Gluon Saturation, Diffraction and Multihadron Production at the EIC: Theory, Simulations and Feasibility of Measurements

Center for Frontiers in Nuclear Science

Brookhaven National Laboratory

In part supported by U.S. DEPARTMENT of ENERGY

Probing Small-x Dynamics in Proton-Nucleus Collisions at STAR

Dener De Souza Lemos (BNL)

ddesouzal@bnl.gov

Stony Brook University, NY, USA

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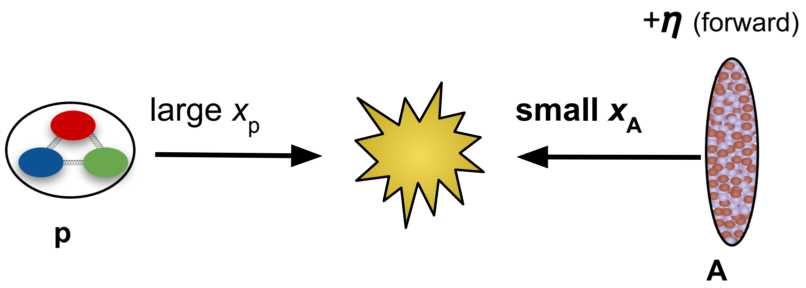
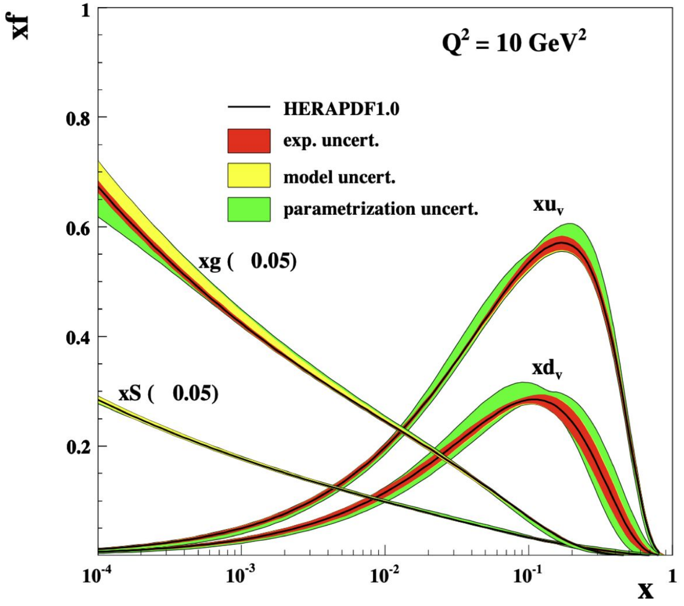
@BrookhavenLab

Motivation

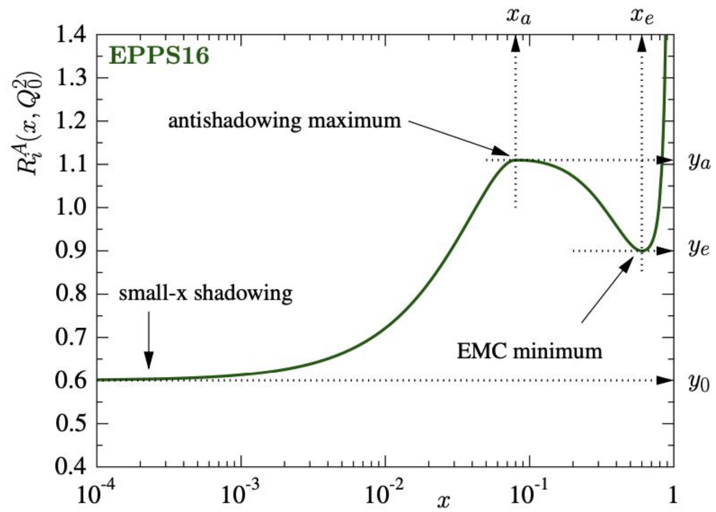
Forward p+A collisions



- ★ p+A: isolate cold nuclear matter (CNM) effects
  - Sensitive to initial-state effects
    - Probe small-*x* physics in the nucleus
      - High gluon density regime
    - Nuclear Parton Distribution Functions (nPDF)
      - e.g. Shadowing
  - Also affected by final-state effects
    - Nuclear Fragmentation Functions (nFF)



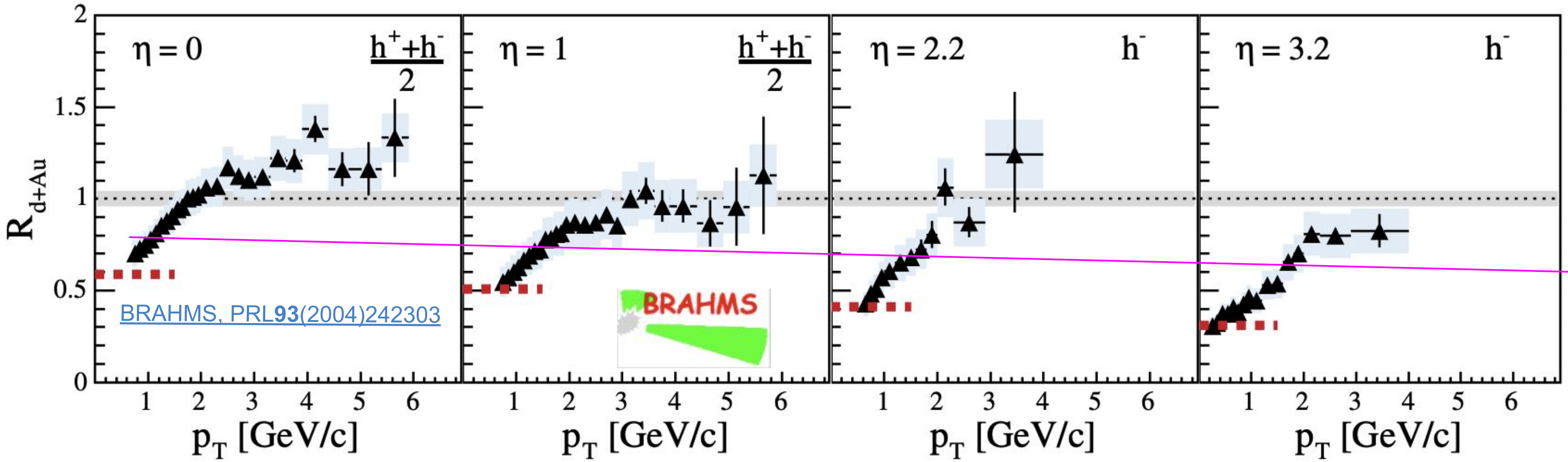
H1 and ZEUS, JHEP01(2010)109

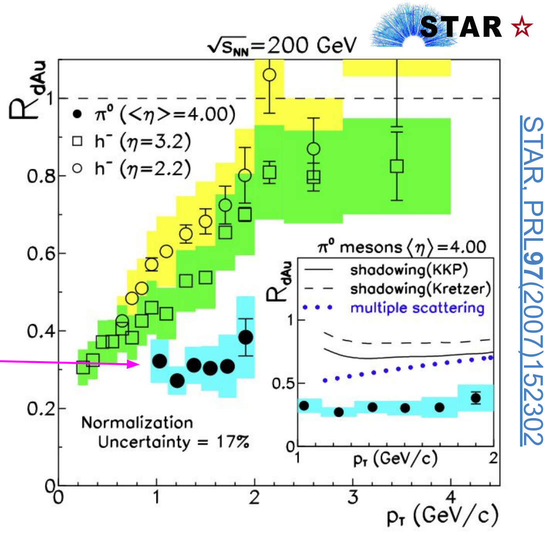


K. Eskola et al., EPJC77(2017)163

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

Nuclear modification factors at RHIC





- ★ Suppression observed for forward (small-*x*) regime in d+Au collisions
  - ○ Also seen in LHCb p+Pb data

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

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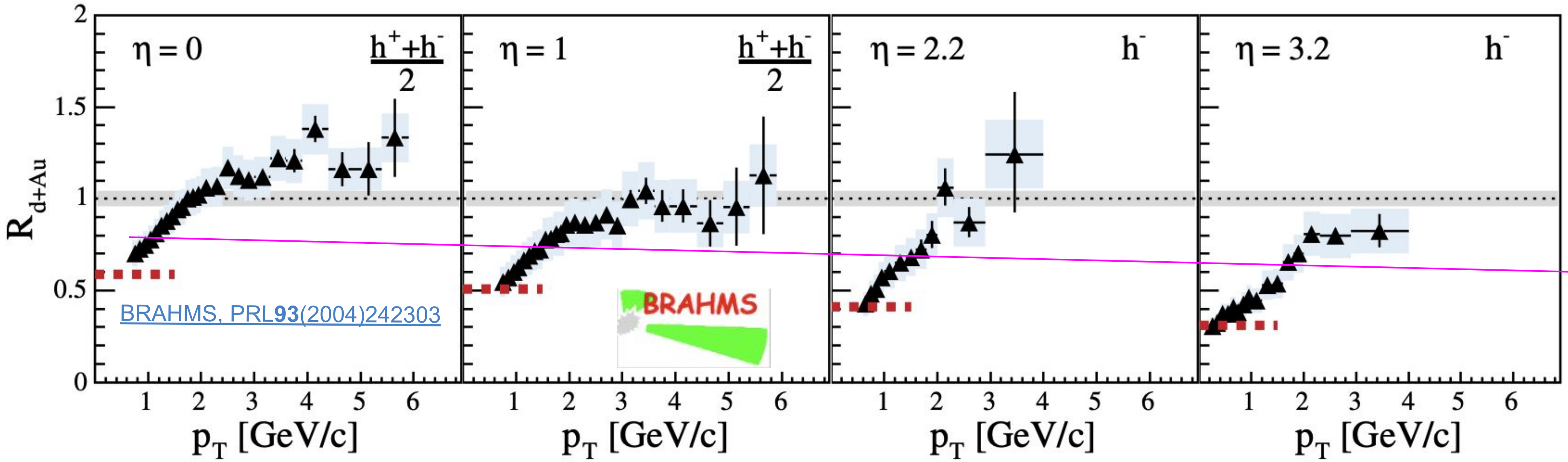
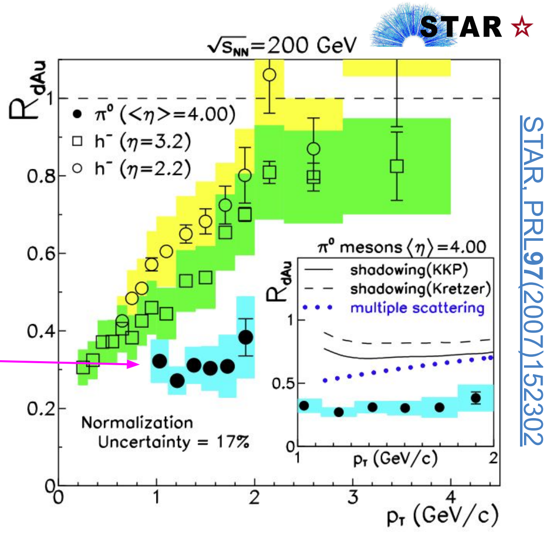




★ Suppression observed for forward (small-*x*) regime in d+Au collisions

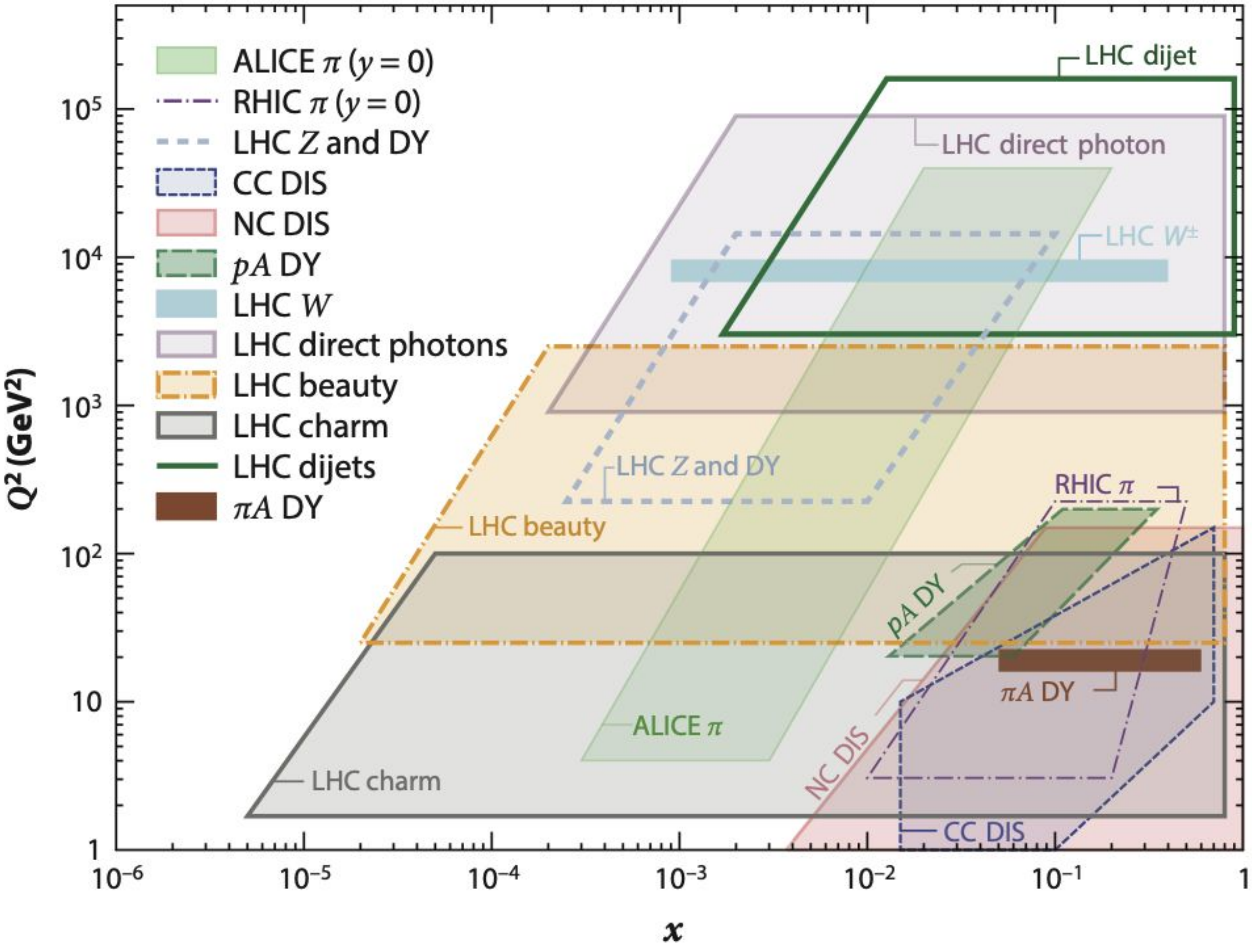
- Also seen in LHCb p+Pb data

★ By comparing p+A to p+p, we disentangle nuclear effects from baseline proton interactions

- **Goal #1: Constraints on nPDFs**
- **Goal #2: Potential sensitivity to gluon saturation effects**
- **Goal #3: Probe the impact of nFF**

STAR data can probe small-*x* at low-to-moderate Q^2

Current Knowledge of nPDFs



M. Klasen and H. Paukkunen, ARNPS74(2024)1

Current Knowledge of nPDFs

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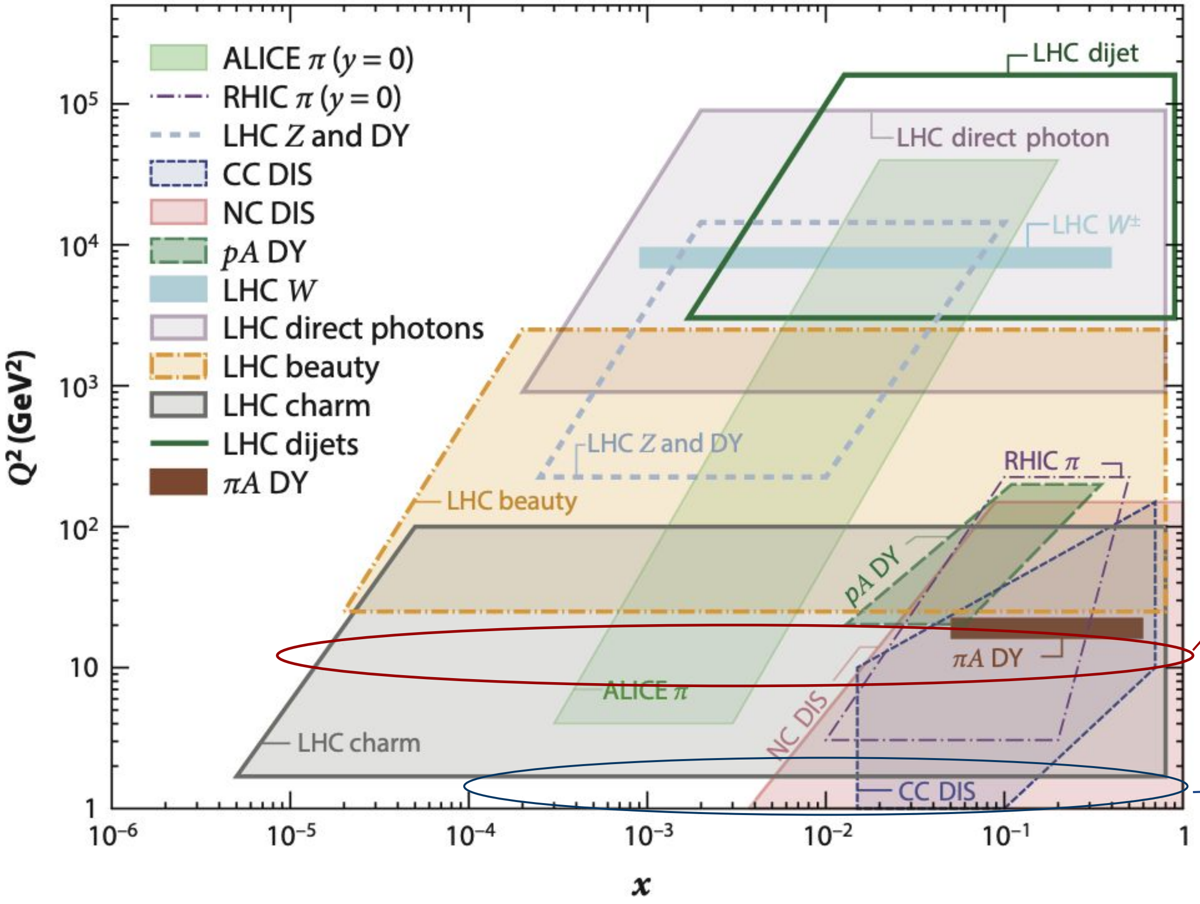

