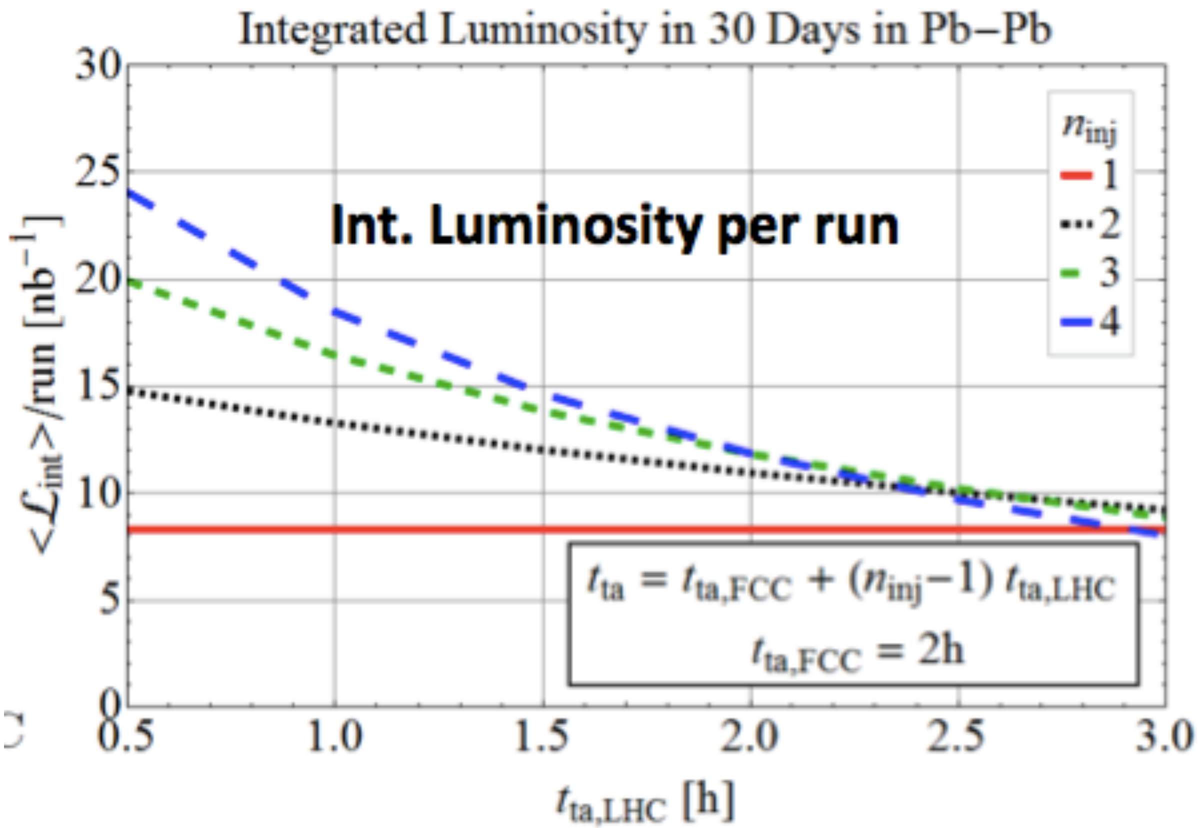
HI-HL-LHC Programme

(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**)

Ions at FCC

M.Schaumann

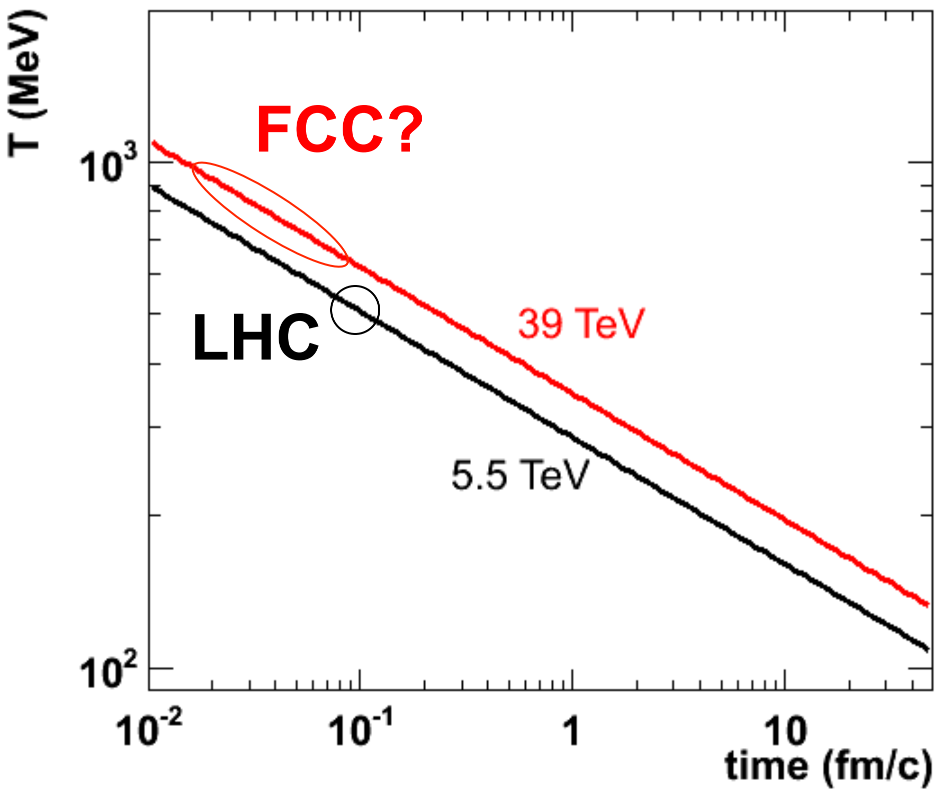


Baseline:
1 injection from LHC
$t_{ta,LHC}$=3h (turn-around time, from inj to beam dump)

