Constraining nPDFs with LHCb

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on behalf of the LHCb collaboration

Implications of LHCb measurements and future prospects
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Reminder of nPDF

- Nuclear parton distribution function (nPDF): describes how quarks and gluons are distributed within atomic nuclei.

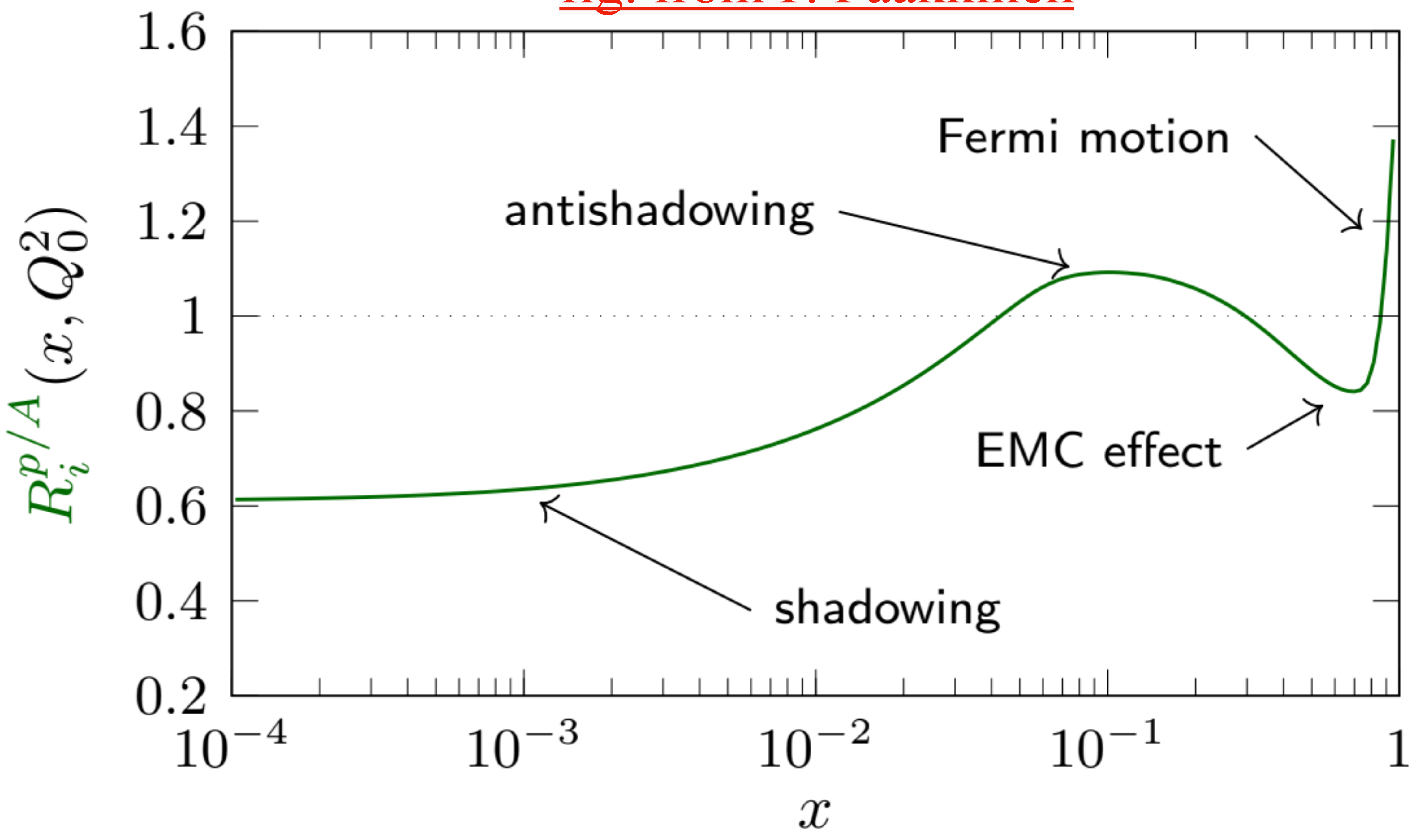
$$f_i^{\mathrm{p}/A}(x,Q^2) = R_i^A(x,Q^2) f_i^{\mathrm{p}}(x,Q^2)$$

The bound proton PDF

Nuclear modification

free proton PDF

fig. from P. Paakkinen



- This nuclear modification is calculated using global analysis approach.

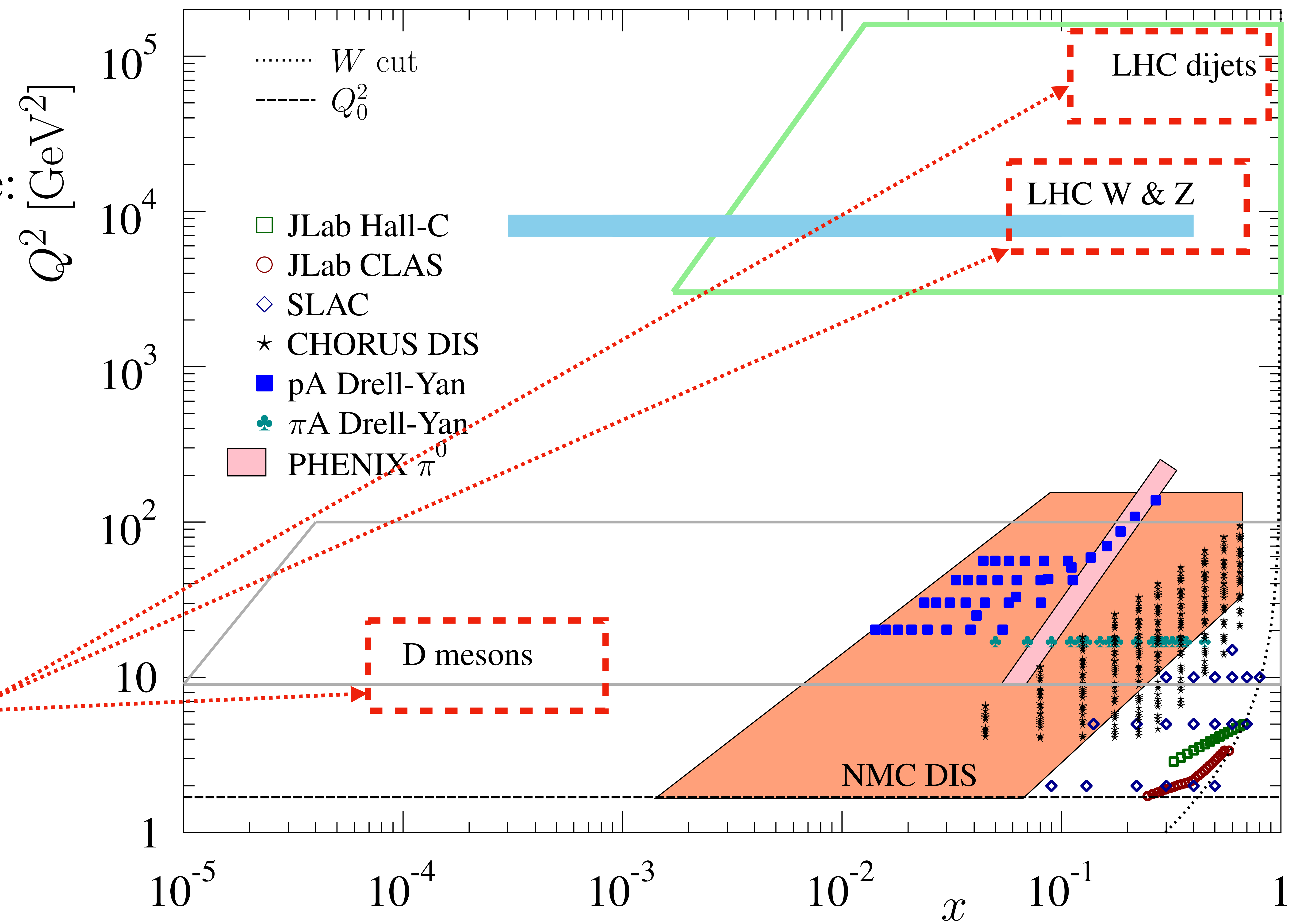
- Use as many processes as we can, combining different data from different experiments.

Q^2: exchange momentum between interacting partons.

x: momentum fraction from nucleus parton.

LHC expands the (x, Q^2) reach by orders of magnitude:

- Q^2: exchange momentum between interacting partons.
- x: momentum fraction from nucleus parton.

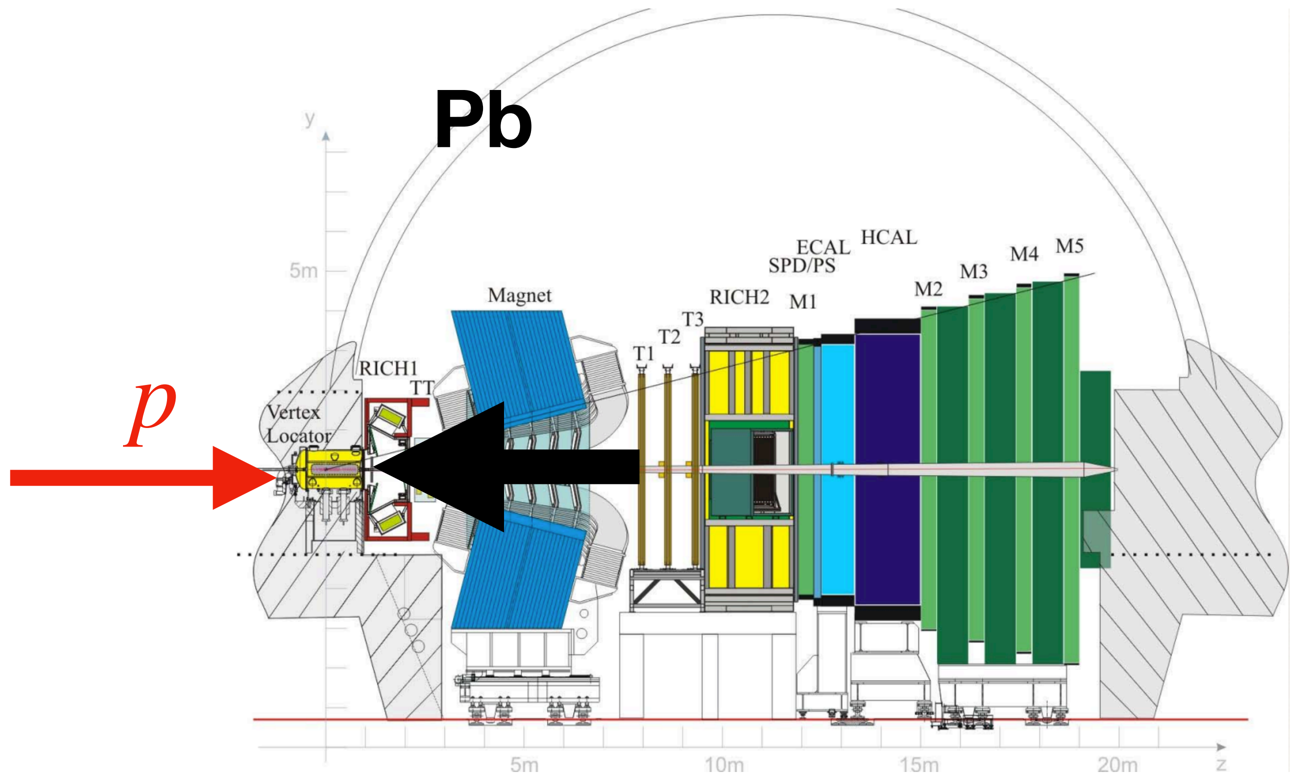


Eur.Phys.J.C 82 (2022) 5, 413

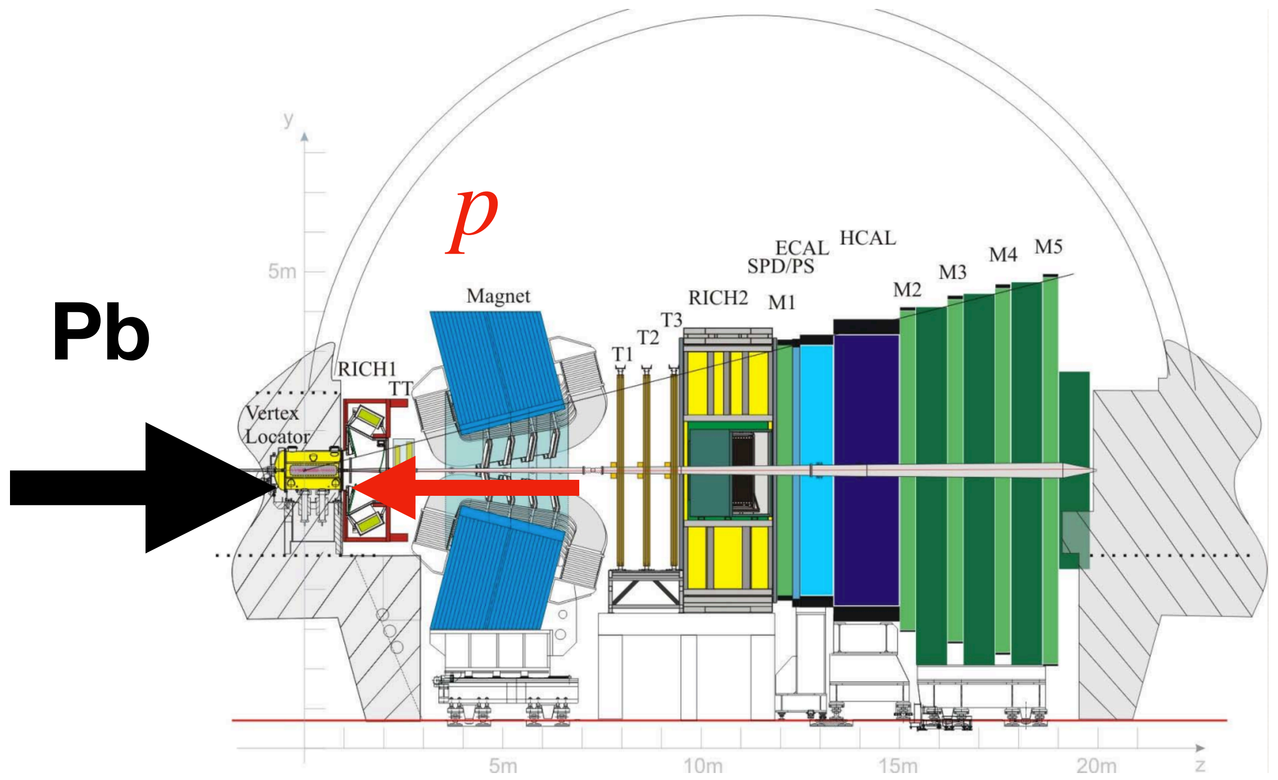
LHCb in the (x, Q^2) plane

LHCb can access unique regions of (x, Q^2) space:

