

Nuclear PDFs Today

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**HARD
PROBES
2018**

Outline

State of the art 2018

New constraints from the LHC

On the case for lighter-than-lead ions

Summary

State of the art 2018

Available nPDF parametrizations in 2018

	EPS09	DSSZ12	KA15	NCTEQ15	EPPS16
Order in α_s	NLO	NLO	NNLO	NLO	NLO
DIS in $\ell^- + A$	✓	✓	✓	✓	✓
Drell-Yan in p+A	✓	✓	✓	✓	✓
RHIC pions d+Au	✓	✓		✓	✓
Neutrino-nucleus DIS		✓			✓
Drell-Yan in $\pi + A$					✓
LHC p+Pb dijets					✓
LHC p+Pb W, Z					✓
Q cut in DIS	1.3 GeV	1 GeV	1 GeV	2 GeV	1.3 GeV
datapoints	929	1579	1479	708	1811
free parameters	15	25	16	16	20
error analysis	Hessian	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	50	30	N.N	35	52
proton baseline PDFs	CTEQ6.1	MSTW2008	JR09	CTEQ6M-like	CT14NLO
Heavy-quark effects		✓		✓	✓
Flavour separation				partial	full
Reference	JHEP 0904 065	PR D85 074028	PR D93, 014026	PR D93 085037	EPJ C77 163

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Expect “soon”:

- Andrés-Zurita nPDFs (successor of DSSZ12) [<https://indico.cern.ch/event/639067/contributions/2642447/>]
- nPDFs in the NNPDF framework (Nikhef group) [PARALLEL TALK ON WED BY KHALEK]
- nPDFs in the XFitter approach (Tübingen group)

IIUC parameters	α_s	α_s	α_s	α_s	α_s
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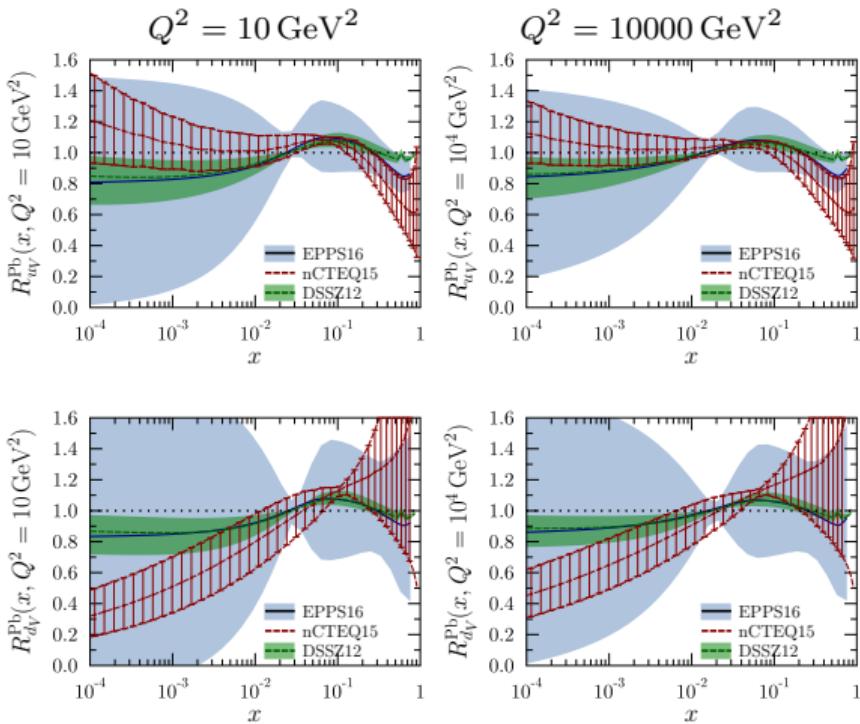
Valence-quark modifications $R_i^{\text{Pb}} = f_i^{\text{p,Pb}} / f_i^{\text{p}}$

- In EPPS16 and nCTEQ15 R_{u_V} and R_{d_V} were free
- In EPPS16 R_{u_V} and R_{d_V} mutually very similar
- In nCTEQ15 behaviour quite different

The key differences are that EPPS16 uses

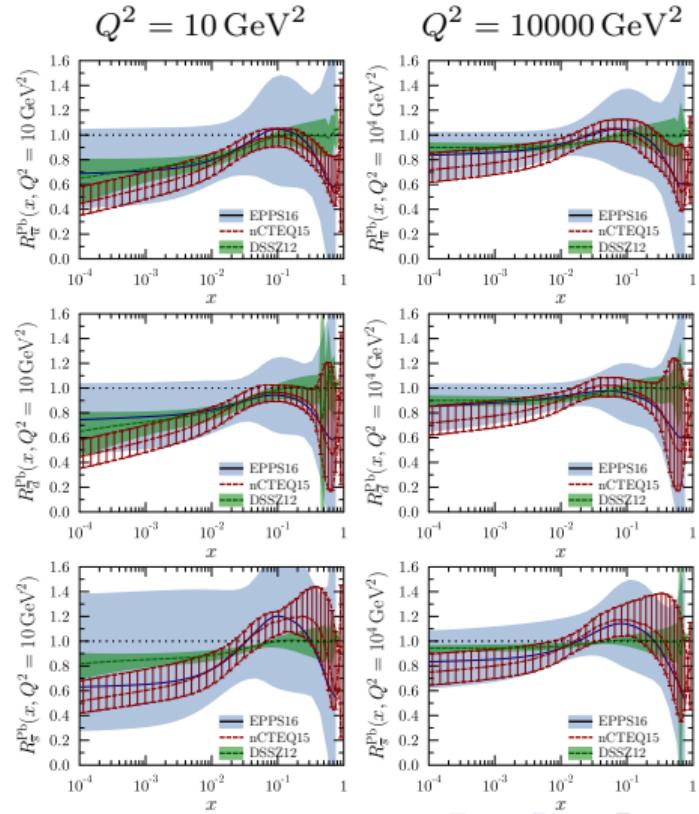
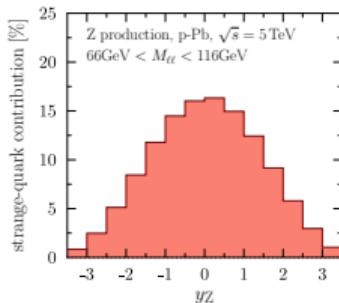
- $\nu + \text{Pb}$ DIS data
- non-isocalar $\ell^- + \text{A}$ DIS data

- No flavour freedom in DSSZ, so R_{u_V} and R_{d_V} almost identical with very small uncertainty



Sea-quark modifications $R_i^{\text{Pb}} = f_i^{\text{p,Pb}} / f_i^{\text{p}}$

- In EPPS16 $R_{\bar{u}}$, $R_{\bar{d}}$ and $R_{\bar{s}}$ were free
- In nCTEQ15 and DSSZ no flavour freedom for the sea quarks
 - ⇒ Larger uncertainties in EPPS16 but less bias
- The constraints for strange quarks only scarce
 - e.g. the contribution of s quarks on the Z production ($s\bar{s}$ channel) is $\sim 17\%$ the highest



