Higgs Width at HL/HE-LHC (theory part)

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HE/HL-LHC WG2 meeting

The quest for Higgs width

Measurements must be interpreted.

Observables at the LHC is the cross section, a convolution of PDF, hard scattering, parton shower, detector response …

For the hard scattering:

$$\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_{tot}}$$

- If $\kappa_{tot} = \kappa_i^2 \kappa_j^2$, the observed rates do not change.

Higgs width measurement is to resolve such big flat direction in its property measurement (once measured, ``model/assumption-independent" extraction of Higgs properties and couplings possible*).

*true for any framework, kappa or EFT that allows BSM decays. (Higgs decay to BSM well motivated, see e.g., ZL et al, Higgs Exotic decays.)

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Higgs global fits with assumptions	~0.8 (??)	~0.4 (??)		No	Assuming $\kappa_V \leq 1$ Or no BrBSM (be clear on the assumptions and avoid over interpretation: not measurement of width)

*some theory assumption does not hurt the picture, e.g., Higgs being CP-even, only consider up to dim6 operators, no new production mode polluting Higgs samples, etc., all can be implemented by enlarging parameter and observable space, so I do not comment on these here.

**effectively LO due to large complex phase arises from 2-loop background virtual diagram.

For more details on some of the projections, see Meng Xiao's talk.

Are they **obviously/already** systematic limited?
All of them are eventually systematically limited.

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I will focus on theory progress after YR4

Refs:
F. Caola and K. Melnikov arXiv:1307.4935
N. Kauer and G.Passarino arXiv:1206.4803

On-shell/off-shell

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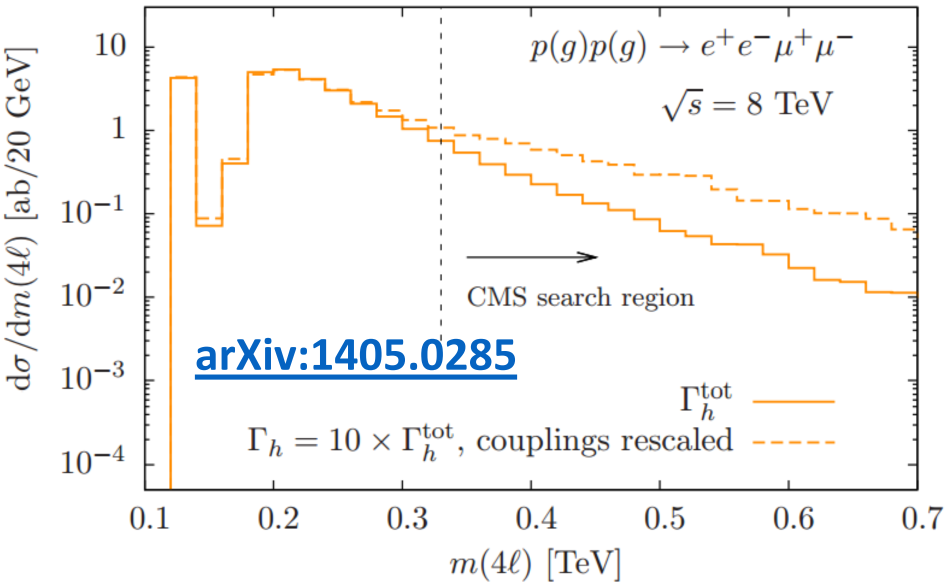

arXiv:1405.0285

Also possible, WW and VBF:
J. Campbell, K. Ellis, C. Williams, 1312.1628
J. Campbell, K. Ellis 1502.02990

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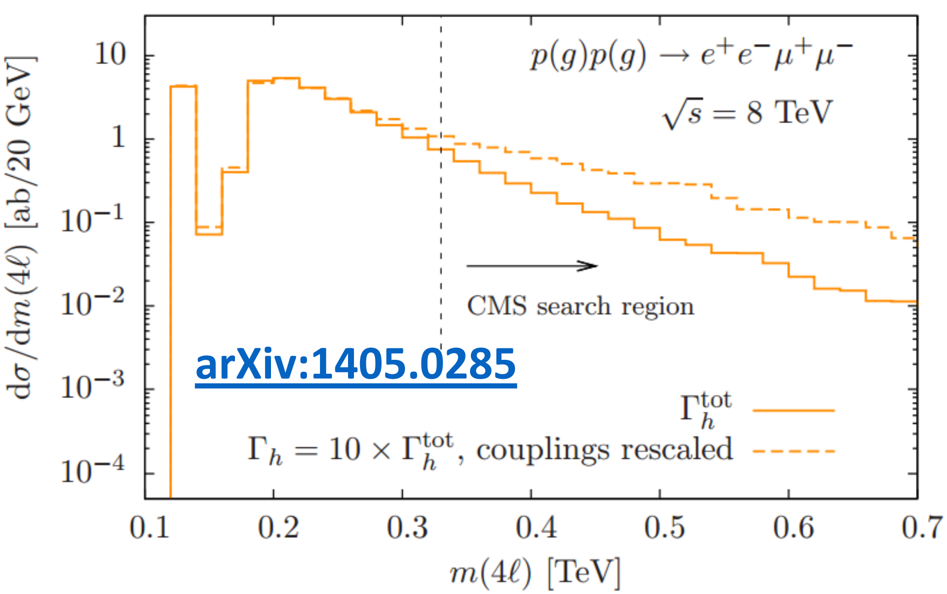

1) On-shell rate uncertainty
2) Loop-running⇔interplay of (at least) undetermined Top Yukawa
3) Many possible NP input at higher inv. masses.
4) Higher order corrections.