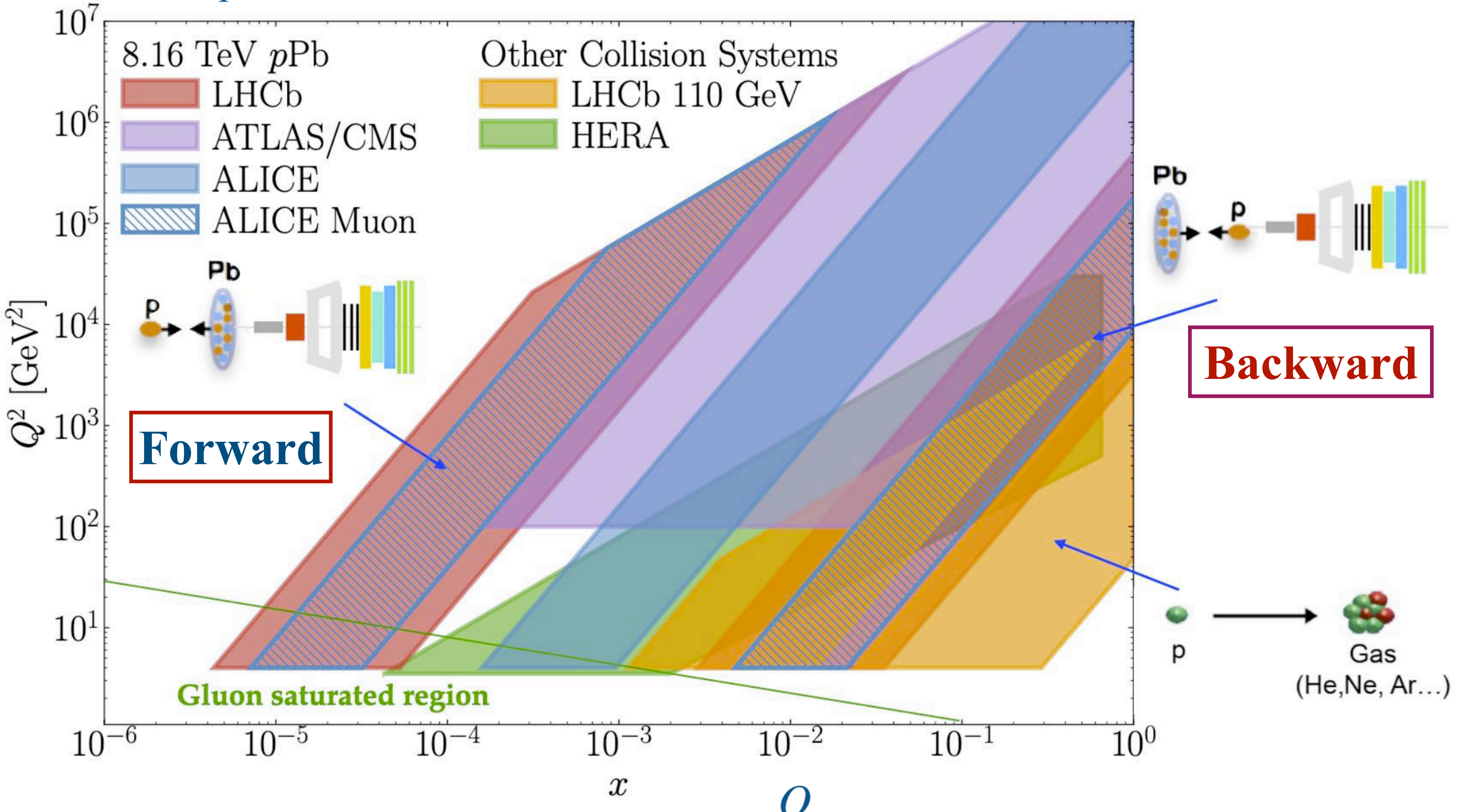
Forward



Backward



$Q^2 \sim m^2 + p_T^2$



$$x \sim \frac{Q}{\sqrt{s_{NN}}} e^{-\eta}$$

LHCb in the (x,Q^2) plane

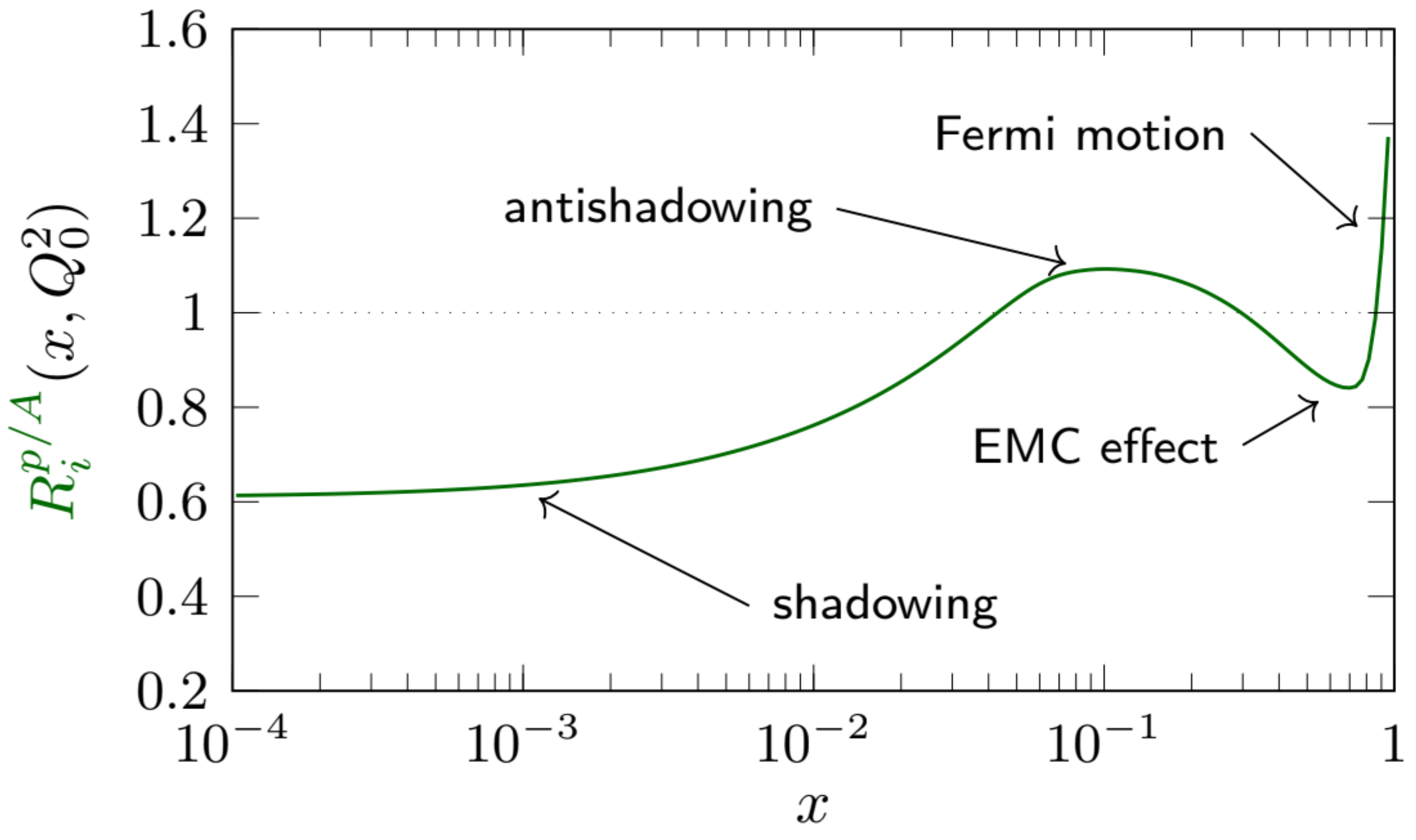
LHCb can access unique regions of (x, Q^2) space:

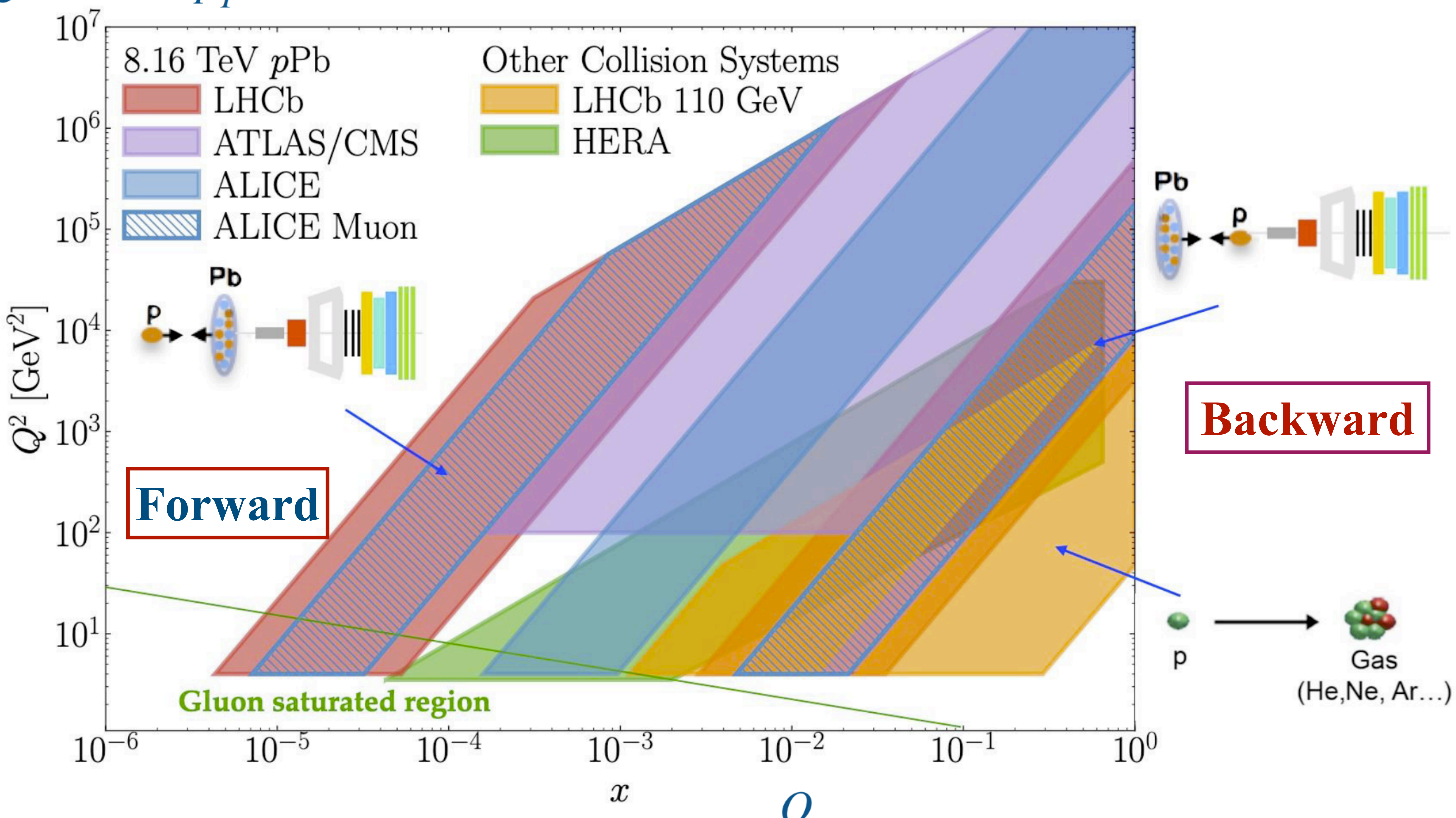
$Q^2 \sim m^2 + p_T^2$

Constrain nPDF at small (**Forward**) and large Björken-x (**Backward**).

Probe gluon saturation in low x and low Q^2 region.

