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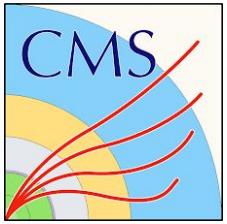

THE ROYAL SOCIETY

V+jets measurements with CMS

Angelo Giacomo Zecchinelli
on behalf of the CMS collaboration

8th Large Hadron Collider Physics Conference - May 25-30, 2020

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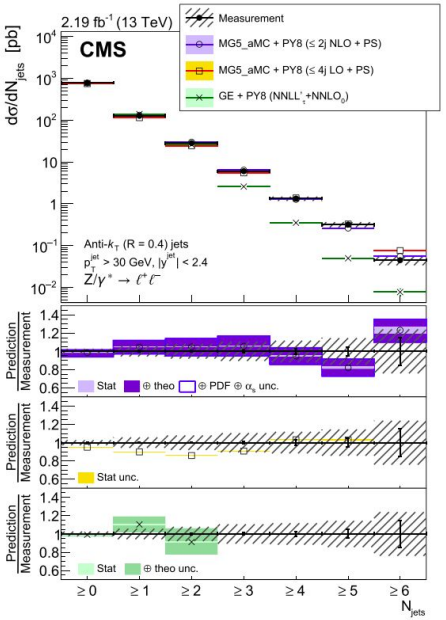
V+jets at CMS

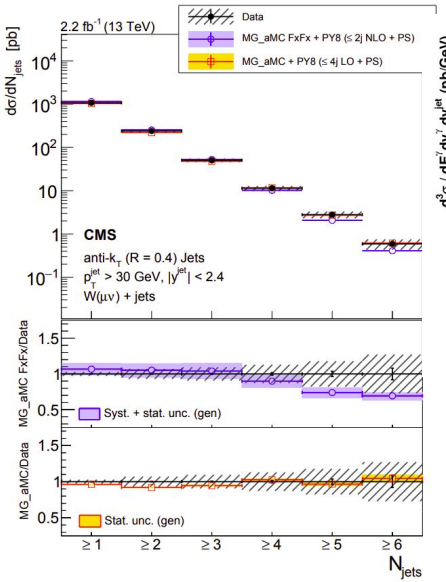
- Provide landmarks to MC and calculations, very active theory developments providing (N)NLO QCD and NLO EW corrections
- Background for many processes and searches
- Important tool for PDF, especially V+HF
- Z,W,γ+jets measured at $\sqrt{s}$ =13 TeV

Selection of newest results from last year in the following slides

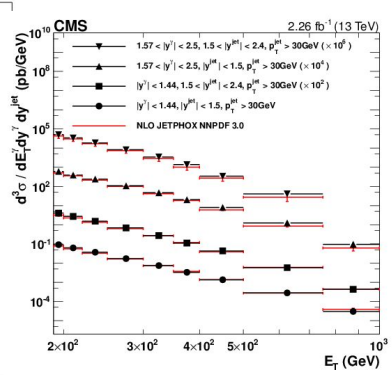
Z+jets
EPJC 78 (2018) 965



W+jets
PRD 96 (2017) 072005



γ+jets
EPJC 79 (2019)20



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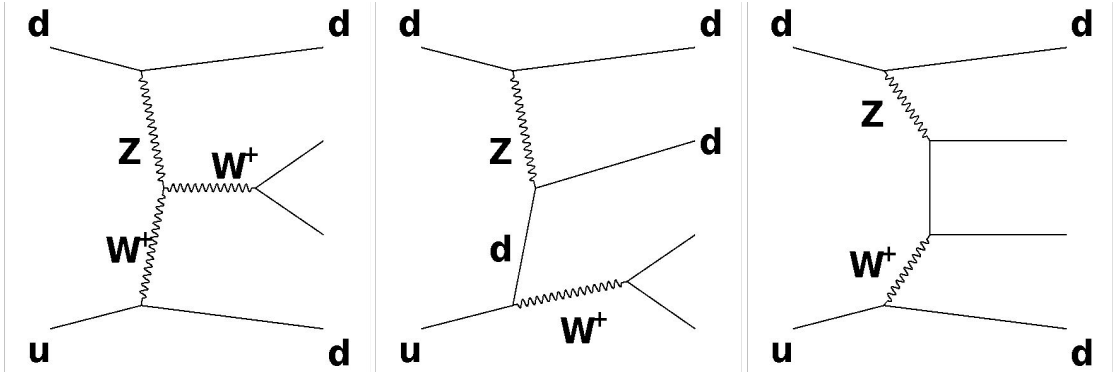
Electroweak production of W+2jets

- 2016 data, lν+jj electron and muon channel
- $M_{jj} > 120$ GeV
- Negative interference between the VBF and other diagrams
- Multivariate analysis to enhance signal over main W+jets background

EPJC 80 (2020) 43



Vector-boson fusion | bremsstrahlung | multi-peripheral

Electroweak production of W+2jets

- BDT discriminating variables:
  - Quark/gluon discriminator for identifying the 2 jets, mainly quarks in signal and gluon in background
  - Zeppenfeld variable

$$y^* = y_W - \frac{1}{2}(y_{j1} + y_{j2})$$

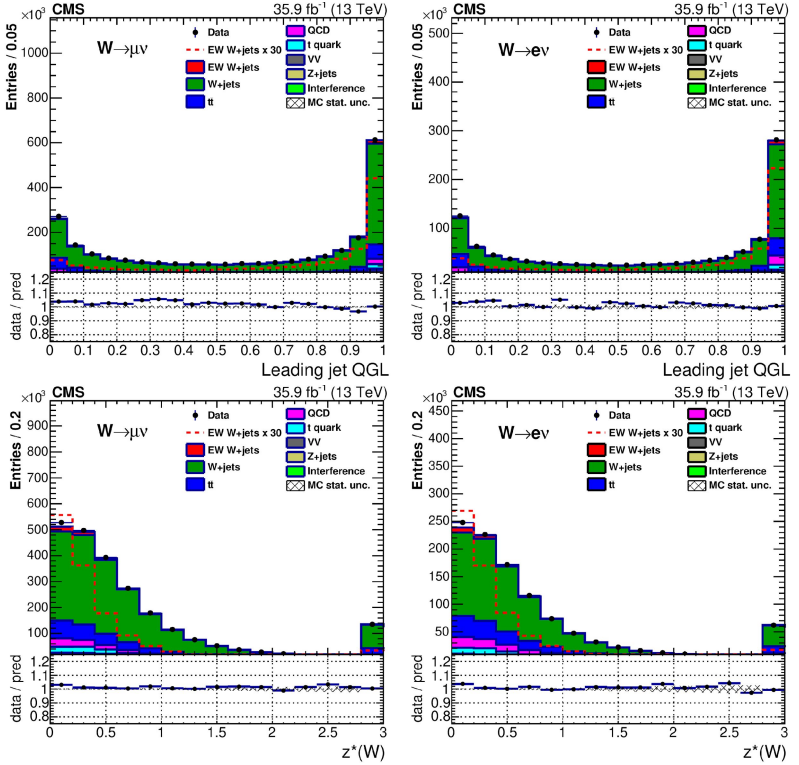
$$z^* = \frac{y^*}{\Delta_{jj}}$$

  - m_{jj} and $\Delta\eta_{jj}$

Signal extracted from fit to BDT distribution

muon channel

electron channel



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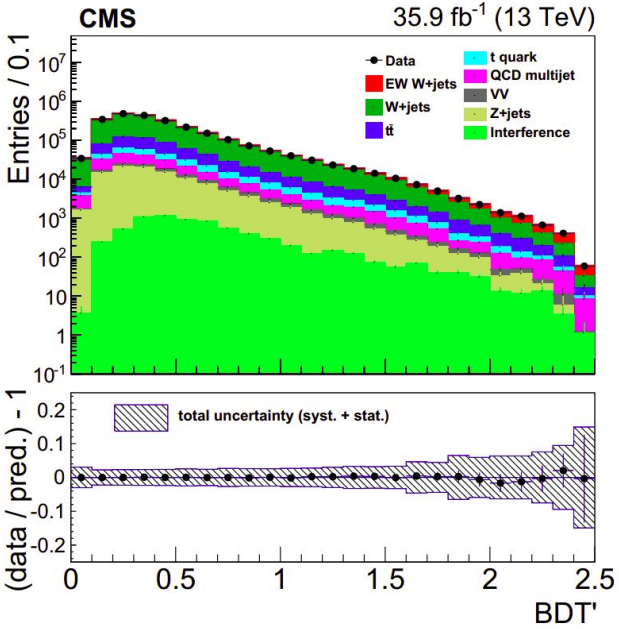
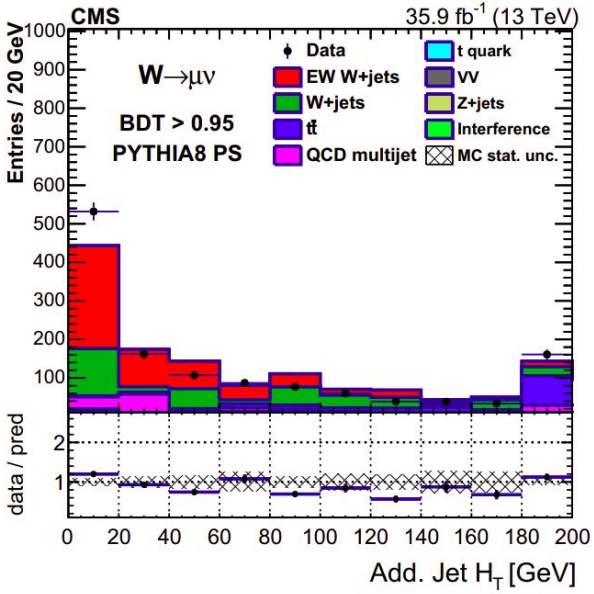
Electroweak production of W+2jets

