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

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GRK seminar

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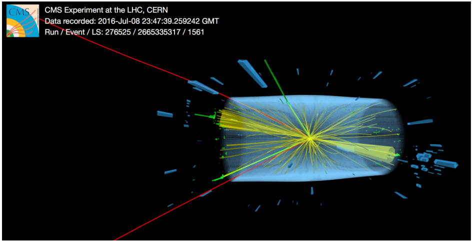
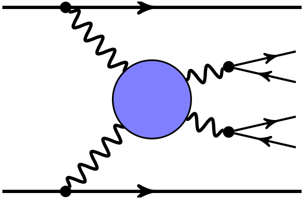
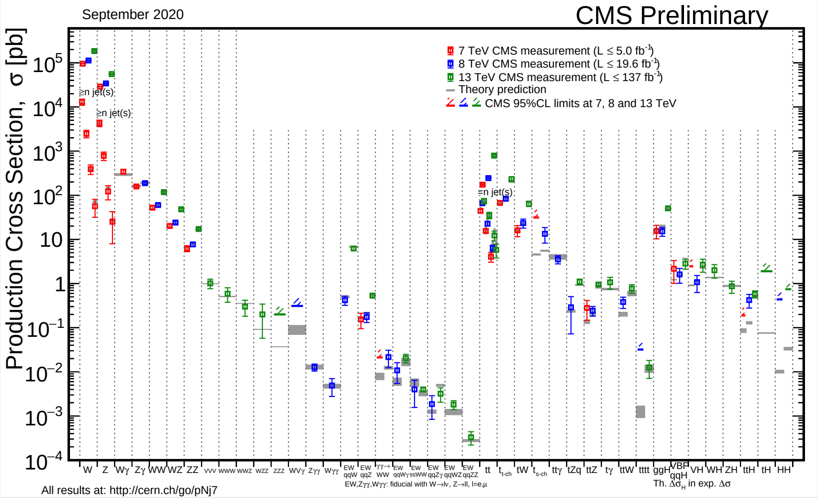
→ Illustration of Giordano Bruno's philosophical ideas (XVIthcentury)

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

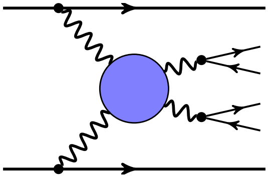






VBS: smallest cross sections at the LHC!

Vector-Boson Scattering (VBS) at the LHC
→ Scattering of vector bosons!



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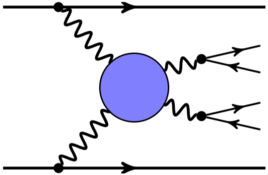


Leptonic signature: $2\mathrm{j} + 4\ell$

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

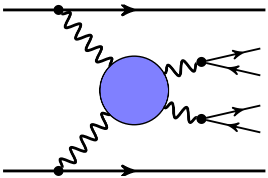
Semi-leptonic signature: $4\mathrm{j} + 2\ell$

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

Fully hadronic signature: 6j

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

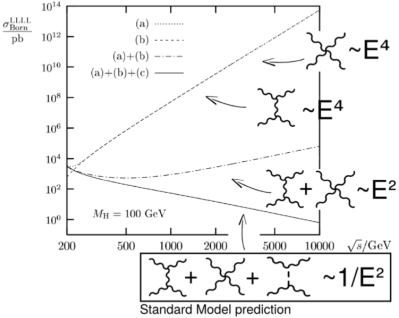
Why this is interesting



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

[Denner, Hahn, 1997]

Cross section for longitudinal W^+W^- scattering.



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

Underlying idea

Delicate structure in the Standard Model:

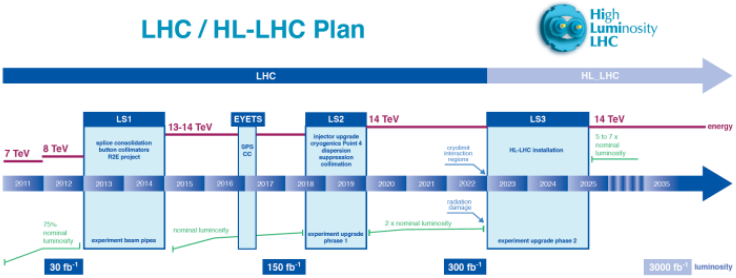
$\rightarrow$ Is it modified/disturbed by new phenomena?

