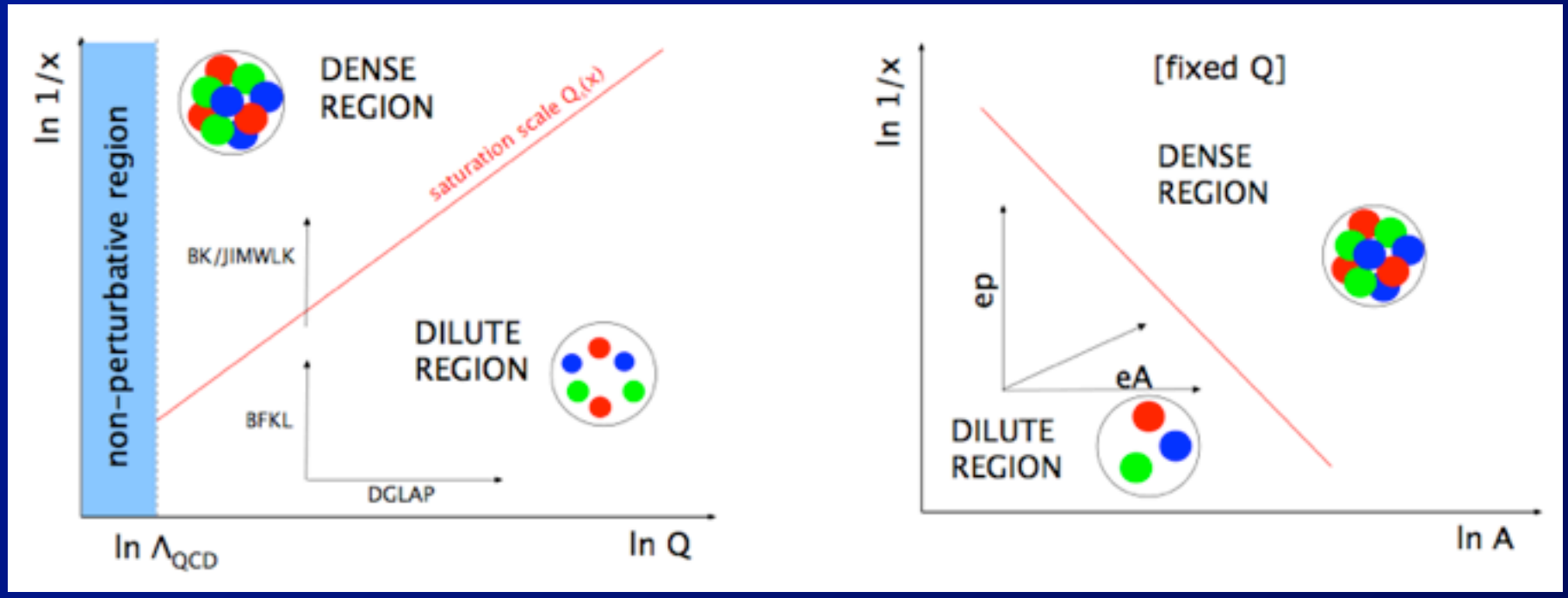
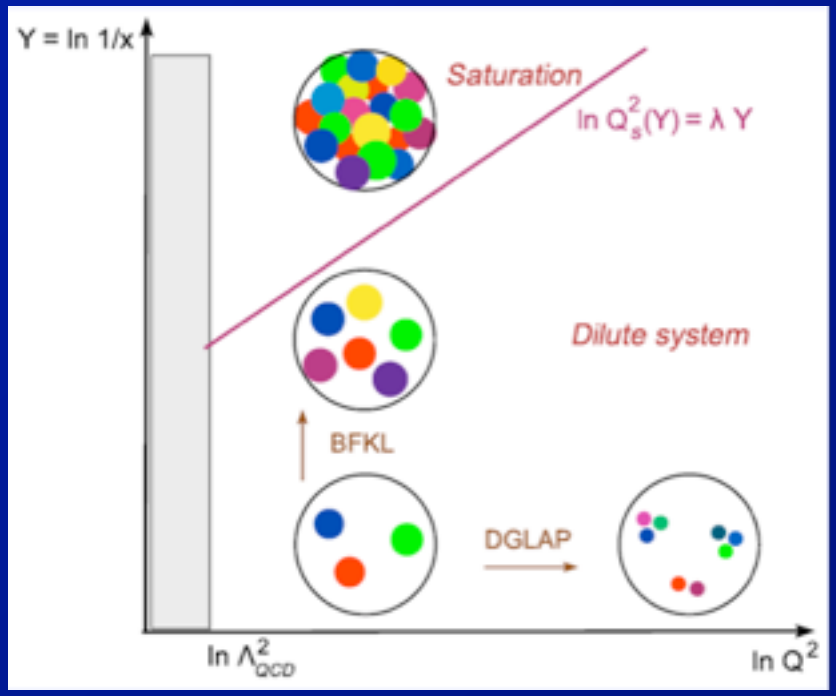
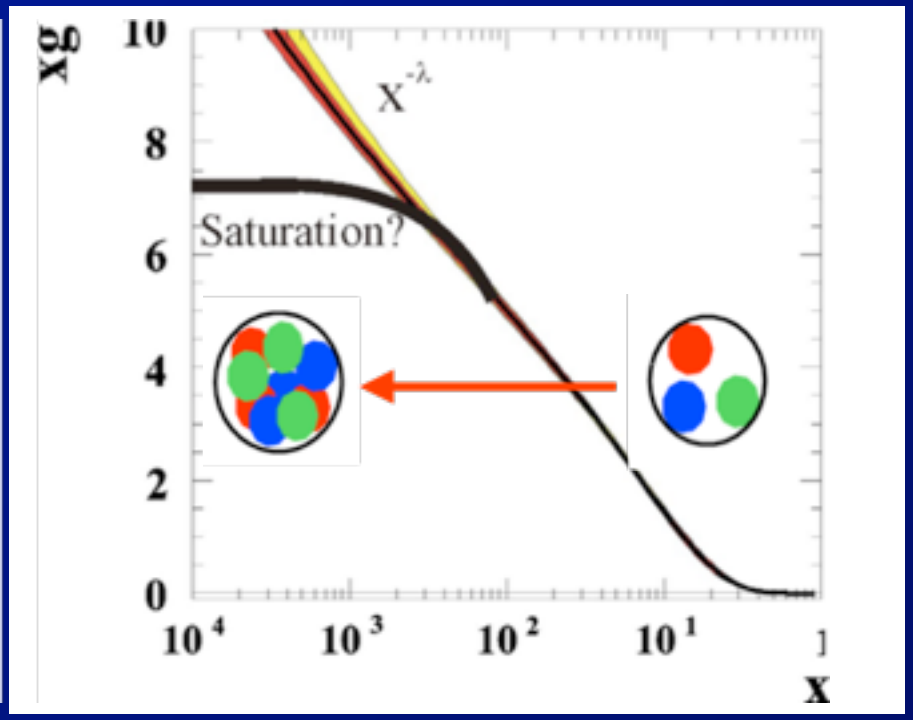
Studying QCD at high field strength in e-A collisions

