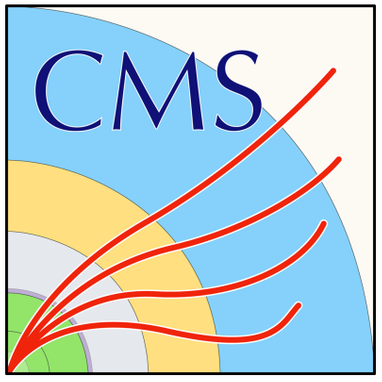


V+heavy flavor jets and constraints to PDFs in CMS

Anton Stepennov on behalf of the CMS Collaboration

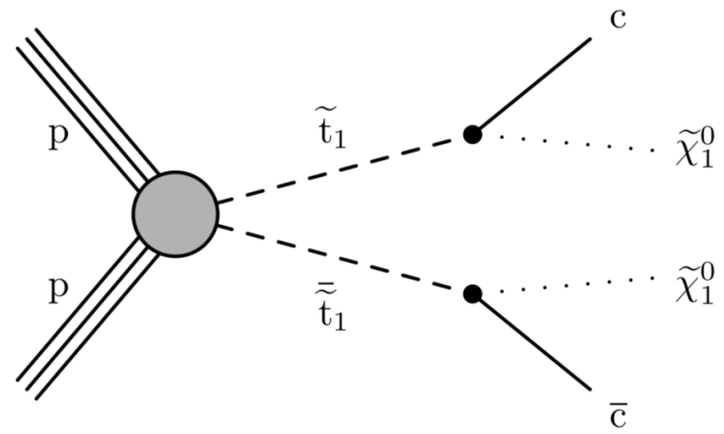
ICHEP 2020: 40th international conference on high energy physics
Prague, Czech Republic - 28 July, 2020

Motivation

1. Test existing models, describing SM processes:

e.g. MadGraph, MCFM, Sherpa

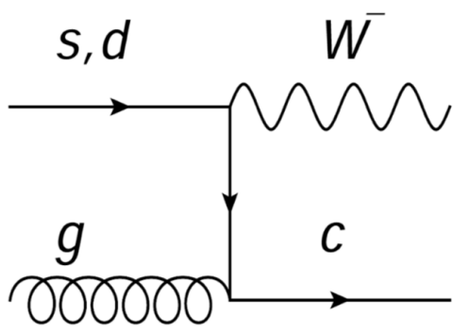
Search for the pair production of third-generation squarks with two-body decays to a bottom or charm quark and a neutralino in proton-proton collisions at sqrt(s) = 13 TeV
arXiv:1707.07274

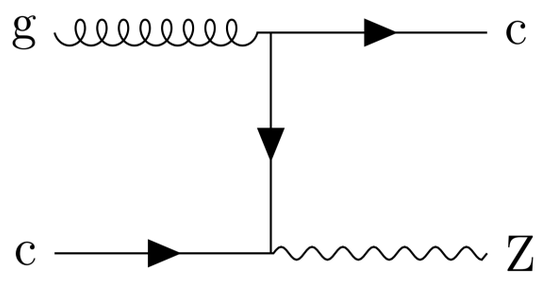


significant background from Z+c-jets processes

2. Precise backgrounds measurement for the searches of the new physics:

3. New measurements for PDF of strange, charm and bottom quarks.





V+heavy flavor jets at CMS

Analysis	**Energy**	**Identifier**
W+c *	8 TeV	CMS-PAS-SMP-18-013
W+c	13 TeV	CMS-SMP-17-014 arXiv:1811.10021 Eur. Phys. J. C 79 (2019)269
Z+c *	13 TeV	CMS-PAS-SMP-19-011
Z+c/b *	13 TeV	CMS-SMP-19-004 arXiv:2001.06899

* This year result

Overview of heavy quark selections

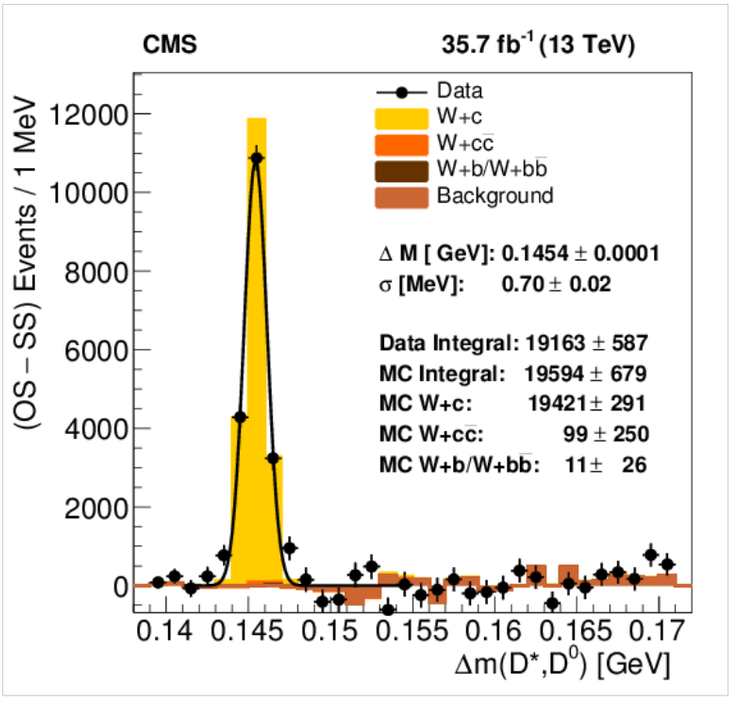
Heavy flavor quarks

Bottom and charm quarks can be identified by products of their decays. Several ways of identifying HF quarks were used:

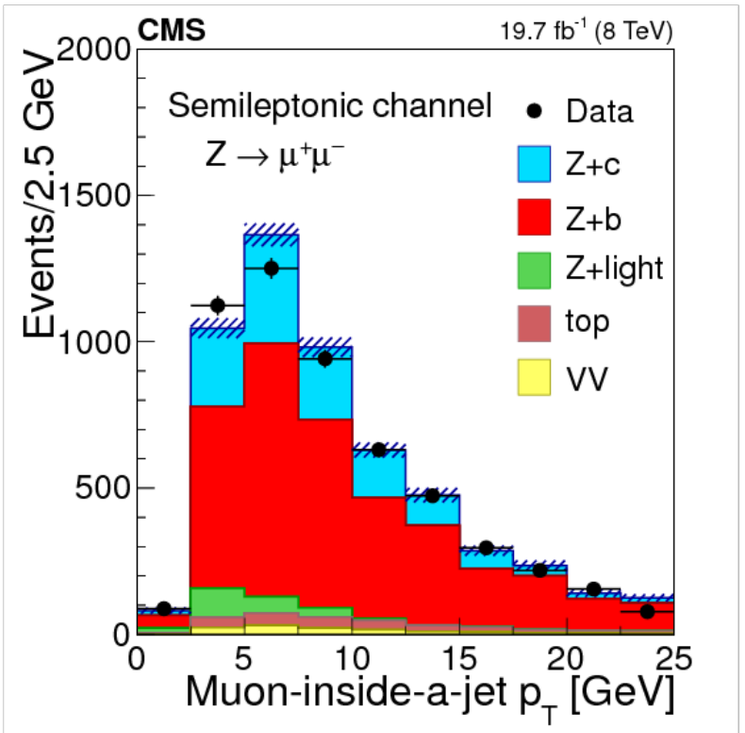
1. **Reconstructing of D/D* mesons** - several tracks, assigned to pions and kaons from decays of D*(2010) can be used to identify the presence of charm quark in the event.
2. **Muon inside the jet** - in semi-leptonic decay of charm quark, muon can be found inside the jet, which is considered as originating from charm quark.
3. **Tagging jets, initiated by a charm or bottom quarks** - different variables, associated with a jet, e.g. mass of secondary vertex, distance from primary vertex, etc. used to discriminate signal from background, e.g. by implementing c-/b- tagger*.

*JINST 13 (2018) P05011, arXiv:1712.07158

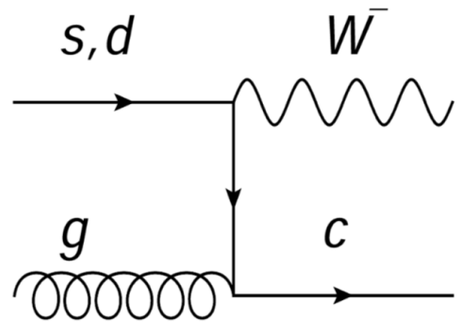
CMS-SMP-17-014



CMS-SMP-15-009



W+c at 13 TeV
CMS-SMP-17-014



Charm quarks: D*(2010) is reconstructed from products of decay chain:

$$\mathrm{D}^*(2010)^{\pm} \rightarrow \mathrm{D}^0 + \pi^{\pm}_{slow} \rightarrow \mathrm{K}^{\mp} + \pi^{\pm} + \pi^{\pm}_{slow}$$

W boson:

- one isolated **muon** with pt > 26 GeV, $|\eta_{e/\mu}| < 2.4$
- Transverse mass $M_{transverse} > 50$ GeV

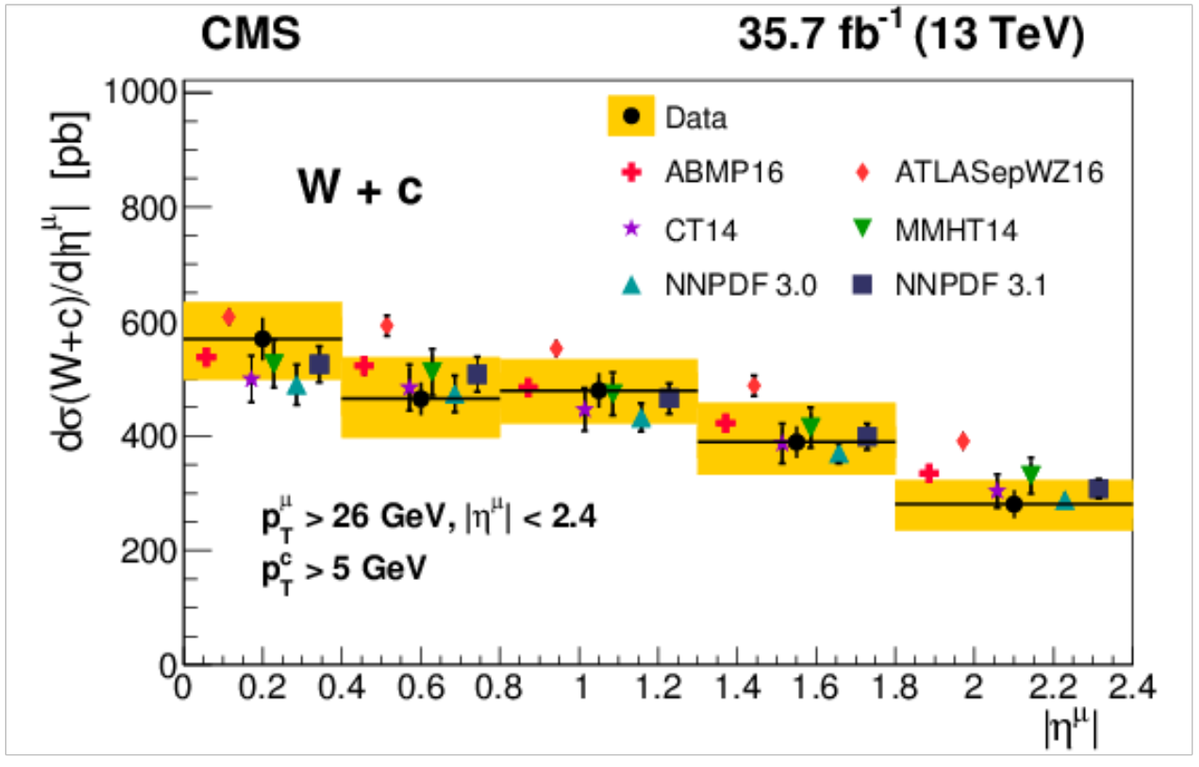
W + c: W boson + at least one D*(2010) candidate, OS-SS subtraction

