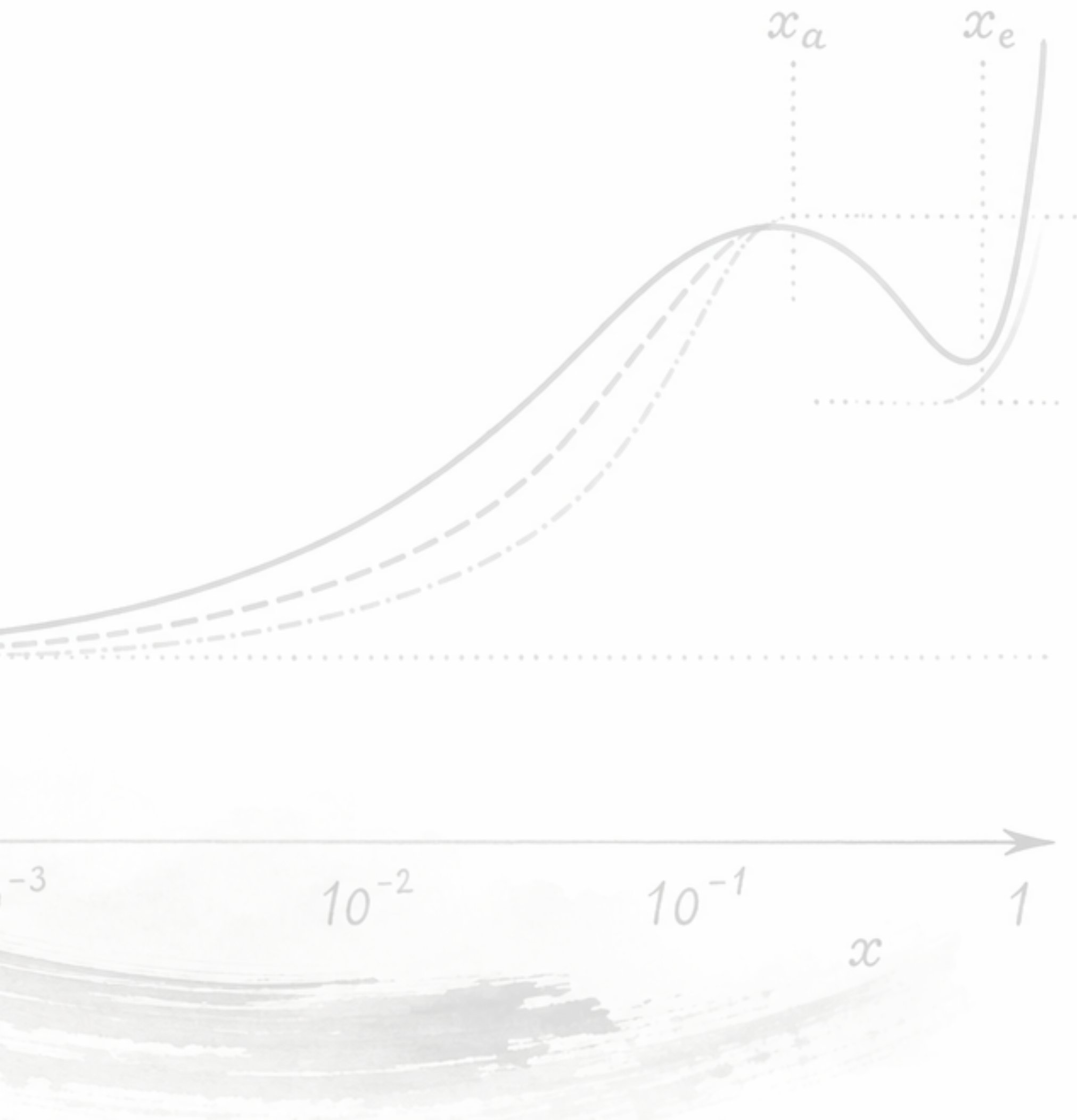




Cold-nuclear matter baselines for jet quenching searches in light-ion collisions

Based on Eur.Phys.J.C 86 (2026), 681

Florian Jonas

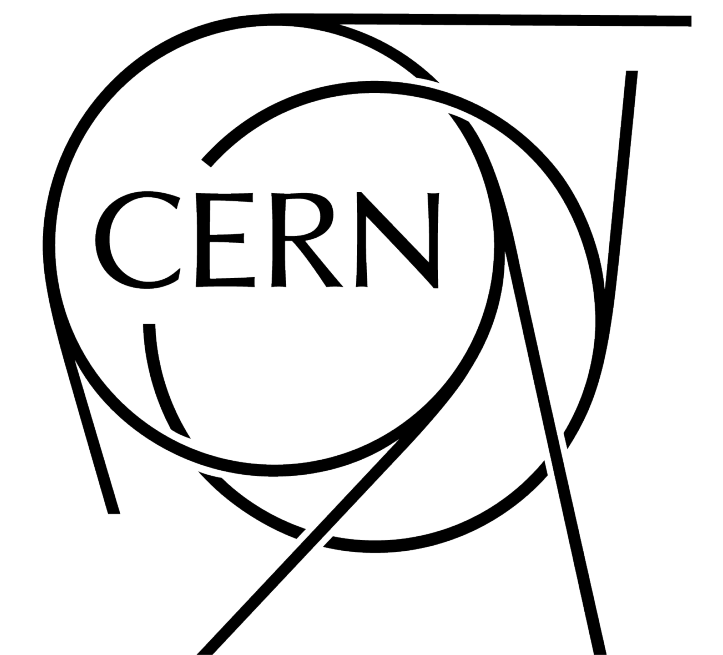
In collaboration with:

Constantin Loizides

Petja Paakkinen

Aleksas Mazeliauskas

Nicolas Strangmann



Introduction: Why this paper?

Light-ion workshop 2025 discussion session (Carlota Andreas et al)

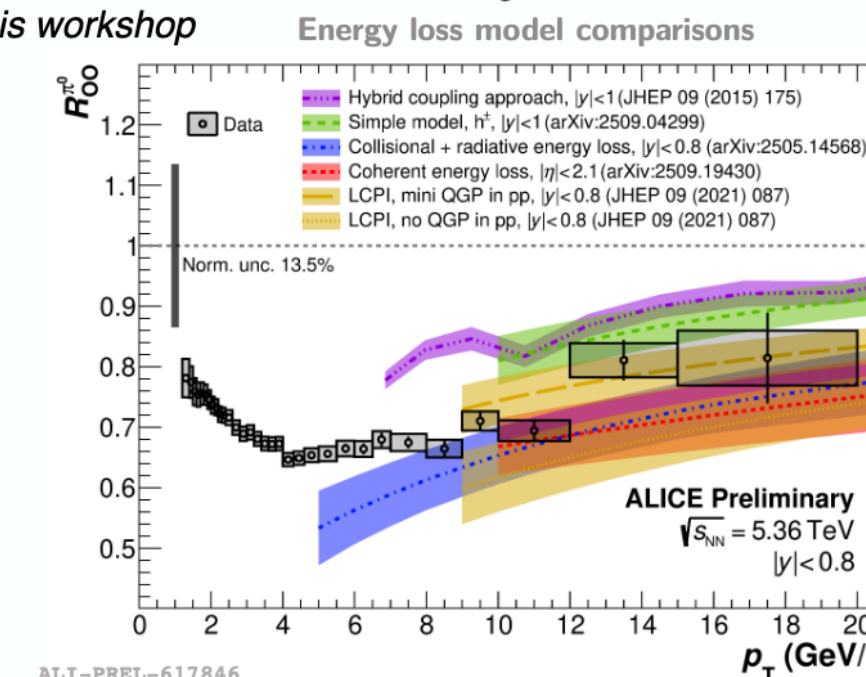
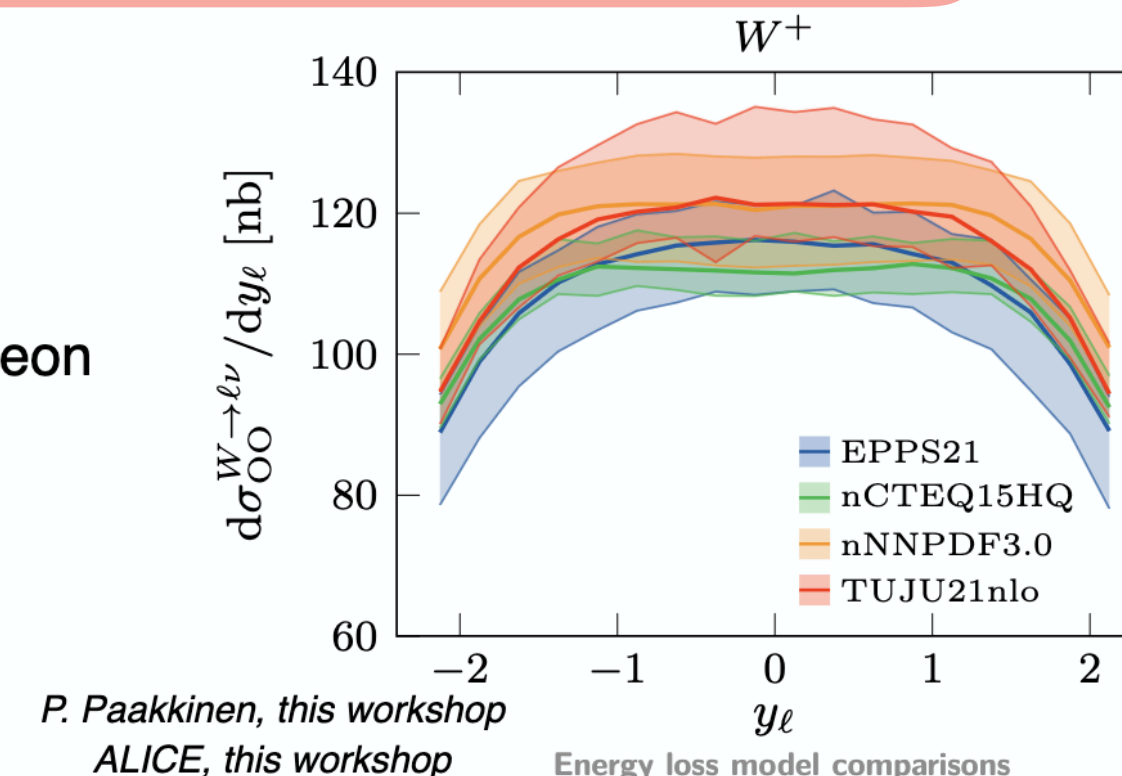
How do we reach a quantitative assessment of jet quenching in light ion systems?

How to make progress on each front?

- **theory**: uniform inputs for nPDF effects, quenching models, nucleon configurations, initial state
- **experiment (O+O + future data)**: treatment of experimental uncertainties (incl. bin-by-bin correlations), uniform (or clearly specified) geometric model inputs
- **experiment (p+O)**: no-quenching baselines directly in data

Do we have a uniform assessment across experiments/observables?

- model comparisons to multiple observables simultaneously
- what (achievable) measurements in existing O+O/Ne+Ne data provide the best additional discriminating power?



Light-Ion Workshop 2025 (CERN), System-size characterization of quenching in small and large AA systems

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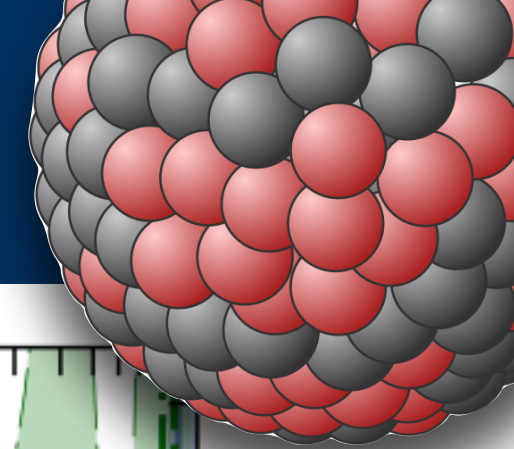
No quenching baselines that include nPDF effects are essential for a quantitative assessment of jet quenching in light-ion systems

Key goals of this work:

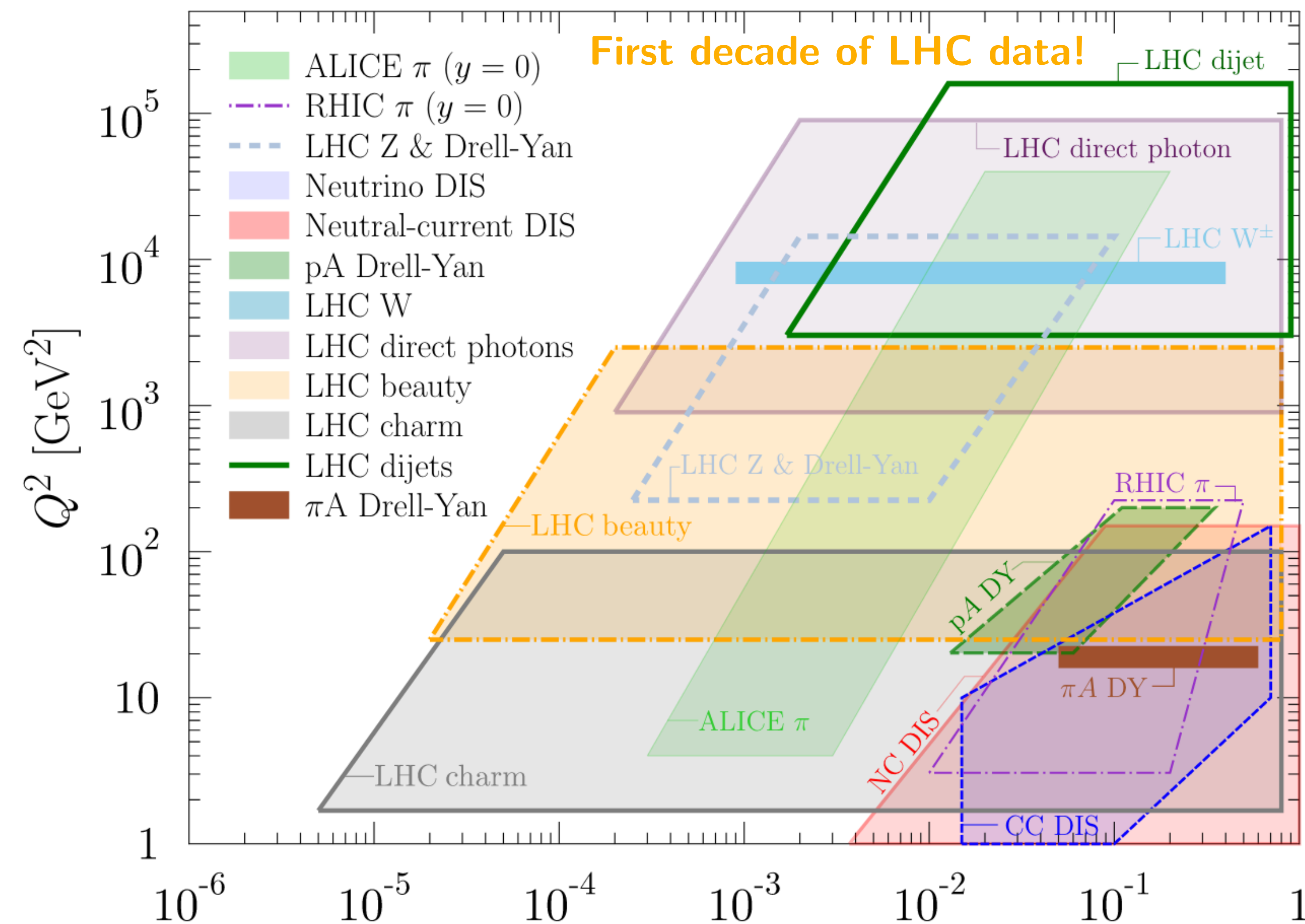
Goal 1: Provide a comprehensive set of pQCD predictions for CNM effects in light-ion collisions

