Proton-nucleus collisions (mostly) at the LHC

Carlos A. Salgado
Universidade de Santiago de Compostela

ALICE week Junior's Day

Proton-nucleus collisions at the LHC: scientific opportunities and requirements arXiv:1105.3919

carlos.salgado@usc.es http://cern.ch/csalgado

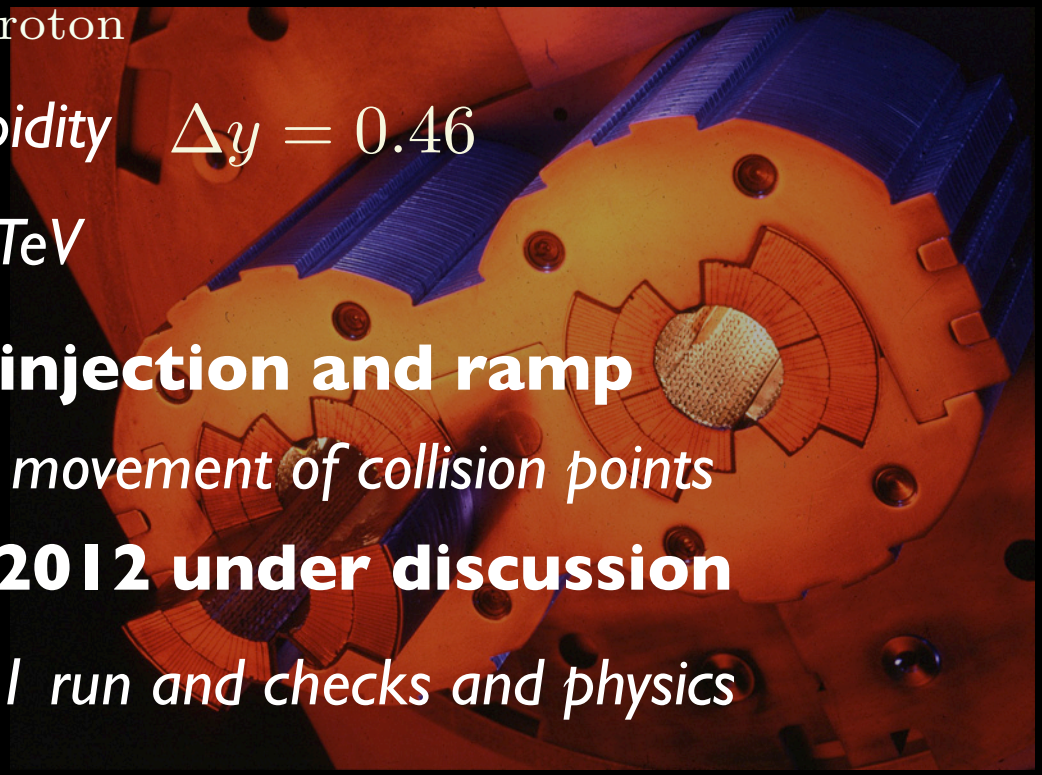
Proton-nucleus at the LHC

Feasibility checks going on now - estimate luminosity

L=10^{29} cm^{-2} s^{-1} (full energy) *[Integrated in 10^{6} s : **L= 100 nb^{-1}**]*

LHC two-in-one magnet

- *Equal rigidity :: $p_{\mathrm{Pb}} = Z\, p_{\mathrm{proton}}$*
- *Center of mass shifted in rapidity* $\Delta y = 0.46$
- *Top LHC energy for pPb: 8.8 TeV*



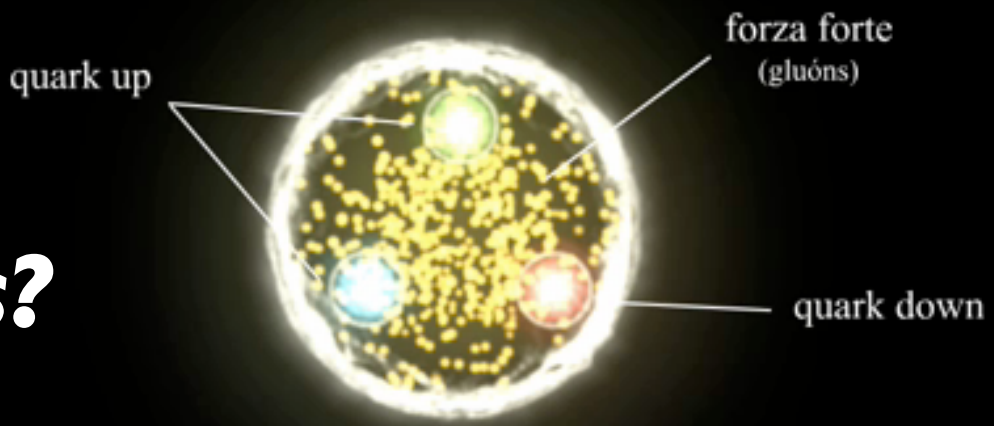
Unequal revolution freq. at injection and ramp

- *RF locked in physics to avoid movement of collision points*

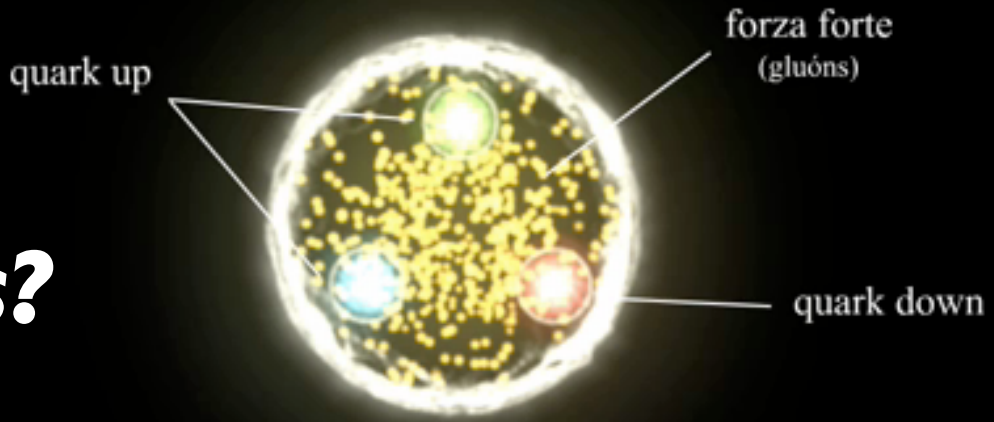
Proposal of first pPb run in 2012 under discussion

- *Decision will depend on 2011 run and checks and physics*

Why proton-nucleus?



To study the structure of a large object make collisions with smaller objects (Rutherford experiment...)



Why proton-nucleus?

Hadrons / nuclei are composed objects

- *Large, in QCD scales: non-perturbative. Experimental data needed*
- *Quantum fluctuations (sea quarks and gluons) given by pQCD*

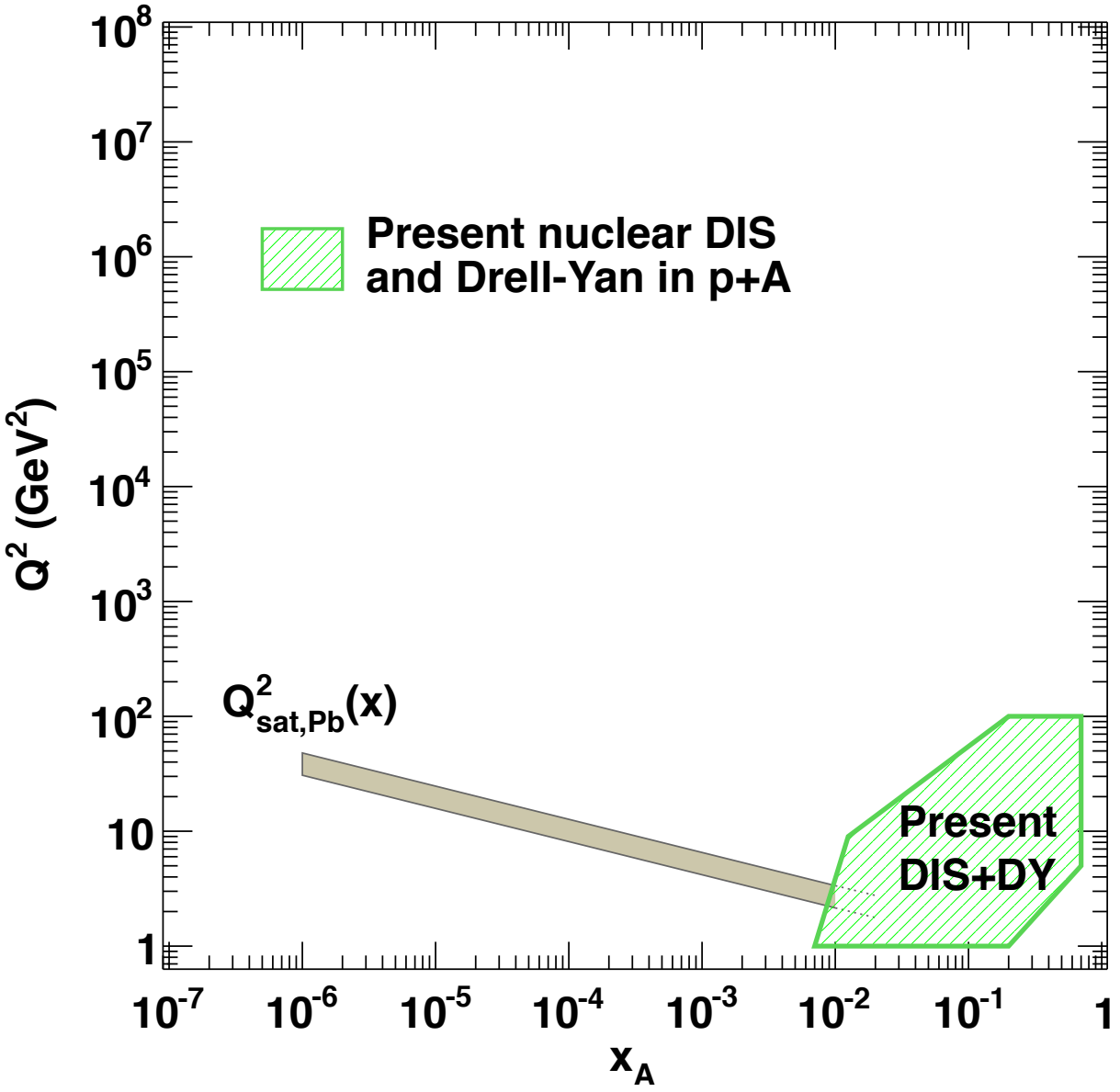
The proton structure is constrained by DIS + other data

- *HERA data of utmost importance*

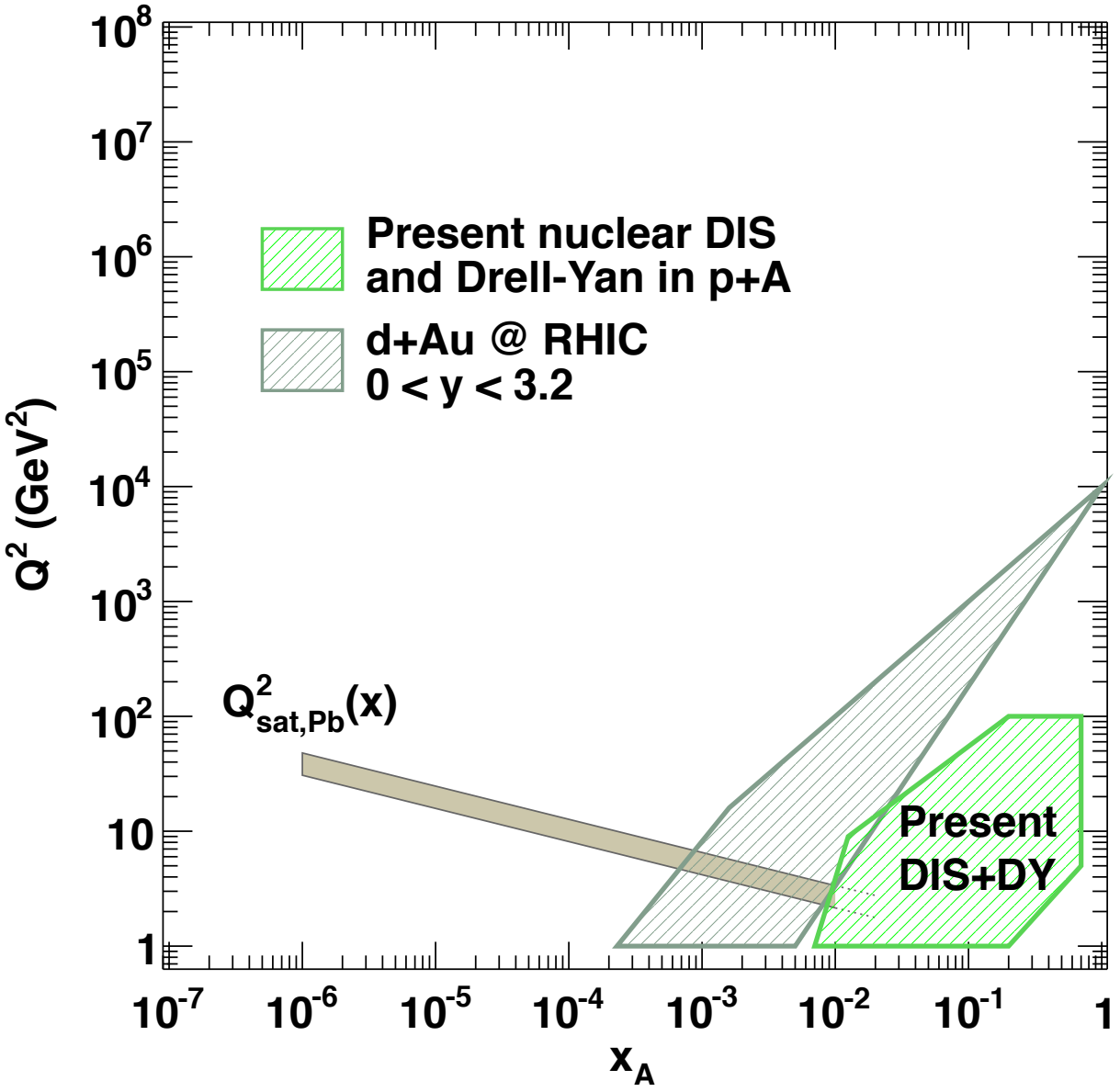
Need pA to study the high-energy nuclear structure

- *DIS data is old (90's) and with limited range*
- *pA@LHC is the only experimental condition available before an eventual lepton-A collider (LHeC?)*

