Precision calculations in Vector-Boson Fusion Higgs production

LoopFest XVI, 31 May 2017, Argonne National Laboratory

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based on Phys.Rev.Lett. 117 (2016) no.7, 072001

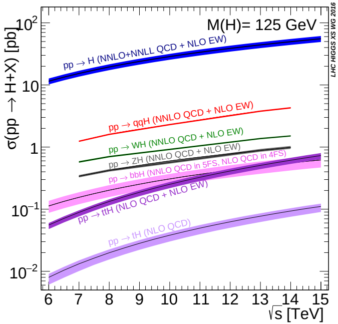
& work in collaboration with Matteo Cacciari, Alexander Karlberg, Gavin Salam & Giulia Zanderighi

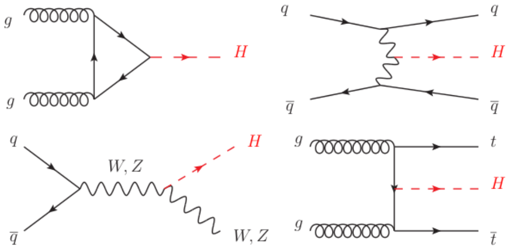
Higgs production at the LHC

Determination of Higgs properties is a priority for ATLAS and CMS collaborations.

The four main production channels are

- Gluon-gluon fusion (ggH) via an intermediate heavy quark loop
- Vector-boson fusion (VBF)
- Associated production with a W or Z boson (VH), $q\bar{q} \to V + H$
- Associated production with top/bottom quarks (ttH/bbH)





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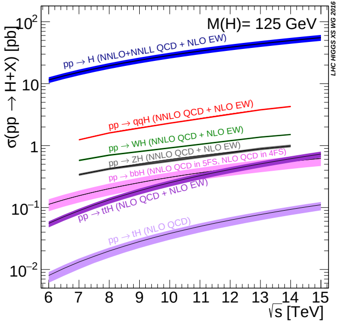
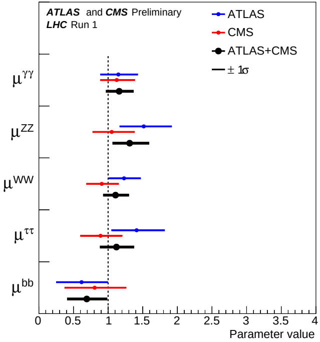


Production process	ATLAS+CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$

Status and prospects for Higgs physics

Gaining a precise understanding of the Higgs sector will be one of the main goals of the LHC experimental program.



[ATLAS-CONF-2015-044]

Current decay signal strength measured to $\mathcal{O}(20\%)$.

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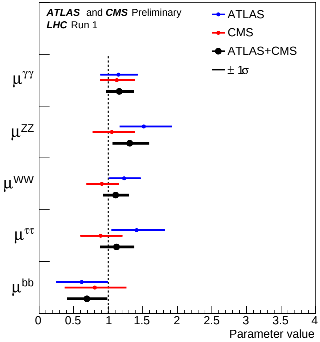

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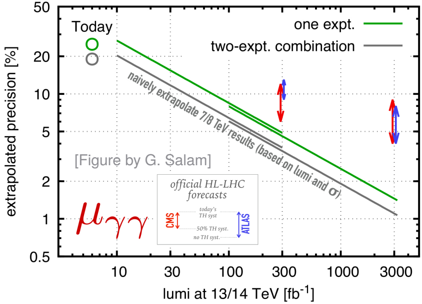
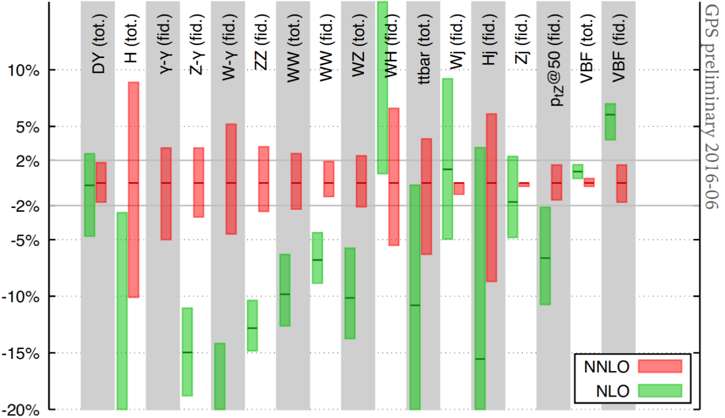


But large improvements can be expected with the HL-LHC.