fig. from P. Paakkinen

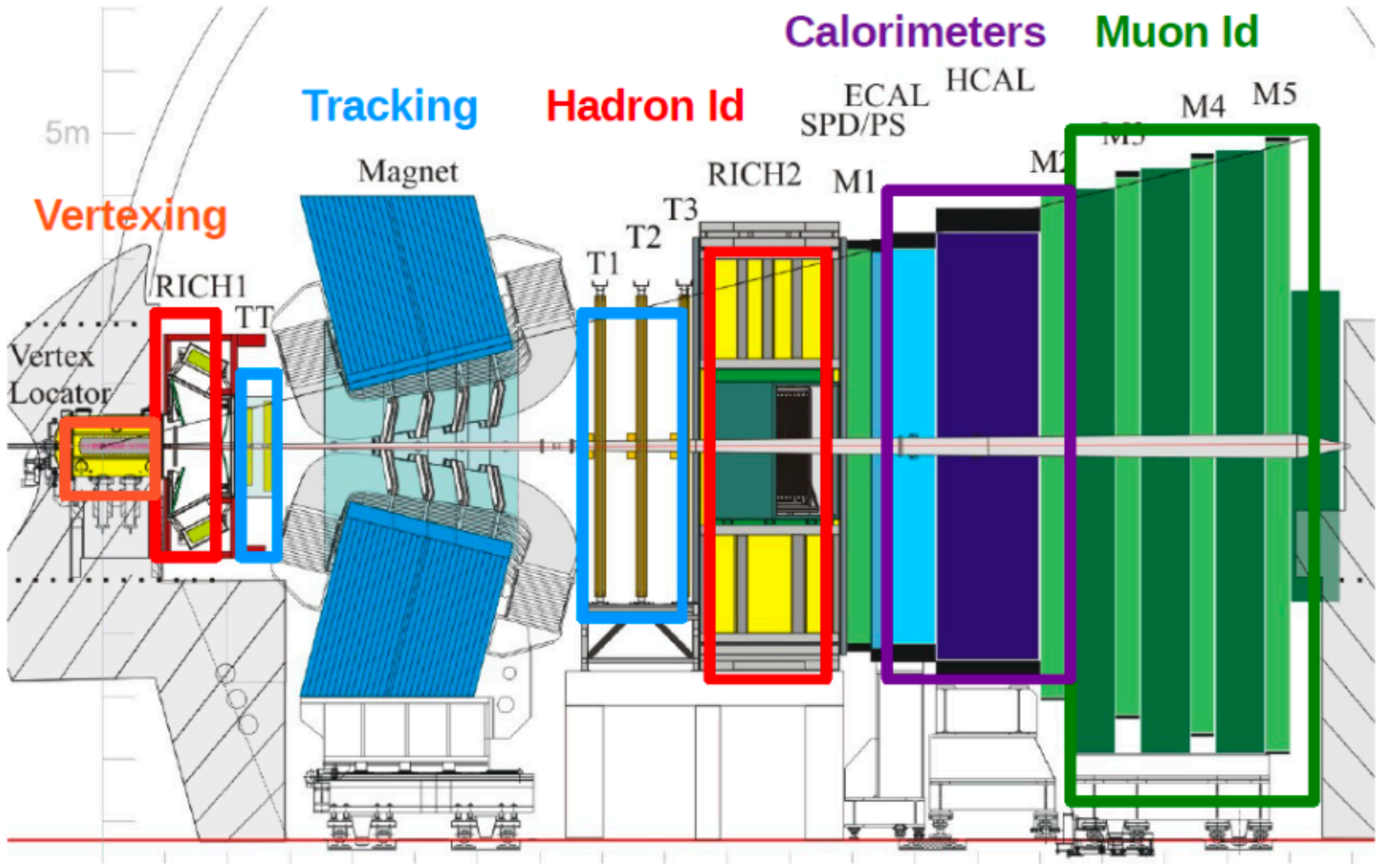




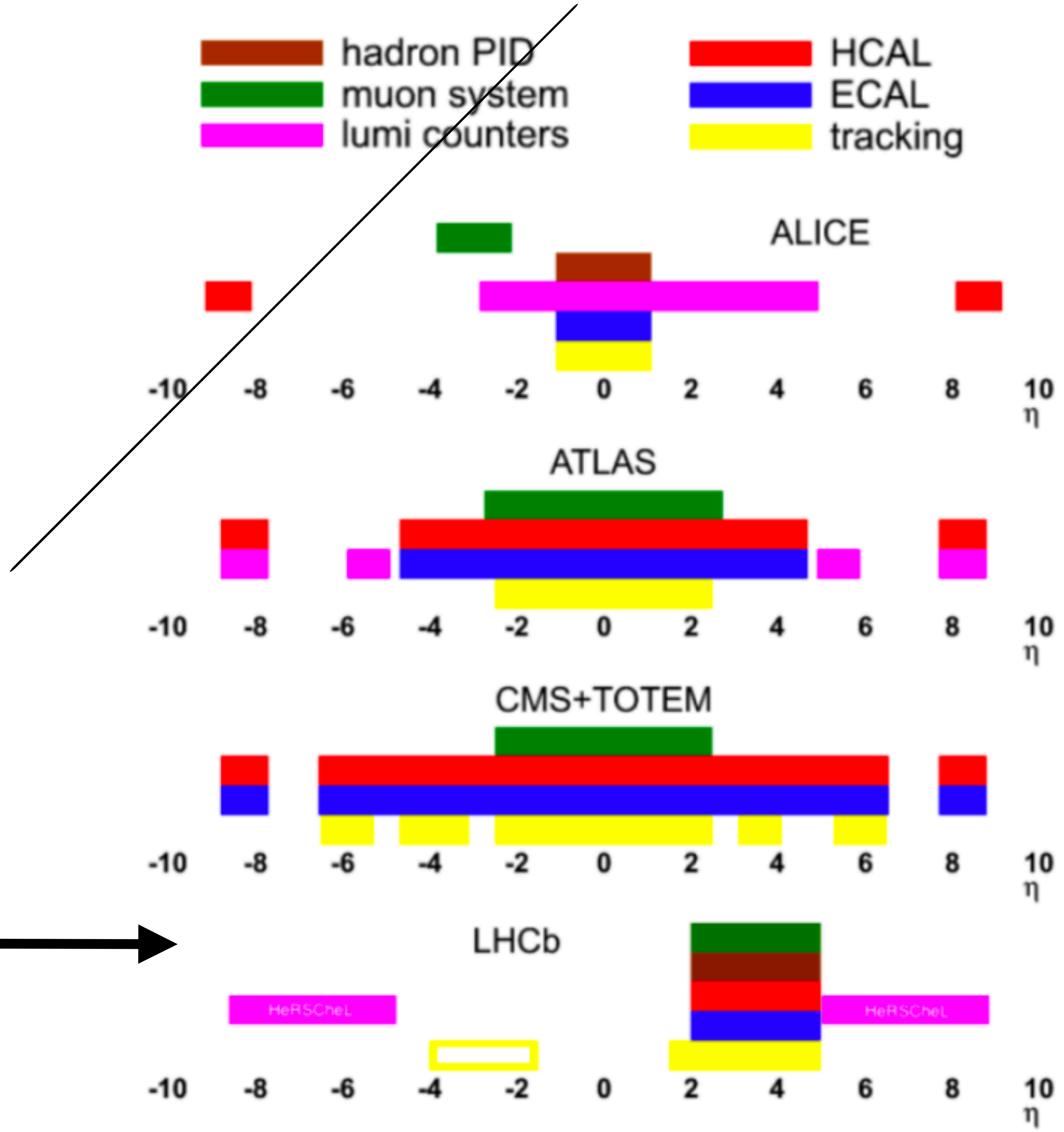
$x \sim \frac{Q}{\sqrt{s_{NN}}} e^{-\eta}$

LHCb Detector

- From heavy flavour physics to a general-purpose detector in the forward region.
- Forward detector fully instrumented in $2 < \eta < 5$.
- Excellent tracking, momentum resolution, and particle identification.



