Vector-boson scattering and the Higgs boson

Mathieu PELLEN

University of Freiburg

Higgs Hunting, Paris, France

16th of July 2025

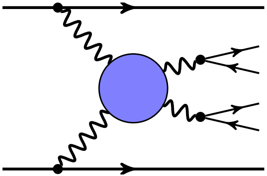
universität freiburg

Higgs Hunting 2025
Results and prospects in the electroweak symmetry breaking sector
15TH
HIGGS HUNTING
15-17 July
Orsay Paris
International Advisory Committee
E. Augé (IJCLab-Orsay, France)
U. Bassler (IN2P3, France)
J. Butler (Fermilab, USA)
T. Camporesi (CERN, Switzerland)
M. Carena (Fermilab, USA)
R. Carlin (Padova, Italy)
M. Cepeda (CIEMAT, Spain)
D. Denisov (BNL, USA)
A. Djouadi (Granada, Spain)
R.K. Ellis (IPPP-Durham, UK)
S. Gascon-Shotkin (IP2I-Lyon, France)
G. Giudice (CERN, Switzerland)
N. Glover (IPPP-Durham, UK)
H. Haber (UC Santa Cruz, USA)
S. Heinemeyer (IFT-Madrid, Spain)
G.Heinrich (KIT, Germany)
A. Hoecker (CERN, Switzerland)
K. Jakobs (Freiburg, Germany)
J. Konigsberg (Florida, USA)
L. Malgeri (CERN, Switzerland)
C. Mariotti (Torino, Italy)
P. McBride (Fermilab, USA)
T.Masubuchi (Osaka, Japan)
A. Nisati (Roma, Italy)
L. Reina (Florida, USA)
L. Ristori (INFN-Pisa/Fermilab, Italy/USA)
F. Sabatié (IRFU, France)
G. Salam (Oxford, UK)
M. Schumacher (Freiburg, Germany)
L. Serin (IJCLab-Orsay, France)
S. Söldner-Rembold (Manchester, UK)
P. Sphicas (CERN/Athens,Switzerland/Greece)
A. Stocchi (IJCLab-Orsay, France)
K. Tokushuku (KEK, Japan)
G. Tonelli (Pisa, Italy)
B. Webber (Cambridge, UK)
S.Willocq (Amherst, USA)
G. Wormser (IJCLab-Orsay, France)
D. Zeppenfeld (Karlsruhe, Germany)
Organising Committee
Nicolas Berger (LAPP-Annecy)
Gregorio Bernardi (APC-Paris)
Valérie Brouillard (IJCLab-Orsay)
Matteo Cacciari (LPTHE-Paris)
Luca Cadamuro (IJCLab-Orsay)
Reina Camacho Toro (LPNHE-Paris)
Arely Cortés González (University of Tokyo)
Adinda De Wit (LLR-Palaiseau)
Emanuele Di Marco (INFN Roma)
Emilian Dudas (CPHT-Palaiseau)
Louis Fayard (IJCLab-Orsay)
Pierre Fayet (ENS-Paris)
Paolo Francavilla (INFN and Università di Pisa)
Christophe Grojean (DESY-Hamburg/Humboldt U.-Berlin)
Gautier Hamel de Monchenault (IRFU-Saclay)
Stéphane Lavignac (IPhT-Saclay)
Anne-Catherine Le Bihan (IPHC-Strasbourg)
Joany Manjares (L2IT-Toulouse)
Giovanni Marchiori (APC-Paris)
Kostas Nikolopoulos (U. of Hamburg/U. of Birmingham)
Jérémie Quevillon (LAPTh-Annecy)
Daniela Rebuzzi (Pavia)
Yves Sirois (LLR-Palaiseau)
Thomas Strebler (CPPM-Marseille)
Meng Xiao (Hangzhou)
www.higgshunting.fr

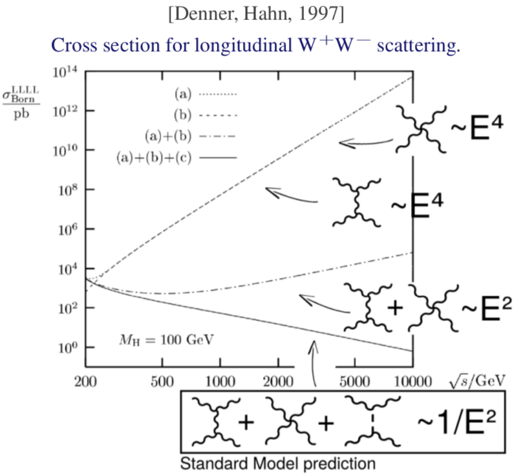
Proposal for Higgs 2026:

[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
- ...