Higher order corrections required for precise predictions

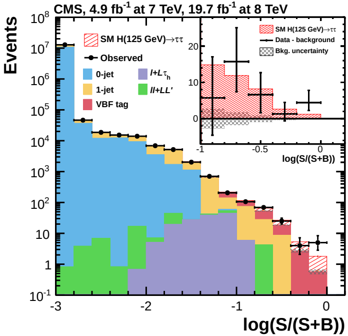
NNLO predictions often outside of NLO scale bands, with corrections frequently above 10% compared to NLO.



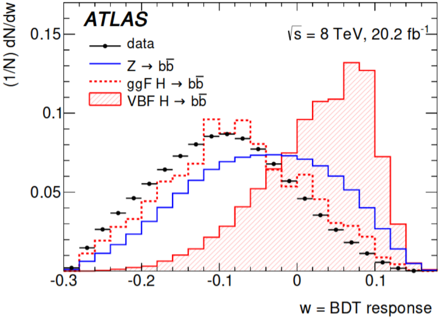
[Figure by G. Salam]

Why study VBF Higgs production?

- Two forward jets allow for better tagging of events and identification of decays with large background (eg. in $H \to \tau\tau$ and $H \to bb$).



[CMS, JHEP 05 (2014) 104]



[ATLAS, JHEP 11 (2016) 112]

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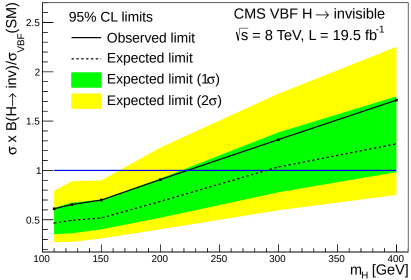
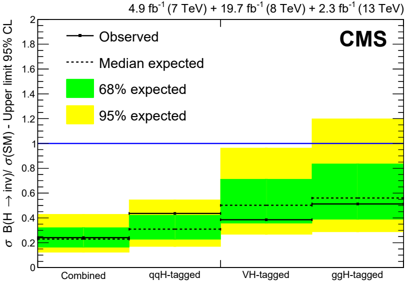


[CMS, EPJC 74 (2014) 2980]



[CMS, arXiv:1610.09218]

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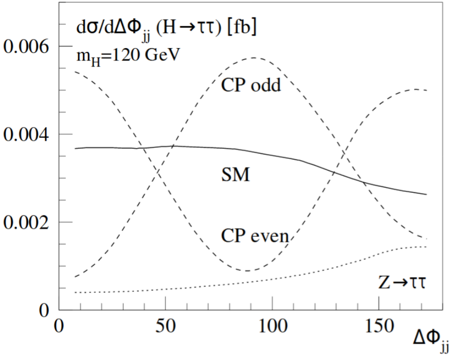
- Angular correlation of tagging jets brings sensitivity to CP properties of the Higgs and to non-SM Higgs interactions (small CP odd component is still allowed)

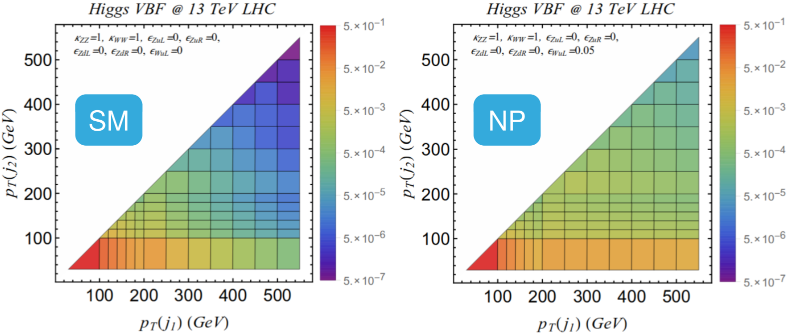


$$\mathcal{L}_6 = \frac{g^2}{2\Lambda_e^2}(\Phi^\dagger\Phi)V_{\mu\nu}V^{\mu\nu} + \frac{g^2}{2\Lambda_o^2}(\Phi^\dagger\Phi)\tilde{V}_{\mu\nu}V^{\mu\nu}$$

[Plehn, Rainwater, Zeppenfeld Phys.Rev.Lett. 88 (2002) 051801]

Why study VBF Higgs production?

