Heavy quarks and dijets as a probe of nuclear partons from LHC pA to γA collisions in UPCs and at EIC

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Elke's talk on Tuesday:

Complementarity

QCD has two concepts which lay its foundation

factorization and universality

To tests these concepts and separate interaction dependent phenomena from intrinsic nuclear properties

different complementary probes are critical

Here, I will discuss the complementarity of hard probes in pA, γA and eA from the nuclear-PDF point of view

At the heart of it all: Collinear factorization of QCD

The cross section for producing an inclusive final state $k+X$ can be described as a convolution of...

...**C**oefficient **F**unctions $\mathrm{d}\hat{\sigma}^{ij\to k+X'}$ which are calculable from perturbative QCD...

$$\mathrm{d}\sigma^{AB\to k+X}(Q^2) \overset{Q\gg\Lambda_{\mathrm{QCD}}}{=} \sum_{i,j,X'} f_i^A(Q^2) \otimes \mathrm{d}\hat{\sigma}^{ij\to k+X'}(Q^2) \otimes f_j^B(Q^2) + \mathcal{O}(1/Q^2)$$

...and **P**arton **D**istribution **F**unctions f_i^A, f_j^B which contain long-range physics and cannot be obtained by perturbative means...

...plus "**H**igher **T**wist" corrections which are suppressed at high enough momentum scale $Q \gg \Lambda_{\mathrm{QCD}}$

parent hadron or nucleus

factorization scale

The PDFs $f_i^A(x, Q^2)$ are *universal*, process independent,

parton flavour

fraction of momentum carried by the parton

splitting functions

and obey the DGLAP equations $Q^2 \dfrac{\partial f_i^A}{\partial Q^2} = \sum_j P_{ij} \otimes f_j^A$

Mellin conv.

...this is the framework which every PDF analysis and application relies on and tests!

Nuclear PDFs from global analyses

Nuclear PDFs (nPDFs)
are fitted with similar global analyses as their free-proton counterparts

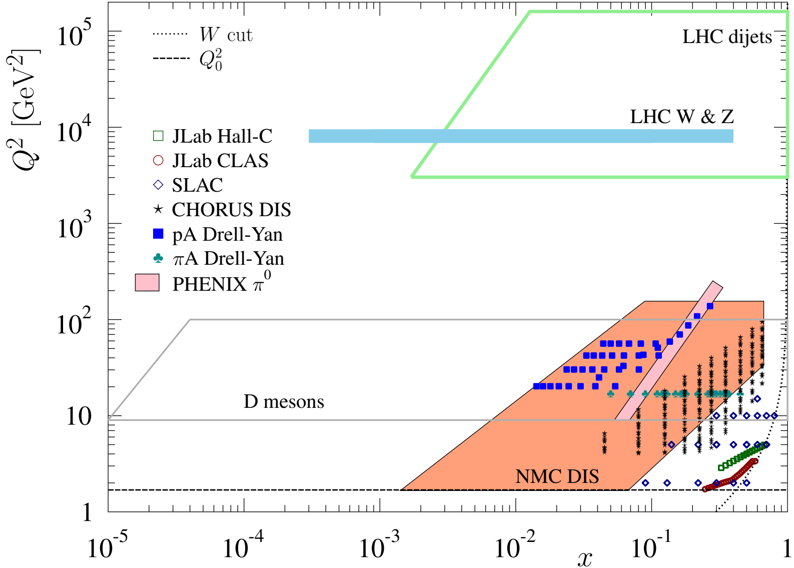
- ➔ rely only to the QCD collinear factorization
- ➔ model-agnostic way to study the nuclear effects

Bulk of data from fixed-target experiments

LHC is extending the x, Q^2 reach of pA by orders of magnitude

EIC will do the same for eA!

Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413



Example parametrization: EPPS21

- Define nuclear PDFs in terms of

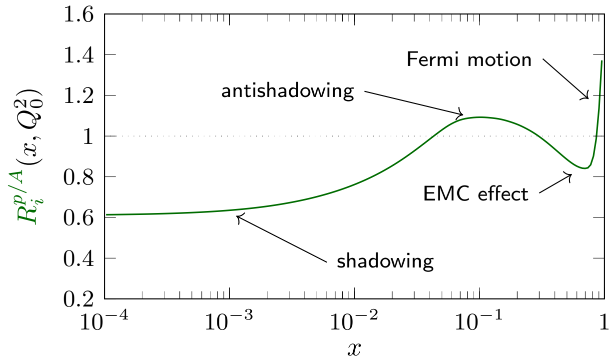
$$\underbrace{f_i^{p/A}}_{\text{bound-proton PDF}}(x,Q^2) = \overbrace{R_i^{p/A}}^{\text{nuclear modification}}(x,Q^2)\,\underbrace{f_i^{p}}_{\text{free-proton PDF}}(x,Q^2)$$

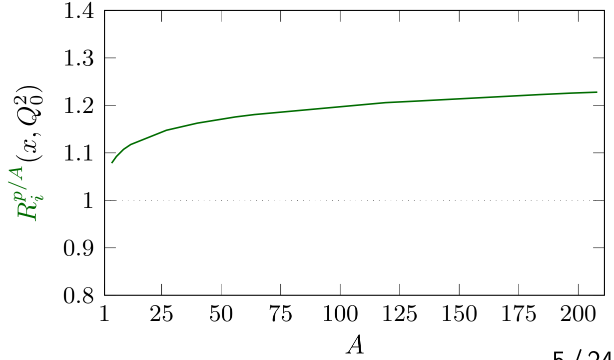
- PDFs of the full nucleus are then constructed with

$$f_i^A(x,Q^2) = Z f_i^{p/A}(x,Q^2) + N f_i^{n/A}(x,Q^2),$$

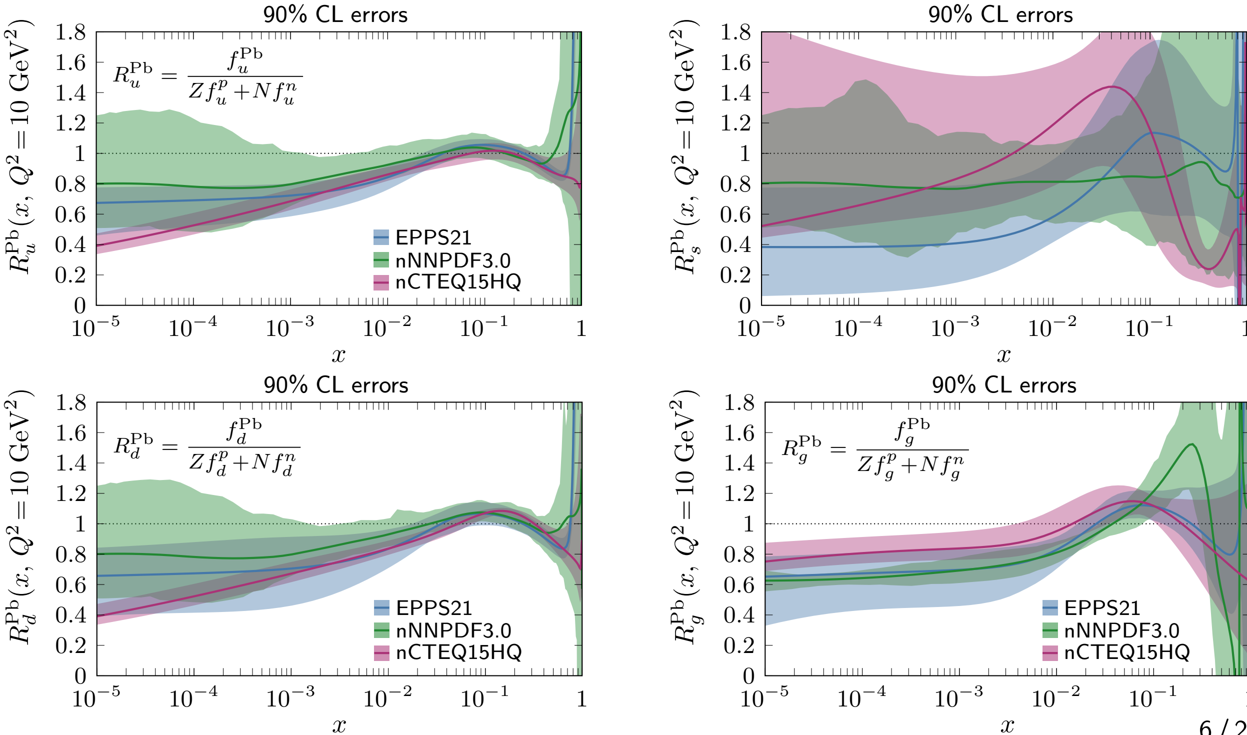
and assuming $f_i^{p/A} \xleftrightarrow{\text{isospin}} f_j^{n/A}$