Prof. Brian A. Cole
Columbia University



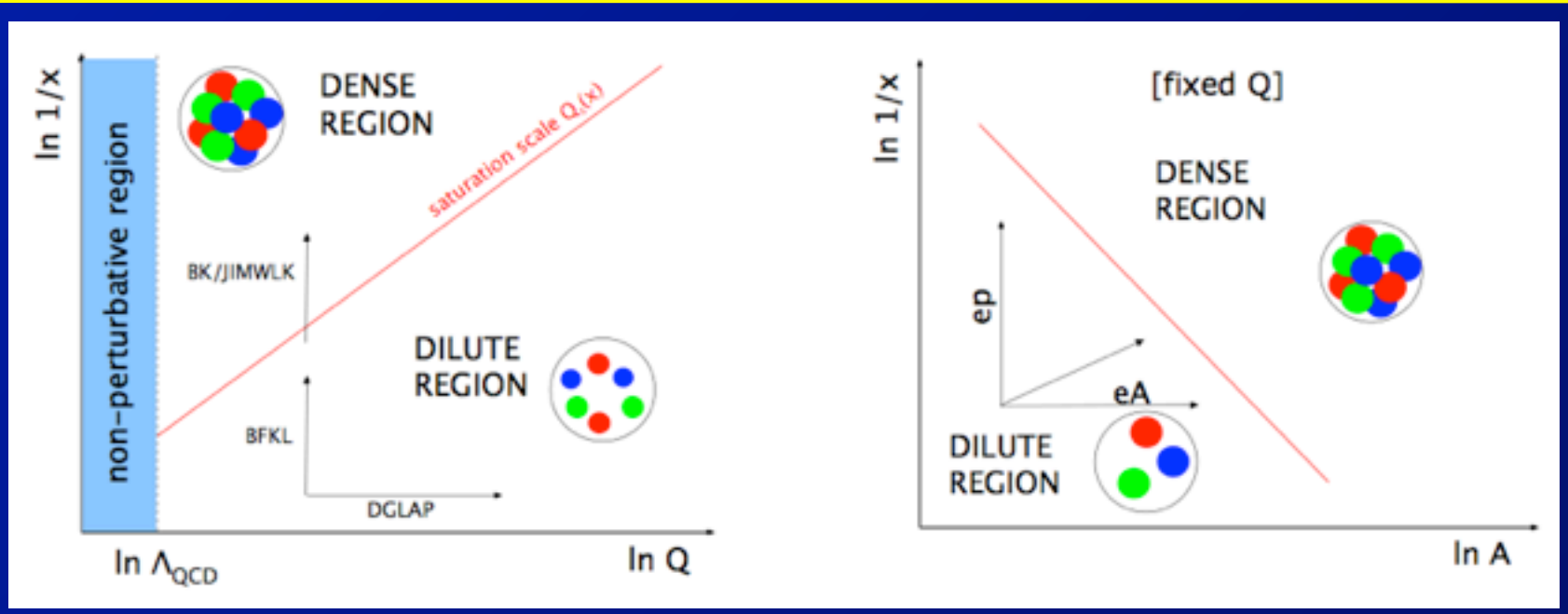
Low-x, saturation





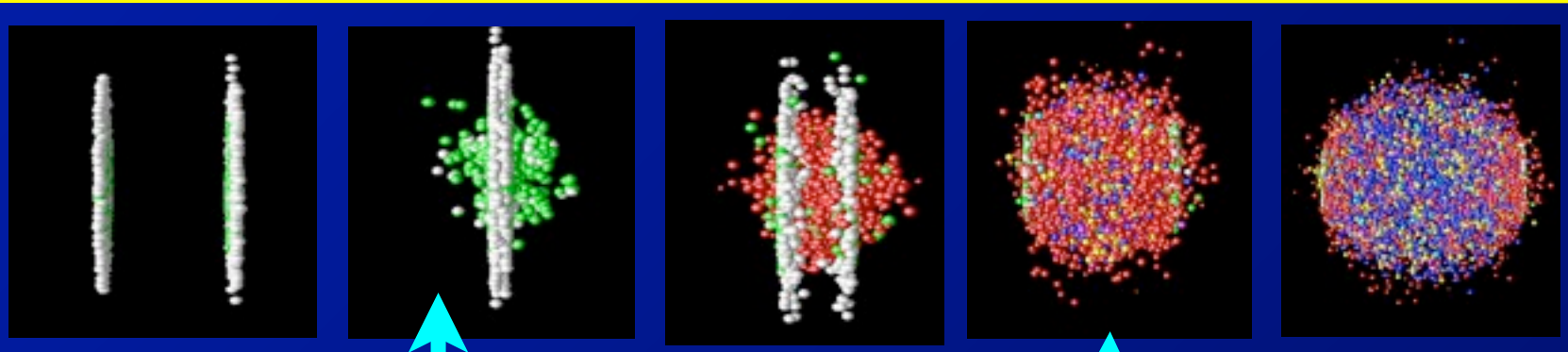
- Well-known problem with breakdown of linear/ independent evolution of parton distributions at high parton density, low-x (unitarity)
  - ⇒"Saturation"
- Saturation regime indicated by dynamical scale: Q_s
  - ⇒When $Q_s >> \Lambda_{QCD}$, unitarity expected to be due to partonic mechanisms (recombination)

Saturation in nuclei



- **Different ways to achieve high parton density in hadron-hadron or e-hadron collisions**
  - Increase energy
    - ⇒Parton density grows by evolution
  - Increase "density" of hadron
    - ⇒Use nuclei
- **In principle, to study parton density effects:**
  - ⇒fix (e.g.) DIS kinematics, increase A

Heavy ion "concordance model"



Initial gluon emission from saturated nuclei

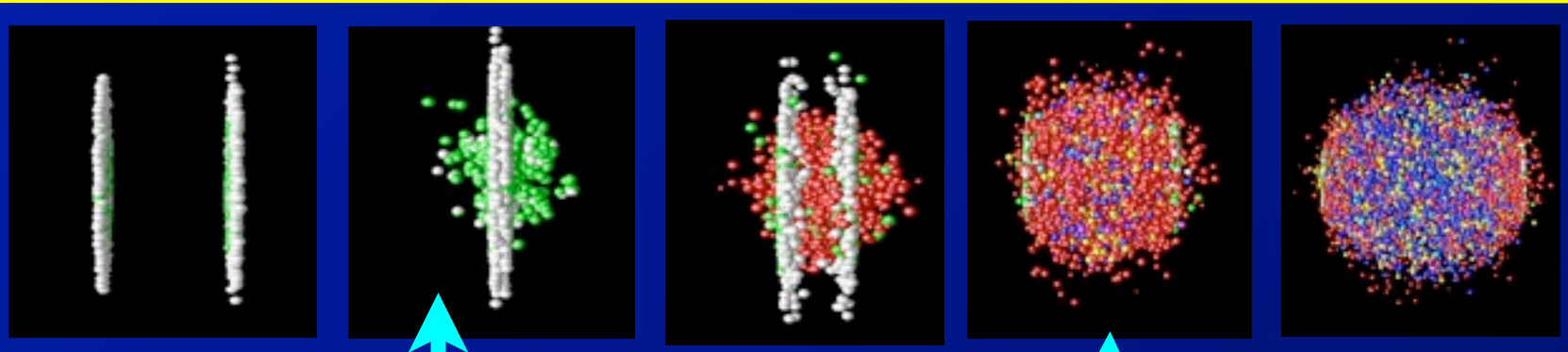
Rapid Thermalization

Hydrodynamic Evolution

Hadronization

- Initial particle production from strong gluon fields (saturated) in the incident nuclei.
- Created particles rapidly (τ < 0.5-1 fm/c!) thermalize into a strongly coupled QGP.
- QGP evolves hydrodynamically with an η/s ratio close to conjectured lower bound.

Heavy ion "concordance model"



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Saturation in nuclei *a la* Mueller

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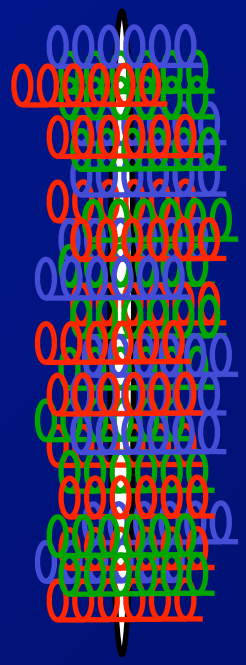
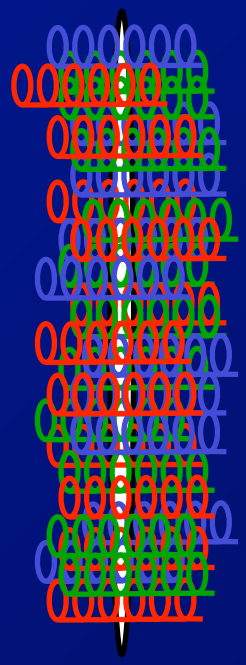
  - Except for low-momentum gluons which have spatial spread $\Delta z \geqslant \hbar/p_z$

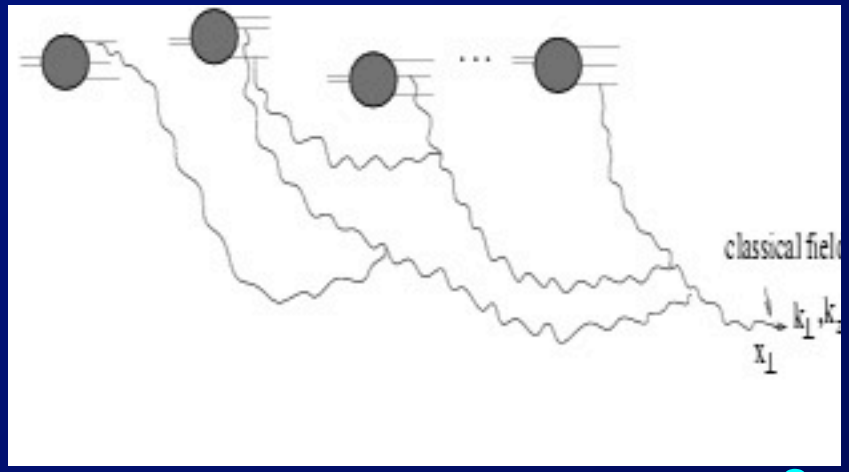
    $\Rightarrow$ Gluons from many nucleons overlap



Saturation in nuclei *a la* Mueller

- @ High energy nuclei are highly Lorentz contracted
  - Except for soft gluons
  - Which overlap longitudinally
  - And recombine