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

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%

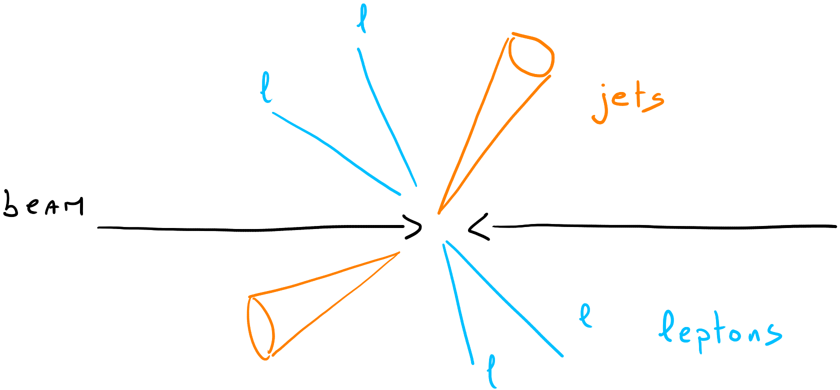
source: Jakob Salfeld-Nebgen, https://indico.cern.ch/event/711256

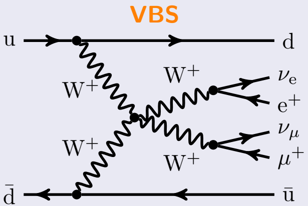
This talk

→ Mainly focused on Standard Model physics

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

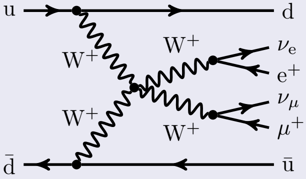
LHC collision producing VBS final state (simplified/theorist's view)





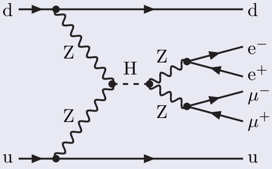
$\rightarrow$ Unitarity / quartic coupling

VBS



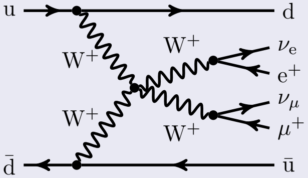
$\longrightarrow$ Unitarity / quartic coupling

