WG1 Status/Progress since Split: $\mathcal{O}(\alpha^6 \alpha_s)$ Calculation of $pp \to e^+ \nu_e \mu^+ \nu_\mu jj + X$

Christopher Schwan
In collaboration with: Simon Brass, Alexander Karlberg, Matthieu Pellen, Michael Rauch, Jürgen Reuter, Pascal Stienemeier, Marco Zaro

VBSCAN meeting after MBI 2017,
Karlsruhe, Aug. 31

Plan and Status

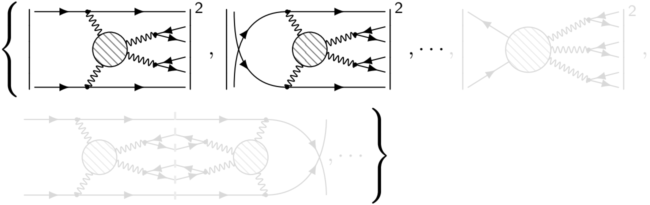
Objective	Deliverables	Inte
Research Coordination 1: A standard for the definition of Vector Boson Scattering signal and background processes to be used in calculations and experimental analyses will be set.	Review of the state-of-the-art analysis techniques.	
	Definition of the vector boson scattering signal for the phenomenological studies and data analyses within the first two years of the action	Math
	Study of an optimal strategy to isolate VBS from background processes in an experimentally sound manner (pile-up, non-perturbative effects, S/B issues, …). The strategy should be suitable to be implemented in theoretical predictions, either at parton or at hadron level	Mich
Research Coordination 2: Signal and background processes will be described with a significantly better precision than available nowadays, with next-to-leading precision in the strong and electro-weak perturbation theory of the Standard Model.	Comparative study of the different tools/computer codes related to signal and background processes (both at fixed order and matched with parton showers), assessing the respective strengths and weaknesses.	Marc
	Set of predictions for the relevant processes including NLO QCD and EW corrections, and recommendations to include the effect of EW corrections (on central values and theoretical uncertainties) in event generators (NLO QCD+PS) used by experimental analyses.	Marc
	State-of-the-art review and comparative study of available tools/computer codes.	Marc
Research Coordination 3: Means will be developed for the isolation of the scattering of longitudinal vector boson modes and establish a protocol to be followed for theoretical predictions and the interpretation of experimental results, which will allow the measurement of the longitudinal component at the High Luminosity Large Hadron Collider.	Search of observables sensitive to the longitudinal polarisation state of the vector bosons, and development of experimental strategies to enhance such a sensitivity.	Mich
	Study of a suitable parameterisation to take into account BSM effects related to longitudinal polarisation, possibly using EFTs (this may be linked to the deliverables of Research Coordination 4)	
	Theoretical motivations for EFT scan in terms of UV-complete theories.	

- calculate LO $\mathcal{O}(\alpha^6)$ and $\mathcal{O}(\alpha^6\alpha_s)$ corrections for the process $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\,\mu^+\nu_\mu\,\mathrm{jj} + \mathrm{X}$
- compare different programs/approximations

Overview of People involved and Approximations used

Contact person	Code	Squares	Interf.	Off-shell	NF QCD	EW Corr.
A. Karlberg	POWHEG	t/u	No	Yes	No	No
M. Pellen	RECOLA+MOCANLO	Yes	Yes	Yes	Yes	Yes
M. Rauch	VBFNLO	Yes	No	Yes	No	No
C. Schwan	BONSAY	t/u	No	V+I PA	No	No
M. Zaro	MG5_AMC	Yes	Yes	Yes	No	No
V. Rothe	WHIZARD	Yes	Yes	Yes	Yes	Yes

$|\mathcal{A}|^2 \ni$



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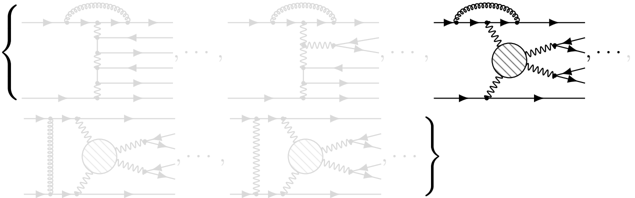

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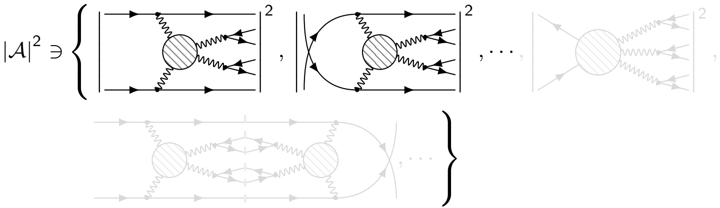