Gluon modification $R_g^{\text{Pb}} = f_g^{\text{p,Pb}} / f_g^{\text{p}}$

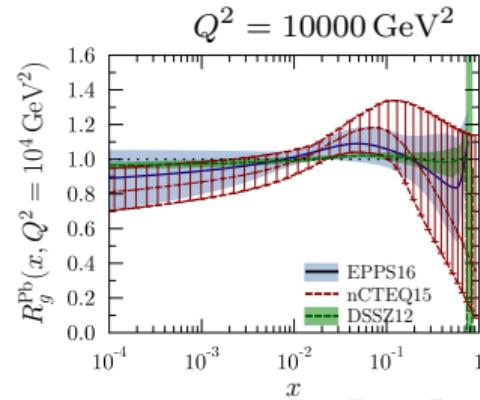
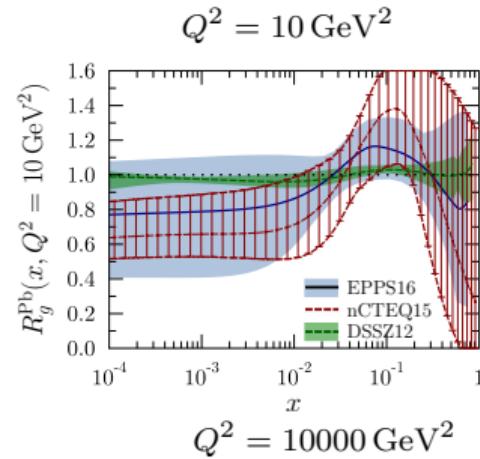
- At high x , larger uncertainty in nCTEQ15 than in EPPS16

The key differences are

- EPPS16 uses CMS dijet data
- different cuts:

$$Q_{\min}^2 = 4.00 \text{ GeV}^2 \text{ for nCTEQ15,}$$
$$Q_{\min}^2 = 1.69 \text{ GeV}^2 \text{ for EPPS16}$$

- At low x the functional form of nCTEQ15 is probably a bit more restrictive \Rightarrow smaller errors
- DSSZ pushed nuclear modifications to fragmentation functions when fitting RHIC pion data \Rightarrow almost no effects in gluons



On the parametrizations

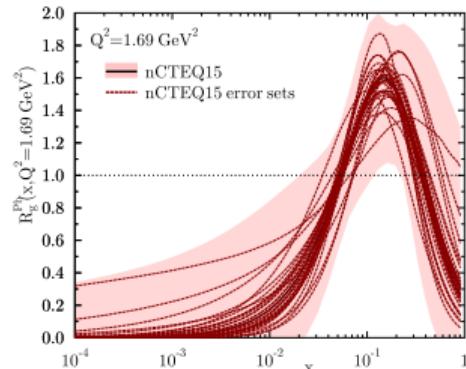
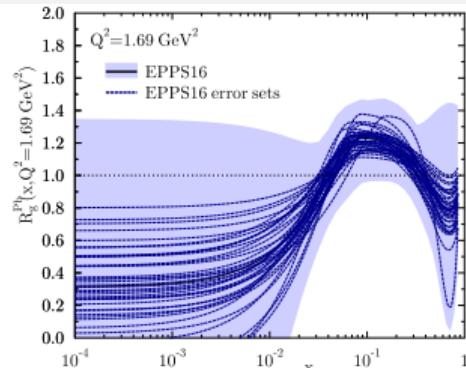
- The fit functions in EPPS16 & nCTEQ15:

$$R^{\text{EPS09}}(x) = \begin{cases} a_0 + a_1(x - x_a)^2 & x \leq x_a \\ b_0 + b_1x^\alpha + b_2x^{2\alpha} + b_3x^{3\alpha} & x_a \leq x \leq x_e \\ c_0 + (c_1 - c_2x)(1-x)^{-\beta} & x_e \leq x \leq 1 \end{cases}$$

$$R^{\text{nCTEQ15}}(x) = [c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1+e^{c_4 x})^{c_5}] / f^p(x)$$

+ assumptions for the A -dependence

- Very little freedom for e.g. the small- x behaviour — both do underestimate the “true” uncertainties [ASCHENAUER ET.AL. PRD96, 114005; PAUKKUNEN, PoS DIS2017, 109]
- The difficulty is in finding an ansatz which is both **flexible** in x and has a **physically reasonable** A -dependence
— more difficult than the free proton case



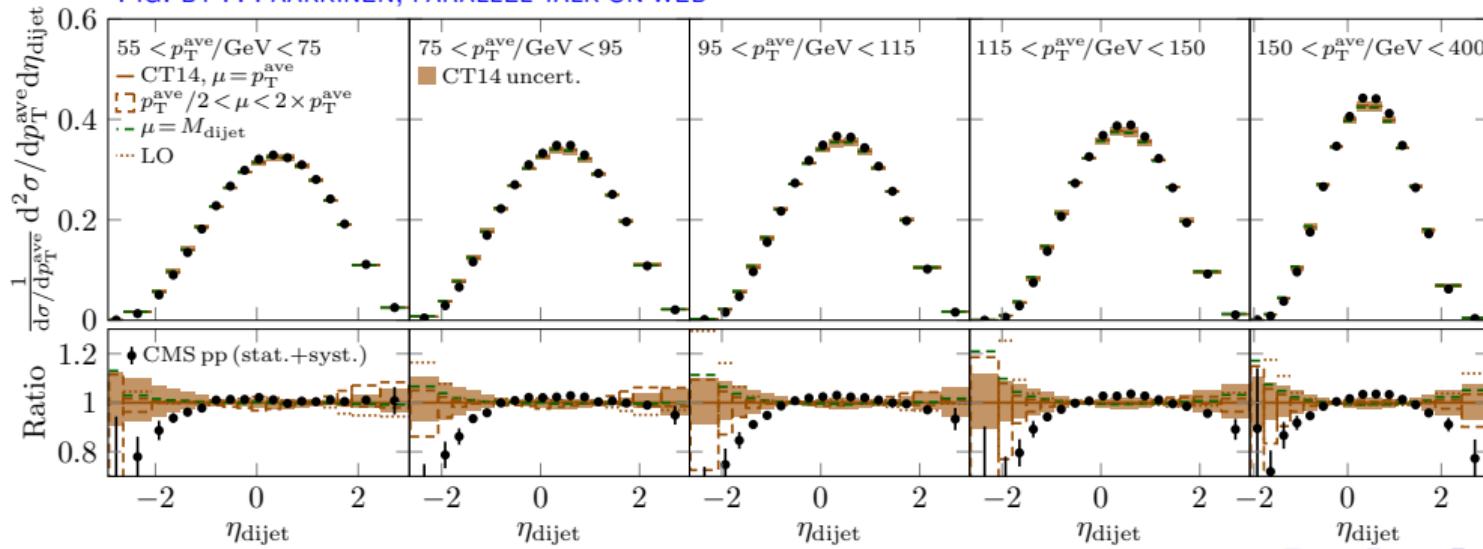
New constraints from the LHC

New constraints from the LHC: dijets

- The CMS 5 TeV dijet data [PRL 121, 062002] in **p-p collisions** not well reproduced by the current NLO PDFs

$$\frac{d\sigma^{\text{PP}}(\eta, p_T^{\text{average}})}{\int d\sigma^{\text{PP}}(\eta, p_T^{\text{average}}) d\eta}$$

