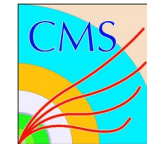


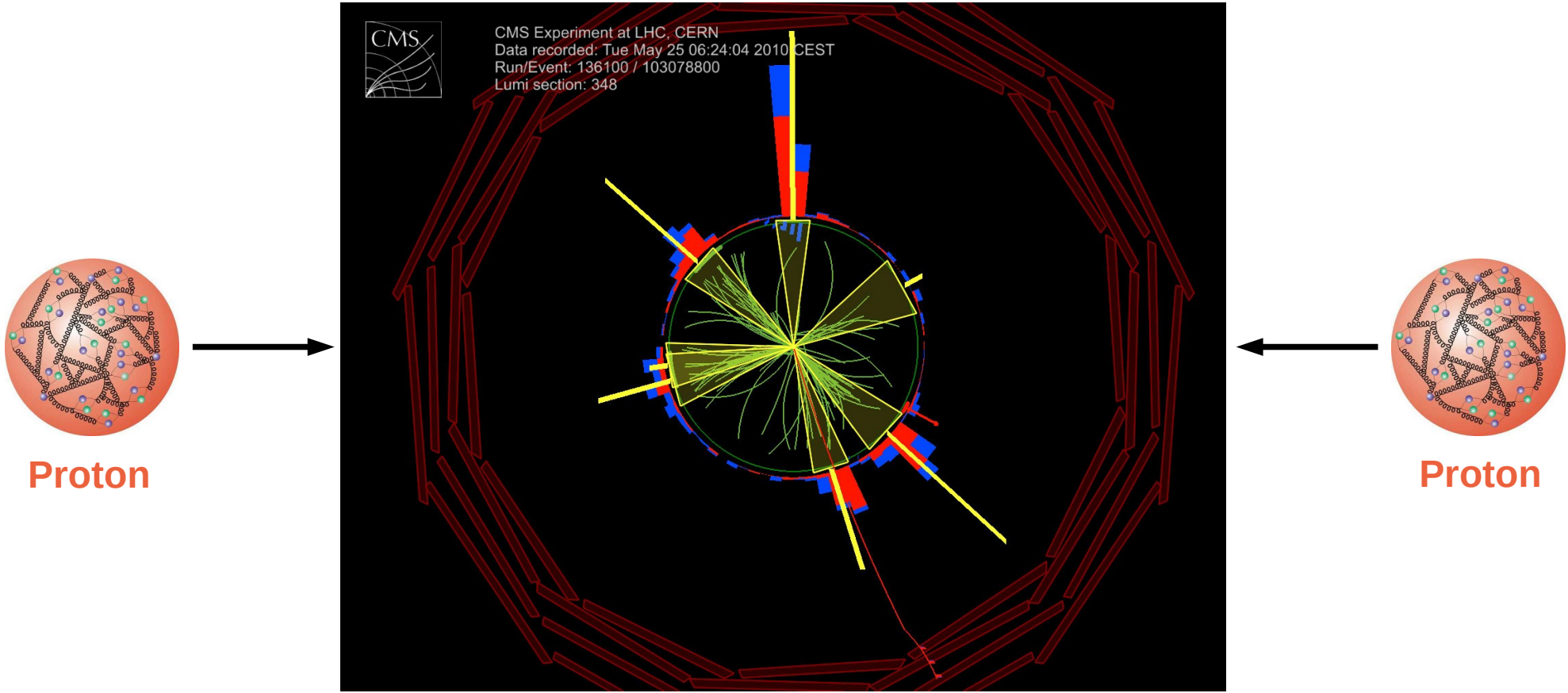
Simultaneous PDF fits and SM parameter extractions at CMS

Klaus Rabbertz
(on behalf of CMS)



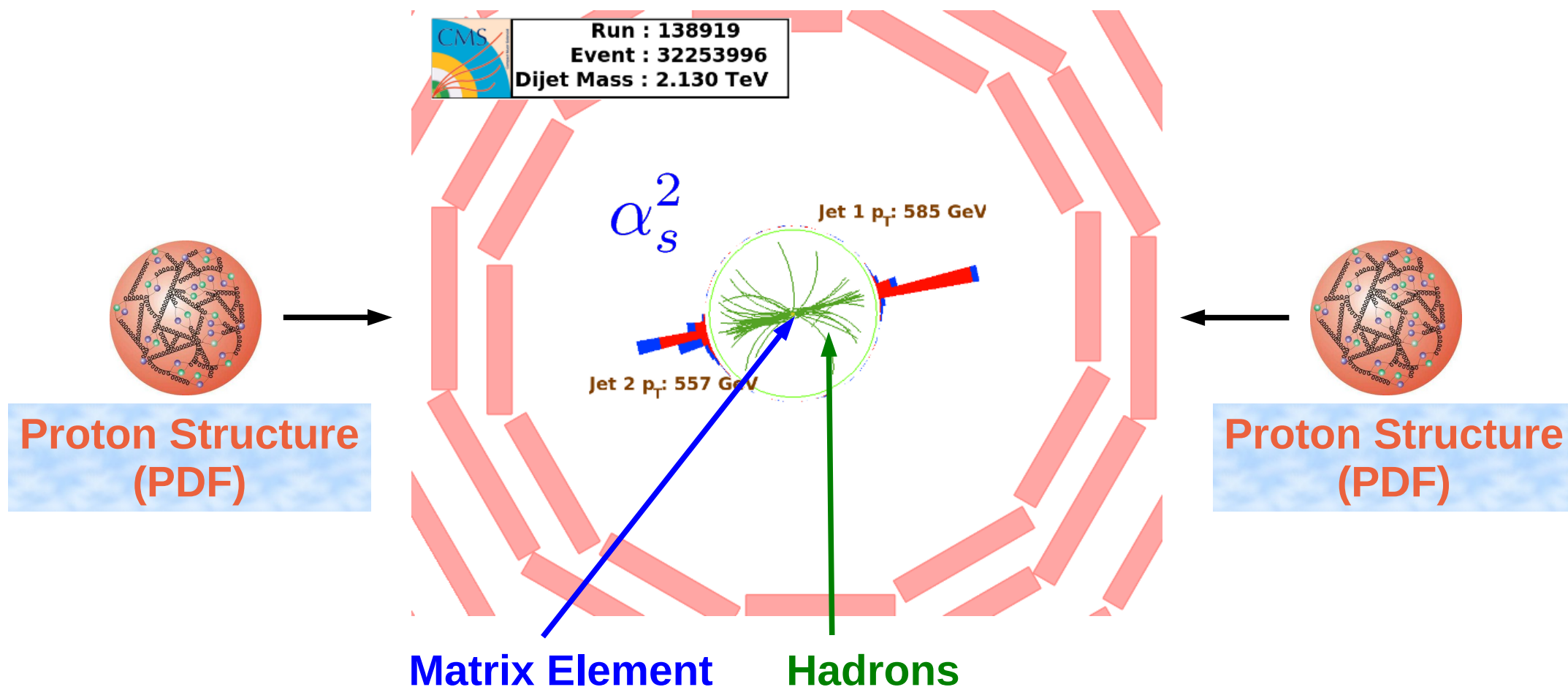
- **Intro**
- **Inclusive jets**
- **Combination with $t\bar{t}$ measurement**
- **Dijet cross sections**
- **Combination of multiple inclusive jet measurements**
- **Forward-backward asymmetry and $\sin^2\theta_w$**
- **Summary & outlook**

Large transverse momenta



Abundant production of jets:

- Highest reach ever in energy scale Q to determine the strong coupling
- Learn about hard QCD, the proton structure, non-perturbative, and electroweak effects at high Q
- Search for new phenomena



- Counting jets or jet events in bins of e.g. momentum and rapidity
- Useful for i.a.:
 - ➔ Determination of $\alpha_s(m_Z)$
 - ➔ Test of running of $\alpha_s(Q)$
 - ➔ Multi-parameter fit of $\alpha_s(m_Z)$ & PDFs
 - ➔ Multi-parameter fit including EFT parameters

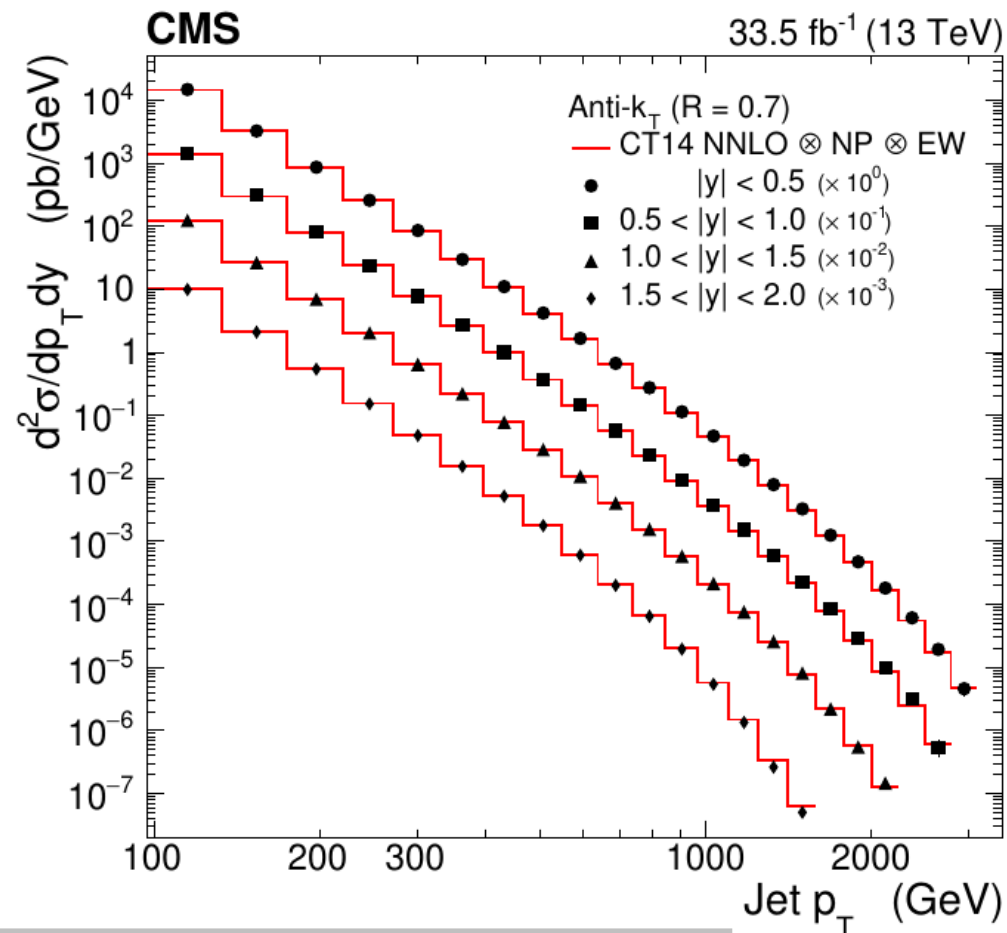
- Counting jets or jet events in bins of e.g. momentum and rapidity
- Useful for i.a.:
 - ➔ Determination of $\alpha_s(m_Z)$
 - ➔ Test of running of $\alpha_s(Q)$
 - ➔ Multi-parameter fit of $\alpha_s(m_Z)$ & PDFs
 - ➔ Multi-parameter fit including EFT parameters
- Subject to many/all systematic uncertainties:
 - ➔ Jet energy calibration (JEC) & resolution (JER)
 - ➔ Luminosity
 - ➔ Missing higher orders

... to name a few

Jet counting in bins of jet transverse momentum and rapidity Comparison of unfolded measurement with theory:

NNLO x nonperturbative x electroweak correction

(NNLO in leading-color (LC) approximation; subleading effects small)



CMS, JHEP02 (2022) 142 & JHEP12 (2022) 035.

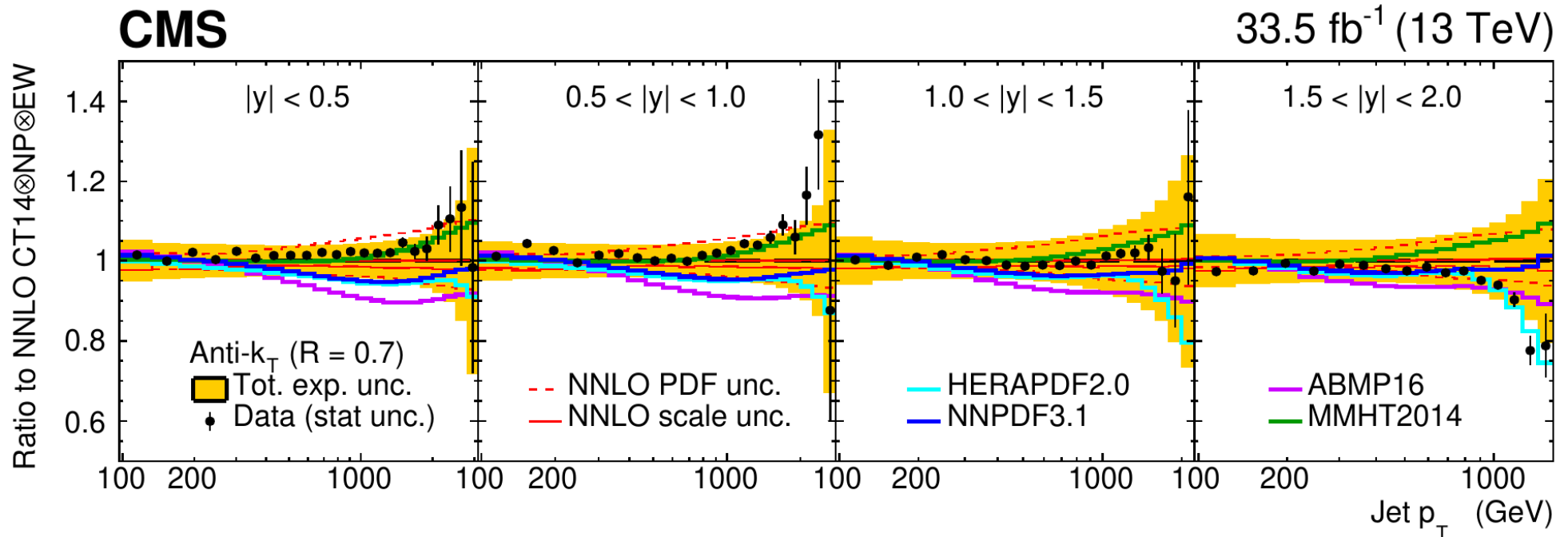
Jet counting in bins of jet transverse momentum and rapidity Comparison of unfolded measurement with theory:

NNLO x nonperturbative x electroweak correction

(NNLO in leading-color (LC) approximation; subleading effects small)

Note: 2016 data only!
Full run 2 and 3 still to come.

