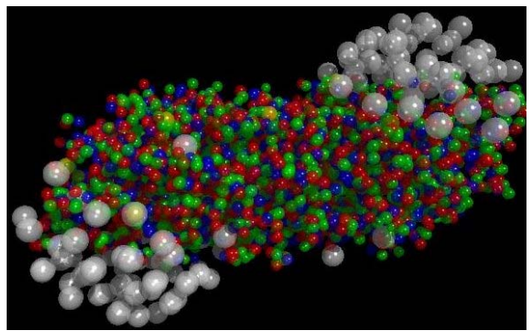
The Future of Cold QCD @ RHIC

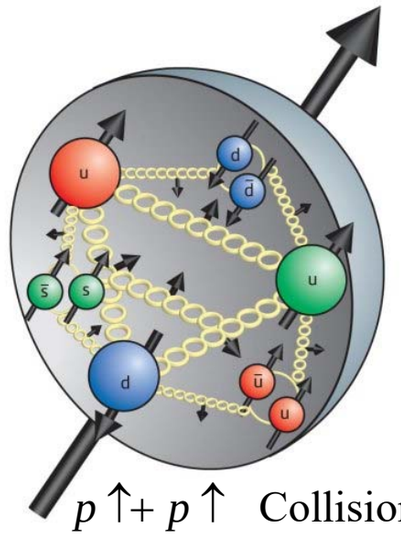
John Lajoie

Iowa State University

The Big Picture at RHIC (and the EIC…)

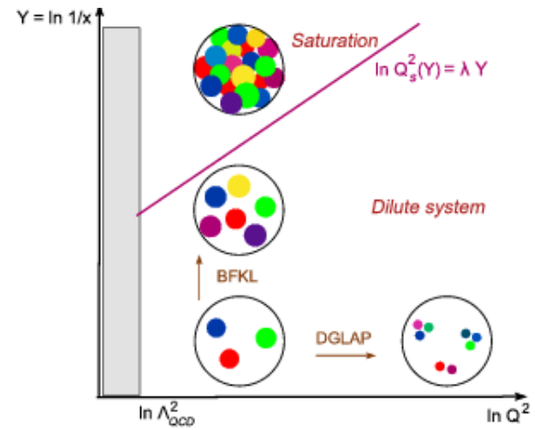
A+A Collisions





$p\uparrow + p\uparrow$ Collisions

p+A Collisions



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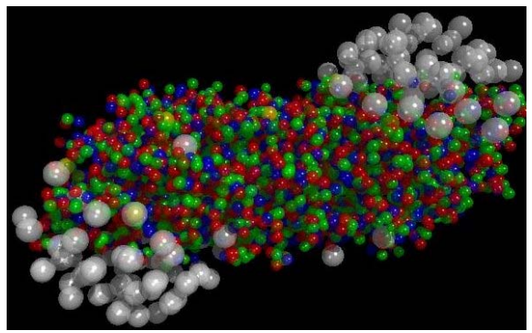

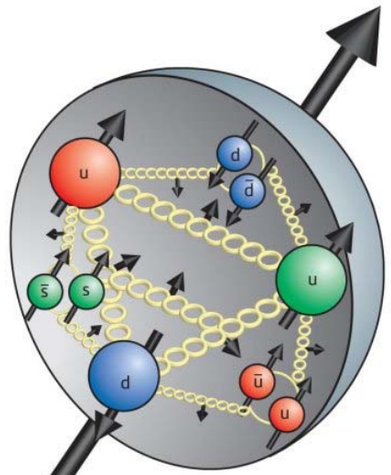

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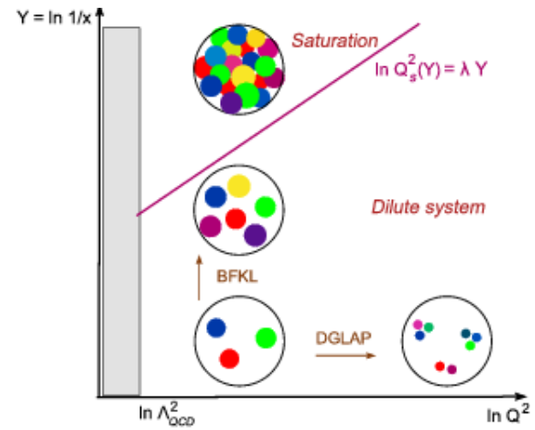

How do collective, many-body phenomena arise from first-principles QCD?

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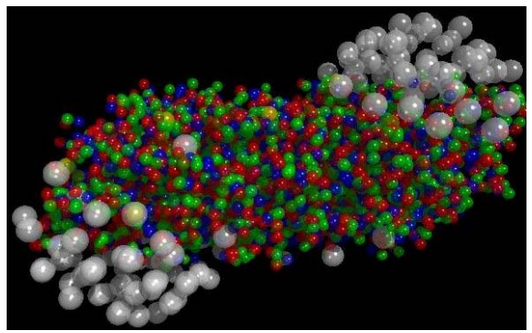

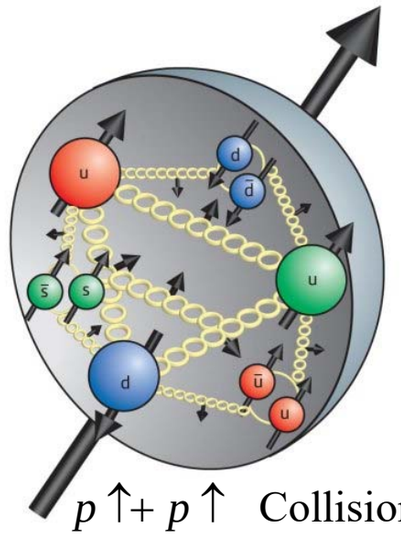

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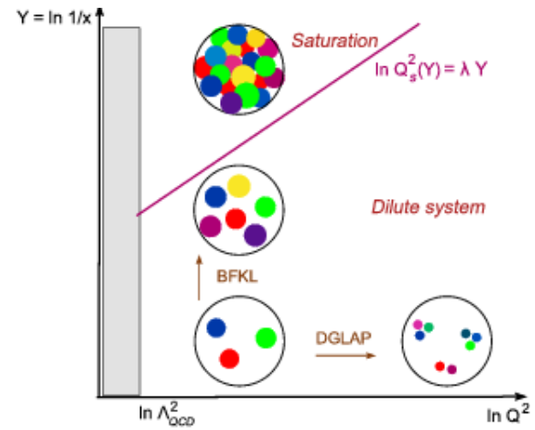

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Two Pillars of QCD:

The Big Picture at RHIC (and the EIC…)

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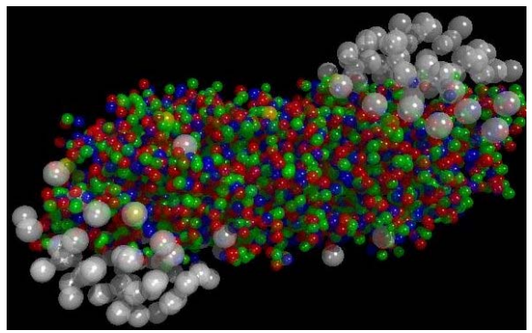

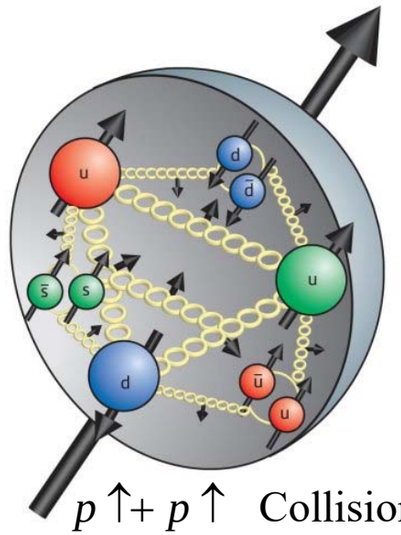

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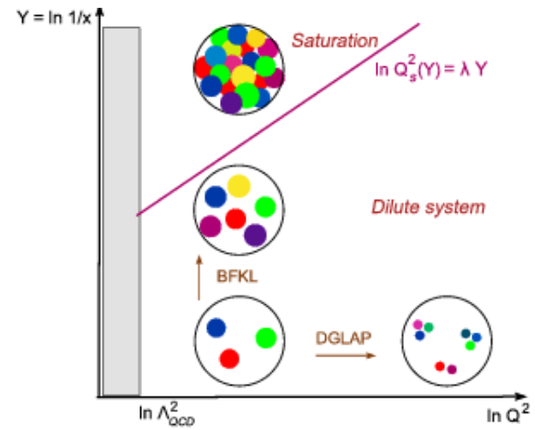

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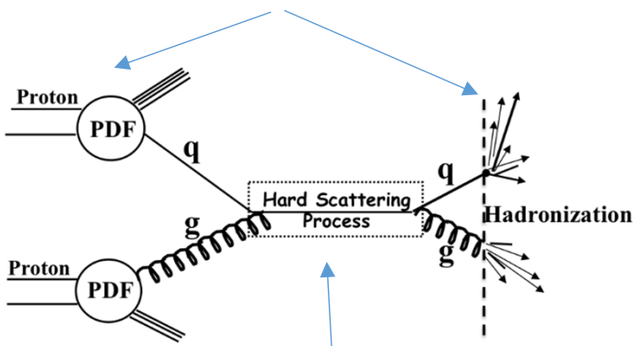
Long-distance physics



pQCD

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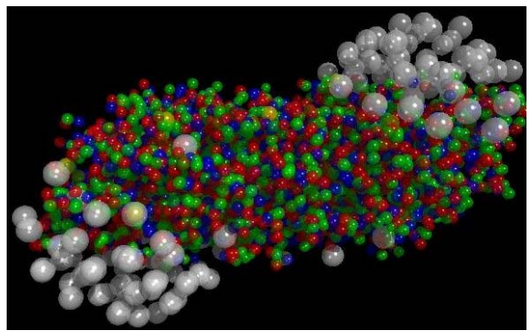

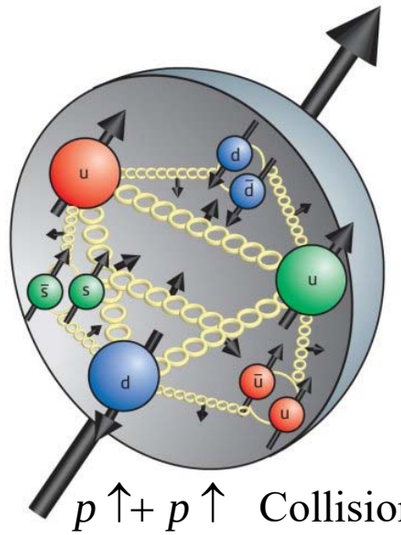

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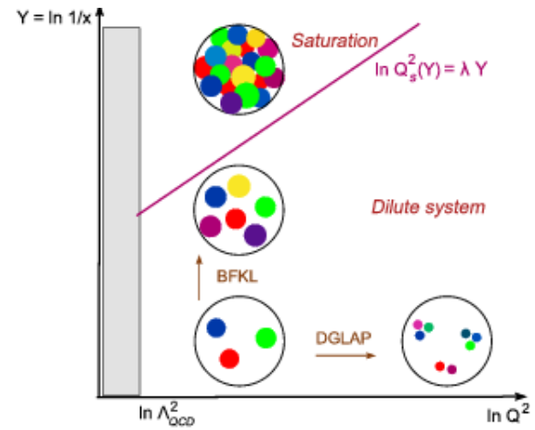

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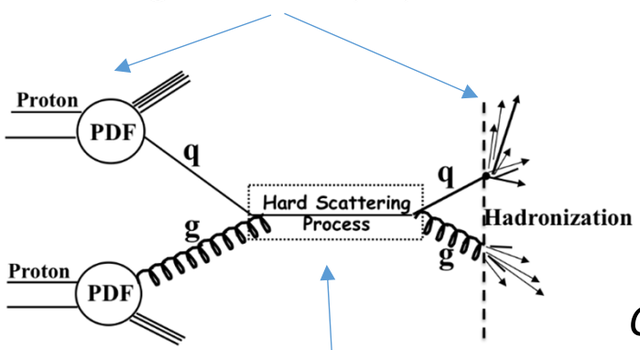

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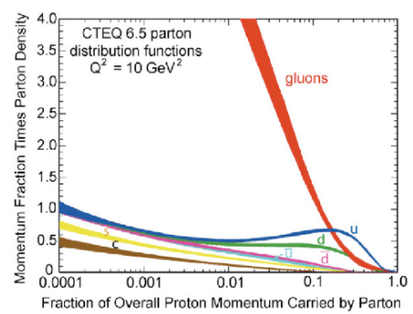
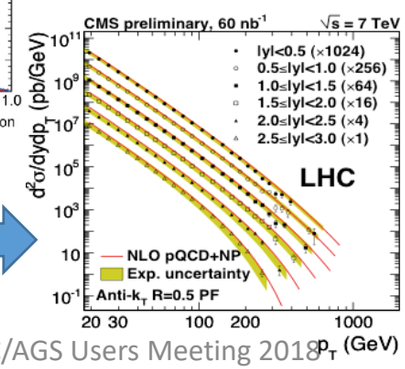


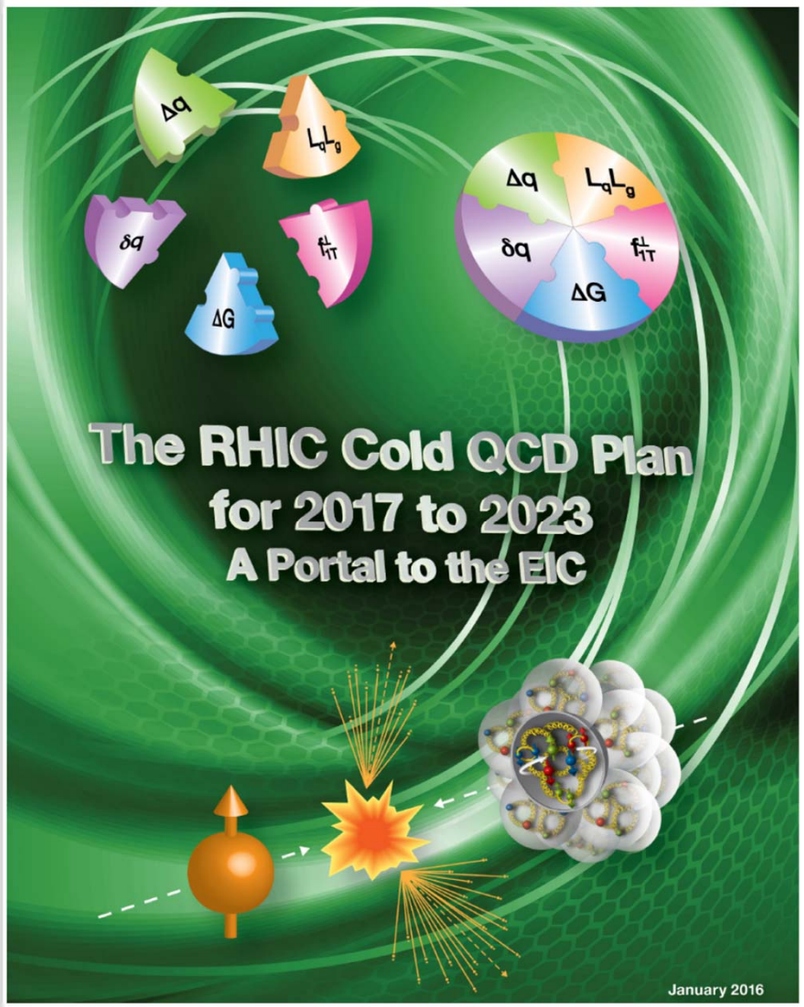
Extract PDF's from Hera..

