Stress testing the Standard Model via vector-boson scattering at the LHC

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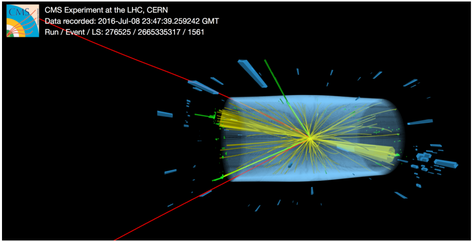
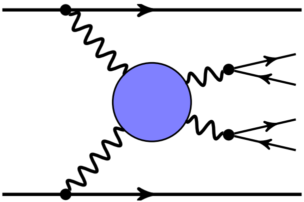
Invited Topical Talk
DPG - Dortmund 2021, Germany

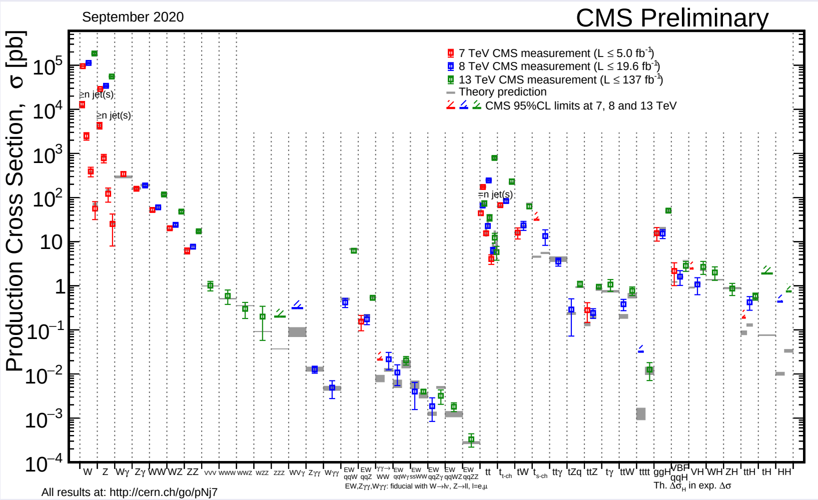
18$^{\text{th}}$ of March 2021

→ Illustration of Giordano Bruno's philosophical ideas (XVIthcentury)

LHC: Great tool to probe fundamental interactions at high energies
→ Cross talk between **experiment** and **theory**



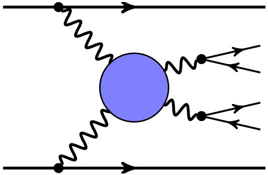




VBS: smallest cross sections at the LHC!

Vector-Boson Scattering (VBS) at the LHC

→ Scattering of vector bosons!



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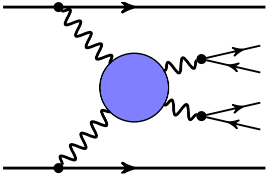


Leptonic signature: $2\mathrm{j} + 4\ell$

- pp $\to \ell^{\pm}\nu_{\ell}\ell'^{\pm}\nu_{\ell'}$jj (ss-WW)
- pp $\to \ell^{\pm}\nu_{\ell}\ell'^{+}\ell'^{-}$jj (WZ)
- pp $\to \ell^{+}\ell^{-}\ell'^{+}\ell'^{-}$jj (ZZ)
- pp $\to \ell^{\pm}\nu_{\ell}\ell'^{\mp}\nu_{\ell'}$jj (os-WW)

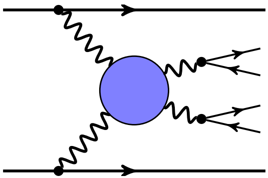
Semi-leptonic signature: $4\mathrm{j} + 2\ell$

- pp $\to \ell^{\pm}\nu_{\ell}$4j (ss-WW, os-WW, WZ)
- pp $\to \ell^{+}\ell^{-}$4j (WZ, ZZ)

Fully hadronic signature: 6j

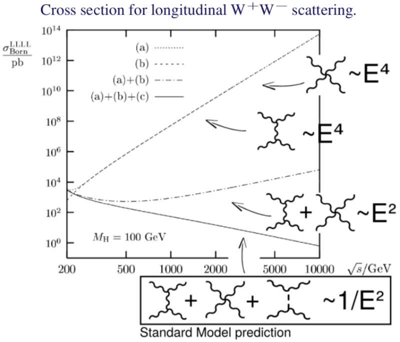
- pp $\to$ 6j (ss-WW, os-WW, WZ, ZZ)

Why this is interesting



- Electroweak symmetry breaking
- Unitarisation due to Higgs boson
- Polarisation measurements
- Measurements of SM parameters
  → Higgs width
- Triple/quartic gauge coupling
  → EFT
- ...