VBF



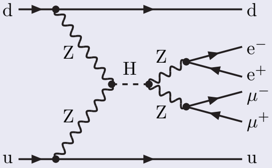
$\longrightarrow$ Higgs properties

VBS



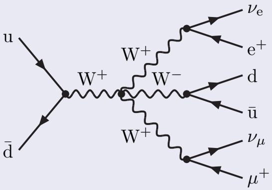
→ Unitarity / quartic coupling

VBF



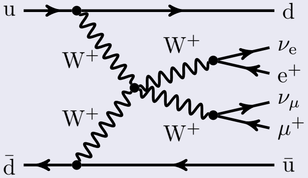
→ Higgs properties

Triboson



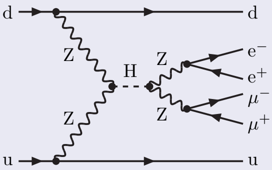
→ Quartic coupling

VBS



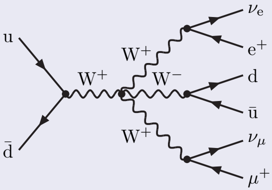
→ Unitarity / quartic coupling

VBF



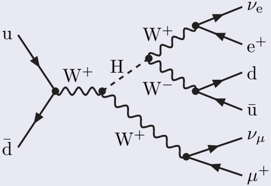
→ Higgs properties

Triboson



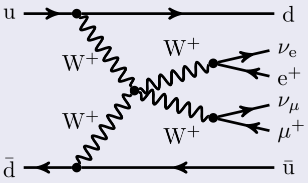
→ Quartic coupling

VH



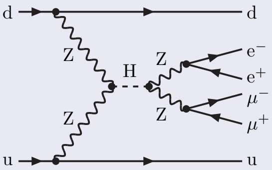
→ Higgs properties

VBS



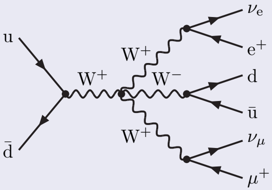
→ Unitarity / quartic coupling

VBF



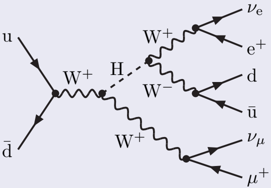
→ Higgs properties

Triboson



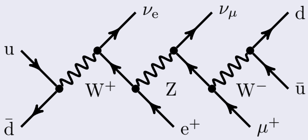
→ Quartic coupling

VH

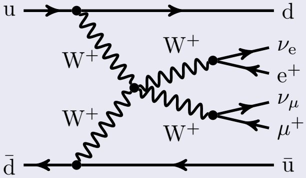


→ Higgs properties

Decay chain

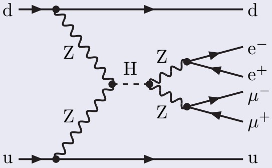


VBS



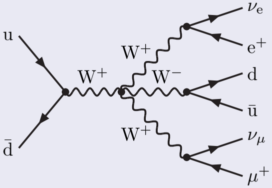
→ Unitarity / quartic coupling

VBF



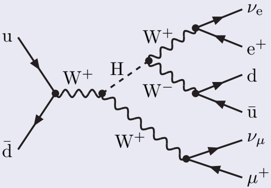
→ Higgs properties

Triboson



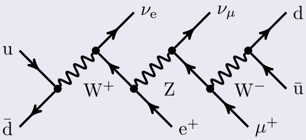
→ Quartic coupling

VH

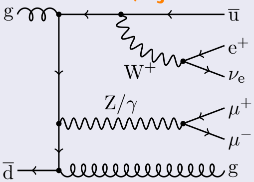


→ Higgs properties

Decay chain

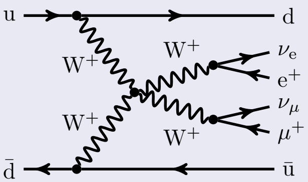


VV+2j



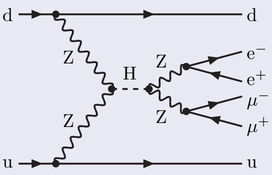
→ QCD

VBS



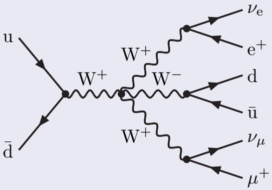
→ Unitarity / quartic coupling

VBF



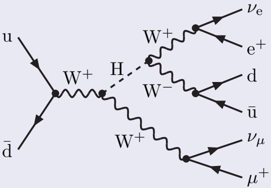
→ Higgs properties

Triboson



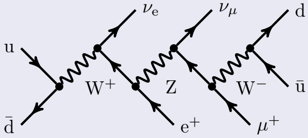
→ Quartic coupling

VH

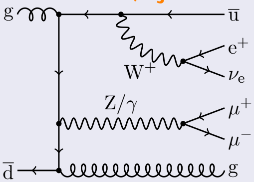


→ Higgs properties

Decay chain



VV+2j



→ QCD

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

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

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

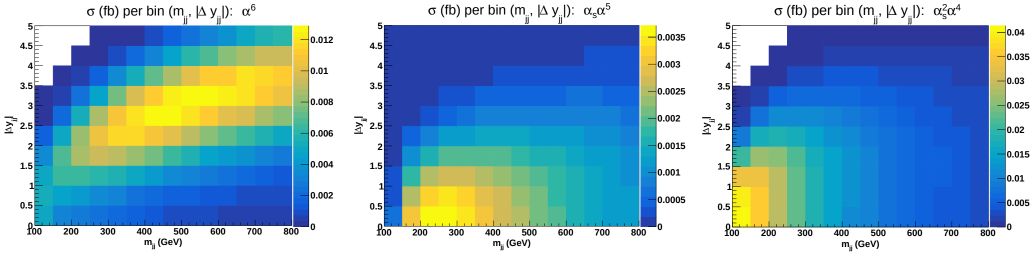
With 2 different amplitudes → 3 different contributions:

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

$$\overbrace{}^{(\mathrm{VBS}+\mathrm{others})\times(\mathrm{QCD})}$$

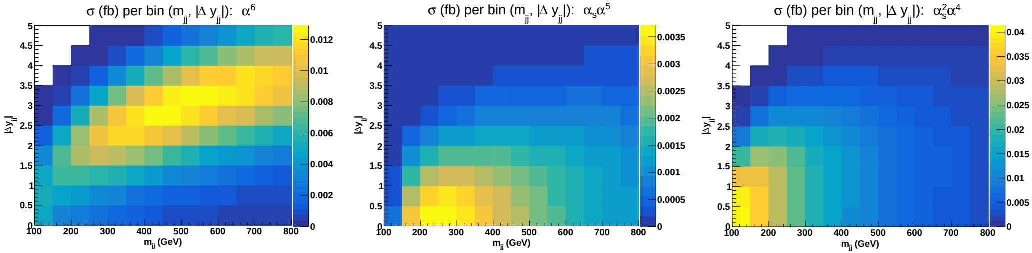
$$\underbrace{\mathcal{O}\left(\alpha^6\right)}_{(\mathrm{VBS}+\mathrm{others})^2} \quad \overbrace{\mathcal{O}\left(\alpha_s\alpha^5\right)}^{(\mathrm{VBS}+\mathrm{others})\times(\mathrm{QCD})} \quad \underbrace{\mathcal{O}\left(\alpha_s{}^2\alpha^4\right)}_{(\mathrm{QCD})^2}$$