Calculate cross sections at LHC



Two Pillars of QCD:

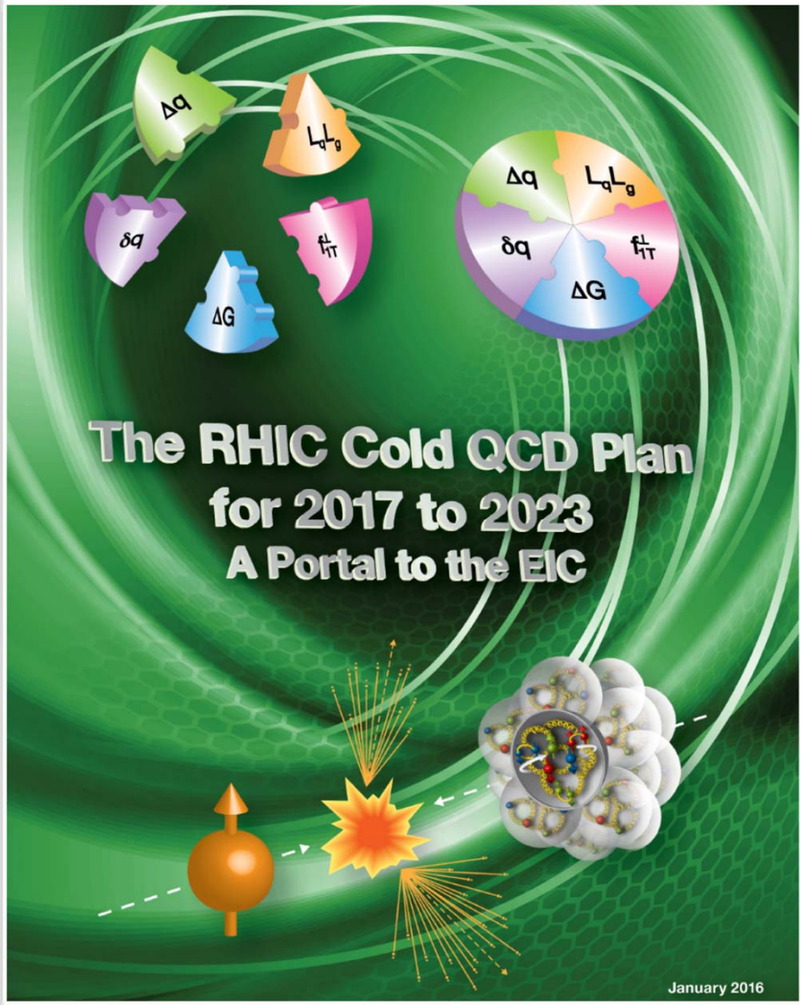
The RHIC Cold QCD Plan



- **Jets in polarized p+p:**
  - Jet A_N : Sivers/Twist-3 for u/d quarks
  - Angular distribution in jets : transversity
  - Di-Jet A_{LL} : Δg at low-x
- **nFF's in p+A:**
  - Important measurement on the road to the EIC
- **Drell-Yan and Direct Photons in p+A:**
  - Measurements of nPDF's, A-scan essential
- **Diffraction in polarized p+p (200 GeV):**
  - A_{UT} from single-diffractive events
- **Ultraperipheral Collisions in p+Au:**
  - "p-shine": gluon impact parameter distribution in Au nucleus via J/Ψ
  - "Au-shine": access GPD E_g in polarized p via J/Ψ production (A_{UT})
    - Sets the scale for a program to measure GPD E_g at the EIC!
  - Gluon Wigner function from di-jets

The RHIC Cold QCD Plan

Need Forward Rapidity Coverage - 2017 LOI's
https://indico.bnl.gov/event/3125/



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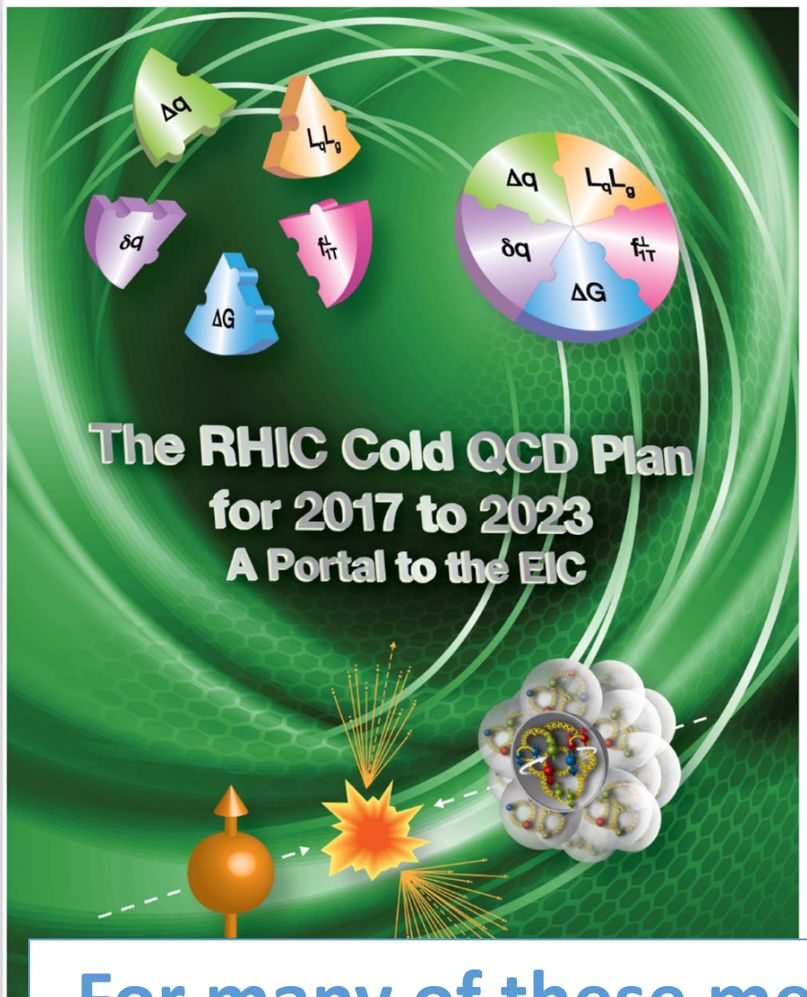

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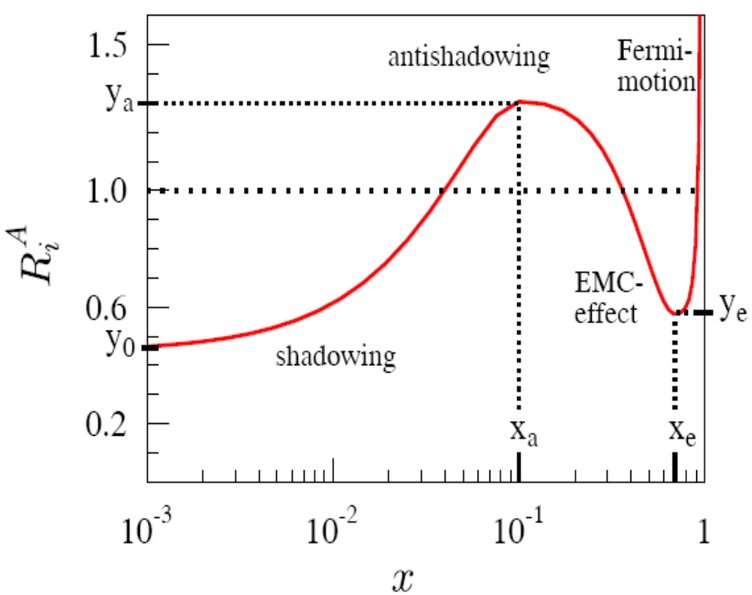
For many of these measurements RHIC offers *unique* capabilities

Partons in Nuclei

Eskola , Paukkunen, Paakkinen, and Salgado, Eur. Phys. J. C (2017) 77:136

shadowing/saturation in nuclei

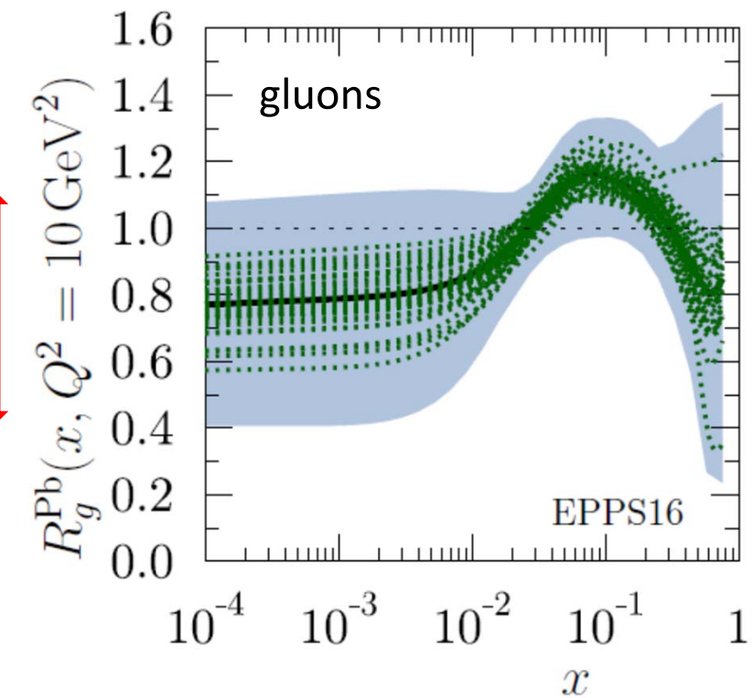


$$R_G^{Pb}(x,Q^2) = \frac{xG_A(x,Q^2)}{AxG_p(x,Q^2)}$$

Fit data on nuclei:
SLAC, NMC, EMC
DIS, DY, **LHC**, …

Lack of data
low-x data…

Large uncertainty At low-x



Large uncertainties in the nuclear gluon PDF at low-x: many important effects to disentangle – *shadowing, antishadowing, nonlinear QCD, saturation*, etc.

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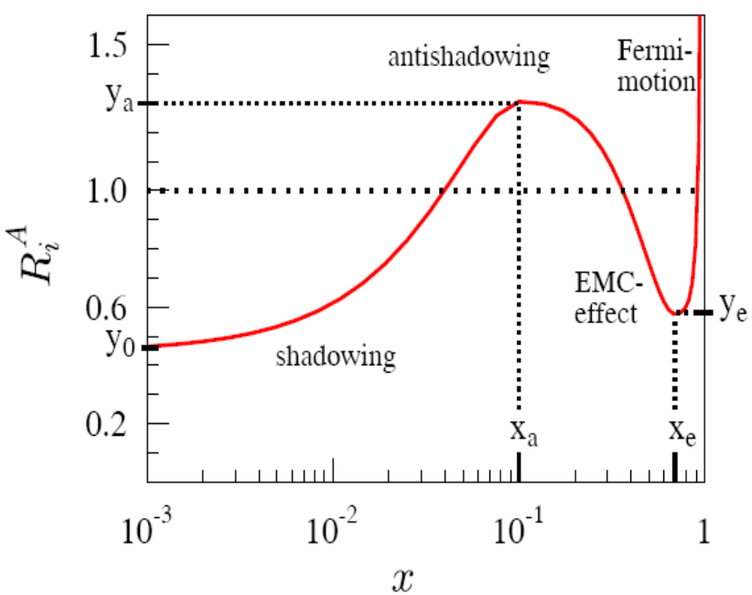

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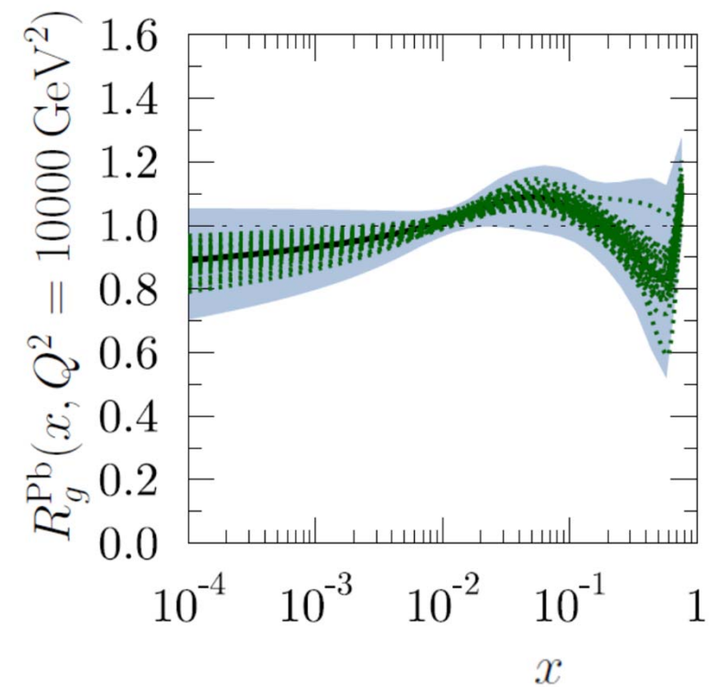

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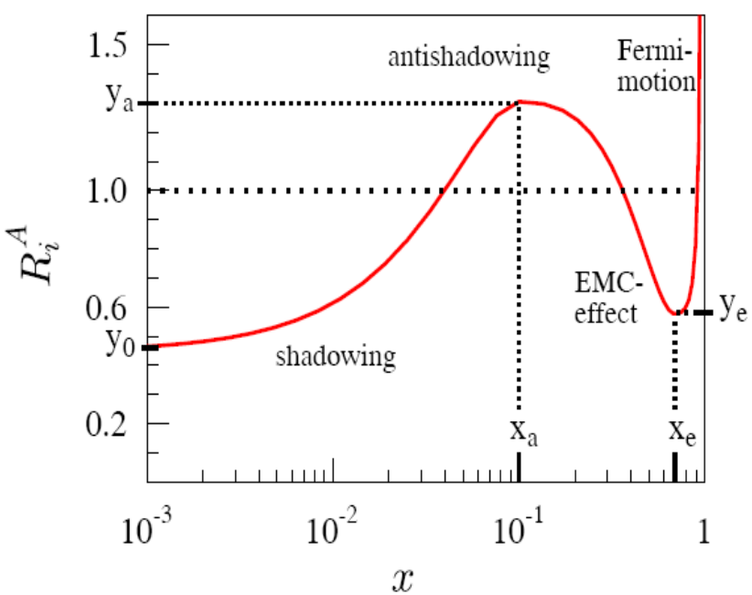

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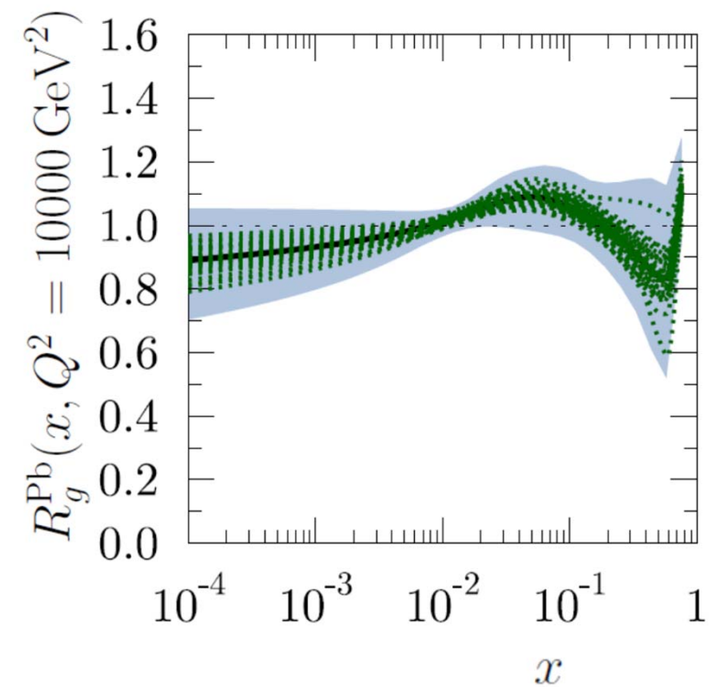
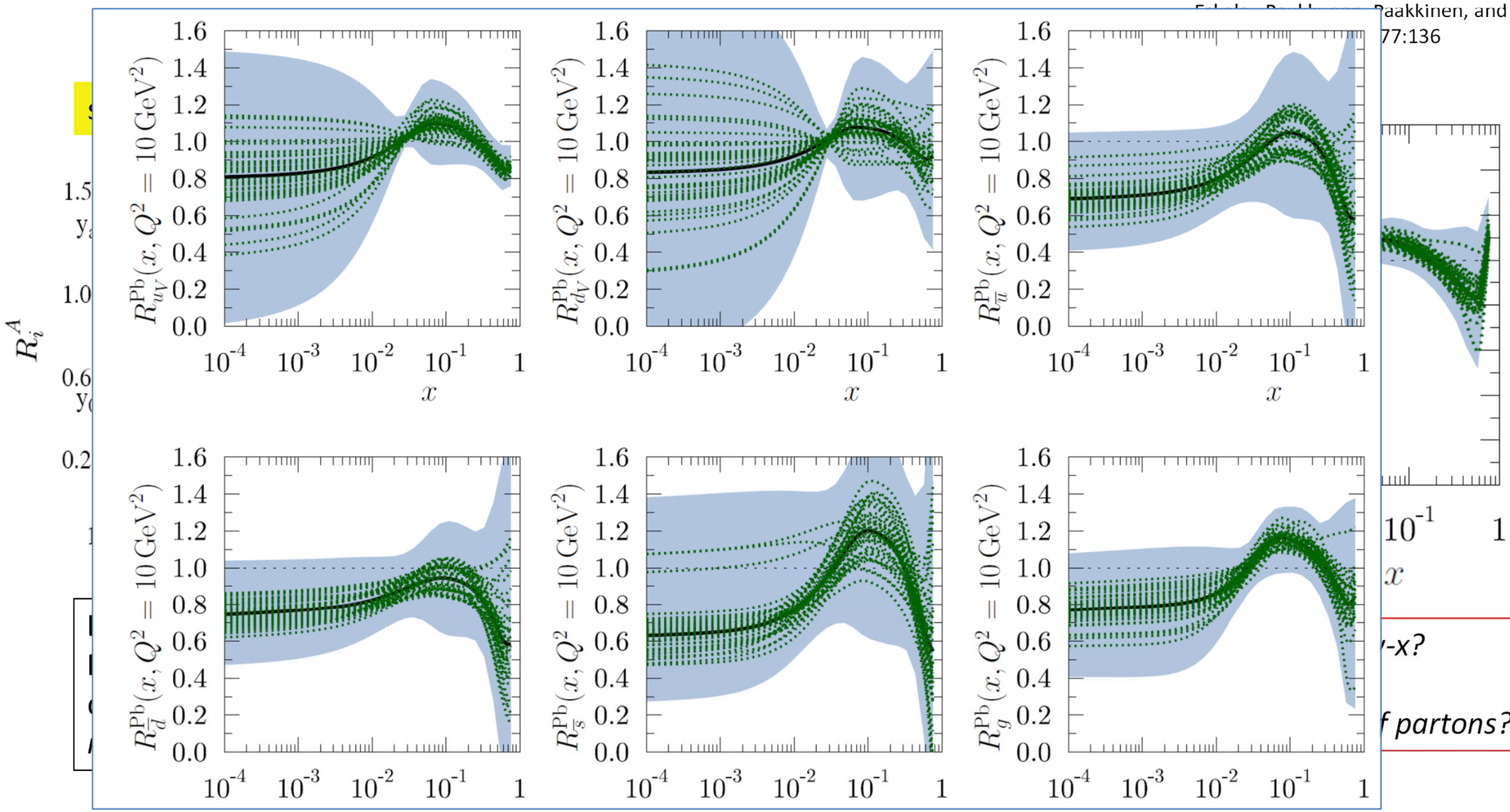


Large uncertainties in the nuclear gluon PDF at low-x: many important effects to disentangle – *shadowing, antishadowing, nonlinear QCD, saturation*, etc.

