Forward Physics (Experiments)

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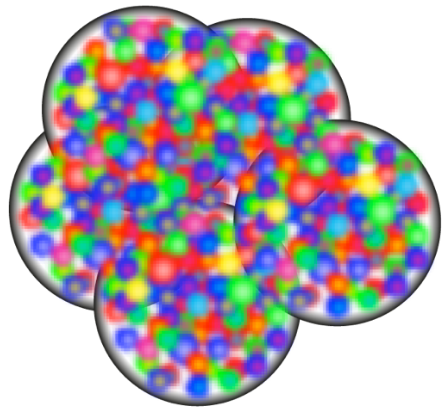


チュートリアル研究会
「重イオン衝突の物理：基礎から最先端まで」

Mar 26, 2015
理化学研究所（和光市）

筑波大学
University of Tsukuba

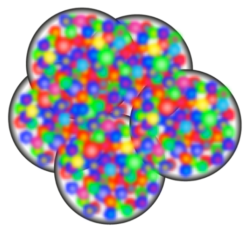
Outline

1. **Introduction**
2. **Forward physics for HIC**
   - QCD Factorization theorem
   - Nucleon parton distributions at small x
   - Gluon saturation (CGC)
   - Nuclear parton distributions
3. **Experimental results from RHIC/ LHC**
4. **Future experiments**
5. **Summary**

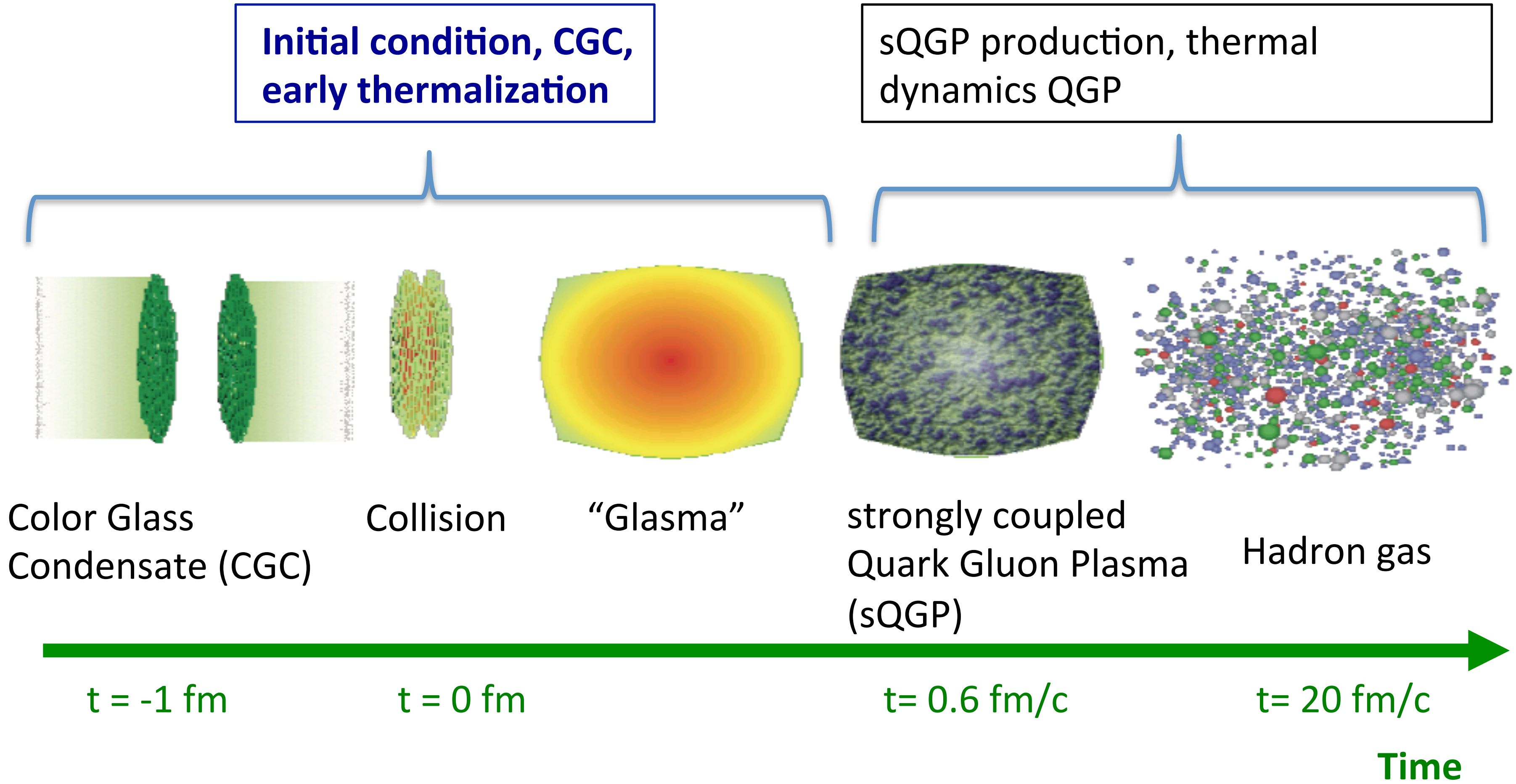
1. Introduction

“My” motivation of this field

- It is often said that CGC is the initial state of heavy ion collisions at RHIC/LHC.
- Do we see a gluon saturation effect at RHIC and LHC?
- How clearly see the effect?
- Are there any links from the initial condition to the early thermalization process of QGP, “Glasma”?
- What is the best probe(s) of CGC in the future experiments?



Initial condition and thermalization



RHIC/LHC data suggests an early thermalization of QGP (~ 0.6 fm), and it is still a **big missing link** between initial condition to QGP.

➠ Need a direct probe to access to initial condition

2. Forward Physics for Heavy Ion Collisions

Factorization theorem of QCD

Hadron production by hard scattering processes

$$E_h \frac{d\sigma_{AB\to h(p)}}{d^3 p_h} = \sum_{abk} \int d^3 x_2 f_{b|B}(x_2) \int d^3 x_1 f_{a|A}(x_1) \int dz D_{h|k}(z) E_k \frac{d\hat{\sigma}_{ab\to k}}{d^3 p_k}$$

Parton (a, b), incoming nucleon (A, B), hadron h

$\boldsymbol{p_{A(B)}}$: momentum for nucleon A (B)

$\boldsymbol{p_{a(b)}}$: momentum for parton a (b)

$\boldsymbol{x_1 = p_A / p_a}$

$\boldsymbol{x_2 = p_B / p_b}$

$\boldsymbol{f(x,Q^2)}$: parton distribution function (PDF)

$\boldsymbol{Q^2}$: momentum transfer

$\boldsymbol{E_k\, d\sigma_{ab\to k}/d^3p_k}$:

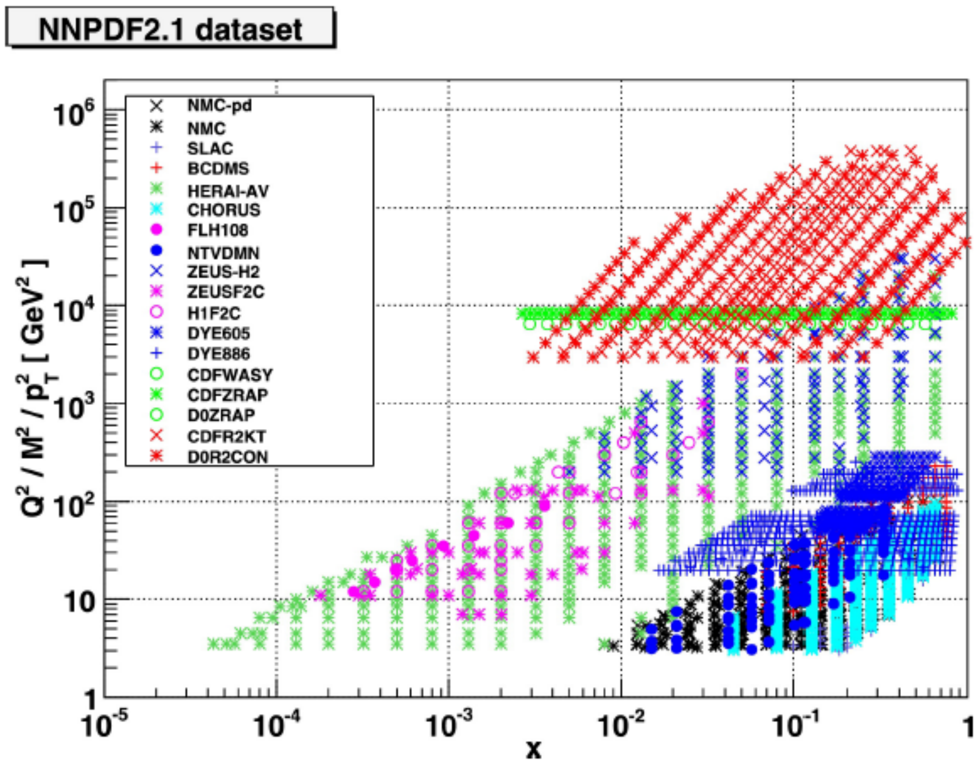
Elementary cross section to produce parton "k" from a and b, in the final momentum p_k

$\boldsymbol{D_{h/k}(z)}$: fragmentation function from parton k to hadron h.

$\boldsymbol{z = p_h/p_k}$: momentum fraction of hadron h carried by parton k

Factorization theorem of QCD

$$E_h \frac{d\sigma_{AB\to h(p)}}{d^3 p_h} = \sum_{abk} \int d^3 x_2 f_{b|B}(x_2) \int d^3 x_1 f_{a|A}(x_1) \int dz D_{h|k}(z) E_k \frac{d\hat{\sigma}_{ab\to k}}{d^3 p_k}$$



R. D. Ball et al., (NNPDF Collaboration), Nucl. Phys. B 849, 296 (2011).

PDFs are determined empirically by the best fit to the data, assuming the factorization theorem and DGLAP (Q^2) evolution.

NNPDF collaboration:

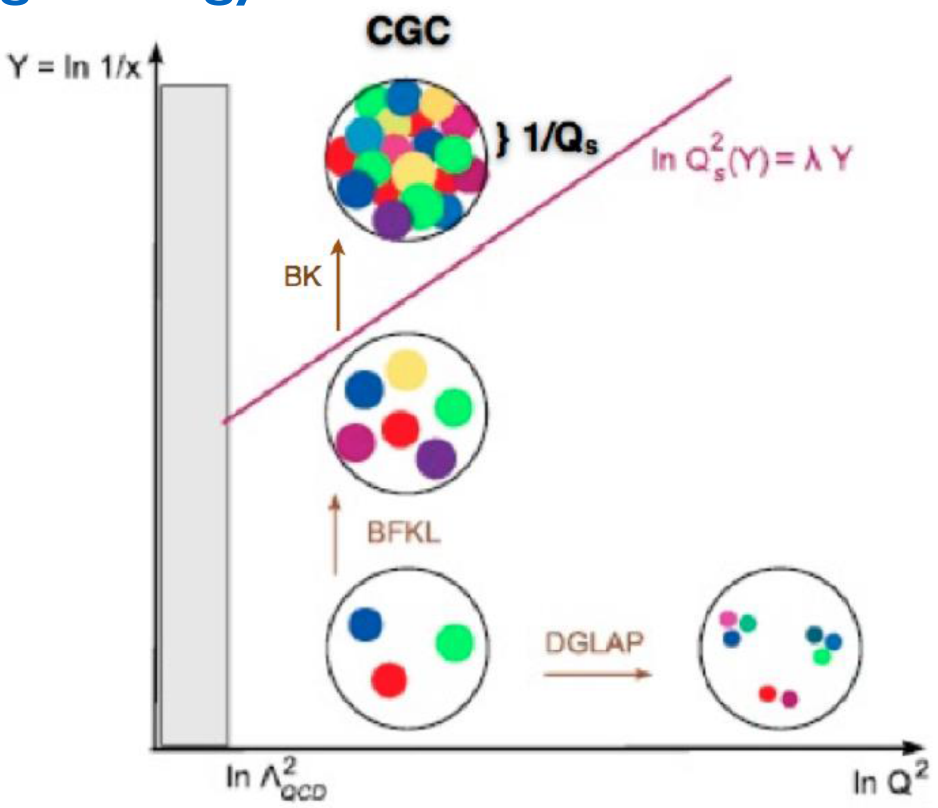
DIS, Drell-Yan, inclusive jet, weak vector boson, and charm

→**determined "NNPDF2.1" PDF**

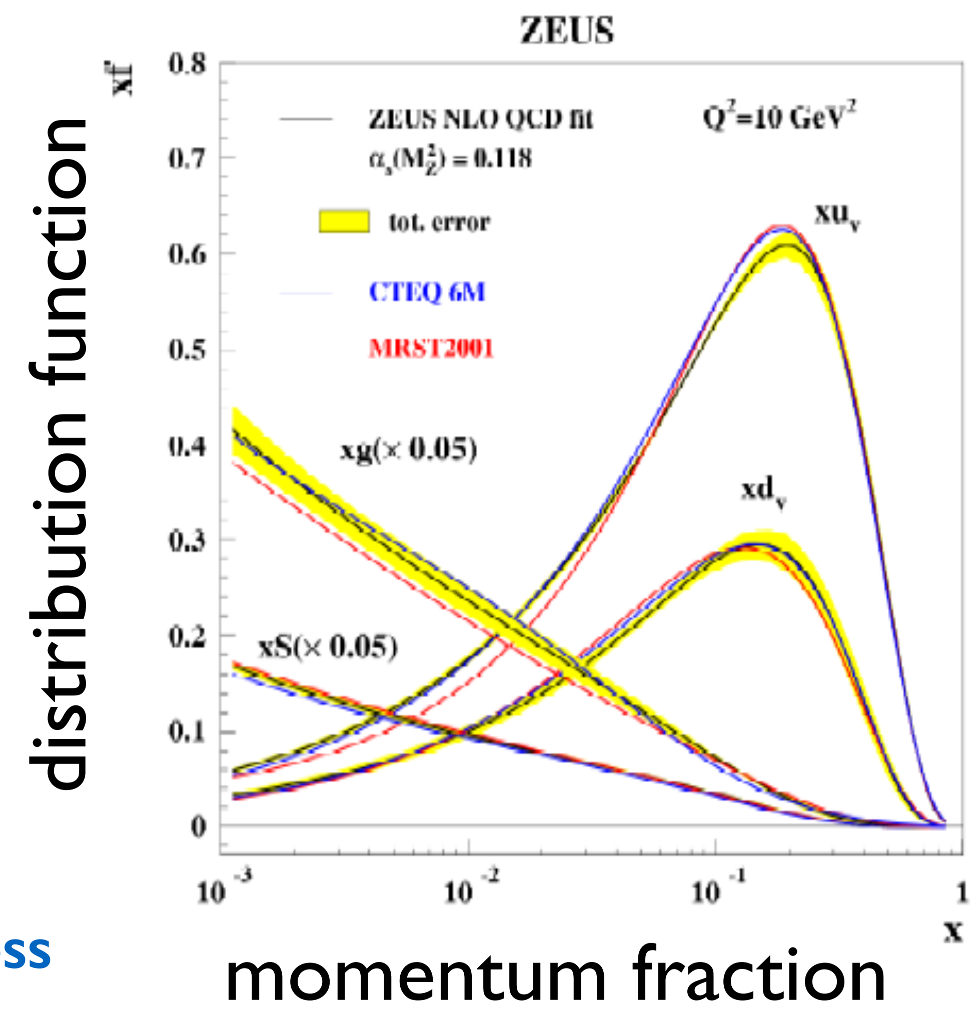
Strong support for factorization assumption with universal PDFs (w/ DGLAP evolution).