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



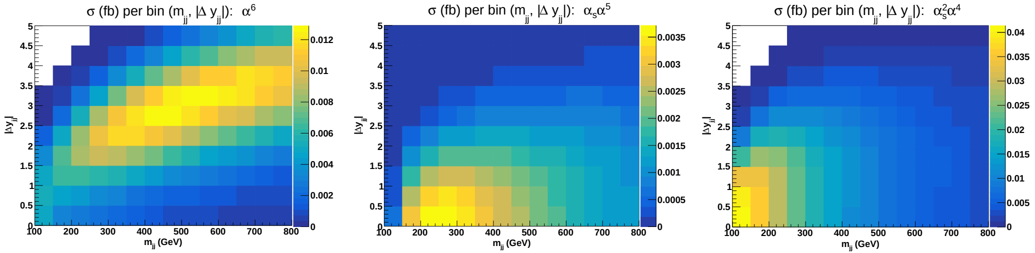
[Ballestrero, MP et al.; 1803.07943]

- The contributions have different kinematics



[Ballestrero, MP et al.; 1803.07943]

- 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 $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$ and $|\Delta y_{\mathrm{jj}}| > 2.5$



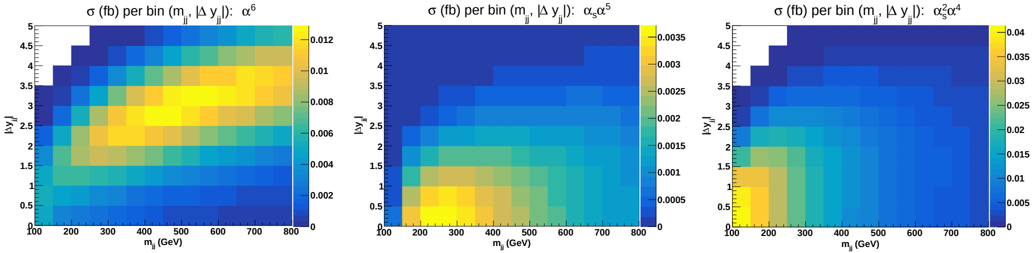
[Ballestrero, MP et al.; 1803.07943]

- 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 $m_{\rm jj} > 500\,\text{GeV}$ and $|\Delta y_{\rm jj}| > 2.5$

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



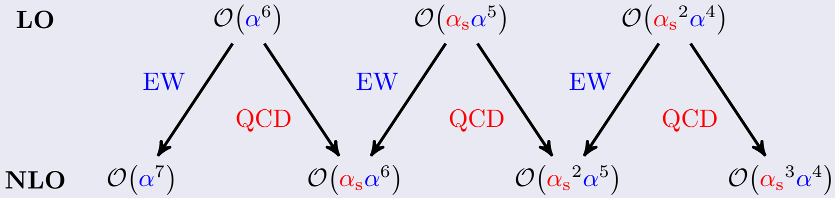
[Ballestrero, MP et al.; 1803.07943]

- 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 $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$ and $|\Delta y_{\mathrm{jj}}| > 2.5$

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

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

Moving on to NLO

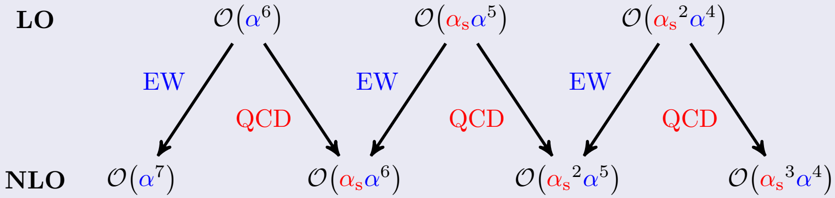


→ Order $\mathcal{O}\left(\alpha_s\alpha^6\right)$ and $\mathcal{O}\left(\alpha_s^2\alpha^5\right)$: QCD and EW corrections mix

