Theoretical Inputs for Vector-Boson Scattering Measurements at the LHC

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March 1977

Weak Interactions at Very High Energies: the Role of the Higgs Boson Mass

BENJAMIN W. LEE, C. QUIGG[*], and H. B. THACKER
Fermi National Accelerator Laboratory[†], Batavia, Illinois 60510

ABSTRACT

We give an S-matrix theoretic demonstration that if the Higgs boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{\frac{1}{2}}$ partial-wave unitarity is not respected by the tree diagrams for two-body scattering of gauge bosons, and the weak interactions must become strong at high energies. We exhibit the relation of this bound to the structure of the Higgs-Goldstone Lagrangian, and speculate on the consequences of strongly-coupled Higgs-Goldstone systems. Prospects for the observation of massive Higgs scalars are noted.

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Because we wish to explore a regime in which the weak interactions can become strong it is natural to approach the problem from an S-matrix point of view[8] with a particular concern for unitarity.[9] Our treatment provides a systematic investigation of the minimal Weinberg-Salam theory from this point of view. In Section II we discuss and calculate in tree approximation the Weinberg-Salam model amplitudes for all two-body reactions of gauge bosons with zero total electric charge in the s-channel. We display only those terms that are potentially relevant to the question of unitarity, omitting, for example, terms which are of ordinary electromagnet strength at all energies. Logarithmic violations of unitarity that occur at exponentially high energies $\sim M_W e^{1/\alpha}$ will be of no concern to us here.

By focusing only on those amplitudes that constitute a potential threat to unitarity one finds a remarkable simplification of the problem. The relevant amplitudes are those which involve only longitudinal gauge bosons and the Higgs boson. The system of these particles is the subject of Section III. There it is shown that at energies large compared with the intermediate boson mass, this system is a clear reflection of the underlying Higgs-Goldstone system of the Weinberg-Salam model, with the longitudinal W^+, W^- and Z^0 behaving much like the Goldstone bosons from which they sprang. Up to terms of order $M_W/\sqrt{s}$, the S-matrix for $W_L^{\pm}$, Z_L, and H (the subscript L denotes longitudinal polarization) is identical to that for the self-interactions of a complex doublet of scalar particles, as we show in detail in an Appendix. Consequently exploration

→ Probe longitudinal polarisation at high energies ...

... to get insight into Electroweak Symmetry Breaking

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→ High energies mean LHC (13.6 TeV)

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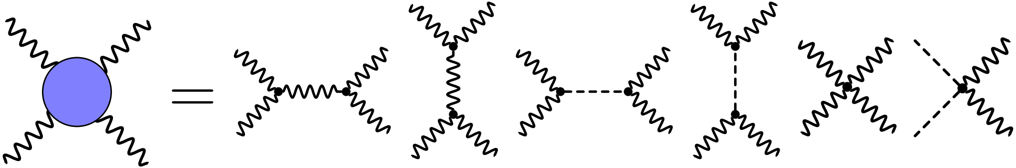

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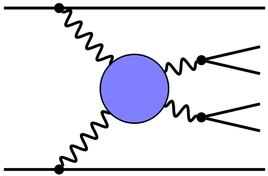
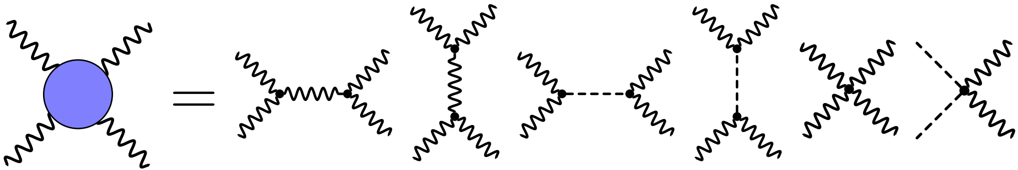
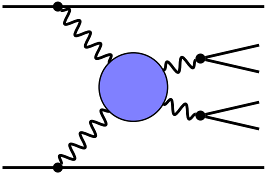
Vector-boson scattering!

