Future heavy ion facilities: FCC-AA

Andrea Dainese
(INFN Padova, Italy)

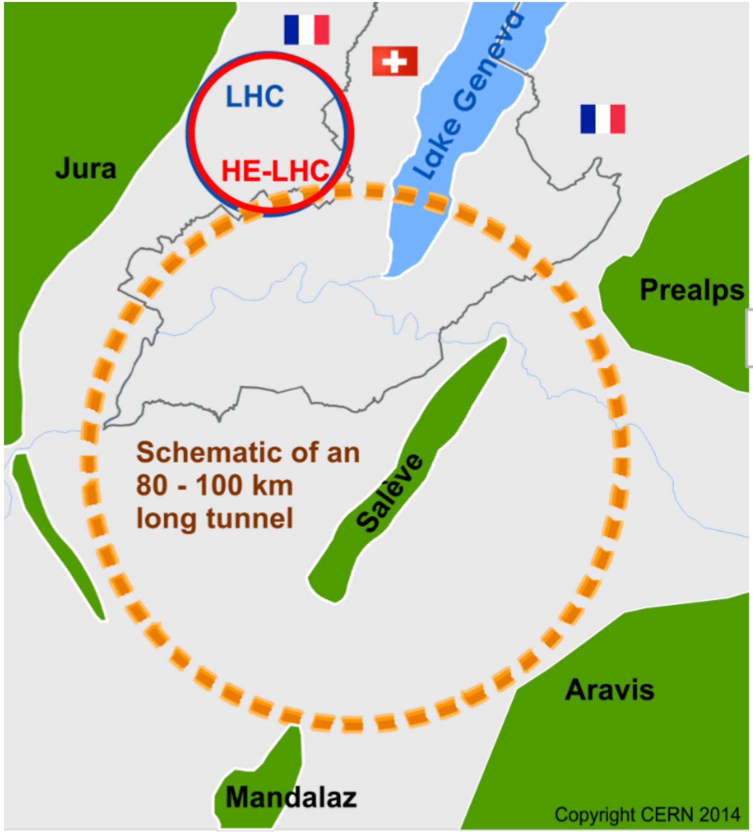
on behalf of the HI Working Group of FCC-hh/Physics&Exp

Outline

- FCC Study activities and timeline
- Ions at the FCC: projected performance
- QGP studies
- nPDFs and gluon saturation

FCC Study

https://fcc.web.cern.ch



International FCC collaboration (CERN as host lab) to study:

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

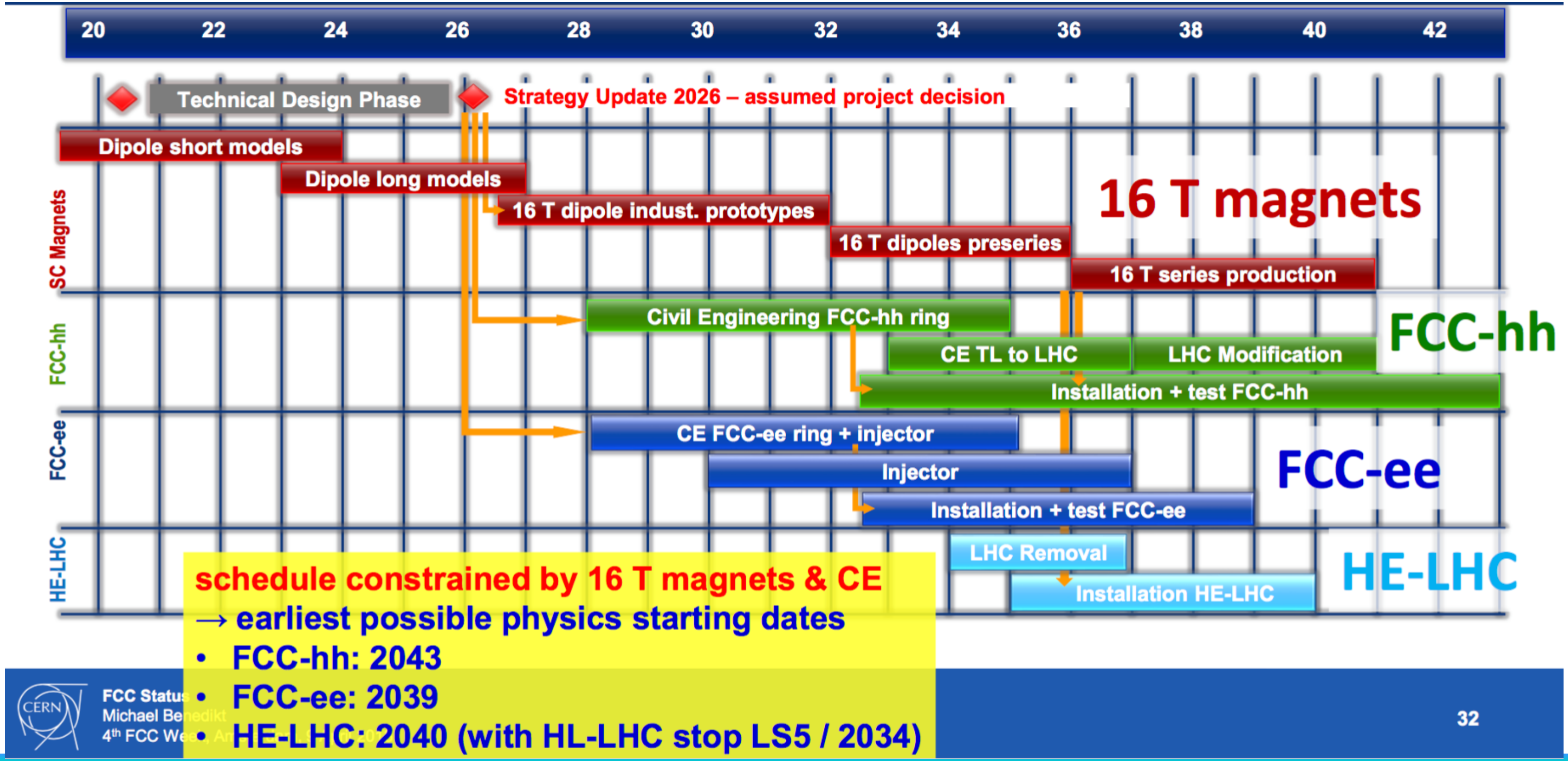
~16 T ⇒ 100 TeV *pp* in 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*)**, as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option**, IP integration, e^- from ERL

