Offshell Status

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19th Workshop of LHC Higgs Working Group

29 November 2022

Many thanks to Nikolas Kauer for all his work as Offshell Subgroup convener over the last ~ 8 years!

A Step Back...

... to 2012

- Higgs width predicted in SM $\Gamma_H \simeq 4\ \mathrm{MeV}$
  ✗ Direct measurement limited by detector resolution $\Gamma_H \lesssim 1\ \mathrm{GeV}$
- Sizeable contribution from high-energy regime: 10% of events in $gg \to H \to VV$ above the $2m_V$ threshold. [Kauer, Passarino '12]
- $\sigma^{\mathrm{onshell}}_{gg\to H\to VV} \sim \frac{c^2_{ggH} c^2_{VVH}}{m_H \Gamma_H}$ $\sigma^{\mathrm{offshell}}_{gg\to H\to VV} \sim \frac{c^2_{ggH} c^2_{VVH}}{m^2_{ZZ}}$ [Caola, Melnikov '13]
- Ratio of onshell and offshell production rates gives indirect measurement $\Gamma_H \lesssim 88\ \mathrm{MeV}$ using 7 and 8 TeV data and cut-and-count analysis.
- Included in & improved on by experimental analyses.
- Highlights importance of exploring Higgs in high-energy regime.
- Important dialogue between theory and experiment!

Recent CMS Results

Nature Physics **18**, 1329 (2022)
[hep-ex/2202.06923]

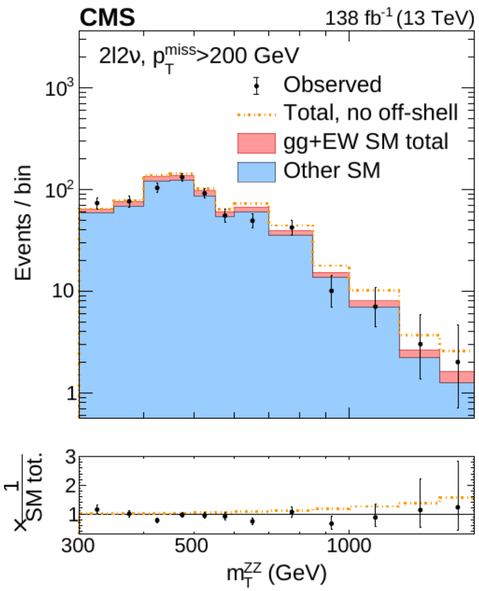
- Consider $H \to ZZ \to 4\ell$ and $H \to ZZ \to 2\ell 2\nu$
- Production modes: gluon fusion and electroweak production (VBF and VH)
- Observed evidence for offshell Higgs production at 3.6σ.
- Measure $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

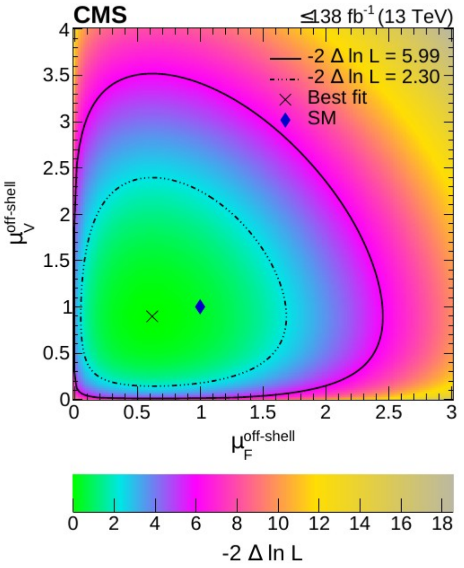
  (assuming same couplings on- and offshell)
- Offshell gluon fusion signal strength:

  $\mu_F^{\text{off.}} = 0.62^{+0.68}_{-0.45}$
- Offshell EW signal strength:

  $\mu_V^{\text{off.}} = 0.90^{+0.9}_{-0.59}$

  (at 68% C.L.)





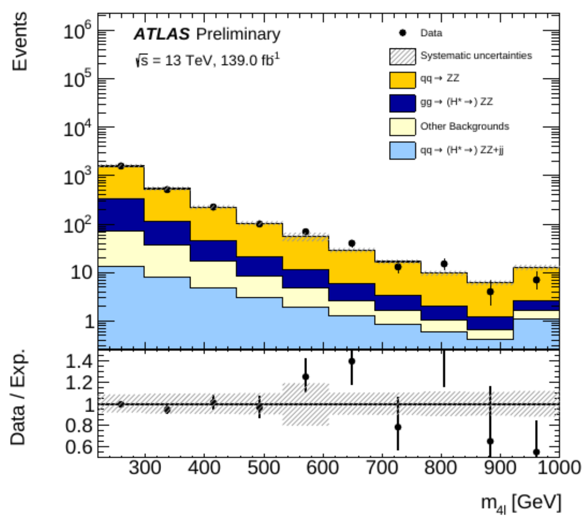
Recent ATLAS Results

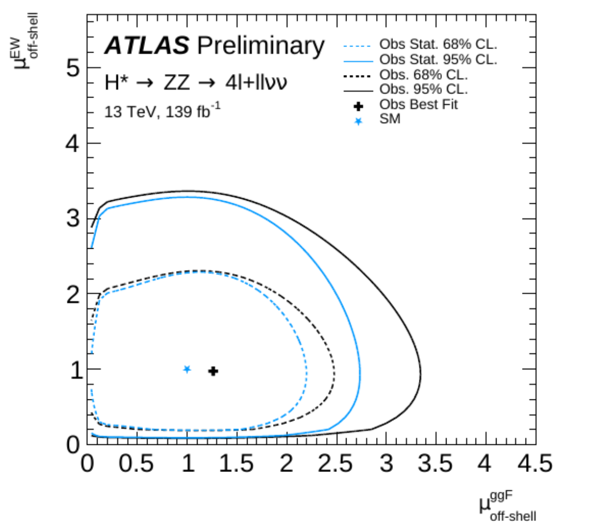
ATLAS-CONF-2022-068

- Consider $H \to ZZ \to 4\ell$ and $H \to ZZ \to 2\ell 2\nu$
- Production modes: gluon fusion and electroweak production (VBF and VH)
- Observed evidence for offshell Higgs production at 3.2σ.
- Measure $\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV (assuming same couplings on- and offshell)
- Assuming SM width:

$$\kappa^2_{g,\mathrm{off.}}/\kappa^2_{g,\mathrm{on.}} = 1.4^{+0.9}_{-1.3}$$

$$\kappa^2_{HVV,\mathrm{off.}}/\kappa^2_{HVV,\mathrm{on.}} = 0.9^{+0.4}_{-0.3}$$

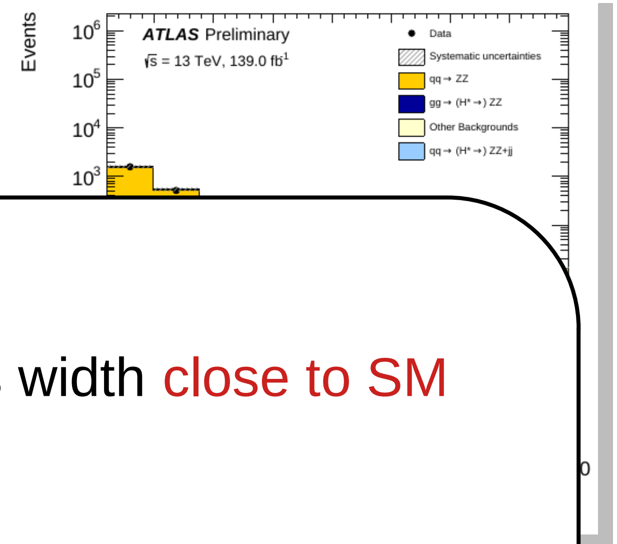


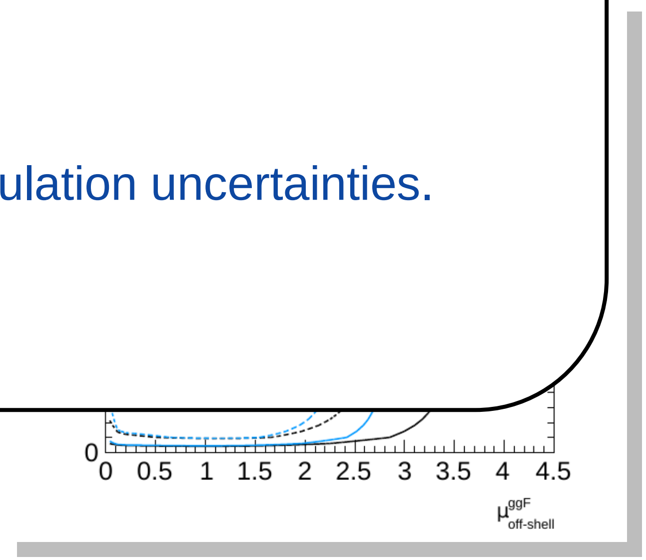


Recent ATLAS Results

ATLAS-CONF-2022-068

- Consider $H \to ZZ \to 4\ell$ and $H \to ZZ \to 2\ell 2\nu$
- P





- Both ATLAS and CMS measure Higgs width close to SM value with errors ~ 50-60%
- Remarkable progress in 10 years!
- Further improvements:
  - Interpretations of results;
  - Understanding/reducing theoretical/simulation uncertainties.

Models and EFT interpretations

LHCHWG-2022-001
[2203.02418]

LHC Higgs Working Group[a]

Public Note

Off-shell Higgs Interpretations Task Force[b]

Models and Effective Field Theories Subgroup Report

Aleksandr Azatov [1,2,c], Jorge de Blas [3,d], Adam Falkowski[4,e], Andrei V. Gritsan[5,f], Christophe Grojean[6,7,g], Lucas Kang[5,h], Nikolas Kauer[8,i] (ed.), Ennio Salvioni[9,10,j], Ulascan Sarica[11,k], Marion Thomas[12,l] and Eleni Vryonidou[12,m]

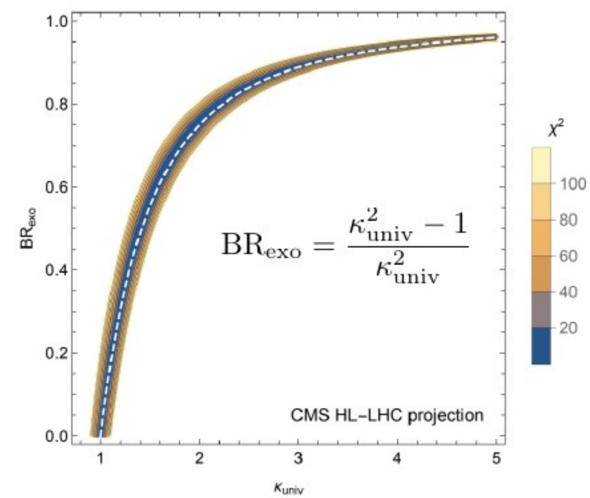
- Public Note edited by Nikolas Kauer (May 2022)
- Main goal: discuss and advance impact of off-shell measurements on BSM physics
- Mostly in EFT framework
- 56 page document: just some highlights here

Universal flat direction in on-shell data:

$$g_{hii} = \kappa_{\text{univ}}\, g_{hii}^{\text{SM}} \qquad \Gamma_h = \kappa_{\text{univ}}^4 \Gamma_h^{\text{SM}}$$