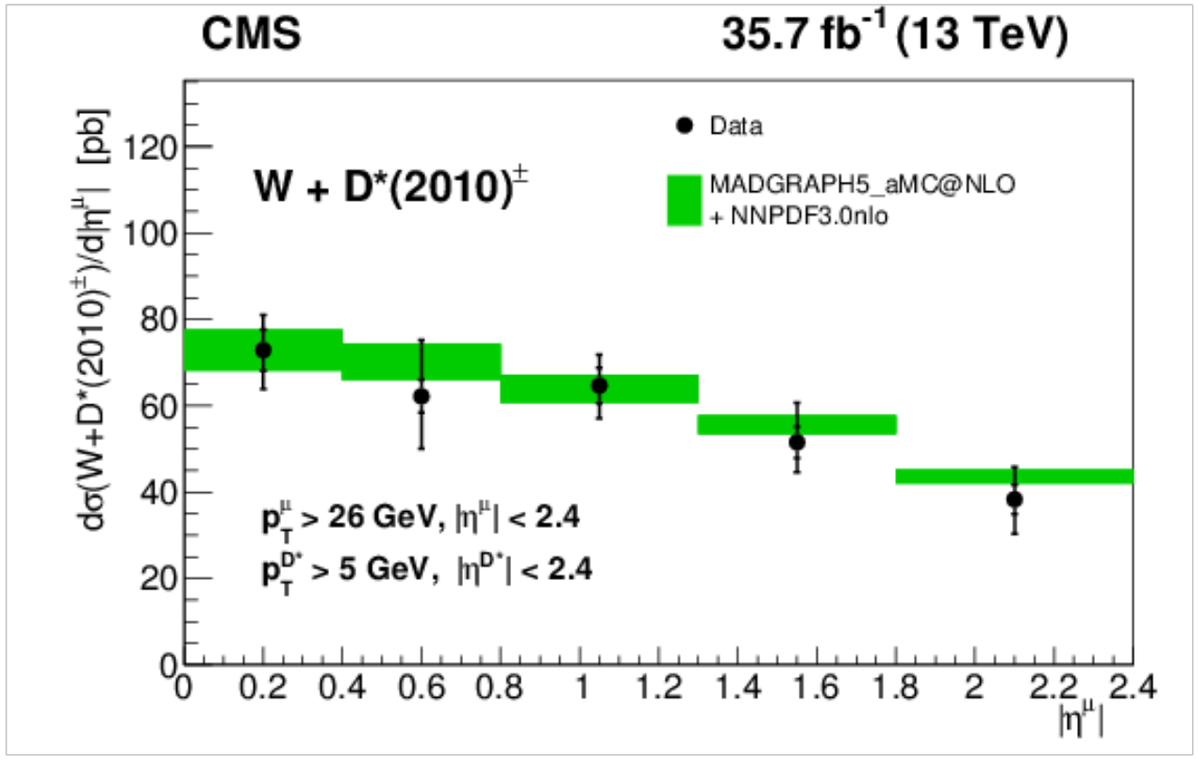
Integral fiducial cross-section:

$$\sigma(\mathrm{W+c}) = 1026 \pm 31\ (\mathrm{stat}) \pm 76\ (\mathrm{syst})\ \mathrm{pb}$$

$$\frac{\sigma(\mathrm{W}^+ + \bar{\mathrm{c}})}{\sigma(\mathrm{W}^- + \mathrm{c})} = 0.968 \pm 0.055\ (\mathrm{stat})^{+0.015}_{-0.028}\ (\mathrm{syst})$$

Differential cross-section:

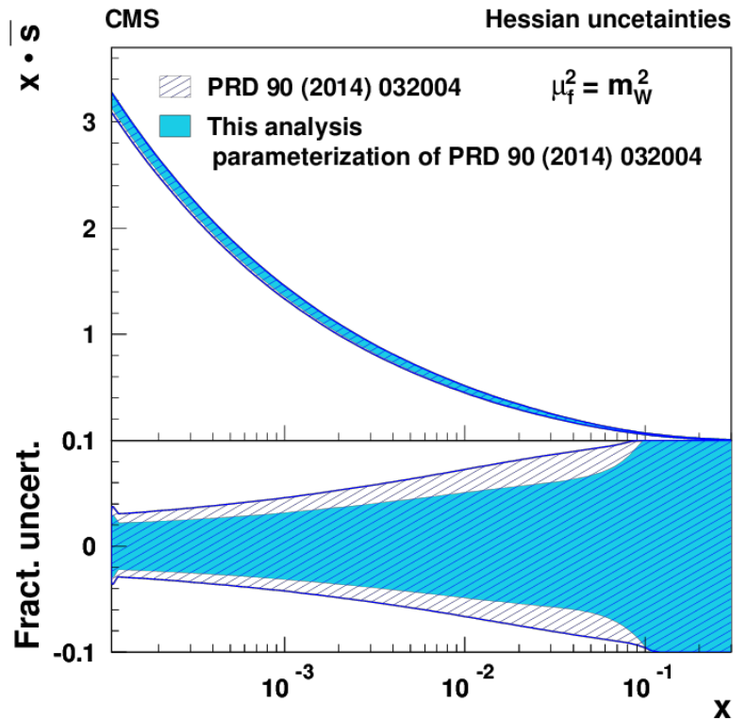


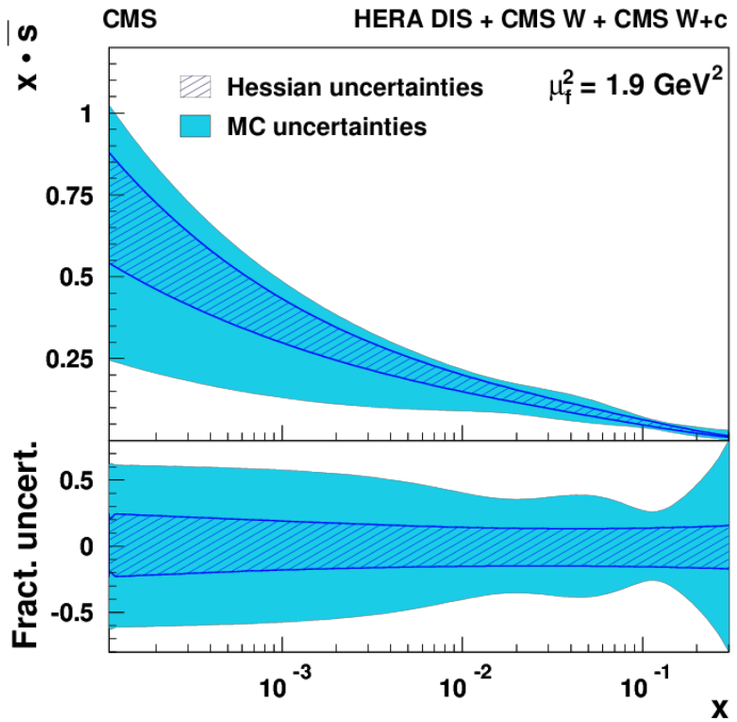


Good agreement between measurements and theoretical predictions.

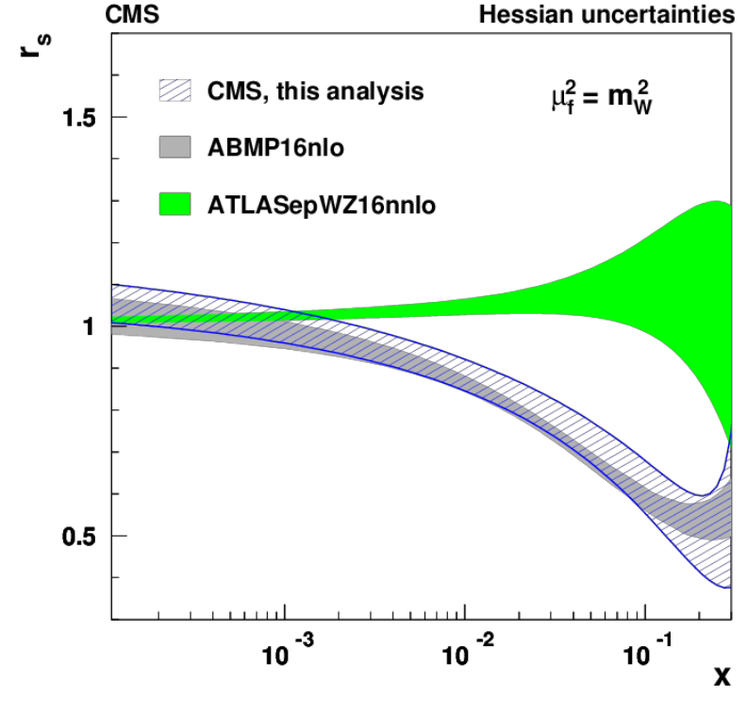
W+c at 13 TeV
CMS-SMP-17-014

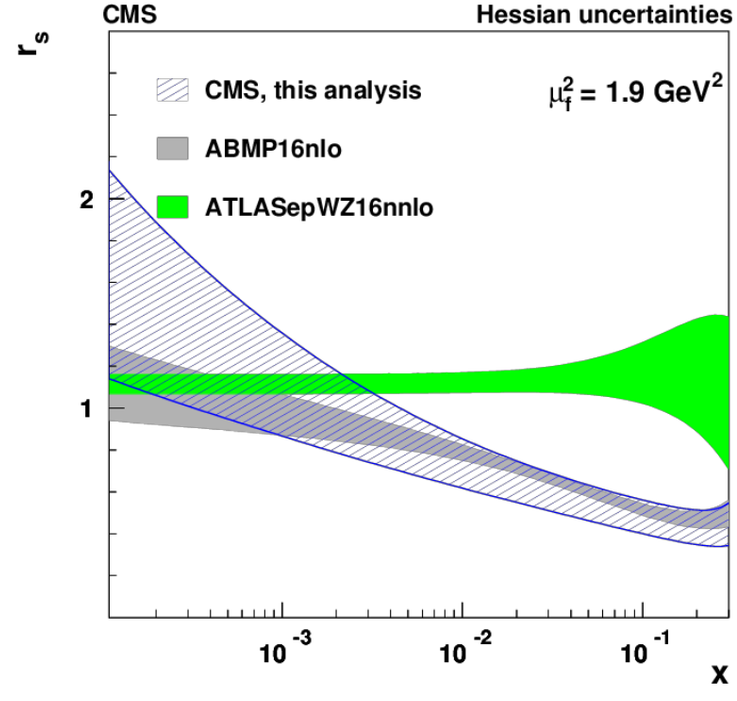
strange quark distribution





strangeness suppression factor





Measured strange quark distribution and strangeness suppression factor agree with neutrino scattering experiments, results of ATLASepWZ16nnlo not supported.