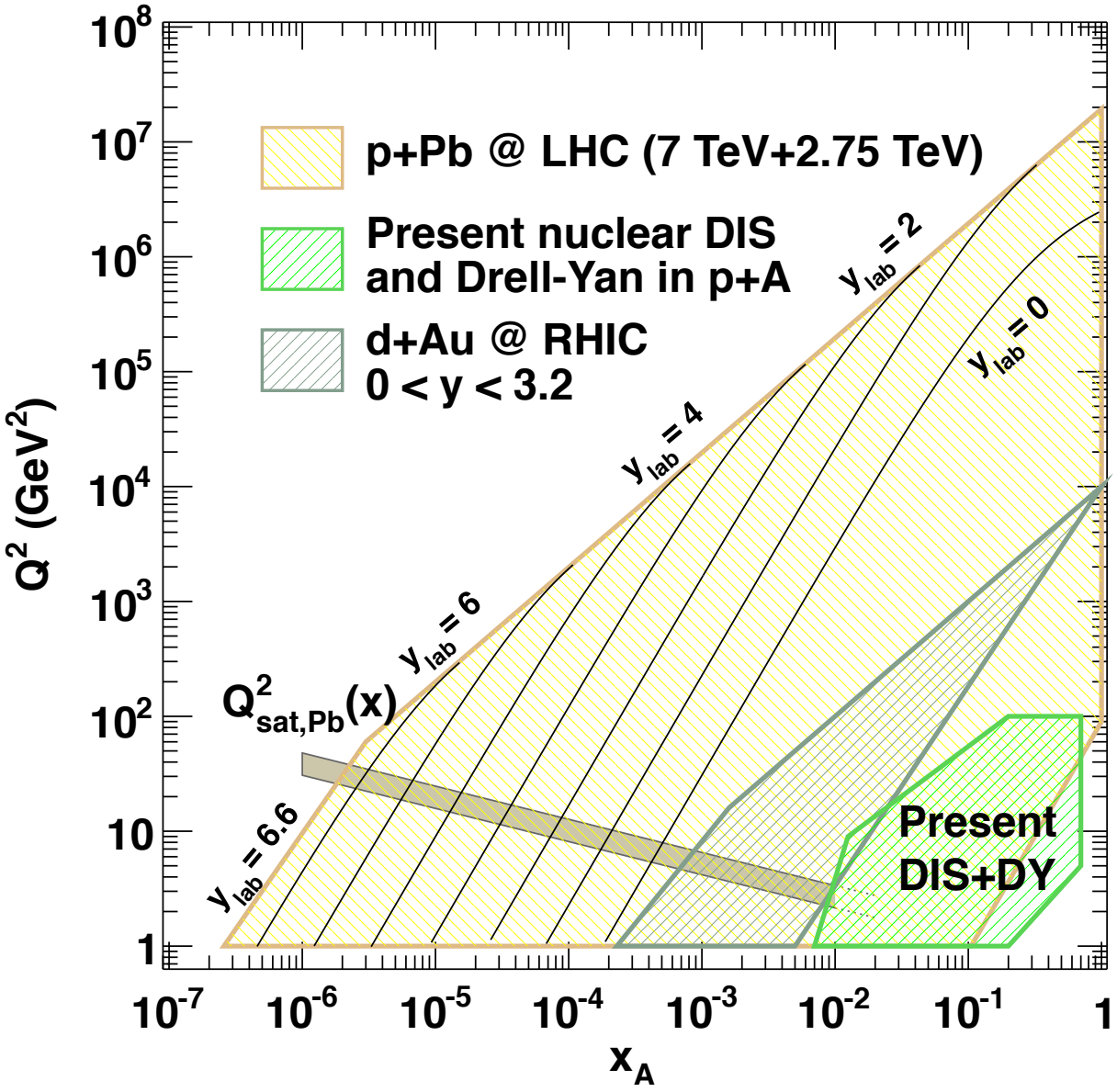
Kinematical reach in nuclear collisions



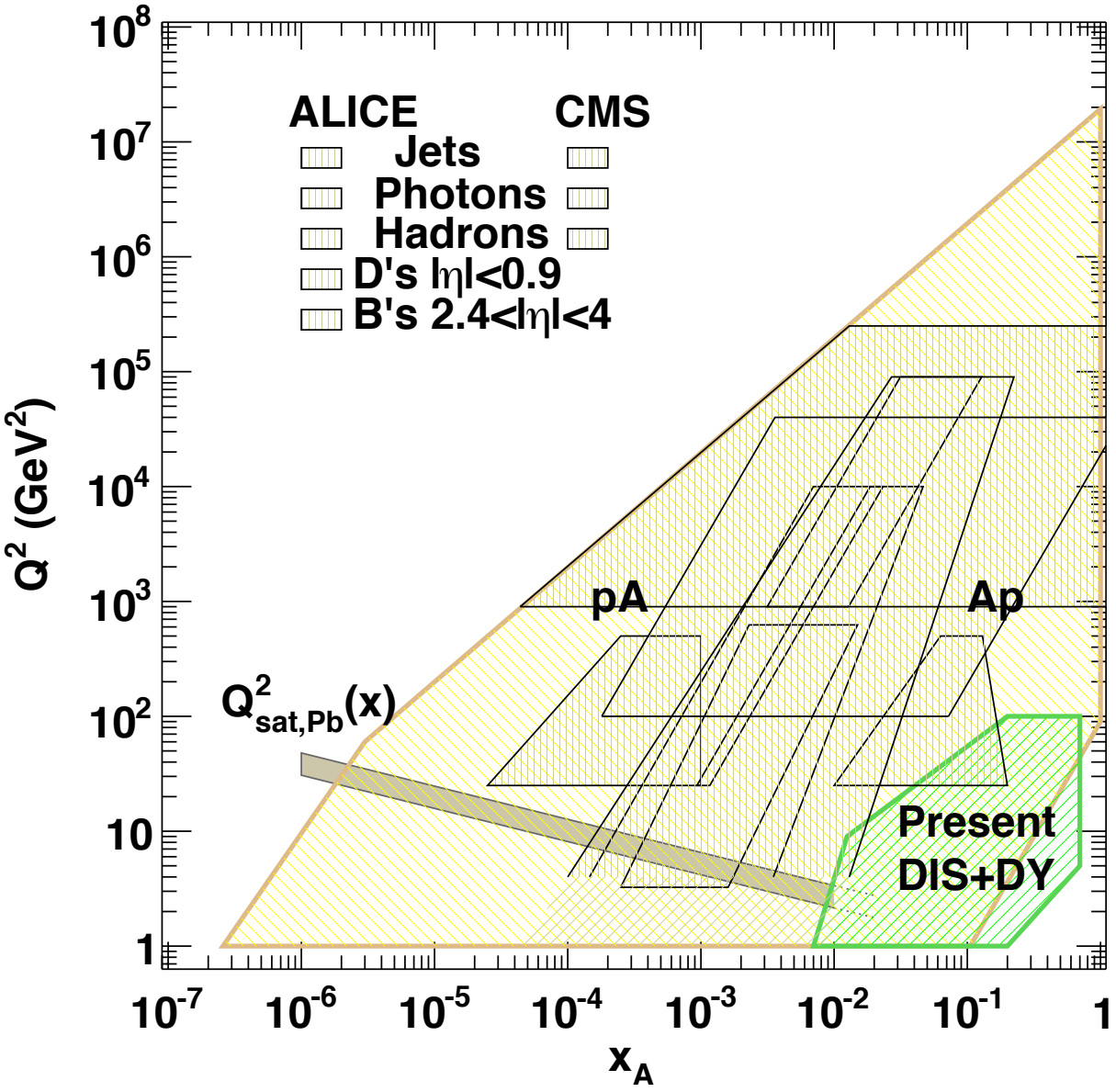
Kinematical reach in nuclear collisions



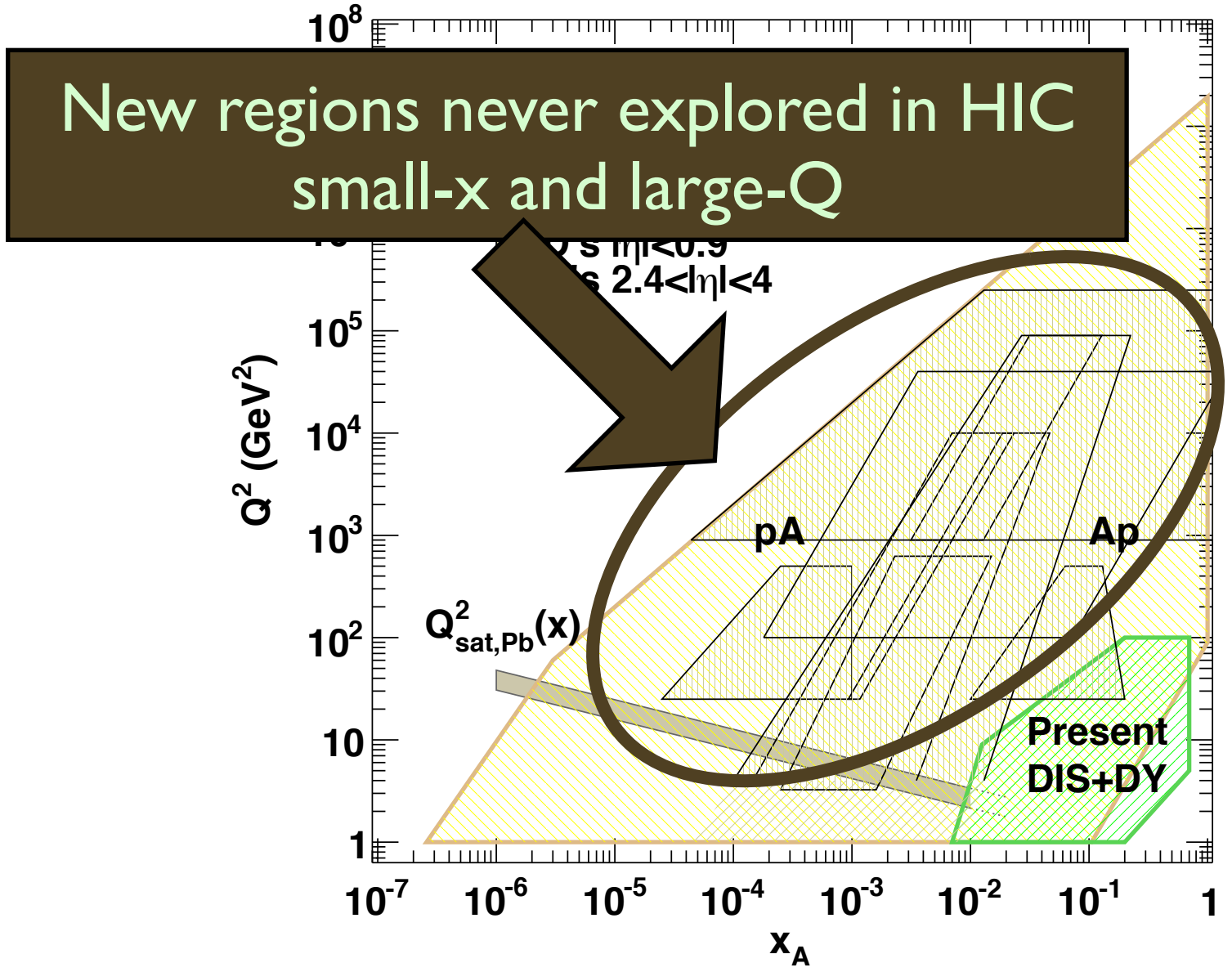
Kinematical reach in nuclear collisions



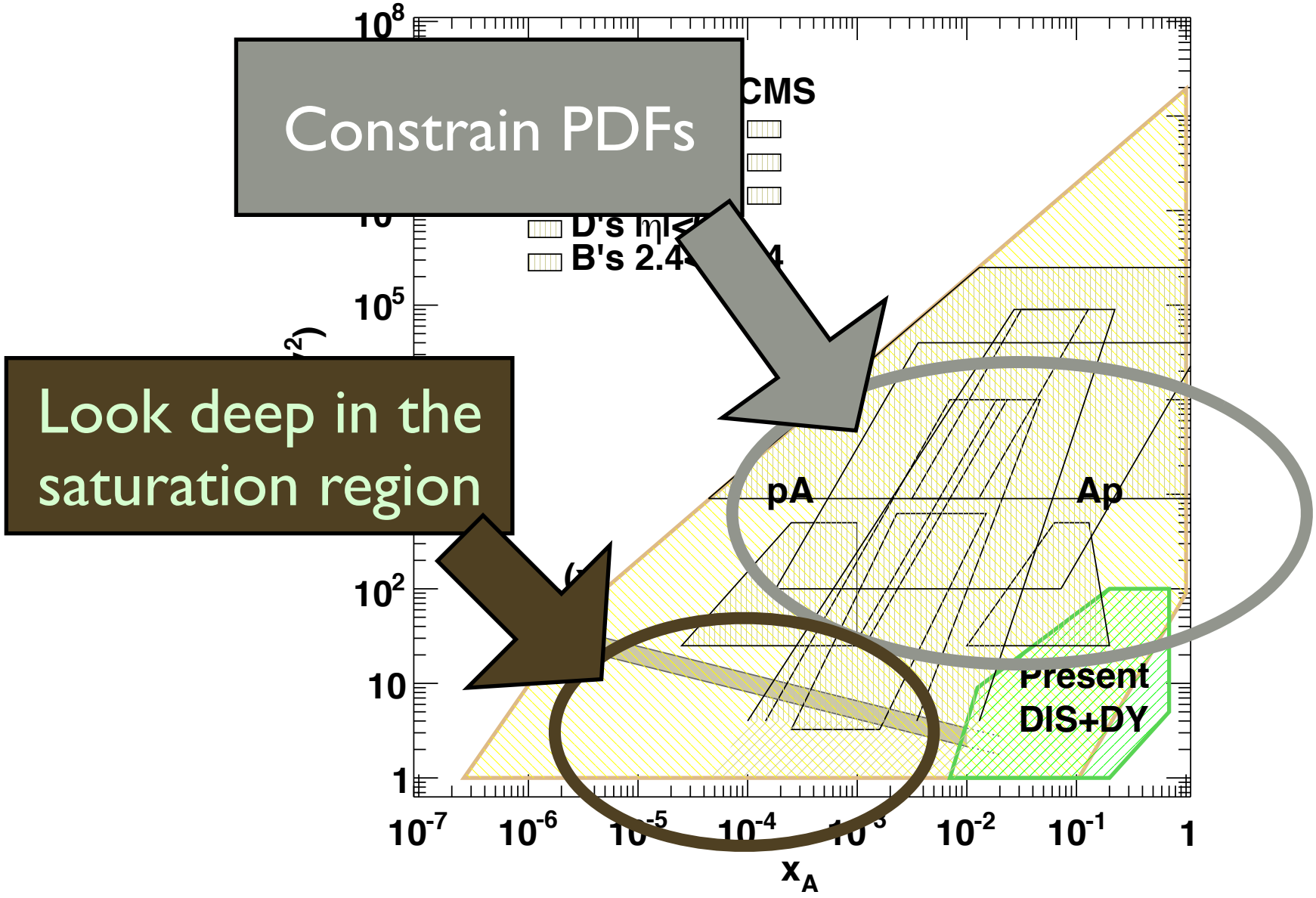
Kinematical reach in nuclear collisions



Kinematical reach in nuclear collisions

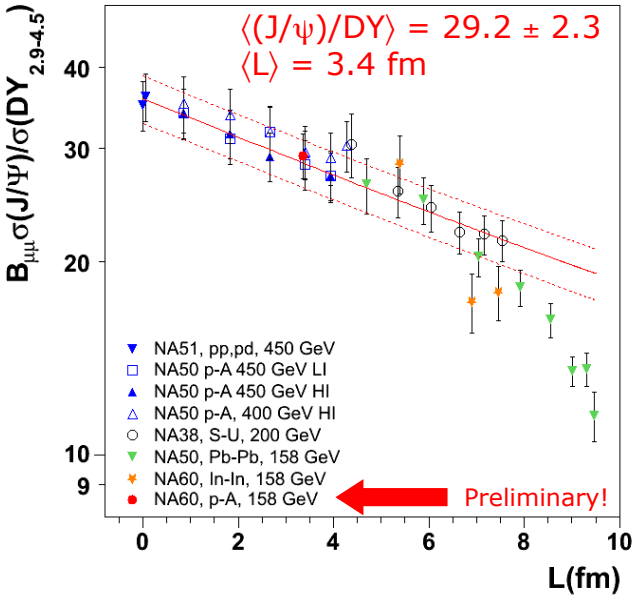


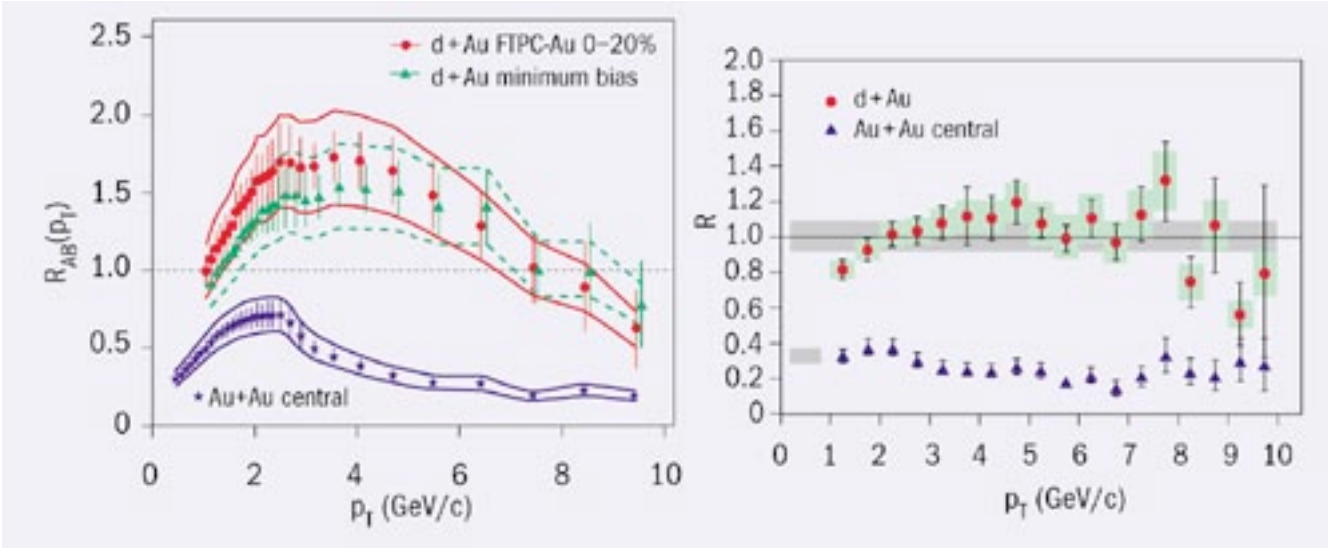
Kinematical reach in nuclear collisions



Dual role of pA/dA collisions

- **Benchmarking**: what are the cold nuclear matter effects?
  - **To understand nucleus-nucleus**





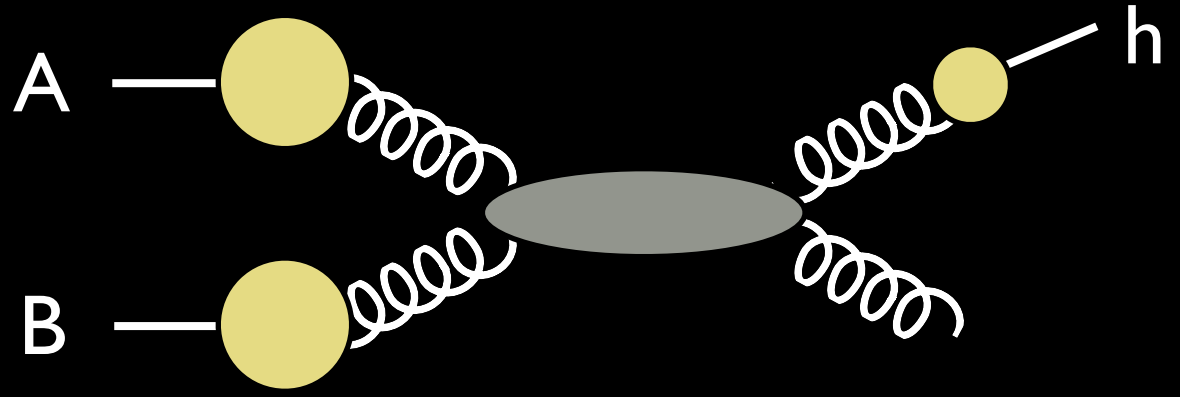
- **Small-x**: structure of the nucleus at asymptotically large energies
  - **To look for new regimes of QCD** - high parton density
  - Saturation of partonic densities by non-linear evolution eqs.
- and more... Ultraperipheral collisions, measurements for astropart...

Benchmarking

- ***Traditional role of pA (dAu) runs***
  - For **hard processes**, long-distance parts are modified

$$\sigma^{AB\to h} = \boxed{f_A^i(x_1,Q^2)\otimes f_B^j(x_2,Q^2)} \otimes \sigma(ij\to k) \otimes \boxed{D_{k\to h}(z,Q^2)}$$

Nuclear PDFs Hadronization

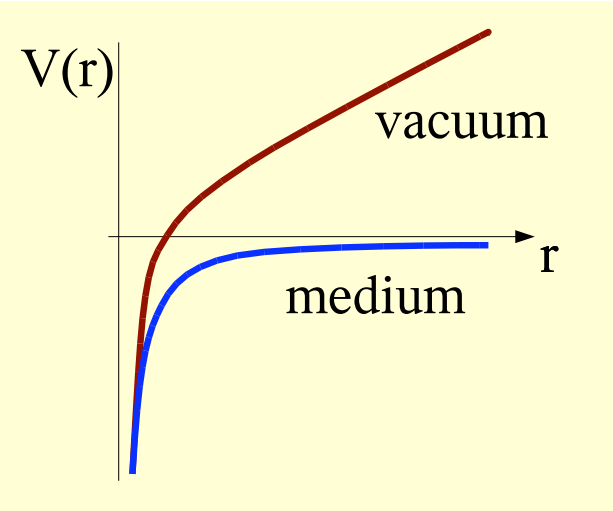


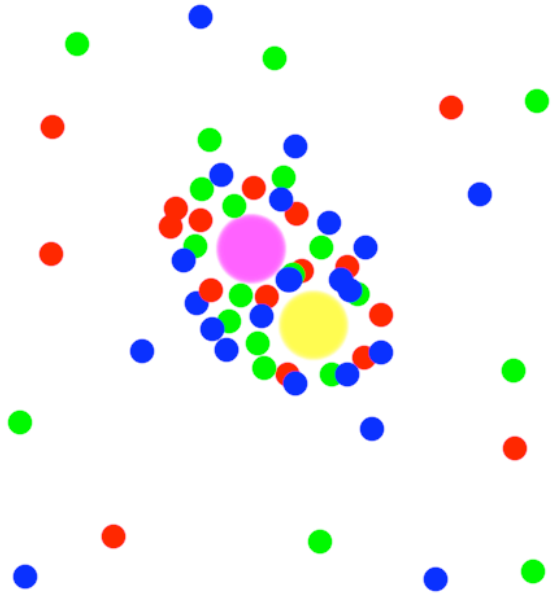
A 'simple' example, J/Ψ suppression

- A J/Ψ is a $c\bar{c}$ bound state.

$$\sigma^{hh\to J/\Psi} = f_i(x_1, Q^2) \otimes f_j(x_2, Q^2) \otimes \sigma^{ij\to[c\bar{c}]}(x_1, x_2, Q^2) \langle \mathcal{O}([c\bar{c}] \to J/\Psi) \rangle$$

- The potential is screened by the medium
  - The long-distance part is modified $\langle \mathcal{O}([c\bar{c}] \to J/\Psi) \rangle \to 0$
- The J/Ψ production is suppressed [Matsui, Satz 1986]



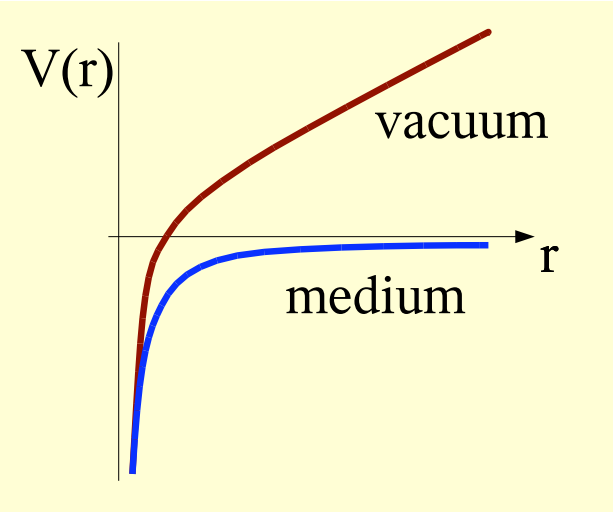


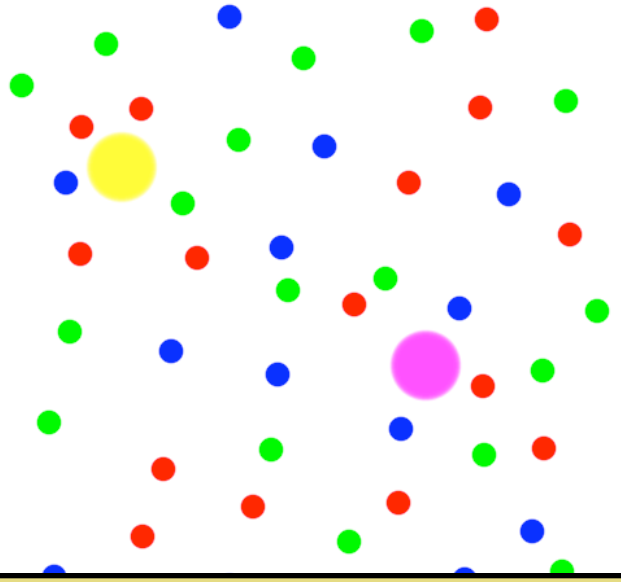
A 'simple' example, J/Ψ suppression

- A J/Ψ is a $c\bar{c}$ bound state.

$$\sigma^{hh\to J/\Psi} = f_i(x_1, Q^2) \otimes f_j(x_2, Q^2) \otimes \sigma^{ij\to[c\bar{c}]}(x_1, x_2, Q^2) \langle \mathcal{O}([c\bar{c}] \to J/\Psi) \rangle$$

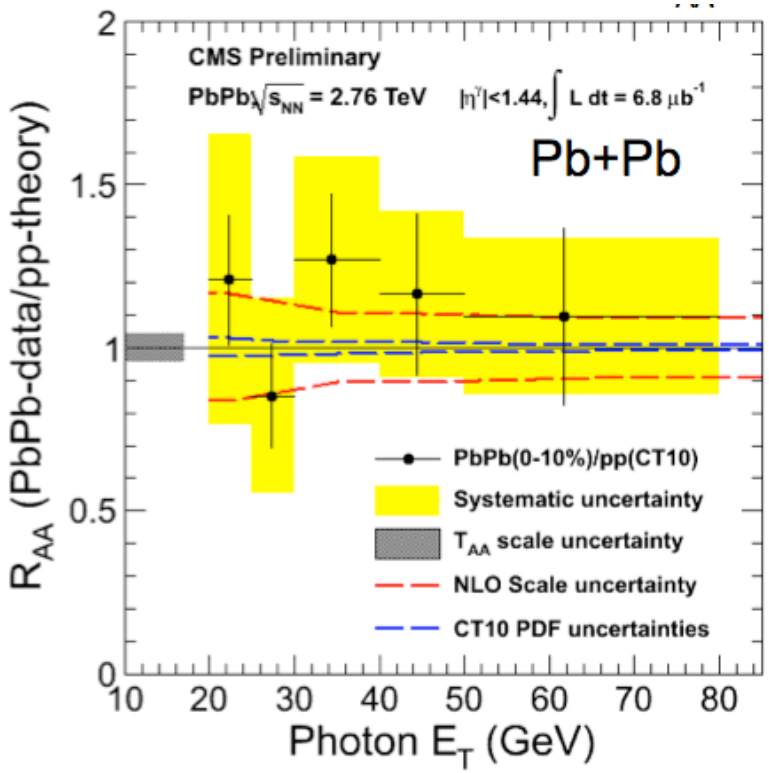
- The potential is screened by the medium
  - The long-distance part is modified $\langle \mathcal{O}([c\bar{c}] \to J/\Psi) \rangle \to 0$
- The J/Ψ production is suppressed [Matsui, Satz 1986]

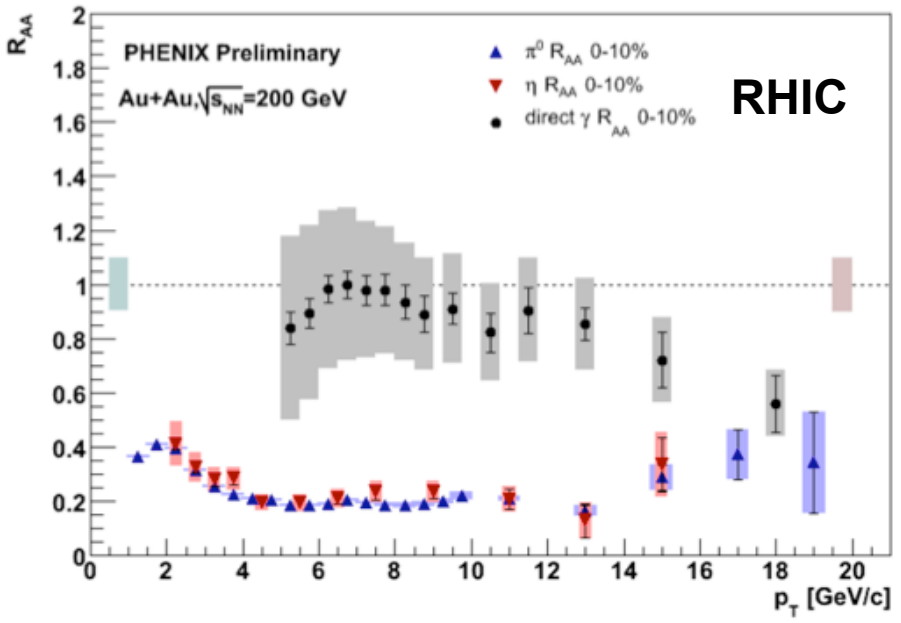




However, J/Psi suppressed also in proton-nucleus

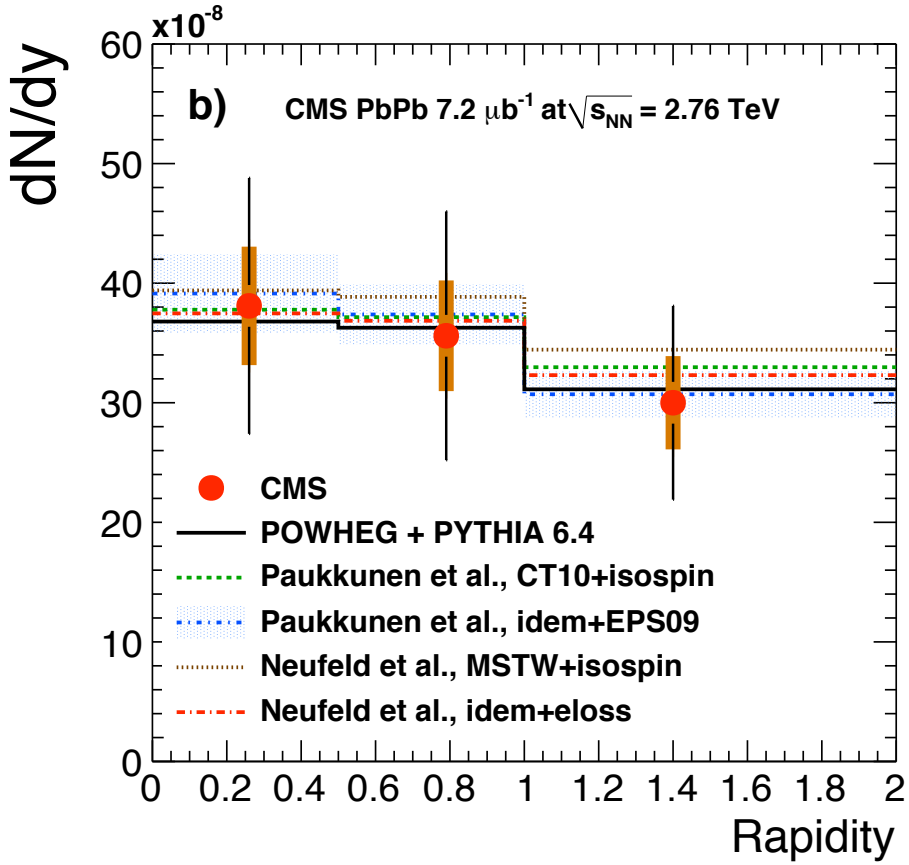
Status from the first LHC PbPb run: photons

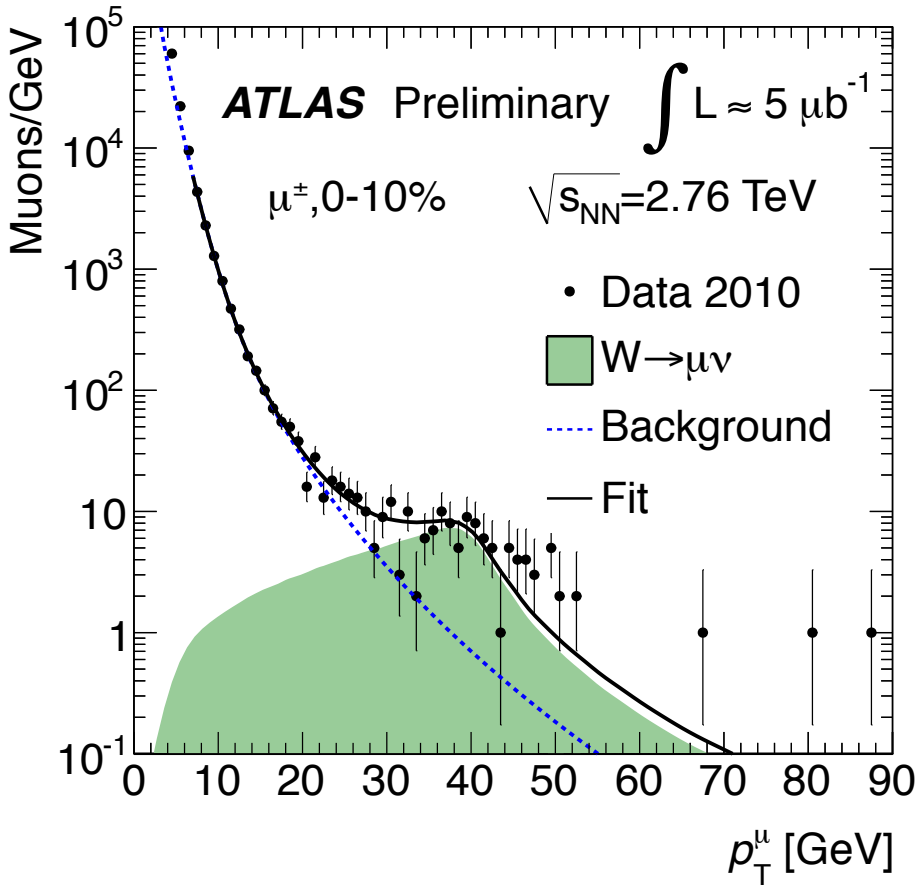




- Photons agree well with the Glauber model
  - No large effects seen
- Large errors still in data - this year's run will improve situation

Status from the first LHC PbPb run: EW bosons



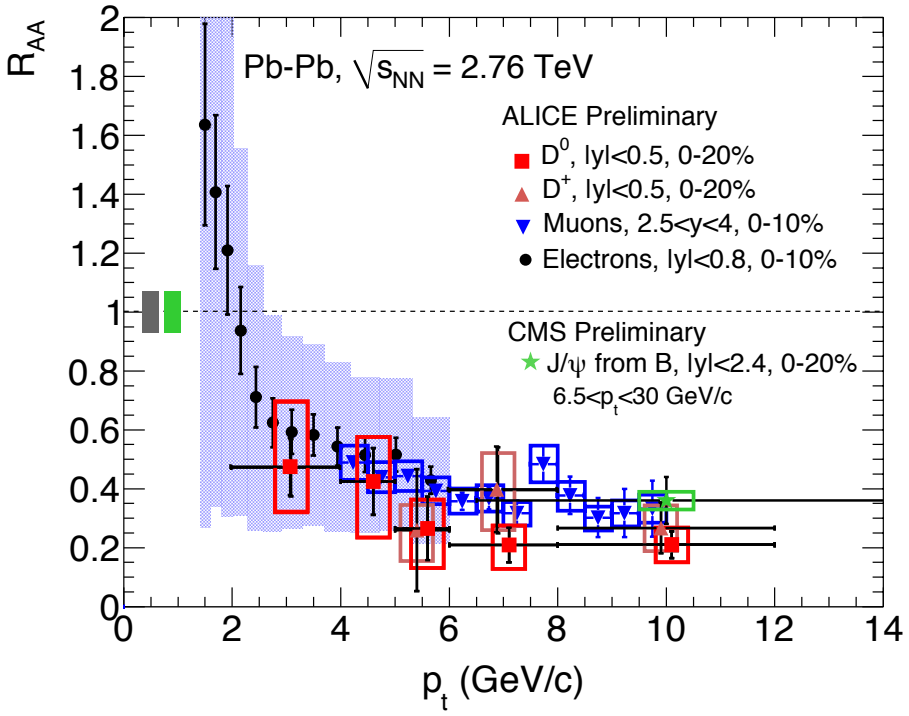


⇛ **First measurement ever in nuclear collisions**

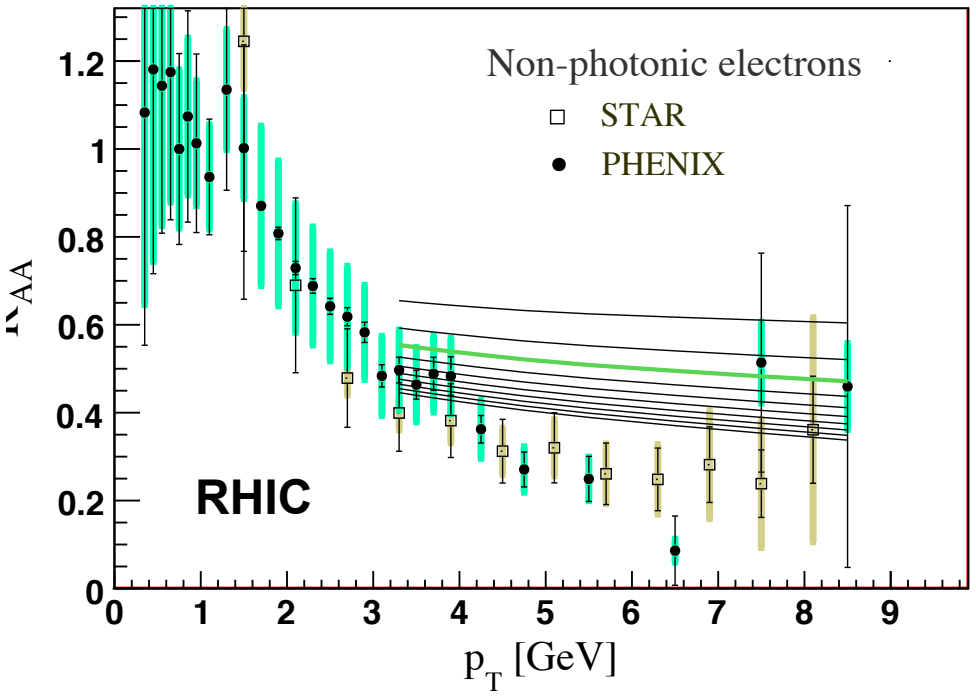
➘ Yields agree with Glauber model

⇛ Large uncertainties

Status from the first LHC PbPb run: HF



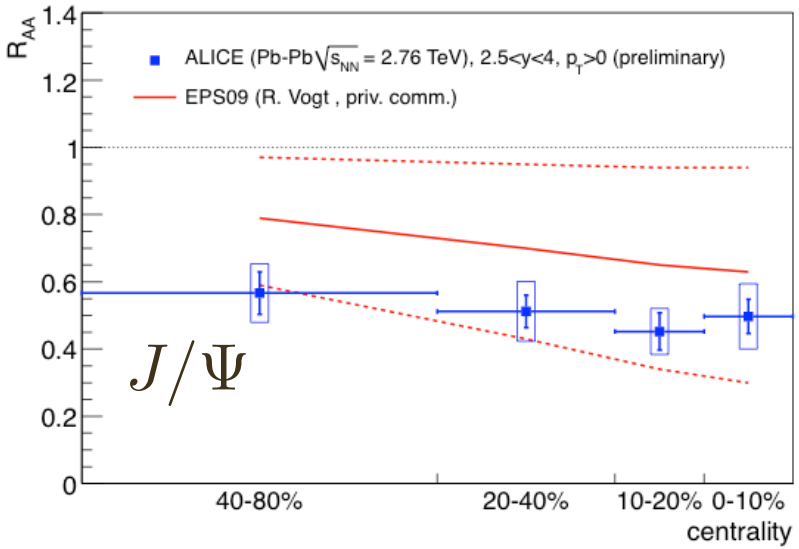
[Armesto et al 2009]