- Parametrize the x and A dependence of $R_i^{p/A}(x,Q_0^2)$ at $Q_0 = m_{\text{charm}} = 1.3$ GeV
  - Use a phenomenologically motivated piecewise function in x
  - Use a power-law type function in A





nPDF comparison



Recent nPDF global fits

	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HQ
Order in α_s	NLO & NNLO	NLO & NNLO	NLO	NLO	NLO
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓	✓	✓	✓	
pA DY	✓		✓	✓	✓
πA DY			✓		
RHIC dAu π^0,$\pi^\pm$			✓		✓
LHC pPb π^0,$\pi^\pm$,$K^\pm$					✓
LHC pPb dijets			✓	✓	
LHC pPb HQ			✓ GMVFN	✓ FO+PS	✓ ME fitting
LHC pPb W,Z		✓	✓	✓	✓
LHC pPb γ				✓	
Q, W cut in DIS	1.3, 0.0 GeV	1.87, 3.5 GeV	1.3, 1.8 GeV	1.87, 3.5 GeV	2.0, 3.5 GeV
p_T cut in HQ,inc.-h	N/A	N/A	3.0 GeV	0.0 GeV	3.0 GeV
Data points	4353	2410	2077	2188	1496
Free parameters	9	16	24	256	19
Error analysis	Hessian	Hessian	Hessian	Monte Carlo	Hessian
Free-proton PDFs	CT18	own fit	CT18A	∼NNPDF4.0	∼CTEQ6M
Free-proton corr.	no	no	yes	yes	no
HQ treatment	FONLL	FONLL	S-ACOT	FONLL	S-ACOT
Indep. flavours	3	4	6	6	5
Reference	PRD 104, 034010	PRD 105, 094031	EPJC 82, 413	EPJC 82, 507	PRD 105, 114043

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pA DY	✓		✓	✓	✓
πA DY			✓		
RHIC dAu π^0,$\pi^\pm$			✓		✓
LHC pPb π^0,$\pi^\pm$,$K^\pm$					✓
LHC pPb dijets			✓	✓	
LHC pPb HQ			✓ GMVFN	✓ FO+PS	✓ ME fitting
LHC pPb W,Z		✓	✓	✓	✓
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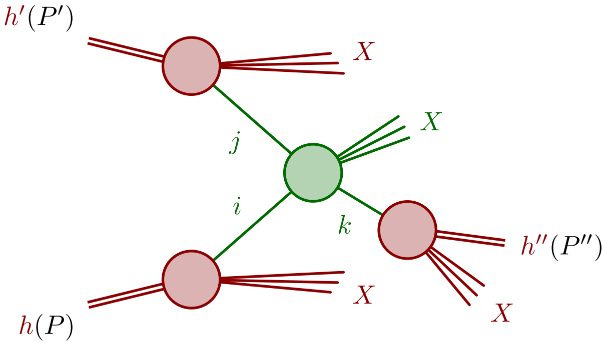
Hadroproduction of hadronic final states

Hadron-production

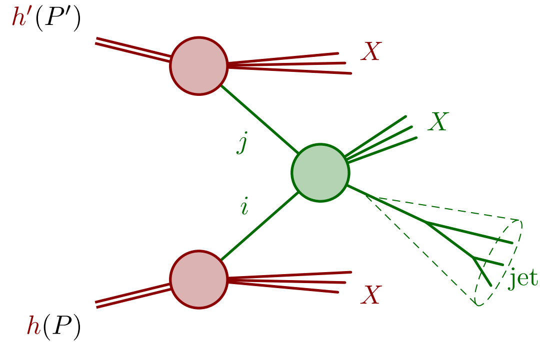


$$\sigma^{h+h'\to h''+X} = \sum_{i,j,k\in\{q,\bar{q},g\}} f_i^h \otimes f_j^{h'} \otimes \hat{\sigma}^{ij\to k+X} \otimes D_k^{h''}$$

Account for the hadronization effects with the *parton to hadron fragmentation functions* $D_k^{h''}$

→ a source of uncertainty for PDF fits

Jet-production



$$\sigma^{h+h'\to \text{jet}+X} = \sum_{i,j\in\{q,\bar{q},g\}} f_i^h \otimes f_j^{h'} \otimes \hat{\sigma}^{ij\to \text{jet}+X}$$

Instead of fragmentation functions:

- need an IR-safe definition of a jet
- non-perturbative corrections

Heavy-flavour production mass schemes

FFNS

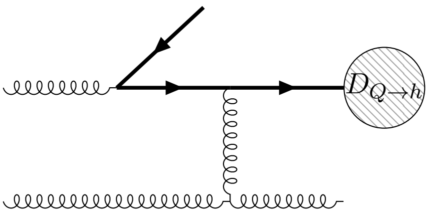
In *fixed flavour number scheme*, valid at small p_{T}, heavy quarks are produced only at the matrix element level

Contains $\log(p_{\mathrm{T}}/m)$ and $\mathcal{O}(m)$ terms

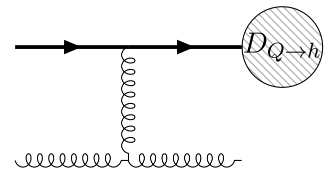
ZM-VFNS

In *zero-mass variable flavour number scheme*, valid at large p_{T}, heavy quarks are treated as massless particles produced also in ISR/FSR

Resums $\log(p_{\mathrm{T}}/m)$ but ignores $\mathcal{O}(m)$ terms



$-$ subtraction term $+$



GM-VFNS

A *general-mass variable flavour number scheme* combines the two by supplementing subtraction terms to prevent double counting of the resummed splittings, valid at all p_{T}

Resums $\log(p_{\mathrm{T}}/m)$ and includes $\mathcal{O}(m)$ terms in the FFNS matrix elements

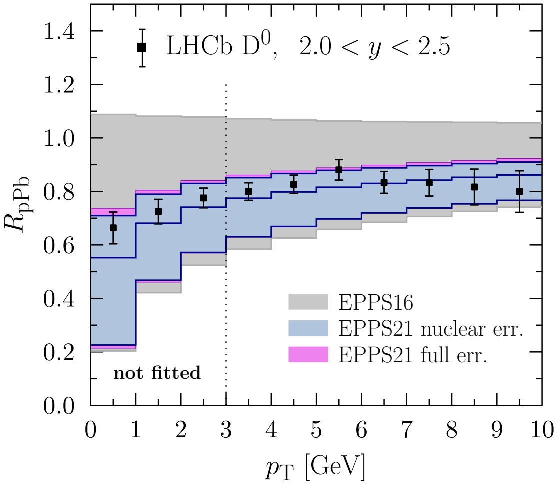
Important: includes also gluon-to-HF fragmentation – large contribution to the cross section!

Helenius & Paukkunen, JHEP 05 (2018) 196

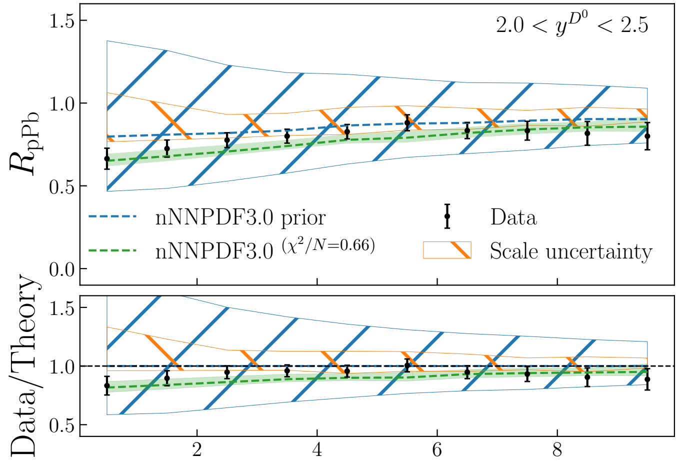
D^0s in EPPS21 and nNNPDF3.0

data from: LHCb Collaboration, JHEP 10 (2017) 090

Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413



Abdul Khalek et al., EPJC 82 (2022) 507



Drastic reduction in the nPDF uncertainties!