If presence of untagged partial width Γ_{exo} is assumed →

Combining with off-shell data lifts this

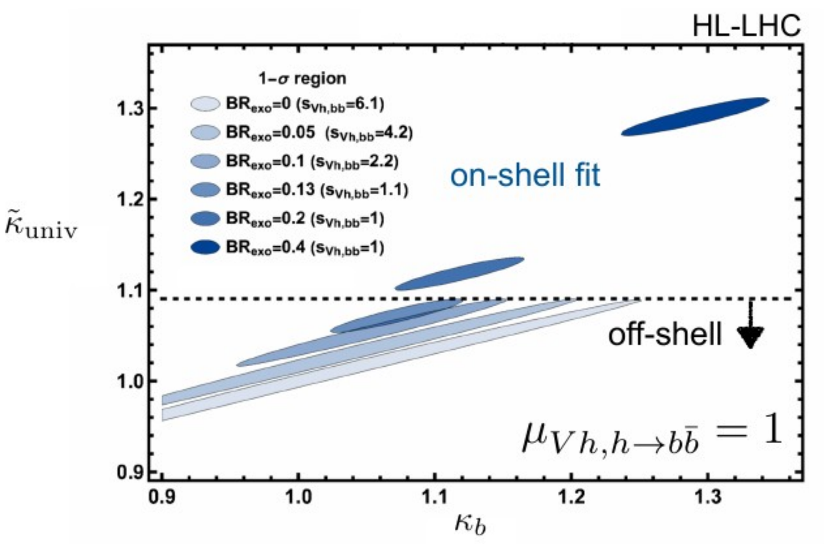


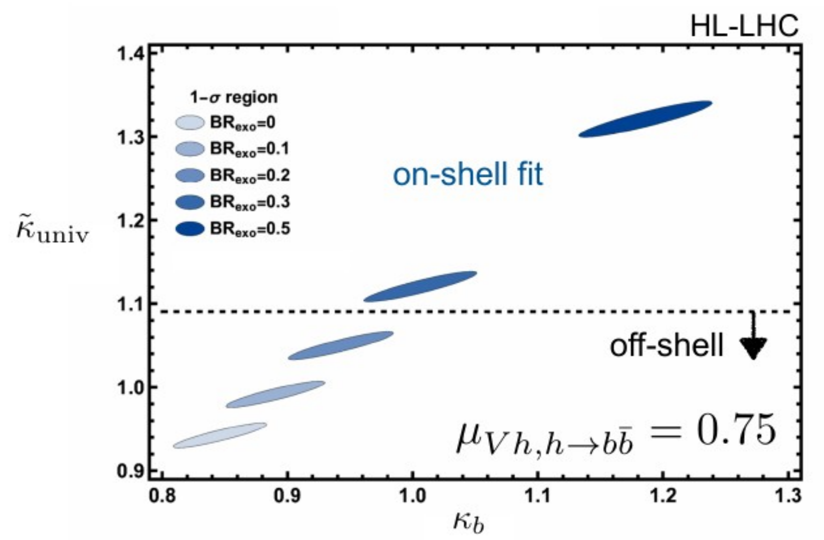
Models and EFT interpretations

- Such universal flat direction is possible in BSM, but requires a specific "compensation" effect between Higgs coupling rescaling $\kappa_{\text{univ}} > 1$ and new width
- Explore impact of off-shell on more general scenarios: relax coupling universality

$$(\tilde{\kappa}_{\text{univ}},\ \kappa_b,\ \text{BR}_{\text{exo}})$$

Complementarity with observables that probe directly $h \to b\bar{b}$





[A.Azatov,J.de Blas, C.Grojean, E.Salvioni]

Off-shell has leading sensitivity for relatively large $\text{BR}_{\text{exo}} \gtrsim 0.2$

EFT interpretations

- Studies within SMEFT: summary of Higgs basis parametrization

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{2499} C_i\, Q_i \qquad\qquad \vec{c}_{\text{HB}} = M_{W\to H}\, \vec{C}_{\text{WB}}$$

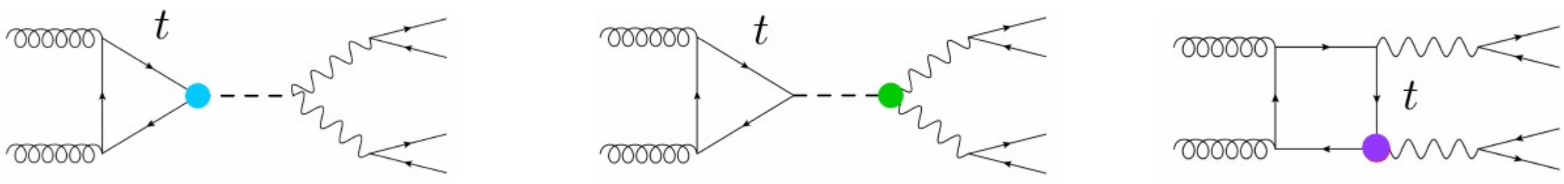
invertible matrix

Warsaw basis coefficients

[A.Falkowski]

- Subset of operators relevant for $gg \to ZZ$ (9 *CP*-even, 5 *CP*-odd coefficients)

$$\begin{aligned}\Delta\mathcal{L} = \frac{h}{v}\Big(& c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^{\mu\nu\,a} - m_t[\delta y_u]_{33}\bar{t}_L t_R + \text{h.c.} + \delta c_z \frac{g_Z^2 v^2}{4} Z_\mu Z^\mu + c_{zz}\frac{g_Z^2}{4} Z_{\mu\nu}Z^{\mu\nu} + c_{z\Box} g_L^2 Z_\mu \partial_\nu Z^{\mu\nu} \\ &+ \tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\widetilde{G}^a_{\mu\nu} + \tilde{c}_{zz}\frac{g_Z^2}{4}Z_{\mu\nu}\widetilde{Z}_{\mu\nu}\Big) - g_Z(\delta g_L^{Zu})_{33} Z_\mu \bar{t}_L\gamma^\mu t_L - g_Z(\delta g_R^{Zu})_{33} Z_\mu \bar{t}_R \gamma^\mu t_R \\ &- \frac{m_t}{4v^2}\left(1+\frac{h}{v}\right)\left(g_s \bar{t}_R\sigma^{\mu\nu}T^a[d_{Gu}]_{33} t_L G^a_{\mu\nu} + g_Z \bar{t}_R \sigma^{\mu\nu} T^a [d_{Zu}]_{33} t_L Z_{\mu\nu}\right) + \text{h.c.}\end{aligned}$$



No real "signal" vs "background" distinction:

motivated new physics can appear in Higgs diagrams, box diagrams, or both

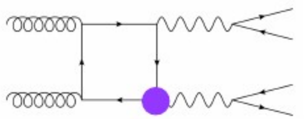
EFT interpretations

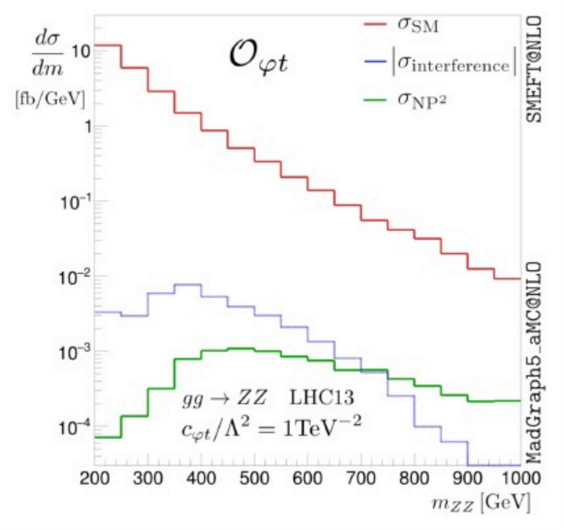
- Begin systematic assessment of impact of EFT operators in off-shell region, using SMEFT@NLO and JHUGen+MCFM

