An Experimental Perspective on Hard Probes in p(d)+A Collisions

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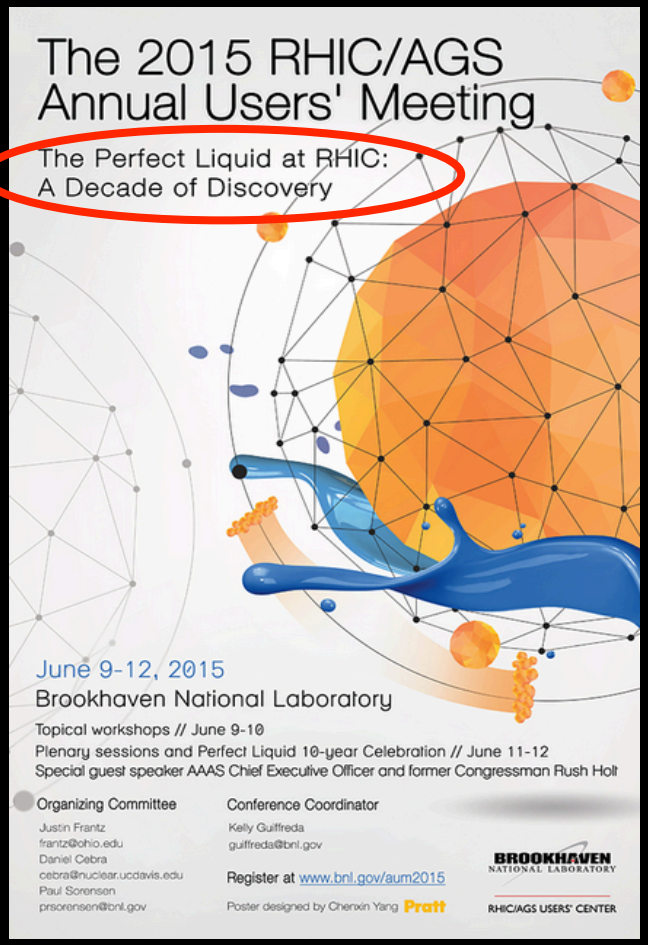
Outline

- Why hard probes in small systems?
- Modification of parton distribution functions in nuclei
- Hard photons as a gateway to low-x phenomena
- Geometry characterization in p(d)+A

Why Small Systems?

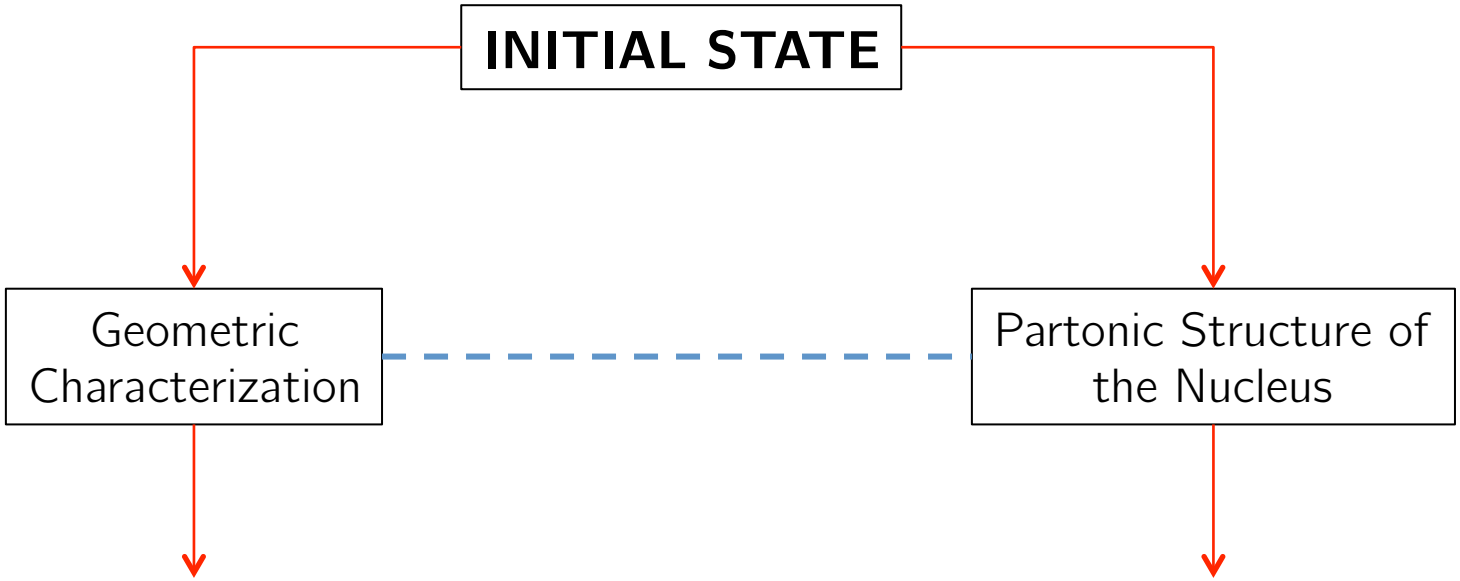
From the Discovery Phase...



We need to understand the initial state of the collision!

...To Precision Measurement

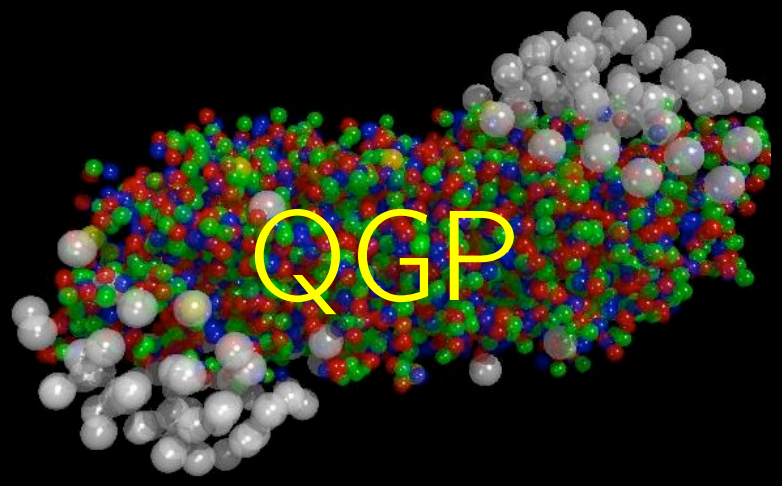
Why Small Systems?



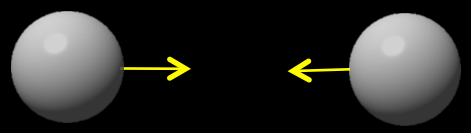
- Centrality
- N_{coll}
- N_{part}
- Eccentricity

- Emergent phenomena
- Nuclear wave function
- Critical for understanding production of hot bulk nuclear matter.

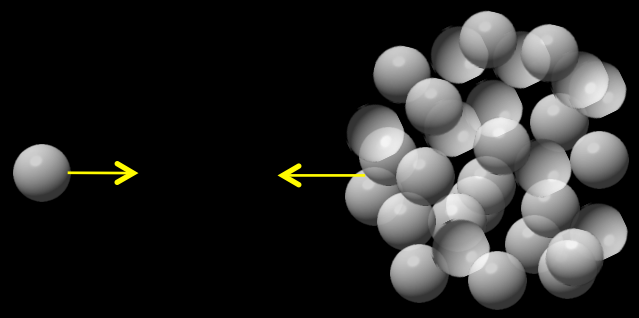
Why Small Systems?



What would constitute an appropriate baseline measurement?

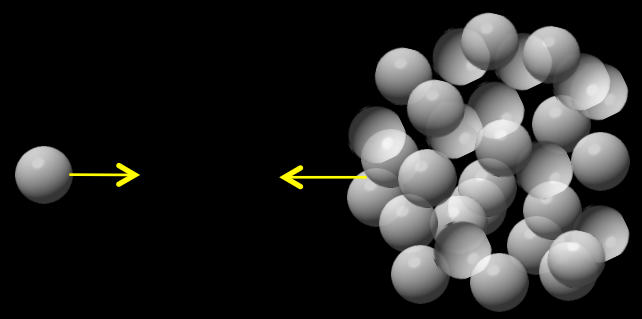


p+p



p(d) + A

Why Small Systems?



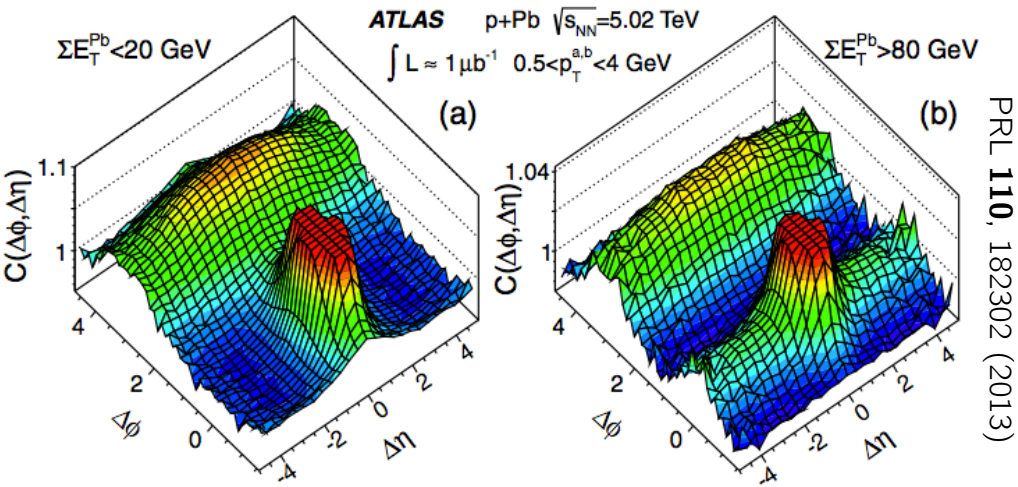
p(d) + A

The presence of the nuclear environment modifies the dynamics of hard partonic scattering, compared to a hadron-hadron collision baseline.