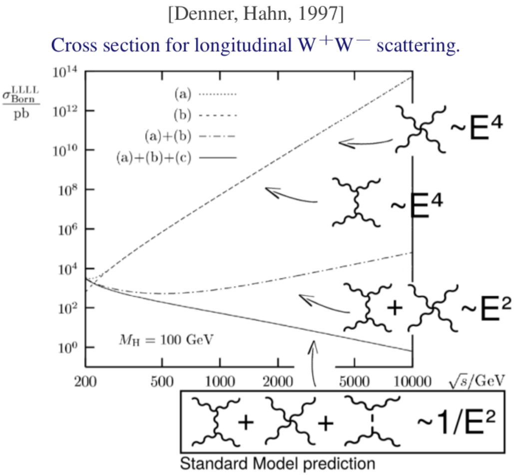




What is VBS and why this is interesting



- Electroweak symmetry breaking
- (longitudinal) Polarisation measurements
- Unitarisation due to Higgs boson
- 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%
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source: Jakob Salfeld-Nebgen, https://indico.cern.ch/event/711256

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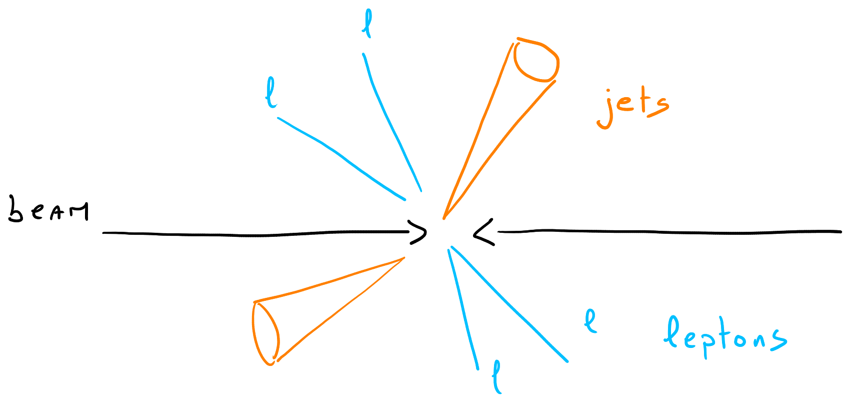
This talk

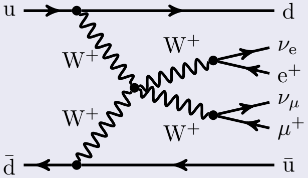
→ Mainly focused on Standard Model physics

- 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)

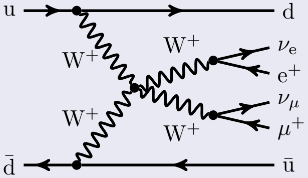


VBS



→ Unitarity / quartic coupling

VBS



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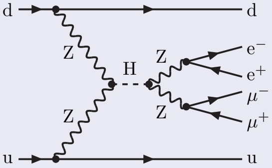
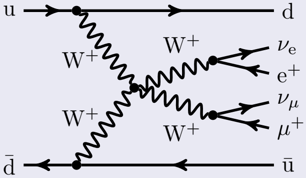


→ Higgs properties

VBS



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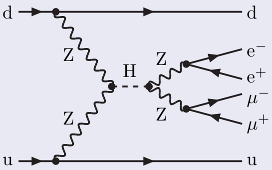
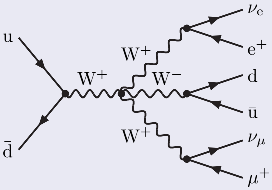


→ Higgs properties

Triboson



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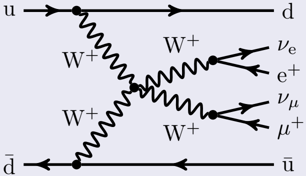
VBS



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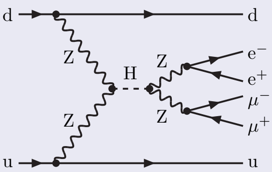

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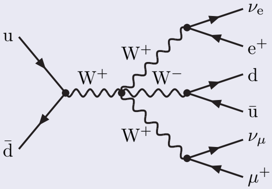
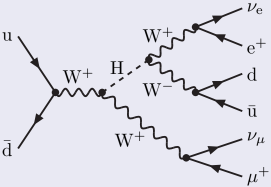


