Theory Overview of Offshell Higgs Physics

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UNIVERSITÀ DEGLI STUDI DI MILANO
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Disclaimer

- I will give an overview of the successes, opportunities and challenges for Higgs studies in the offshell regime.
- Try to be as comprehensive as possible.
- Focus mostly on Higgs production through gluon fusion and decay to massive EW boson pair, $gg \to (H) \to VV$.
- Will not discuss:
  - Non-interfering *VV* background → John's talk
  - BSM effects (including SMEFT) → Alejo's talk

Why study the Higgs boson?

Goals of Higgs physics studies:

- Determine properties of Higgs boson (mass, spin, CP properties, …).
- Determine interactions with other SM particles.

→ **Is the Higgs (solely) responsible for EWSB?**

- Can the Higgs lead us to NP?

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Prediction in SM:

Coupling to Higgs is proportional to mass

$$g_{Hf\bar{f}} \sim \frac{m_f}{v} \qquad g_{HVV} \sim M_V$$

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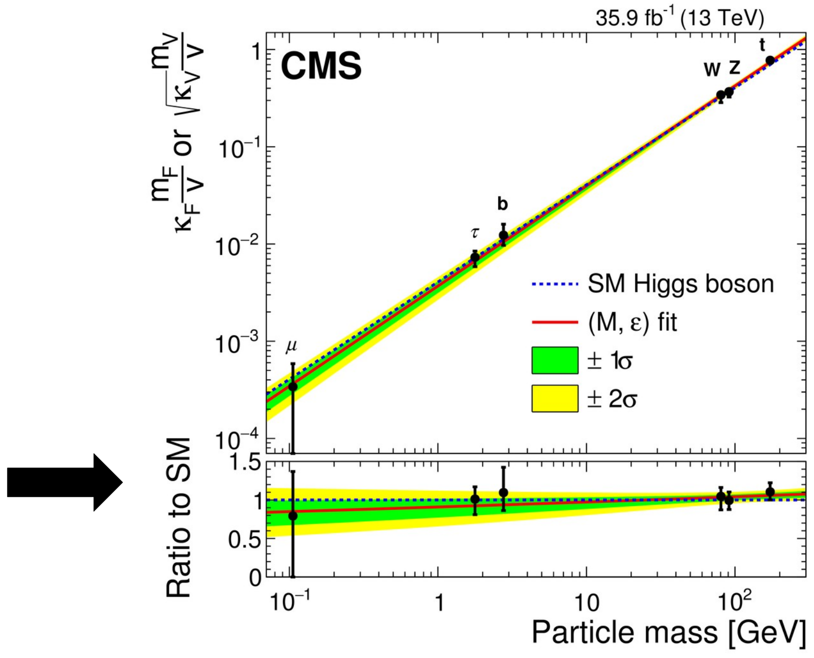
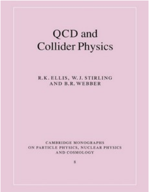
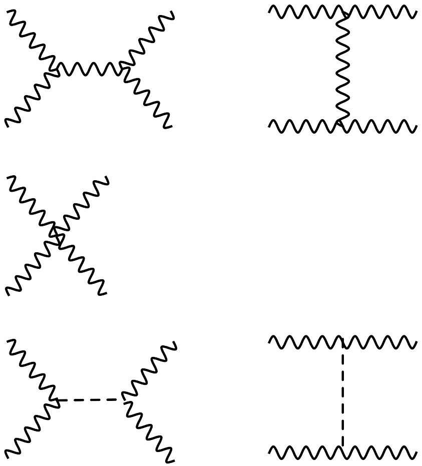


Unitarization of massive amplitudes

Apart from generating masses, EWSB mechanism also unitarizes massive scattering amplitudes.

Textbook example: $W^+(p_+) + W^-(p_-) \to W^+(k_1) + W^-(k_2)$ $\qquad p_\pm = (E, 0, 0, \pm p)$





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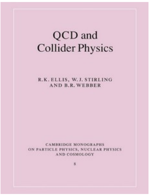

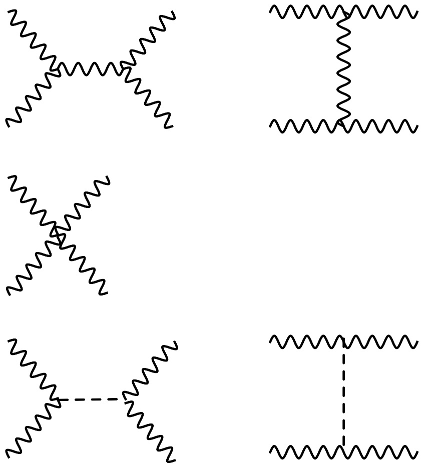

$$\sim A\left(\frac{p^2}{m_W^2}\right)^2 + B\left(\frac{p^2}{m_W^2}\right)$$

$$\sim -A\left(\frac{p^2}{m_W^2}\right)^2 + \tilde{B}\left(\frac{p^2}{m_W^2}\right)$$

Violation of unitarity due to longitudinal vector boson modes.

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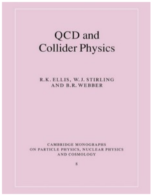

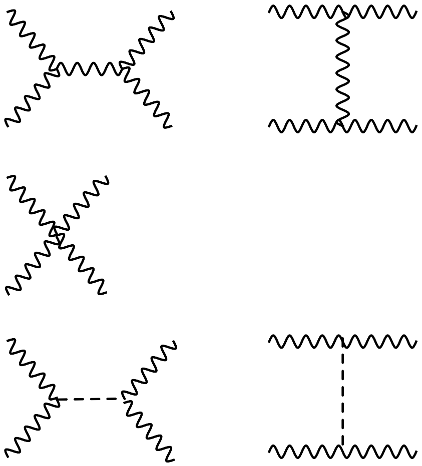

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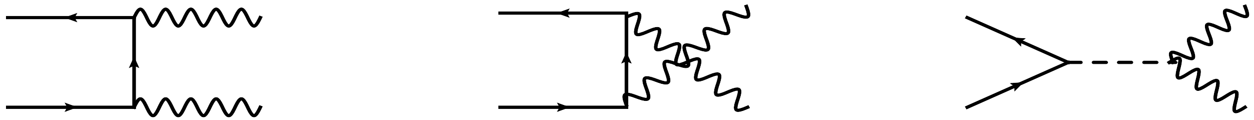
→ Violation of unitarity due to longitudinal vector boson modes.

$$\sim -(B + \tilde{B})\frac{p^2}{m_W^2}$$

→ Higgs boson cancels out high-energy behavior of longitudinal modes – amplitude remains finite in high-energy limit.

