Lecture 5: The Higgs $\to \gamma\gamma$ signal at the LHC

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Outline

- Motivation

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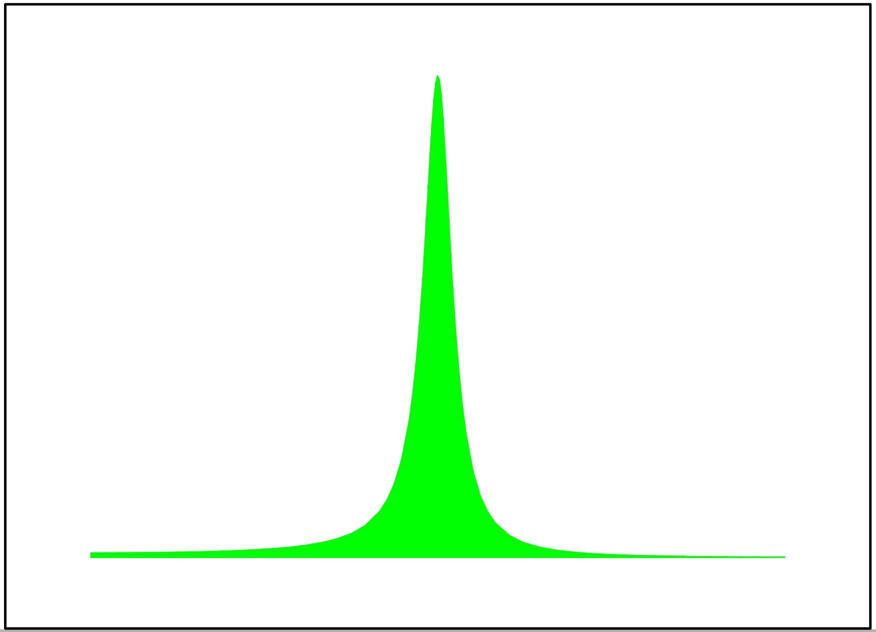
- Signal



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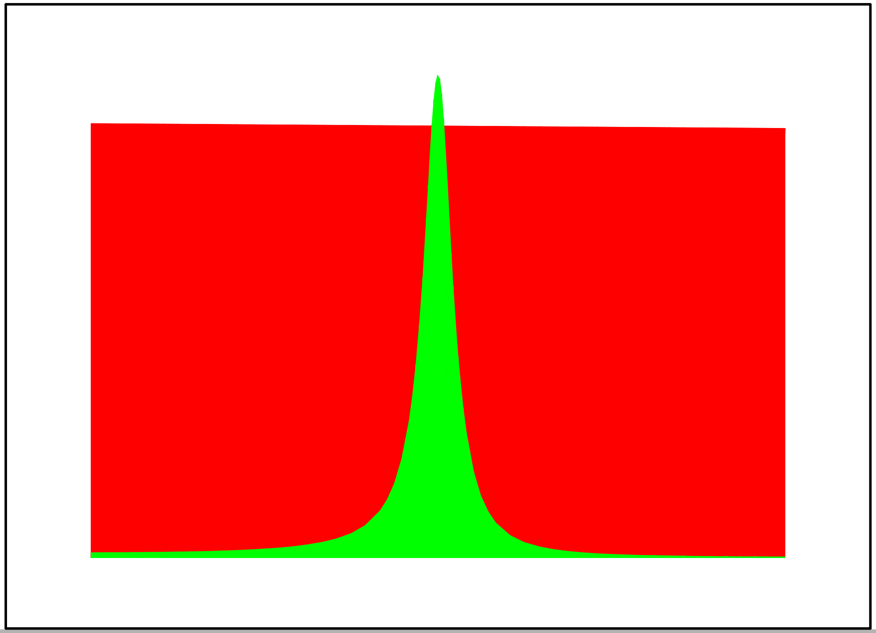

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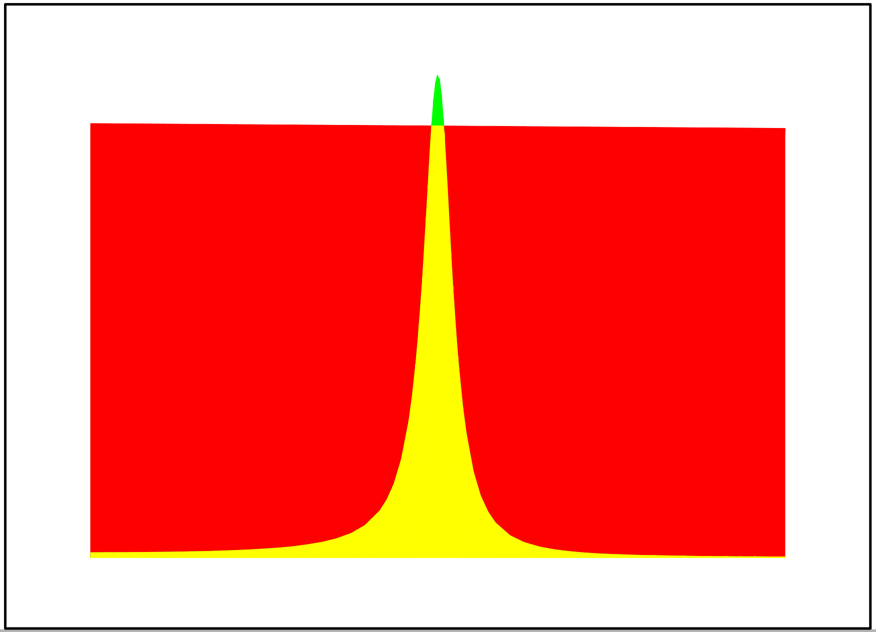
- Interference



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- In the SM, all Higgs boson properties dictated by m_H:
  $V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \quad \Rightarrow \quad \mu^2 = \lambda v^2 = \frac{1}{2}m_H^2$
  $v = 246$ GeV from μ decay; $\quad m_H = ???$

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  $v = 246$ GeV from μ decay; $m_H = ???$
- Tevatron Run II has an opportunity to discover it; otherwise the task will fall to the LHC.