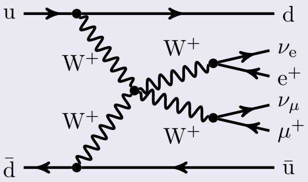
→ Quartic coupling

VH



→ Higgs properties

VBS



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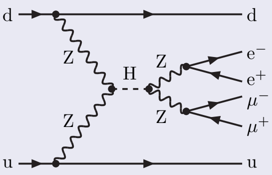

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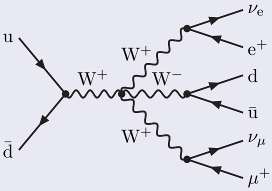

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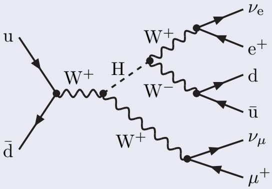
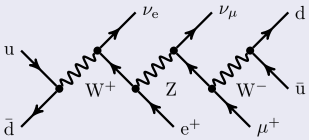
VH

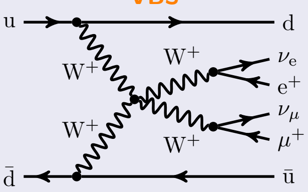


→ Higgs properties

Decay chain



VBS



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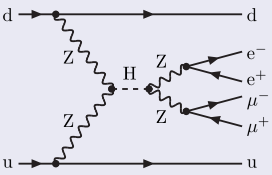

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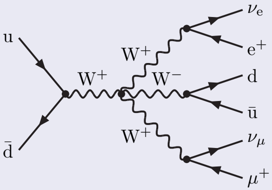

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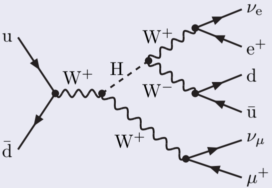

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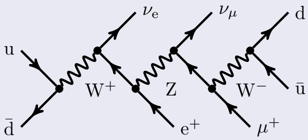
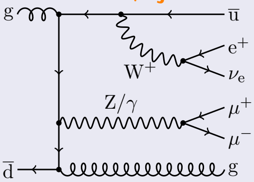
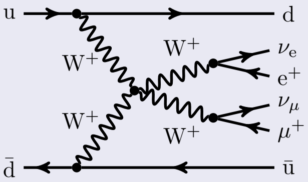


VV+2j



→ QCD

VBS



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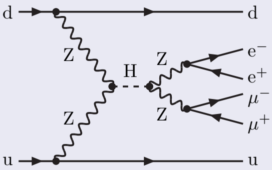

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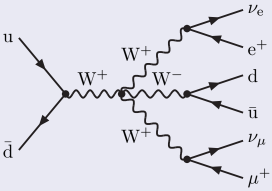

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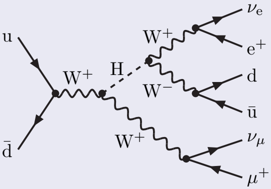

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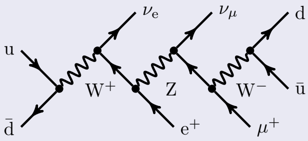

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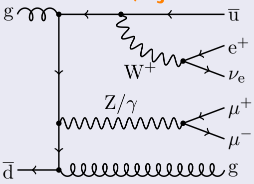

→ QCD

NB: For all contributions, interesting physics and access to 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

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

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

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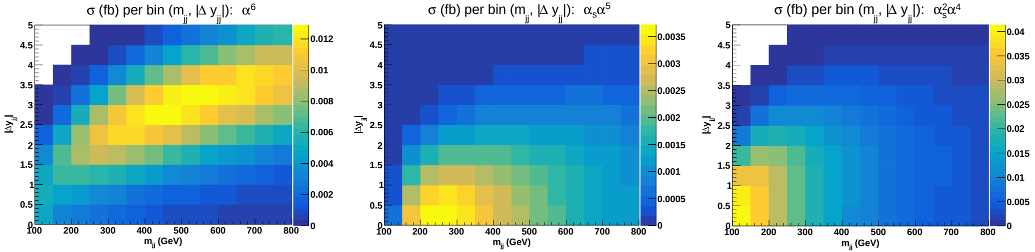
→ How to measure the EW component (including VBS) then?