	Pb-Pb	p-Pb
FCC-hh	39 TeV	63 TeV
HE-LHC	10.6 TeV	17 TeV

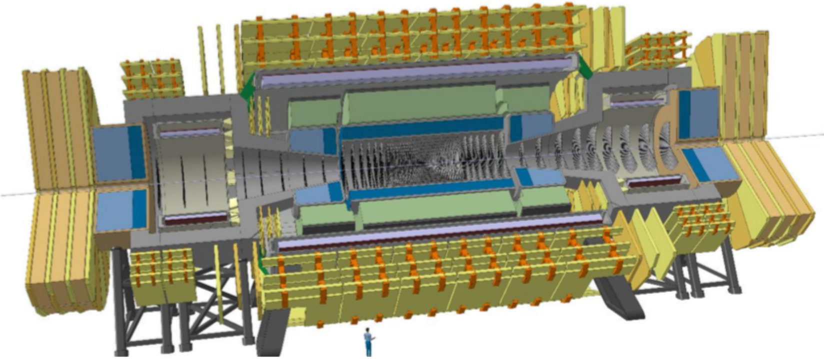
Timeline

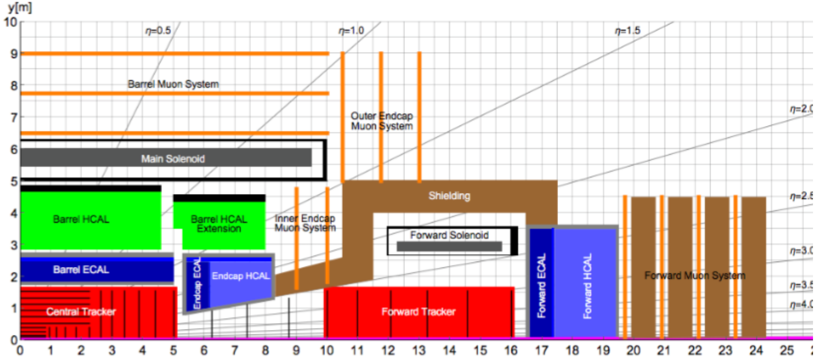
2014: Study kickoff, formation of international collaboration
2018: CDR as input for European Strategy for Particle Physics Update



schedule constrained by 16 T magnets & CE
→ earliest possible physics starting dates
- **FCC-hh: 2043**
- **FCC-ee: 2039**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

FCC-hh reference detector

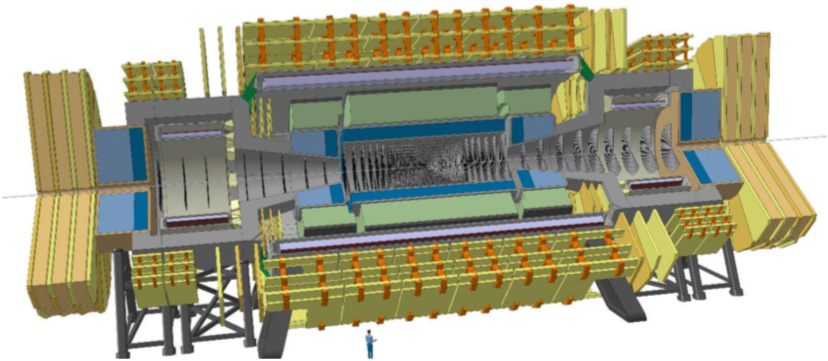


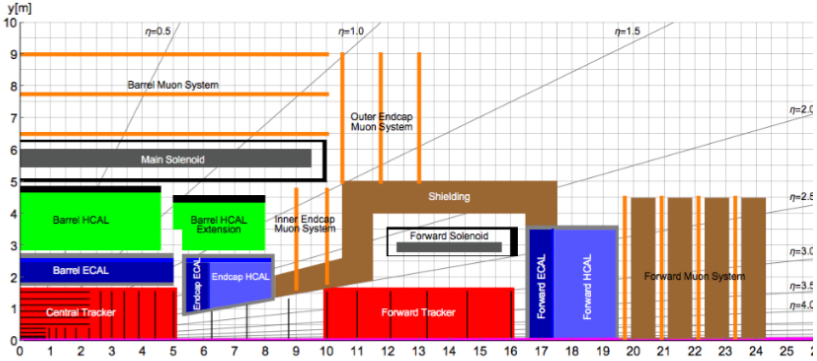


FCC Status
Michael Benedikt
4th FCC Week, Amsterdam, 9 April 2018

- Detector concept; could be implemented in two experiments
- Central solenoid (4T) + two forward solenoids (4T)
- Si-tracker 400 m^2 surface $|\eta|<6$
- ECAL&HCAL $|\eta|<6$, granularity about x4 ATLAS/CMS
- Muon system à la ATLAS/CMS

FCC-hh reference detector





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Same detector for heavy ions?

- pp with pile-up of 1000 more challenging than Pb-Pb environment
- Excellent performance for hard probes also in HI collisions
- Coverage for forward measurements up to $|\eta|$ = 6
- Operation with reduced field would give access to low-p_T observables
- Silicon timing layers for pile-up rejection could be used for hadron PID

FCC HI working group and documents

- Ions at FCC-hh Working Group:
  - Sub-group of “FCC-h Physics, Experiments, Detectors”
  - Machine studies: M. Schaumann, J. Jowett, E. Logothetis Agaliotis
  - Twiki https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HeavyIons

- Workshops/meetings 2013-17
  - https://indico.cern.ch/event/331669/ and links therein

- In FCC-hh Physics Yellow Report 3, 635–692, arXiv:1605.01389
  - Section editors: N. Armesto, A. Dainese, D. d’Enterria, J. Jowett, J.P.Lansberg, G. Milhano, C. Salgado, M. Schaumann, M. van Leeuwen, U. Wiedemann

- Contribution to FCC CDR 2018

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HI luminosity projections

- Two scenarios considered for FCC: Baseline and Ultimate
  - reduced bunch spacing (50 ns) and β^* (0.3 m)

	Unit	Baseline		Ultimate	
Operation mode	-	Pb–Pb	p–Pb	Pb–Pb	p–Pb
Number of Pb bunches	-	2760		5400	
Bunch spacing	[ns]	100		50	
Peak luminosity (1 experiment)	$[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	80	13300	320	55500
Integrated luminosity (1 experiment, 30 days)	$[\mathrm{nb}^{-1}]$	35	8000	110	29000

Includes 50% operation efficiency

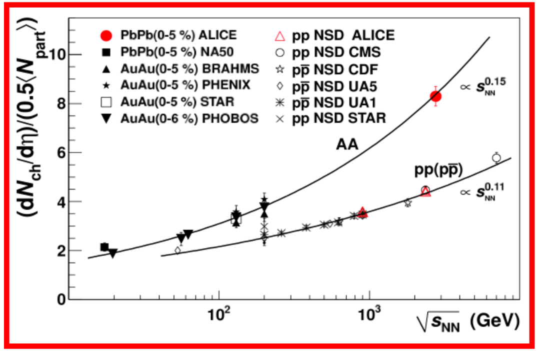
- >100 nb^{-1}/month in Pb-Pb in ultimate scenario: ~ 10x full LHC programme
- 15 1-month HI runs in tentative FCC-hh schedule → **~150 x LHC programme**
- HE-LHC, first estimate: x2 lumi than at LHC; further improvement with lighter nuclei (reduced BFPP), e.g. L_{NN} for Xe-Xe at HE-LHC ~ 5x Pb-Pb at LHC

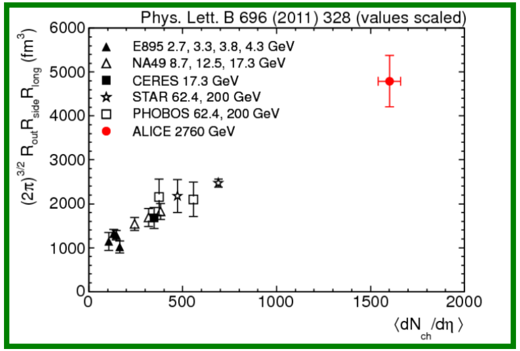
Outline

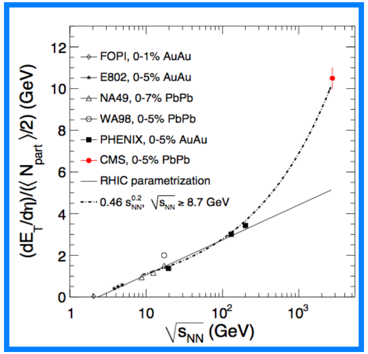
- FCC Study activities and timeline
- Ions at the FCC: projected performance
- QGP studies
  - Global properties and collective effects
  - Hard probes and jet quenching
- nPDFs and gluon saturation

