Karlsruher Institut für Technologie

Higgs Physics at the LHC

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Phenomenology 2017 Symposium, Pittsburgh

KIT Center Elementary Particle and Astroparticle Physics - KCETA

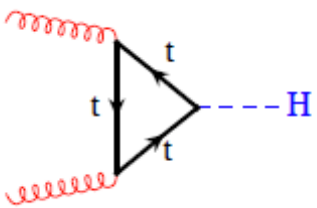
Outline

- Higgs production and decay
- SM vs recent measurements
- QCD corrections to VBF
- Effective Lagrangian description of general couplings
- Conclusions

Higgs production at the LHC in the SM

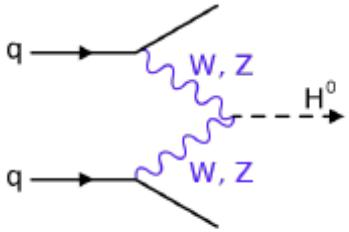
Four major production modes

Gluon Fusion gg→H

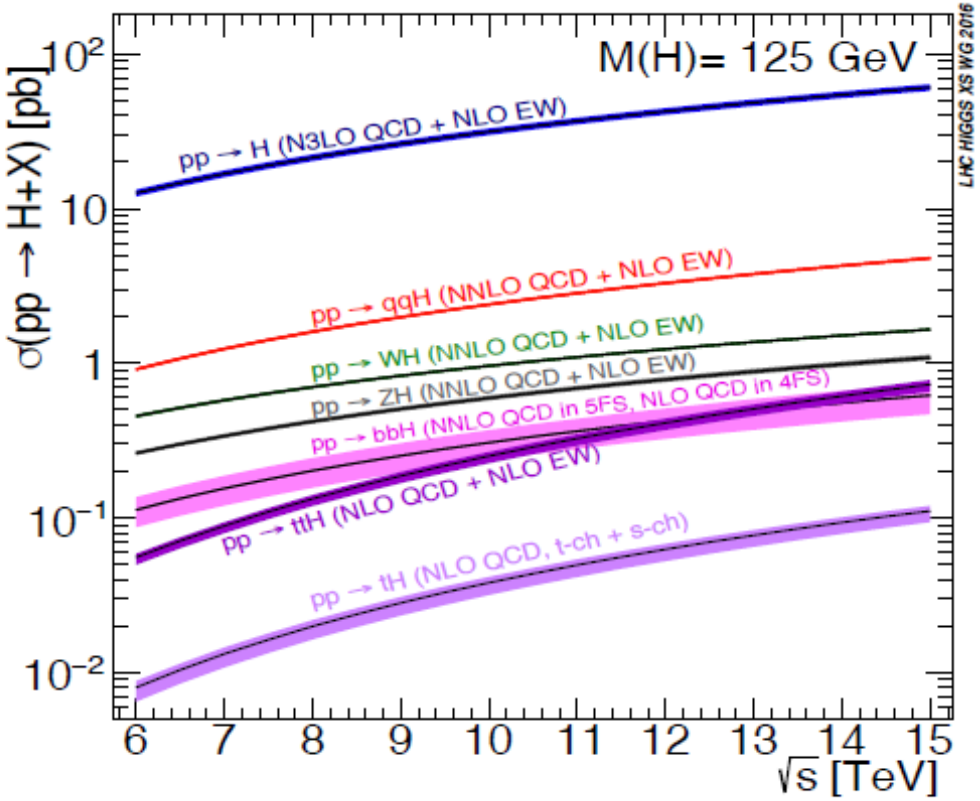


~ 88%

Vector Boson Fusion (VBF)



~ 7%



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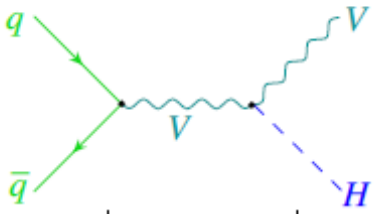
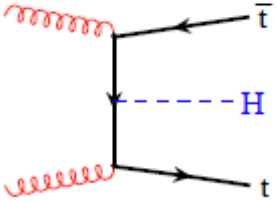
Higgs-Strahlung VH



~ 4%

ttH production



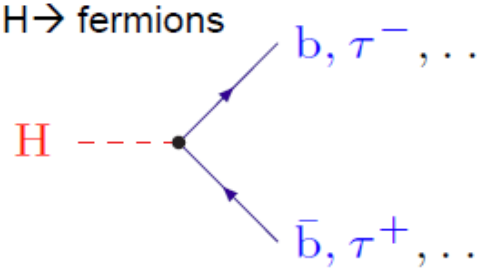
~ 1%

From $\sqrt{s}$=8 to 13 TeV:
increase of $\sigma_{H,tot}$ by factor 2.3

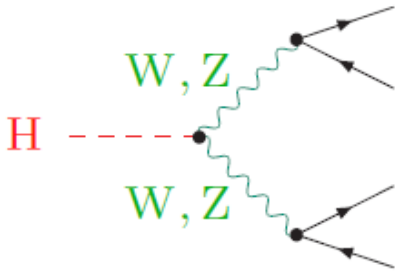
Major theoretical effort to reach this precision: LHCHXSWG

Major decay modes

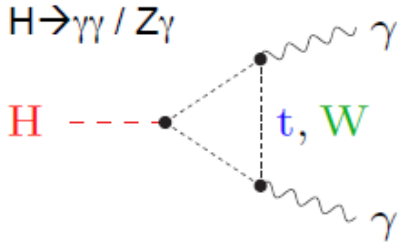
H→ fermions



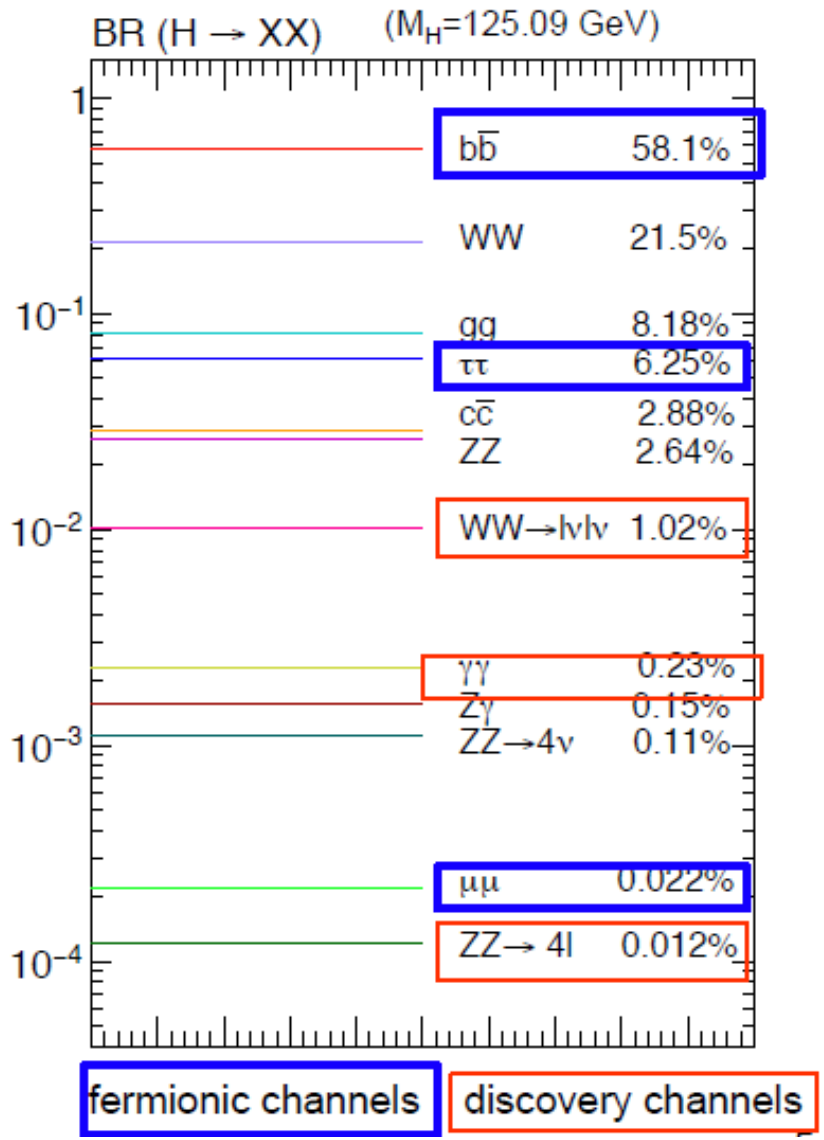
H→WW(ZZ)→4 fermions (l=e,μ)



