Offshell Status

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17th Workshop of LHC Higgs Working Group

9 November 2020

Introduction

- Focus on processes with sizeable contribution from offshell Higgs.
- E.g: $gg \to H \to VV$:

  10% of events above the $2m_V$ threshold. [Kauer, Passarino '12]
- Large offshell rates also in EW production (*VH,* VBF).

  [cf. Campbell, Ellis '15; Gritsan *et al.* '20]
- Allows the exploration of the Higgs properties in a new kinematic regime:
  - Width [Caola, Melnikov '13]
  - Couplings
  - Unitarization properties
  - ...

Focuses of Offshell Subgroup

- Interpretation of offshell measurements:
  - Width extraction *not* model independent – constraints on NP through EFT operators + width determinations?
  - Higgs or Warsaw basis?
- Tools for simulations:
  - Account for higher order corrections?
  - Include EFT effects.
- Theory uncertainties:
  - Inclusion of extra radiation through jet merging.
  - Combining QCD and EW corrections in *VV* background.
  - EW corrections in *VV* background.

Overlap between these areas!

- Documentation of studies in progress – thanks to our theory, ATLAS, and CMS colleagues who have contributed!
- See our Twiki for more information.

Models, EFT, & Interpretations: Guidelines

- discuss and make recommendations on which models/AnomCoupls/EFTs should be investigated with what priority in the context of off-shell $gg \to H \to VV$ analyses
- carefully consider and compare theoretical assumptions/choices made
- explore to what degree compatibility/translatability between ATLAS and CMS results is feasible

Aleksandr Azatov, Adam Falkowski, Andrei Gritsan, Christophe Grojean, NK, Ennio Salvioni, Eleni Vryonidou

See also:

- Offshell & Interference Meeting (25 November 2019) [link]
- HXSWG Offshell Interpretations 1st Joint Meeting (10 March 2020) [link]
- HXSWG Offshell Interpretations 2nd Joint Meeting (16 April 2020) [link]
- HXSWG Offshell Interpretations 3rd Joint Meeting (8 July 2020) [link]
- HXSWG Offshell Interpretations 3rd Joint Meeting (23 September 2020) [link]

Models, EFT, & Interpretations: Discussion points

- EFT effects in gg ($\rightarrow H$) $\rightarrow ZZ$ (see below)
- Relation between the Higgs and Warsaw bases (see below)
- What types of BSM benchmark models should be analysed? Light degrees of freedom up to what scale? In particular to uncover limitations of EFT fits. Are common models sufficient (MSSM, 2HDM, SM+scalar)? What toy models (composite inspired, ...)?
- Interplay with other channels due to shared couplings, e.g. top production. How to disentangle coefficients? Independent subsets? Proper treatment? Best use of limited number of degrees of freedom in fits. How to expand? Take into account (better) bounds on relevant Wilson coefficients obtained in other channels.
- Can off-shell data resolve on-shell parameter degeneracy?
- Statistics/data analysis methods available to include BSM effects in backgrounds (relative to Higgs production) when determining bounds on Wilson coefficients/model parameters?

Models, EFT, & Interpretations: Road map

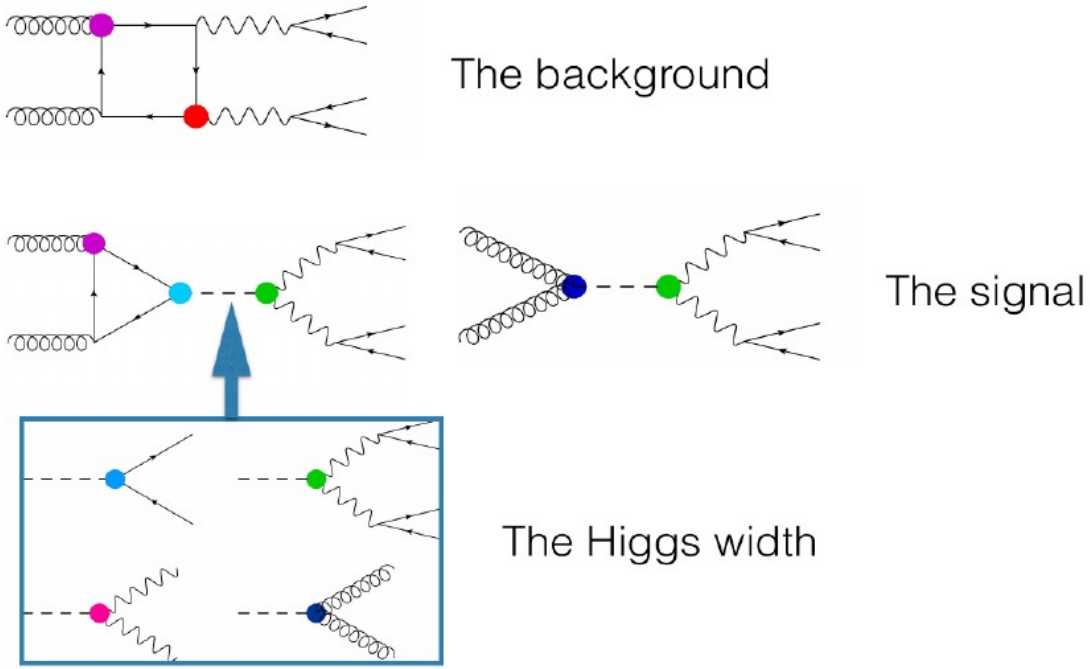
1. Immediate issues:
   - discuss and converge to a "minimal" list of couplings/operators that deserve priority at this stage
   - clarify basis issues and make recommendations
   - take into account bounds on relevant Wilson coefficients obtained in other channels
2. Medium-term issues:
   - what types of BSM benchmark models should be analysed? Light degrees of freedom up to what scale? In particular to uncover limitations of EFT fits.
   - interplay with other channels due to shared couplings, e.g. top production. How to disentangle operators? Proper general treatment? Independent subsets?
   - take into account VBF $\rightarrow$ H $\rightarrow$ VV (VBF/VH)
3. Long-term issues:
   - take into account SMEFT effects in background amplitudes
   - take into account NLO effects in EFT studies
   - study specific BSM extended with higher-dimensional operators

