

# Vector Boson Scattering (VBS) at the LHC

$\text{pp} \rightarrow e^+ \nu_e \mu^+ \nu_\mu jj + X @ \mathcal{O}(\alpha^6 \alpha_s)$ ,  
Approximations, PDF uncertainties, and  $M_H = \infty$

Christopher Schwan

VBS CAN Workshop,  
Amsterdam, Nov. 16

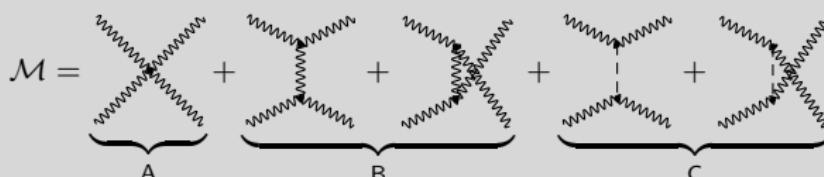


# Motivation

At the LHC the process  $pp \rightarrow e^+ \nu_e \mu^+ \nu_\mu jj + X$  contains the actual vector boson scattering subprocess. I will refer to the whole process as VBS, though.

$$W^+ W^+ \rightarrow W^+ W^+$$

©  $M_H = 125$  GeV



- Constrain anomalous quartic gauge couplings (AQGC),
- **probe EW symmetry breaking**

In the SM, for longitudinal gauge boson scattering (pseudo-goldstone bosons at high energy) there are

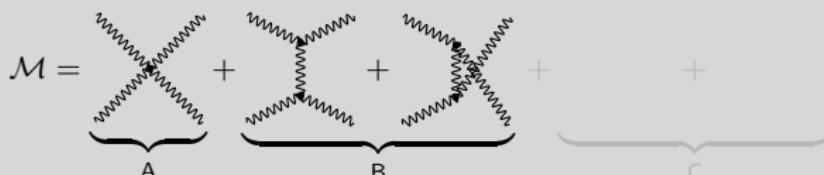
- gauge cancellations between QGC diagram (A) and TGC diagrams (B);
  - further cancellations between remainders and diagrams containing Higgs(es) (C, restores perturbative unitarity)
  - violation of perturbative unitarity, **maximum effect of different Higgs sector**
- different Higgs sector/AQGC can change this

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$\text{@ } M_H = \infty$

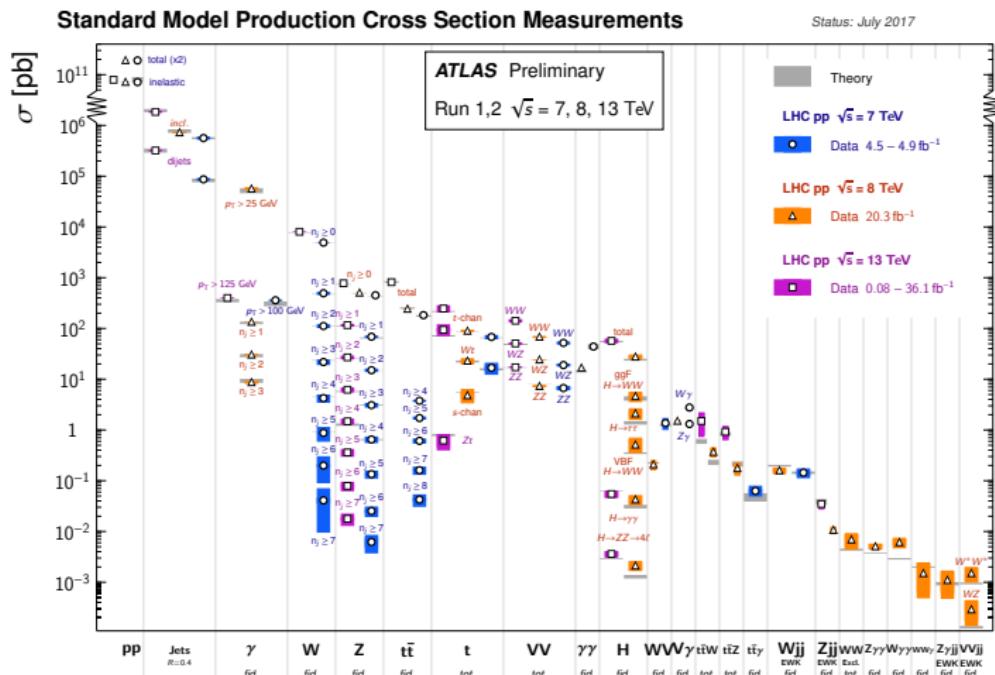


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# Why study the same sign (SS) W scattering case?



→ SS VBS processes at the LHC are  $\sim \text{fb}$ , others are smaller or have large backgrounds

<sup>0</sup>Dinosaur plot from <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults>

# Outline

- How does one distinguish between Signal ( $\mathcal{O}(\alpha^6)$ , containing VBS diagrams) and Backgrounds ( $\mathcal{O}(\alpha^5 \alpha_s^1)$  and  $\mathcal{O}(\alpha^4 \alpha_s^2)$ , interferences or no VBS diagrams)? → **VBS cuts**
- What approximations are possible and what can we learn from them about VBS? → **double-pole approximation (DPA)** and **VBS approximation (VBSA)**
- How large are PDF uncertainties? → Calculate them for NLO QCD  $\mathcal{O}(\alpha^6 \alpha_s)$
- What are good/bad scale choices? → **Investigate static and dynamic scale**
- How does an extended Higgs sector affect the differential distributions? → **Compare with  $M_H = \infty$  to see maximum effect of perturbative non-unitarity**

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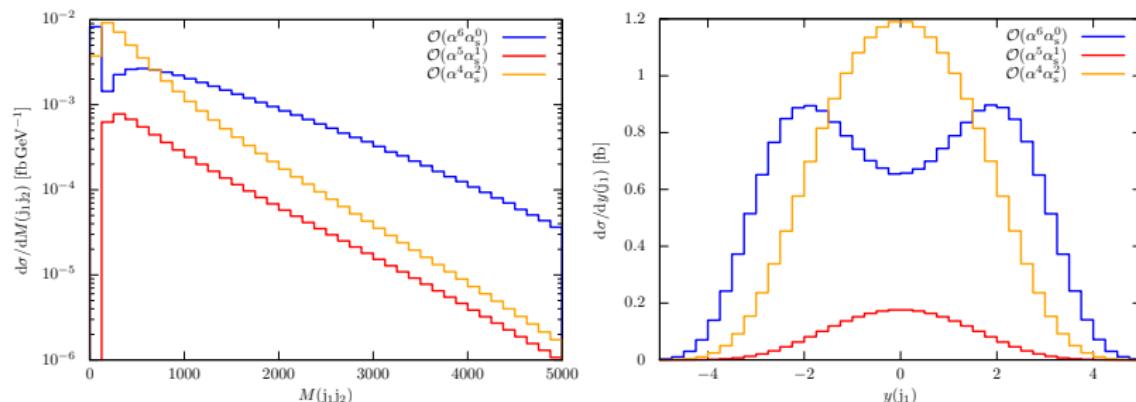
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# How does one distinguish between signal and background?

Inclusive cross sections (two  $R = 0.4$  anti- $k_T$  jets with  $p_T > 30 \text{ GeV}$ : taggings jets  $j_1$  and  $j_2$ ):



→  $\mathcal{O}(\alpha^6)$  similar in size as  $\mathcal{O}(\alpha^4 \alpha^2)$

→ interference  $\mathcal{O}(\alpha^5 \alpha_s)$  is suppressed by colour and kinematics

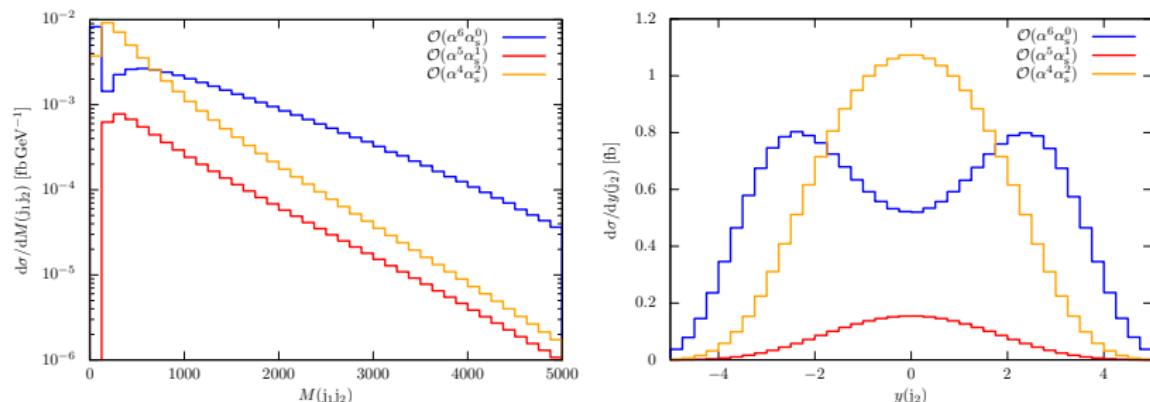
- ATLAS<sup>1</sup> 8 TeV/CMS<sup>2</sup> 13 TeV analyses:  $M(j_1 j_2) > 500 \text{ GeV}$
- $\mathcal{O}(\alpha^6)$  peaks at higher rapidity because of (two) space-like W propagators of the VBS subprocess

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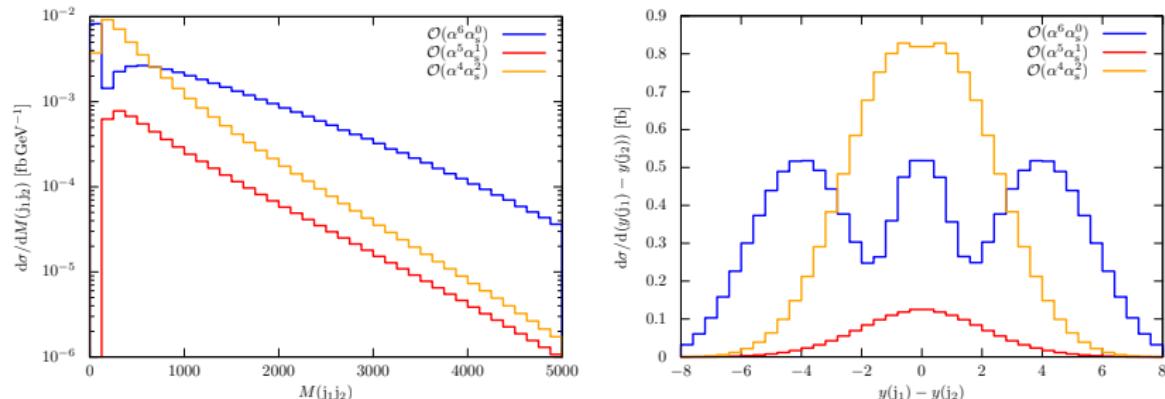
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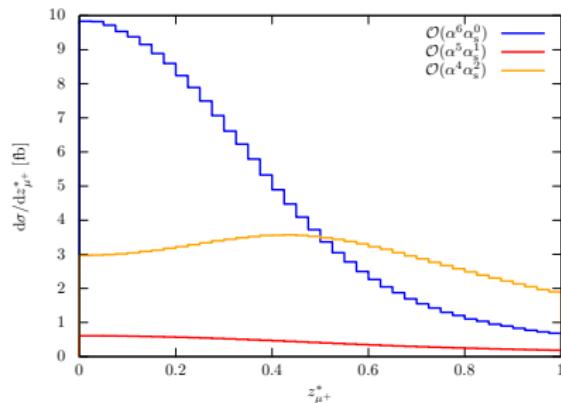
- ATLAS<sup>1</sup> 8 TeV/CMS<sup>2</sup> 13 TeV analyses:  $M(j_1 j_2) > 500 \text{ GeV}$ , and  $|y(j_1) - y(j_2)| > 2.4/2.5$
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Inclusive cross sections (two  $R = 0.4$  anti- $k_T$  jets with  $p_T > 30 \text{ GeV}$ : taggings jets  $j_1$  and  $j_2$ ):



$$z_\ell^* = \frac{|y(\ell) - (y(j_1) + y(j_2))/2|}{|y(j_1) - y(j_2)|}$$

“Zeppenfeld variable”<sup>3</sup>, divides phase space in two regions:

- $z_\ell^* > 0.5 \Rightarrow$  either  $y(\ell) > \max\{y(j_1), y(j_2)\}$  or  $y(\ell) < \min\{y(j_1), y(j_2)\}$ ; “lepton outside taggings jets”
- $z_\ell^* < 0.5 \Rightarrow \min\{y(j_1), y(j_2)\} < y(\ell) < \max\{y(j_1), y(j_2)\}$ ; “lepton between taggings jets”
- Advantage of  $z_\ell^*$ : continuous, being more inclusive easy
- CMS 13 TeV:  $z_\ell^* < 0.75$
- ATLAS 8 TeV: no cut on  $z_\ell^*$

<sup>3</sup>arXiv:1709.05822, The CMS Collaboration

# Setup for $pp \rightarrow e^+ \nu_e \mu^+ \nu_\mu jj + X$

VBSCAN WG1 cuts:

- At least two  $R = 0.4$  Anti- $k_t$  jets with  $p_T > 30 \text{ GeV}$  and  $|y| < 4.5$  and  $\Delta R(j\ell^+) > 0.3$
- $M(j_1 j_2) > 500 \text{ GeV}$  and  $|y(j_1) - y(j_2)| > 2.5$
- $p_T(\ell^+) > 20 \text{ GeV}$  and  $|y(\ell^+)| < 2.5$
- $p_T(\nu_e \nu_\mu) > 40 \text{ GeV}$
- $\Delta R(e^+ \mu^+) > 0.3$

Other parameters:

- $\sqrt{s} = 13 \text{ TeV}$
- NNPDF3.0 ( $\alpha_s(M_Z) = 0.118$ ) PDFs

Complex mass scheme<sup>4,5</sup> input parameters:

- $G_\mu = 1.6637 \times 10^{-5} \text{ GeV}^{-2}$
- $M_W^{\text{OS}} = 80.385 \text{ GeV}$ ,  $\Gamma_W^{\text{OS}} = 2.085 \text{ GeV}$
- $M_Z^{\text{OS}} = 91.1876 \text{ GeV}$ ,  $\Gamma_Z^{\text{OS}} = 2.4952 \text{ GeV}$
- $M_H = 125.0 \text{ GeV}$ ,  $\Gamma_H = 4.07 \times 10^{-3} \text{ GeV}$

with coupling calculated as:

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left( 1 - \frac{M_W^2}{M_Z^2} \right)$$

Scale choices ( $\mu_F = \xi_F \mu$ ,  $\mu_R = \xi_R \mu$ ):

- static:  $\mu = M_W$
- dynamic:  $\mu = \sqrt{p_T(j_1) \cdot p_T(j_2)}$

<sup>4</sup> arXiv:hep-ph/9904472; A. Denner, S. Dittmaier, M. Roth, D. Wackerlo

<sup>5</sup> arXiv:hep-ph/0505042; A. Denner, S. Dittmaier, M. Roth, L.H. Wieders

# Setup and cross checks

BONSAY (C.S.)  
“BOsoN Scattering with (NLO)  
AccuracY”

- MC written from scratch
- Matrix elements from M. Billoni, S. Dittmaier
- Loops calculated by COLLIER<sup>6</sup>
- Dipole subtraction for IR singularities

- Uses **VBS approximation (VBSA)** for everything and **double pole approximation (DPA)** for virtuals ( $\rightarrow$  next slides and M. Pellen)

checked  
against

MADGRAPH, PHANTOM,  
POWHEG, RECOLA, VBFNLO,  
WHIZARD

- $p_T(j_1), p_T(j_2), y(j_1), y(j_2), M(j_1 j_2), M(e^+ \mu^+), z_e^*, z_\mu^*$

- PDF/Scale errors and  $M_H = \infty$  result are preliminary

# Pole approximation for virtual matrix elements

$$\mathcal{M}_{\text{virt}} = \begin{array}{c} \text{Diagram 1: Two horizontal lines with arrows, a vertical gluon loop (wavy line), and a vertical quark loop (dotted line).} \\ + \end{array} \begin{array}{c} \text{Diagram 2: Similar to Diagram 1, but the gluon loop has a small horizontal tail extending right.} \\ + \end{array} \begin{array}{c} \text{Diagram 3: Similar to Diagram 1, but the gluon loop has a large horizontal tail extending right, which is shaded with diagonal lines.} \\ + \dots \end{array}$$

# Pole approximation for virtual matrix elements

$$\begin{aligned}
 \mathcal{M}_{\text{virt,PA}} &= \text{Diagram 1} + \text{Diagram 2} + \dots \\
 &= \sum_{\lambda_1, \lambda_2} \mathcal{M}_{\text{virt}}^{q_1 q_2 \rightarrow W_1 W_2 q_3 q_4} \mathcal{M}_{\text{LO}}^{W_1 \rightarrow e^+ \nu_e} \mathcal{M}_{\text{LO}}^{W_2 \rightarrow \mu^+ \nu_\mu} \Bigg|_* \frac{1}{K_1 K_2}
 \end{aligned}$$

- Drop all diagrams that are not doubly-resonant → Factorization of **production** and **decay**
- ∗: set all widths to zero, project momenta of resonances on-shell → gauge invariance
- **Resonant propagator denominators** are kept off-shell:  $K_i = \bar{k}_i^2 - M_W^2 + iM_W\Gamma_W$ , where  $\bar{k}_1$  is the off-shell momentum of the first  $W^+$ ,  $\bar{k}_2$  the one of the second  $W^+$
- Procedure modifies IR singularities, taken care of by modified insertion operator:

$$2 \operatorname{Re}(\mathcal{M}_{\text{LO}}^* \mathcal{M}_{\text{virt}}) + |\mathcal{M}_{\text{LO}}|^2 \otimes \mathbf{I} \quad \rightarrow \quad 2 \operatorname{Re}(\mathcal{M}_{\text{LO,PA}}^* \mathcal{M}_{\text{virt,PA}}) + |\mathcal{M}_{\text{LO,PA}}|^2 \otimes \mathbf{I}$$

# Uncertainty of the PA

Use uncertainty estimation of Biedermann, et. al.<sup>7</sup> and modify it for QCD corrections:

$$\Delta_{\text{PA}}^{\text{NLO}} \sim \max \left( \frac{\alpha_s}{2\pi} \frac{\Gamma_W}{M_W} \log(\dots), |\delta^{\text{PA}}| \times \delta^{\text{LO}} \right), \quad \delta^{\text{LO}} = \frac{\sigma_{\text{LO}} - \sigma_{\text{LO}}^{\text{PA}}}{\sigma_{\text{LO}}^{\text{PA}}}$$

$\delta^{\text{LO}}$  can be large, e.g. di-boson production  $p_T$  distributions PA underestimates by 10–20%

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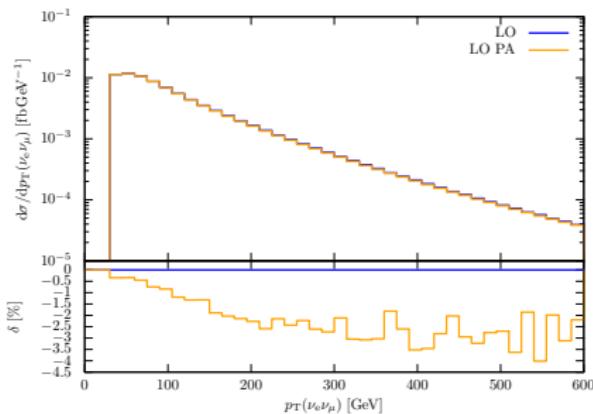
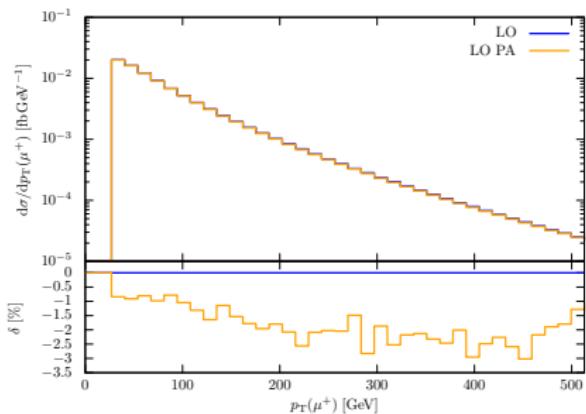
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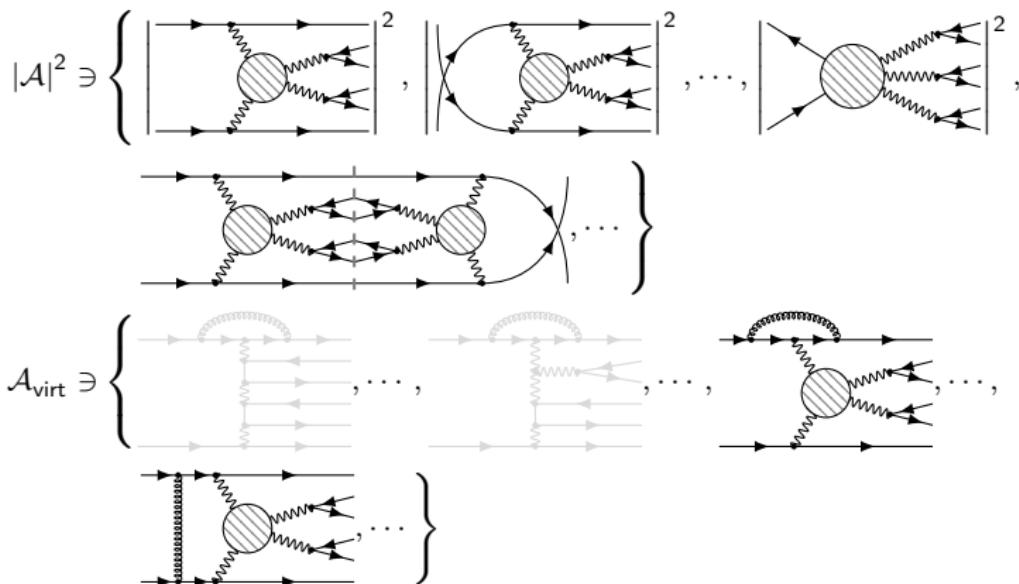
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- LO PA differs by 1–3%  $\sim \Gamma_W/M_W \Rightarrow$  No large non-/single-/triple-resonant contributions due to same sign W bosons!