- Double differential cross section in jet p_t's can provide a powerful probe into properties of Higgs boson.



[Greljo, Isidori, Lindert, Marzocca, Eur.Phys.J. C76 (2016) no.3, 158]

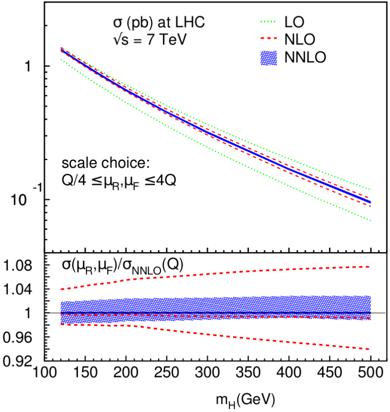
Requires precise and differential theoretical calculations.

QCD CORRECTIONS IN VBFH

Inclusive NNLO VBF Higgs production

Fully inclusive VBF Higgs production is known at NNLO.

[Bolzoni, Maltoni, Moch, Zaro Phys.Rev.Lett. 105 (2010) 011801]



Calculation suggests tiny renormalization and factorization scale variations ($\sim 1-2\%$), with NNLO values within NLO bands.

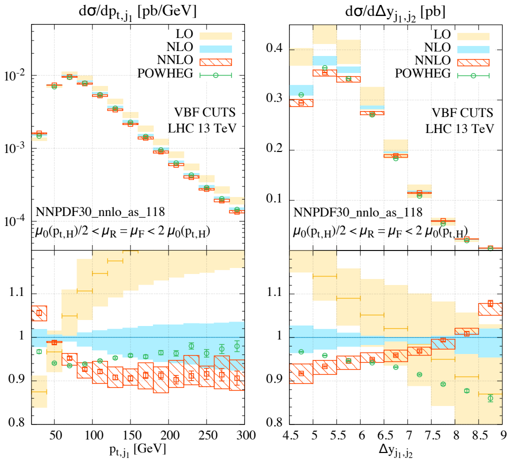
This calculation is **inclusive** over all hadronic final states.

Result is obtained using the structure function approach.

Differential NNLO VBF Higgs production

Using novel "projection-to-Born" method, differential results derived recently in the DIS×DIS limit.

[Cacciari, FD, Karlberg, Salam, Zanderighi
Phys.Rev.Lett. 115 (2015) no.8, 082002]



NNLO corrections are up to $\sim 10 - 12\%$ after VBF cuts.

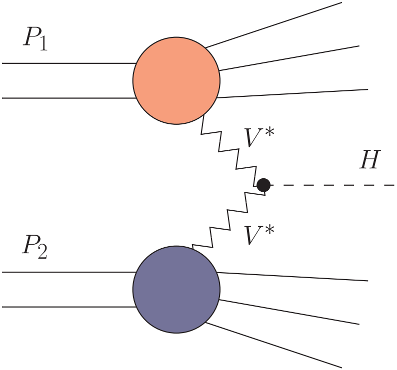
There is a non-trivial kinematic dependence of K-factors.

No reduction of theoretical uncertainty at NNLO after VBF cuts.

Structure function approach

Assume that lower and upper sector factorize from each other (i.e. no cross-talk).

[Han, Valencia, Willenbrock Phys.Rev.Lett. 69 (1992) 3274-3277]



One can then think of VBFH as DIS×DIS.

This picture is accurate to better than 1%.

[Bolzoni et al. PRD85 (2012) 035002, Ciccolini et al. PRD77 (2008) 013002, Andersen et al. JHEP 0802 (2008) 057]

Since DIS coefficients are inclusive over hadronic final states, this calculation cannot provide differential results for the jets.