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%
EW (VBS) WZ	35% personally anticipated	18%	13%	6%

source: Jakob Salfeld-Nebgen, https://indico.cern.ch/event/711256

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This talk

→ Focused on Standard Model physics

- How to get to per-cent uncertainties from the theory side
- Importance of interplay between experiment and theory

Outline:

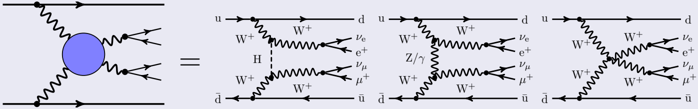
- Vector-boson scattering at the LHC
  $\rightarrow$ Theory definition and how to measure it

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

- Going beyond current work
  $\rightarrow$ Few directions

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

VBS diagrams



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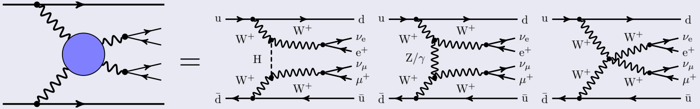
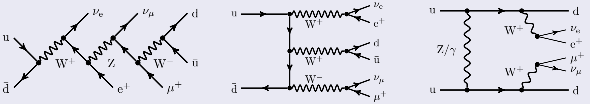


More diagrams contribute ...



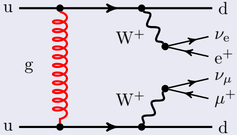
⚠ Gauge invariance: diagrams cannot be cherry picked!

VBS *signatures* possess more than VBS *contributions*:

→ All contributions are experimentally measured

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

Even more (QCD) diagrams ...



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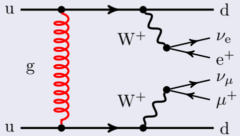
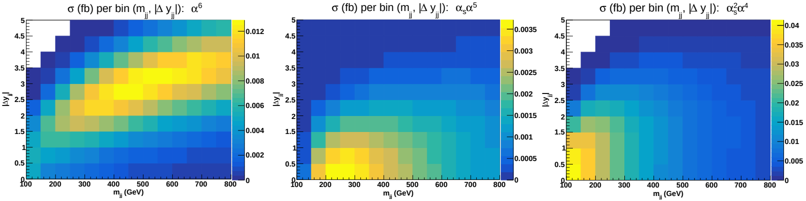


With 2 different amplitudes → 3 different contributions:

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

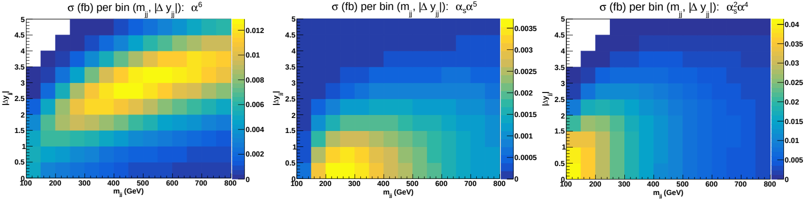
$$\underbrace{\mathcal{O}\left(\alpha^6\right)}_{(\mathrm{VBS}\,+\,\mathrm{others})^2} \quad \overbrace{\mathcal{O}\left(\alpha_s \alpha^5\right)}^{(\mathrm{VBS}\,+\,\mathrm{others})\times(\mathrm{QCD})} \quad \underbrace{\mathcal{O}\left({\alpha_s}^2 \alpha^4\right)}_{(\mathrm{QCD})^2}$$

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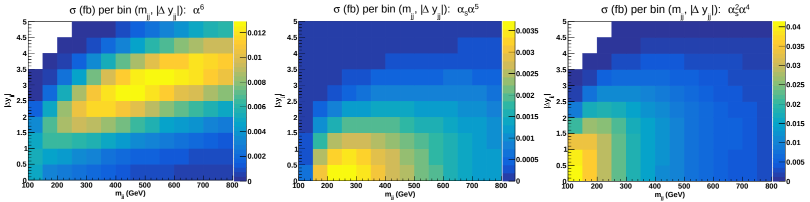
$\rightarrow$ Solution: Exclusive phase-space with ...
... irreducible background (interference+QCD) subtracted



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$\rightarrow$ Solution: Exclusive phase-space with ...
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⚠ VBS contributions appear also in the interference
⚠ Theory dependent measurement