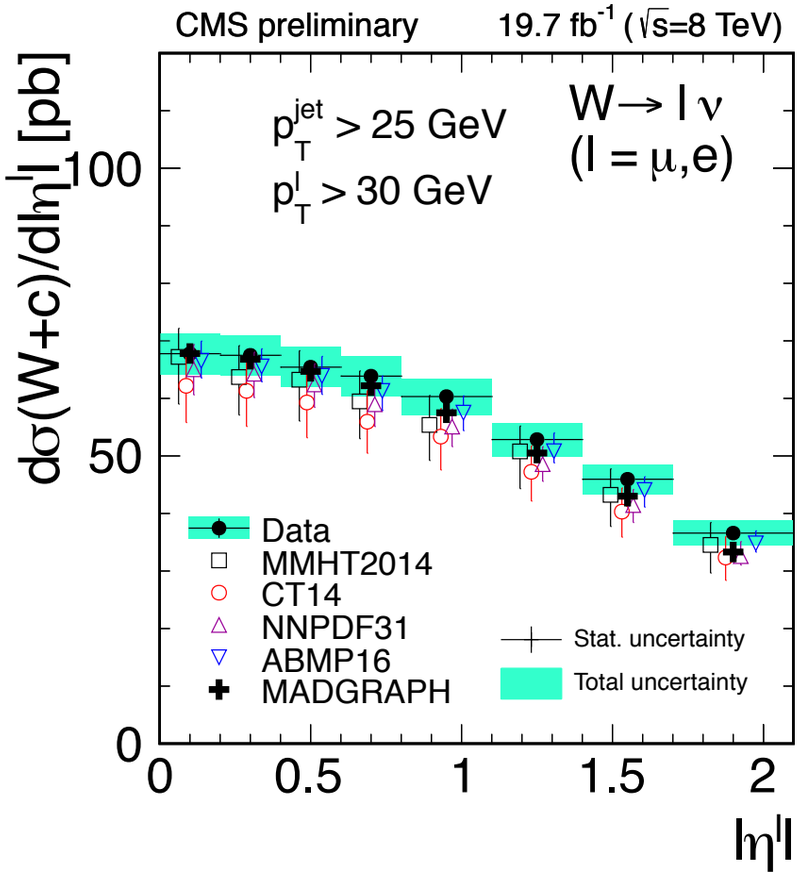
W+c at 8 TeV
CMS-PAS-SMP-18-013

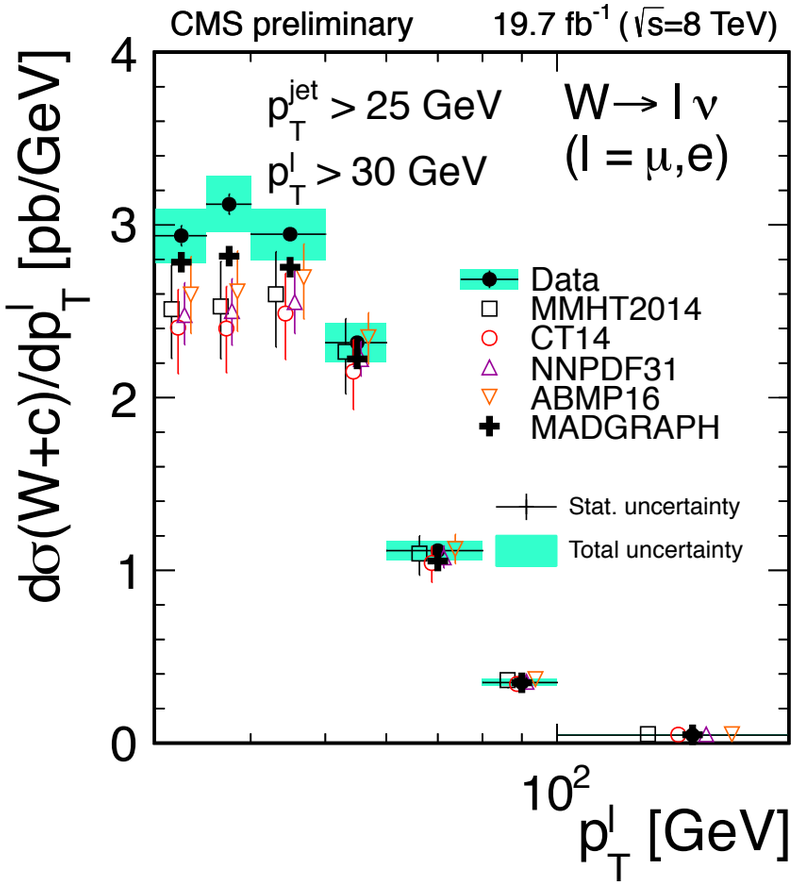
Charm quarks: **Semileptonic channel** - reconstructed muon inside the jet with $pt_\mu < 25$ GeV, $|\eta_\mu| < 2.1$, $pt_\mu / pt_{jet} < 0.6$, **Secondary channel** - reconstructed secondary vertex (SV), mass of SV > 0.55 GeV
W boson: isolated **muon or electron** with pt > 26 GeV, $|\eta_{e/\mu}| < 2.4$, $M_{transverse} > 55$ GeV
W + c: W boson + at least one D*(2010) candidate, OS-SS subtraction

Integral fiducial cross-section:

$$\sigma(\mathrm{W} + \mathrm{c} + \mathrm{X}) \times \mathcal{B}(\mathrm{W} \to \ell\nu) = 116.3 \pm 0.7\ (\mathrm{stat}) \pm 5.2\ (\mathrm{syst})\ \mathrm{pb}$$

Differential cross-section:





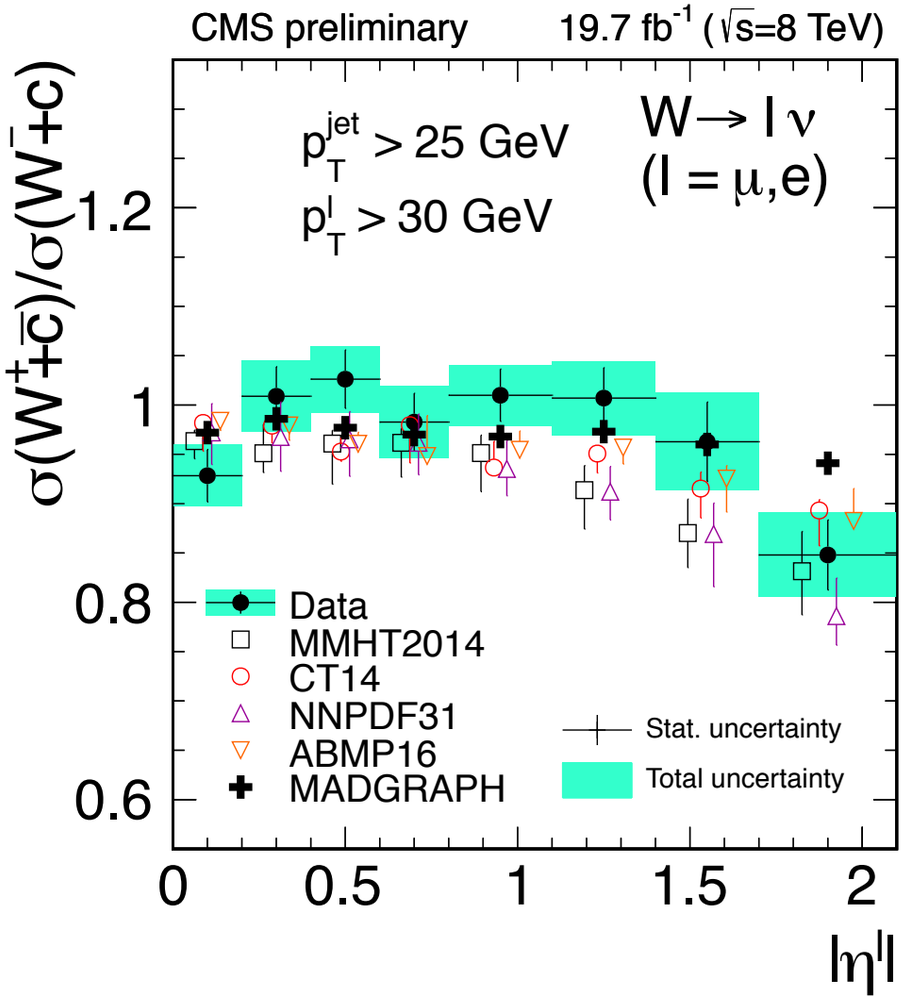
Results are consistent with the predictions of Madgraph LO and calculations from MCFM.

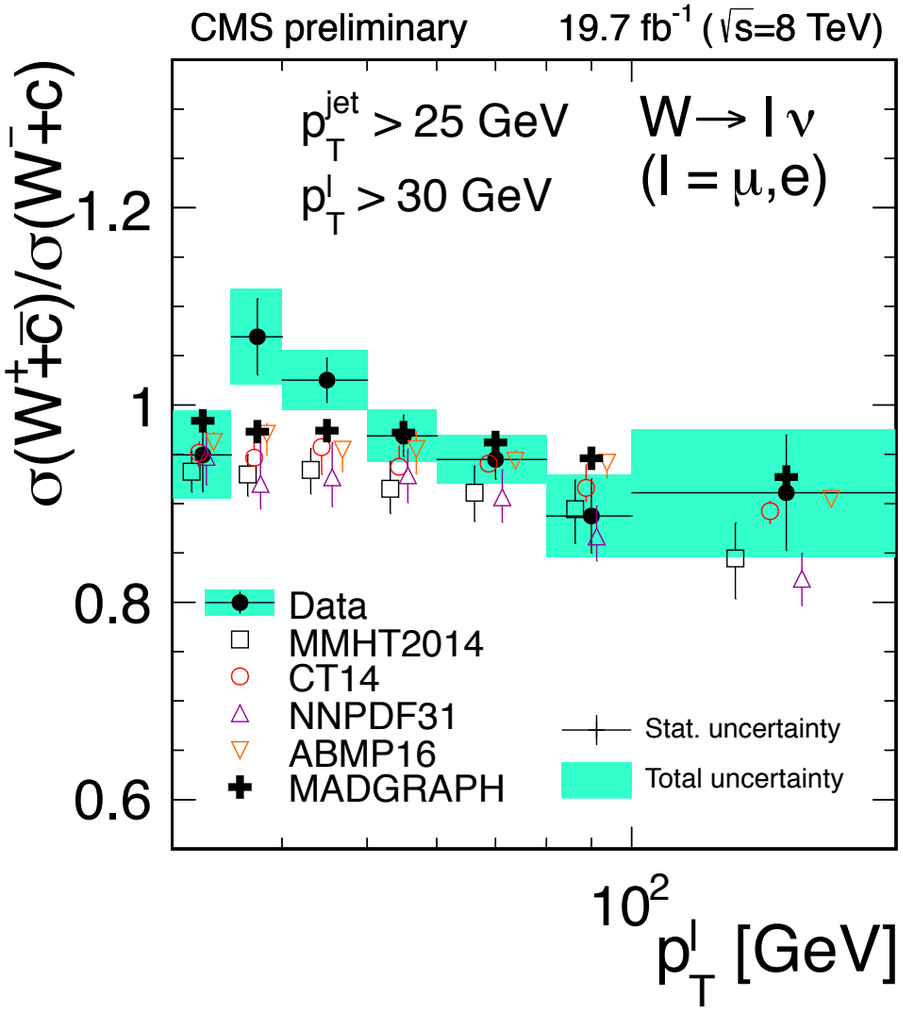
W+c at 8 TeV
CMS-PAS-SMP-18-013

Integral fiducial cross-sections ratios:

$$\frac{\sigma(\mathrm{W}^{+}+\bar{\mathrm{c}})}{\sigma(\mathrm{W}^{-}+\mathrm{c})} = 0.986 \pm 0.011\ (\mathrm{stat}) \pm 0.013\ (\mathrm{syst})$$

Differential cross-sections ratios:

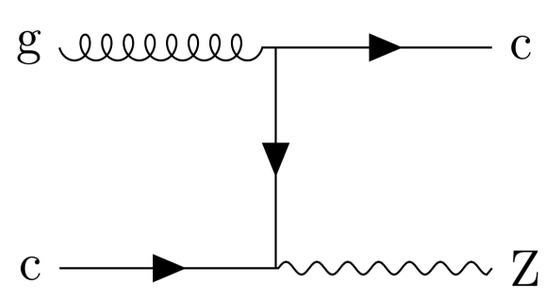




Results are consistent with the predictions of Madgraph LO and calculations from MCFM.