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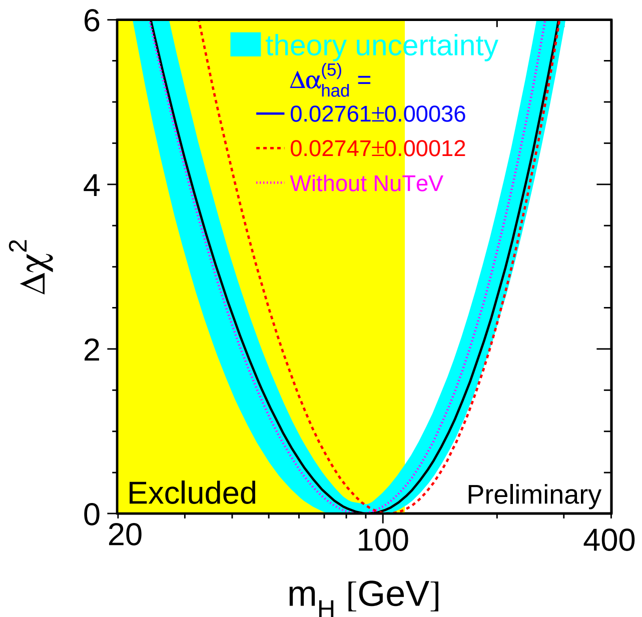
- Precision electroweak data favor $m_H < 195$ GeV LEP



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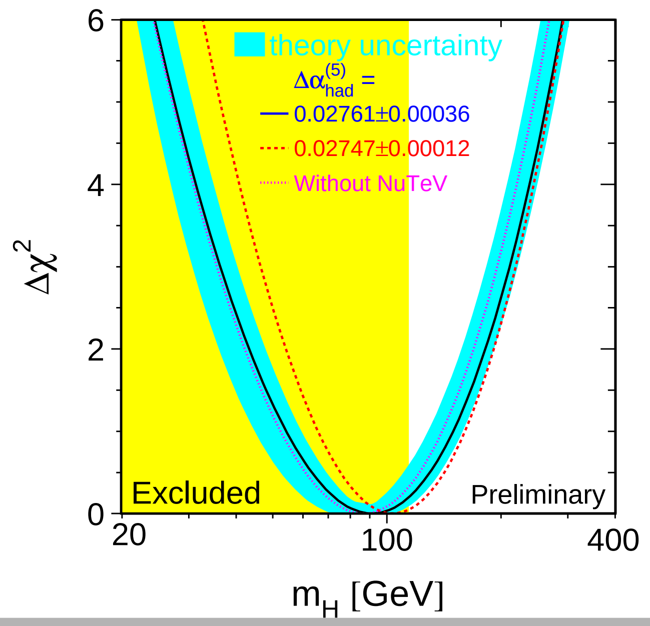

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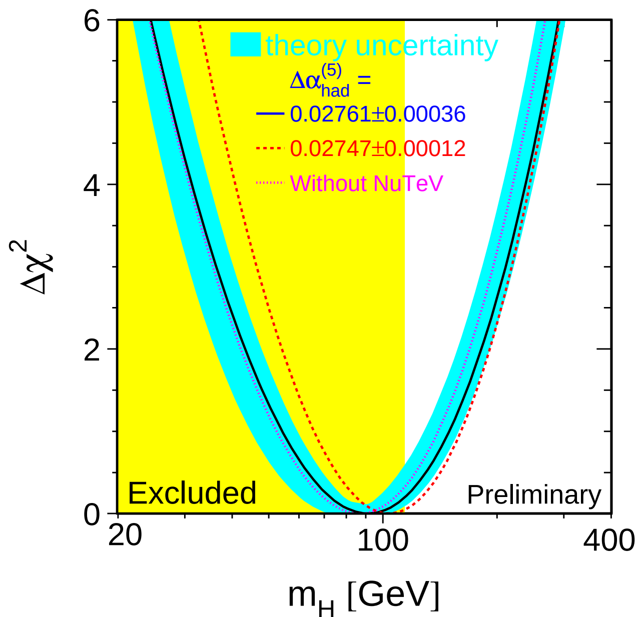