$|y|_{\max} = 2$

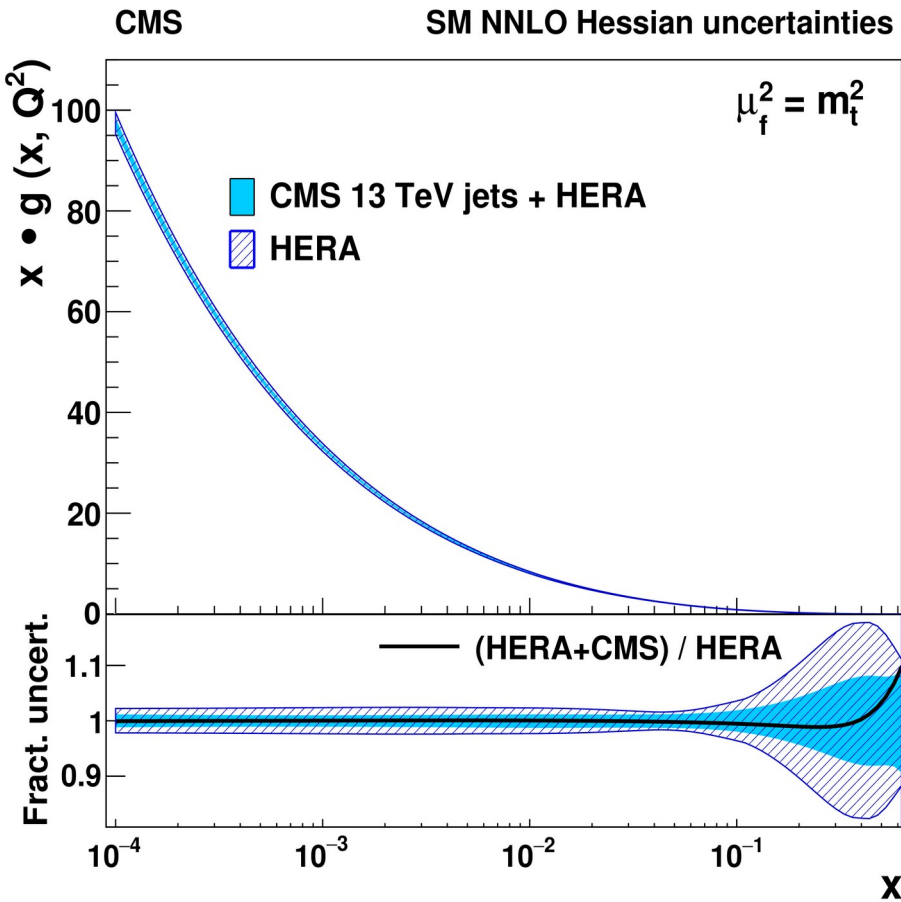
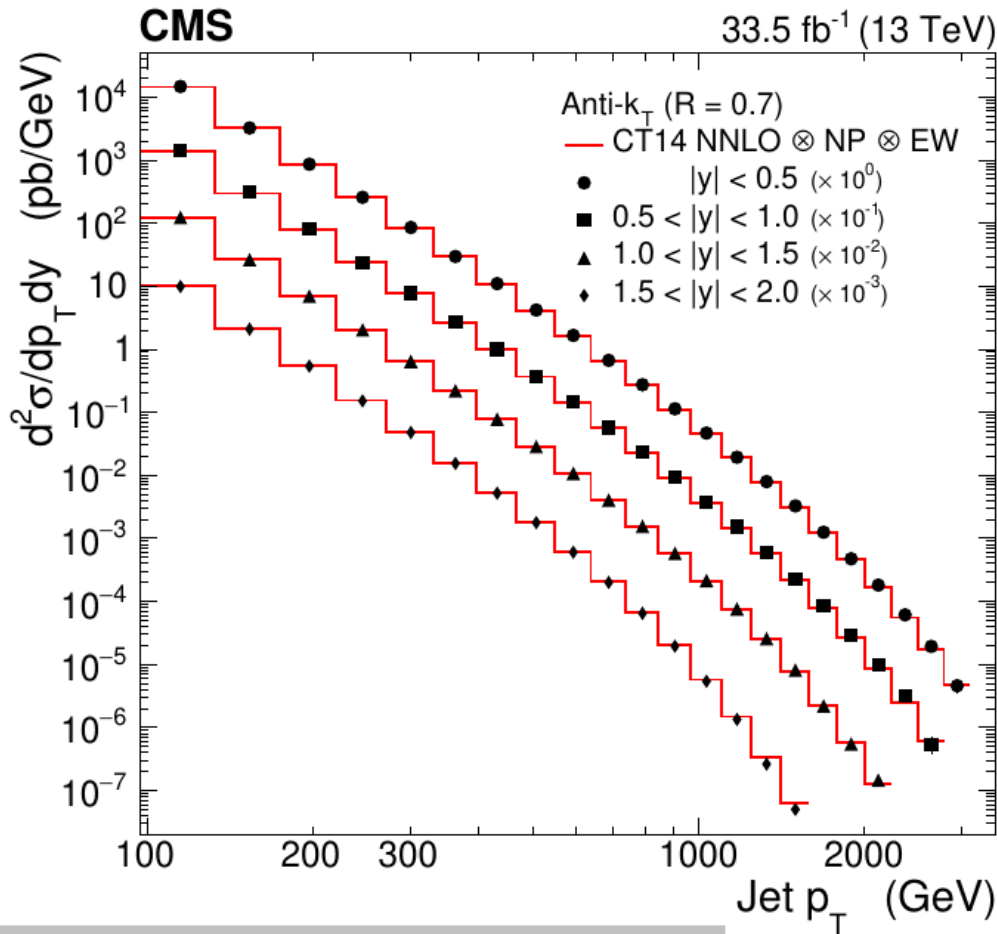


CMS, JHEP02 (2022) 142 & JHEP12 (2022) 035.

First determination of $\alpha_s(m_Z)$ from jets at NNLO-LC:

$$\alpha_s(m_Z^2) = 0.1166 \pm 0.0016(\text{fitall}) \pm 0.0004(\text{scl})$$

Simultaneous fit with PDFs
 → reduced uncertainties of gluon as compared to HERA DIS only

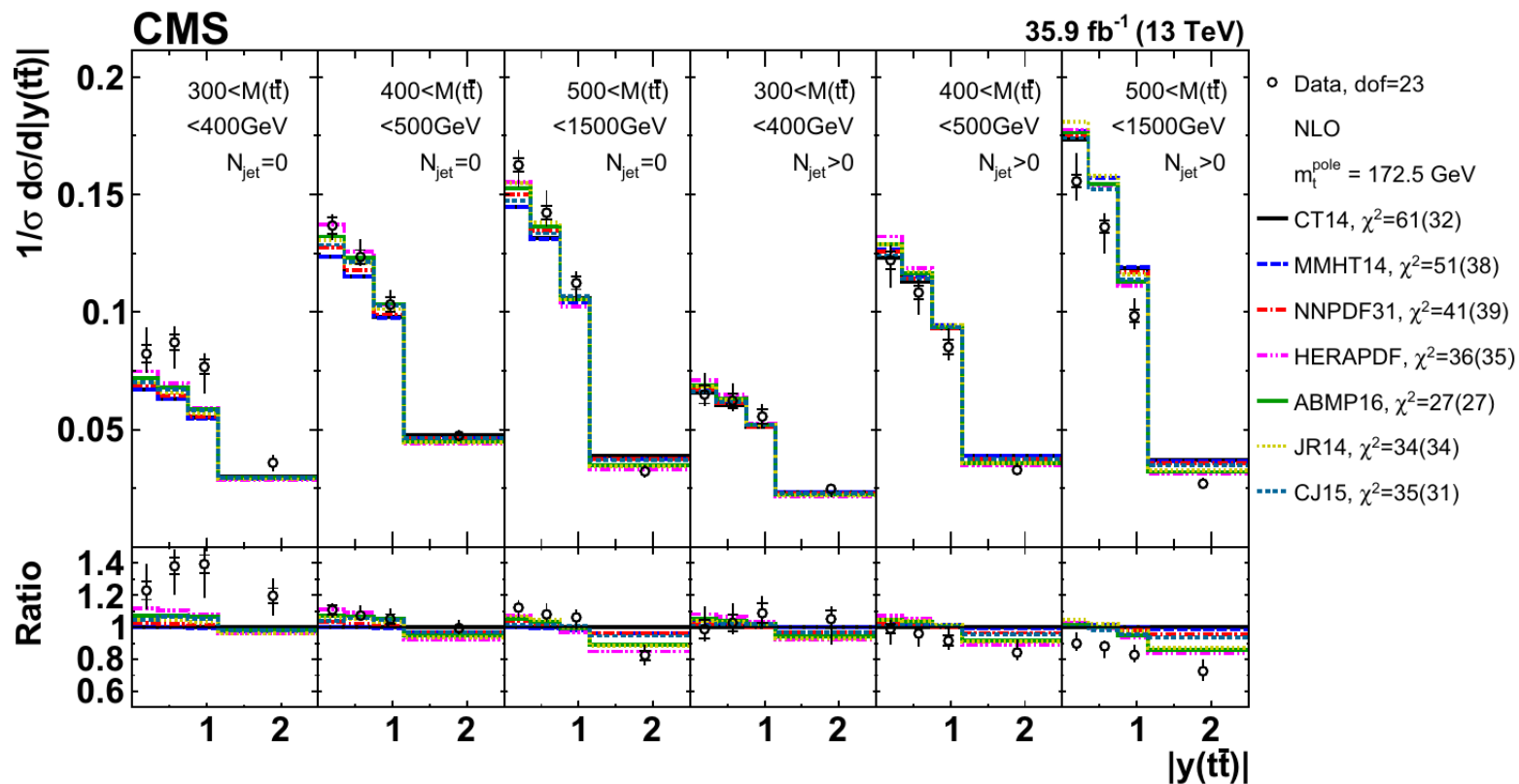


CMS, JHEP02 (2022) 142 & JHEP12 (2022) 035.

Simultaneous fit combining HERA DIS & CMS jet & CMS normalised $t\bar{t}$ data

NLO only: $\alpha_s(m_Z^2) = 0.1188 \pm 0.0017(\text{fitall}) \pm 0.0025(\text{scl})$
 $m_t^{\text{pole}} = 170.4 \pm 0.6(\text{fitall}) \pm 0.1(\text{scl})$

2016 data only!

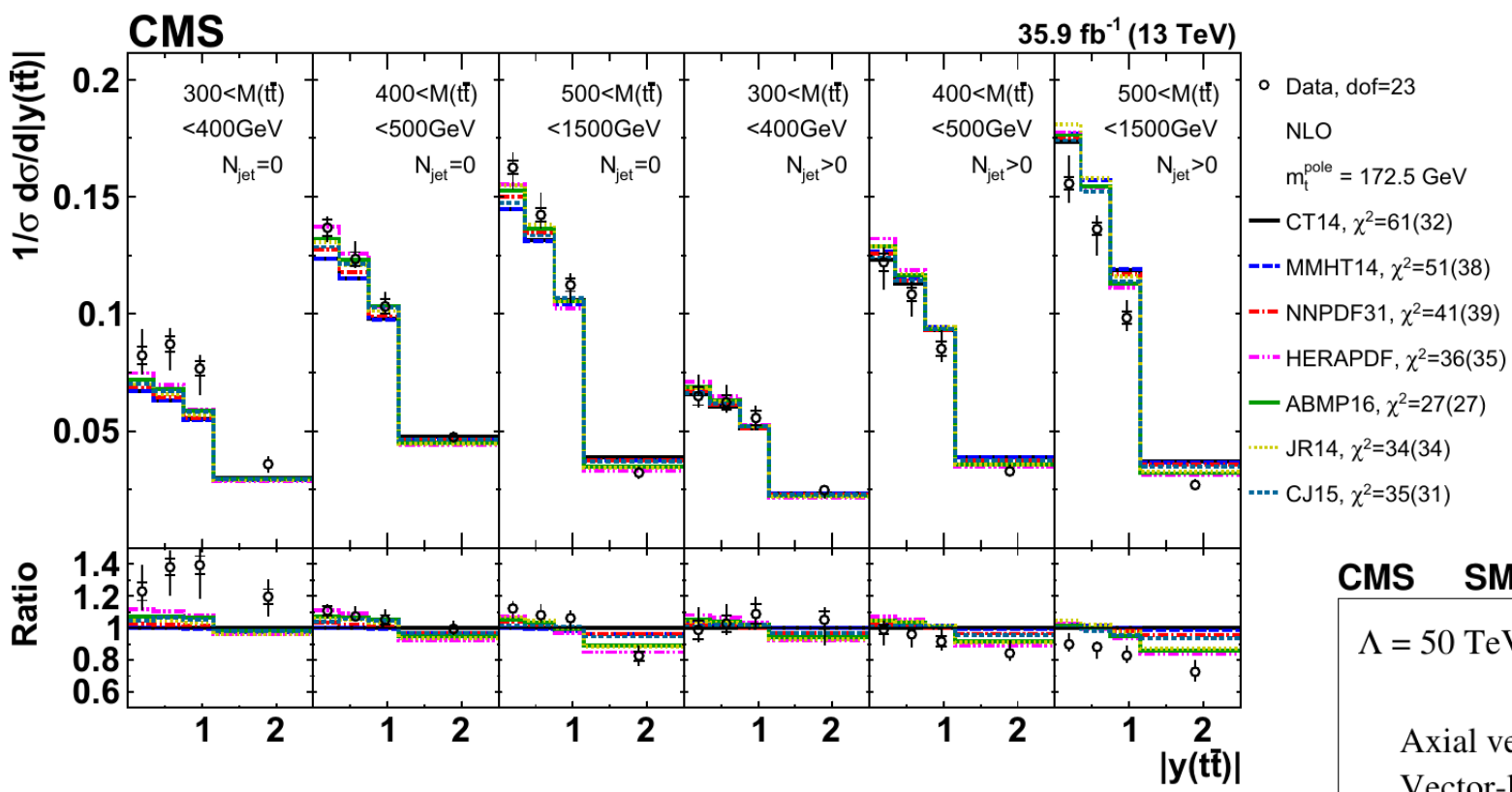


CMS, JHEP02 (2022) 142 & JHEP12 (2022) 035.