Gluon Density

high energy

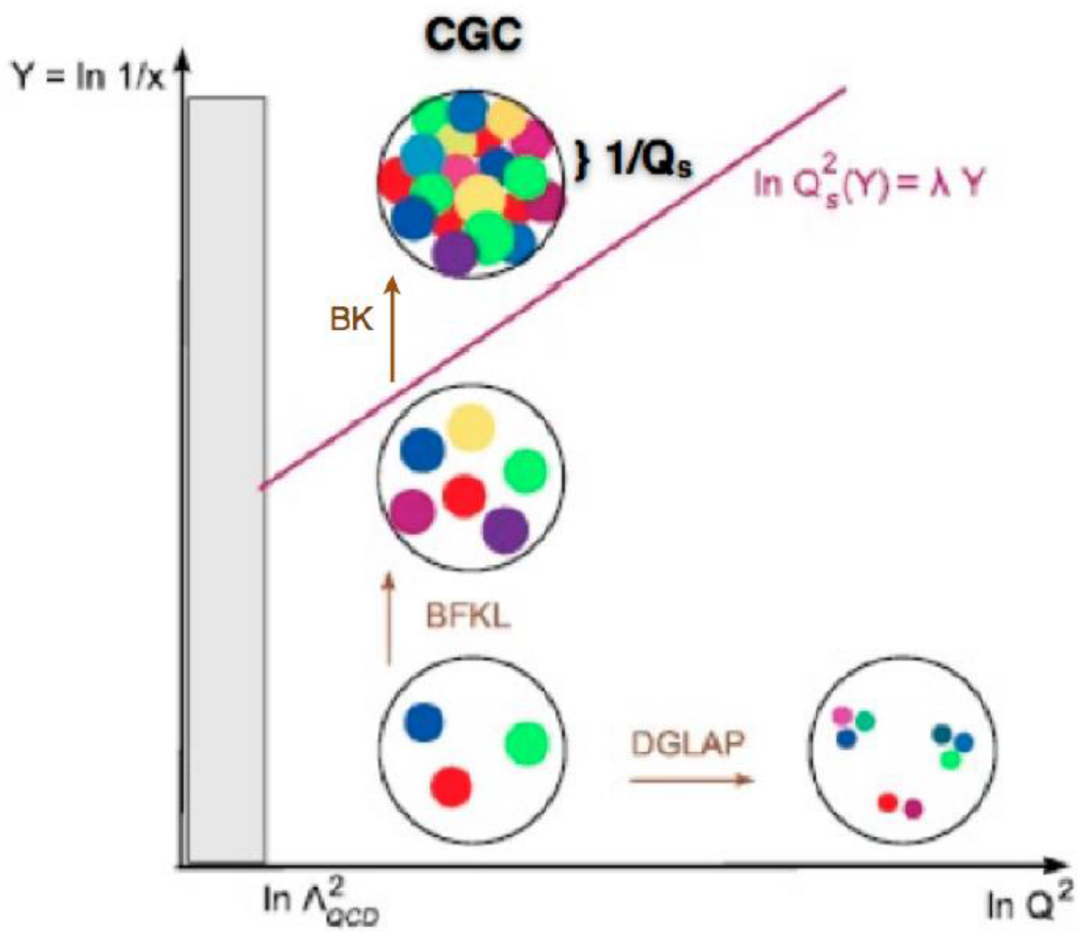


hard process



At small x and small Q^2, the parton density will become large by non-linear effects due to gluon fusion

Gluon saturation (CGC)



Gluon density per area
(nucleon cross section: πr^2)

$$\rho \sim xg(x, Q^2)/\pi r^2$$

Gluon fusion cross section

$$\sigma_{gg \to g} \sim \alpha_s / Q^2$$

When; $\rho \sigma_{gg \to g} \gtrsim 1$

➡Gluon density saturate, called;

- Gluon Saturation, or
- Color Glass Condensate (CGC)

<u>Saturation scale:</u>

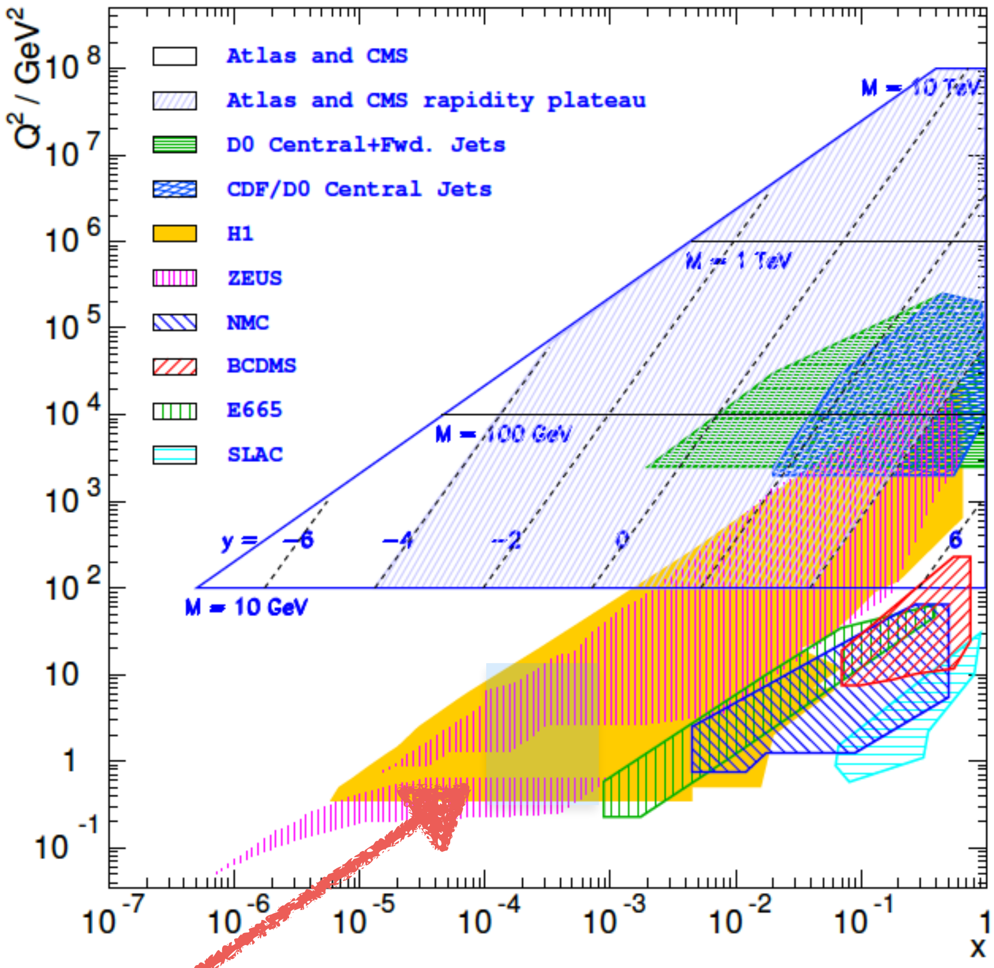
$$Q_s^2 \sim \alpha_s \frac{xg(x, Q^2)}{\pi r^2} \sim x^{-0.3}$$

gluon saturation: $Q_s < Q$

→ Exclusion of small x and Q^2 region, better PDF determination by the exp. data fit (NNPDF)

kinemacis (x-Q^2)

- Large increase in beam energy at LHC,
- Measurements at the LHC probe the nucleon PDFs over a **wide region of x and Q^2** that is much greater than that previously accessible.



Bulk properties in HI
and gluon saturation physics
→ low Q^2 and low x

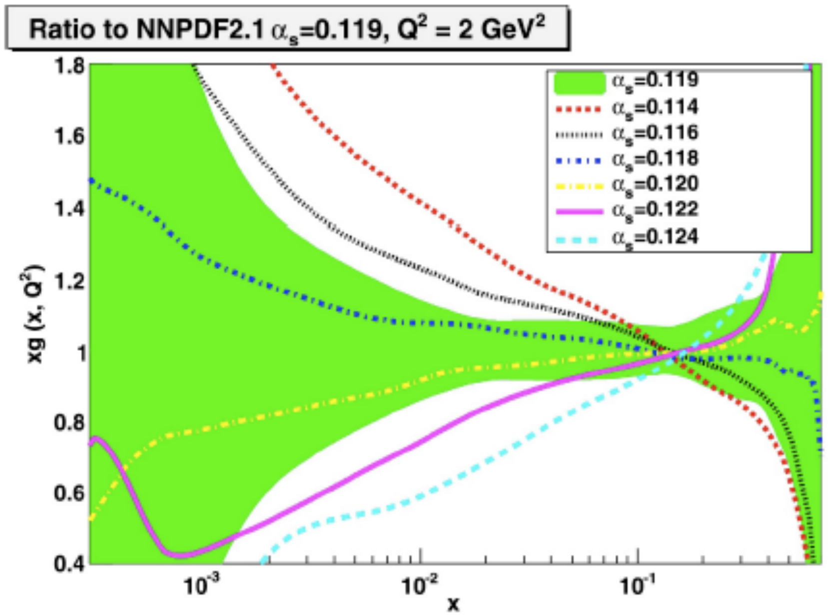
$Q^2(\approx p_T^2) \lesssim 10\ \mathrm{GeV}^2$ and $x \sim 10^{-3} - 10^{-4}$

only PDF determined by DIS,
but there are uncertainties of gluon PDF

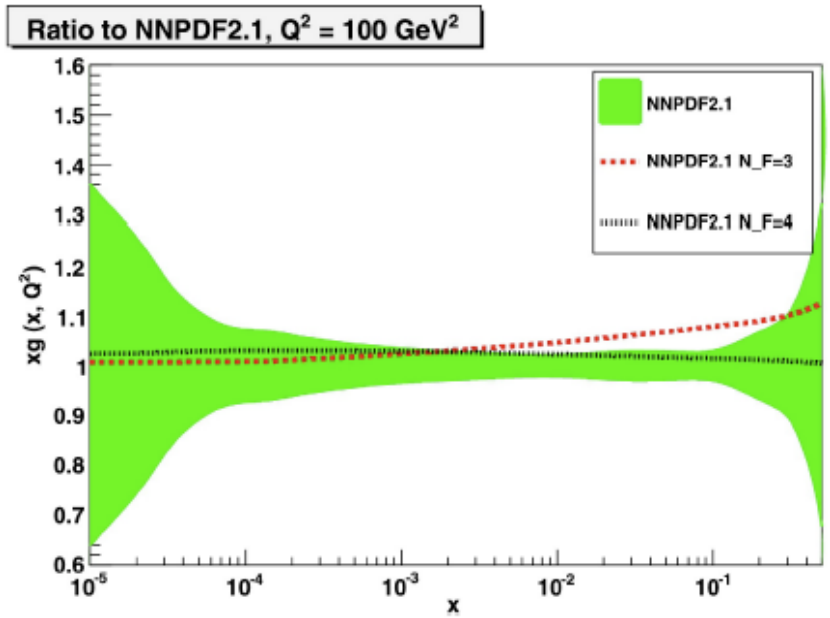
Uncertainty of Gluon PDF at low x and Q^2

Gluons are **uncharged** they are not directly probed in the DIS process,
Constrained only indirectly way
→ gluon PDFs have rather large uncertainties in the low-x and low Q^2.

Ratio of the gluon distribution function $xg(x;Q^2)$ to the nominal value with shaded region



low Q^2 (=2GeV^2)



high Q^2 (=100GeV^2)

R. D. Ball et al., (NNPDF Collaboration),
Nucl. Phys. B 849, 296 (2011).

Nuclear PDF (nPDF) for gluons

- Ratio of the gluon distribution function of a Pb nucleus to that of the proton

- **A large spread for small x**
  → lack of constraints due to the limited set of relevant measurements (nuclear targets)

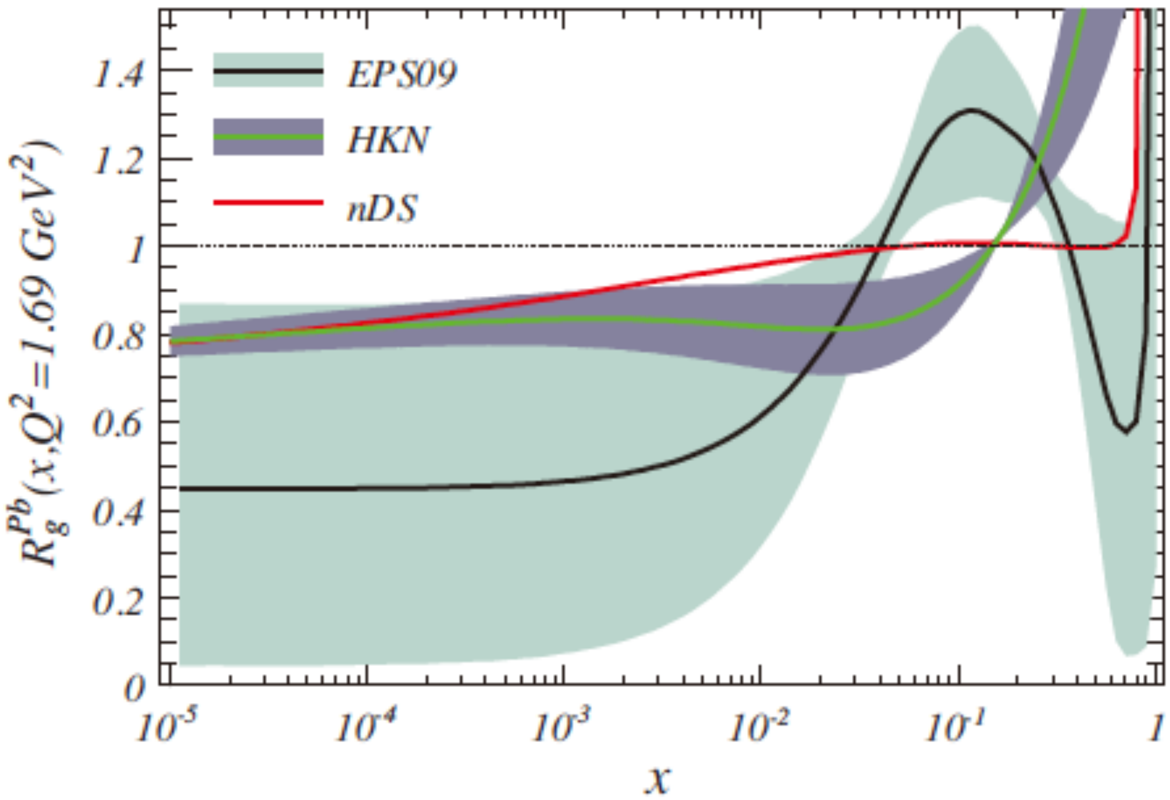
- Gluon density of a nucleus of mass number A can be written as (approximately);

$$xG(x,Q^2) \approx Axg(x,Q^2)$$

$$\pi R^2 \approx \pi (rA^{1/3})^2$$

$$Q_s^2 \sim \alpha_s \frac{xG(x,Q^2)}{\pi R^2} \sim A^{1/3} x^{-\lambda}$$

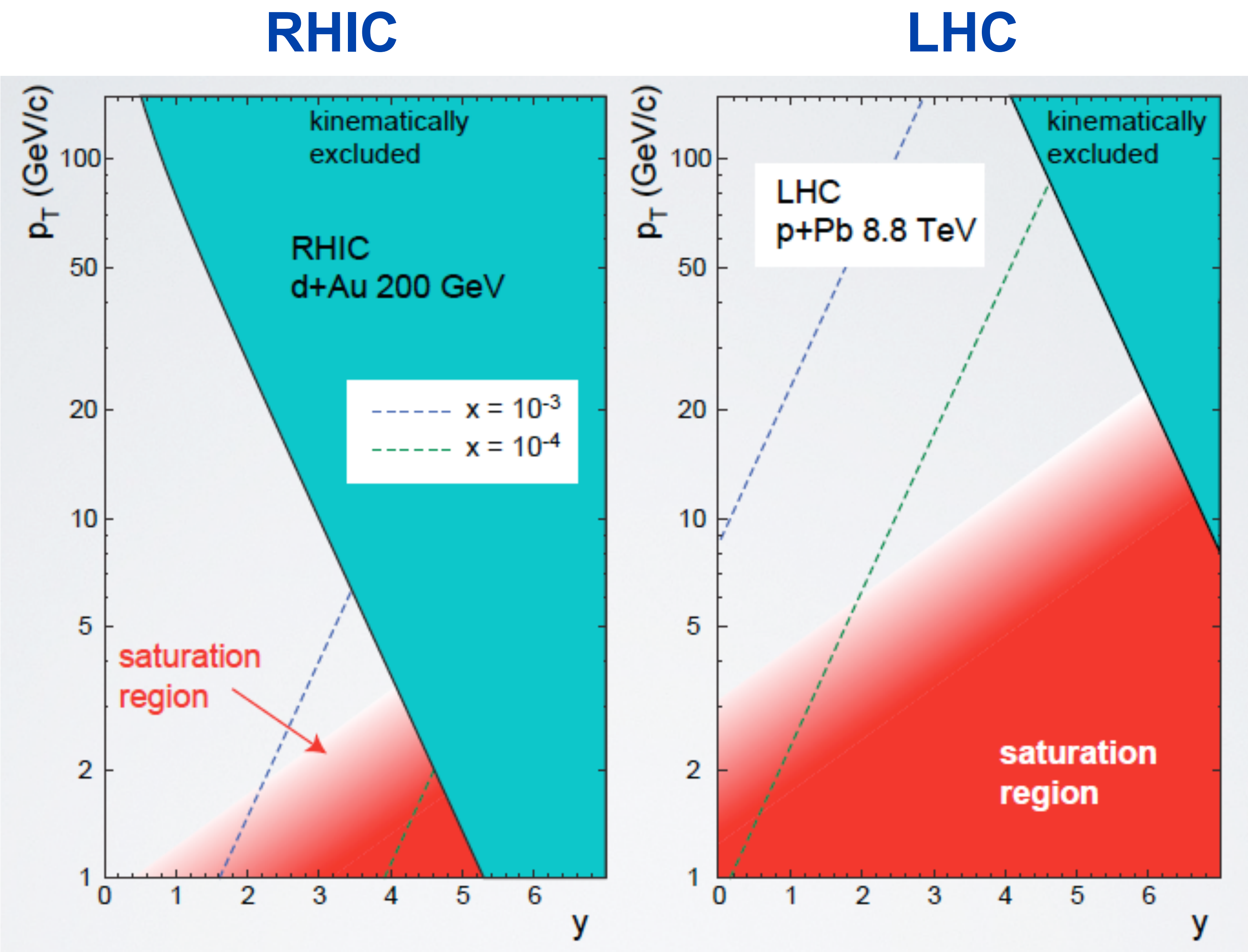
C. A. Salgado et al., J. Phys. G 39, 115010 (2012)