Global properties at FCC (and HE-LHC)

FCC wrt LHC: $dN_{ch}/d\eta$ x 1.8 | Volume x1.8 | $dE_T/d\eta$ (& ε) x2.2





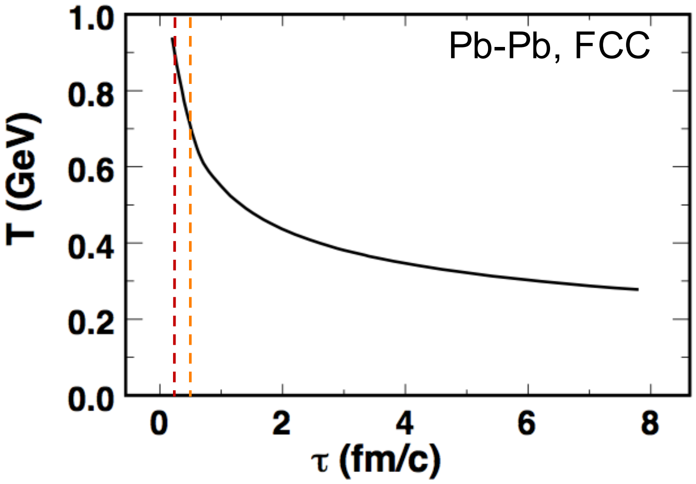


Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 10.6 TeV	Xe–Xe 11.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	2400	1500	3600
$dE_T/d\eta$ at $\eta = 0$	1.7–2.0 TeV	2.3–2.6 TeV	3.1–3.4 TeV	≈ 1.5 TeV	5.2–5.8 TeV
Homogeneity volume	5000 fm^3	6200 fm^3	7400 fm^3	4500 fm^3	11000 fm^3
Decoupling time	10 fm/c	11 fm/c	11.5 fm/c	10 fm/c	13 fm/c
ε at $\tau = 1$ fm/c	12–13 GeV/fm^3	16–17 GeV/fm^3	22–24 GeV/fm^3	≈ 15 GeV/fm^3	35–40 GeV/fm^3

- Xe-Xe at HE-LHC: similar "medium" as Pb-Pb 2.76 TeV, with ~5 times larger L_{NN} wrt Pb-Pb at 5.5 TeV → optimal scenario for HE-LHC ?

Higher temperature: thermal charm?

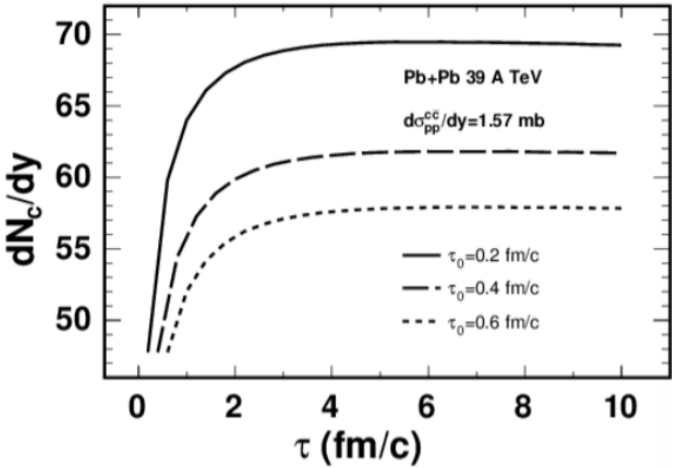
- T evolution from hydrodynamic simulation



900 MeV at τ = 0.2 fm/c

650 MeV at τ = 0.5 fm/c

- Large secondary production of charm pairs in the medium $gg \to c\bar{c},\ q\bar{q} \to c\bar{c}$

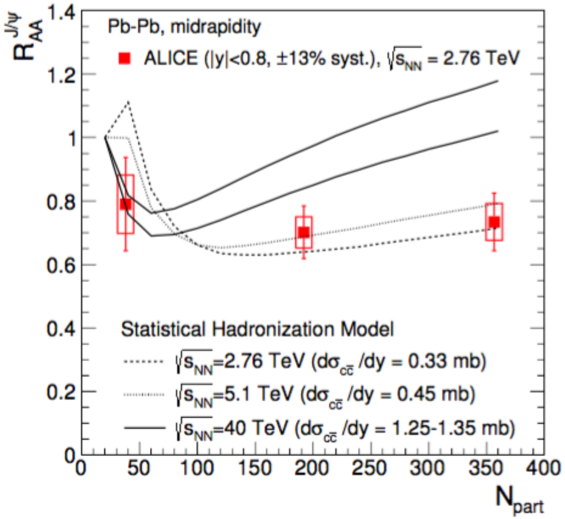


- Up to 50-100% “enhancement” wrt primary charm
- Sensitive to QGP properties: T vs τ, and τ_0

C.M. Ko, Y. Liu, JPG43 (2016) no. 12, 125108
K. Zhou et al., PLB758 (2016) 434

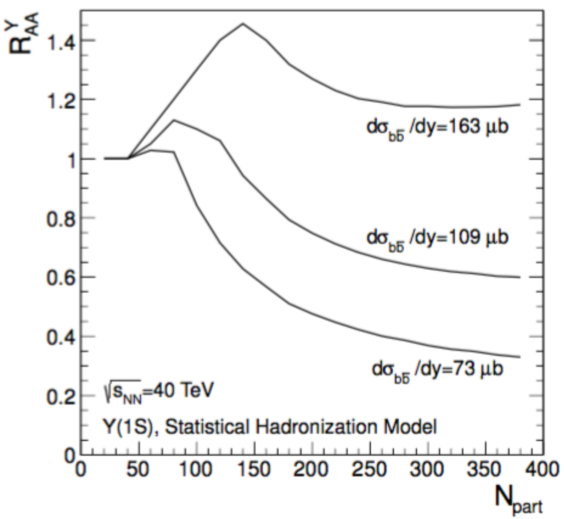
Quarkonia: large ψ enhancement? full Υ melting?

