Vector-boson scattering and the Higgs boson

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Higgs Hunting, Paris, France

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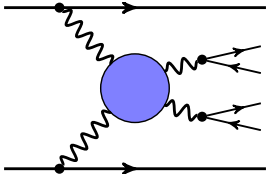
universität freiburg


Higgs Hunting 2025
Results and prospects in the electroweak symmetry breaking sector
15TH
HIGGS HUNTING
15-17
July
Orsay
Paris
International Advisory Committee
Organising Committee
www.higgshunting.fr

Proposal for Higgs 2026:

[Source: Bing image creator]

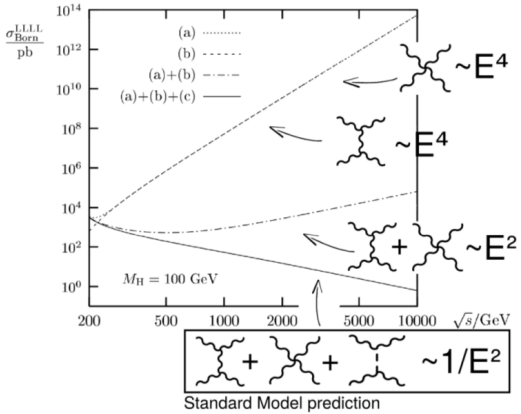
What is VBS and why this is interesting



- Unitarisation due to Higgs boson
- (longitudinal) Polarisation measurements
- Electroweak symmetry breaking
- 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/

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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Assume scaling of uncertainties with $1/\sqrt{L}$

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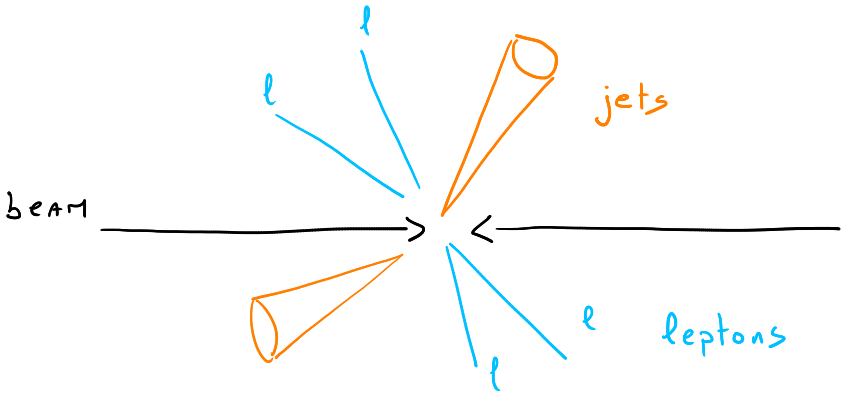
This talk

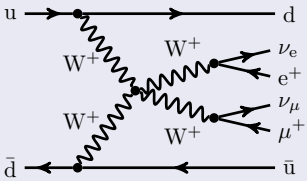
→ Mainly focused on Standard Model physics

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

LHC collision producing VBS final state (simplified/theorist's view)

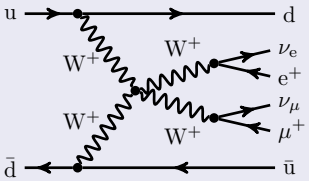


VBS



$\rightarrow$ Unitarity / quartic coupling

VBS



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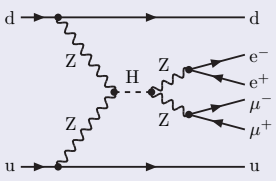
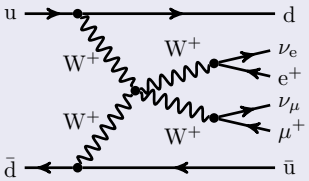
VBF



→ Higgs properties

VBS



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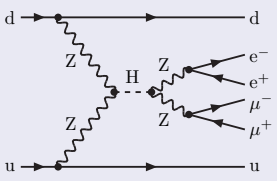
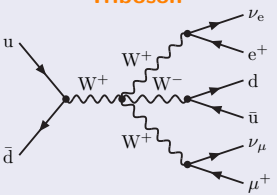


→ Higgs properties

Triboson



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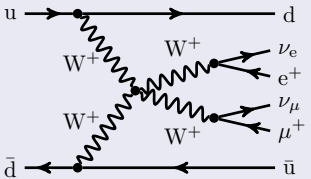