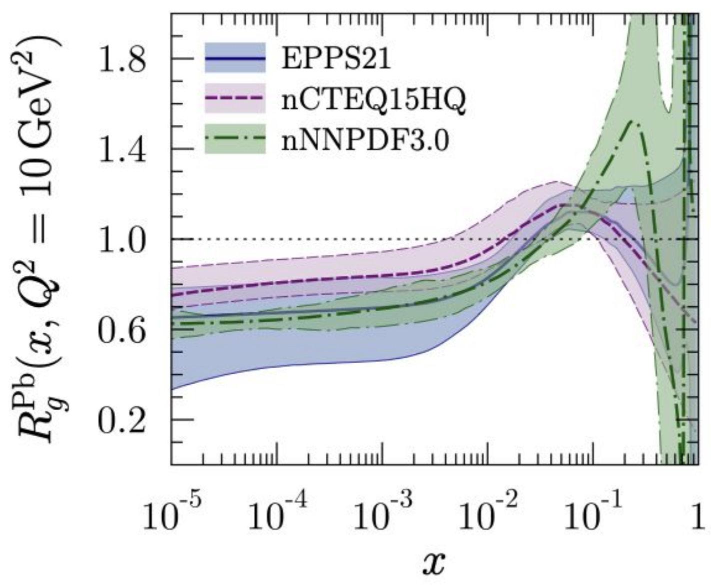

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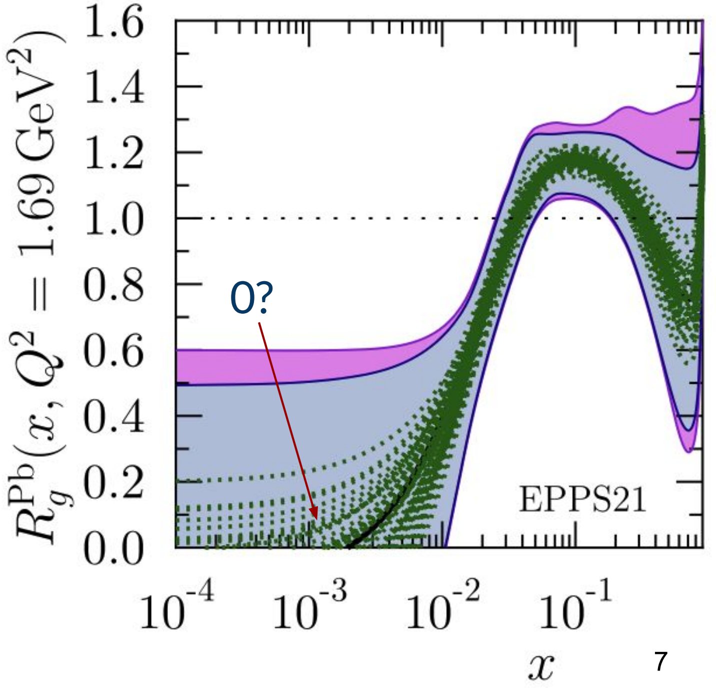
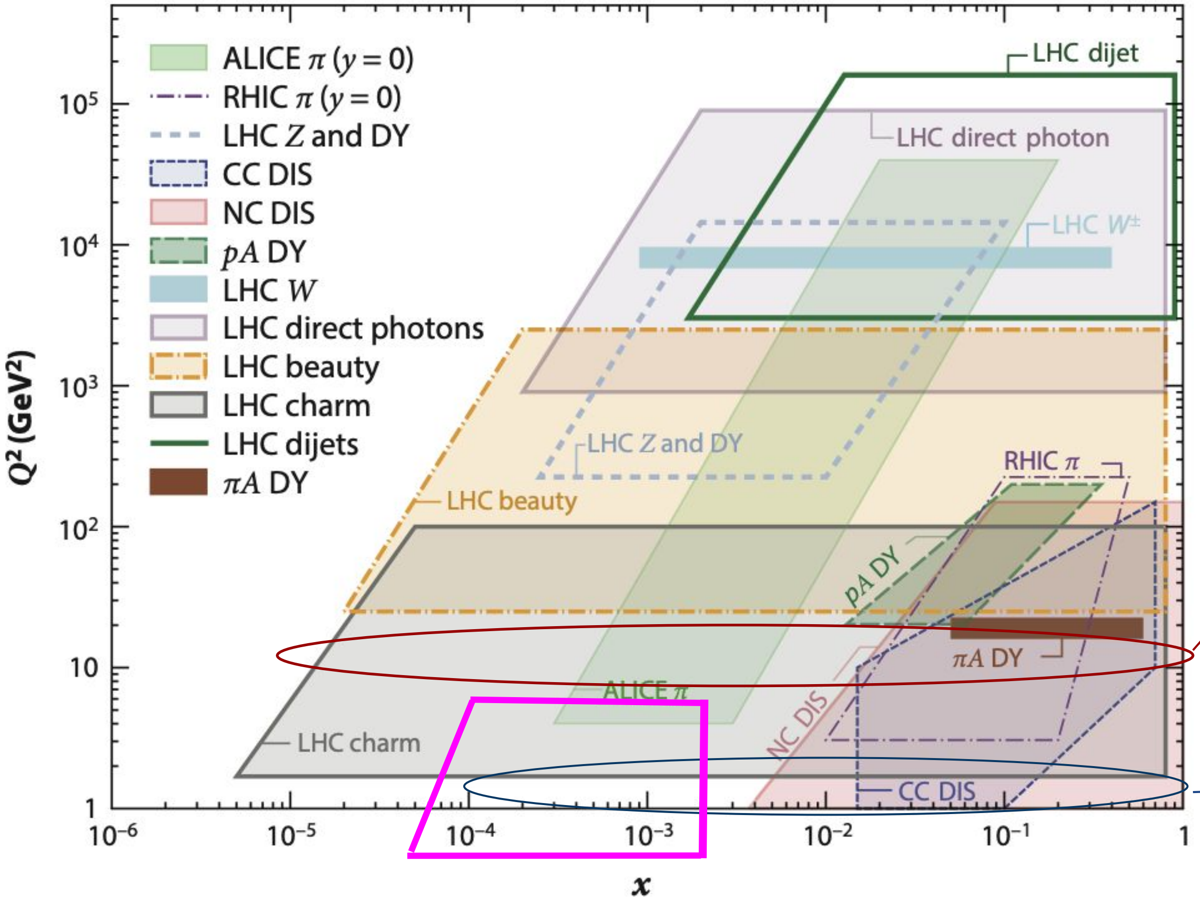


K. Eskola et al., EPJC82(2022)413

- ★ Gluon density becomes 0 at small-*x* ? Fitting artifact?
    - ○ Strong effect from LHCb D-meson R_{pA}

Current Knowledge of nPDFs



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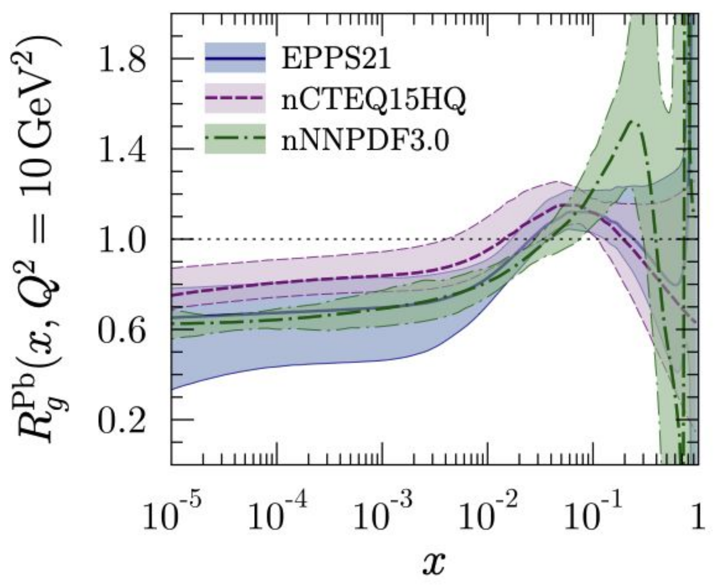

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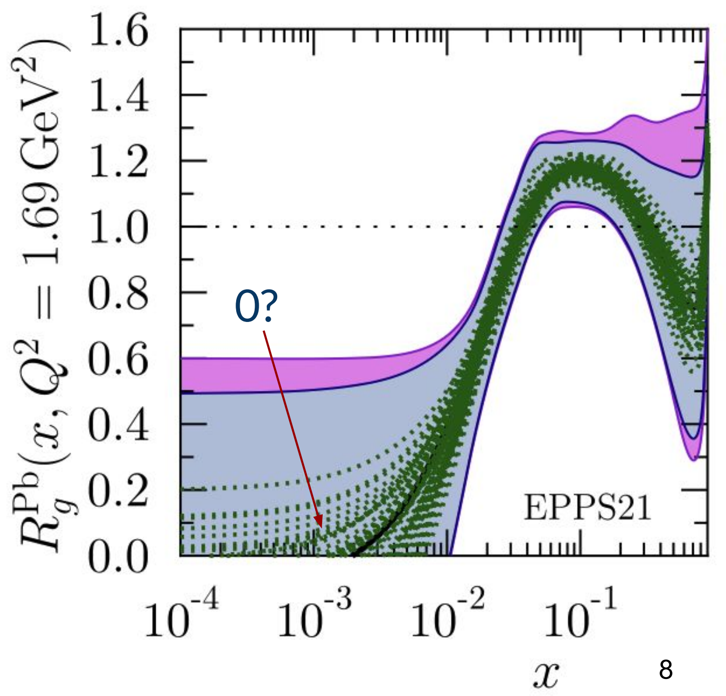


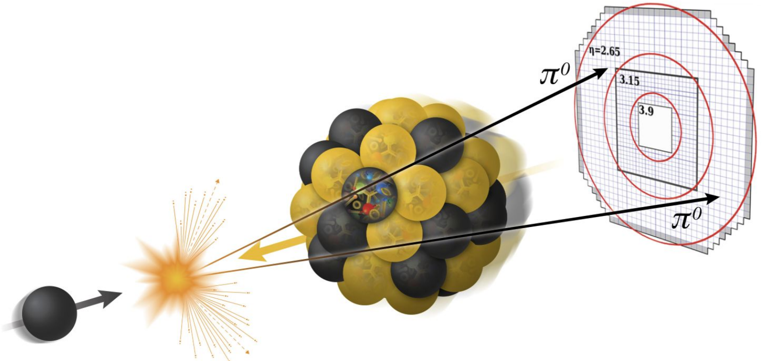
K. Eskola et al., EPJC**82**(2022 413

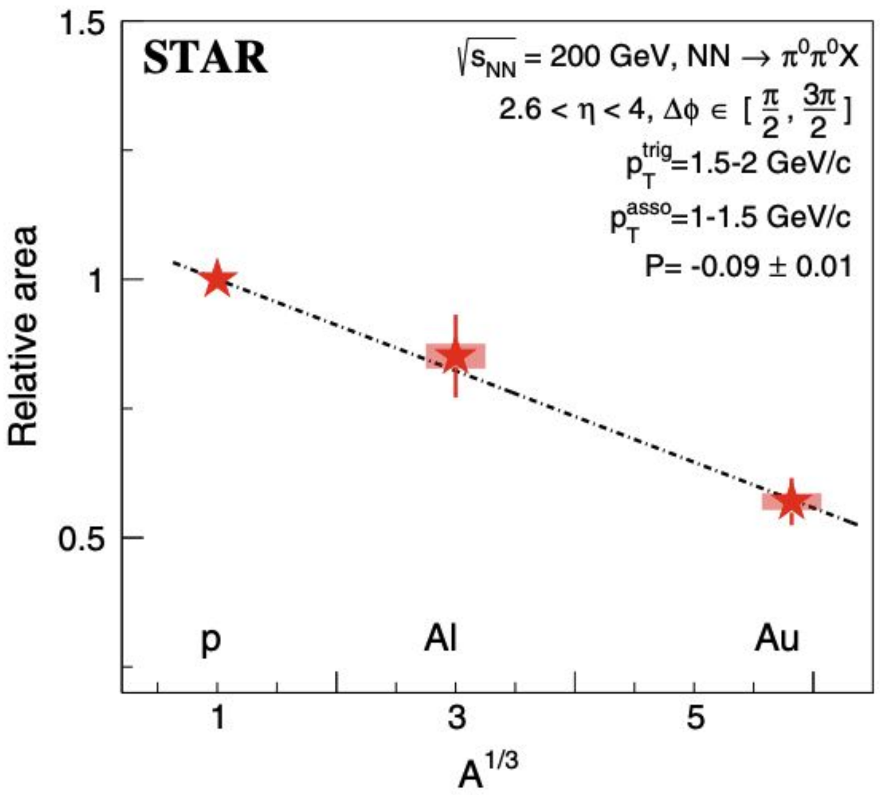
★ Gluon density becomes 0 at small-*x* ? Fitting artifact?

- Strong effect from LHCb D-meson R_{pA}

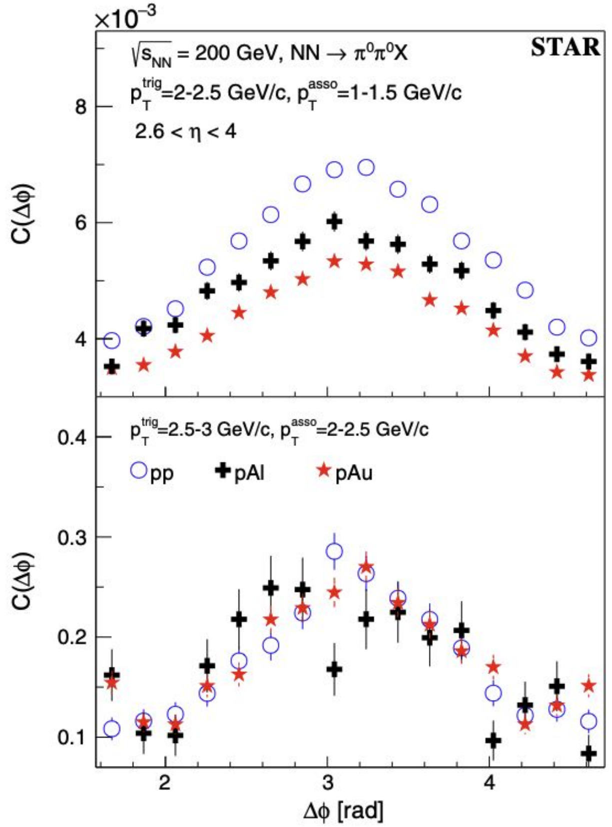
Gluon Dynamics in small-x at STAR

- ★ Forward two-particle correlations
- ★ Suppression observed at low p_T (not seen in high p_T)
  - ○ Linearly depends on $A^{1/3}$ for fixed p_T (x and Q^2)
  - ○ Broadening expected from theory is not observed