- Large charm yield from hard scattering + thermal production would lead to J/ψ enhancement (R_{AA}>>1)
  - J/ψ yield could be sensitive to secondary/thermal charm production

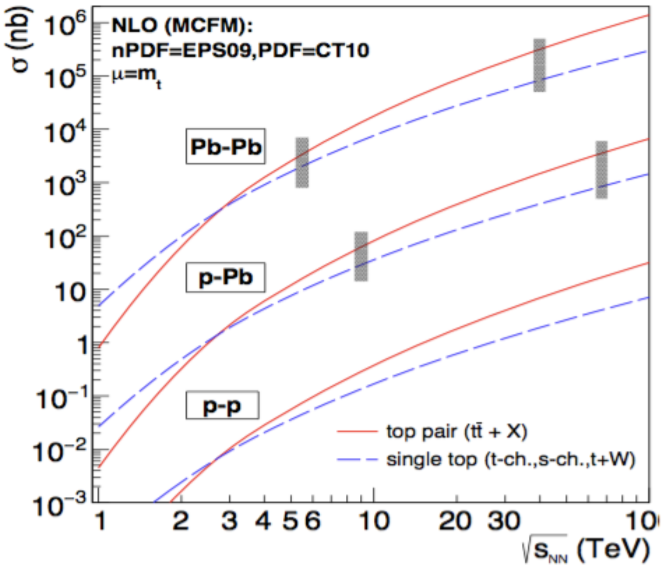


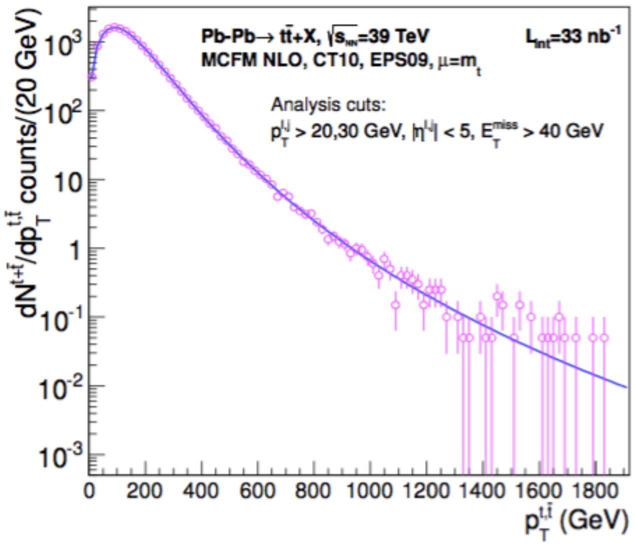
A.Andronic, et al., based on JPG38 (2011) 124081

- Υ(1S) would melt when T > 350 MeV, may be reached only at FCC G. Aarts et al, JHEP 07 (2014) 097
- However, large $b\bar{b}$ yields (~20 pairs in central Pb-Pb) could lead to regeneration in the bottomonium sector (Υ R_{AA} > 1)



New hard probes at FCC energy: top events

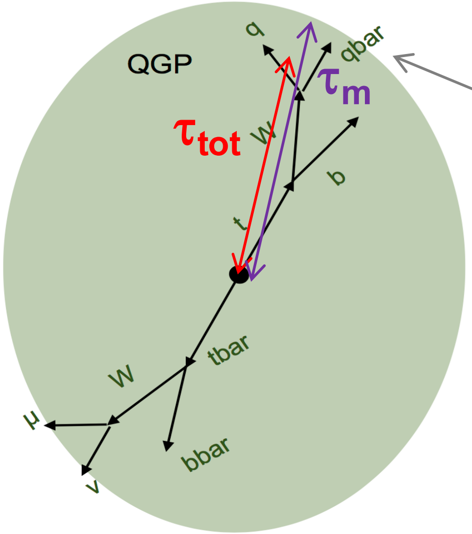




- Increase of √s and L_{int} /month by ~ x30 at FCC will enable new ways to probe the QGP
- Top cross section increases by x80 from 5.5 TeV to 39 TeV
  - Kinematic simulation study: 3x10^5 $t\bar{t} \rightarrow b\bar{b}\,\ell\ell\,\nu\nu$ per run in the baseline scenario (35/nb)
  - Top p_T distribution up to ~ 2 TeV/c

D. d'Enterria, et al. PLB746 (2015) 64

Boosted color singlets from top events



$$t\bar{t} \rightarrow b\bar{b} + q\bar{q} + \ell + \nu$$

This $q\bar{q}$ is produced as a color singlet and it "sees" the QGP with a **time delay τ_{tot} of up to several fm/*c*** given by the boost of the top and of the W

The rest of the final state

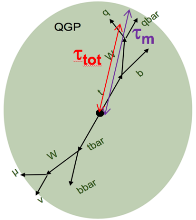
$$2\ b - jets + \ell + \not{E}_T$$

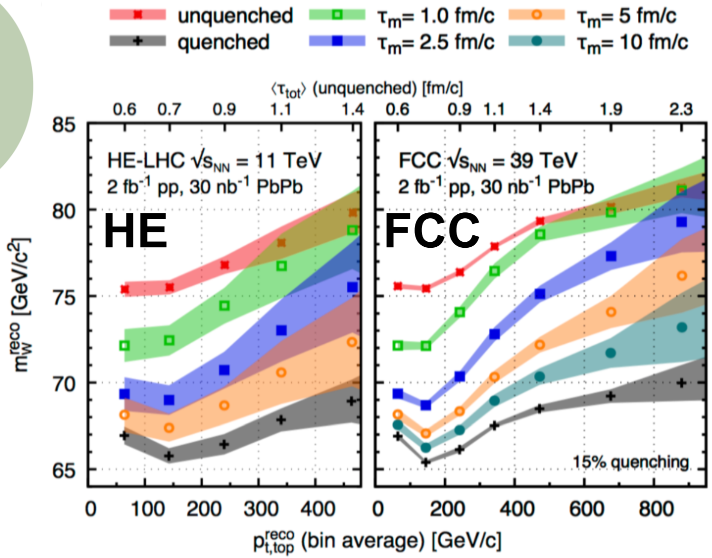
is used to tag the event topology

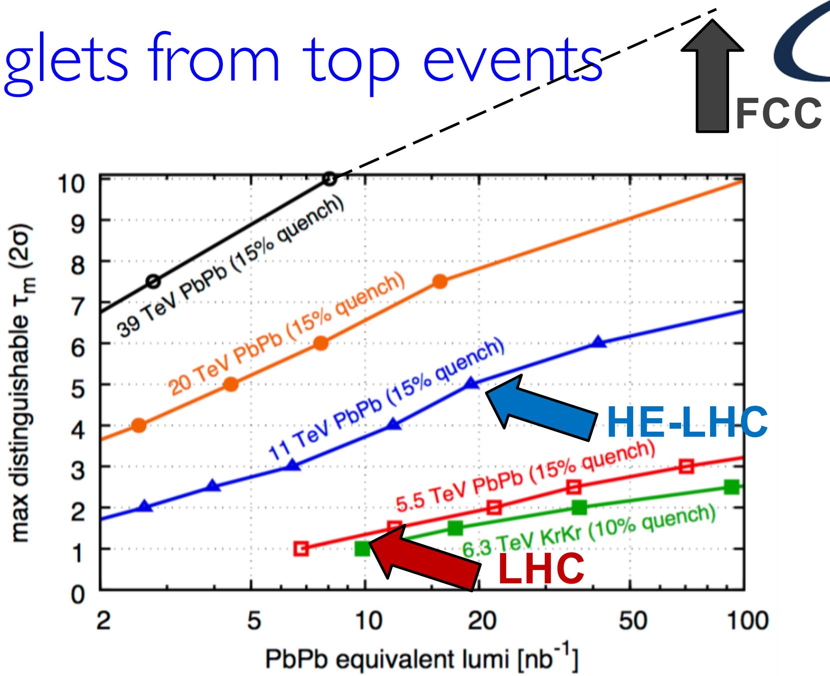
- Boosted-top events can therefore be used to address two novel studies in the sector of parton energy loss:
  1. Time-evolution of QGP opacity → **at which time τ_m does the quenching "stop"?**
  2. Role of color coherence in parton energy loss

