Vector boson associated with jets in CMS

Philippe Gras[1]
On behalf of the CMS collaboration

[1] CEA/IRFU - Saclay

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Introduction

V+jets

- The clean final state and the abundant production at LHC makes it a good test of pQCD calculation
- Its large cross-section allows validation of calculation techniques common with Higgs production cross section calculation
- Playground to explore non-perturbative terms: soft gluon radiation, PDFs.
- Background for many LHC analyses, whose modeling is essential.

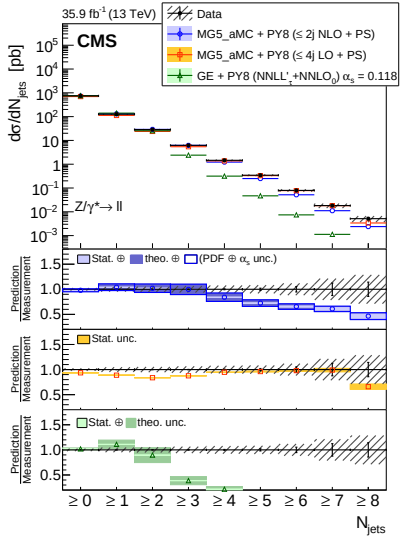
I will present the most recent results from CMS

Z + any jets differential cross section

- CMS-SMP-19-009 submitted to PRD.
  35.9fb^{-1}@13 TeV
  - N_{jets}, H_{T}, $p_{\text{T}}(\text{j}_i)$, $y(\text{j}_i)$, $m(\text{j}_1,\text{j}_2)$
  - y_{diff}, y_{sum}, and $\Delta\varphi$ between Z, three leading jets, and jet_1+jet_2
  - 2D: $(p_{\text{T}}(\text{jet}_1), y(\text{jet}_1))$, $(y(\text{Z}), y(\text{jet}_1))$, $(p_{\text{T}}(\text{Z}), y(\text{Z}))$
- $m_{\ell\ell}$ in 71…110 GeV; ℓ: p_{T}>30, 20 GeV, $|\eta| < 2.4$; jets: $p_{\text{T}} > 30$ GeV, $|y| < 2.4$

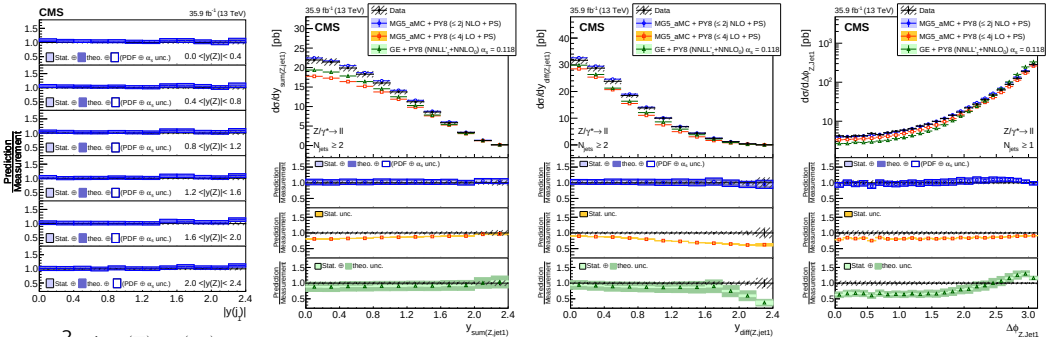
Compared with predictions:

- from MG5_aMC + Pythia 8 with: 0,1,2 jets @NLO merged with FxFx;
- from MG5_aMC + 0,1,2,3,4 jets @LO merged with k_{T}MLM;
- from Geneva NNLL′$_\tau$ + NNLO$_0$ + Pythia8;



Z + any jet differential cross section: rapidities and $\Delta\phi$

Good description from merged FxFx sample of Z and jet 1 rapidities and angular correlations