FIG. BY P. PAAKKINEN, PARALLEL TALK ON WED

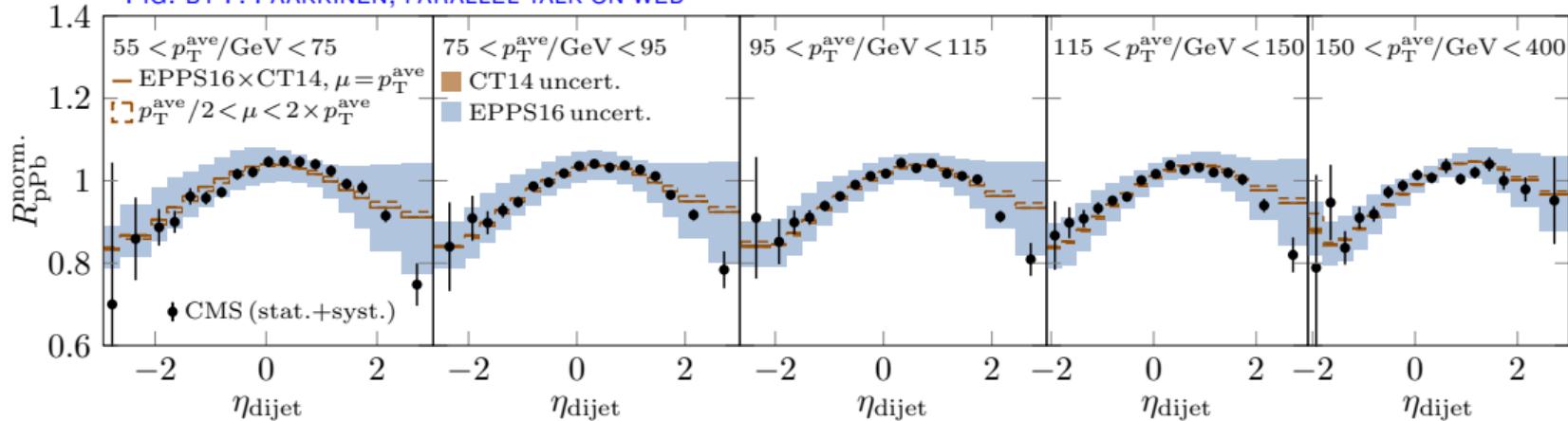


New constraints from the LHC: dijets

- The same problem in **p-Pb case** — the ratio in line with NLO predictions using EPPS16

$$\frac{d\sigma^{\text{pPb}}(\eta, p_T^{\text{average}})}{\int d\sigma^{\text{pPb}}(\eta, p_T^{\text{average}})d\eta} / \frac{d\sigma^{\text{pp}}(\eta, p_T^{\text{average}})}{\int d\sigma^{\text{pp}}(\eta, p_T^{\text{average}})d\eta}$$

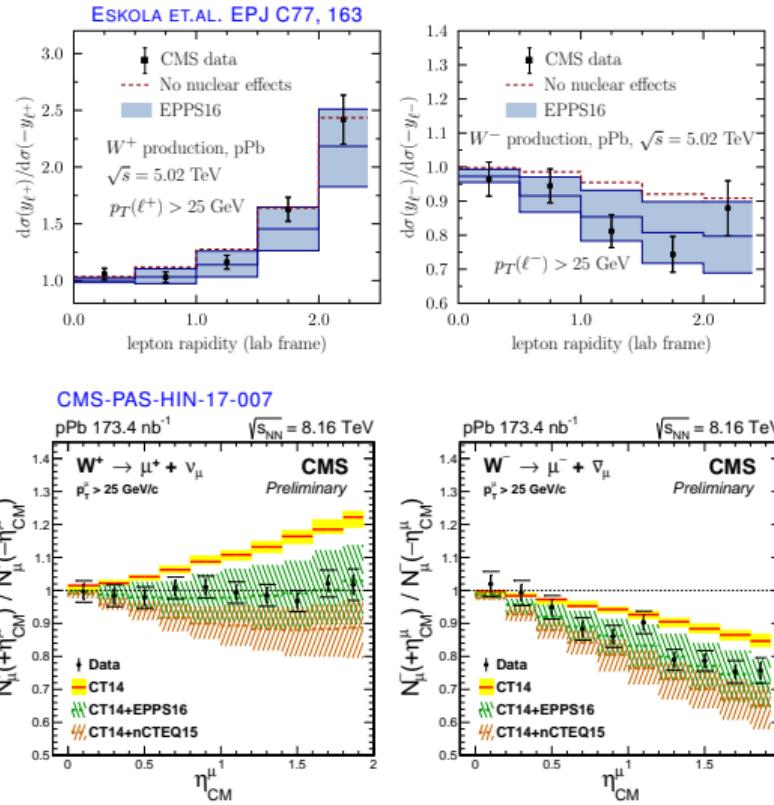
FIG. BY P. PAAKKINEN, PARALLEL TALK ON WED



- Promises a **major impact** on the nuclear gluons — hint of a stronger shadowing?

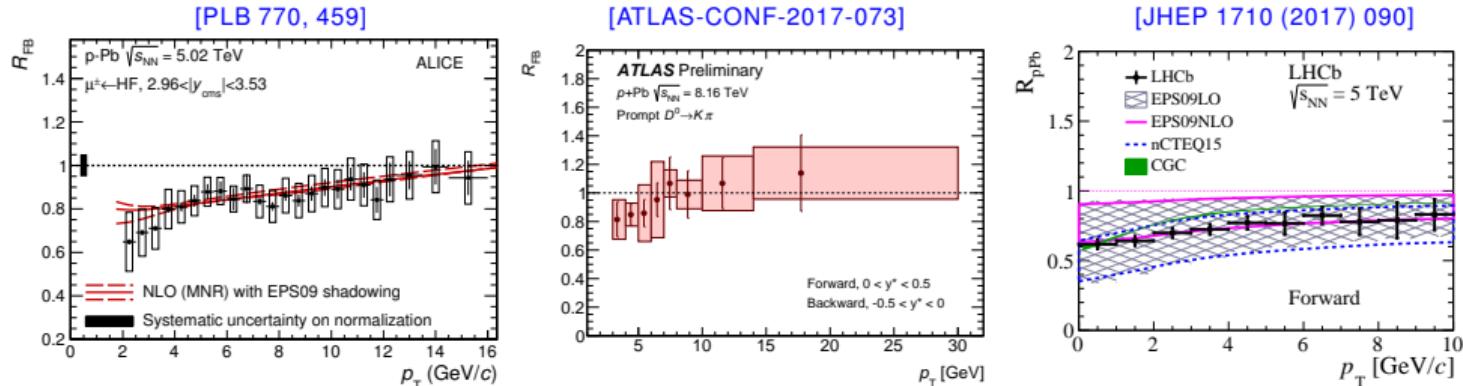
New constraints from the LHC: W^\pm/Z measurements

- The 5 TeV W^\pm data used in EPPS16 had still relatively little impact for their small statistical weight
- The new 8.16 TeV W^\pm data [CMS-PAS-HIN-17-007] significantly more precise.
- Would expect a similar increase in precision for Z bosons
- The p_T distributions of Z and W^\pm are in principle excellent probes, but also vulnerable to resummation
[BRANDT ET.AL. NPA 927, 78 ; GUZEY ET.AL. EPJ A49, 35]



New constraints from the LHC: open heavy flavour

- The D (and B) mesons as PDF constraints under intense investigation in p-p and p-Pb
[GAULD, Rojo, PRL 118, 072001 ; PROSA, EPJ C75, 396 ; KUSINA ET.AL. PRL 121,052004]
- Recent $R_{p\text{Pb}}$ data from LHCb show rather **compelling evidence** of small- x shadowing.

