

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



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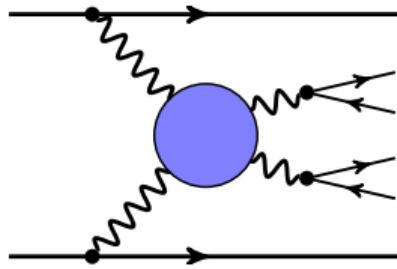


Proposal for Higgs 2026:



[Source: Bing image creator]

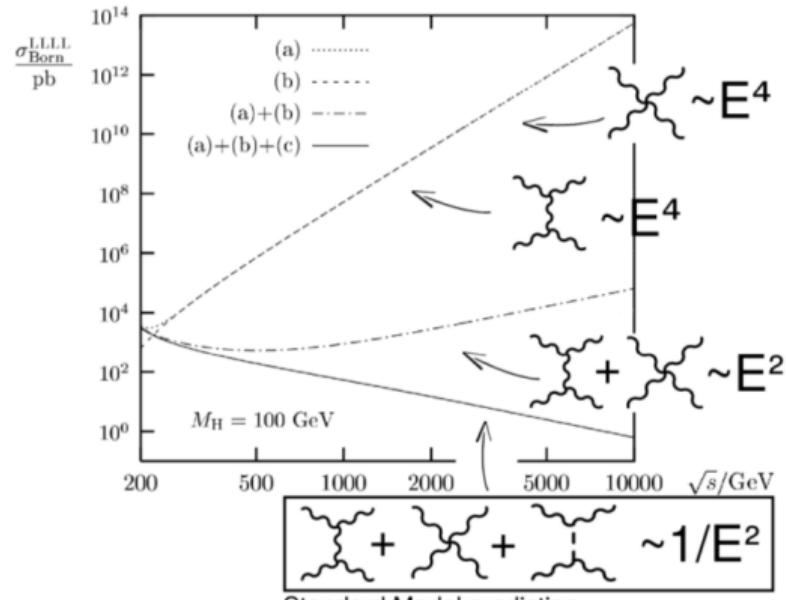
What is VBS and why this is interesting



- 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.



Precision physics for VBS

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

► 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% <small>personally anticipated</small>	18%	13%	6%

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

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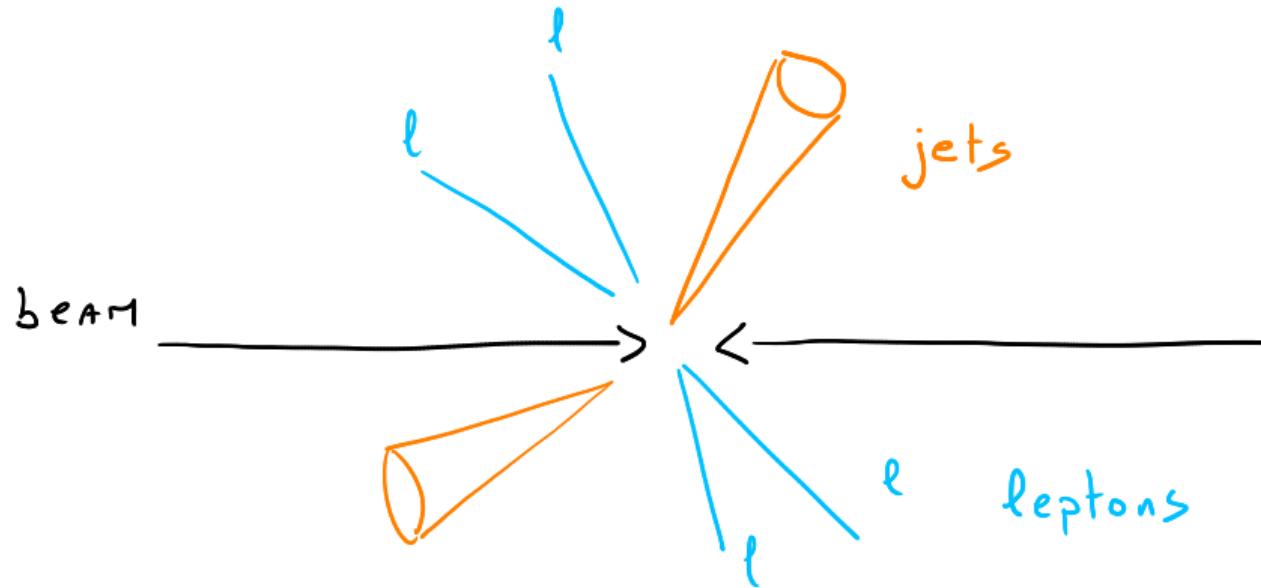
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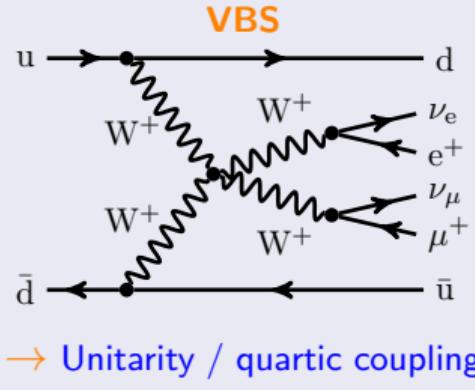
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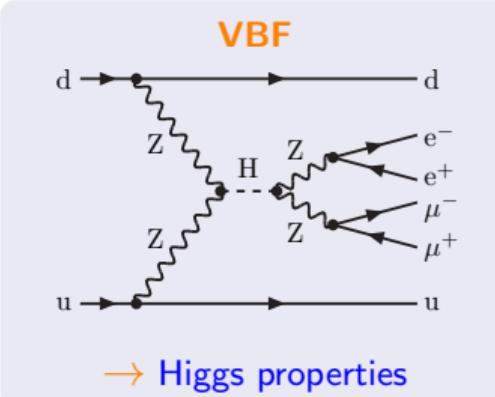
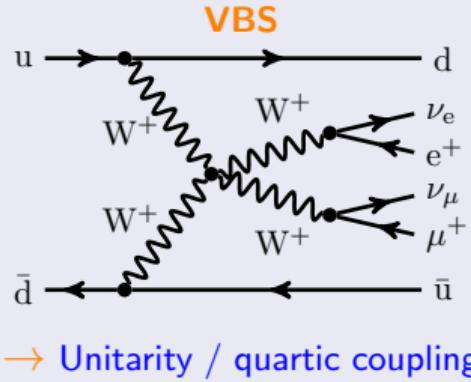
This talk

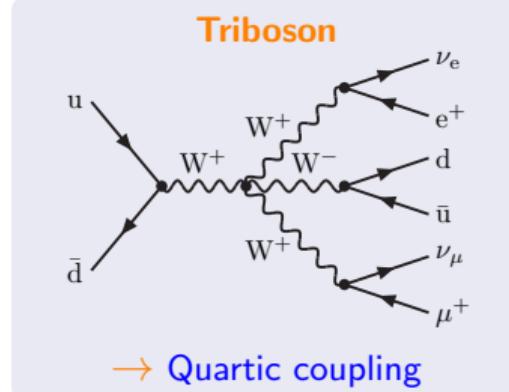
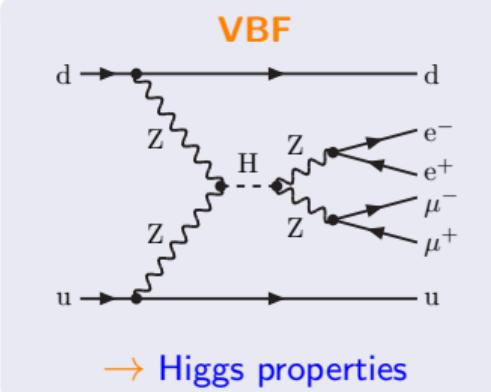
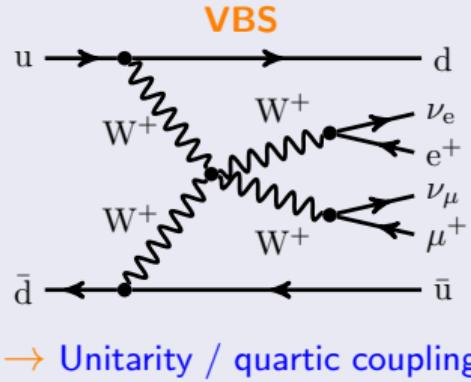
- Mainly focused on Standard Model physics
 - How to get to per-cent uncertainties from the theory side
 - Importance of interplay between experiment and theory

