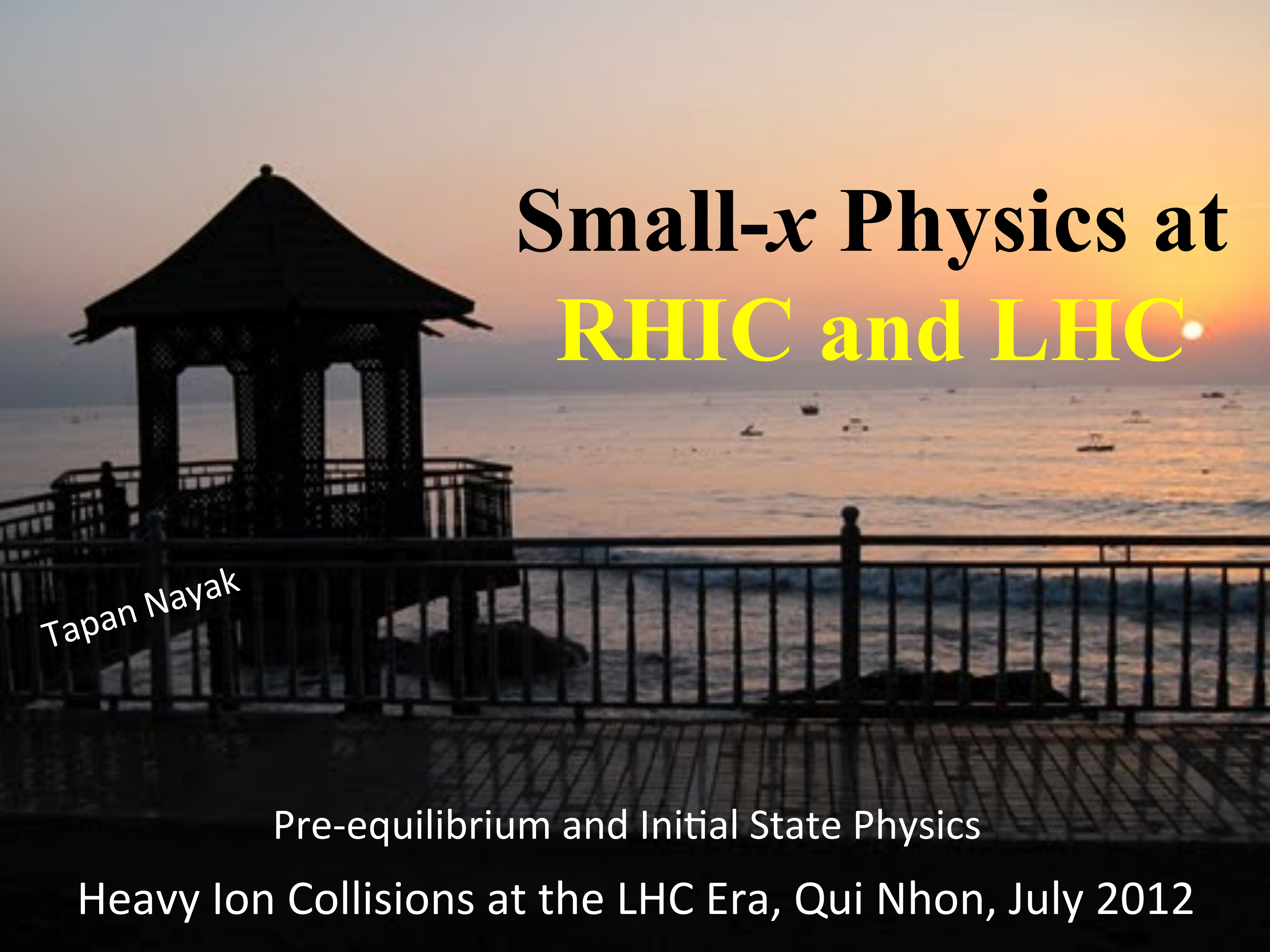


Small-*x* Physics at RHIC and LHC

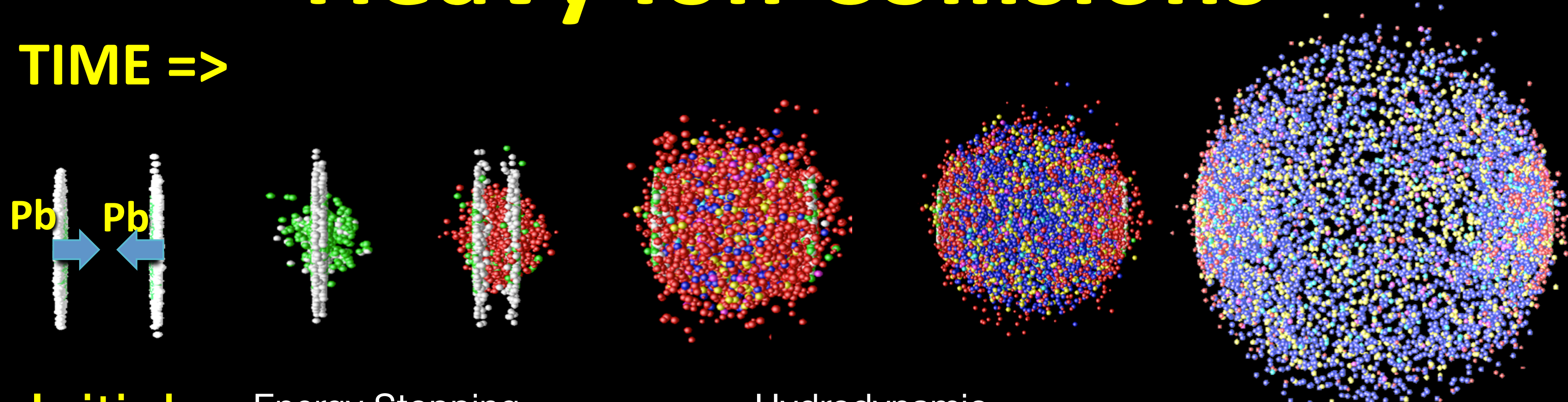
Tapan Nayak

Pre-equilibrium and Initial State Physics

Heavy Ion Collisions at the LHC Era, Qui Nhon, July 2012

Heavy Ion Collisions

TIME =>



Initial state (CGC)

Energy Stopping
Hard Collisions

Hydrodynamic
Evolution

Hadron
Freezeout

Hard Probes
- **Energy Loss**
- **Jets**

Direct Probes
- **Quarkonia**
- **Heavy Flavour**
- **Photons**

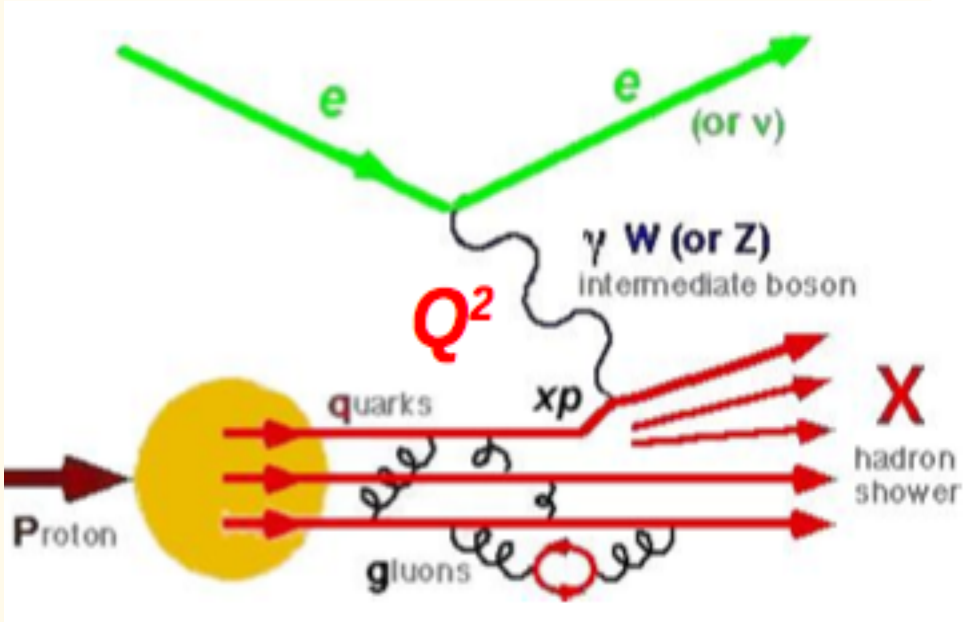
Freezeout Conditions & Global properties
- **Particle Multiplicities**
- **Fluctuations**
- **Spectra**
- **Particle Flow**
- **Particle Correlations**

Is there any way to get a handle on the initial state?

Do these observables care about the initial states?
Can we think of other ways like p-Pb collision?

Parton Distribution Functions

Deep Inelastic Scattering: Probing distribution of partons inside hadrons

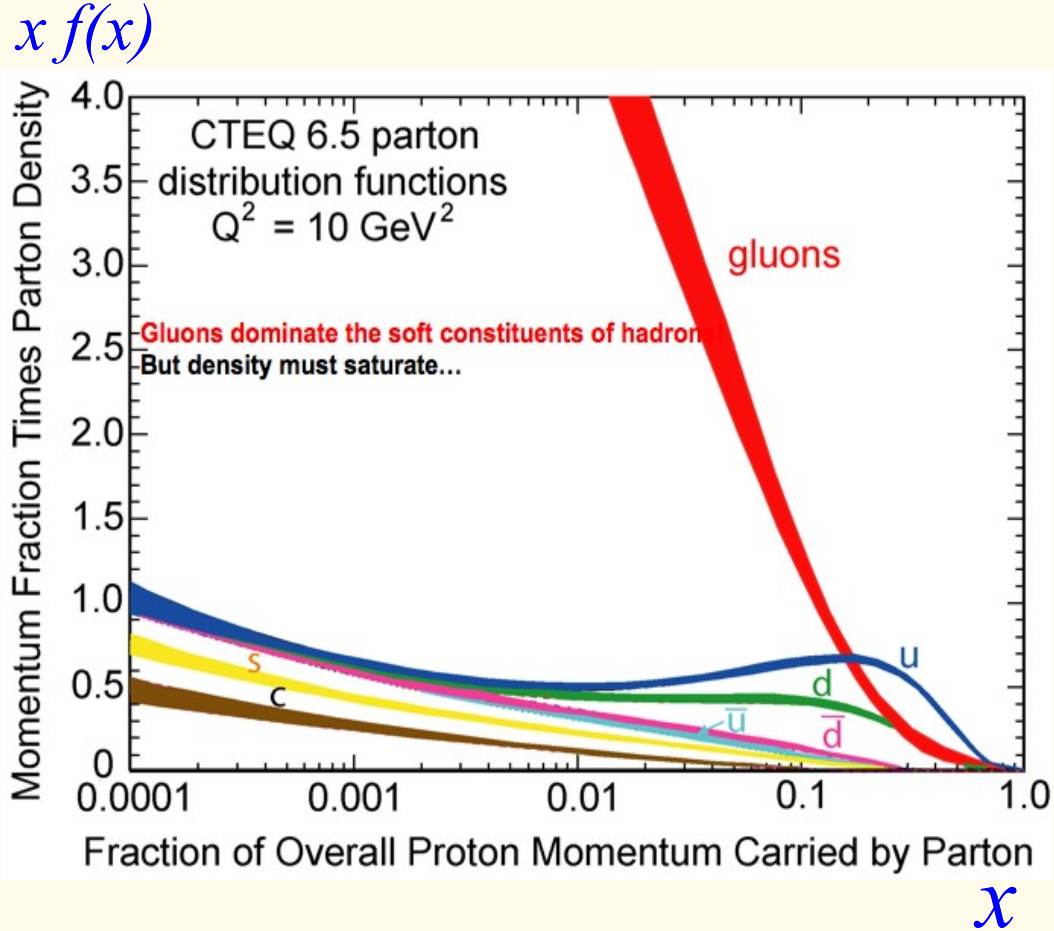


$$Q^2 = 2(EE' - \vec{k}\cdot\vec{k}')$$
$$\nu = E - E'$$
$$x = Q^2/2M\nu$$

x: the overall proton momentum carried by the parton

- Gluons drive a significant fraction of the scattering processes at LHC
- Precise determination of the PDFs of the proton in a wide range of x and Q^2, especially of the gluons
- Gluon-gluon (fusion) channel is a dominant channel for the production of SM Higgs

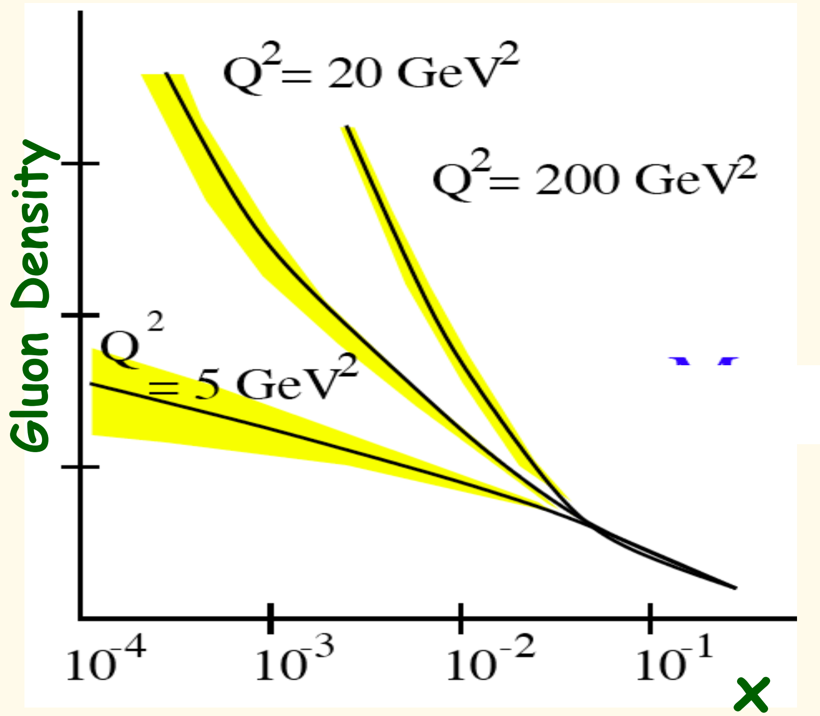
Gluon Distribution: Proton

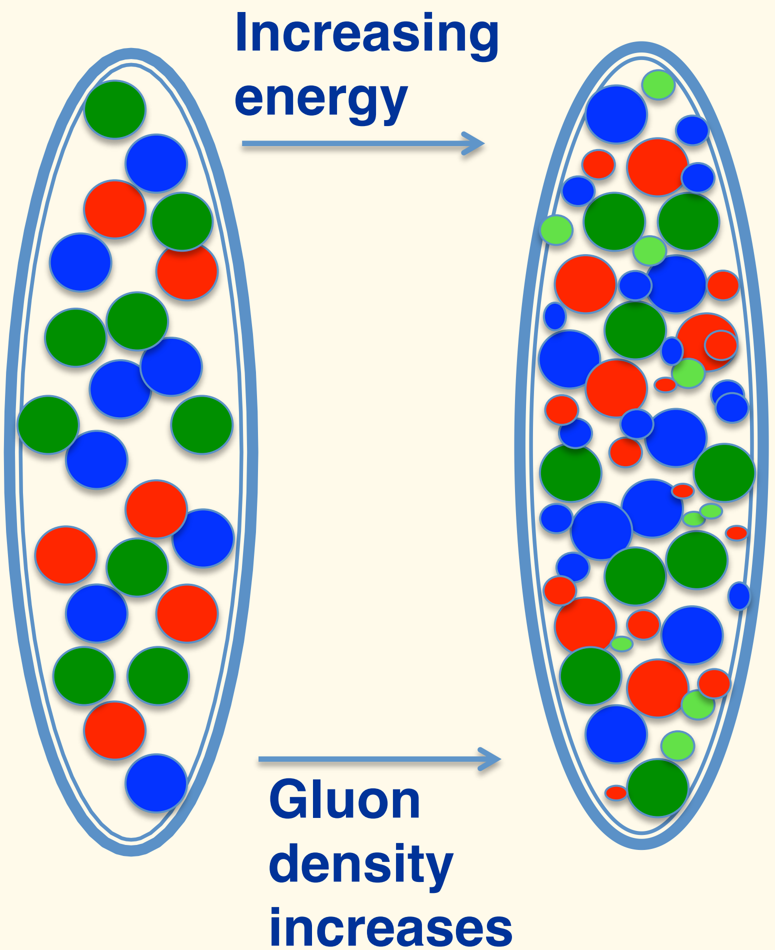


- **Small-*x* gluon density is large and continues to increase as $x \rightarrow 0$**
- **Where does the saturation set in?**

$x < 0.01$: virtually unknown and large uncertainties in the theoretical calculations (non –pertubative).

