2nd International Conference on the Initial Stages
in High-Energy Nuclear Collisions
Napa Valley, December 6th 2014

Future at the LHC: LHeC, FCC

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Current LHC schedule:

'New' (as of 2014) LHC schedule beyond LS1

Only EYETS (19 weeks) (no Linac4 connection during Run2)
LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)
LS3 LHC: starting in 2023 => 30 months + 3 BC
injectors: in 2024 => 13 months + 3 BC

Here we are

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators
Monday 2nd December 2013

Contents:

1. FCC-hh(AA):
   - Accelerator.
   - Physics.

   (no AA-specific detector foreseen).

2. LHeC/FCC-he *(for the LHeC Study Group)*:
   - Accelerator.
   - Detector.
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3. Summary and outlook.

FCC-hh: Kickoff workshop, Geneva, Feb 2014: https://indico.cern.ch/event/282344/; espace2013.cern.ch/fcc/; A. Dainese in QM2014, https://indico.cern.ch/event/219436/session/20/contribution/480/material/slides/0.pdf; workshop 9/14, https://indico.cern.ch/event/331669/, 1407.7649.

LHeC/FCC-he: CDR, arXiv:1206.2913, J. Phys. G 39 (2012) 075001; arXiv:1211.4831; arXiv:1211.5102; cern.ch/lhec; LHeC 2014 workshop http://indico.cern.ch/event/278903/; CERN Courier https://cds.cern.ch/record/1704948/files/CERN%20Courier%20June%202014.pdf.

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This is NOT a review of the full menu of future opportunities at CERN!!! I will focus on those aspects of interest for this conference.

The Future Circular Collider:

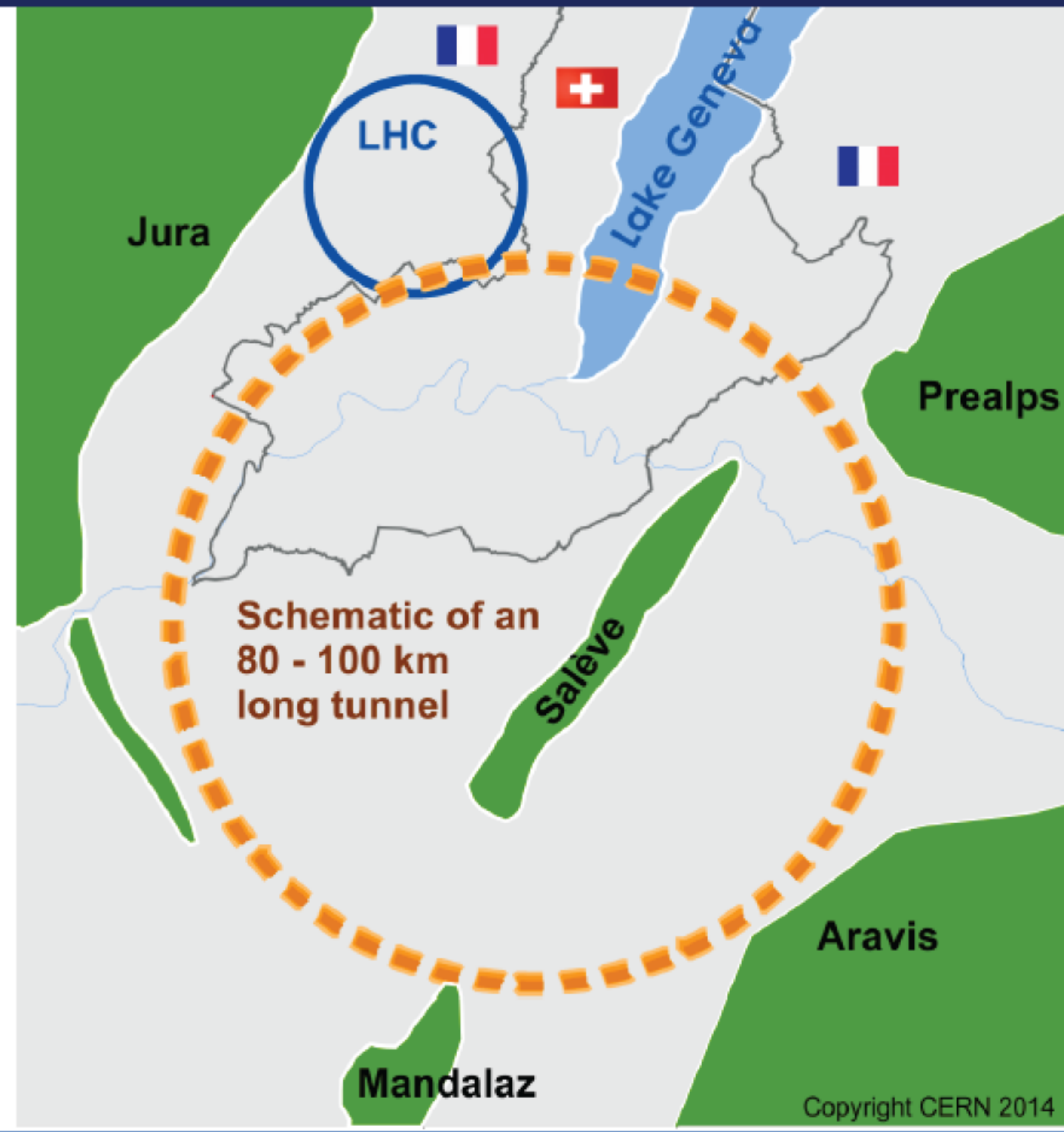
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

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
  120-350 GeV
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



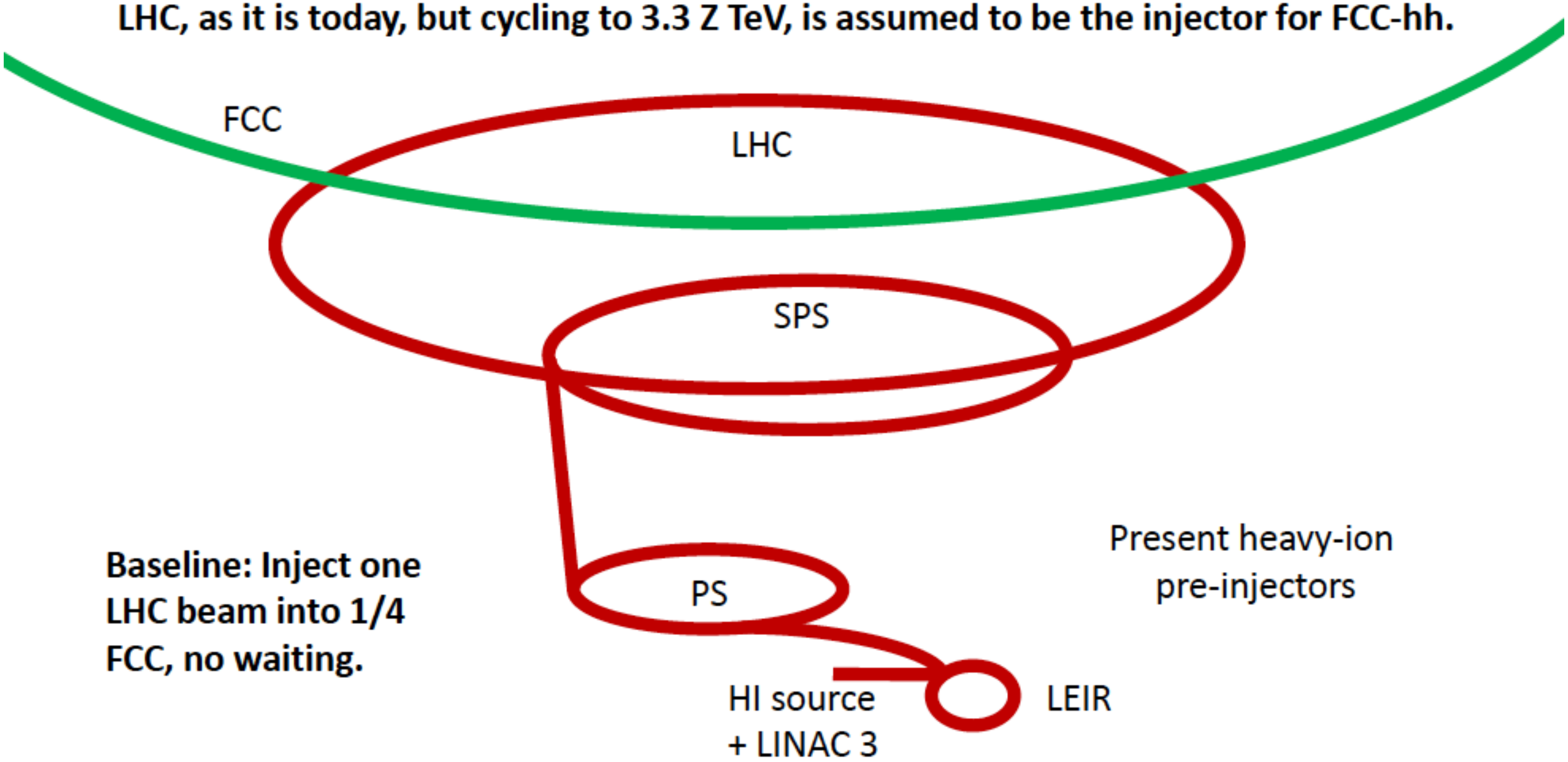
The accelerator:

Heavy Ion Pre-Accelerator Chain

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.



The accelerator:

Conservative filling scheme!!!

	Unit	LHC Design	FCC Collision	FCC Collision
Luminosity				
Operation mode	-	Pb-Pb	Pb-Pb	p-Pb
β-function at the IP	[m]	0.5	1.1	
Initial RMS beam size at IP	[μm]	15.9	8.8	
Initial luminosity	[Hz/mb]	1	2.6	213
Peak luminosity	[Hz/mb]	1	7.3	1192
Integrated luminosity per fill	[μb^{-1}]	<15	57.8	21068
Integrated luminosity per run	[nb^{-1}]	-	8.3	1784
Initial bb tune shift per IP	[10^{-4}]	1.8	3.7	3.7
Total cross-section	[b]	515	597	2
Peak BFPP beam power	[W]	26	1705	0
Initial beam current lifetime	[h]	<11.2 (2 exp.)	10.9	39.3
Luminosity lifetime ($\mathcal{L}_0/e$)	[h]	<5.6 (2 exp.)	6.2	14.0

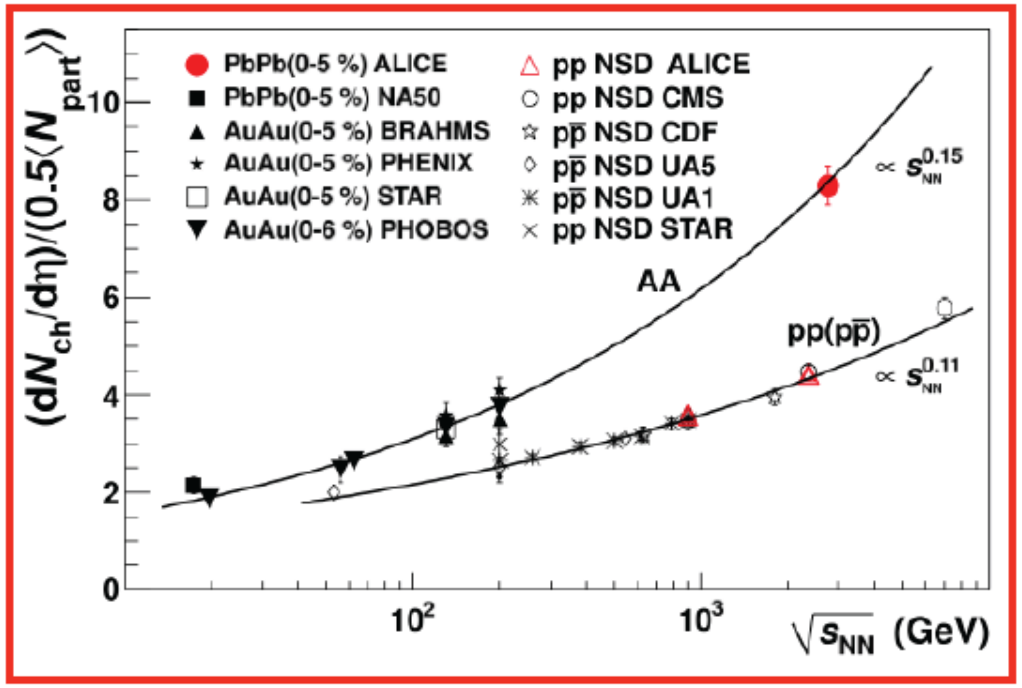
Schaumann

Note: the ALICE goal for Run 3/4 is 10 nb^{-1} in PbPb; the 2013 pPb run got ~30 nb^{-1}.

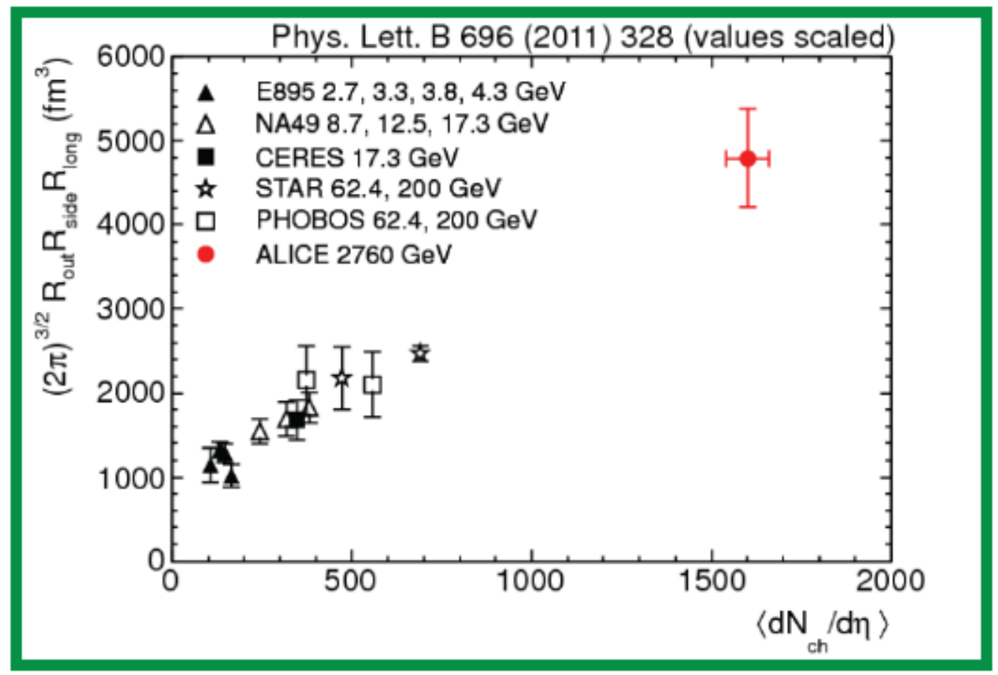
Physics: global properties

- Using data-driven extrapolations from lower energies to the LHC:

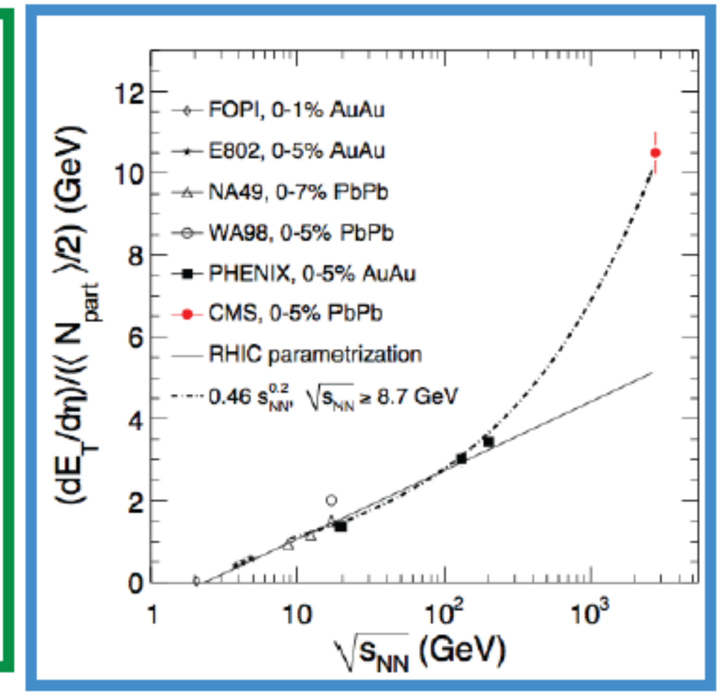
$dN_{ch}/d\eta$ x 1.8



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

A. Dainese at QM2014

pPb: 63 TeV/n

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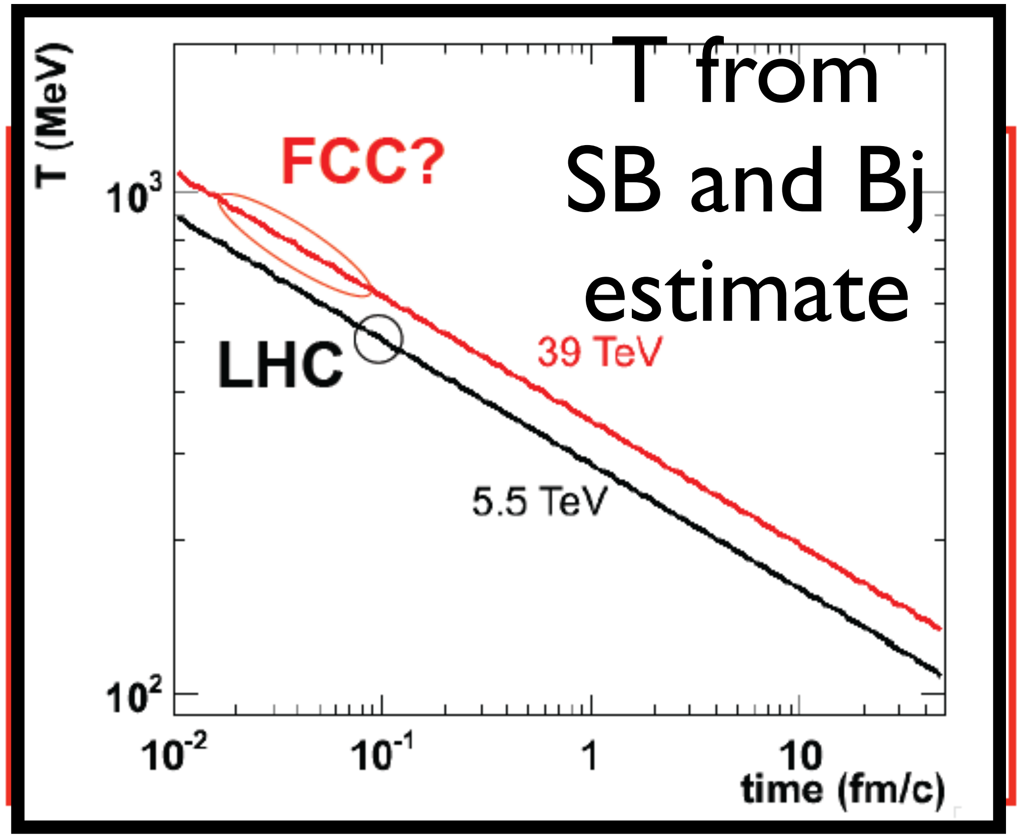

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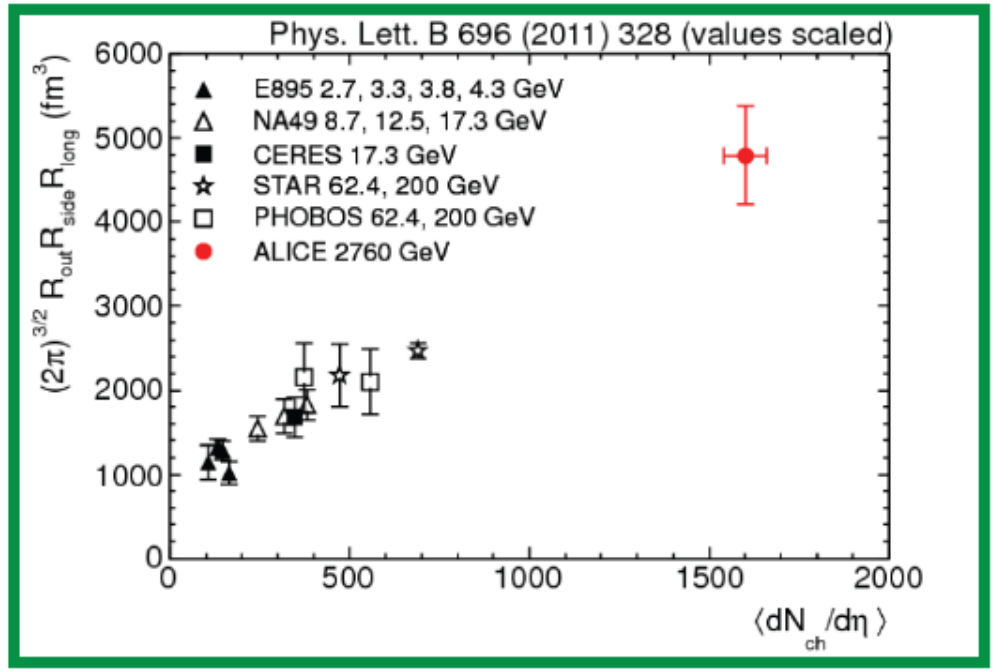

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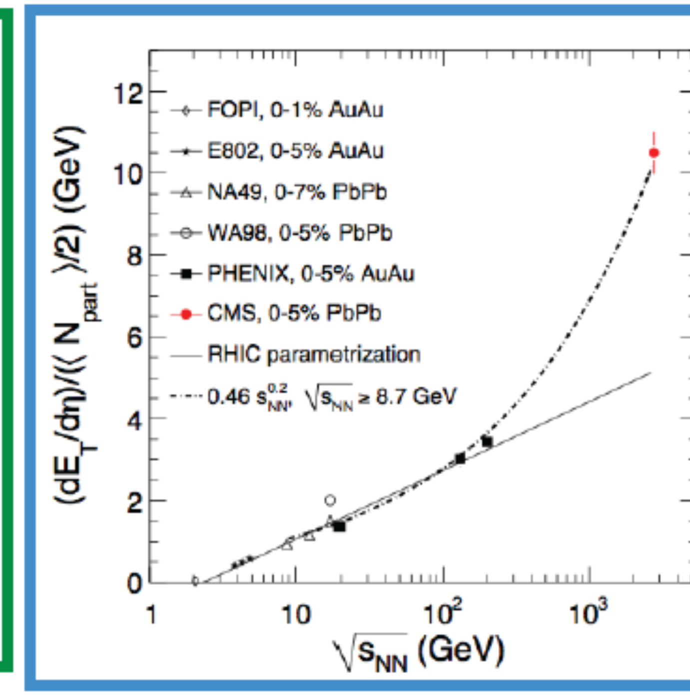

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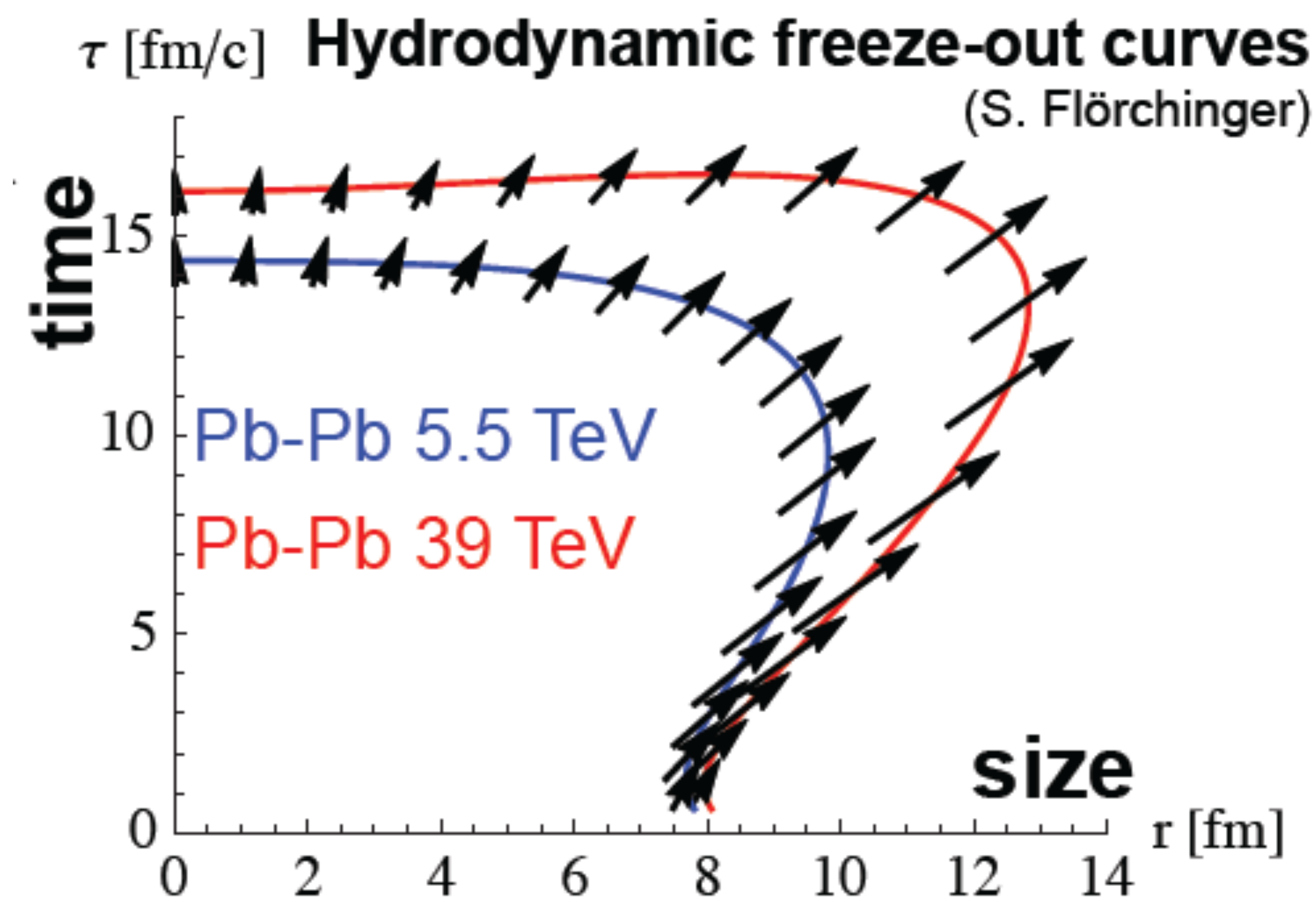


The medium:
- Is larger;
- Lives longer;
- Reaches higher T's;
- Equilibrates faster.

⇒ larger opportunities

to see collective effects.