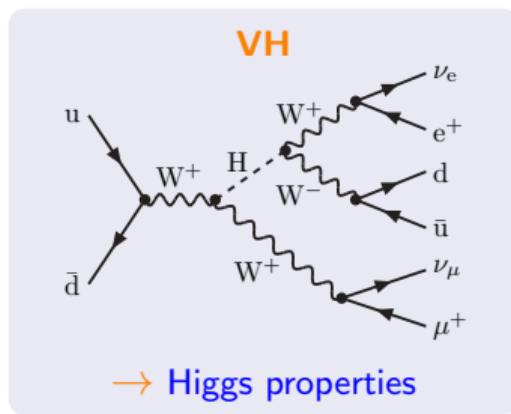
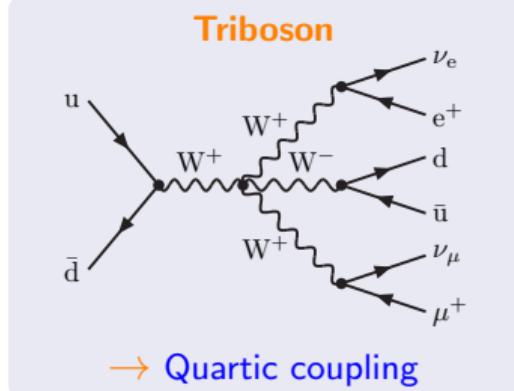
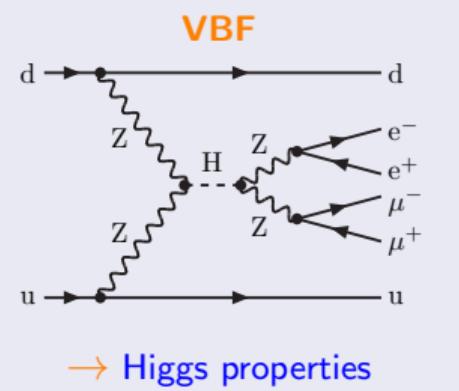
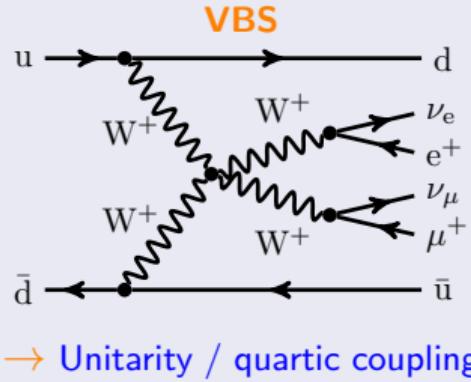
LHC collision producing VBS final state (simplified/theorist's view)

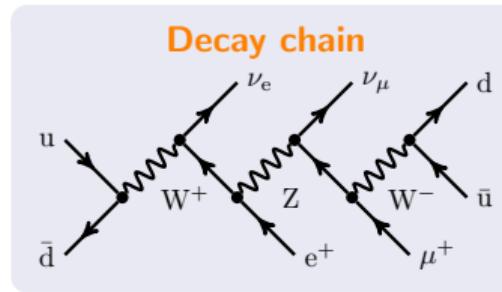
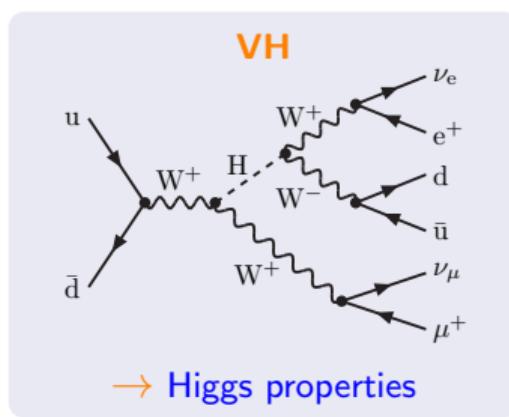
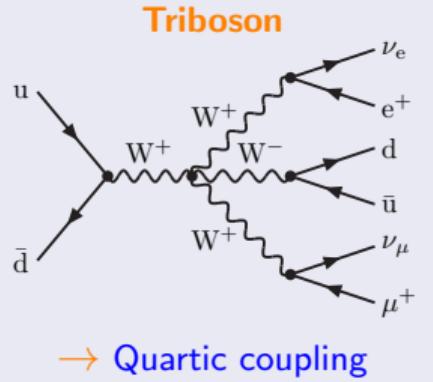
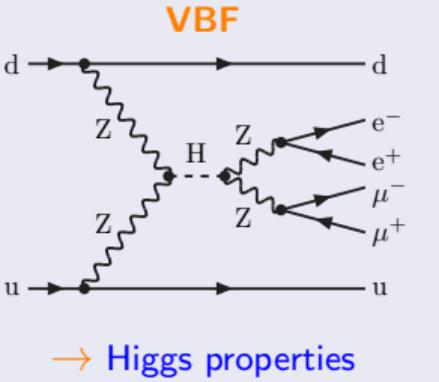
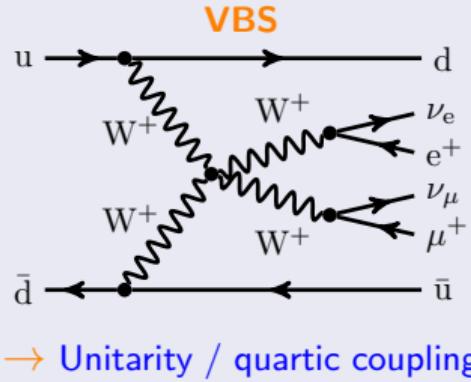


