XXIV QUARK MATTER
DARMSTADT 2014

Heavy-ion physics studies for the Future Circular Collider

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Outline

- Introduction: the FCC design study
- Ions at the FCC
- High-density QCD in the initial state: small-x and saturation
- High-density QCD in the final state: deconfinement and QGP
- High-multiplicity events in small systems (pp, pA)
- Connection with cosmic-ray physics
- Summary

The FCC design study

- Kickoff workshop, Geneva, Feb 2014: https://indico.cern.ch/event/282344/

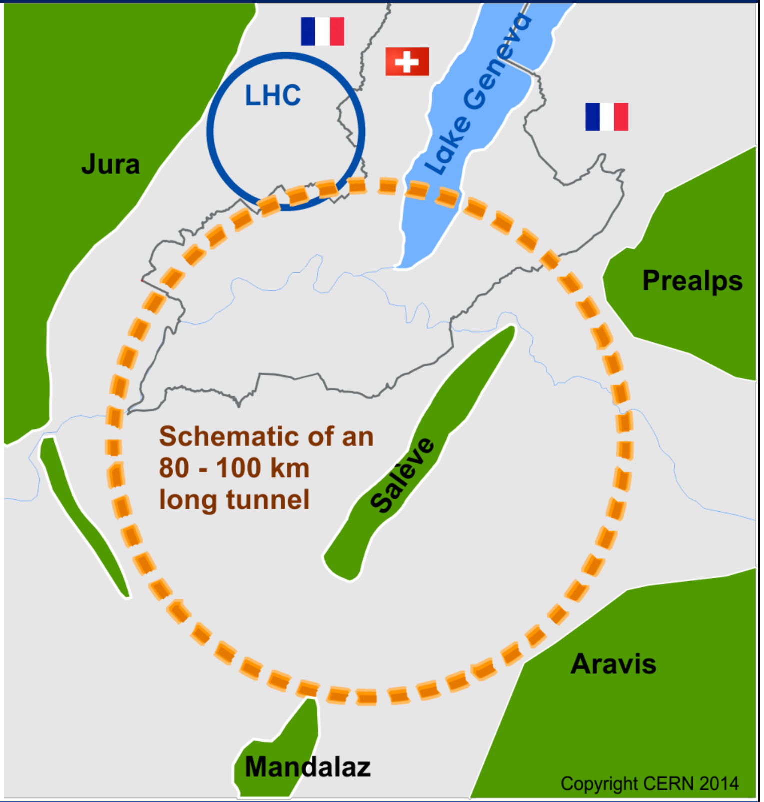
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- ***e^+e^-* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



Future Circular Collider Study
Michael Benedikt
FCC Kick-Off 2014
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Ions at FCC: energies and luminosities

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

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

- First (conservative) estimates of luminosity (in comparison with LHC): x5 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 $L_{\rm int}$ / month (nb^{-1})	0.8	1	5
p–Pb peak $\mathcal{L}$ (cm^{-2}s^{-1})	10^{29}	t.b.d.	3.5×10^{30}
p–Pb $L_{\rm int}$ (nb^{-1})	80	t.b.d.	1000

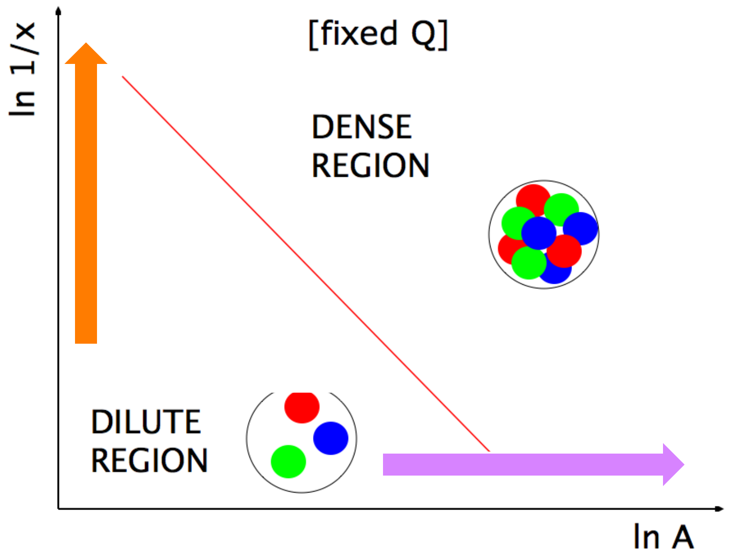
- Possibility to increase L_{int} using nuclei with slightly smaller *Z*?
  - Some of the limiting factors (e.m. process) go with “large” powers of *Z*
- Could (optimistically) aim for programme of 100/nb (LHC x10)

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



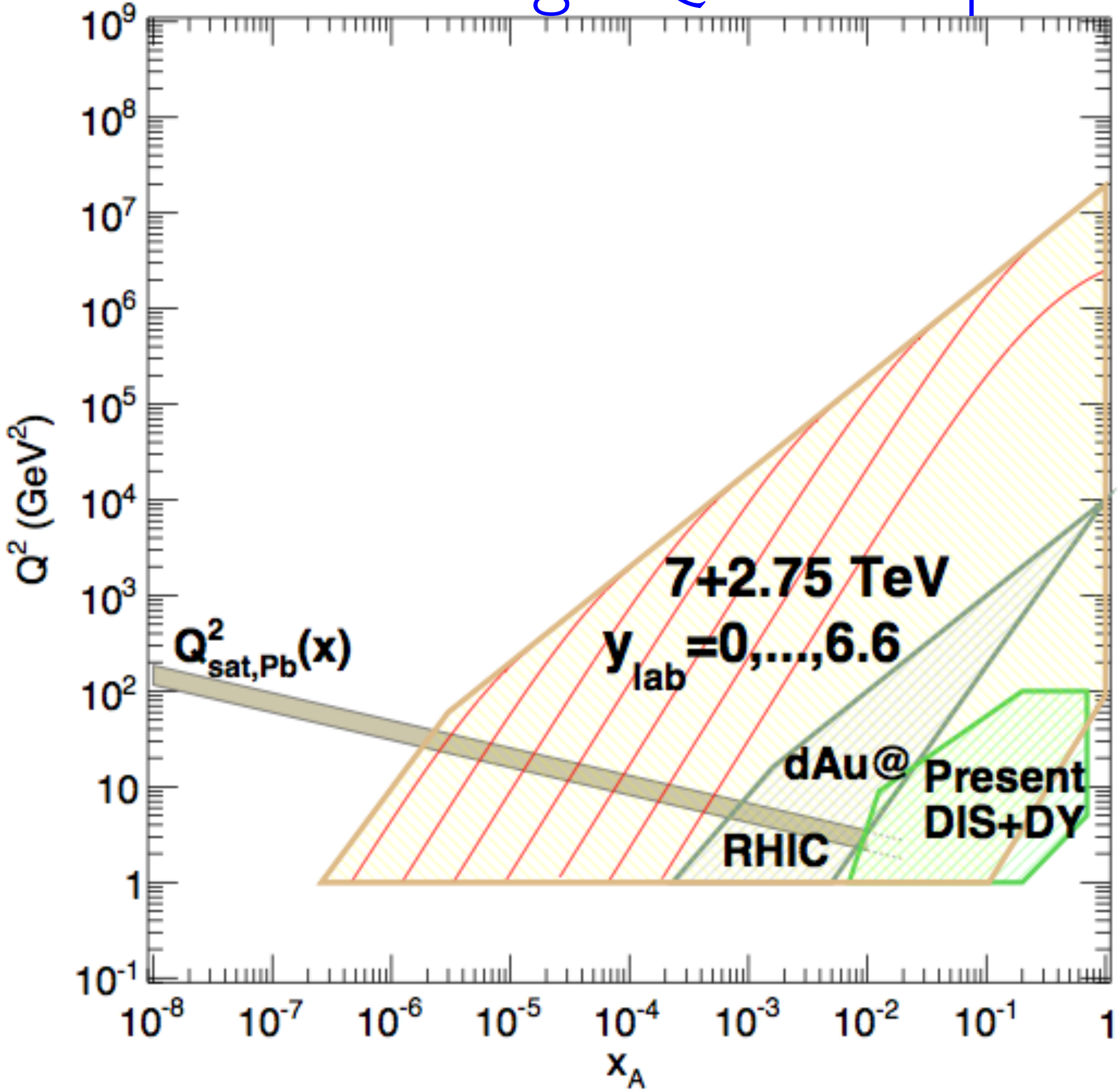
Saturation affects process with $Q^2 < Q_S^2$

Explore saturation region:

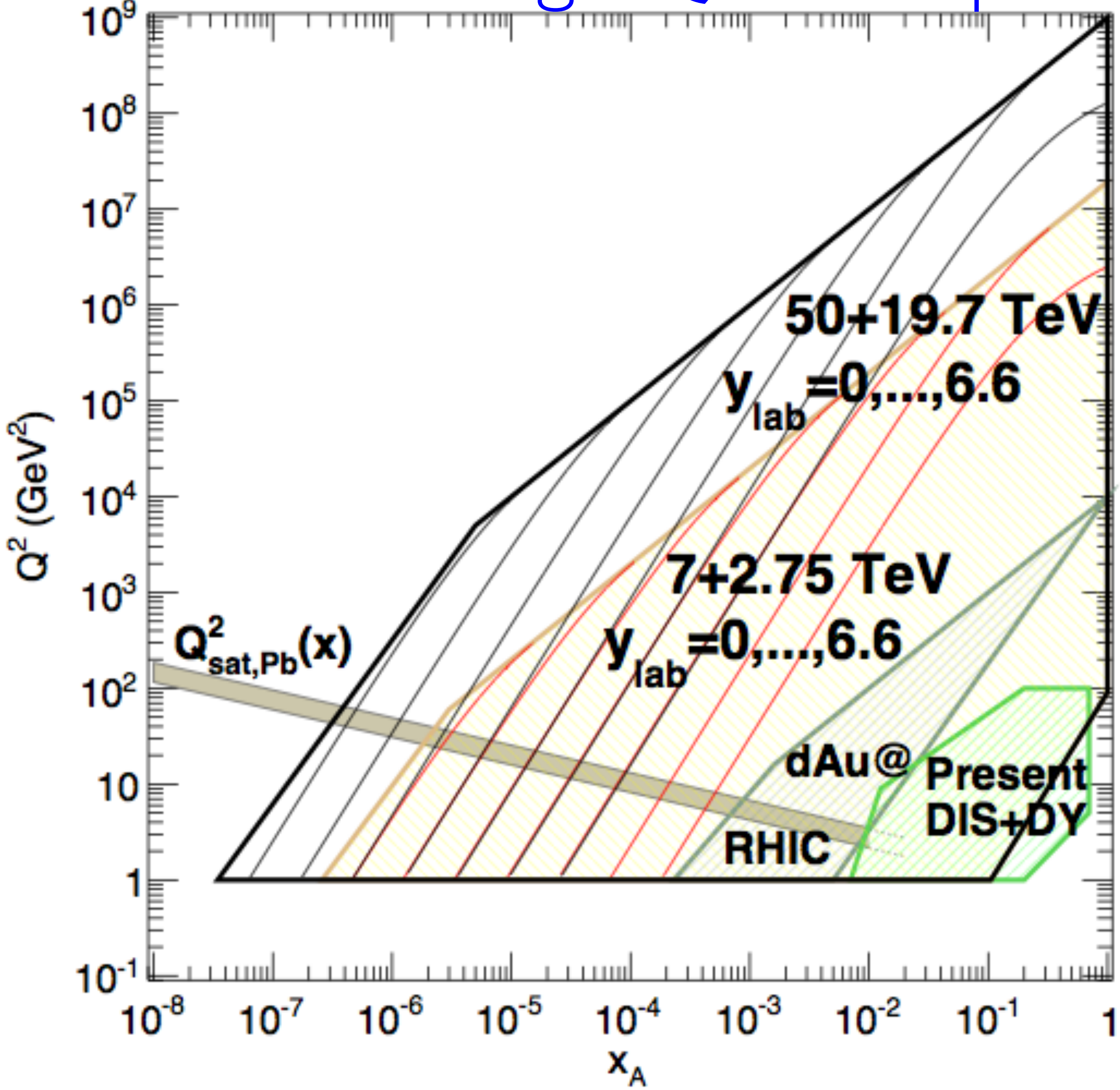
→ **decrease x (larger √s, larger y)**

→ **increase A**

Kinematic coverage Q^2 vs. x: pA LHC



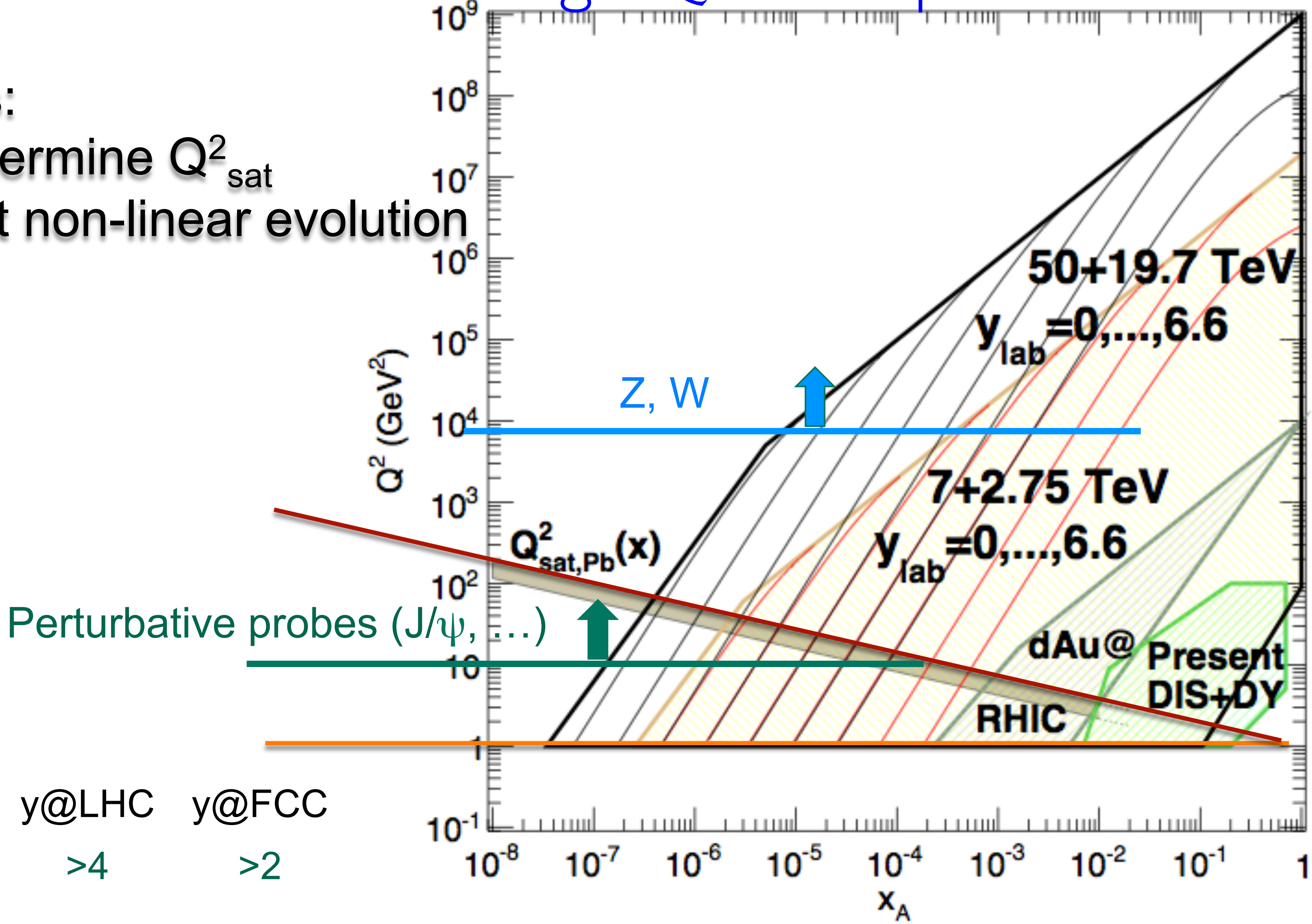
Kinematic coverage Q^2 vs. x: pA FCC



Kinematic coverage Q^2 vs. x: pA FCC

Goals:

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

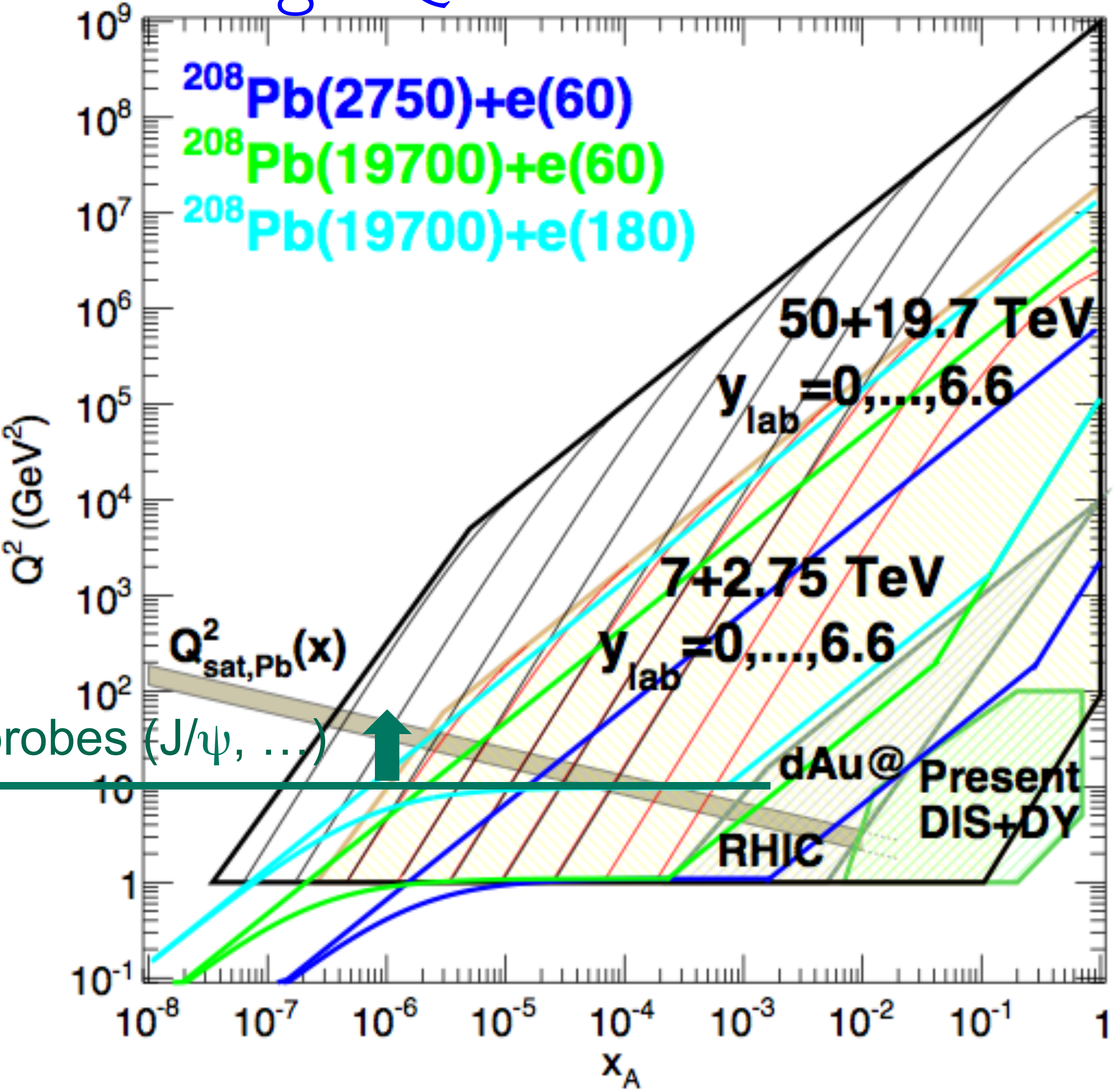


	y@LHC	y@FCC
Charm	>4	>2

Kinematic coverage Q^2 vs. x: eA FCC

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

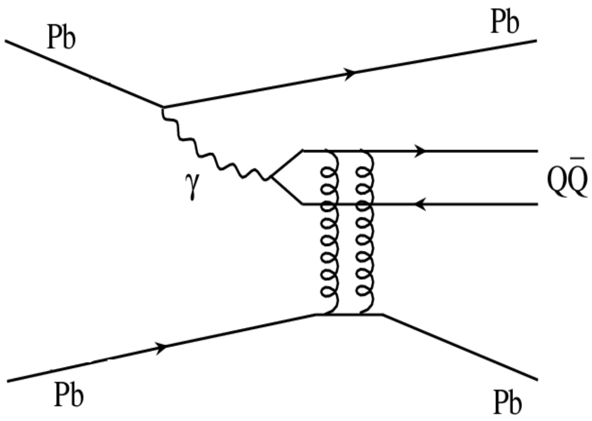
eA at FCC:
down to $x<10^{-5}$ with perturbative probes, but fully constrained parton kinematics



Perturbative probes (J/ψ, …)

γ-Pb physics at FCC (Pb-Pb)

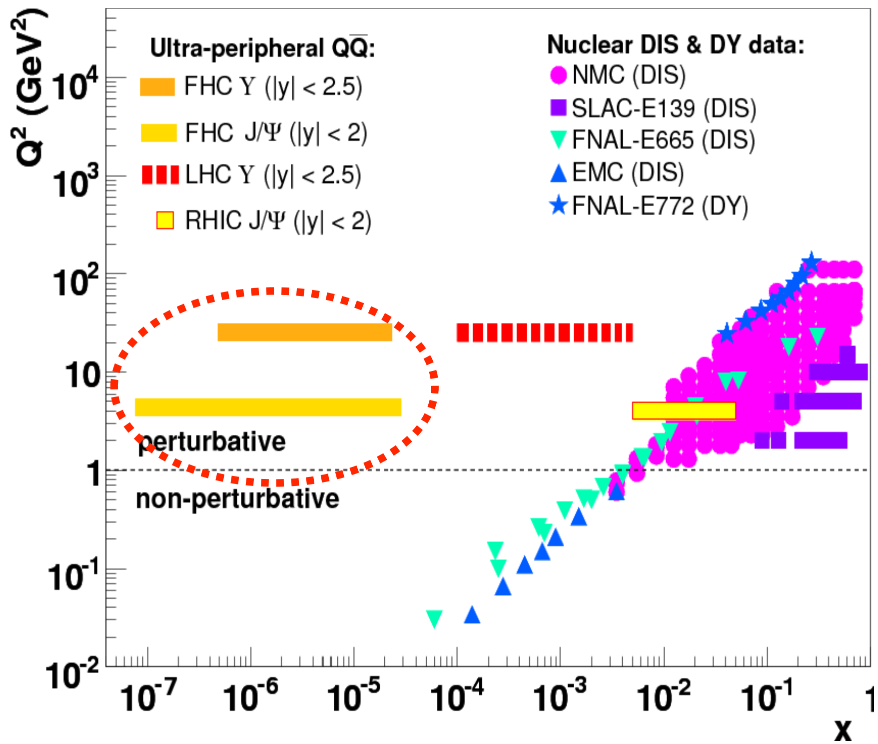
- Sensitive to gluon density at <u>very</u> small x: powerful handle on saturation region with perturbative probes
- E.g. exclusive Q-Qbar: $x \sim m^2_{QQ}/s_{\gamma Pb}$, $Q^2 \sim m^2_{QQ}/4$



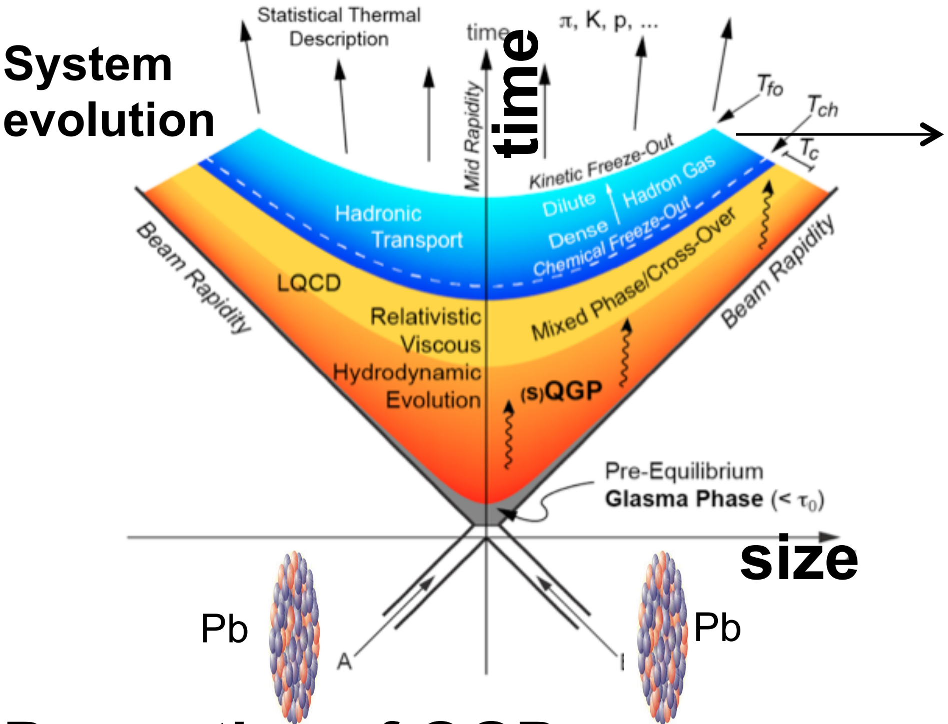
$\sqrt{s_{\gamma Pb}} \sim$ 7 TeV

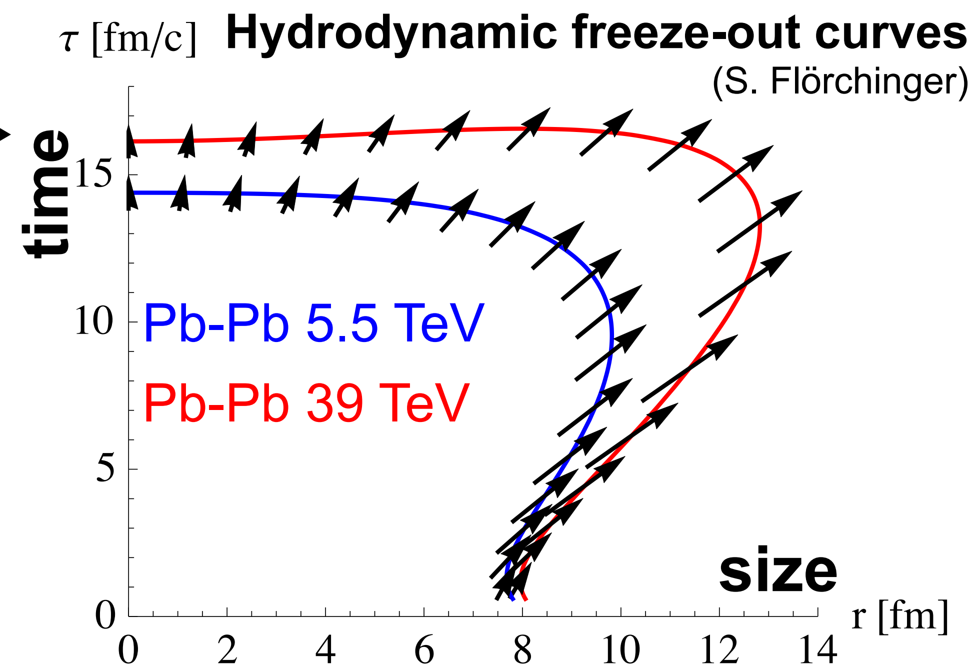
→ $x \sim 10^{-7}$

~2 orders of magnitude below LHC!



