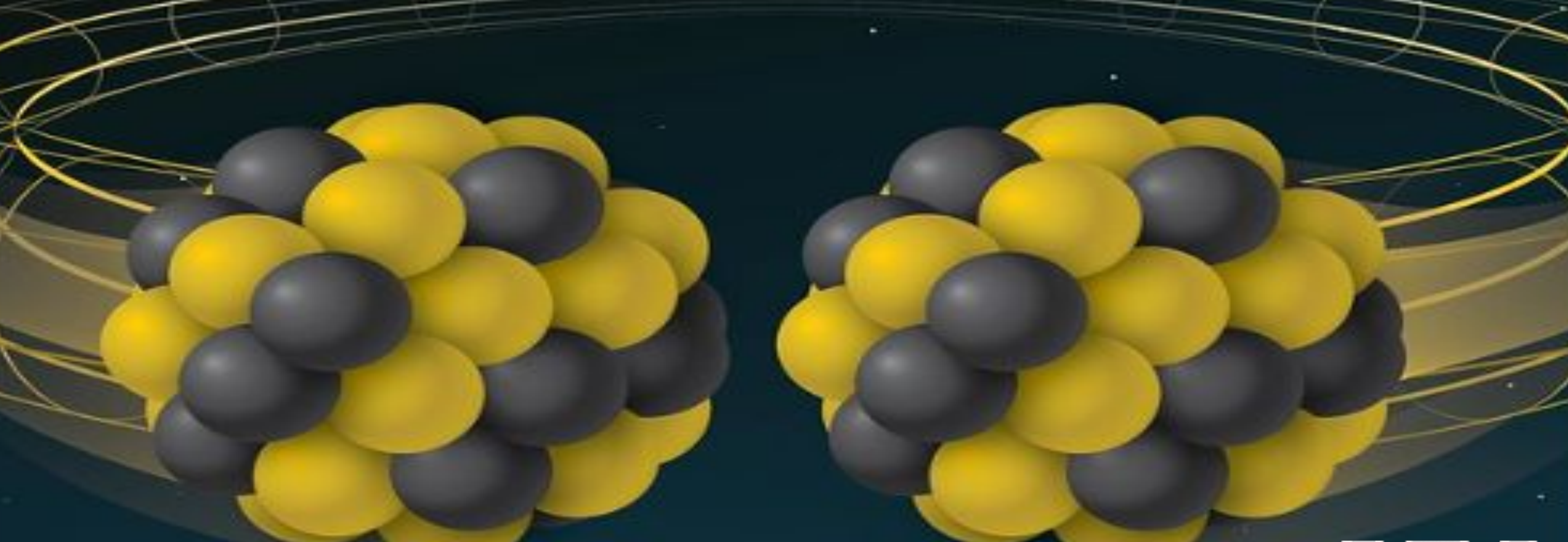


U.S. DEPARTMENT OF
ENERGY
Office of Science

KU

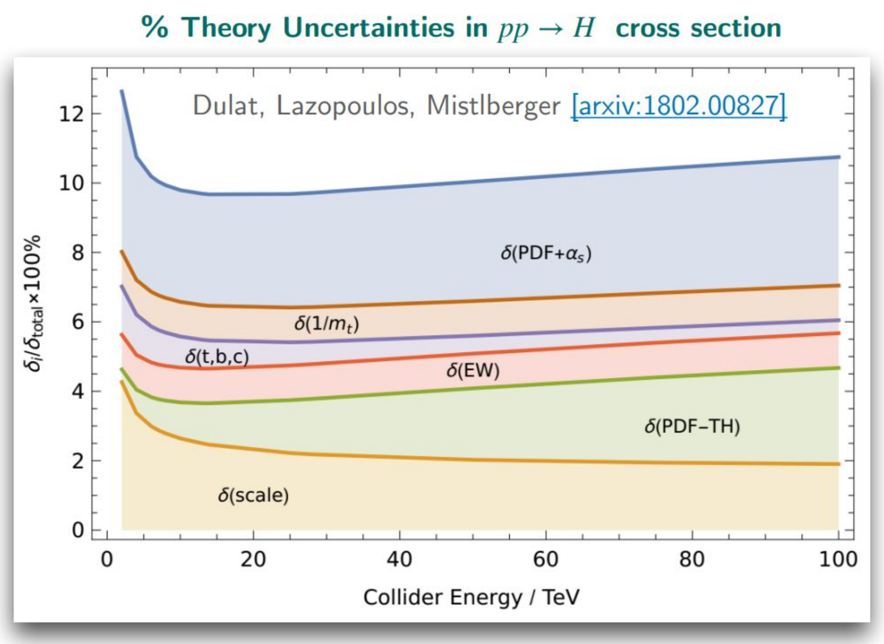
Recent results relevant for PDFs at low and high x, saturation in pp and HI collisions from CMS

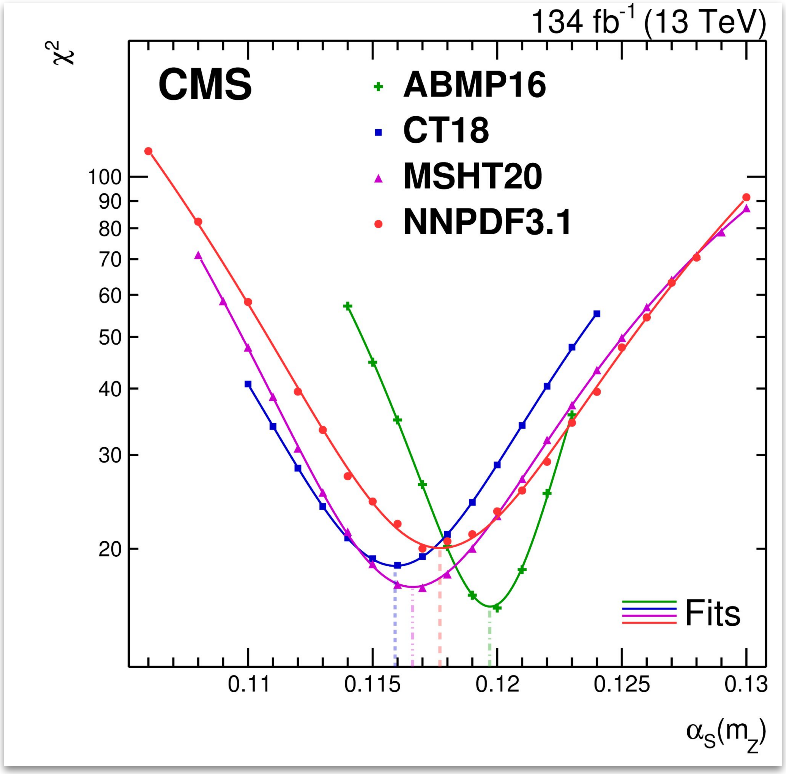
Georgios K Krintiras

Diffraction and Low-x 2024

PDF precision

Eur. Phys. J. C 84 (2024) 842



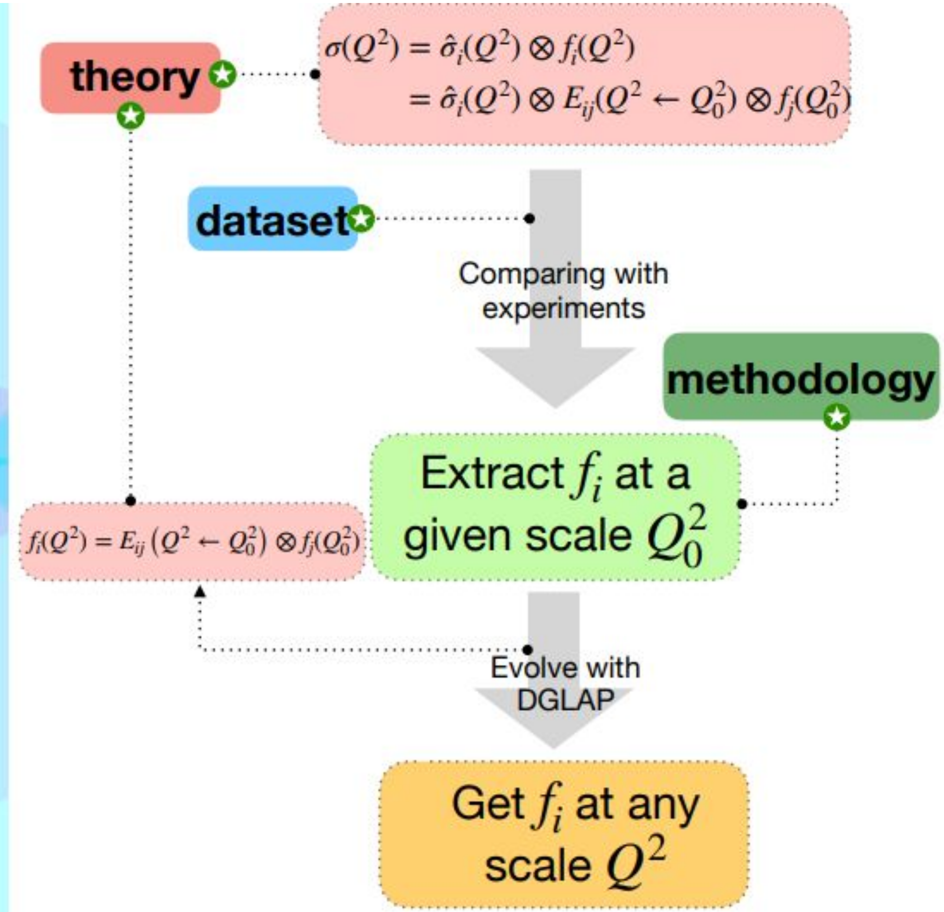


- Many $2 \longrightarrow 1$ processes available at N^3 LO QCD
- PDF+α_s uncertainties **bottleneck** for LHC precision
- Nontrivial differences in PDF sets

