FCC heavy-ion physics studies

Andrea Dainese
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Outline

- Introduction, organization
- Future timeline with heavy ions at the LHC
- 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)
- γ-induced collisions and connections to cosmic rays
- Detector design ideas (pp-driven)
- Summary

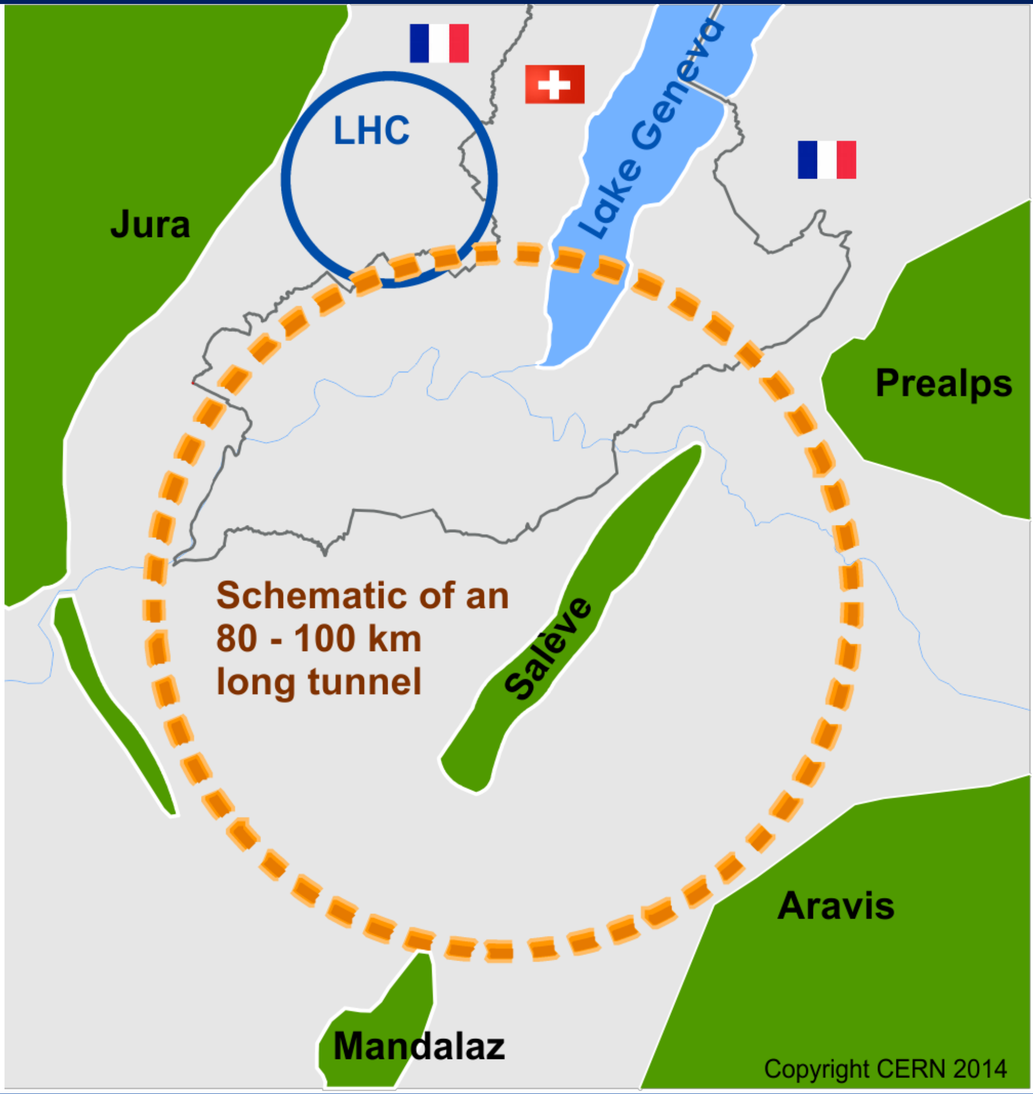
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

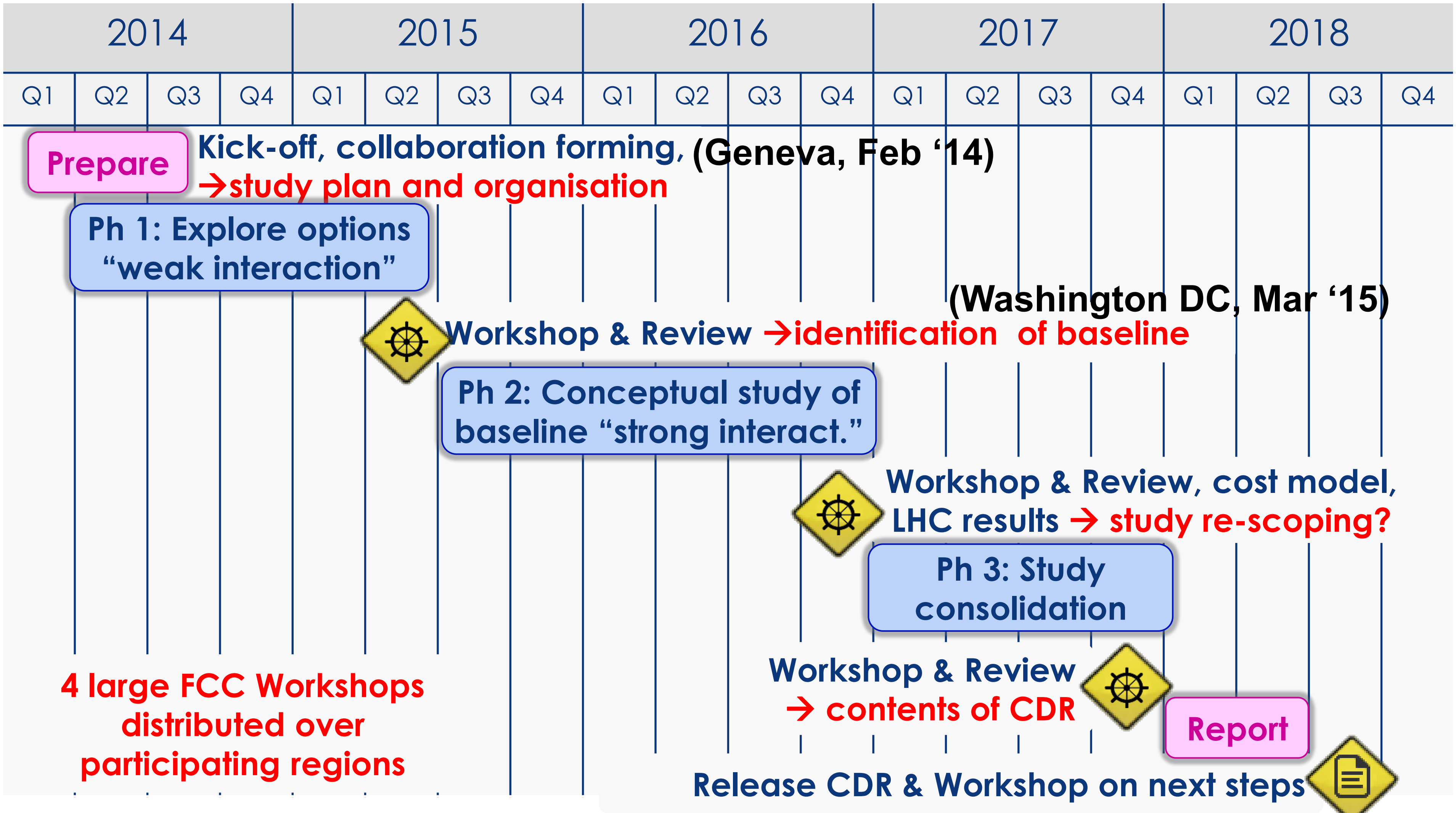
- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~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



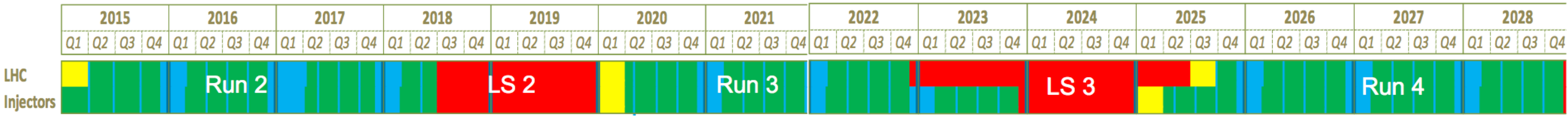
Proposal for FCC Study Time Line



Organization

- A discussion group on "Ions at the FCC" started: coordinated by A.D., S. Masciocchi, C. Salgado, U. Wiedemann
  - Sub-group of "FCC-h Physics, Experiments, Detectors" (Mangano, Gianotti, Ball)
- 4 meetings up now
  - https://indico.cern.ch/event/331669/ and links therein
- Goal: explore opportunities with HI at the FCC
  - Saturation (contacts: N. Armesto, M. van Leeuwen)
  - Soft physics (contact: U. Wiedemann)
  - Hard probes (contacts: A. Dainese, C. Roland, C. Salgado)
  - $\gamma\gamma$ / UPC (contact: D. d'Enterria)
- Work in progress! Just few initial ideas presented here

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 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

Ions at FCC: energies and luminosities

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

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

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

Ions at FCC

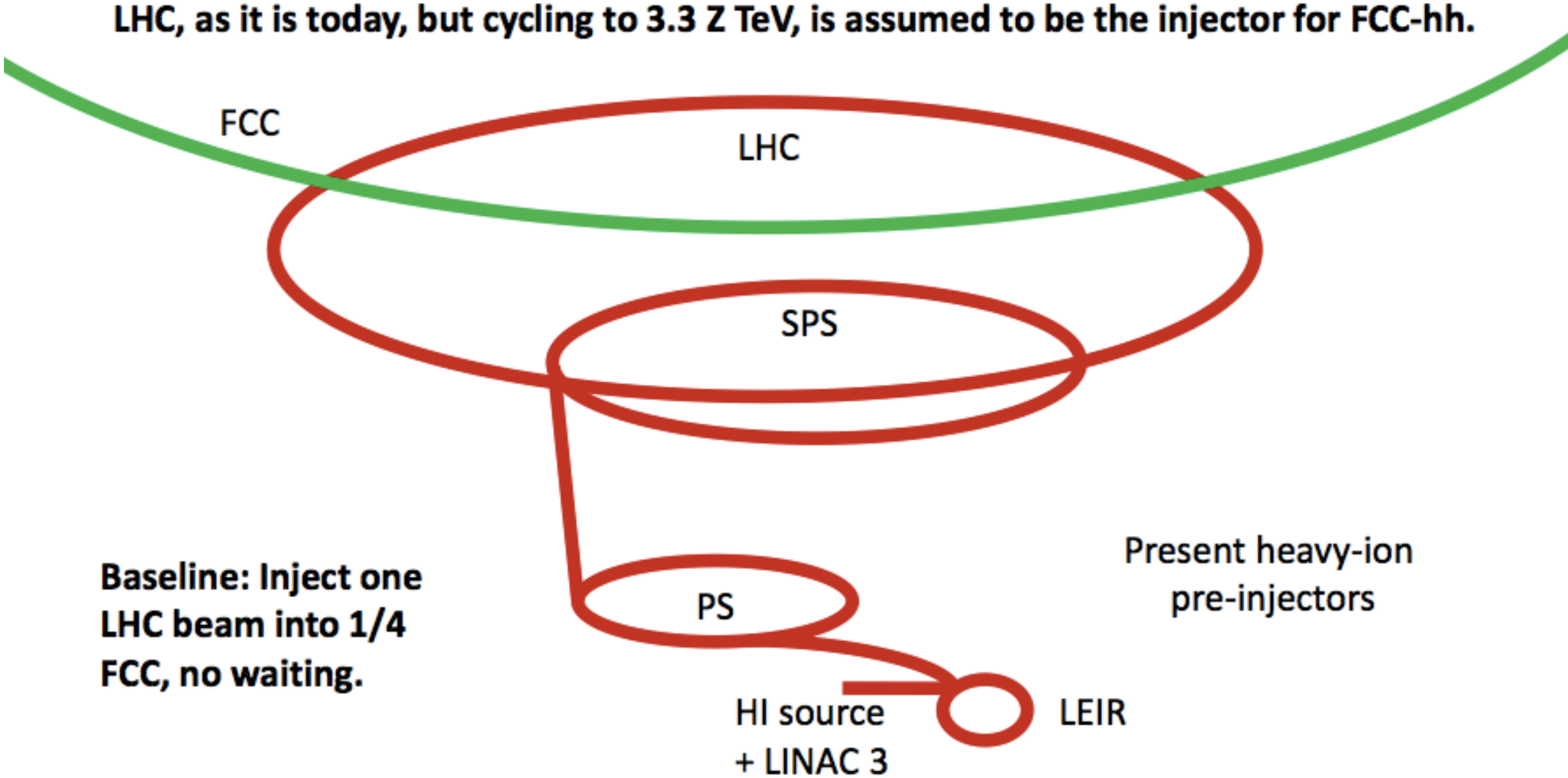
Heavy Ion Pre-Accelerator Chain

M.Schaumann

The requirements and performance of the pre-accelerator chain for FCC are under studied.

R&D

Straw-man assumption to estimate (conservative) beam parameters and luminosity:
LHC, as it is today, but cycling to 3.3 Z TeV, is assumed to be the injector for FCC-hh.

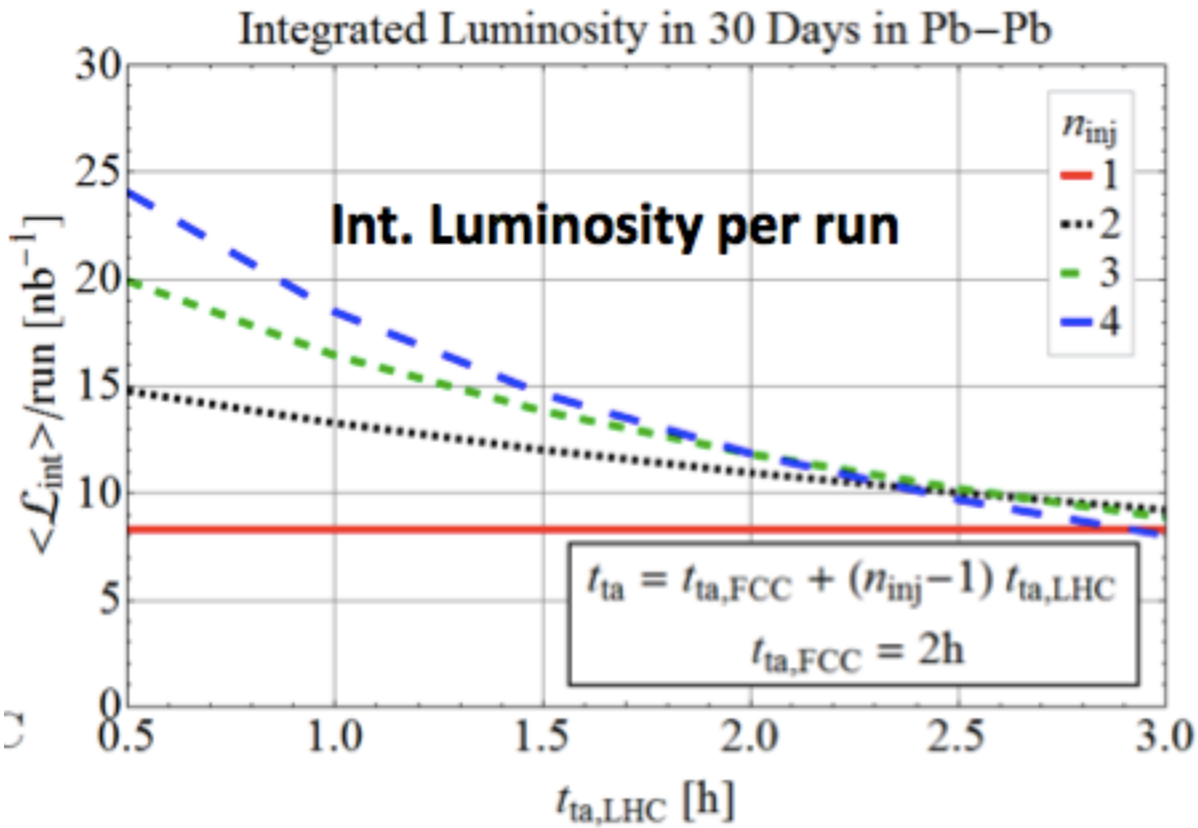


Baseline: Inject one LHC beam into 1/4 FCC, no waiting.