Quark-Gluon Plasma studies at FCC





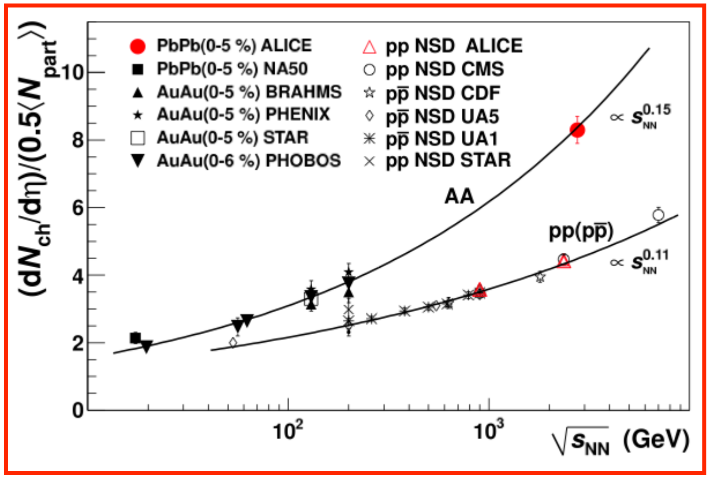
Properties of QGP:

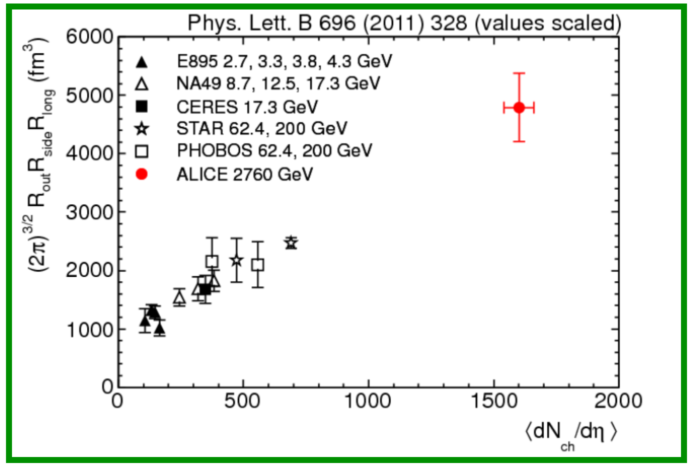
- QGP volume increases strongly
- QGP lifetime increases
- Collective phenomena enhanced (better tests of QGP transport)
- Initial temperature higher
- Equilibration times reduced

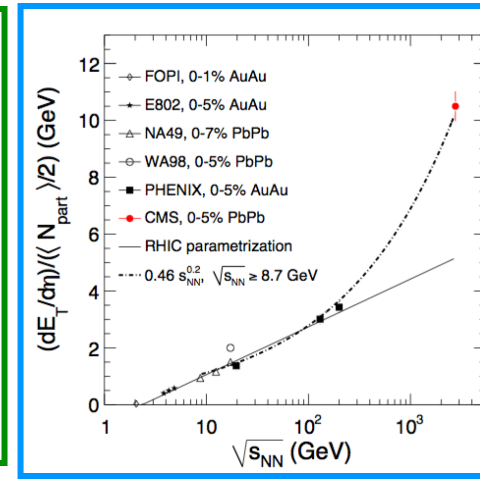
QGP studies at the FCC: global properties

- 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**



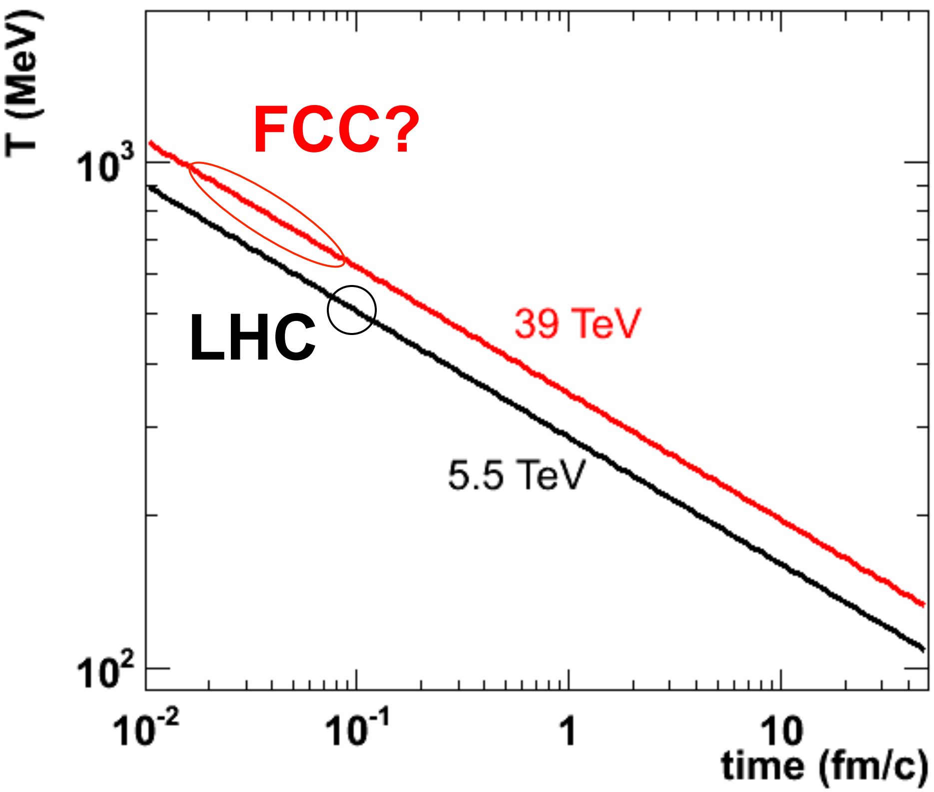




Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	2 TeV	2.6 TeV	5.8 TeV
BE homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
BE decoupling time	10 fm/c	11 fm/c	13 fm/c

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: $T(\tau) = \sqrt[4]{\varepsilon(\tau)\frac{30}{\pi^2 n_{d.o.f.}}}$

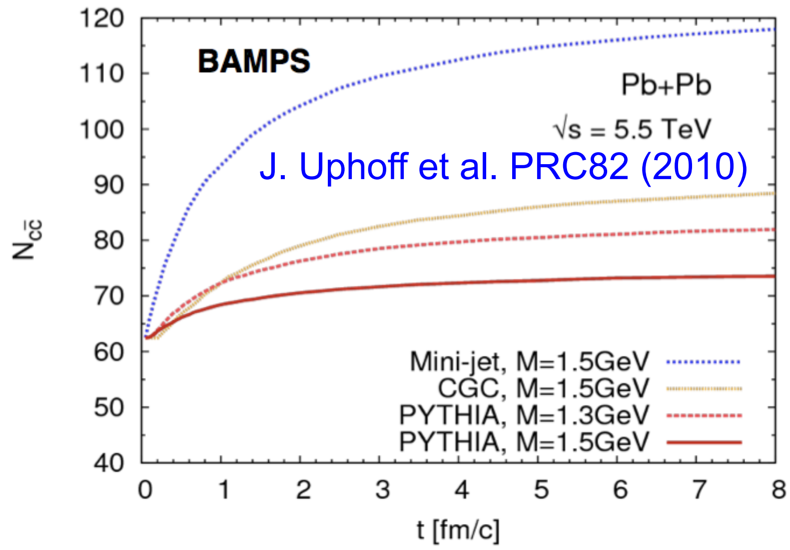


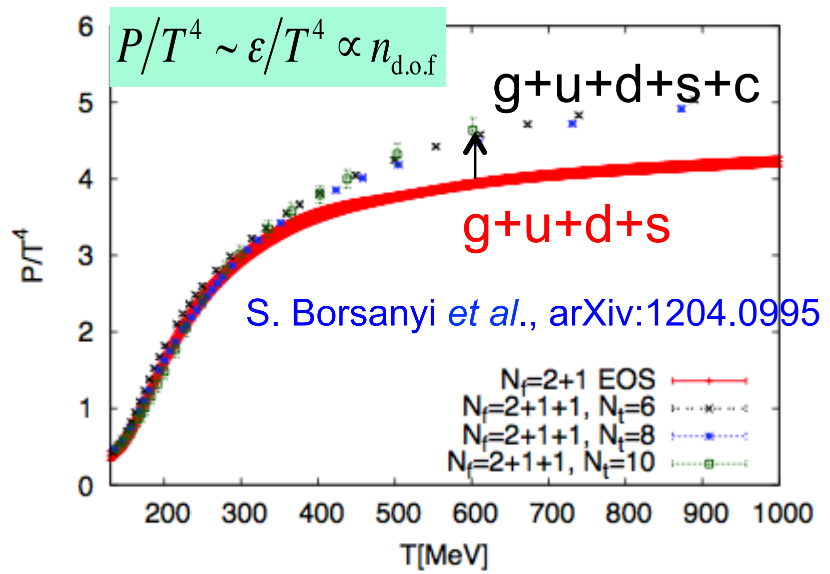
- 20% larger for the same time
  - E.g. 360 MeV at 1 fm/c
- Initial time (QGP formation time)?
  - Usually ~0.1 fm/c for LHC
  - Could be smaller at FCC
- Significantly larger initial temperature? Could reach close to 1 GeV?

Secondary/thermal charm?