Unitarization of massive amplitudes

The same thing happens in e.g. $t\bar{t} \to VV$



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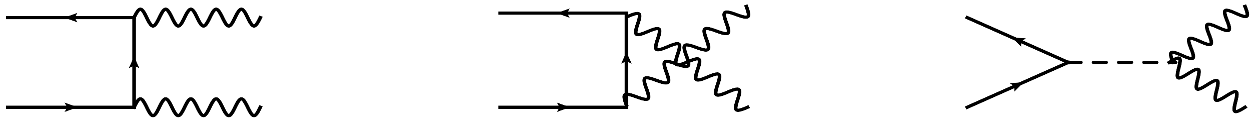
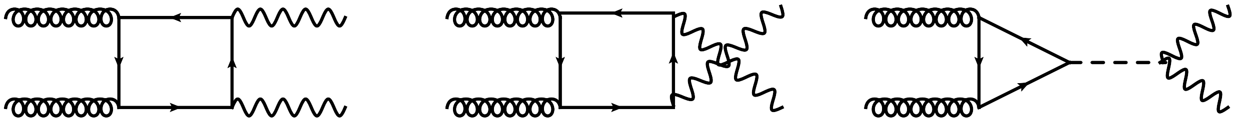


… and in $gg \to (H) \to VV$



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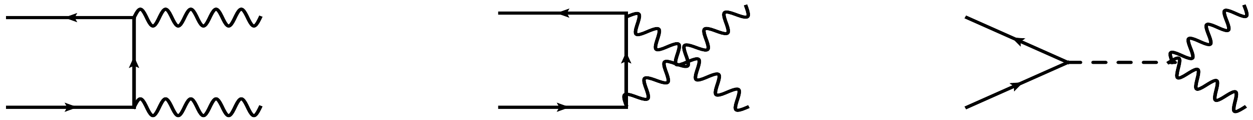

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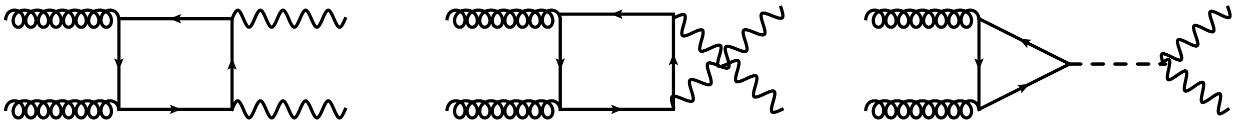


Studying offshell Higgs production allows us to confirm that the Higgs is indeed unitarizing scattering amplitudes – essential part of EWSB.

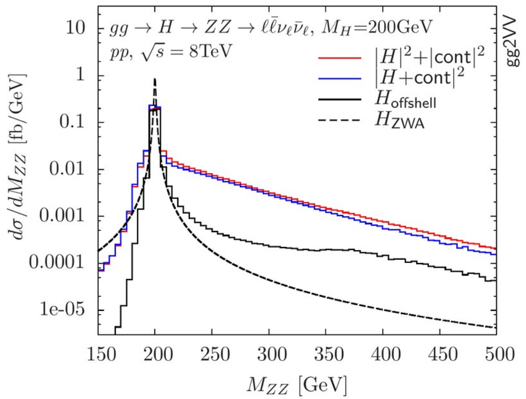
Offshell Higgs

➡ $gg \to H \to VV$ must have a large contribution in the offshell region.

- ~ 10% of events have $m_{VV} > 2m_V$. [Kauer, Passarino (2012); Kauer (2013)]
- Contrary to expectations from narrow width approximation:

$$\frac{\Gamma_H}{m_H} \simeq \frac{4\ \text{MeV}}{125\ \text{GeV}} \sim 10^{-5}$$

→ Naively expect a very narrow resonance and hence offshell cross section highly suppressed.



[Kauer, Passarino, 2012]:

- Instead, relatively large number of offshell events – dramatic failure of NWA.
- *What else can we do with offshell Higgs?*

Higgs Width Determination

- Direct measurement of Higgs width limited by detector resolution:

  $\Gamma_H \lesssim 1\ \mathrm{GeV}$ with $\Gamma_H^{\mathrm{SM}} \simeq 4\ \mathrm{MeV}$

- Consider $i \to H \to f$:
- Onshell cross section: $M_{VV} \approx m_H^2$ $\sigma \propto g_i^2 g_f^2 / \Gamma_H$
- Offshell cross section: $M_{VV} \gg m_H^2$ $\sigma \propto g_i^2 g_f^2$

[Caola, Melnikov (2013)]

- Consider rescaling couplings and width such that onshell rate is unchanged:

  $g_i \to \alpha g_i; \quad \Gamma_H \to \alpha^4 \Gamma_H$

- Offshell cross section is $\sigma_{\mathrm{off}} = \alpha^4 \sigma_H^{\mathrm{off}} - \alpha^2 \sigma_{\mathrm{intf}} = \frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}} \sigma_H^{\mathrm{off}} - \sqrt{\frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}}} \sigma_{\mathrm{intf}}$

Interference term with different scaling of width!

- Comparing this with number of observed events → bound on Higgs width.