2014/09/22 M. Schaumann, Workshop on Ions at the FCC, CERN 5

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

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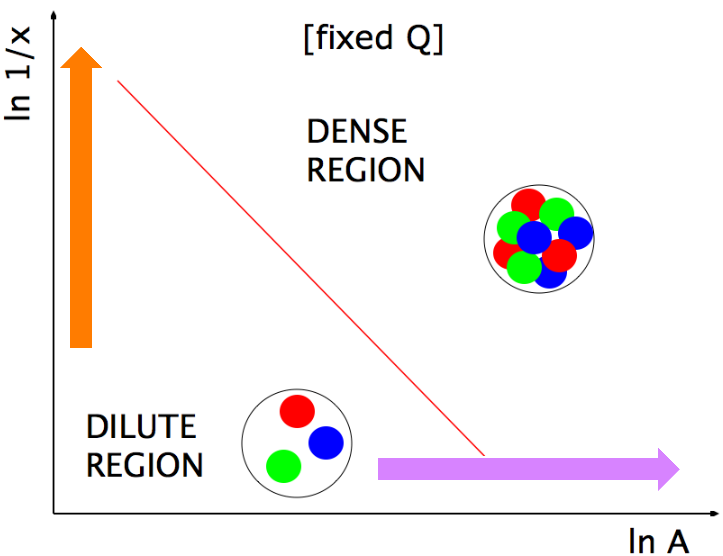
High-density QCD in the initial state: Saturation at low *x*

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



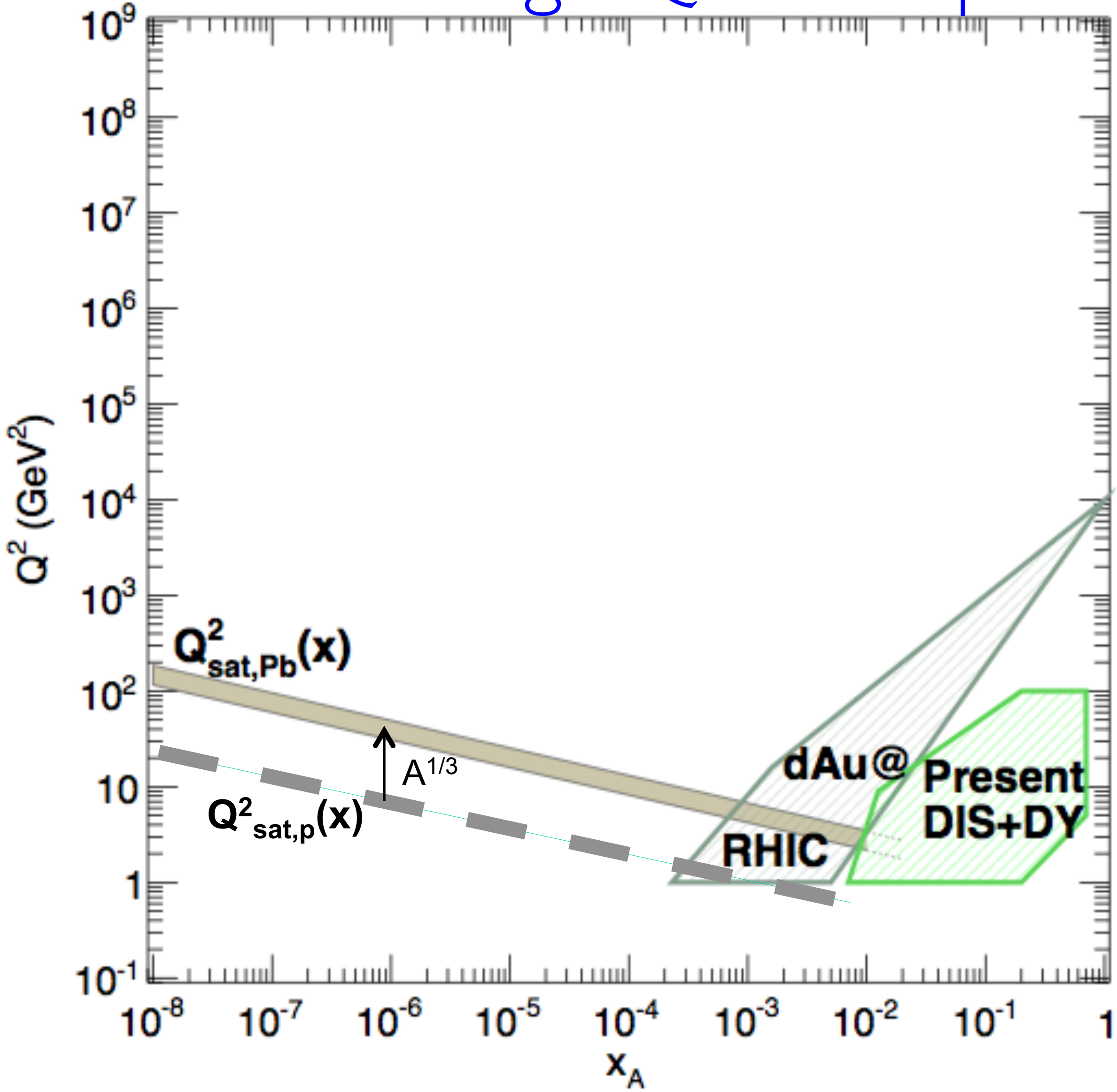
Saturation affects process with $Q^2 < Q_S^2$

Explore saturation region:

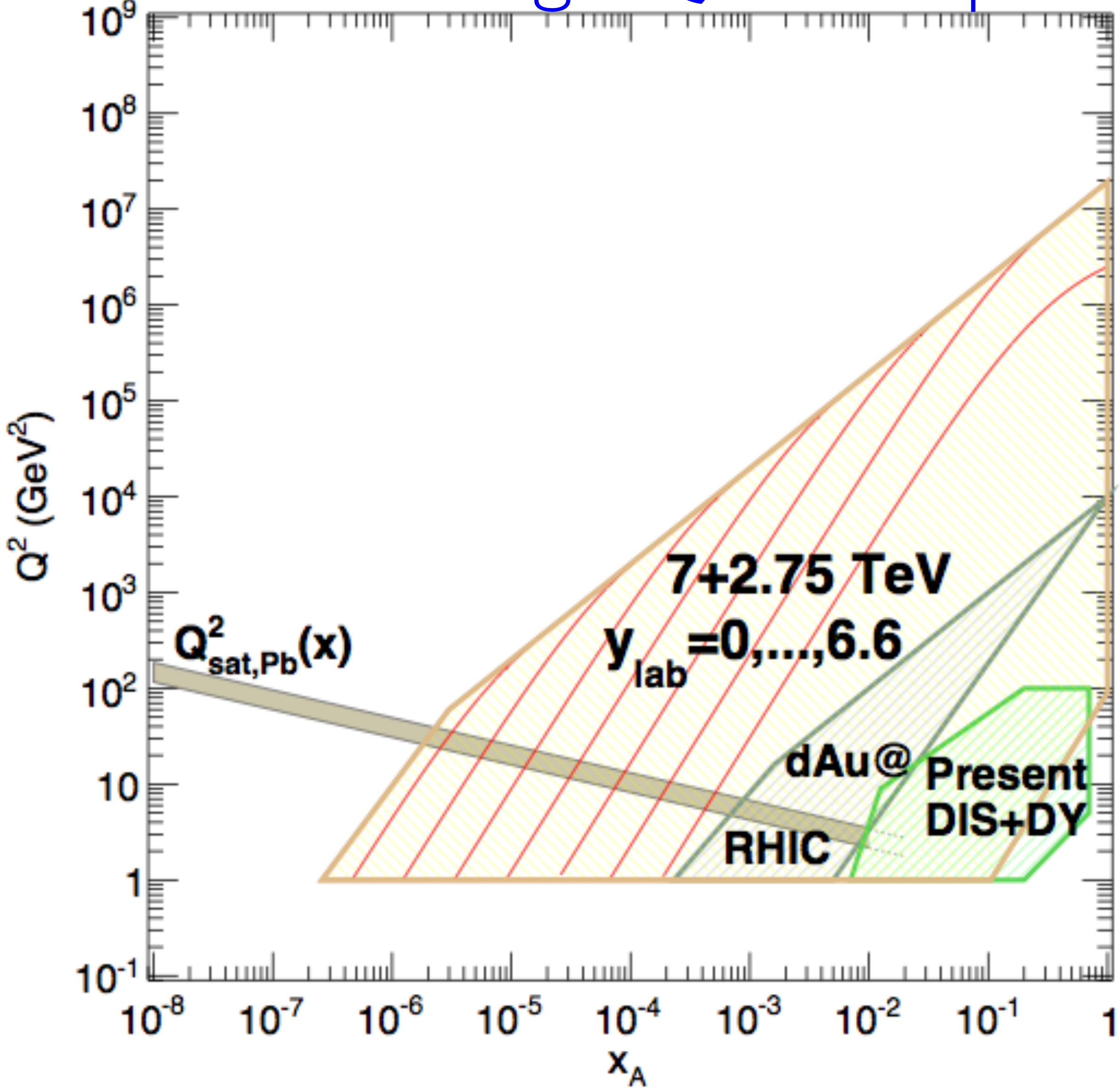
→ **decrease *x* (larger √s, larger *y*)**

→ **increase A**

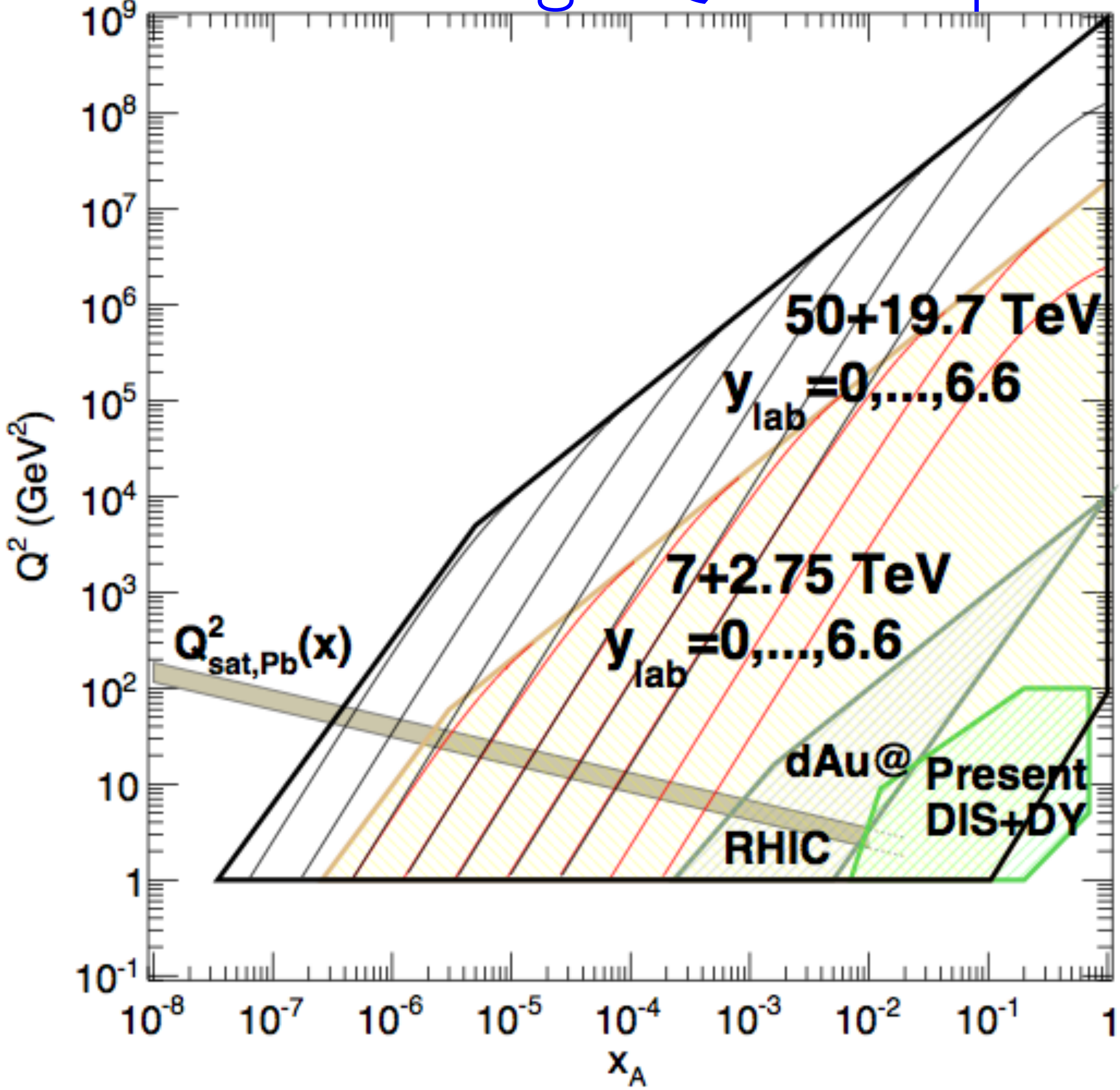
Kinematic coverage Q^2 vs. x: pre-LHC



Kinematic coverage Q^2 vs. x: pA LHC



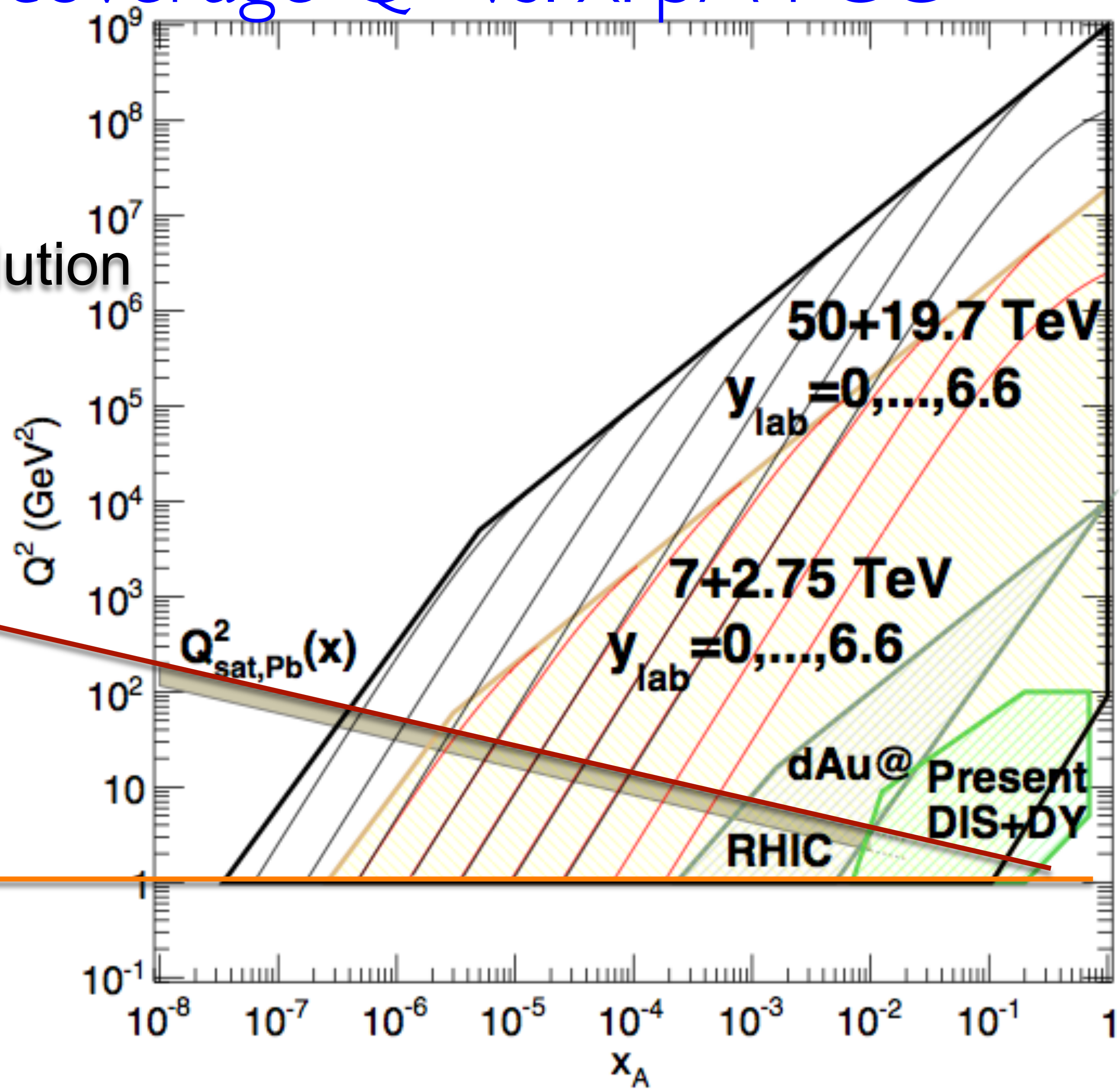
Kinematic coverage Q^2 vs. x: pA FCC



Kinematic coverage Q^2 vs. x: pA FCC

Goals:

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

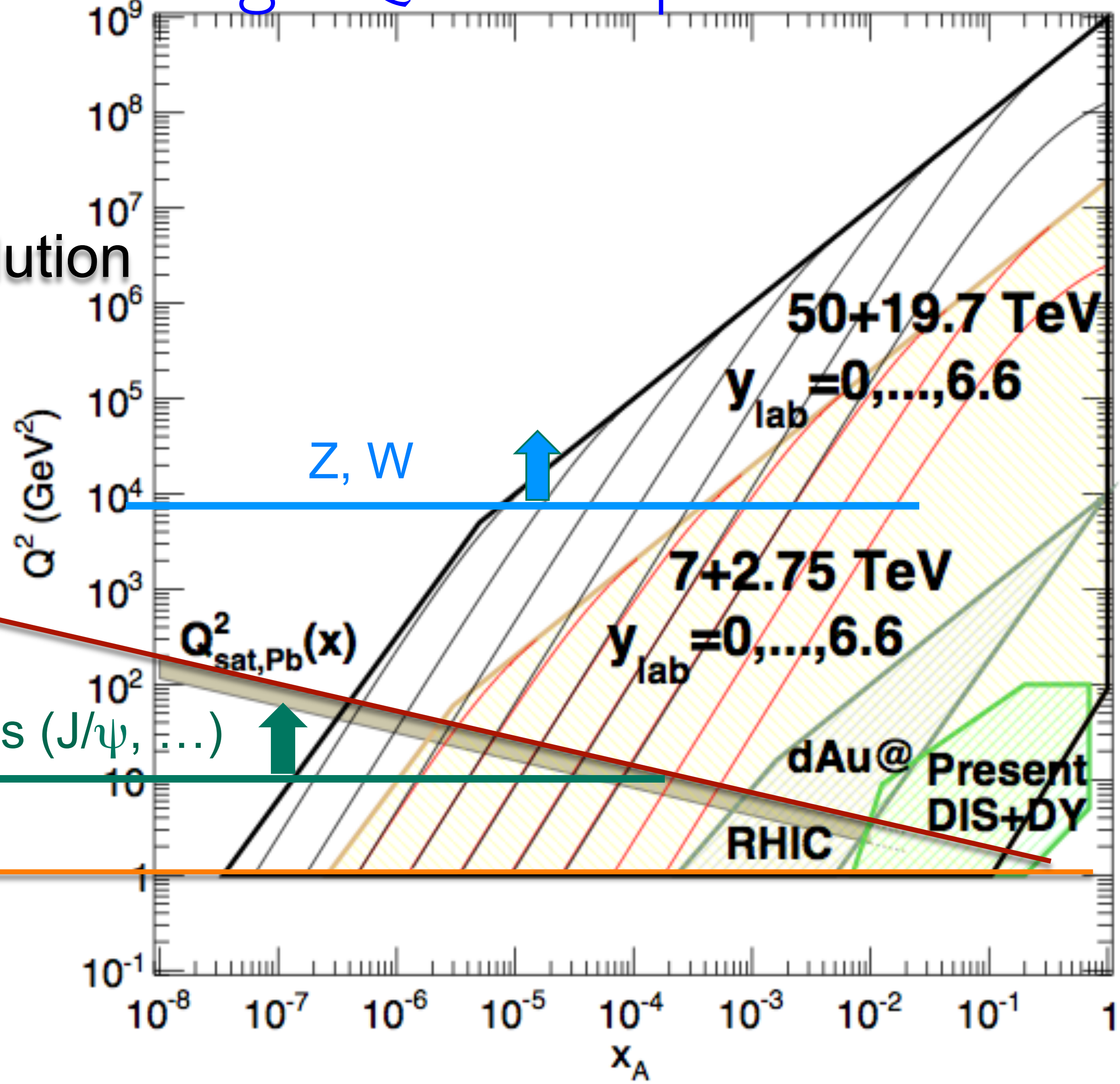


Non-Linear evolution for $Q^2 < Q^2_{sat}$

Low Q^2: initial conditions

Kinematic coverage Q^2 vs. x: pA FCC

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

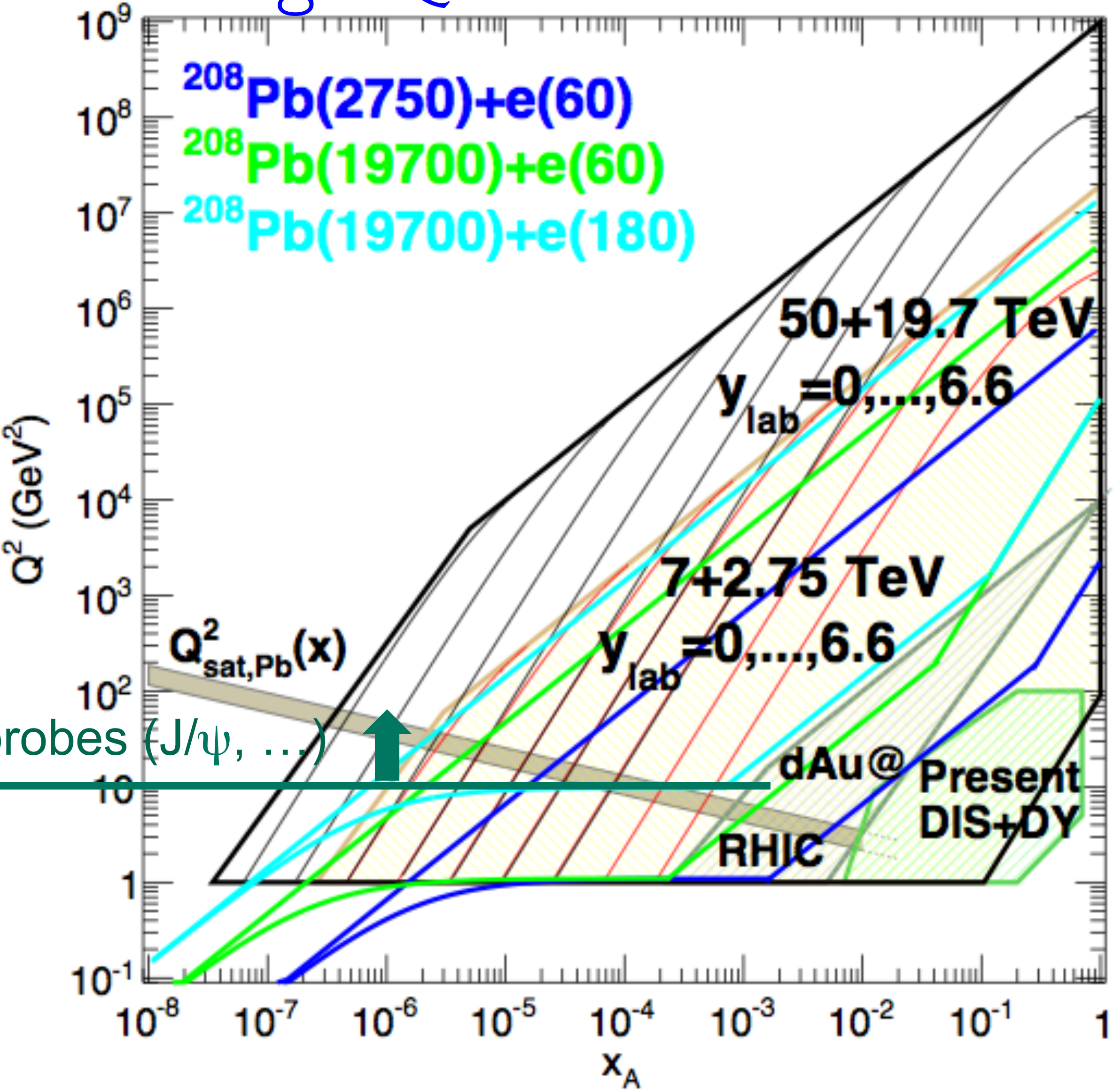


	y@LHC	y@FCC
Charm	>4	>2

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



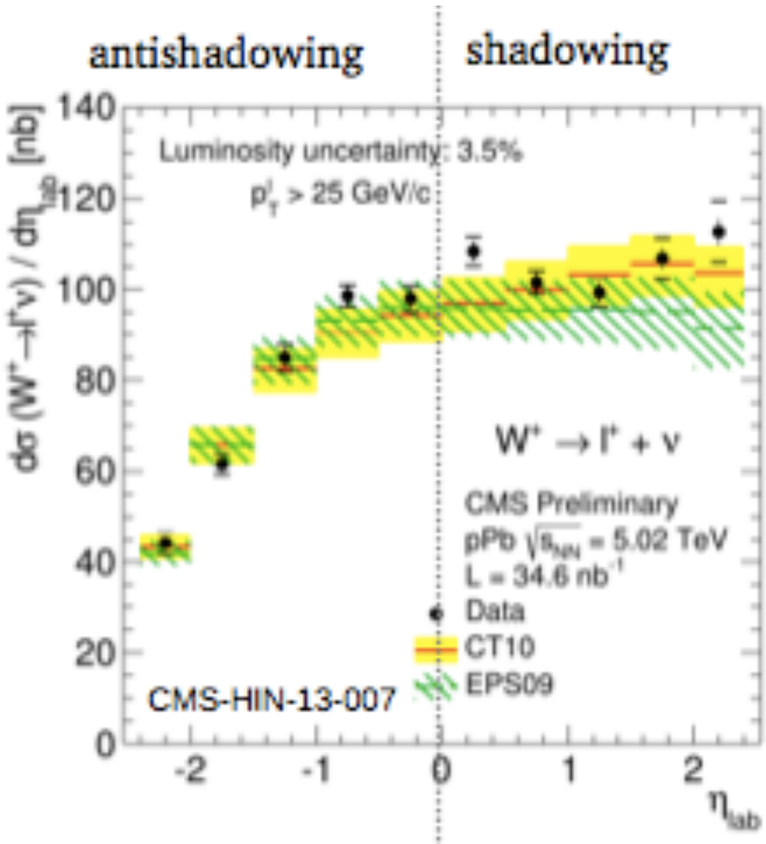
Testing non-linear evolution

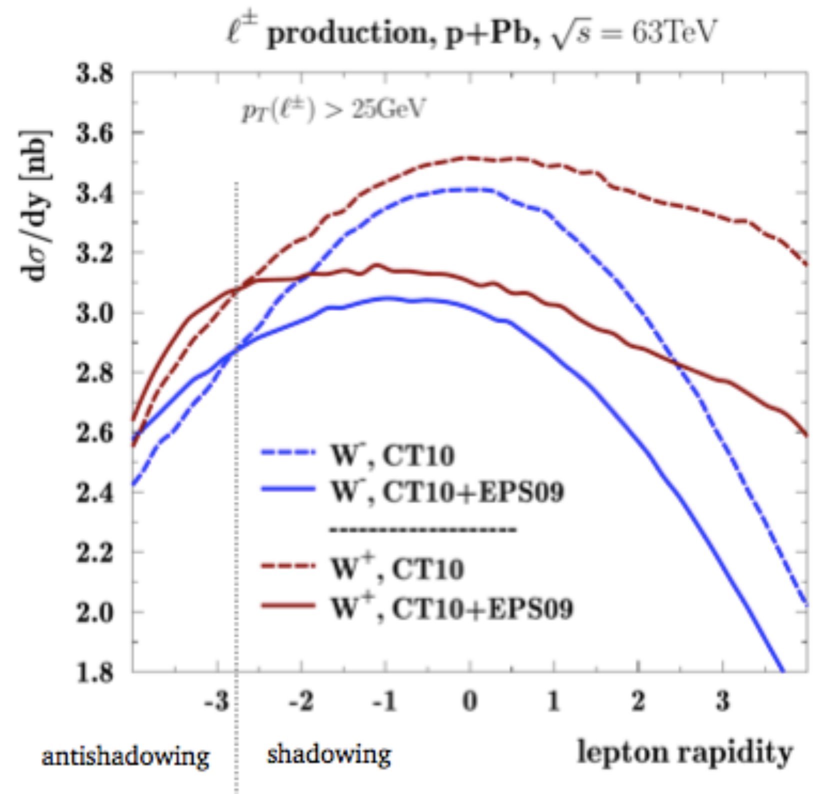
- Cover significant range in (x, Q^2) → next slides
- Multiple observables with sensitivity to quarks and gluons
  - At FCC expect significant charm contribution in sea
- Kinematics is cleanest for partonic observables: photons, Drell-Yan, W/Z bosons
  - + no interactions in the final state
- Hadronic observables potentially very interesting (e.g. forward pion+jets)
  - Validation and sensitivity will come from LHC data (including possible impact of final-state effects in pA)

Plan: quantify impact of observables on nuclear PDF fits; expect constructive overlaps with ongoing LHC studies

Example: W and Z

H.Paukkunen



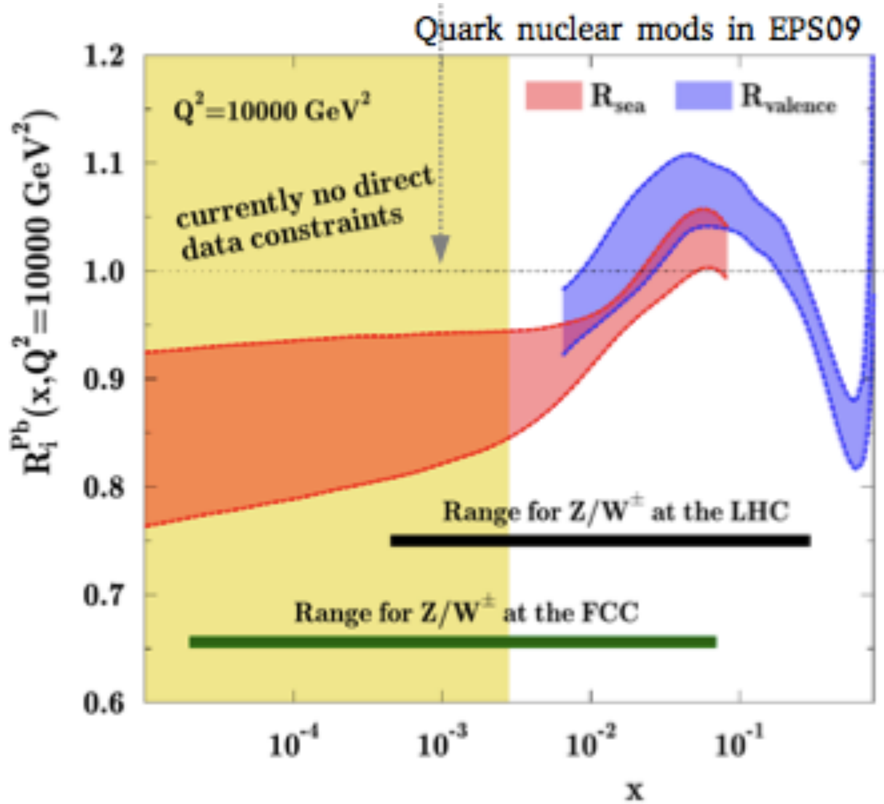


LHC: sensitivity to shadowing at η>2

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

Example: W and Z

H.Paukkunen

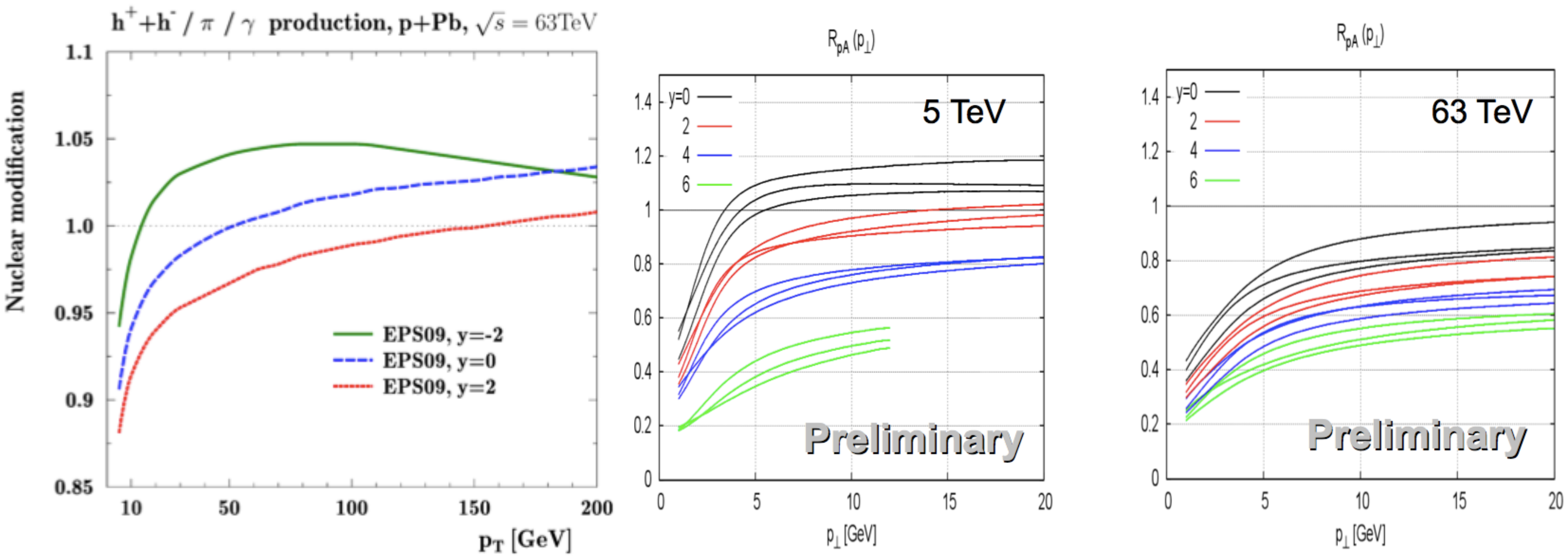


LHC: sensitivity to shadowing at η>2

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

Example: charged-particle R_{pA}

H.Paukkunen
H.Fujii



Collinear factorization with nPDFs: no strong suppression even at FCC energy

CGC: significantly larger suppression than at LHC at central rapidity

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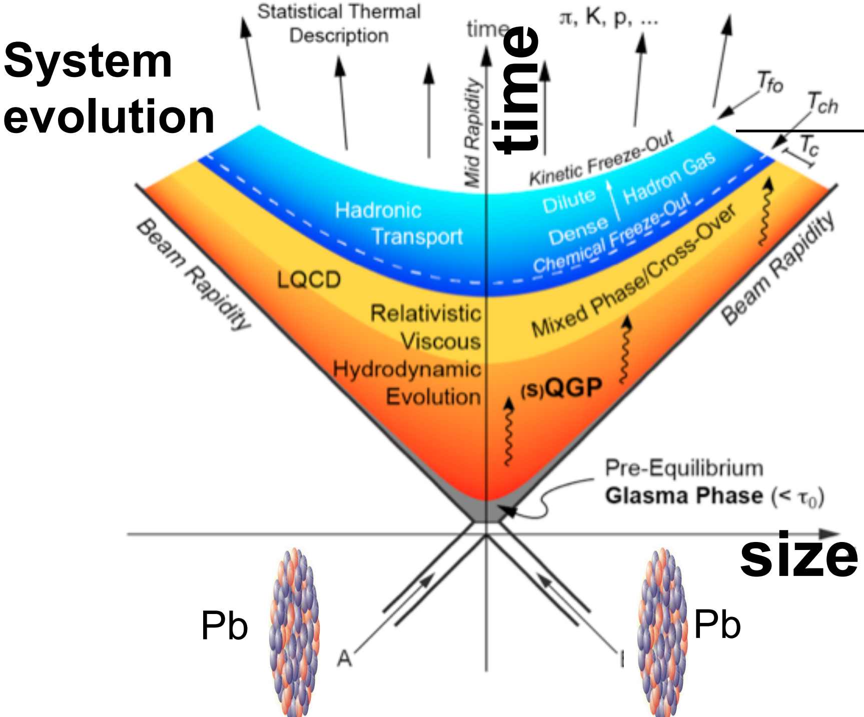
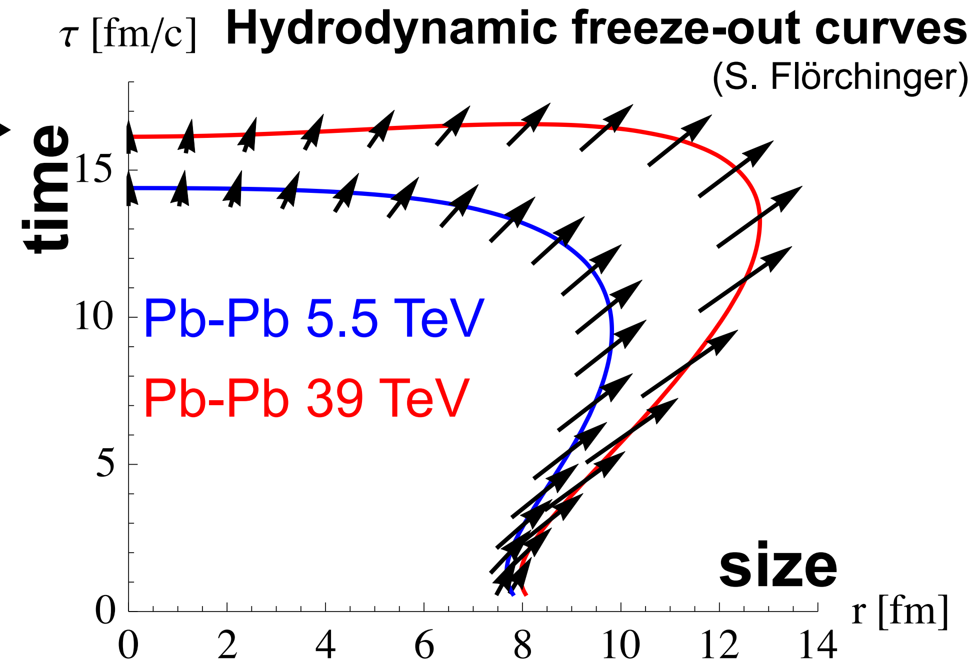
Quark-Gluon Plasma studies at FCC





Properties of QGP:

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

Quark-Gluon Plasma studies at FCC

INFN

Questions to be addressed in future studies include:

Higher Temp.