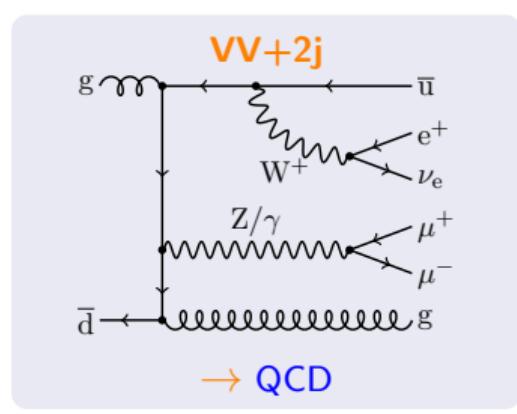
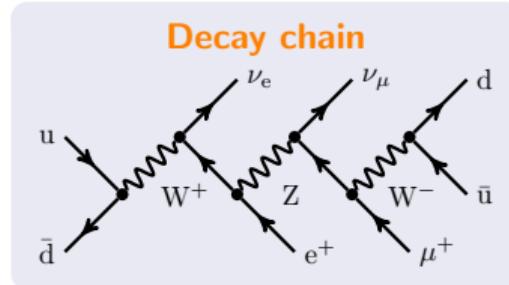
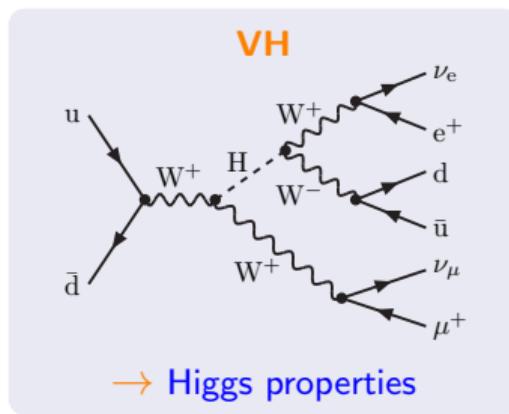
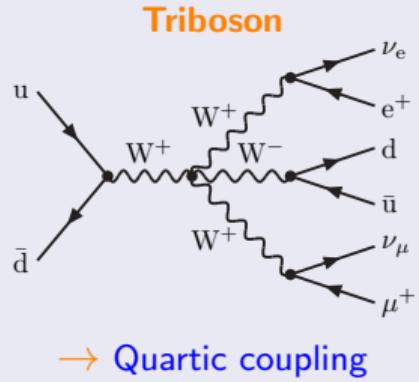
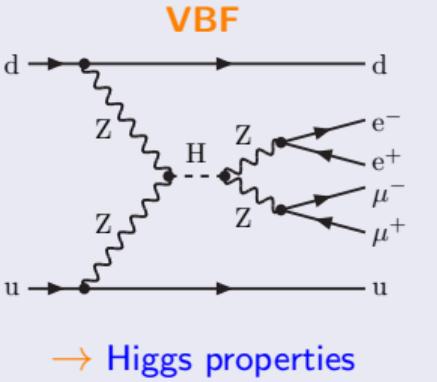
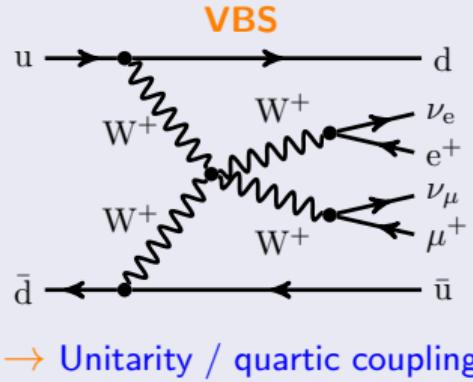


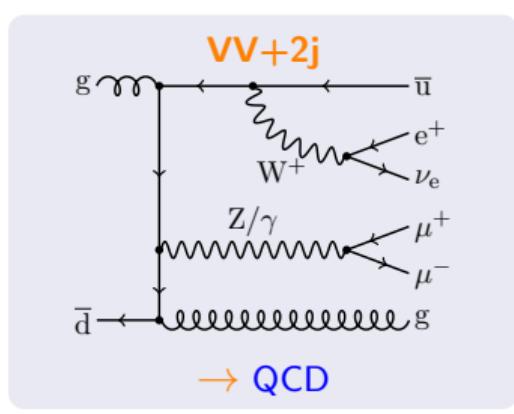
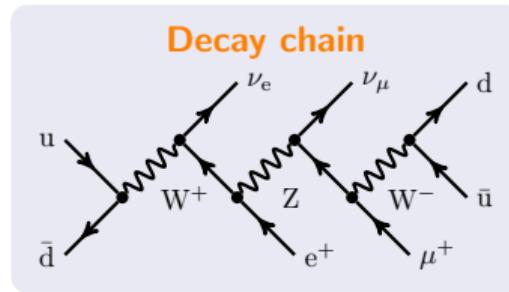
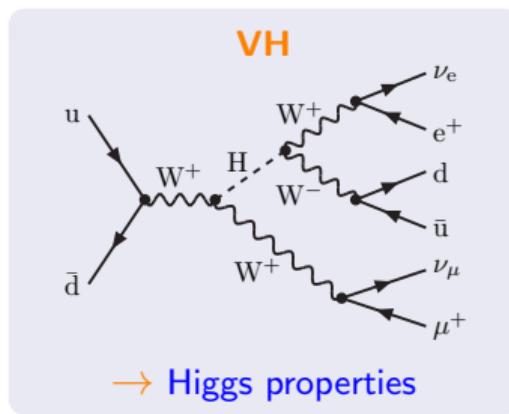
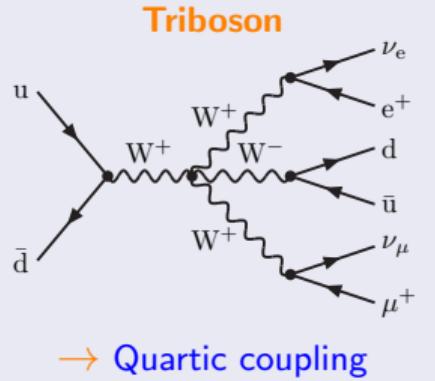
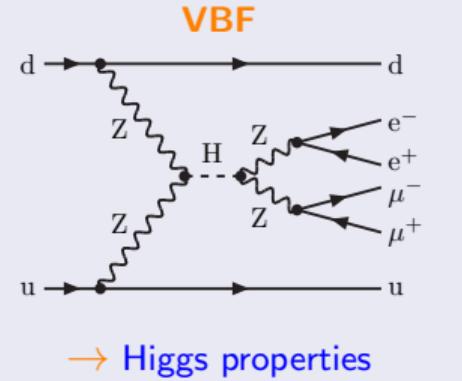
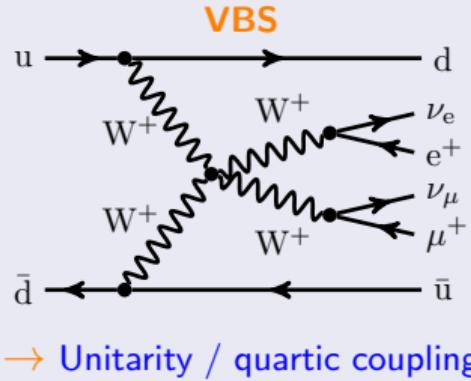












→ For all: Standard Model physics and gauge-boson polarisation

With 2 different amplitudes \rightarrow 3 different contributions:

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

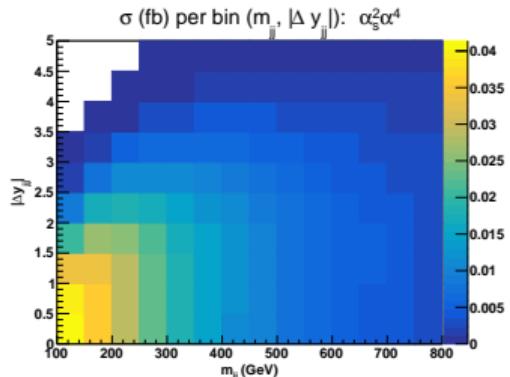
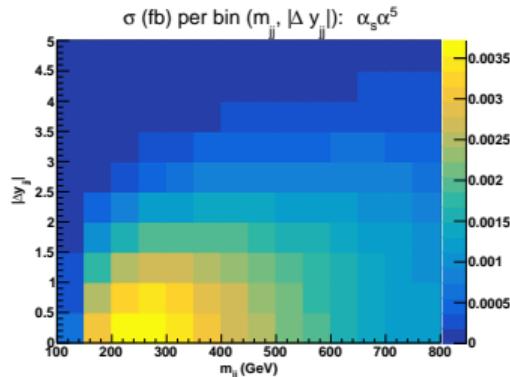
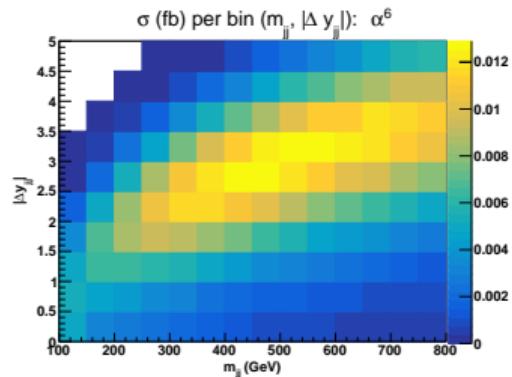
$$\begin{array}{c} (\text{VBS} + \text{others}) \times (\text{QCD}) \\ \\ \overbrace{\quad\quad\quad}^{\mathcal{O}(\alpha^6)} \quad \overbrace{\quad\quad\quad}^{\mathcal{O}(\alpha_s \alpha^5)} \quad \overbrace{\quad\quad\quad}^{\mathcal{O}(\alpha_s^2 \alpha^4)} \\ \\ \overbrace{\quad\quad\quad}^{(\text{VBS} + \text{others})^2} \quad \quad \quad \overbrace{\quad\quad\quad}^{(\text{QCD})^2} \end{array}$$