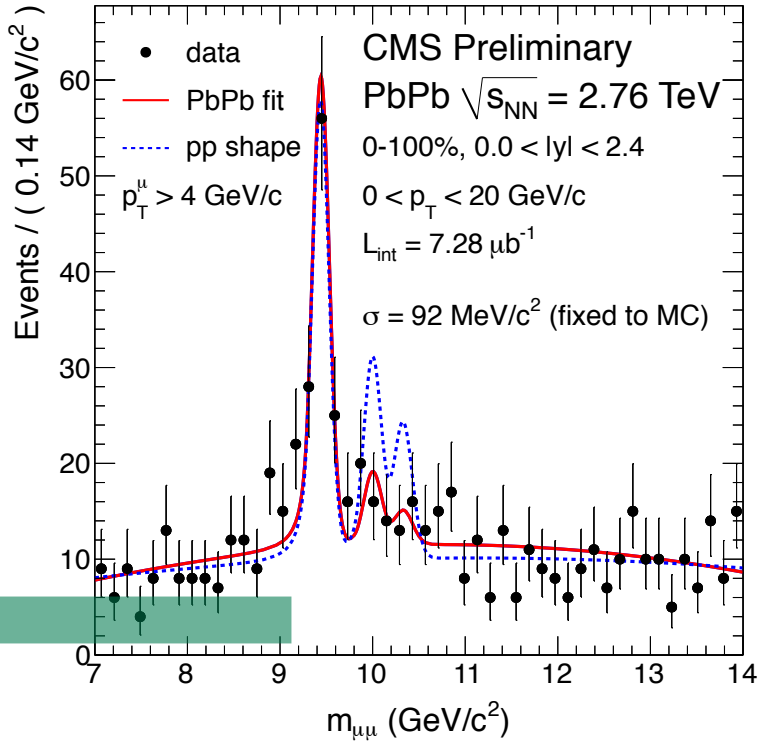


- Dead-cone: **less suppression for massive quarks**
  - Suppression of non-photonic electrons - **puzzle at RHIC**
- Suppression of **open charm first measured by ALICE**
  - The answer of the HF puzzle is in the beauty
- Quantitative analysis needs pA control

Quarkonia at the LHC

- Different quarkonia states are suppressed differently





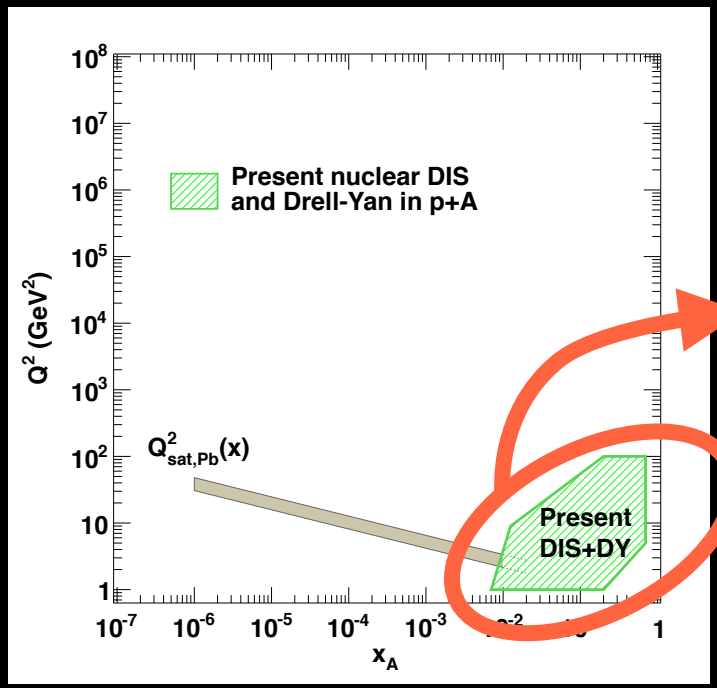
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Sequential suppression?
  - Lattice QCD suggest that 1S quarkonia states melt at $T \sim 2T_c$
  - Excited states melt at $T \sim T_c$
- RHIC+LHC: several states, different energies, different systems...

solve the long standing quarkonia problem?

nPDFs: global analyses. Status

- Main goals
  - Check the factorization of nPDFs for hard processes
  - Fix the benchmark for HI hot matter or saturation



EKS98 [Eskola, Kolhinen, Ruuskanen, Salgado 1998]

HKM [Hirai, Kumano, Miyama, 2001]

nDS [de Florian, Sassot, 2003]

HKN [Hirai, Kumano, Nagai, 2004; 2007]

EPS08, EPS09 [Eskola, Paukkunen, Salgado, 2008; 2009]

nCTEQ [Kovarik et al, 2011]

Also FGS [Frankfurt, Guzey, Strikman, 2004-2010]

The DGLAP equations

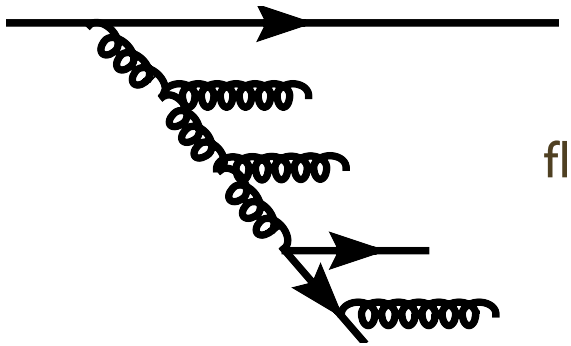
⇒ Describe the evolution of parton distribution functions (PDFs)

$$\frac{\partial q_i(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\left[\int_x^1 \frac{dz}{z}\sum_j P_{q_i q_j}(z) q_j\left(\frac{x}{z},Q^2\right) + P_{q_i g}(z) g\left(\frac{x}{z},Q^2\right)\right]$$

$$\frac{\partial g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\left[\int_x^1 \frac{dz}{z}\sum_j P_{g q_j}(z) q_j\left(\frac{x}{z},Q^2\right) + P_{g g}(z) g\left(\frac{x}{z},Q^2\right)\right]$$

[DGLAP: Dokshitzer, Gribov, Lipatov, Altarelli, Parisi]

⇒ Initial non-perturbative input <u>taken from experiment</u> $f_i(x,Q_0^2)$



Encode the quantum QCD fluctuations as parton splittings

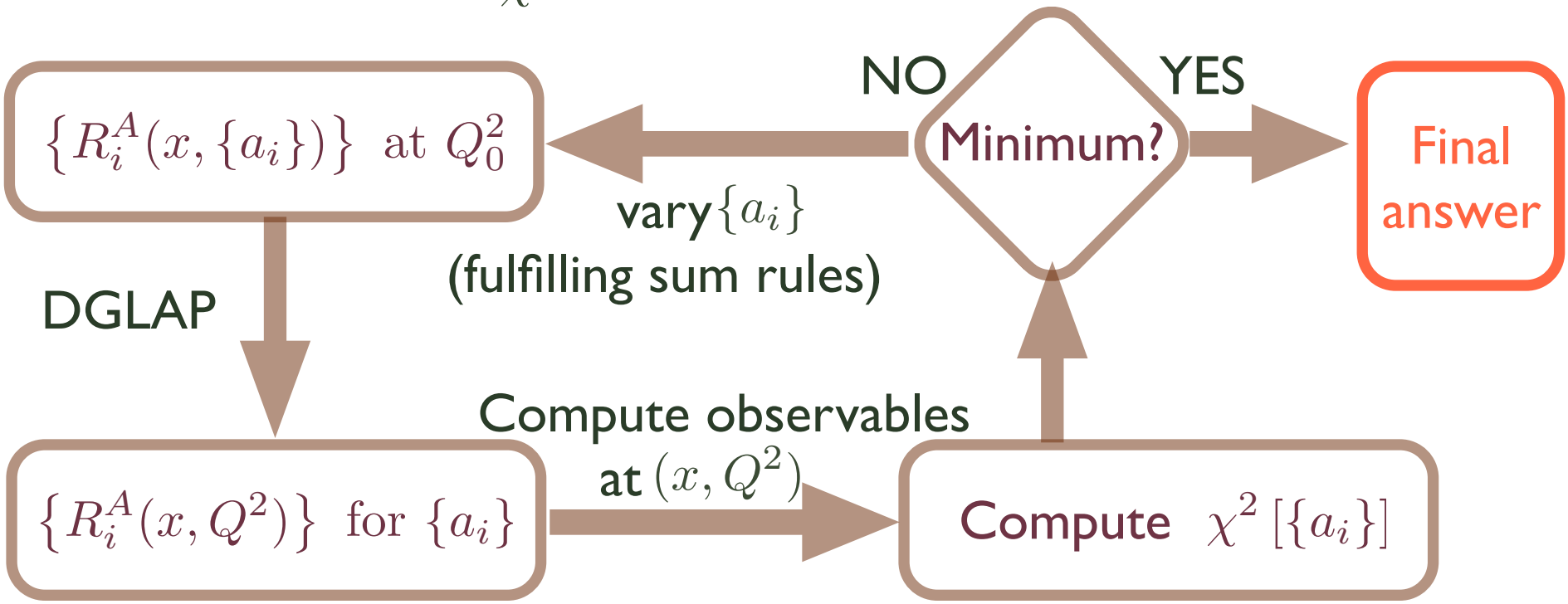
Mergings neglected

How?: follow free proton approach

- Cross sections computed in collinear factorization
- Define

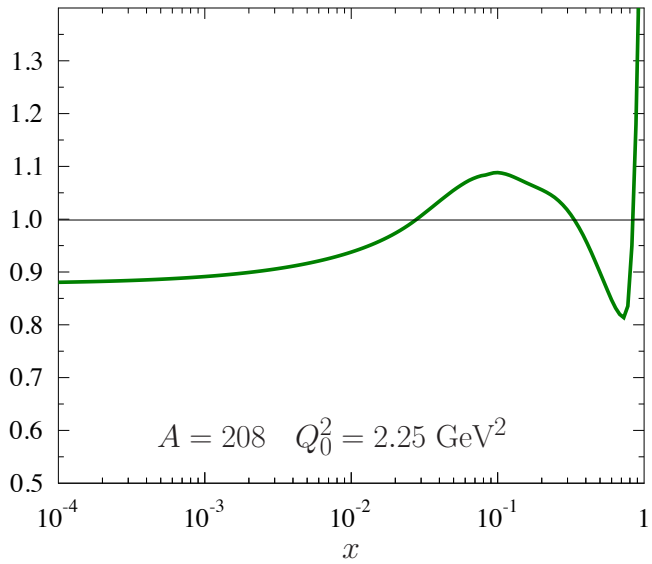
$$R_i^A(x,Q^2) = \frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}$$

- Using a known set for free protons (CTEQ, MRST....)
- and DGLAP evolution of the nuclear and free proton PDFs
- Find the minimum of χ^2