- Expect abundant production of c-cbar pairs in the medium
- Calculations for LHC 5.5TeV: + 15-45% wrt hard scattering
  - At 39 TeV could become comparable with initial production
- Should show up as “thermalized” component at 1-2 GeV
- Secondary charm yield very sensitive to the initial temperature and to the temperature evolution

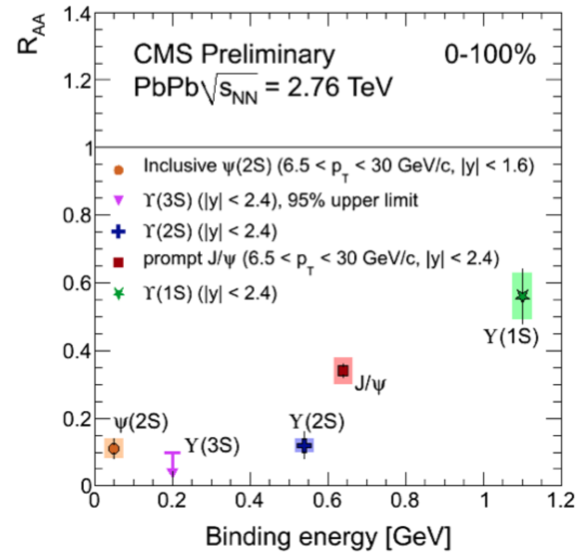
- If charm is produced abundantly during the equilibration of the medium, the additional d.o.f. should have impact on the equation of state



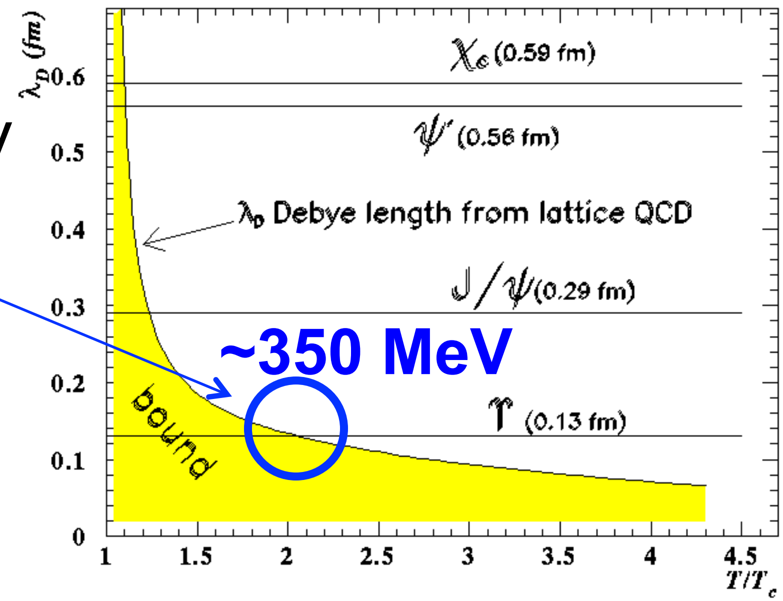


Y(1S) melting at the FCC

- Sequential quarkonium melting (according to binding energy), one of the most direct probes of deconfinement
- Indication of sequential melting at LHC
- Y(1S) R_{AA}~0.5: consistent with suppression of higher states only?
- Y(1S) expected to melt at ~350 MeV



Digal,Petrecki,Satz PRD64(2001)
confirmed by recent calculations, e.g.
Miao, Mócsy, Petreczky, NPA (2011)

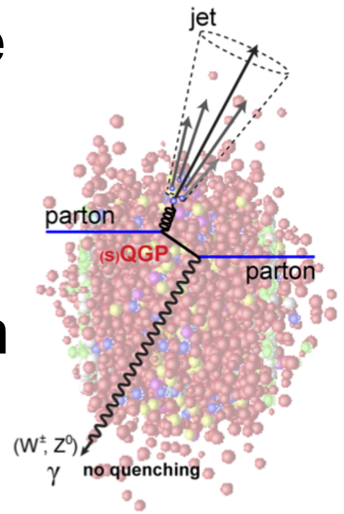


→ May not melt at LHC

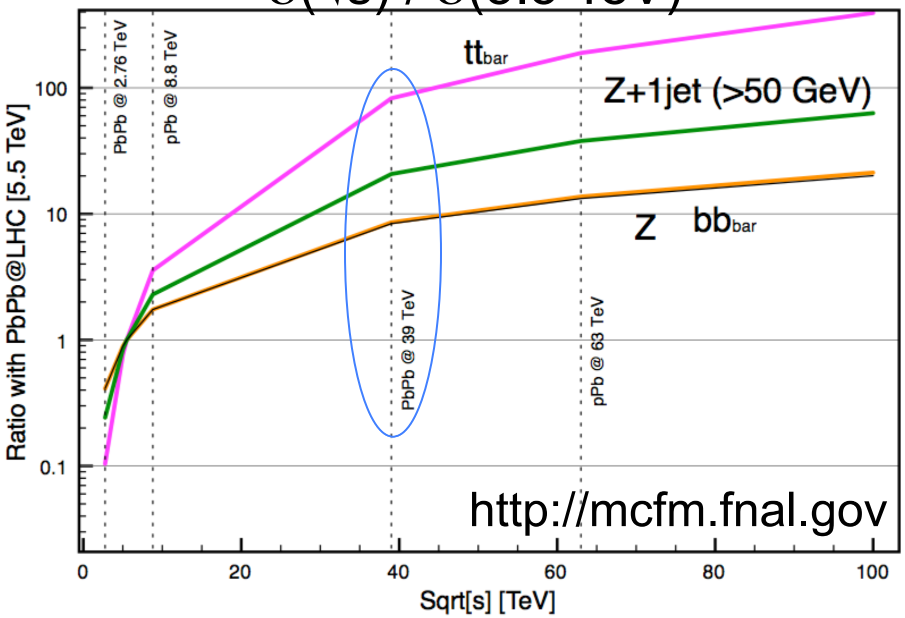
→ Full quarkonium melting at FCC?

A new 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



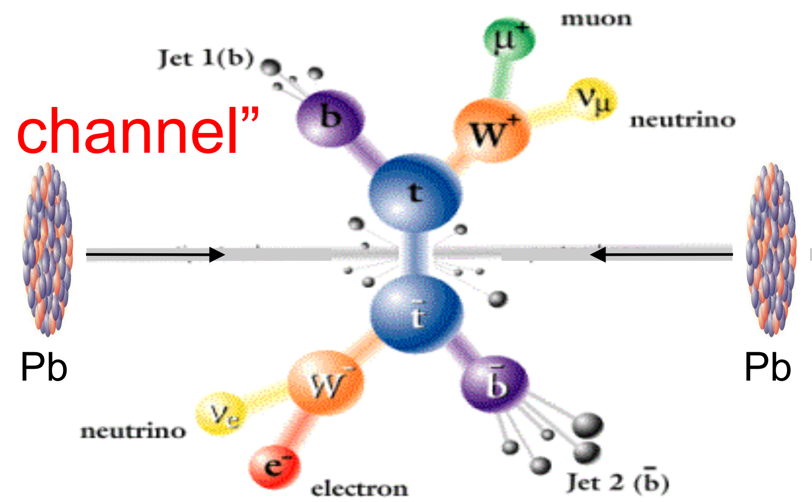
$\sigma(\sqrt{s})$ / σ(5.5 TeV)



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

Example: Top quarks

- $t\bar{t}$ 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 (LHC Runs-3-4)**

- FCC: with 100 nb^{-1}, x800 more wrt HL-LHC

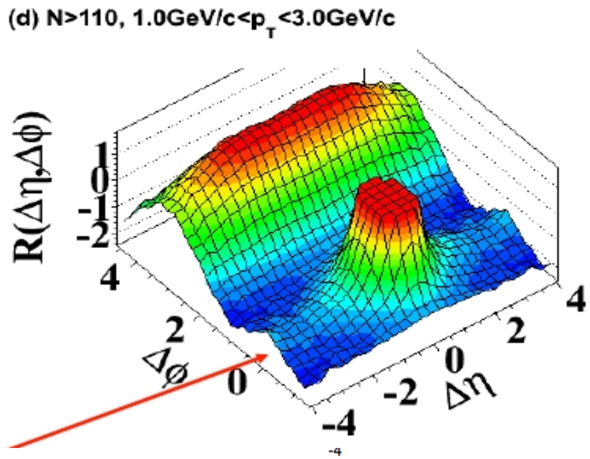
→ **FCC** with CMS-like setup, **~4x10^{5}** for “observation channel”

  - could be 4-5x more in the other channels (but higher background)

High-multiplicity events in small systems

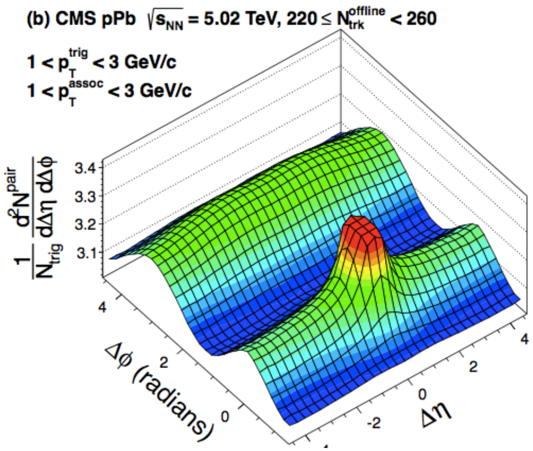
- One of the most interesting findings from LHC Run-1: similarity of long-range correlations (ridge) in high-mult pp, pPb as in Pb-Pb collisions
- Similar mechanism? Collectivity in small high-density systems? Initial or final state collectivity?