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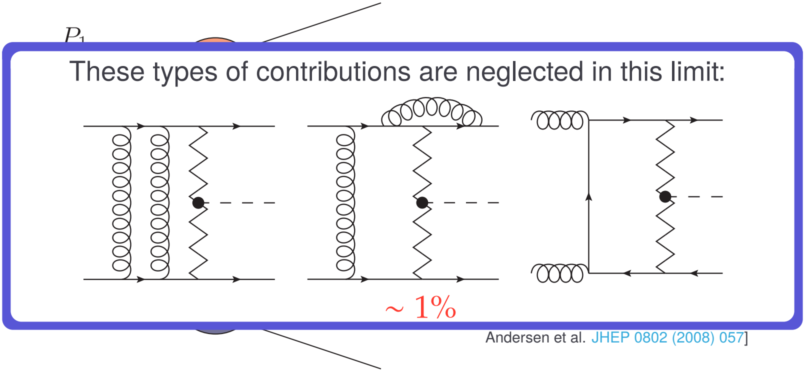

Andersen et al. JHEP 0802 (2008) 057]

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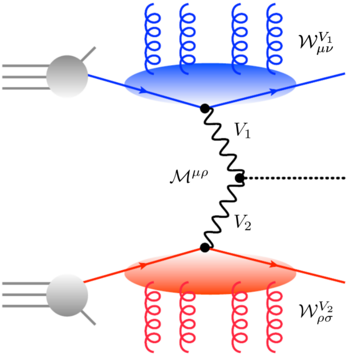
Structure function approach

More explicitly, cross section can be expressed as

$$d\sigma = \frac{4\sqrt{2}}{s} G_F^3 m_V^8 \Delta_V^2(Q_1^2)\Delta_V^2(Q_2^2) \times \mathcal{W}_{\mu\nu}^V(x_1, Q_1^2)\mathcal{W}^{V,\mu\nu}(x_2, Q_2^2) d\Omega_{\text{VBF}} ,$$



with the hadronic tensor

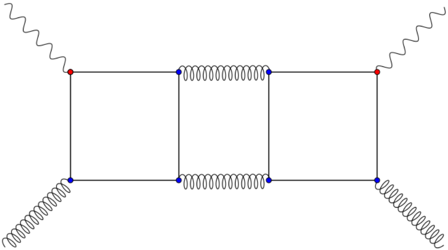
$$\mathcal{W}_{\mu\nu}^V(x_i, Q_i^2) = \left(-g_{\mu\nu} + \frac{q_{i,\mu}q_{i,\nu}}{q_i^2}\right) F_1^V(x_i, Q_i^2) + \frac{\hat{P}_{i,\mu}\hat{P}_{i,\nu}}{P_i \cdot q_i} F_2^V(x_i, Q_i^2) + i\epsilon_{\mu\nu\rho\sigma} \frac{P_i^\rho q_i^\sigma}{2P_i \cdot q_i} F_3^V(x_i, Q_i^2) .$$

Structure functions

Structure functions expressed as convolution of short distance DIS coefficient functions and PDFs

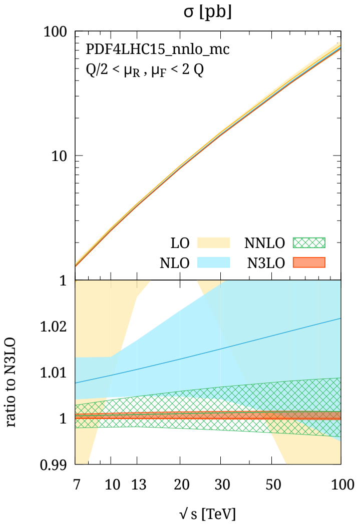
$$F_i^V = \sum_{a=q,g} C_i^{V,a} \otimes f_a\,, \quad i = 1,2,3,\ V = Z, W^\pm\,.$$

- DIS coefficient functions are known up to third order in α_s.
- Same concept from LO to N^{3}LO, but at higher orders more complicated flavour topologies start appearing.