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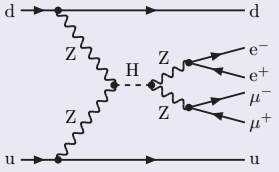

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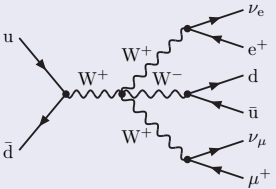
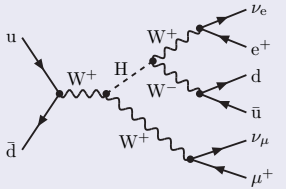


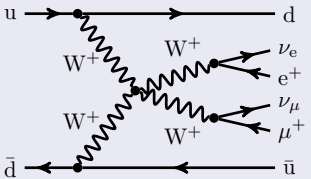
→ Quartic coupling

VH



→ Higgs properties

VBS



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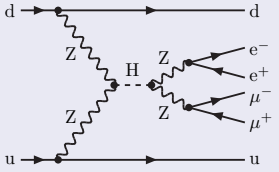

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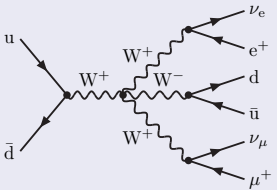

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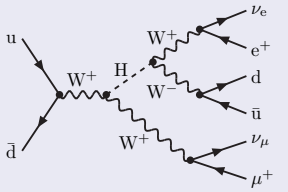
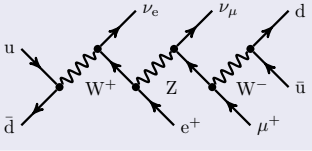


→ Higgs properties

Decay chain



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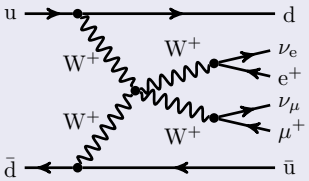

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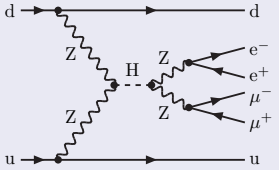

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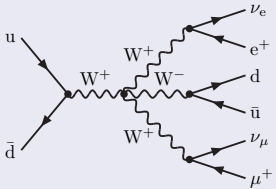

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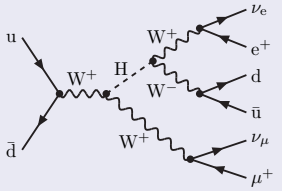

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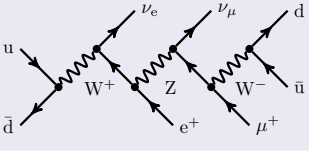
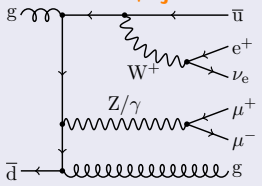
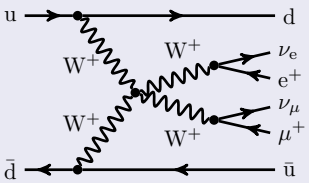


VV+2j



→ QCD

VBS



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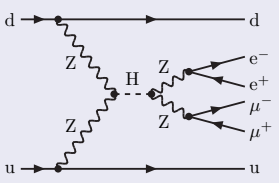

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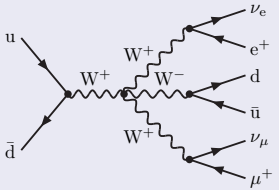

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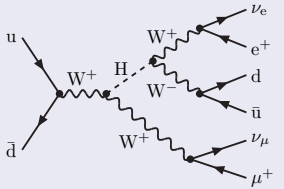

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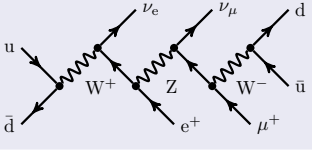

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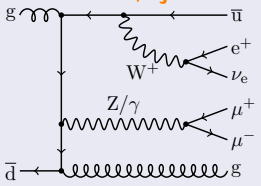
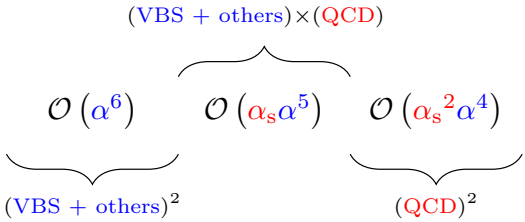