H→γγ / Zγ



Higgs-Boson life time 1.6 x 10^{-22} s

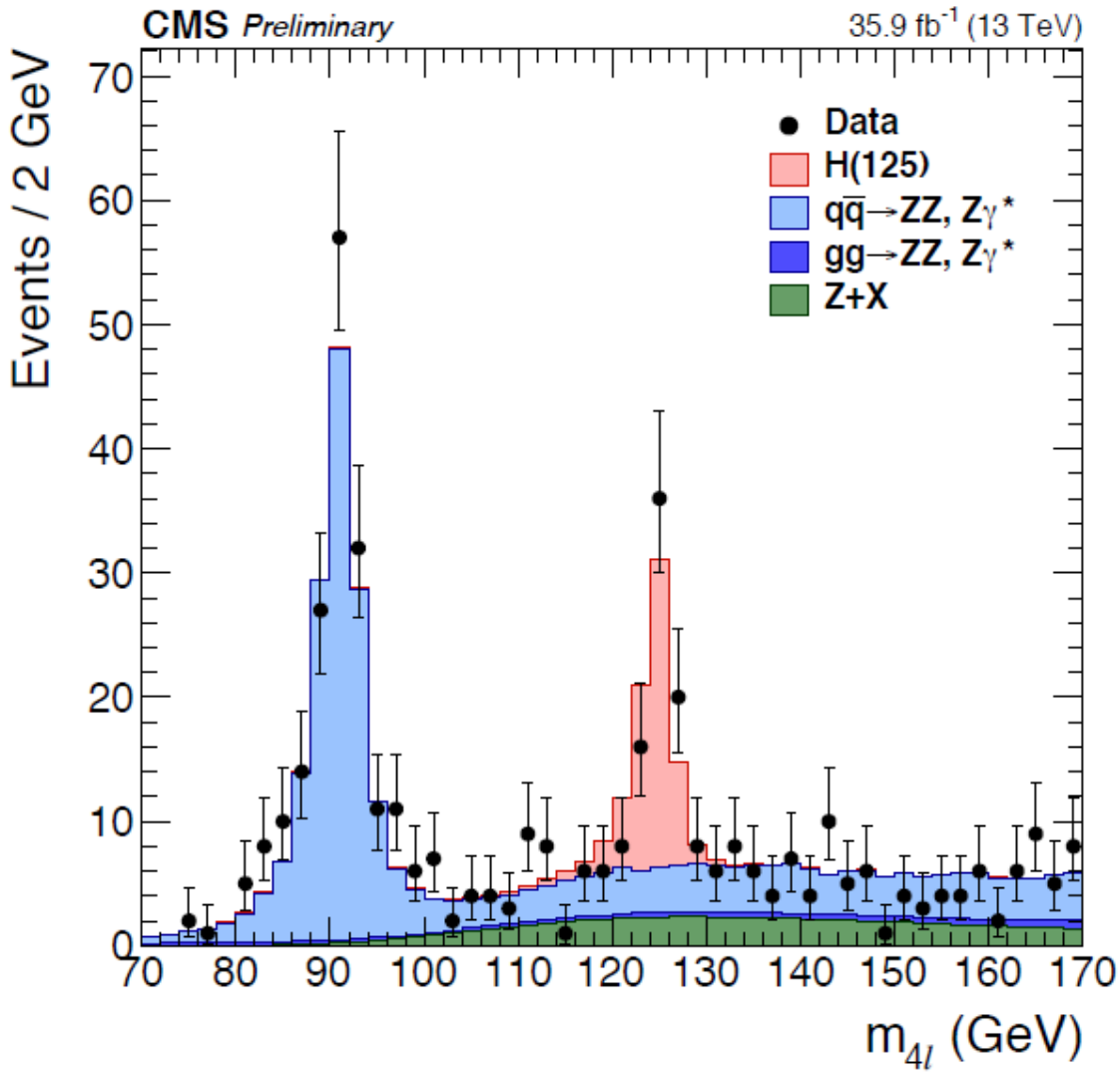


Cleanest Higgs observation: H→ZZ→4l

- Even cleaner Higgs peak in run 2 data of CMS and ATLAS

- Compare to SM by looking at signal strength

$$\mu = \frac{(\sigma \cdot B)_{observed}}{(\sigma \cdot B)_{SM}}$$



ATLAS+CMS combination available for run 1 of LHC

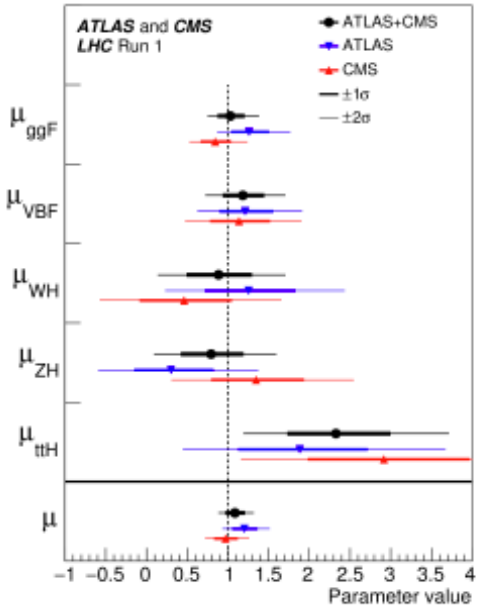
Global signal strength : all μ_i in production and μ^f in decay are the same

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig}).$$

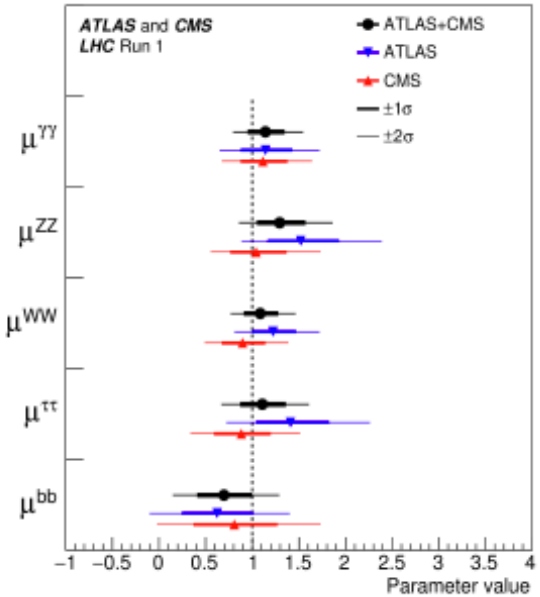
Statistical and signal theory uncertainty of same size

$N^2LO \rightarrow N^3LO$+new PDFs for gg→H: σ up by 10%, uncertainty reduced by 40%

μ in Production: assume $\mu^f = 1$



μ in Decay: assume $\mu_i = 1$



gg→H, H→γγ/WW/ZZ observed individually in ATLAS and CMS

Combination yields

Observation of VBF and H→ττ

Evidence for VH and ttH (Z=4.4, exp. =2.0)

Excess in ttH (2.3σ)

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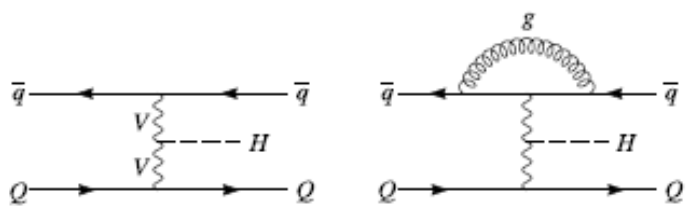
- In order to match (future) experimental accuracy, theoretical precision has to be improved to the percent level
- Beyond NLO QCD corrections to fiducial cross sections and distributions also NNLO QCD (and more) and NLO EWK corrections are desirable
- Heroic efforts have achieved N3LO accuracy for gluon fusion

  Anastasiou, Duhr, Dulat, Herzog, Mistlberger arXiv:1503.06056
- Here: QCD corrections to VBF production

Generic features of NLO QCD corrections to VBF and VBS

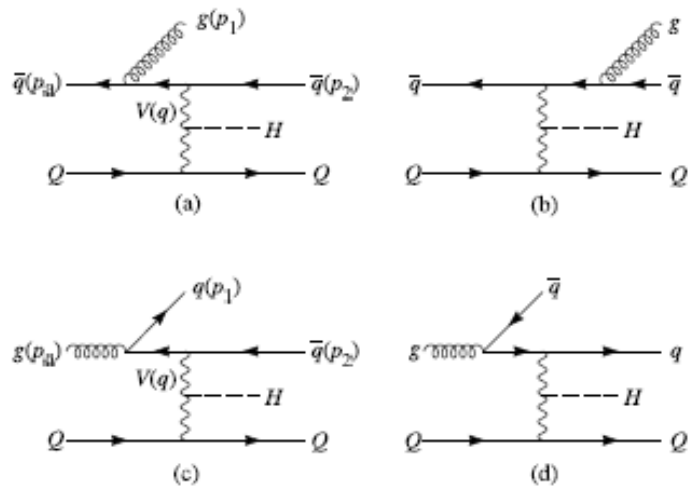
t-channel color singlet exchange $\Longrightarrow$ QCD corrections to different quark lines are independent

Born and vertex corrections to upper line



No t-channel gluon exchange at NLO

real emission contributions: upper line



Treat s-channel contributions (here VH production with $V \to jj$ decay)
and QCD processes (e.g. $VVjj$ production at order $\alpha_s^2\alpha^2$) as separate processes.
Neglect interference for identical fermions: small effects in phase space where VBF/VBS is visible
Features are generic for all VBF/VBS processes

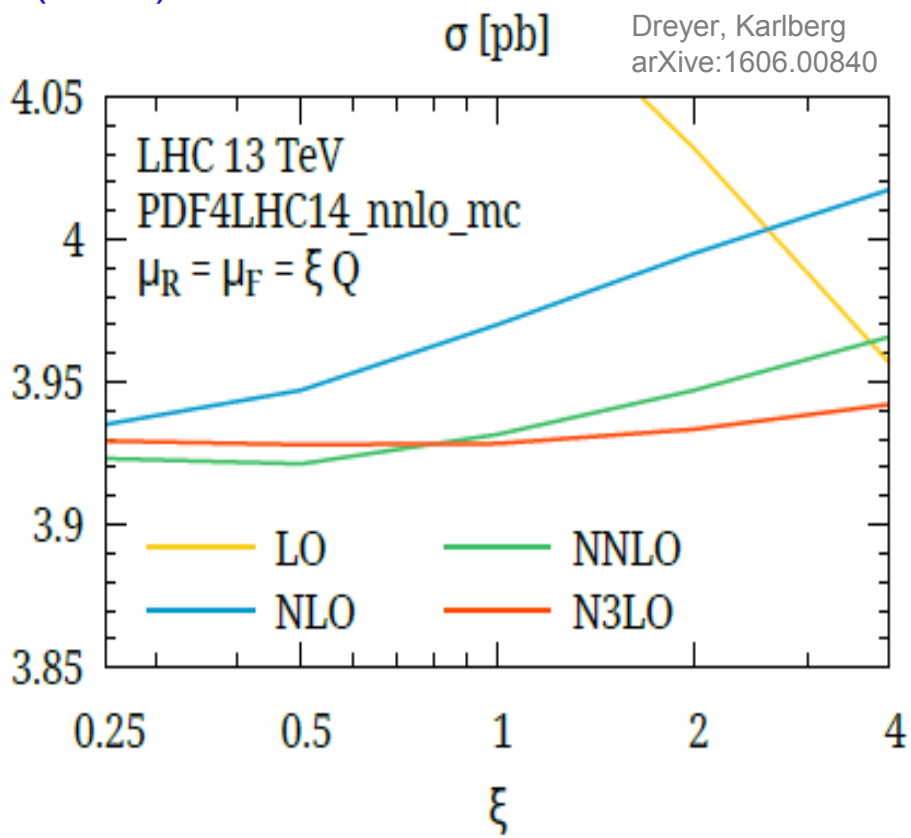
VBF Higgs in Structure Function Approach

QCD corrections on 2 quark lines independent, inclusive over „DIS jet hadronization“

- NLO: Han, Valencia, Willenbrock (1992)
- NNLO: Bolzoni, Maltoni, Moch, Zaro (2010)
- N3LO: Dreyer, Karlberg (2016)