PDF phenomenology

N. Laurenti (ICHEP 2024)

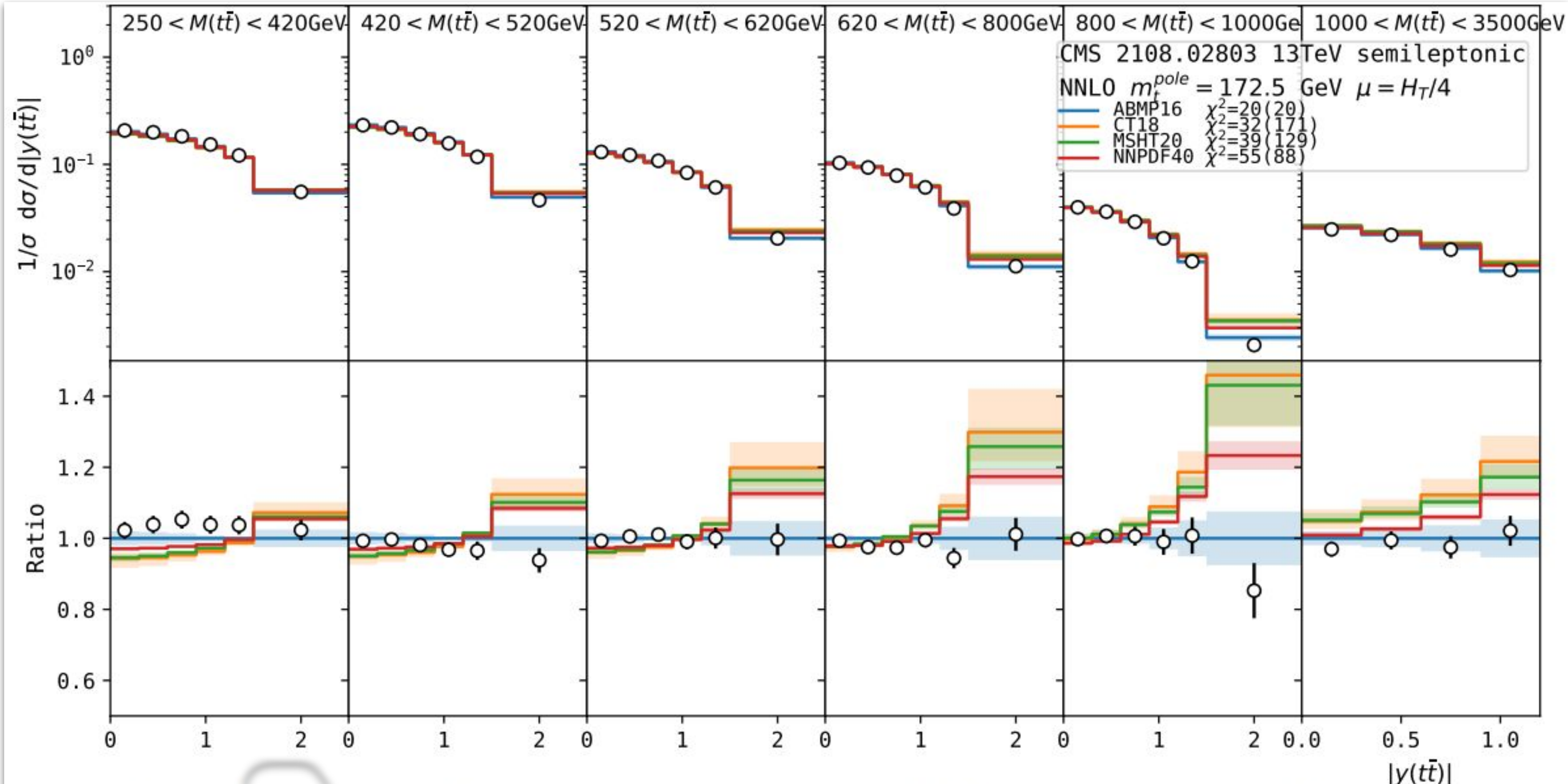
- How are the PDFs fitted?
- We have to define a **theory**
- We have to choose a **dataset**
- We have to choose a fitting **methodology**



- **aN^{3}LO QCD PDFs become available**
- **QED effects comparable to aN^{3}LO QCD corrections**
- **To constrain gluons: heavy-quark and jet production**

Differential tt production

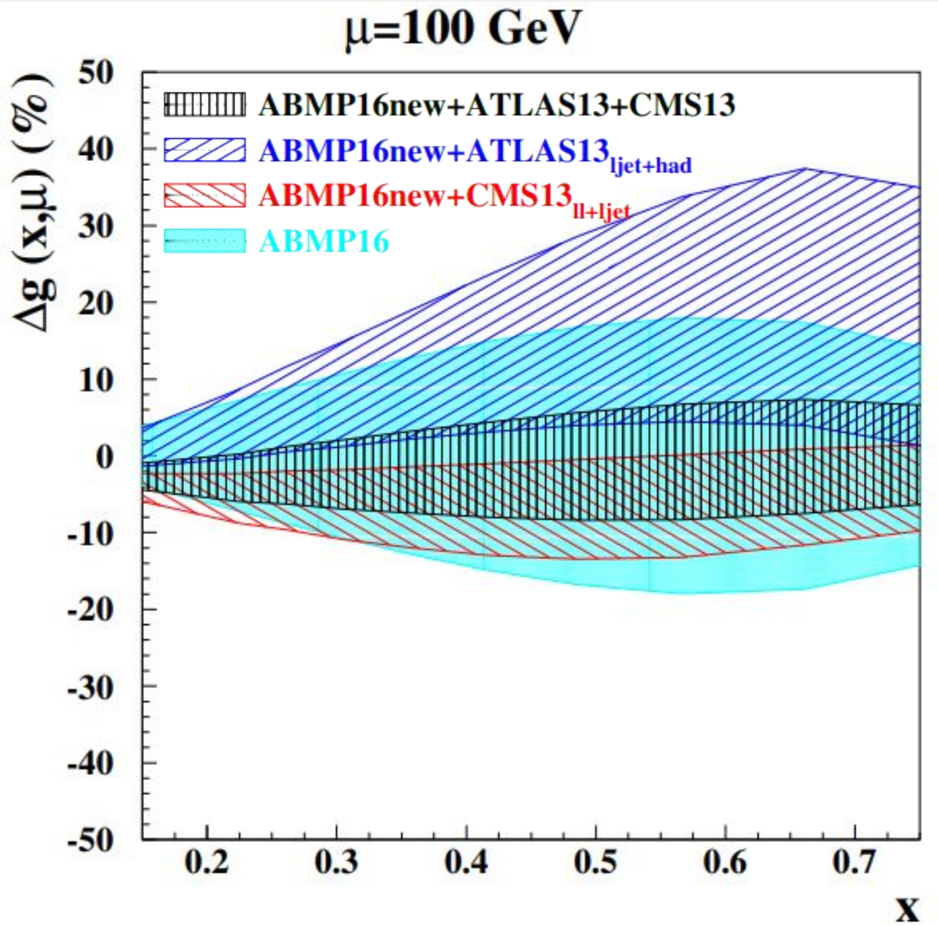
JHEP 05 (2024) 321

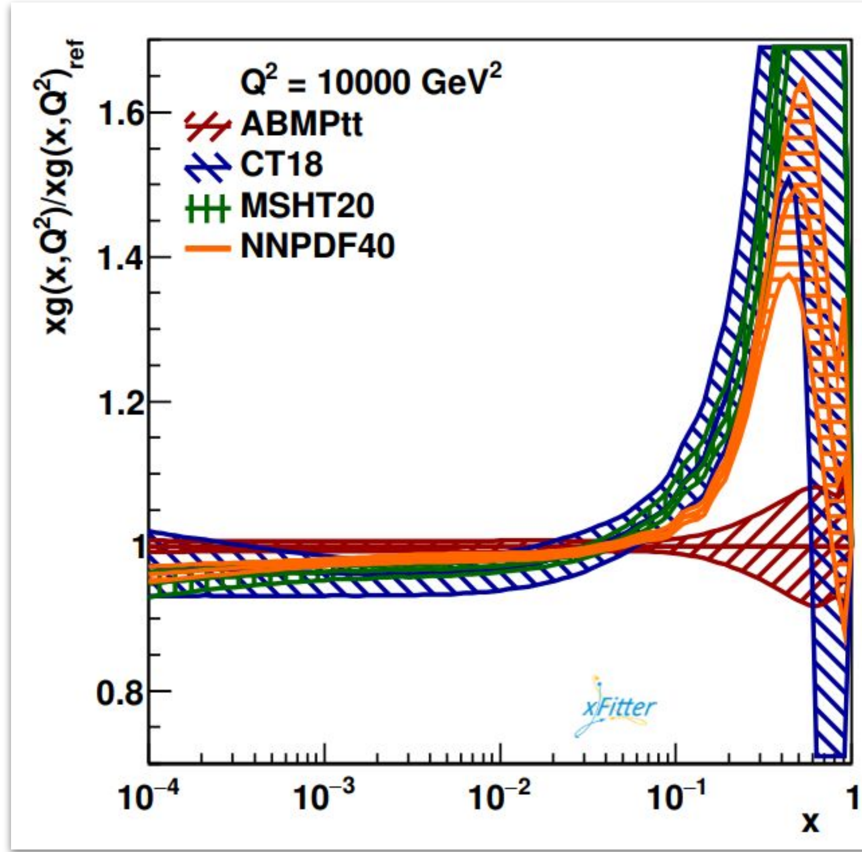


- **PDF sets describe tt data reasonably well**
- **Clear trend at high y (large *x*)**

