Prospects for heavy ions at HL-LHC and FCC

Andrea Dainese
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Outline

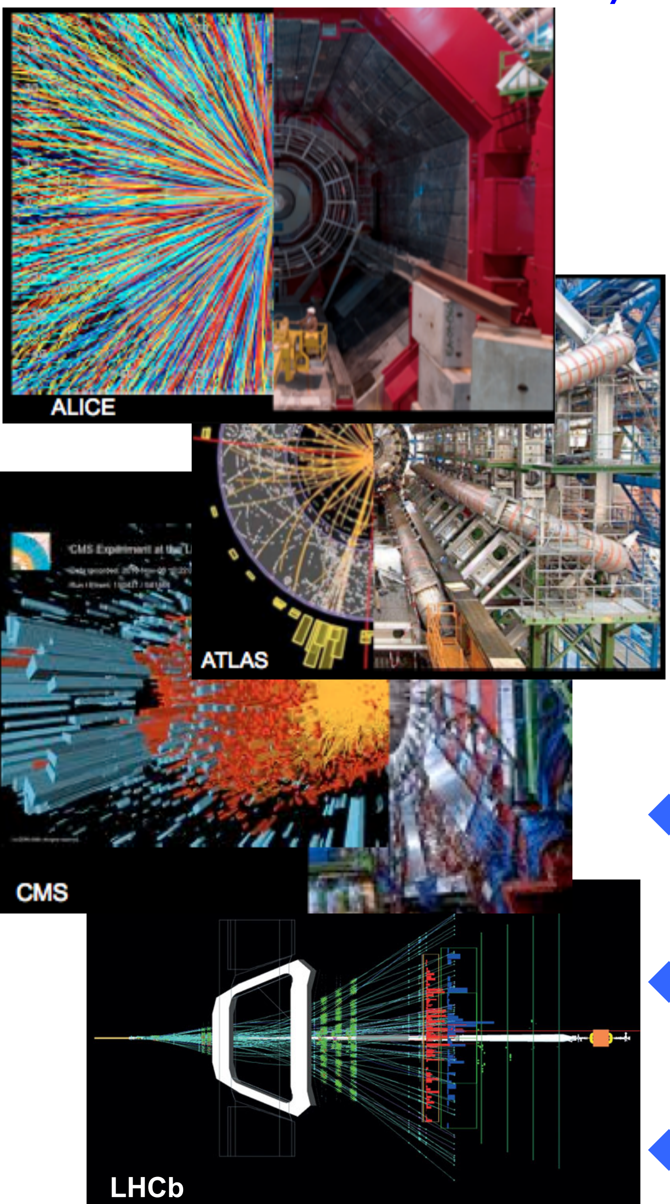
- Timeline of future HI running at LHC
- HI physics programme at HL-LHC
- Detector upgrades
- Examples of projected performance

HI@HL-LHC
2020-28

- The FCC design study
- Ions at the FCC
- High-density QCD in the initial state: saturation
- High-density QCD in the final state: QGP

HI@FCC
> 2035

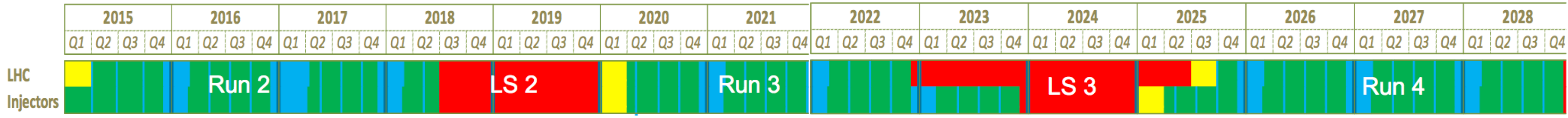
Heavy Ions at the LHC: Run I



year	system	$\sqrt{s_{NN}}$ (TeV)	L_{int}
2010	**Pb-Pb**	**2.76**	**~ 10 μb^{-1}**
2011	pp	2.76	~ 250 nb^{-1}
2011	**Pb-Pb**	**2.76**	**~ 150 μb^{-1}**
2013	p-Pb	5.02	~ 30 nb^{-1}
2013	pp	2.76	~ 5 pb^{-1}

- 2011 Pb-Pb run: $5x10^{26}$! already above nominal luminosity
- First, very successful, p-Pb run (with all four large exp!)
- Two short pp reference runs at Pb-Pb $\sqrt{s}$

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
- Runs 3+4 ("HL-LHC" phase for ions):
  - Experiments request: >10/nb Pb-Pb (ALICE: 10/nb at 0.5T + 3/nb at 0.2T)
  - p-Pb high lumi, pp reference 5.5 TeV, possibly light ions (e.g. Ar-Ar)

→ focus on rare probes, study their coupling with QGP medium and their (medium-modified) hadronization process

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**)

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- **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**)

Focus on ALICE

- Main observables:
  - Low-p_T heavy flavour
  - Low-p_T charmonia
  - (Very) low-p_T and low-mass di-leptons
- Exploit detector specificities (strengthened with the upgrades):
  - hadron and lepton ID
  - light-weight and precise tracker
  - low magnetic field
- Mostly “untriggerable” because of extremely low S/B

→ Trigger approach: write all events with continuous central barrel readout at up to 50 kHz in Pb-Pb (currently 0.5 kHz)

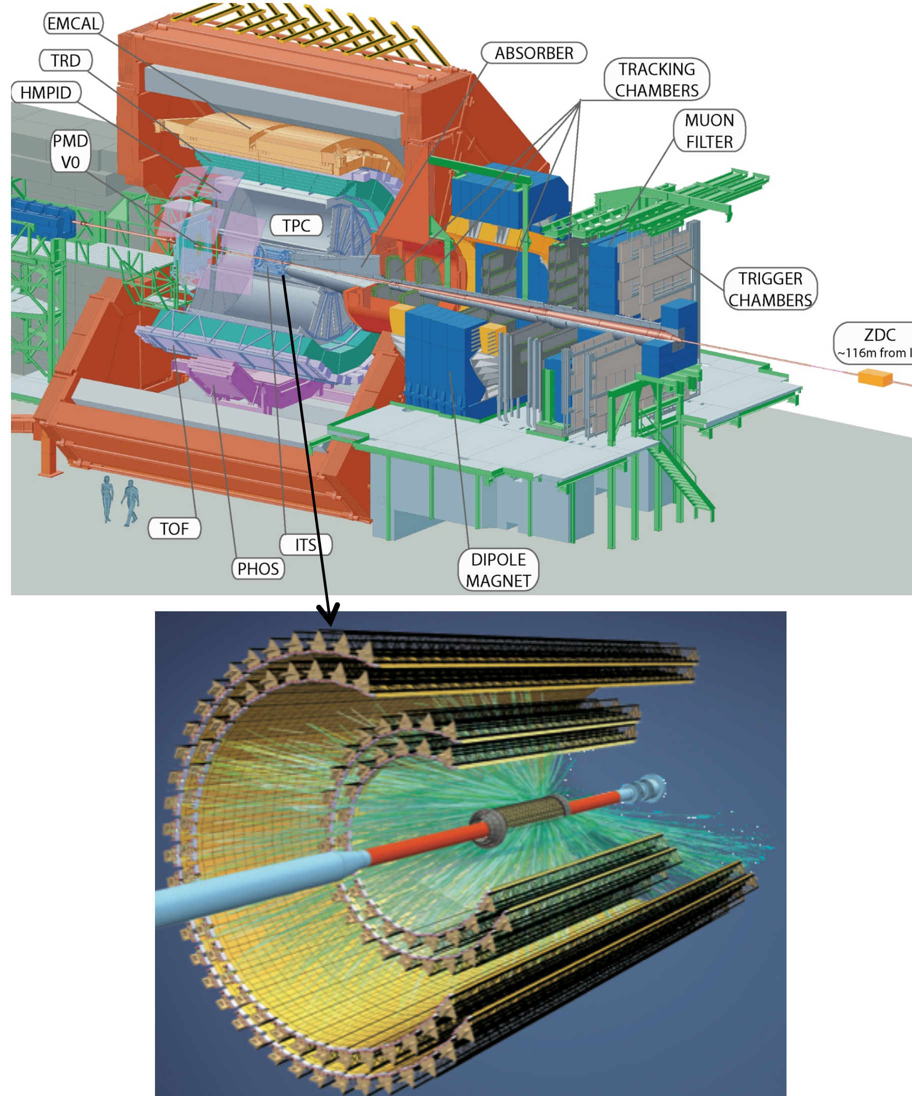
~1 TB/s **HLT/DAQ** → **~10 GB/s**

→ HL-LHC: increase of minimum-bias sample **x100** wrt Run 2

ALICE Upgrade: strategy

→ New Inner Tracking System (ITS)

- Improved resolution, Smaller material budget, Faster readout



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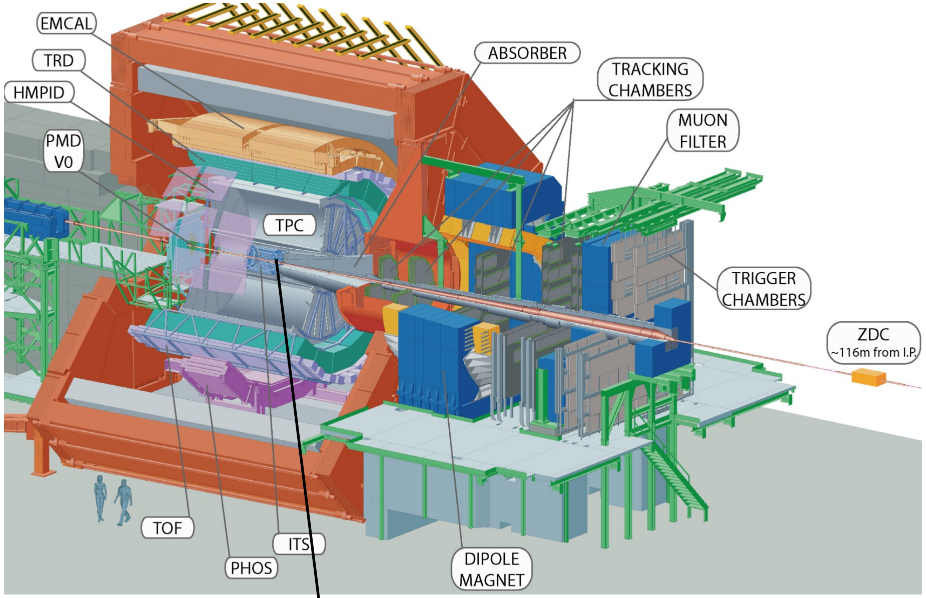
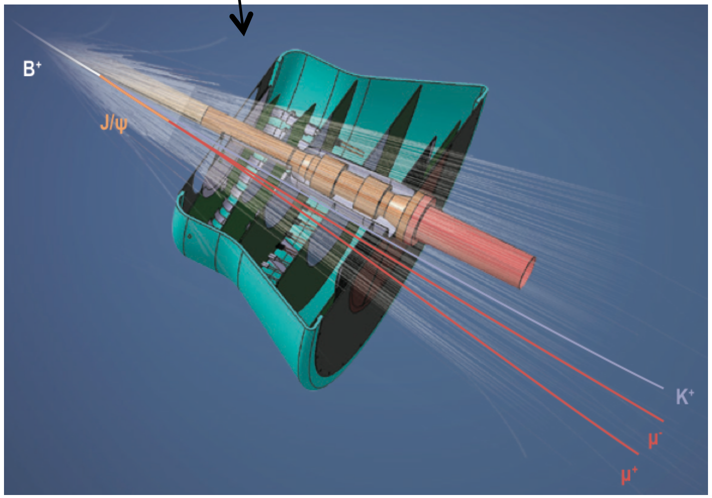
- Heavy flavour vertices also at forward rapidity





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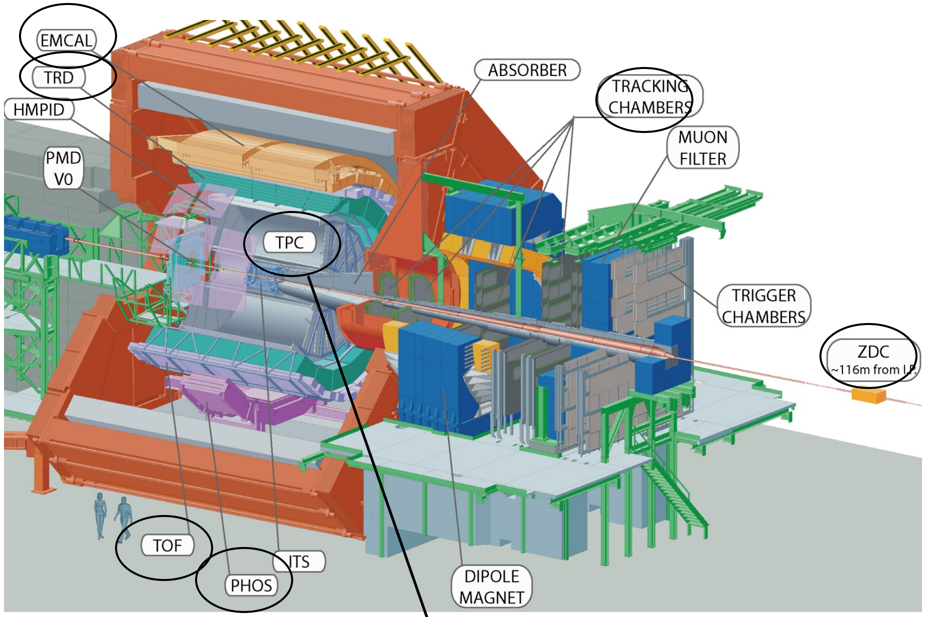
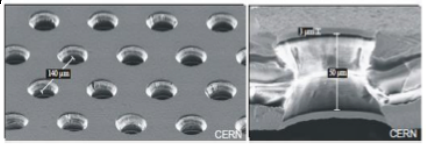
→ Upgraded read-out for TPC (GEM), TOF, TRD, PHOS, EMCAL, MUON, ZDC, Upgraded DAQ/HLT/Offline, new Fast Interaction Trigger detector

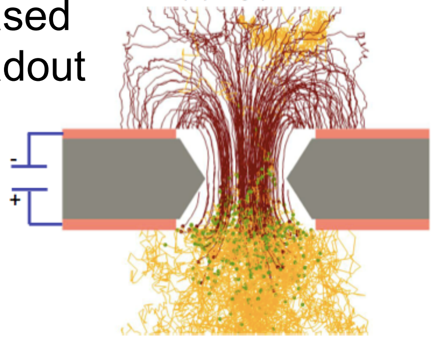
- Target LHC Pb-Pb luminosity after LS2 (~6×10^{27} $cm^{-2}s^{-1}$= 10 x current)
- Upgraded ALICE records Pb-Pb data at 50 kHz (currently <0.5 kHz)
- Integrate L_{int}=10 nb^{-1} after LS2 (~10^{11} minimum-bias Pb-Pb events)