More details in:
Xiaoxuan's talk
and
Gabriel's talk

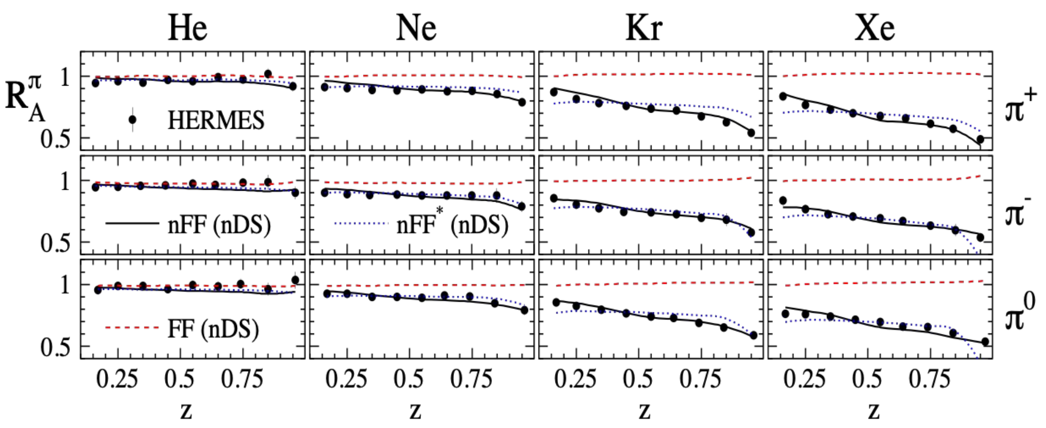


STAR, PRL129(2022)092501

Nuclear Fragmentation Functions

★ Hermes/HERA (fixed-target mode)
  ○ Production differs between ep and eA

Hadron-level observable: $R_A = (N_h / N_{DIS})^{-1}_{ep} (N_h / N_{DIS})_{eA}$

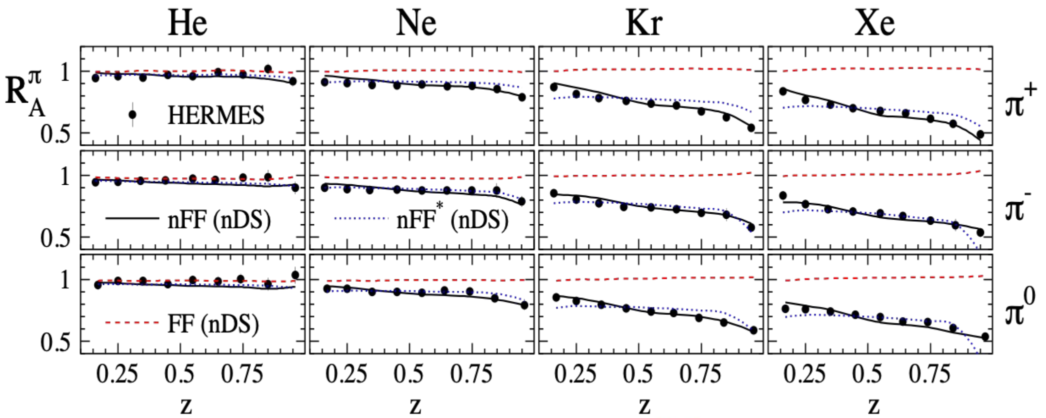


R. Sassot, PRD81(2010)054001

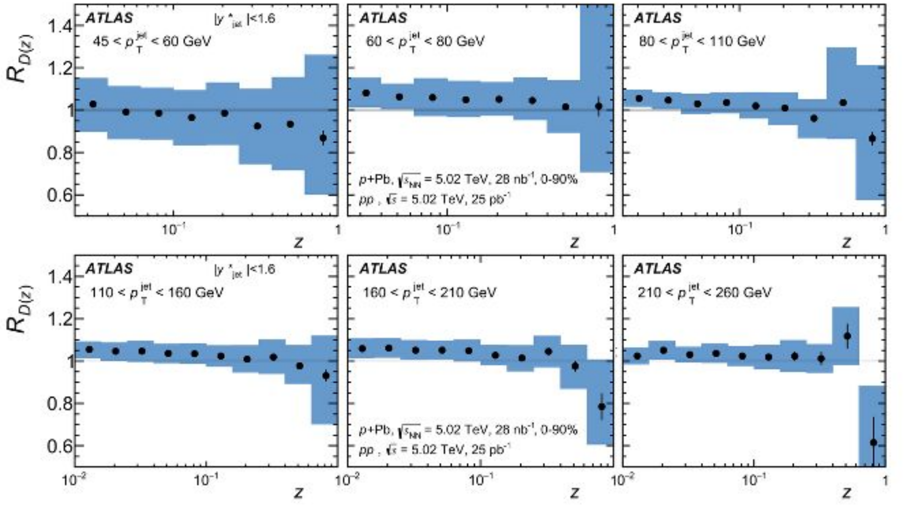
Nuclear Fragmentation Functions

- ★ Hermes/HERA (fixed-target mode)
  - ○ Production differs between ep and eA
- ★ ATLAS/LHC
  - ○ pA/pp consistent with unity

Hadron-level observable: $R_A = (N_h/N_{DIS})^{-1}_{ep}\,(N_h/N_{DIS})_{eA}$



R. Sassot, PRD**81**(2010)054001

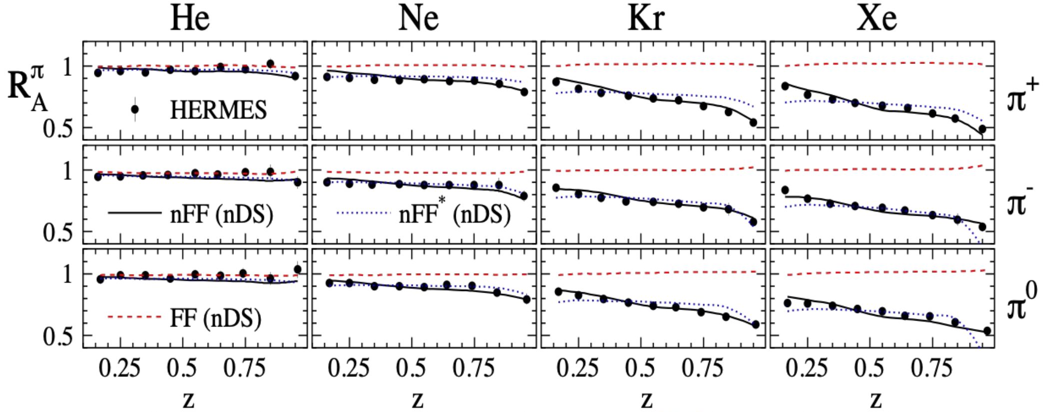


ATLAS,NPA**978**(2018)65

Nuclear Fragmentation Functions

- ★ Hermes/HERA (fixed-target mode)
  - ○ Production differs between ep and eA
- ★ ATLAS/LHC
  - ○ pA/pp consistent with unity
- ★ STAR/RHIC
  - ○ Non-unity observed in p+Al and p+Au

Hadron-level observable: $R_A = (N_h/N_{DIS})^{-1}_{ep}\,(N_h/N_{DIS})_{eA}$



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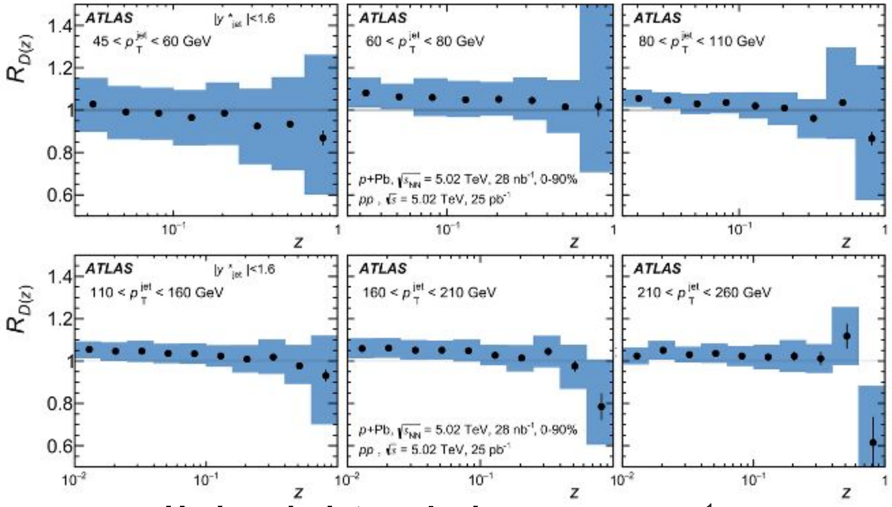
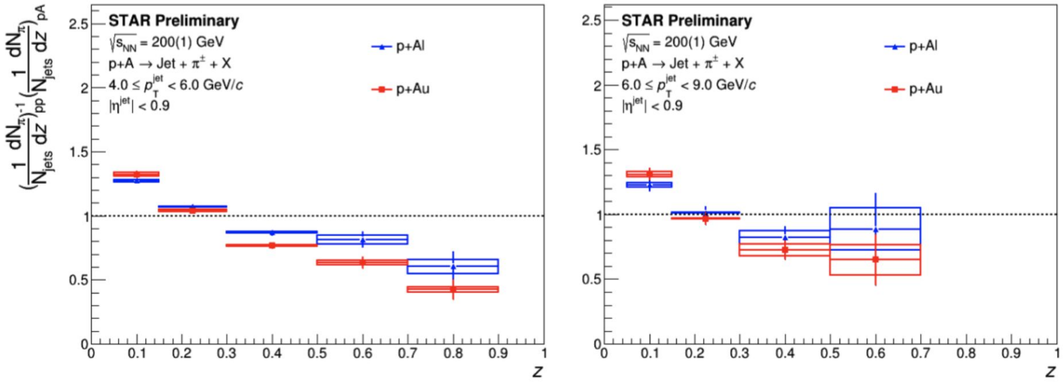


ATLAS,NPA978(2018)65

Hadron-in-jet analysis: $R_D = (N_h/N_{jet})^{-1}_{pp}\,(N_h/N_{jet})_{pA}$



G. Garcia, STAR, DIS2026

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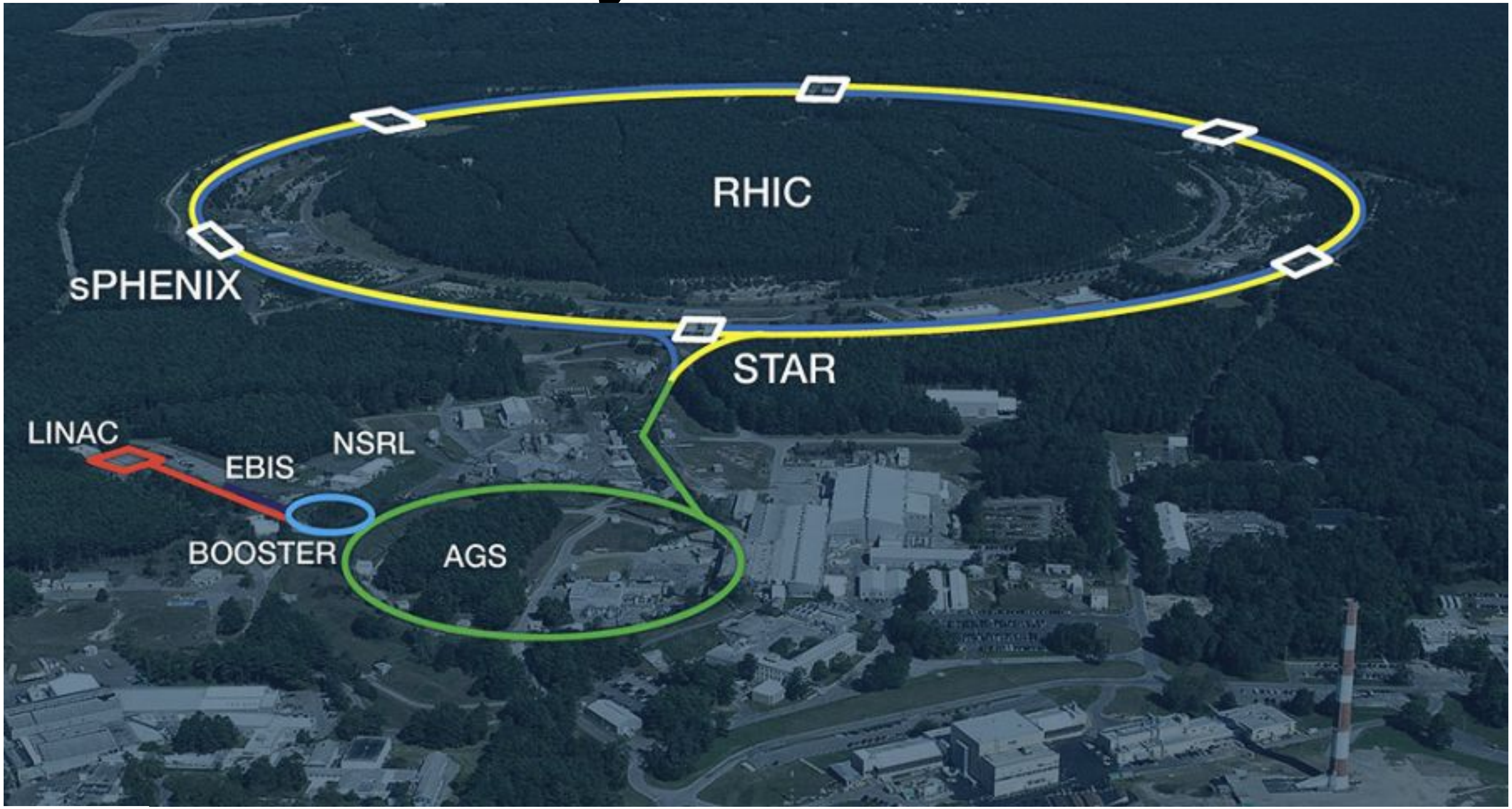
Experimental Setup

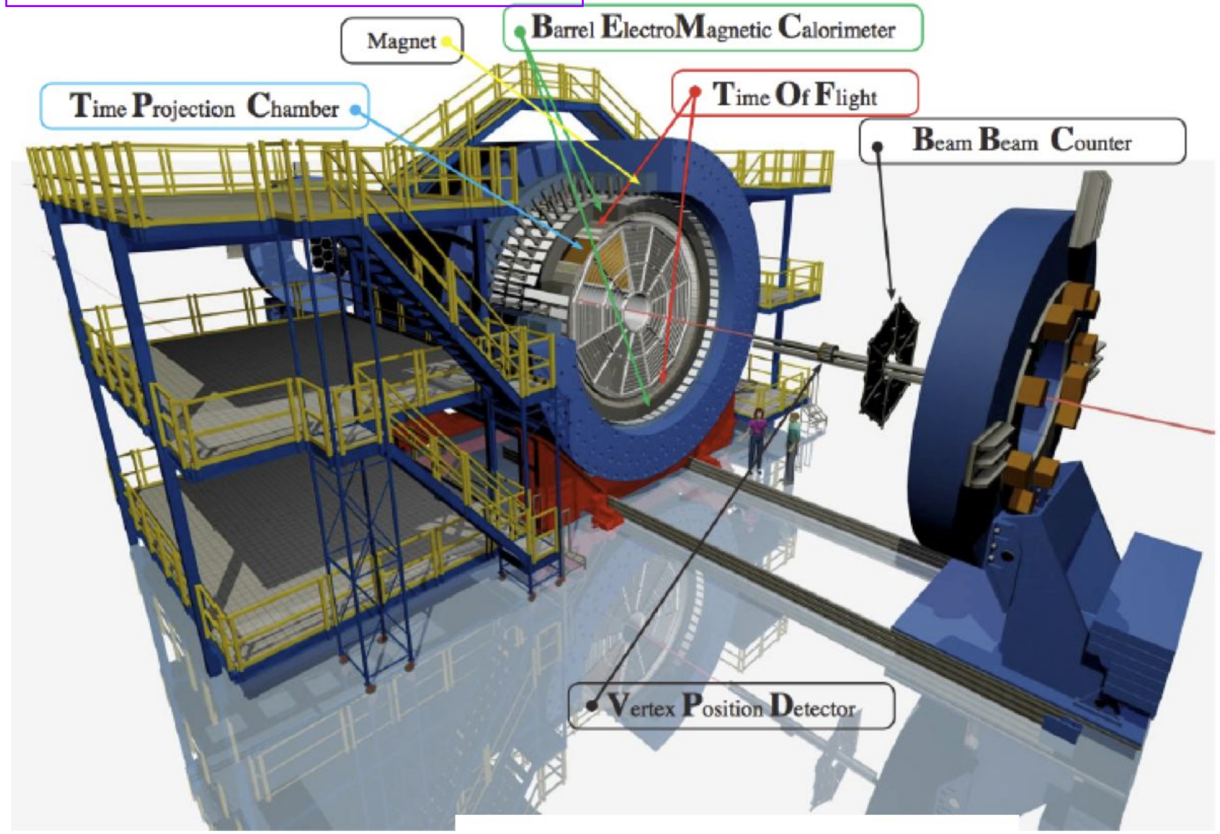
Relativistic Heavy Ion Collider: RHIC



★ Datasets: p+p, p+Al and p+Au from 2015 Run and d+Au from 2016 Run at $\sqrt{s_{_{NN}}} \approx 200\ \mathrm{GeV}$