Simultaneous fit combining HERA DIS & CMS jet & CMS normalised ttbar data

NLO only: $\alpha_s(m_Z^2) = 0.1188 \pm 0.0017(\text{fitall}) \pm 0.0025(\text{scl})$
 $m_t^{\text{pole}} = 170.4 \pm 0.6(\text{fitall}) \pm 0.1(\text{scl})$

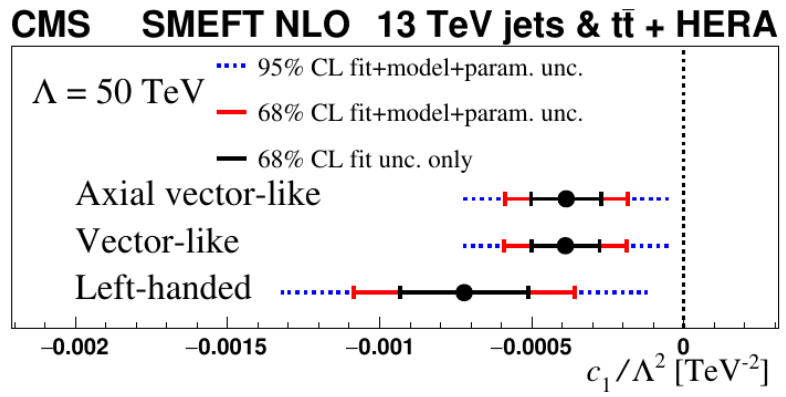
2016 data only!



+ EFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{2\pi}{\Lambda^2} \sum_{n \in \{1,3,5\}} c_n O_n.$$

SM compatible
→ excl. limits

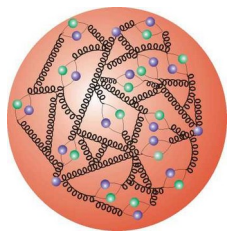


See also

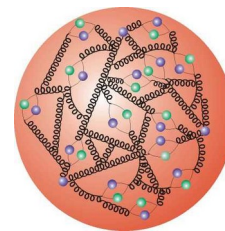
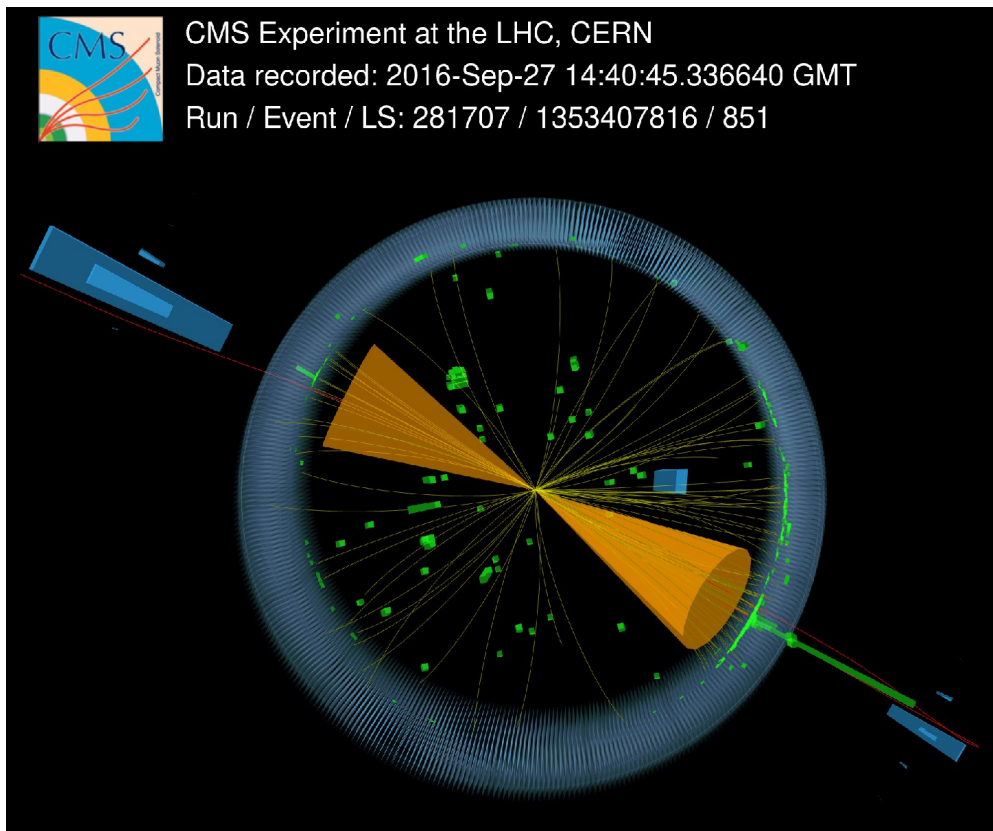
CMS, JHEP02 (2022) 142 & JHEP12 (2022) 035.

Recent update outside of CMS:
Mendizabal et al., arXiv:2607.22390

Large masses



Proton



Proton

Jet event counting in bins of dijet mass or average transverse momentum (x) and

rapidity separation

$$y^* = \frac{1}{2} |y_1 - y_2| \rightarrow \text{scattering angle}$$

boost of dijet system

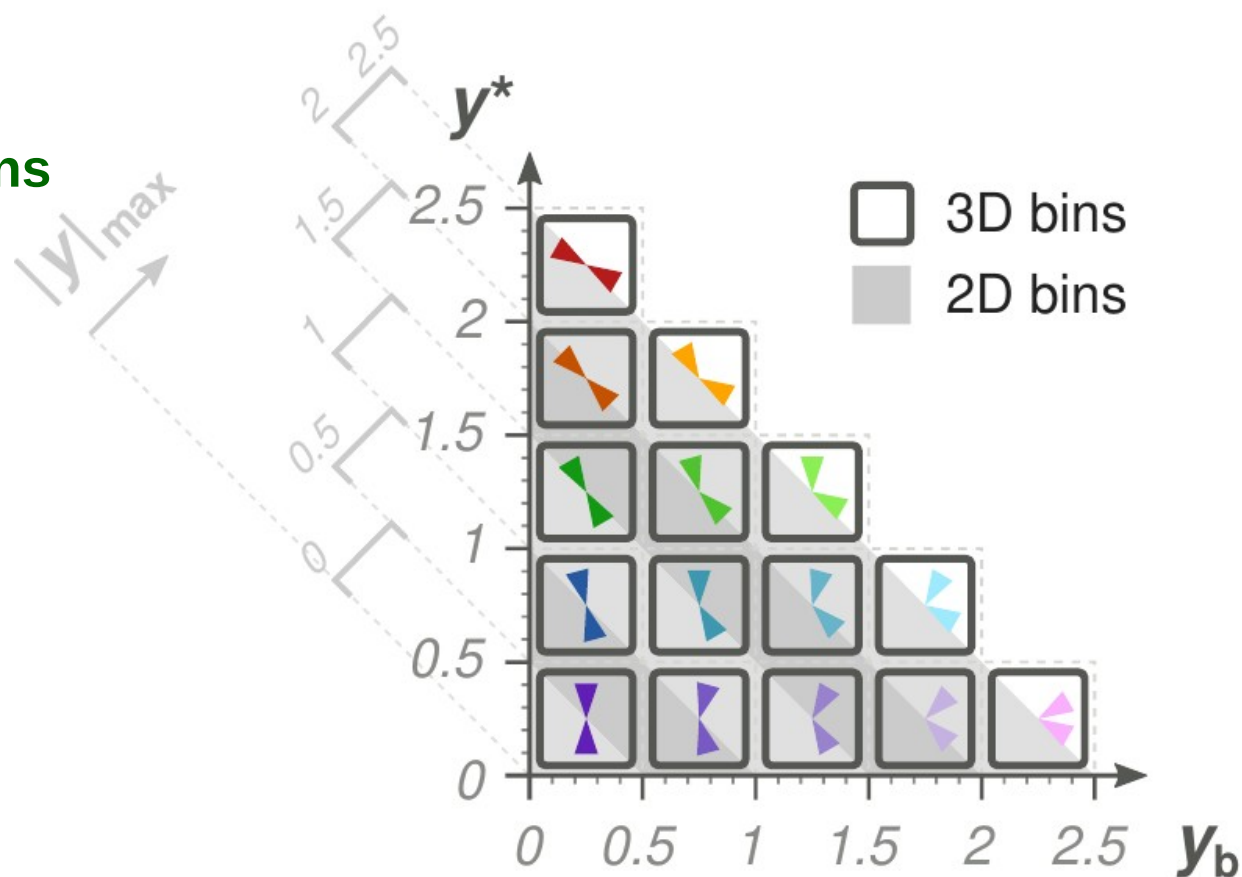
$$y_b = \frac{1}{2} |y_1 + y_2| \rightarrow \mathbf{x}_1 \text{ and } \mathbf{x}_2 \text{ fractions}$$

$$\frac{d^3\sigma}{dy^* dy_b dx} = \frac{1}{\epsilon \mathcal{L}_{\text{int}}} \frac{N}{\Delta y^* \Delta y_b \Delta x}$$

$$x \in \{m_{1,2}, \langle p_T \rangle_{1,2}\}$$

Alternativ: 2D binning in maximum rapidity of $|y_1|, |y_2|$

Illustration of dijet event topologies



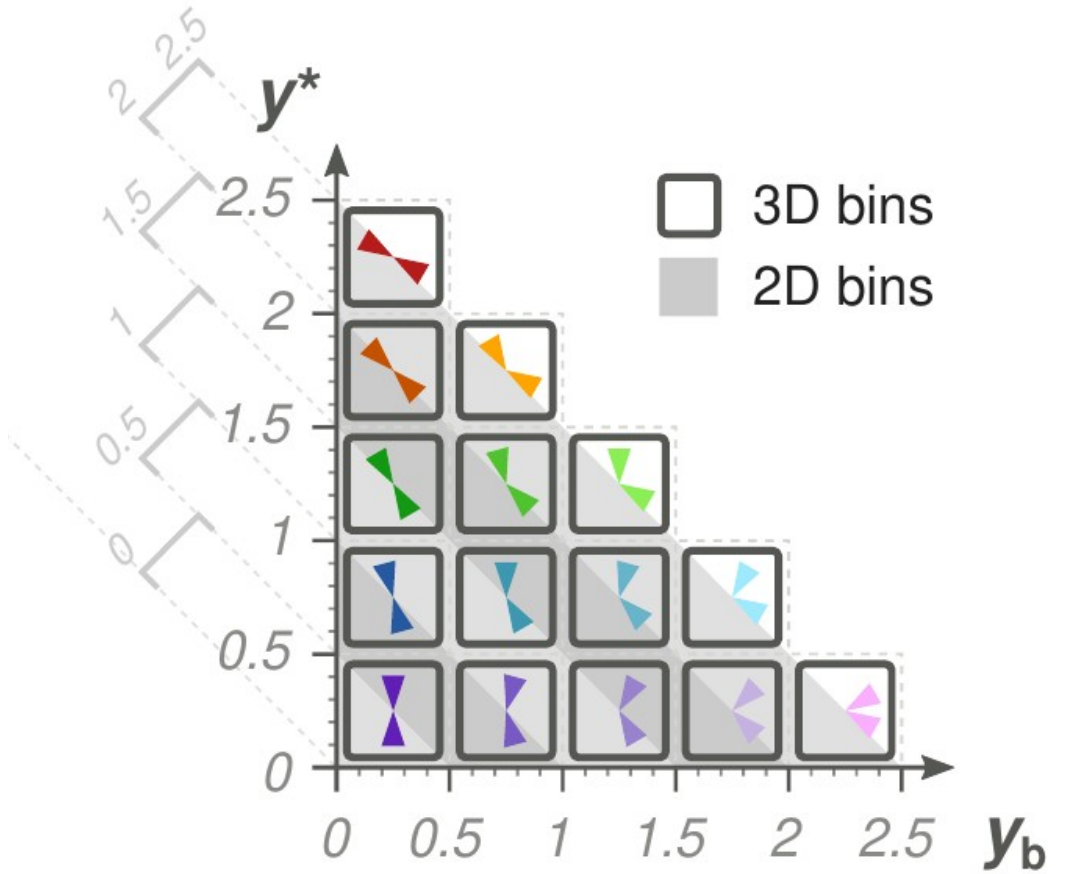
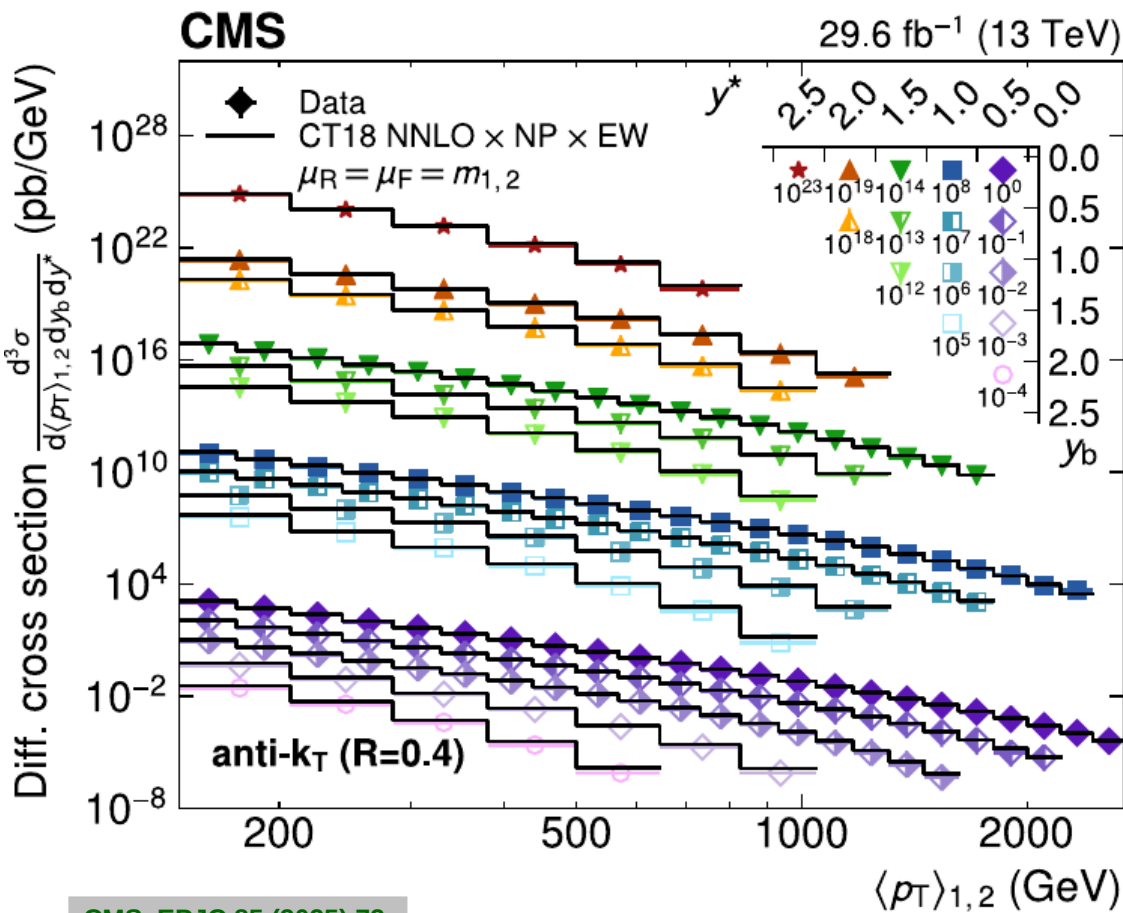
Jet event counting in bins of x, y^*, y_b 2016 data only!