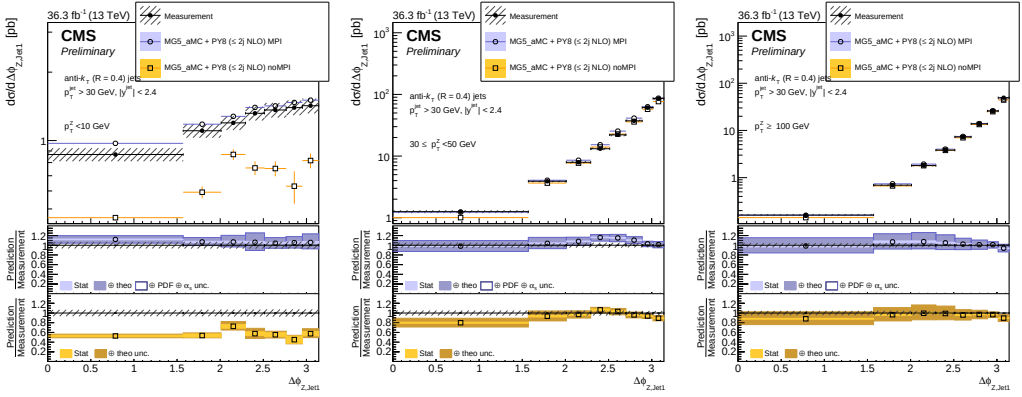
$\mathrm{d}^2\sigma/\mathrm{d}y(\mathrm{Z})\mathrm{d}y(j_1)$

$y_{\mathrm{sum(Z,j_1)}} = (y(\mathrm{Z}) + y(\mathrm{j_1}))/2$

$y_{\mathrm{diff(Z,j_1)}} = |y(\mathrm{Z}) - y(\mathrm{j_1})|/2$

Z + any jet differential cross section: $\Delta\phi$

- We have also measured the azimuthal angles as function of Z p_T: $< 10\,\text{GeV}$, $30 \ldots 50\,\text{GeV}$, $> 100\,\text{GeV}$
  - Results released last Summer, CMS-PAS-SMP-21-003



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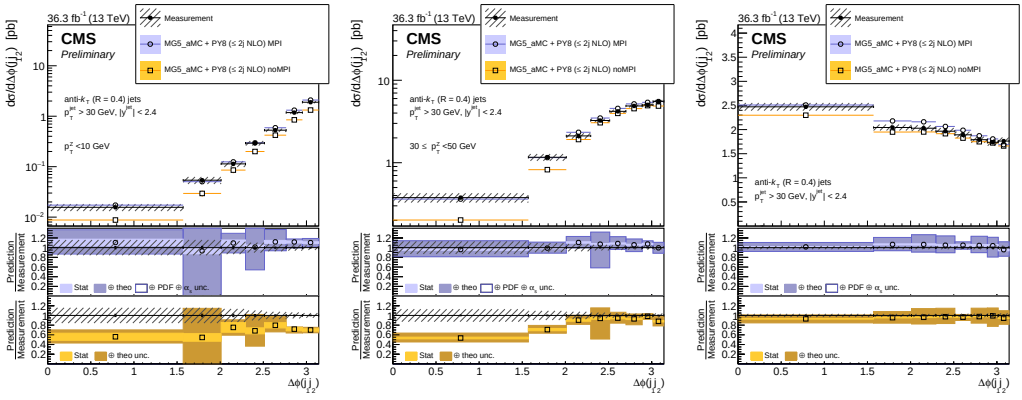
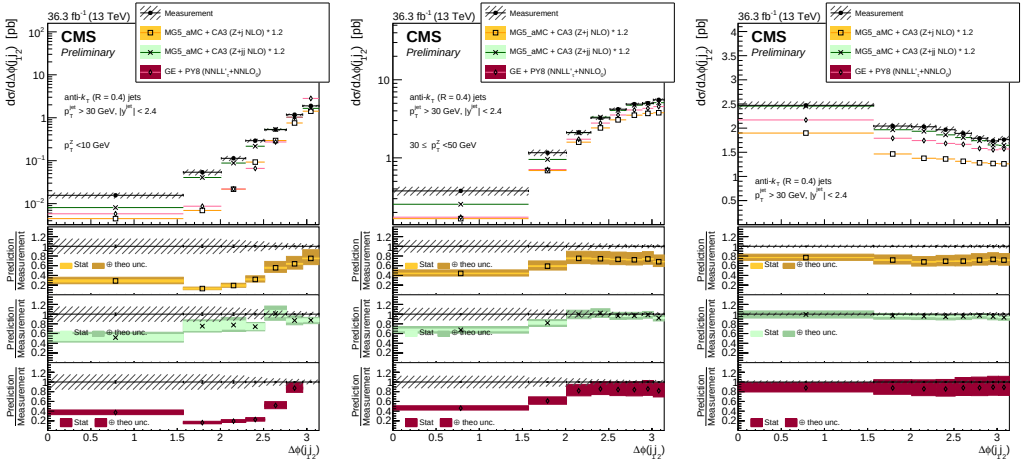
Z + any jet differential cross section: $\Delta\phi(j_1,j_2)$