STAR and FMS

Forward **M**eson **S**pectrometer



→ TOF and TPC: $1 < |\eta|$

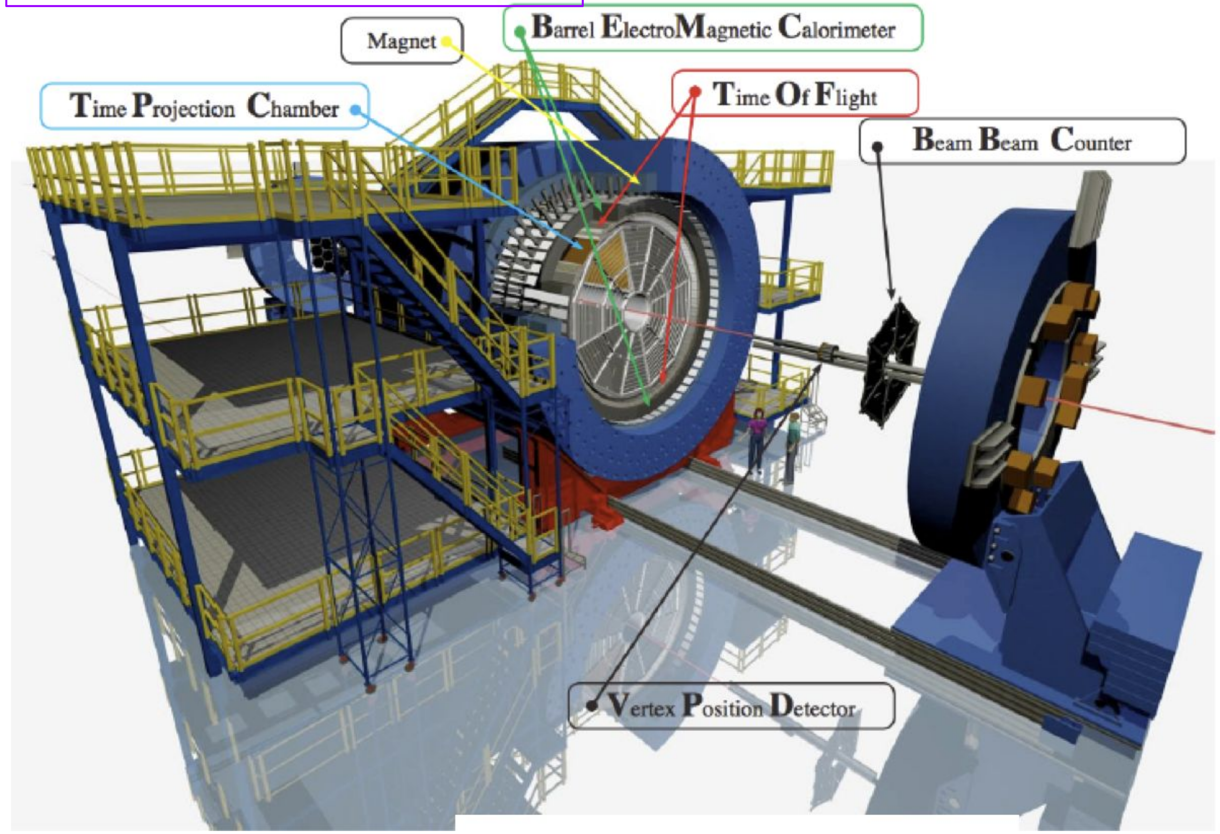
→ BBC: $3.3 < |\eta| < 5$

→ VPD: $4.2 < |\eta| < 5$

→ FMS: $2.6 < \eta < 4$

STAR and FMS

Forward **M**eson **S**pectrometer



→ TOF and TPC: 1 < |η|

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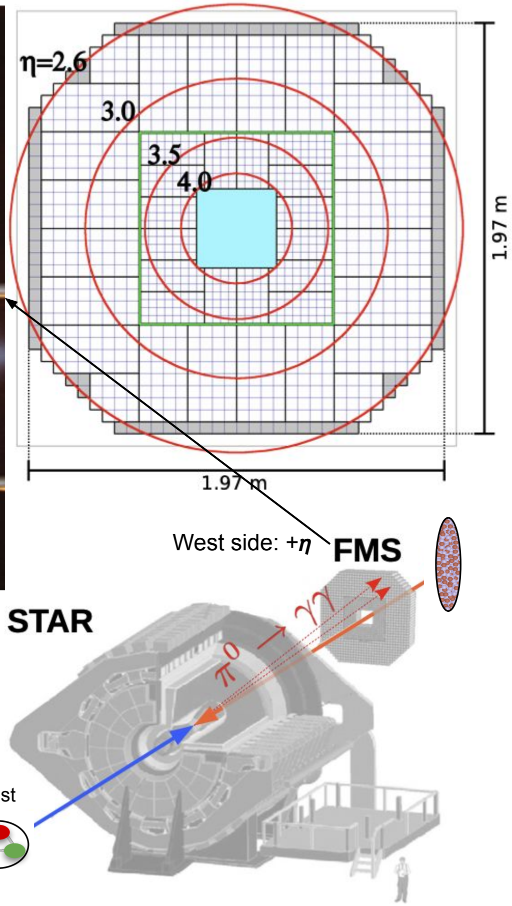
→ FMS: 2.6 < η < 4



Forward Meson Spectrometer (FMS)

→ EM calorimeter with ~2m square

→ 7.5 m from STAR IP

→ 1264 Pb-glass array

⇒ Small cells: 3.8cm sq. (~3.3 < η < 4.0)

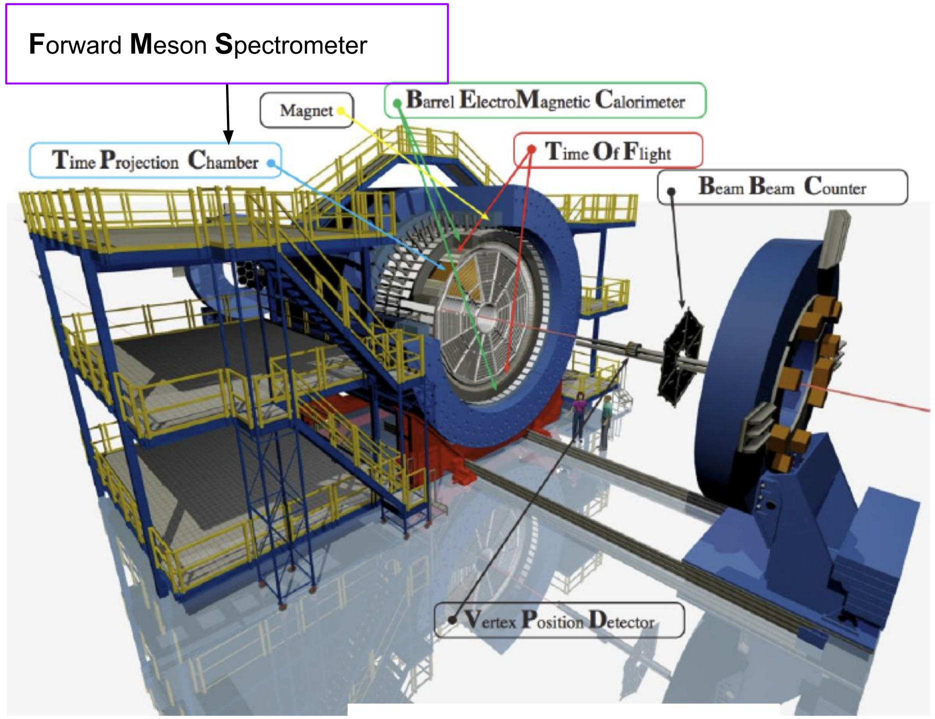
⇒ Large cells: 5.8 cm sq. (~2.6 < η < 3.3)

Analysis Methods

Analysis Methods

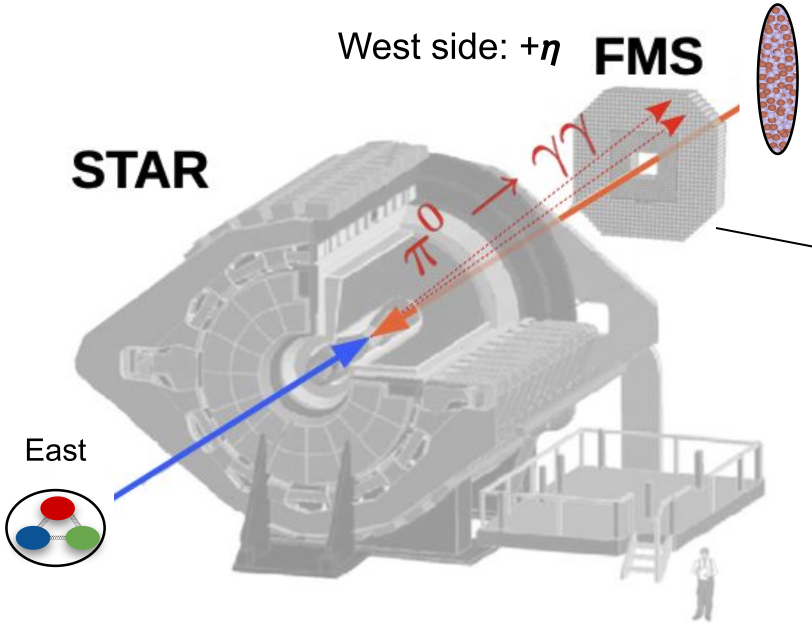
Event Selection → γ selection → π^0 reconstruction → Mixing Events → Yield Extraction → Nuclear Modification Factor → Systematic Uncertainties

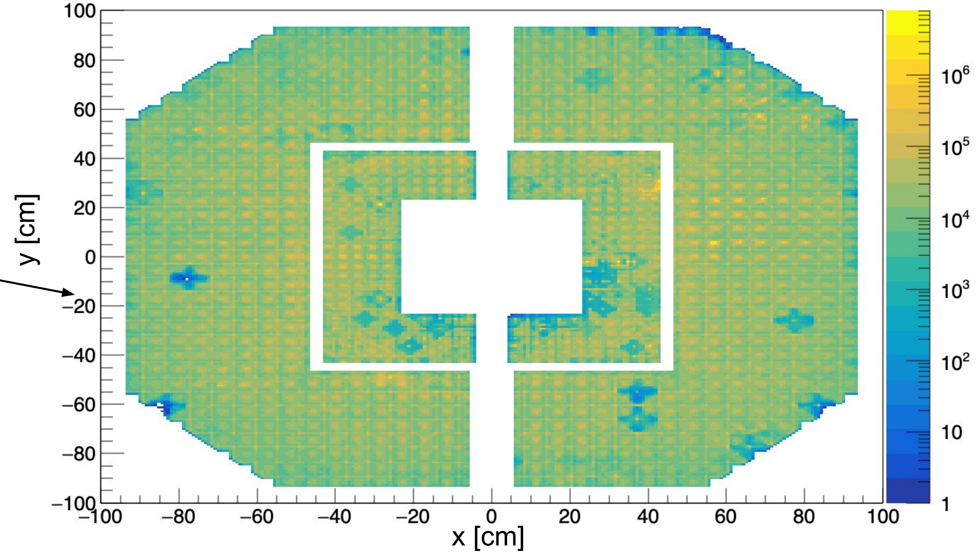
- ★ Trigger: Minimum Bias (MB) using VPD
- ★ TOF multiplicity > 2
- ★ BBC multiplicity > 0
- ★ $Z_{vtx} < 2\sigma_{RMS}$ (based on BBC and VPD)



Analysis Methods

Event Selection → γ selection → π^0 reconstruction → Mixing Events → Yield Extraction → Nuclear Modification Factor → Systematic Uncertainties



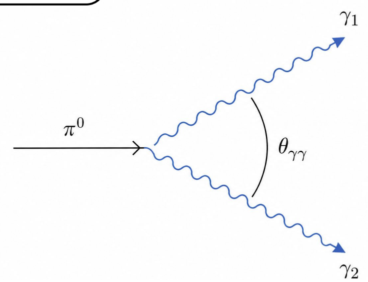


- ★ Energy > 1 GeV
- ★ p_T > 0.1 GeV/c
- ★ 2.6 < η < 4.0

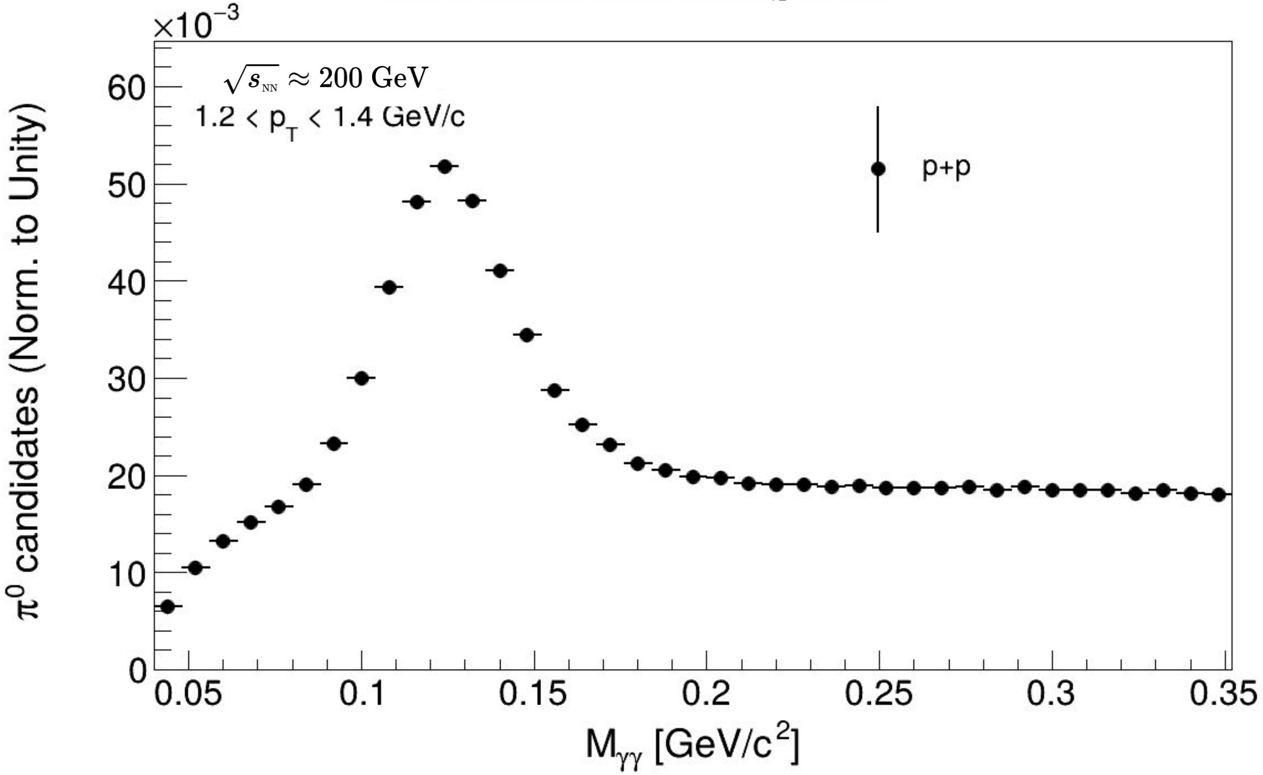
Analysis Methods

Event Selection → γ selection → π^0 reconstruction → Mixing Events → Yield Extraction → Nuclear Modification Factor → Systematic Uncertainties

- ★ $p_T > 0.6$ GeV/c
- ★ $2.6 < \eta < 4.0$
- ★ $Z_{\gamma\gamma} = (E_\gamma^1 - E_\gamma^2) / (E_\gamma^1 + E_\gamma^2) < 0.7$



$$m_{\gamma\gamma} = \sqrt{2\,E_1\,E_2\,(1 - \cos\theta_{\gamma\gamma})}$$



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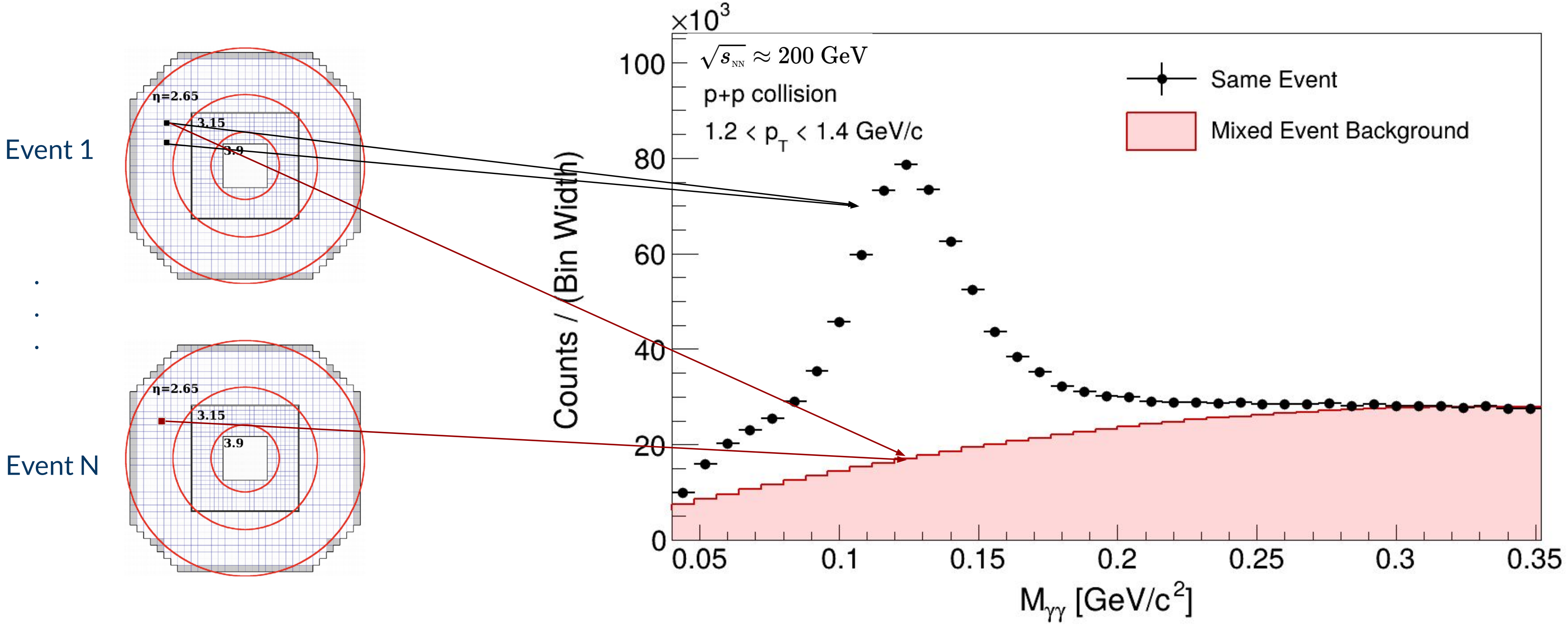
Analysis Methods

Event Selection → γ selection → π^0 reconstruction → Mixing Events → Yield Extraction → Nuclear Modification Factor → Systematic Uncertainties