[Denner, Hahn, 1997]



source: Stefanie Todt,
https://indico.cern.ch/event/777988/contributions/3410603

Underlying idea

Delicate structure in the Standard Model:

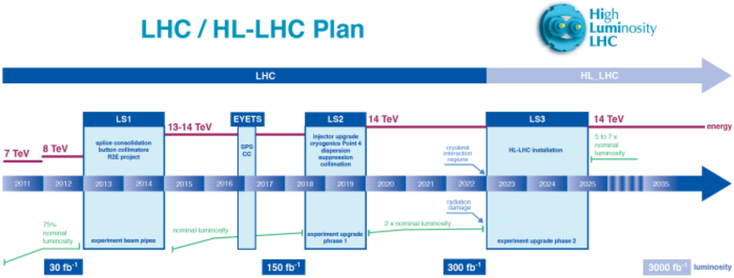
$\rightarrow$ Is it modified/disturbed by new phenomena?

Underlying idea

Delicate structure in the Standard Model:

→ Is it modified/disturbed by new phenomena?

→ **To help in this quest: HL-HE LHC programme**



→ Great jump in precision

Precision physics for VBS

Assume scaling of uncertainties with 1/√L

- **dedicated studies with detector simulation for example in** CMS-PAS-SMP-14-008

Integrated Luminosity	36 fb	150 fb	300 fb	3000 fb-
Year	2016	2019	2022	2038
EW(VBS) W±W±	20%	10%	7%	2%
EW (VBS) ZZ	35%	18%	13%	6%
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source: Jakob Salfeld-Nebgen, https://indico.cern.ch/event/711256

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This talk

- How to get to per-cent uncertainties from the theory side
- Importance of interplay between experiment and theory
- (Some) Pitfalls to avoid

→ Focused on Standard Model physics

Outline:

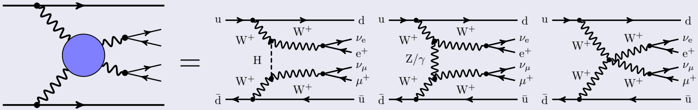
- Vector-boson scattering at the LHC
  $\rightarrow$ Theory definition and how to measure it

- *The devil is in the detail*
  $\rightarrow$ Kinematics and theory approximations

- Going beyond current work
  $\rightarrow$ an outlook

Example: pp $\rightarrow \mu^+\nu_\mu e^+\nu_e jj$ (aka *same-sign WW VBS*)

VBS diagrams



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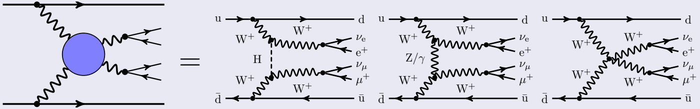
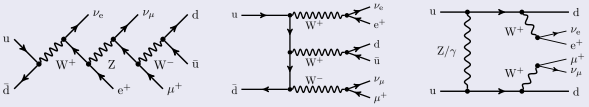


More diagrams contribute ...

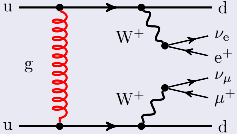


⚠ Gauge invariance: diagrams cannot be cherry picked!

VBS *signatures* possess more than VBS *contributions*:
$\to$ All contributions are experimentally measured

(VBS, tri-boson, decay chains, etc.)

Even more (QCD) diagrams ...