Global fits with top quark data

2407.00545

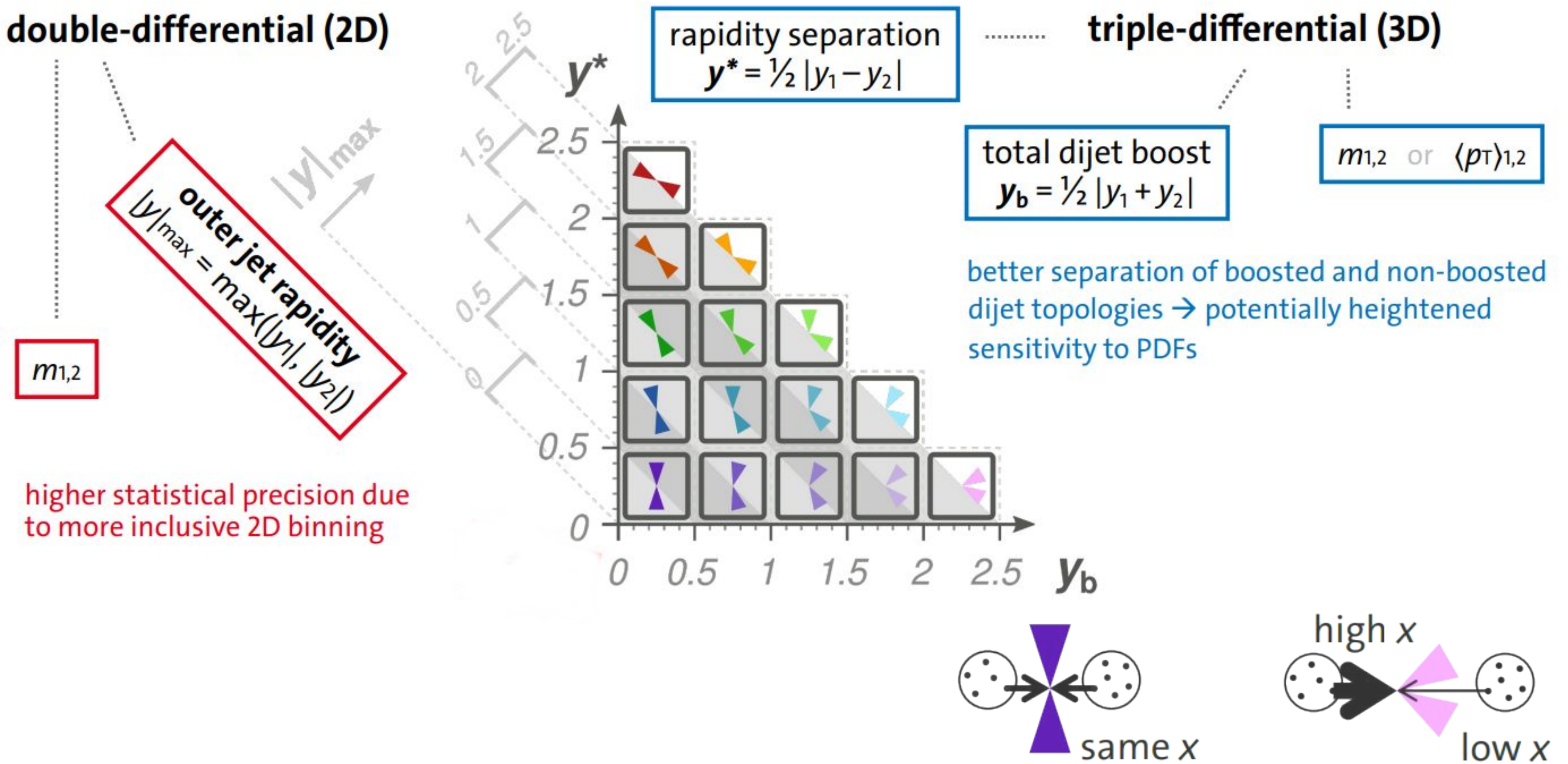




- **Improvements** when including tt and single t data
- **Differences at high *x*** among global fits persist

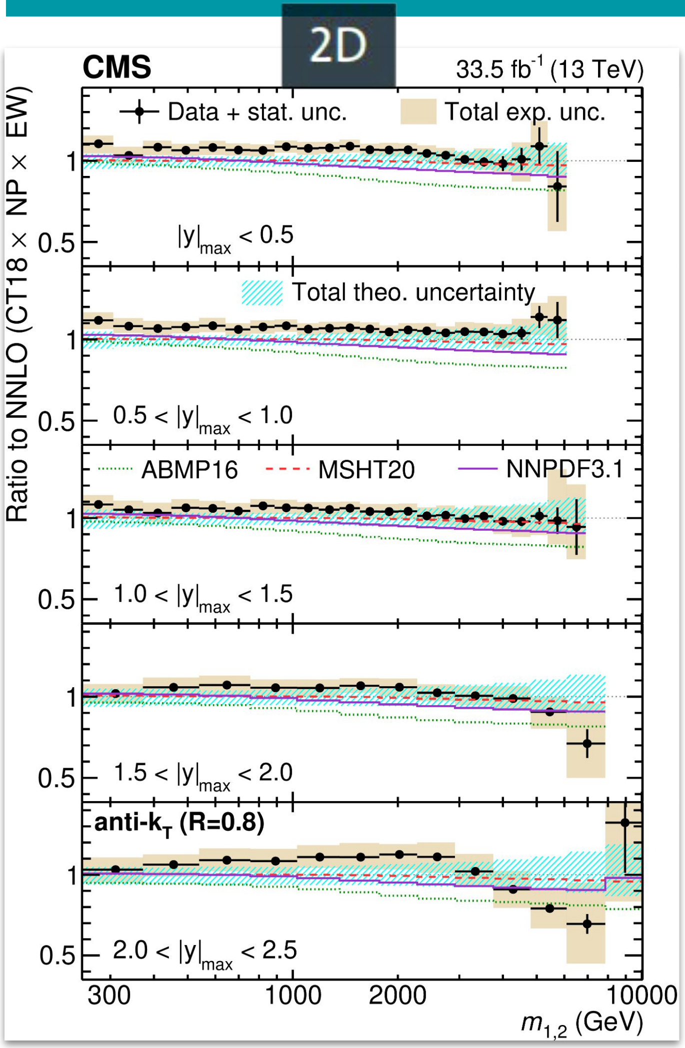
Dijet topologies

2312.16669

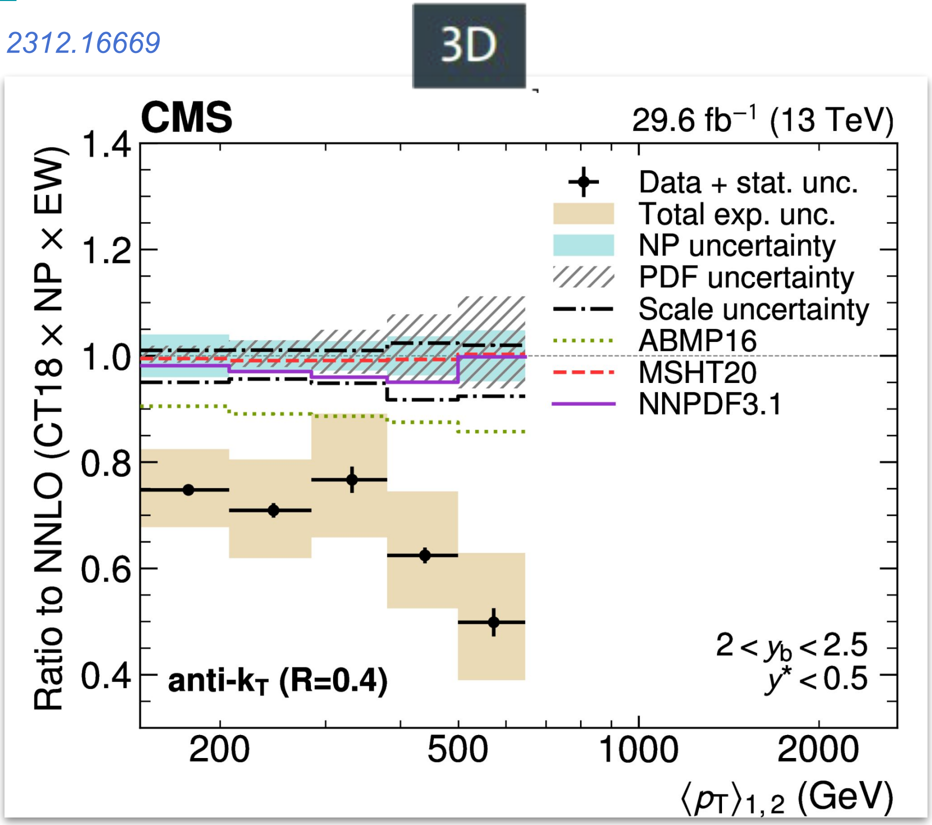


- **Disentangling regions of different x → PDF fits**

2D&3D dijet cross sections



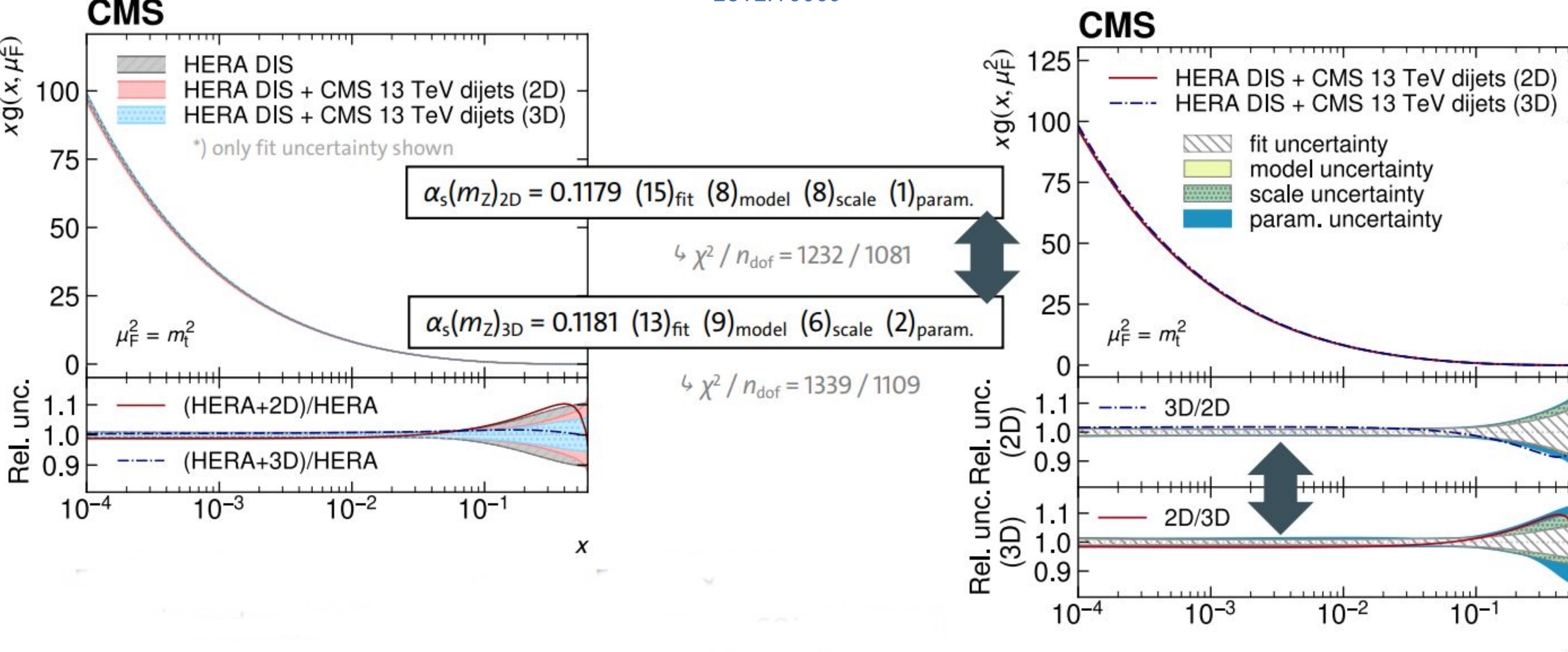
2312.16669



- **Predictions for different PDFs in agreement with each other**
- **Better description for R = 0.8 than 0.4 anti-k_T jets**