Cold Nuclear Matter Effects

- Modification of parton distribution functions in nuclei
- Gluon saturation
- Partonic energy loss
- Transverse momentum broadening of partons

Additionally... Collectivity in Small Systems

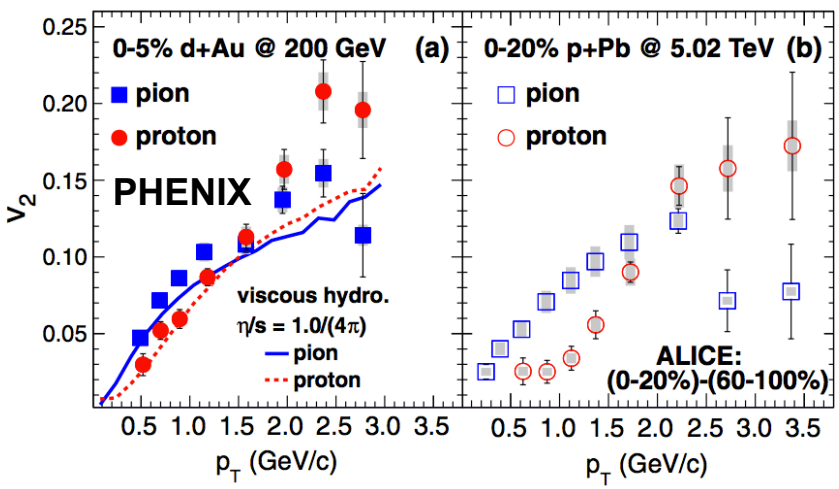


PRL **110**, 182302 (2013)

Is an understanding based on hydrodynamics valid?

Are there initial state effects at play?

How to disentangle them?



PRL **114**, 192301 (2015)

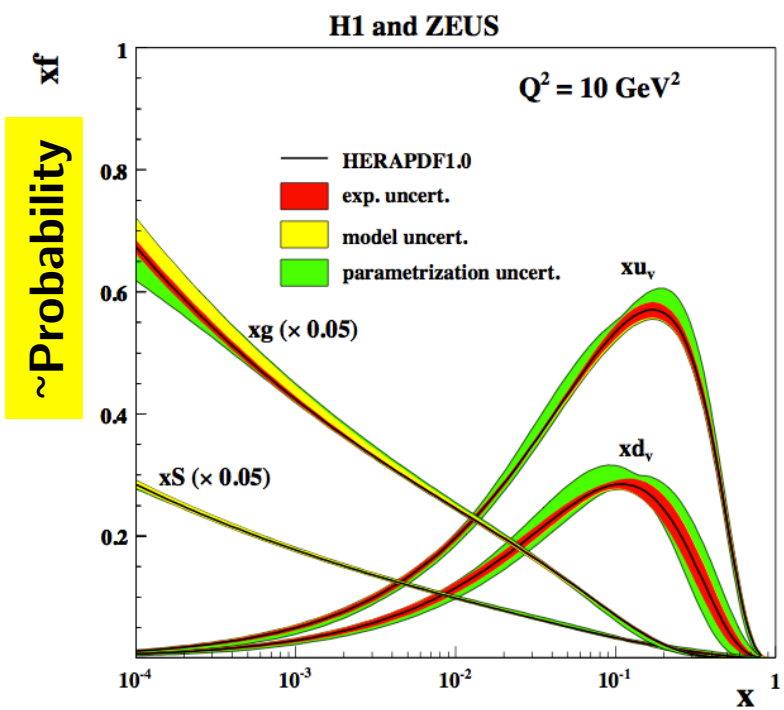
Recent results paint a more subtle picture of p(d)+A, one in which we can't neatly separate CNM from final-state effects.

In any case, knowledge of the initial state remains crucial.

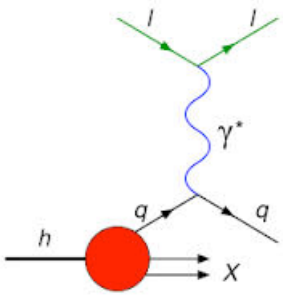
QCD From the Bottom Up: Parton Distributions

We can use perturbative QCD to understand hard processes involving quarks and gluons. Hadrons, however, are not amenable to such treatment.

Processes at Parton Level (High Q^2) ⟷ **Parton Distribution Function** ***f*** ⟷ Processes at Hadron Level



Pick a 'resolution' Q^2.



Probability of finding a parton carrying a given fraction of the hadron momentum.

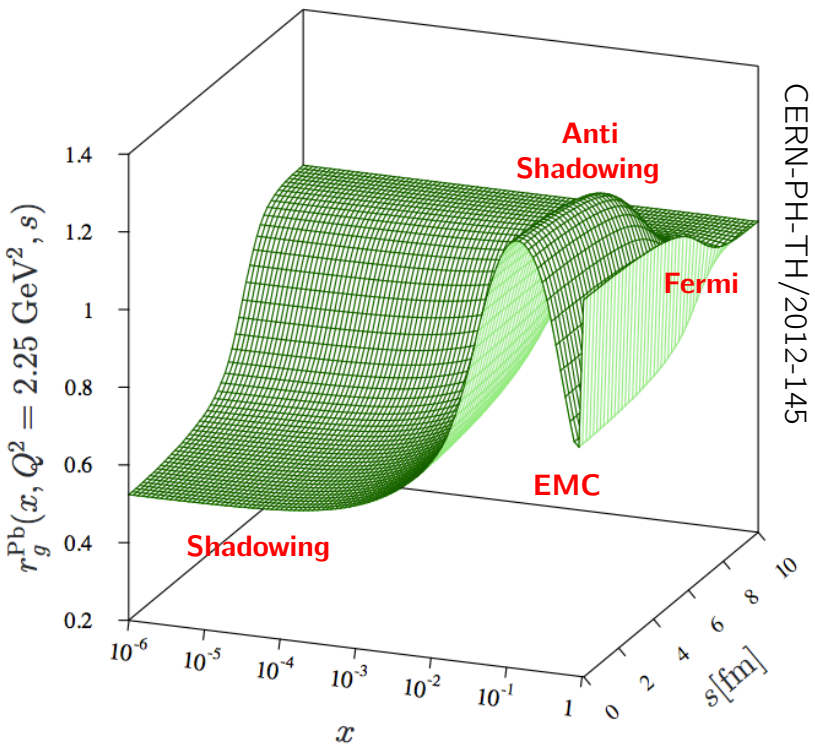
Important for understanding QCD bound states!

One Step Further: Nuclear Parton Distributions

The nuclear medium gives rise to modifications of the PDFs of nuclei relative to their individual nucleon counterparts.

$$R_i^A(x, Q^2) = \frac{1}{A} \frac{f_i^A(x, Q^2)}{f_i^p(x, Q^2)}$$

Universal in x and Q^2



CERN-PH-TH/2012-145

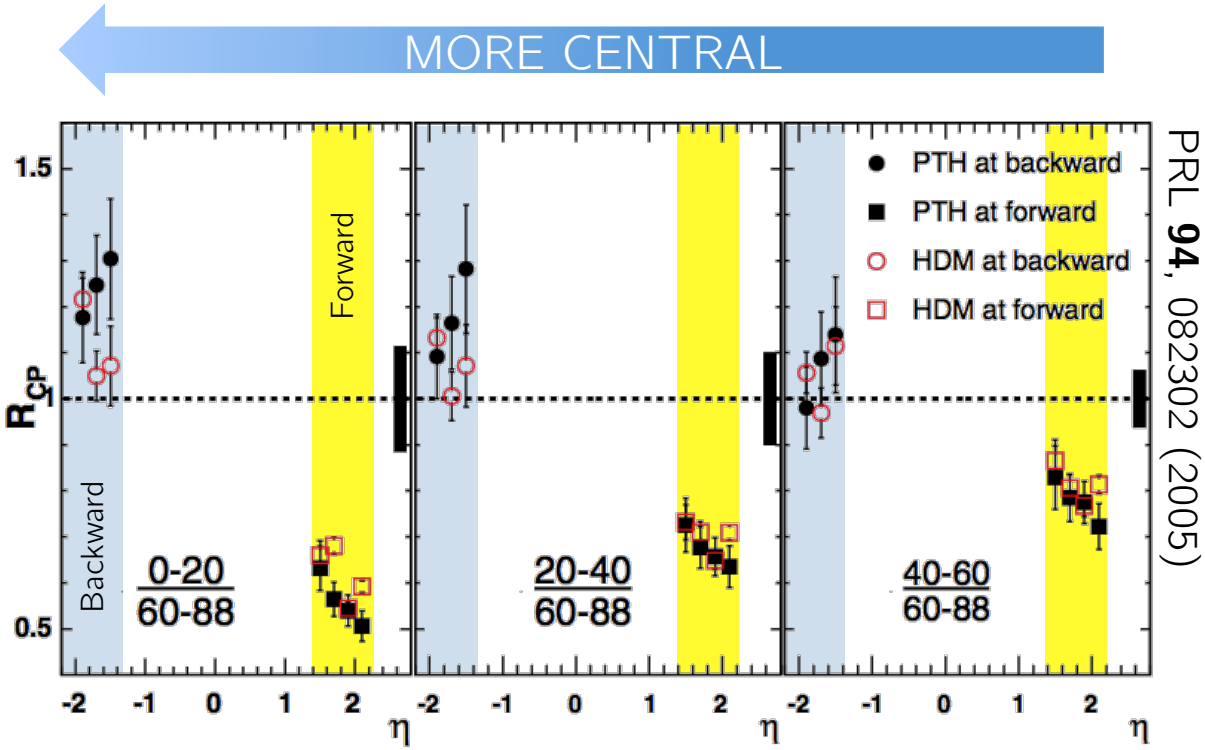
Precise knowledge of the nPDF is crucial for the interpretation of hard processes in heavy ion collisions.