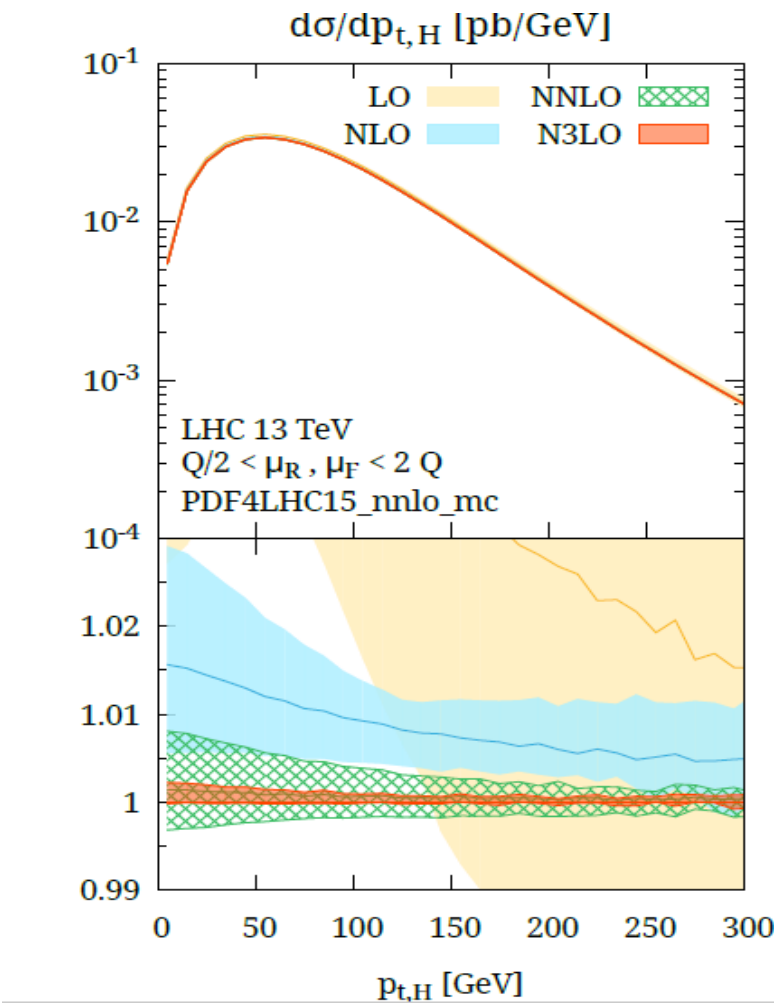
- Inclusive cross section
  has 1-2 permille scale uncertainty
  pdf errors, alphas uncertainty,
  EW corrections dominate and are
  substantially larger, in percent
  range

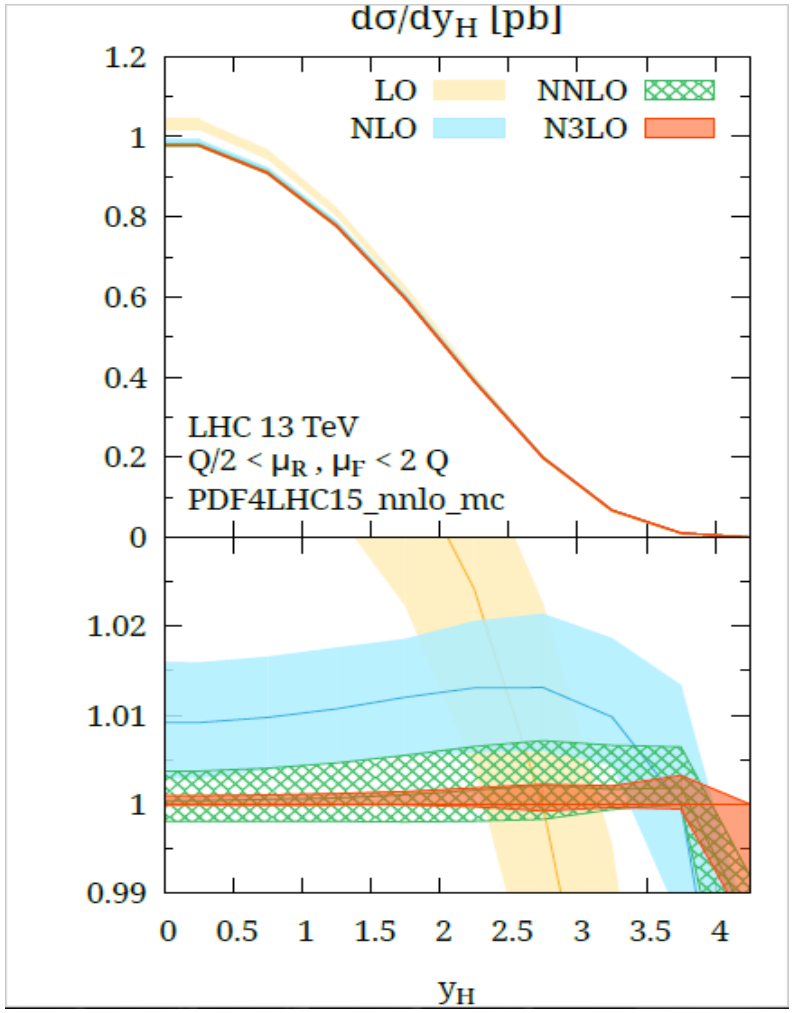
- Some distributions for
  inclusive production



Distributions for inclusive production up to N3LO

Extreme stability of predictions at the 2 percent (NLO) to 1 permille level (N3LO)





Dreyer, Karlberg arXive:1606.00840

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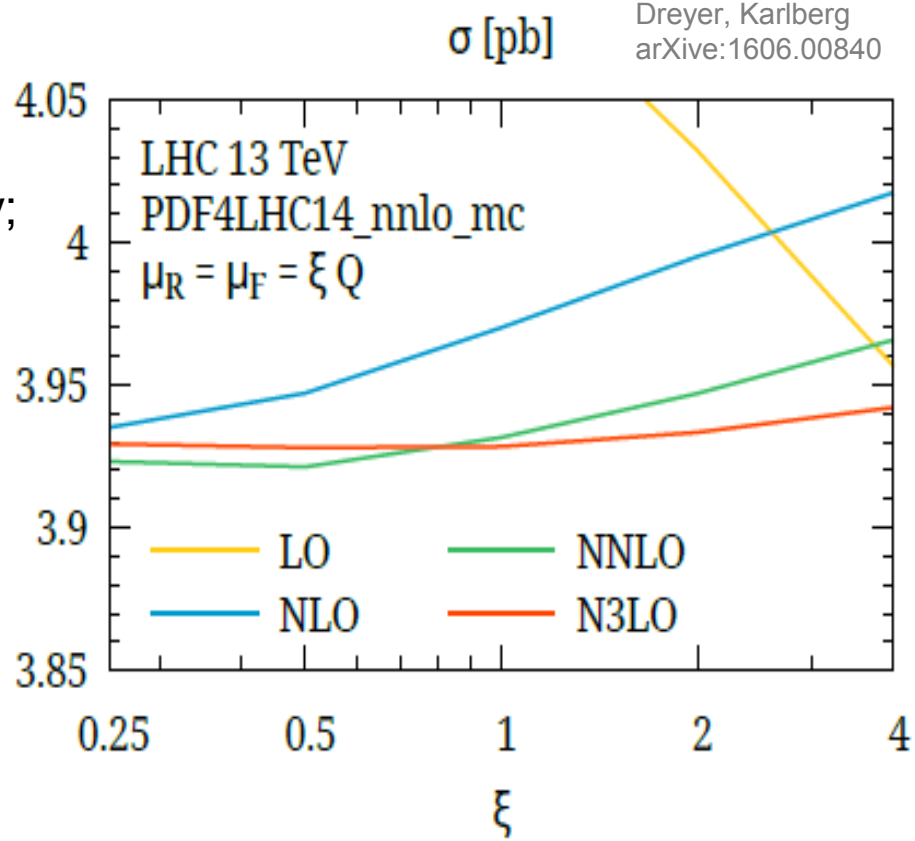


- Inclusive cross section
  has 1-2 permille scale uncertainty;
  pdf errors, alphas uncertainty,
  EW corrections dominate

- Some distributions for
  inclusive production

- No VBF cuts to distinguish VBF
  from gluon fusion Higgs signal
  or from backgrounds

- Need tagging jets and their
  distributions

Fully differential VBF Higgs cross section and fiducial cross section at NNLO

Cacciari, Dreyer, Karlberg, Salam, Zanderighi, arXiv:1506.02660
DIS approximation: treat QCD corrections to 2 quark lines as independent
no t-channel gluon ladders

	$\sigma^{(\text{no cuts})}$ [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	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