Apolinario, Milhano, Salam, Salgado, PRL120 (2018) 23, 232301

Boosted color singlets from top events







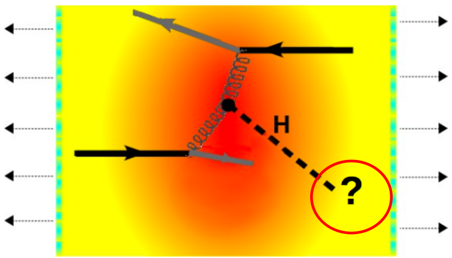
- Energy loss of the $q\bar{q}$ pair → shift of reconstructed W mass
- Shift vs. top p_T probes the time-evolution of the QGP density
- A first glimpse at LHC? (possibly with lighter ions)
- Scan entire QGP lifetime at FCC, and up to 6-7 fm/c at HE-LHC

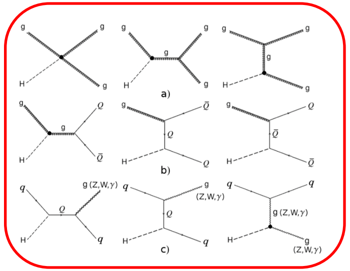
Apolinario, Milhano, Salam, Salgado, PRL120 (2018) 23, 232301

Probing the QGP with Higgs bosons at FCC ?

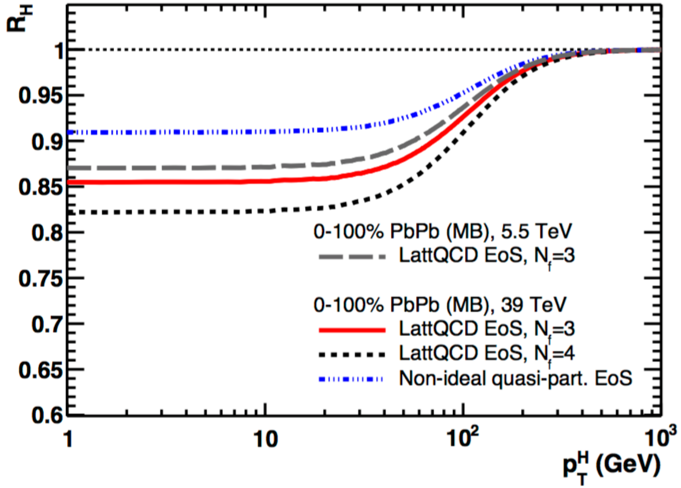
- Higgs lifetime τ ~50 fm/c > QGP lifetime ~10 fm/c
- Strong interaction with QGP induces decay to gg depleting its decay channels to $\gamma\gamma$ and ZZ*
- Detailed calculation of "absorption" cross section in 2D+1 hydro medium with different EoSs

→ suppression by 15% at p_T<50 GeV/c





→ **see talk by C. Loizides**



D. d'Enterria, C. Loizides, arXiv:1809.06832

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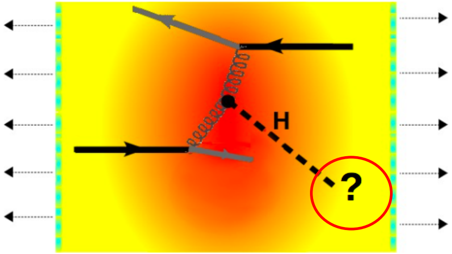
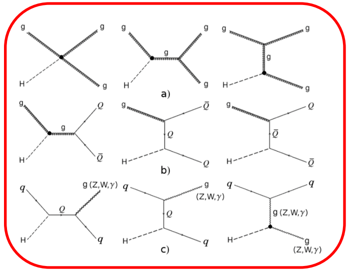
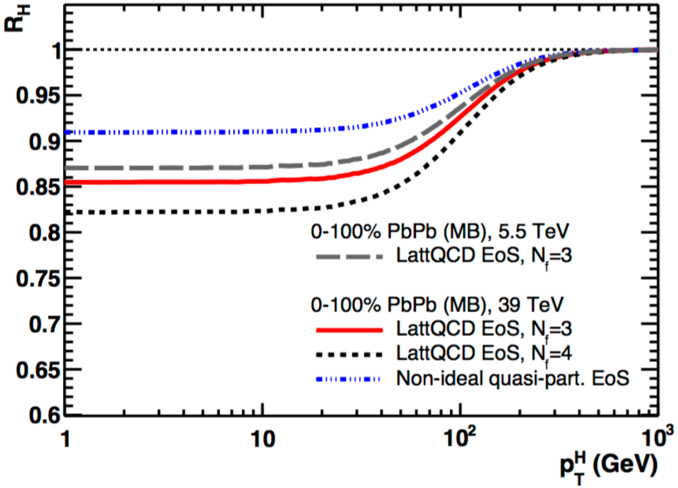


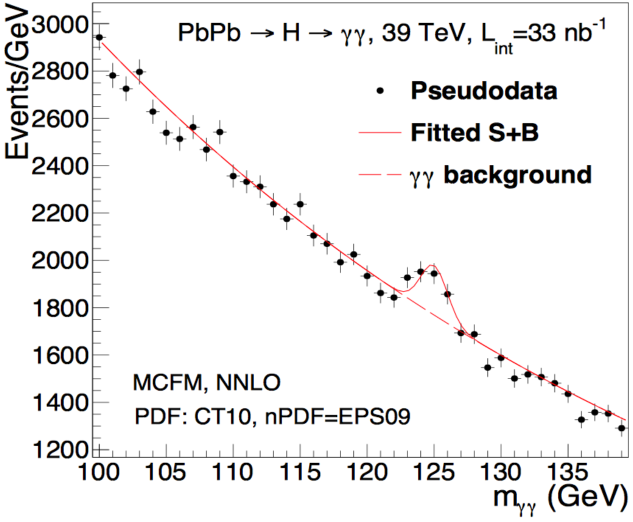




D. d'Enterria, C. Loizides, arXiv:1809.06832

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

  → **Promising!**



D. d'Enterria, arXiv:1701.08047

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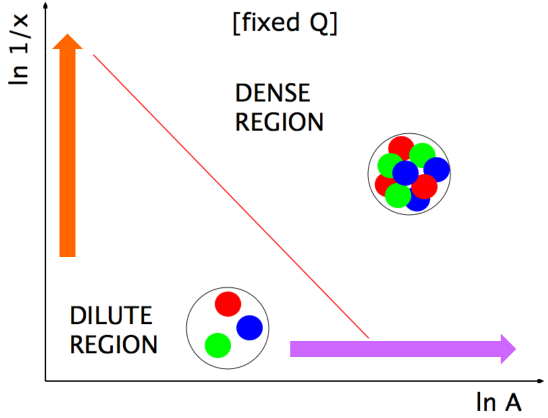
High-density QCD in the initial state: Saturation at low x

- 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)