Spatial (i.e., s) dependence of nPDF

Careful geometric characterization of experimental data

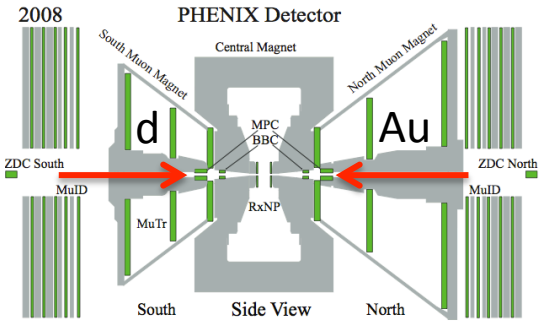
The Importance of Low-x

Experimental evidence for shadowing in d+Au. Hadron suppression at forward rapidity.



Low-x in Target

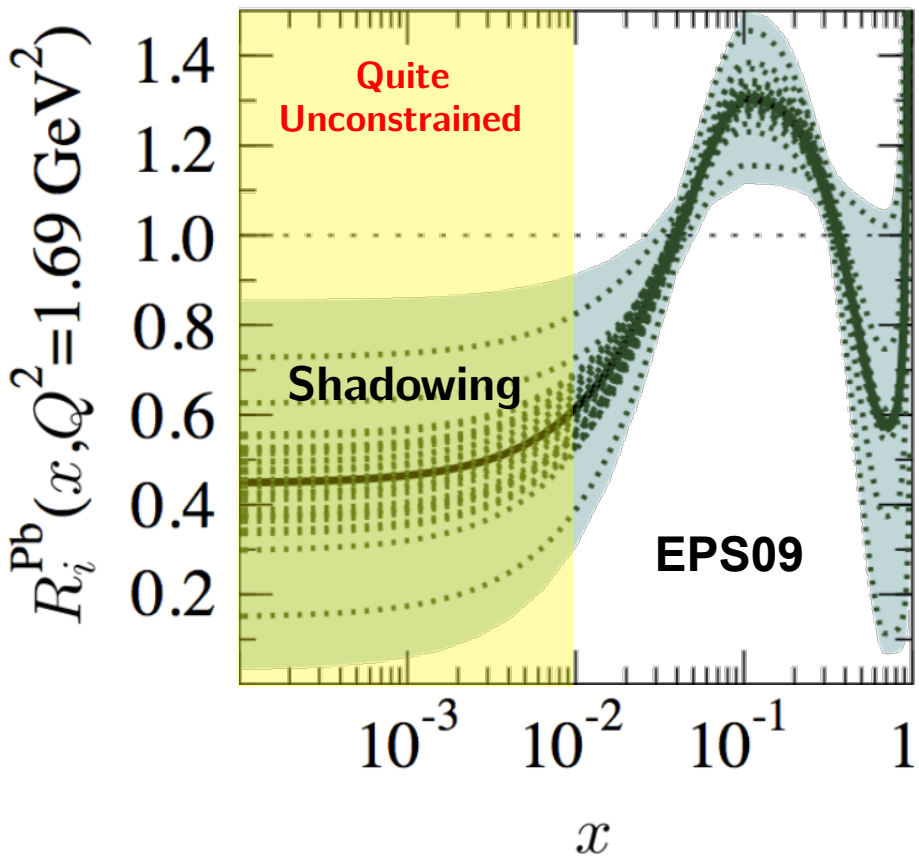
Forward Rapidity



However, 10 years later, we still need to fully understand nPDFs at low-x...

Unlocking Low-x Phenomena

Eskola, Paukkunen, Salgado JHEP 0904:065,2009



How to model low-x physics?

pQCD + NP Extensions?

Color Glass Condensate?

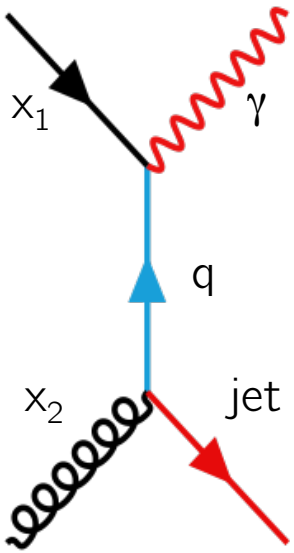
We currently lack data to fully characterize G at low x

→ Direct Photons

Critical region to understand the formation of bulk hot nuclear matter and the dynamics of partons in nuclei.

Unlocking Low-x Phenomena in PHENIX

Si-W EM Preshower + Tracking



PROMPT PHOTON
+
HIGH-ENERGY π^0 IN JET

Characterize gluon PDF at low x through measurement of **prompt photons**.

$$x_{gluon} = \frac{p_{T\gamma}}{\sqrt{s}}\left[e^{-\eta_\gamma} + e^{-\eta_\pi}\right]$$

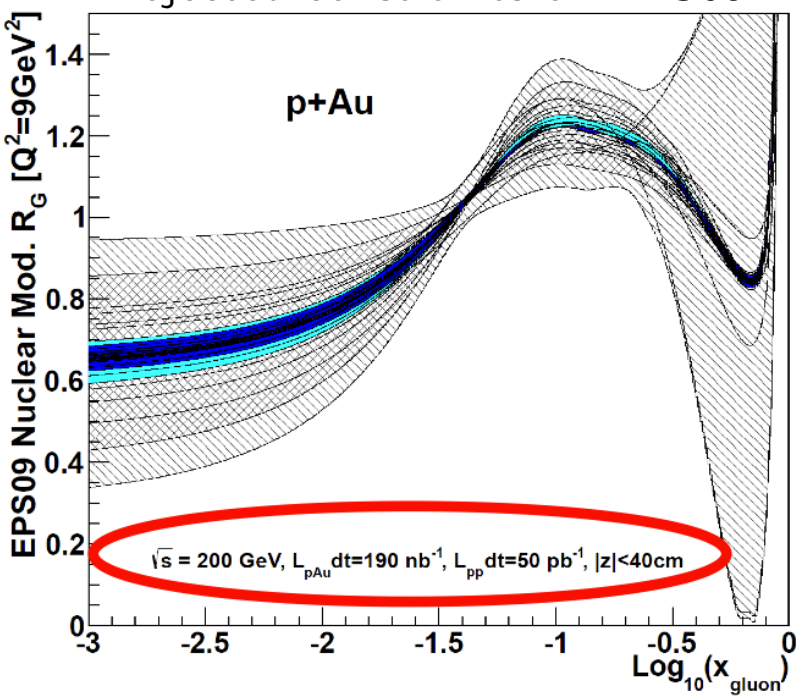
Extend the kinematic reach by correlating with pions at various rapidities

Measurements with Prompt Photons Alone

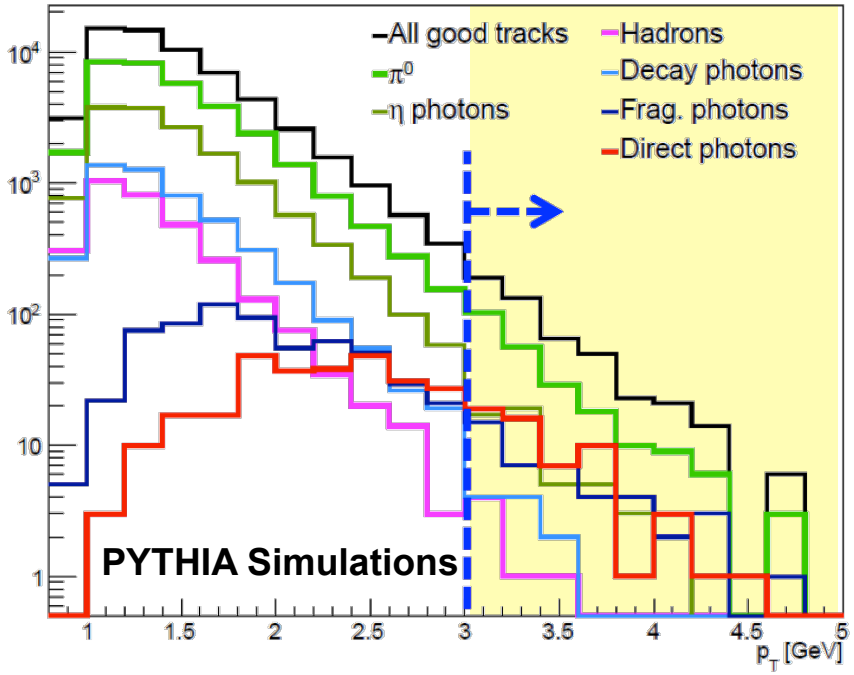
$$R_{pA} = \frac{1}{N_{coll}} \frac{\gamma^{pA}_{\text{prompt}}}{\gamma^{pp}_{\text{prompt}}}$$