Constraints to large-x gluons

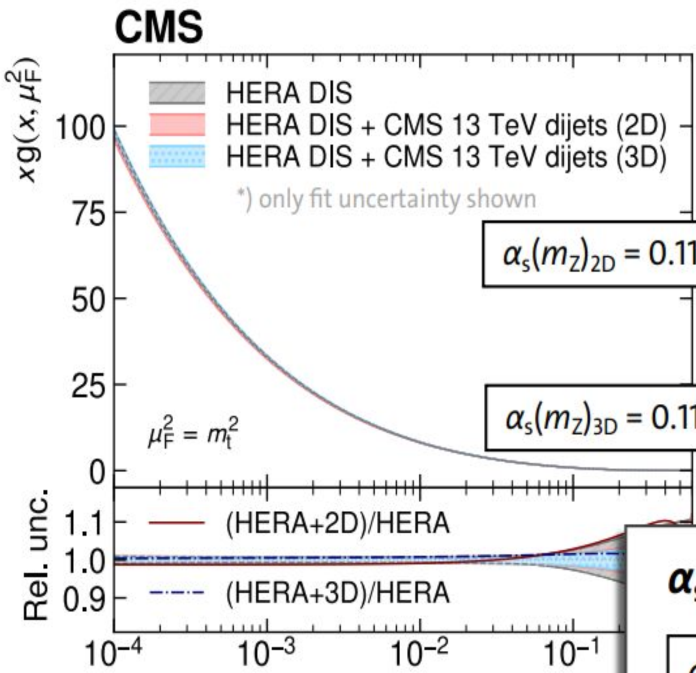
2312.16669



- gluon PDF uncertainty **halved** at x > 0.1
- 2D & 3D fits largely compatible

Comparison to inclusive jet production

2312.16669

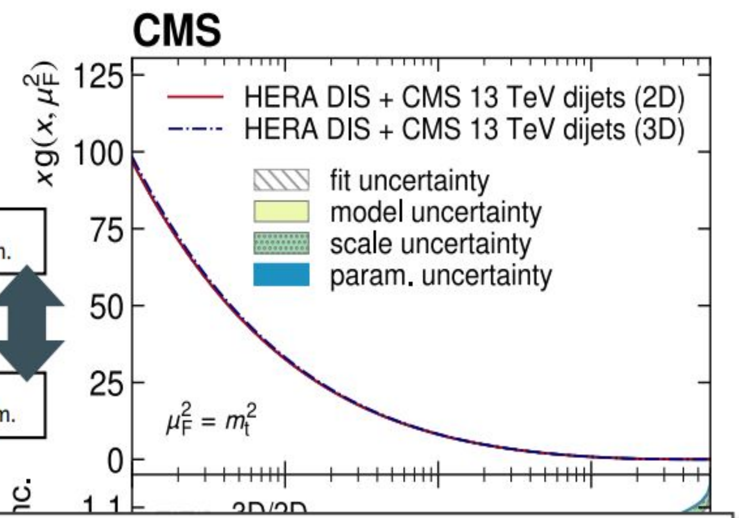


$\alpha_s(m_Z)_{2D} = 0.1179\ (15)_{fit}\ (8)_{model}\ (8)_{scale}\ (1)_{param.}$

↳ $\chi^2 / n_{dof} = 1232 / 1081$

$\alpha_s(m_Z)_{3D} = 0.1181\ (13)_{fit}\ (9)_{model}\ (6)_{scale}\ (2)_{param.}$

↳ $\chi^2 / n_{dof} = 1339 / 1109$



α_s from inclusive jet production at $\sqrt{s}$ = 13 TeV

[arXiv:2111.10431]
[JHEP 02 (2022) 142]
+ add. [JHEP 12 (2022) 035]

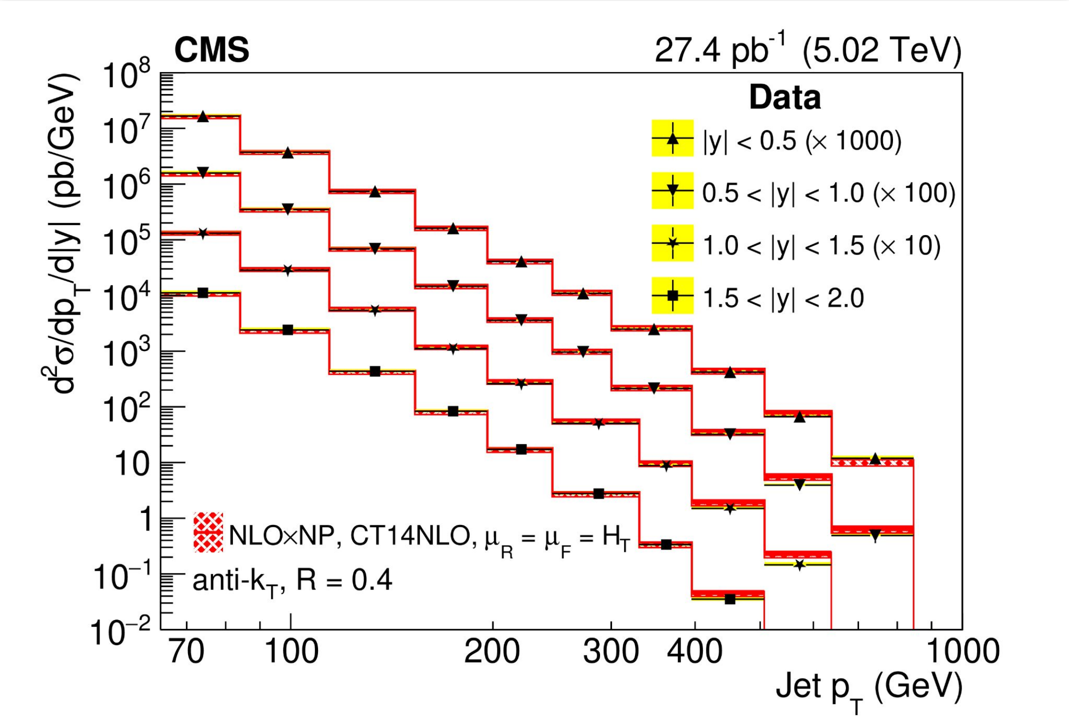
$\alpha_s(m_Z)_{incl.\,jet} = 0.1166\ (14)_{fit}\ (7)_{model}\ (4)_{scale}\ (1)_{param.}$

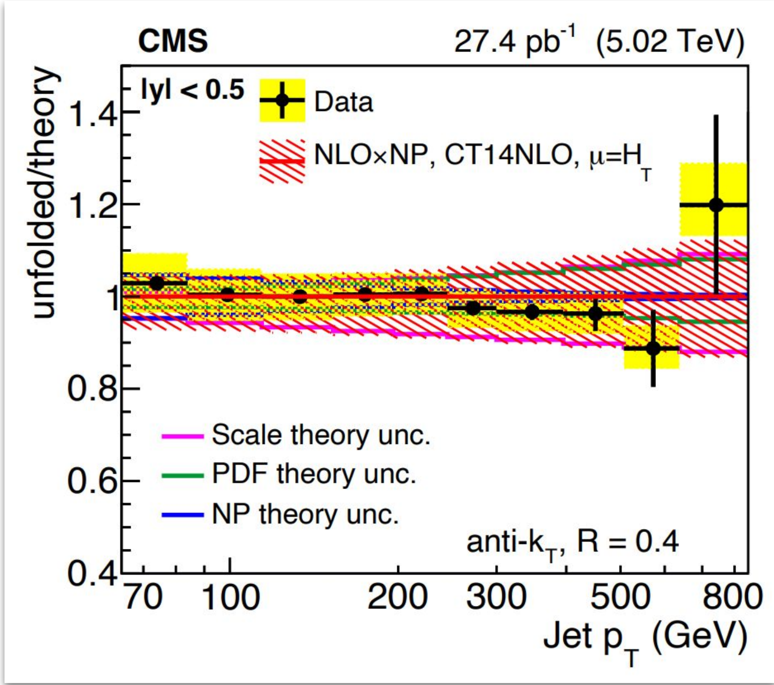
↳ $\chi^2 / n_{dof} = 1302 / 1118$

- **Comparable in precision**
- **In good agreement, also with the world average**

Inclusive jet production at 5.02 TeV

2401.11355





- **Complementary measurement at lower √s**
- **Studied for NLO & NNLO pQCD, diferent PDFs and $\mu_{R,F}$**
- **Can be used as an input to future QCD fits**