Comparison of unfolded measurement with theory:

NNLO x nonperturbative x electroweak correction

Illustration of dijet event topologies

(Impact of subleading-color corrections up to few %)



CMS, EPJC 85 (2025) 72.

$R=0.8$

Determine $\alpha_s(m_Z)$ + PDFs

2016 data only!

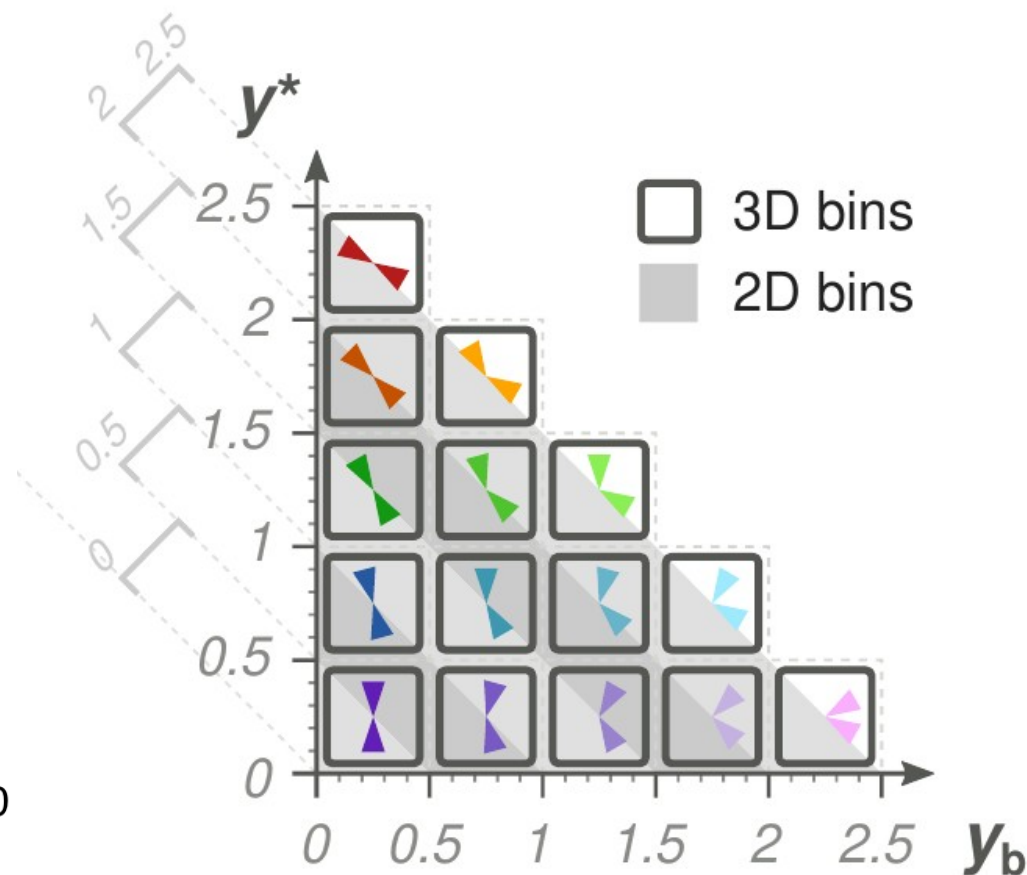
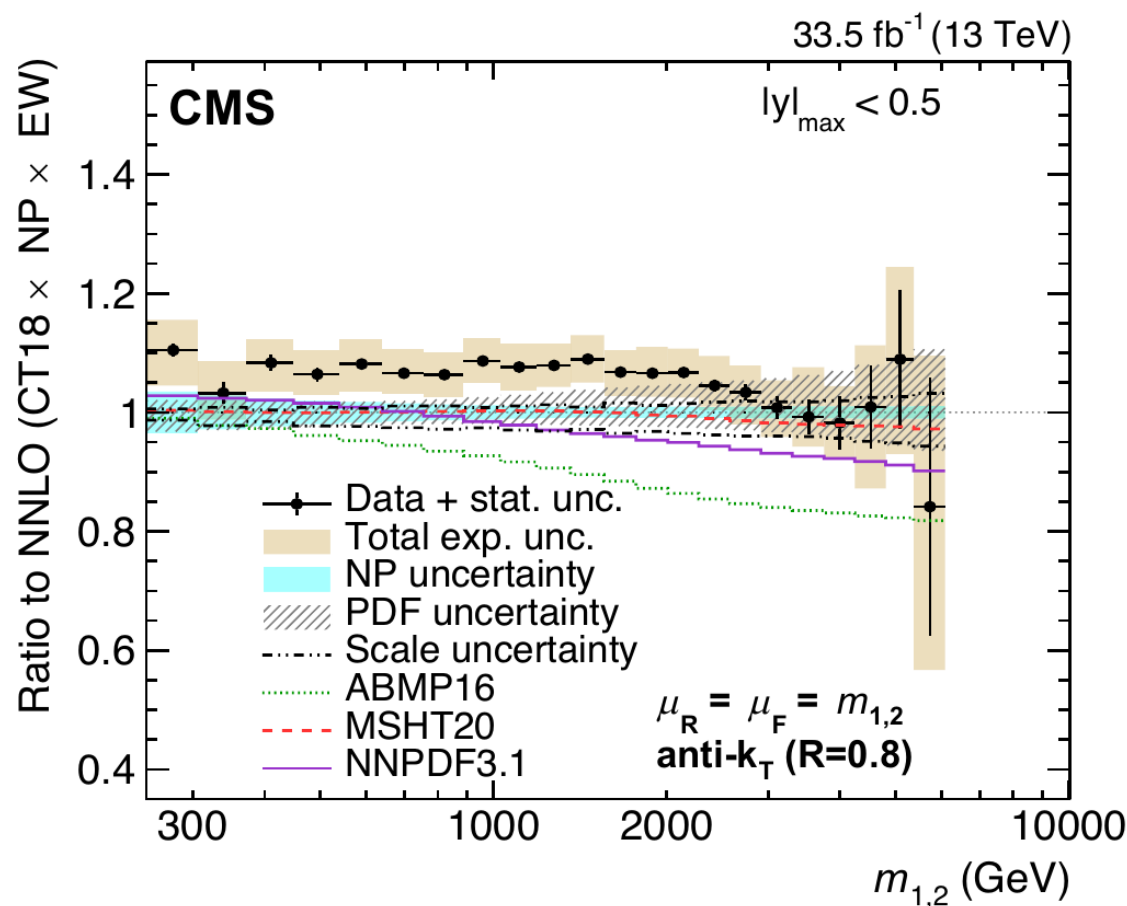
Example of ratio
data / theory

2D

$$\alpha_s(m_Z) = 0.1179 \pm 0.0017(\text{fitall}) \pm 0.0008(\text{scl})$$

3D

$$\alpha_s(m_Z) = 0.1181 \pm 0.0019(\text{fitall}) \pm 0.0009(\text{scl})$$



Combining HERA & all LHC dijet data

→ running α_s : 7 GeV – 7 TeV

Combination beyond CMS:
Ahmadvova et al., PRL 135 (2025) 031903.

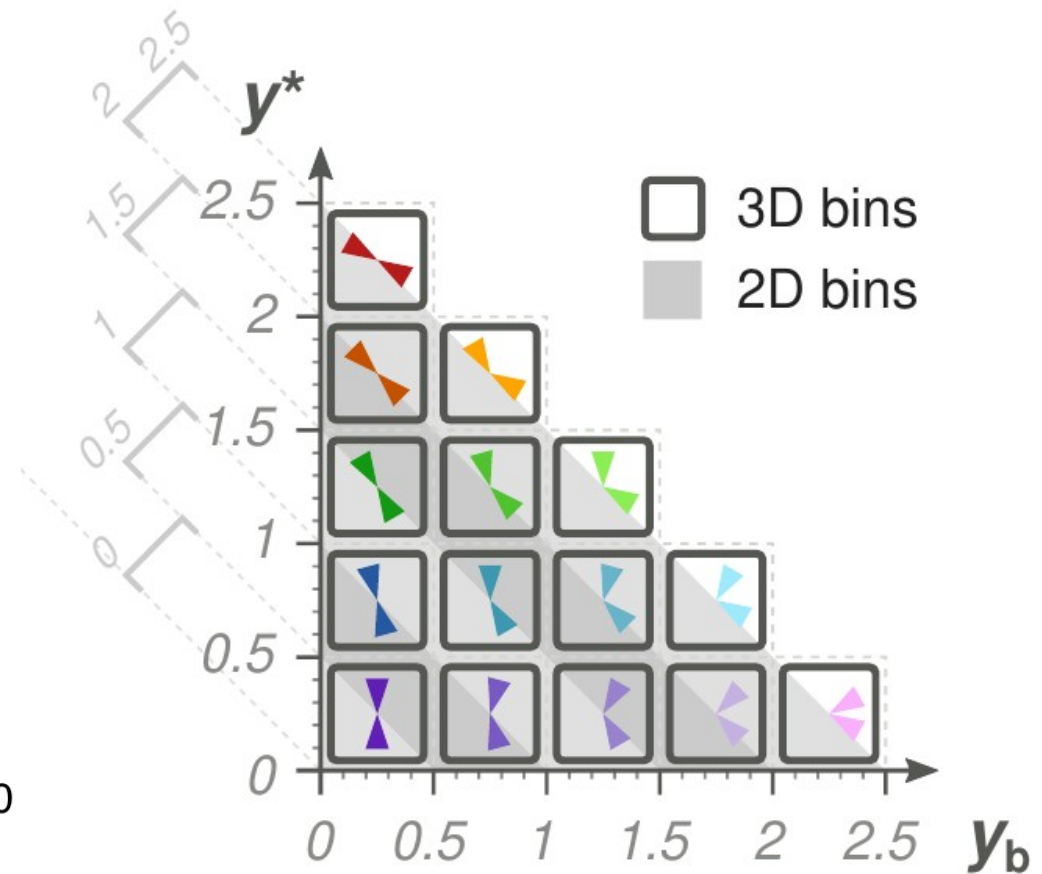
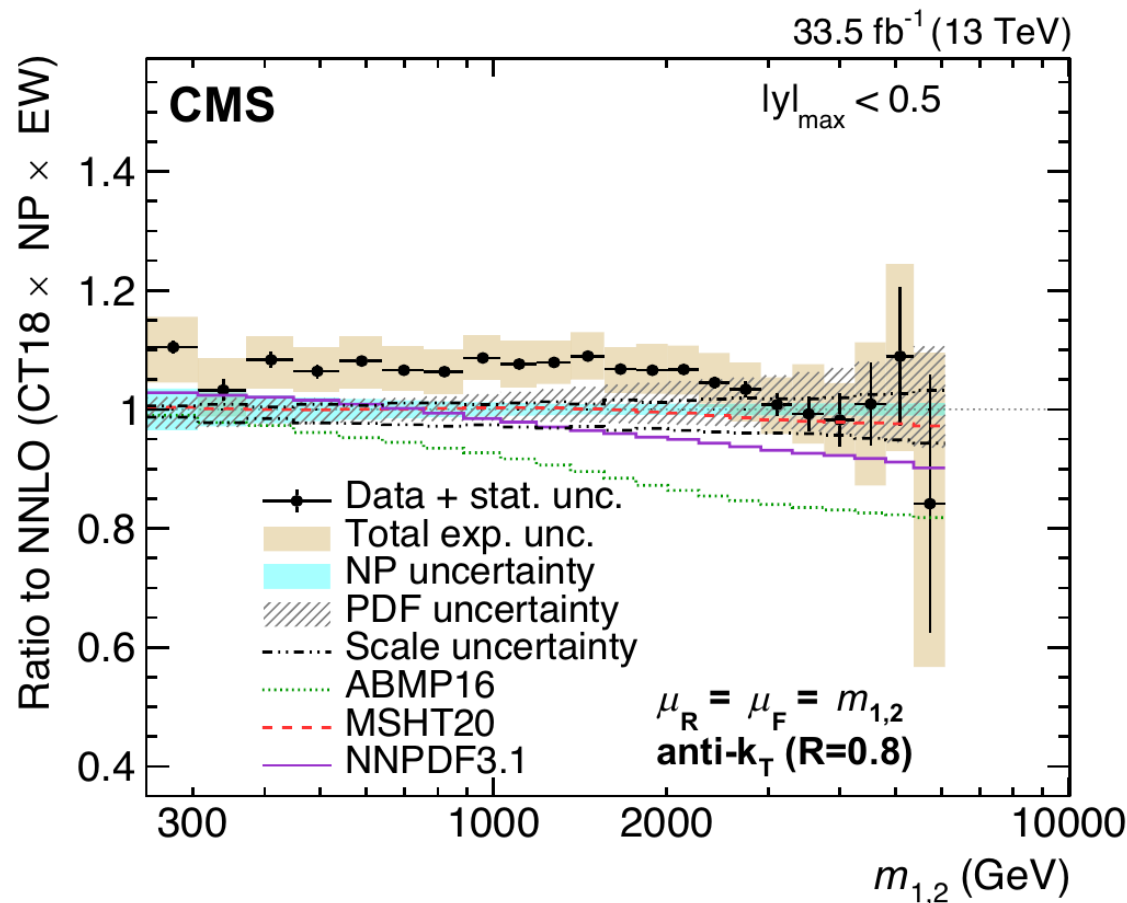
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$$\alpha_s(m_Z) = 0.1181 \pm 0.0019(\text{fitall}) \pm 0.0009(\text{scl})$$



CMS, EPJC 85 (2025) 72.