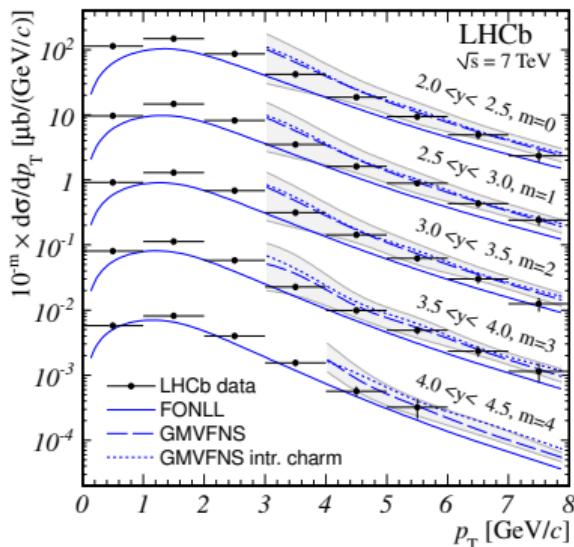


- The challenge here is in the theoretical treatment. Several frameworks, including
 - FONLL + phenomenological fragmentation functions
 - Powheg + Pythia shower & hadronization
 - General-mass variable flavour number scheme (GM-VFNS) [PAUKKUNEN, PARALLEL TALK ON WED]

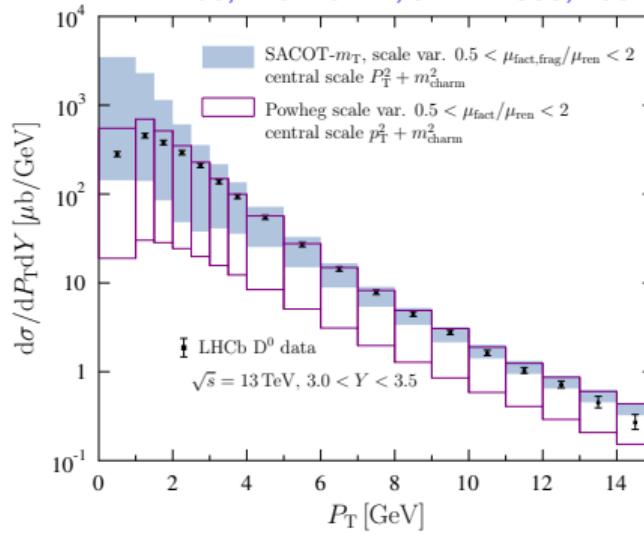
New constraints from the LHC: open heavy flavour

- On the level of absolute spectra, FONLL and Powheg tend to **underpredict** the LHCb p-p spectra — still within the large scale uncertainties, though
- GM-VFNS [Kniehl et.al. PRD71, 014018 ; Helenius, Paukkunen, JHEP 1805, 196] consistent with the data — smaller scale uncertainty at large p_T than in FONLL

FIG. FROM NP B871, 1



HELENIUS, PAUKKUNEN, JHEP 1805, 196



New constraints from the LHC: open heavy flavour

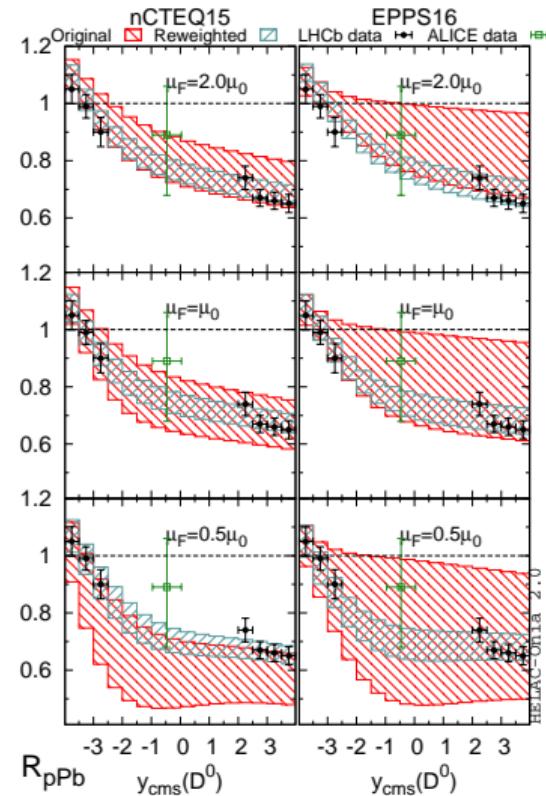
- A method introduced in [LANSBERG, SHAO, EPJ C77, 1] and later on applied in [KUSINA ET.AL., PRL 121,052004]:

$$\frac{d\sigma^{a+b}(D^0)}{dP_T dY} = f_g^a(x_1, Q_f^2) \otimes d\sigma_{gg}^{D^0}(Q_f^2, Q_r^2) \otimes f_g^b(x_2, Q_f^2)$$