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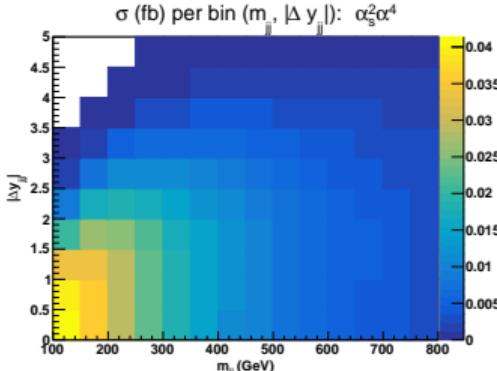
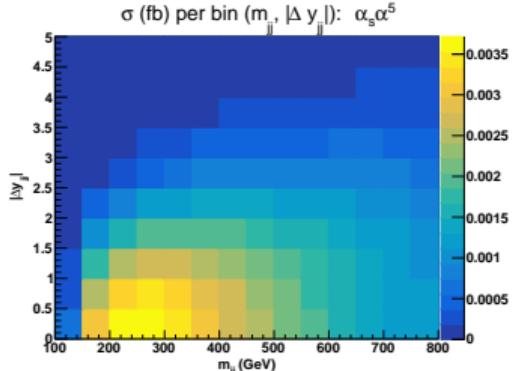
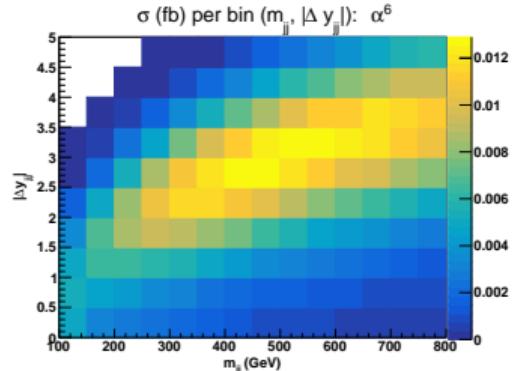
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\rightarrow How to measure the EW component (including VBS) then?



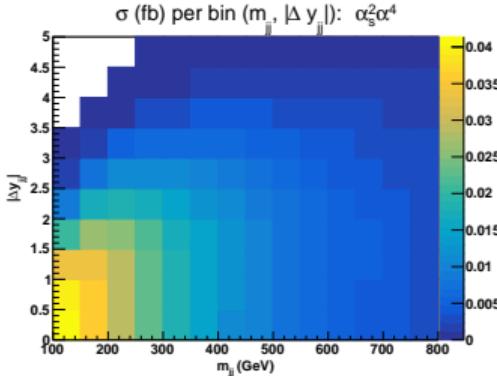
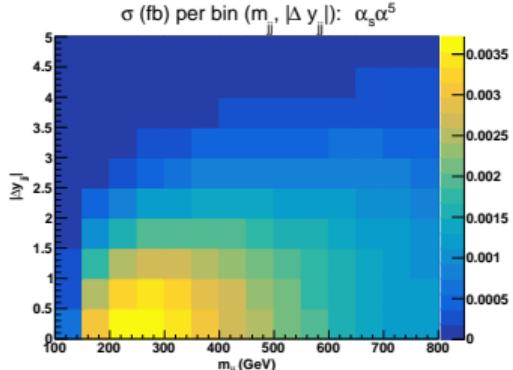
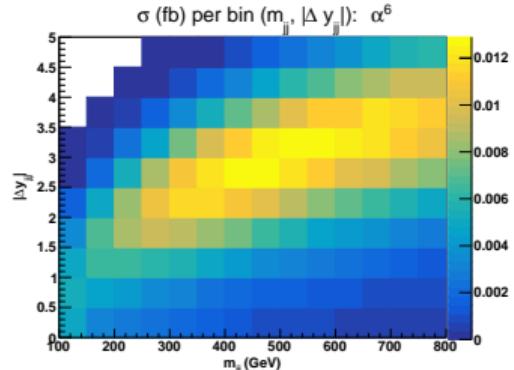
[Ballestrero, MP et al.; 1803.07943]

- The contributions have different kinematics



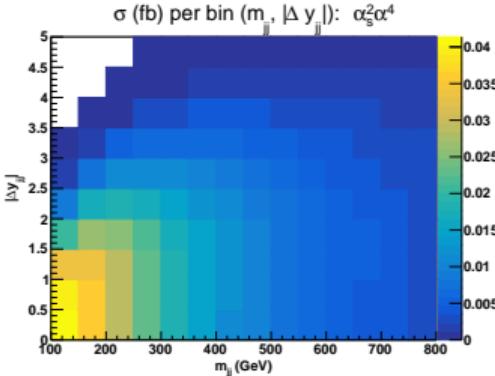
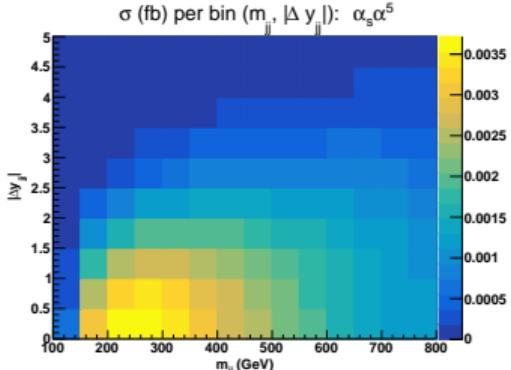
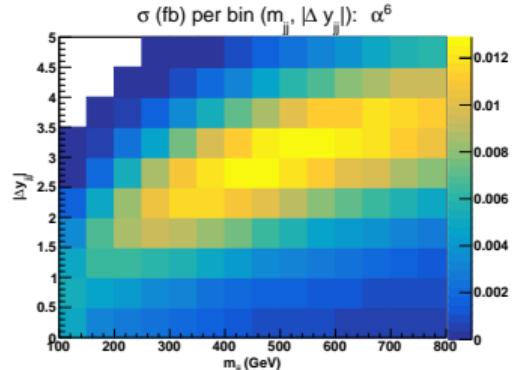
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- The contributions have different kinematics
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 - typical kinematic: back-to-back jets at large rapidities + central gauge bosons
 - typical cuts are $m_{jj} > 500 \text{ GeV}$ and $|\Delta y_{jj}|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