Goal 2: Introduce observables in which CNM effects are reduced, guiding experimental searches for jet quenching

“Nuclear PDFs after the first decade of LHC data”

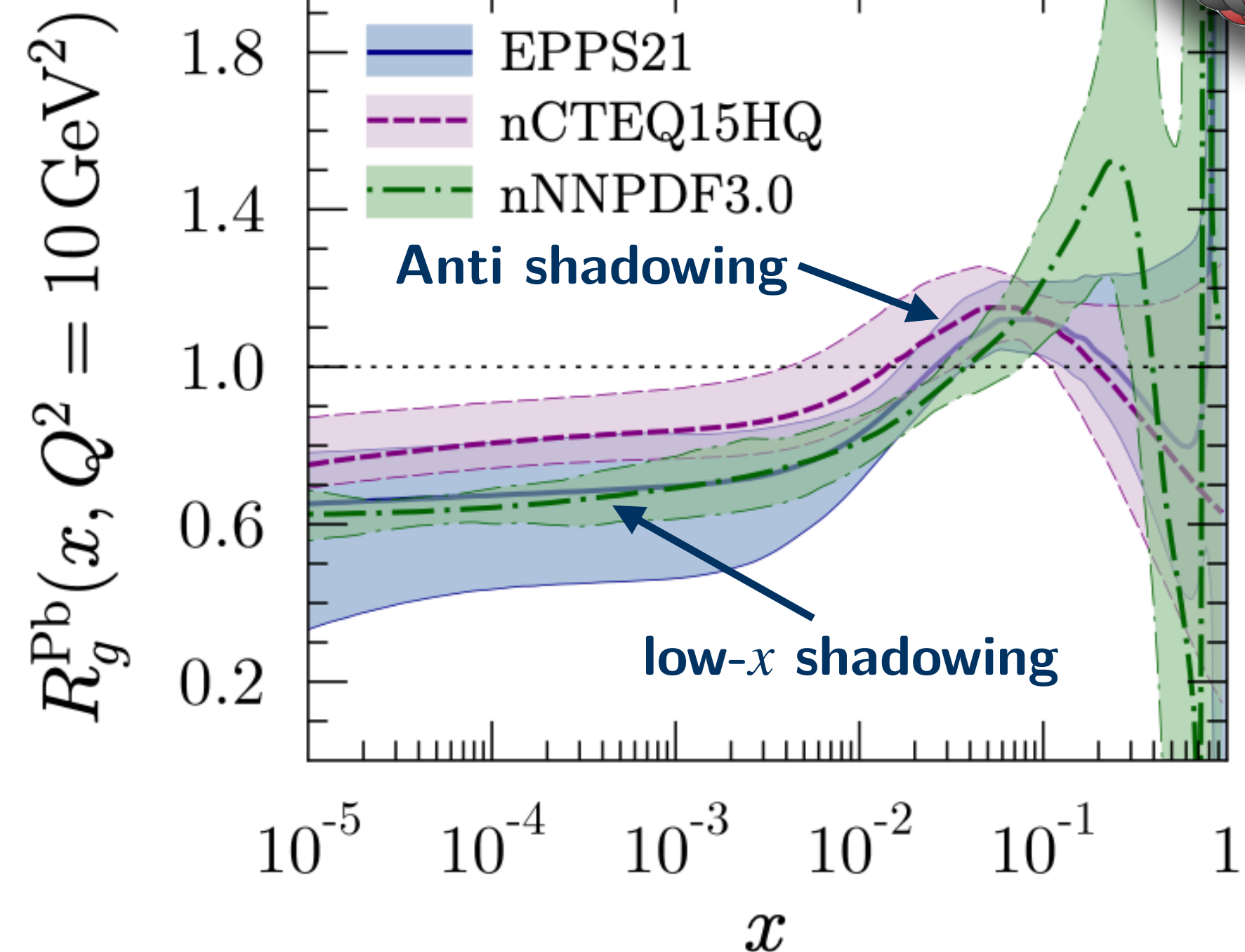


Coverage of lepton-A, pion-A and proton-A data in nPDFs



M. Klasen & H. Paukkunen

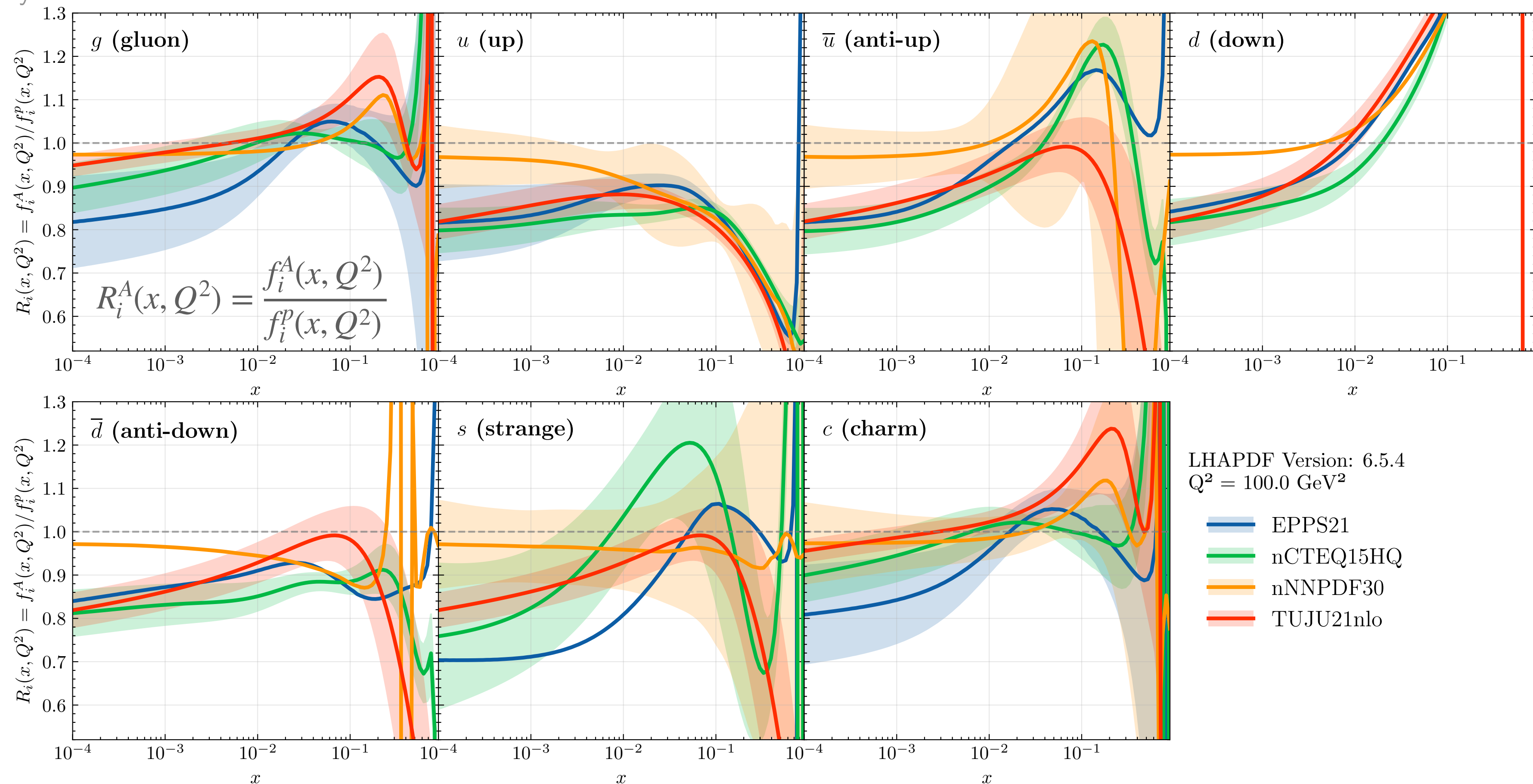
Ann.Rev.Nucl.Part.Sci. 74 (2024) 1, 49-87 x



- A decade of LHC data provided significant constraints for nPDF in novel phase space
- Increase of exp. data included in global fits: EPS09 ($N_{\text{dat}} = 929$) $\rightarrow$ EPPS21 ($N_{\text{dat}} = 2077$)
- Sizeable gluon shadowing at low- x , but slight tension between different global fits

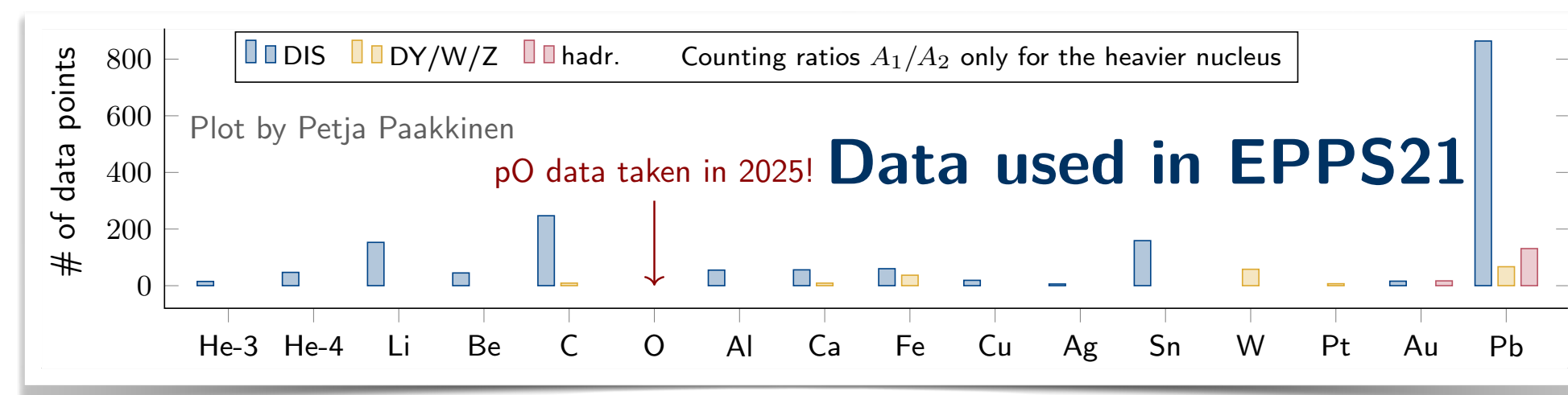
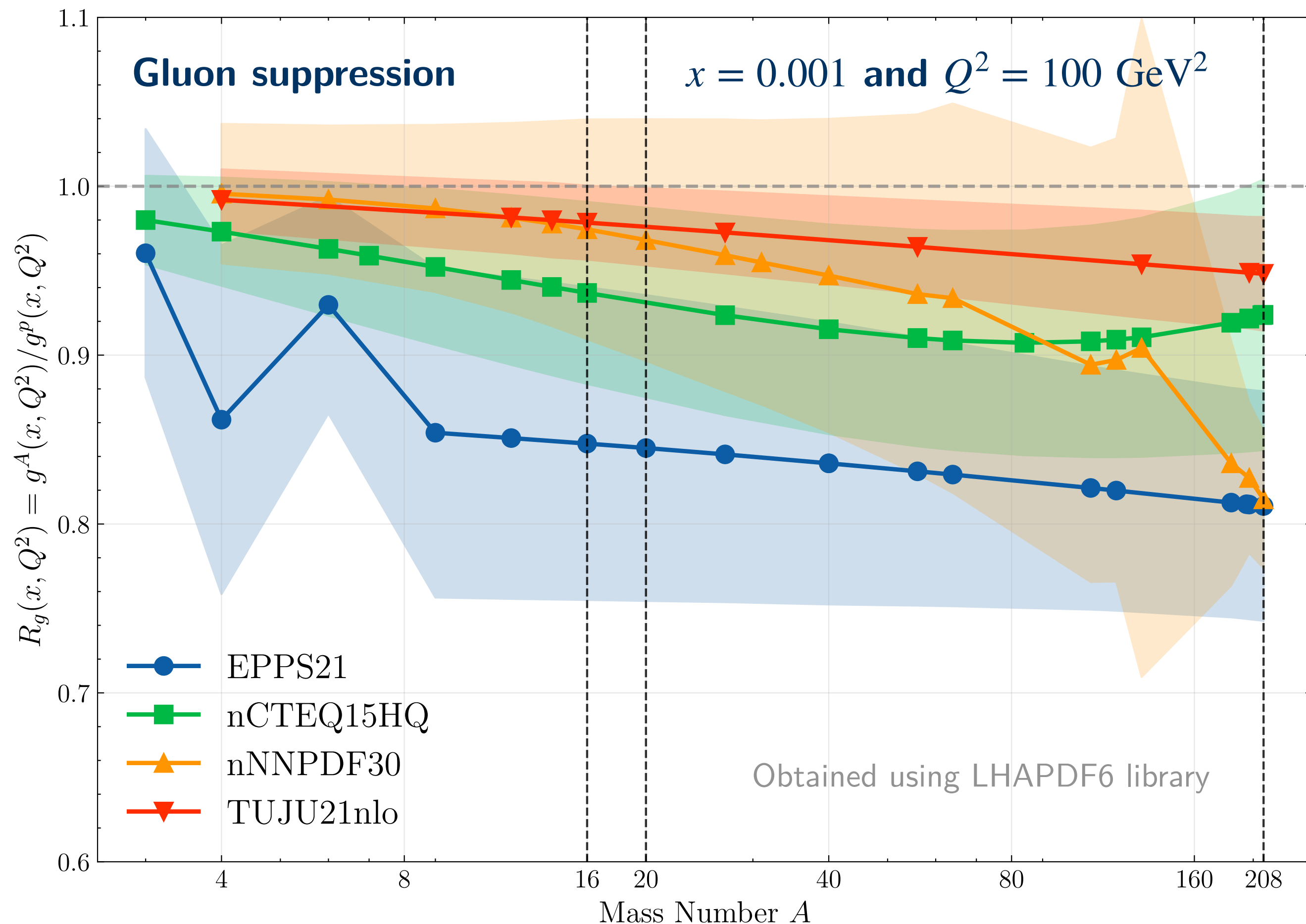
Status quo: Nuclear PDFs of oxygen

Obtained using LHAPDF6 library



- Ratio $R_i^A(x, Q^2)$ quantifies modification of PDF in nucleus vs. free-proton baseline
- None of the nPDFs use Oxygen data directly $\rightarrow$ assuming functional form of A -dependence and interpolating to Oxygen
- Sizable modifications observed but also sizable uncertainties