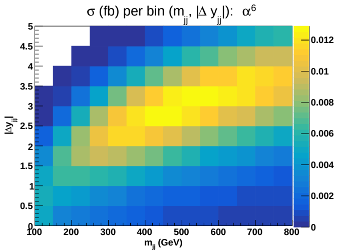
EW **Interference** **QCD**

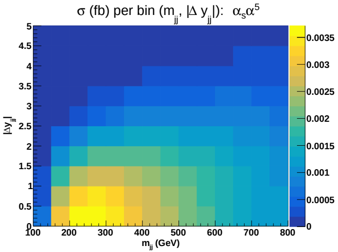


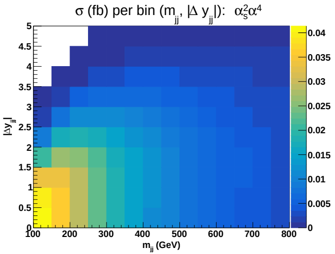
[Ballestrero, MP et al.; 1803.07943]

- The contributions have different kinematics
  $\rightarrow$ Back-to-back jets at large rapidity differences + central gauge bosons

EW **Interference** **QCD**







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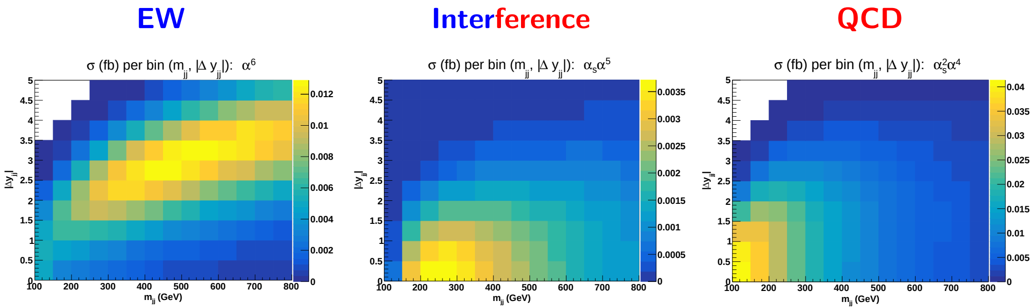
→ Strategy: Use exclusive cuts and subtract irreducible background (int.+QCD)



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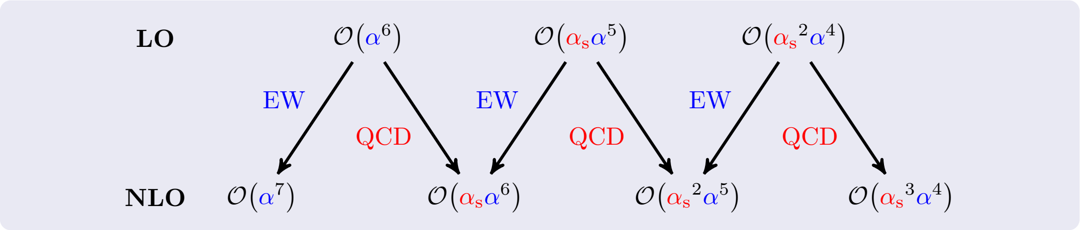
⚠ VBS contributions appear also in the interference
⚠ Theory-dependent measurement



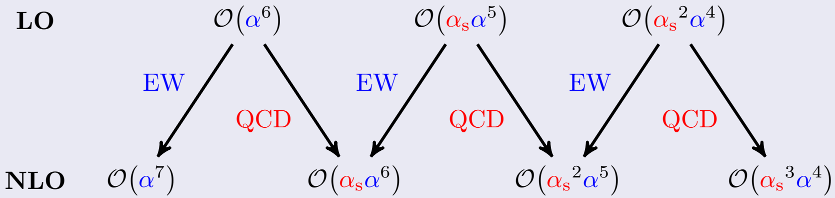
NB: leading order (LO), next to leading order (NLO)