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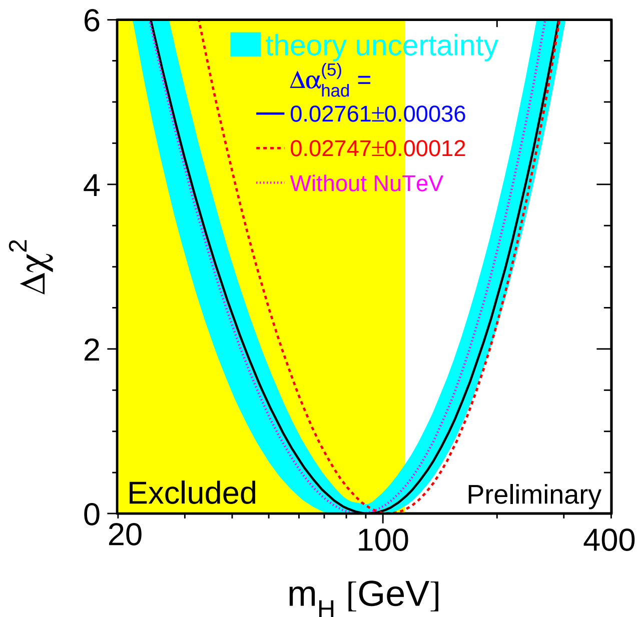
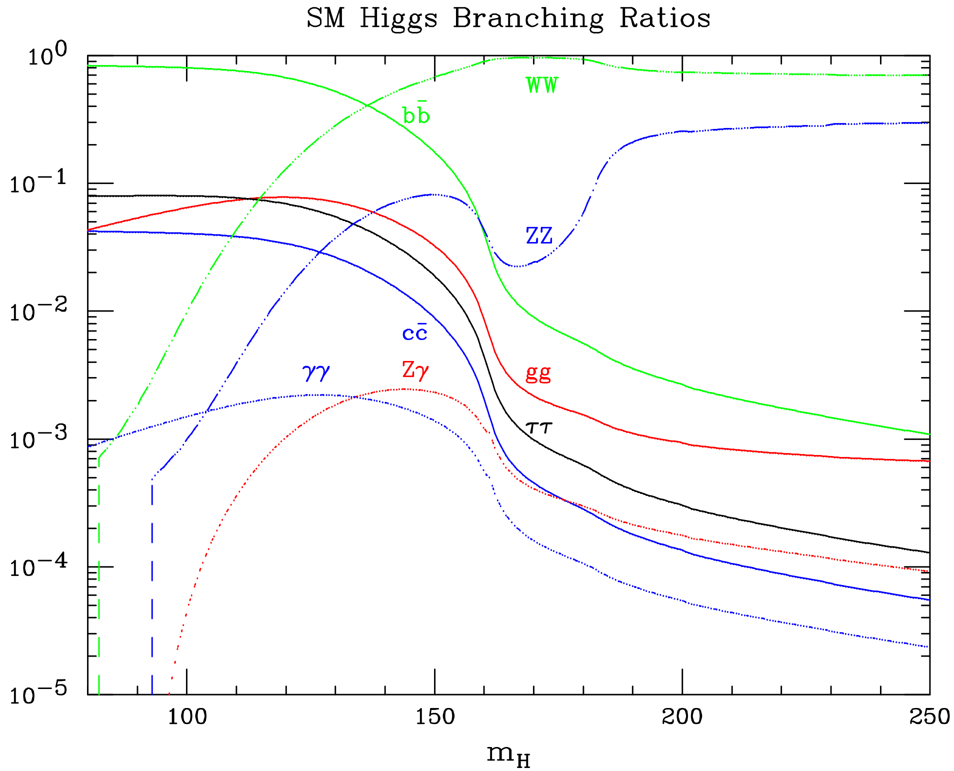
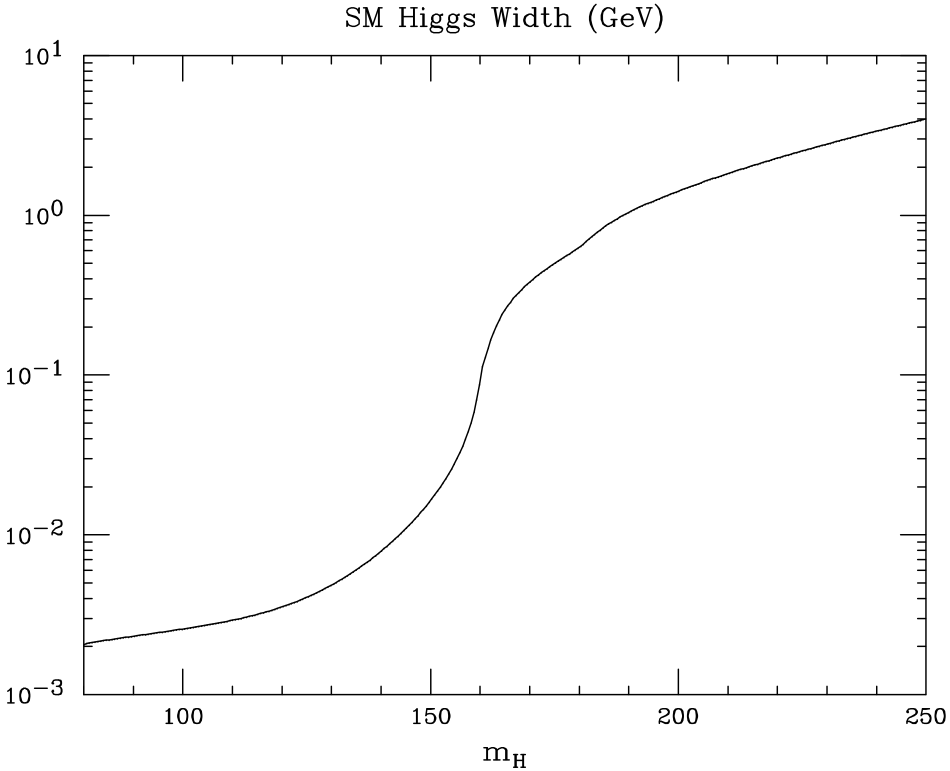
- For $m_H < 140$ GeV, best decay mode at LHC is $H \to \gamma\gamma$