See discussions in e.g., arXiv:1405.0285, arXiv:1410.5440, arXiv:1412.7577, arXiv:1502.04678 , …

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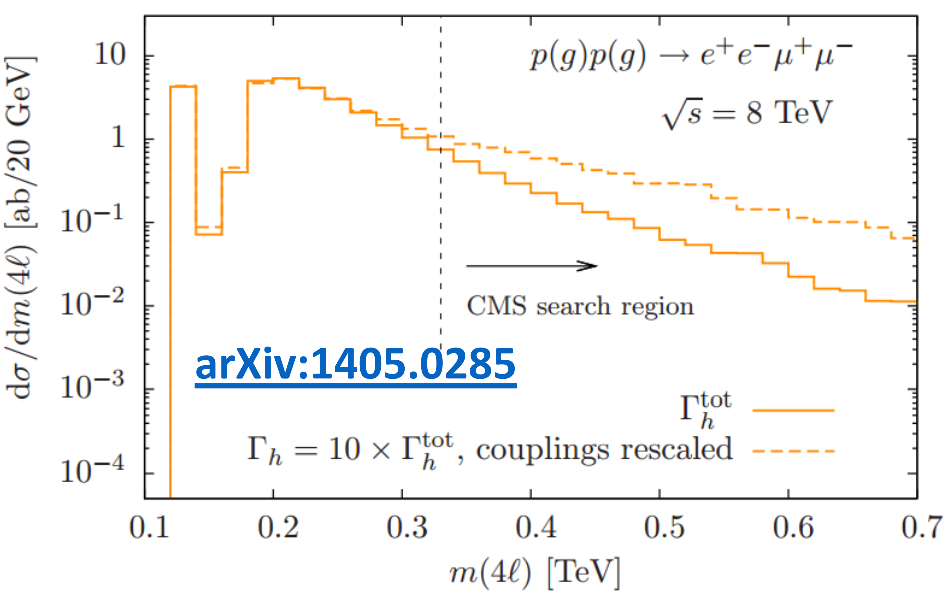

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Solution: performing a global EFT fit

NNLO Ref:
J. Campbell, J. Ellis, M. Czakon, S. Kirchner
[1605.01380](1605.01380)

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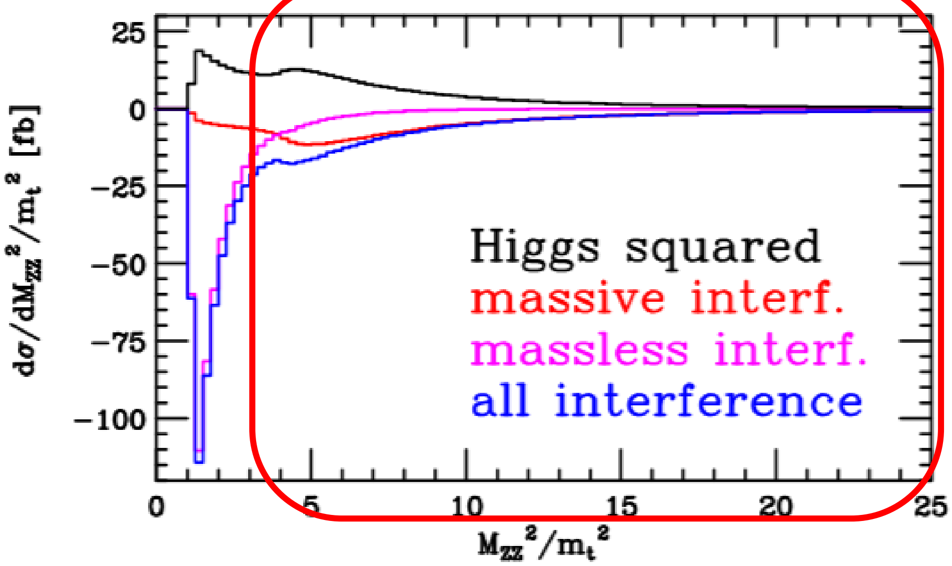

4) Higher order corrections.

An nearly flat direction around SM width between the squared term and interference term.

$$\frac{\sigma_{4\ell}^{NLO}(m_{4\ell} > 300\text{ GeV})}{\sigma_{4\ell}^{NLO}(m_{4\ell} < 130\text{ GeV})} = \boxed{(0.094^{+0.000}_{-0.002}) \times \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - (0.135^{+0.000}_{-0.008}) \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}}$$

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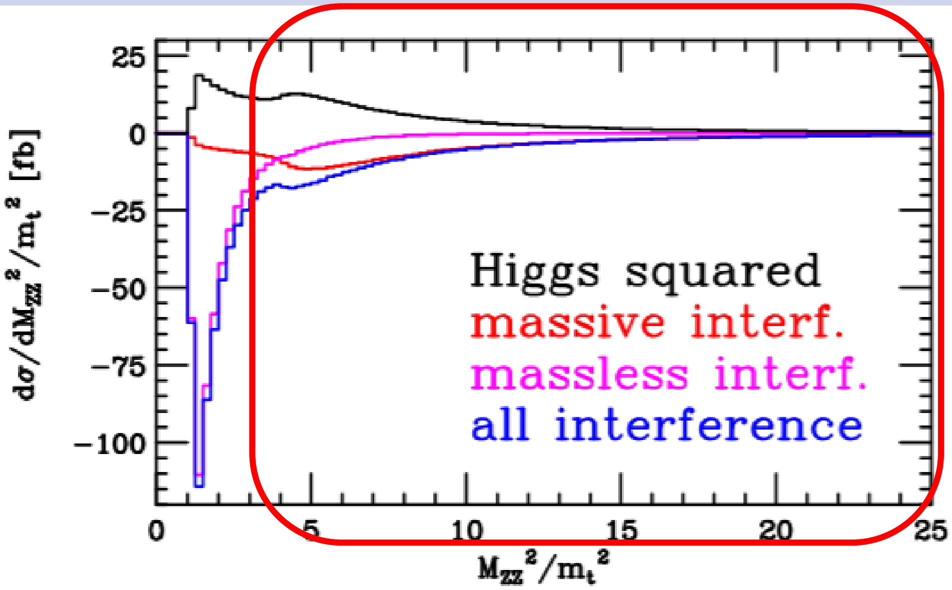

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Maybe go differential?
Exploiting 180~300 GeV bin?