SMEFT analysis

Extension of the SM by dimension-6 operators Q_i composed of SM fields, which are invariant under the SM gauge symmetries (C_i: Wilson coefficients):

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i C_i Q_i$$

detailed Higgs basis definition $\rightarrow$ Adam's contribution to write-up (finished)



graphs by Eleni Vryonidou

What can $gg \rightarrow ZZ$ including off-shell tell us about the SMEFT?

$\rightarrow$ Ennio's slides joint meetings (contribution to write-up in preparation)

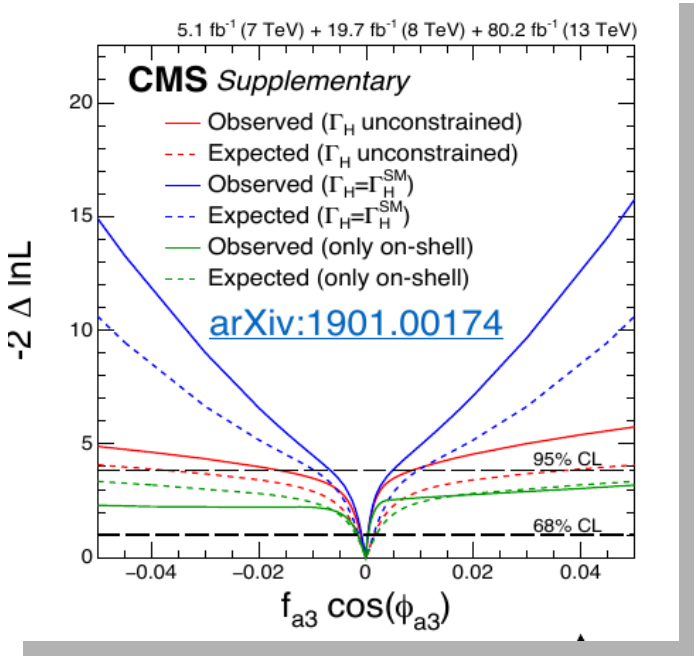
Models, EFT, & Interpretations: Contributions

- Adam Falkowski: *Summary of the Higgs basis parametrization of the SMEFT* (finished)
- Alex Azatov, Christophe Grojean, Ennio Salvioni with Jorge de Blas: *Effect of relaxing coupling universality in the fit to on-shell and off-shell data* (in preparation)
- Eleni Vryonidou: *EFT effects in the off-shell region (in progress)*
- ...

Tools for simulation

JHUGen: [Gao *et al.* '10; ...; Gritsan *et al.* '20] [Talk by Andrei Gritsan]

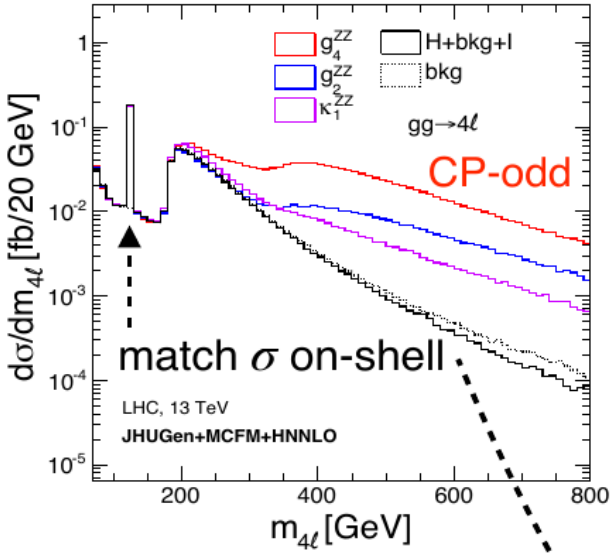
- Simulation tool for studies of anomalous couplings/EFT effects in Higgs physics.
- Supports offshell Higgs production through gluon fusion, VBF, *VH*, including background and interference effects.
- Offshell effects from:
  - EFT in Higgs couplings;
  - Anomalous vector boson scattering;
  - width modification;
  - (New resonances).
- Offshell studies typically involve low statistics
  - ➡ optimal observables through MELA.