➔ Important constraints for the nuclear gluons!

Kusina et al., PRL 121 (2018) 052004
Eskola, Helenius, PP, Paukkunen, JHEP 05 (2020) 037
Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413
Abdul Khalek et al., EPJC 82 (2022) 507

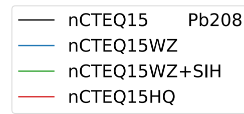
nNNPDF3.0 with POWHEG+PYTHIA finds a large scale uncertainty ➔ fit only forward data

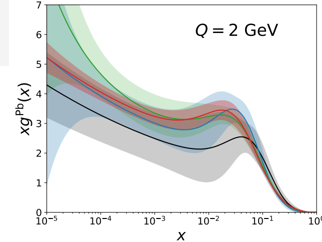
not seen in the S-ACOT-m_T GM-VFNS used in EPPS21

Helenius & Paukkunen, JHEP 05 (2018) 196
Eskola, Helenius, PP, Paukkunen, JHEP 05 (2020) 037

A data-driven approach – nCTEQ15HQ

Duwentäster et al., PRD 105, 114043



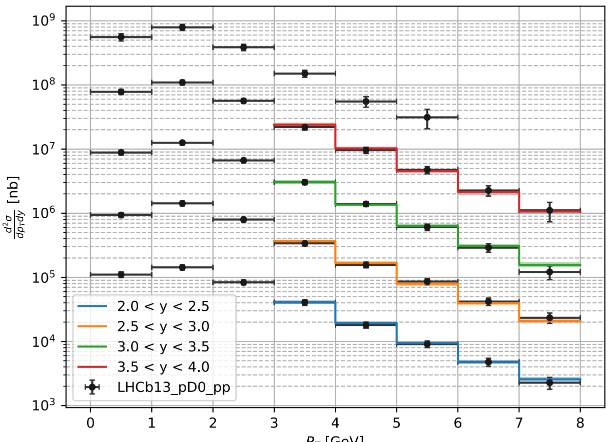


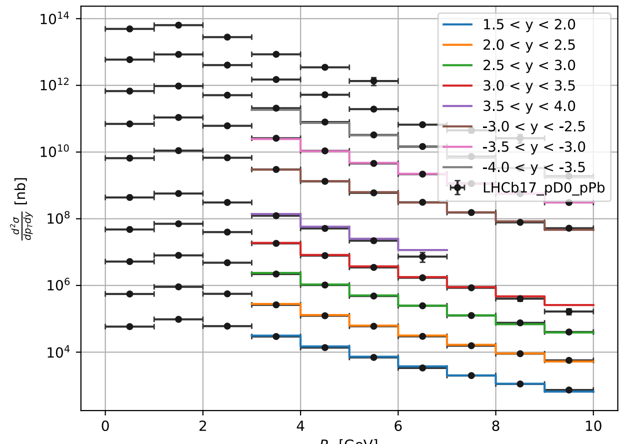
nCTEQ15HQ uses a data-driven approach

Lansberg & Shao, EPJC 77 (2017) 1
Kusina et al., PRL 121 (2018) 052004

to fit the D^0 and J/ψ data:

1. Fit the matrix elements to pp data...
   (assume $2 \to 2$ kinematics, neglect IS quarks)
2. ...use the fitted matrix elements to fit nuclear PDFs with pPb data





New LHCb measurement at 8.16 TeV
(not included in the nPDF analyses yet)

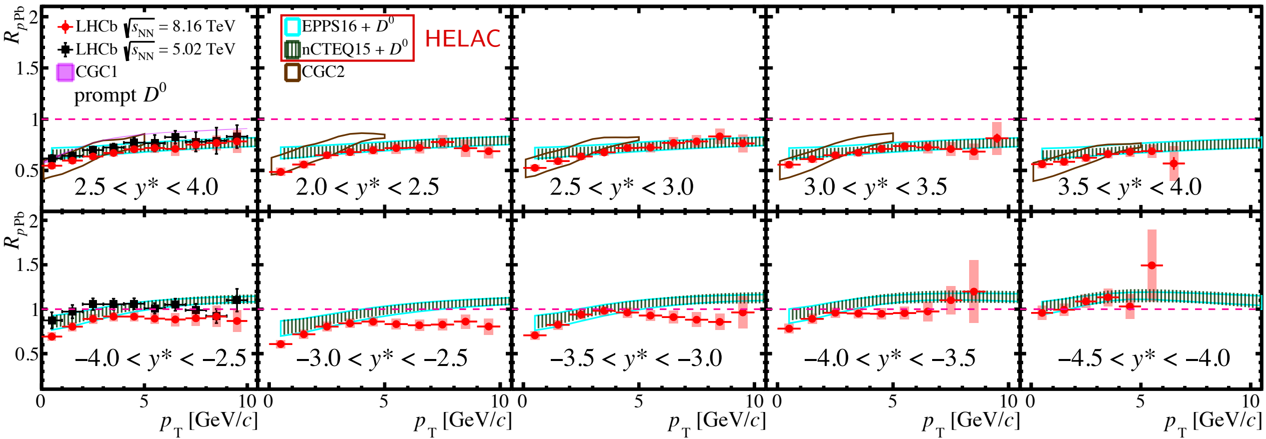
pp reference interpolated from 5 and 13 TeV measurements

So far compared only against the HELAC matrix-element-fitting results

Kusina et al., PRL 121 (2018) 052004

→ to be scrutinised with the direct pQCD calculations

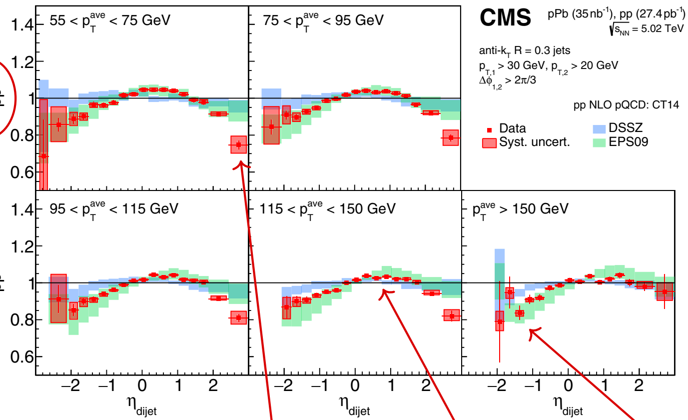
LHCb Collaboration, arXiv:2205.03936



Dijets in pPb at 5.02 TeV

Ratio of ratios: $R^{\text{norm.}}_{\text{pPb}} = \dfrac{\mathrm{d}^2\sigma^{\mathbf{pPb}}/\mathrm{d}p_T^{\text{ave}}\mathrm{d}\eta_{\text{dijet}}}{\mathrm{d}\sigma^{\mathbf{pPb}}/\mathrm{d}p_T^{\text{ave}}} \Bigg/ \dfrac{\mathrm{d}^2\sigma^{\mathbf{pp}}/\mathrm{d}p_T^{\text{ave}}\mathrm{d}\eta_{\text{dijet}}}{\mathrm{d}\sigma^{\mathbf{pp}}/\mathrm{d}p_T^{\text{ave}}}$

CMS Collaboration, PRL 121 (2018) 062002

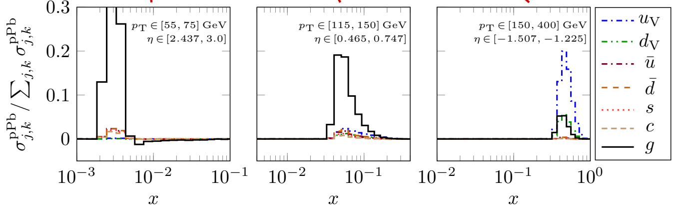


Double ratio convenient for:

- Cancellation of hadronization and luminosity uncertainties separately for pPb and pp
  - ➔ do not expect strong non-pert. effects
- Cancellation of free-proton-PDF and scale uncertainties in pPb/pp
  - ➔ direct access to nuclear modifications

Eskola, PP, Paukkunen, EPJC 79 (2019) 511

NLO pQCD:

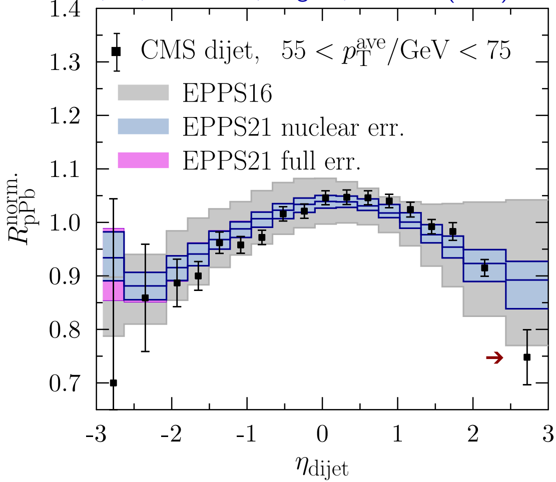


Good resolution to gluon nuclear modifications for $10^{-3} < x < 0.5$

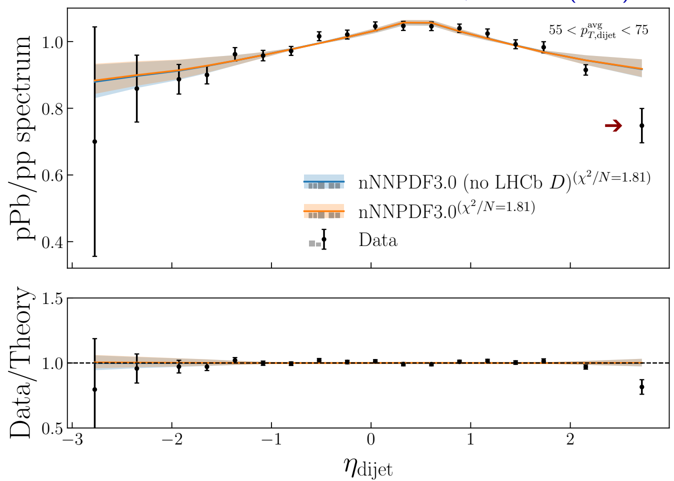
Dijets in EPPS21 and nNNPDF3.0

data from: CMS Collaboration, PRL 121 (2018) 062002

Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413



Abdul Khalek et al., EPJC 82 (2022) 507



Drastic reduction in the nPDF uncertainties!

→ Important constraints for the nuclear gluons!

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Eskola, PP, Paukkunen, Salgado, EPJC 82 (2022) 413
Abdul Khalek et al., EPJC 82 (2022) 507

Both EPPS21 and nNNPDF3.0 find difficulties in reproducing the most forward data points

→ missing data correlations important?

→ NNLO? non-pert. effects?

→ new & complementary data would help!

‘Novel probes’ from photoproduction in UPCs

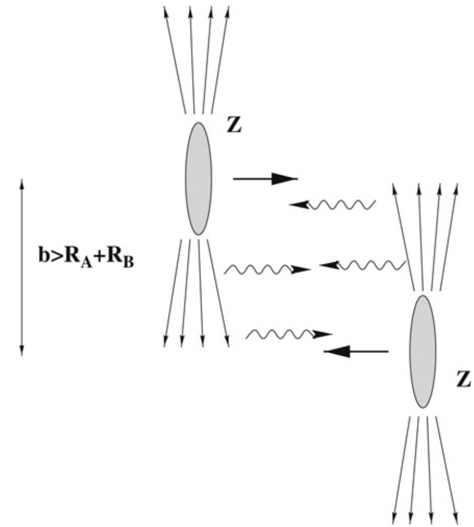
Baltz et al., Physics Reports 458 (2008) 1

In ultra-peripheral heavy-ion collisions (UPCs), two nuclei pass each other at an impact parameter larger than the sum of their radii

- ➔ hadronic interactions suppressed

Hard interactions of one nucleus with the electric field of the other can be described in equivalent photon approximation

- ➔ access to photo-nuclear processes



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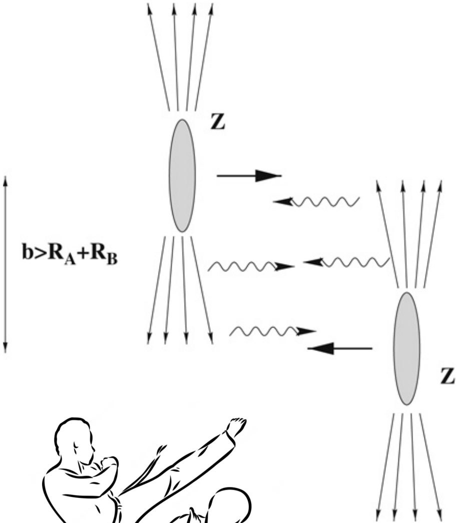
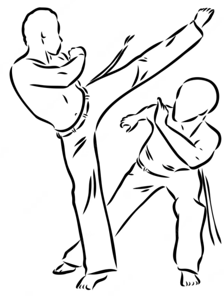


Just like two capoeiristas who interact without touching!



‘Novel probes’: Exclusive UPC J/ψ photoproduction in collinear factorization

First phenomenological implementation of the NLO corrections

Ivanov et al., EPJC 34 (2004) 297
Jones et al., J. Phys. G 43 (2016) 035002

in ultrapheripheral Pb+Pb

Eskola et al., PRC 106 (2022) 035202

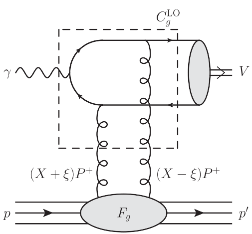
Exclusive process

- ➔ need a mapping between GPDs and traditional PDFs (Shuvaev transform)

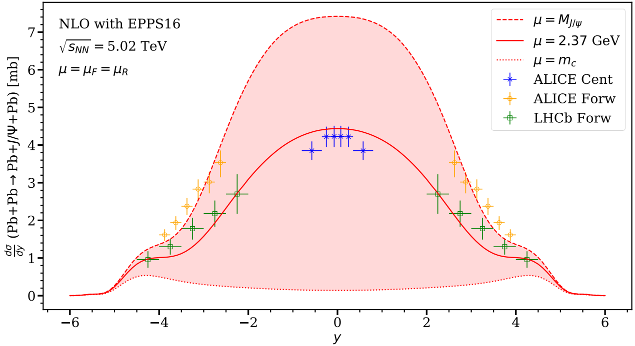
Large scale uncertainty

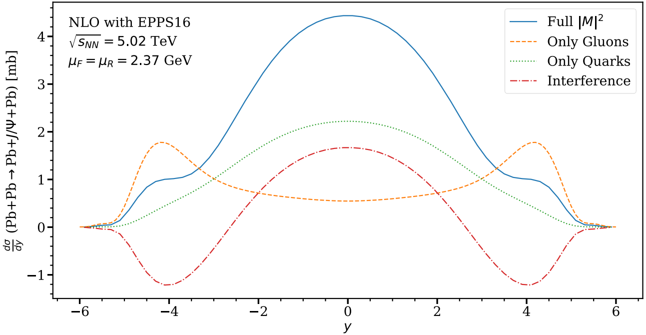
- ➔ perturbative convergence?