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On-shell rate reference: J. Campbell, M. Carena, R. Harnik, ZL 1704.08259
On-shell mass shift reference: L. Dixon, Y. Li 1305.3854, + de Florian et al 1504.05215

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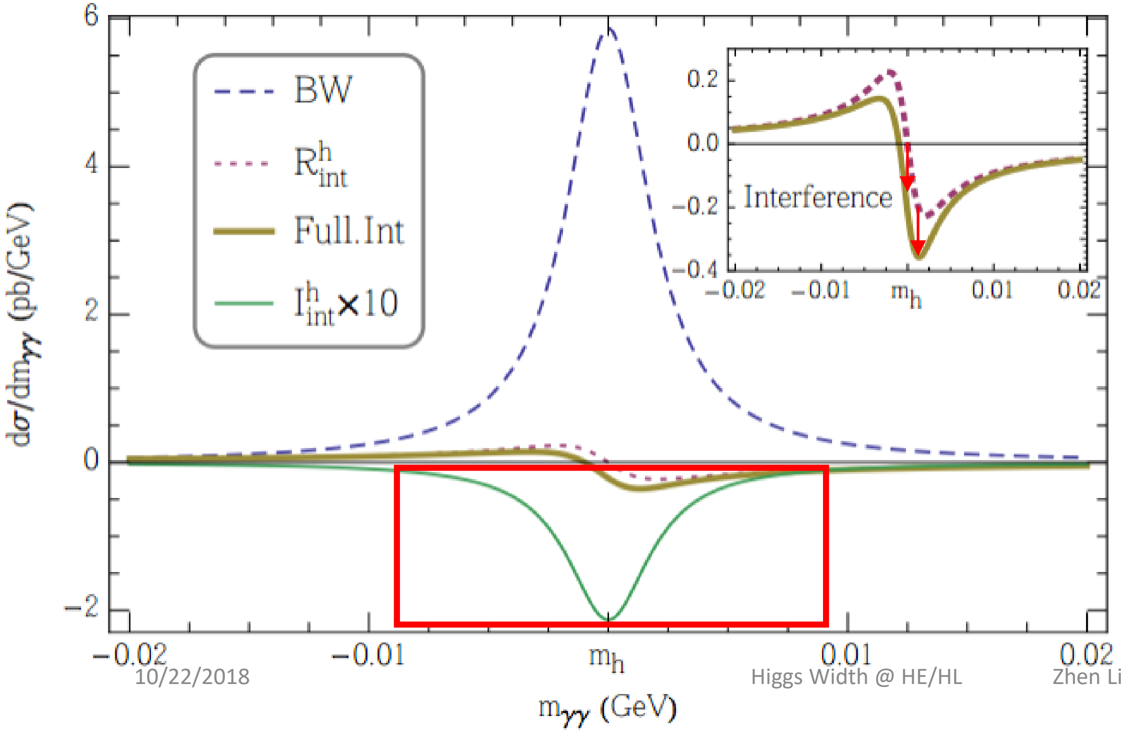

Two sides of the coin,
Interference proportional to
the **real** part
the **imaginary** part (rare at LO, hard to track)
of the scalar propagator

J. Campbell, M. Carena, R. Harnik, ZL 1704.08259

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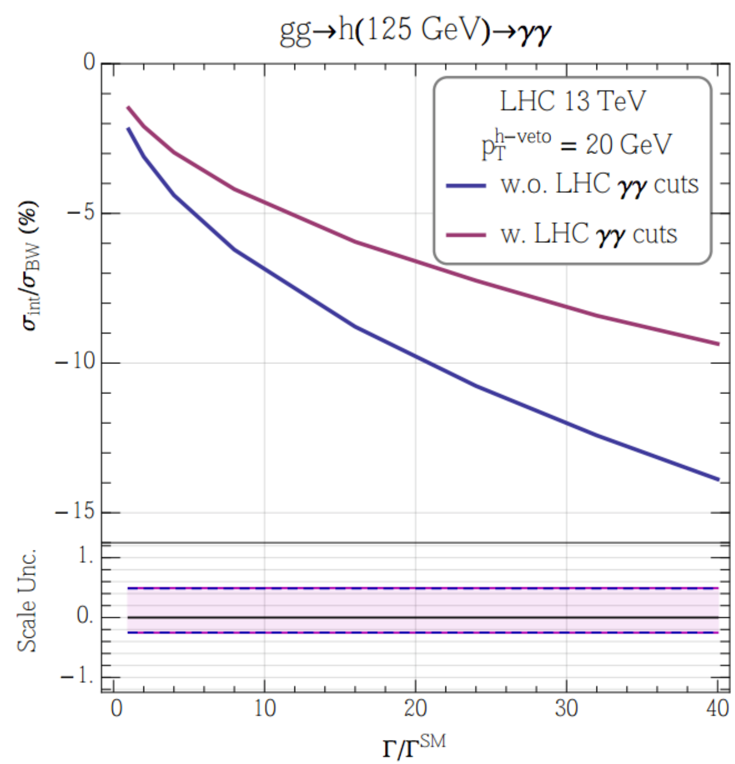
Major advantage of free from theory assumption