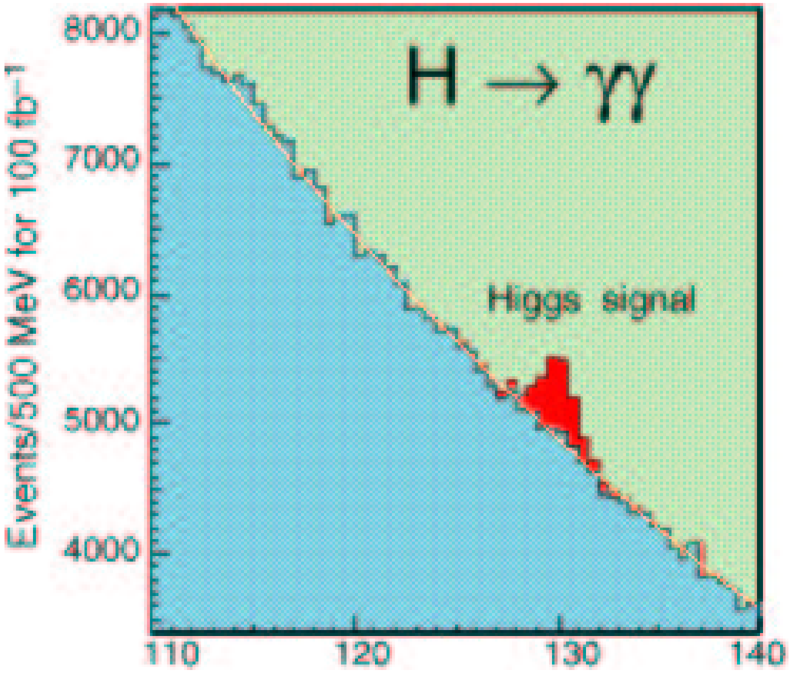
Higgs branching ratios & width





- For $m_H < 2m_W$, Higgs resonance is narrow, $\Gamma_H \sim$ MeV
  Excellent experimental photon energy resolution, $\approx 1\%$
  $\Rightarrow \gamma\gamma$ signal visible even though $\mathrm{Br}(H \to \gamma\gamma) \approx 10^{-3}$.

Simulated $H \to \gamma\gamma$ signal



CMS

- $S/B \approx 1/20$ (!)
- However, $S/\sqrt{B} \approx 5$ still achievable with roughly 20 fb^{-1}

Signal

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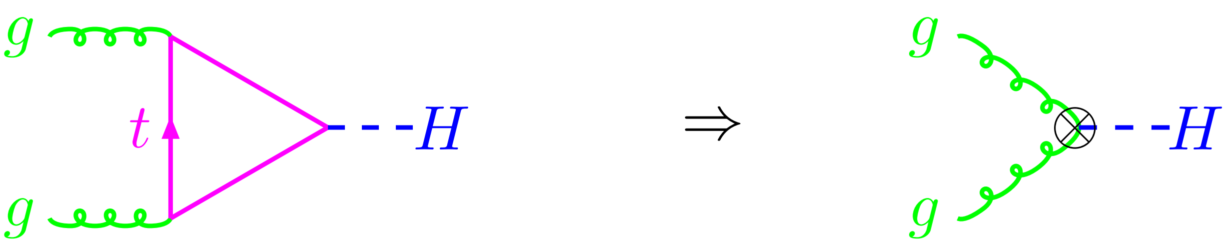
- To test the SM, need best theoretical prediction for the product $\sigma_H \times \mathrm{Br}(H \to \gamma\gamma)$.
- $\mathrm{Br}(H \to \gamma\gamma)$ under pretty good control:
  - QCD corrections to $\Gamma(H \to \gamma\gamma)$ are small
  - error $\approx 6\%$, mostly from uncertainty in m_b entering Γ_H.

Higgs total cross section σ_H

- $\mathrm{pp} \to H + X$ at LHC (or Tevatron) is dominated by gluon-gluon fusion through a top quark loop



- NLO QCD K factor for σ_H is huge, about 1.7–1.8 at LHC.

Djouadi, Spira, Zerwas; Dawson; Spira, Djouadi, Graudenz, Zerwas

- NNLO computation required.
For $m_H < 2m_t$, approximate top quark loop by effective ggH vertex to make it feasible.

σ_H at NNLO

NNLO terms obtained in successive approximations:

- Soft/virtual/collinear terms

Catani, De Florian & Grazzini; Harlander & Kilgore

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- Can also now resum threshold logarithms, to NNLL accuracy — Catani, De Florian & Grazzini; Grazzini