→ 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 higher order

Meaningless distinction between EW and QCD component

Moving to higher orders in perturbation theory



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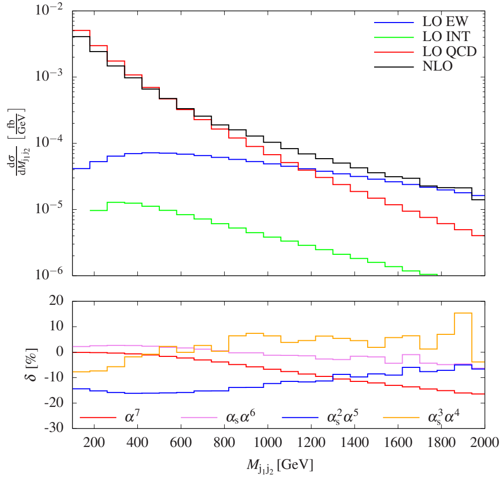
At higher order

Meaningless distinction between EW and QCD component

Solution: Combined measurement of all the contributions

→ clear physical interpretation

→ Example of ZZ channel



[Denner, Franken, MP, Schmidt; 2107.10688]

- Series of articles computing full NLO corrections for all VBS channels:

  ssWW: [Biedermann, Denner, MP; 1611.02951, 1708.00268], [Chiesa, Denner, Lang, MP; 1906.01863],
  WZ: [Denner, Dittmaier, Maierhöfer, Schwan, MP; 1904.00882],
  ZZ: [Denner, Franken, MP, Schmidt; 2009.00411, 2107.10688],
  W+W-: [Denner, Franken, Schmidt, Schwan; 2202.10844],

- Complex structure

  → Intricate link between higher-order corrections and experimental cuts

- Large EW corrections

  [Biedermann, Denner, MP; 1611.02951]

  → $\sim -15\%$ for total cross section!

Comparison with data

→ same-sign 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)	Theory NLO (%)
EW WW	$3.98 \pm 0.37\,\mathrm{stat} \pm 0.25\,\mathrm{syst}$	3.93 ± 0.57	3.31 ± 0.47	-15.8
EW+QCD WW	$4.42 \pm 0.39\,\mathrm{stat} \pm 0.25\,\mathrm{syst}$	4.34 ± 0.69	3.72 ± 0.59	-14.3
EW WZ	$1.81 \pm 0.39\,\mathrm{stat} \pm 0.14\,\mathrm{syst}$	1.41 ± 0.21	1.24 ± 0.18	-12.1
EW+QCD WZ	$4.97 \pm 0.40\,\mathrm{stat} \pm 0.23\,\mathrm{syst}$	4.54 ± 0.90	4.36 ± 0.88	-4.0

→ "LO": MadGraph5_aMC@NLO + PYTHIA

→ "NLO": MadGraph5_aMC@NLO + PYTHIA + NLO corr. (**non-trivial part**):

- [Biedermann, Denner, MP; 1708.00268]
- [Denner, Dittmaier, Maierhöfer, MP, Schwan; 1904.00882]

→ Set basis of future precision measurements

More physical -
Difficult interpretation

Less physical -
Easy interpretation

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

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2. **Full measurement - QCD background (MC)** vs. **Full EW** (pb of interference)
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... extract quantities
(mass, coupling, EFT coefficients, polarisation...)

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→ Is it enough?

No... kinematics can also play a crucial role

- Typically cuts $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$
  - → Relaxed for rarest processes
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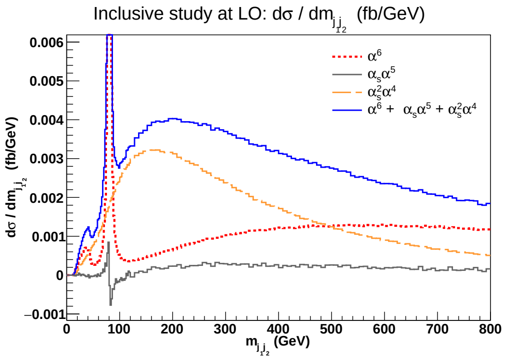
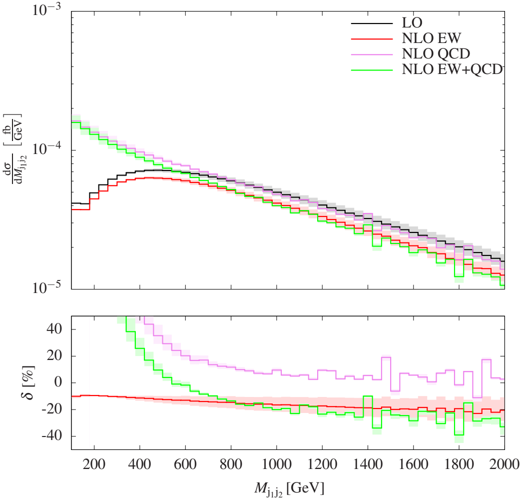