pp, high mult



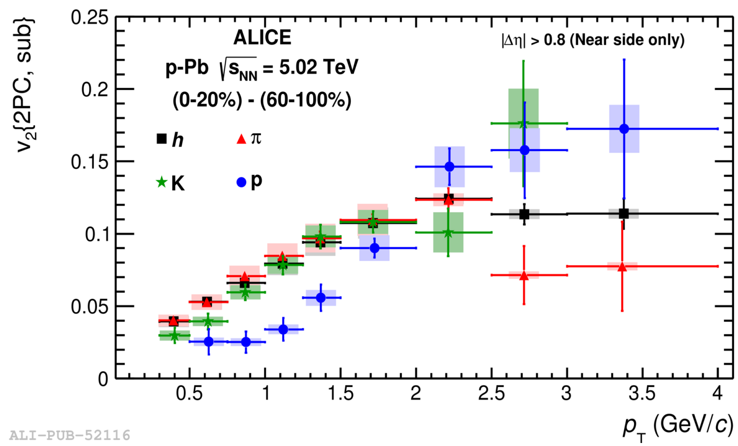
CMS, JHEP 1009 (2010) 091

pPb, high mult



CMS, PLB 724 (2013) 213

pPb, high mult

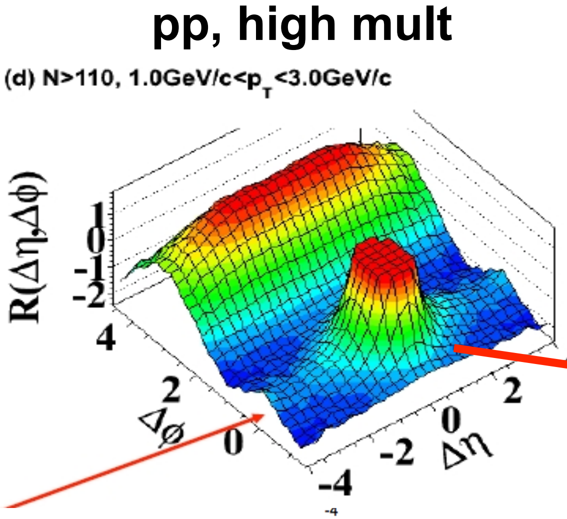


ALICE, PLB726 (2013) 164

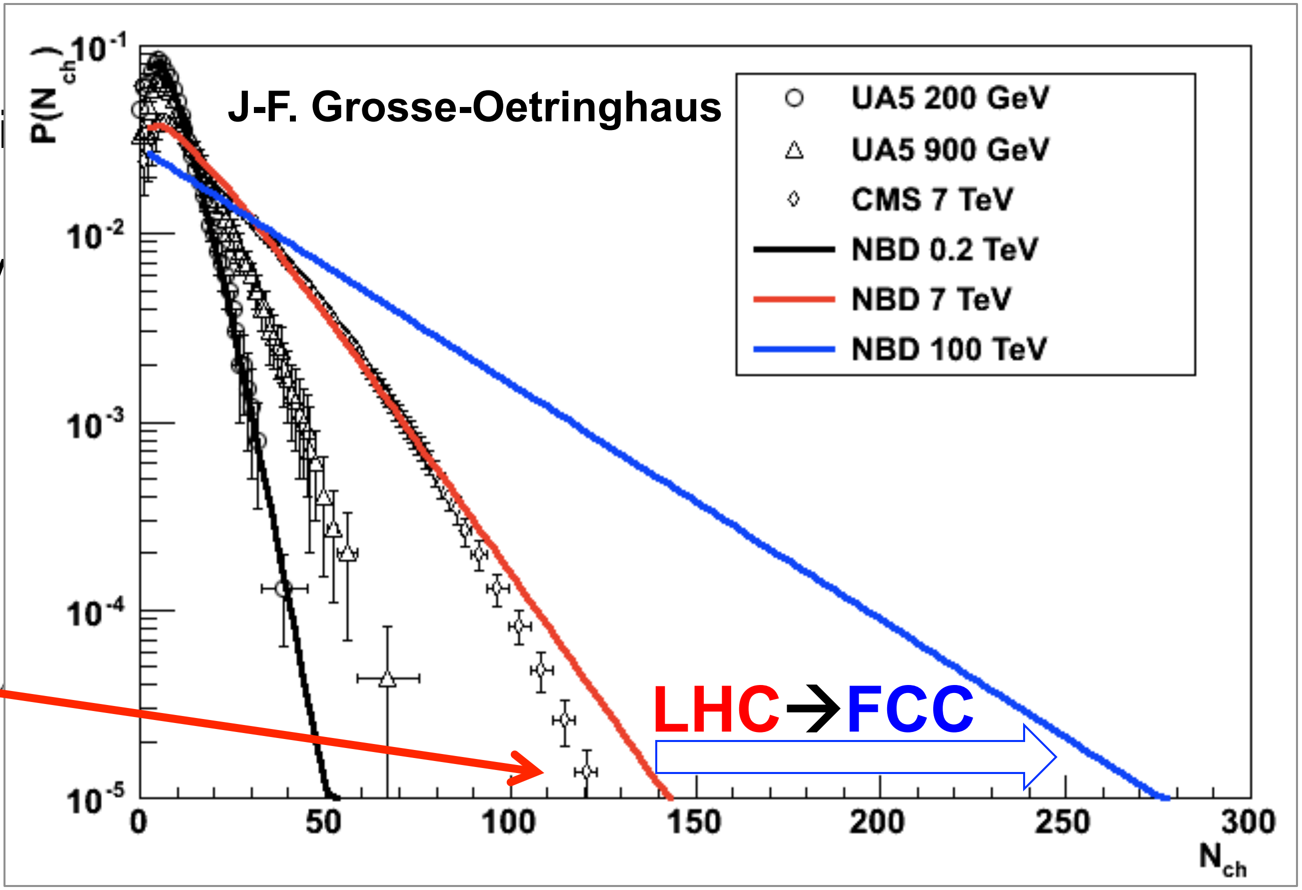
- Increased energy and luminosity of FCC could be a unique opportunity to explore more extreme multiplicities and study QCD mechanisms that lead to thermalization/collectivity

High-multiplicity events in small systems

- One of the most inte range correlations (ri
- Similar mechanism? final state collectivity

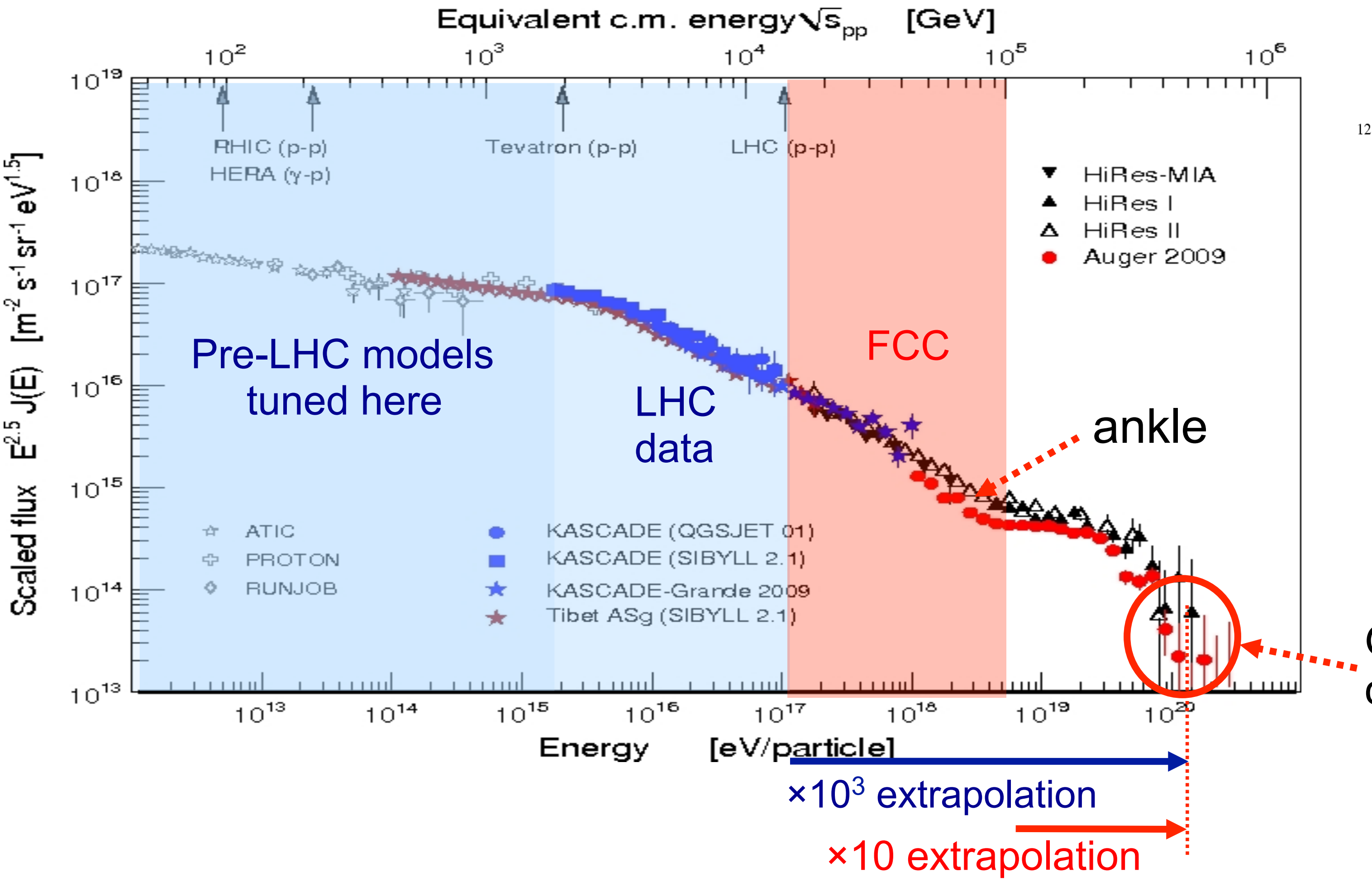


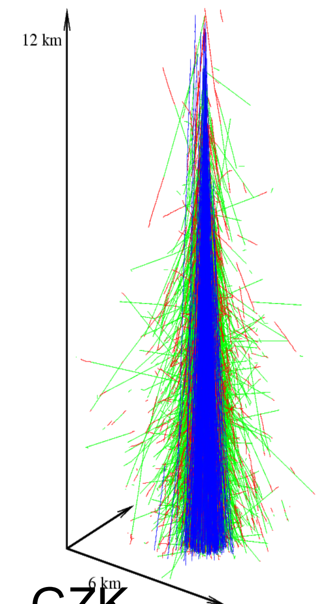
CMS, JHEP 1009 (2010) 091



- 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)