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# VBS approximation



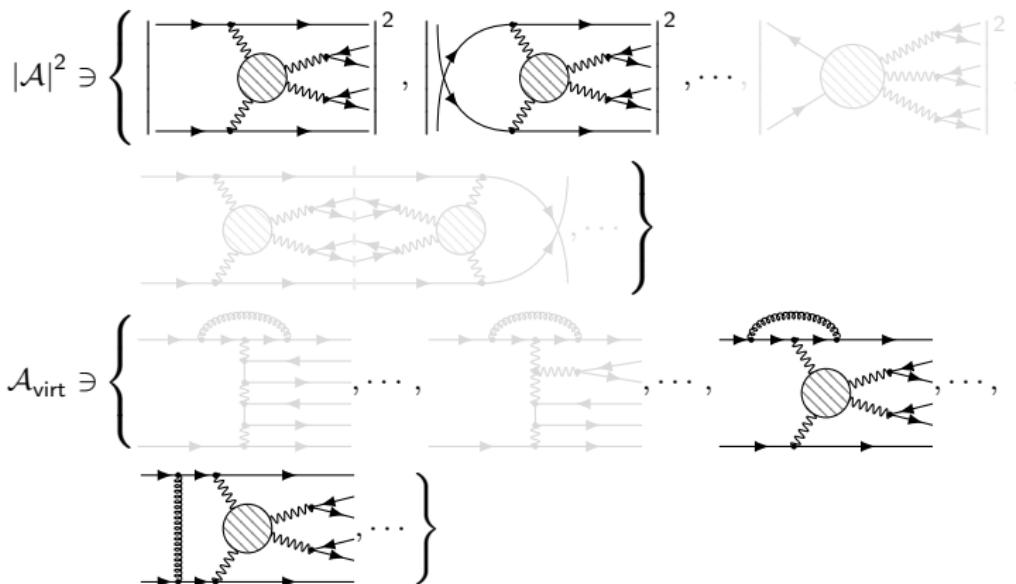
- $q\bar{q}$ -Annihilation (only for  $Q = 1$  processes) suppressed by cut  $M(j_1 j_2) > 500 \text{ GeV} \rightarrow$  real ME: gluon in the initial state does not couple to other initial state quark ( $\rightarrow \text{SU}(3) \times \text{SU}(3)$  quarks)
- t-u interferences are suppressed in the fiducial volume
- no gluons connecting different quark lines, because they are either zero (squares) or kinematically suppressed (interferences)

# VBS approximation

$$|\mathcal{A}|^2 \ni \left\{ \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \\ \vdots \\ \text{Diagram n} \end{array} \right\}^2, \quad \left\{ \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \\ \vdots \\ \text{Diagram n} \end{array} \right\}, \quad \dots, \quad \left\{ \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \\ \vdots \\ \text{Diagram n} \end{array} \right\}^2,$$
$$\mathcal{A}_{\text{virt}} \ni \left\{ \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \\ \vdots \\ \text{Diagram n} \end{array} \right\}, \quad \dots, \quad \left\{ \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \\ \vdots \\ \text{Diagram n} \end{array} \right\}$$

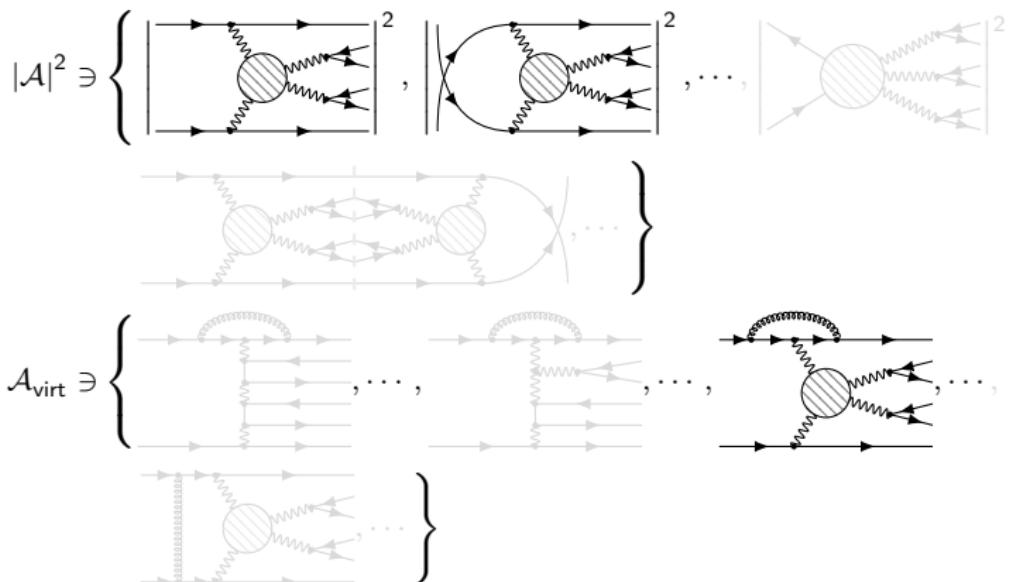
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# Integrated cross sections for $\text{pp} \rightarrow e^+ \nu_e \mu^+ \nu_\mu jj + X$ at $\mathcal{O}(\alpha^6 \alpha^{0,1})$

Scale	LO [fb]	NLO $n_j = 2, = 3, \geq 2$	$\delta$	$\Delta_{\text{PDF}}^{\text{NLO}}$	LO $M_H = \infty$ [fb]
static	1.552	$0.830 + 0.517 = 1.347$	-15.2%		
dynamic	$1.434^{+8.7\%}_{-7.5\%}$	$0.931 + 0.417 = 1.348^{+0.6\%}_{-1.4\%}$	-6.0%	$\pm 1.9\%$	1.568 (+9.3%)

with  $\delta = \frac{\text{NLO} - \text{LO}}{\text{LO}}$ .

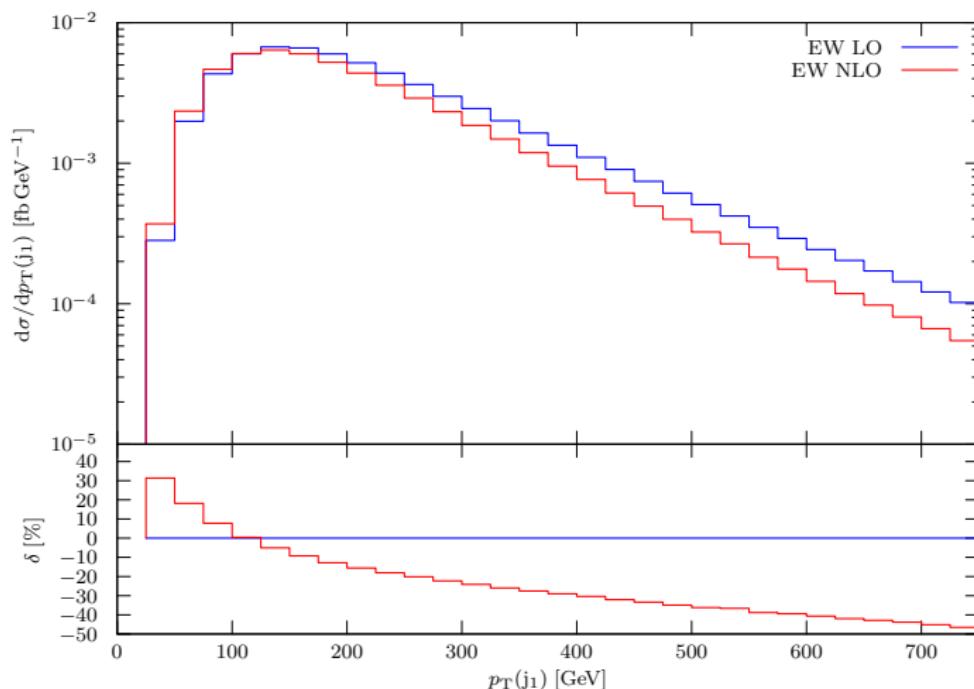
Perturbative uncertainties estimated from scale variation by factors  $\xi_{R,F} \in (0.5, 1, 2)$  for a seven-point variation

- static scale (DS):  $\mu_R = \mu_F = M_W$
- dynamic scale (DS):  $\mu_R = \mu_F = \xi \sqrt{p_T(j_1) \cdot p_T(j_2)}$

PDF uncertainties for NNPDF3.0 (replicas, 68% CL):

$$\Delta_{\text{PDF}}^2 = \frac{1}{99} \sum_{i=1}^{100} [\sigma(z_i) - \sigma(z^0)]^2$$

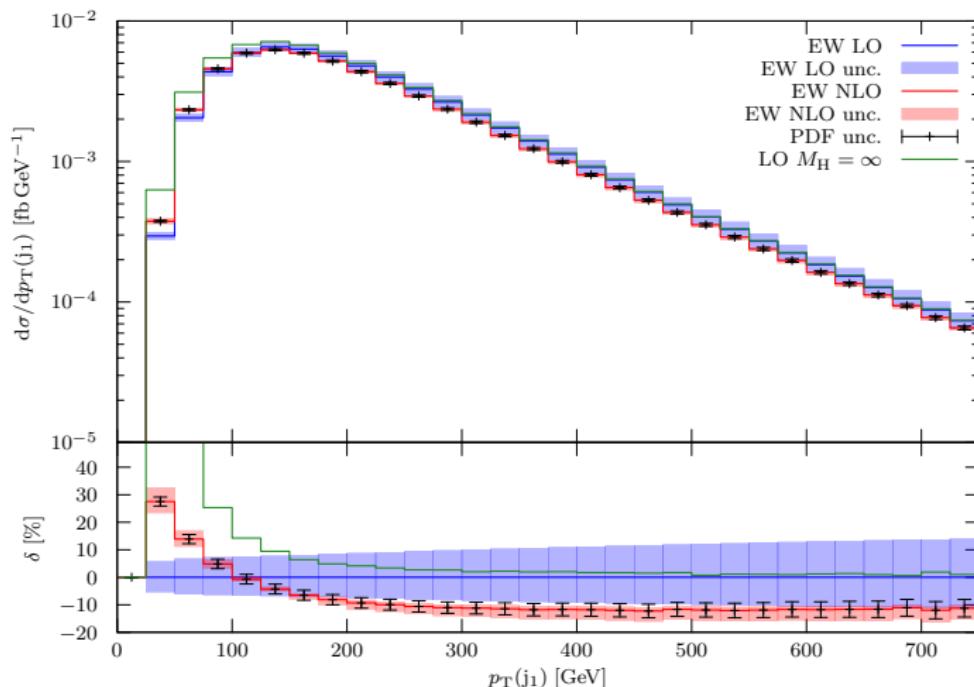
$z^0$  central PDFs  
 $z_i$  i-th replica PDF with different fitparameter

Leading jet transverse momentum ( $\mu = M_W$ )

- very large corrections for high  $p_T$

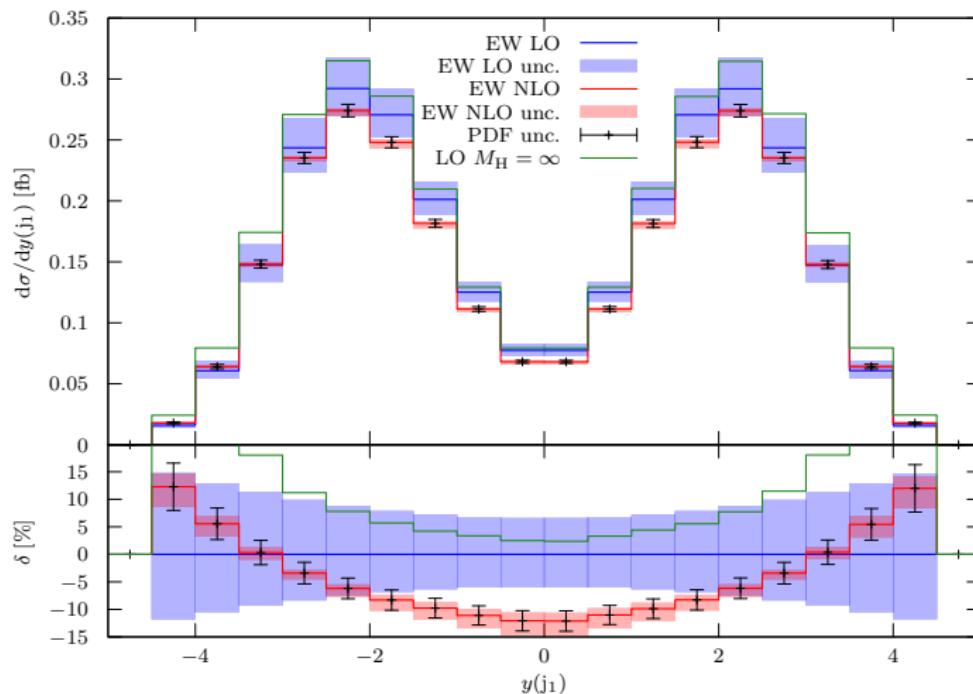
- use dynamic scale!