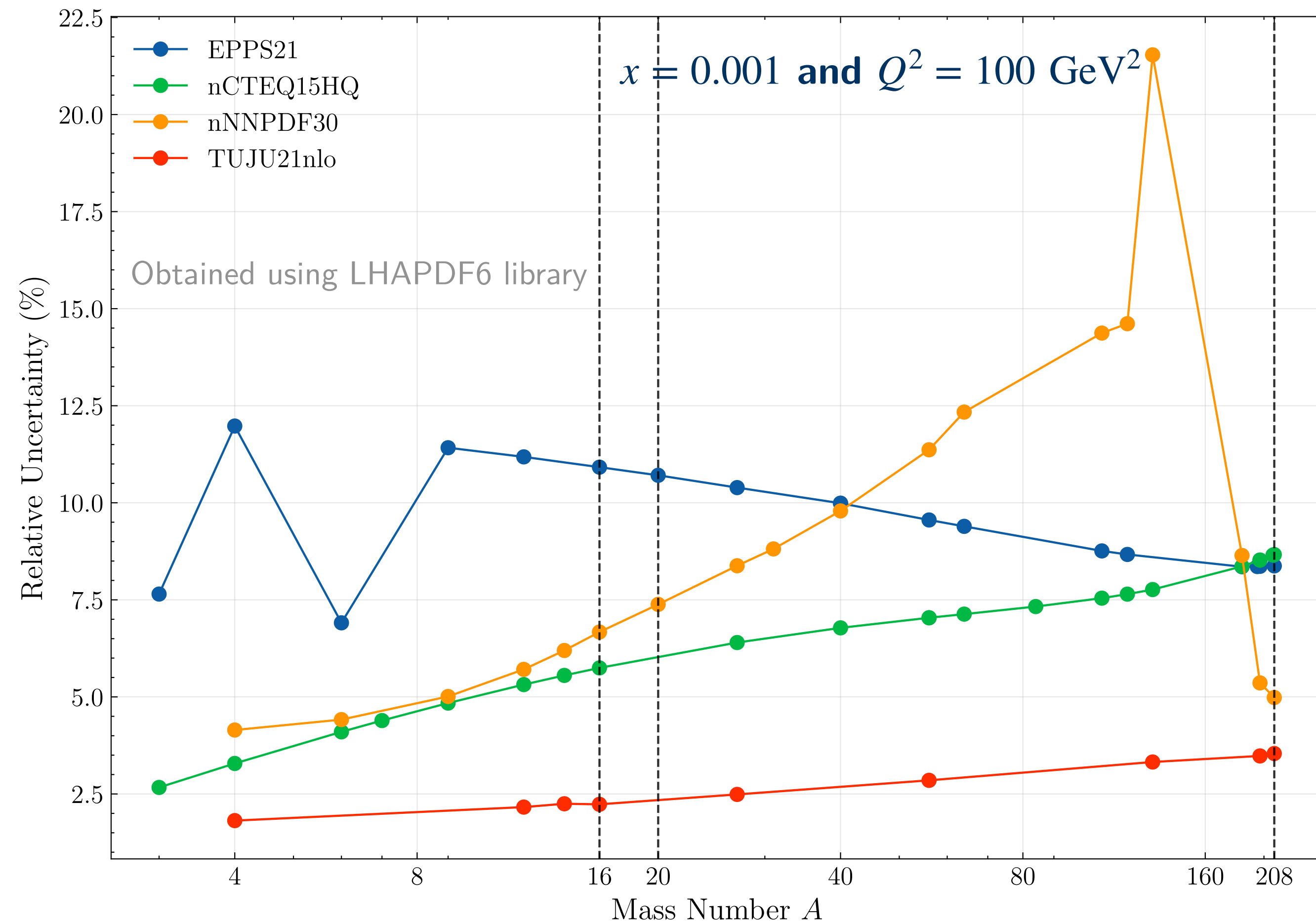
A-dependence of nPDFs



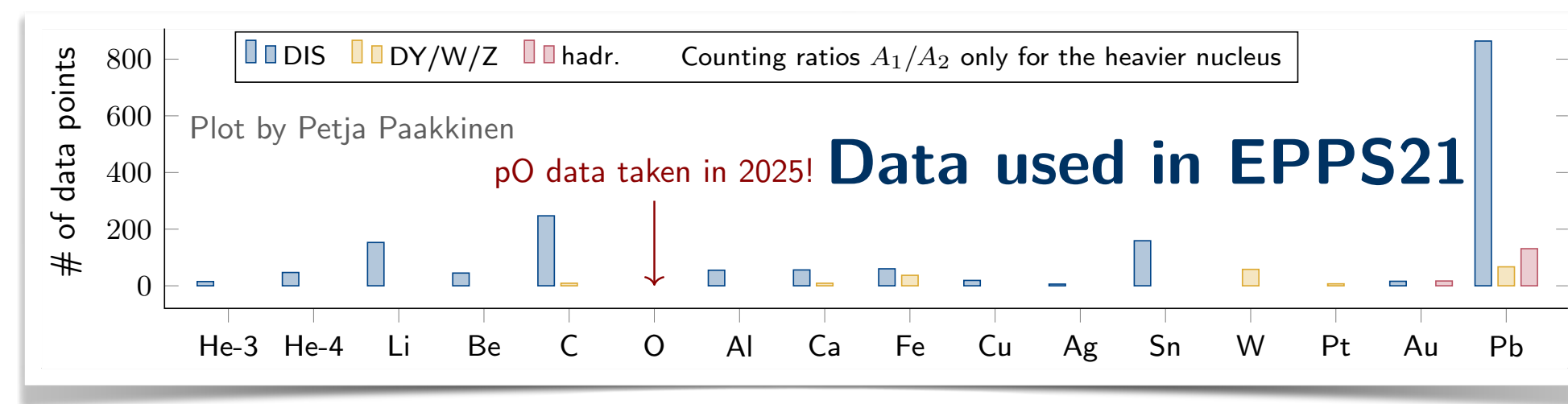
- For EPPS21, nCTEQ15HQ and TUJU21:
 - A-dependence introduced in global fit as an analytical parametrization at starting scale Q_0
 - A-dependence might not be strictly monotonic after evolution in Q
- For nNNPDF30:
 - A-dependence introduced directly in the neural net component
- Significant differences in A -dependence of nPDFs AND their uncertainties**
- the right parametrization of the A -dependence is not known

Experimental data in pO collisions is crucial to improve our knowledge of the A dependence of CNM effects

A-dependence of nPDFs



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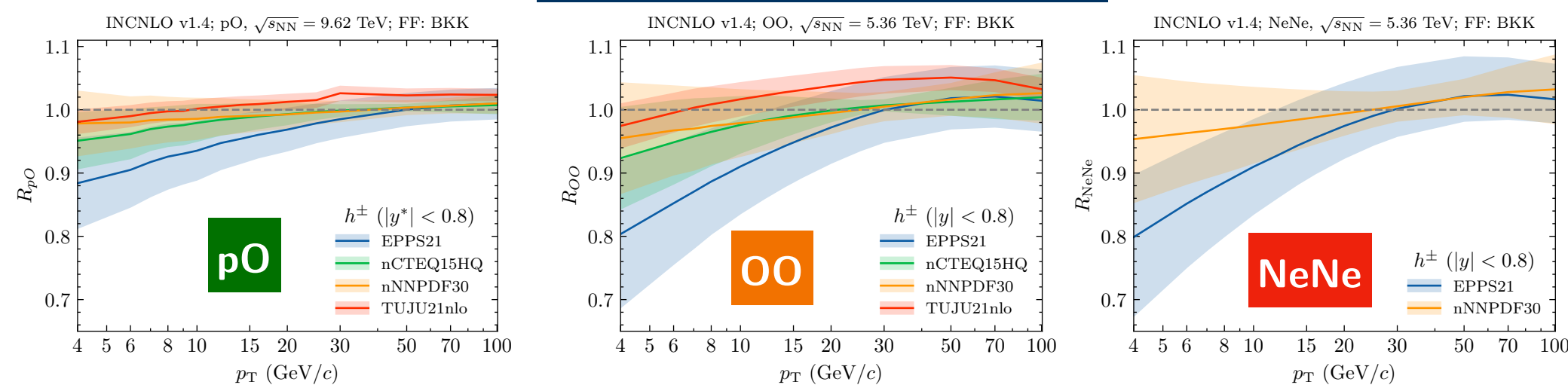
Experimental data in pO collisions is crucial to improve our knowledge of the A dependence of CNM effects

Comprehensive set of pQCD baseline predictions

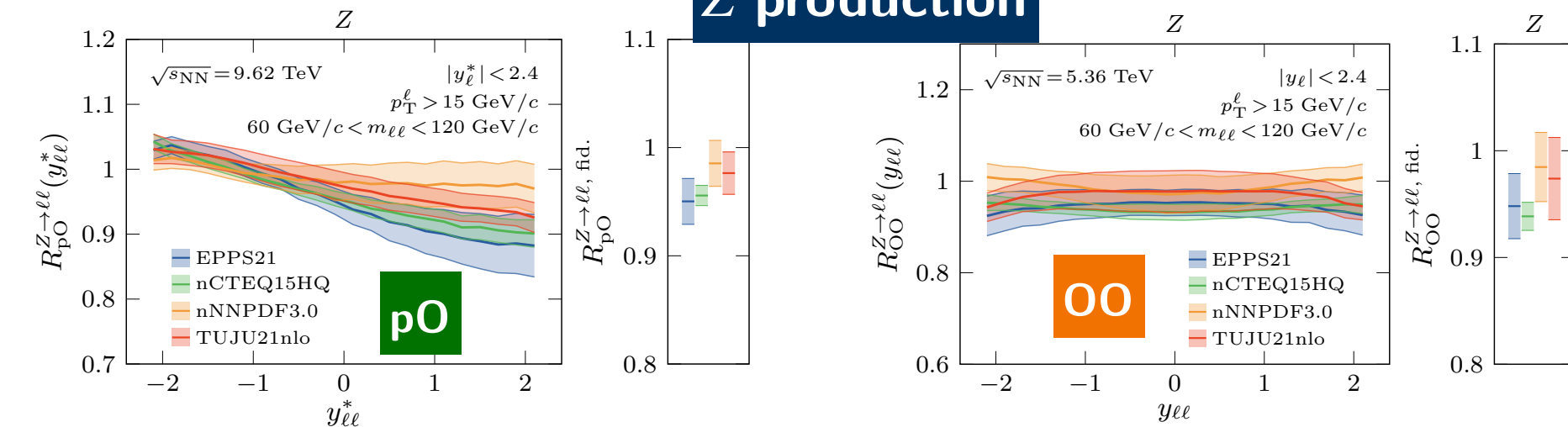
Goal 1: Provide a comprehensive set of pQCD predictions for CNM effects in light-ion collisions

- Sizable modification due to CNM for all observables
- Large nPDF uncertainties are dominant uncertainty for pQCD calculations
- Predictions for all most recent nPDFs available “on the market”
- All calculations done at NLO & **publicly available** for download!

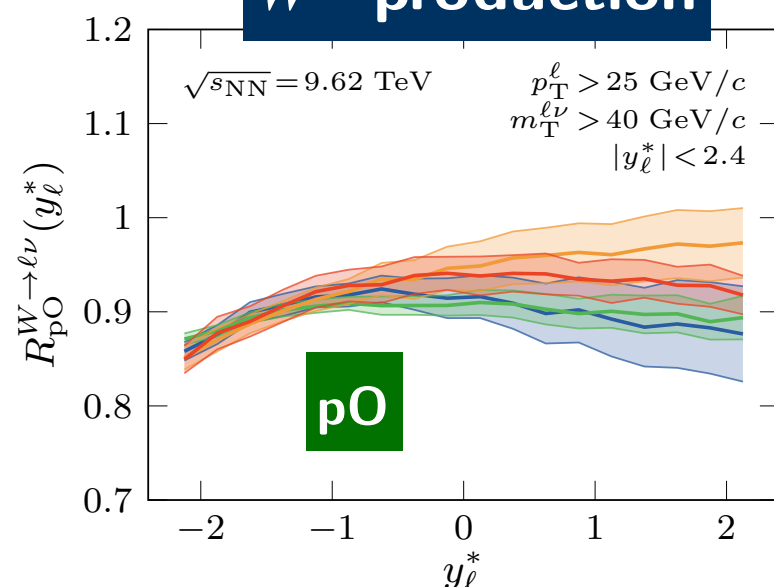
Charged hadrons and π^0



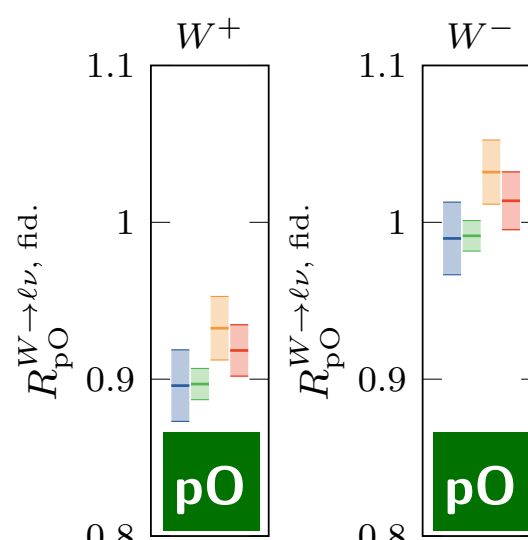
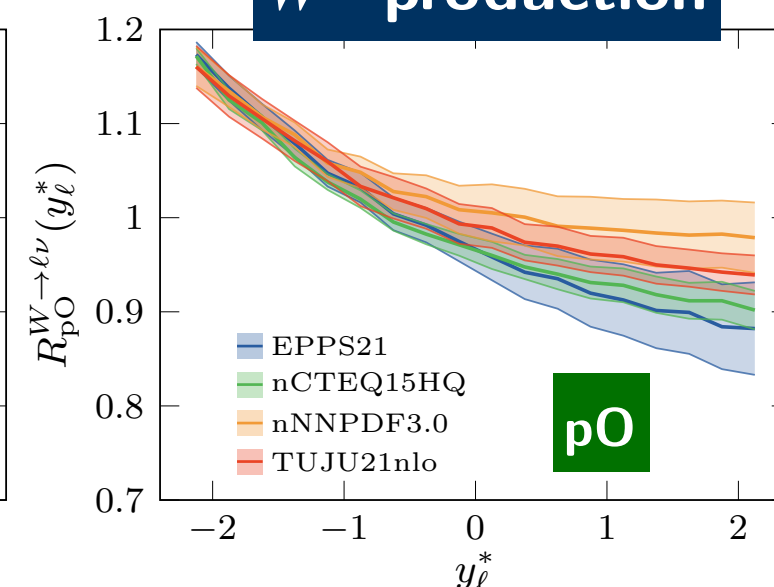
Z production



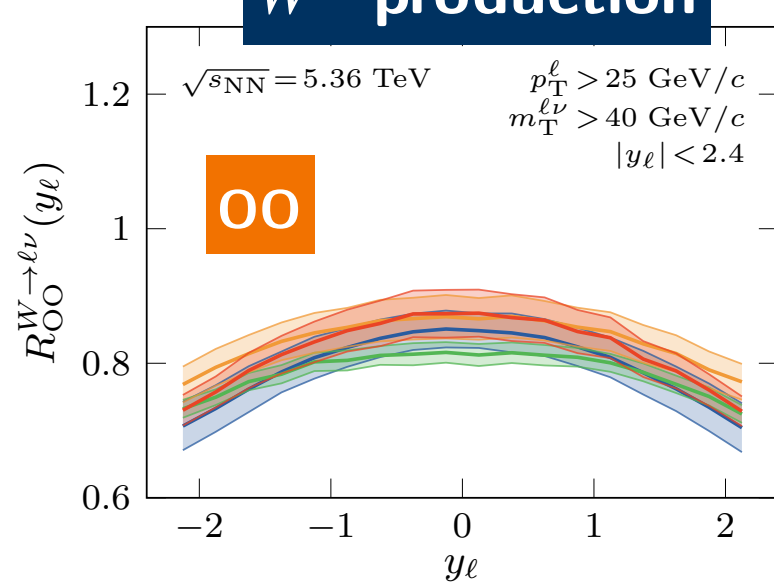
W^+ production



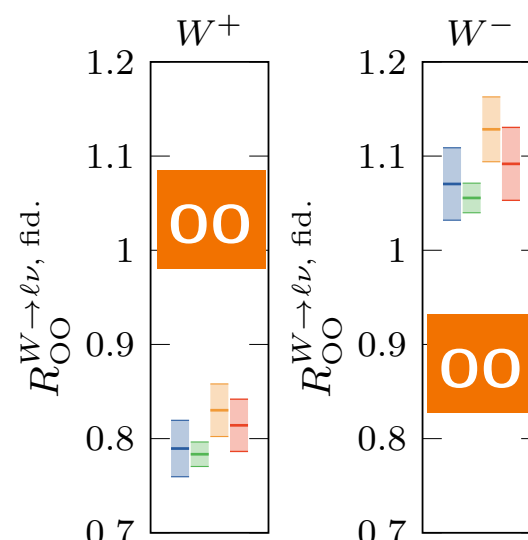
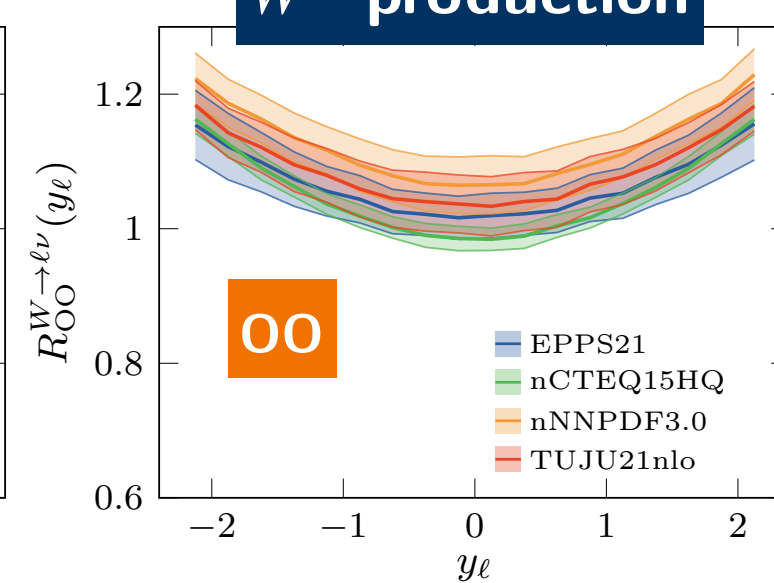
W^- production