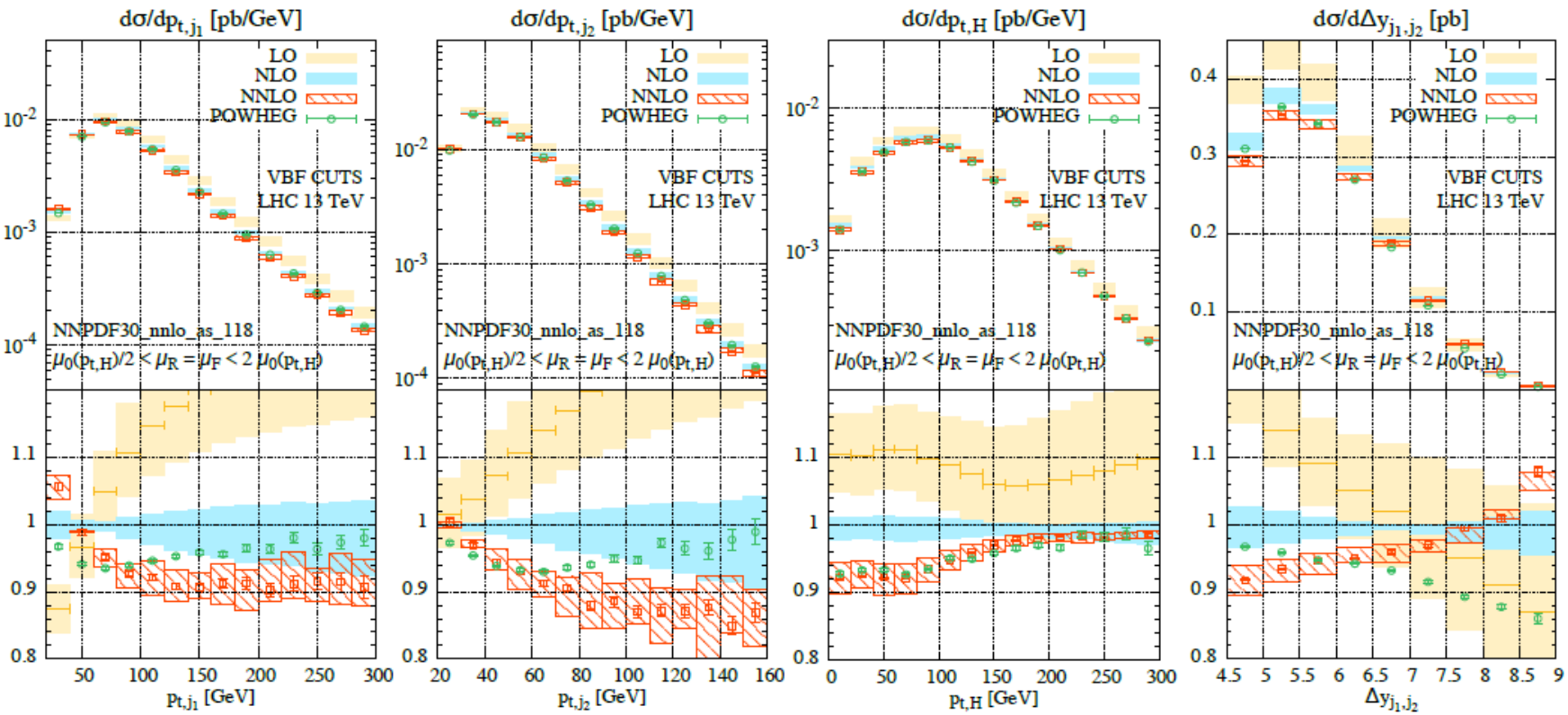
VBF cuts:
m(jj) > 600 GeV,
Δy(jj)> 4.5,
pT(j) > 25 GeV,
Opposite hemispheres for tagging jets

NNLO correction to inclusive cross section: 1%
with VBF cuts: 6%

NNLO distributions with VBF cuts

Anti-kT jets with R=0.4: m(jj) > 600 GeV Δy(jj)> 4.5

Corrections at NNLO (as compared to NLO): up to 10%



Cacciari, Dreyer, Karlberg, Salam, Zanderighi, arXiv:1506.02660

Energy flow in DIS jets: NLO correction to Jet shape

Kauer, Reina, Repond, DZ,hep-ph/9904500

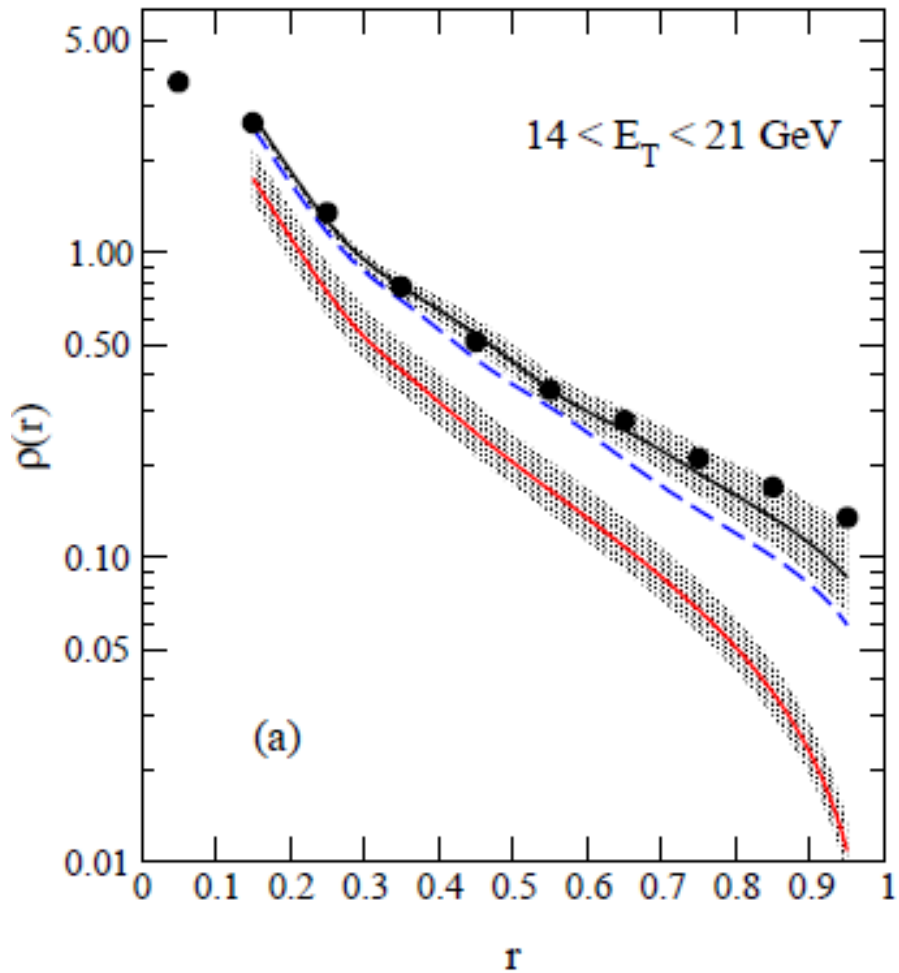
Definition: Jet shape =
ψ(r) = fraction of jet ET in cone of radius r

Differential jet shape: ρ(r) = dψ/dr

Observation for DIS at HERA (1999)

Energy flow is considerably narrower in NLO quarks jets (=LO jet shape) than in NNLO jets (with up to 3 partons)

Small cone (R=0.4) misses some fraction of jet energy →reduced m(jj) → fewer events survive m(jj)> 600 GeV cut



VBFNLO study using NLO hjjj code (with Michael Rauch)

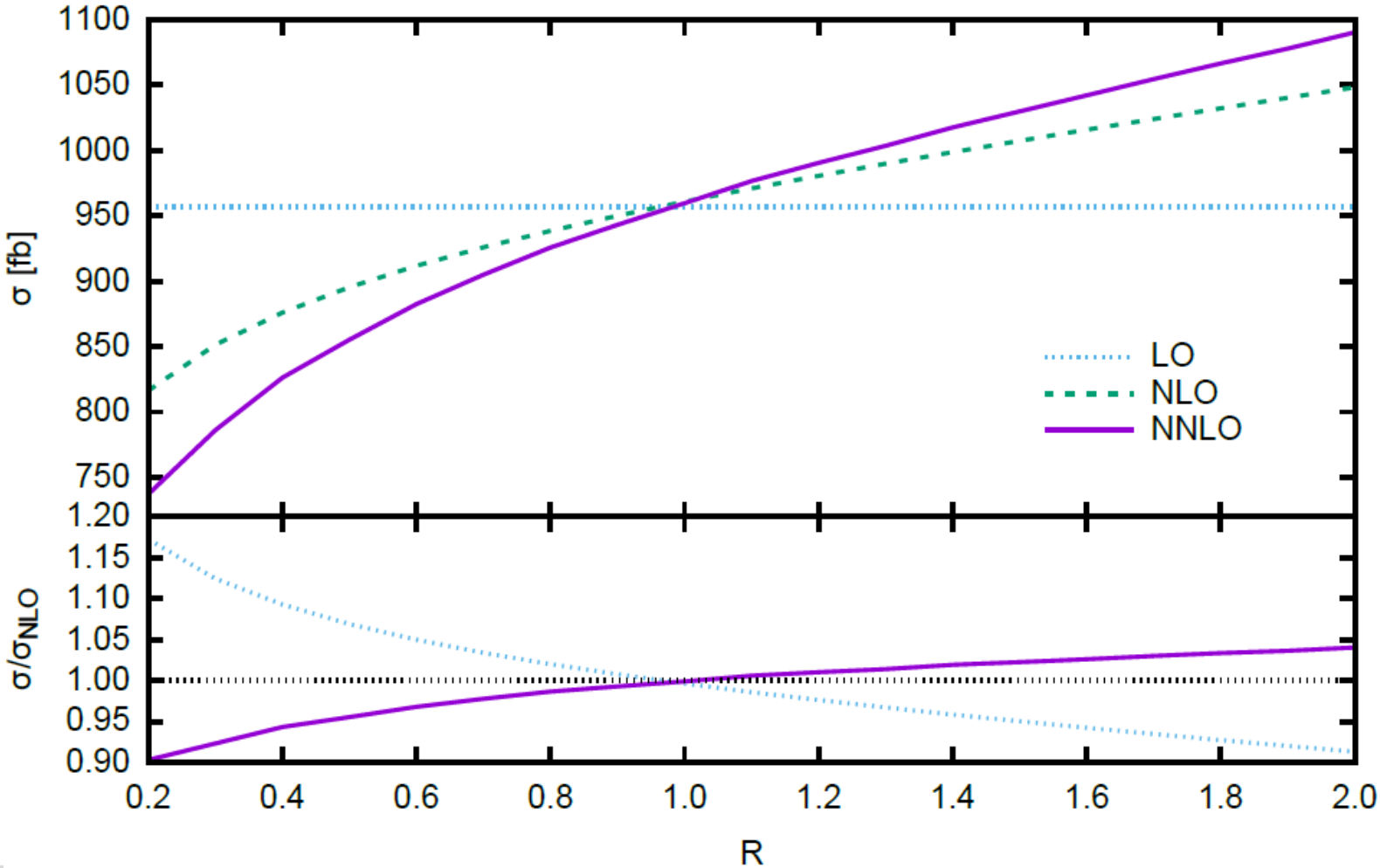
- hjjj (NLO) code has virtual corrections to h+3partons and real emission of 4 partons.
- h+2parton 2-loop corrections are missing. They only contribute to jet shape at r=0
- Change (in cross sections or distributions) between R=0.4 and other values does not require 2-loop contributions
- Start from Cacciari et al. results and study dependence on jet radius R in anti-kT algorithm at full NNLO
  - Cuts and parameters identical to arXiv:1506.02660

- We find dependence on jet algorithm (kT vs anti-kT vs Durham/Aachen) to be small at NNLO