*https://arxiv.org/abs/1712.07158

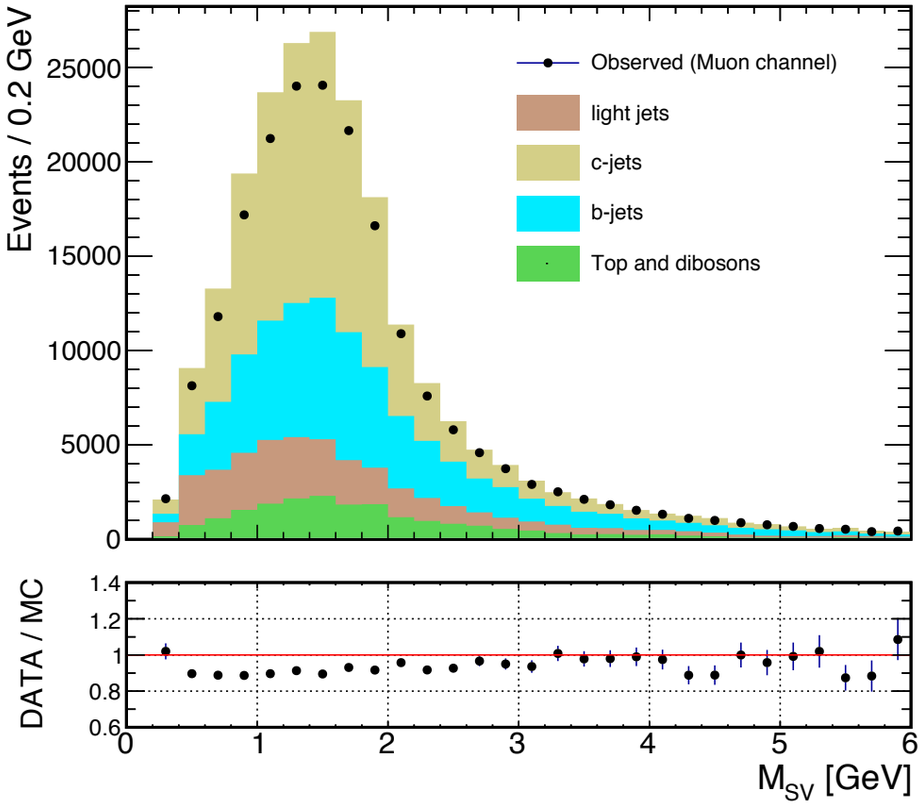
Z+c at 13 TeV
CMS-PAS-SMP-19-011



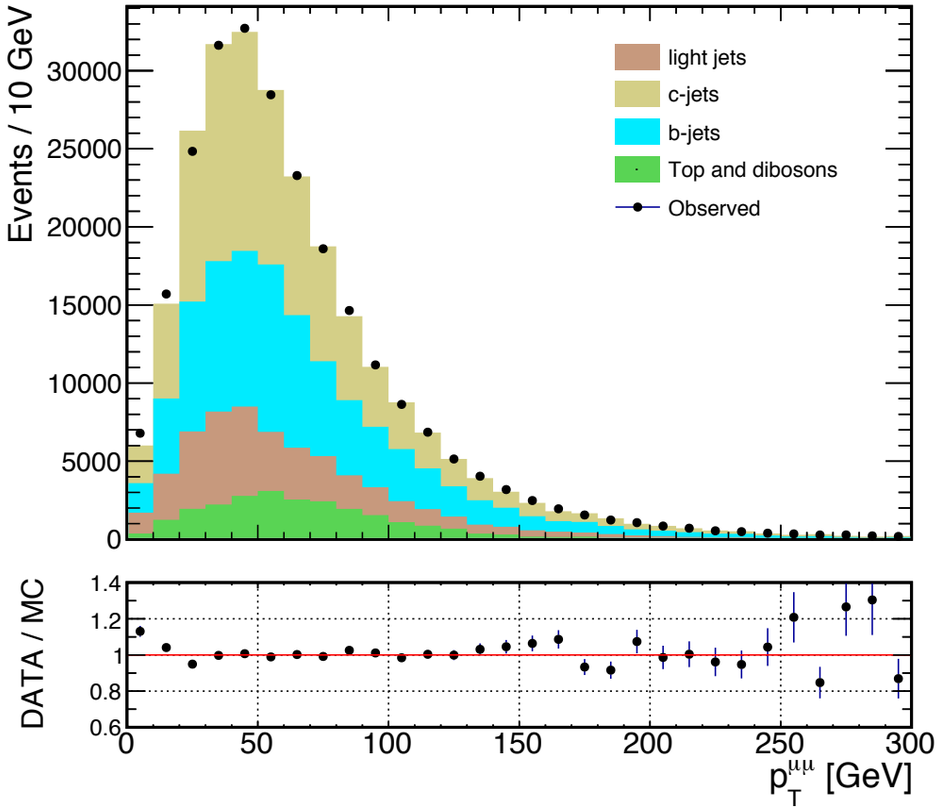
Charm quarks: $pt_{jet} > 30$ GeV, $|\eta_{jet}| < 2.4$, **c-tagging*** using neural network output
Z boson: **$\mu^+\mu^-$** or **e^+e^-** with pt > 26 (10) GeV for leading (subleading) lepton, $|\eta_{e/\mu}| < 2.4$, $|m_{ee/\mu\mu} - m_Z| < 20$ GeV
Z + c: Yield of Z+c was found from distribution fit of secondary vertex mass of selected c-tagged jet.

Discriminating Z+c from Z+b and Z+light jets

Secondary vertex mass distribution:



pT distribution after applying fit results:



Bottom component of secondary vertex mass distribution tends to have longer tail for higher SVM values, which allows to separate it from charm component.

Z+c at 13 TeV
CMS-PAS-SMP-19-011

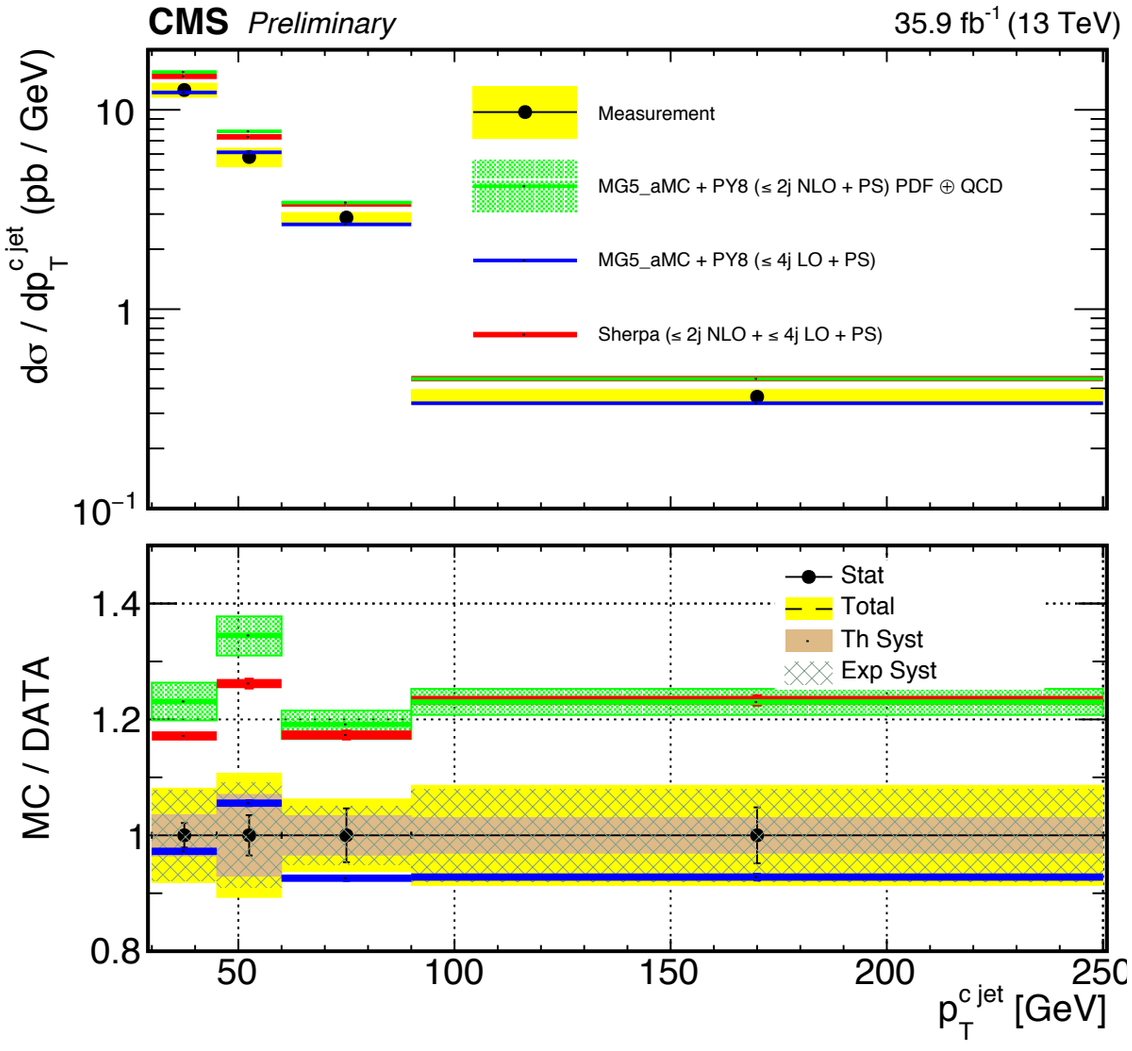
Integral fiducial cross-section:

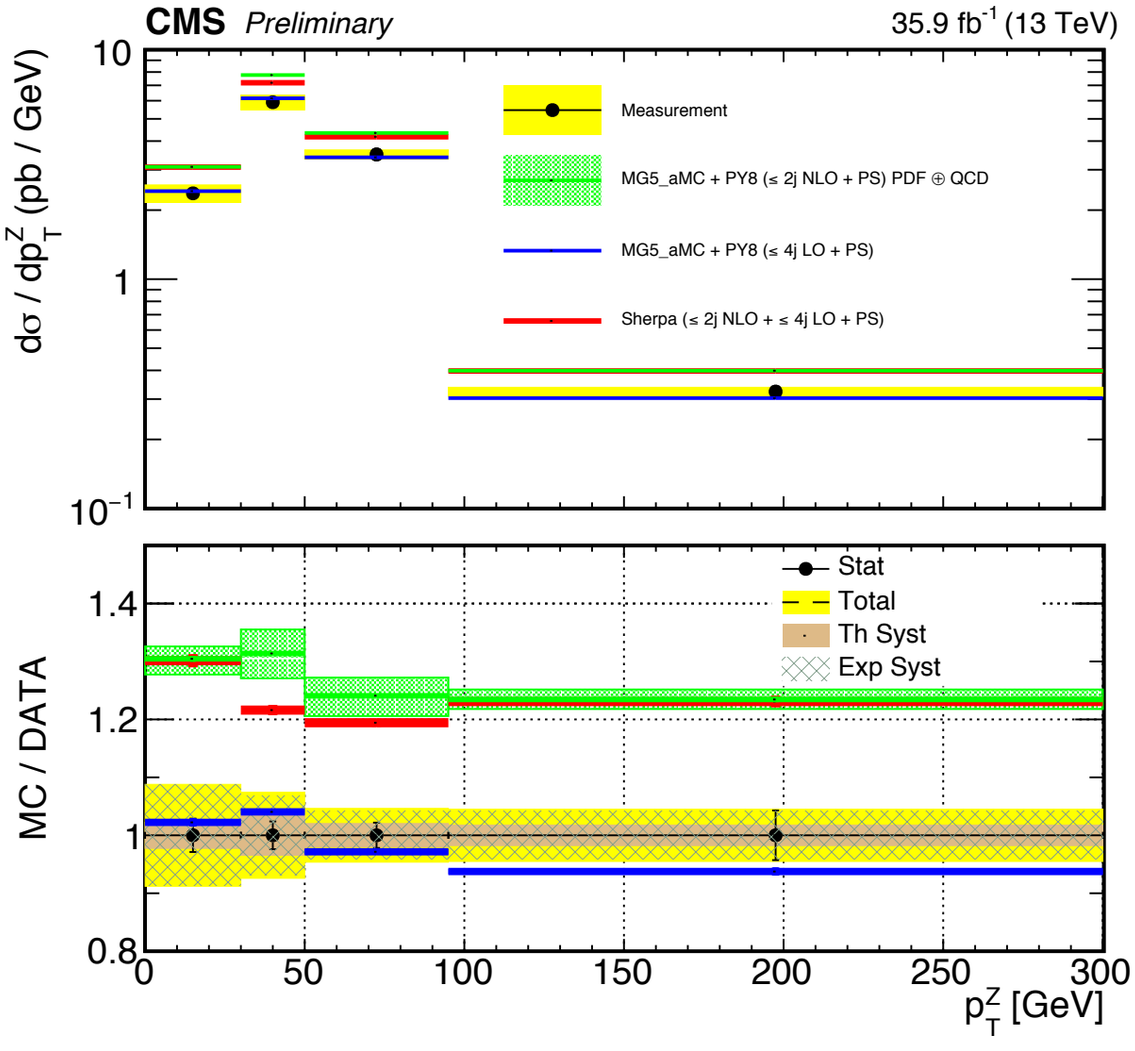
$$\sigma(\mathrm{Z{+}c}) = 413.5 \pm 5.6(\mathrm{stat}) \pm 19.5(\mathrm{exp}) \pm 5.9(\mathrm{th})\ \mathrm{pb}$$

Madgraph NLO predictions on integral fiducial cross-section

$$\sigma(\mathrm{Z + c}) = 524.9 \pm 11.7(\mathrm{th})\ \mathrm{pb}$$

Differential cross-section:





Measurements are in good agreement with Madgraph LO predictions. Madgraph NLO and Sherpa tend to overestimate the data.