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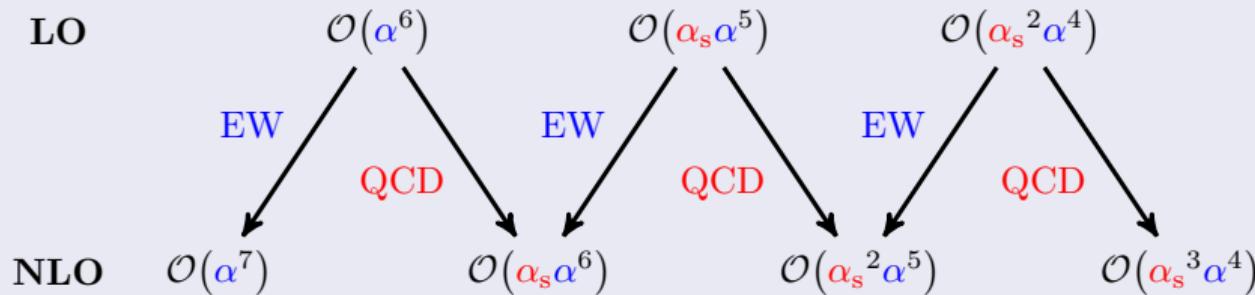


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- ⚠ VBS contributions appear also in the interference
 ⚠ Theory-dependent measurement

Moving on to NLO

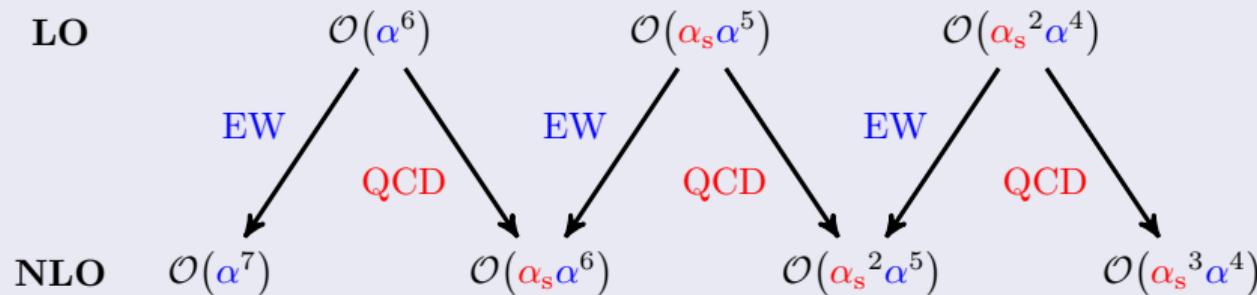


→ Order $\mathcal{O}(\alpha_s \alpha^6)$ and $\mathcal{O}(\alpha_s^2 \alpha^5)$: QCD and EW corrections mix

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

→ 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	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s \alpha^6)$	$\mathcal{O}(\alpha_s^2 \alpha^5)$	$\mathcal{O}(\alpha_s^3 \alpha^4)$
$\delta\sigma_{\text{NLO}}/\sigma_{\text{LO}} [\%]$	-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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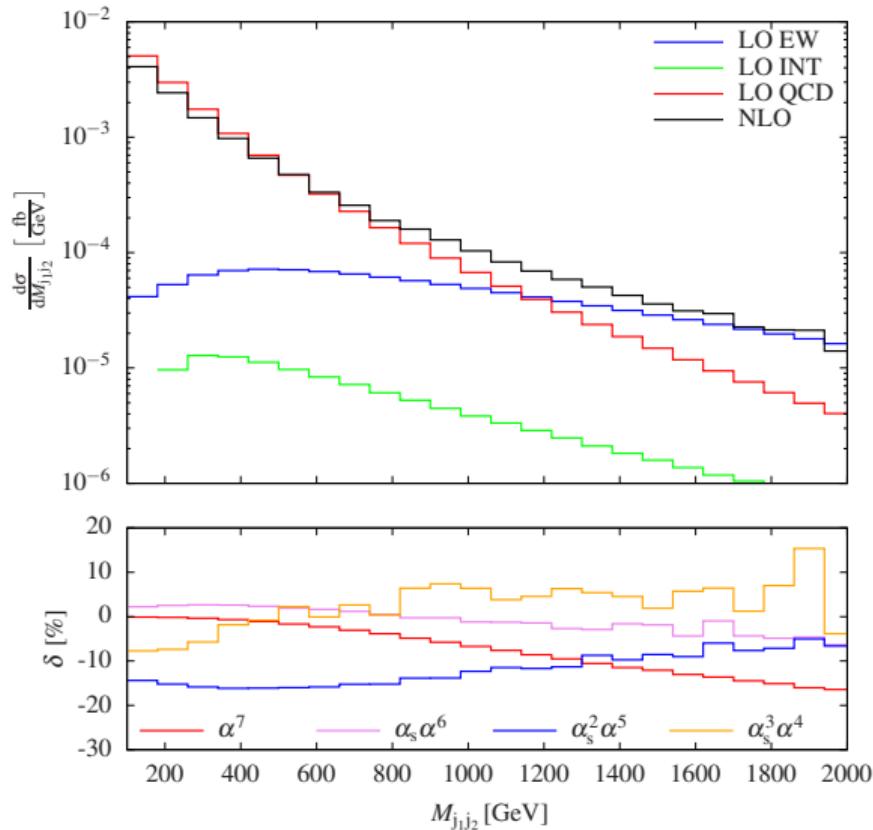
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⚠ NLO (EW) corrections should be included in exp. analyses!

→ Example: ZZ for $m_{jj} > 100$ 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 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

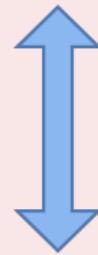


Less physical/
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→ [Meas. of leptons and jets]

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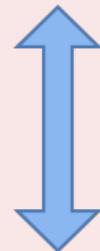


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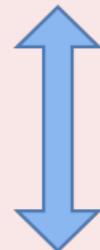


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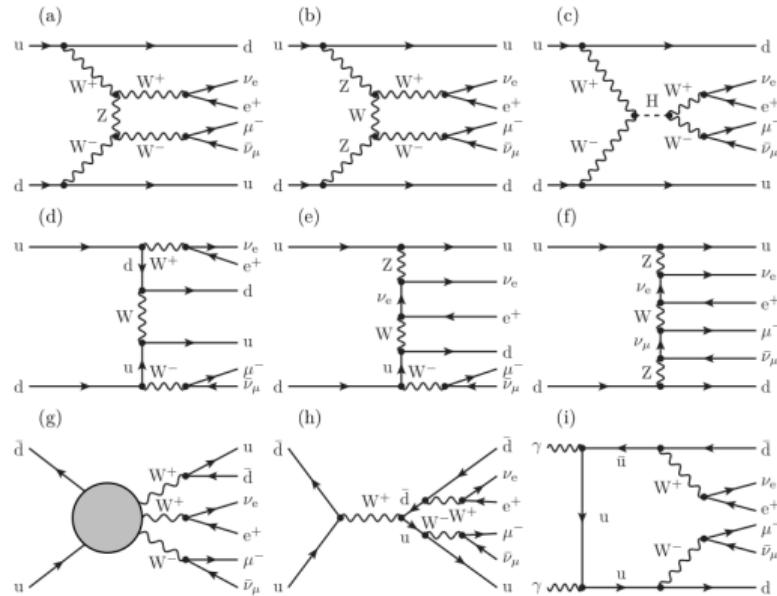
Less physical/
more sexy

→ Is it enough?