Saturation in nuclei *a la* Mueller

- @ High energy nuclei are highly Lorentz contracted
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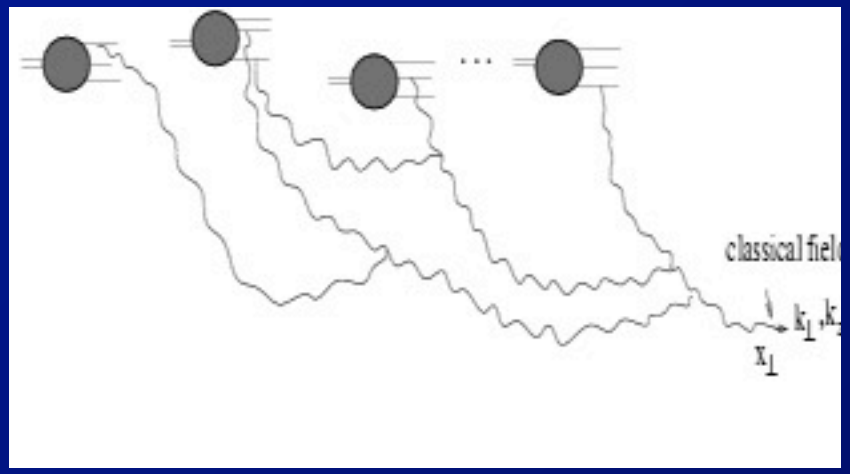
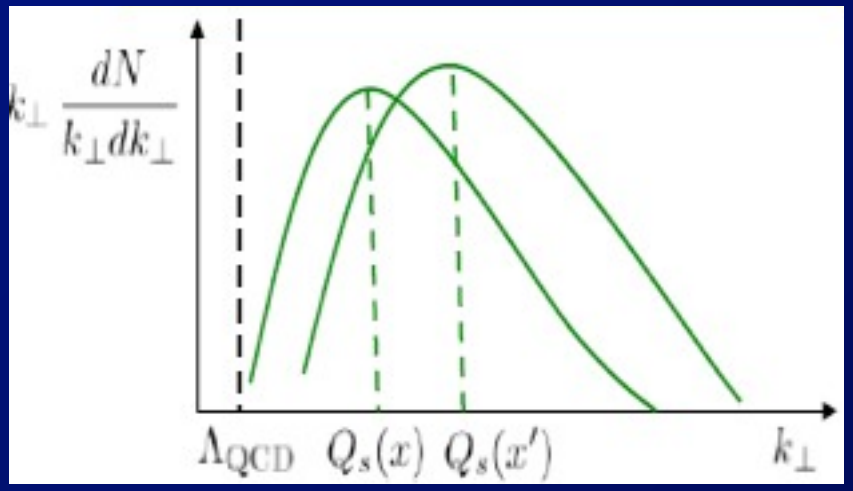
  - Broadening k_T distribution

    ⇒Generates a new scale: Q_s





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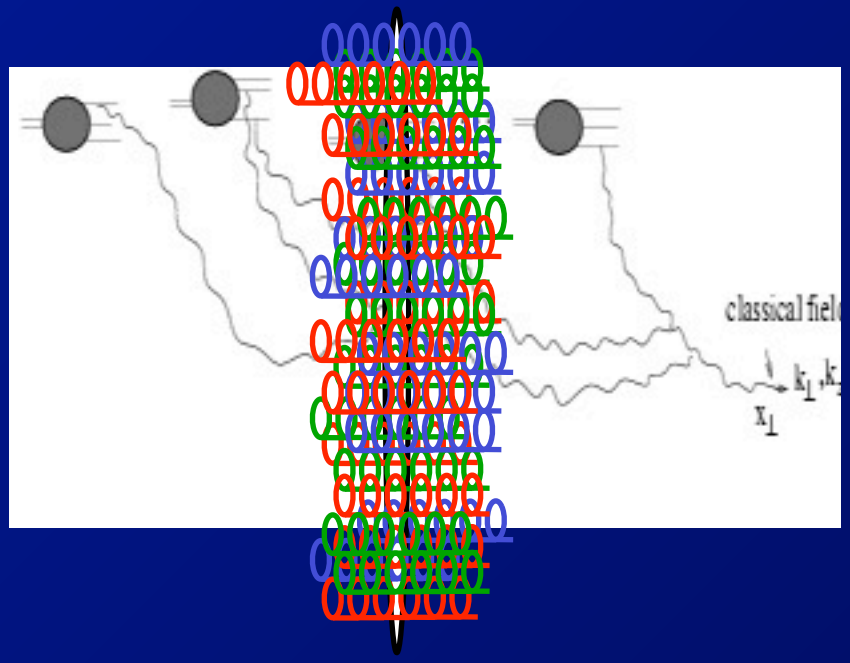
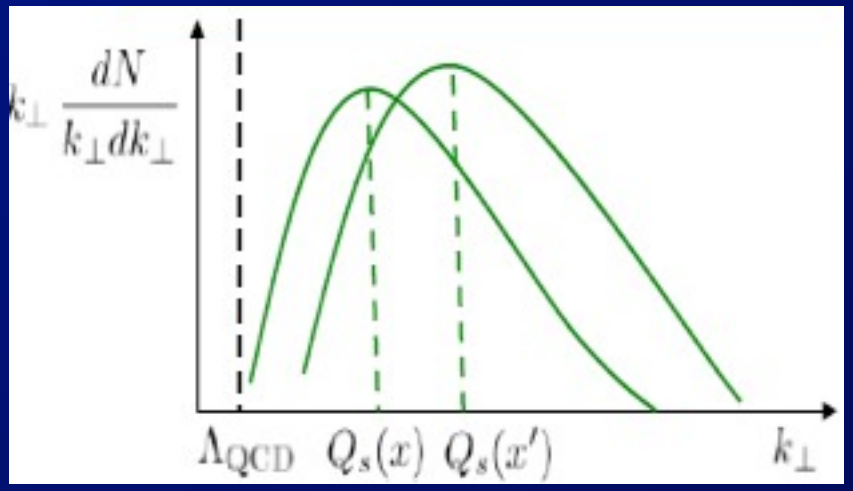


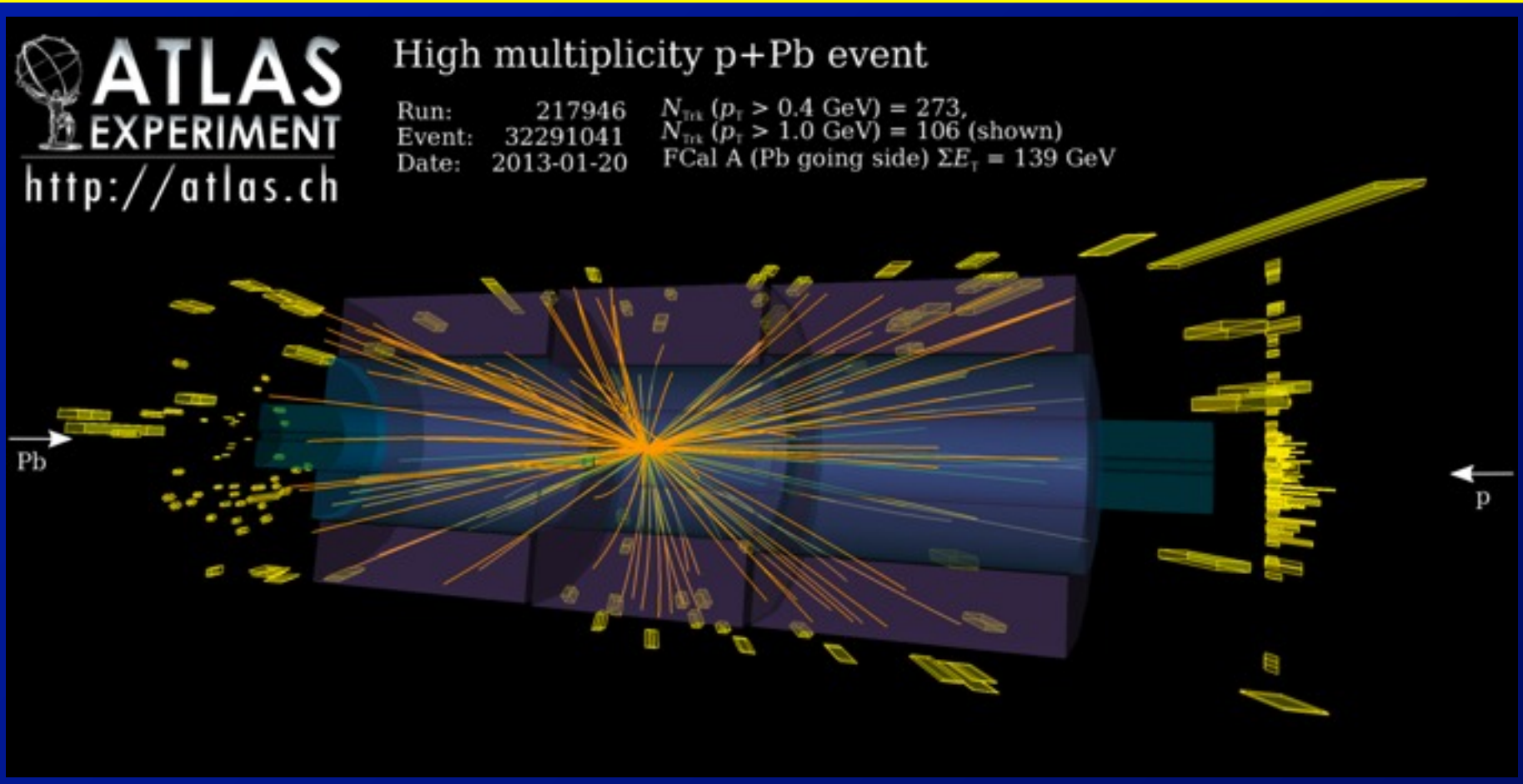
- Naively, for $Q_s >> \Lambda_{QCD}$, perturbative calculations