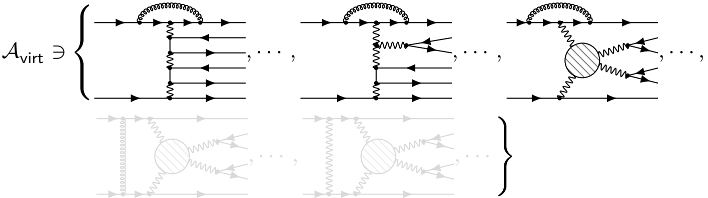

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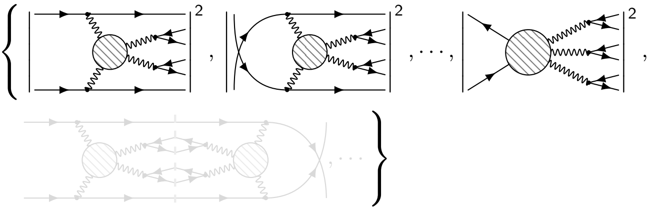

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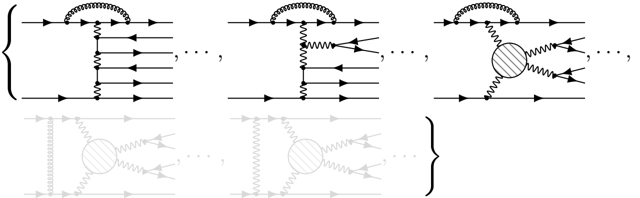

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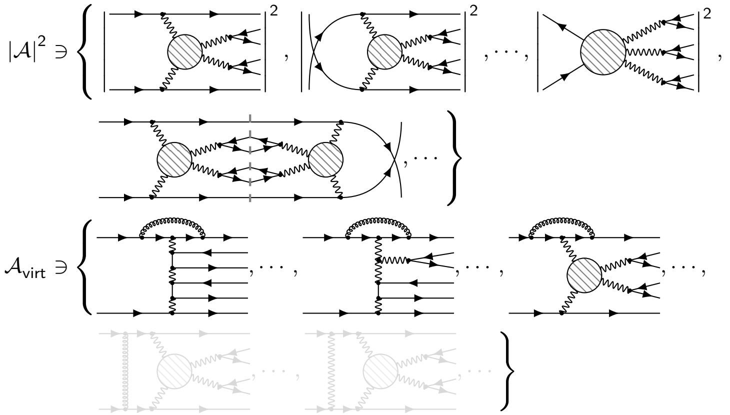

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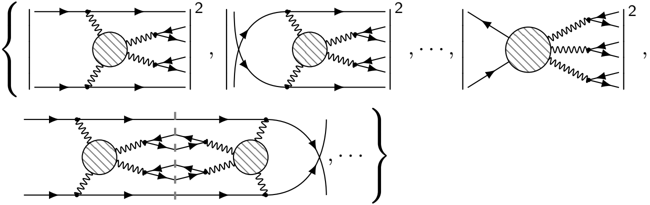

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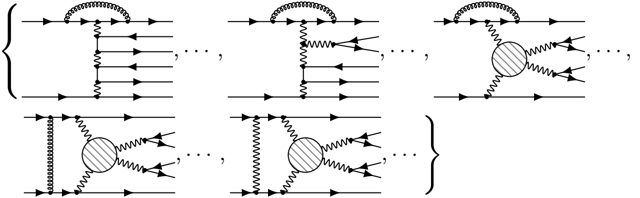


Setup for $pp \to e^+\nu_e\,\mu^+\nu_\mu\,jj + X$

Parameters:

- Complex-mass scheme with input parameters

$$
\begin{aligned}
m_t &= 173.21\,\text{GeV} & \Gamma_t &= 0\,\text{GeV}\\
m_H &= 125.00\,\text{GeV} & \Gamma_H &= 4.07\times10^{-3}\,\text{GeV}\\
m_Z^{OS} &= 91.1876\,\text{GeV} & \Gamma_Z^{OS} &= 2.4952\,\text{GeV}\\
m_W^{OS} &= 80.385\,\text{GeV} & \Gamma_W^{OS} &= 2.085\,\text{GeV}
\end{aligned}
$$

  and $G_\mu = 1.16637\times10^{-5}\,\text{GeV}$,

- and the following relations, $V = W, Z$,

$$M_V = M_V^{OS}/\sqrt{1+(\Gamma_V/M_V)^2}$$

$$\Gamma_V = \Gamma_V^{OS}/\sqrt{1+(\Gamma_V/M_V)^2}$$

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

Cuts:

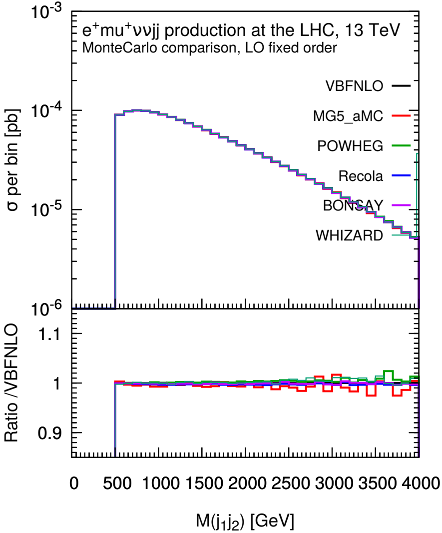
- Jet definition: ≥ 2 Anti-k_T jets ($R = 0.4$) with $p_T > 30$ GeV, $|y| < 4.5$, and $\Delta R_{j\ell} > 0.3$[1]
- Tagging jets: $\Delta y_{j_1 j_2} > 2.5$ and $M_{j_1 j_2} > 500$ GeV
- Leptons: $p_T > 20$ GeV, $|y| < 2.5$, $\Delta R_{\ell\ell} > 0.3$
- Neutrinos: $p_{T,\text{miss}} > 40$ GeV

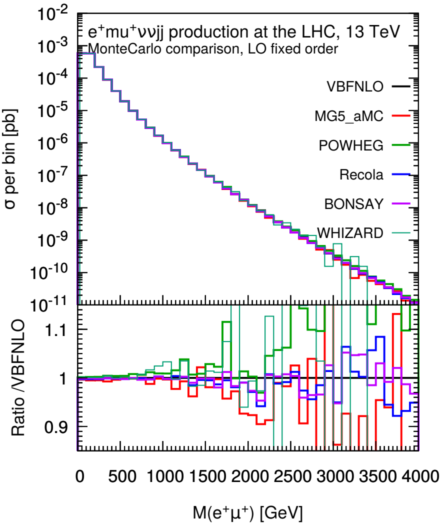
PDFs and Scales:

- NNPDF3.0 PDFs, with $\alpha_s(M_Z) = 0.118$
- $\mu_F = \mu_R = M_W$

[1] ATLAS 8 TeV: "At least two jets reconstructed with the anti-k t algorithm with jet size $R = 0.4$ and with $p_T > 30$ GeV, $|y| < 4.5$, and separated from the leptons by $\Delta R_j > 0.3$ are also required."

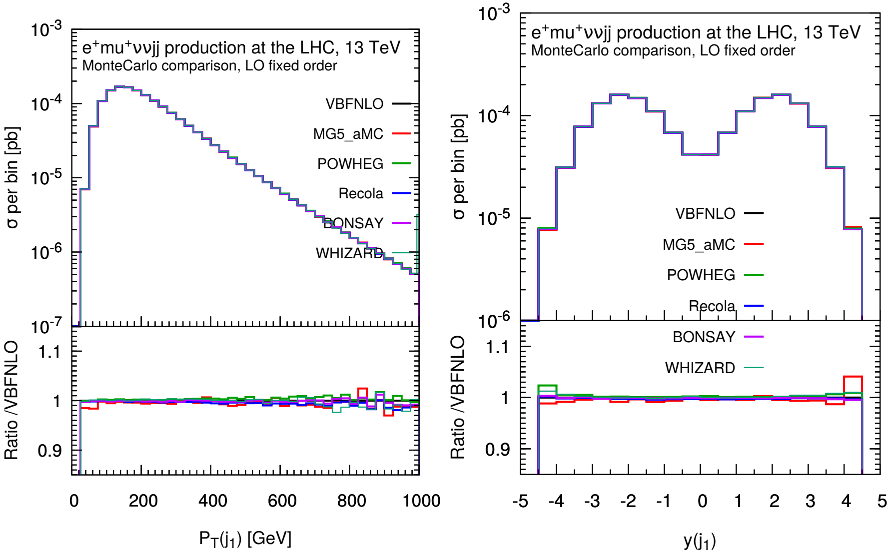
LO comparison: $M_{j_1 j_2}$ and $M_{\ell\ell}$