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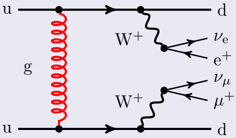
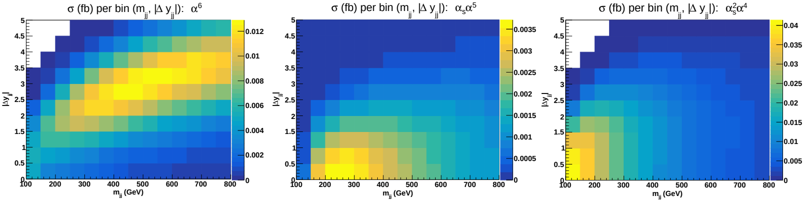


With 2 different amplitudes → 3 different contributions:

- $\mathcal{O}\left(\alpha^6\right)$: EW contribution/signal
- $\mathcal{O}\left(\alpha_s\alpha^5\right)$: interference
- $\mathcal{O}\left(\alpha_s{}^2\alpha^4\right)$: QCD contribution/background

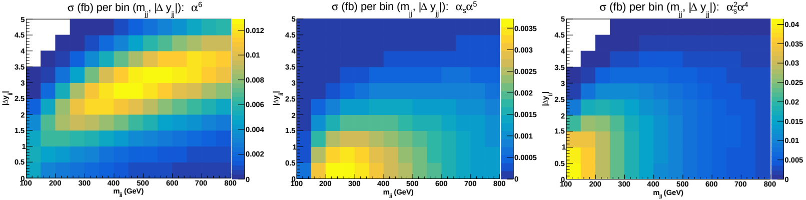
$$\underbrace{\mathcal{O}\left(\alpha^6\right)}_{(\text{VBS + others})^2} \quad \overbrace{\mathcal{O}\left(\alpha_s\alpha^5\right)}^{(\text{VBS + others})\times(\text{QCD})} \quad \underbrace{\mathcal{O}\left(\alpha_s{}^2\alpha^4\right)}_{(\text{QCD})^2}$$

→ How to measure the EW component (including VBS) then?



[Ballestrero, MP et al.; 1803.07943]

- The contributions have different kinematic
- Use of exclusive cuts to enhance the EW contribution
  $\rightarrow$ typical cuts are $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$ and $|\Delta y_{\mathrm{jj}}| > 2.5$
  $\rightarrow$ typical kinematic:
  back-to-back jets at large rapidities $+$ central gauge bosons



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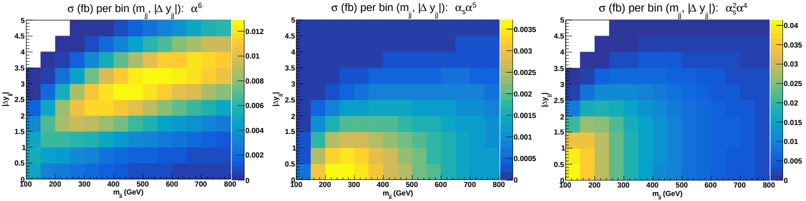
→ Solution: Exclusive phase-space with ...

... irreducible background (interference+QCD) subtracted



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$\rightarrow$ Solution: Exclusive phase-space with ...
... irreducible background (interference+QCD) subtracted

⚠ VBS contributions appear also in the interference
⚠ Theory dependent measurement

Moving on to NLO

$$\begin{tikzcd}
\textbf{LO} & & \mathcal{O}(\alpha^6) \arrow[dl, "\text{EW}"'] \arrow[dr, "\text{QCD}"] & & \mathcal{O}(\alpha_s\alpha^5) \arrow[dl, "\text{EW}"'] \arrow[dr, "\text{QCD}"] & & \mathcal{O}(\alpha_s{}^2\alpha^4) \arrow[dl, "\text{EW}"'] \arrow[dr, "\text{QCD}"] & \\
\textbf{NLO} & \mathcal{O}(\alpha^7) & & \mathcal{O}(\alpha_s\alpha^6) & & \mathcal{O}(\alpha_s{}^2\alpha^5) & & \mathcal{O}(\alpha_s{}^3\alpha^4)
\end{tikzcd}$$

→ Order $\mathcal{O}\left(\alpha_s\alpha^6\right)$ and $\mathcal{O}\left(\alpha_s{}^2\alpha^5\right)$: QCD and EW corrections mix

