Vector Boson Production in association with jets in CMS

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On behalf of the CMS Collaboration

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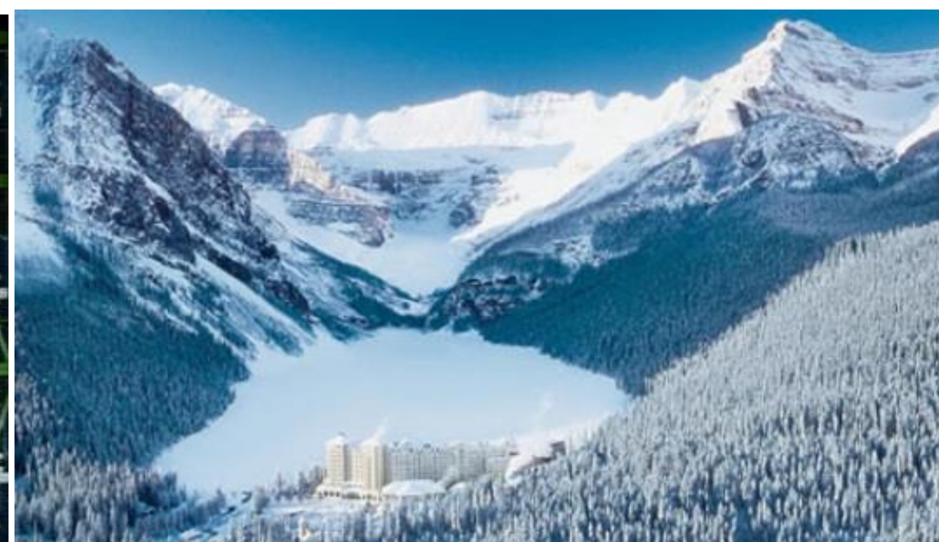
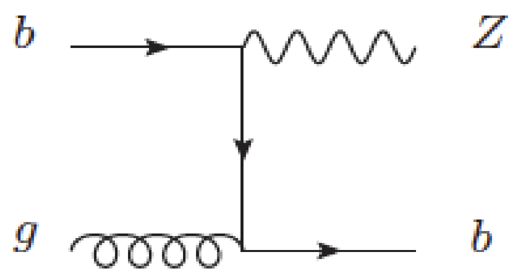


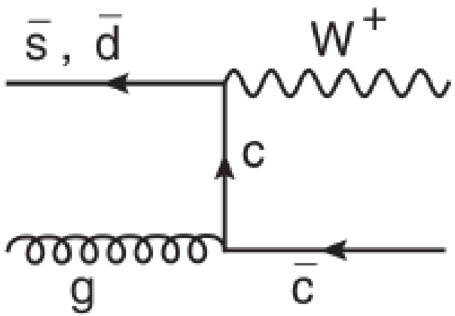
Outline

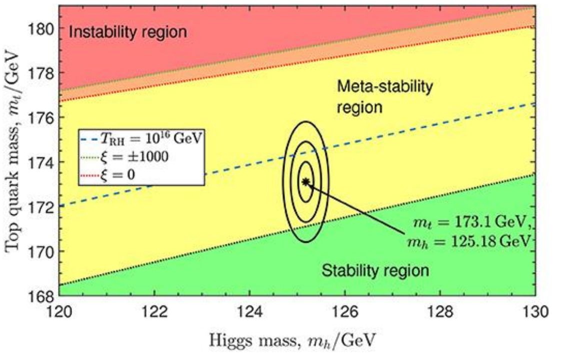
- Introduction and motivation
  - Precision verification of pQCD and impact on new physics searches
- Measurements involving heavy flavor
  - W + c differential cross-section
  - Z + c differential cross-section
  - Z + b differential cross-section
  - Z + HF differential cross-section
- Summary

Motivation for V+jets

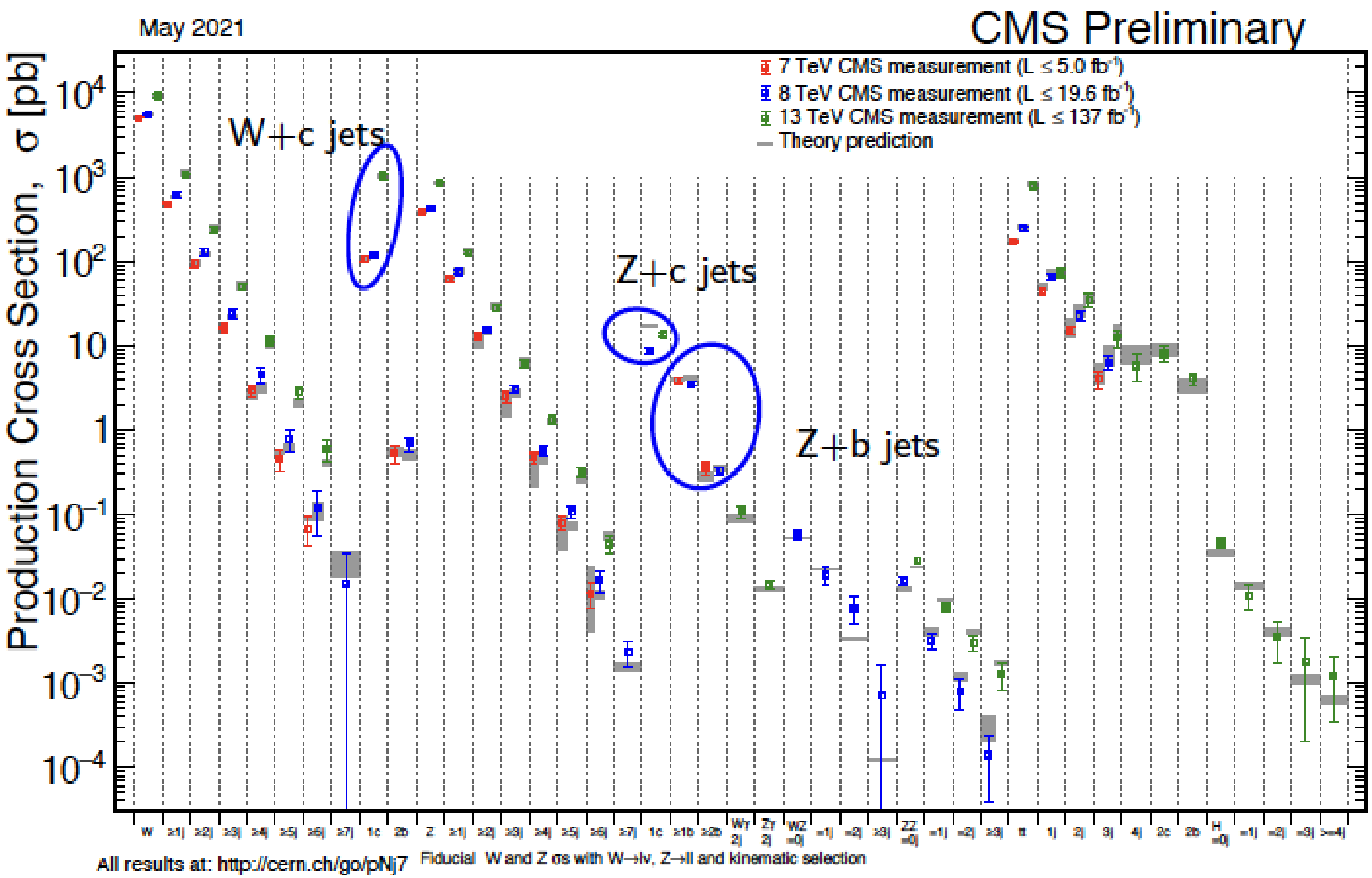
- High precision verification of the pQCD predictions
  - Higher order calculations N(N)LO
  - Matching schemas
  - PDFs (including heavy flavor content)
- A key ingredient in other critical high precision SM measurements:
  - E.g. W mass and top mass that are critical SM tests (self-consistency, limits of applicability and potential new physics scales, vacuum stability etc.)
- An important (and difficult) background for new physics searches in the Higgs sector:
  - W/Z+H, Non-SM Higgs, new heavy quarks etc.