Effectively measure gluon nPDF

Projected constraints on EPS09

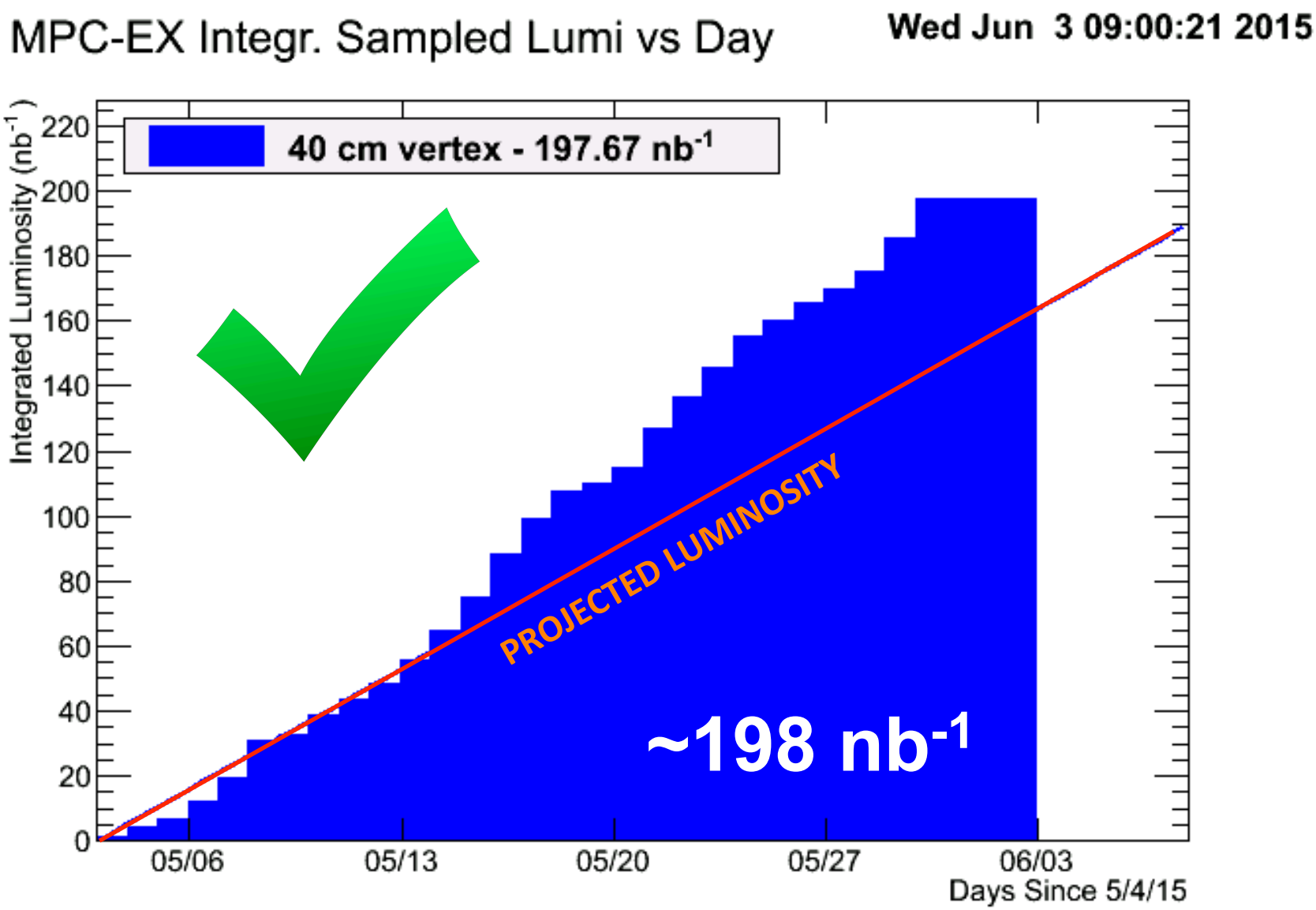


A lot of background to account for…

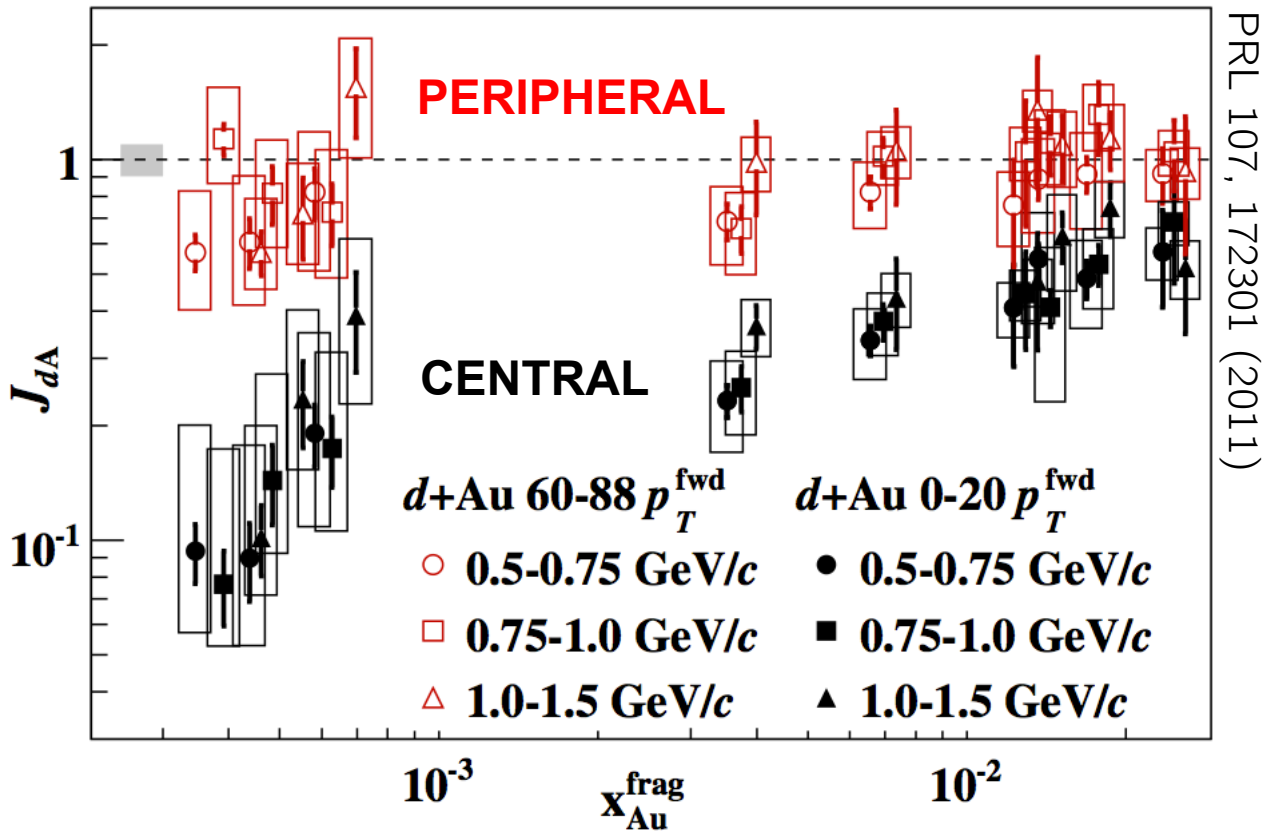


43% signal to π^0 ratio
30% photon efficiency
3% π^0 efficiency

Measurements with Prompt Photons Alone

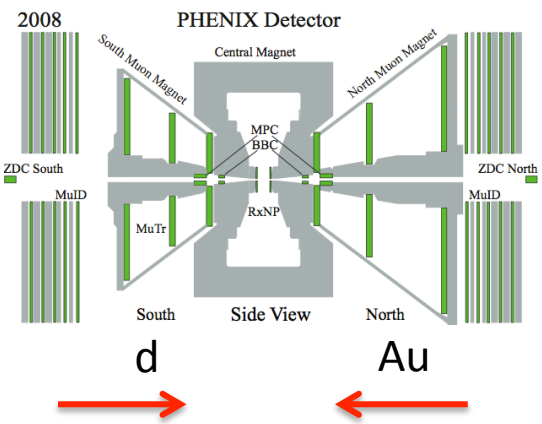


Measurements with Pions



PRL 107, 172301 (2011)

Measure forward-forward and mid-forward dihadron correlations with π^0s, leveraging the ability to measure pions out to high p_T.