At NLO

Meaningless distinction between EW and QCD component

Moving on to NLO

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

EW QCD EW QCD EW QCD

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

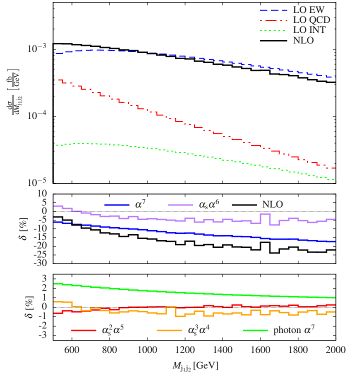
$\rightarrow$ Order $\mathcal{O}\left(\alpha_s\alpha^6\right)$ and $\mathcal{O}\left(\alpha_s{}^2\alpha^5\right)$: QCD and EW corrections mix

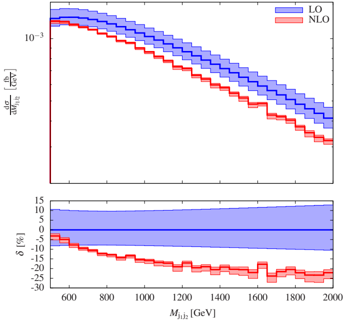
At NLO

Meaningless distinction between EW and QCD component

Solution: Combined measurement of all the contributions
$\rightarrow$ clear physical interpretation

$pp \to W^{\pm}W^{\pm}jj$ @ full NLO





[Biedermann, Denner, MP; 1708.00268]

- Different LO and NLO behaviours

  ⚠ Large EW corrections: intrinsic feature of VBS at the LHC

  → Now available in POWHEG [Chiesa, Denner, Lang, MP; 1906.01863]

Comparison with data

→ Recent ss-WW and WZ analysis of CMS with 137 fb^{-1} [2005.01173]

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

→ LO: MadGraph5_aMC@NLO+PYTHIA

→ 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

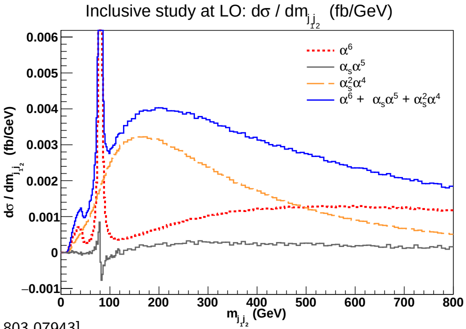
NB: Uncertainty for the NLO numbers are from the LO 7-scales variation.

→ Set basis of future precision measurements

- *The devil is in the detail*
  $\rightarrow$ Kinematics and theory approximations

Kinematics and approximations

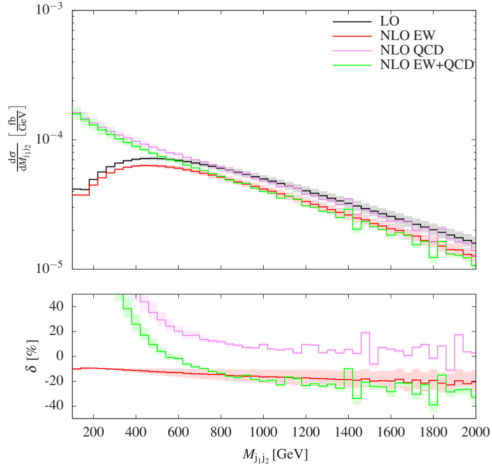
- Typically cuts $m_{\rm jj} > 500\,{\rm GeV}$
  $\rightarrow$ Relaxed for rarest processes
  $\rightarrow$ $m_{\rm jj} > 100\,{\rm GeV}$ (ZZ analysis of [arXiv:1708.02812])

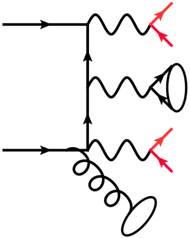


[Ballestrero, MP et al.; 1803.07943]