At NLO

Meaningless distinction between EW and QCD component

Moving on to NLO



$\rightarrow$ 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

→ Example: $\mathrm{W}^+\mathrm{W}^+$ (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

→ Example: $\mathrm{W^+W^+}$ (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

- 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

→ Example: $\mathrm{W^+W^+}$ (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

- 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]

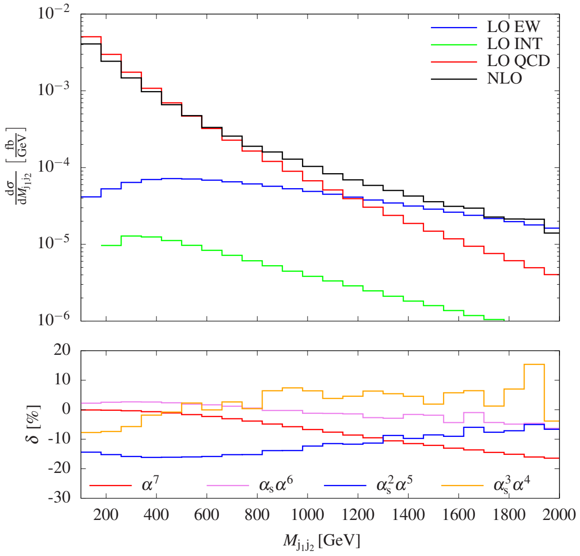
- Large EW corrections as intrinsic feature of VBS [Biedermann, Denner, MP; 1611.02951]
- EW corrections are the dominant NLO correction

⚠ 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 ± 0.37 stat $\pm\, 0.25$ syst	3.93 ± 0.57	3.31 ± 0.47
EW+QCD WW	4.42 ± 0.39 stat $\pm\, 0.25$ syst	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.39 stat $\pm\, 0.14$ syst	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.40 stat $\pm\, 0.23$ syst	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.45 stat $\pm\, 0.18$ syst	3.12 ± 0.70	3.12 ± 0.70

→ LO: MadGraph5_aMC@NLO+PYTHIA

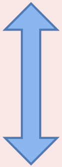
→ NLO: MadGraph5_aMC@NLO+PYTHIA + NLO corr. from [Biedermann, Denner, MP; 1708.00268] or [Denner, Dittmaier, Maierhöfer, MP, Schwan; 1904.00882] but only to EW signal

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]

Physical/less sexy

↕

Less physical/
more sexy

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]

Physical/less sexy

↕

Less physical/ more sexy

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

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?

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., ...)

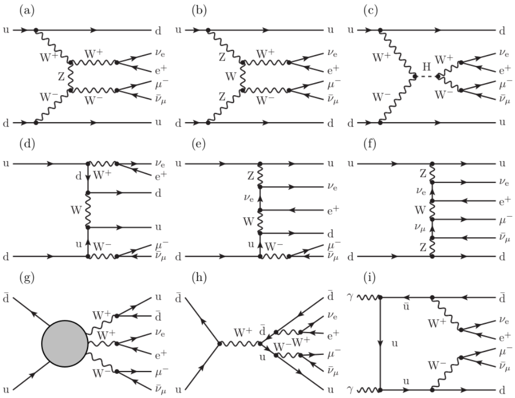
Physical/less sexy

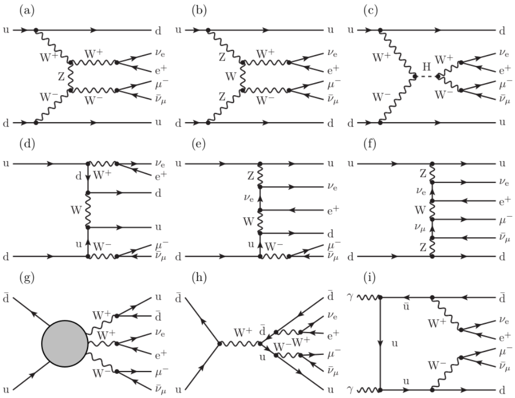
Less physical/
more sexy

→ 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]





- 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)
$\Delta\sigma^{\alpha^7}_{\mathrm{NLO}}$[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

Process	W^+W^+	W^+Z	ZZ	W^+W^- (VBS setup)	W^+W^- (Higgs setup)
$\Delta\sigma^{\alpha^7}_{\rm NLO}$[fb]	−0.2169(3)	−0.04091(2)	−0.015573(5)	−0.307(1)	−0.103(1)
$\sigma^{\alpha^6}_{\rm LO}$[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