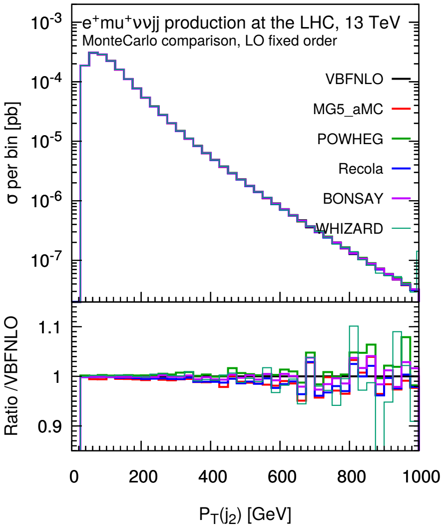
New: WHIZARD

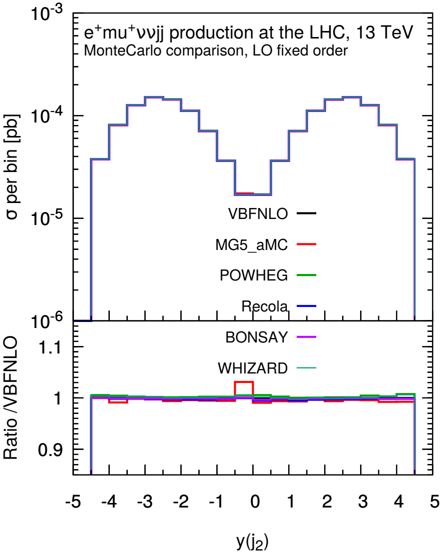
LO comparison: Leading jet p_T and y



New: WHIZARD

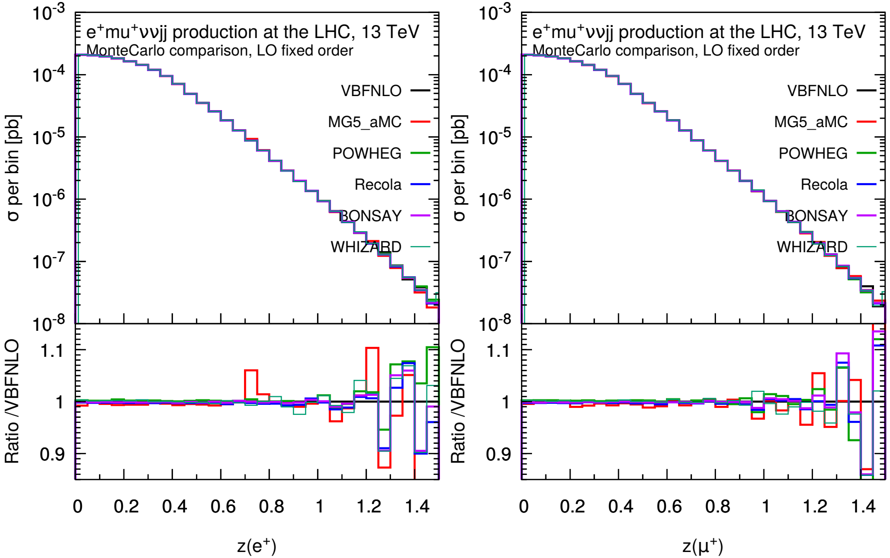
LO comparison: Subleading jet p_{T} and y





New: WHIZARD

LO comparison: $z_\ell^* = (y_\ell - (y_{j_1} + y_{j_2})/2)/\Delta y_{j_1 j_2}$



New: WHIZARD

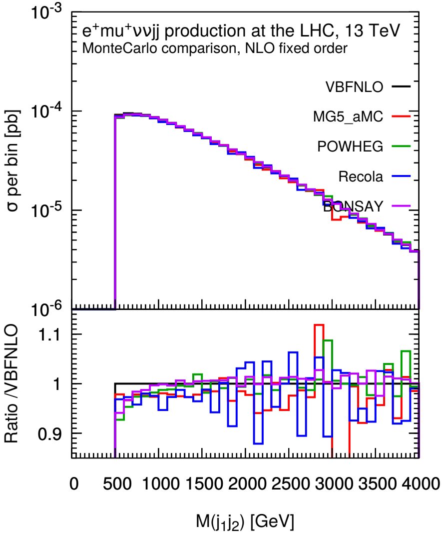
$\mathcal{O}(\alpha^6)$ Integrated Cross Sections for $pp \to e^+\nu_e\,\mu^+\nu_\mu\,jj + X$

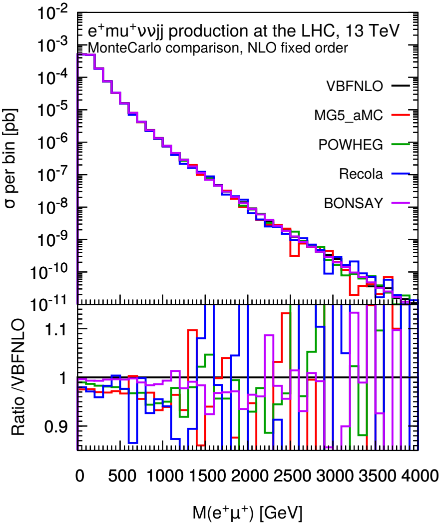
Code	LO σ [fb]
BONSAY	1.5524 ± 0.0002
MG5_aMC	1.547 ± 0.001
POWHEG	1.5573 ± 0.0003
Recola+MoCaNLO	1.5503 ± 0.0003
VBFNLO	1.5538 ± 0.0002
WHIZARD	1.5539 ± 0.0004

