Hot QCD Matter

Peter Jacobs

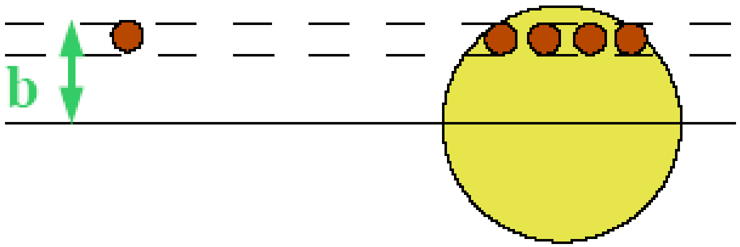
Lawrence Berkeley National Laboratory/CERN

Lecture 1: Tools
Lecture 2: Initial conditions: partonic structure and global observables
Lecture 3: Collective flow and hydrodynamics
Lecture 4: Jets and other hard probes

Nuclear geometry and hard processes: Glauber theory

Glauber scaling for hard processes with large momentum transfer

- short coherence length ⇒ successive NN collisions independent
- p+A is incoherent superposition of N+N collisions



Normalized nuclear density r(*b*,*z*):

$$\int dz\, db\, \rho(b,z) = 1$$

Nuclear thickness function

$$T_A(b) = \int_{-\infty}^{\infty} dz\, \rho(b,z)$$

Inelastic cross section for p+A collisions:

$$\sigma_{pA}^{inel} = \int d\vec{b} \left(1 - \left[1 - T_A(b)\,\sigma_{NN}^{inel}\right]^A\right)$$

$$\sigma_{pA}^{hard} \simeq A \cdot \sigma_{NN}^{hard} \int d\vec{b}\, T_A(b) = A\sigma_{NN}^{hard}$$

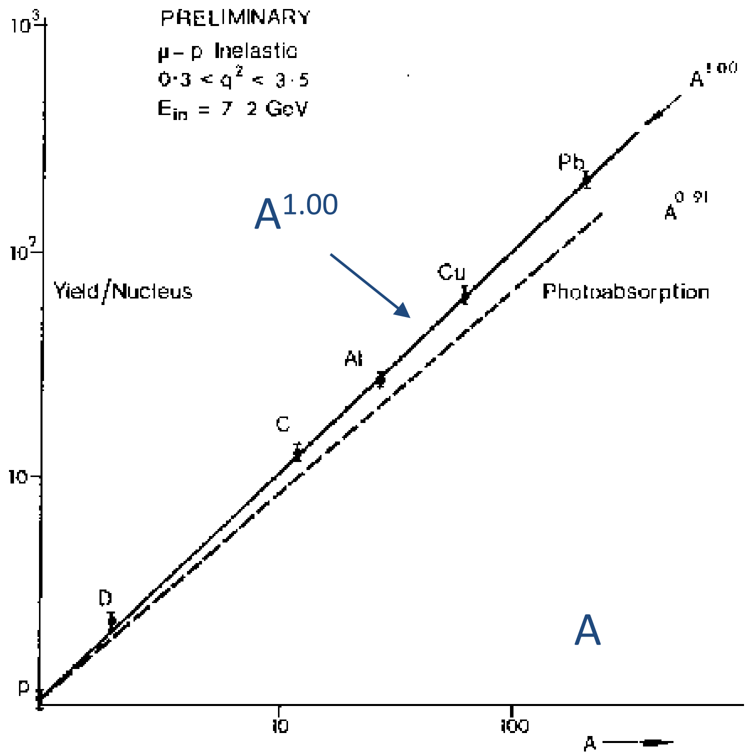
Experimental tests of Glauber scaling: hard cross sections in p(μ)+A collisions

Glauber scaling expectation:

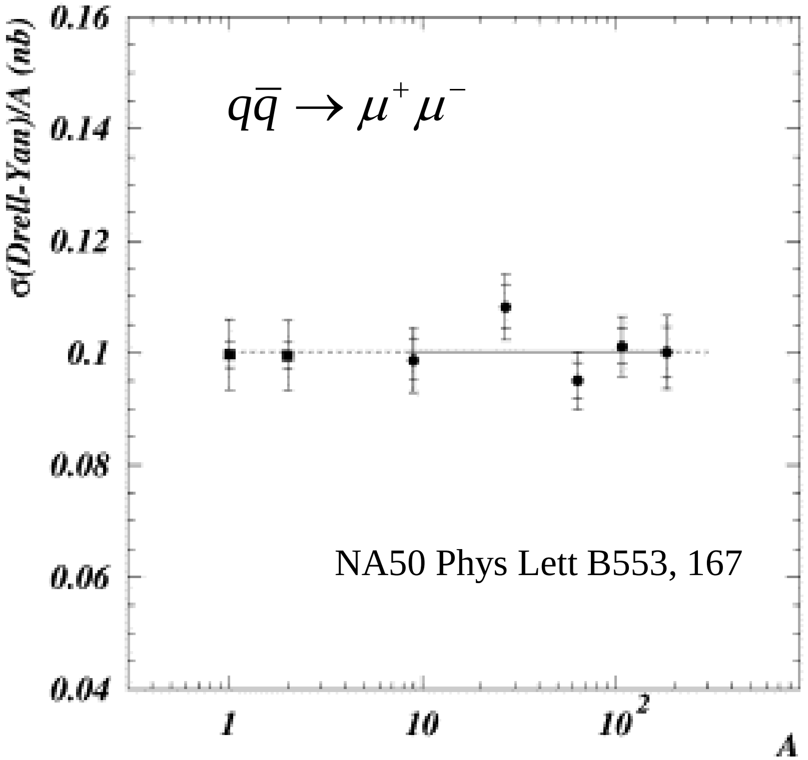
$$\sigma_{pA}^{hard} = A\sigma_{NN}^{hard}$$

σ_{inel} for 7 GeV muons on nuclei

M.May et al, Phys Rev Lett 35, 407 (1975)



$\sigma_{Drell\text{-}Yan}/A$ in p+A at SPS

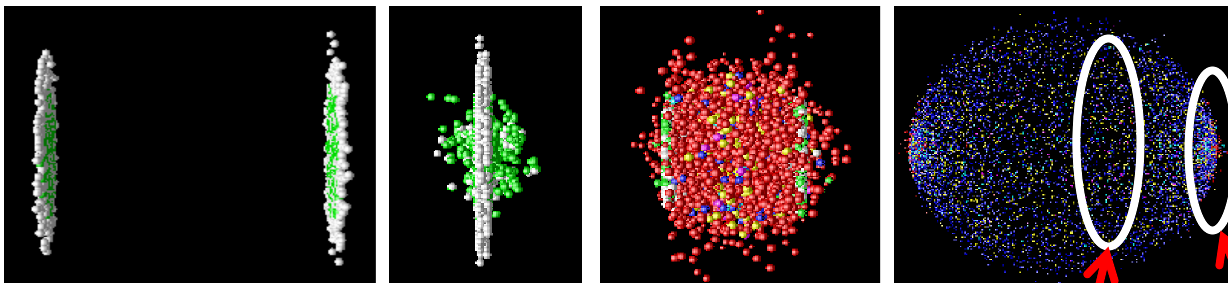


Hard cross sections in p+A scale as $A^{1.0}$

Measuring collision geometry I

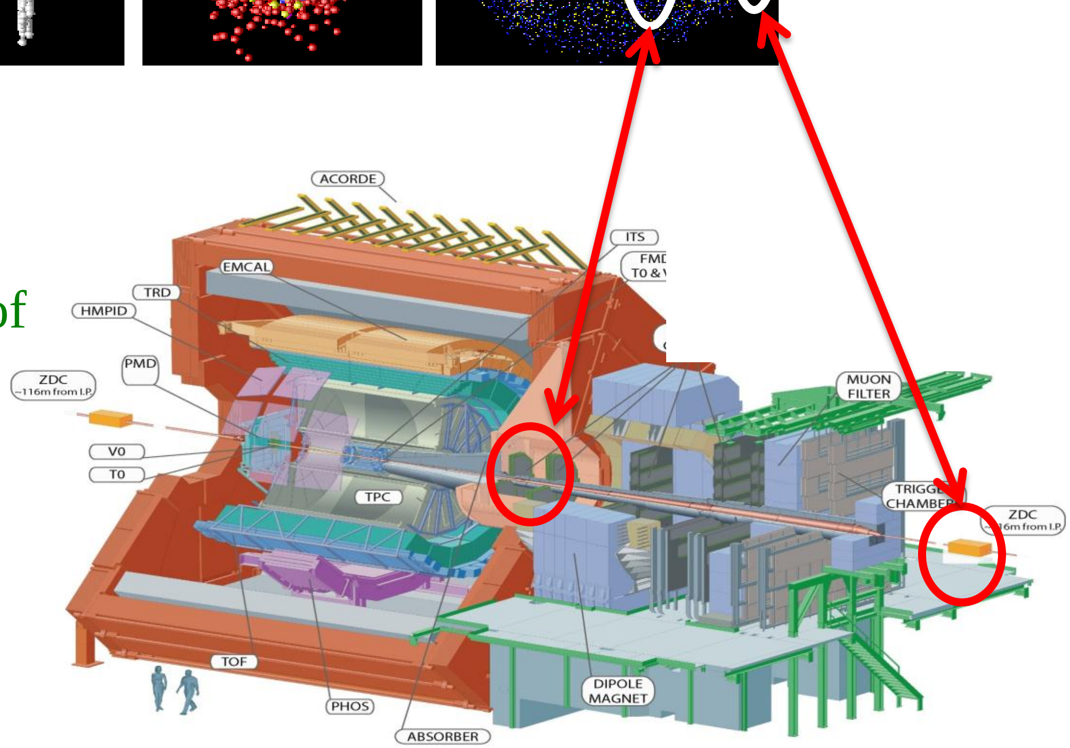
Nuclei are "macroscopic"

➔characterize collisions by impact parameter

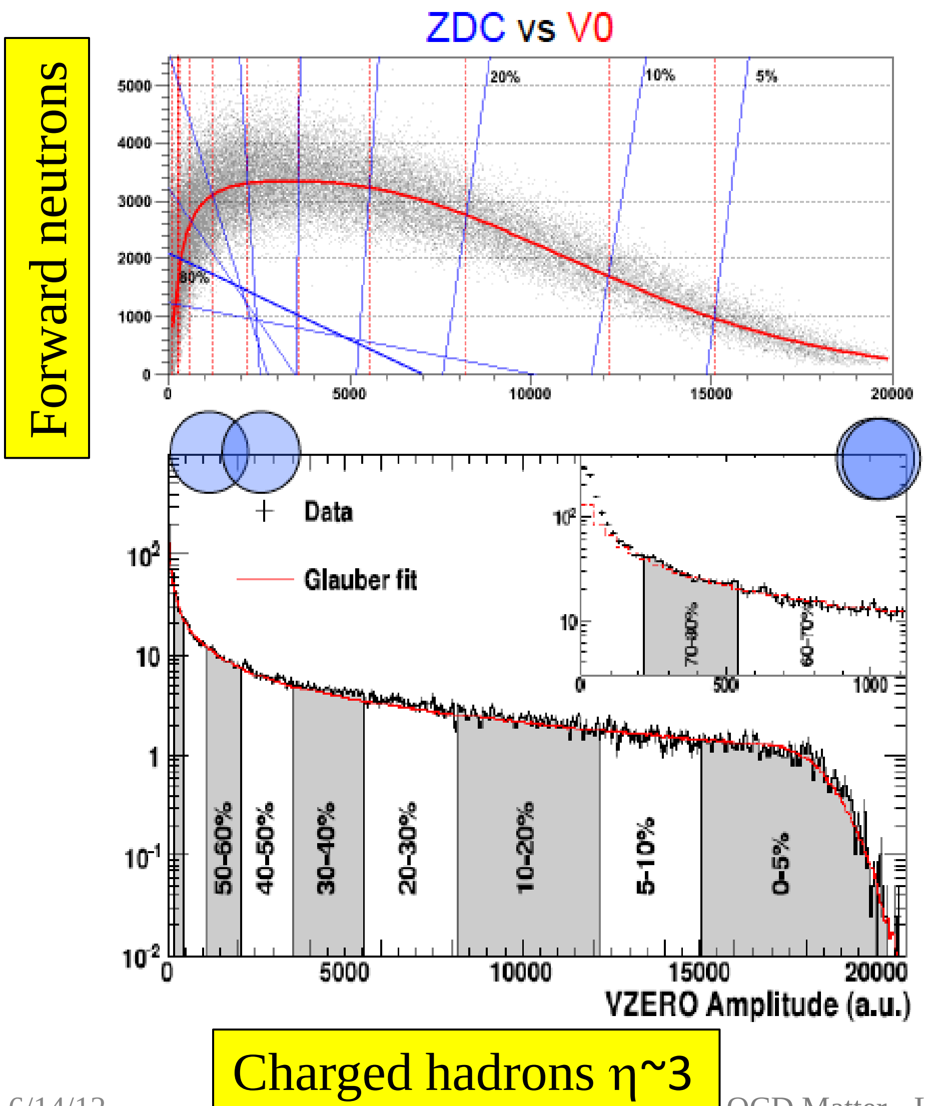


Correlate particle yields from ~causally disconnected parts of phase space

➔ correlation arises from common dependence on collision impact parameter



Measuring collision geometry II



- Order events by centrality metric
- Classify into percentile bins of "centrality"

HI jargon: "0-5% central"

Connect to Glauber theory via particle production model:

- N_{bin}: effective number of binary nucleon collisions (~5-10% precision)
- N_{part}: number of (inelastically scattered) "participating" nucleons

Scaling of cross sections using Glauber theory plays a central role in quantitative analysis of experimental measurements and connection to theory.