LO cross sections in fiducial volume

- $\mathrm{W^+W^+}$:

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$
σ_{LO} [fb]	1.4178(2)	0.04815(2)	0.17229(5)
δ[%]	86.5	2.9	10.5

[Biedermann, Denner, MP; 1708.00268]

- $\mathrm{W^+Z}$:

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$
σ_{LO} [fb]	0.25416(6)	0.006833(6)	0.9912(2)
δ[%]	20.3	0.5	79.2

[Andersen, MP et al.; 1803.07977 LH proceedings]

→ The relative size of the EW contribution is process dependent
→ Background can be overwhelming
→ Interference usually small but not negligible

⚠ Background is as important as the signal!

Moving on to NLO

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

→ 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

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

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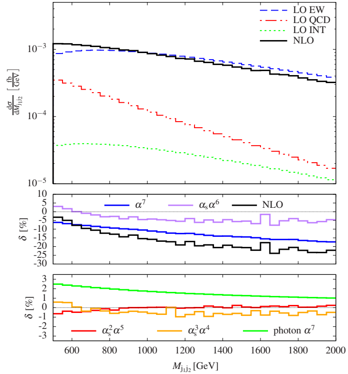
At NLO

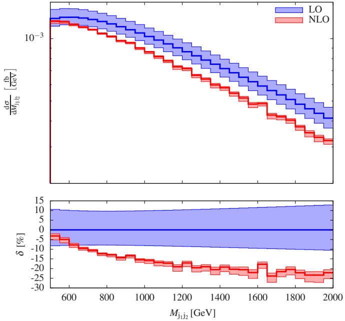
Meaningless distinction between EW and QCD component

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

  $\to$ 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 $0.37\,\text{stat} \pm 0.25\,\text{syst}$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD WW	4.42 ± 0.47 $0.39\,\text{stat} \pm 0.25\,\text{syst}$	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 $0.39\,\text{stat} \pm 0.14\,\text{syst}$	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 $0.40\,\text{stat} \pm 0.23\,\text{syst}$	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 $0.45\,\text{stat} \pm 0.18\,\text{syst}$	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

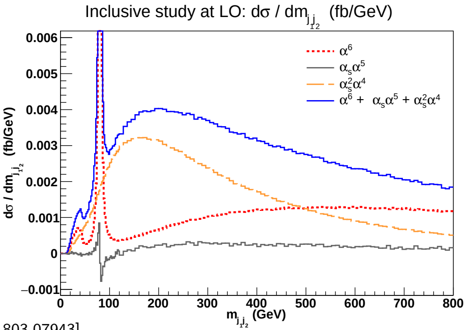
NB: Uncertainty for the NLO numbers are from the LO 7-scales variation.

→ Set basis of future precision measurements

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

Kinematics and approximations

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



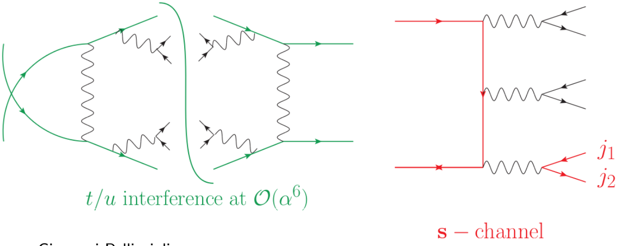
[Ballestrero, MP et al.; 1803.07943]

⚠ EW component possesses VBS+tri-boson+other contributions
$\rightarrow$ Naively, 100 GeV cut should do the job. Is it really the case?

VBS approximation

Neglecting s-channel contributions and t/u interferences

→ Implemented in POWHEG and VBFNLO (possibly including s-channel)

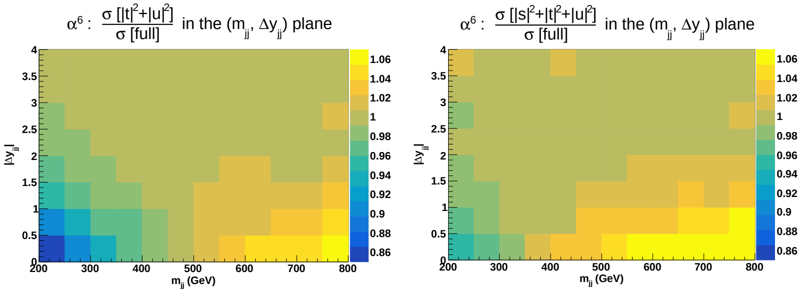


Source: Giovanni Pelliccioli

→ Comparison of approximations against full computations at NLO

[Ballestrero, MP et al.; 1803.07943]