This rate change as a new probe of Higgs total width (all quantities normalized to the SM)

$$\sigma(gg \to h \to \gamma\gamma) \propto \frac{g_{ggh}^2 g_{\gamma\gamma h}^2}{\Gamma_{tot}} - (\sim 2.\%) g_{ggh} g_{\gamma\gamma h}$$

- Unique piece that does not depend on total width;
- Similar to off-shell ZZ measurement;
- Negligible dependence on coupling at different scales.
- Many uncertainties can be cancelled by taking cross section ratios ($\gamma\gamma/ZZ$)



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Kinematic feature also applicable to mass-shift

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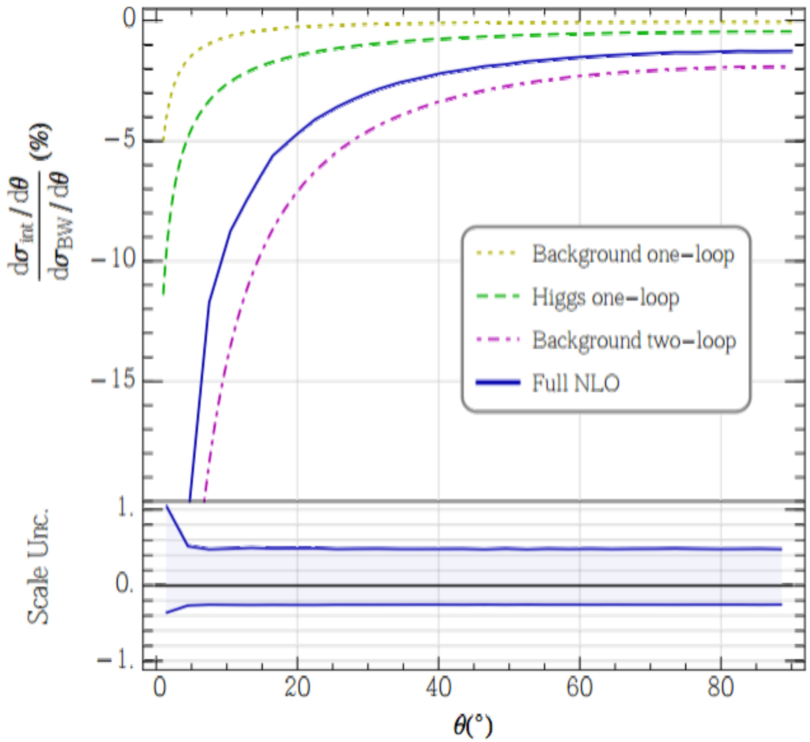

Angular distribution:

- Interference effects larger in the forward direction, driven by background amplitude kinematics;
- Interference effects ~0.5% at LO
- Interference effects increases to ~2% at NLO, driven by the 2-loop MHV amplitude's large imaginary part
- Fully inclusive cross section has larger B.W. cross section while the interference effect does not increase much, resulting in a smaller relative correction.

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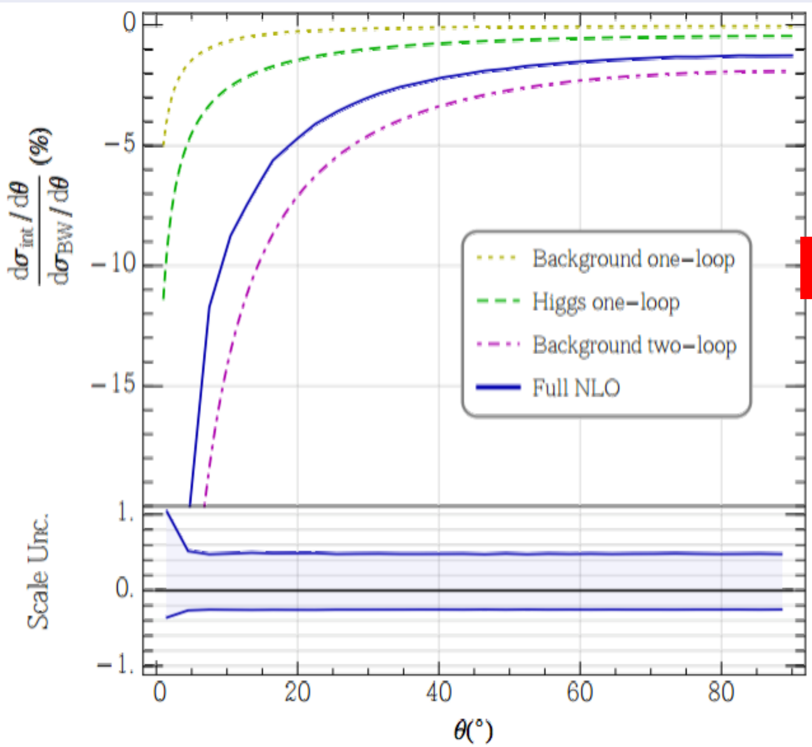