BE homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
BE decoupling time	10 fm/c	11 fm/c	13 fm/c

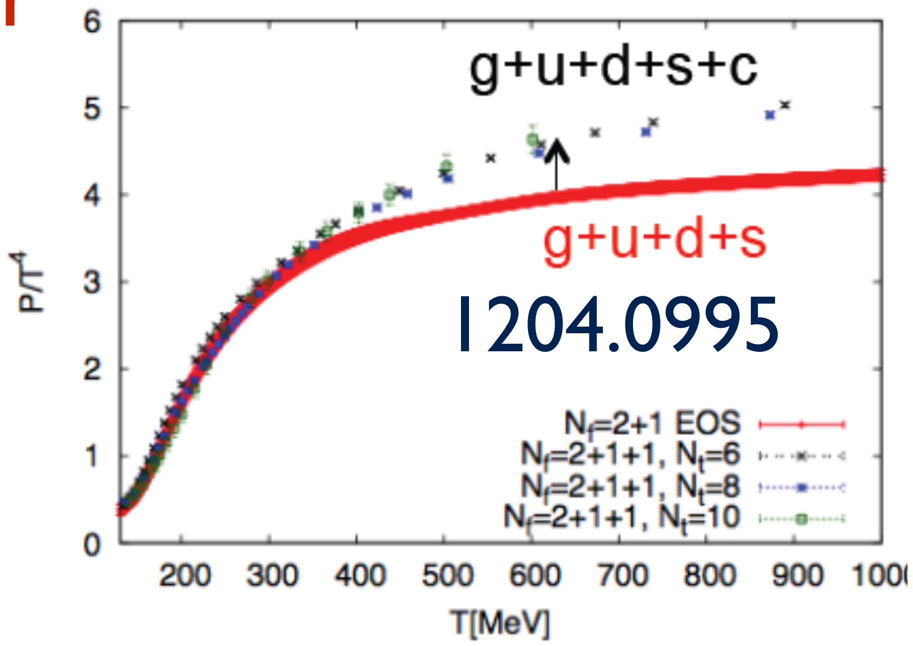
A. Dainese at QM2014

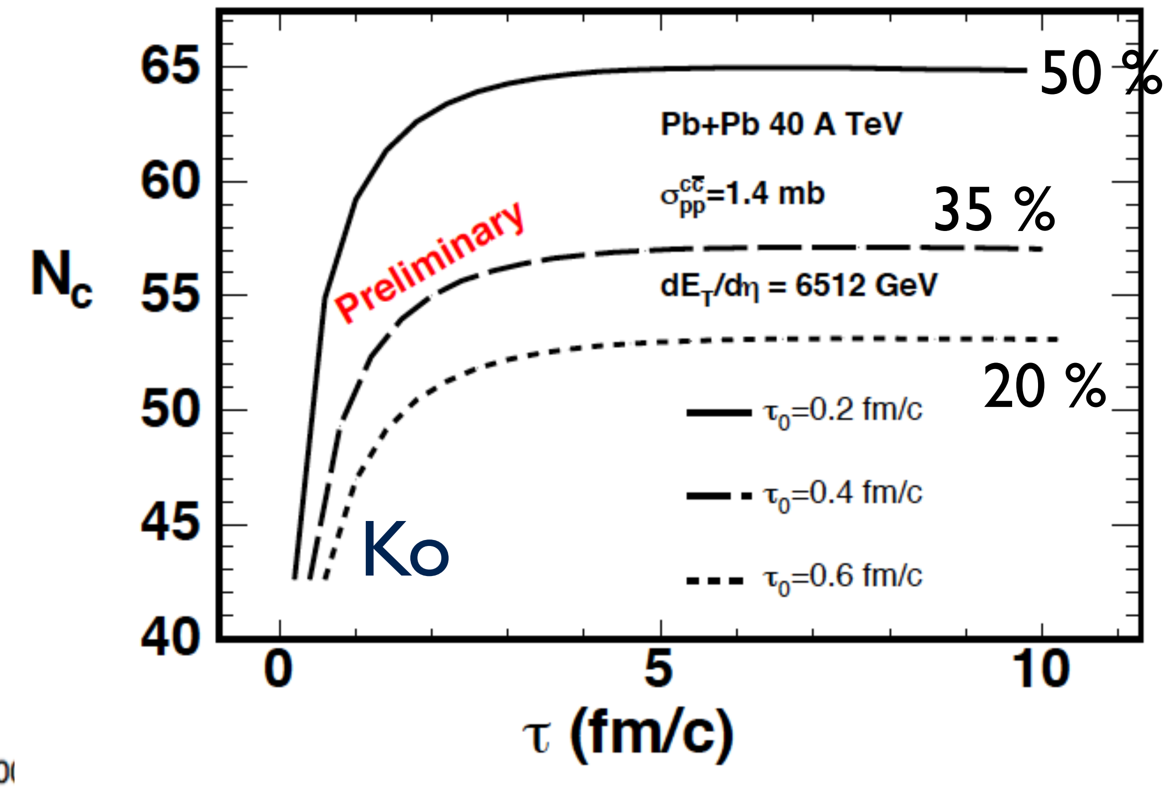
pPb: 63 TeV/n

Physics: global properties (II)

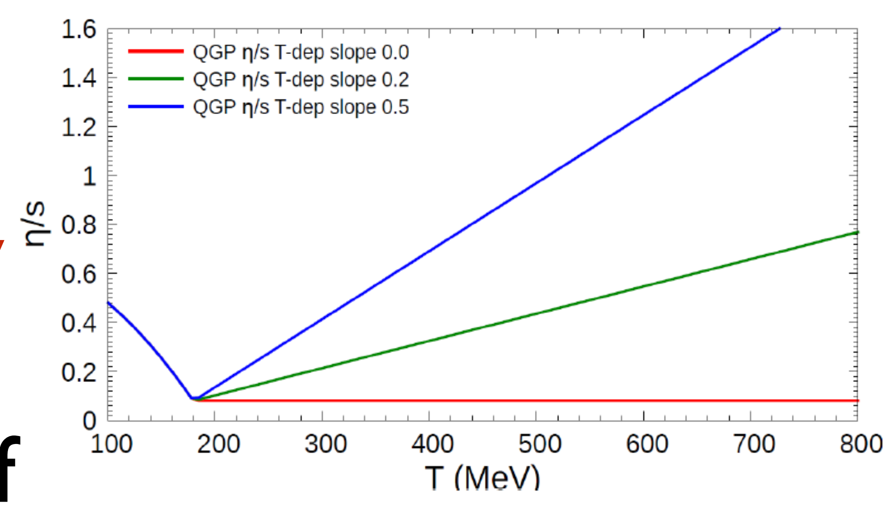
- Charm becomes an active flavour and can be abundantly produced secondary interactions:

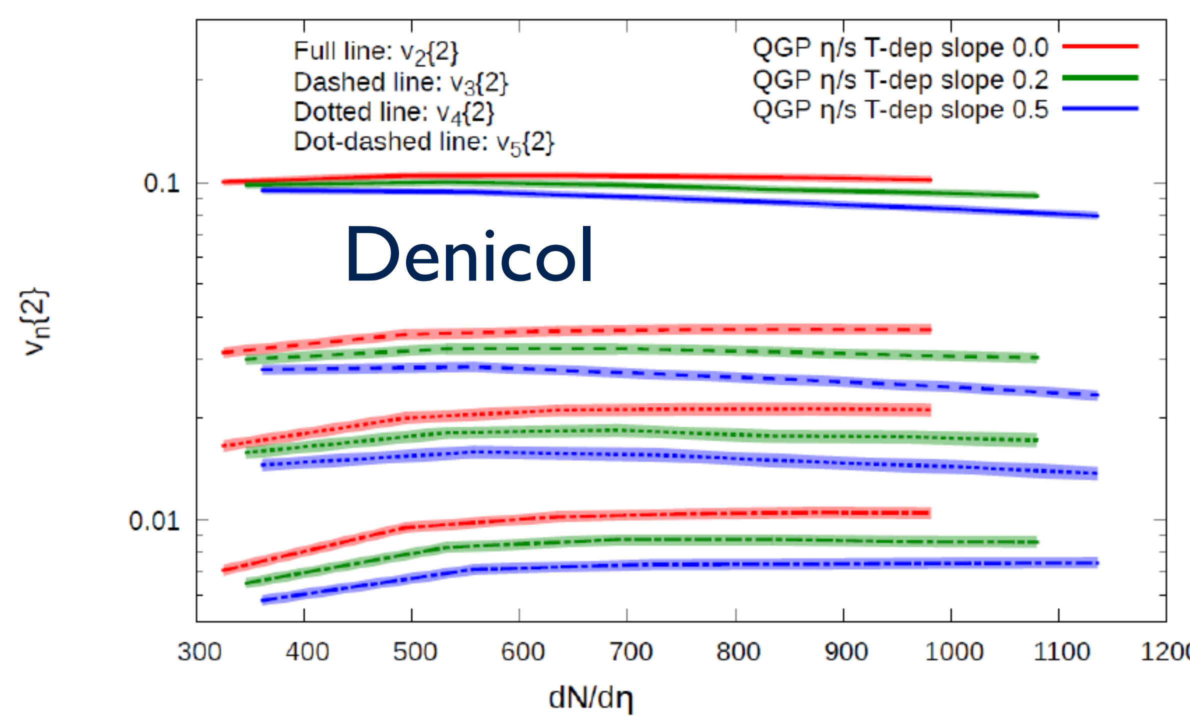
$$P/T^4 \sim \varepsilon/T^4 \propto n_{\mathrm{d.o.f}}$$





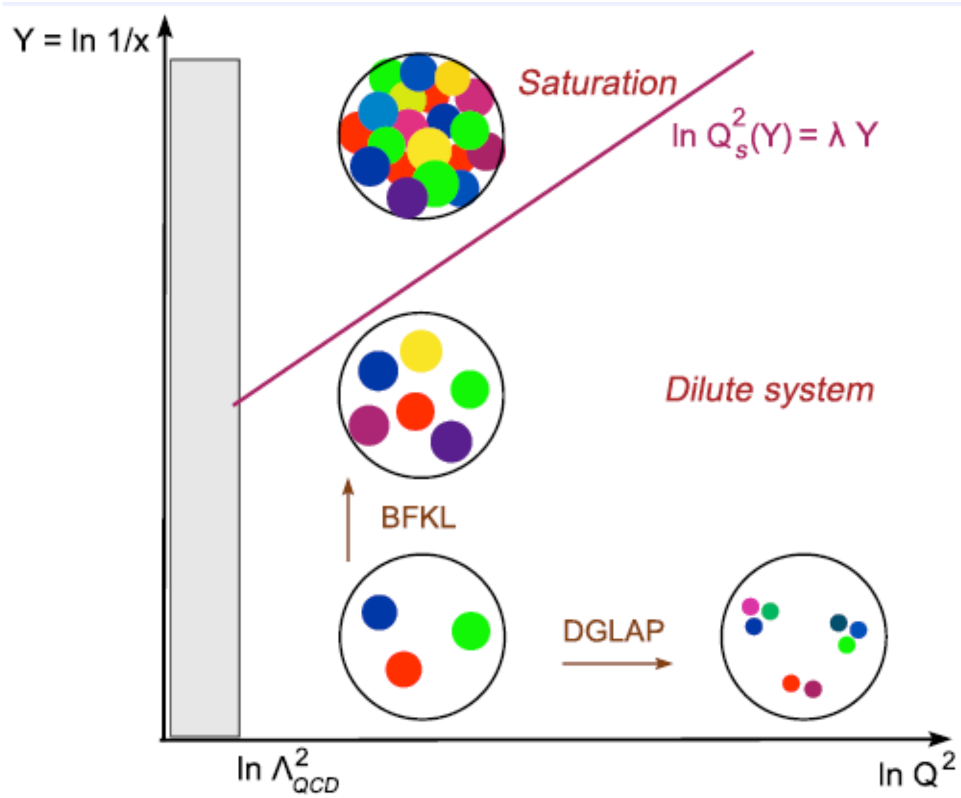
- Higher multiplicity may profit collective flow studies e.g. T dependence of η/s.



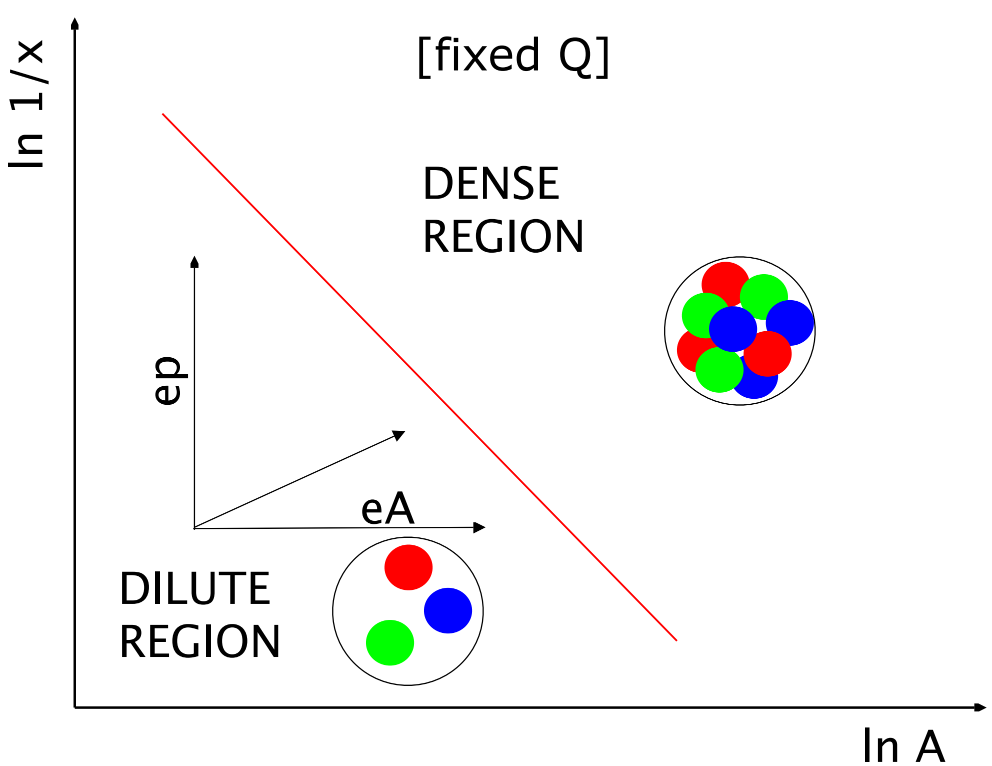


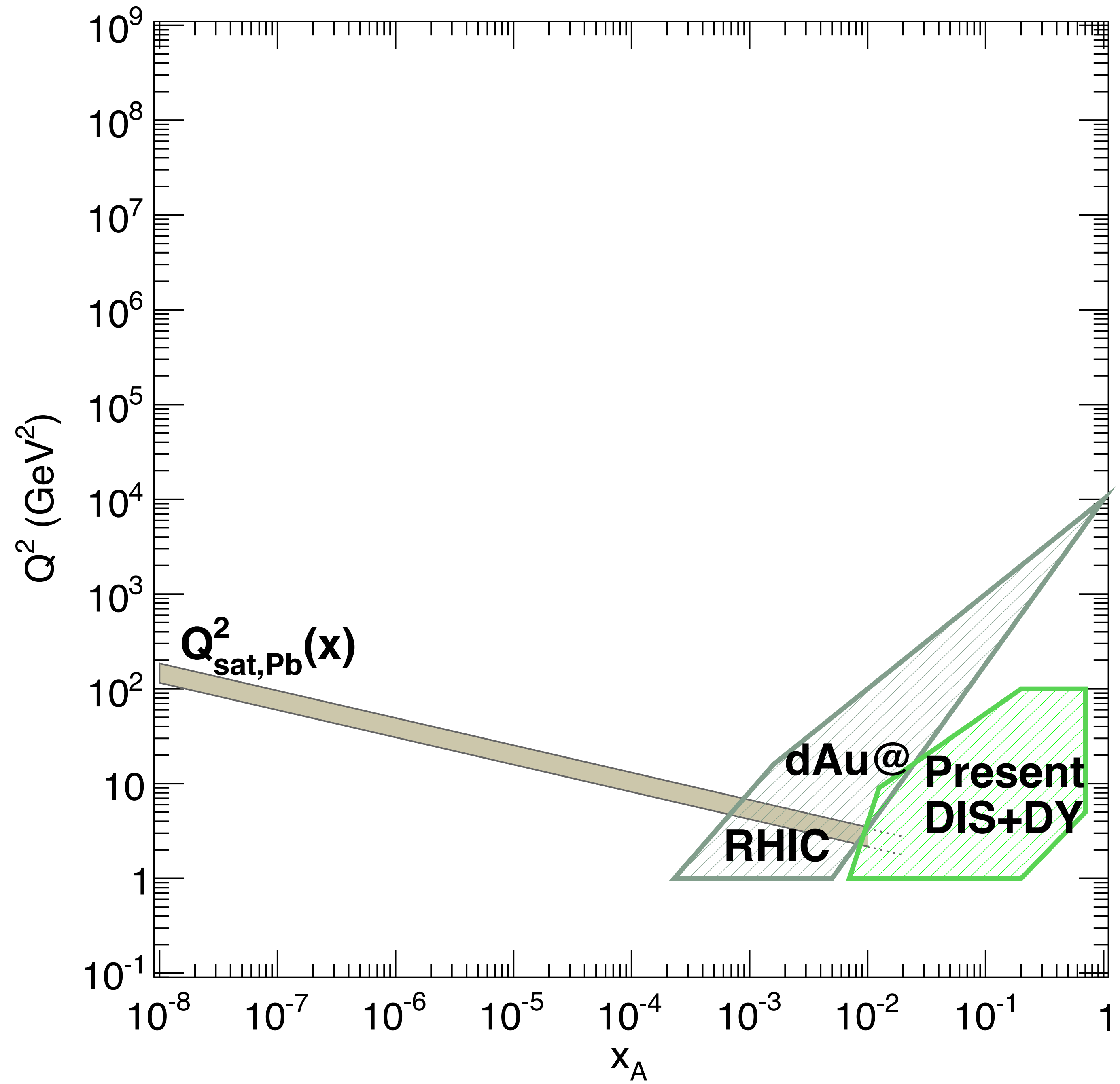
Physics: small x

- Test whether (perturbative) saturation lies in the accessible kinematic region, and understand how it works.



$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$





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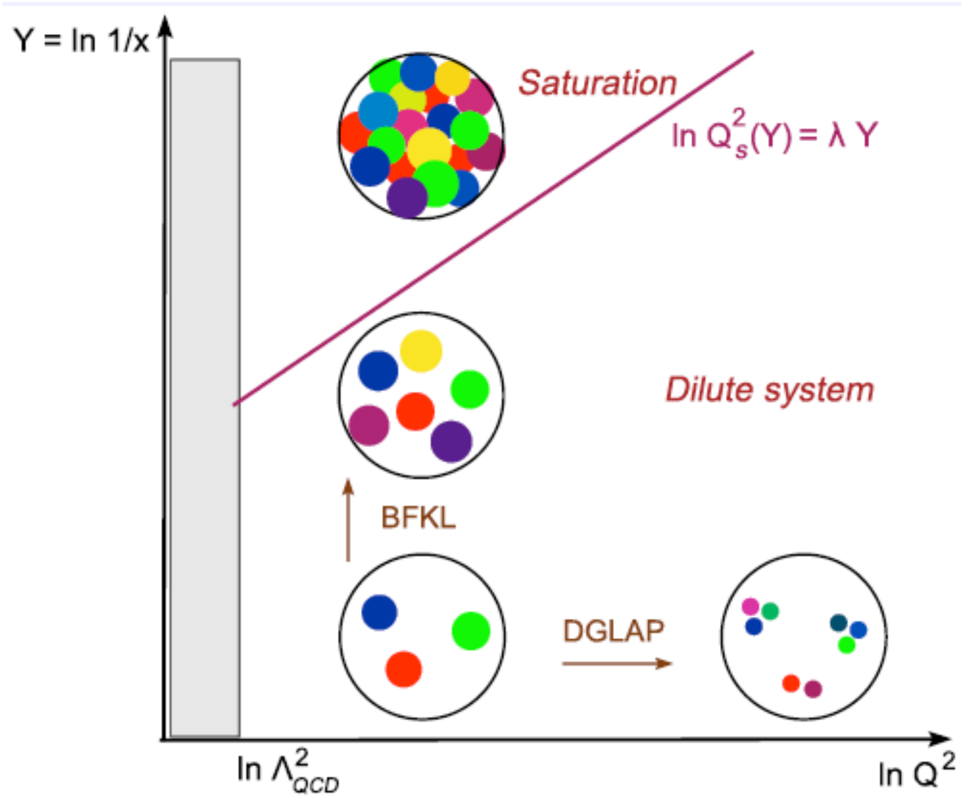

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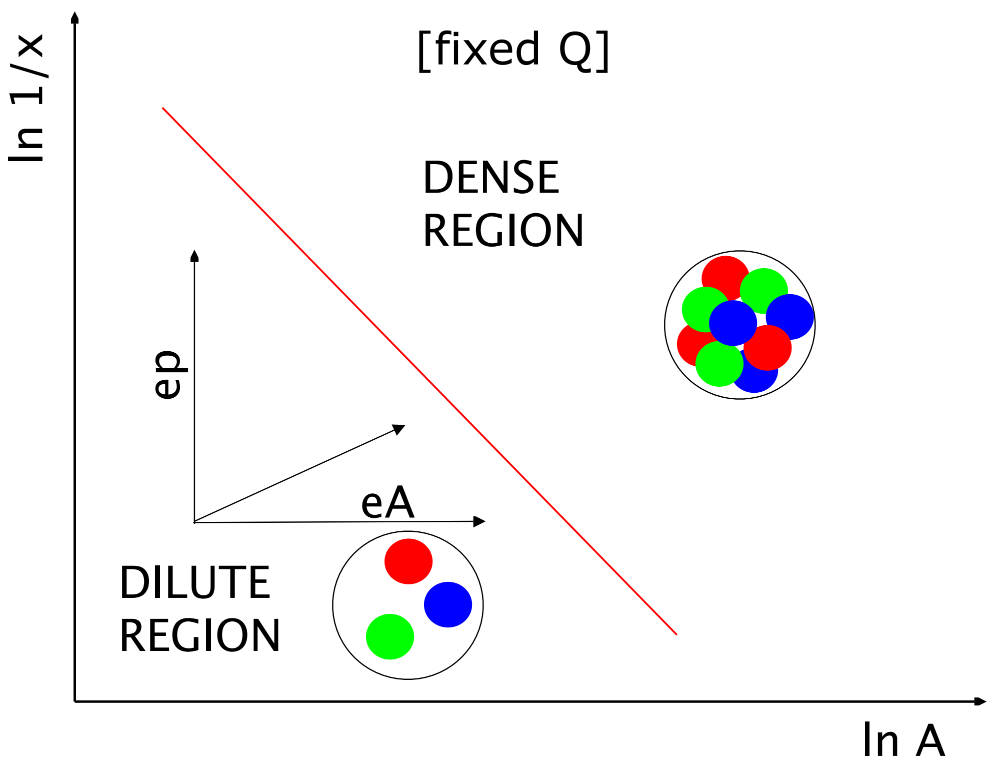

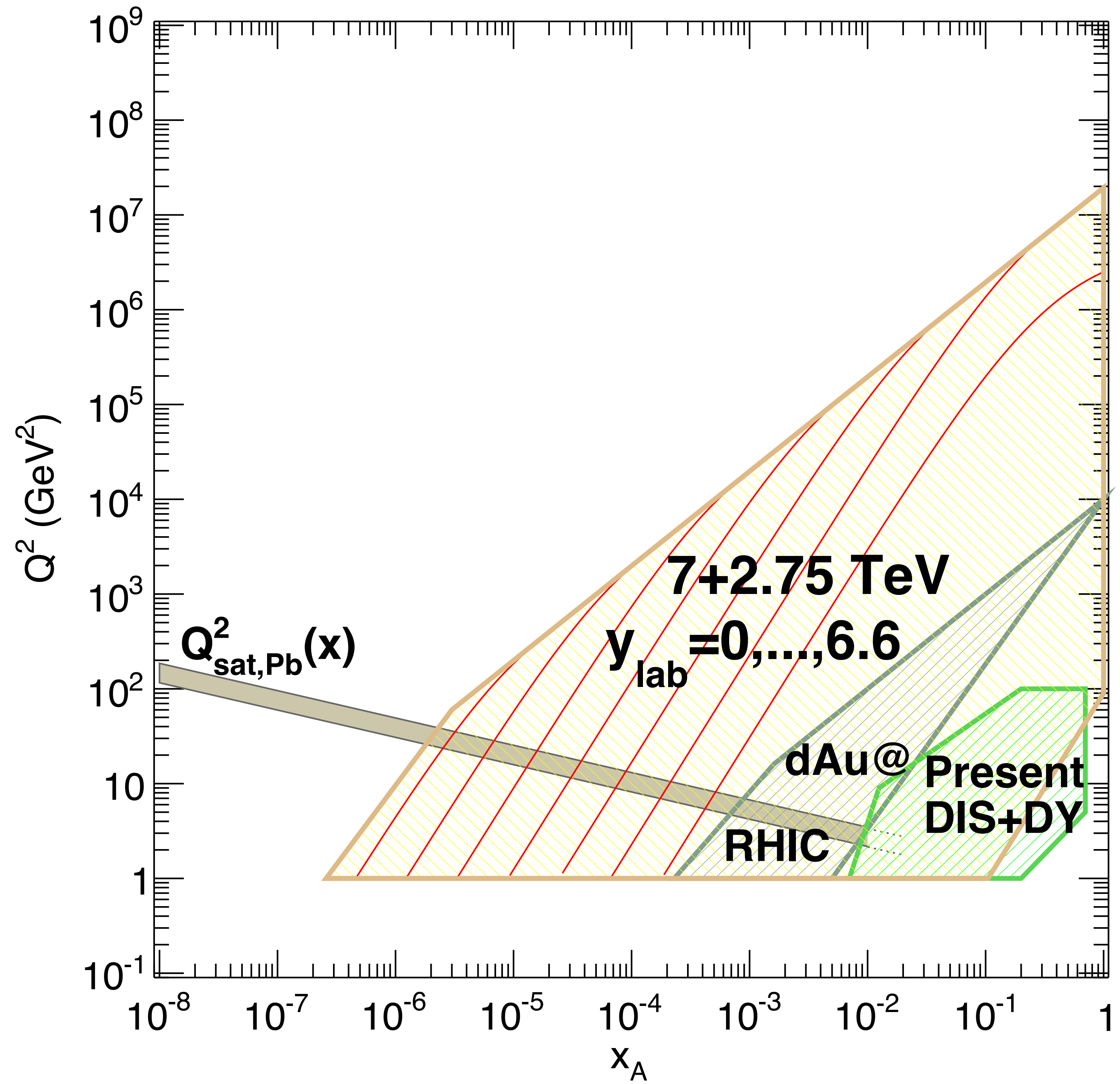

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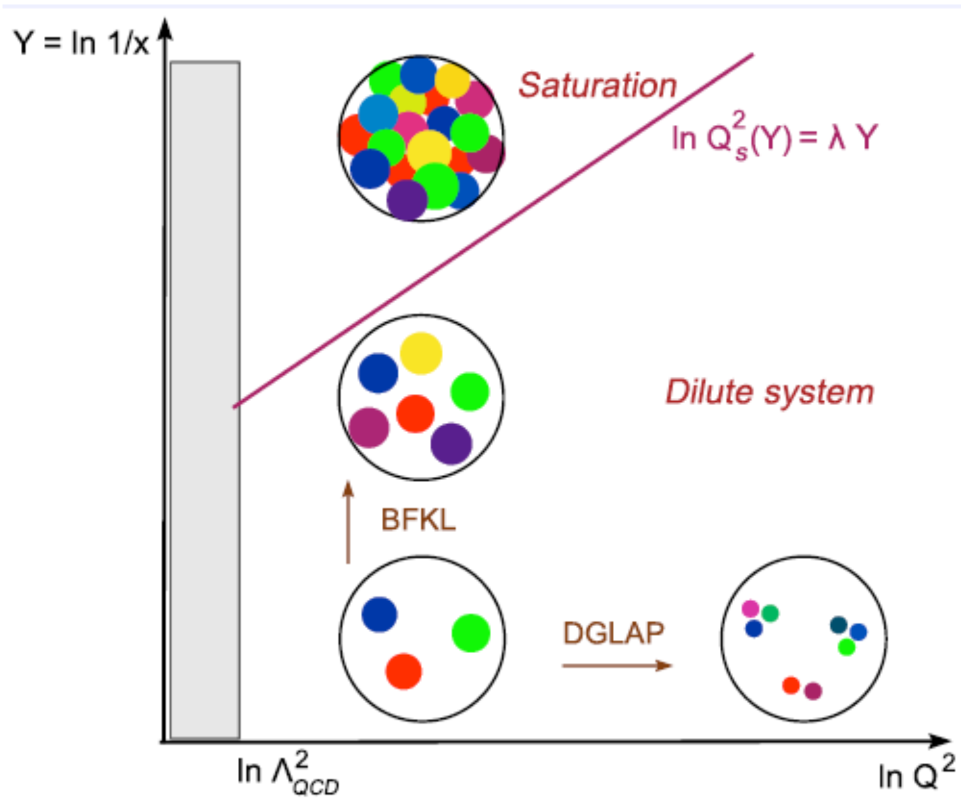

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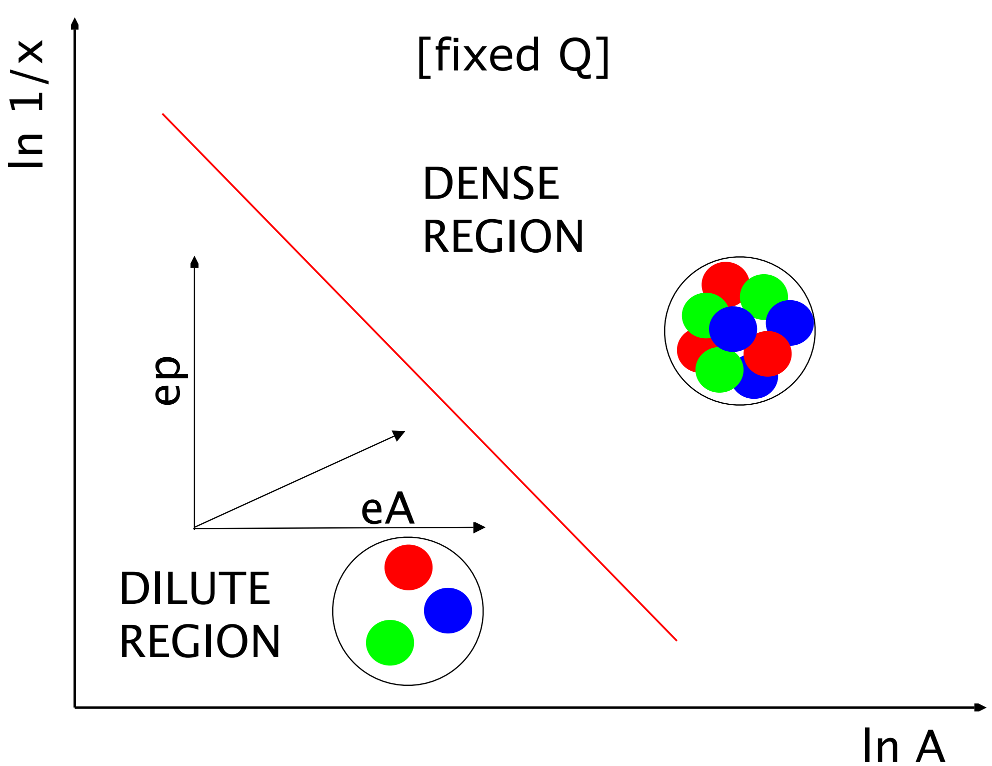