Gluon saturation at high density





Saturation at high density

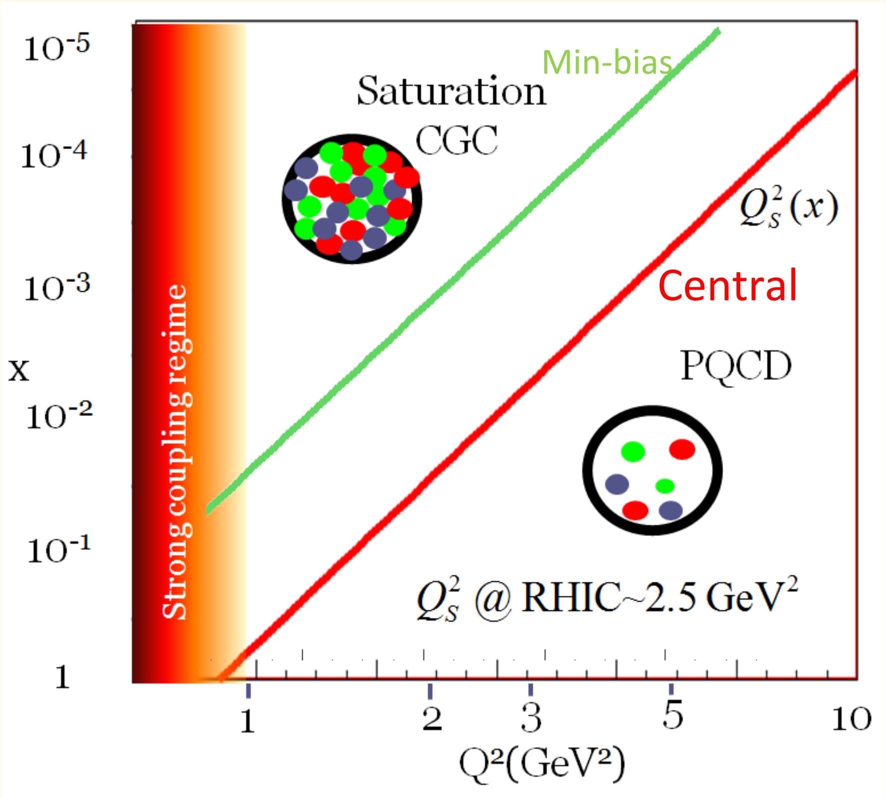
Q_S : Saturation momentum

Q_S larger in A than in p

Nuclei → $Q_s^2 \propto A^{1/3}$

The Color Glass Condensate

See e.g., F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan, arXiv:1002.0333

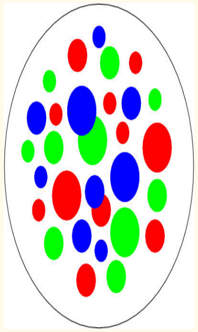


- **Gluons are colored**
- **Glass: The sources of gluon field are static, evolving over much longer time scales than natural one – resulting theory of classical field and real distribution of stochastic source is similar to spin glass**
- **Condensate: Gluon occupation number is very large.**

Parton distributions are replaced by ensemble of coherent classical fields:

Individual gluons arise from coherent sum of nucleon sources. Evolution to small x involve coherent sum of fields from several sources. This coherent sum of fields is the CGC

Study of Small-*x* Parton Distributions

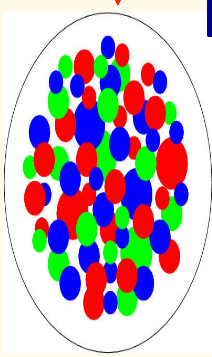


Low energy

Large *x*

$$x \approx \frac{p_T}{\sqrt{s}} \exp(-y) \approx \frac{p_T}{\sqrt{s}} \exp(-\eta)$$

Gluon density increases

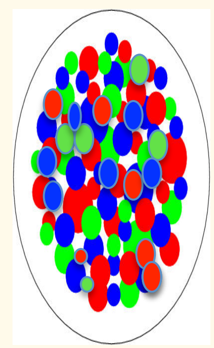


High energy

Small *x*

Mid Rapidity

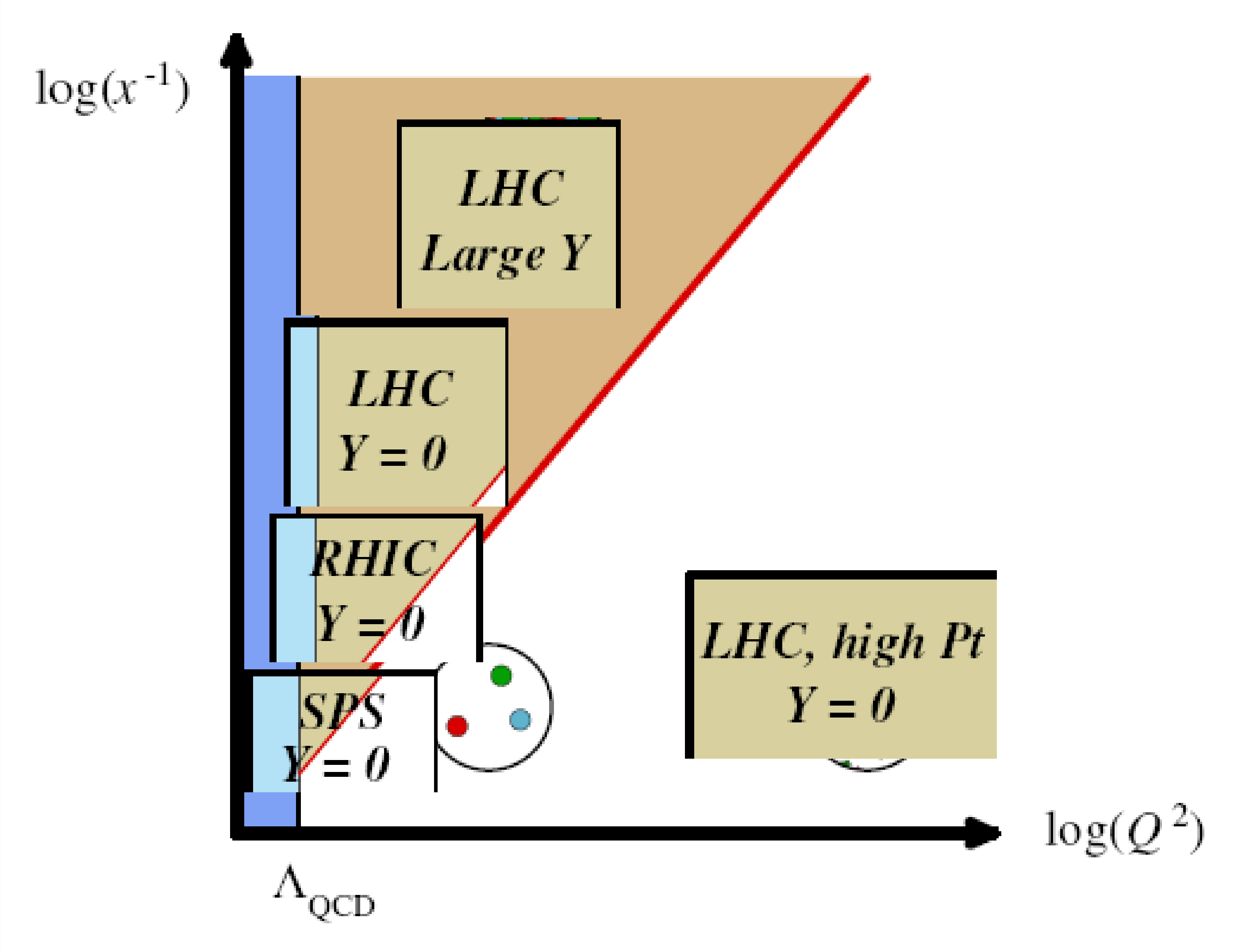
Further increase in Gluon Density? Saturation?



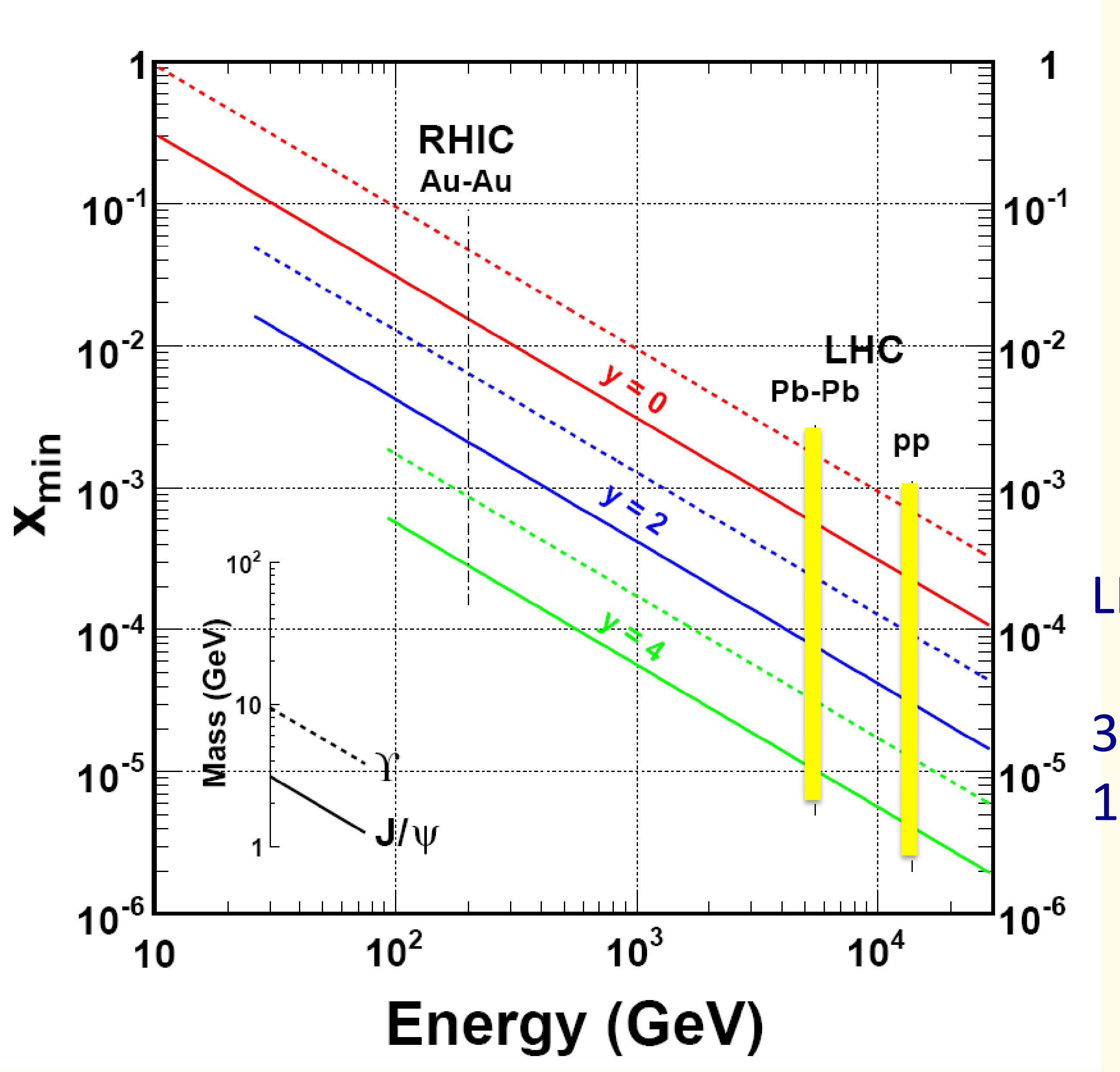
Forward Rapidity

Smaller *x*

Accessing the saturation domain



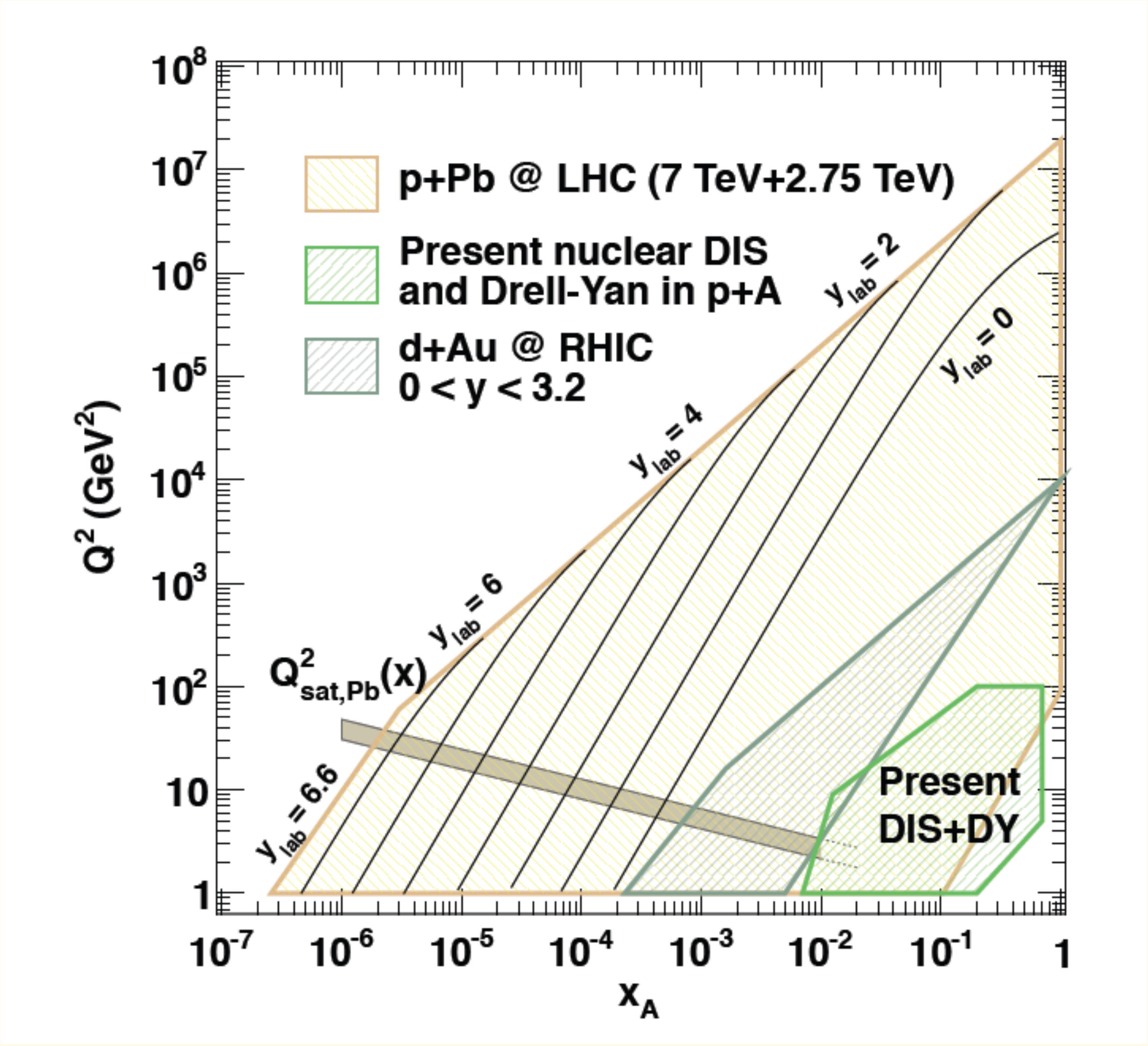
Low-*x* Reach of RHIC and LHC



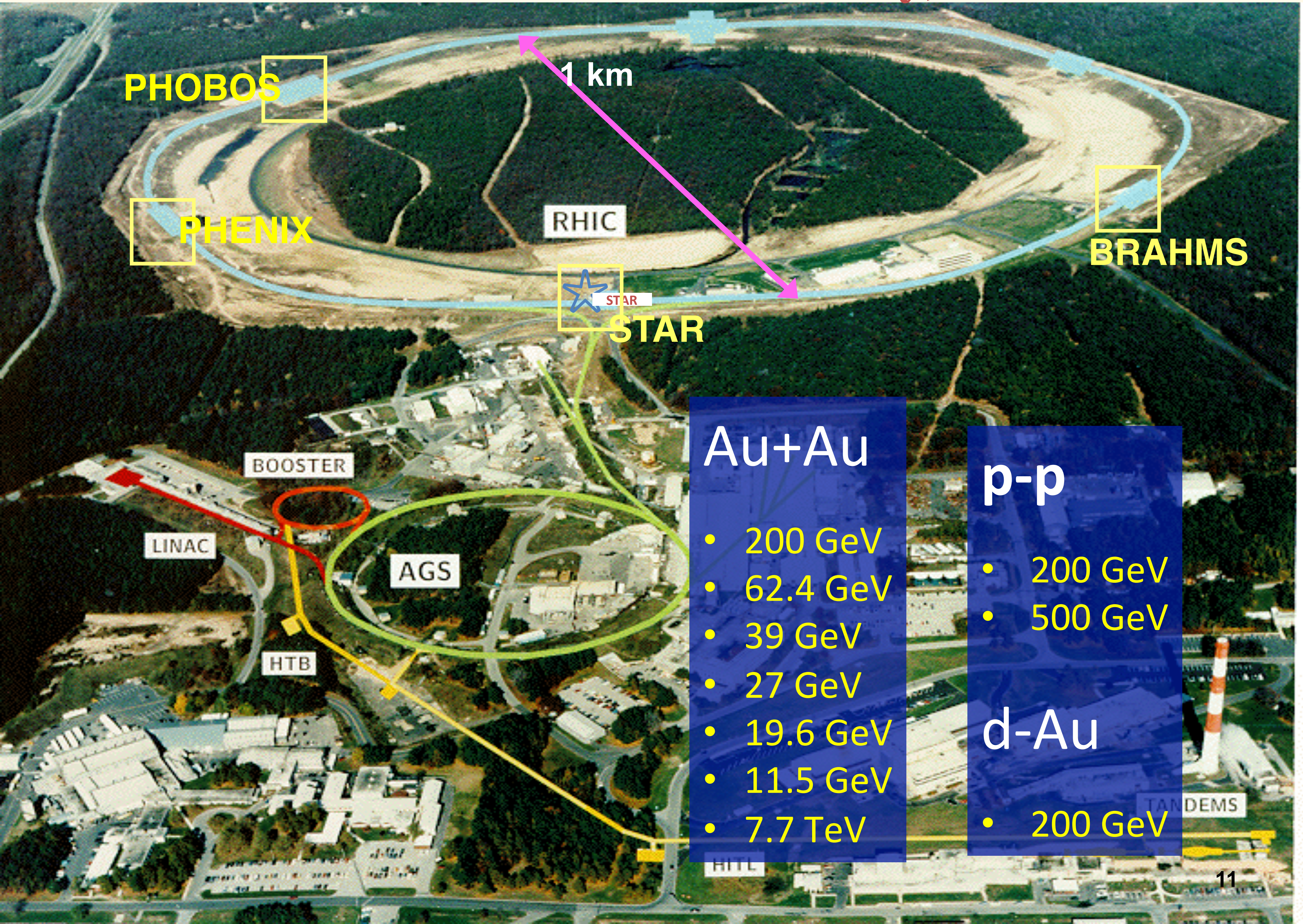
LHC:

$3 * 10^{-6}$ in pp
$1 * 10^{-5}$ in PbPb

Kinematic Reach in pA



Brookhaven National Laboratory, New York



Au+Au

- 200 GeV
- 62.4 GeV
- 39 GeV
- 27 GeV
- 19.6 GeV
- 11.5 GeV
- 7.7 TeV

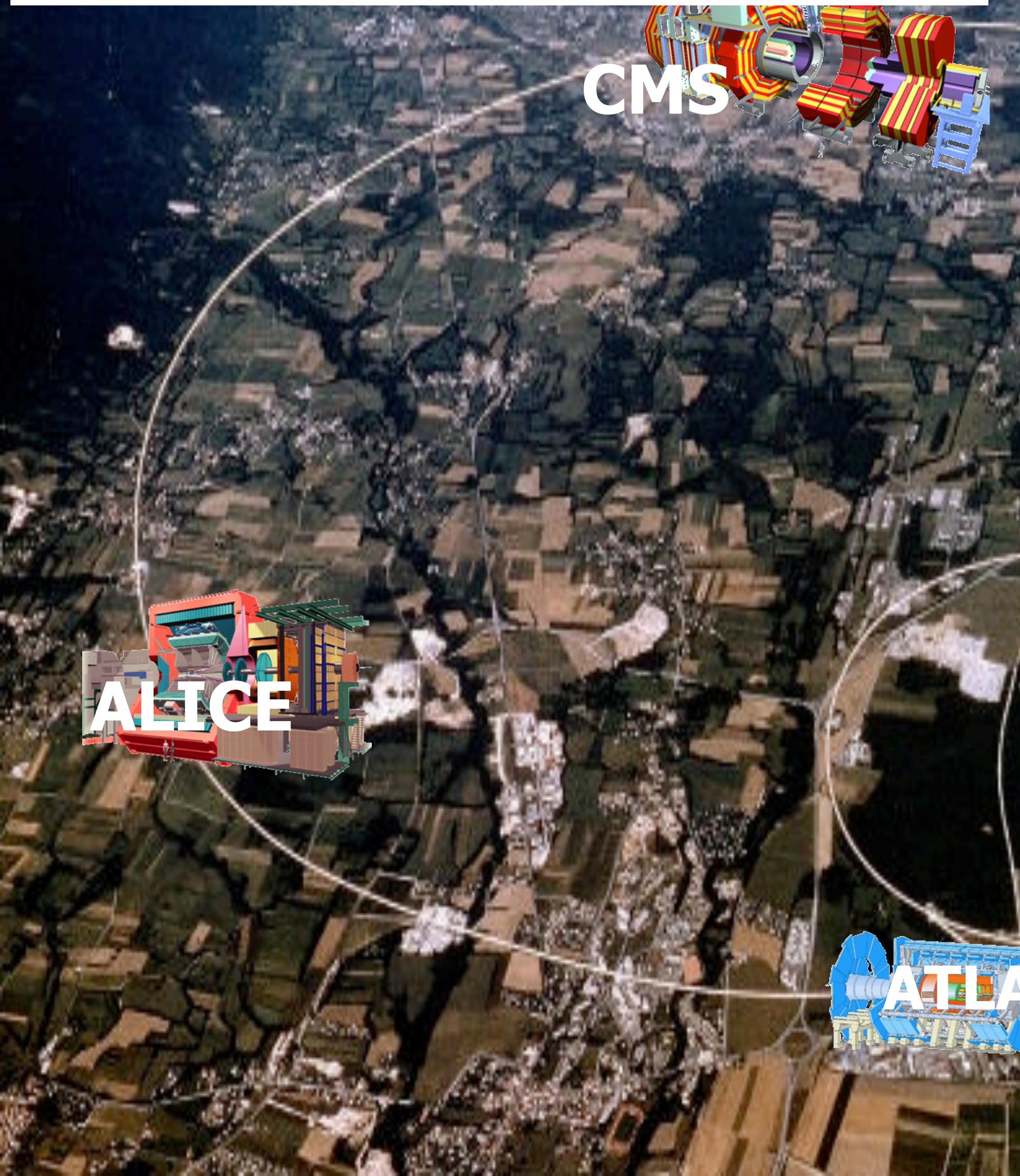
p-p

- 200 GeV
- 500 GeV

d-Au

- 200 GeV

Heavy Ions at the LHC



2009:

pp: $\sqrt{s}$ = 0.9 and 2.3 TeV

2010:

pp: $\sqrt{s}$ = 7 TeV

PbPb: $\sqrt{s_{NN}}$ = 2.76 TeV

2011:

pp: $\sqrt{s}$ = 7 TeV

PbPb: $\sqrt{s_{NN}}$ = 2.76 TeV

2012:

pp: $\sqrt{s}$ = 8 TeV

2013:

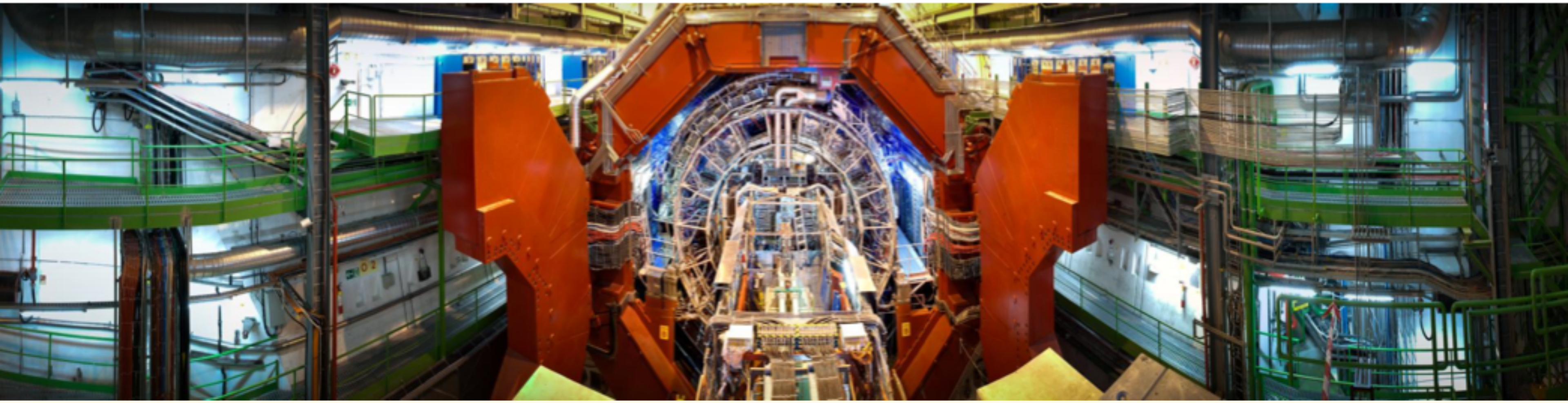
p-Pb & Pb-p = 4 TeV

Collisions at the LHC

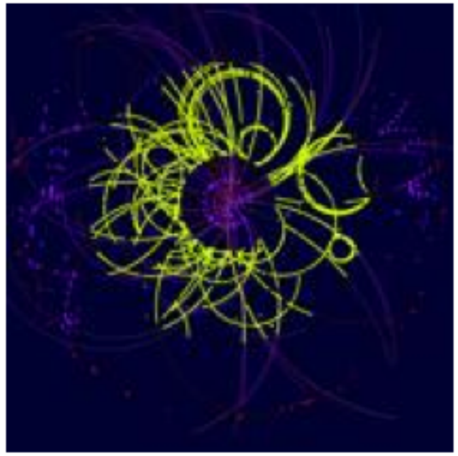
p-p: $\sqrt{s}$ = 14 TeV
p-Pb: $\sqrt{s}$ = 8.8 TeV
Pb-Pb: $\sqrt{s_{NN}}$ = 5.5 TeV

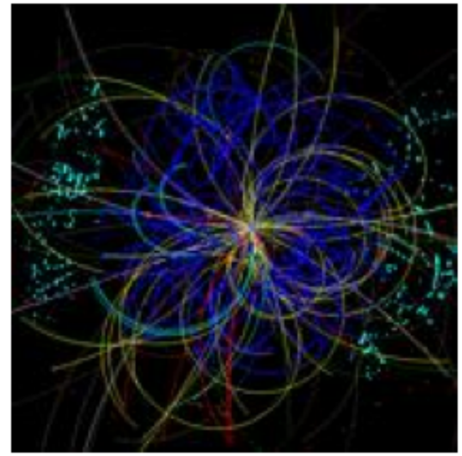
- **p-p collisions**
  - Test of pQCD and saturation models in a new $\sqrt{s}$ and *x* regime
  - Baseline for Pb-Pb
- **p-Pb collisions**
  - Probe nuclear PDFs
  - Disentangle initial and final state effects
- **Pb-Pb collisions**
  - Probe the hot and dense medium

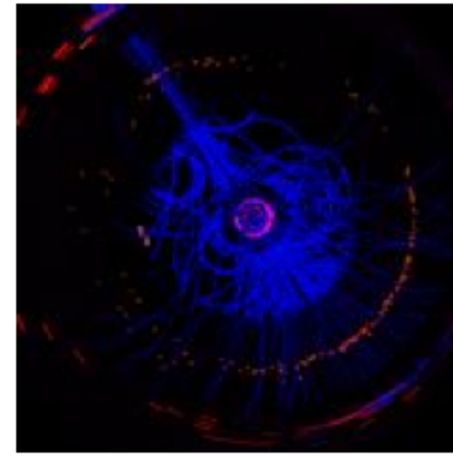
• Unexplored small-*x* region
• Window on the rich phenomenology of high-density PDFs:
Shadowing, Gluon saturation, Color Glass Condensate