Electron microscope photograph of a GEM foil

GEM-based TPC readout



Focus on ATLAS and CMS

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  - Differential studies of jets at very high p_T
  - b-jets
  - Multi-differential studies of Υ states
- Exploit detector specificities (strengthened with the upgrades):
  - muon ID
  - precise tracker
  - calorimetry
- Mostly based on muon, jet, displaced track triggers

→ Trigger/DAQ approach: strong data reduction

50 kHz → **L1** → **~ few kHz** → **HLT** → **~ 100 Hz**

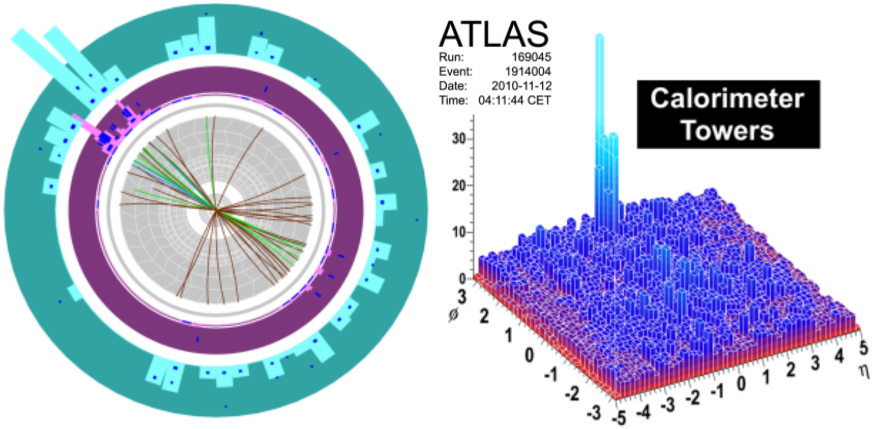
→ HL-LHC: increase of sample **x10** wrt Run 2

ATLAS, CMS, LHCb: upgrades most relevant to HI

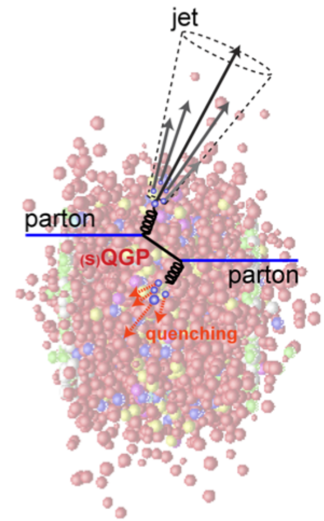
- ATLAS
  - Additional pixel layer (LS1), then new tracker (LS3): tracking and b-tag
  - Fast tracking trigger (LS2): high-multiplicity tracking
  - Calorimeter and muon upgrades (LS2): electron, γ, muon triggers
- CMS
  - New pixel tracker (LS2), then new tracker (LS3): tracking and b-tag
  - Extension of forward muon system (LS2): muon acceptance
  - Upgrade of trigger and DAQ (LS2): HI-specific development to reach necessary L1 rejection at 95%, from 50 kHz to <3 kHz (HLT)
- LHCb (LS2)
  - Upgrade includes new vertexing and tracking detectors (not focused on HI)

Jet quenching

- Pb-Pb events with large di-jet imbalance

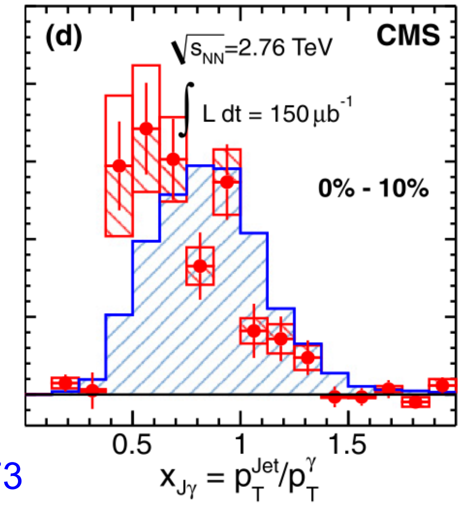


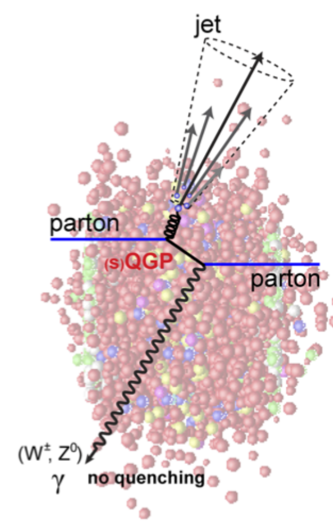
Direct observation of in-medium parton energy loss



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}

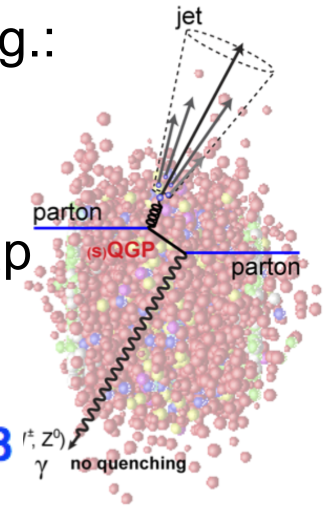


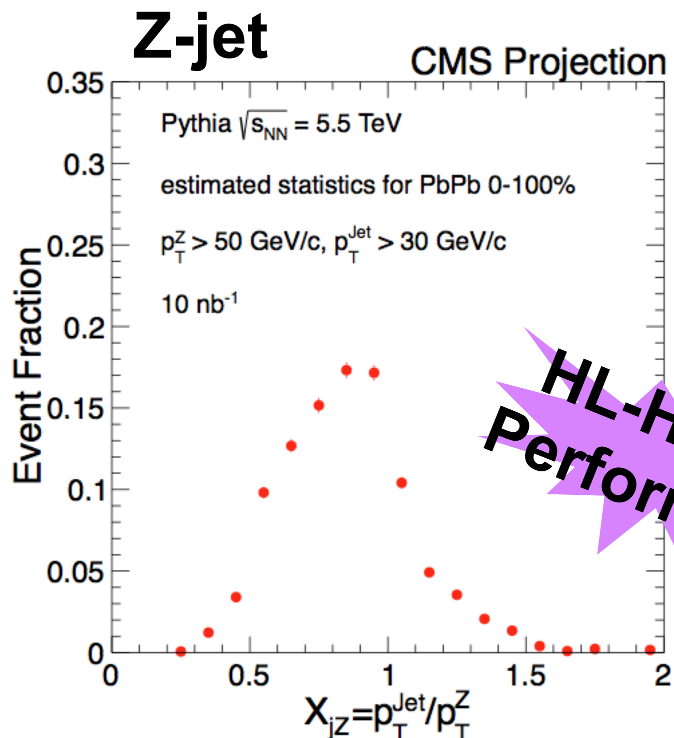


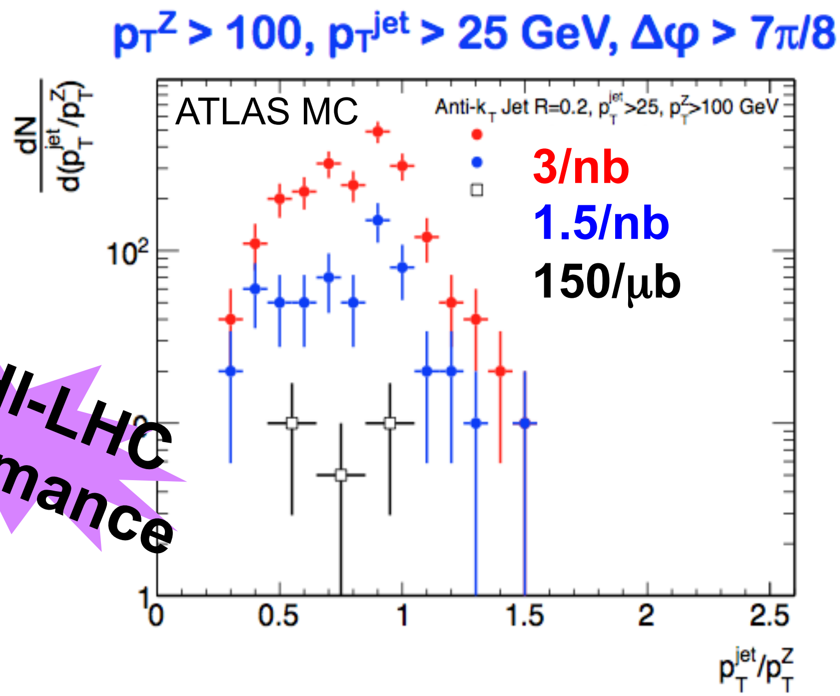
CMS, PLB718 (2013) 773

Jets: performance

- High precision γ-jet, Z-jet, di-jet correlations, also with b-jets. E.g.:
  - 10M di-jets with $p_{T,1}$>120 GeV/c (CMS, 10/nb)
  - 140k b-jets with p_T > 120 GeV/c (CMS, 10/nb)
- Understand medium response and energy radiation details, map path-*L*ength dependence (e.g. radiative ~L^2, collisional ~L)







CMS, PAS-FTR-13-025

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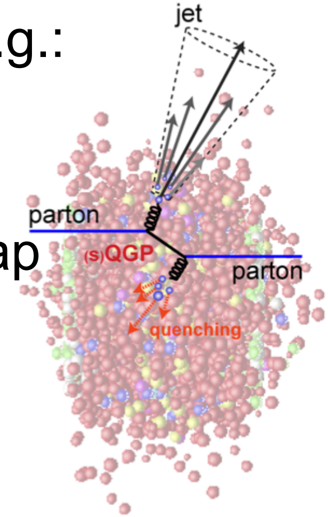
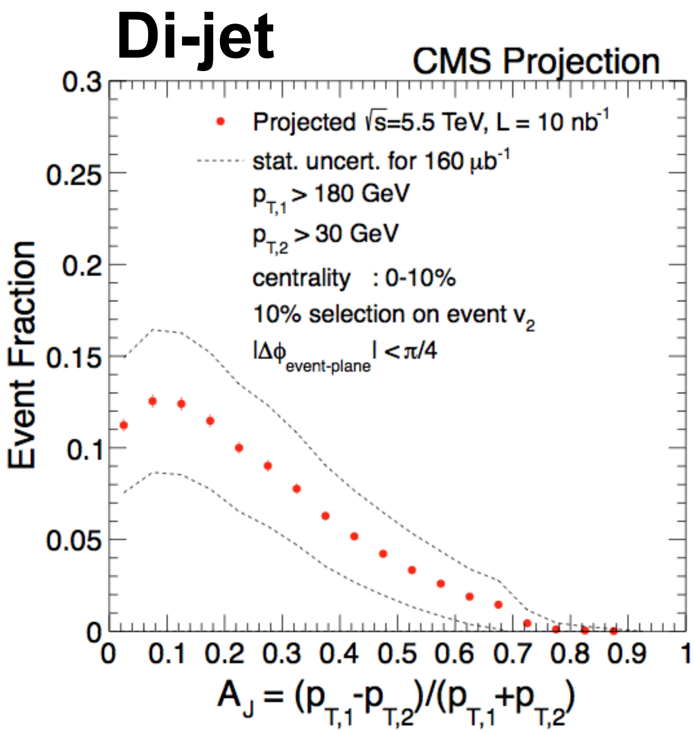
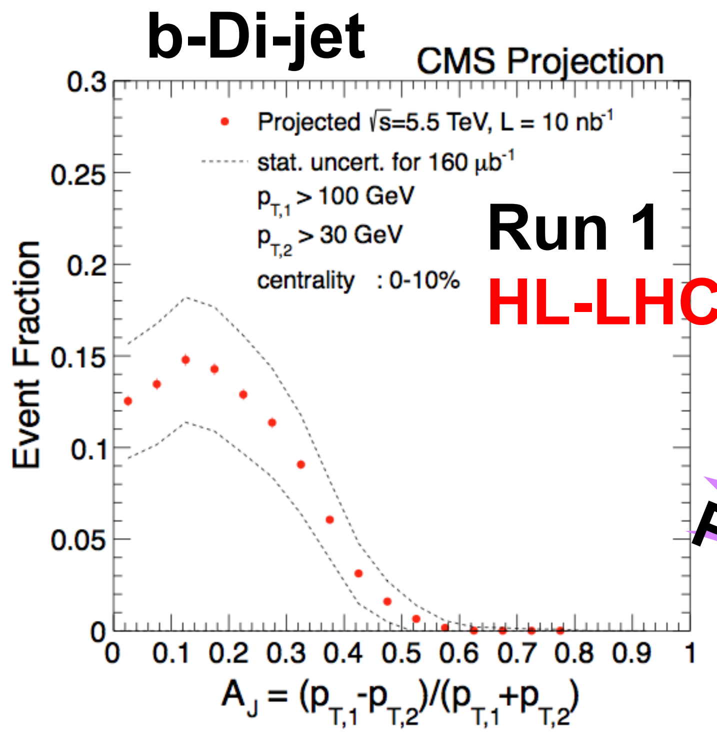




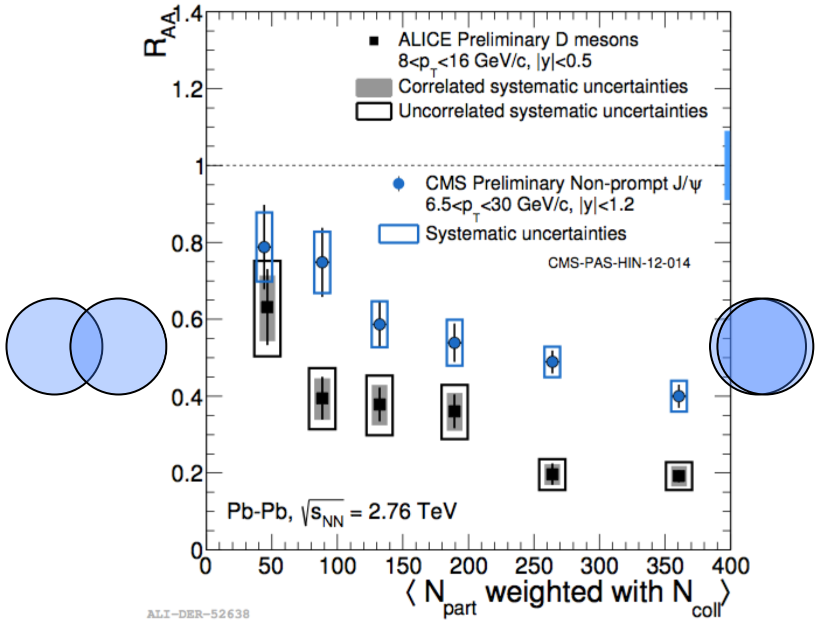


CMS, PAS-FTR-13-025

Heavy quark probes of the medium

- Energy loss expected to depend on parton mass
- First indication at LHC:

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



R_{AA}^{B} (CMS) > R_{AA}^{D} (ALICE)

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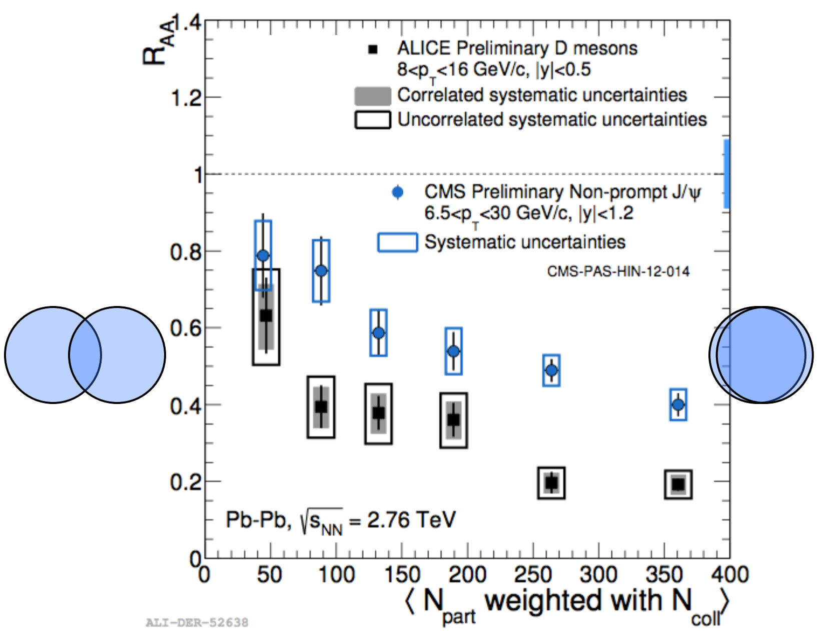
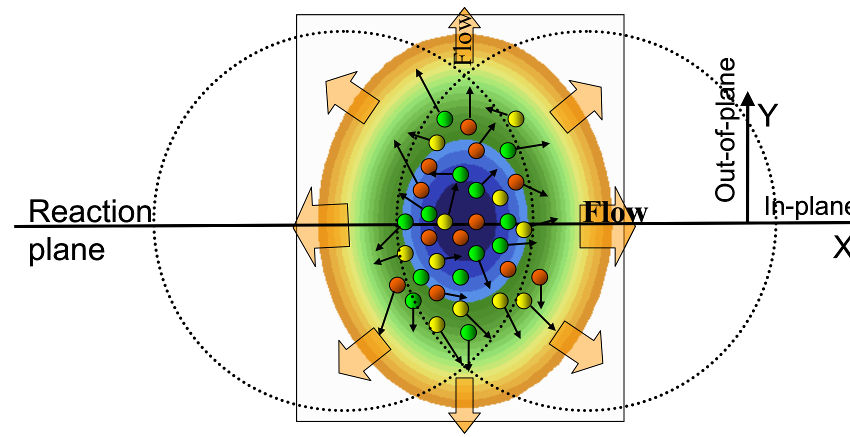


R_{AA}^{B} (CMS) > R_{AA}^{D} (ALICE)

- Azimuthal anisotropy v_2
  - strength of collectivity
  - mean free path of partons



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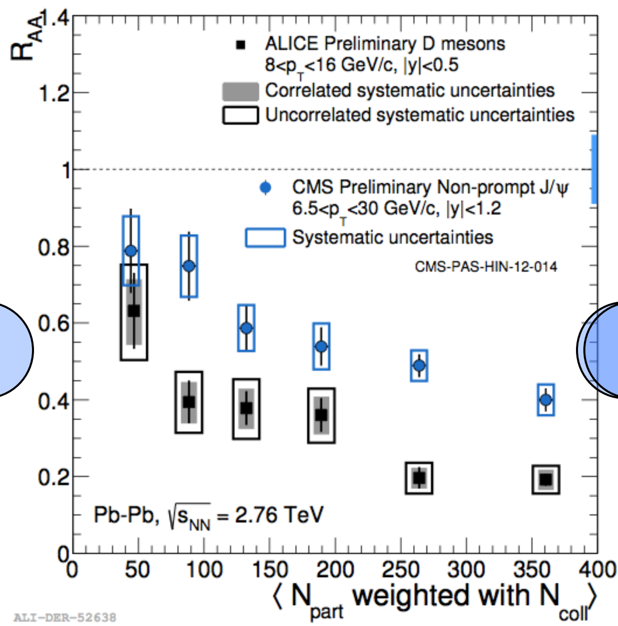
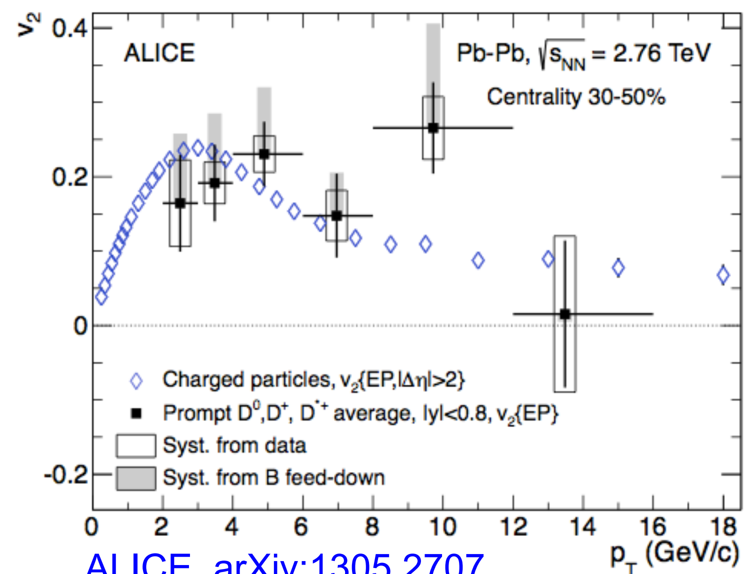


$R_{AA}{}^{B}$ (CMS) > $R_{AA}{}^{D}$ (ALICE)

- Azimuthal anisotropy v_2
  - strength of collectivity
  - mean free path of partons
- Charm hadrons have $v_2>0$, comparable to light hadrons



ALICE, arXiv:1305.2707

- Heavy quark collective flow?

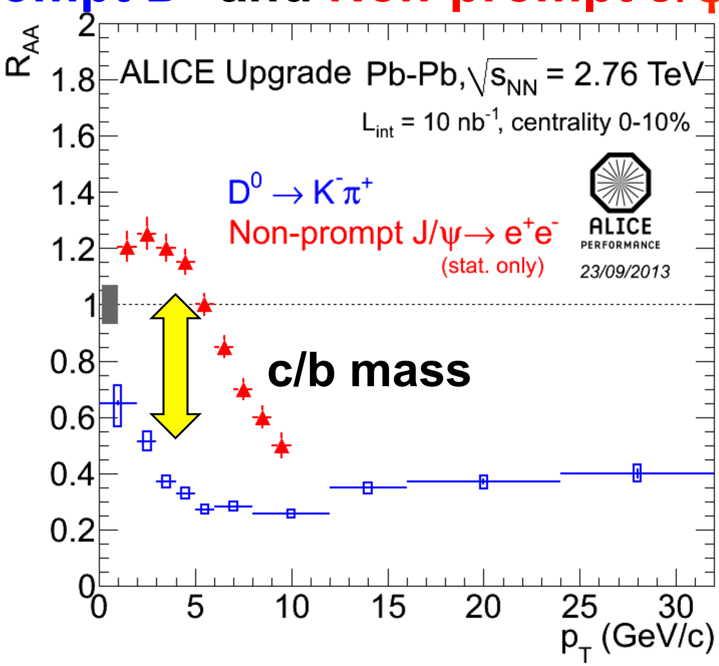
HF suppression and flow: performance

HL-LHC → exploit the potential of HQ as probes the in-medium interactions and of its thermalization

- Pin down mass dependence of energy loss
- Investigate transport of heavy quarks in the QGP
  - Sensitive to medium viscosity and equation of state

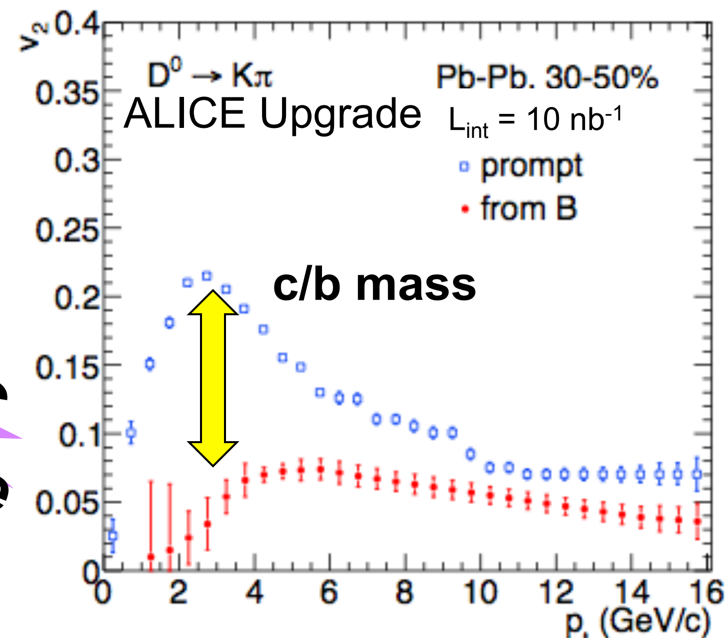
→ R_{AA} and v_2 of D and B in a wide p_T range

Prompt D⁰ and Non-prompt J/ψ R_{AA}



HL-HI-LHC Performance

Prompt and non-prompt D⁰ v_2



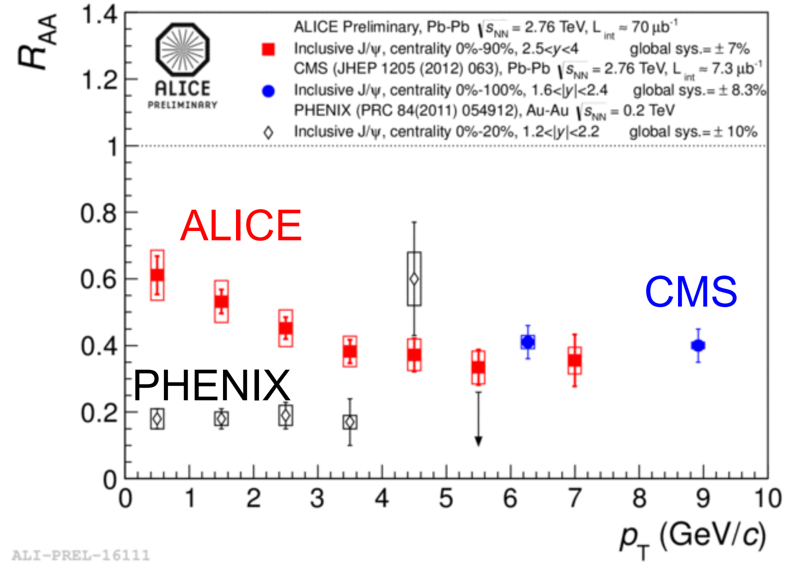
Input values from BAMPS model:
C. Greiner et al. arXiv:1205.4945

ALICE, CERN-LHCC-2012-012

Low-p_T charmonium: performance

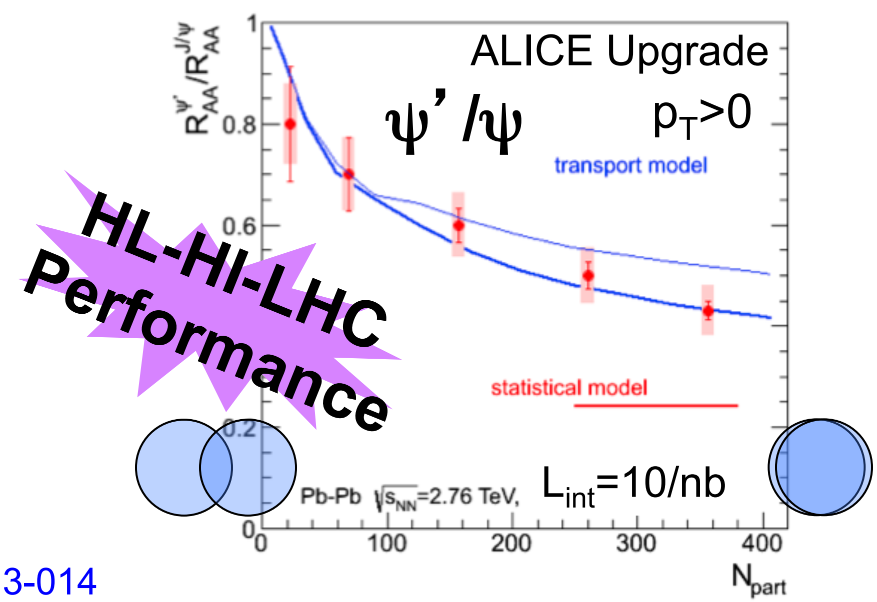
- Low-p_T J/ψ at the LHC is less suppressed than at RHIC
  - Despite the x2-3 higher density
- ψ regeneration from uncorrelated c and $\bar{c}$ in a deconfined medium?

Braun-Muzinger and Stachel, PLB490(2000) 196
Thews et al, PRC63 (2001) 054905



High statistics → explore this "new" probe of deconfinement

- Understand the underlying mechanism that binds deconfined heavy quark pairs
- Add information! E.g. low-p_T ψ'/ψ discriminates between models



ALICE, CERN-LHCC-2013-014

Besides Pb-Pb: pp reference, pA, light nuclei ?