  ⇒Large occupation #s for $k_T<Q_s$ ⇒ classical fields



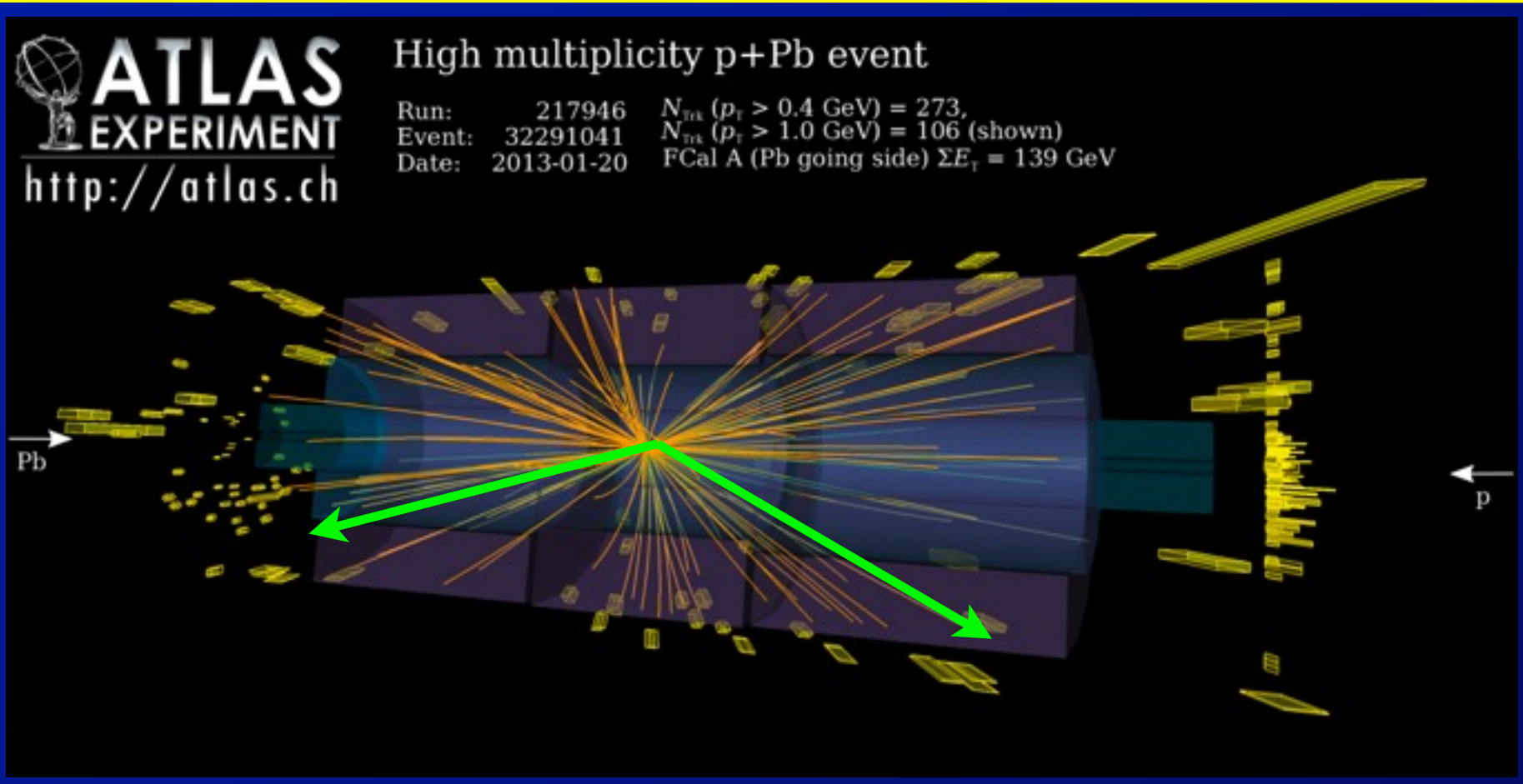
- Saturation associated with ultra-strong gluon fields

proton-lead collisions @ LHC



- Another way to probe high parton density and/or strong gluon fields in nuclei:
  - High-energy proton nucleus collisions
    - ⇒(e.g.) proton-lead collisions at the LHC

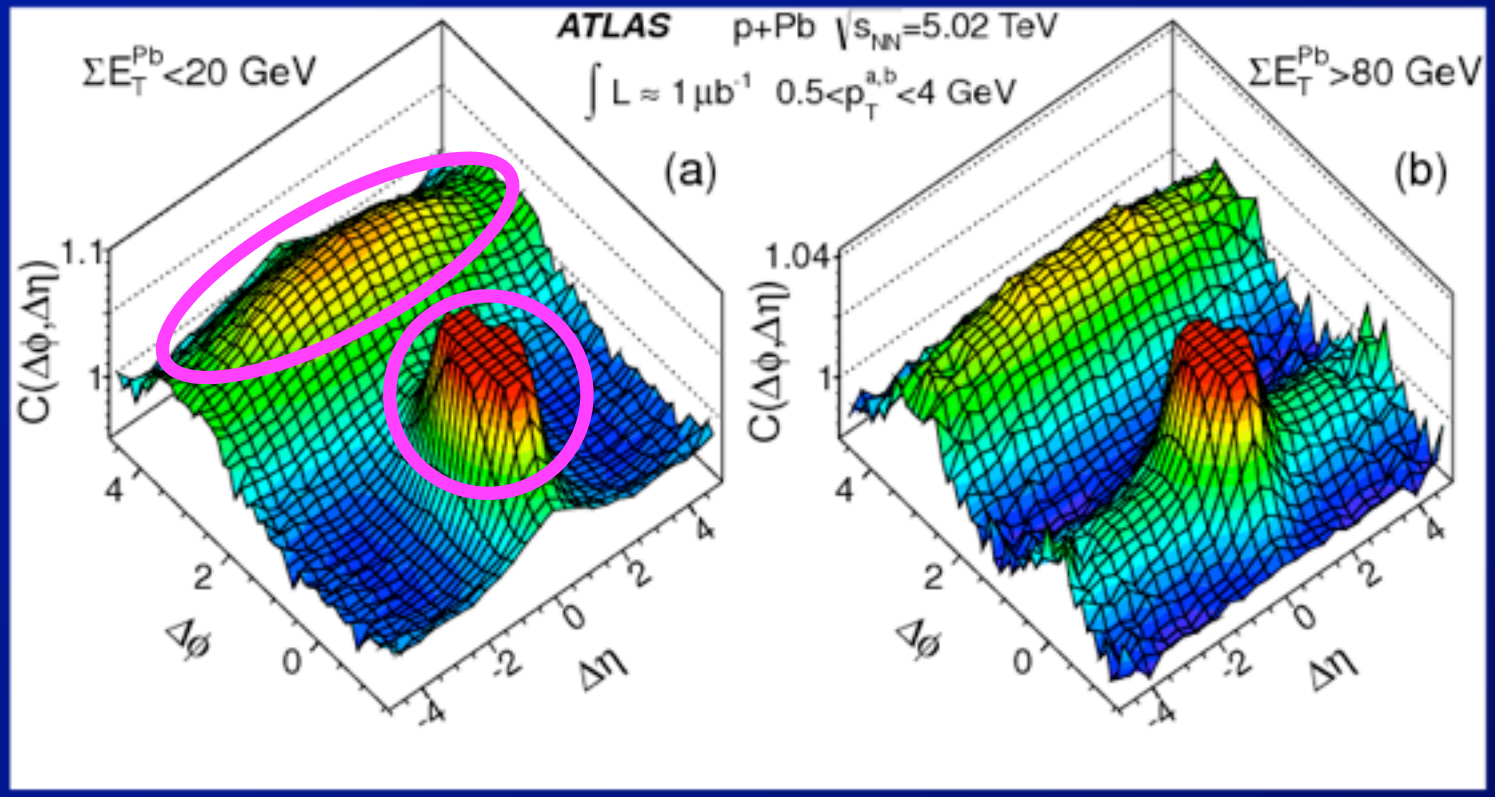
proton-lead collisions @ LHC



- Study angular correlations between pairs of particles to look for saturation, other effects.

Surprise: p+Pb Ridge(s)

"low multiplicity" "high multiplicity"



- Study azimuthal (Δφ) and longitudinal (Δη) correlations between pairs of particles
  - ⇒usual correlations in low-multiplicity events (jets)