Flett et al., PRD 101 (2020) 094011



Eskola et al., PRC 106 (2022) 035202



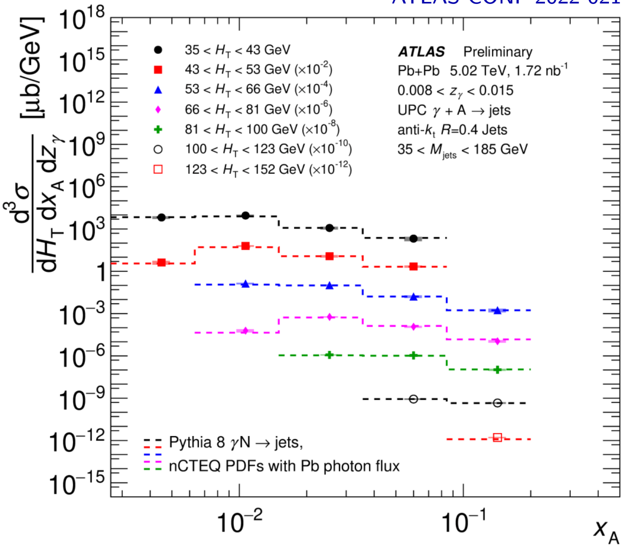


'Novel probes': Inclusive dijets in UPCs

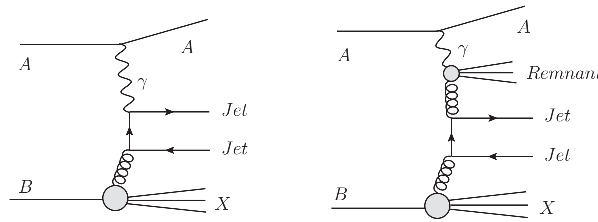
Dijet photoproduction in UPCs has been promoted as a probe of nuclear PDFs

ATLAS measurement now fully unfolded!

ATLAS-CONF-2022-021



Guzey & Klasen, PRC 99 (2019) 065202



Triple differential in

$$H_T = \sum_{i \in \text{jets}} p_{T,i}, \quad z_\gamma = \frac{M_{\text{jets}}}{\sqrt{s_{NN}}} e^{+y_{\text{jets}}},$$

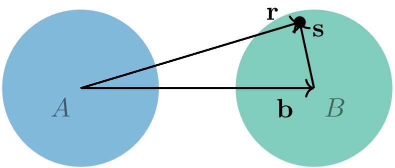
$$x_A = \frac{M_{\text{jets}}}{\sqrt{s_{NN}}} e^{-y_{\text{jets}}}$$

Previous NLO predictions have been performed in a pointlike approximation of the photon flux

Guzey & Klasen, PRC 99 (2019) 065202

➔ Can/should we do better?

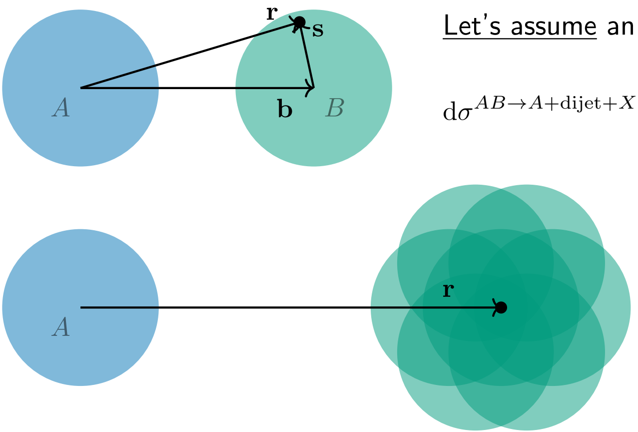
Impact-parameter dependence



Let's assume an impact-parameter dependent factorization similar to
Greiner et al., PRC 51 (1995) 911

$$\mathrm{d}\sigma^{AB\to A+\mathrm{dijet}+X} = \sum_{i,j,X'} \int \mathrm{d}^2\mathbf{b}\, \Gamma_{AB}(\mathbf{b}) \int \mathrm{d}^2\mathbf{r}\, f_{\gamma/A}(y,\mathbf{r}) \otimes f_{i/\gamma}(x_\gamma, Q^2)$$
$$\otimes \int \mathrm{d}^2\mathbf{s}\, f_{j/B}(x, Q^2, \mathbf{s}) \otimes \mathrm{d}\hat{\sigma}^{ij\to\mathrm{dijet}+X'} \delta(\mathbf{r}-\mathbf{s}-\mathbf{b})$$

Impact-parameter dependence



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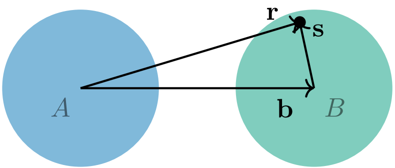
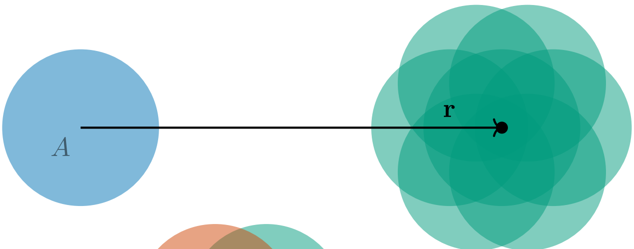
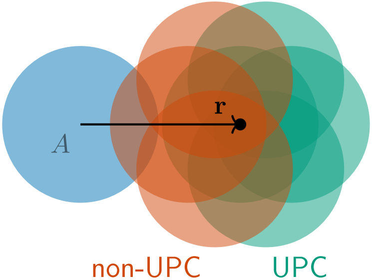
$|\mathbf{r}| \sim |\mathbf{b}| \gg |\mathbf{s}|$ 'jogo de fora'







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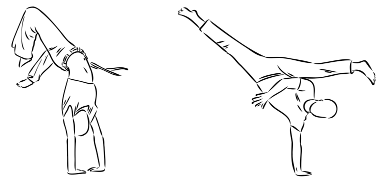
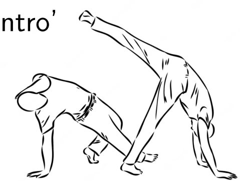
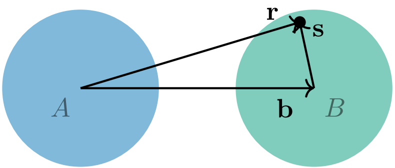


$|\mathbf{r}| \sim |\mathbf{b}| \sim |\mathbf{s}|$ 'jogo de dentro'



Impact-parameter dependence

Work in progress!



Let's assume an impact-parameter dependent factorization similar to

Greiner et al., PRC 51 (1995) 911

$$d\sigma^{AB\to A+\text{dijet}+X} = \sum_{i,j,X'} \int d^2\mathbf{b}\, \Gamma_{AB}(\mathbf{b}) \int d^2\mathbf{r}\, f_{\gamma/A}(y,\mathbf{r}) \otimes f_{i/\gamma}(x_\gamma, Q^2) \otimes \int d^2\mathbf{s}\, f_{j/B}(x,Q^2,\mathbf{s}) \otimes d\hat{\sigma}^{ij\to\text{dijet}+X'} \delta(\mathbf{r}-\mathbf{s}-\mathbf{b})$$

Now, if $f_{j/B}(x,Q^2,\mathbf{s}) = \frac{1}{B} T_B(\mathbf{s}) \cdot f_{j/B}(x,Q^2)$, we can write

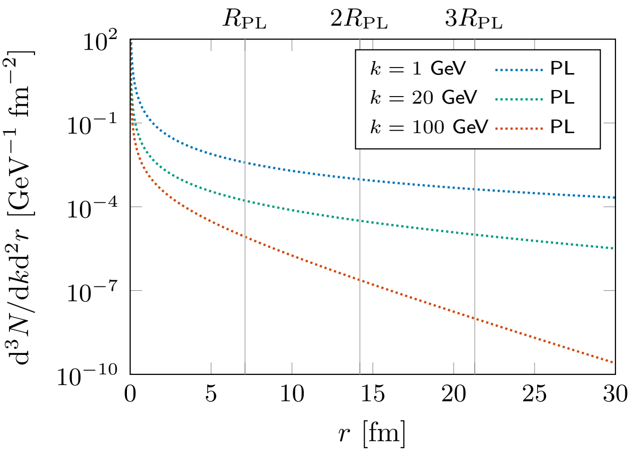
$$d\sigma^{AB\to A+\text{dijet}+X} = \sum_{i,j,X'} f^{\text{eff}}_{\gamma/A}(y) \otimes f_{i/\gamma}(x_\gamma, Q^2) \otimes f_{j/B}(x,Q^2) \otimes d\hat{\sigma}^{ij\to\text{dijet}+X'}$$

