

# Vector bosons plus jets at the LHC

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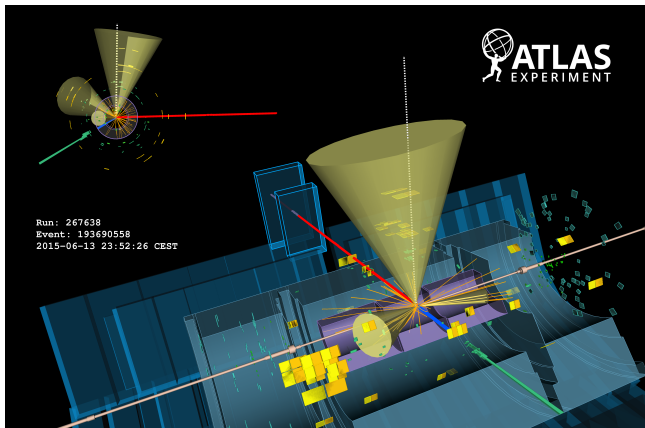


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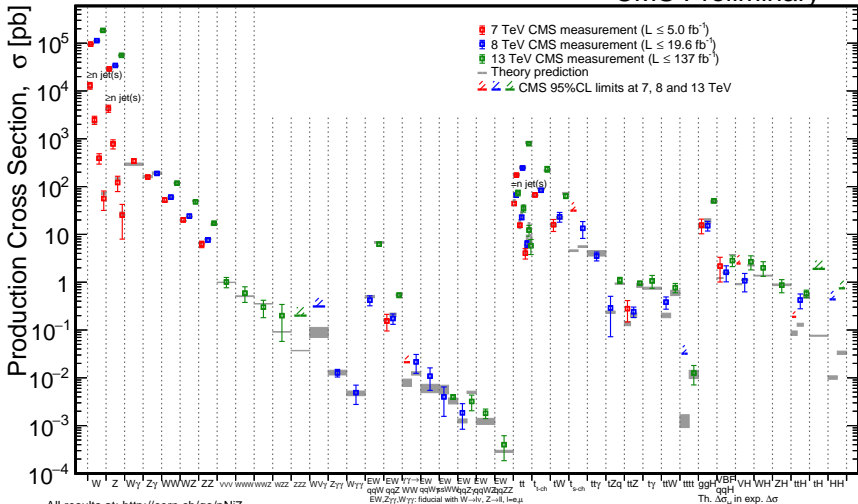


European Research Council

LHC: Great tool to probe fundamental interactions at high energies  
→ Great to measure jets and bosons leptons



- $W \rightarrow \ell\nu/q\bar{q}'$
- $Z/\gamma \rightarrow \ell^+\ell^-/q\bar{q}$



→ Huge variety of  $pp \rightarrow Vs + \text{jets}$  processes ...  
 .. with very different phenomenology!

## Master formula:

$$pp \rightarrow Vs + \text{jets}$$

- $pp \rightarrow Z + b$   
→ NNLO QCD with mass effects

[Gauld, Gehrmann-De Ridder, Glover, Huss, Majer; 2005.03016]

- $pp \rightarrow W^+W^-j$   
→ NLO QCD+EW with Parton shower

[Bräuer, Denner, MP, Schönherr, Schumann; 2005.12128]

- $pp \rightarrow W^+W^+jj$   
→ Full NLO [Biedermann, Denner, MP; 1708.00268]

Disclaimer: Not a review but a selection of some results

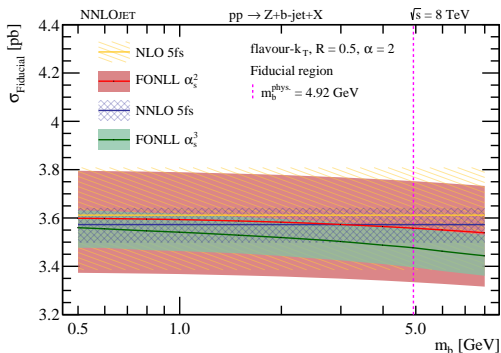
- $pp \rightarrow Z + b$   
→ NNLO QCD with mass effects

[Gauld, Gehrmann-De Ridder, Glover, Huss, Majer; 2005.03016]