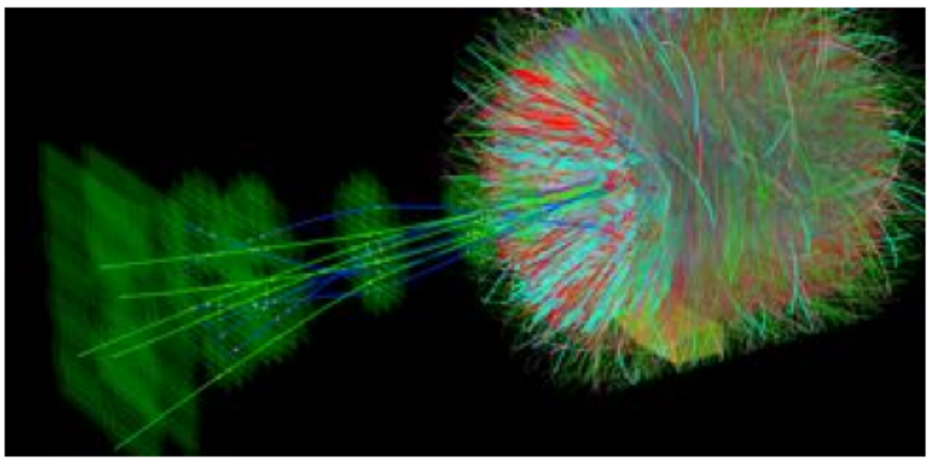


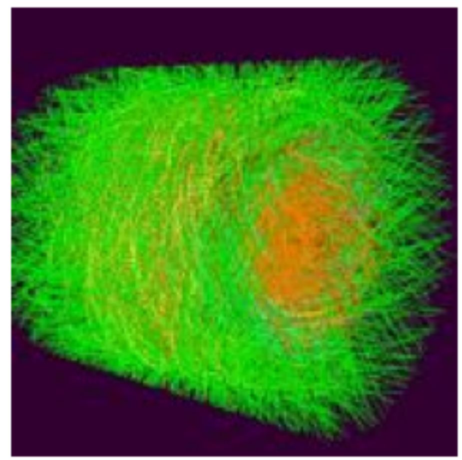
ALICE

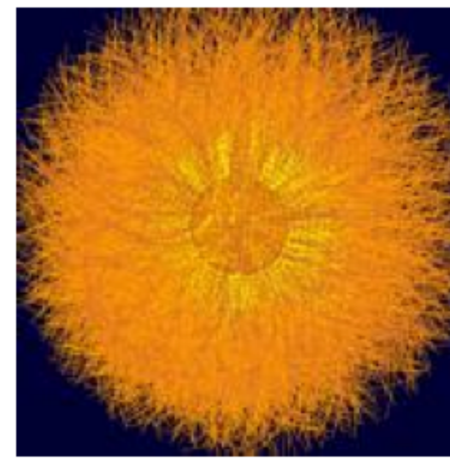


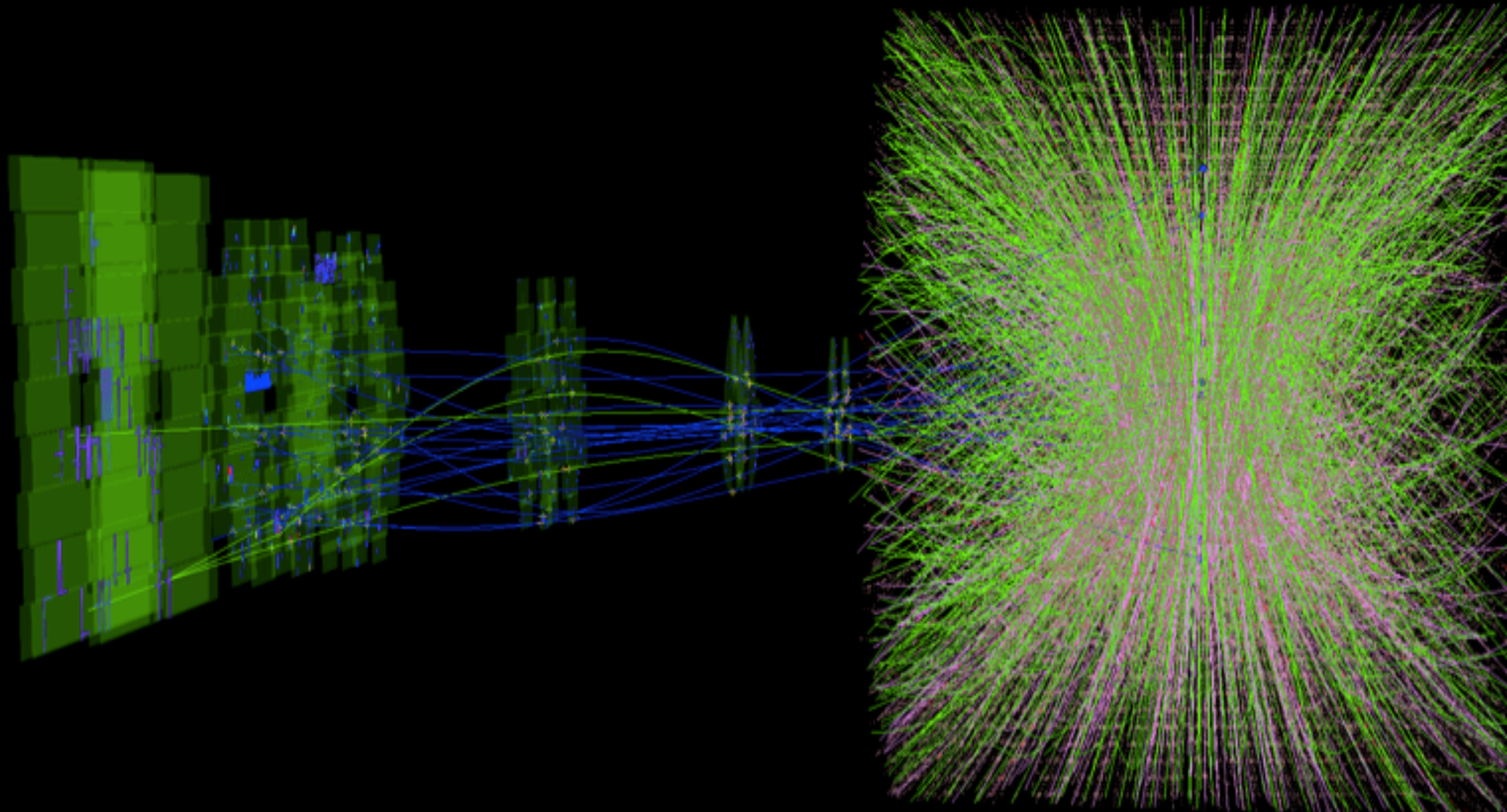


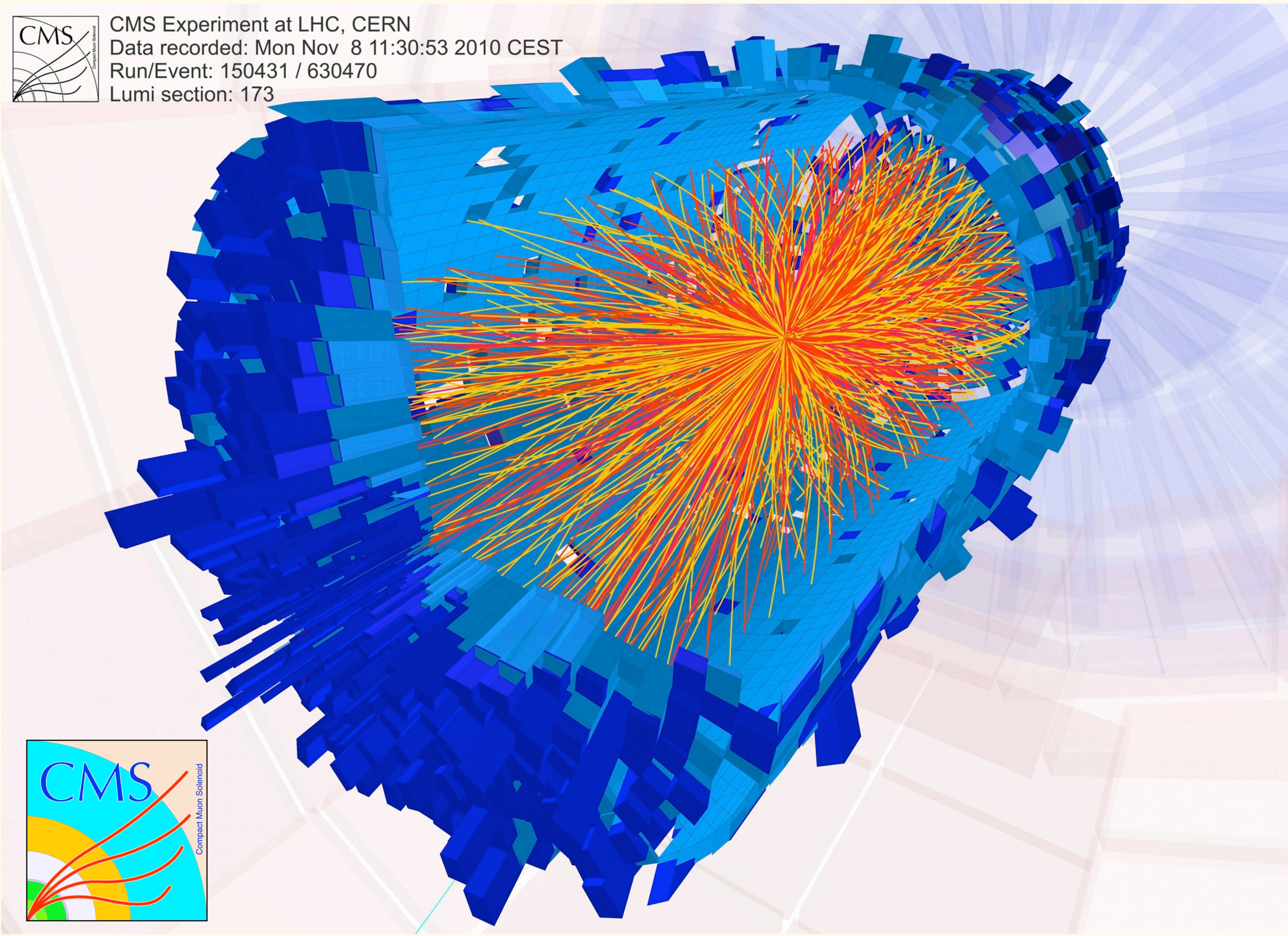


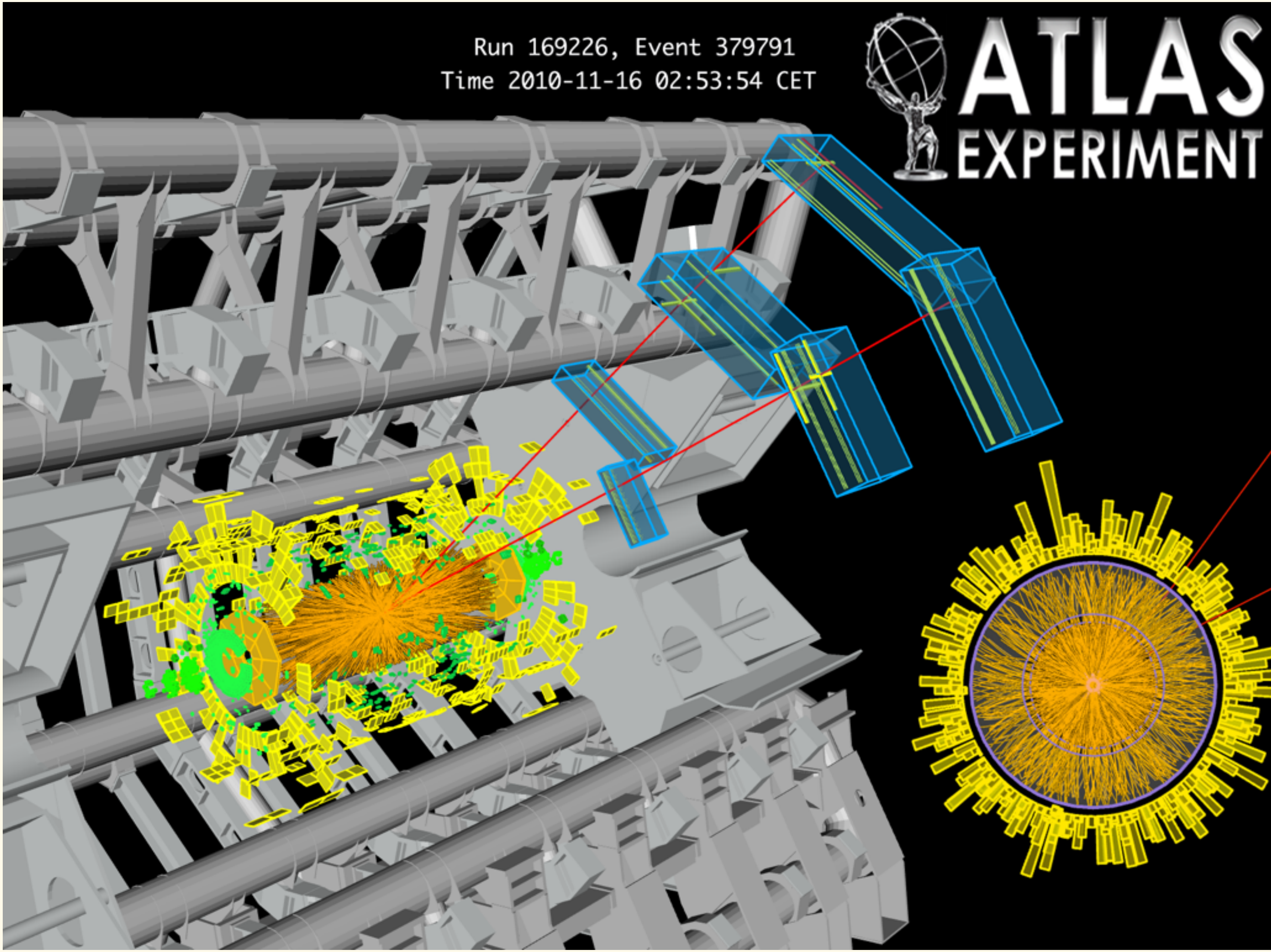








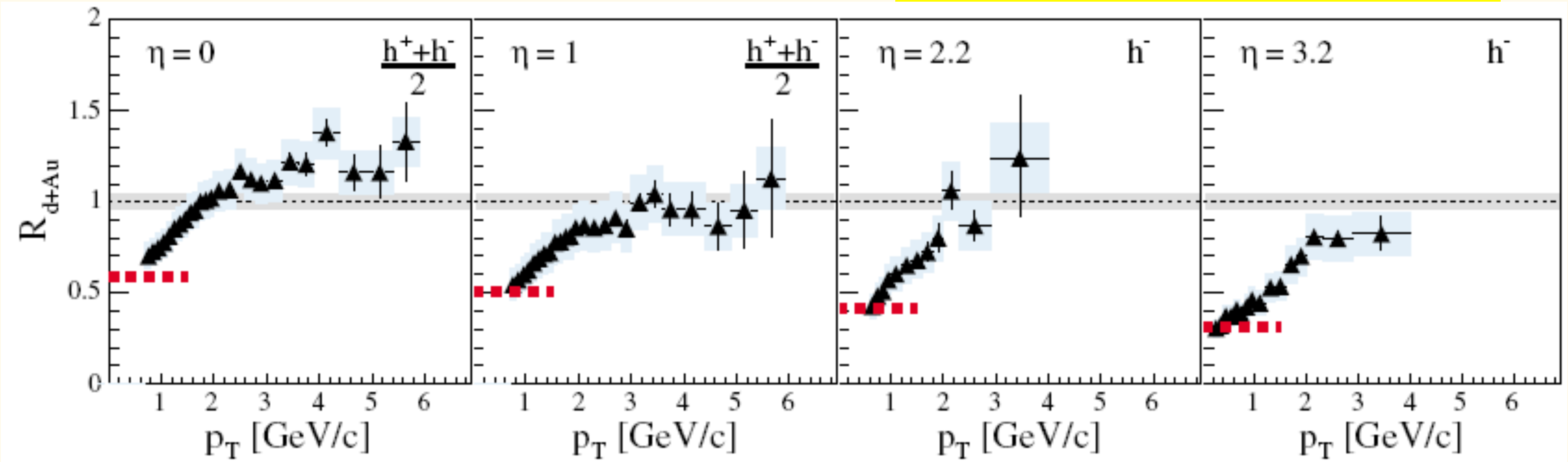

CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173


Run 169226, Event 379791
Time 2010-11-16 02:53:54 CET
ATLAS
EXPERIMENT

RHIC

R_{d+Au} at forward rapidities

BRAHMS: PRL **93,** 242303 (2004)



$$R_{dAu} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N^{d+Au}/dp_T d\eta}{d^2N^{pp}_{inel}/dp_T d\eta}$$

where $\langle N_{coll} \rangle = 7.2 \pm 0.3$

- Cronin-like enhancement at η=0
- Consistent with PHOBOS at η=1

PHOBOS, PHYS. REV. C70 (2004) 061901(R)

Clear suppression as η changes from 0 to 3.2

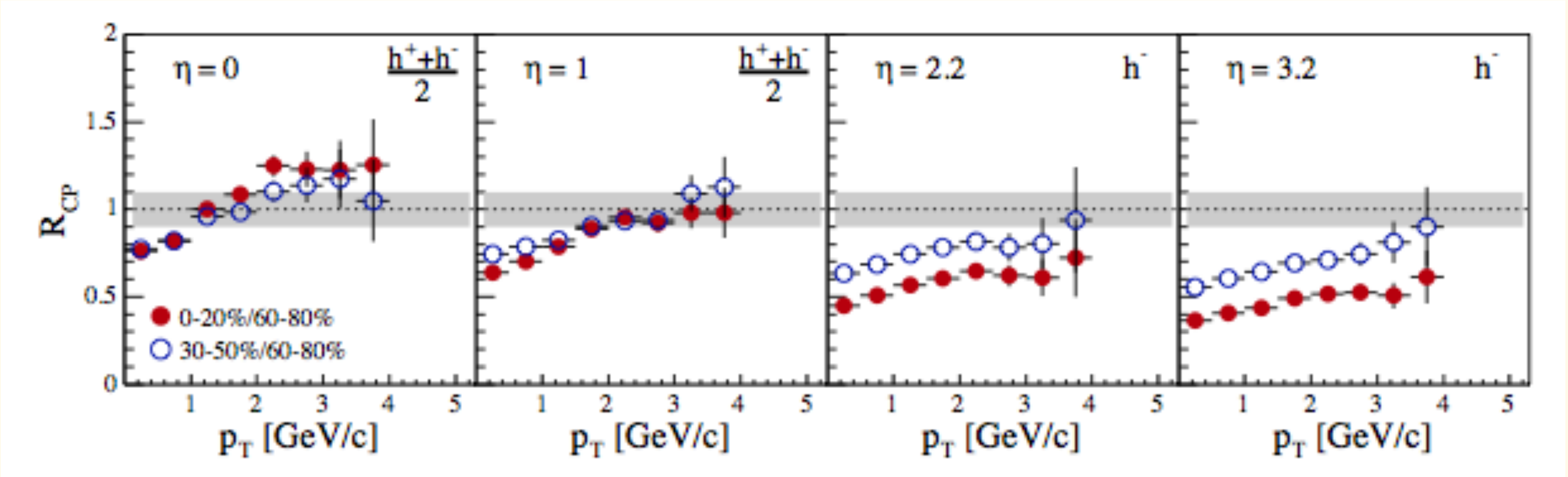
RHIC

R_{CP} at forward rapidities

BRAHMS

NPA 757 (2005) 1 - 27

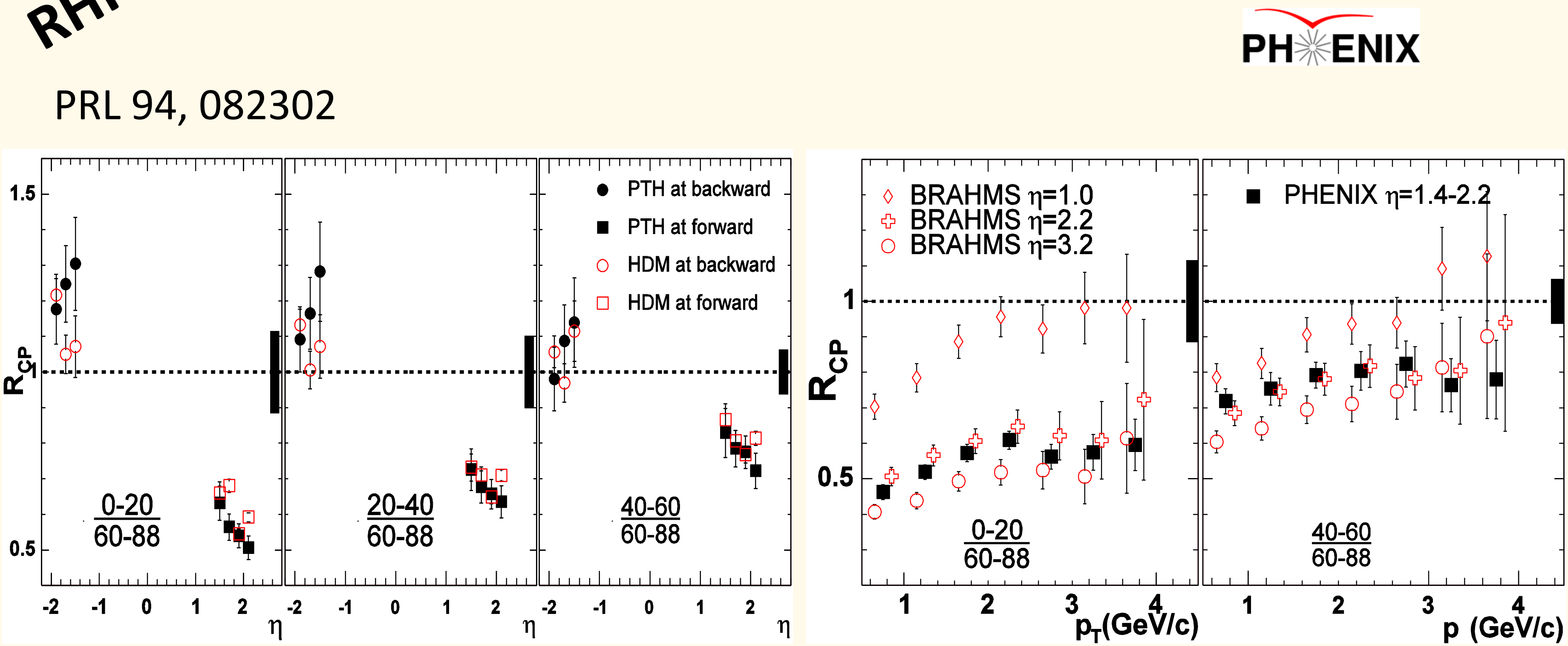
d+Au collisions



Hadron production suppressed at forward rapidity

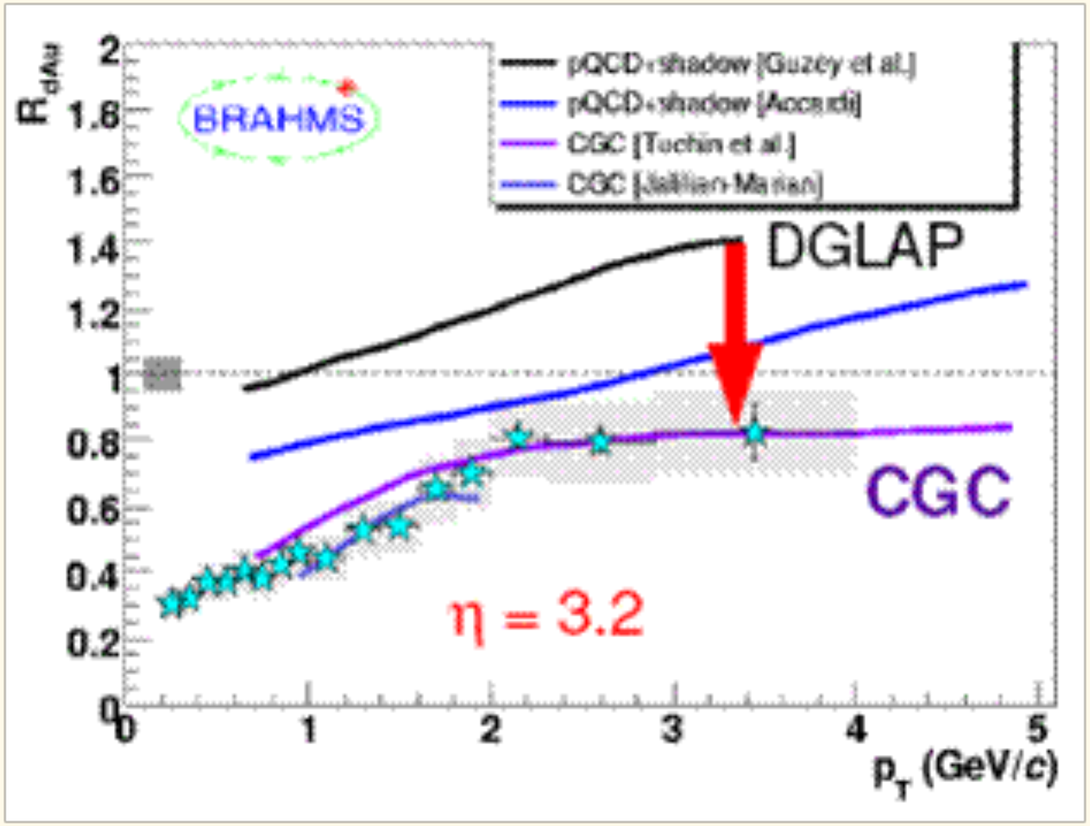
RHIC

PRL 94, 082302



- Charged particles and π^0 are suppressed in the forward direction
- pQCD+shadowing calculations overpredict R_{dAu} at $\eta = 4$

RHIC



Suppression of forward hadron production in d+Au collisions by BRAHMS.
NPA 757 (2005) 1 - 27

Kharzeev, Kovchegov, Tuchin

Jallian-Marian

K. J. Eskola, V. J. Kolhinen, H. Paukkunen, C. A. Salgado

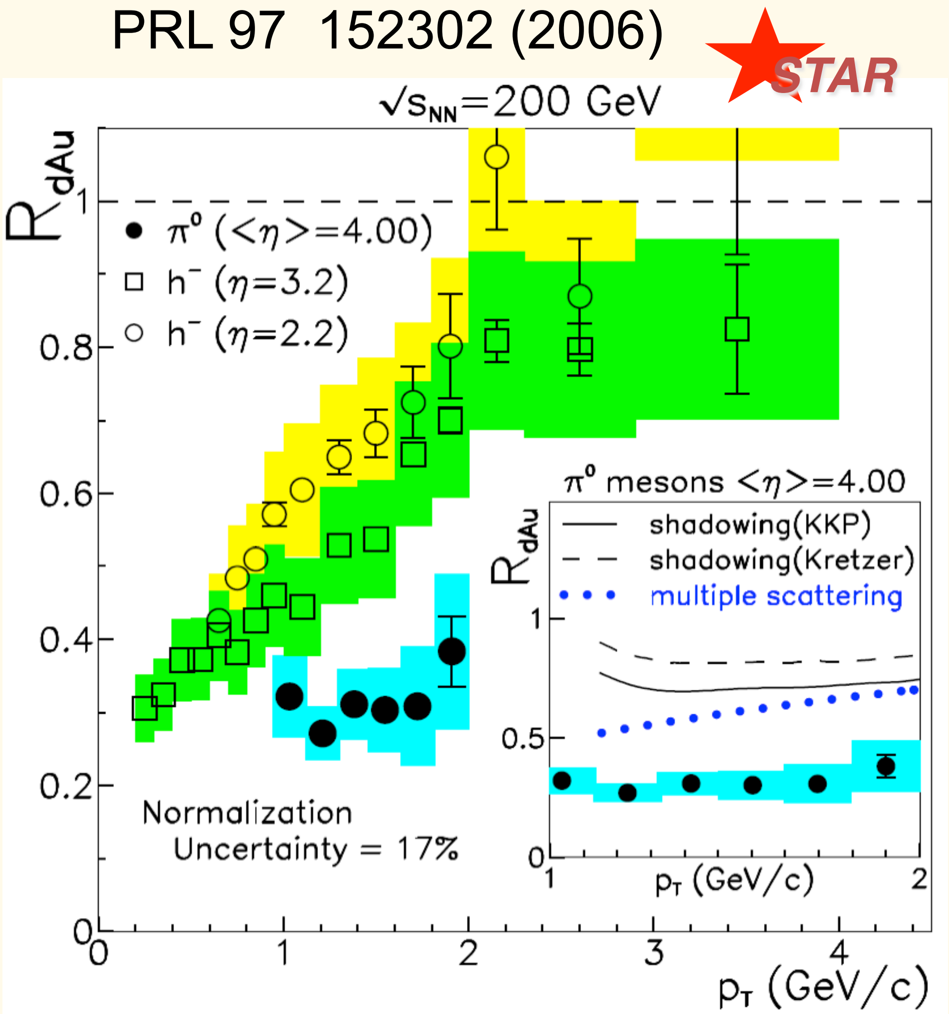
Dumitru

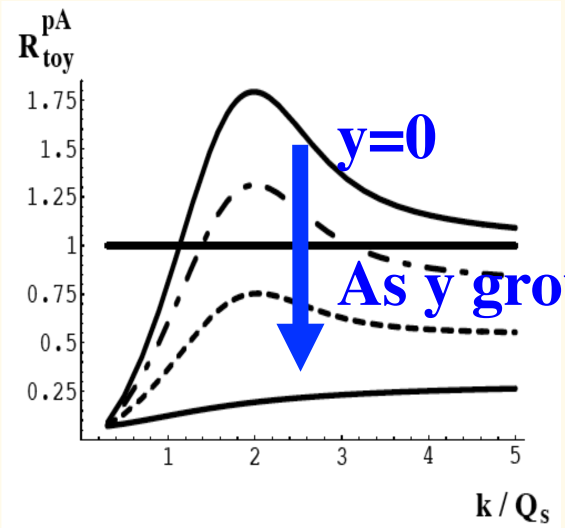
- **Saturation / CGC effects appear to manifest at $x \sim 10^{-3}$ and p_T up to 3.5 GeV/c for Au nuclei at RHIC**

Results : d+Au Collisions at RHIC

RHIC

PRL 97 152302 (2006)





Kharzeev, Kovchegov, and Tuchin, Phys. Rev. D **68** , 094013 (2003)

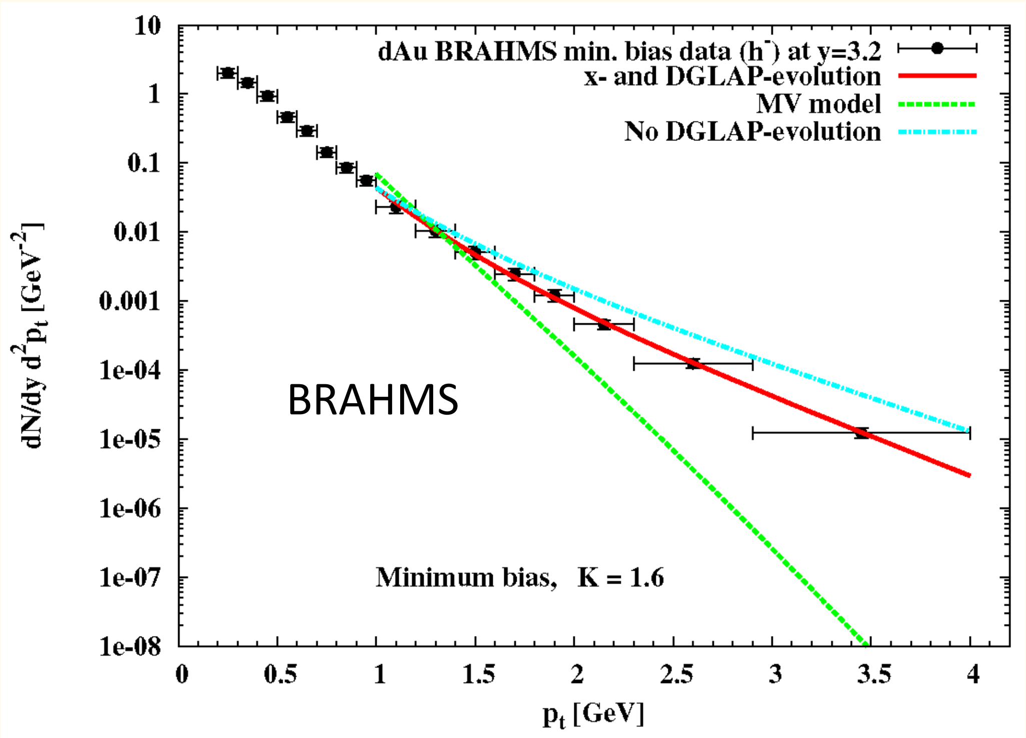
J. Jalilian-Marian, Nucl. Phys. **A739**, 319 (2004)

Significant rapidity dependence similar to expectations from R_{pA} within the Color Glass Condensate framework.