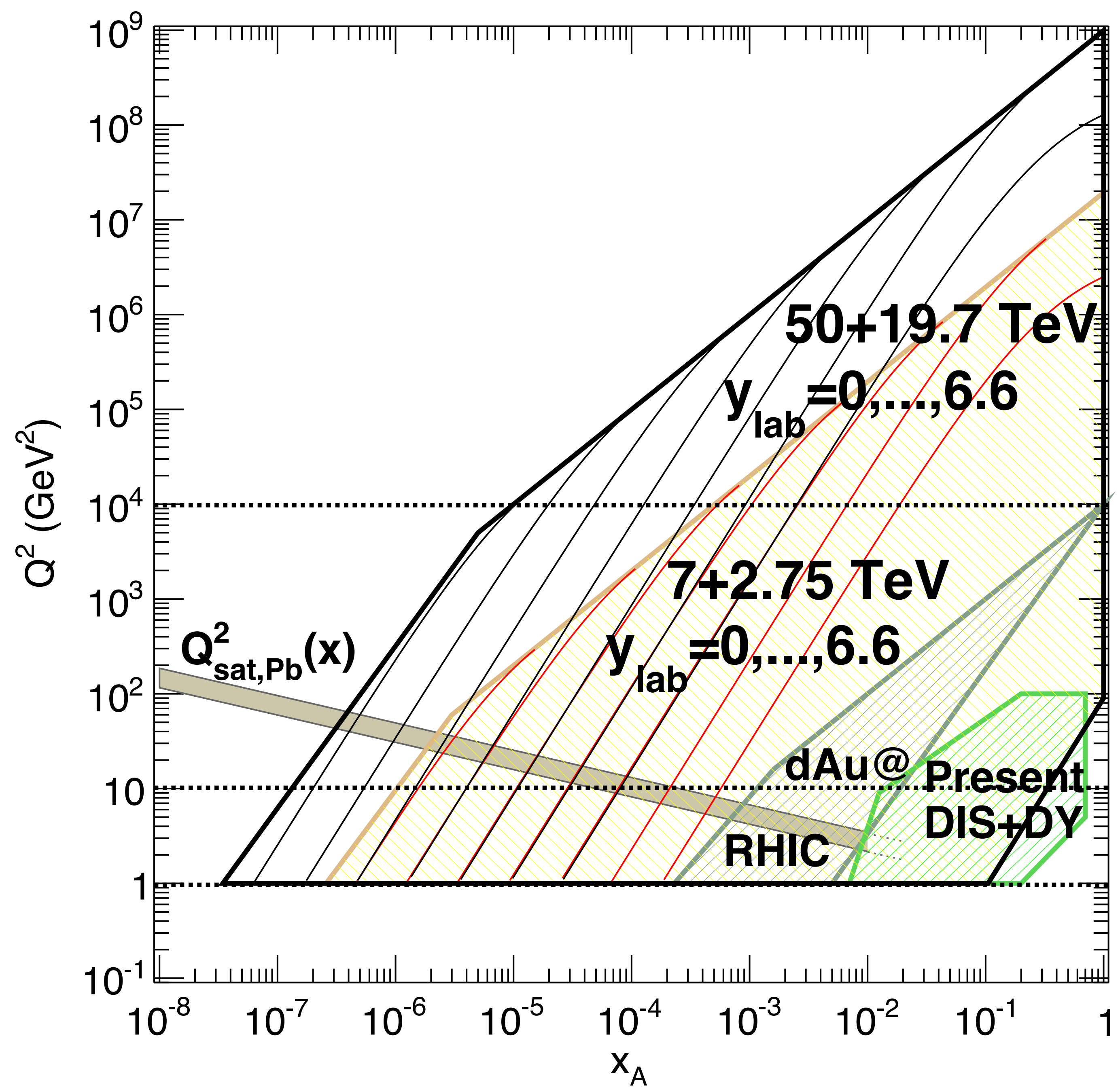

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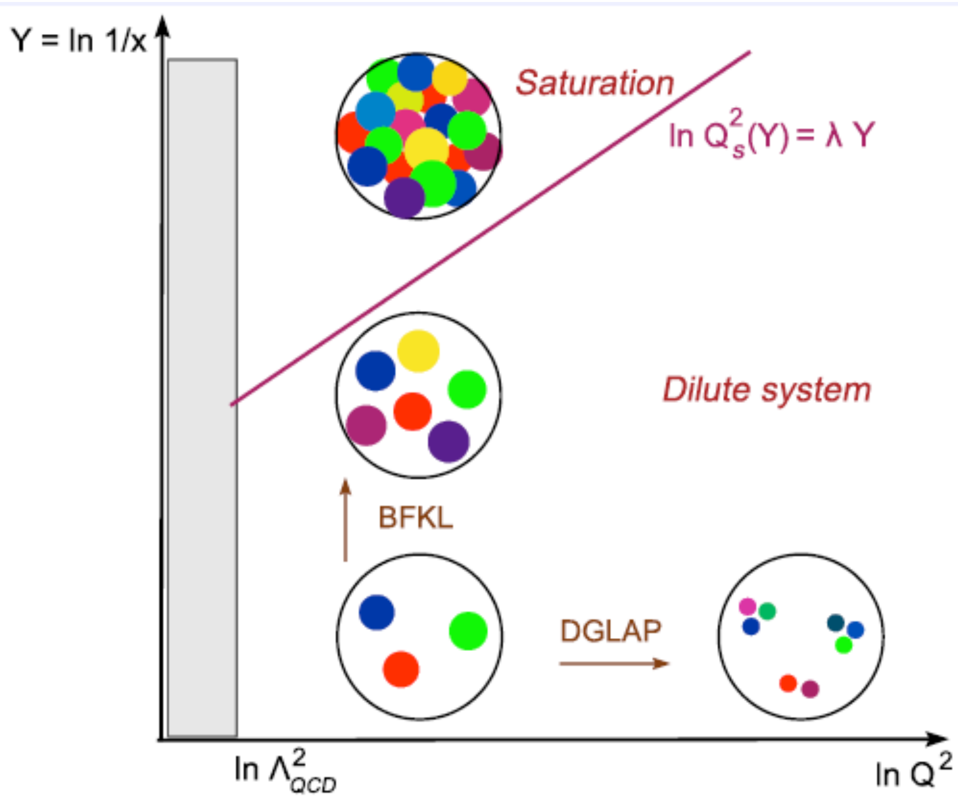
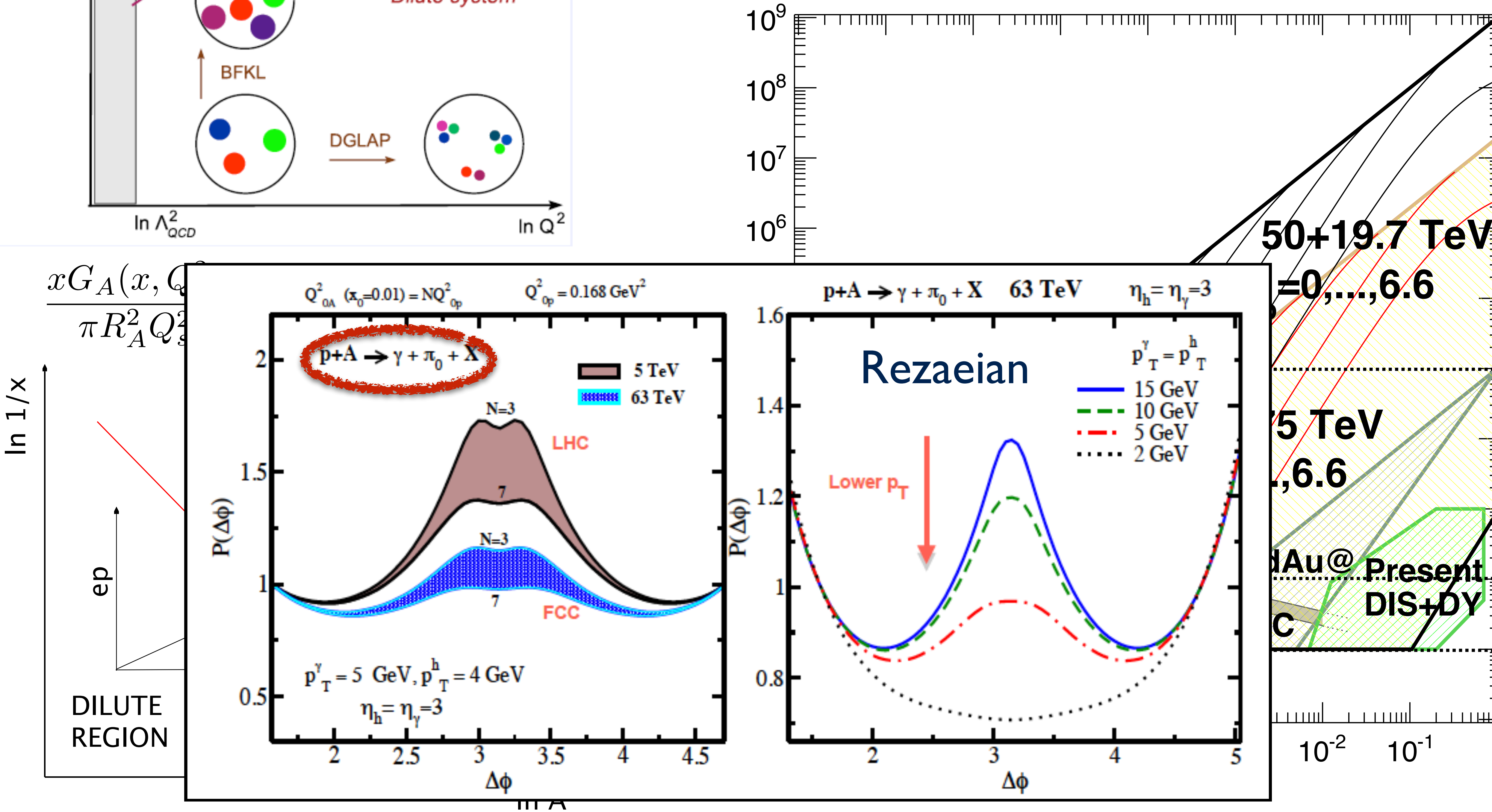
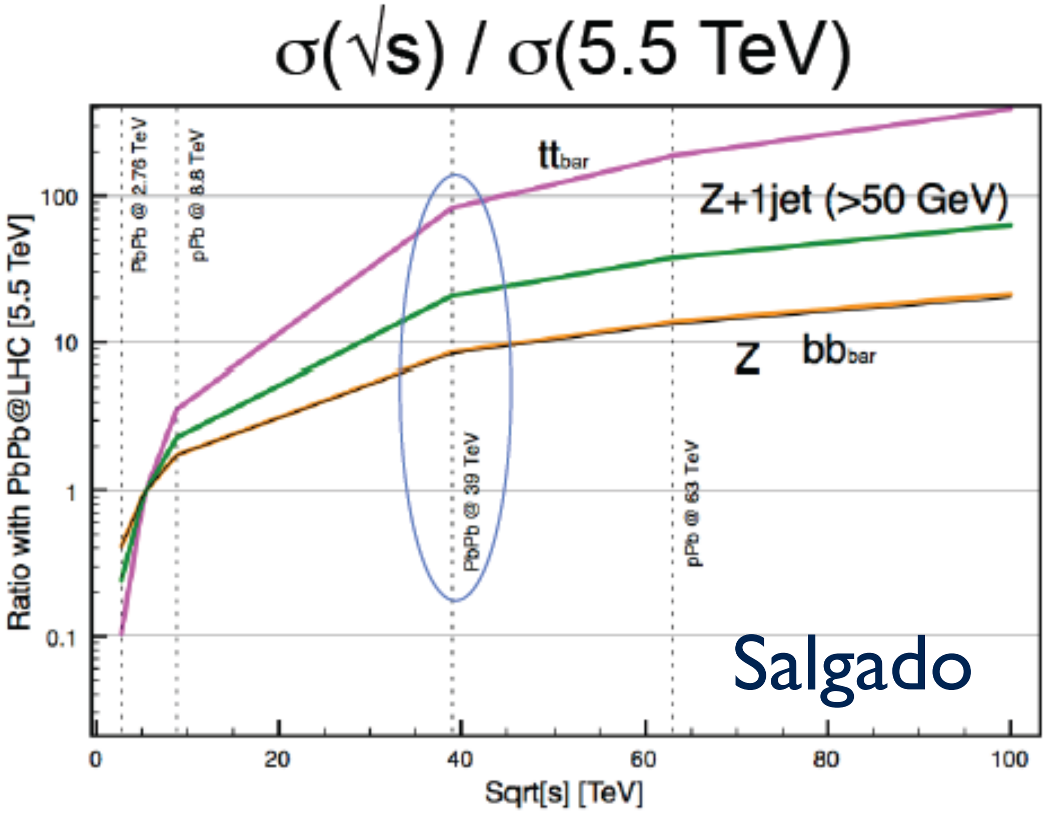
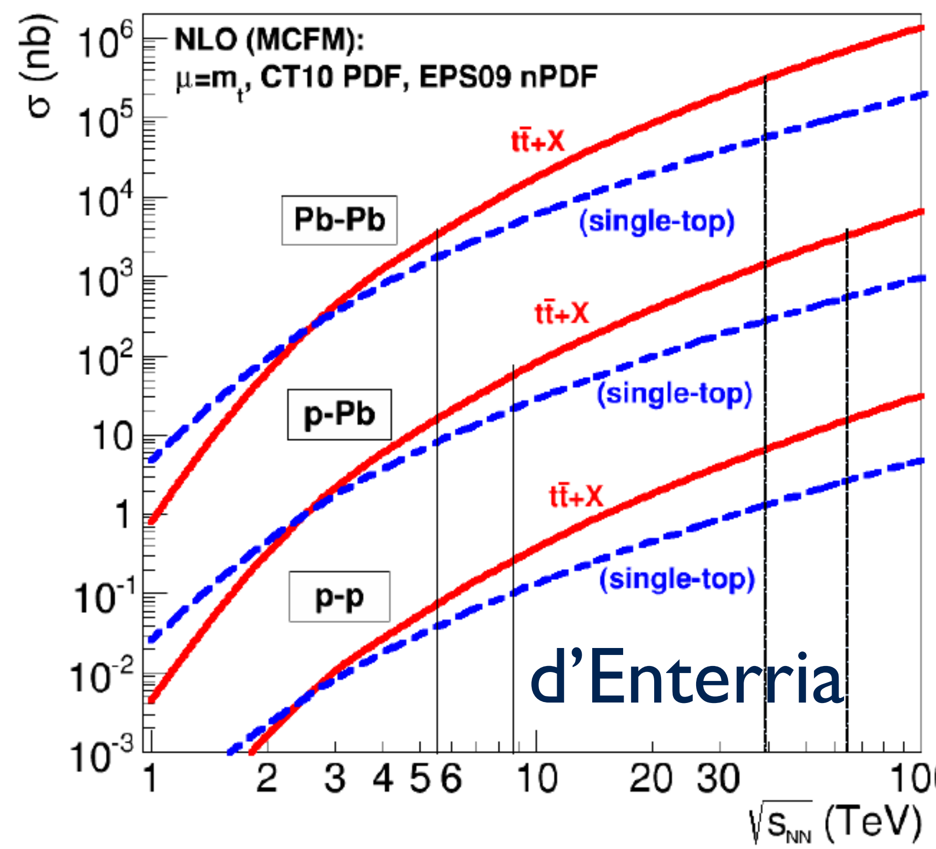




Physics: hard probes

- Hard probes are much abundantly produced: tops, Z+jets,…





- This could make possible the study of boosted tops, boosted colour singlets, mapping the medium evolution via hard probes,…

- New temperature and density range may affect hard probes: ϒ melting, bbar regeneration,…

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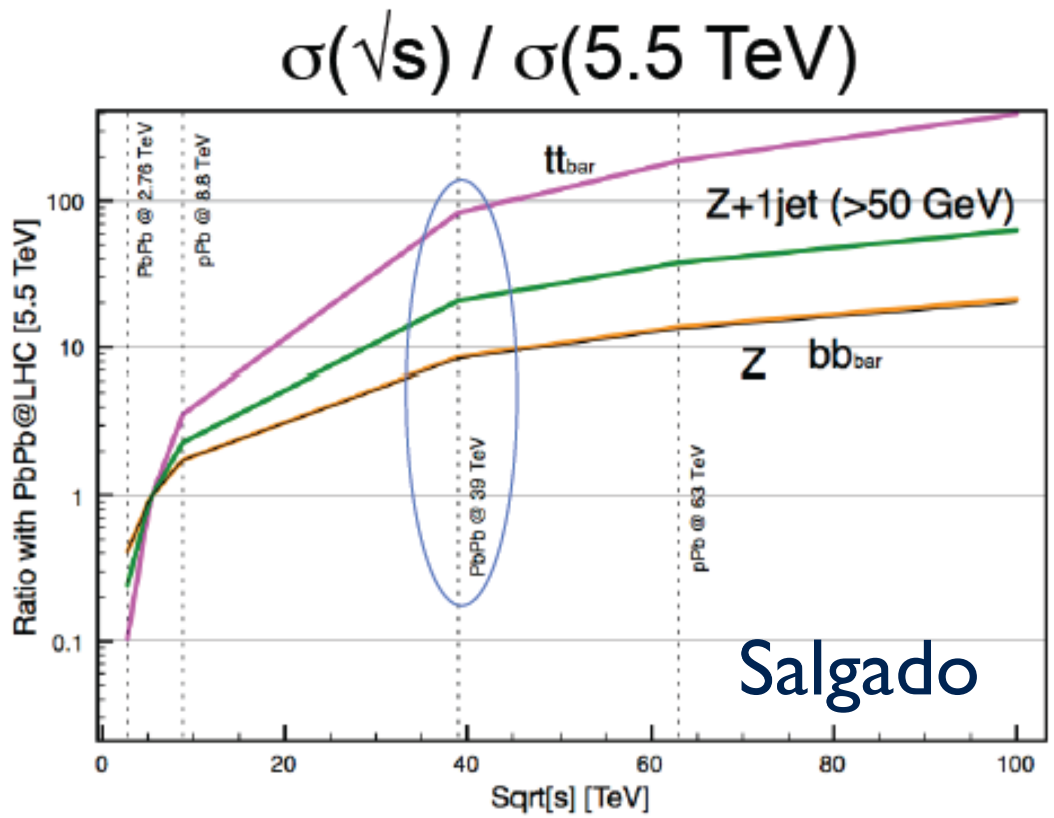

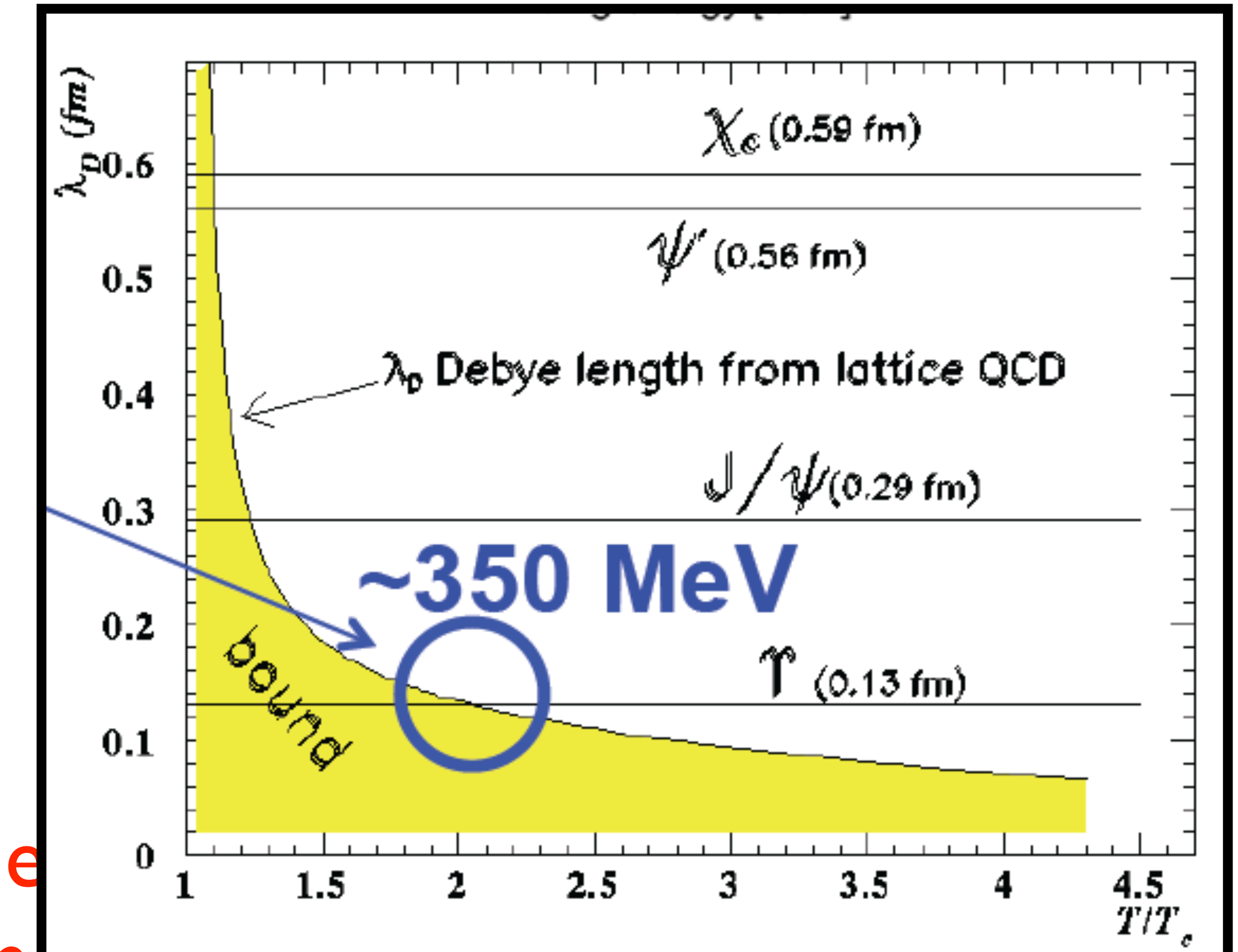

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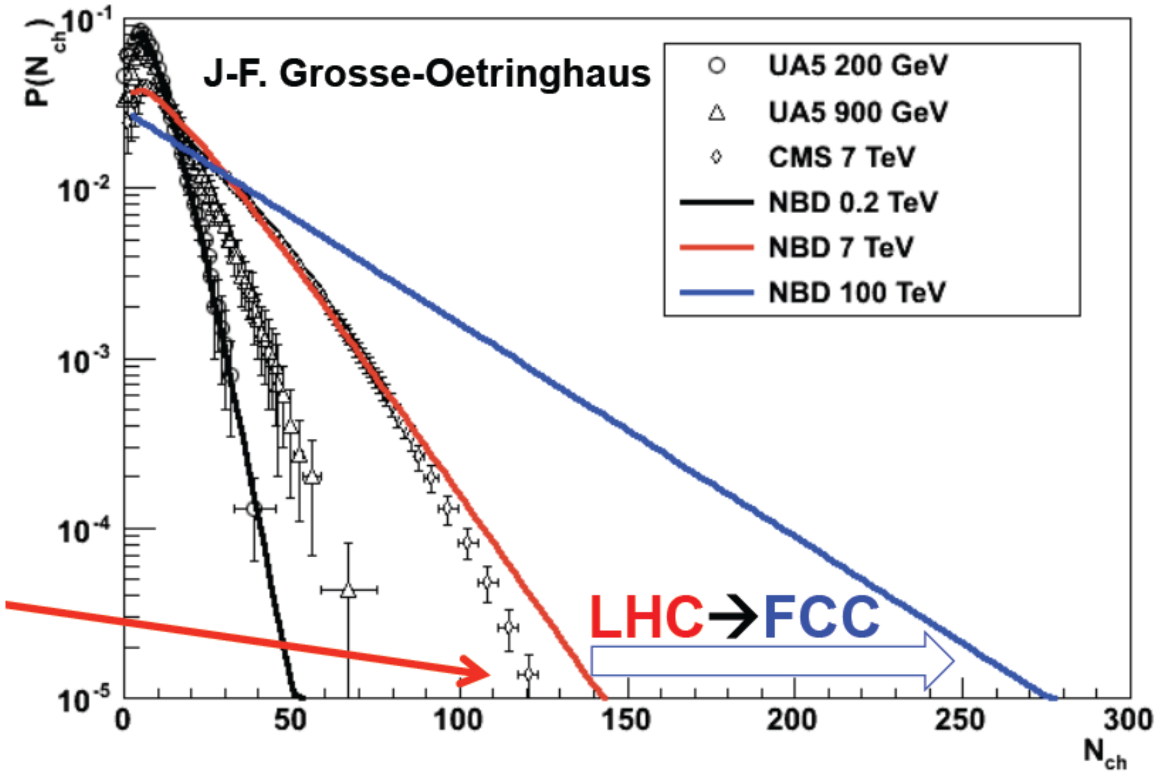
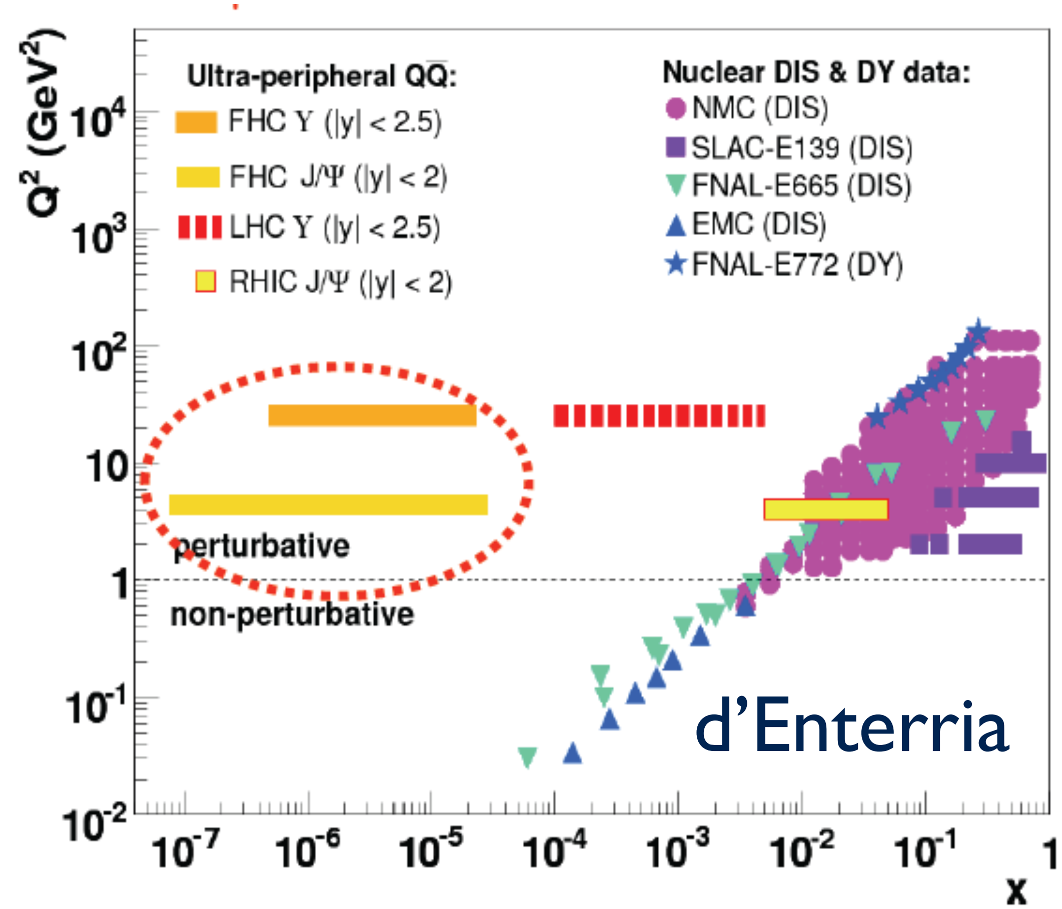
Physics: UPCs, high multi pp



- Much larger multiplicity in pp would help to understand the eventual onset of collectivity in pp and pA: flow-like features, ridge, <p_T>,…

- Exclusive VM production in UPCs will explore new regions of the kinematic plane.

- HE collider data essential to construct models for VHE hadronic interactions of use for UHECR.