- pp reference at 5.5 TeV required
- p-Pb run at high luminosity (exploit upgraded detectors)
- p-Ar and Ar-Ar: a possibility to be considered for schedule after LS2
- p-Ar, d-Pb, α-Pb: vary initial conditions/geometry and study effects on collectivity observables
  - e.g. d-Pb and α-Pb provide highly-asymmetric initial state
- Ar-Ar: interesting from the point of view of changing the geometry?
  - Much larger luminosity should be possible (~ 2 orders of magnitude: peak ~10^{30}, compared to <10^{28} for Pb-Pb)
    - However, hard process scale with A^2, Pb/Ar = 27

  → 1 month Ar-Ar, could give equiv hard yields as 2-3 months Pb-Pb

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HI@HL-LHC
2020-28

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- High-density QCD in the final state: QGP

HI@FCC
> 2035

The FCC design study

INFN

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

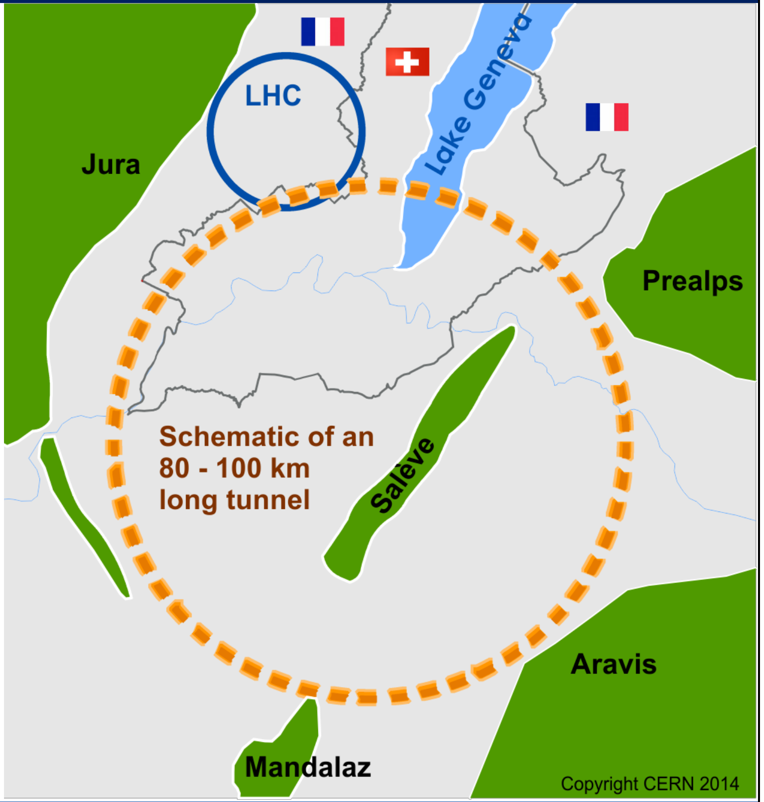
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

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



CERN
Future Circular Collider Study
Michael Benedikt
FCC Kick-Off 2014
5

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): 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_{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_{int} (nb^{-1})	80	t.b.d.	1000

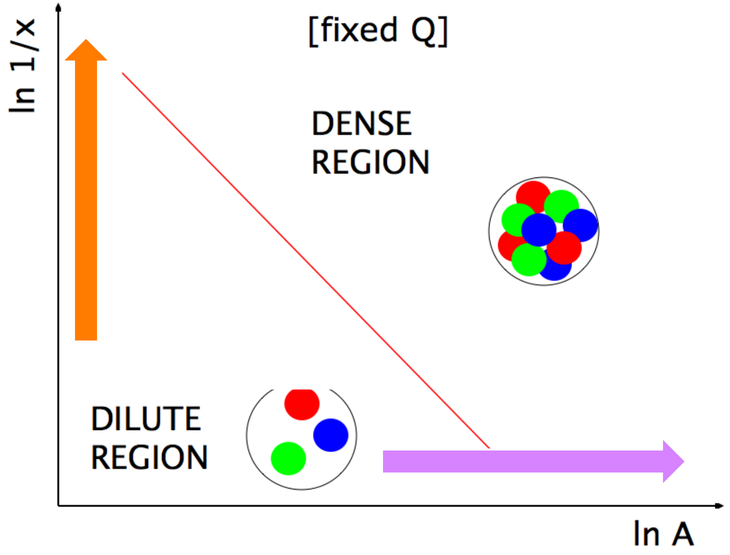
- Possibility to increase L_{int} using nuclei with slightly smaller *Z*?
  - Some of the limiting factors (e.m. process) go with "large" powers of *Z*
- Could (optimistically) aim for programme of 100/nb (LHC x10)

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



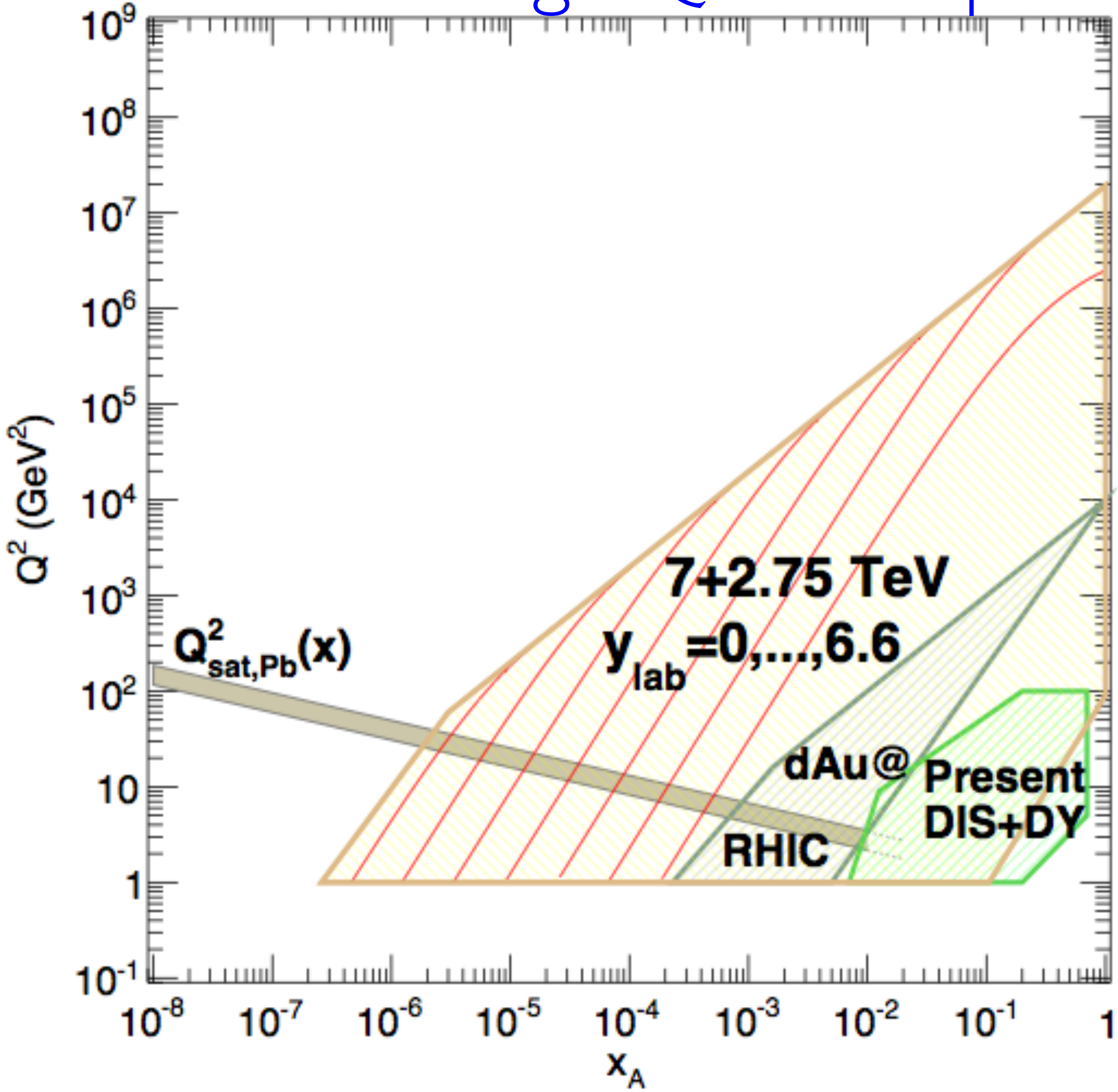
Saturation affects process with $Q^2 < Q_S^2$

Explore saturation region:

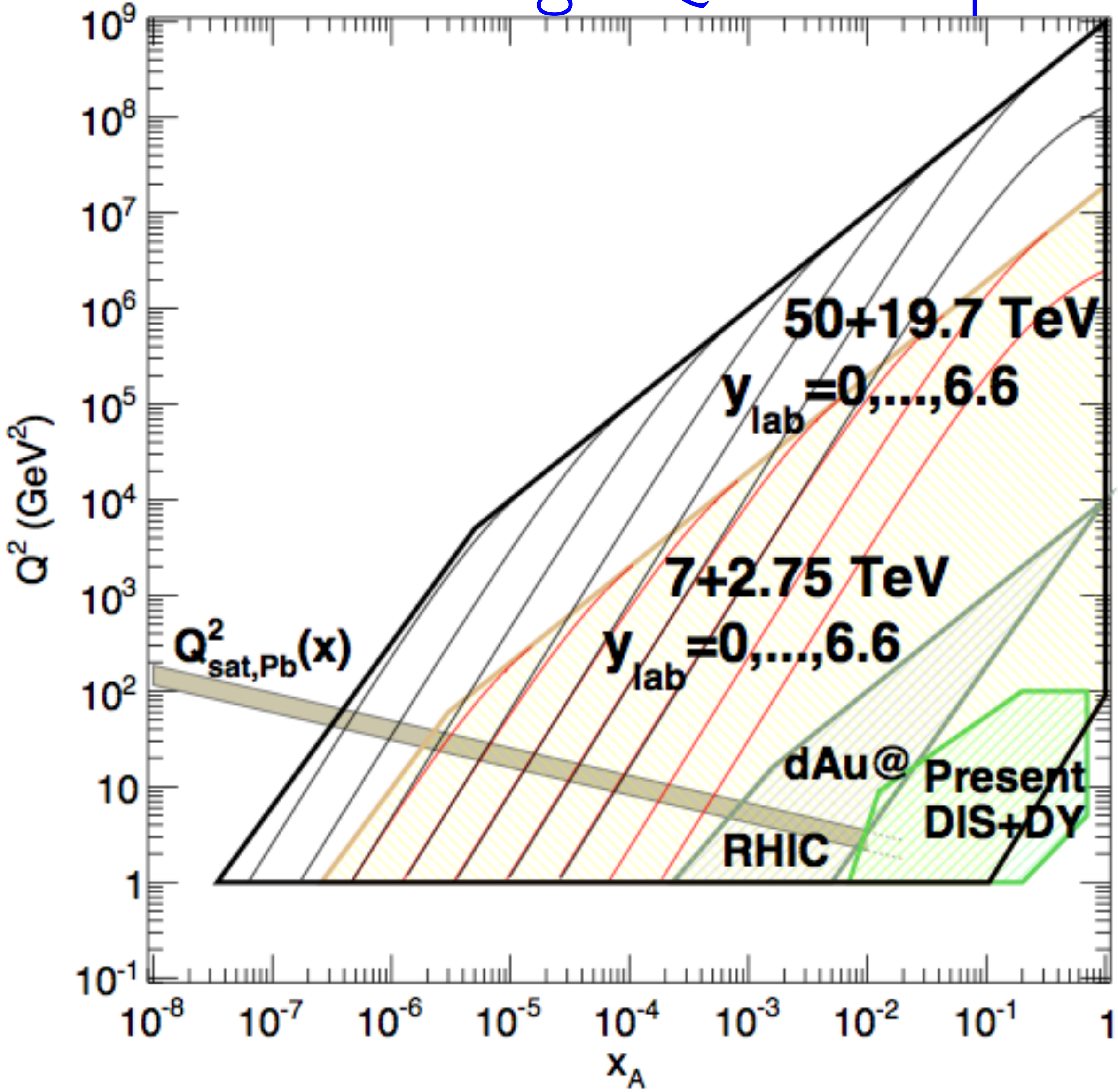
→ **decrease x (larger $\sqrt{s}$, larger y)**

→ **increase A**

Kinematic coverage Q^2 vs. x: pA LHC



Kinematic coverage Q^2 vs. x: pA FCC



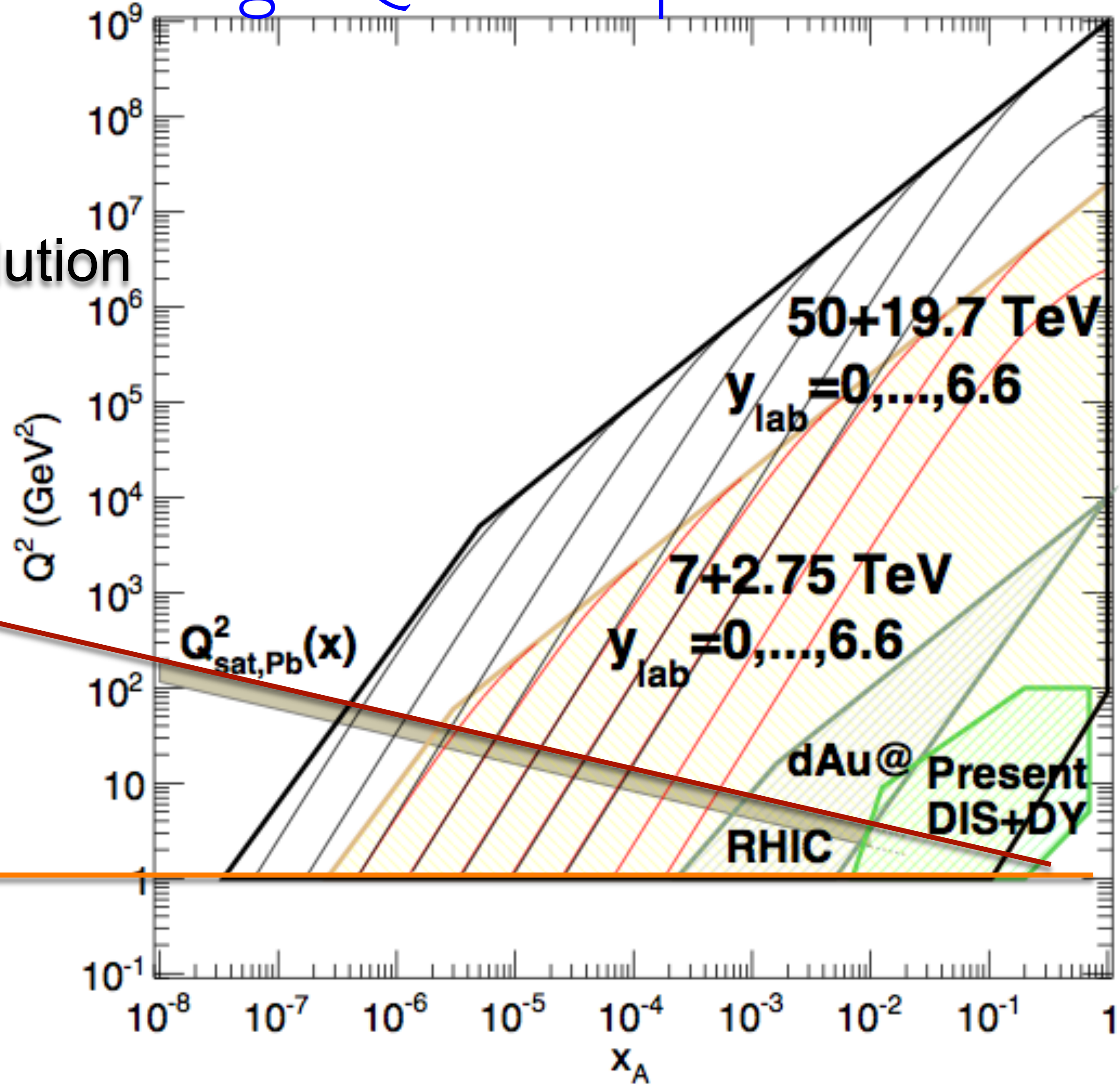
Kinematic coverage Q^2 vs. x: pA FCC

Goals:

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

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

Low Q^2:
initial conditions



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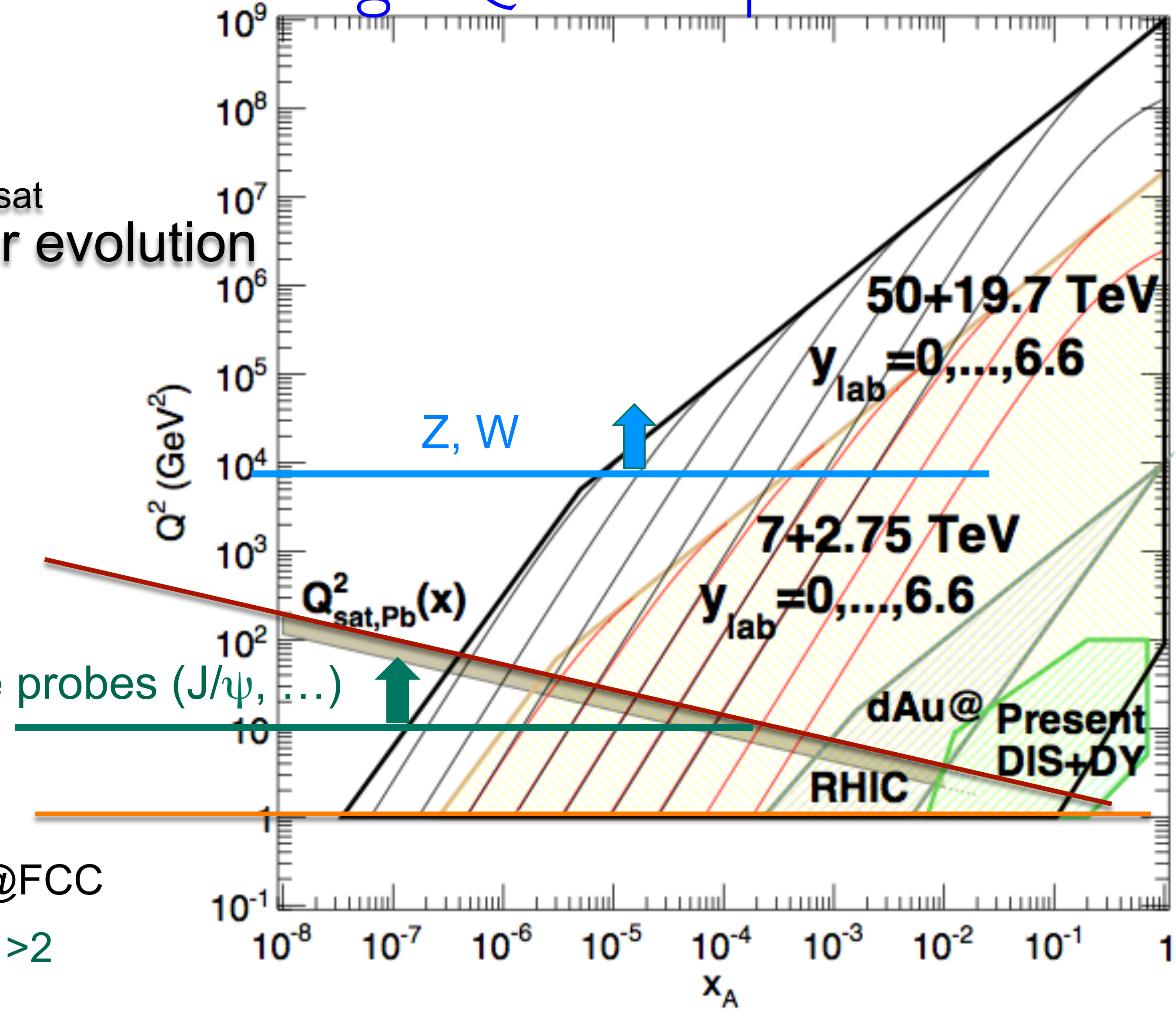
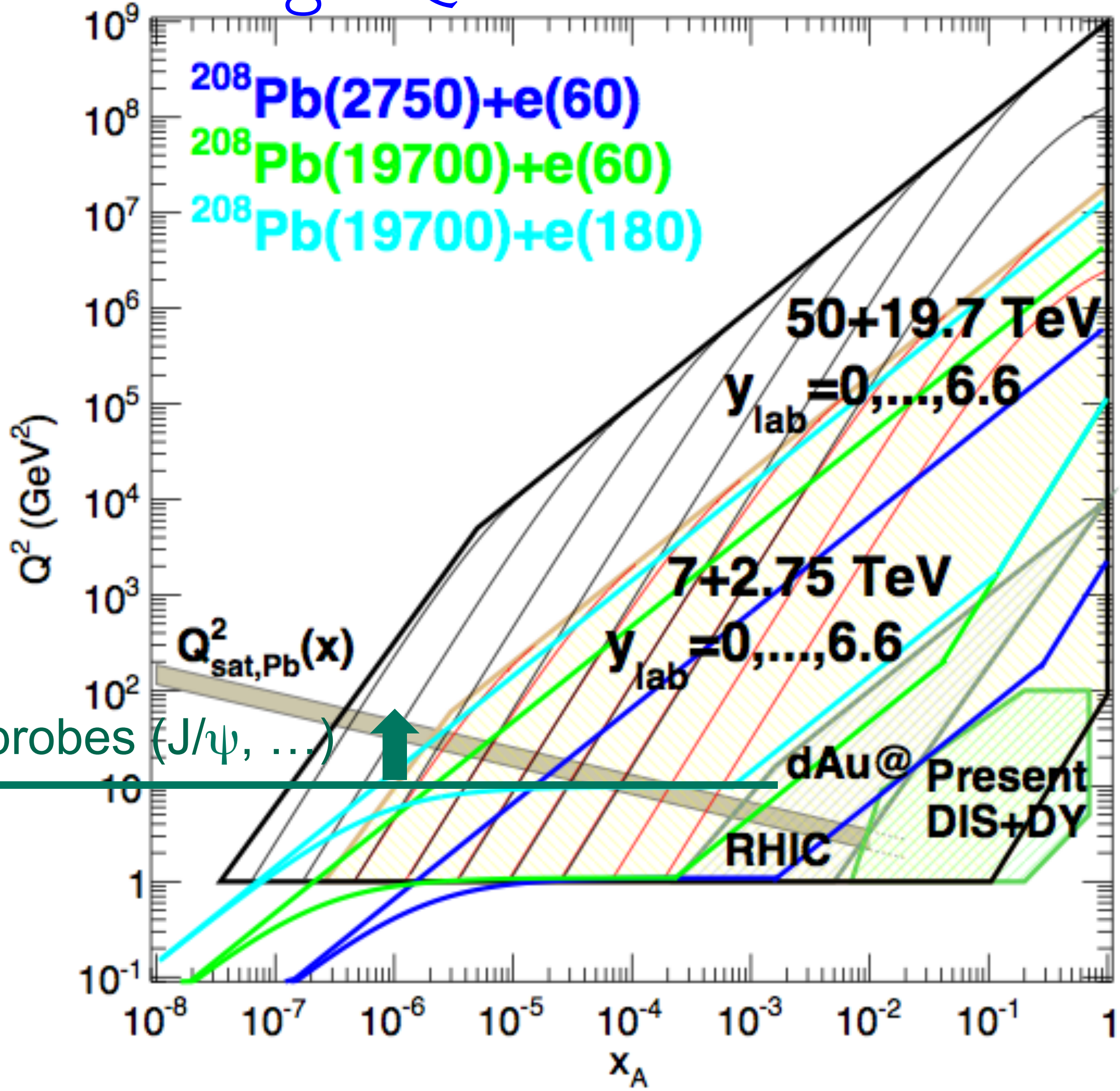


	y@LHC	y@FCC
Charm	>4	>2

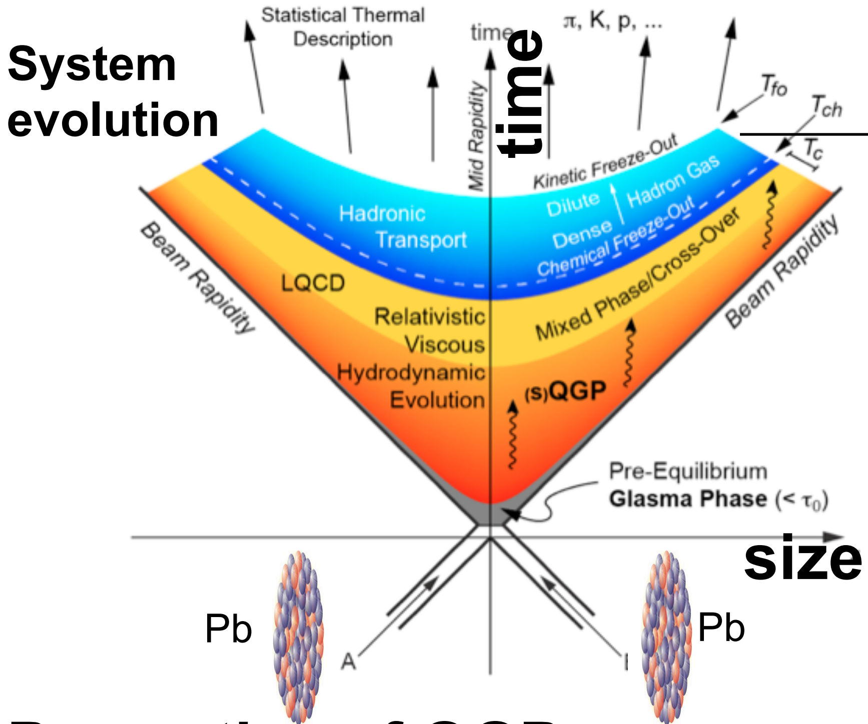
Kinematic coverage Q^2 vs. x: eA FCC

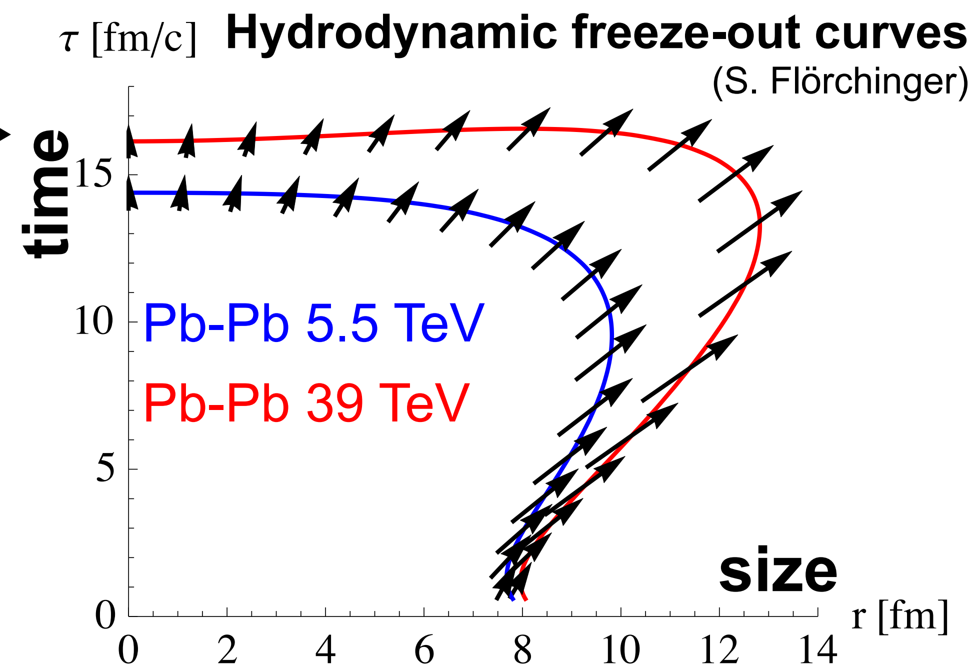
pA at FCC:
unique access down to $x<10^{-6}$ with perturbative probes

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



Quark-Gluon Plasma studies at FCC





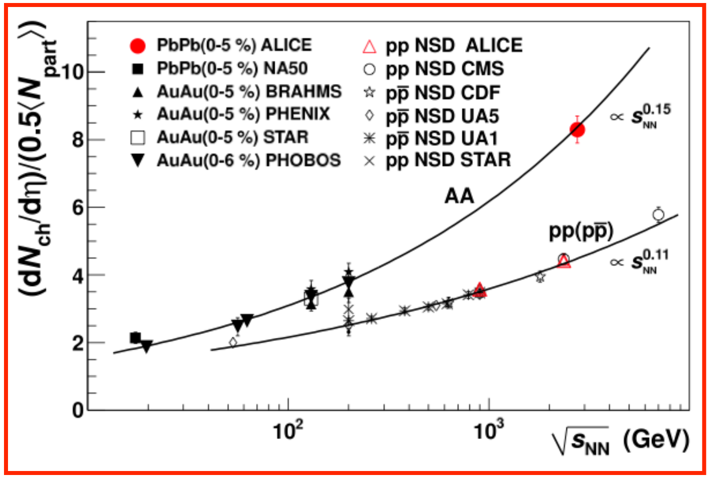
Properties of QGP:

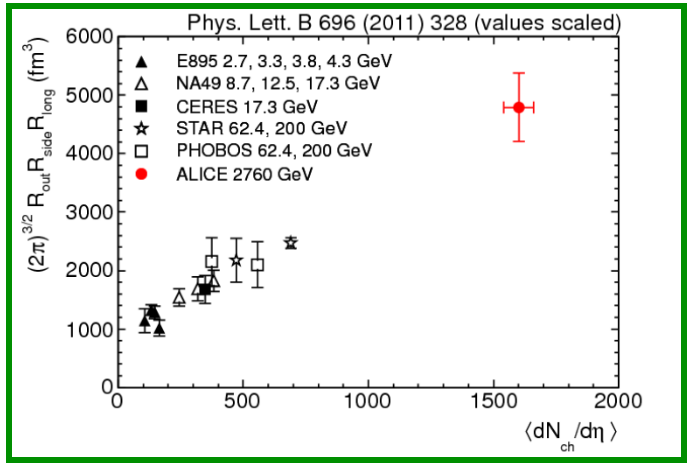
- QGP volume increases strongly
- QGP lifetime increases
- Collective phenomena enhanced (better tests of QGP transport)
- Initial temperature higher
- Equilibration times reduced