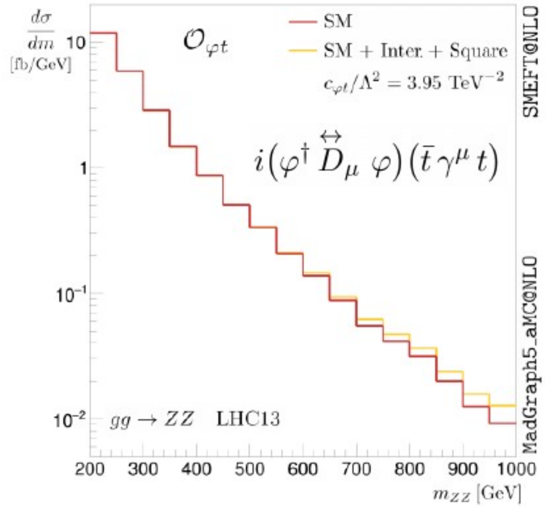
$\mathcal{O}_i$	UFO	Squared term (fb)	Interference term (fb)
$\mathcal{O}_{\varphi WB}$	cpwb	2.797(7)	118.9(3)
$\mathcal{O}_{\varphi d}$	cdp	1.273(3)	0.921(4)
$\mathcal{O}_{\varphi W}$	cpw	1.162(3)	16.83(7)
$\mathcal{O}_{\varphi B}$	cpbb	0.1083(4)	5.17(1)
$\mathcal{O}_{\varphi q}^{(3)}$	cpq3i	23.04(5)	370.0(7)
$\mathcal{O}_{\varphi q}^{(-)}$	cpqmi	0.1973(1)	34.18(7)
$\mathcal{O}_{\varphi Q}^{(3)}$	cpq3	5.78(1)	185.1(2)
$\mathcal{O}_{\varphi Q}^{(-)}$	cpqm	1.800(4)	94.5(2)
$\mathcal{O}_{\varphi u}$	cpu	0.788(2)	68.07(4)
$\mathcal{O}_{\varphi t}$	cpt	0.4794(7)	−1.85(1)
$\mathcal{O}_{\varphi d_i}$	cpd	0.434(1)	−50.5(1)
$\mathcal{O}_{t\varphi}$	ctp	0.3245(6)	−0.51(4)
$\mathcal{O}_{tZ}$	ctz	0.1546(3)	−3.53(1)
$\mathcal{O}_{tG}$	ctg	45.18(4)	0.47(6)
$\mathcal{O}_{\varphi D}$	cpdc	0.03983(3)	8.23(4)

Warsaw basis

Example: operator modifying Zt_Rt_R vertex







- SMEFT@NLO: $d\sigma/dm_{ZZ}$ distributions for bosonic and 2-fermion operators

  Important interplay with other measurements (on-shell Higgs, top, EW precision): incorporate constraints from global fits

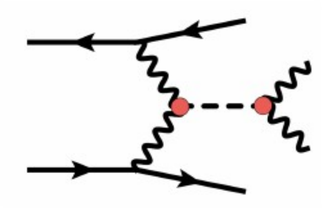
[M.Thomas, E.Vryonidou] [Ethier et al. 2105.00006]

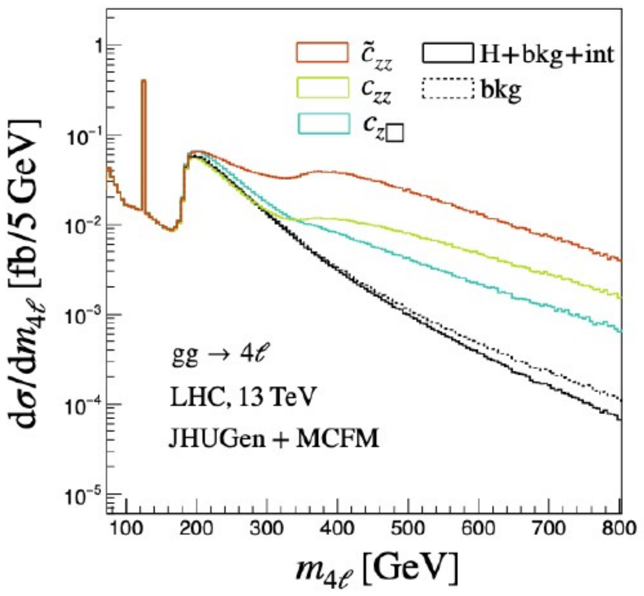
EFT interpretations

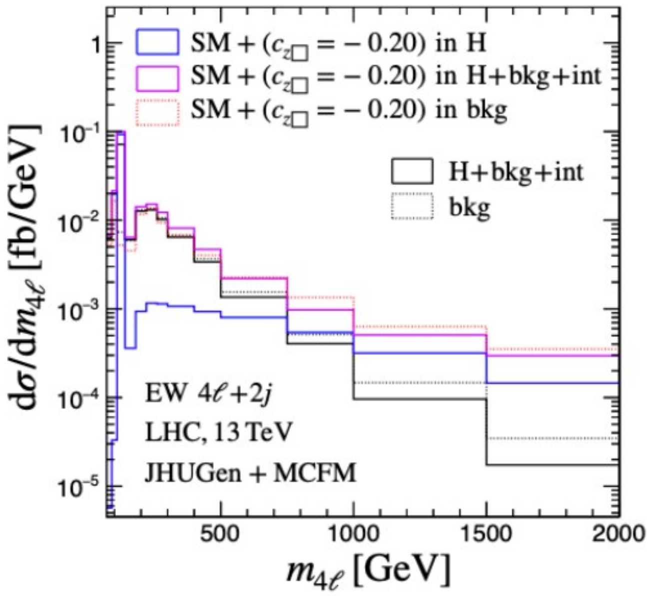
- Begin systematic assessment of impact of EFT operators in off-shell region, using SMEFT@NLO and JHUGen+MCFM