Tools for simulation

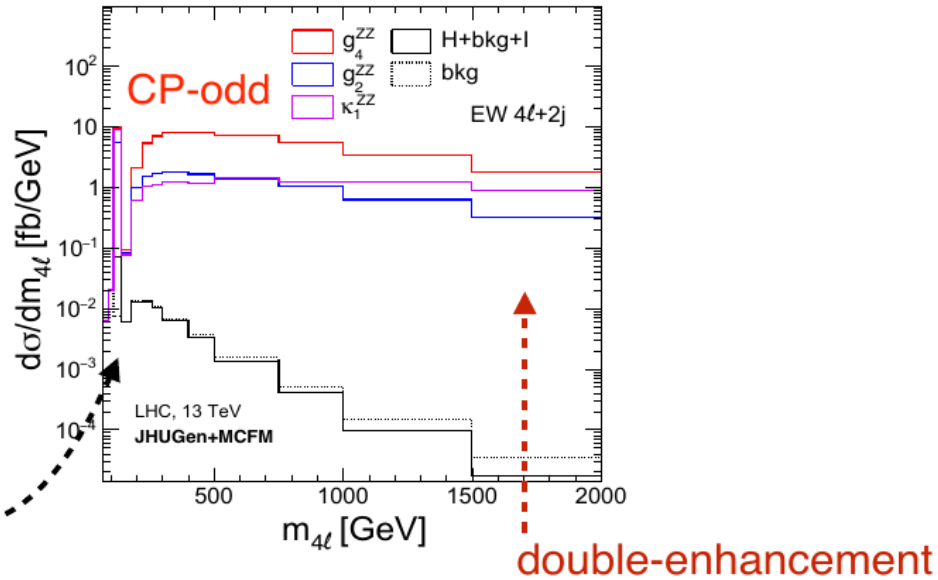
JHUGen

- sig.+bkg.+interference in $gg \to (H^*) \to VV \to 4f$



- in $qqVV \to (qqH^*) \to qqVV \to 6f$

  including $(VH^*) \to VVV \to 6f$



- cut off q^2 growth:

$$\frac{\Lambda_{V1,i}^2 \Lambda_{V2,i}^2 \Lambda_{H,i}^2}{(\Lambda_{V1,i}^2 + |q_{V1}^2|)(\Lambda_{V2,i}^2 + |q_{V2}^2|)(\Lambda_{H,i}^2 + |(q_{V1} + q_{V2})^2|)}$$

Slide from Andrei Gritsan

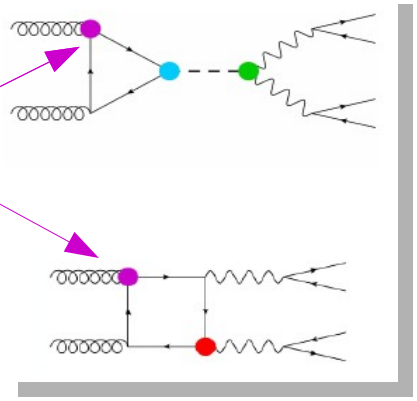
Tools for simulation

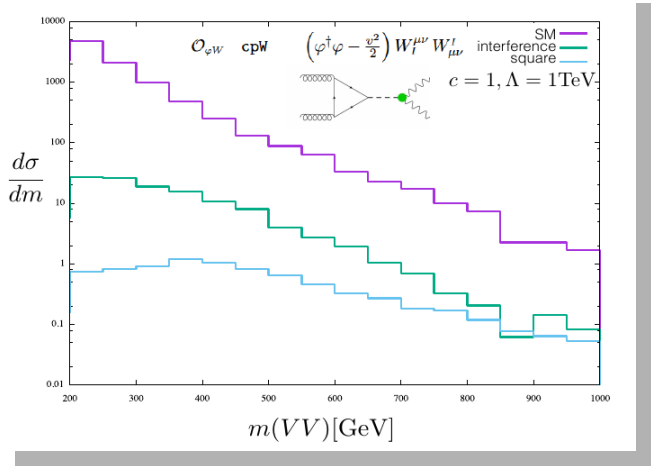
SMEFT @ NLO + MadGraph: [Degrande *et al.* '20] [Talk by Eleni Vyronidou]

- Automation of one-loop calculations in SMEFT with dimension-6 operators:
  - Warsaw basis
  - Includes Higgs, top, gauge boson interactions
  - Now with four-fermion operators
  - CP & flavor conserving
- Passed to MadGraph for simulation.

E.g. in offshell Higgs production through gluon fusion

Top-gluon coupling appears in both "signal" and "background" amplitudes





Tools for simulation

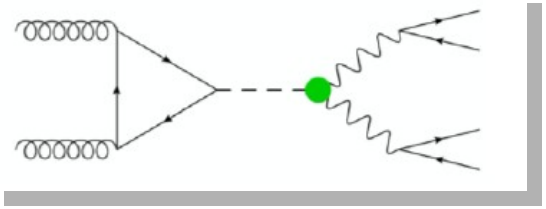
Talk by Ashley McDougall

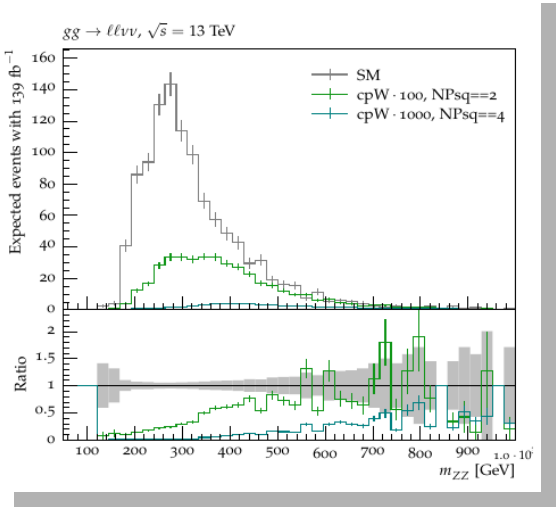
Preliminary results!

Experimental study using SMEFT+MG

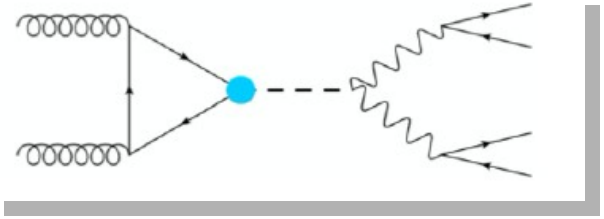
- SM @ NLO + MadGraph used to generate events.
- $gg \to (H) \to ZZ \to l^+l^-\nu\bar{\nu}$
- Basic final state selections and fiducial cuts applied in Rivet.