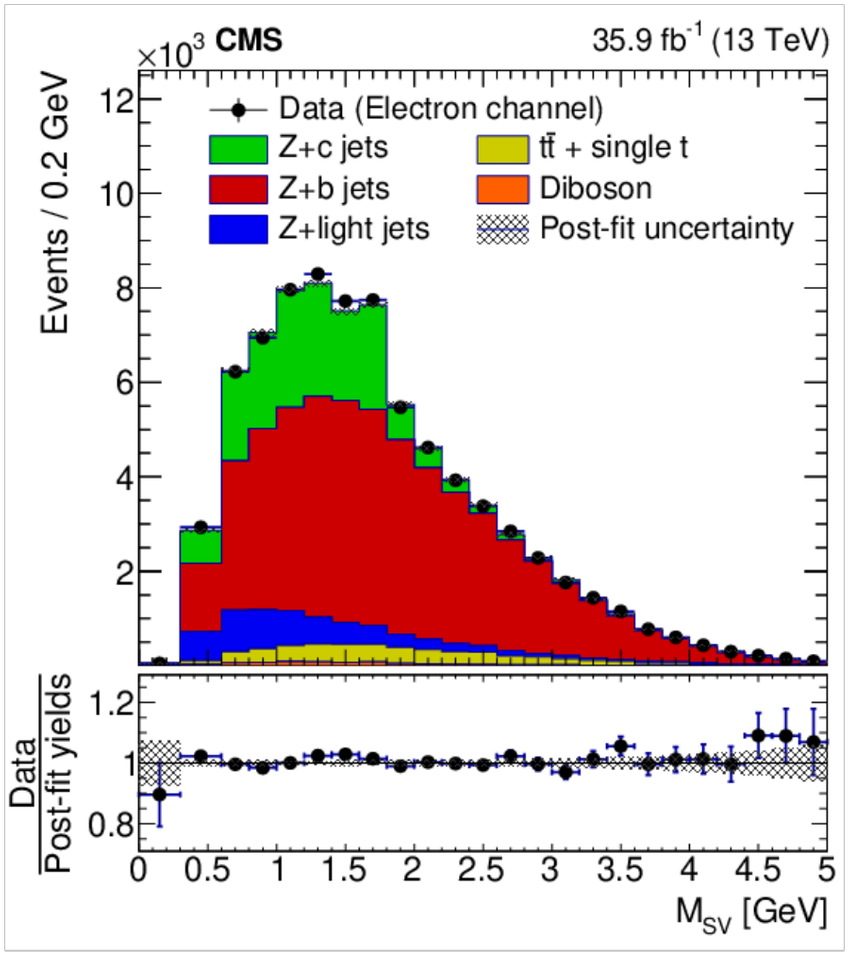
*https://arxiv.org/abs/1712.07158

Z+c/b at 13 TeV
CMS-SMP-19-004

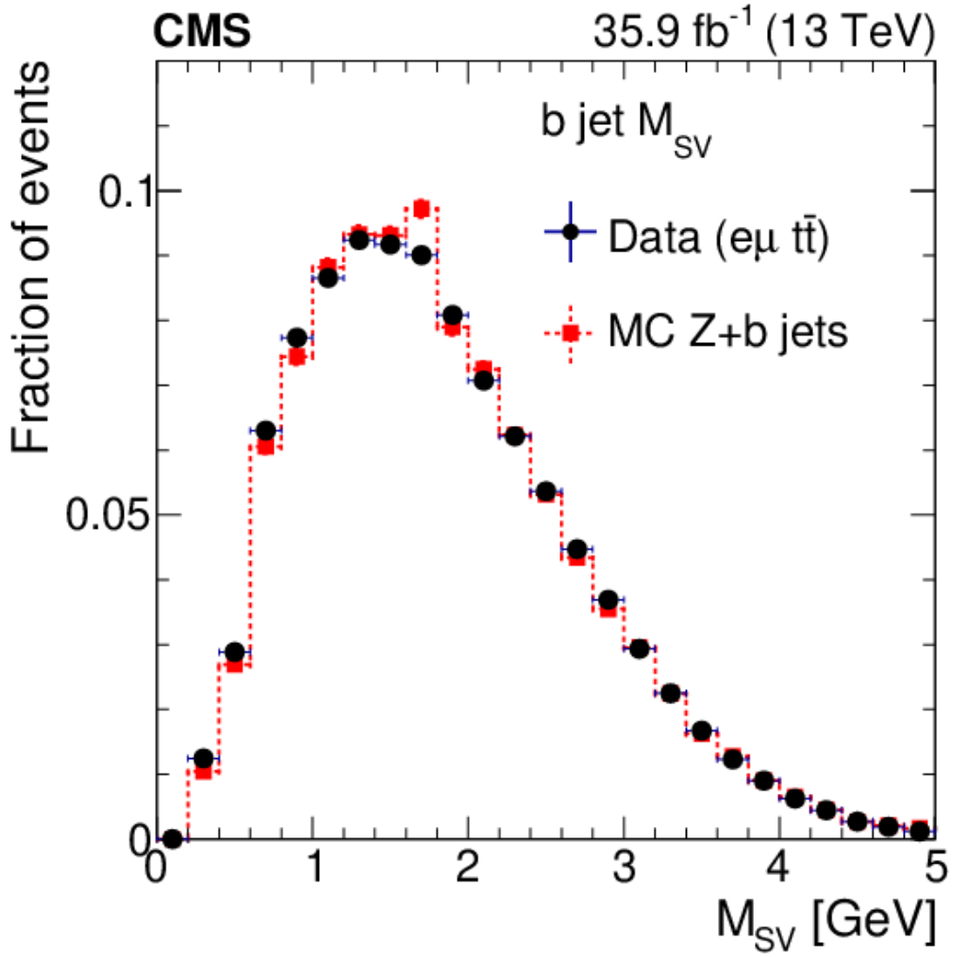
Charm quarks: $pt_{jet} > 30$ GeV, $|\eta_{jet}| < 2.4$, **b-tagging*** using neural network output
Z boson: with pt > 25 GeV, $|\eta_{e/\mu}| < 2.4$, $|m_{ee/\mu\mu} - m_Z| < 20$ GeV, $E_{missing} < 40$ GeV
Z + c/b: Yield of Z+c and Z+b was found from distribution fit of secondary vertex mass of selected b-tagged jet.

Discriminating Z+c from Z+b

Secondary vertex mass distribution (after fit):



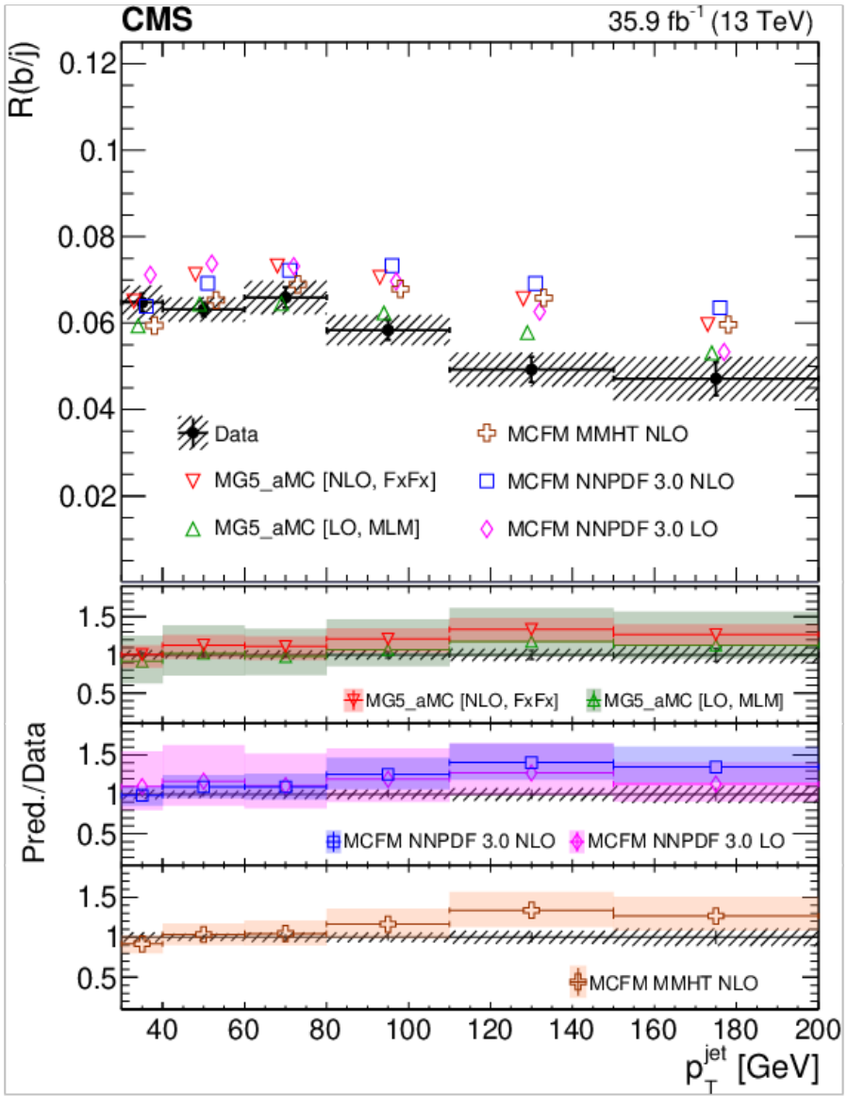
Validation of secondary vertex mass distribution in ttbar events:

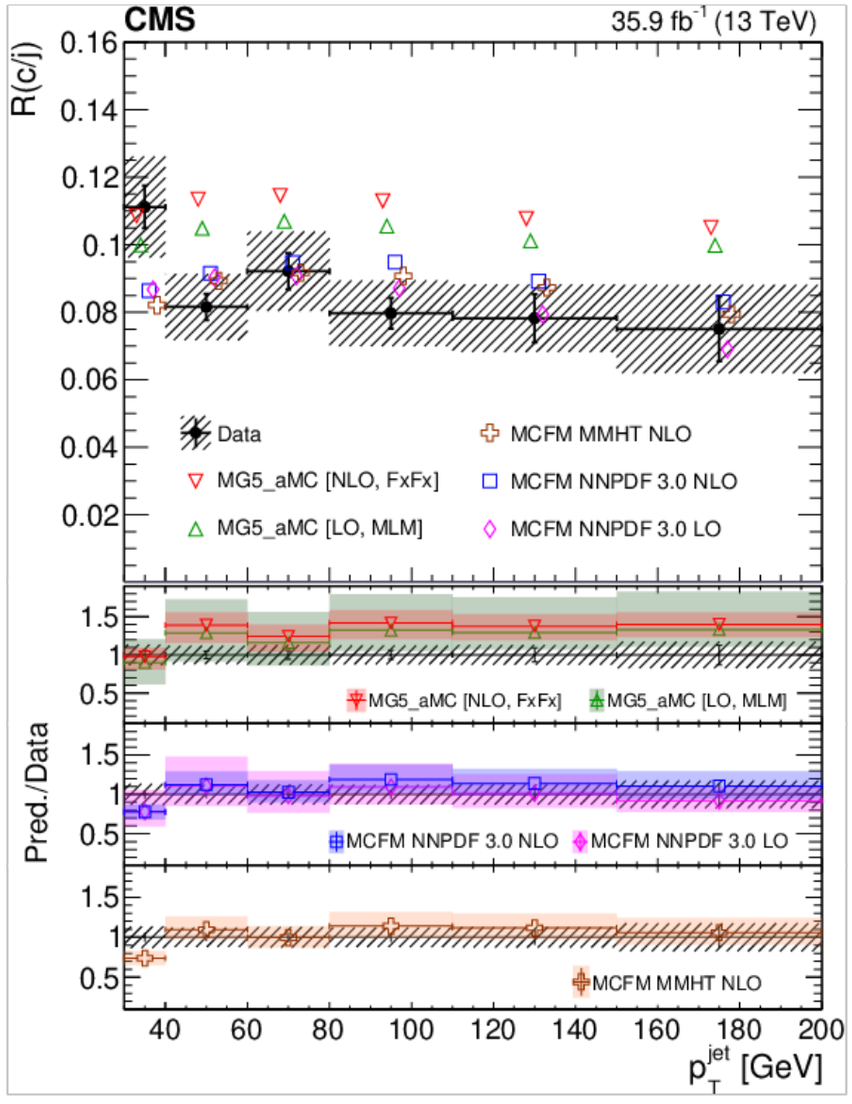


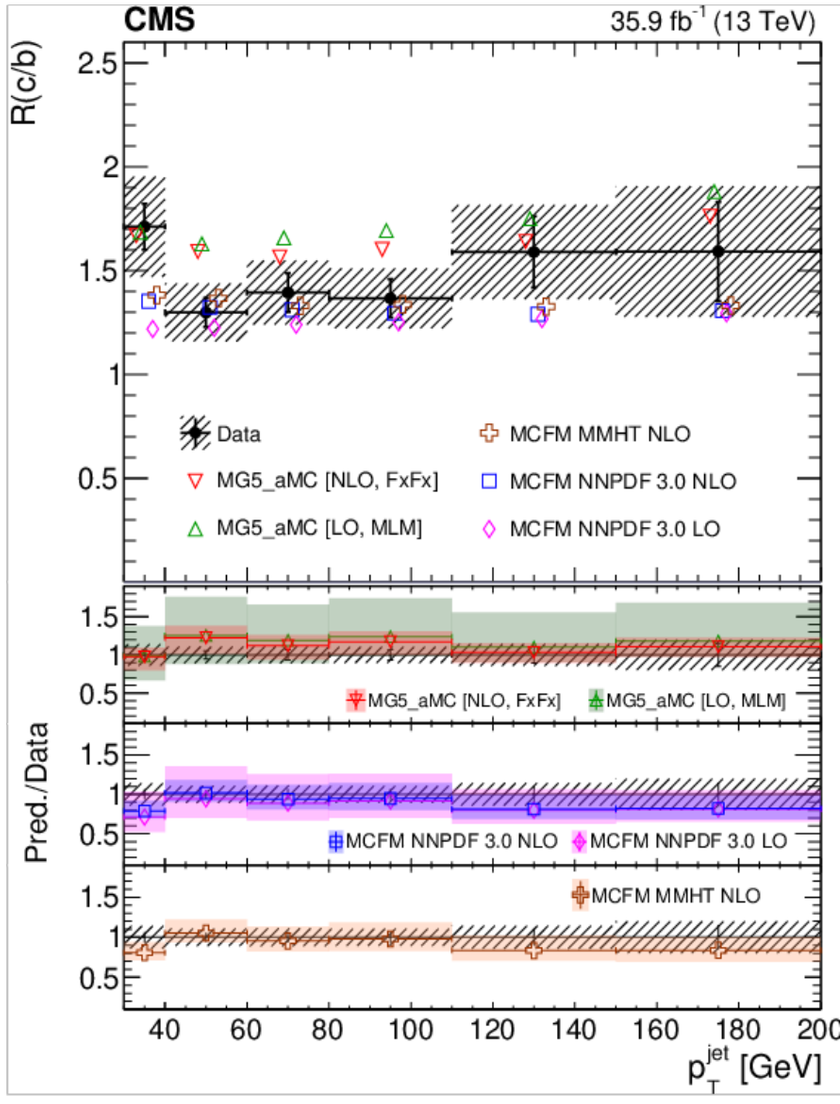
Secondary vertex mass after b-tagging provides good separation of charm and bottom components. Validation of secondary vertex mass modeling was performed using ttbar events.

Z+c/b at 13 TeV
CMS-SMP-19-004

Differential cross-sections ratios:







Some disagreement between measurements and theoretical predictions is observed, e.g. for R(c/j) for madgraph LO and NLO and R(b/j) for MCFM.

Summary

- W+HF and Z+HF measured using Run1 and Run2 data
- Difference between predictions and measurements observed in some cases - models require tuning
- Updates on PDF
- More V+HF results with Run2 data upcoming!

Z+c at 8 TeV
CMS-SMP-15-009

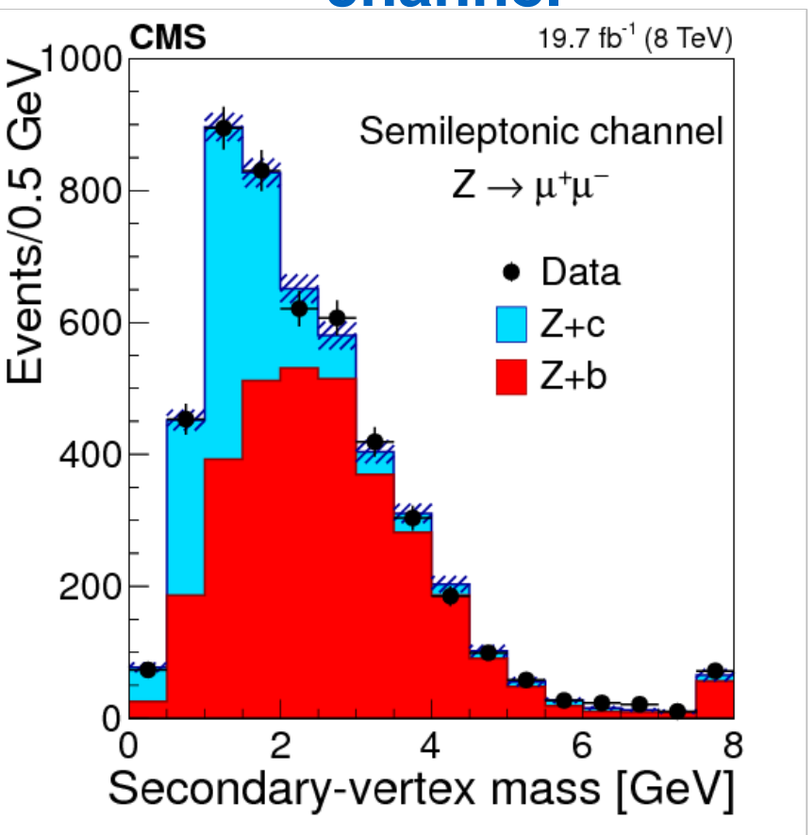
Charm quarks: $pt_{jet} > 25$ GeV, $|\eta_{jet}| < 2.5$ **Semileptonic channel** - reconstructed muon inside the jet with $pt_{\mu} < 25$ GeV, $|\eta_{\mu}| < 2.1$, $pt_{\mu}/pt_{jet} < 0.6$, **$D^{\pm}$ channel** - reconstructed $\pi^{\pm}\pi^{\pm}K$, **$D^*(2010)^{\pm}$ channel** - reconstructed $D^0\pi^{\pm}$

Z boson: **$\mu^+\mu^-$** or **e^+e^-** with pt > 20 GeV, $|\eta_{e/\mu}| < 2.1$, $|m_{ll} - m_Z| < 20$ GeV

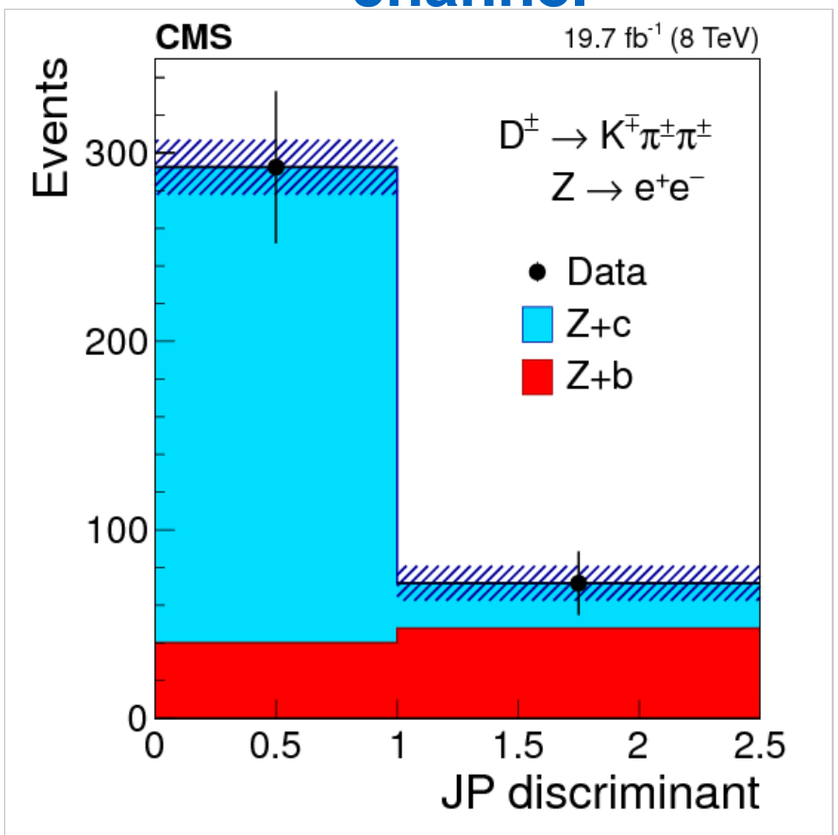
Z + c: Yield of Z+c was found from distribution fit of secondary vertex mass (Semileptonic channel) or Jet probability discriminant ($D^{\pm}$ channel or $D^*(2010)^{\pm}$ channel)