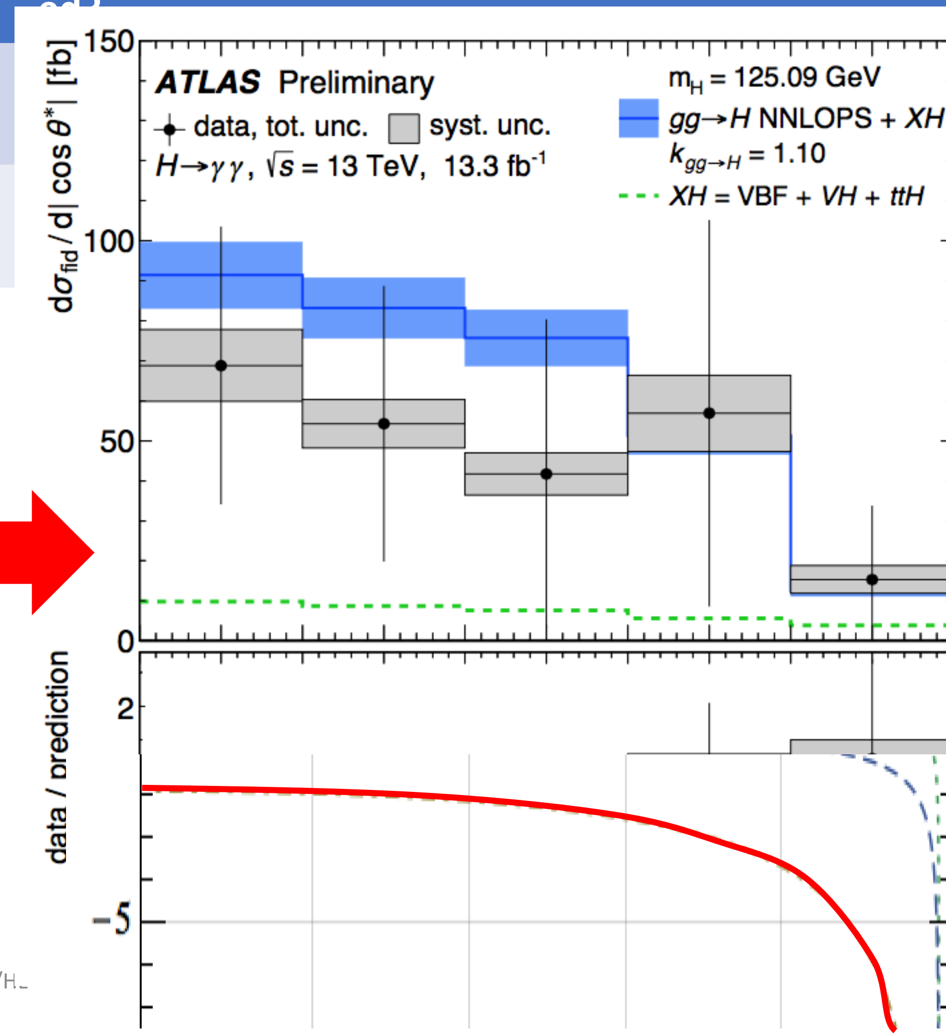

NLO: J. Campbell, M. Carena, R. Harnik, ZL 1704.08259
NLO+NLL: L. Cieri, F. Coradeschi, D. de Florian, N. Fidanza 1706.07331

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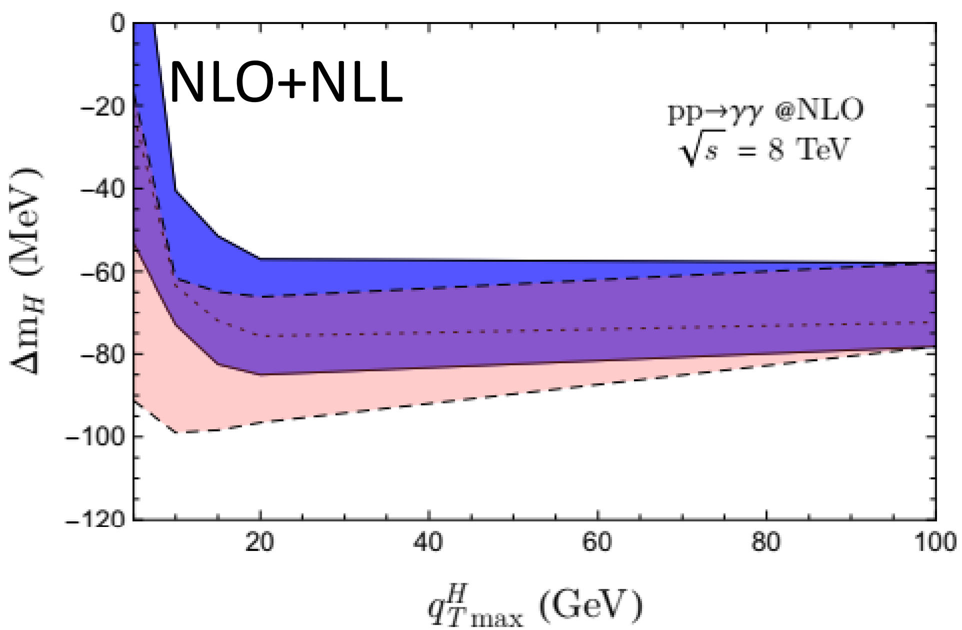