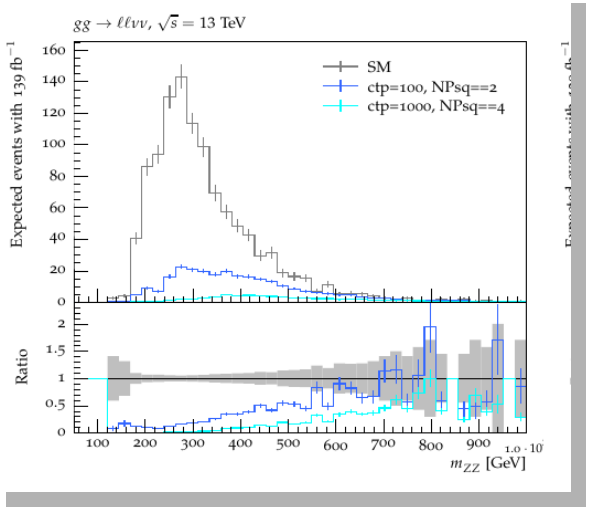
Higgs-gauge couplings: cpW



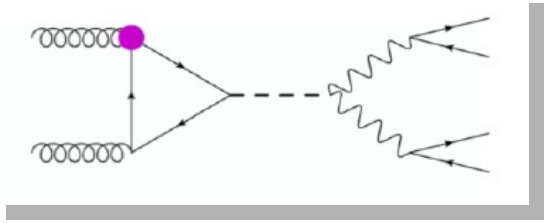


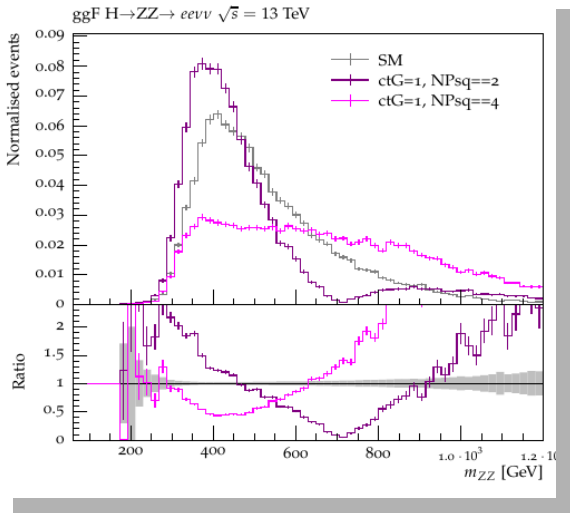
Top Yukawa couplings: ctp





Top Gluon couplings: ctG

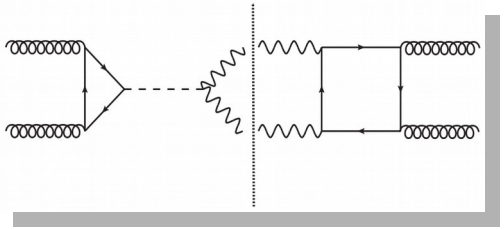




Higher Order Corrections: Jet Merging

- Offshell Higgs production through gluon fusion is loop-induced

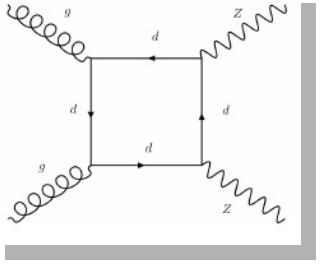
  ➡ NLO corrections complicated, only available in *1/m*$_t$ expansion in SM [Campbell *et al.* '16; Caola *et al.* '16]

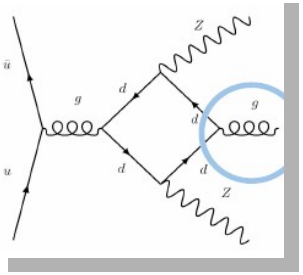


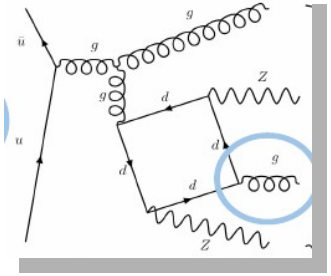
- Additional difficulties when taking into account EFT effects.
- Use merging to simulate effect of additional radiation.

[Li *et al.* '20] [Talk by Congqiao Li]

- Merging of 0, 1- and 2-jet samples in gluon fusion $gg \to ZZ$
- Higgs-mediated diagrams not **(yet)** included [work in progress].
- Z decay not included yet [work in progress] ➡ $m_{ZZ} > 2m_Z$
- MadGraph for matrix element simulation, matched to Pythia with MLM scheme.