★ Mix norm. range: 0.25 to 0.35 GeV/c^2

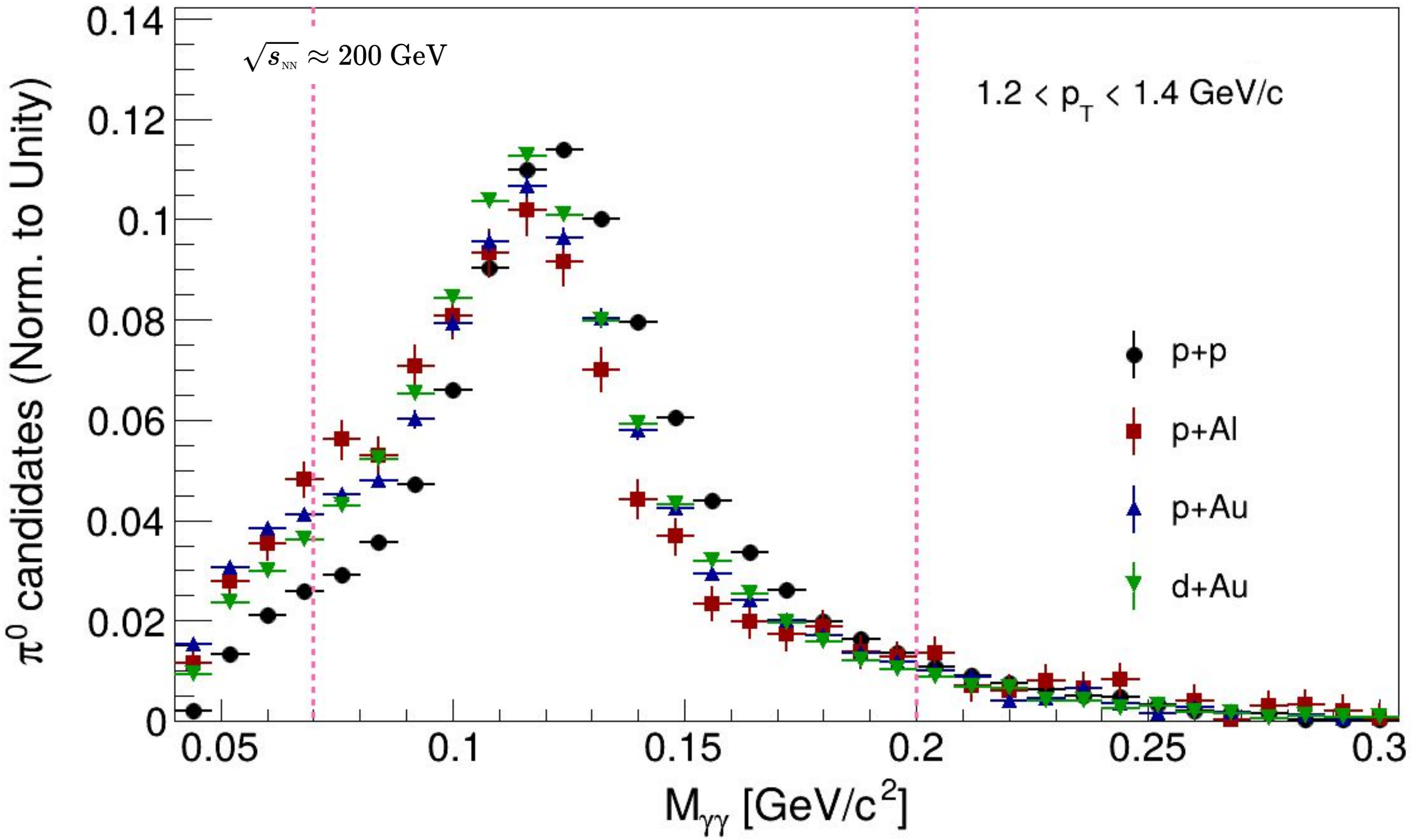
★ Mixing with 10 events

★ $|\Delta Z_{vtx}| < 2$ cm

Analysis Methods

Event Selection → γ selection → π^0 reconstruction → Mixing Events → **Yield Extraction** → Nuclear Modification Factor → Systematic Uncertainties

- ★ Yield = Raw Signal - Mixing
  - ○ $d^2N/dp_Td\eta$ → Yield extracted in the range 0.07 to 0.2 GeV/c^2



Analysis Methods

Event Selection → γ selection → π^0 reconstruction → Mixing Events → Yield Extraction → **Nuclear Modification Factor** → Systematic Uncertainties

★ R_{pA} can be written as (LHCb, PRL131(2023)102301):

$$R_{pA}(p_T, \eta) = \frac{1}{A} \cdot \frac{d^2\sigma_{pA}^{\pi^0}}{dp_T\, d\eta} \Big/ \frac{d^2\sigma_{pp}^{\pi^0}}{dp_T\, d\eta}$$

where

$$\frac{d^2\sigma^{\pi^0}}{dp_T\, d\eta} = \frac{1}{\mathcal{L} \cdot \mathrm{BR} \cdot \varepsilon^{\mathrm{det}} \cdot \varepsilon^{\mathrm{trig}}} \cdot \frac{d^2 N^{\pi^0}}{dp_T\, d\eta}$$

Analysis Methods

Event Selection → γ selection → π^0 reconstruction → Mixing Events → Yield Extraction → **Nuclear Modification Factor** → Systematic Uncertainties

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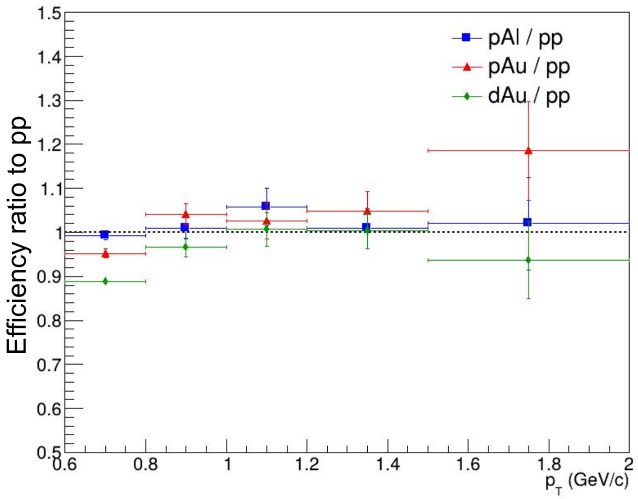
★ Replacing the cross-section at R_{pA}, we have

$$R_{pA}(p_T,\eta) = \frac{1}{A}\cdot\left[\frac{\mathcal{L}_{\mathrm{pp}}\cdot\cancel{\mathrm{BR}_{\mathrm{pp}}}\cdot\cancel{\varepsilon^{\mathrm{det}}_{\mathrm{pp}}}\cdot\cancel{\varepsilon^{\mathrm{trig}}_{\mathrm{pp}}}}{\mathcal{L}_{\mathrm{pA}}\cdot\cancel{\mathrm{BR}_{\mathrm{pA}}}\cdot\cancel{\varepsilon^{\mathrm{det}}_{\mathrm{pA}}}\cdot\cancel{\varepsilon^{\mathrm{trig}}_{\mathrm{pA}}}}\right]\cdot\left[\frac{d^2N^{\pi^0}_{\mathrm{pA}}}{dp_T\,d\eta} \Big/ \frac{d^2N^{\pi^0}_{\mathrm{pp}}}{dp_T\,d\eta}\right]$$

★ Efficiencies will cancel out:

$$R_{pA}(p_T,\eta) = \frac{1}{A}\cdot\frac{\mathcal{L}_{\mathrm{pp}}}{\mathcal{L}_{\mathrm{pA}}}\cdot\left[\frac{d^2N^{\pi^0}_{\mathrm{pA}}}{dp_T\,d\eta} \Big/ \frac{d^2N^{\pi^0}_{\mathrm{pp}}}{dp_T\,d\eta}\right]$$



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Analysis Methods

Event Selection → γ selection → π^0 reconstruction → Mixing Events → Yield Extraction → **Nuclear Modification Factor** → Systematic Uncertainties

★ R_{aA} is calculated as:

$$R_{aA}(p_T,\eta) = \frac{1}{\alpha A}\cdot\frac{L_{pp}}{L_{aA}}\cdot\frac{d^2N_{aA}^{\pi^0}}{dp_T\,d\eta}\Big/\frac{d^2N_{pp}^{\pi^0}}{dp_T\,d\eta}$$

★ *a* can be p or d with α = 1 or 2, respectively

★ Detector and trigger effects largely cancel out

★ A_{Al} = 27 and A_{Au} = 197

★ Integrated Luminosities (L):

- p+p: 0.091 pb^{-1}
- p+Al: 0.028 nb^{-1}
- p+Au: 0.027 nb^{-1}
- d+Au: 0.222 nb^{-1}

Analysis Methods

Event Selection → γ selection → π^0 reconstruction → Mixing Events → Yield Extraction → Nuclear Modification Factor → Systematic Uncertainties

Source of Systematics	R_{pAl} (%)	R_{pAu} (%)	R_{dAu}(%)
Trigger Bias	10.0	10.0	10
Detector Efficiency	0.0	0.0 – 5.0	0.0 – 4.0
Z vertex selection	0.45 – 2.97	2.19 – 3.14	0.42 – 0.97
Mix Events	0.48 – 2.25	0.34 – 1.97	0.24 – 1.66
Luminosity Normalization	4	4	4
Center-of-mass shift	< 1	< 1	< 1
Total Systematic Uncertainty	**10.79 – 11.44**	**11.00 – 12.48**	**10.78 – 11.69**

- ★ **Trigger bias is the dominant uncertainty**
  - ○ **Defined as the variation across MB triggers**
    - ■ **Conservative estimation is used**

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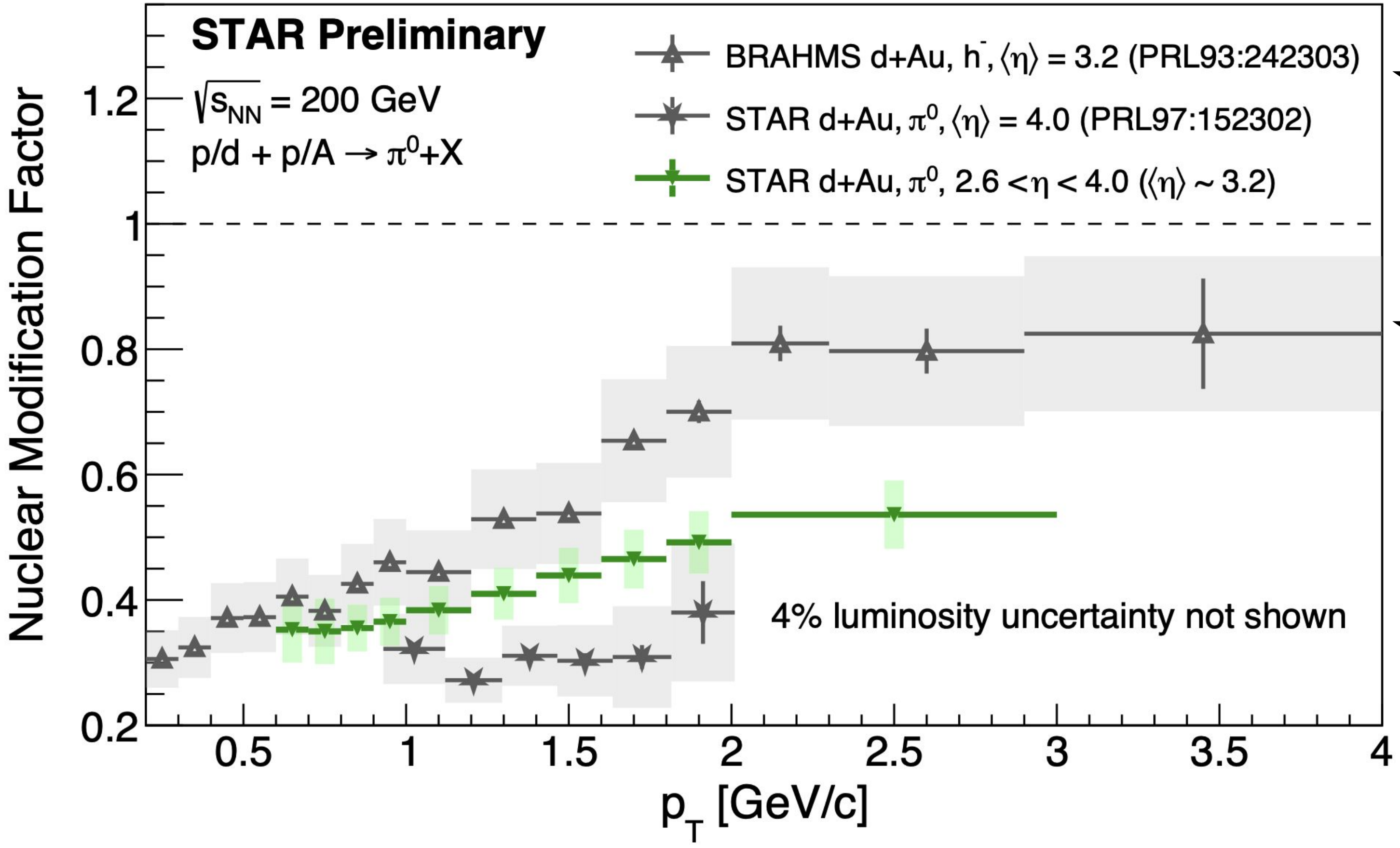
Results

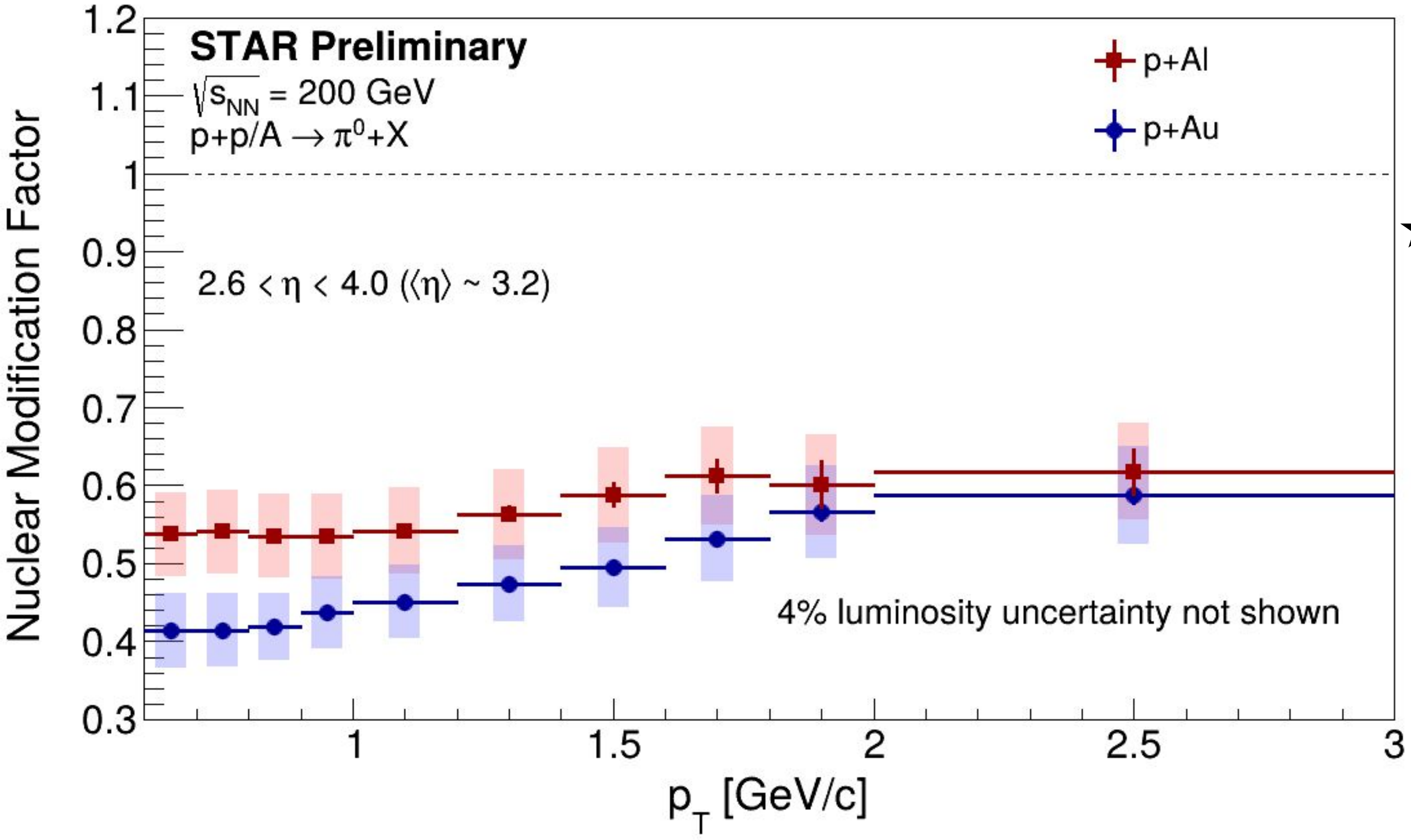
Nuclear modification factor: R_{dAu}



- ★ Compared to previous STAR results
  - ○ Follows the expected ***η***-dependency
- ★ Compared to BRAHMS (h^-):
  - ○ Similar pseudorapidity range
  - ○ The suppression observed by STAR is stronger than that reported by BRAHMS
    - ■ BRAHMS result are less suppressed due to proton/deuteron isospin effects