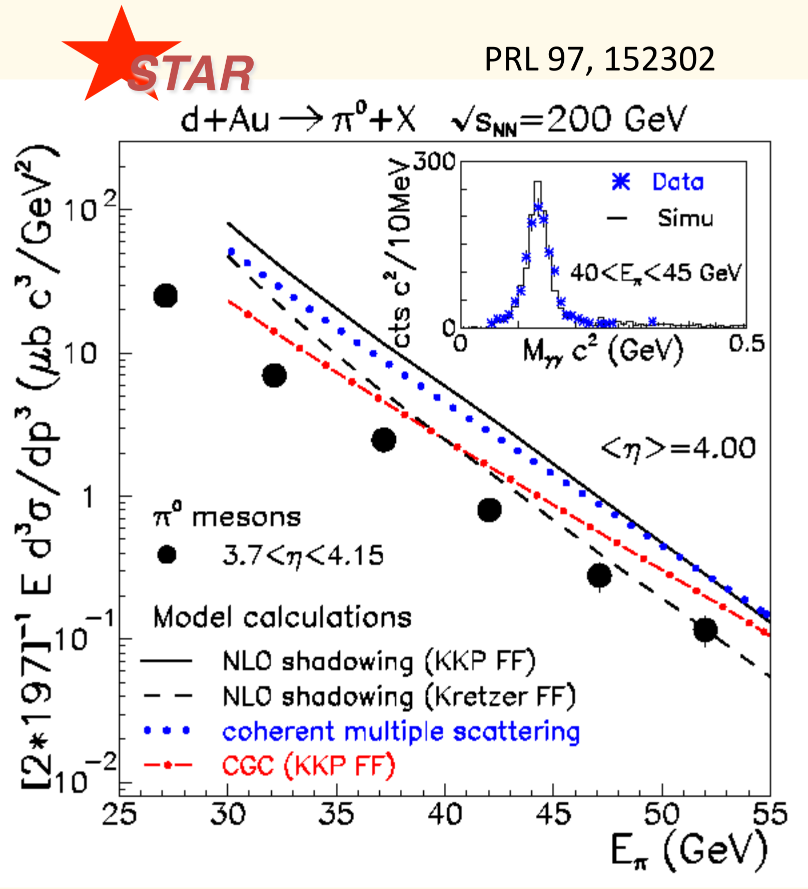
Saturation model calculation

(Dumitru, Hayashigaki, and Jalilian-Marian, NP A765, 464)

RHIC



PRL 97, 152302

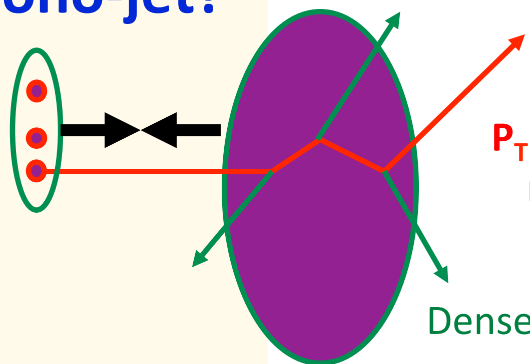


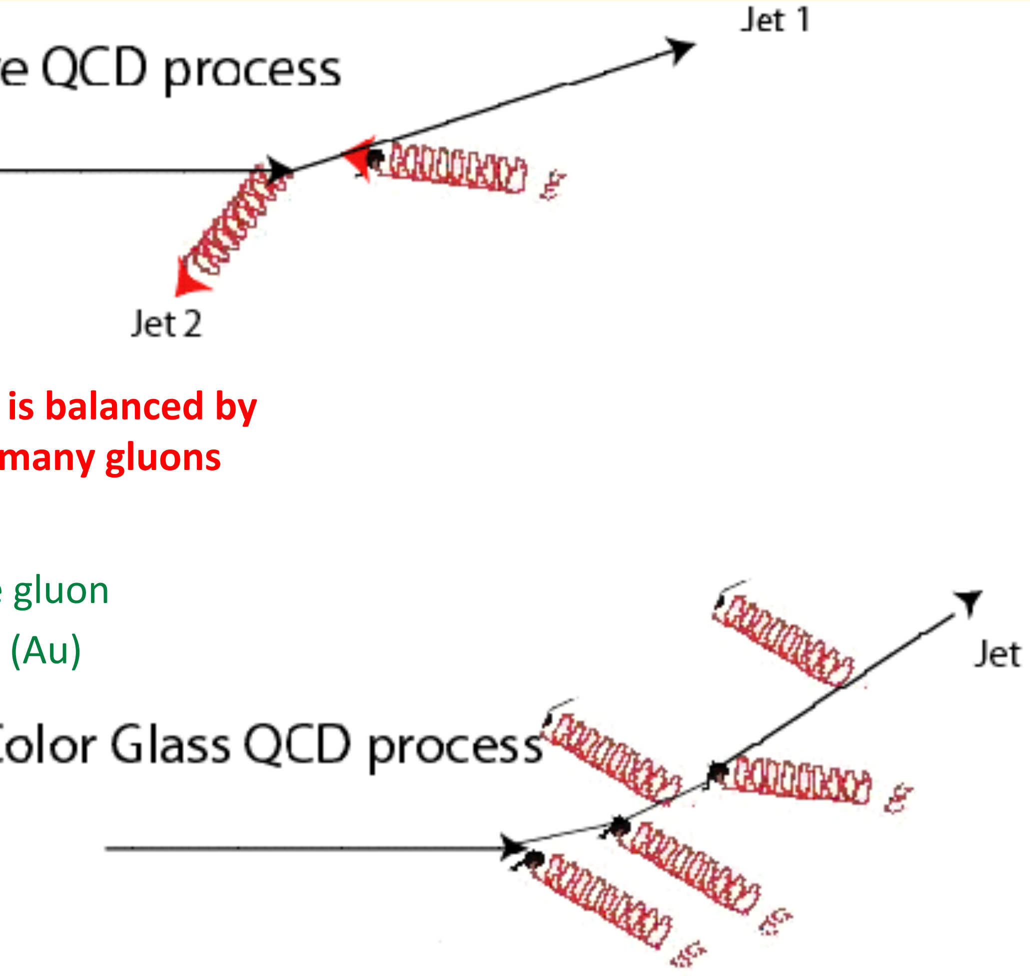
Good description of the p_T dependence for negatively charged hadrons at $\eta = 3.2$ and identified π^0 at $\eta = 4.0$, but the data prefer different K factors

Back to Back correlations

p+p: **Di-jet**

d+Au: **Mono-jet?**

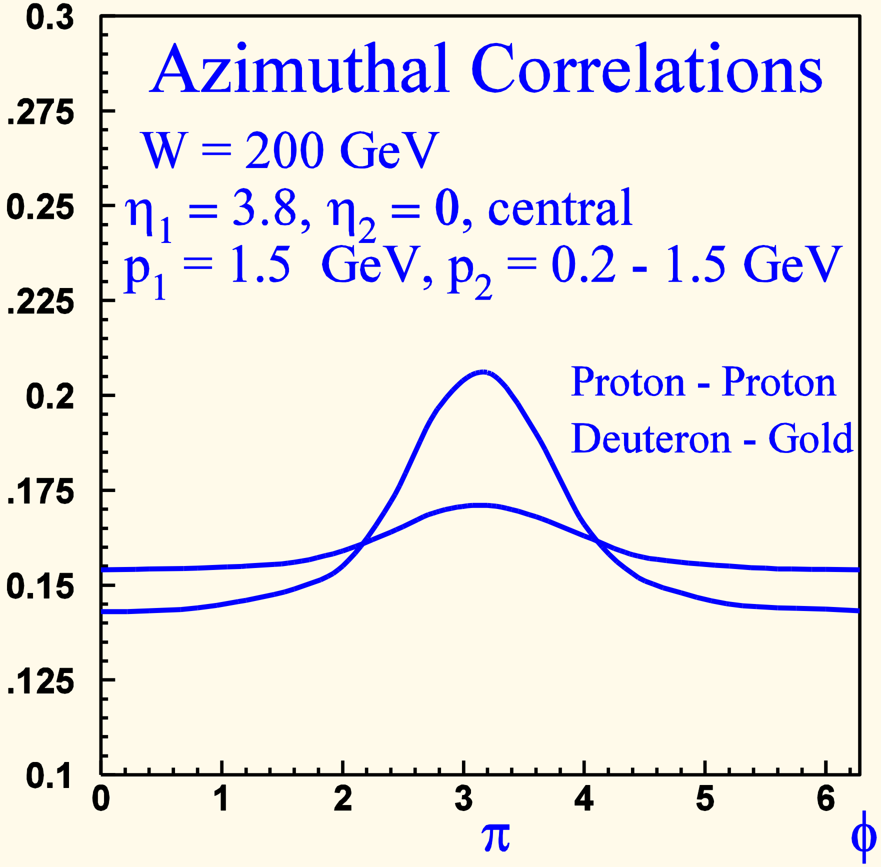




Kharzeev, Levin, McLerran gives physics picture (NPA748, 627)

Color glass condensate predicts that the **back-to-back correlation should be suppressed in d+Au**

Back-to-back correlations with the color glass



The evolution between the jets makes the correlations disappear.

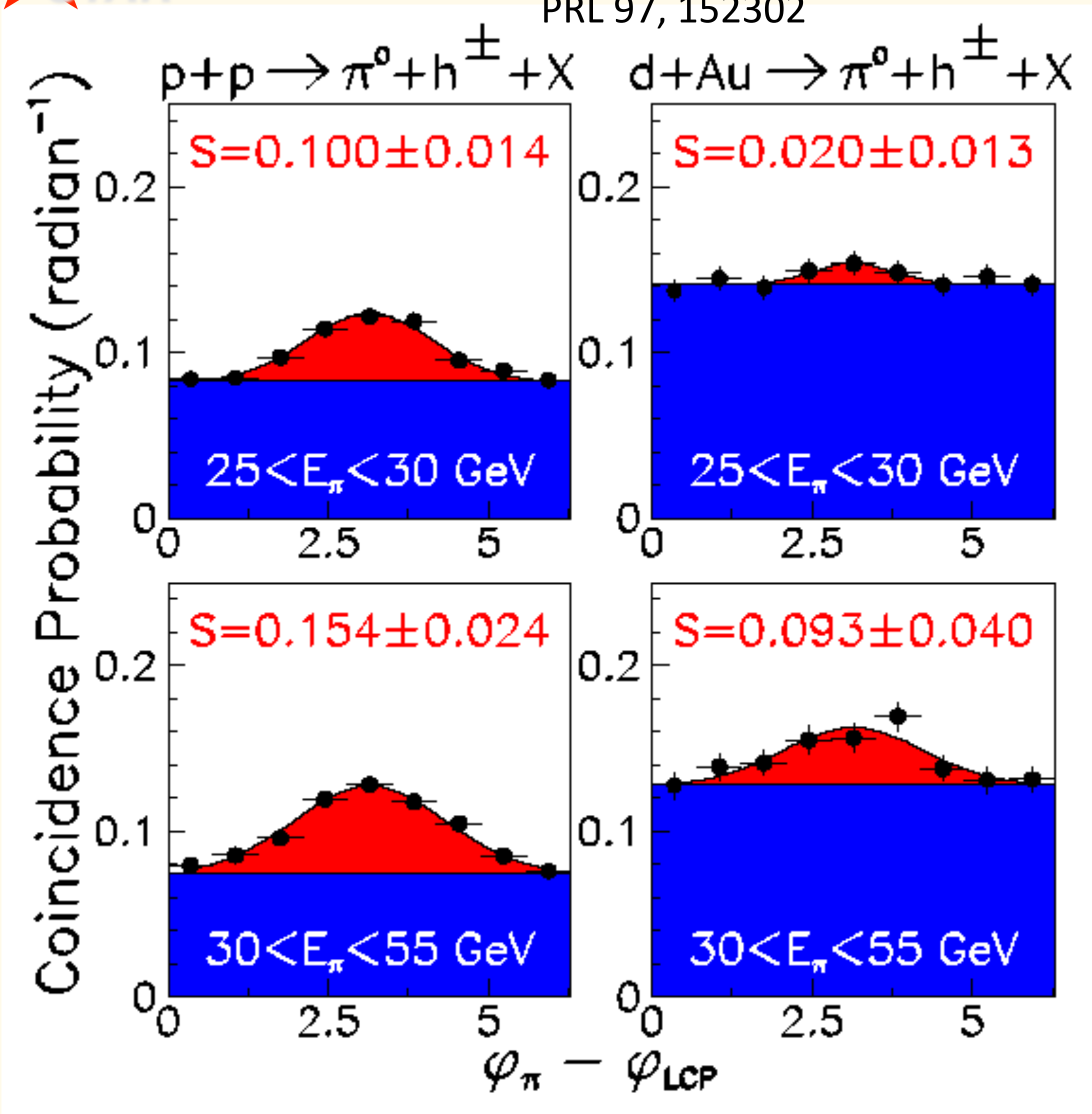
(Kharzeev, Levin, and McLerran, NP A748, 627)

Forward-midrapidity correlations in d+Au

STAR

RHIC

PRL 97, 152302



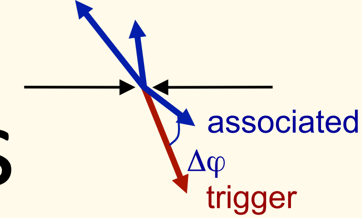
π^0: $|\langle\eta\rangle| = 4.0$

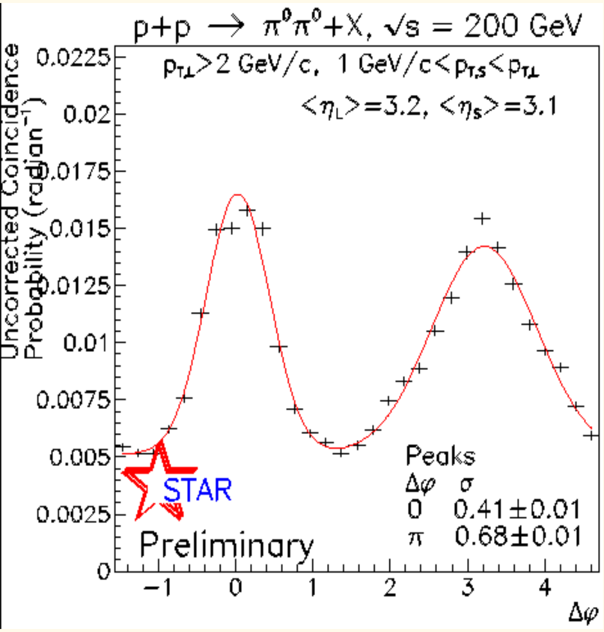
$h^{\pm}$: $|\eta| < 0.75$

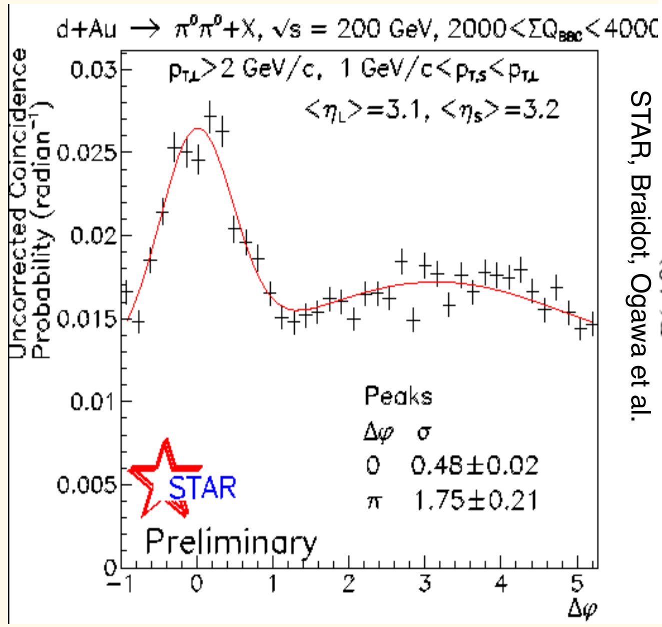
$p_T > 0.5$ GeV/c

RHIC

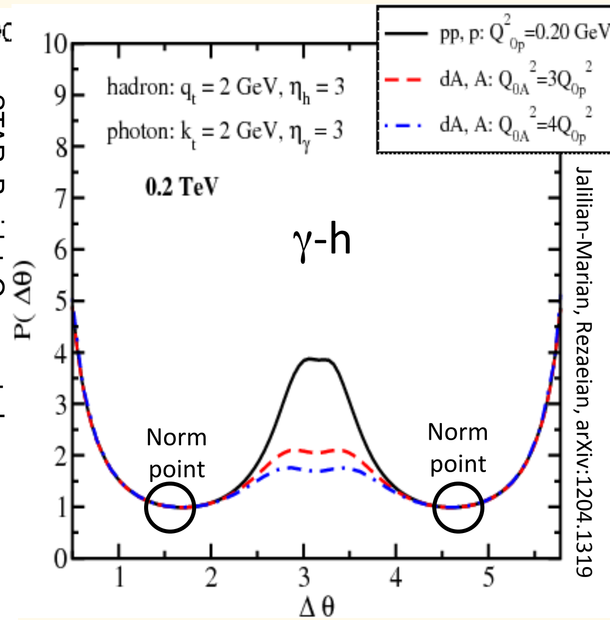
Two-particle correlations







STAR, Braidot, Ogawa et al.