- Larger **number of degrees of freedom** in QGP at FCC energy? → g+u+d+s**+charm** ?
- Changes in the **quarkonium spectra**? does **Y(1S) melt** at FCC?

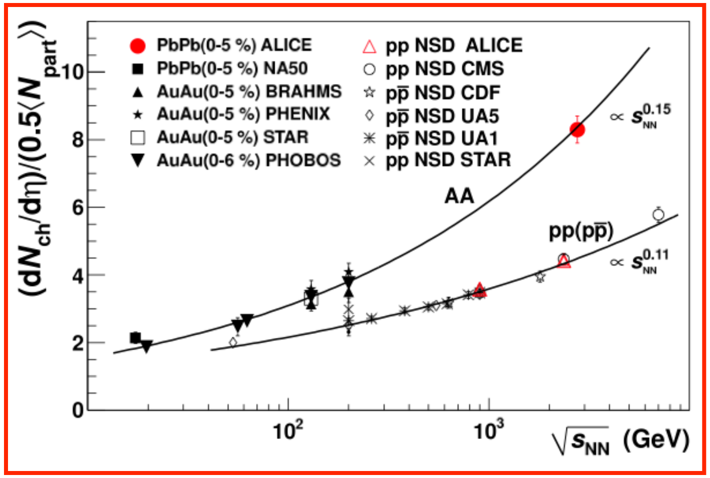
Higher energy

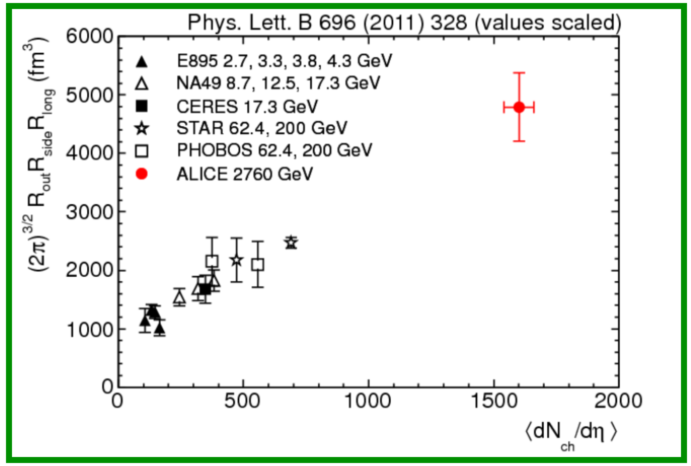
- How do studies of **collective flow** profit from **higher multiplicity and stronger expansion**? More stringent **constraints on transport properties** such as shear viscosity or other properties not accessible at the LHC
- **Hard probes** are sensitive to medium properties. At FCC, **longer in-medium path length and new, rarer probes** become accessible. How can both features be exploited?

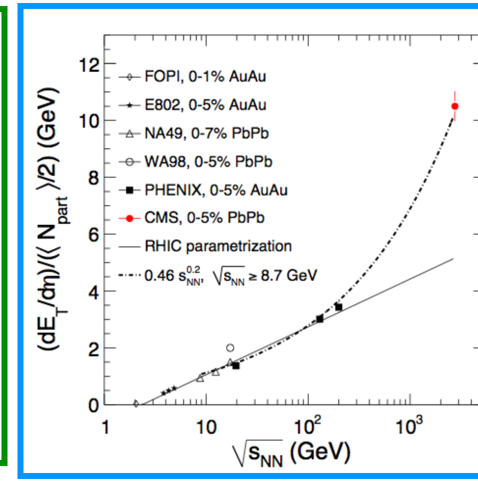
QGP studies at the FCC: global properties

- 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**





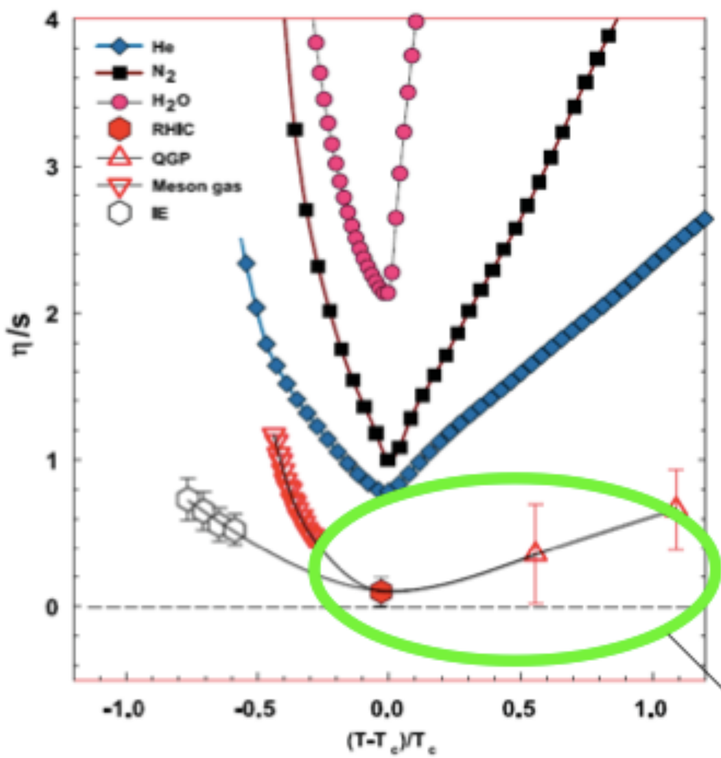


Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	2 TeV	2.6 TeV	5.8 TeV
BE homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
BE decoupling time	10 fm/c	11 fm/c	13 fm/c

Example: sensitivity of flow to η/s

Denicol, Luzum, Paquet

→ **η/s is not constant!**



Lacey *et al*(2007)

In principle, T-dependence can be strong

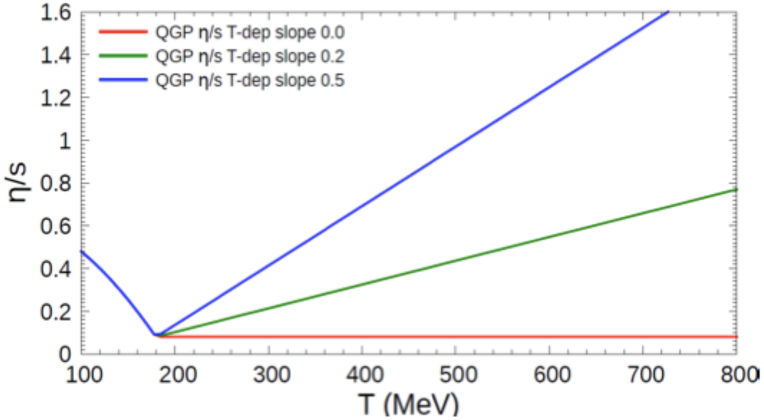
η/s only expected to be small around the transition region

η/s=cte is only an effective viscosity. Not simply related to the real viscosity

Unknown!!

Can we measure the T-dependence of η/s?

Example:
sensitivity of flow to η/s

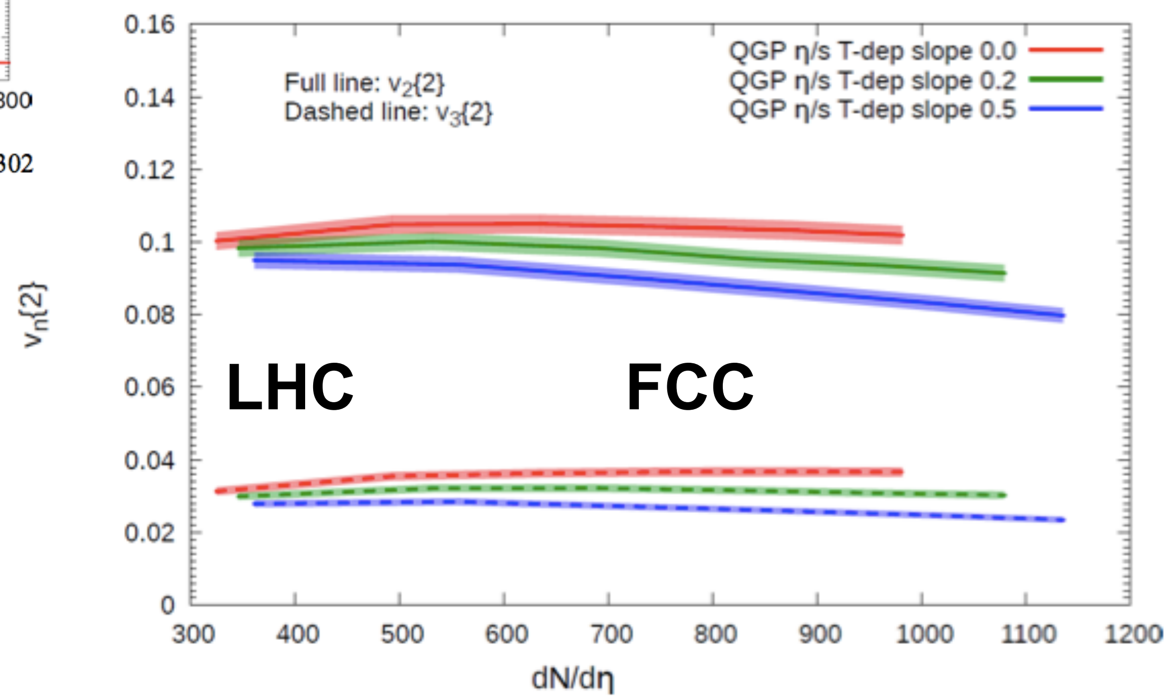


Hadronic phase : Noronha-Hostler *et al*, PRL 103 (2009) 172302

QGP phase : parametrizations

Denicol, Luzum, Paquet

Energy Scan 30-40%



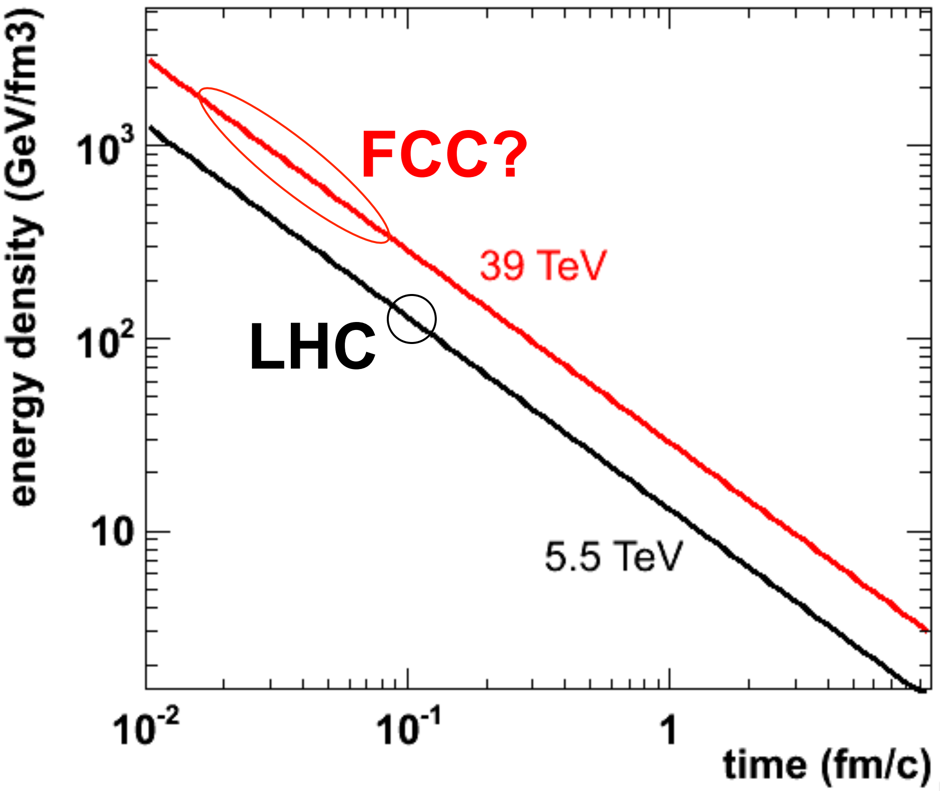
Large effect!

Depending on η/s(T), Vn can start to decrease at larger energies

QGP studies at the FCC: energy density

- Energy density with Bjorken formula

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

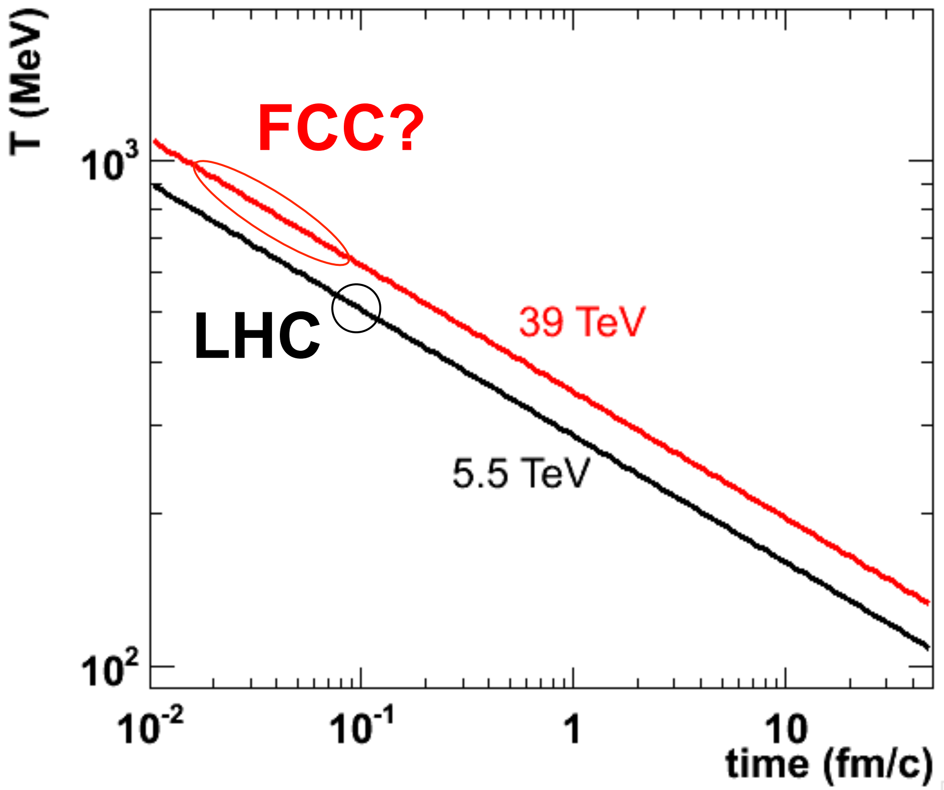


- x2.2 larger for the same time
  - E.g. 35 GeV/fm^3 at 1 fm/c
- Initial time (QGP formation time)?
  - Usually ~0.1 fm/c for LHC
  - Could be smaller at FCC
- Significantly larger initial energy density?

QGP studies at the FCC: temperature

- Temperature from S-B equation

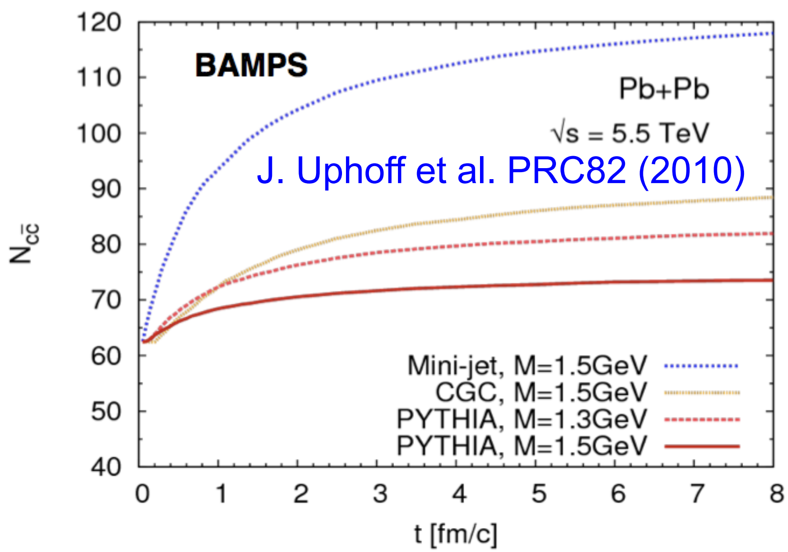
$$T(\tau) = \sqrt[4]{\varepsilon(\tau)\frac{30}{\pi^2 n_{d.o.f.}}}$$

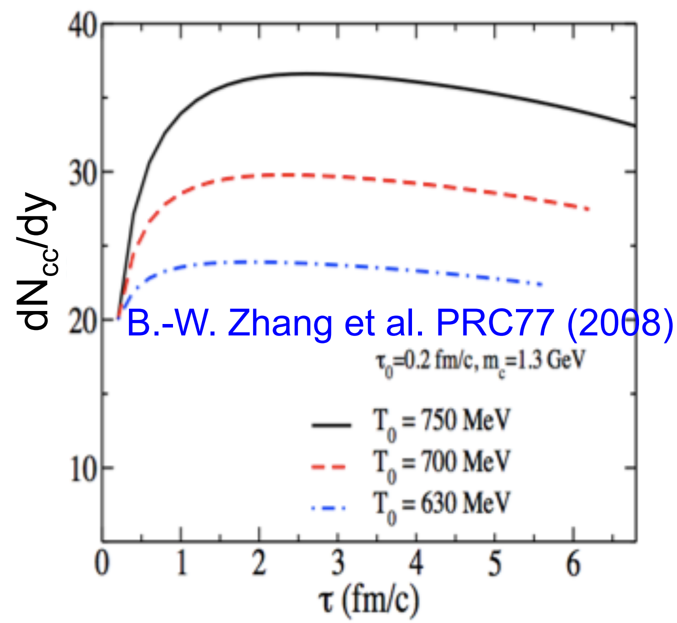


- 20% larger for the same time
  - E.g. 360 MeV at 1 fm/c
- Initial time (QGP formation time)?
  - Usually ~0.1 fm/c for LHC
  - Could be smaller at FCC
- Significantly larger initial temperature? Could reach close to 1 GeV?