Fit the coefficient functions to p-p data with

$$|\mathcal{M}_{gg \rightarrow D^0 + X}|^2 = x_1 x_2 \times F(\sqrt{s}, P_T)$$

- Only gluon-gluon channel and assumes $2 \rightarrow 2$ kinematics



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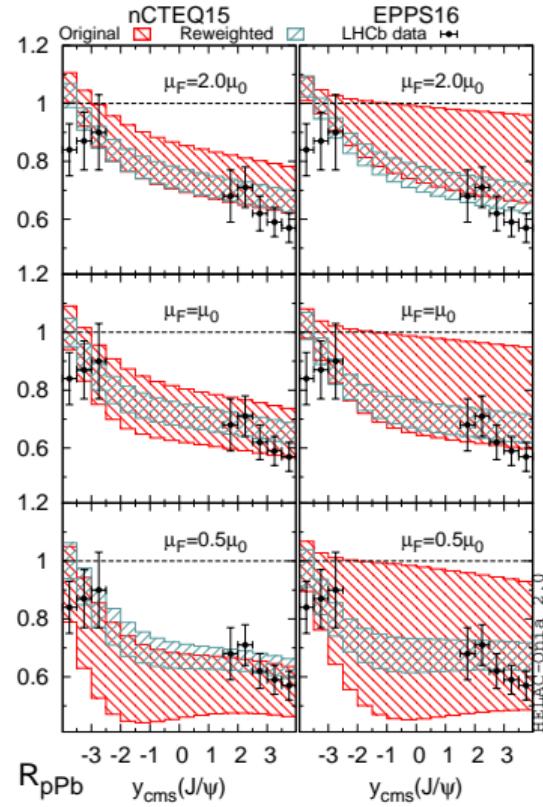
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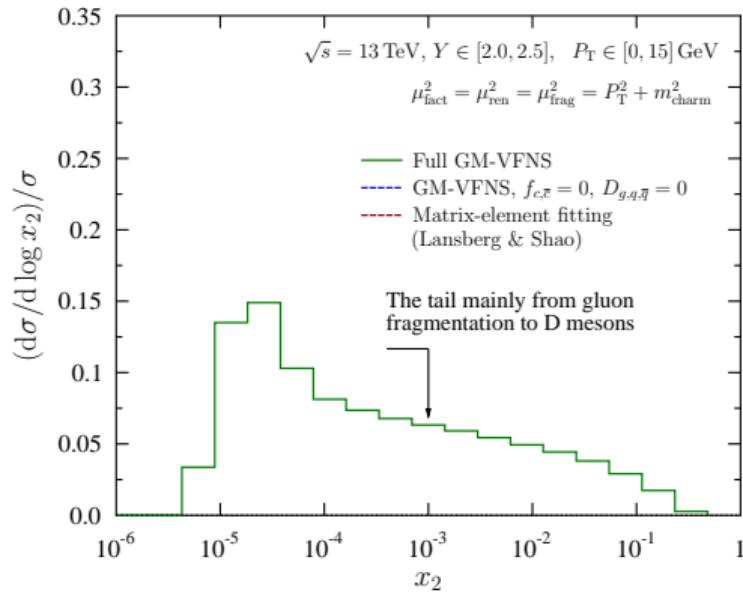
- Only gluon-gluon channel and assumes $2 \rightarrow 2$ kinematics
- Also applied e.g. to prompt J/ψ
 - Consistent description of R_{pPb} with nPDF-effects-only hypothesis (no need for energy loss)



New constraints from the LHC: open heavy flavour

- Typical x_2 distributions for D^0 at $Y \gg 0$, $\sqrt{s} = 13$ TeV: GM-VFNS vs. matrix-element fitting

FIG. ADAPTED FROM HELENIUS, PAUKKUNEN, JHEP 1805, 196

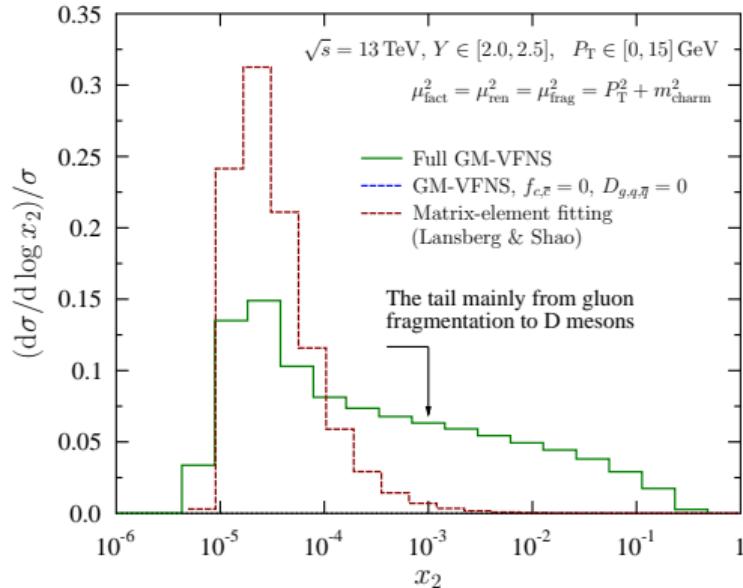


- Significant contribution from the large- x region in full GM-VFNS

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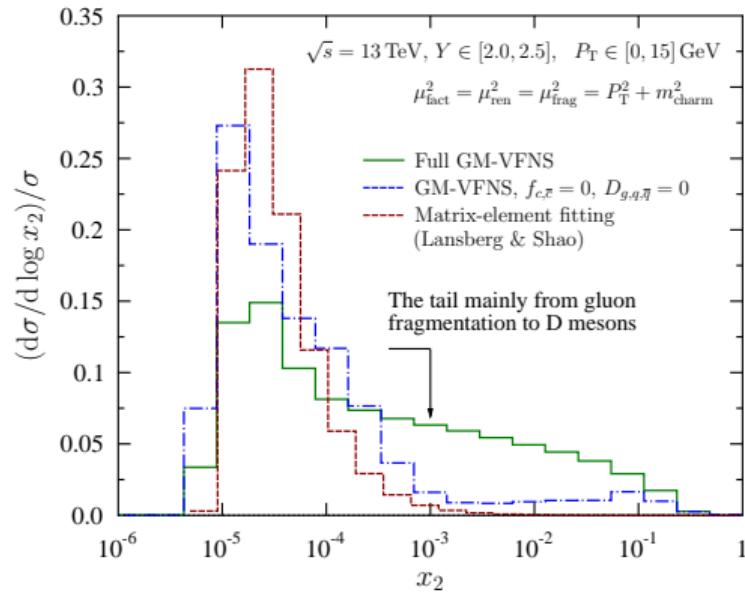