Broadening, 'disappearance' of di-hadron, γ-hadron correlations are a compelling measurement

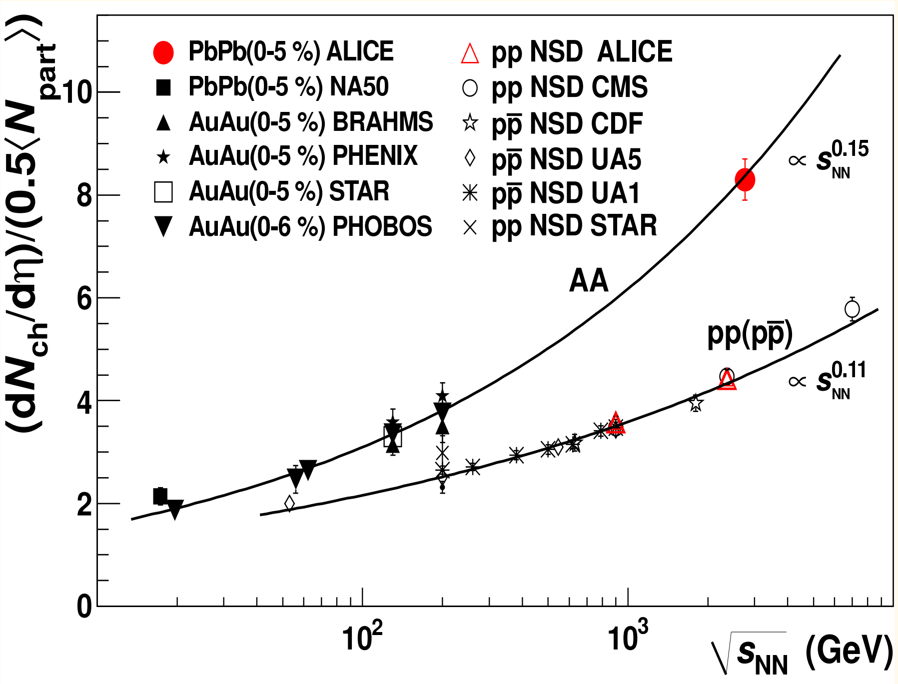
Interpretation: quark scatters off multiple guons (gluon field)

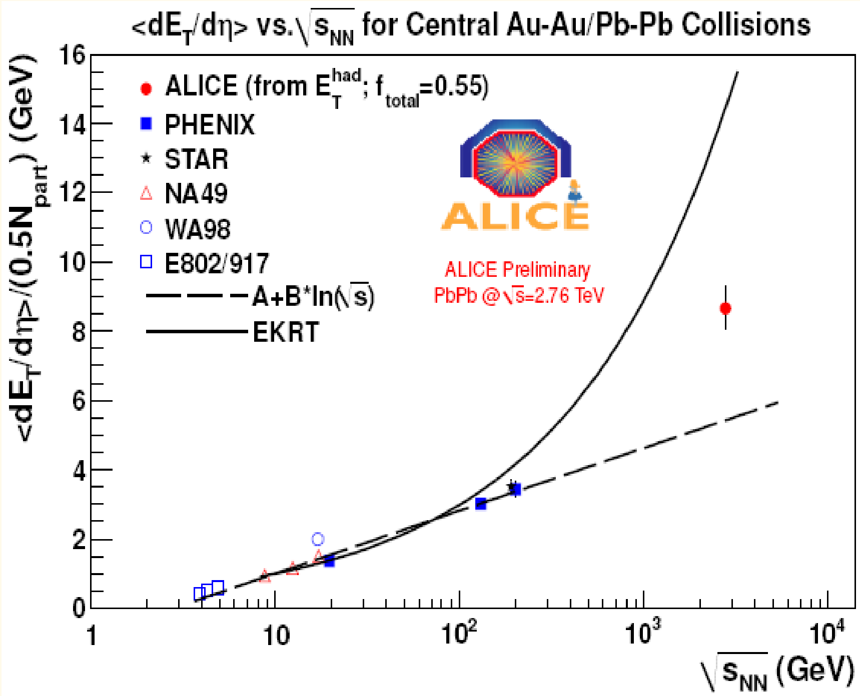
However, calculations in CGC framework difficult (4-point function)
Some progress being made

Multiplicity & Energy Density

RHIC and LHC

Phys. Rev. Lett. 105, 252301 (2010)





$$\varepsilon_{Bj}(\tau) = \frac{1}{\pi R^2 \tau}\frac{dE_T}{dy}$$

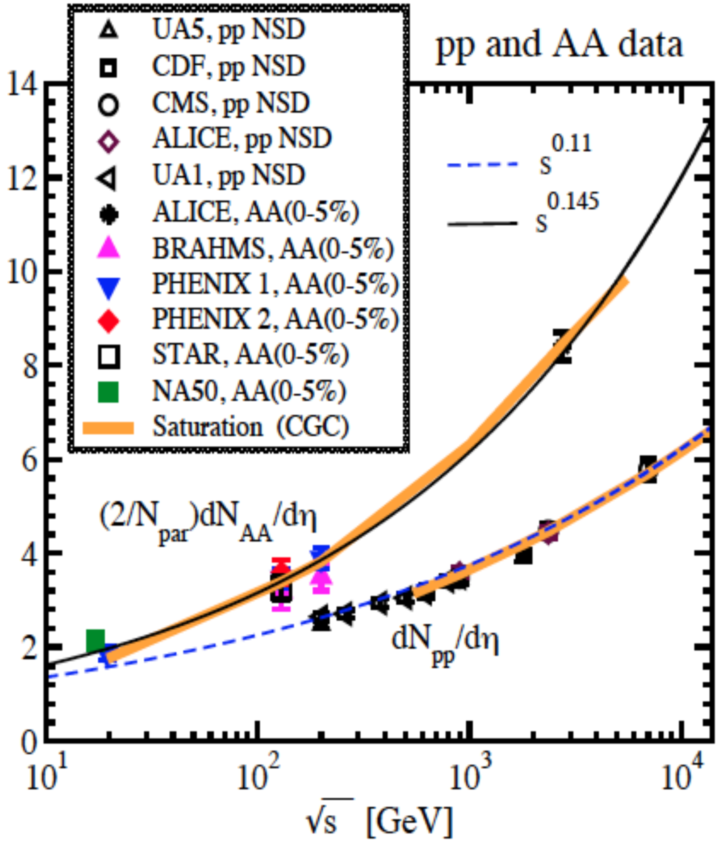
$\varepsilon.\tau$~ 16 GeV/fm^{2}c

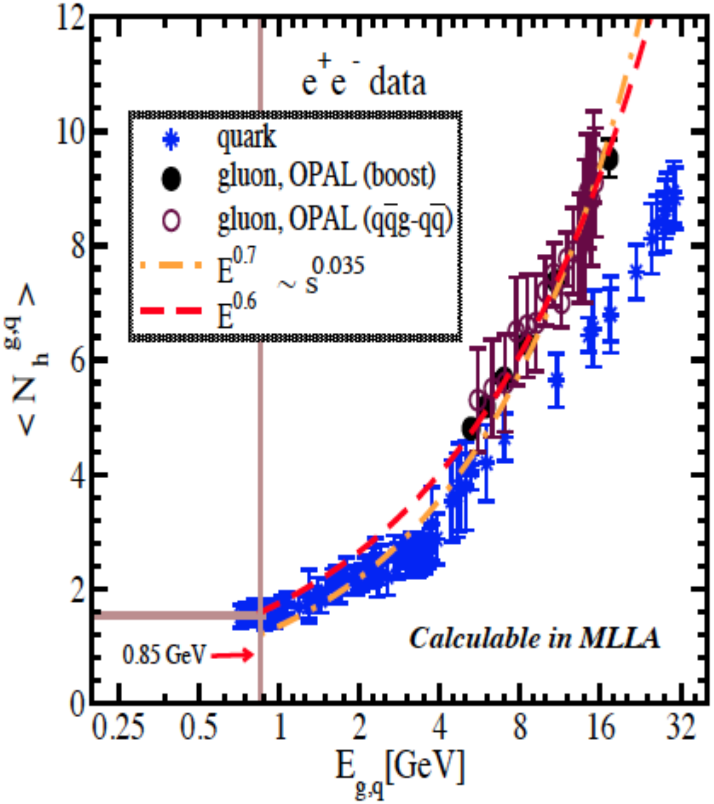
Charged particle per participant pair is seen to rise like $s^{0.15}$, stronger than pp($s^{0.11}$).

Energy Density at LHC is at least 3 times more than that at RHIC

Dependence of Multiplicity on Energy

Levin et al. 1102.2385

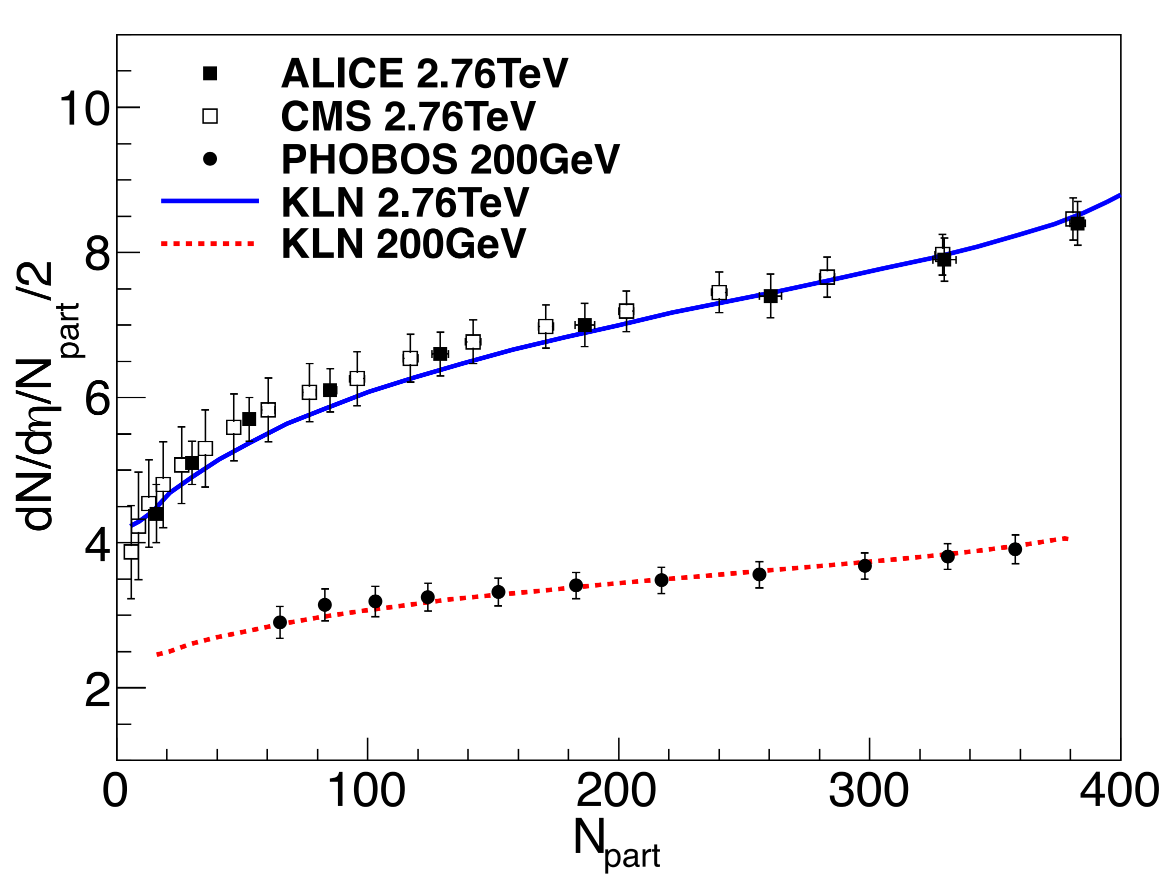




$$\frac{dN_h}{d\eta} \propto Q_s^2 \propto s^{0.11} \quad \text{for} \quad Qs \leq 1 \text{ GeV}$$

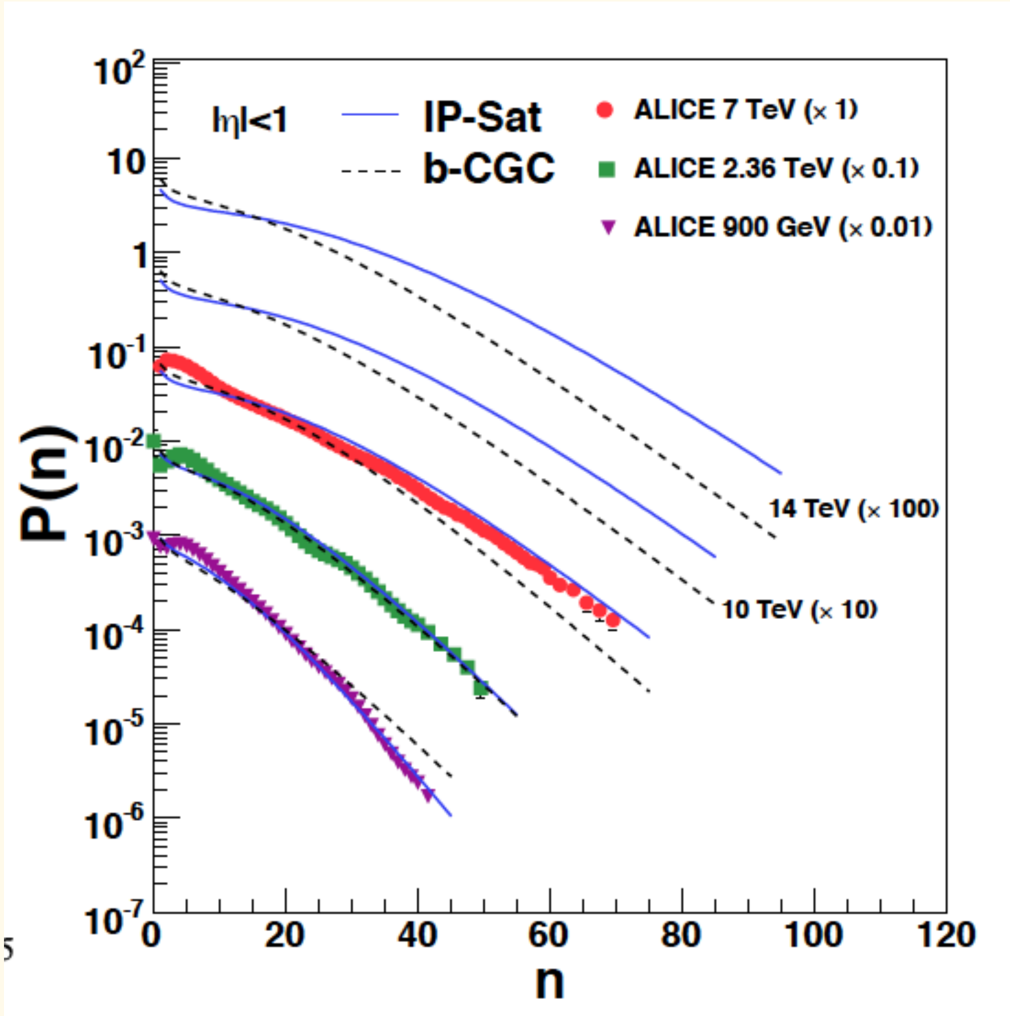
$$\frac{dN_h}{d\eta} \propto s^{0.11} * s^{0.035} = s^{0.145} \quad \text{for} \quad Qs > 1 \text{ GeV}$$

Multiplicity distributions



Negative binomial distribution parameters and KNO scaling predicted by CGC

Important for further analysis: higher order vn flow analysis, and inclusive ridge



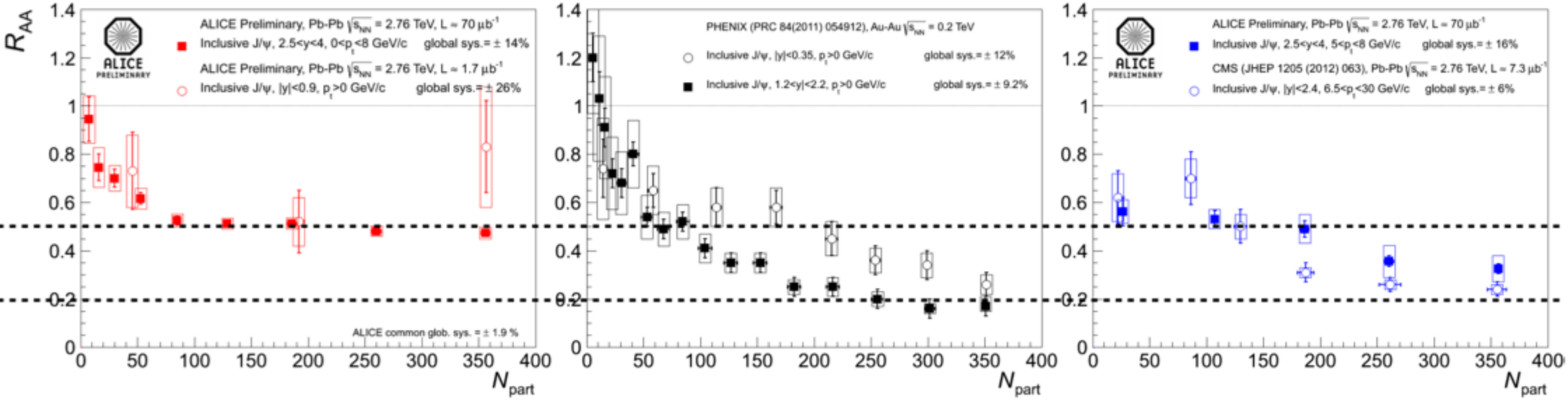
- Negative binomial and KNO quantitatively predicted by CGC-Glasma
- Fluctuations in pp collisions follow predictions form CGC-Glasma