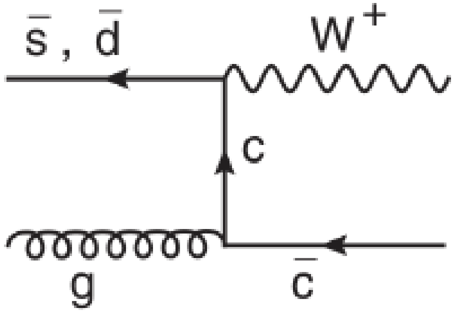
The Overall Landscape



- Overall good agreement of the data with SM predictions
  - Latest addition is the Z+b measurement for 13 TeV

W+c Differential Cross Section

- W+c cross sections are measured in the muon channel
- Charm identified via reconstruction of the c hadrons:
  - $c \to D^{*\pm} \to D^0 + \pi^{\pm}_{slow} \to K^{\mp}\pi^{\pm}\pi^{\pm}_{slow}$



- W+c signal:
  - c quark with $p_T > 5$ GeV in the final state
  - W boson and the charm quark have opposite signs (OS)
  - Require odd number of c quarks (3, 5, ...) the one with OS and the highest p_T is chosen
- Backgrounds
  - $W + c\bar{c}$: a large background from gluon splitting $g \to c\bar{c}$
  - Yields both SS and OS pairs (wrt lepton from W), which allows estimating and subtracting

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W + c Differential Cross Section

W+c: $W(\rightarrow \mu\bar{\nu}) + D^{*}(2010)^{\pm} \rightarrow \mu\nu + D^0 + \pi^{\pm}_{slow} \rightarrow \mu\bar{\nu} + K^{\mp}\pi^{\pm}\pi^{\pm}_{slow}$

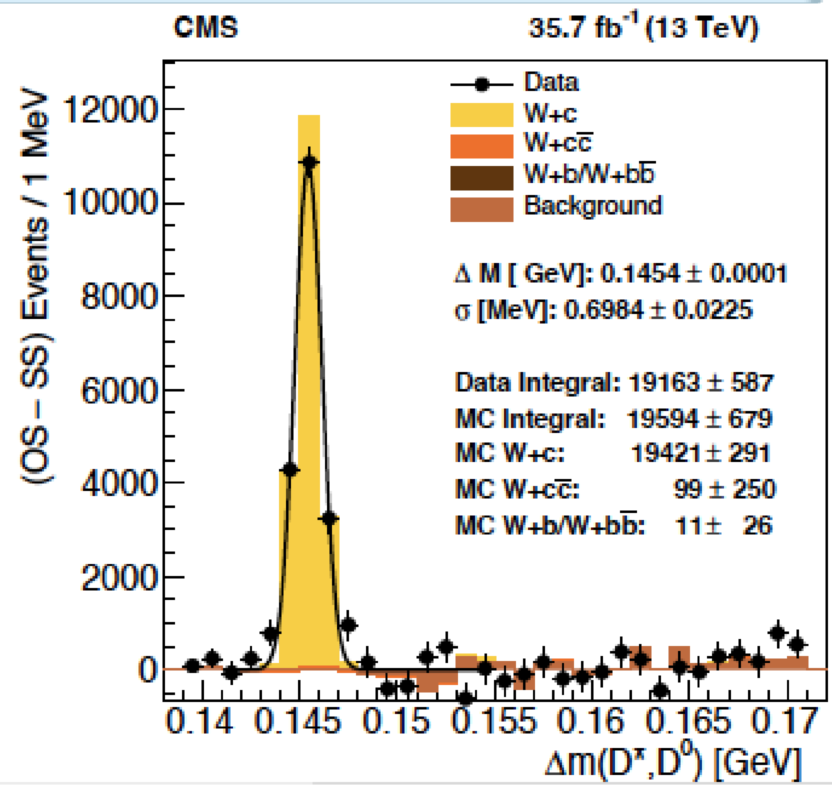
Muon(μ): $p_T > 26$ GeV, $|\eta| < 2.4$

Transverse mass (M_T): ≥ 50 GeV, $[M_T := \sqrt{2.p_T^{\mu}.E_T^{miss}.(1 - cos(\phi_\mu - \phi_{E_T^{miss}}))}]$

D^0: $p_T^{K,\pi} > 1$ GeV, $|K^{\mp}+\pi^{\pm}$- $D^0_{pdg}| < 35$ MeV, $K^{\mp}+\pi^{\pm}$ must originate from Secondary vertex,

$D^{*\pm}$: $p_T^{\pi slow} > 0.35$ GeV, $\Delta R(D^0, \pi_{slow}) < 0.15$, $p_T^{D*\pm}/\Sigma p_T > 0.2$ $p_T^{D*\pm} > 5$ GeV

- A very clean signature from the $D^{*\pm} \rightarrow D^0$ mass difference
  - Good agreement with the MC predictions



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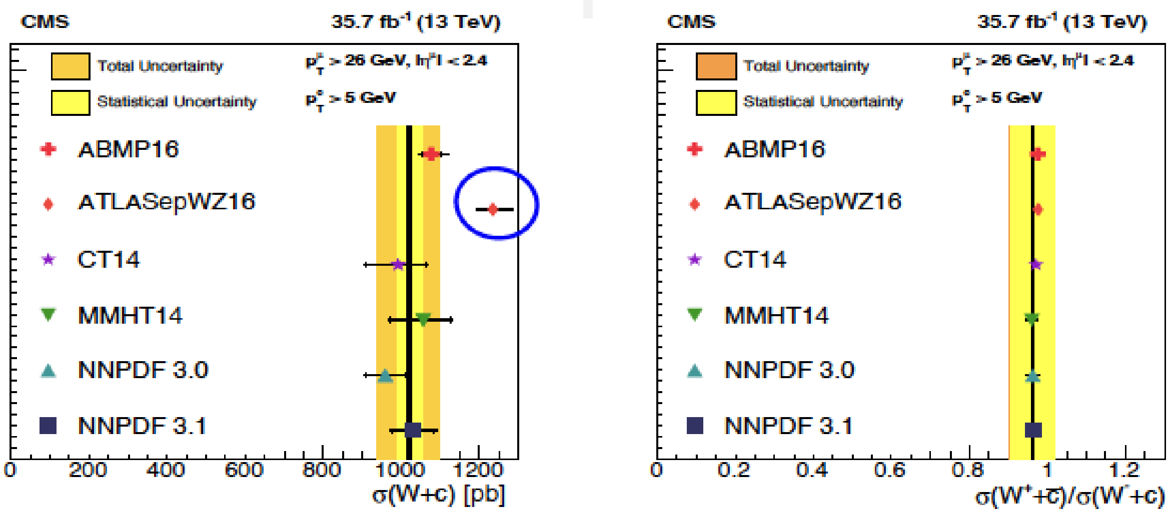
W + c Differential Cross Section

- Compare data measurements to MCFM 6.8 NLO QCD calculation for several PDF sets (NLO):