Comparison of different approximations

- MC errors probabably underestimated?
- very good agreement between different approximations (s-channels, interferences)
- differences basically not visible in distributions

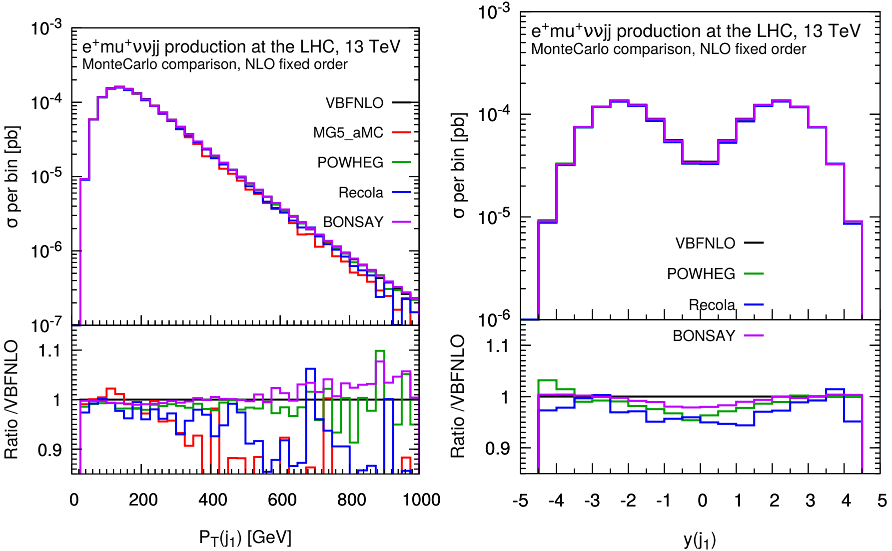
NLO comparison: $M_{j_1 j_2}$ and $M_{\ell\ell}$





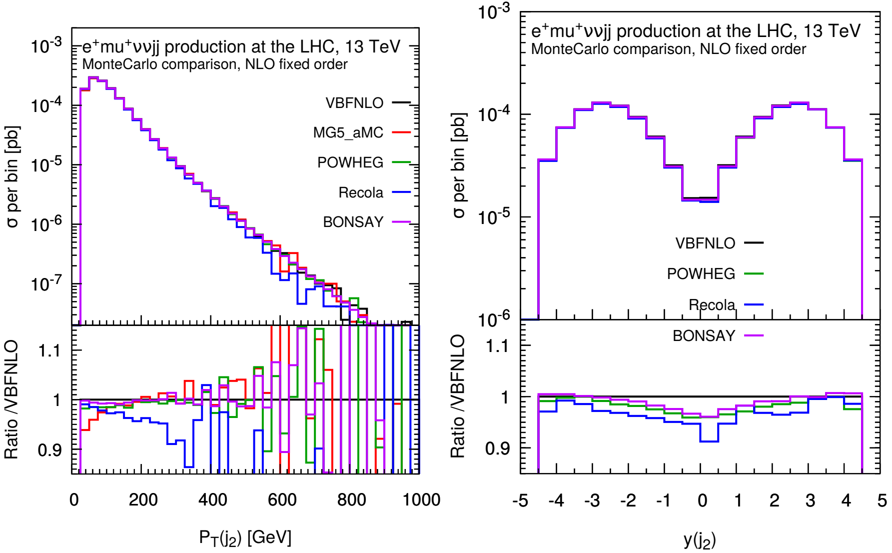
New: Updated numbers from RECOLA

NLO comparison: Leading jet p_{T} and y



New: Updated numbers from RECOLA, Rapidity distributions for BONSAY

NLO comparison: Subleading jet p_T and y



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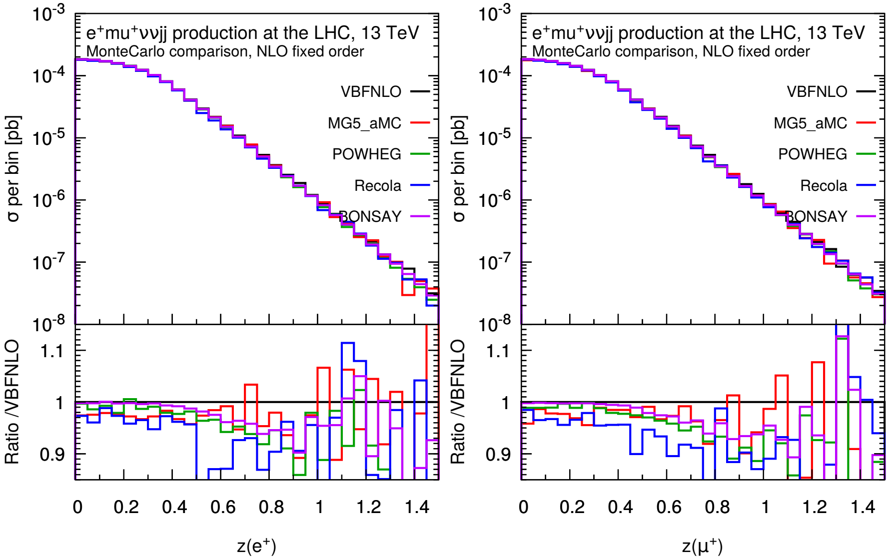

