EPPS views on nuclear PDFs

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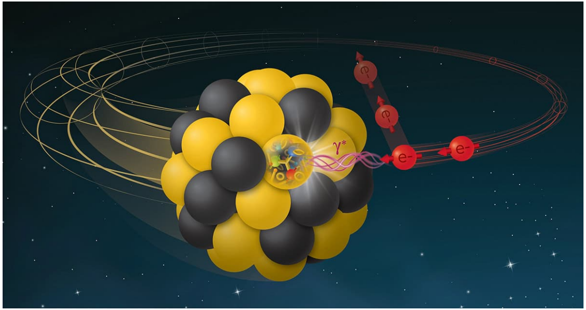
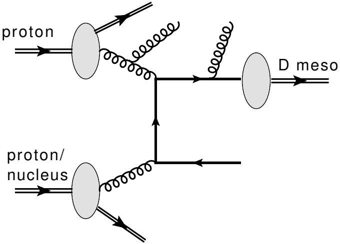
Cold Nuclear Matter Effects: from LHC to EIC, Jan 14th 2025



Collinear factorization in collisions involving nuclei



Parton distributions (PDFs) — Parton distributions (PDFs) — Fragmentation functions (FFs)

$$\frac{d\sigma^{\mathrm{pPb}}}{dP_{\mathrm{T}}dY} = \sum_{ijk} f_i^p(x_1,\mu^2) \otimes \frac{d\hat{\sigma}^{ij\to k+X}(\mu^2)}{dp_{\mathrm{T}}dy} \otimes f_j^{\mathrm{Pb}}(x_2,\mu^2) \otimes D_{k\to\mathrm{D}}(x_3,\mu^2) + \mathcal{O}\left(\frac{Q_s^2}{P_{\mathrm{T}}^2}\right)$$

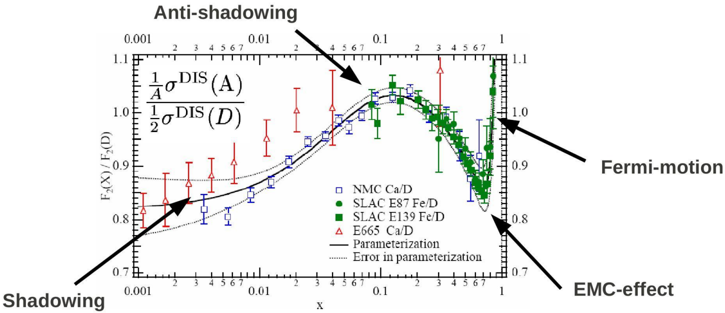
Partonic coefficient functions

- PDFs & FFs obey the linear DGLAP renormalization group equations (resums collinear radiation)

$$\frac{df_i^A(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dz}{z} P_{ik}\left(\frac{x}{z}\right) f_k^A(x,Q^2) + \mathcal{O}\left(\frac{Q_{\mathrm{s}}^2}{Q^2}\right)$$

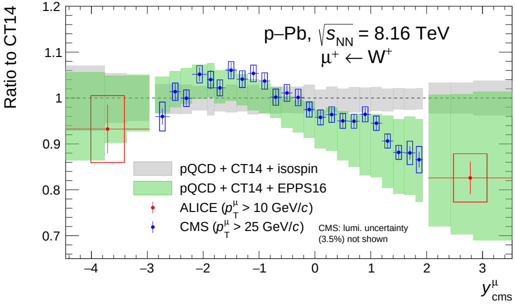
Nuclear effects first discovered in deeply inelastic scattering (DIS)...

- Nuclear effects in hard processes first observed in deep inelastic scattering in the 80's:

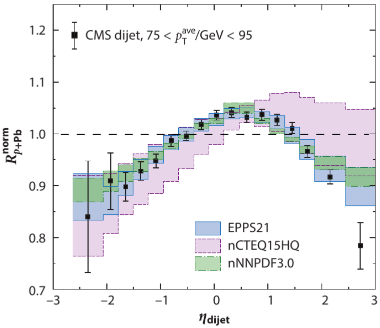


- The very same pattern of nuclear effects has been seen at the LHC in p-Pb/p-p

[ALICE Coll., JHEP 05 (2023) 036]



[Klasen & Paukkunen, Ann. Rev. of Nucl. Part. Sci. Vol. 74, 2024]



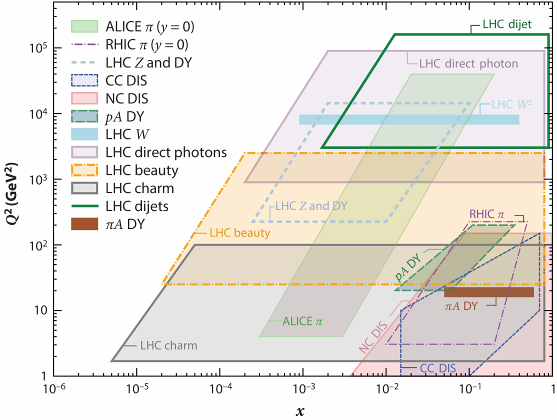
- Global analysis: **To what extent these effects due to the modified structure of nucleons?**

The kinematic/virtuality reach in global analysis of nuclear PDFs

- The variety & precision of data begins to be high enough to challence the picture of collinear factorization and to look for e.g.
  - **onset of non-linear dynamics**
  - **partonic energy loss**
  - **collectivity in small systems**
  - **...**

  in p-Pb type collisions
- Non-factorizable non-universal effects should become visible in global fits, $\chi^2/N_{\rm data} \gg 1$
- Global analysis of nuclear PDFs can be seen as a **search** for these effects – not something that overlooks them

[Klasen & Paukkunen, Ann. Rev. of Nucl. Part. Sci. Vol. 74, 2024]