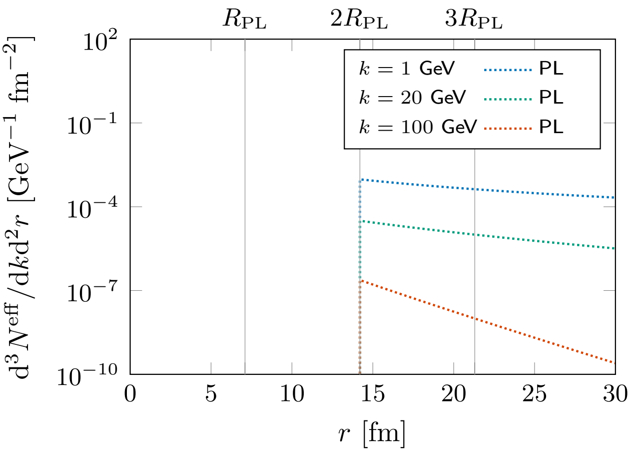
where the effective photon flux reads

$$f^{\text{eff}}_{\gamma/A}(y) = \frac{1}{B} \int d^2\mathbf{r} \int d^2\mathbf{s}\, f_{\gamma/A}(y,\mathbf{r})\, T_B(\mathbf{s})\, \Gamma_{AB}(\mathbf{r}-\mathbf{s})$$

as in ATLAS-CONF-2022-021 (see Appendix A)!

Effective photon flux in UPC PbPb (1: PL approx.)



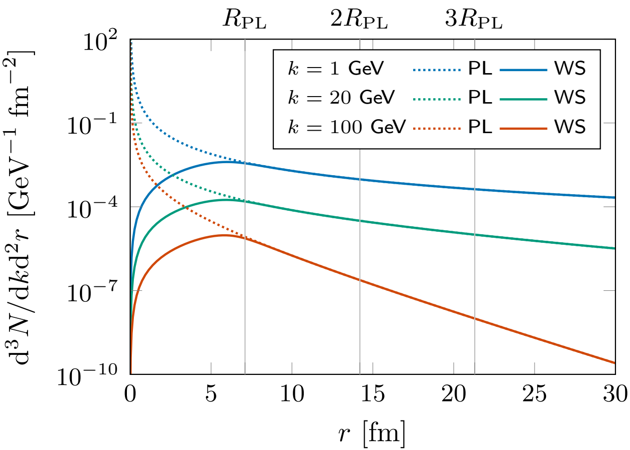


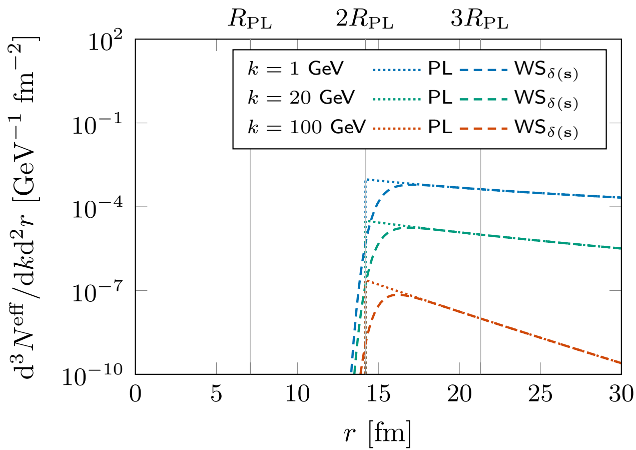
Pointlike (PL) approximation: $T_B(\mathbf{s}) = B\delta(\mathbf{s})$, $\Gamma_{AB}(\mathbf{b}) = \theta(|\mathbf{b}| - b_{\min})$, $b_{\min} = 2R_{\mathrm{PL}} = 14$ fm

$$\Rightarrow f^{\mathrm{eff,PL}}_{\gamma/A}(y) = \int \mathrm{d}^2\mathbf{r}\, \underbrace{f^{\mathrm{PL}}_{\gamma/A}(y,\mathbf{r})}_{=\frac{Z^2\alpha_{\mathrm{e.m.}}}{\pi^2} m_p^2 y [K_1^2(\zeta)+\frac{1}{\gamma_L}K_0^2(\zeta)]_{\zeta=ym_p|\mathbf{r}|}}\, \theta(|\mathbf{r}|-b_{\min}) = \frac{2Z^2\alpha_{\mathrm{e.m.}}}{\pi y}\left[\zeta K_0(\zeta)K_1(\zeta) - \frac{\zeta^2}{2}[K_1^2(\zeta) - K_0^2(\zeta)]\right]_{\zeta=ym_pb_{\min}}$$

➔ Coincides with Guzey & Klasen, PRC 99 (2019) 065202

Effective photon flux in UPC PbPb (2: WS with $T_B(\mathbf{s}) = B\delta(\mathbf{s})$)



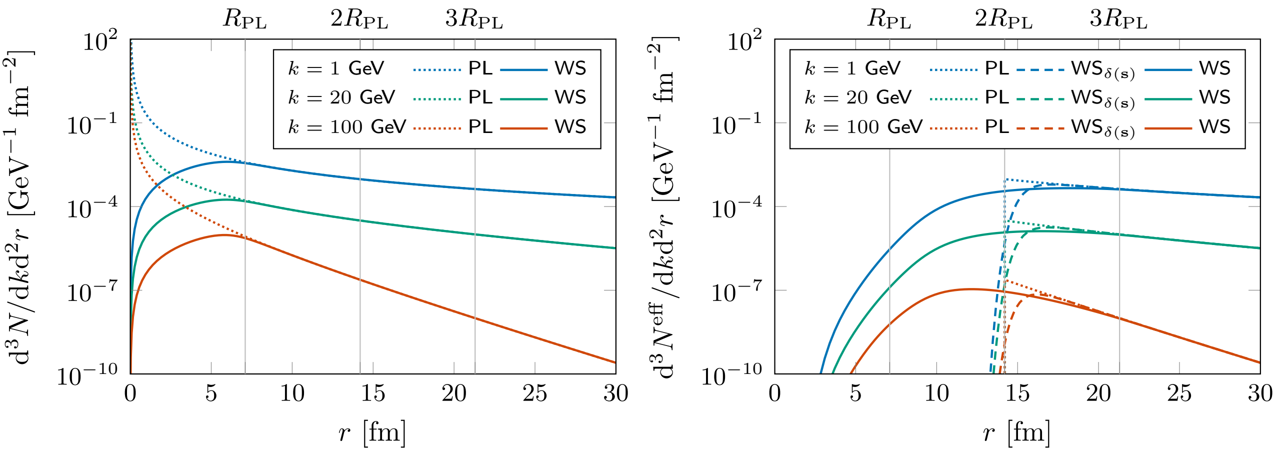


Woods-Saxon source on point-like target (WS$_{\delta(\mathbf{s})}$): $T_B(\mathbf{s}) = B\delta(\mathbf{s}), \quad \Gamma_{AB}(\mathbf{b}) = \exp[-\sigma_{\rm NN}T_{AB}(\mathbf{b})]$

$$\Rightarrow f_{\gamma/A}^{\mathrm{eff,WS}_{\delta(\mathbf{s})}}(y) = \int \mathrm{d}^2\mathbf{r}\ \underbrace{f_{\gamma/A}^{\rm WS}(y,\mathbf{r})}_{= \frac{Z^2\alpha_{\rm e.m.}}{\pi^2 y E_{\rm beam}^2}\left|\int_0^\infty \mathrm{d}k_\perp \frac{k_\perp^2 F(k_\perp^2 + k^2/\gamma_L^2)}{k_\perp^2 + k^2/\gamma_L^2} J_1(|\mathbf{r}|k_\perp)\right|^2_{k = yE_{\rm beam}}} \Gamma_{AB}(\mathbf{r})$$