- Dominant systematics scale variations and m_{jj} corrections
- EWK W+2jets cross section measured σ(EWK lνjj) = 6.23±0.62 pb
- Improved limits on ATGC combined with EWK Zjj
- Study of additional hadronic activity in central region

muon channel





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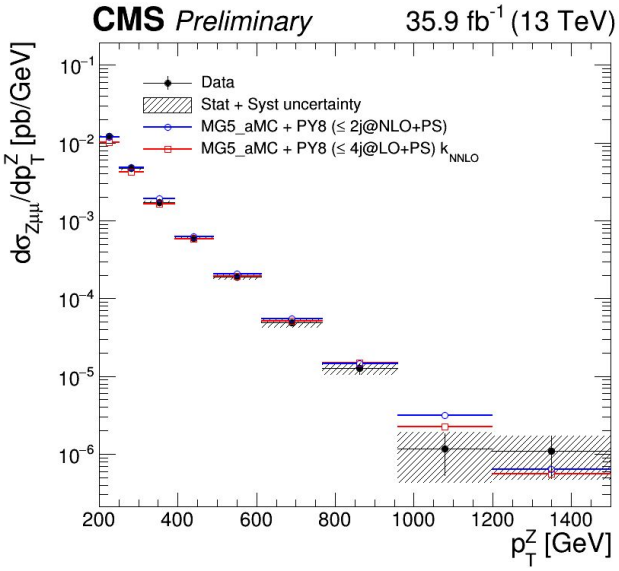
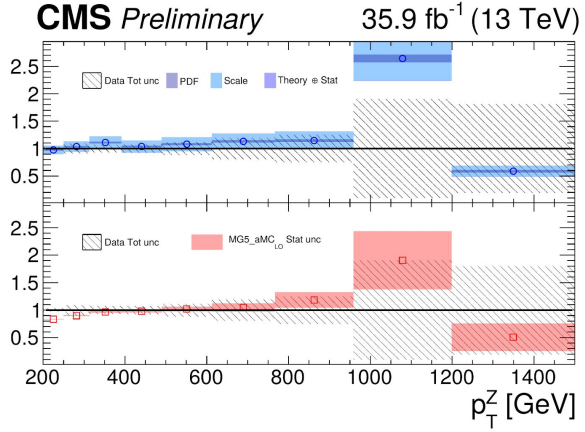
Z/γ+jets at 13 TeV

- Z/γ ratio sensitive to high order EW corrections in the high p_T range
- Important input to constrain backgrounds in searches
- 2016 dataset, Z boson reconstructed from muons
- Z+jets selection:
  - Z p_T > 200 GeV, |y| < 1.4
  - ≥1 jets p_T > 100 GeV, |η| < 2.4



CMS-PAS-SMP-19-010



- Unfolded data compared to Madgraph_aMC@NLO
  - DY+2j NLO
  - DY+4j LO k_{NNLO}

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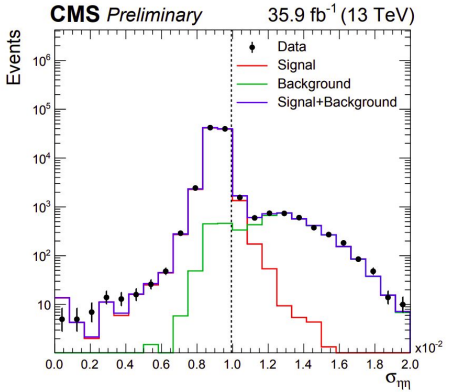
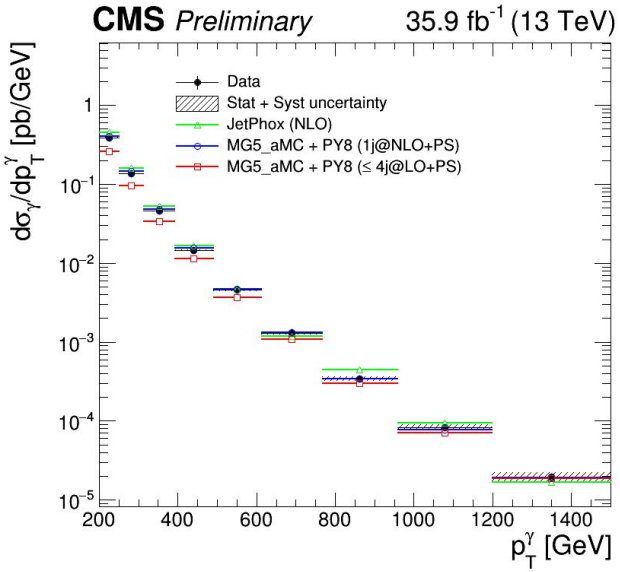
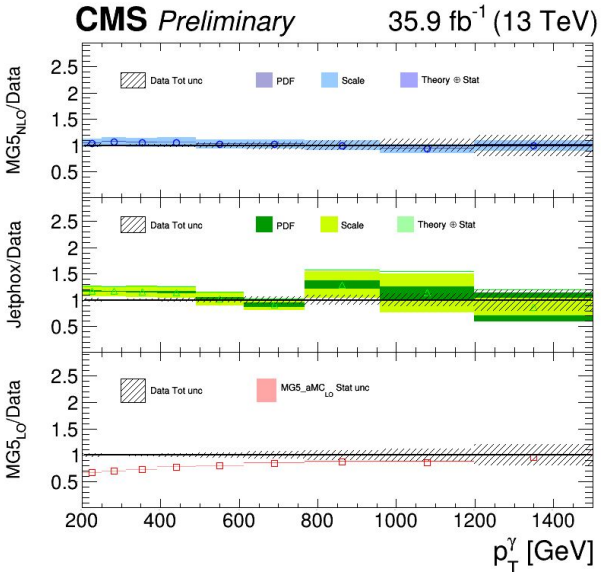
Z/γ+jets at 13 TeV

- γ+jets selection:
  - 1 prompt, isolated γ
  - $p_T^\gamma > 200$ GeV, $|y^\gamma| < 1.4$
  - ≥1 jets $p_T > 100$ GeV, $|\eta| < 2.4$
- Data driven purity estimation







- Unfolded data compared to:
  - MG5_aMC DY+2j NLO
  - JetPhox NLO
  - MG5_aMC DY+4j LO

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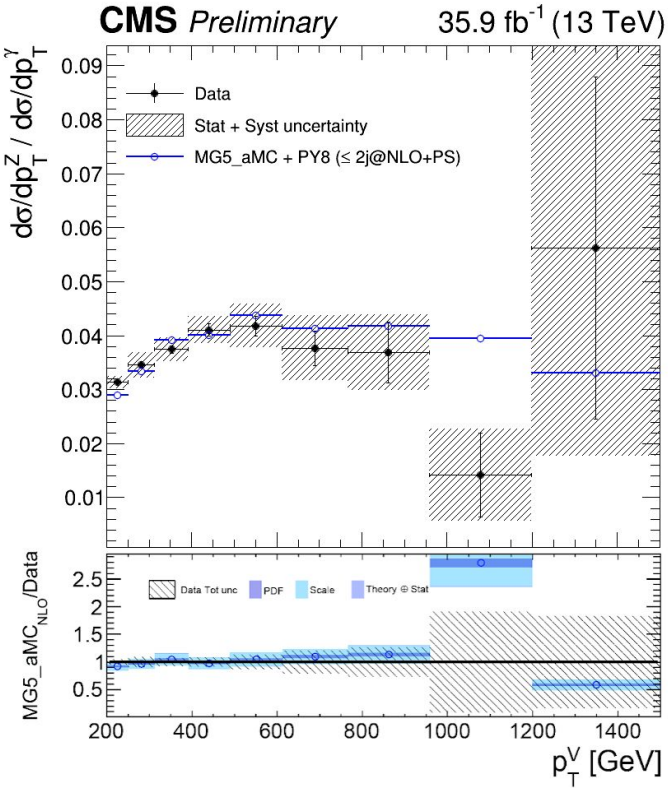
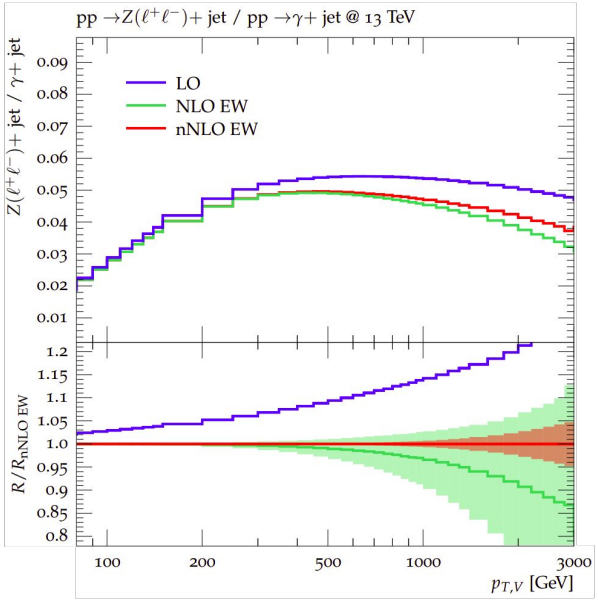
Z/γ+jets at 13 TeV