Higgs Width Determination

- Cut-and-count: $\Gamma_H \lesssim 21 \times \Gamma_H^{\mathrm{SM}}$ [Caola, Melnikov (2013)]
- Matrix element methods: $\Gamma_H \lesssim 25 \times \Gamma_H^{\mathrm{SM}}$ [Campbell, Ellis, Williams (2013)]
- $H \to WW$ $\Gamma_H \lesssim 45 \times \Gamma_H^{\mathrm{SM}}$ [Campbell, Ellis, Williams (2013)]

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10 years of work….

ATLAS: $\Gamma_H = 4.5^{+3.3}_{-2.5}\ \mathrm{MeV}$

CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}\ \mathrm{MeV}$

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Remarkable progress: from constraint of three orders of magnitude to 50% error in a decade!

Caveat

- Underlying assumption: Higgs onshell couplings same as offshell couplings.
- Valid in SM, but Higgs width fully predicted by SM → consistency check.
- New Physics could change the behavior of the couplings in such a way that the Higgs width is the same as in SM!

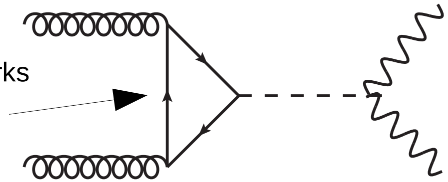
[Englert, Spannowksy (2014); Englert, Soreq, Spannowsky (2014), Azatov,Grojean, Paul, Salvioni (2016), ...]

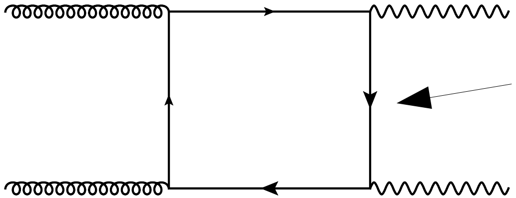
- Parametrize couplings using e.g. SMEFT and perform simultaneous determinations of these and Higgs width using offshell data.
- → constraints on light quark Yukawa couplings. [Balzani, Gröber, Vitti (2023)]

→ Talk by Alejo

Ingredients for theoretical predictions

Need to include both signal and background amplitudes:





"signal" A_s "background" A_b

$$|A_{ZZ}|^2 = |A_s|^2 + |A_b|^2 + 2\mathrm{Re}[{}_s A_b^*]$$

$$\rightarrow \sigma_{\mathrm{full}} = \sigma_{\mathrm{sigl}} + \sigma_{\mathrm{bkgd}} + \sigma_{\mathrm{intf}}$$

Physical observable

Large and negative

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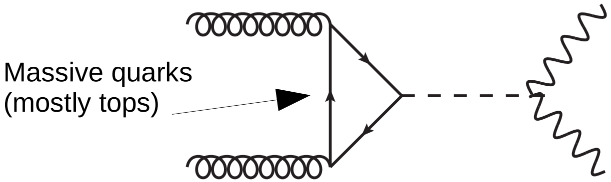

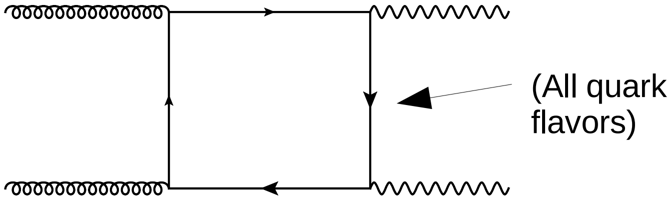

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Physical observable

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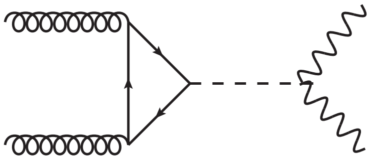
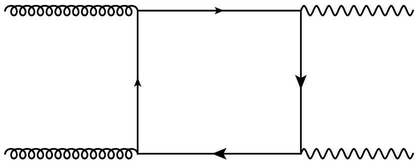
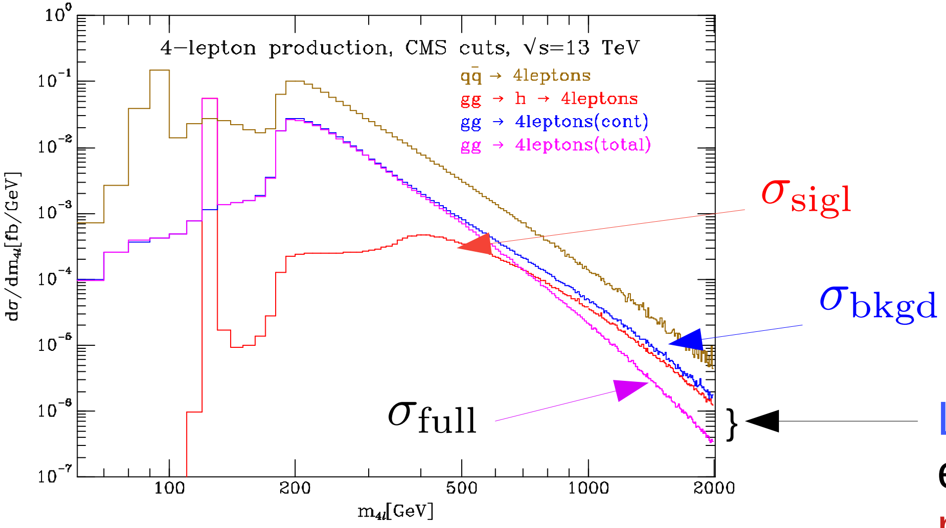
Loop-induced processes → challenging calculations!