- JHUGen+MCFM: include also EW production

  Focusing on hVV modifications (Higgs basis):







[A.Gritsan, L.Kang, U.Sarica]

[Gritsan et al. 2002.09888]

EFT interpretations: plans

- Goal: for each SMEFT operator that can in principle contribute to off-shell region, assess impact after accounting for constraints from other measurements

→ systematically identify EFT directions where off-shell has most competitive sensitivity

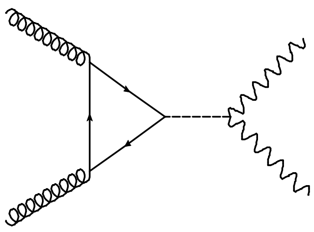
- Start from simple observables (ex.: m_{VV}), then focus on most relevant subset of operators and study more refined approach
- Fully understand interplay of ggF versus EW productions
- Estimates of higher order corrections in SMEFT?

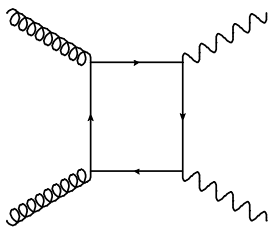
- Complementarity of generators: for *CP*-odd effects need JHUGen+MCFM, for ttZ and dipoles need SMEFT@NLO
- Basis translations using Rosetta and JHUGenLexicon
- Suggested timeline: Summer 2023. Slides of kick-off discussion (Nov 16) available at:

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWGOFFSHELL

Offshell Higgs calculations

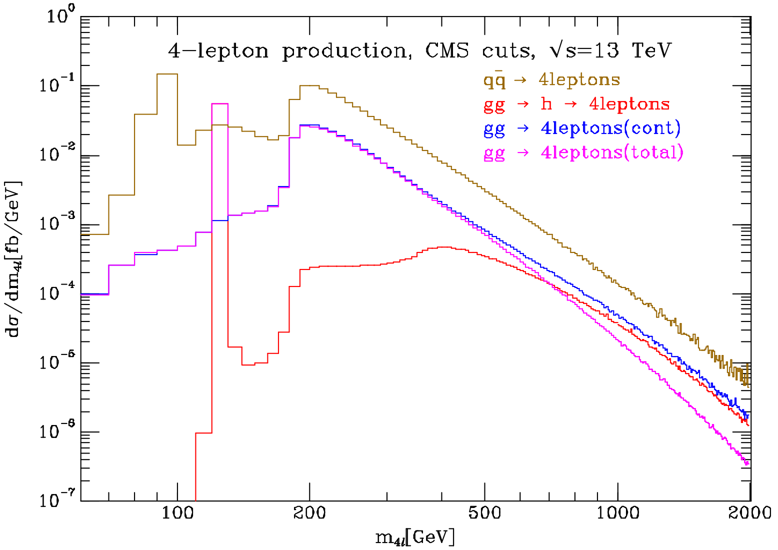
- Need to consider:
  - Signal $gg \to H^* \to VV$
  - Background $gg \to VV$
  - Interference
  - Full (physical) result S+B+I





$$|A_{ZZ}|^2 = |A_s|^2 + |A_b|^2 + 2\mathrm{Re}[A_s A_b^*] \ \to \sigma_{\mathrm{full}} = \sigma_{\mathrm{sigl}} + \sigma_{\mathrm{bkgd}} + \sigma_{\mathrm{intf}}$$

- Strong destructive interference at high energies.

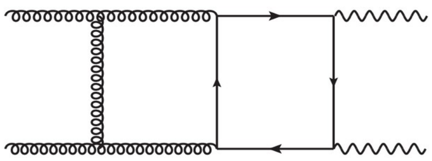


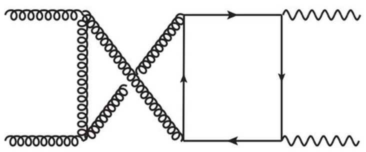
[Campbell, Ellis, Williams ('13)]

Higher order corrections: Status

- Corrections to background $gg \to VV$ very difficult to compute!
- Two-loop QCD amplitudes for $gg \to ZZ$ and $gg \to WW$ including massive quark effects now known.

[Agarwal, Jones, von Manteuffel (‘20); Brønnum-Hansen, Chen (‘20,’21)]





- Substantial computing resources required: still not used in cross section calculations...
- Exact NLO corrections to $gg \to H \to VV$ still not known:
  - Approximations in heavy top limit or with reweighting of two-loop amplitudes.

    [Campbell, Czakon, Ellis, Kirchner (‘15); Caola, Dowling, Melnikov, RR, Tancredi (‘15); Grazzini, Kallweit, Wiesemann, Yook (19, ‘20, ‘21)]

  - Matched to parton showers in POWHEG-BOX.

    [Alioli, Ferrario Ravasio, Lindert, RR (‘21)]

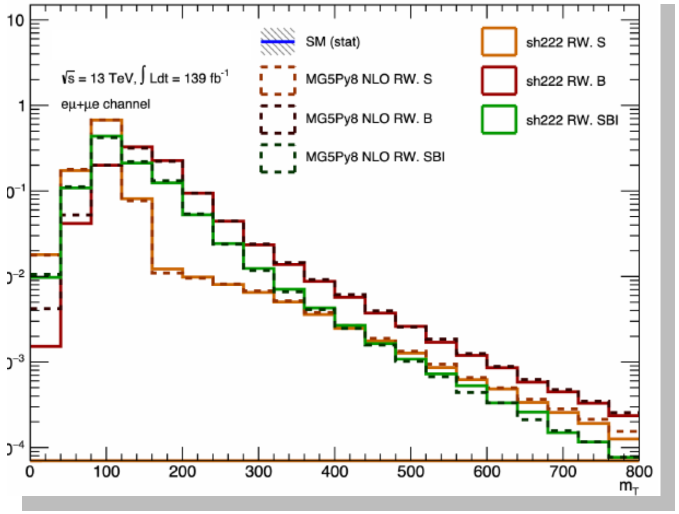
Higher Order Corrections: Jet Merging

- Radiative corrections taken into account using jet merging:
  - Up to 1 or 2 jets, generated according to matrix elements.
  - Virtual corrections not included.
- PS matching:
  - Hardest jet generated according to matrix elements.
  - Softer jets generated through PS.
  - Virtual corrections included.
- Combined study of jet merging and parton shower effects.
- Recent meeting in October.

