Fully differential VBF Higgs production at NNLO

Giulia Zanderighi (CERN, University of Oxford & ERC)

Based on 1506.02660, in collaboration with
Matteo Cacciari, Frédéric Dreyer, Alexander Karlberg, Gavin Salam

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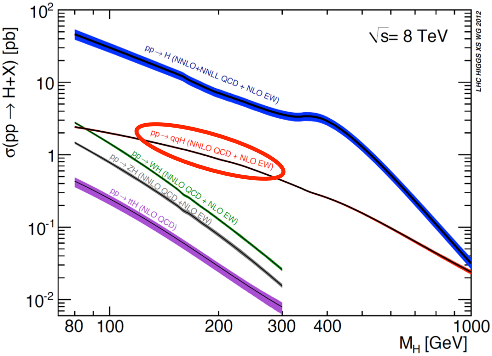
VBF Higgs production

Five good reasons to study VBF Higgs production:

1. VBF is the largest cross-section that involves tree-level production, and the second of all production processes (after gluon-gluon-fusion)



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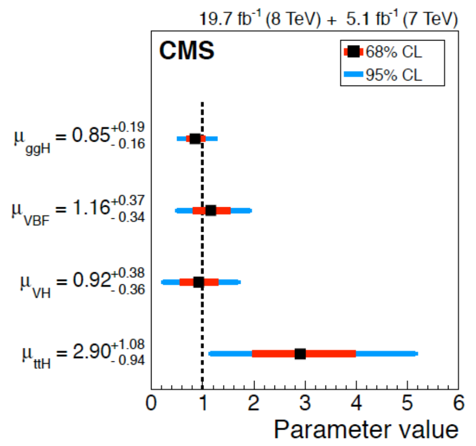
CMS 1412.8662



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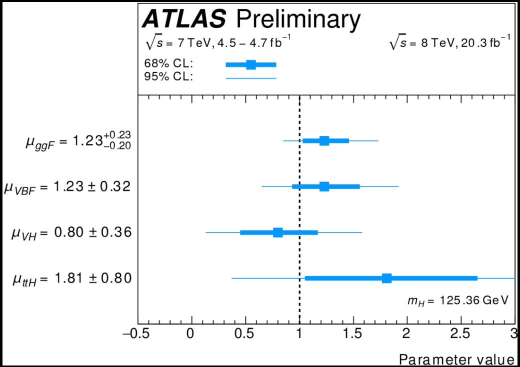
ATLAS-CONF-2015-007

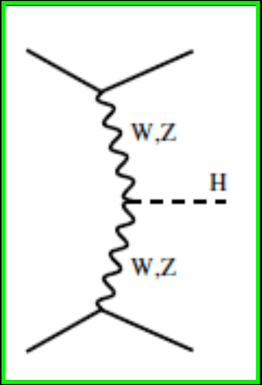


VBF Higgs production

Five good reasons to study VBF Higgs production:

2. It has a distinctive signature that involves two forward jets (tagging jets).

   Color singlet exchange between quark lines: little jet activity in the central region, with Higgs decay products typically between the jets

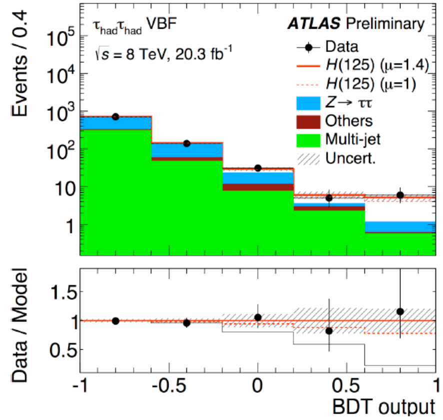


VBF Higgs production

Five good reasons to study VBF Higgs production:

3. Tagging jets allow one to better tag events and identify Higgs decays that have very large backgrounds (notably H → $\tau\tau$ and H → bb)

CMS JHEP05(2014)104



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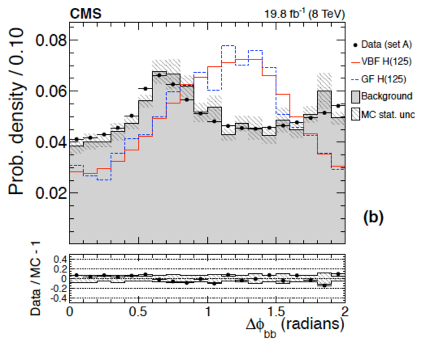
CMS 1506.01010



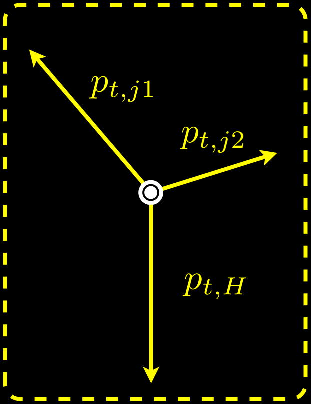
Signal strength for VBF H with H → bb

$$\mu = \frac{\sigma}{\sigma_{SM}} = 2.8^{+1.6}_{-1.4}$$

VBF Higgs production

Five good reasons to study VBF Higgs production:

4. Higgs transverse momentum is non-zero at LO. Facilitates searches of invisible decay modes



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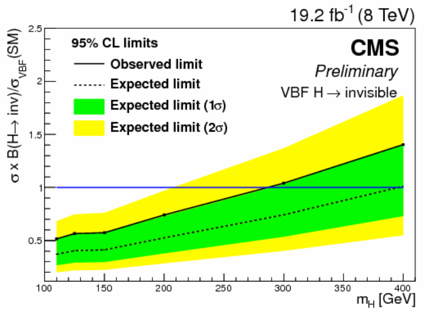
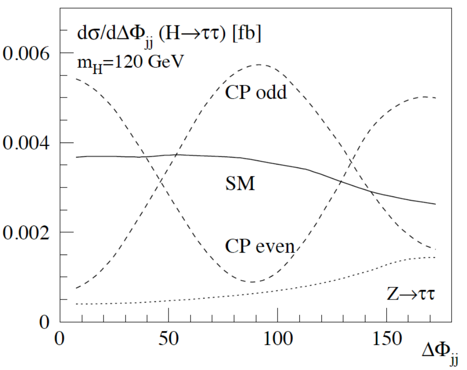


VBF Higgs production

Five good reasons to study VBF Higgs production:

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

Plehn et al ’01



Tensor structure of HVV coupling

$$V^{\mu\nu} = a_1 g^{\mu\nu} + a_2 \left(q_1 q_2 g^{\mu\nu} - q_1^\mu q_2^\nu \right) + a_3 \epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

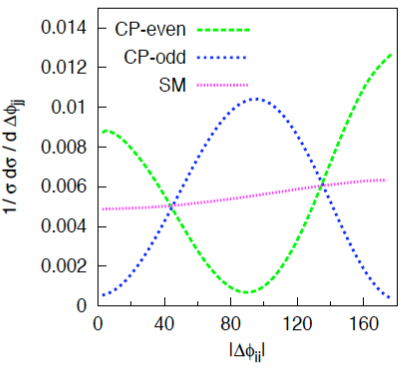
$\underline{a_1:}$ SM Higgs scenario

$\underline{a_2:}$ additional CP even component

$\underline{a_3:}$ additional CP odd component

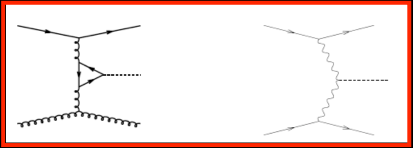
CP can be studied just from angle between the jets, no need to look at decay products (little dependence on actual size of form factor, QCD corrections, Higgs mass ...)

Figy et al ’06

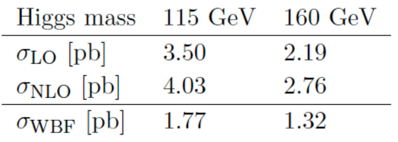


pp → H + dijets via gluon fusion

VBF production is contaminated by double-real radiation in gluon-fusion Higgs production



Inclusive, LHC 14 TeV



Higgs mass	115 GeV	160 GeV
σ_{LO} [pb]	3.50	2.19
σ_{NLO} [pb]	4.03	2.76
σ_{WBF} [pb]	1.77	1.32

Known at NLO but has sizable QCD corrections

Campbell et al ’06; Greiner et al. ’13

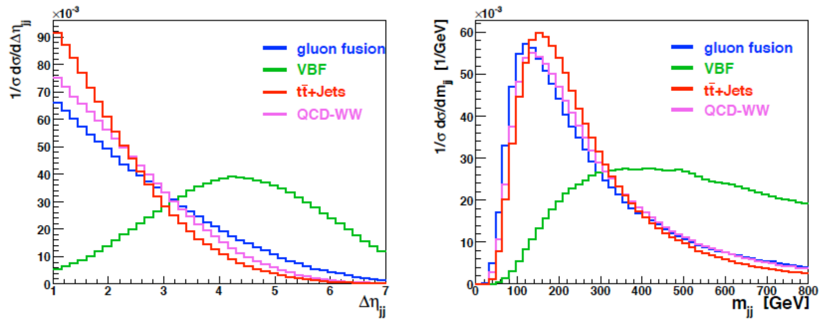
Need to understand the phenomenology of both to distinguish them

pp → H + dijets via gluon fusion

Apply cuts to separate gluon-fusion from VBF ⇒ VBF cuts

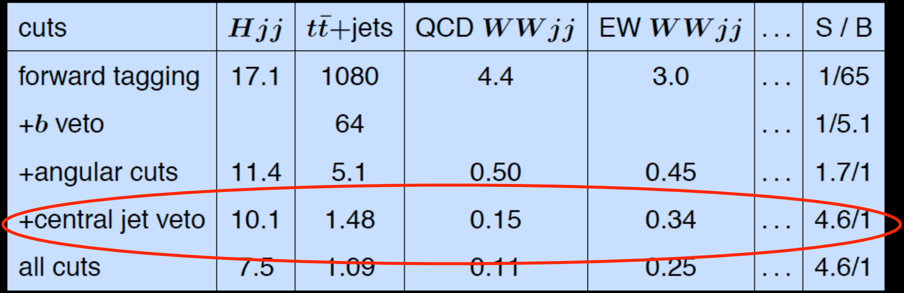
Crucial elements: 2 forward jets, large invariant mass of dijet system, large rapidity separation, little activity in the central region (central jet veto)

Klaemke, Zeppenfeld '07



Other important backgrounds

Signal and background production rates at the LHC for M_H=160 GeV, in the decay channel H → $e^+ \mu^-$+MET