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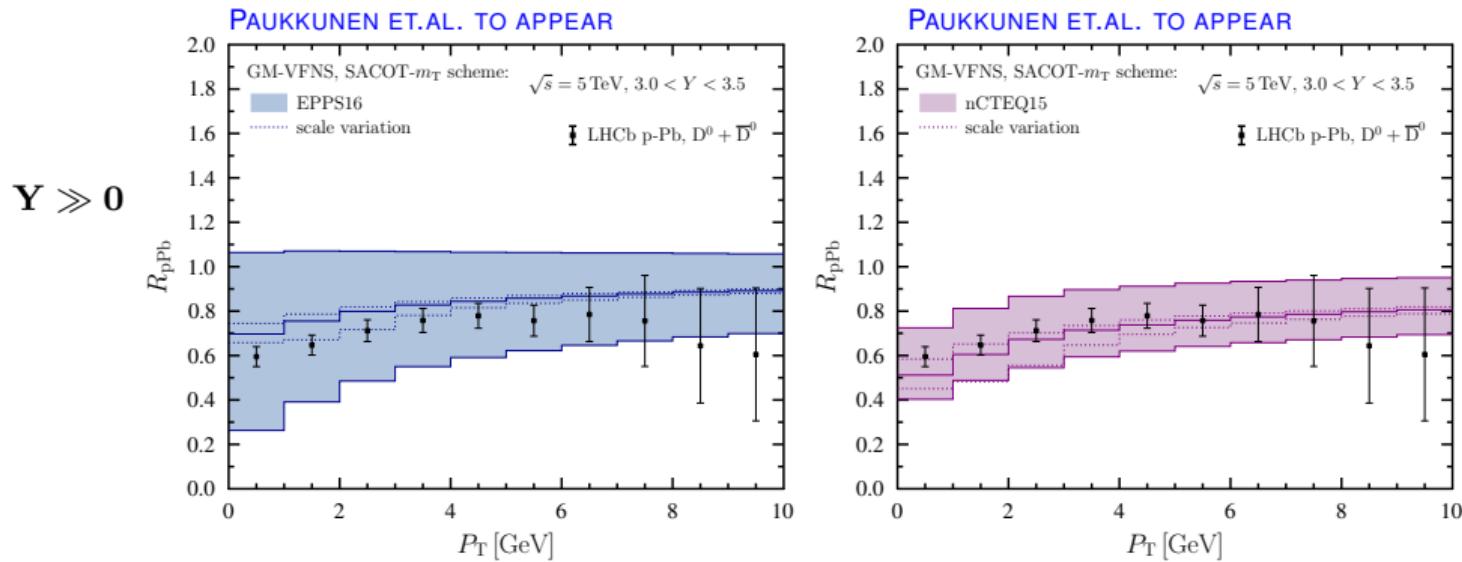
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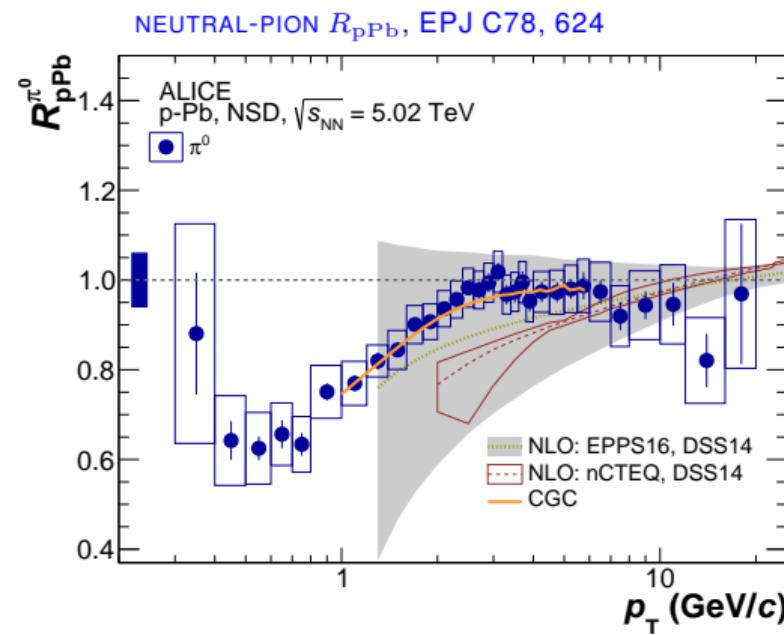
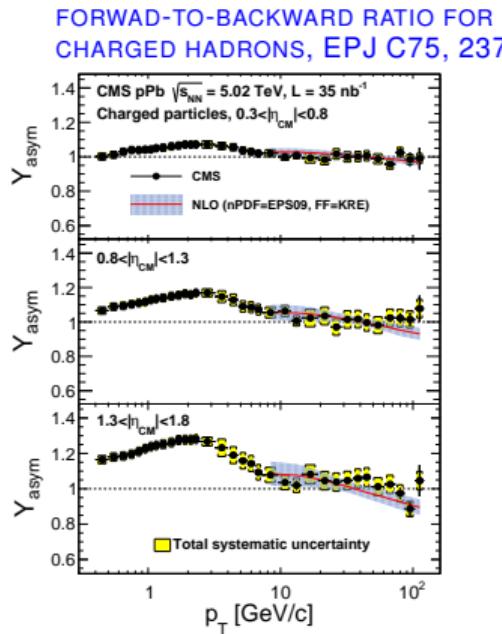
New constraints from the LHC: open heavy flavour

- Nuclear modifications in full GM-VFNS with EPPS16 and nCTEQ15
- Scales set to $\mu = \sqrt{P_T^2 + m_{\text{charm}}^2}$ — below $P_T \approx 3 \text{ GeV}$ the downward scale variation not reliable (since $\mu_{\min} = m_{\text{charm}}$ in EPPS16/nCTEQ15).



New constraints from the LHC: π^0 and h^+h^- production

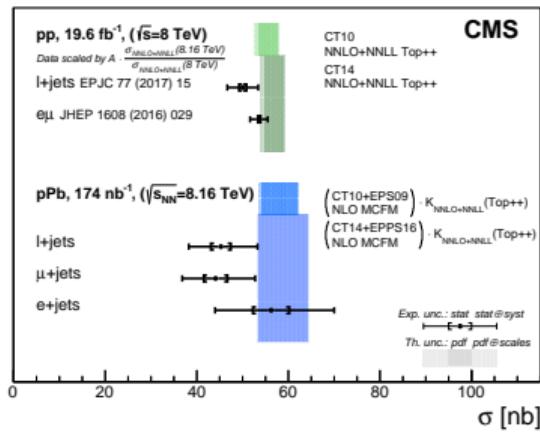
- Charged-hadron forward-to-backward ratio consistent with nPDFs at $p_T > 10 \text{ GeV}$
- Recent π^0 consistent with EPPS16 error bands but disagrees with nCTEQ15



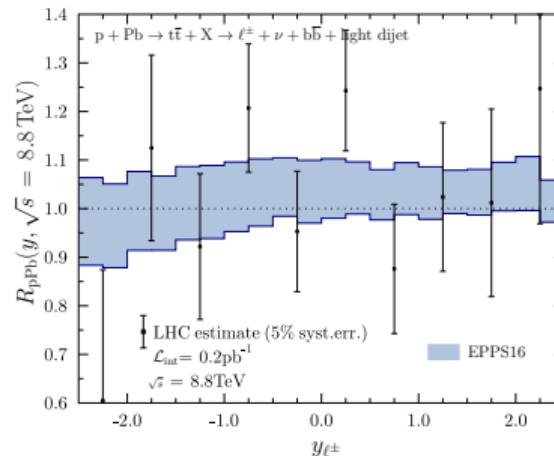
New constraints from the LHC: top-quark pair production

- $t\bar{t}$ observed in p-Pb by CMS [PRL 119, 242001] in $t\bar{t} \rightarrow \ell^\pm + \nu + b\bar{b} + \text{light dijet}$