- Up to now: Fit of whole dataset $\rightarrow \alpha_s(m_Z)$ & PDFs (running used implicitly)

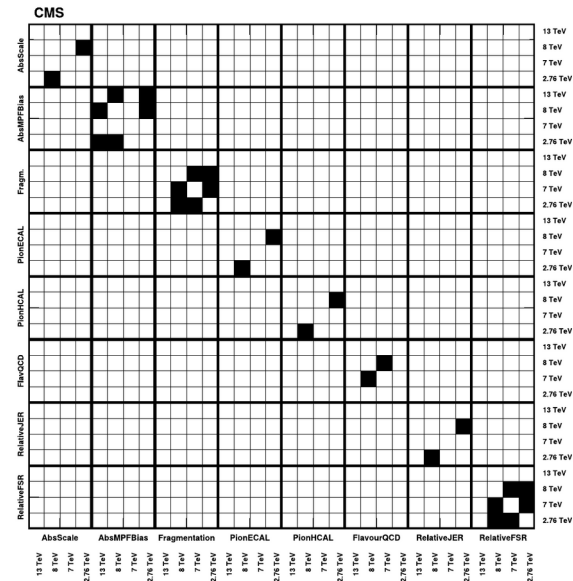
QCD analysis from CMS

- Combination of multiple datasets
- Subdivide into ranges of jet p_T
- Multi-parameter fit of $\alpha_s(m_Z)$ & PDFs in each range separately

$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb $^{-1}$]	N_p	p_T [GeV]	$ y $
2.76	0.0054	80	74–592	0.0–3.0
7	5.0	130	114–2116	0.0–2.5
8	20	165	74–1784	0.0–3.0
13	33.5	78	97–3103	0.0–2.0

- Uncertainty correlations vs. E_{cms} studied and varied

- Some correlation in JEC among cms energies, insignificant in JER



- MHOU (scale variation) fully correlated

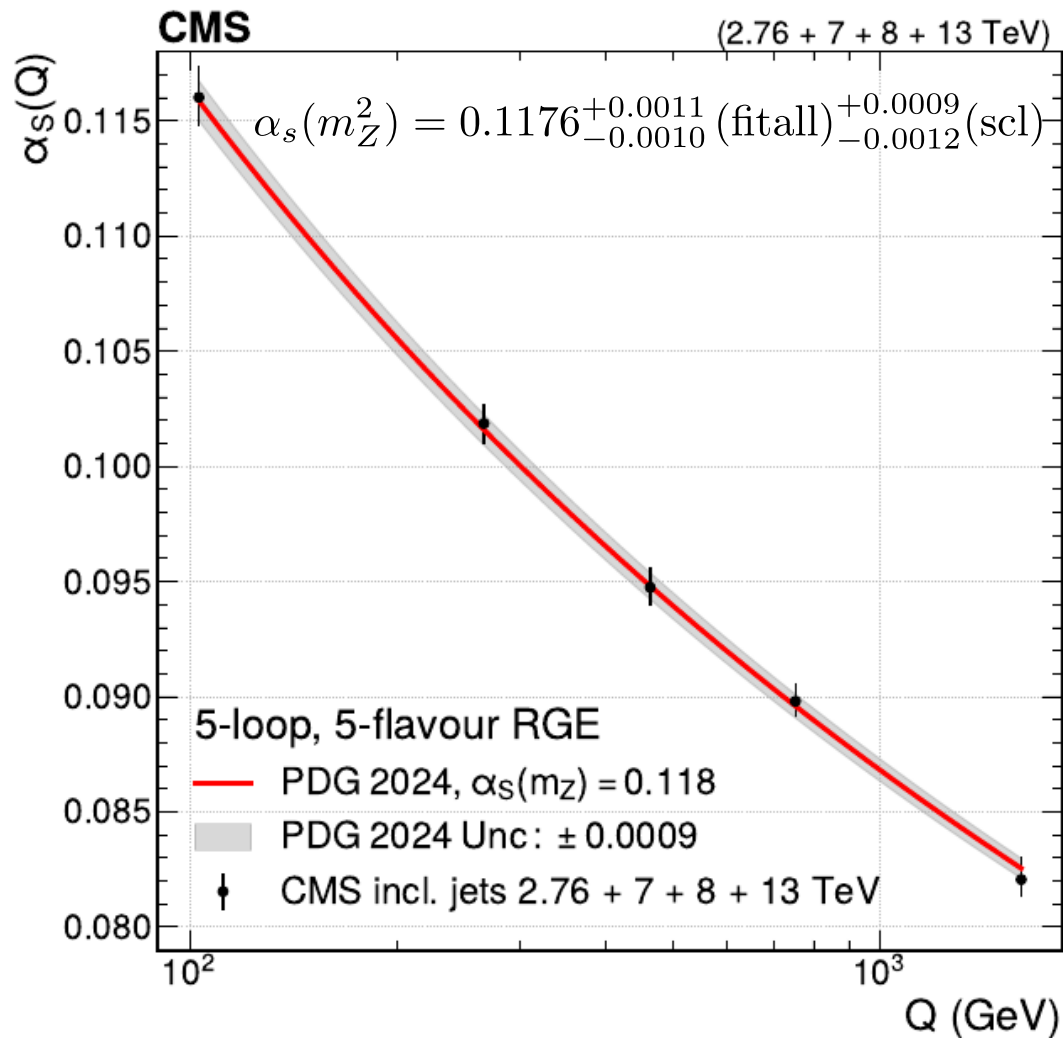
Up to now: Fit of whole dataset $\rightarrow \alpha_s(m_Z)$ & PDFs (running used implicitly)

QCD analysis from CMS

- Combination of multiple datasets
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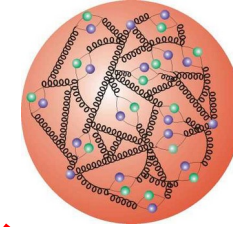
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Running of $\alpha_s(Q)$ in five ranges of jet p_T

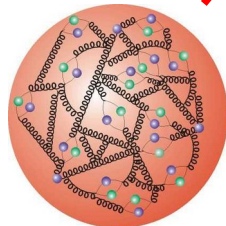
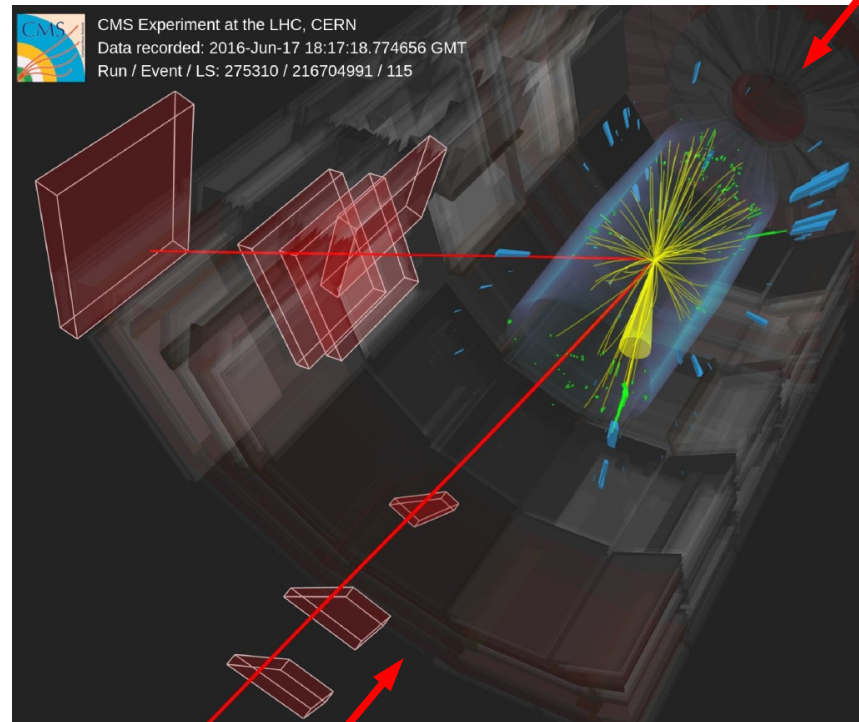


CMS, PLB 868 (2025) 139651.

**Drell-Yan $Z + X \rightarrow$ FB-asymmetry
 $\rightarrow \sin^2\theta_{\text{eff}}^l$**



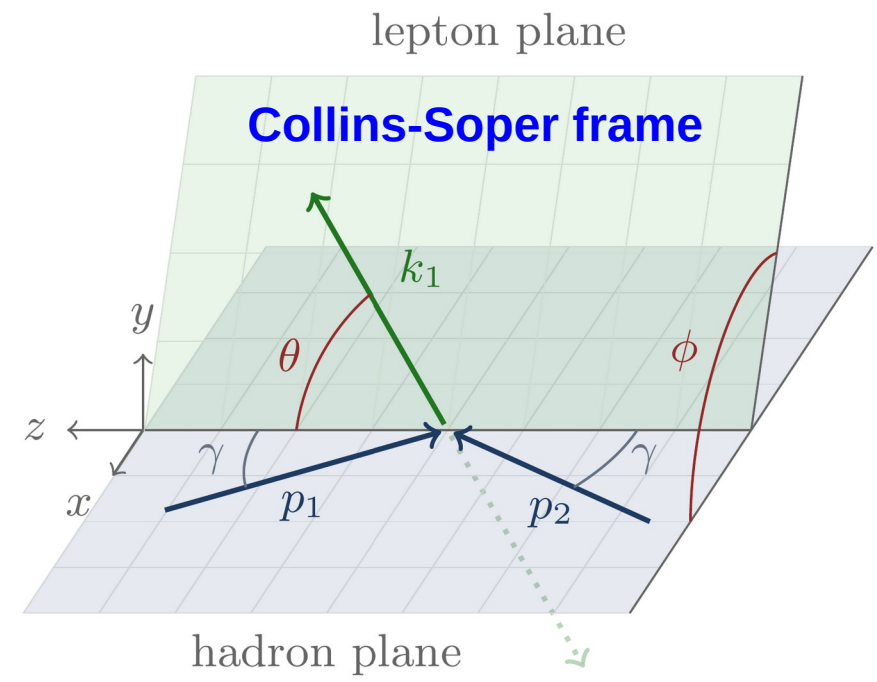
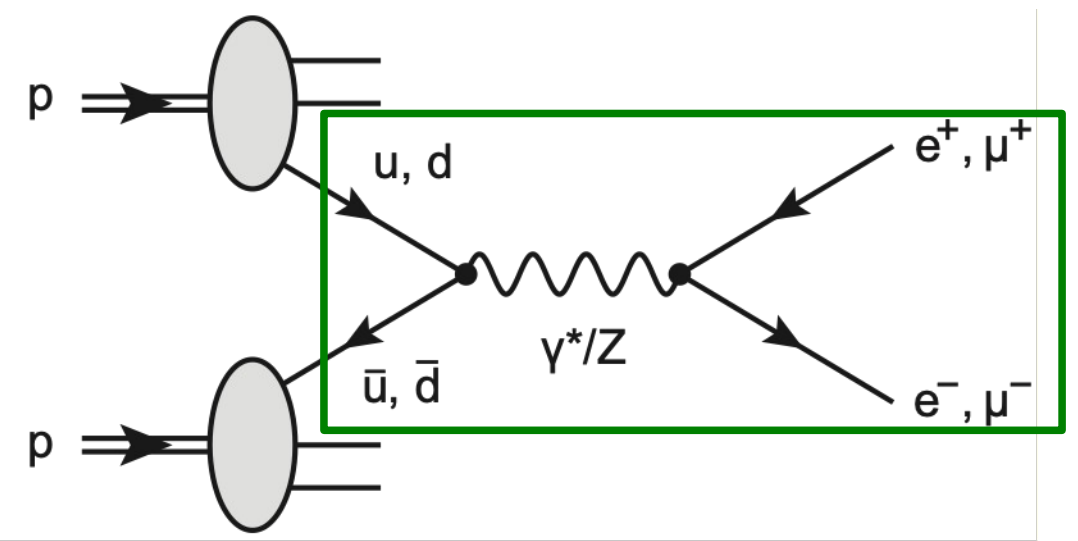
Proton



Proton

**$Z + \text{jet} + X \rightarrow$ i.a. complementary gluon information
 $\rightarrow$ previous talk by Cedric Verstege**

- **Best proxy for e^+e^- annihilation**
 - **FB asymmetry through**
 - ➔ γ^*/Z interference except at m_Z
 - ➔ Z exchange
 - **Sensitive to $\sin^2\theta_W$**
 - **Use input scheme $m_Z, G_F, \sin^2\theta_{\text{eff}}^l$**
 - **Reduce small p_T effects & uncertainties**
→ **Collins-Soper frame**
 - **A_{FB} flavour dependent**
 - **Initial flavours & momenta unknown**
 - **pp collisions → q direction ambiguous**
- ⇒ **Fix q direction (larger x) statistically.**
Kinematic constraints can strengthen Correlation.
- ⇒ **Strong PDF dependence!**



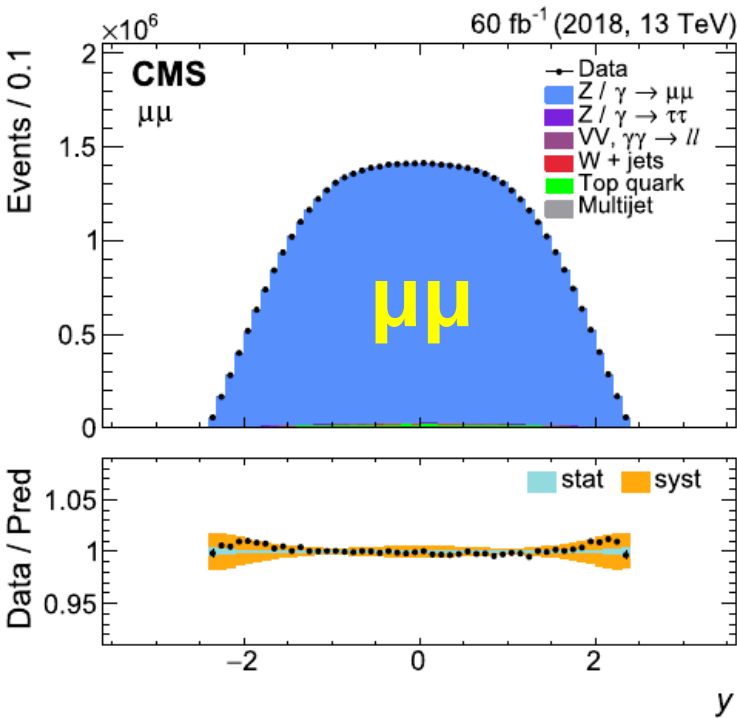
R. Gauld et al., JHEP11 (2017) 003.; A. Gehrmann-De Ridder et al., JHEP05 (2023) 002.