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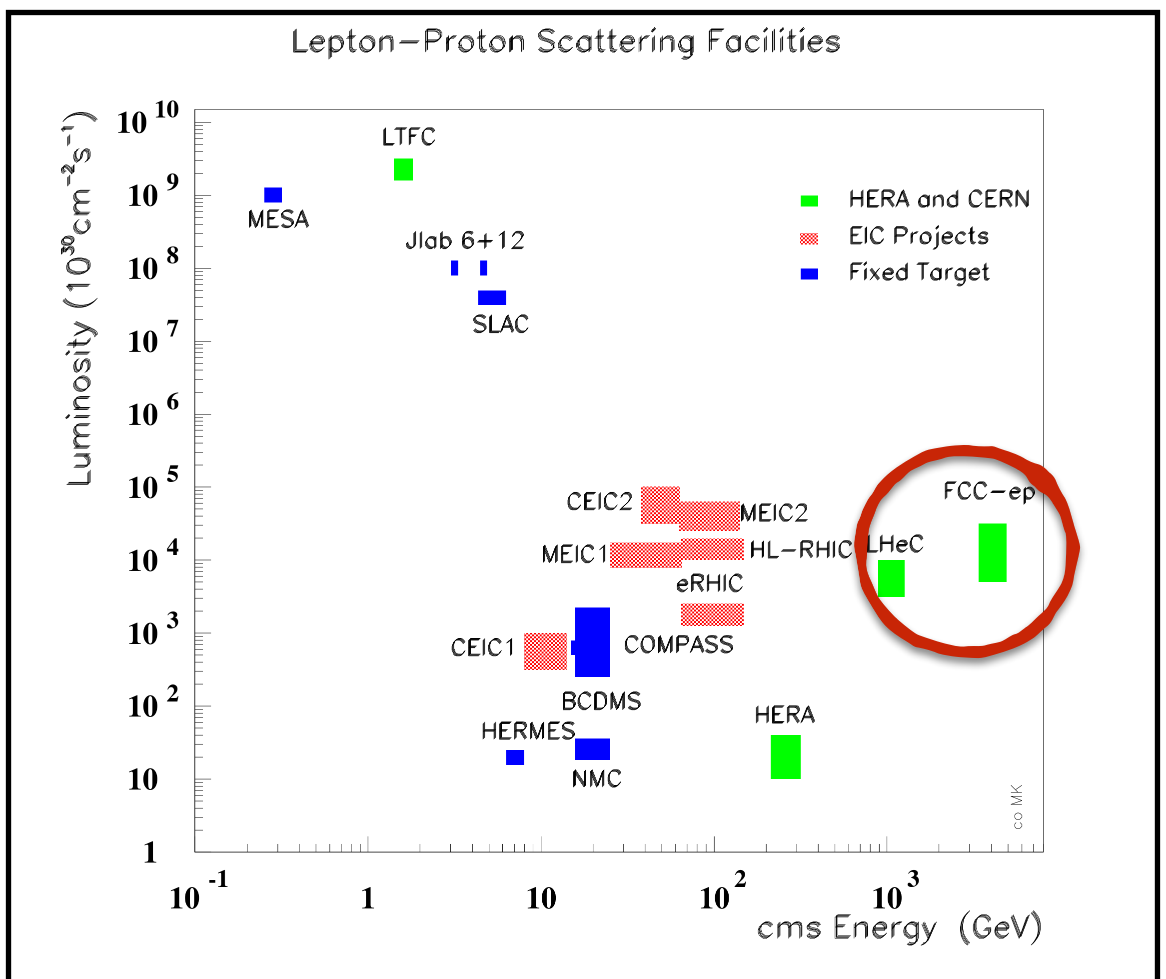
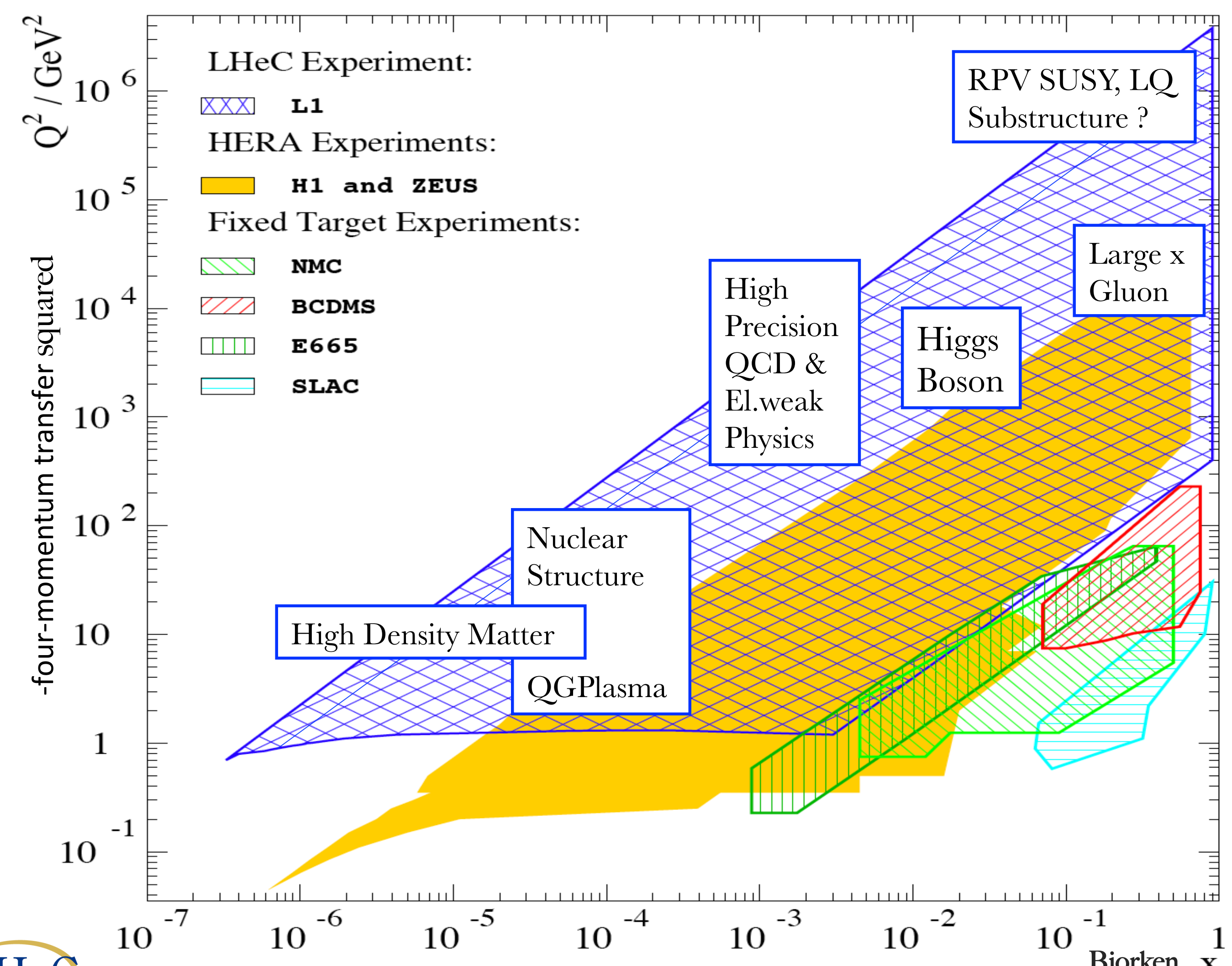
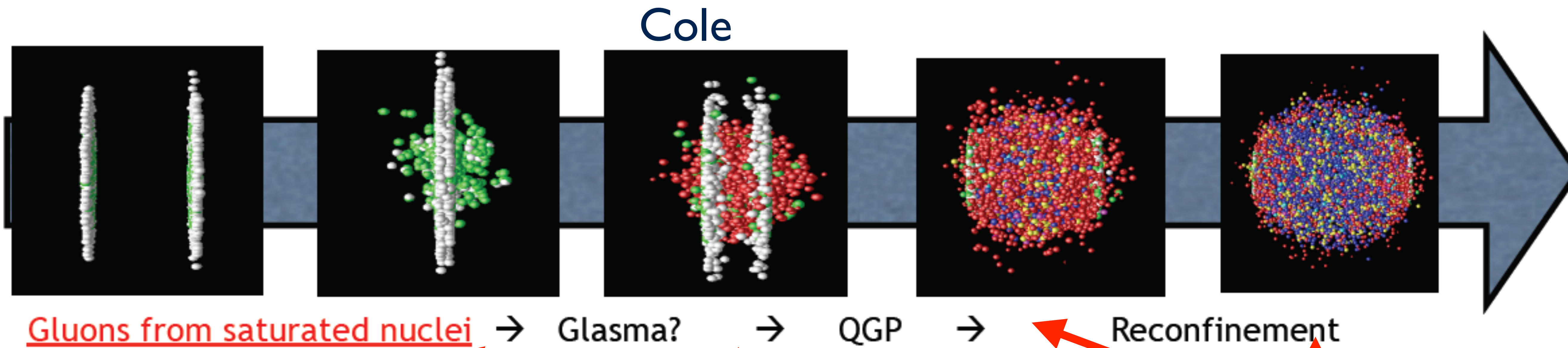
LHeC/FCC-he:

- **LHeC, FCC-he** → ep/eA experiment using p/A from the LHC/FCC: E_p=7/50 TeV, E_A=(Z/A)E_p=2.76/19.7 TeV/nucleon for Pb.
- New e^+/e^- accelerator: E_{cm}~several TeV/nucleon (E_e=50-175 GeV).
- **Compatible with synchronous LHC/HL-LHC/FCC operation.**
- Large physics case beyond our interests: precision QCD and EW, small x, eA, Higgs, BSM.





Relevance for the HI program:



- Nuclear wave function at small x: nuclear structure functions.

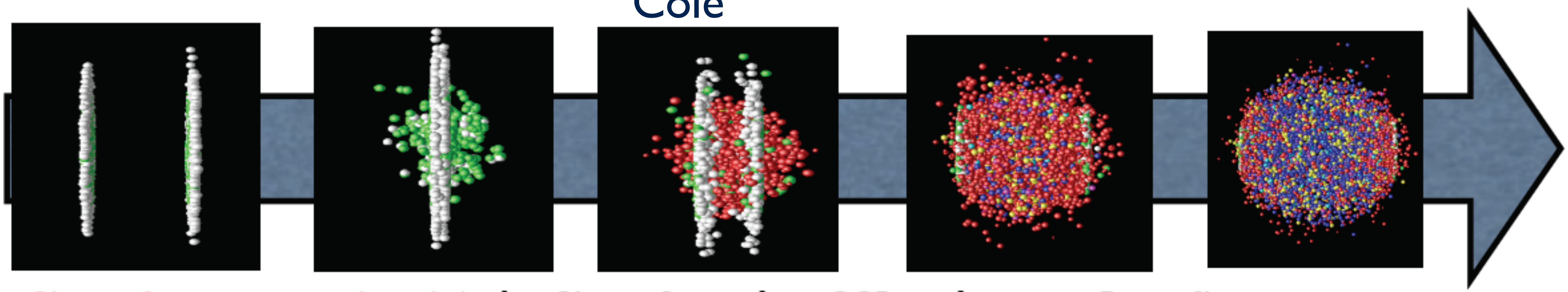
- Particle production at the very beginning: which factorisation in eA?

- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

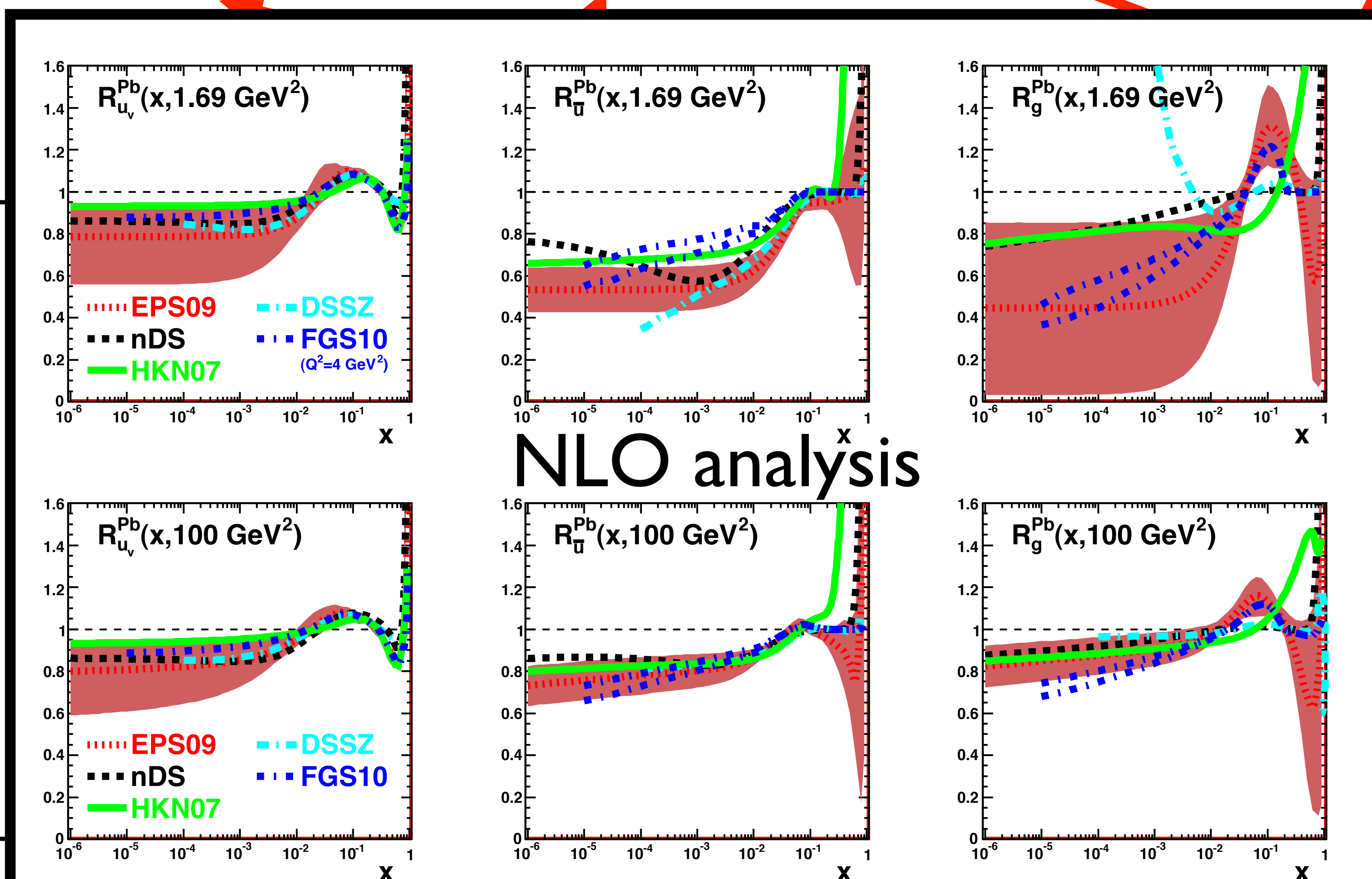
- Probing the medium through energetic particles (jet quenching etc.): modification of QCD radiation and hadronization in the nuclear medium.

LHeC Relevance for the HI program:

Cole



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement



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LHeC: Linac-Ring option

Post CDR ←——— CDR

10^{34} cm^{-2} s^{-1} Luminosity reach	Post CDR PROTONS	Post CDR ELECTRONS	CDR PROTONS	CDR ELECTRONS
Beam Energy [GeV]	7000	60	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	16	16	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20	3.75	50
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10	0.1	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4	7	7
rms Beam divergence $\sigma'^*_{x,y}$ [μrad]	80	40	70	58
Beam Current [mA]	1112	25	430 (860)	6.6
Bunch Spacing [ns]	25	25	25 (50)	25 (50)
Bunch Population	$2.2*10^{11}$	$4*10^{9}$	$1.7*10^{11}$	$(1*10^{9})$ $2*10^{9}$
Bunch charge [nC]	35	0.64	27	(0.16) 0.32

LHeC: Linac-Ring option

Post CDR ⟵ CDR

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Bu		25	25 (50)	25 (50)
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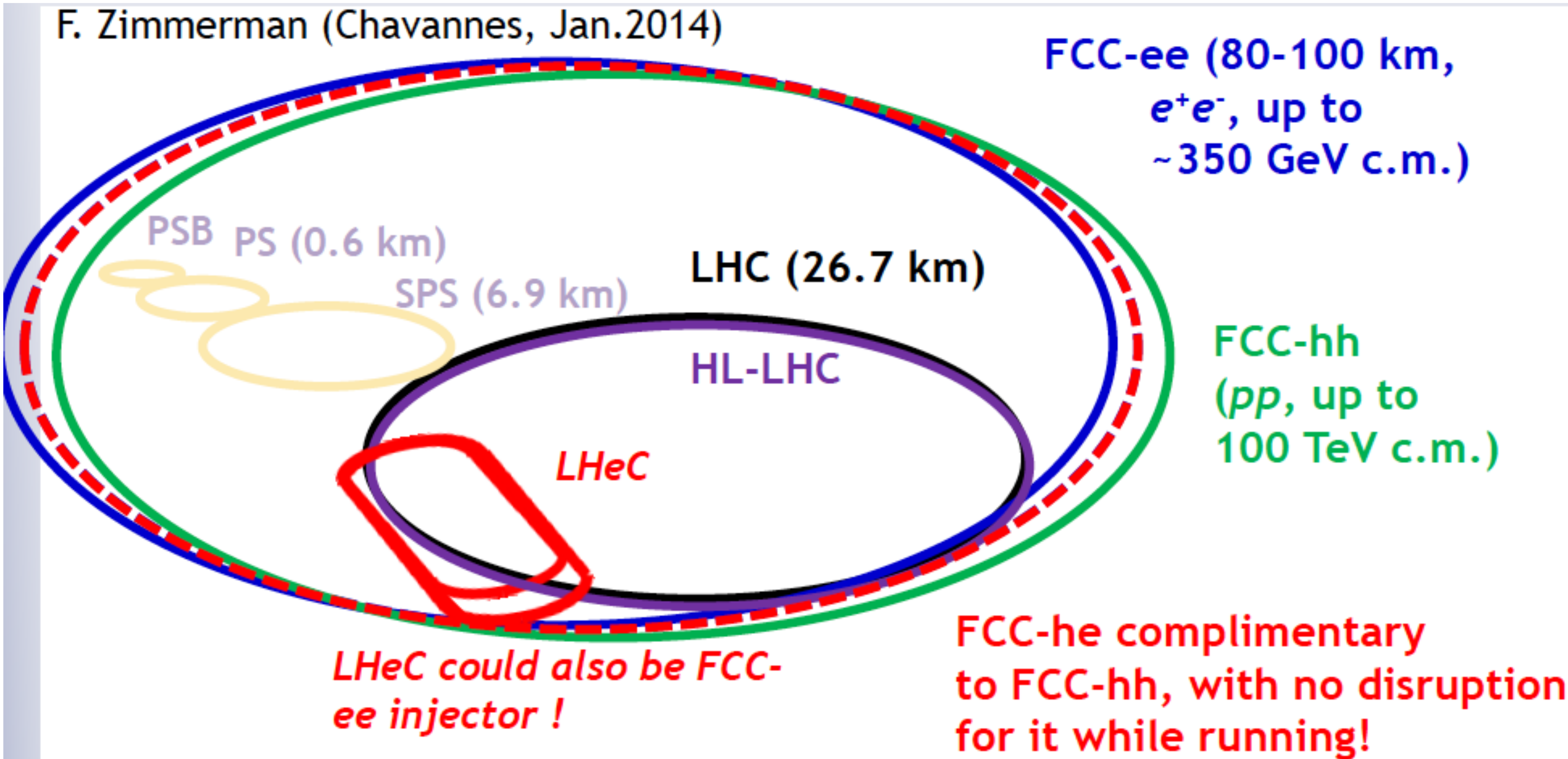
Luminosity per nucleon (CDR)

$$L_{eN} = \begin{cases} 9\times10^{31}\ \mathrm{cm^{-2}s^{-1}} & \text{(Nominal Pb)} \\ 1.6\times10^{32}\ \mathrm{cm^{-2}s^{-1}} & \text{(Ultimate Pb)} \end{cases}$$

FCC-he:

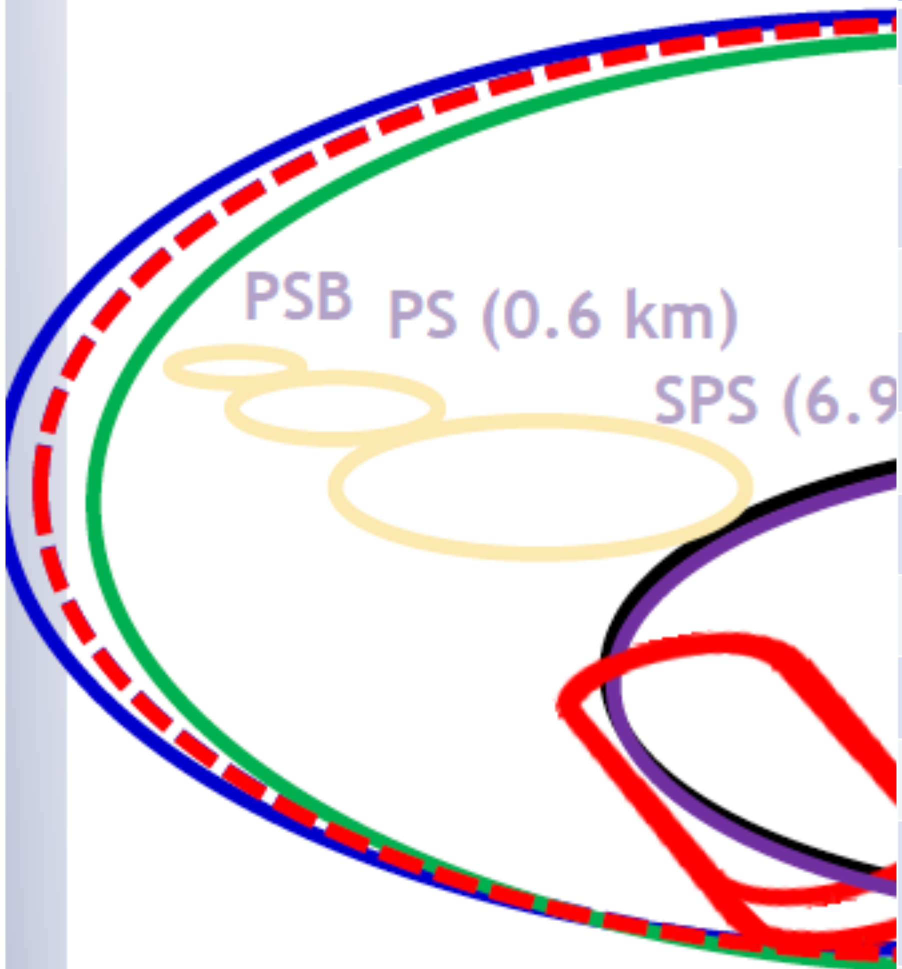


LHeC/FCC-he: $e^{\pm}$ (60-175 GeV) - p (7 and/or 50 TeV) collisions

≥50 years e^+e^-, pp, $e^{\pm}p/A$ physics at highest energies!

FCC-he:

F. Zimmerman (Chavannes,



collider parameters	FCC ERL	FCC-ee ring		protons
species	e^- (e^+?)	$e^\pm$	$e^\pm$	p
beam energy [GeV]	60	60	120	50000
bunches / beam	-	10600	1360	10600
bunch intensity [10^{11}]	0.05	0.94	0.46	1.0
beam current [mA]	25.6	480	30	500
rms bunch length [cm]	0.02	0.15	0.12	8
rms emittance [nm]	0.17	1.9 (x)	0.94 (x)	0.04 [0.02 y]
$\beta_{x,y}$*[mm]	94	8, 4	17, 8.5	400 [200 y]
$\sigma_{x,y}$* [μm]	4.0	4.0, 2.0		equal
beam-b. parameter ξ	(D=2)	**0.13**	**0.13**	0.022 (0.0002)
hourglass reduction	0.92 (H_D=1.35)	**~0.21**	~0.39	
CM energy [TeV]	3.5	3.5	4.9	
luminosity[10^{34}cm^{-2}s^{-1}]	**1.0**	**6.2**	**0.7**	

F.Zimmermann
ICHEP14, June

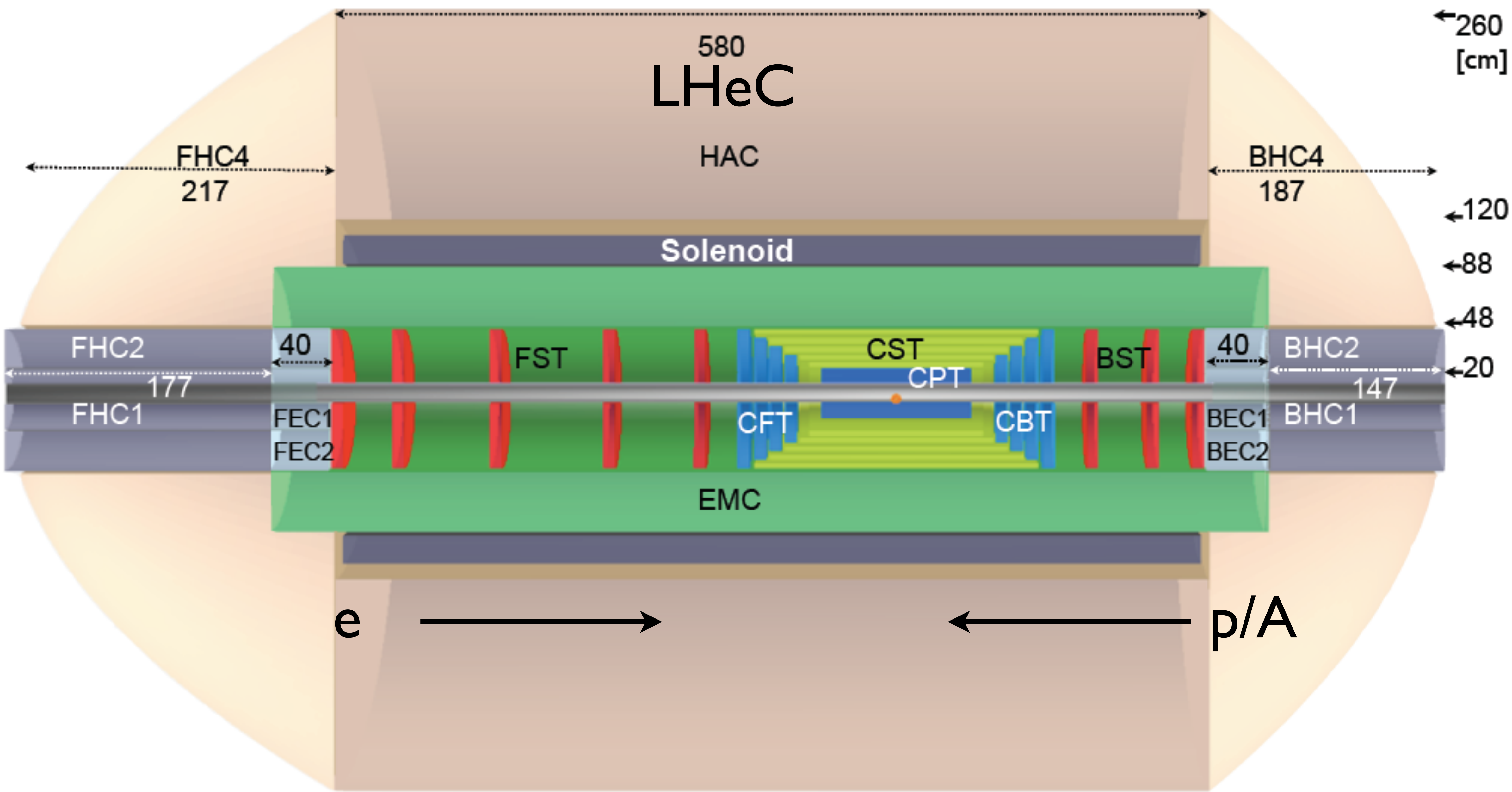
PRELIMINARY
L is 1000*HERA

LHeC could
ee injector
on
for it while running!

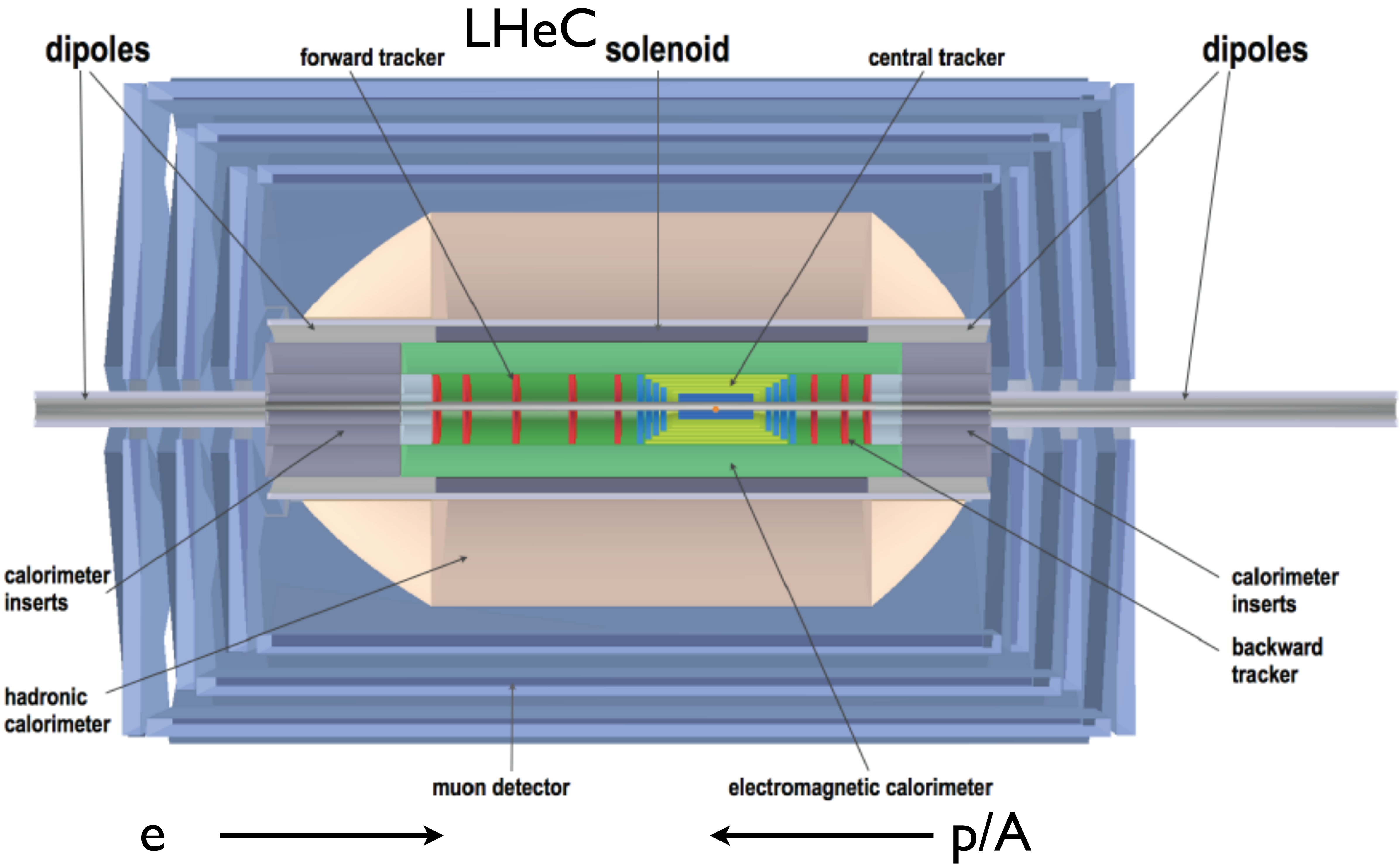
LHeC/FCC-he: $e^\pm$ (60-175 GeV) - p (7 and/or 50 TeV) collisions

≥50 years e^+e^-, pp, $e^\pm p/A$ physics at highest energies!