Effects of gluon saturation in nucleus:
set in at a factor 6 x higher Q^2 with a heavy nuclear target

- **Impact parameter dep. in p+A collisions**
  - **central: $A^{1/3} \sim 6$ (for Pb)**
  - **peripheral: ~1**

Probing CGC at RHIC/ LHC



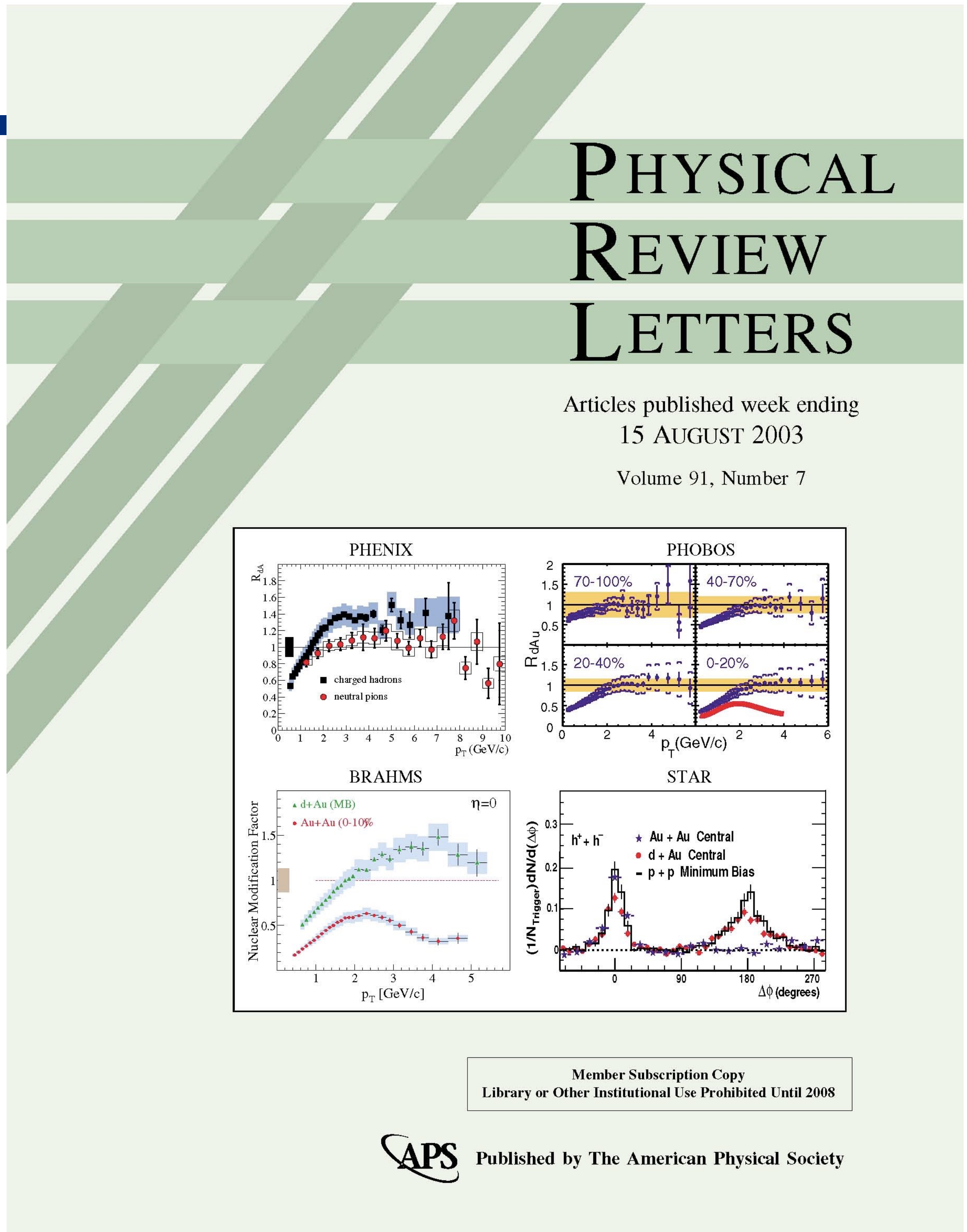
$$x_2 = \frac{p_T}{\sqrt{s}}(e^{-y_3} + e^{-y_4})$$

$$Q^2 = (\frac{1}{2}x_2 e^{y}\sqrt{s})^2 = p_T^2$$

Larger kinematic reach in saturation region at LHC, compared to that at RHIC.

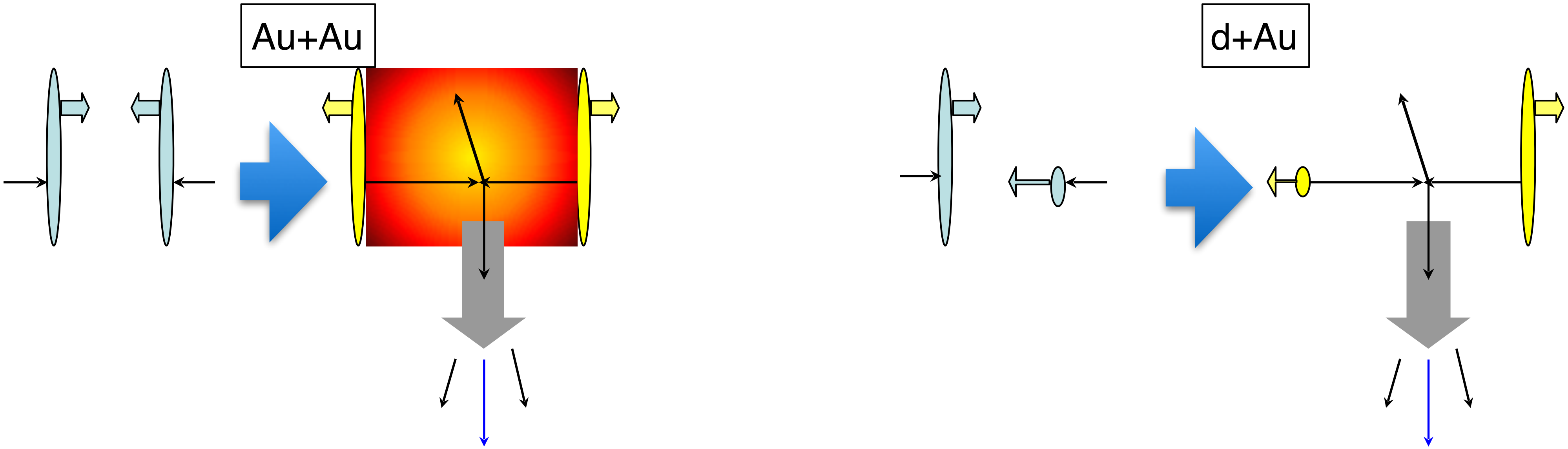
3. Experimental results from RHIC/ LHC

RHIC d+Au (2003)



PRL 91, Number 7 (2003)

d+Au: “Control” Experiment



= hot and dense medium

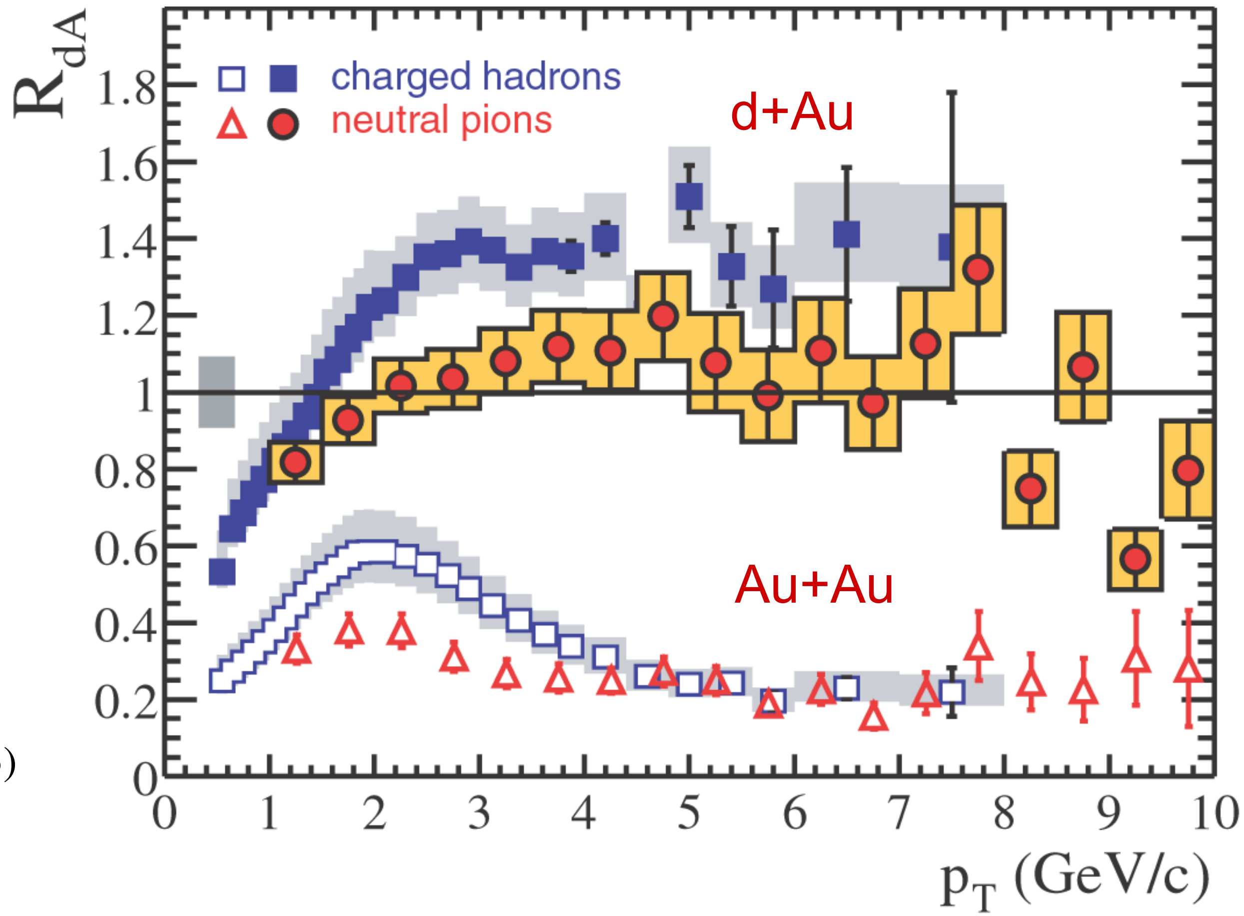
Initial + Final State Effects

= cold medium

Initial State Effects Only

- The “Color Glass Condensate” model predicts the suppression in both Au+Au and d+Au (due to the initial state effect).
- d+Au experiment **can tell us whether the observed hadron suppression at high p_T central Au+A is the final state effect or initial state effect.**

R_{AA} vs. R_{dA} for charged hadrons and π^0



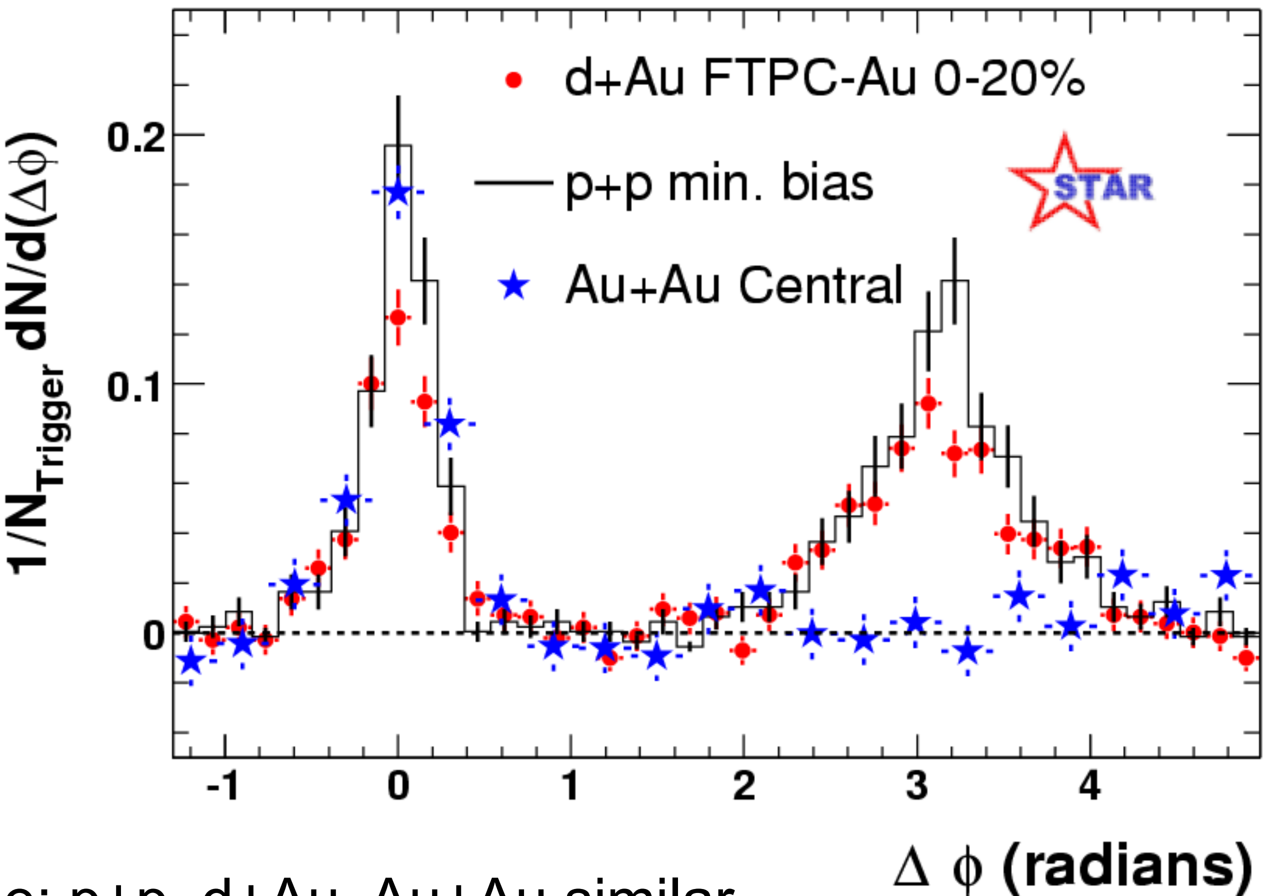
Initial State Effects Only

Initial + Final State Effects

PHENIX (d+Au)
PRL 91, 072303 (2003)

- **No Suppression in d+Au, small enhancement observed (Cronin effect).**
- **d-Au results rule out CGC as the explanation for high p_T Suppression of hadrons in AuAu central.**

Azimuthal Distributions in d+Au (STAR)