Discriminating Z+c from Z+b

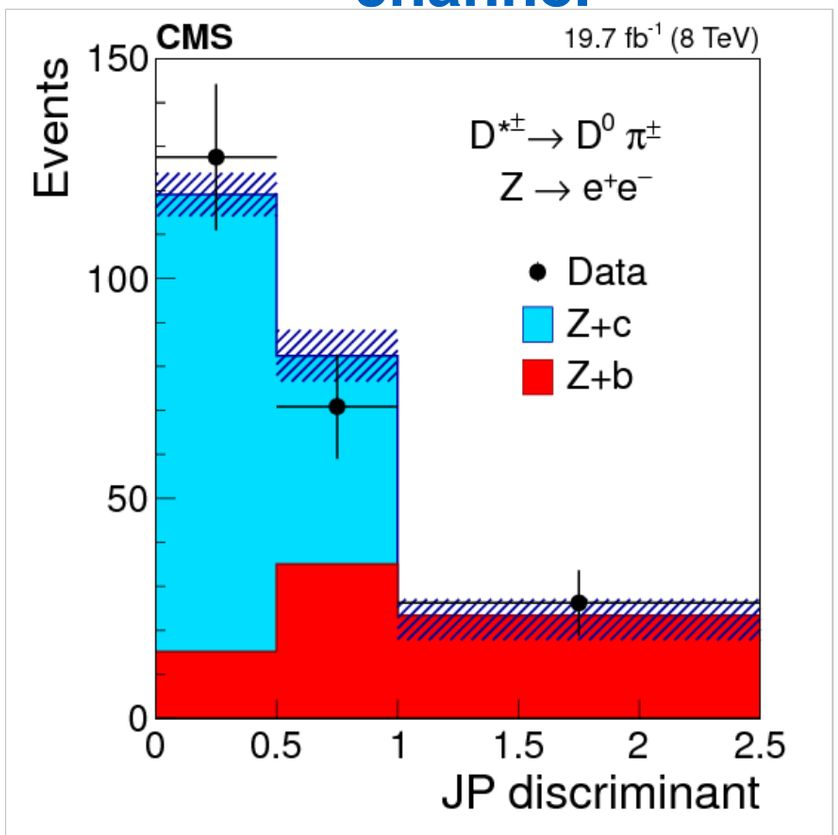
Semileptonic channel



D -> Kππ channel



D* -> D⁰π channel



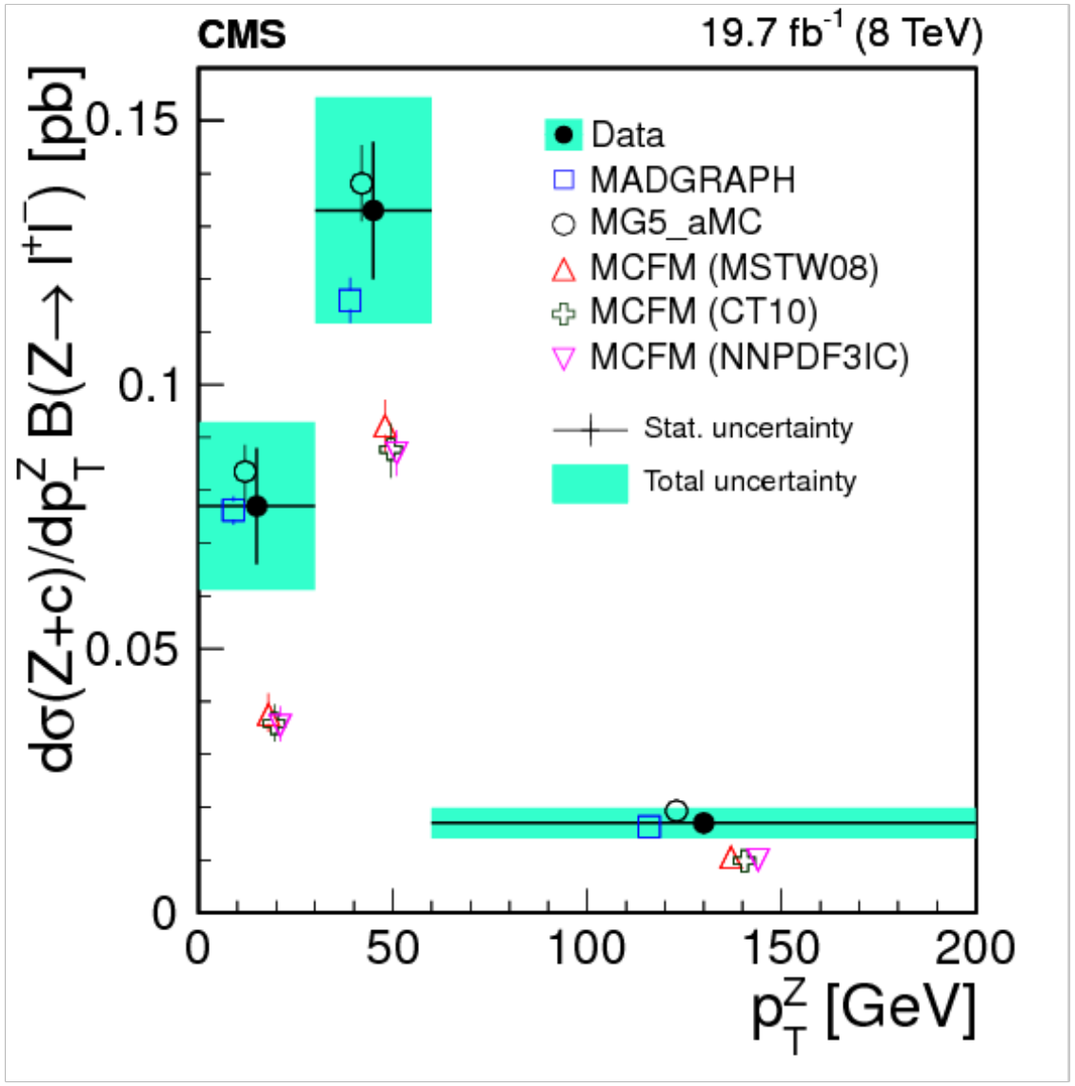
Secondary vertex mass and JP discriminant provide good separation of charm and bottom components of Z+HF jet, used to calculate Z+c yield. Secondary vertex mass distribution validated in ttbar events (b template) and in W+jets (c template)

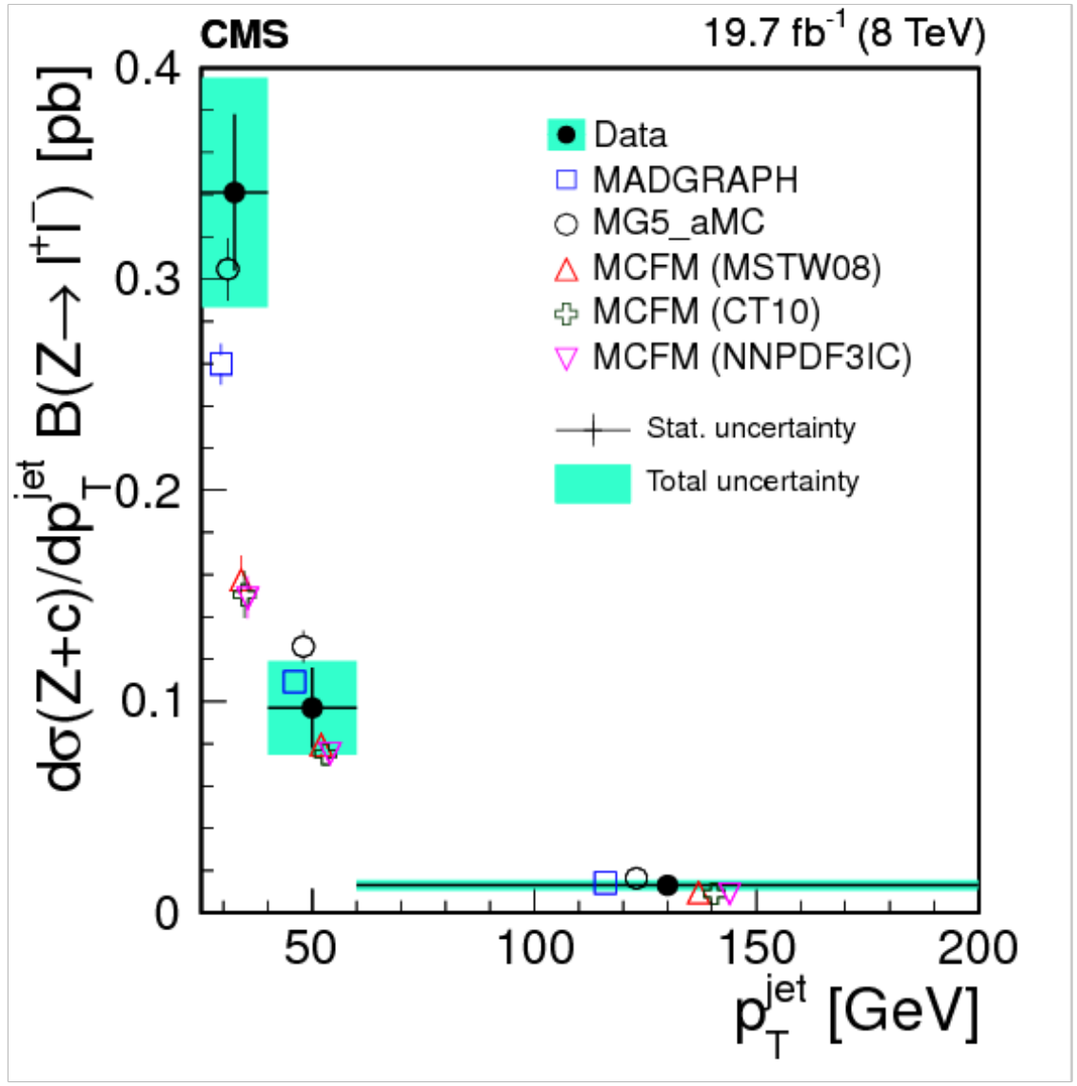
Z+c at 8 TeV
CMS-SMP-15-009

Integral fiducial cross-section:

$$\sigma(\mathrm{Z{+}c})\mathcal{B} = 8.8 \pm 0.5\ (\mathrm{stat}) \pm 0.6\ (\mathrm{syst})\ \mathrm{pb}$$

Differential cross-sections:





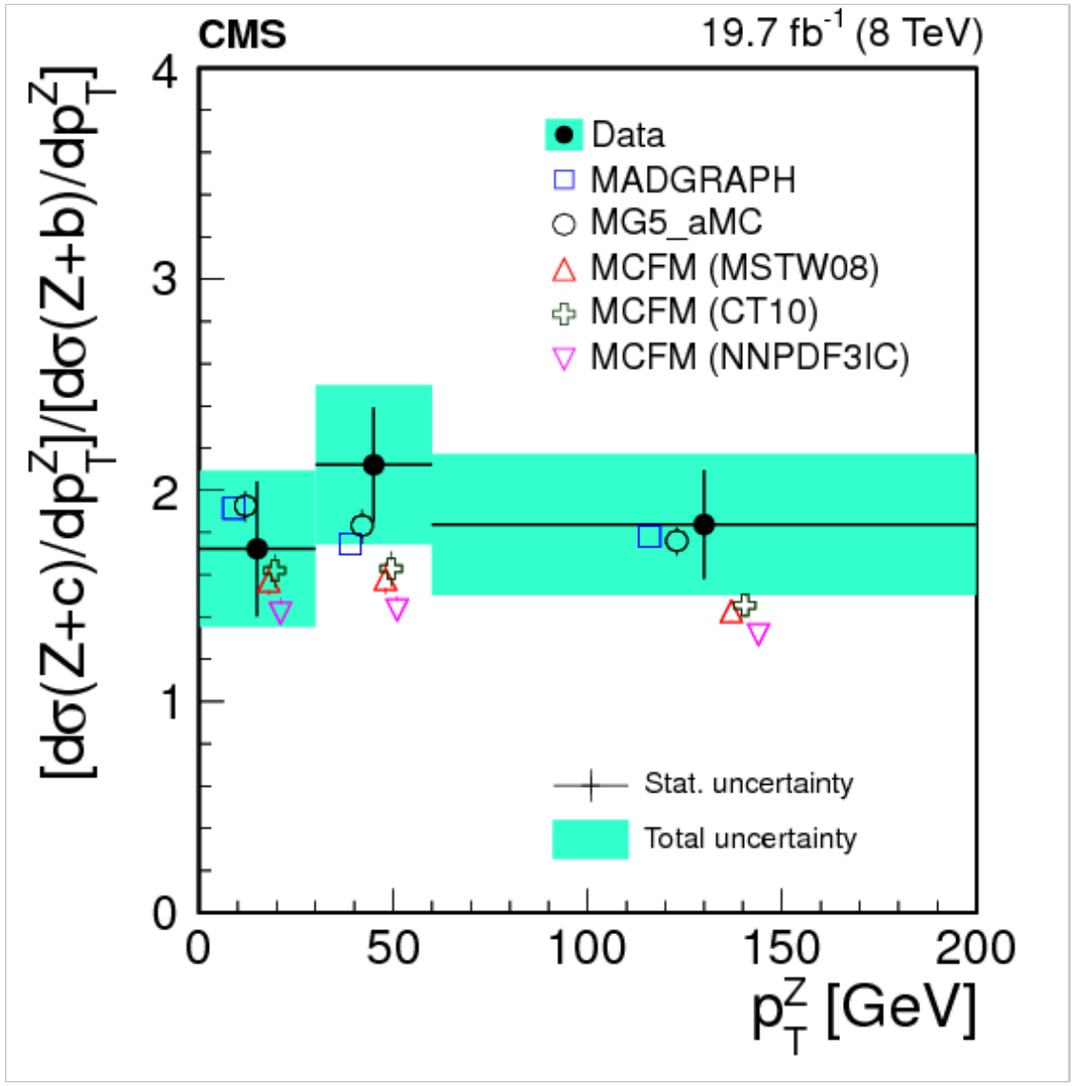
Measurements are in good agreement with LO and NLO predictions by Madgraph, MCFM predictions tend to underestimate the data.

