Introduction
Hard scattering
Extra radiations
Tests of SM
Summary & Conclusions
Back-up

Standard Model Physics

with the CMS experiment

Patrick L.S. Connor

(on behalf of the CMS collaboration)

Universität Hamburg

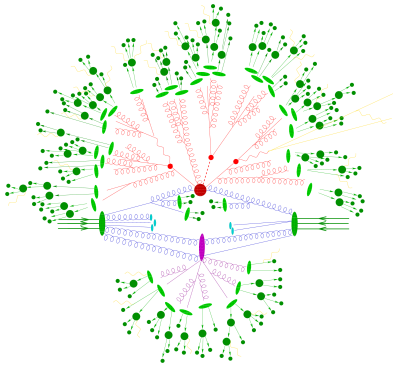
24 August 2021

Introduction

Introduction

Factorisation theorem/property [1]

$$\underbrace{\sigma_{pp}}_{\text{experimental data}} = \sum_{ij \in gq\bar{q}} \underbrace{f_i(x_i, \mu_F^2) \otimes f_j(x_j, \mu_F^2)}_{\text{PDFs}} \otimes \underbrace{\hat{\sigma}_{ij}\left(x_i, x_j, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}, \alpha_S(\mu_R^2)\right)}_{\text{SM(EFT)}}$$



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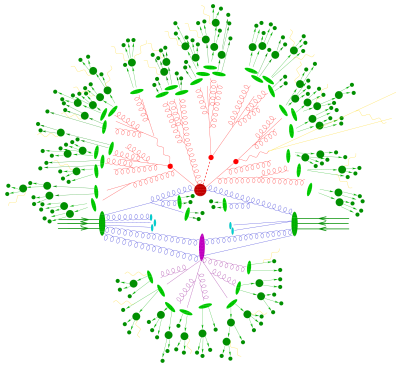


Programme

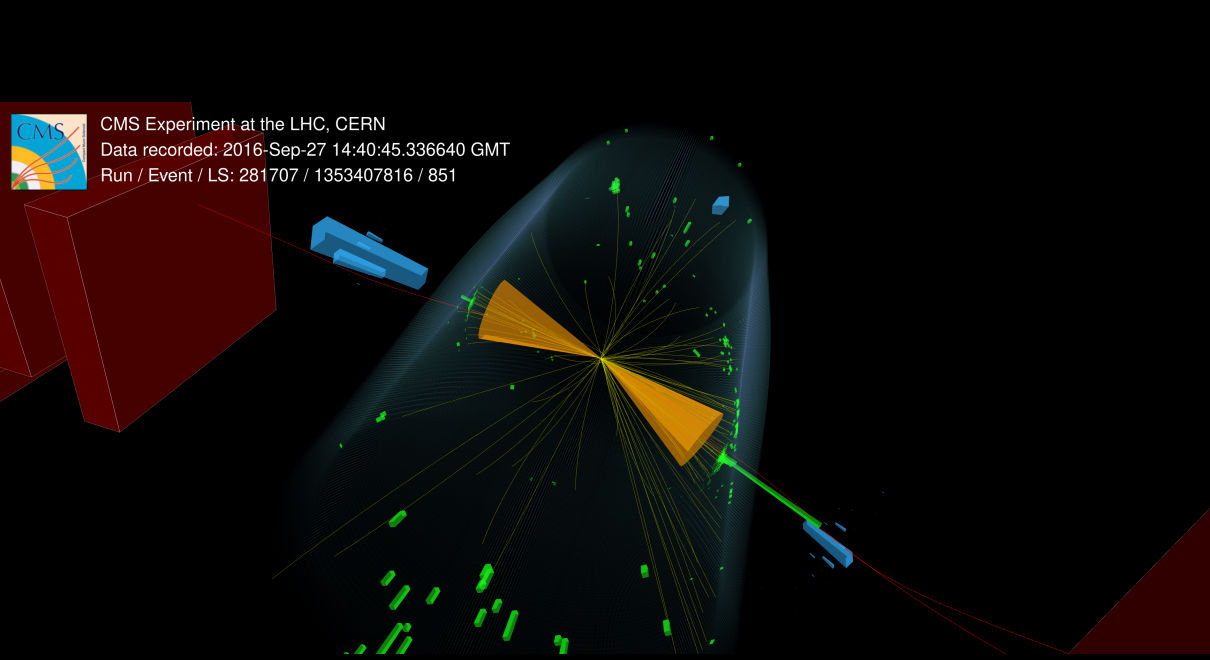
With 5.02 and $13\ \mathrm{TeV}$ pp collision data:

- Investigate **state-of-the art calculations**
  $\longrightarrow$ *e.g.* NNLO FO predictions with interpolation tables, NLO MC event generators with TMDs, etc.
- **Extract** PDFs and SM **parameters**
  $\longrightarrow$ *e.g.* gluon PDF, α_S, ...
- **Test** SM and **search** BSM signal.
  $\longrightarrow$ invisible Z, VBS, DPS, 4-quark CI

Hard scattering

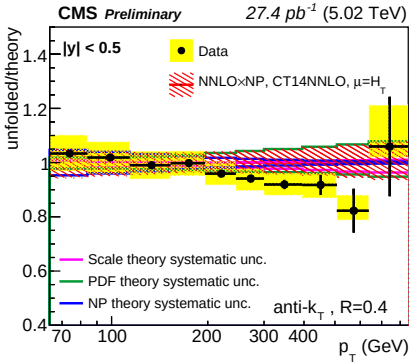
Inclusive jet

Z + jets


CMS Experiment at the LHC, CERN
Data recorded: 2016-Sep-27 14:40:45.336640 GMT
Run / Event / LS: 281707 / 1353407816 / 851

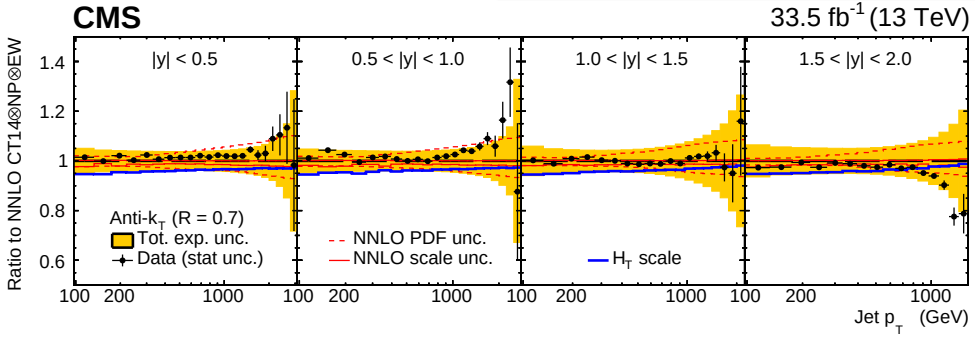
Ref. [2]

Inclusive jet

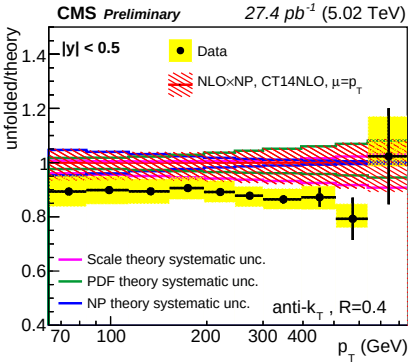


Inclusive jet cross sections (SMP-20-011 & SMP-21-009 [3, 4])

- **Two recent analyses** at different c.m.s. energies.
- Comparison to (N)NLO obtained with NNLOJET [5, 6, 7] from **interpolation tables** [8, 9, 10, 11].

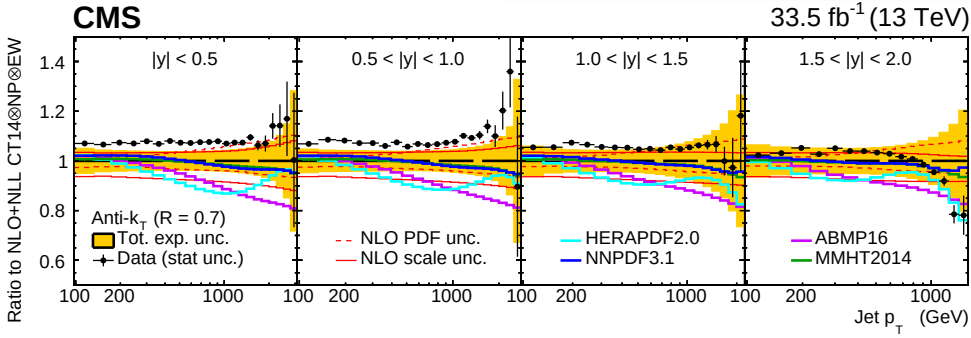


Inclusive jet



Inclusive jet cross sections (SMP-20-011 & SMP-21-009 [3, 4])

- Comparison to various **global PDF sets** also available [12, 13, 14, 15, 16].
- **NLO+NLL** with k-factor technique tested at $13\ \mathrm{TeV}$.



Inclusive jet

QCD interpretation w. xFitter [17, 18]

- HERA DIS data [12],
- CMS $t\bar{t}$ 3D cross section at 13 TeV [19],
- CMS inclusive jet 2D cross section at 13 TeV [3].

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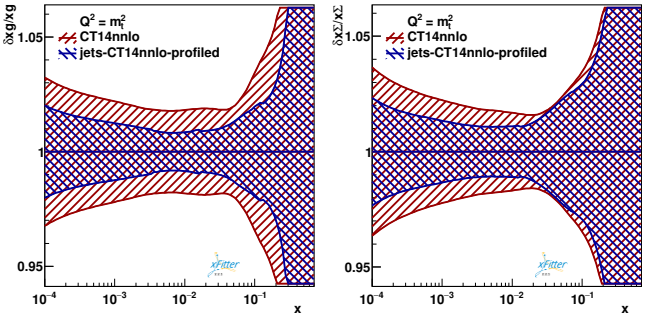

SM fits

- **Profiling** CT14 at NLO & NNLO.

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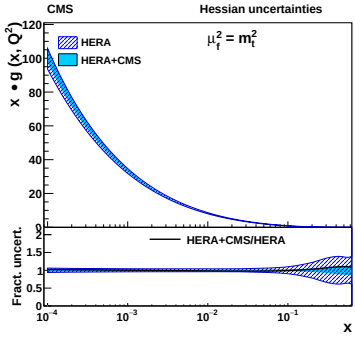

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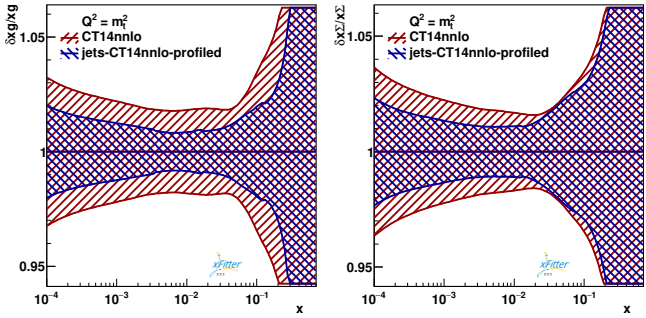
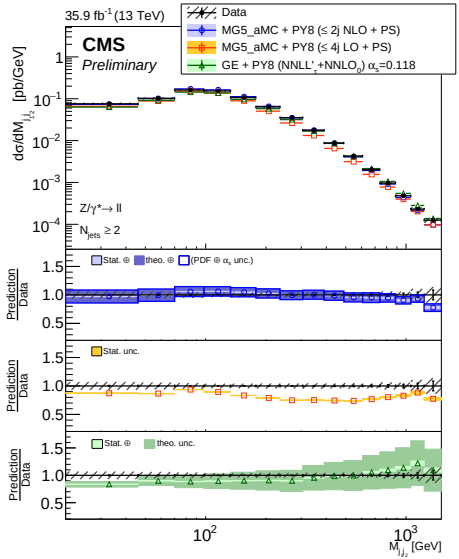


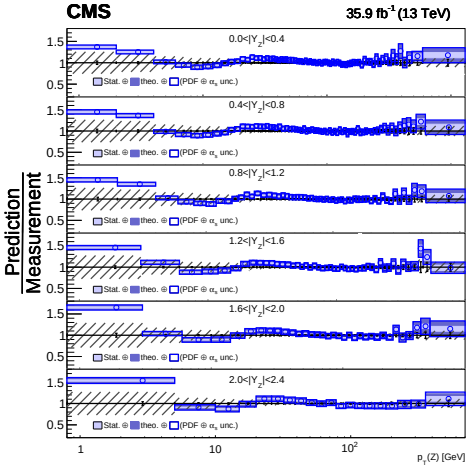
SM fits

- **Profiling** CT14 at NLO & NNLO.
- **QCD fits** follow the approach of HERAPDF2.0 [12].

$\longrightarrow$ Strong **reduction of the gluon** PDF uncertainty.



Z + jets



Z + jet (SMP-19-009 [20])

Invariant mass of leading jets and **p_T^Z spectrum** well described by various generators [21, 22, 23, 24].

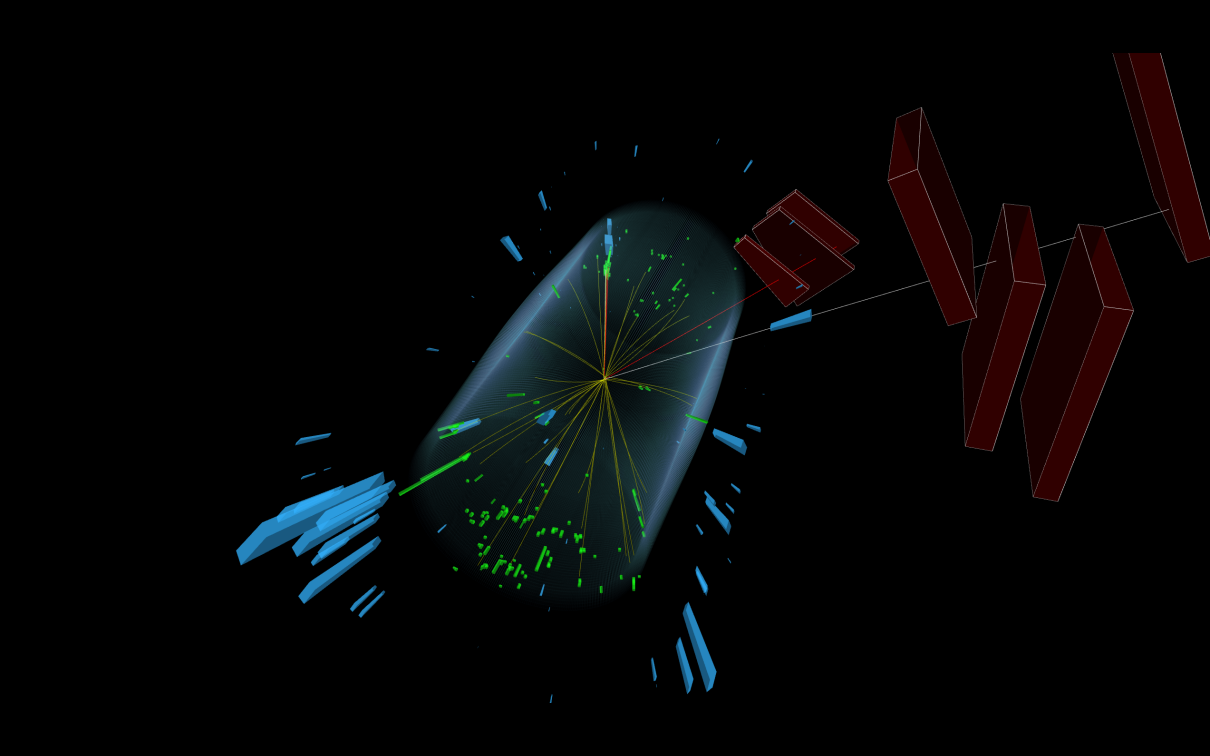
$\longrightarrow$ Largest deviations at low p_T^Z (discussed further below).

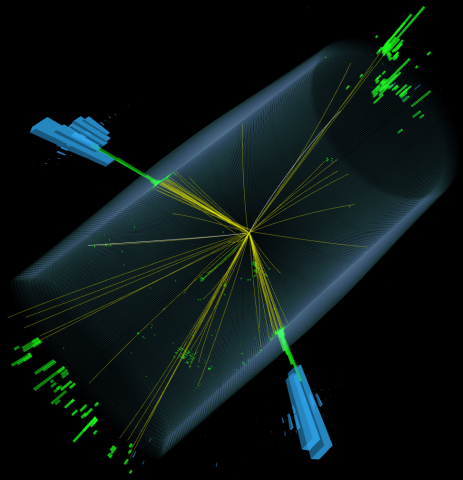
Extra radiations

Multiplicities & Decorrelations

Single-jet spectra

Heavy flavours





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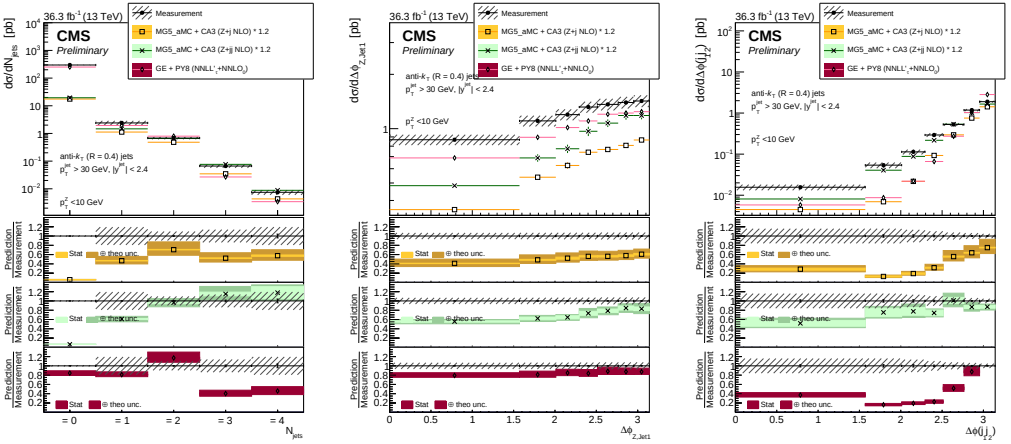
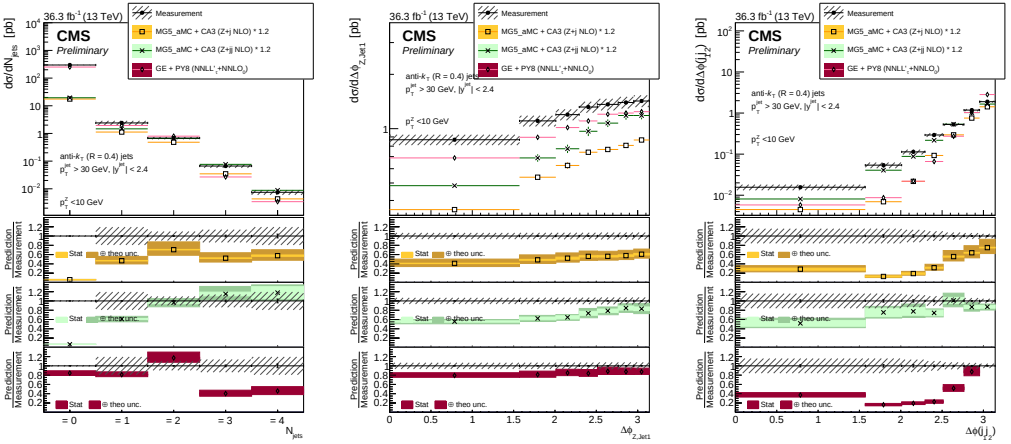


Z + jet cross sections (SMP-21-003 [25])

- Investigating production of **radiations in the shower**.
- Predictions are **normalised** to the measured inclusive di-jet cross section.

Multiplicities & Decorrelations

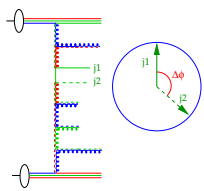


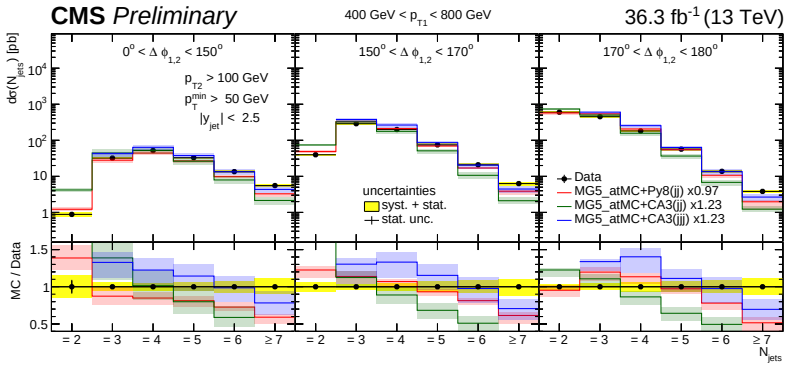
Z + jet cross sections (SMP-21-003 [25])

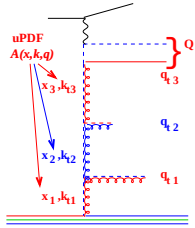
- Investigating production of **radiations in the shower**.
- Predictions are **normalised** to the measured inclusive di-jet cross section.

$\longrightarrow$ Testing MC@NLO [21] using PB-TMD calculations [26, 27] and GENEVA [23, 24].

Multiplicities & Decorrelations



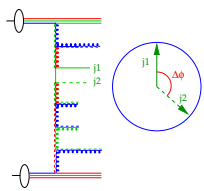


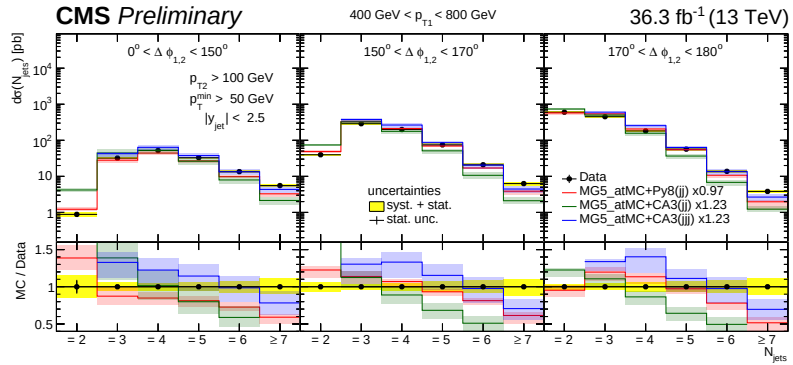


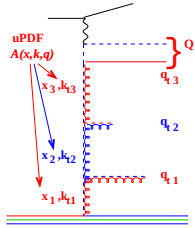
Multijet cross sections (SMP-21-006 [28])

- Similar investigations were performed in dijet events with a **3D measurement**.

Multiplicities & Decorrelations

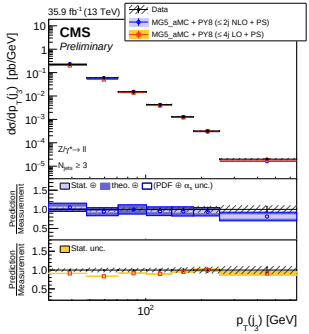


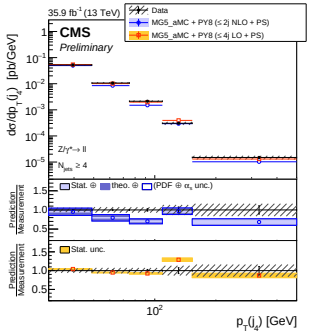




Multijet cross sections (SMP-21-006 [28])

- Similar investigations were performed in dijet events with a **3D measurement**.
- **None** of the generators are **able** to describe the data within uncertainties.





Single-jet spectra

Multijet cross section (SMP-21-006 [28]) & Z + jet (SMP-19-009 [20])

- MC@NLO [21] using **PB-TMD** [26, 27] rather successful.
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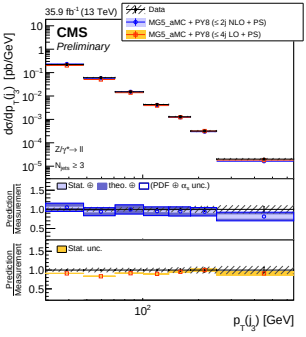

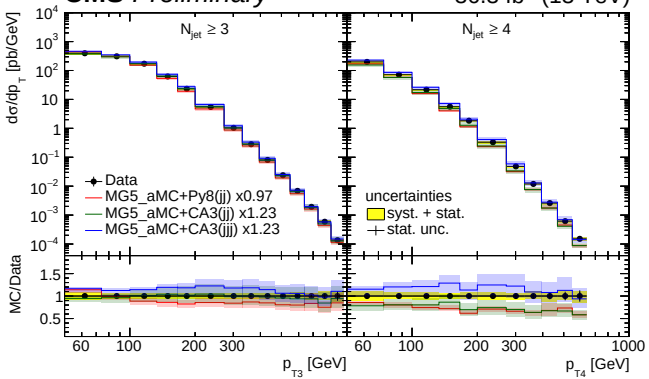

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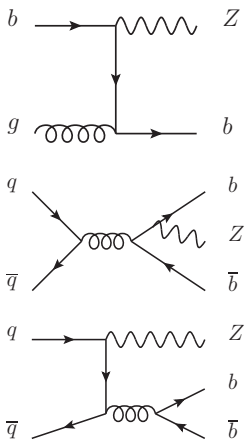
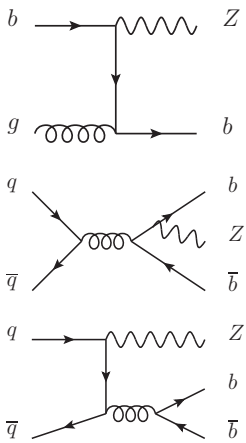
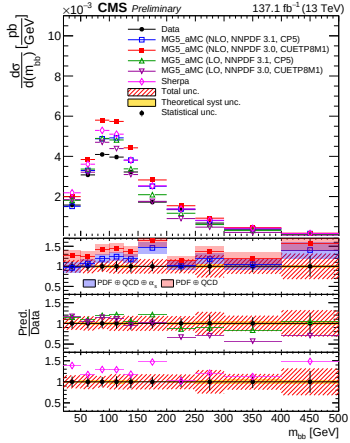


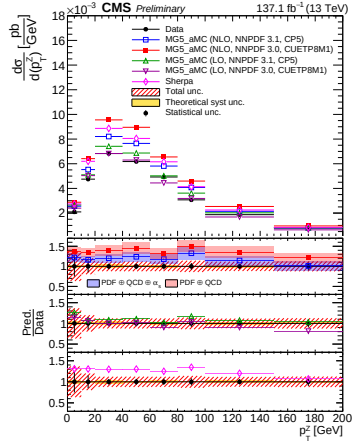
$Z + b(b)$ (SMP-20-015 [29])

- Many b quarks originate from **extra radiations**.