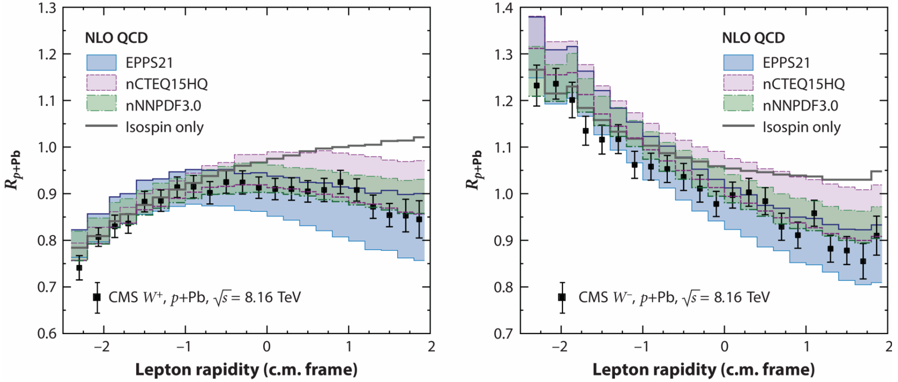


Klasen M, Paukkunen H. 2024
Annu. Rev. Nucl. Part. Sci. 74:49–87

Electroweak boson production

- The CMS p-Pb 8.16TeV $W^{\pm}$-bosons [Phys.Lett.B 800 (2020) 135048] vs. global fits

[Klasen & Paukkunen, Ann. Rev. of Nucl. Part. Sci. Vol. 74, 2024]

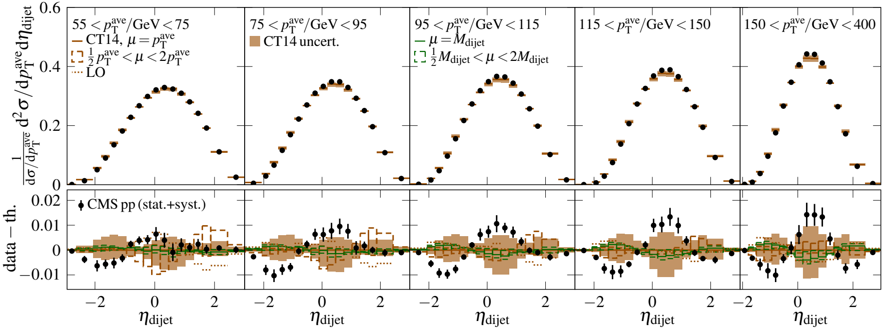


- At the parametrization scale these data constrain **almost exclusively gluons** [Eur.Phys.J.C 82 (2022) 3, 271]
- The long lever arm in rapidity helps to tame the normalization uncertainty

Inclusive 5 TeV dijets

- A precision dijet observable by CMS [PHYS.REV.LETT. 121 (2018) 6, 062002]

$$\frac{d^2\sigma^{\rm pp}}{dp_{\rm T}^{\rm ave}\, d\eta_{\rm dijet}} \left(\frac{d\sigma^{\rm pp}}{dp_{\rm T}^{\rm ave}} \right)^{-1}$$



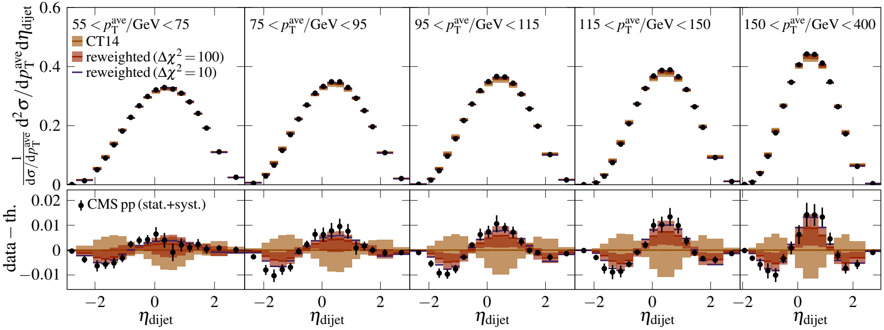
[EUR.PHYS.J.C 79 (2019) 6, 511]

- NLO QCD differs significantly from the data. **NNLO? Resummation due to smallish cone $R = 0.3$?**

Inclusive 5 TeV dijets

- A precision dijet observable by CMS [Phys.Rev.Lett. 121 (2018) 6, 062002]

$$\frac{d^2\sigma^{\rm pp}}{dp_{\rm T}^{\rm ave}\,d\eta_{\rm dijet}}\left(\frac{d\sigma^{\rm pp}}{dp_{\rm T}^{\rm ave}}\right)^{-1}$$

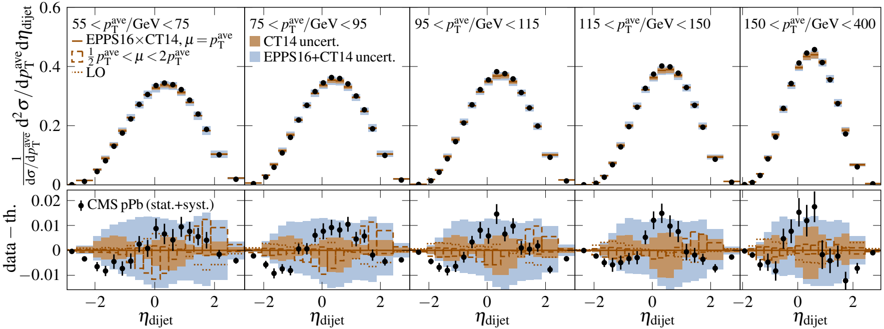


[Eur.Phys.J.C 79 (2019) 6, 511]

- Can improve (but not cure) the description by **refitting the proton PDFs** (reweighting/profiling)

- A precision dijet observable by CMS [Phys.Rev.Lett. 121 (2018) 6, 062002]

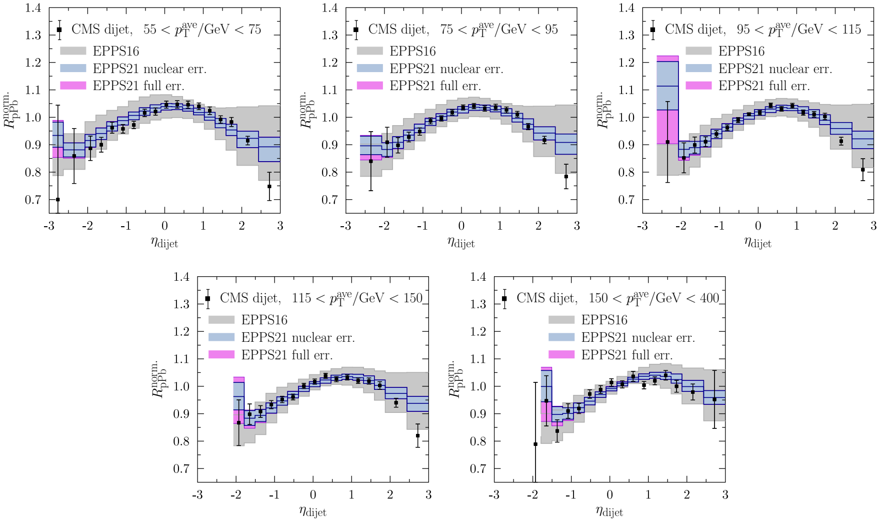
$$\frac{d^2\sigma^{\rm pPb}}{dp_{\rm T}^{\rm ave}d\eta_{\rm dijet}}\left(\frac{d\sigma^{\rm pPb}}{dp_{\rm T}^{\rm ave}}\right)^{-1}$$