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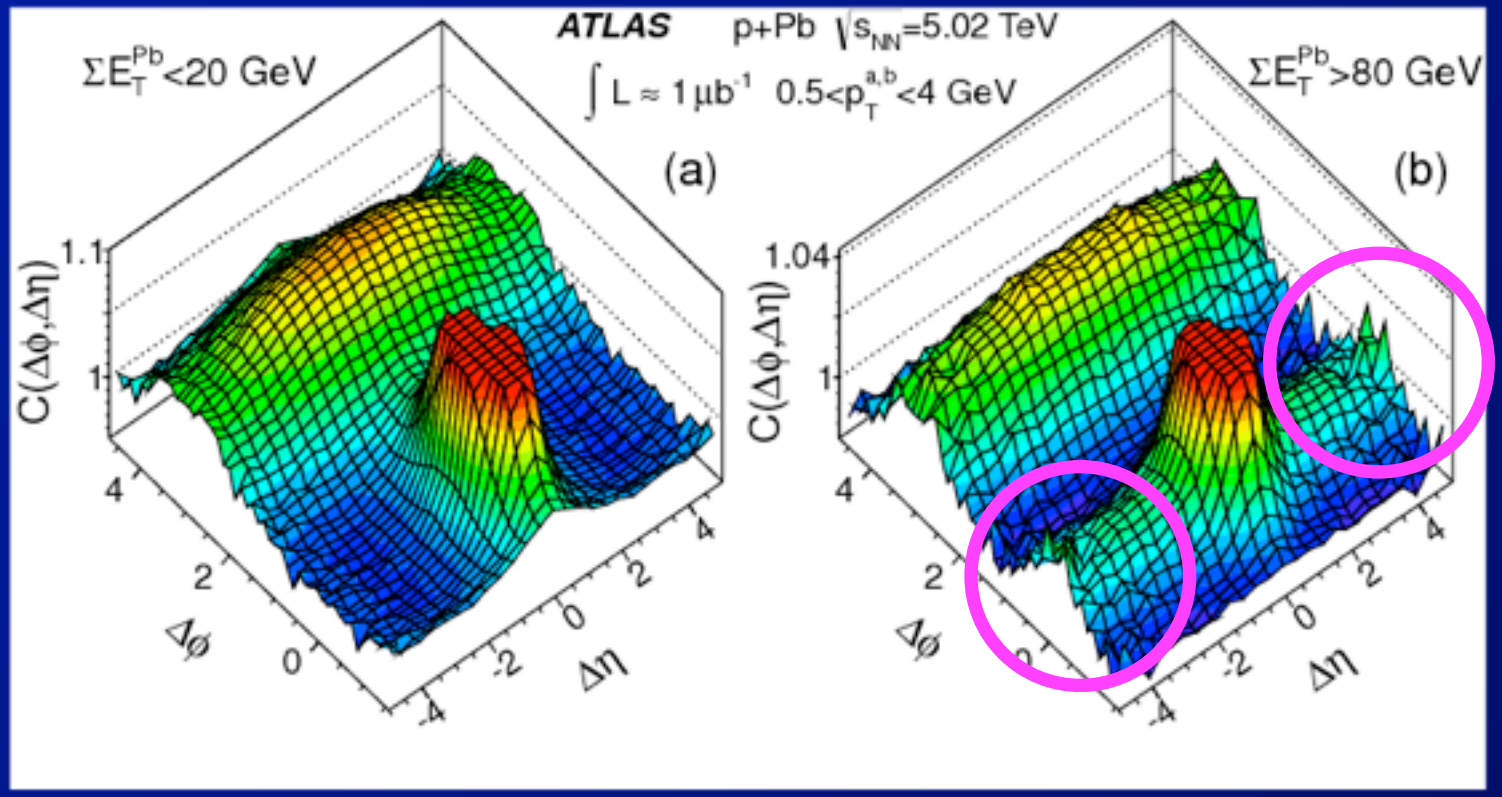
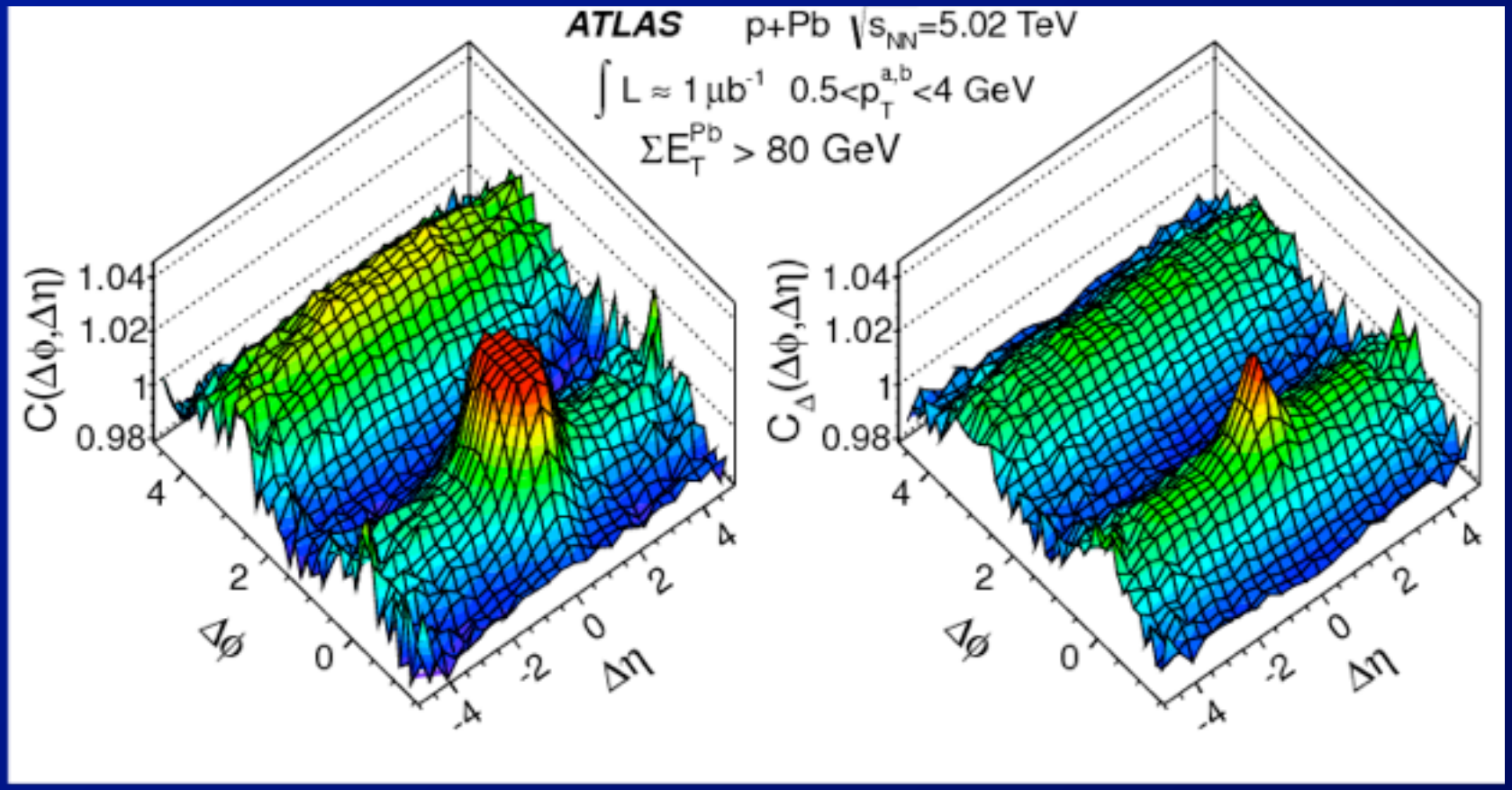


- Study azimuthal (Δφ) and longitudinal (Δη) correlations between pairs of particles
  - ⇒usual correlations in low-multiplicity events
  - ⇒additional "ridge" in high-multiplicity events

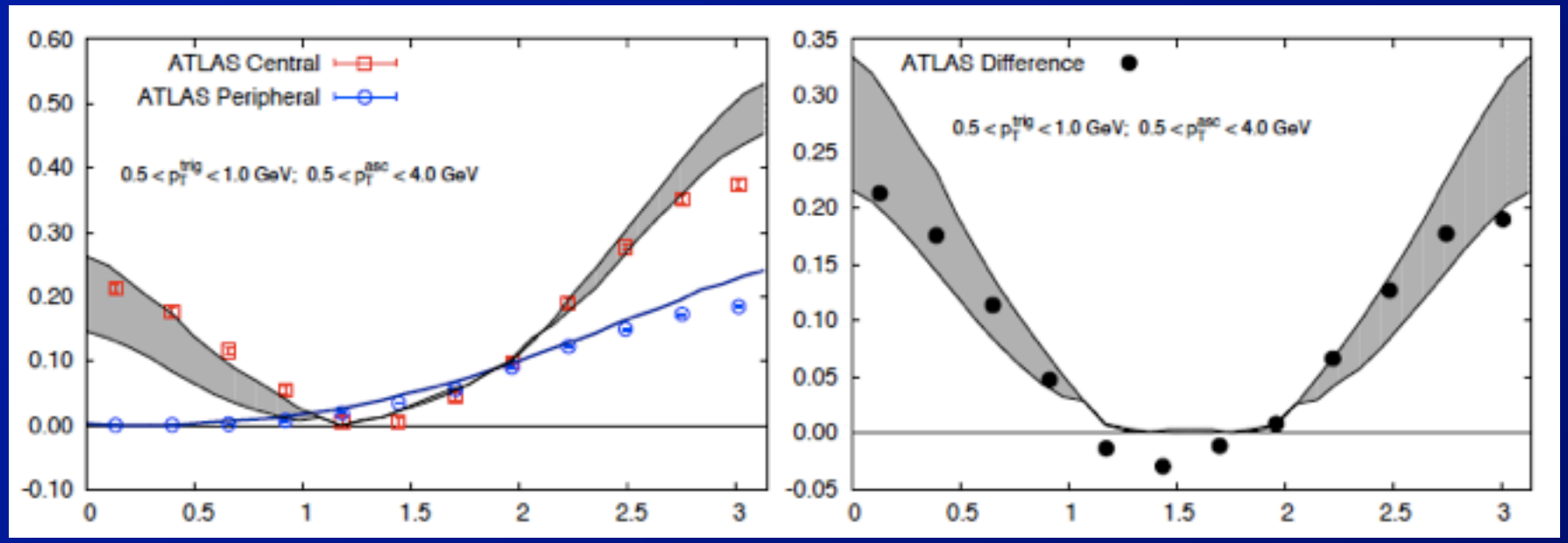
Surprise: p+Pb Ridge(s)

- Use the peripheral p+Pb data to subtract uninteresting part of the correlation



⇒Similar to collective effects in Pb+Pb

Explained by saturation?