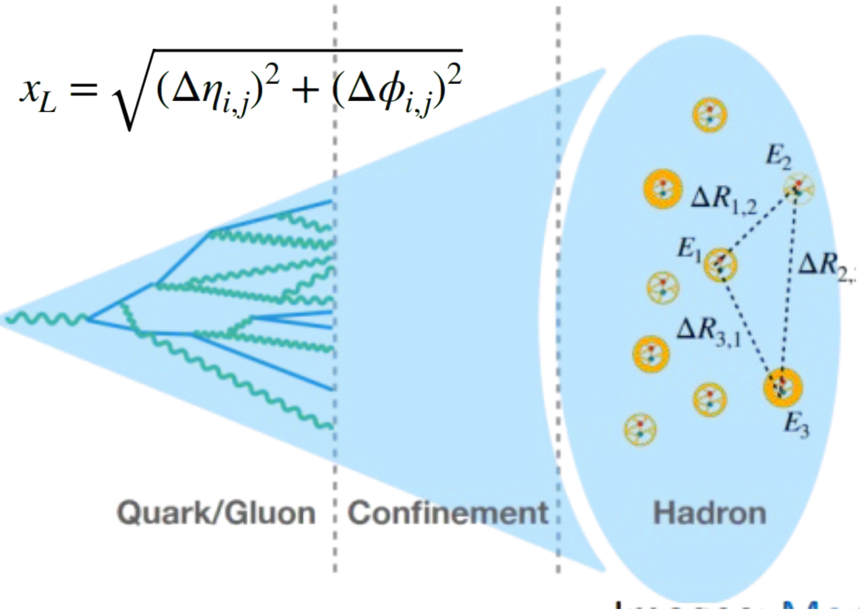
Energy correlators inside jets

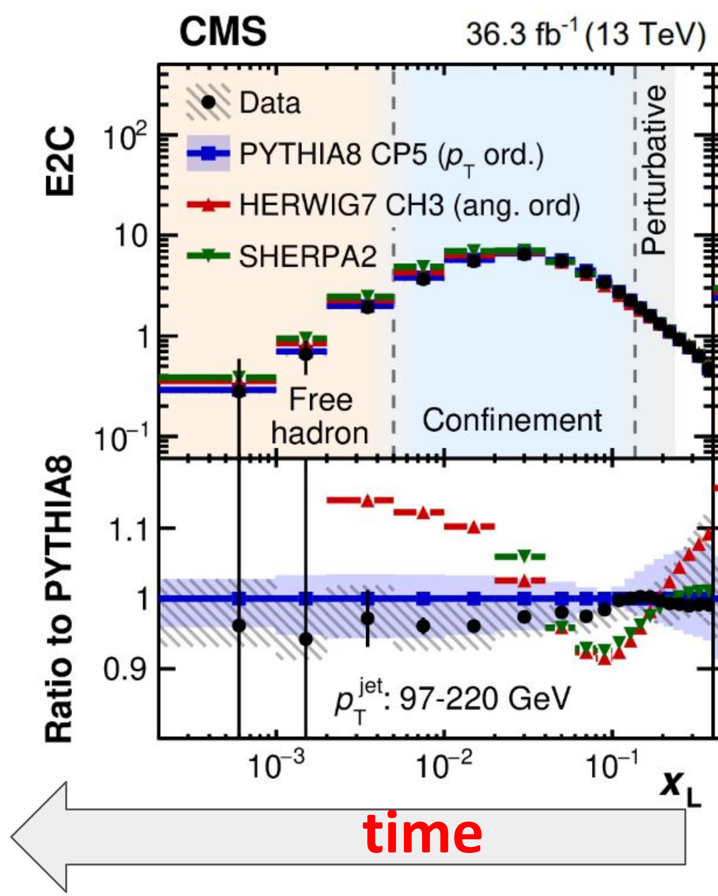
PRL **133** (2024) 071903

E2C$= \sum_{i,j} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j})$,

E3C$= \sum_{i,j,k} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k}))$

$x_L = \sqrt{(\Delta\eta_{i,j})^2 + (\Delta\phi_{i,j})^2}$



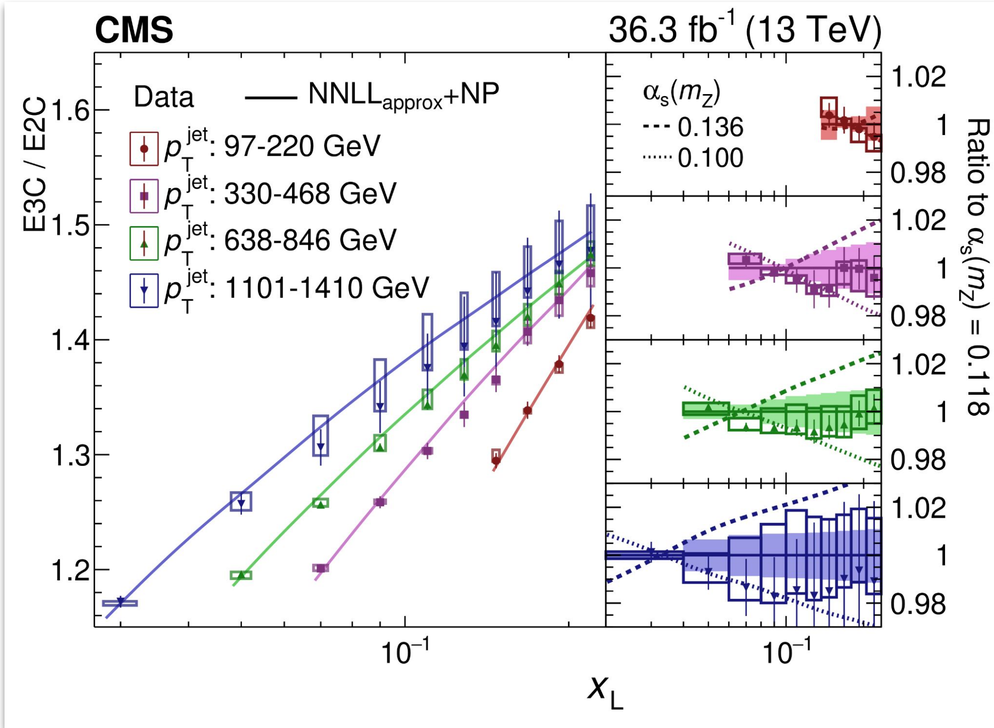


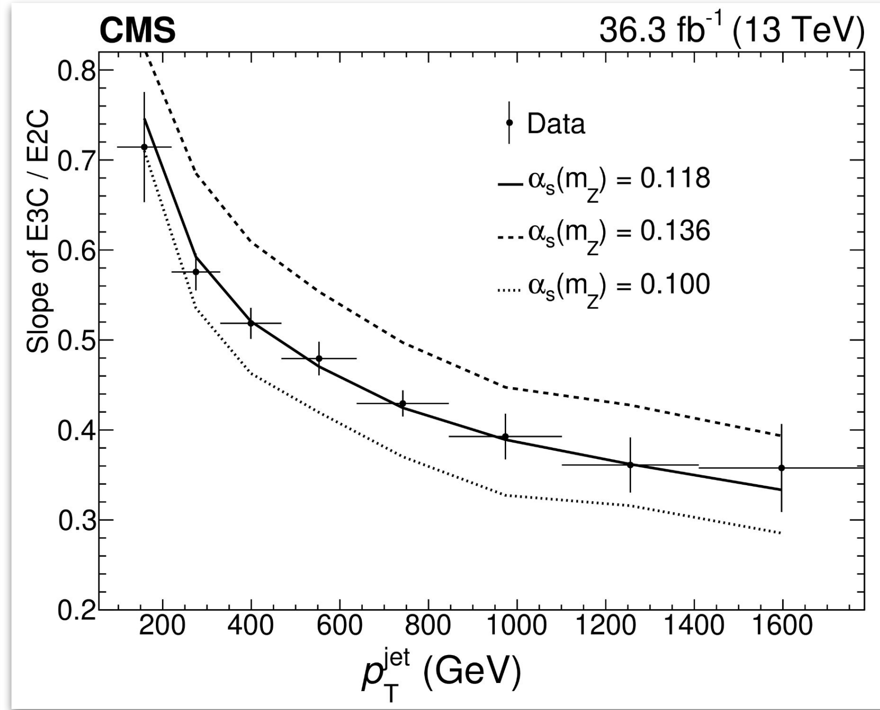
- EEC sensitive to energy flow (here both charged and neutrals)
- x_L distribution sensitive to time scale of hadron formation
- E3C/E2C ~ $\alpha_s(Q) \ln x_L + O(\alpha_s^2)$ with no PDF dependence

Energy correlators inside jets

*PRL **133** (2024) 071903*

$$\alpha_s(m_Z) = 0.1229^{+0.0014}_{-0.0012}\ (\text{stat})^{+0.0030}_{-0.0033}(\text{theo})^{+0.0023}_{-0.0036}(\text{exp})$$

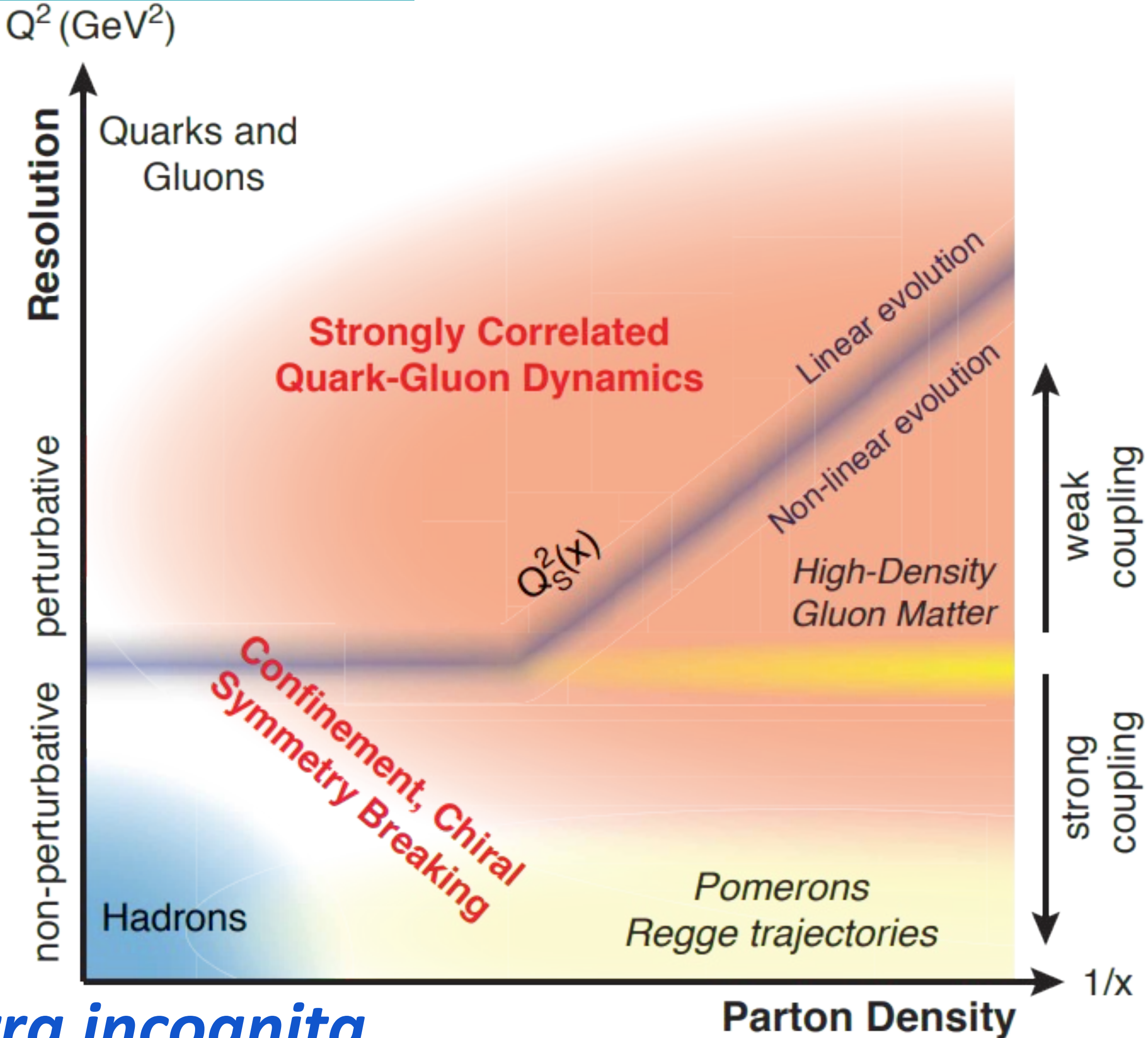




- Extracted α_s at NLO + NNLL$_{\text{approx}}$ (large x_L region)
- The most precise α_s measurement from jet substructure
- Δ(E3C/E2C)/Δ log x_L ~ $\alpha_s(Q)$ → running of α_s