[Eur.Phys.J.C 79 (2019) 6, 511]

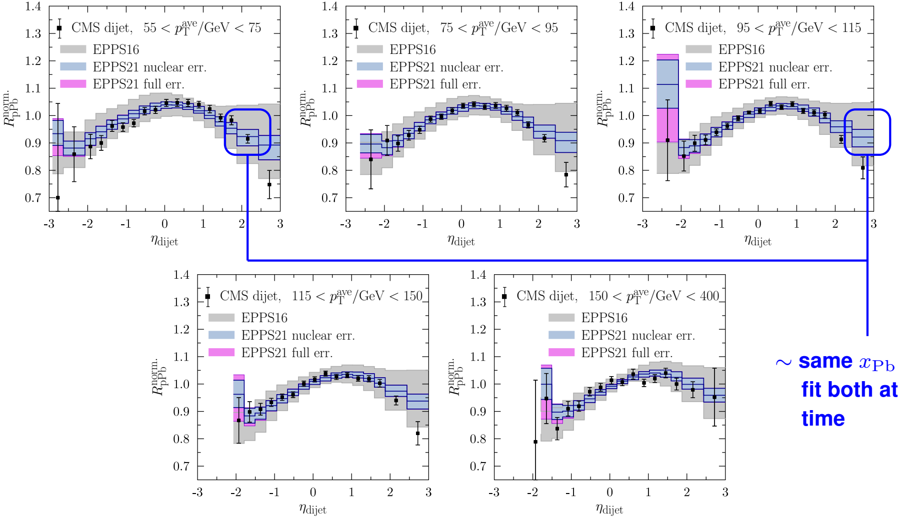
- The p-Pb data show similar differences w.r.t NLO calculation as p-p

Inclusive 5 TeV dijets



- EPPS21 and nNNPDF3.0 accommodate these data in the fits **except the most forward data points**

Inclusive 5 TeV dijets

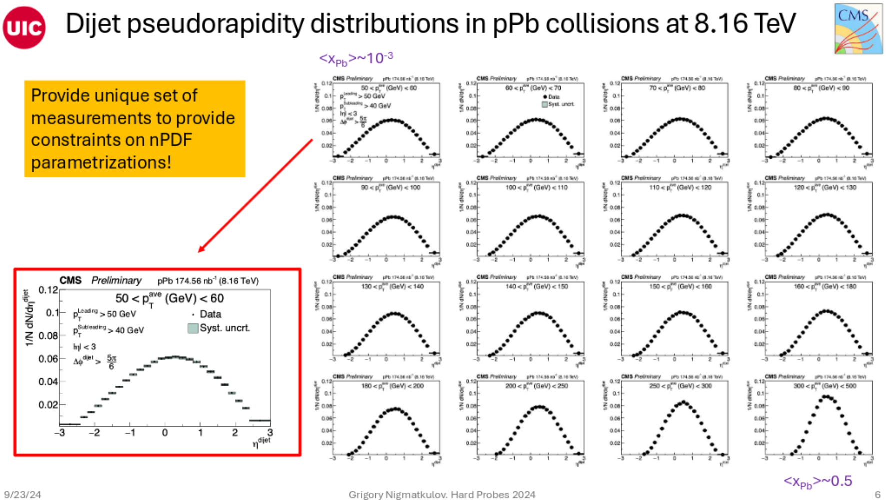


∼ same x_{Pb} – can't fit both at the same time

- EPPS21 and nNNPDF3.0 accommodate these data in the fits **except the most forward data points**

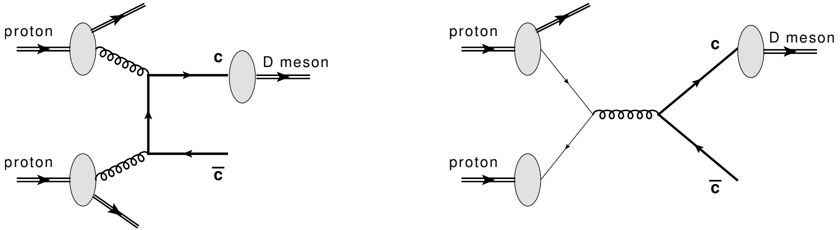
Inclusive 5 TeV dijets

- The $8\,\mathrm{TeV}$ CMS measurement on the way [Nigmatkulov, Hard Probes'24']



Open heavy-flavour

- Open heavy flavour in p-Pb collisions used in EPPS, nCTEQ and nNNPDF global fits



- Differing theoretical setups:

  - Fixed-order + Pythia parton shower [Frixione et.al. JHEP 0709, 126] – **Used in nNNPDF fits**

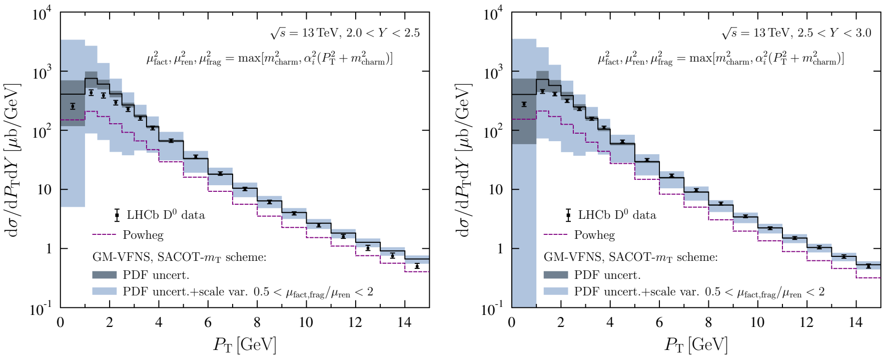
  - General-mass variable-flavour-number scheme (GM-VFNS) – **Used in EPPS fits**
    [Kniehl et.al PRD71, 014018; Helenius, Paukkunen, JHEP 1805 (2018) 196]