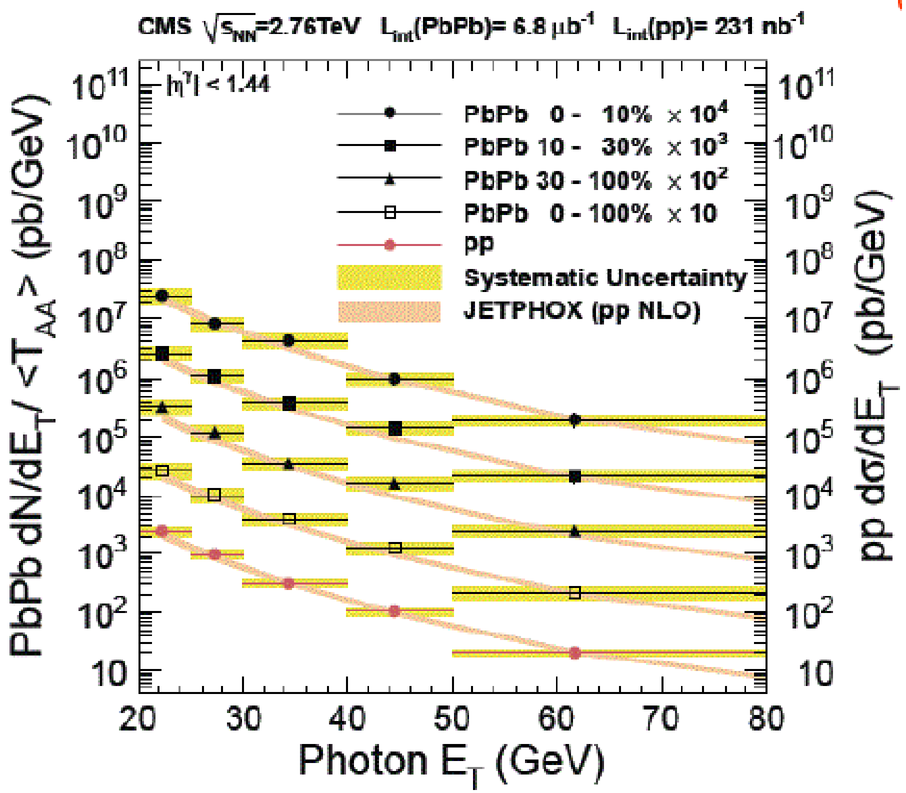
Let’s test it experimentally in A+A collisions…

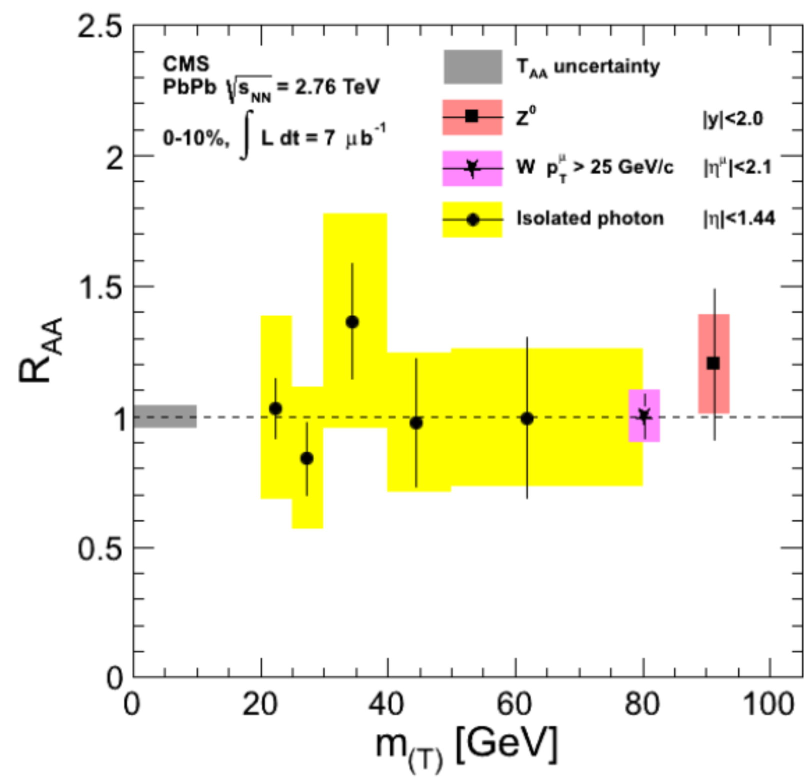
Glauber scaling tests at LHC:

Scaling of direct photon, Z, W yields in Pb+Pb vs p+p

EW bosons do not interact with Quark-Gluon Plasma – should see perturbative production rates in Pb+Pb collisions

$$R_{AA} = \frac{d\sigma_{AA}^{hard}/dp_T}{\langle T_{AA}\rangle \cdot d\sigma_{pp}^{hard}/dp_T}$$

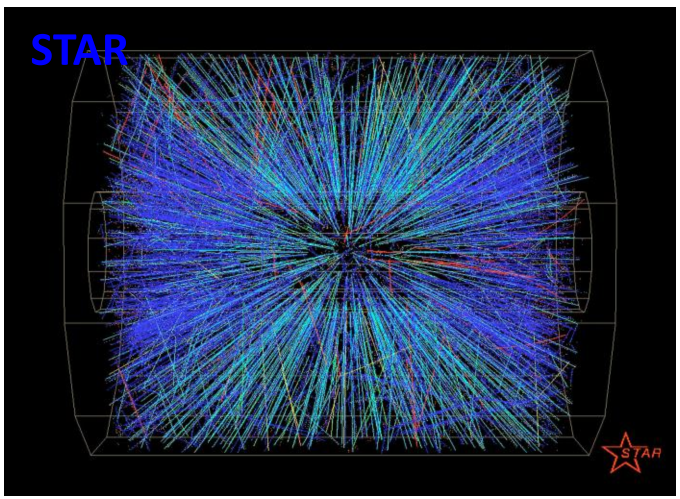




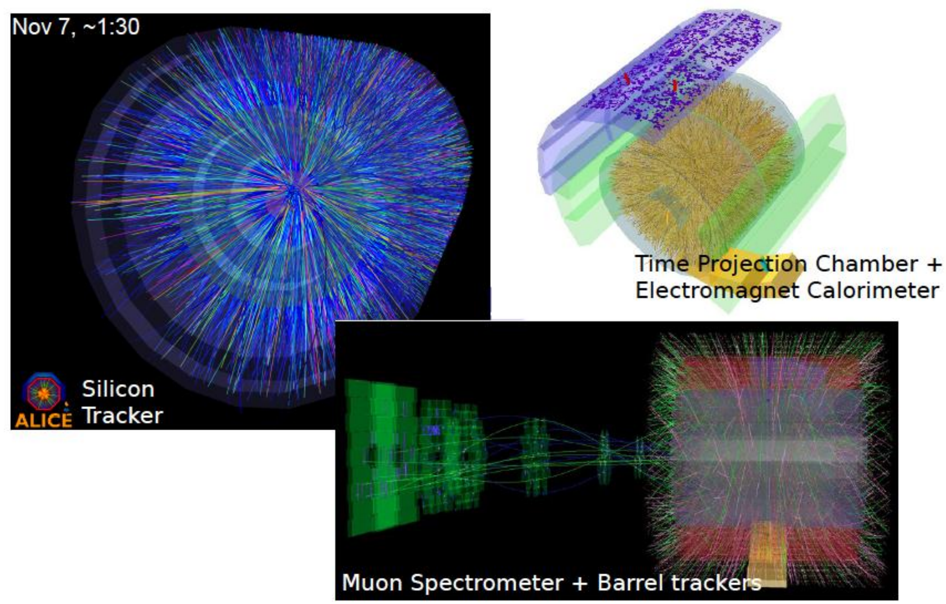
Yields all scale with N_{bin}: Glauber scaling OK for hard processes

Very simple question: can we understand the total number of particles generated in a heavy ion collision (a.k.a. "multiplicity")?

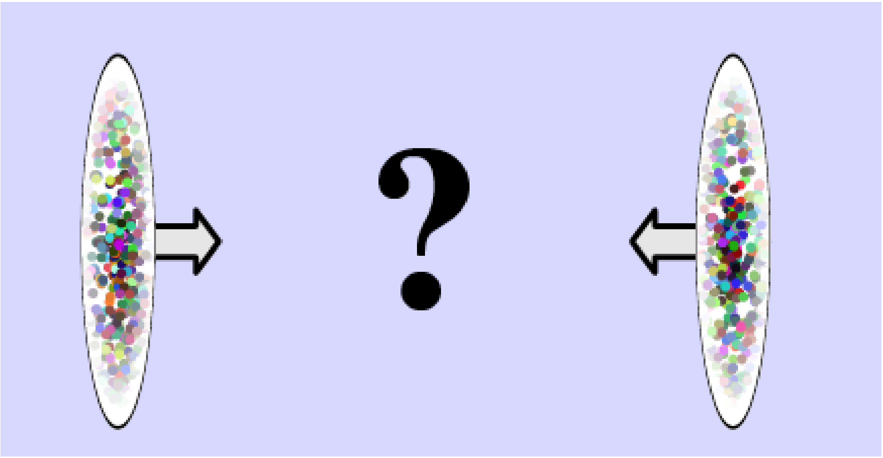
RHIC

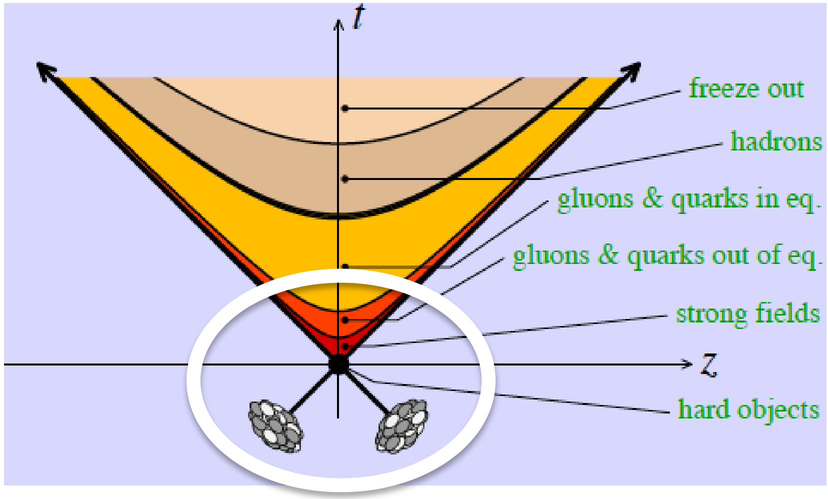


LHC



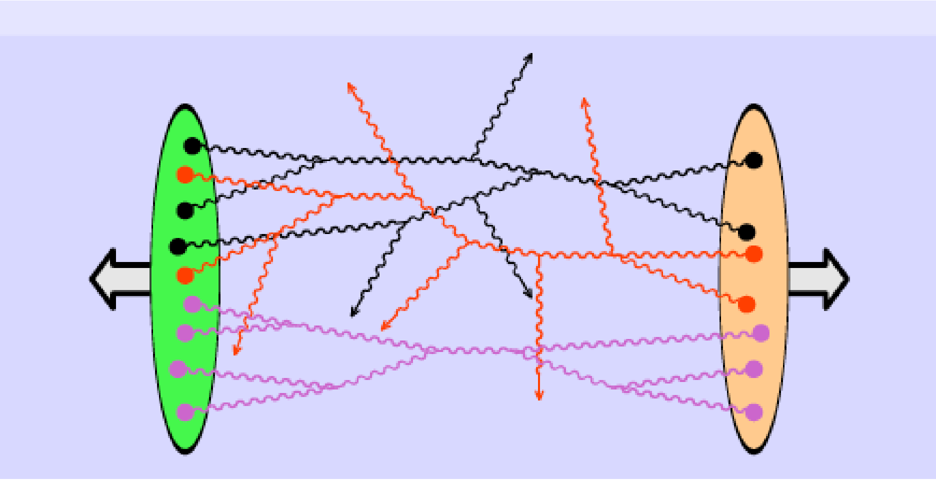
Let's start with the "initial state": what is the role of the partonic structure of the projectiles?