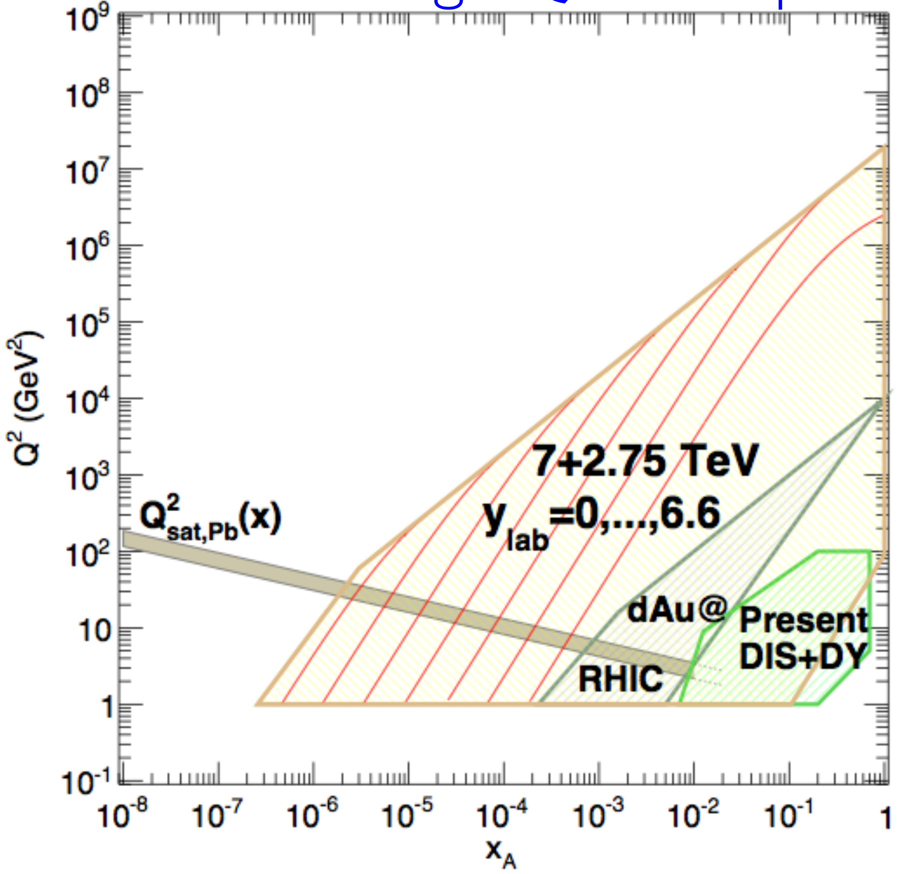
Saturation affects process with $Q^2 <$ *few* × Q_S^2

Explore saturation region:

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

→**increase A**

Kinematic coverage Q^2 vs. x: pA LHC



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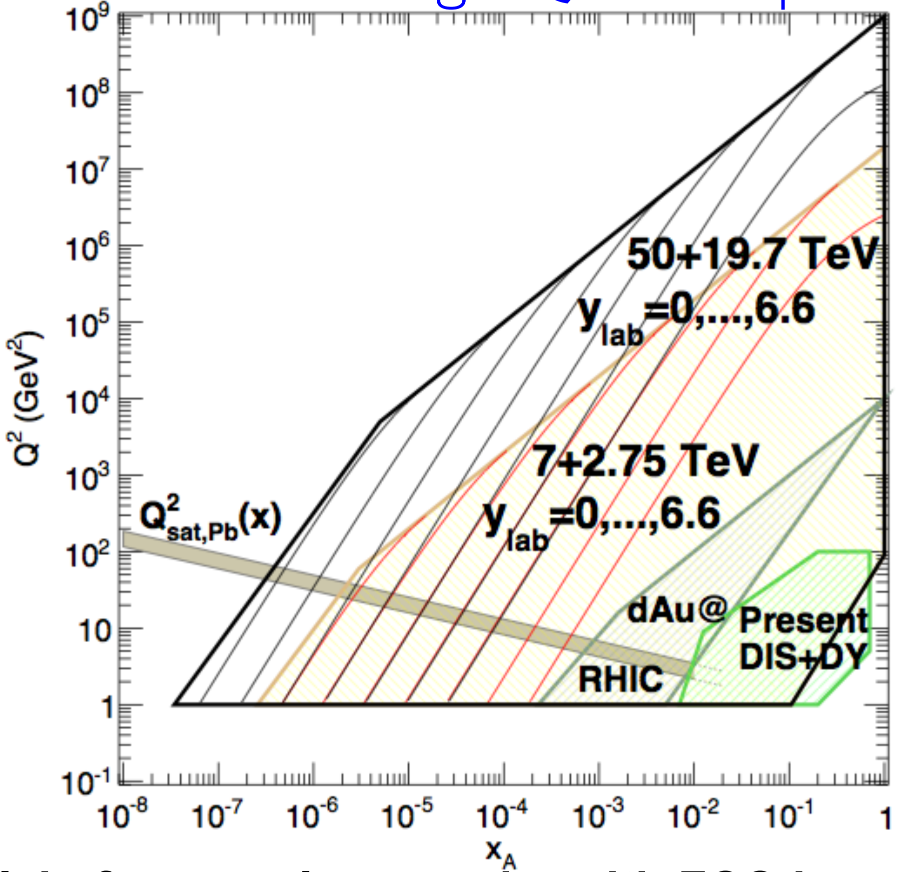
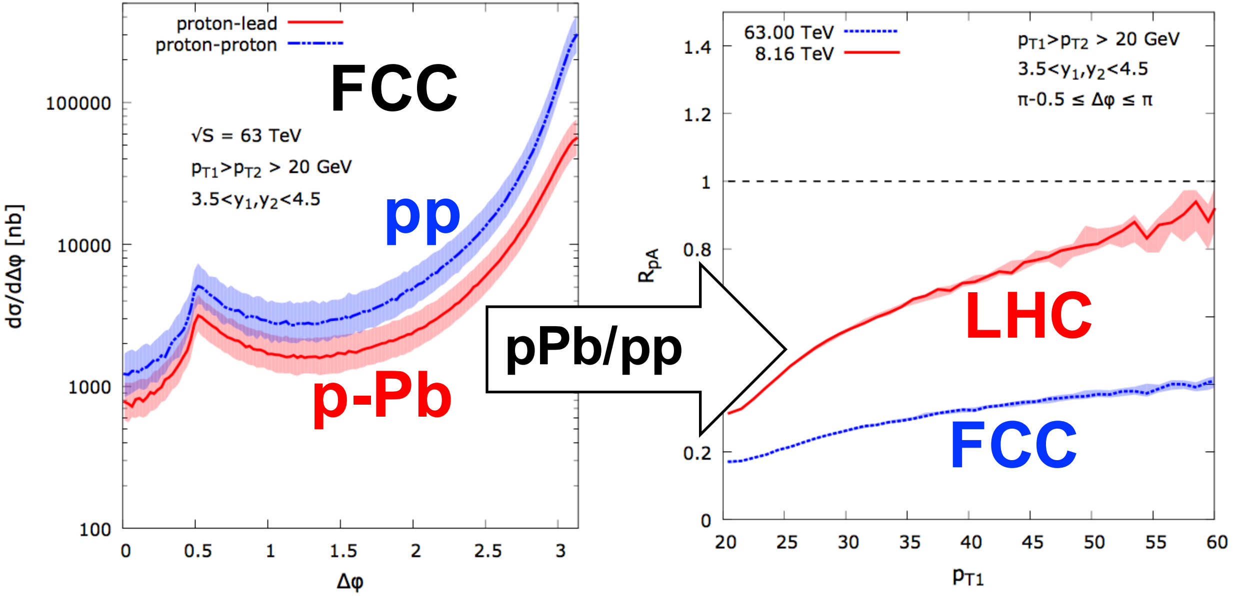
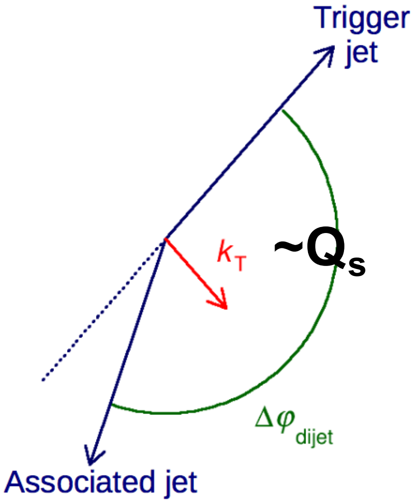