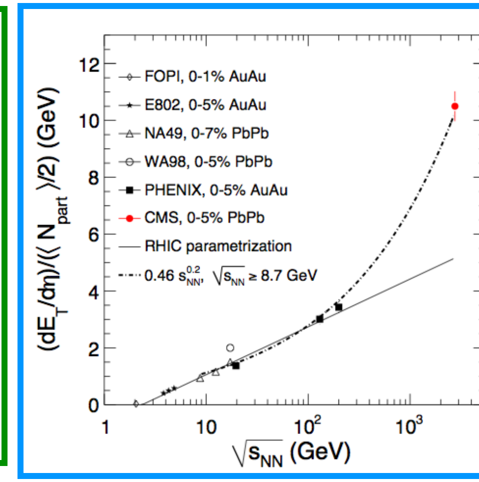
QGP studies at the FCC: global properties

- 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**



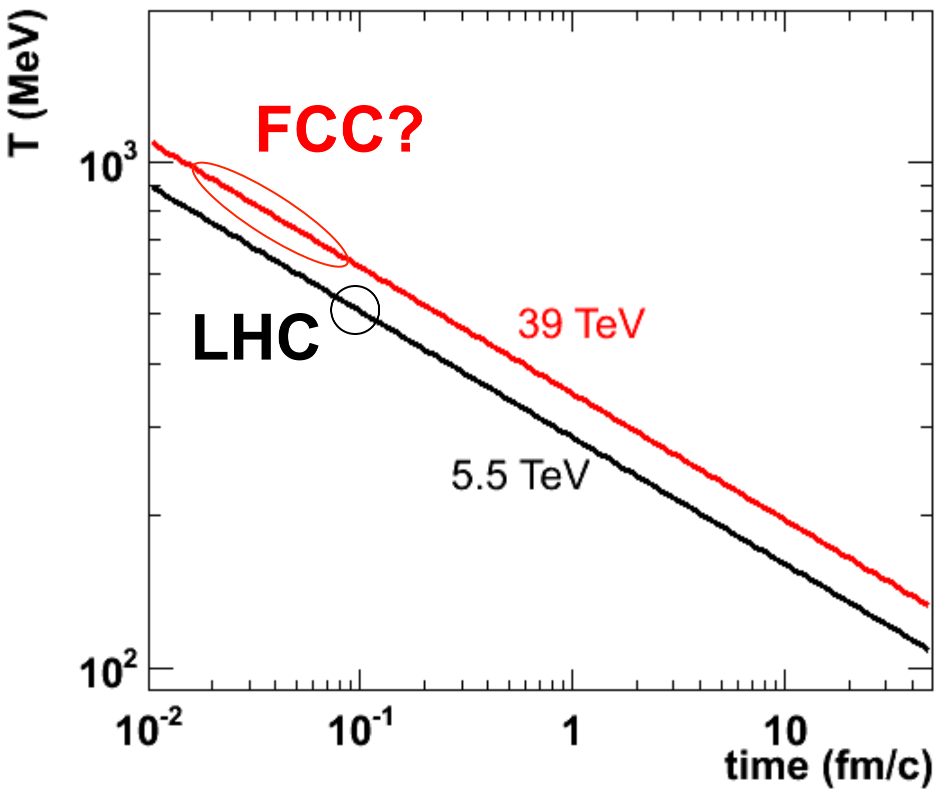




Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	2 TeV	2.6 TeV	5.8 TeV
BE homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
BE decoupling time	10 fm/c	11 fm/c	13 fm/c

QGP studies at the FCC: temperature

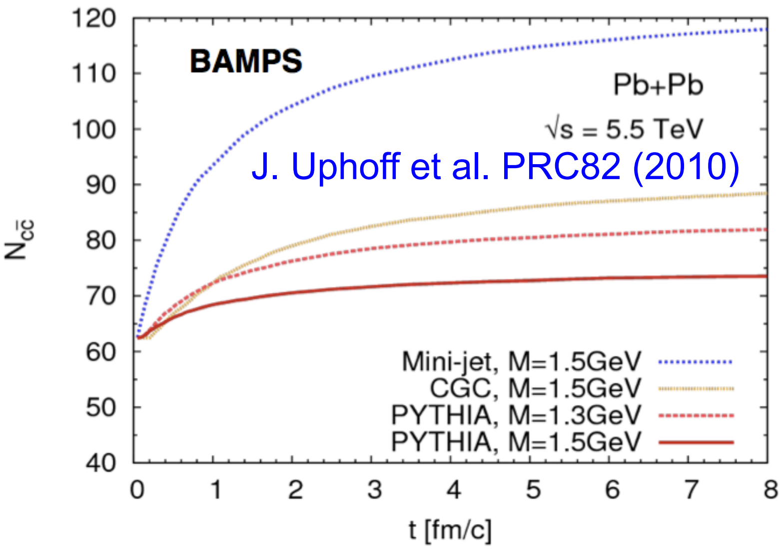
- Energy density with Bjorken formula: $$\varepsilon(\tau) = \frac{E}{V(\tau)} = \frac{1}{c\tau\ \pi R_A^2}\frac{dE_T}{d\eta}$$
- Temperature from S-B equation: $$T(\tau) = \sqrt[4]{\varepsilon(\tau)\frac{30}{\pi^2 n_{d.o.f.}}}$$



- 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?

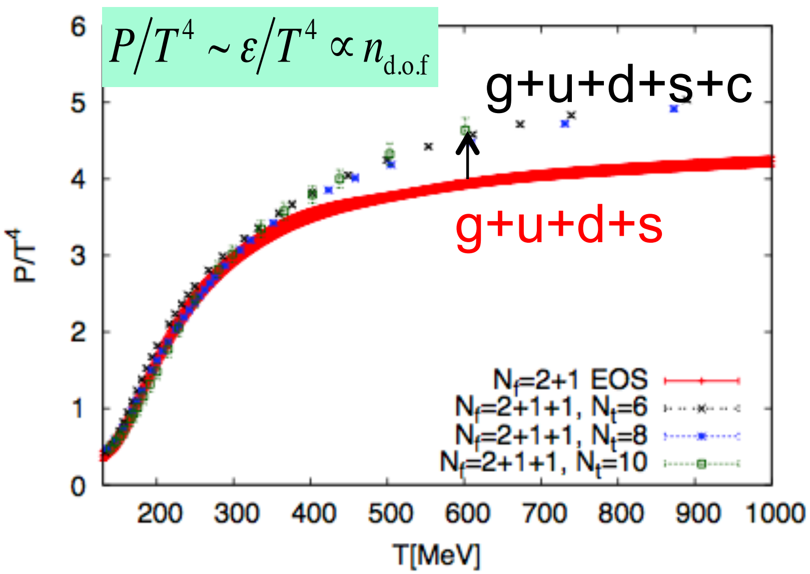
Charmed QGP? Secondary/thermal charm?

- 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



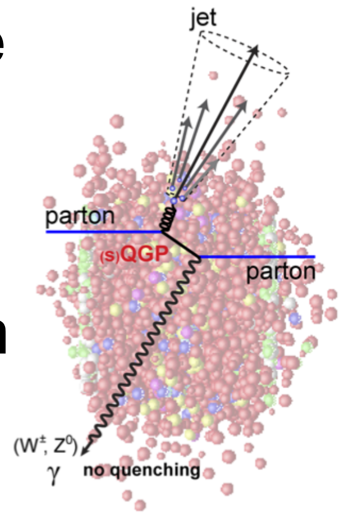
- If charm is produced abundantly during the equilibration of the medium, the additional d.o.f. should have impact on the equation of state

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

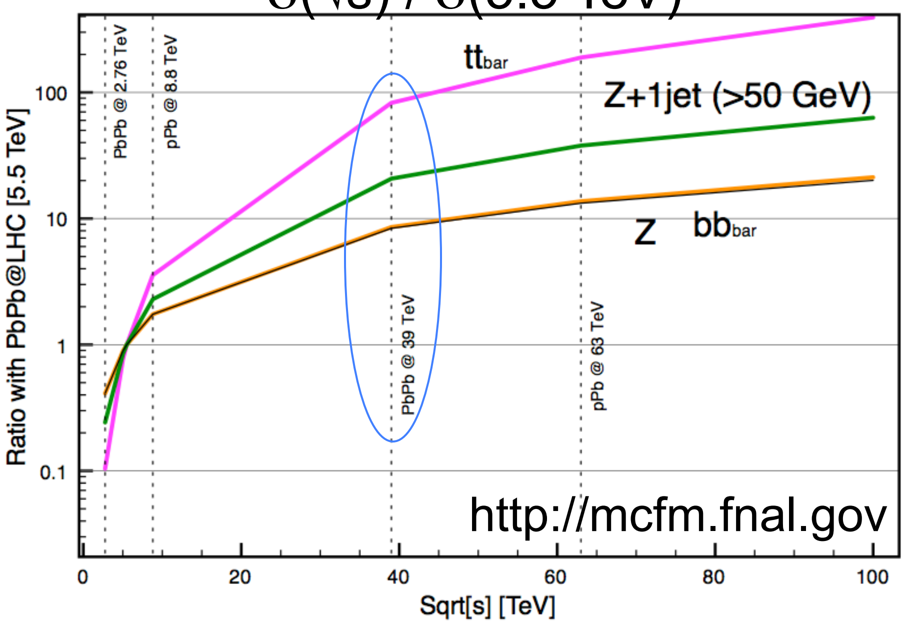


A new set of Hard Probes

- 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



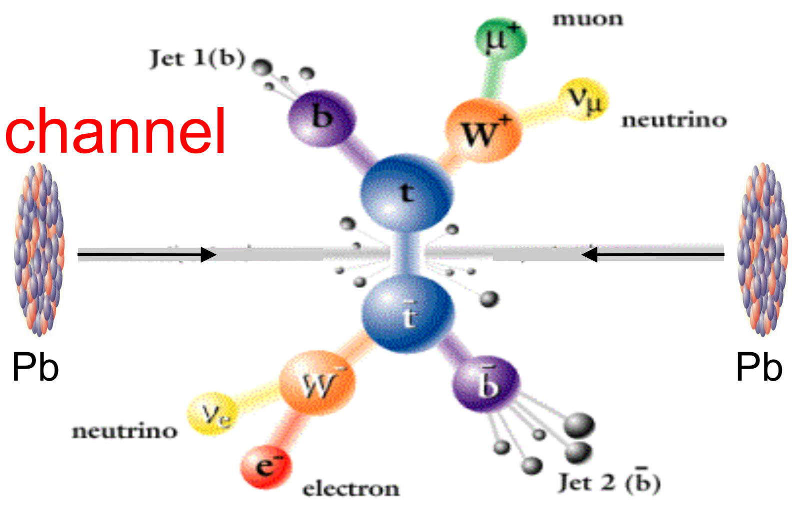
$\sigma(\sqrt{s})$ / σ(5.5 TeV)



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

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

Summary

- "HL-HI-LHC" (Runs 3+4): fully exploit the potential of the machine as a high-luminosity HI collider
  - Pb-Pb >10/nb → x10 wrt Run 2, x100 for minimum bias (ALICE)
  - pp reference at Pb-Pb energy; p-Pb; possibly light ions
- Rich Physics programme prepared by the experiments
  - Upgraded detectors, very large statistics, diverse trigger approaches, complementary strengths of the experiments
- Discussions started on opportunities with heavy ions at FCC
  - Saturation physics in pA, eA and γA
  - QGP physics
  - New inputs and ideas are most welcome!

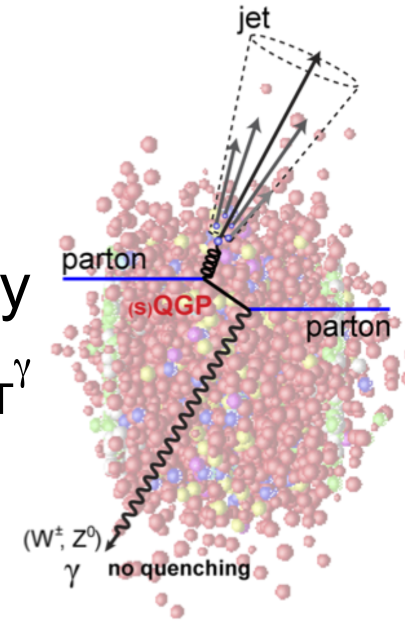
  → WS at CERN Sept 22-23: https://indico.cern.ch/event/331669/

EXTRA SLIDES

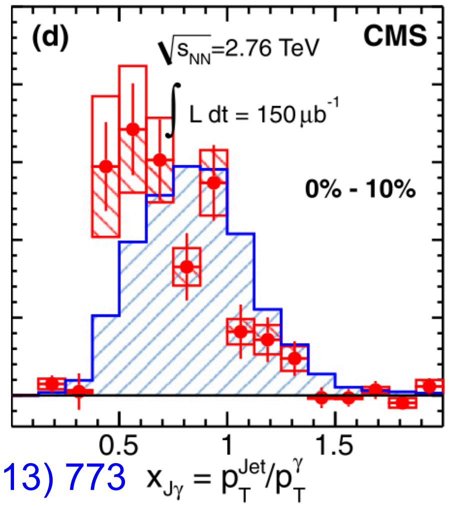
Available Documents

- ALICE Upgrade LOI: CERN-LHCC-2012-012
  - Addendum (Muon Forward Tracker): CERN-LHCC-2013-014
- ALICE inner tracker upgrade CDR: CERN-LHCC-2012-013
  - TDR in preparation (also for TPC, electronics, DAQ-HLT-Offline)
- CMS HI HL-LHC projections: CMS-PAS-FTR-13-025
- Presentations at the Heavy Ion Town Meeting (June 2012):
  - http://indico.cern.ch/event/HItownmeeting
- Inputs by ALICE, ATLAS, CMS to the ESPG meeting Cracow (Sep 2012)
  - http://indico.cern.ch/confId=182232
  - HI community presentation (H. Appelshaeueser) http://indico.cern.ch/getFile.py/access?contribId=16&sessionId=2&resId=0&materialId=slides&confId=182232