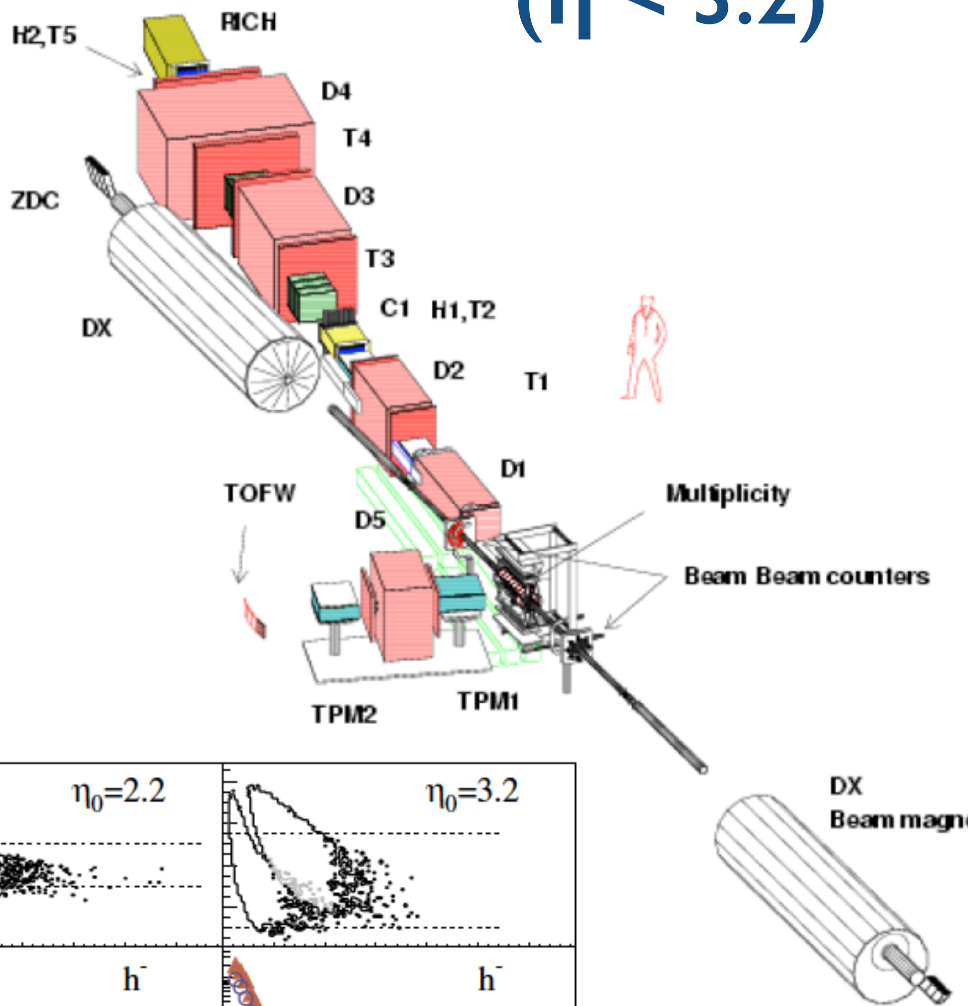
* Pedestal and flow subtracted

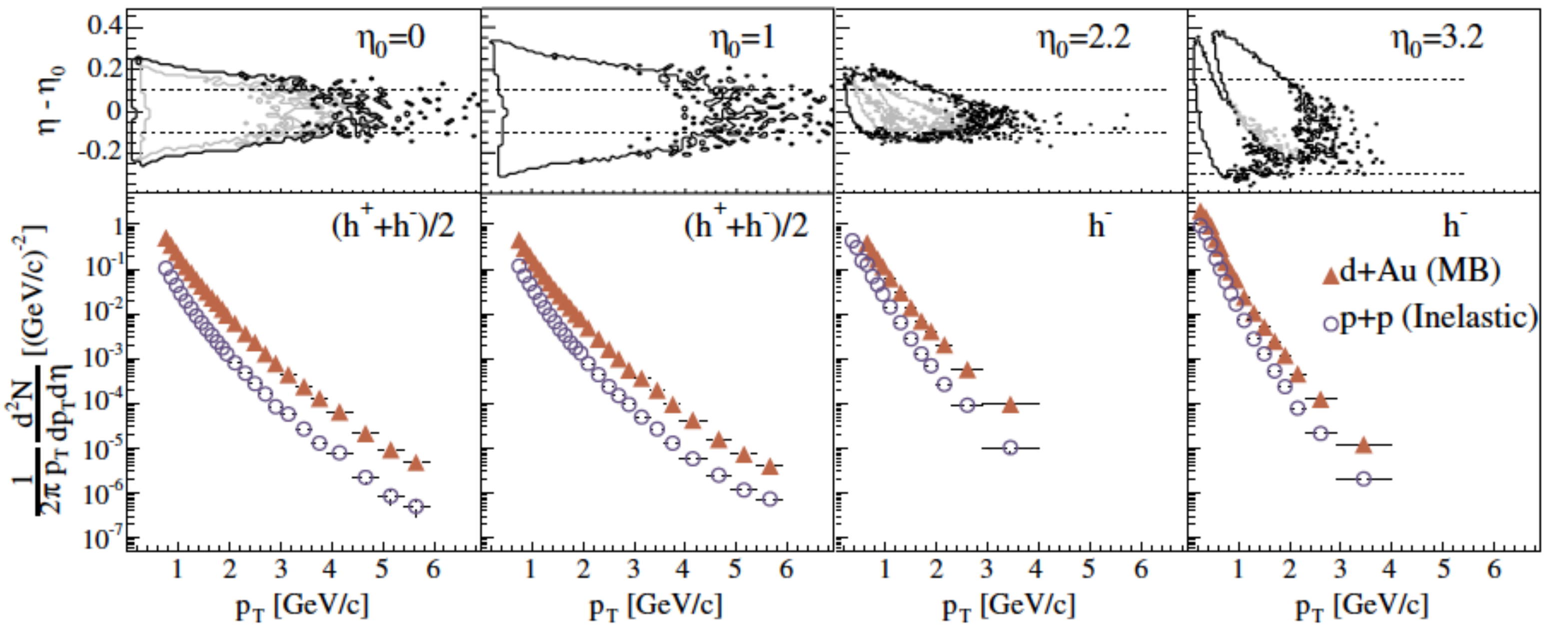
- Near-side: p+p, d+Au, Au+Au similar
- Back-to-back: Au+Au strongly suppressed relative to p+p and d+Au

Suppression of the back-to-back correlation in central Au+Au is a final-state effect

- Wide kinematic coverage ($|\eta| < 3.5$)
- Particle Identification by TOF

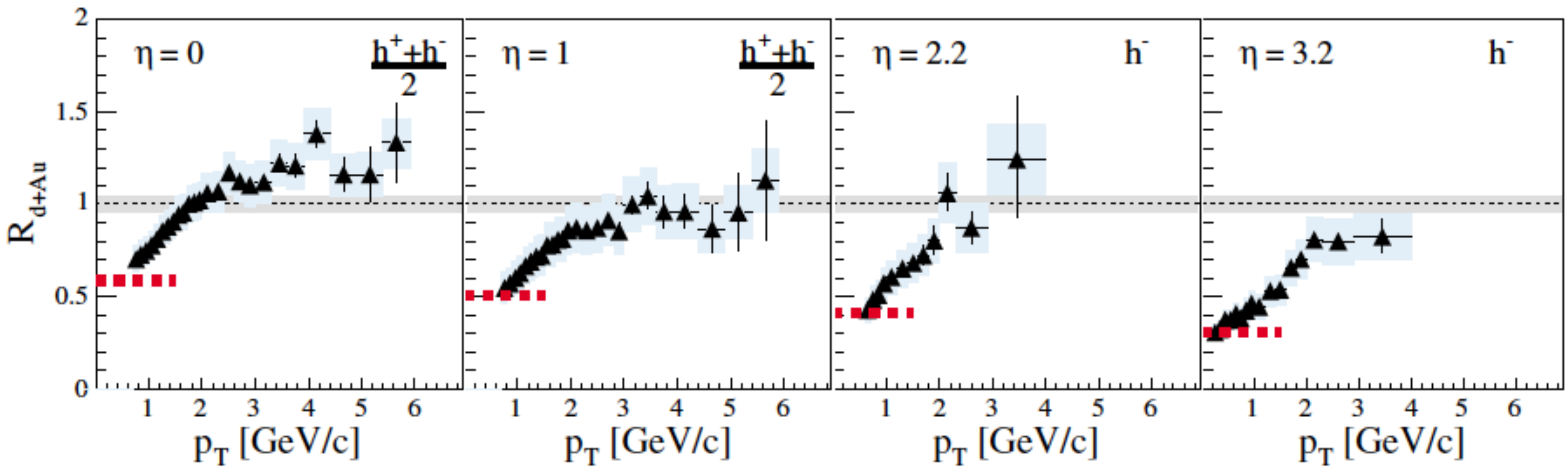
Access to forward region ($\eta < 3.2$)





PRL 93, 242303 (2004)
BRAHMS

BRAHMS R_{d+Au} (MB) at forward rapidity



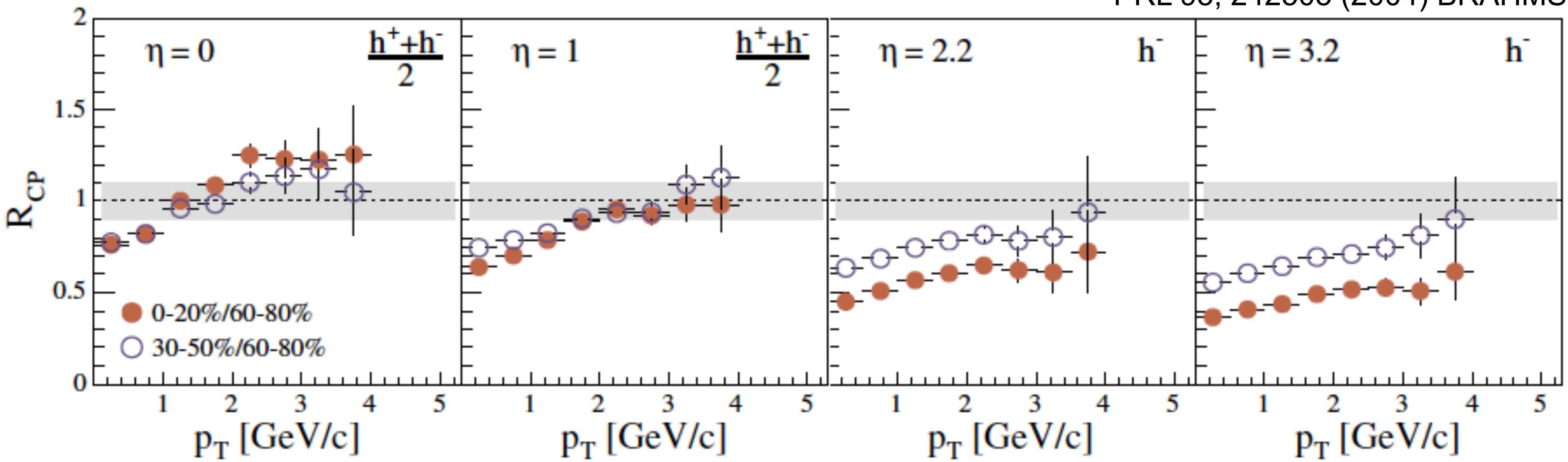
$$R_{dAu} \equiv \frac{1}{\langle N_{coll} \rangle} \frac{d^2N^{d+Au}/dp_T d\eta}{d^2N^{p+p}_{inel}/dp_T d\eta}.$$

PRL 93, 242303 (2004)
BRAHMS

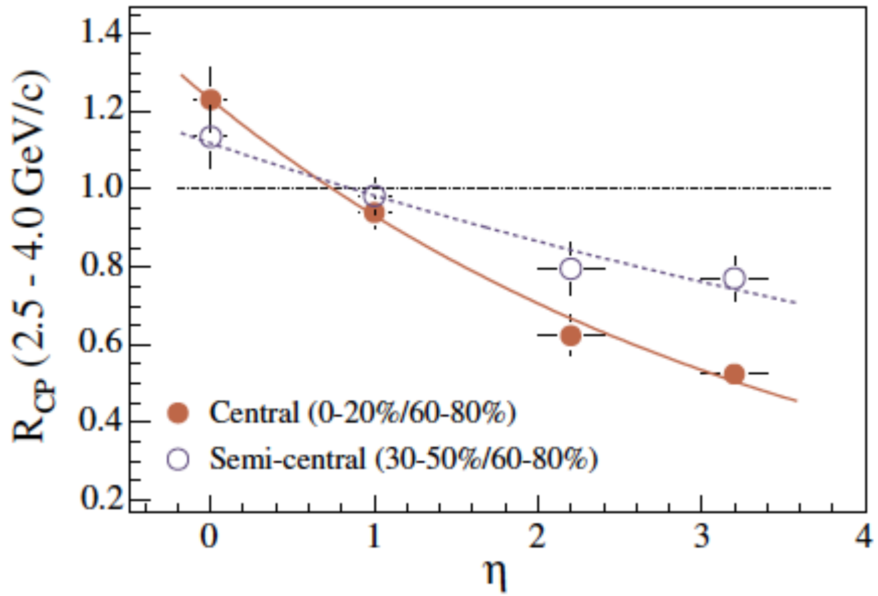
- Stronger suppression at low p_T hadrons at forward rapidity.
- **At forward rapidities, data show a suppression at all p_T.**
- Consistent with dN/dη ratio in d+Au and p+p (red dashed lines)
- Consistent with CGC pictures.

BRAHMS R_{CP} at forward rapidity

PRL 93, 242303 (2004) BRAHMS



$$R_{CP} = \frac{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{evt}} \frac{d^2 N_{ch\,jet}}{dp_{T,jet} d\eta} \Big|_{central}}{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{evt}} \frac{d^2 N_{ch\,jet}}{dp_{T,jet} d\eta} \Big|_{peripheral}}$$

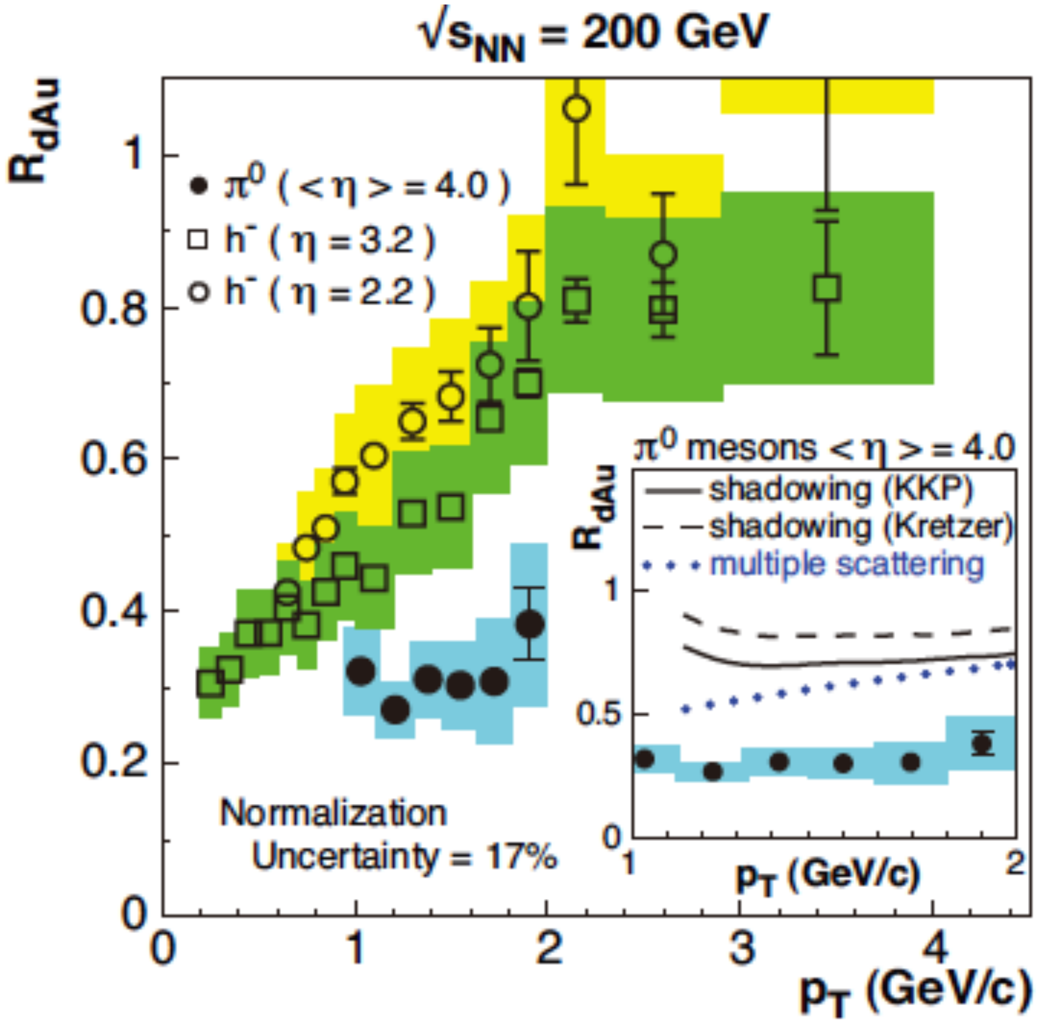


- R_{CP}: Central to Perial ratio (N_{coll} scaled)

- Substantial evolution form η = 0 to 3.2
- Suppression larger at forward and central 0-20%.