Inclusive cross section at N^{3}LO

Inclusive calculation can be extended to VBF Higgs production at N^{3}LO



using third order coefficient functions:

[Moch, Vermaseren, Vogt PLB606 (2005) 123-129]
[Vermaseren, Vogt, Moch NPB724 (2005) 3-182]
[Vermaseren, Moch, Vogt NPPS 160 (2006) 44-50]
[Moch, Rogal, Vogt NPB790 (2008) 317-335]

which have been implemented in HOPPET v1.2.0-devel. [Salam, Rojo CPC 180 (2009) 120-156]

Perturbative series converges extremely well.

Very small change in central value, but large reduction in theoretical uncertainty.

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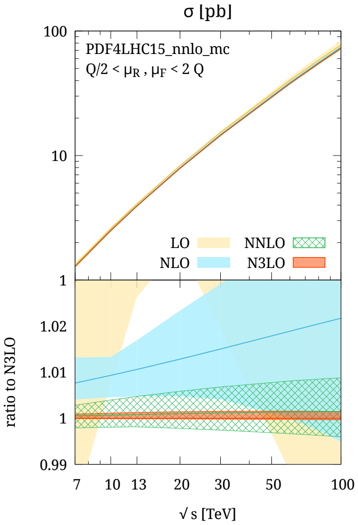

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First calculation at N^{3}LO of a process beyond $2 \to 1$!

Total cross-sections

We consider pp collisions, and use PDF4LHC15_nnlo_mc.

Central scale is set to the vector boson energies, Q_1, Q_2, and varied up and down by a factor two keeping $0.5 < \mu_R/\mu_F < 2$.

Inclusive cross section (no cuts)

	$\sigma^{(13\,\text{TeV})}$ [pb]	$\sigma^{(14\,\text{TeV})}$ [pb]	$\sigma^{(100\,\text{TeV})}$ [pb]
LO	$4.099^{+0.051}_{-0.067}$	$4.647^{+0.037}_{-0.058}$	$77.17^{+6.45}_{-7.29}$
NLO	$3.970^{+0.025}_{-0.023}$	$4.497^{+0.032}_{-0.027}$	$73.90^{+1.73}_{-1.94}$
NNLO	$3.932^{+0.015}_{-0.010}$	$4.452^{+0.018}_{-0.012}$	$72.44^{+0.53}_{-0.40}$
N^{3}LO	$3.928^{+0.005}_{-0.001}$	$4.448^{+0.006}_{-0.001}$	$72.34^{+0.11}_{-0.02}$

N^{3}LO corrections tiny, at 2‰ level, but reduce theoretical uncertainties by a factor of 5.

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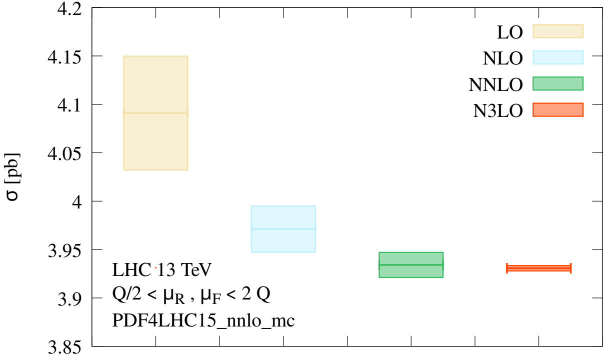
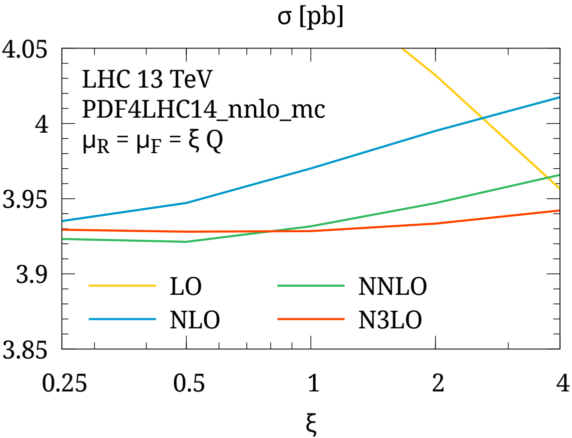