- Applying unphysical cut in addition:

$$|M_{4\ell} - M_{\rm H}| \lessgtr 20\Gamma_{\rm H}$$

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

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

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

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

- Applying unphysical cut in addition:

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

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

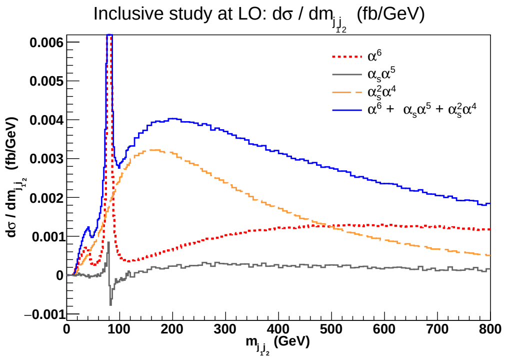
  - Excluding resonance: $\delta_{\mathrm{NLO\,EW}} = -13.2\%$
  - Selection only resonance: $\delta_{\mathrm{NLO\,EW}} = -6.5\%$

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

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

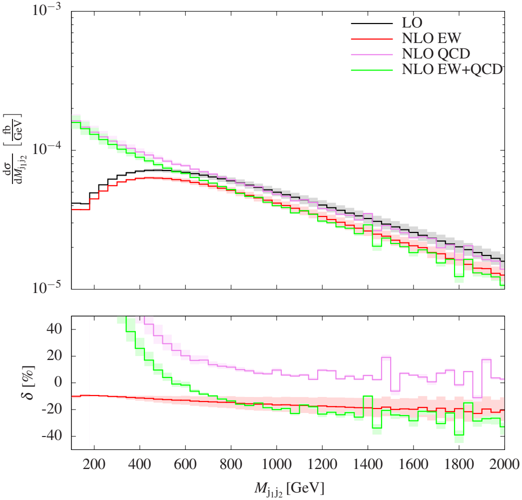
- Typically cuts $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$
  $\rightarrow$ Relaxed for rarest processes
  $\rightarrow$ $m_{\mathrm{jj}} > 100\,\mathrm{GeV}$ (ZZ analysis of [CMS; 1708.02812])

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

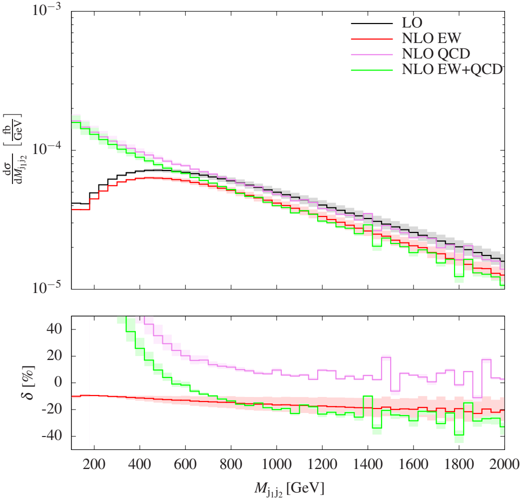


[Ballestrero, MP et al.; 1803.07943]

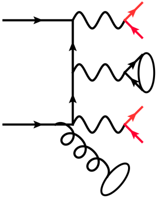
⚠ EW component possesses VBS+tri-boson+other contributions
→ Naively, 100 GeV cut should do the job. Is it really the case?



[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?

→ How to ensure that all effects are under control?

Solution:

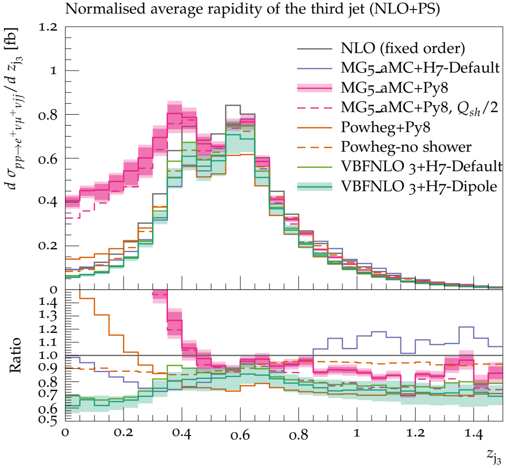
- Different definition of the process
  → With and without QCD component
- Different phase spaces
  → Sensitive to different effects
- Example:
  → CMS ZZ measurement with 137 fb^{-1}

[2008.07013]