STAR R_{d+Au}: π^0 at forward rapidity (<η>=4.0)

J. Adams et al. (STAR), Phys. Rev. Lett. 97, 152302 (2006)

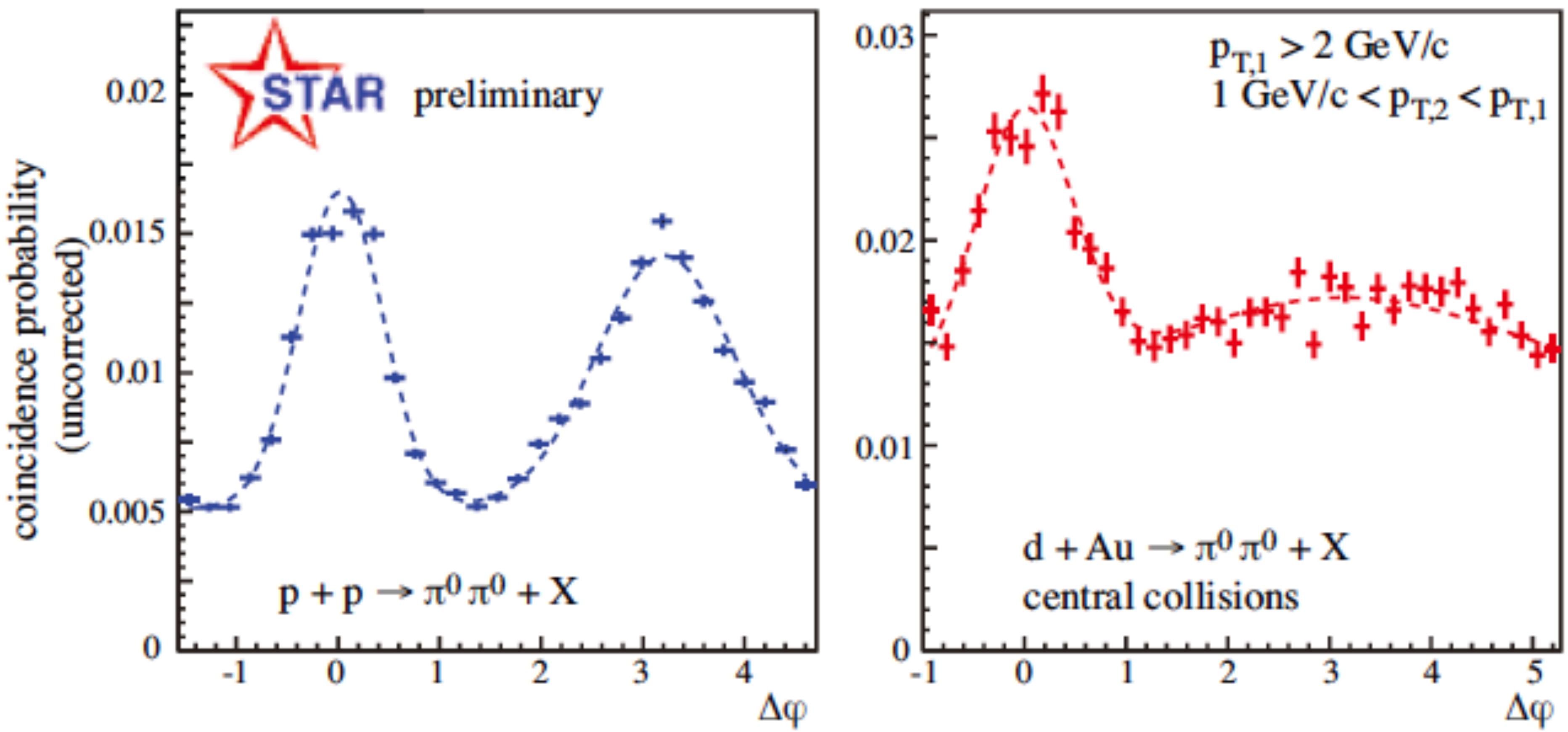


- Hadron productions are **suppressed at forward region.**
- Suppression evolves as a function of η
- Qualitatively consistent with the expectations for gluon saturation.

STAR: π^0-π^0 correlations at forward rapidity

E. Braidot et al. (STAR collaboration),arXiv:1005.2378

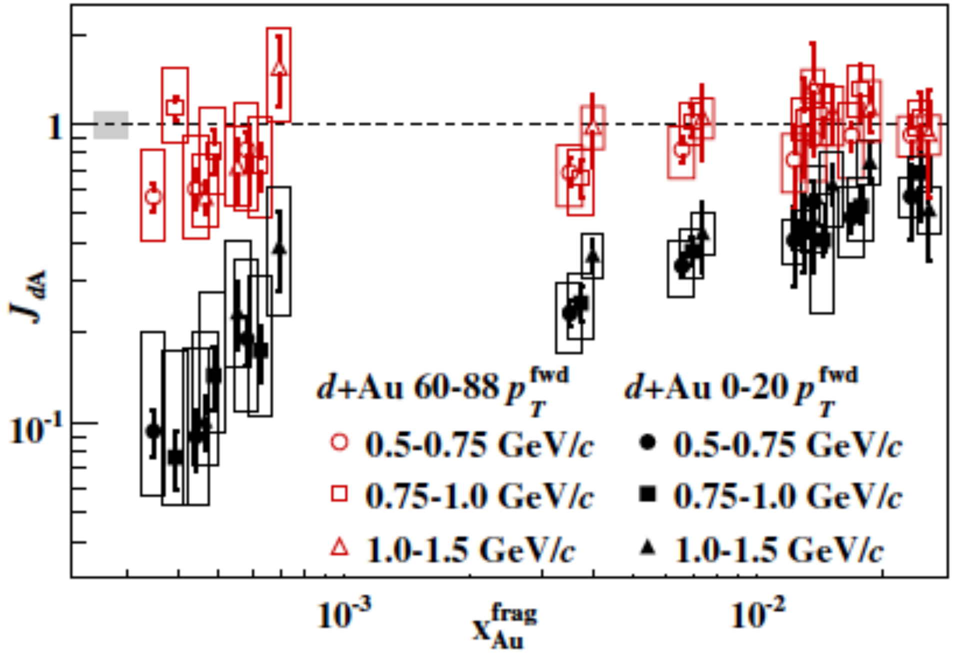
p+p   d+Au



- p+p: a strong peak at $\Delta\phi = \pi$, associated with the recoil jet opposite to the trigger particle
- d+Au (central): suppressed and/or broadened.

  ➡qualitative agreement with expectations from gluon saturation.

PHENIX, J_{dA} of away side peak (π^0-π^0) in d+Au



PRL 107, 172301 (2011), PHENIX

$$J_{AB} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{AB}^{pair}/\sigma_{AB}}{\sigma_{pp}^{pair}/\sigma_{pp}}$$

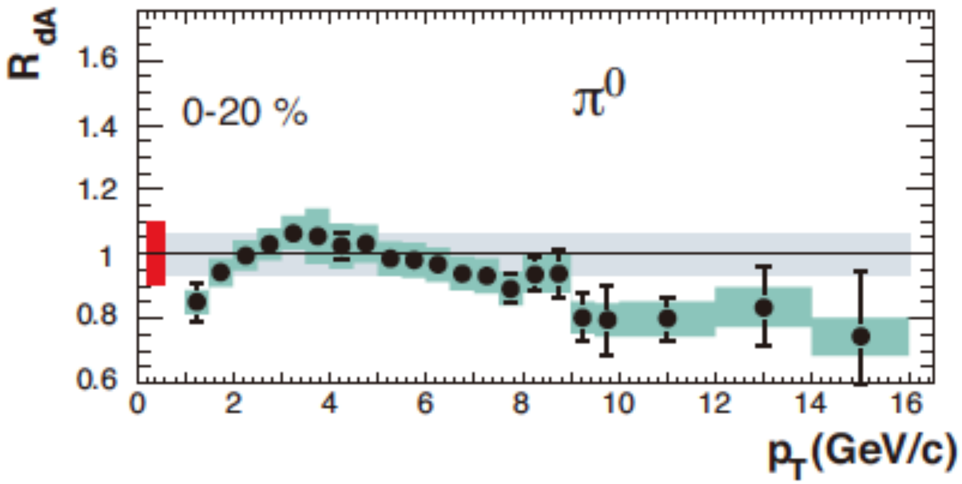
- π^0-π^0Correlations w/ p_T and rapidity cut on near & away side jets.
  → tight constraint on x_2 and Q^2 of hard process.
- J_{dA}: correlated pair yield suppression factor on away side.
  - x_2 like property:

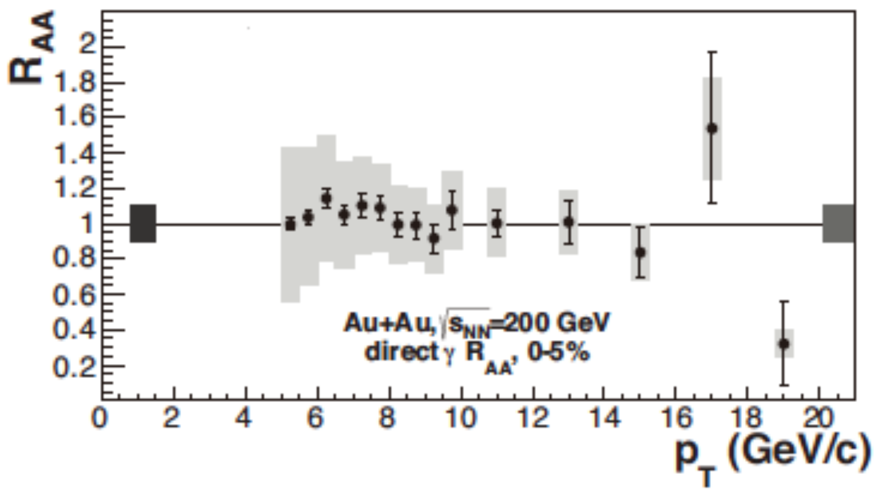
$$x_{Au}^{frag} = (\langle p_{T3} \rangle e^{-\langle \eta_3 \rangle} + \langle p_{T4} \rangle e^{-\langle \eta_4 \rangle}) / \sqrt{s_{NN}}$$

  - Strong suppression at low x, consistent with CGC expectation.
  - Little or no suppression for peripheral.

Now, go back to R_{dA}, R_{AA} (RHIC) again…

π^0 (d+Au) PRL 98, 172302 (2007) PHENIX **Direct γ (Au+Au)**

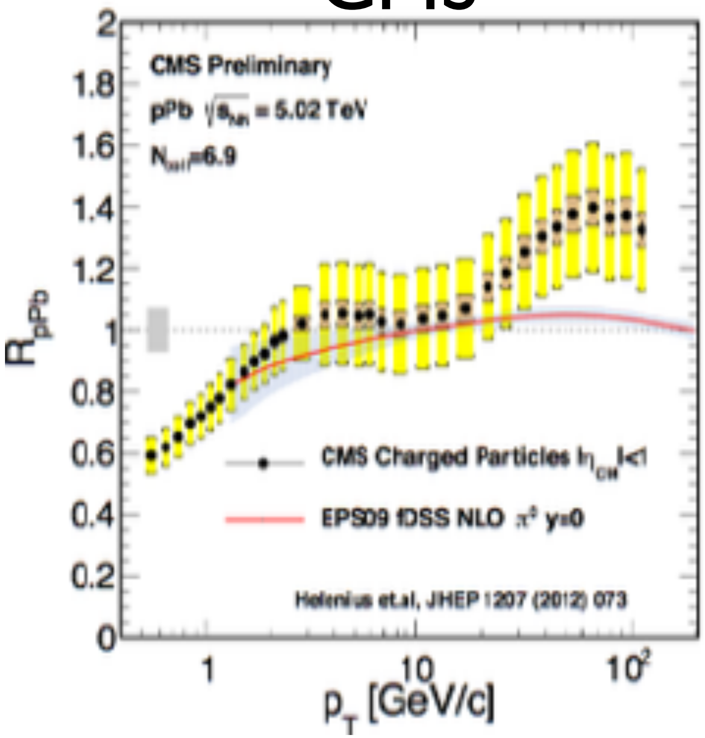




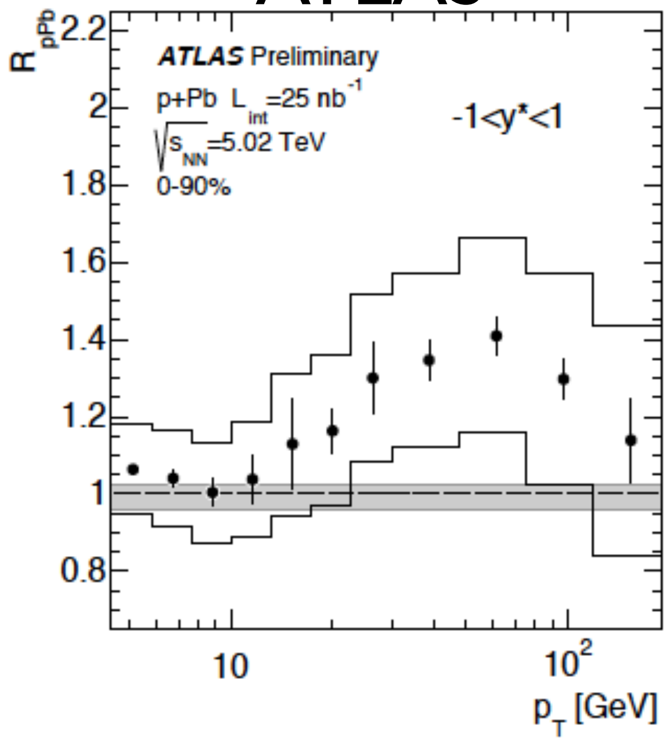
- **Direct γ (Au+Au)**: no deviation from unity, no indication of initial (or final) state nuclear effect.
- **π^0 (d+Au)**: **suppression at high p_T (> 10 GeV/c)** in central (0-20%)
  - initial state effect should be similar to that of direct γ in dAu, AuAu.
  - Suggesting the final sate effect in **“π^0 data”** shown here.
  - **Illustrate the difficulty to extract initial effect from the hadronic observables,**
  - **Difficult to constraint the parton kinematics by hadrons**

In case of LHC…

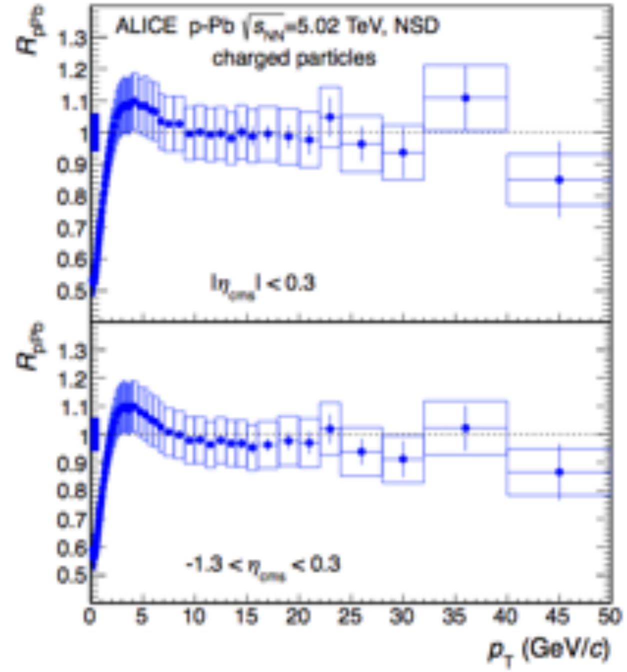
CMS



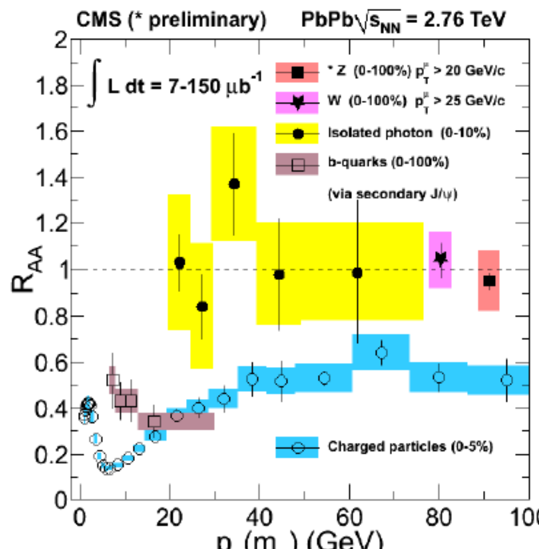
ATLAS



ALICE

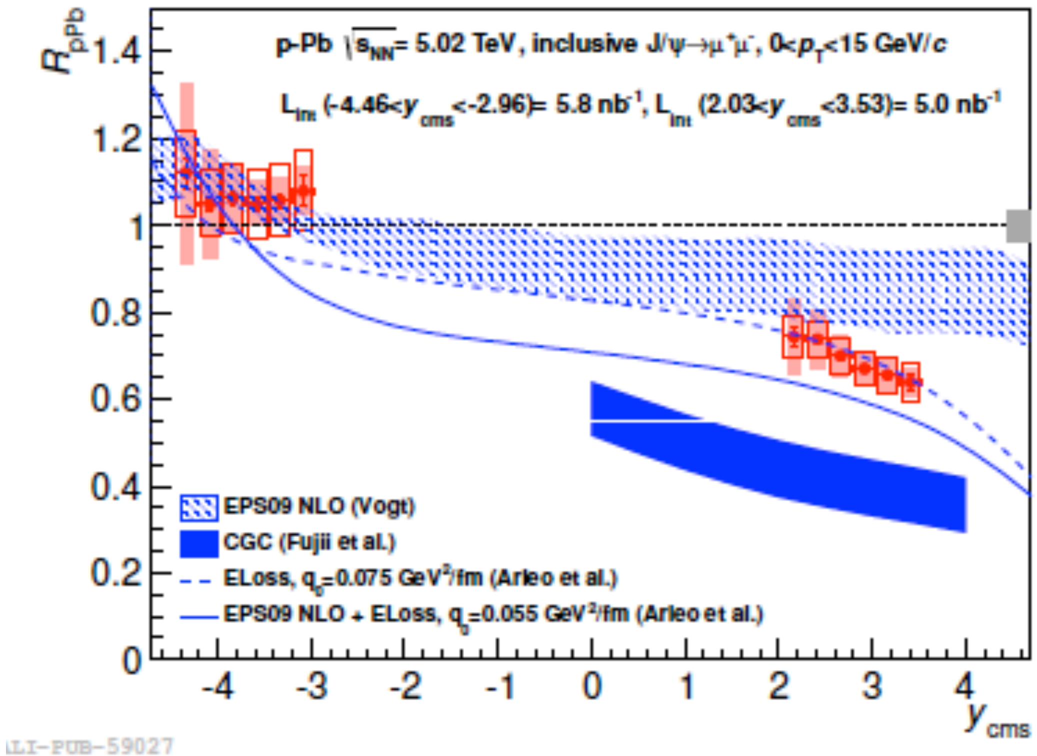


- Charged hadron R_{pPb}
- Enhancement or unity at high p_T?
- (direct photon: unity at LHC in PbPb)