→ QCD

→ For all: Standard Model physics and gauge-boson polarisation

With 2 different amplitudes $\rightarrow$ 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



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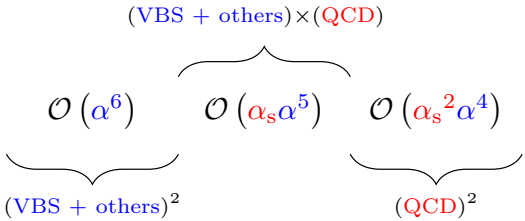
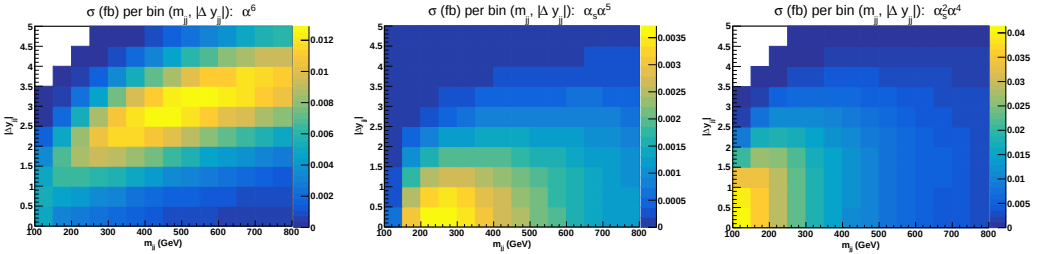
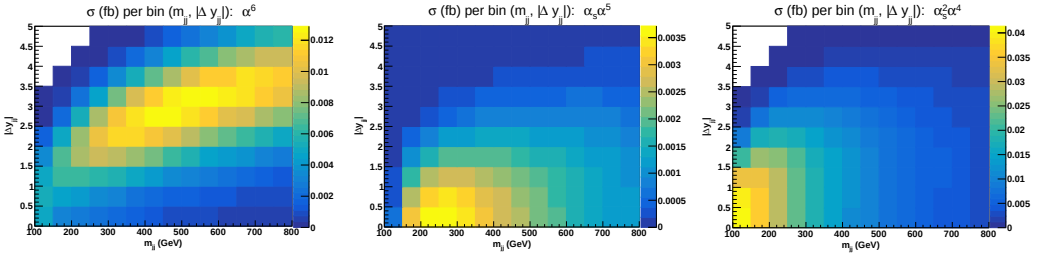


$\rightarrow$ How to measure the EW component (including VBS) then?



[Ballestrero, MP et al.; 1803.07943]

- The contributions have different kinematics



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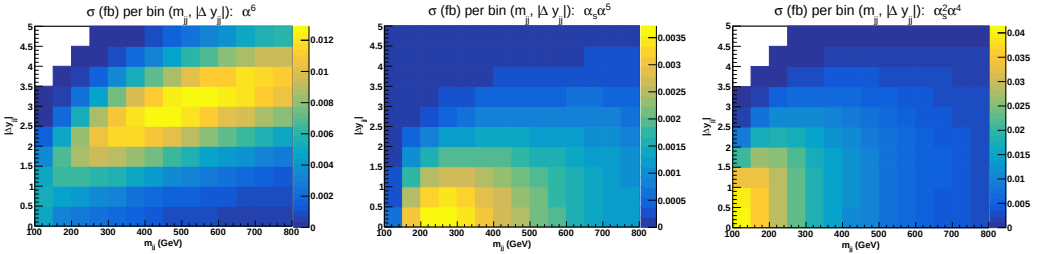
- The contributions have different kinematics
- Use of exclusive cuts to enhance the EW contribution
  - → typical kinematic: back-to-back jets at large rapidities + central gauge bosons
  - → typical cuts are $m_{jj} > 500\,\text{GeV}$ and $|\Delta y_{jj}| > 2.5$