d going to +**η**

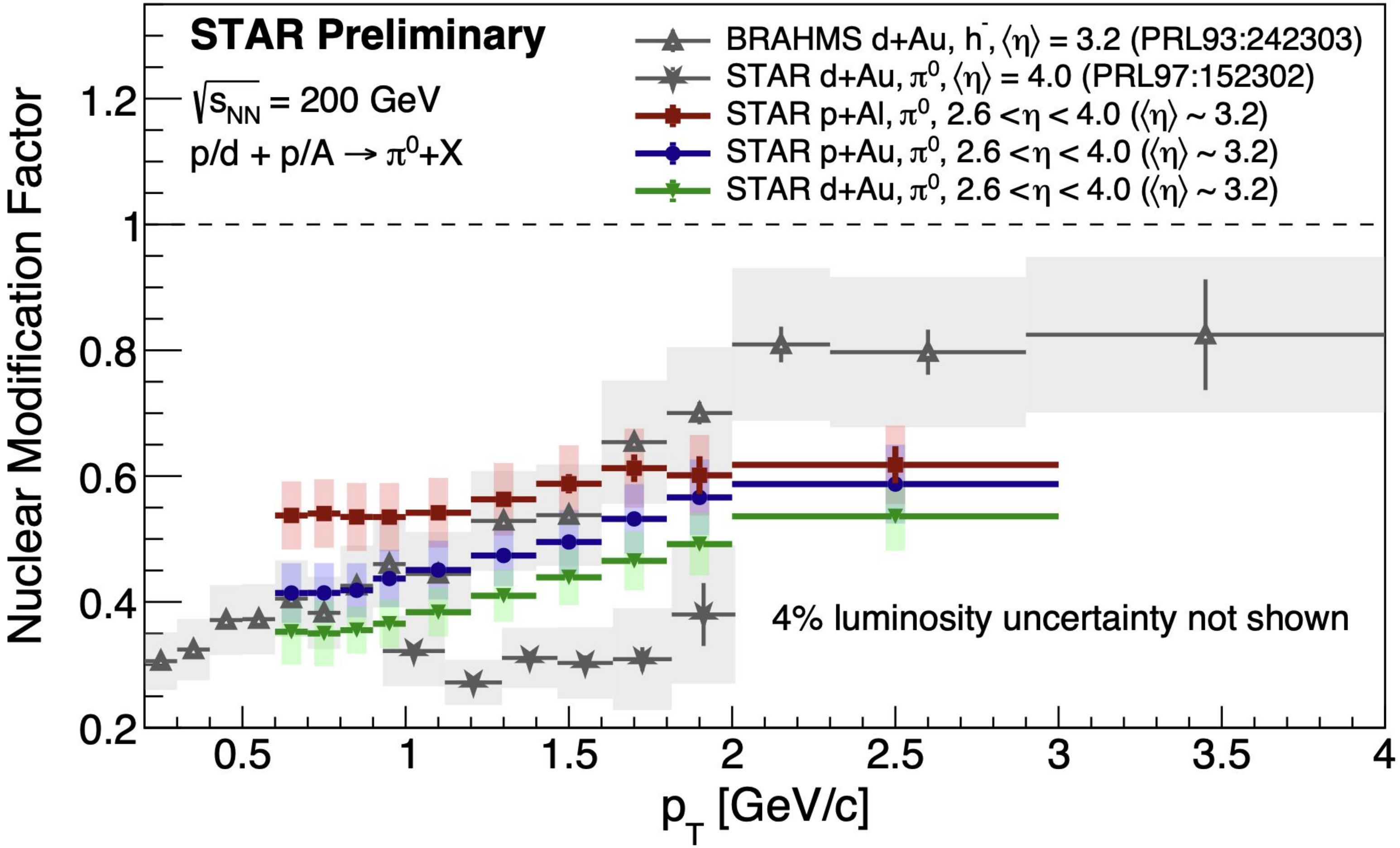
Nuclear modification factor: R_{pA}



p going to +**η**

- ★ A-dependent suppression observed
  - ○ $R_{pAl} > R_{pAu}$
    - ■ Suggest stronger nuclear effects in larger nuclei
  - ○ Hierarchy weakens with increasing p_T

Comparing with previous RHIC results



p/d going to +**η**

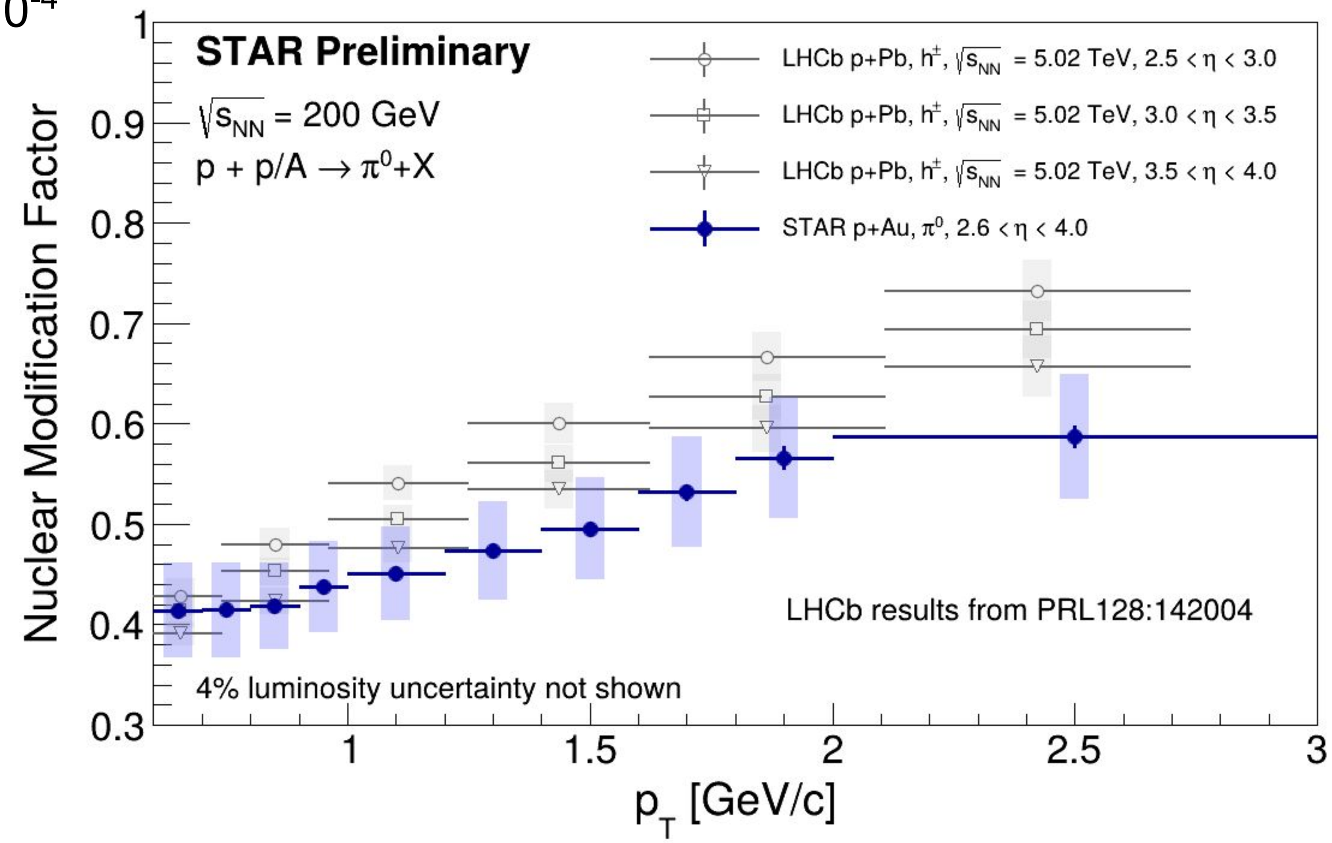
★ A-dependent suppression observed: $R_{pAl} > R_{pAu} \geq R_{dAu}$

○ Hierarchy weakens with increasing p_T

Comparing with LHCb results

p going to $+\eta$

- ★ LHCb x goes down to 10^{-6} while STAR goes to 10^{-4}
- ★ Similar R_{pA} at low-p_T
- ★ STAR results are more suppressed than LHCb at higher p_T
  - ○ Nuclear effects in hadronization due to the different fragmentation regimes (z ranges) probed at RHIC and the LHC



A_{Au} = 197
A_{Pb} = 208

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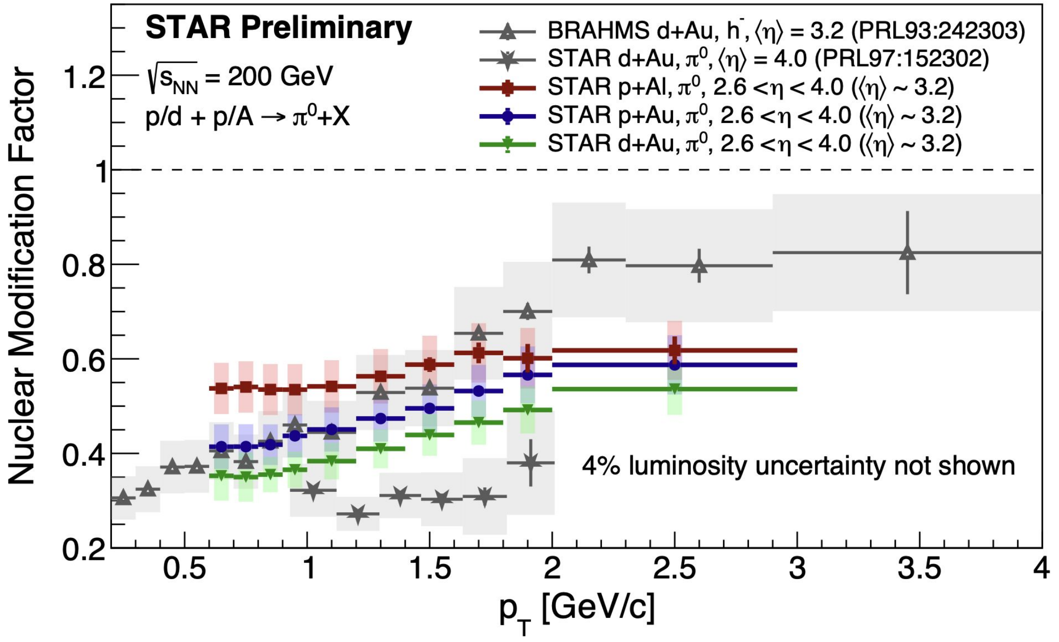
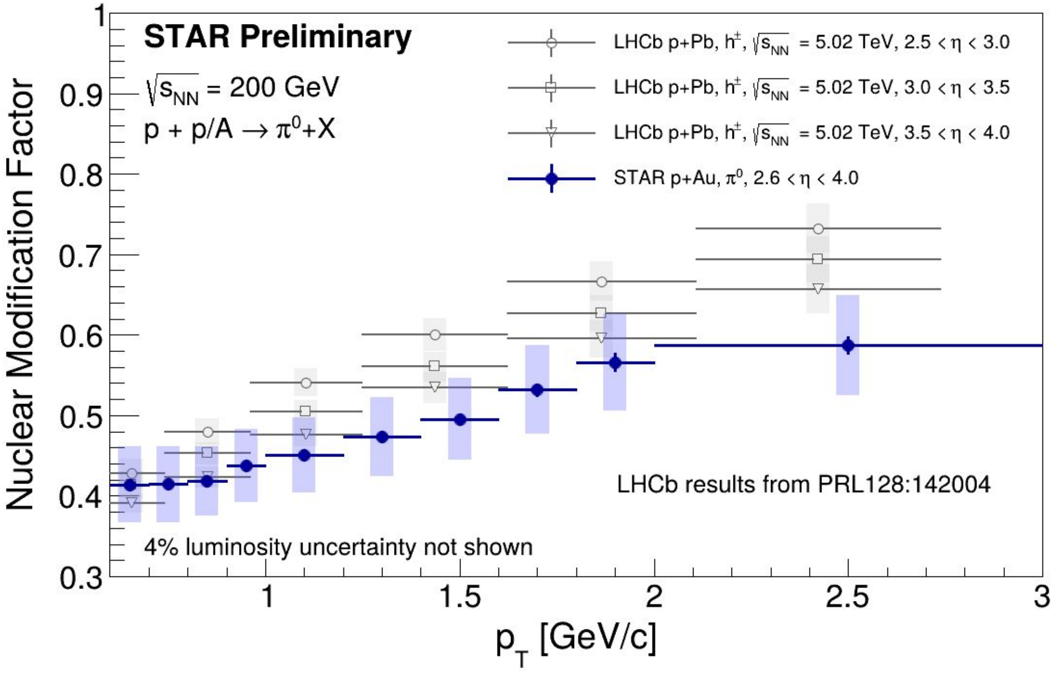
Summary and Outlook

★ 1st measurement of very forward R_{pA} at RHIC energies
  - Sequential A-dependent suppression observed
    - $R_{pAl} > R_{pAu} \geq R_{dAu}$
  - STAR data more suppressed than LHCb
    - Likely due nuclear effects in hadronization
  - Next Steps:
    - Expand systematic uncertainty studies
    - Explore higher p_T region
    - Comparison with theory/models

★ The EIC will enable multidifferential measurements of R_{eA}
  - *x*, *z*, PID, A-dependency and more





p/d going to +η

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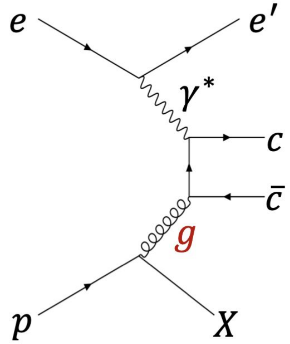
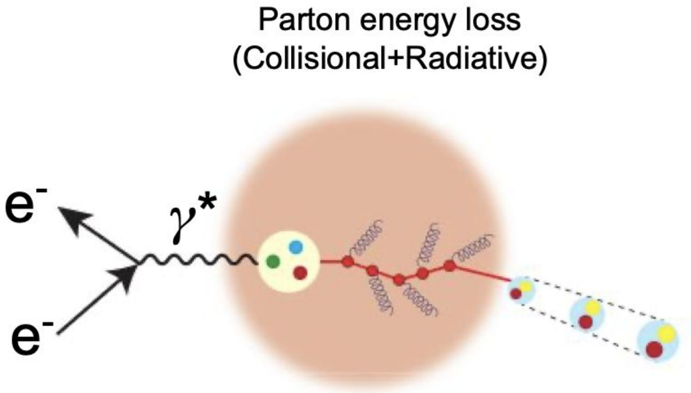
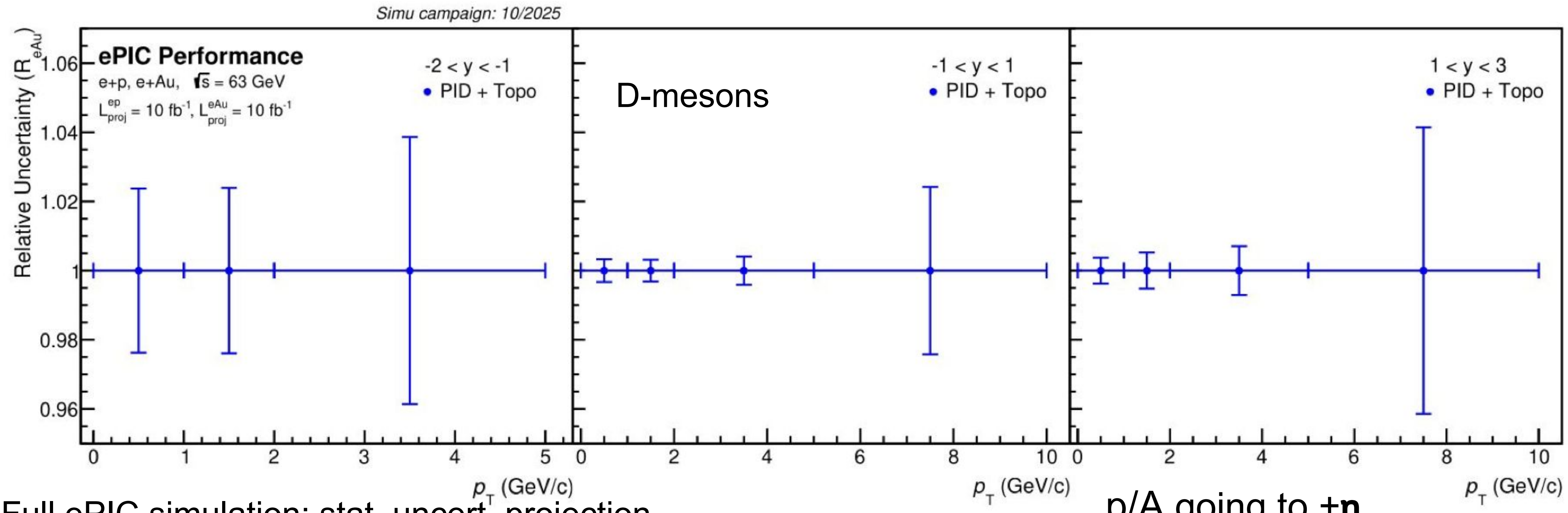
How about R_{eA} at EIC?