## Leading jet transverse momentum (DS)



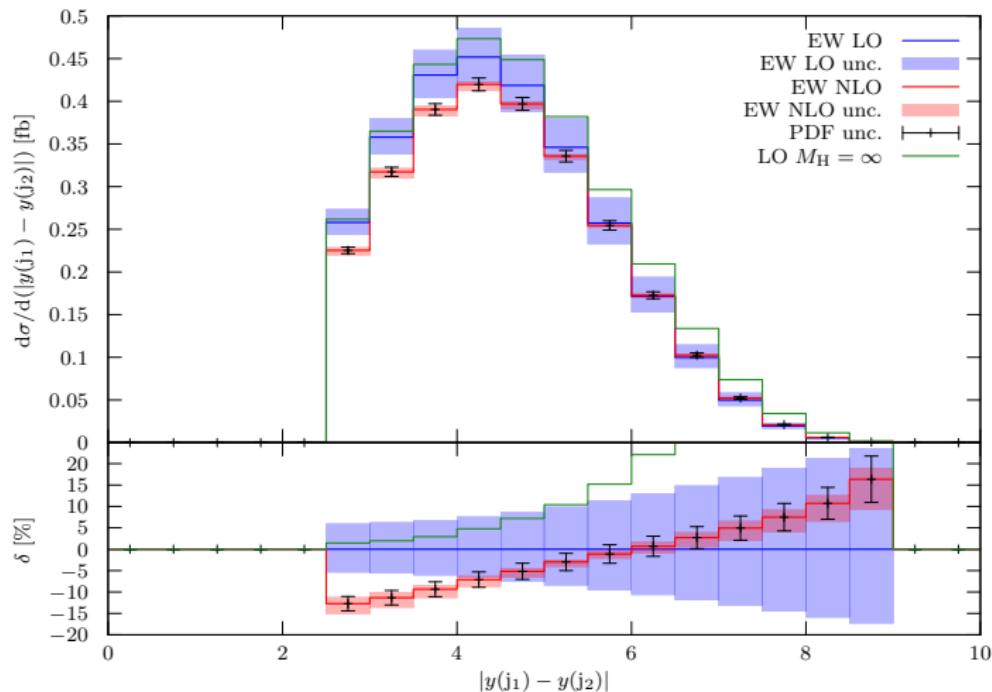
- No  $\alpha_s(\mu_R)$  @ LO: uncertainty band by  $\mu_F$  alone
- smaller corrections for high  $p_T$
- PDF errors are uniformly  $\sim 2\%$
- **low  $p_T$  region sensitive to modified Higgs sector**, large  $p_T$  is unaffected

## Leading jet rapidity (DS)



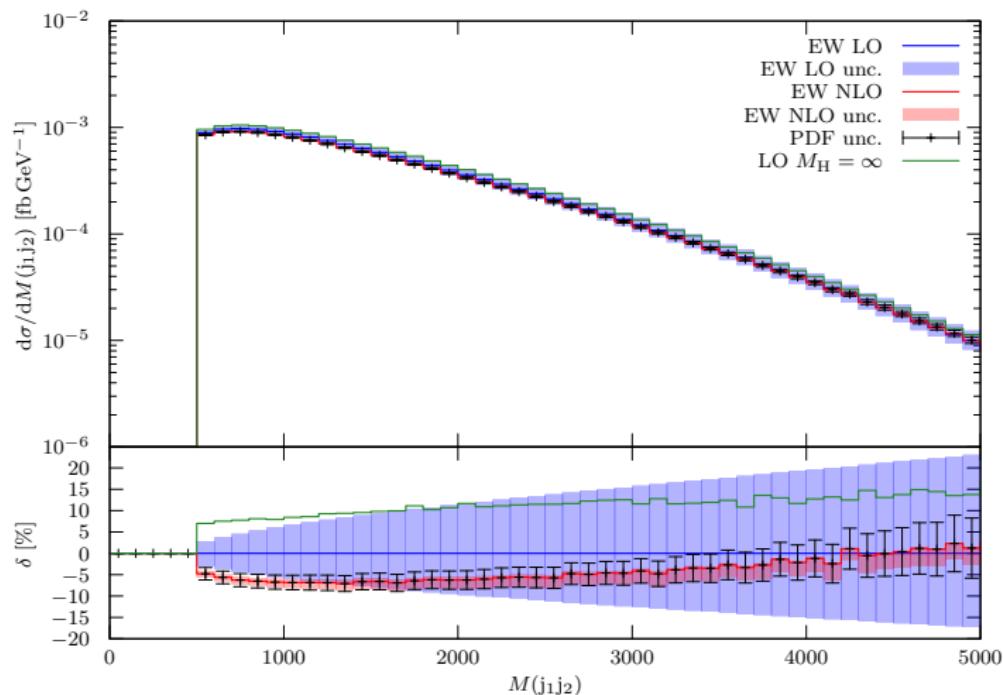
- QCD corrections increase the rapidity of the jet(s)
- forward region most sensitive to mod. Higgs sector, difference up 80%

## Leadings jets rapidity gap (DS)



- QCD correction widens the separation in rapidity

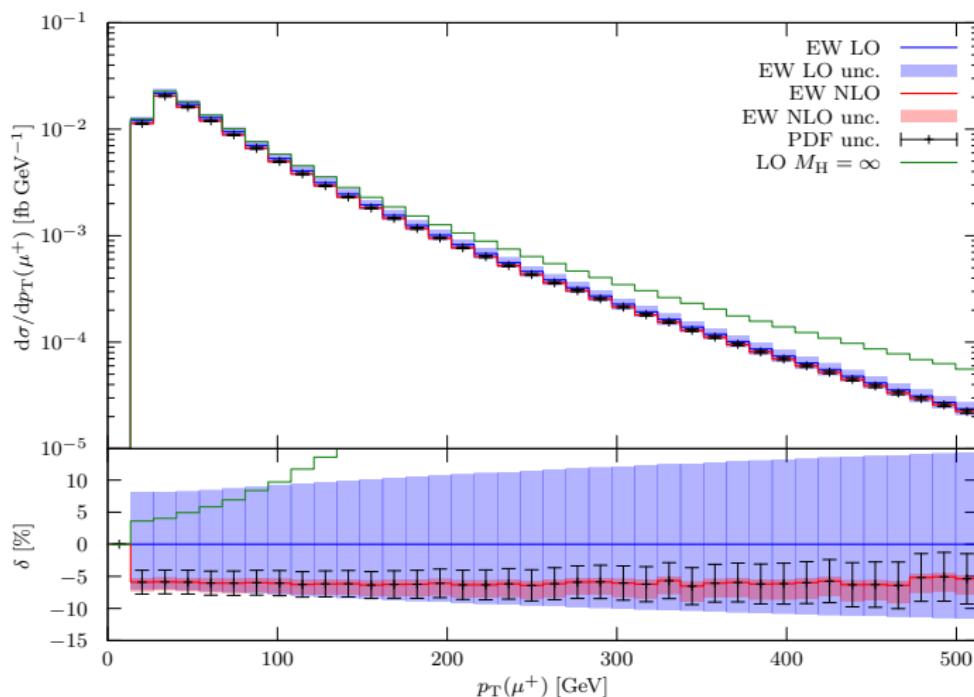
## Leadings jets invariant mass (DS)



- Long overlap of LO/NLO unc. bands

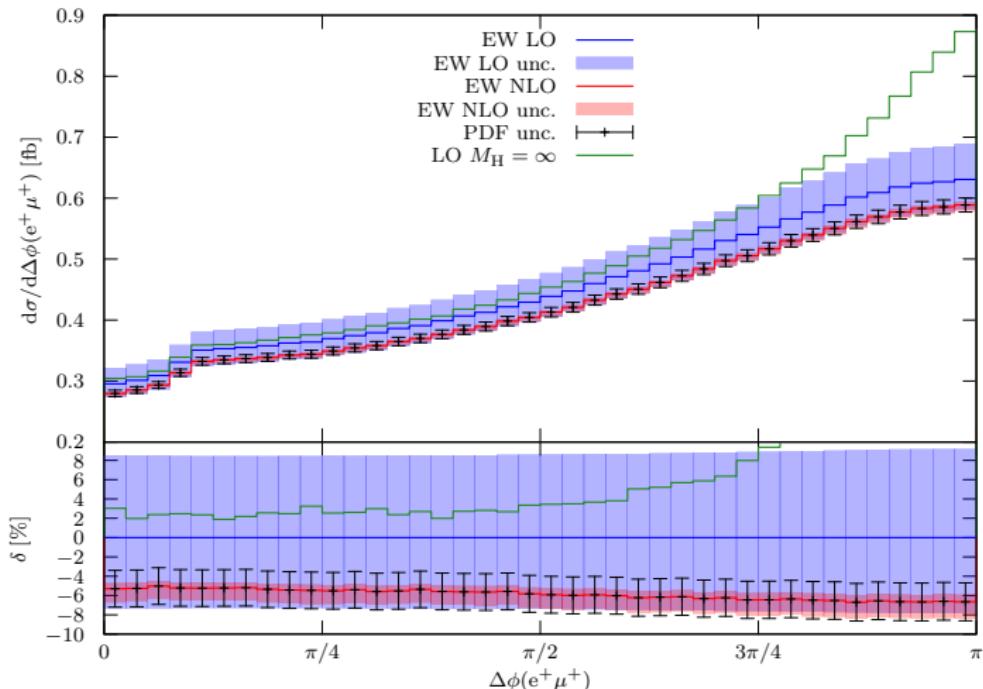
- larger PDF unc. for large inv. mass,  $\sim 7\%$
- $M_H = \infty$ : impact is rather uniform