	$\sigma(\mathrm{W+c})$	$\sigma(\mathrm{W^+ + \bar{c}})/\ \sigma(\mathrm{W^- + c})$
Measured	$1026 \pm 31\ (\mathrm{stat})^{+76}_{-72}\ (\mathrm{syst})$	$0.968 \pm 0.055\ (\mathrm{stat})^{+0.015}_{-0.028}\ (\mathrm{syst})$.
ABMP16nlo	1077.9 pb $\pm\ 2.1\%(\mathrm{pdf})^{+3.4\%}_{-2.4\%}(\mathrm{scale})$	$0.975^{+0.002}_{-0.002}$
ATLASepWZ16nnlo	1235.1 pb $^{+1.4\%}_{-1.6\%}(\mathrm{pdf})^{+3.7\%}_{-2.8\%}(\mathrm{scale})$	$0.976^{+0.001}_{-0.001}$
CT14nlo	992.6 pb $\pm\ ^{+7.2\%}_{-8.4\%}(\mathrm{pdf})^{+3.1\%}_{-2.1\%}(\mathrm{scale})$	$0.970^{+0.005}_{-0.007}$
MMHT14nlo	1057.1 pb $\pm\ ^{+6.5\%}_{-8.0\%}(\mathrm{pdf})^{+3.2\%}_{-2.2\%}(\mathrm{scale})$	$0.960^{+0.023}_{-0.033}$
NNPDF3.0nlo	959.5 pb $\pm\ 5.4\%(\mathrm{pdf})^{+2.8\%}_{-1.9\%}(\mathrm{scale})$	$0.962^{+0.034}_{-0.034}$
NNPDF3.1nlo	1030.2 pb $\pm\ 5.3\%(\mathrm{pdf})^{+3.2\%}_{-2.2\%}(\mathrm{scale})$	$0.965^{+0.043}_{-0.043}$

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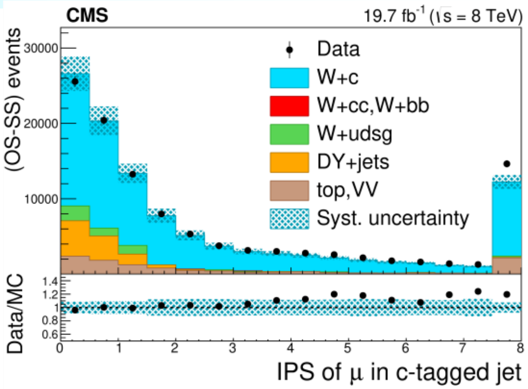
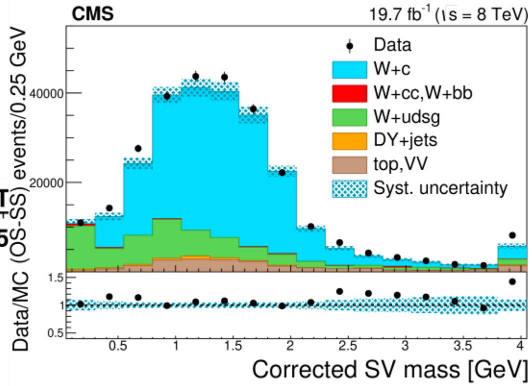
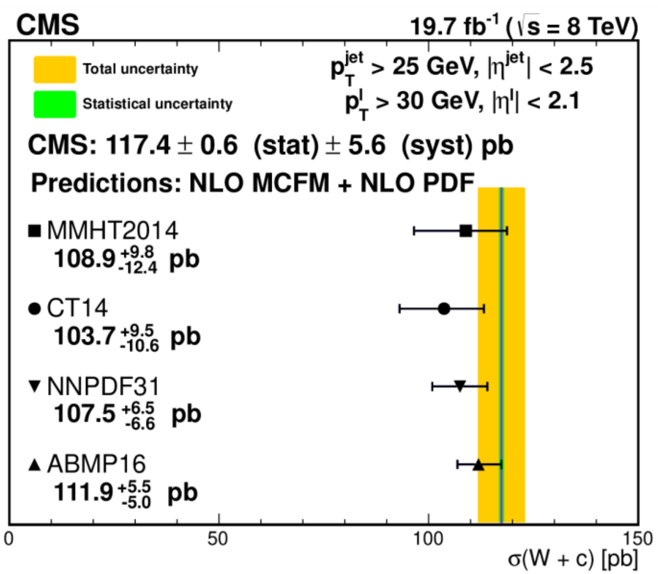
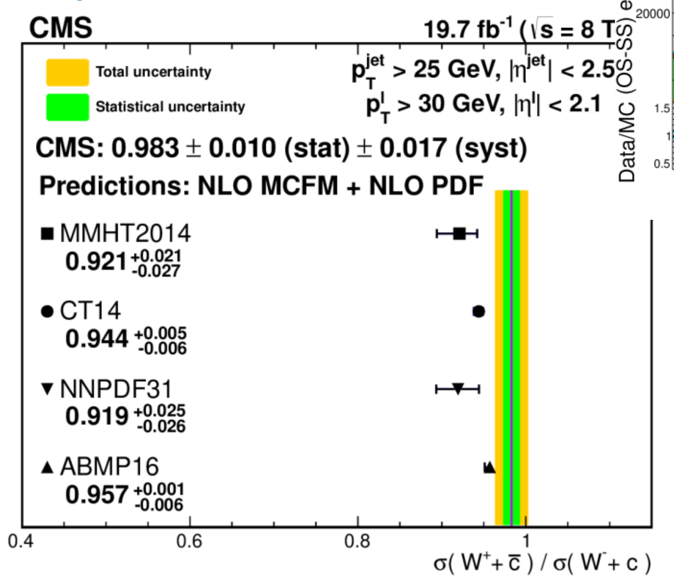
W+c Measurement at 8 TeV

- Analysis combines data selected via:
  - A muon from a SL charm hadron decay w/ substantial impact parameter
  - A secondary vertex arising from a visible charm hadron
- Yields a very large sample
  - Reduced statistical/ systematic errors







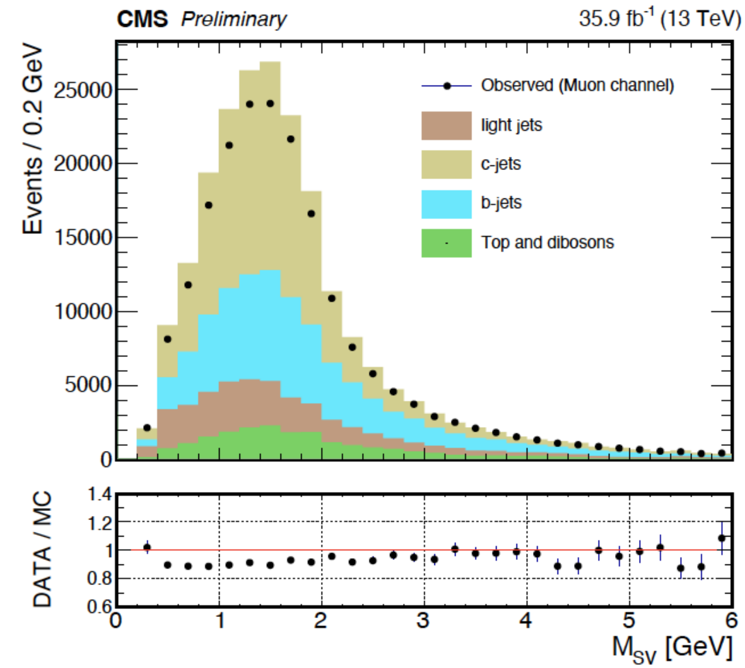


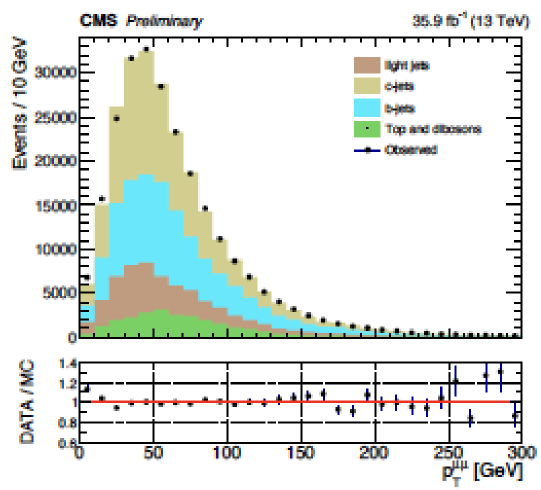
NNLO corrections expected to bring the predictions closer to data