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$\mathcal{O}(\alpha^6\alpha_s)$ Integrated Cross Sections for $pp \to e^+\nu_e\mu^+\nu_\mu jj + X$

Code	LO σ [fb]	NLO σ[fb]	$\sigma(n_j = 2)$ [fb]	$\sigma(n_j = 3)$ [fb]
BONSAY	1.5524 ± 0.0002	1.3469 ± 0.0008	0.8303 ± 0.0008	0.51662 ± 0.00008
MG5_AMC	1.547 ± 0.001	1.318 ± 0.003	0.781 ± 0.004	0.5374 ± 0.0016
POWHEG	1.5573 ± 0.0003	1.334 ± 0.003	0.808 ± 0.001	0.5260 ± 0.0005
RECOLA+MOCANLO	1.5503 ± 0.0003	1.317 ± 0.004		
VBFNLO	1.5538 ± 0.0002	1.3531 ± 0.0003	0.8264 ± 0.0003	0.5267 ± 0.0001
WHIZARD	1.5539 ± 0.0004			

Comparison of different approximations

- 2.74% diff. betw. VBFNLO/RECOLA+MOCANLO
- BONSAY vs. POWHEG: NLO V+I pole approximation very good
- Comparison using the $M_{j_1j_2}$ distribution:
  - BONSAY/POWHEG vs. VBFNLO: s-channels make a difference for small $M_{j_1j_2}$?
  - previous vs. MG5_AMC and RECOLA+MOCANLO: Negative Corrections from NF QCD diagrams?
  - EW corrections to interference smaller than NF QCD diagrams?

Plan for the near future

- Calculate irreducible backgrounds at $\mathcal{O}(\alpha^4\alpha_s^2)$ and $\mathcal{O}(\alpha^5\alpha_s)$ and use them to define a "control region" and "signal region"
- Improve calculations with parton showers
- Questions/Suggestions/Wishes?

BONSAY with $\Delta_{j\ell}$ EVENT CUT

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BONSAY	1.5524 ± 0.0002	1.3358 ± 0.0008	0.8192 ± 0.0008	0.51663 ± 0.00007
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BONSAY with $\Delta_{j\ell}$ JET DEFINITION

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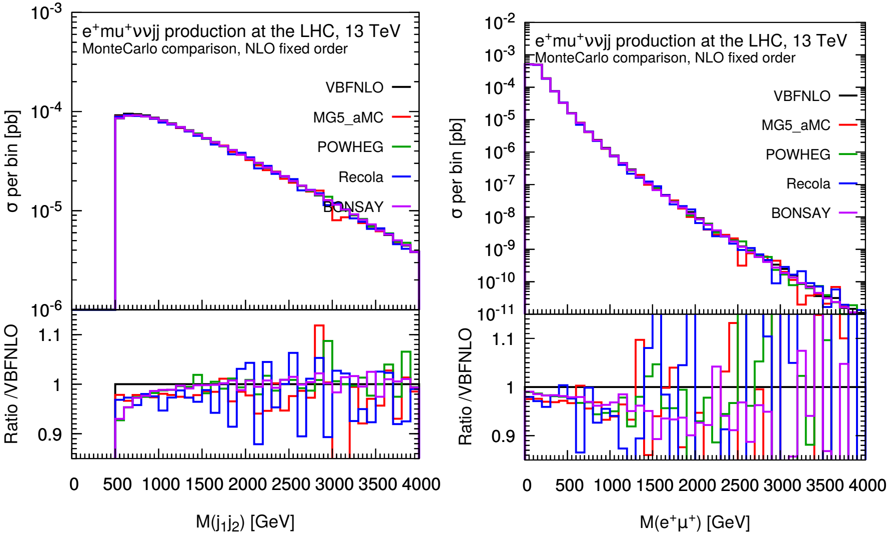
NLO BONSAY: $M_{j_1 j_2}$ and $M_{\ell\ell}$ with $\Delta_{j\ell}$ EVENT CUT