Jet Merging and Parton Shower Matching

Highlight two studies:

- $gg \to (H^*) \to WW + 0/1\,\mathrm{j}$ generated with `SHERPA 2.2.2.`
- Merged using MLM merging.
- Fixed order k-factors applied to m_{WW} distribution at LO (generated with `MG5+PYTHIA)`
  - ➔ NLO sample differential in m_{WW}
- `SHERPA` sample reweighted to $m_{WW.}$
- Done separately for signal (S), background (B) and S+B+interferfence (SBI).

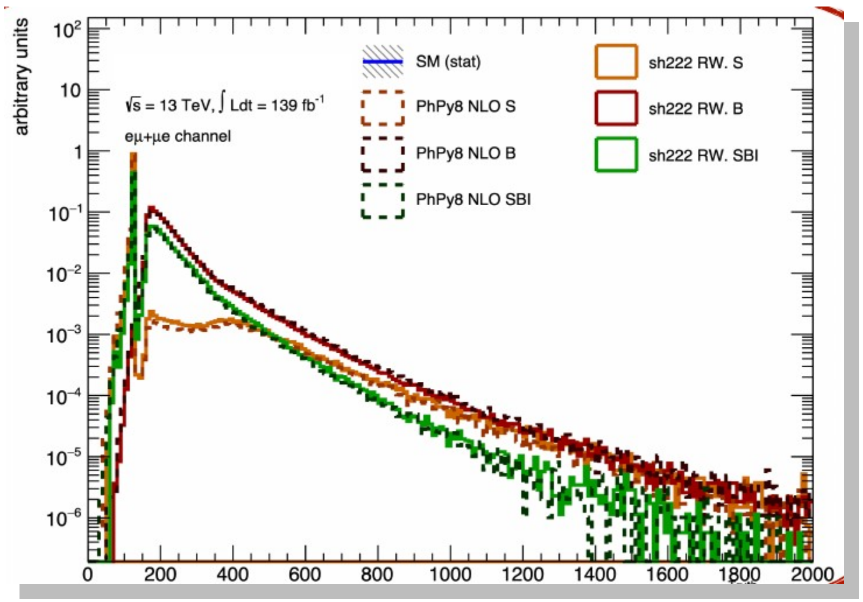


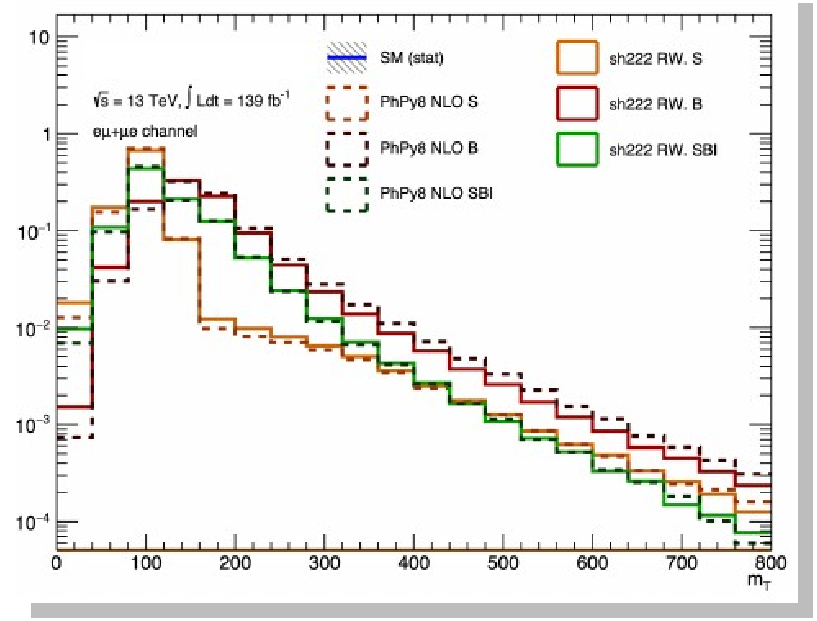
➡ 1-D reweighting looks promising...

Talk by B. Kortman

Jet Merging and Parton Shower Matching

- Compare reweighted 0+1 jet merged `SHERPA` samples against `POWHEG-BOX-gg4l+PHYTHIA`.



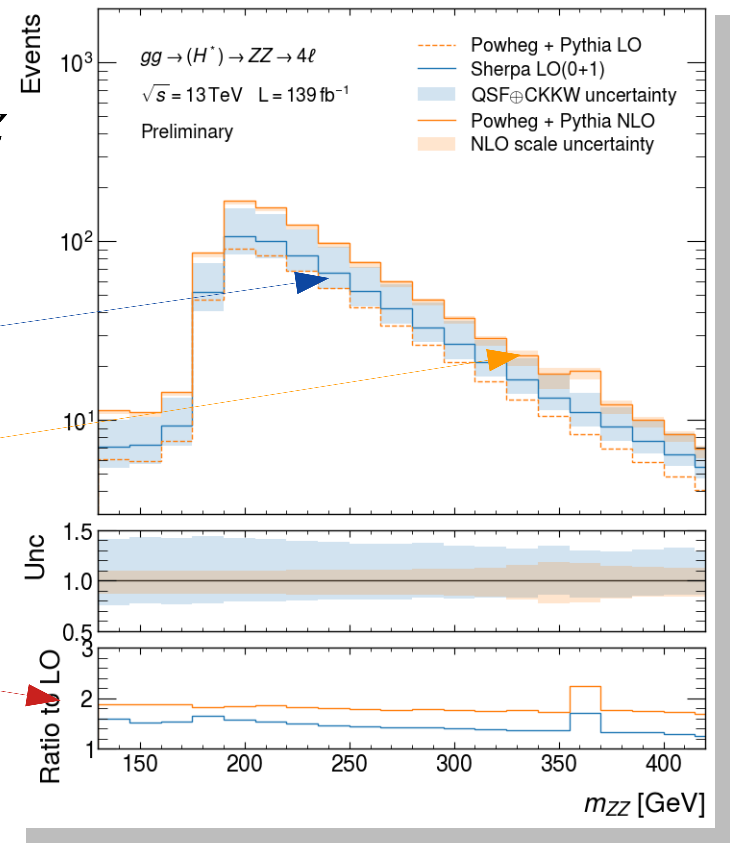


- Not more than 5% difference in normalized distributions.
- Further studies: compare parton shower and merging scale uncertainties; compare samples in different jet multiplicities, ...