The “cold QCD” landscape

arXiv: 1708.01527

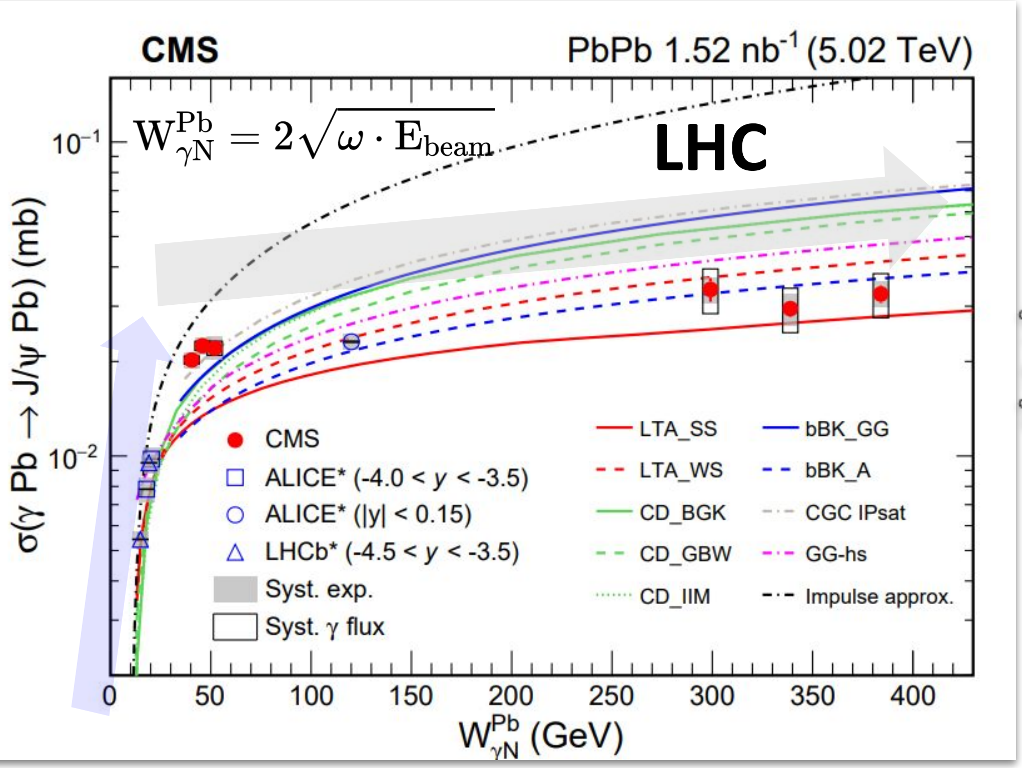


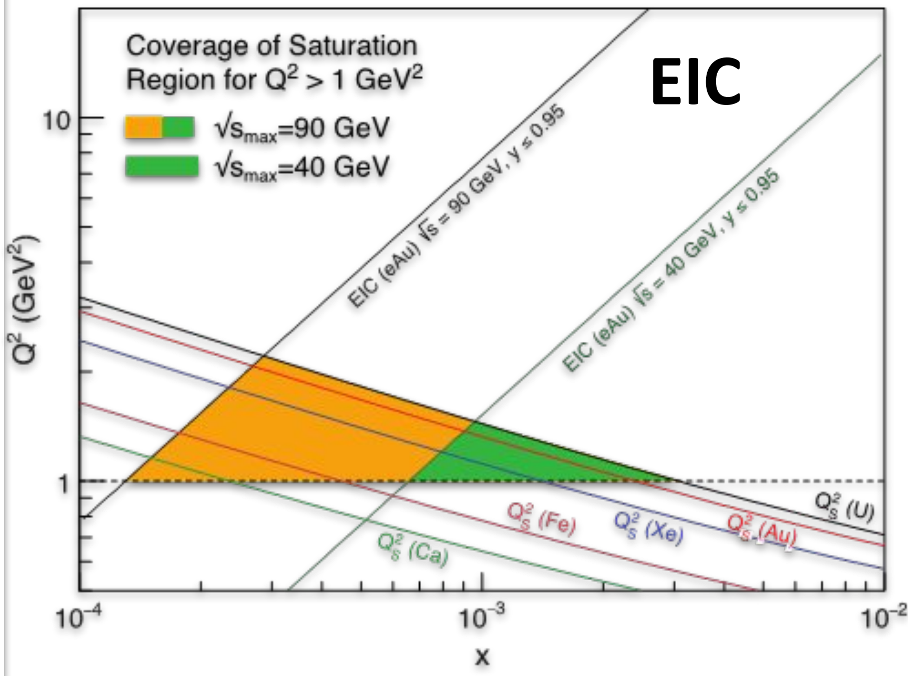
- Mostly *terra incognita*
- Hadron properties the result of the confined q/g
- A novel regime of QCD may exist: gluons saturate?

Gluon factories

arXiv: 2303.16984
arXiv: 2103.05419

$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$



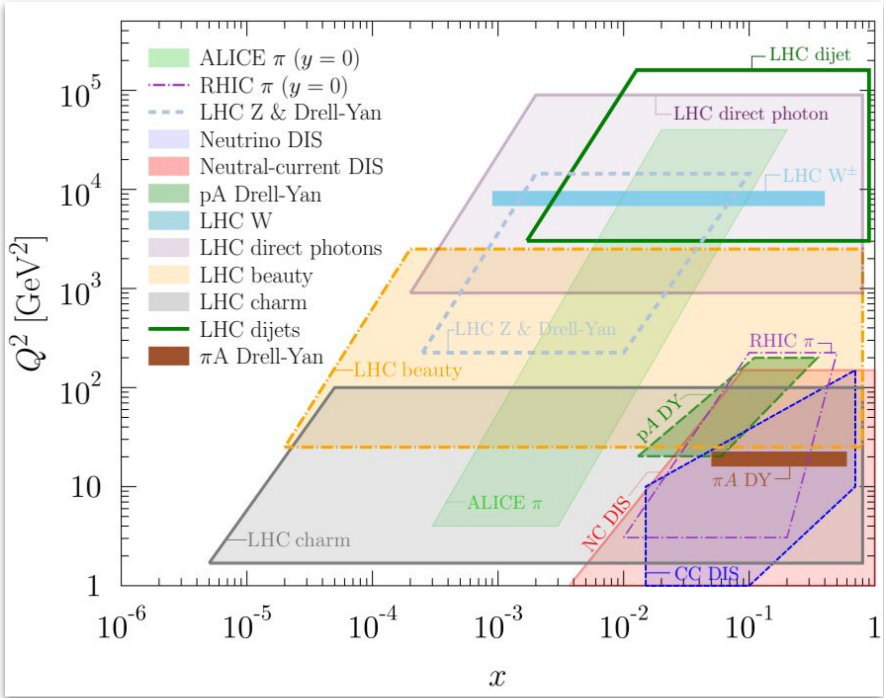


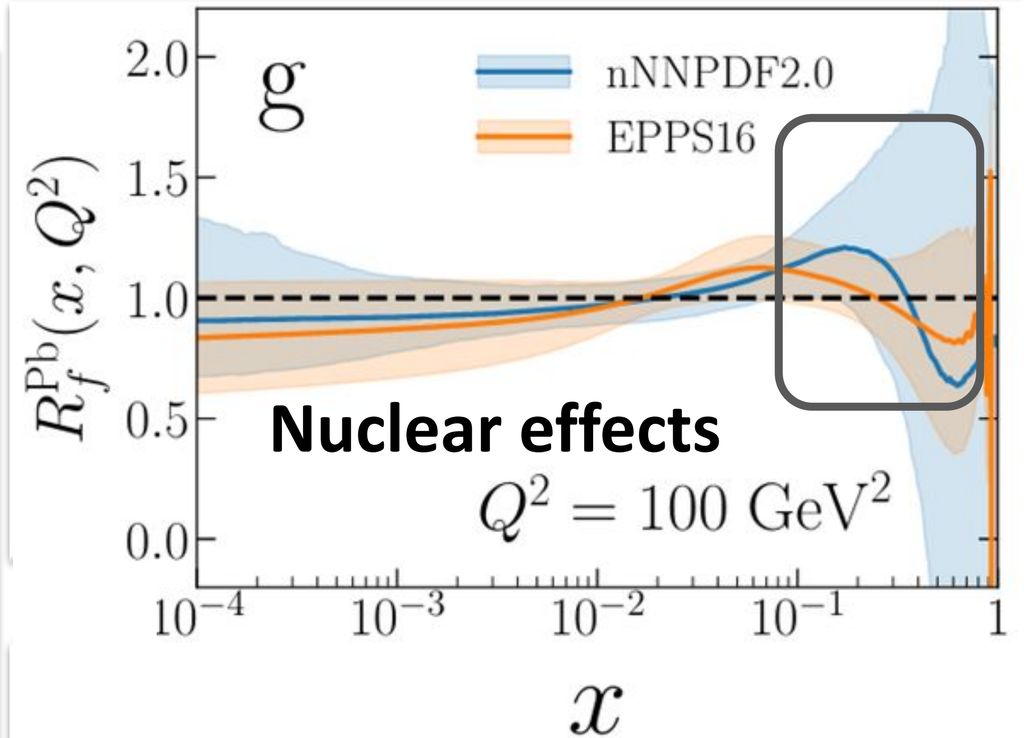
- **We see a milder energy dependence than predicted**
  - gluon saturation? if so, independent of particle species
- **Accessible Q_s values at EIC thanks to ion species and energies**