➔ cf. Eskola et al., PRC 106 (2022) 035202; Zha et al., PLB 781 (2018) 182

Effective photon flux in UPC PbPb (3: Full WS profile)



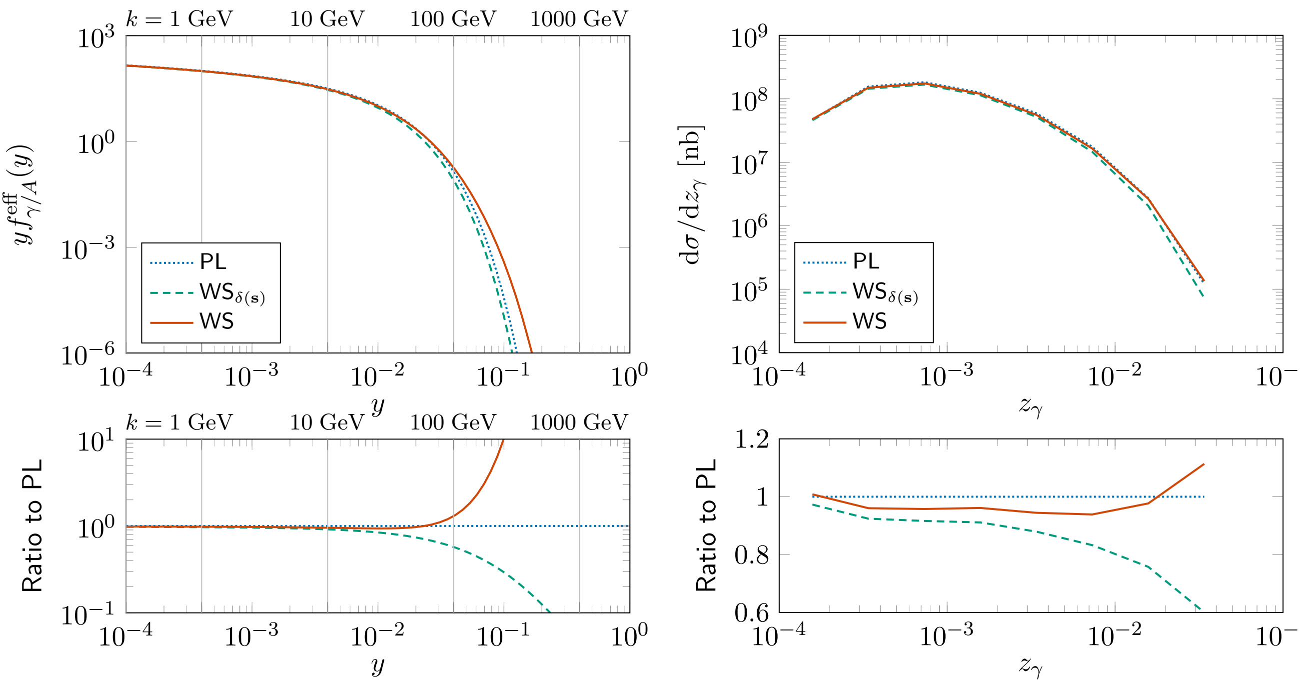
Woods-Saxon nuclear profile (WS): $T_B(\mathbf{s}) = \int_{-\infty}^{\infty} \mathrm{d}z \rho_B(z,\mathbf{s})$, $\Gamma_{AB}(\mathbf{b}) = \exp[-\sigma_{\rm NN} T_{AB}(\mathbf{b})]$

$$\Rightarrow f^{\rm eff,WS}_{\gamma/A}(y) = \int \mathrm{d}^2\mathbf{r}\, \underbrace{f^{\rm WS}_{\gamma/A}(y,\mathbf{r})}_{= \frac{Z^2\alpha_{\rm e.m.}}{\pi^2 y E^2_{\rm beam}} \left| \int_0^\infty \mathrm{d}k_\perp \frac{k_\perp^2 F(k_\perp^2 + k^2/\gamma_L^2)}{k_\perp^2 + k^2/\gamma_L^2} J_1(|\mathbf{r}|k_\perp) \right|^2_{k=yE_{\rm beam}}} \Gamma^{\rm eff}_{AB}(\mathbf{r}), \quad \text{where} \quad \Gamma^{\rm eff}_{AB}(\mathbf{r}) = \int \mathrm{d}^2\mathbf{s}\, T_B(\mathbf{s})\, \Gamma_{AB}(\mathbf{r}-\mathbf{s})$$

➔ Accounting for the s dependence important at small $|\mathbf{r}|$!

Effective photon flux and UPC dijet cross section

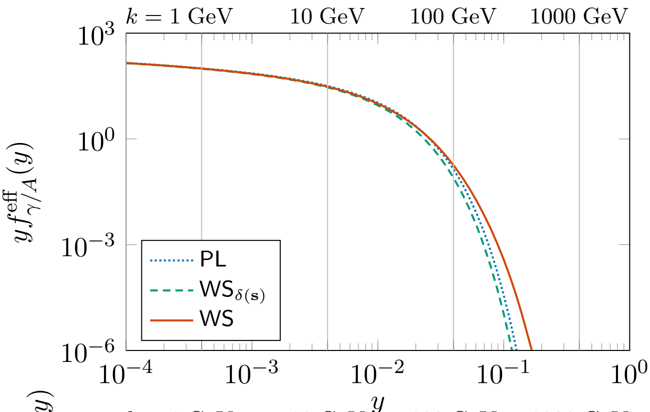
Work in progress!

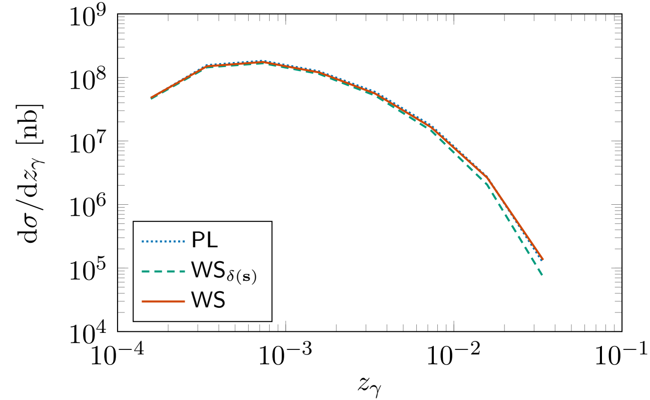


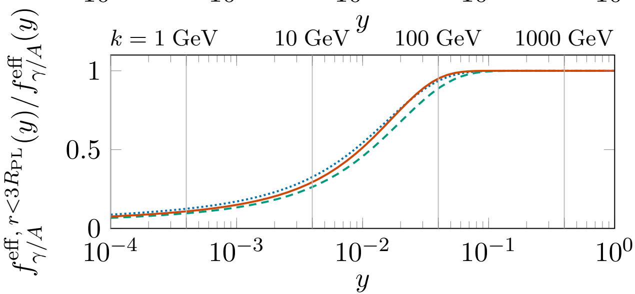
$\sim$ 10% effect in PL vs. full WS cross sections

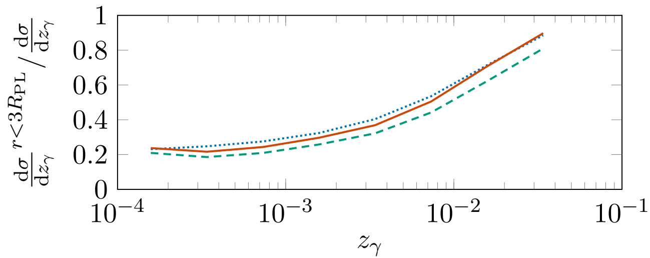
Effective photon flux and UPC dijet cross section

Work in progress!