J/ψ Production in pA at LHC

$J/\psi \rightarrow \mu^+ + \mu^-$

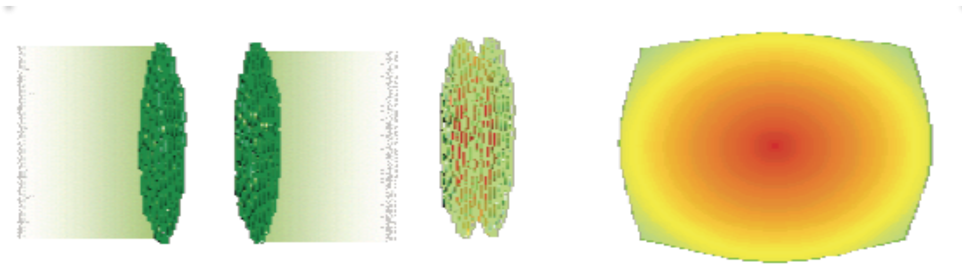


ALICE, 10.1007/JHEP02(2014)073, arXiv:1308.6726

- **Hadron suppression on forward (proton-going) side at low p_T.**
- J/ψ yield: not described by nPDFs nor by a CGC calculation
- Uncertainties on:
  - Production mechanism (x sensitivity etc.)
  - Other nuclear modifications (e.g. energy loss, thermalization in pA?)

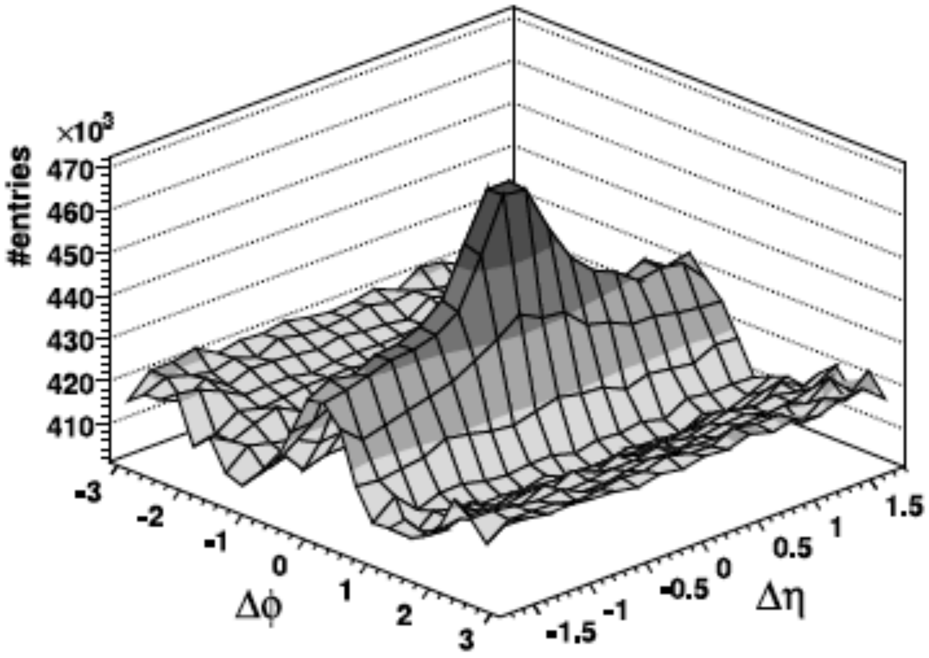
Difficult to obtain conclusive data by hadrons only.

Towards understanding from initial state to QGP evolution

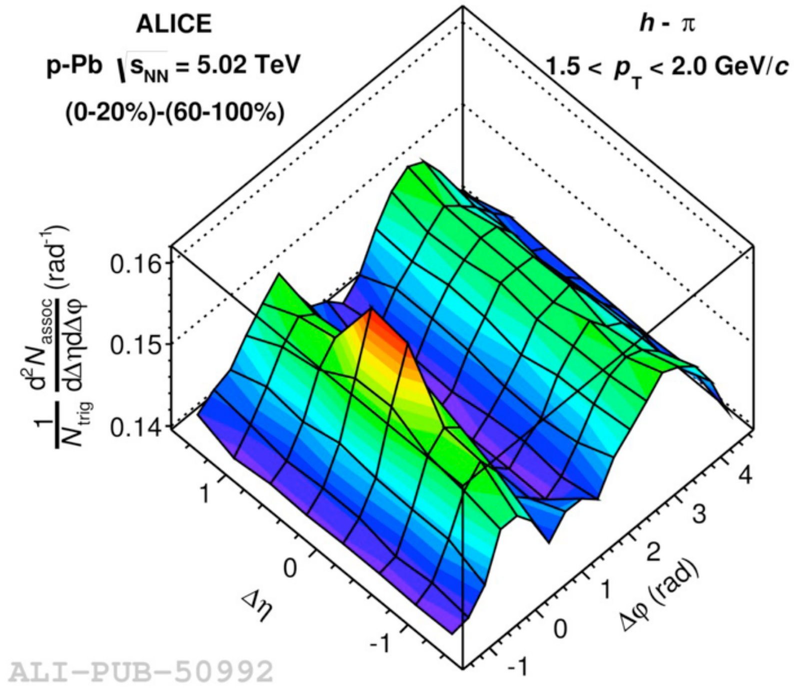


Medium properties in AA ("Ridge")

RHIC (STAR, Au+Au 200 GeV)

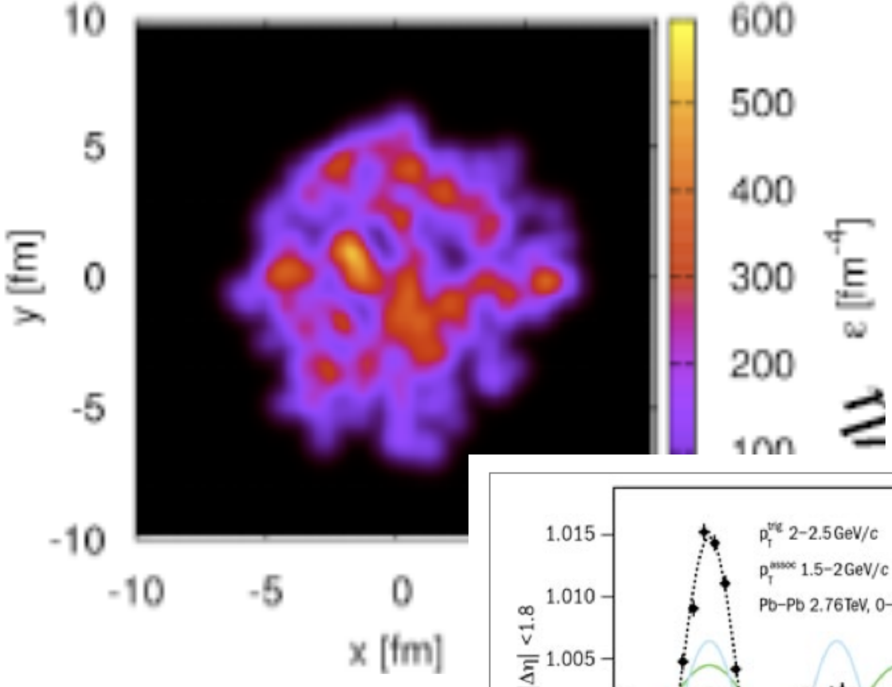


LHC (ALICE, pPb, 5.02 TeV)

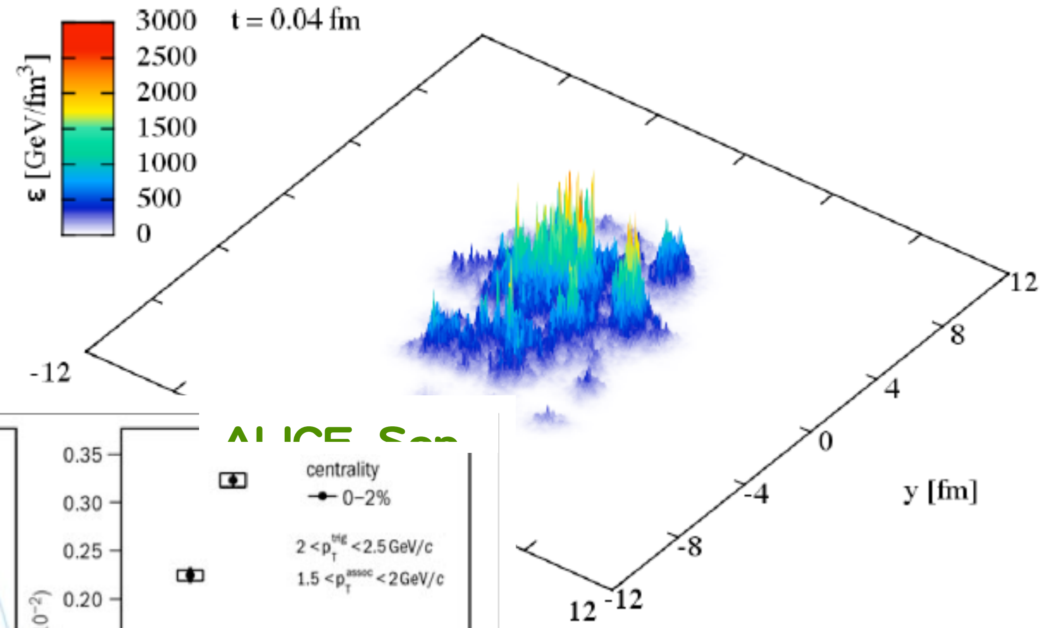


- long range Δη correlations (ridge) at RHIC and LHC.
- Originated from CGC ?

Initial conditions of Heavy Ion Collisions



IP-Glasma: Color charges and gluon fields fluctuation



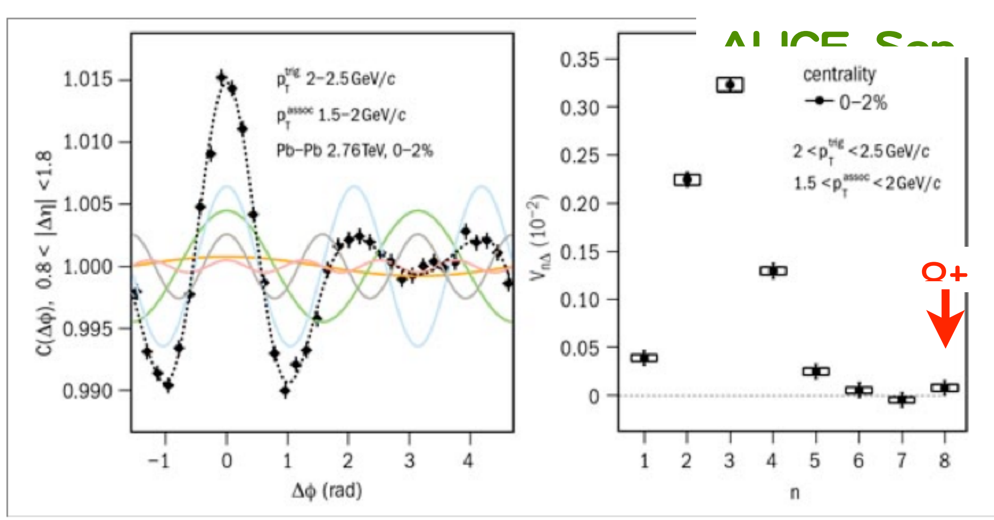
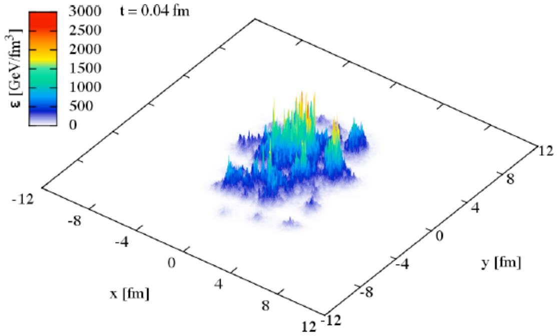


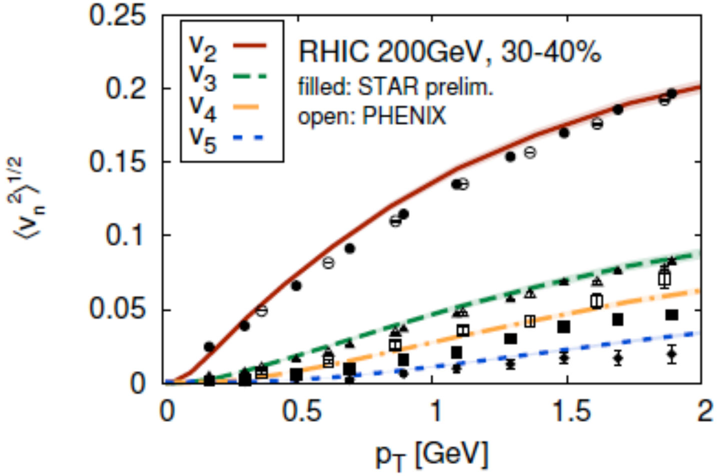
Fig. 1. Left: correlation function for charged hadron pairs from head-on Pb–Pb collisions. Right: corresponding spectrum of Fourier harmonic amplitudes vs n.

Understanding of initial condition:
→key to understand the QGP properties (e.g. η/s), early thermalization.

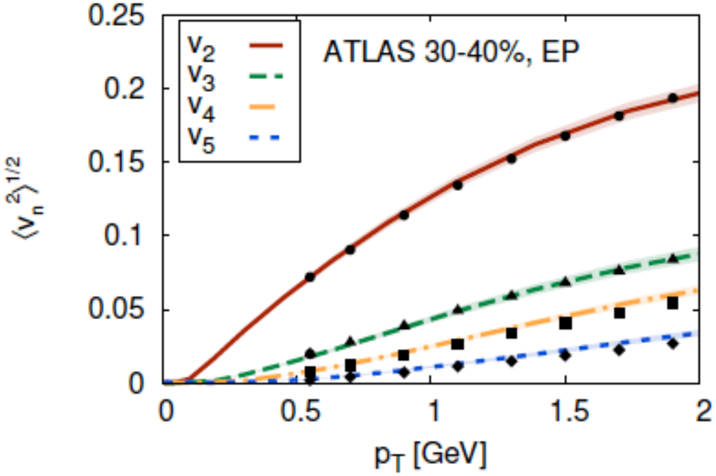


Minimum η/s at RHIC?