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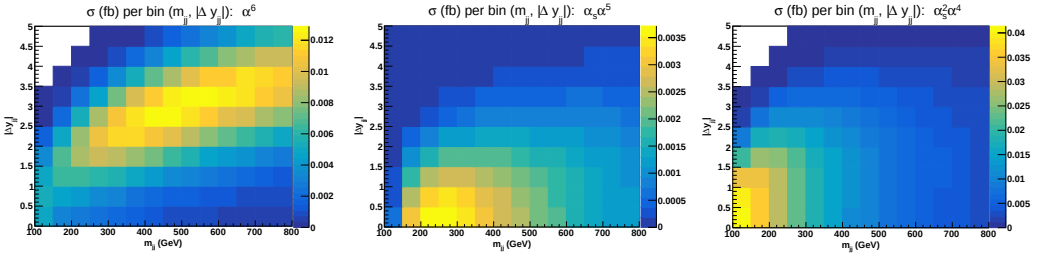
→ Strategy: Exclusive cuts with irreducible background (int.+QCD) subtracted



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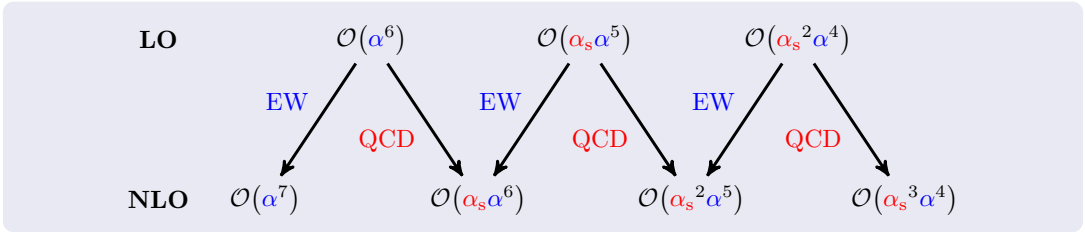
⚠ VBS contributions appear also in the interference
⚠ Theory-dependent measurement

Moving on to NLO

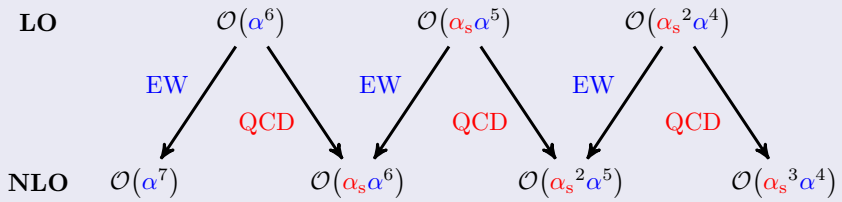


$\rightarrow$ Order $\mathcal{O}\left(\alpha_s\alpha^6\right)$ and $\mathcal{O}\left(\alpha_s{}^2\alpha^5\right)$: QCD and EW corrections mix

At NLO

Meaningless distinction between EW and QCD component

Moving on to NLO



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At NLO

Meaningless distinction between EW and QCD component

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

→ Example: W^+W^+ (golden channel)

- LO

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$
fraction [%]	86.5	2.9	10.5

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- NLO

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$[%]	-13.2	-3.5	0.0	-0.4

[Biedermann, Denner, MP; 1708.00268]

- Large EW corrections as intrinsic feature of VBS [Biedermann, Denner, MP; 1611.02951]
- EW corrections are the dominant NLO correction

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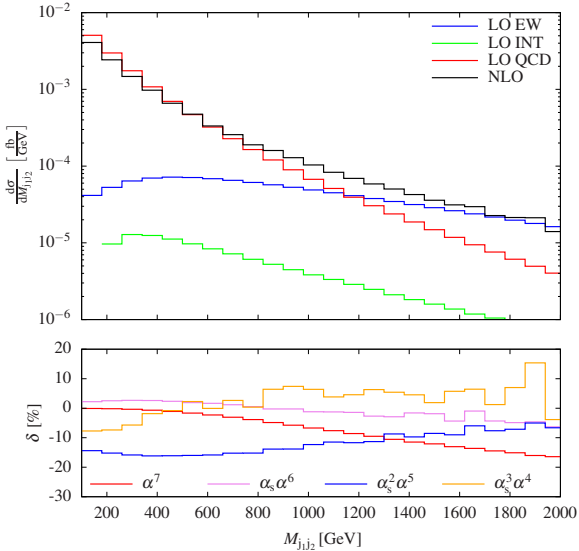
⚠ NLO (EW) corrections should be included in exp. analyses!