Heavy flavours







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- Many b quarks originate from **extra radiations**.
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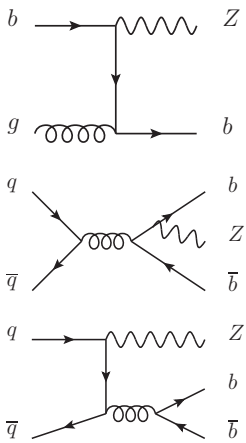
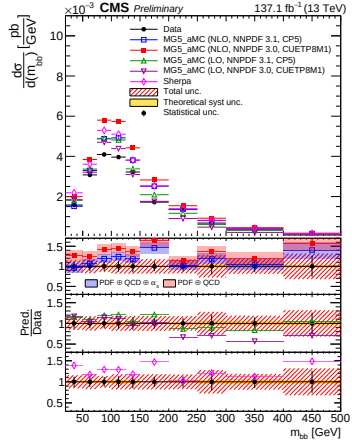
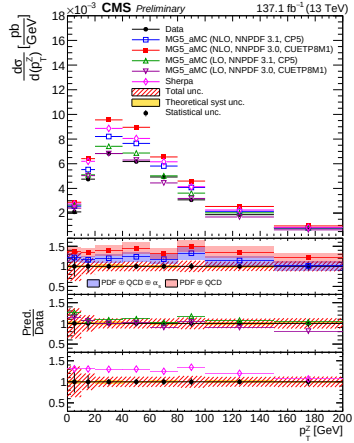
Heavy flavours







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- Many b quarks originate from **extra radiations**.
- **Invariant mass** of leading b jets and p_T^Z **spectrum** are more difficult to describe.

$\longrightarrow$ b jet production is again **sensitive to the shower algorithm and to the tunes** [22].

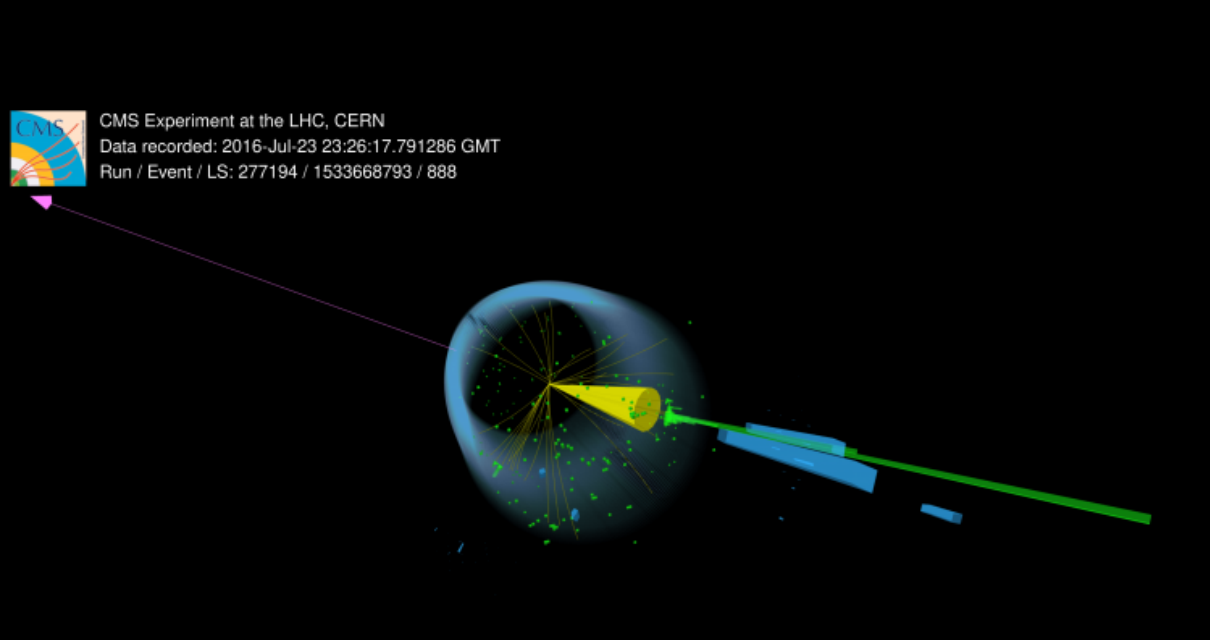
Tests of SM

Invisible Z

VBS

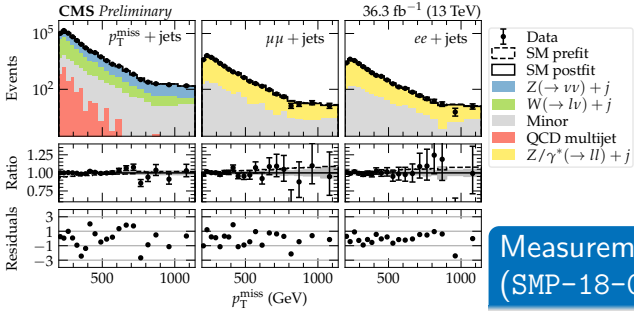
DPS

4-quark CI


CMS Experiment at the LHC, CERN
Data recorded: 2016-Jul-23 23:26:17.791286 GMT
Run / Event / LS: 277194 / 1533668793 / 888

Ref. [30]

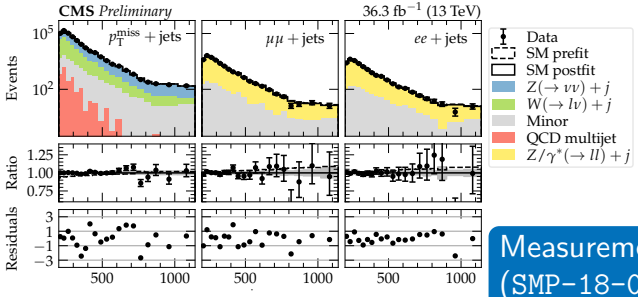
Invisible Z

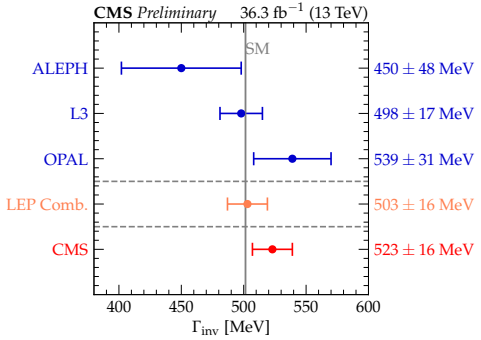


Measurement of decay width (SMP-18-014 [30])

- Γ_Z constrains **number of neutrino species** coupling to Z boson.
- **First direct measurement** of invisible width of Z boson at a hadron collider.
- **Global likelihood fit** includes regions dominated either by $Z \rightarrow \nu\nu$, or by $Z \rightarrow ee/\mu\mu$, or by $W \rightarrow e\mu$.

Invisible Z





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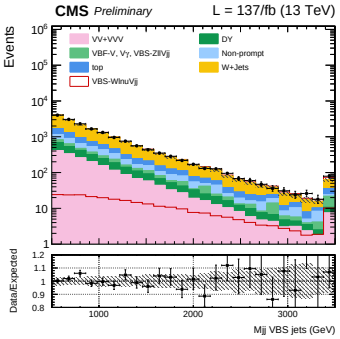
$\longrightarrow$ **Complementary and competitive test** to LEP combined measurement.

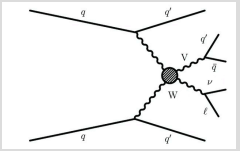
VBS

Evidence in semileptonic mode



First measurement with $WV \to l\nu q\bar{q}$ channel (SMP-20-013 [31])

- Analysis covers **resolved** and **boosted** topologies.



VBS

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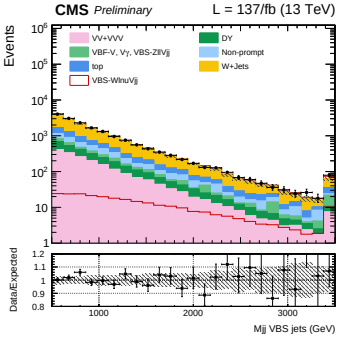
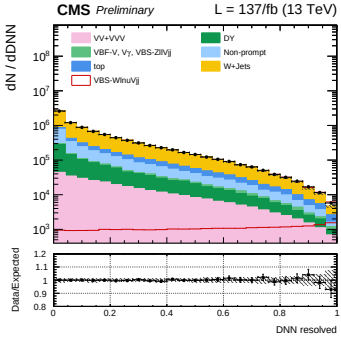
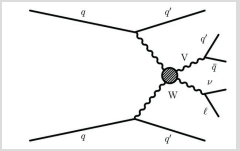




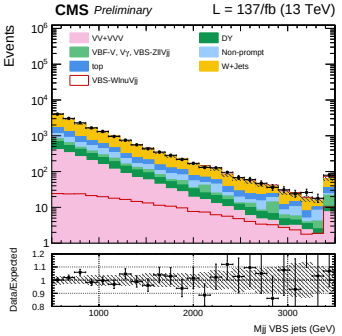
First measurement with $WV \to l\nu q\bar{q}$ channel (SMP-20-013 [31])

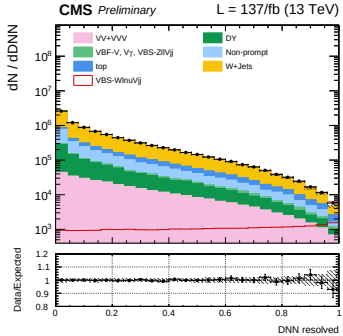
- Analysis covers **resolved** and **boosted** topologies.
- Using DNN techniques to analyse **complex topology**.

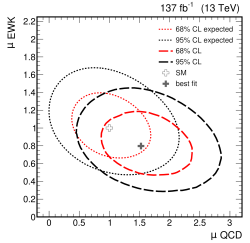


VBS

Evidence in semileptonic mode





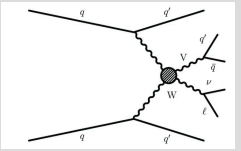


First measurement with $WV \to l\nu q\bar{q}$ channel (SMP-20-013 [31])

- Analysis covers **resolved** and **boosted** topologies.
- Using DNN techniques to analyse **complex topology**.
- Results **compatible w. SM** pred. within the 68% conf. interval.

$$\mu_{\text{EW}}^{\text{SM}} = 1^{+0.24}_{-0.22}(\text{expected}) \qquad \mu_{\text{EW}}^{\text{CMS}} = 0.85^{+0.21}_{-0.17}(\text{syst})\ ^{+0.12}_{-0.12}(\text{stat})$$

$$\mu_{\text{EW+QCD}}^{\text{SM}} = 1^{+0.19}_{-0.18}(\text{expected}) \qquad \mu_{\text{EW+QCD}}^{\text{CMS}} = 0.98^{+0.19}_{-0.16}(\text{syst})\ ^{+0.07}_{-0.07}(\text{stat})$$



DPS

Observation of triple J/ψ

Double-Parton Scattering (DPS) (BPH-21-004 [32])

$$\sigma_{\text{DPS}}^{pp\to\psi^1\psi^2 \quad +X} = \left(\frac{m}{2}\right) \frac{\sigma_{\text{SPS}}^{pp\to\psi^1+X}\,\sigma_{\text{SPS}}^{pp\to\psi^2+X}}{\sigma_{\text{DPS}}^{\text{eff}}}$$

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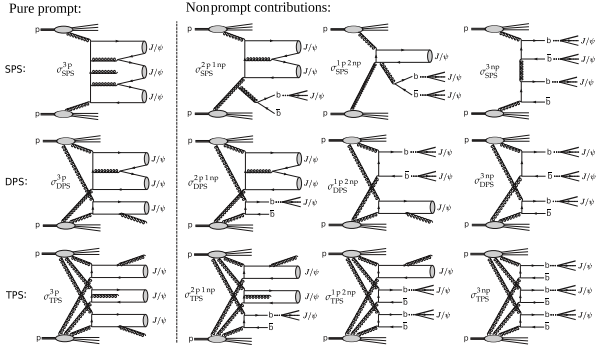

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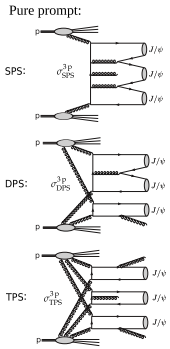

Results

- $\sigma_{\text{TPS}}^{\psi\psi\psi} = 272^{+141}_{-104}(\text{stat}) \pm 17(\text{syst})$ fb
  $\longrightarrow$ three different methods to estimate statistical significance: **all beyond 5 standard deviations**!
- $\sigma_{\text{DPS}}^{\text{eff}} = 2.7^{+1.4}_{-1.0}(\text{exp}) \pm {}^{+1.5}_{-1.0}(\text{theo})$ fb

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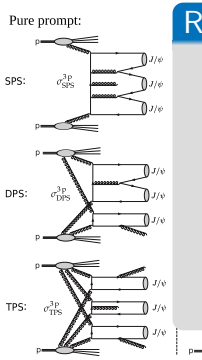

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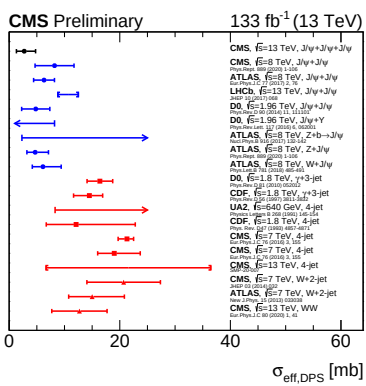
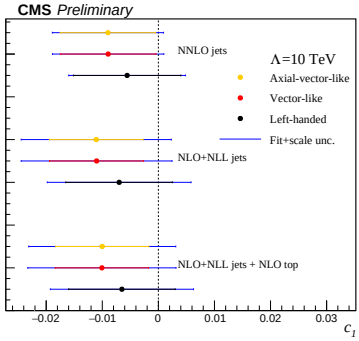
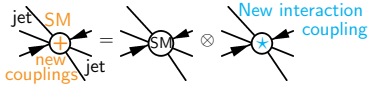


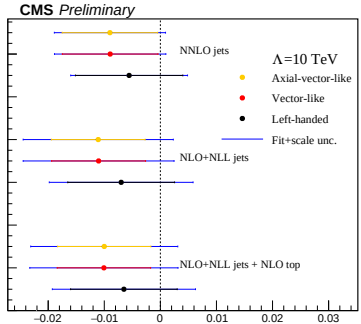


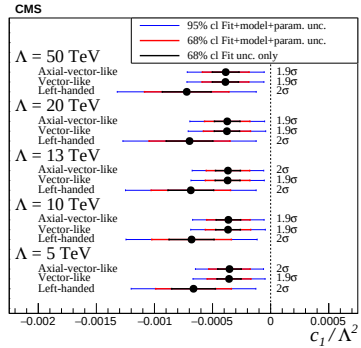
4-quark contact interactions



SMEFT fits of inclusive jets [3]

- **Profiling** CT14 at NLO & NNLO.





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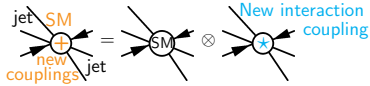

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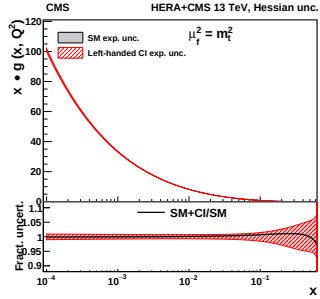

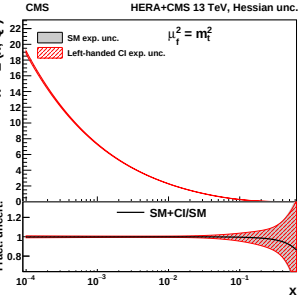

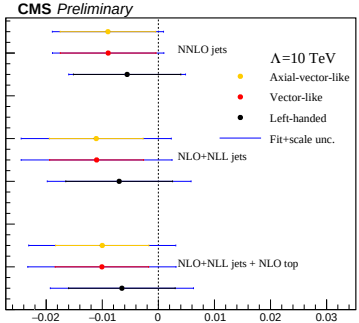

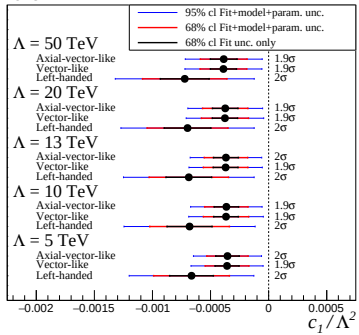

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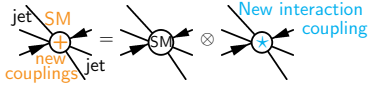

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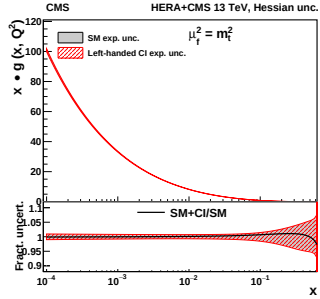
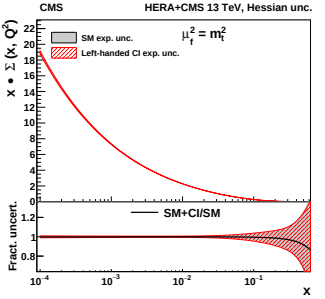
$\longrightarrow$ SMEFT fits lead to results **compatible w. SM**.





Summary & Conclusions

Introduction
Hard scattering
Extra radiations
Tests of SM
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Back-up

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- The CMS Collaboration is prepraring several publications covering many aspects of the **production of jets, Z + jets, and vector bosons** with LHC Run 2 data.

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Thank you for your attention!

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Inclusive jet at 13 TeV
Multijet production
Z + jet
Decorrelations in Z + jet
$Z + b(b)$
VBS
TPS
Acronyms
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Inclusive jet at 5 TeV

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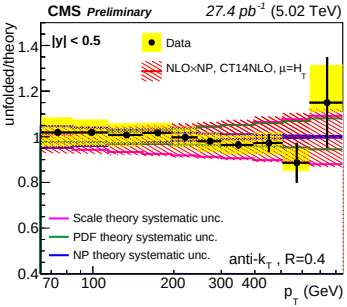

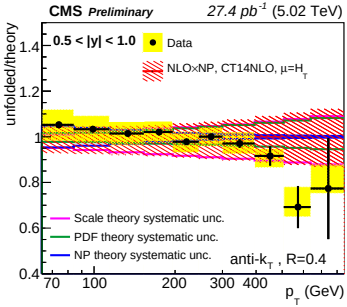

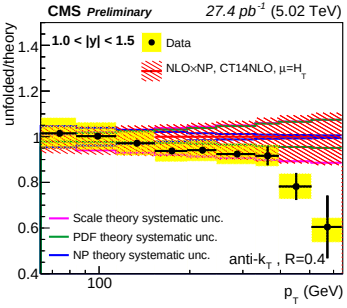

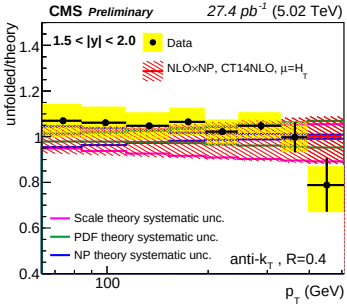

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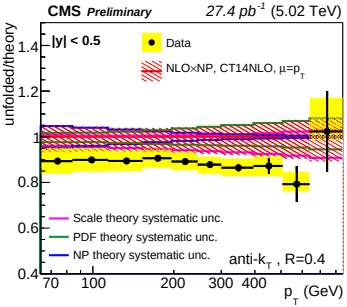

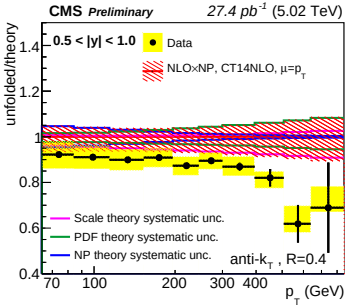

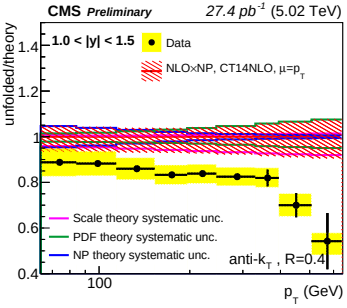

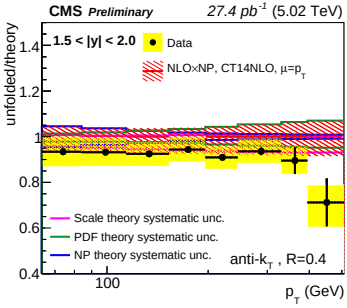

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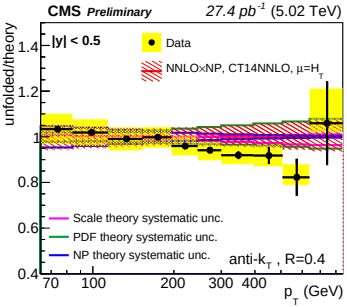

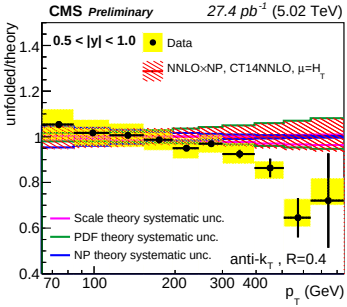

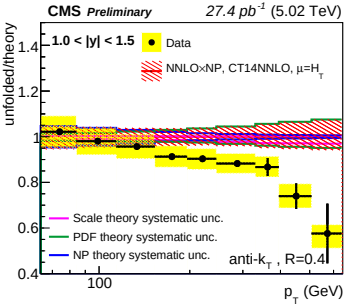

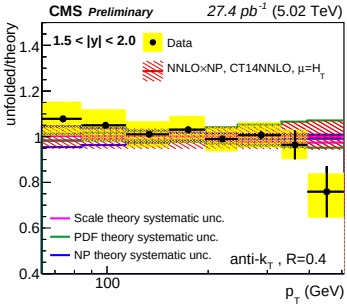

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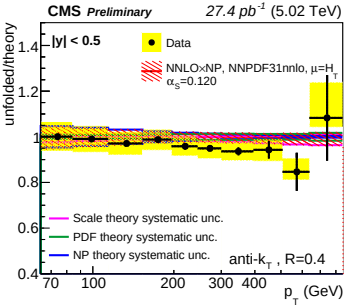

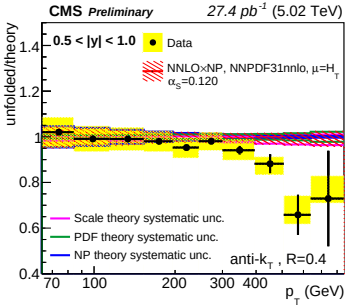

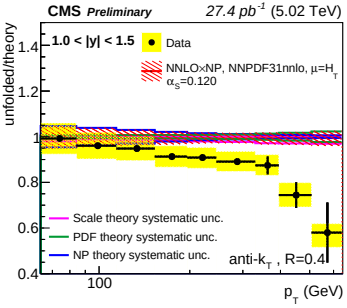

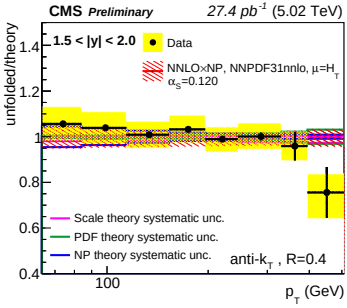

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Perform **simultaneous fit** of PDFs, α_S, m_t, and **Wilson coefficient** c_1**!**

Phase space [33]

- $p_T > 97$ GeV
- $|y| < 2.0$

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- High-pile-up 2016 data using AK4 & AK7.
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- HERA DIS data [12],
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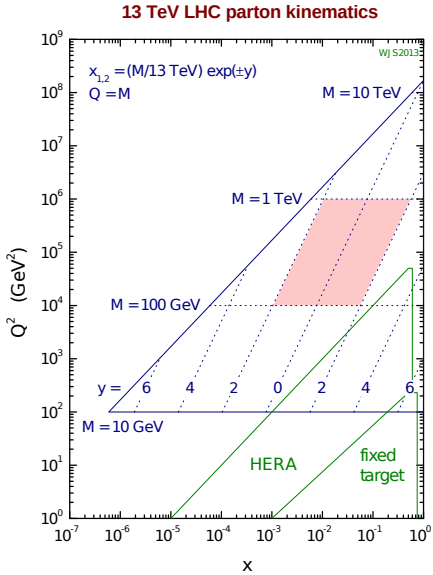
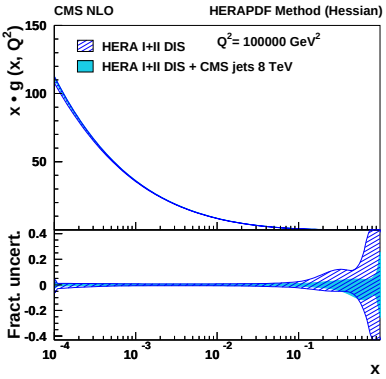




Inclusive jet at 13 TeV

Inclusive jet measurements at LHC

$\sqrt{s}$	ATLAS	CMS
2.76 TeV	0.0002 fb^{-1} [34]	0.0054 fb^{-1} [35]
7 TeV	4.5 fb^{-1} [36]	5.0 fb^{-1} [37, 38]
8 TeV	20 fb^{-1} [39]	20 fb^{-1} [40]
13 TeV	3.2 fb^{-1} [41]	0.071 fb^{-1} [42]

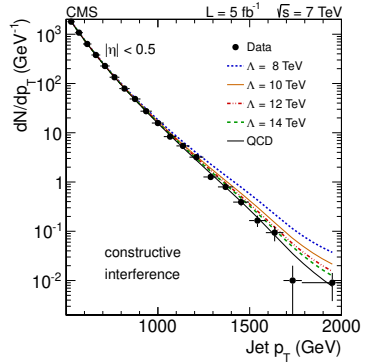
- Unfold data.
- Constrain α_S and PDFs with SM predictions.