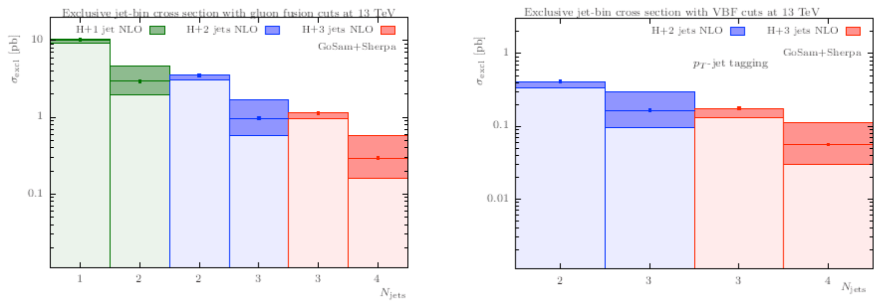
cuts	Hjj	$t\bar{t}$+jets	QCD $WWjj$	EW $WWjj$	. . .	S / B
forward tagging	17.1	1080	4.4	3.0	. . .	1/65
+b veto		64			. . .	1/5.1
+angular cuts	11.4	5.1	0.50	0.45	. . .	1.7/1
+central jet veto	10.1	1.48	0.15	0.34	. . .	4.6/1
all cuts	7.5	1.09	0.11	0.25	. . .	4.6/1

Central Jet Veto (CJV): remove events with extra jets with $p_{t,j}$ > 20 GeV in the central rapidity region (e.g. between the tagging jets)

pp → H + 3jets at NLO

Pheno study of gluon-fusion H+jets in inclusive and VBF setup, now possible at NLO with up to 3 jets (important for central jet veto)

Greiner et al. ’15



Constant improvements in the description of the background

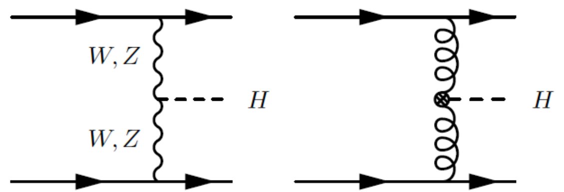
pp → H + dijets via VBF × GF

Can interference pollute the clean signal (compromise extraction of Higgs properties)?

Interference between VBF and GF very suppressed at leading order

- vanishes without crossings because of color
- needs t ↔ u crossing, hence identical quarks and kinematical suppression

Andersen and Smillie ’06

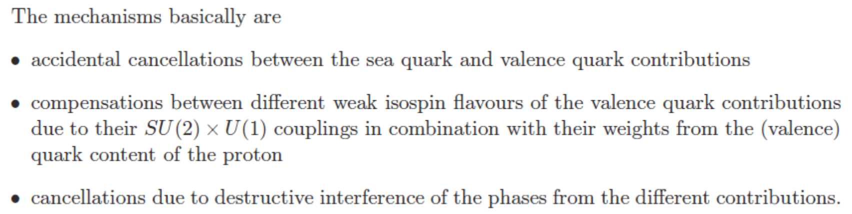


Found to be negligible (however NLO effects suggested to be larger)

pp → H + dijets via VBF × GF

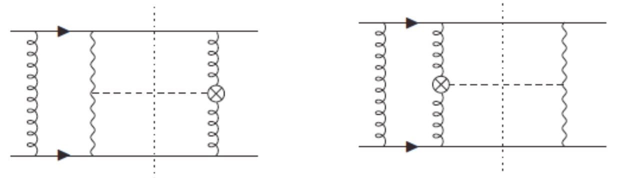
Interference calculated also at NLO and found to be completely negligible as expected (at the ato-barn level)

Andersen, Binoth, Heinrich, Smillie ’07
Bredenstein, Hagiwara, Jaeger ’08



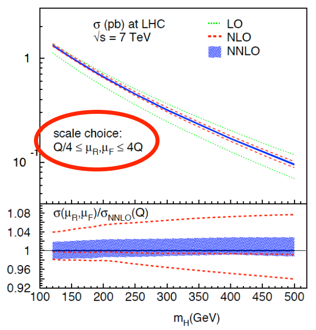
The mechanisms basically are

- accidental cancellations between the sea quark and valence quark contributions
- compensations between different weak isospin flavours of the valence quark contributions due to their $SU(2) \times U(1)$ couplings in combination with their weights from the (valence) quark content of the proton
- cancellations due to destructive interference of the phases from the different contributions.

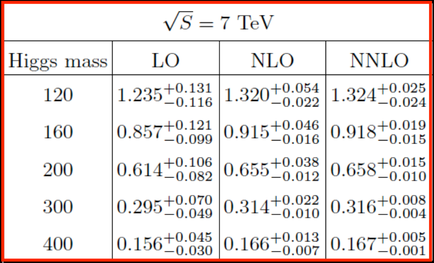


VBF Higgs production

Fully inclusive VBF Higgs production was known at NNLO in the structure function approach



Bolzoni et al ’10 - ’11



$\sqrt{S} = 7$ TeV			
Higgs mass	LO	NLO	NNLO
120	$1.235^{+0.131}_{-0.116}$	$1.320^{+0.054}_{-0.022}$	$1.324^{+0.025}_{-0.024}$
160	$0.857^{+0.121}_{-0.099}$	$0.915^{+0.046}_{-0.016}$	$0.918^{+0.019}_{-0.015}$
200	$0.614^{+0.106}_{-0.082}$	$0.655^{+0.038}_{-0.012}$	$0.658^{+0.015}_{-0.010}$
300	$0.295^{+0.070}_{-0.049}$	$0.314^{+0.022}_{-0.010}$	$0.316^{+0.008}_{-0.004}$
400	$0.156^{+0.045}_{-0.030}$	$0.166^{+0.013}_{-0.007}$	$0.167^{+0.005}_{-0.001}$

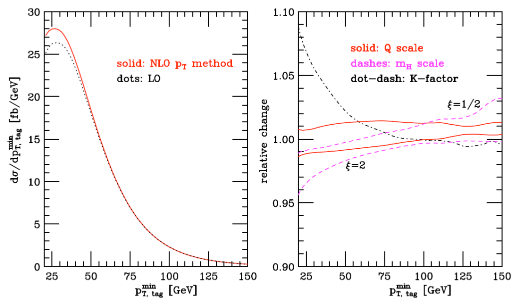
The calculation suggests tiny renormalization/factorization scale uncertainties (~ 1-2%). NNLO well within the NLO band