- Systematics on jet energy and luminosity cancel in the ratio
- Dominant systematics at high p_T are from energy resolution and MC statistic
- Unfolded data compared to Madgraph_aMC@NLO
- Higher order EW effects expected to reduce Z/γ ratio at high p_T



Lindert, J.M., Pozzorini, S., Boughezal, R. *et al.*
arXiv:1705.04664



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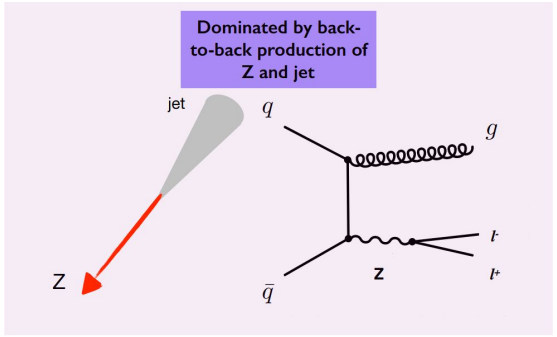
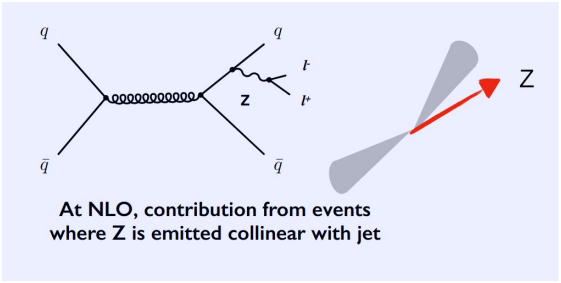
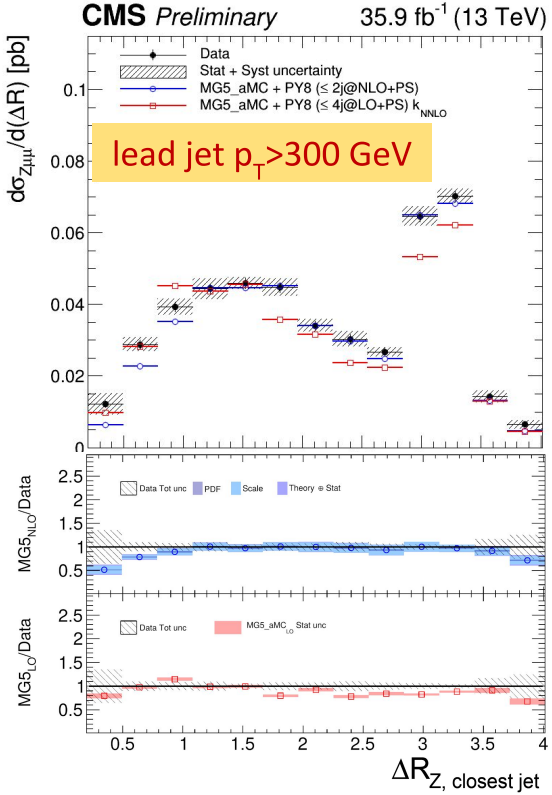
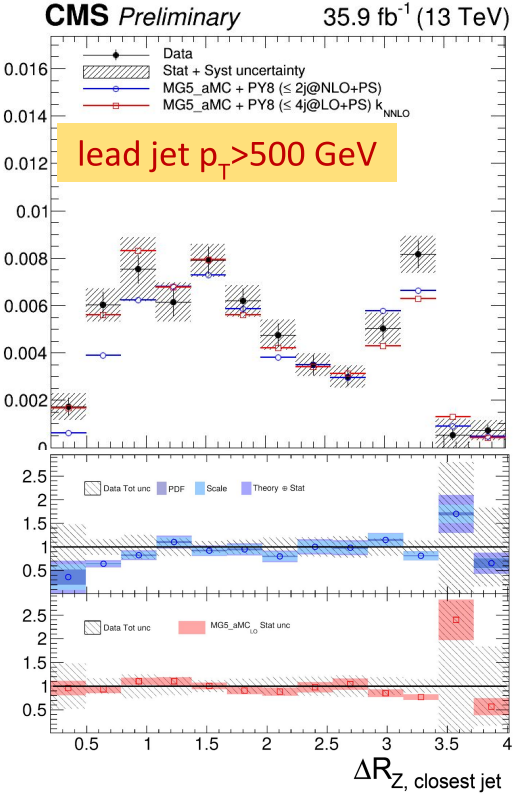
Collinear Z emission at 13 TeV

- 2016 dataset, Z → μμ + jets
- Hard threshold on lead jet to enhance collinear Z emission









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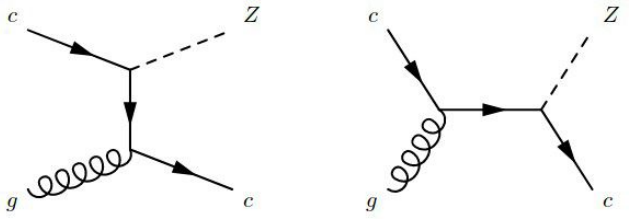
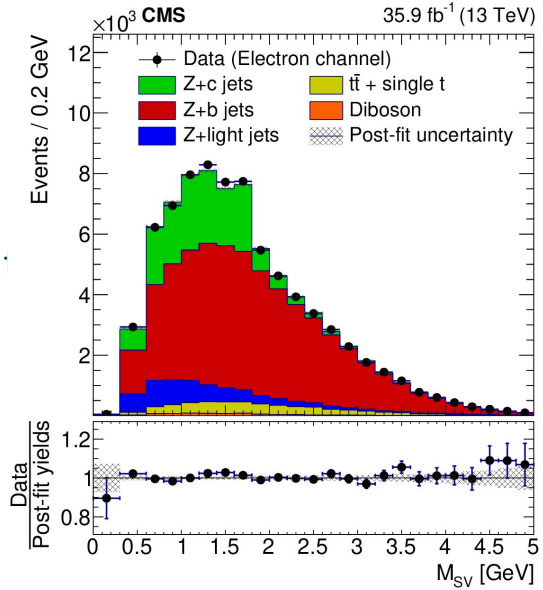
Z+b, Z+c production at 13 TeV

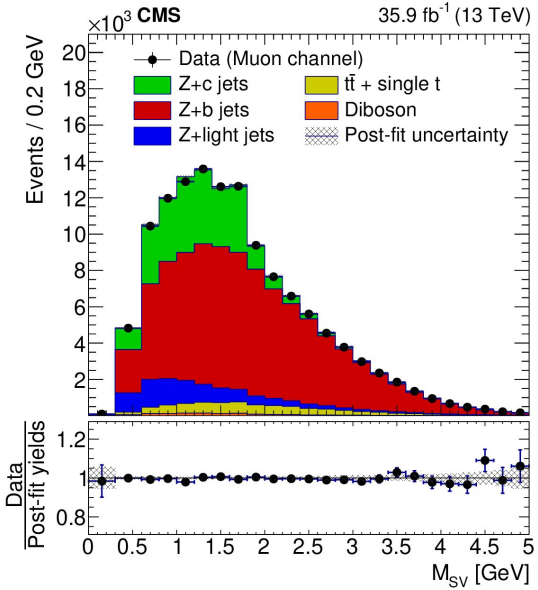
- 2016 data, electron and muon channel
- Interesting process to study the charm contribution in the proton
- Z+b/Z+c component extracted from a fit to the secondary vertex mass in Z+HF events
- Z+c and Z+b templates validated with data samples
- Measure ratios, many systematics cancel



arXiv:2001.06899



electron channel



muon channel

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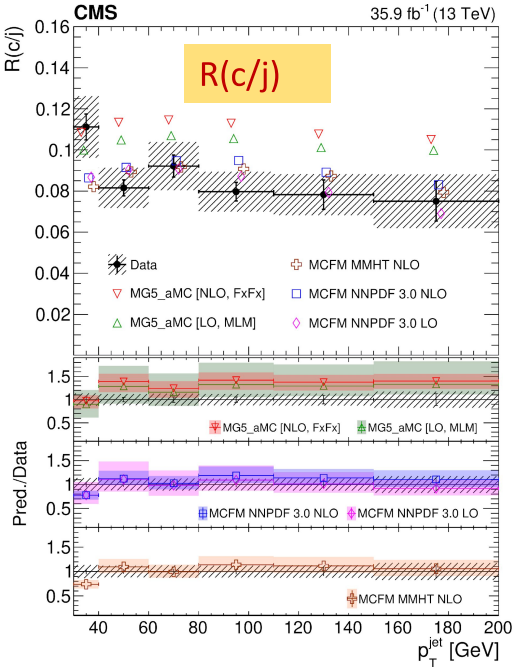
Z+b, Z+c production at 13 TeV - jet p_T