  - Matrix-element fitting [Lansberg, Shao, Eur.Phys.J.C 77 (2017) 1, 1] – **Used in nCTEQ fits**

Open heavy-flavour in GM-VFNS – comparison with the LHCb 13 TeV D^0 p-p data

- LHCb p-p cross sections well reproduced by the GM-VFNS approach (SACOT-m_T scheme)

Helenius, Paukkunen, JHEP 1805 (2018) 196



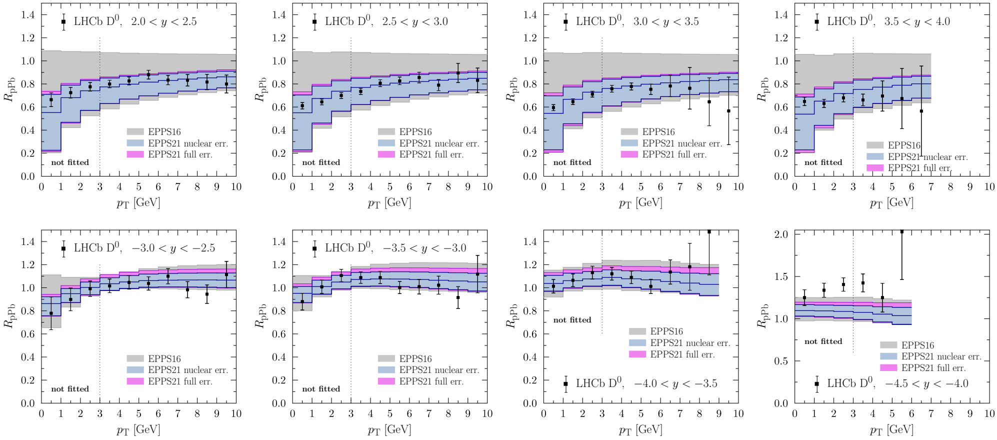
PDF = NNPDF3.1NLO (pch)
FF = KKKS08

- Sizable theory uncertainties at low p_T – nearly all cancel in σ_{pPb}/σ_{pp} for $p_T > 3\,\text{GeV}$

[Eskola et.al. JHEP 05 (2020) 037]

Open heavy-flavour in GM-VFNS – comparison with the LHCb 5 TeV D^0 p-Pb data

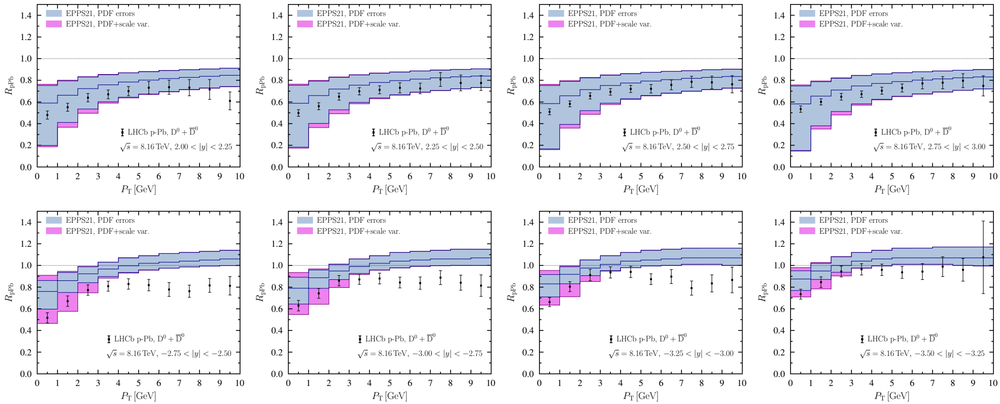
- In EPPS21 we fitted to LHCb 5 TeV D^0 p-Pb data [LHCb coll., JHEP 10 (2017) 090]



- Good fit across a wide range of kinematics – no tensions with the dijets

Open heavy-flavour in GM-VFNS – comparison with the LHCb 8 TeV D^0 p-Pb data

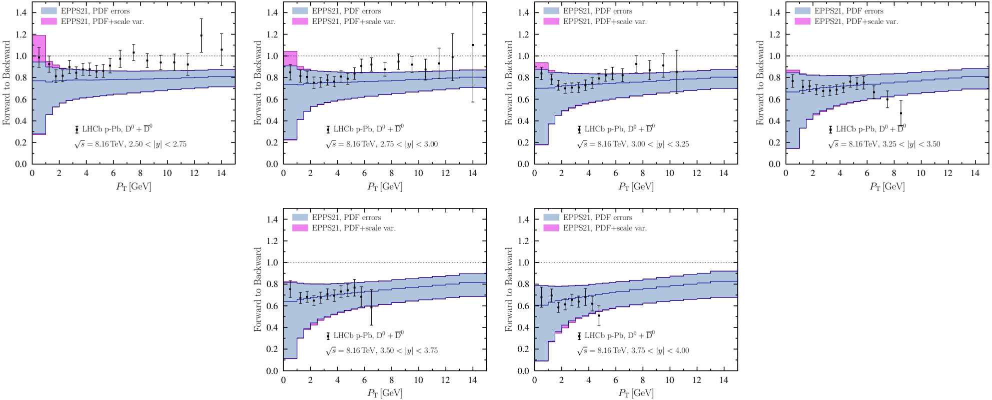
- LHCb 8 TeV D^0 p-Pb data [LHCb coll., PRL 131 (2023) 10, 102301] contradicts in the backward direction



- No nuclear PDF can fit the 5 TeV and 8 TeV data simultaneously at $y < 0$

Open heavy-flavour in GM-VFNS – comparison with the LHCb 8 TeV D^0 p-Pb data

- The 8 TeV p-p reference data interpolated – check the forward-to-backward ratio