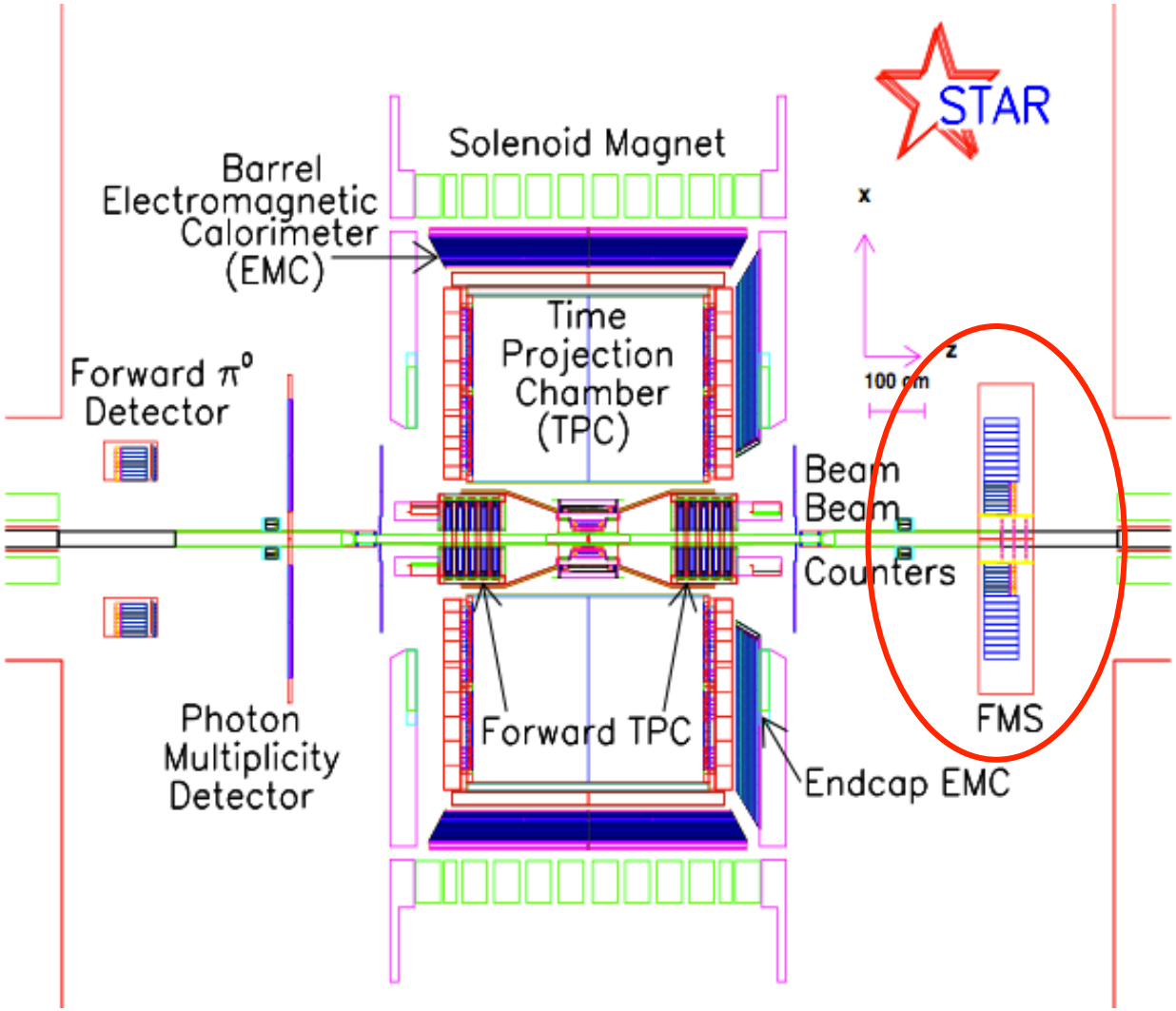


Two-pion correlations as a probe of saturation effects

$$J_{dA} = I_{dA} \times R^t_{dA} = \frac{1}{\langle N_{\rm coll}\rangle} \frac{\sigma^{\rm pair}_{dA}/\sigma_{dA}}{\sigma^{\rm pair}_{pp}/\sigma_{pp}}$$

= Relative yield of correlated back-to-back hadron pairs

Probing Low-x in STAR



Forward Meson Spectrometer + Preshower

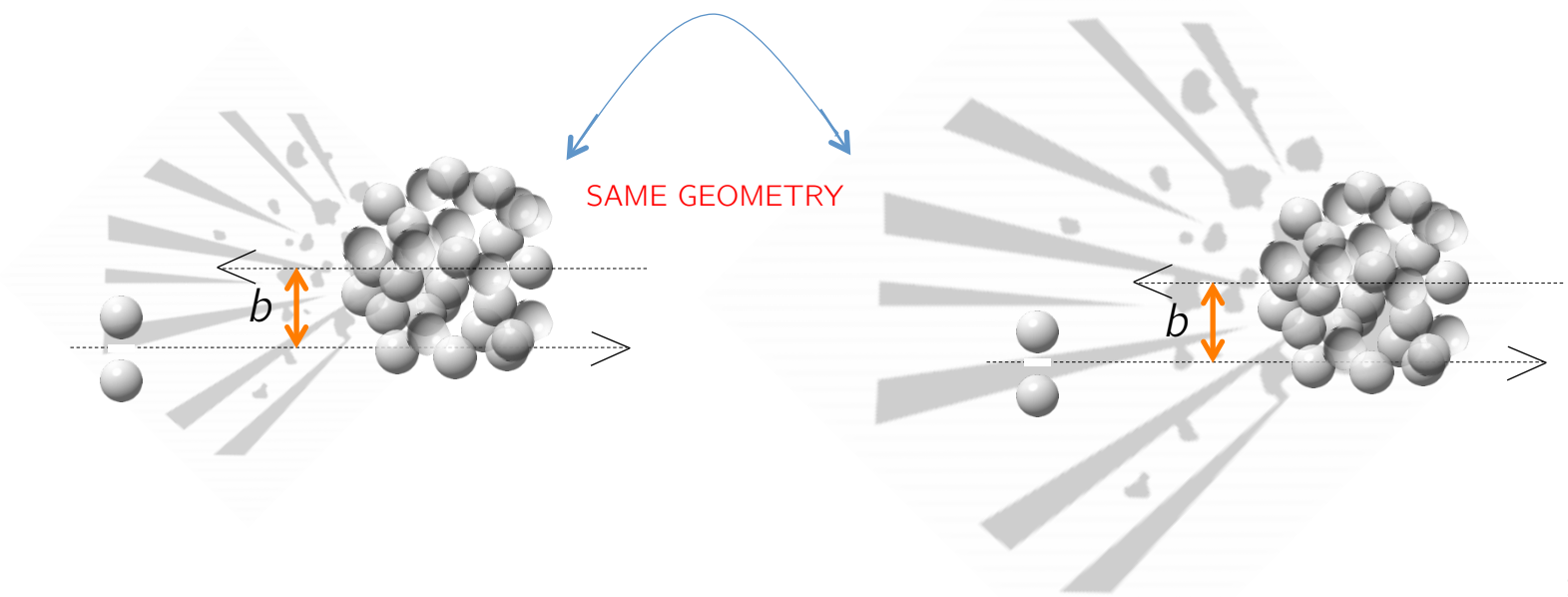
Categorizing Centrality in p(d)+Au

Physical Observable
Charge in Au-going Direction

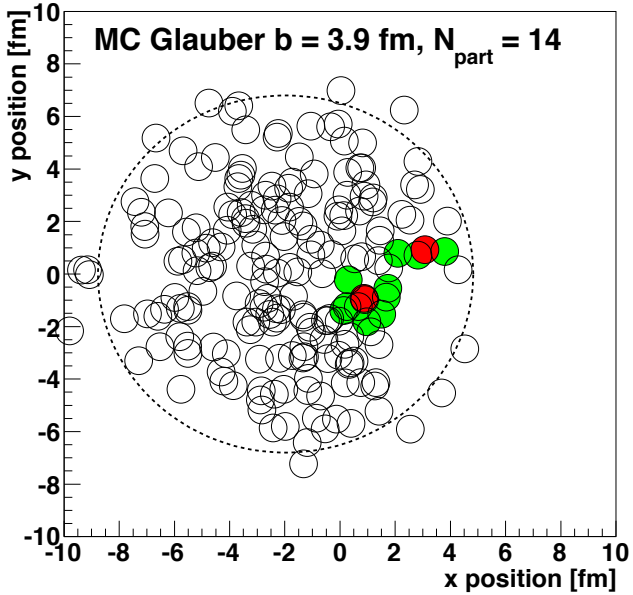
Event Geometry
N_{coll}, N_{part}, etc.

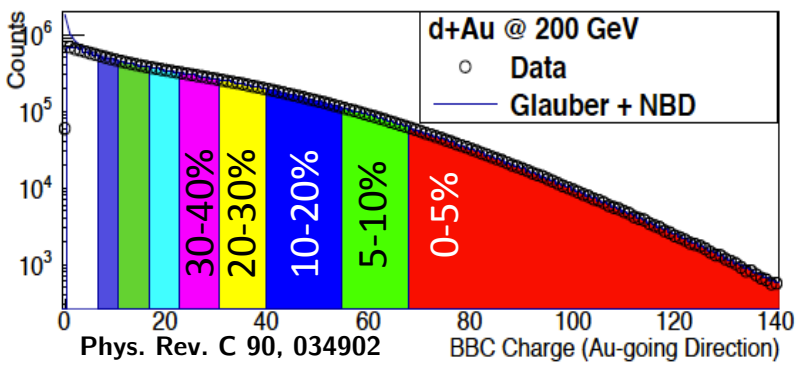
What is the nature of the relation between geometry and A-going charge?

How does this relation change in collisions with a hard scattering compared to minimum bias?



Centrality and the Glauber Model in a Nutshell





Phys. Rev. C 90, 034902

Au-going Charge $\propto$ N_{coll}

Fluctuations from Negative Binomial Distribution

$$NBD(x;\mu,\kappa) = \left(1+\frac{\mu}{\kappa}\right)\frac{(\kappa+x-1)!}{x!(\kappa-1)!}\left(\frac{\mu}{\mu+\kappa}\right)^{x}$$

μ,κ determined from fitting experimental data.

Fold in the Glauber N_{coll} distribution *Gl(n)*

$$P(x) = \sum_{n=1}^{N_{binary}(max)} Gl(n) \times NBD(x; n\mu, n\kappa)$$

Categorizing Centrality in p(d)+Au – Glauber Model

Au-going Multiplicity → **Event Geometry** → **Invariant Yields**

Consider p+p @ 200 GeV

BBC MB trigger fires 52% of the time

BBC MB trigger fires 75% of the time for events with charged particle at midrapidity

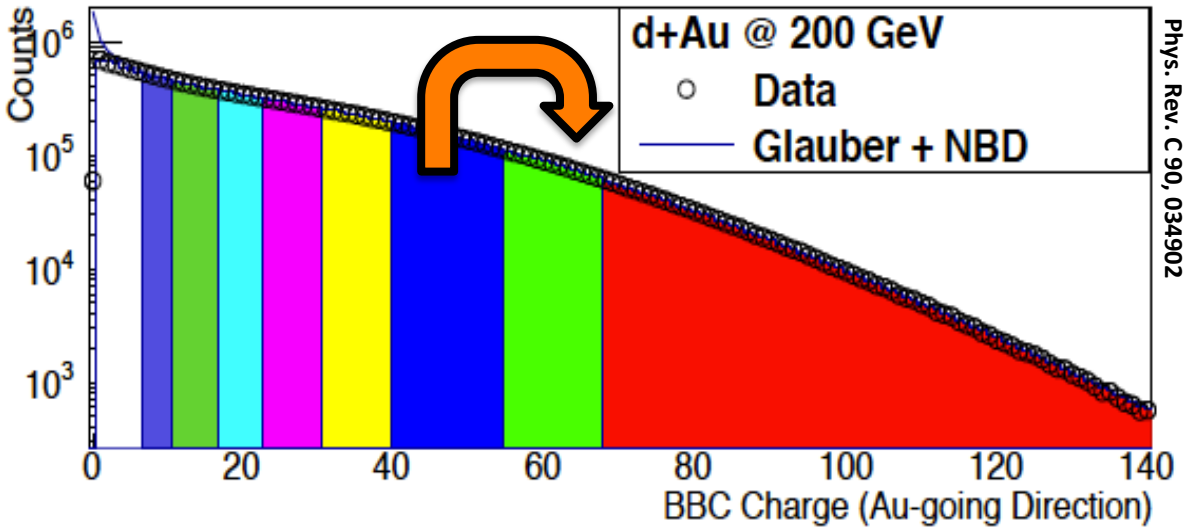
$$\sigma_{inel} = \sigma_{non-diff} + \sigma_{s-diff} + \sigma_{d-diff}$$

Small chance of particle production at midrapidity

MB Trigger biased towards non-diffractive events with greater particle production at midrapidity!