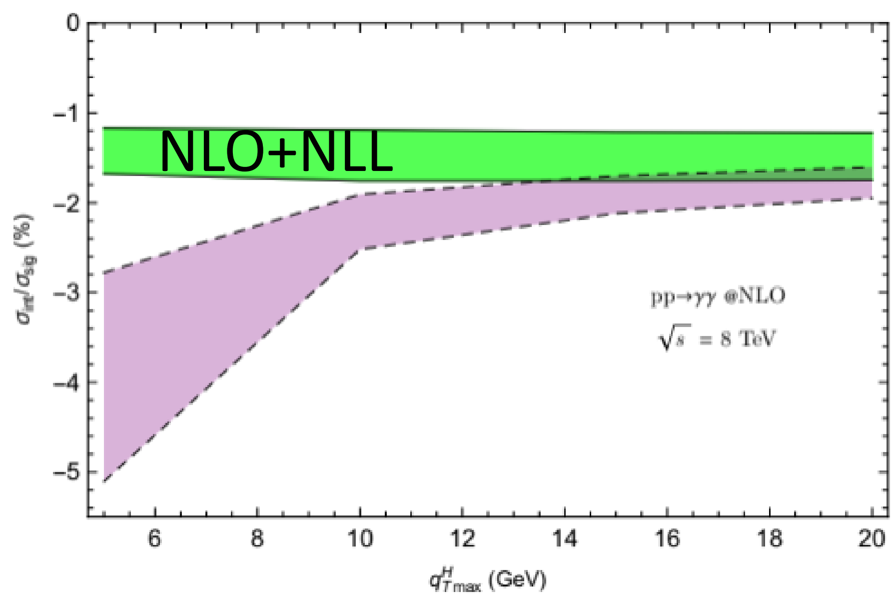

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- The task is unique and challenging at hadron colliders
- Progress made in theory for both higher order corrections, and new effect (on-shell interference)
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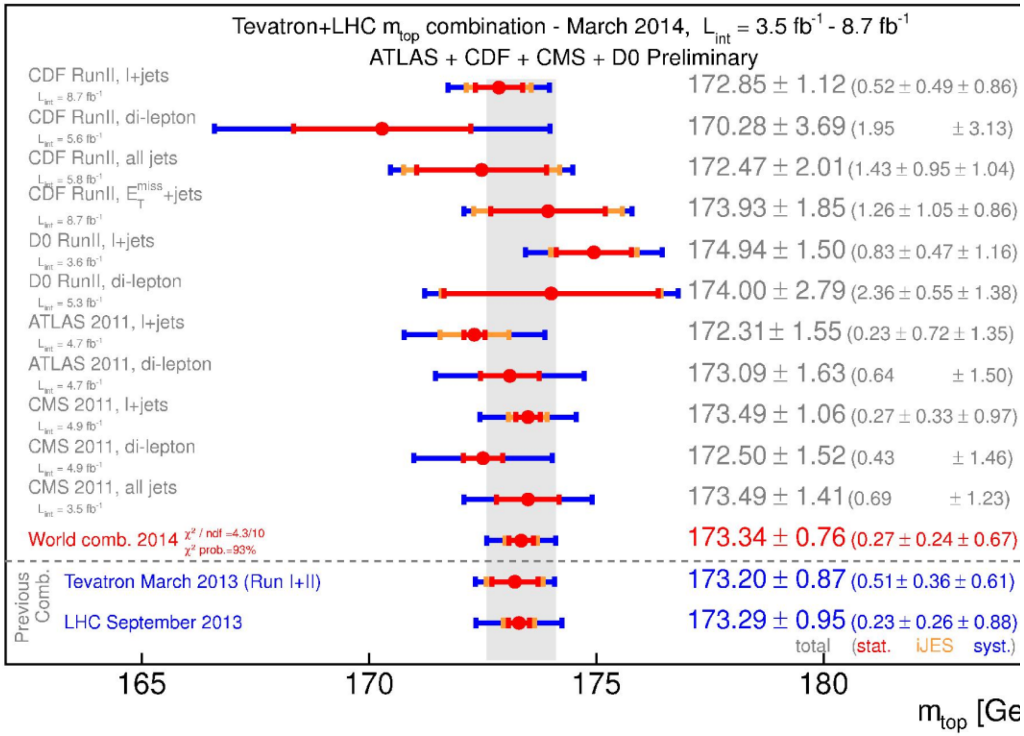
Thank you!

Summary



In some sense like the top quark mass determination. All methods have their own merits.

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Back to the basics of interference

$$A_{sig} = c_{sig} \frac{\hat{s}}{\hat{s} - m^2 + i\,\Gamma m} = \mathrm{c}_{sig}\ \mathrm{P}(\hat{s})$$

$A_{bkg} = c_{bkg}$ (slowing varying function of $\hat{s}$)

$$|A|^2 = \left|A_{sig} + A_{bkg}\right|^2 = \left|A_{sig}\right|^2 + \left|A_{bkg}\right|^2 + 2Re\left[A_{sig}A_{bkg}^*\right]$$
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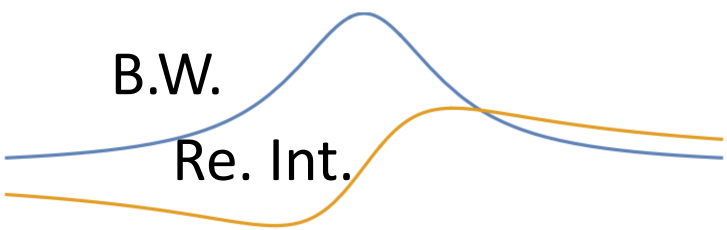

Background real

Re. Int.– Interference from the real part of the propagator

- normal interference, parton level no contribution to the rate, shift the mass peak
- When convoluting with PDF, may generate residual contribution to signal rate;
- conventional wisdom, interference only important when width is large)

$$Re[P(\hat{s})] = \frac{\hat{s}(\hat{s} - m^2)}{(\hat{s} - m^2)^2 + \Gamma^2 m^2}$$

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Interesting example of learning J/Psi spin