VBF Higgs production

However, no realistic VBF cuts can be applied to it, as the calculation is totally inclusive over hadronic final states that give the same vector-boson momenta

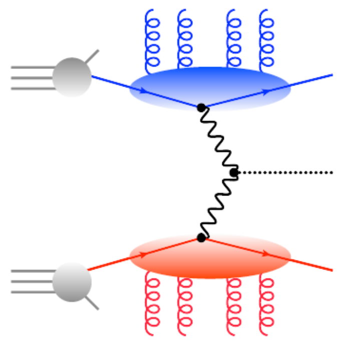
Differential VBF Higgs production known up to now only to NLO (+PS) and also suggests small uncertainties

Figy, Oleari, Zeppenfeld '03



The structure function approach

Schematically, think of VBF as DIS × DIS with no cross-talk between radiation from the upper and lower sector (factorized approximation). Since the DIS coefficients used are inclusive over the hadronic final state, the calculation cannot provide differential results

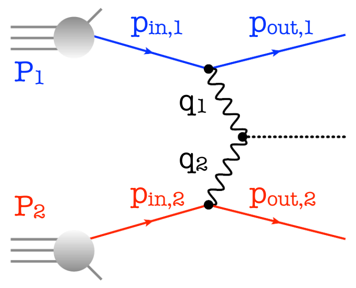


Simple kinematics

Key observation:

If the scattering is Born like, then the vector boson-momenta q_i, and on-shell conditions, fix the incoming and outgoing parton momenta:

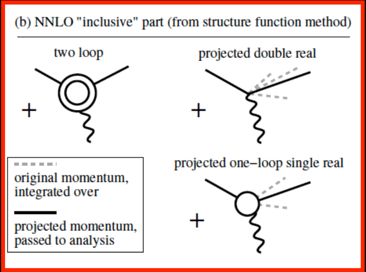
$$p_{\text{in,i}} = x_i P_i \qquad p_{\text{out,i}} = x_i P_i - q_i \qquad x_i = \frac{q_i^2}{2q_i P_i}$$



Going fully differential

This work: going beyond structure function approach.
Based on two ingredients

1. the inclusive contribution
   - use the SF approach and use four-vectors q_1,q_2 to assign Born-like (i.e. 2 → H + 2) kinematics using the previous eqs.
   - use the projected Born-like momenta to compute differential distributions



Going fully differential

This work: going beyond structure function approach.

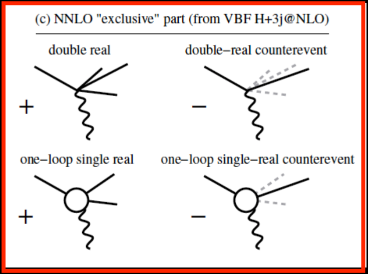
Based on two ingredients

2. the exclusive contribution

- use the VBF H + 3 jet NLO calculation in the factorized approximation

Figy et al ’07 [NLO]; Jaeger et al ’14 [NLO+PS]

- keep track, for each parton, whether it belongs to upper/lower sector; this makes it possible to deduce vector-boson momenta, q_1,q_2
- for each event (weight w), add a counter-event with projected Born kinematics (weight -w) deduced from q_1, q_2



(c) NNLO "exclusive" part (from VBF H+3j@NLO)

Going fully differential

Schematically:

P2B = Projection to Born

$$\sigma = \int d\Phi_B(B+V) + \int d\Phi_R R$$

$$= \underbrace{\int d\Phi_B(B+V) + \int d\Phi_R R_{P2B}}_{\text{From inclusive contribution}} + \underbrace{\int d\Phi_R R - \int d\Phi_R R_{P2B}}_{\text{Finite, from exclusive contribution}}$$

Combining the two pieces:

- from the exclusive contributions we get the full contributions from double-real and one-loop single-real
- after integration over phase-space, counter-events cancel projected tree-level double real and one-loop single real contributions from the inclusive

The sum gives thus the complete, fully differential NNLO result

Going fully differential

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$$\sigma = \int d\Phi_B (B+V) + \int d\Phi_R R$$

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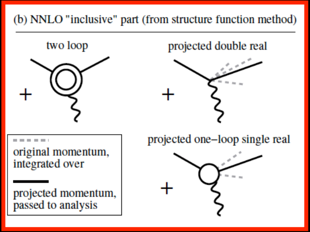
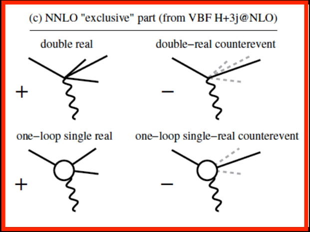




The sum gives thus the complete, fully differential NNLO result

Practicalities

For the inclusive part we have

- taken the phase-space from `POWHEG`'s `VBF_H`
- matrix elements coded with structure functions evaluated using parametrized versions of the DIS coefficient functions
- the structure functions evaluated with the package `HOPPET`

https://hoppet.hepforge.org

Checks

- against private version of structure-function calculation (thanks to Marco Zaro)
- of structure functions with `APFEL 2.4.1`
- approx vs exact coefficient functions (negligible difference)

Practicalities

For the exclusive part we have

- taken the `VBF_HJJJ` calculation in `POWHEG`
- extended `POWHEG`'s tags to uniquely associate radiation with each sector
- for each event, uniquely determine the vector-boson momenta q_1, q_2 and hence the counter-event (with weight -w)