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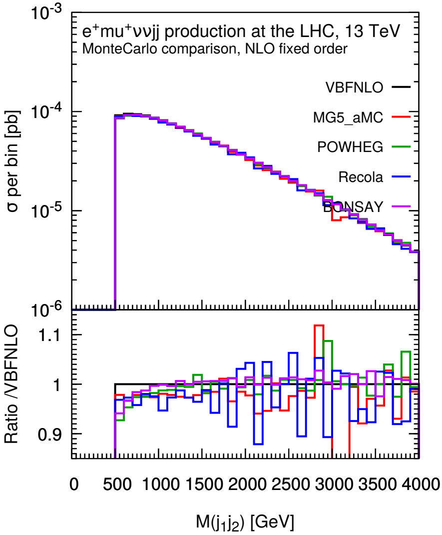
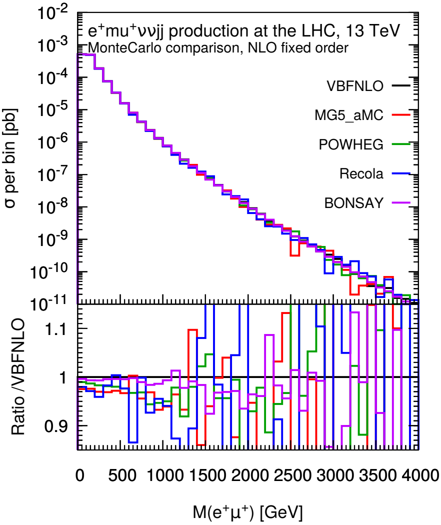
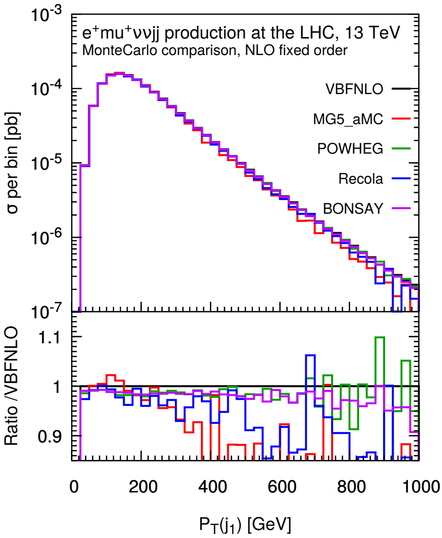
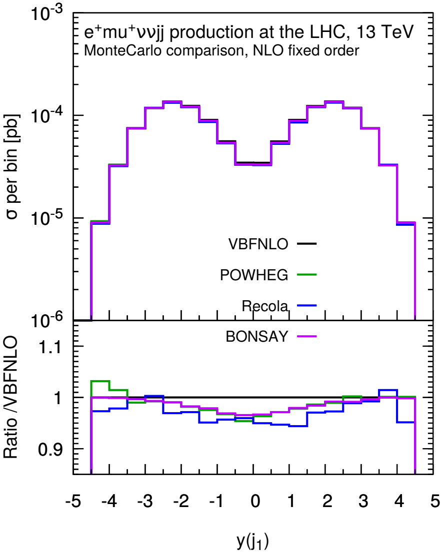




NLO BONSAY: Leading jet p_T and y with $\Delta_{j\ell}$ EVENT CUT





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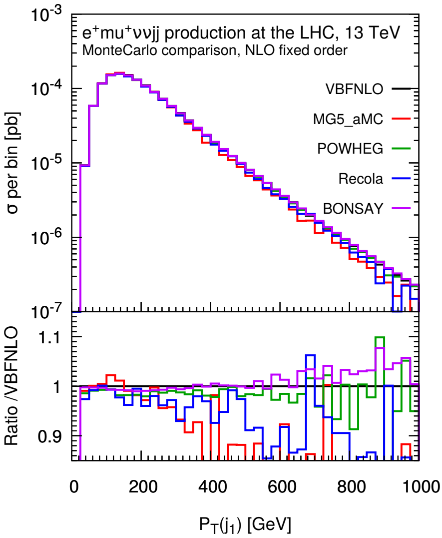

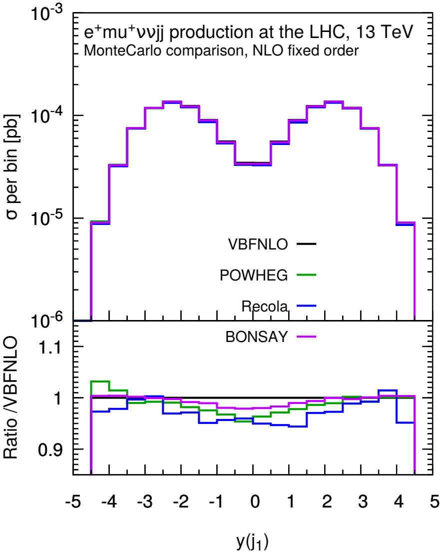

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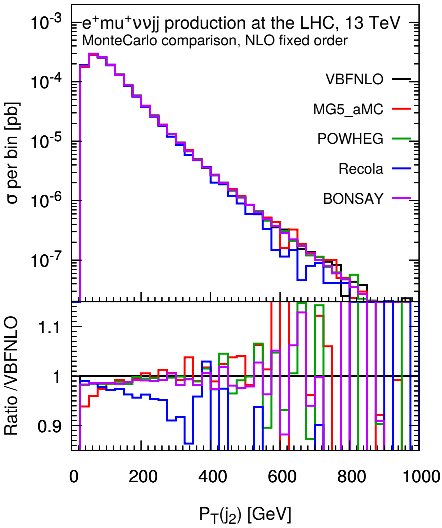