RHIC $\eta/s = 0.12$



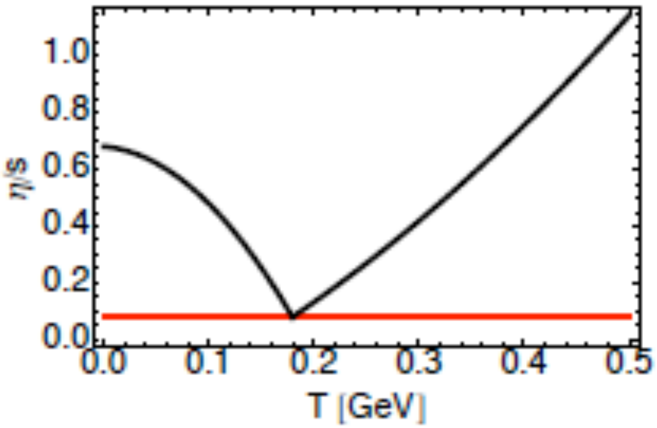
LHC $\eta/s = 0.2$



- IP-Glasma Model (color charge fluctuation)
- Higher harmonics ➔ η/s constraints

Minimum η/s at RHIC？

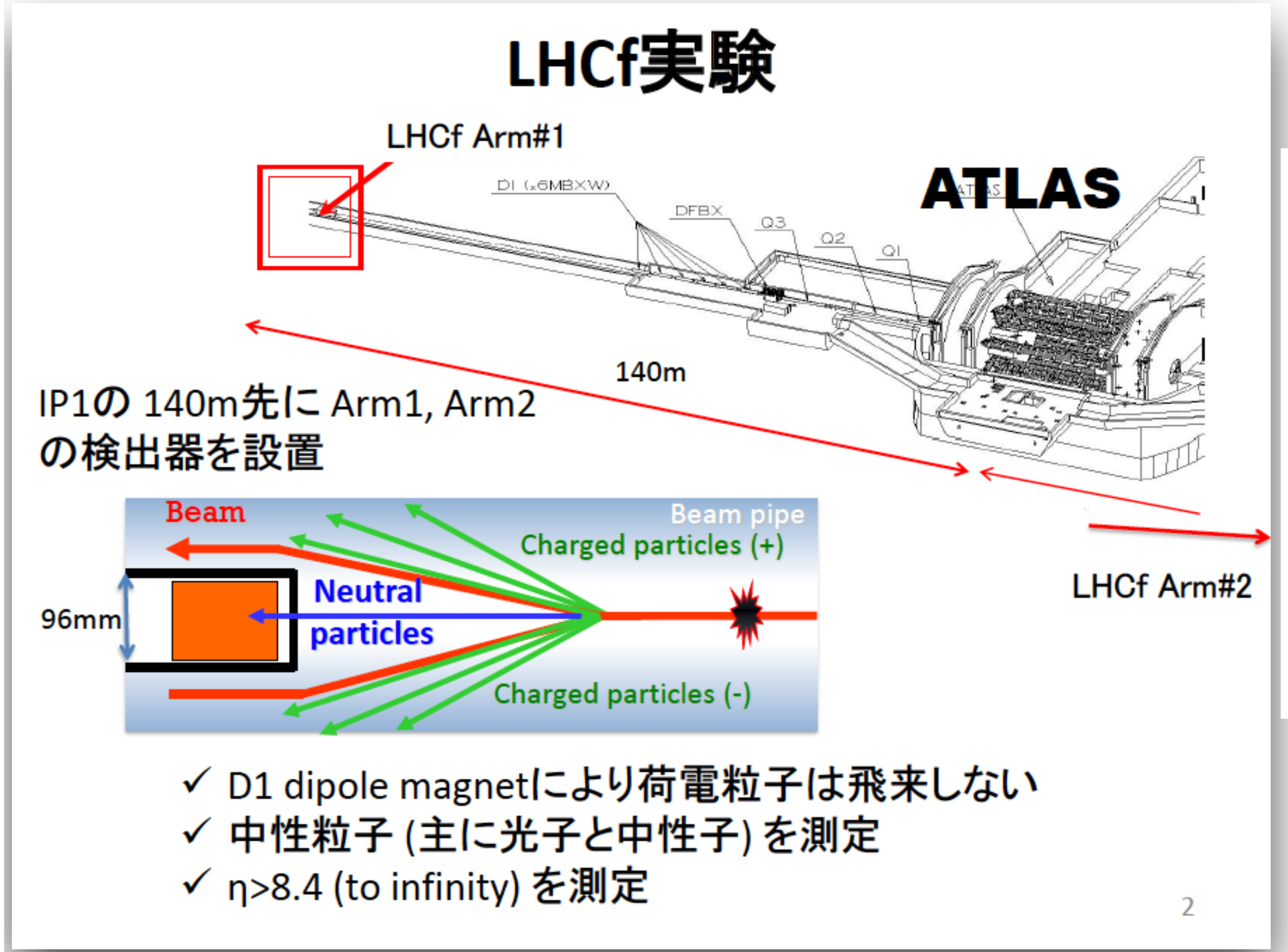
- Temperature dep?



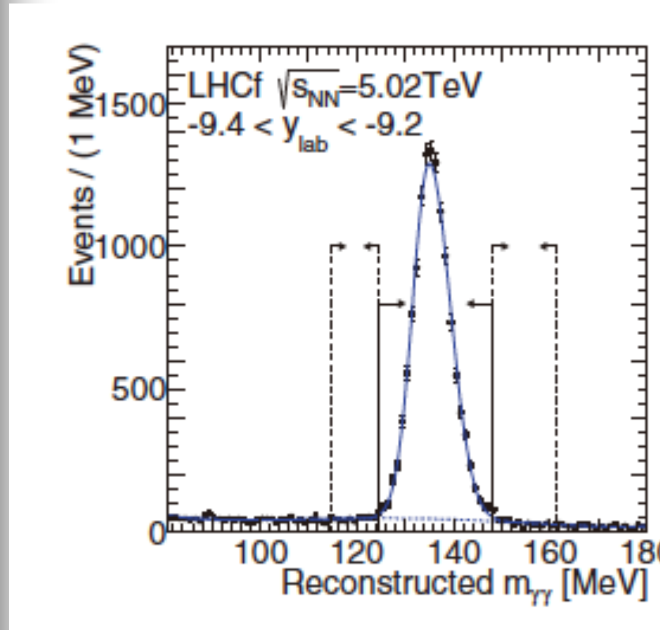
Björn Schenke (BNL) RHIC AGS Users' Meeting 2013, BNL

C. Gale, S. Jeon, B.Schenke, P.Tribedy, R.Venugopalan, PRL110, 012302 (2013)

LHCf Experiment



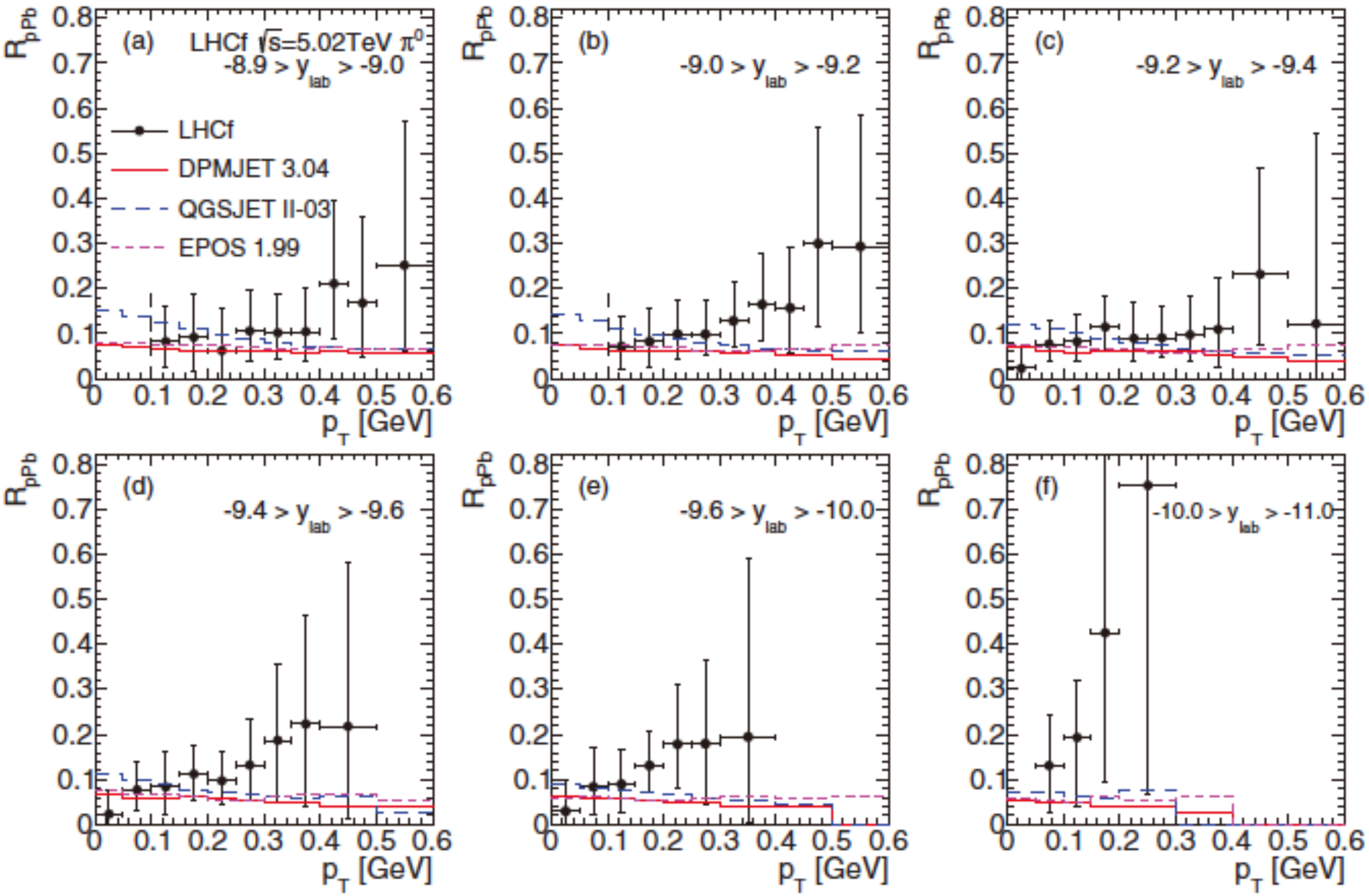
PHYSICAL REVIEW C 89, 065209 (2014) (LHCf)



by T. Sako

LHCf π^0 (R_{pPb} @ very forward and low p_T)

PRC 89, 065209 (2014) (LHCf)



- Strong suppression at very low p_T, at very forward region.
- CGC effect?
- (I think) difficult to interpret, due to “too” soft hadron.

4. Future Experiments

Isolated photons

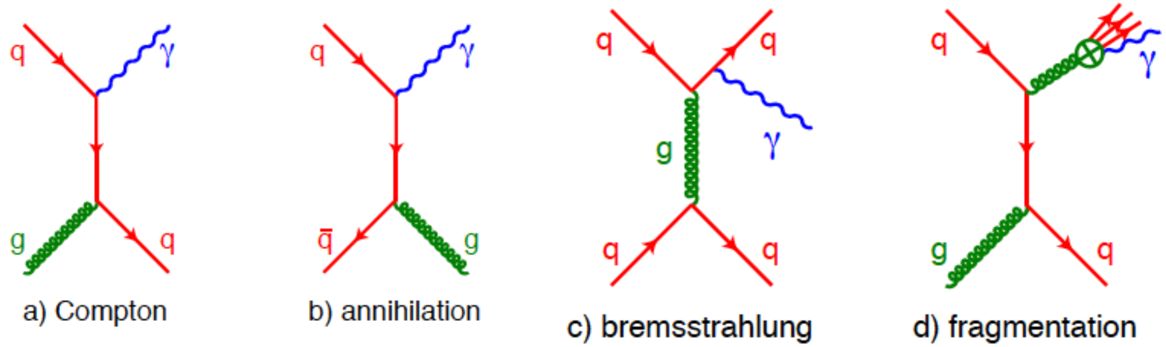
Isolated direct photons can provide strong constraints on the gluon PDFs

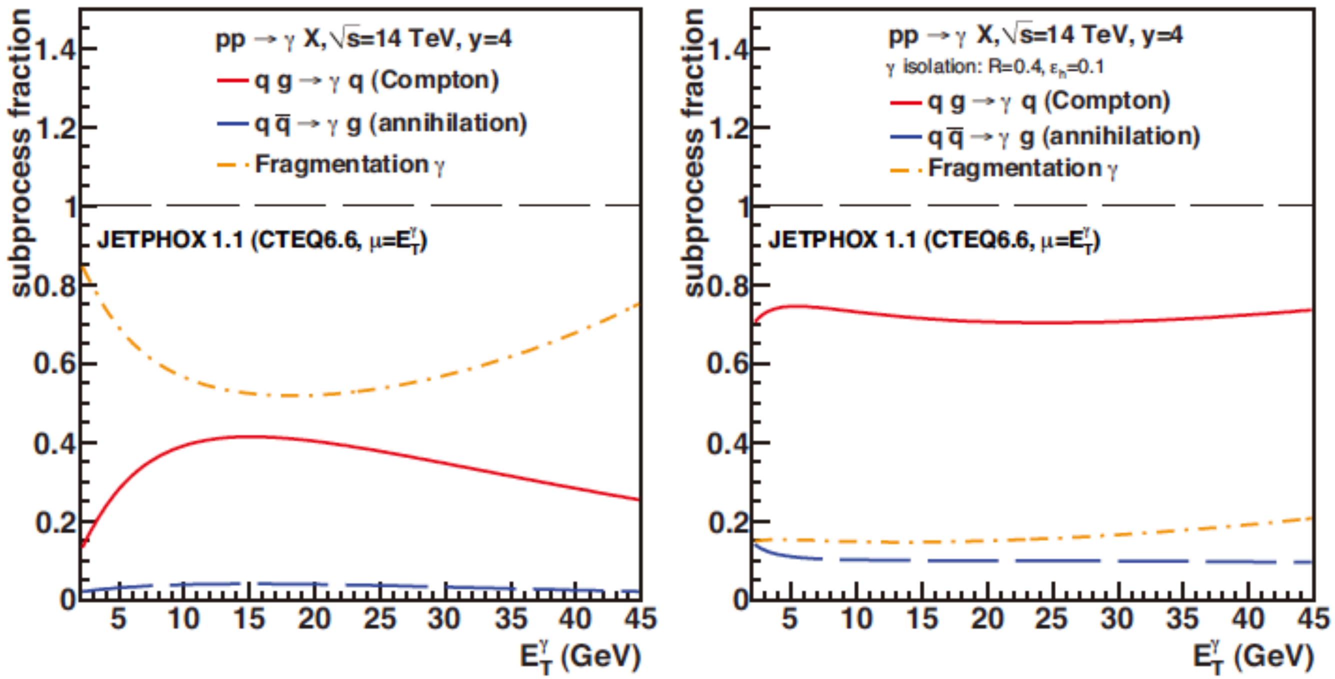
- LO dominant process: quark-gluon Compton.
- Quark-anti-quark annihilation contributing mostly at large x.

- NLO: At LHC, the majority of prompt photons are produced in the fragmentation process

- Fragmentation photon can be largely suppressed by the isolation cut.

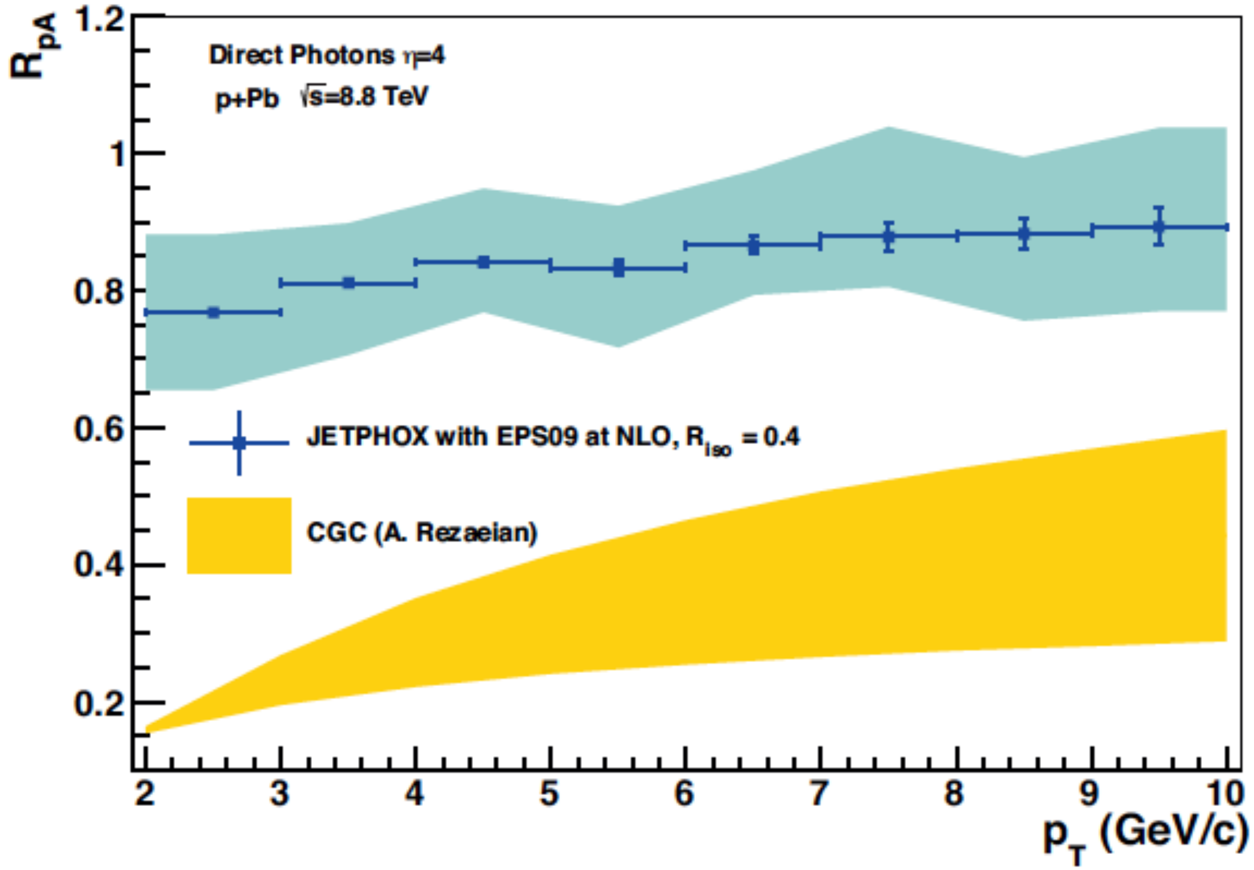
→quark-gluon Compton process dominant, more direct access to the gluon PDFs.