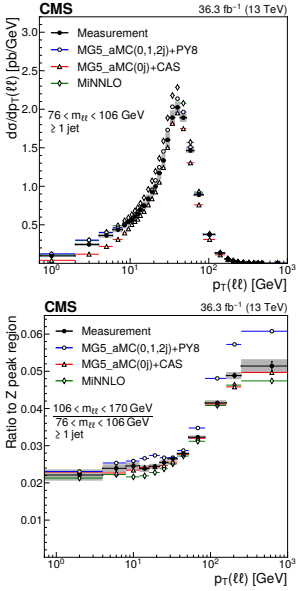
Z + any jet differential cross section: $\Delta\phi(j_1, j_2)$

- In this analysis we have also compared the measurements with TMD-based PS:
  - from MG5_aMC and with 1 jet @NLO, a TMD-based PS using CASCADE3 and Pythia6 for hadronisation (orange);
  - same with 2 jet @NLO ($p_T > 15$ GeV) (green)

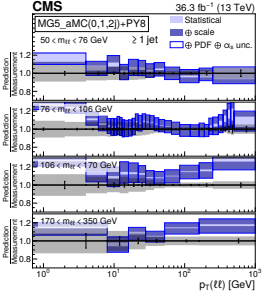


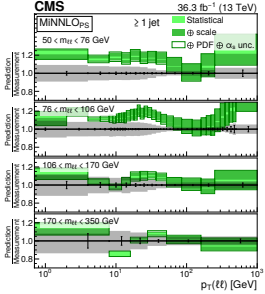
Mass dependency of dilepton pair p_T in Drell-Yan production

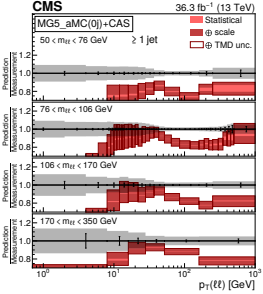
- Submitted to EPJC in May 22, CMS-SMP-20-003
- $p_T(\ell\ell)$ and $\varphi^*_\eta = \tan((\phi - \Delta\varphi)/2)\sin(\theta^*)$ distribution measured as function of $m_{\ell\ell}$ for a Z boson in and out of the mass peak.
- Measurement performed with and without requiring one jet with $p_T > 30\,\text{GeV}$ and $|y| < 2.4$
- Low p_T regions, $p_T < \mathcal{O}(m_{\ell\ell})$, provides a good test of soft gluon radiation resummation, while high p_T region provides test of calculation including higher QCD orders.
- Compared with six predictions with different soft initial state QCD radiation:
  - The four mentioned before;
  - MiNNLO$_{PS}$, NNLO matched with PS;
  - arTeMiDe: using TMDs obtained from fits to DY measurements at different energies: N^{3}LL, valid for $p_T < 0.2 m_{\ell\ell}$;
  - Geneva with resummation of higher orders at N^{3}LL in q_T matched with NNLO and PS.