⚠ EW component possesses VBS+tri-boson+other contributions

Example of ZZ VBS at NLO

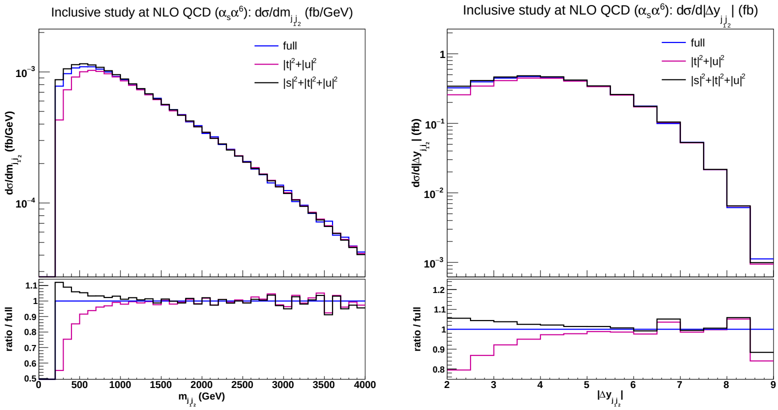




[Denner, Franken, MP, Schmidt; 2009.00411]

→ Effects of tri-boson (at NLO) even when using $m_{jj} > 100$ GeV

Quality of the VBS approximation (neglecting tri-boson contributions)



[Ballestrero, MP et al.; 1803.07943]

- The approximations are worse at NLO
- Approximation can fail by up to 20% even in fiducial regions

Lessons learnt

- For inclusive phase spaces, use full computations (including tri-bosons)
- For exclusive phase spaces, approximate computations OK
- Subtracting tri-boson in measurements is dangerous

⚠ Cross talks between theory and experiment are crucial

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Solution:

- Different phase spaces
  → Sensitive to different effects
  → Great for exp./th. comparisons
- CMS ZZ measurement with $137\,\mathrm{fb}^{-1}$ [2008.07013]

→ Disentangles all physical effects

Particle type	Selection
	ZZjj inclusive
Leptons	$p_T(\ell_1) > 20\,\mathrm{GeV}$ $p_T(\ell_2) > 10\,\mathrm{GeV}$ $p_T(\ell) > 5\,\mathrm{GeV}$ $\lvert\eta(\ell)\rvert < 2.5$
Z and ZZ	$60 < m(\ell\ell) < 120\,\mathrm{GeV}$ $m(4\ell) > 180\,\mathrm{GeV}$
Jets	at least 2 $p_T(\mathrm{j}) > 30\,\mathrm{GeV}$ $\lvert\eta(\mathrm{j})\rvert < 4.7$ $m_{\mathrm{jj}} > 100\,\mathrm{GeV}$ $\Delta R(\ell,\mathrm{j}) > 0.4$ for each ℓ, j
	VBS-enriched (loose)
Jets	ZZjj inclusive + $\lvert\Delta\eta_{\mathrm{jj}}\rvert > 2.4$ $m_{\mathrm{jj}} > 400\,\mathrm{GeV}$
	VBS-enriched (tight)
Jets	ZZjj inclusive + $\lvert\Delta\eta_{\mathrm{jj}}\rvert > 2.4$ $m_{\mathrm{jj}} > 1\,\mathrm{TeV}$

- Going beyond current work
  $\rightarrow$ an outlook

Going beyond current work (I)
$\rightarrow$ Full use of NLO+PS simulations (example ss-WW)

$\rightarrow$ NLO+PS accuracy not yet fully used in experimental analyses

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→ Full use of NLO+PS simulations (example ss-WW)

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Order	$\mathcal{O}\left(\alpha^7\right)$	$\mathcal{O}\left(\alpha_s\alpha^6\right)$	$\mathcal{O}\left({\alpha_s}^2\alpha^5\right)$	$\mathcal{O}\left({\alpha_s}^3\alpha^4\right)$
NLO	✓	✓	✓	✓
NLO+PS	✓	✓*	X	✓