R. Ichou and D. d'Enterria, Phys. Rev. D 82, 014015 (2010)

nPDF/DGLAP vs. CGC (direct photon)



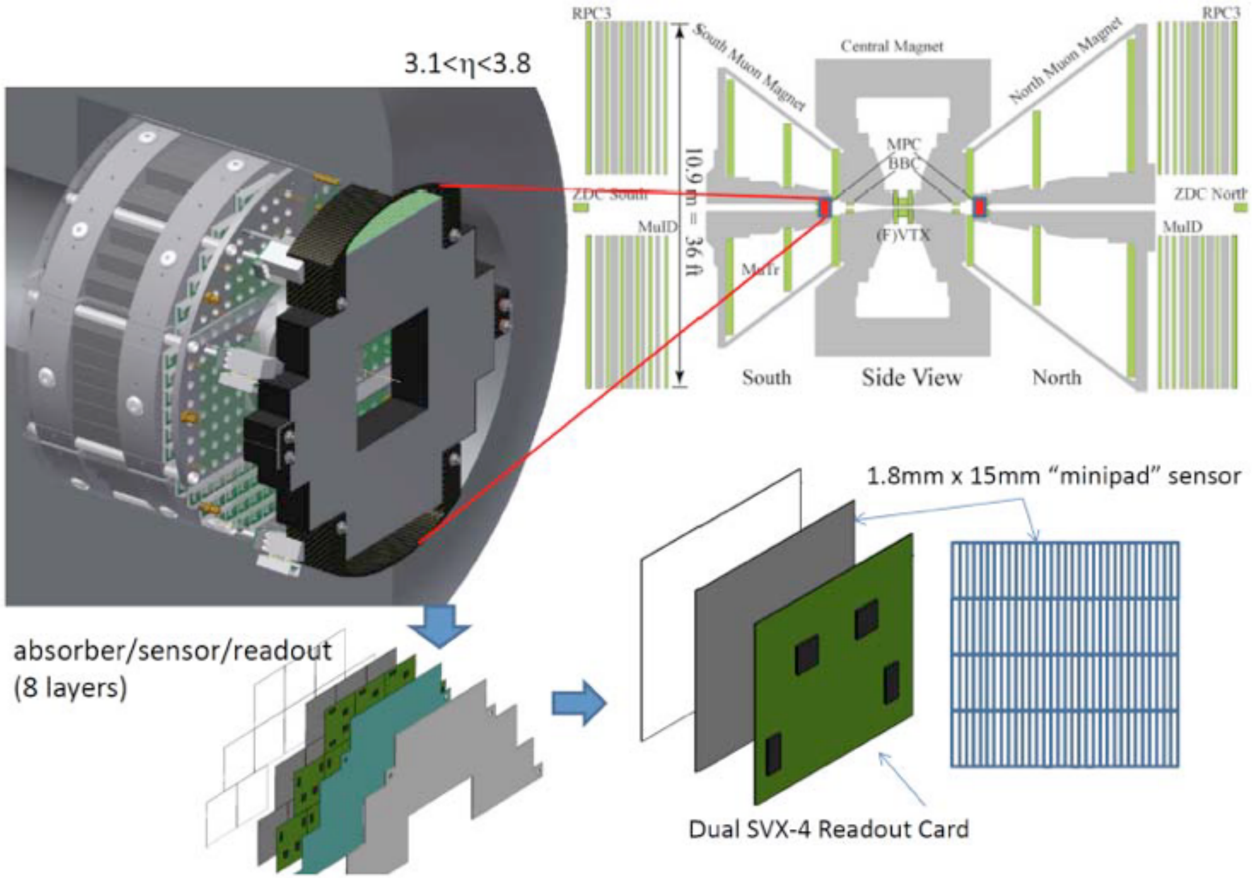
Two scenarios for forward γ production in p+A at LHC:

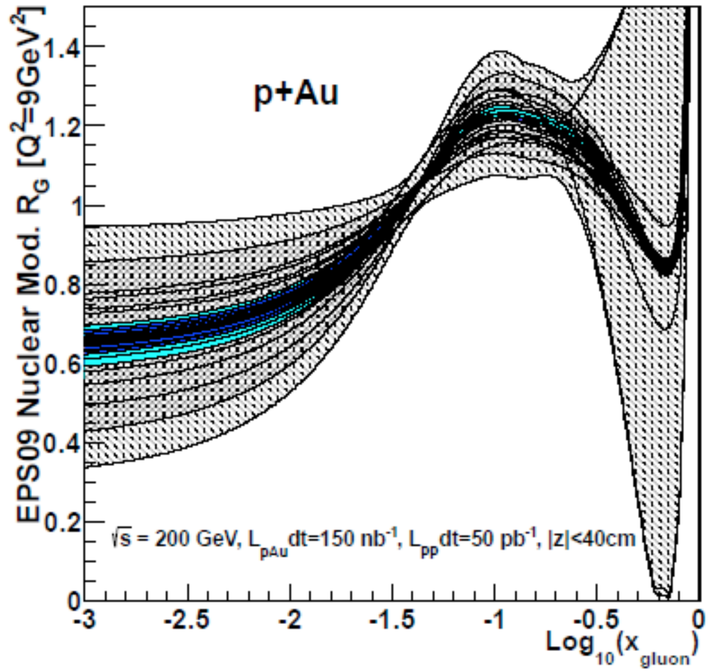
– Normal nuclear effects linear evolution, shadowing

– Saturation/CGC running coupling BK evolution

- Strong suppression in direct γ R_{pA}.
- Signals expected at forward η, low-intermediate p_T.

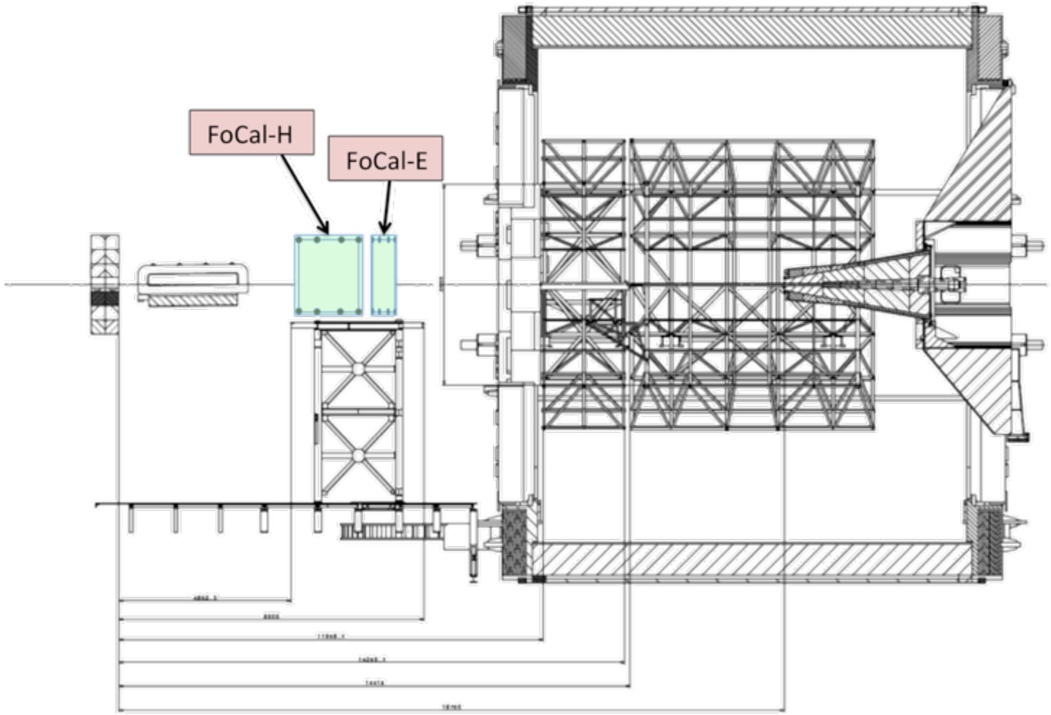
Forward Photon detector (MPC-EX) in PHENIX





- Si tracking detector + pre shower: direct gamma + high mom. π^0.
- $3.1 < \eta < 3.8$
- Start data taking in 2015 (p-Au).

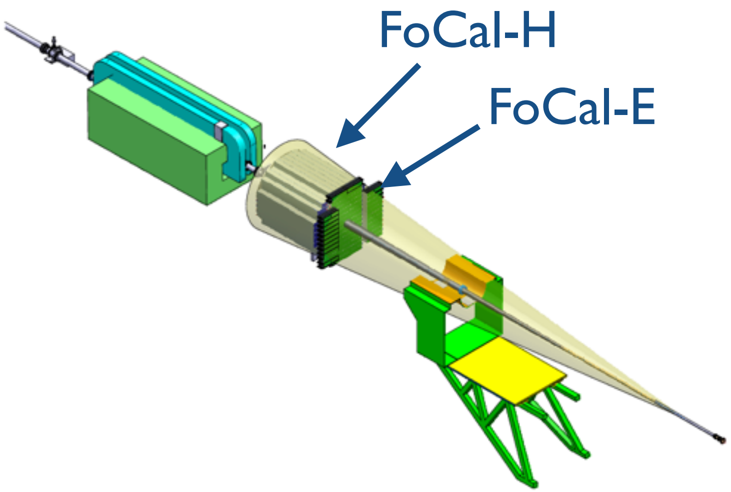
Forward Calorimeter (FoCal) in ALICE



•Electromagnetic calorimeter for γ and π^0 measurements, with Hadron Calorimeter.

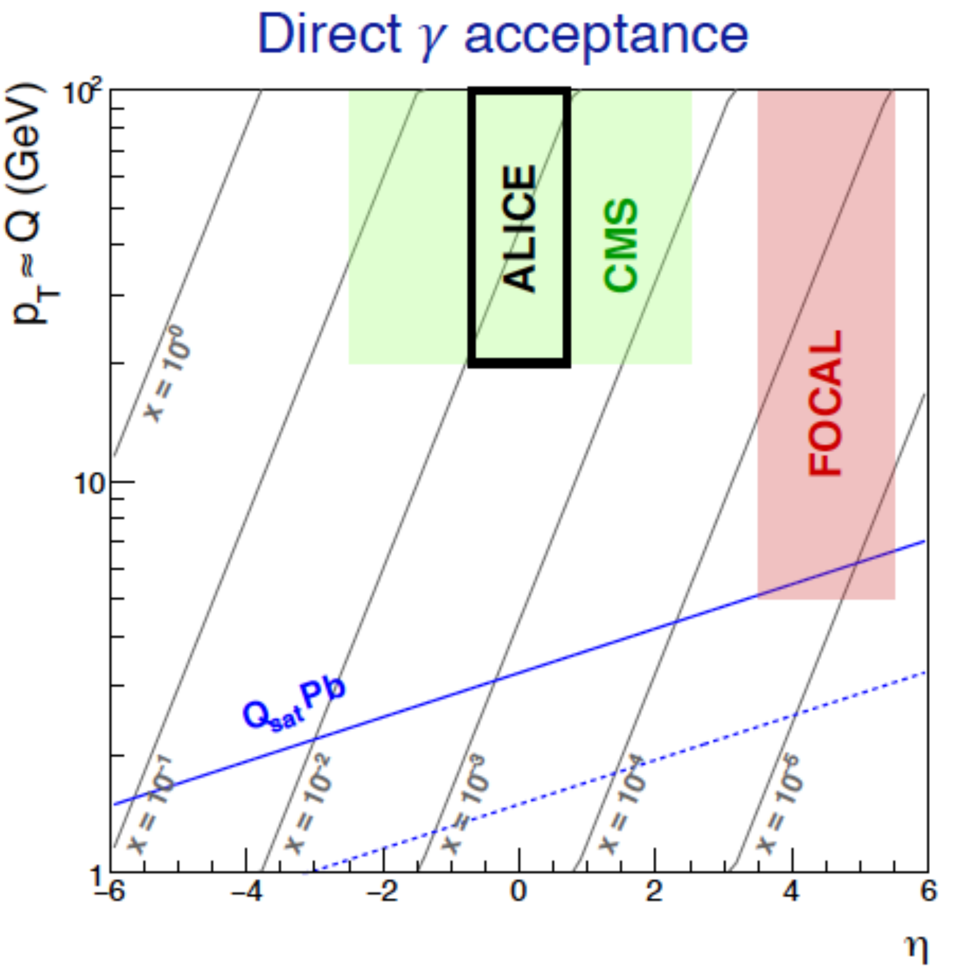
• At z ≈ 7m (outside magnet) $3.3 < \eta < 5.3$

- **Proposed schedule:**
  - mini-FoCal: 2018- (after LS2)
  - full FoCal: 2023- (after LS3)



Main challenge: **separate γ/π^0** at high energy
• Need small Molière radius, high-granularity read-out
• Si-W calorimeter, granularity ≈ 1mm^2

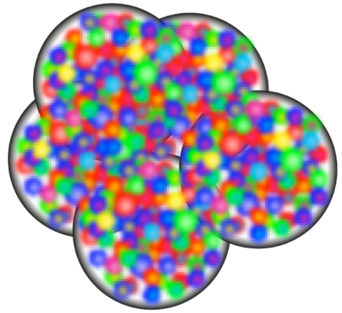
Uniqueness of FoCal at LHC



- FoCal can access:
  - $3.3 < \eta < 5.1$
  - few to 100 GeV (low to high Q^2)
  - Direct photon & π^0

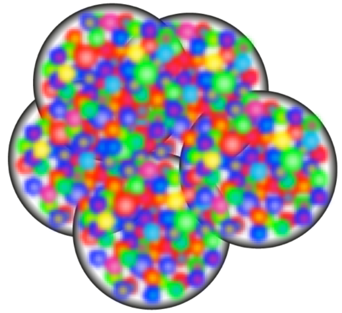
	ATLAS Inner Wheel	CMS EndCap	LHCb ECAL	ALICE FoCal@3.5m	ALICE FoCal@8m
η range	2.5 - 3.2	1.5 - 3.0	1.8 - 4.3	2.5 - 4.5	3.3 - 5.1
granularity [deg]	5.7	0.5	≥ 0.18	≈ 0.016	≈ 0.007

質問群 (1)



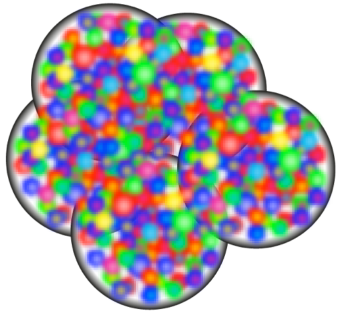
- カラーグラス凝縮とは何か？
- LHC における CGC の役割は? その他の初期条件は排除できるのか
- pA衝突におけるカラーグラス凝縮、 早期熱平衡化に関する話題
- CGCについて教えてほしいです
- 衝突前(CGC)と衝突初期過程 流体化のダイナミクスの現状 ミクロな記述からマクロな記述へ乗り移る際の粗視化の考え方, グルーオンのボーズ－アインシュタイン凝縮と有効化学ポテンシャルによる記述 との違い
- pA衝突, cold nuclear matter effectについて

質問群 (2)



- CGCによって、現状、初期の物理をどの程度記述することに成功/失敗しているのか
- 初期条件から熱化に至る動的過程をどう実験的に理解できるか？理論の不定性は？それが物性に与える影響はどうなのか？巷にある流体の初期条件と正しくリンクされているのか？
- CGCや原子核効果はどこまで理解されているのか？

Summary



- Overview of experimental data at RHIC and LHC, regarding the CGC.
- The data from RHIC and LHC at both mid-rapidity and forward rapidity are “qualitatively” consistent with CGC picture.
- But they are **not conclusive**, just because of the strong final state effect by using the hadronic observables.
- Future directions:
  - **From “qualitative agreement” to the conclusive evidence of CGC.**
  - Direct (isolated) photon at forward rapidity is one of the good “controlled” probes for CGC effect
  - Important step for understating of initial condition, QGP properties, and early thermalization.