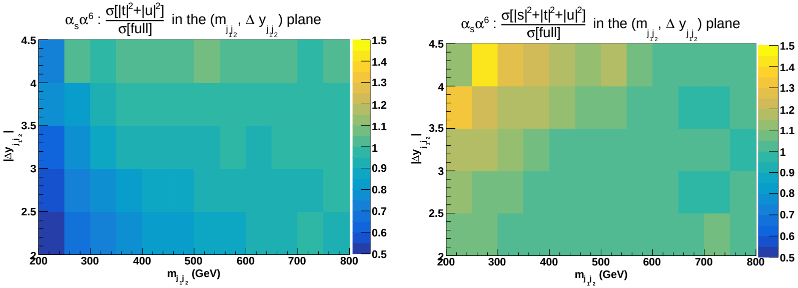
Quality of the VBS approximation (LO)



[Ballestrero, MP et al.; 1803.07943]

- For low m_{jj} and low Δy_{jj}, significant s-channel contributions
  $\rightarrow$ tri-boson contributions with resonant W-boson
- Good approximation in fiducial regions!

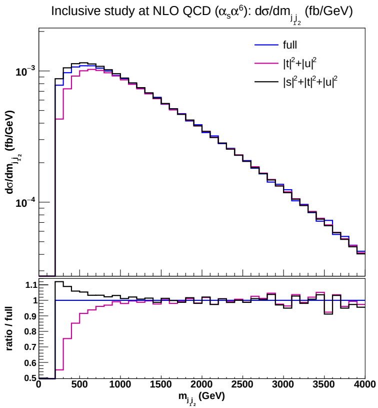
Quality of the VBS approximation (NLO)

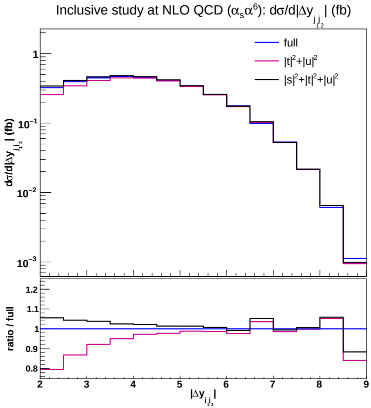


[Ballestrero, MP et al.; 1803.07943]

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

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





[Ballestrero, MP et al.; 1803.07943]

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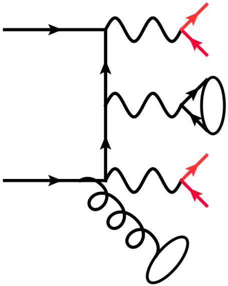
Quality of the VBS approximation (NLO)

Why are NLO approximations worth than LO ones?

→ Typical *s*-channel contribution:

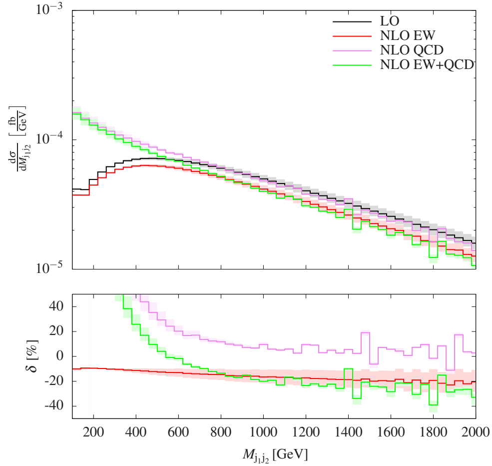


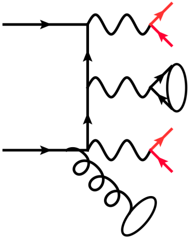
→ Less suppressed at NLO due to extra jet in the real

Similar effect for tt production at NLO QCD in lepton+jet channel [Denner, MP; 1711.10359]

LO cuts are not safe at NLO and beyond

Example of ZZ VBS at NLO





[Denner, Franken, MP, Schmidt; 2009.00411]