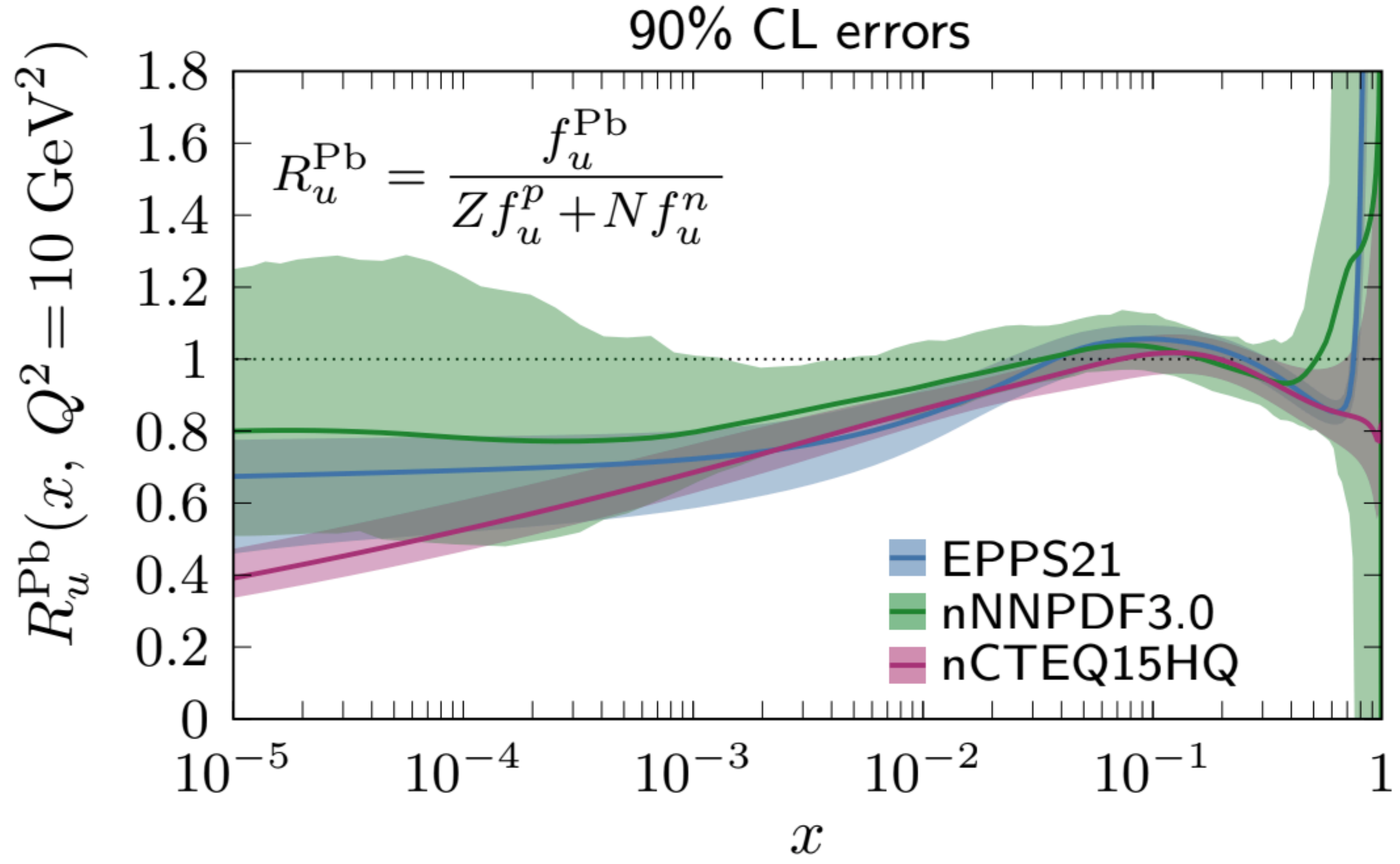
JINST 3 (2008)S08005

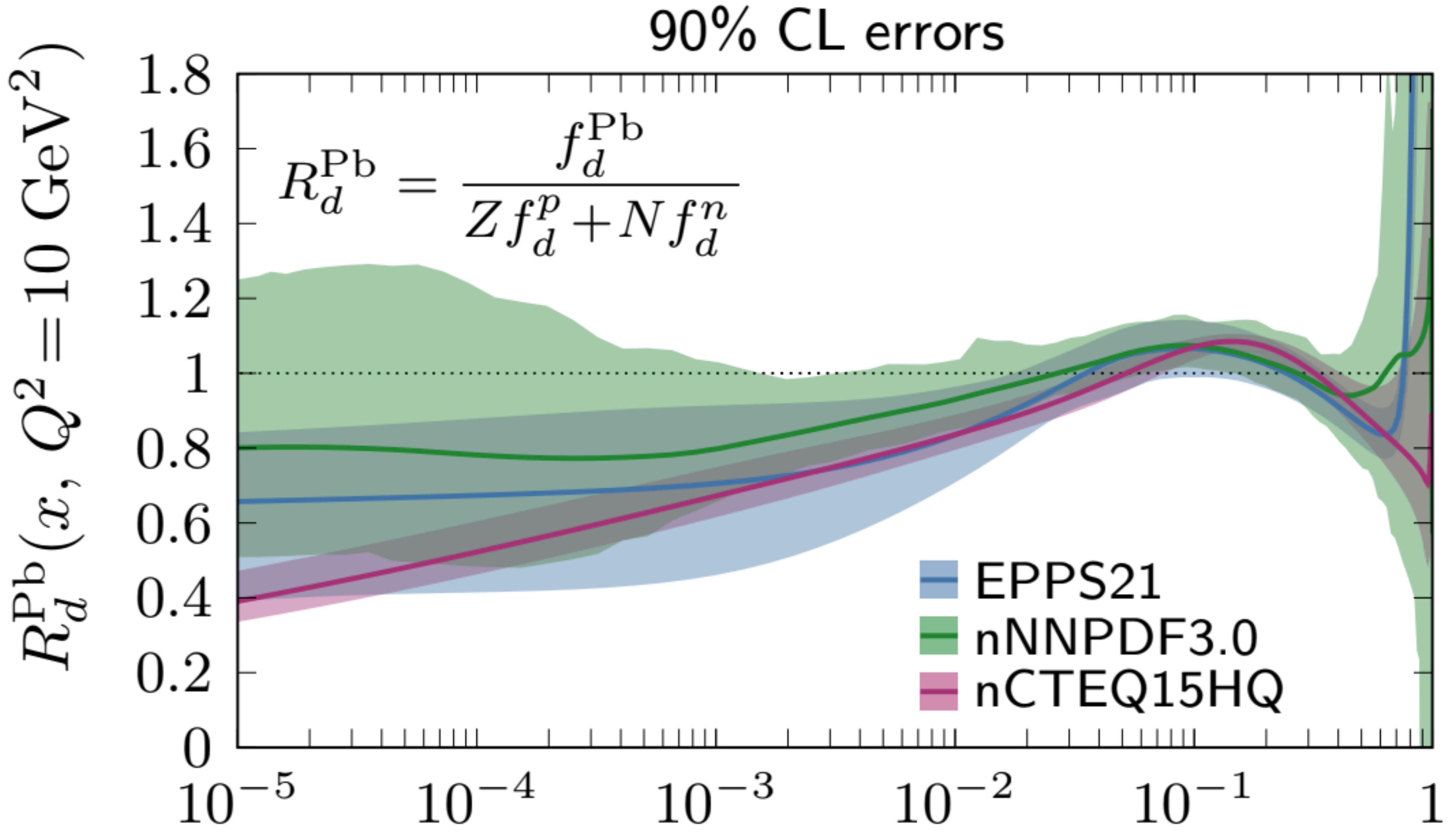


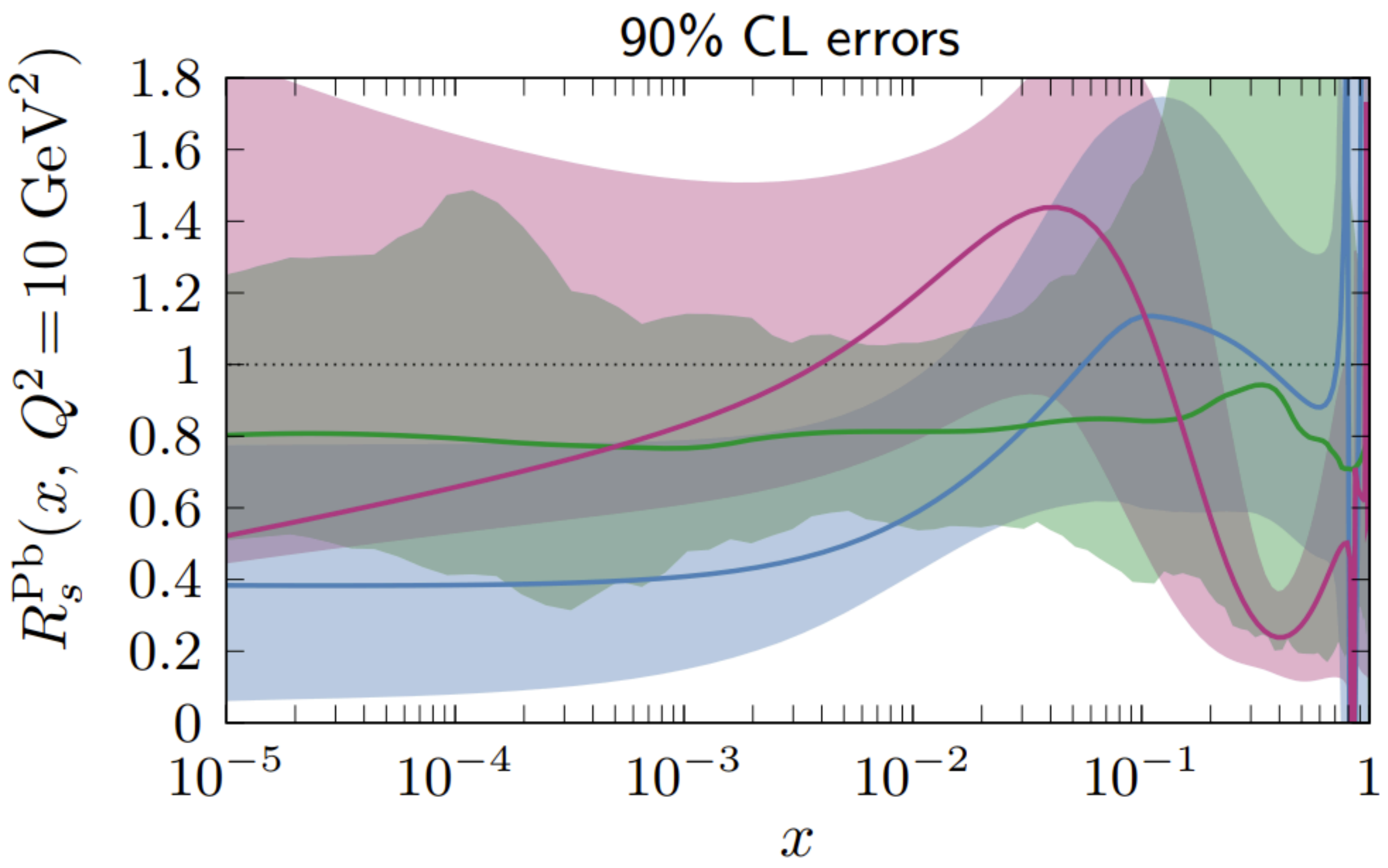
IJMPA 30 (2015) 1530022

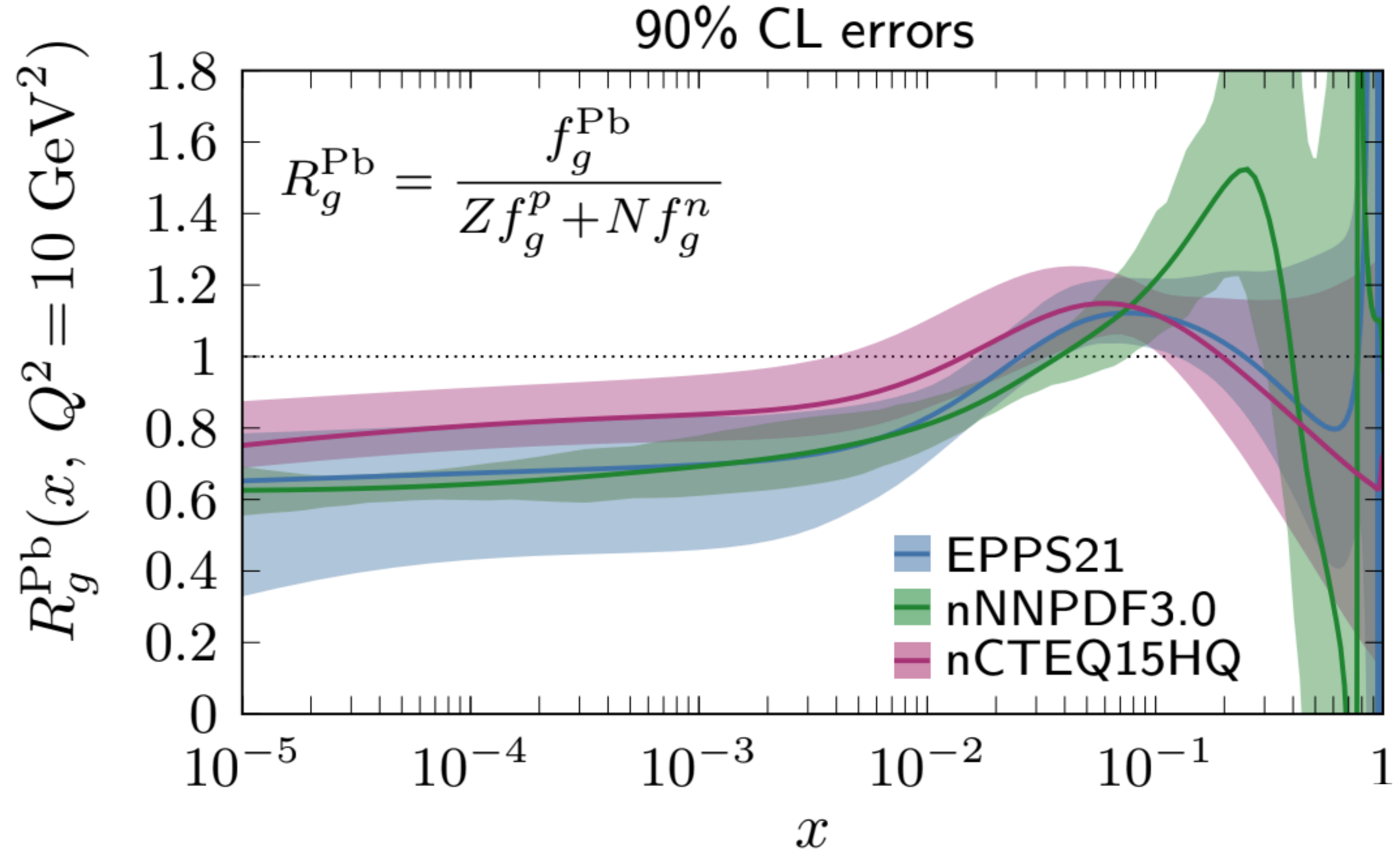
nPDF: what we know so far ?

figs. from P. Paakkinen



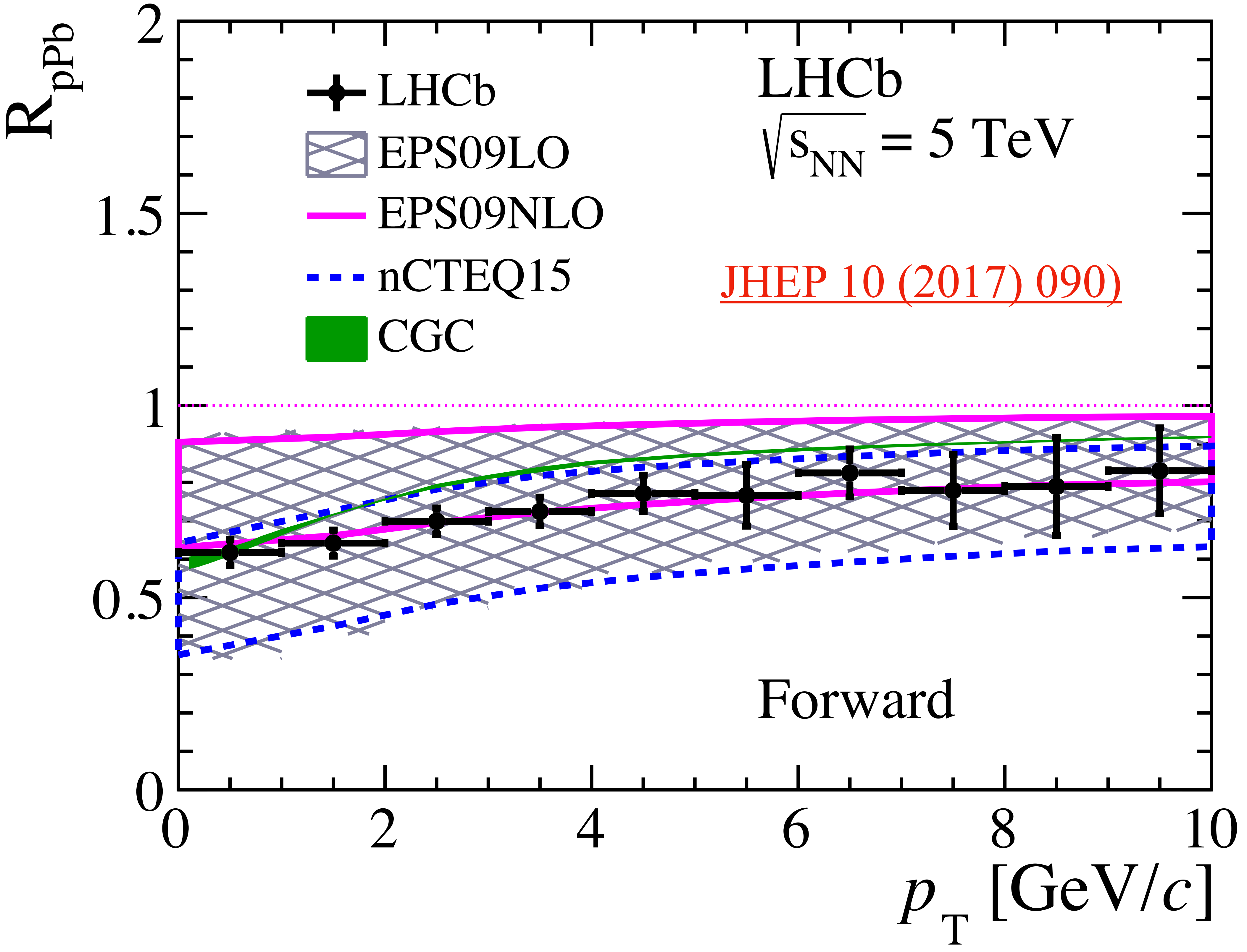


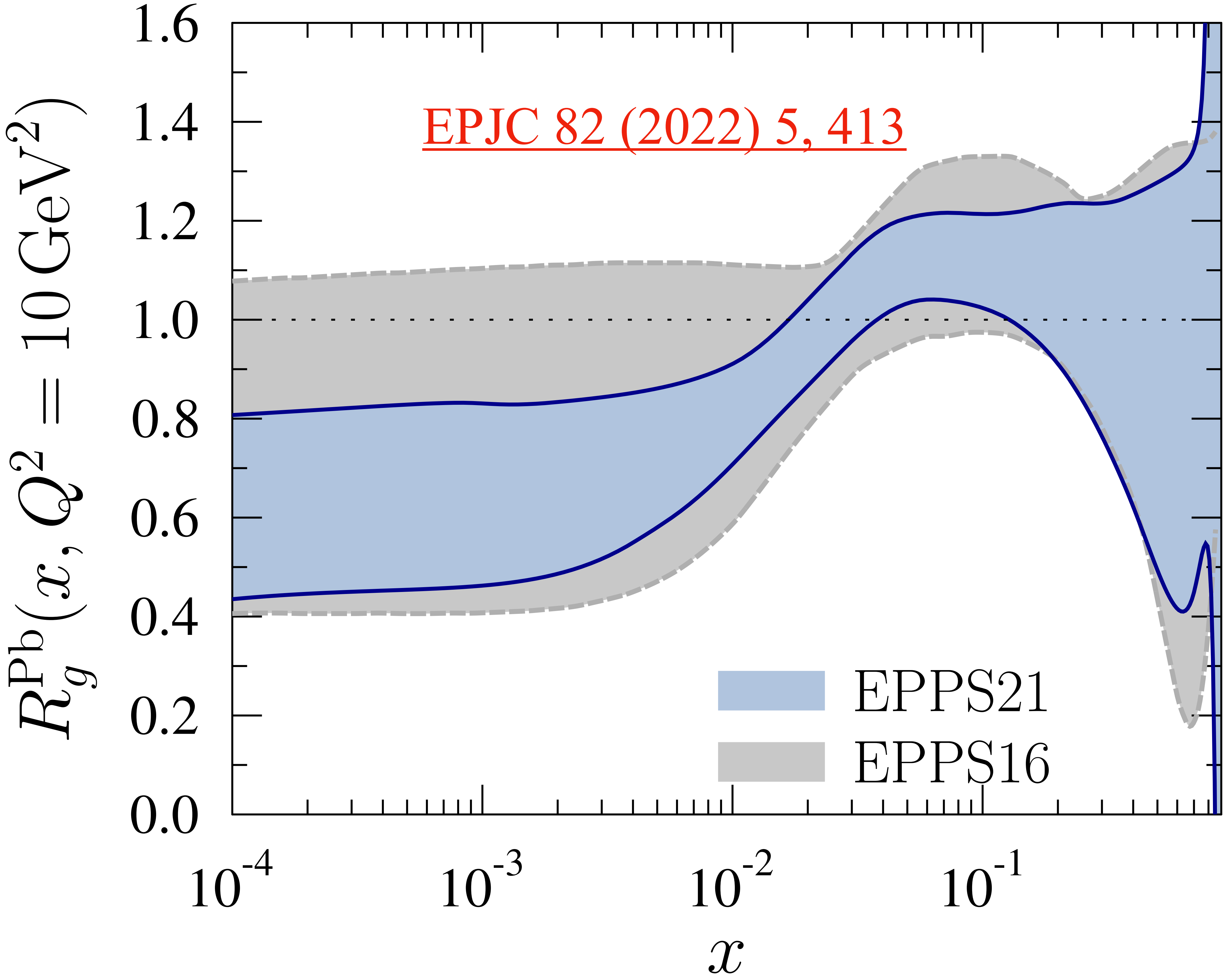




LHCb's impact on nPDF fits: EPPS21

Nuclear modification factor: $R_{pPb} = \dfrac{d\sigma_{pPb}/dp_T d\eta}{208 \cdot d\sigma_{pp}/dp_T d\eta}$