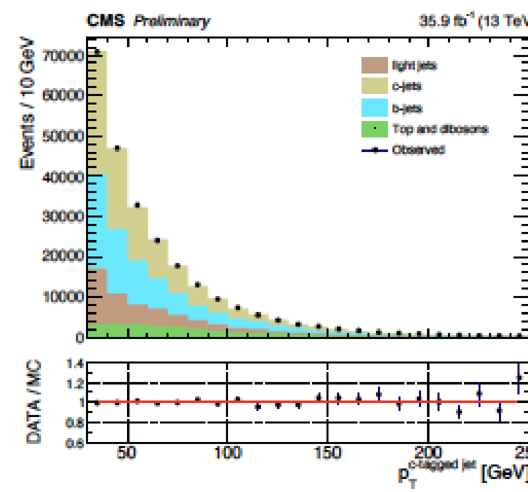
CMS-SMP-18-013

Z + ≥1c Jet Cross Section

- Event Selection:
  - *ll*= ee or μμ, $p_T(\mu)$>26(10) GeV, $p_T(e)$>29(10) GeV
- Z(ll): 71 < M_{ll} < 111 GeV, |η(ll)| < 2.4
- Particle-level jets: p_T > 30 GeV, |η(jet)| < 2.4
  - pileup jet id (tag and remove)
  - c-tag (using DeepCSV: eff~30%, mistag rate for light jets ~1.2%, for b's – 20%)
- Using MSV to differentiate between signal and background
  - Plot on the right (note the scale factors for MS not yet applied!)
- Diboson, tt-bar, W+jets are small and taken from MC
  - With appropriate scale factors







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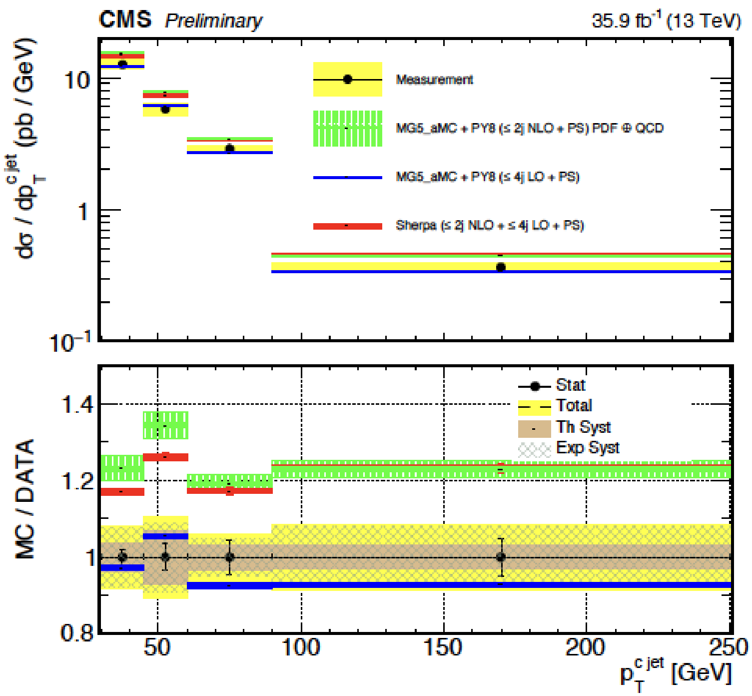
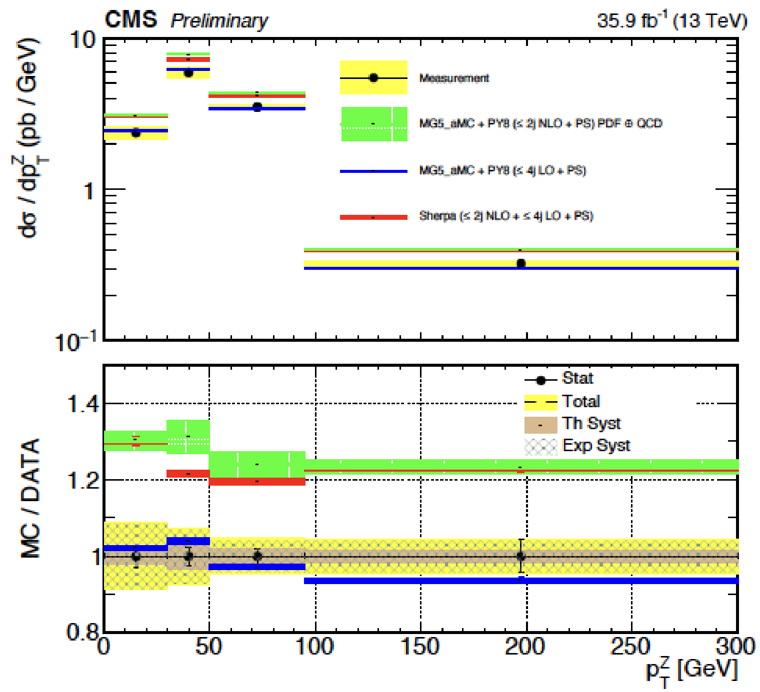
Z + ≥1c Jet Cross Section



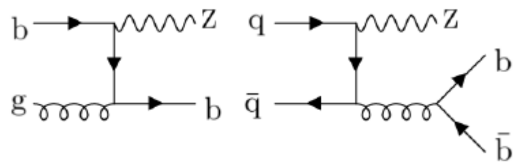


- Integral cross section Z(ll) + c jet
  - σ (p_T(j)<300 GeV)=413.5±5.6(stat)±24.3(exp)±3.7(th) pb
  - c.f. MG5_aMC(NLO)=524.9±11.7(th) pb, SHERPA (NLO)=485pb
- MG5 aMC(LO) describes differential cross section vs p_T(ll) and p_T(j) reasonably well (within 10%), but both MG5_aMC &SHERPA at NLO tend to deviate up to 20-30%.
- Indication that NLO PDFs overestimate c-content in proton