Secondary/thermal charm?

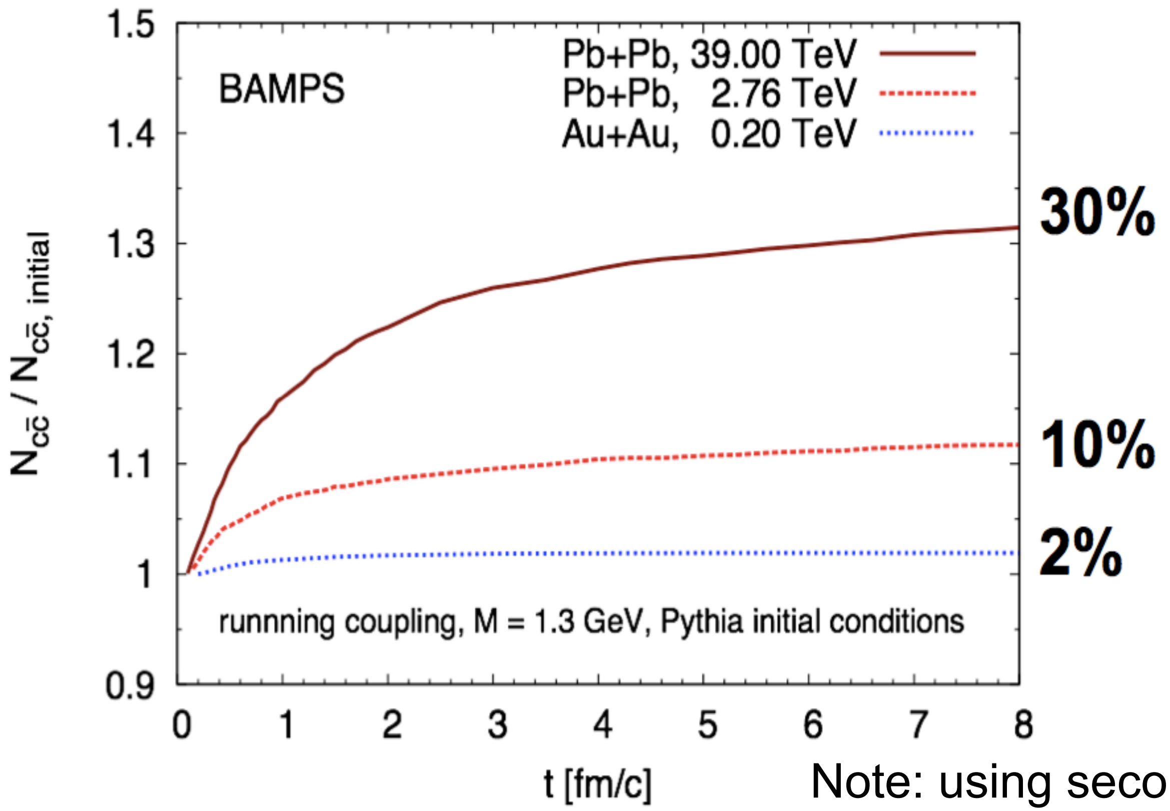
- Expect abundant production of c-cbar pairs in the medium
- Example: two “pre-LHC” calculations for 5.5TeV: + 15-45% wrt hard scattering
  - However, strong dependence on initial conditions, initial temperature and formation time, c-quark mass





Secondary/thermal charm?

- Expect abundant production of c-cbar pairs in the medium
- Calculation for FCC energy provided by J.Uphoff

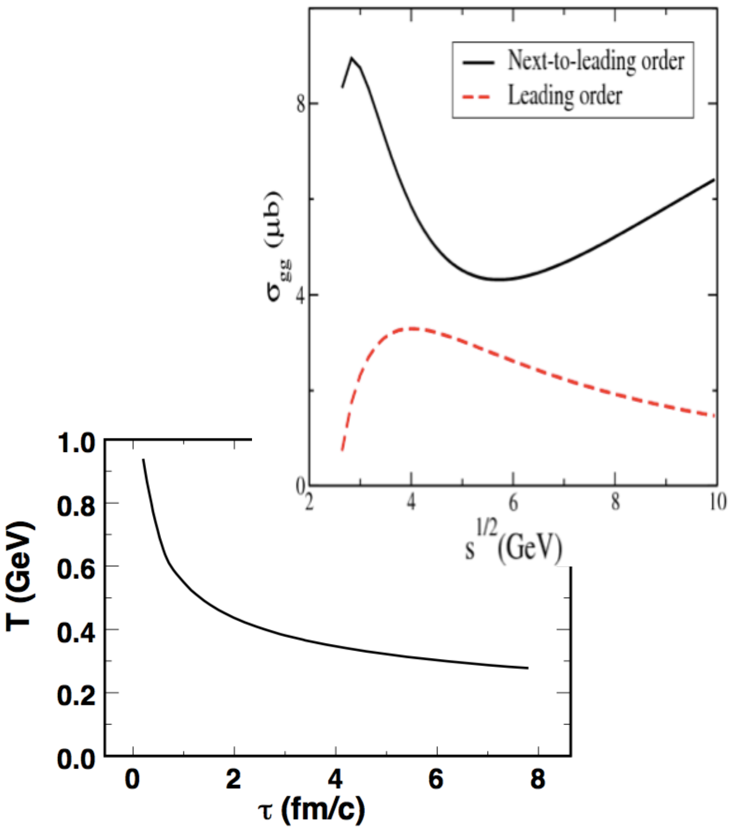


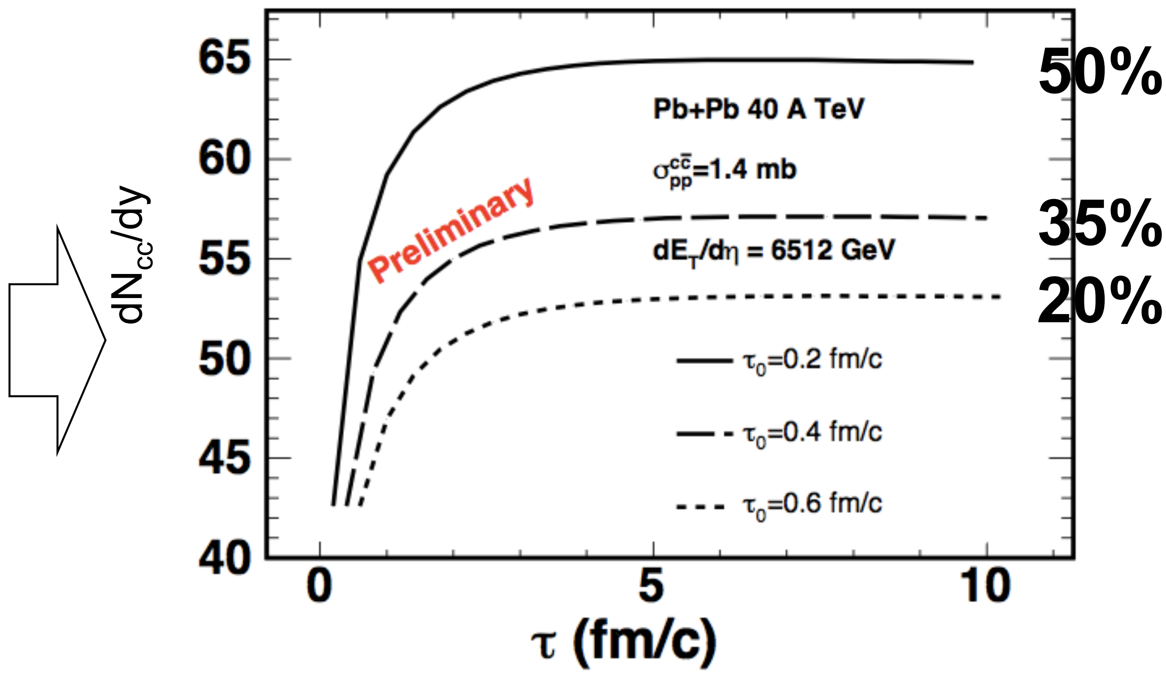
Note: using secondary production cross sections at LO (probably underestimated)

J. Uphoff, private communication, based on J. Uphoff et al. PRC82 (2010)

Secondary/thermal charm?

- Expect abundant production of c-cbar pairs in the medium
- Calculation for FCC energy provided by C.M.Ko





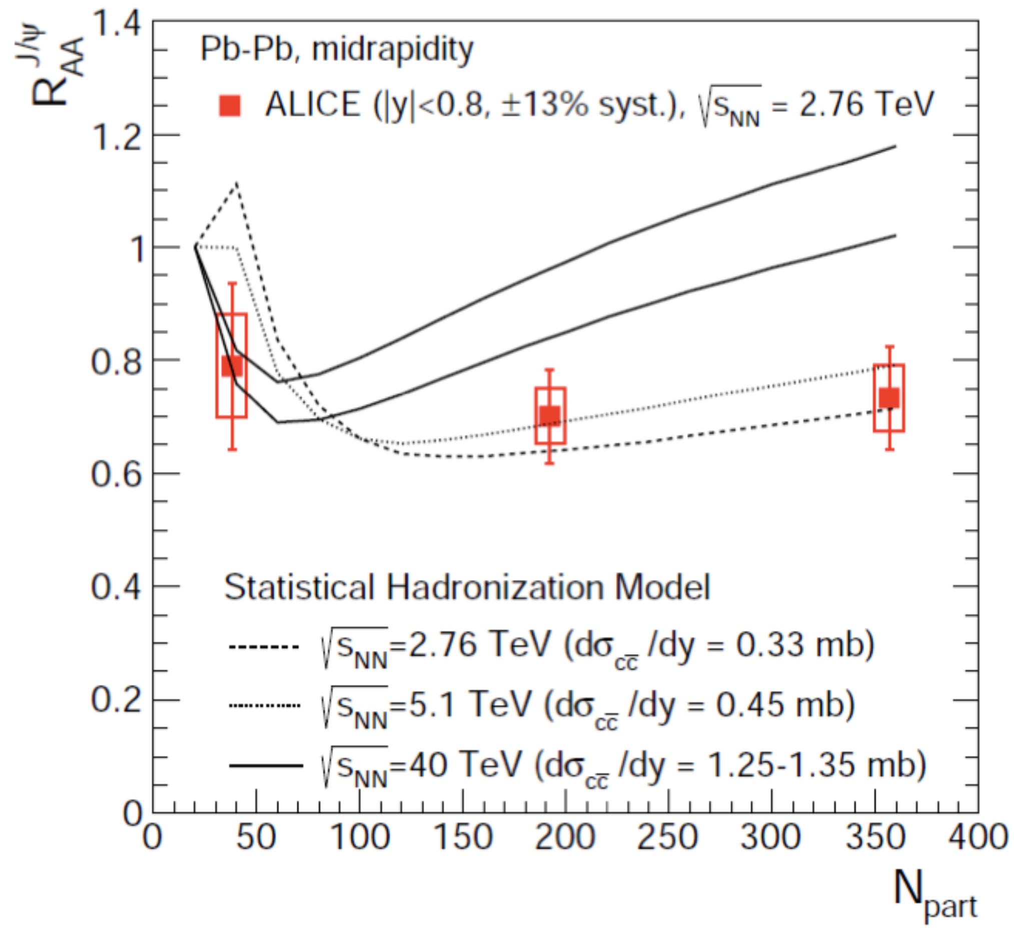
C.M. Ko, Y. Liu, private communication, based on B.-W. Zhang et al. PRC77 (2008)

Potentially sensitive to medium properties (T_0, τ_0)

J/ψ regeneration

- Increase of charm (hard scattering) cross section by about x3 with respect to top LHC energy
- Regeneration of J/ψ could give $R_{AA}>1$ (enhancement)
- J/ψ yield could be sensitive to secondary/ thermal charm production

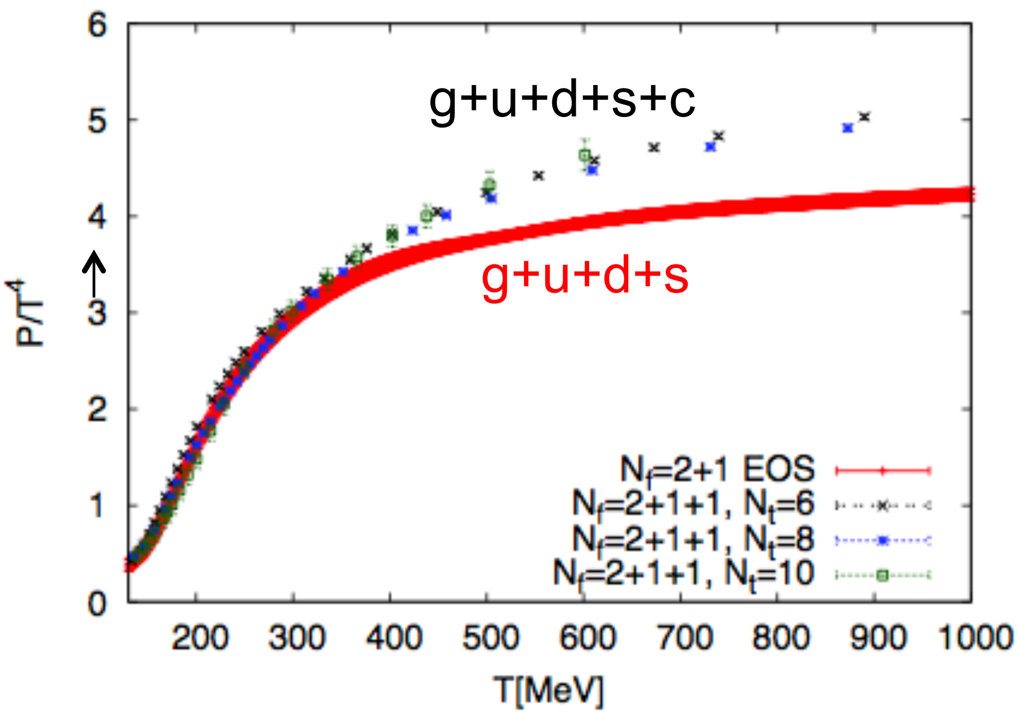
Braun-Munzinger et al.



Charmed QGP?
Equation of state and charm deconfinement

- If charm is produced abundantly during the equilibration of the medium, this should show up in the equation of state

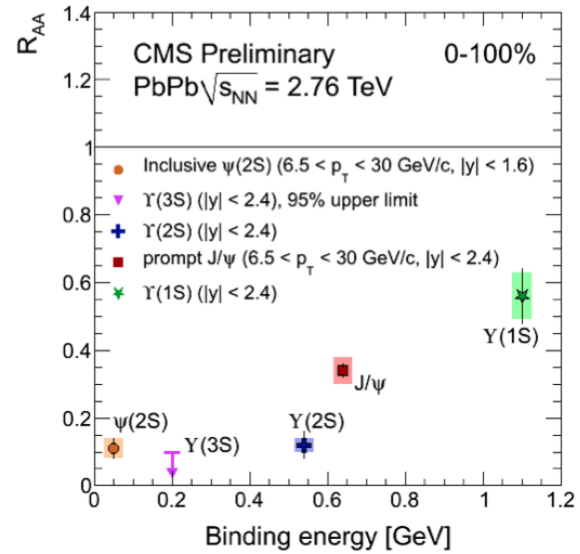
$$P/T^4 \sim \varepsilon/T^4 \propto n_{\mathrm{d.o.f}}$$



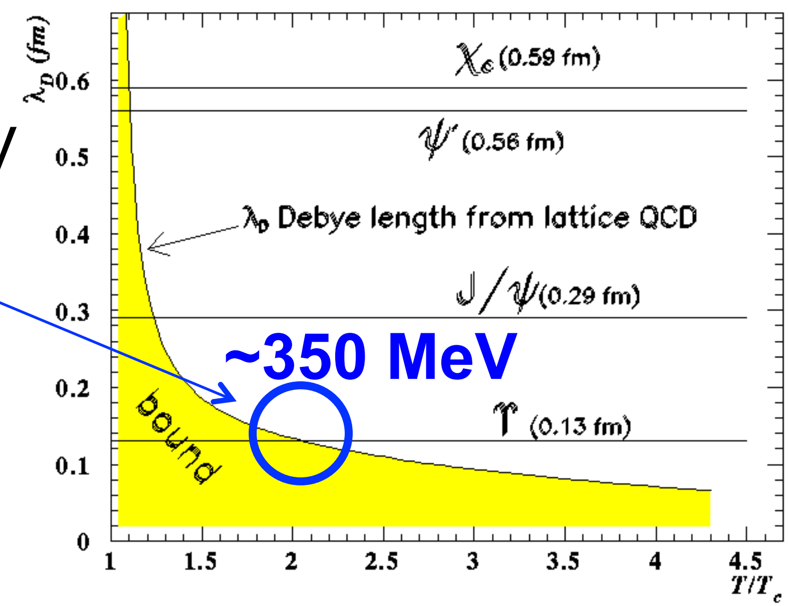
S. Borsanyi *et al*., arXiv:1204.0995

Υ(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, but…
- Υ(1S) R_{AA}~0.5: consistent with suppression of higher states only
- Υ(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