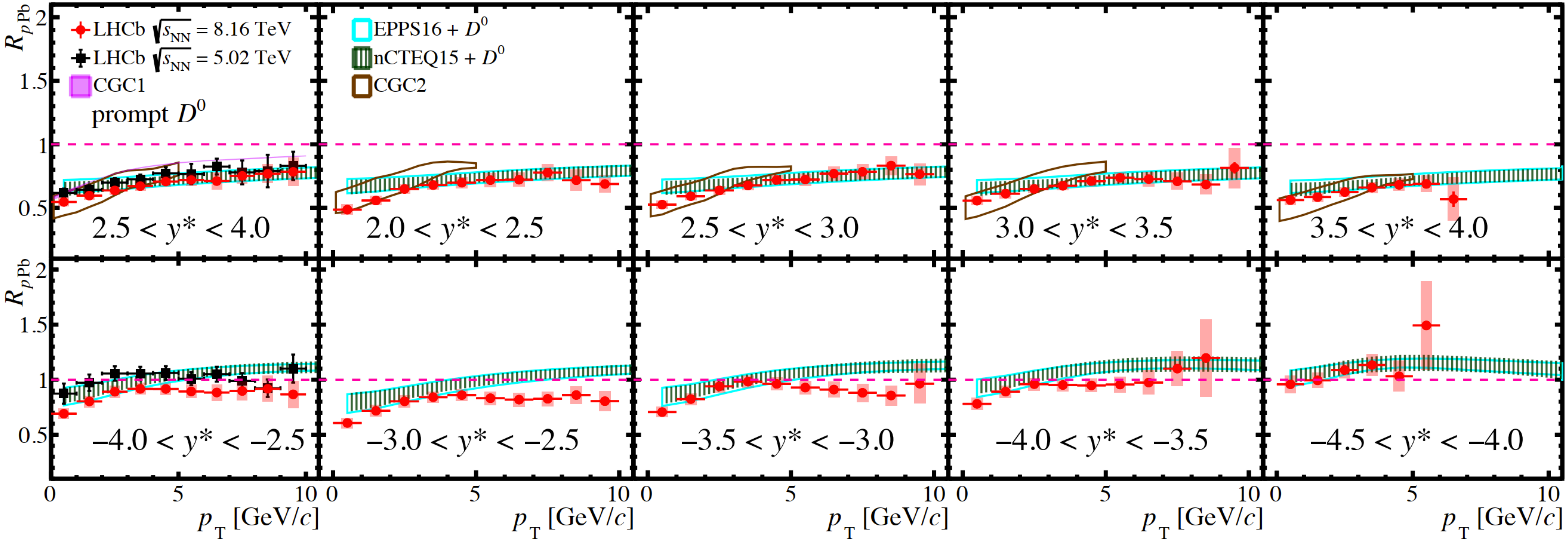
LHCb D^0 meson data have a huge impact on the nPDF uncertainties.

Updated nPDF fits and D^0 in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

- The D^0 measurement has been updated with approximately 20 times more statistics compared to 5 TeV.
- Probe both shadowing and anti-shadowing regions.

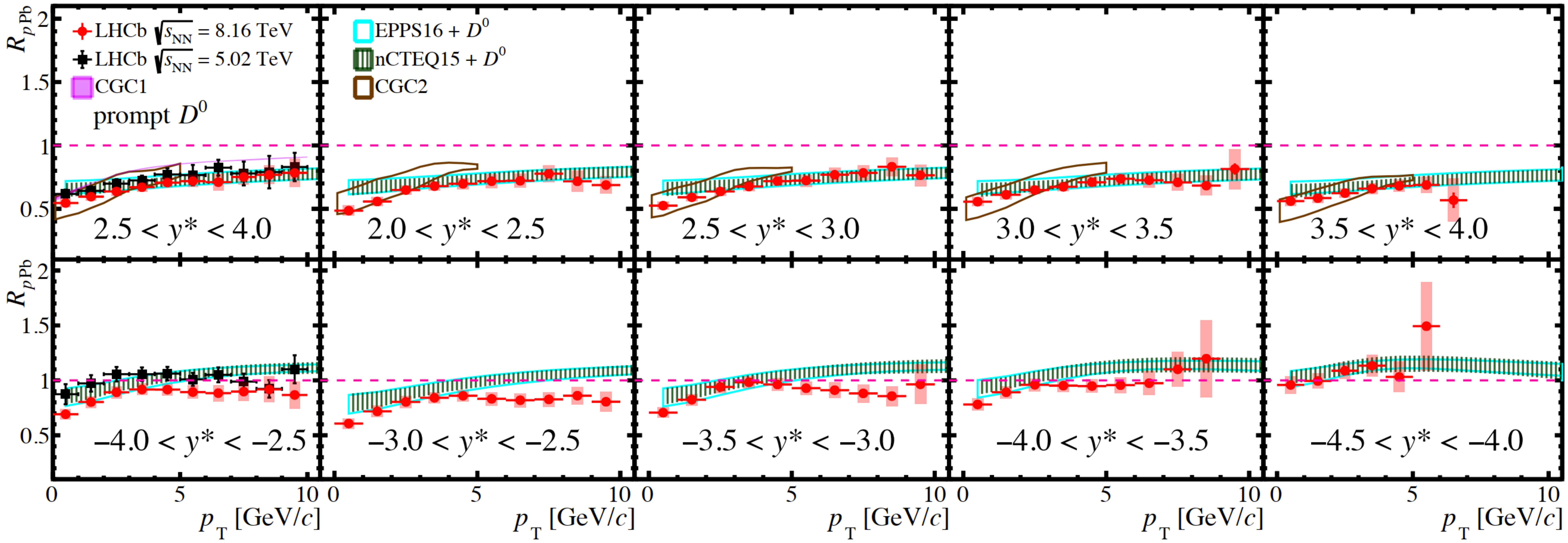
pp reference from interpolation between 5&13 TeV data

Phys. Rev. Lett. 128, 142004



Updated nPDF fits and D^0 in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

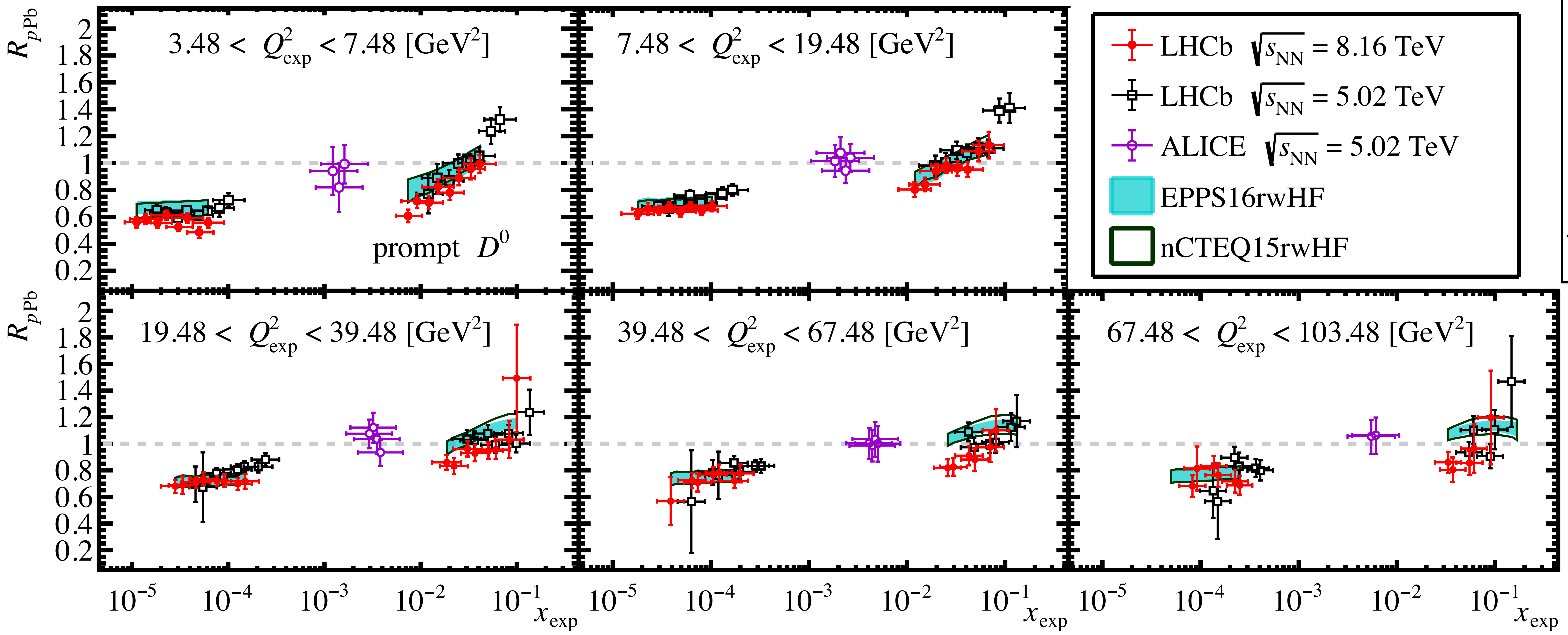
Phys. Rev. Lett. 128, 142004



- Forward: data are well described by nPDFs.
- Backward: discrepancy with nPDFs calculations at high p_T indicating additional initial/ final state effects.

D^0 results in (x_{exp}, Q^2_{exp}) plane

Phys. Rev. Lett. 128, 142004



Experimental proxies for x and Q^2 to compare results in different energy and kinematic regions:

$$Q^2_{exp} \equiv m^2_{D^0} + p^2_T$$

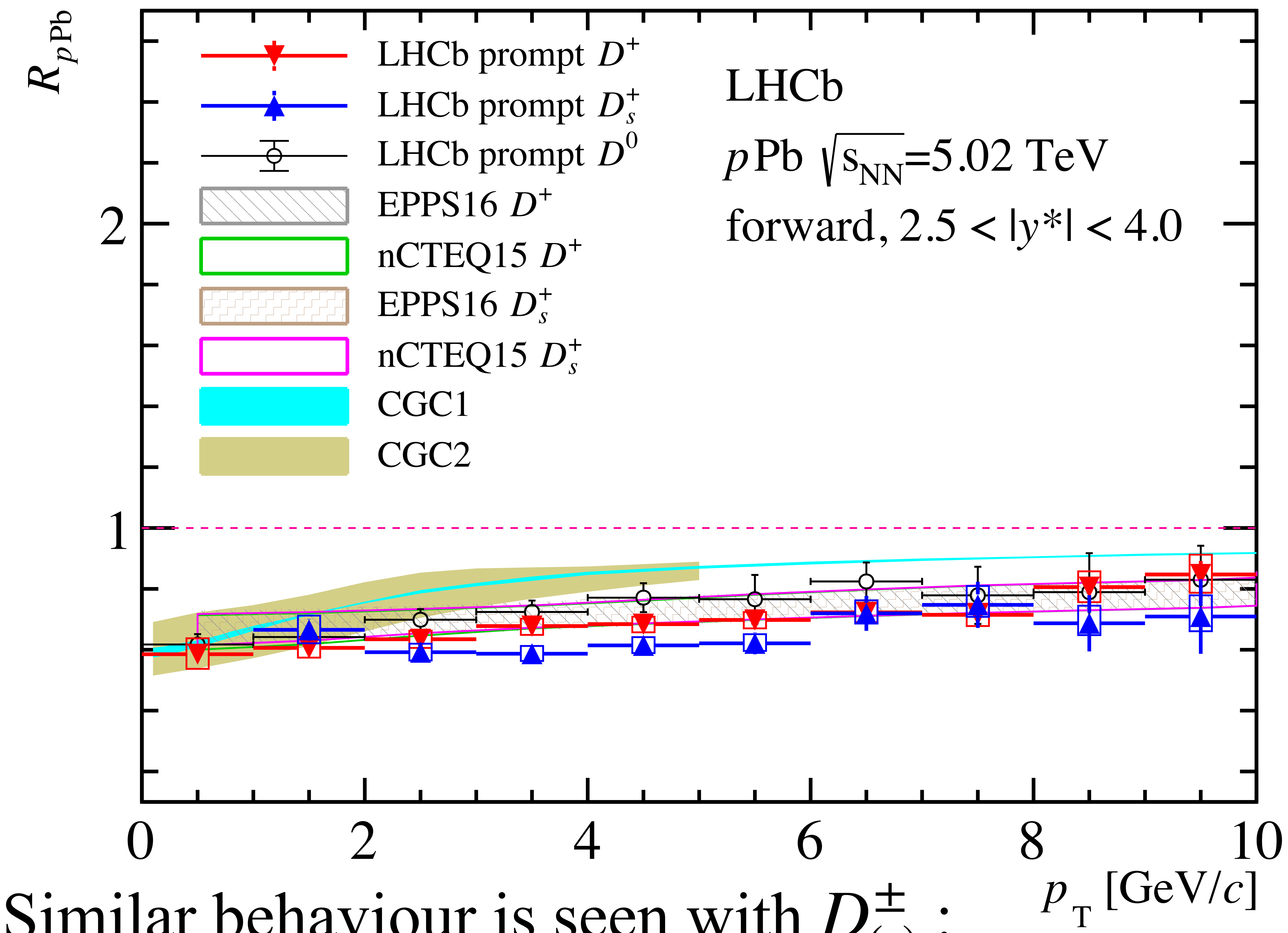
$$x_{exp} \equiv 2\frac{Q_{exp}}{\sqrt{s_{NN}}} e^{-y^*}$$

- 8 TeV and 5 TeV data consistent with each other.
- Forms a continuous trend over a wide x coverage.
- Lower than nPDF at large x_{exp} and large Q^2_{exp}.