Leading order results







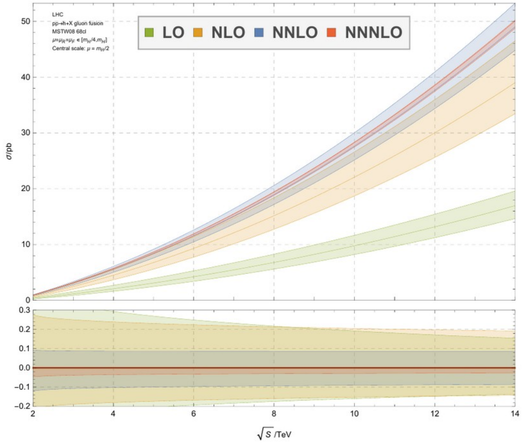
[Campbell, Ellis, Williams (2013)]

- Stable V bosons [Dicus, Kao, Repko (1987); Glover, van der Bij (1989)]
- Including decays [Matsuura, van der Bij (1991); Zecher, Matsuura, van der Bij (1994)]
- `gg2VV` [Binoth, Kauer, Mertsch (2008)]
- `MCFM` [Campbell, Ellis, Williams (2011)]

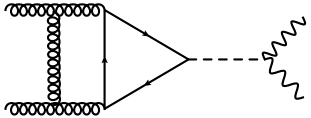
Large destructive interference at high energies – sign of Higgs unitarizing massive scattering amplitudes.

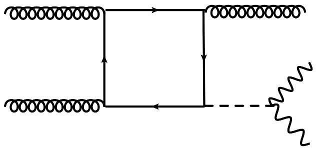
NLO Calculations

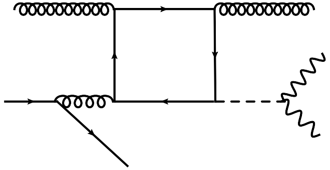
- Observe **large QCD corrections** to Higgs production through gluon fusion in infinite top limit.
- Two challenges in computing higher order results:
  - Loop amplitude
  - IR singularities
- Since LO process is loop-induced, NLO results requires two-loop amplitude **– bottleneck.**
- IR singularities are NLO-like and can be treated with standard NLO subtraction techniques.
- Relevant amplitudes for signal process have been known for many years.



[Anastasiou, Duhr, Dulat, Herzog, Mistlberger, (2015)]







[Dawson (1991)
Djouadi, Spira, Zerwas (1991);
Djouadi, Graudenz, Spira, Zerwas (1995)
Harlander, Kant (2005)
Anastasiou, Beerli, Bucherer, Daleo, Kunszt (2006)
Aglietti, Bonciani, Degrassi, Vicini (2007)]

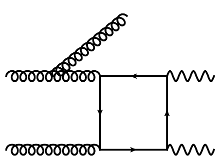
[Ellis, Hinchcliffe, Soldate, van der Bij (1988)
Baur, Glover, van der Bij (1991)]

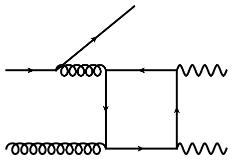
+ modern one-loop generators, e.g.

- MadGraph [Alwall et al, (2014)]
- OpenLoops [Cascioli, Maierhöfer, Pozzorini (2012); Buccioni, Pozzorini, Zoller (2018); Buccioni et al (2019)]
- ...

NLO Calculations

Background amplitudes are more demanding:

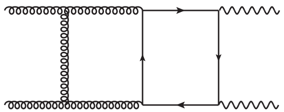




Massless quarks: analytic results

[Caola, Melnikov, RR, Tancredi (2015)]

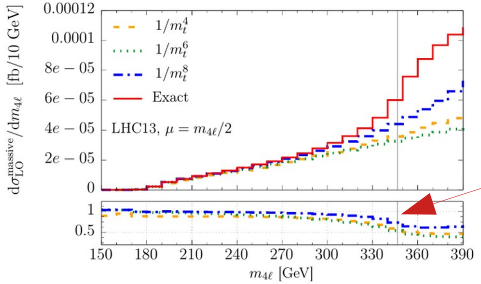
Massless + massive quarks: automated one-loop tools `(OpenLoops, MadGraph,...)`



- Massless quarks: challenging but achievable

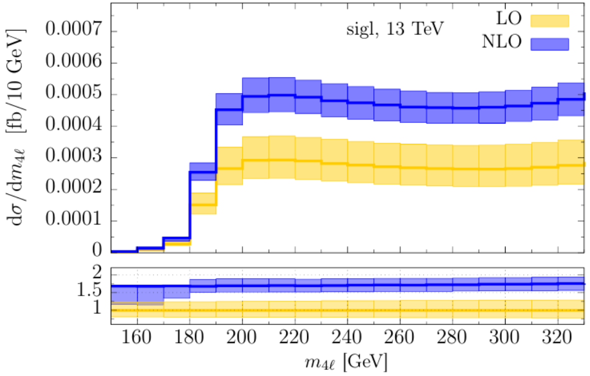
  [von Manteuffel, Tancredi (2015); Caola, Henn, Melnikov, Smirnov, Smirnov (2015)]
- **Massive quarks in the loop: very demanding – bottleneck for many years**
- Computed using expansion in $1/m_t$

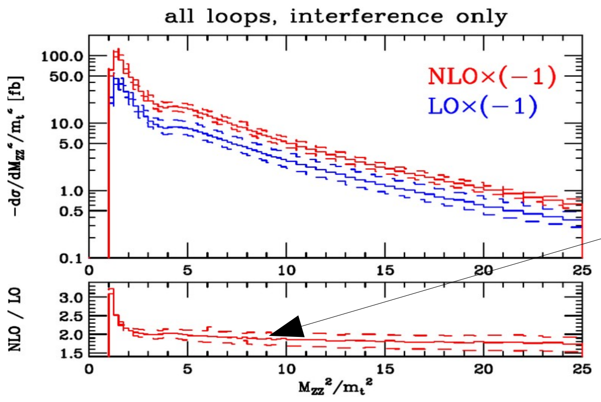
  [Dowling, Melnikov (2015); Czakon, Campbell, Kirchner, Ellis (2016); Caola, Dowling, Melnikov, RR, Tancredi (2016)]



- Expansion valid for $m_{VV} < 2m_t$.
- Breaks down above top-pair production threshold.