- NNLO QCD in 5 flavour (5fs) combined with ...  
... NLO QCD in 4 flavours (4fs) at  $\mathcal{O}(\alpha_s^3\alpha^2)$

$$d\sigma^{\text{FONLL}} = d\sigma^{5\text{fs}} + \left( d\sigma_{m_b}^{4\text{fs}} - d\sigma_{m_b \rightarrow 0}^{4\text{fs}} \right)$$

- Allows to incorporate exact b-mass effects



- Flavoured jet in the final state
  - Beyond NLO in QCD, flavoured jet algorithm required  
[Banfi, Salam, Zanderighi; hep-ph/0601139]
  - Modified  $k_T$  algorithm to account for soft wide-angle  $q\bar{q}$
  - Infrared-safe definition of flavoured jet
- But experimental data [CMS; 1611.06507]
  - 1) reconstructed with anti- $k_T$  algorithm
  - 2) flavour of these jets identified
- Unfolding procedure:
  - Computation of non-perturbative correction to data using:
    - 5fs at NLO QCD + PS
    - 4fs at NLO QCD + PS

## Fiducial cross section

- Applying non-perturbative correction to the data gives

$$\sigma_{\text{Fiducial},f-k_T}^{\text{CMS}} = 3.119 \pm 0.212_{-0.032}^{+0.021} \text{ pb}$$

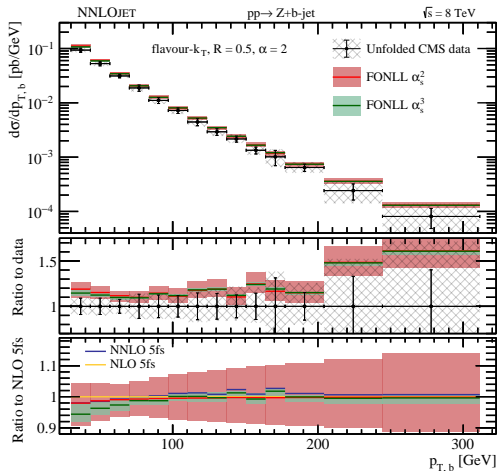
- At  $\mathcal{O}(\alpha_s^3)$ , the FONLL prediction is

$$\sigma_{\text{Fiducial}}^{\text{FONLL}}(m_b^{\text{phys.}}) = 3.477_{-0.081}^{+0.081}(\text{scales}) \text{ pb}$$

NB:

$\delta\sigma(\text{PDF}, \alpha_s) = \pm 0.074 \text{ pb}$  estimated at NLO





- $\chi^2/N_{\text{dat}}(\alpha_s^2, p_{T,b}) = 24.9/14$
- $\chi^2/N_{\text{dat}}(\alpha_s^3, p_{T,b}) = 21.6/14$

- $pp \rightarrow W^+W^-j$   
→ NLO QCD+EW with Parton shower

[Bräuer, Denner, MP, Schönherr, Schumann; 2005.12128]

First measurement of pp  $\rightarrow$   $W^+W^-j$  by ATLAS [1608.03086]

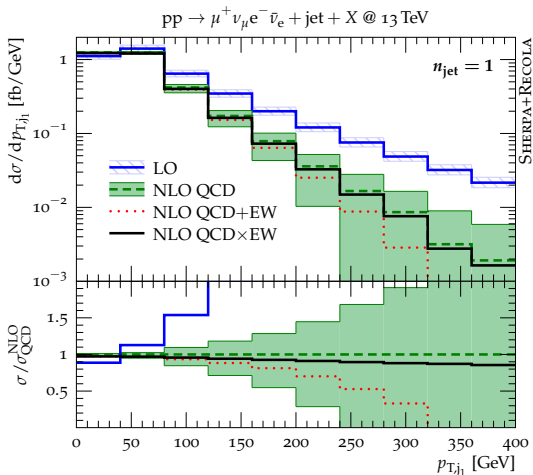
- $\rightarrow$  Combined analysis of pp  $\rightarrow$   $W^+W^-$  and pp  $\rightarrow$   $W^+W^-j$
- $\rightarrow$  Inclusion of jet veto