Searches for CI at CMS [43, 44]

- Fold SMEFT predictions with existing PDF.
- Constrain CI.

Question

But **what if** the CIs have already been **absorbed** in the PDF?



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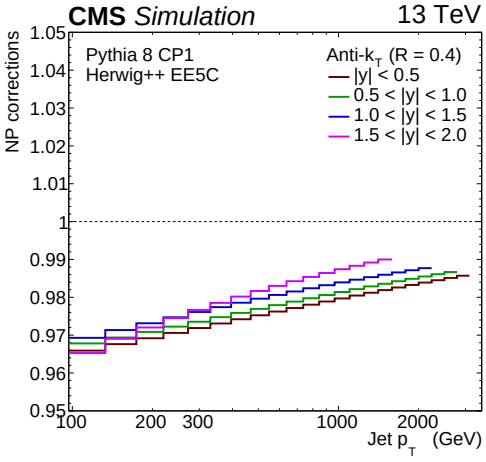
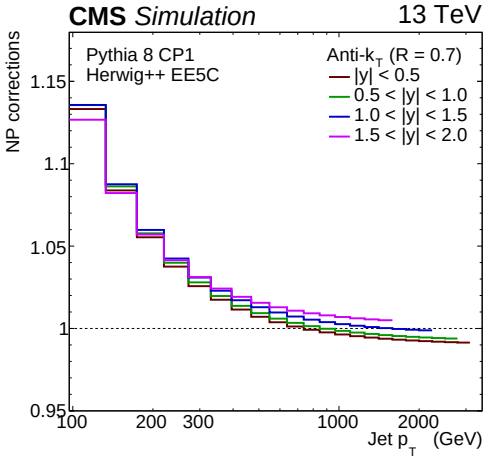
NP Corrections





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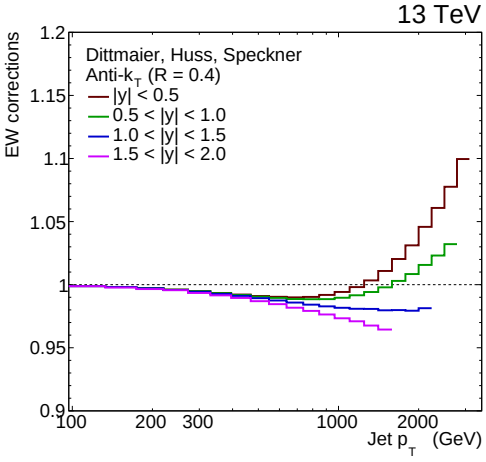
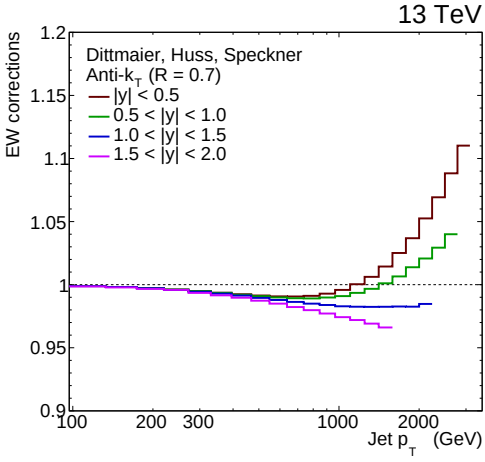
EW Corrections





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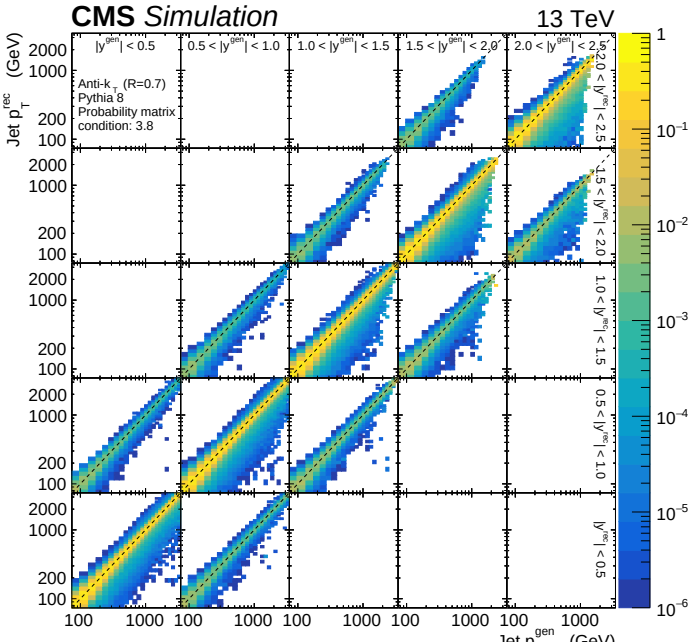
Cross sections



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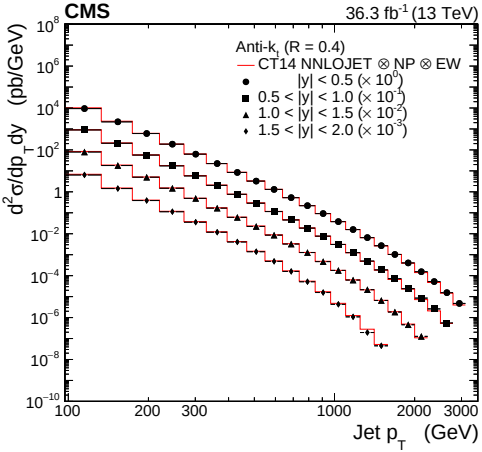
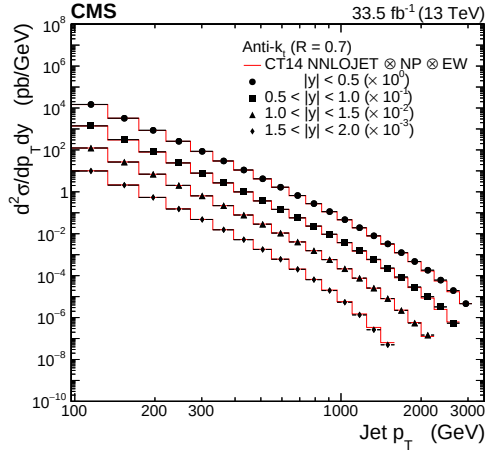
Cross sections





Inclusive jet at 5 TeV
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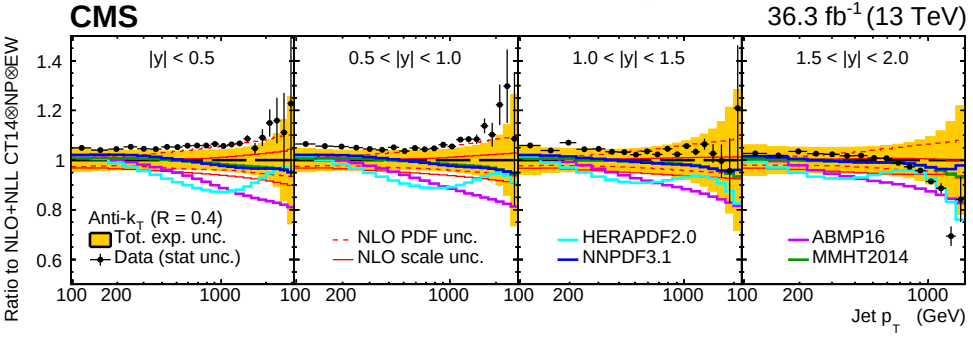

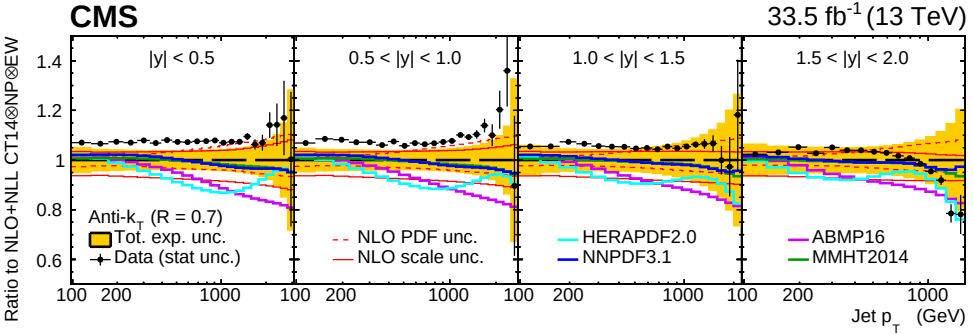

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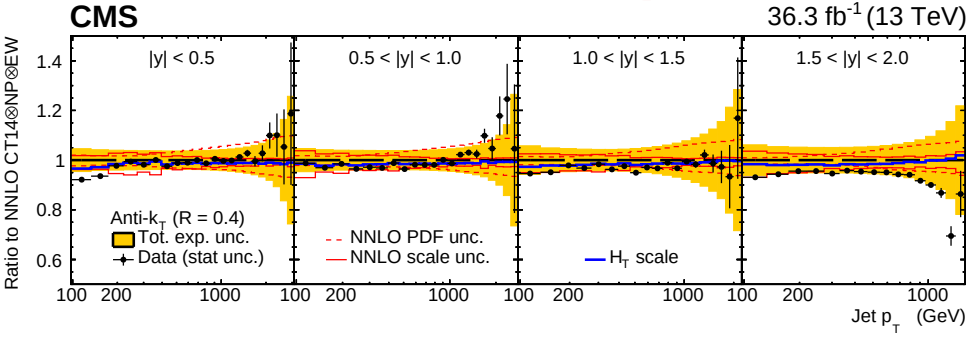
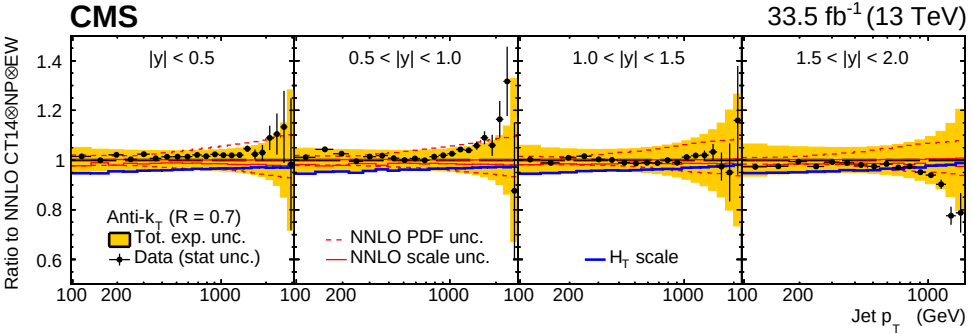
Inclusive jet at 13 TeV





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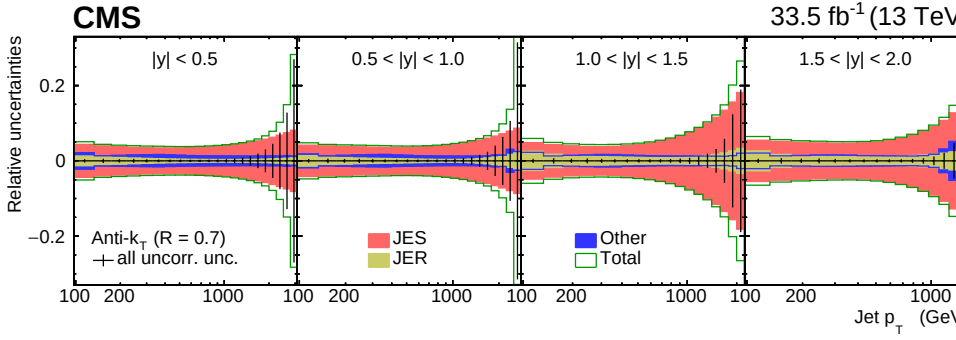
Cross sections



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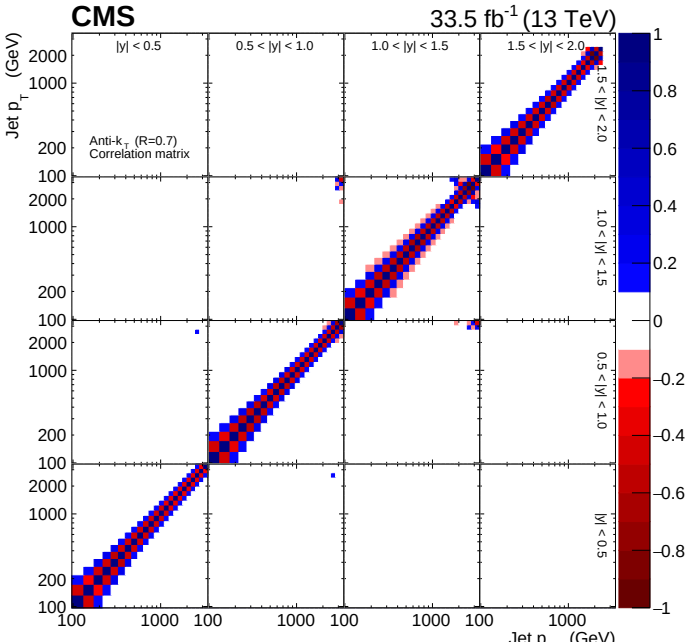

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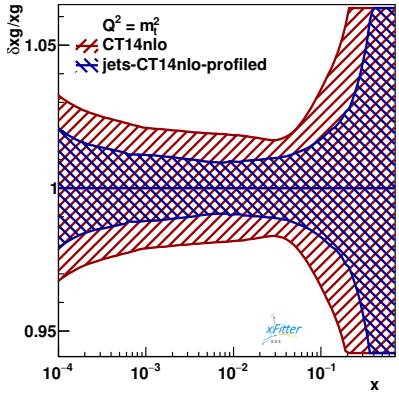

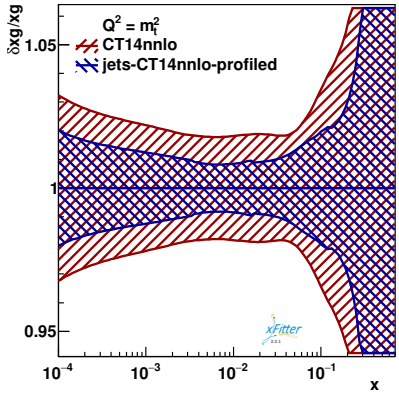

Impact on PDF, α_S, m_t, and c_1

- Using 13-TeV CMS data on top of CT14
- Both NLO & NNLO predictions.

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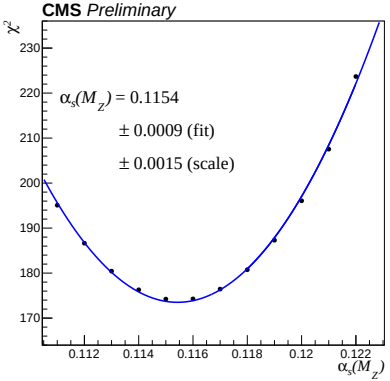

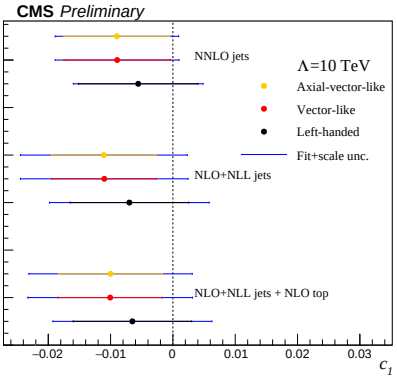

Impact on PDF, α_S, m_t, and c_1

- **Profiling** method is applied on the various parameters separately.

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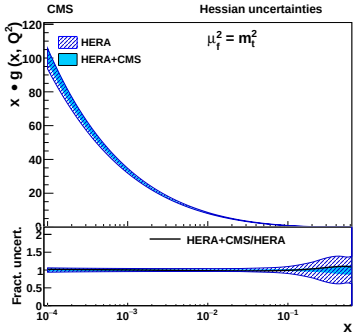

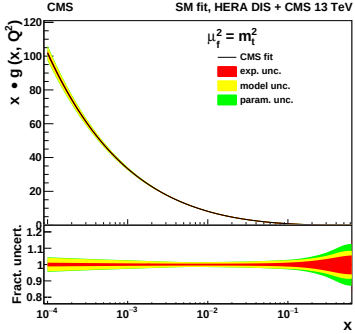

Inclusive jet at 13 TeV

Fits

Parameterisation

$$xg(x) = A_g x^{B_g}(1-x)^{C_g}(1+E_g x^2)$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v} x)$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$
$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}}$$
$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}}$$

Results

- Strong reduction of the gluon PDF uncertainty.

SM parameters

$$\alpha_S = 0.1188 \pm 0.0017(\text{fit}) \pm 0.0022(\text{model and param.})$$
$$m_t^{\text{pole}} = 170.4 \pm 0.6(\text{fit}) \pm 0.1(\text{model and param.})$$

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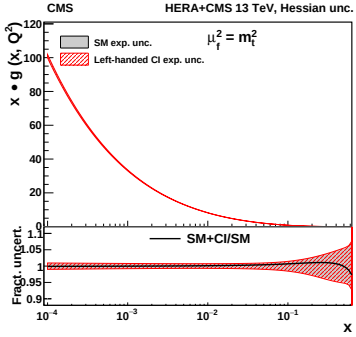

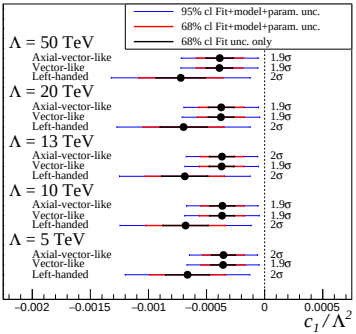

Inclusive jet at 13 TeV

Parameterisation

$$xg(x) = A_g x^{B_g}(1-x)^{C_g}(1+E_g x^2)$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v} x + E_{u_v} x^2)$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}(1+D_{d_v} x)$$
$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}}$$
$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}}$$

Results

- SMEFT fits lead to results compatible w. SM.

SM parameters

$$\alpha_S = 0.1187 \pm 0.0016(\text{fit}) \pm 0.0030(\text{model and param.})$$
$$m_t^{\text{pole}} = 170.4 \pm 0.6(\text{fit}) \pm 0.3(\text{model and param.})$$

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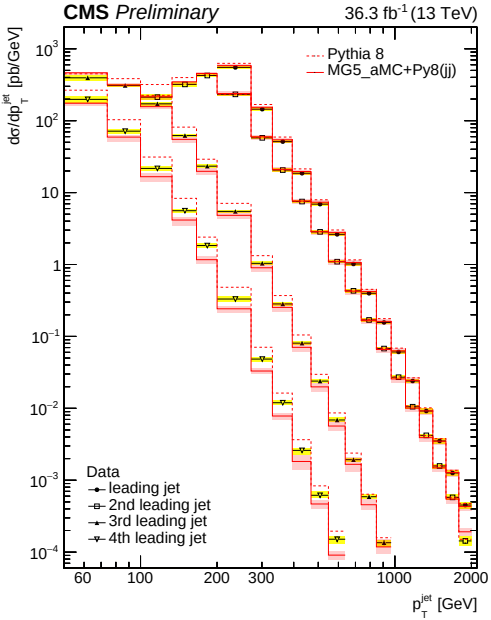

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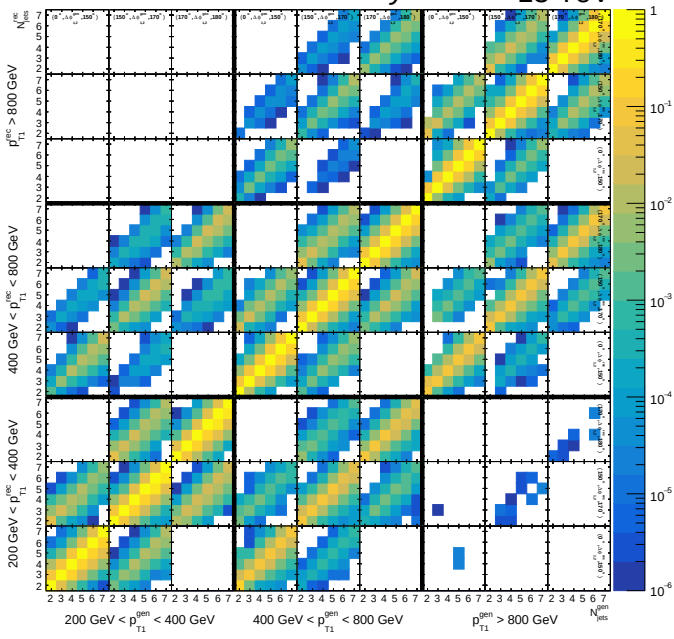

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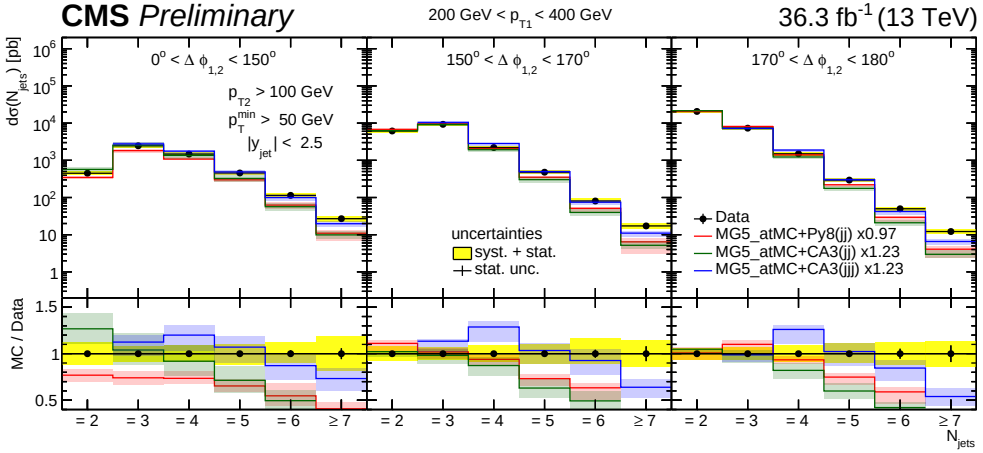

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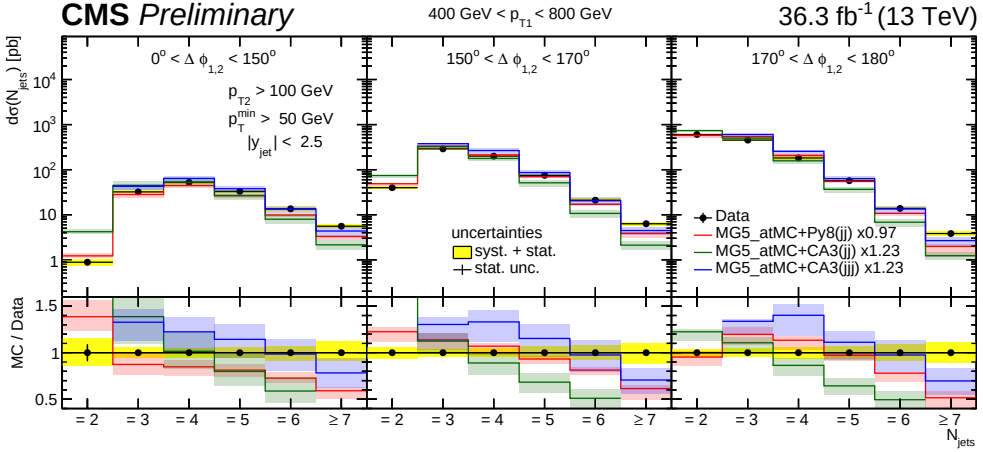

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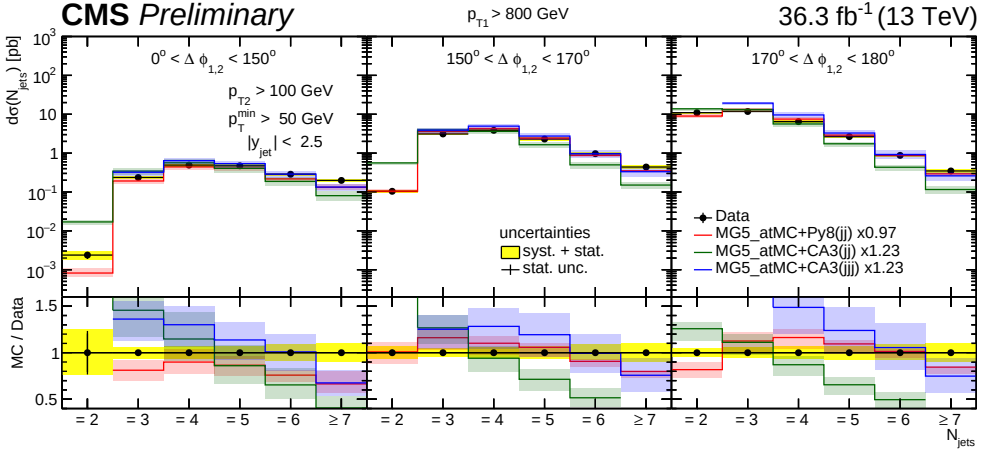