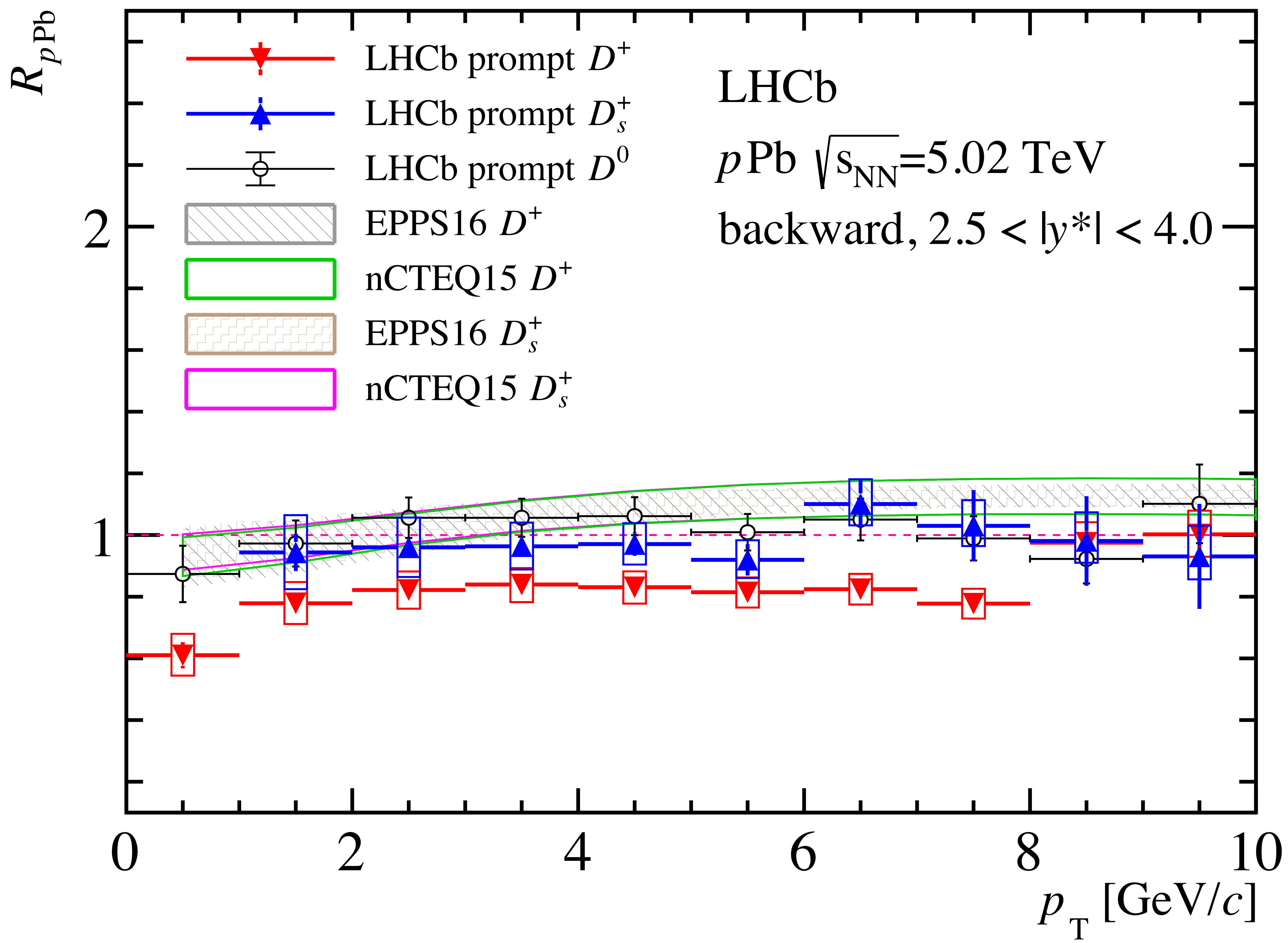
New : prompt D_s^+ and D^+ production in pPb at $\sqrt{s_{NN}} = 5.02$ TeV

arXiv:2309.14206v2

Forward



Backward



Similar behaviour is seen with $D_{(s)}^{\pm}$:

- Forward: good agreement with the data.
- Backward: D_s^+ and D^0 are in good agreement unlike the D^+ which is systematically lower.
  Possible change in charm hadronisation ?

New : prompt D_s^+ and D^+ production in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

LHCB-PAPER-2023-021

Forward:

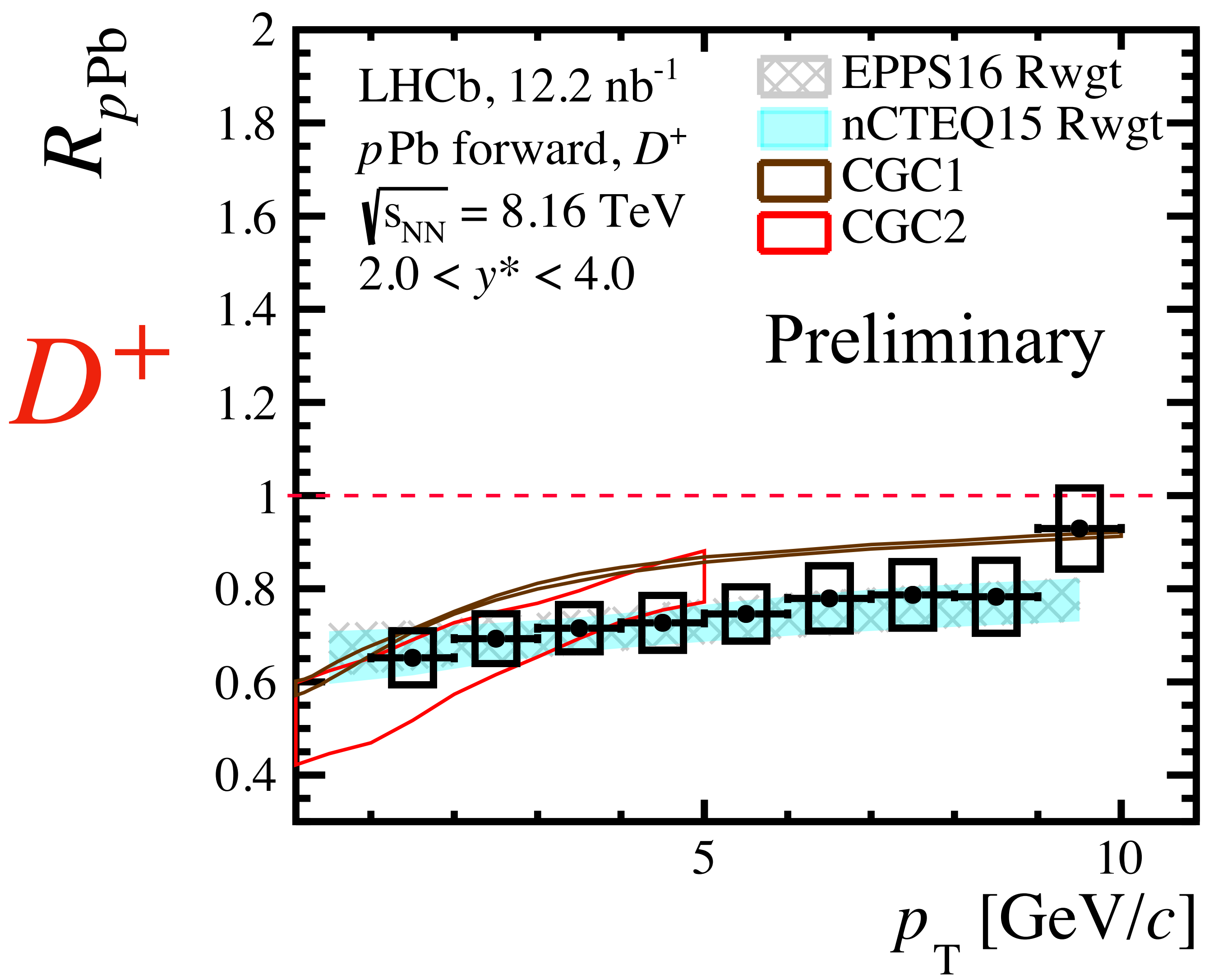
- The nuclear modification factor is found to be consistent with D^0 mesons.
- The measurement shows a significant suppression consistent with nPDFs.

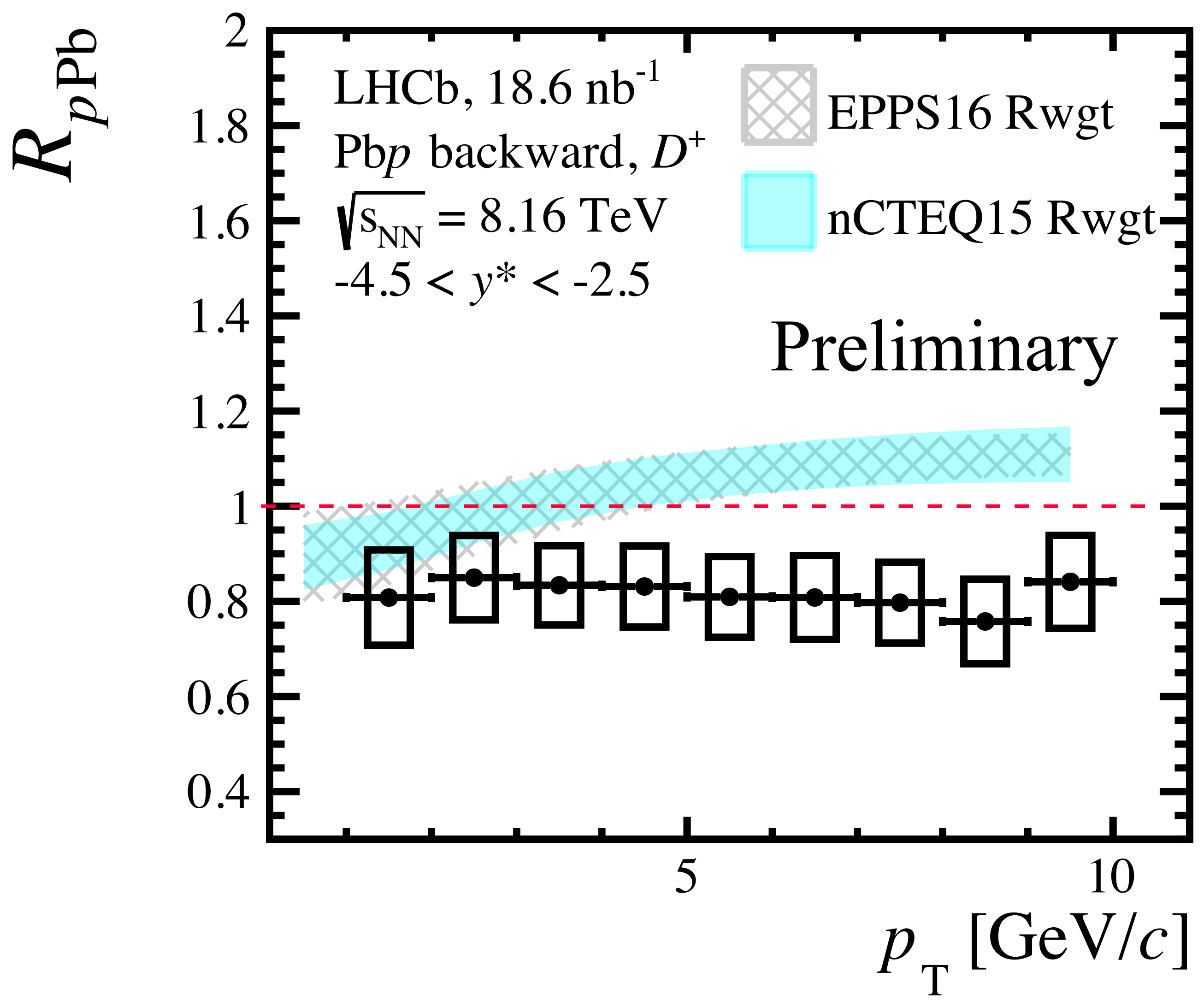
Backward:

- $D^+_{(s)}$ data are lower than the nPDF calculations.
- Possible final state effects that depends weakly on charm hadronisation.