- *What is the structure of nuclei at low-x?*
- *What role does saturation play?*
- *What is the transverse distribution of partons?*

Partons in Nuclei

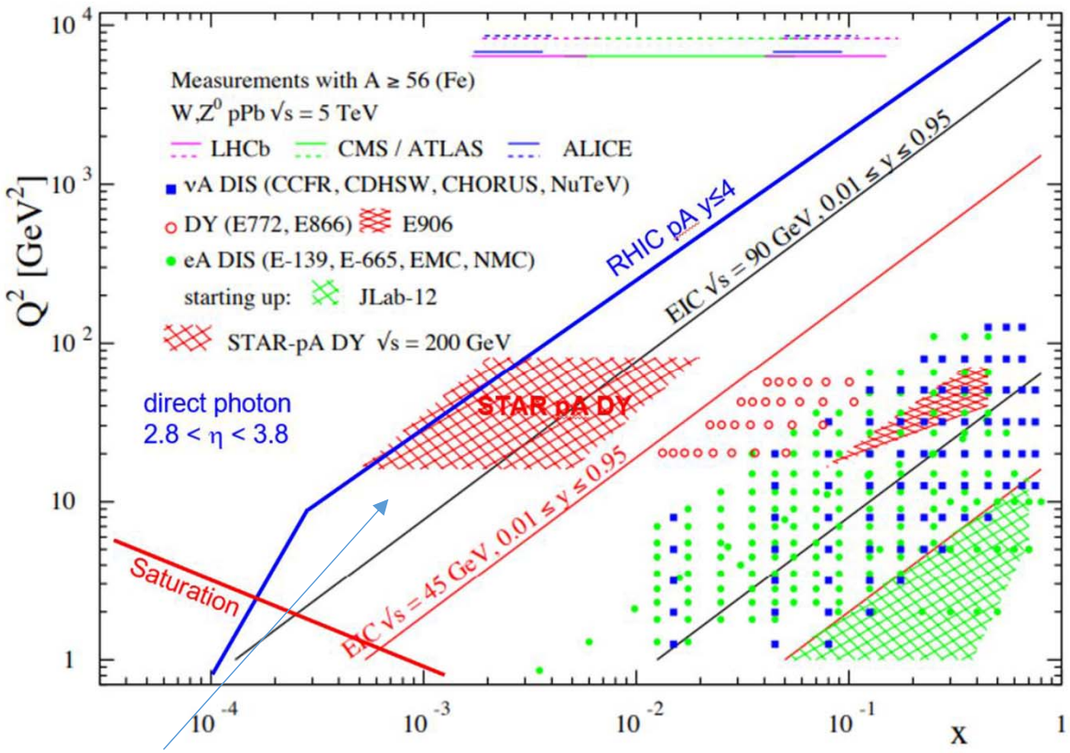
Paakkinen, and Salgado,
77:136



-x?

f partons?

A Future Example – Forward DY @ 200GeV



DY measurements in p+A offer a unique physics reach compared to the EIC!

details at https://www.sphenix.bnl.gov/web/node/450

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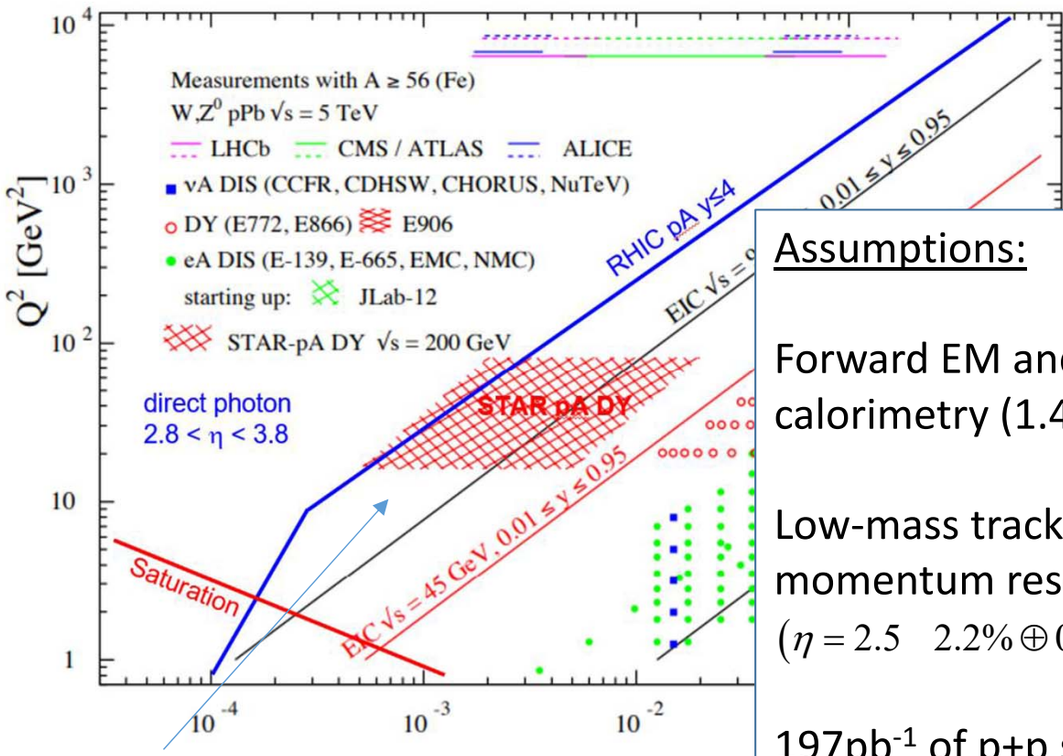

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Assumptions:

Forward EM and HAD calorimetry (1.4<η<4.0)

Low-mass tracking with good momentum resolution:
$(\eta = 2.5 \quad 2.2\% \oplus 0.21\% \times p(GeV))$

197pb^{-1} of p+p sampled lumi.
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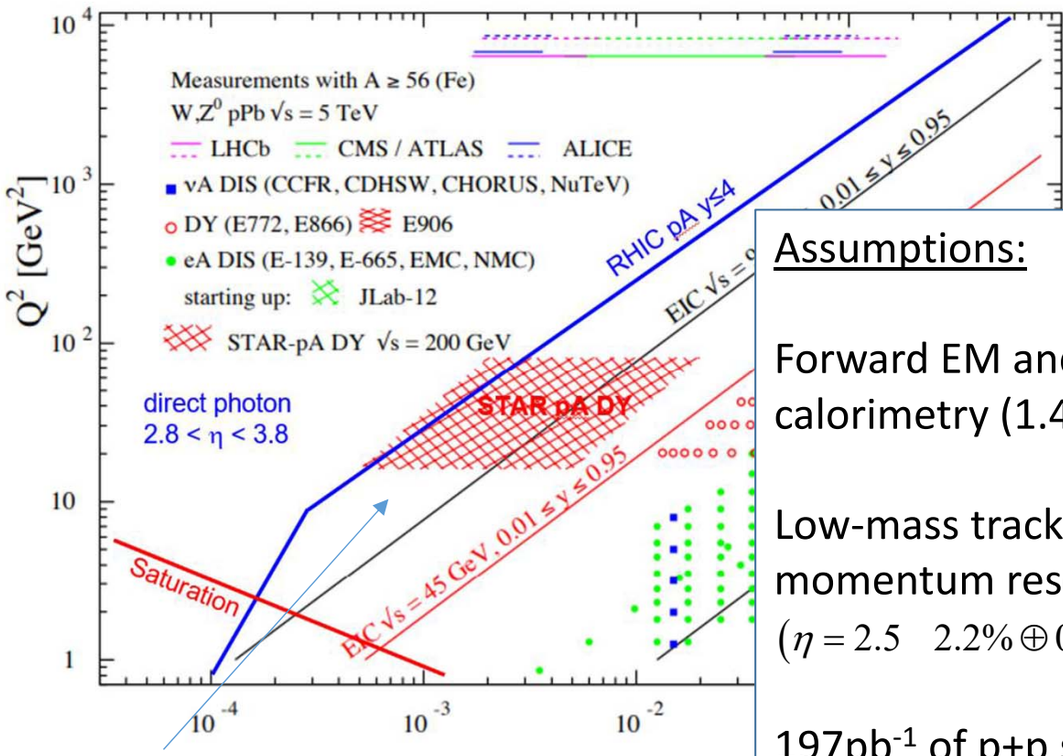

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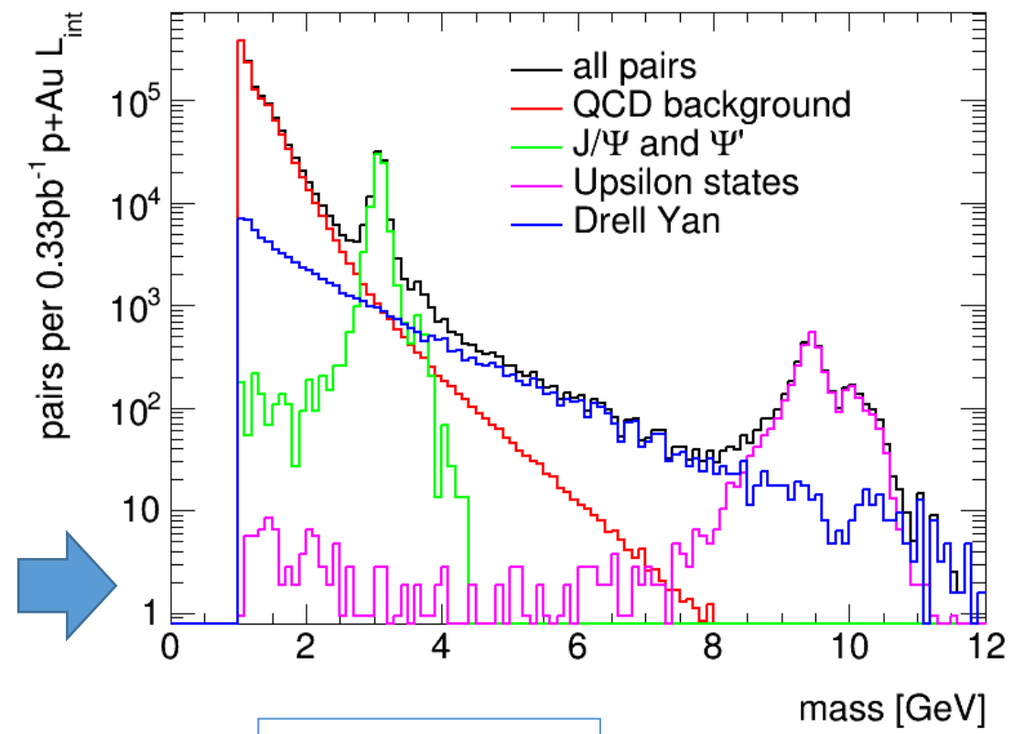

S/B > 1 above 5 GeV

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EPPS16 Reweighting

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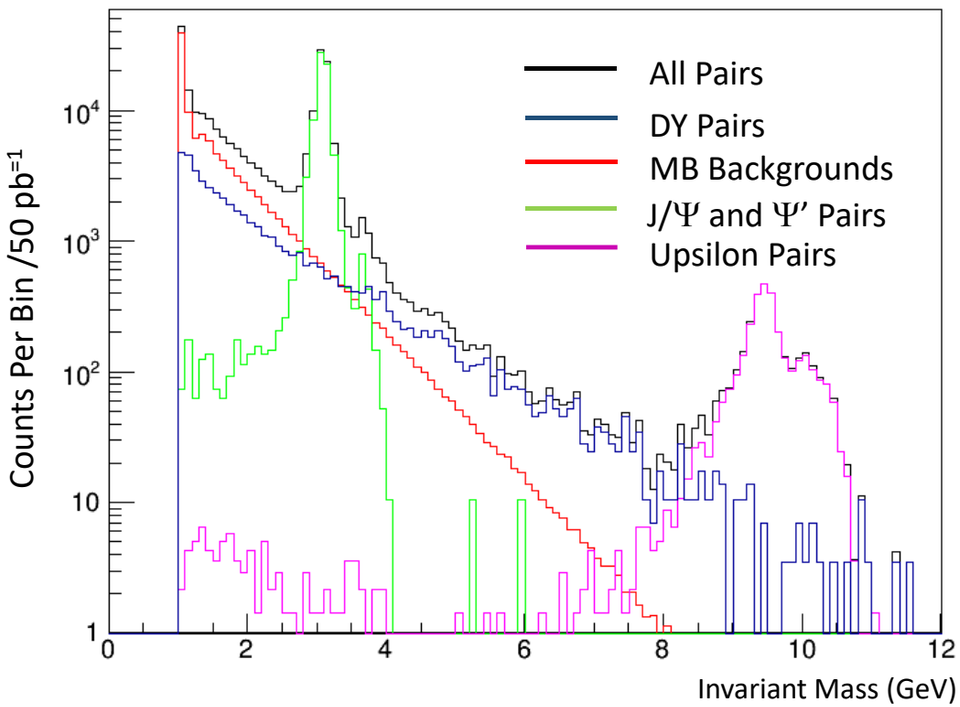
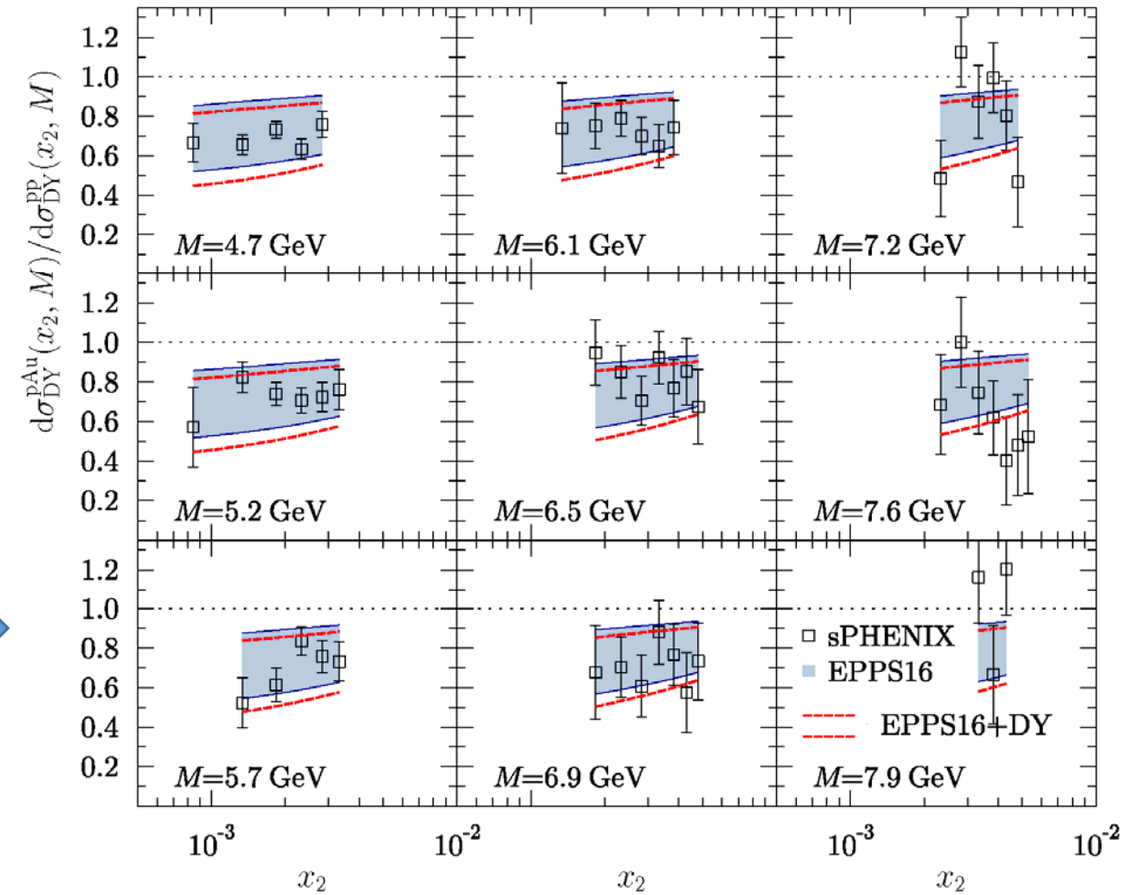


Include pseudo data in EPPS16

EPPS16 reweighting by H. Paukunen and P. Paakkinen



Pseudo data included with statistical uncertainties <u>and</u> a 10% normalization systematic error – the normalization error defeats the power of the data!