R_{eA} for charm-hadrons at EIC

★ Charm production probes gluon distributions (γ+g fusion at LO)
  - R_{eA} vs p_T: collisional and radiative energy loss
  - R_{eA} vs x: nPDF's
  - R_{eA} vs z: modified fragmentation in nuclear matter





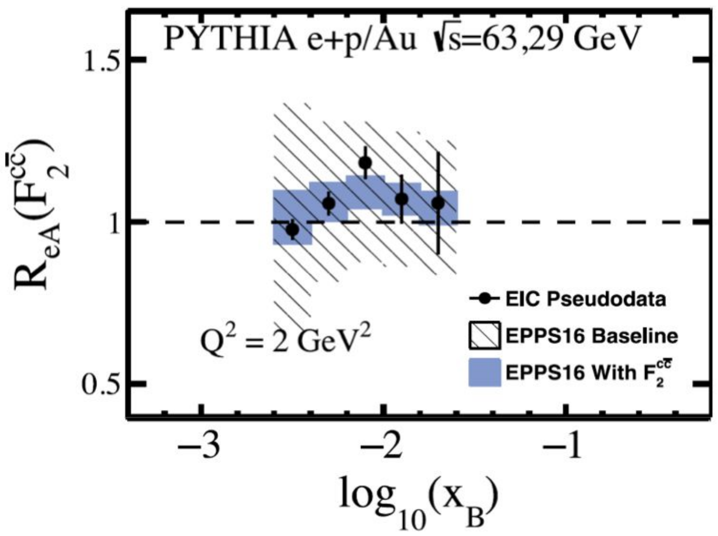


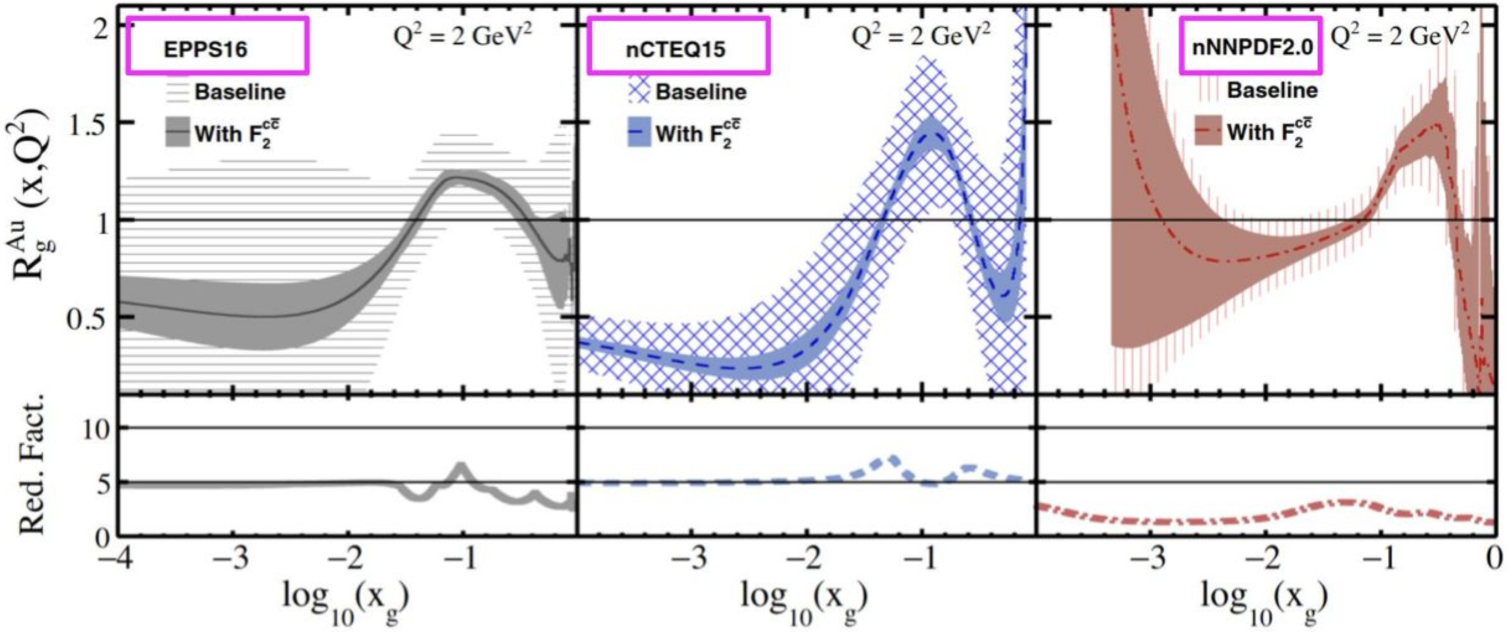
Full ePIC simulation: stat. uncert. projection

p/A going to +η

D. Elia, ePIC, DIS2026

Impact of charm-hadron R_{eA} on nPDF's





M. Kelsey, et. al., PRD**104**(2021)054002

- ★ Significant reduction of uncertainties in gluon nPDF
- ★ Note: not the most up-to-date projection

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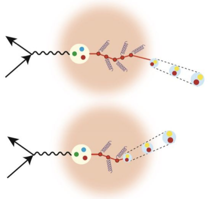
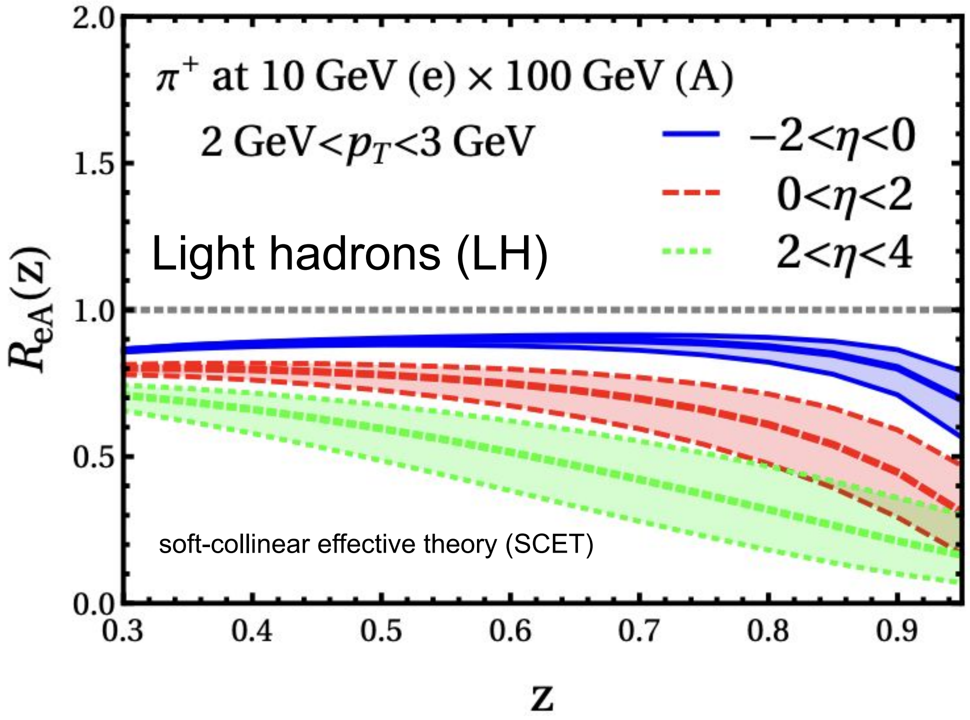
R_{eA} as probe of fragmentation in nuclei

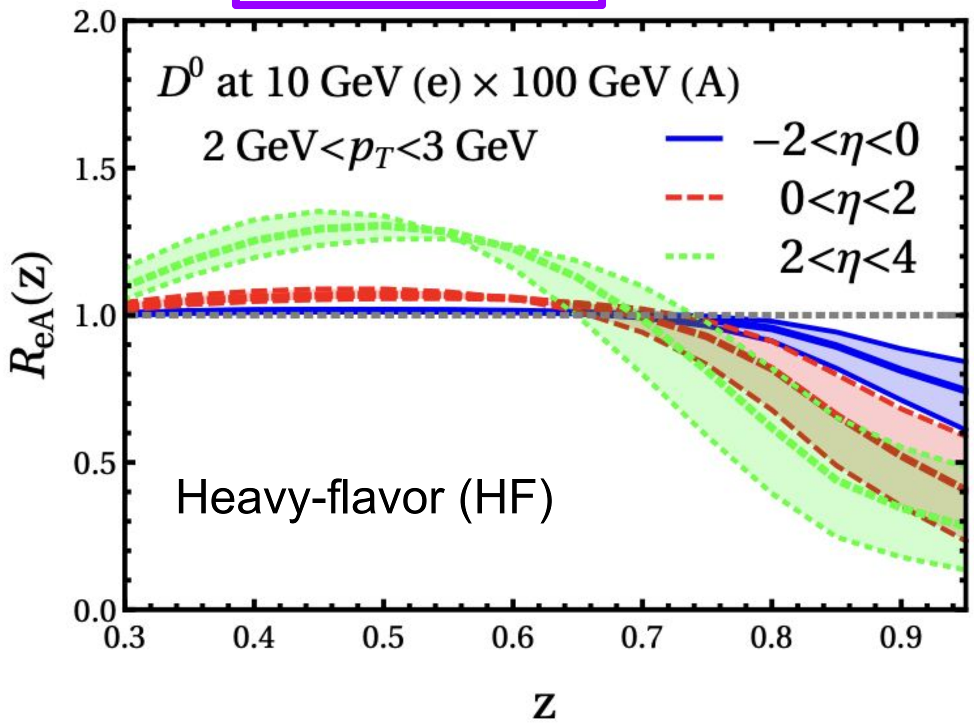
ν: virtual photon energy



$$R_{eA}(p_T, z, \nu) = \frac{N^{D0}(p_T, z, \nu)|_{eAu}}{N^{D0}(p_T, z, \nu)|_{ep}} \times \boxed{\frac{N^{inc}(\nu)|_{ep}}{N^{inc}(\nu)|_{eAu}}}$$

Minimize initial-state effects





Y.-T. Chien, PLB**816**(2021)136261

★ LH: suppression at all z and rapidities

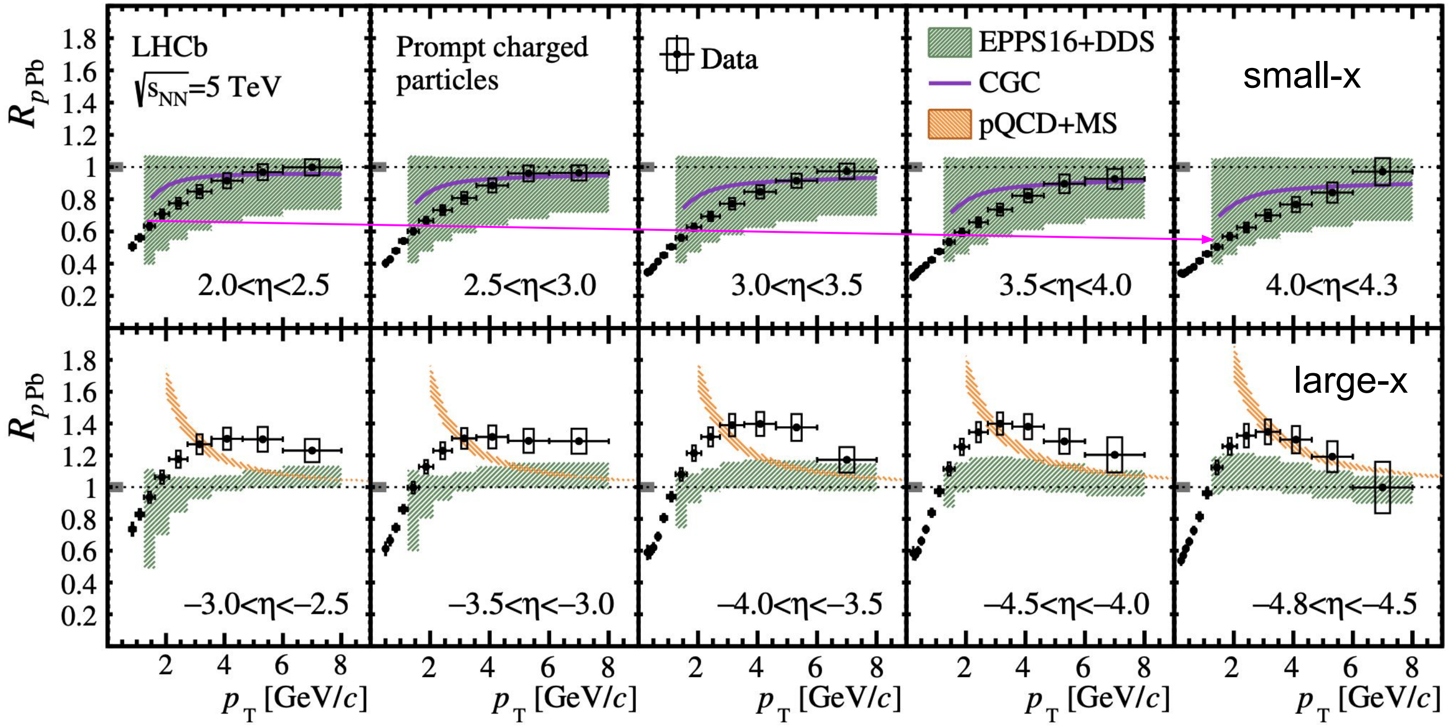
★ HF: enhancement at low-moderate *z* and suppression at large *z* (especially at forward)

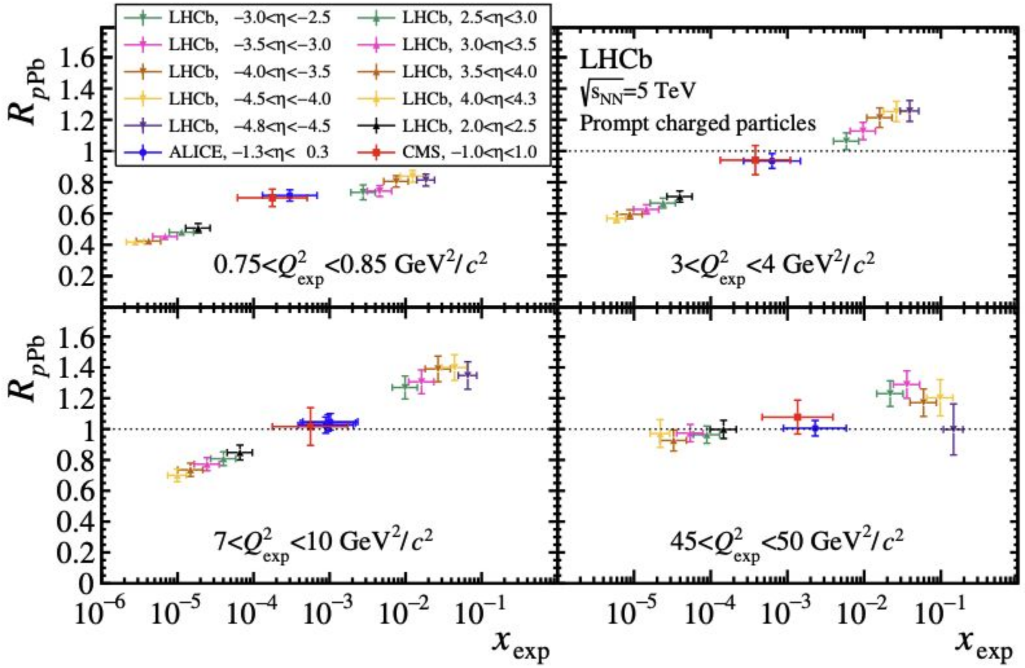
★ Consistent with the effective modification of fragmentation functions

شكراً جزيلاً
ngiyabonga
рахмат
danke
謝謝
teşekkür ederim
Баярлалаа
mersi
kia ora
barka
welalin
tack
spas
спасибо
faafetai lava
vinaka
спасибі
blagodaram
dank je
misaotra
matondo
paldies
grazzi
mahalo
tapadh leat
thank you
gracias
kiitos
dankie
nanni
nandri
dhanyavad
хвала
asante
manana
obrigada
tenki
bedankt
bayarlalaa
gràçie
hvala
mauruuru
köszönöm
dankon
aciu
akun
enkosi
djiere dieuf
tau
mochchakkeram
murakoze
dziękuję
дякую
mamnun
chokrane
chnorakaloutioun
gratias ago
gràcies
sulpáy
go raibh maith agat
sobodi
dėkuji
obrigado
sagolun
sukriya
kop khun krap
taiku
takk
arigatô
dakujem
trugarez
mèsi
didi madloba
ありがとう
najis tuke
tanemirt
grazie
terima kasih
rahmet
kam sah hamnida
rahmat
diolch
dhanyavadagalu
shukriya
mercè
мерси
ευχαριστώ
merci
তোমাকে ধন্যবাদ
감사합니다
xièxie

Backup

Nuclear modification factors at LHC





$$Q^2_{\mathrm{exp}} \equiv m^2 + p_T{}^2 \quad \text{and} \quad x_{\mathrm{exp}} \equiv \frac{Q_{\mathrm{exp}}}{\sqrt{s_{NN}}} e^{-\eta}$$