→ Example: ZZ for $m_{jj} > 100\,\text{GeV}$

→ Non-trivial structure
→ All NLO corrections are relevant and dependent on phase-space!

[Denner, Franken, MP, Schmidt; 2107.10688]



Comparison with data

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

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

Lessons learned

Physical/less sexy

Less physical/
more sexy

Lessons learned

1. Full measurement vs. Full calculation (EW+QCD)
   → [Meas. of leptons and jets]

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   ... extract quantities (mass, coupling, EFT op., ...)

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→ Is it enough?

Lessons learned

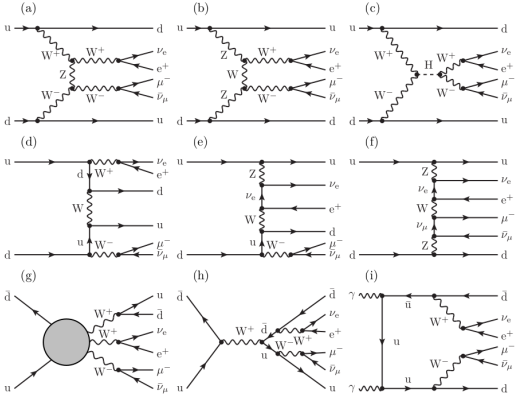
1. Full measurement vs. Full calculation (EW+QCD)
   → [Meas. of leptons and jets]
2. Full measurement - QCD background (MC) vs. full EW (pb of int.)
   → [Meas. of EW production]
3. Full measurement - undesired (MC) vs. desired EW proc.
   → [Meas. of process X] ...
   ... extract quantities (mass, coupling, EFT op., ...)

Physical/less sexy

Less physical/
more sexy

→ Is it enough?
No... kinematics can also play a crucial role

→ NLO QCD and EW for VBS W^+W^- [Denner, Franken, Schmidt, Schwan; 2202.10844]



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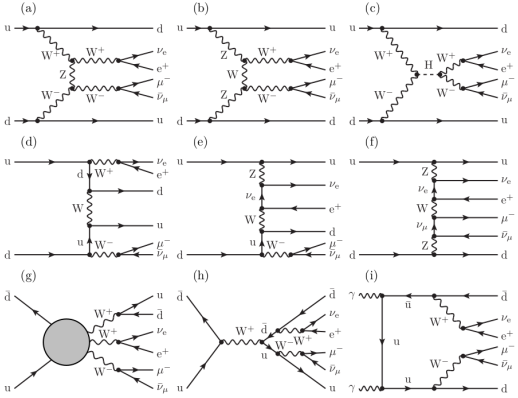

- Interplay between VBS W^+W^- and VBF ($H \to W^+W^-$)
  - → NLO EW corrections are large for VBS [Biedermann, Denner, MP; 1611.02951]
  - → NLO EW corrections are moderate for VBF [Ciccolini, Denner, Dittmaier; 0707.0381, 0710.4749]

Process	W^+W^+	W^+Z	ZZ	W^+W^- (VBS setup)	W^+W^- (Higgs setup)
$\Delta\sigma^{\alpha^7}_{\mathrm{NLO}}$[fb]	$-0.2169(3)$	$-0.04091(2)$	$-0.015573(5)$	$-0.307(1)$	$-0.103(1)$
$\sigma^{\alpha^6}_{\mathrm{LO}}$[fb]	$1.4178(2)$	$0.25511(1)$	$0.097683(2)$	$2.6988(3)$	$1.5322(2)$
δ^{α^7}[%]	-15.3	-16.0	-15.9	-11.4	-6.7

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- Applying unphysical cut in addition:

$$|M_{4\ell} - M_{\mathrm{H}}| \lesssim 20\Gamma_{\mathrm{H}}$$

→ in the VBS setup (following [ATLAS; 1905.04242], [CMS; 2009.00119, 2205.05711]):

- Excluding resonance: $\delta_{\mathrm{NLO\,EW}} = -13.2\%$
- Selection only resonance: $\delta_{\mathrm{NLO\,EW}} = -6.5\%$

→ Size of corrections driven by typical scales of the process and kinematic cuts!