Inclusive J/Ψ

Results at 2.76 TeV useful for ALICE as a reference for the R_{AA} extraction in *PbPb* collisions:

$$R^i_{AA} = \frac{Y^{PbPb,i}_{J/\psi}}{T^i_{AA} \times \sigma^{pp}_{J/\psi}}$$

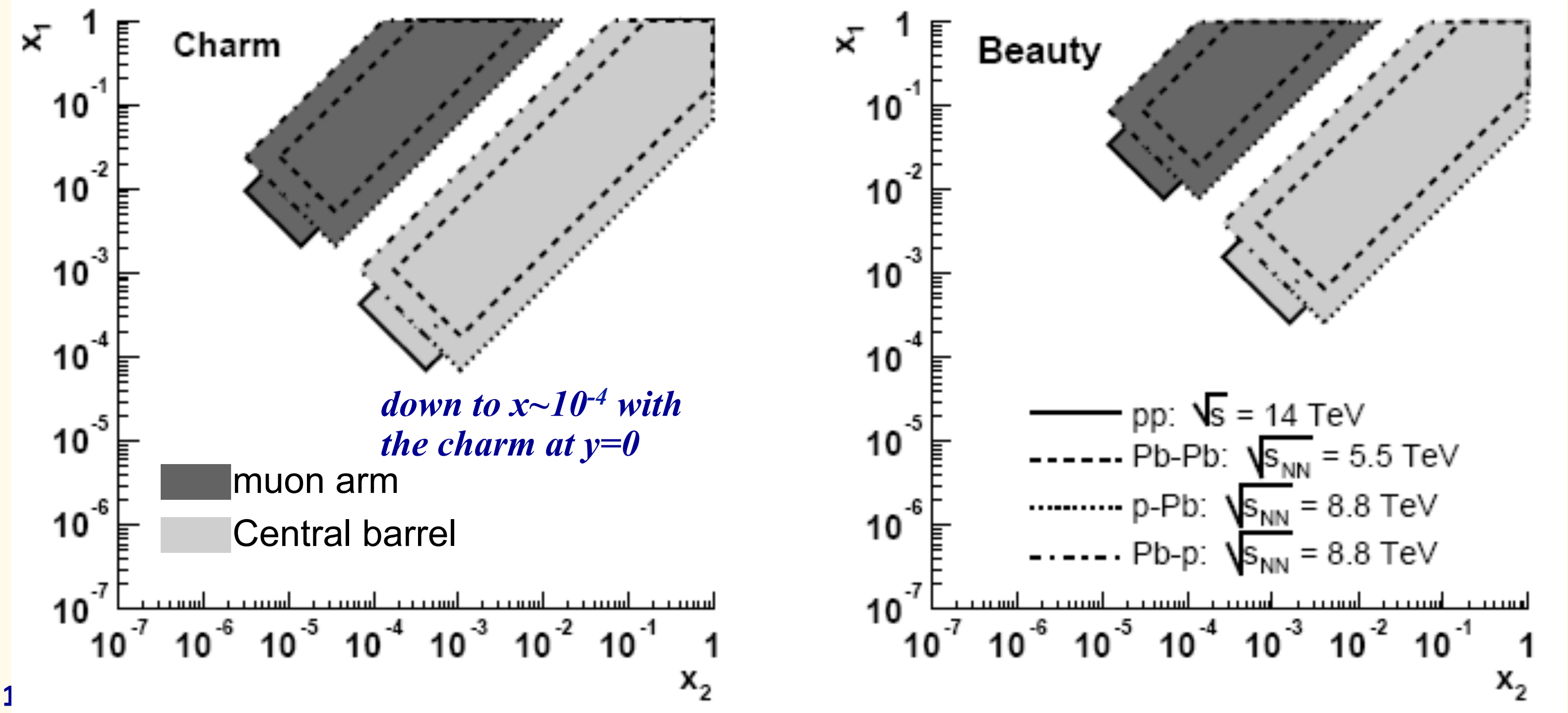
ALICE $p_t > 0$ PHENIX $p_t > 0$ ALICE/CMS high p_t



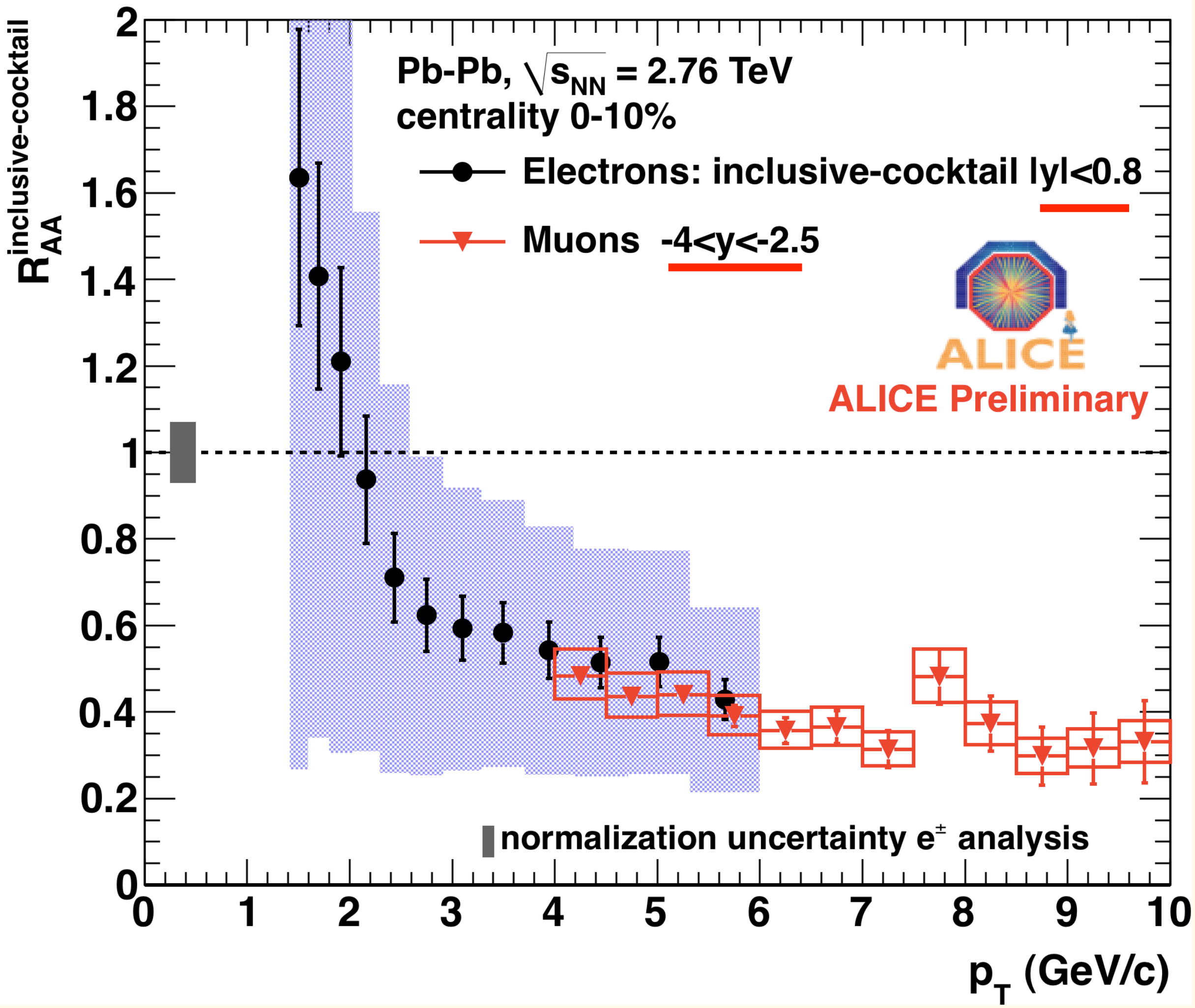
- ALICE: Suppression (R_{AA}) is ~0.5, independent of centrality
- This suppression is about factor 2 less at LHC than at RHIC
- Larger suppression seen at LHC for higher p_T cuts
- pPb collision will be important to understand these results

x-values for charm and beauty at y=0 and p_T ->0

	SPS Pb-Pb 17 GeV	RHIC Au-Au 200 GeV	LHC Pb-Pb 5.5 TeV	LHC pp 14 TeV
c-cbar	$x = 10^{-1}$	$x = 10^{-2}$	$x = 4 \times 10^{-4}$	$x = 2 \times 10^{-4}$
b-bbar	-	-	$x = 2 \times 10^{-3}$	$x = 6 \times 10^{-4}$



R_{AA} for e and μ from Heavy Quarks

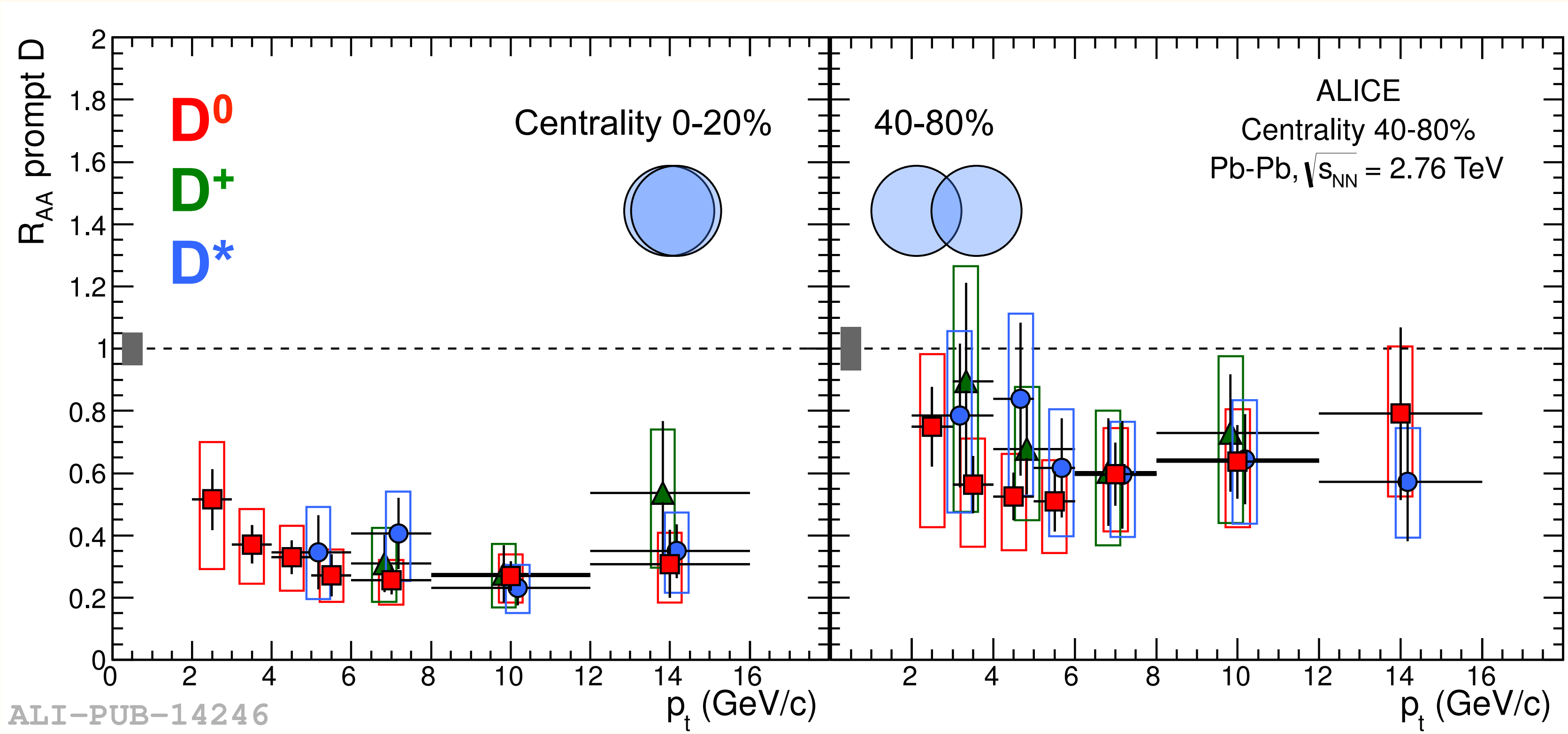


R_{AA} of electrons and muons are consistent within errors.

From FONLL:
B-decays dominate above ~ 5-6 GeV/c.

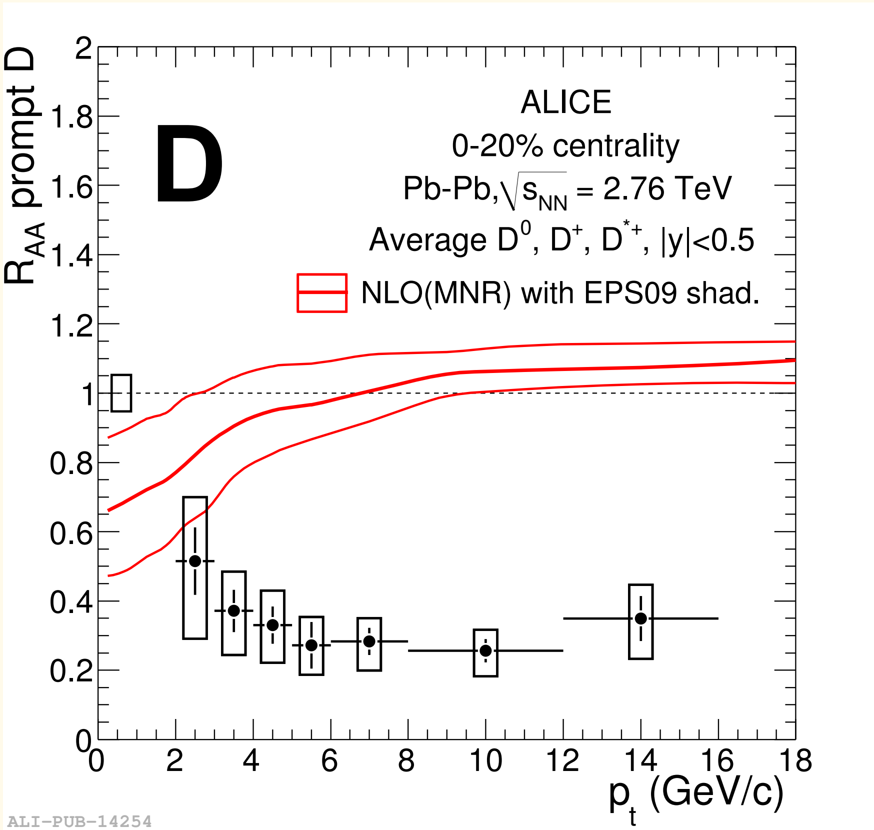
Thus:
b suppression appears to be large as well!

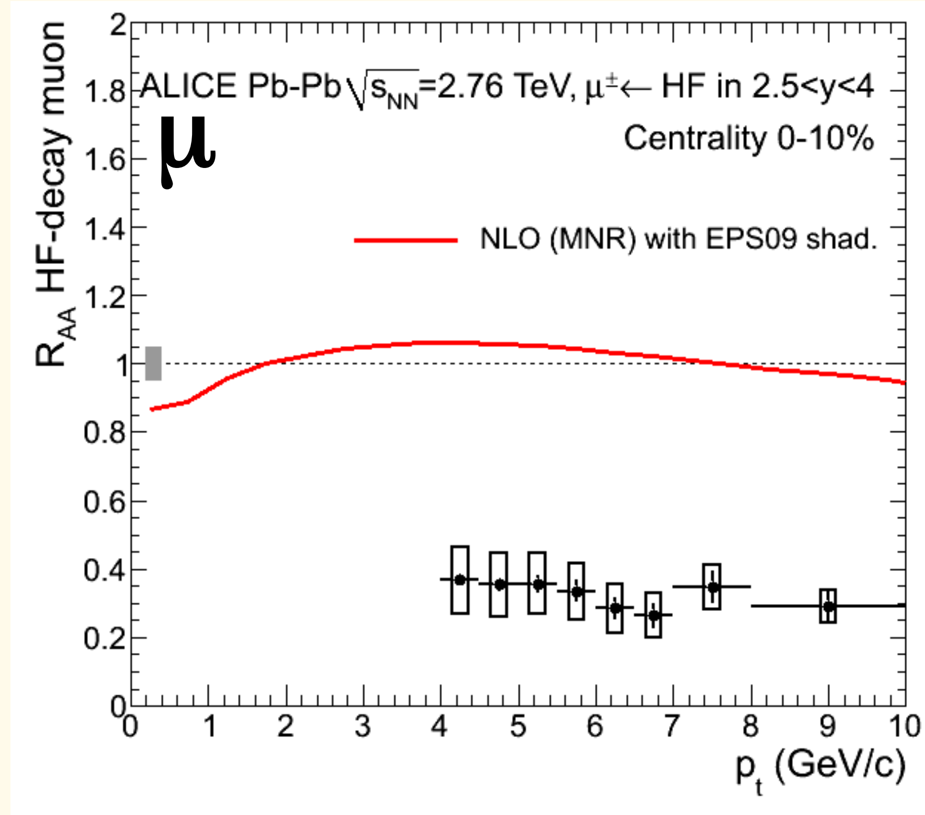
The D meson nuclear modification



- Suppression for charm with respect to binary scaling is a factor 3-4 above 5 GeV/*c*
- Compatible among the three species
- Less suppression in peripheral collisions

arXiv:1203.2160





- Small effect expected from PDFs shadowing above 5 GeV/c
- p-Pb run at LHC crucial to measure initial-state effects

p-Pb Collisions at LHC: Feb 2013

- proton – Pb collisions in Feb 2013
- 24 days of LHC operation
- Cross section (p-Pb) about 2 barn
- Initial Luminosity: 10^{28} cm^{-2} s^{-1}
- Rate: 20 – 200 kHz

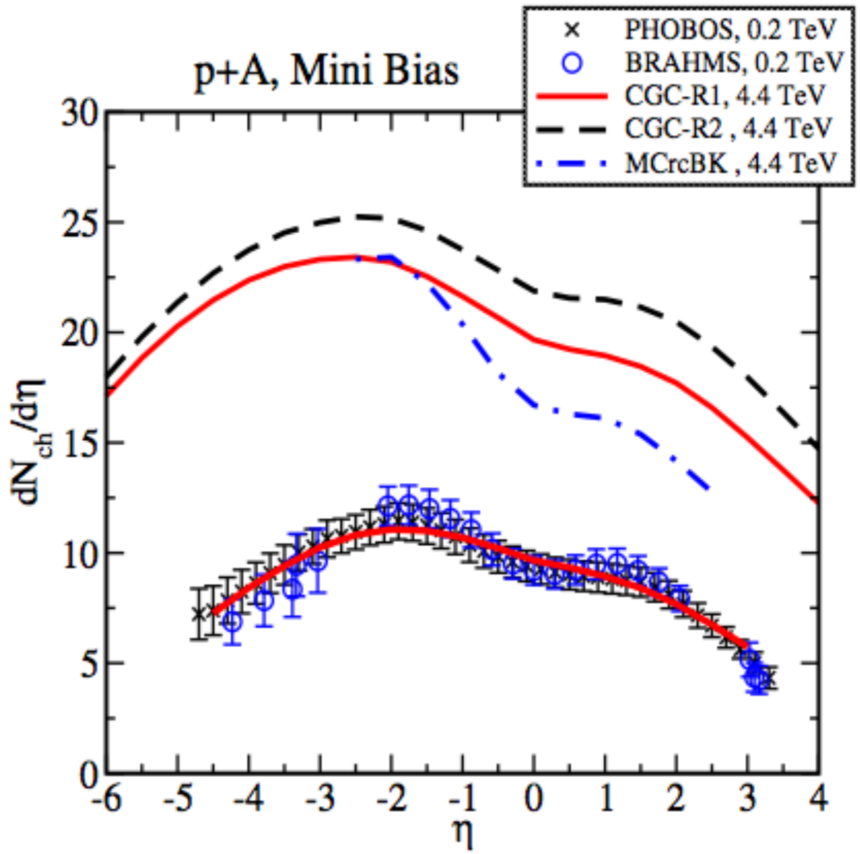
Aim:

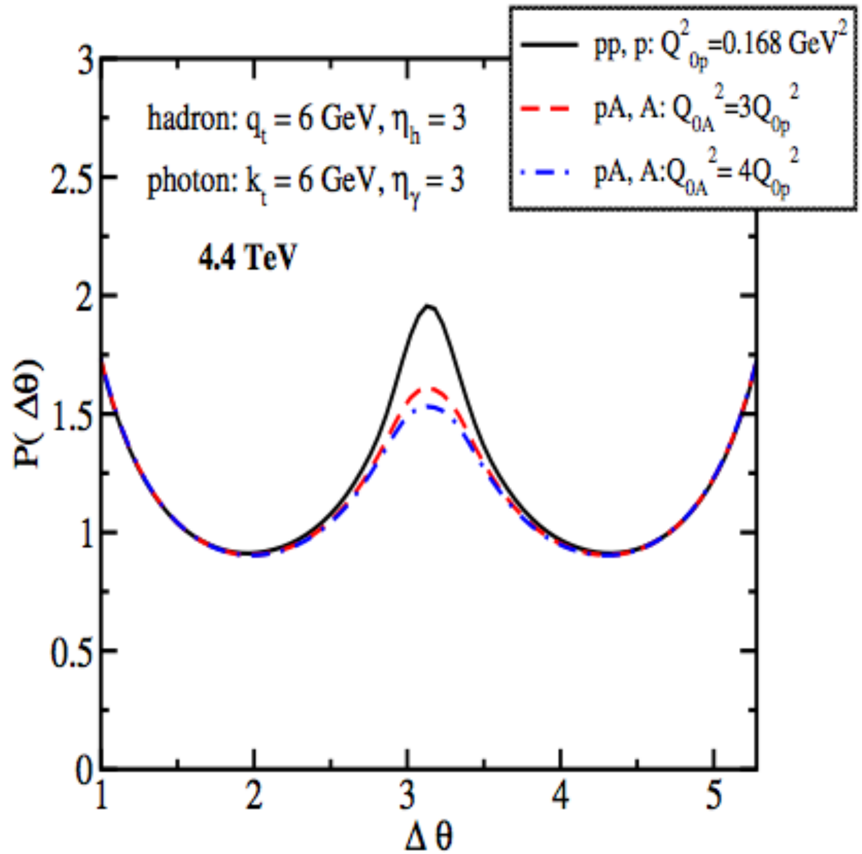
- p-Pb as reference for PbPb
  - Particle production
  - Particle correlation
  - Energy loss
  - Jets
  - quarkonia
  - Heavy flavor
  - W, Z production
- Low-x QCD dynamics
- Gamma-induced processes in ulraperipheral collisions

ALICE< ATLAS and CMS will be ready for p-Pb collisions

p-Pb Collisions at LHC

Ferenc Sickler, CMS





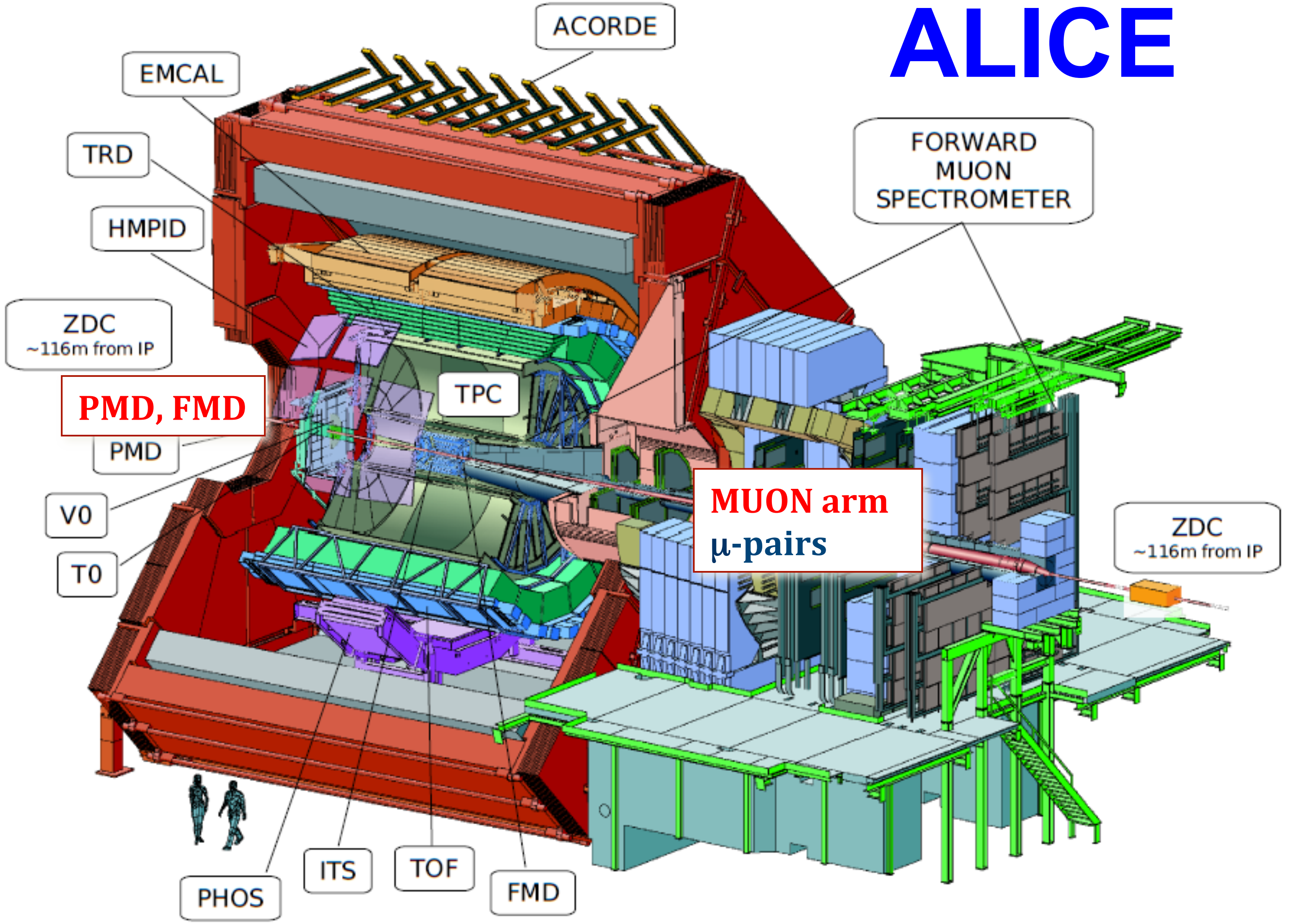
Rezaeian, arXiv:1111.2312

Jalilian-Marian and Rezaeian, arXiv:1204.1319

Sensitive to various CGC model ingredients and initial conditions

p-Pb: inclusive hadron production ($dN_{ch}/d\eta$ and dN/dp_T) at $y \approx 0$
p-Pb: azimuthal decorrelations of forward-backward dijets (dihadrons)

ALICE



Future: FoCal (350 to 450 cm away from IP)

Figure 2.2: Layout of the ALICE experiment.

Coverages of detector subsystems and their functionality in ALICE expt.

Detector	Functionality	Acceptance (η, ϕ)
ITS (SPD, SDD, SSD)	vertexing, tracking, PID at low p_T	± 2, 360°
TPC	Tracking, PID	± 0.9, full ϕ
TRD	Electron ID	± 0.84, full ϕ
TOF	PID	± 0.9, full ϕ
HMPID	PID at high p_T	$\pm 0.6, 1.2° - 360°$
PHOS	Photon spectrometer	± 0.12, $220° - 320°$
EMCAL	EM Calorimeter	± 0.7, $80° - 187°$
ACORDE	Cosmic trigger	± 1.3, $-60° - 60°$
Muon Spectrometer	Muon pairs	-2.5 to -4.0, full ϕ
PMD	Photon Multiplicity	2.3 to 4.0, full ϕ
FMD	Charged Multiplicity	-1.7 to -3.4, full ϕ 1.7 to 5.03, full ϕ
V0	Trigger	-1.7 to -3.4, full ϕ 2.8 to 5.1, full ϕ
T0	Trigger, timing	-2.97 to -3.28, full ϕ 4.71 to 4.92, full ϕ
ZDC(ZN and ZP) ZEM	Zero Degree Calorimeter EM Calorimeter	8.8 4.8 to 5.7, partial ϕ
Proposed Forward Calorimeter	EM Calorimeter	2.5 to 5.0, full ϕ

A new detector: Forward Calorimeter (FoCal) in ALICE

FoCal: (i) $2.3<\eta<4$, (ii) $3.5<\eta<5.5$

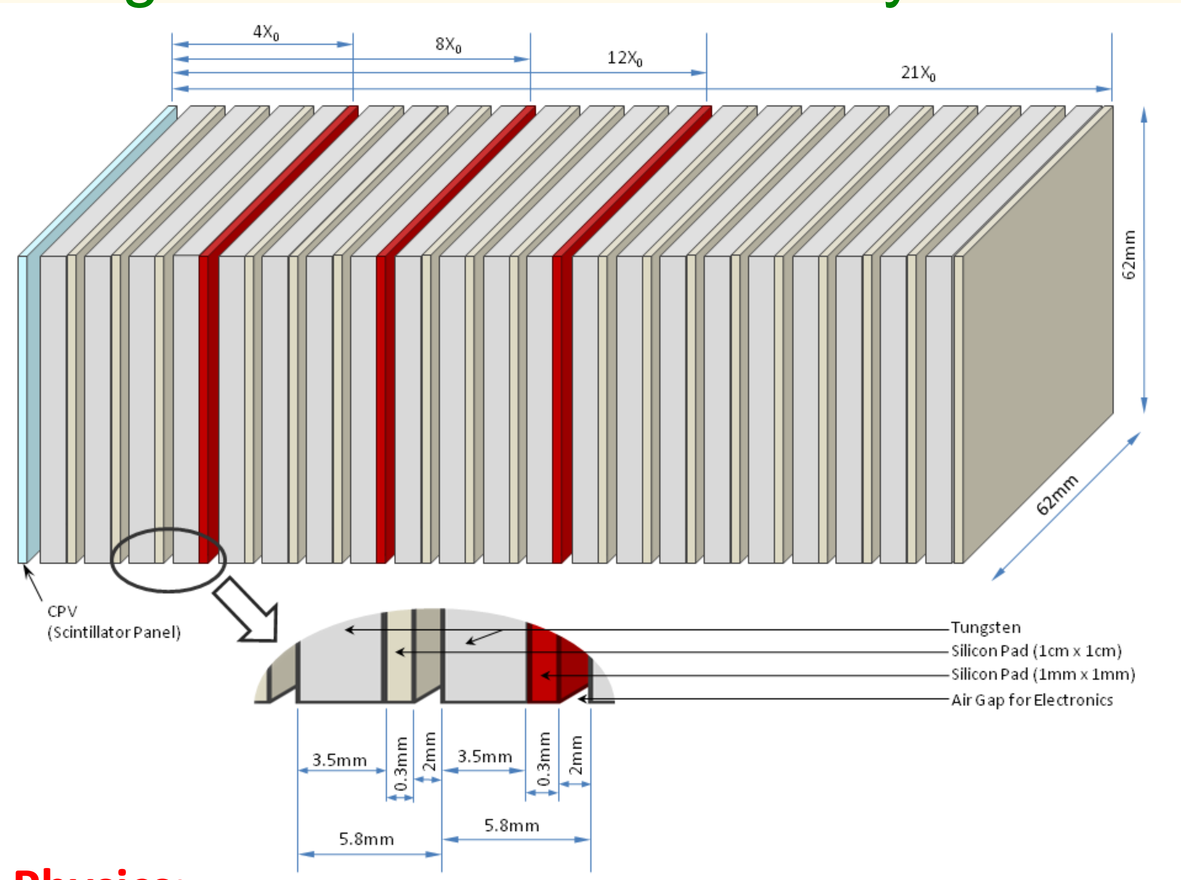
- Major Physics of FoCal
  - Investigate new details of parton Eloss in Pb+Pb with detailed fragmentation information (PID) about coincident jet in the Central Barrel.

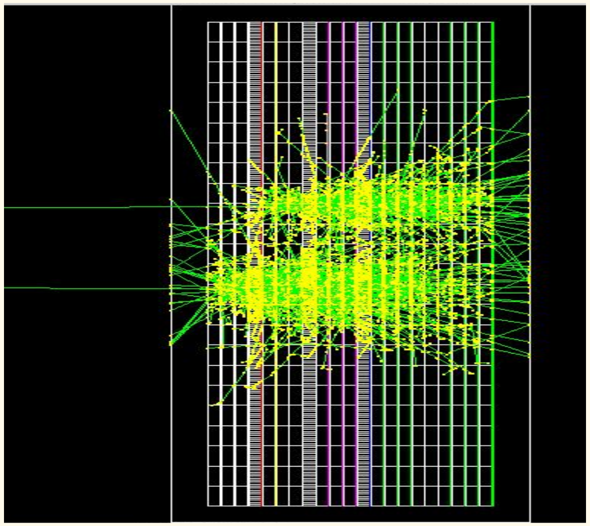
    - Gamma (FoCal) + Jet (Central Barrel) coincidence cleanly tags a recoiling <u>quark</u> jet (i.e. parton ID) with "<u>known</u>" <u>quark momentum</u>.
    - Jet+Jet (or π^0+X,X=jet or hadron) coincidence cleanly tags a recoiling <u>gluon</u> jet (mostly) with constrained initial parton kinematics. Probes initial state PDFs over a much broader kinematic regime than with CB alone.

- FoCal Design Criteria: (Direct γ driven)
  - Rates $\longrightarrow$ Energy range
    - Yields for direct γ, γ+jet
    - Yields for jets (π^0, decay γ background)
  - Energy resolution: Moderate requirements due to boost
  - Excellent lateral segmentation for γ/π^0 discrimination to optimize direct/decay γ (S/B)
    - This is where ALICE must beat other LHC experiments
    - Studies with realistic geometries and algorithms are just getting underway
  - Trigger capability for γ's and jets is essential

Forward Calorimeter in ALICE

Tungsten – Silicon Calorimetry





25 Layers (each 1m^2 area)

- **22 layers of 1cm x 1cm silicon pads**
- **3 layers of 1mmx1mm silicon pads**

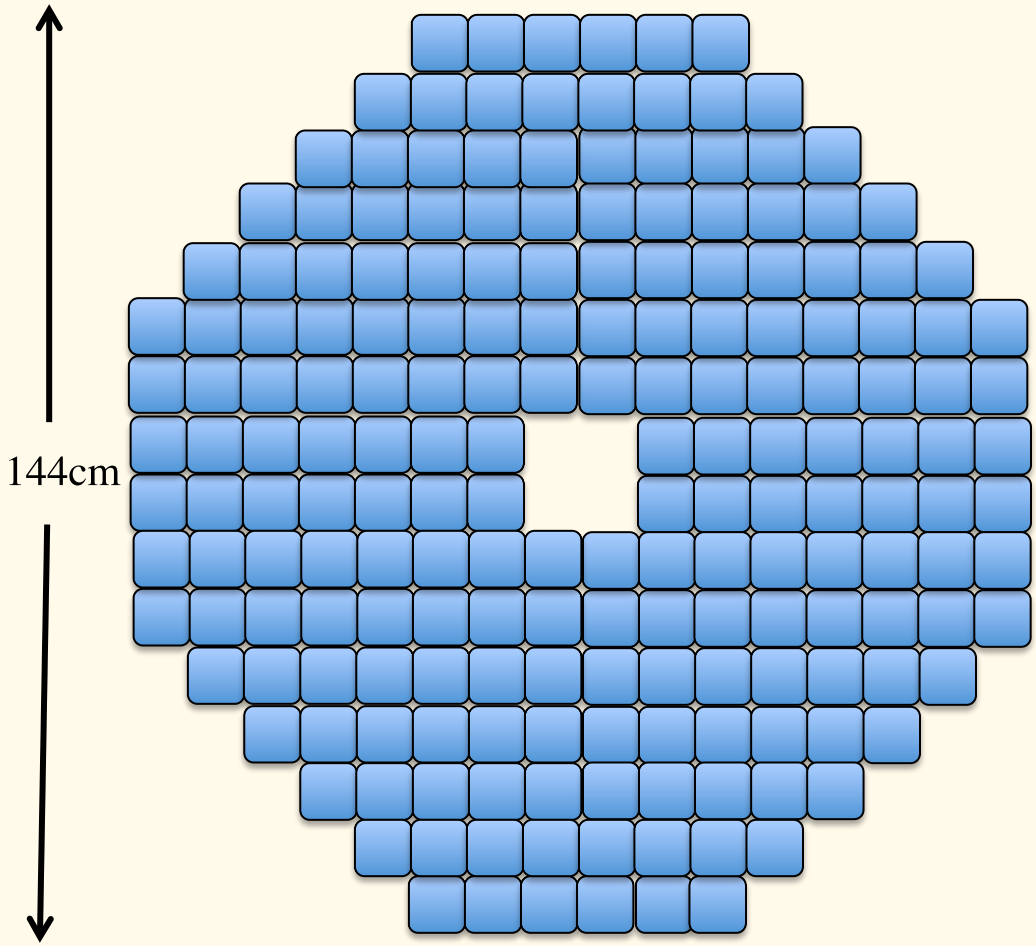
OR

- **MAPS**

Physics:

- **Initial State: Low-x Gluon Saturation**
- **Initial State: Nuclear PDFs**
- **Probing the strongly interacting matter thru the study of jet quenching, flow and long range correlations.**

(A possible) FoCal Geometry



192 FoCal Module geometry
2200kg; $1.55m^2$

9x9cm modules@360m gives:

$\Theta_{min} = 2.0^o$; $\eta_{max} = 4.0$ (Full ϕ)
$\Theta_{max} = 11.3^o$; $\eta_{min} = 2.3$ (Full ϕ)

Expression of Interest

A Forward Electromagnetic Calorimeter (FoCal) for the ALICE experiment

For installation in 2017-18

The FoCal Collaboration

April 26, 2011

Abstract

As an upgrade of the ALICE experiment at the CERN-LHC, we would like to build and install a Forward Electromagnetic Calorimeter (FoCal) to be placed in the pseudorapidity region of $2.5 < \eta < 4.7$, at the position of the existing Photon Multiplicity Detector (PMD). The basic motivation of including the calorimeter in the forward direction is to study outstanding fundamental QCD problems at low Bjorken-x values, such as parton distributions in the nuclei, test of pQCD predictions and to probe high temperature and high density matter in greater detail. A comprehensive measurement of p-p, p-Pb and Pb-Pb collisions at the highest LHC energies will be required. For these measurements, the detector needs to be capable of measuring photons for energies up to at least $E \sim 200$ GeV/c. It should allow discrimination of direct photons from neutral pions in a large momentum range and should also provide reasonable jet energy measurements. At present, two possible designs are being considered based on silicon-tungsten calorimetry. It is envisaged to install one more detector of similar technology at even larger pseudorapidity (up to 7) region in future.

Additional:
Hadronic Calorimeter
behind the FoCal

LoI Due: September 2012

- RHIC has given us guidance which way to go
- Lots of new results to come at LHC – for pp, p-Pb and Pb-Pb.

Thanks to ALICE Collaborators, FoCal Collaborators, CMS colleagues …. and
Several speaker, whose slides I have borrowed from pA workshop which was held at CERN recently.