Scale variation up to N^{3}LO

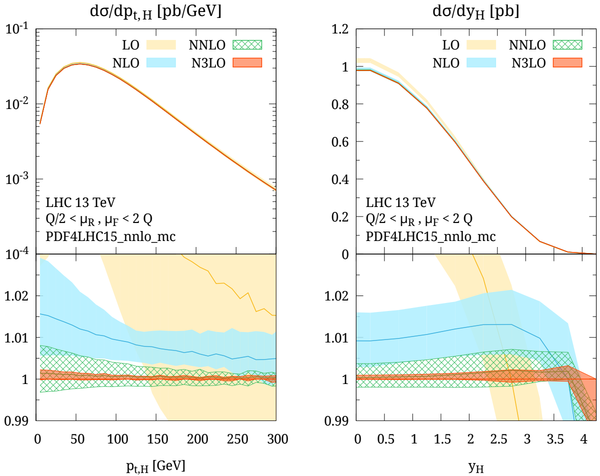
Dependence of cross section on renormalisation and factorisation scale



Very stable convergence of perturbative series.

Differential distributions: Higgs p_t and rapidity

Using vector-boson momenta, we can reconstruct the Higgs momentum and obtain differential distributions w.r.t. Higgs kinematics.



N[3]LO corrections are tiny and within NNLO scale variation bands.

But no information on kinematics of tagging jets.

Theoretical PDF uncertainties

One source of unknown N^3LO corrections: missing higher orders in PDF determination.

Only NNLO PDF sets are available, which are missing two main contributions:

- Higher order splitting functions in PDF evolution
- Higher order corrections to coefficient functions relating observables to PDFs

Theoretical PDF uncertainties

One source of unknown N^3LO corrections: missing higher orders in PDF determination.

Only NNLO PDF sets are available, which are missing two main contributions:

- Higher order splitting functions in PDF evolution $\Rightarrow$ less than $\mathcal{O}(1‰)$
- Higher order corrections to coefficient functions relating observables to PDFs

Theoretical PDF uncertainties

We provide two estimates of impact of missing higher orders in PDFs

A. Estimate from difference between NLO and NNLO PDF

$$\delta_A^{\text{PDF}} = \frac{1}{2}\left|\frac{\sigma^{\text{NNLO}}_{\text{NNLO-PDF}} - \sigma^{\text{NNLO}}_{\text{NLO-PDF}}}{\sigma^{\text{NNLO}}_{\text{NNLO-PDF}}}\right| = 1.1\%$$

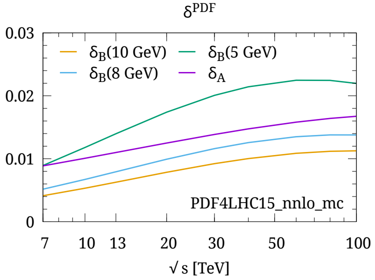
[Anastasiou et al. JHEP 1605 (2016) 058]

B. Estimate using N^{3}LO structure functions

$$\delta_B^{\text{PDF}}(Q_0) = \left|\frac{\sigma^{\text{N}^3\text{LO}} - \sigma^{\text{N}^3\text{LO}}_{\text{rescaled}}(Q_0)}{\sigma^{\text{N}^3\text{LO}}}\right| = 7.9‰$$

where rescaled cross section is obtained with

$$f^{\text{N}^3\text{LO,approx.}}(x,Q) = f^{\text{NNLO}}(x,Q)\frac{F_2^{\text{NNLO}}(x,Q_0)}{F_2^{\text{N}^3\text{LO}}(x,Q_0)}$$



Contributions beyond DIS^2 picture

Non-factorizable corrections are suppressed, but contribute at the 1% level:

- Gluon exchanges between upper and lower hadronic sectors $\sim \mathcal{O}(1‰)$
- Heavy-quark loop induced contributions $\sim \mathcal{O}(1‰)$
- t/u channel interferences $\sim \mathcal{O}(0.5‰)$ with VBF cuts
- s channel production $\sim \mathcal{O}(0.5‰)$ with VBF cuts
- Single-quark line contributions $\sim \mathcal{O}(1‰)$ with VBF cuts
- Loop-induced interference effects $< \mathcal{O}(1‰)$

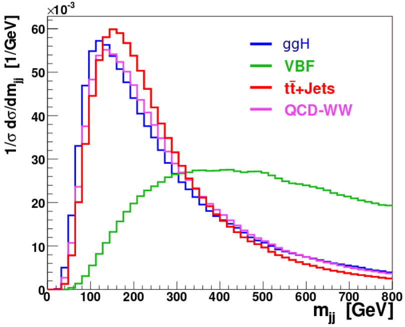
Further corrections from NLO electroweak and photon-induced channels need to be included.