★ Suppression observed also in p+Pb collisions

STAR

LHCb: h± vs π^0

LHCb, PRL**131(**2023)042302

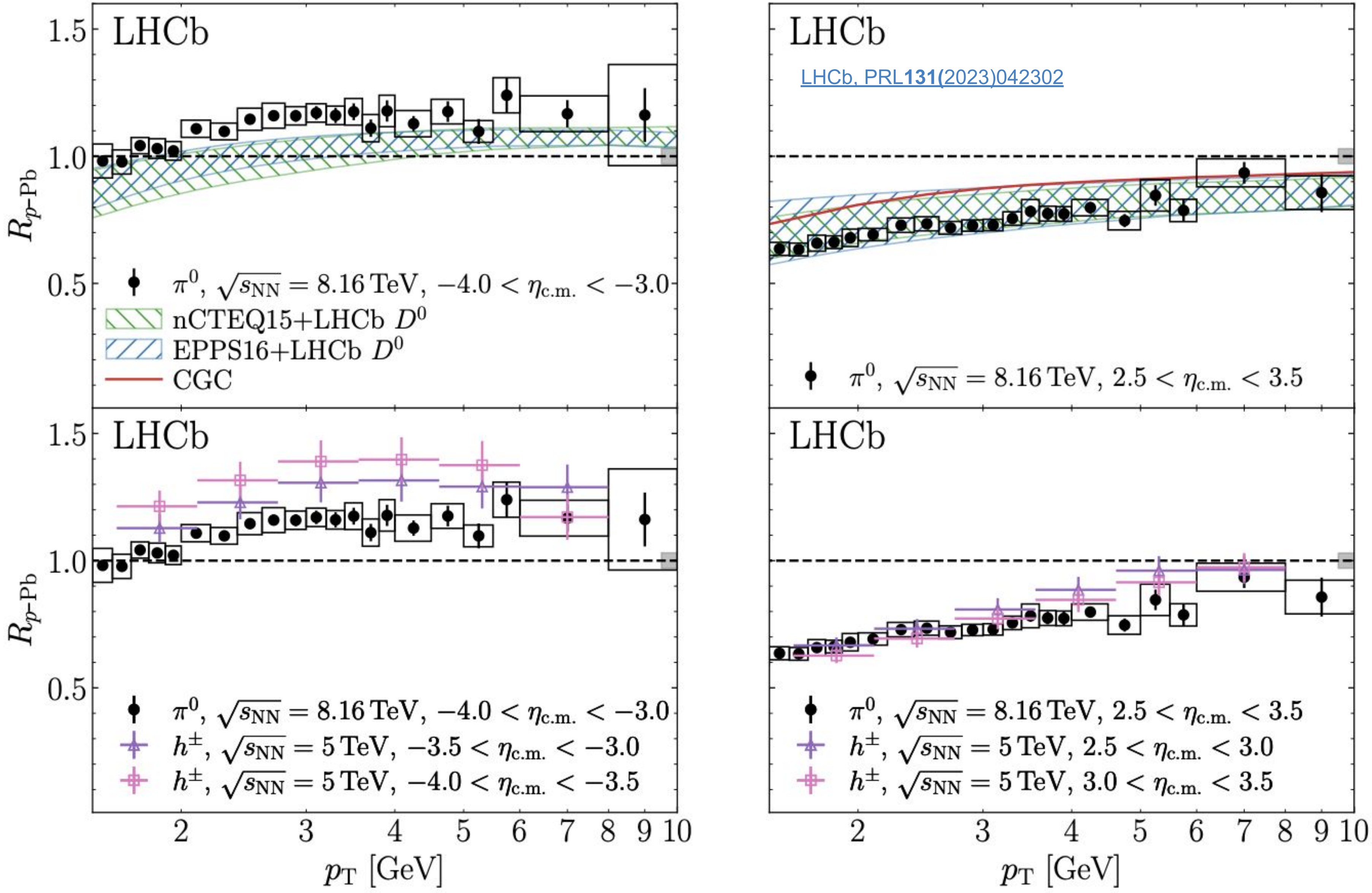


Table of nPDF's

Table 1 Key features of recent global analyses of nuclear PDFs

Analysis	nCTEQ15HQ (50)	EPPS21 (51)	nNNPDF3.0 (52)	TUJU21 (80)	KSASG20 (81)
Theoretical input					
Perturbative order	NLO	NLO	NLO	NNLO	NNLO
Heavy quark scheme	SACOT-χ	SACOT-χ	FONLL	FONLL	FONLL
Value of $\alpha_s(M_Z)$	0.118	0.118	0.118	0.118	0.118
Charm mass	1.3 GeV	1.3 GeV	1.51 GeV	1.43 GeV	1.3 GeV
Bottom mass	4.5 GeV	4.75 GeV	4.92 GeV	4.5 GeV	4.75 GeV
Input scale Q_0	1.3 GeV	1.3 GeV	1.0 GeV	1.3 GeV	1.3 GeV
Data points	1,484	2,077	2,188	2,410	4,353
Independent flavors	5	6	6	4	3
Parameterization	Analytic	Analytic	Neural network	Analytic	Analytic
Free parameters	19	24	256	16	18
Error analysis	Hessian	Hessian	Monte Carlo	Hessian	Hessian
Tolerance	$\Delta\chi^2 = 35$	$\Delta\chi^2 = 33$	N/A	$\Delta\chi^2 = 50$	$\Delta\chi^2 = 20$
Proton PDF	~CTEQ6.1	CT18A	~NNPDF4.0	~HERAPDF2.0	CT18
Proton PDF correlations	—	✓	✓	—	—
Deuteron corrections	(✓)[a,b]	✓[c]	✓	✓	✓
Fixed-target data					
SLAC/EMC/NMC NC DIS	✓	✓	✓	✓	✓
Cut on Q^2	4 GeV^2	1.69 GeV^2	3.5 GeV^2	3.5 GeV^2	1.2 GeV^2
Cut on W^2	12.25 GeV^2	3.24 GeV^2	12.5 GeV^2	12.0 GeV^2	—
JLab NC DIS	(✓)[a]	✓	—	—	✓
CHORUS/CDHSW CC DIS	(✓/—)[b]	✓/—	✓/—	✓/✓	✓/✓
NuTeV/CCFR 2μ CC DIS	(✓/✓)[b]	—	✓/—	—	—
pA DY	✓	✓	✓	—	✓
πA DY	—	✓	—	—	—
Collider data					
Z bosons	✓	✓	✓	✓	—
$W^{\pm}$ bosons	✓	✓	✓	✓	—
Light hadrons	✓	✓[d]	—	—	—
Cut on p_T	3 GeV	3 GeV	—	—	—
Jets	—	✓	✓	—	—
Prompt photons	—	—	✓	—	—
Prompt D^0	✓	✓	✓[e]	—	—
Cut on p_T	3 GeV	3 GeV	0 GeV	—	—
Quarkonia (J/ψ, ψ', Υ)	✓	—	—	—	—

Abbreviations: CC DIS, charged-current deep inelastic scattering; DY, Drell–Yan process; FONLL, fixed-order plus next-to-leading logarithms; N/A, not applicable; NC DIS, neutral-current deep inelastic scattering; NLO, next-to-leading order; NNLO, next-to-next-to-leading order; PDF, parton distribution function; SACOT, simplified Aivazis–Collins–Olness–Tung.

[a]Included in the nCTEQ15HIX analysis (26).

[b]Included in the nCTEQ15ν analysis (158).

[c]Through CT18A.

[d]Only π^0 in D+Au.

[e]Only forward ($y > 0$).

M. Klasen and H. Paukkunen, ARNPS **74**(2024)1

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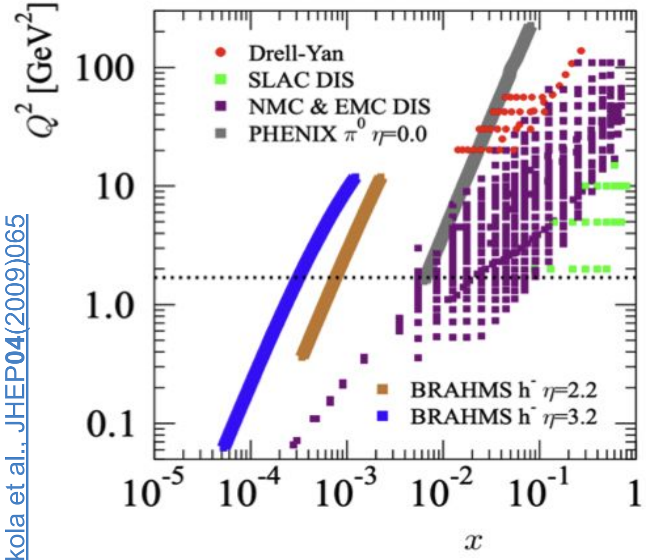
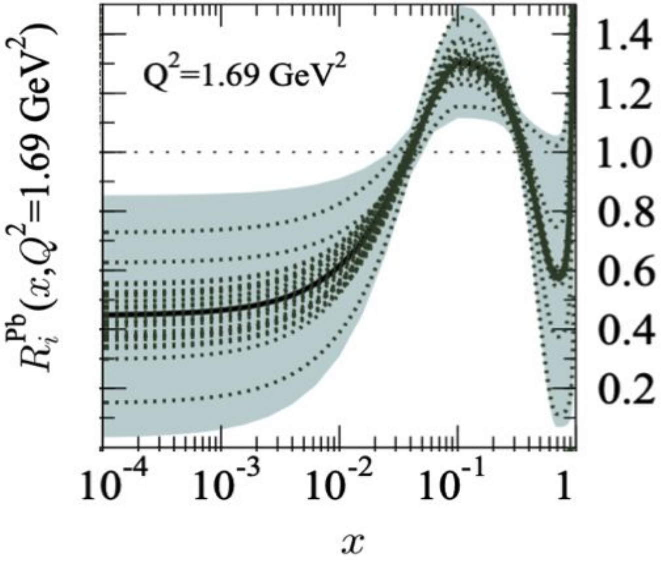
nPDFs: EPPS Evolution

★ Strong effect from LHCb D-meson R_{pA}

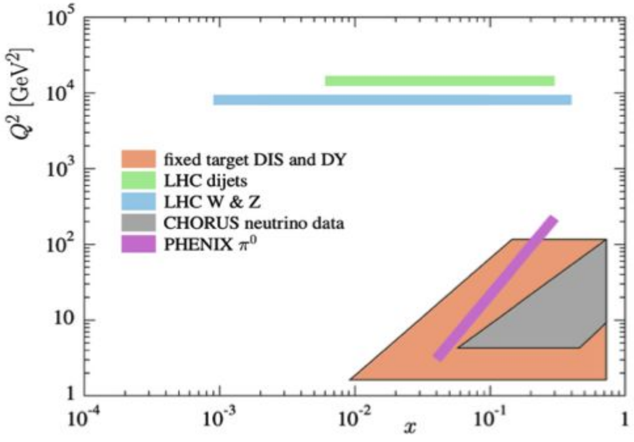
EPS09

K. Eskola et al., JHEP**04**(2009)065

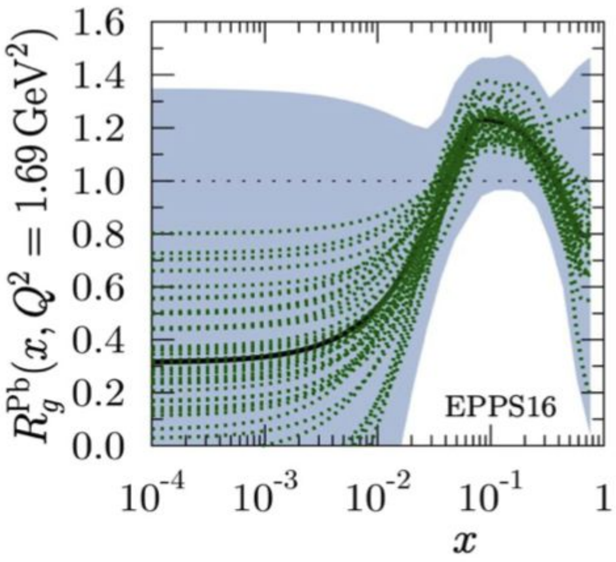




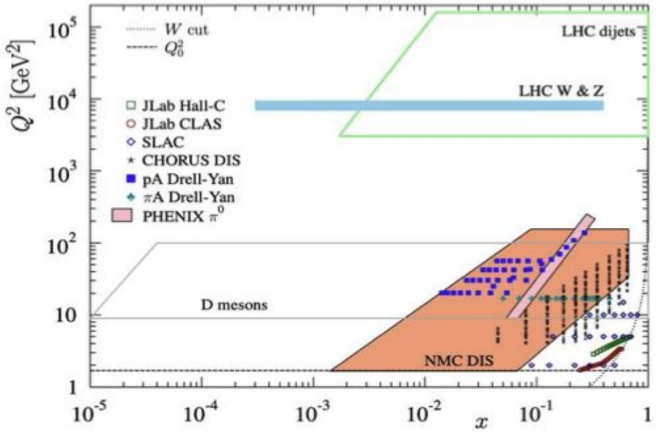
EPPS16

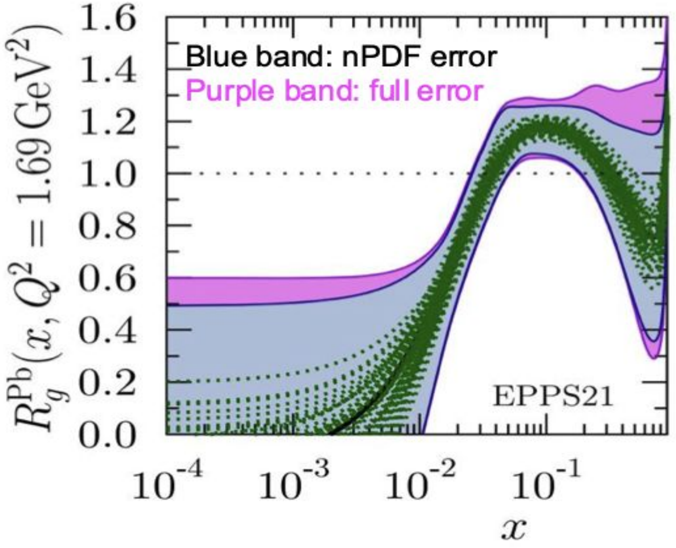


K. Eskola et al., EPJC**77**(2017)163



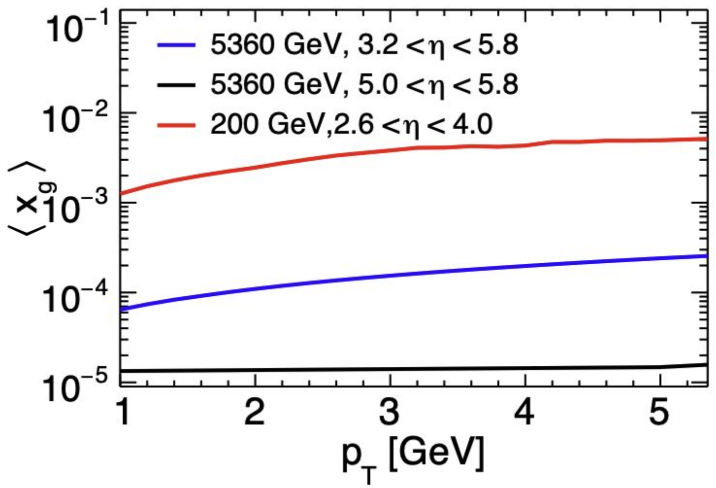
EPPS21

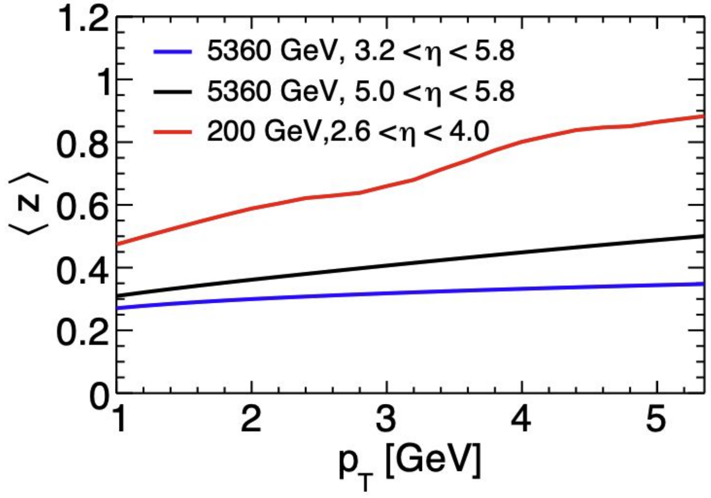




K. Eskola et al., EPJC**82**(2022)413

z dependency in 2PC

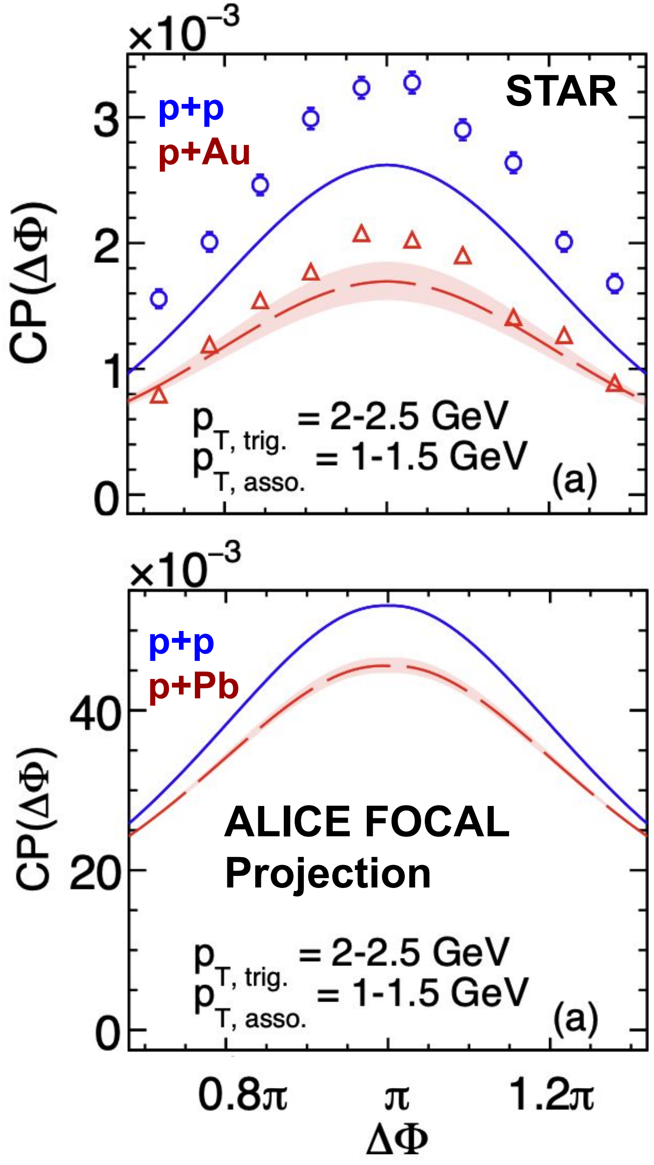




[P. Caucal et al., PLB**879**(2026)140599]

$\langle x_g \rangle$: gluon momentum fraction of the nucleus

$\langle z \rangle$: fragmentation energy fraction of hadron



Ratio of fragmentation functions