R-dependence of hjj cross section with VBF cuts

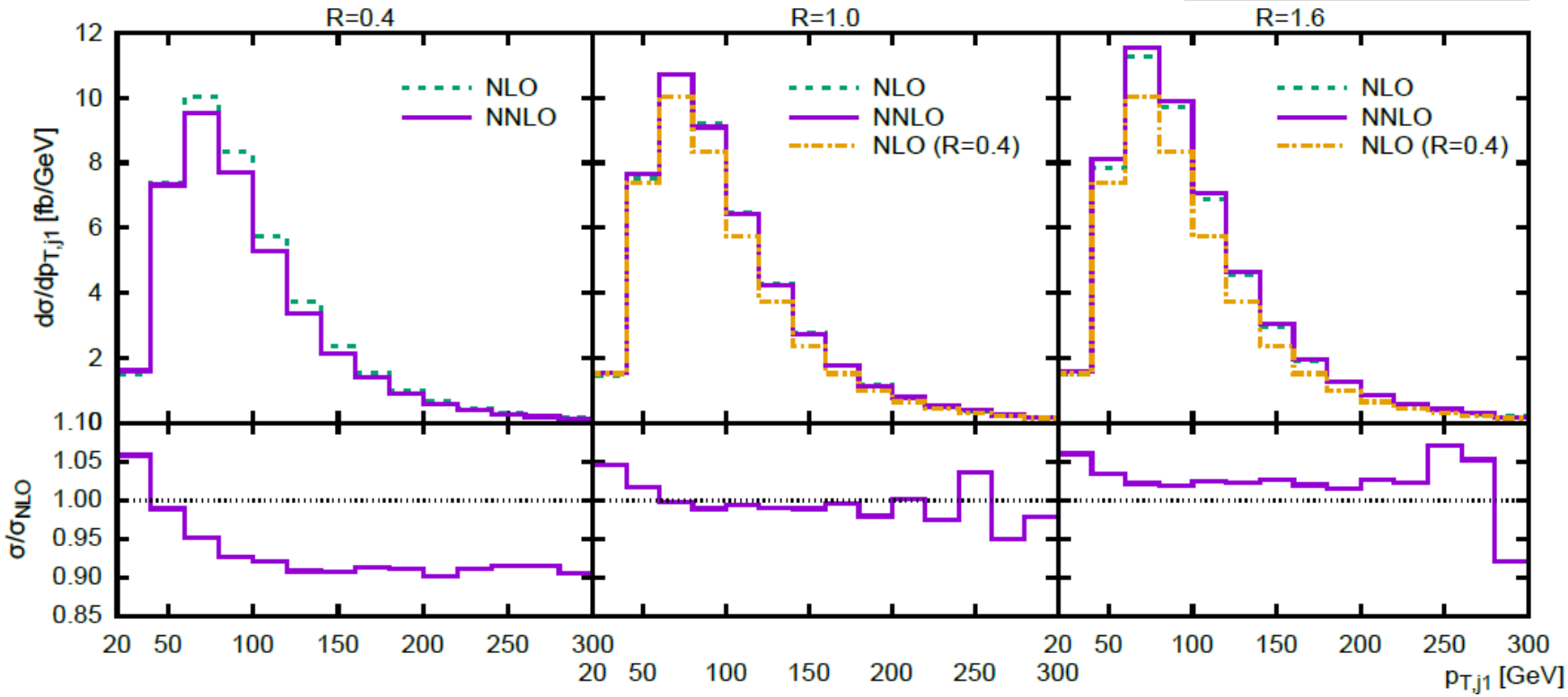
Anti-kT jets m(jj) > 600 GeV Δy(jj)> 4.5

(M. Rauch and D.Z., **arXiv:1703.05676**)



pT of hardest tagging jet: anti-kT, R=0.4, 1.0, 1.6

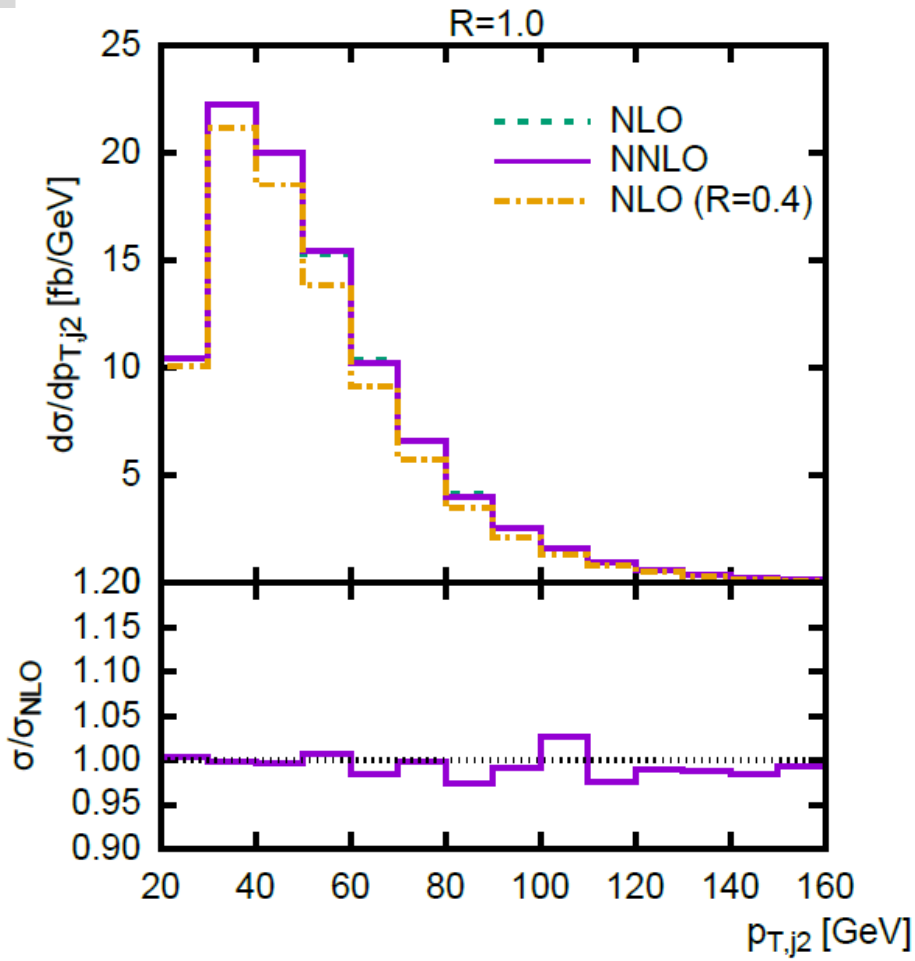
(M. Rauch and D.Z., **arXiv:1703.05676**)

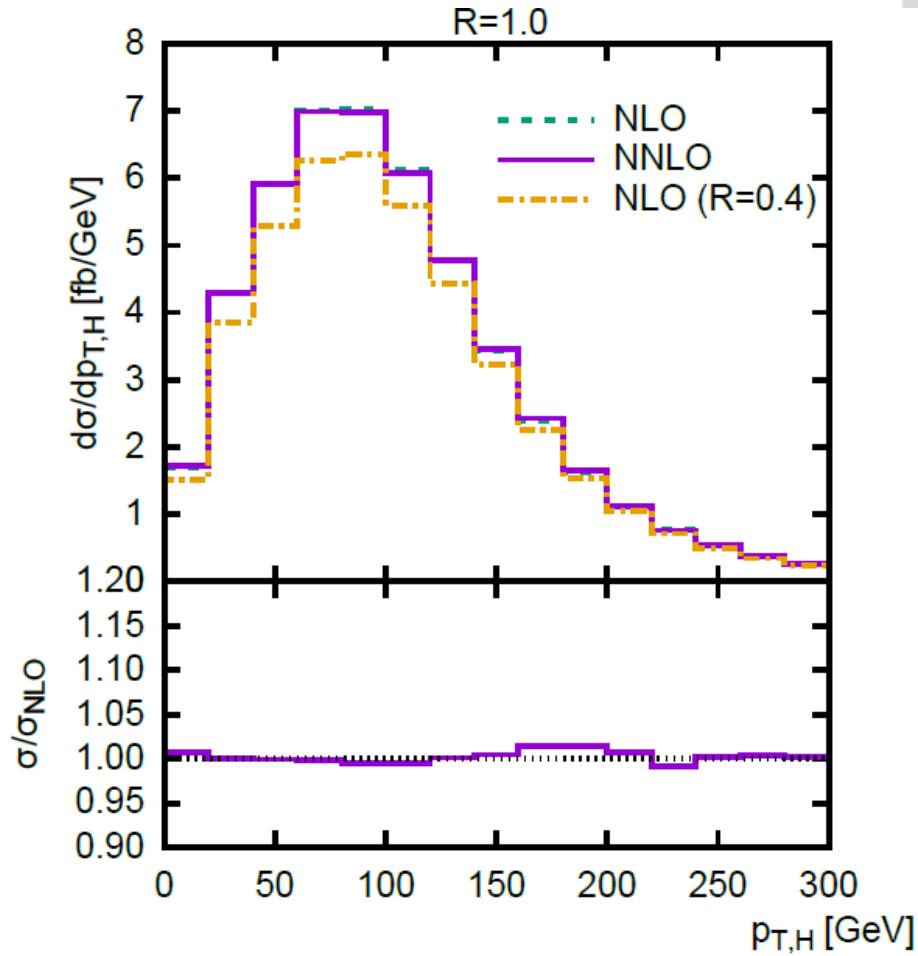


At R=1 also most distributions show best agreement between NLO and NNLO

pT(j2) and Higgs pT at R=1

(M. Rauch and D.Z., **arXiv:1703.05676**)