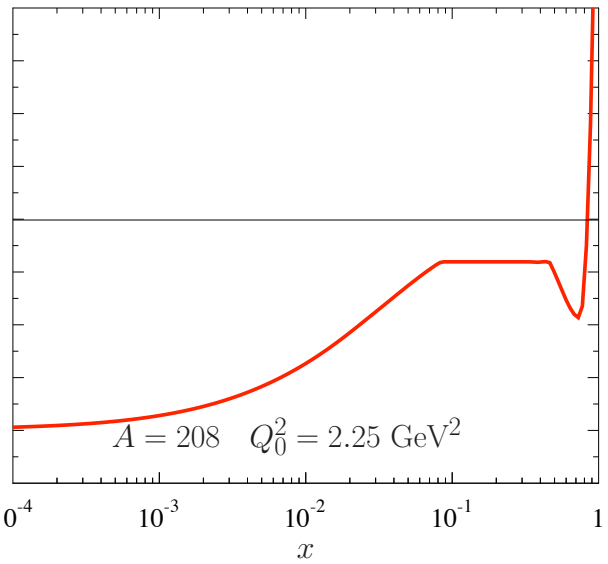


Approximate ranges and constrains in EPS09

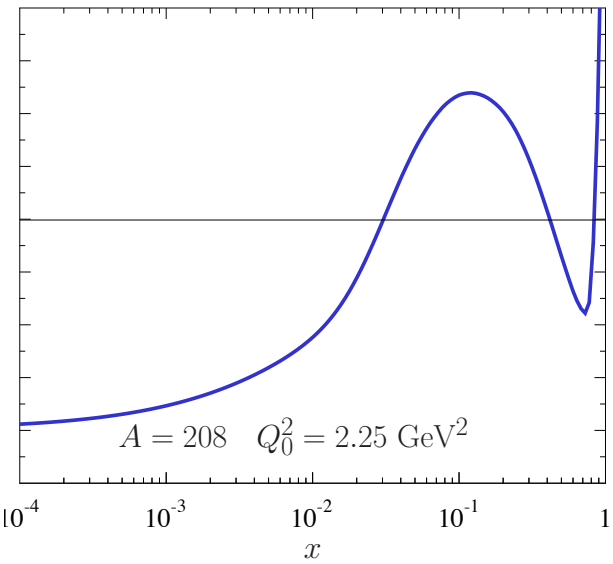
Valence



Sea quarks

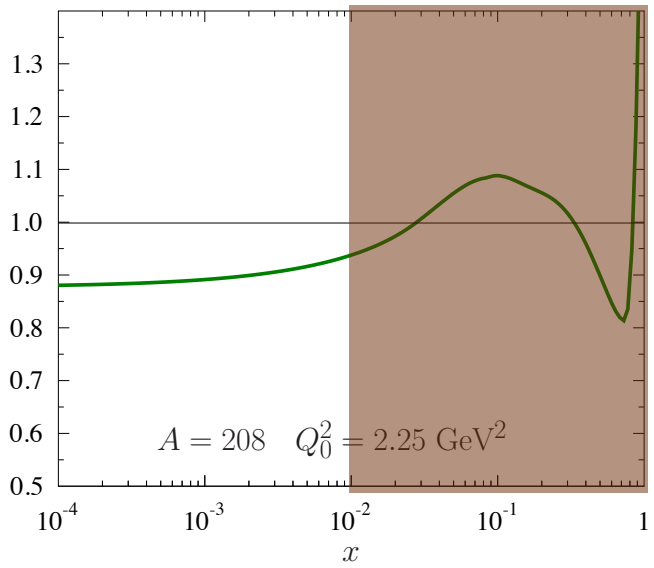


Gluons

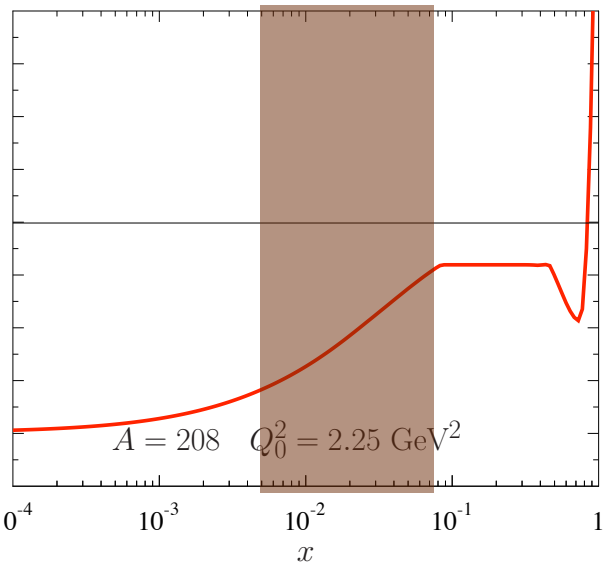


Approximate ranges and constrains in EPS09

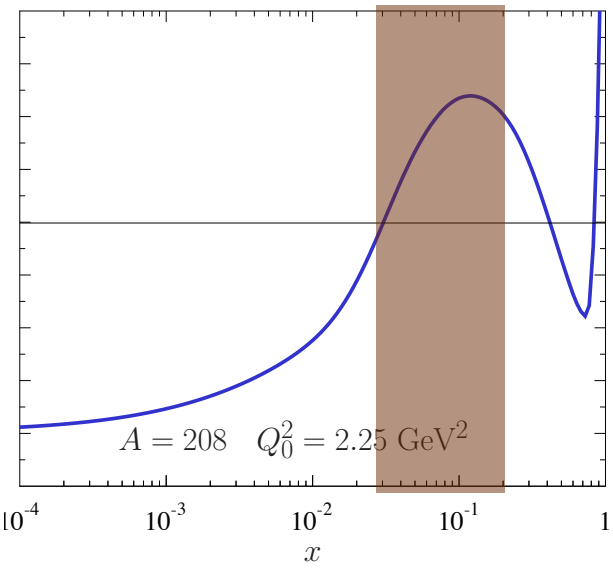
Valence



Sea quarks



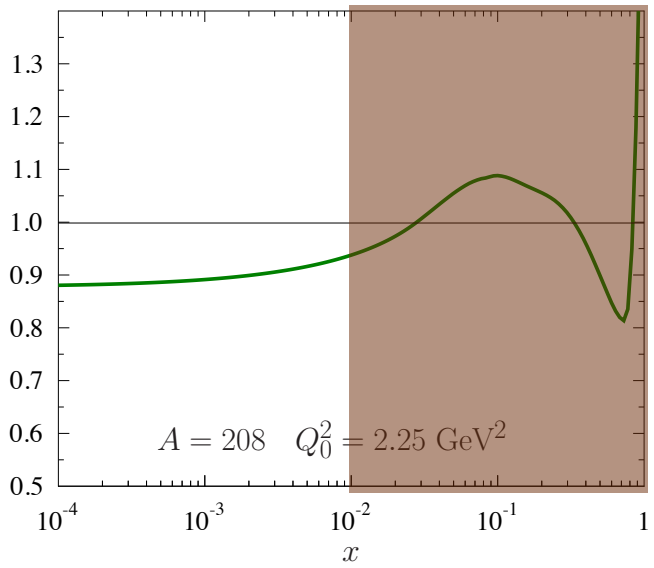
Gluons



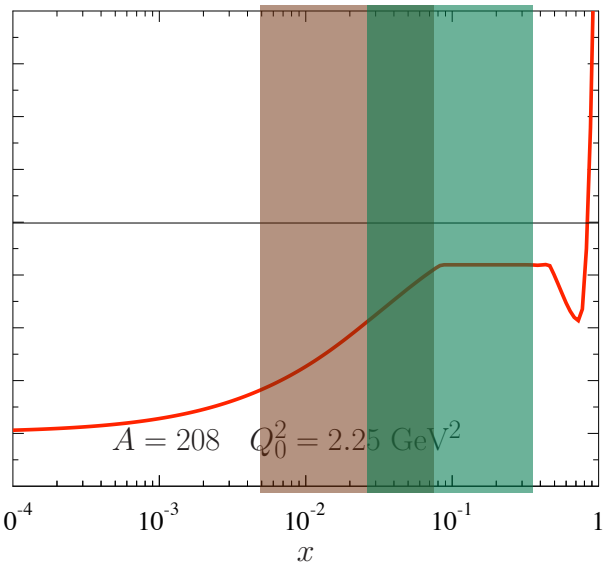
Constrained by DIS

Approximate ranges and constrains in EPS09

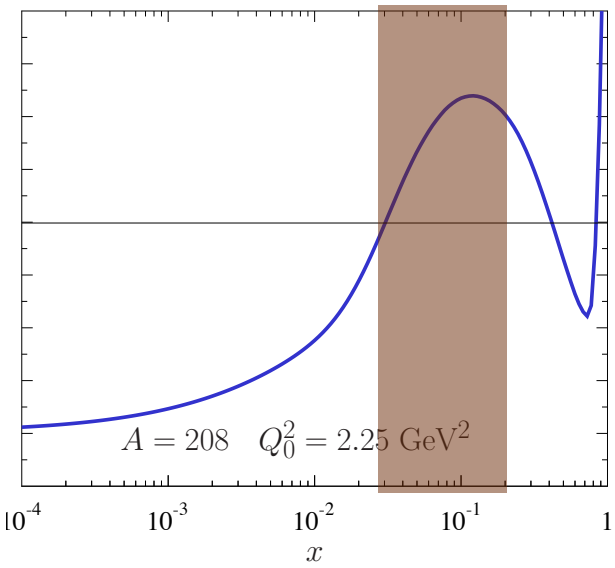
Valence



Sea quarks



Gluons

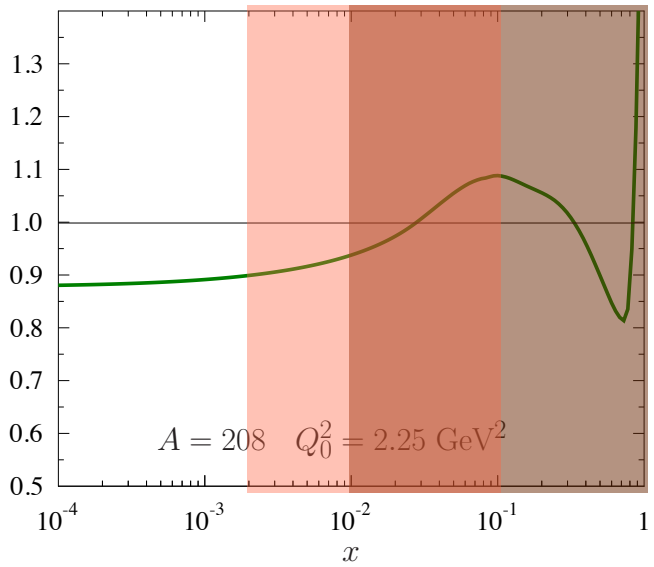


Constrained by DIS

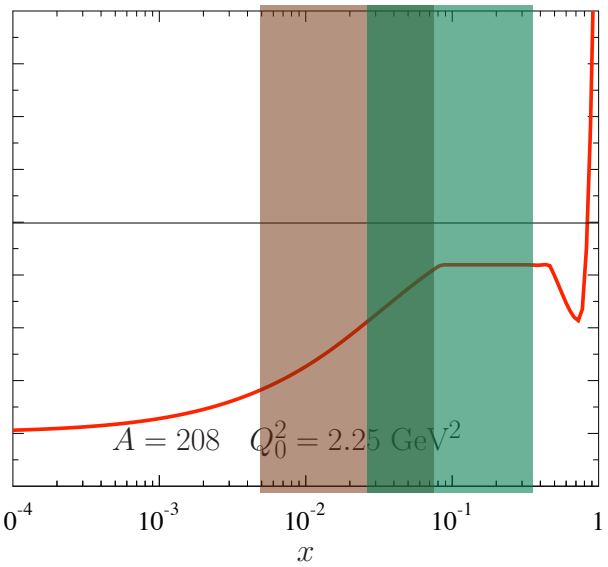
Constrained by DY

Approximate ranges and constrains in EPS09

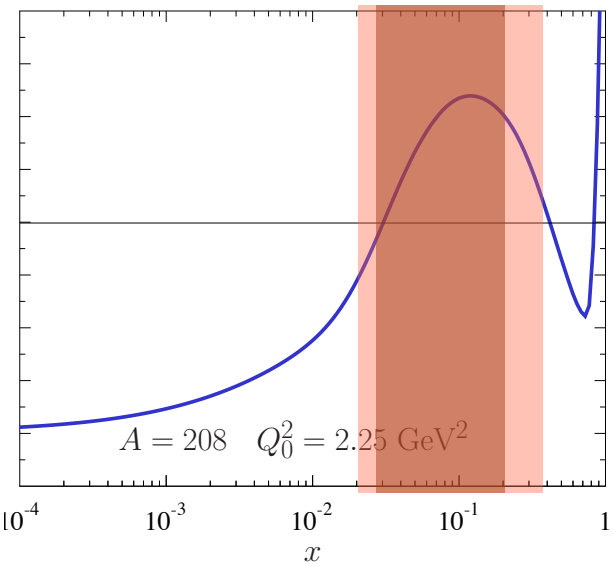
Valence



Sea quarks



Gluons



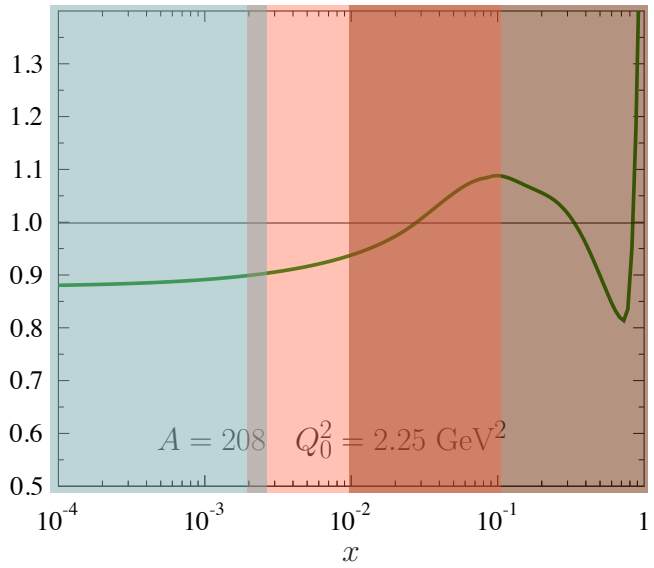
Constrained by DIS

Constrained by DY

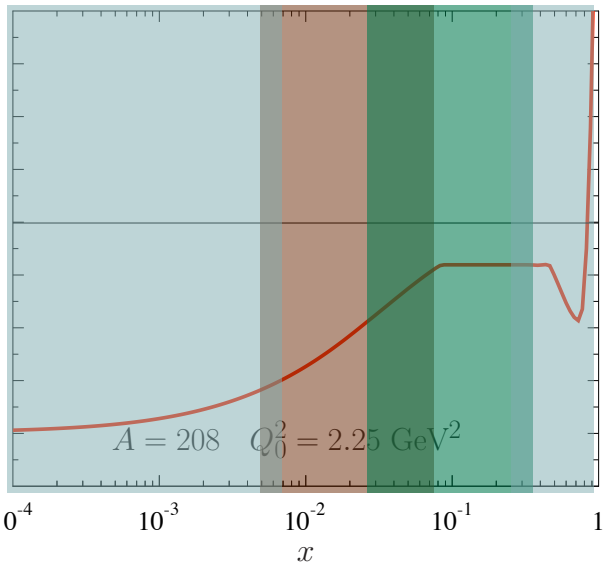
Sum rules and dAu@RHIC

Approximate ranges and constrains in EPS09

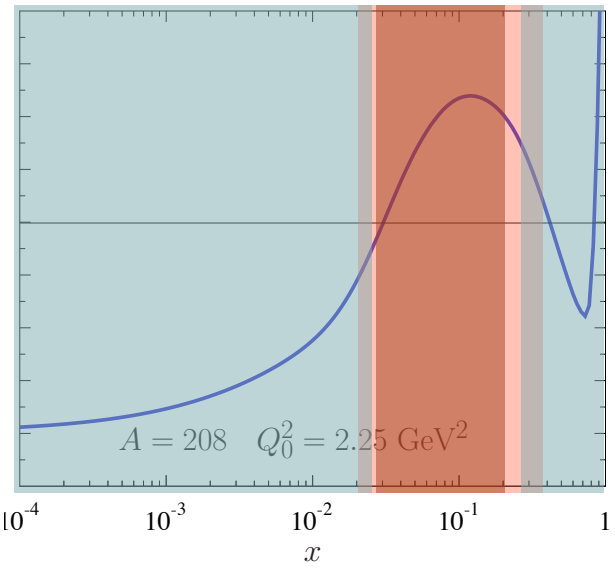
Valence



Sea quarks



Gluons



Constrained by DIS

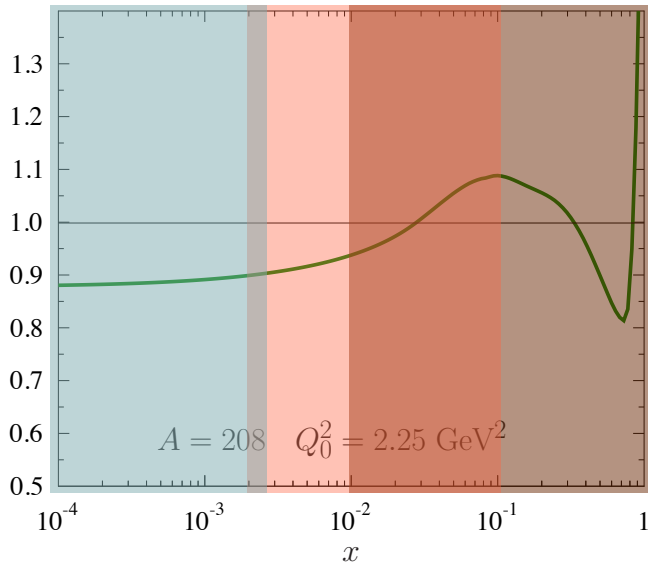
Constrained by DY

Sum rules and dAu@RHIC

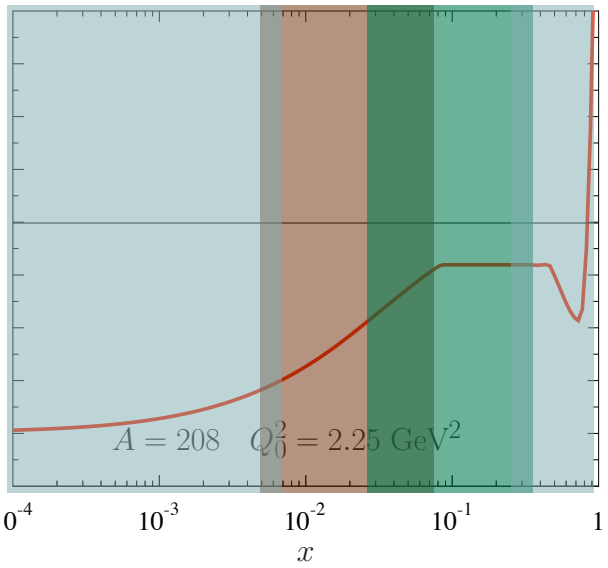
Unconstrained

Approximate ranges and constrains in EPS09

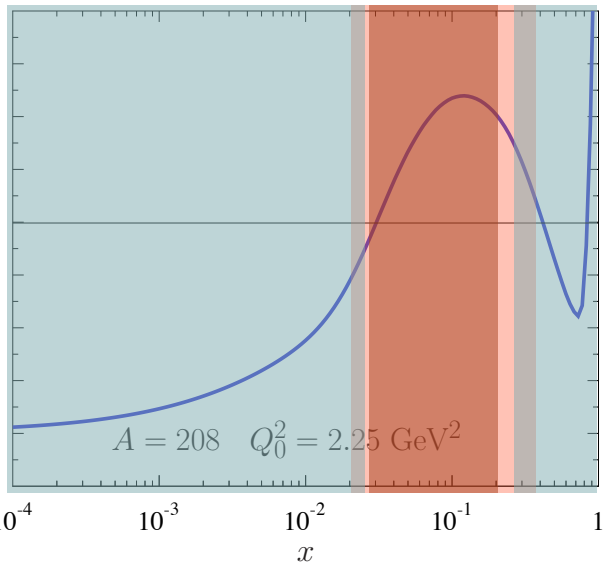
Valence



Sea quarks



Gluons



Constrained by DIS

Constrained by DY

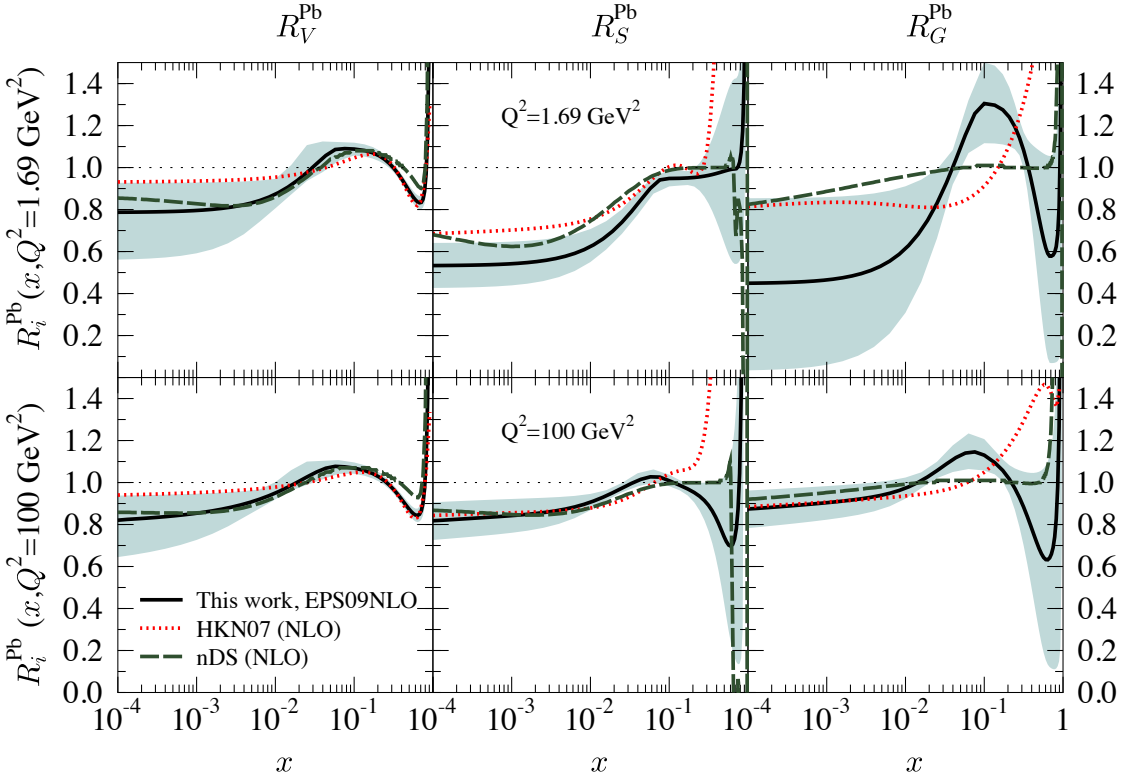
Sum rules and dAu@RHIC

Unconstrained

[these ranges are very approximative... but valid in general for other analyses]

Results of the fits

⇛ Initial conditions and error analysis for different NLO sets



	Chi^2/dof
EPS09	0.79
HKN	1.58
nDS	0.76

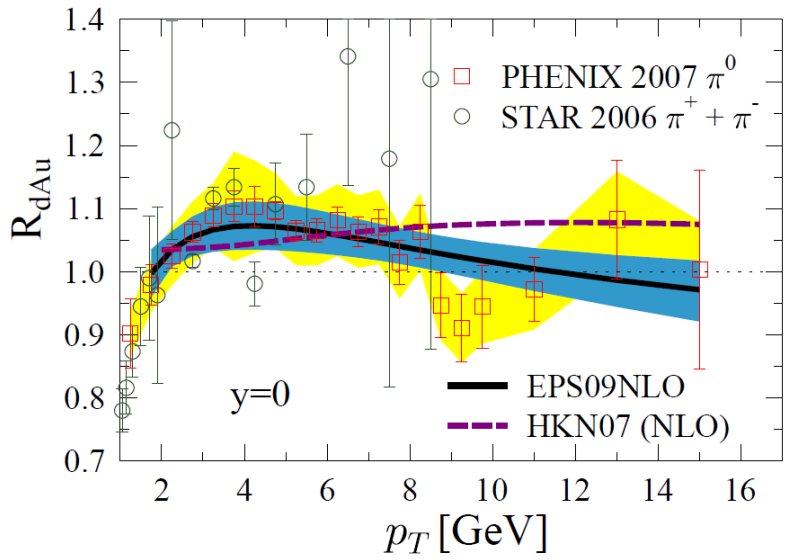
⇛ Large uncertainties especially for gluons - smaller at large virtuality

⇛ Notice that parametrization bias effects are present

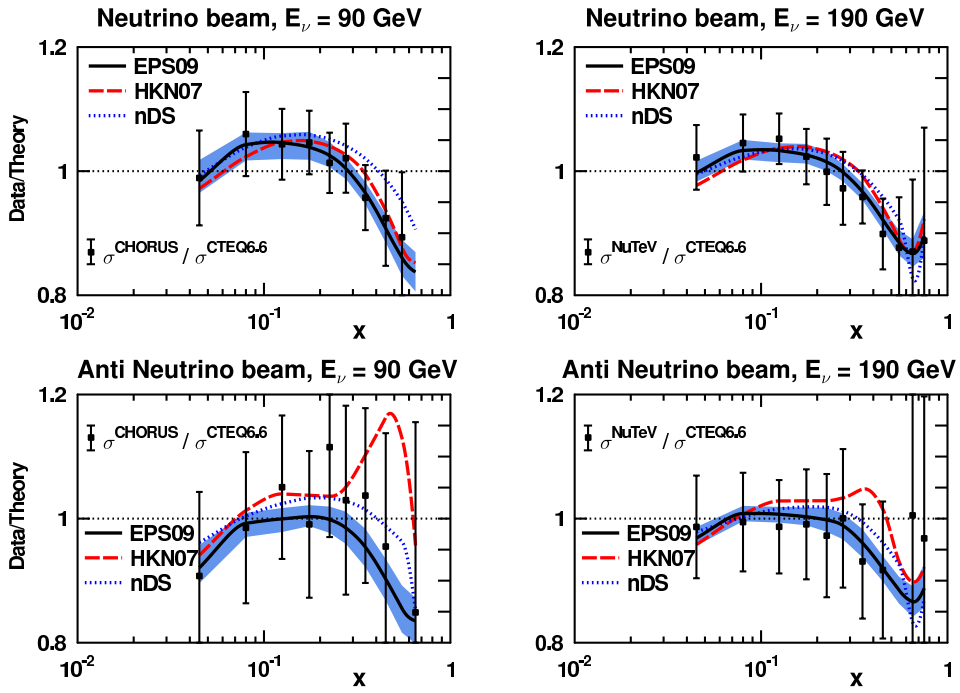
➘ Bands to be considered as lower bounds

Checks of factorization

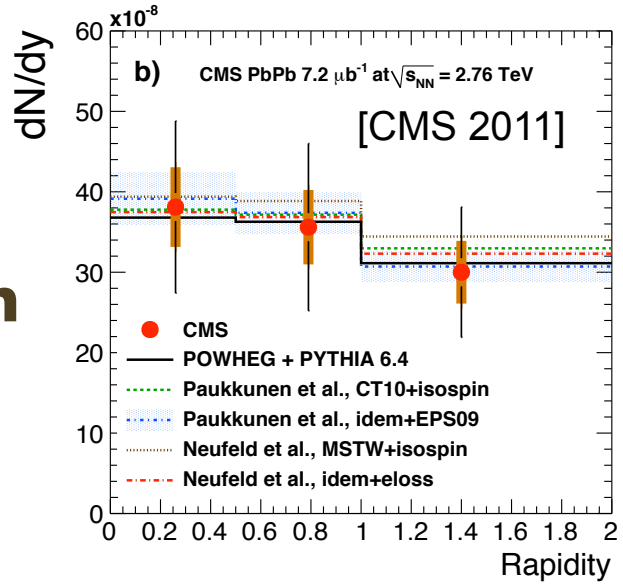
[Eskola, Paukkunen, Salgado, 2010]



[Paukkunen, Salgado, 2010]



Z's from CMS



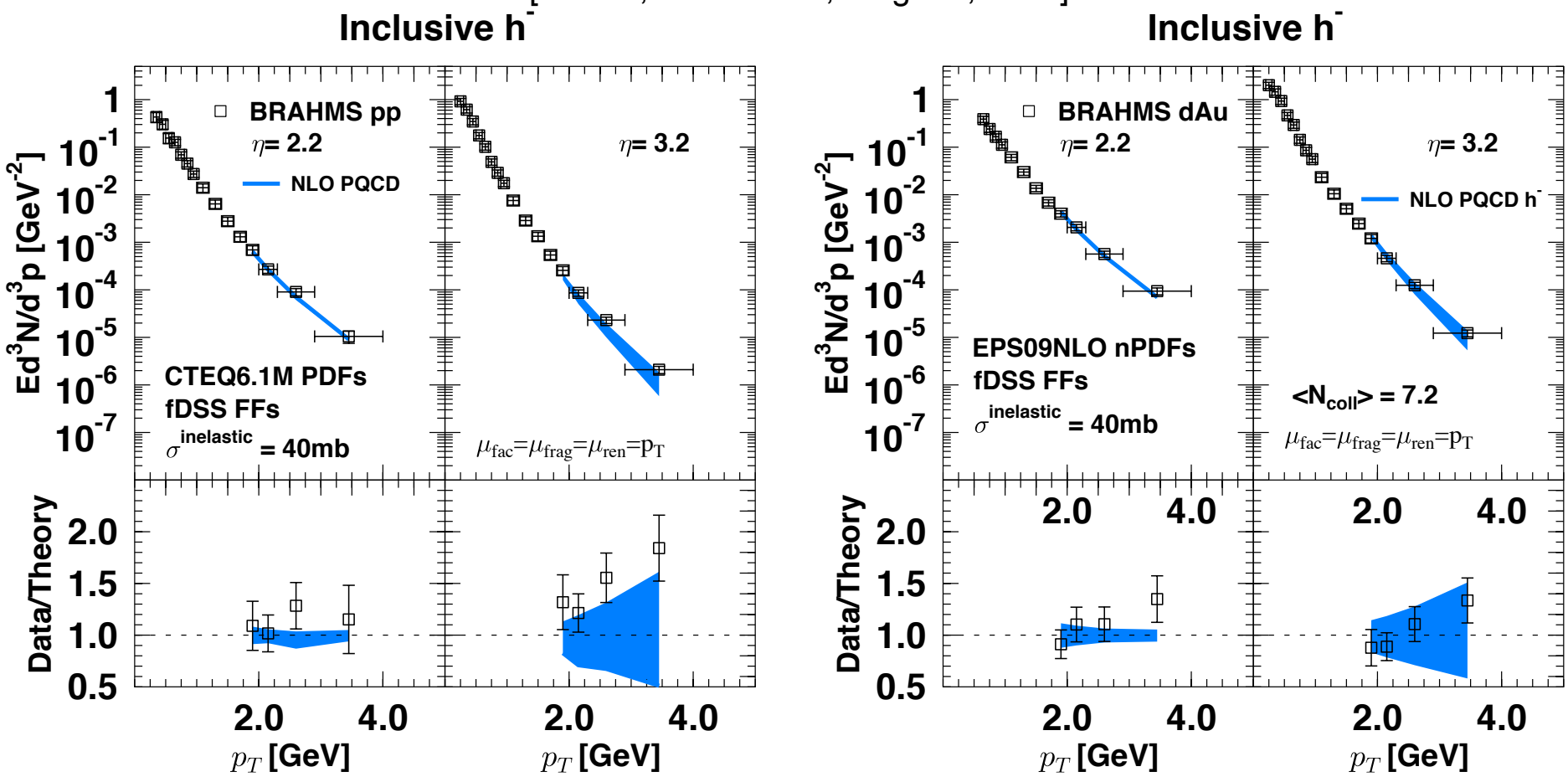
Non-trivial check: different couplings

[Kovarik et al. (2011) : tension among data sets]

Include neutrino data in global fits for **flavor decomposition**

Checks of factorization: forward@RHIC

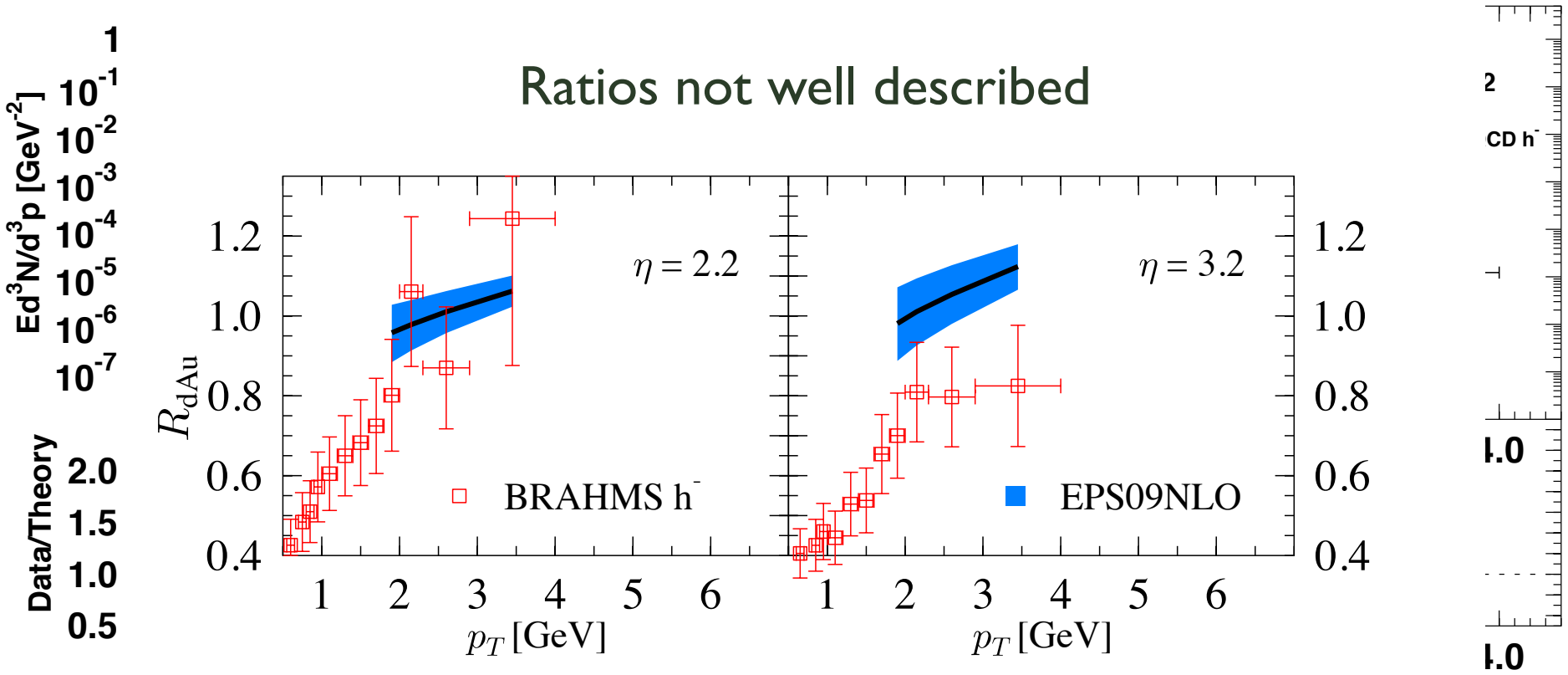
[Eskola, Paukkunen, Salgado, 2010]



- Good description except for pp @ y=3.2
- Notice that only yields are provided: need to use Glauber

Checks of factorization: forward@RHIC

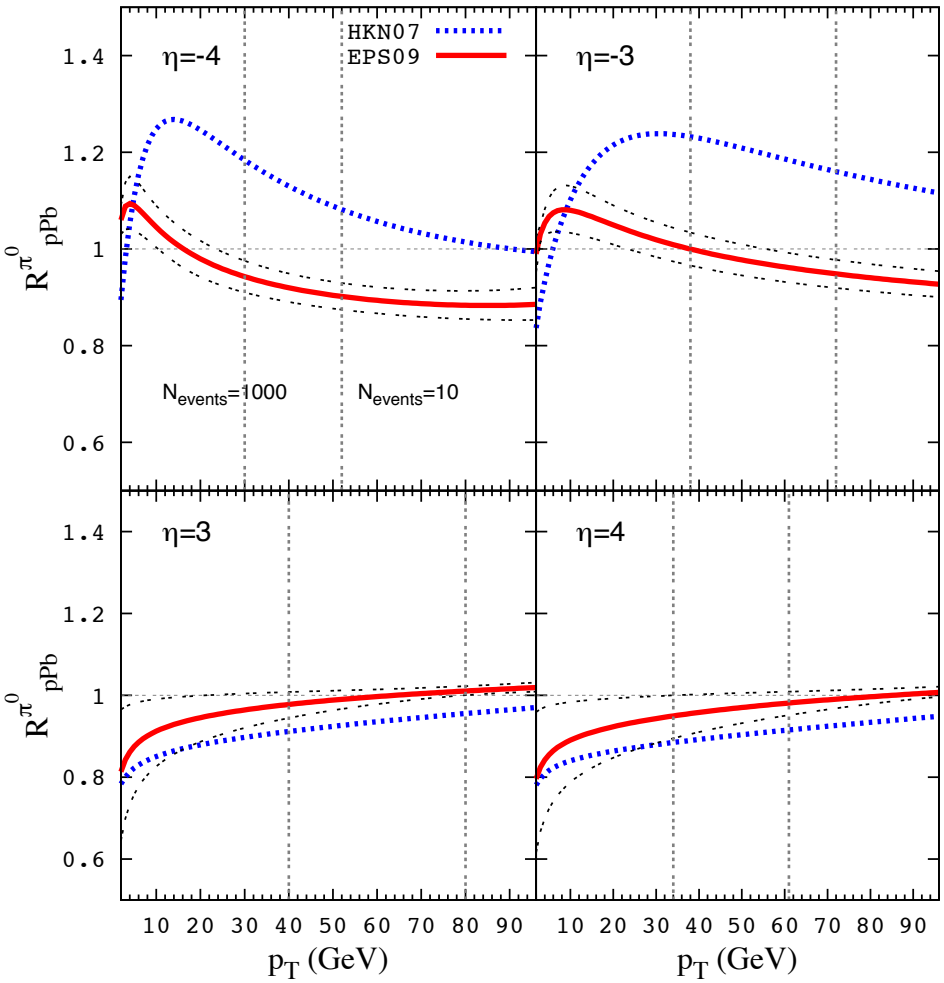
[Eskola, Paukkunen, Salgado, 2010]



- Good description except for pp @ y=3.2
- Notice that only yields are provided: need to use Glauber

Inclusive pion production at LHC

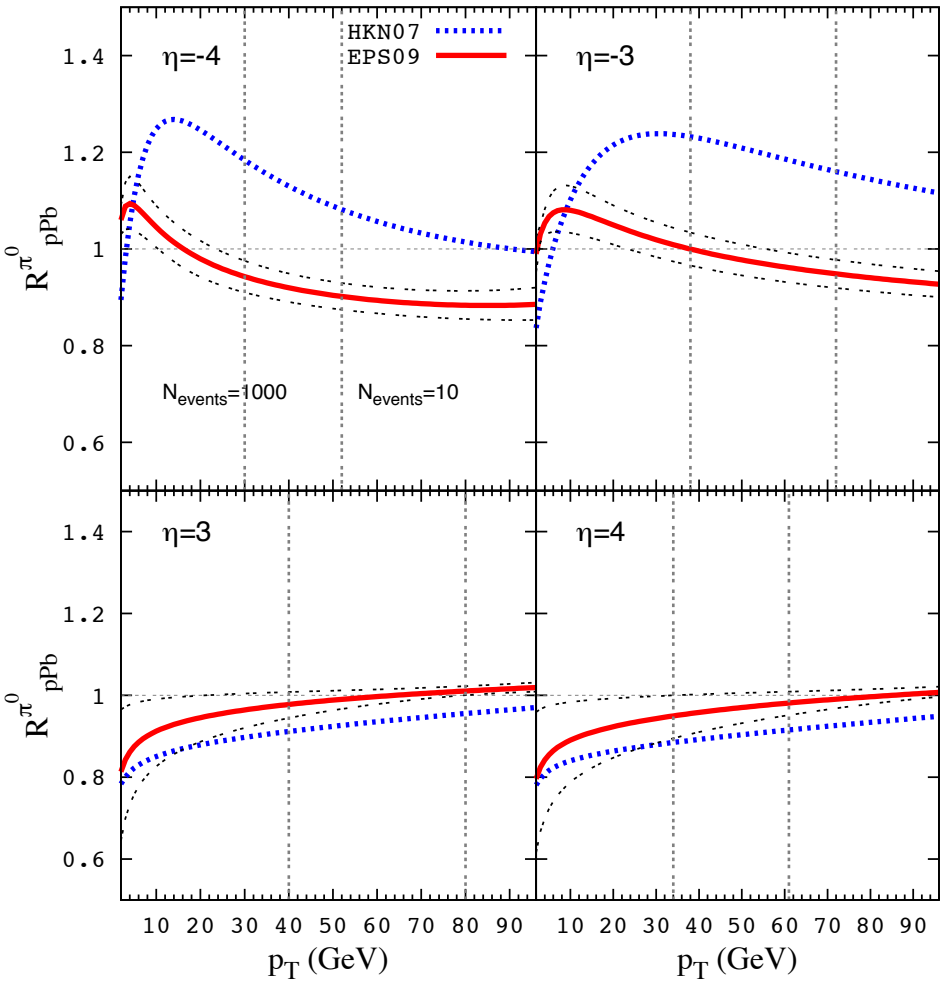
[Milhano, Quiroga, Wiedemann, 2010]