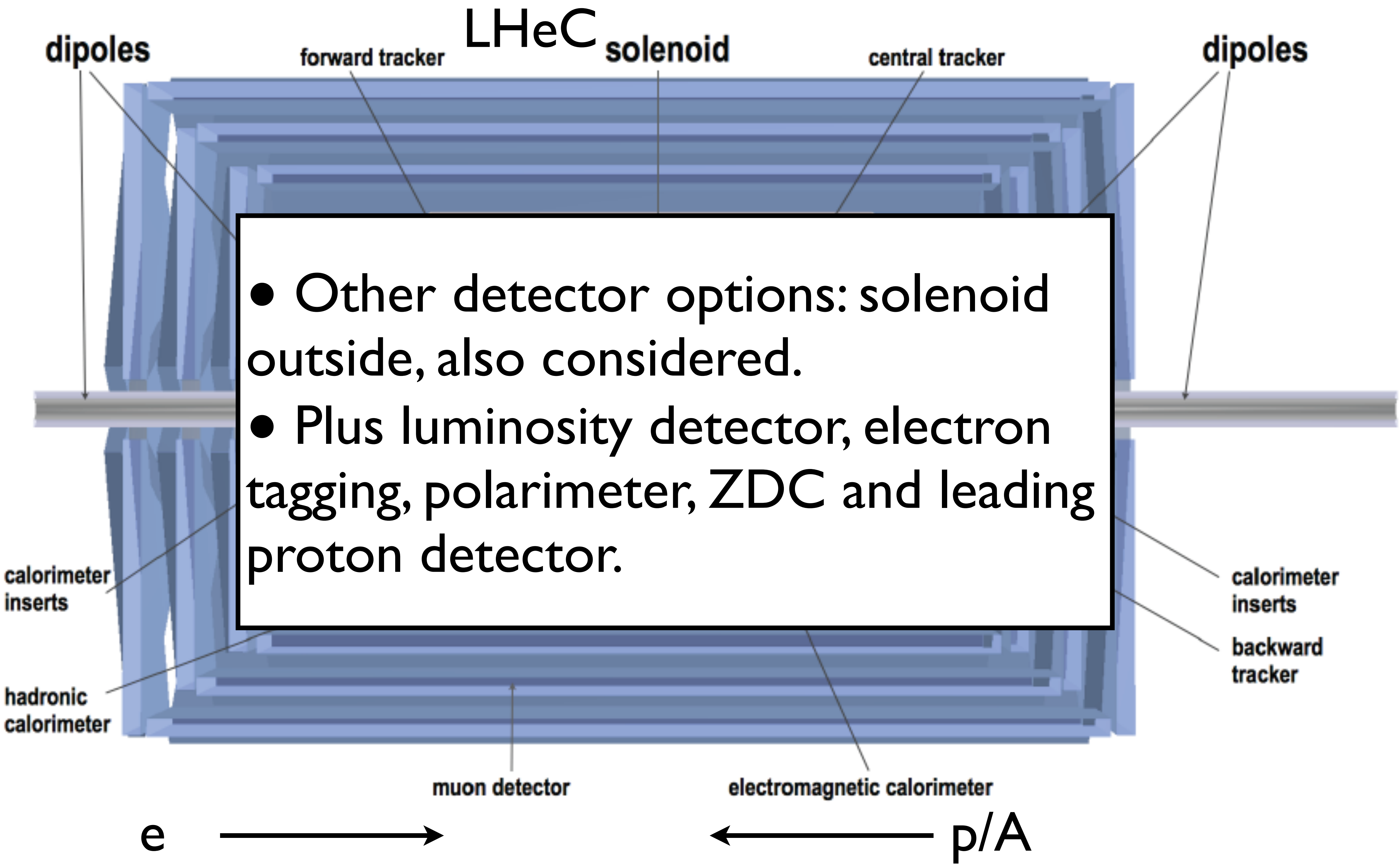
The detector:



The detector:

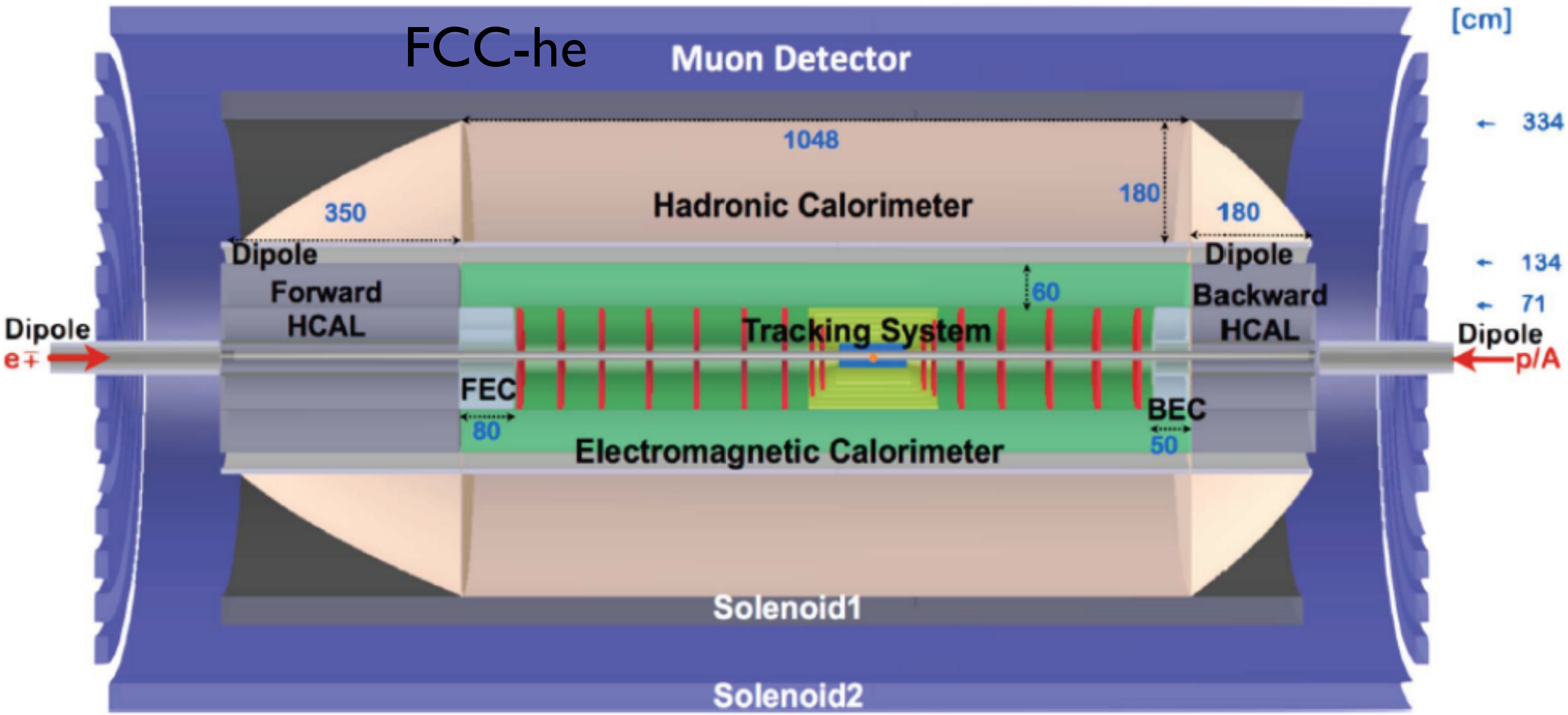


The detector:



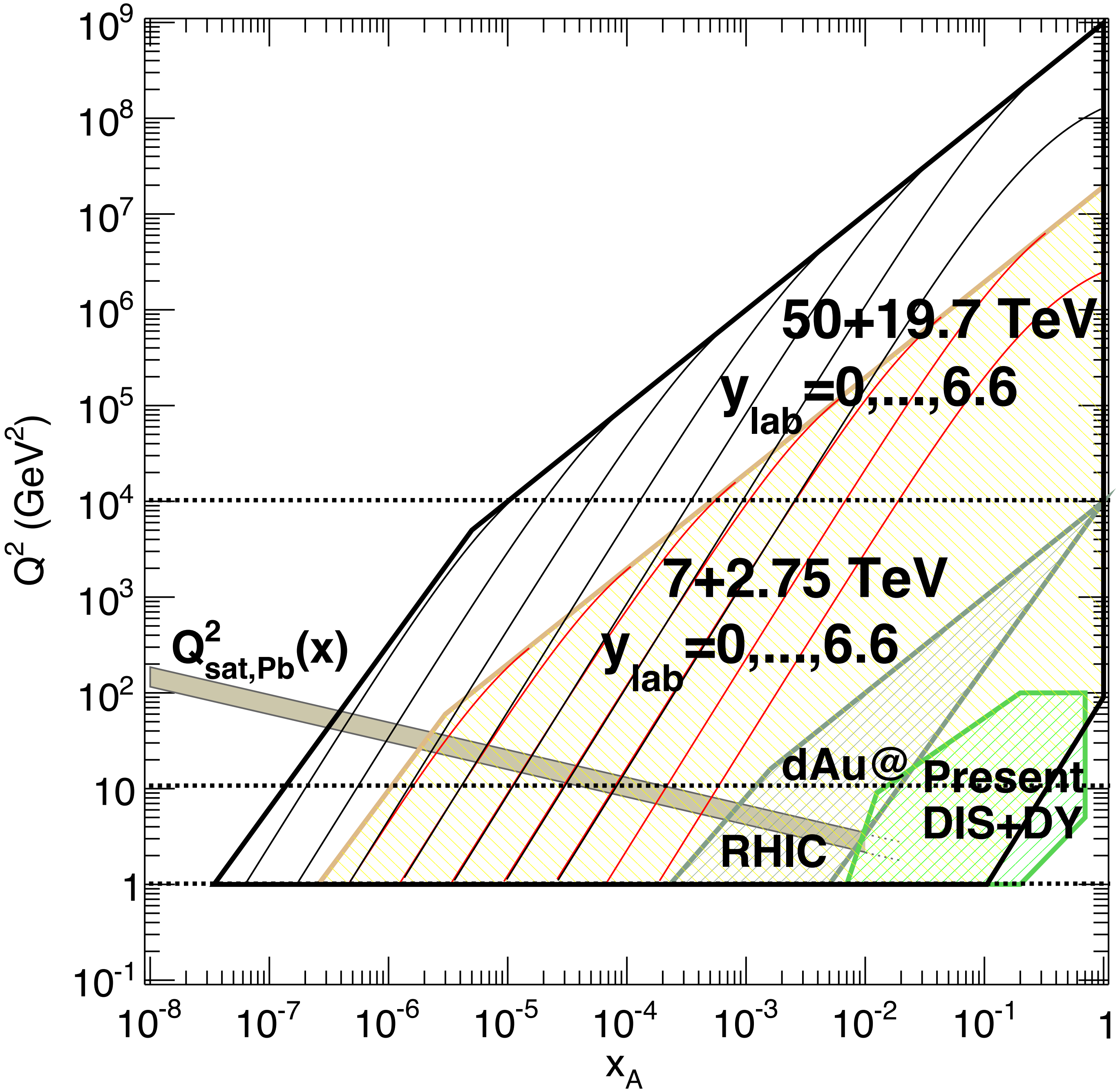
- Other detector options: solenoid outside, also considered.
- Plus luminosity detector, electron tagging, polarimeter, ZDC and leading proton detector.

The detector:



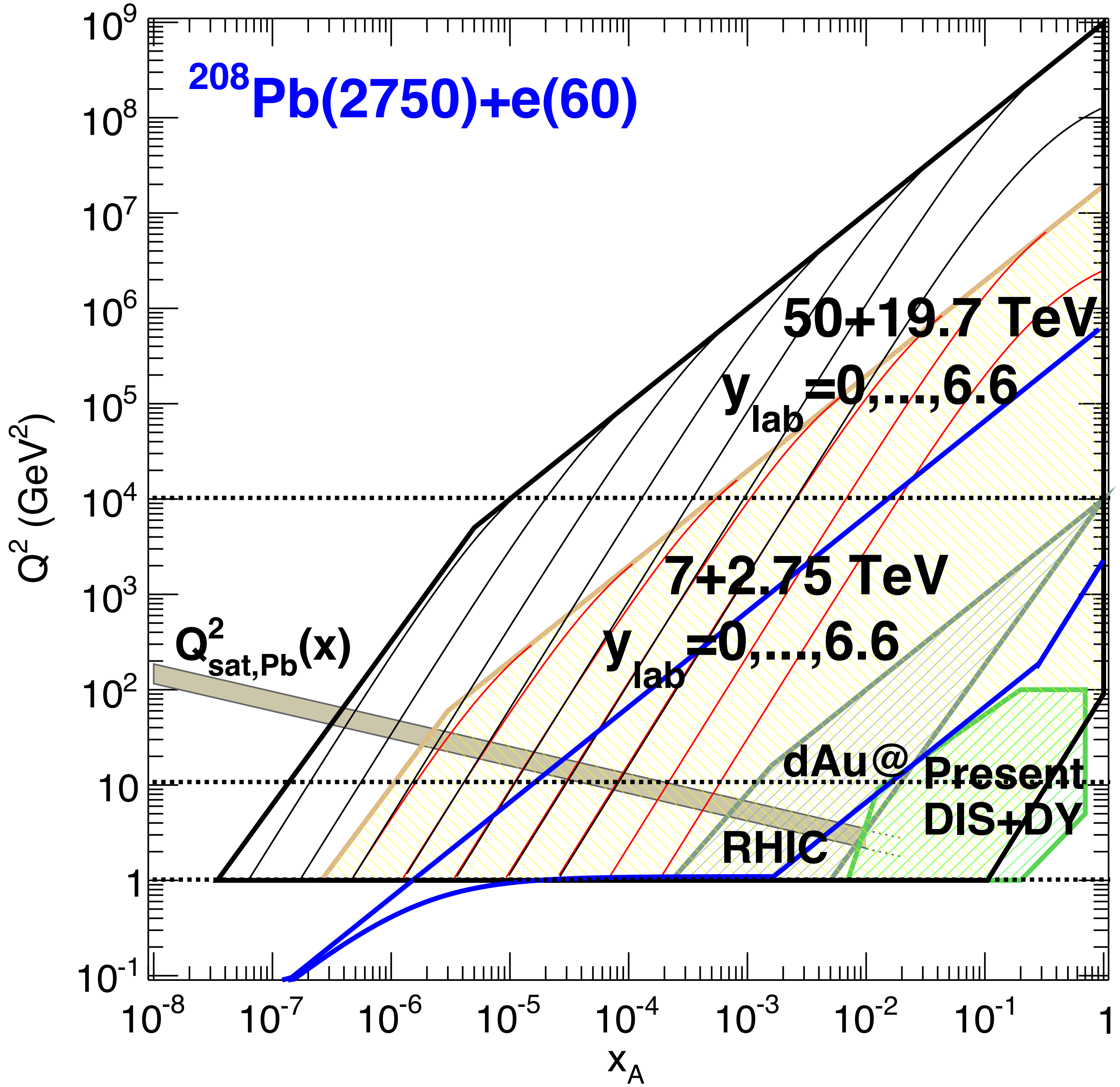
Crab cavities for p instead of dipole magnet for e bend to ensure head on collisions
1000 H → μμ may call for better muon momentum measurement
H→ HH → 4b (and large/low x) call for large acceptance and optimum hadr. E resolution
Detector for FCC scales by about ln(50/7) ~2 in fwd, and ~1.3 in bwd direction
Full simulation of LHeC and FCC-he detectors vital for H and H-HH analysis

Kinematics:



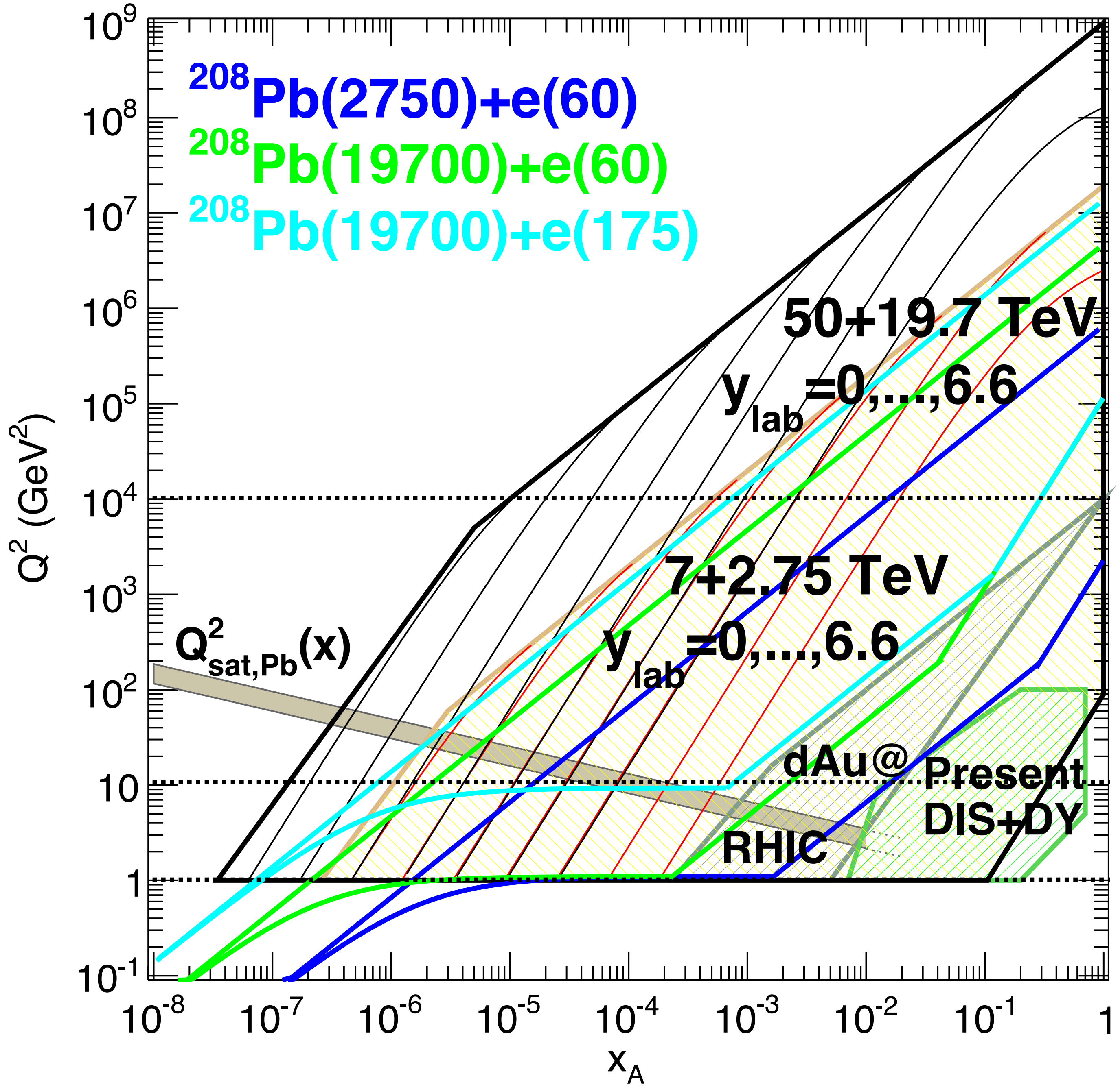
50+19.7 TeV
y_lab=0,...,6.6
7+2.75 TeV
y_lab=0,...,6.6
Q²_sat,Pb(x)
dAu@
RHIC
Present
DIS+DY
Q² (GeV²)
x_A

Kinematics:



^{208}Pb(2750)+e(60)
50+19.7 TeV
y_{lab}=0,...,6.6
7+2.75 TeV
y_{lab}=0,...,6.6
$Q^2_{sat,Pb}(x)$
dAu@
RHIC
Present
DIS+DY
Q^2 (GeV^2)
x_A

Kinematics:



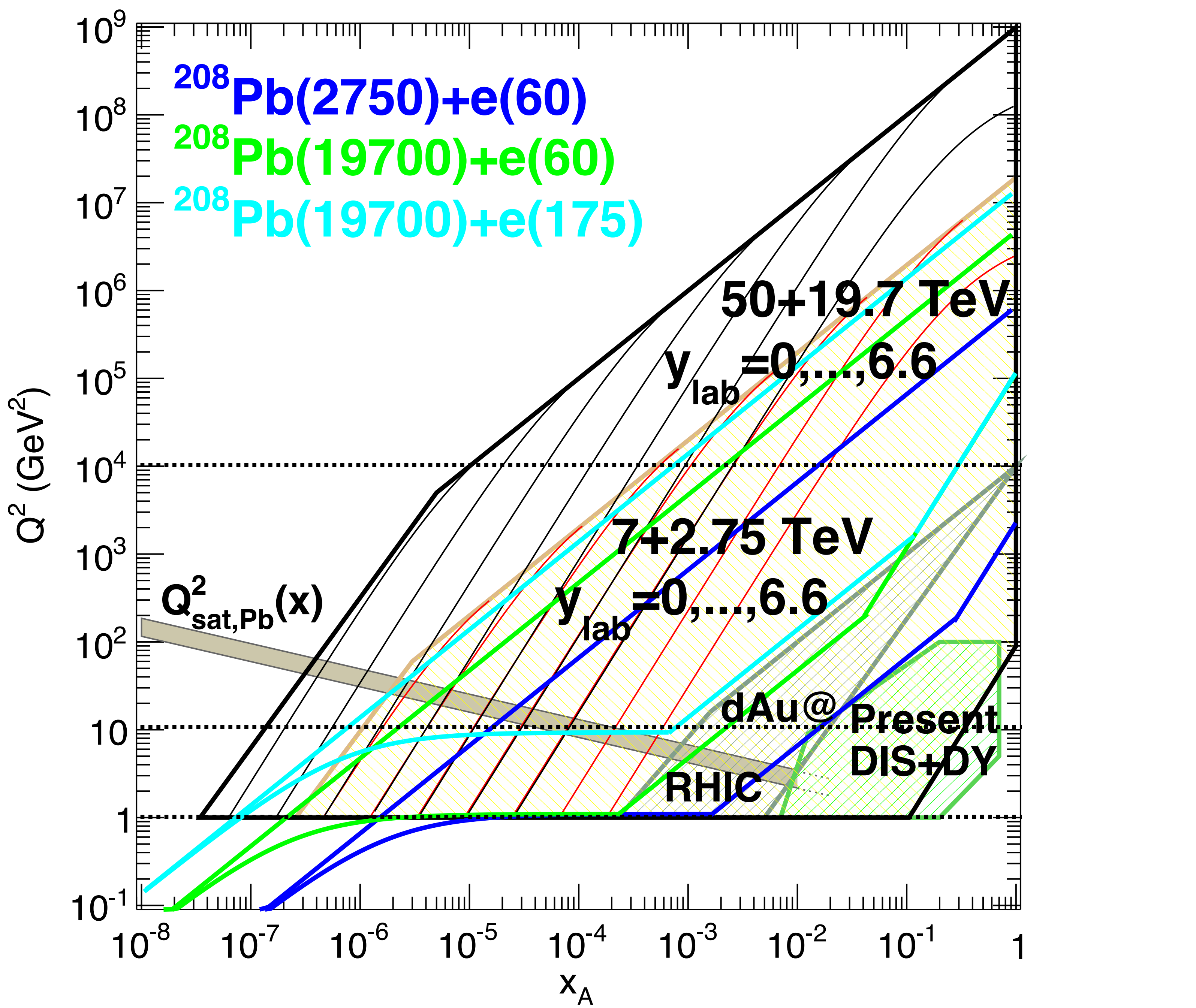
^{208}Pb(2750)+e(60)
^{208}Pb(19700)+e(60)
^{208}Pb(19700)+e(175)
50+19.7 TeV
y_{lab}=0,...,6.6
7+2.75 TeV
y_{lab}=0,...,6.6
$Q^2_{sat,Pb}(x)$
dAu@
RHIC
Present
DIS+DY
Q^2 (GeV^2)
x_A
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1

Kinematics:

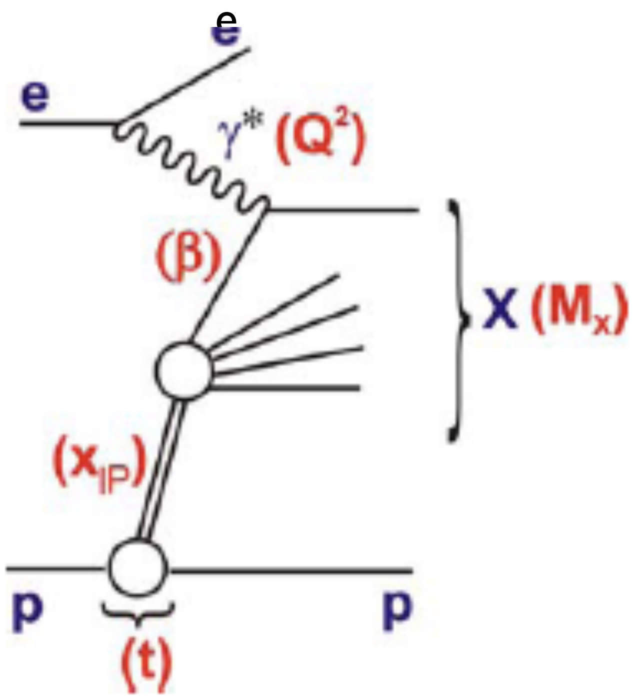
- The LHeC/FCC-he will explore a region overlapping with the LHC/FCC-hh:

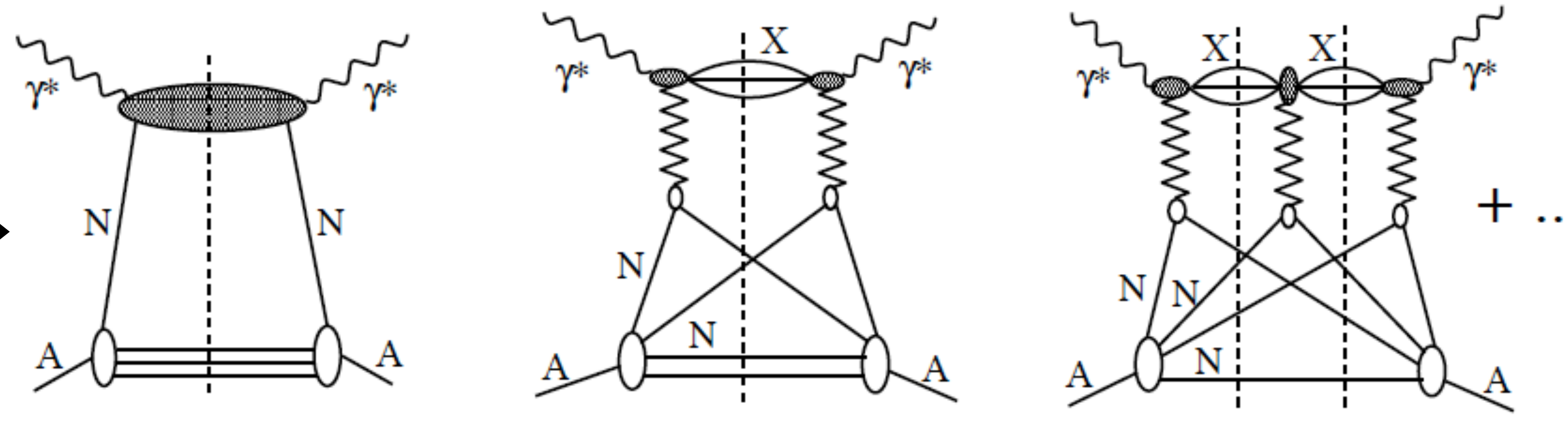
➜ in a cleaner experimental setup;

➜ on firmer theoretical grounds.



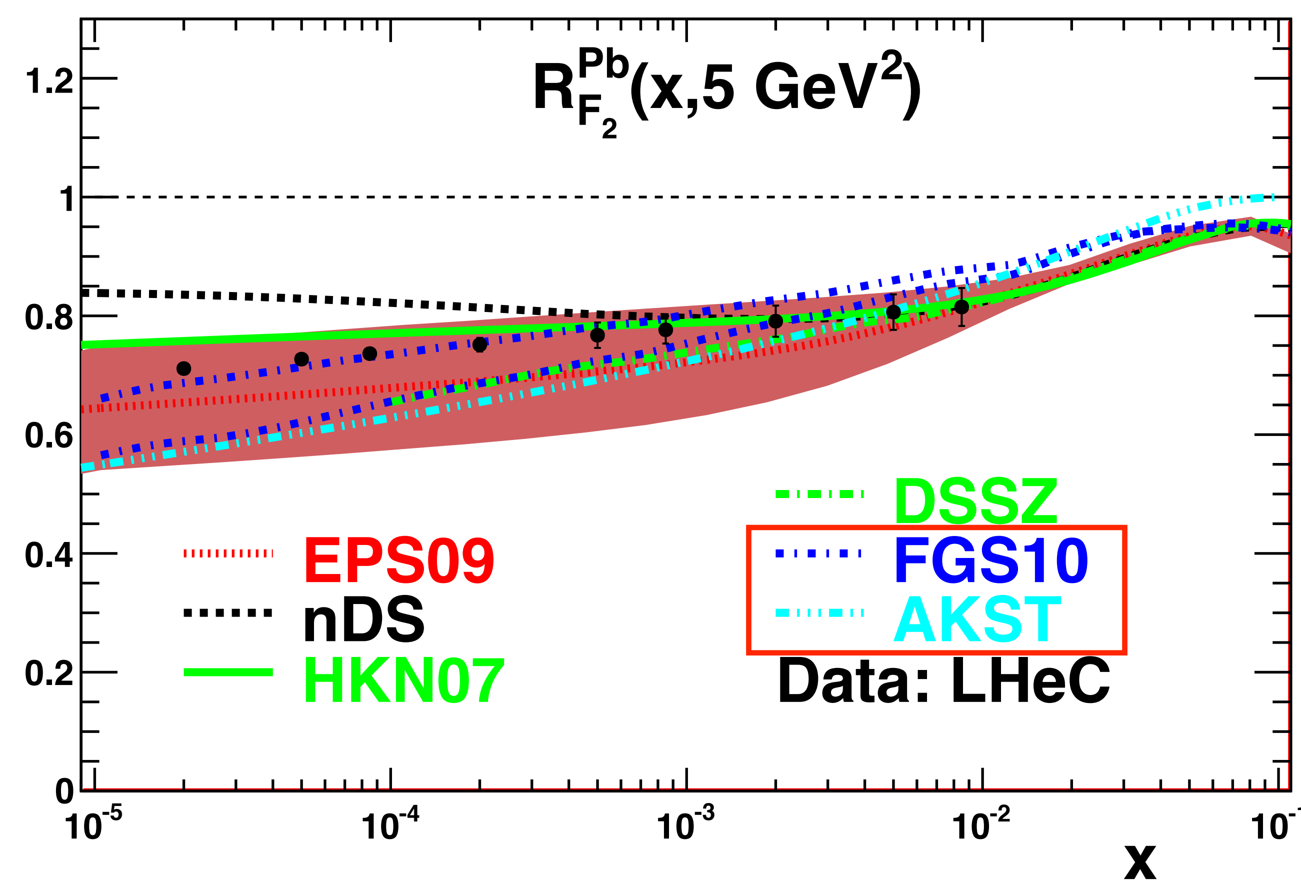
Diffraction in ep and shadowing:





1106.2019

- Diffraction is linked to nuclear shadowing through basic QFT (Gribov): eD to test and set the 'benchmark' for new effects.