Four measurement channels

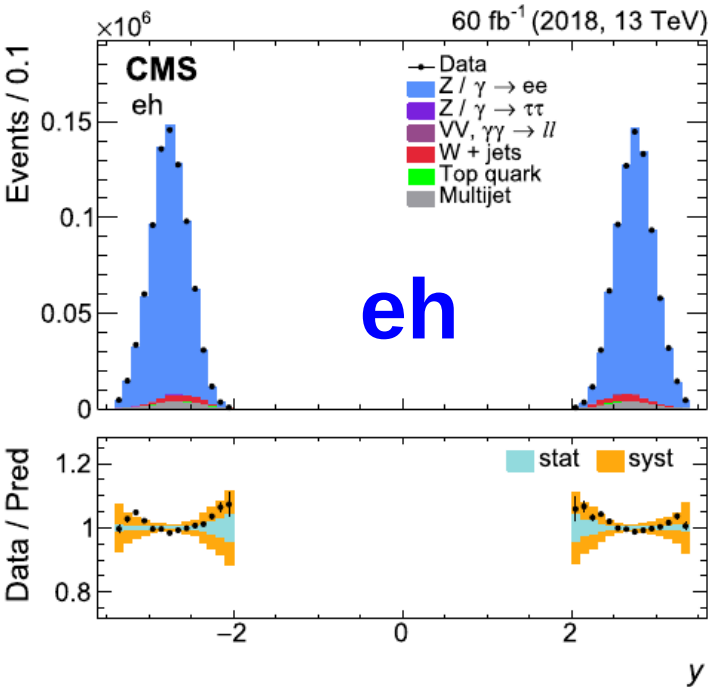
	$ \eta $	$p_{T,\min}^{\text{leading}}$	$p_{T,\min}^{\text{trailing}}$
$\mu\mu$	0.00–2.40	20 GeV	10 GeV
ee	0.00–2.50	25 GeV	15 GeV

	$ \eta_e $	$ \eta_{g,h} $	$p_{T,\min}^e$	$p_{T,\min}^{g,h}$
eg	0.00–2.50	2.50–2.87	30 GeV	20 GeV
eh	1.57–2.50	3.14–4.36	30 GeV	20 GeV

“central-central” leptons



“central-forward” electrons

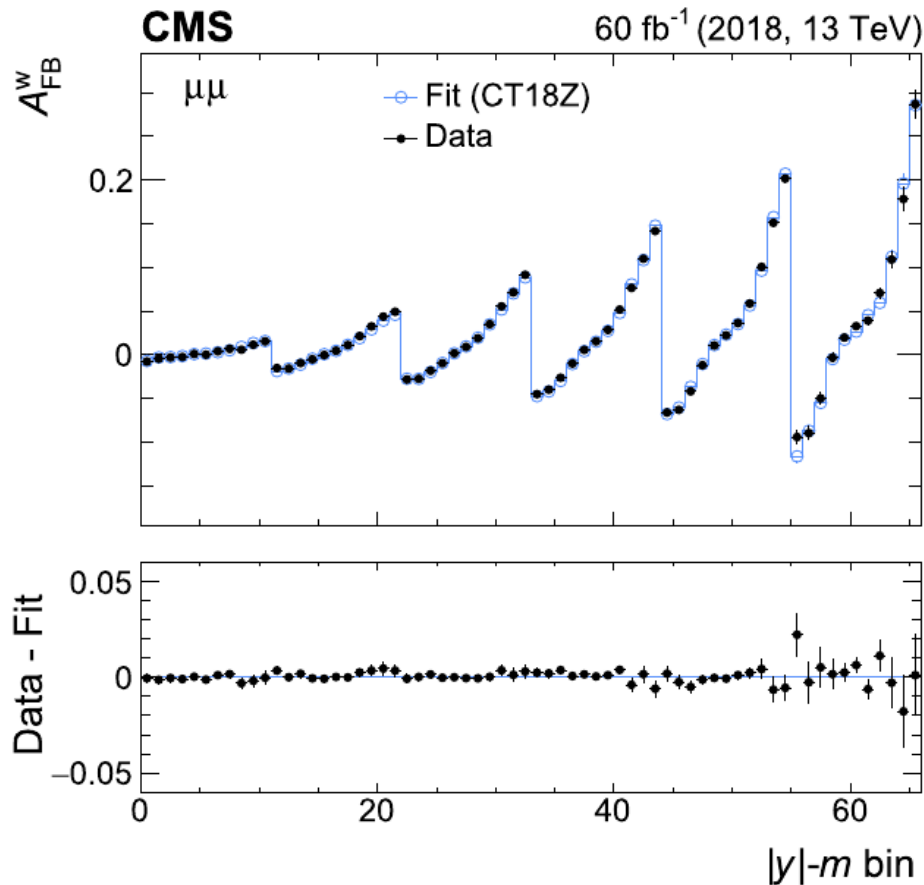


- Five kinematic quantities: $p_T, y_{ll}, m_{ll}, \theta, \Phi$ for full description of $Z \rightarrow ll$ production.
- Cross section depends on 8 angular coefficient functions A_i of θ, Φ
- $A_{FB} = 3/8 A_4$

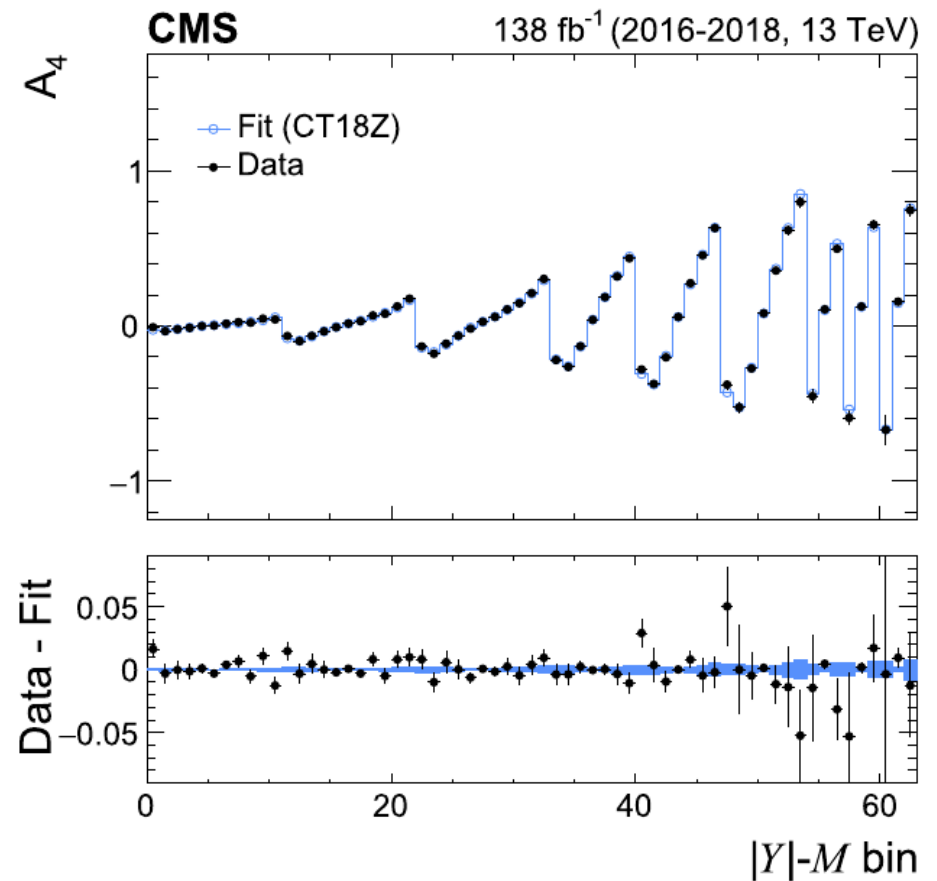
- ⇒ Two possibilities
1. Derive A_{FB} directly
 2. Unfold A_4

Two extraction methods

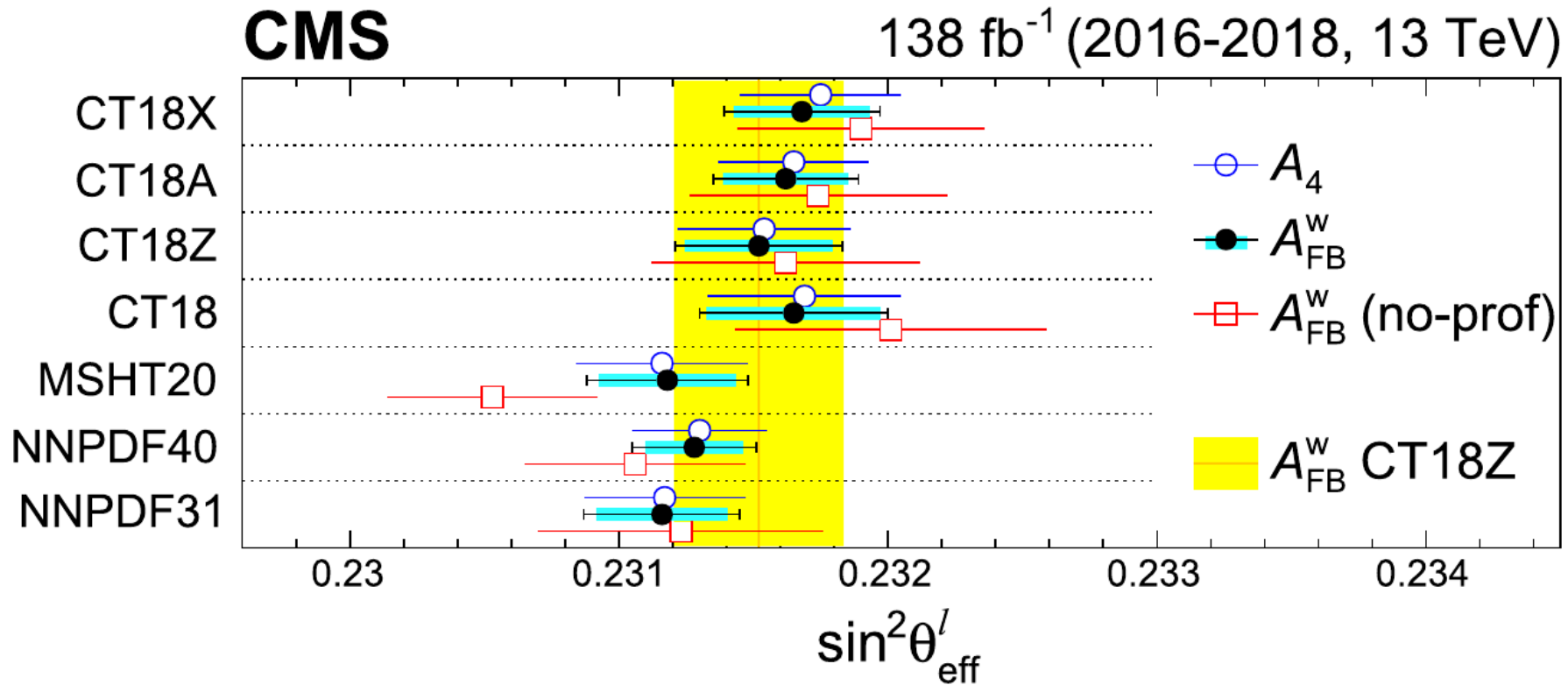
1. Fitting reconstructed weighted $A_{FB}^w(y, m)$ (incl. PDF profiling as for 8 TeV result)



2. Fitting unfolded $A_4(y, m)$ (incl. PDF profiling using xfitter)



(3.) Cross-check only: Fit directly observed $\cos\theta_{cs}(y, m)$ distributions
Also: Check for bias with xfitter HERAPDF fit of PDFs + $\sin^2\theta_{eff}^l$

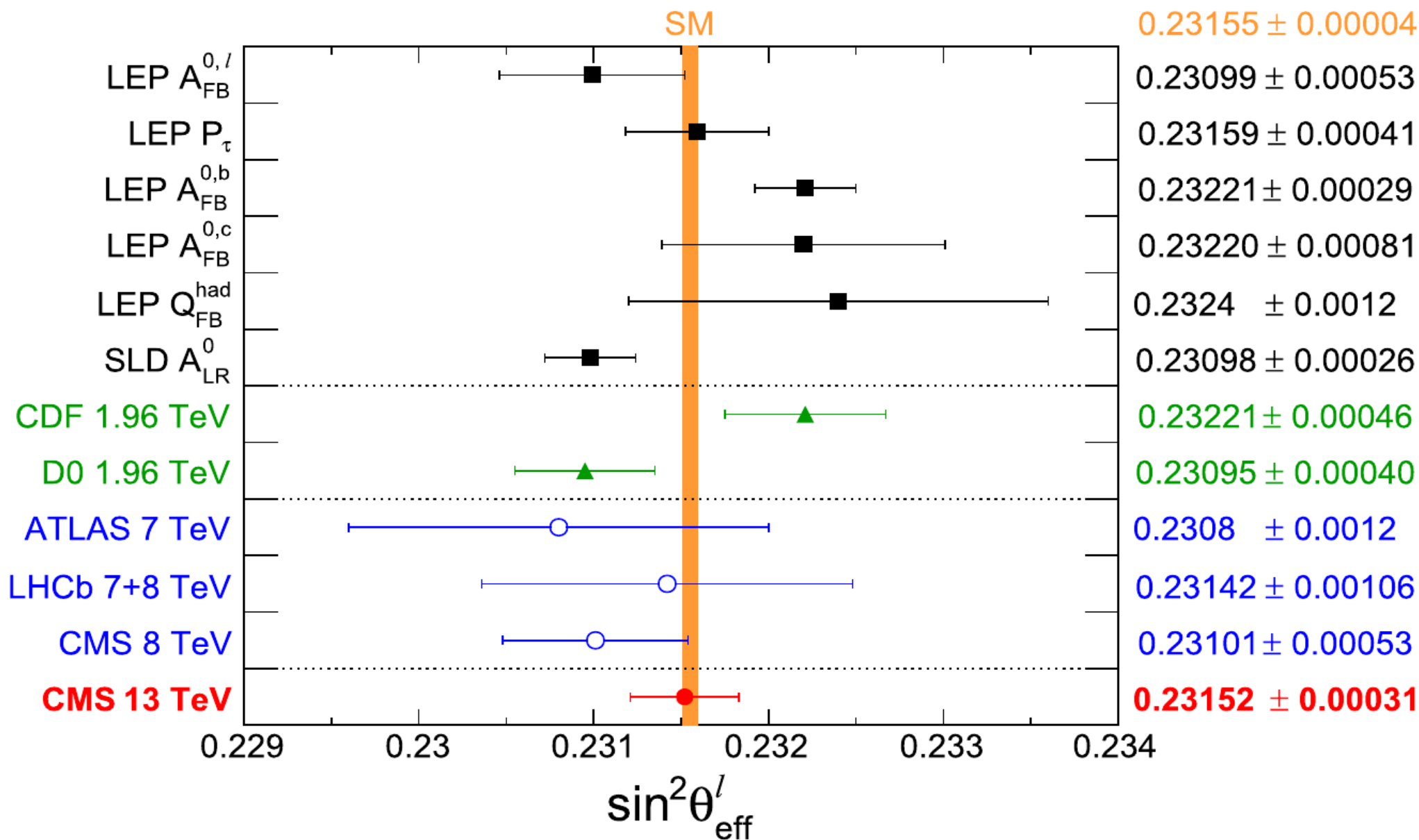


After profiling results compatible among:

- various PDF sets
- the two methods using A_{FB} or A_4

PDF	A_{FB}^{W} (816 bins)		A_4 (63 bins)			
	χ^2_{min}	$\sin^2 \theta_{\text{eff}}^{\ell}$	χ^2_{min}	$\sin^2 \theta_{\text{eff}}^{\ell}$	χ^2_{min}	$\sin^2 \theta_{\text{eff}}^{\ell}$
NNPDF31_nnlo_as_0118_hessian [45]	725	$23\,116 \pm 29$	61	$23\,117 \pm 30$	61	$23\,117 \pm 29$
NNPDF40_nnlo_as_01180_hessian [46]	731	$23\,128 \pm 23$	66	$23\,130 \pm 25$	66	$23\,131 \pm 24$
MSHT20nnlo_as118 [64]	736	$23\,118 \pm 30$	76	$23\,116 \pm 32$	75	$23\,115 \pm 30$
CT18NNLO [47]	729	$23\,165 \pm 35$	65	$23\,169 \pm 36$	65	$23\,166 \pm 36$
CT18ZNNLO [47]	731	$23\,152 \pm 31$	64	$23\,154 \pm 32$	65	$23\,152 \pm 32$
CT18ANNLO [47]	731	$23\,162 \pm 27$	67	$23\,165 \pm 28$	67	$23\,164 \pm 28$
CT18XNNLO [47]	729	$23\,168 \pm 29$	64	$23\,175 \pm 30$	64	$23\,171 \pm 30$
Additional PDF sets used with A_4	MSHT20qed_an3lo [64]				69	$23\,137 \pm 31$
	NNPDF40_an3lo_as_01180 [67]				65	$23\,132 \pm 25$
	NNPDF40_an3lo_as_01180_mhou [68]				65	$23\,120 \pm 26$
	NNPDF40_nnlo_as_01180_mhou [68]				64	$23\,110 \pm 27$
	ABMP16_5_nnlo [69]				59	$23\,082 \pm 25$
	PDF4LHC21_40 [70]				62	$23\,133 \pm 33$
	CT18As_LatNNLO [71]				64	$23\,108 \pm 43$

Future: Full fit of PDFs + $\sin^2 \theta_{\text{eff}}^{\ell}$ (+ α_s + ...)