Baseline is 8/nb/run, but could be increased with more than 1 injection from LHC, if the LHC turn-around time can be shorted

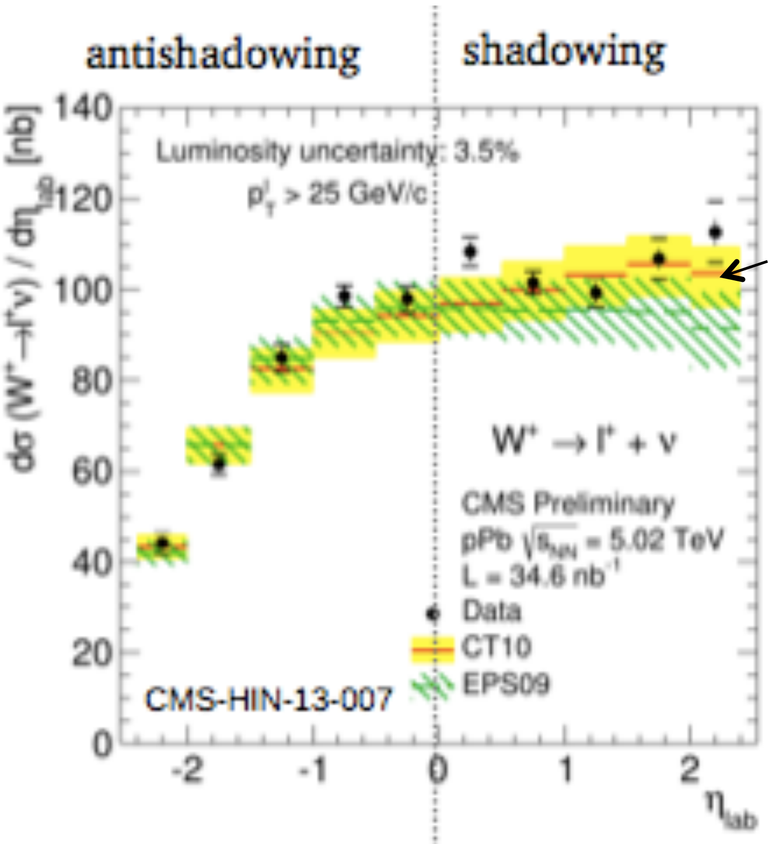
QGP studies at the FCC: temperature

- Energy density with Bjorken formula: $$\varepsilon(\tau) = \frac{E}{V(\tau)} = \frac{1}{c\tau\ \pi R_A^2}\frac{dE_T}{d\eta}$$
- Temperature from S-B equation: $$T(\tau) = \sqrt[4]{\varepsilon(\tau)\frac{30}{\pi^2 n_{d.o.f.}}}$$

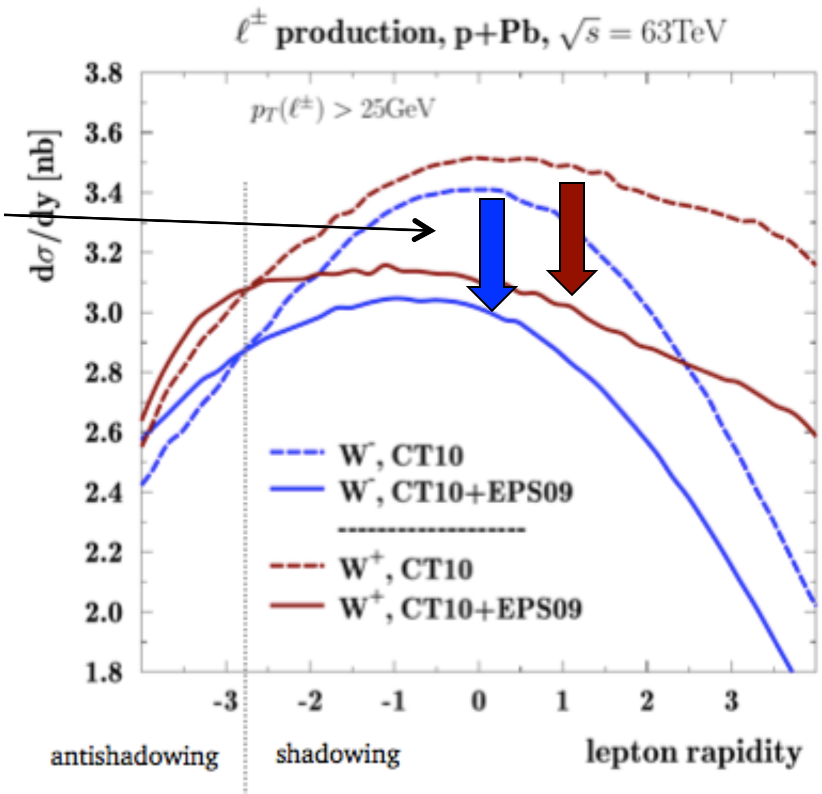


- 20% larger for the same time
  - E.g. 360 MeV at 1 fm/c
- Initial time (QGP formation time)?
  - Usually ~0.1 fm/c for LHC
  - Could be smaller at FCC
- Significantly larger initial temperature? Could reach close to 1 GeV?

Example: W and Z in p-Pb at LHC and FCC



Shadowing (reduction of PDFs in nuclei)



LHC: sensitivity to shadowing at η>2

FCC: sensitivity to shadowing at η> -2 (much larger kinematic coverage)

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