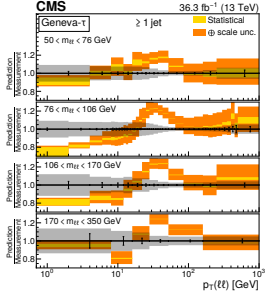


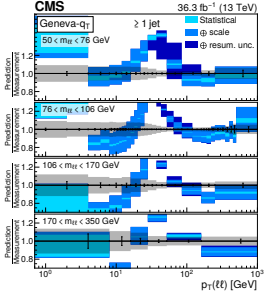
Mass dependence of dilepton pair p_T in Drell-Yan production











- Z+ ≥1 jet(s)
- No prediction describes perfectly the data in full explored phase space
- Region below the 30 GeV jet p_T requires two jets leading to a phase space where only the MG5_aMC prediction has an NLO accuracy.
- See talk "Recent measurements of W and Z bosons with the CMS experiment" Marco Cipriani gave this morning for $Z+ \geq 0$ jets resultsxs

Production in association with heavy flavor jets

Latest results

- W + c 8TeV: CMS-SMP-18-013 submitted to EPJC
- W + c with full Run 2 dataset: CMS-PAS-21-005, new preliminary result
- Z + b with full Run 2 dataset: CMS-SMP-20-015 accepted by PRD

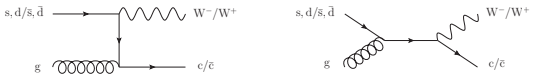
W + c, 8 and 13 TeV

Interest

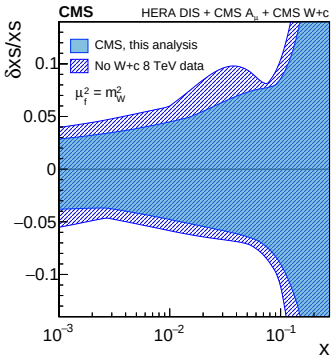
- sensitive to the strange PDF
- Test pQCD
- Background for other analyses.

Measurement

- Integrated and differential fiducial cross-sections; $W^+\bar{c}$,/W^-c ratio.
- $W \rightarrow e\nu$, $W \rightarrow \mu\nu$
- Phase space 13 TeV (8 TeV):
  - $p_T^{\ell} > 35(30)\,\text{GeV}$, $|\eta^{\ell}| < 2.4(2.1)$
  - $p_T(c-jet) > 30\,\text{GeV}$, $|\eta^{\text{c-jet}}| < 2.4$
    ($p_T(c-quark) > 25\,\text{GeV}$ $|\eta^{\text{c-quark}}| < 2.5$)
    $R(\text{jet},\ell) < 0.4(0.5)$, anti-kt jet with $R = 0.4(0.5)$

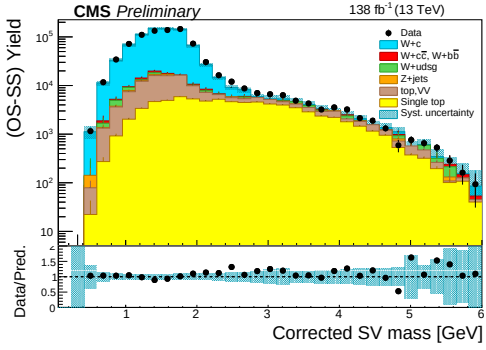


W and c have opposite charges



Effect of including CMS Wc 8 TeV measurement on the strange PDF relative uncertainty.

W + c, 8 and 13 TeV



c-tagging: two categories

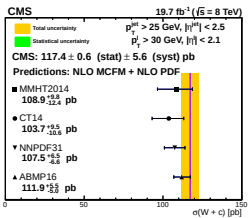
- One muon in the jet: from semi-leptonic decay (SL)
- Secondary vertex in the jet (SV)

Background

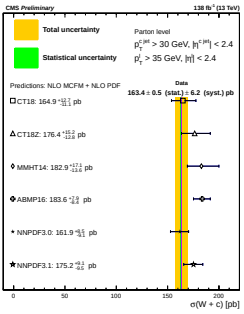
- The dominant background, $t\bar{t}$ with a b-jet misidentified as a c-jet, is suppressed by the OS-SS subtraction method
- Signal purity after OS-SS subtraction (13TeV):

	SL	SV
SL W$\rightarrow$ e ν	81.0%	82.1%
SL W$\rightarrow \mu\nu$	74.2%	80.9%

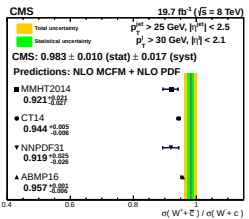
W + c, 8 and 13 TeV



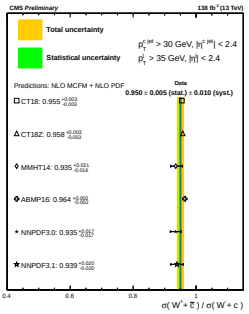
$117.4 \pm 0.6\,(\text{stat}) \pm 5.6\,(\text{syst})\,\text{pb}$