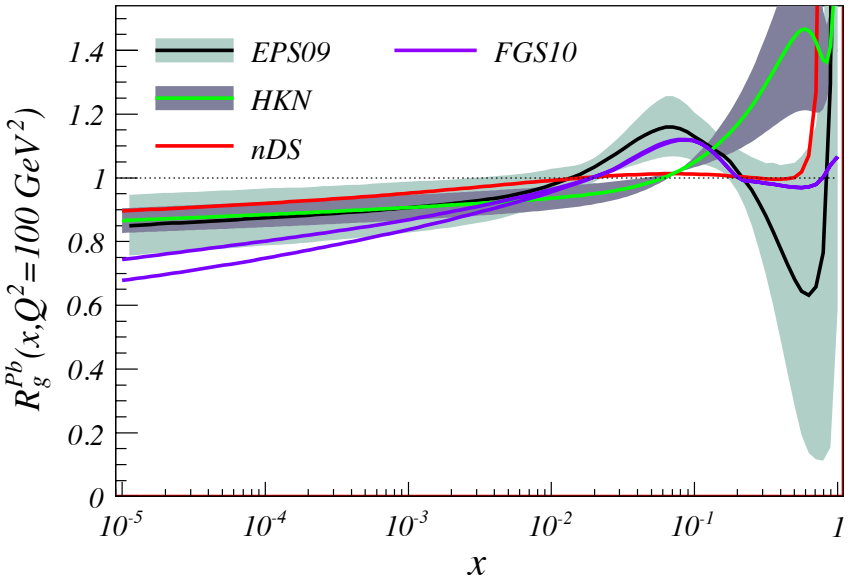


⇒ Rapidity dependence able to constrain parametrizations

Inclusive pion production at LHC

[Milhano, Quiroga, Wiedemann, 2010]

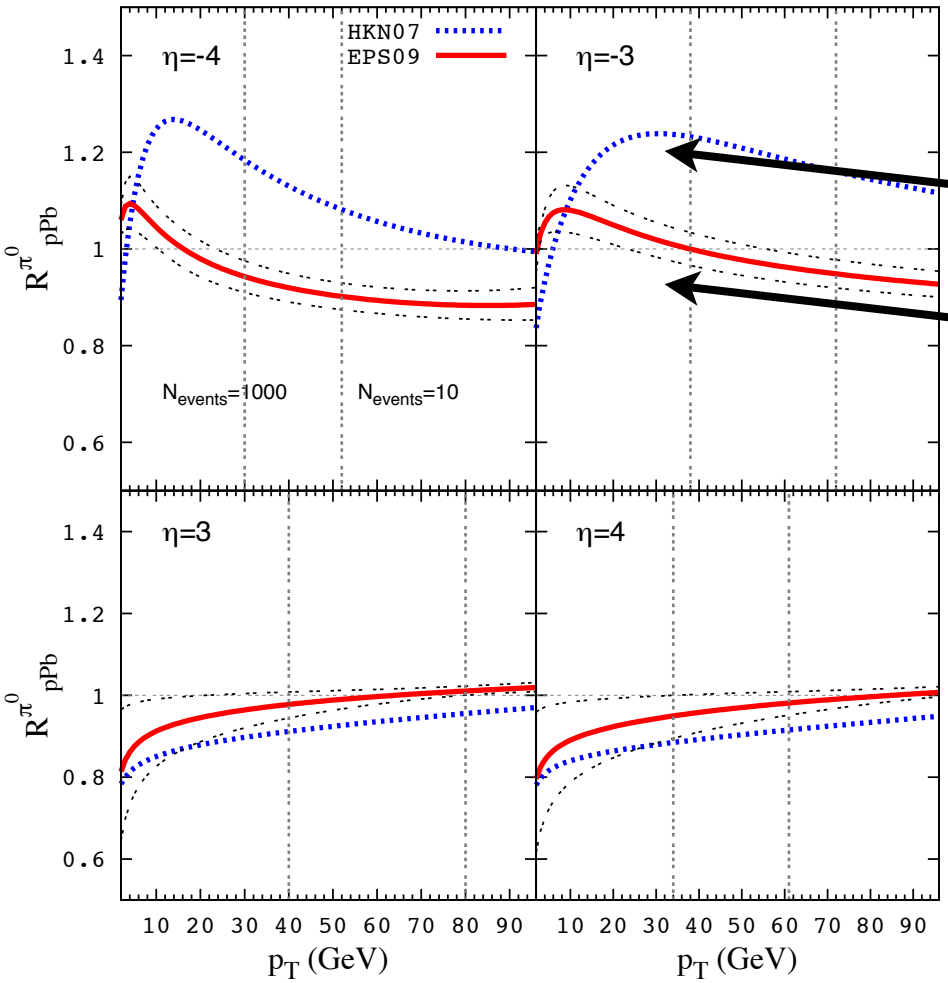


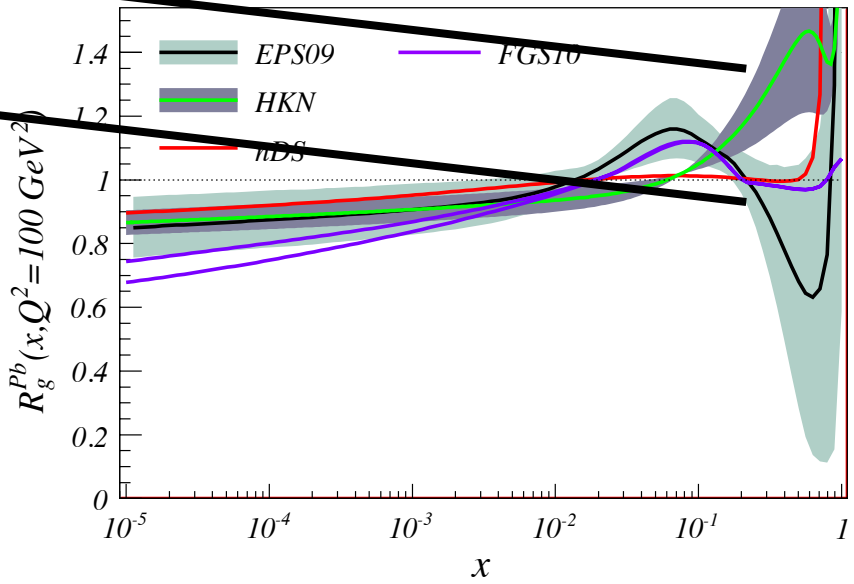


⇒ Rapidity dependence able to constrain parametrizations

Inclusive pion production at LHC

[Milhano, Quiroga, Wiedemann, 2010]

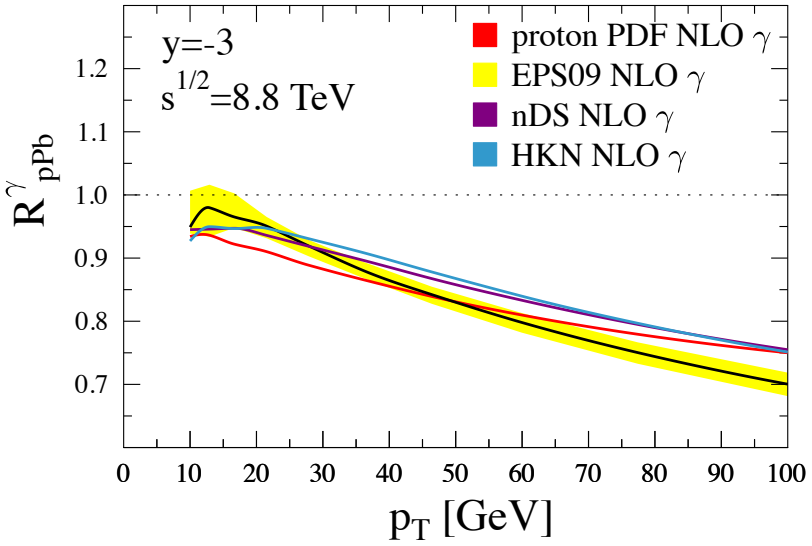


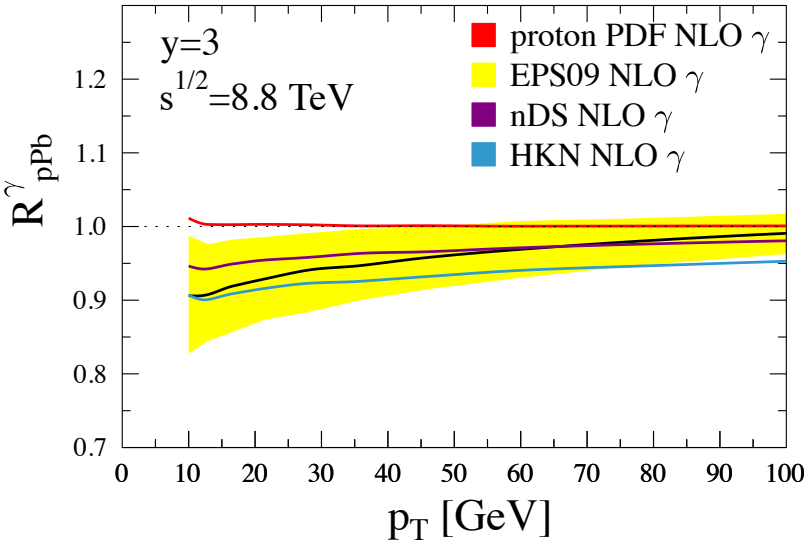


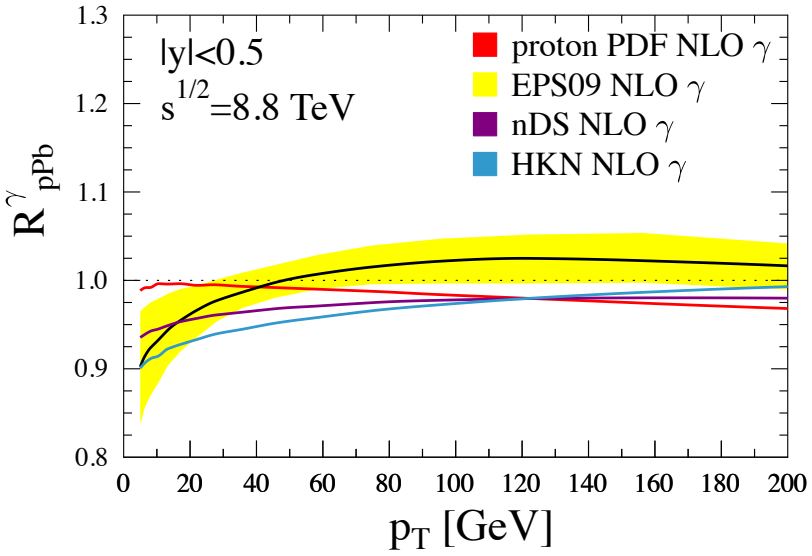
⇒ Rapidity dependence able to constrain parametrizations

Photons

[Arleo, Eskola, Paukkunen, Salgado 2011]



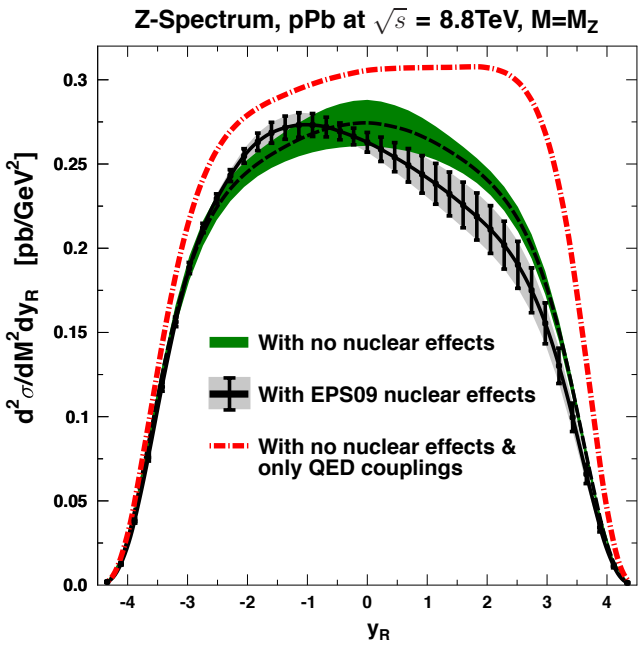


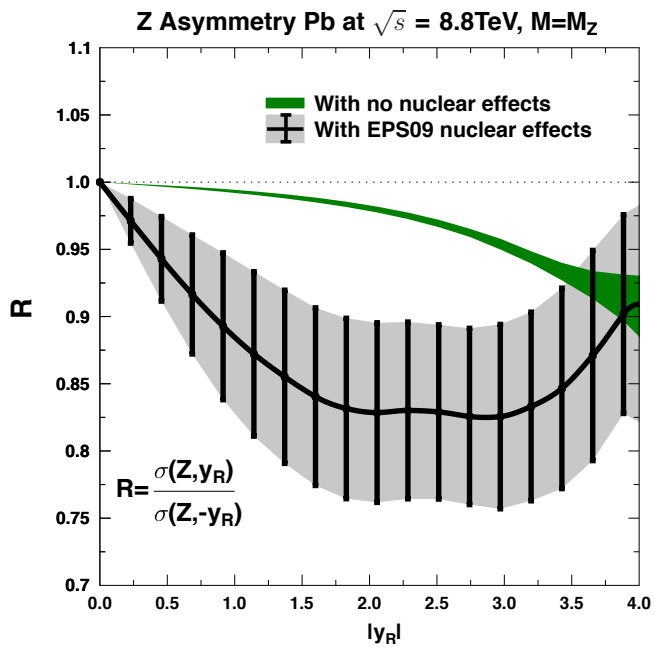


- ⇛ Shadowing, antishadowing and EMC
- ⇛ Moderate effects at small-x
  - ↘ Other effects easy to identify
- ⇛ Isolation cuts
- ⇛ Isolated virtual photons? (DY)
  - ↘ Interesting: 2→1 process

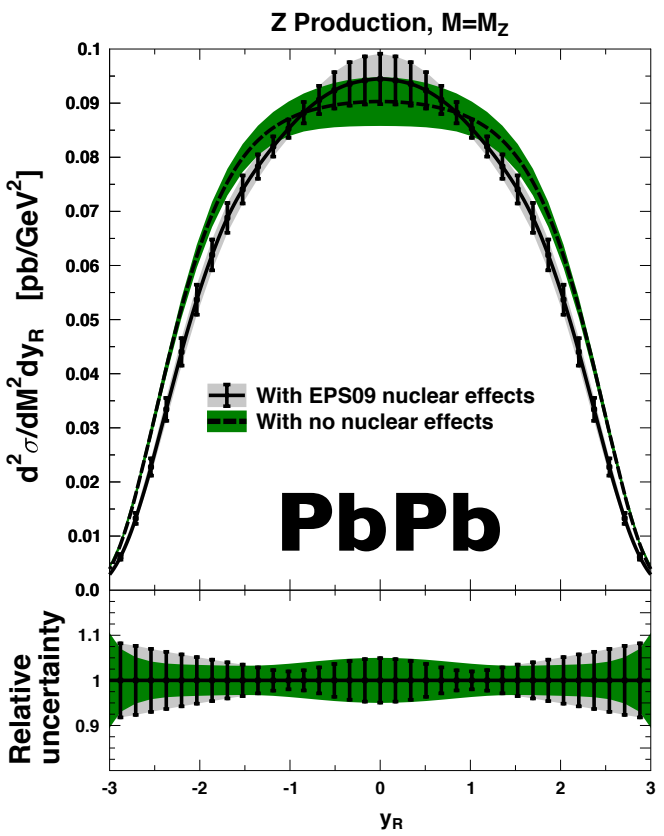
W/Z bosons in pA: a very promising tool

⇛ The rapidity asymmetry in pA can be exploited for nPDF studies





[Paukkunen, Salgado 2011]



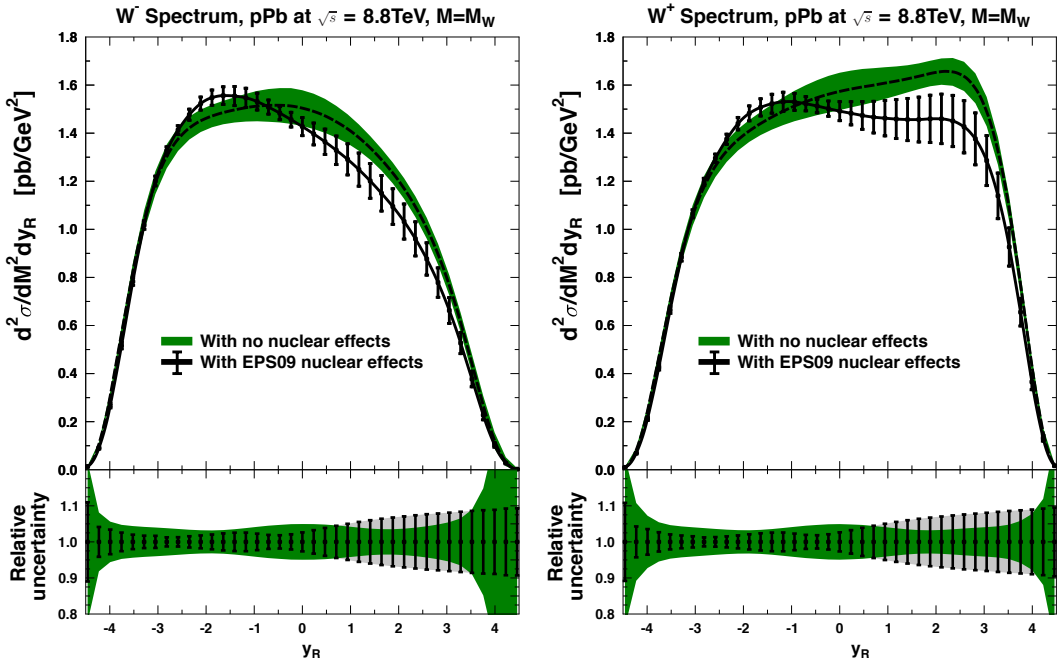
⇛ Small isospin effects on Z production

↘ Asymmetry provides constraints **without pp reference**

↘ AA much less constraining

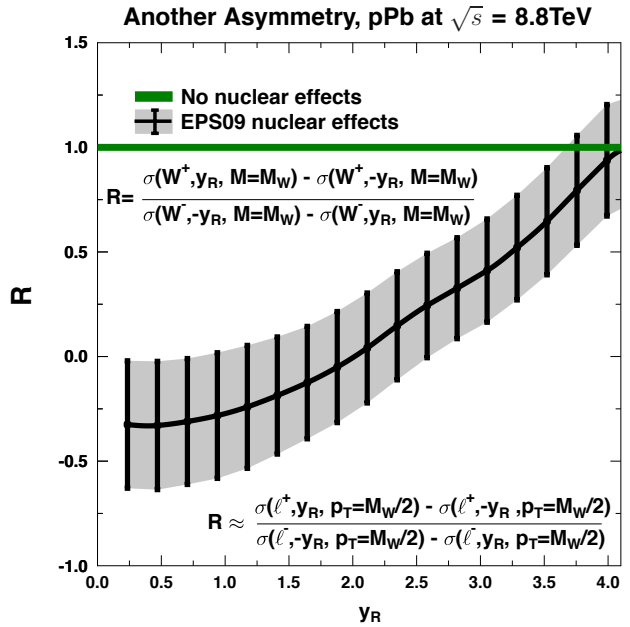
W/Z bosons in pA: a very promising tool

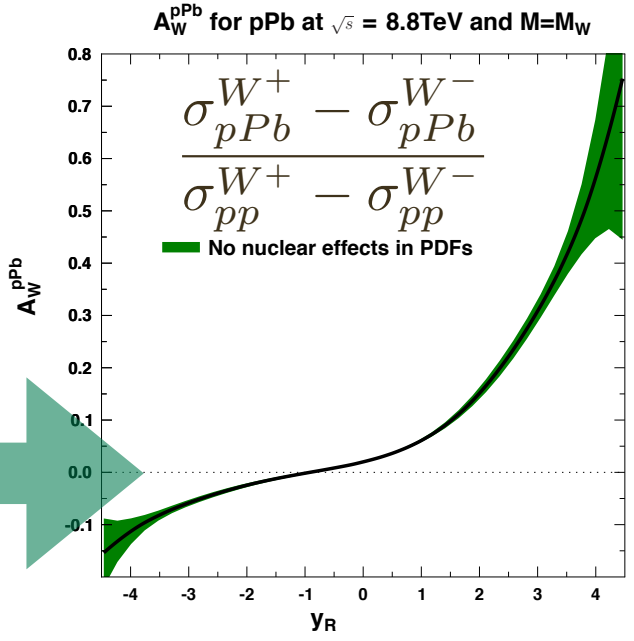
⇒ Isospin effects important in W production



⇒ More difficult for nPDF studies

nPDFs negligible here
proton uncertainties

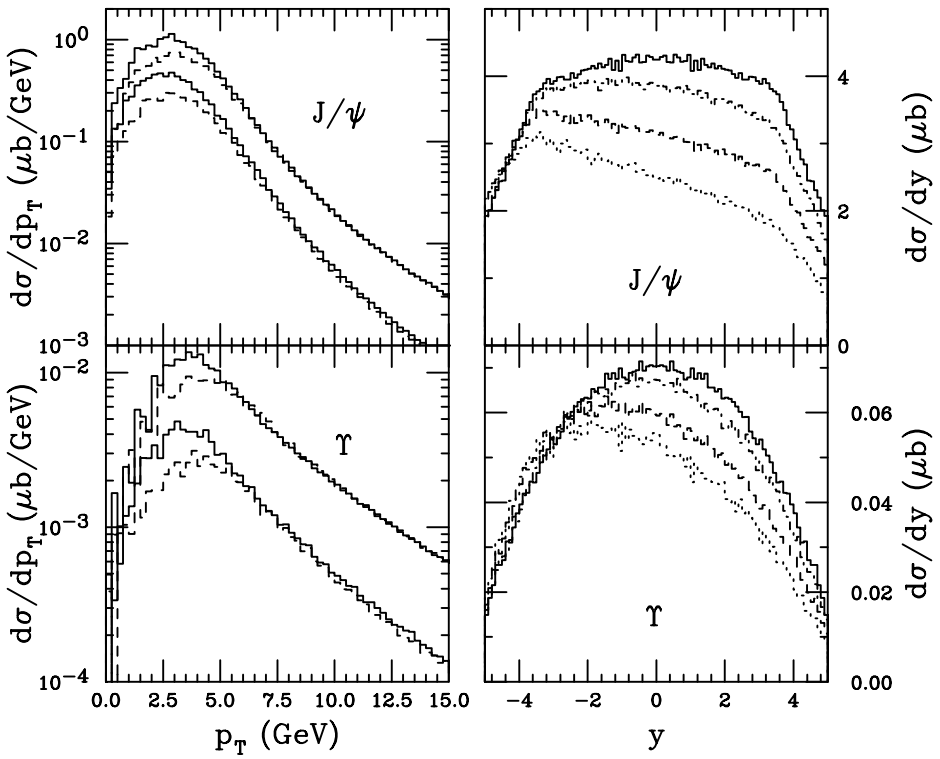


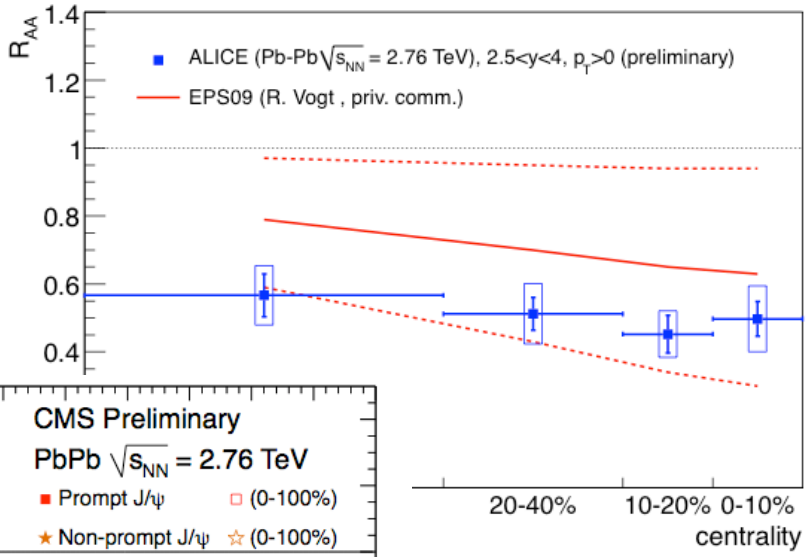


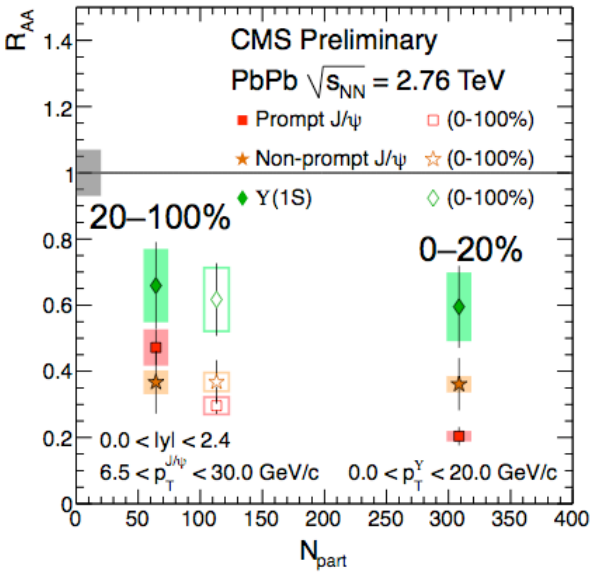
- ***DGLAP global fits provide the technology***
  - *One of the most standardized methods in HEP*
- ***Provide the data and checks of (collinear) factorization will be performed***
  - *(& sets of nPDF released)*