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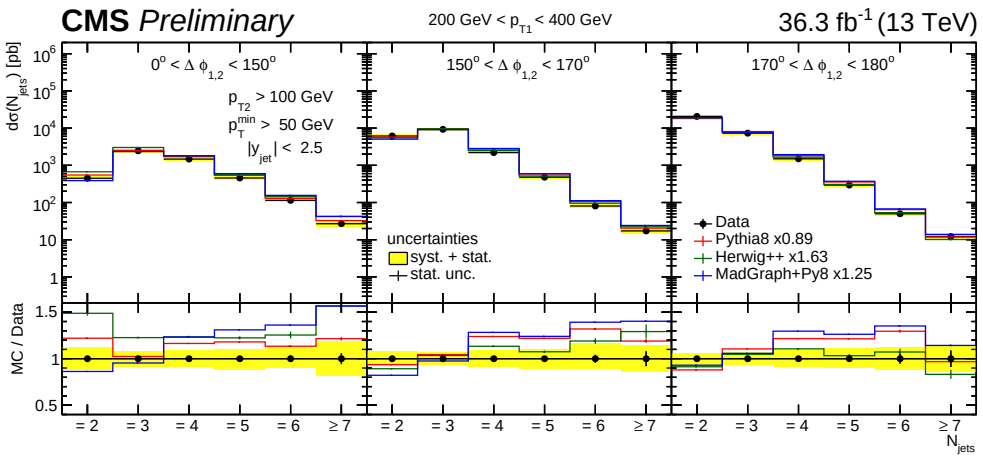

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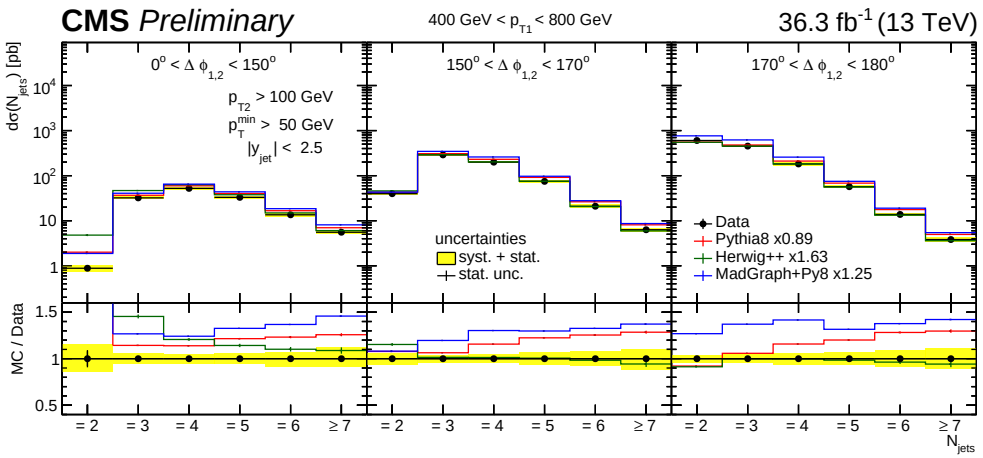

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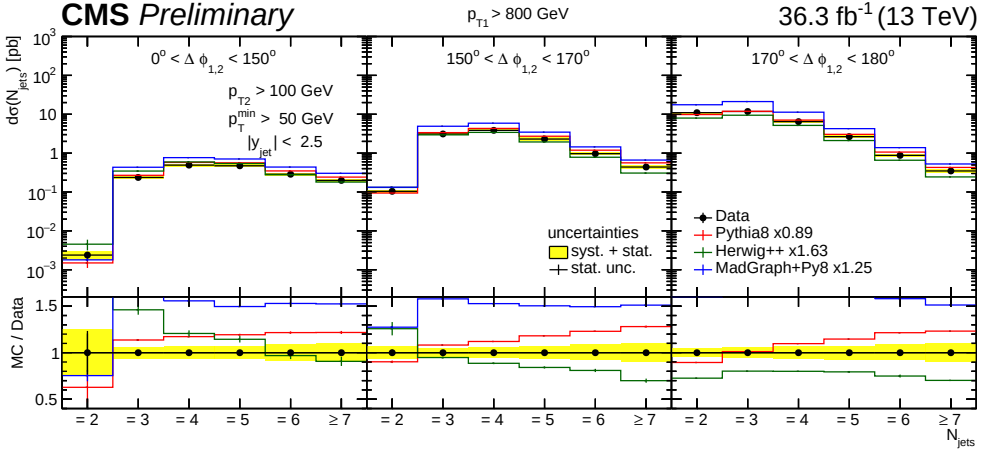

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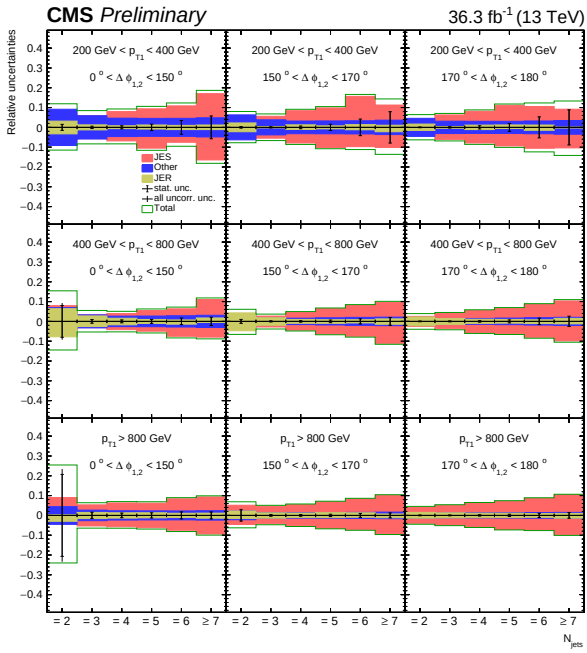

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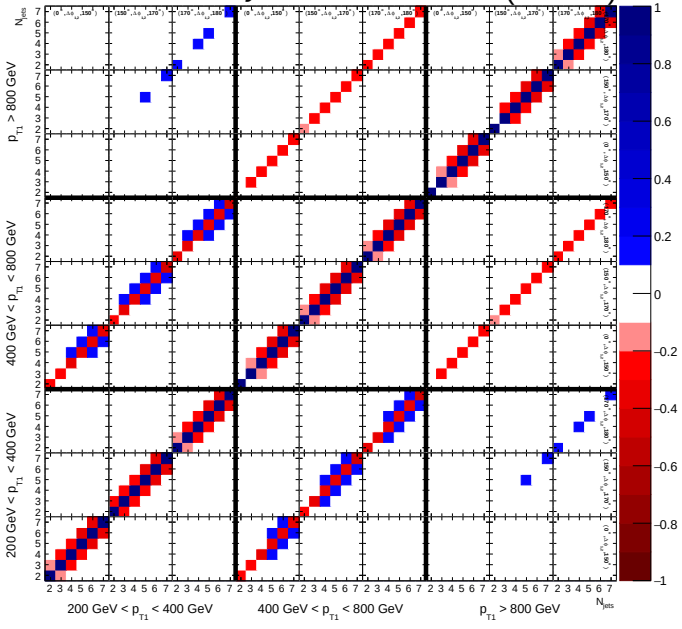

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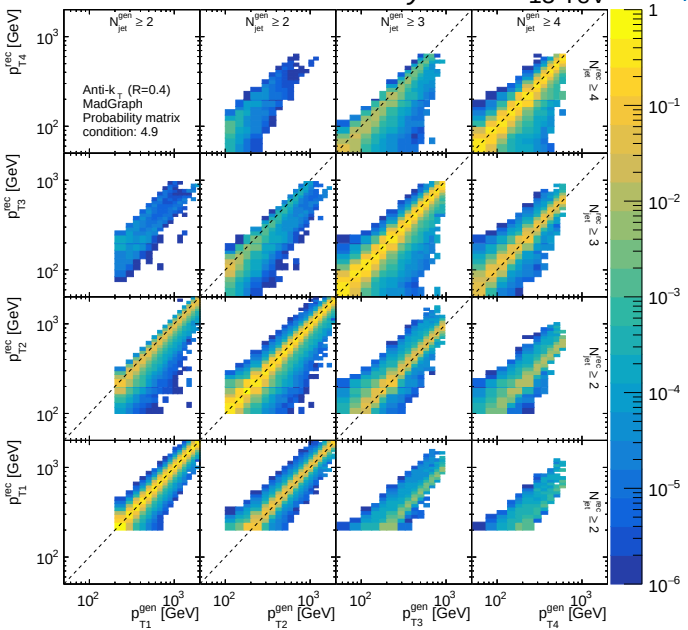

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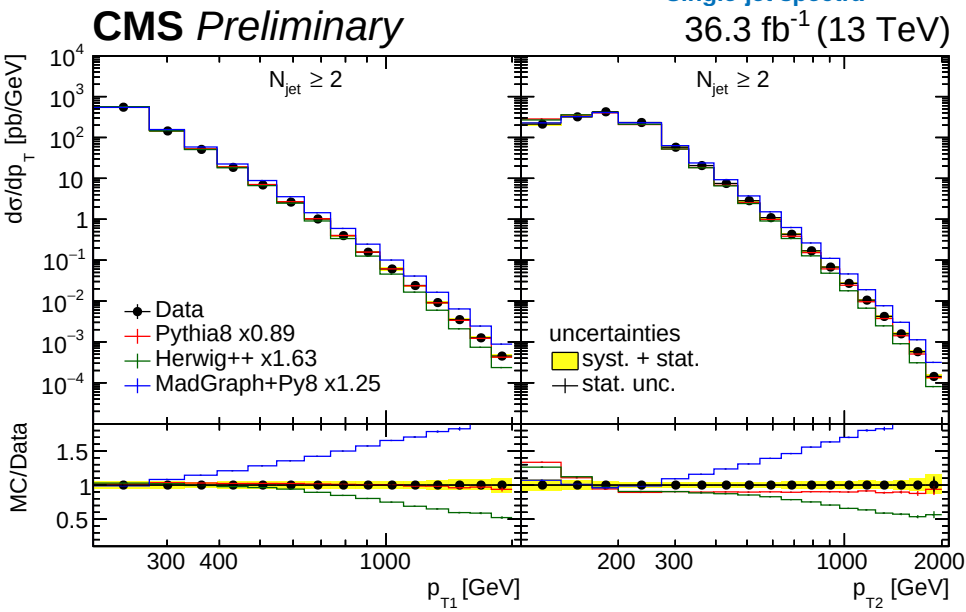

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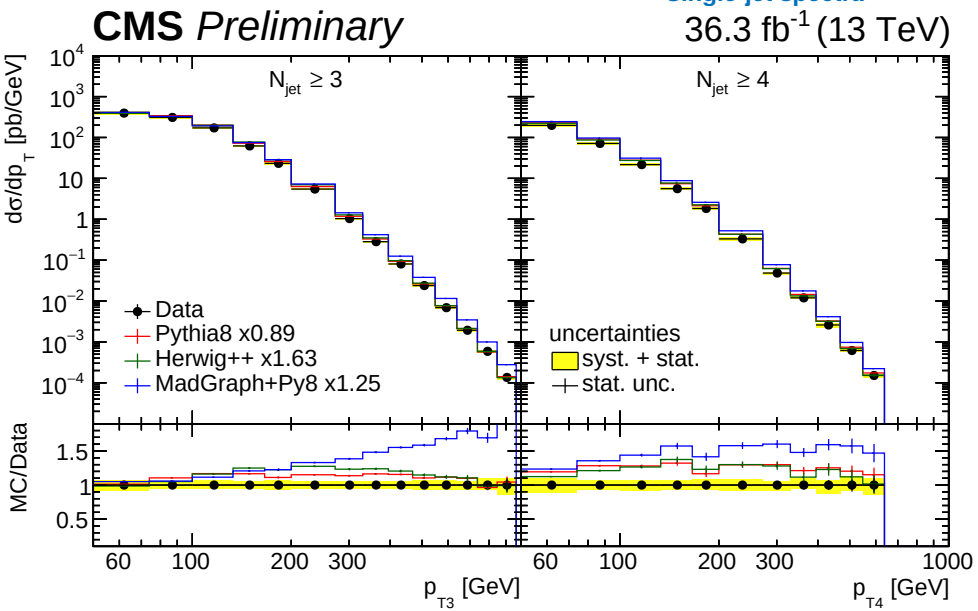

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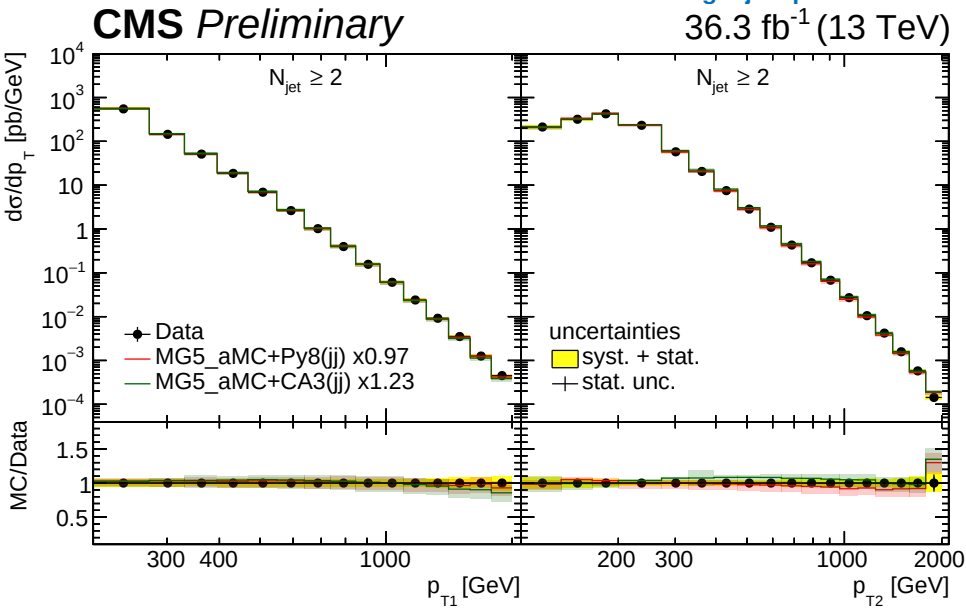

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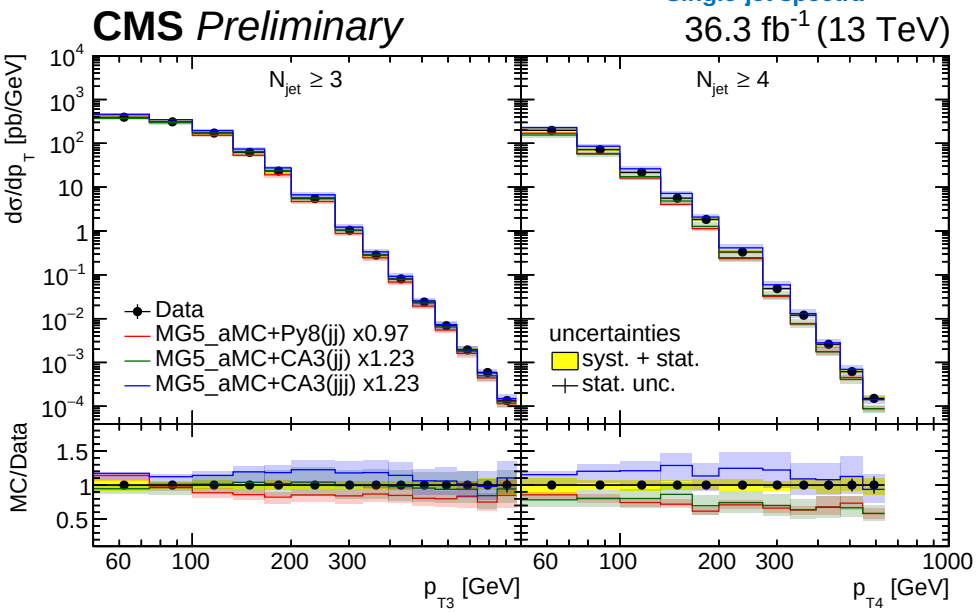

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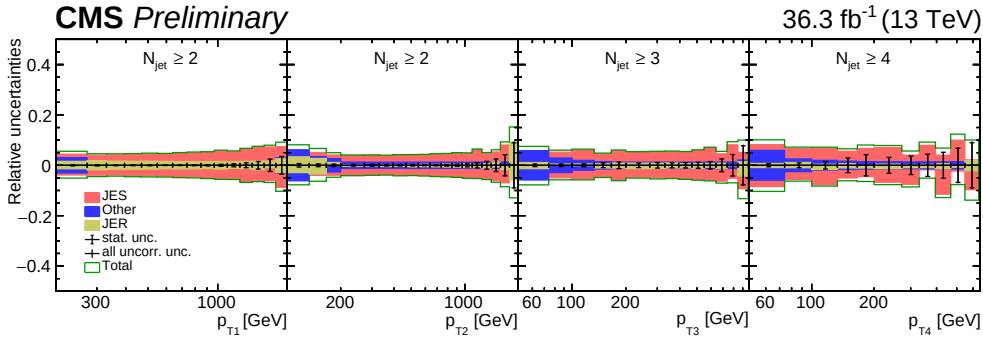

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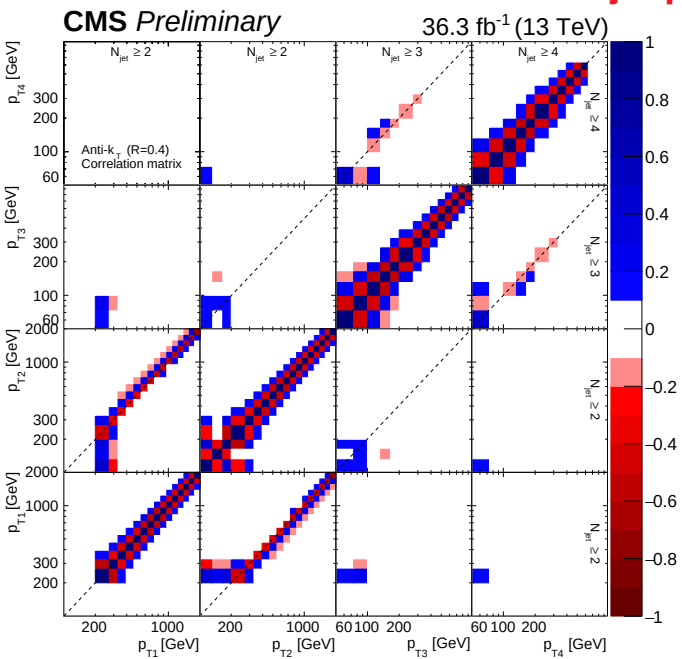
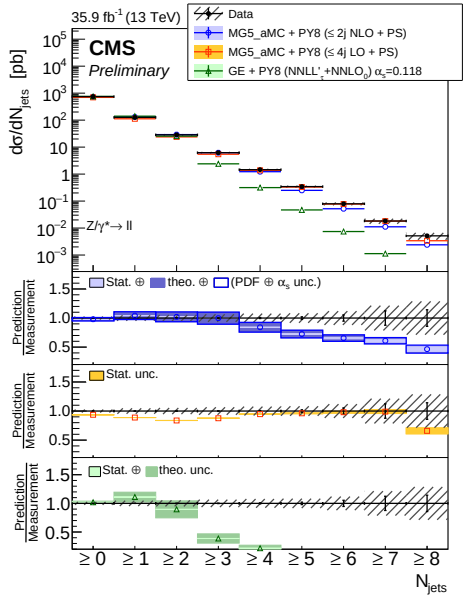
Multijet production

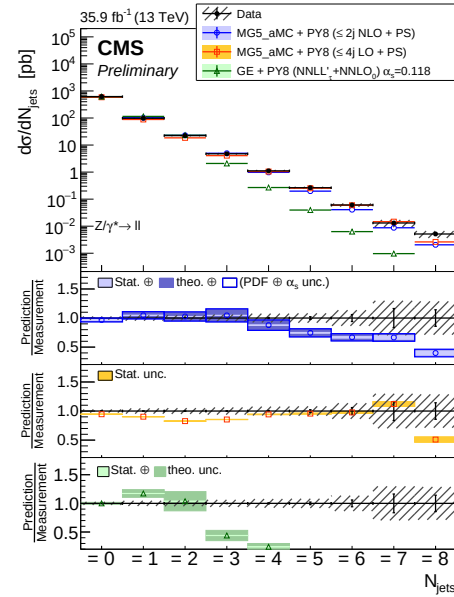
ingle-jet spectra



Inclusive jet at 5 TeV
Inclusive jet at 13 TeV
Multijet production
Z + jet
Decorrelations in Z + jet
$Z + b(b)$
VBS
TPS
Acronyms
References

Z + jet





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TPS
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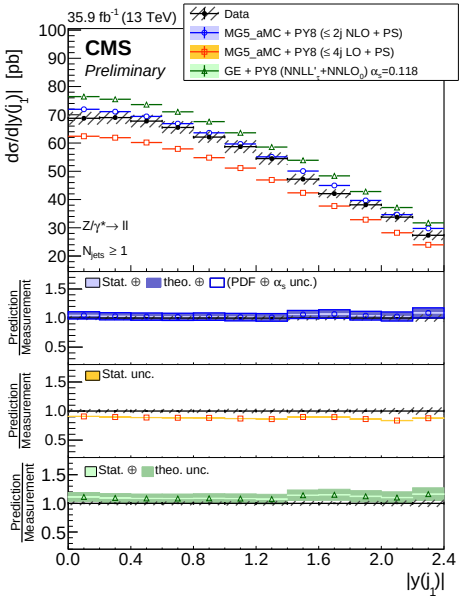

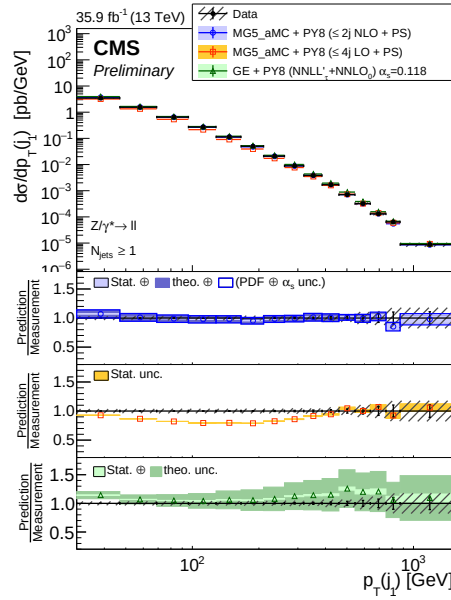

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$Z + b(b)$
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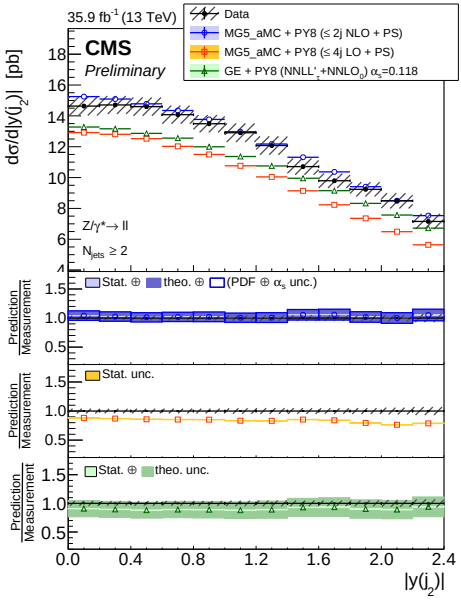

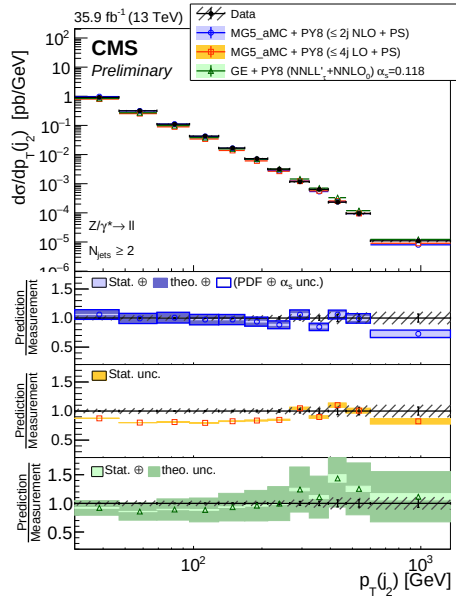

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Acronyms
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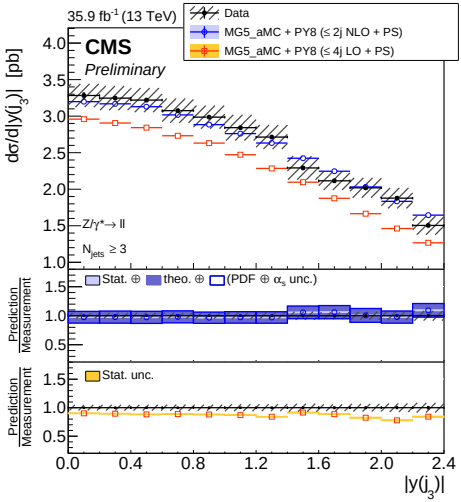