$163.4 \pm 0.5\,(\text{stat}) \pm 6.2\,(\text{syst})\,\text{pb}$



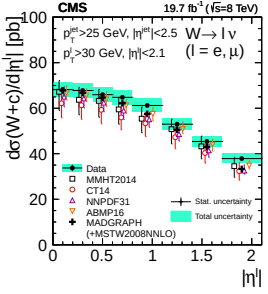
$0.983 \pm 0.010\,(\text{stat}) \pm 0.017\,(\text{syst})\,\text{pb}$

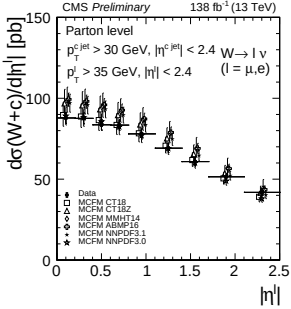


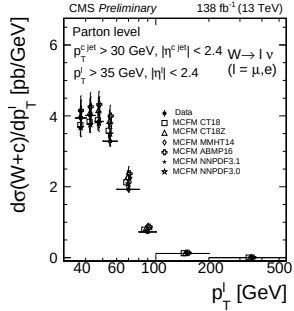
$0.950 \pm 0.005\,(\text{stat}) \pm 0.010\,(\text{syst})\,\text{pb}$

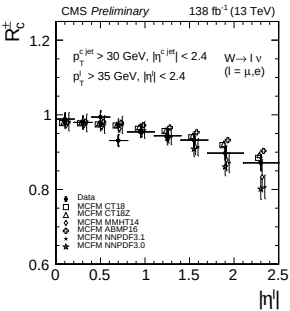
W + c, 8 and 13 TeV

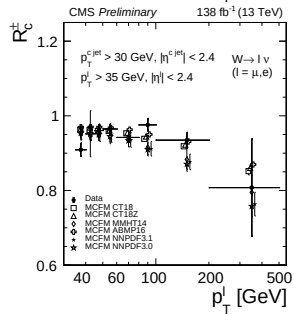
Differential cross sections











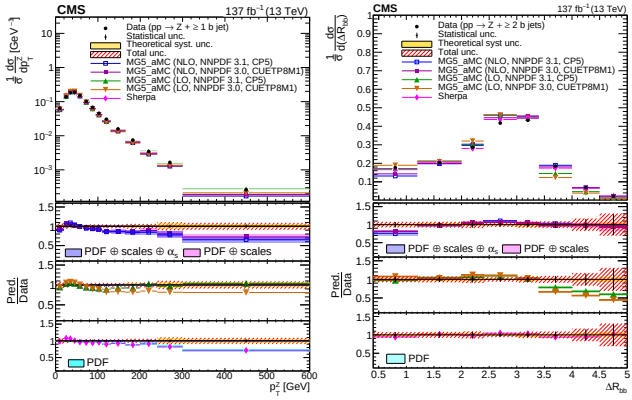
Z + b(b)

Interest

- Measurement important to test the cross-section calculations, 4FS and 5FS
- Background to ZH, H→bb
- Sensitive to b PDF

Measurements

- Integrated cross-section
- $d\sigma/dX$ in: q_T; b-jet p_T and $|\eta|$; $\Delta\phi$, y, and R between Z and b-jet; m_{bb}, m_{Zbb}, ΔR_{bb}.
- $p_T(\ell) > 35, 25\,\text{GeV}$, $|\eta| < 2.4$
- $m_{\ell\ell}$ in 71…111 GeV
- b-jet: $p_T > 30\,GeV$, $|\eta| < 2.4$
- Compared with three 5FS calculations



Many observables explored. Shapes are not always well described by the predictions