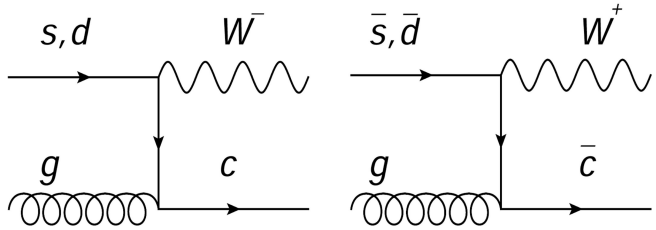


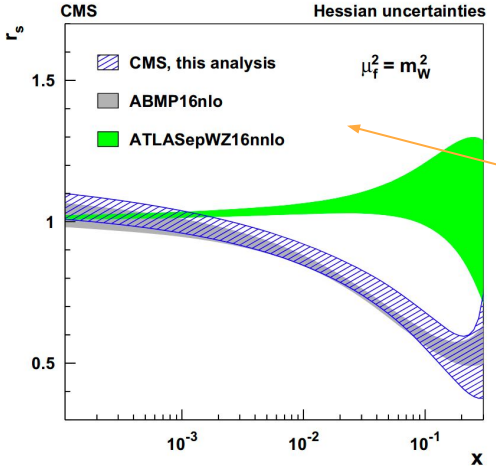
- Madgraph at particle level, MCFM at parton level.
- Madgraph NLO in general higher than data in c,b/j ratio.
- Experimental uncertainties smaller than theoretical uncertainties.

W+c at 8 TeV

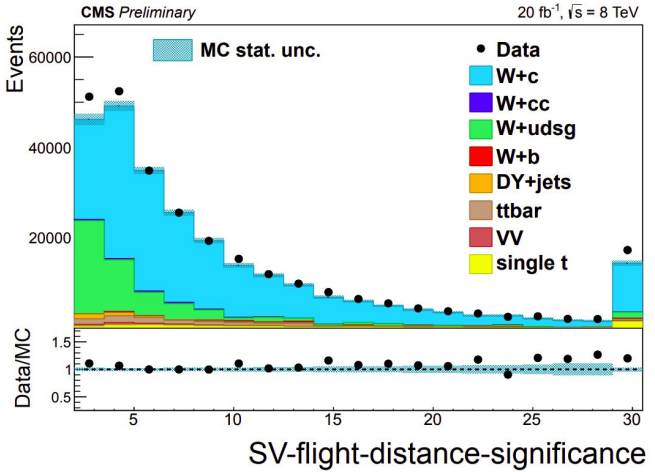
- Identify charm through semileptonic (SL) and hadronic (SV) inclusive decays, W from electron and muon
- qg processes give only OS W-c pairs, while background from W+ $q\bar{q}$ or top give both OS and SS pairs and evaluated from OS-SS subtraction
- Sensitive to the strange content of the proton

CMS-PAS-SMP-18-013





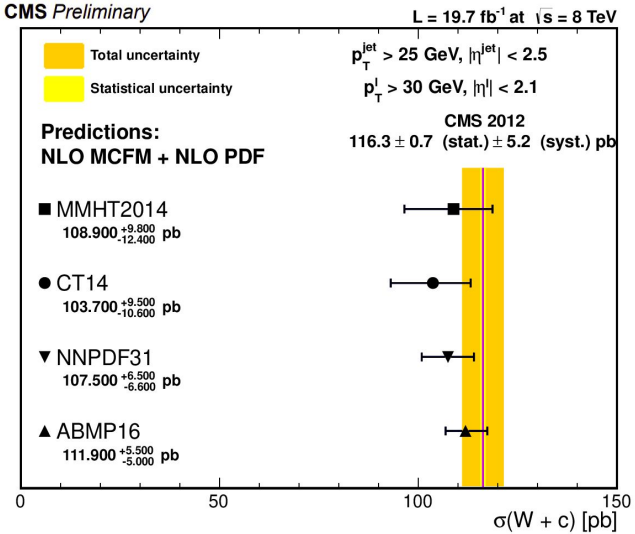
W+charm at $\sqrt{s}$ = 13 TeV,
EPJ C79 (2019),269
CMS results in good agreement with results from neutrino scattering



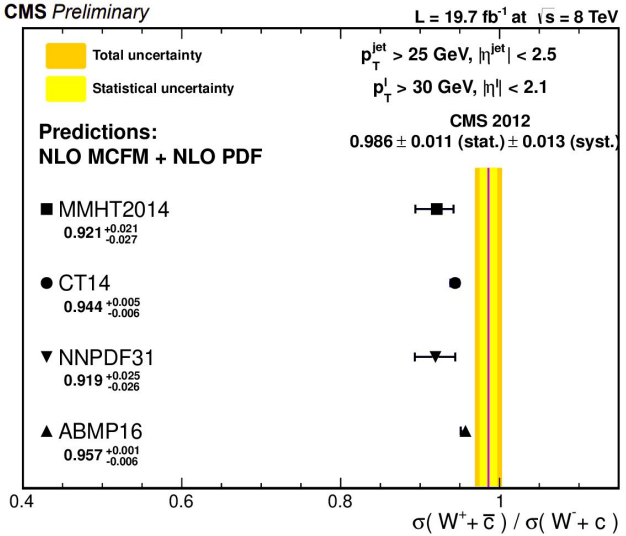
W+c at 8 TeV - inclusive cross-section

- Cross sections compared to NLO MCFM+different PDFs
- Uncertainties: 7% for the SL channel, 5% for the SV channel

W + c



W⁺ + c̄ / W⁻ + c



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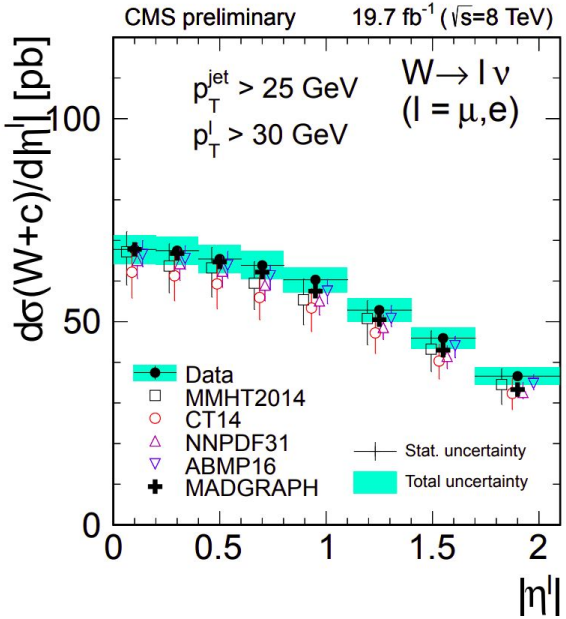
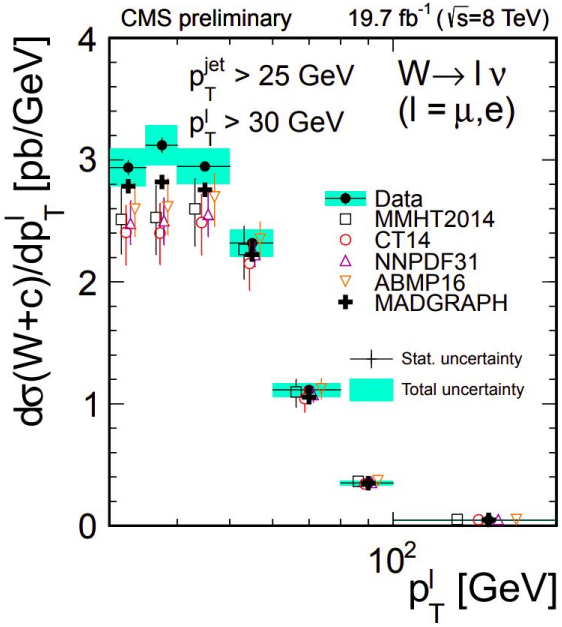
W+c at 8 TeV - differential cross-section