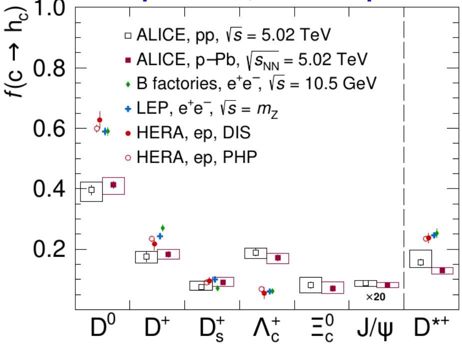


- The data prefer a stronger $\sqrt{s}$ dependence – in the backward direction in particular

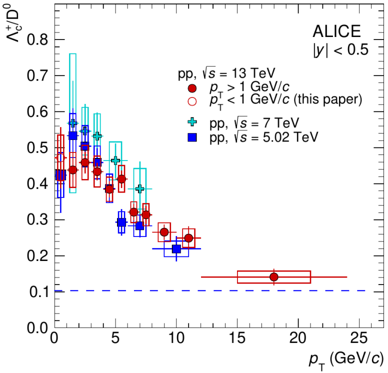
Can we use heavy flavour in p-Pb to constrain nuclear PDFs?

- Evidence of enhanced baryon yields low p_T vs. LEP/HERA

[ALICE COLL, 2405.14571]



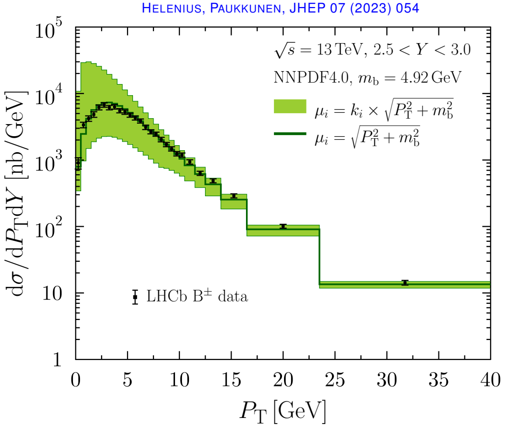
[ALICE COLL, JHEP 12 (2023) 086]

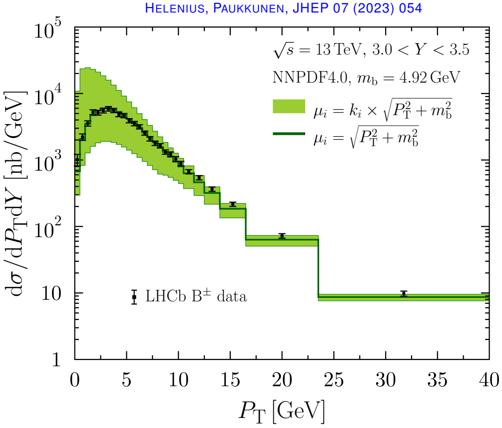


- Could categorize this as a higher-twist effect in baryon production?
- If yes, why isn't it enhanced in p-Pb vs. p-p?

GMVFNS CALCULATION WOULD BE A NEARLY CONSTANT CURVE

- Absolute p-p cross sections vs. GM-VFNS (SACOT-$m_{\rm T}$ scheme)



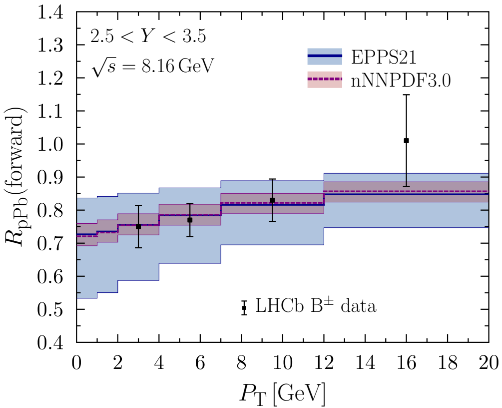


- The p-p baseline well reproduced within the uncertainties

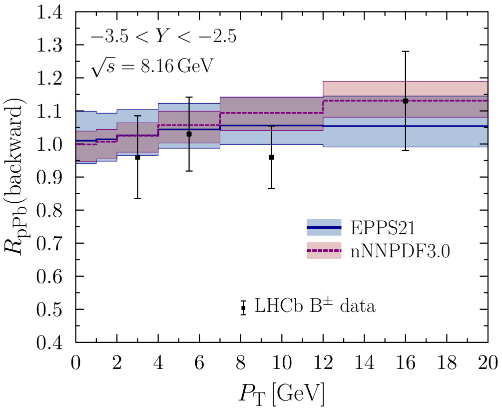
LHCb 8 TeV B-meson data [Phys. Rev. D99 052011 (2019)] $\sigma_{\rm pPb}/\sigma_{\rm pp}$

- Nuclear modifications

Helenius, Paukkunen, JHEP 07 (2023) 054



Helenius, Paukkunen, JHEP 07 (2023) 054



- No similar discrepancy as in the case of $8\,\mathrm{TeV}$ D mesons
- More data for e.g. $\mathrm{B} \rightarrow J/\psi$ decay channel – not yet implemented in our setup

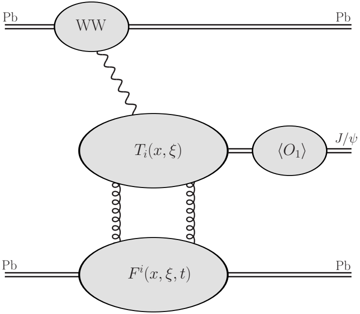
Nuclear PDFs from exclusive J/ψ production in ultraperipheral Pb-Pb?