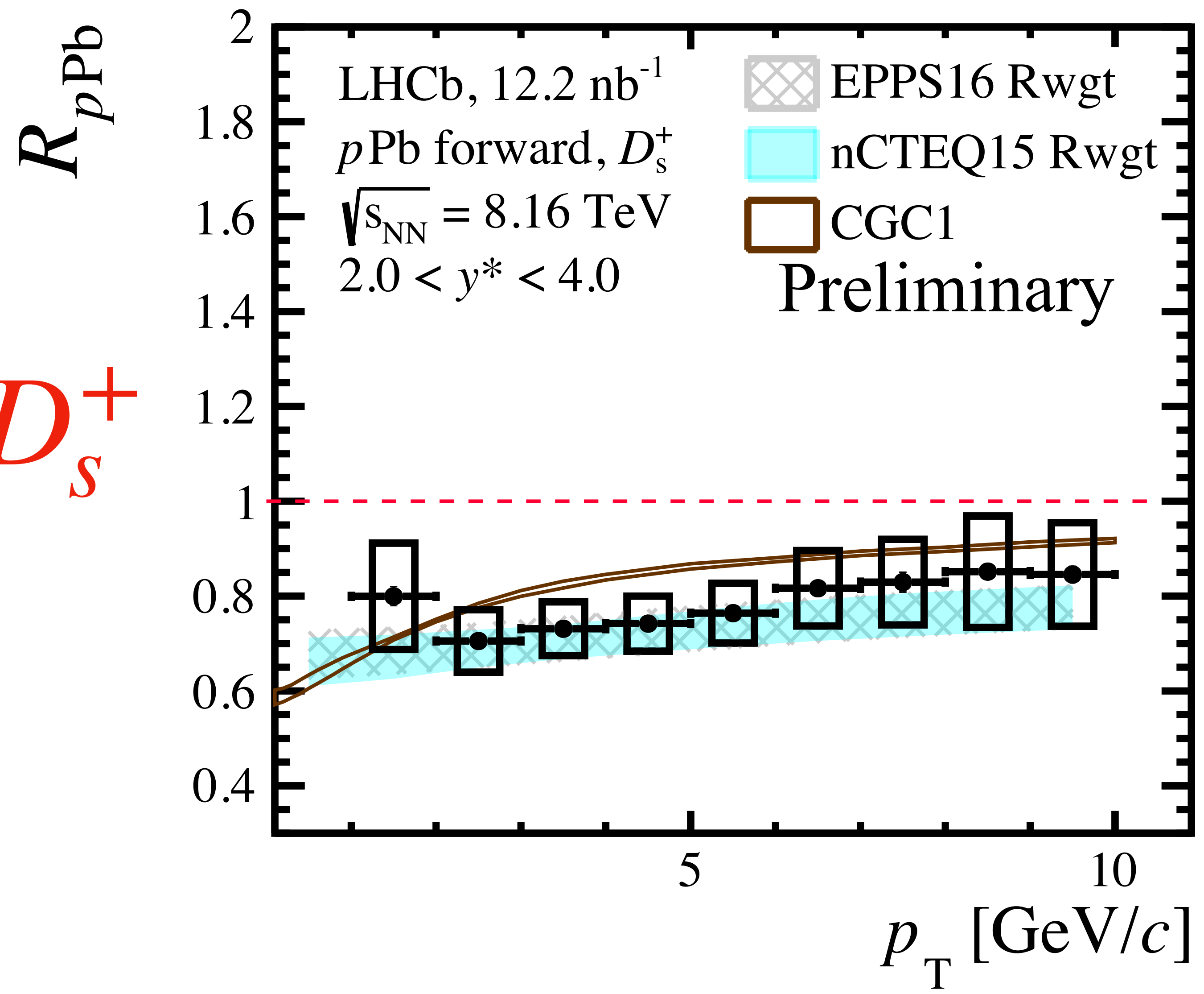
Forward **Backward**

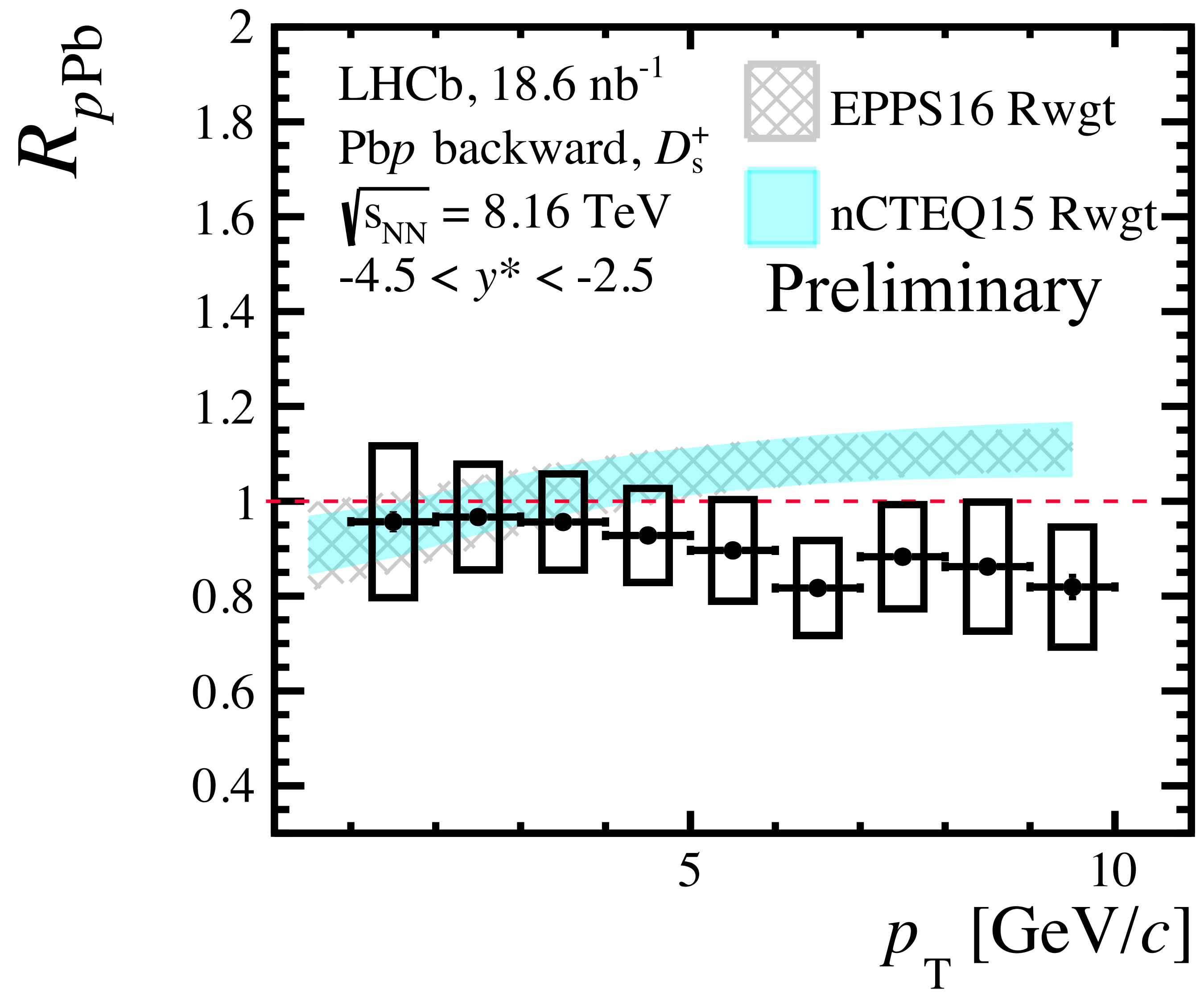
D^+





D_s^+





Neutral pion production in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

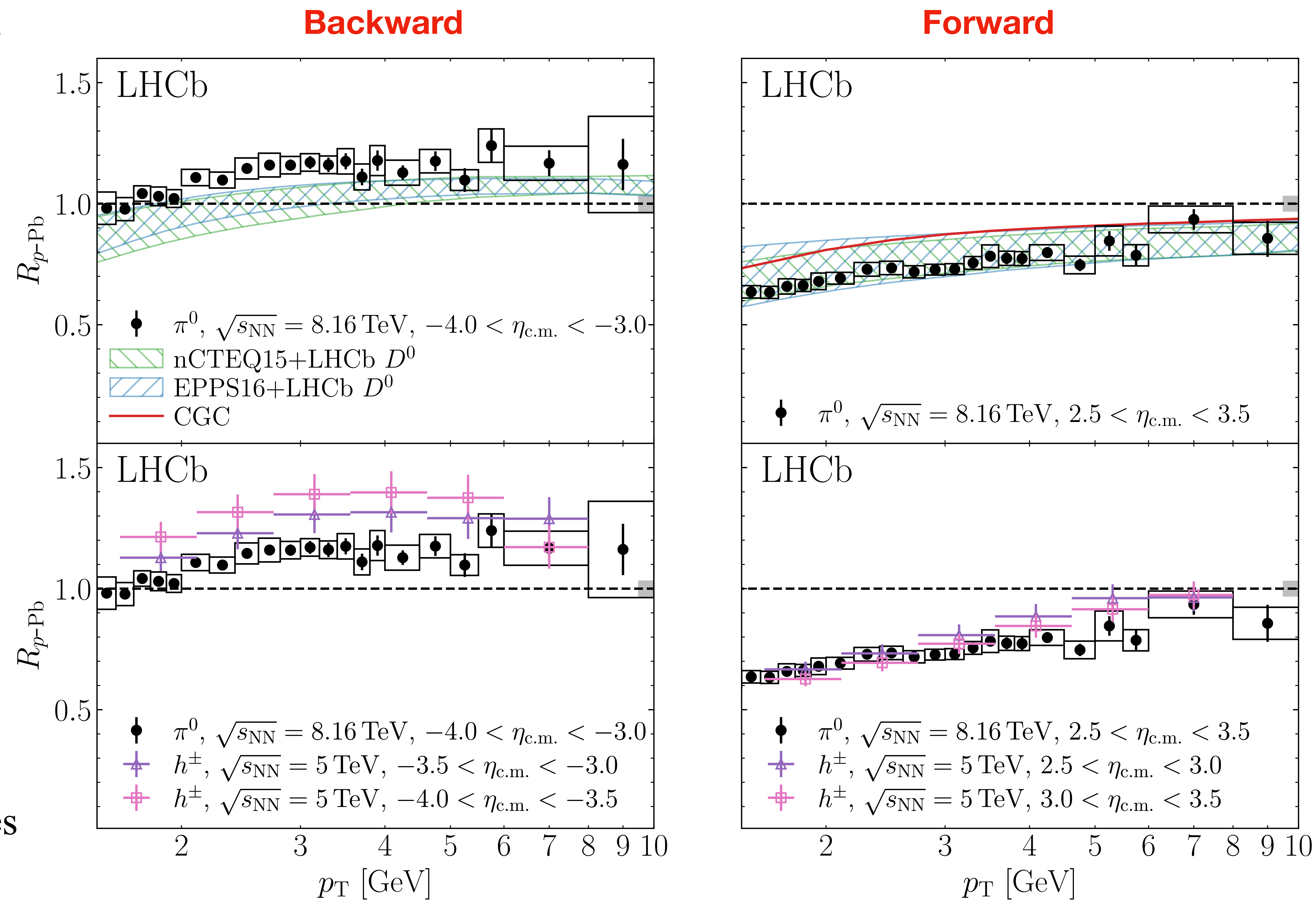
Phys. Rev. Lett. 131 (2023) 042302

Forward

- The nuclear modification factor shows a strong suppression.
- The measurement is also compared to the charged-particle nuclear modification factor by LHCb.
- The data can provide powerful constraints on nPDF at low x.

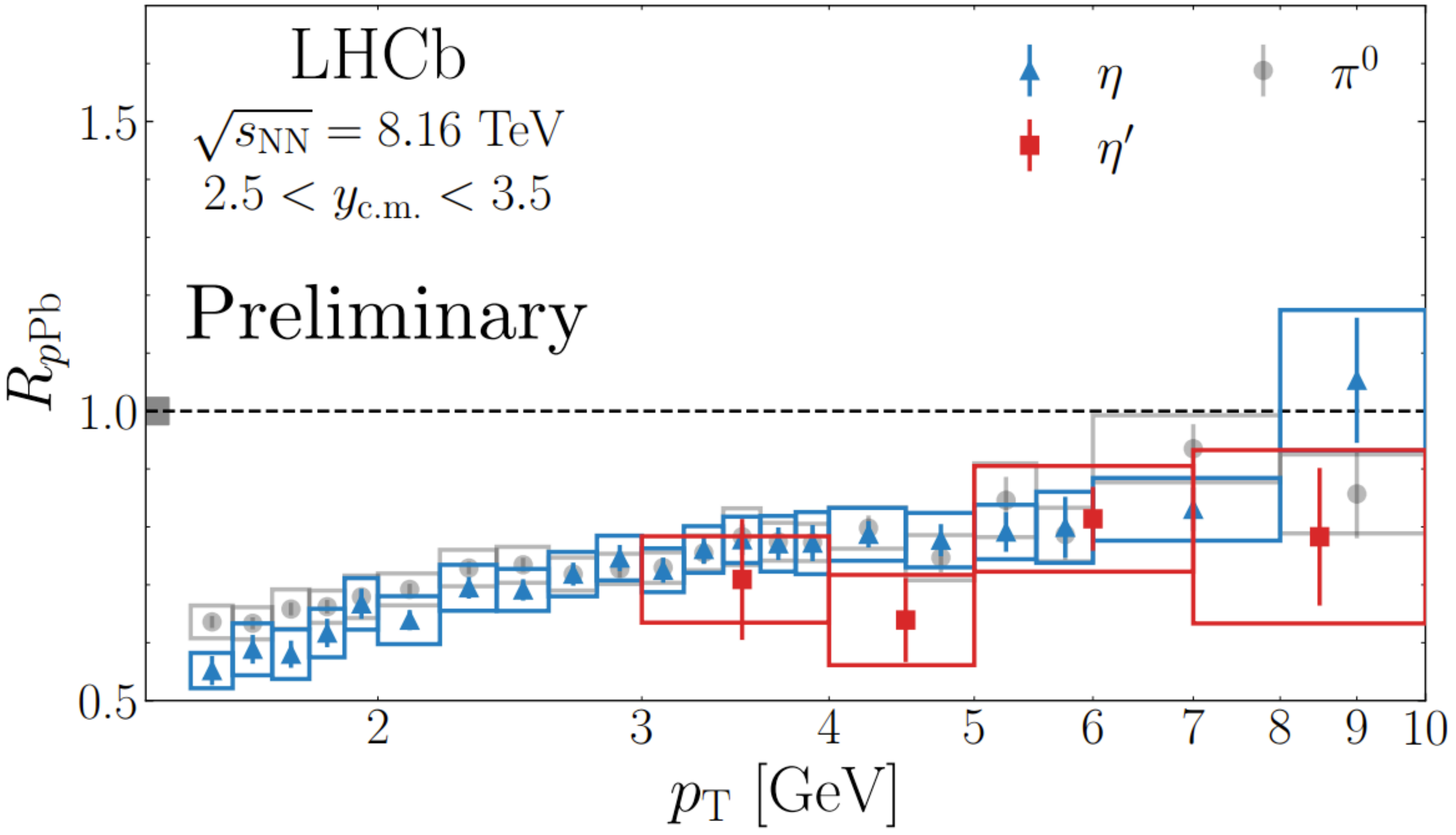
Backward

- Enhancement of π^0 production with respect to pp at intermediate p_T.
- The enhancement is smaller than the charged particles, presence of heavier baryons may explain this : studies of other identified particles $(p, K, \eta^{(\prime)})$.

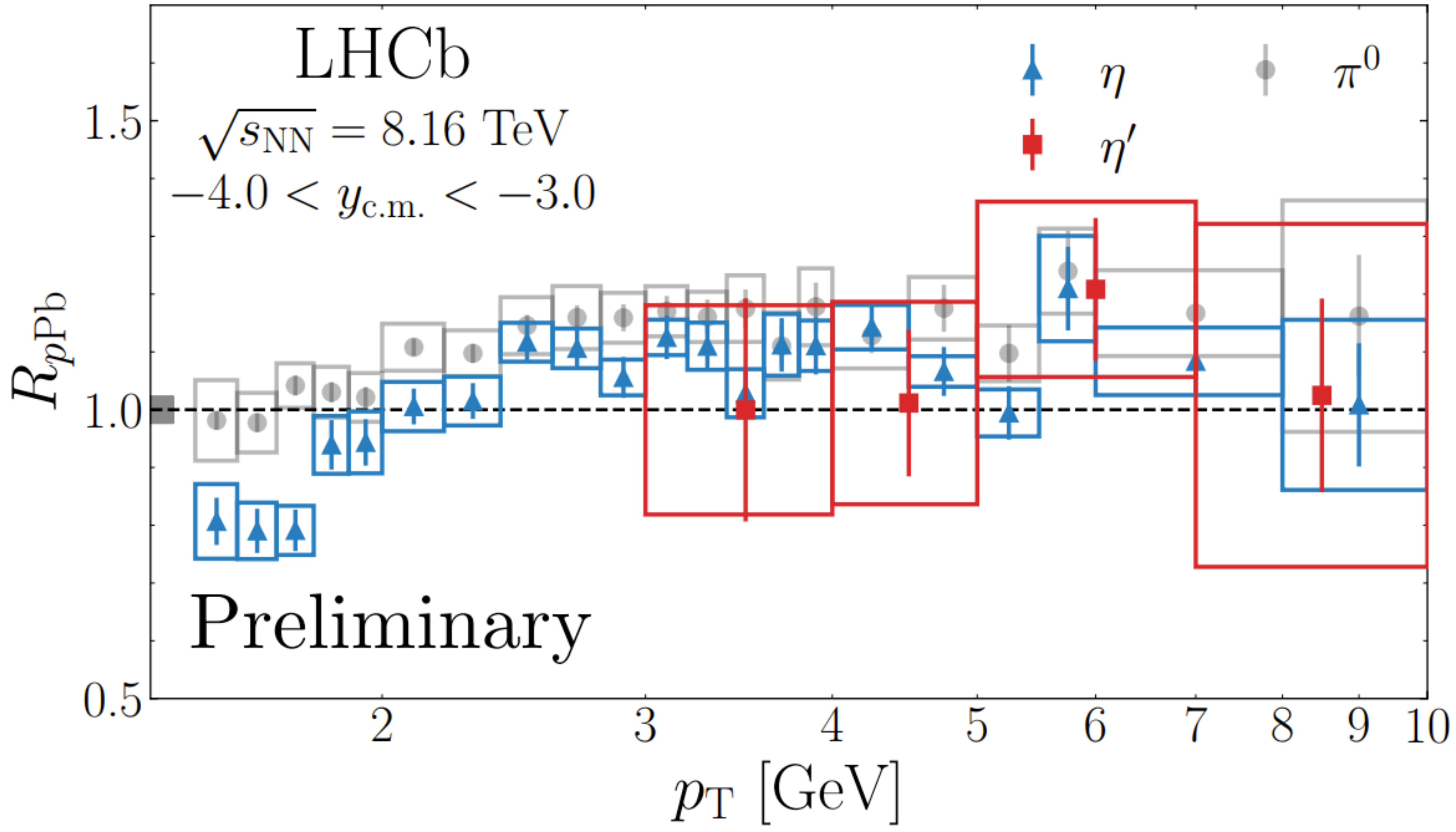


New : η and η' production in pPb at $\sqrt{s_{NN}} = 8.16$ TeV

Forward



Backward LHCb-PAPER-2023-030



- Forward: the observed suppression is consistent with the effect of nuclear shadowing.
- Backward: the π^0 and η measurements deviates at low p_T then converge at $p_T > 3$ GeV.