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

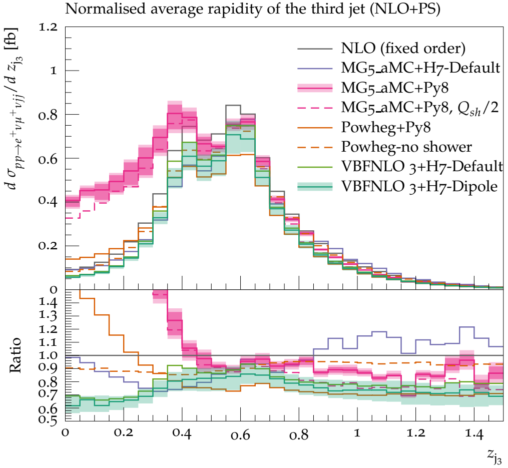
Particle type	Selection
	ZZjj inclusive
Leptons	$p_T(\ell_1) > 20\,\mathrm{GeV}$
	$p_T(\ell_2) > 10\,\mathrm{GeV}$
	$p_T(\ell) > 5\,\mathrm{GeV}$
	$\lvert\eta(\ell)\rvert < 2.5$
Z and ZZ	$60 < m(\ell\ell) < 120\,\mathrm{GeV}$
	$m(4\ell) > 180\,\mathrm{GeV}$
Jets	at least 2
	$p_T(\mathrm{j}) > 30\,\mathrm{GeV}$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

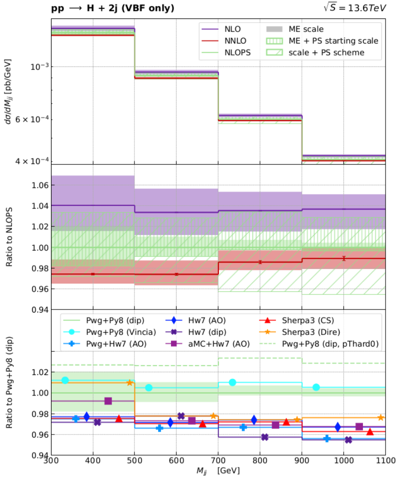
NLO+PS for VBS



[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	✓	✓*	✗	✓

- $\mathcal{O}\left(\alpha^7\right)$ [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]*. Also, +1j: [Jäger, Lopez Portillo Chavez; 2408.12314]*
- $\mathcal{O}\left({\alpha_s}^2\alpha^5\right)$ [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

→ 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	✓	✓*	X	✓

- $\mathcal{O}(\alpha^7)$ [Biedermann, Denner, MP; 1611.02951, 1708.00268]
  → +PS: [Chiesa, Denner, Lang, MP; 1906.01863]
- $\mathcal{O}(\alpha_s \alpha^6)$ [Biedermann, Denner, MP; 1708.00268], [Jäger, Oleari, Zeppenfeld; 0907.0580],* [Denner, Hošeková, Kallweit; 1209.2389]*
  → +PS: [Jäger, Zanderighi; 1108.0864]*. Also, +1j: [Jäger, Lopez Portillo Chavez; 2408.12314]*
- $\mathcal{O}(\alpha_s{}^2 \alpha^5)$ [Biedermann, Denner, MP; 1708.00268]
- $\mathcal{O}(\alpha_s{}^3 \alpha^4)$ [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

- 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, Pellicciioli; 2409.03620]

Theory:

- [Denner, Haitz, Pellicciioli; 2409.03620]

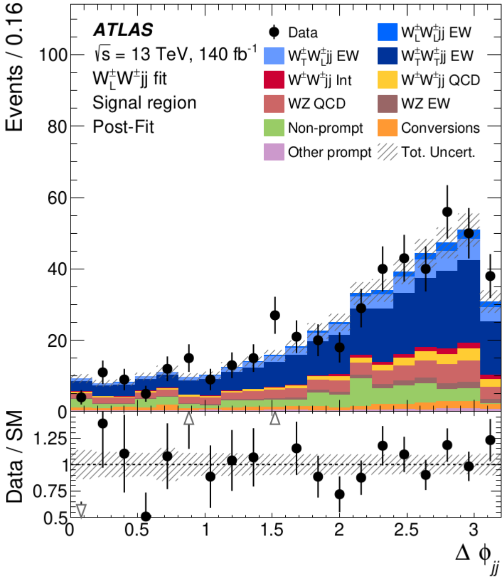
  → NLO QCD+EW for ss-WW

- [Hoppe, Schönherr, Siegert; 2310.14803]