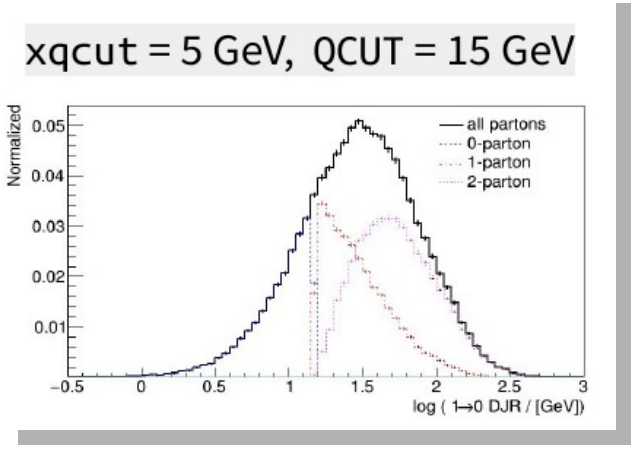


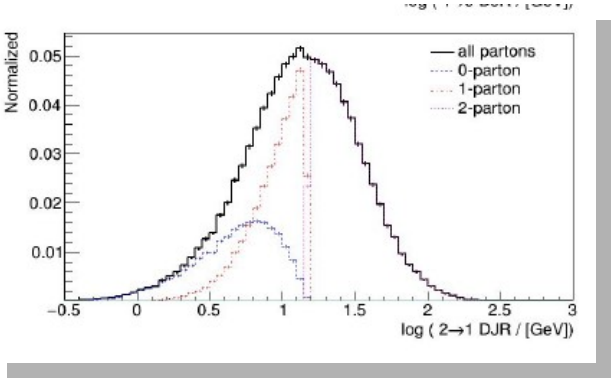


Higher Order Corrections: Jet Merging

Jet merging in $gg \to ZZ$

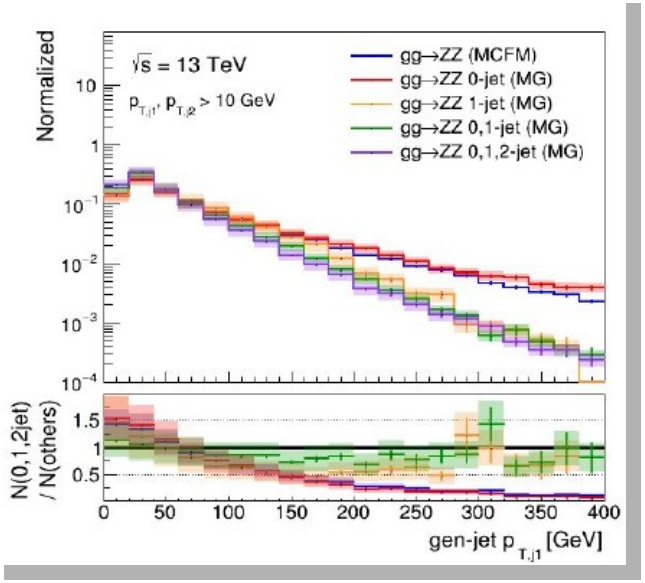
[Talk by Congqiao Li]

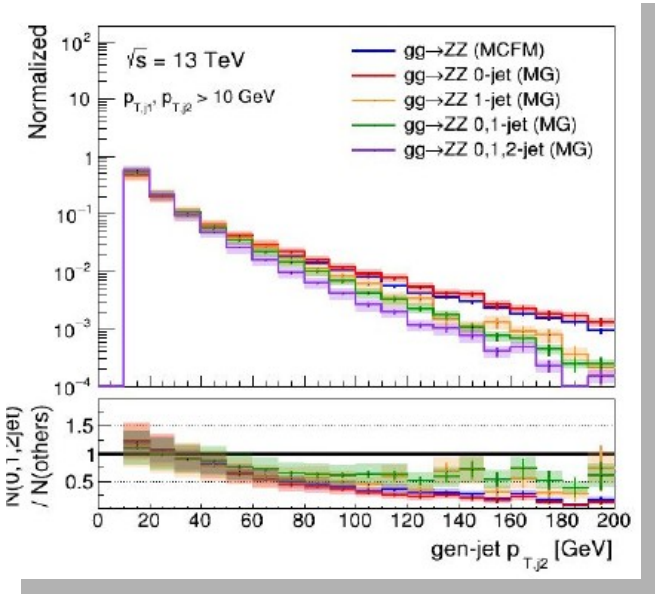




sub-process	core-hour
0-jet	0.085
1-jet	10.9
2-jet	15300

Massive increase in computational time for 2 jet emission!



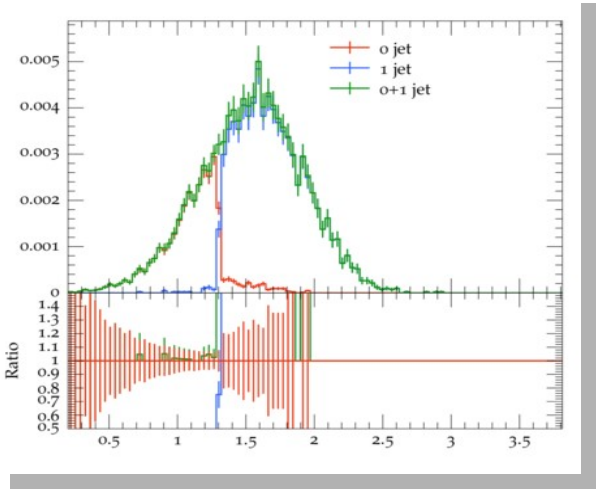


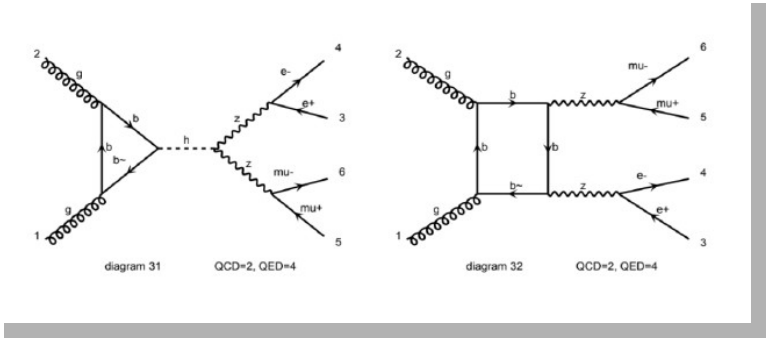
Higher Order Corrections: Jet Merging

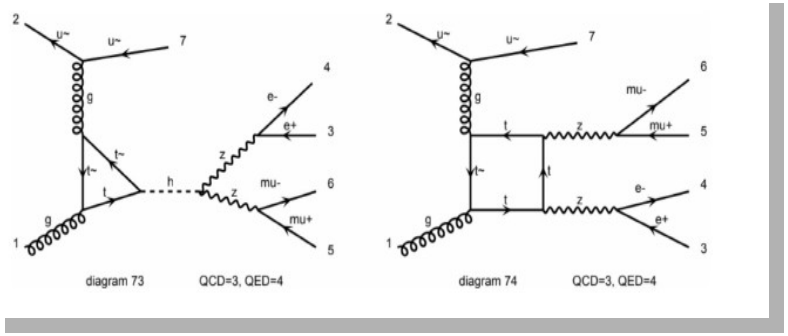
Jet merging in $gg \to ZZ$

Similar study: Talk by Jay Sandesara, based on work with Rafael Coelho Lopes de Sá.