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

Lessons learnt

⚠ Strong correlations between:

theory approximations and experimental event selection

$\rightarrow$ Theory approximations valid only for certain fiducial region

Lessons learnt

⚠ Strong correlations between:
theory approximations and experimental event selection
→ Theory approximations valid only for certain fiducial region

- For inclusive phase spaces, use full computations (including tri-bosons contributions)
- For exclusive phase spaces, approximate computations OK (with current experimental precisions)
  → Not at high-luminosity LHC
- Subtracting tri-boson in measurements is dangerous

⚠ Cross talks between theory and experiment are crucial

$\rightarrow$ How to ensure that all effects are under control?

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Solution:

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

$\rightarrow$ Disentangles all physical effects

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

- Going beyond current work
  $\rightarrow$ Few directions

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

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]
  $\rightarrow$ +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]* $\rightarrow$ +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] $\rightarrow$ +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

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

Theory challenge

- Why $\mathcal{O}\left(\alpha_s \alpha^6\right)$ and $\mathcal{O}\left({\alpha_s}^2 \alpha^5\right)$ not NLO+PS yet?
  → These are mixed QCD/EW corrections:
  real QCD and photon radiation at NLO at the same order
  → No consistent matching to parton/photon shower yet

Phenomenology

• NLO+PS accuracy not yet fully used in experimental analyses

(difficult but necessary step)

→ Precise comparisons between theory and experiment
→ Precise probe of EW sector

Going beyond current work (II)

$\rightarrow$ Large EW corrections: intrinsic feature of VBS at the LHC

Large EW corrections: $\sim 16\%$ at the level of the cross section

Going beyond current work (II)

$\longrightarrow$ Large EW corrections: intrinsic feature of VBS at the LHC

Large EW corrections: $\sim 16\%$ at the level of the cross section

$$\sigma_{\mathrm{LL}} = \sigma_{\mathrm{LO}} \left[1 - \frac{\alpha}{4\pi} 4 C^{\mathrm{ew}}_{\mathrm{W}} \log^2 \left(\frac{Q^2}{M^2_{\mathrm{W}}} \right) + \frac{\alpha}{4\pi} 2 b^{\mathrm{ew}}_{\mathrm{W}} \log \left(\frac{Q^2}{M^2_{\mathrm{W}}} \right) \right]$$

- For $Q = \langle m_{4\ell} \rangle \sim 390\,\mathrm{GeV}$

$$\delta^{\mathrm{LL}}_{\mathrm{EW}} \simeq \delta^{\mathrm{NLO}}_{\mathrm{EW}} \text{ (!)}$$

Going beyond current work (II)

$\longrightarrow$ Large EW corrections: intrinsic feature of VBS at the LHC

Large EW corrections: $\sim 16\%$ at the level of the cross section

$$\sigma_{\rm LL} = \sigma_{\rm LO}\left[1 - \frac{\alpha}{4\pi} 4\, C_{\rm W}^{\rm ew} \log^2\left(\frac{Q^2}{M_{\rm W}^2}\right) + \frac{\alpha}{4\pi} 2 b_{\rm W}^{\rm ew} \log\left(\frac{Q^2}{M_{\rm W}^2}\right)\right]$$

- For $Q = \langle m_{4\ell}\rangle \sim 390\,\mathrm{GeV}$

$$\delta_{\rm EW}^{\rm LL} \simeq \delta_{\rm EW}^{\rm NLO} \quad (!)$$

$\rightarrow$ Corrections 3-4 times larger than for $q\bar{q} \rightarrow \mathrm{W^+W^-}$

- $C^{\rm ew}$ larger for bosons than fermions
- $\langle m_{4\ell}\rangle$ larger for VBS (massive t-channel [Denner, Hahn; hep-ph/9711302])
  NB: $\langle m_{4\ell}\rangle \sim 250\,\mathrm{GeV}$ for $q\bar{q} \rightarrow \mathrm{W^+W^-}$

Going beyond current work (II)

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

Large EW corrections: $\sim 16\%$ at the level of the cross section

$$\sigma_{\mathrm{LL}} = \sigma_{\mathrm{LO}} \left[1 - \frac{\alpha}{4\pi} 4 C_{\mathrm{W}}^{\mathrm{ew}} \log^2 \left(\frac{Q^2}{M_{\mathrm{W}}^2} \right) + \frac{\alpha}{4\pi} 2 b_{\mathrm{W}}^{\mathrm{ew}} \log \left(\frac{Q^2}{M_{\mathrm{W}}^2} \right) \right]$$