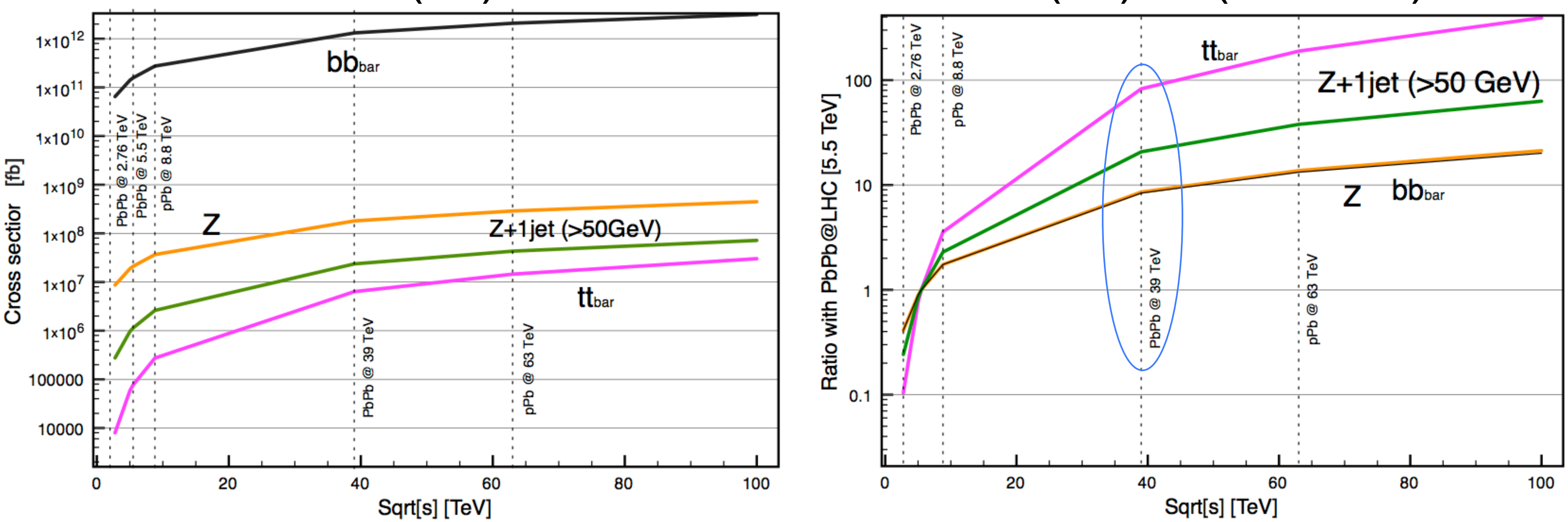
FCC: a new set of Hard Probes

- The current 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 …
- HI performance in future detectors should reach the pp performance level of current LHC detectors
- The large cross section and luminosity of the FCC will allow tagging more complex decay topologies to isolate defined initial state parton configurations and their propagation in the medium
  - Probe the earliest phases of the collision
  - Defined parton configurations traversing the medium
    - e.g Z^0+n-jets, top quarks in $t\bar{t} \rightarrow \ell^+\ell^- + b\bar{b} + \not{E}_T$

Hard probes cross sections: LHC→FCC

Computed for pp with MCFM (Campbell, Ellis, Williams, http://mcfm.fnal.gov)

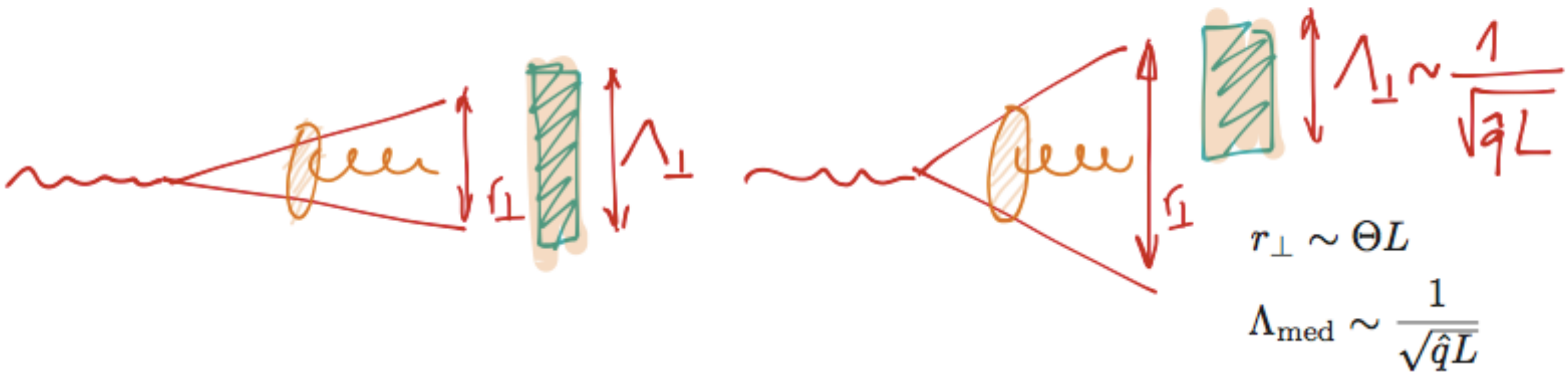
$\sigma(\sqrt{s})$ | $\sigma(\sqrt{s})$ / σ(5.5 TeV)



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

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



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

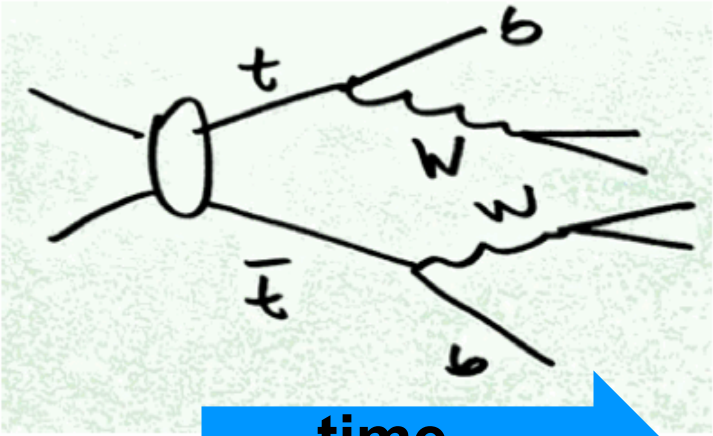
→ Boosted color singlet states can be used to probe the medium opacity / density at different time scales

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

$$t\bar{t} \rightarrow b\bar{b} + \ell + 2\,jets + \not{E}_T$$



time →

time ↓

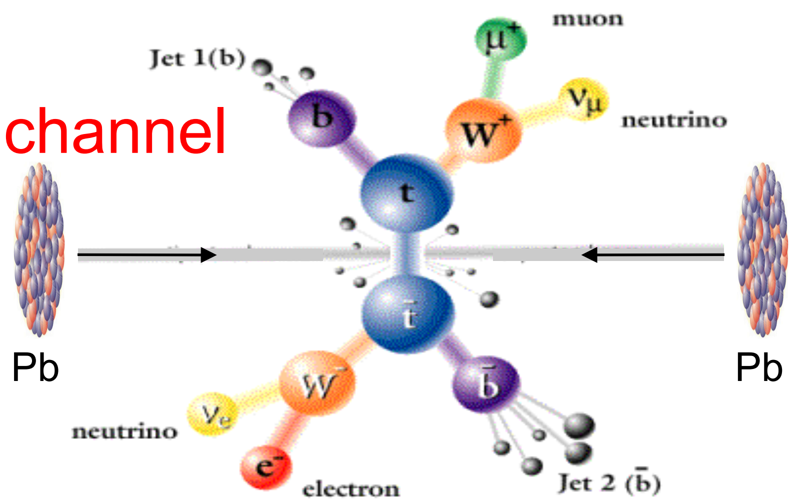
	Pt=1 TeV	Pt=500 GeV
ttbat produced	0 fm/c	0 fm/c
top → W+b	1 fm/c	0.5 fm/c
W decay	1.6 fm/c	0.8 fm/c
qqbar in singlet	2.3 fm/c	1.3 fm/c

→ Interaction with the medium starts

A tool to probe timescale of medium evolution?

Top 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

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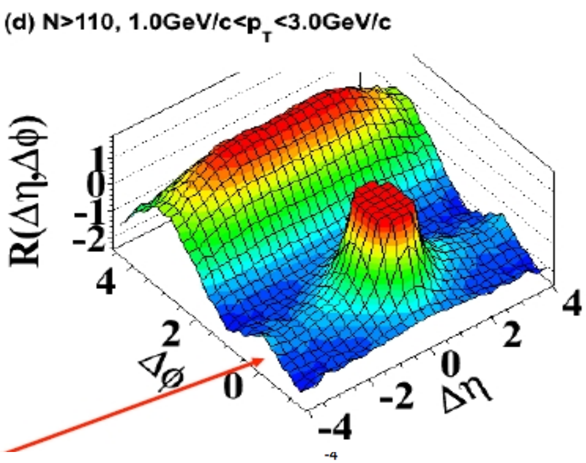
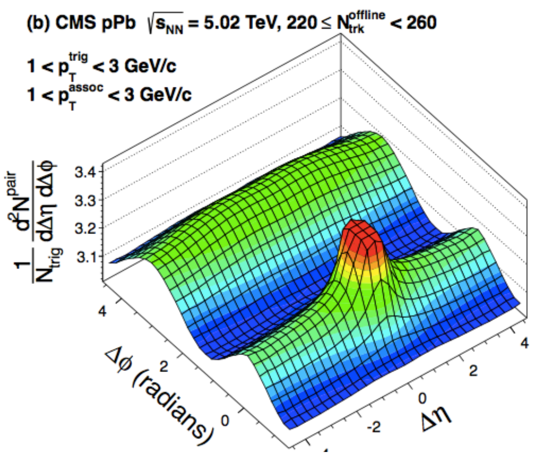
High-multiplicity events in small systems

- 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?

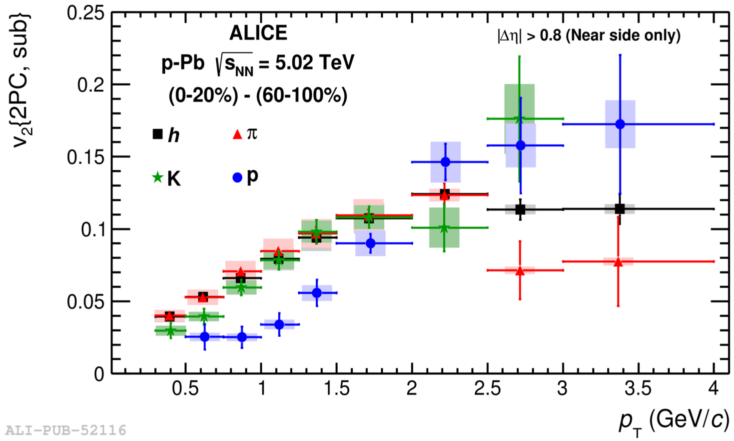
pp, high mult **pPb, high mult** **pPb, high mult**



CMS, JHEP 1009 (2010) 091



CMS, PLB 724 (2013) 213



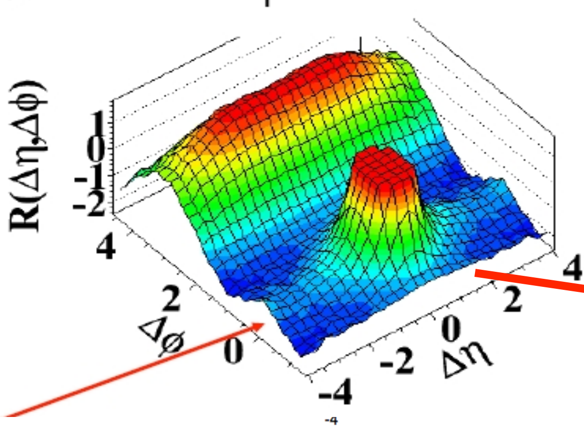
ALICE, PLB726 (2013) 164

- 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

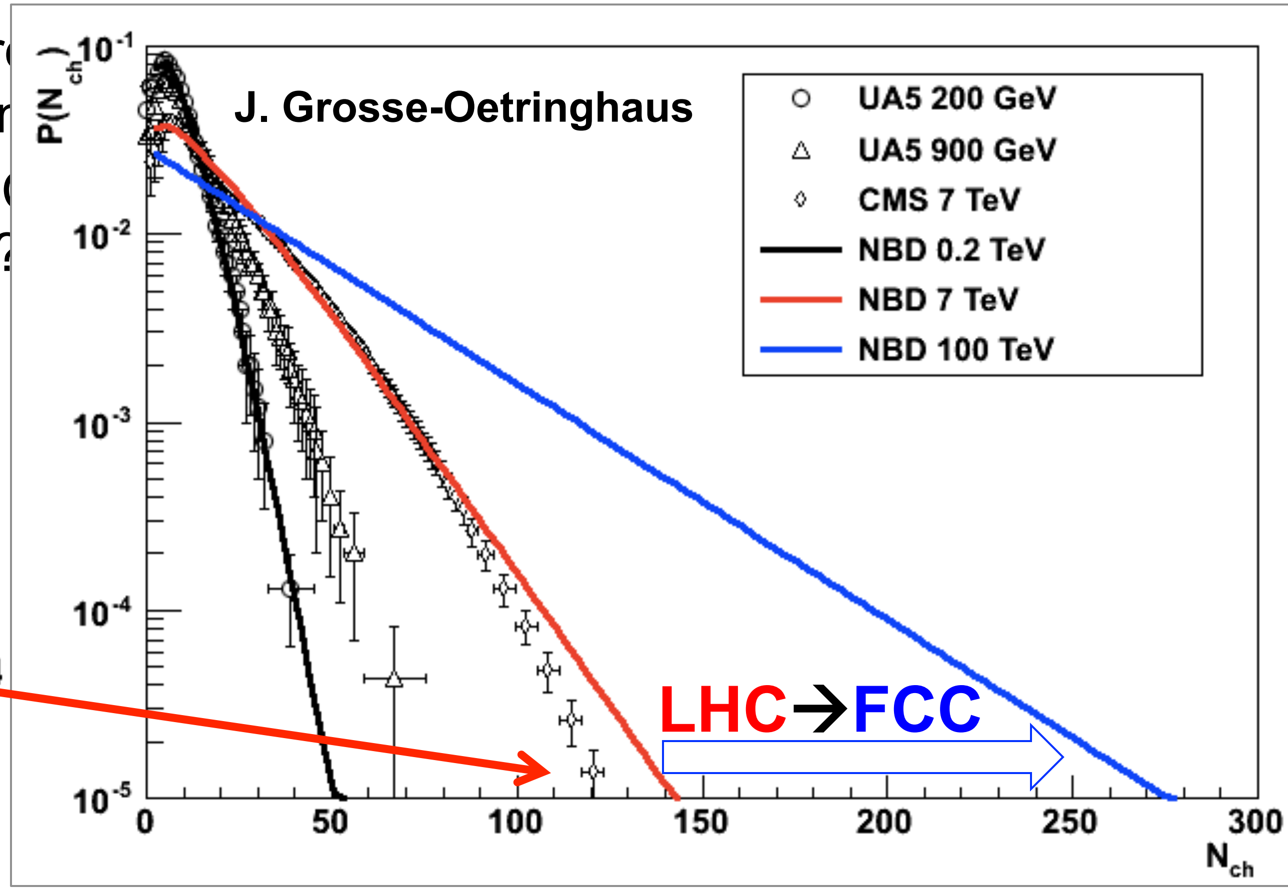
High-multiplicity events in small systems

- One of the most inter
long-range correlatior
- Similar mechanism? (
final state collectivity?

pp, high mult



CMS, JHEP 1009 (2010) 091



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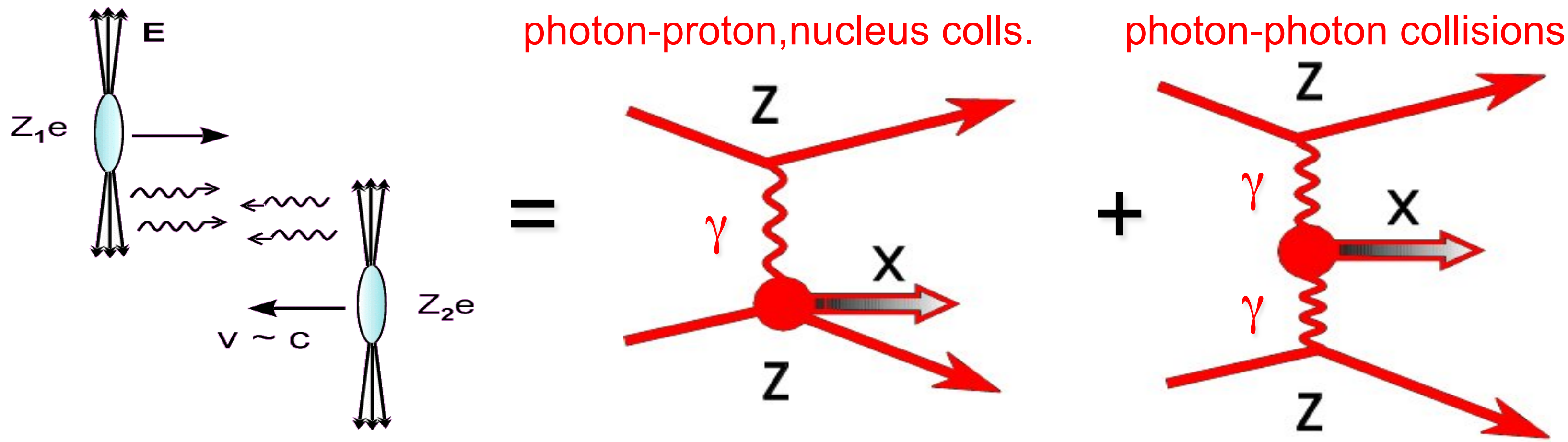
γ-induced collisions at FCC (Pb-Pb)