- Main systematics: c-hadron production and decay in MC and charm ID efficiency
- Theoretical predictions undershoots data at low p_T





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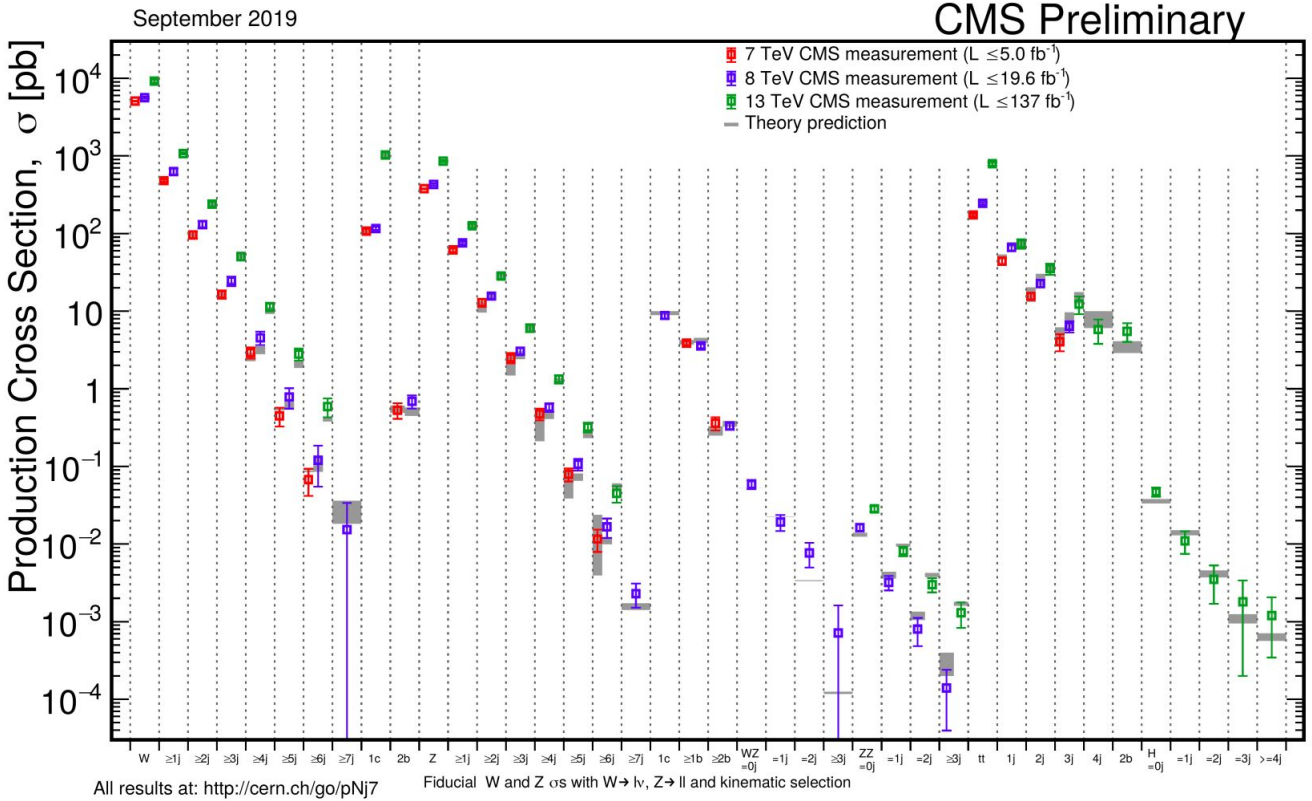
Summary

- V+jets measurements provide crucial test for the Standard Model
- Pushing precision measurements frontiers
- Important tool for pdf, jets
- Discovery potential relies on precision measurements in the tails
- Many analysis in the pipeline for publication



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Summary

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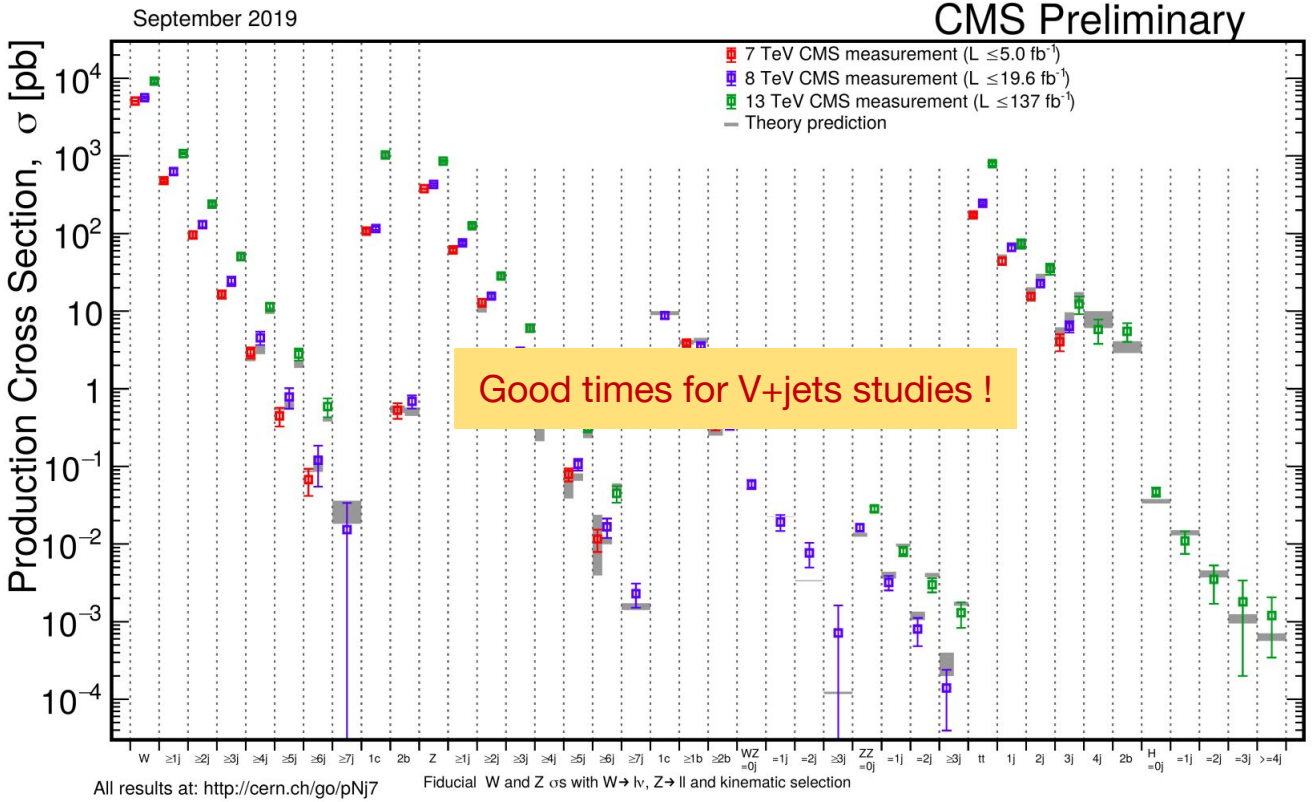