Talk by B. Kortman

Jet Merging and Parton Shower Matching

- Preliminary comparisons for $gg \to (H^*) \to ZZ$



- Very large jet merging uncertainty, much smaller NLO uncertainty.
- Shape of merged 0+1jet similar to that of NLO+PS.
- Merging uncertainty is one of main systematics in recent ATLAS measurement – NLO+PS could lead to improved measurements.

Offshell Higgs simulation in CMS

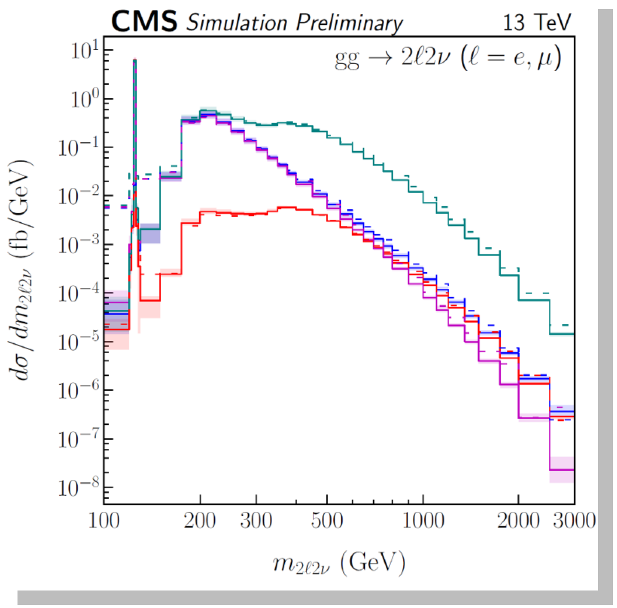
[CMS Note] Talk by U. Sarica

Comparison of parton shower tools:

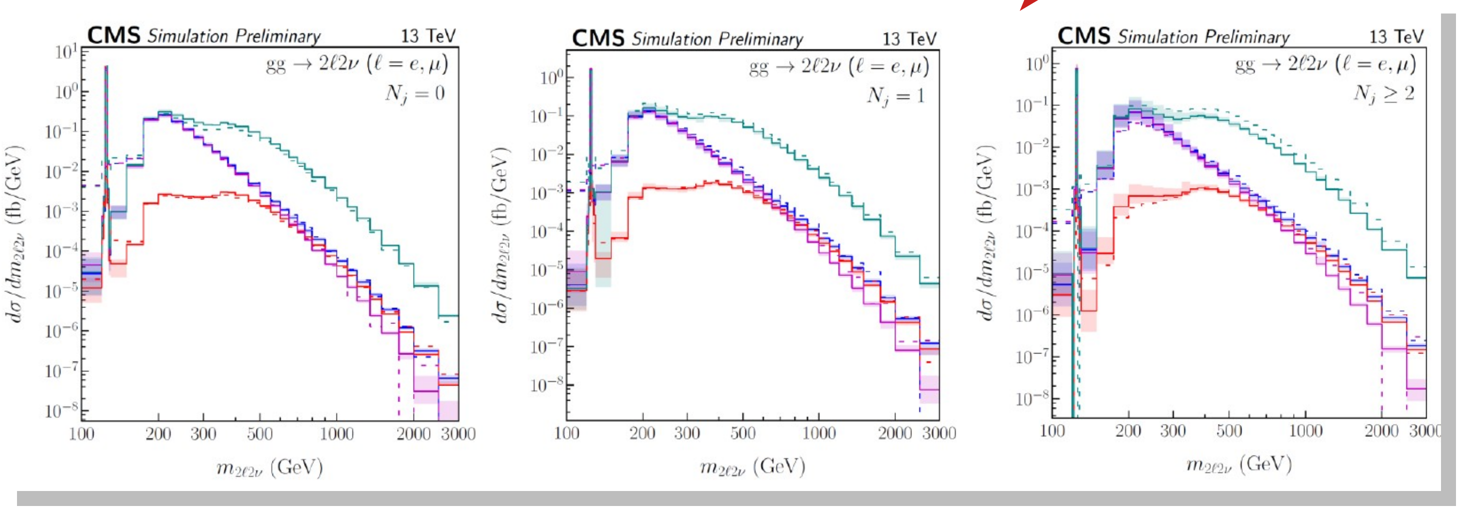
- LO generator with k-factors + parton shower:
  - LO samples from `JHUGen/MCFM` for signal, background and interference.
  - Apply NNLO signal k-factors for m_{ZZ} & N3LO normalization.

    (Assumption: k-factors similar across signal, background and interference.)
  - Generate jets using `PYTHIA`.
- NLO generator + parton shower:
  - NLO samples for Higgs production from `POWHEG` using different Higgs masses, reweighted to NNLO in m_{ZZ}.
  - Decay $H \rightarrow ZZ$ from `JHUGen`.
  - Generate jets using `PYTHIA`.
  - Reweighting of propagator to $m_H = 125$ GeV using MELA.