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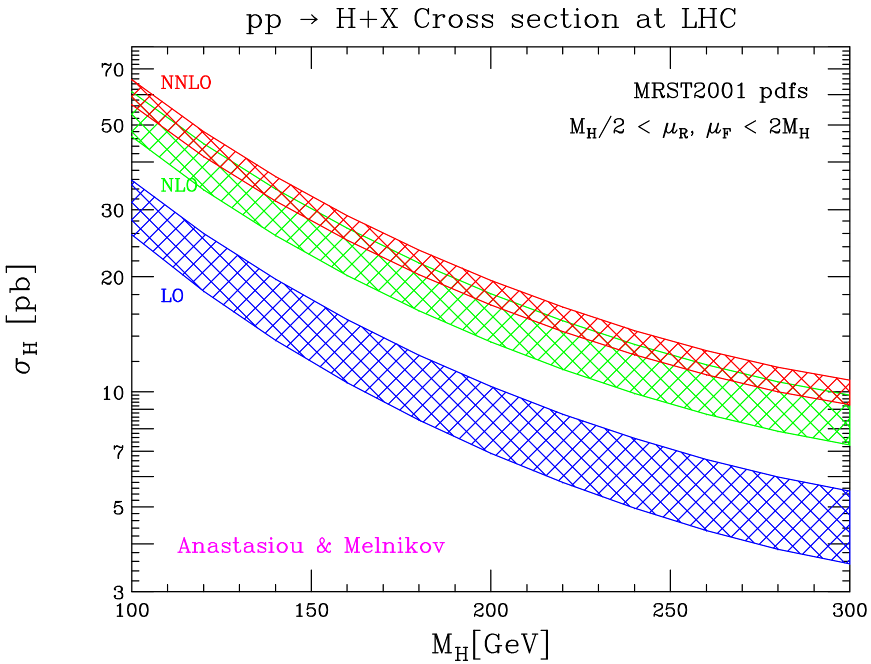
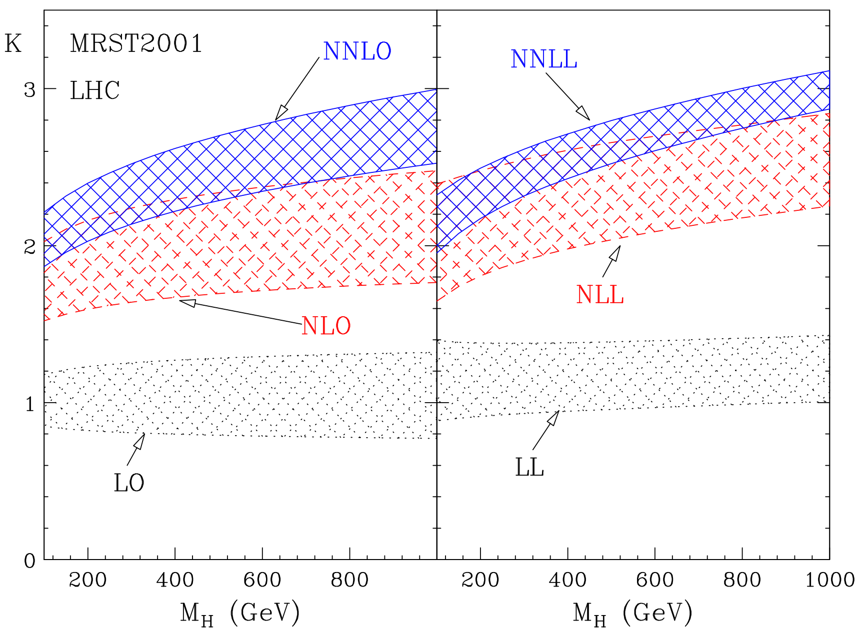
- Series is beginning to stabilize

σ_H at NNLO (cont.)





NNLO Exact

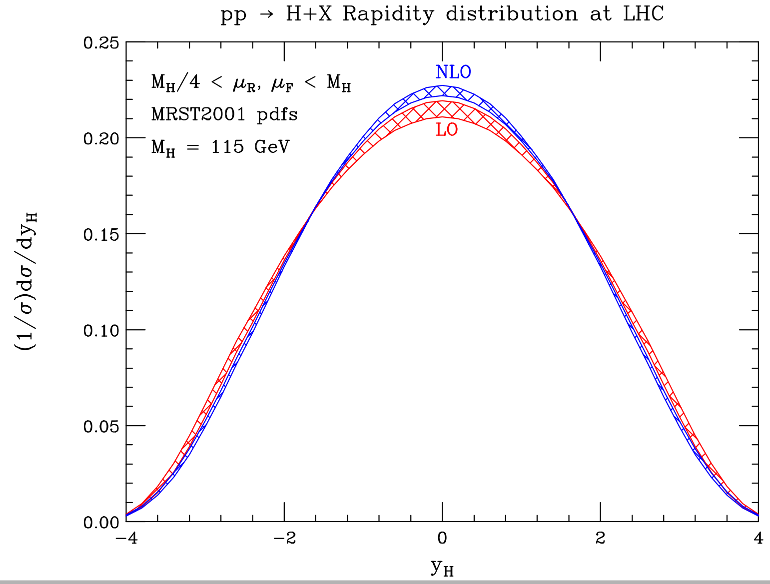
NNLL resummed

Grazzini

- Note different m_H scale, K **factor** $\equiv \sigma/\sigma_{\rm LO}$, on right
- Assumes $m_t \to \infty$ “expansion” works even for $m_H > 2m_t$; it does at NLO.

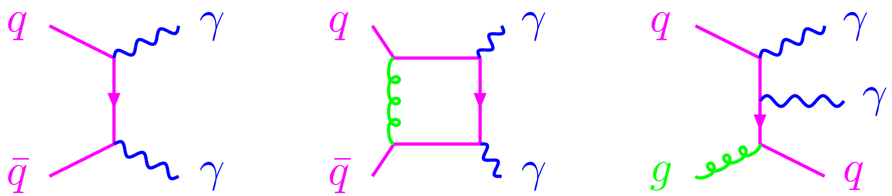
σ_H at NNLO (cont.)

- Residual (scale) uncertainties on σ_H still about 10-20%.
- What about acceptance issues? Anastasiou, LD, Melnikov
  - Rapidity distribution $\frac{d\sigma_H}{dy}$ now known at NLO.
  - Correction to normalized distribution is modest
  - Same techniques will work at NNLO (& for $\frac{d\sigma_{\gamma^*,W,Z}}{dy}$)



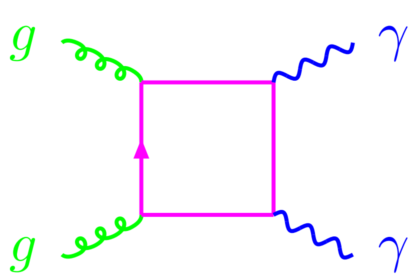
Background: pp $\to \gamma\gamma X$

- Measured experimentally; don't need so precise prediction. Focus on irreducible background (true γs, not π^0s).
- Leading and NLO direct QCD subprocesses:



e.g., Binoth *et al.* (DIPHOX)

- But LHC is a glue factory (for low mass Higgs) $\Rightarrow$ gluon fusion is important background (formally NNLO):



NLO corrections to $gg \rightarrow \gamma\gamma X$

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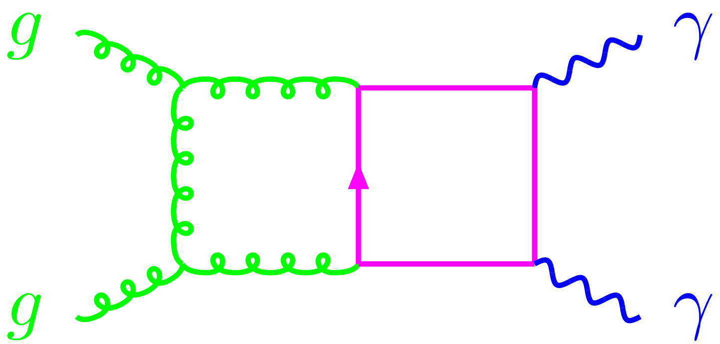
- Virtual term $\Rightarrow$ 2-loop $gg \to \gamma\gamma$ helicity amplitudes.