- Exclusive J/ψ production very sensitive to nuclear (generalized) PDFs

WEIZÄCKER-WILLIAMS PHOTON FLUX

PHOTOPRODUCTION CROSS SECTION

$$\frac{d\sigma}{dy} = \left[k \frac{N_\gamma^{\mathrm{Pb}}(k)}{dk} \sigma^{\gamma(k)\mathrm{Pb}\to J/\psi \mathrm{Pb}} \right]_{k=Me^{y}/2} + \left[k \frac{N_\gamma^{\mathrm{Pb}}(k)}{dk} \sigma^{\mathrm{Pb}\gamma(k)\to J/\psi \mathrm{Pb}} \right]_{k=Me^{-y}/2}$$



- The PDFs enter at the level of matrix element

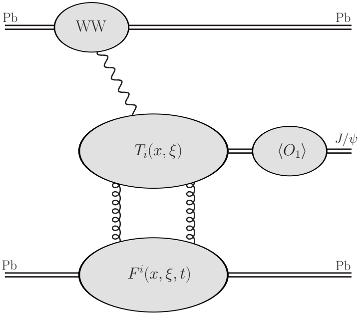
$$\mathcal{M}^{\gamma A \to J/\psi A} \sim f^A_{\mathrm{gluon}}(\mu) \otimes T_g(\mu) + f^A_{\mathrm{quark}}(\mu) \otimes T_q(\mu)$$

- Quadratic dependence of PDFs at the level of cross section

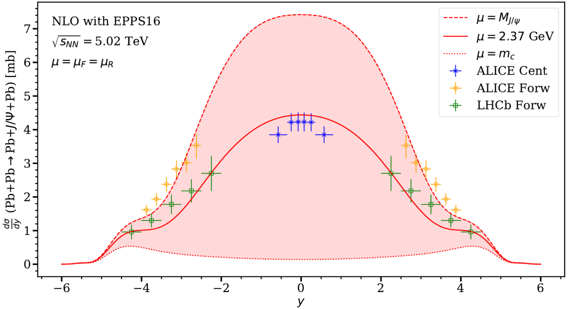
Nuclear PDFs from exclusive J/ψ production in Pb-Pb?

- Significantly large scale dependence still at NLO

$$\mathcal{M}^{\gamma A \to J/\psi A} \sim f^A_{\rm gluon}(\mu) \otimes T_g(\mu) + f^A_{\rm quark}(\mu) \otimes T_q(\mu)$$



[Eskola et.al., Phys.Rev.C 106 3, 035202 + Phys.Rev.C 107 4, 044912]



- Need to implement resummation of $\log(1/x)$ terms to bring the calculation under a better control?

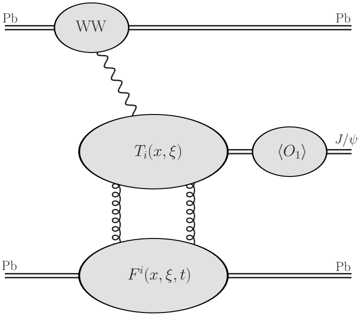
  [Flett et.al., Phys.Lett.B 859 (2024) 139117]

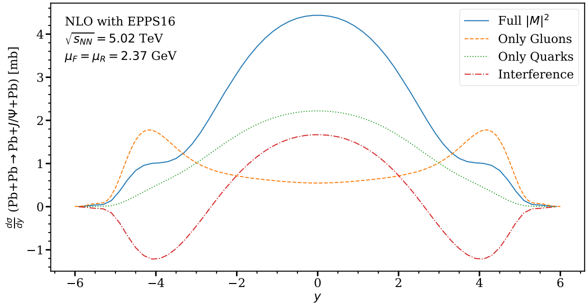
- Significantly large scale dependence still at NLO

quarks enter at NLO

$$\mathcal{M}^{\gamma A \to J/\psi A} \sim f^A_{\rm gluon}(\mu) \otimes T_g(\mu) + f^A_{\rm quark}(\mu) \otimes T_q(\mu)$$

[Eskola et.al., Phys.Rev.C 106 3, 035202 + Phys.Rev.C 107 4, 044912]





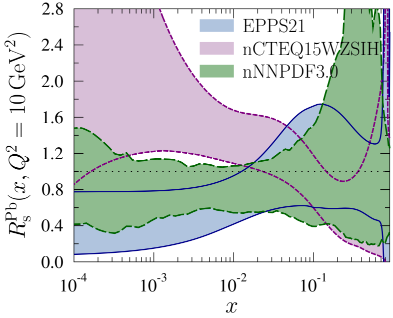
- Perturbatively unstable: only gluons at LO – quarks dominate at NLO

Nuclear PDFs from exclusive J/ψ production in Pb-Pb?

- Significantly large scale dependence still at NLO

quarks enter at NLO

$$\mathcal{M}^{\gamma A \to J/\psi A} \sim f^{A}_{\text{gluon}}(\mu) \otimes T_g(\mu) + f^{A}_{\text{quark}}(\mu) \otimes T_q(\mu)$$



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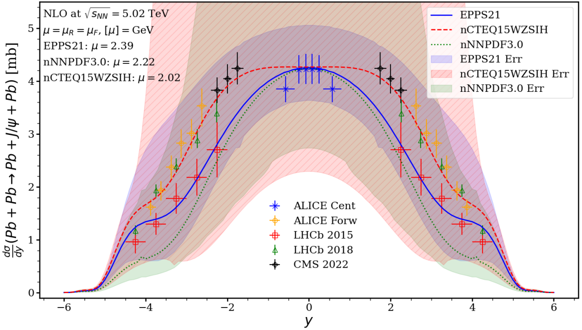
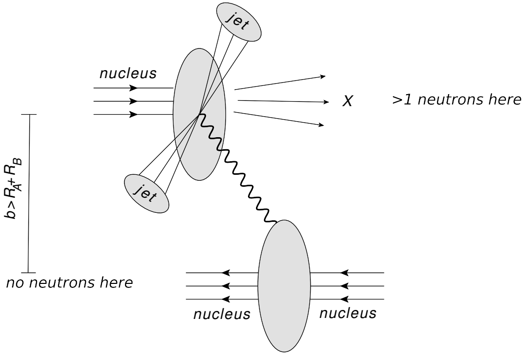


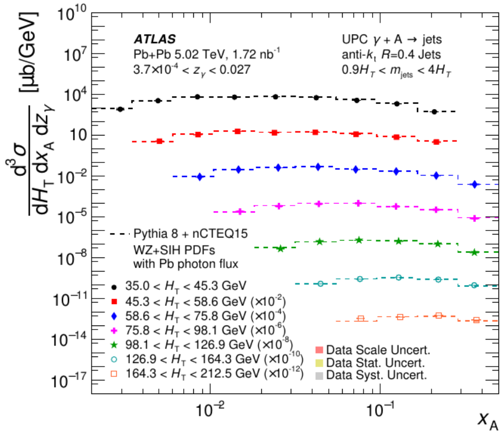
- nCTEQ15WZSIH reproduces the shape due to its hugely enhanced **strange-quark PDFs!**

Nuclear PDFs from dijets in ultraperipheral Pb-Pb collisions?