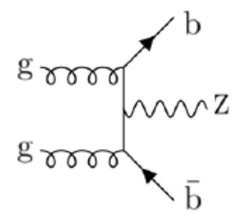
CMS-SMP-19-011

Z + ≥1b and Z + ≥2b Jets

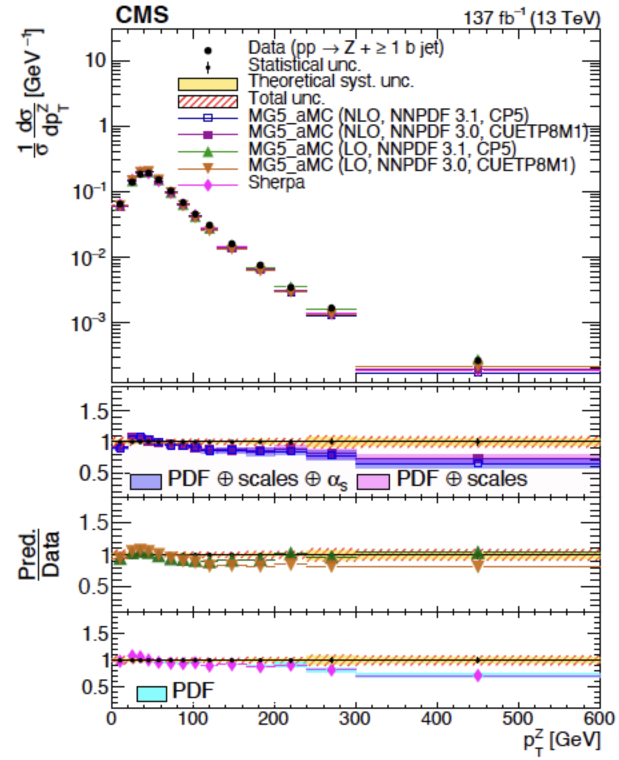
- Only small variations in selections from the Z+c analysis
  - $p_T(l) > 35(25)$ GeV
  - $+ p_T^{miss} < 50$ GeV



- Measurements:
  - Integral cross-sections for Z+≥ 1b and Z+≥2b jets and their ratio



- Extensive comparisons of cross-sections and shapes with various MC+PDF calculations:
  - $p_T(Z)$, $p_T(b_{1/2})$, $\eta(b_{1,2})$, ΔY_{Zb}, $\Delta\phi_{Zb}$, ΔR_{Zb}, ΔR_{Zbb}, A_{Zbb}

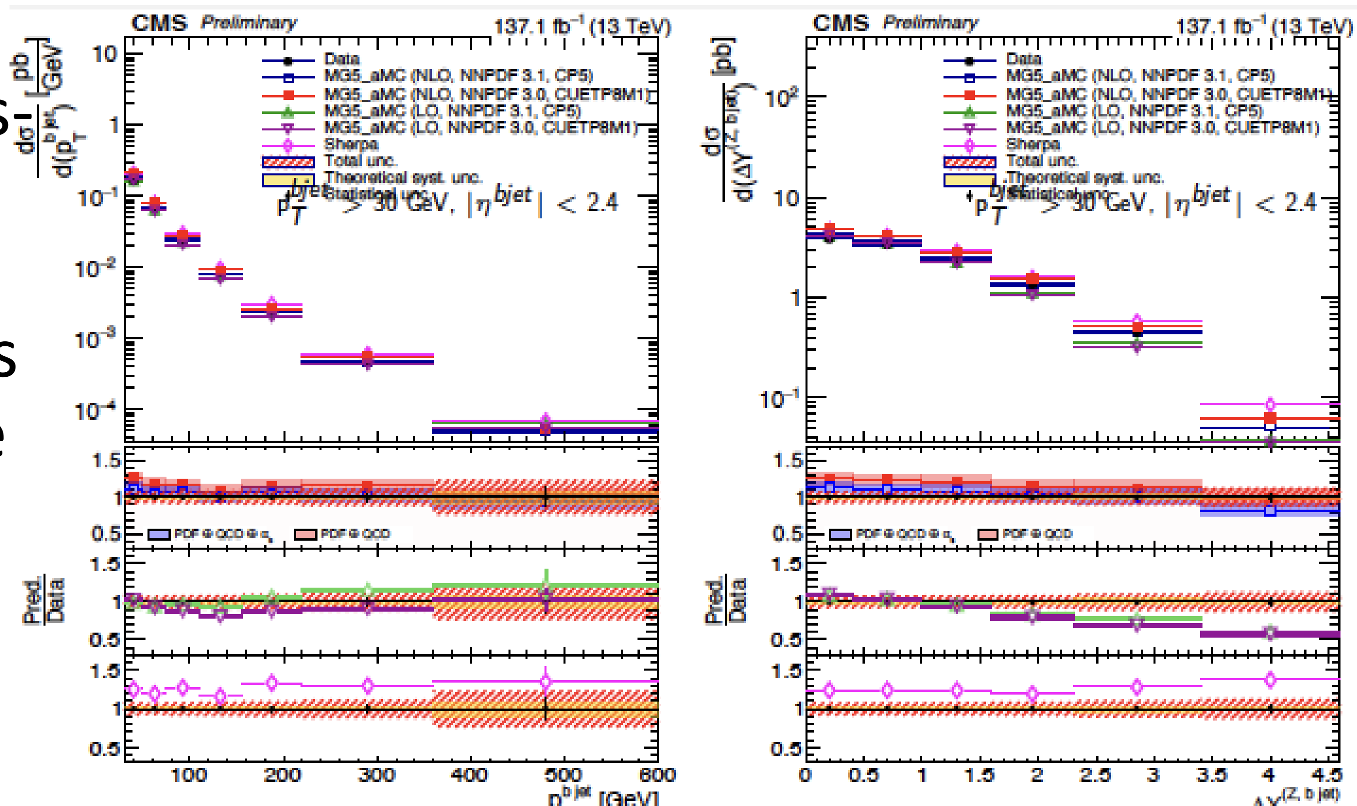


Channel		Measured	MG5_aMC LO NNPDF 3.0 CUETP8M1	MG5_aMC LO NNPDF 3.1 CP5	MG5_aMC NLO NNPDF 3.0 CUETP8M1	MG5_aMC NLO NNPDF 3.1 CP5	SHERPA
$Z + \geq 1$ b jet	ee	$6.45 \pm 0.06 \pm 0.49 \pm 0.17$	6.25	6.33	7.86 ± 0.52	7.05 ± 0.48	8.05
	$\mu\mu$	$6.55 \pm 0.05 \pm 0.39 \pm 0.19$	6.26	6.34	7.86 ± 0.51	7.02 ± 0.47	7.98
	$\ell\ell$	$6.52 \pm 0.04 \pm 0.40 \pm 0.14$	6.25	6.34	7.86 ± 0.51	7.03 ± 0.47	8.02
$Z + \geq 2$ b jets	ee	$0.66 \pm 0.05 \pm 0.07 \pm 0.02$	0.62	0.72	0.89 ± 0.08	0.77 ± 0.07	0.84
	$\mu\mu$	$0.65 \pm 0.04 \pm 0.06 \pm 0.02$	0.64	0.71	0.91 ± 0.09	0.77 ± 0.07	0.84
	$\ell\ell$	$0.65 \pm 0.03 \pm 0.07 \pm 0.02$	0.63	0.71	0.90 ± 0.09	0.77 ± 0.07	0.84
Ratio	ee	$0.102 \pm 0.008 \pm 0.008 \pm 0.004$	0.100	0.113	0.113 ± 0.016	0.110 ± 0.013	0.104
	$\mu\mu$	$0.100 \pm 0.006 \pm 0.006 \pm 0.004$	0.103	0.112	0.116 ± 0.016	0.110 ± 0.013	0.105
	$\ell\ell$	$0.100 \pm 0.005 \pm 0.007 \pm 0.003$	0.102	0.112	0.114 ± 0.016	0.110 ± 0.013	0.105