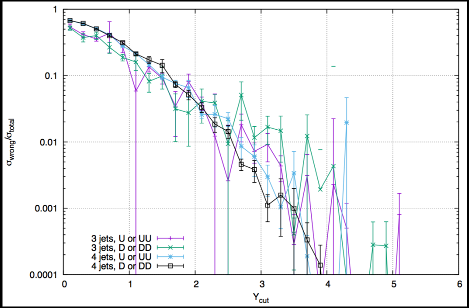
Checks

- results for `VBF_HJJJ` unchanged
- sum of inclusive + exclusive at NLO, agrees with `VBF_H` (NLO)
- once the rapidity between the two jets increases, there is a decreasing rate of partons assigned to the “wrong” sector

Check of tagging

- partons are tagged as up or down (U/D)
- classify events into 3- or 4- jet events
- check if the U/D assignment of the partons in a given jet corresponds to the jet rapidity (positive or negative)
- the rate for “non-correspondence” must decrease when the rapidity separation between the leading jets increases

similar plots available for gluons in opposite side (UD,DU)



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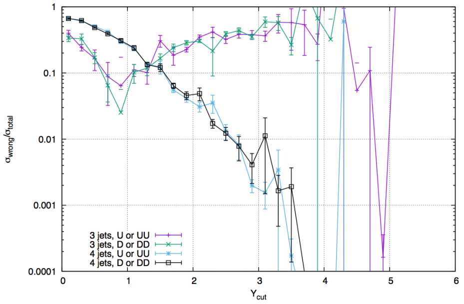


same plot with O(1) bug in the virtual contribution

Phenomenology

Take 13 TeV LHC collisions. Jets: anti-k$_t$ with R=0.4. M$_H$ = 125 GeV, NNPDF3.0_nnlo_as0118 (*also at LO, NLO*), standard EW parameters.

Choose as central scale (which approximates well $\sqrt{Q_1 Q_2}$)

$$\boxed{\mu_0^2(p_{t,H}) = \frac{M_H}{2}\sqrt{\left(\frac{M_H}{2}\right)^2 + p_{t,H}^2}}$$

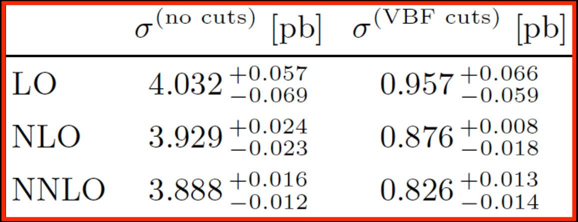
Take VBF cuts

- at least two jets with $p_{t,j} > 25 GeV$
- the two hardest (tagging jets) should have

$$\Delta y_{j1j2} > 4.5 \qquad m_{j1j2} > 600\, GeV \qquad |y_j| < 4.5 \qquad y_{j1} y_{j2} < 0$$

Phenomenology

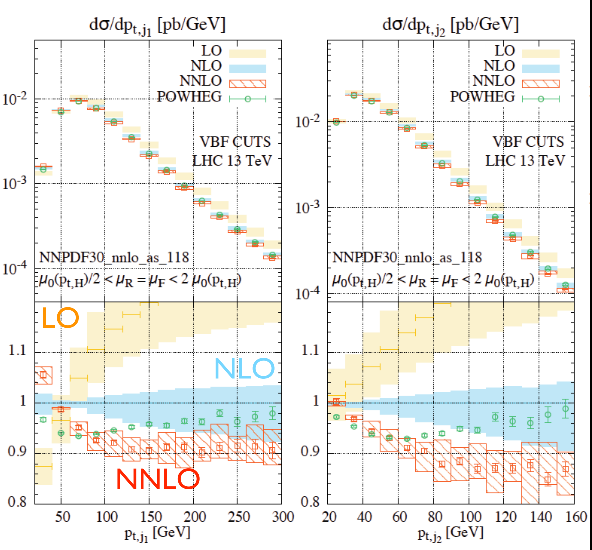
Cross-sections: inclusive and with VBF cuts



	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

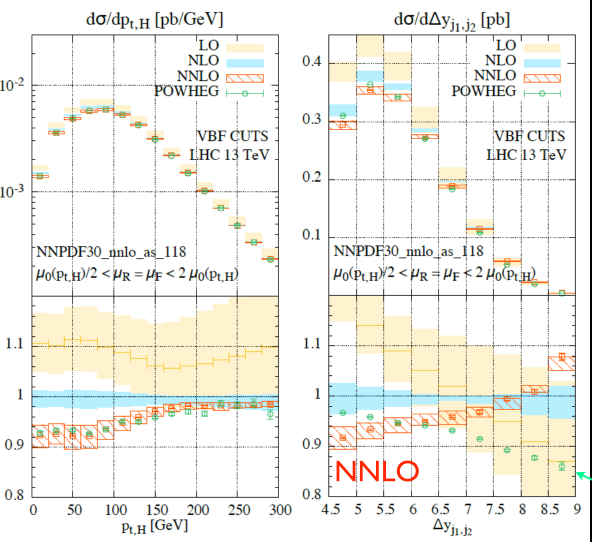
- NNLO outside the NLO band
- NNLO about **5%** (1%) with (without) VBF cuts
- NNLO corrections appear to make jets softer, hence fewer events pass the VBF cuts (see next plots)

Distributions: $p_{t,j1}$ and $p_{t,j2}$



- NNLO corrections appear to make jets softer
- NNLO corrections up to ~**10-12%**, typically outside the NLO band