- Photoproduction of dijets potentially a good constraint on nuclear PDFs



[ATLAS Coll., 2409.11060]



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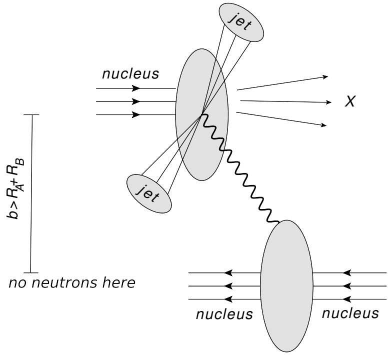
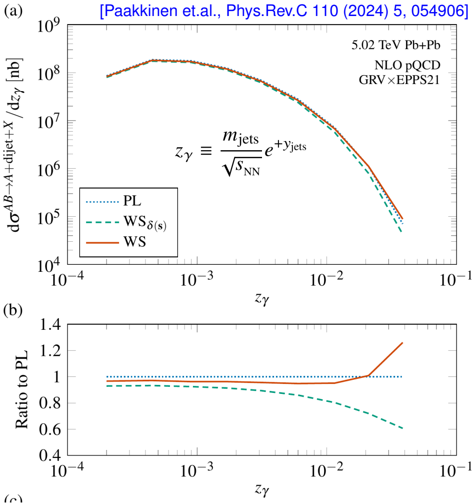
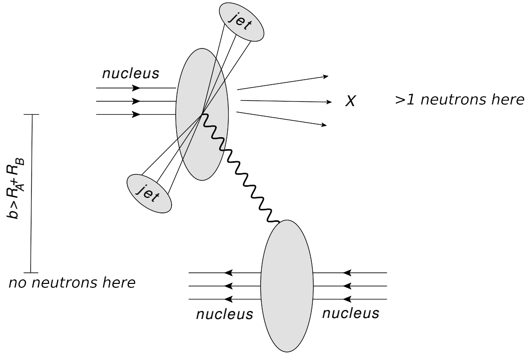




- Nuclei in UPCs often approximated as point-like (PL) objects – not always the most optimal approximation

Nuclear PDFs from dijets in ultraperipheral Pb-Pb collisions?

- Photoproduction of dijets potentially a good constraint on nuclear PDFs



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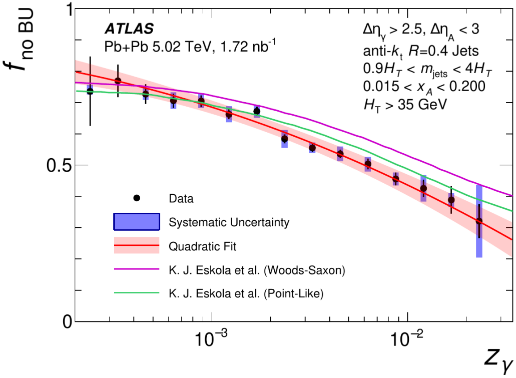


- The neutron-class selection introduces additional modeling uncertainty

The fraction of events in which the photon-emitting nucleus didn't break up

Dimuon production in neutrino DIS [Helenius, Paukkunen, Yrjänheikki, JHEP 09 (2024) 043]

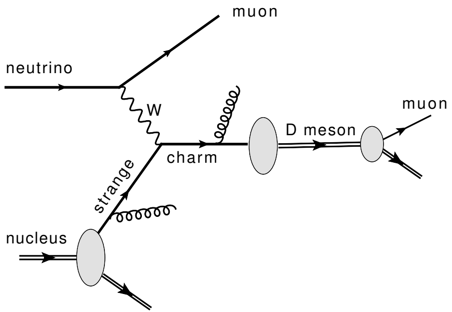
- Dimuon production in νA collisions is an essential strange-quark constraint in fits of proton PDFs

- The usual practice:

$$\frac{d^2\sigma(\nu A \to \mu^-\mu^+ X)}{dxdy} \approx \frac{d^2\sigma(\nu A \to \mu^- c X)}{dxdy} \times \mathcal{A} \times \mathcal{B}_\mu$$

$\mathcal{A}$ = acceptance correction given by the experiment to account for the cut $E_\mu > E_\mu^{\min}$

$\mathcal{B}_\mu$ = average branching fraction from PDG

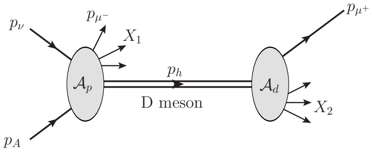


- **Potential prolem:** the acceptance correction $\mathcal{A}$ also depends on the PDFs, the α_s order of the calculation, and heavy-quark scheme

- Assuming the cross section is of the Breit-Wigner form

$$\sigma(\nu A \to \mu^- \mu^+ X) = \frac{1}{2s} \sum_h \int d\Pi(p_{\mu^+}) d\Pi(p_{\mu^-}) d\Pi(p_{X_1}) d\Pi(p_{X_2})$$

$$(2\pi)^4 \delta^{(4)} \left(p_\nu + p_A - p_{\mu^-} - p_{\mu^+} - p_{X_1} - p_{X_2}\right) \times \frac{|\mathcal{A}_p|^2 |\mathcal{A}_d|^2}{(p_h^2 - m_h^2)^2 + m_h^2 \Gamma_{\rm tot}^2}$$



it follows that

$$\frac{d^2\sigma(\nu A \to \mu^- \mu^+ X)}{dxdy} = \sum_h \int dz \frac{d^3\sigma(\nu A \to \mu^- h X_1)}{dxdydz} B_{h\to\mu} \left(E_h = zyE_\nu, E_\mu^{\rm min}\right)$$

where $B_{h\to\mu}$ is an energy-dependent branching fraction

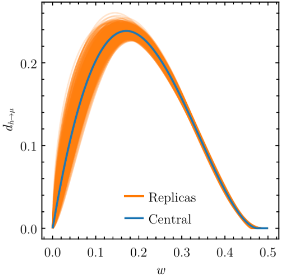
$$B_{h\to\mu} \left(E_h, E_\mu^{\rm min}\right) = \frac{1}{\Gamma_{\rm tot}} \int d^3p_\mu \frac{d^3\Gamma_{h\to\mu}}{d^3p_\mu}\Big|_{E_\mu > E_\mu^{\rm min}}$$