CMS $\sigma_{t\bar{t}}$ measurement



Expectation for $\sigma_{t\bar{t}}/dy(\ell^\pm)$

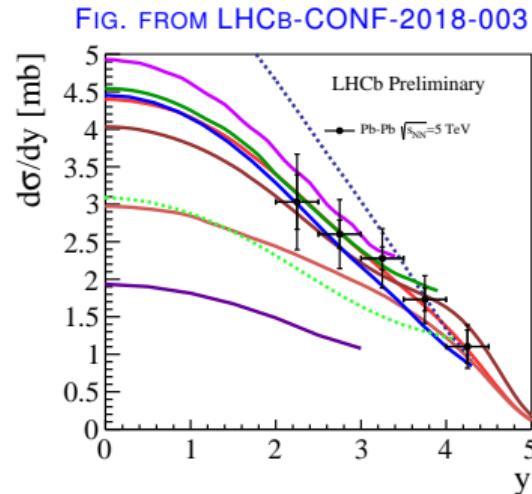
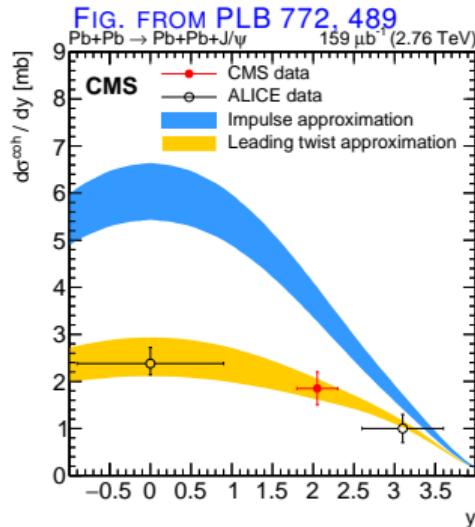


- Higher luminosity needed to get precision constraints.

New constraints from the LHC: ultra peripheral collisions (UPC)

- Exclusive J/ψ production in UPC at $t = 0$ can be related to the gluon PDF [RYSKIN, Z.PHYS. C57, 89]

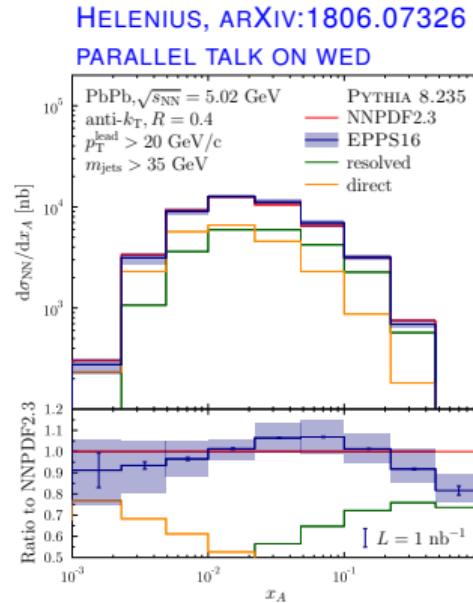
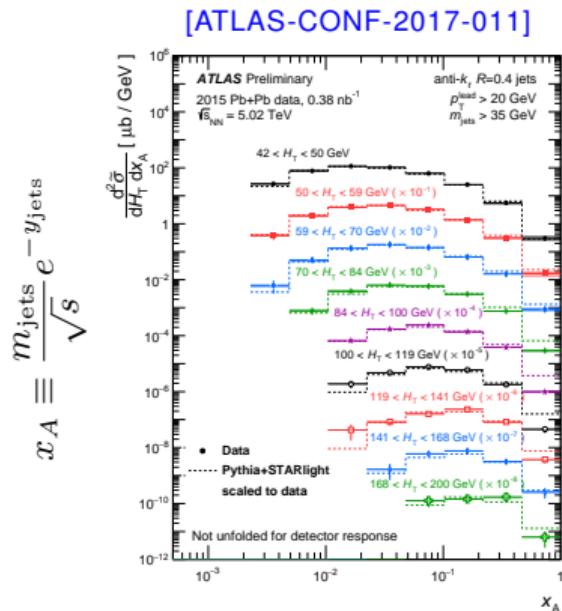
$$\sigma^{\gamma A \rightarrow J/\psi + \gamma A} \propto \left[g^A(x, Q^2) \right]^2$$



- In experiment $t \neq 0$ so the relation to $g^A(x, Q^2)$ comes with an uncertainty

New constraints from the LHC: ultra peripheral collisions (UPC)

- Inclusive dijet photo production in UPC Pb+Pb collision
- Theoretically more robust nPDF probe than the exclusive observables

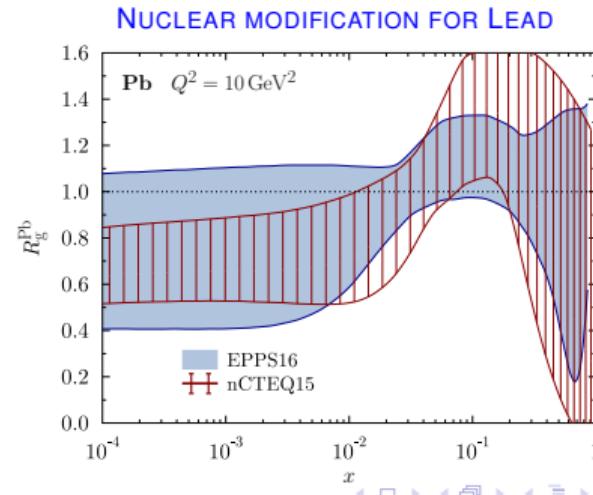
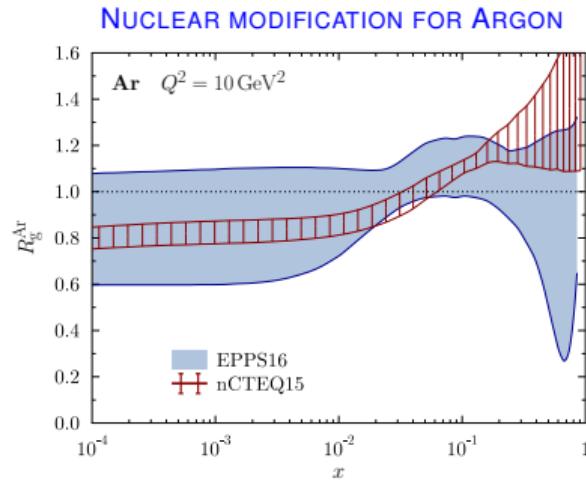


- Other inclusive observables (e.g. heavy flavour)?

On the case for lighter-than-lead ions

On the case for lighter-than-lead ions

- The nuclear-PDF fits will soon be **dominated by ^{208}Pb data** — only fixed-target data for light nuclei
- The impact of $p\text{-}A$ data with $A \ll 208$ would be clearly larger
 - also in astrophysical applications it's mostly scattering on ^{16}O and ^{14}N
- The A dependence of nuclear PDFs is not well constrained — e.g. in EPPS16 only 3 free parameters to control the A systematics