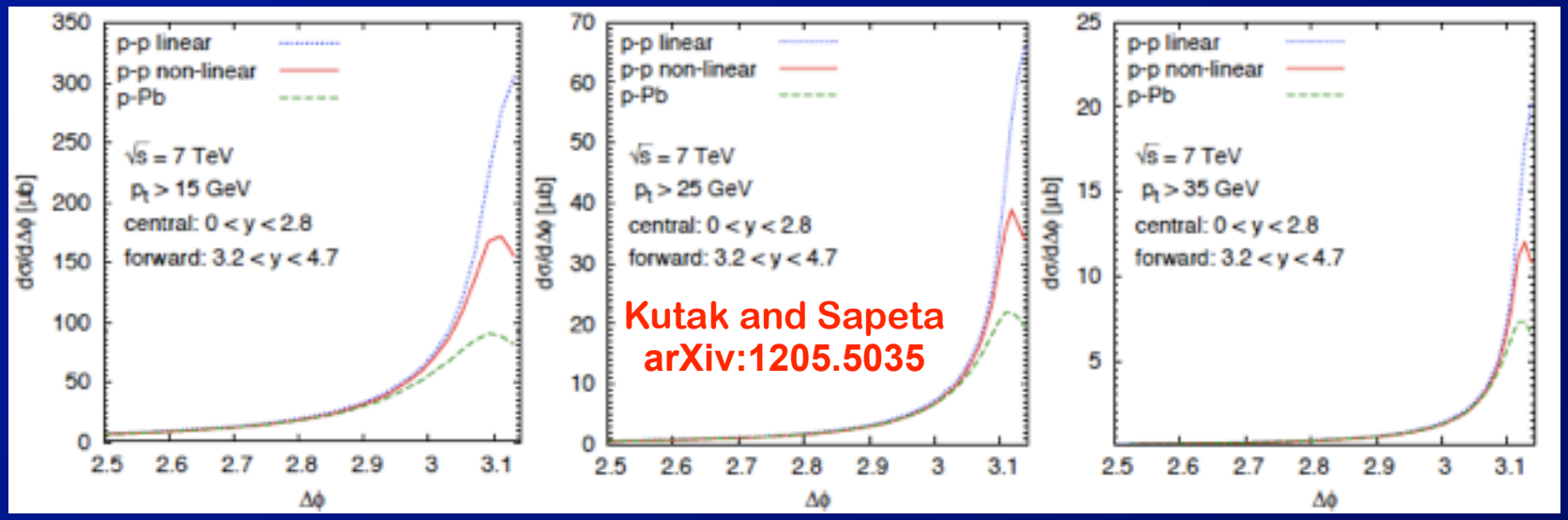


- Theoretical calculations of the effects of saturation can reproduce the data.
- However, there are additional measurements that challenge the saturation explanation
  - Support interpretation that the ridge(s) result from "collective" effects similar to Pb+Pb ??!

    ⇒In my opinion, can only be understood as resulting from strong gluon fields in initial and final state.

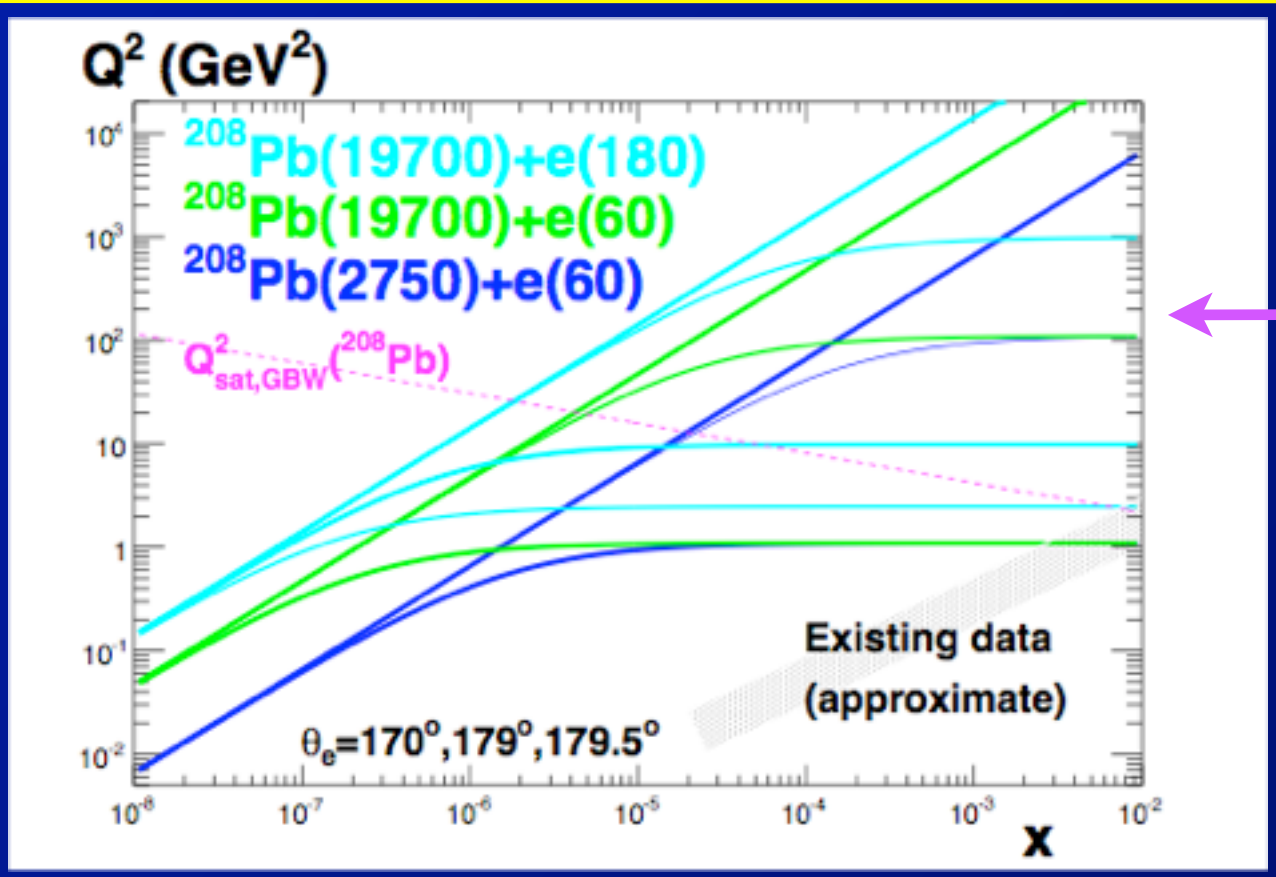
LHC p+Pb progam

- Still early in studying/understanding high parton density effects in p+Pb collisions
  - Several ongoing measurements intended to more specifically test saturation
    - ⇒e.g. forward dijet acoplanarity



- But, p+Pb measurements, while they may show qualitative effects will be “looking through the glass darkly”

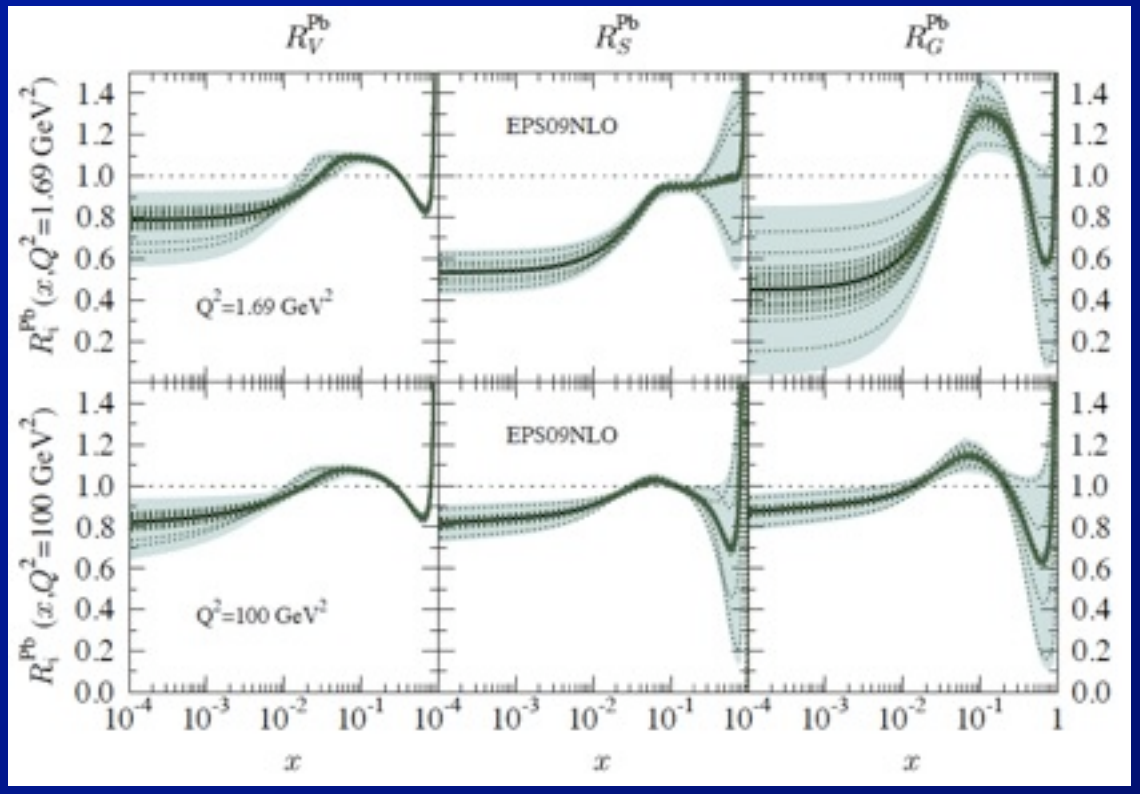
Ultra-high energy e+A collisions



Impact of assuming detector electron acceptance down to 10, 1, 0.5°

- Want to study physics near or below $Q^2 = Q_s^2$
  - But also not too low in Q^2
    - ⇒Increased A energy from FCC helpful, increased electron energy an issue for low-Q^2 acceptance