No... kinematics can also play a crucial role

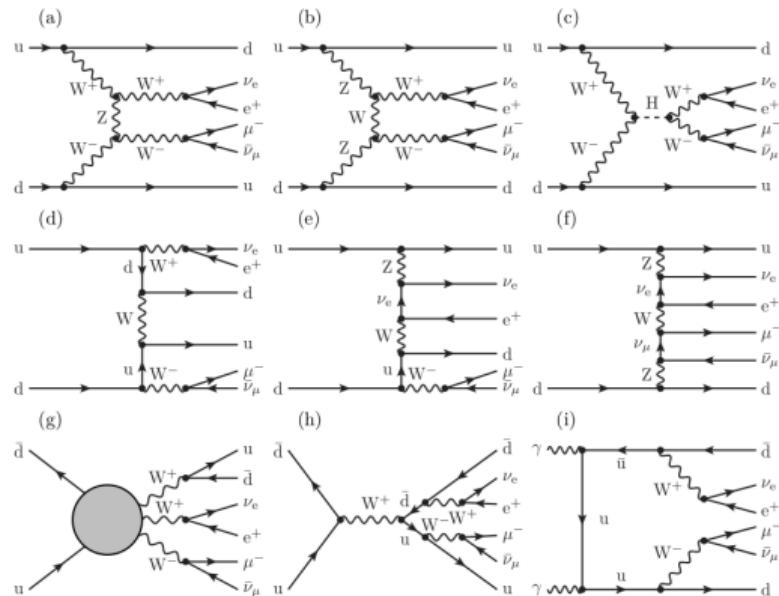
→ NLO QCD and EW for VBS W^+W^-

[Denner, Franken, Schmidt, Schwan; 2202.10844]



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- Interplay between VBS W^+W^- and VBF ($H \rightarrow W^+W^-$)
 - 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)
$\Delta\sigma_{\text{NLO}}^{\alpha^7} [\text{fb}]$	-0.2169(3)	-0.04091(2)	-0.015573(5)	-0.307(1)	-0.103(1)
$\sigma_{\text{LO}}^{\alpha^6} [\text{fb}]$	1.4178(2)	0.25511(1)	0.097683(2)	2.6988(3)	1.5322(2)
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- Applying unphysical cut in addition:

$$|M_{4\ell} - M_H| \leqslant 20\Gamma_H$$

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

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

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

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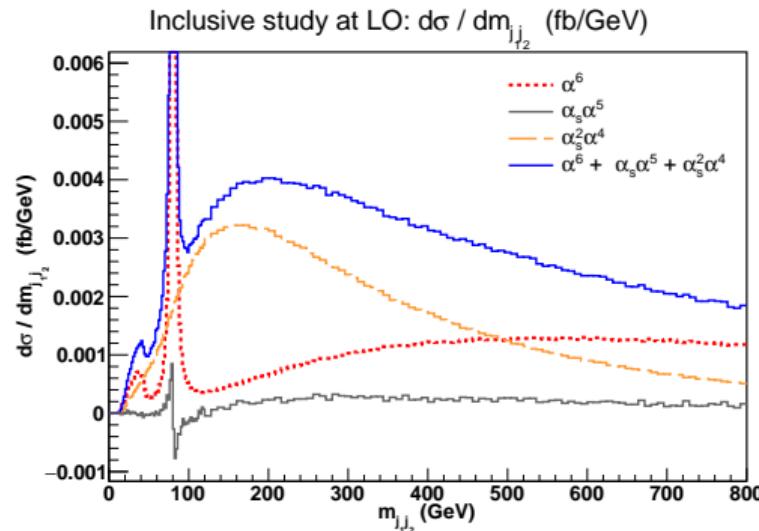
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→ Size of corrections driven by typical scales of the process and kinematic cuts!

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

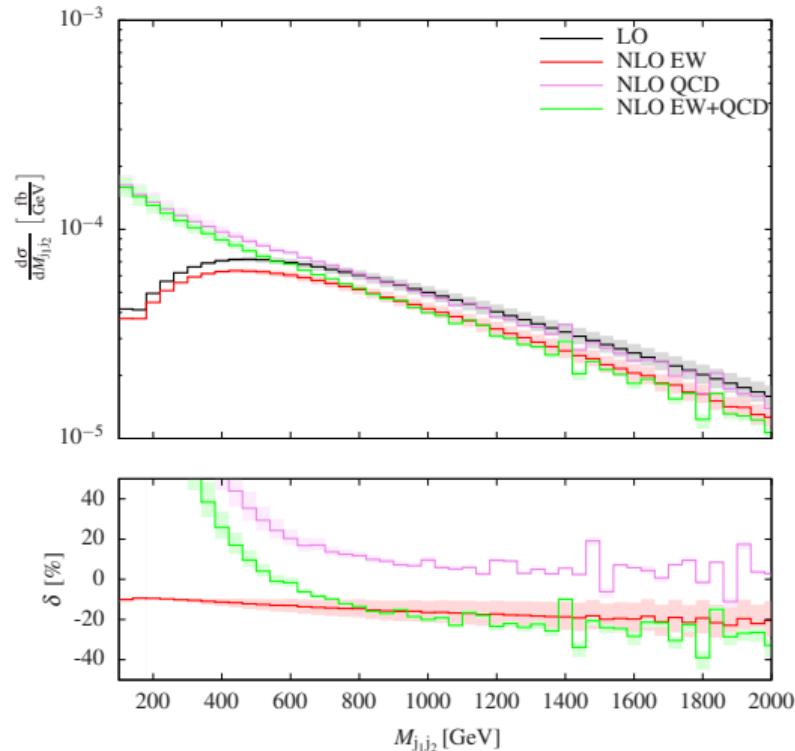
- Typically cuts $m_{jj} > 500$ GeV
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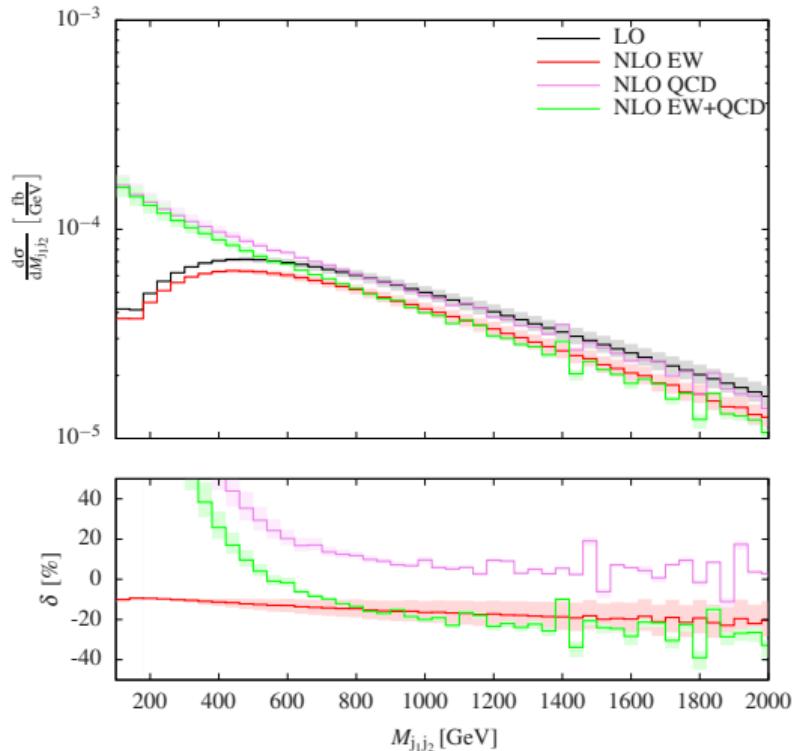


[Ballestrero, MP et al.; 1803.07943]

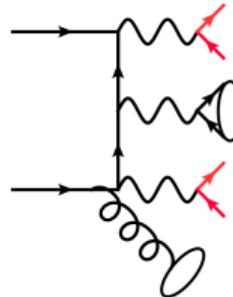
- ⚠ EW component possesses VBS+tri-boson+other contributions
- Naively, 100 GeV cut should do the job. Is it really the case?



[Denner, Franken, MP, Schmidt; 2009.00411]



→ Example: ZZ VBS at NLO



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

[Denner, Franken, MP, Schmidt; 2009.00411]

→ How to ensure that all effects are under control?