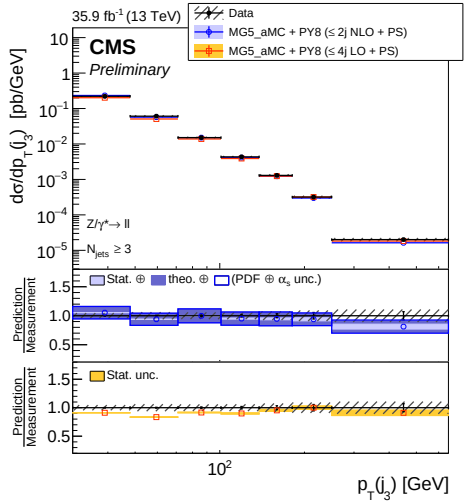

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$Z + b(b)$
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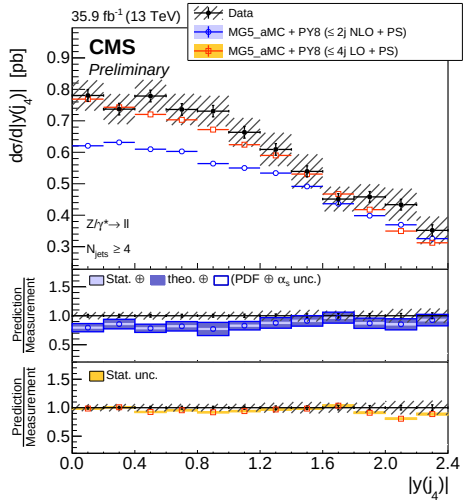
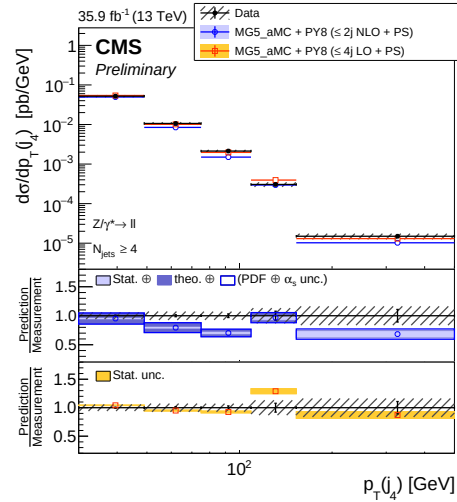
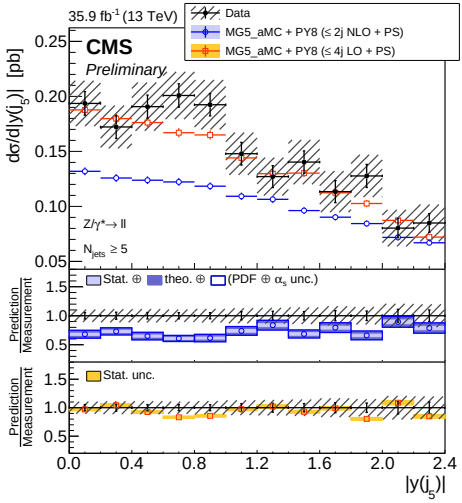
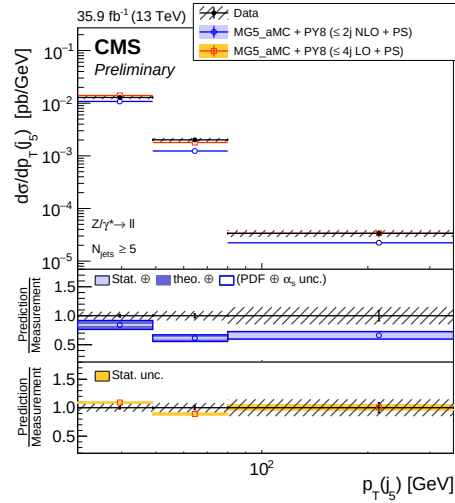




Z + jet


35.9 fb^{-1} (13 TeV)
CMS
Preliminary
Data
MG5_aMC + PY8 (≤ 2j NLO + PS)
MG5_aMC + PY8 (≤ 4j LO + PS)
dσ/d|y(j$_5$)| [pb]
Zl/γ*→ ll
N$_{jets}$ ≥ 5
Stat. ⊕ theo. ⊕ (PDF ⊕ α$_s$ unc.)
Stat. unc.
Prediction / Measurement
|y(j$_5$)|


35.9 fb^{-1} (13 TeV)
CMS
Preliminary
Data
MG5_aMC + PY8 (≤ 2j NLO + PS)
MG5_aMC + PY8 (≤ 4j LO + PS)
dσ/dp$_T$(j$_5$) [pb/GeV]
Zl/γ*→ ll
N$_{jets}$ ≥ 5
Stat. ⊕ theo. ⊕ (PDF ⊕ α$_s$ unc.)
Stat. unc.
Prediction / Measurement
p$_T$(j$_5$) [GeV]

Inclusive jet at 5 TeV
Inclusive jet at 13 TeV
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Z + jet
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VBS
TPS
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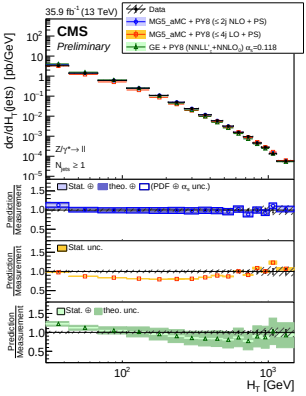
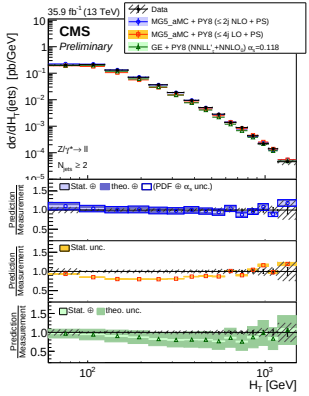
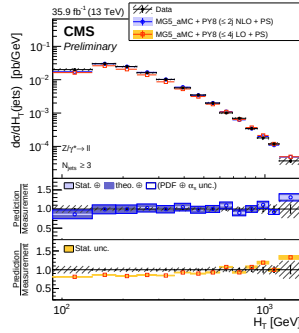
Z + jet







Inclusive jet at 5 TeV
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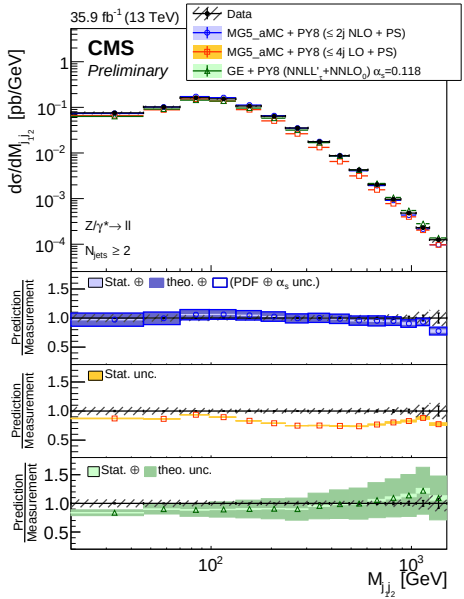
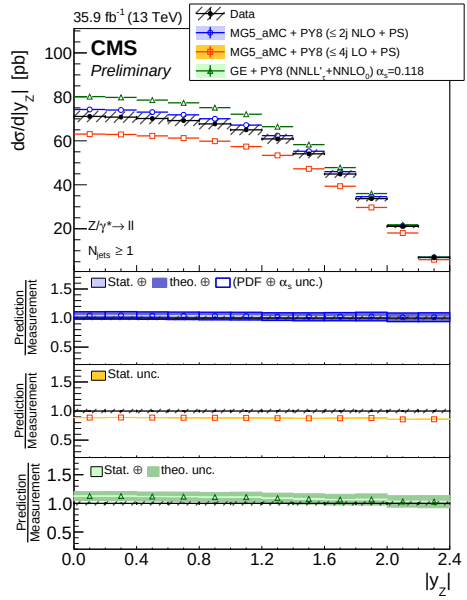
Z + jet



Z + jet


35.9 fb^{-1} (13 TeV)
CMS
Preliminary
Data
MG5_aMC + PY8 (≤ 2j NLO + PS)
MG5_aMC + PY8 (≤ 4j LO + PS)
GE + PY8 (NNLL'$_z$+NNLO$_\beta$) α_s=0.118
dσ/d|y$_Z$| [pb]
Z/γ*→ ll
N$_{jets}$ ≥ 1
Stat. ⊕ theo. ⊕ (PDF ⊕ α_s unc.)
Stat. unc.
Stat. ⊕ theo. unc.
Prediction / Measurement
|y$_Z$|

Inclusive jet at 5 TeV
Inclusive jet at 13 TeV
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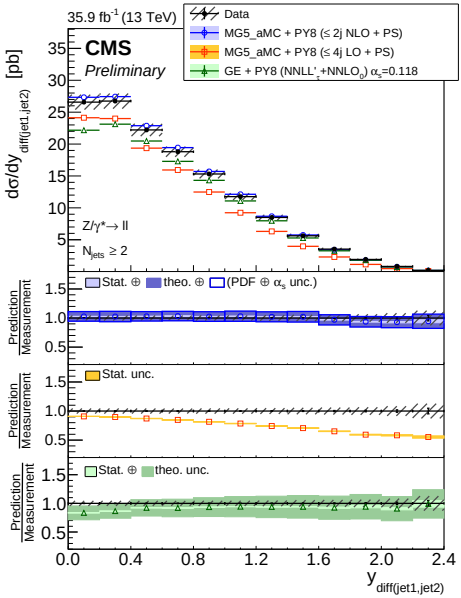
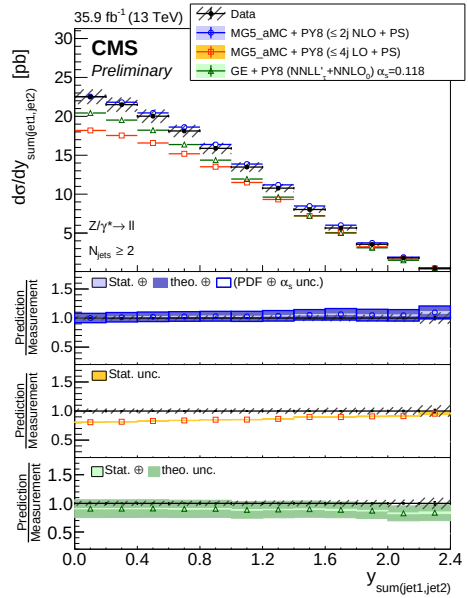
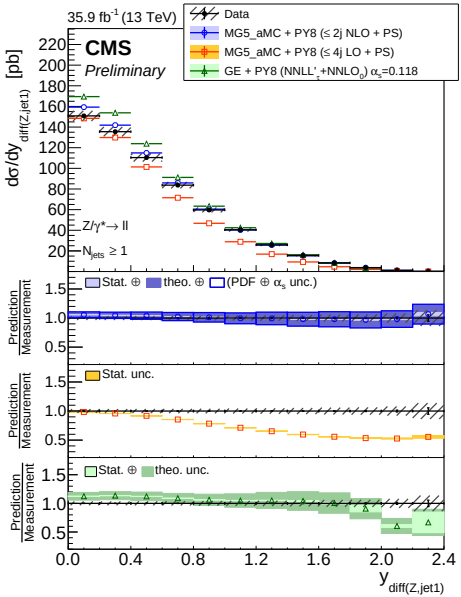
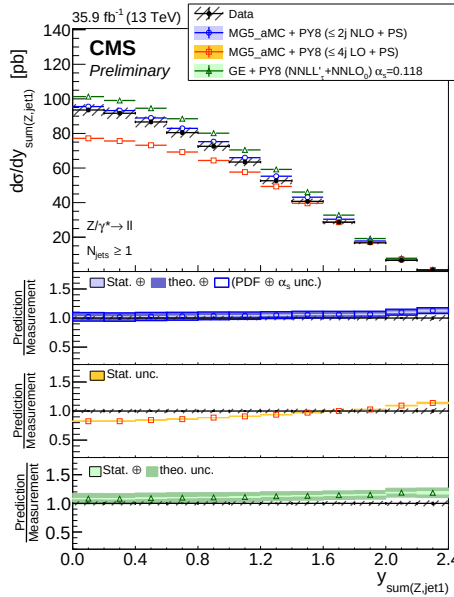
Z + jet





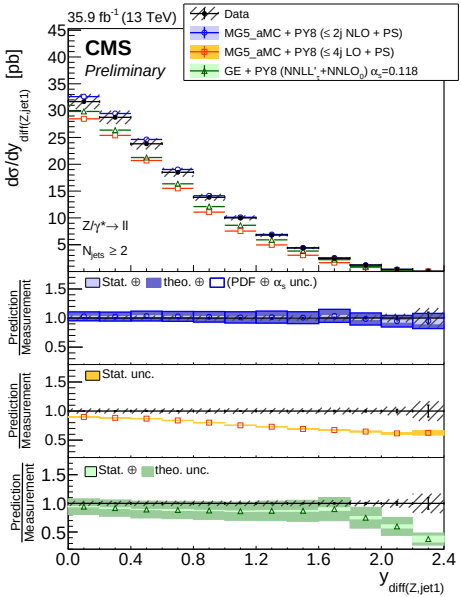
Z + jet

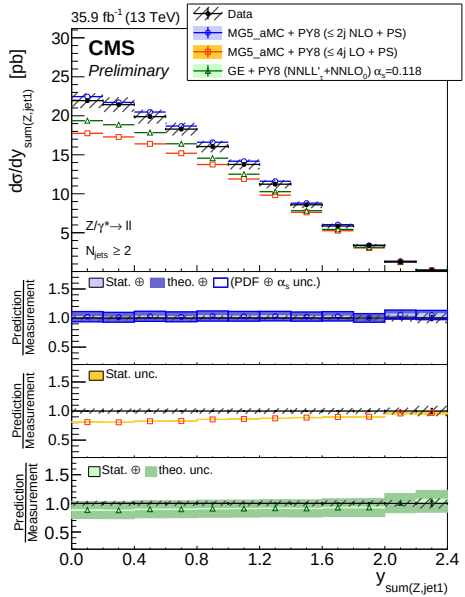

35.9 fb-1 (13 TeV)
CMS
Preliminary
Data
MG5_aMC + PY8 (≤ 2j NLO + PS)
MG5_aMC + PY8 (≤ 4j LO + PS)
GE + PY8 (NNLL'+NNLO) αs=0.118
dσ/dy diff(Z,jet1) [pb]
Z/γ*→ ll
Njets ≥ 1
Stat. ⊕ theo. ⊕ (PDF ⊕ αs unc.)
Stat. unc.
Stat. ⊕ theo. unc.
Prediction / Measurement
ydiff(Z,jet1)


35.9 fb-1 (13 TeV)
CMS
Preliminary
Data
MG5_aMC + PY8 (≤ 2j NLO + PS)
MG5_aMC + PY8 (≤ 4j LO + PS)
GE + PY8 (NNLL'+NNLO) αs=0.118
dσ/dy sum(Z,jet1) [pb]
Z/γ*→ ll
Njets ≥ 1
Stat. ⊕ theo. ⊕ (PDF ⊕ αs unc.)
Stat. unc.
Stat. ⊕ theo. unc.
Prediction / Measurement
ysum(Z,jet1)

Inclusive jet at 5 TeV
Inclusive jet at 13 TeV
Multijet production
Z + jet
Decorrelations in Z + jet
$Z + b(b)$
VBS
TPS
Acronyms
References

Z + jet





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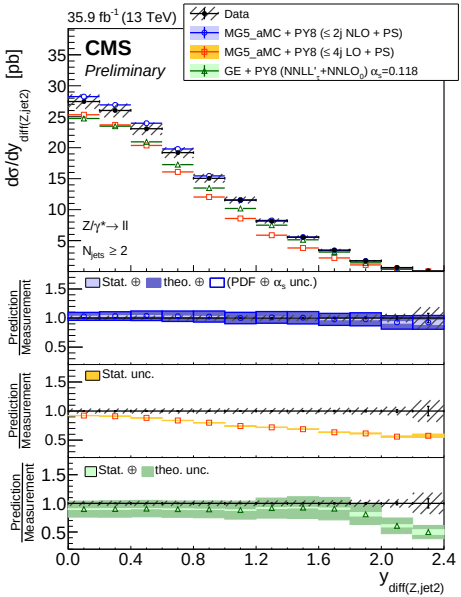

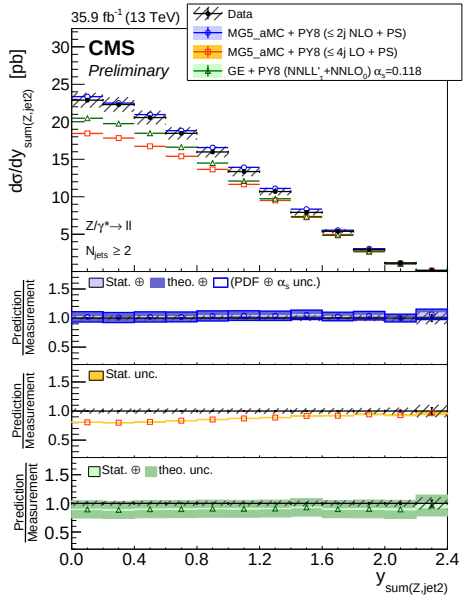

Inclusive jet at 5 TeV
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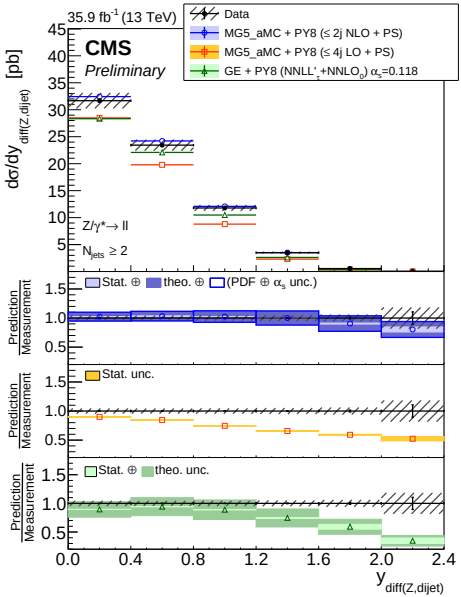

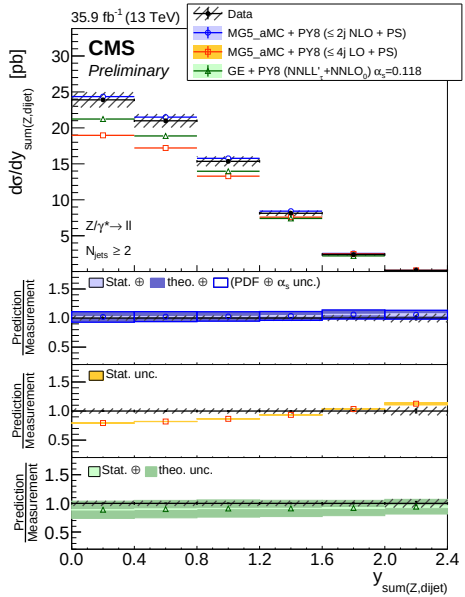

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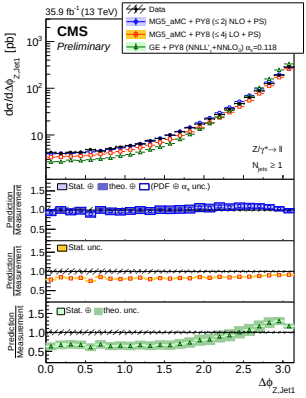

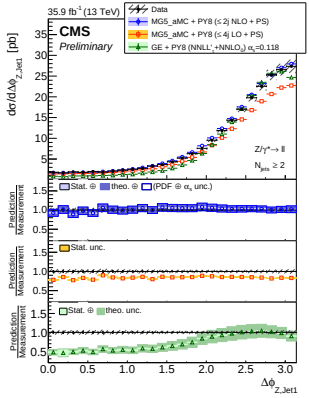

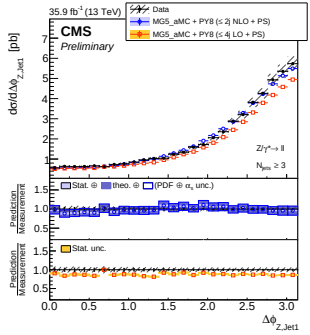

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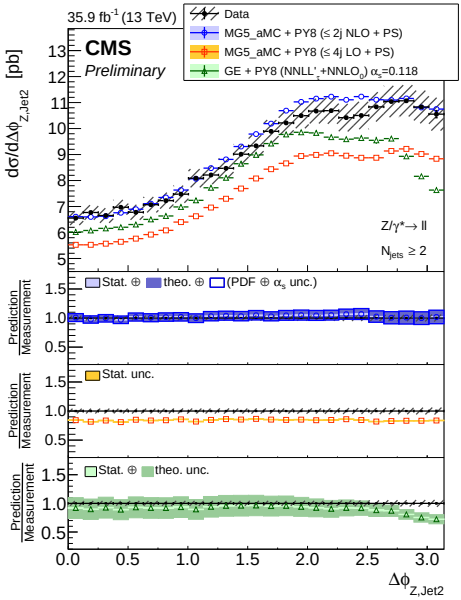

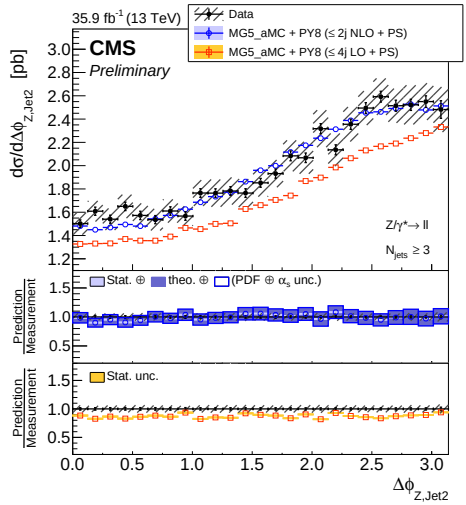

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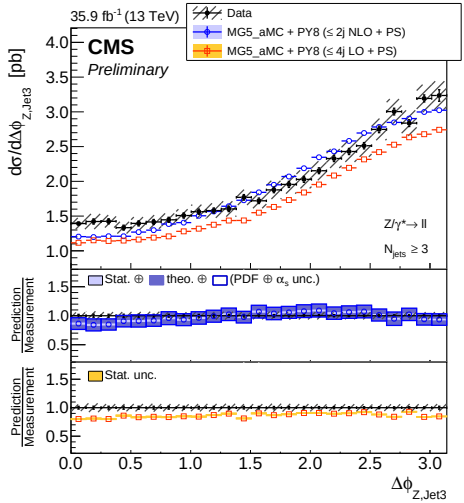

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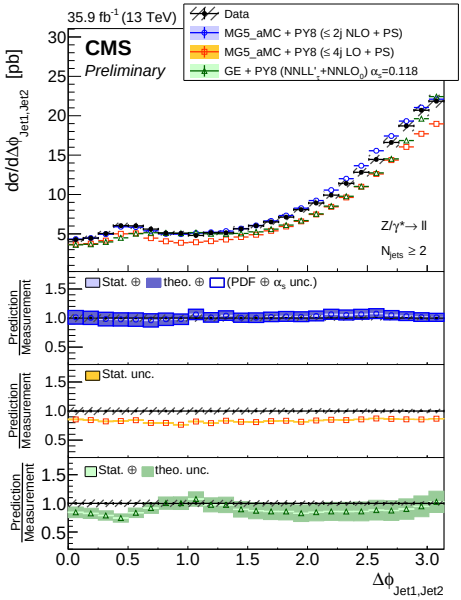

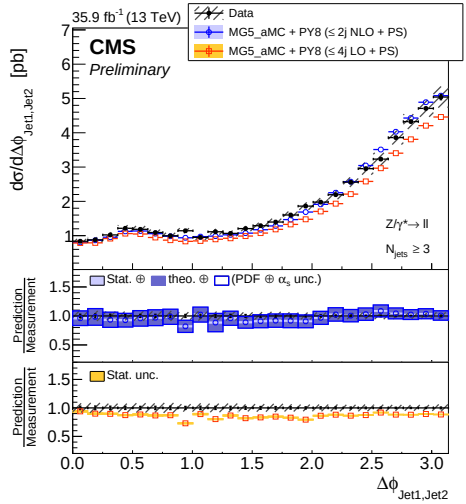

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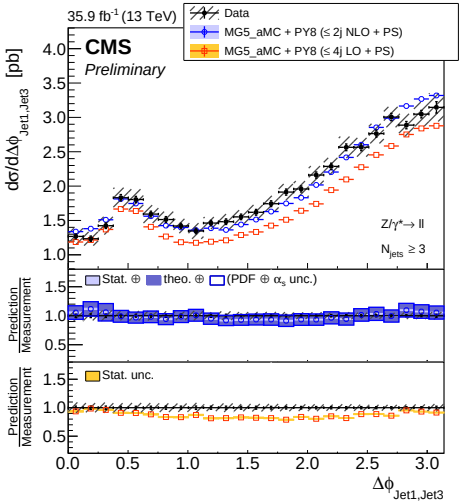