Multiple interactions drive the collision dynamics

➔we need to understand the initial (incoming) state…



Perturbative QCD factorization in hadronic collisions

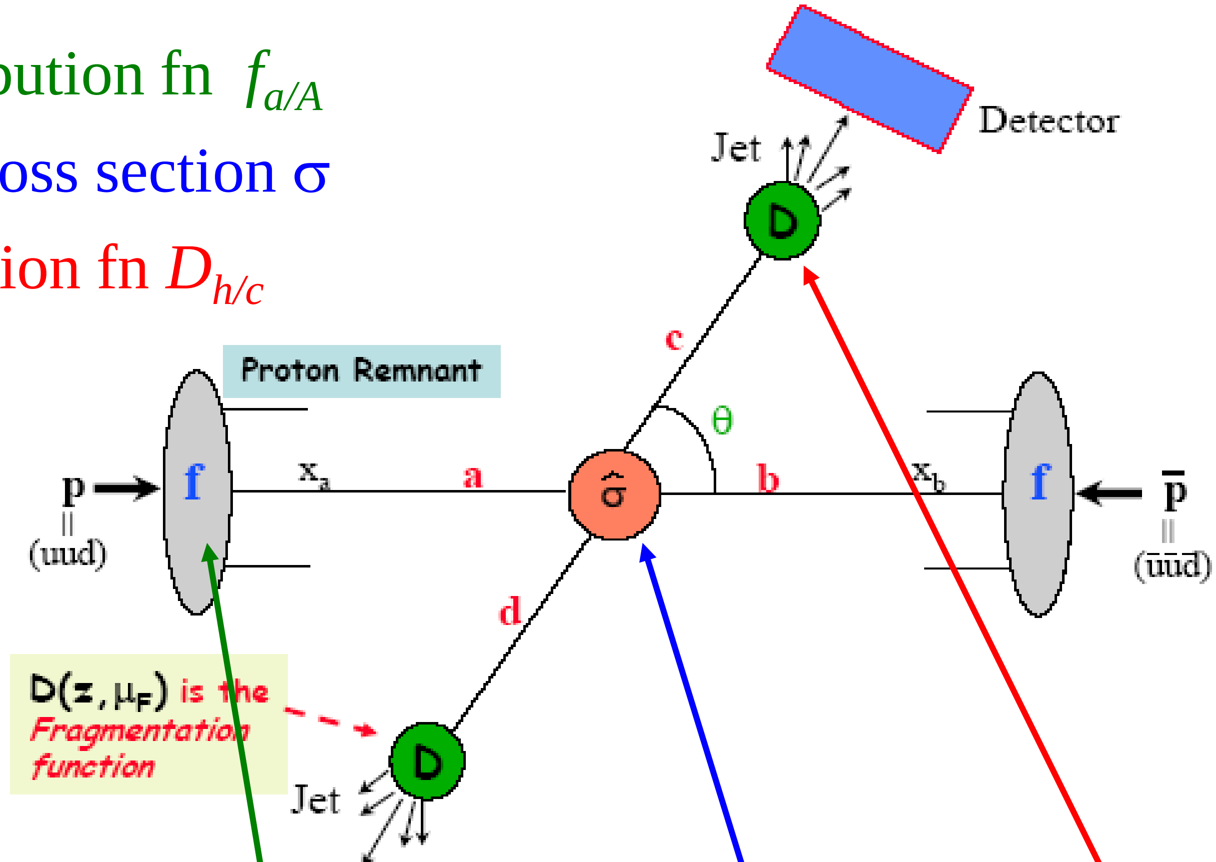
Hard process scale $Q^2 >> \Lambda^2_{QCD}$

pQCD factorization:

parton distribution fn $f_{a/A}$

+ partonic cross section σ

+ fragmentation fn $D_{h/c}$



x=momentum fraction of hadron carried by parton (infinite momentum frame)

$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}\left(x_a,Q^2\right)\otimes f_{b/B}\left(x_b,Q^2\right)\otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt}\otimes D_{h/c}\left(z_c,Q^2\right)$$

Q^2 evolution of Parton Distribution and Fragmentation Functions

$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}(z_c, Q^2)$$

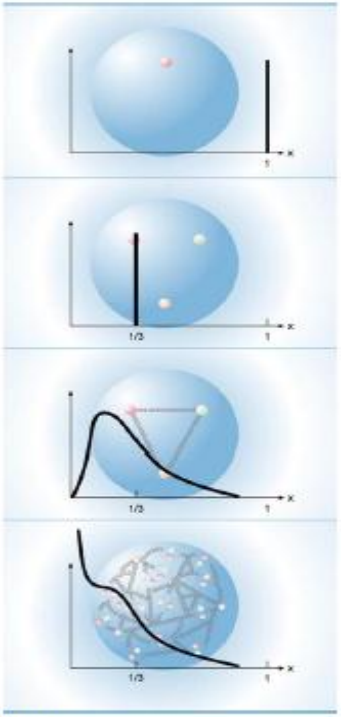
Parton Distribution Fucntions (PDFs) and fragmentation functions are not calculable *ab initio* in pQCD

They are essentially non-perturbative in origin (soft, long distance physics) and must be extracted from data at some scale Q_0^2

pQCD then specifies how PDFs and fragmentation functions evolve from Q_0^2 to any other scale Q^2 (DGLAP evolution equations)

Q^2 evolution

small Q^2

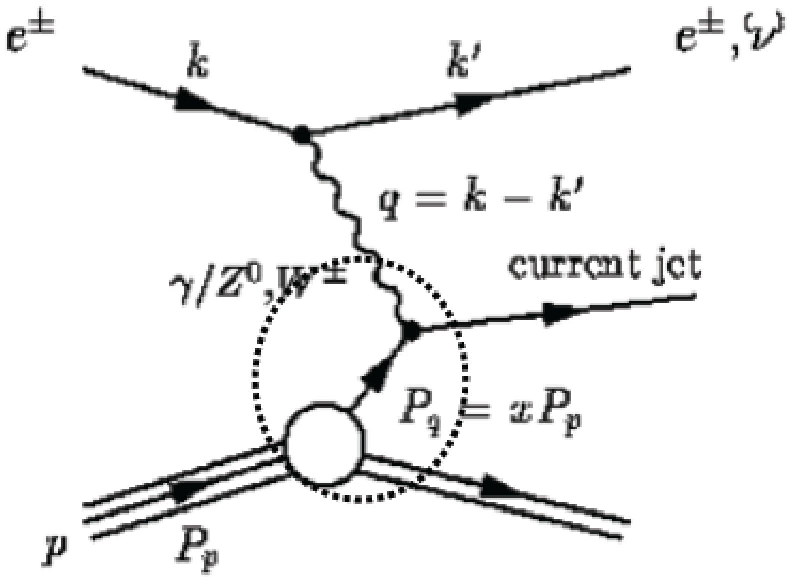


large Q^2

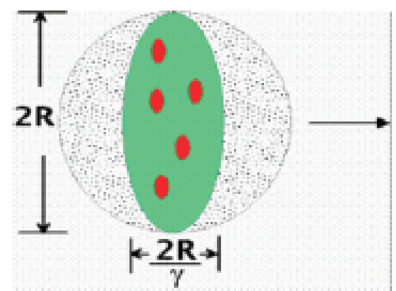
0.1 1.0 x

Precision measurements of proton structure: Deep Inelastic Scattering (DIS) of e+p

ep collision



proton in "∞" momentum frame



No transverse momentum

$0 \leq x \leq 1$

x = fractional longitudinal momentum carried by the struck parton

√s = ep cms energy

$Q^2 = -q^2$ = 4-momentum transfer squared (or virtuality of the "photon")

Probing the structure of the proton with DIS

Define a new quantity F_2:

parton density for flavor *i*

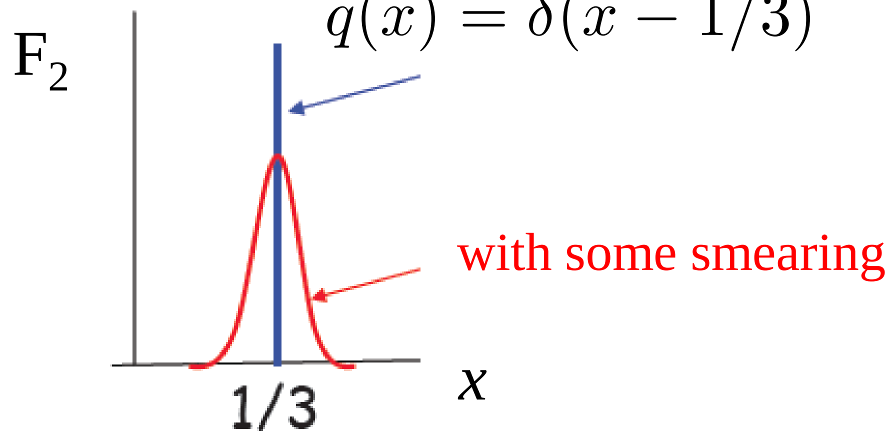
$$F_2 = \sum_{i=u,d,s,\ldots} e_i^2 \cdot xq_i(x)$$

Sum over quark flavors

charge for flavor *i*

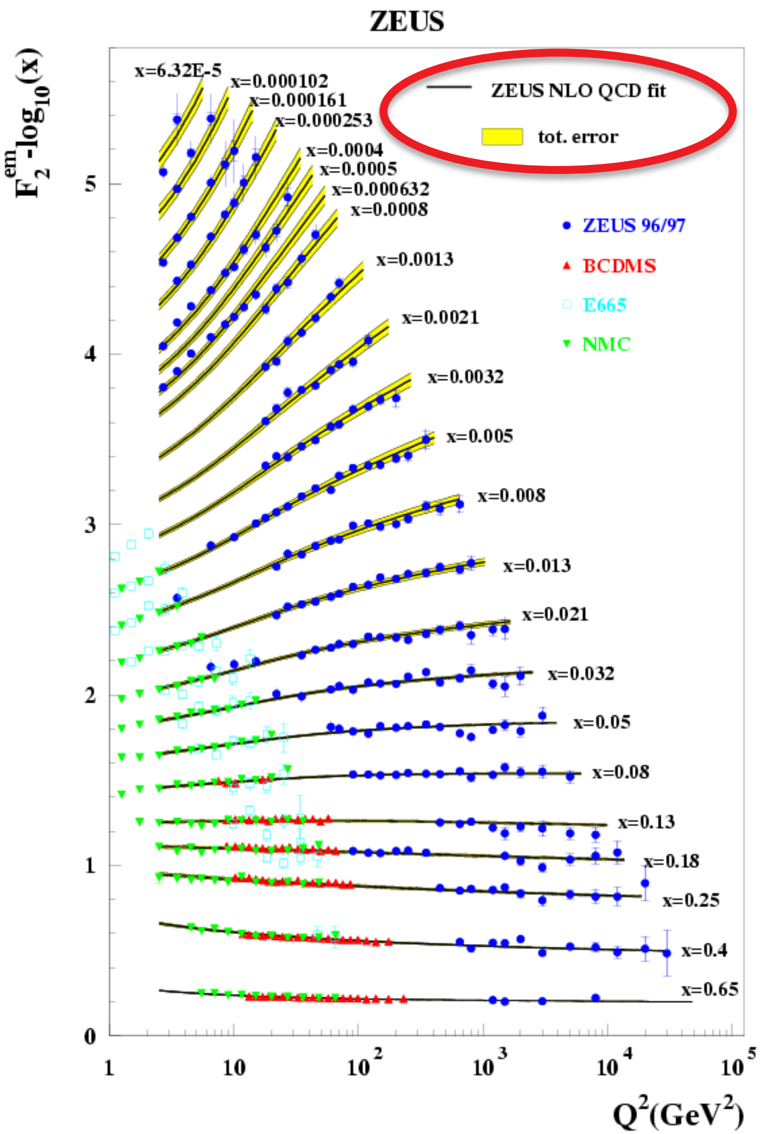
If a proton were made up of 3 quarks, each carrying 1/3 of proton's momentum:

$$q(x) = \delta(x - 1/3)$$



- If partons are point-like and incoherent then Q^2 shouldn't matter
- Bjorken scaling: F_2 has no Q^2 dependence

Measurement of proton F_2



Tour de force for perturbative QCD:

Q^2 does matter!

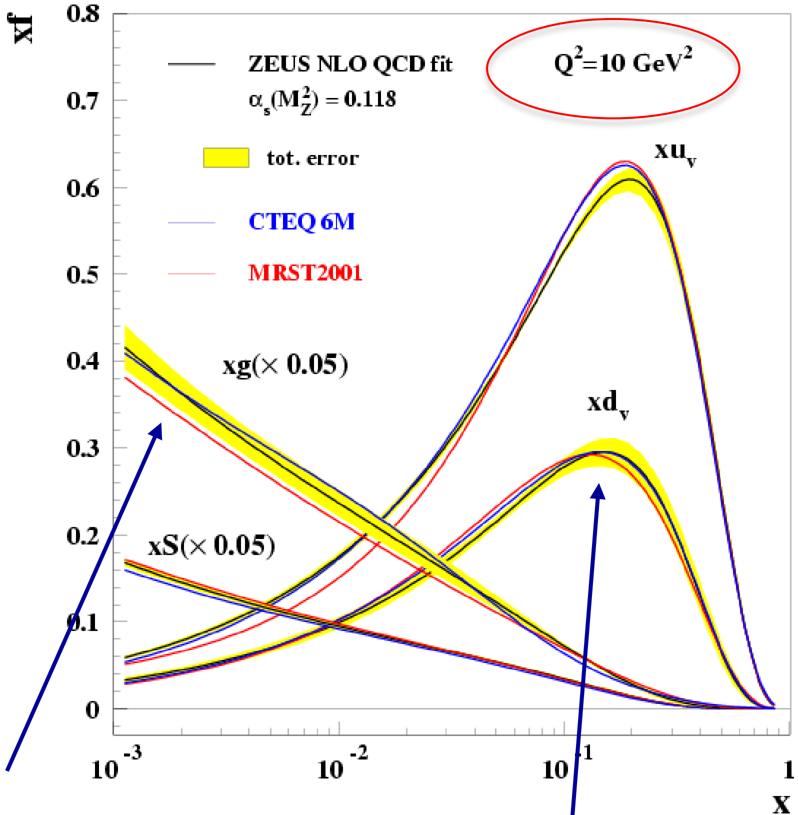
- Partons are not point-like and incoherent.
- Hadronic structure depends on the scale at which you probe it!