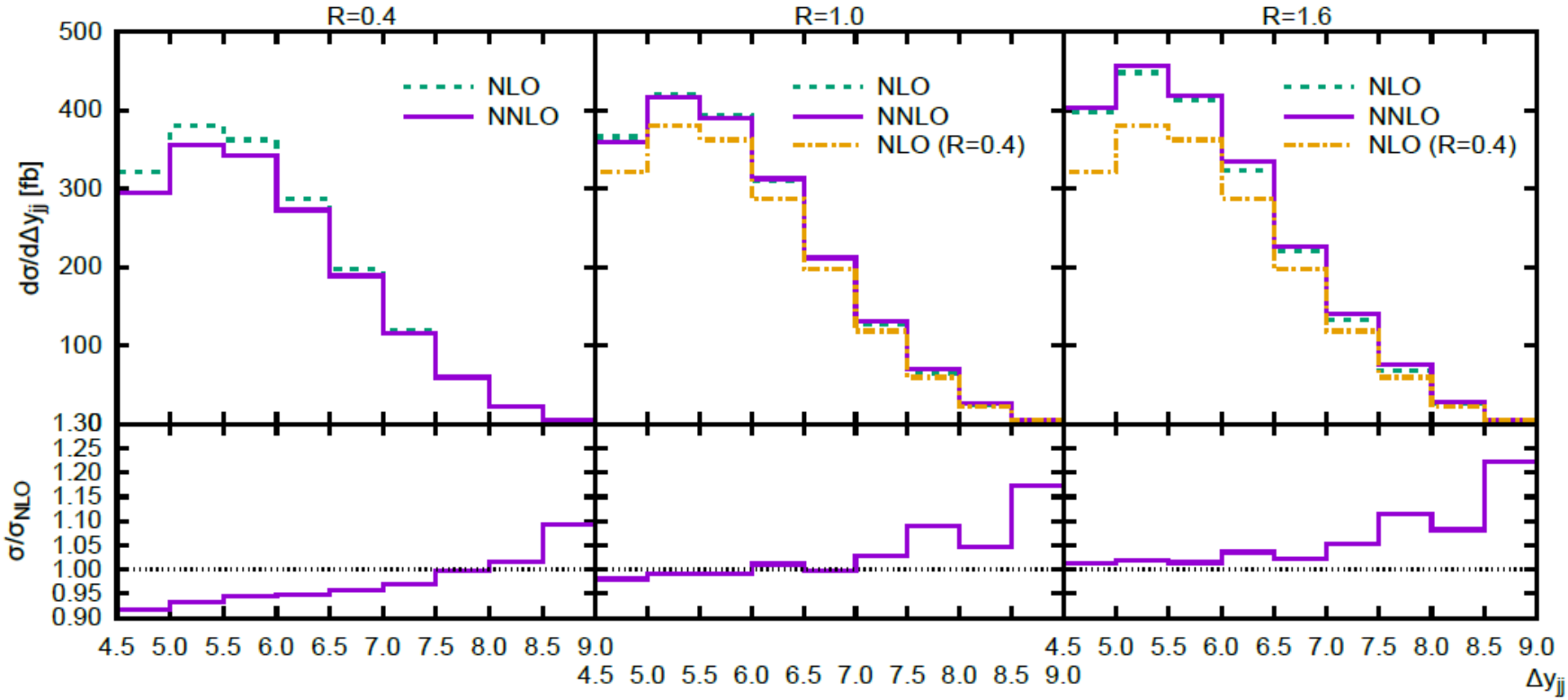


Rapidity separation of tagging jet pair

Change in shape of the $\Delta y(jj) = |y(j1) - y(j2)|$ distribution is not simply a result of the change in jet-shape. Possible explanations:

- Suppressed radiation between tagging jets
- Effect of 2-loop contribution

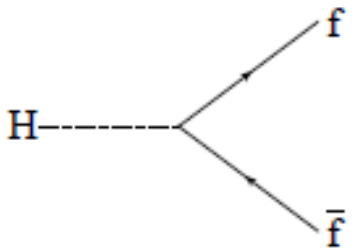
(M. Rauch and D.Z., **arXiv:1703.05676**)



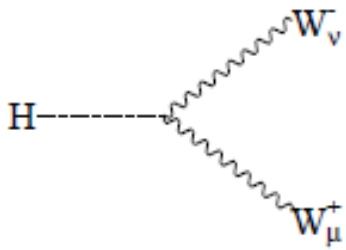
Beware of jet observables

- For any process with jets at LO, an NLO cross section calculation simulates only LO jet shapes (and LO dependence on jet algorithms)
- This results in sizable QCD corrections at higher order since jet shapes change substantially from LO to NLO (i.e when going to an NNLO calculation). NLO and NNLO results cannot agree at all jet radii R
- Jet shape variation, R-dependence and jet algorithm dependence is not captured by scale variation of NLO cross sections. From VBF Higgs example, assign an additional (order 10%) uncertainty to NLO cross sections with jets in the final state, especially when scale variation is exceptionally small, like in VBF
- Uncertainty will depend on number of jets in LO process, quark vs gluon jet, steepness of jet pT distributions etc.
- Disclaimer: There is nothing special or good about a fat jet choice with R=1 in the case of VBF Higgs production. It would induce large corrections due to underlying event or pile-up…

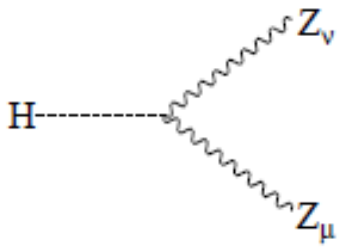
Observations test Higgs interactions



$$-i\frac{m_f}{v} \quad \text{from} \quad \mathcal{L}_{Yukawa}$$



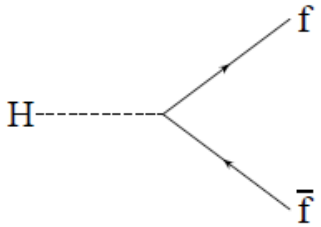
$$i2\frac{m_W^2}{v}g_{\mu\nu} \quad \text{from} \quad \mathcal{L}_{kin} = (D^\mu\Phi)^\dagger(D_\mu\Phi)$$



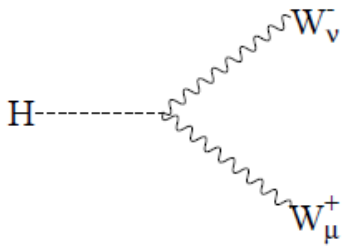
$$i2\frac{m_Z^2}{v}g_{\mu\nu} \quad \text{from} \quad \mathcal{L}_{kin} = (D^\mu\Phi)^\dagger(D_\mu\Phi)$$

Couplings predicted in SM by observed particle masses

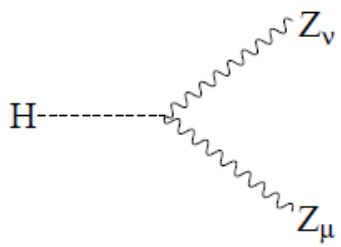
Couplings modified in BSM: effective Lagrangian parameterization



$$-i\frac{m_f}{v}\cdot\kappa_f \qquad \text{from} \quad \mathcal{L}_{EFT} = \frac{1}{v^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)(\kappa_f - 1)\mathcal{L}_{Yukawa}$$



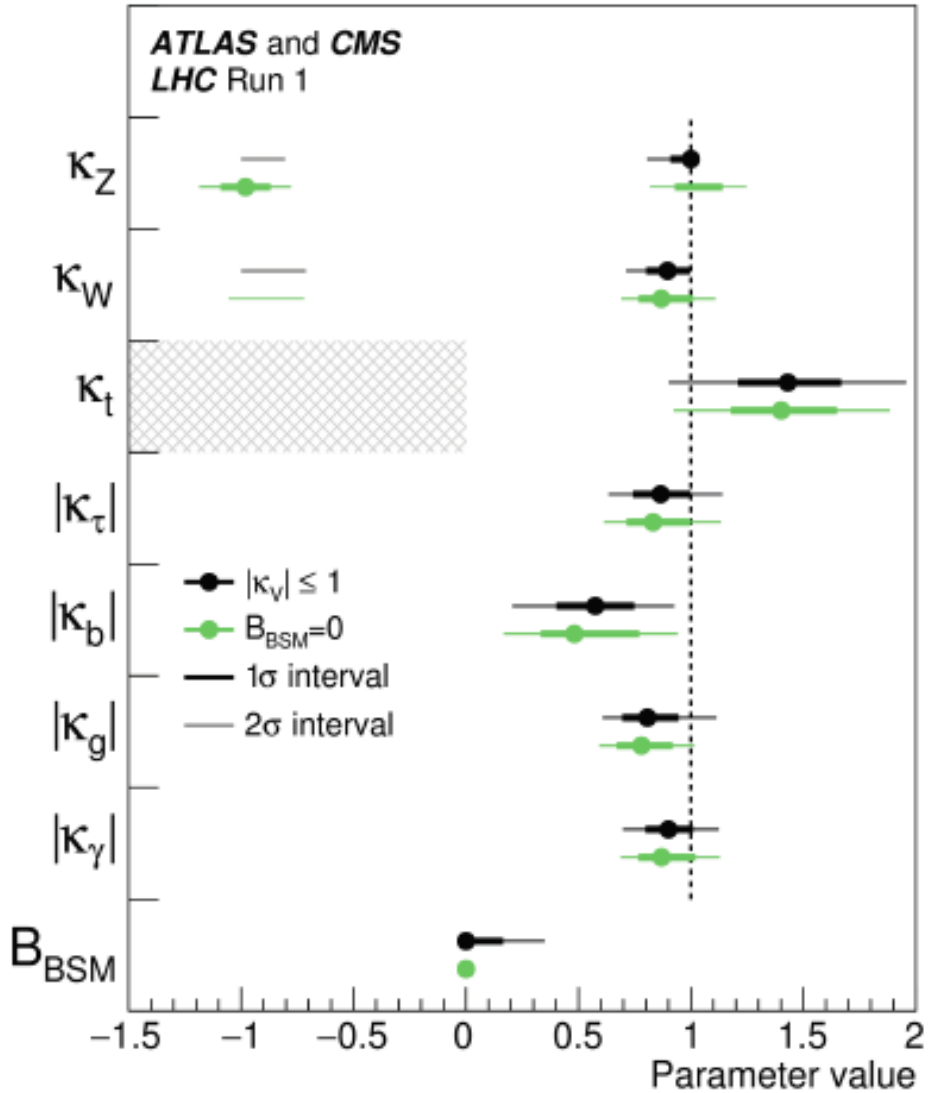
$$i2\,\frac{m_W^2}{v}\,g_{\mu\nu}\cdot\kappa_W \qquad \text{from} \quad \mathcal{L}_{EFT} = \frac{2}{v^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)(\kappa_W - 1)\mathcal{L}_{kin}$$



$$i2\,\frac{m_Z^2}{v}\,g_{\mu\nu}\cdot\kappa_Z \qquad \text{from} \quad \mathcal{L}_{EFT} = \frac{2}{v^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)(\kappa_Z - 1)\mathcal{L}_{kin}$$

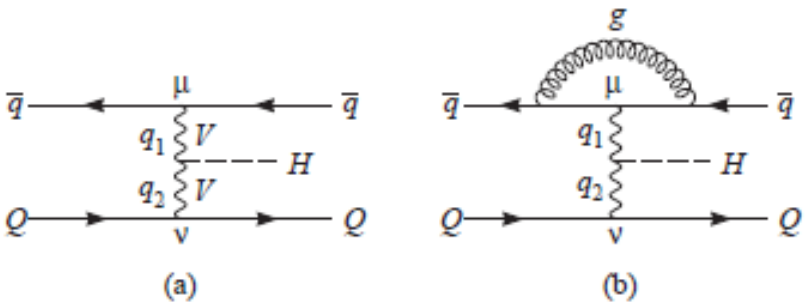
Combined analysis of kappas by ATLAS+CMS