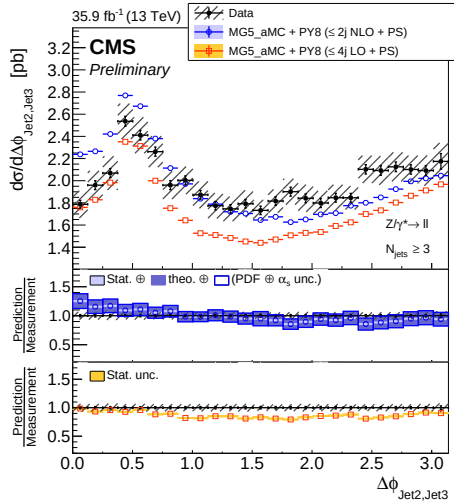

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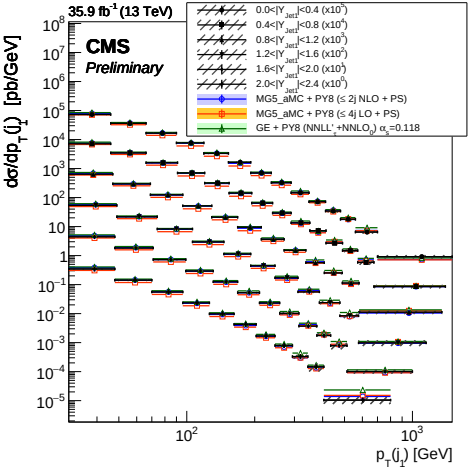

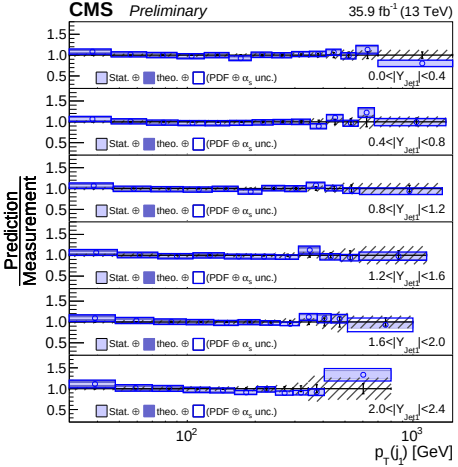

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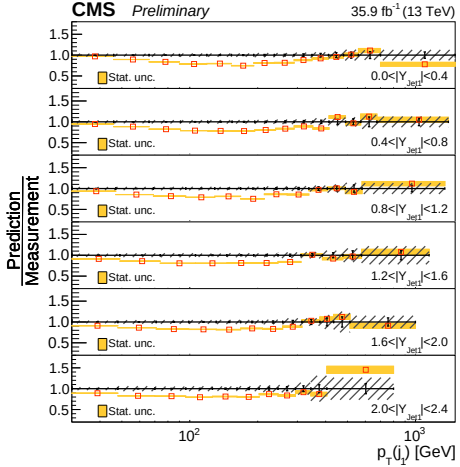

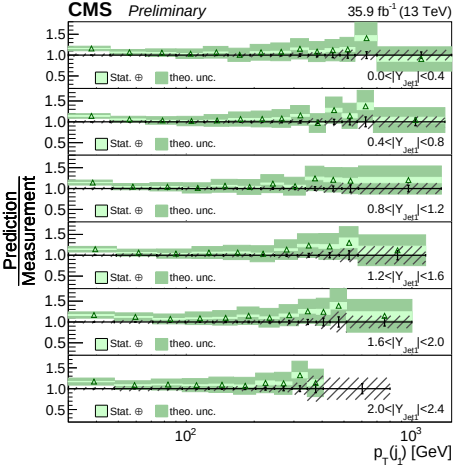

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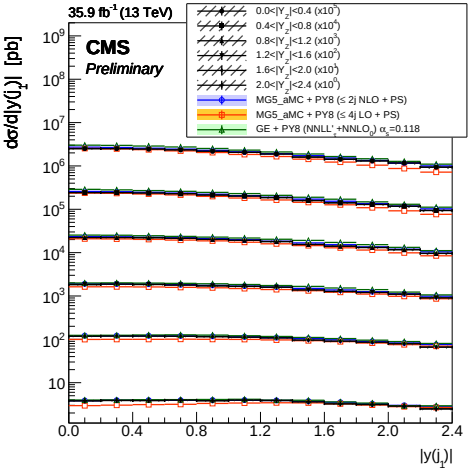
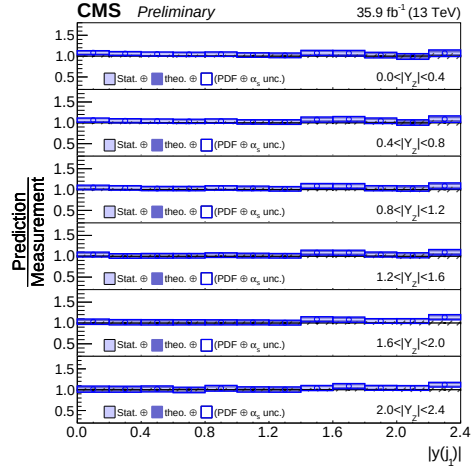
Z + jet





Inclusive jet at 5 TeV
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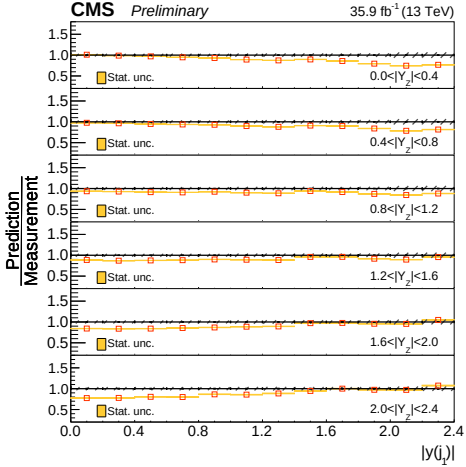

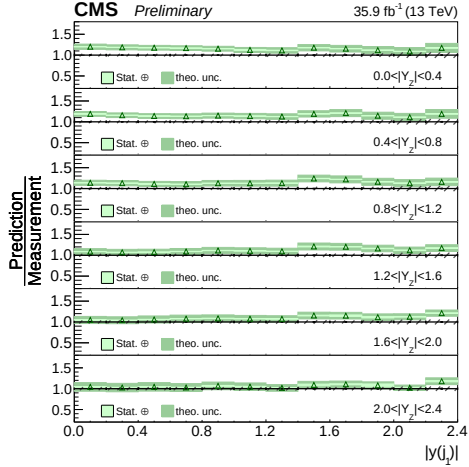

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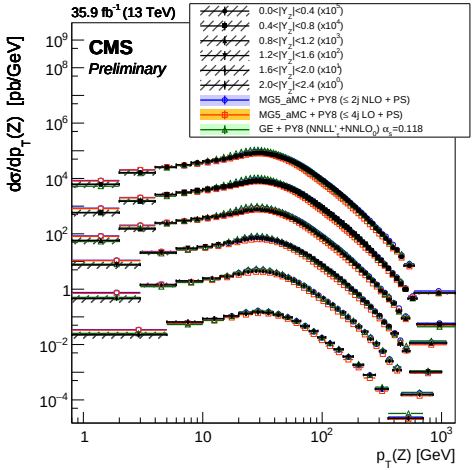

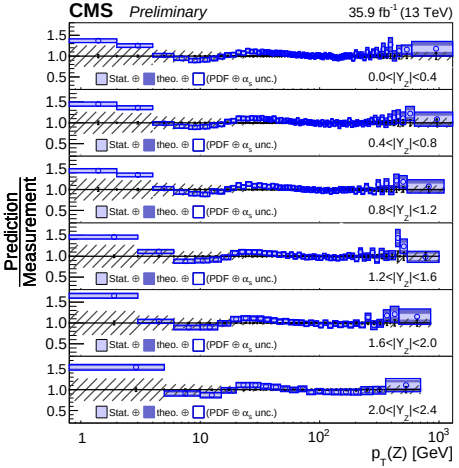

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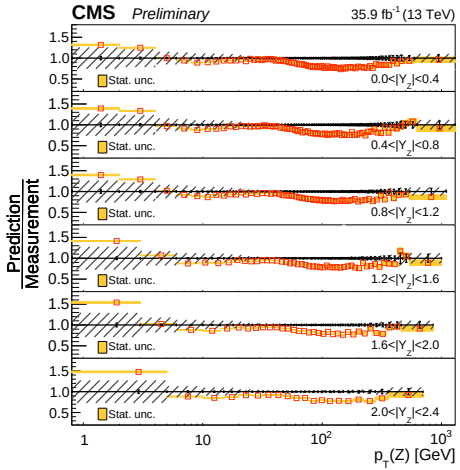

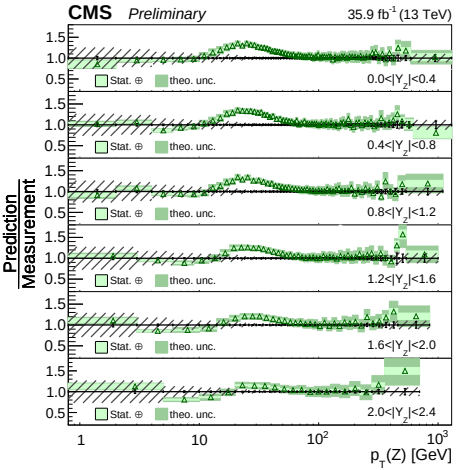

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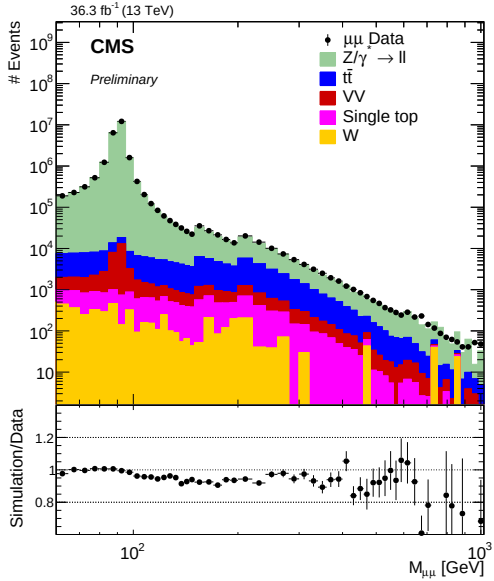

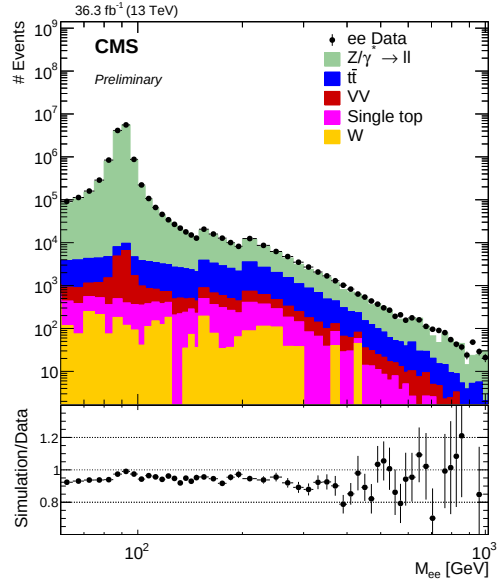

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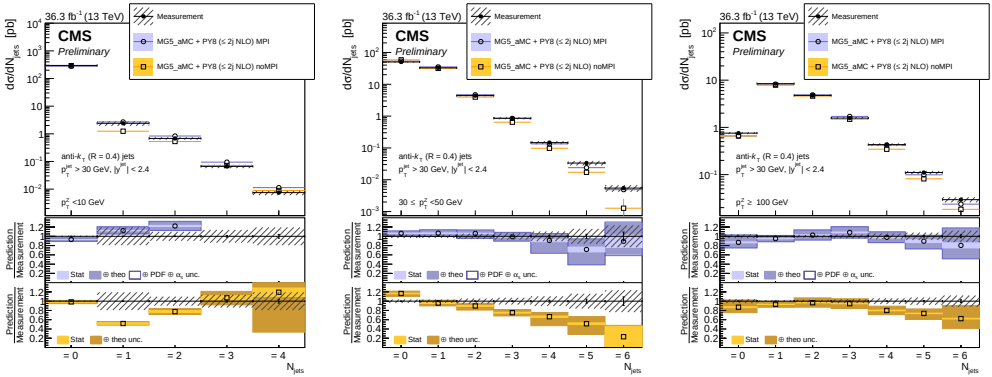

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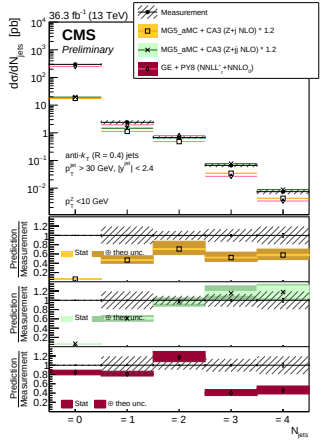

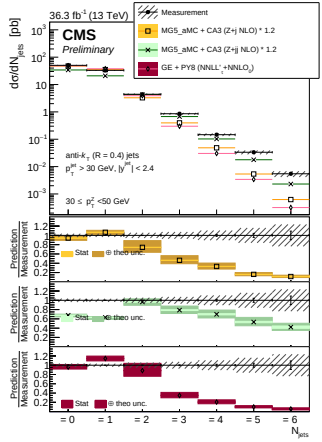

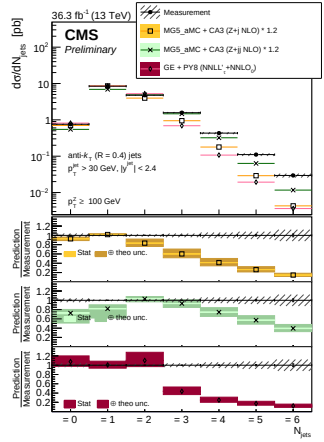

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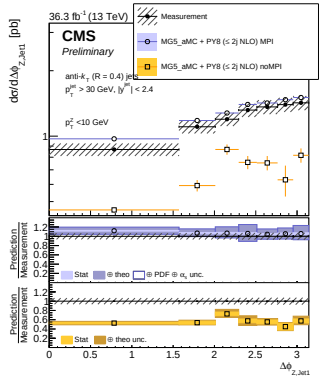

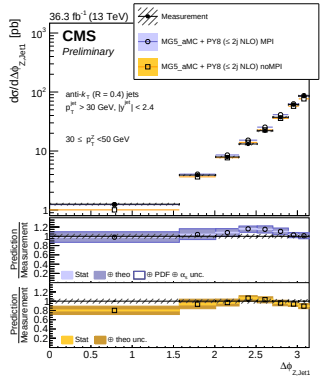

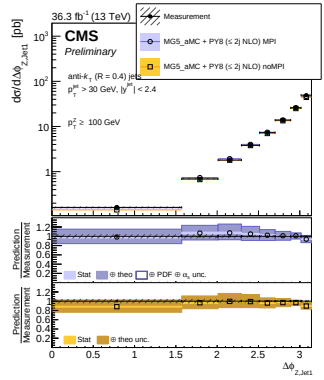

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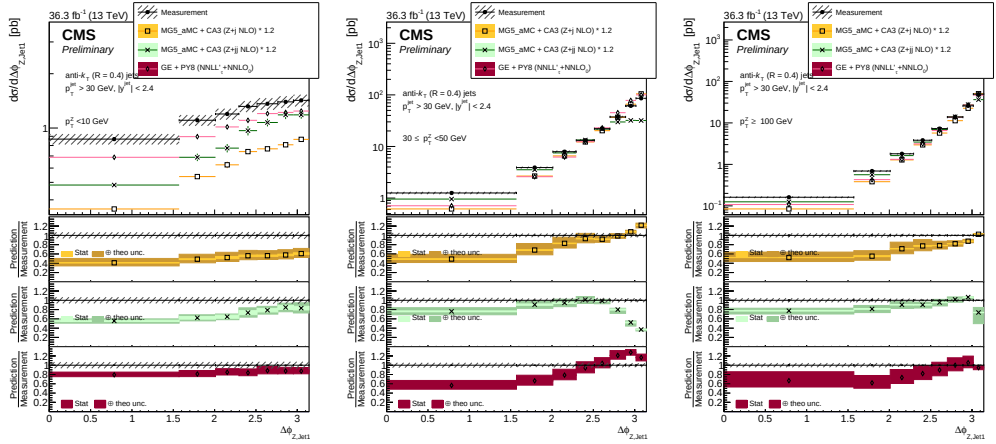

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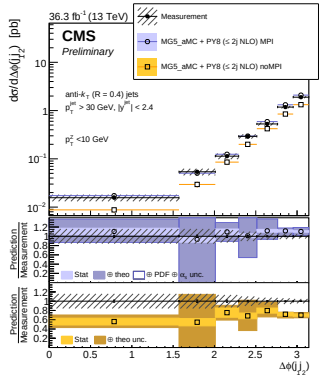

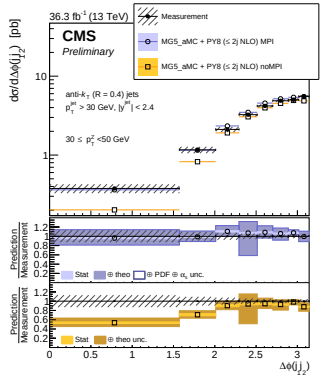

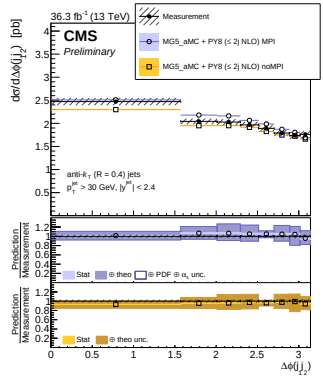

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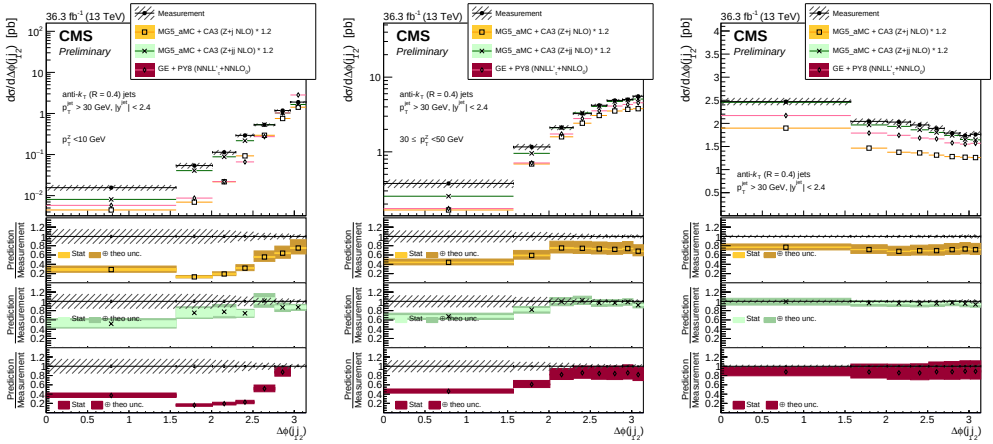

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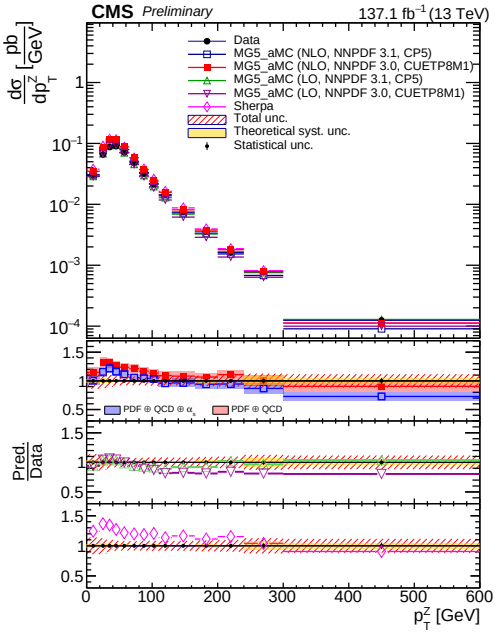

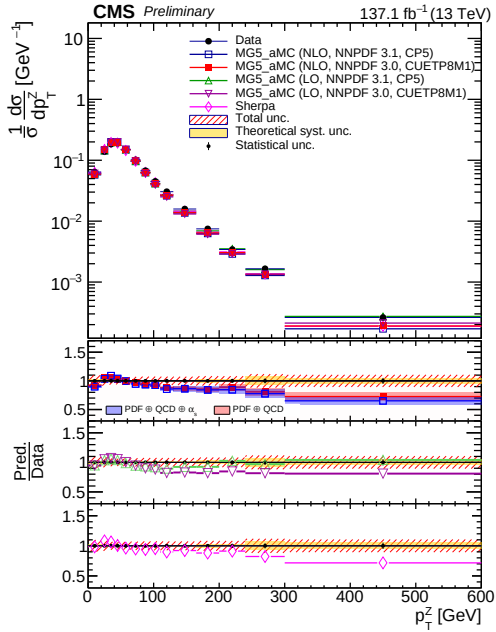

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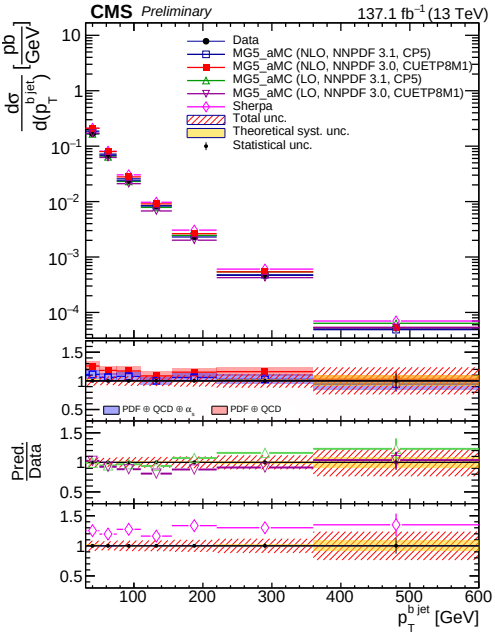

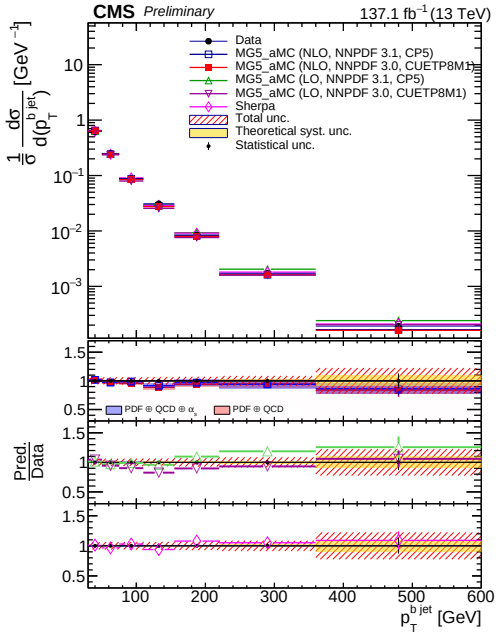

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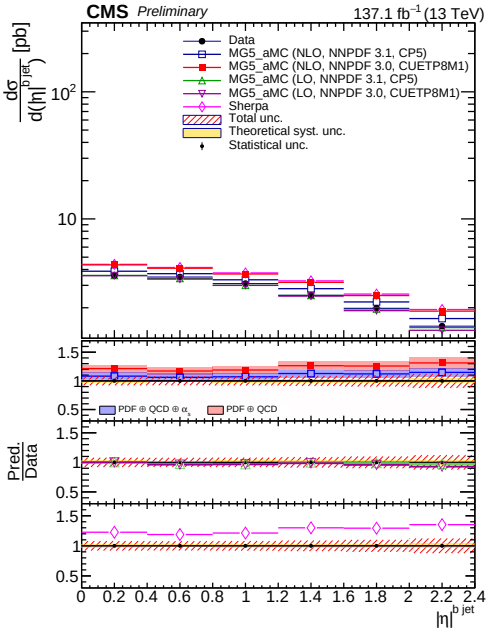

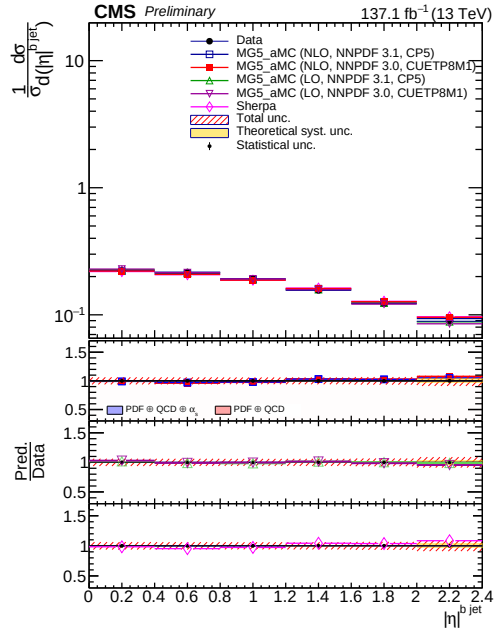

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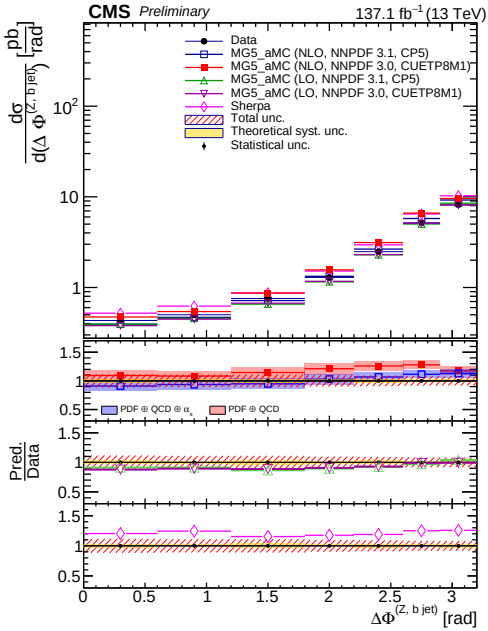