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NB: Same effect for ZZ but mass-windows on Z prevent Higgs resonance

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

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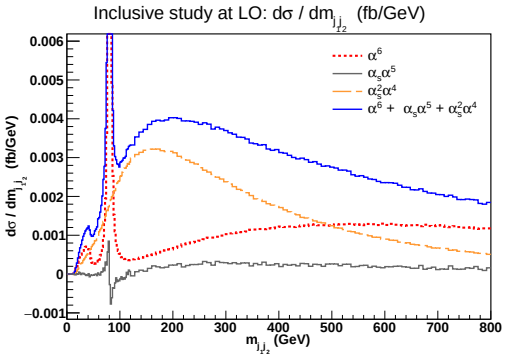
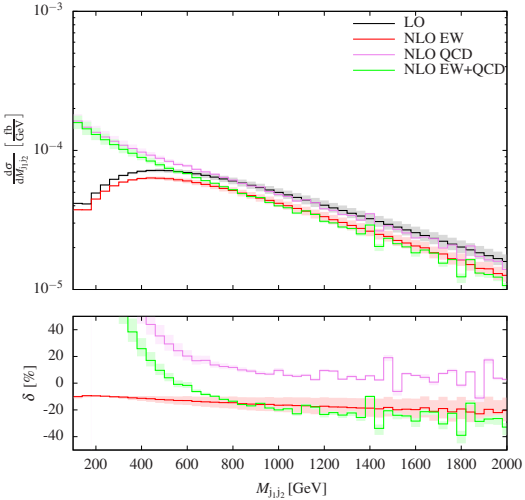
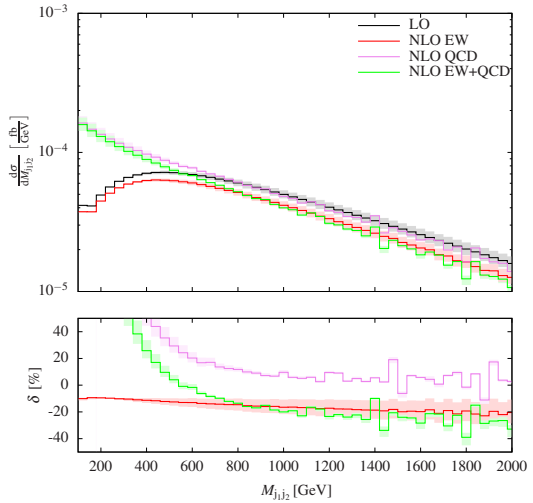


[Ballestrero, MP et al.; 1803.07943]

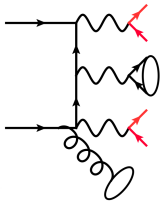
⚠ EW component possesses VBS+tri-boson+other contributions
→ Naively, 100 GeV cut should do the job. Is it really the case?



[Denner, Franken, MP, Schmidt; 2009.00411]



→ Example: ZZ VBS at NLO



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

[Denner, Franken, MP, Schmidt; 2009.00411]

→ How to ensure that all effects are under control?

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Solution:

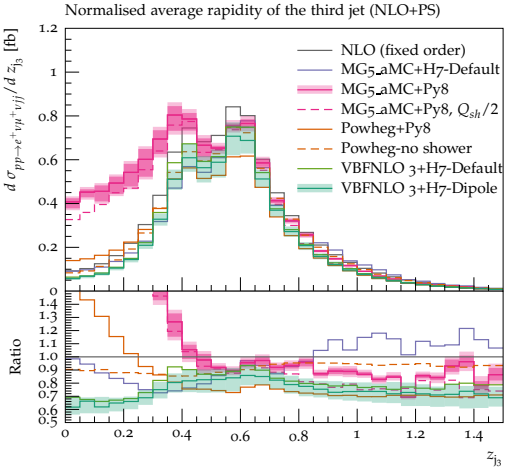
- Different definition of the process
  → With and without QCD component
- Different phase spaces
  → Sensitive to different effects
- Example:
  → CMS ZZ measurement with 137 fb^{-1}

  [2008.07013]