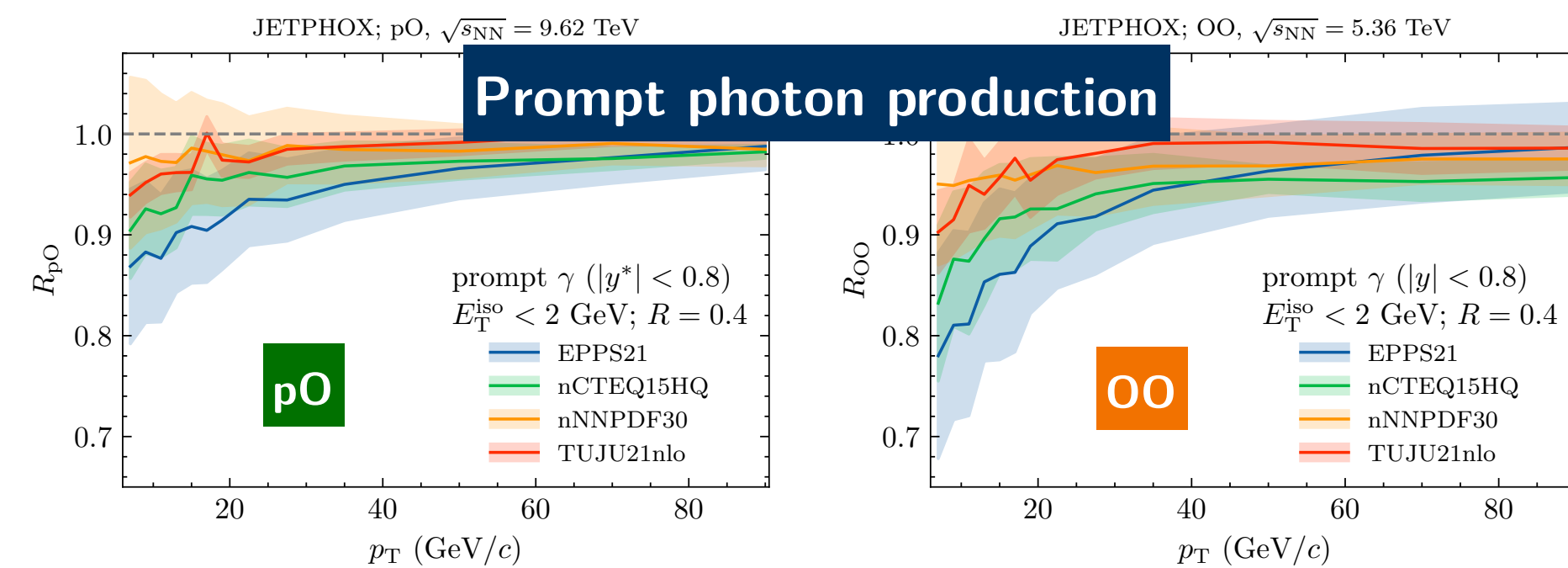
W^+ production



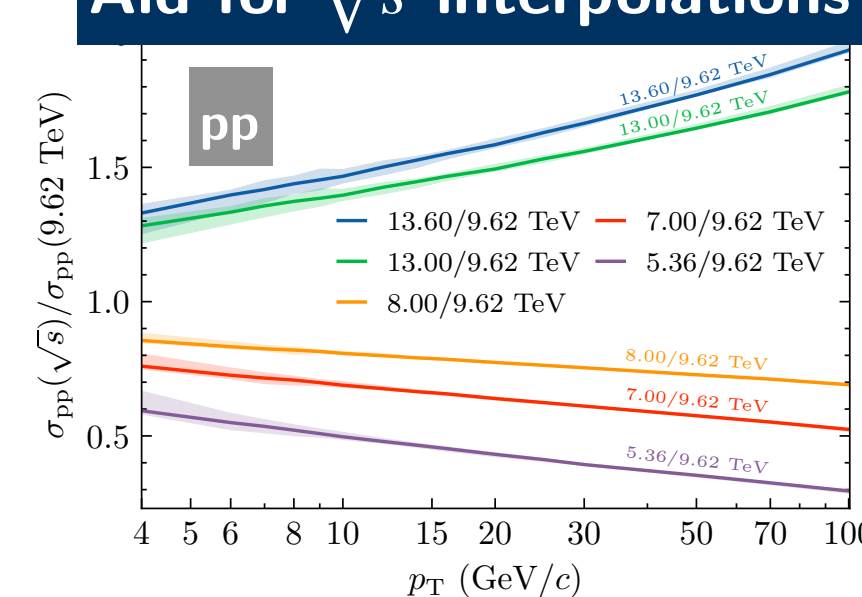
W^- production



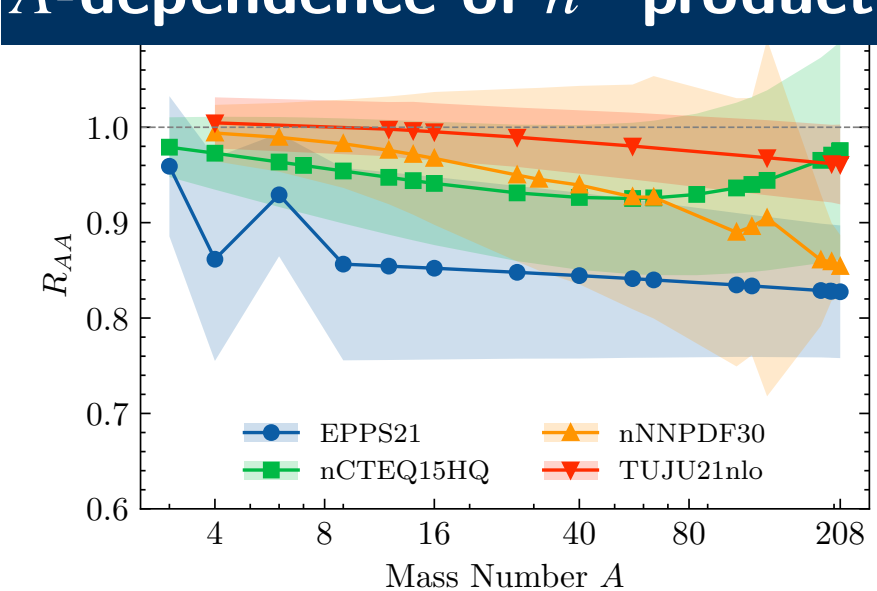
Prompt photon production



Aid for $\sqrt{s}$ interpolations



A-dependence of $h^\pm$ production



INCNLO

MCfM

MCfM

MCfM

JETPHOX

INCNLO

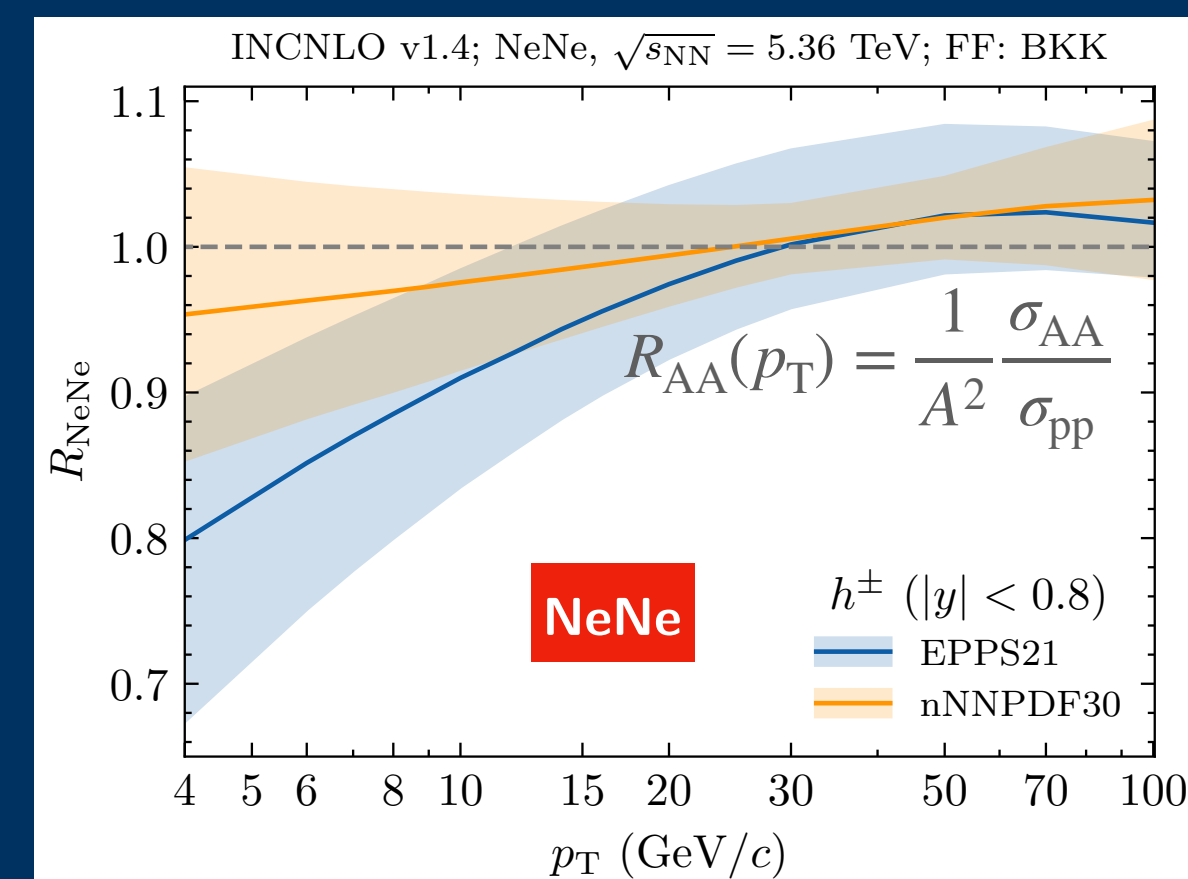
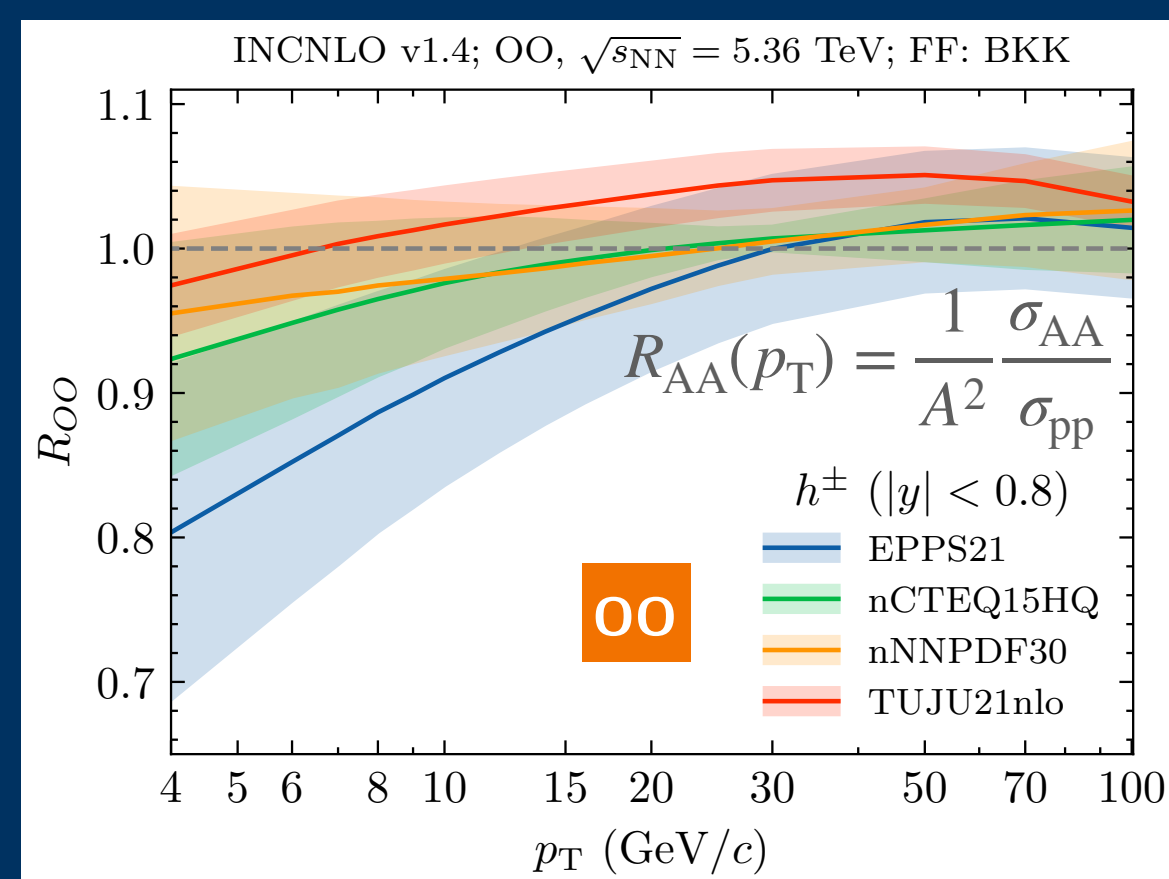
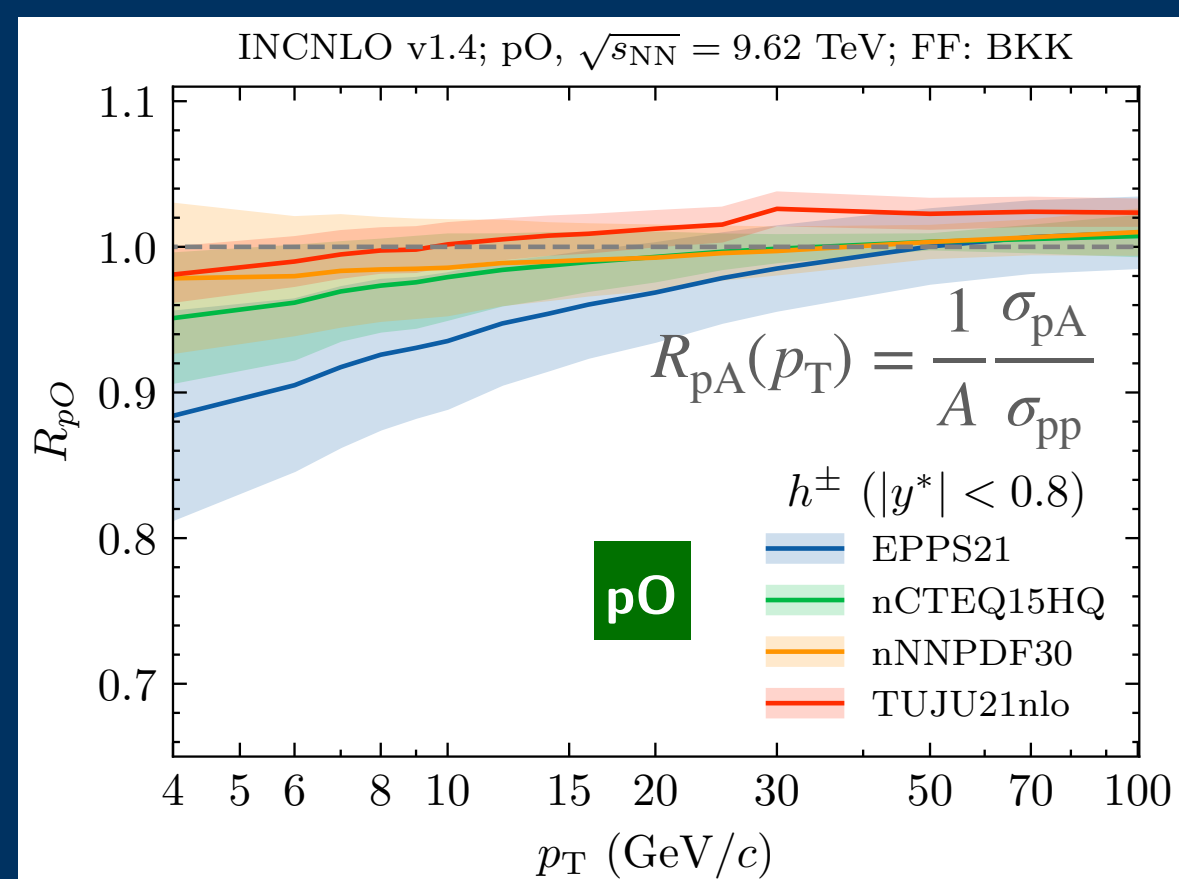
Comprehensive set of pQCD baseline predictions

Goal 1: Provide a comprehensive set of pQCD predictions for CNM effects in light-ion collisions

- Sizable modification due to CNM for all observables
- Predictions for all most recent nPDFs available “on the market”
- Large nPDF uncertainties are dominant uncertainty for pQCD calculations
- All calculations done at NLO & **publicly available** for download!