Summary

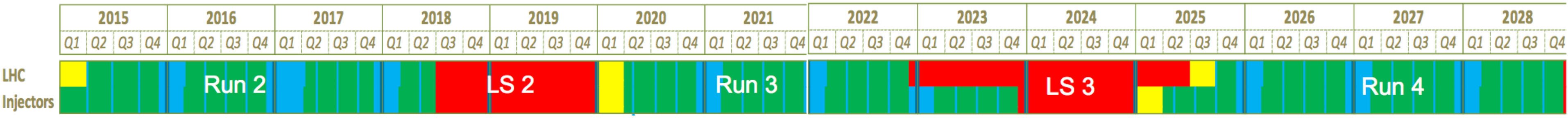
- Discussions started on opportunities with heavy ions, within the FCC design study

- Saturation physics in pA, eA and γA
  - Higher energy and large nuclei → unique access to saturation region (down to x<10^{-6}) with perturbative probes
- QGP physics
  - Larger initial temperature and volume entail potentially unique aspects, e.g. thermal production of charm
  - Larger $\sqrt{s}$ and L_{int} give access to new hard observables, e.g. top or Z + N-jets
- Also: benefit for UHECR studies

- New inputs and ideas are most welcome!

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 5.1TeV | PbPb 5.1TeV | pPb? 8.2TeV

Also corresponding pp reference

ArAr pPb 5-8 TeV PbPb

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

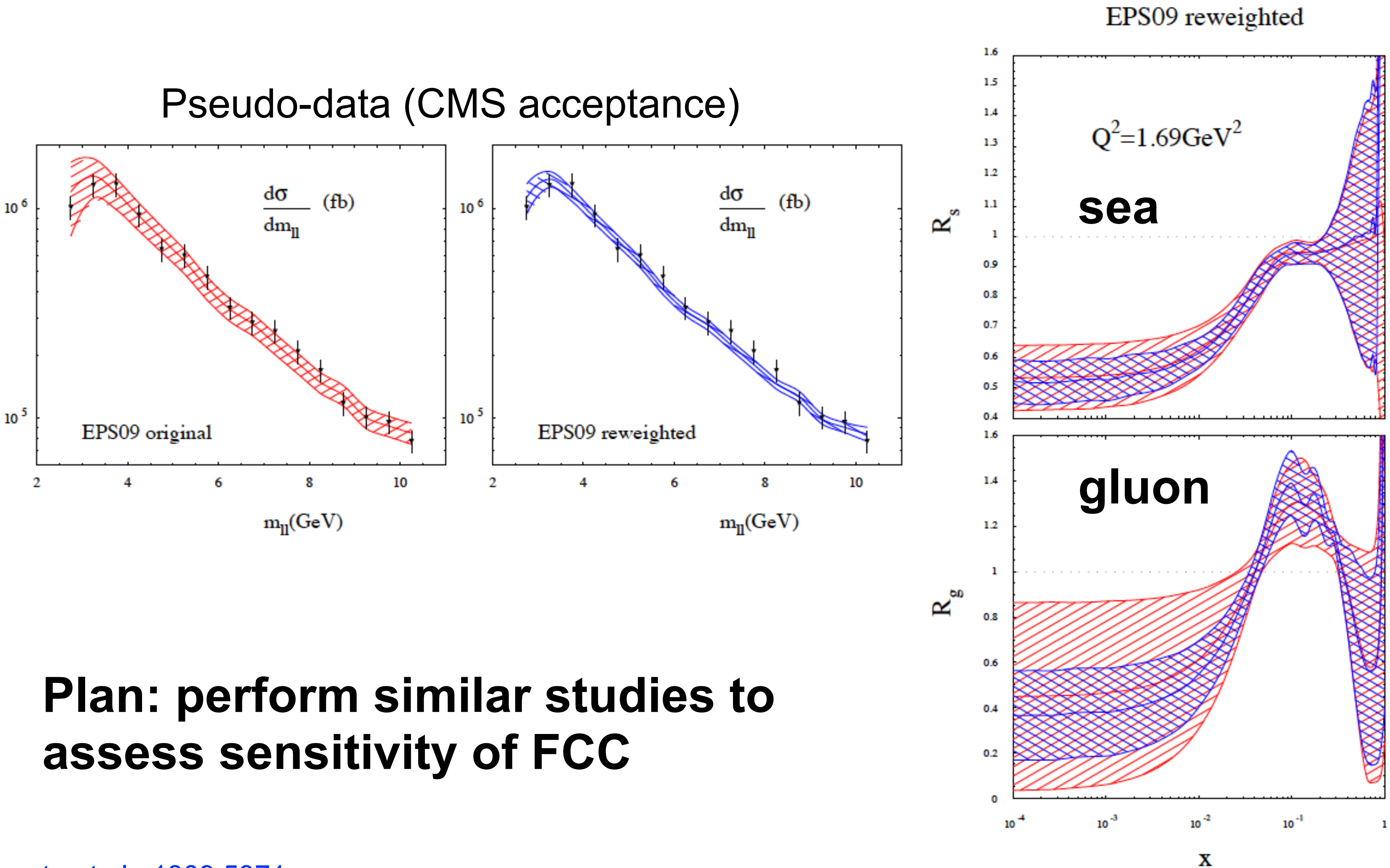
HI-HL-LHC Programme

(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**)

For illustration: Drell-Yan in p-Pb at LHC

Pseudo-data (CMS acceptance)

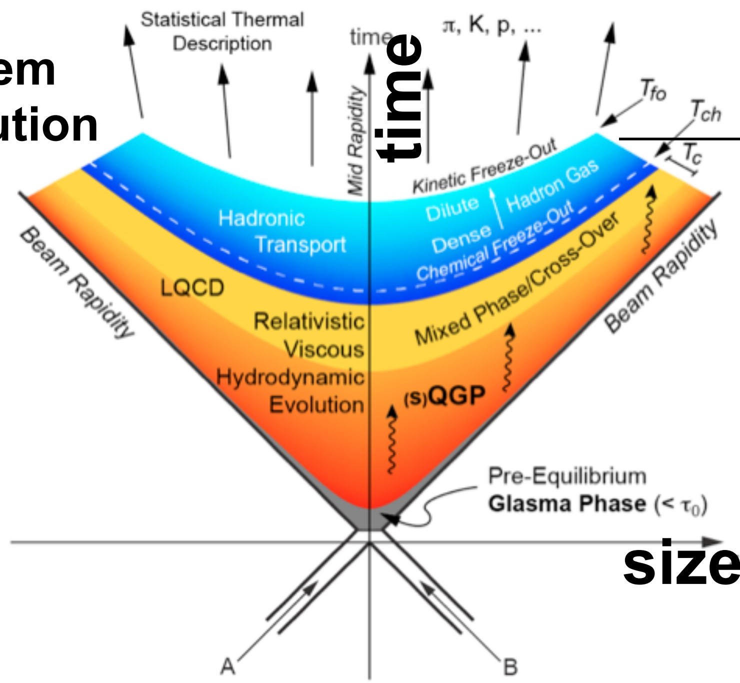


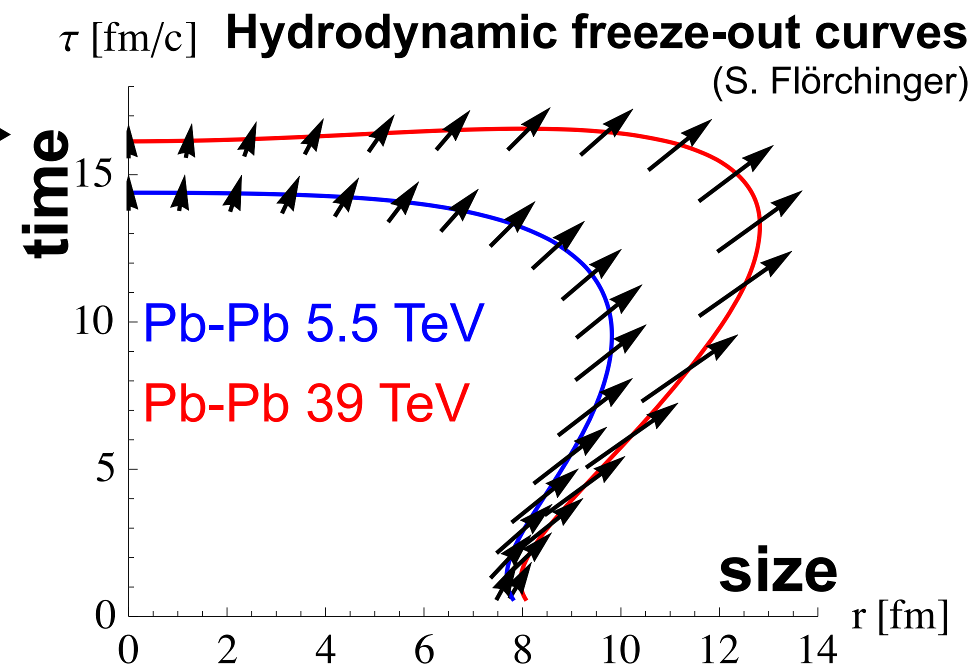
Plan: perform similar studies to assess sensitivity of FCC