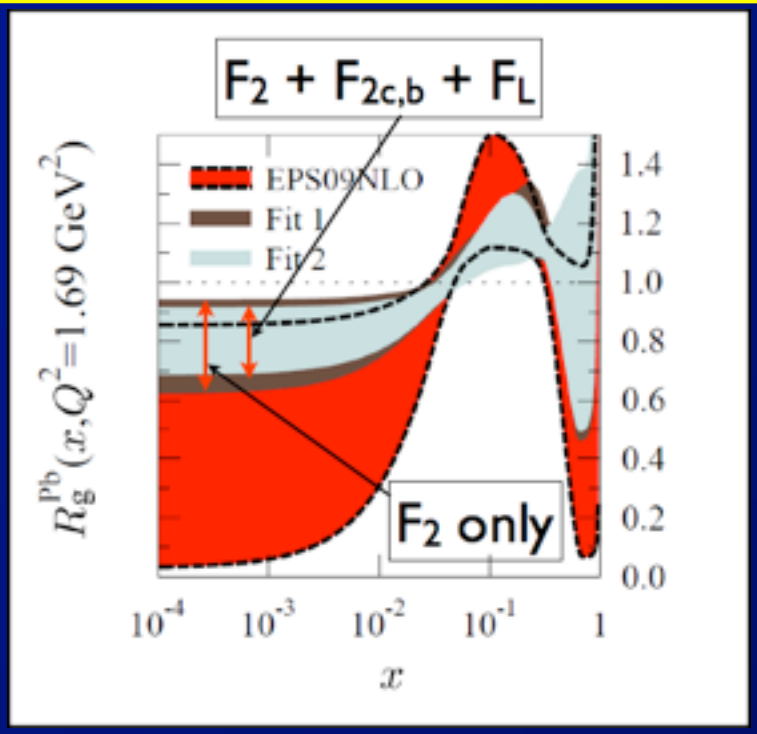
What do we already know?



- **Nuclear PDFs at low Q^2 poorly determined at lower Q^2 where we expect saturation effects.**
  - Extensive studies in the context of LHeC re: sensitivity of proton and nuclear PDFs to saturation
    - ⇒ A dependence is a valuable handle
    - ⇒ But then we need good control at larger x

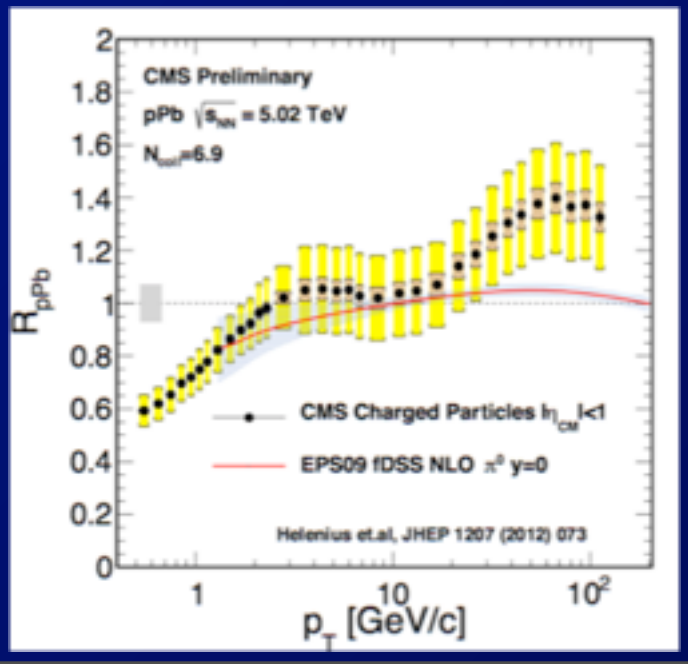
Studies for LHeC

- Combination of different structure function measurements at LHeC or future e-A machine
  - will substantially improve knowledge re: nuclear PDFs



- May be already relevant:
  - Interesting result from CMS on charged particle spectrum in proton-lead collisions

    ⇒Unexpected feature at high p_T, due to nuclear PDF?



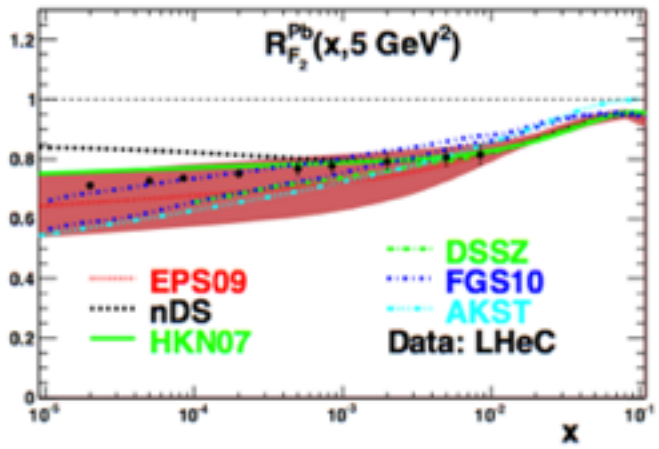
From N. Armesto LHeC (Chevannes) talk

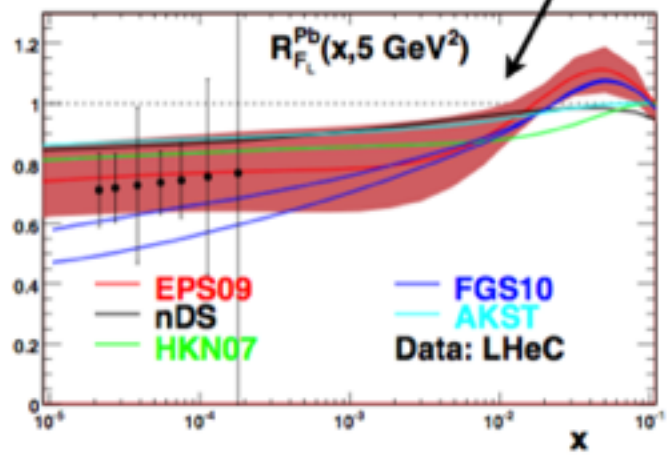
eA inclusive: comparison

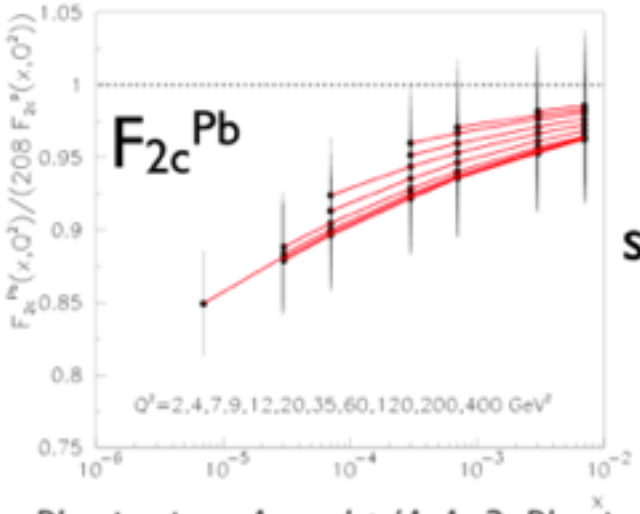
- Good precision can be obtained for $F_{2(c,b)}$ and F_L at small x

(Glauberized 3-5 flavor GBW model, NA '02).

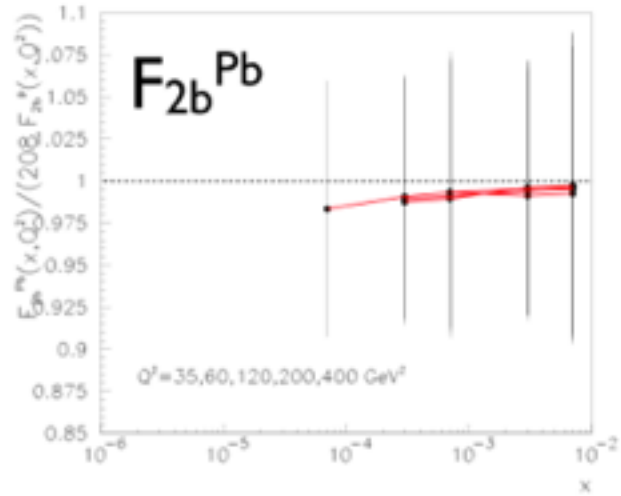
Not optimized!