Explore LHC with more particles; EIC can probe a new state of matter

nPDFs: long way to go

arXiv: 2203.13923
JHEP 09 (2020) 183



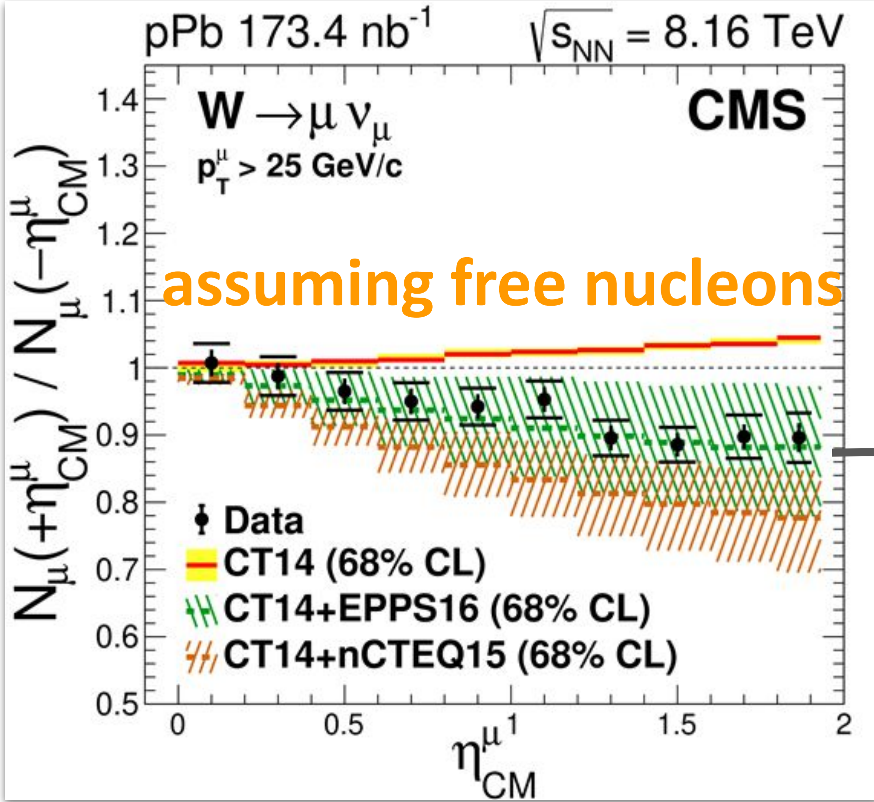


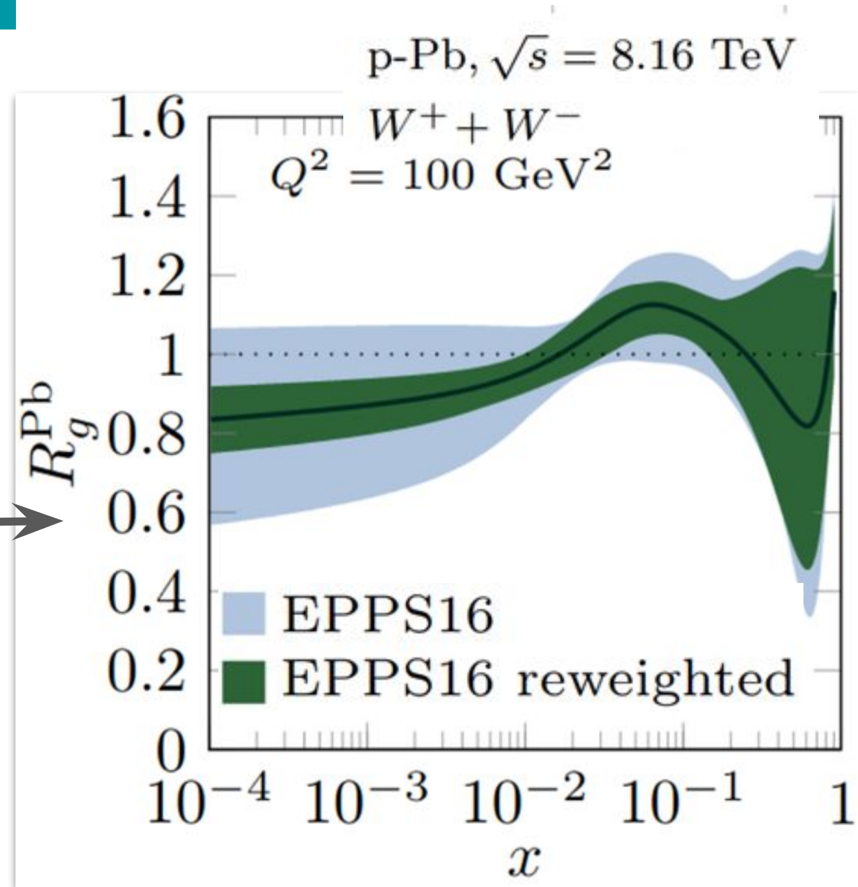
- **LHC data gave an increase in kinematic coverage**
- **The modification of gluons not well understood (especially at high *x*)**
  - **available data sets limited**

Can we do better?

Tools for **precise** nPDF extraction

PLB 800 (2020) 135048





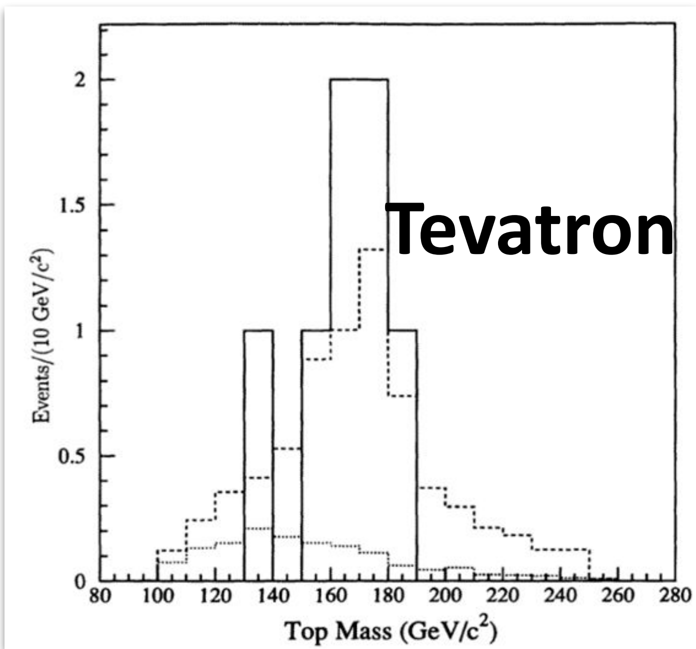
- **LHC data reduced the gluon nPDF uncertainty**
- **The large-*x* (> 0.1) region is not affected though**
  - **only dijets and top quarks probe this *x* region**

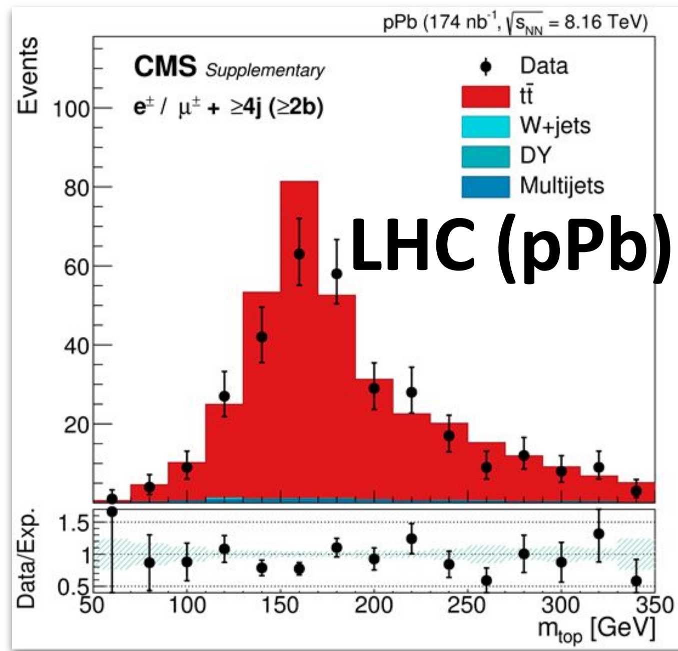
LHC data unique chance to pin down nPDF uncertainties

Tools for "inaccessible" nPDFs

PRL 119 (2017) 242001 (**editor's suggestion**)
PRL 73 (1994) 225 (PRL Retrospective)

- **Top quark observed at Tevatron**
  - **further studied in pp collisions at LHC**
- **Established a top quark program in the nuclear environment**
  - **going from baseline ("reference" pp) → pPb → PbPb data**





1995	2009	2015	2016	2017	2020
Top at Tevatron	*Top at LHC (7 TeV)*	*Top at 13 TeV*	*Top at 5.02 TeV*	*Top in pPb*	*Top in PbPb*

Top quarks can constrain gluons in so far inaccessible regions

Heavy flavor data

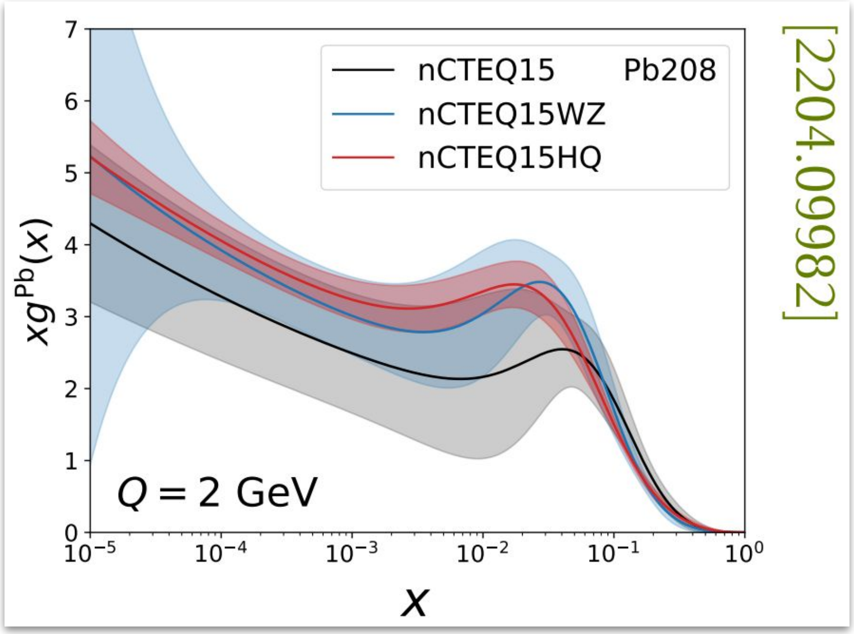
Ann. Rev. Nucl. Part. Sci. (2024)

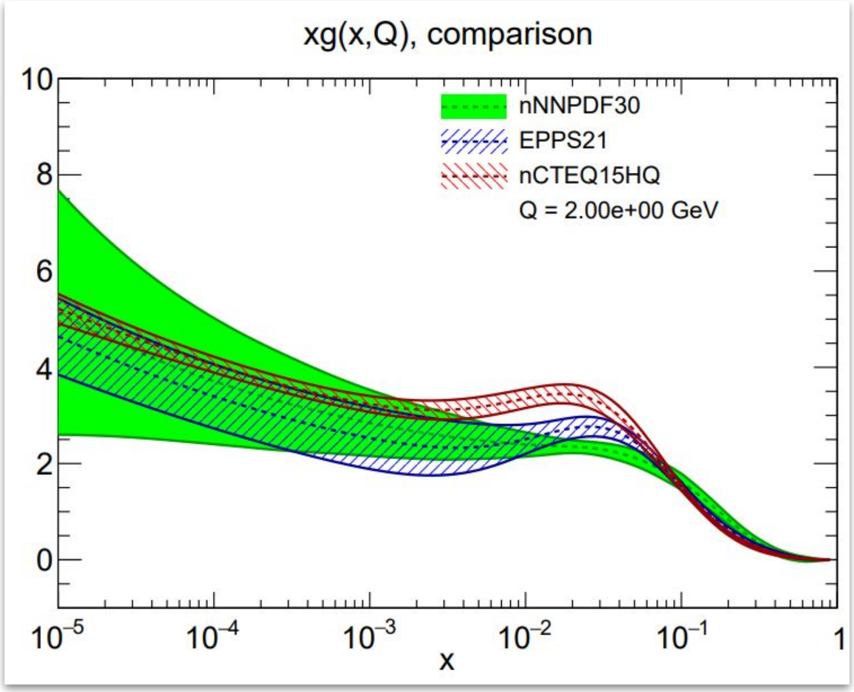
Observable $\mathcal{O}$	D^0	J/ψ	$\Upsilon(1S)$	$\psi(2S)$	B^0, $B^\pm$	c jet	b jet
Run-I:							
ATLAS		(240, 241)[a]	(241)[a]	(241)[a]			
CMS		(242)[a]	(243)	(244)[a]		(245)	(246)
ALICE	(247, 248, 249)[a]	(250, 251)[a], (252)	(253)	(254)[a]			(255)
LHCb	(256)[a,b,c]	(257)[a]	(258)				
Run-II:							
ALICE		(259)[a], (260)	(261)[a]	(262)[a]			
LHCb	(263)	(264)[a]	(265)[a]		(266)		
Fixed target:							
LHCb	(267, 268)	(267, 269)		(269)			

[a] included in nCTEQ15HQ (50); [b] included in EPPS21 (51); [c] included in nNNPDF3.0 (52).