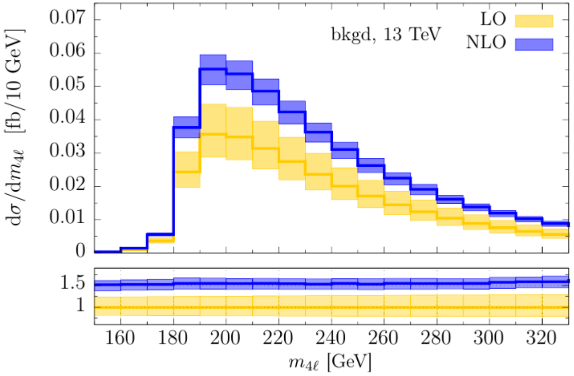
NLO results: *ZZ* final state

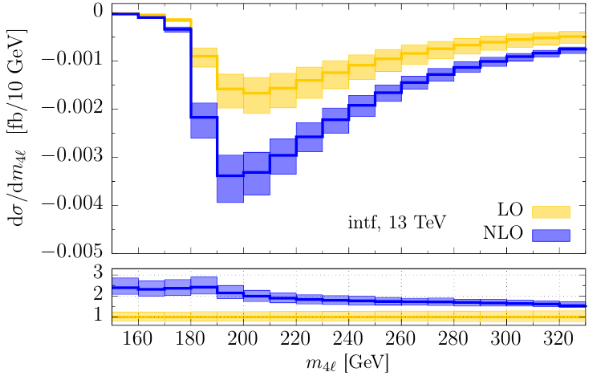




[Czakon, Campbell, Kirchner, Ellis (2016)]

Padé approximant above top-pair threshold.





[Caola, Dowling, Melnikov, RR, Tancredi (2016)]

- Minor differences between two calculations, but qualitative agreement on impact of NLO effects.
- Corrections for signal, background, interference are large and similar, but not identical.
- Similar results for *WW* final state.

NLO Results

- NLO corrections combined with NNLO QCD + NLO EW results for *ZZ* production:

  [Grazzini, Kallweit, Wiesemann, Yook (2018), (2021)]

  - All partonic channels included.
  - Two-loop background amplitudes estimated through reweighting procedure.
  - Idea: Assume QCD effects are similar for massless and massive quark loops.

$$\frac{A_b^{2-\text{loop}}(u,d,s,c,b,t)}{A_b^{1-\text{loop}}(u,d,s,c,b,t)} \approx \frac{A^{2-\text{loop}}{}_b(u,d,s,c,b)}{A_b^{1-\text{loop}}(u,d,s,c,b)}$$

$$\Rightarrow A_b^{2-\text{loop,rwgt.}}(u,d,s,c,b,t) = \frac{A_b^{2-\text{loop}}(u,d,s,c,b)}{A_b^{1-\text{loop}}(u,d,s,c,b)} A_b^{1-\text{loop}}(u,d,s,c,b,t)$$

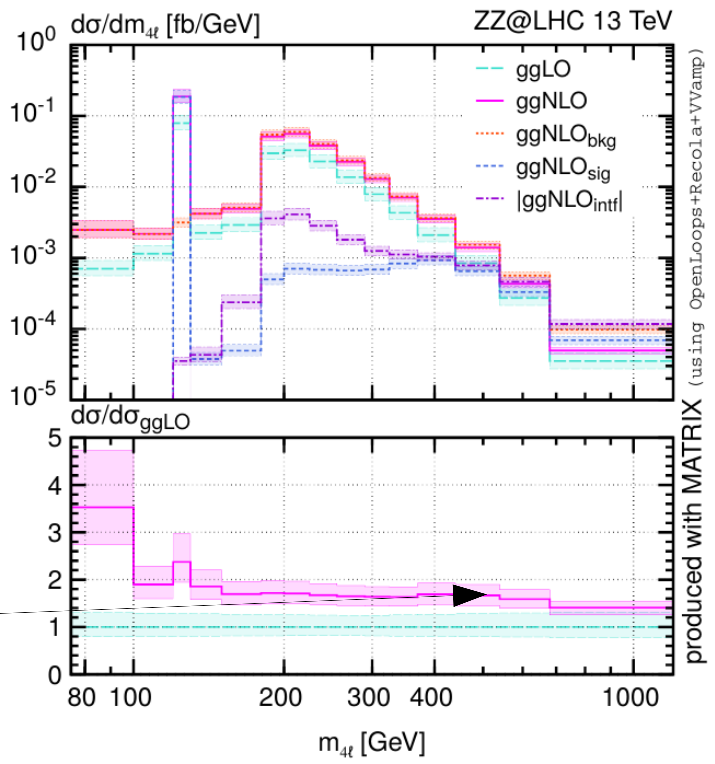
(implemented at amplitude-squared level).

➡ results above top-pair threshold.

Publicly available through `MATRIX`.

  - *WW* channel also included.