- Fixed-order analysis at NLO QCD+EW

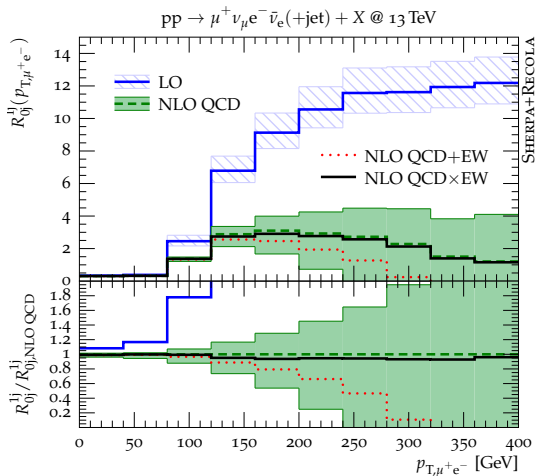
- $\rightarrow$  for off-shell pp  $\rightarrow$   $\mu^+\nu_\mu e^-\bar{\nu}_e$
- $\rightarrow$  for off-shell pp  $\rightarrow$   $\mu^+\nu_\mu e^-\bar{\nu}_e j$

- Inclusive sample with:

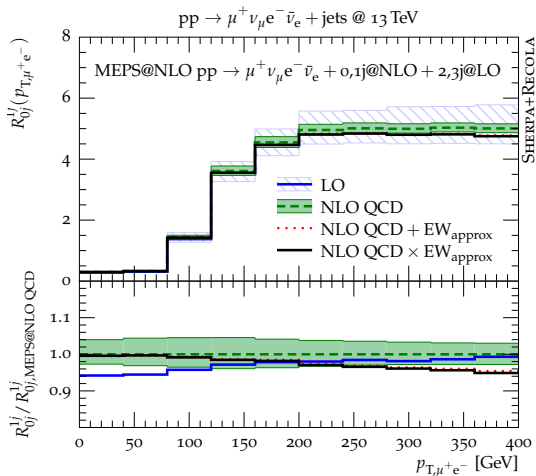
- merged predictions + PS + approximate EW corrections
  - $\rightarrow$  pp  $\rightarrow$   $\mu^+\nu_\mu e^-\bar{\nu}_e + 0, 1j@NLO + 2, 3j@LO$
- $\rightarrow$  Can be studied with  $n_j = 0$  or  $n_j = 1$



- Large QCD corrections: effect of the jet veto
- EW corrections: Sudakov logarithms



- Very large ratios between WWj and WW

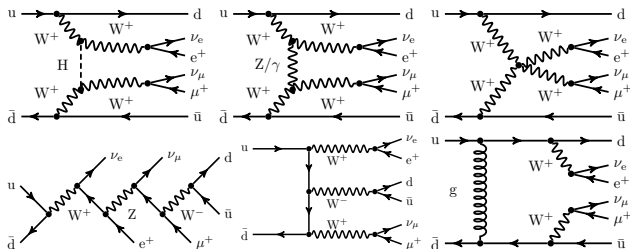


- For multi-jet merged parton-shower: much more stable ratios

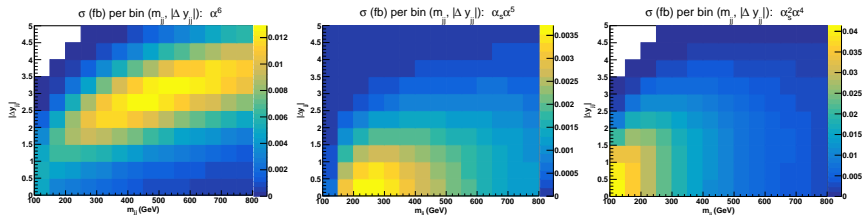
- $pp \rightarrow W^+W^+jj$

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$\rightarrow$  Tree amplitudes of order  $\mathcal{O}(g^6)$  and  $\mathcal{O}(g_s^2g^4)$



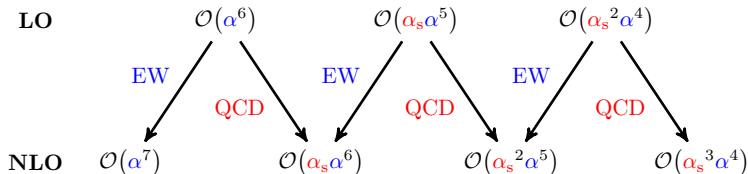
$\rightarrow$  LO contributions:  $\mathcal{O}(\alpha^6)$ ,  $\mathcal{O}(\alpha_s\alpha^5)$ , and  $\mathcal{O}(\alpha_s^2\alpha^4)$