Experimental Limitations in nPDF's

- Experimentally we measure a ratio of cross sections:

$$R_{pA} = \frac{\dfrac{d\sigma_{p+A\to X}}{2\pi p_T dp_T dy}}{A\dfrac{d\sigma_{p+p\to X}}{2\pi p_T dp_T dy}} = \frac{\dfrac{1}{N_{p+A}^{inel}}\dfrac{dN_{p+A\to X}}{2\pi p_T dp_T dy}}{\langle N_{coll}\rangle \dfrac{1}{N_{p+p}^{inel}}\dfrac{dN_{p+A\to X}}{2\pi p_T dp_T dy}}$$

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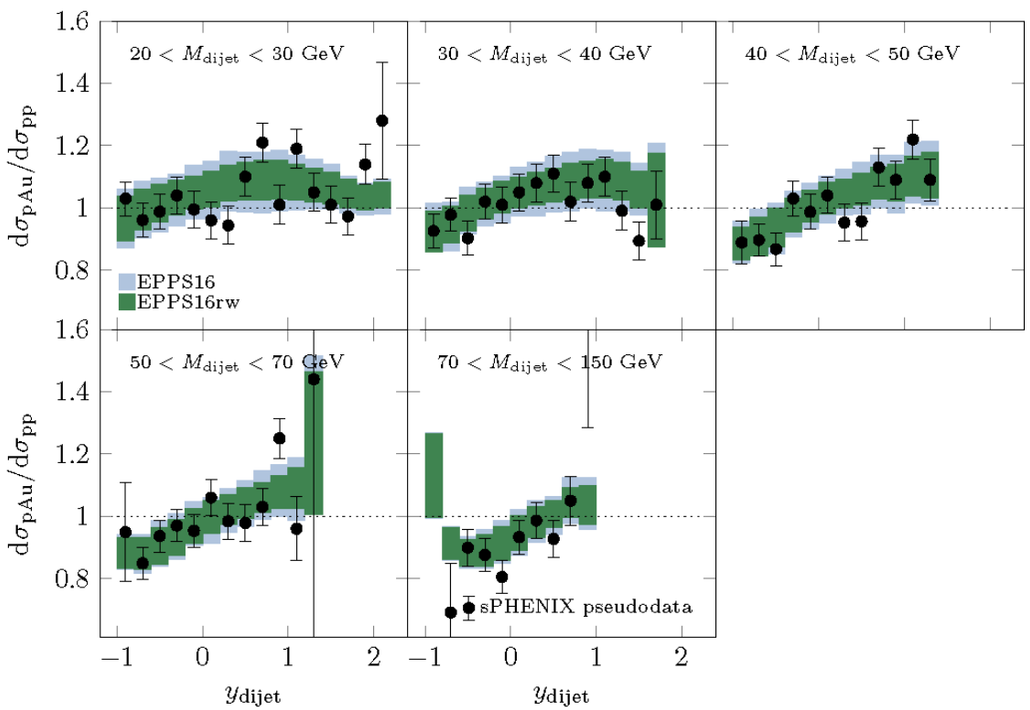
$\langle N_{coll}\rangle$ is usually estimated with a Glauber model and a minimum-bias interaction detector. This will inherently have <u>model-dependent systematic errors</u> that can <u>at best</u> be limited to $O(10\%)$.

A systematic error in $\langle N_{coll}\rangle$ is an overall scale error in R_{pA} – very bad when data is essentially flat as this mimics an nPDF effect!

Multiple Datasets…

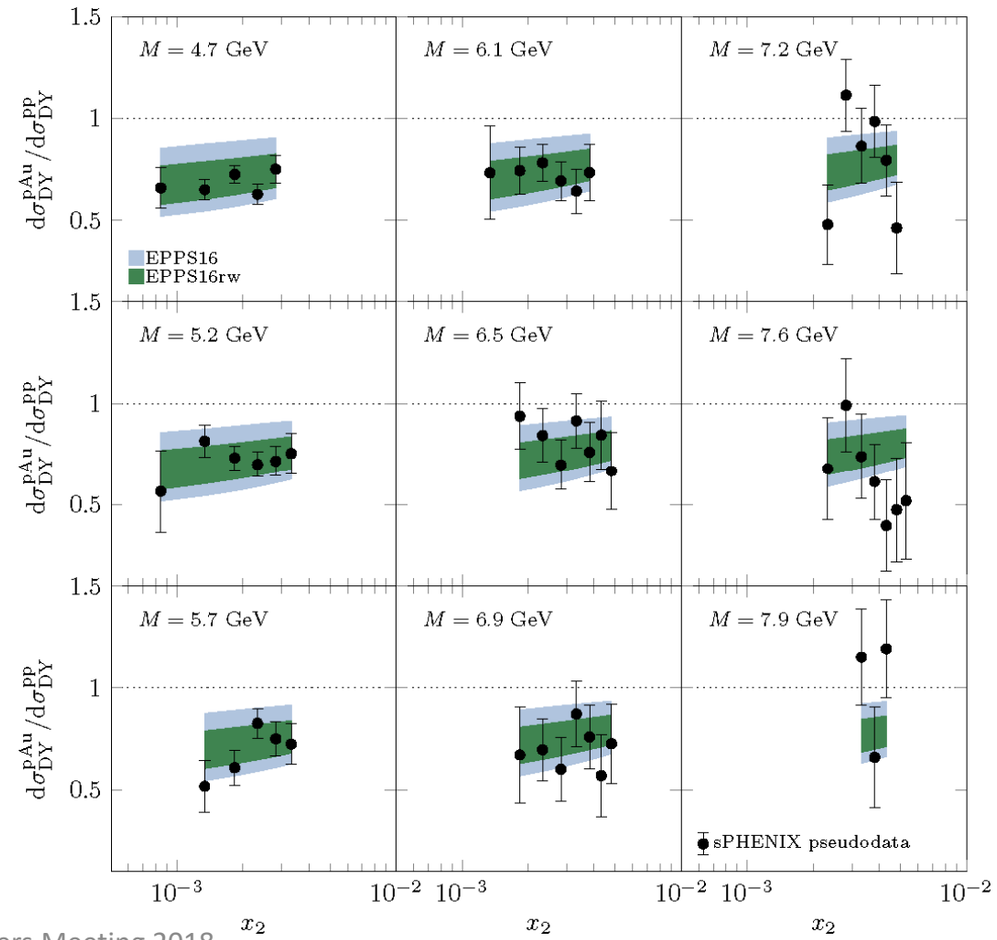
Can we use multiple datasets (with similar systematics) to overcome the normalization limitation?

Central (|η|<1) + Forward dijets (1.6<η<3.6)
(used primarily to fix normalization)



EPPS16 reweighting by H. Paukunen and P. Paakkinen

Forward DY (same pseudo data as before)



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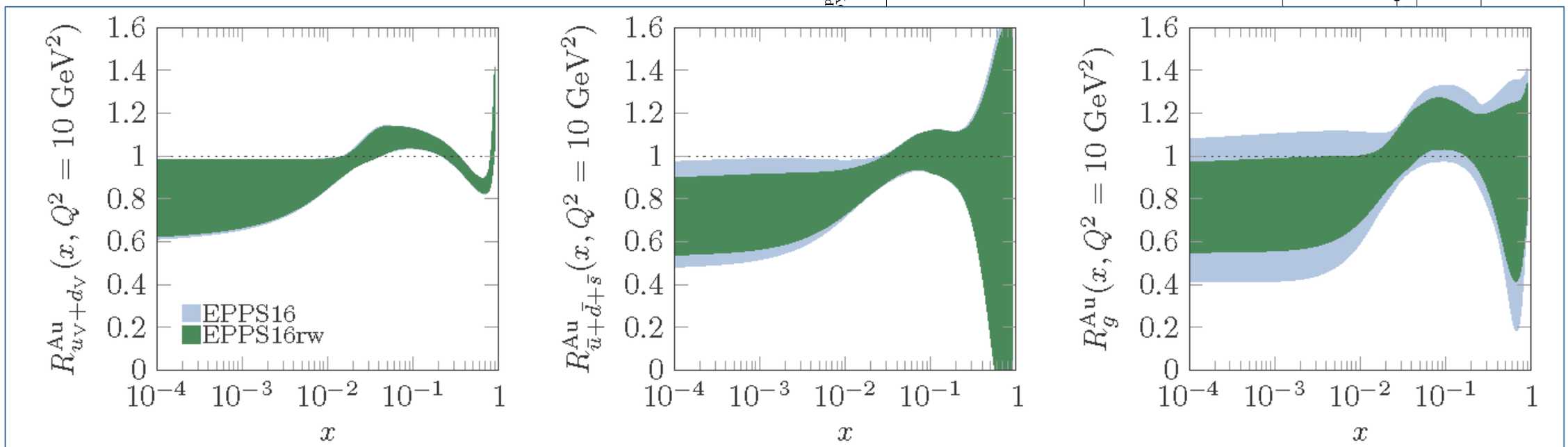

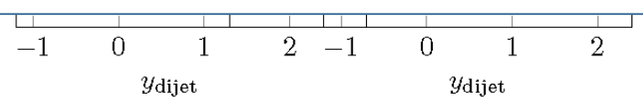

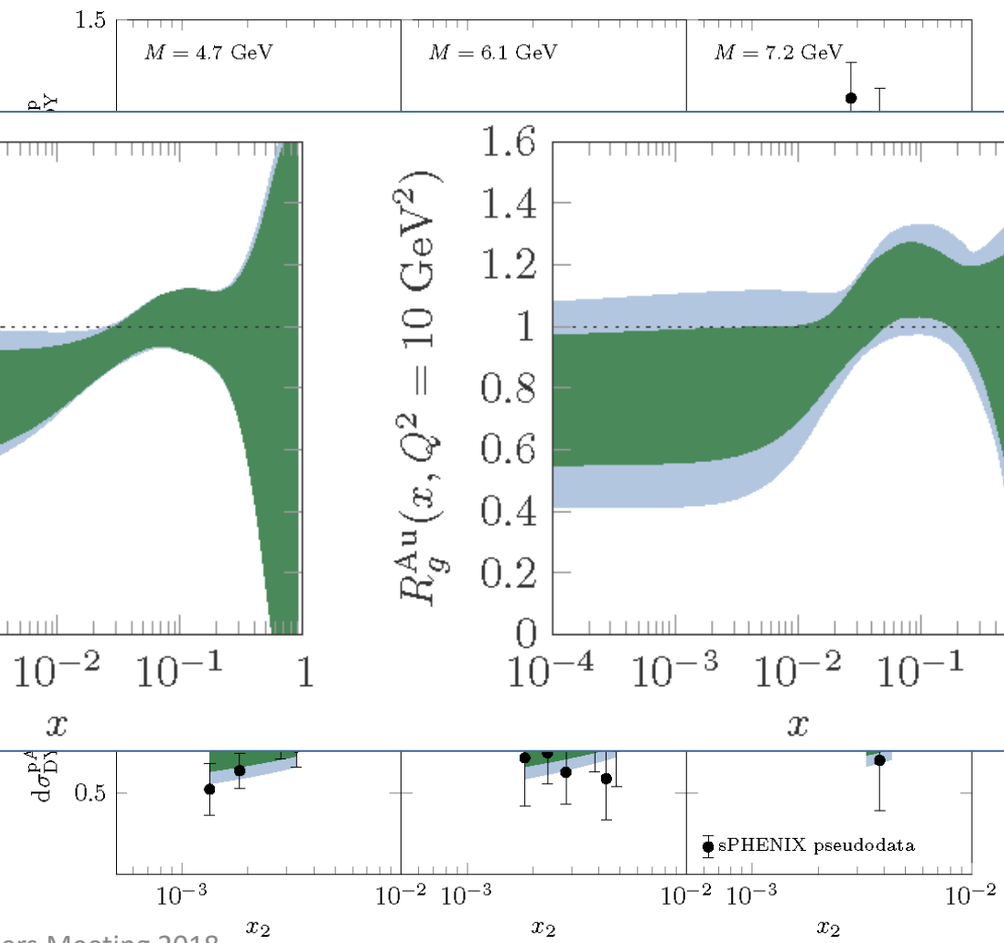

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A Comprehensive nPDF Program…

- Existing RHIC data will provide some info to the nPDF global fits…
- Real progress will require comprehensive set of measurements made with the same detector, in the same run, with the same MB trigger conditions…
  - Of course, two detectors doing complementary things would allow for a suite of systematic crosschecks

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- <u>Additional Observables</u>
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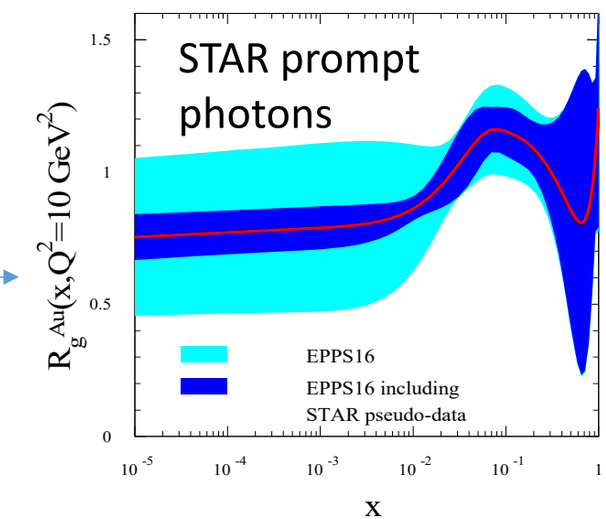

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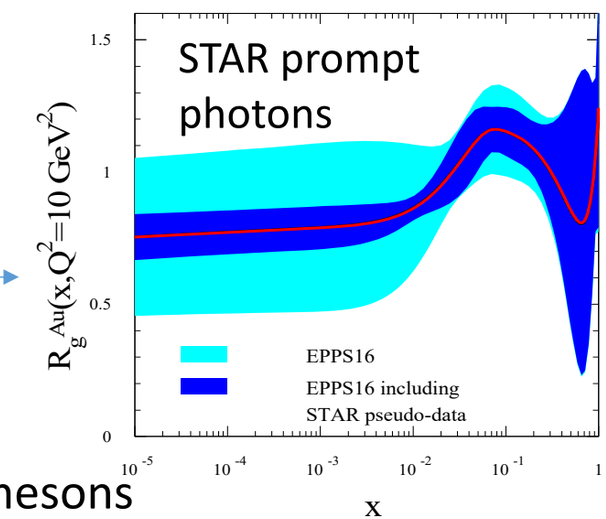

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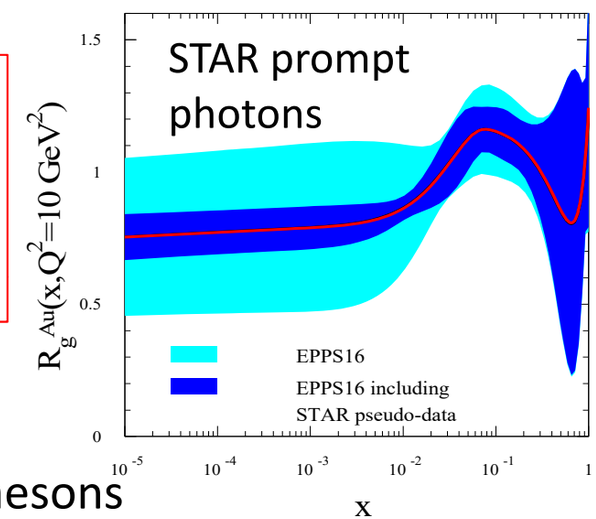
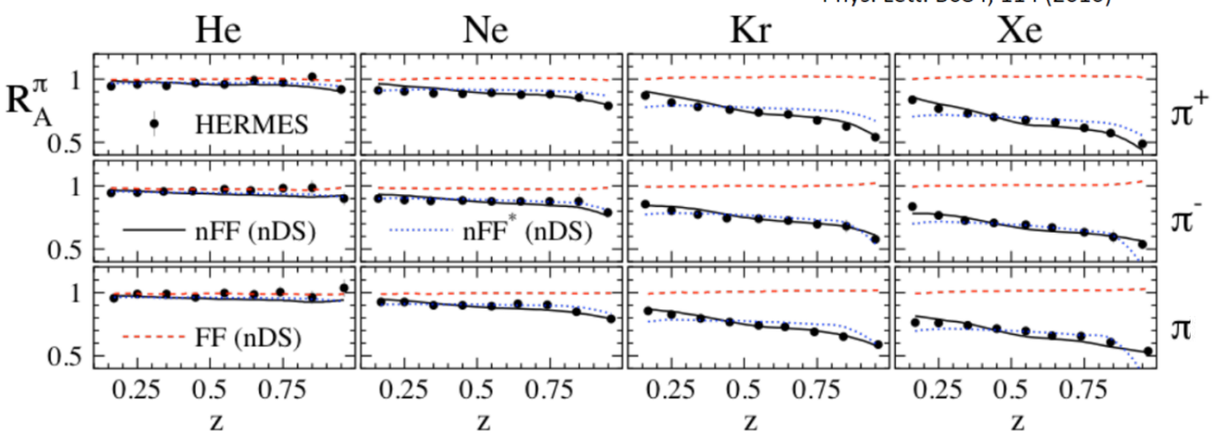
A comprehensive p+A program at RHIC, with already planned running time, could make significant progress in improving our understanding of nPDF's!