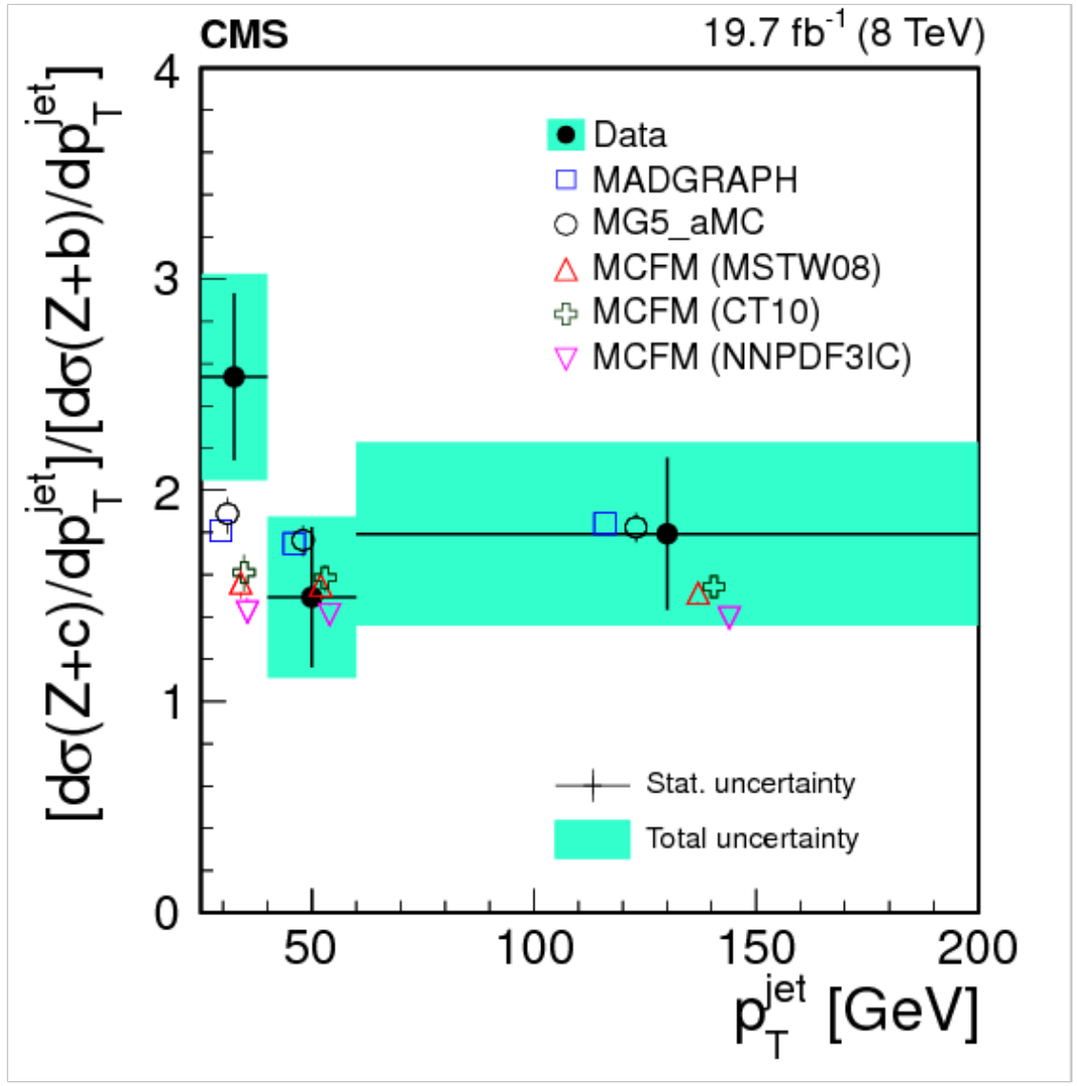
Z+c at 8 TeV
CMS-SMP-15-009

Integral fiducial cross-sections ratios:

$$\sigma(\mathrm{pp} \to \mathrm{Z} + \mathrm{c} + X)/\sigma(\mathrm{pp} \to \mathrm{Z} + \mathrm{b} + X) = 2.0 \pm 0.2(stat.) \pm 0.2(syst.)$$

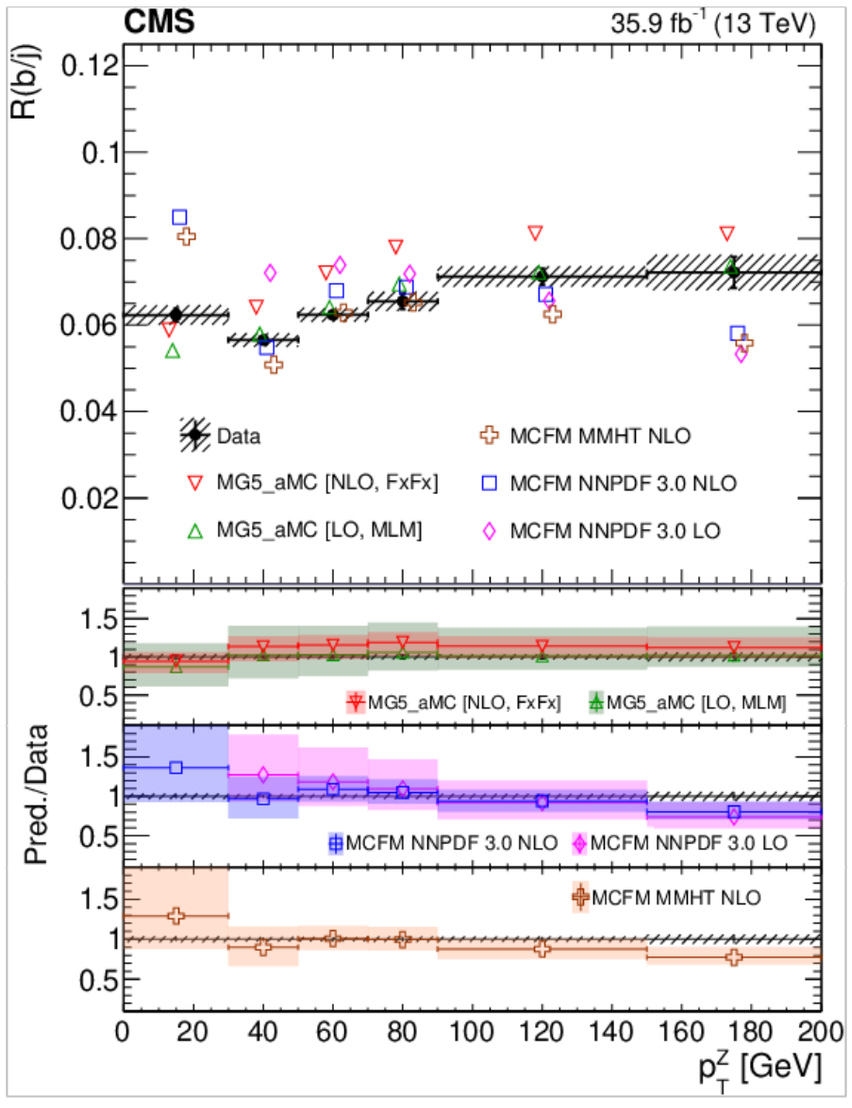
Differential cross-sections ratios:

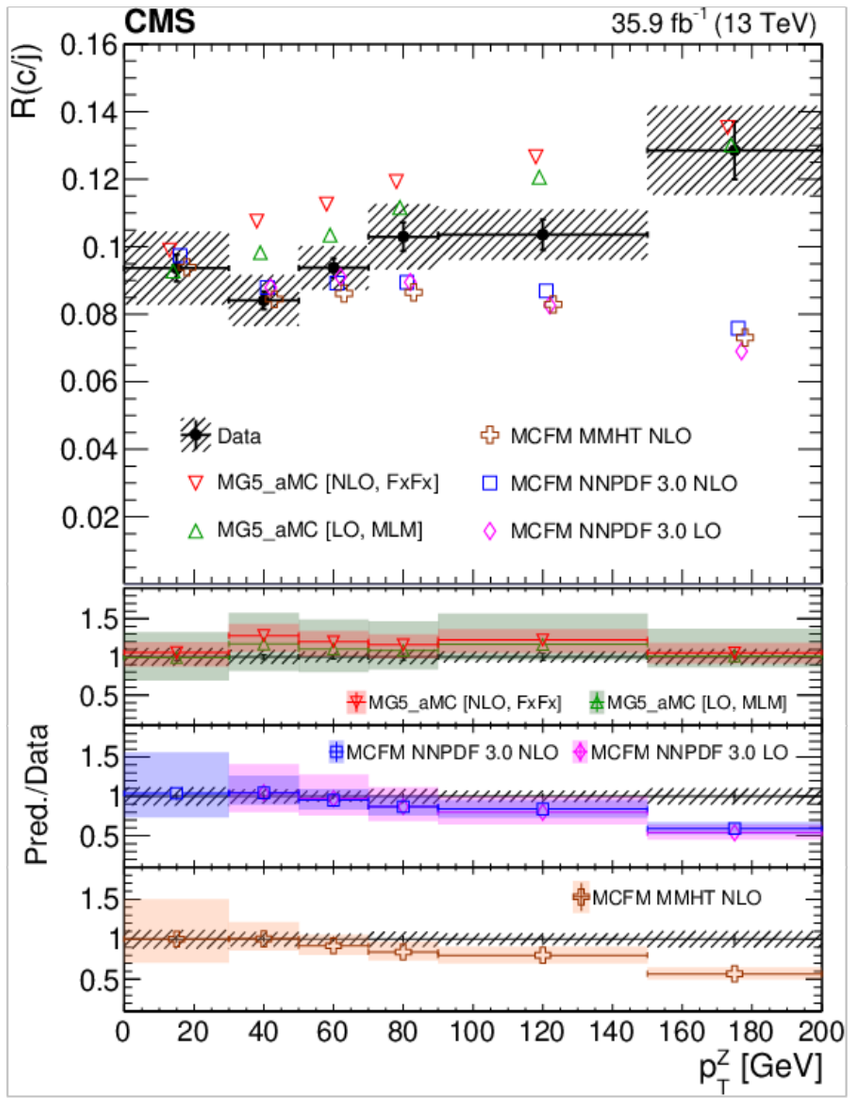


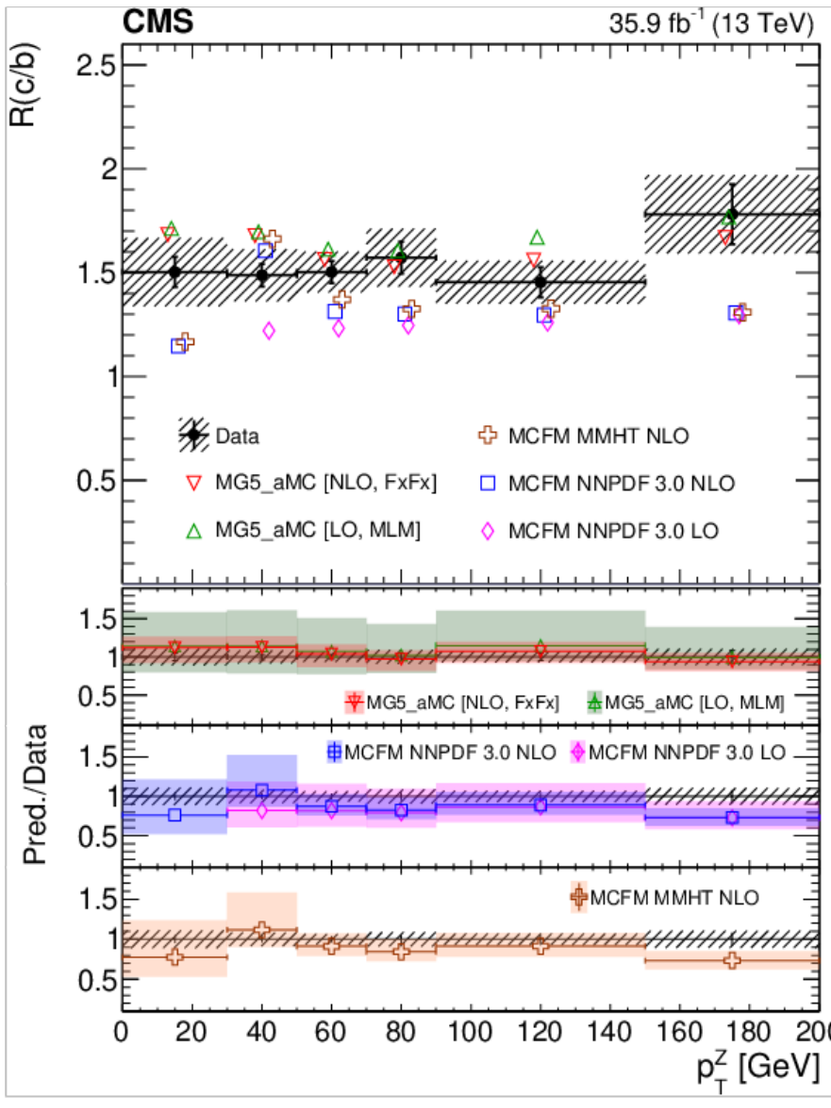


Z+c/b at 13 TeV
CMS-SMP-19-004

Differential cross-sections ratios:







Some disagreement between measurements and theoretical predictions is observed, e.g. for R(c/j) for madgraph LO and NLO and R(b/j) for MCFM.