- **A series of HF (quarkonia and open HF) data included in nPDFs**

Impact on low-*x* gluons





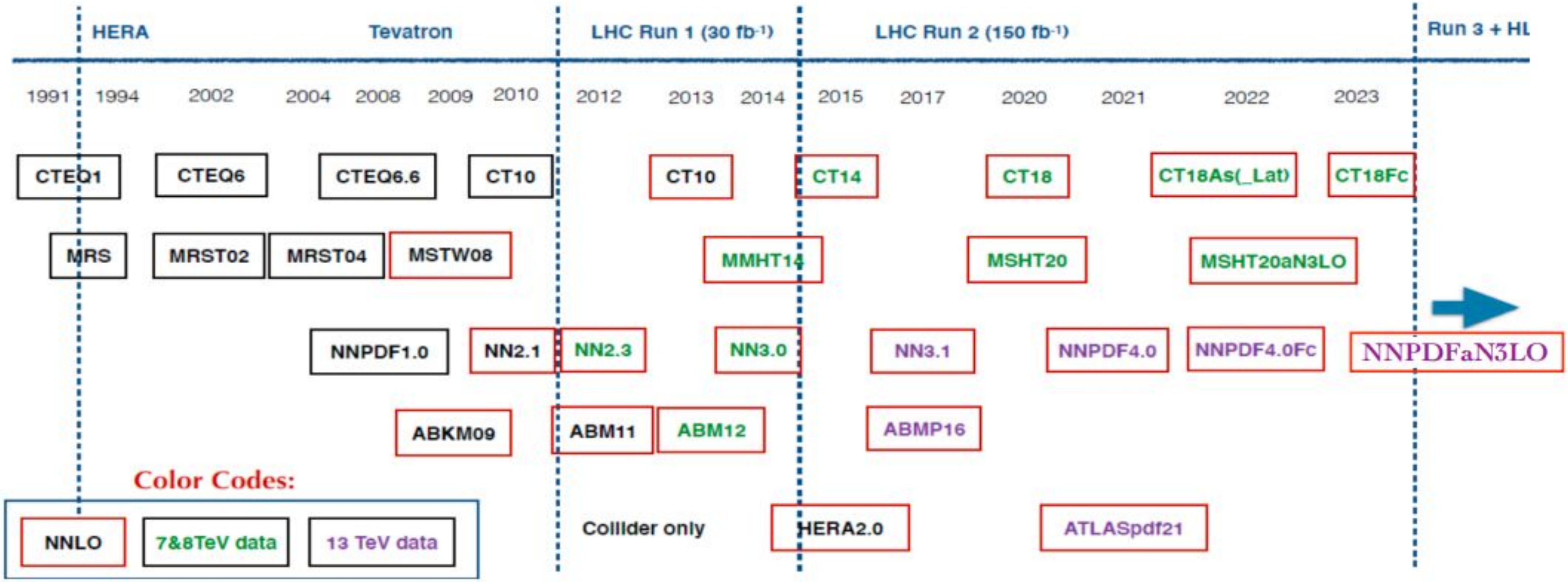
- **Clear impact of HF data on top of the EW production**
- **Similar shapes, but reduced uncertainties in nCTEQ15HQ**

Outlook

- The interpretation of LHC measurements depends on the the PDF+α_s accuracy and precision
  - wrong PDFs can in principle mimic EFT corrections
- PDF coverage and precision is increasing, uncert. reduce
  - agreement among sets not always as good though
- Bound gluon PDFs poorly known
  - EW and HF data provided constraints
  - integration of quarkonium photoproduction into a framework ongoing (cf backup)

Questions?

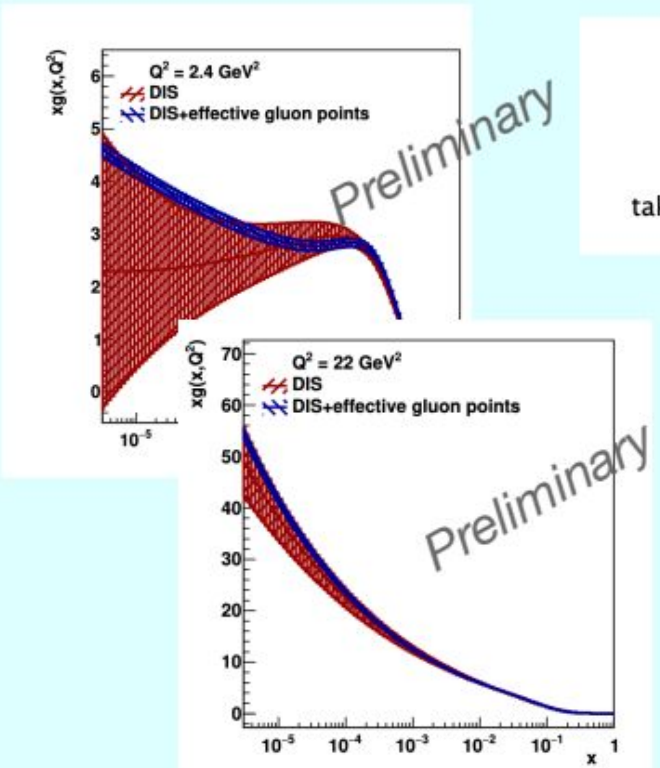
J. Roho



slides

(ii) Fitting: approach 1: gluon pseudodata: **Results**

- Default xFitter set up supplemented with generated effective gluon PDF data



$$g_{\rm eff}(x_i,\mu_{\rm opt}) = g_{\rm fit}(x_i,\mu_{\rm opt})\sqrt{\frac{\sigma_+({\rm data})_i}{\sigma_+({\rm fit})_i}}$$

taken from 2006.13857

$$\delta g_{\rm eff}(x_i) = \frac{1}{2}\; g_{\rm eff}(x_i)\;\frac{\delta\sigma_+({\rm data})_i}{\sigma_+({\rm data})_i}$$

Dataset	$\chi^2_{\rm min}$/d.o.f (DIS)	$\chi^2_{\rm min}$/d.o.f (DIS+eff. gluon pts.)
HERA1+2 NCep 820	80/73	79/73
HERA1+2 NCep 460	220/207	220/207
HERA1+2 CCep	43/39	44/39
HERA1+2 NCem	221/159	220/159
HERA1+2 CCem	54/42	56/42
HERA1+2 NCep 575	223/257	227/257
HERA1+2 NCep 920	465/391	470/391
LHC excl. J/ψ pp 7 TeV	N/A	8.95/10
LHC excl. J/ψ pp 13 TeV	N/A	3.51/10
LHC excl. Υ pp 7,8 TeV	N/A	3.23/3
Total $\chi^2_{\rm min}$/d.o.f	1412/1154 $\sim$ 1.22	1444/1177 $\sim$ 1.23

11

Theoretical input and experimental data

Analysis	nCTEQ15HQ	EPPS21	nNNPDF3.0	TUJU21	KSASG20
Theoretical input:					
Perturbative order	NLO	NLO	NLO	NNLO	NNLO
Heavy-quark scheme	SACOT$-\chi$	SACOT$-\chi$	FONLL	FONLL	FONLL
Data points	1484	2077	2188	2410	4353
Independent flavors	5	6	6	4	3
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
Deuteron corrections	$(\checkmark)^{a,b}$	$\checkmark^{c}$	✓	✓	✓
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	$(\checkmark)^{a}$	✓			✓
CHORUS/CDHSW CC DIS	$(\checkmark/\text{-})^{b}$	✓/-	✓/-	✓/✓	✓/✓
NuTeV/CCFR 2μ CC DIS	$(\checkmark/\checkmark)^{b}$		✓/-		
pA DY	✓	✓	✓		✓
Collider data:					
Z bosons	✓	✓	✓	✓	
$W^{\pm}$ bosons	✓	✓	✓	✓	
Light hadrons	✓	$\checkmark^{d}$			
Jets		✓	✓		
Prompt photons			✓		
Prompt D^0	✓	✓	$\checkmark^{e}$		
Quarkonia (J/ψ, ψ', Υ)	✓				

QCD analysis

- 2D & 3D dijet cross sections as a function $m_{1,2}$ using with R = **0.8** are investigated as part of a QCD analysis
  - procedure based on ***HERAPDF2.0*** analysis[1], similar to CMS 13 TeV ***inclusive jet*** analysis [2] (SMP-20-011)

- fit ***deep inelastic scattering*** (DIS) data from HERA in addition to the CMS dijet measurements
  - limit DIS data to $Q^2 > 10$ GeV^2 to minimize impact of higher-twist corrections

- x dependence of PDFs is parametrized by the general form

$$x f(x) = A_f \, x^{B_f} \, (1-x)^{C_f} \, (1 + D_f x + E_f x^2)$$

  - ***A***, ***B*** & ***C*** parameters always included (some fixed by sum rules)
  - ***D*** & ***E*** parameters added as needed based on χ^2 scan

- PDFs determinations are performed both for a fixed value of the strong coupling constant $\alpha_s(m_Z) = 0.118$ and in simultaneous ***PDF*** + $\boldsymbol{\alpha_s(m_Z)}$ fits

[1] H1, ZEUS Collaborations. *"Combination of measurements of inclusive deep inelastic ${e^{\pm }p}$ scattering cross sections and QCD analysis of HERA data"*, *Eur. Phys. J. C* **75** (2015) 12, doi:10.1140/epjc/s10052-015-3710-4, arXiv:1506.06042

[2] CMS Collaboration, *"Measurement and QCD analysis of double-differential inclusive jet cross sections in proton-proton collisions at √s = 13 TeV"*, *JHEP* **02** (2022) 142, doi:10.1007/JHEP02(2022)142, arXiv:2111.10431