→ **See talk by M. Klein for complementarity with FCC-he**

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

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

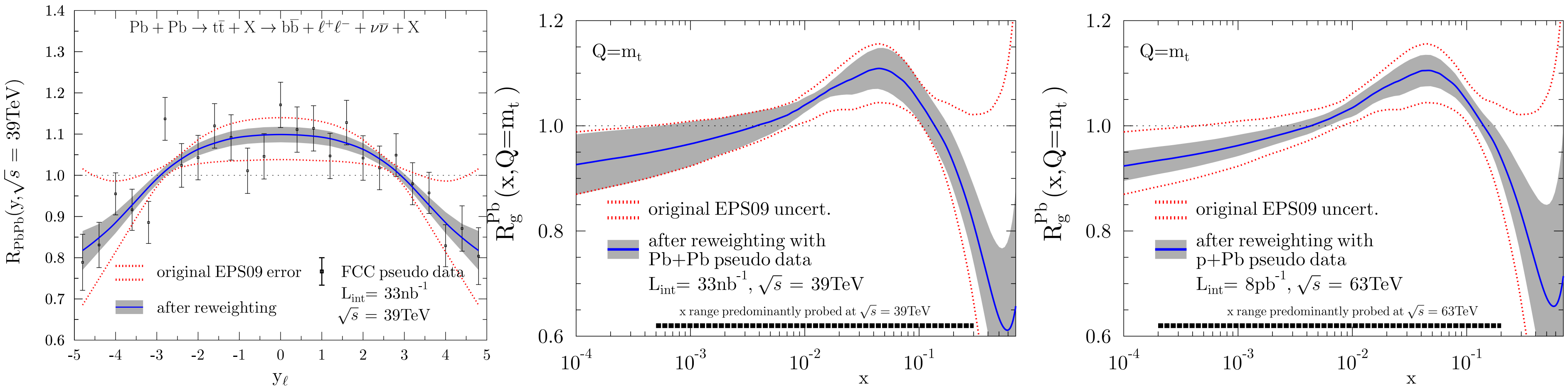




C. Marquet et al., *based on* JHEP 1612 (2016) 034

Constraining nuclear PDFs with top

- Within collinear factorisation, nuclear effects (including high-density effects at small-x) described using nuclear modifications to the proton PDFs:



- Top production measurements at FCC in p-Pb and in Pb-Pb can reduce by a factor ~2 the present uncertainty on the nPDFs at Q = m_{top}, in particular at x > 0.1 (EMC region)

D. d'Enterria et al., PLB746 (2015) 64

Summary

- Pb-Pb at FCC: **39 TeV**; **L_{int} projections >100x LHC programme**

- Unique studies of the Quark-Gluon Plasma
  - Larger temperature → **thermal production of charm, Υ(1S) melting**
  - Larger $\sqrt{s}$ and L_{int} → **new hard observables, e.g. top, Higgs, to characterize the QGP**

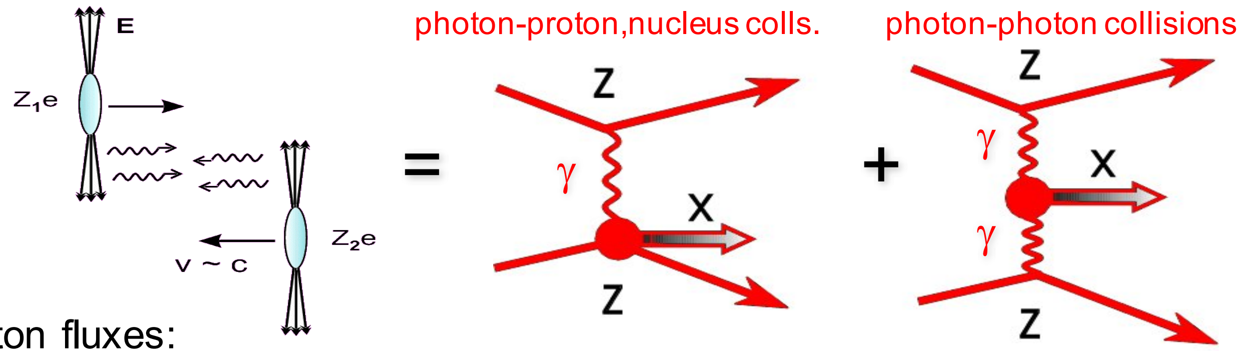
- Unique studies of high-density initial state
  - Access to **saturation region (down to $x<10^{-6}$)** with perturbative probes, e.g. forward-*y* di-jets
  - Access to **[small-x, large-Q^2] region with top**, W, Z

- Unique contributions to other sectors of HEP (see Extra Slides)
  - $\gamma\gamma$ collisions (search for axion-like particles, see new limits presented by CMS)
  - Fixed-target collisions with extracted beams or internal gas targets
  - Input to collision models for ultra-high-energy cosmic rays

EXTRA SLIDES

Photon-induced collisions

- Nuclei generate strong EM fields from coherent emission of Z=82 p's
- Photon-induced collisions can occur when two nuclei cross without interacting hadronically



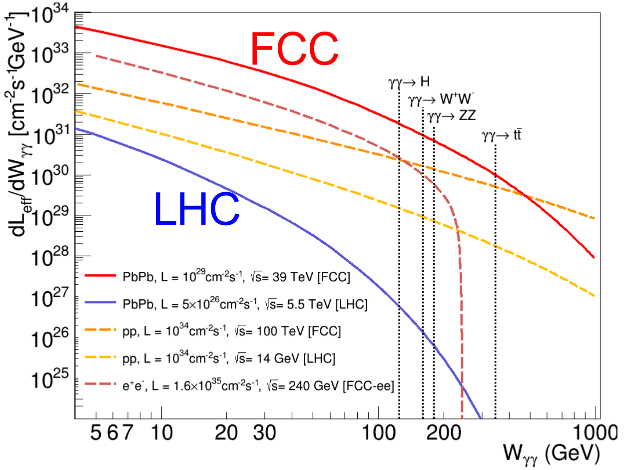
- Huge photon fluxes:
  - $\sigma(\gamma\text{-Pb}) \sim Z^2$ ($\sim 10^4$ for Pb) larger than in pp
  - $\sigma(\gamma\text{-}\gamma) \sim Z^4$ ($\sim 5\cdot 10^7$ for Pb-Pb) larger than in pp

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

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

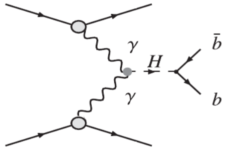
$\gamma\gamma$ physics at FCC (Pb-Pb)

- Effective lumi $dL_{eff}/dW_{\gamma\gamma}$ for $\gamma\gamma$ processes from LHC to FCC: x10^2 at low masses, x10^4 for Higgs, x10^5 for ZZ production
  - Unique tests for EW sectors of the SM