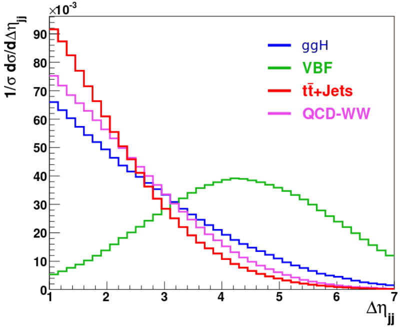
$$\sigma = \sigma_{\text{QCD}}(1 + \underbrace{\delta_{\text{EW}}}_{\sim 5\%}) + \underbrace{\sigma_\gamma}_{\sim 1\%}$$

DIFFERENTIAL CALCULATION AND VBF CUTS

VBF cuts

To reduce background noise, cuts on rapidity separation and jet p_t are essential.





Cuts discriminate against background, such as gluon-fusion $H + 2j$ production and $t\bar{t}$ production.

VBF cuts

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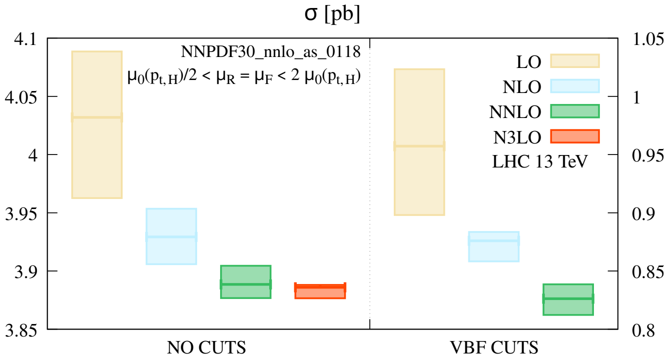
Example event selection

- At least two jets with $p_t > 25\,\mathrm{GeV}$ and $|y| < 4.5$.
- Rapidity separation $|\Delta y_{j_1,j_2}| > 4.5$.
- Dijet invariant mass $m_{j_1,j_2} > 600\,\mathrm{GeV}$.

Cuts discriminate against background, such as gluon-fusion $H + 2j$ production and $t\bar{t}$ production.

Impact of VBF cuts on convergence

- VBF cuts require a fully differential calculation (including on the jet kinematics).
- Perturbative convergence worsens considerably after VBF cuts.
- Higher order corrections mainly driven by jet fragmentation.

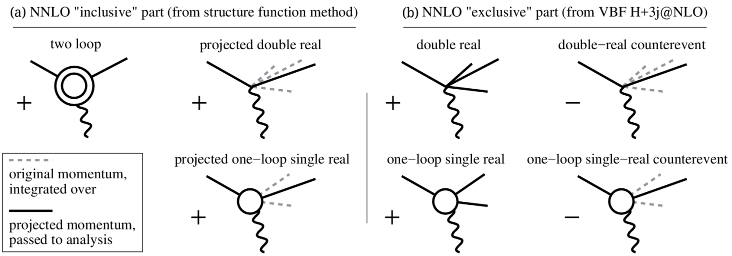


Towards a differential calculation at N^{3}LO

Fully differential N^{3}LO calculation is the next frontier

- One of the first achievable calculation at this order
- Could contribute significantly in very exclusive kinematics, such as VBF cuts with a central jet veto.

With *projection-to-Born* method, requires a factorised exclusive calculation.



CONCLUSIONS

Conclusions

- VBF channel has been calculated to unprecedented accuracy.
- Inclusive N^3LO corrections are tiny, few permille, but reduce theoretical uncertainties substantially.
- First step towards a calculation differential in the parton kinematics.
  $\Longrightarrow$ How will **VBF cuts** affect the size of the N^3LO QCD corrections?
- How "small" are neglected non-factorisable corrections at NNLO and other suppressed contributions?

First public version of **proVBFH-inclusive** available online at *provbfh.hepforge.org*