Spectacular agreement with DGLAP evolution

Parton Distribution Function in the proton

$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}\left(x_a, Q^2\right) \otimes f_{b/B}\left(x_b, Q^2\right) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}\left(z_c, Q^2\right)$$

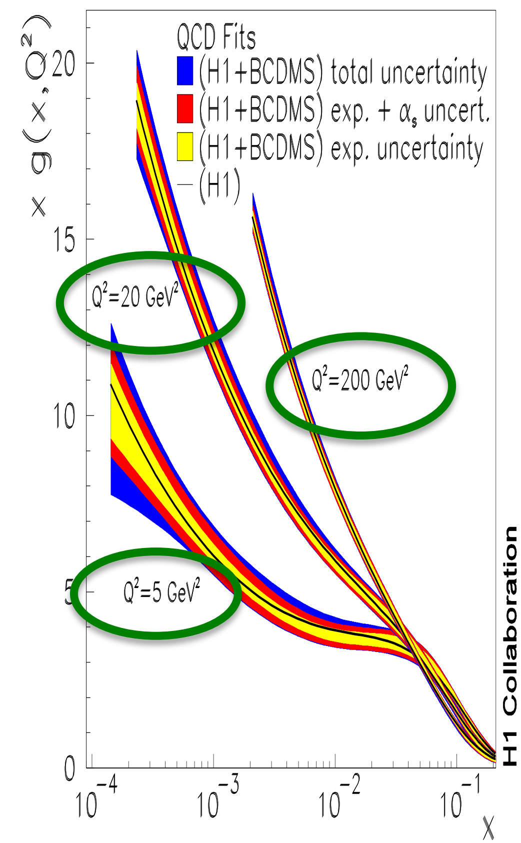
Low Q^2: valence structure



Soft gluons

Valence quarks (p = uud)
x ~ 1/3

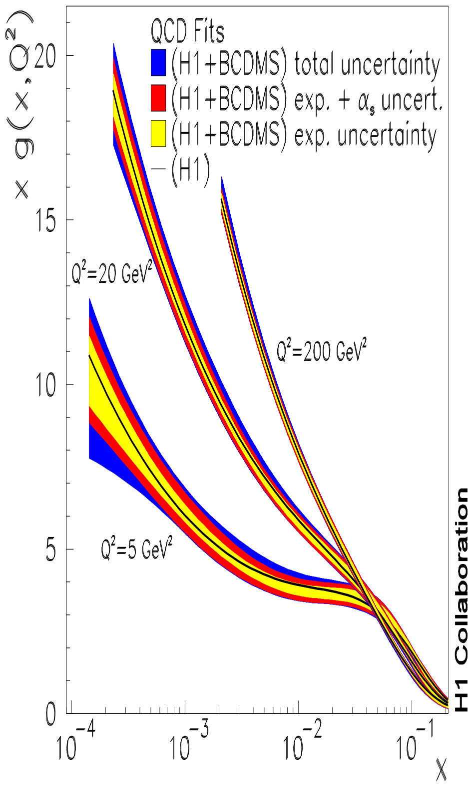
Q^2 evolution (gluons)

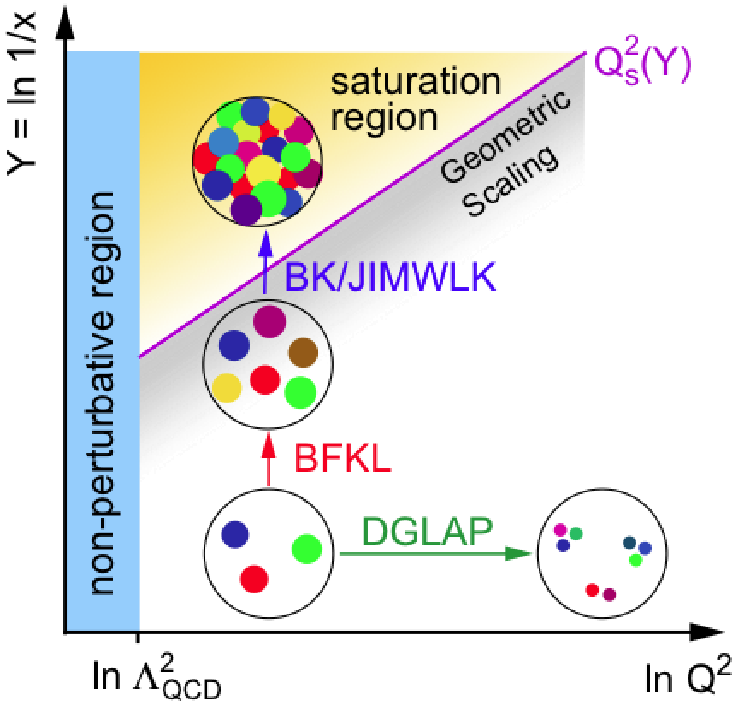


Gluon density decreases towards lower Q^2

Gluon saturation at low *x*

Fix Q^2 and consider what happens as *x* is decreased…





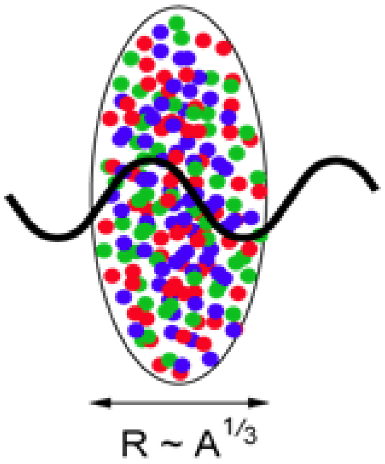
Problem: low x gluon density cannot increase without limit (unitarity bound)

Solution:

- gluons carry color charge
- if packed at high enough density they will recombine
  - ➔gluon density is self-limiting
  - ➔gluon saturation !

Gluon recombination in nuclei

Uncertainty principle: wave fn. for very low momentum (low x) gluons extends over entire depth of nucleus



Define gluon density per unit area in nucleus of mass A:

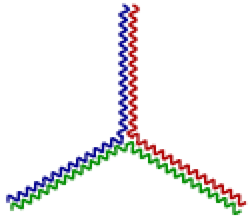
$$\rho \sim \frac{xG_A\left(x, Q^2\right)}{\pi R_A^2};\ G_A\left(x, Q^2\right) \sim A \cdot G_N\left(x, Q^2\right)$$

Gluon recombination cross section:

$$\sigma_{gg\to g} \sim \frac{\alpha_S}{Q^2}$$

Recombination occurs if:

$$\rho \cdot \sigma_{gg\to g} > 1$$



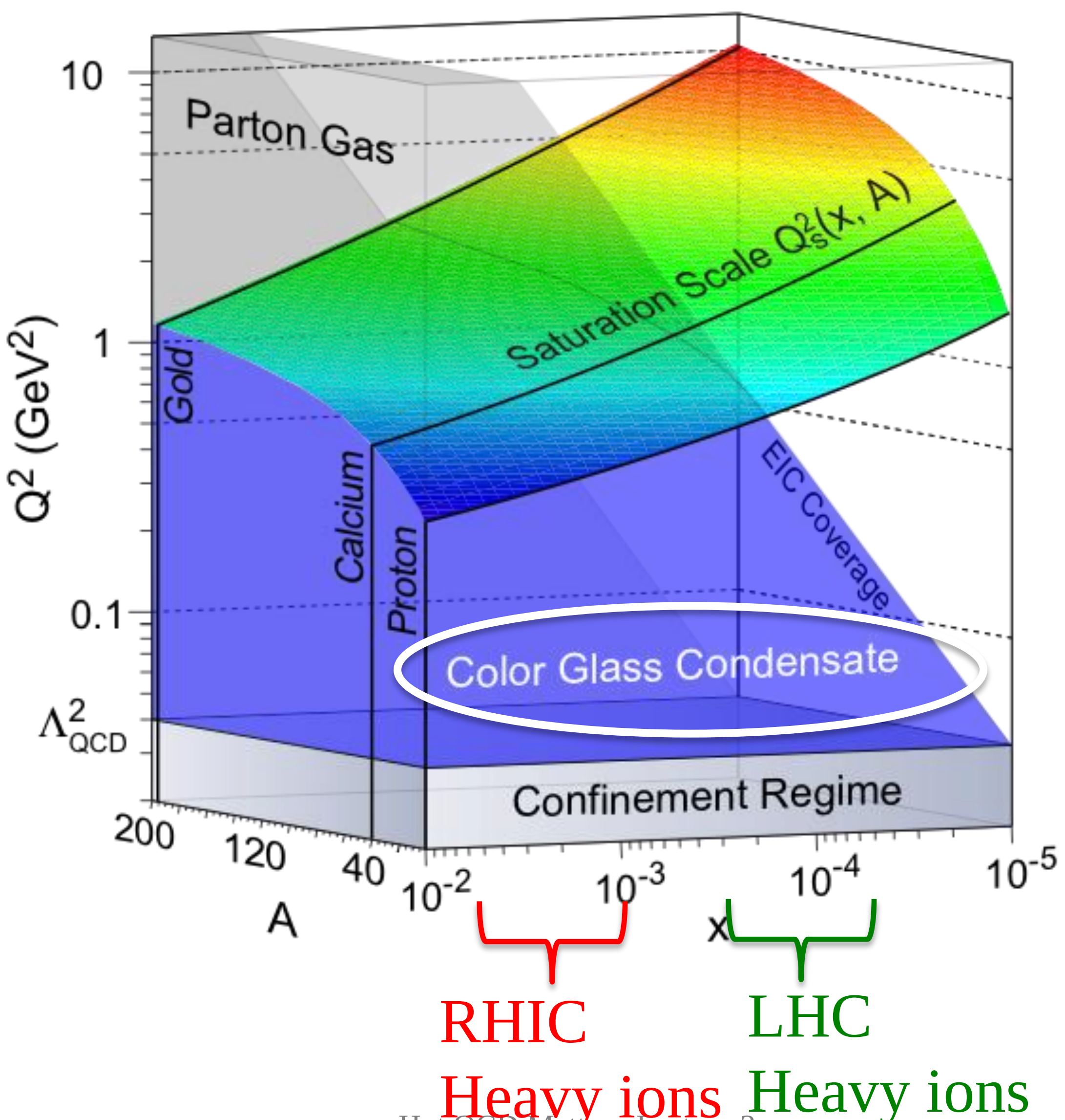
Saturation momentum scale Q_{sat}^2 satisfies self-consistent condition:

$$Q_{sat}^2 \sim \frac{\alpha_S \cdot xG_A\left(x, Q_{sat}^2\right)}{\pi R_A^2} \sim A^{1/3}\frac{1}{x^{0.3}}$$

Nuclear enhancement of Q_{sat}

Gluon recombination for $Q^2 < Q_{sat}^2$

Saturation scale vs nuclear mass



What's that?

Color Glass Condensate (CGC)

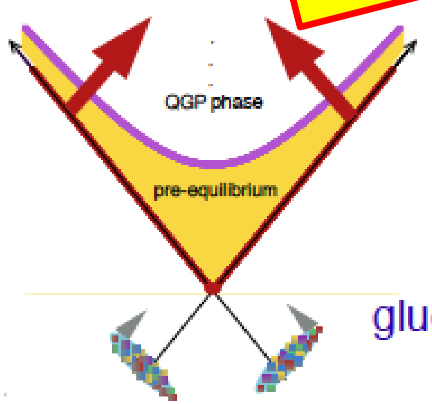
Semi-classical effective theory of satur…

Wave function: gluon recombination tame th… small-x (high-energies)

Translation: number of (final-state) charged particles seen in the detector in a heavy ion collision is proportional to number of gluons scattered early in the collision (K~1), which is suppressed due to saturation effects

Predicts specific scaling with collision centrality and √s

charged par… gluons in the wave functions of the colliding nuclei



LO kt-factorization: $$\left.\frac{dN^g}{d\eta\, d^2p_t}\right|_{\eta=0} \propto \frac{1}{p_t^2}\int d^2k_t\, \alpha_s\, \phi(x_1,k_t)\,\phi(x_2,|p_t-kt|)$$

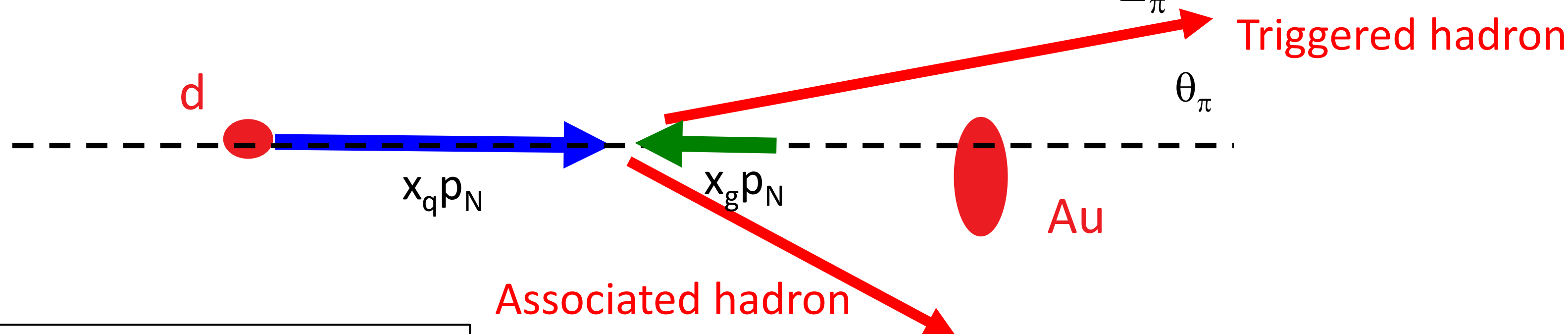
$\lambda \approx 0.24 \div 0.3$

gluon-hadron duality: $$\left.\frac{dN^{ch}}{d\eta}\right|_{\eta=0} = \frac{2}{3}K\left.\frac{dN^g}{d\eta}\right|_{\eta=0} \propto Q_s^2(\sqrt{s},b) \sim \sqrt{s/s_0}^{\lambda} N_{part}$$

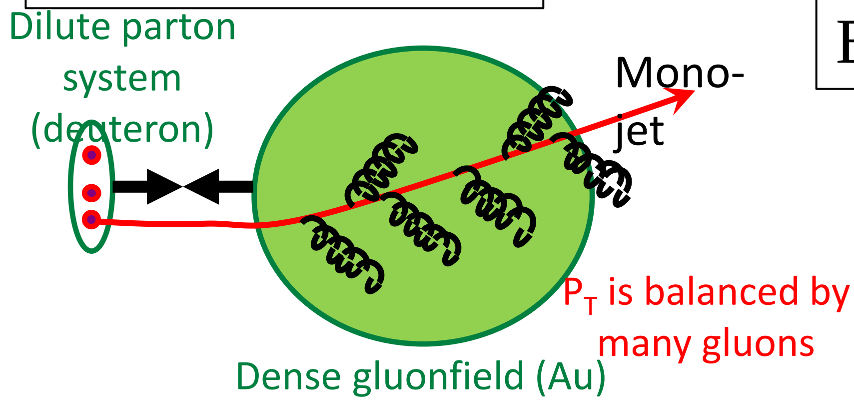
Can we see Saturation experimentally?