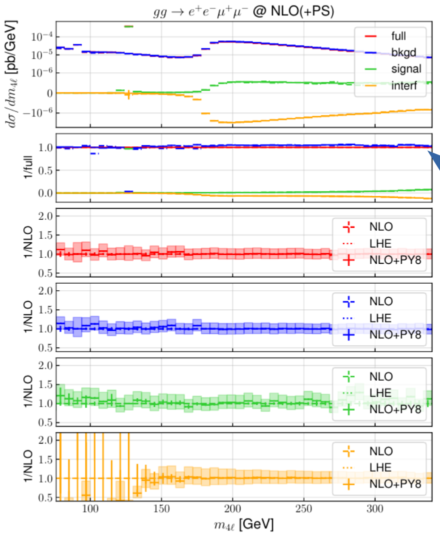
[Grazzini, Kallweit, Lindert, Pozzorini, Wiesemann (2019)]



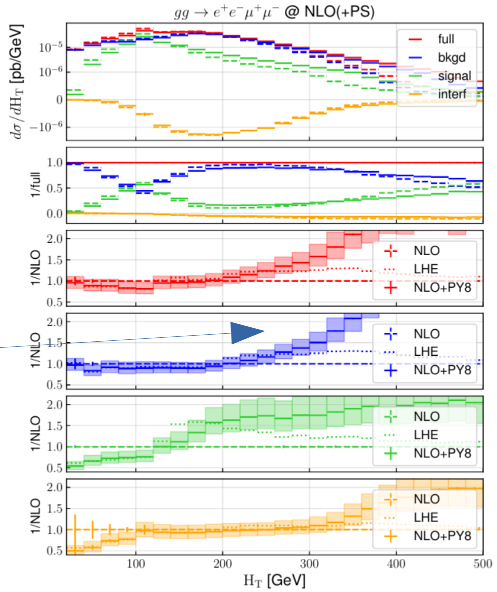
NLO + PS Results

- NLO-accurate calculation matched to parton showers in `POWHEG−BOX`.

[Alioli, Ferrario Ravasio, Lindert, RR (2021); Alioli, Caola, Luisoni, RR (2016)]



- Two-loop background amplitudes either computed in $1/m_t$ expansion or through reweighting.
- Main observable m_{VV} is inclusive – effect of PS is small.
- For exclusive observables, e.g. H_T , it can be substantial.



→ Talk by Simone

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Summary: where are we today?

- ☹ Most advanced calculation available: (approximate) NLO
  - Difficulty of computing background amplitudes at two-loops with massive (virtual) quarks.
  - Approximations:
    - Expansion in $1/m_t$ – limited to $m_{VV} < 2m_t$
    - Reweighting
- ☺ (Approximate) NLO matched to PS $\rightarrow$ unweighted events
- ☺ Public: `MATRIX` and `POWHEG-BOX`

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☺ Public: `MATRIX` and `POWHEG-BOX`.

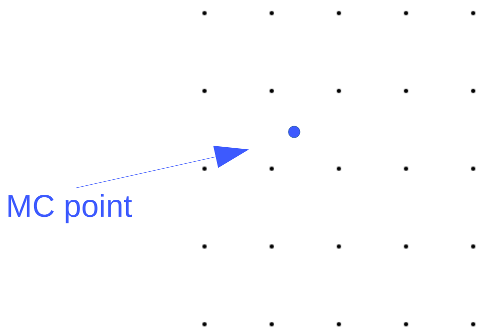
Where should we go from here?

1. Complete NLO corrections
2. Beyond NLO
3. EW effects

Towards Complete NLO Corrections

- Two-loop massive background amplitudes have been computed numerically.
  - Fixed values of top, W, Z masses.
- Evaluation time: 1-24 hours/phase space point.
- Typical number of points in MC integration ~ 100k.
- Interfacing these calculations with MC integrators is tricky but doable.
- Better idea (?) : Pre-generate a grid and then interpolate between them to obtain virtual amplitude at MC point.
  - Re-use grid for runs with minor differences in inputs (e.g. pdf sets).

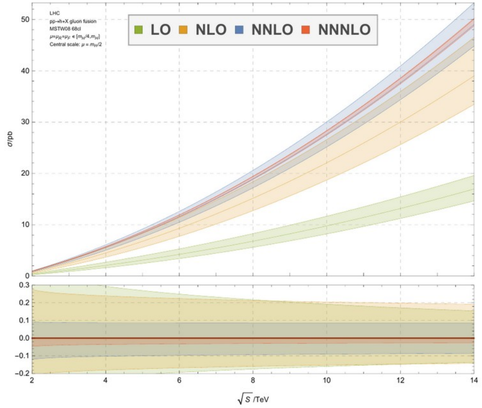
[Agarwal, Jones, von Manteuffel (2020), Brønnum-Hansen, Chen (2020, 2021)]



Shouldn't be any major obstacles to including these amplitudes in NLO codes and obtaining complete NLO results.

Beyond NLO in QCD

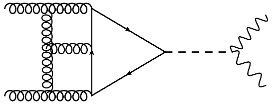
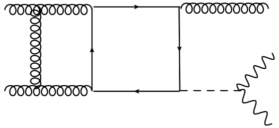
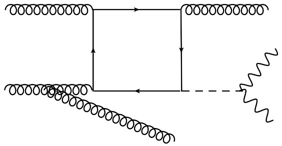
- Onshell Higgs production (in infinite top limit):
  - NNLO corrections large (k ~ 1.2-1.3).
  - Scale uncertainty at NLO doesn't capture higher order corrections.
  - Top mass effects are small. [Czakon, Harlander, Klappert, Niggetiedt (2021)]



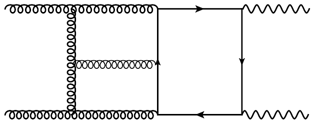
[Anastasiou, Duhr, Dulat, Herzog, Mistlberger, (2015)]

- Assuming same is true for offshell Higgs → need NNLO corrections (with full top mass dependence).

- NNLO corrections for signal process known.

- Background requires three-loops corrections
  → beyond current abilities.