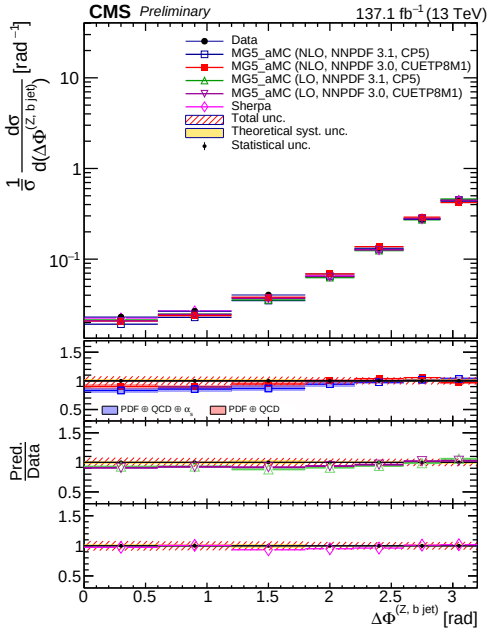

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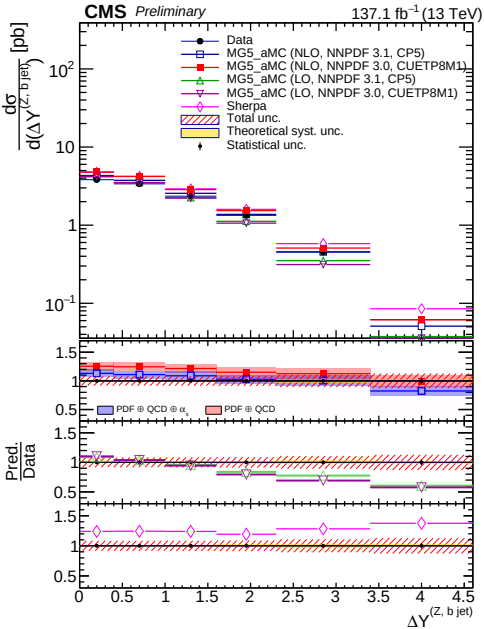

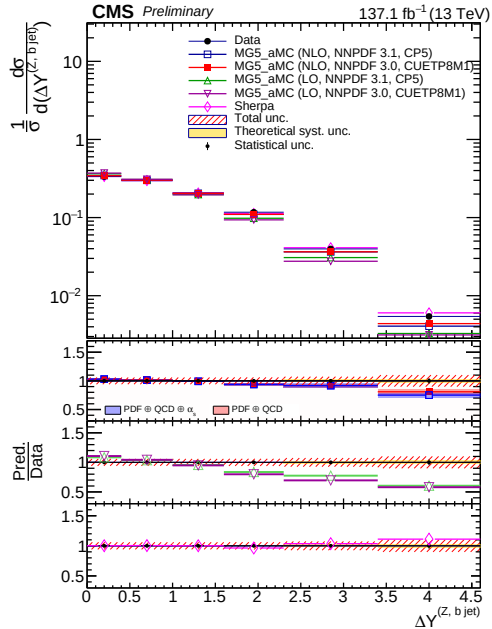

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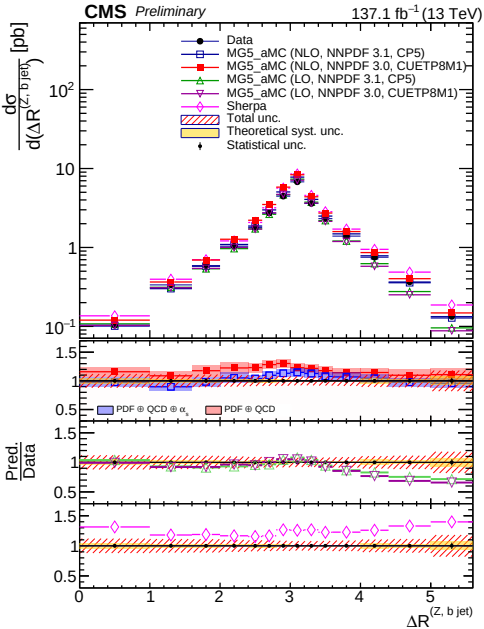

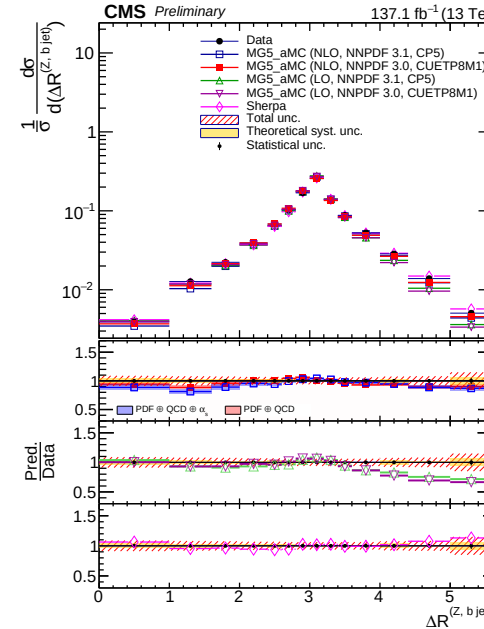

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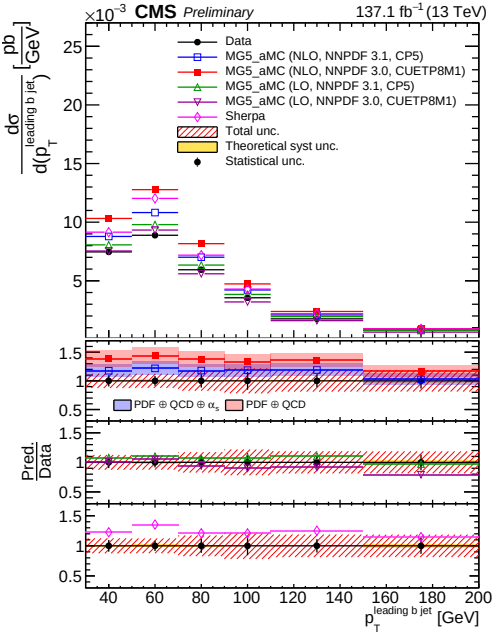

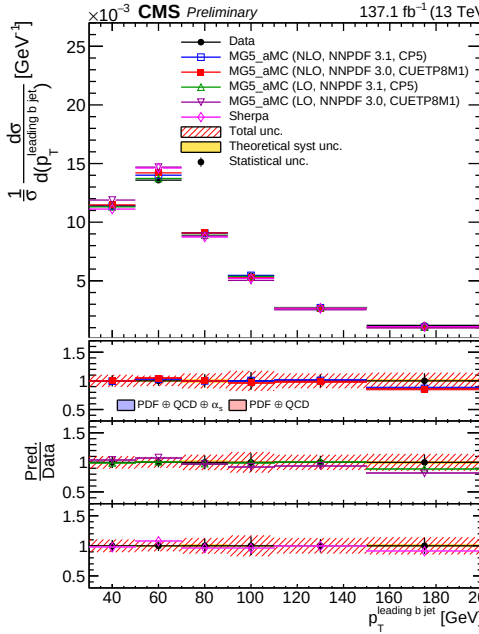

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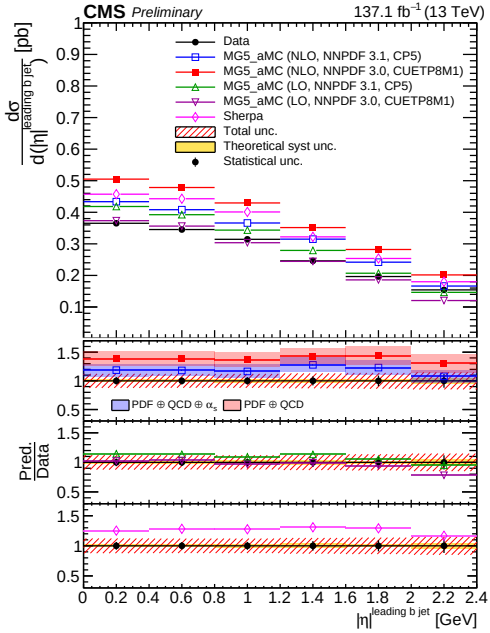

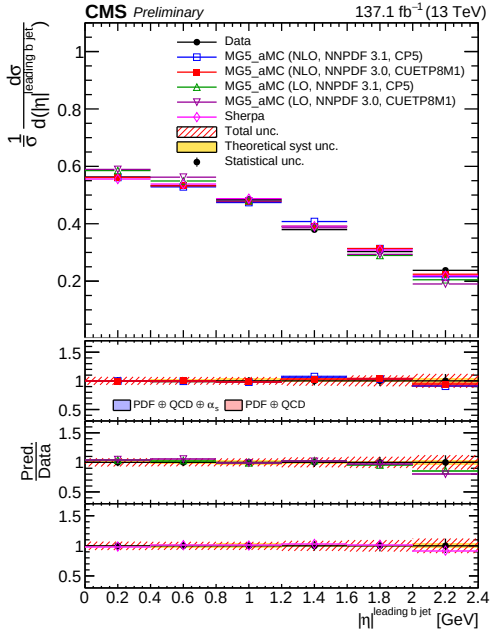

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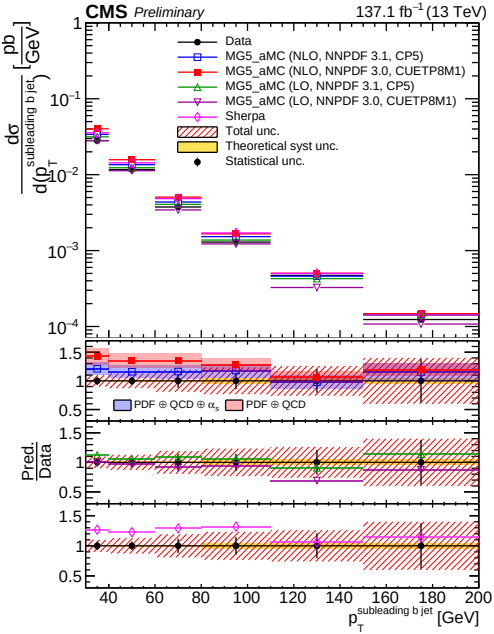

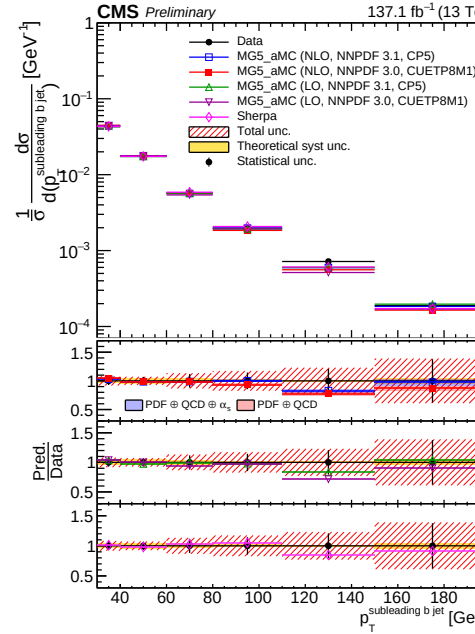

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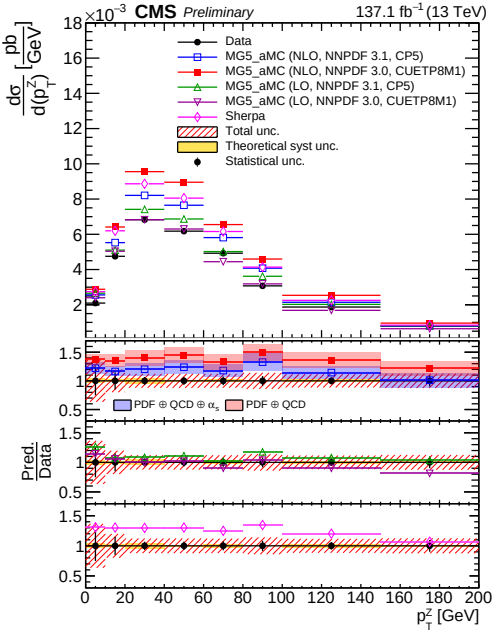

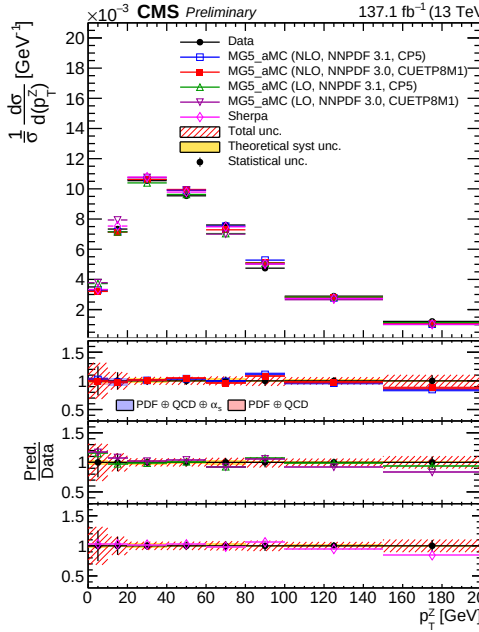

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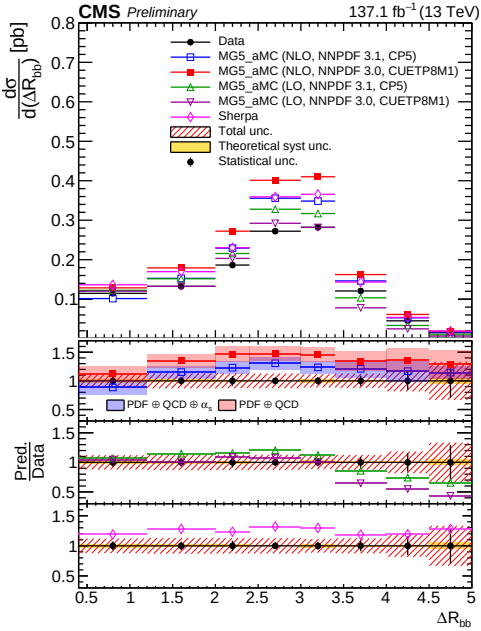

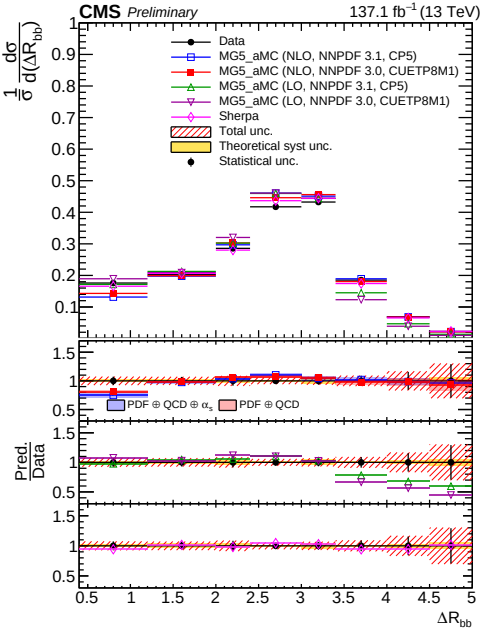

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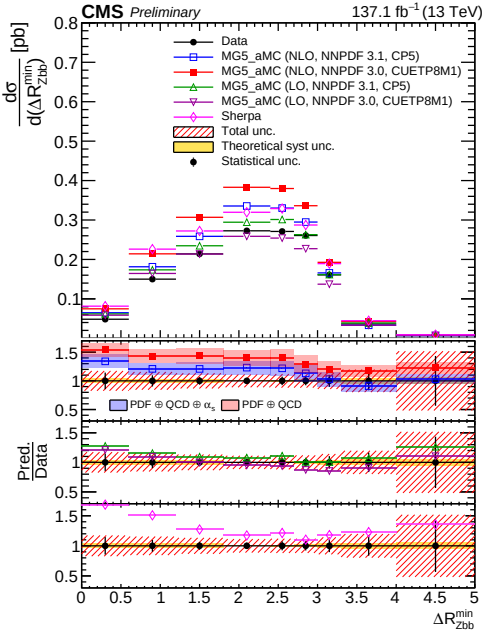

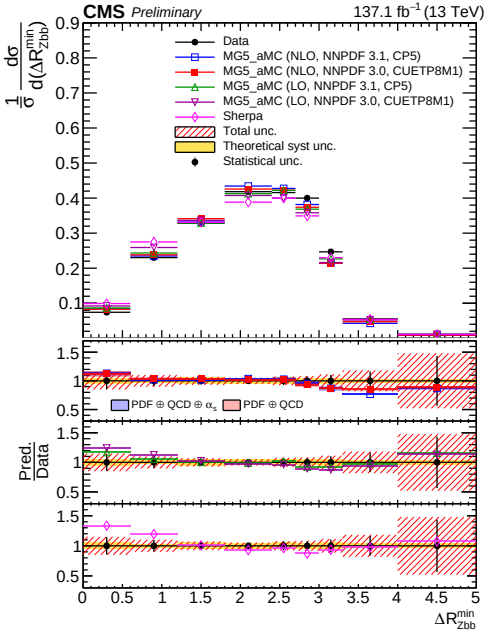

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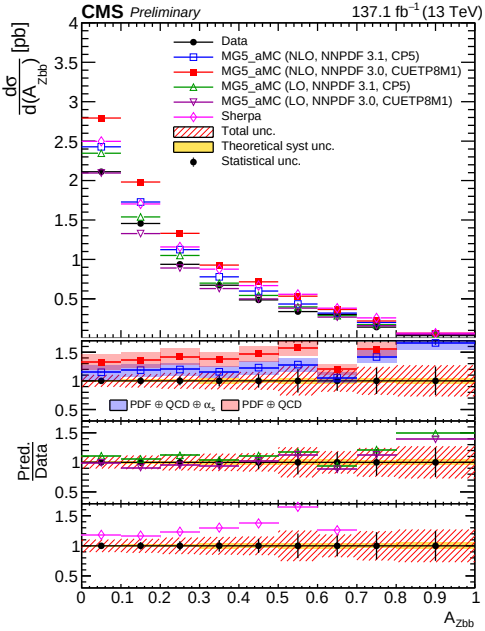

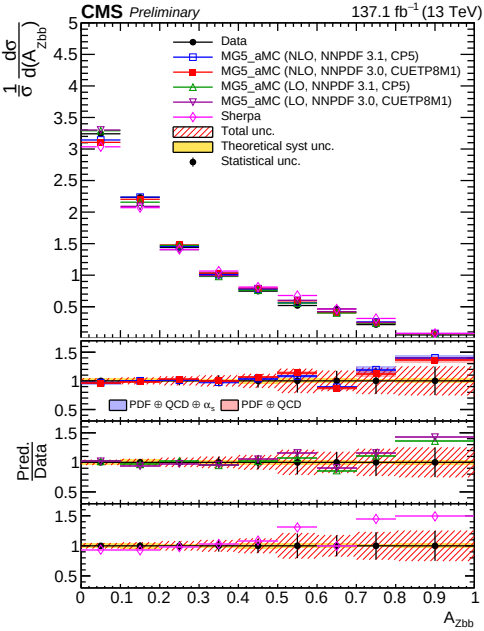

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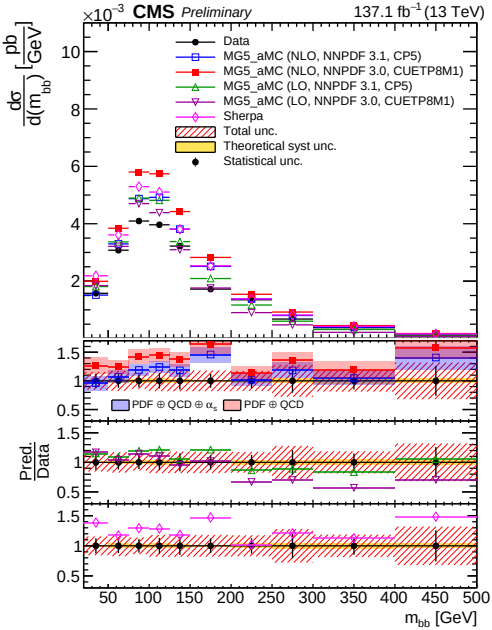
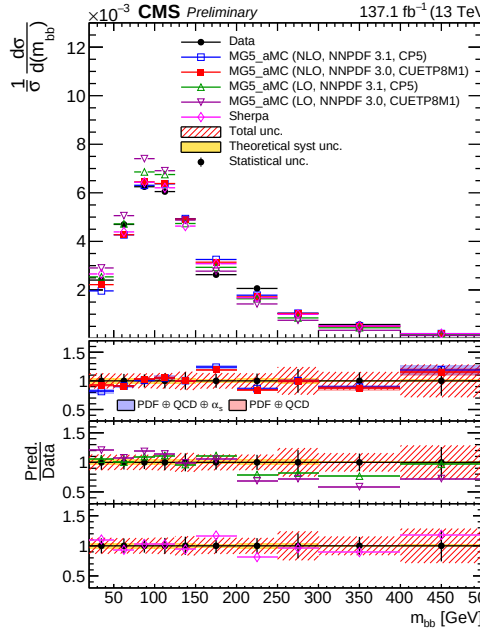
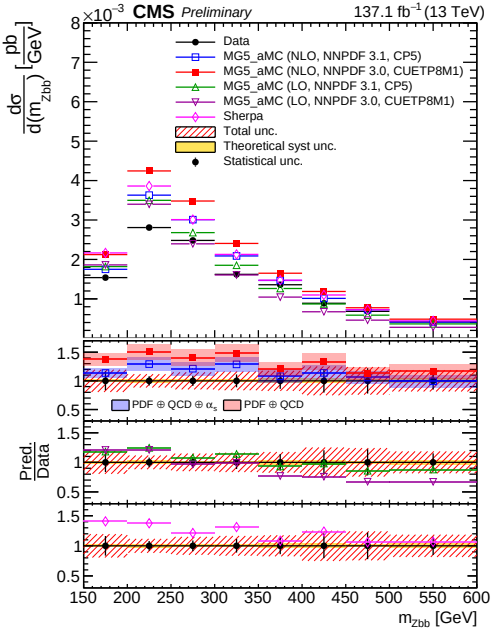
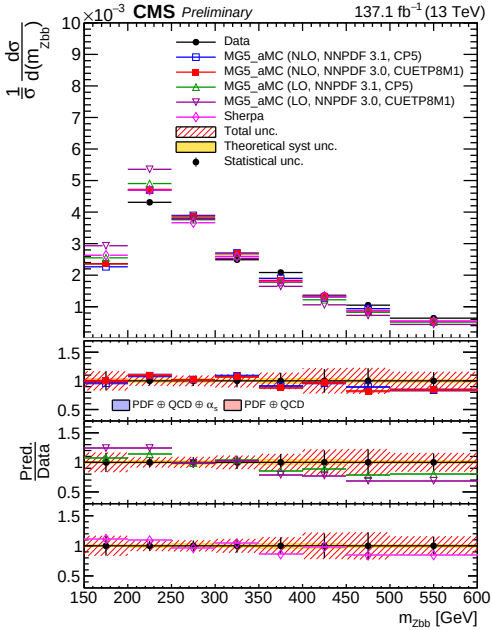




Inclusive jet at 5 TeV
Inclusive jet at 13 TeV
Multijet production
Z + jet
Decorrelations in Z + jet
$Z + b(b)$
VBS
TPS
Acronyms
References

$Z + b(b)$





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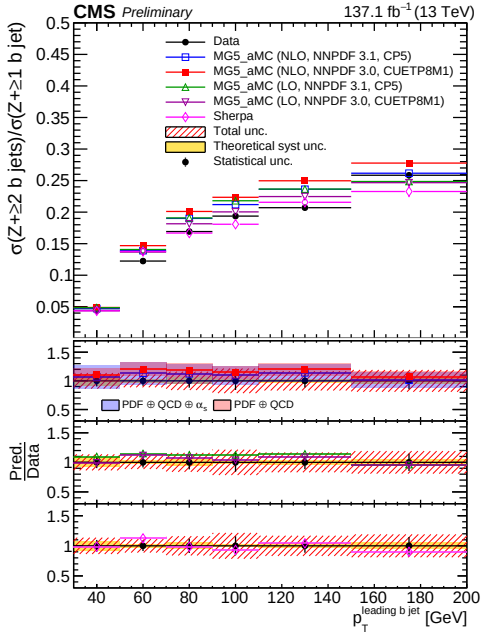

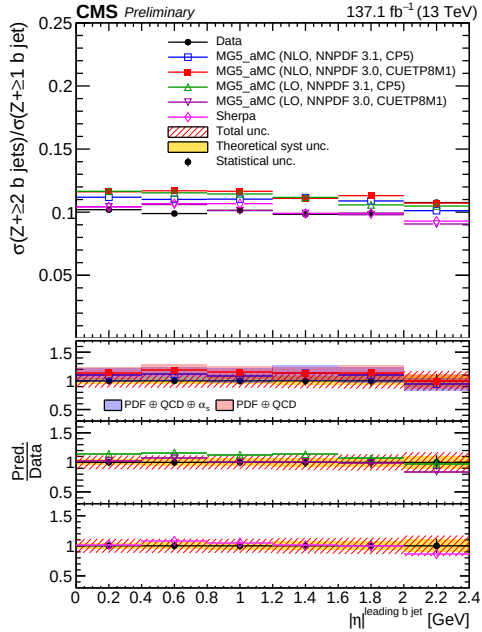

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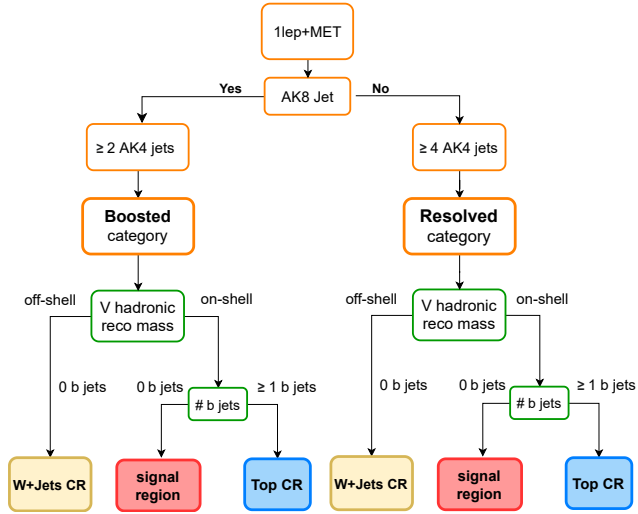