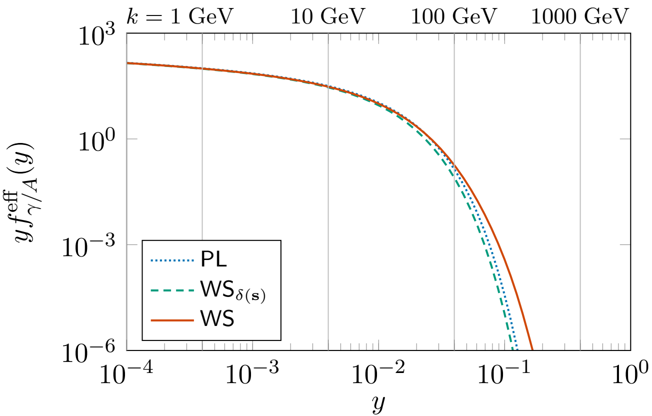


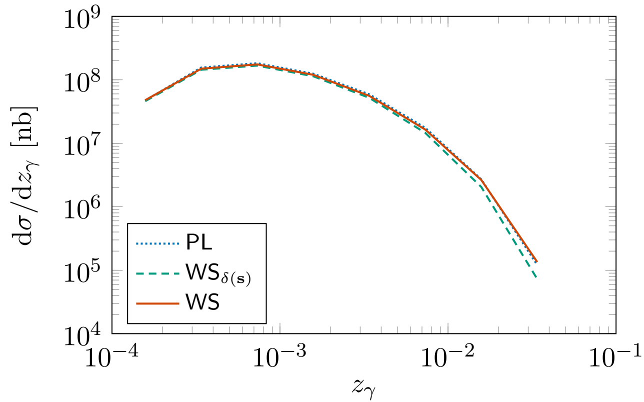


!! most of the events with large z_γ (correspondingly small x_A) come from small r !!

Effective photon flux and UPC dijet cross section

Work in progress!





Questions for further investigation:

- All of this assumed that we can factorize $f_{j/B}(x, Q^2, \mathbf{s}) = \frac{1}{B} T_B(\mathbf{s}) \cdot f_{j/B}(x, Q^2)$, but we know this might not be valid. Are we then actually probing impact-parameter dependent nPDFs?
- If so, are these objects we probe here in a (more or less) inclusive process related the GPDs extracted in exclusive processes?

Dijet photoproduction at EIC

The experimental condition for photoproduction at EIC is much simpler - depends only on electron scattering angle!

$$f_{\gamma/e}(y) = \frac{\alpha_{\mathrm{e.m.}}}{2\pi}\left[\frac{1+(1-y)^2}{y}\log\frac{Q^2_{\max}(1-y)}{m_e^2y^2} + 2m_e^2y\left(\frac{1}{Q^2_{\max}} - \frac{1-y}{m_e^2y^2}\right)\right],$$

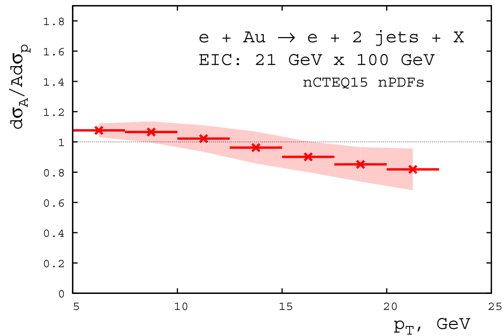
where $Q^2_{\max}$ is the maximal photon virtuality

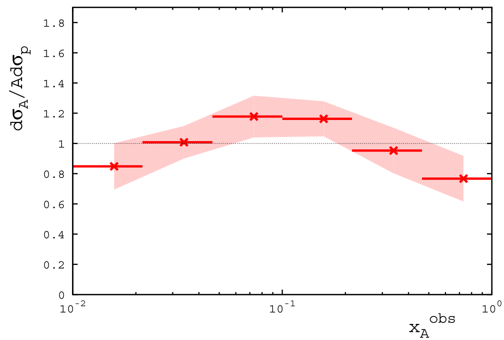
Probe nPDFs down to $x \sim 10^{-2}$

Klasen & Kovarik, PRD 97 (2018) 114013
Guzey & Klasen, PRC 102 (2020) 065201

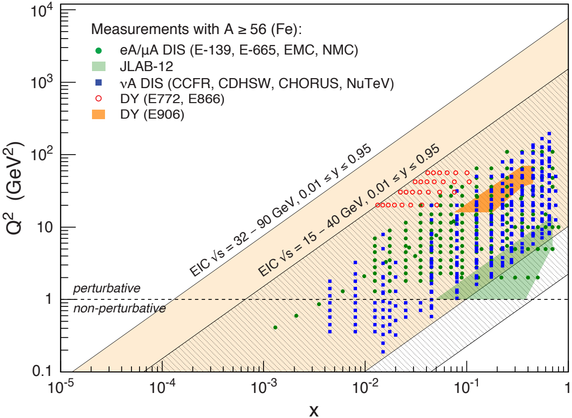
Complementary to pA dijets and other EIC observables

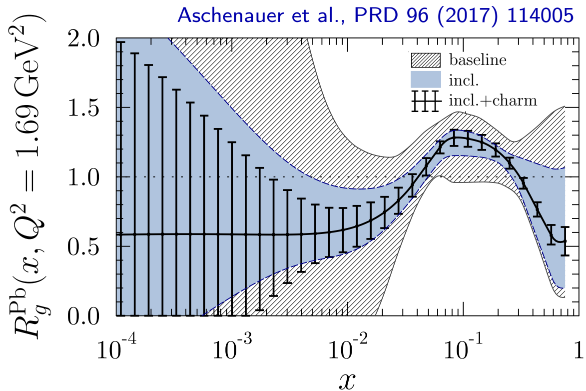
Guzey & Klasen, PRC 102 (2020) 065201





Gluon constraints from DIS at EIC





EIC will significantly widen the kinematic range of DIS constraints for nPDFs

- Comparing with LHC measurements will put collinear factorization with nuclei to a stringent test

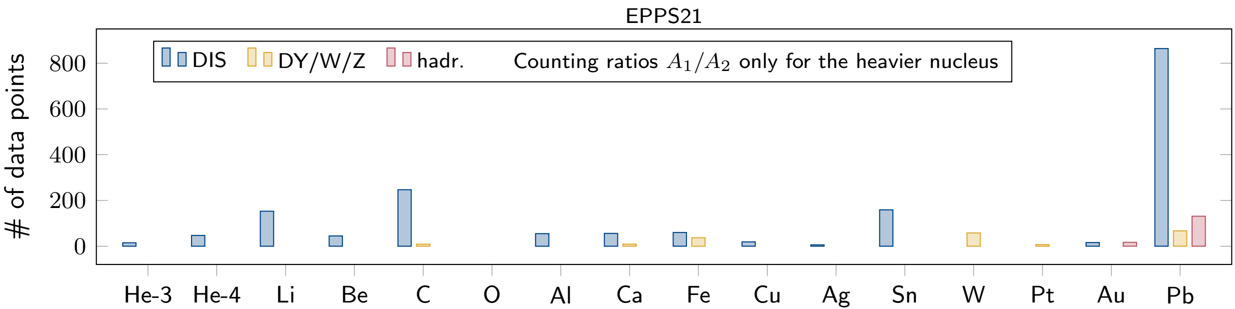
With the F_L extraction capability, EIC provides a clean probe to study small-x gluons

- Good constraining power to well down to $x \sim 10^{-2}$

Charm-tagged cross-section measurement can vastly reduce high-x gluon uncertainty

see also: Kelsey et al., PRD 104 (2021) 054002

Data availability w.r.t. A



$\sim 50\%$ of the data points are for Pb!

- ☺ Good coverage of DIS measurements for different A (but only fixed target!)
- 😐 DY data more scarce, but OK A coverage
- ☹ Hadronic observables available only for heavy nuclei!

A lot of room for improvement from EIC with inclusive DIS and heavy quarks & jets!

Summary

- A lot of progress in constraining nPDFs with the LHC pA data, but methodological choices and data selection cause differences in the extracted gluon distributions

- Photoproduction in UPCs offer novel probes, but theoretical uncertainties may prevent their use as actual nPDF constraints

- EIC is going to be *essential* in providing clean probes and ensuring complementary view from multiple observables on the nuclear structure

- Having measurements with different nuclei is *key*. We want to understand the onset of nuclear effects from the lightest all the way to the heaviest nuclei

Thank you!