Backup

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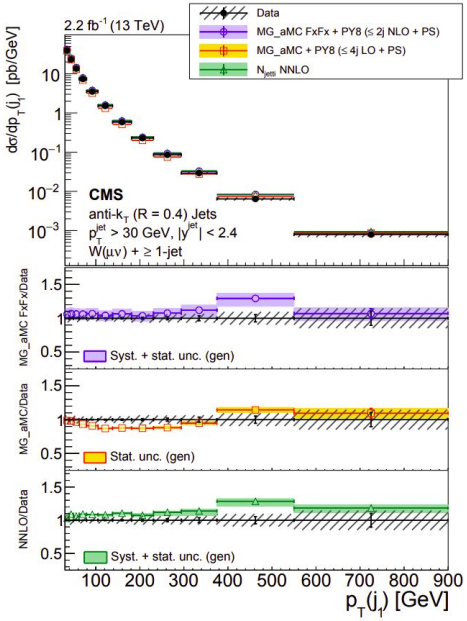
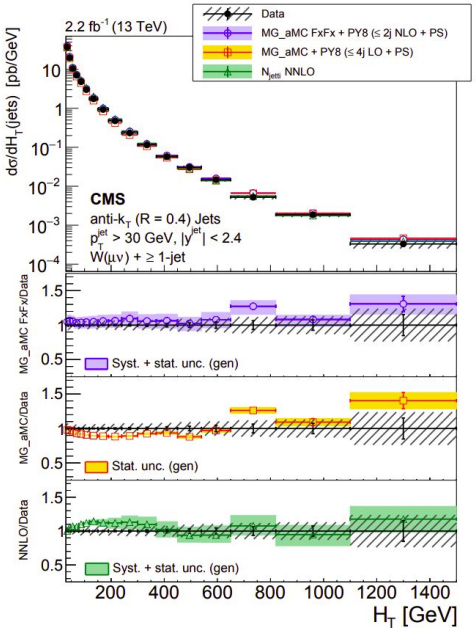
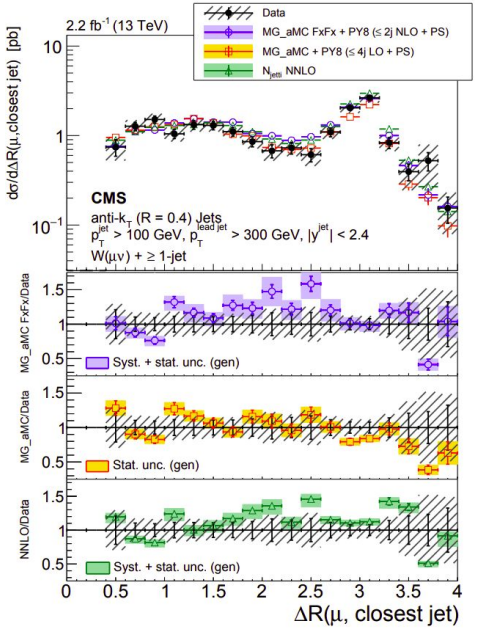
W+jets at 13 TeV

- Event selection:
  - 1 muon, $p_T > 25$ GeV and $|y| < 2.4$
  - ≥1 jets, $p_T > 30$ GeV and $|y| < 2.4$
  - $m_T > 50$ GeV
  - b-quark veto
- ΔR studies:
  - lead jet $p_T > 300$ GeV
  - any other jet $p_T > 100$ GeV







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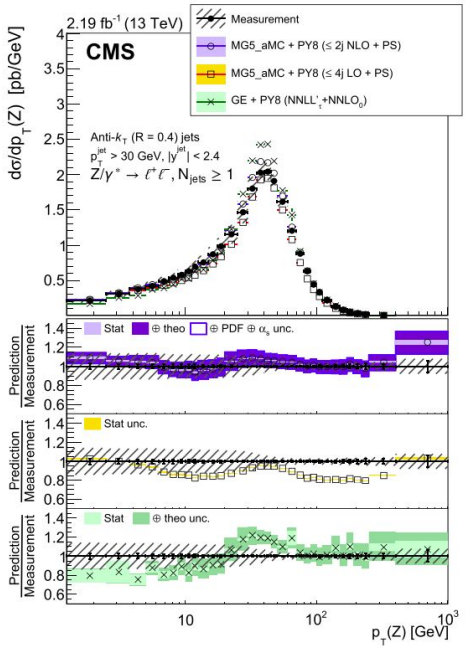
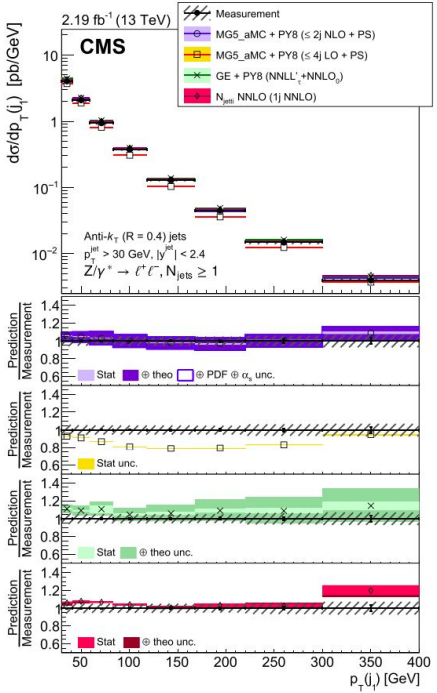
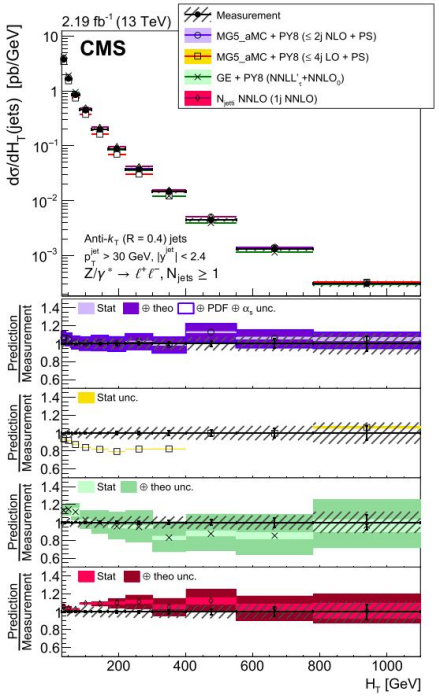
Z+jets at 13 TeV

- Event selection:
  - 2 opposite charged leptons, $p_T > 20$ GeV and $|y| < 2.4$
  - 71 Gev $< m_{ll} <$ 111 GeV
  - ≥1 jets, $p_T > 30$ GeV and $|y| < 2.4$







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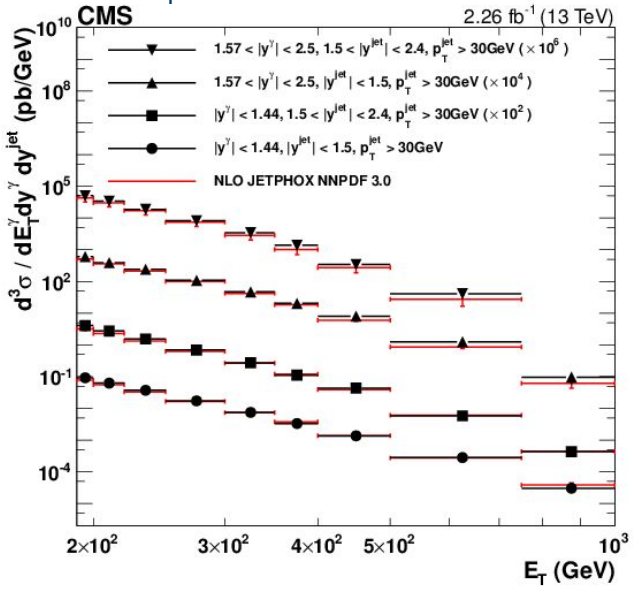
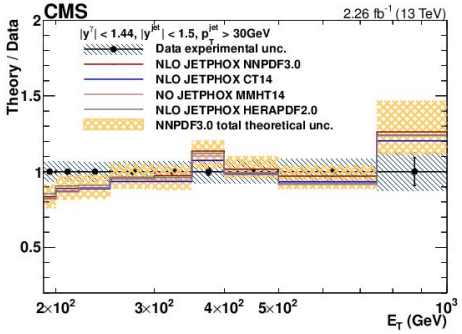
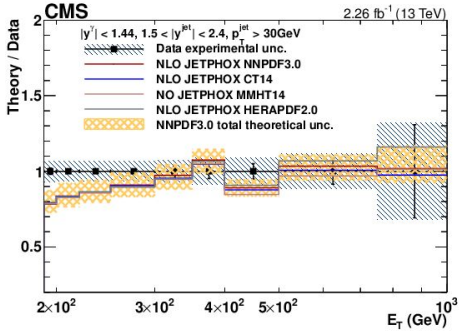
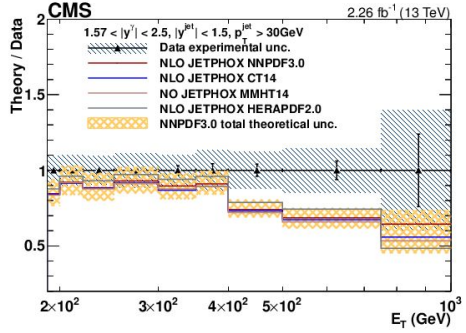
γ+jets at 13 TeV

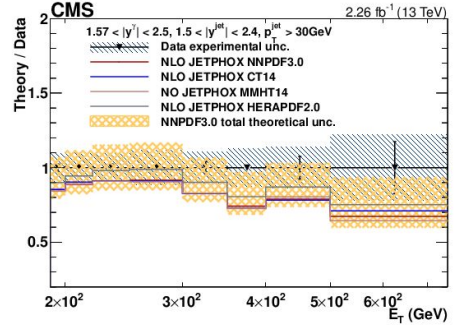
- Triple differential γ+jets cross-section measured at $\sqrt{s}$ =13 TeV, 2015 dataset
- $E_T^{\gamma} > 190$ GeV, $|y^{\gamma}| < 2.5$











- NLO Calculation JetPHOX agrees with data, potential to constrain PDF in low-middle photon E_T
- Sensitive to gluon density