Charged hadrons and π^0

Example: Charged hadron nuclear modification factors



Sizable nPDF uncertainties translate to hadron R_{AA}

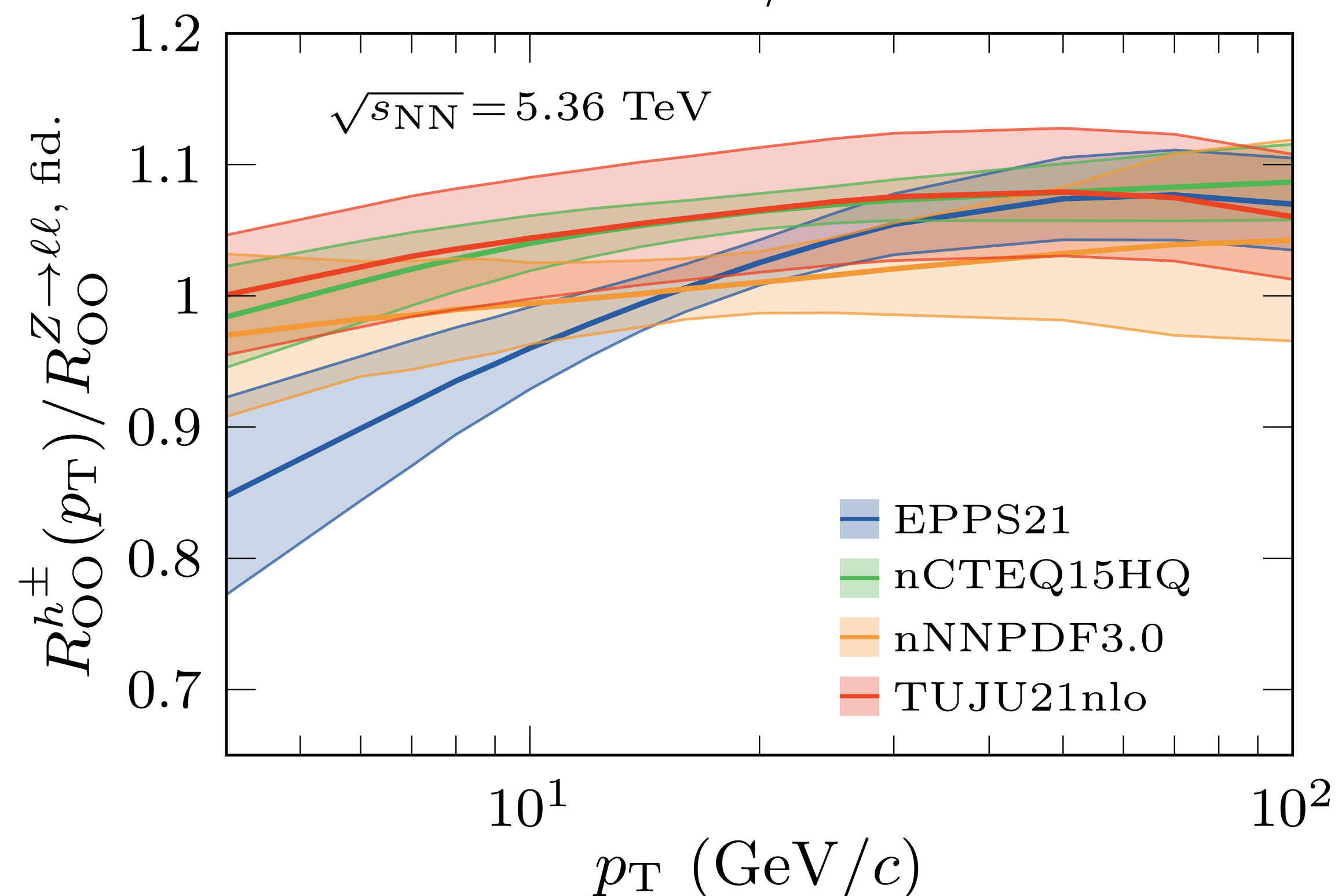
Limits interpretation of nuclear modification factor in search for energy loss

Can we find observables in which impact of CNM effects is reduced?

Hadron to electroweak-boson ratios

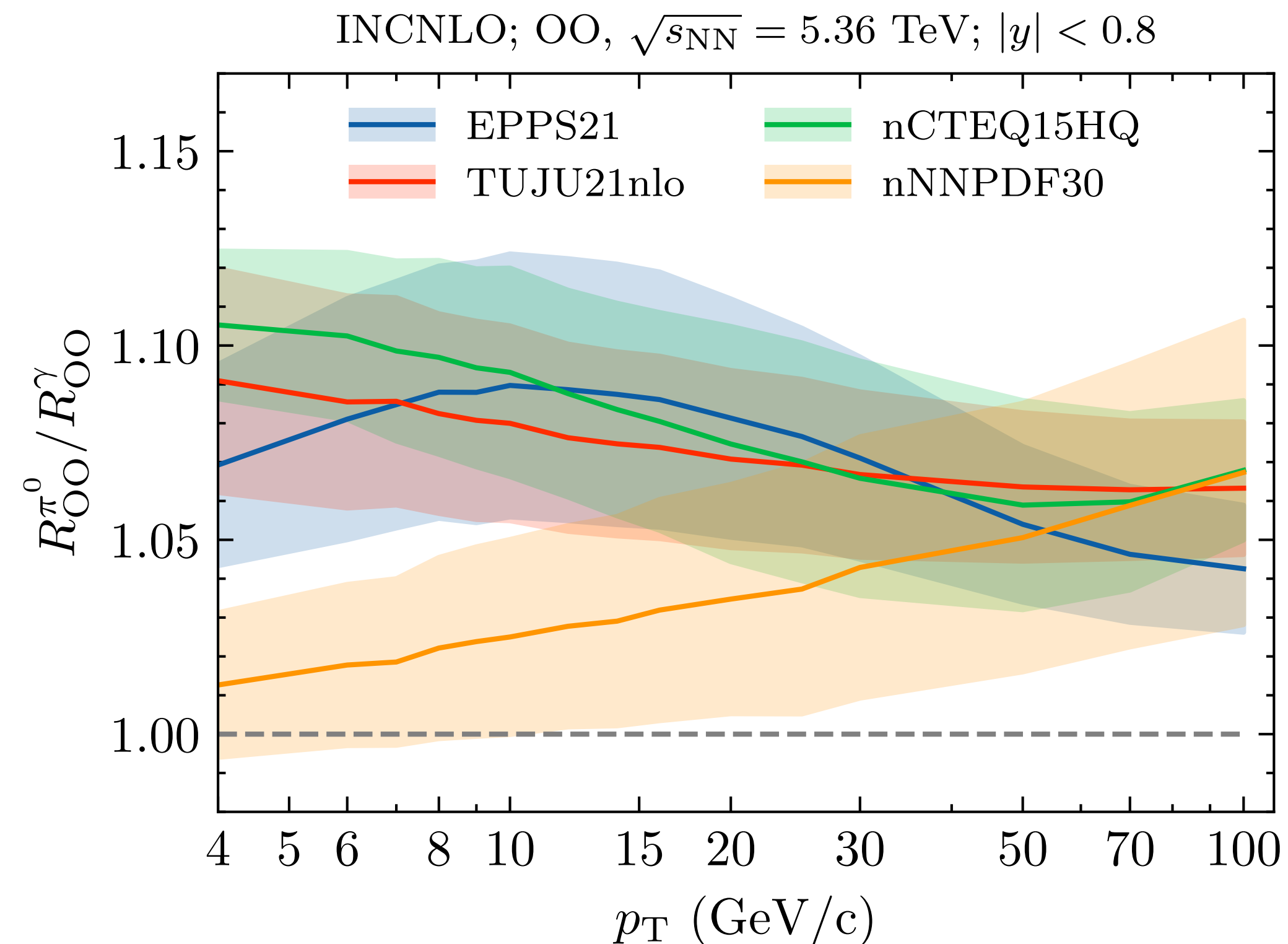
$$R_{OO}^{h^\pm/Z}(p_T) = \frac{R_{OO}^{h^\pm}(p_T)}{R_{OO}^{Z \rightarrow \ell^+ \ell^-, \text{fid.}}} = \frac{\sigma_{pp}^{Z, \text{fid.}}}{\sigma_{OO}^{Z, \text{fid.}}} \frac{\frac{d\sigma_{OO}^{h^\pm}}{dp_T}}{\frac{d\sigma_{pp}^{h^\pm}}{dp_T}}$$

$h^\pm / Z$



$$R_{OO}^{\pi^0/\gamma}(p_T) = \frac{R_{OO}^{\pi^0}(p_T)}{R_{OO}^{\gamma}(p_T)}$$

Related approach used by
PHENIX to determine N_{coll}
see Phys.Rev.Lett. 134
(2025) 2, 022302



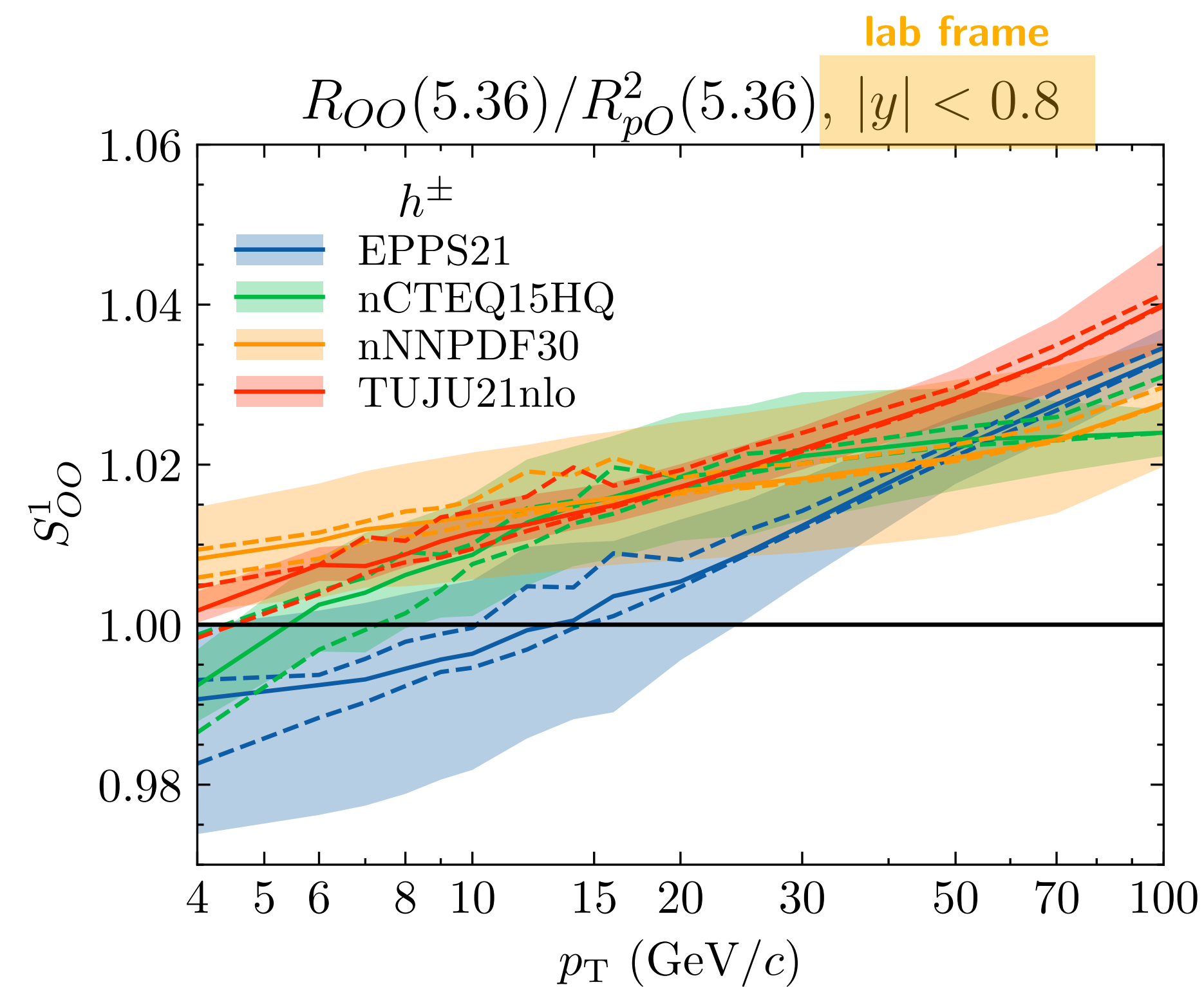
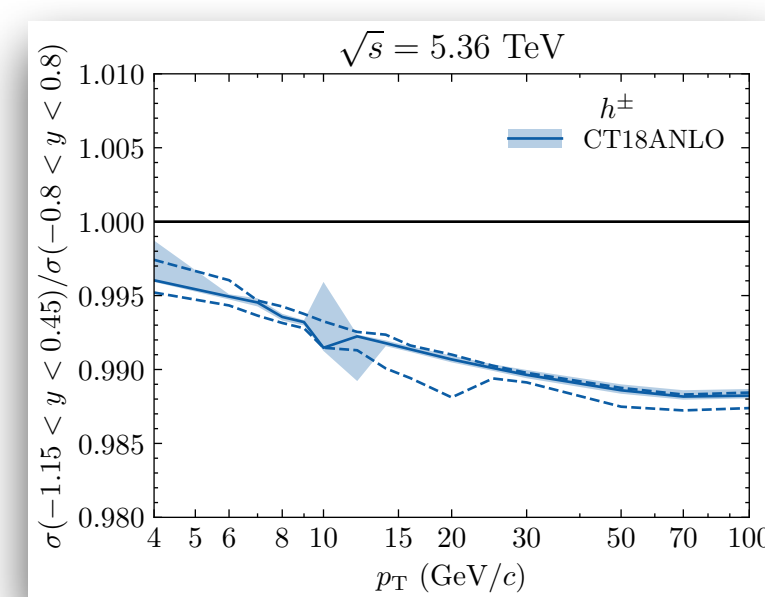
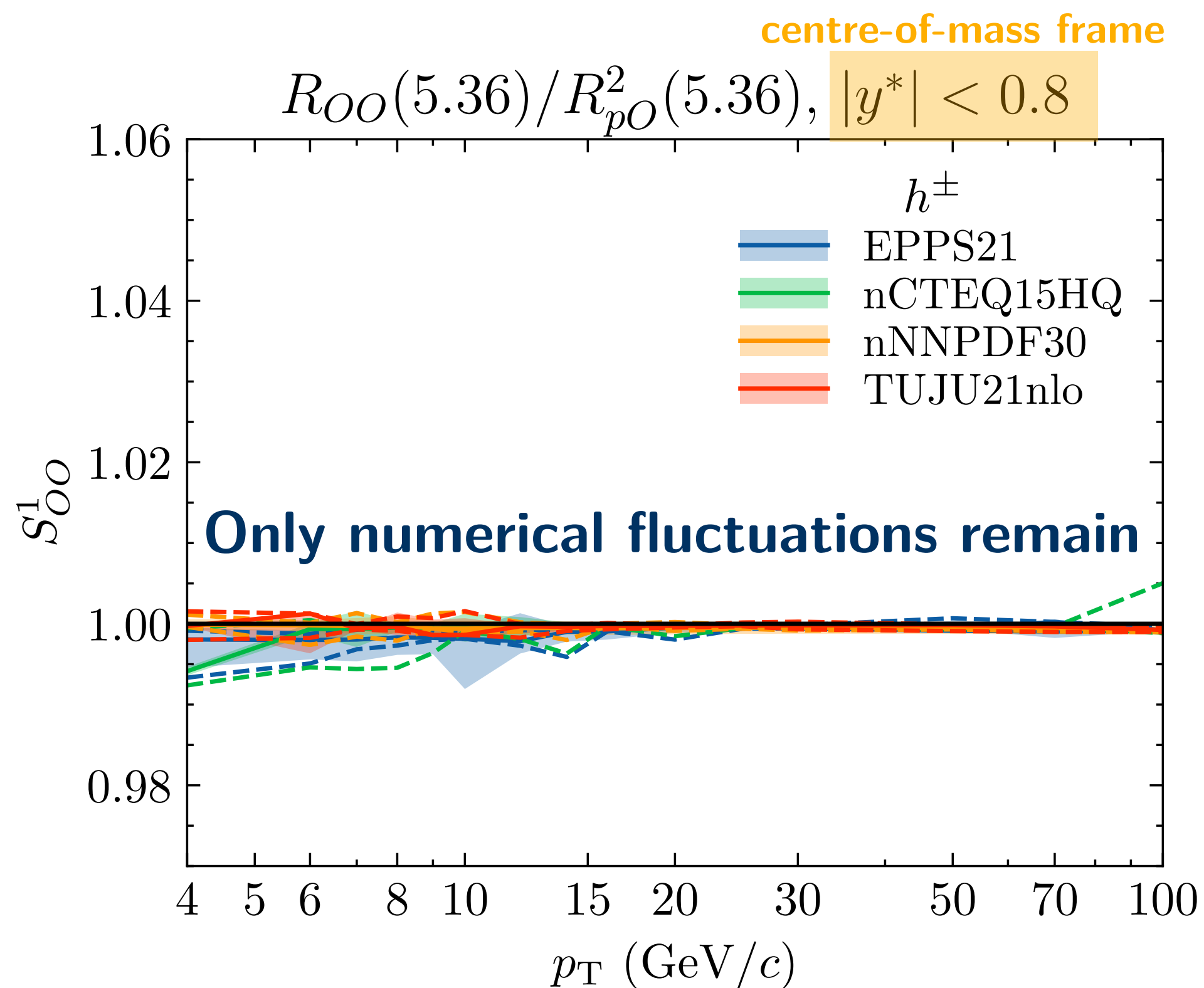
- Sizable nPDF uncertainties remain (may exceed 10%)
- Reason: different flavor sensitivity & different x sensitivity