- Electromagnetic ultra-peripheral collisions (UPC): $b_{min} > R_A + R_B$
- HE ions generate strong EM fields from coherent emission of Z=82 p's:

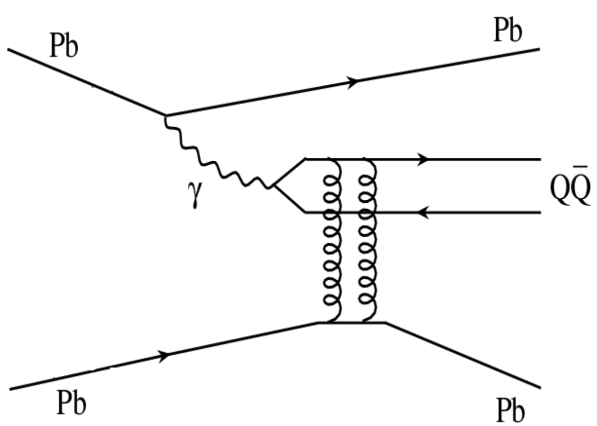


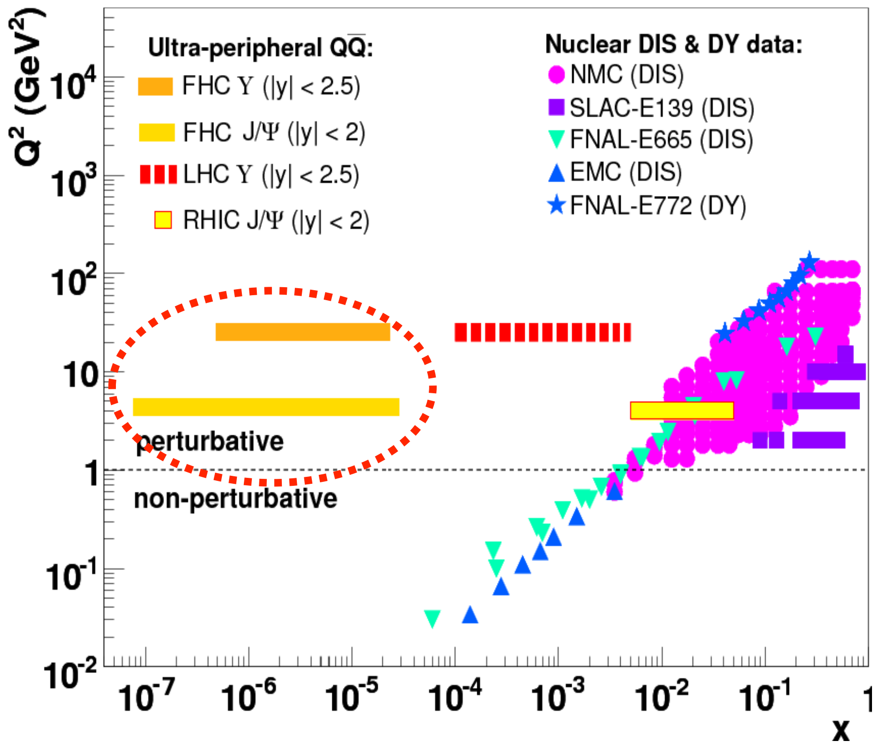
- Huge photon fluxes:
  - $\sigma(\gamma\text{-Pb}) \sim Z^2$ (~10^4 for Pb) larger than in pp
  - $\sigma(\gamma\text{-}\gamma) \sim Z^4$ (~$5 \cdot 10^7$ for PbPb) larger than in pp
- Max. FCC γγ, γN √s energies:

PbPb: $\sqrt{s_{\gamma\gamma}} \sim$ 1.2 TeV $\sqrt{s_{\gamma Pb}} \sim$ 7 TeV
pPb: $\sqrt{s_{\gamma\gamma}} \sim$ 6 TeV $\sqrt{s_{\gamma p}} \sim$ 10 TeV

γ-Pb physics at FCC (Pb-Pb)

- Sensitive to <u>very</u> small *x* gluon density: powerful handle on saturation region with perturbative probes

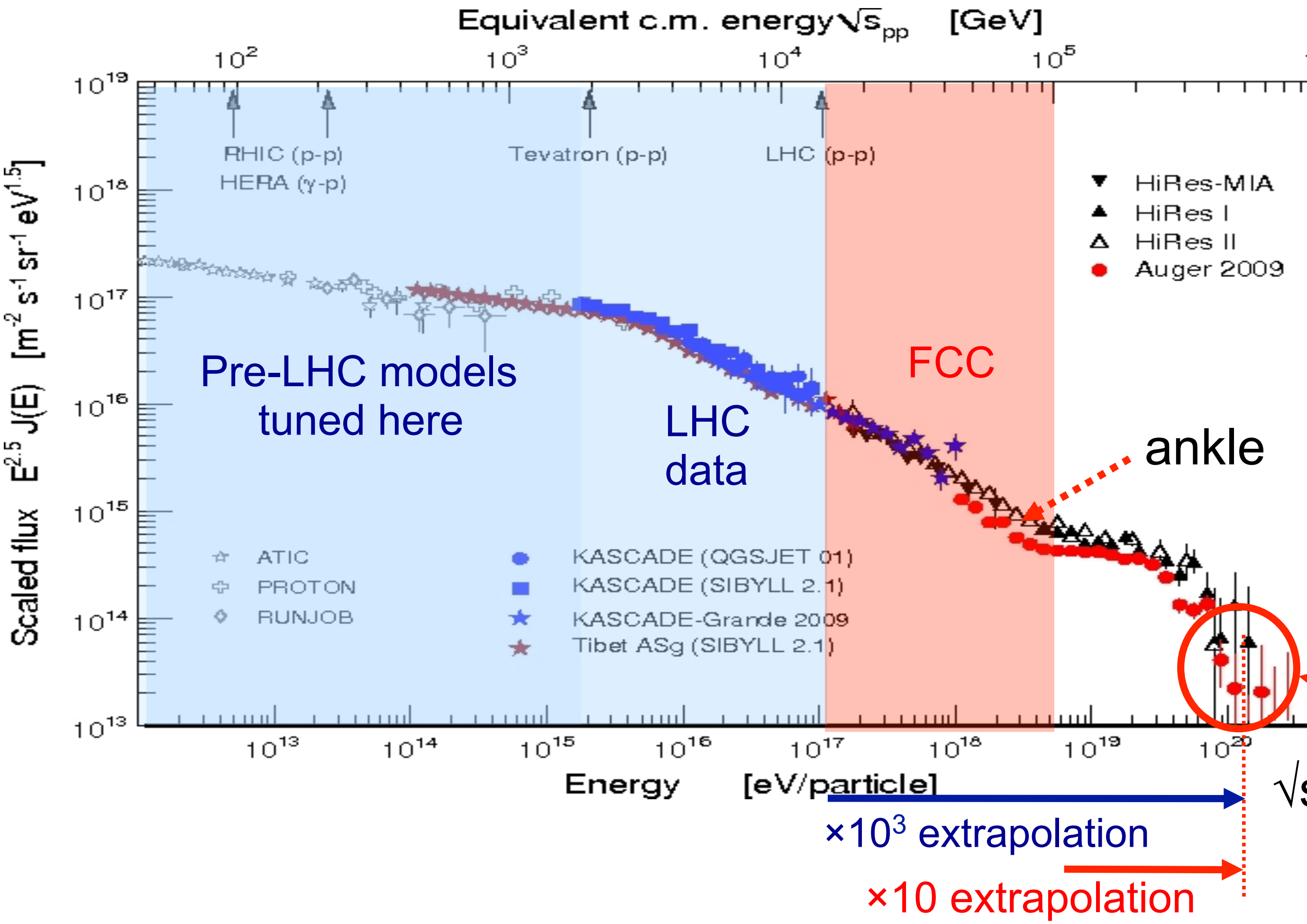


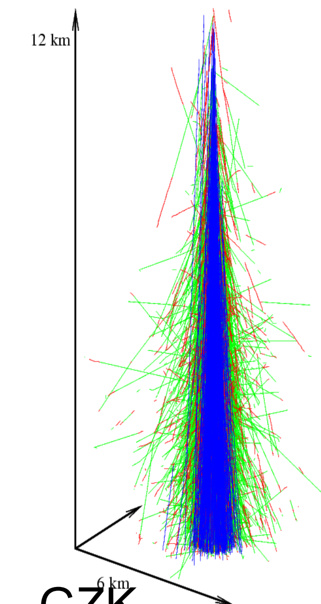


~2 orders of magnitude below LHC!

- Exclusive Q-Qbar: $x \sim m^2_{QQ}/s_{\gamma p,\gamma Pb} \sim 10^{-7}$
- Also: inclusive dijet, heavy-Q (also t-tbar)

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)

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Detector design ideas (pp)

W. Riegler

1. Requirements, design drivers

Bending power: higher collision energy 14>100TeV, same tracking resolution

BL^2 has to be increased by factor 7!

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

---> higher field, in single solenoid, up to 6.0 T

---> higher field, longer track in inner solenoid around ID, 3.5T/3m or 2T/4m, and a toroid of 1.8T useful field and increase of tracking length.

Low angle coverage in forward direction, solenoid useless, toroid difficult since all current has to pass the inner bore

---> add a dipole for on-beam bending, some 10Tm!

HCAL depth from 10 λ to 12λ (iron) radial thickness some 3.0 m!

---> bore of big solenoid or inner radius toroid increases to 6m and length increases accordingly.

ECAL to cover low angles, move unit out, from 5 to 15 m, system gets longer.

Thus: higher field, larger bore and longer system. 3 options analyzed.

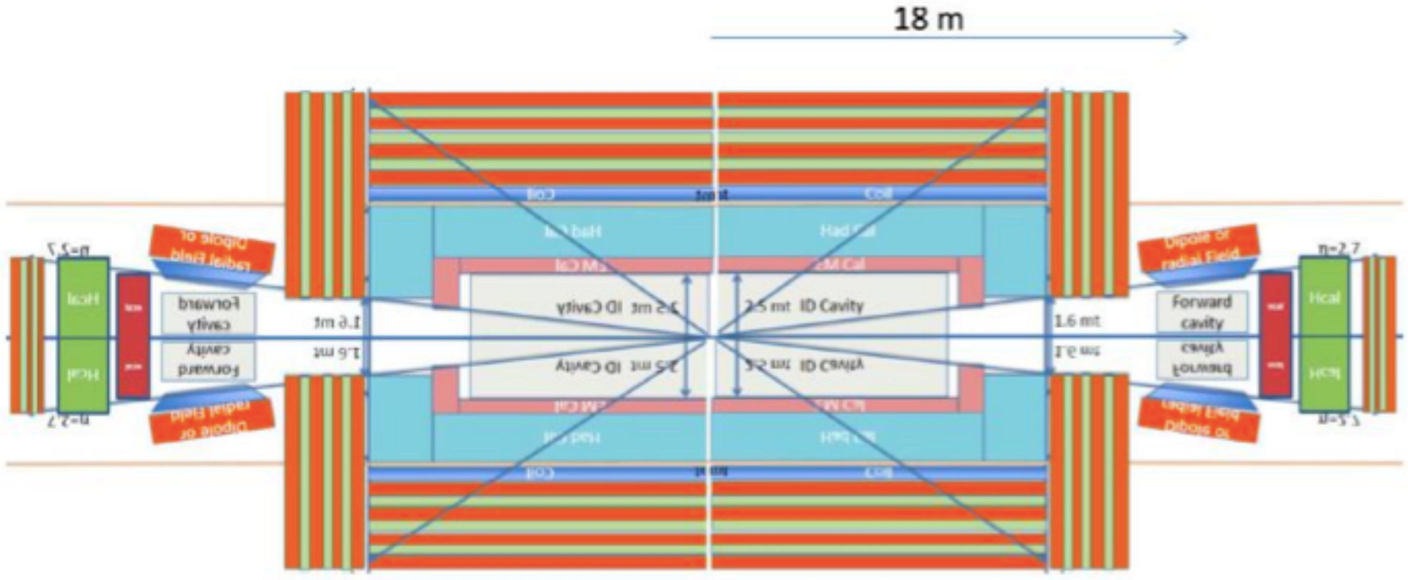
H. Ten Kate

2

Detector design ideas (pp)

W. Riegler

Option 1: Solenoid-Yoke + Dipoles (CMS inspired)



Solenoid: 5-6 m diameter, 5-6 T, 23 m long

+ massive Iron yoke for flux return (shielding) and muon tagging.

Dipoles: 10 Tm with return yoke placed at 18 m.

Practically no coupling between dipoles and solenoid.

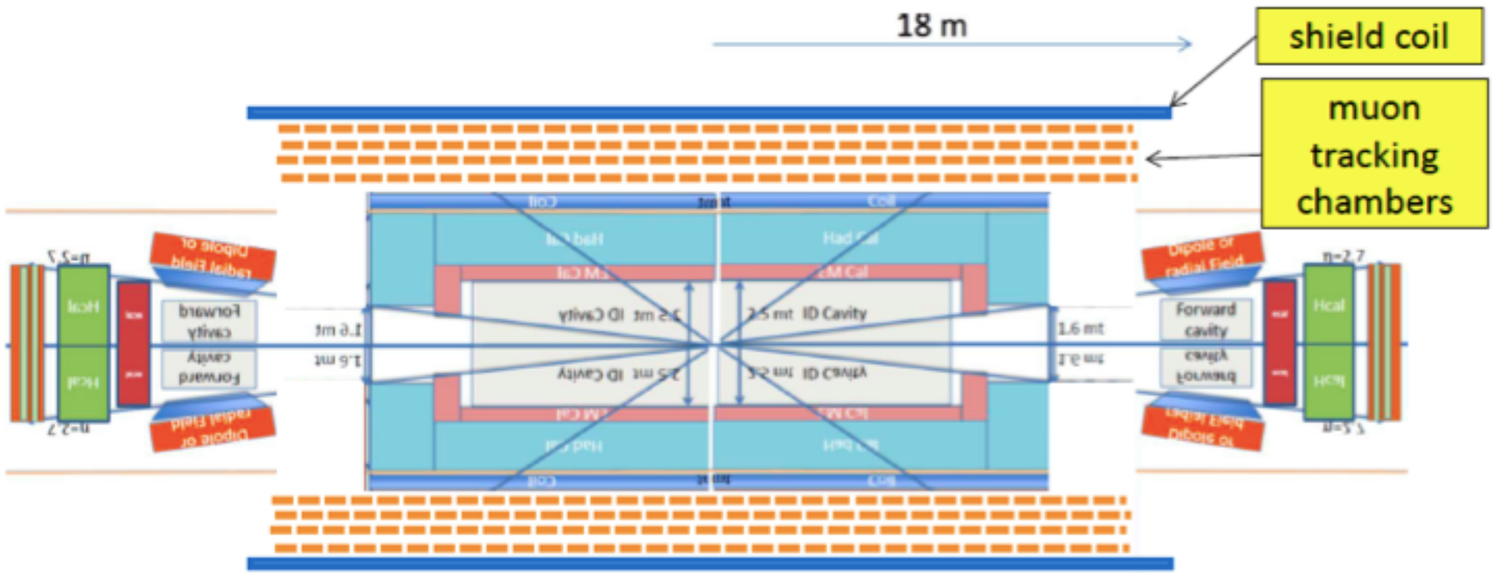
They can be designed independently at first.

H. Ten Kate

Detector design ideas (pp)

W. Riegler

Option 2: Twin Solenoid + Dipoles



Twin Solenoid: the original 6 T, 12 m x 23 m solenoid + now with a shielding coil {concept proposed for the 4th detector @ILC, also an option for the LHeC in the case of large solenoid; and this technique is in all modern MRI magnets!}.

Gain?

- **+ Muon tracking space:** nice new space with 3 T for muon tracking in 4 layers.
- **+ Very light:** 2 coils + structures, ≈ 5 kt, only ≈4% of the option with iron yoke!
- **+ Smaller:** outer diameter is less than with iron .