CMS-SMP-20-015

Z + $\geq$1b Jets

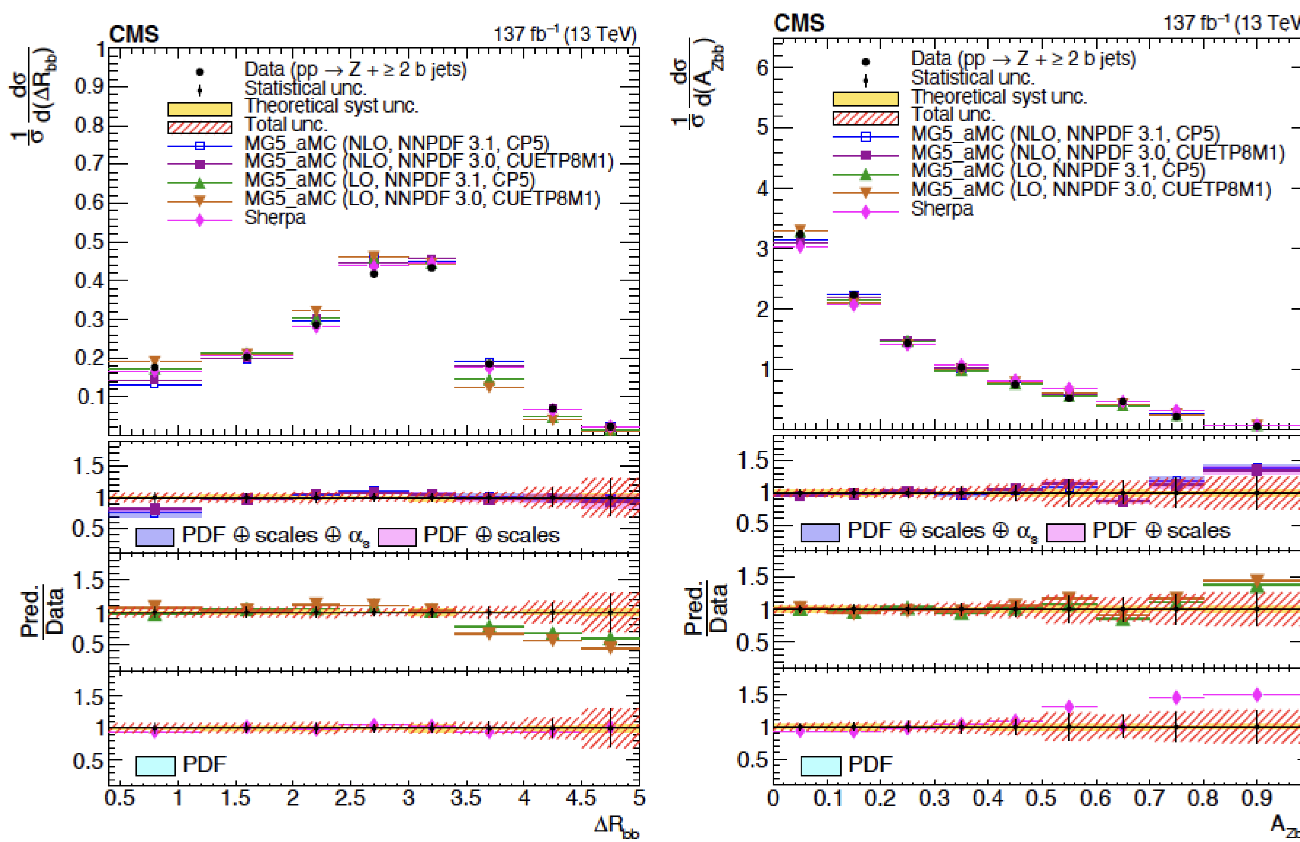
- p_T shape is well described by all pQCD calculations
  - Except for MG5 aMC (LO, NNPDF 3.1, CP5) combination - up to 25% deviation for higher p_T region.
- ΔY: the agreement improves with MG5_aMC at NLO w.r.t LO (high ΔY)
- Integral cross-sections indicate that the NLO PDFs overestimate b quark content



CMS-SMP-20-015

Z + ≥2b Jets

- ΔR(bb): the agreement improves with MG5_aMC at NLO w.r.t LO (c.f. high ΔR)
- A_{Zbb} shows trends with both LO and NLO predictions
- Integral cross-sections indicate that the NLO PDFs overestimate b quark content



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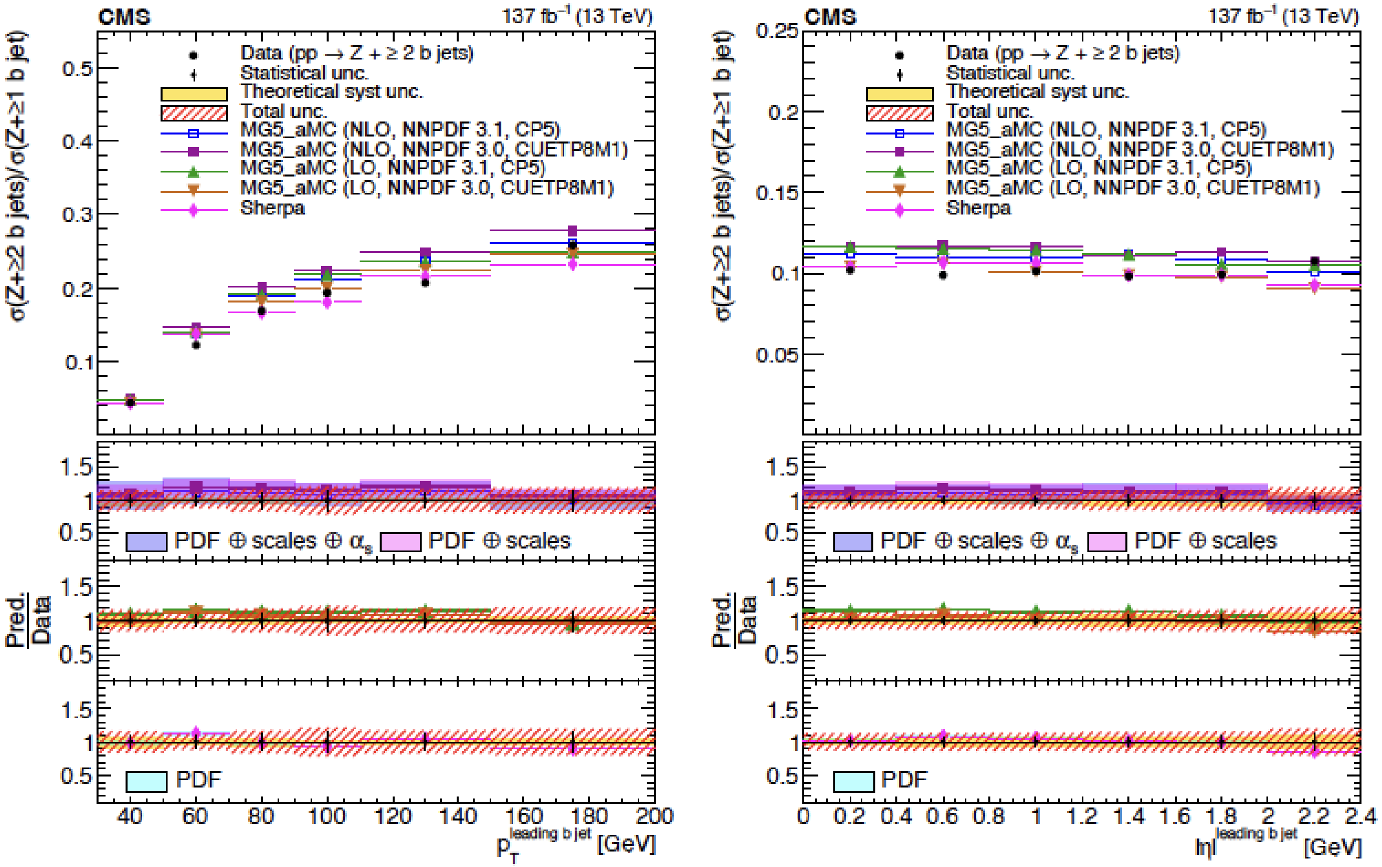
Ratio Z + ≥1b / Z + ≥2b