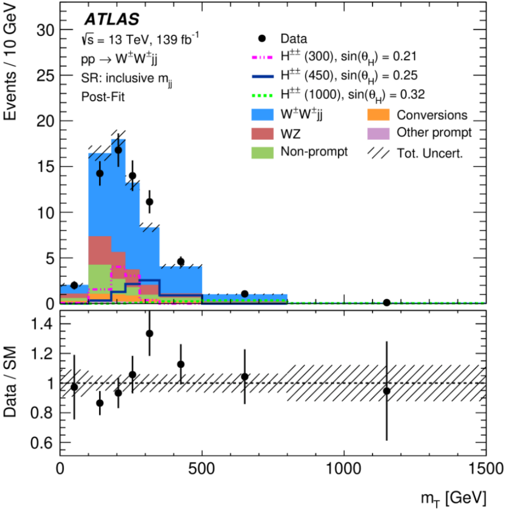
  → Approximate NLO QCD+PS in SHERPA

- [Carrivale et al.; 2505.09686] (for diboson)

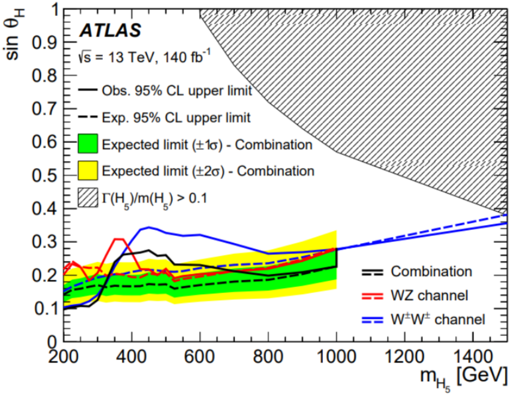
  → Benchmarking exercise + description of tools + references



→ 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:

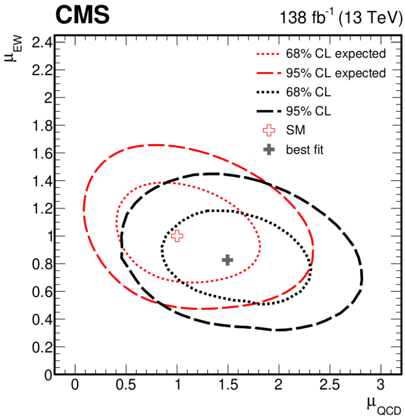
- [CMS; 2112.05259]

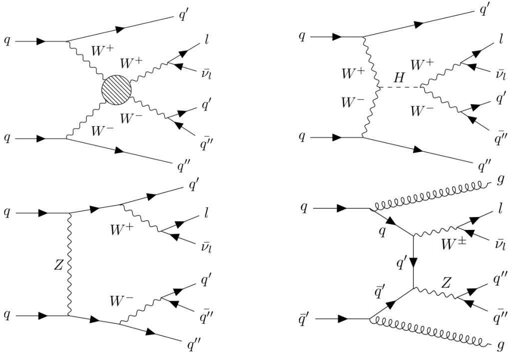
  → $\ell\nu$4j channel

Theory:

- [Denner, Lombardi, Schwan; 2406.12301]

  → LO with pole approximation





Summary

- Many production mechanisms for one signature
  $\rightarrow$ Make interpretation difficult

Summary

- Many production mechanisms for one signature
  $\rightarrow$ Make interpretation difficult
- Due to experimental precision,
  theory predictions should be even better
  $\rightarrow$ Make interpretation even more complicated

Summary

- Many production mechanisms for one signature
  → Make interpretation difficult
- Due to experimental precision,
  theory predictions should be even better
  → Make interpretation even more complicated
- Challenges at High Luminosity:
  - Better measurements
  - Better theory predictions
  - More complex interpretation

"High-luminosity LHC vicious circle"

[source: bing image creator]

Summary

- Many production mechanisms for one signature
  → Make interpretation difficult
- Due to experimental precision,
  theory predictions should be even better
  → Make interpretation even more complicated
- Challenges at High Luminosity:
  - Better measurements
  - Better theory predictions
  - More complex interpretation

- 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 vicious circle"

[source: bing image creator]

Outlook

Exciting physics at the LHC!

→ **VBS is just one example**

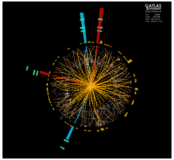
→ Explore fundamental aspect of particle physics
→ Precision and new ideas more than ever needed
→ Crosstalk between exp. and th. is even more needed!

Outlook

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!

Continue to explore even deeper the infinitesimally small!



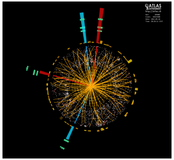
Outlook

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!

Continue to explore even deeper the infinitesimally small!



Thank you to

Claude Charlot and Joany Manjarres for their experimental inputs!

BACK-UP