Distributions: $p_{t,H}$ and $\Delta y_{j1,j2}$

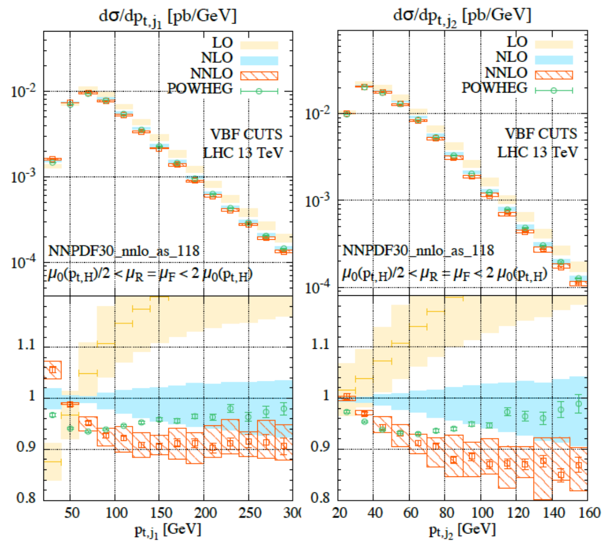


NNLO

NLOPS

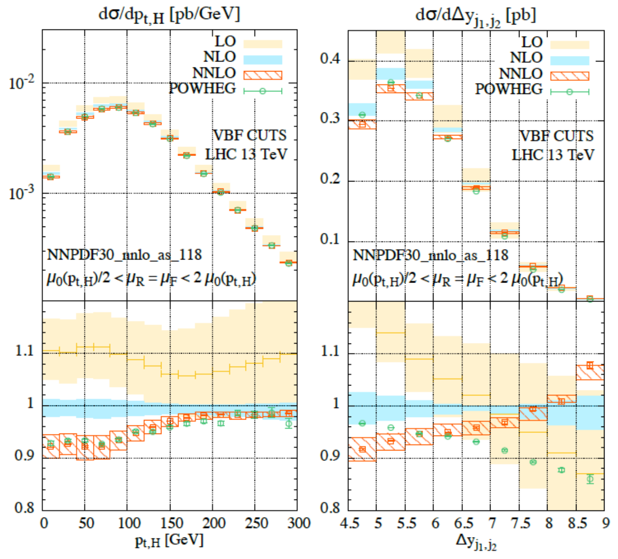
- sometimes parton-shower (NLOPS) agrees well with NNLO ($p_{t,H}$) sometimes it does not ($\Delta y_{j1,j2}$)
- non-trivial kinematic dependence of K-factors (NLO/LO and NNLO/NLO)

Different PDFs at various orders



- LO with LO PDFs
- NLO with NLO PDFs
- NNLO with NNLO PDFs

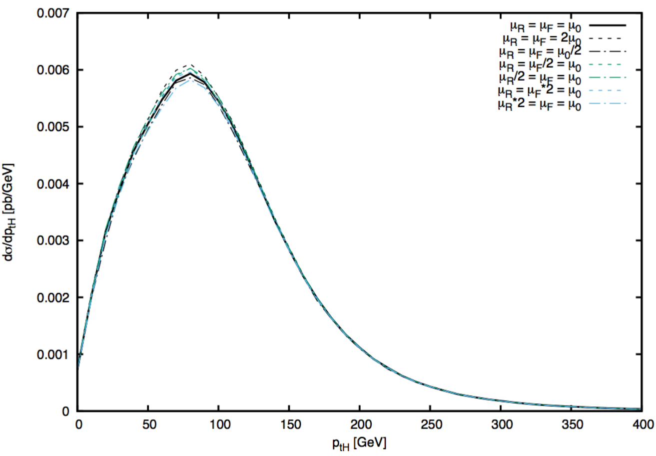
Different PDFs at various orders



- LO with LO PDFs
- NLO with NLO PDFs
- NNLO with NNLO PDFs

3 versus 7 scale bands for $p_{t,H}$

3 scales: black lines; 7 scales: all lines

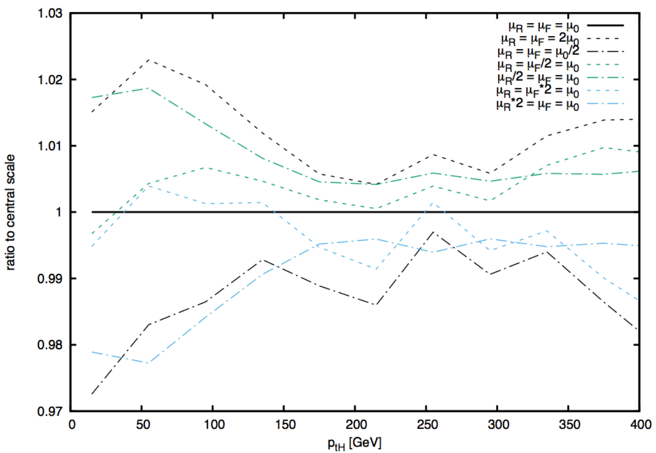


3 scales: $\mu_R = \mu_F = \mu_0\{1/2, 1, 2\}$

7 scales: $(\mu_R, \mu_F) = \mu_0\{(1/2, 1/2), (1/2, 1), (1, 1/2), (1, 1), (1, 2), (2, 1), (2, 2)\}$

3 versus 7 scale bands for $p_{t,H}$

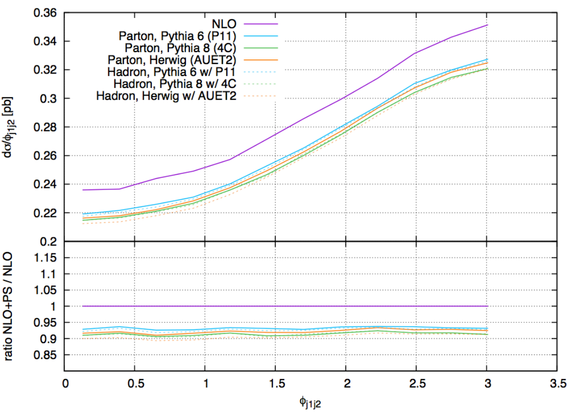
3 scales: black lines; 7 scales: all lines



<u>Conclusion</u>: 3 and 7 scale bands very similar

Different NLOPS with POWHEG

Different showers with and without hadronization within NLOPS-POWHEG. Similar effects for other observables.