Asymmetric deuteron+Au collisions at RHIC:

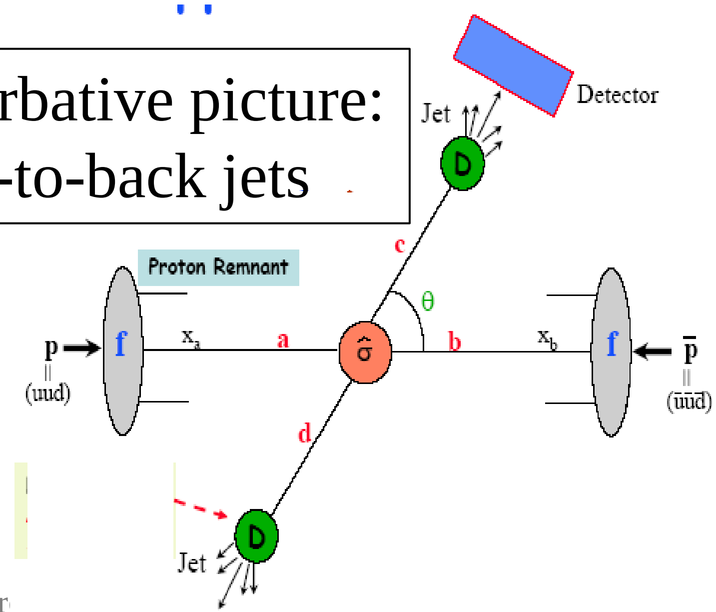
- Look at forward 2-particle correlations
- Back-scatter off Au-nucleus: low x in Au



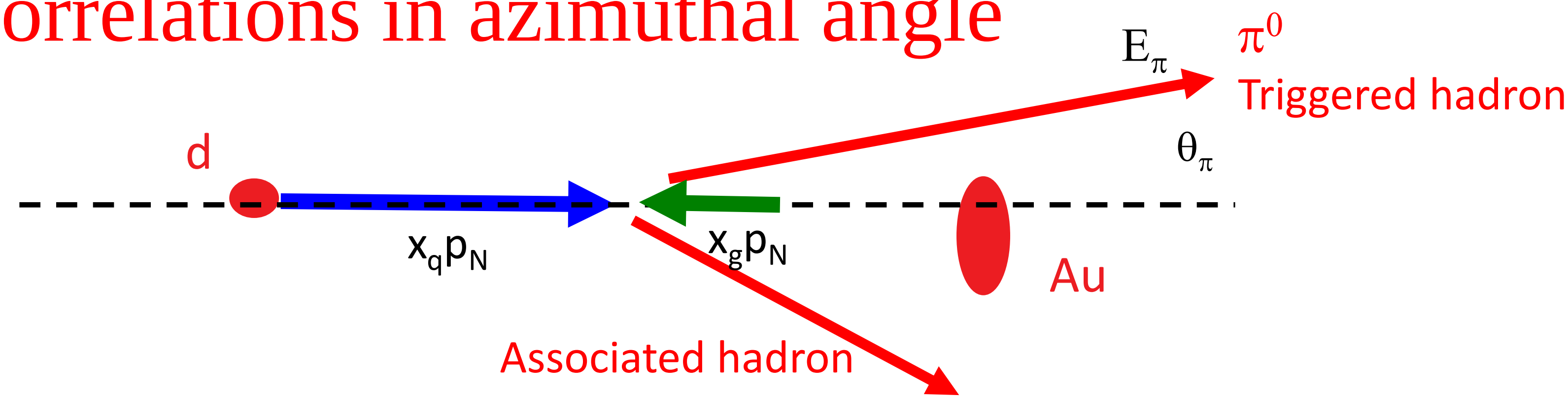
Saturation picture:
"mono-jets"



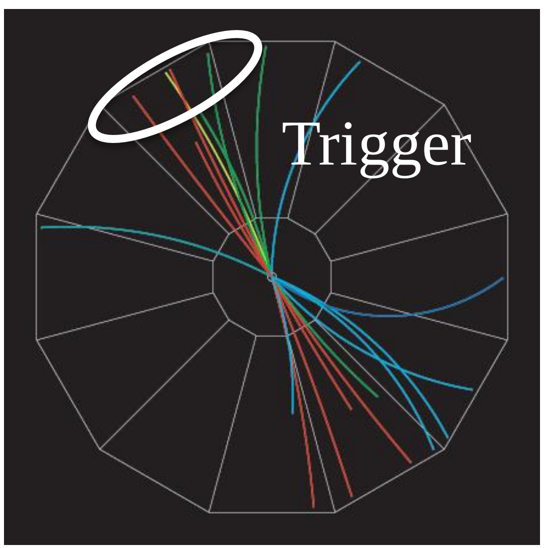
Perturbative picture:
Back-to-back jets

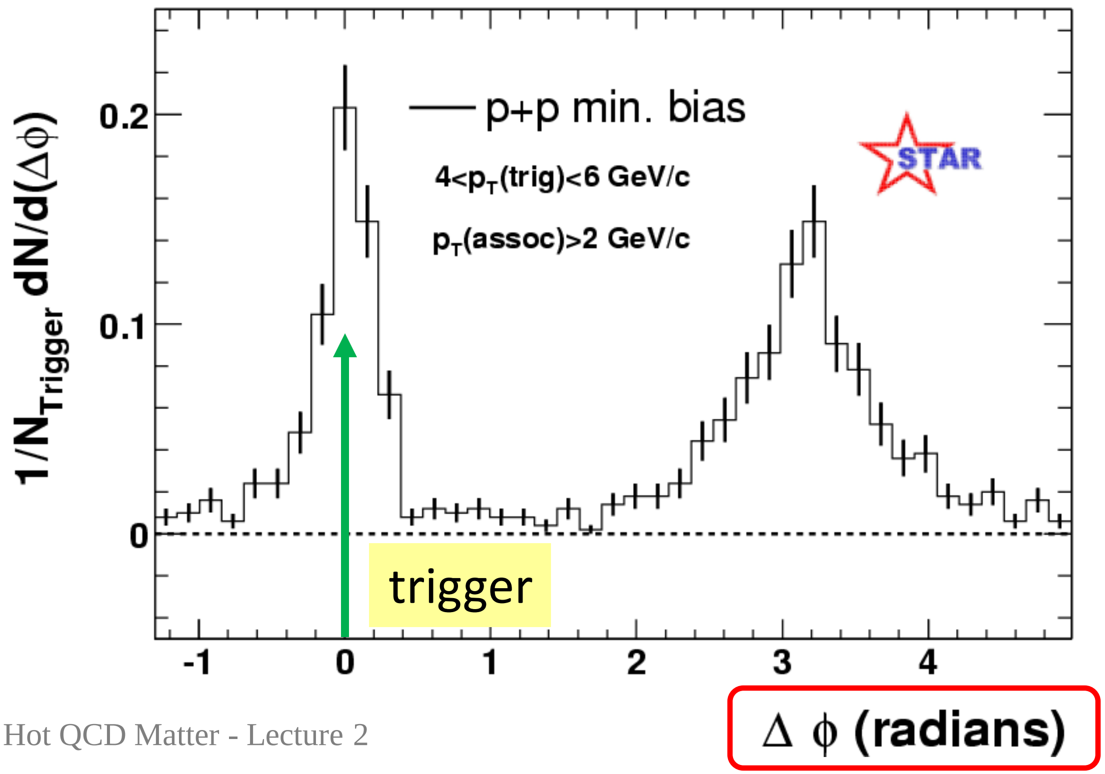


What are we plotting? 2-particle correlations in azimuthal angle

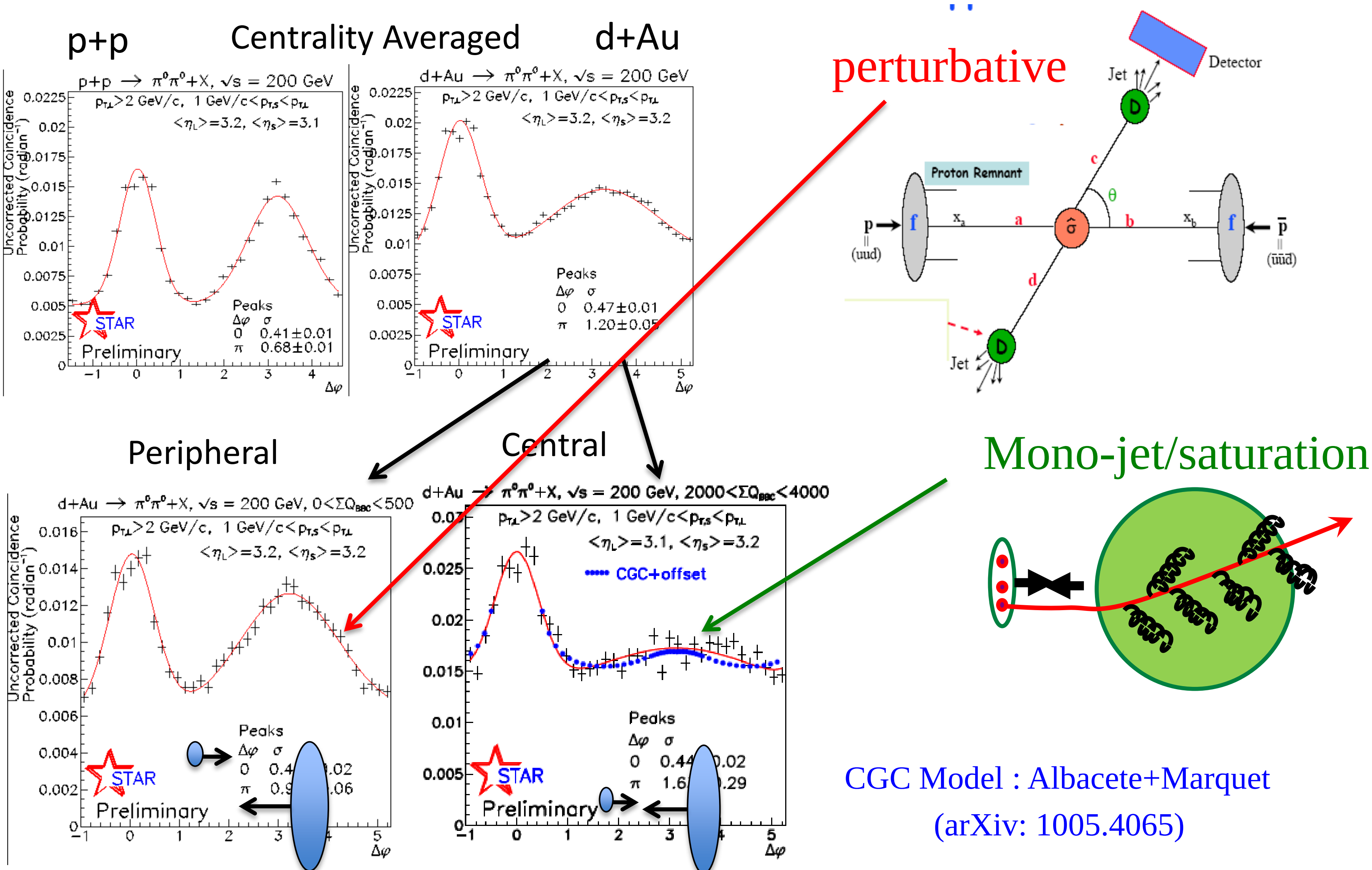


Transverse plane





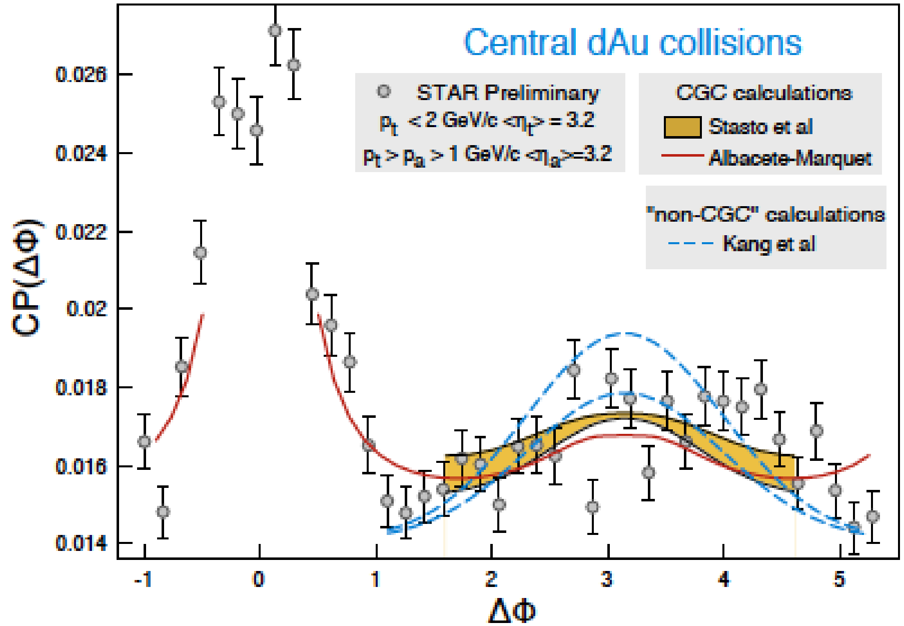
STAR: d+Au forward azimuthal correlations



CGC Model : Albacete+Marquet

(arXiv: 1005.4065)

Forward di-hadron angular correlations in RHIC dAu data



But maybe not:

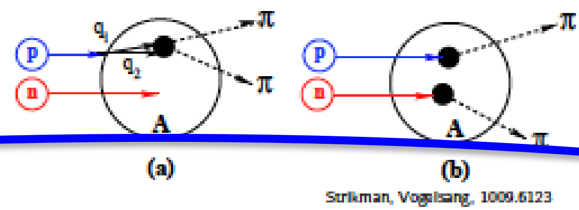
Conventional pQCD mechanisms plus conventional nuclear effects work as well…

Uncertainties in current CGC phenomenological works:

- Need for a better description of n-point functions: [D. Triantafyllopoulos's and T. Lappi's talk]
- Better determination of the pedestal: K-factors in single inclusive production? Role of double parton scattering?