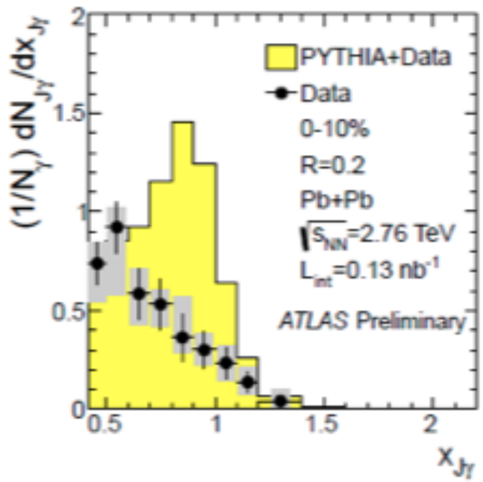
A powerful tool: jet-boson (γ, Z) correlation



- $E^{\gamma} = E^{jet}$! Direct measurement of total jet energy
- First measurement of γ-jet p_T imbalance p_T^{Jet}/p_T^{γ}



CMS, PLB718 (2013) 773



Large imbalance observed in central collisions

Needs HL-HI-LHC

High statistics:

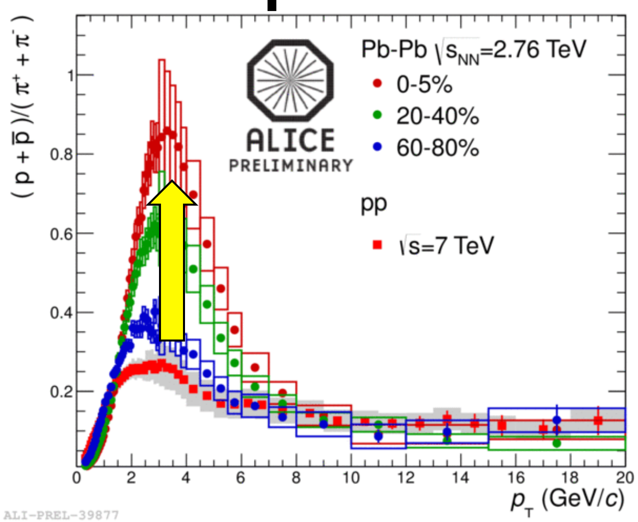
→ Precise measurement of the medium-modified fragmentation function

→ Differential studies as a function of event geometry

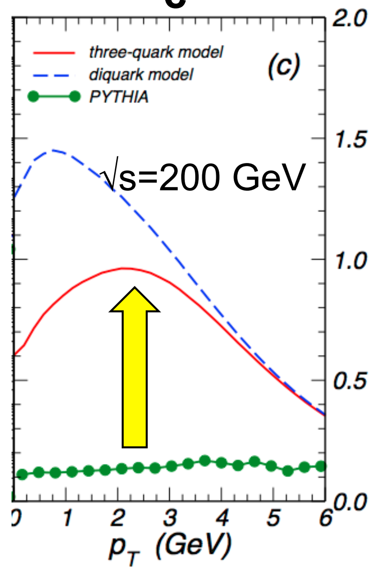
Heavy flavour in-medium hadronization?

- Baryon/meson enhancement and strange-enh. → most direct indication of light-quark hadronization in a partonic system
  - Measure this in the HF sector! Does it hold for charm?
  - Charm baryons (Λ_c) and charm-strange mesons (D_s)

p/π

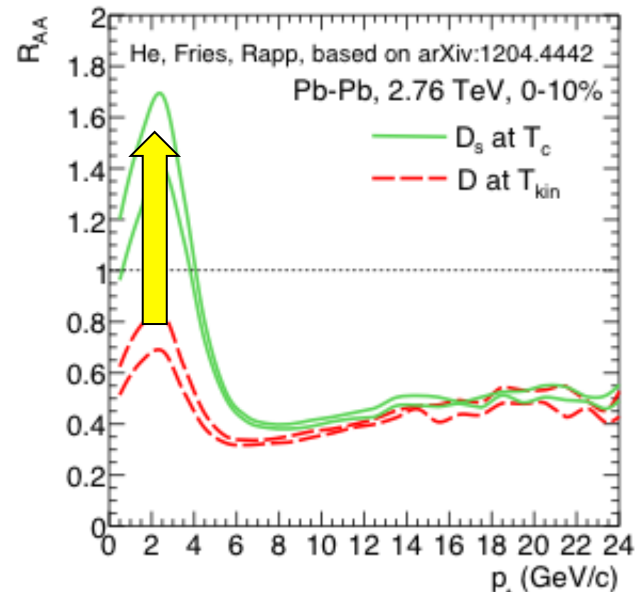


Λ_c/D



Ko et al. PRC79

D_s vs D

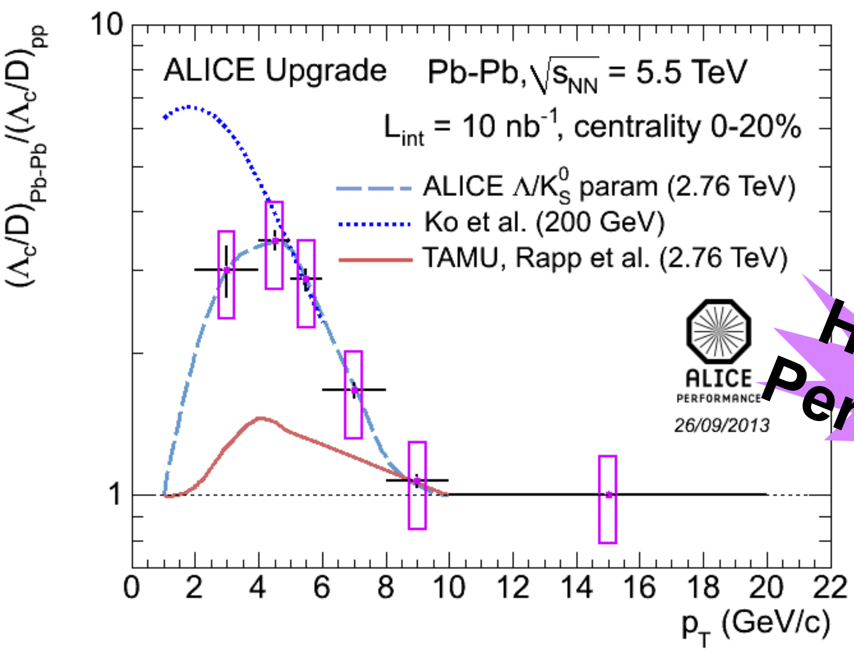


Rapp et al. arXiv:1204.4442

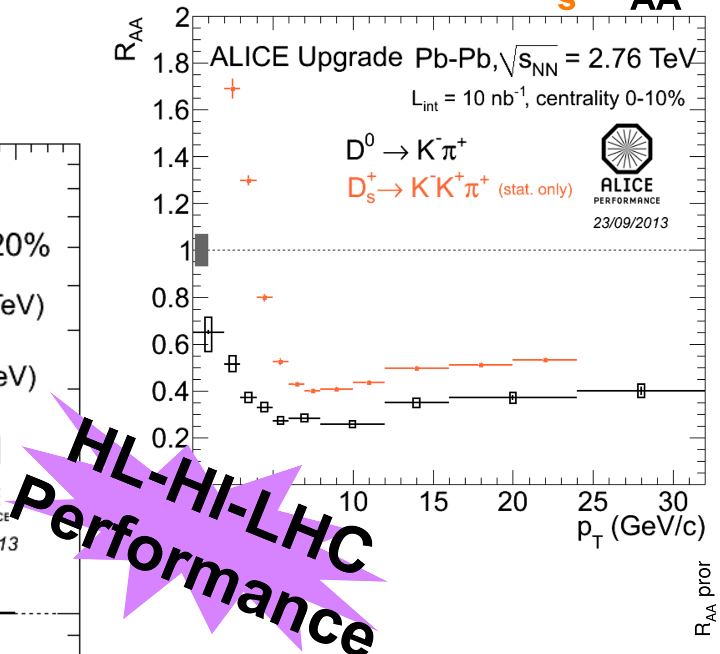
Low-p_T charm: performance

- $\Lambda_c \rightarrow pK\pi$ and $D_s \rightarrow KK\pi$ ($c\tau$=60 and 150 μm) measured with good precision in ALICE with upgrades and 10/nb

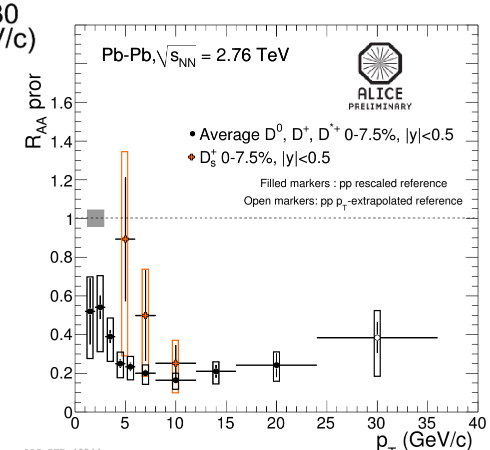
Λ_c/D enhancement
(full detector sim.)



D^0 and D_s R_{AA}



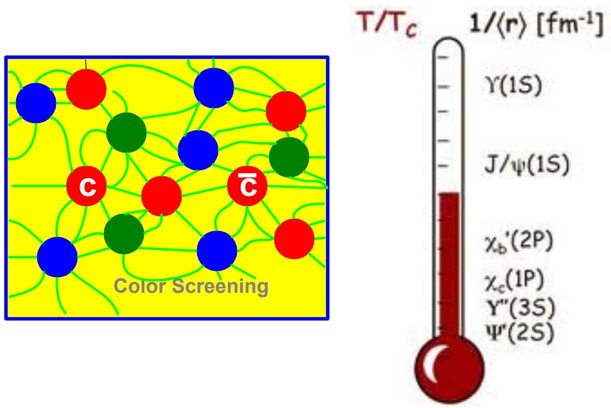
2011 data

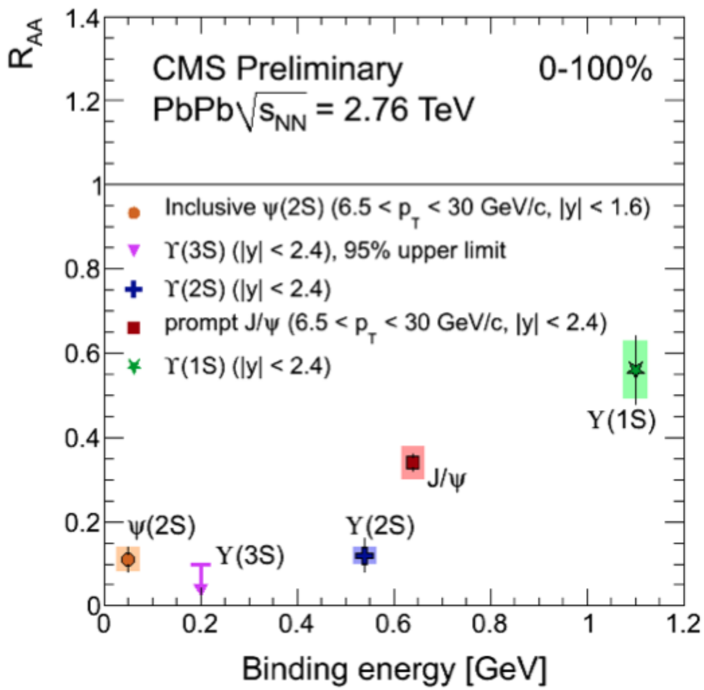


Needs minimum-bias trigger (low S/B)
→ HL-LHC = 100x Run2 stat.

Quarkonium suppression

- Quarkonium sequential dissociation: direct probe of deconfinement and of the medium temperature
- First hint of sequential pattern





High statistics → precise multi-differential measurements
E.g. (CMS, 10/nb):

Υ(1s)	Υ(2s)	Υ(3s)
270k	40k	7k

CMS, arXiv:1208.2826 and PRL 109 (2012) 222301

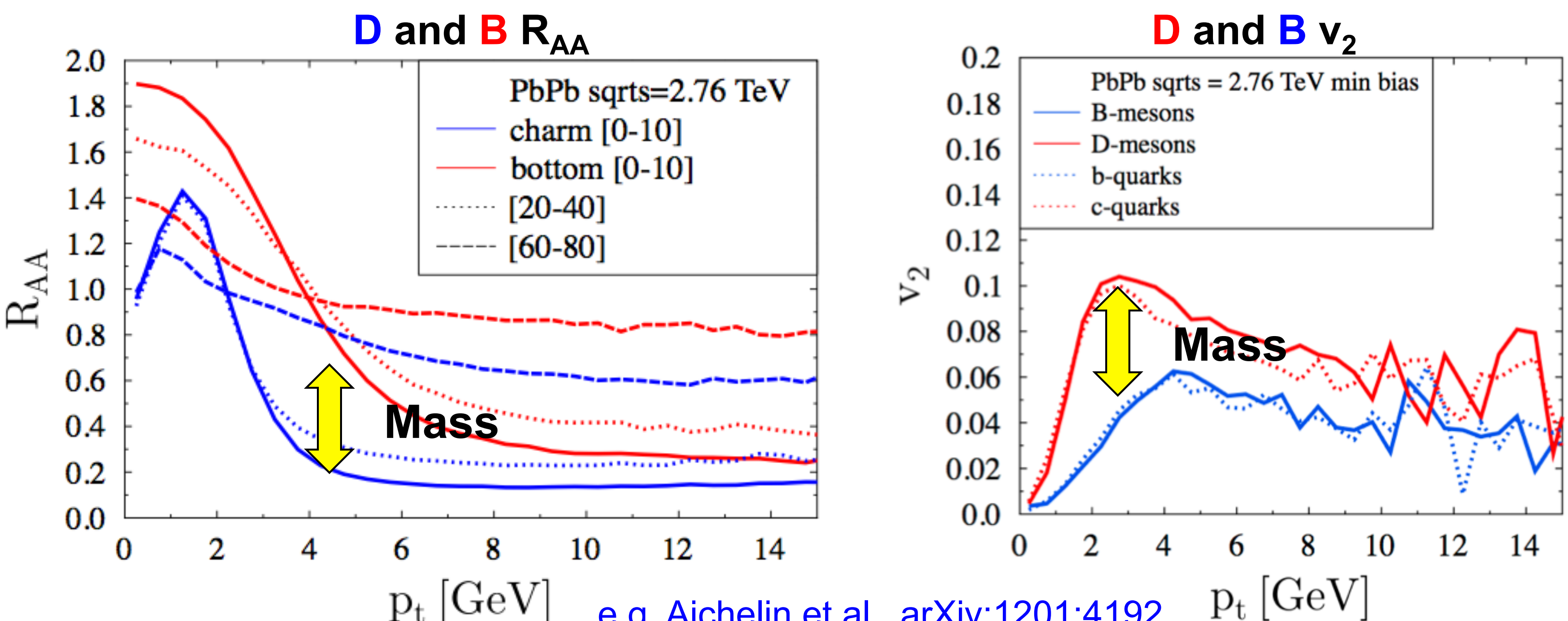
CMS, PAS-FTR-13-025

Heavy quark probes of the medium

HL-LHC → exploit the potential of HQ as probes the in-medium interactions and of its thermalization