→ Inbetween 3σ discrepant LEP & SLD results.

● CMS today

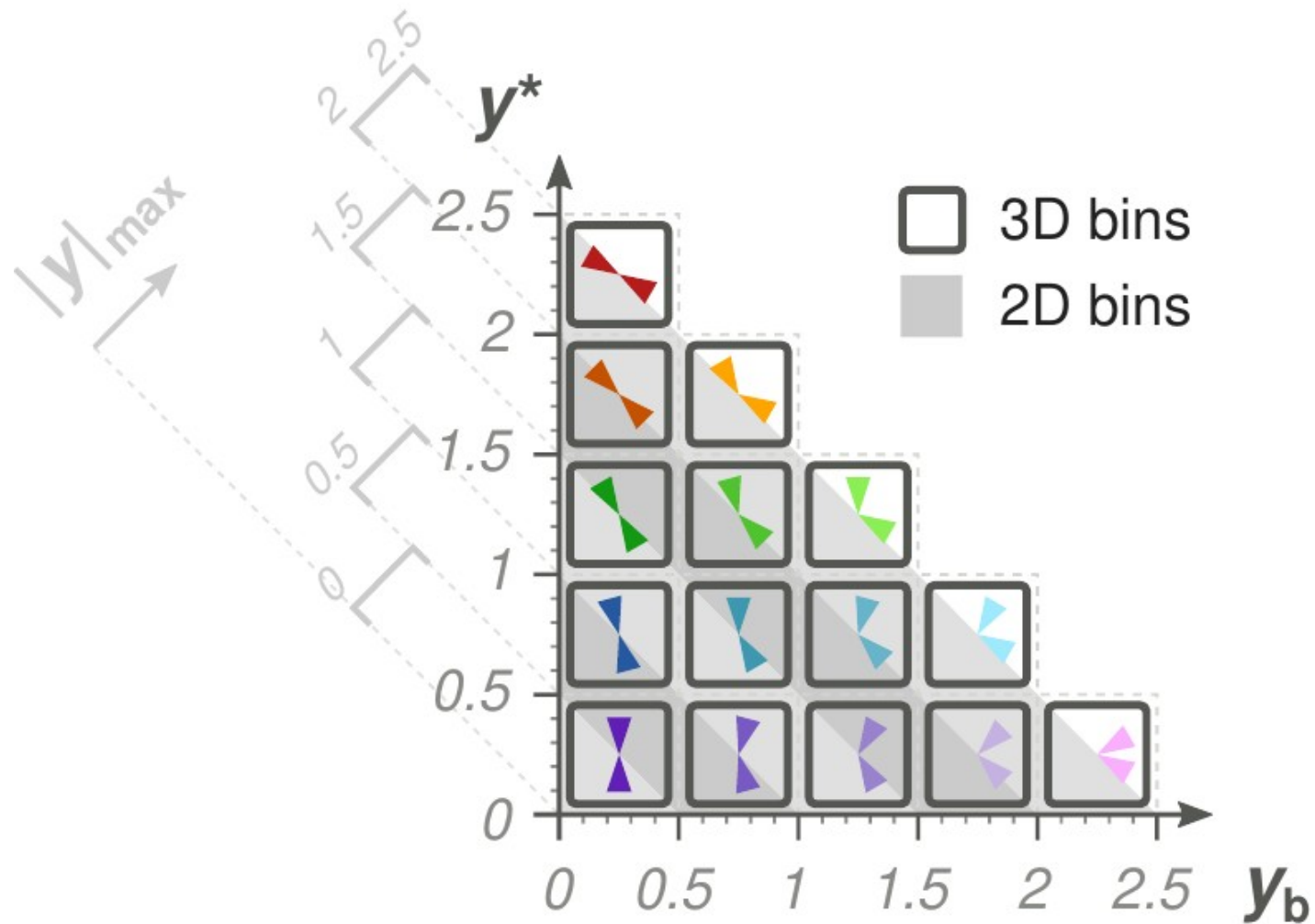
- ➔ Data more and more differential, more precise, with many uncertainty sources, often without a single dominating one
- ➔ Published simultaneous determinations of PDFs & α_s , ... & m_t , ... & EFT, PDFs & $\sin^2\theta_{\text{eff}}^l$
- ➔ Moving from “fixed PDFs” or PDF profiling towards full PDF fits
- ➔ Started combining CMS datasets

● TODO

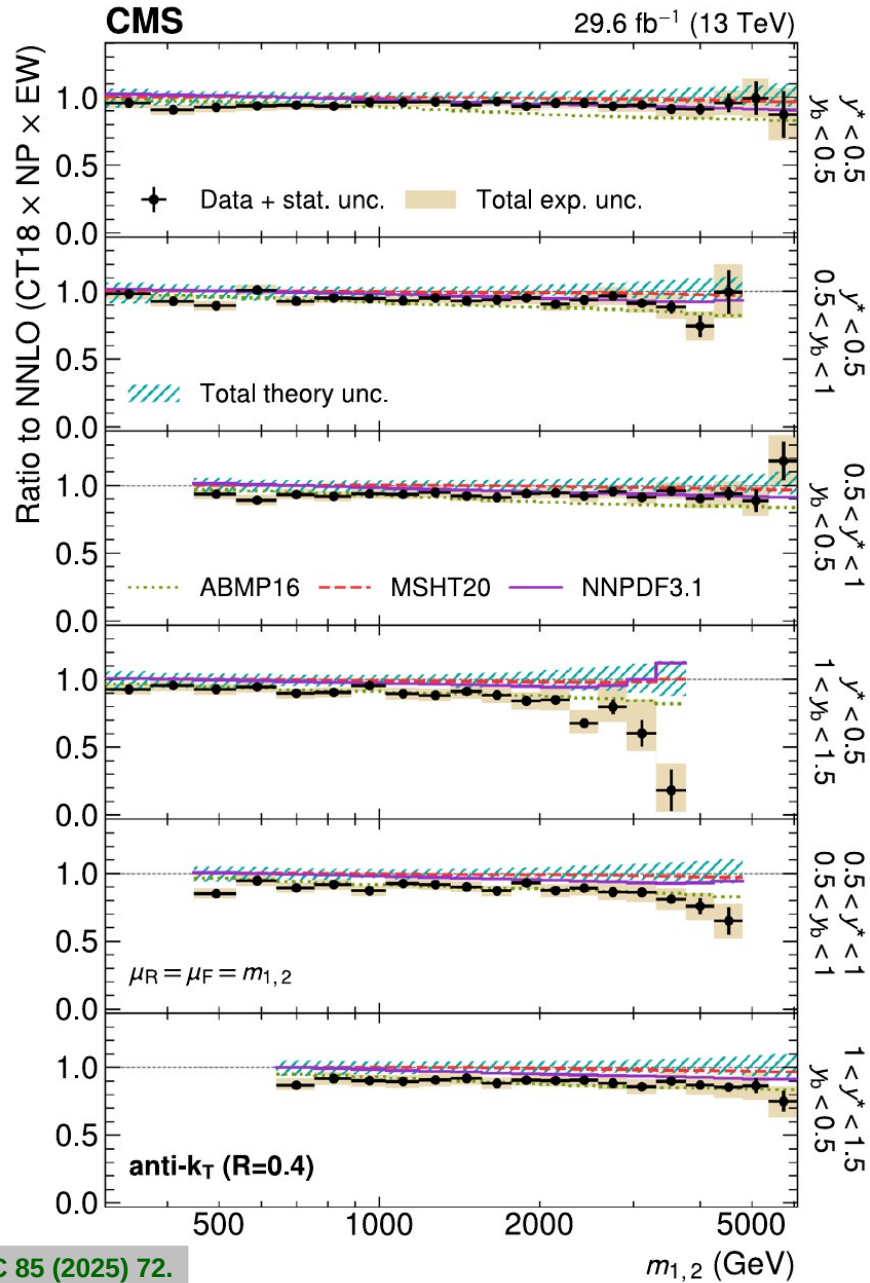
- ➔ Deriving uncertainty correlations among datasets (→ CMS)
- ➔ Estimate correlations wrt. other experiments (→ EWWGs)
- ➔ Need better methods & tools for theory uncertainties & correlations (→ EWWGs)

Thank you for your attention!





R=0.4



CMS, EPJC 85 (2025) 72.