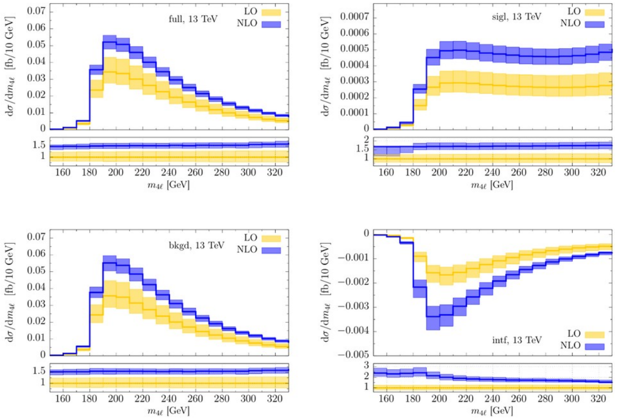


- *What can we do?*
  - ➢ Reweighing
  - ➢ Additional radiation
  - ➢ (Better) approximations

Reweighting

- Corrections to signal, background and interference are similar.
- Rescale background and interference by corrections to signal at NNLO.

$$d\sigma^{\text{NNLO}}_{\text{bkgd.}} \approx \frac{d\sigma^{\text{NNLO}}_{\text{sigl.}}}{d\sigma^{\text{NLO}}_{\text{sigl.}}} d\sigma^{\text{NLO}}_{\text{bkgd.}}$$



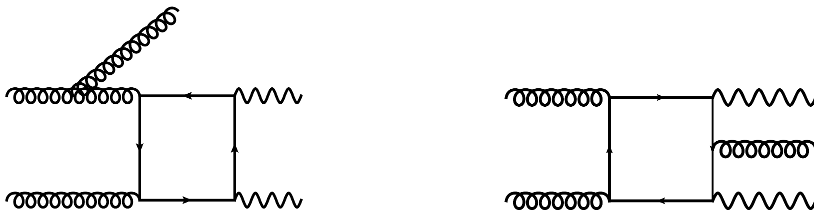
In conclusion, in all cases radiative corrections have the effect of increasing the absolute size of the individual contributions. However, the relative size of the corrections for the individual contributions is quite different, especially at small $m_{4\ell}$ values, and the full result is a combination of all of those effects. Only at large invariant masses ($m_{4\ell} \gtrsim 400$ GeV) the relative size of the corrections becomes similar for signal, background and interference. It is therefore difficult to make a direct connection between the QCD corrections beyond NLO for the signal, which are known to be relatively large (see Ref. [92] and references therein), and the other contributions, where they are not known. Nevertheless, the NLO corrections in the off-shell region are not that different among the three contributions, and the QCD effects beyond NLO are expected to be significant. Therefore, in order to approximately take higher-order corrections into account, one might be tempted to rescale our NLO result for the off-shell cross section by using the relative impact of the QCD corrections beyond NLO evaluated in the off-shell region for the signal contribution [92]. Needless to say, much care should be taken when following such approach.

[Grazzini, Kallweit, Wiesemann, Yook (2021)]

- How to evaluate uncertainties?
- Use NLO results?

Adding radiation

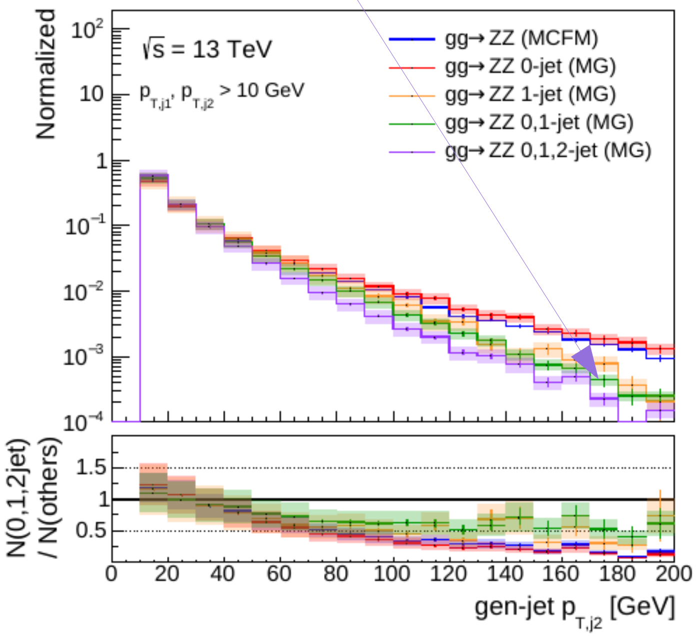
- NLO calculation supplies one jet (matrix-element level).
- Further jets through PS – from radiation from IS and FS partons.
- Miss radiation from virtual quarks in loop.



- Can include second jet at ME level using jet merging.

See also [Cascioli et al (2013)] for 0 and 1-jet merging in SHERPA.

- [Li et al (2020)] using MadGraph and MLM merging.
- Softer second jets from ME compared to PS.

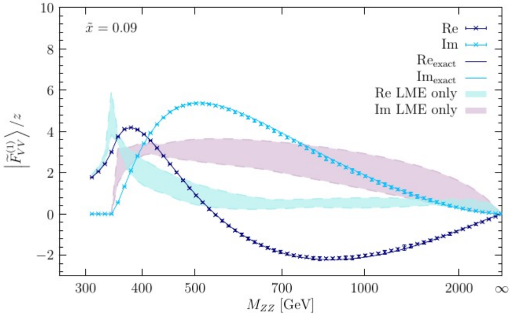


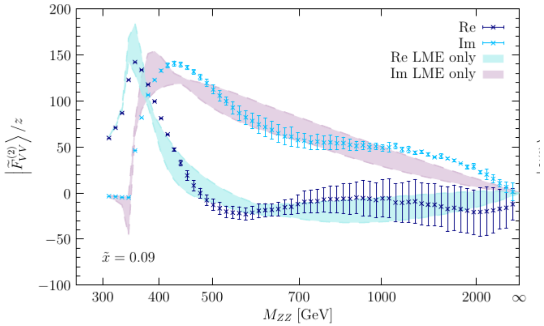
Better approximations

- Expansion in $1/m_t$ valid for $m_{VV} < 2m_t$.
- Also include expansion around top production threshold and in small mass limit $m_t \to 0$.
- Combine using Padé approximants.

➡ Results valid across all of phase space.

[Gröber, Maier, Rauh (2017), (2019); Davies, Gröber, Maier, Rauh, Steinhauser (2020)]





Extend to 3-loop for NNLO corrections?