- Pin down mass dependence of energy loss
- Investigate transport of heavy quarks in the QGP
  - Sensitive to medium viscosity and equation of state

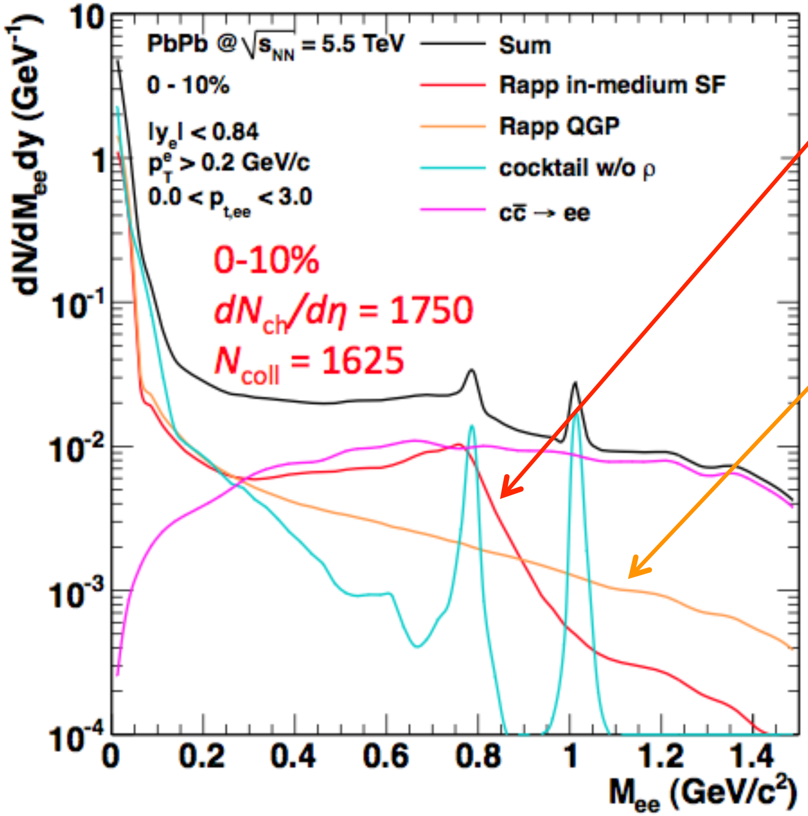
➡ Measure precisely R_{AA} and v_2 of D and B in a wide p_T range



e.g. Aichelin et al., arXiv:1201:4192

Low-mass di-leptons

- Comprehensive measurement of low-mass di-leptons allows to address these fundamental questions:



Restoration of the chiral symmetry → Melting/broadening of the ρ meson, via $\rho \rightarrow l^+l^-$

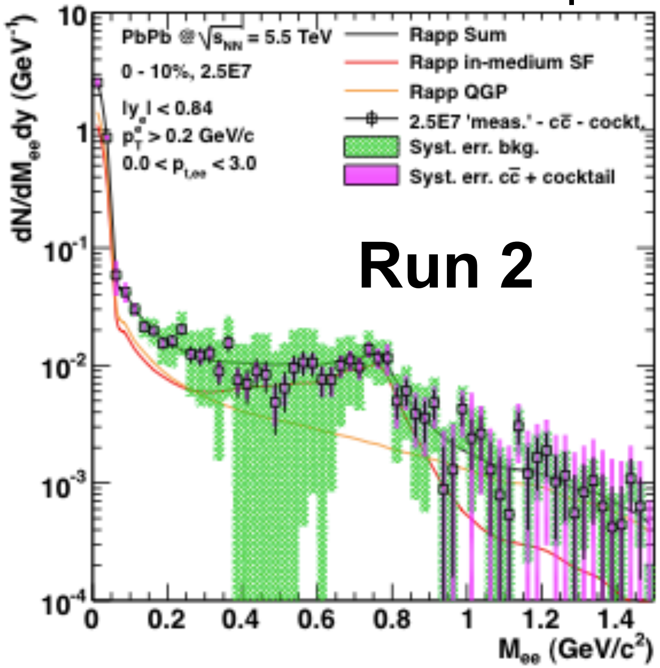
Profile system temperature during its evolution → Di-leptons from real and virtual photons $\gamma \rightarrow l^+l^-$

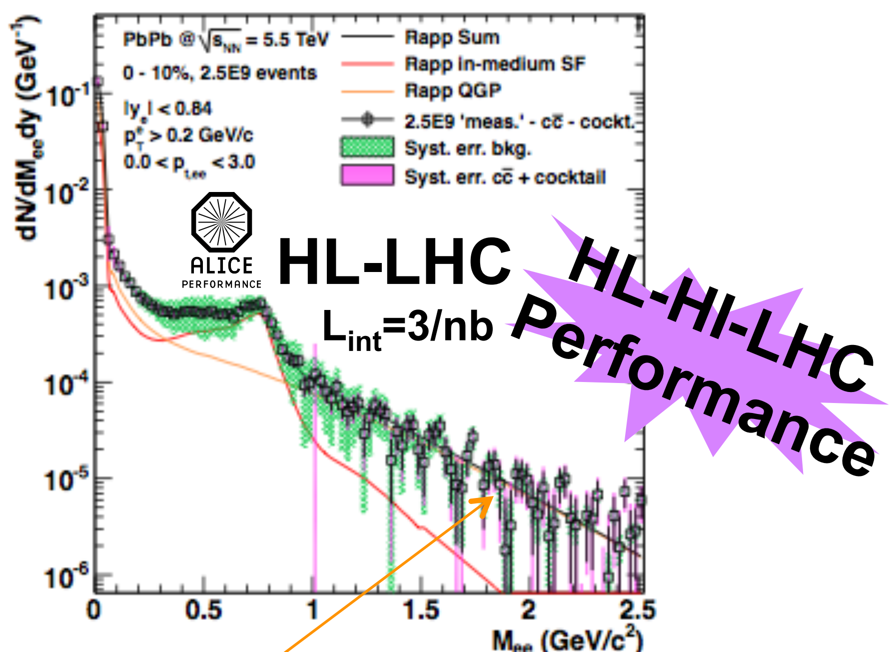
Low-mass di-leptons: performance

- ALICE: new inner tracker **+ dedicated run at 0.2 T (+3/nb)**
  → electron acceptance down to p_T = 50 MeV/c

Needs minimum-bias trigger (low S/B)
→ HL-LHC = 100x Run2 stat.

Di-electron mass spectrum after bkg subtraction:



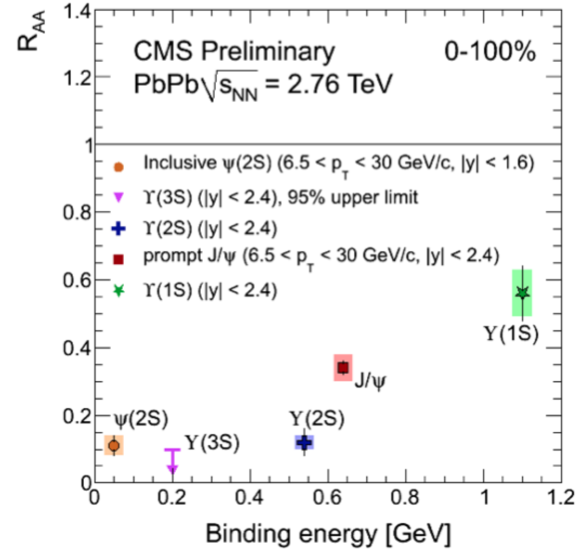


Precision of ~10% on the inverse slope → T

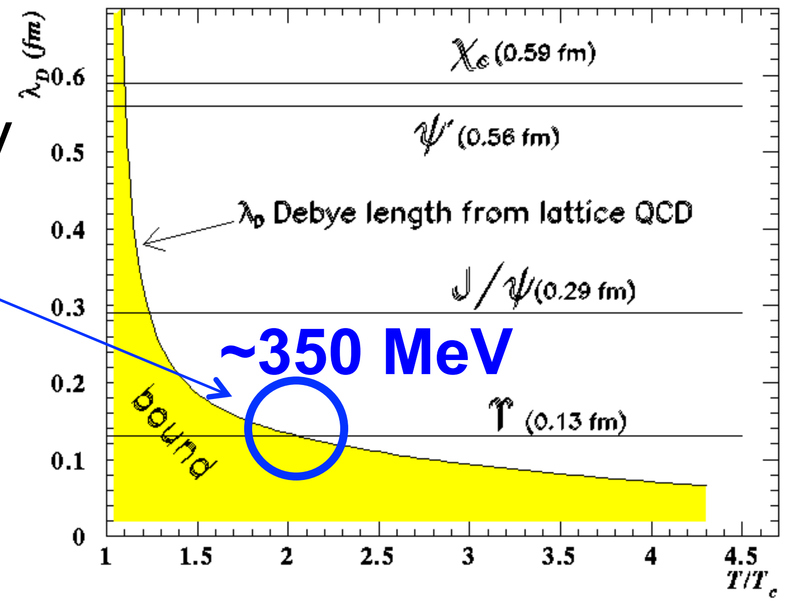
ALICE, CERN-LHCC-2012-012

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, but…
- 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)

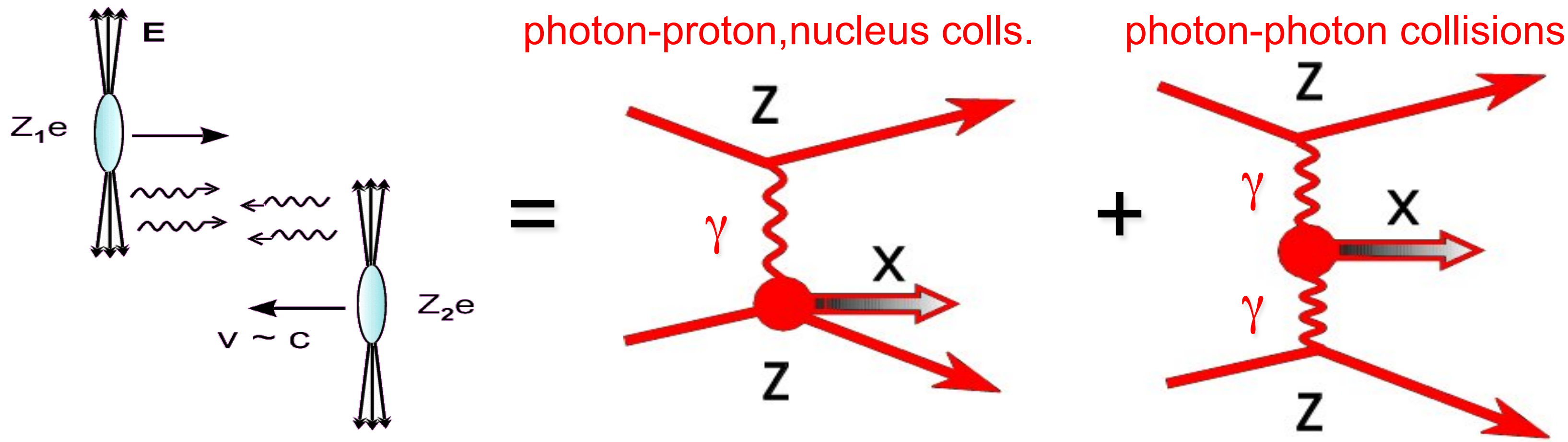


→ May not melt at LHC

→ Full quarkonium melting at FCC?

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:

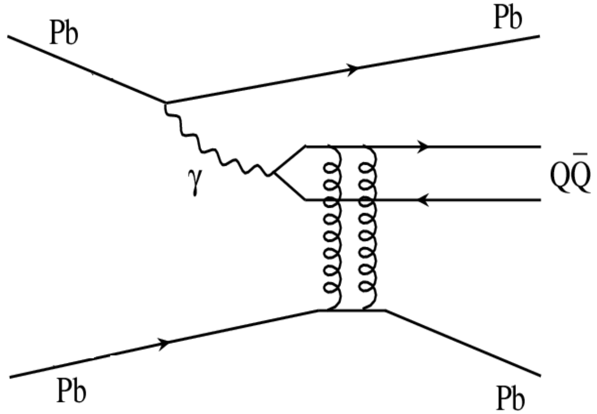


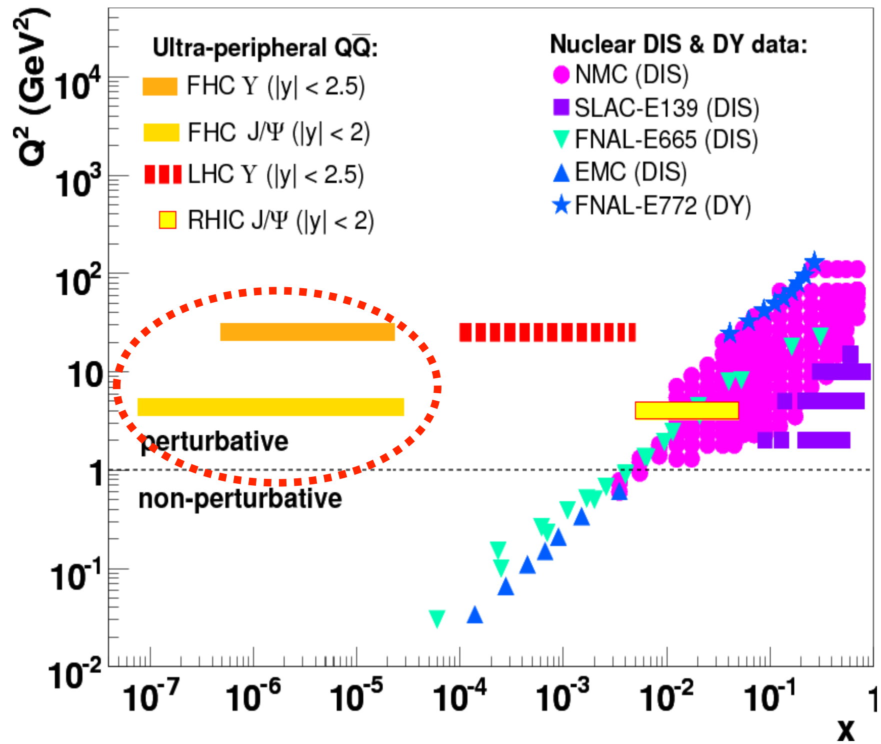
- Huge photon fluxes:
  - $\sigma(\gamma\text{-Pb}) \sim Z^2$ (~10^4 for Pb) larger than in pp
  - $\sigma(\gamma\text{-}\gamma) \sim Z^4$ (~$5\cdot10^7$ for PbPb) larger than in pp
- Max. FCC γγ, γN √s energies:

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)