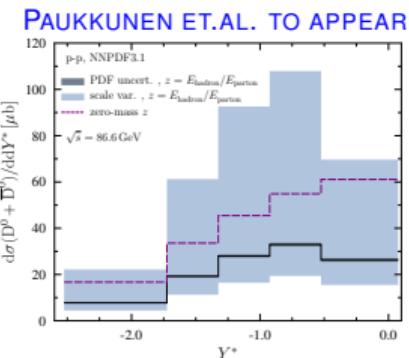
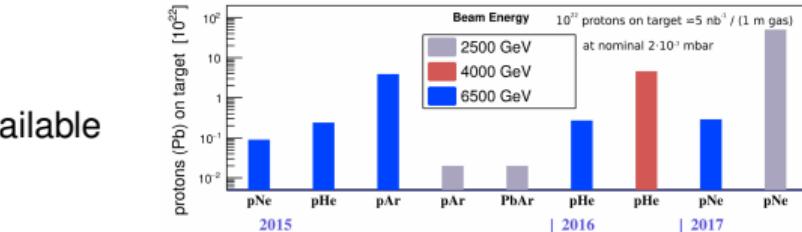
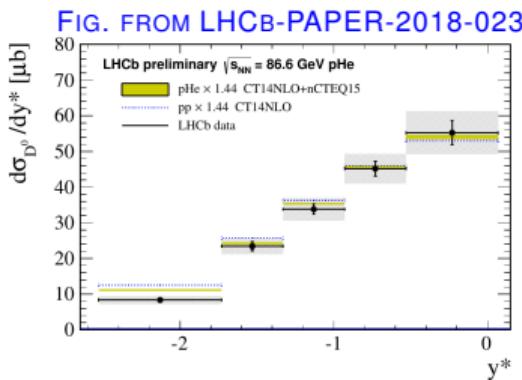


On the case for lighter-than-lead ions: Fixed-target programme of LHCb

- LHCb can measure large- x physics with several noble-gas targets with $\sqrt{s} \sim 100$ GeV

- E.g. D-meson measurements becoming available

[LHCb-PAPER-2018-023]



FIXED-TARGET CASE FROM PDF VIEW
DISCUSSED IN A PARALLEL TALK ON
WED BY KUSINA

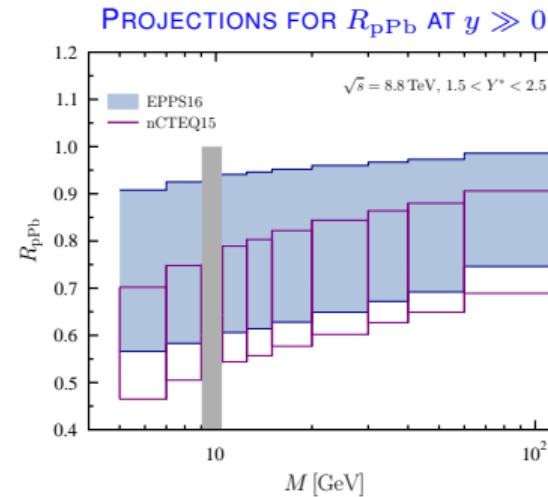
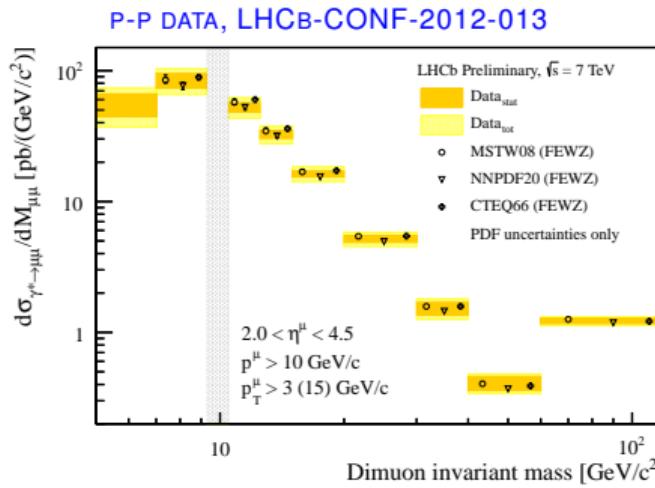
- Ratios p-Ar/p-He, p-Ne/p-He may shed light on the **A-dependence of large-x gluons** — but beware e.g. for intrinsic charm...

Summary

- Described the current status of the global analysis of nuclear PDFs
- The most important recent developments :
 - inclusion of LHC Run I data \rightsquigarrow completely novel constraints
 - use of neutrino DIS data $\rightsquigarrow R_{u_V} \sim R_{d_V}$
 - full flavour dependence \rightsquigarrow less bias but larger uncertainties
 - development towards NNLO precision \rightsquigarrow NLO vs. NNLO comparable to data precision
- The inclusion of Run-II data should decrease the uncertainties significantly
 - Will allow to reduce parametrization bias
 - The availability of correlated systematics would help to make most out of the data
- From nPDF (and astrophysics) view point p- A data with $A \ll 208$ would have a significant impact

New constraints from the LHC: The Drell-Yan process

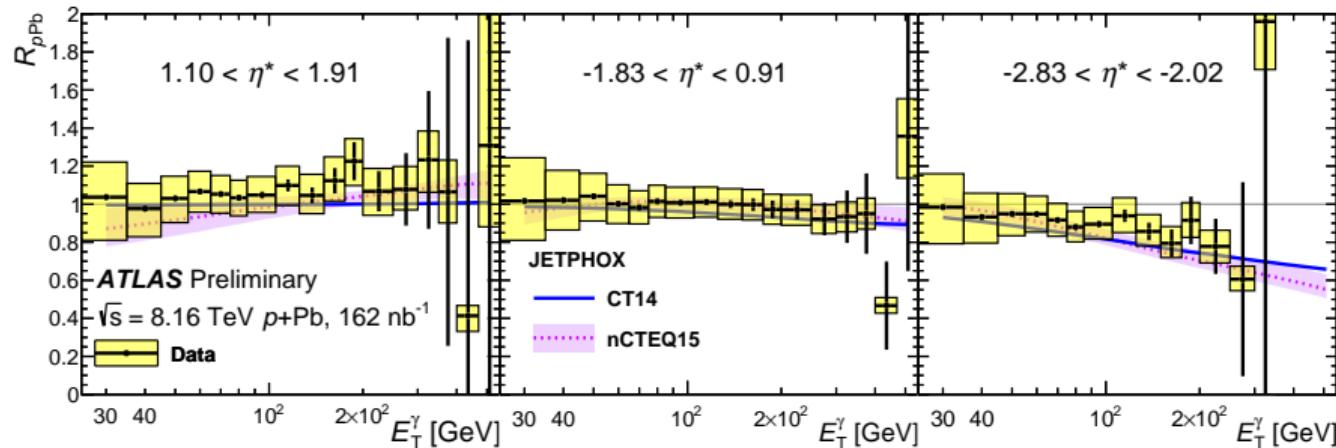
- Low- and intermediate-mass Drell-Yan process at $y \gg 0$ direction would provide a strong probe of small- x sea quarks [ARLEO ET.AL, PRD95, 011502]



- The low-mass part within the reach of e.g. LHCb with the Run-II luminosity [LHCb-PUB-2016-011].
- New low-mass Drell-Yan measurements expected also from Fermilab SeaQuest experiment [FERMILAB-THESIS-2016-13].

New constraints from the LHC: Isolated photons

- ATLAS $\sqrt{s} = 8$ TeV p-Pb/p-p measurement [ATLAS-CONF-2017-072] consistent with nCTEQ15 & EPPS16



- Triggering on the recoiling jet would allow for better focused x distributions [KLASEN ET.AL. JHEP 1803, 081] — larger sensitivity to resummation, hadronization and MPI