- Good cancellation of nPDF uncertainties ($\sim 2\%^*$ remain)
- High potential for cancellation of experimental uncertainties

*per nPDF

OO to pO ratios: $S_{OO}^1 = R_{OO}(5.36)/R_{pO}^2(5.36)$

- The ratio $S = R_{OO}/R_{pO}^2$ is proposed as an observable to cancel CNM effects, following Phys. Rev. C 81(2010) 044903 and JHEP 06 (2015) 055
- In the ideal case (same $\sqrt{s}$ and same y) the cancellation of CNM effects is excellent (within numerical precision)
- Considering the pO system is boosted by $\Delta y \approx 0.35$, ratio deviates a few percent from unity but still excellent cancellation
- **Problem:** There is no pO data at $\sqrt{s} = 5.36$ TeV!

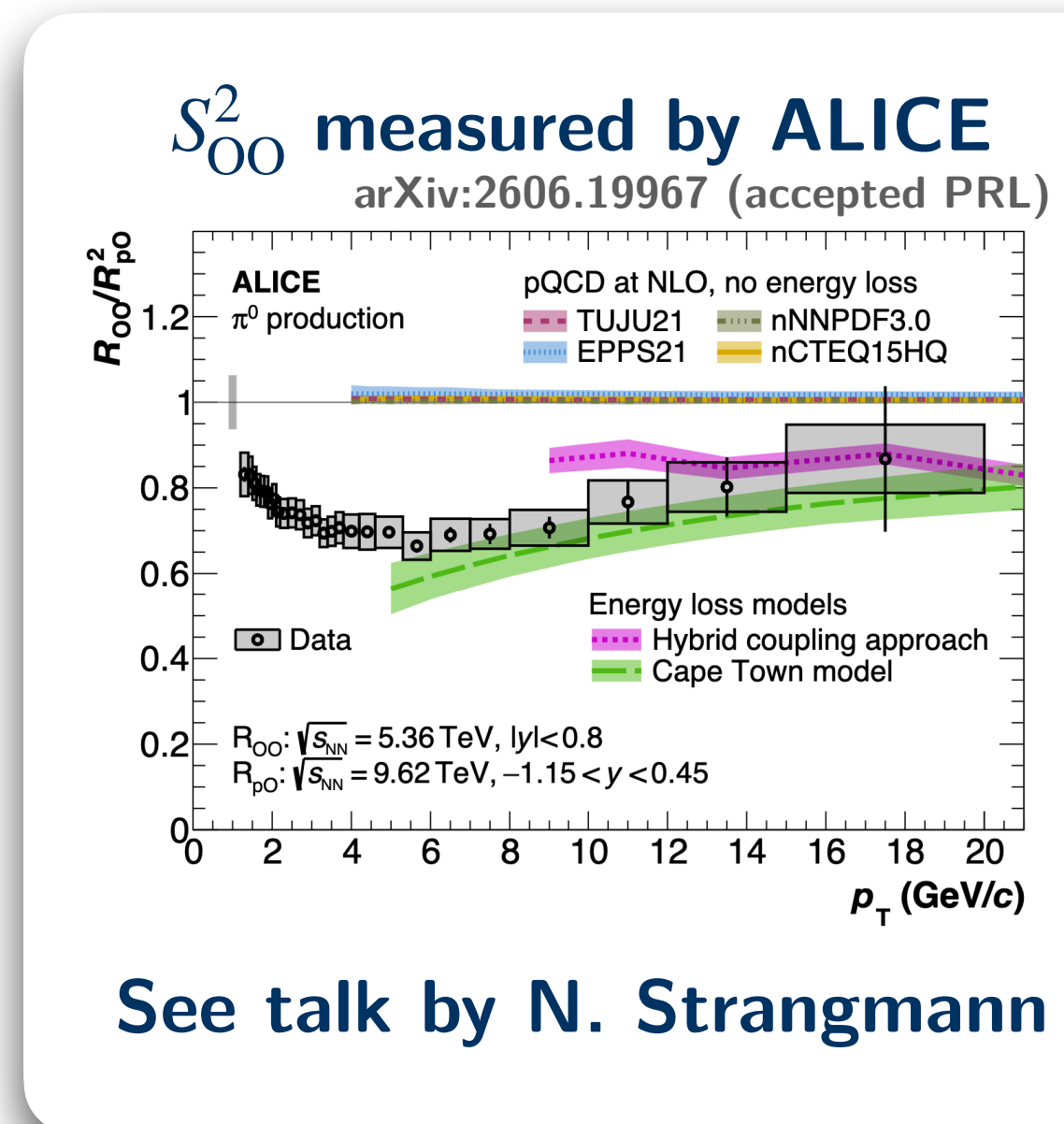
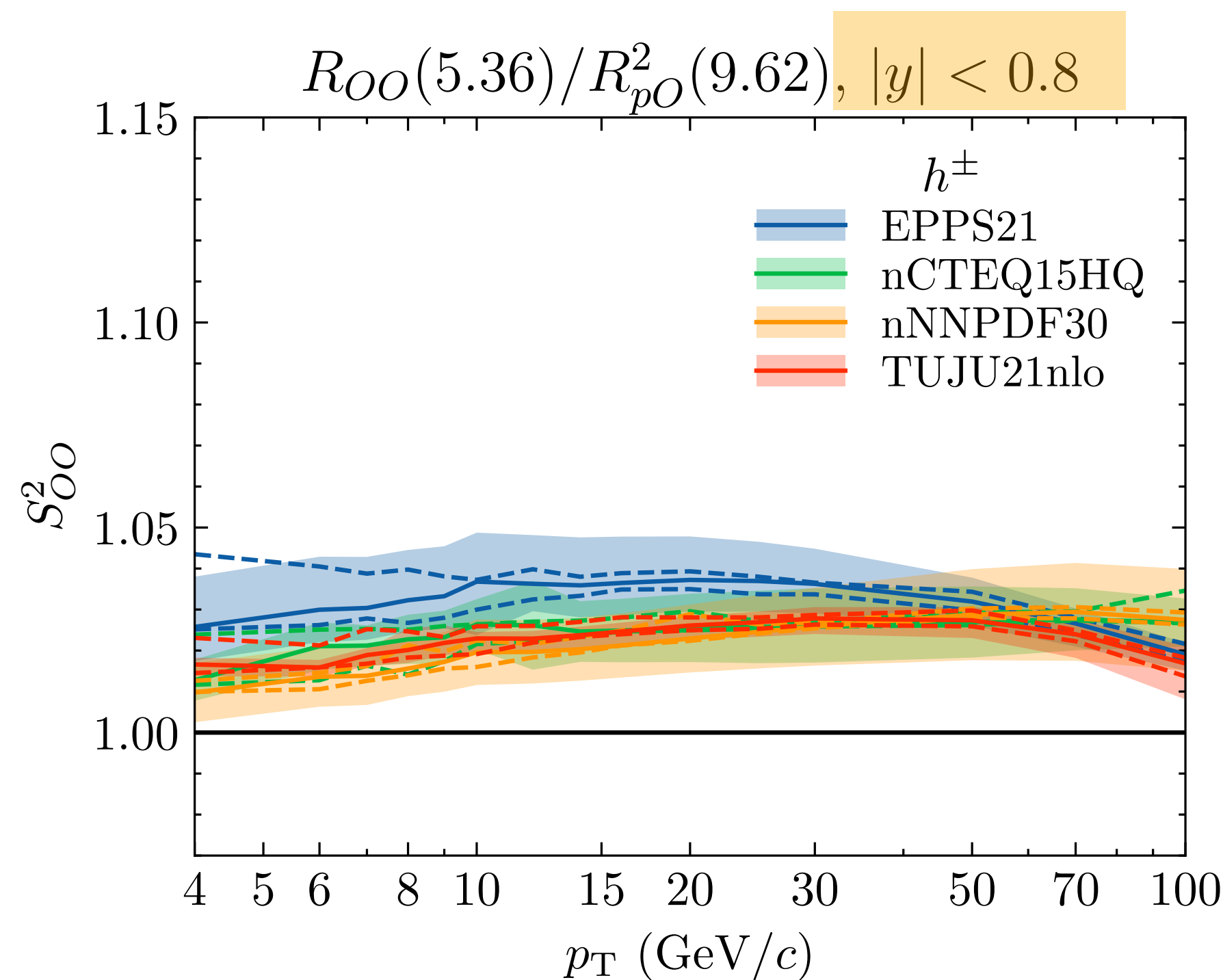
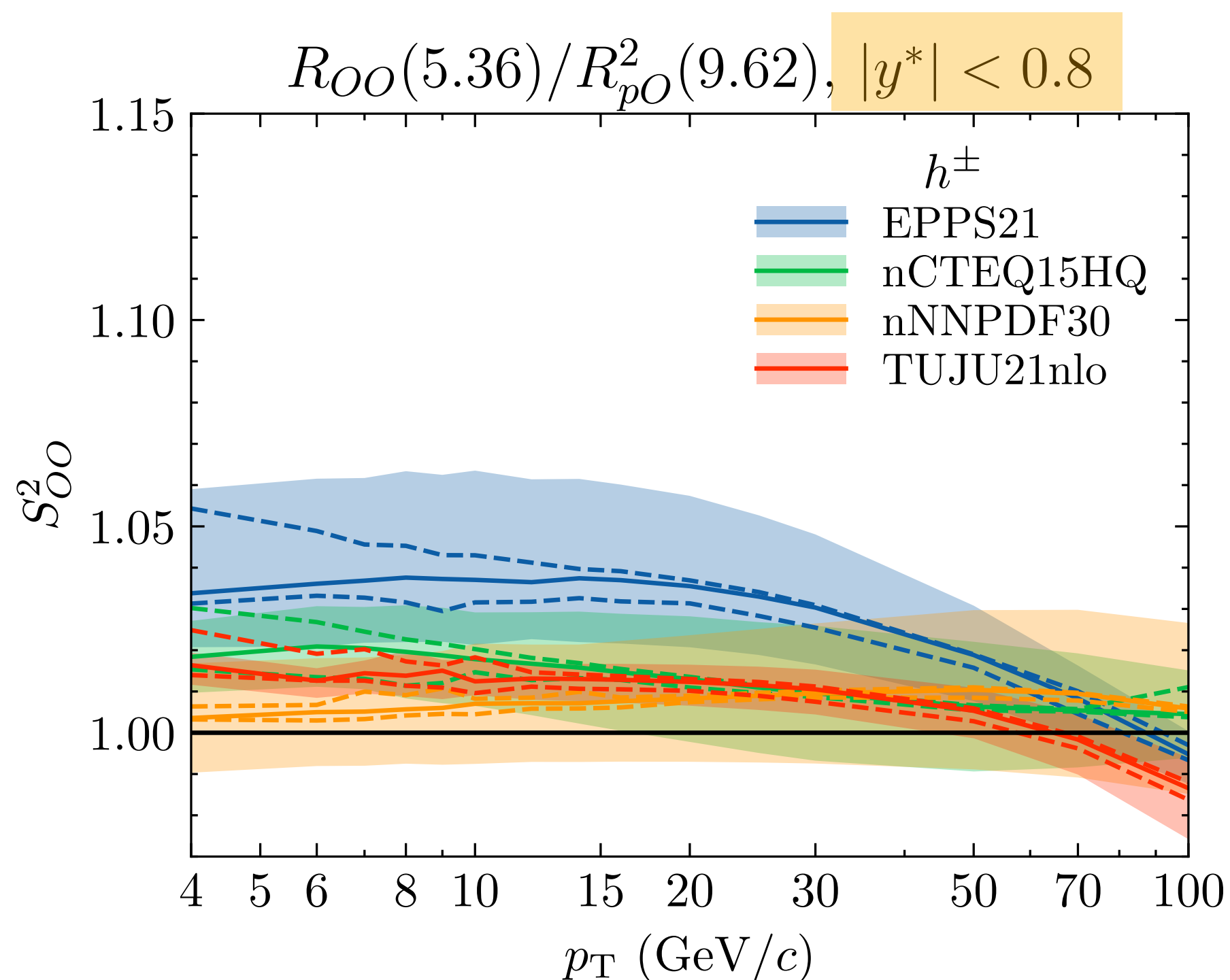