Armesto et al., 1309.5371

Hydro simulation at FCC

System evolution



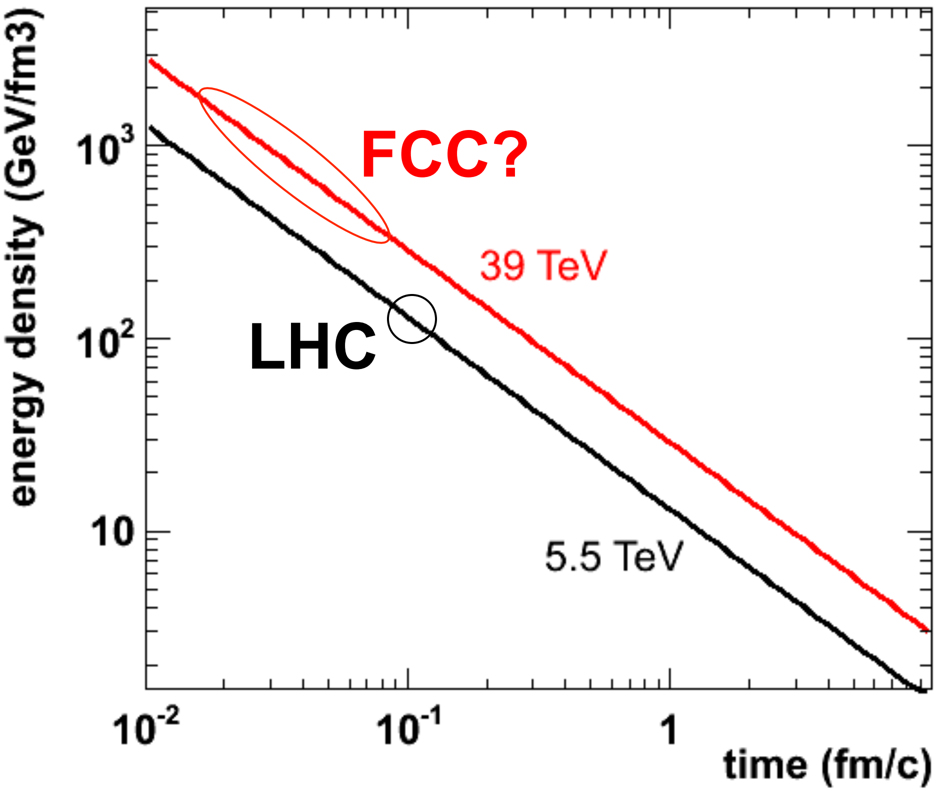


- Hydro-simulation (b=0, eta/s = 1/4pi, dN_{ch}/dy 3600 @ FCC) without
- initial fluctuations.
- In the simulation, the difference between FHC and LHC results from adjusting the initial temperature in the same geometry such that the final charged multiplicity increases to 3600 (instead of 1600 at LHC).
- The arrows along the curves indicate the direction and strength of flow

QGP studies at the FCC: energy density

- Energy density with Bjorken formula

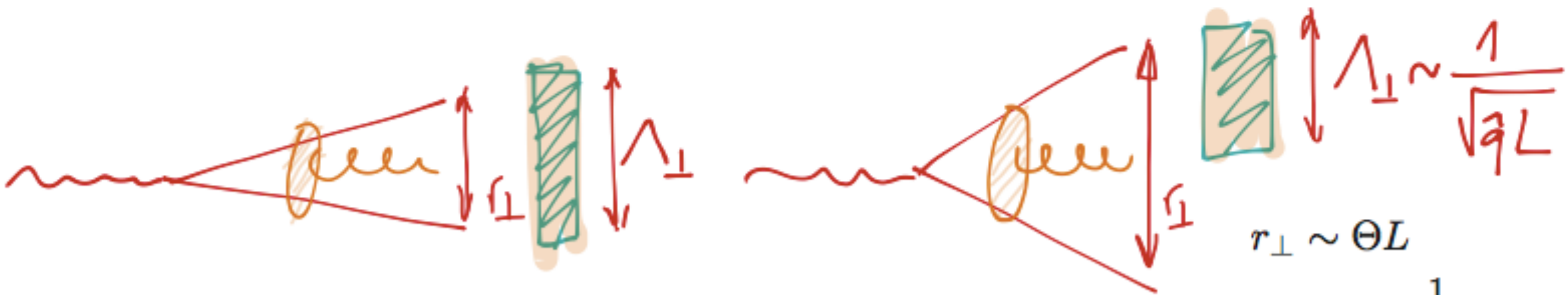
$$\varepsilon(\tau) = \frac{E}{V(\tau)} = \frac{1}{c\tau\ \pi R_A^2}\frac{dE_T}{d\eta}$$



- x2.2 larger for the same time
  - E.g. 35 GeV/fm^3 at 1 fm/c
- Initial time (QGP formation time)?
  - Usually ~0.1 fm/c for LHC
  - Could be smaller at FCC
- Significantly larger initial energy density?

An interesting physics case: boosted color singlets in the medium

Basic idea: the QCD medium does not affect colored objects smaller than its resolving power Λ



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

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

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

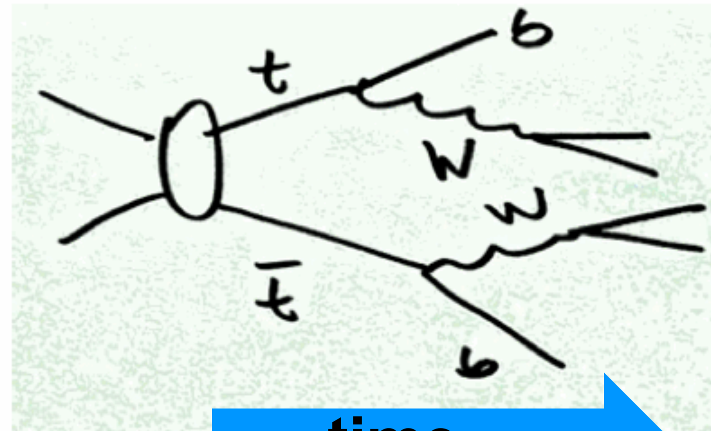
→ Boosted color singlet states can be used to probe the medium opacity / density at different time scales

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

An interesting physics case: boosted color singlets in the medium

First estimation of the timescales for boosted objects in the medium

$$t\bar{t} \rightarrow b\bar{b} + \ell + 2\,jets + \cancel{E}_T$$



time

time

	Pt=1 TeV	Pt=500 GeV
ttbat produced	0 fm/c	0 fm/c
top → W+b	1 fm/c	0.5 fm/c
W decay	1.6 fm/c	0.8 fm/c
qqbar in singlet	2.3 fm/c	1.3 fm/c

→ Interaction with the medium starts

A tool to probe timescale of medium evolution?

Top quark projection (FCC)

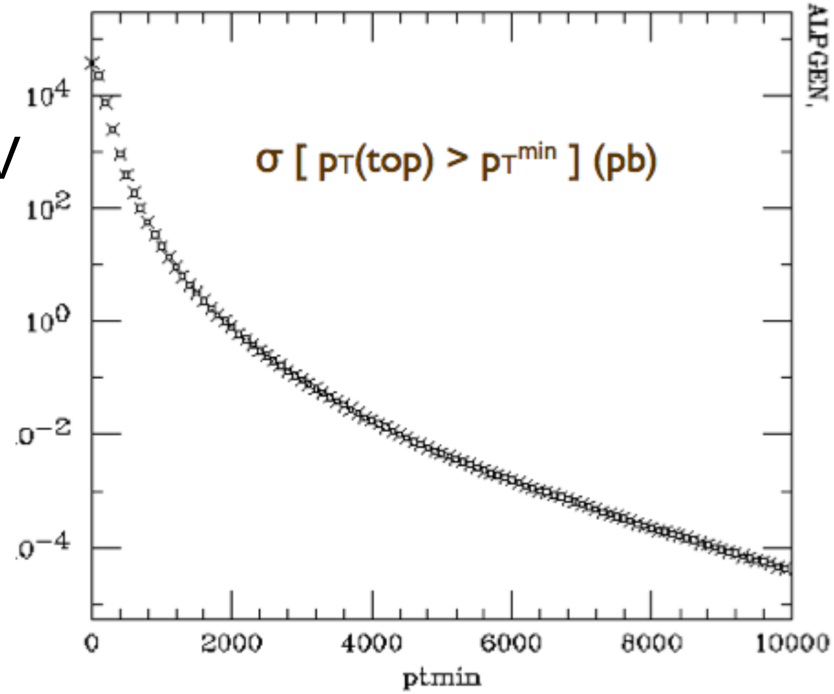
- ttbar cross section x80 from 5.5 to 39 TeV
- With L_{int}=100/nb, x800 top wrt 10/nb@LHC5.5

→ With a detector similar to CMS, we have ~4x10^5 in the "observation (cleanest) channel"

- Top cross section drops by 2 (3.5) orders of magnitude at p_T = 0.5 (1) TeV

→ few 10^3 with p_T > 0.5 TeV

→ few 10^2 with p_T > 1 TeV



M.Mangano, FHC informal meeting Nov 2013