# Muon transverse momentum (DS)



- $M_H = \infty$ : large effects in high  $p_T$  bins,  $\sim 200\%$

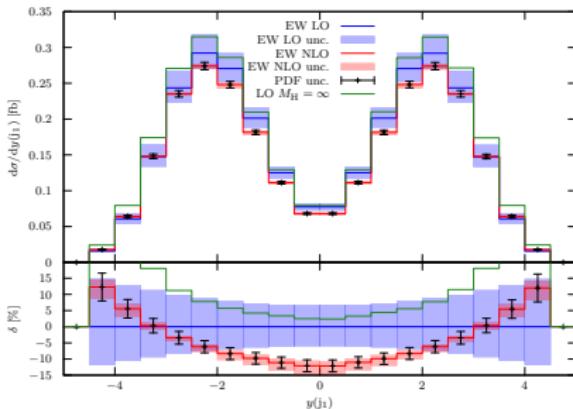
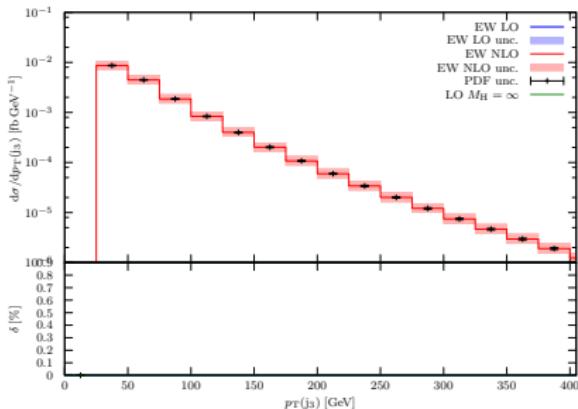
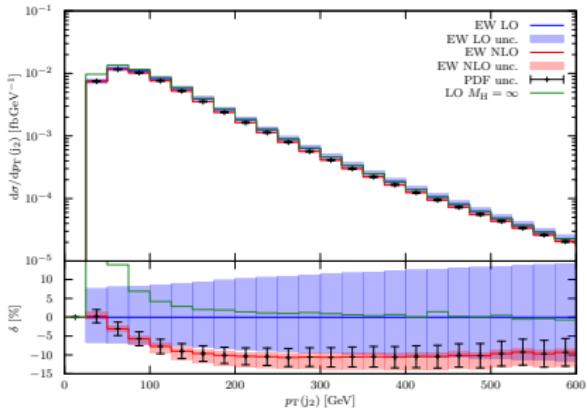
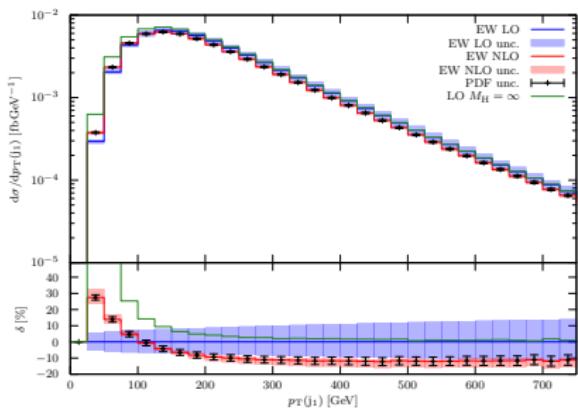
# Lepton azimuthal angle distance (DS)

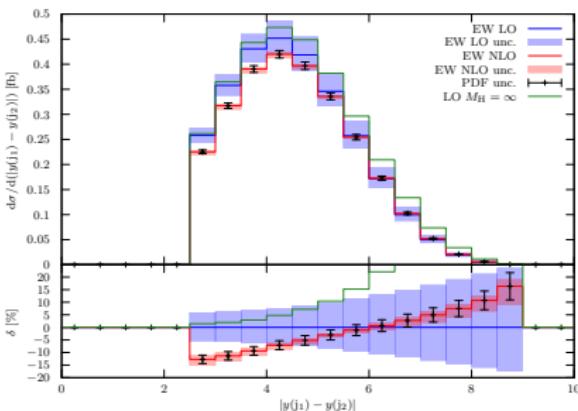
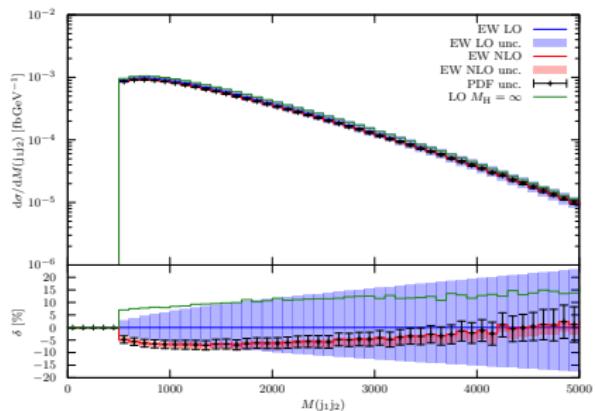
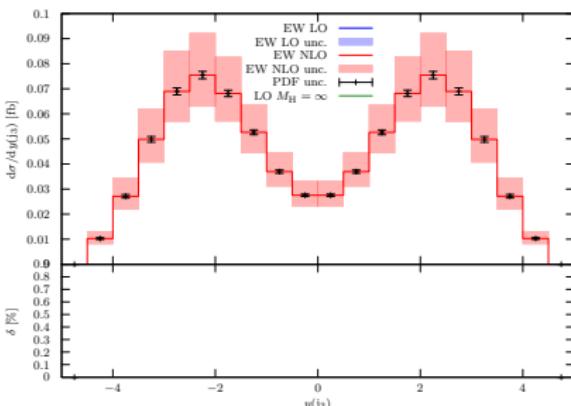
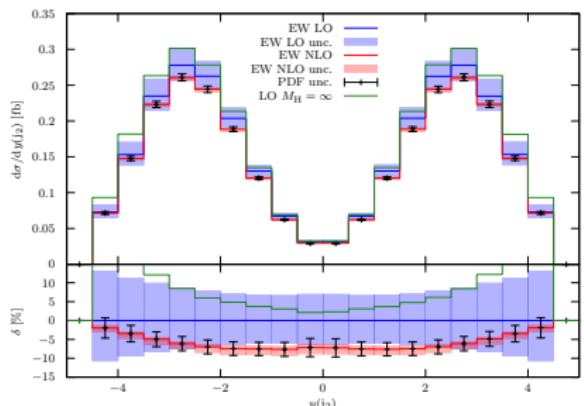


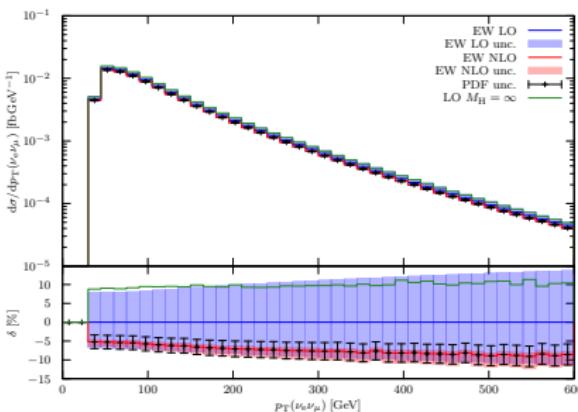
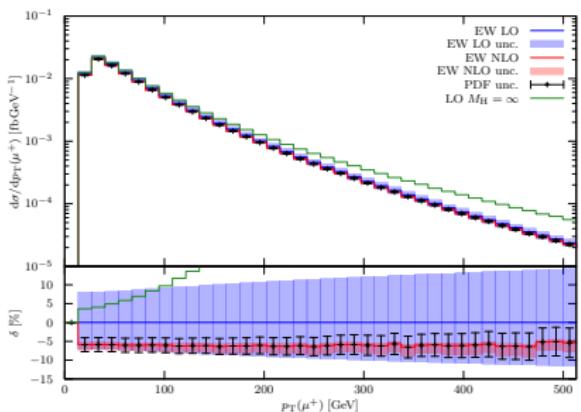
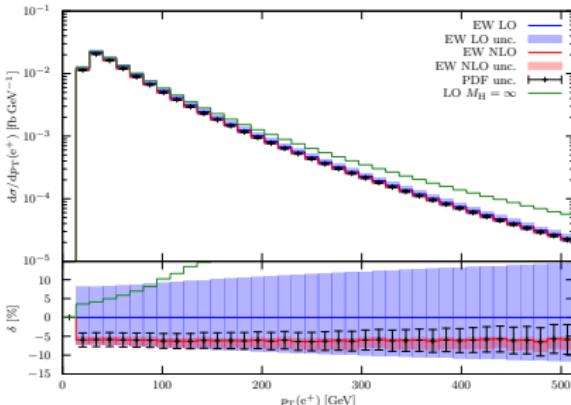
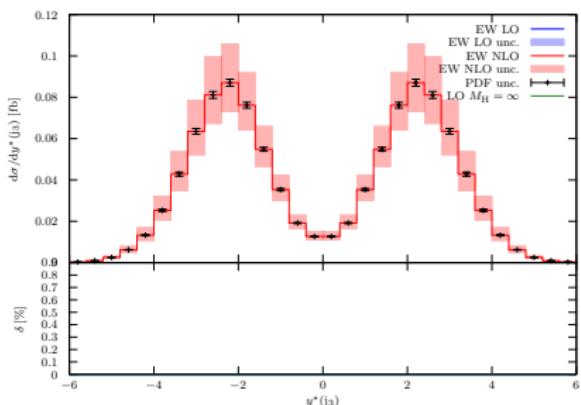
- $M_H = \infty$ : differences up to 38% in the bins with highest cross section

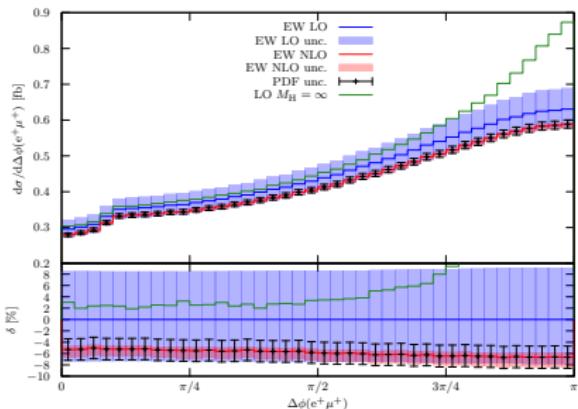
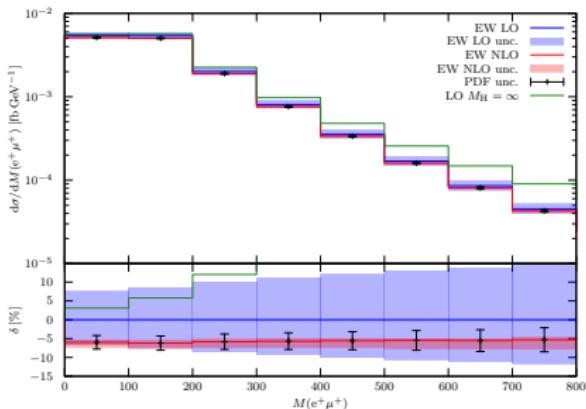
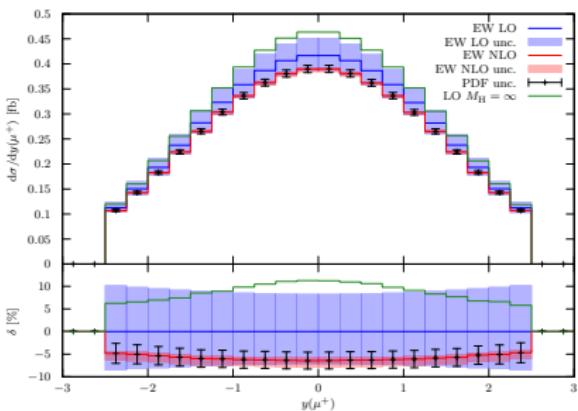
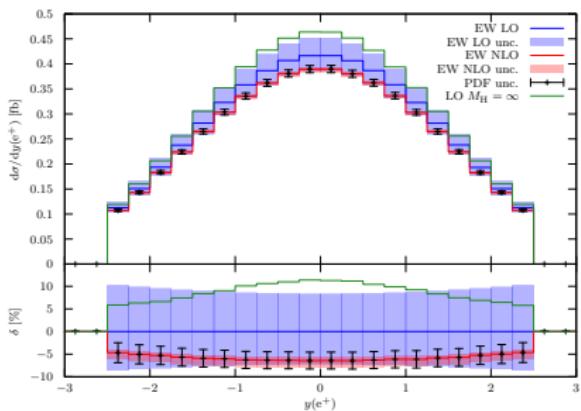
## Summary