[Ballestrero, MP et al.; 1803.07943]

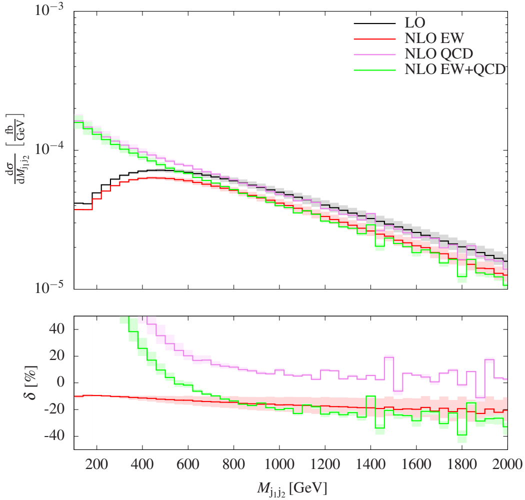
⚠ EW component = VBS+tri-boson+other contributions

→ Naively, 100 GeV cut should do the job. Is it really the case?



→ Example: ZZ VBS at NLO

[Denner, Franken, MP, Schmidt; 2009.00411]



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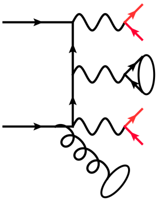

→ Effects of tri-boson (at NLO) even when using $m_{jj} > 100\,\text{GeV}$

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

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

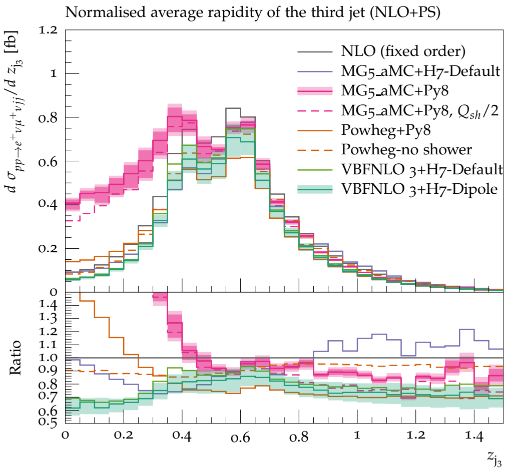
Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s{}^2\alpha^5)$	$\mathcal{O}(\alpha_s{}^3\alpha^4)$
NLO	✓	✓	✓	✓
NLO+PS	✓	✓*	X	✓

- $\mathcal{O}(\alpha^7)$ [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! NNLO QCD might even be needed...
  → Effect of non-perturbative physics
  [Jäger, Karlberg, Scheller; 1812.05118], [Bittrich, Kirchgaeßer, Papaefstathiou, Plätzer, Todt; 2110.01623]
  → **What about parton shower?**

NLO+PS for VBS



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→ Huge differences, uncovered inconsistent use of Pythia for VBS/VBF topologies

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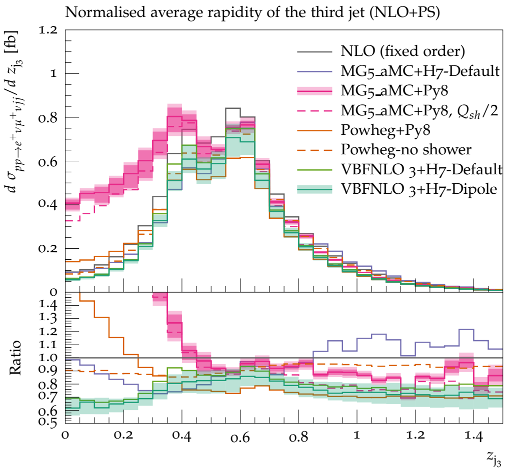