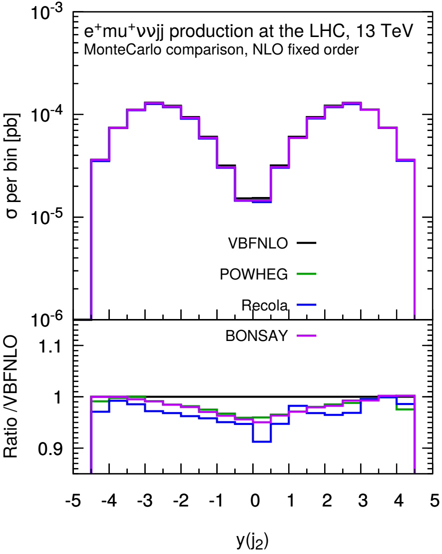

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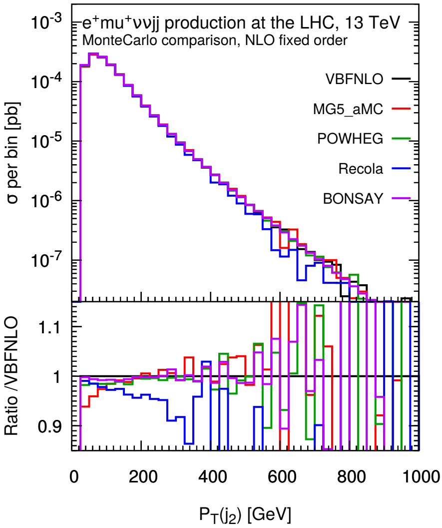
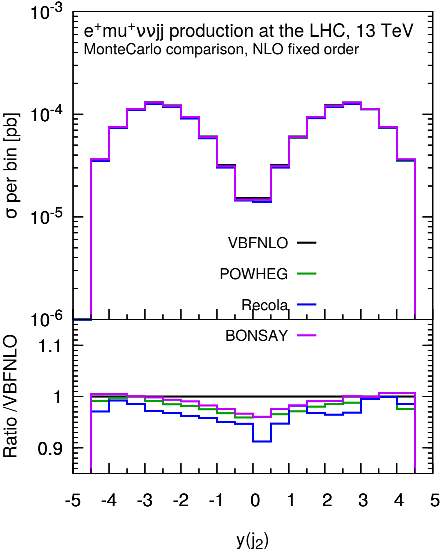
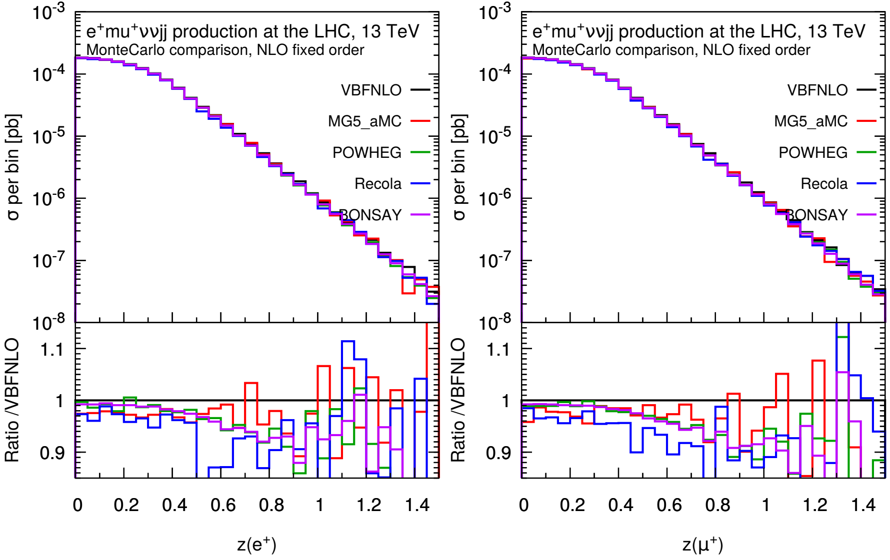




NLO BONSAY: $z_\ell^* = (y_\ell - (y_{j_1} + y_{j_2})/2)/\Delta y_{j_1 j_2}$ with $\Delta_{j\ell}$ JET DEFINITION



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