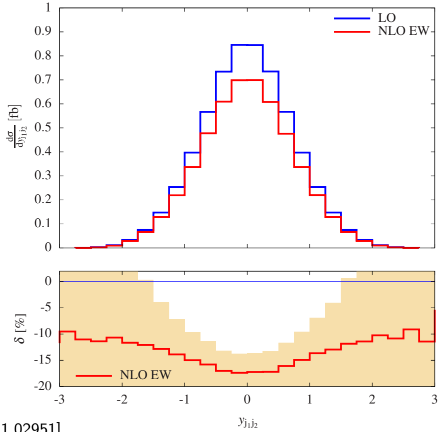
- $\mathcal{O}\left(\alpha^7\right)$ [Biedermann, Denner, MP; 1611.02951, 1708.00268]
  → +PS: [Chiesa, Denner, Lang, MP; 1906.01863]
- $\mathcal{O}\left(\alpha_s\alpha^6\right)$ [Biedermann, Denner, MP; 1708.00268] [Jäger, Oleari, Zeppenfeld; 0907.0580]* [Denner, Hošeková, Kallweit; 1209.2389]* → +PS: [Jäger, Zanderighi; 1108.0864]*
- $\mathcal{O}\left({\alpha_s}^2\alpha^5\right)$ [Biedermann, Denner, MP; 1708.00268]
- $\mathcal{O}\left({\alpha_s}^3\alpha^4\right)$ [Biedermann, Denner, MP; 1708.00268] [Melia et al.; 1007.5313, 1104.2327], [Campanario et al.; 1311.6738] → +PS: [Melia et al.; 1102.4846], [Melia et al.; 1102.4846]

(*) Computations in the VBS-approximation *i.e.* t-u interferences and tri-boson contributions neglected

Soon similar accuracy for other channels
→ Precise comparison against experimental measurements

Going beyond current work (II)

→ Large EW corrections: intrinsic feature of VBS at the LHC

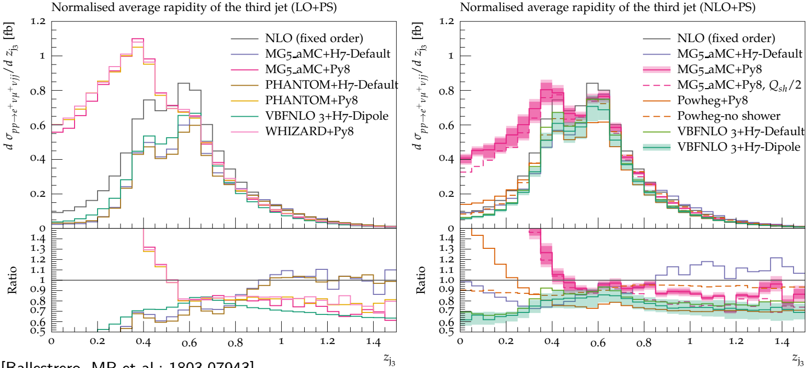


[Biedermann, Denner, **MP**; 1611.02951]
(error band: statistically uncertainty at 3000 fb^{-1})

Sensitive to EW corrections at High-Luminosity LHC
→ Homework for theorists: compute them in new-physics models

Going beyond current work (III)

→ Exploit theory understanding in parton shower



[Ballestrero, MP et al.; 1803.07943]

Large differences for third-jet observables (only at NLO)

→ Understood now (recoil scheme) [Jäger, Karlberg, Plätzer, Scheller, Zaro; 2003.12435]

Allows for the use of jet veto in experimental analyses

→ Homework for theorists: compute VBS+1j at NLO QCD

Going beyond current work (IV)
→ Semi-leptonic signatures

Next step after leptonic measurements of VBS:
→ measuring the EW production of $\ell\nu_\ell + 4\mathrm{j}$ and $\ell^+\ell^- + 4\mathrm{j}$

- Large cross sections
- Great potential for new physics studies
- Huge and complicated backgrounds

→ Challenge for both theory and experiment!

- Limit of current (LO/NLO) predictions (very CPU intensive)
- Difficult experimental analyses

Summary

Vector-boson scattering at the LHC

- Physical definition
- Comparisons between theory and experiment
  - Full measurement vs. full predictions
  - Subtracted measurements vs. approximate predictions
  - Use of different phase-space regions

  $\rightarrow$ Best way to get most of VBS physics in a transparent way
- Possible directions to go beyond current work
  $\rightarrow$ Precision programme at the LHC

- Potential for exciting studies in Standard Model and beyond
  $\rightarrow$ Polarisation, concrete new-physics models, EFT, ...

⚠ Cross talk between theory and experiment is crucial

Going even beyond ...

Review

Vector-Boson Scattering at the LHC: unravelling the Electroweak sector

[arXiv:2102.10991]

Roberto Covarelli, MP, Marco Zaro

Thank you

BACK-UP