Benchmarking for some processes: quarkonia

arXiv:1105.3919





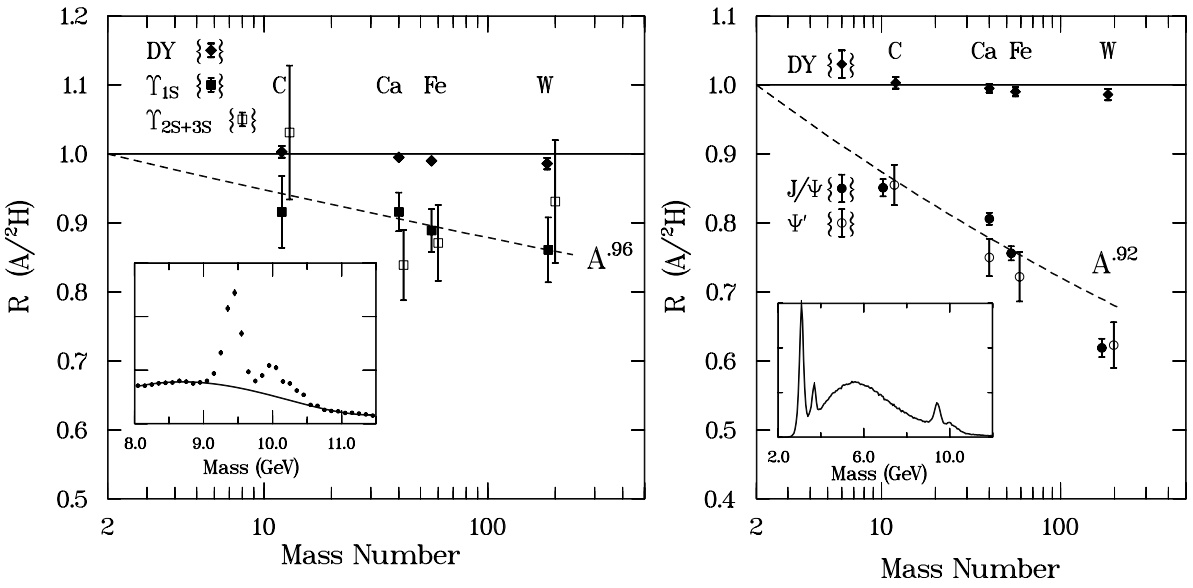


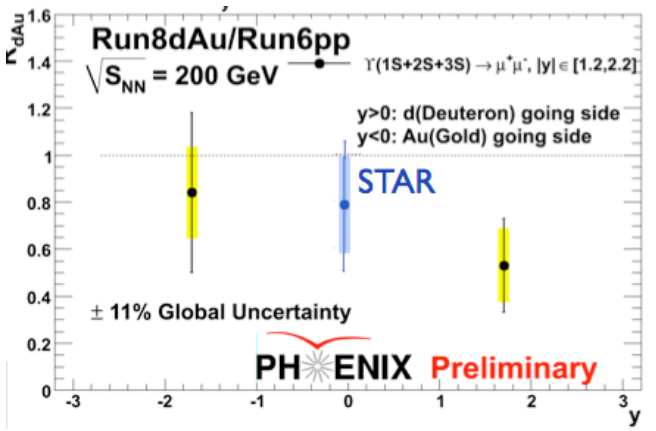
- Taken at face value, J/Psi agrees with binary scaling
  - No need for extra cold or hot matter effects
  - Uncertainties in nPDFs and CNM need to be reduced

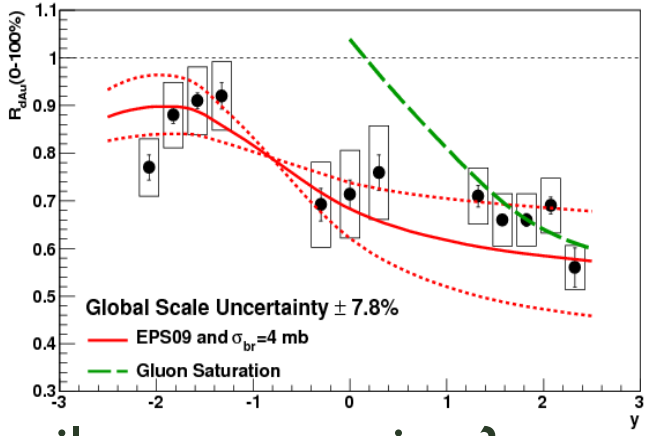
More on quarkonia

- Upsilon measured looong ago in pA collisions at p_{lab}=800 GeV
  - Less suppression than charmonia
  - All Upsilon states similar suppression

[E772 Collaboration 1991]





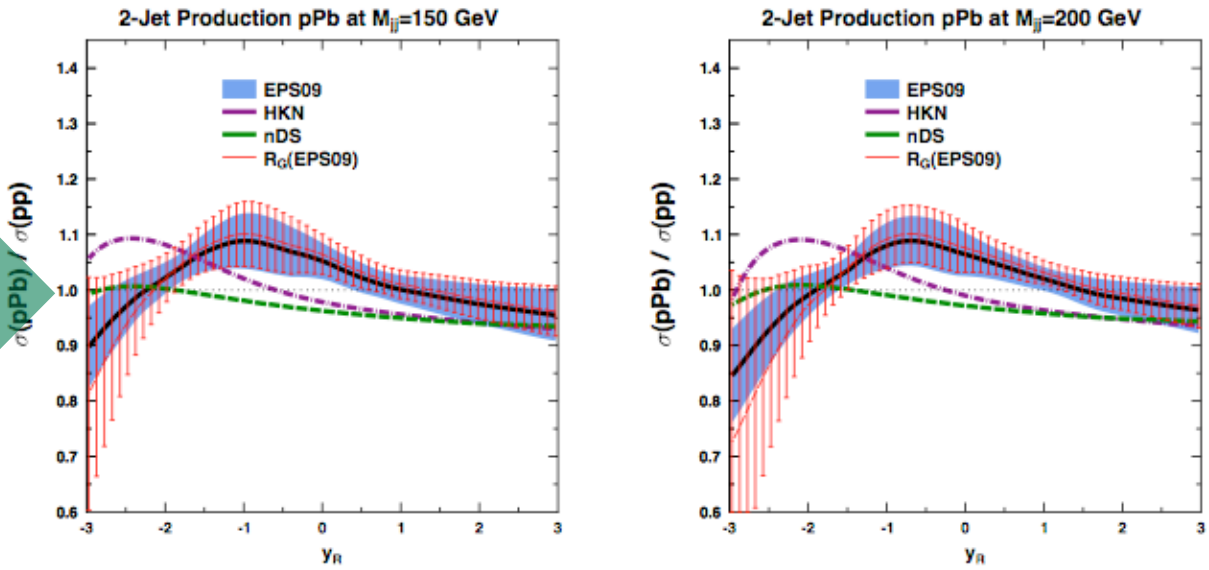


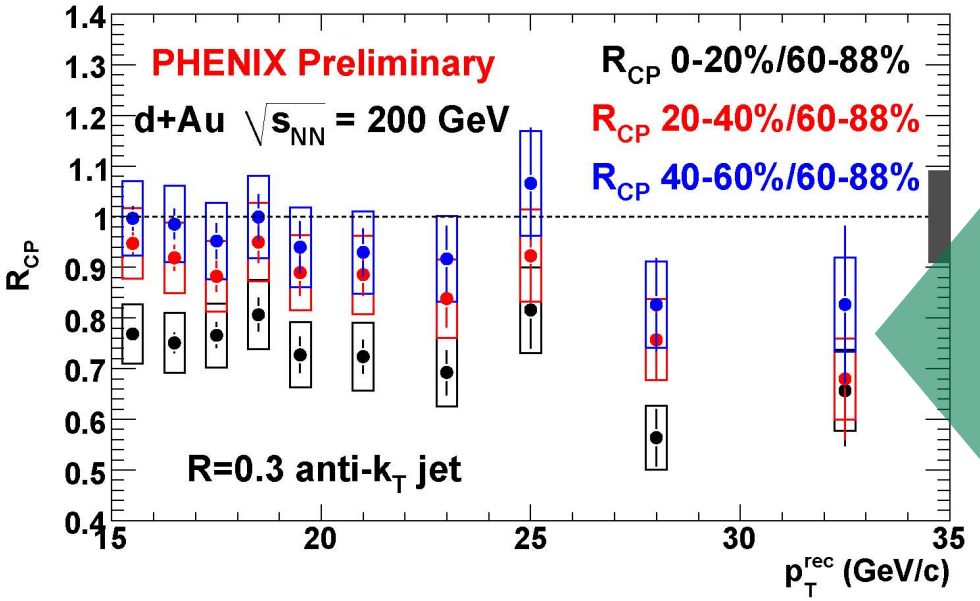
- dAu [PHENIX] : charmonia and bottonia similar suppression?
  - What is the picture in AA? What is the picture at the LHC?

Benchmarking for some processes: jets

Effects of nPDFs not large at the LHC

[Paukkunen et al. in preparation]



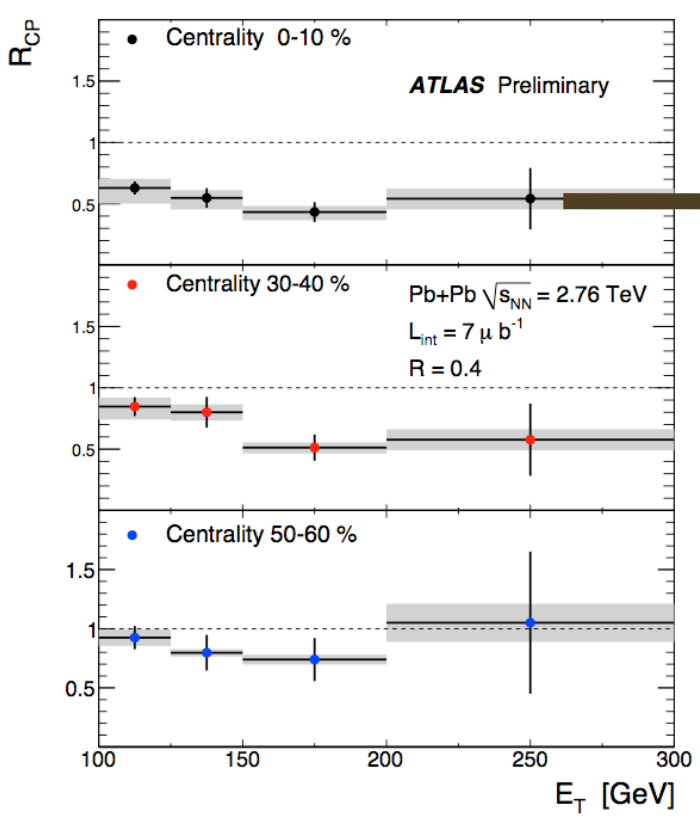


New results from PHENIX

- Is this nPDFs (EMC)?
- CNM broadening of jets?

(also **STAR** has indications of jet-broadening in dAu)

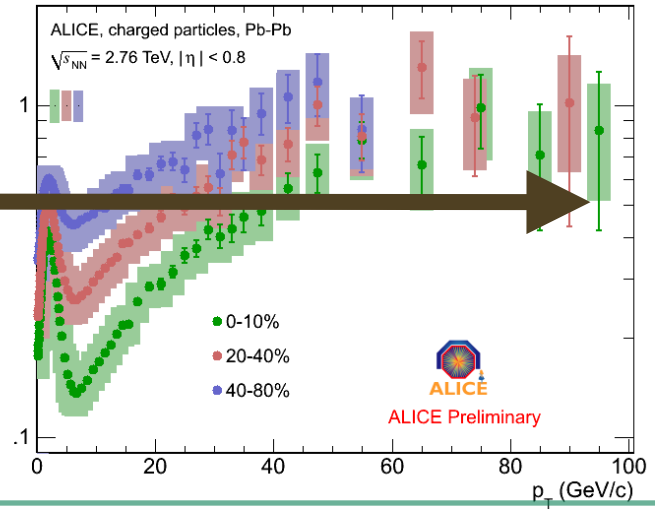
Inclusive charged less suppressed than jets?



Rough comparison

many issues

to understand



Broadening and energy loss related

$$\Delta E \sim \alpha_s \, L \, \langle k_\perp^2 \rangle$$

Quite generic relation if gluon multiple scattering

- However, medium-decoherence mechanism breaks this relation
  - Vacuum-like radiation [Mehtar-Tani, CAS, Tywoniuk 2010-2011]
- Color coherence building block in vacuum jets
  - Can coherence/decoherence be identified in pA?

Benchmarking: a personal view

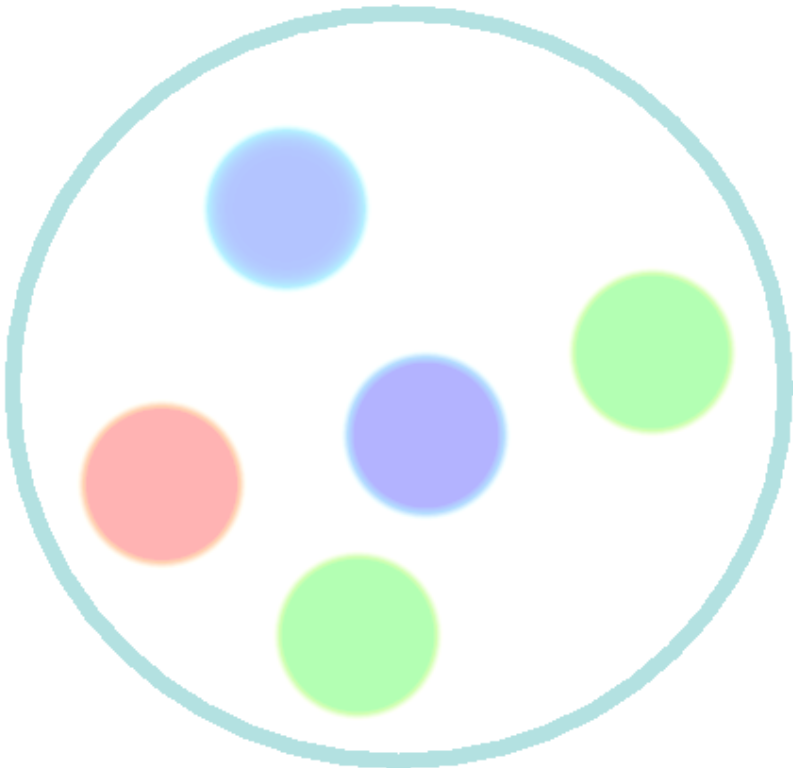
[Recent results from LHC & past experience in the field]

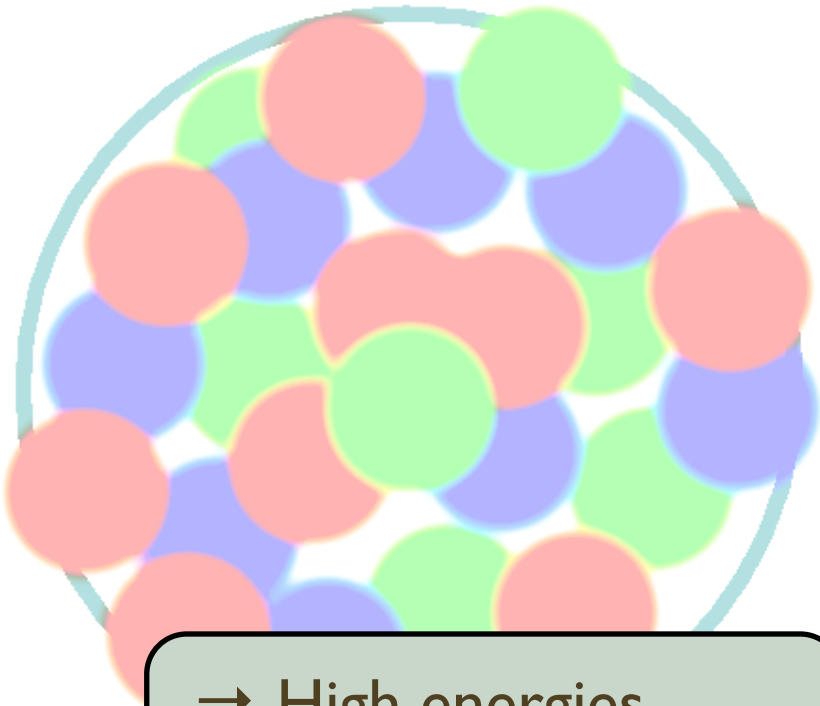
	Qualitative	Quantitative
Quarkonia		CNM reference inc. nPDFs
Bulk		b-dependence, i.c. for evolution
High-pt / HF & Jets		nPDFs, CNM, coherence?
EW bosons		precision nPDFs

- Different observables may require different strategies
  - [Also depending on the detector]
  - In general smaller virtualities imply larger uncertainties

Saturation of partonic densities

(Color Glass Condensate)

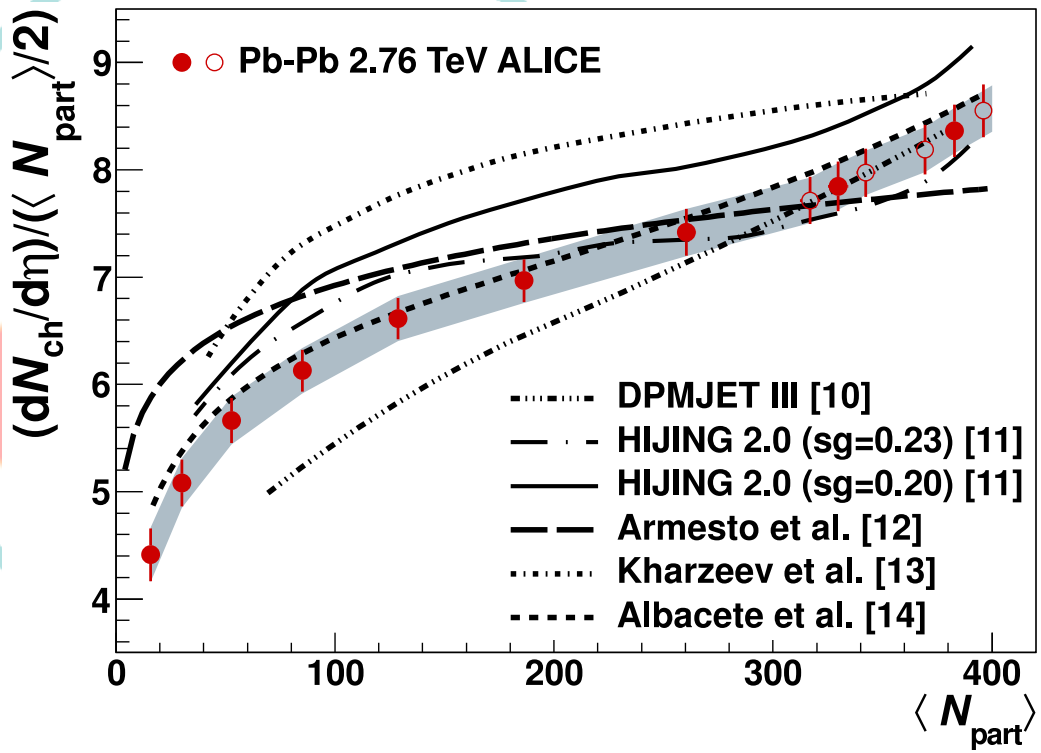


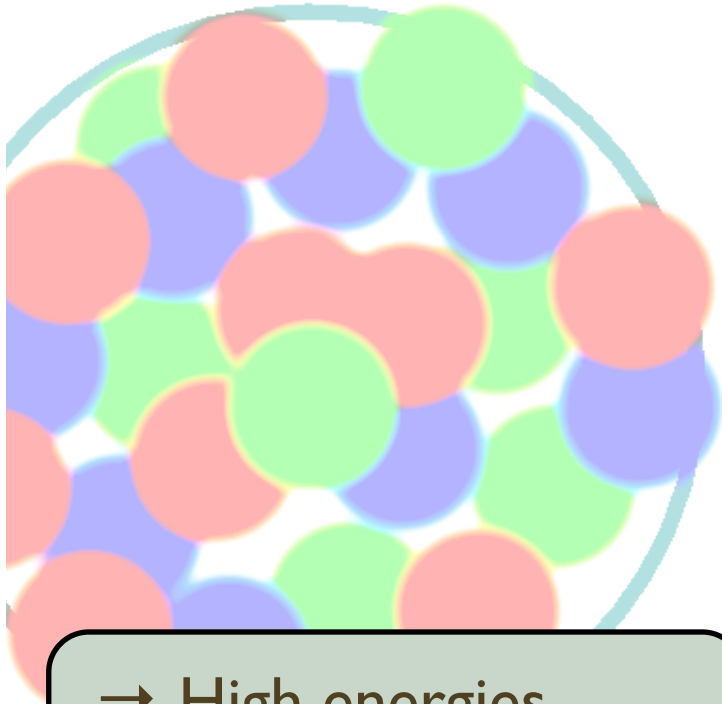


→ High energies
→ Forward rapidities
→ Nuclei
→ Better in pA

Saturation of partonic densities

(Color Glass Condensate)





→ High energies
→ Forward rapidities
→ Nuclei
→ Better in pA

pA as a benchmark for the bulk particle production

The nuclear structure at high energies

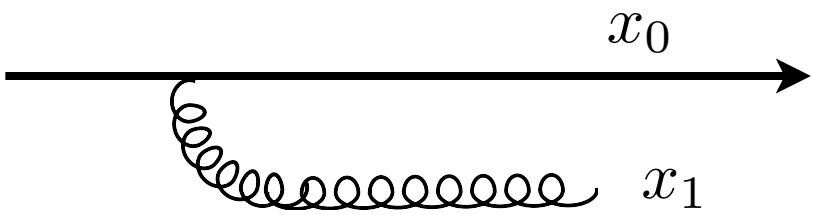
⇒ We want to know the structure of the colliding system at high energies - and eventually the initial state of the medium

The nuclear structure at high energies

⇛ We want to know the structure of the colliding system at high energies - and eventually the initial state of the medium

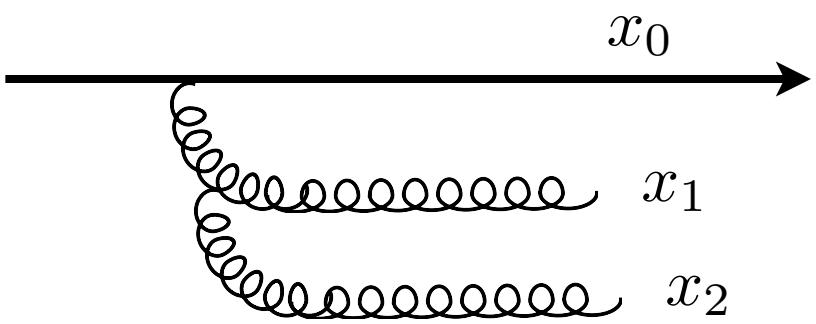
⇛ Start by a simpler one: dipole-nucleus collision

Gluon multiplication: heuristic argument



$$dP(x_1) = \alpha_s \frac{dx_1}{x_1}$$

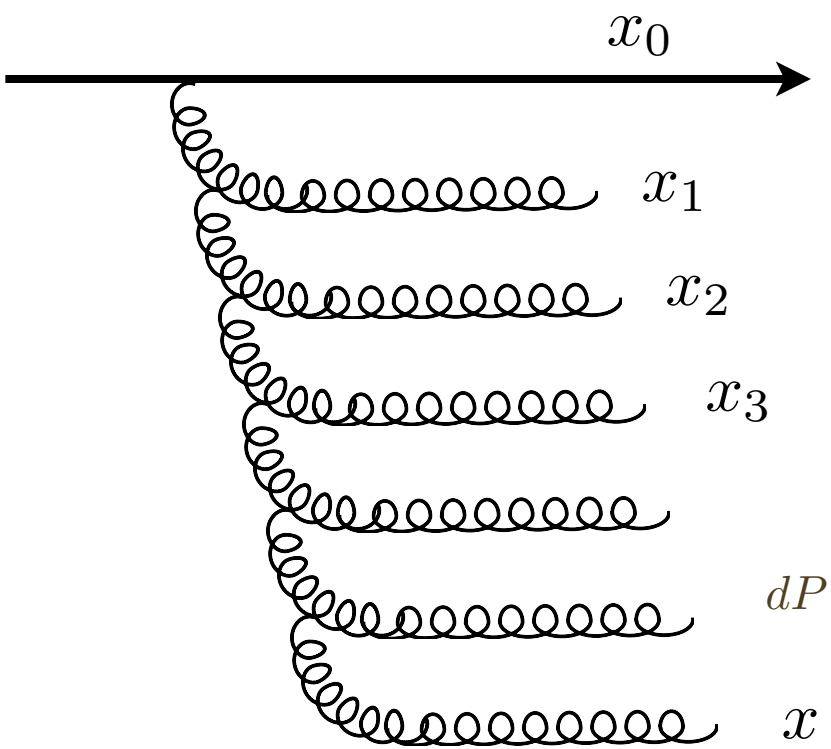
Gluon multiplication: heuristic argument



$$dP(x_1) = \alpha_s \frac{dx_1}{x_1}$$

$$dP(x_2) = \alpha_s \frac{dx_2}{x_2} \int_{x_2}^{x_0} \alpha_s \frac{dx_1}{x_1}$$