Categorizing Centrality in p(d)+Au – Glauber Model

What are the implications for d+Au?



N collisions

1 Biased

***N-1* Unbiased**

Au-going charge deposition is scaled up!

	0%-20%	20-40%	40-60%	60%-88%
Bias Factor Correction	0.94 ± 0.01	1.00 ± 0.01	1.03 ± 0.02	1.03 ± 0.006

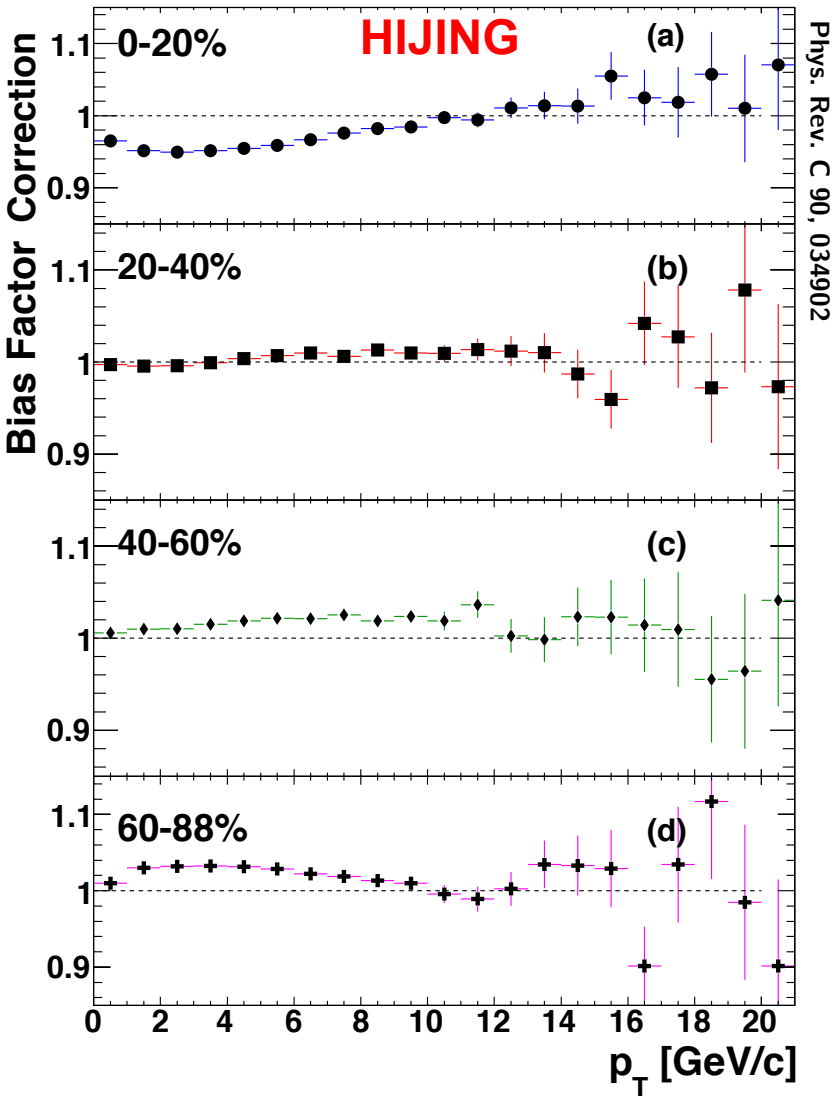
Categorizing Centrality in p(d)+Au

d+Au @ 200 GeV

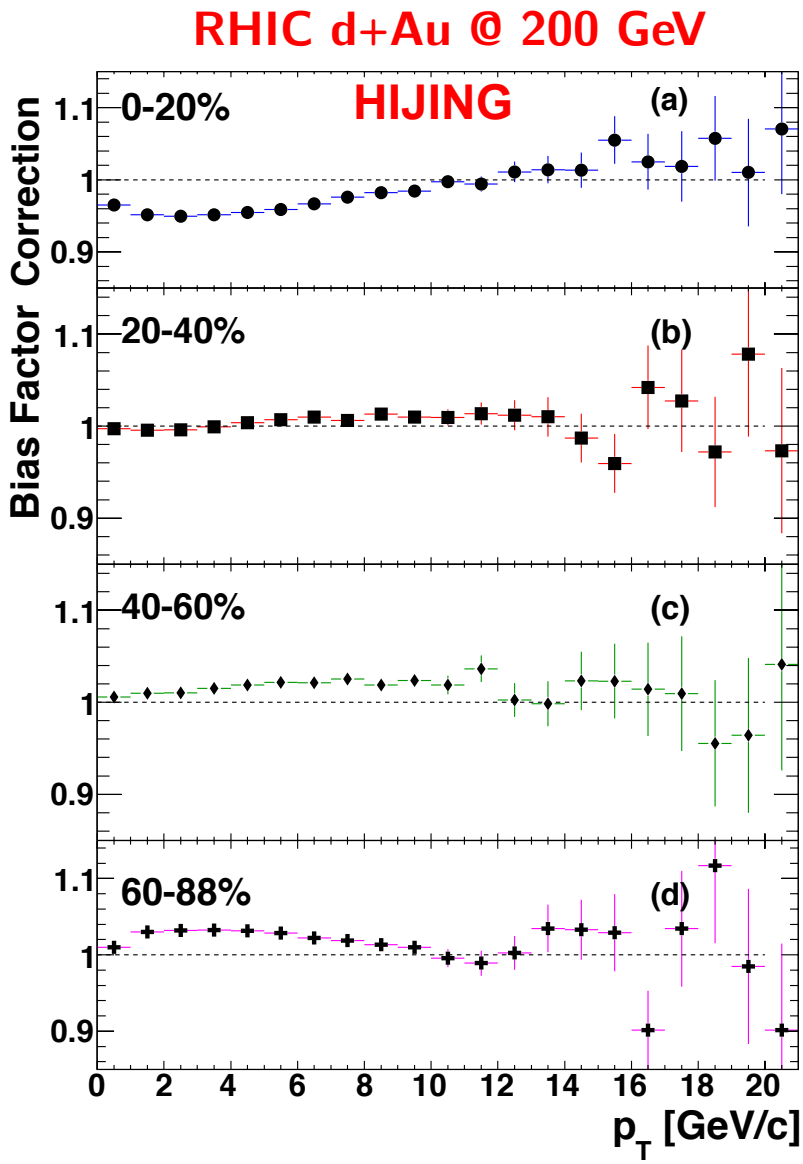
	Glauber Model	HIJING
Centrality	**Bias Correction Factor**	**Mean Bias Factor 1< p_T <5 GeV/c**
0-20%	0.94 ± 0.01	0.951 ± 0.001
20-40%	1.00 ± 0.01	0.996 ± 0.001
40-60%	1.03 ± 0.02	1.010 ± 0.001
60-88%	1.03 ± 0.06	1.030 ± 0.001

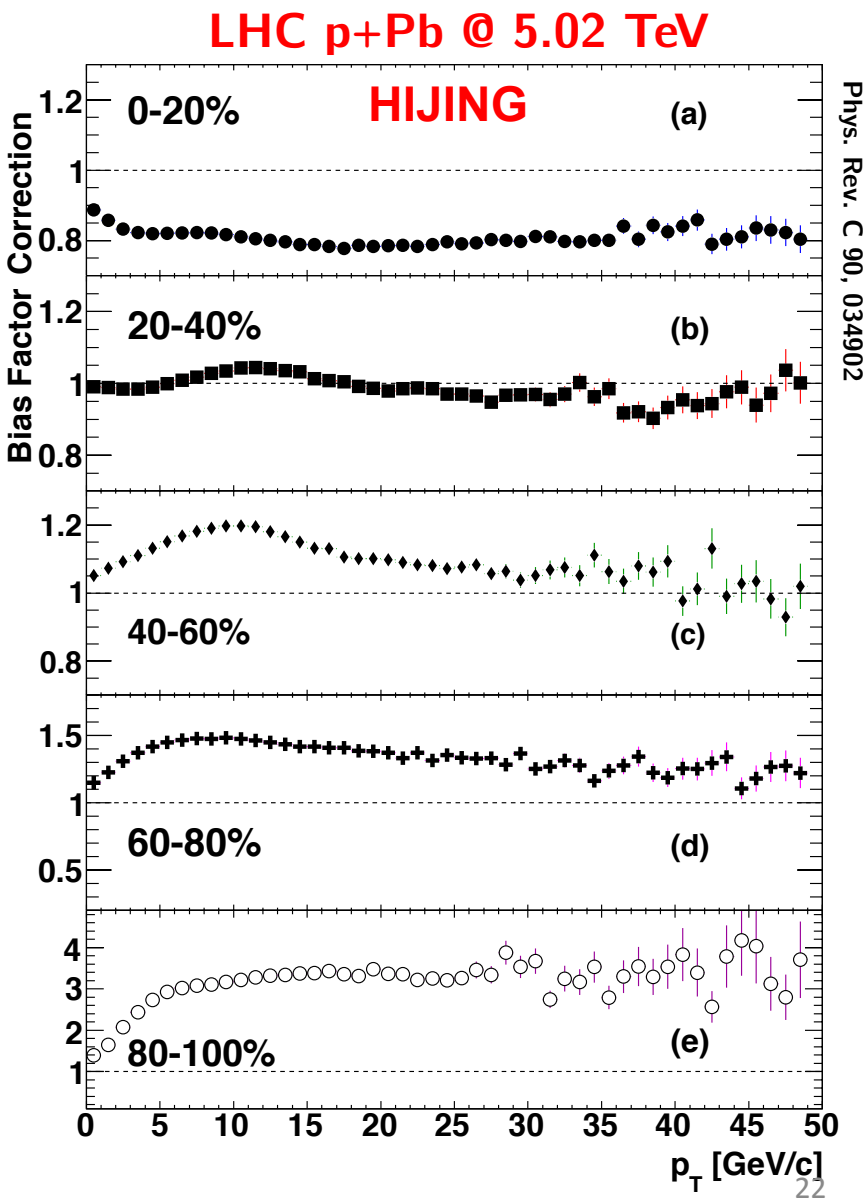
We observe a slight p_T dependence of the bias factors. Less than 5% variation.