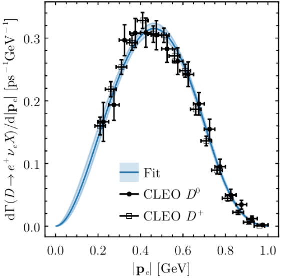
- Generic form of the decay width dictated by the Lorentz invariance

$$\frac{d^3\Gamma_{h\to\mu}}{d^3p_\mu} = \frac{d_{h\to\mu}(w)}{2m_h E_\mu}, \quad w = \frac{p_\mu \cdot p_h}{m_h^2}$$

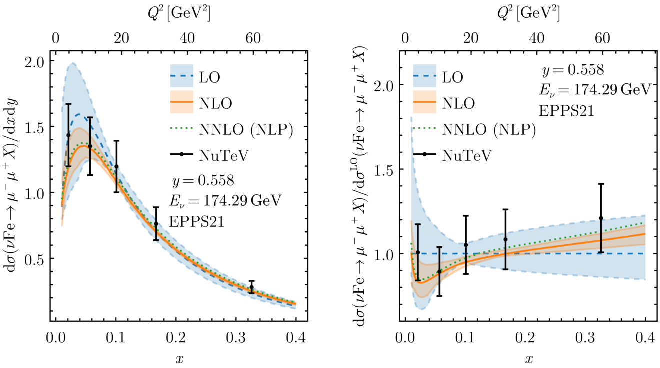
- The **decay function** $d_{h\to\mu}(w)$ encodes the weak decay – fitted to CLEO e^+e^- data

$$d_{h\to\mu}(w) = N w^\alpha (1-\gamma w)^\beta$$





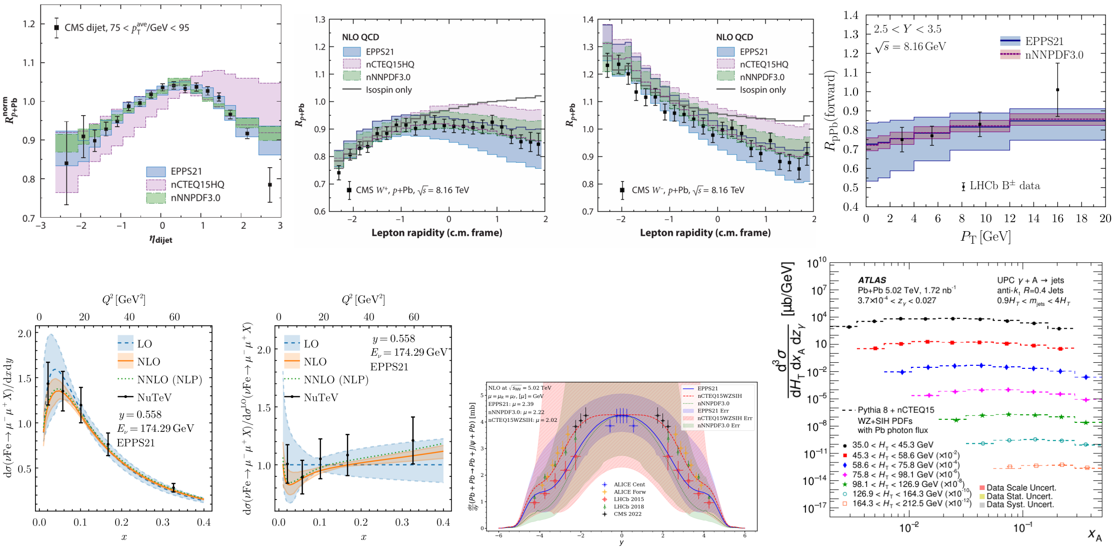
- SIDIS cross section at NLO with leading “kinematic” mass corrections
  – NNLO (NLP) = next-to-leading power NNLO corrections



- Working on the full mass dependence + including further known NNLO corrections

$\Longrightarrow$ eventually study the constraints within the EPPS global fits

Summary



CMS dijet, 75 < p_T^{ave}/GeV < 95
R_{p+Pb}^{norm}
η_{dijet}
EPPS21
nCTEQ15HQ
nNNPDF3.0
NLO QCD
Isospin only
CMS W^+, p+Pb, $\sqrt{s}$ = 8.16 TeV
CMS W^-, p+Pb, $\sqrt{s}$ = 8.16 TeV
R_{p+Pb}
Lepton rapidity (c.m. frame)
$2.5 < Y < 3.5$
$\sqrt{s} = 8.16$ GeV
LHCb B$^\pm$ data
R_{pPb}(forward)
P_T [GeV]
Q^2 [GeV^2]
LO
NLO
NNLO (NLP)
NuTeV
$y = 0.558$
$E_\nu = 174.29$ GeV
$d\sigma(\nu Fe \to \mu^- \mu^+ X)/dxdy$
$d\sigma(\nu Fe \to \mu^- \mu^+ X)/d\sigma^{LO}(\nu Fe \to \mu^- \mu^+ X)$
x
NLO at $\sqrt{s_{NN}} = 5.02$ TeV
EPPS21
nCTEQ15WZSIH
nNNPDF3.0
EPPS21 Err
nCTEQ15WZSIH Err
nNNPDF3.0 Err
ALICE Cent
ALICE Forw
LHCb 2015
LHCb 2018
CMS 2022
y
ATLAS
Pb+Pb 5.02 TeV, 1.72 nb^{-1}
$3.7\times10^{-4} < z_\gamma < 0.027$
UPC $\gamma + A \to$ jets
anti-k_t R=0.4 Jets
$0.9H_T < m_{jets} < 4H_T$
Pythia 8 + nCTEQ15
WZ+SIH PDFs
with Pb photon flux
$35.0 < H_T < 45.3$ GeV
$45.3 < H_T < 58.6$ GeV ($\times10^{-2}$)
$58.6 < H_T < 75.8$ GeV ($\times10^{-4}$)
$75.8 < H_T < 98.1$ GeV ($\times10^{-6}$)
$98.1 < H_T < 126.9$ GeV ($\times10^{-8}$)
$126.9 < H_T < 164.3$ GeV ($\times10^{-10}$)
$164.3 < H_T < 212.5$ GeV ($\times10^{-12}$)
Data Scale Uncert.
Data Stat. Uncert.
Data Syst. Uncert.
$\frac{d^3\sigma}{dH_T dx_A dz_\gamma}$ [μb/GeV]
x_A