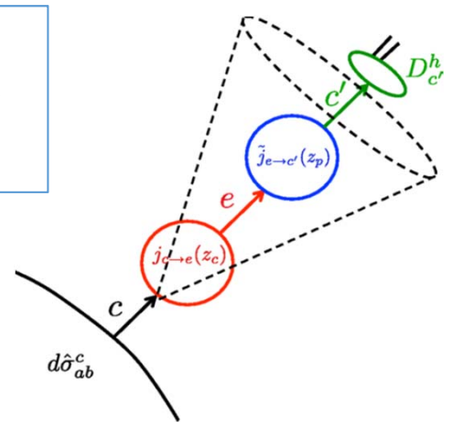
Fragmentation in a Nuclear Environment

Phys. Lett. B577, 37 (2003)
Phys. Lett. B684, 114 (2010)

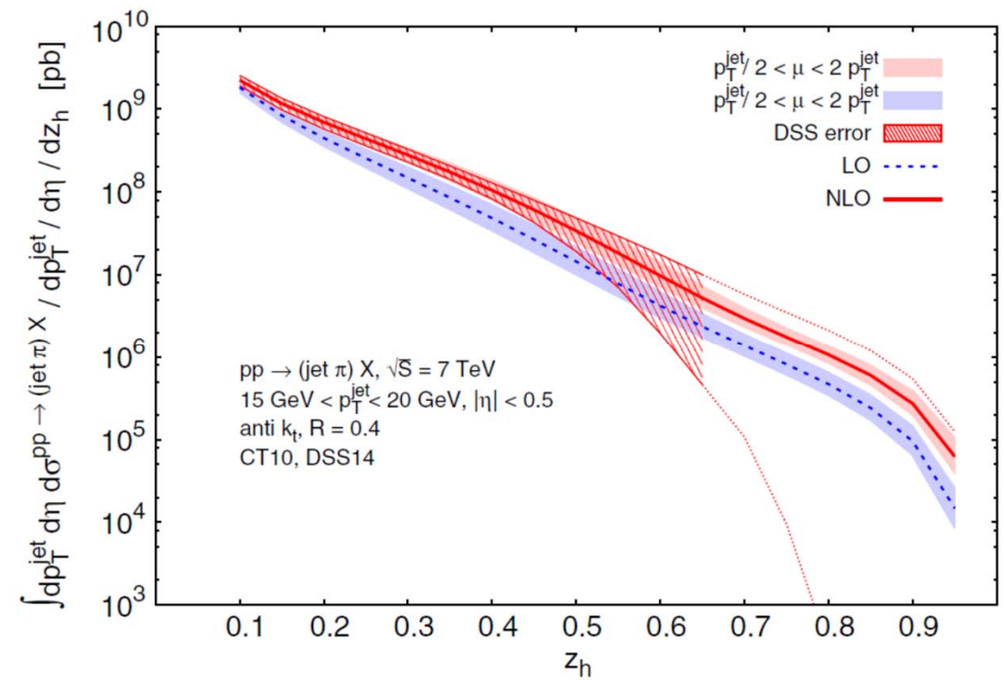


Hadron production in e+A suppressed compared to e+p – must be a fragmentation effect!

Access fragmentation functions (FF) through p+p(A) -> (jet *h*) X



Kaufmann, Mukherjee and VogelsangPhys.Rev.D 92 5, 054015



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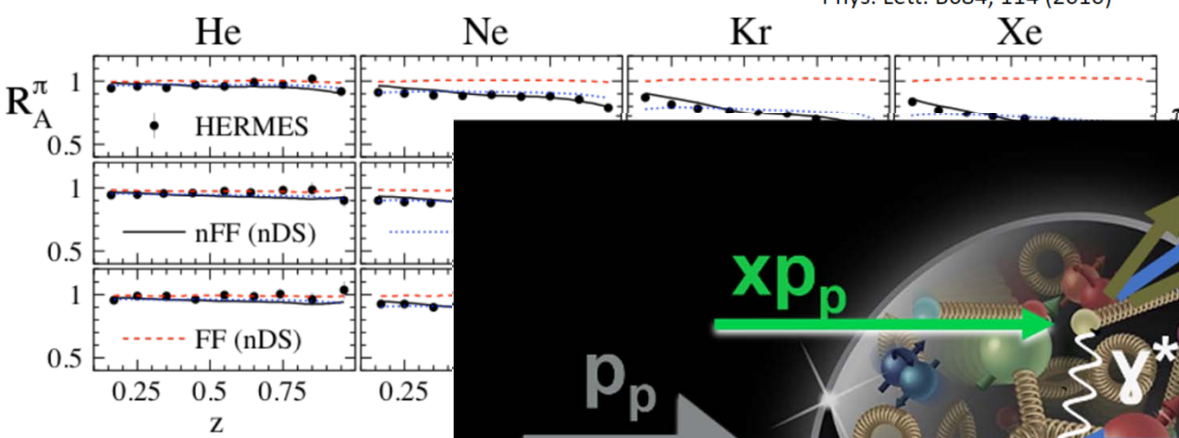

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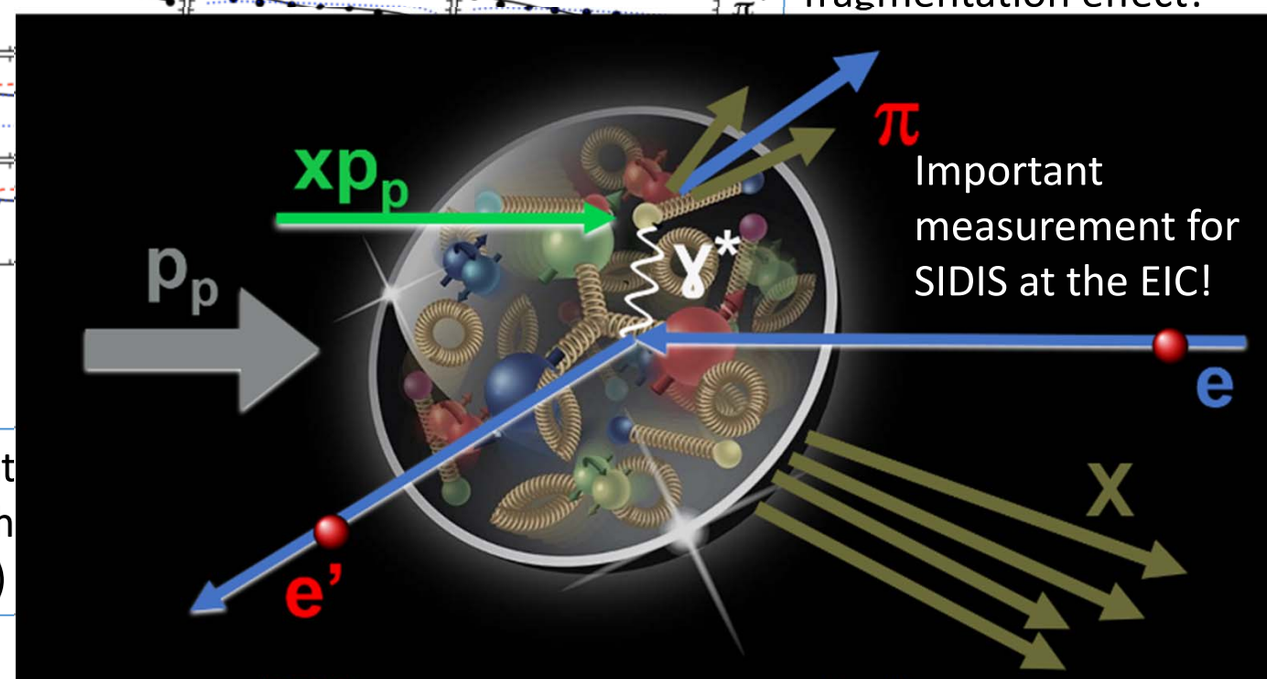
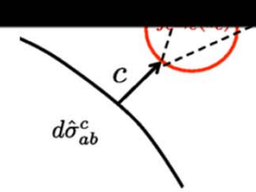
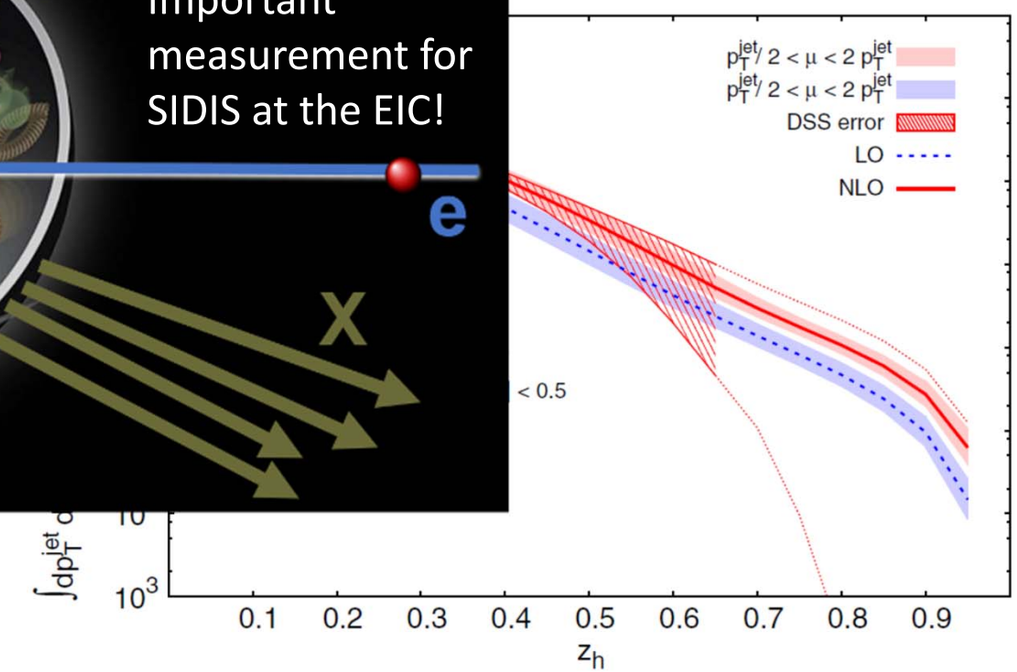


Important measurement for SIDIS at the EIC!

Access fragment
functions (FF) th
p+p(A) -> (jet *h*)