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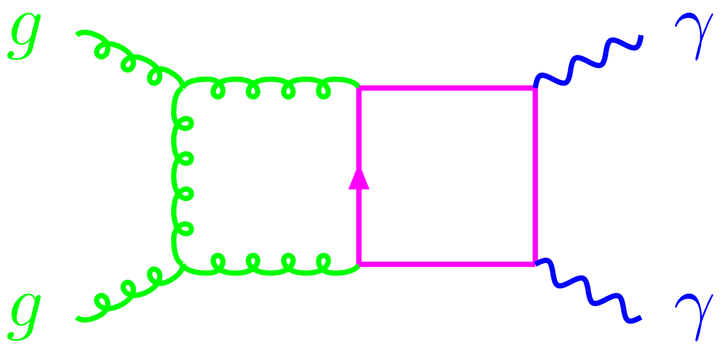


- Computed using 2-loop technology discussed earlier

  Bern, De Freitas, LD

1-loop $gg \rightarrow \gamma\gamma$ amplitude

$$\mathcal{A}^{1-\text{loop}}_{gg\to\gamma\gamma} = 4\alpha\,\alpha_s(\mu)\delta^{a_1a_2}\left(\sum_i Q_i^2\right)A^{(1)}(s,t)$$

- Through $\mathcal{O}(\epsilon^0)$,

$$\begin{aligned}
A^{(1)}_{++++} &= A^{(1)}_{-+++} = A^{(1)}_{+-++} = A^{(1)}_{++-+} = A^{(1)}_{+++-} = 1 \\
A^{(1)}_{--++} &= -\frac{1}{2}\frac{t^2+u^2}{s^2}\left[\ln^2\left(\frac{t}{u}\right)+\pi^2\right] - \frac{t-u}{s}\ln\left(\frac{t}{u}\right) - 1 \\
A^{(1)}_{-+-+} &= -\frac{1}{2}\frac{t^2+s^2}{u^2}\ln^2\left(-\frac{t}{s}\right) - \frac{t-s}{u}\ln\left(-\frac{t}{s}\right) - 1 \\
&\quad - i\pi\left[\frac{t^2+s^2}{u^2}\ln\left(-\frac{t}{s}\right) + \frac{t-s}{u}\right] \\
A^{(1)}_{+--+} &= A^{(1)}_{-+-+}(t \leftrightarrow u)
\end{aligned}$$

- Actually need through $\mathcal{O}(\epsilon^2)$ for 2-loop case. . .

2-loop $gg \to \gamma\gamma$ amplitude

$$\mathcal{A}^{2-\text{loop}}_{gg\to\gamma\gamma} = \frac{2\alpha\,\alpha_s^2(\mu)}{\pi}\delta^{a_1 a_2}\left(\sum_i Q_i^2\right)\Bigg\{ \left[\boldsymbol{I}^{(1)}(\epsilon) + \frac{11N - 2N_f}{6}\left(\ln(\mu^2/s) + i\pi\right)\right] A^{(1)}(s,t) + N F^{\text{L}}(s,t) - \frac{1}{N}F^{\text{SL}}(s,t)\Bigg\}$$

where $N = 3$, $N_f = 5$ (below m_t), and IR poles are given in dim. reg. by: Catani

$$\boldsymbol{I}^{(1)}(\epsilon) = -N\frac{e^{-\epsilon\psi(1)}}{\Gamma(1-\epsilon)}\left[\frac{1}{\epsilon^2} + \left(\frac{11}{6} - \frac{1}{3}\frac{N_f}{N}\right)\frac{1}{\epsilon}\right]\left(\frac{\mu^2}{-s}\right)^{\epsilon}$$

Now let

$$x = \frac{t}{s}, \quad y = \frac{u}{s}, \quad X = \ln\left(-\frac{t}{s}\right), \quad Y = \ln\left(-\frac{u}{s}\right)$$