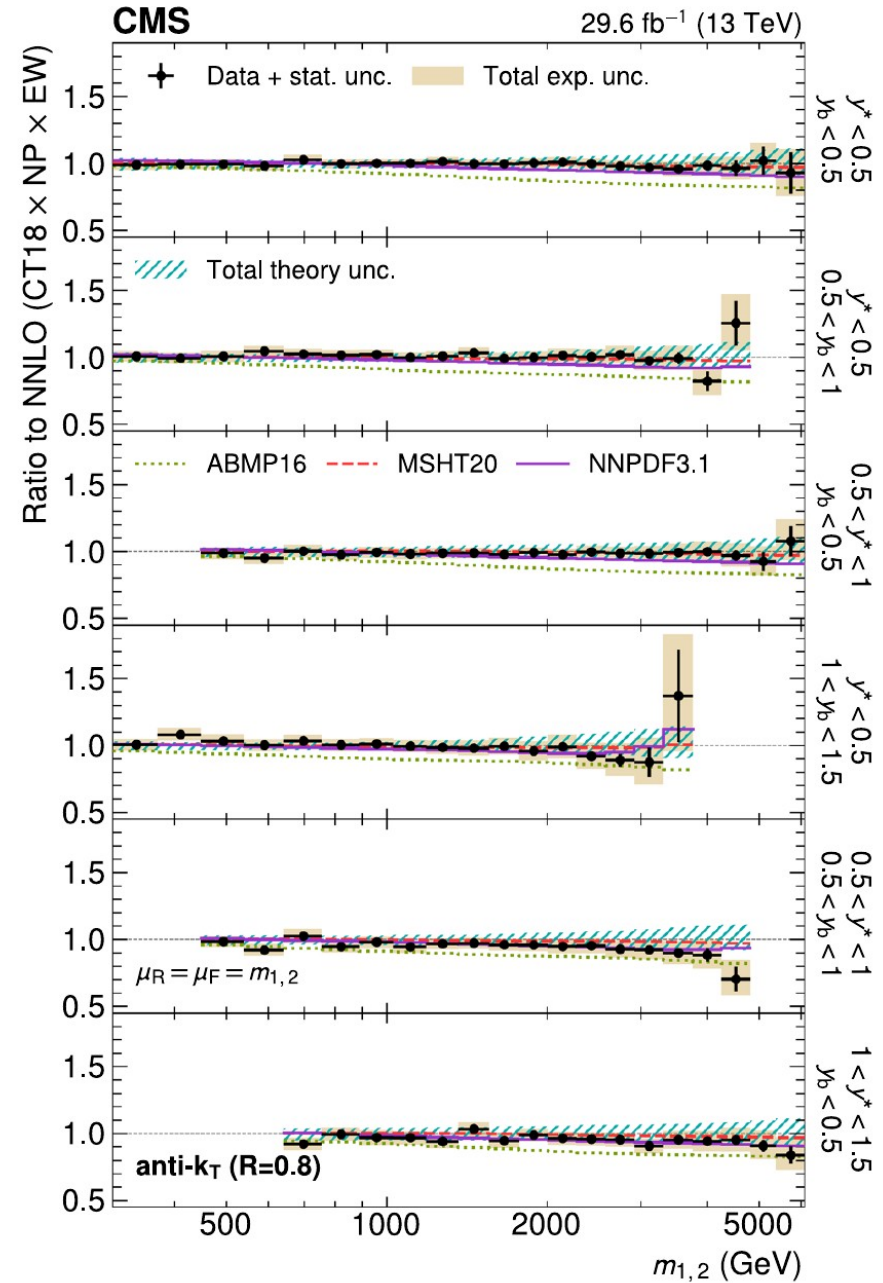
K. Rabbertz

Oxford, UK, 29.09.2026

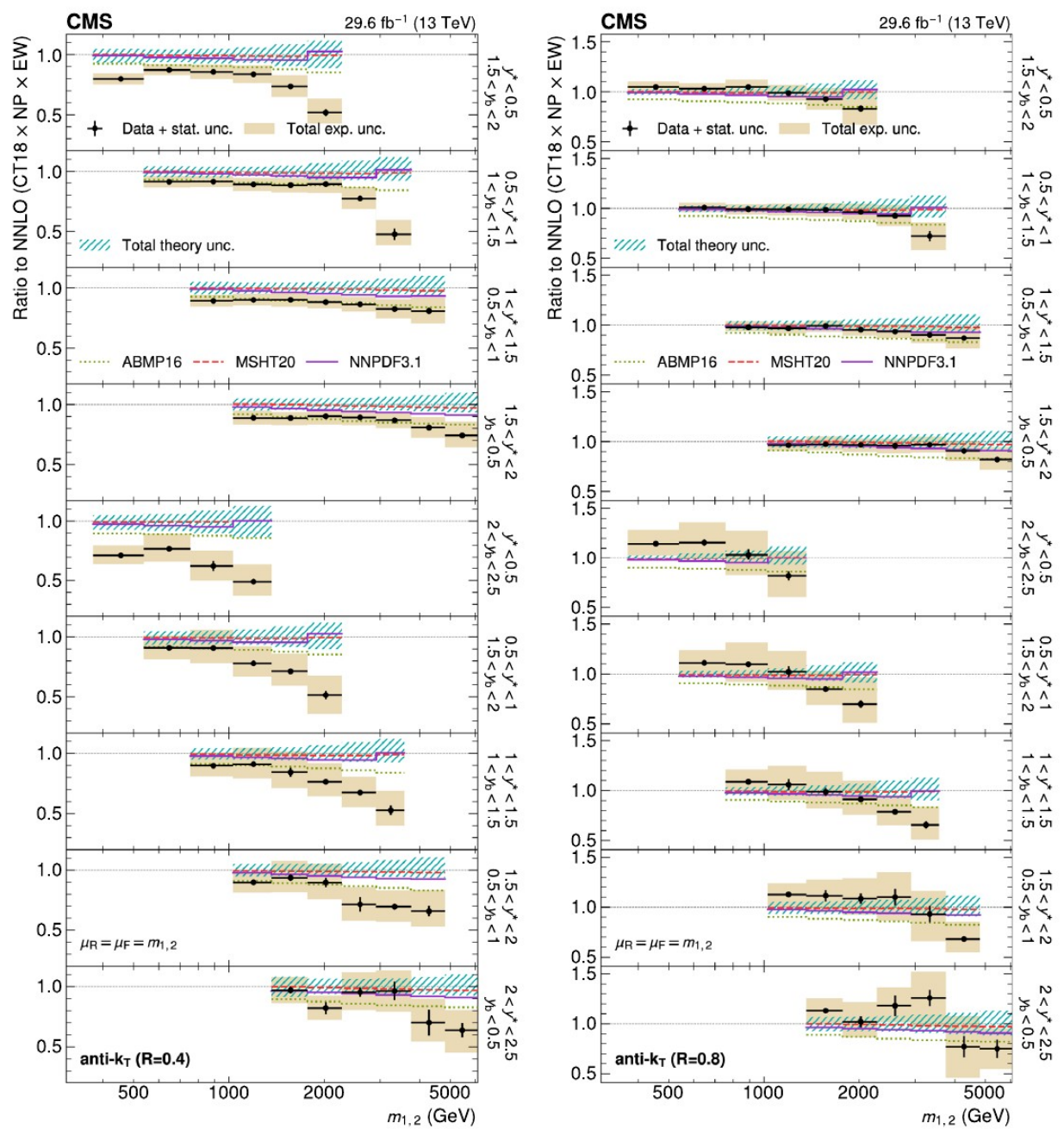
QCD@LHC 2026

29

R=0.8



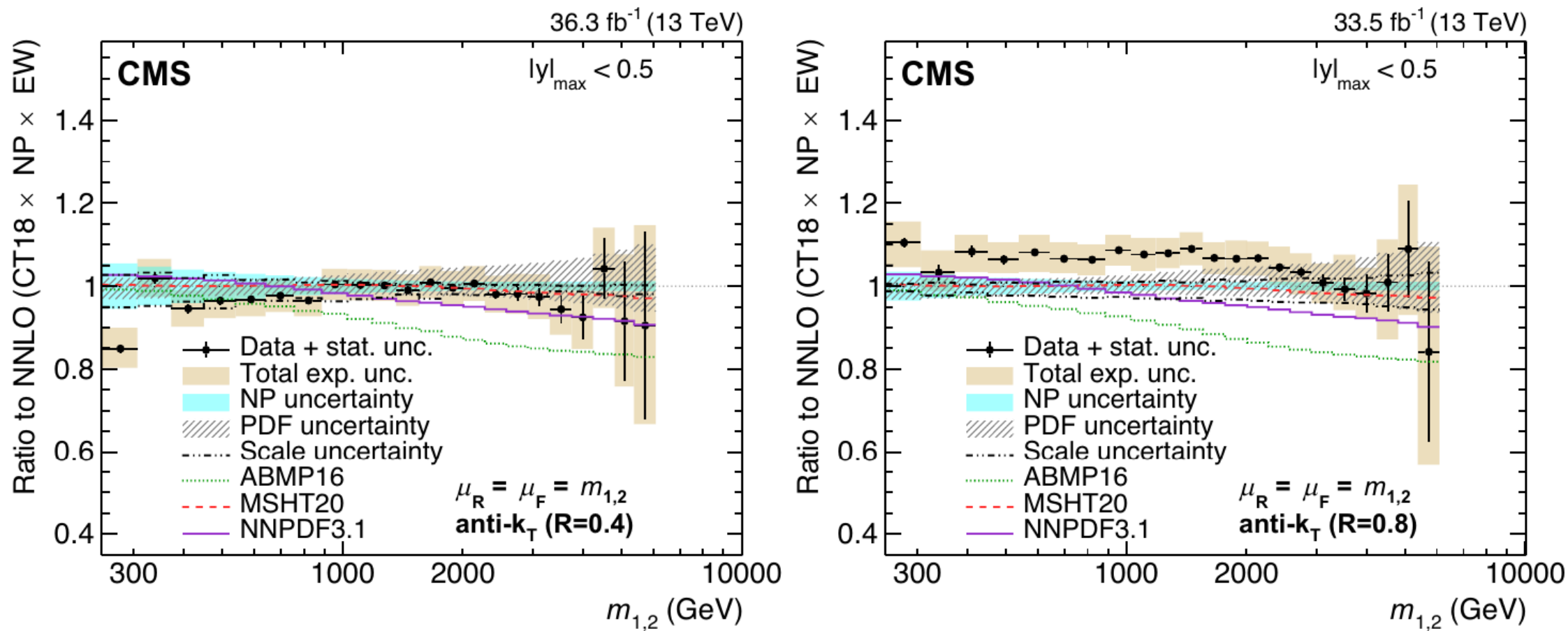
R=0.8



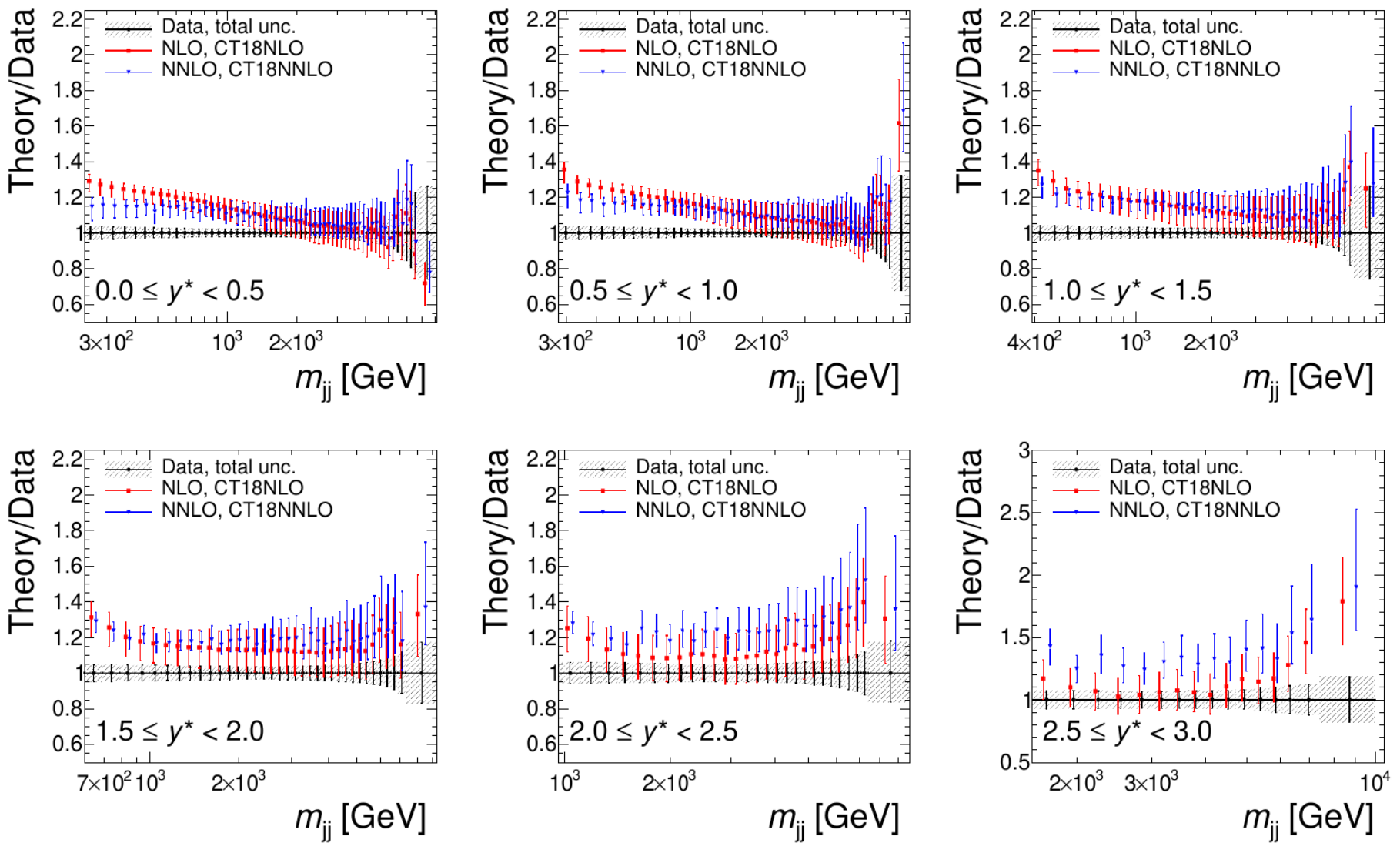
R=0.4

Binning in y_{max} , here $y_{\text{max}} < 0.5$

R=0.8



Binning in y^*



ATLAS
Particle level

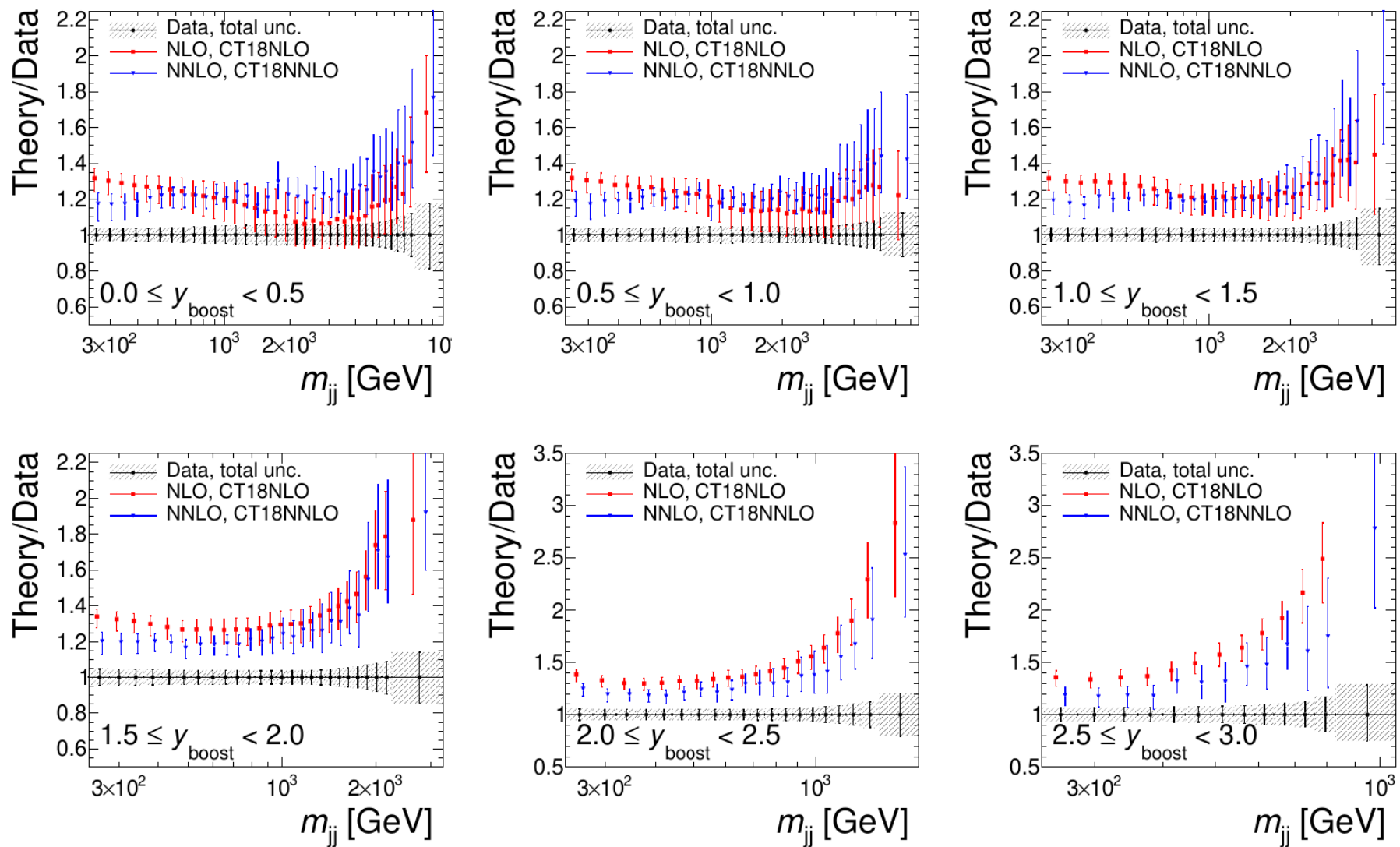
$\sqrt{s} = 13 \text{ TeV}, 140 \text{ fb}^{-1}$
anti- k_t $R=0.4$

$\mu_R = \mu_F = m_{jj}$
 $\alpha_s(m_Z) = 0.118$

pQCD
 $\otimes$ EW $\otimes$ NPC

ATLAS, arXiv:2512.19073.

Binning in y_b



ATLAS

Particle level

$\sqrt{s} = 13 \text{ TeV}, 140 \text{ fb}^{-1}$

anti- k_t $R=0.4$

$\mu_R = \mu_F = m_{jj}$

$\alpha_s(m_Z) = 0.118$

pQCD

$\otimes \text{EW} \otimes \text{NPC}$

ATLAS, arXiv:2512.19073.