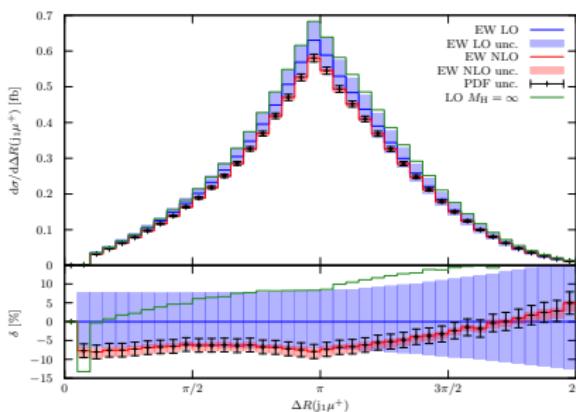
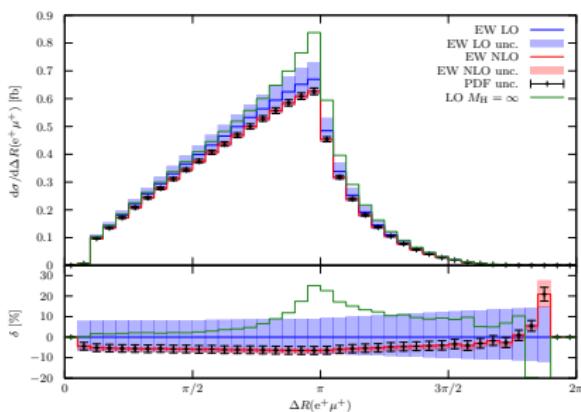
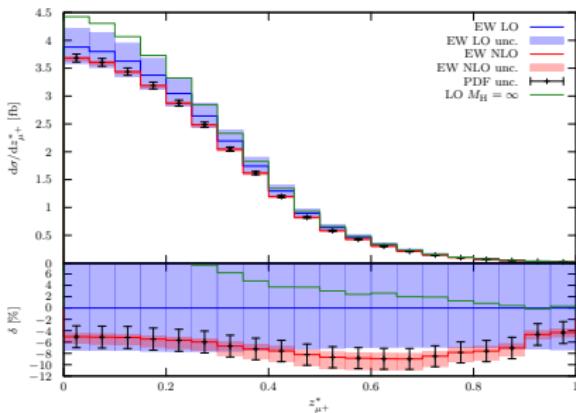
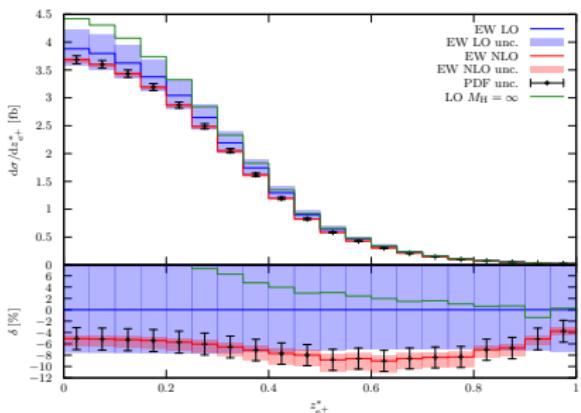
- Pole approximation differs by 1% to 3%  $\Rightarrow$  no large triple-/single-/non-resonant phase space regions
- PDF uncertainties  $\sim 2\%$ , for large  $M(j_1 j_2)$  up to  $\sim 7\%$
- $\mu = M_W$ : large negative QCD corrections
- $\mu = \sqrt{p_T(j_1)p_T(j_2)}$ : smaller negative corrections, mostly within the LO band
- $M_H = \infty$ : forward jets (low  $p_T$ , high  $y$ ), high lepton  $p_T$ , and  $\Delta\phi(e^+ \mu^+)$  sensitive to different Higgs sector

$\mathcal{O}(\alpha^6 \alpha_s)$ : Differential distributions (I)


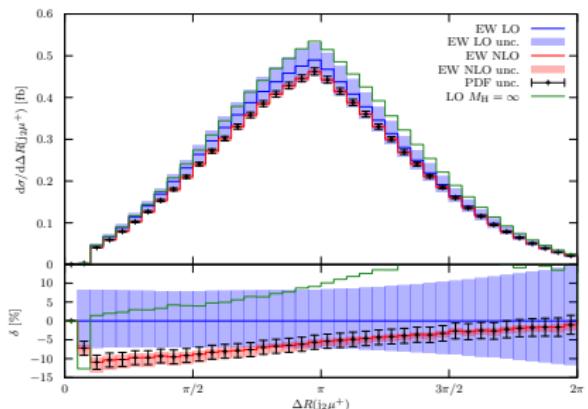
$\mathcal{O}(\alpha^6 \alpha_s)$ : Differential distributions (II)


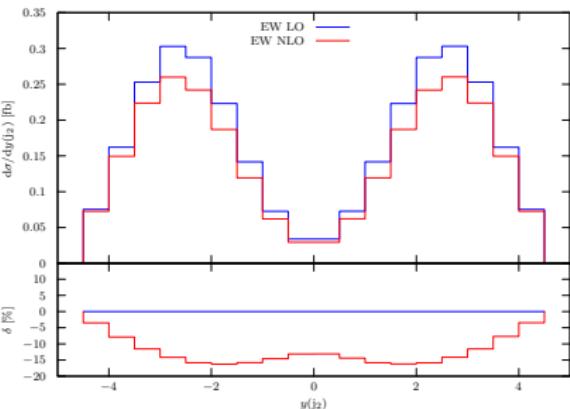
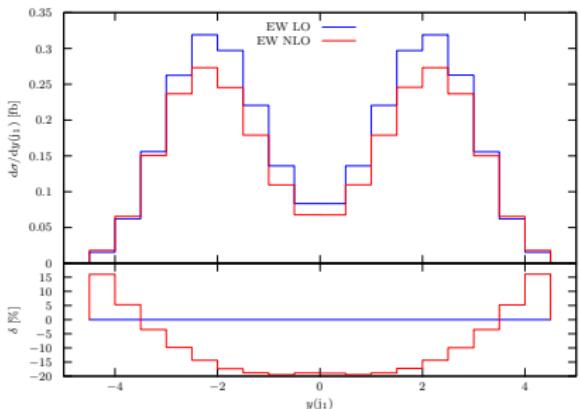
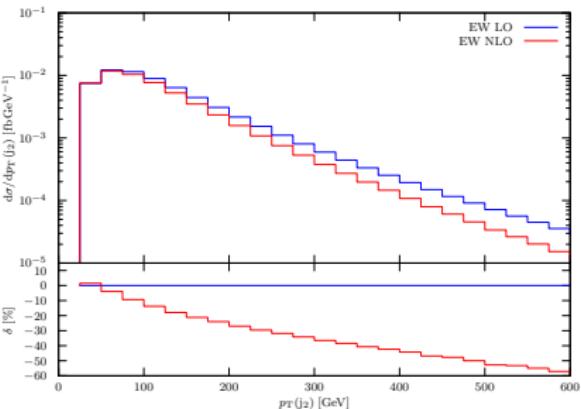
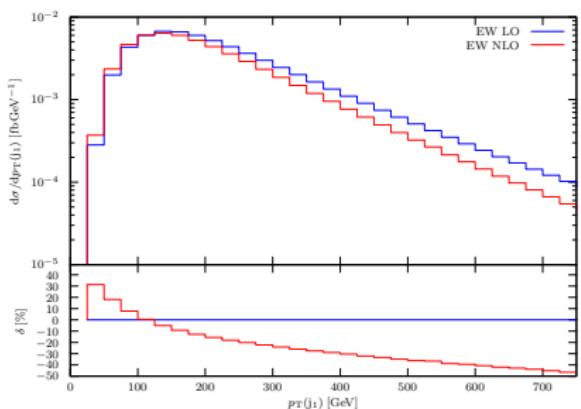
$\mathcal{O}(\alpha^6 \alpha_s)$ : Differential distributions (III)


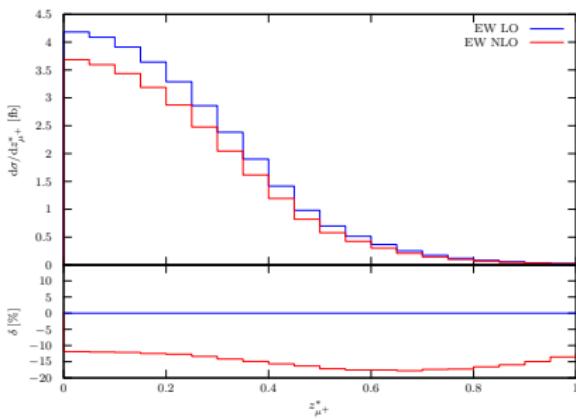
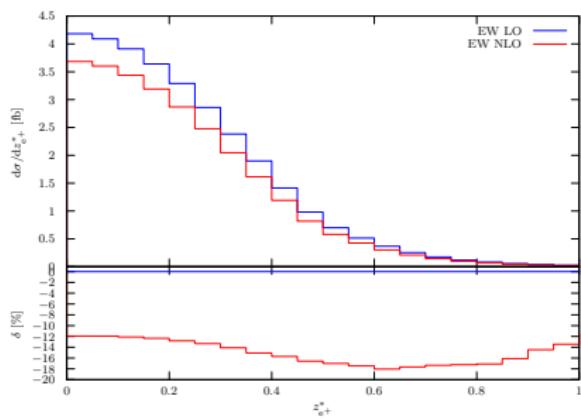
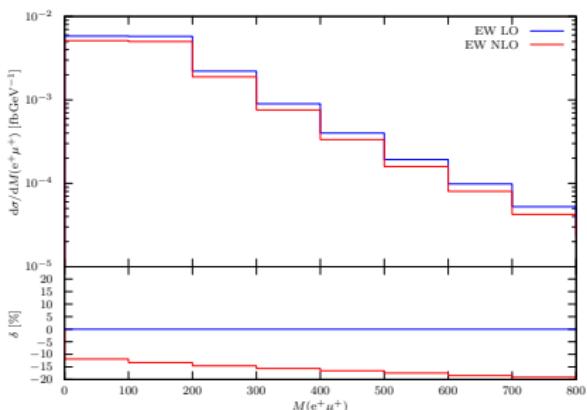
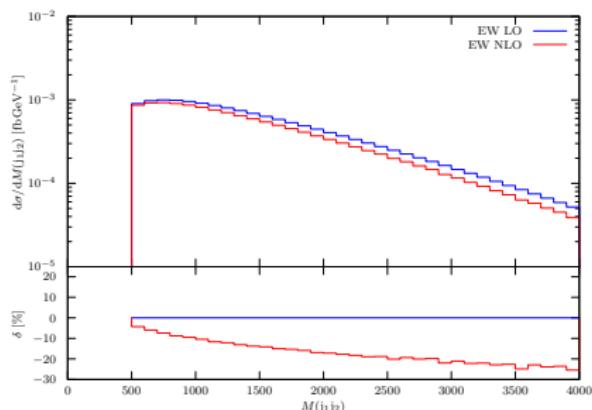
$\mathcal{O}(\alpha^6 \alpha_s)$ : Differential distributions (IV)


$\mathcal{O}(\alpha^6 \alpha_s)$ : Differential distributions (V)