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Solution:

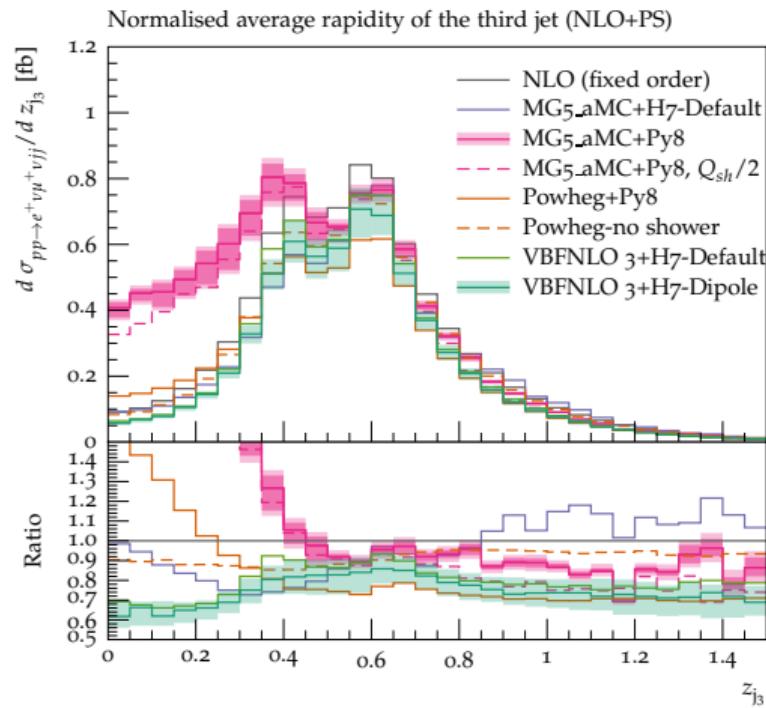
- Different definition of the process
 - With and without QCD component
- Different phase spaces
 - Sensitive to different effects
- Example:
 - CMS ZZ measurement with 137 fb^{-1}

[2008.07013]

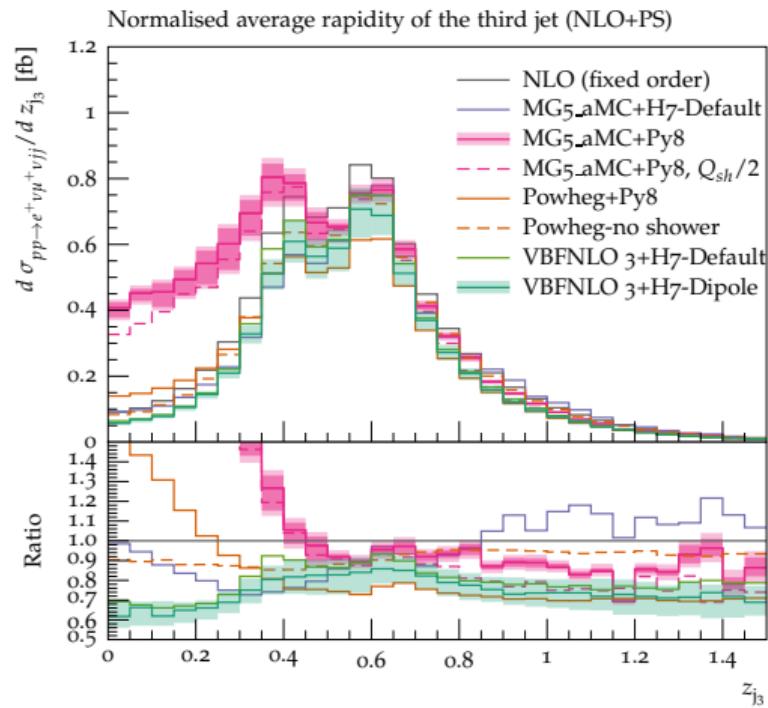
- Disentangles all physical effects
- Great for exp./th. comparisons

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

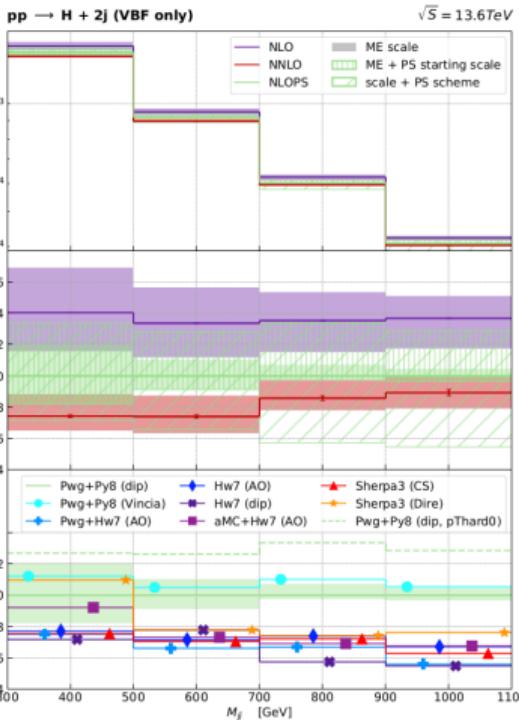
NLO+PS for VBS



[Ballestrero, MP, et al.; 1803.07943]



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[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	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s \alpha^6)$	$\mathcal{O}(\alpha_s^2 \alpha^5)$	$\mathcal{O}(\alpha_s^3 \alpha^4)$
NLO	✓	✓	✓	✓
NLO+PS	✓	✓*	✗	✓

- $\mathcal{O}(\alpha^7)$ [Biedermann, Denner, MP; 1611.02951, 1708.00268]
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- Experimental uncertainty \sim 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, Kirchgæßer, Papaefstathiou, Plätzer, Todt; 2110.01623]
 - NNLO QCD might even be needed...

Polarisation studies

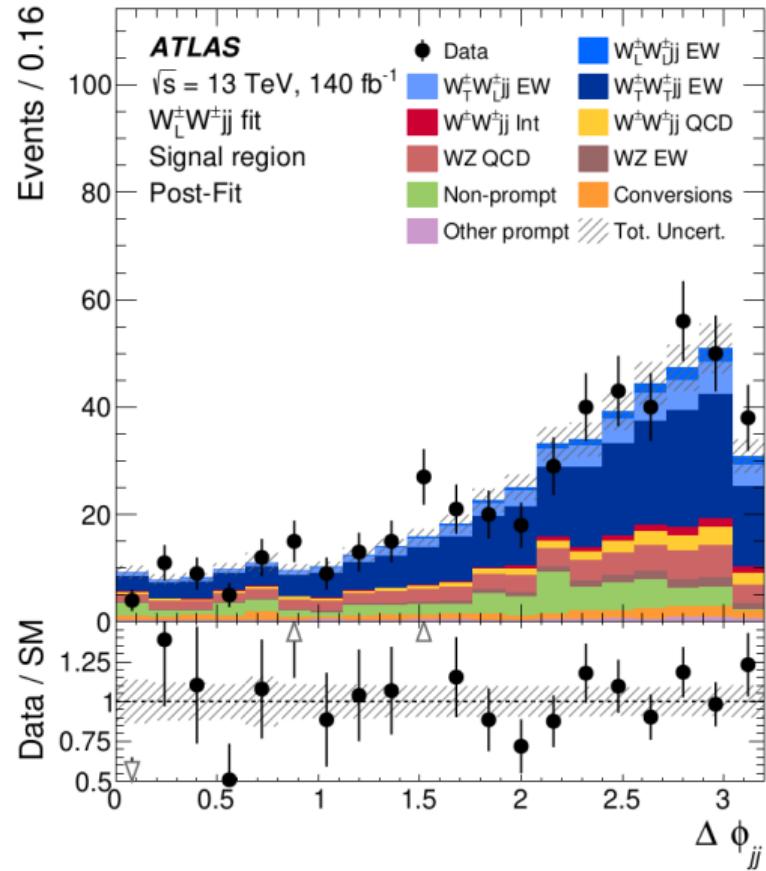
Experiment:

→ Measurements in ss-WW

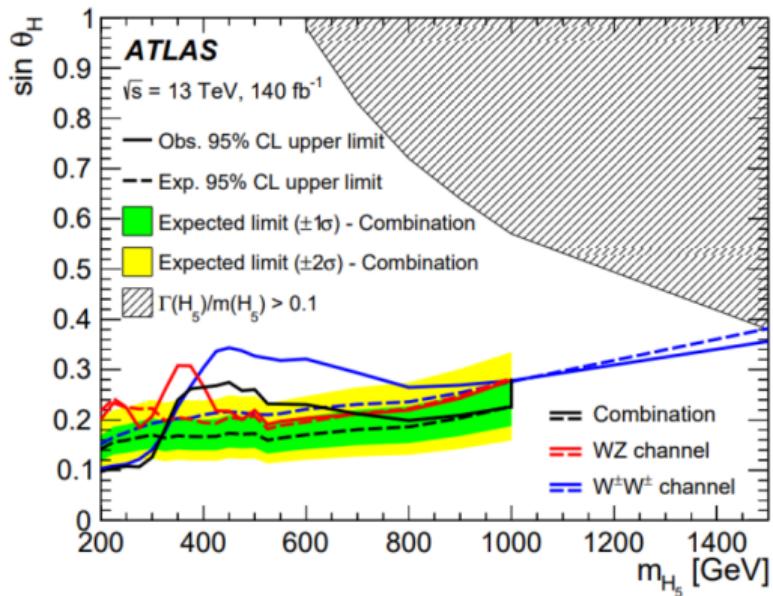
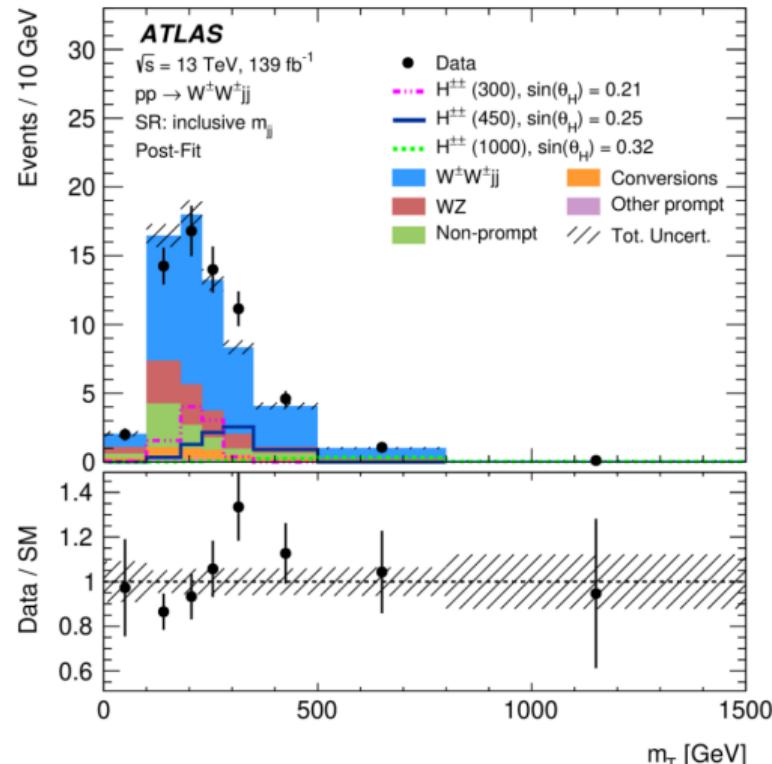
- [CMS; 2009.09429]
- [ATLAS; 2503.11317]
 - Compared to [Hoppe, Schönherr, Siegert; 2310.14803]
 - + [Denner, Haitz, Pelliccioli; 2409.03620]

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⁺⁺**



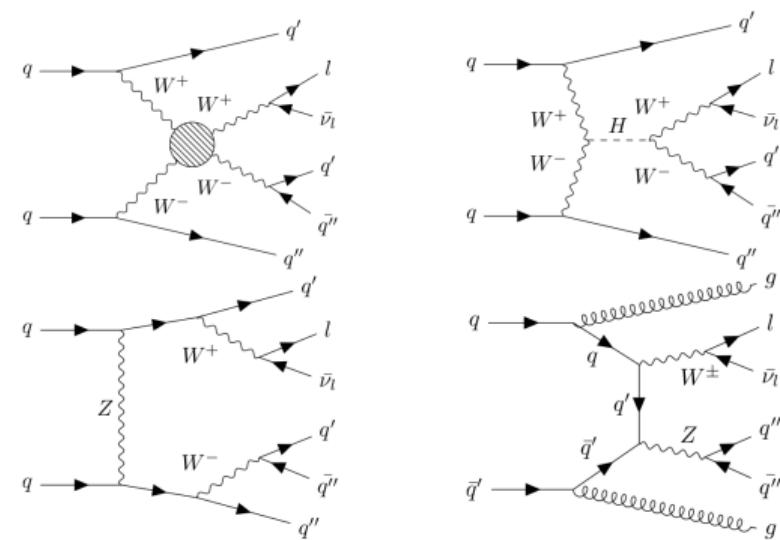
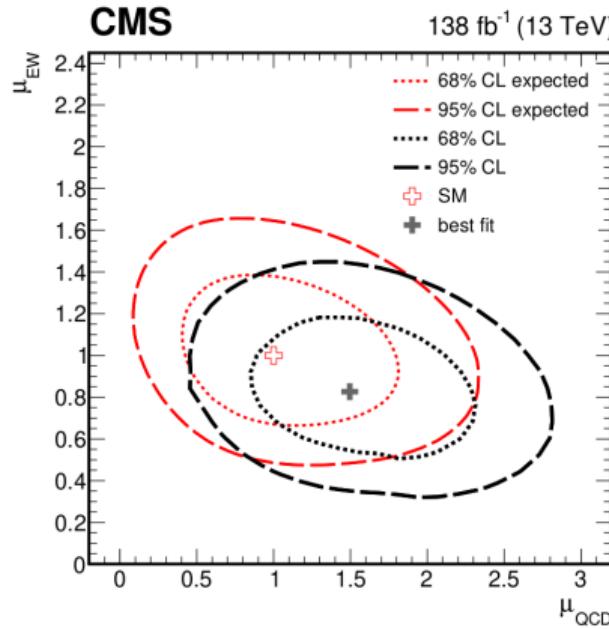
Semi-leptonic channels → challenging on both sides

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
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[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]

**"High-luminosity LHC
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[source: bing image creator]

Exciting physics at the LHC! → VBS is just one example

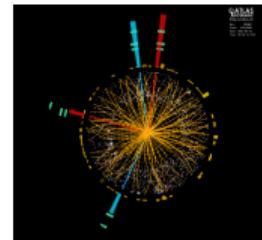
- Explore fundamental aspect of particle physics
- Precision and new ideas more than ever needed
- Crosstalk between exp. and th. is even more needed!

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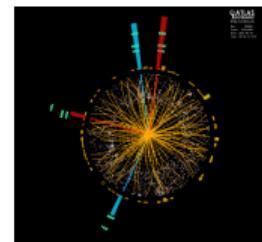


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Thank you to

Claude Charlot and Joany Manjarres for their experimental inputs!

BACK-UP