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→ Huge differences, uncovered inconsistent use of Pythia for VBS/VBF topologies

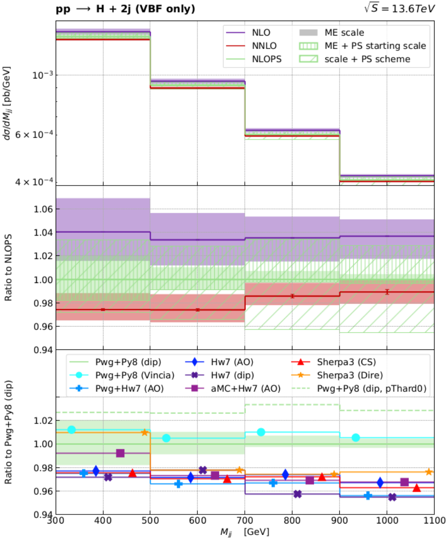
$H \to WW$

Uncertainty source	$\Delta\mu/\mu$	$\Delta\mu_{ggH}/\mu_{ggH}$	$\Delta\mu_{VBF}/\mu_{VBF}$	$\Delta\mu_{WH}/\mu_{WH}$	$\Delta\mu_{ZH}/\mu_{ZH}$
Theory (signal)	4%	5%	13%	2%	<1%
Theory (background)	3%	3%	2%	4%	5%
Lepton misidentification	2%	2%	9%	15%	4%
Integrated luminosity	2%	2%	2%	2%	3%
b tagging	2%	2%	3%	<1%	2%
Lepton efficiency	3%	4%	2%	1%	4%
Jet energy scale	1%	<1%	2%	<1%	3%
Jet energy resolution	<1%	1%	<1%	<1%	3%
p_T^{miss} scale	<1%	1%	<1%	2%	2%
PDF	1%	2%	<1%	<1%	2%
Parton shower	<1%	2%	<1%	1%	1%
Backg. norm.	3%	4%	6%	4%	6%
Stat. uncertainty	5%	6%	28%	21%	31%
Syst. uncertainty	9%	10%	23%	19%	11%
Total uncertainty	10%	11%	36%	29%	33%

[CMS; 2206.09466]

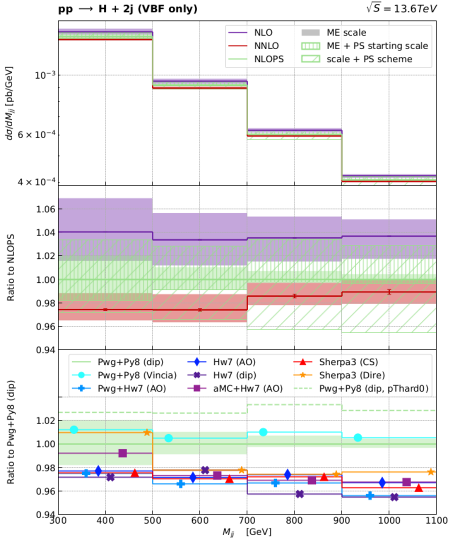
→ Still > 10% error on parton-shower uncertainty

NLO+PS for VBF



[Barone, MP, et al.; 2507.22574]

NLO+PS for VBF



[Barone, MP, et al.; 2507.22574]

→ Work in between:

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

→ [Barone, MP, et al.; 2507.22574]:

- Part of the Higgs Cross section WG Yellow Report 5
- State-of the art predictions at fixed order + Parton-shower study
- Recommendations for parton-shower uncertainty (usable also for VBS):

Based on these observations, we propose the following recommendation for a more robust estimation of NLOPS uncertainty, which comprises both the matching and the shower variations:

1. Generate (at least) three predictions:
   - one with POWHEG-BOX and any PYTHIA 8 shower;
   - one with any HERWIG 7 shower;[12]
   - one with any SHERPA 3 shower.

   Make sure that at least one of these prediction is based on POWHEG matching, and one on MC@NLO matching.[13] Then, construct an envelope[14] out of these predictions.
2. For one of the curves computed in step 1:
   - compute a shower starting scale variation band (or a pThard variation in the context of POWHEG-BOX +PYTHIA 8 matching);
   - compute the renormalisation and factorisation scale variation band, possibly including also scale variations in the shower.