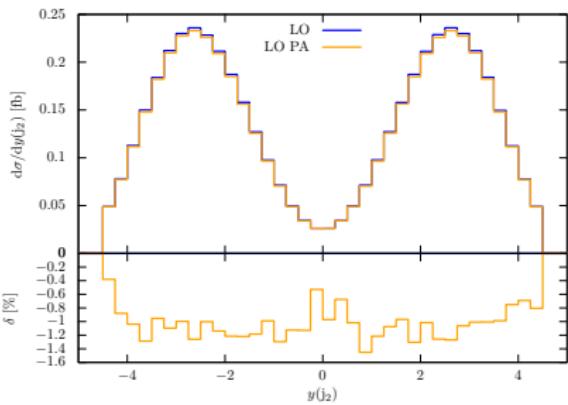
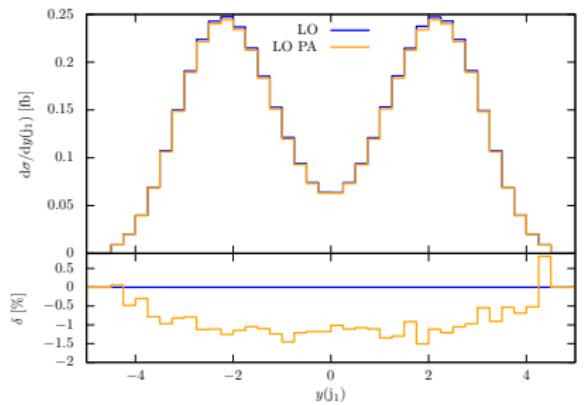
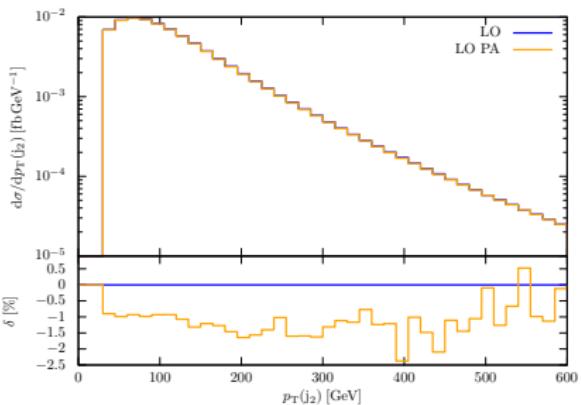
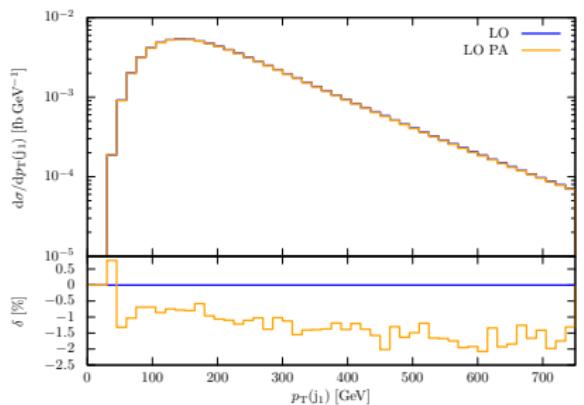
# $\mathcal{O}(\alpha^6 \alpha_s)$ : Differential distributions (V)



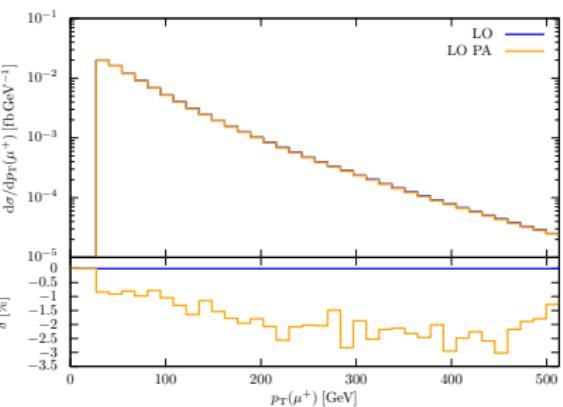
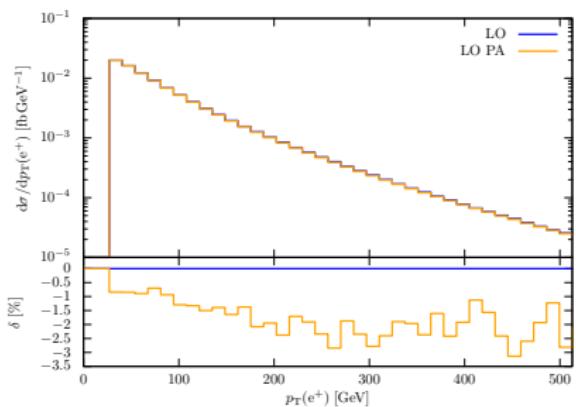
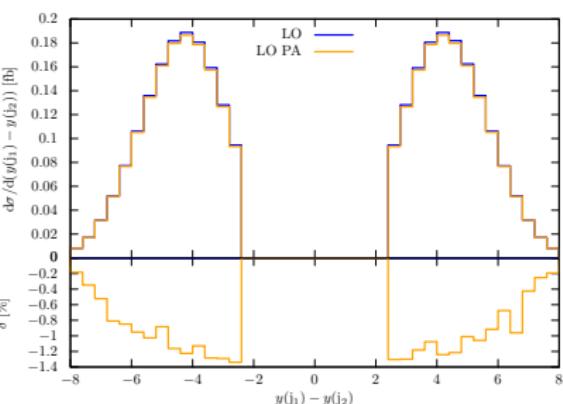
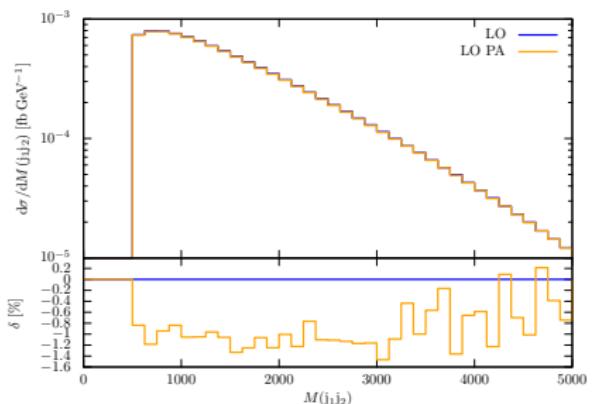
$\mathcal{O}(\alpha^6 \alpha_s)$ : Differential distributions (I)

$\mathcal{O}(\alpha^6 \alpha_s)$ : Differential distributions (II)


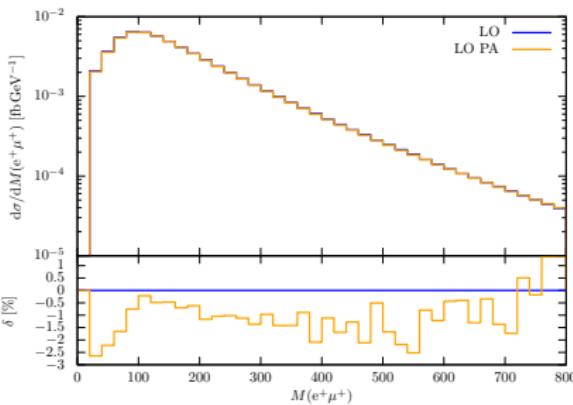
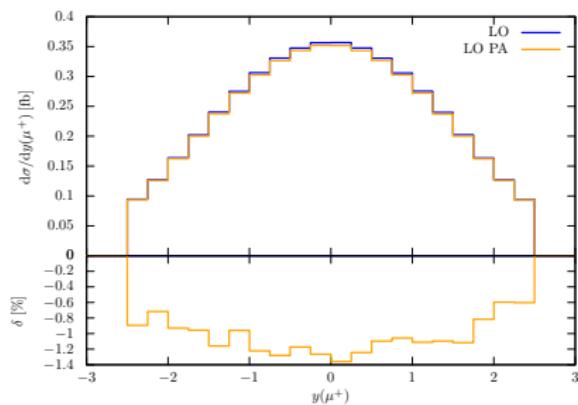
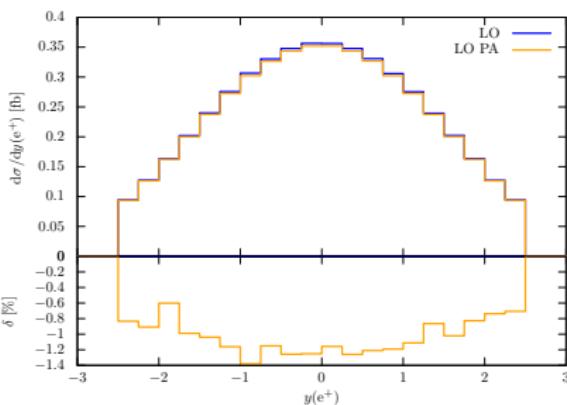
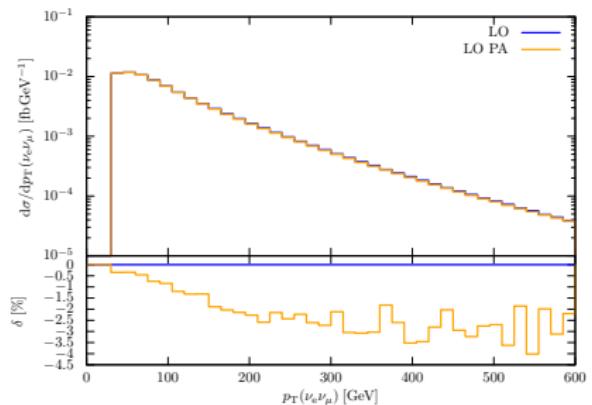
## Full LO vs. PA (I)



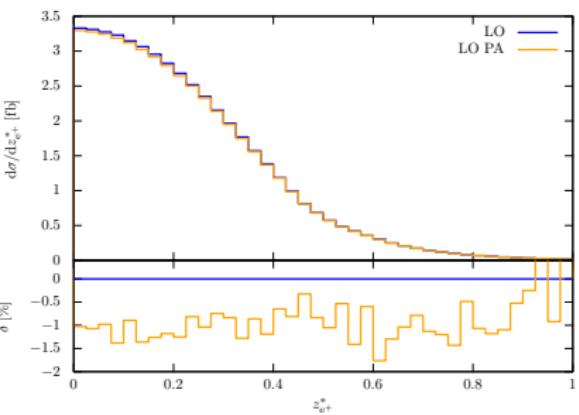
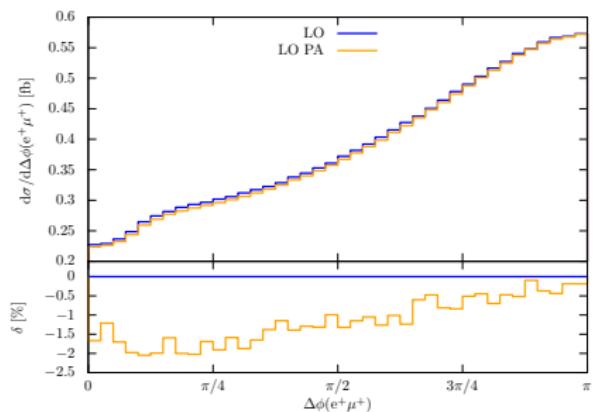
## Full LO vs. PA (II)