Some finite terms in $\mathcal{A}_{gg\to\gamma\gamma}^{2-\text{loop}}$

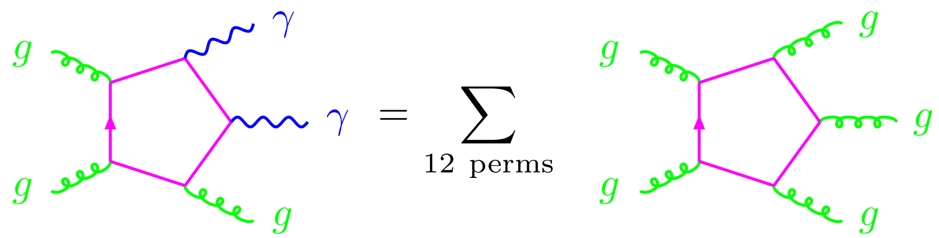
$$F^{\rm L}_{++++} = \frac{1}{2}$$

$$\begin{aligned}
F^{\rm L}_{--++} = & -(x^2+y^2)\Big[4\mathrm{Li}_4(-x) + (Y-3X-2i\pi)\mathrm{Li}_3(-x) \\
& + ((X+i\pi)^2+\pi^2)\mathrm{Li}_2(-x) + \frac{1}{48}(X+Y)^4 \\
& + i\frac{\pi}{12}(X+Y)^3 + i\frac{\pi^3}{2}X - \frac{\pi^2}{12}X^2 - \frac{109}{720}\pi^4\Big] \\
& + \frac{1}{2}x(1-3y)\Big[\mathrm{Li}_3(-x/y) - (X-Y)\mathrm{Li}_2(-x/y) - \zeta_3 + \frac{1}{2}Y((X-Y)^2+\pi^2)\Big] \\
& + \frac{1}{4}x^2\Big[(X-Y)^3 + 3(Y+i\pi)((X-Y)^2+\pi^2)\Big] \\
& + \frac{1}{8}\left(14(x-y) - \frac{8}{y} + \frac{9}{y^2}\right)((X+i\pi)^2+\pi^2) \\
& + \frac{1}{16}(38xy-13)((X-Y)^2+\pi^2) - \frac{\pi^2}{12} - \frac{9}{4}\left(\frac{1}{y}+2x\right)(X+i\pi) + \frac{1}{4} \\
& + \Big\{t \leftrightarrow u\Big\}
\end{aligned}$$

Radiative term in $gg \rightarrow \gamma\gamma X$

- Requires 1-loop $gg \rightarrow \gamma\gamma g$ amp., obtained from $gg \rightarrow ggg$

Bern, LD, Kosower; de Florian, Kunszt; Balazs, Nadolsky, Schmidt, Yuan



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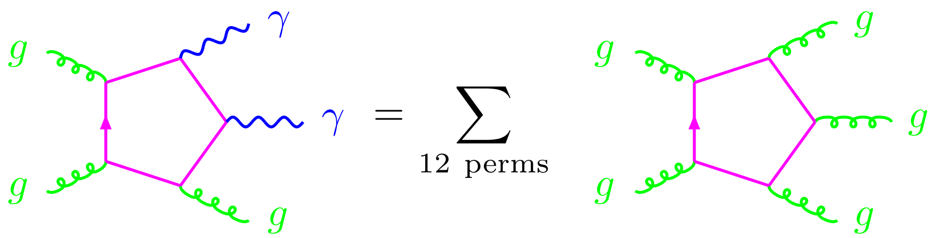

- Permutation sum cancels IR and UV virtual divergences.

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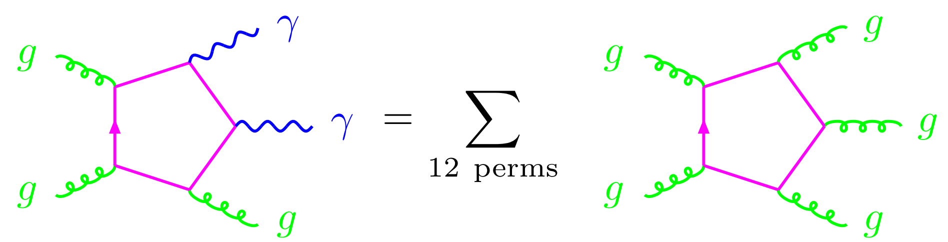


- Permutation sum cancels IR and UV virtual divergences.
- Integral over final g phase space diverges when g is soft, or collinear with initial g. Like typical NLO computation.
  - Add & subtract dipole terms. Catani, Seymour
  - Integrate subtracted result numerically in $D = 4$.
  - Integral of dipole terms cancels poles in ϵ from 2-loop $gg \to \gamma\gamma$ amplitude ($\boldsymbol{I}^{(1)}(\epsilon)$), plus collinear counterterms.

Other contributions to $\mathrm{pp} \to \gamma\gamma X$

- NLO corrections to $q\bar{q} \to \gamma\gamma$ computed by several groups

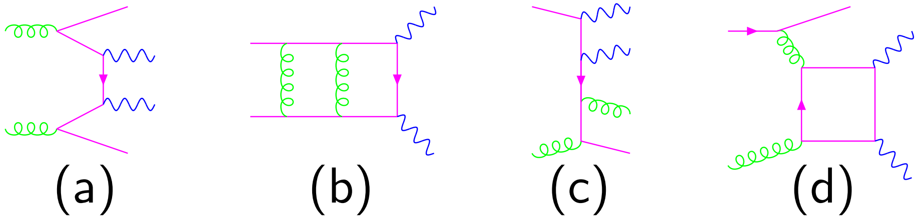
  Aurenche, Douiri, Baier, Fontannaz, Schiff; Bailey, Graudenz, Owens, Ohnemus

  Balazs, Berger, Mrenna, Yuan; Binoth, Guillet, Pilon, Werlen

- Prompt photons produced not only directly by hard processes, but also by fragmentation of quarks and gluons.

- All (except NLO $gg \to \gamma\gamma X$) incorporated at NLO in DIPHOX

- Some omitted contributions at order α_s^2 (especially (c)):



Photon Isolation

- Required to reject jets or π^0s faking γs, reduce fragmentation terms
- Either
  - **standard cone**: Circle, radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ in (η, ϕ) plane. Require $E_\mathrm{T} < E_{\mathrm{T}\,\max}$ inside circle.
  - **smooth cone**: Require $E_\mathrm{T}(r)$ less than