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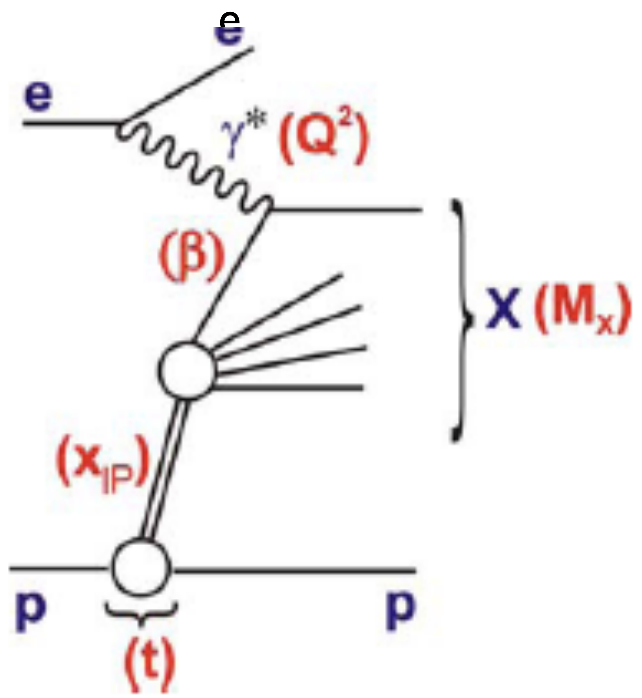

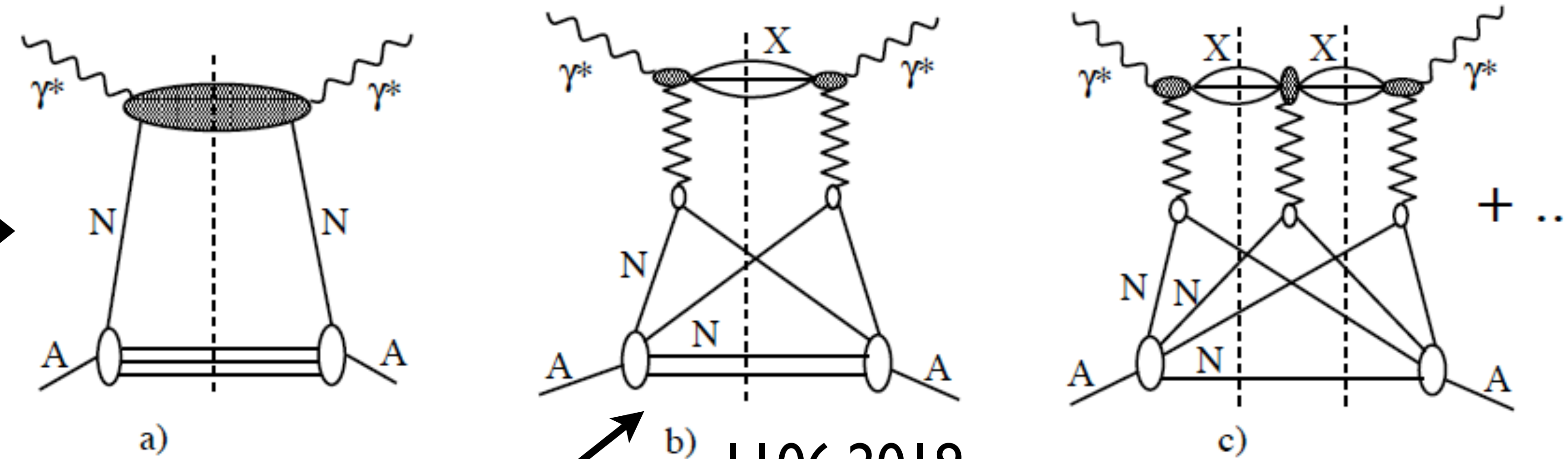

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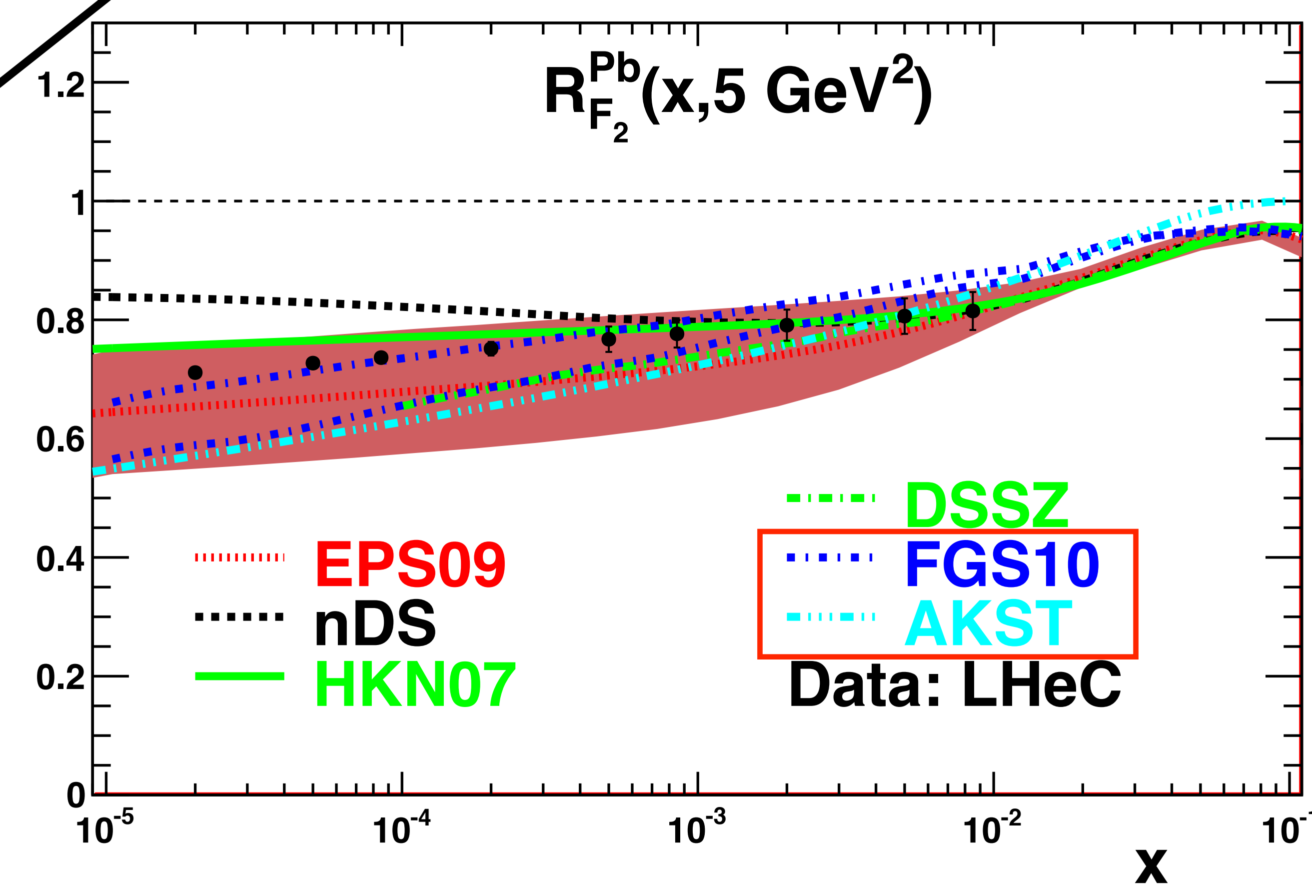
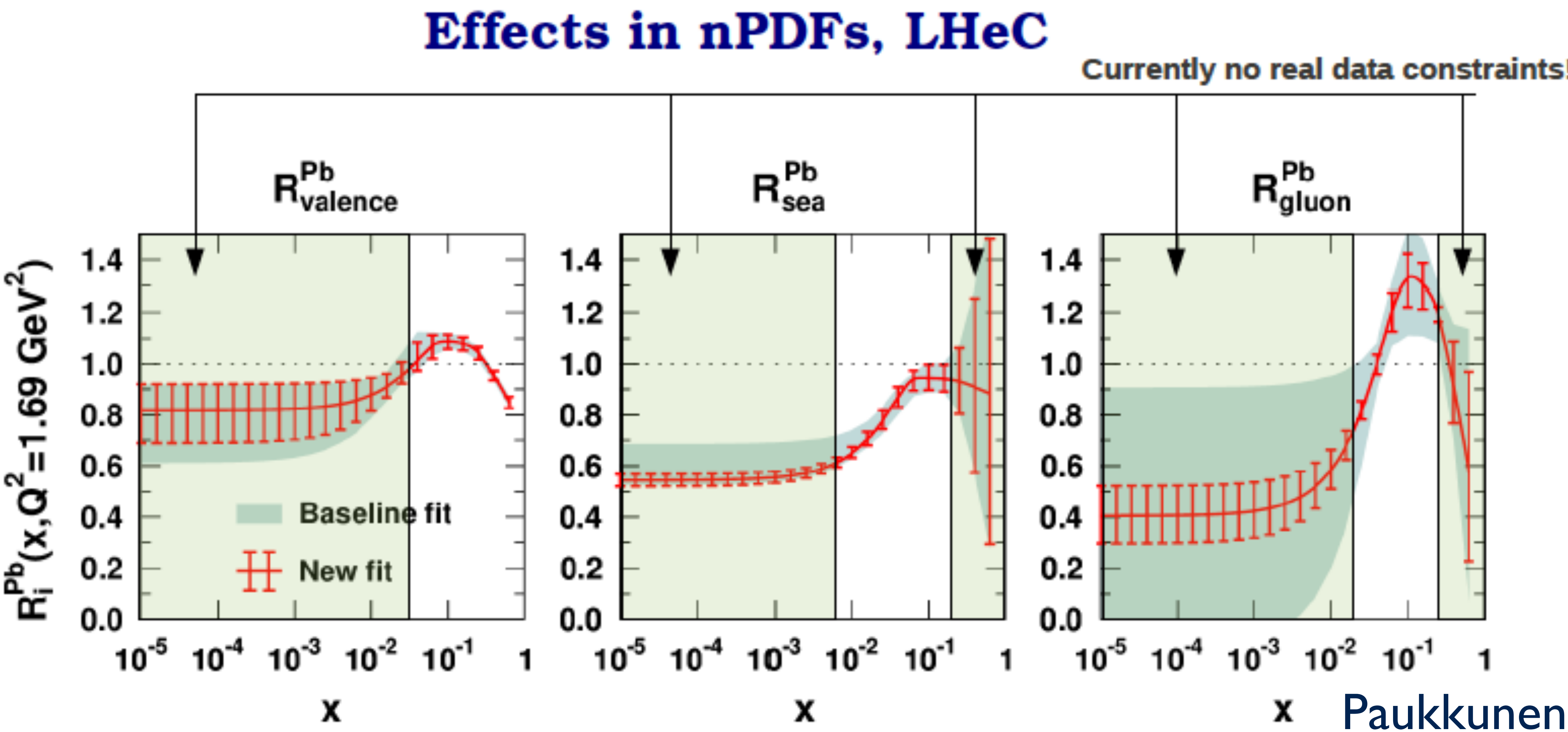


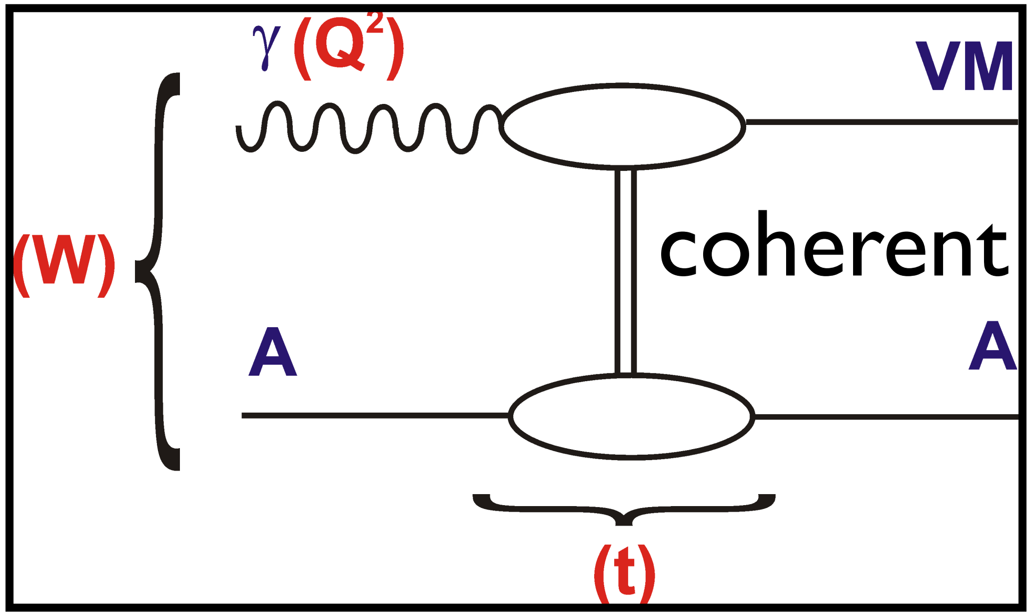
eA inclusive: constraining PDFs



Paukkunen

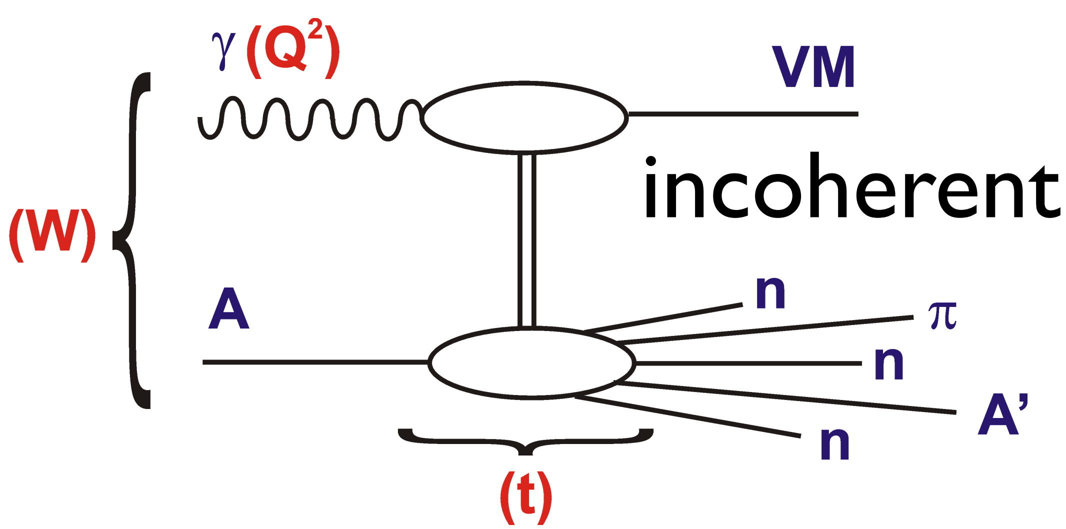
- New realm in nPDFs, to put them at the same level as those in p:
  - ➜ Reduction of uncertainties at small and large x.
  - ➜ Getting rid of assumptions in fits.
  - ➜ Addition of CC to perform flavour separation.

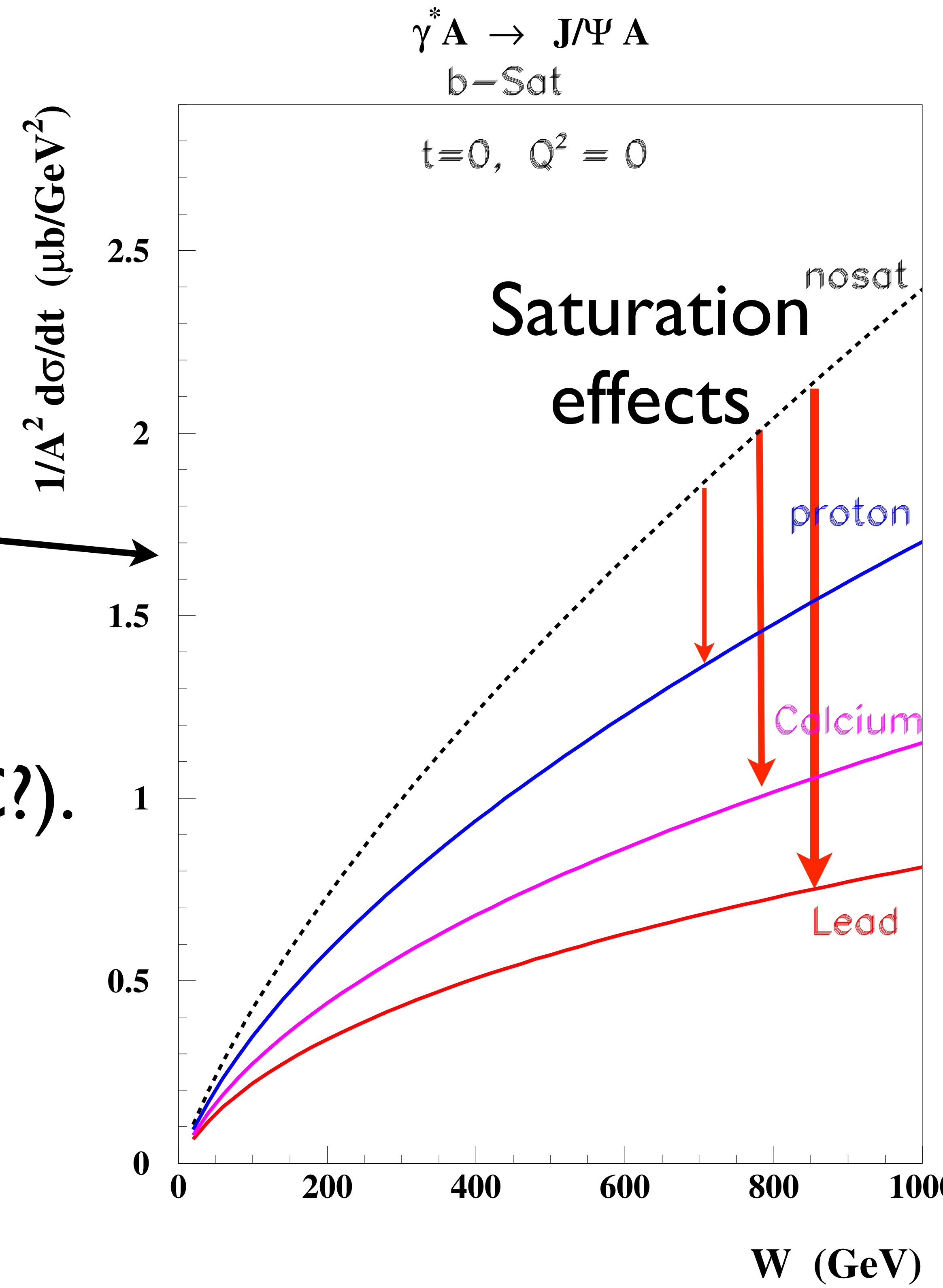
Elastic VM production in eA:



- For the coherent case, predictions available.

- Challenging experimental problem (neutron tagging in ZDC?).





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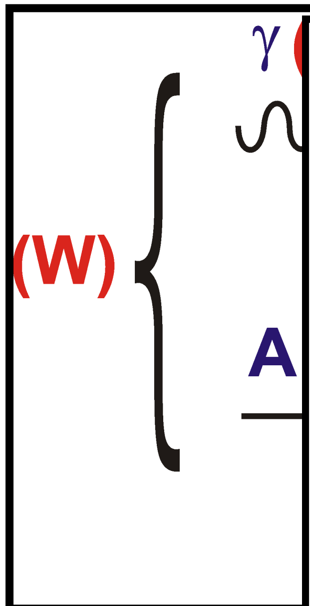
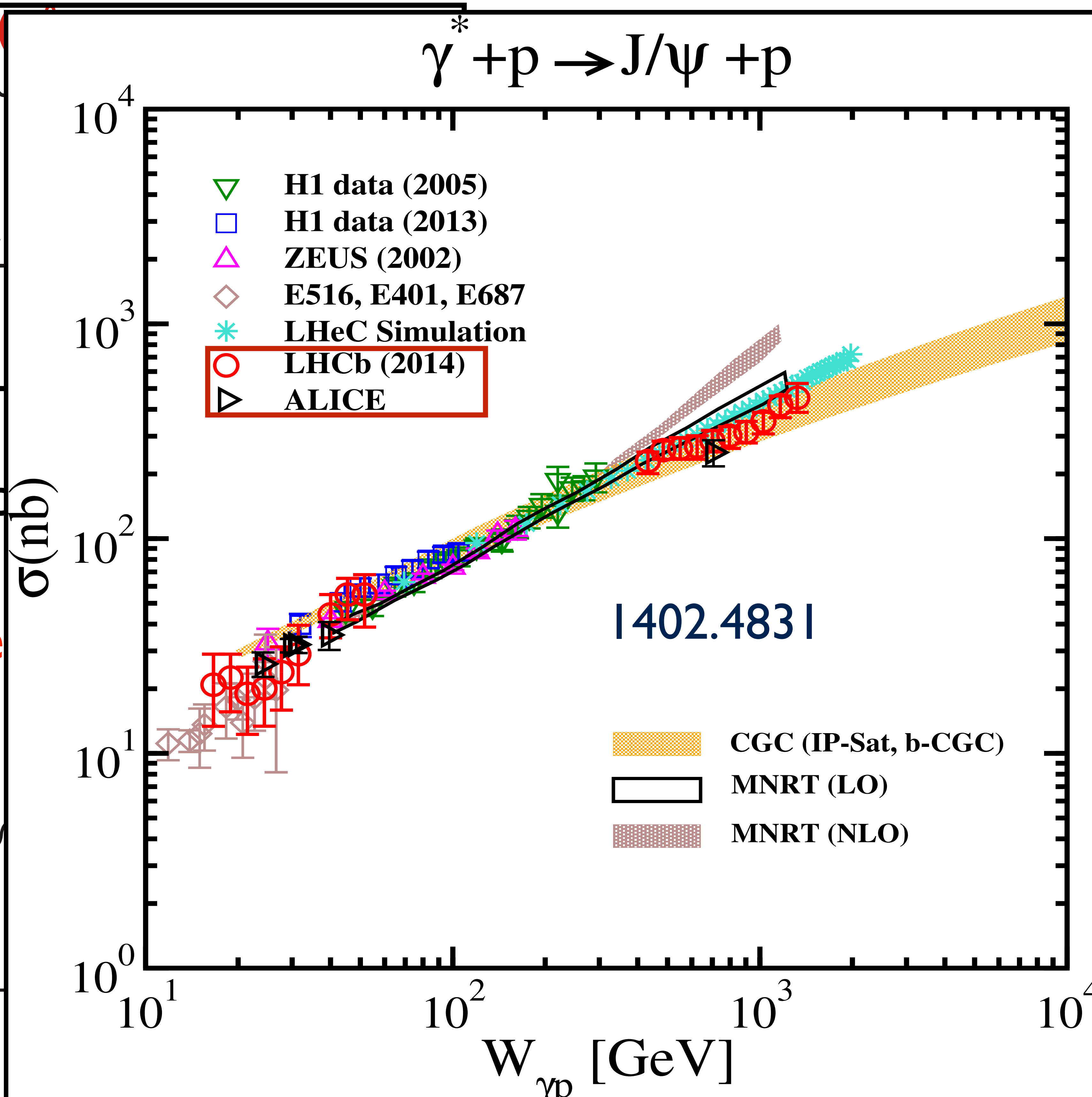
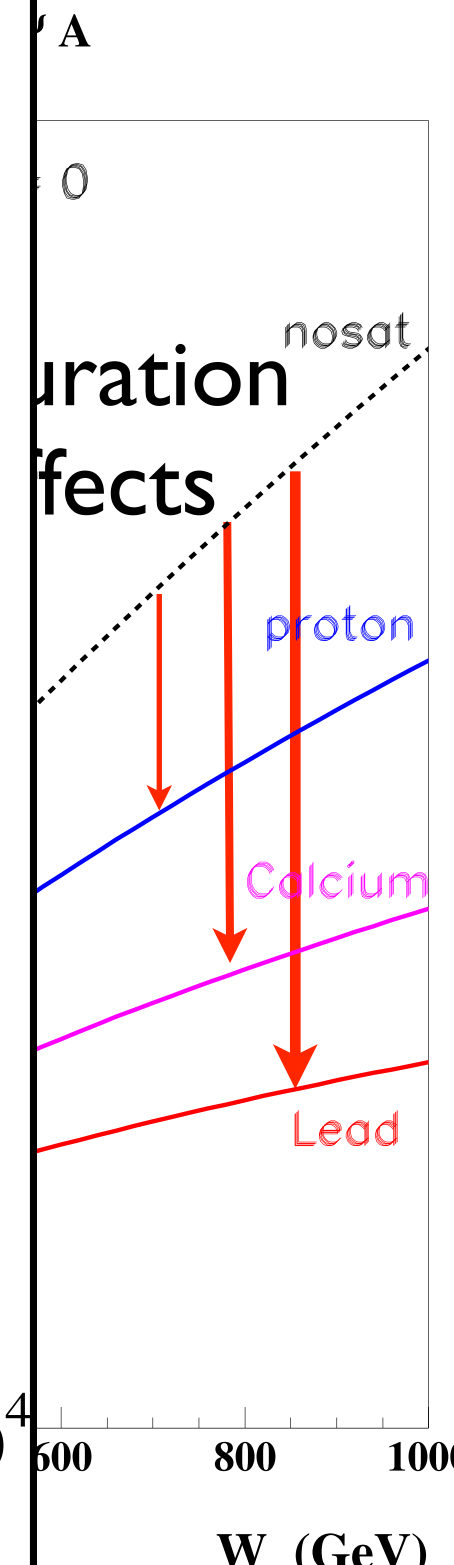
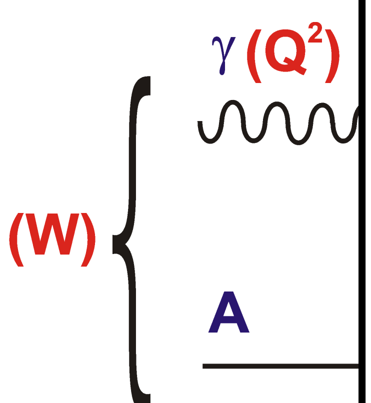




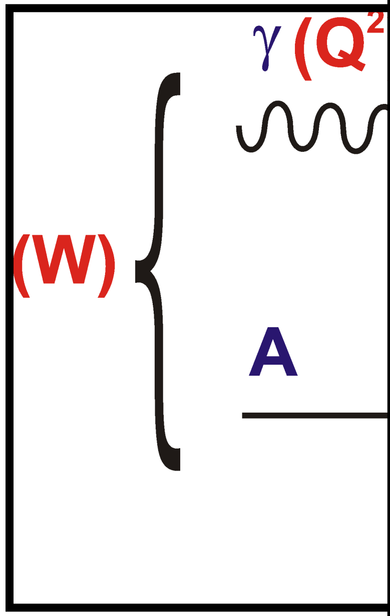


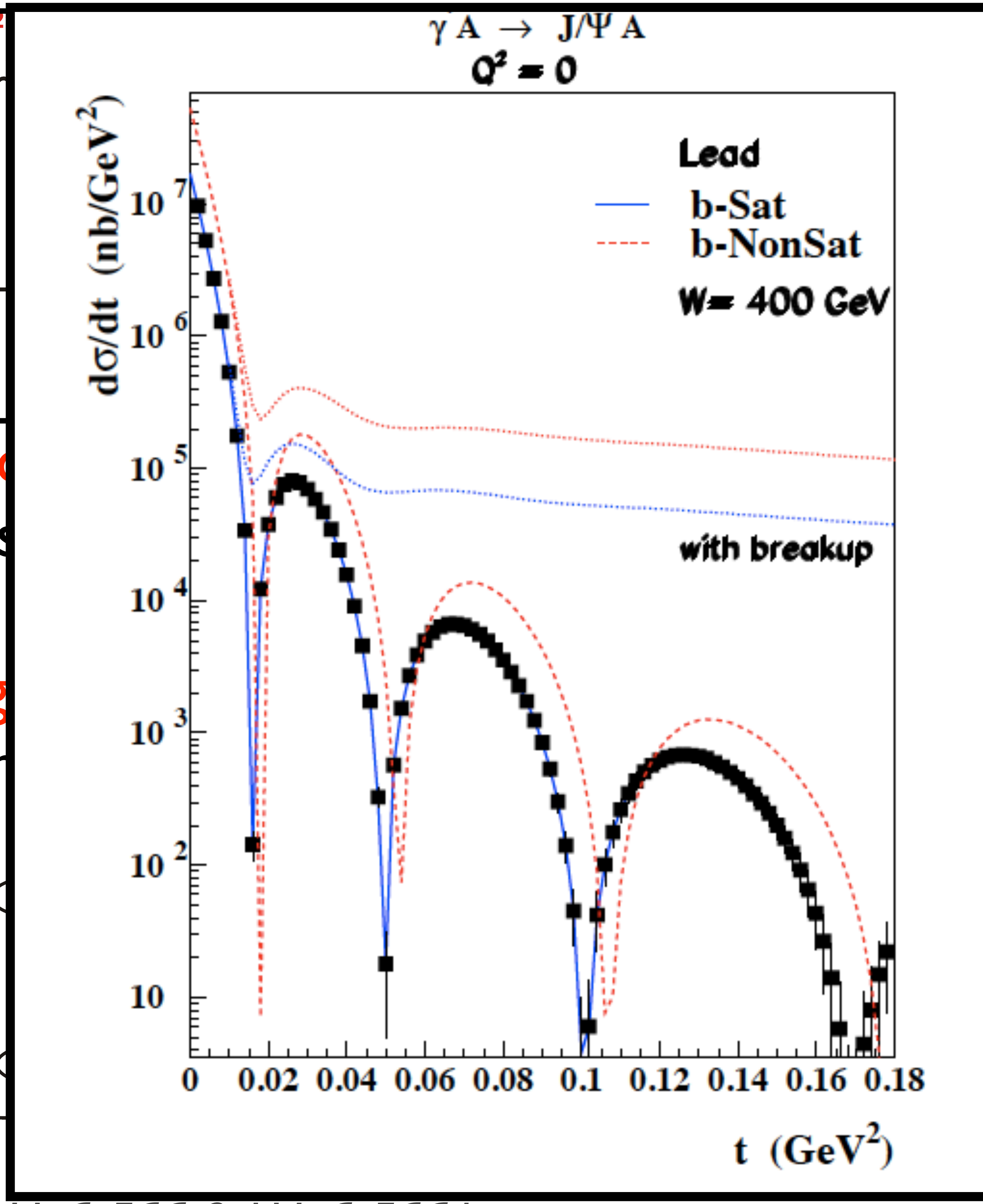
- For th
predictio

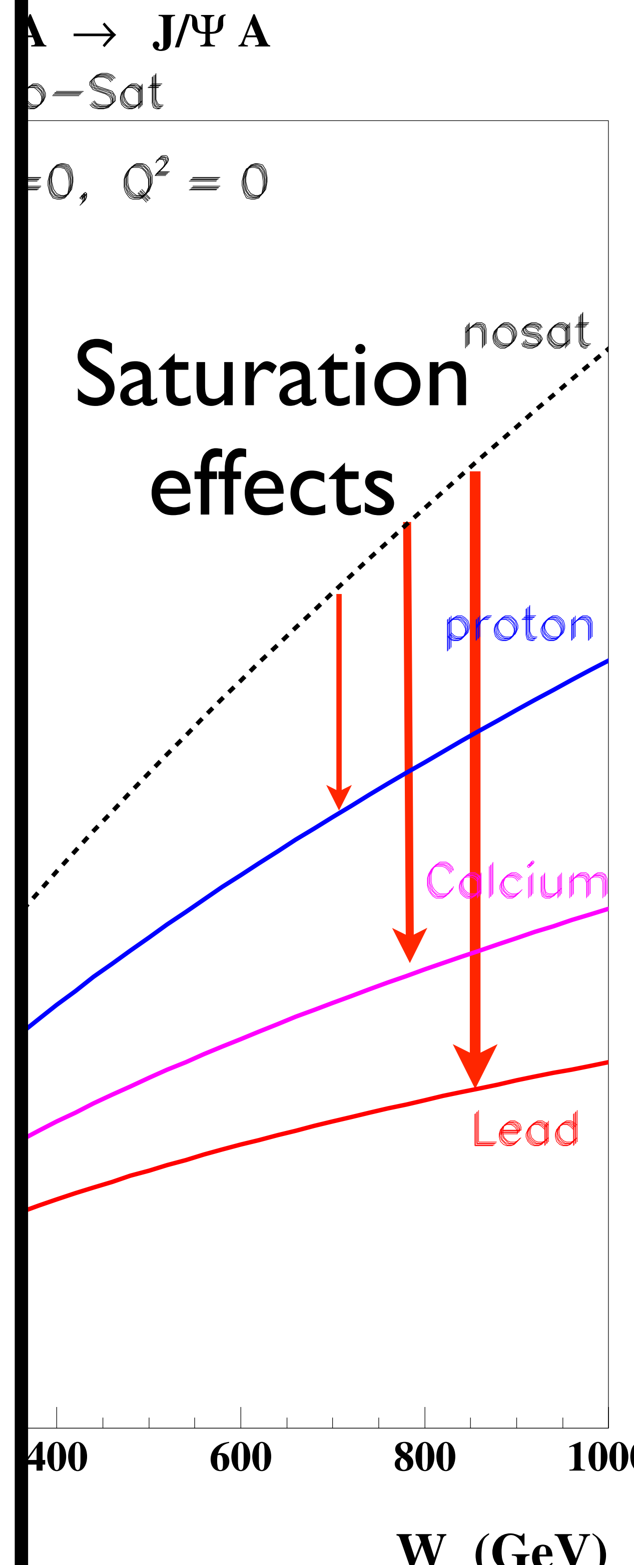
- Challe
problem



Elastic VM production in eA:

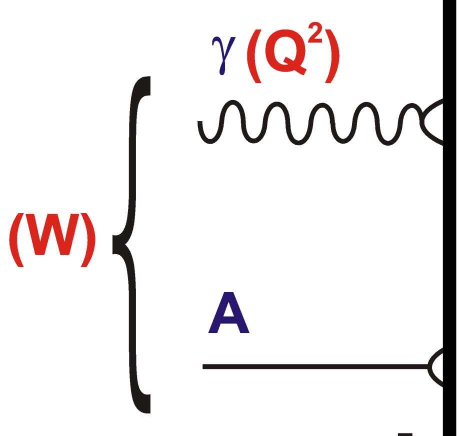




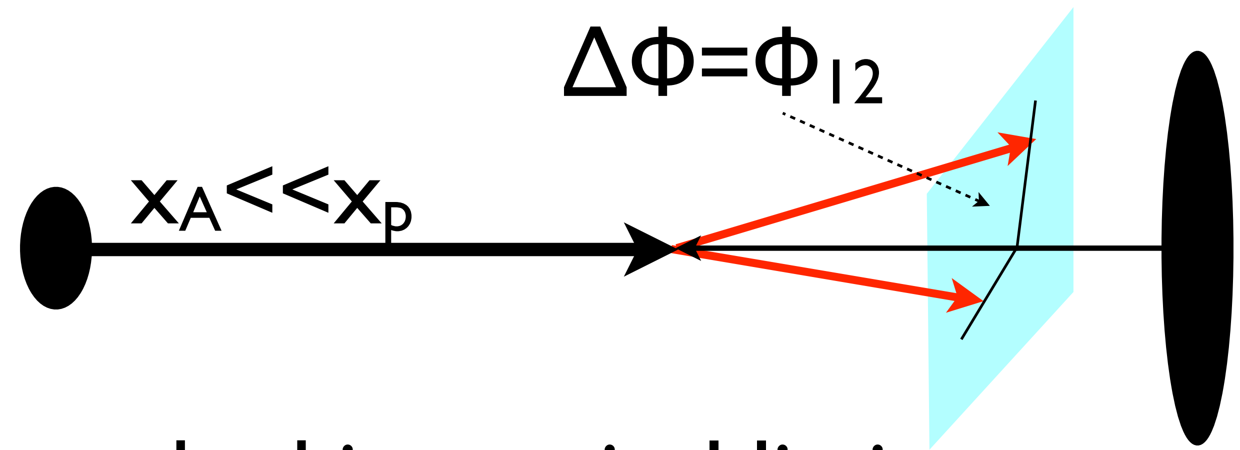


- For the
predictions

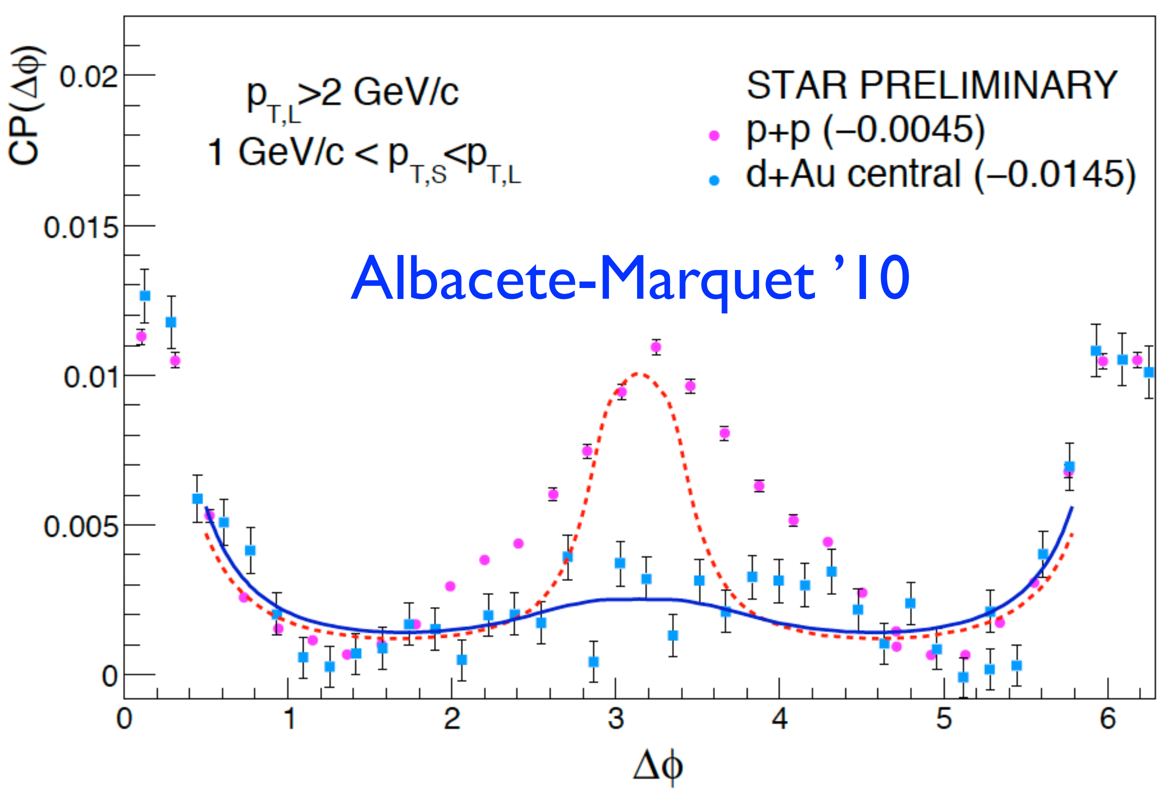
- Challeng
problem (r



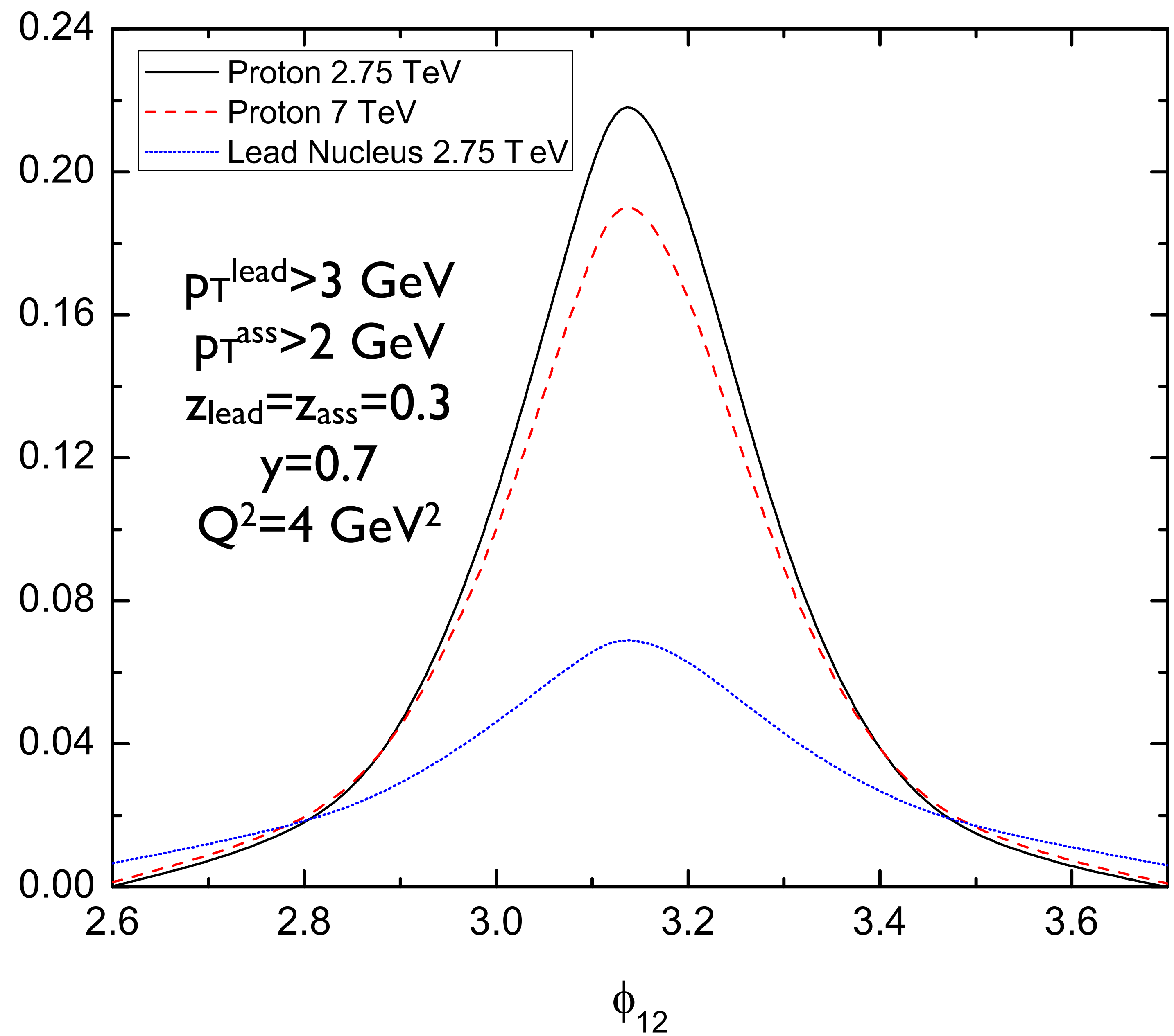
Dihadron azimuthal decorrelation:



- Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
- At HE eA it could be studied far from the kinematical limits.



$$C(\phi_{12}) = \frac{1}{\frac{d\sigma(\gamma^* N \to h_1 X)}{dz_{h1}}} \frac{d\sigma^{\gamma^* N \to h_1 h_2 + X}}{dz_{h1} dz_{h2} d\phi_{12}}$$



Summary:

- **FCC-AA:** extension of the pA/AA program to higher energies leading to
  - ➜ Hotter, longer-lived medium with larger opportunities to observe collectivity from small to large systems.
  - ➜ New degrees of freedom may become active.
  - ➜ Access to a large perturbative domain at small x: saturation.
  - ➜ Larger rates of harder probes, with new possibilities.
  - ➜ Tests of interaction models of wider interest.

- **LHeC, FCC-he:** eA colliders in the TeV cms regime providing
  - ➜ Clean access to a large perturbative domain at small x: saturation?
  - ➜ Determination of nPDFs for nuclear colliders, with the possibility of releasing many of the current assumptions.
  - ➜ Studies of QCD radiation and hadronisation inside the nuclear medium.
  - ➜ Transverse scan of hadrons and nuclei: nGPDs.
  - ➜ Diffraction.
  - ➜ … with implications on our understanding of pA and AA collisions.

Outlook:

- **FCC-AA** (espace2013.cern.ch/fcc/):
  ➜ CDR for the next European Strategy for Particle Physics in 2017/2018.
  ➜ Organisation: collaboration established, with FCC-hh, FCC-ee and FCC-he groups.
  ➜ Initial physics document to be produced for next summer.
  ➜ FCC-AA coordinators: A. Dainese, S. Maschiocci, C.A. Salgado, U.A. Wiedemann.
  ➜ Regular workshops: 12/13, 09/14.

- **LHeC, FCC-he** (cern.ch/lhec):
  ➜ TDR for the next European Strategy for Particle Physics in 2017/2018.
  ➜ Organisation: new IAC, new Coordination Group, several working groups, in the Study Group.
  ➜ Updated physics summary to be produced for next June.
  ➜ ERL Test Facility in CERN mid term plan since last June: LoI for end 2015.
  ➜ Small-x/eA coordinators: NA, Paul Newman, Anna Stasto.
  ➜ Regular workshops: 01/14, **24-26/06/15 Chavannes-de-Bogis**.

- **FCC week 2015**: Washington D.C., 23-27/03/2015, hh, ee, he.

Visit the web pages: everybody is more than welcome to join!!!

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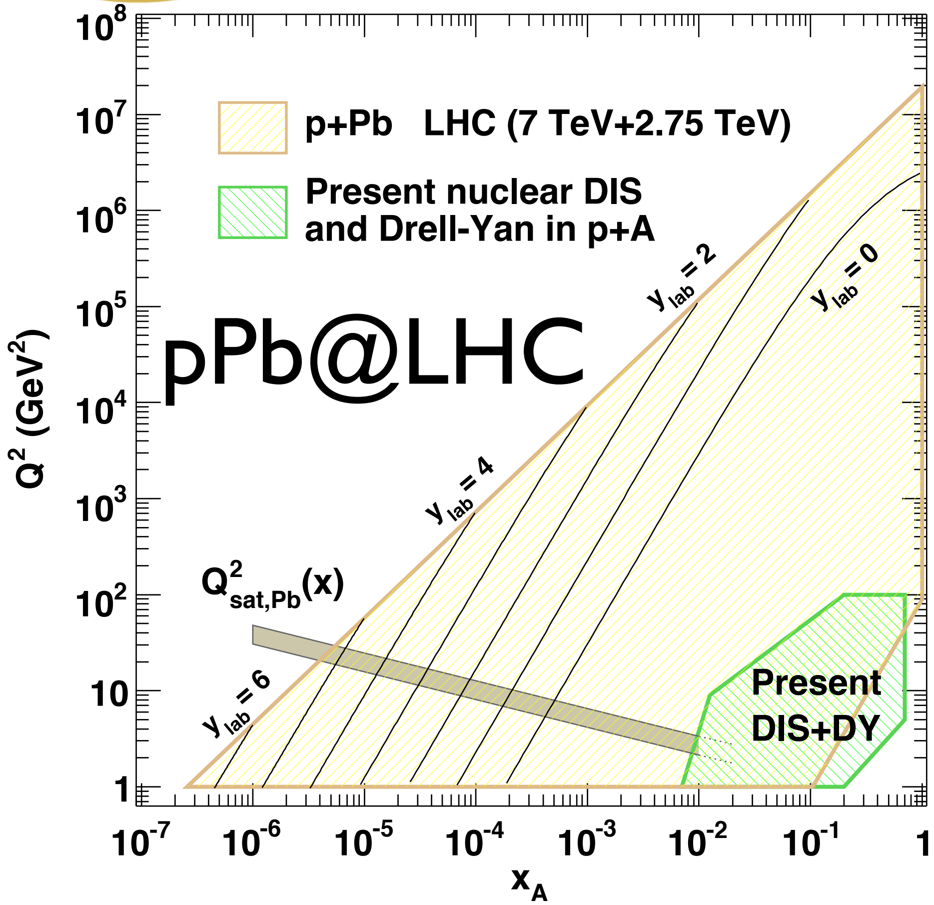
Thanks a lot to the organisers for the invitation, to Andrea, Max Klein and Paul for comments, and to you for your attention!!!

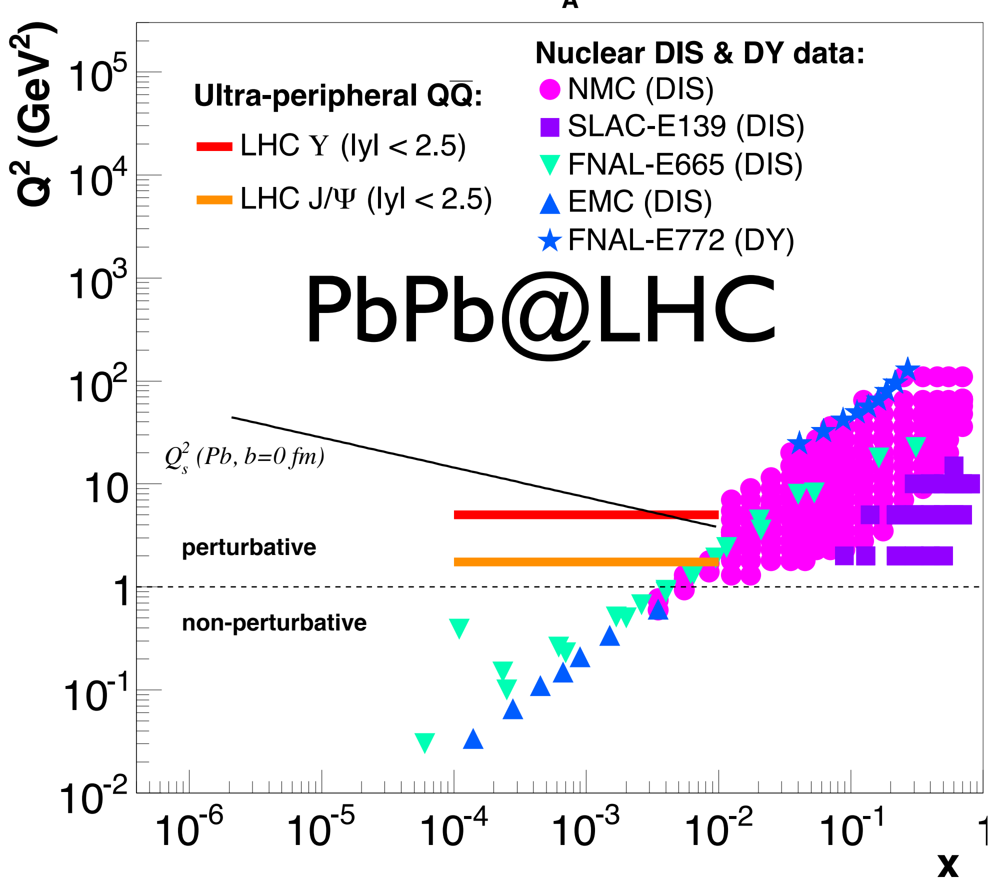
- **FCC week 2015**: Washington D.C., 23-27/03/2015, hh, ee, he.

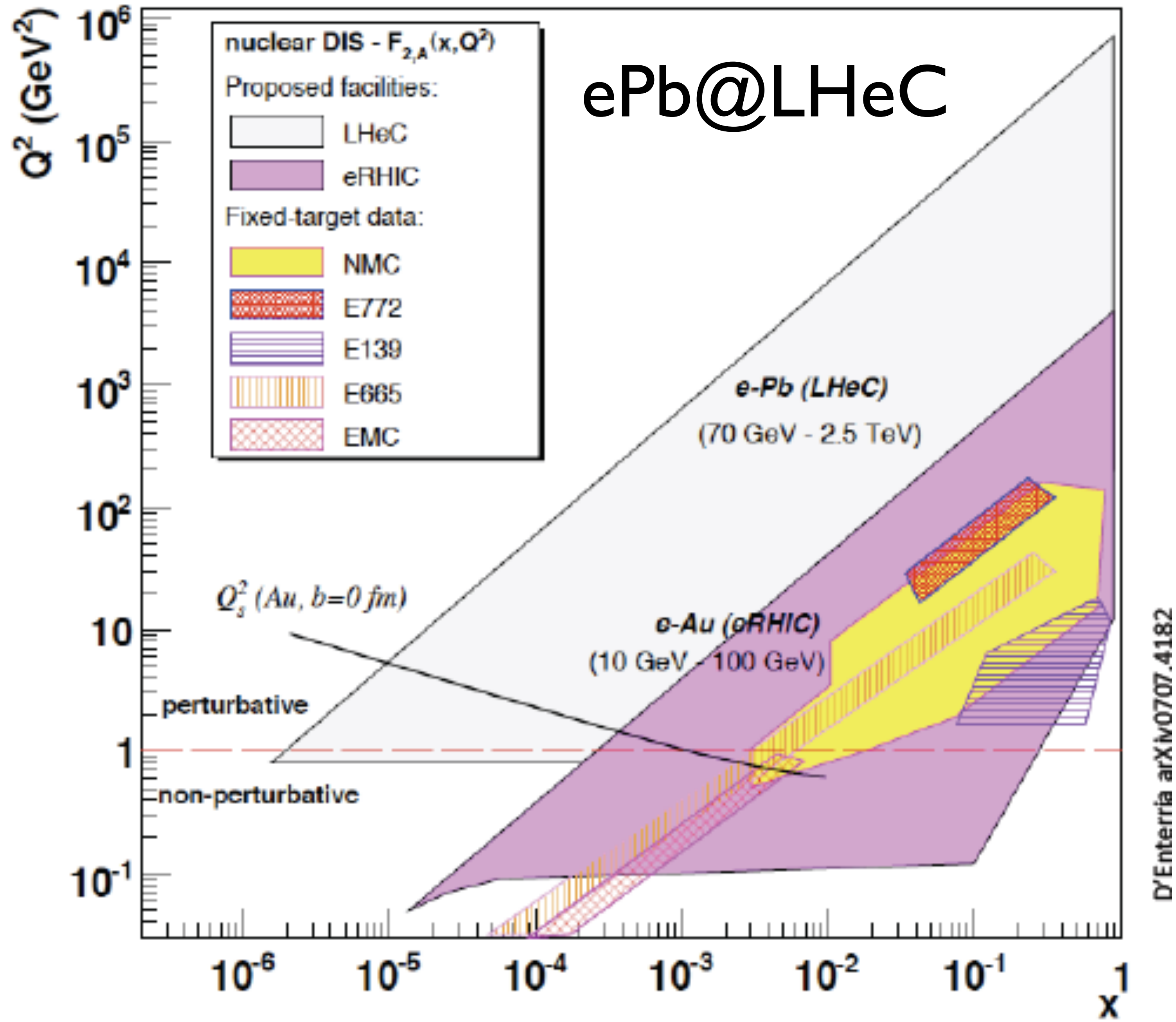
Visit the web pages: everybody is more than welcome to join!!!

Backup:

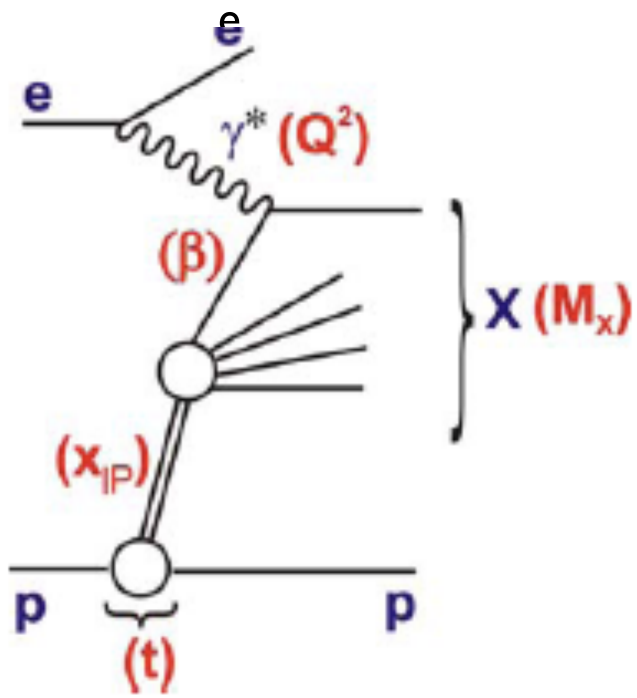
LHC vs. LHeC:

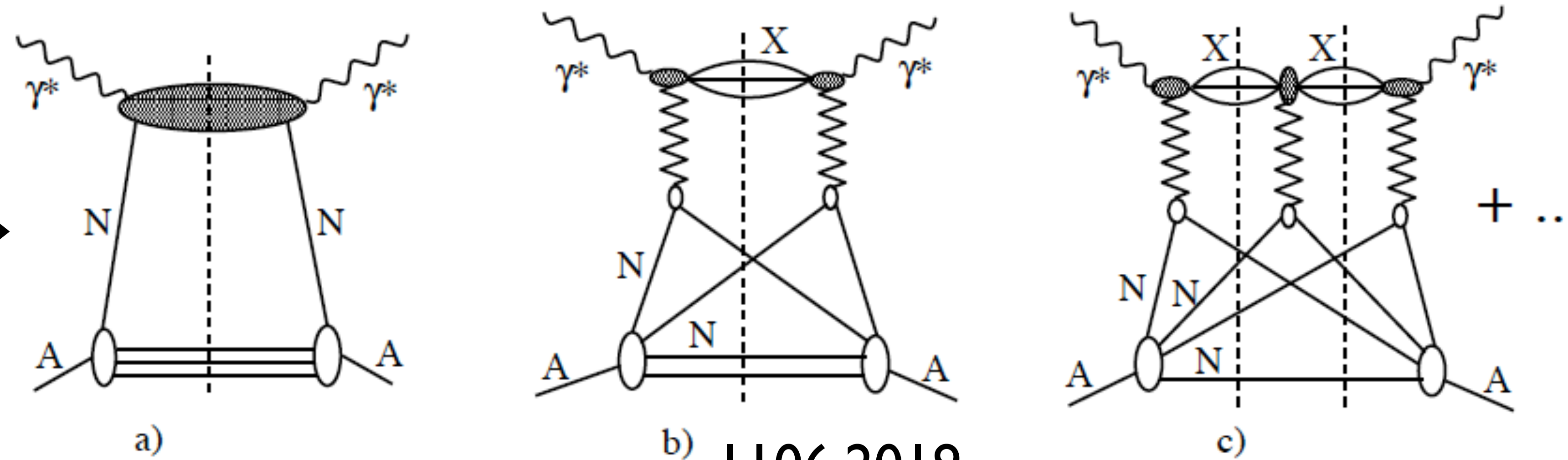

p+Pb LHC (7 TeV+2.75 TeV)
Present nuclear DIS and Drell-Yan in p+A
pPb@LHC
$y_{lab} = 2$
$y_{lab} = 0$
$y_{lab} = 4$
$y_{lab} = 6$
$Q^2_{sat,Pb}(x)$
Present DIS+DY
Q^2 (GeV^2)
x_A


Ultra-peripheral $Q\bar{Q}$:
LHC Υ (|y| < 2.5)
LHC J/Ψ (|y| < 2.5)
Nuclear DIS & DY data:
NMC (DIS)
SLAC-E139 (DIS)
FNAL-E665 (DIS)
EMC (DIS)
FNAL-E772 (DY)
PbPb@LHC
Q_s^2 (Pb, b=0 fm)
perturbative
non-perturbative
Q^2 (GeV^2)
x


nuclear DIS - $F_{2,A}(x,Q^2)$
Proposed facilities:
LHeC
eRHIC
Fixed-target data:
NMC
E772
E139
E665
EMC
ePb@LHeC
e-Pb (LHeC)
(70 GeV - 2.5 TeV)
e-Au (eRHIC)
(10 GeV - 100 GeV)
Q_s^2 (Au, b=0 fm)
perturbative
non-perturbative
Q^2 (GeV^2)
x
D'Enterria arXiv0707.4182

Diffraction in ep and shadowing:





1106.2019

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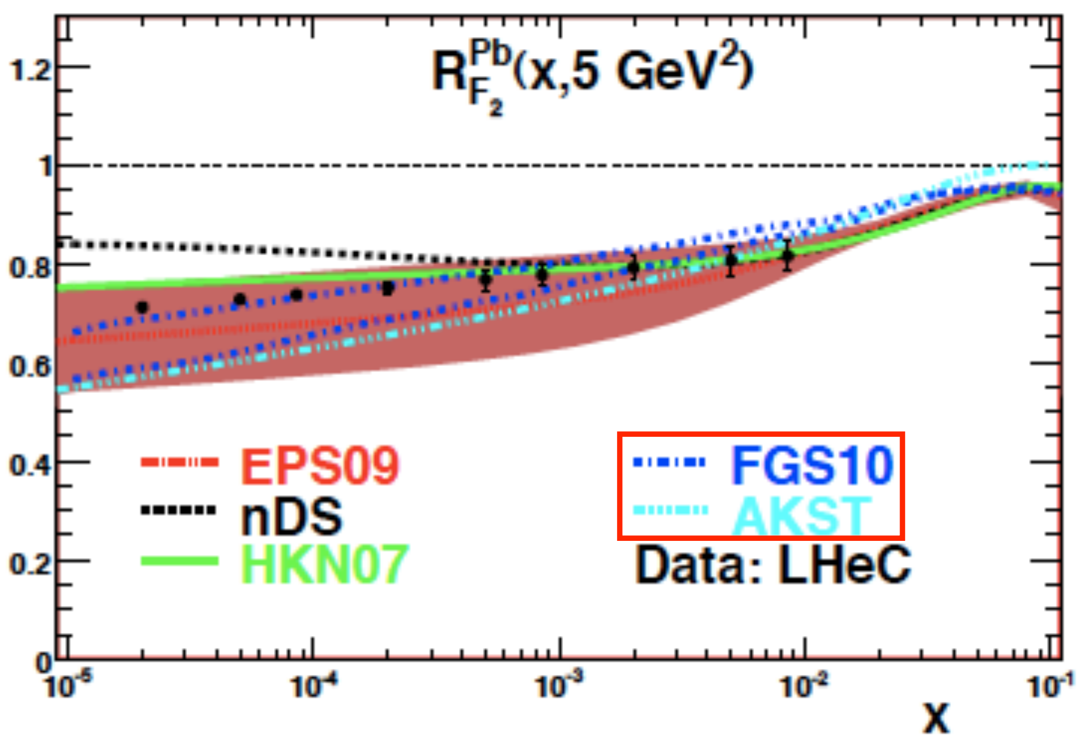

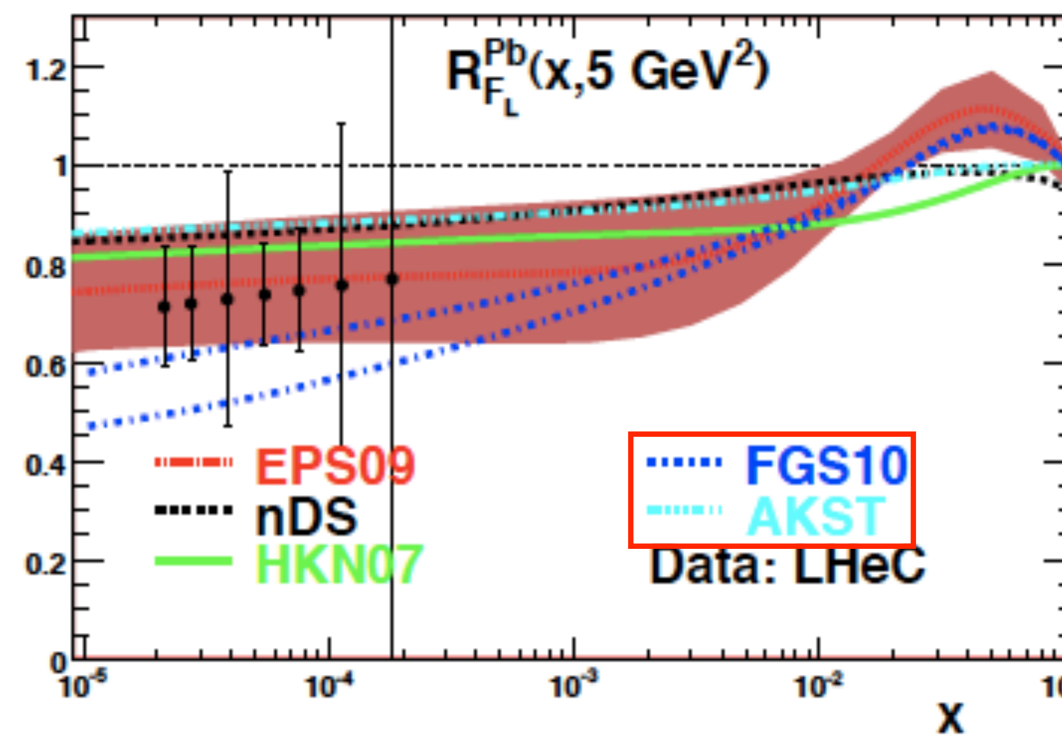

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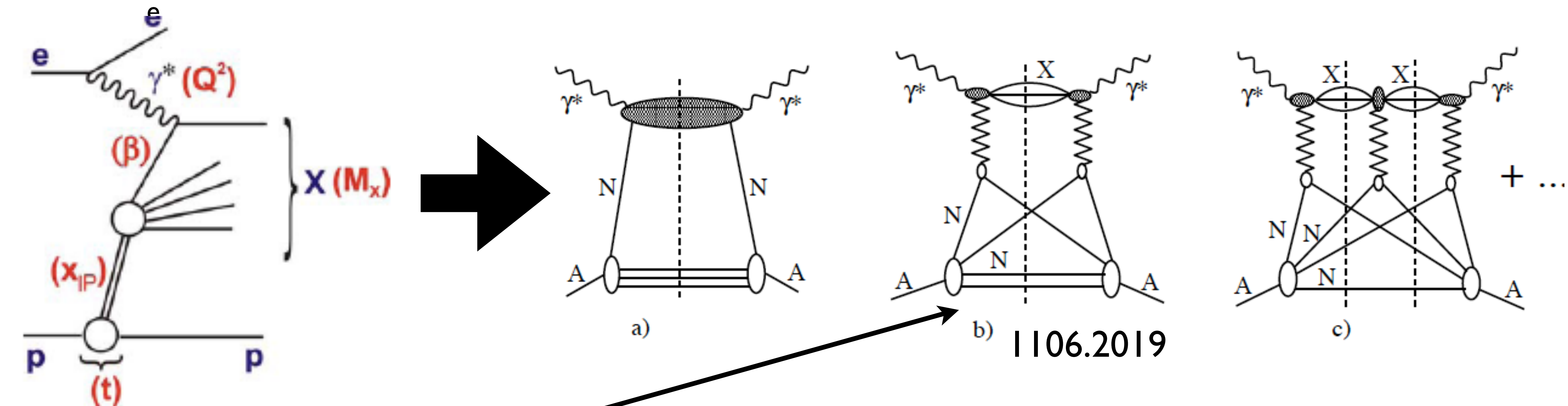

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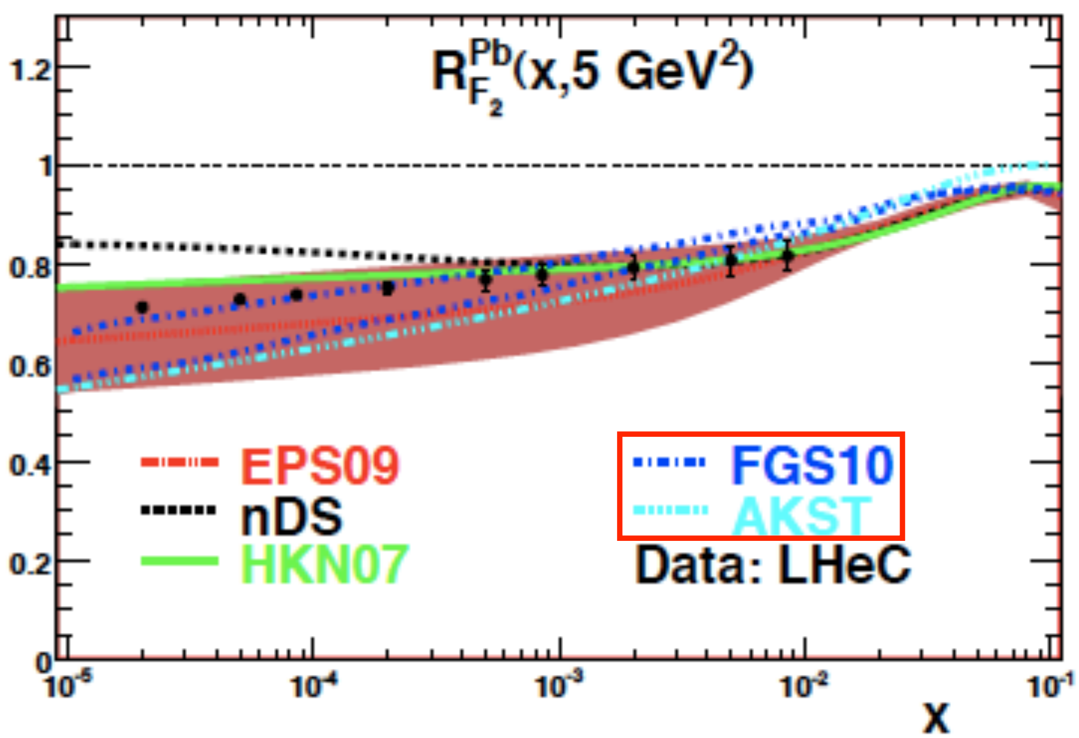
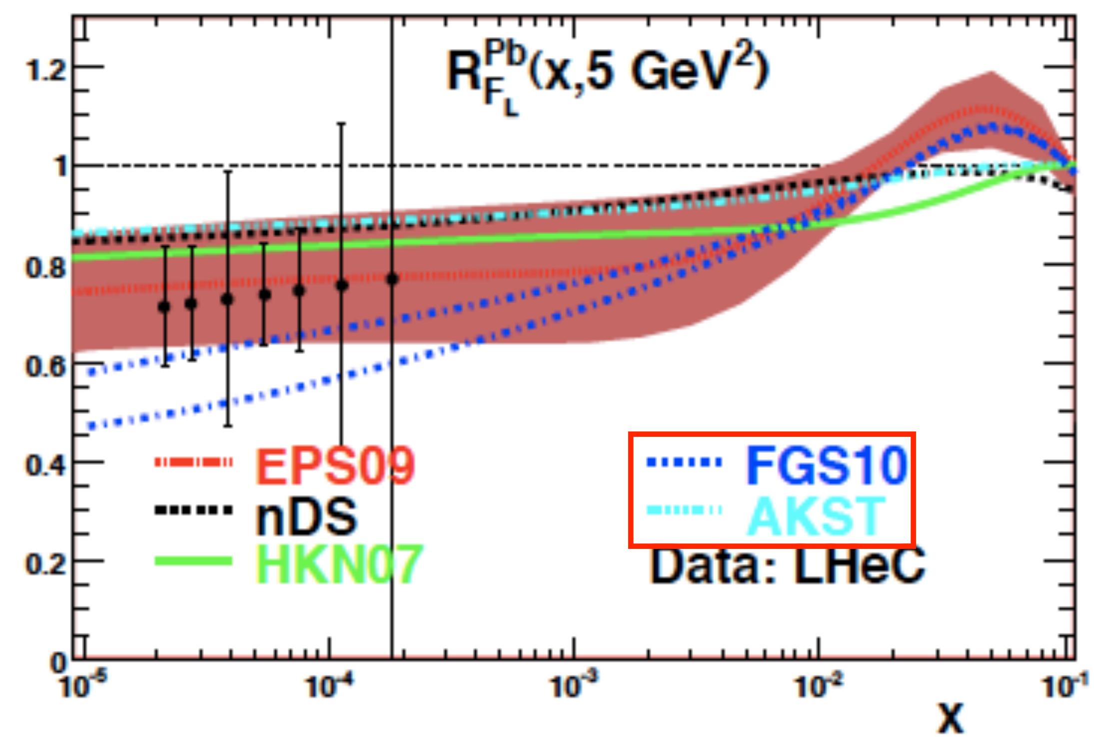
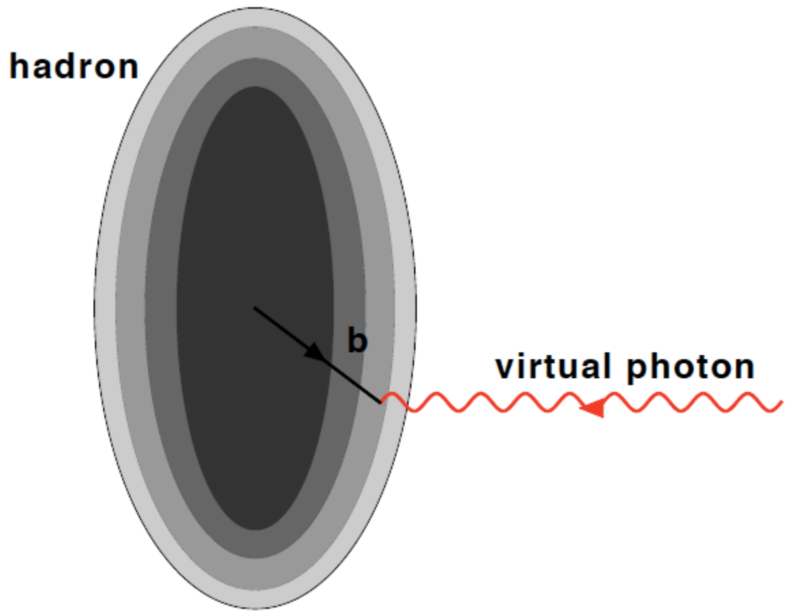
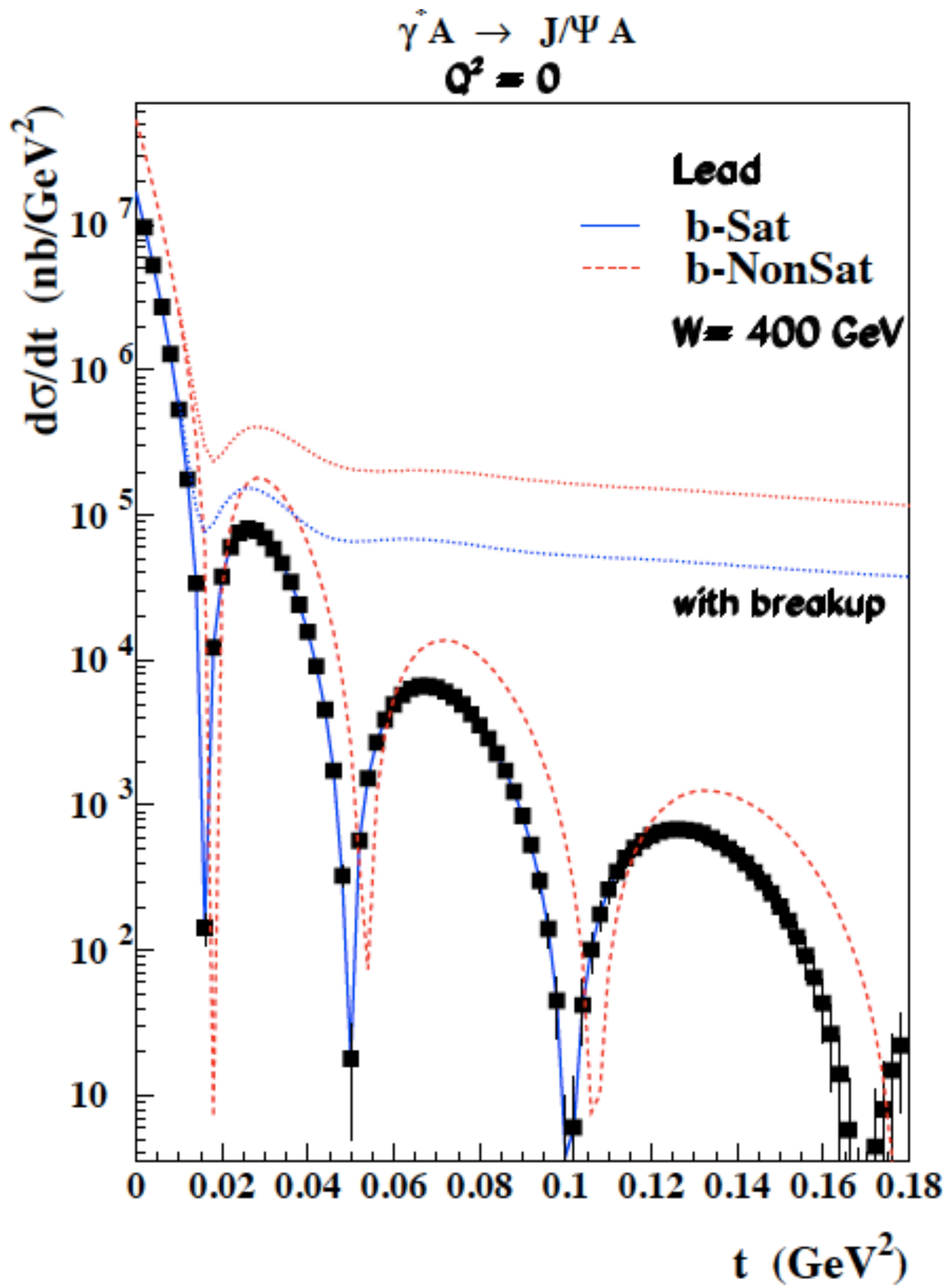




Transverse scan: elastic VM

- t-differential measurements give a gluon tranverse mapping of the hadron/nucleus.





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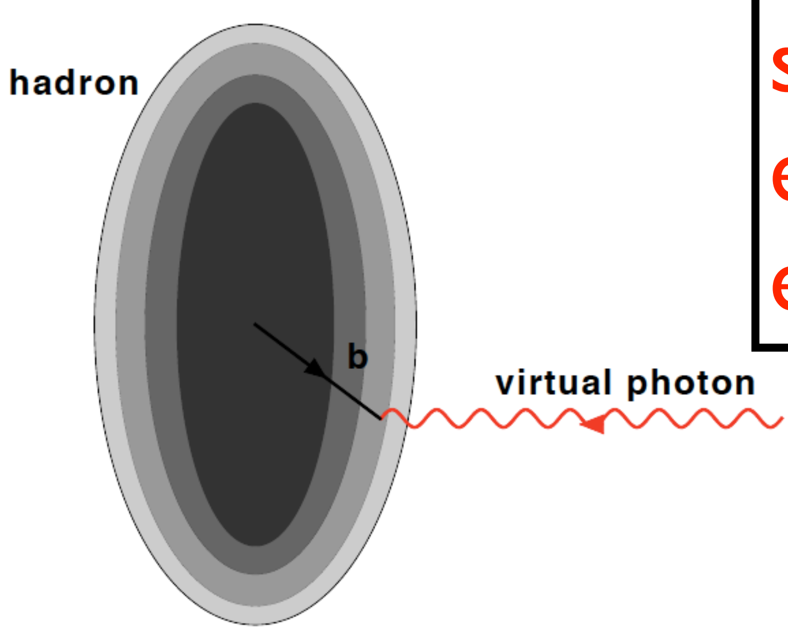
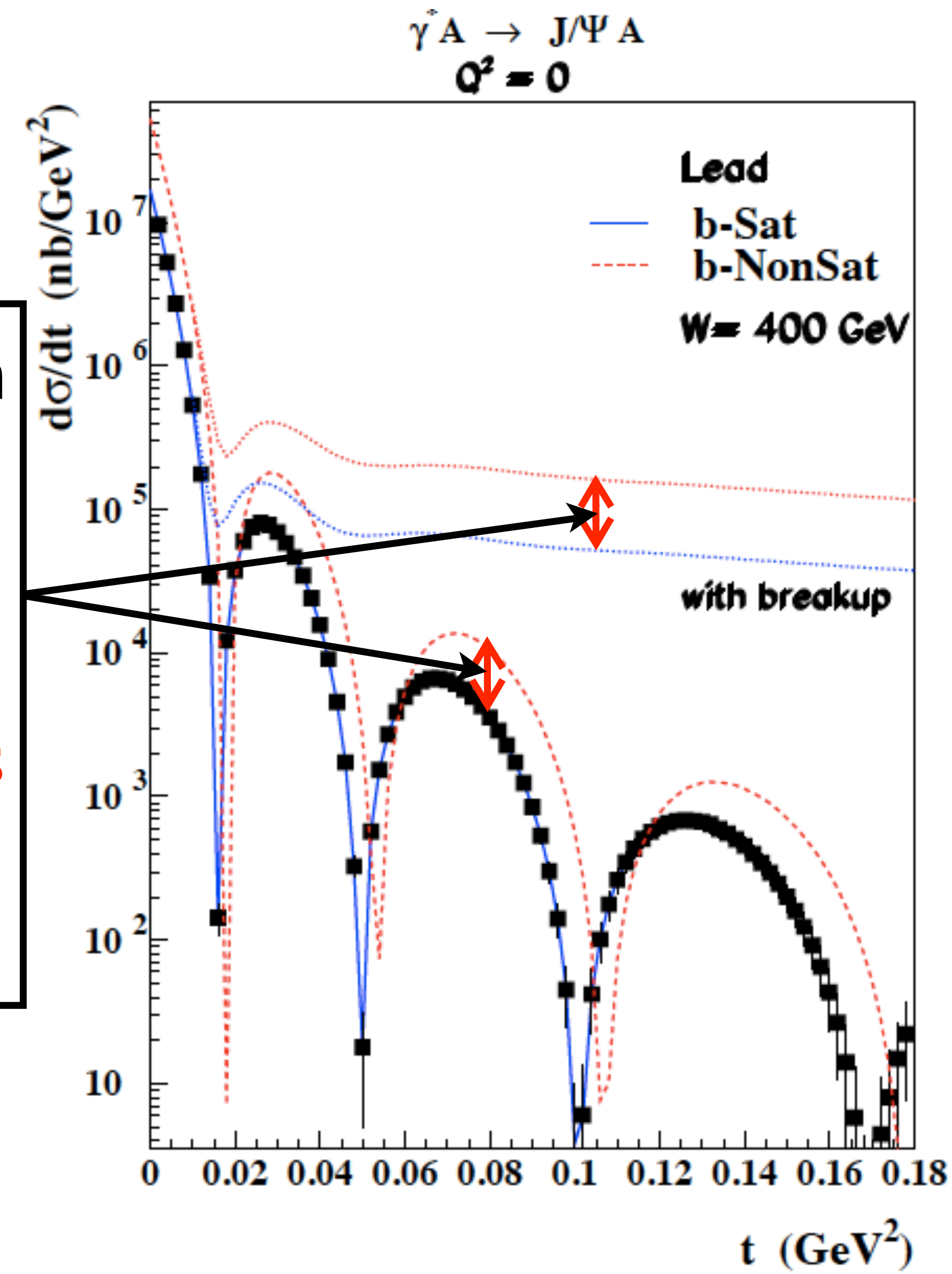


- Large extent in t with good precision.
- Sizable saturation effects expected (also in ep, 1402.4831).

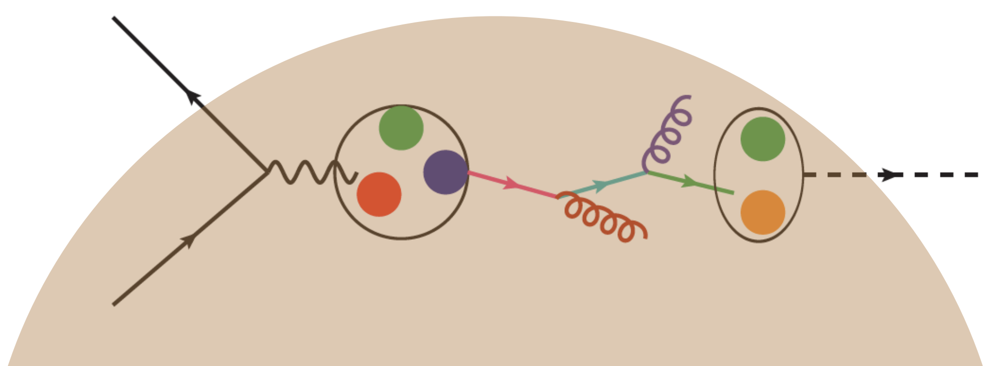


Radiation and hadronization:

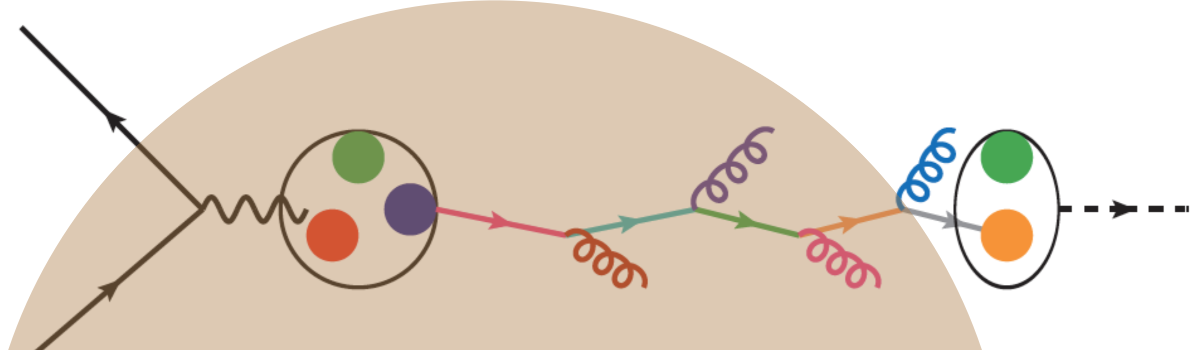
- LHeC: dynamics of QCD radiation and hadronization.
- Most relevant for particle production off nuclei and for QGP analysis in HIC.

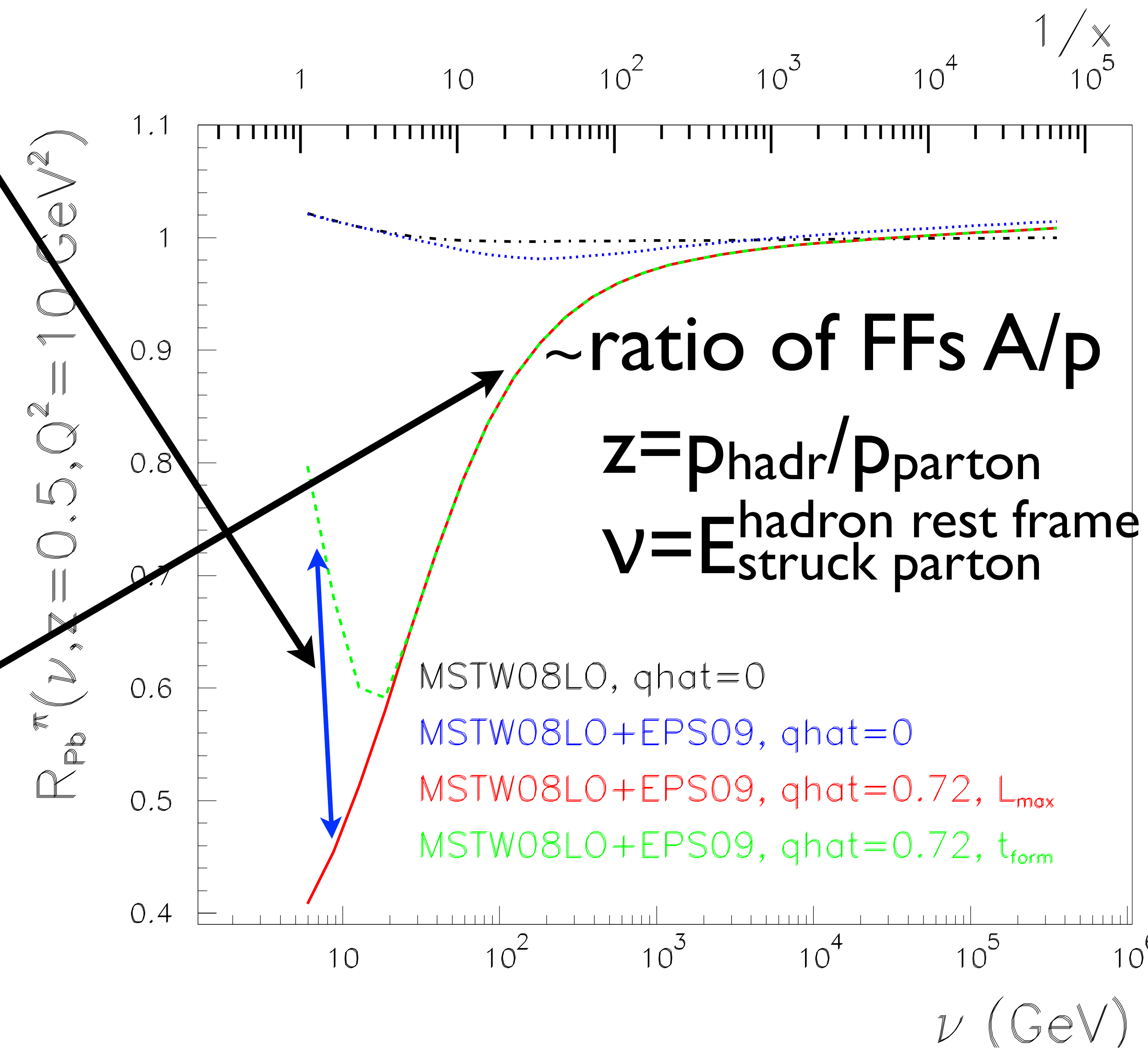
$$R_A^h(z,\nu) = \frac{1}{N_A^e}\frac{dN_A^h(z,\nu)}{d\nu\, dz} \Big/ \frac{1}{N_D^e}\frac{dN_D^h(z,\nu)}{d\nu\, dz}$$

- Low energy: hadronization inside → formation time, (pre-)hadronic absorption,...



- High energy: partonic evolution altered in the nuclear medium.





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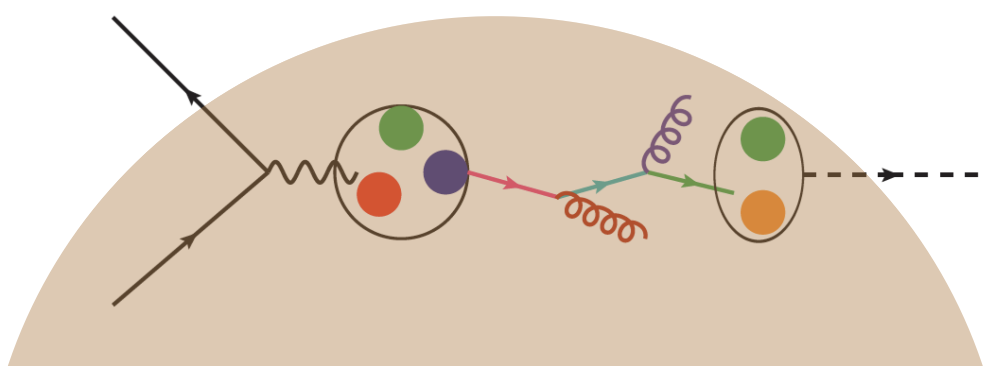

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