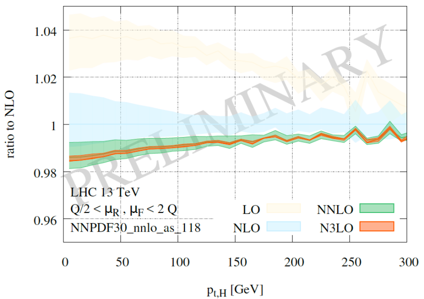
hadronization has small effect and small uncertainty (but not U.E)

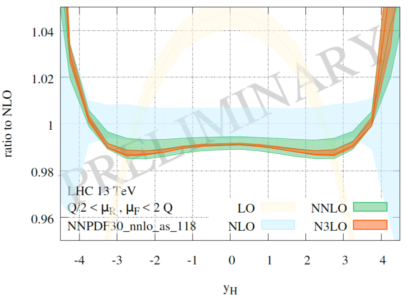
G. Zanderighi

One order higher ...?

Extension to N^{3}LO possible within this approach. Ongoin work on extension of inclusive part to one order higher. Very preliminary results available

Dreyer & Karlberg



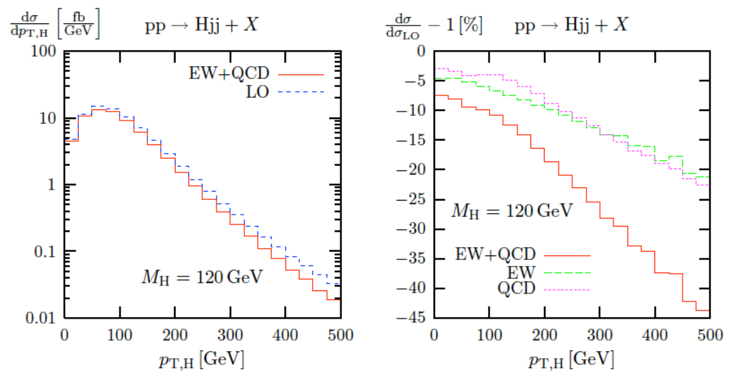


currently without 3rd order correction to α_s running

Electroweak corrections

Electroweak corrections also known, are numerically important (distortion of distributions of about 15%), and should be combined with NNLO QCD corrections.

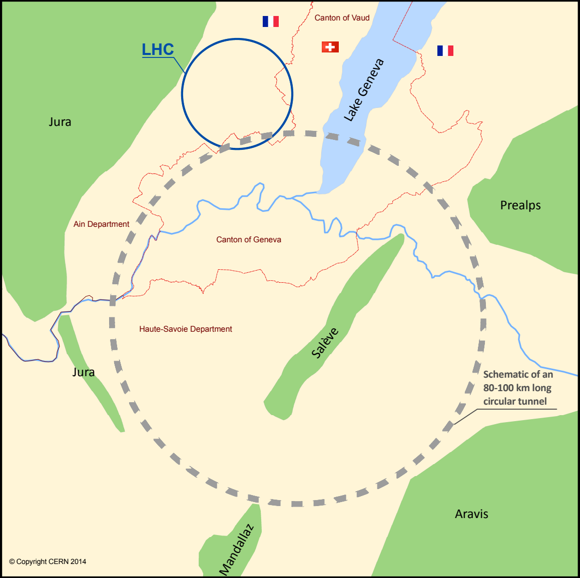
Ciccolini, Denner, Dittmaier '07
HAWK2.0: Denner, Dittmaier, Kallwait, Muck '14



After the LHC

- LHC Run II is ongoing. Hopefully coming results will guide us in choice of the next colliders
- the time scale design and build a new collider is about 30 ys
- we have to starting thinking now about what should come after the LHC
- most likely possibilities include FCC-e^+e^- circular colliders (at energies up to ttbar threshold), electron-proton machine, or 100 TeV proton-proton collider (FCC-hh)
- machine type, site (CERN, China, ...?), etc. still all to be decided

100 TeV FCC at CERN



100 TeV FCC

It is now the time to think about

- what physics one can do at 100 TeV (that one can't at 14 TeV), both in terms of reach for New Physics, but also in terms of new limits for precision determinations of SM parameters, and in the measurements of rare processes etc.
- how does our physical intuition change when going to 100 TeV (e.g. what is the effect of the different parton luminosities? how many jets come with the emission of a soft W/Z boson? ...)
- once interesting questions are formulated, one can set requirements on the detectors of the 100 TeV machine that are necessary to address these questions (e.g. rapidity coverage, size of detectors needed to contain events, resolutions, etc.)
- new ideas on how to best exploit the immense potential of the machine

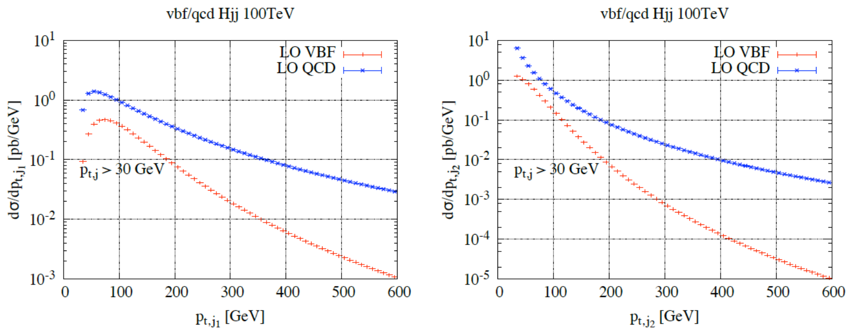
VBF Higgs at a 100 TeV FCC

Example: let's consider the process discussed here VBF Higgs production.