- Includes prompt *ZZ* production as well as Higgs-mediated ("*SBI*").
- Leptonic decays included*.
- MLM merging to Pythia.







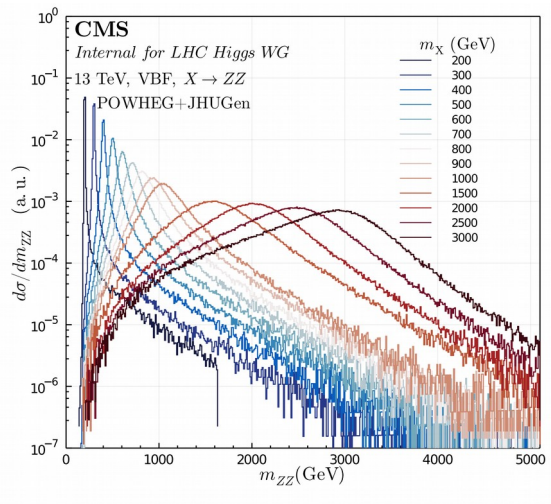
In progress: combined study on 0+1 jet merging, including Higgs-mediated diagrams and Z decay, and comparison to NLO results.

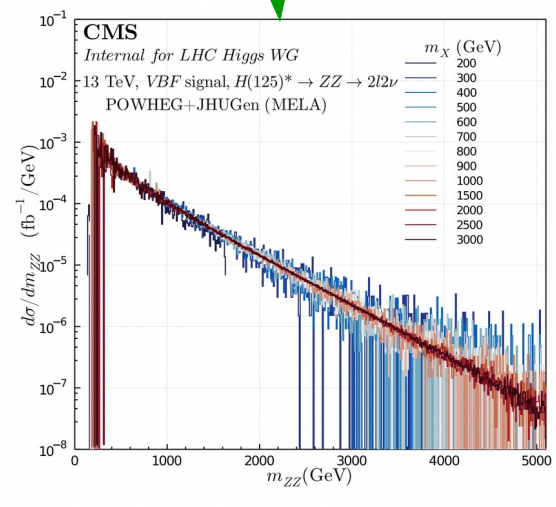
* 2 jet sample has onshell Z decays and no spin correlations.

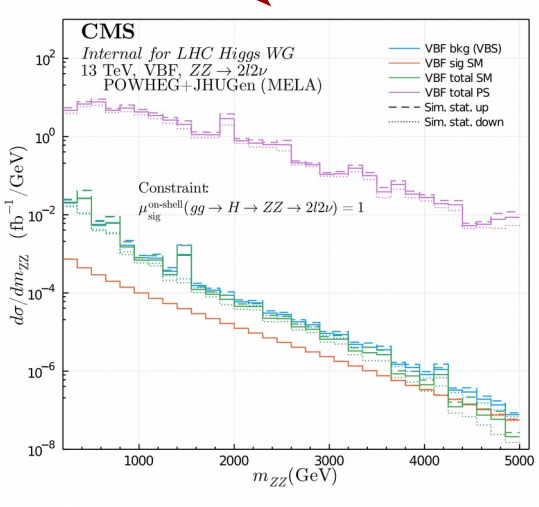
Higher Order Corrections: Reweighting

For off-shell simulation techniques, CMS has studied a **reweighting technique of high mass signal samples**, produced using POWHEG, decayed via JHUGen, and reweighted via their matrix element (MELA) framework.

The three plots exemplify the distributions of the VBF process before reweighting for each sample separately, that after reweighting the samples to the H(125) signal, and the combined distribution of SM or pseudoscalar (PS) hypotheses after combining them.







Thanks to Jerry Ling for the plots and the details of the technique

Higher Order Corrections: QCD and EW

- EW corrections to background process $q\bar{q} \to VV$ also important at high energies.
- NNLO QCD + NLO EW corrections available in MATRIX code [Grazzini *et al.*, '19] [Talk by Jonas Lindert] *(to be made public soon; beta version on request)*

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{LO}} + \alpha_s \mathrm{d}\sigma_{\mathrm{NLOQCD}} + \alpha_s^2 \mathrm{d}\sigma_{\mathrm{NNLOQCD}} + \alpha_{EW} \mathrm{d}\sigma_{\mathrm{NLOEW}} + \ldots$$

How to combine the QCD and EW corrections?

Additive: $$\mathrm{d}\sigma_{\mathrm{NNLOQCD+EW}} = \mathrm{d}\sigma_{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}} + \delta_{\mathrm{EW}}\right) + \mathrm{d}\sigma_{\mathrm{LO}}^{gg}$$

Multiplicative: $$\mathrm{d}\sigma_{\mathrm{NNLOQCD\times EW}} = \mathrm{d}\sigma_{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}}\right)\left(1 + \delta_{\mathrm{EW}}\right) + \mathrm{d}\sigma_{\mathrm{LO}}^{gg}$$

$$= \mathrm{d}\sigma_{\mathrm{NNLOQCD+EW}} + \delta_{\mathrm{QCD}}\delta_{\mathrm{EW}}\mathrm{d}\sigma_{\mathrm{LO}}$$