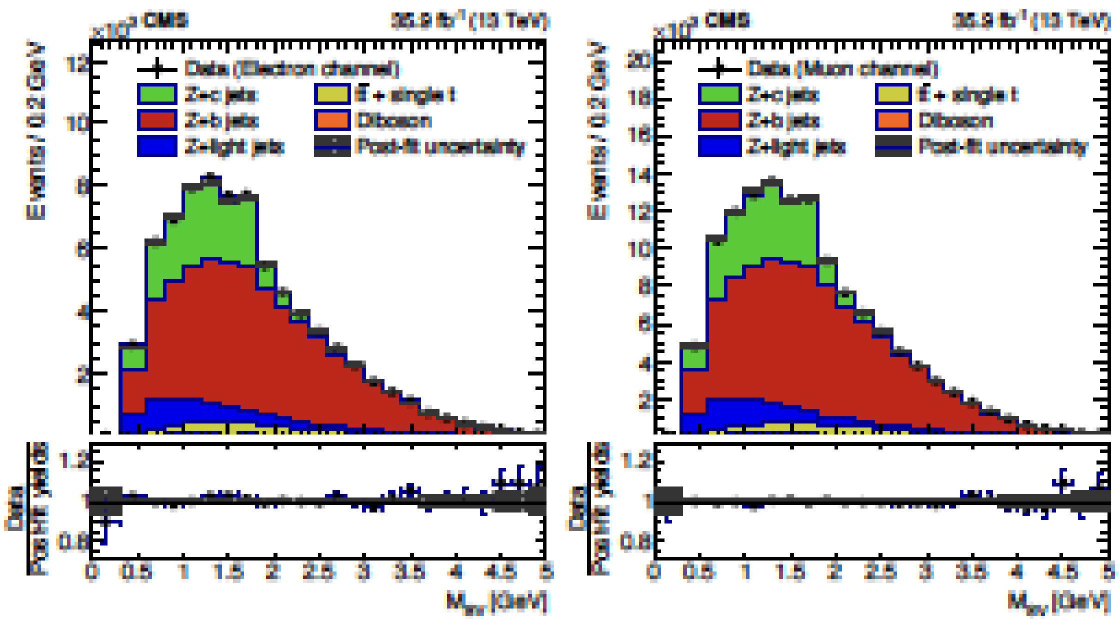


- For the ratios, all combinations of pQCD calculations & PDFs describe data well within the experimental uncertainties

CMS-SMP-20-015

Ratios Z + ≥1b(c) / Z + ≥1c(j)

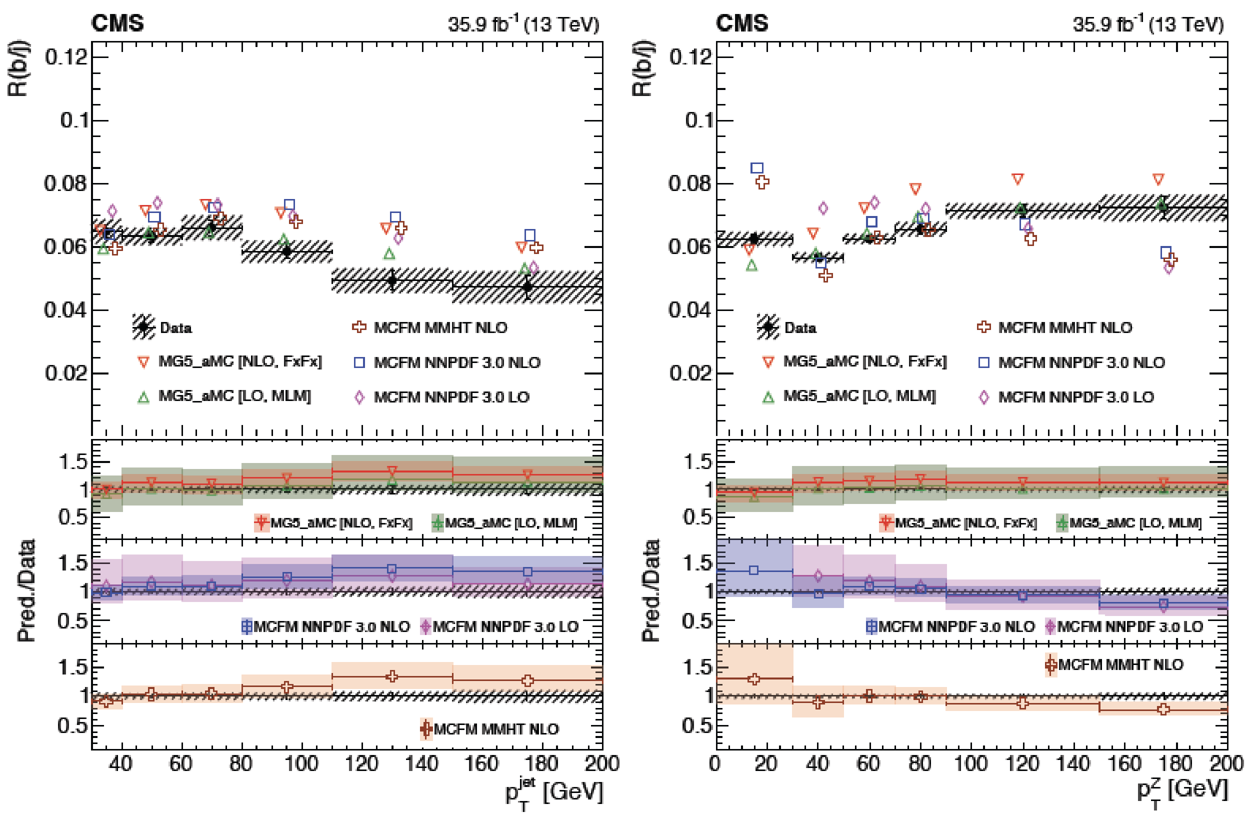
- Various ratios obtained in the same analysis
  - Better control (cancelation) of systematic effects
  - Reduced theoretical uncertainties in the calculations of the ratios (e.g. parton showering and hadronization)
  - Larger statistics, better techniques for heavy flavor jets identification
- Looking at different ratios allows to better identify the most likely source of the discrepancy with the theory:
  - Higher order contributions in the calculations, PDFs parameterizations, imperfections in matching schemas etc.
- First measurement at 13 TeV
  - Larger statistics
  - A number of technical improvements over the 8 TeV results, e.g. better techniques for heavy flavor jets identification



CMS-SMP-19-004

Ratios Z + ≥1b / Z + ≥1j

- The MG5_aMC predictions for the cross section ratios are higher in most of the bins, although still compatible with the data given the large uncertainties.
  - The data are better described with MG5_aMC at LO compared to MG5_aMC at NLO.
- The MCFM predictions for R(b/j) disagree with data at high jet p_T and $p_T(Z)$