What changes at 100 TeV?

[Study performed by Alexander Karlberg for the "QCD, EW and tools at 100 TeV" workshop. Here I will just summarize some of his main findings]

VBH at a 100 TeV FCC



- hardness of the VBF jets set but the EW boson exchanged (jet remain soft)
- as a consequence, QCD background greatly increased (S/B=1:4, compared to 2:3 at 13 TeV)
- VBF cuts will be less efficient at 100 TeV compared to 13 TeV

VBH at a 100 TeV FCC

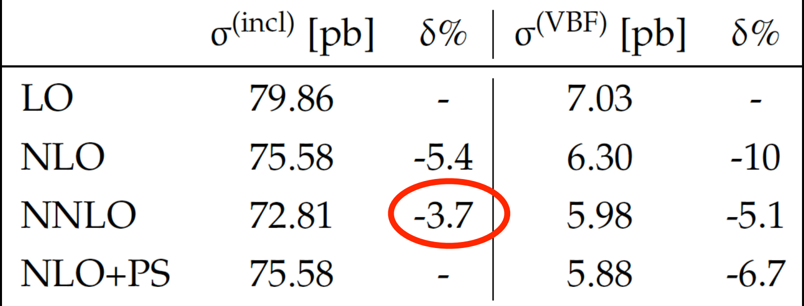
By studying different kinematical distributions for QCD and VBF Higgs production, one finds that good VBF cuts at 100 TeV are

$$p_{t,j} > 30GeV \qquad y_{j1,j2} < 0 \qquad |\Delta y_{jj}| > 6.5$$

$$|M_{jj}| > 1600\mathrm{GeV} \qquad \frac{\pi}{4} < \phi_{jj} < \frac{3\pi}{4}$$

VBH at a 100 TeV FCC

With this cuts one obtains the following cross-sections:

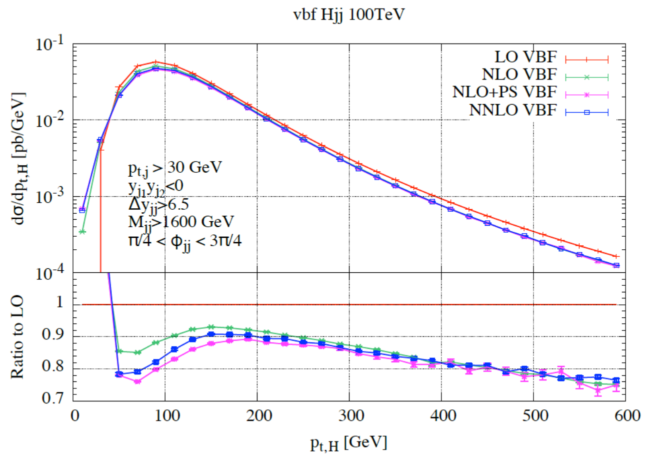


	$\sigma^{(\text{incl})}$ [pb]	$\delta\%$	$\sigma^{(\text{VBF})}$ [pb]	$\delta\%$
LO	79.86	-	7.03	-
NLO	75.58	-5.4	6.30	-10
NNLO	72.81	-3.7	5.98	-5.1
NLO+PS	75.58	-	5.88	-6.7

NB: was 1% at 13 TeV

$$\sigma^{(\text{incl})}_{100\text{TeV}}/\sigma^{(\text{incl})}_{13\text{TeV}} \sim 17 \qquad \sigma^{(\text{VBF})}_{100\text{TeV}}/\sigma^{(\text{VBF})}_{13\text{TeV}} \sim 7$$

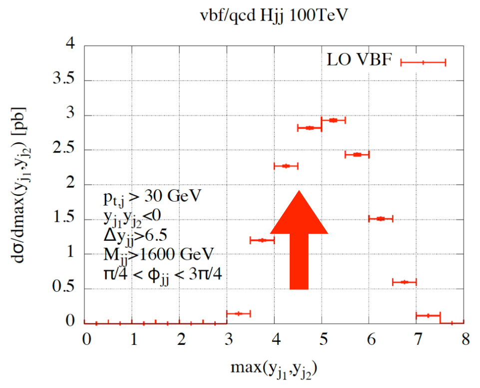
VBH at a 100 TeV FCC



- Higgs transverse momentum receives moderate corrections
- NLO+PS approximated NNLO well (but different for other observables)

VBH at a 100 TeV FCC

With the current rapidity reach for jets (4.5) one would loose most of the VBF signal



VBF physics (Higgs, boson, di-bosons, di-Higgs...) will be an important part of a 100 TeV physics program. This sets an important requirement on rapidity reach of detectors.

Conclusions

- shown first fully differential NNLO results for VBF Higgs production using a new “projection to Born” method
- NNLO reveals that practical VBF (i.e. with cuts) has non-trivial effects beyond NLO, hence differential NNLO is necessary for precision phenomenology (corrections up to 10-12% at 13 TeV)
- power of the method highlighted by the fact that NNLO has been achieved for the first time for a 2 → 3 LHC process (thanks also to the fact. approx)
- study of VBF Higgs at 100 TeV sets important requirement on rapidity reach of detectors
- this method opens up the prospect for the only N^3LO hadron-collider calculation in the foreseeable future beyond 2 → 1, for a process involving jets at lowest order