- Upper limit on Higgs width from either
  i) $|\kappa_V| < 1$ or
  ii) no BSM decay channel
- Couplings consistent with SM predictions
- Slight tension for Hbb coupling



Tensor structure of the HVV coupling

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



$$
\begin{aligned}
T^{\mu\nu} \quad = \quad & a_1 \, g^{\mu\nu} \; + \\
& a_2 \; \left(q_1 \cdot q_2 \, g^{\mu\nu} - q_1^{\nu} q_2^{\mu}\right) + \\
& a_3 \; \varepsilon^{\mu\nu\rho\sigma} \; q_{1\rho} q_{2\sigma}
\end{aligned}
$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Physical interpretation of terms:

SM Higgs $\quad \mathcal{L}_I \sim H V_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

CP even $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

CP odd $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow a_3$

Must distinguish a_1, a_2, a_3 experimentally

Connection to effective Lagrangian

We need model of the underlying UV physics to determine the form factors $a_i(q_1, q_2)$

Approximate its low-energy effects by an effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{f_{WW}}{\Lambda^2}\phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi + \frac{f_\phi}{\Lambda^2}\left(\phi^\dagger\phi - \frac{v^2}{2}\right)(D_\mu\phi)^\dagger D^\mu\phi + \cdots + \sum_i \frac{f_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

Gives leading terms for form factors, e.g. for hWW coupling

$$a_1 = \frac{2m_W^2}{v}\left(1 + \frac{f_\phi}{\Lambda^2}\frac{v^2}{2}\right) + \sum_i c_i^{(1)}\frac{f_i^{(8)}}{\Lambda^4}v^2q^2 + \cdots$$

$$a_2 = c^{(2)}\frac{f_{WW}}{\Lambda^2}v + \sum_i c_i^{(2)}\frac{f_i^{(8)}}{\Lambda^4}vq^2 + \cdots$$

$$a_3 = c^{(3)}\frac{\tilde{f}_{WW}}{\Lambda^2}v + \sum_i c_i^{(3)}\frac{\tilde{f}_i^{(8)}}{\Lambda^4}vq^2 + \cdots$$

Describe same physics (for a particular vertex) by taking some minimal set of effective Lagrangian coefficients f_i as form factors

Monte Carlo implementation, e.g. in VBFNLO

Start from effective Lagrangians (set PARAMETR1=.true. in anom_HVV.dat)

$$\mathcal{L} = \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W^{\mu\nu}_- + \frac{g_{5o}^{HWW}}{\Lambda_5} H \tilde{W}^+_{\mu\nu} W^{\mu\nu}_- + \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \tilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \tilde{A}_{\mu\nu} A^{\mu\nu}$$

or , alternatively, (set PARAMETR3=.true. in anom_HVV.dat)

$$\mathcal{L}_{\text{eff}} = \frac{f_{WW}}{\Lambda_6^2} \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi + \frac{f_{BB}}{\Lambda_6^2} \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi + \text{ CP-odd part} + \cdots$$

see VBFNLO manual for details on how to set the anomalous coupling choices

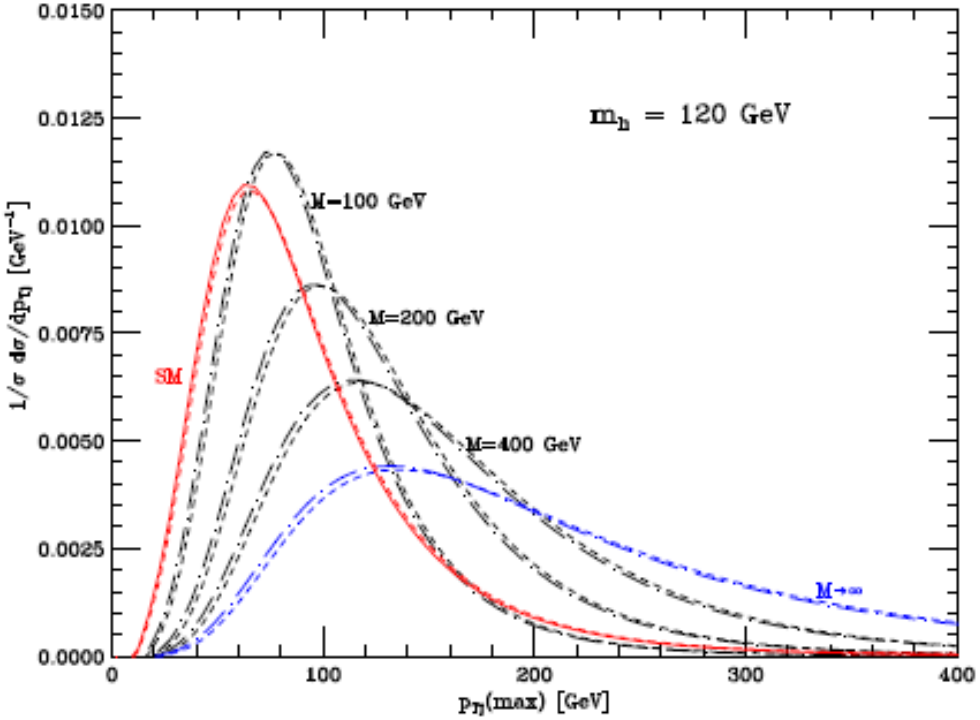
Remember to choose form factors in anom_HVV.dat

$$F_1 = \frac{M^2}{q_1^2 - M^2} \frac{M^2}{q_2^2 - M^2} \qquad \text{or} \qquad F_2 = -2\, M^2\, C_0\left(q_1^2, q_2^2, (q_1+q_2)^2, M^2\right)$$

Effect on tagging jet transverse momentum

Form factors affect momentum transfer and thus jet transverse momenta (Here: a_2 only)

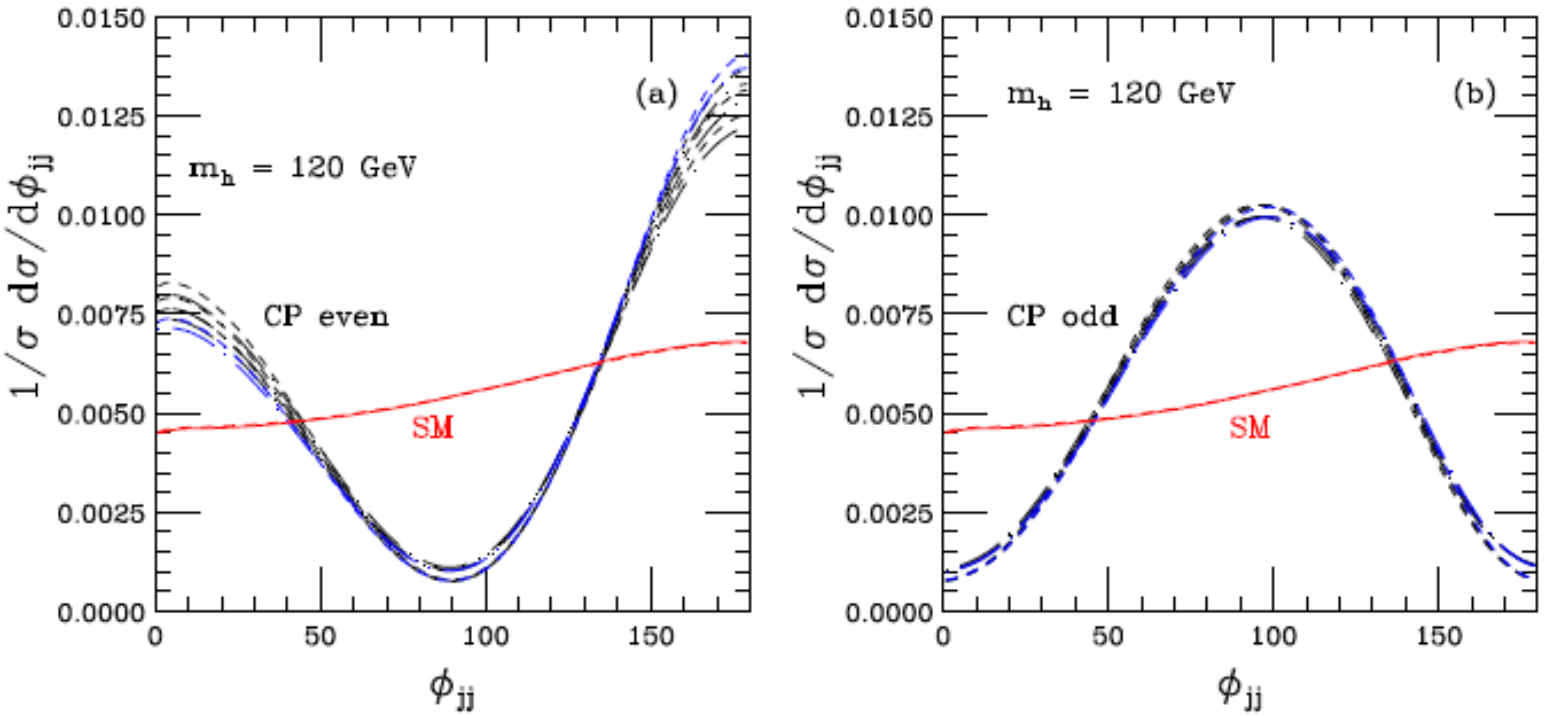
Figy, DZ hep-ph/0403297



- Change in tagging jet p_T distributions is sensitive indicator of anomalous couplings
- Can choose form-factor such as to approximate SM p_T distributions of the two tagging jets

Azimuthal angle between tagging jets

Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



Dip structure at 90° (CP even) or 0/180° (CP odd) only depends on tensor structure of hVV vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.