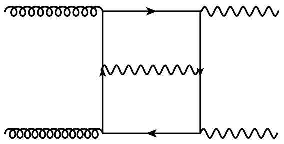
[Gröber, Maier, Rauh (2019)]

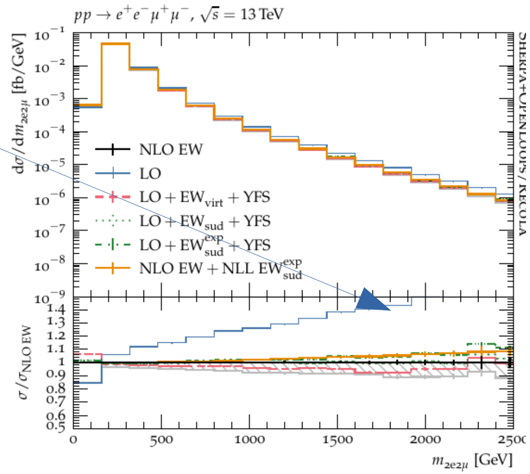
Electroweak Corrections

- EW corrections expected to be enhanced in high-energy regime.
- NLO EW corrections + NLL EW Sudakov corrections computed for *ZZ* and *ZZj*, merged with MEPS@NLO.

  [Bothmann, Napoletano, Schönherr, Schumann, Villani (2021)]

  - EW corrections to $\mathcal{O}(\alpha_s)$ processes only.
  - EW corrections to $gg \to (H) \to ZZ$ not included.
- Would require challenging two-loop amplitudes.

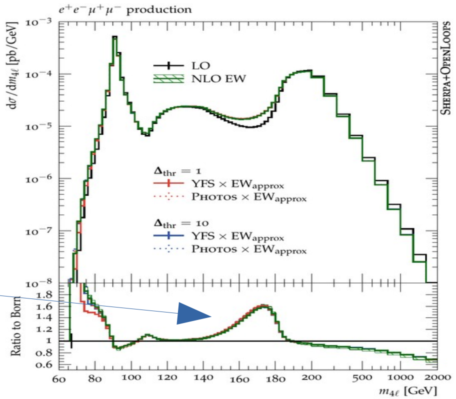




- QED radiation provided by parton showers (e.g. `SHERPA, PHOTOS`)

  → provide accurate approximation of EW effects in $q\bar{q} \to 4\ell$

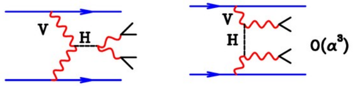
  [Gütschow, Schönherr (2020)]



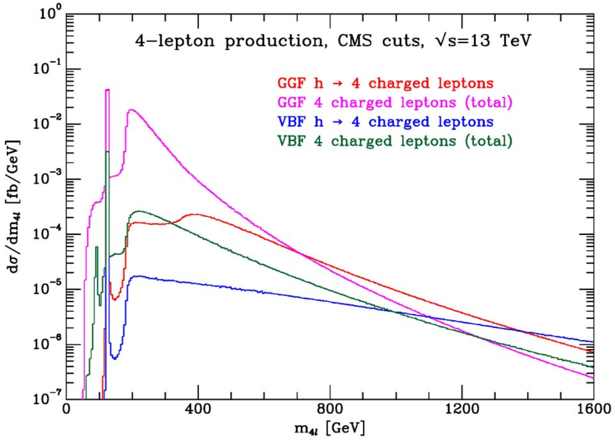
- `SHERPA:` [Krauss, Schönherr (2008)]
- `PHOTOS:` [Barberio, van Eijk, Was (1991); Barberio, Was (1994); Golonka, Was (2006); Davidson, Przedzinski, Was (2016)]

Other production processes

Offshell Higgs in VBF: [Campbell, Ellis (2015)]



- Higgs exchange in s- and t-channels.
- Same pattern of large destructive interference at high energies.
- Less stringent constraints on Higgs width.



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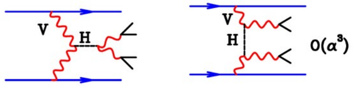

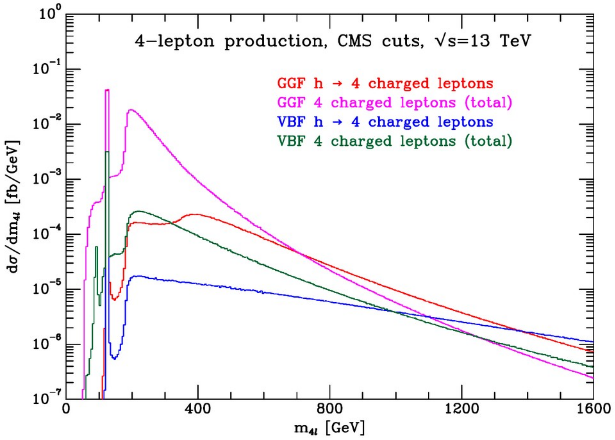

- Not loop-induced: NLO QCD corrections can be obtained in e.g. `MadGraph`.

  [Alwall et al, (2014)]

- NNLO QCD results unknown but feasible.
- QCD corrections mild (~ few percent at NNLO) so NNLO might not be necessary.

Conclusions

- Theoretical predictions for offshell Higgs production in gluon-fusion:
  - (Approximate) NLO QCD + PS.
  - Publicly available codes: `POWHEG` and `MATRIX`
  - Full NLO QCD corrections should be feasible.
  - As experimental precision improves, this might not be sufficient.
  - Ideas to include higher order effects:
    - Reweighting;
    - Jet merging;
    - Approximating multi-loop amplitudes using simultaneous expansions and Padé approximants;
    - QED effects in parton showers.

- We have made remarkable progress in ~ 10 years, largely due to dialogue between theorists and experimentalists.
- I'm excited to see what the next decade will bring for offshell Higgs phenomenology!

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THANK YOU FOR YOUR ATTENTION