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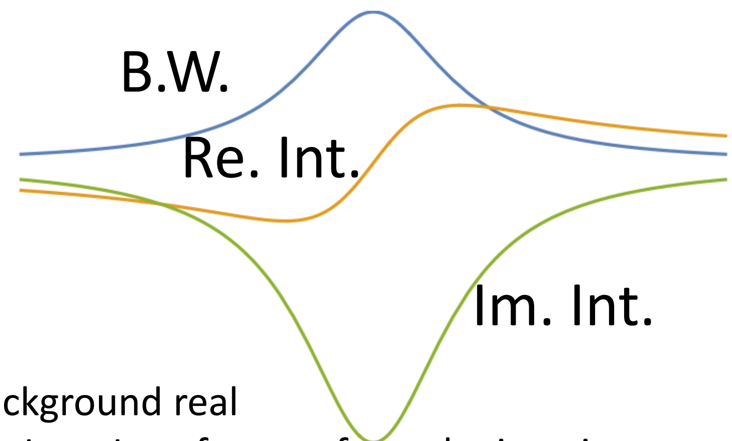

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Background real

Im. Int.– Interference from the imaginary part of propagator

- rare case (at LO);
- changes signal rate;
- cannot be dropped even if the width is narrow*

*the measure of interference/resonance do not decrease, as the size of signal amplitude decrease as well

Back to the basics of interference

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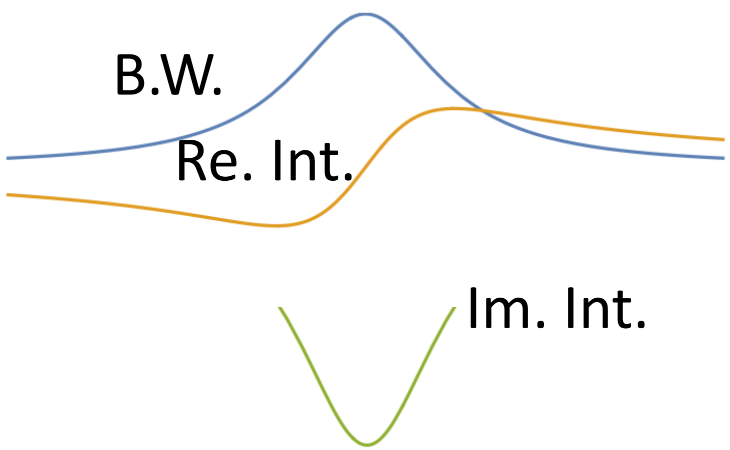
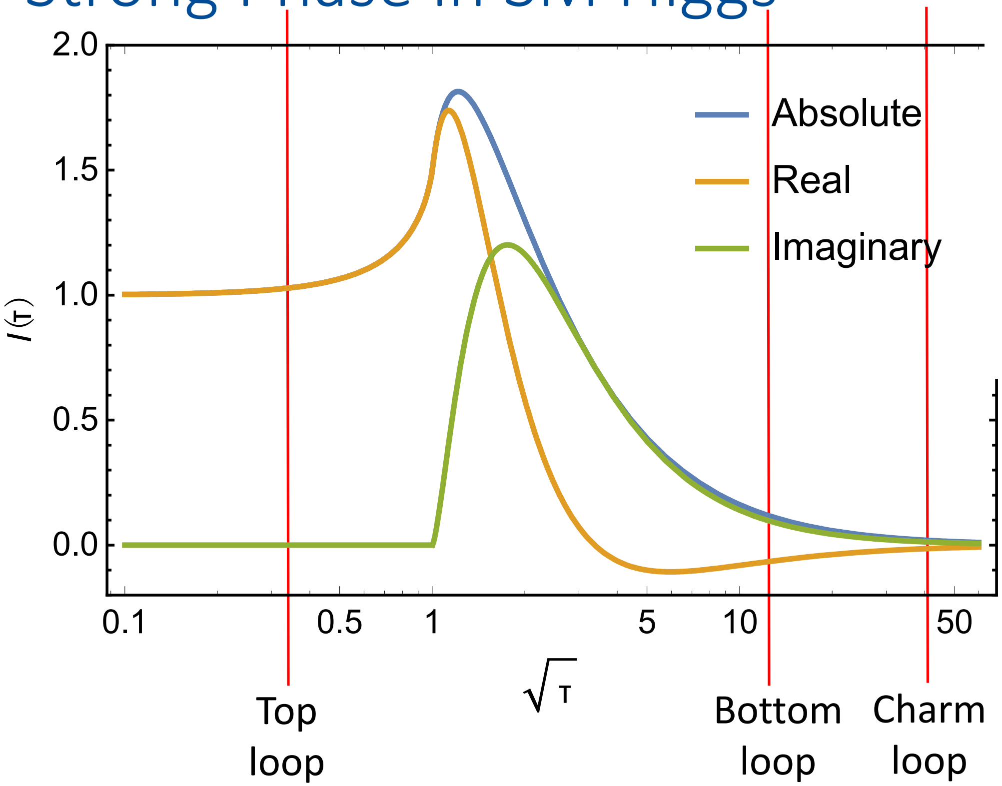
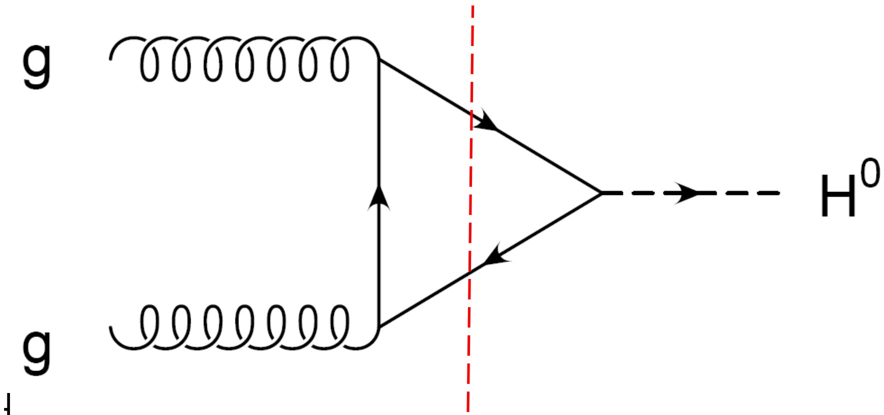