Same physics in decay plane correlations for $h \to ZZ^* \to 4$ leptons

Size estimates for a_2 terms

a_2 for the four HVV combinations can be derived from effective Lagrangian

$$\mathcal{L} = \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W^+_{\mu\nu} W^{\mu\nu}_- + \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu}$$

- SU(2) multiplets in triangle graphs producing these effective couplings tend to produce all four of same order of magnitude
- However
  - $H \to ZZ \to 4\ell$ and $H \to WW \to \ell^+\ell^-\nu\bar{\nu}$ partial widths are strongly suppressed by being off-shell and by small leptonic branching ratios
  - No such suppressions for $H \to \gamma\gamma$

  $\Longrightarrow$ Need $g_{5e}^{HZZ} \approx g_{5e}^{HWW} \approx 1000\, g_{5e}^{H\gamma\gamma}$ in absence of SM a_1 term
- $HZ\gamma$ coupling must also be suppressed (would see on-shell $H \to Z\gamma \to \ell^+\ell^-\gamma$ otherwise)

$\Longrightarrow$ Substantial fine tuning needed

$\Longrightarrow$ Loop induced HWW and HZZ couplings, i.e. a_2 or a_3 couplings as primary origin of observed $H \to WW$ and $H \to ZZ$ decays can be ruled out

Conclusions

- SM description of Higgs couplings works very well (so far) to describe LHC data
- Excellent theoretical understanding of Higgs production is needed to match (anticipated) experimental precision
- Surprisingly large NNLO corrections to distributions are observed in VBF. They are related to energy flow inside jets, which is modeled at LO only in NLO cross section calculations
- Dependence on jet-shape and hence on jet radius R should be considered as an additional uncertainty for (N)NLO cross sections of processes with jets at LO
- Effective Lagrangian approach, combined with form factors or other unitarization procedure, provides adequate tool for analyzing general tensor structure of Higgs couplings to gauge bosons and fermions

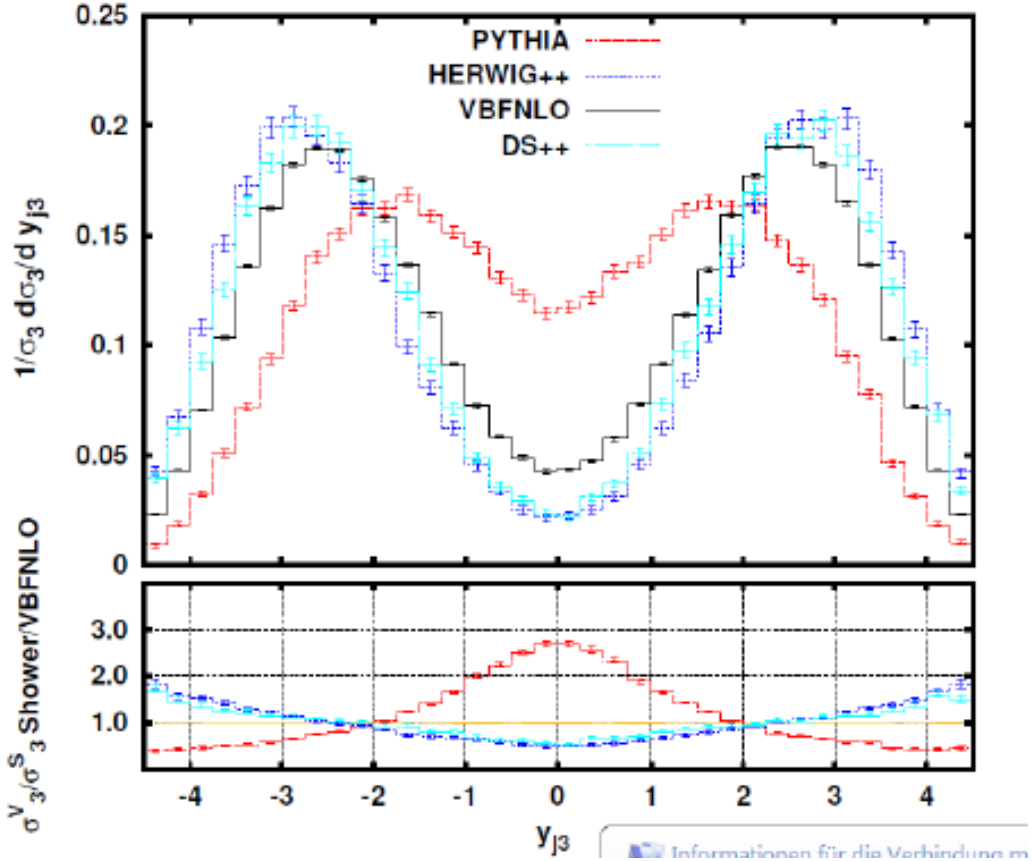
Veto Jets beyond fixed order: Parton Shower interface

Interface of NLO calculations with Herwig and PYTHIA via Powheg Box has been implemented by Franziska Schissler

- How well can “veto jets” be modeled directly by parton shower approach?
- Differences between basic shower models (PYTHIA vs. default Herwig shower vs. dipole shower)
- Improvements when adding true NLO corrections

Veto jet distribution: LO $qq \to qqh$ matrix elements

Schissler thesis, 2014



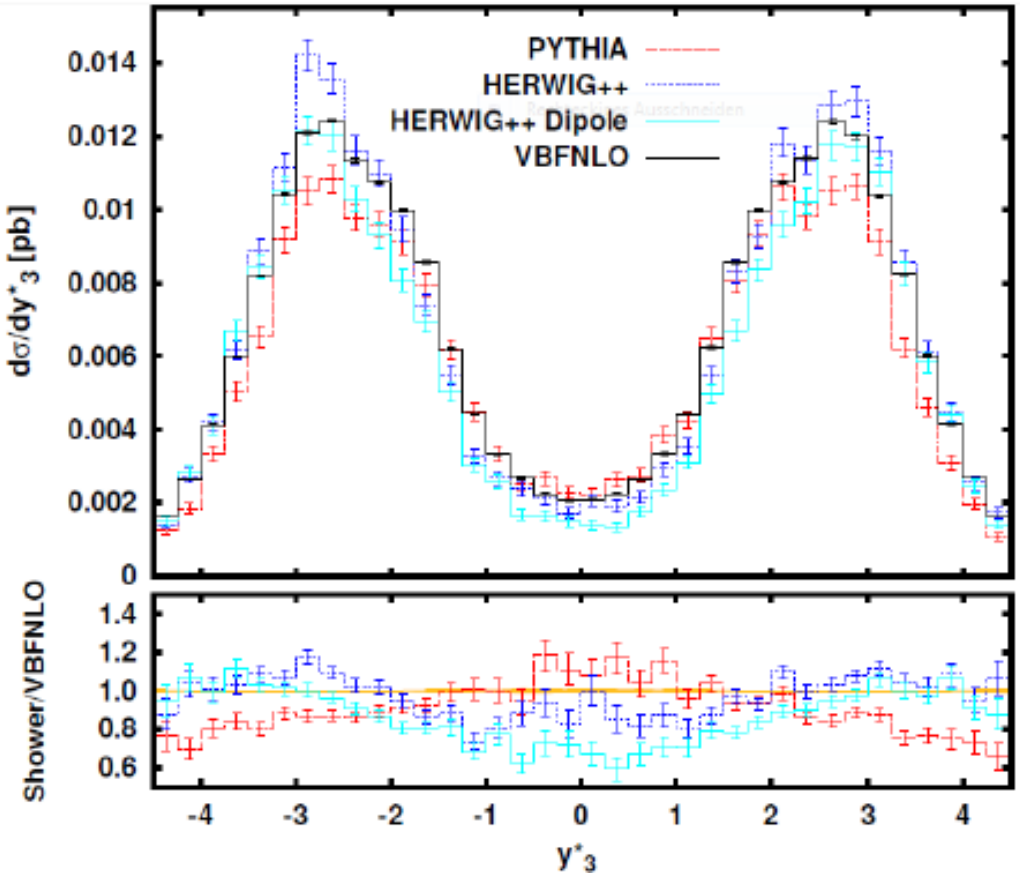
Pure parton-shower generation of central jets does not produce reliable results

Collinear approximation inherent in PS approach is not valid in veto region for VBF events

Extra parton must be included in hard matrix element

Veto jet distribution: VBF $Wjjj$ production at LO

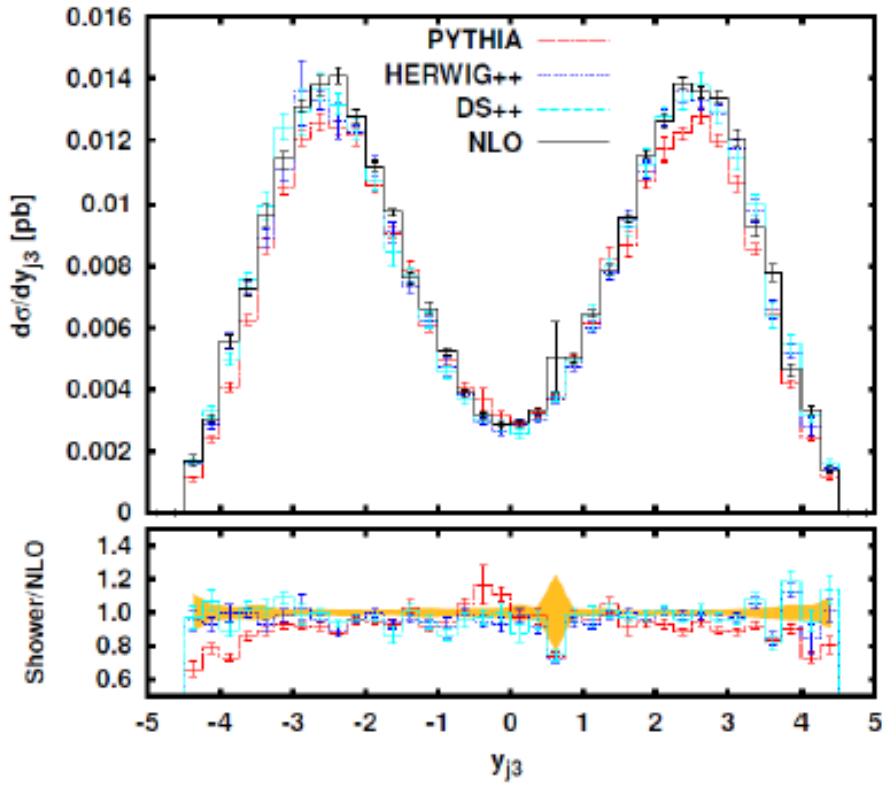
Schissler,DZ arXiv:1302.2884



Inclusion of third parton at ME level produces reasonable agreement between NLO Vjj calculations and parton shower programs

Veto jet distribution: VBF $hjjj$ production at NLO

Jäger, Schissler, DZ arXiv:1405.6950



Further improvement with NLO $hjjj$ calculation matched to PS programs

Reliable simulation of veto jet candidates is possible but requires matrix elements with sufficiently high parton multiplicity