00 to p0 ratios: $S_{00}^2 = R_{00}(5.36)/R_{p0}^2(9.62)$

- Assuming the availability of a (potentially interpolated) pp reference at $\sqrt{s} = 9.62$ TeV one can construct:

$$S_{00}^2 = \frac{R_{00}(5.36)}{R_{p0}(9.62)^2} = \frac{\frac{d\sigma_{00}(5.36)}{dp_T}}{\frac{d\sigma_{p0}(9.62)}{dp_T}} \frac{\frac{d\sigma_{pp}(9.62)}{dp_T}}{\frac{d\sigma_{pp}(5.36)}{dp_T}}$$

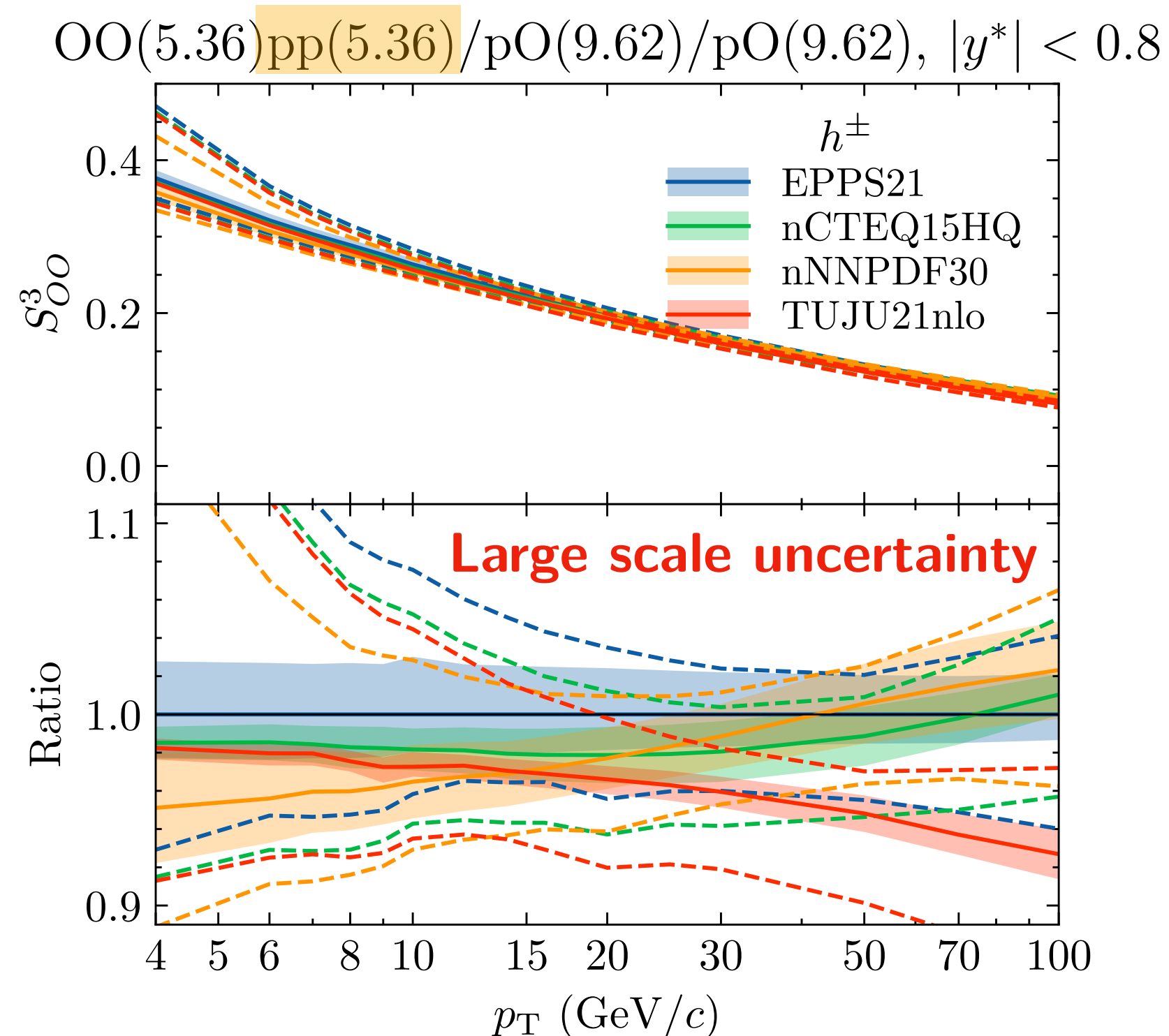
- Very promising for experimental searches:** few-percent level nPDF uncertainties and small scale uncertainties!
- Cancellation is better in in lab frame: **higher $\sqrt{s} \rightarrow$ lower x** vs. **boost $\rightarrow$ higher x** (competing effects cancel partially)



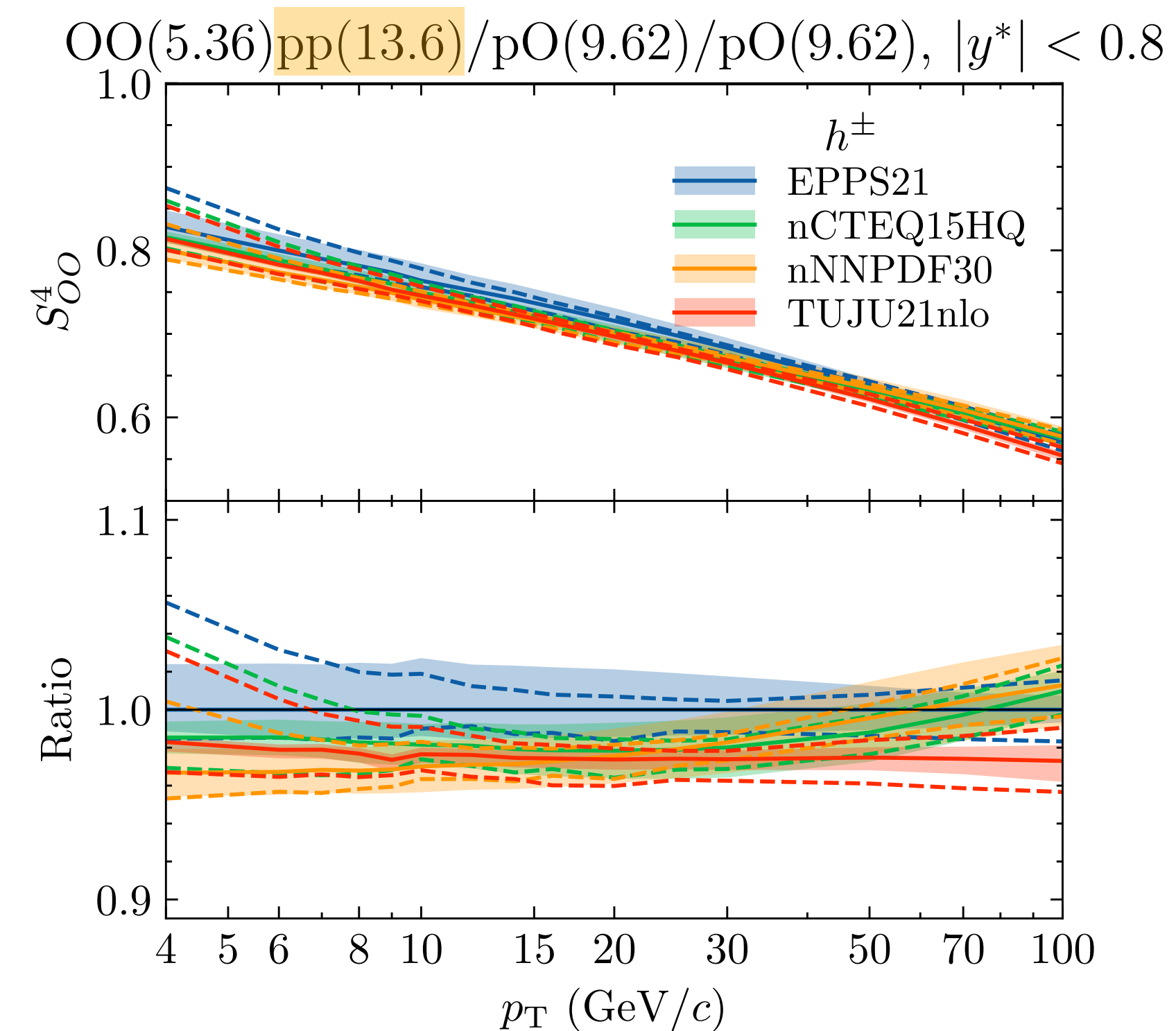
OO to pO ratios: Mixed-energy R_{pO}

- What if we do not want to interpolate our pp reference? What if we just use whatever pp baseline we have available?

$$S_{OO}^3 = \frac{\frac{d\sigma_{OO}(5.36)}{dp_T}}{\frac{d\sigma_{pO}(9.62)}{dp_T}} \frac{\frac{d\sigma_{pp}(5.36)}{dp_T}}{\frac{d\sigma_{pO}(9.62)}{dp_T}}$$

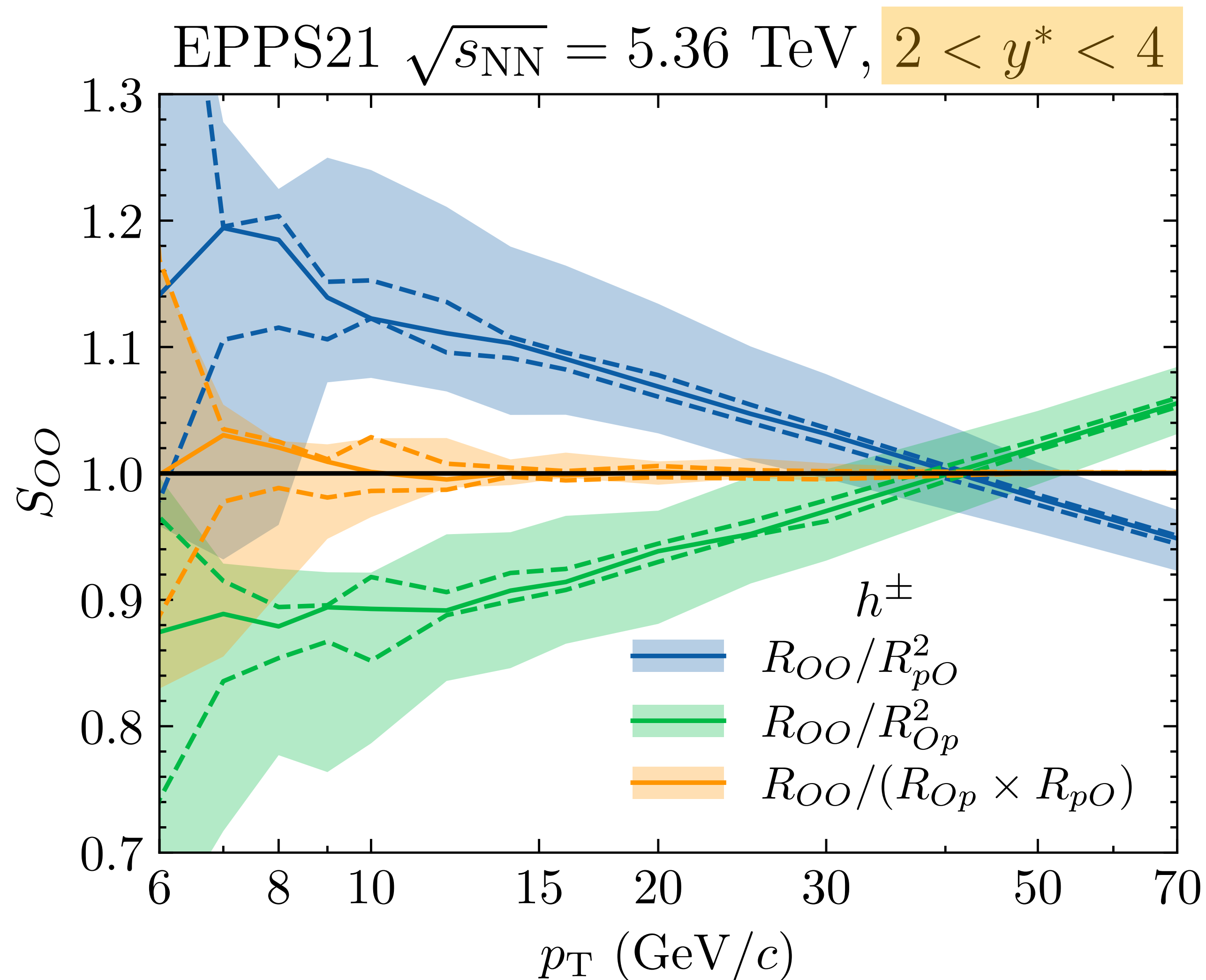


$$S_{OO}^4 = \frac{\frac{d\sigma_{OO}(5.36)}{dp_T}}{\frac{d\sigma_{pO}(9.62)}{dp_T}} \frac{\frac{d\sigma_{pp}(13.6)}{dp_T}}{\frac{d\sigma_{pO}(9.62)}{dp_T}}$$



If one mixes centre-of-mass energies, the ratio S_{OO}^4 using pp at $\sqrt{s} = 13.6$ TeV is preferable