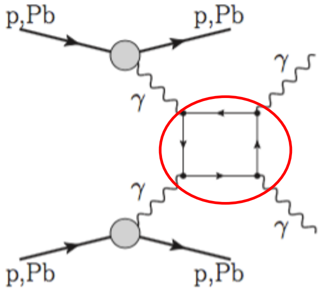


$$N_X = \int \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} W_{\gamma\gamma} \sigma_X^{\gamma\gamma}(W_{\gamma\gamma})$$

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



- $\gamma\gamma \rightarrow \gamma\gamma$ process has potential sensitivity to New Physics



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

Fixed-target collisions with FCC beams

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

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

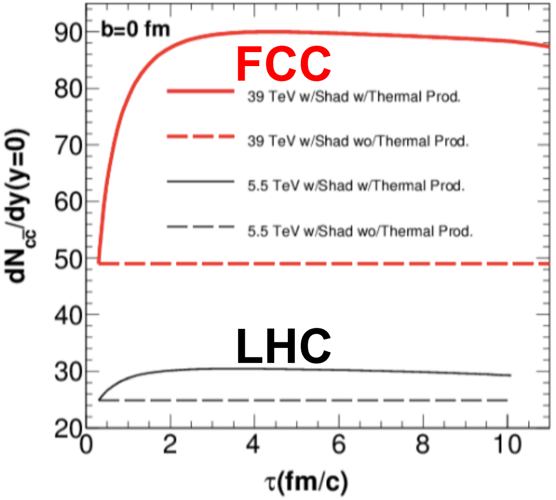
- Luminosity and physics opportunities for LHC case are discussed in detail in the context of the AFTER@LHC proposal
- Heavy ion studies:
  - c.m.s. energy similar to RHIC energies
  - much larger luminosity and access to (very) backward rapidity region would enable unique and high-precision studies, e.g. related to quarkonium production and its cold and hot nuclear matter effects

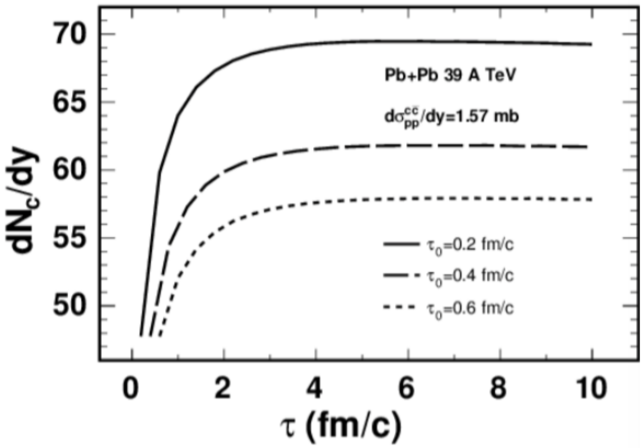
AFTER: see e.g. S. J. Brodsky, et al., Phys. Rept. 522 (2013) 239–255, arXiv:1202.6585

Thermal charm production?

- Expect abundant secondary production of $c\bar{c}$ pairs in the medium

$$gg \rightarrow c\bar{c},\ q\bar{q} \rightarrow c\bar{c} \quad + \text{higher orders}$$





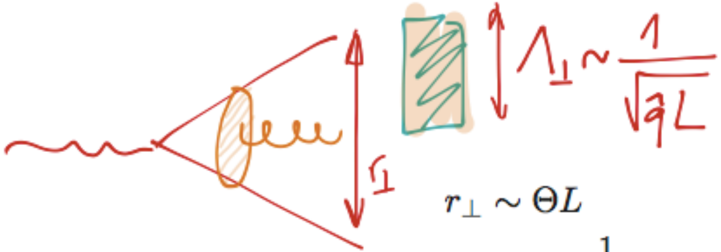
- Up to 50-100% "enhancement" wrt primary charm
- Sensitive to QGP properties: T vs τ, and τ_0

K. Zhou et al., PLB758 (2016) 434

C.M. Ko, Y. Liu, JPG43 (2016) no. 12, 125108

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

2) Testing the role of color coherence



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

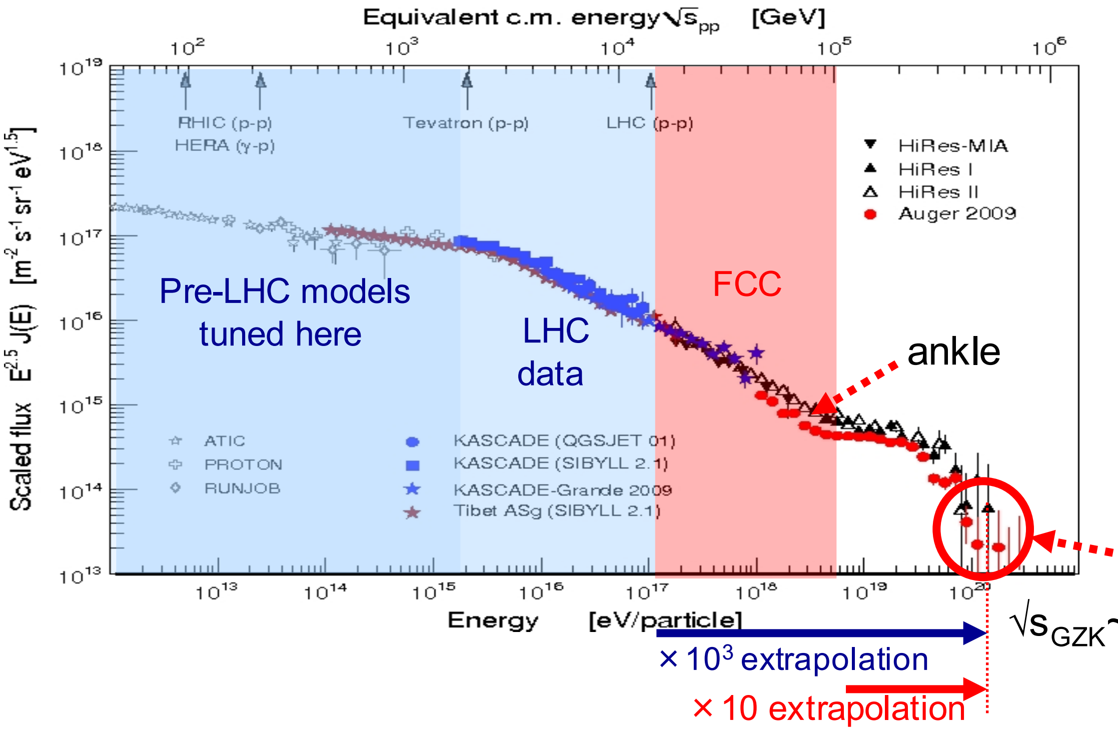
$$\Lambda_{\rm med} \sim \frac{1}{\sqrt{\hat{q} L}}$$

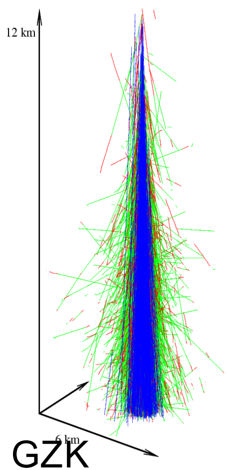
q-qbar with small opening angle; seen as color-singlet by the medium, **no interaction expected**

Medium induces decoherence, opening angle increases → **energy loss of color-octet's in the medium**

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

Cosmic-rays MC tuning with FCC (Pb-Pb)





FCC pA and AA probe ankle-energy and provides strong constraints for hadronic Monte Carlos for UHECR (p,Fe+Air)