- First study of $\eta \to \gamma\gamma$ and $\eta' \to \pi^+\pi^-\eta$ at forward rapidity at the LHC.
- Nuclear modification of η, η' and π^0 all agree with each other within large uncertainties.
- No clear evidence of mass dependence.

Recent nPDF global fits: Where can LHCb contribute?

PoS LHCP2022 (2023) 137

Data from LHC

	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

Recent nPDF global fits: Where can LHCb contribute?

LHCb has huge impact on nPDFs, future plans include:

- Identified hadron production measurements ($\pi^{\pm}, K^{\pm}, p$) that will help to disentangle low-x effects from hot QCD.

PoS LHCP2022 (2023) 137

π^0 pPb data from LHCb are still to be included.

	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

Recent nPDF global fits: Where can LHCb contribute?

LHCb has huge impact on nPDFs, future plans include:

- Drell-Yan production in high luminosity pPb will provide a clean probe of nPDFs.

PoS LHCP2022 (2023) 137

	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
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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

Recent nPDF global fits: Where can LHCb contribute?

LHCb has huge impact on nPDFs, future plans include:

- Possible proton-Oxygen data during Run 3.

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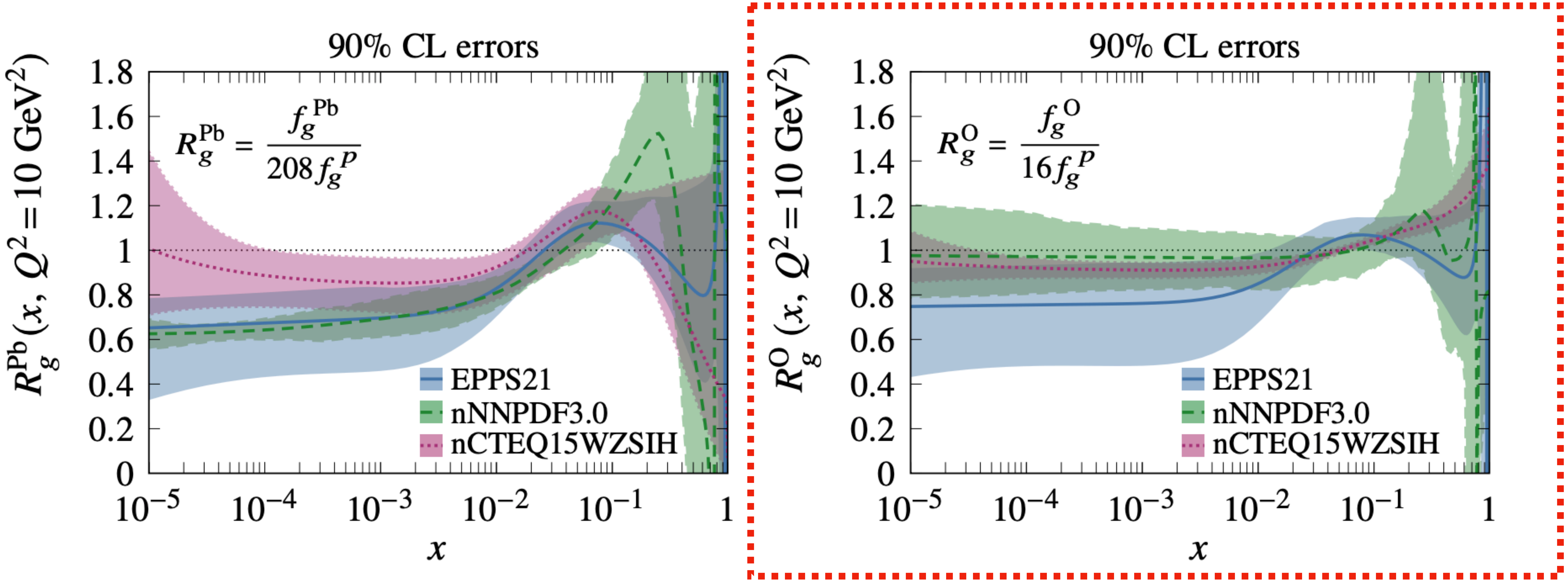


At large x: the gluon modification is poorly constrained for also light nuclei.
p- (lighter-than-lead) data are needed.

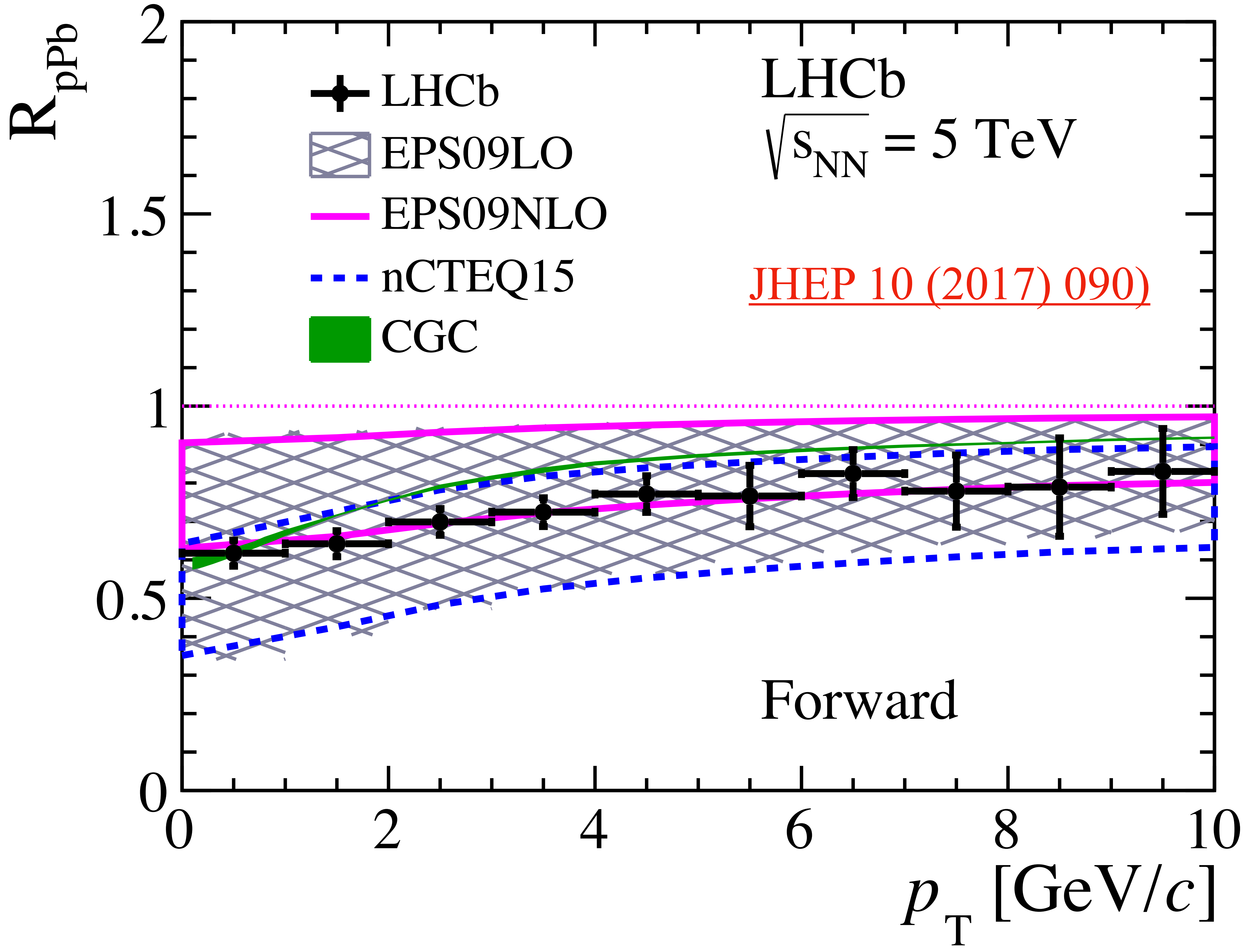
Conclusion

- LHCb previous data had a huge impact on the nPDFs.
- Measurements of identified particles in *p*Pb are currently being studied and will shed the light on the mass-ordering effect.
- Sample size limitation in some measurements will be improved with Run3 data.
- Fixed-target *p*A collisions with SMOG2 can provide future measurements that can constraint the nPDFs at high-x. (see Kara Mattioli talk).

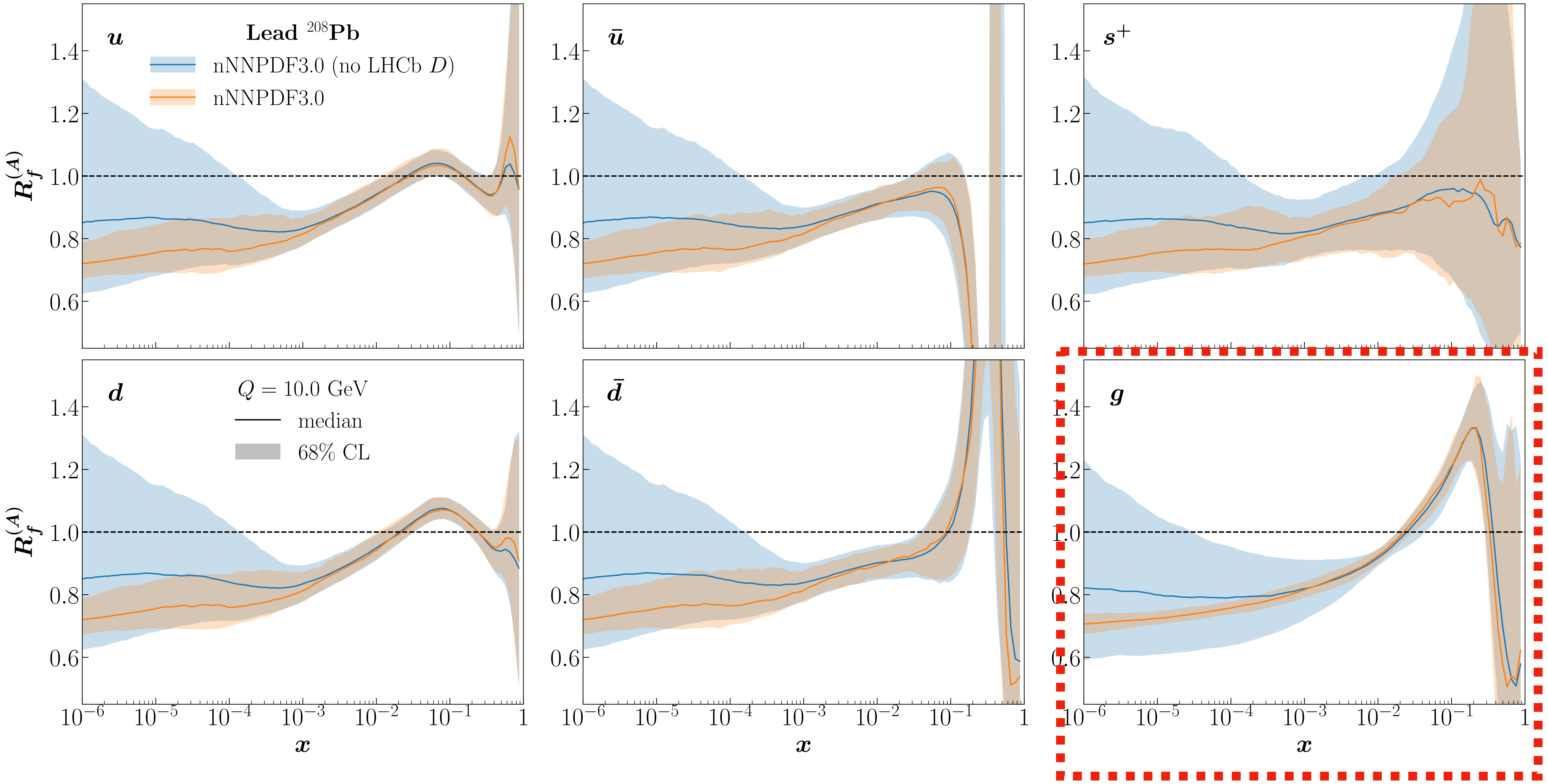
Backup

LHCb's impact on nPDF fits: nNNPDF3.0

Nuclear modification factor: $R_{pPb} = \dfrac{d\sigma_{pPb}/dp_T d\eta}{208 \cdot d\sigma_{pp}/dp_T d\eta}$



EPJC 82 (2022) 6, 507



LHCb D^0 meson data have a huge impact on the nPDF uncertainties.