   Sum these bands in quadrature and combine this uncertainty in quadrature with the first envelope uncertainty.

FERMILAB-Pub-77/30-THY
March 1977

Weak Interactions at Very High Energies: the Role of the Higgs Boson Mass

BENJAMIN W. LEE, C. QUIGG*, and H. B. THACKER
Fermi National Accelerator Laboratory†, Batavia, Illinois 60510

ABSTRACT

We give an S-matrix theoretic demonstration that if the Higgs boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{\frac{1}{2}}$ partial-wave unitarity is not respected by the tree diagrams for two-body scattering of gauge bosons, and the weak interactions must become strong at high energies. We exhibit the relation of this bound to the structure of the Higgs-Goldstone Lagrangian, and speculate on the consequences of strongly-coupled Higgs-Goldstone systems. Prospects for the observation of massive Higgs scalars are noted.

After almost 50 years, exciting time!

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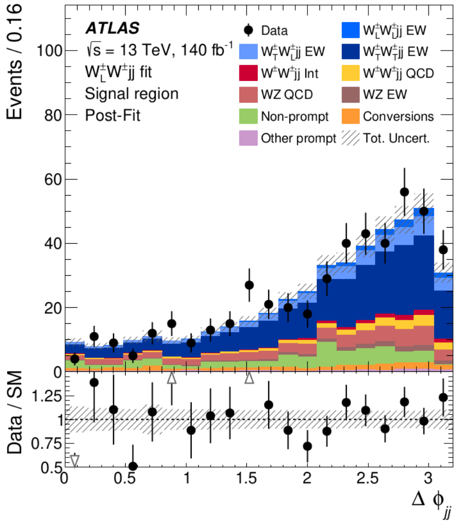
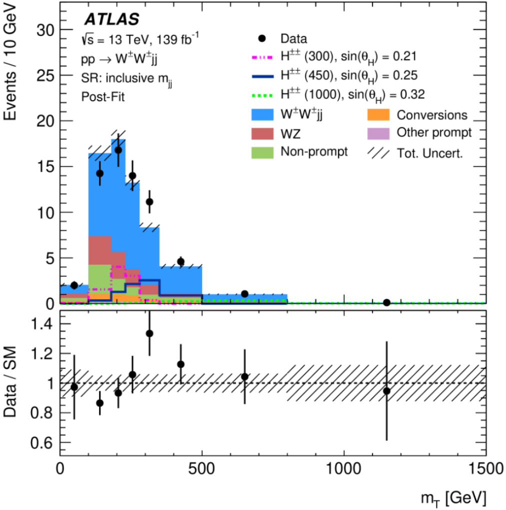
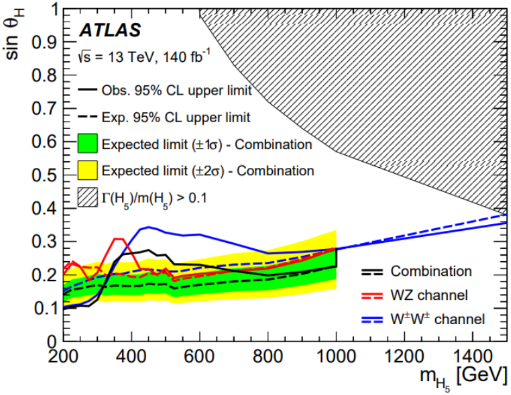


[ATLAS; 2503.11317]

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



[ATLAS; 2312.00420]



[ATLAS; 2407.10798]

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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!
  → STXS for multiboson - activity in LHC EW WG
  `https://indico.cern.ch/event/1593081`

"High-luminosity LHC vicious circle"

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Outlook

VBS physics at the LHC is Exciting physics!

→ Explore fundamental aspect of particle physics
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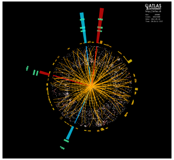
~~A bit of propaganda~~ Final word:

MoCaNLO [Denner, Lombardi, Lopez Portillo Chavez, MP, Pelliccioli] about to be public!
(code used for many of the computations presented above)



BACK-UP

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