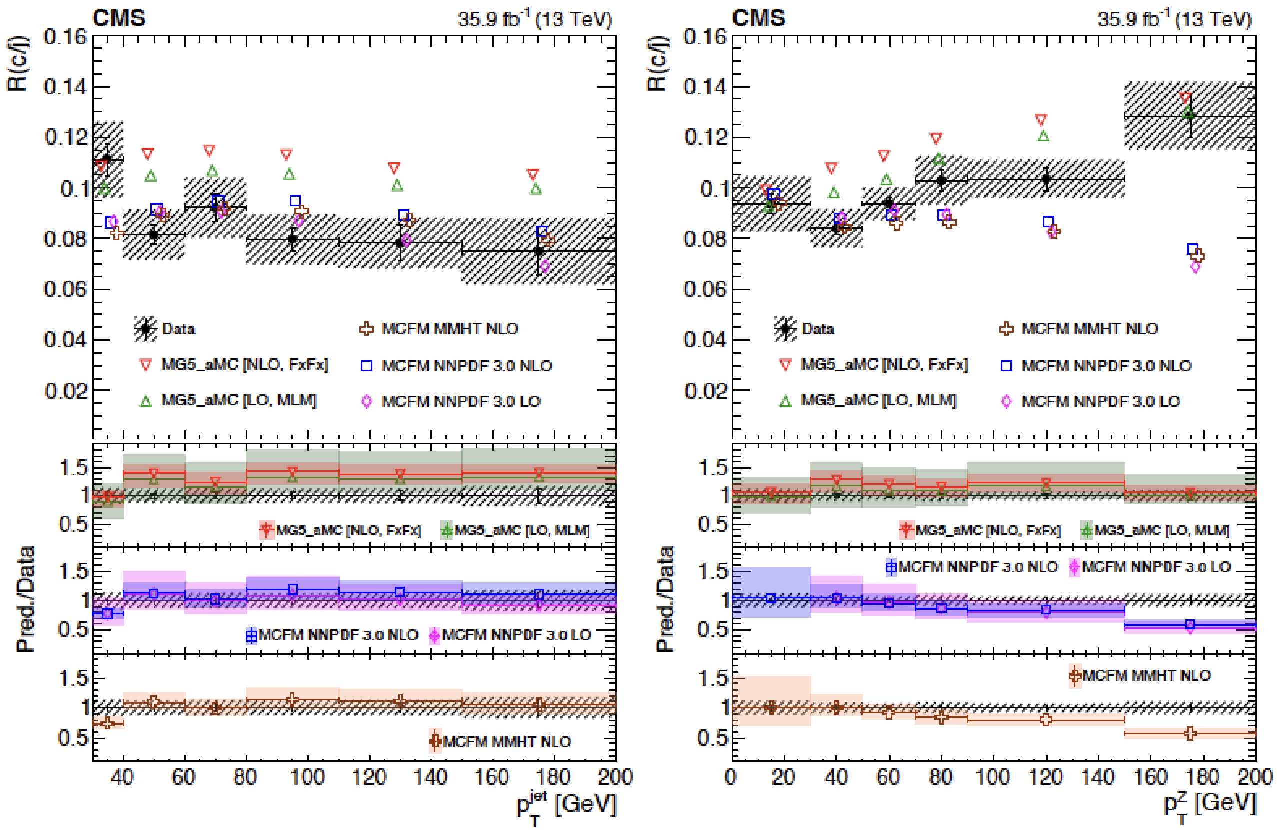


CMS-SMP-19-004

Ratios Z + ≥1c / Z + ≥1j

- The MG5_aMC predictions for the cross section ratios are again higher in most of the bins and even more pronounced, c.f. R(c/j) versus jet p_T. The data are again better described with MG5_aMC at LO compared to MG5_aMC at NLO.

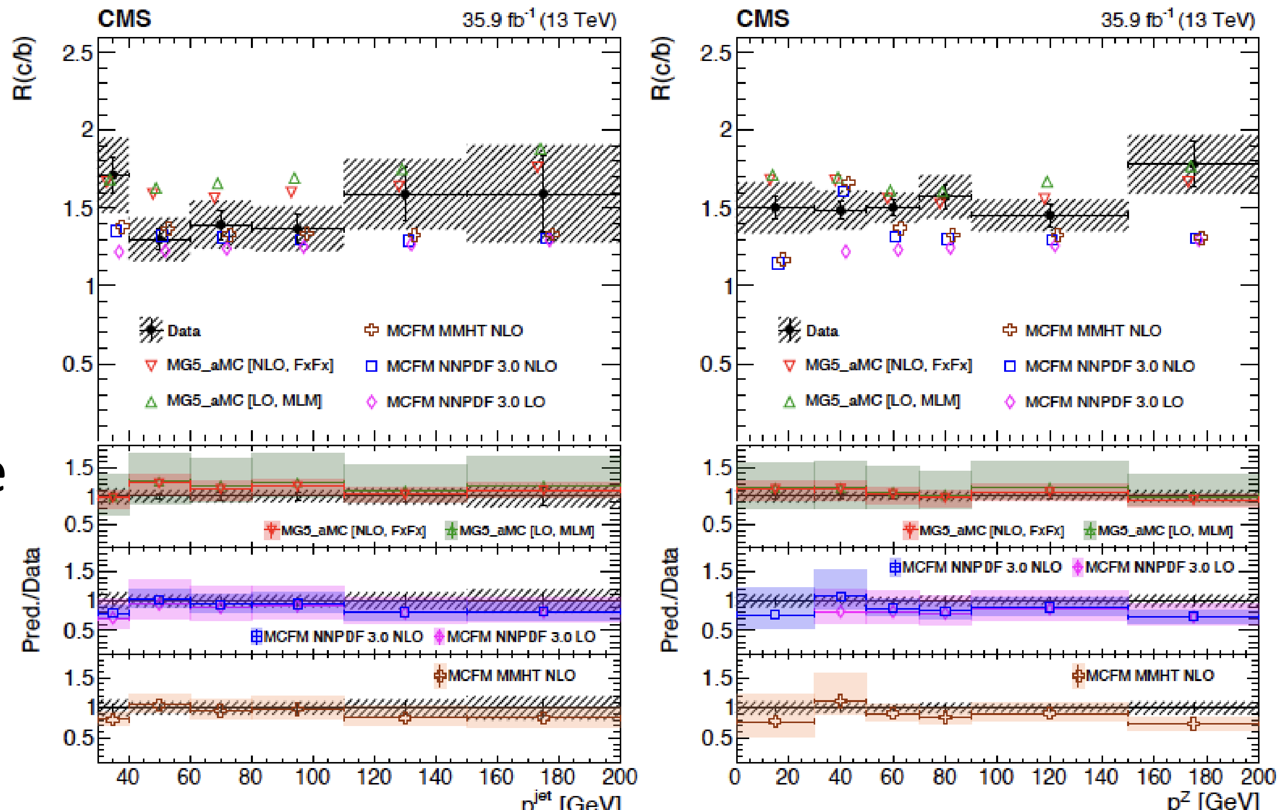
- The MCFM predictions for R(c/j) disagree with data at high p_T(Z), but for jet p_T, there is in good agreement with LO or NLO calculations, and for both PDFs considered.



CMS-SMP-19-004

Ratios Z + ≥1c / Z + ≥1b

- For R(c/b), all theoretical predictions are consistent with the measured ratios, except for the MCFM prediction for the highest $p_T(Z)$ bin.
  - The difference between the parton- and particle-level jets may affect the MCFM predictions, although the corresponding effects are significantly reduced or vanish in the cross section ratios.
- Alternatively, higher order pQCD calculations might be needed to improve the description of the data



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Conclusions

- Precision measurements in V+jets provide a direct test of the perturbative QCD calculations
  - A variety of measurements, including ratios that are less sensitive to systematics and some theoretical uncertainties
- Experimental feedback allows for continuous improvement of the higher order calculations
  - Better understanding of the components going into these calculations, e.g. PDFs, parton showering
  - Important on its own, but also for correctly predicting background contributions to
    - Other precision measurements testing Standard Model's self-consistency and limits of applicability
    - New physics searches in a range of scenarios, including Higgs sector