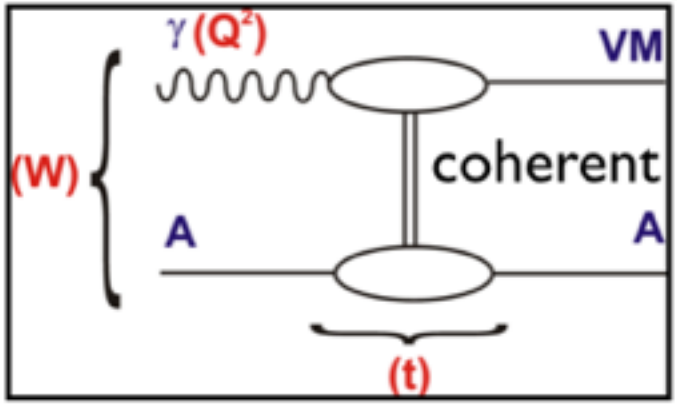
Note the scale!!!



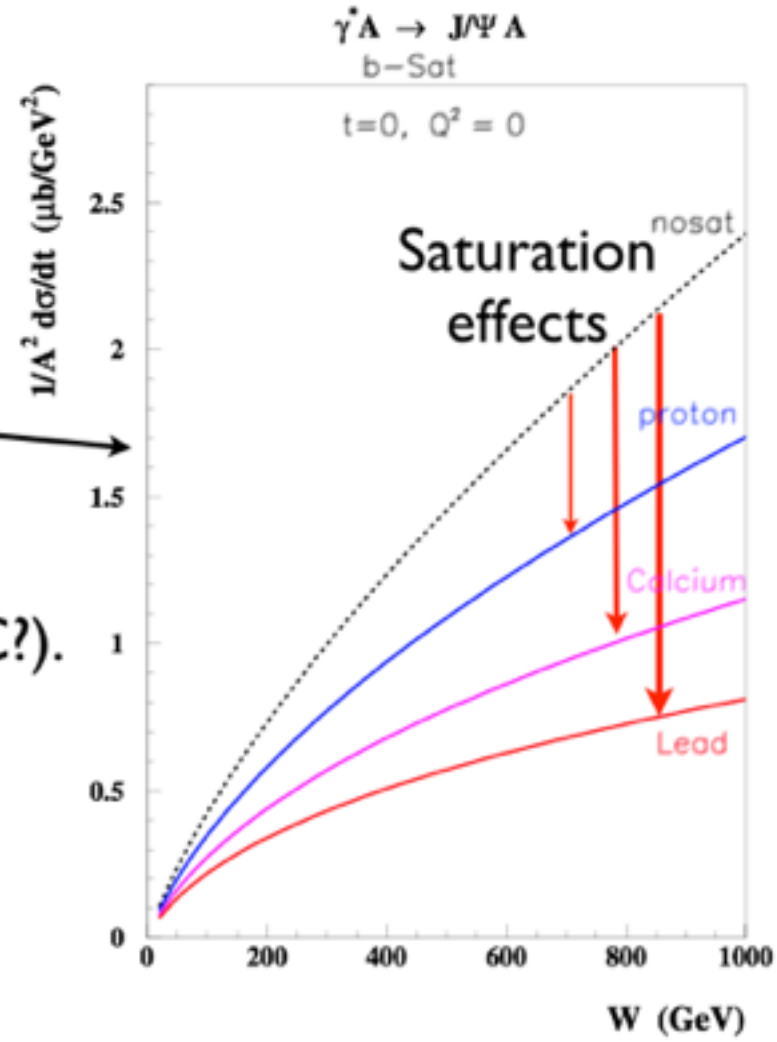
Heavy Ion Physics in e-A and p/A-A: 3. Physics case in eA.

Diffraction as a low-x probe

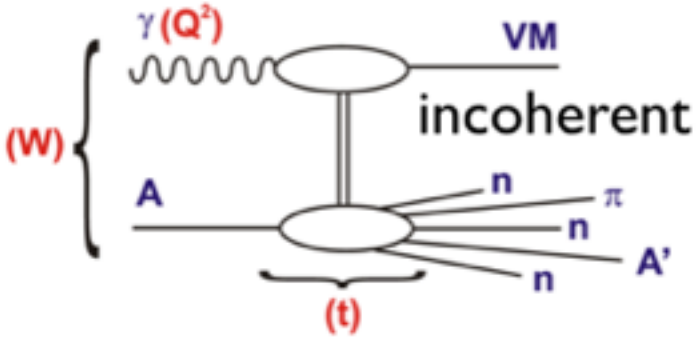
Elastic VM production in eA:



- For the coherent case, predictions available.



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



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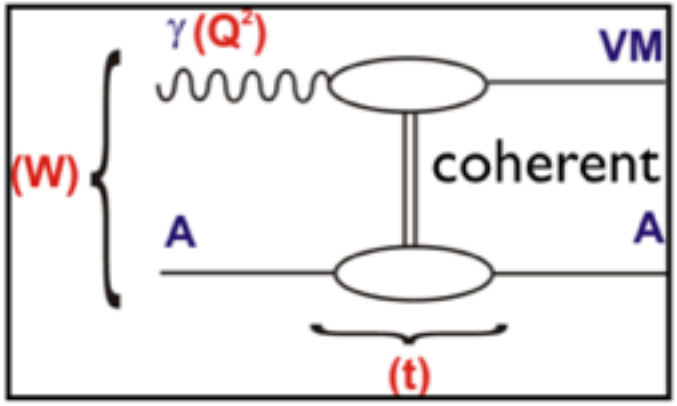

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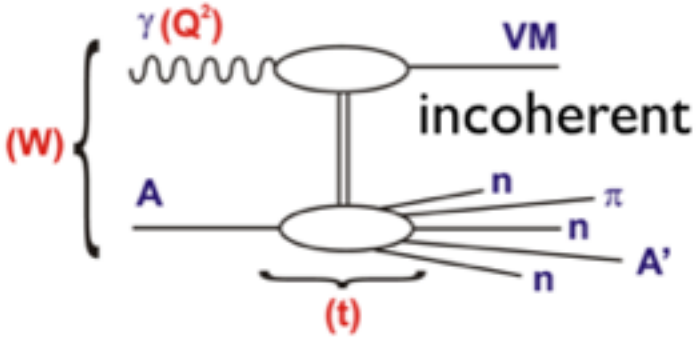

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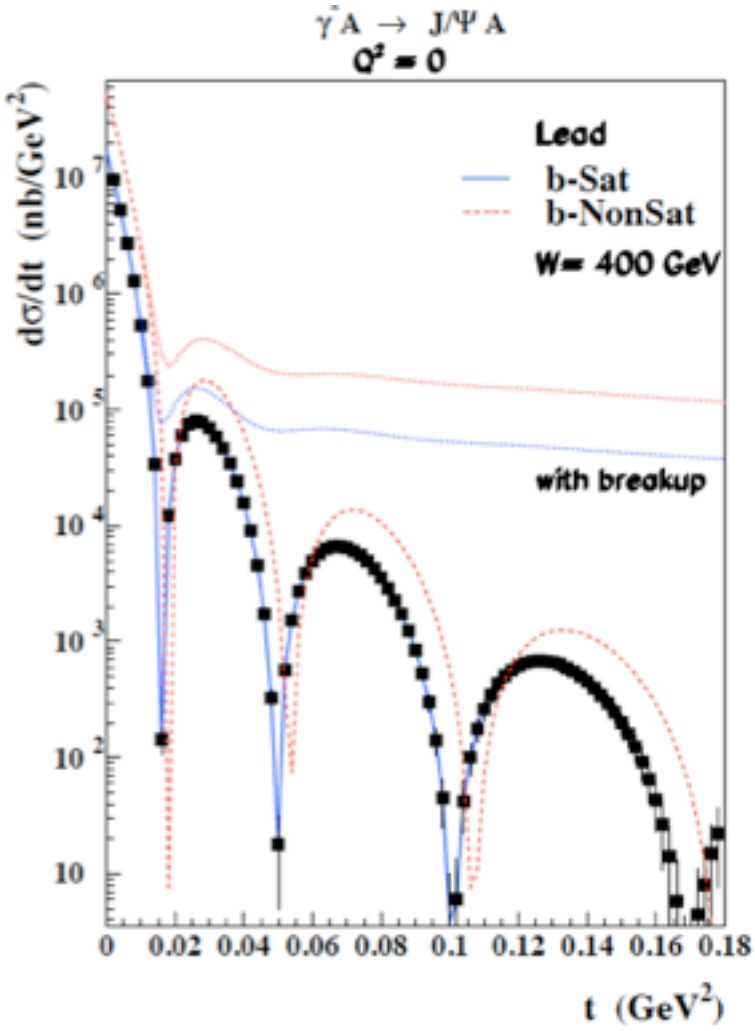

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Summary

- High-energy collisions with nuclei a valuable way to study high parton density/strong color field effects
  - "Trivial" way to enhance parton density
  - Different from enhancement due to evolution in proton
- proton-lead collisions have shown features compatible with saturation / strong color fields
  - ⇒But unlikely to obtain the precision needed to properly understand QCD and test theory
- e+A program at LHeC and future FLHeC would provide unique probe of saturation physics
  - ⇒While also radically improving knowledge of nPDFs
  - ⇒Providing critical insight on the initial conditions of heavy ion collisions