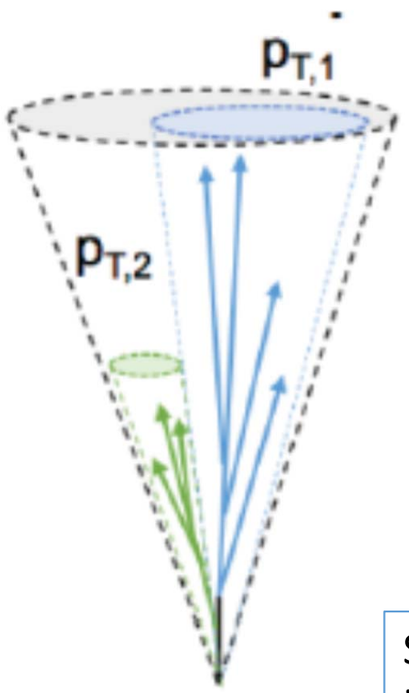


VogelsangPhys.Rev.D 92 5, 054015

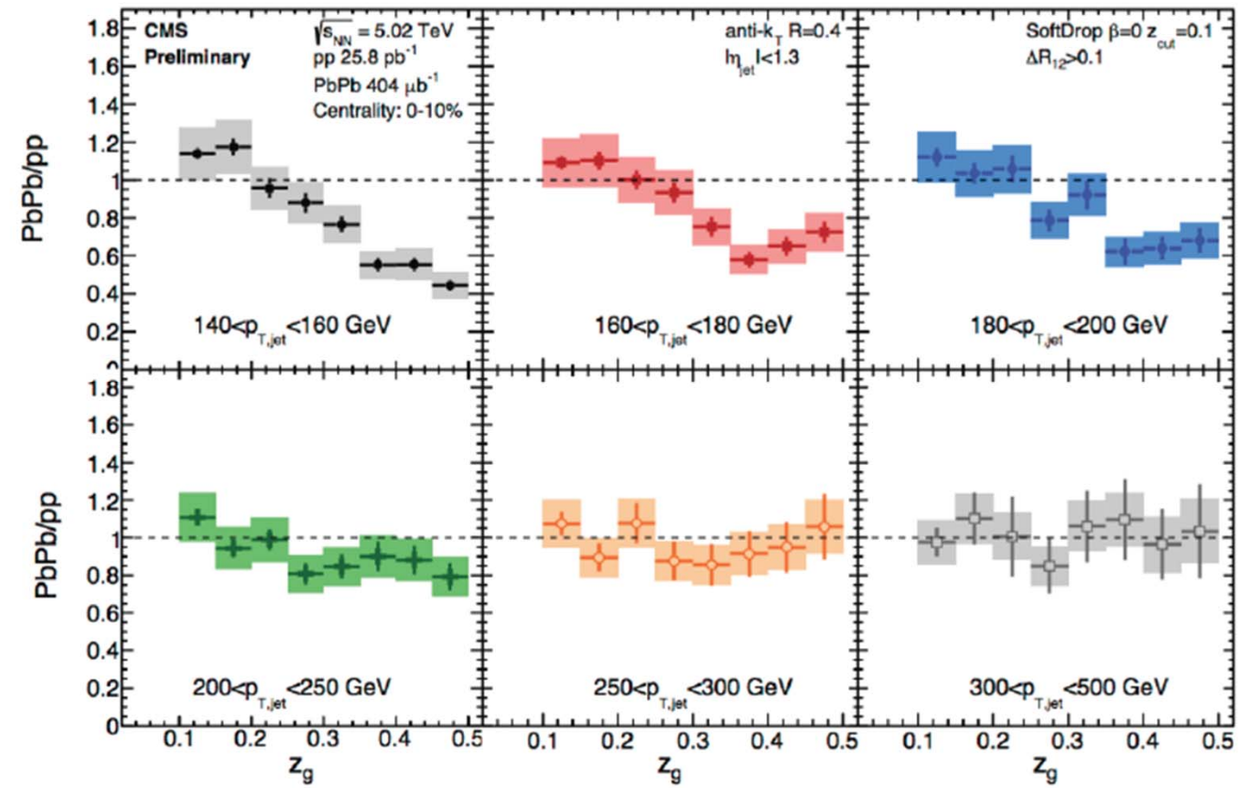


Jet Substructure

CMS PAS HIN-16-006



$$z_g = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

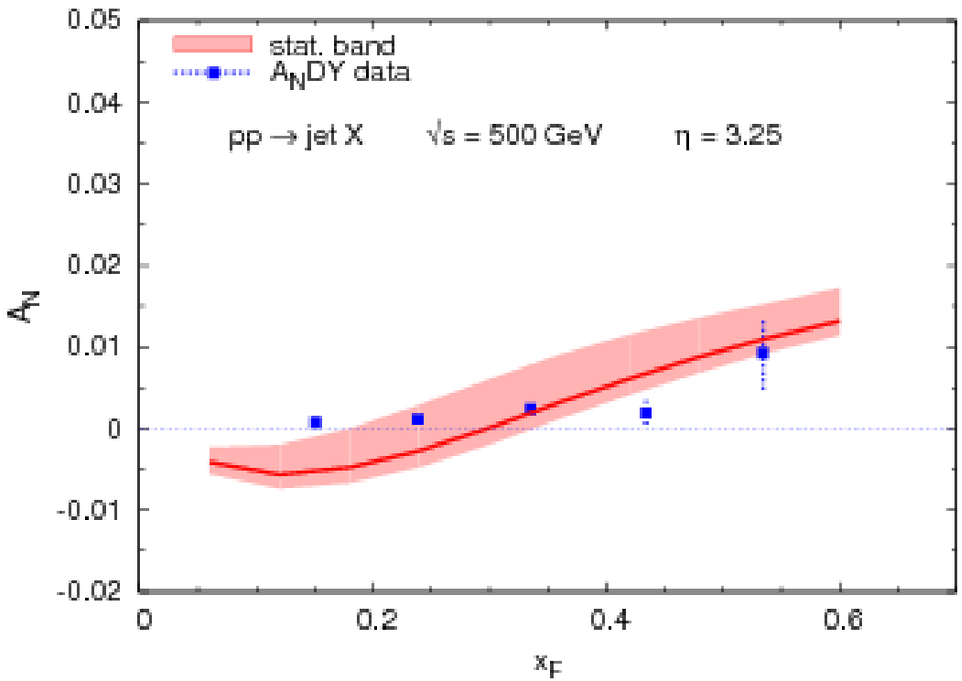


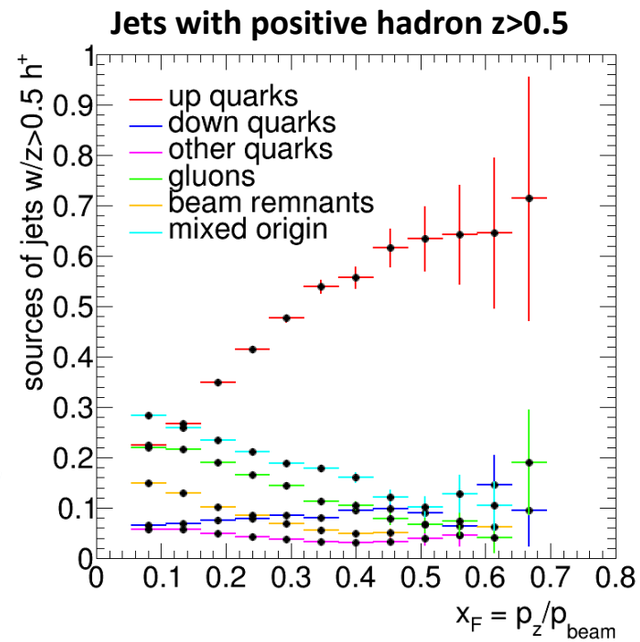
Soft-drop grooming combined with a Cambridge-Aachen type decomposition of a jet found with an anti-k_T algorithm – provides detailed information about the first parton splitting!

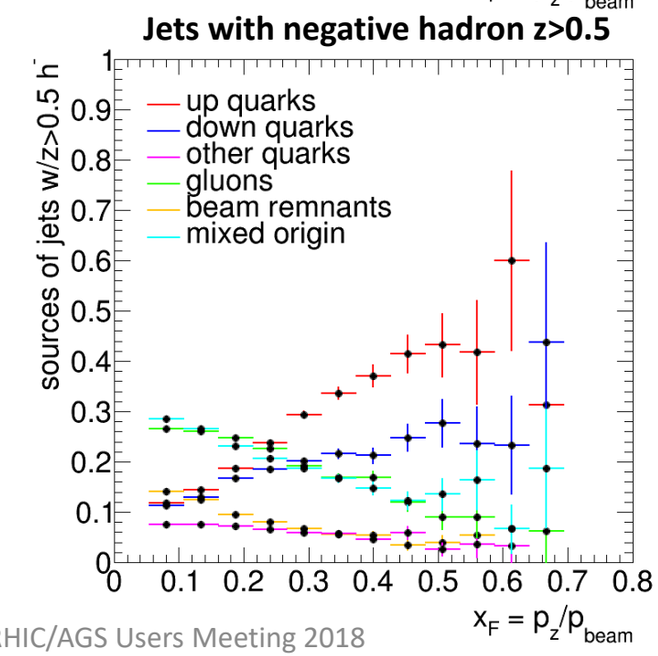
An excellent way to study cold QCD effects in fragmentation <u>in detail</u>!

An Unresolved Mystery…

AnDY: Phys. Lett. B750 (2015) 660







A cut on the charge of the leading hadron changes the composition of the jet sample (Pythia simulation).

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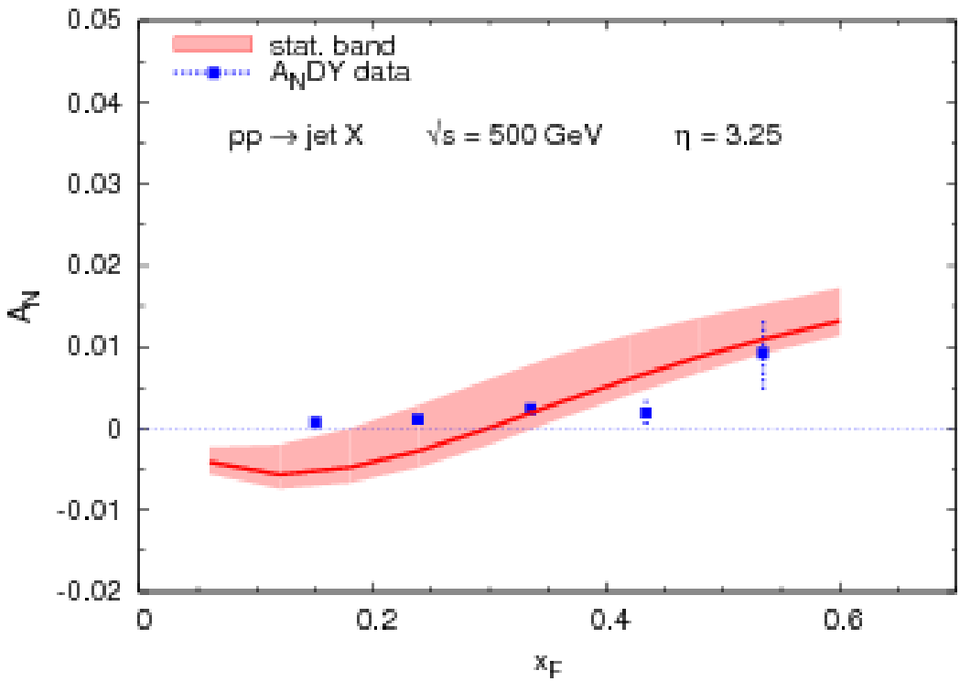

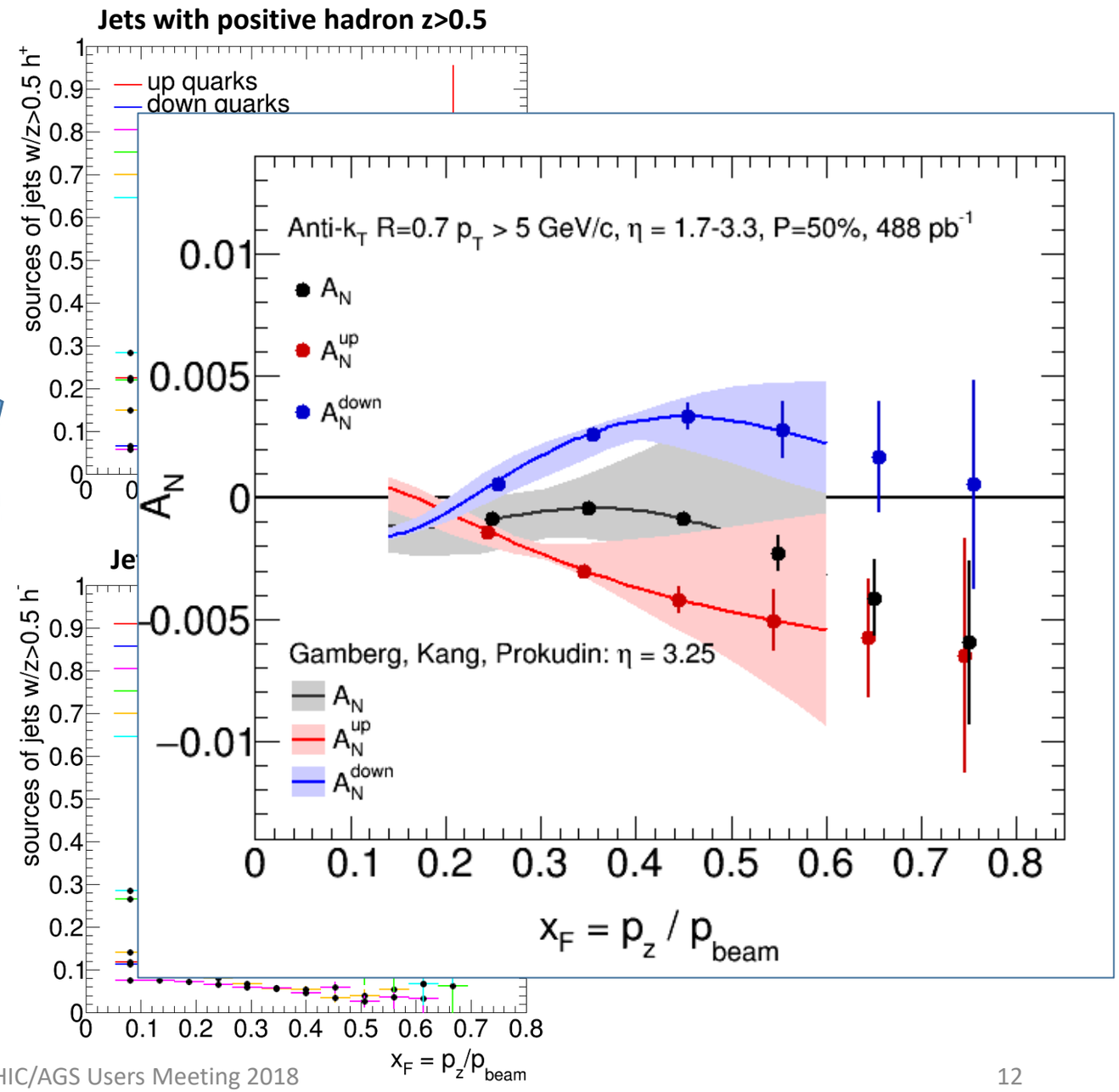

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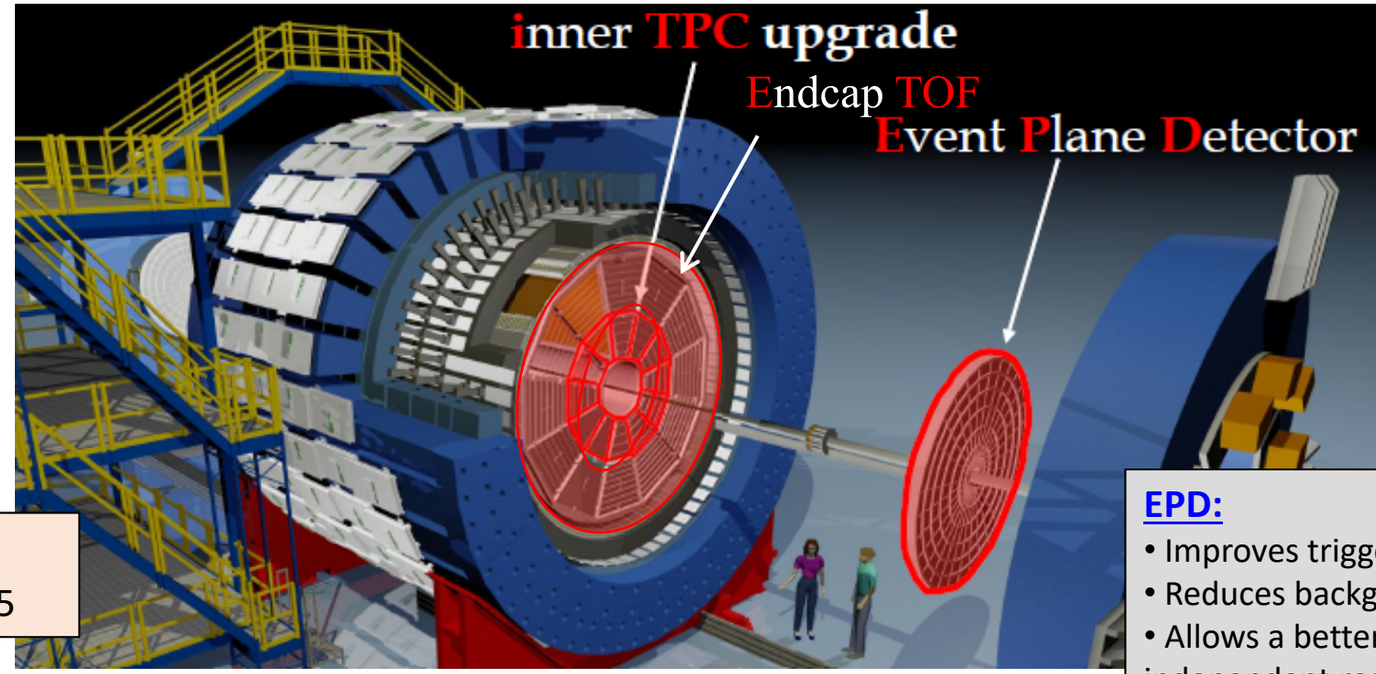
STAR Implementation (2020+)

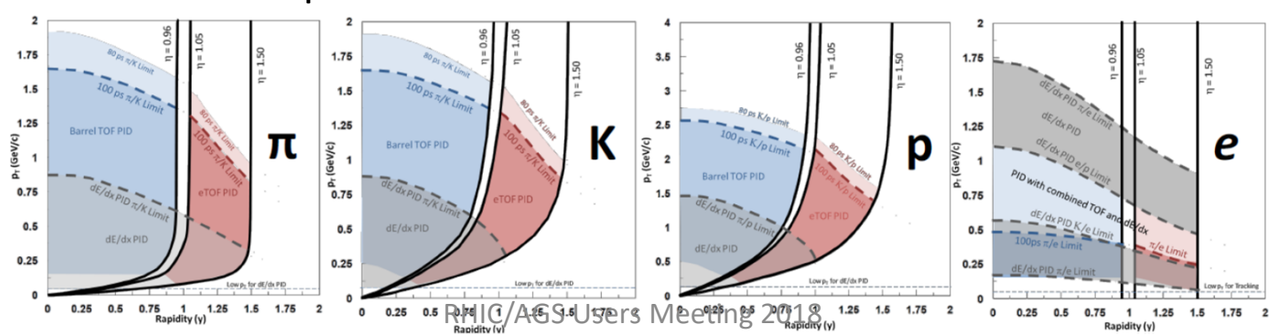
iTPC:
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c



EndCap TOF:
PID at η = 0.9 to 1.5

EPD:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane

π,K,p,e Acceptance and PID capabilities with the combination of iTPC and eTOF:

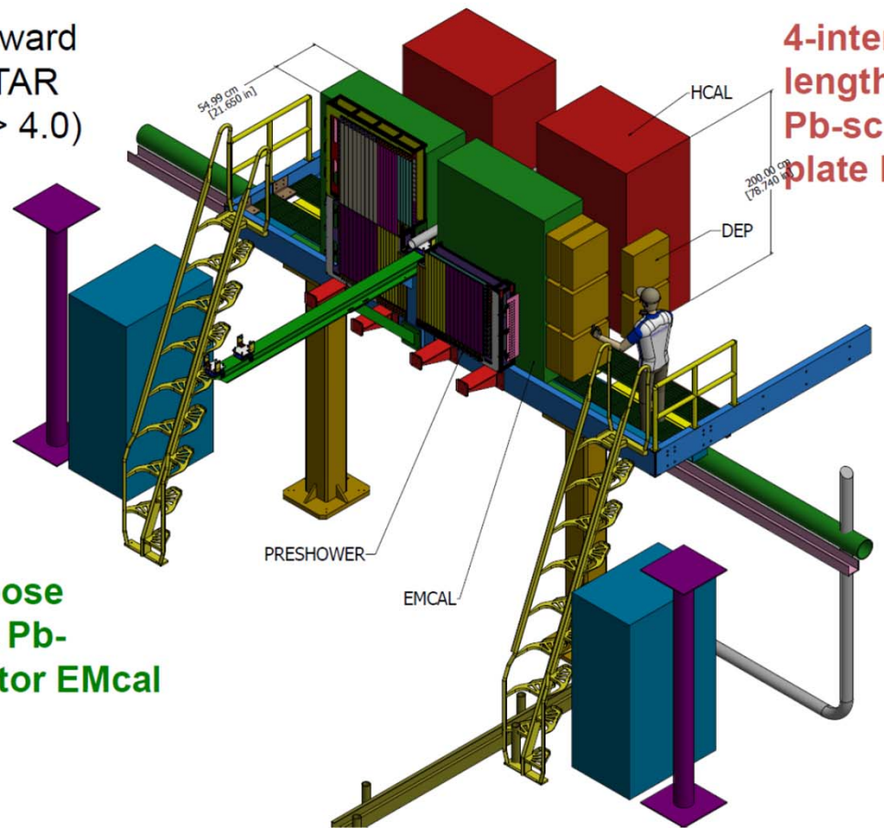


STAR Implementation

3 Silicon disks: at 90, 140, 187 cm from IP
Built on successful experience with STAR IST
- Single-sided double-metal mini-strip sensors
  - Granularity: fine in ϕ and coarse in R

4 sTGC disks: at 270, 300, 330, 360 cm from IP (outside Magnet)
- Position resolution: ~100 μm
- Material budget: ~0.5% per layer, 2 layers / disk
- Readout: reuse current STAR TPC electronics
- 1st sTGC prototype to be installed in STAR in 2019

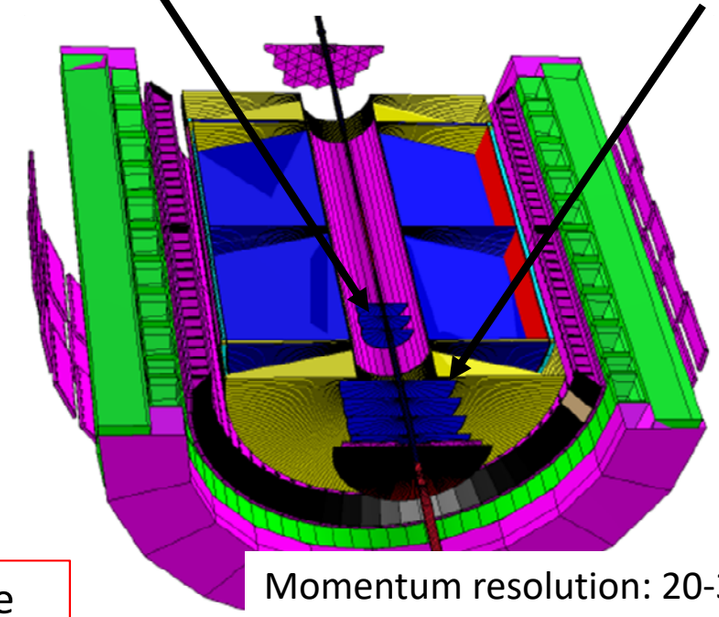
Install in forward region at STAR (2.3 > eta > 4.0)



4-interaction length thick Pb-scintillator plate HCAL

Re-purpose PHENIX Pb-scintillator EMcal

21

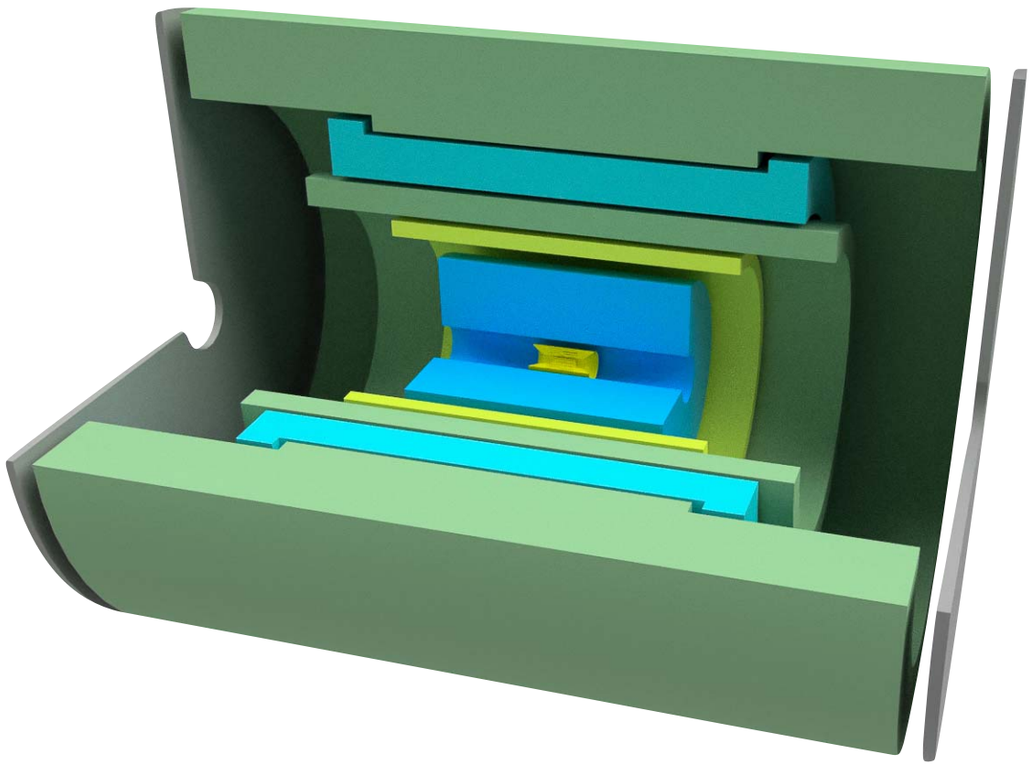


Momentum resolution: 20-30%
for $0.2 < p_T < 2$ GeV/c
track finding efficiency: 80%@100 tr/ev

Substantial re-use of existing equipment and infrastructure. Extensive R&D program underway, leverages STAR and EIC detector R&D.

sPHENIX Implementation

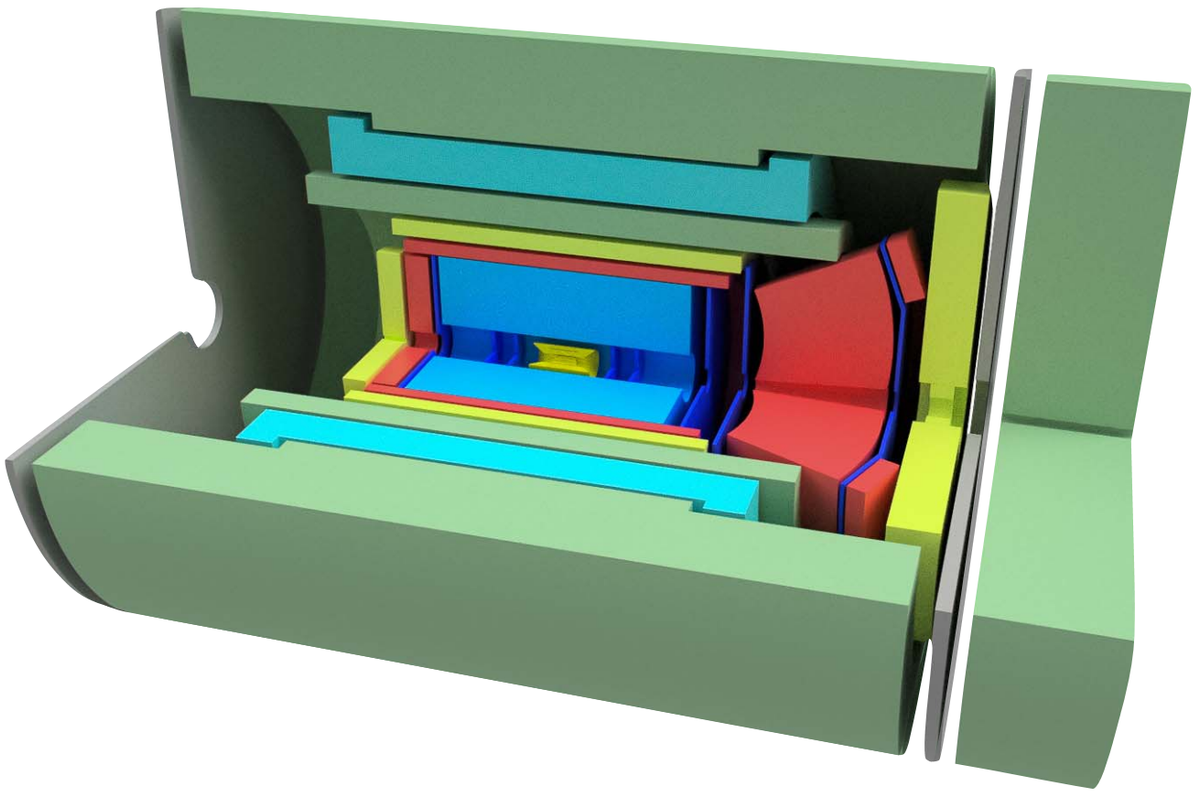
A next-generation state-of-the-art jet detector for A+A physics at RHIC. Successful CD-1/3a review!



- sPHENIX
  - HCal/Flux return
  - Solenoid
  - Central EMCal
  - Silicon strip tracking
  - TPC
  - MAPS

sPHENIX Implementation

A solid foundation for EIC physics – LOI requested by BNL ALD.



- EIC-sPHENIX detector
  - HCal/Flux return
  - Solenoid
  - Extended Central EMCal
  - Central hadron PID
  - TPC
  - MAPS
  - Forward and backward tracking
  - Forward and backward hadron PID
  - Backward crystal EMCal
  - Forward EMCal
  - Forward HCal

sPHENIX Implementation

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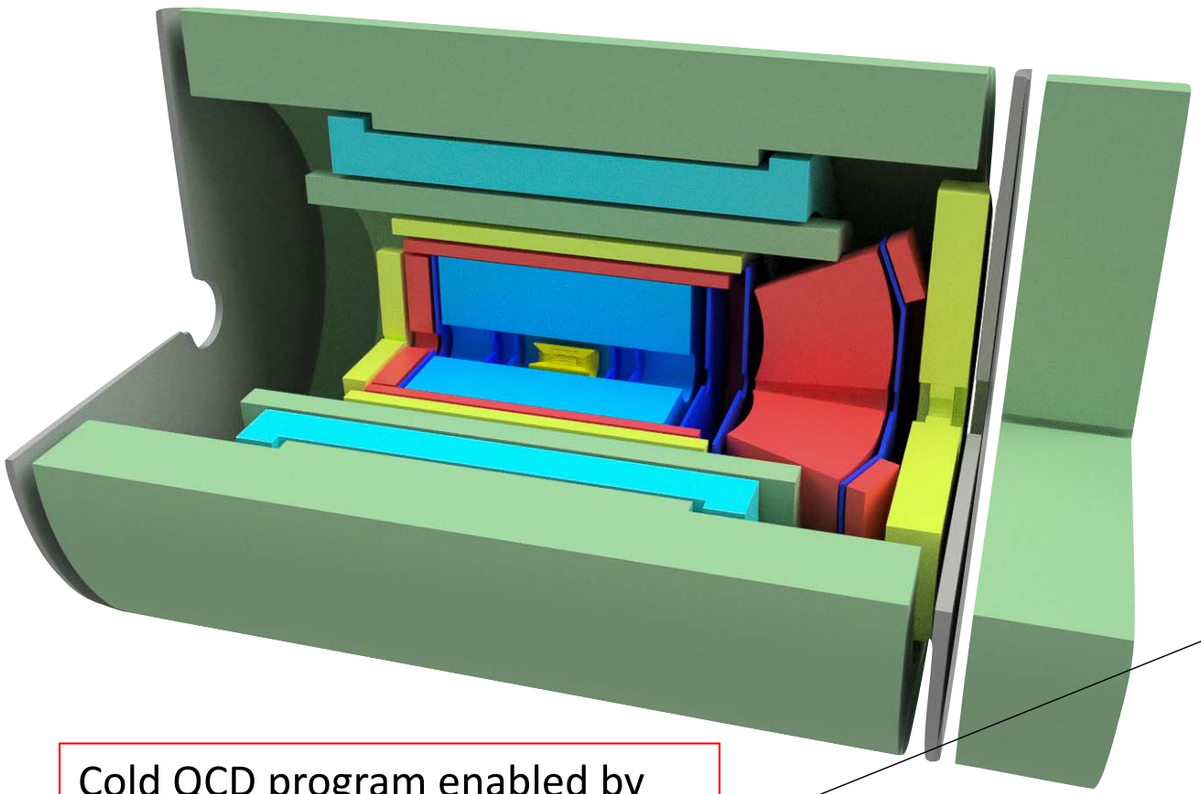

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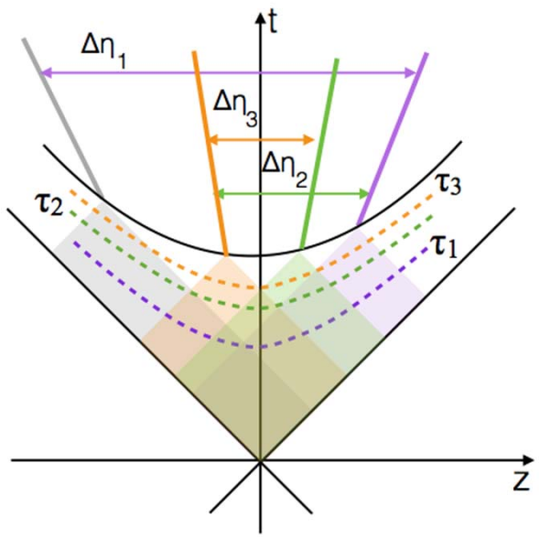
  - Forward and backward tracking
  - Forward and backward hadron PID
  - Backward crystal EMCal
  - Forward EMCal
  - Forward HCal

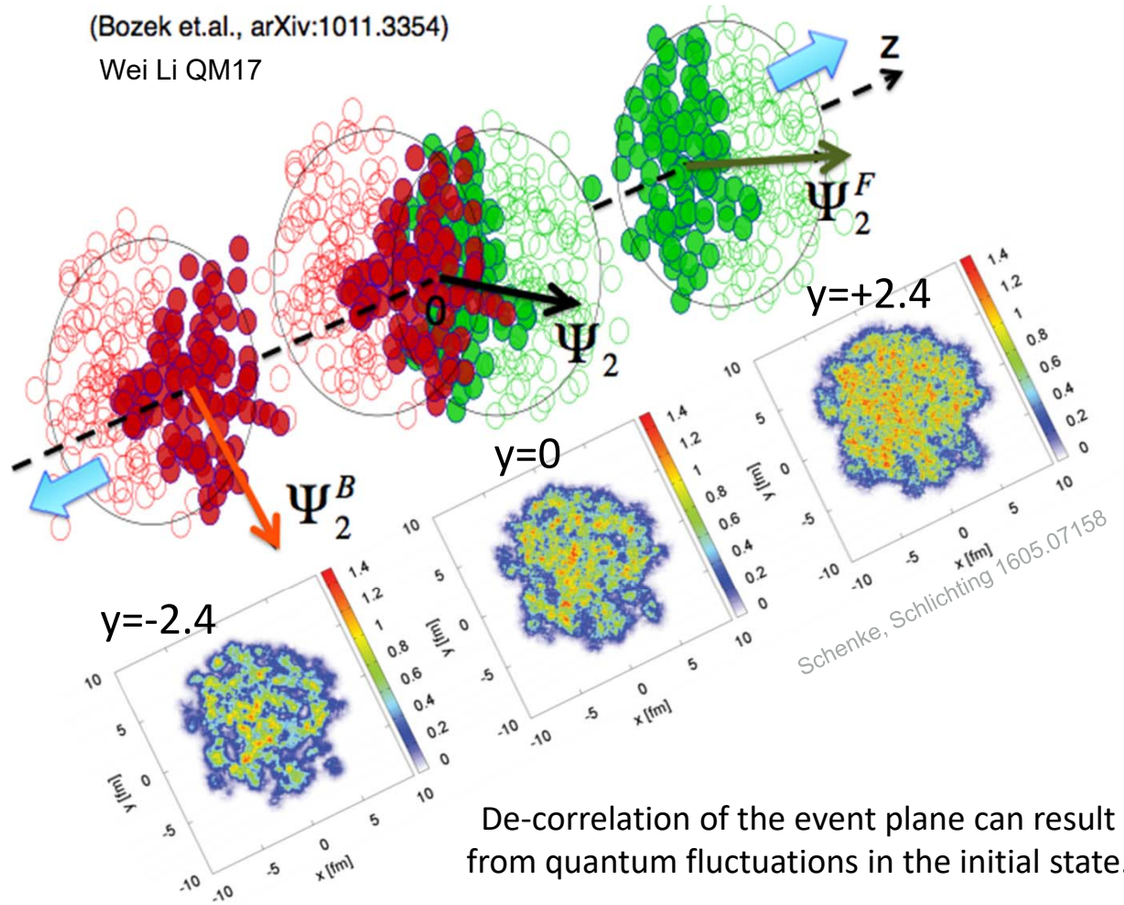
Cold QCD program enabled by early realization of some EIC-sPHENIX detector components!