Gluon multiplication: heuristic argument

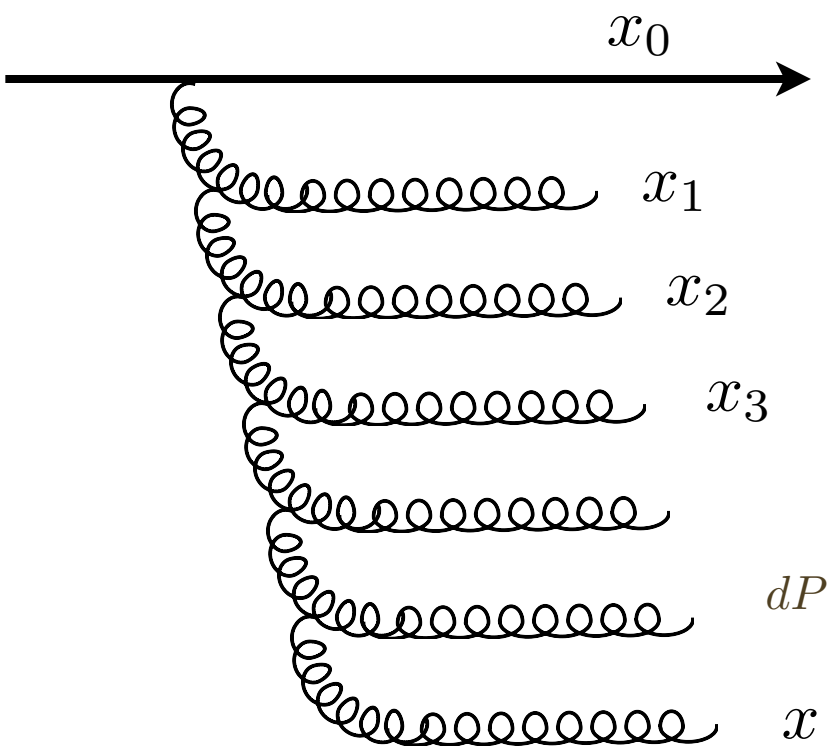


$$dP(x_1) = \alpha_s \frac{dx_1}{x_1}$$

$$dP(x_2) = \alpha_s \frac{dx_2}{x_2} \int_{x_2}^{x_0} \alpha_s \frac{dx_1}{x_1}$$

$$dP(x) = \alpha_s \frac{dx}{x} \int_{x}^{x_0} \alpha_s \frac{dx_{n-1}}{x_{n-1}} \int_{x_{n-1}}^{x_0} \alpha_s \frac{dx_{n-2}}{x_{n-2}} \cdots \int_{x_2}^{x_0} \alpha_s \frac{dx_1}{x_1}$$

Gluon multiplication: heuristic argument



$$dP(x_1) = \alpha_s \frac{dx_1}{x_1}$$

$$dP(x_2) = \alpha_s \frac{dx_2}{x_2} \int_{x_2}^{x_0} \alpha_s \frac{dx_1}{x_1}$$

$$dP(x) = \alpha_s \frac{dx}{x} \int_{x}^{x_0} \alpha_s \frac{dx_{n-1}}{x_{n-1}} \int_{x_{n-1}}^{x_0} \alpha_s \frac{dx_{n-2}}{x_{n-2}} \cdots \int_{x_2}^{x_0} \alpha_s \frac{dx_1}{x_1}$$

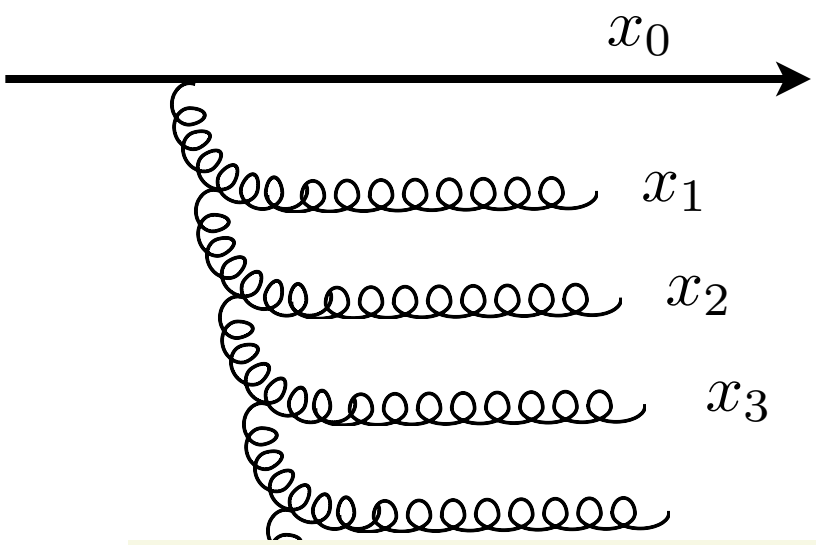
$$P_n(x) = \frac{1}{n!}\left[\int_x^{x_0} \alpha_s \frac{dx}{x}\right]^n = \frac{1}{n!}\left[\alpha_s \log \frac{x_0}{x}\right]^n \quad \Longrightarrow \quad P(x) = \sum_n P_n(x) = \exp\left[\alpha_s \log \frac{x_0}{x}\right]$$

⇛ This can be written as an evolution equation

$$\frac{dP(x)}{d\log x} = -\alpha_s\, P(x) \longrightarrow P(x) \sim x^{-\alpha_s}$$

Rise strongly with x

Gluon multiplication: heuristic argument



$$dP(x_1) = \alpha_s \frac{dx_1}{x_1}$$

$$dP(x_2) = \alpha_s \frac{dx_2}{x_2} \int_{x_2}^{x_0} \alpha_s \frac{dx_1}{x_1}$$

$$\frac{x_{n-2}}{x_{n-2}} \cdots \int_{x_2}^{x_0} \alpha_s \frac{dx_1}{x_1}$$

In fact (BFKL eq.)

$$N_{\text{linear}}(x) \sim x^{-\lambda} \qquad \text{with} \qquad \lambda = \frac{\alpha_s N_c}{\pi} 4 \log 2$$

$$P_n(x) = \frac{1}{n!} \left[\int_x^1 \frac{\alpha_s}{x} \right]^n = \frac{1}{n!} \left[\alpha_s \log \frac{1}{x} \right]^n \longrightarrow P(x) = \sum_n P_n(x) = \exp\left[\alpha_s \log \frac{x_0}{x} \right]$$

⇒ This can be written as an evolution equation

$$\frac{dP(x)}{d \log x} = -\alpha_s P(x) \longrightarrow P(x) \sim x^{-\alpha_s}$$

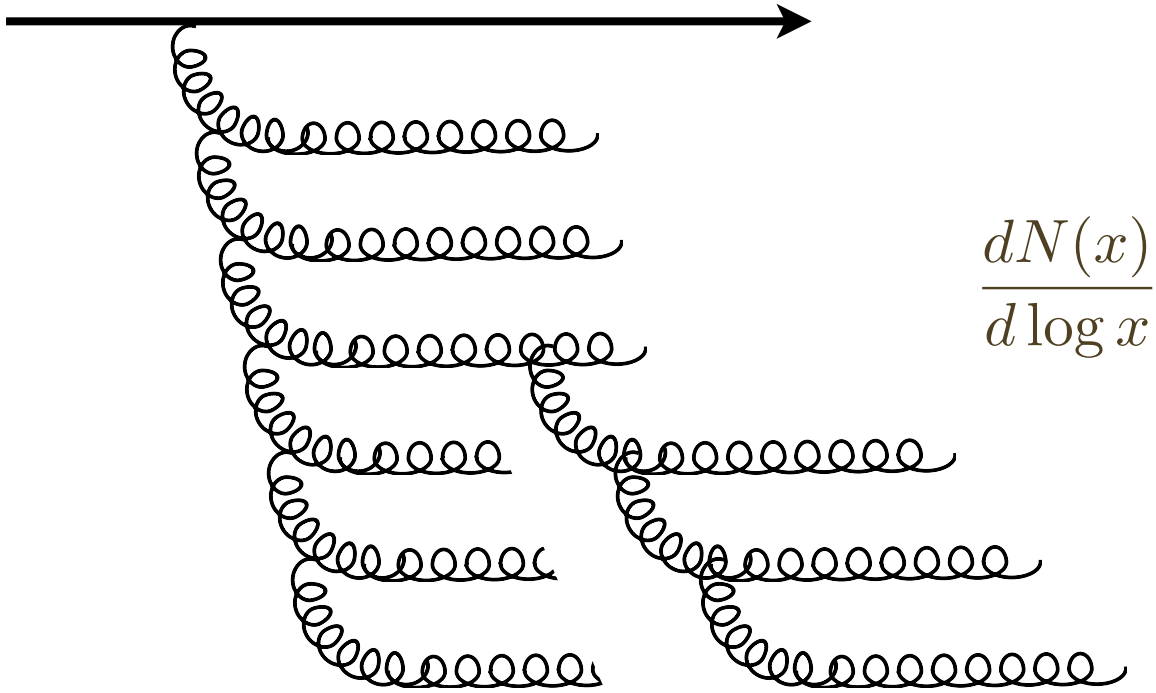
Rise strongly with x

Unitarity

⇛ However, unitarity implies that $N(x) \sim x^{-\lambda} \leq 1$

⇛ For a given value of x the above description is no longer valid

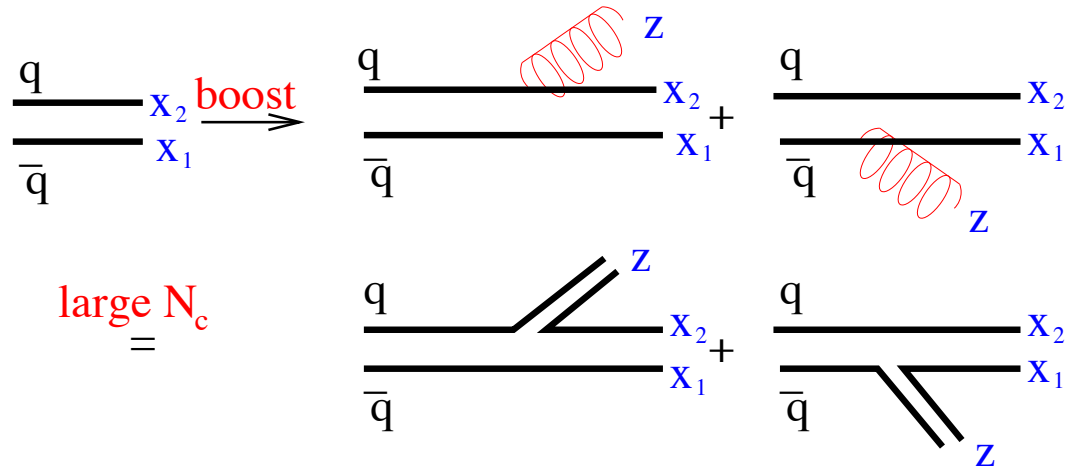
➘ Non-linear terms appear in the evolution equation



$$\frac{dN(x)}{d\log x} = -\alpha_s \left[N(x) - N(x)^2\right]$$

The Balitsky-Kovchegov equation

- In the large-N limit, a gluon as a double line
- Two new dipoles appear, both of which can interact independently



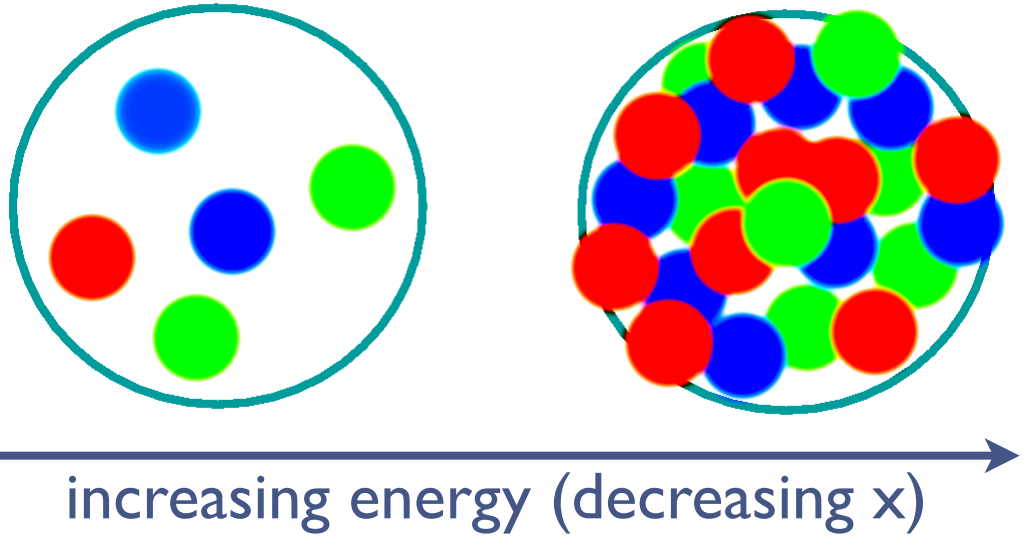
- The evolution equation for the forward scattering amplitude reads

$$\frac{\partial N(r,x)}{\partial \log x} = -\frac{\alpha_s N_c}{\pi} \int \frac{d^2 z}{2\pi} \frac{r^2}{r_1^2 r_2^2} \left[N(r_1,x) + N(r_2,x) - N(r,Y) - N(r_1,x) N(r_2,x) \right]$$

- Improvement in the last ~3 years: compute NLO corrections
  - Allows comparison with experimental data

Color screening in partonic densities: picture

Saturation scale when interaction probability becomes $\mathcal{O}(1)$



increasing energy (decreasing x)

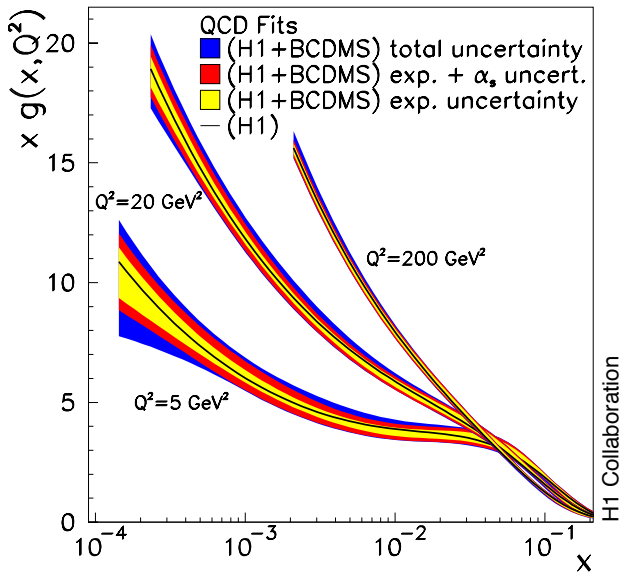
transverse area of the gluon

$$\alpha_s \frac{1}{Q^2_{\rm sat}} A N_g(x, Q^2_{\rm sat}) \sim \pi R_A^2$$

transverse area of the nucleus

$$R_A \sim A^{1/3}$$

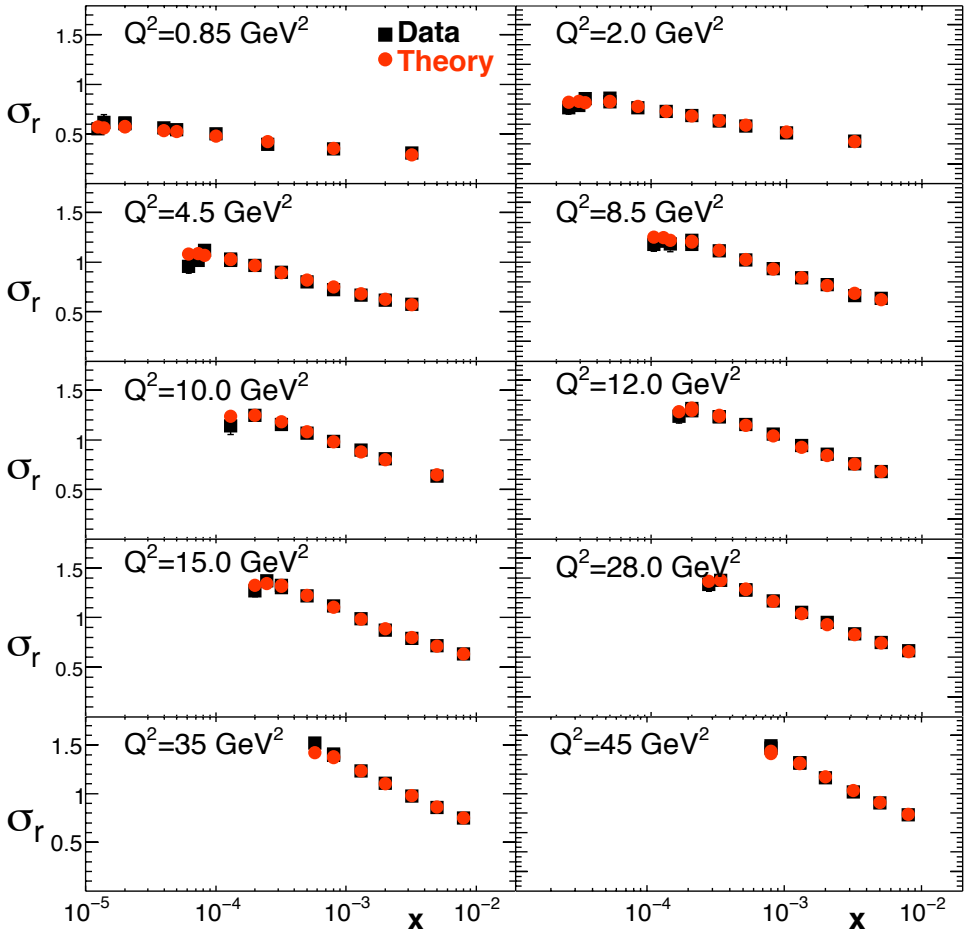
$$N_g \sim \frac{1}{x^\lambda} \quad \Longrightarrow \quad Q^2_{\rm sat} \sim \frac{A^{1/3}}{x^\lambda}$$



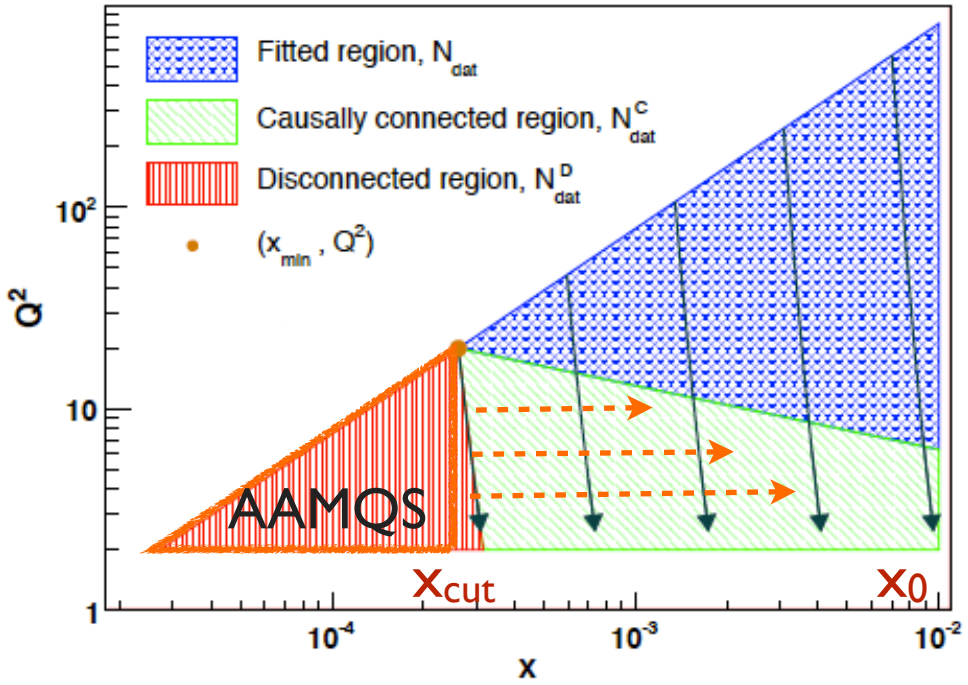
Strong fields and large occupation numbers.
Semiclassical approach: Color Glass Condensate
Geometric scaling

Precision checks of saturation boundary

[AAMQS 2010]



[Quiroga et al in preparation]

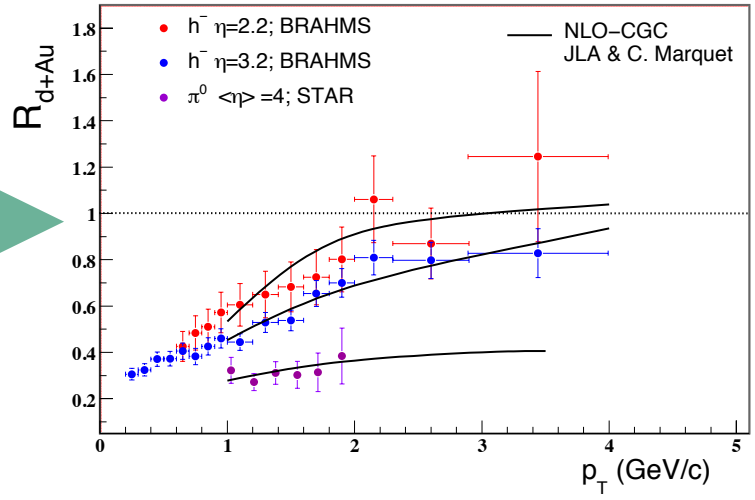


Check evolution in an (as much as possible) unbiased way

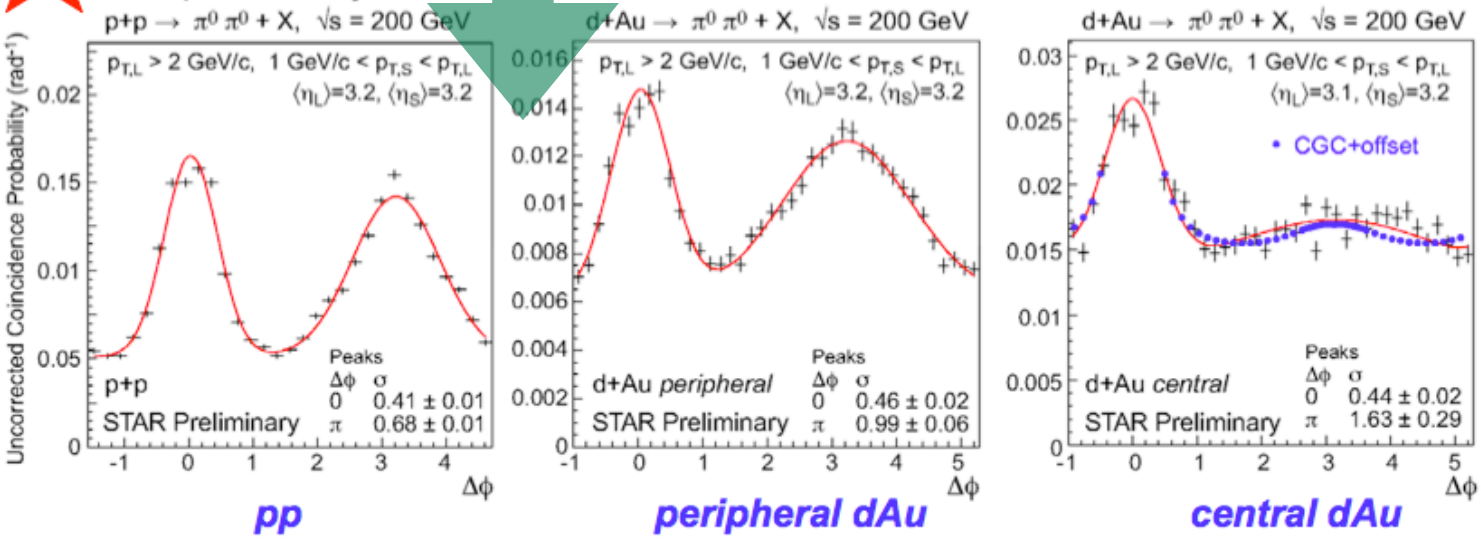
Fits to HERA data with rcBK equations rather successful

Hits of saturation: RHIC@forward rapidities

- Suppression of yields
  - Small-x evolution



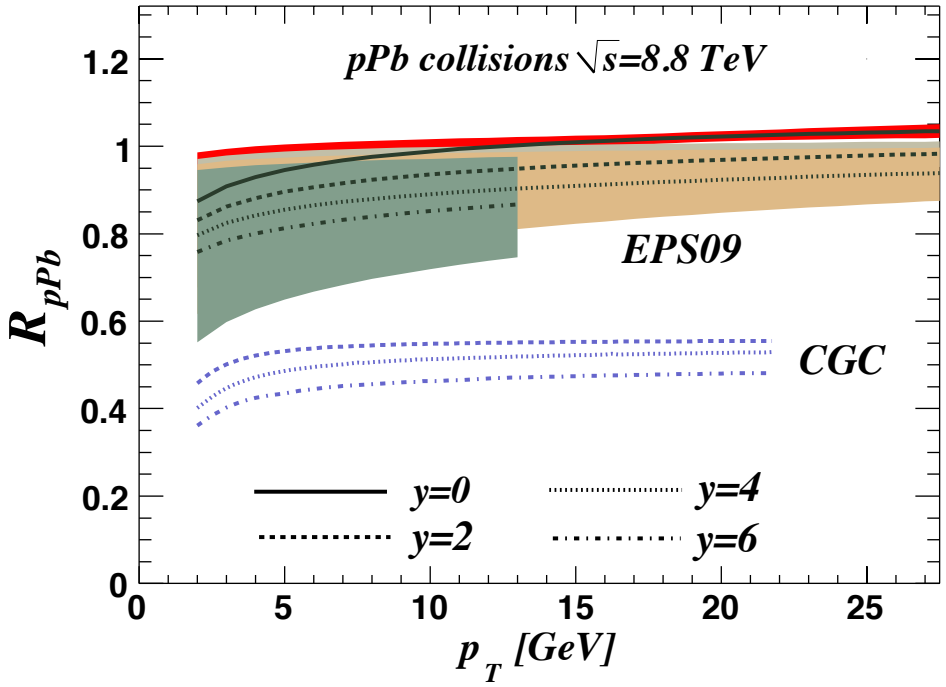
- Disappearance of back-to-back
  - Broadening



- PHENIX: forward-forward and central-forward studied

Extrapolating to the LHC

Normalization of the ratio is model dependent if cross-sections not measured



[Milhano, Quiroga, Wiedemann, 2010]

[Albacete, Marquet, 2010]

CGC computed with yields (+Glauber)

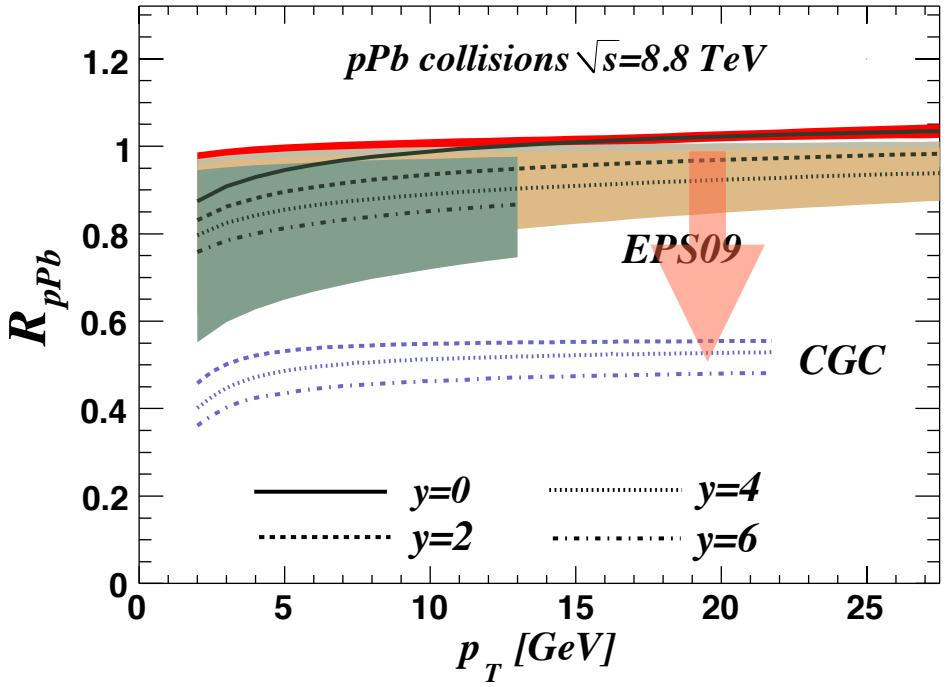
EPS09 computed with cross-sections

$$R_{\rm pA} \equiv \frac{1}{A}\frac{d\sigma^{\rm pA}/dp_T}{d\sigma^{\rm pp}/dp_T} = \frac{\sigma^{\rm inel}_{\rm pA}}{A\,\sigma^{\rm inel}_{\rm pp}}\frac{dN^{\rm pA}/dp_T}{dN^{\rm pp}/dp_T} \simeq \frac{1}{\langle N_{\rm coll}\rangle}\frac{dN^{\rm pA}/dp_T}{dN^{\rm pp}/dp_T}$$