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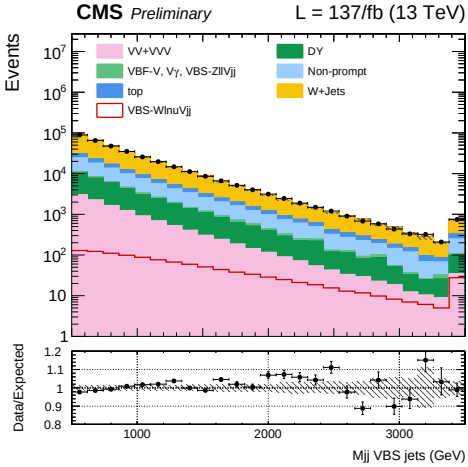

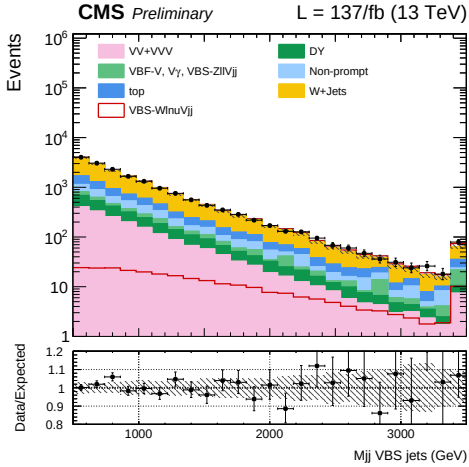

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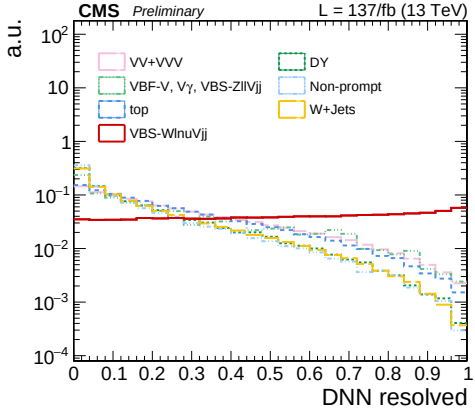

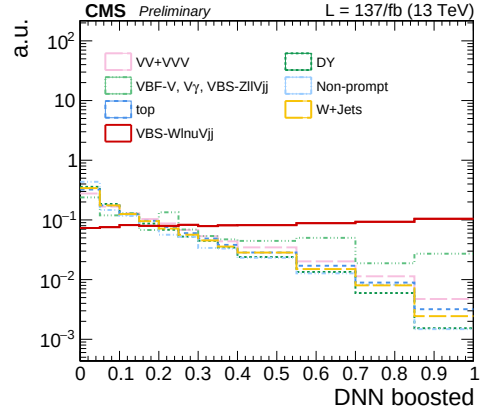

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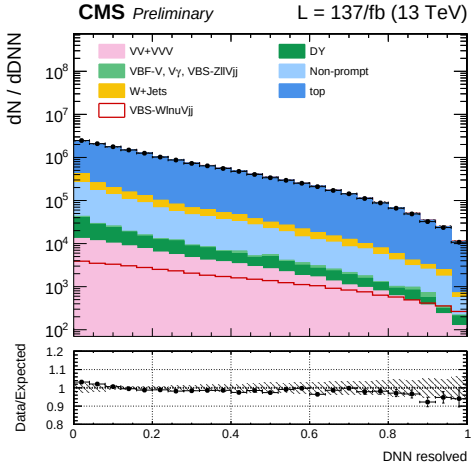

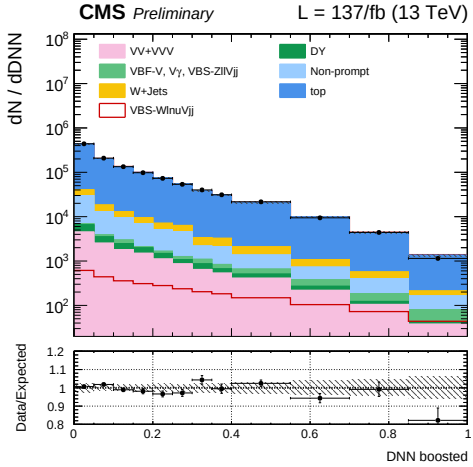

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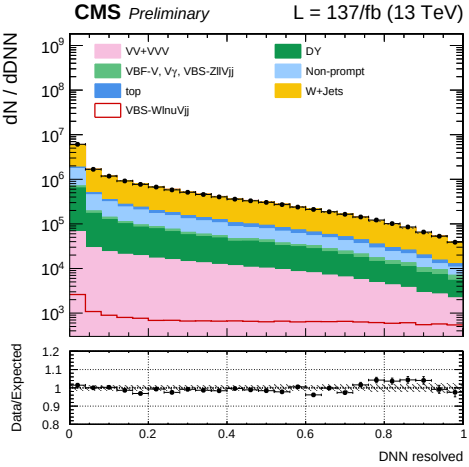

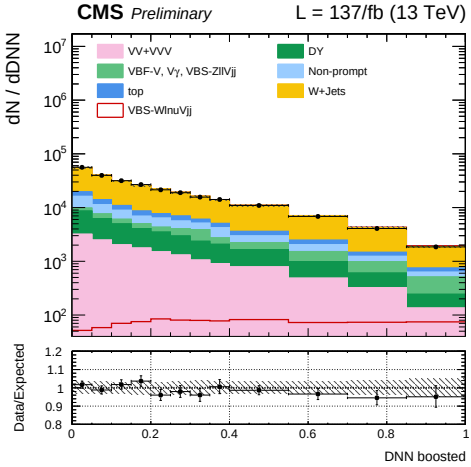

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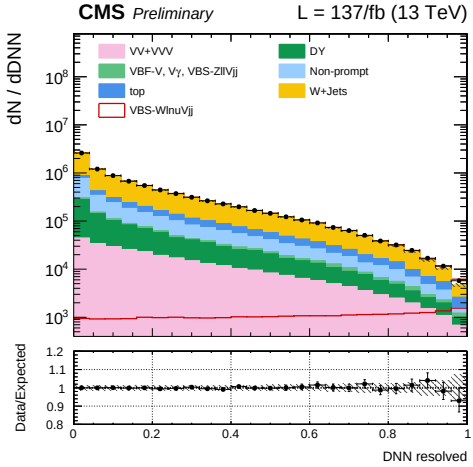

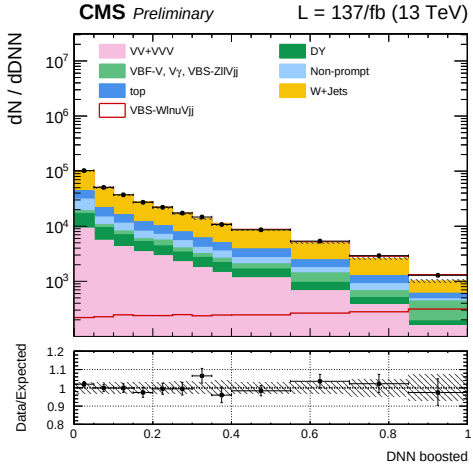

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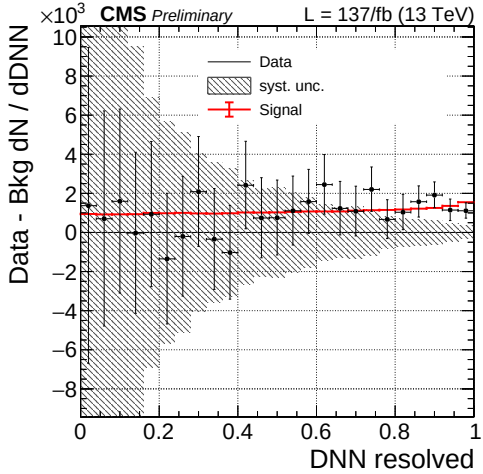

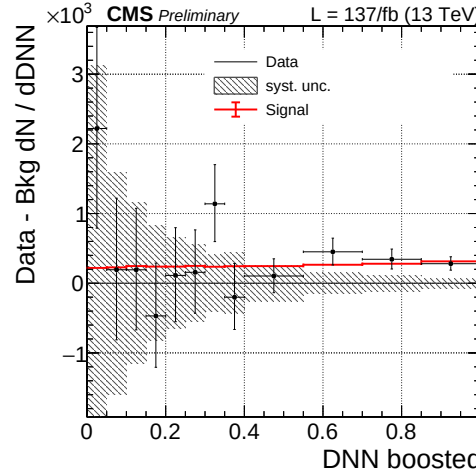

Inclusive jet at 5 TeV
Inclusive jet at 13 TeV
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Z + jet
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$Z + b(\bar{b})$
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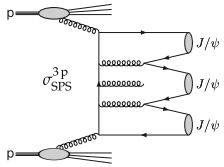
References

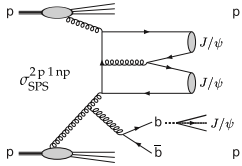
TPS

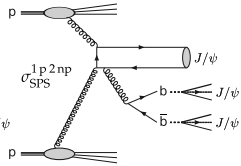
Pure prompt:

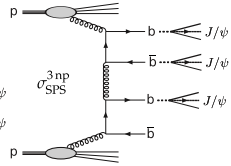
Nonprompt contributions:

SPS:









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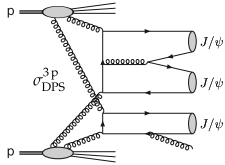

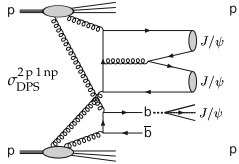

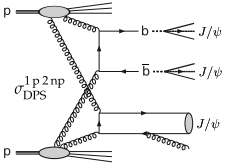

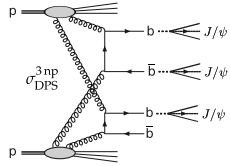

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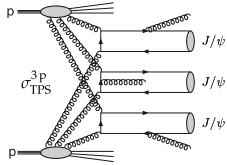
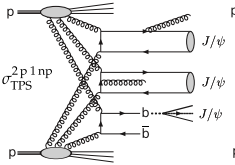
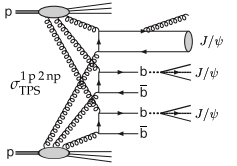
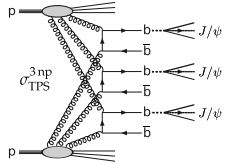








Acronyms I

AK4 anti k_T algorithm ($R = 0.4$). 45, 50, 51

AK7 anti k_T algorithm ($R = 0.7$). 50, 51

BSM searches Beyond the SM. 3, 4

c.m.s. centre-of-mass. 7

CI Contact Interaction. 3, 4, 40–43, 52

CMS Compact Muon Solenoid. 9–11, 40–43, 50–52, 61

DIS Deeply Inelastic Scattering. 9–11, 50, 51

DNN Dense Neural Network. 29–31

DPS Double-Parton Scattering. 3, 4, 32–35, 40–43

EFT Effective Field Theory. 3, 4

FO fixed order. 3, 4

HERA *Hadron-Elektron-RingAnlage*. 9–11, 50, 51

LEP Large Electron Positron Collider. 27, 28

LHC Large Hadron Collider. 40–43, 52

MC Monte Carlo. 3, 4

NLL Next to Leading Logarithm. 8

NLO Next to Leading Order. 3, 4, 7–11, 20, 21, 36–38, 61

NNLO Next to Next to Leading Order. 3, 4, 9–11, 36–38, 61

PB Parton Branching. 16, 17, 20, 21

PDF Parton Distribution Function. 3, 4, 8–11, 45, 50–52, 61–63

QCD Quantum Chromodynamics. 9–11, 36–38, 50, 51

SM Standard Model. 3, 4, 9–11, 29–31, 36–38, 40–43, 52, 63, 64

SMEFT Standard Model Effective Field Theory. 36–38, 52, 64

SPS Single-Parton Scattering. 32–35

TMD Transverse-Momentum-Dependent. 3, 4, 16, 17, 20, 21

TPS Triple-Parton Scattering. 32–35

VBS Vector Boson Scattering. 3, 4, 40–43

References I

John C. Collins, Davison E. Soper, and George F. Sterman. "Factorization of Hard Processes in QCD". In: **Adv. Ser. Direct. High Energy Phys.** 5 (1989), pp. 1–91. DOI: 10.1142/9789814503266_0001. arXiv: hep-ph/0409313 [hep-ph].

CMS Collaboration and Thomas Mc Cauley. "Displays of an event with two jets with transverse momentum of more than 3 TeV as seen in the CMS detector". CMS Collection. 2021. URL: https://cds.cern.ch/record/2775841.

Measurement and QCD analysis of double-differential inclusive jet cross sections in pp collisions at $\sqrt{s} = 13\text{TeV}$. Tech. rep. Geneva: CERN, 2021. URL: http://cds.cern.ch/record/2776732.

Measurement of the double-differential inclusive jet cross section in proton-proton collisions at $\sqrt{s} = 5.02\text{TeV}$. Tech. rep. Geneva: CERN, 2021.

J Currie, E. W. N. Glover, and J Pires. "Next-to-Next-to Leading Order QCD Predictions for Single Jet Inclusive Production at the LHC". In: **Phys. Rev. Lett.** 118 (2017), p. 072002. DOI: 10.1103/PhysRevLett.118.072002. arXiv: 1611.01460 [hep-ph].

James Currie et al. "Single Jet Inclusive Production for the Individual Jet p_{T} Scale Choice at the LHC". In: **Acta Phys. Polon. B** 48 (2017), p. 955. DOI: 10.5506/APhysPolB.48.955. arXiv: 1704.00923 [hep-ph].

References II

Thomas Gehrmann et al. "Jet cross sections and transverse momentum distributions with NNLOJET". In: **PoS** RADCOR2017 (2018). Ed. by Andre Hoang and Carsten Schneider, p. 074. DOI: 10.22323/1.290.0074. arXiv: 1801.06415 [hep-ph].

T. Carli et al. "A posteriori inclusion of parton density functions in NLO QCD final-state calculations at hadron colliders: The APPLGRID Project". In: **Eur. Phys. J. C** 66 (2010), p. 503. DOI: 10.1140/epjc/s10052-010-1255-0. arXiv: 0911.2985 [hep-ph].

T. Kluge, K. Rabbertz, and M. Wobisch. "FastNLO: Fast pQCD calculations for PDF fits". In: **Deep inelastic scattering. Proceedings, 14th International Workshop, DIS 2006, Tsukuba, Japan**. 2006, p. 483. DOI: 10.1142/9789812706706_0110. arXiv: hep-ph/0609285 [hep-ph].

M. Wobisch et al. "Theory-Data Comparisons for Jet Measurements in Hadron-Induced Processes". 2011.

Daniel Britzger et al. "New features in version 2 of the fastNLO project". In: **Proceedings, 20th International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2012): Bonn, Germany**. 2012, p. 217. DOI: 10.3204/DESY-PROC-2012-02/165. arXiv: 1208.3641 [hep-ph].

References III

H. Abramowicz et al. "Combination of measurements of inclusive deep inelastic $e^{\pm}p$ scattering cross sections and QCD analysis of HERA data". In: **Eur. Phys. J. C** 75 (2015), p. 580. DOI: 10.1140/epjc/s10052-015-3710-4. arXiv: 1506.06042 [hep-ex].

Sayipjamal Dulat et al. "New parton distribution functions from a global analysis of quantum chromodynamics". In: **Phys. Rev. D** 93 (2016), p. 033006. DOI: 10.1103/PhysRevD.93.033006. arXiv: 1506.07443 [hep-ph].

Richard D. Ball et al. "Parton distributions from high-precision collider data". In: **Eur. Phys. J. C** 77 (2017), p. 663. DOI: 10.1140/epjc/s10052-017-5199-5. arXiv: 1706.00428 [hep-ph].

L. A. Harland-Lang et al. "Parton distributions in the LHC era: MMHT 2014 PDFs". In: **Eur. Phys. J. C** 75 (2015), p. 204. DOI: 10.1140/epjc/s10052-015-3397-6. arXiv: 1412.3989 [hep-ph].

S. Alekhin et al. "Parton distribution functions, α_s, and heavy-quark masses for LHC Run II". In: **Phys. Rev. D** 96 (2017), p. 014011. DOI: 10.1103/PhysRevD.96.014011. arXiv: 1701.05838 [hep-ph].

V. Bertone et al. "xFitter 2.0.0: An Open Source QCD Fit Framework". In: **PoS** DIS2017 (2018), p. 203. DOI: 10.22323/1.297.0203. arXiv: 1709.01151 [hep-ph].

References IV

S. Alekhin et al. "HERAFitter, open source QCD fit project". In: **Eur. Phys. J. C** 75 (2015), p. 304. DOI: 10.1140/epjc/s10052-015-3480-z. arXiv: 1410.4412 [hep-ph].

Albert M Sirunyan et al. "Measurement of $\mathrm{t\bar{t}}$ normalised multi-differential cross sections in pp collisions at $\sqrt{s} = 13$ TeV, and simultaneous determination of the strong coupling strength, top quark pole mass, and parton distribution functions". In: **Eur. Phys. J. C** 80 (2020), p. 658. DOI: 10.1140/epjc/s10052-020-7917-7. arXiv: 1904.05237 [hep-ex].

Measurement of multi-differential cross sections for the production of a Z boson in association with jets in proton-proton collisions at $\sqrt{s} = 13$ TeV. Tech. rep. Geneva: CERN, 2021. URL: https://cds.cern.ch/record/2767703.

J. Alwall et al. "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations". In: **JHEP** 07 (2014), p. 079. DOI: 10.1007/JHEP07(2014)079. arXiv: 1405.0301 [hep-ph].

Albert M Sirunyan et al. "Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements". In: **Eur. Phys. J. C** 80 (2020), p. 4. DOI: 10.1140/epjc/s10052-019-7499-4. arXiv: 1903.12179 [hep-ex].

References V

Simone Alioli et al. "Combining higher-order resummation with multiple NLO calculations and parton showers in GENEVA". In: **Journal of High Energy Physics** 2013.9 (Sept. 2013). ISSN: 1029-8479. DOI: 10.1007/jhep09(2013)120. URL: http://dx.doi.org/10.1007/JHEP09(2013)120.

Simone Alioli et al. "Drell-Yan production atNNLL +NNLOmatched to parton showers". In: **Physical Review D** 92.9 (Nov. 2015). ISSN: 1550-2368. DOI: 10.1103/physrevd.92.094020. URL: http://dx.doi.org/10.1103/PhysRevD.92.094020.

Azimuthal correlations in Z+jets events at 13 TeV. Tech. rep. Geneva: CERN, 2021. URL: https://cds.cern.ch/record/2777194.

A Bermudez Martinez et al. "Collinear and TMD parton densities from fits to precision DIS measurements in the parton branching method". In: **Physical Review D** 99.7 (2019), p. 074008.

S. Baranov et al. "CASCADE3 A Monte Carlo event generator based on TMDs". In: **Eur. Phys. J. C** 81 (2021), p. 425. DOI: 10.1140/epjc/s10052-021-09203-8. arXiv: 2101.10221 [hep-ph].

References VI

Cross section measurements of jet multiplicity and jet transverse momenta in multijet events at $\sqrt{s} = 13$ TeV. Tech. rep. Geneva: CERN, 2021. URL: https://cds.cern.ch/record/2776772.

Measurement of Z+b jets cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV. Tech. rep. Geneva: CERN, 2021.

Precision measurement of the Z invisible width with the CMS experiment in pp collisions at $\sqrt{s} = 13$ TeV. Tech. rep. Geneva: CERN, 2021. URL: https://cds.cern.ch/record/2775364.

Search for vector boson scattering at the LHC Run 2 with CMS data in the semi-leptonic $l\nu qq$ final state. Tech. rep. Geneva: CERN, 2021. URL: https://cds.cern.ch/record/2776799.

Observation of triple J/ψ meson production in proton-proton collisions at $\sqrt{s} = 13$ TeV. Tech. rep. Geneva: CERN, 2021. URL: https://cds.cern.ch/record/2776769.

W.J. Stirling. **Private communication**. http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html. 2012.

References VII

Georges Aad et al. "Measurement of the inclusive jet cross section in pp collisions at $\sqrt{s} = 2.76$ TeV and comparison to the inclusive jet cross section at $\sqrt{s} = 7$ TeV using the ATLAS detector". In: **Eur. Phys. J. C** 73 (2013), p. 2509. DOI: 10.1140/epjc/s10052-013-2509-4. arXiv: 1304.4739 [hep-ex].

Vardan Khachatryan et al. "Measurement of the inclusive jet cross section in pp collisions at $\sqrt{s} = 2.76$ TeV". In: **Eur. Phys. J. C** 76 (2016), p. 265. DOI: 10.1140/epjc/s10052-016-4083-z. arXiv: 1512.06212 [hep-ex].

Georges Aad et al. "Measurement of the inclusive jet cross-section in proton-proton collisions at $\sqrt{s} = 7$ TeV using 4.5 fb^{-1} of data with the ATLAS detector". In: **JHEP** 02 (2015). [Erratum: JHEP09,141(2015)], p. 153. DOI: 10.1007/JHEP02(2015)153. arXiv: 1410.8857 [hep-ex].

Serguei Chatrchyan et al. "Measurements of Differential Jet Cross Sections in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the CMS Detector". In: **Phys. Rev. D** 87 (2013). [Erratum: JHEP09,141(2015)], p. 112002. DOI: 10.1103/PhysRevD.87.112002. arXiv: 1212.6660 [hep-ex].

References VIII

Serguei Chatrchyan et al. "Measurement of the Ratio of Inclusive Jet Cross Sections using the Anti-k_T Algorithm with Radius Parameters $R = 0.5$ and 0.7 in pp Collisions at $\sqrt{s} = 7$ TeV". In: **Phys. Rev. D** 90 (2014), p. 072006. DOI: 10.1103/PhysRevD.90.072006. arXiv: 1406.0324 [hep-ex].

Morad Aaboud et al. "Measurement of the inclusive jet cross-sections in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector". In: **JHEP** 09 (2017), p. 020. DOI: 10.1007/JHEP09(2017)020. arXiv: 1706.03192 [hep-ex].

Vardan Khachatryan et al. "Measurement and QCD analysis of double-differential inclusive jet cross sections in pp collisions at $\sqrt{s} = 8$ TeV and cross section ratios to 2.76 and 7 TeV". In: **JHEP** 03 (2017), p. 156. DOI: 10.1007/JHEP03(2017)156. arXiv: 1609.05331 [hep-ex].

M. Aaboud et al. "Measurement of inclusive jet and dijet cross-sections in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector". In: **JHEP** 05 (2018), p. 195. DOI: 10.1007/JHEP05(2018)195. arXiv: 1711.02692 [hep-ex].

Vardan Khachatryan et al. "Measurement of the double-differential inclusive jet cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV". In: **Eur. Phys. J. C** 76 (2016), p. 451. DOI: 10.1140/epjc/s10052-016-4286-3. arXiv: 1605.04436 [hep-ex].

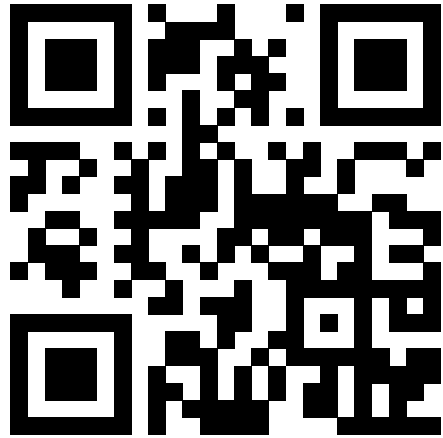
References IX

Serguei Chatrchyan et al. "Search for Contact Interactions Using the Inclusive Jet p_T Spectrum in pp Collisions at $\sqrt{s} = 7$ TeV". In: **Phys. Rev. D** 87 (2013), p. 052017. DOI: 10.1103/PhysRevD.87.052017. arXiv: 1301.5023 [hep-ex].

Serguei Chatrchyan et al. "Search for quark compositeness in dijet angular distributions from pp collisions at $\sqrt{s} = 7$ TeV". In: **JHEP** 05 (2012), p. 055. DOI: 10.1007/JHEP05(2012)055. arXiv: 1202.5535.

Inclusive jet at 5 TeV
Inclusive jet at 13 TeV
Multijet production
Z + jet
Decorrelations in Z + jet
$Z + b(b)$
VBS
TPS
Acronyms
References

Patrick L.S. Connor
Universität Hamburg
https://www.desy.de/~connorpa

MIN-Fakultät
Institut für Experimentalphysik
Tel.: +49 40 8998-2617
Geb.: DESY Campus 68/121

Center for Data Computing and natural Sciences
Tel.: +49 42838-6109
Geb.: Notkestraße 9