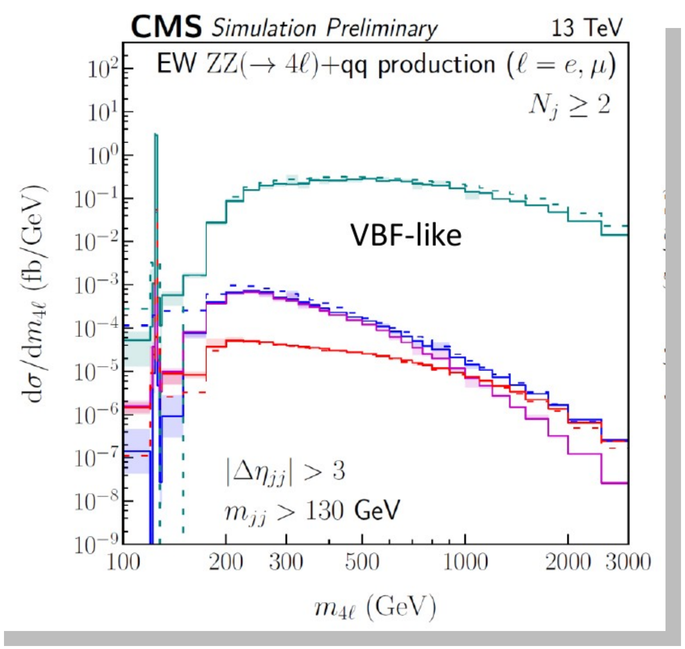
Offshell Higgs simulation in CMS

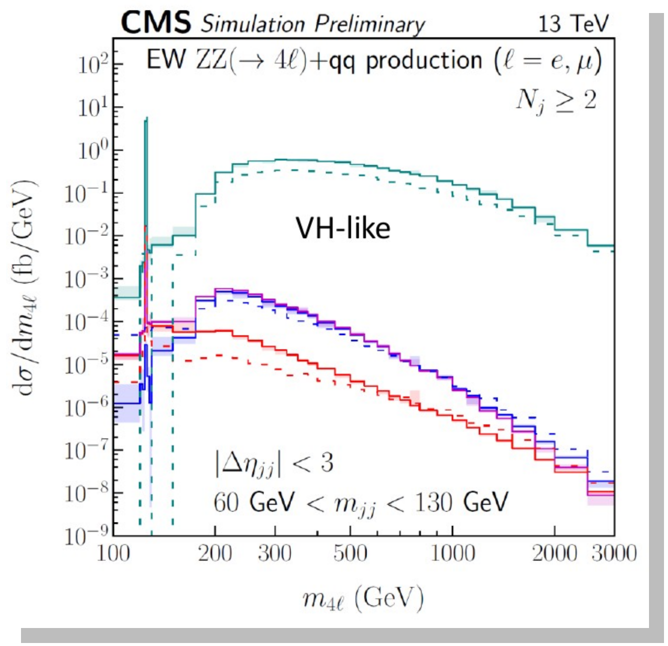


- Gluon fusion: extremely good agreement, also in jet-binned distributions.



Offshell Higgs simulation in CMS





- Decent agreement for VBF-like topology.
- Disagreement for VH-like topology.

Summary

- **Incredible progress in offshell studies over last decade:**
  - ATLAS and CMS have evidence for offshell production.
  - ATLAS: $\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV
- Identified relevant EFT operators for offshell production and assessed their impacts.
- Future plans: systematic identification of EFT operators which are most sensitive to offshell effects.
- Work in progress: comparison of simulation tools using parton shower matching and jet merging.
- Welcome new ideas and contributors!
- Twiki

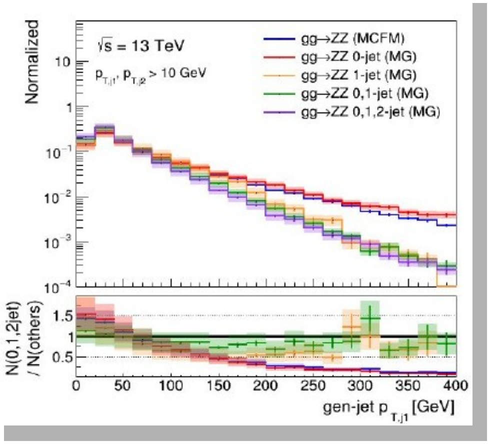
THANK YOU FOR YOUR ATTENTION

Higher Order Corrections: Jet Merging and PS

Use merging to simulate effect of additional radiation.

[Li *et al.* ‘20] [Talk by C. Li]

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



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

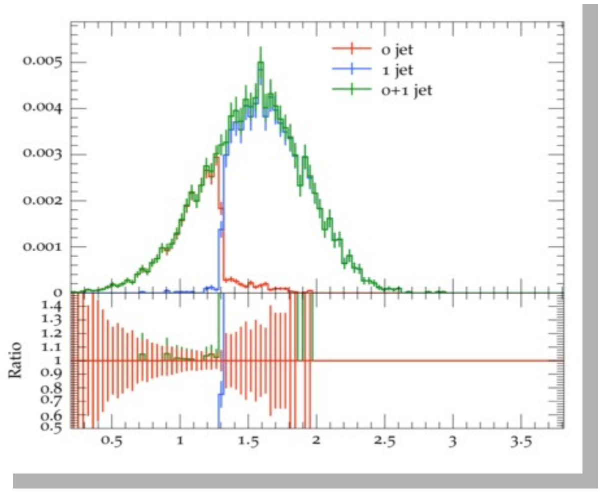
Massive increase in computational time for 2 jet emission!

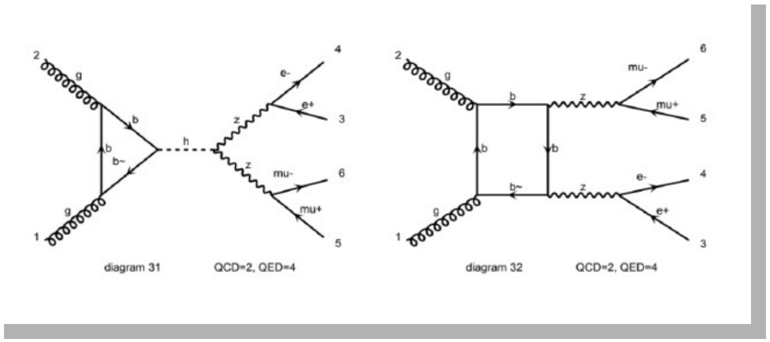
Higher Order Corrections: Jet Merging and PS

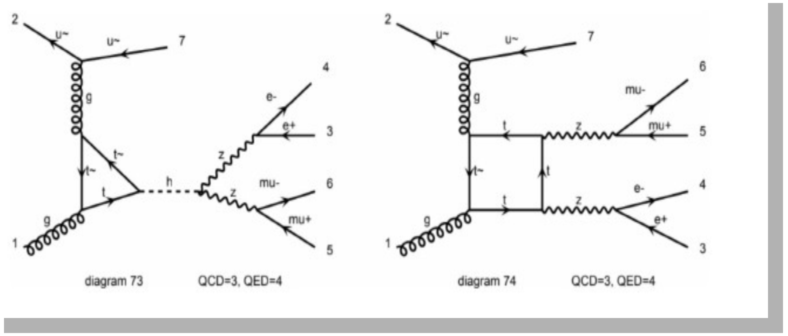
Use merging to simulate effect of additional radiation.

Talk by J. Sandesara

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







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