$$Im\left[c_{sig}c_{bkg}^*\right] = i\left|\mathrm{c_{sig}}\right|\left|\mathrm{c_{bkg}^*}\right|\sin(\delta_{sig} - \delta_{bkg})$$

When phase $\delta_{sig} - \delta_{bkg}$ is none-zero, this new interference effect exists and cannot be neglected however narrow the resonance is!

Strong Phase in SM Higgs





- All quark contributions normalized the same way, the plot represents the relative contributions
- Numerically:
  - t-loop $+1.034$
  - b-loop $-0.035 + 0.039i$
  - c-loop $-0.004 + 0.002i$

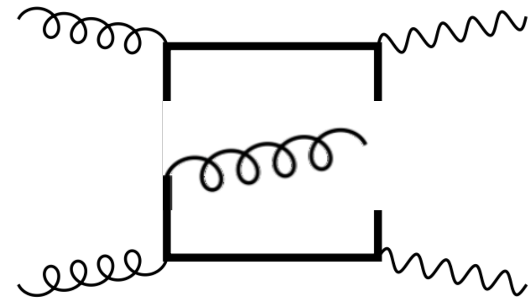
A strong phase in the gluon-gluon fusion production at hadron colliders (imaginary part)

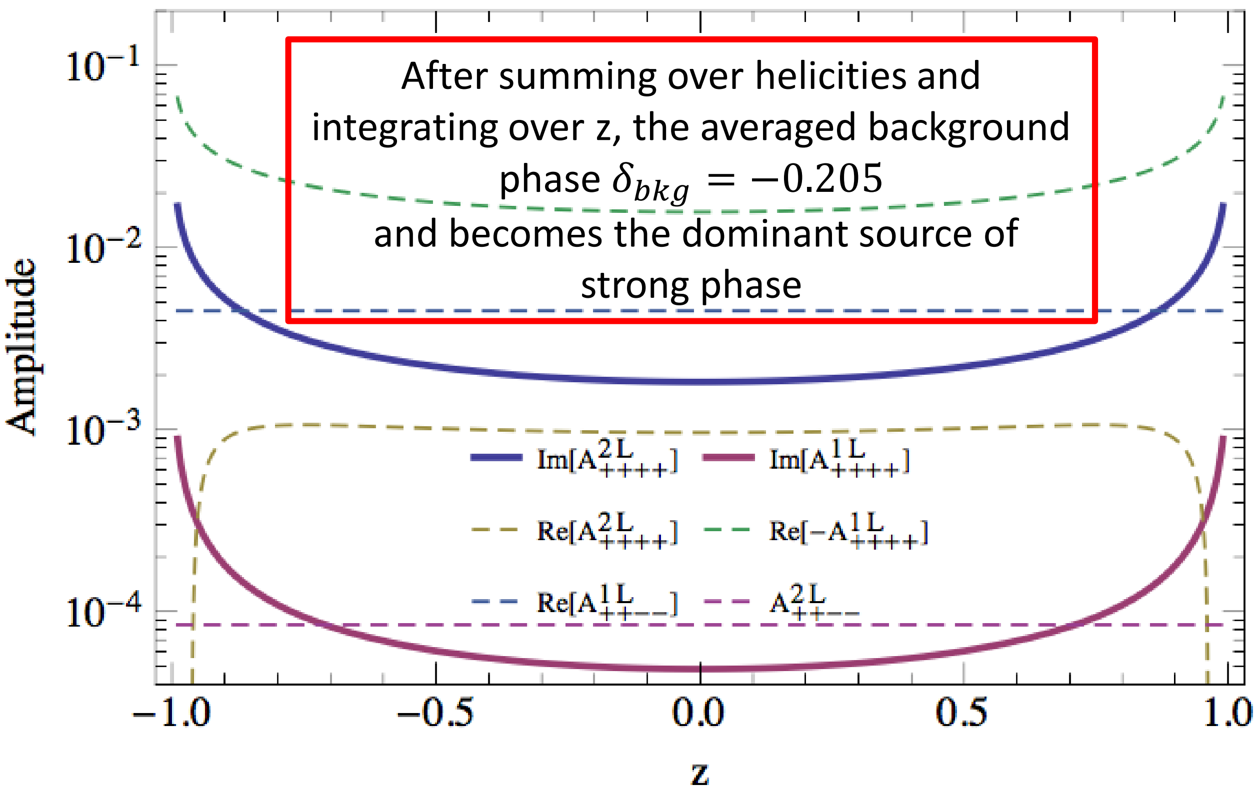
Phase in gluon-gluon-fusion $\mathbf{0.042}$

Phase from interfering background

Interfering background are from SM box diagram of $gg \to \gamma\gamma$

There is also a strong phase in the background:





- Angular dependence
- a smaller but negative phase w.r.t to the signal
- At l-loop, the imaginary part is mainly from $A_{++++} = A_{----}$ with bottom and charm contributions
- Imaginary part dominated by the 2-loop MHV amplitude.