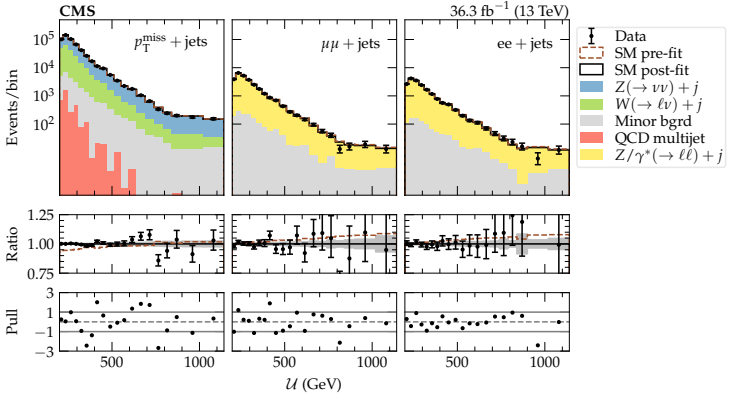
Nice inputs for calculation improvements.

Z boson invisible width measurements

- CMS-SMP-18-014 submitted to PLB
- Invisible width extracted from $Z(\to \nu\bar{\nu})$+jets and $Z(\to \ell^+\ell^-)$+jets, $\ell = \mu, e$ cross sections:

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z(\to \nu\bar{\nu}) + \text{jets})}{\sigma(Z(\to \ell\ell) + \text{jets})} \Gamma(Z \to \ell\ell)$$

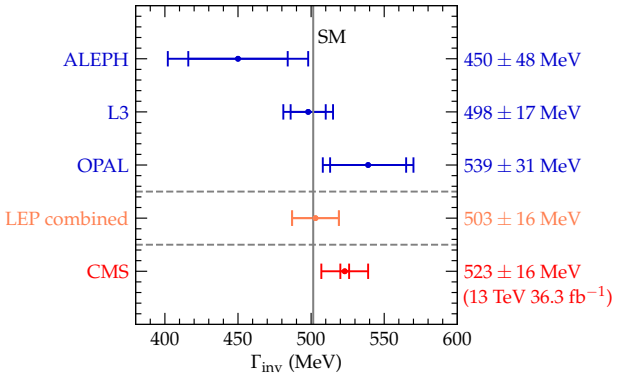
- Background estimated with data driven methods



Z boson invisible width measurements

	$p_{\mathrm{T}}^{\mathrm{miss}}$+jets	$\mathrm{Z}/\gamma^* \to \mu\mu$	$\mathrm{Z}/\gamma^* \to \mathrm{ee}$
$\mathrm{Z}(\nu\nu)$+jets	310000	—	—
$\mathrm{Z}/\gamma^* \to \ell\ell$	2680	25900	17300
$\mathrm{W}(\ell\nu)$+jets	195000	—	—
QCD multijet	3360	—	—
Minor	25600	1720	1090
Total SM	537000	27600	18400
Data	537326	27631	18326

Source of systematic uncertainty	Uncertainty (%)
Muon identification efficiency (syst.)	2.1
Jet energy scale	1.8–1.9
Electron identification efficiency (syst.)	1.6
Electron identification efficiency (stat.)	1.0
Pileup	0.9–1.0
Electron trigger efficiency	0.7
τ_h veto efficiency	0.6–0.7
$p_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiency (jets plus $p_{\mathrm{T}}^{\mathrm{miss}}$ region)	0.7
$p_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiency ($\mathrm{Z}/\gamma^* \to \mu\mu$ region)	0.6
Boson p_{T} dependence of QCD corrections	0.5
Jet energy resolution	0.3–0.5
$p_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiency (μ+jets region)	0.4
Muon identification efficiency (stat.)	0.3
Electron reconstruction efficiency (syst.)	0.3
Boson p_{T} dependence of EW corrections	0.3
PDFs	0.2
Renormalization/factorization scale	0.2
Electron reconstruction efficiency (stat.)	0.2
Overall	3.2



Summary

Latest V+jets CMS results presented

- Z + jets, including q_T dependency of angular correlations
- Mass dependency of q_T in Drell-Yan
- W + c with full run 2 dataset and with full 8TeV dataset
- Z + b with full run 2 dataset
- Invisible Z width measurement achieving LEP precision

They complement a large legacy of measurements @ 7, 8, and 13 TeV