→ Disentangles all physical effects
→ Great for exp./th. comparisons

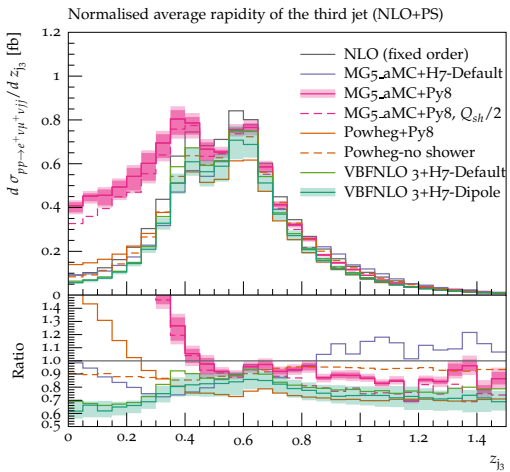
Particle type	Selection
	ZZjj inclusive
Leptons	$p_{\text{T}}(\ell_1) > 20\,\text{GeV}$
	$p_{\text{T}}(\ell_2) > 10\,\text{GeV}$
	$p_{\text{T}}(\ell) > 5\,\text{GeV}$
	$\lvert\eta(\ell)\rvert < 2.5$
Z and ZZ	$60 < m(\ell\ell) < 120\,\text{GeV}$
	$m(4\ell) > 180\,\text{GeV}$
Jets	at least 2
	$p_{\text{T}}(\text{j})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

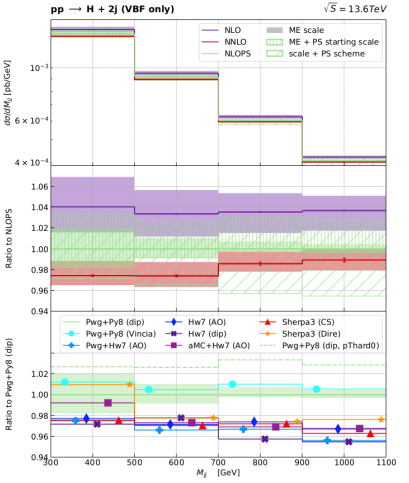
NLO+PS for VBS



[Ballestrero, MP, et al.; 1803.07943]

NLO+PS for VBS → → → → NLO+PS for VBF





[Ballestrero, MP, et al.; 1803.07943] → → → → [Barone, MP, et al.; 2507.XXXX]

https://cds.cern.ch/record/2936976

In between:

[Jäger, Karlberg, Plätzer, Scheller, Zaro; 2003.12435], [Buckley et al.; 2105.11399], [Höche, Mrenna, Payne, Preuss, Skands; 2106.10987]

→ Theory status for ss-WW: (more in Review [Covarelli, MP, Zaro; 2102.10991])

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]
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  → +PS: [Jäger, Zanderighi; 1108.0864]*. Also, +1j: [Jäger, Lopez Portillo Chavez; 2408.12314]*
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- Experimental uncertainty ∼ few per cent at high-luminosity LHC
  → We should tick all the boxes by then!
  → Effect of non-perturbative physics
  [Jäger, Karlberg, Scheller; 1812.05118], [Bittrich, Kirchgaeßer, Papaefstathiou, Plätzer, Todt; 2110.01623]
  → NNLO QCD might even be needed...

Polarisation studies

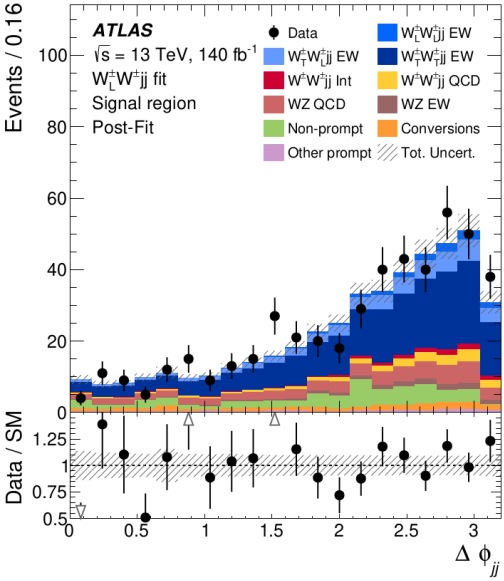
Experiment:

→ Measurements in ss-WW

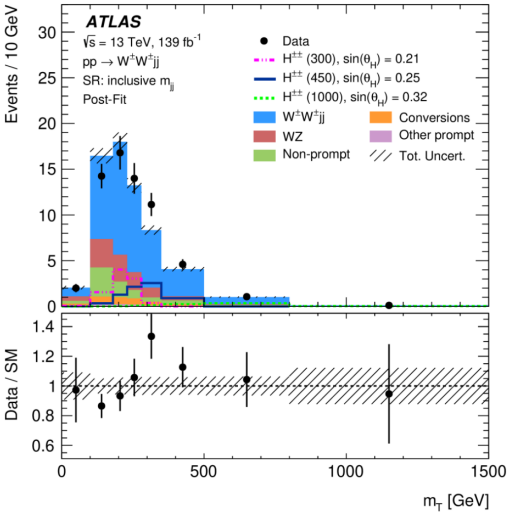
- [CMS; 2009.09429]
- [ATLAS; 2503.11317]
  → Compared to [Hoppe, Schönherr, Siegert; 2310.14803]
  + [Denner, Haitz, Pelliccioli; 2409.03620]

Theory:

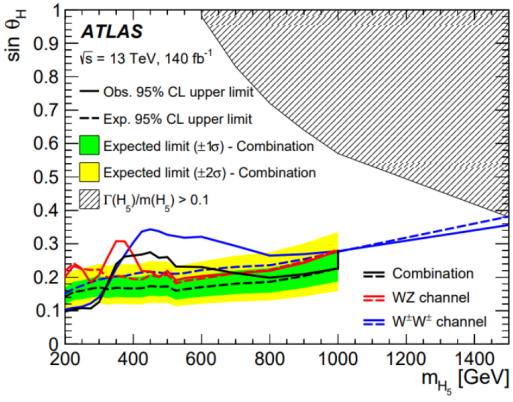
- [Denner, Haitz, Pelliccioli; 2409.03620]
  → NLO QCD+EW for ss-WW
- [Hoppe, Schönherr, Siegert; 2310.14803]
  → Approximate NLO QCD+PS in SHERPA
- [Carrivale et al.; 2505.09686] (for diboson)
  → Benchmarking exercise + description of tools + references



→ With this precision programme, we might find new physics! **Example of H^{++}**



[ATLAS; 2312.00420]



[ATLAS; 2407.10798]

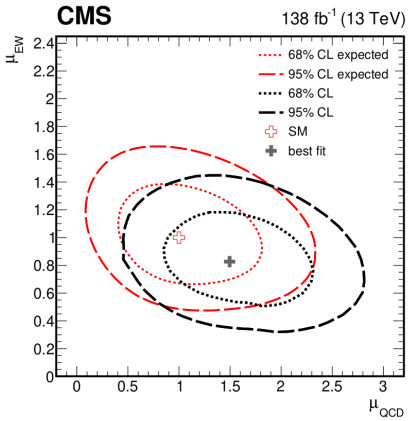
Semi-leptonic channels → challenging on both sides

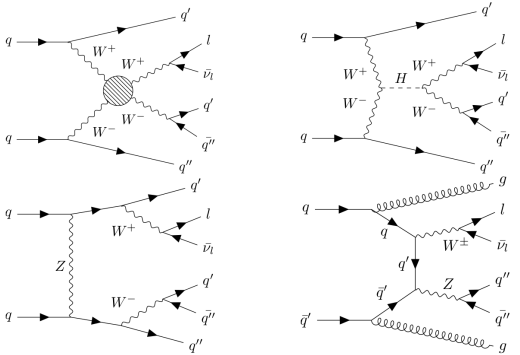
Experiment:

- [CMS; 2112.05259]
  → $\ell\nu$4j channel

Theory:

- [Denner, Lombardi, Schwan; 2406.12301]
  → LO with pole approximation





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"High-luminosity LHC vicious circle"

[source: bing image creator]

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- One way out:
  Different meas. in different fiducial regions!
  → Some steps in this direction,
  STXS for multiboson [Andersen, MP et al.; 2406.00708]

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[source: bing image creator]

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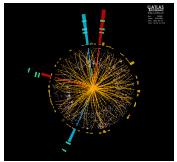

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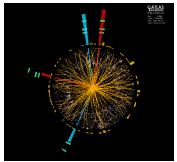

Thank you to

Claude Charlot and Joany Manjarres for their experimental inputs!

BACK-UP