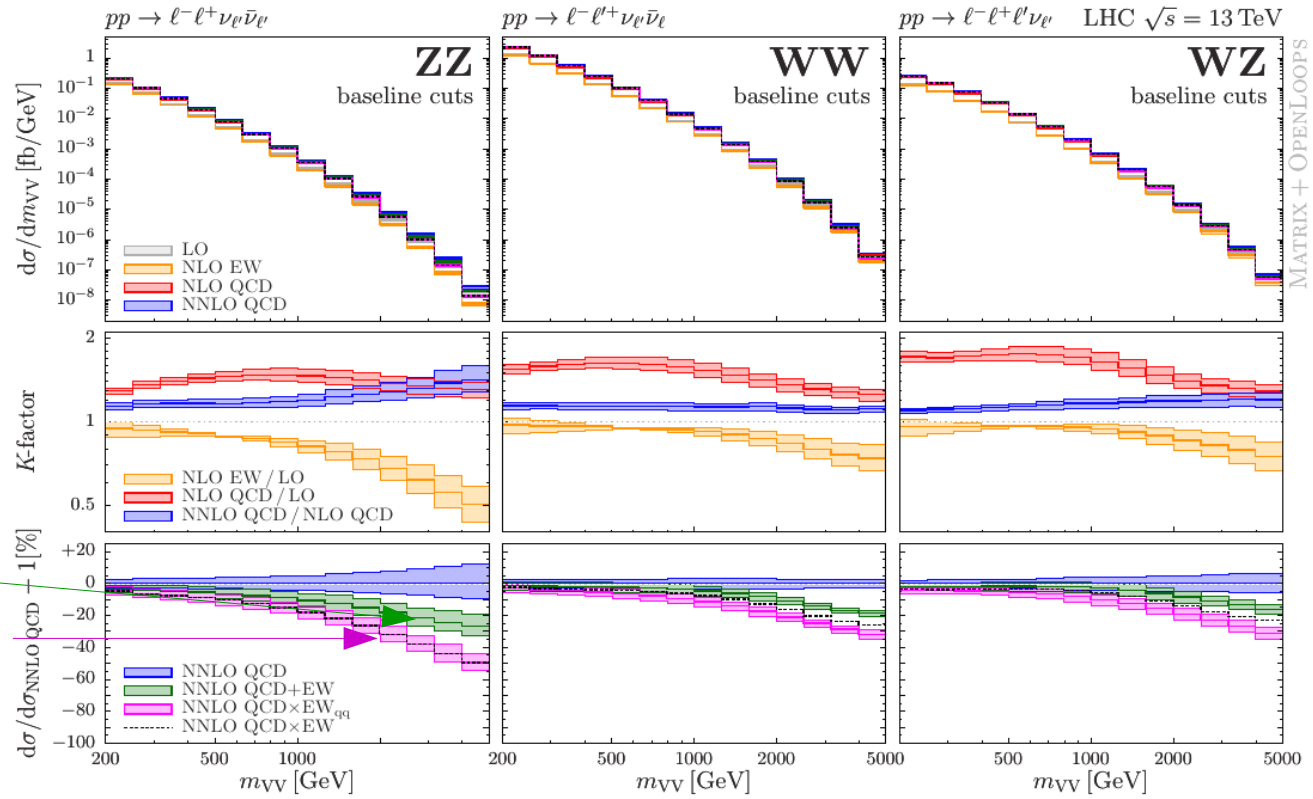
Captures EW Sudakov logs x soft QCD

(Conservative) estimate of $\mathcal{O}(\alpha_s \alpha_{\mathrm{EW}})$ effects

Higher Order Corrections: QCD and EW

Important observable for offshell studies!

NNLO QCD + NLO EW for dibosons: mVV



- NLO QCD/LO = 30-70%
- NNLO QCD/NLO = 10-20%
- NLO EW = -30/-20/-20% at 2 TeV
- multiplicative combinations should be seen as superior

Additive

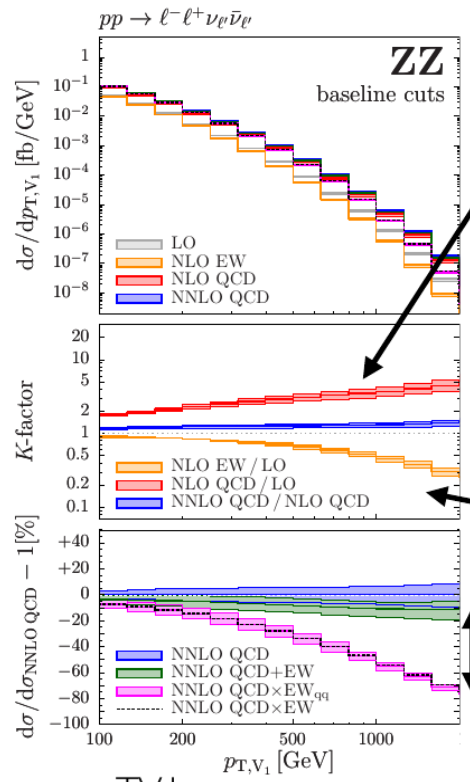
Multiplicative

Slide from Jonas Lindert

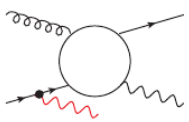
Higher Order Corrections: QCD and EW

Not always the case! -- e.g. transverse momentum of hardest EW boson

Giant QCD K-factors and EW corrections: pTV1



- NLO QCD/LO=2-5! ("giant K-factor")
- at large pTV1:VV phase-space is dominated by V+jet (w/ soft V radiation)



$$\frac{d\sigma^{V(V)j}}{d\sigma^{\mathrm{LO}}_{VV}} \propto \alpha_S \log^2\left(\frac{Q^2}{M_W^2}\right) \simeq 3 \quad \text{at} \quad Q = 1\,\mathrm{TeV}$$

- NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- NLO EW/LO=-(40-50)%
- Very large difference $d\sigma_{\mathrm{NNLO\,QCD+EW}}$ vs. $d\sigma_{\mathrm{NNLO\,QCD\times EW}}$
- Problems:
  1. In additive combination dominant Vj topology does not receive any EW corrections
  2. In multiplicative combination EW correction for VV is applied to Vj hard process
- Pragmatic solution: take average as nominal and spread as uncertainty
- Rigorous solution: merge VVj incl. EW corrections with VV retaining NNLO QCD + EW

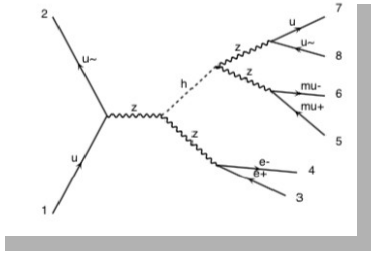
Slide from Jonas Lindert

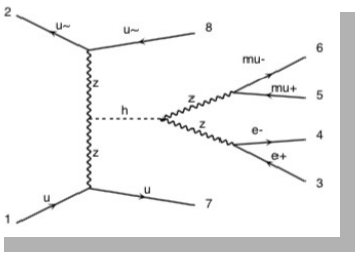
Higher Order Corrections: EW production

- Possibility to probe offshell effect in EW Higgs production: VBF and *VH.*
- Impact of higher order corrections?

Talk by Martina Javurkova

- Consider offshell *VH* and VBF production with at least two jets, generated with MadGraph and showered with Pythia.



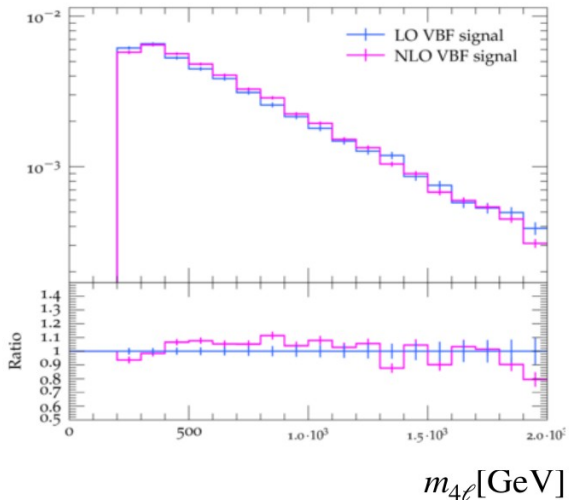


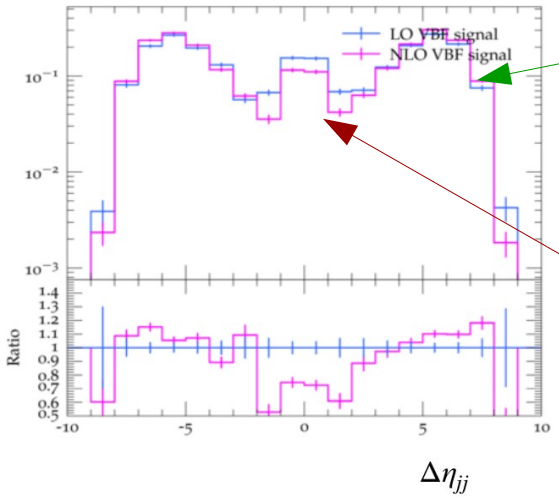
- Two caveats:
  - "Background" process (i.e. without Higgs) not considered.
  - Dipole-recoil scheme corrects for default Pythia which produces too much central radiation – might not be compatible with aMC matching.
- Work in progress
  - Include background processes (with interference).
  - Shower using HERWIG.

Higher Order Corrections: EW production

- Inclusive production with $220\ \mathrm{GeV} < m_{4\ell} < 2000\ \mathrm{GeV}$

Preliminary results!

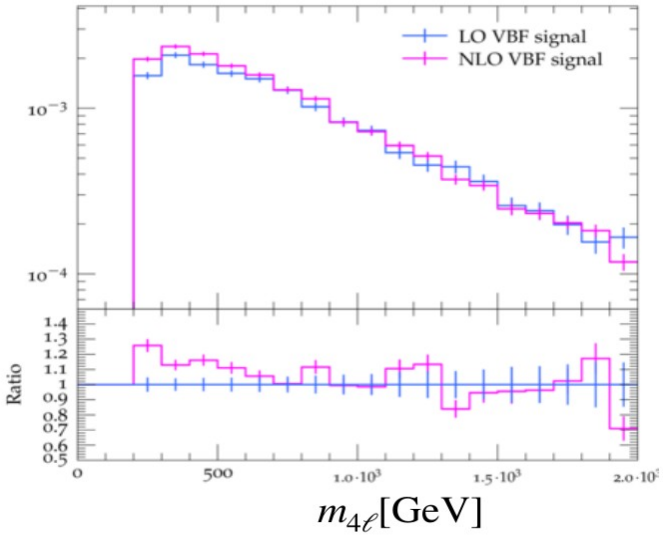




Small correction for VBF region

Large correction for small rapidity gap

- VBF-enhanced region: $\Delta\eta_{jj} > 4$



Summary

- Focuses of Offshell Subgroup:
  - **Interpretation** of offshell results, taking into account EFTs and their impact on Higgs width determinations.
  - **Tools for simulations**, considering their theoretical uncertainties.
  - **Higher order corrections** to signals, interfering and non-interfering backgrounds, primarily for gluon fusion but also EW production.
- Documentation in progress, preliminary material should be linked from our Twiki in the next few weeks.

THANK YOU FOR YOUR ATTENTION