[Heikki Mäntysaari's talk]

correlated

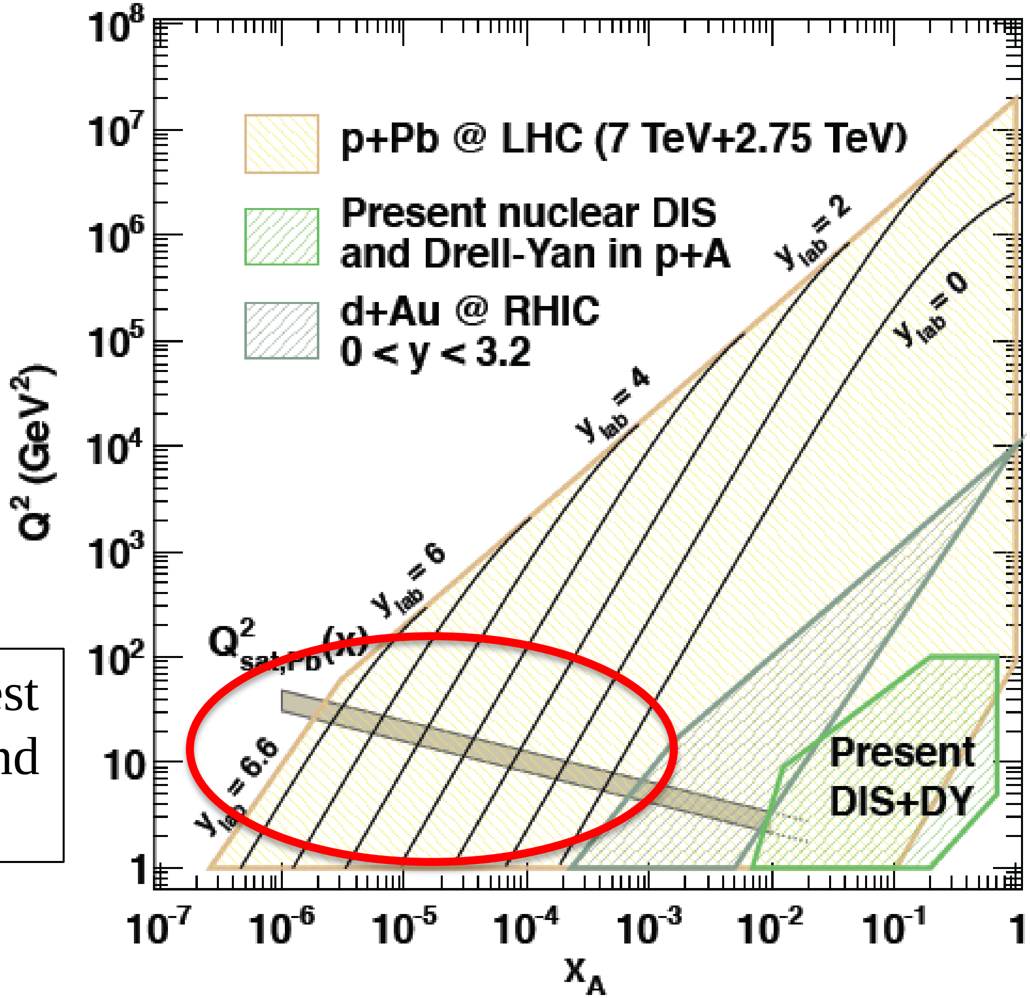


uncorrelated

- Alternative descriptions including resummation of multiple scatterings, nuclear shadowing and cold nuclear matter energy loss seem possible...

Next step: p+A at LHC (November 2012 run)

C. Salgado, Hard Probes 2012



Region of greatest interest: low *x* and low Q^2

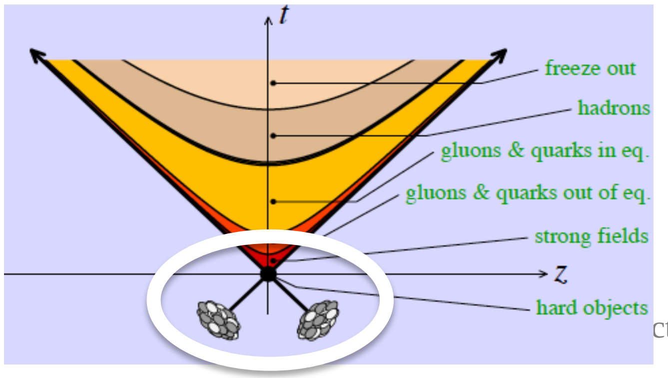
Summary thus far

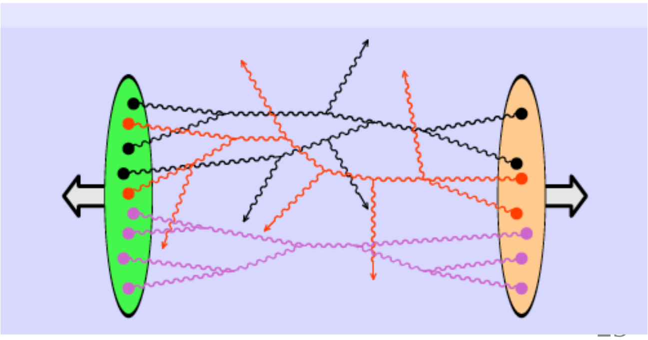
QCD is remarkably successful in describing the partonic stucture of the proton over a vast kinematic range

There are good reasons to expect signficant modification of this structure in heavy nuclei ➔ saturation

- Some experimental evidence in favor of saturation in forward d+Au correlations at RHIC
- LHC p+A run this November will provide a wealth of new data to address the issue in more detail (crucially: much smaller *x*)

Does any of this play a role in high energy nuclear collisions?
Let's go back to our original question: what generates all the particles?





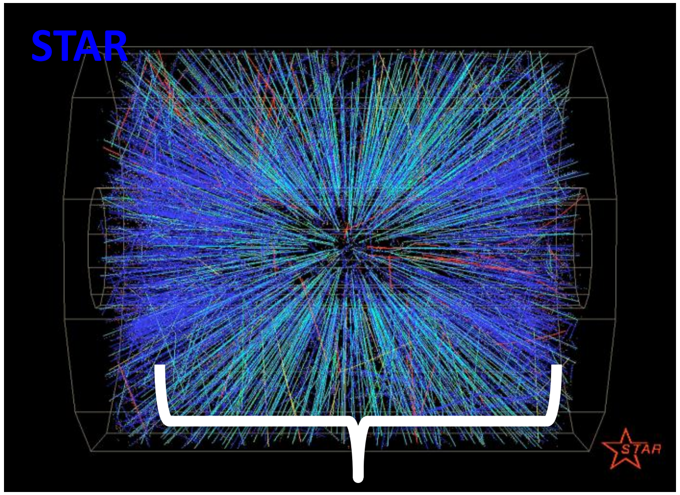
Multiplicity measurements

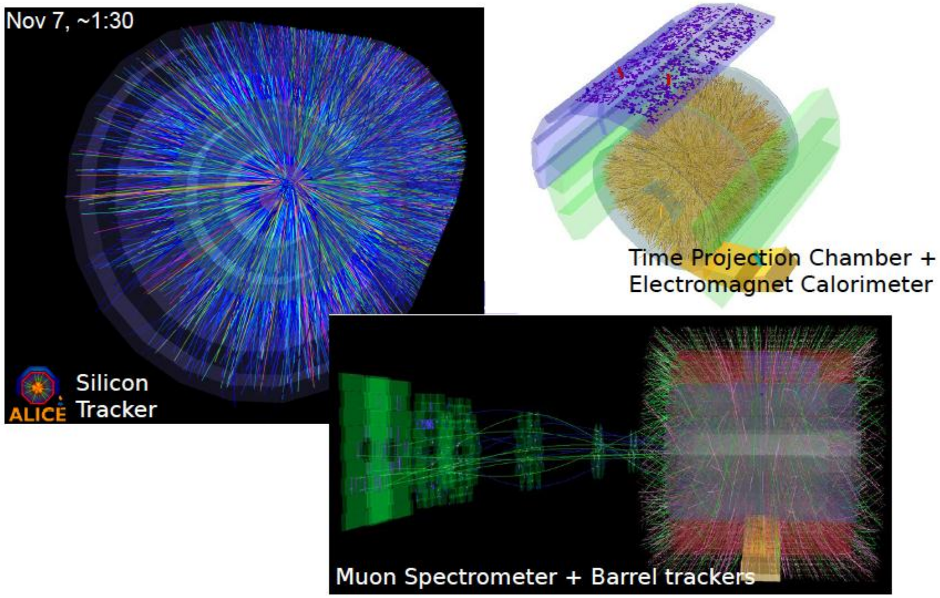
Count the number of charged particles per unit pseudo-rapidity