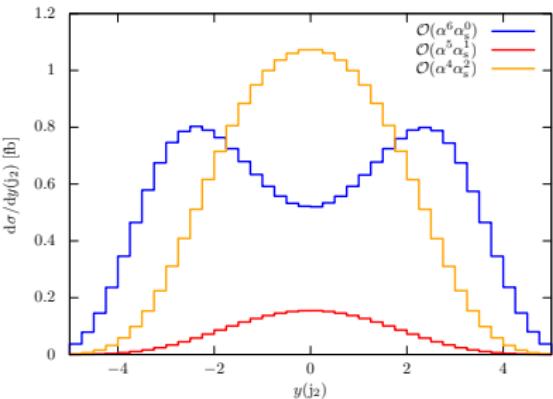
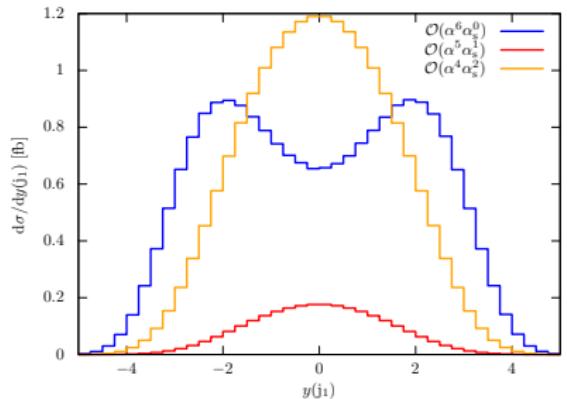
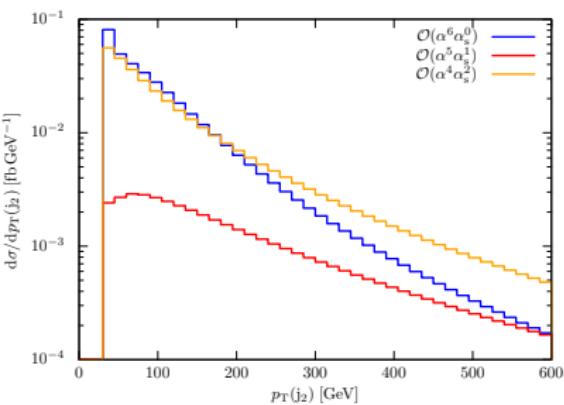
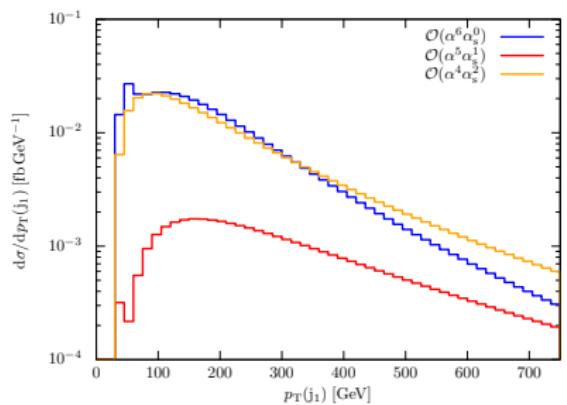
## Full LO vs. PA (III)



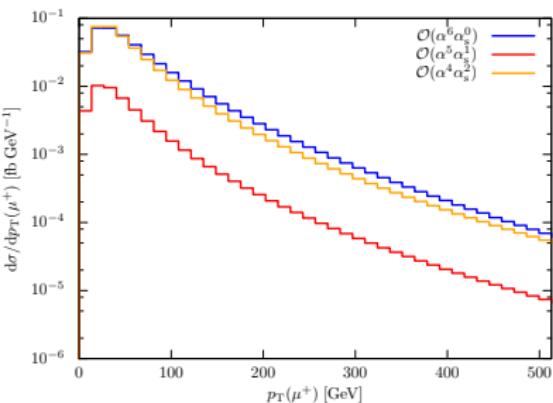
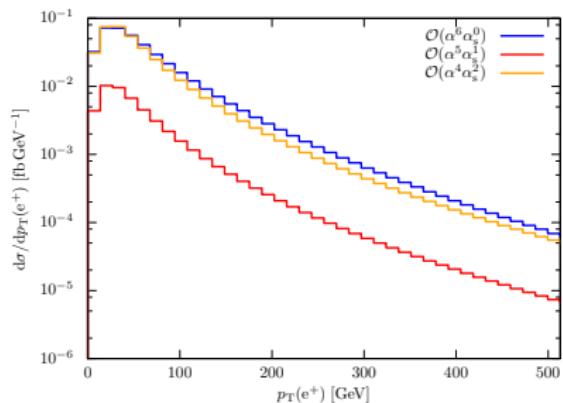
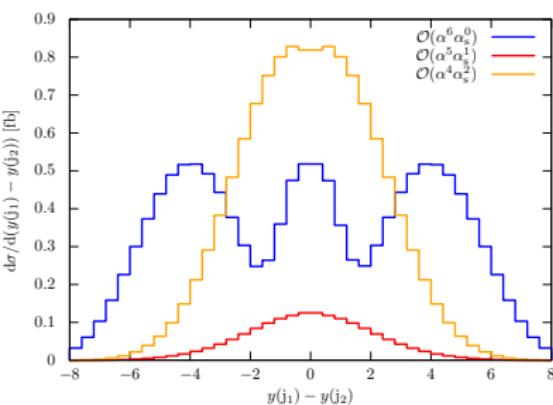
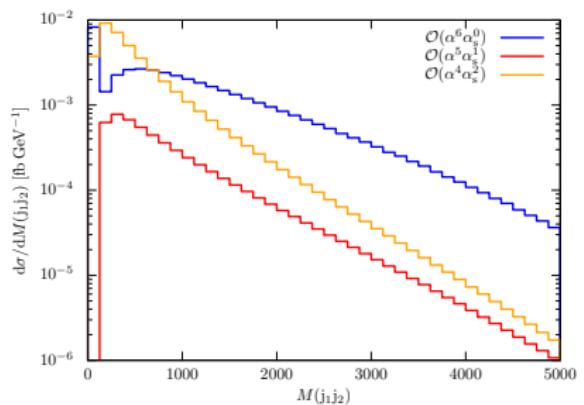
## Full LO vs. PA (IV)



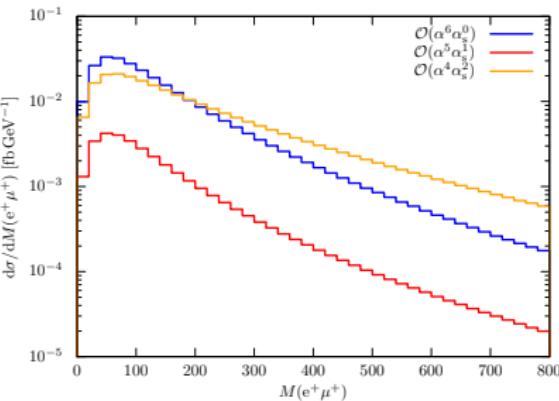
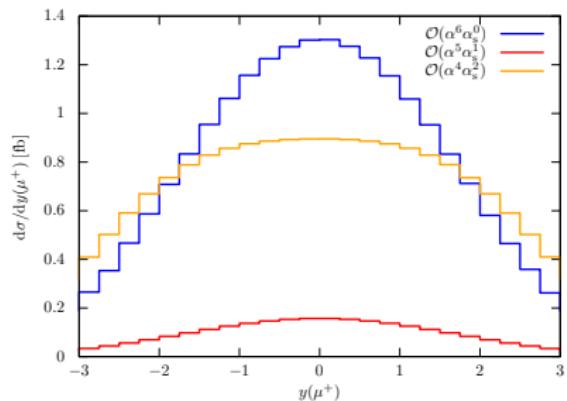
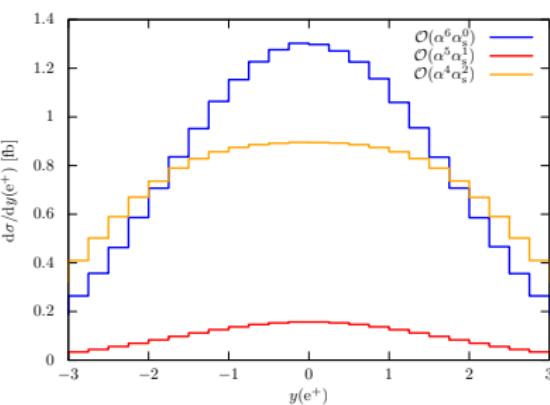
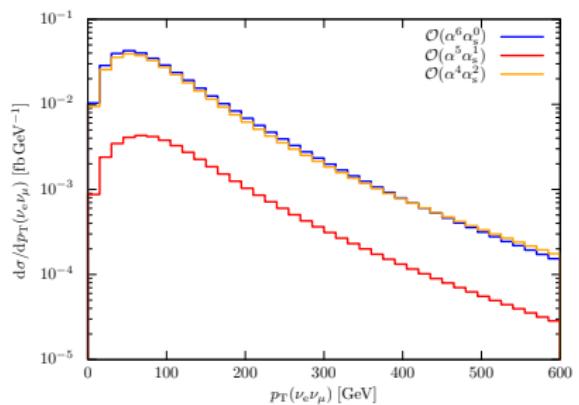
## LO Inclusive Cross Sections (I)



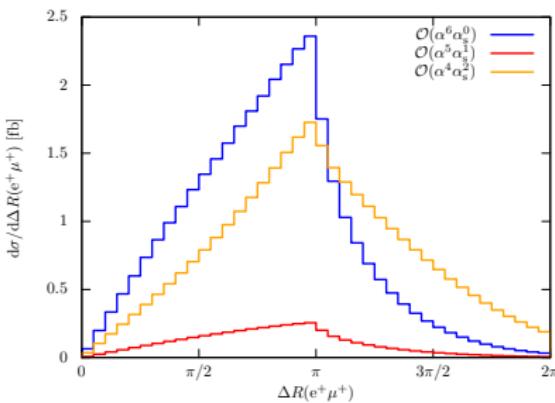
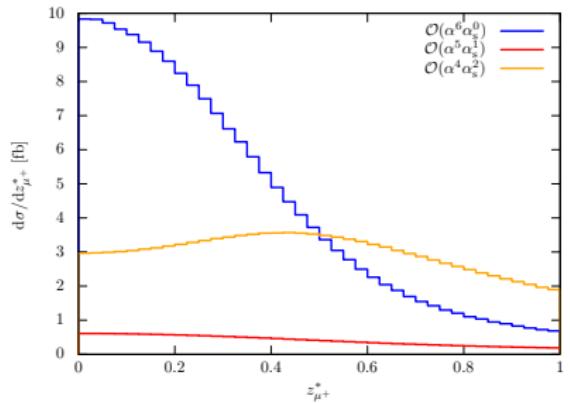
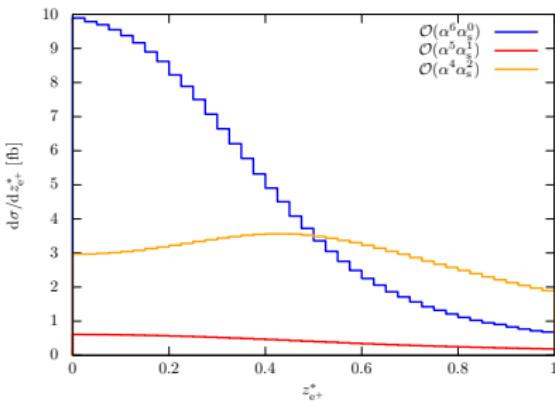
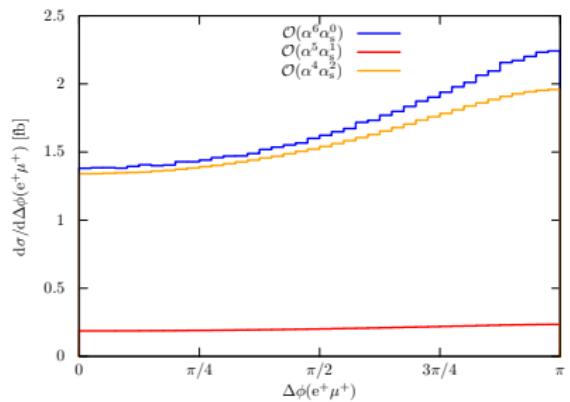
## LO Inclusive Cross Sections (II)



## LO Inclusive Cross Sections (III)



## LO Inclusive Cross Sections (IV)



## LO Inclusive Cross Sections (V)