• Contributions with different kinematic: exclusive cuts for EW/VBS

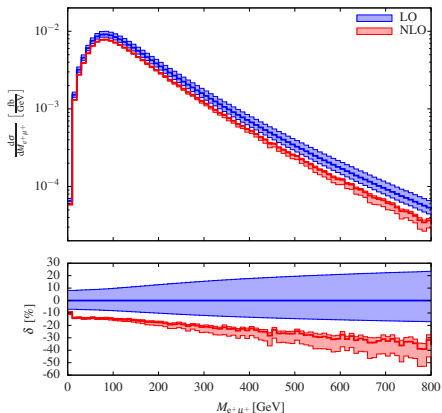
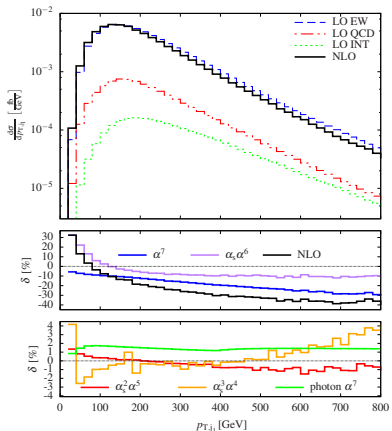


LO contributions at  $\mathcal{O}(\alpha^6)$ ,  $\mathcal{O}(\alpha_s\alpha^5)$ , and  $\mathcal{O}(\alpha_s^2\alpha^4)$



NLO contributions at  $\mathcal{O}(\alpha^7)$ ,  $\mathcal{O}(\alpha_s\alpha^6)$ ,  $\mathcal{O}(\alpha_s^2\alpha^5)$ , and  $\mathcal{O}(\alpha_s^3\alpha^4)$

- $\rightarrow$  Order  $\mathcal{O}(\alpha_s\alpha^6)$  and  $\mathcal{O}(\alpha_s^2\alpha^5)$ : QCD and EW corrections mix
- $\rightarrow$  Meaningless distinction between EW signal and QCD background
- $\rightarrow$  Combined measurement!



- Different behaviour of the NLO corrections (normalised to the full LO)
- Large EW corrections: intrinsic feature of VBS at the LHC

[Biedermann, Denner, MP; 1611.02951]

## Comparison with data

$\rightarrow$  Recent  $ss$ - $WW$  and  $WZ$  analysis of CMS with  $137 \text{ fb}^{-1}$  [2005.01173]:

Process	$\sigma \mathcal{B}$ (fb)	Th. pred. LO (fb)	Th. pred. NLO (fb)
EW $WW$	$3.98 \pm 0.45$	$3.93 \pm 0.57$	$3.31 \pm 0.47$
	$0.37 \text{ stat} \pm 0.25 \text{ syst}$		
EW+QCD $WW$	$4.42 \pm 0.47$	$4.34 \pm 0.69$	$3.72 \pm 0.59$
	$0.39 \text{ stat} \pm 0.25 \text{ syst}$		
EW $WZ$	$1.81 \pm 0.41$	$1.41 \pm 0.21$	$1.24 \pm 0.18$
	$0.39 \text{ stat} \pm 0.14 \text{ syst}$		
EW+QCD $WZ$	$4.97 \pm 0.46$	$4.54 \pm 0.90$	$4.36 \pm 0.88$
	$0.40 \text{ stat} \pm 0.23 \text{ syst}$		
QCD $WZ$	$3.15 \pm 0.49$	$3.12 \pm 0.70$	$3.12 \pm 0.70$
	$0.45 \text{ stat} \pm 0.18 \text{ syst}$		

$\rightarrow$  LO: MADGRAPH5\_AMC@NLO+PYTHIA

$\rightarrow$  NLO: MADGRAPH5\_AMC@NLO+PYTHIA + NLO corr. from [Biedermann, Denner, MP; 1708.00268] or [Denner, Dittmaier, Maierhöfer, MP, Schwan; 1904.00882] but only to EW signal

NB: Uncertainty for the NLO numbers are from the LO 7-scales variation.

Very rich phenomenology of vector bosons plus jets!

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→ NNLO QCD with mass effects  
[Gauld, Gehrmann-De Ridder, Glover, Huss, Majer; 2005.03016]
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# Thank you