Good agreement with Glauber calculation!



Categorizing Centrality in p(d)+Au



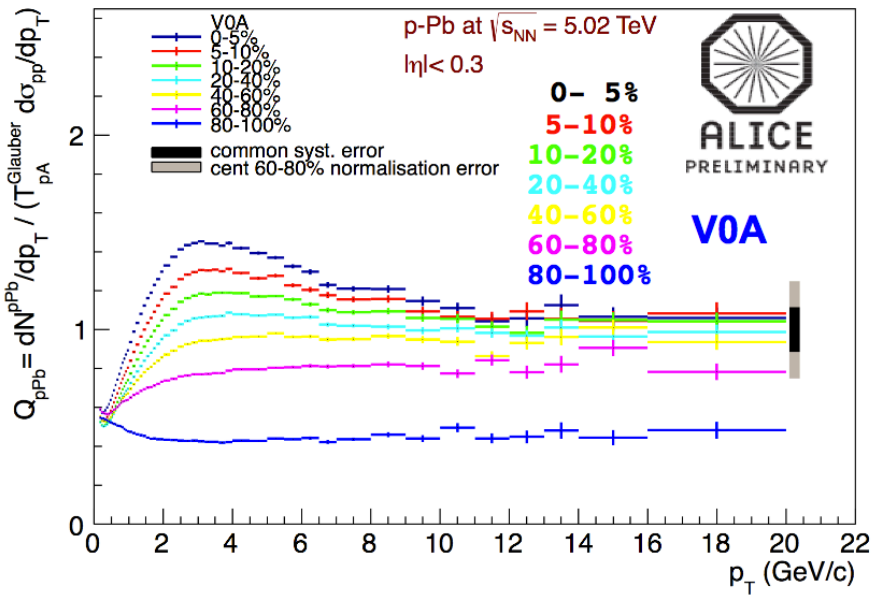


Categorizing Centrality in p(d)+Au

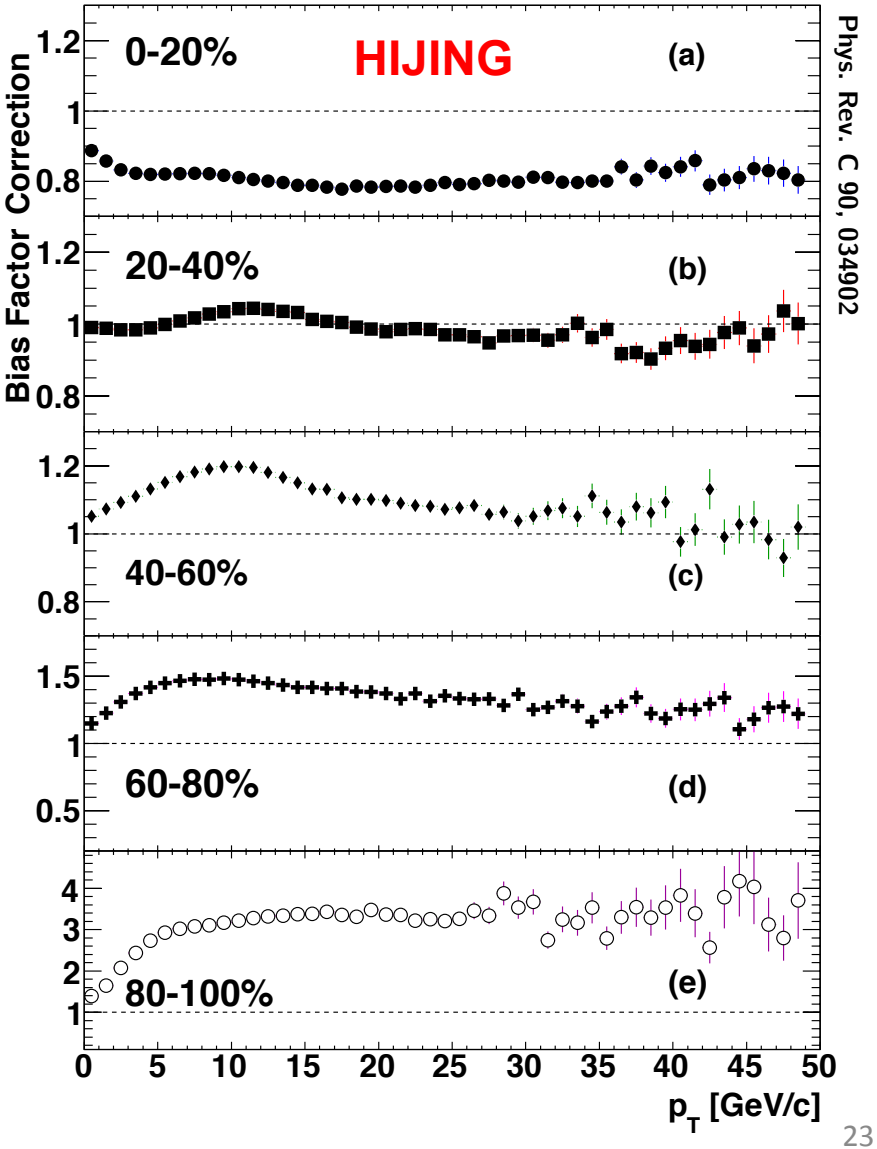
p+Pb @ 5.02 TeV

Large auto-correlation in p+p.

Large and strongly p_T-dependent bias correction factors.