Difficult to compare theoretical expectations and to distinguishing the relevant dynamics. A solid proof of saturation needs improvements on these issues

Extrapolating to the LHC

Normalization of the ratio is model dependent if cross-sections not measured



[Milhano, Quiroga, Wiedemann, 2010]

[Albacete, Marquet, 2010]

CGC computed with yields (+Glauber)

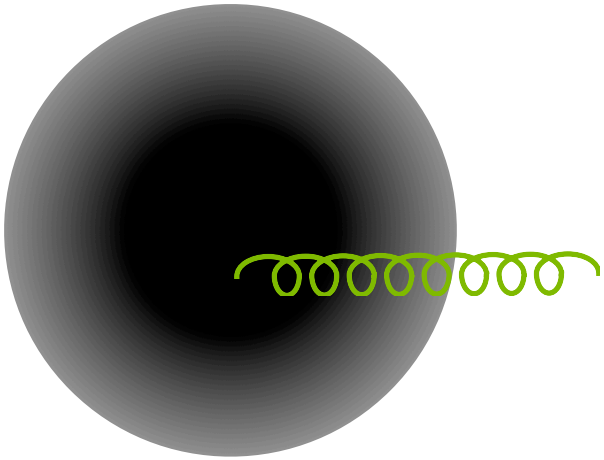
EPS09 computed with cross-sections

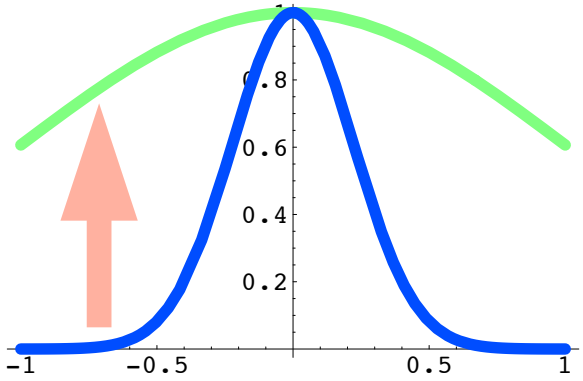
Glauber model

$$R_{\rm pA} \equiv \frac{1}{A}\frac{d\sigma^{\rm pA}/dp_T}{d\sigma^{\rm pp}/dp_T} = \frac{\sigma^{\rm inel}_{\rm pA}}{A\,\sigma^{\rm inel}_{\rm pp}}\frac{dN^{\rm pA}/dp_T}{dN^{\rm pp}/dp_T} \simeq \frac{1}{\langle N_{\rm coll}\rangle}\frac{dN^{\rm pA}/dp_T}{dN^{\rm pp}/dp_T}$$

Difficult to compare theoretical expectations and to distinguishing the relevant dynamics. A solid proof of saturation needs improvements on these issues

The problem of impact parameter

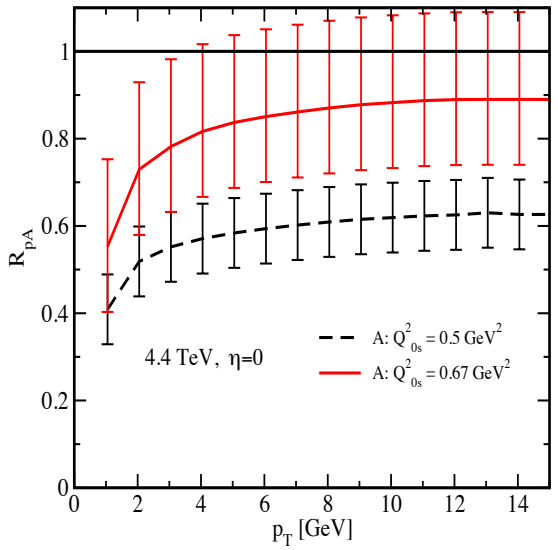


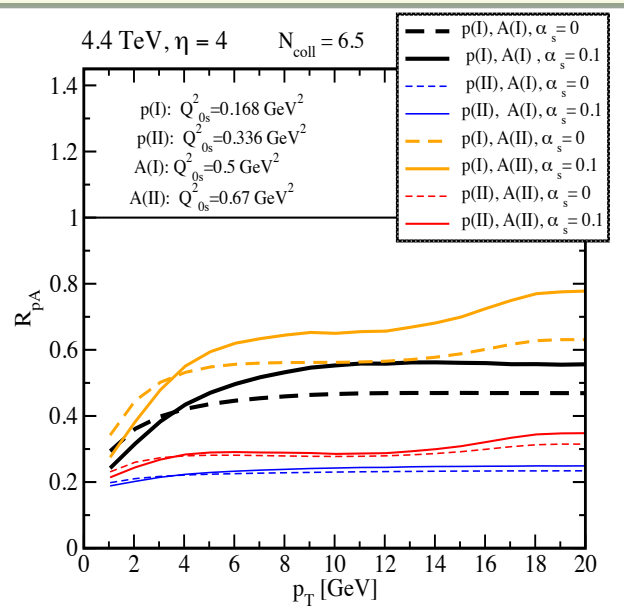


Impact parameter

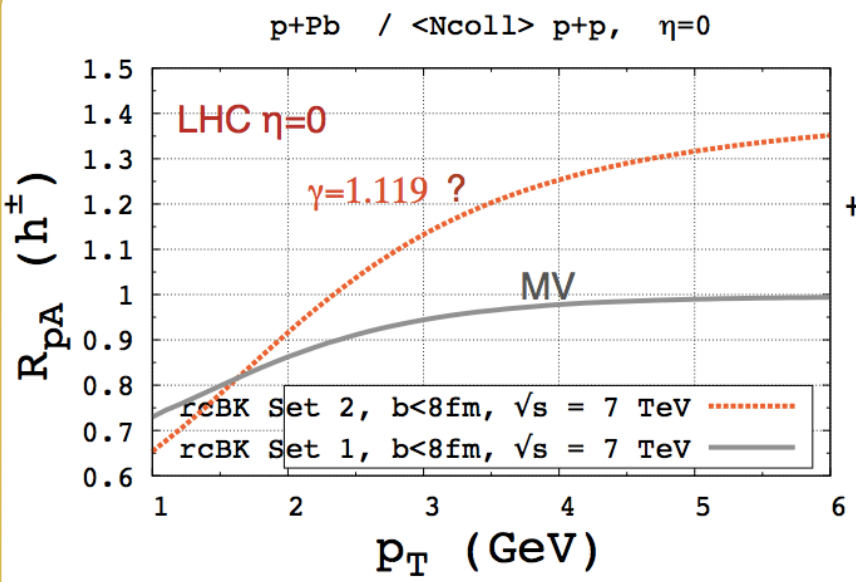
- The BK equations are perturbative
  - The gluon (dipole) can be emitted at arbitrary distances
  - Equivalent to Weizsacker-Williams photons in QED
- Tails grow too fast to describe experimental data
- Impact parameter integration difficult
  - Groth knows about confinement (not included in pert. BK)
  - Needs of regulator/cut-off

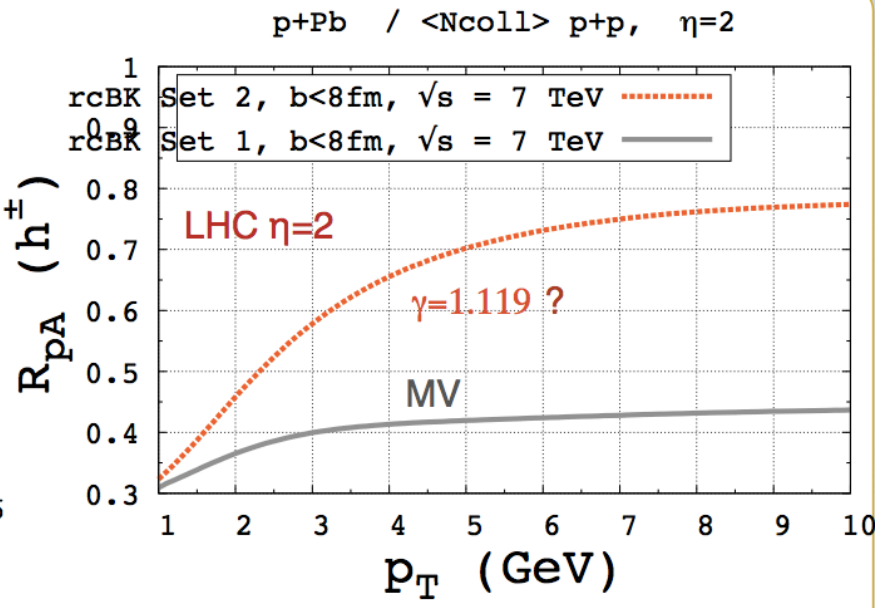
Geometry implemented by Monte Carlo





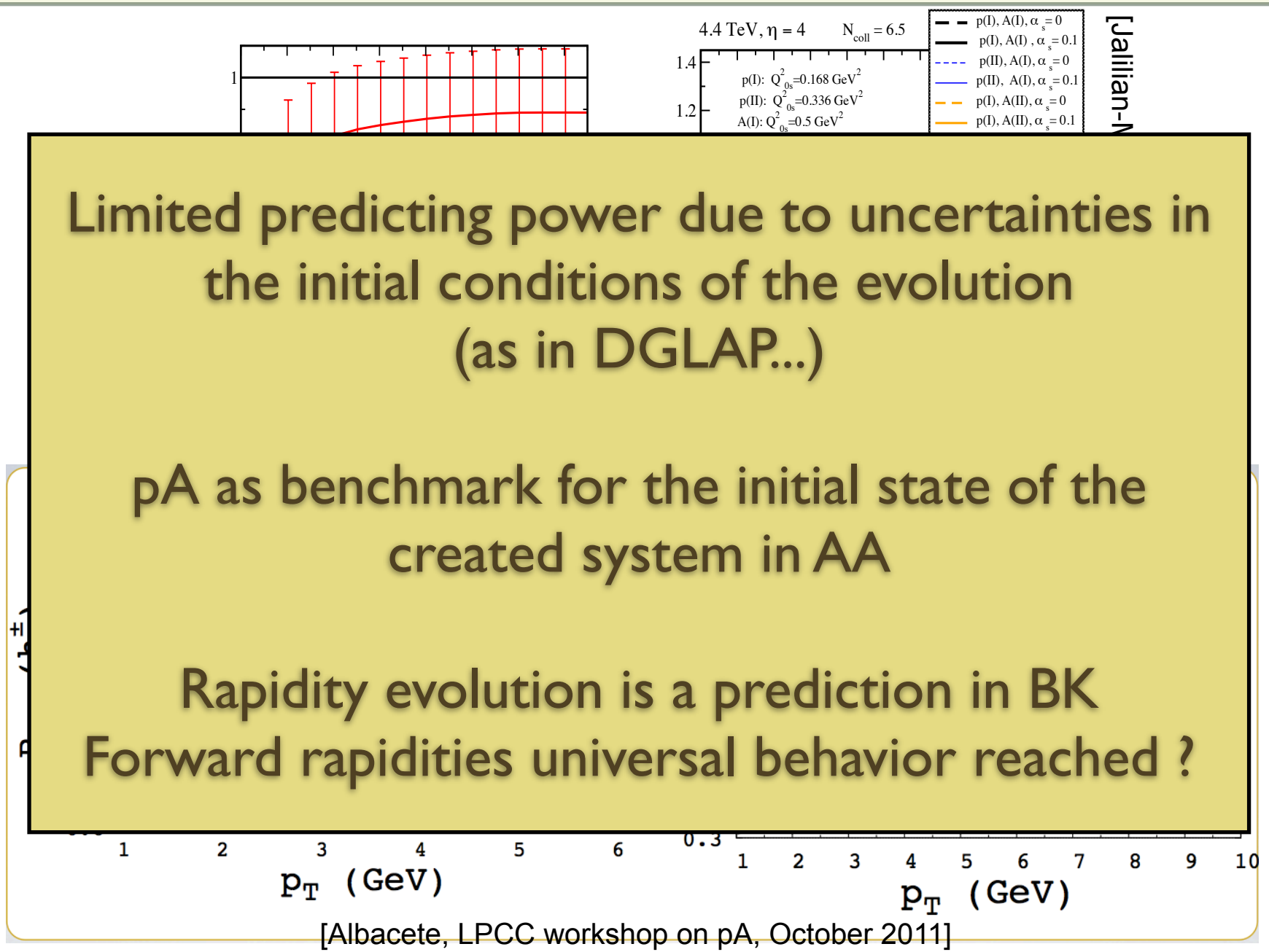
[Jalilian-Marian, Rezaeian 2011]





[Albacete, LPCC workshop on pA, October 2011]

Geometry implemented by Monte Carlo



Limited predicting power due to uncertainties in the initial conditions of the evolution (as in DGLAP...)

pA as benchmark for the initial state of the created system in AA

Rapidity evolution is a prediction in BK
Forward rapidities universal behavior reached ?

[Albacete, LPCC workshop on pA, October 2011]

GGC: Short list of theoretical developments

Evolution Equations BK-JIMWLK: $\frac{\partial \phi(x,k)}{\partial \ln(1/x)} = \mathcal{K} \otimes \phi(x,k) - \phi^2(x,k)\,; \quad \frac{\partial W[\rho]}{\partial Y} = ..$

- ✓ -Running coupling corrections [Balitsky, Kovchegov-Weigert, Gardi et at]
- ✗ -Full NLO kernel [Balitsky]
- ✗ -High-Q^2 effects (CCFM + saturation) [Avsar-Iancu]
- ✗ -Kinematic constraints & b-dependence in BK evolution [Berger-Stasto]
- ✗ - Subleading-N(c) corrections [kovchegov-Weigert]
- ...

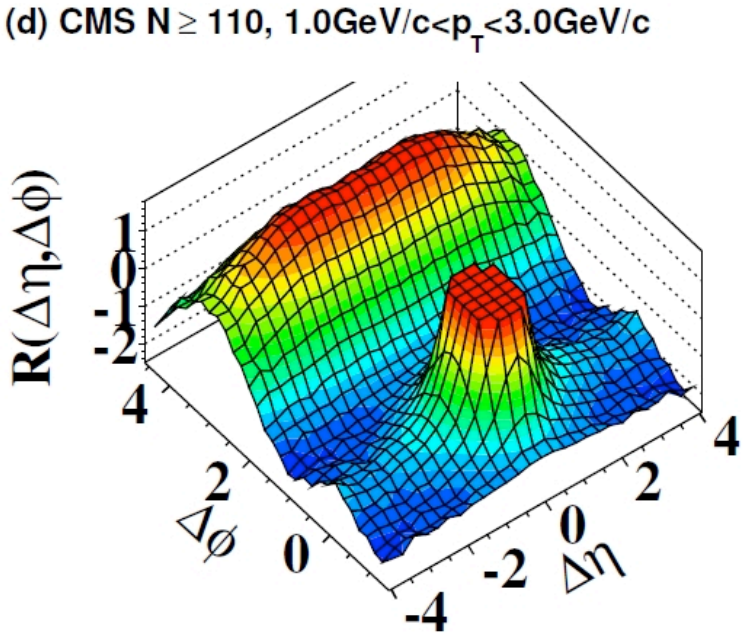
Production processes: $\frac{dN^{AB\to X}}{d^3p_1\ldots}[\phi(x,k); W_Y[\rho]]$

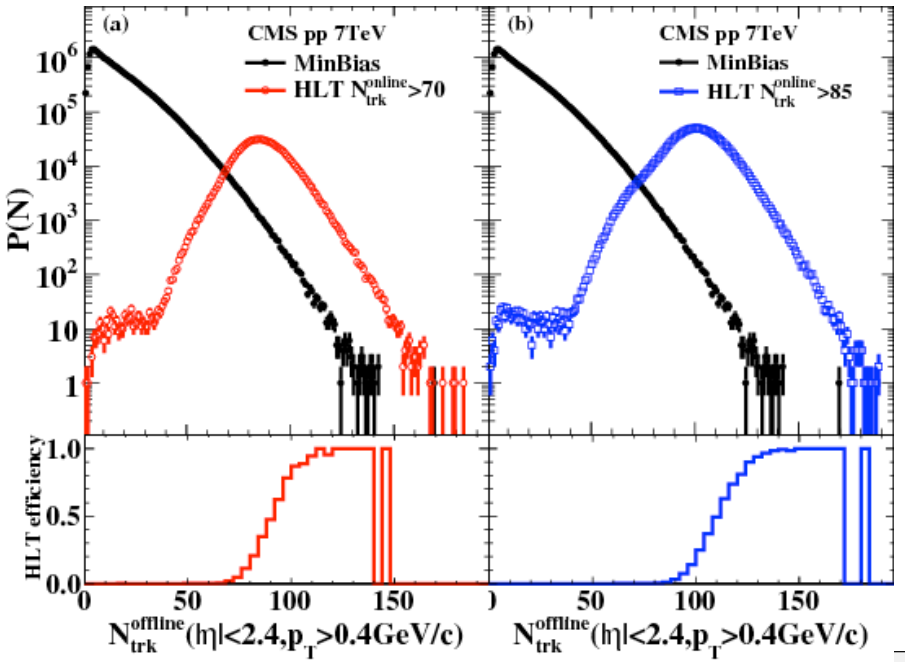
Slide shamelessly stolen from Albacete at QM

- ✓ - Factorization of multiparticle production processes [Gelis-Lappi-Venugopalan]
- ✗ - Analytic solutions to Yang-Mills EOM [Blaizot-Mehtar Tani-Lappi]
- ✗ - Running coupling corrections to kt-factorization [Kovchegov-Horowitz]
- ✗ - DIS NLO photon impact factors [Balitsky-Chirilli]
- ✓ - Di-hadron correlations [Dumitru-Jalilian Marian, Dominguez et al]
- ✗ - Progress in the hybrid formalism (CGC+pdf's) [Altinoluk-Kovner]
- ✗ - New observables beyond the large-Nc limit [Marquet-Weigert]
- ...

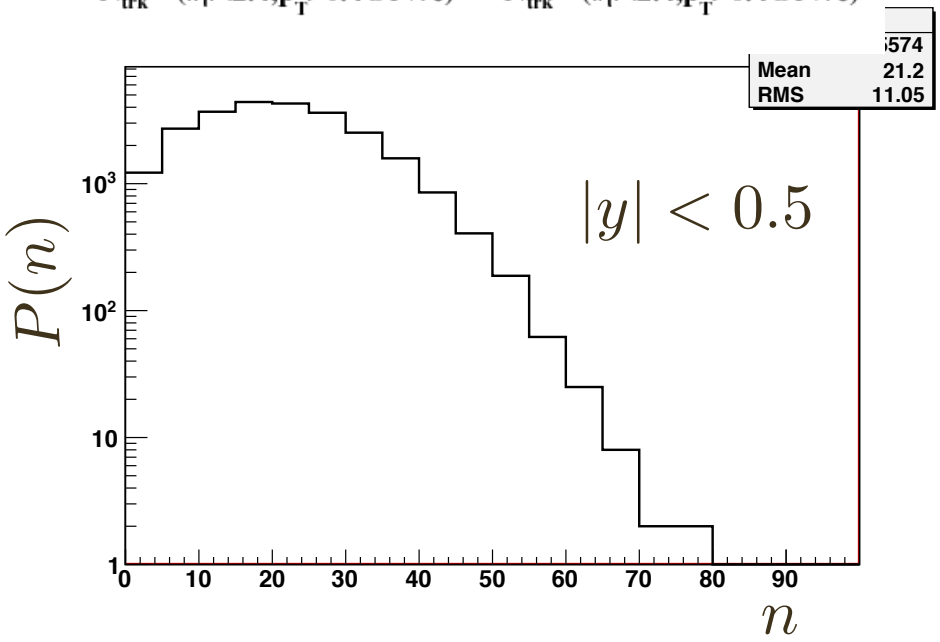
Used in phenomenological works? ✓ Yes ✗ No ✓A bit :)

High-multiplicity events in pPb



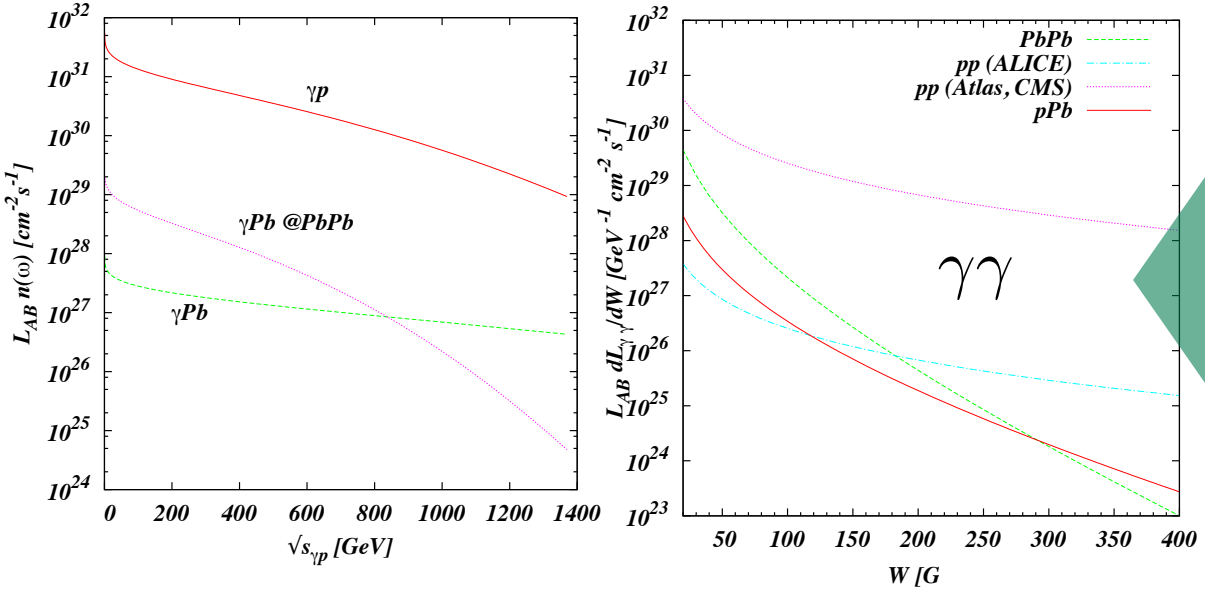


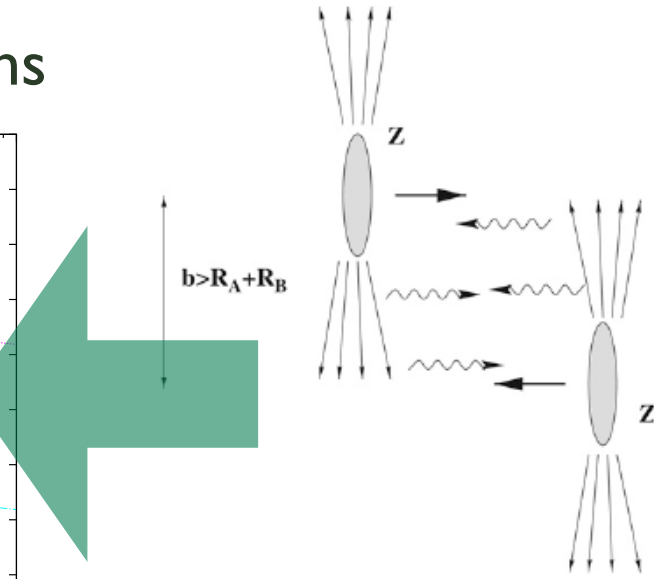
- Ridge measured in pp and AA
  - Interesting to see in pA
  - Large multiplicities possible
- Correlate with hard probes?
  - jets + pA high multiplicity
  - quarkonium + high mult....



Ultraperipheral collisions

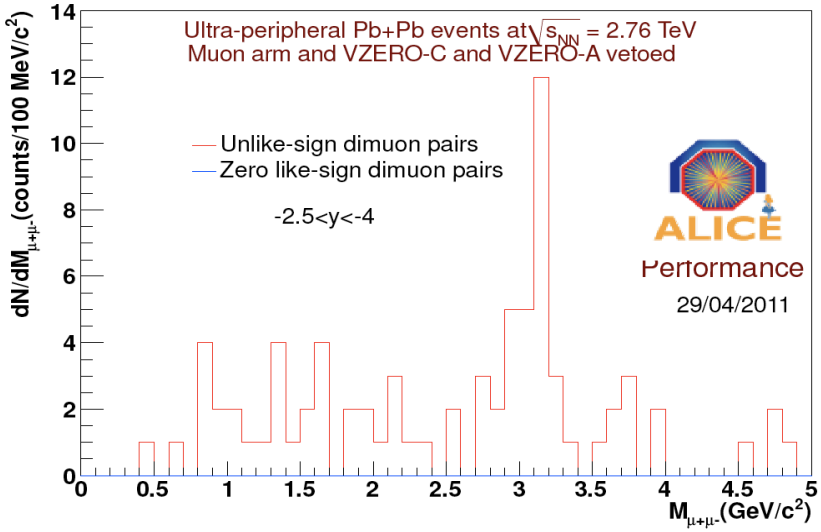
- Strong EM fields: flux of quasireal photons





[Baltz et al, Phys. Rept. 458 (2008) 1; also arXiv:1105.3919]

- A rich physics menu
  - Small-x physics
  - Spectroscopy
  - EW & BSM measurements
  - Luminosity monitor



Summary

- ***Proton-nucleus essential for benchmarking***
  - Hard processes
  - Bulk particle production
- ***Nuclear PDFs badly constrained at small-x***
  - pA only possibility to reduce uncertainties
  - Very standard technology but data needed
- ***Saturation of partonic densities***
  - pA provide excellent opportunities
  - (only chance before a ep/eA collider)
- ***More opportunities***
  - High-multiplicity events
  - Ultraperipheral collisions
  - Measurements of astrophysical interest