- For $Q = \langle m_{4\ell} \rangle \sim 390\,\mathrm{GeV}$

$$\delta_{\mathrm{EW}}^{\mathrm{LL}} \simeq \delta_{\mathrm{EW}}^{\mathrm{NLO}} \text{ (!)}$$

→ Corrections 3-4 times larger than for $q\bar{q} \to \mathrm{W}^+\mathrm{W}^-$

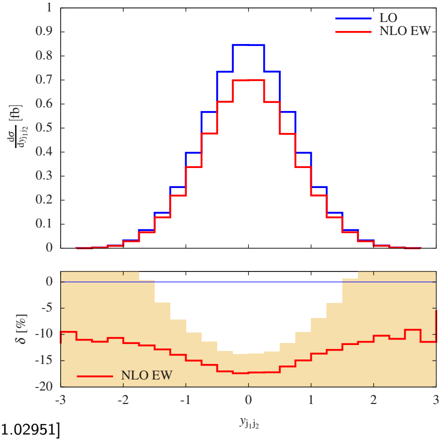
- C^{ew} larger for bosons than fermions
- $\langle m_{4\ell} \rangle$ larger for VBS (massive t-channel [Denner, Hahn; hep-ph/9711302])
  NB: $\langle m_{4\ell} \rangle \sim 250\,\mathrm{GeV}$ for $q\bar{q} \to \mathrm{W}^+\mathrm{W}^-$

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

[Biedermann, Denner, MP; 1611.02951]

Going beyond current work (II)

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

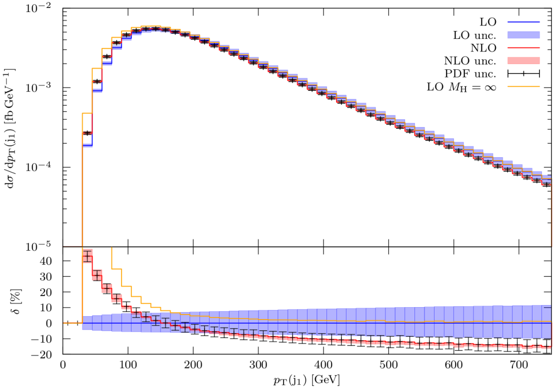


[Biedermann, Denner, MP; 1611.02951]
(error band: statistically uncertainty at 3000 fb^{-1})

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

Going beyond current work (II)

→ Effects from Higgs sector



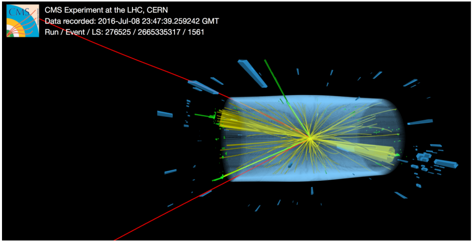
[Dittmaier, Maierhöfer, Schwan, Siegert, In: PoS RADCOR2017]

→ low p_T region sensitive to modified Higgs sector

→ large p_T is unaffected

Test our SM understanding of VBS at the LHC → EW sector

Going beyond current work (III)
→ Exploit theory understanding in parton shower



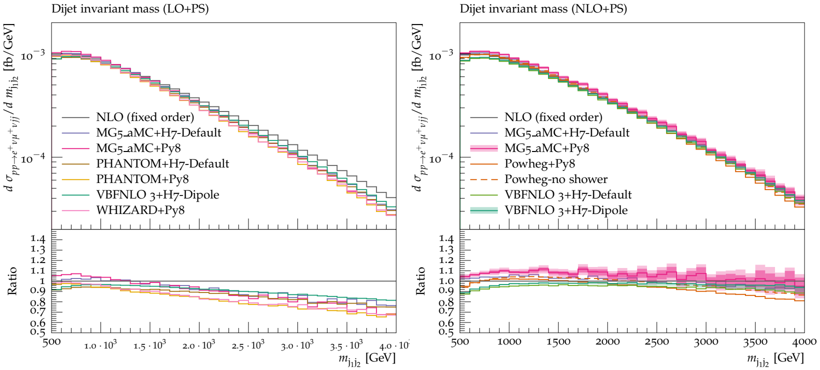
⚠ Typical kinematic:

back-to-back jets at large rapidities + central gauge bosons

→ Low hadronic activity in central region

→ Higher-order and PS corrections crucial

Going beyond current work (III)
→ Exploit theory understanding in parton shower

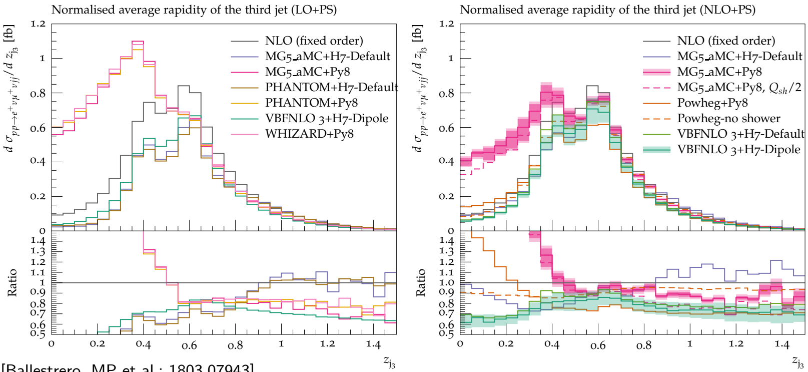


[Ballestrero, MP et al.; 1803.07943]

→ Reasonable agreement at both LO (left) and NLO (right) for observables defined at LO

→ NB: input parameters (masses, widths, PDF, scales) all set to common values

Going beyond current work (III)
→ Exploit theory understanding in parton shower



[Ballestrero, MP et al.; 1803.07943]

Large differences for third-jet observables
→ $z_{j_3} = (j_3 - (j_1 + j_2)/2)/|\Delta y_{jj}|$ (how central is the third jet)

→ Prevented experimental analyses to use jet veto
→ Understood now (recoil scheme) [Jäger, Karlberg, Plätzer, Scheller, Zaro; 2003.12435]

Going beyond current work (III)
→ Exploit theory understanding in parton shower

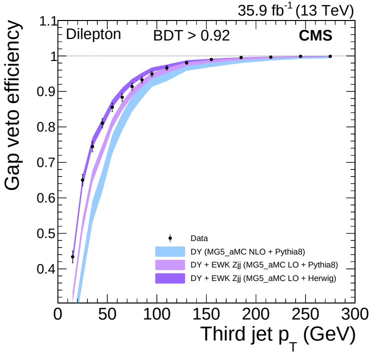
→ Allows for the use of jet veto in experimental analyses

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

[Jäger, Karlberg, Plätzer, Scheller, Zaro; 2003.12435] for VBF Higgs

→ Further studies of PS with similar processes

VBF-Z production [CMS; 1712.09814] (*i.e.* pp → jjZ)



Going beyond current work (IV)
$\rightarrow$ Semi-leptonic signatures

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

- Large cross sections (W/Z hadronic branching ratio)
- Great potential for new physics studies
- Huge and complicated backgrounds

$\rightarrow$ Challenge for both theory and experiment!

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

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

Theory challenges

- Large number of partonic channels:
  - $\ell\nu_\ell + 4\mathrm{j}$: $\mathrm{W}^\pm(\mathrm{W}^\pm \to \mathrm{jj}) + \mathrm{W}^\pm(\mathrm{W}^\mp \to \mathrm{jj}) + \mathrm{W}^\pm(\mathrm{Z} \to \mathrm{jj})$
  - $\ell^+\ell^- + 4\mathrm{j}$: $\mathrm{Z}(\mathrm{Z} \to \mathrm{jj}) + \mathrm{Z}(\mathrm{W}^\pm \to \mathrm{jj})$
- Complicated final state with 4 QCD particles:

  → Only available computations at NLO QCD:

  $\mathrm{pp} \to \ell\nu_\ell\mathrm{jjbb}$ [Denner, MP; 1711.10359] [Anger, Febres Cordero, Ita, Sotnikov; 1712.05721]
- Huge CPU cost

  → Experimental analysis limited size of sample

  → New computing methods welcome

- *Conclusion*

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

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

- Potential for exciting studies in Standard Model and beyond
  → 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