What about A+A?



Due to causality, correlations that are widely separated in rapidity probe the <u>earliest times</u>.

Adding forward capabilities at RHIC will enable a new, complementary physics program to study the initial conditions in HI collisions.



De-correlation of the event plane can result from quantum fluctuations in the initial state.

Need to understand this to be able to extract $\eta/s(T)$ from hydrodynamic models.

Summary

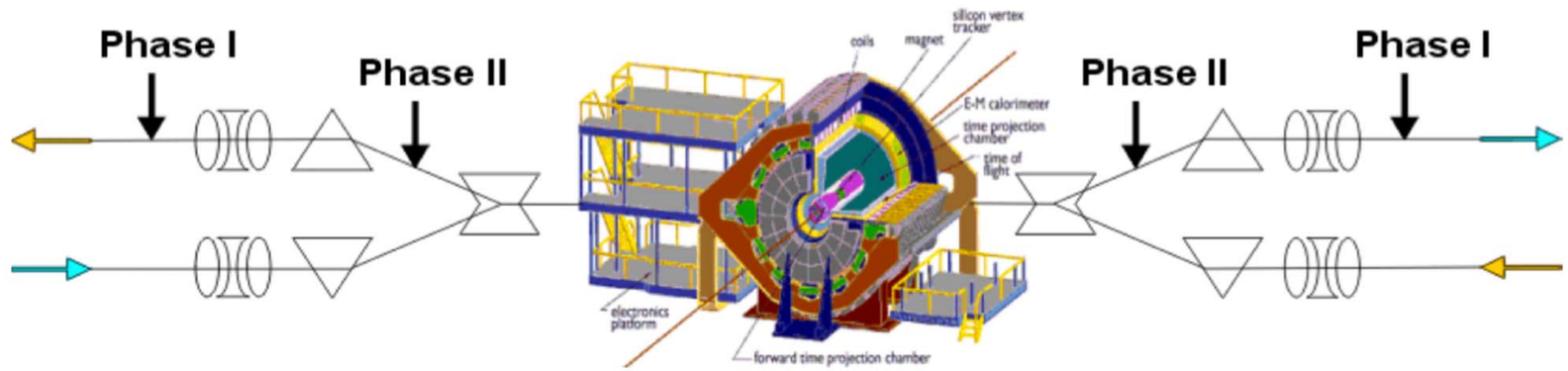
- A wealth of important Cold QCD physics results could be had for a relatively modest investment in detector upgrades:
  - Enables important Cold QCD measurements on the road to the EIC
  - Will enhance the planned A+A program
  - Some of this investment could be recovered for a future EIC detector
- Many measurements could be accomplished within currently planned RHIC running for 2021+
  - A long 500 GeV p+p run would also be required
- Provides a real opportunity to coalesce a Medium Energy NP community at RHIC in anticipation of an EIC

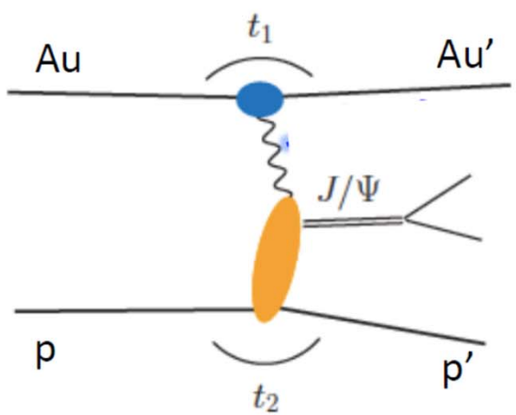
My nickel…

BACKUP

Diffraction/UPC

Data taken in 2015/17 by STAR will elucidate the diffractive contribution to A_N at RHIC.





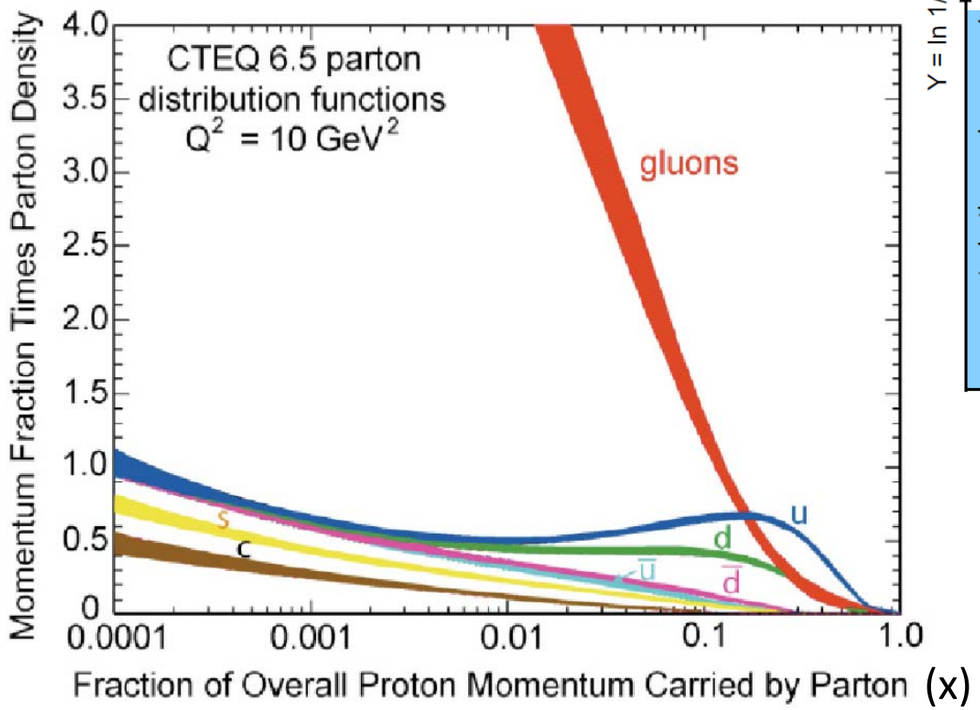
$$A_{UT}(\tau,t) \sim \frac{\sqrt{t_0 - t}}{m_p} \frac{\mathrm{Im}(E * H)}{|H|} \qquad t = \frac{M_{J/\Psi}^2}{s}$$

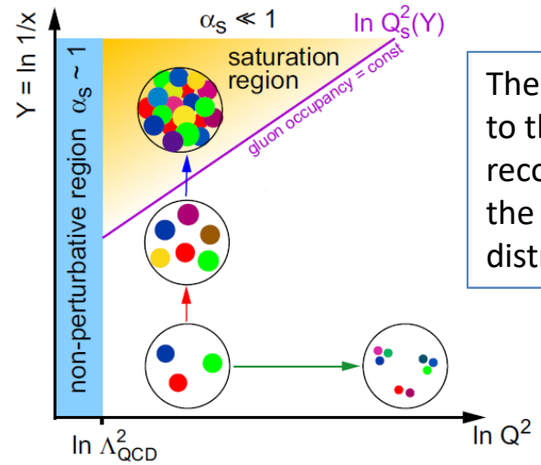
UPC collisions in p+A will allow study of:

- The gluon spatial distribution in nuclei ("proton shine")
- The gluon helicity flip Generalized Parton Distribution (GPD) E_g ("A-shine")

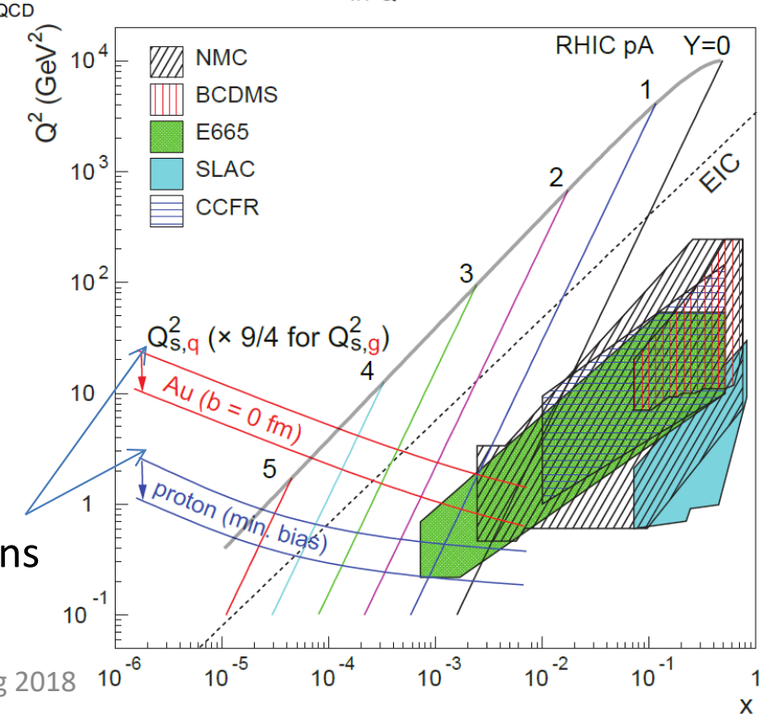
Requires Roman Pots, good t-acceptance and high luminosity

Gluon Saturation





The gluon density grows to the point where recombination tames the growth of the gluon distribution at small x.



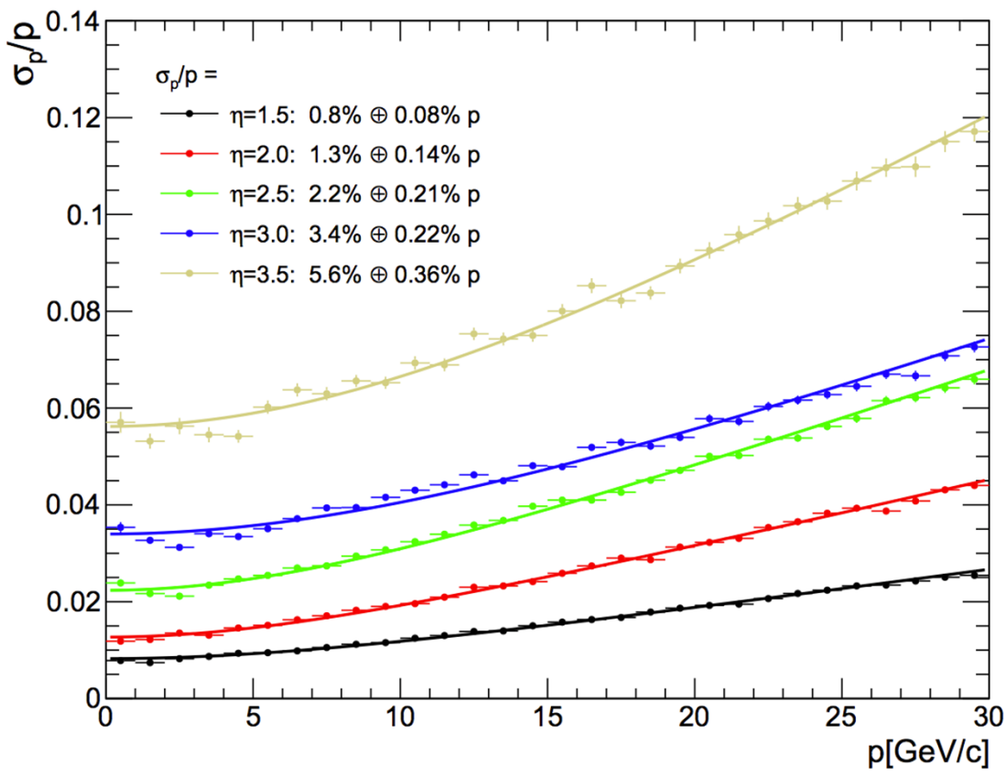
The nucleus is an *amplifier* of high gluon densities.

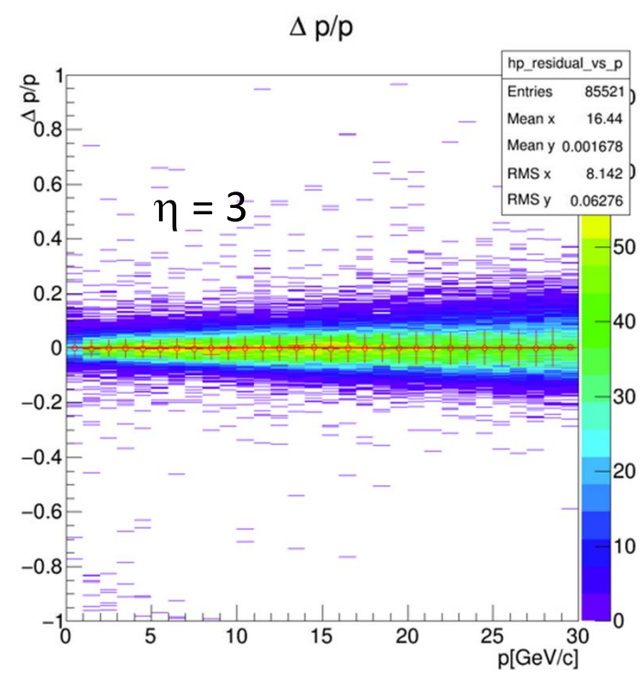
$$\left(Q_S^A\right)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$

gluons

Forward Tracking

- **G4 Simulation and (PH)GenFit** to extract $(p_{Reco} - p_{True})/p_{True}$ vs. p_{True} (right plot)
- For each slice of p_{True}, fit with Gaussian, extract mean as offset, sigma as resolution





Excellent momentum resolution!

Tracking simulations by Haiwang Yu

Multi-year sPHENIX run plan

Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

- Guidance from ALD to think in terms of a multi-year run plan
- Consistent with language in DOE CD-0 "mission need" document
- Based on BNL C-AD guidance on projected luminosity
- Incorporates commissioning time in first year
- Structured so that first three years delivers at least minimum science program

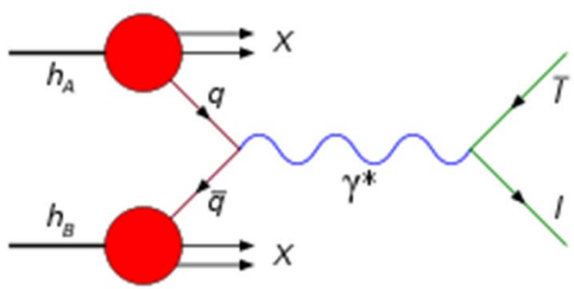
Minimum bias Au+Au at 15 kHz for |z| < 10 cm:

47 billion (Year-1) + **96 billion** (Year-2) + **96 billion** (Year-3) = Total **239 billion events**

For topics with Level-1 selective trigger (e.g. high p_T photons), one can sample within |z| < 10 cm a total of 550 billion events. One could sample events over a wider z-vertex for calorimeter only measurements, 1.5 trillion events.

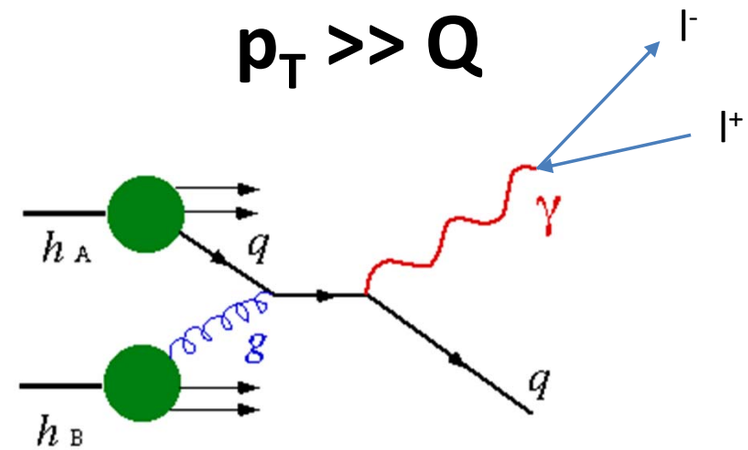
Drell-Yan vs. p_T

$p_T << Q$



- Dominant process is quark-antiquark annihilation
- TMD factorization valid
- Direct comparison of modified universality with SIDIS

$p_T >> Q$



- Dominant process is gluon-Compton scattering to virtual photon
- Same information as direct photon
- TMD factorization NOT valid
- Can be interpreted in Twist-3 approach

Berger, Qiu and Zhang, Phys. Rev. D 65, 034006
Kang, Qiu and Vogelsang, Phys. Rev. D 79, 054007