Electroweak production of W+2jets- ATGC

- Dim 6 operators in EFT framework

$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho},$$

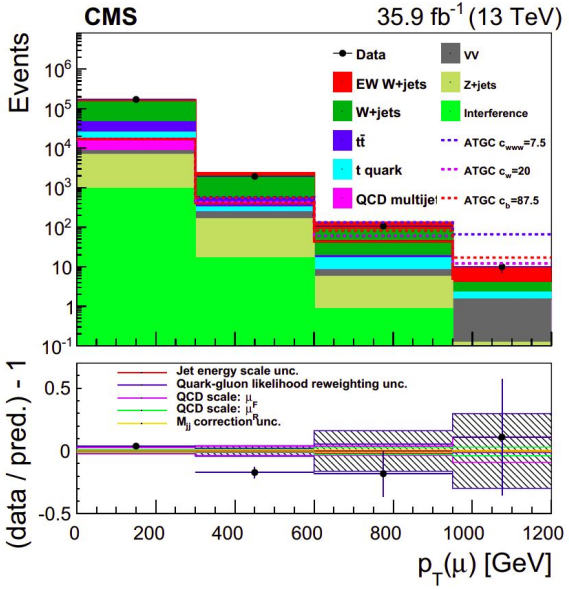
$$\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} W_{\mu\nu} (D^{\nu}\Phi),$$

$$\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} B_{\mu\nu} (D^{\nu}\Phi),$$

$$\tilde{\mathcal{O}}_{WWW} = \frac{\tilde{c}_{WWW}}{\Lambda^2} \tilde{W}_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho},$$

$$\tilde{\mathcal{O}}_{W} = \frac{\tilde{c}_{W}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} \tilde{W}_{\mu\nu} (D^{\nu}\Phi),$$

- Template in $p_T(\ell)$ where signal is included with different hypothesis of dim-6 operators

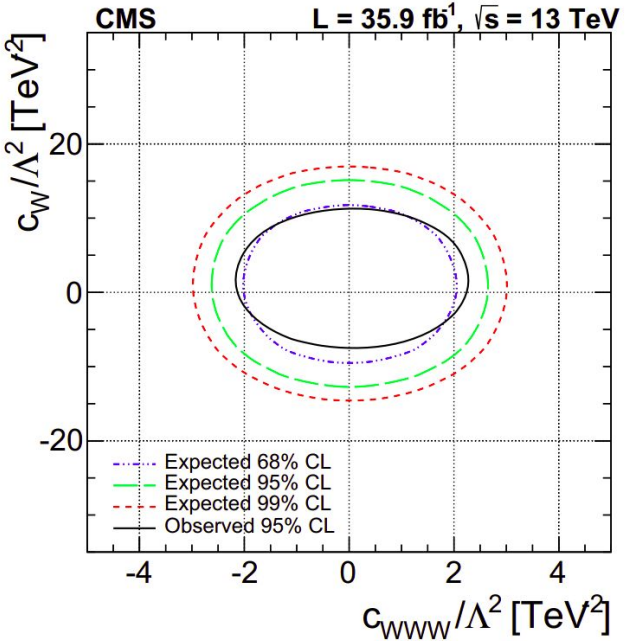


Electroweak production of W+2jets- ATGC

- Combine fit performed including EWK Zjj analysis

Coupling constant	Expected 95% CL interval (TeV^{-2})	Observed 95% CL interval (TeV^{-2})
c_{WWW}/Λ^2	$[-2.3, 2.4]$	$[-1.8, 2.0]$
c_W/Λ^2	$[-11, 14]$	$[-5.8, 10.0]$
c_B/Λ^2	$[-61, 61]$	$[-43, 45]$

- This analysis is most sensitive to c_{WWW}



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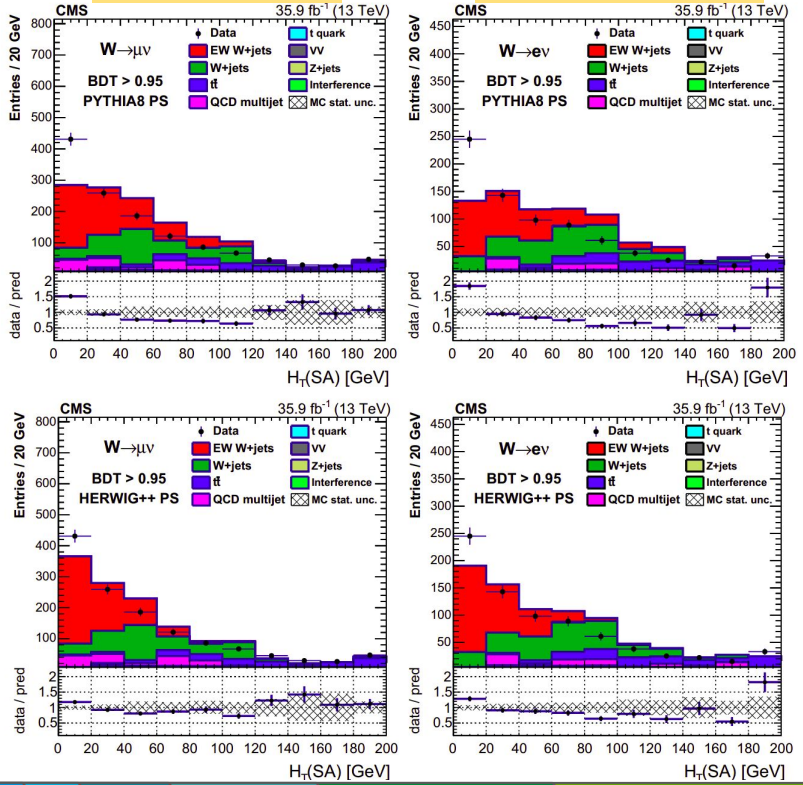
Electroweak production of W+2jets

- Significant suppression of hadronic activity in EWK Wjj is expected
- Studies performed in signal enriched region
- “Soft Activity”: jets from tracks associated with PV, found in the rapidity gap
- Such jets in simulation comes only from PS, important tool for testing PS modelling
- Comparison between PYTHIA 8 and HERWIG++

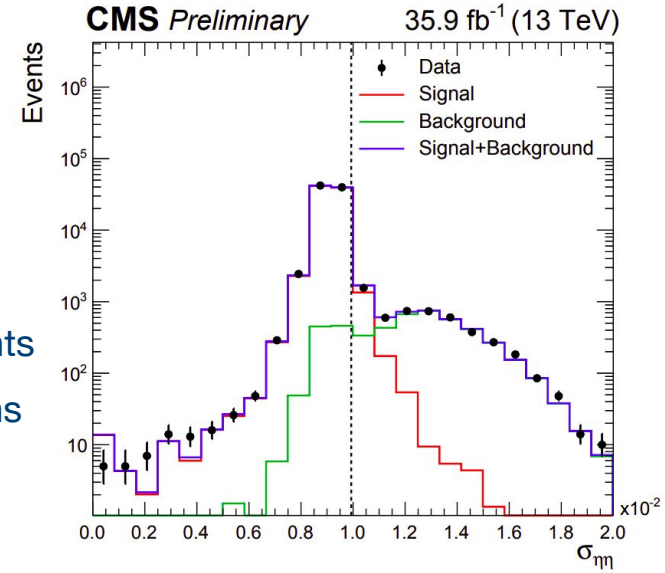
muon channel

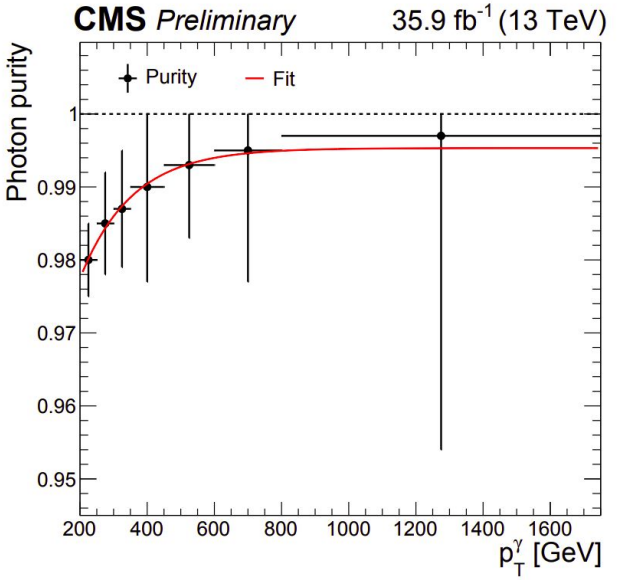
electron channel



Z/γ+jets at 13 TeV

- Purity extracted from template fit to the shower shape variable $\sigma_{\eta\eta}$
- Signal template from γ+jets MC events, corrected with data
- Background template from sideband in data, inverting photon isolation requirements
- Data fitted in different p_T bins
- Beeston-Barlow method to take into account finite template statistic
- Alternative templates for systematic effects