Simplest "bulk" observable that characterizes the collision

RHIC

LHC

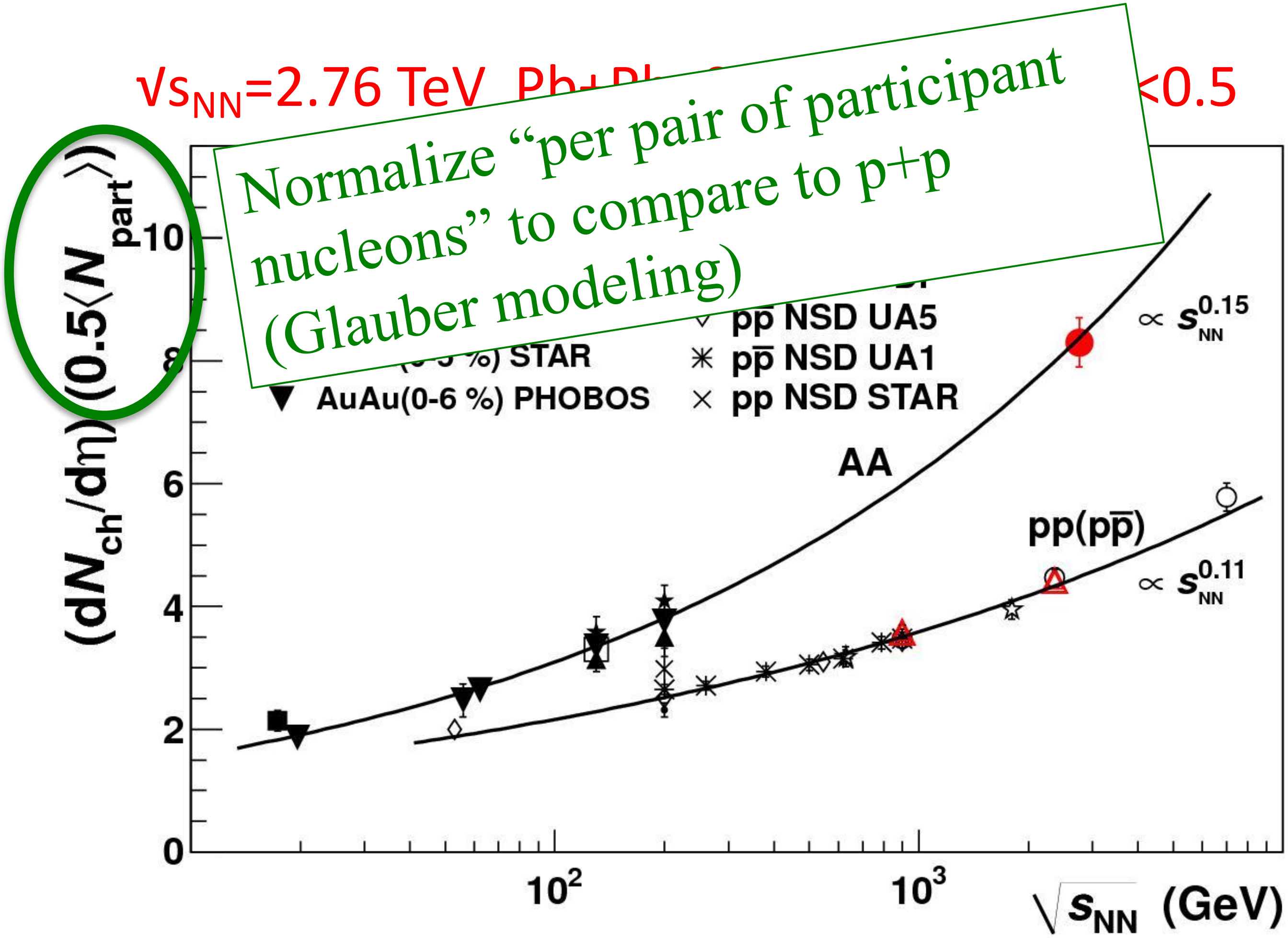




Charged particle multiplicity

ALICE PRL, 105, 252301 (2010), arXiv:1011.3916

$\sqrt{s_{NN}}$=2.76 TeV Pb+Pb ... <0.5



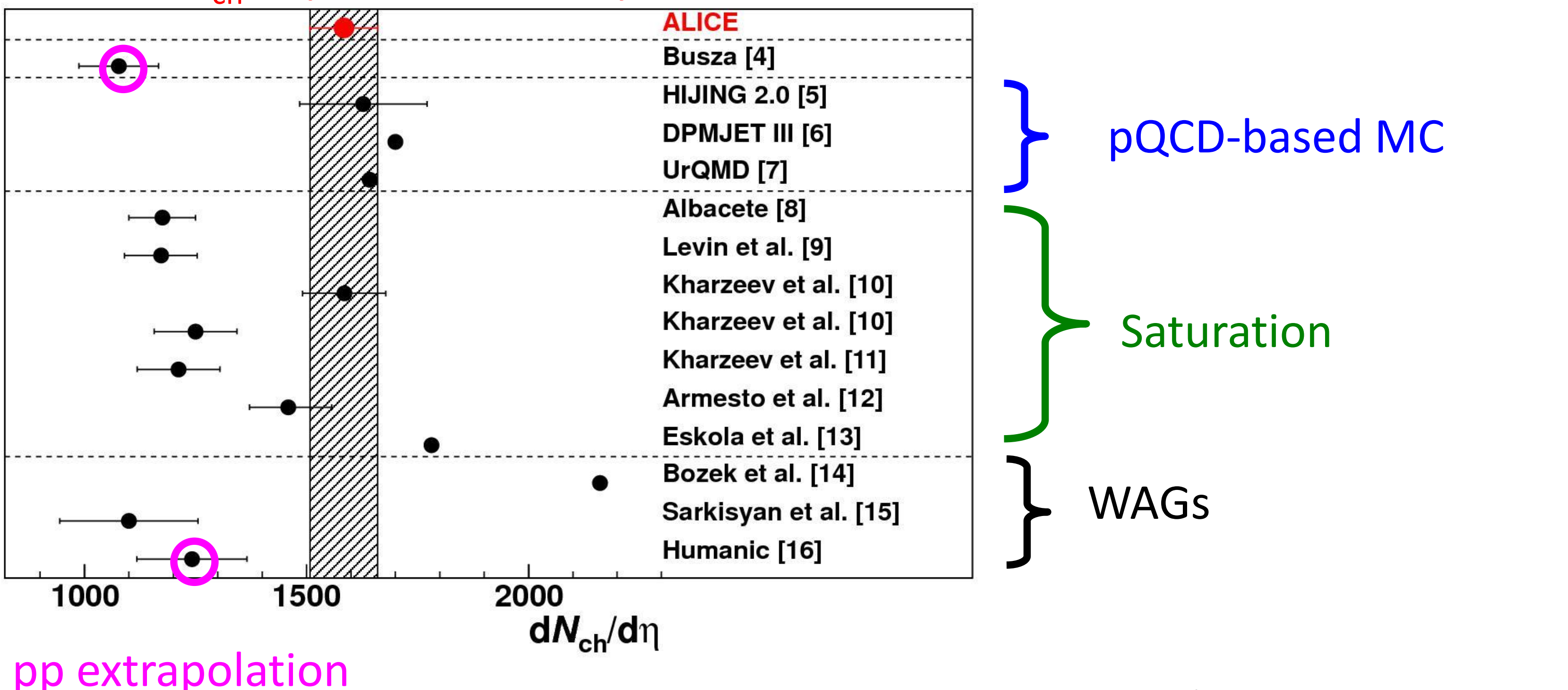
LHC: 2 $dN_{ch}/d\eta$ / $\langle N_{part}\rangle$ = 8.3 ± 0.4 (sys.)

$dN_{ch}/d\eta$: model comparisons

PRL, 105, 252301 (2010), arXiv:1011.3916

$\sqrt{s_{NN}}$=2.76 TeV Pb+Pb, 0-5% central, |η|<0.5

$dN_{ch}/d\eta$ = 1584 ± 76 (sys.)

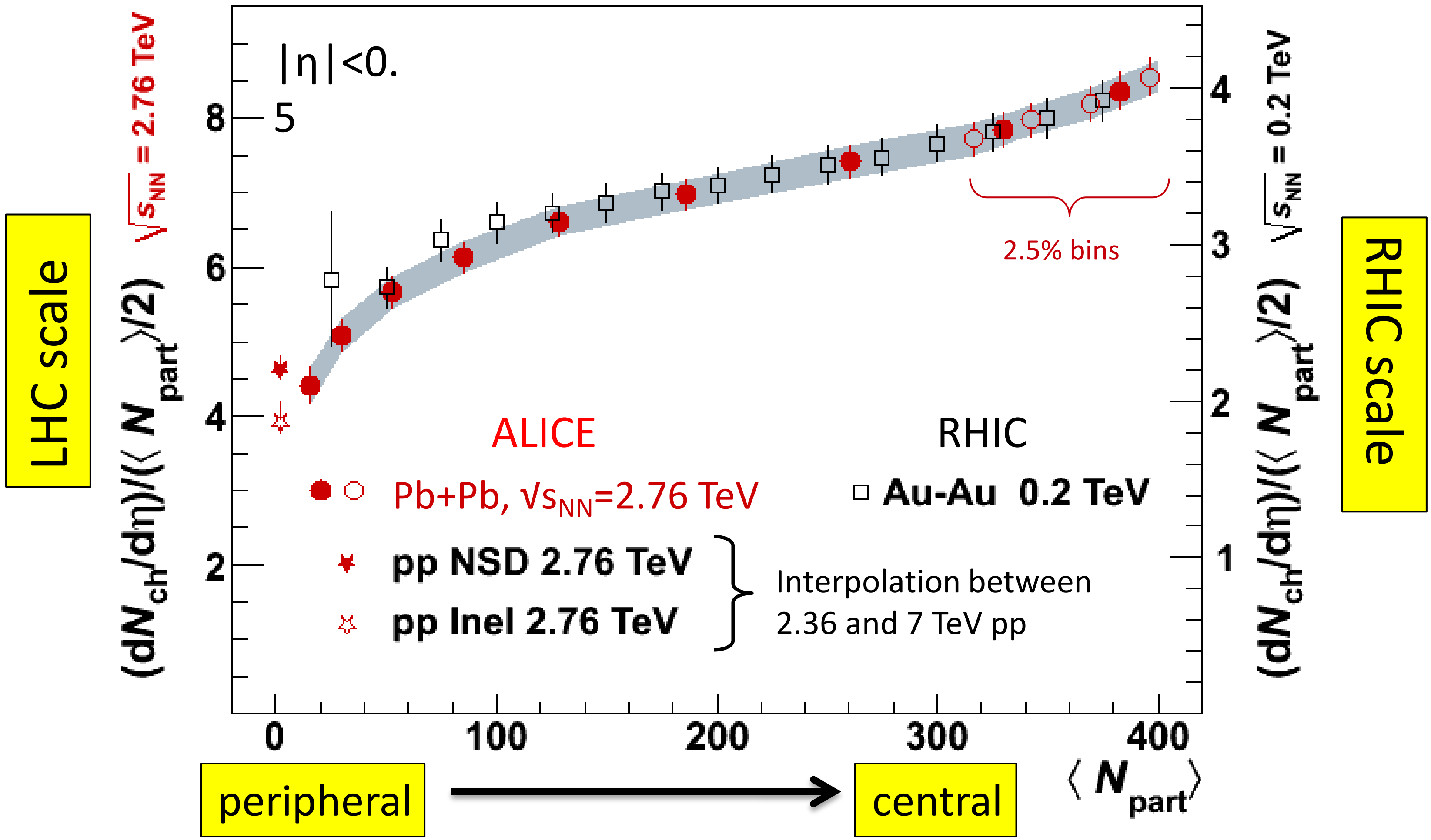


Energy density estimate (Bjorken): $\epsilon(\tau) = \frac{E}{V} = \frac{1}{A\tau}\frac{dN}{d\eta}\langle m_T \rangle$

$\epsilon(\tau_0)_{LHC} \geq 3 \times \epsilon(\tau_0)_{RHIC}$

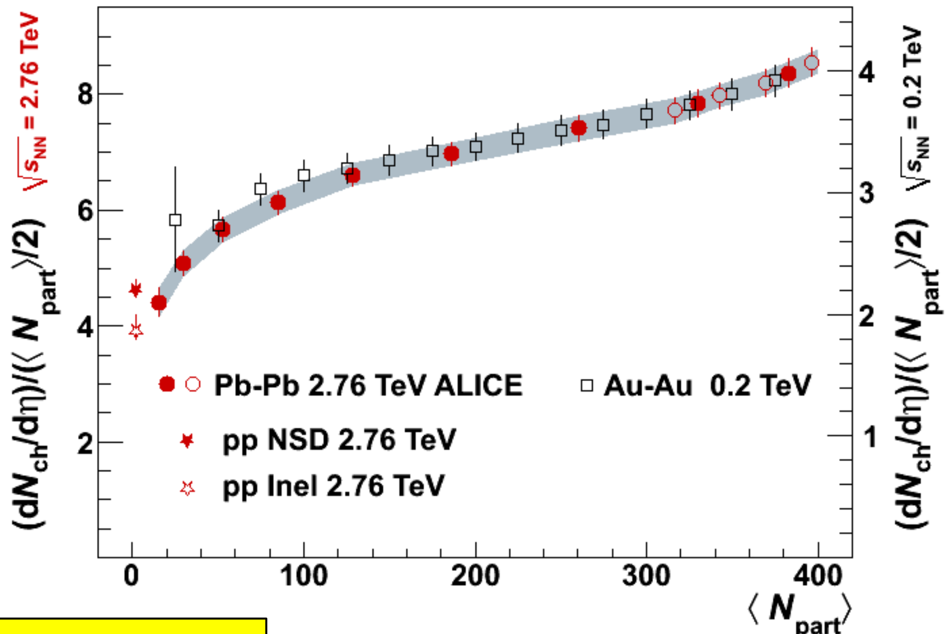
dNch/dη: Centrality dependence

PRL, 106, 032301 (2011), arXiv:1012.1657

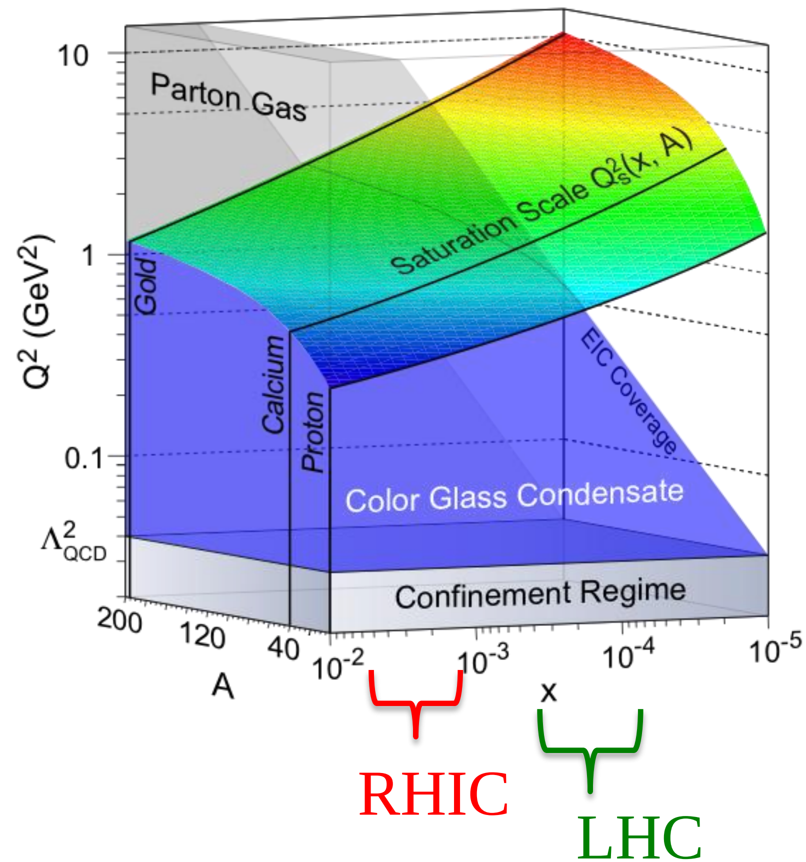


Striking centrality-independent scaling RHIC➔LHC

Does saturation play a role?