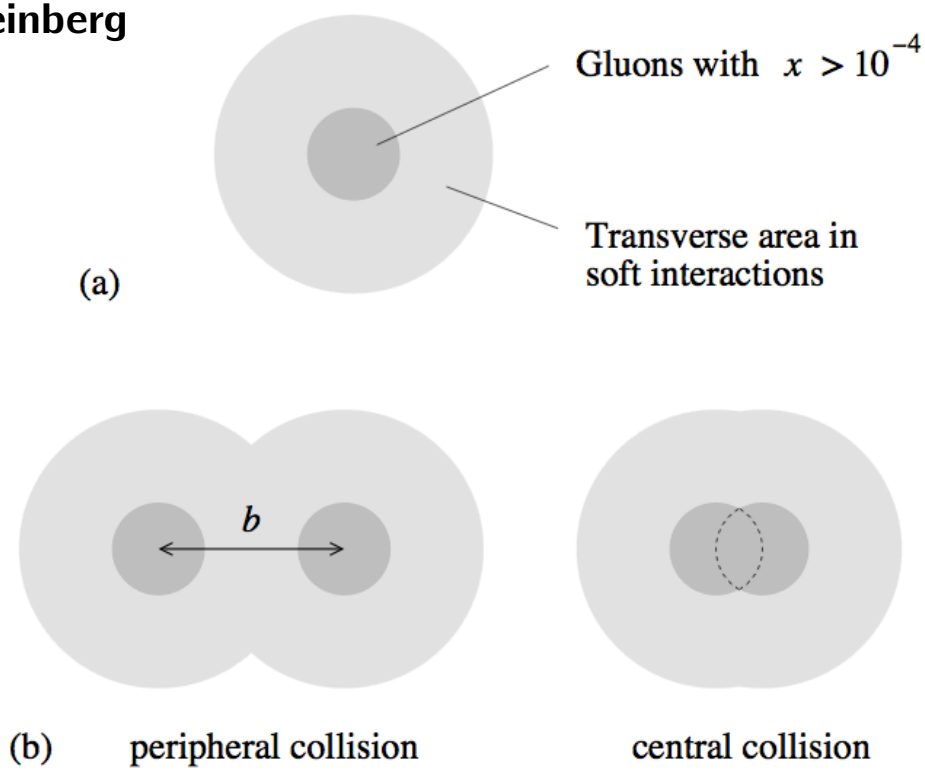
Recall Q_{pPb} ~ 1/Bias Factor



Categorizing Centrality in p(d)+Au

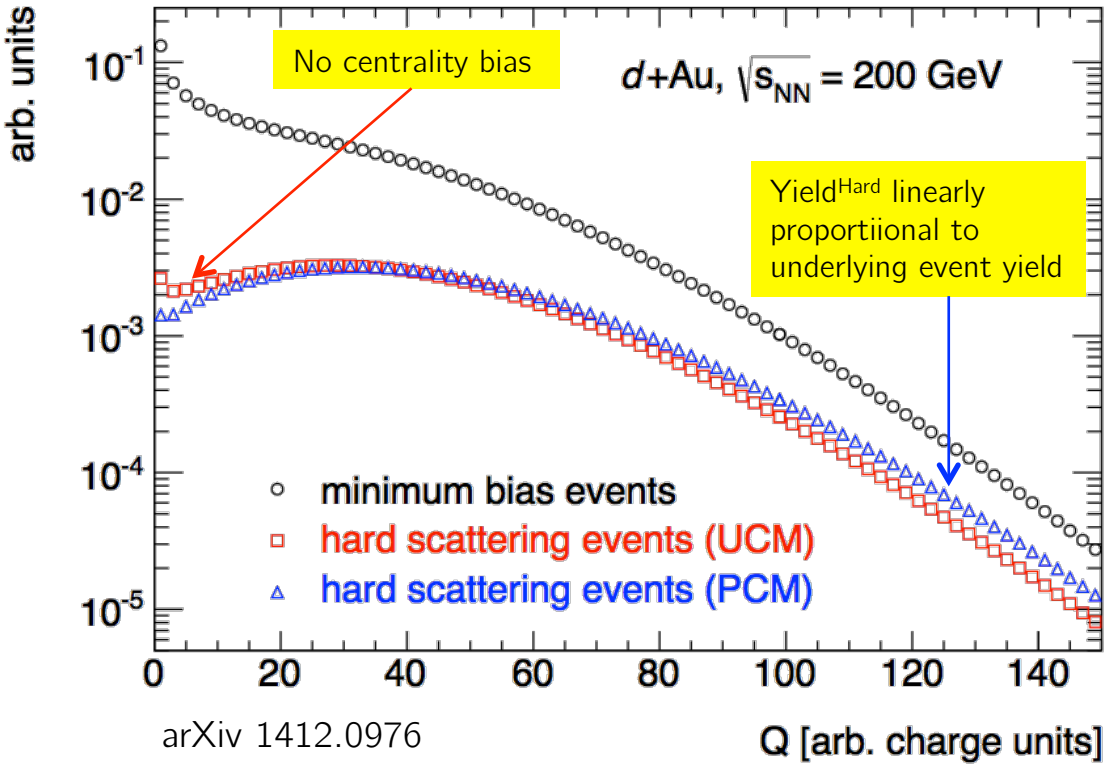
What if we assume a positive correlation between the yield from hard scattering and the underlying event activity? We can motivate this assumption geometrically.

Perepelitsa and Steinberg
arXiv 1412.0976



Frankfurt, Strickman, Weiss. JLAB-THY-10-1228
arXiv:1009.2559

Categorizing Centrality in p(d)+Au



arXiv 1412.0976

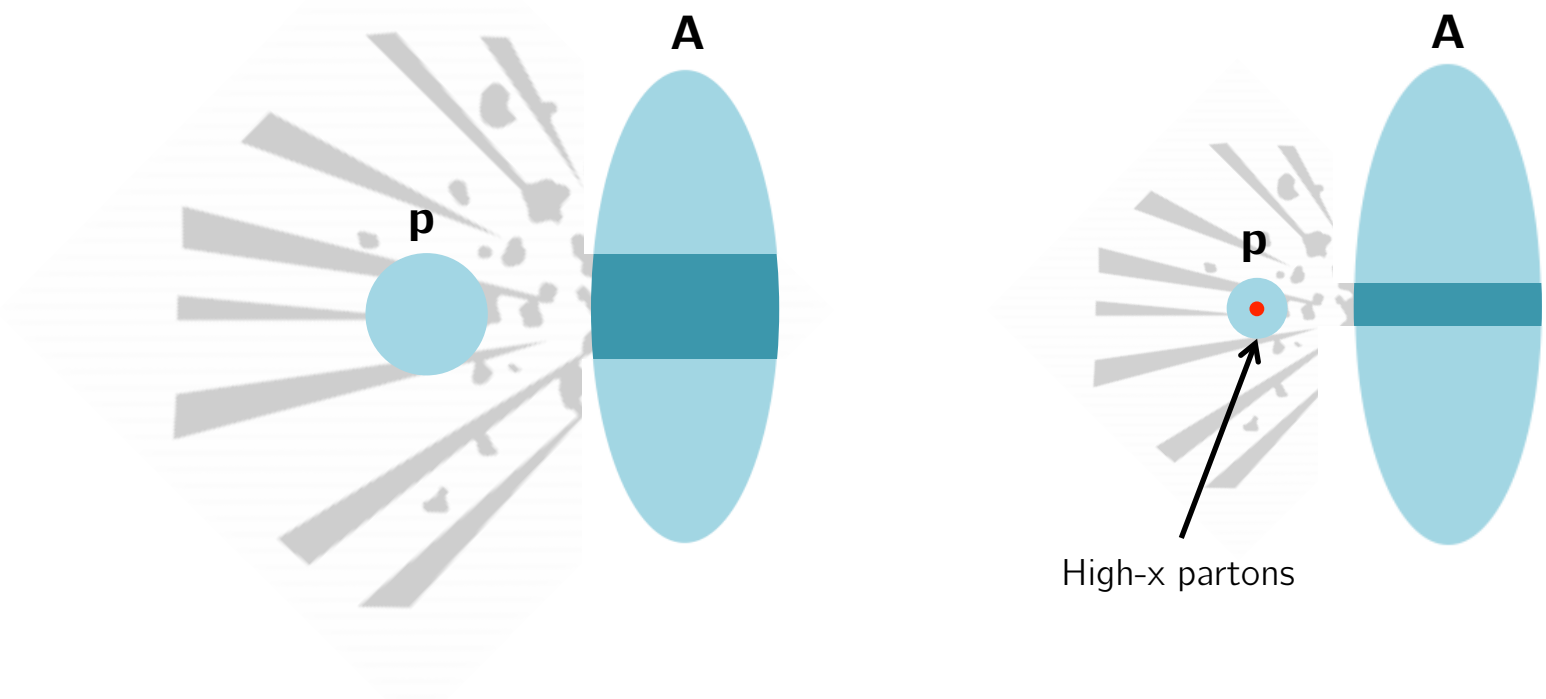
To determine bias factors from this model, pick a given centrality quantile and integrate the red and blue curves to find the yield.

The ratio is related to the bias factors computed by PHENIX.

centrality	ρ	1/BF (PHENIX)
0–20%	1.15 ± 0.07	1.06 ± 0.01
20–40%	0.99 ± 0.01	1.00 ± 0.01
40–60%	0.92 ± 0.04	0.97 ± 0.02
60–88%	0.82 ± 0.09	0.86 ± 0.06

The Shrinking Proton and Centrality Bias

Alvioli, Cole, Frankfurt, Perepelitsa, Strikman. arXiv:1409.7381

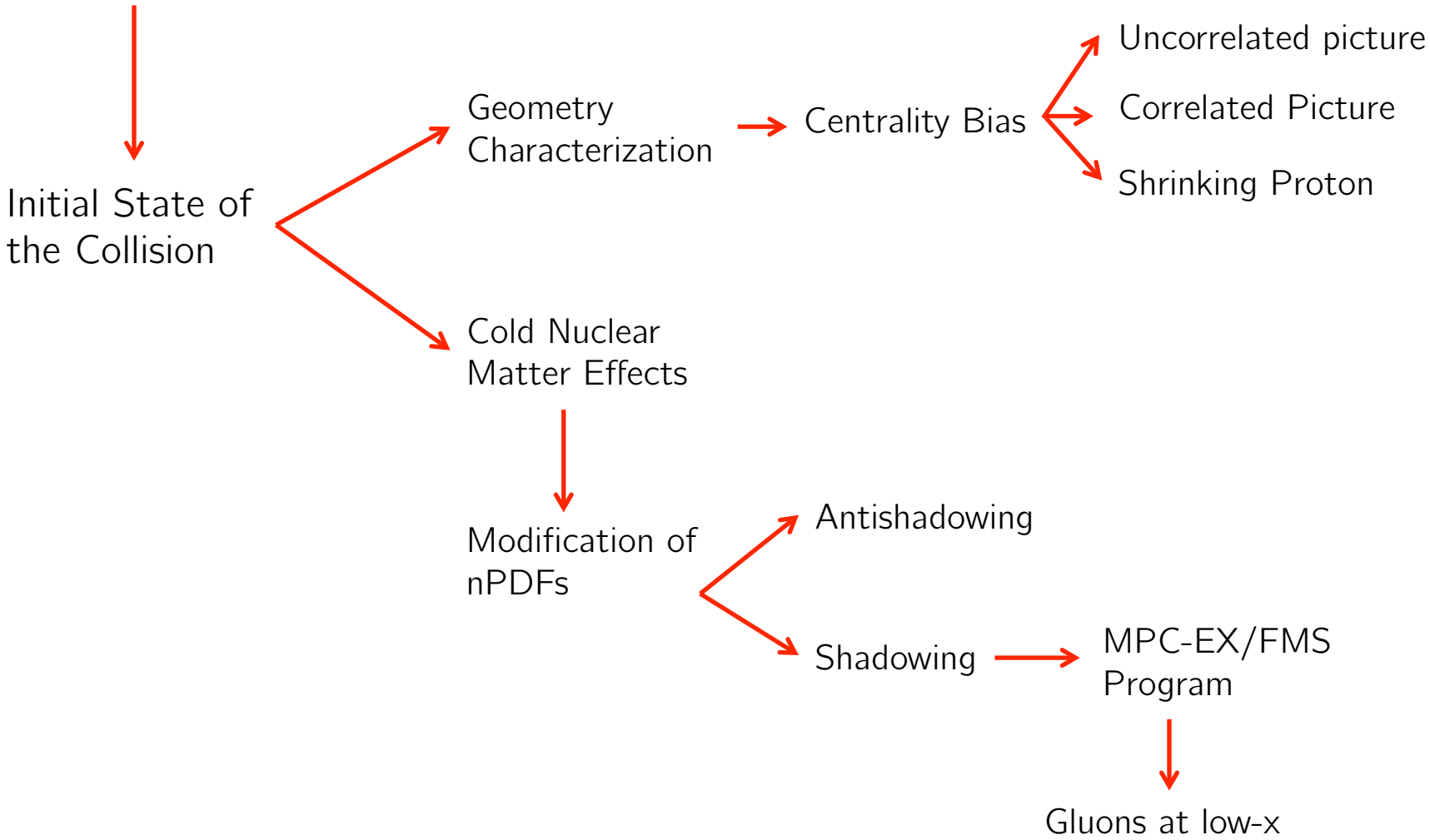


Same geometry (i.e., b) but different number of binary collisions!

High-x parton negatively correlated with proton-nucleus interaction strength
In other words, we have a smaller cross section, implying a 'smaller' proton.

Summary

Small Systems



Thank You!