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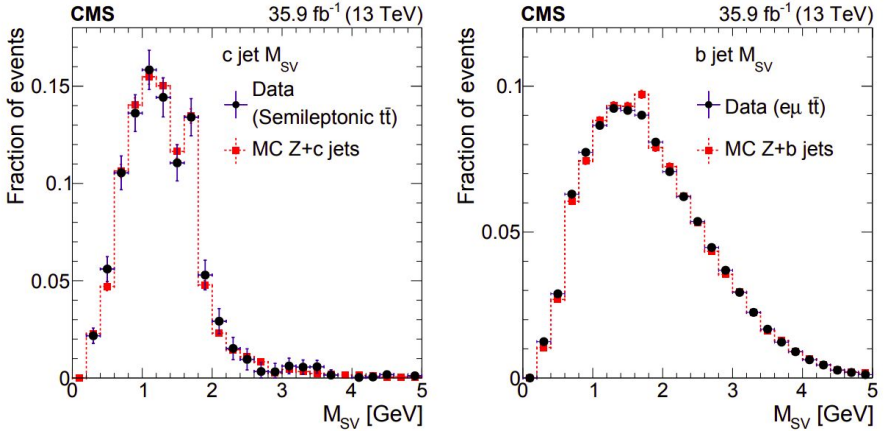
Z+b, Z+c production at 13 TeV

- Event selection:
  - 2 leptons $p_T > 25$ GeV, $|\eta| < 2.4$
  - 71 GeV $< m_{ll} <$ 111 GeV
  - $p_T^{miss} < 40$ GeV (reducing $t\bar{t}$)
  - ≥1 jets $p_T > 40$ GeV, $|\eta| < 2.4$
  - ≥1 HF tagged jets
- HF tagger working point:
  - 10 % c-jets
  - 60 % b-jets
  - 1 % light jets

- Data driven template validation:



- Inclusive cross section measurement:

	Electron	Muon	Combined
R(c/j)	$0.105 \pm 0.003 \pm 0.009$	$0.101 \pm 0.002 \pm 0.009$	$0.102 \pm 0.002 \pm 0.009$
R(b/j)	$0.0639 \pm 0.0006 \pm 0.0015$	$0.0629 \pm 0.0005 \pm 0.0014$	$0.0633 \pm 0.0004 \pm 0.0015$
R(c/b)	$1.65 \pm 0.04 \pm 0.15$	$1.61 \pm 0.04 \pm 0.15$	$1.62 \pm 0.03 \pm 0.15$

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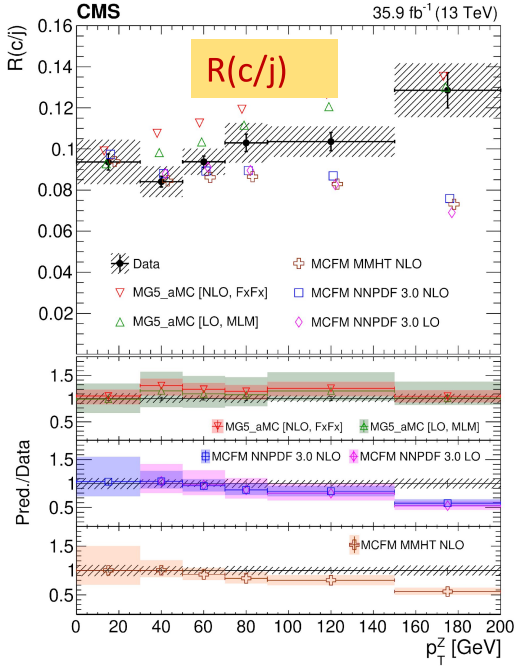
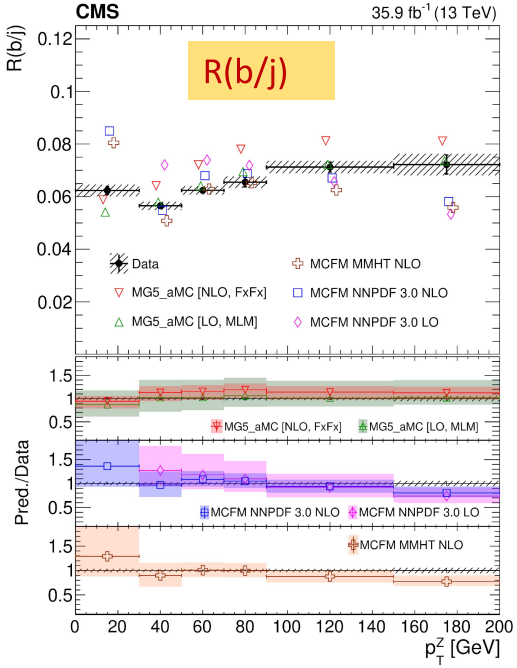
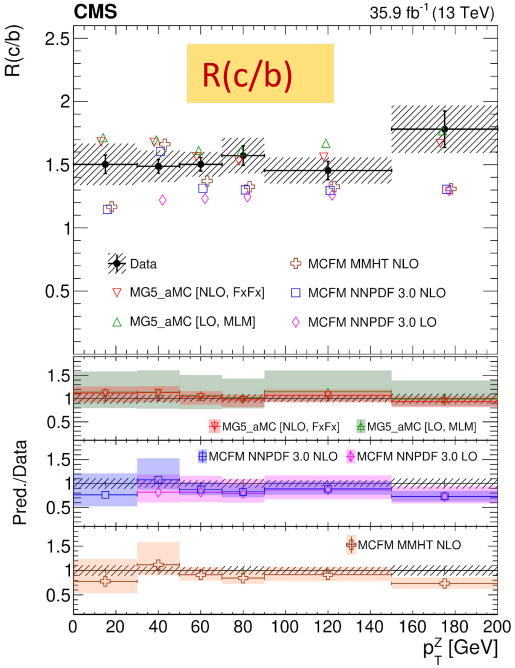
Z+b, Z+c production at 13 TeV - Zp_T







- Madgraph at particle level, MCFM at parton level.
- Madgraph NLO in general higher than data in c,b/j ratio.
- Experimental uncertainties smaller than theoretical uncertainties.

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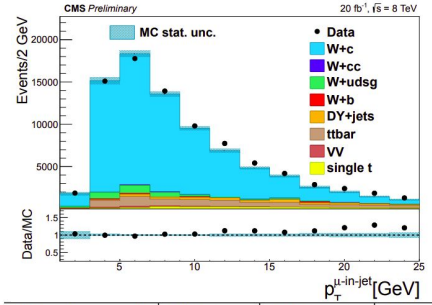
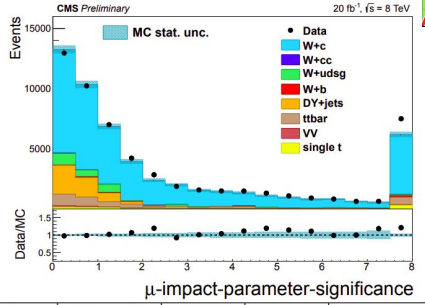
W+c at 8 TeV

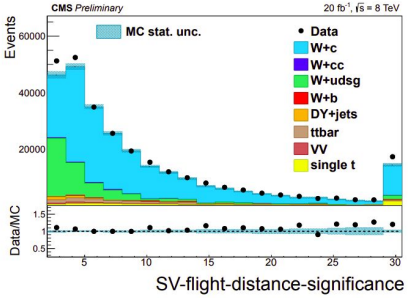
- Semileptonic (SL) channel:
  - semileptonic decay of a c hadron to muon inside the jet
  - charge of c-quark measured from muon

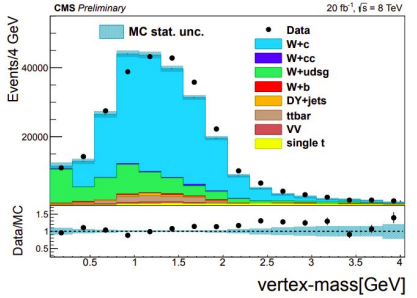




SL channel	W + c	W + cc̄	W + udsg	W + b	DY	tt̄	single top	VV
W → eν	82.6%	0.2%	4.6%	0.4%	0.5%	8.4%	2.3%	1.0%
W → μν	77.7%	0.4%	3.2%	0.6%	6.9%	7.8%	2.5%	0.9%

- Secondary vertex (SV) channel :
  - reconstructed displaced secondary vertex inside the jet
  - c-quark charged determined summing over the jet tracks





SV channel	W + c	W + cc̄	W + udsg	W + b	DY	tt̄	single top	VV
W → eν	73.8%	0.5%	15.1%	0.7%	1.9%	3.8%	3.2%	1.0%
W → μν	74.5%	0.7%	16.0%	0.5%	0.6%	3.2%	3.5%	1.0%