peripheral → central



Expectation from saturation models: factorization of centrality and energy dependence:

$$\frac{dN^{ch}}{d\eta} \sim \sqrt{s/s_0}^{\lambda} \cdot f(N_{part})$$

$dN_{ch}/d\eta$ vs. centrality: models

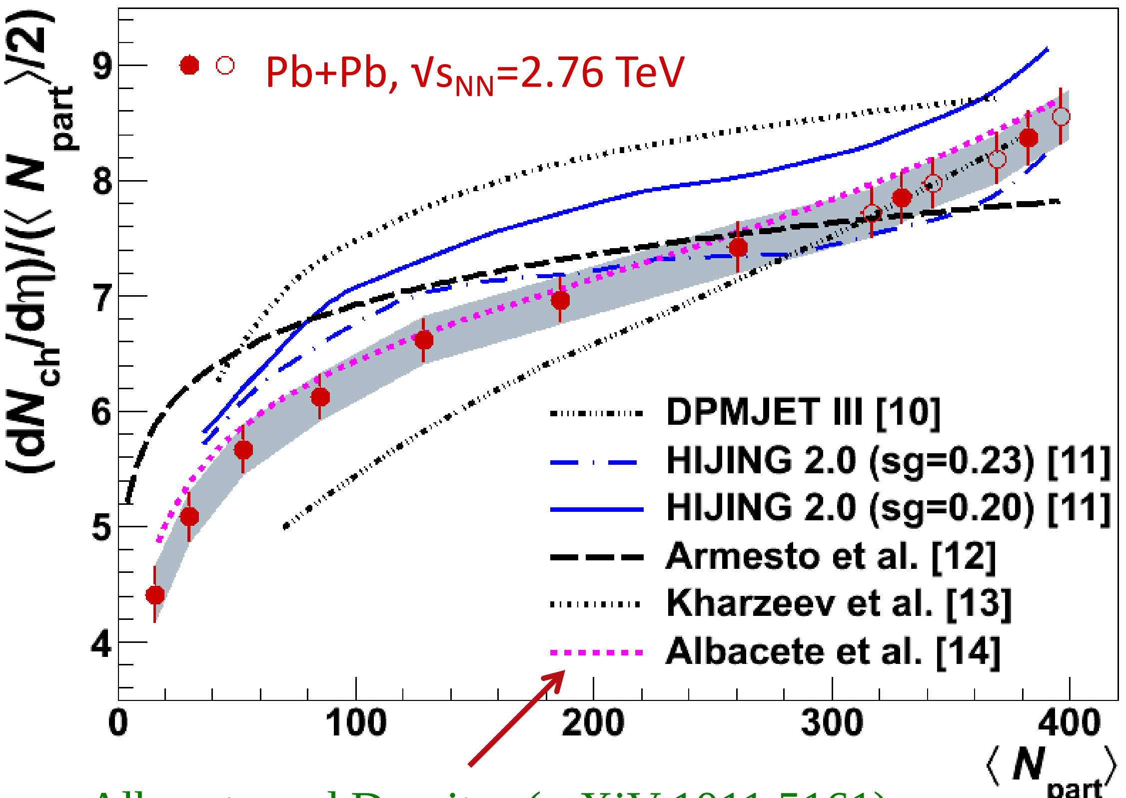
PRL, 106, 032301 (2011), arXiv:1012.1657

Two-component perturbative models

- Soft (~Npart) and hard (~Nbin) processes

Saturation-type models

- Parametrization of the saturation scale with centrality



Albacete and Dumitru (arXiV:1011.5161):

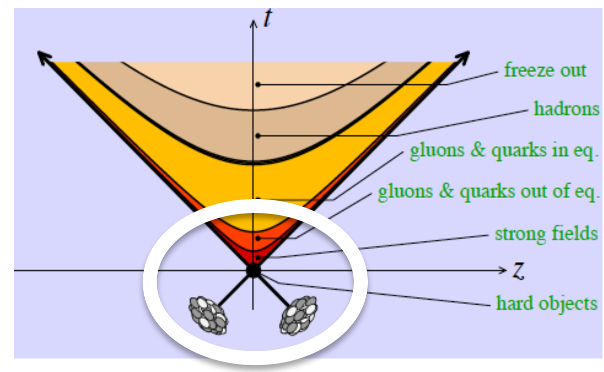
- Most sophisticated saturation model: evolution, running coupling
- Captures full centrality dependence…?

Summary of Lecture 2

Initial state: approaching quantitative control

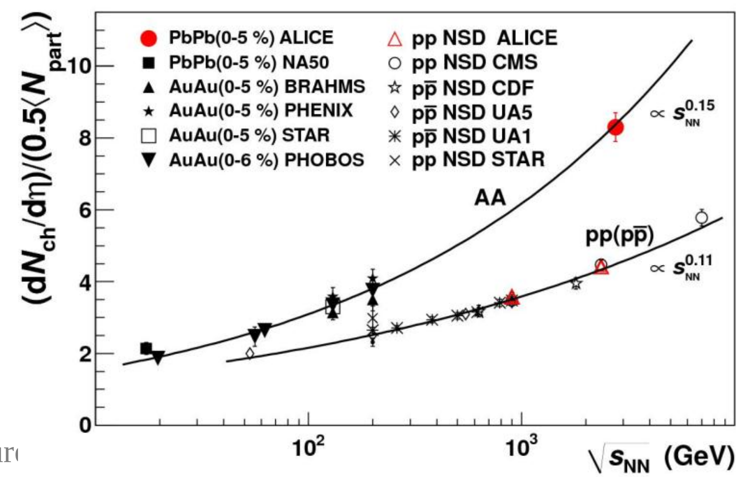
Final charged multiplicity closely related to initial gluon multiplicity:

$$\frac{dN^{ch}}{d\eta} \sim \frac{2}{3} \cdot \mathbf{K} \cdot \frac{dN^{g}}{d\eta}$$



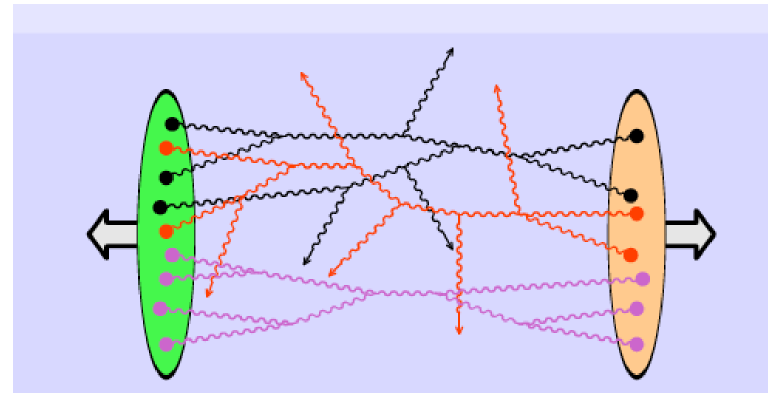
Good evidence that gluon saturation in nuclei plays a role

Smooth evolution of multiplicity with collision energy and system size

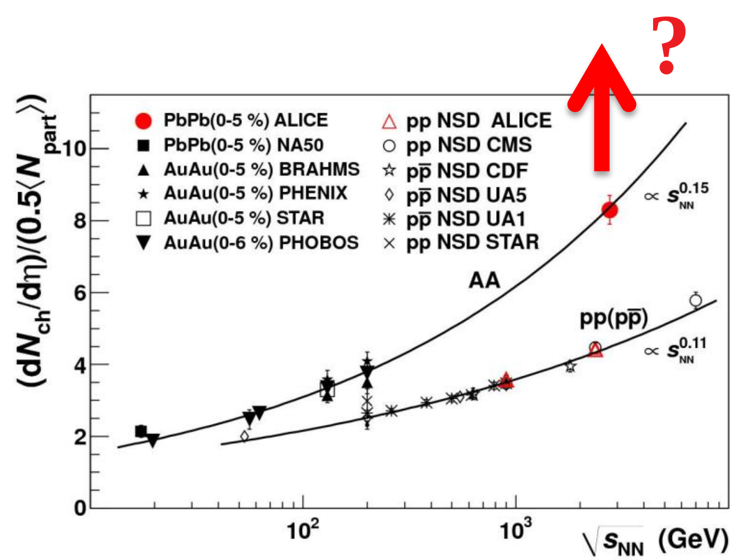


Why is any of this surprising? How could it be different?

Thermalized system: massive re-interactions, generation of large numbers of particles and softening of momentum spectra



expect stronger dependence on energy and system size…?



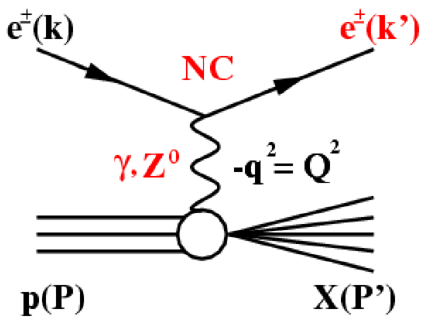
Apparently not the case

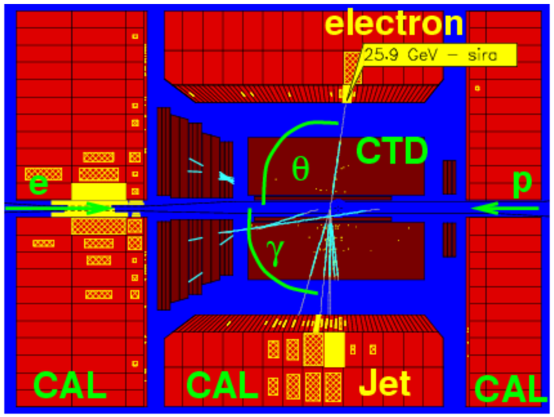
Next lecture: additional news about equilibration.

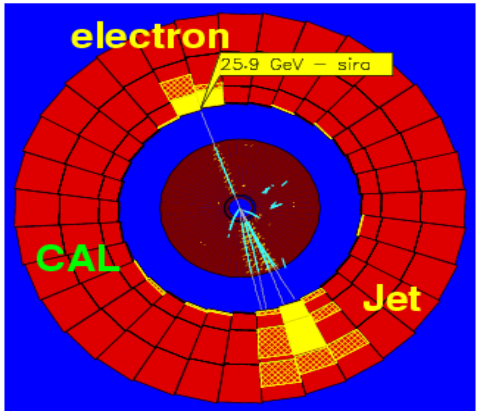
Backup

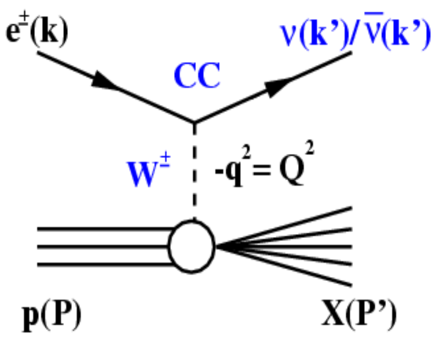
Simpler case: deep inelastic scattering (DIS) of e+p

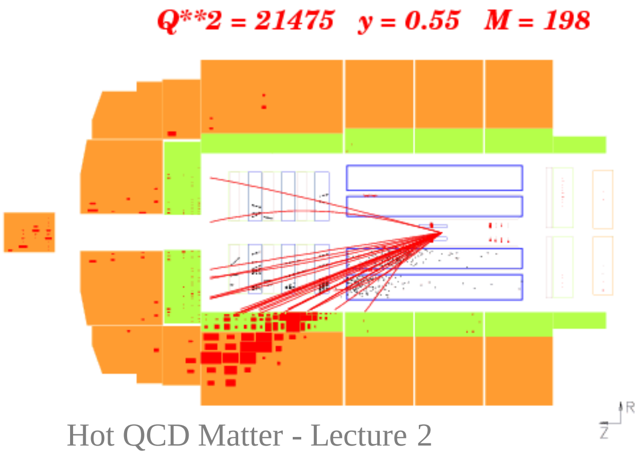
$$\mathrm{NC:}\quad e^{\pm} + p \rightarrow e^{\pm} + X, \qquad \mathrm{CC:}\ \ e^{\pm} + p \rightarrow \bar{\nu}_e(\nu_e) + X$$

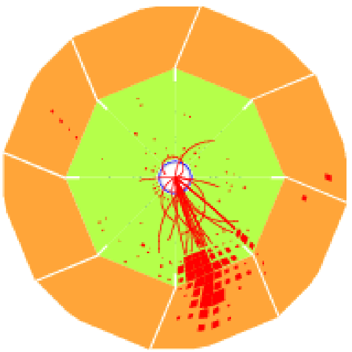








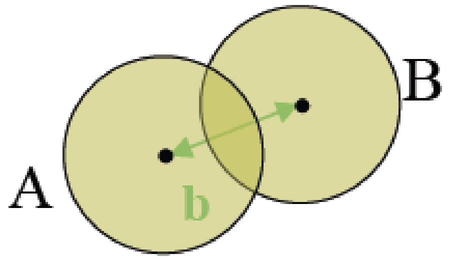




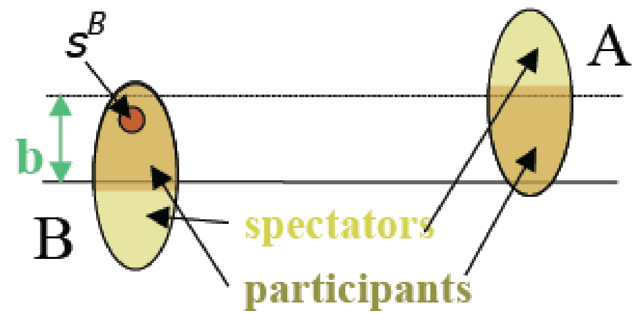
Glauber Theory for A+B Collisions

Nuclear overlap function:

$$T_{AB}\left(\vec{b}\right) = \int d\vec{s}\, T_A\left(\vec{s}\right) T_B\left(\vec{s} - \vec{b}\right)$$



Average number of binary NN collisions for B nucleon at coordinate $\mathbf{s_B}$:



$$N_{bin}^{nA}\left(\vec{b} - \vec{s}_B\right) = A \cdot T_A\left(\vec{b} - \vec{s}_B\right) \cdot \sigma_{nn}^{inel}$$

Average number of binary NN collisions for A+B collision with impact parameter b:

$$\begin{aligned} N_{bin}^{AB}(b) &= B \int d\vec{s}_B\, T_B\left(\vec{s}_B\right) \cdot N_{bin}^{nA}\left(\vec{b} - \vec{s}_B\right) \\ &= AB \cdot T_{AB}(b) \cdot \sigma_{nn}^{inel} \end{aligned}$$