H. Ten Kate

Detector design ideas (pp)

W. Riegler

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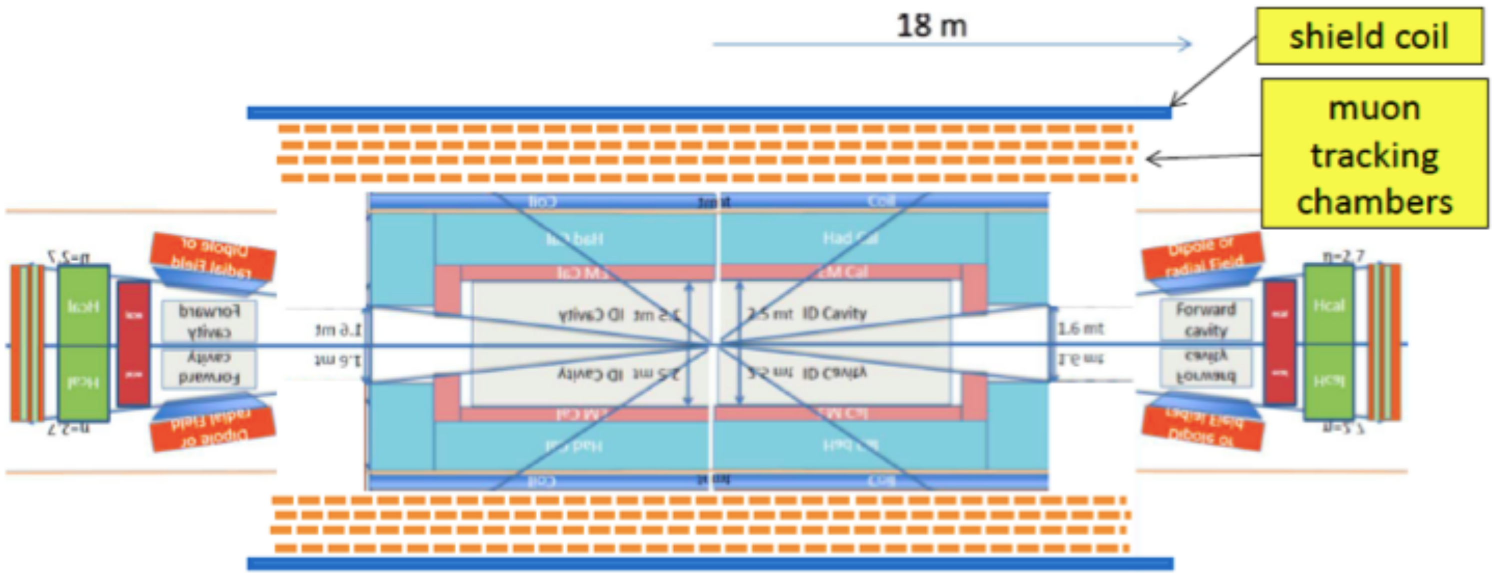

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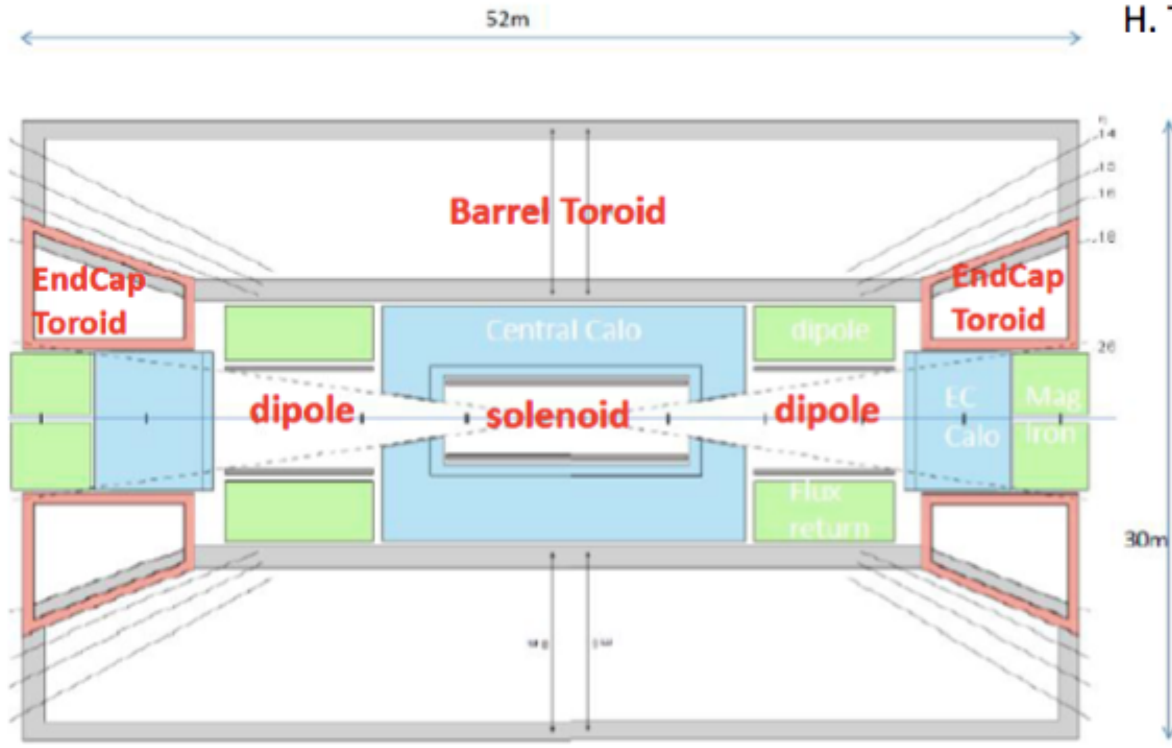
H. Ten Kate

Detector design ideas (pp)

W. Riegler

Option 3: Toroids + Solenoid + Dipoles (ATLAS +)

H. Ten Kate



- Air core Barrel Toroid with 7 x muon bending power BL^2.
- 2 End Cap Toroids to cover medium angle forward direction.
- 2 Dipoles to cover low-angle forward direction.
- Overall dimensions: 30 m diameter x 51 m length (36,000 m^3).

Detector design: HI requirements?

- Number of experiments not yet defined: most likely 2
- In the assumption that the HI community decides to "go for it" (to be defined…):
  - probably unpractical and unnecessary to have a dedicated HI experiment
  - HI community should give inputs on HI-specific requirements for general purpose detectors
  - Examples:
    - Possibility to reduce magnetic field for low-pT tracking
    - Particle ID (for soft physics, eg flow, and low pT charm?)
    - Forward coverage for small-x studies
    - …

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} → new hard observables, e.g. top, sensitive to early stages and time evolution of the medium
- Also: benefit for UHECR studies

- New inputs and ideas are most welcome!

EXTRA SLIDES

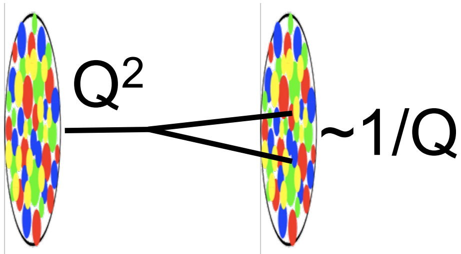
HI-HL-LHC Programme

(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**)

Saturation scale

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



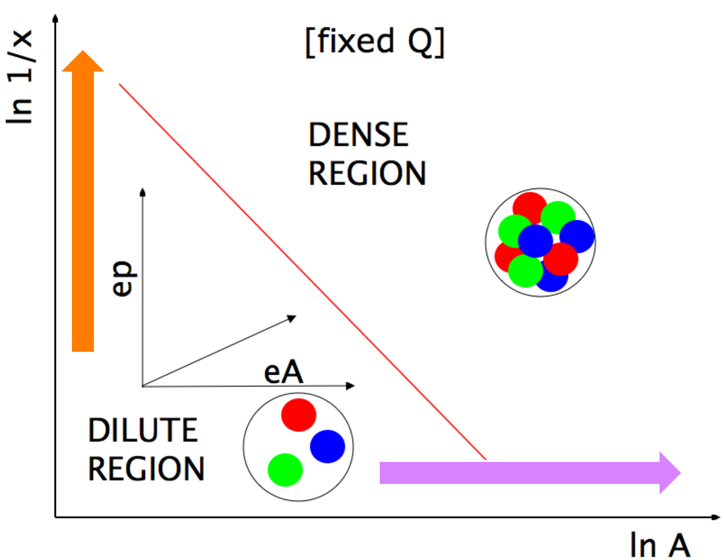
$$\frac{1}{Q^2} \cdot Ag(x,Q^2) \sim \pi R_A^2 \sim \pi A^{2/3}$$

gluon "area" — number of gluons — nuclear overlap

Saturation scale:

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

(λ~0.3)



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

Explore saturation region:

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

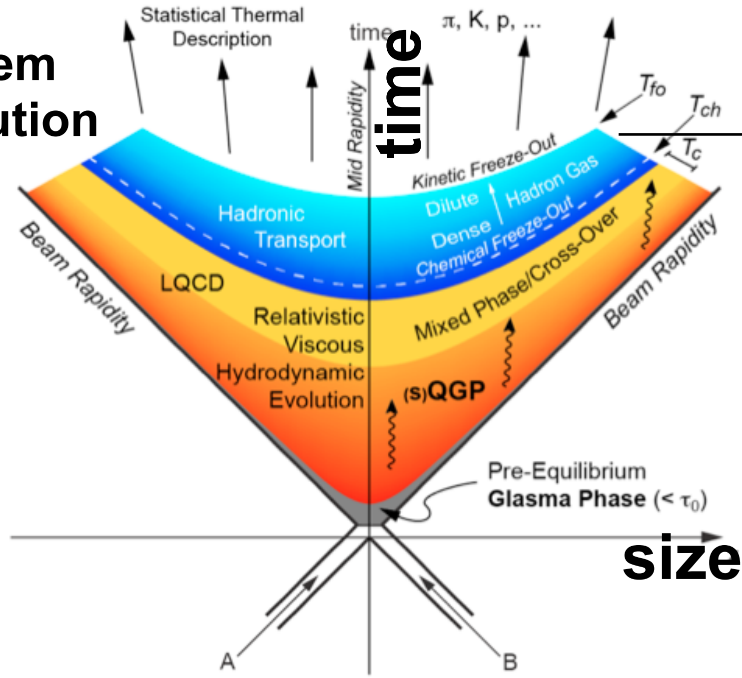
→ **increase A**

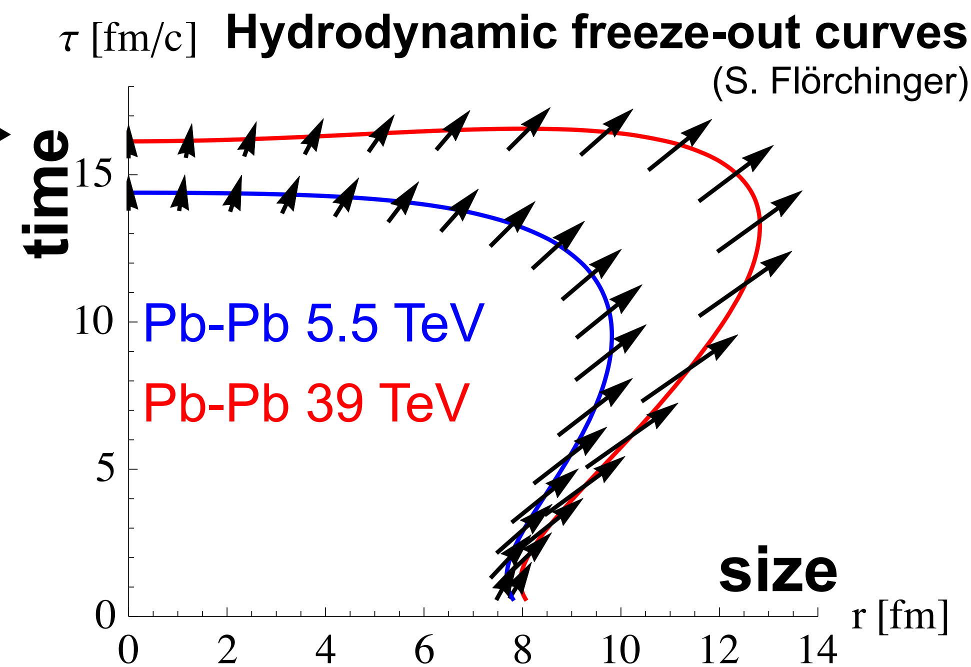
Saturation: possible observables

Observable	Sensitivity: Initial condition	Sensitivity: Evolution
Charged single inclusive at fixed rapidity, HF: glue	yes	p_T dependence
DY, photons: sea and glue	yes	p_T dependence
Rapidity/energy evolution of single inclusive	yes	yes
Back-to-back correlations (charged, photons, jets,…): central-central, forward-forward	yes	p_T dependence
Back-to-back correlations: central-forward (charged, photons, jets,…)	yes	yes
Ridge	yes	???
…		

Hydro simulation at FCC

System evolution

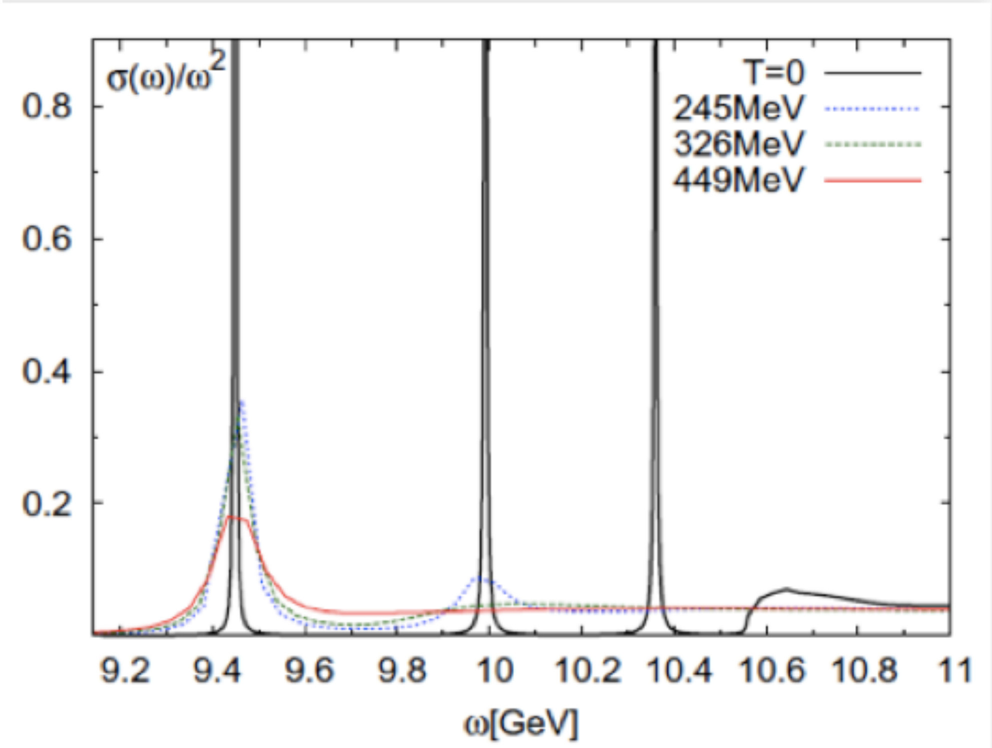




- Hydro-simulation (b=0, eta/s = 1/4pi, dN_{ch}/dy 3600 @ FCC) without
- initial fluctuations.
- In the simulation, the difference between FHC and LHC results from adjusting the initial temperature in the same geometry such that the final charged multiplicity increases to 3600 (instead of 1600 at LHC).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

Υ(1S) melting at the FCC

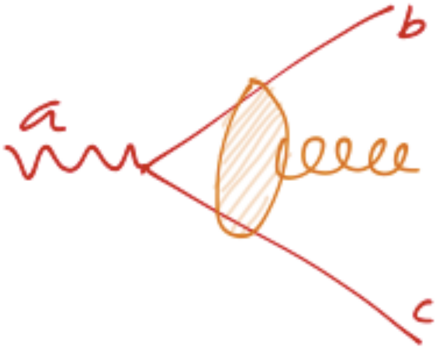
Miao, Mócsy, Petreczky, NPA (2011)



Υ(2S) and Υ (3S) melts by *T ~ 250* MeV and Υ(1S) melts by ~*350* MeV

Coherence and decoherence in the antenna

Antenna in the vacuum



$$r_\perp \sim \Theta\, t_{\rm form} \sim \frac{\Theta}{\theta^2 \omega}$$

$$\lambda_\perp \sim \frac{1}{k_\perp} \sim \frac{1}{\omega\theta}$$

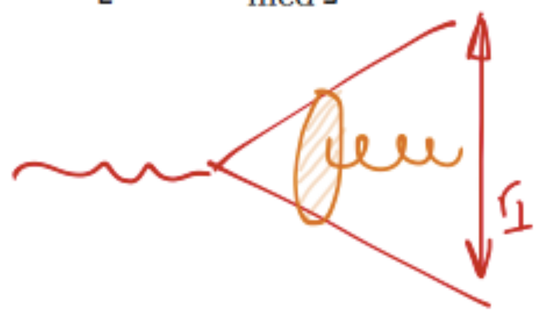
$r_\perp > \lambda_\perp \iff \Theta > \theta$

Coherent emission

Antenna in the medium

- Decoherence parameter

$$\Delta_{\rm med} = 1 - \exp\left[-\frac{1}{12}\frac{r_\perp^2}{\Lambda_{\rm med}^2}\right]$$



$r_\perp \sim \Theta L$

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

- The medium color-rotates the antenna which eventually looses color coherence

Coherence for a singlet

- Decoherence parameter $\Delta_{\rm med}=1-\exp\left[-\frac{1}{12}\frac{r_\perp^2}{\Lambda_{\rm med}^2}\right]$

- For a given time t :::

$$r_\perp \sim \Theta t$$
$$\Lambda_{\rm med}\sim\frac{1}{\sqrt{\hat q t}}$$
$$\Delta_{\rm med}\sim 1-\exp\left[-\frac{1}{12}\hat q\,\Theta^2\,t^3\right]$$

- So, the quark-antiquark pair remains in a color singlet during the time

$$t_{\rm sing}\sim\left[\frac{12}{\hat q\Theta^2}\right]^{1/3}$$

Top quark projection (FCC)

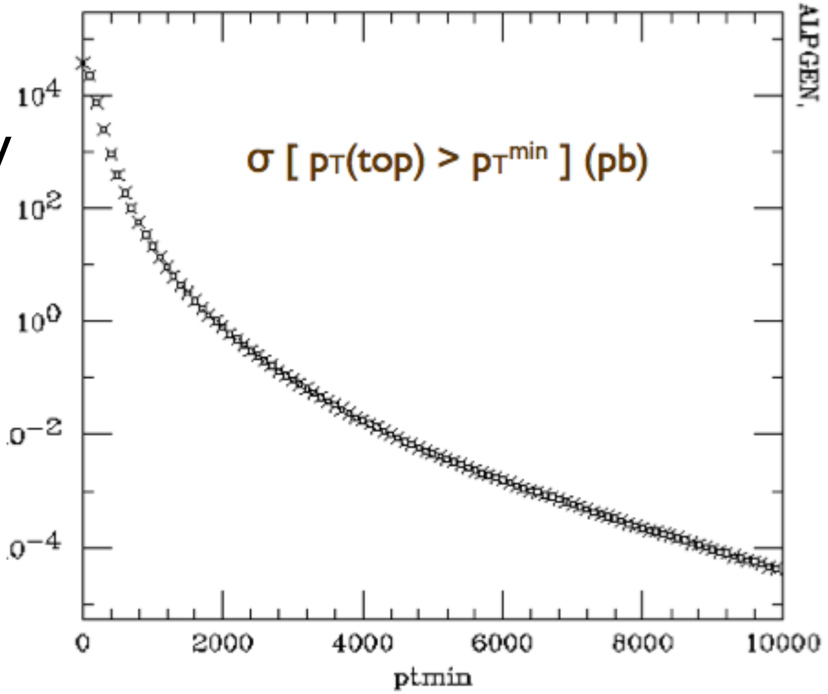
- ttbar cross section x80 from 5.5 to 39 TeV
- With L_{int}=100/nb, x800 top wrt 10/nb@LHC5.5

→ 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