A few words on measurements at forward rapidities

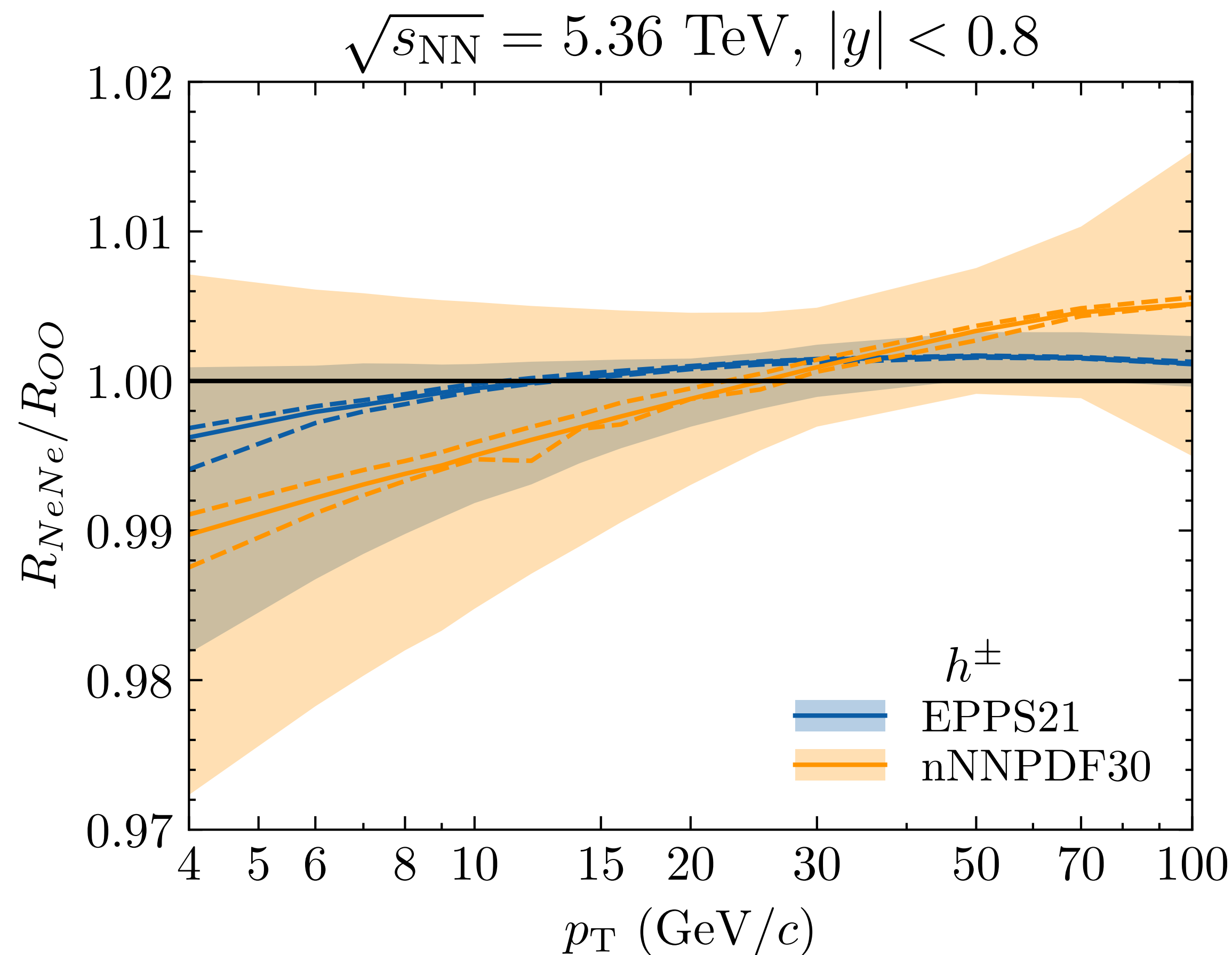


- When performing a measurement at forward rapidities, S_{OO}^1 has to be constructed as

$$S = \frac{R_{OO}}{R_{pO} \times R_{Op}}$$

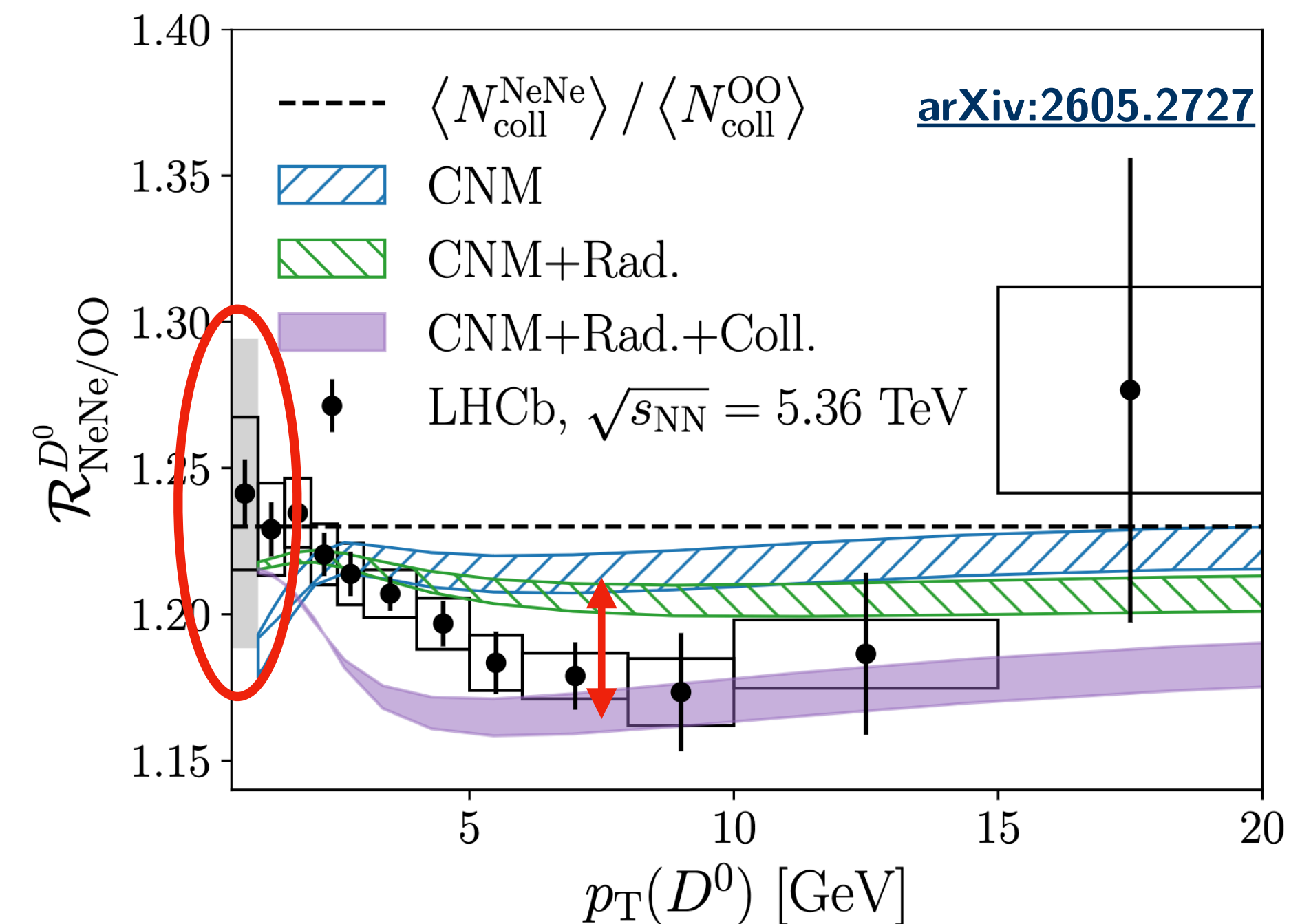
- If not, one over-/undercompensates for the low- x structure of the nucleus
- Effect of up to 20% at low p_T (neglecting boost)
- LHC only provided pO collisions in 2025 (p going in pos y direction, aka negative rapidity in ALICE convention)

One should push for running pA and Ap whenever possible!



Similar approach used by LHCb

$$\mathcal{R}_{\text{NeNe}/\text{OO}}^{D^0} = \frac{Y_{D^0}^{\text{NeNe}}}{Y_{D^0}^{\text{OO}}} \times \frac{\epsilon_{\text{OO}}}{\epsilon_{\text{NeNe}}} \times \frac{N_{\text{inel}}^{\text{OO}}}{N_{\text{inel}}^{\text{NeNe}}}$$



- Differences of CNM between Neon and Oxygen at most 1% and high cancellation of uncertainties
- However, energy loss will also largely cancel! Assuming $R_{\text{OO}} \approx 0.7$ and $1 - R_{\text{AA}} \propto A^{1/3} \Rightarrow R_{\text{NeNe}}/R_{\text{OO}} \approx 0.95$ (5% energy loss is signal)

High experimental precision needed to find e-loss signal

Goal 1: Provide a comprehensive set of pQCD predictions for CNM effects in light-ion collisions

- Charged hadron production calculated at NLO using INCNLO
- EW boson production calculated at NLO using MCFM
- Prompt photon production calculated at NLO using JETPHOX

⇒ sizable suppression and sizable uncertainties of nPDF baselines due to lack of oxygen data in global fits

Goal 2: Introduce observables in which CNM effects are reduced, guiding experimental searches for jet quenching

- Double ratio $R_{\text{OO}}^{\pi^0/\gamma}(p_T)$ offers good cancellation of CNM effects; preferred over ratio w.r.t Z boson
 - pO-based double ratios $S = R_{\text{OO}}/R_{\text{pO}}^2$ offer excellent cancellation for CNM effects
 - Oxygen/Neon double ratios: allow for high cancellation of CNM effects but jet quenching signal also partially cancels
- ⇒ the proposed observables may (and have been) used to search for jet quenching in light-ion collisions

Backup

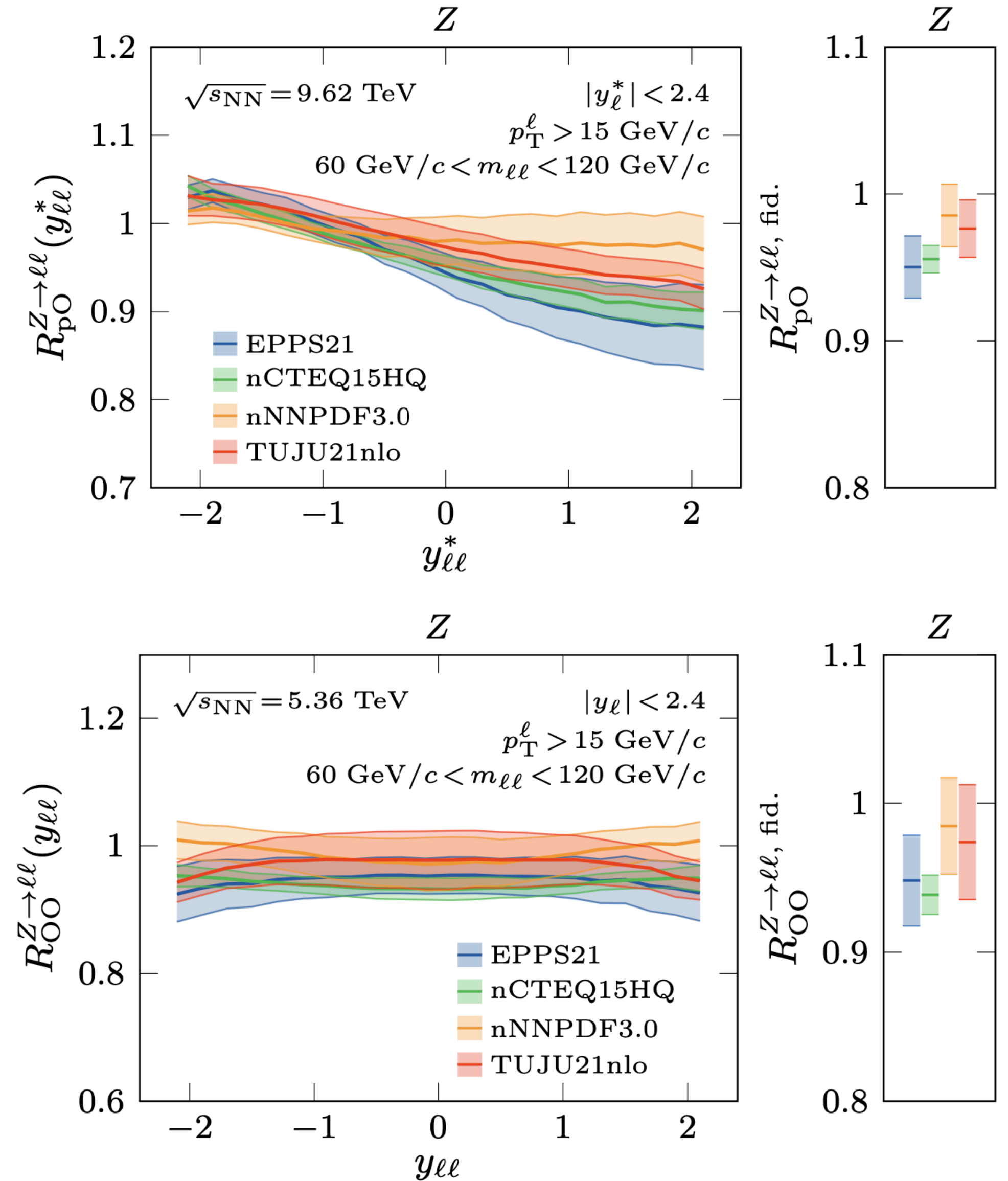
	Name	LHAPDF name	Proton reference
Oxygen	EPPS21 [73]	EPPS21nlo_CT18Anlo_016	CT18ANLO
	nCTEQ15HQ [74]	nCTEQ15HQ_FullNuc_16_8	CT18NLO
	nNNPDF30 [75]	nNNPDF30_nlo_as_0118_A16_Z8	nNNPDF30_nlo_as_0118_p
	TUJU21nlo [76]	TUJU21_nlo_16_8	TUJU21_nlo_1_1
Neon	EPPS21 [73]	EPPS21nlo_CT18Anlo_Ne20	CT18ANLO
	nNNPDF30 [75]	nNNPDF30_nlo_as_0118_A20_Z10	nNNPDF30_nlo_as_0118_p

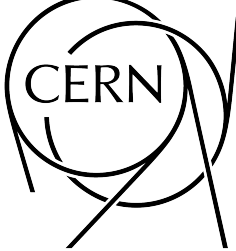
Table 1: Overview of n PDFs used in this work, including their name in the LHAPDF6 [72] library¹. In addition, for each n PDF the corresponding PDF used to calculate the pp reference is given.

Projections for $W^\pm$ and Z boson measurements

	lumi [nb ⁻¹]		xsec [nb]	est. num. events	proj. stat. unc.
pO	50.0	W^+	59.0	2950	1.8 %
		W^-	46.3	2315	2.1 %
		Z	10.2	510	4.4 %
OO	10.0	W^+	529.7	5297	1.4 %
		W^-	443.7	4437	1.5 %
		Z	95.4	954	3.2 %

Table 2: Estimated statistics and projected statistical uncertainties for $W^\pm$ and Z boson production with example luminosities mimicking those delivered to CMS during the 2025 light-ion campaign. The total fiducial cross sections are estimated by taking a simple average of the predictions from the four different nPDFs studied in this work. The impact of efficiency corrections is not taken into account in the statistical estimates.





Key features of recent nPDFs

Taken from
Ann.Rev.Nucl.Part.Sci. 74 (2024) 1, 49-87

Table 1: Key features of recent global analyses of nuclear PDFs.

ANALYSIS	nCTEQ15HQ (50)	EPPS21 (51)	nNNPDF3.0 (52)	TUJU21 (80)	KSASG20 (81)
THEORETICAL INPUT:					
Perturbative order	NLO	NLO	NLO	NNLO	NNLO
Heavy-quark scheme	SACOT- χ	SACOT- χ	FONLL	FONLL	FONLL
Value of $\alpha_s(M_Z)$	0.118	0.118	0.118	0.118	0.118
Charm mass m_c	1.3 GeV	1.3 GeV	1.51 GeV	1.43 GeV	1.3 GeV
Bottom mass m_b	4.5 GeV	4.75 GeV	4.92 GeV	4.5 GeV	4.75 GeV
Input scale Q_0	1.3 GeV	1.3 GeV	1.0 GeV	1.3 GeV	1.3 GeV
Data points	1484	2077	2188	2410	4353
Independent flavors	5	6	6	4	3
Parameterization	Analytic	Analytic	Neural network	Analytic	Analytic
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	$\sim$ CTEQ6.1	CT18A	$\sim$ NNPDF4.0	$\sim$ HERAPDF2.0	CT18
Proton PDF correlations		✓	✓		
Deuteron corrections	(✓) ^{a,b}	✓ ^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	(✓) ^a	✓			✓
CHORUS/CDHSW CC DIS	(✓/-) ^b	✓/-	✓/-	✓/✓	✓/✓
NuTeV/CCFR 2 μ CC DIS	(✓/✓) ^b		✓/-		
pA DY	✓	✓	✓		✓
πA DY		✓			
COLLIDER DATA:					
Z bosons	✓	✓	✓	✓	
$W^\pm$ bosons	✓	✓	✓	✓	
Light hadrons	✓	✓ ^d			
– Cut on p_T	3 GeV	3 GeV			
Jets		✓	✓		
Prompt photons			✓		
Prompt D ⁰	✓	✓	✓ ^e		
– Cut on p_T	3 GeV	3 GeV	0 GeV		
Quarkonia (J/ψ , ψ' , Υ)	✓				

^a nCTEQ15HIX (26); ^b nCTEQ15 ν (114); ^c through CT18A; ^d only π^0 in DAu; ^e only forward ($y > 0$).