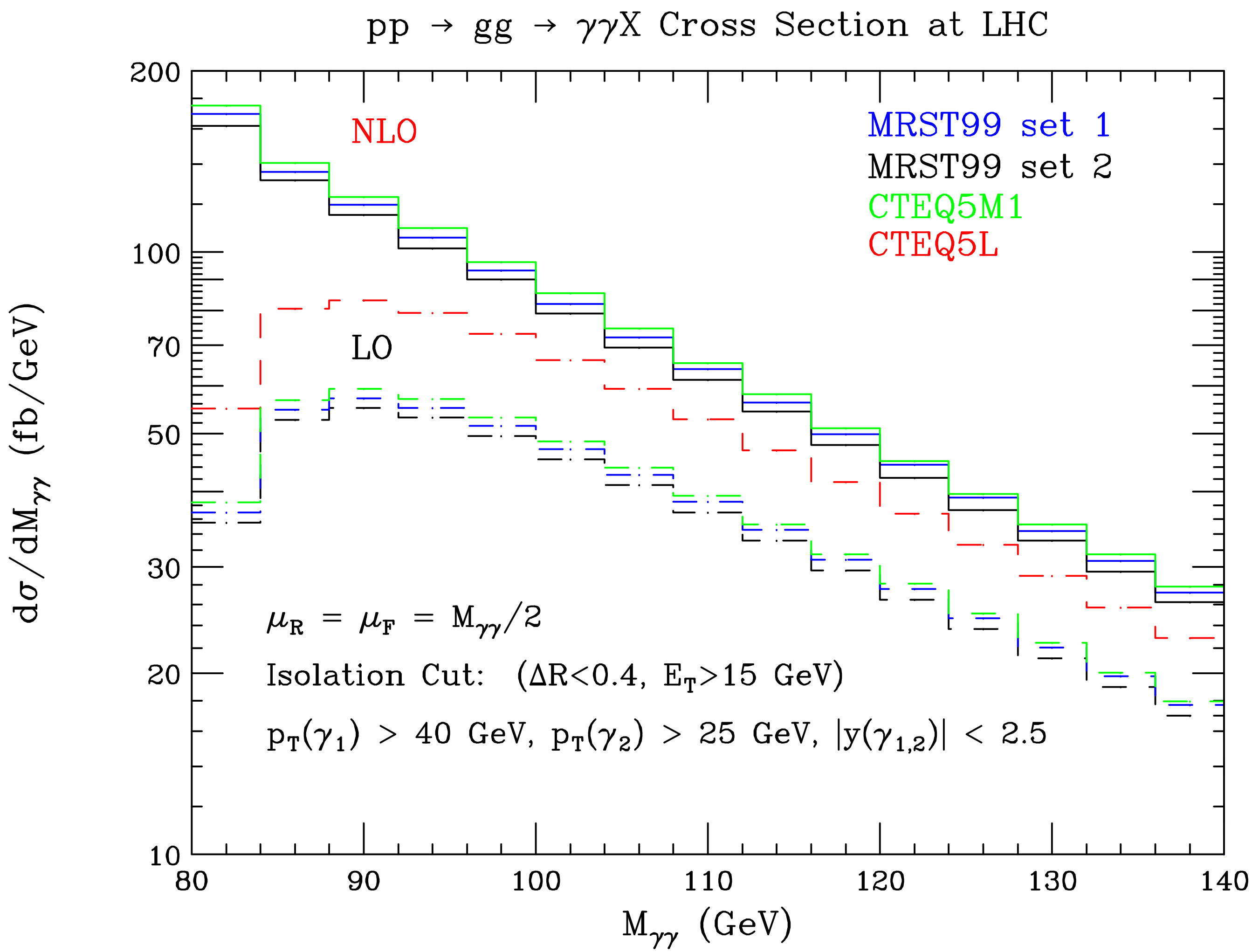
$$E_{\mathrm{T}\,\max}(r) \equiv p_\mathrm{T}(\gamma)\, \epsilon \, \frac{1 - \cos r}{1 - \cos R}$$

for all circles with $r < R$.

Frixione

- Smooth cone has no fragmentation contribution, but may be difficult to exploit experimentally (transverse shower extent, finite detector granularity).

NLO corrections to $gg \to \gamma\gamma X$



$gg \to H$ vs. $gg \to \gamma\gamma$ K factors

- $K_{gg\to H} \approx K_{\text{Higgs}}$ used by exp't'lists to estimate $K_{gg\to\gamma\gamma}$

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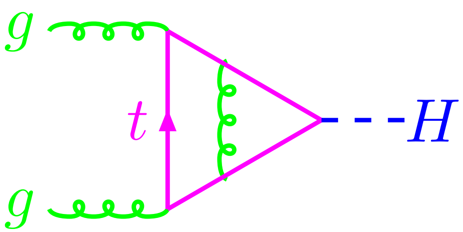
- One difference:



$$\Rightarrow \quad K^{\text{s.d.}}_{\text{Higgs}} = 1 + \frac{11}{2}\frac{\alpha_s}{\pi} \approx 1.2$$

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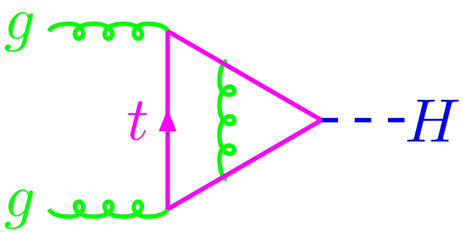

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- "Removing" $K^{\text{s.d.}}_{\text{Higgs}}$, $K_{gg\to\gamma\gamma}$ still significantly less than K_{Higgs}:

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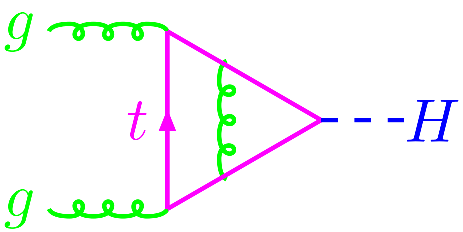

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$M_{\gamma\gamma}$ (GeV)	K_{Higgs}	$K_{\text{Higgs}}/K^{\text{s.d.}}_{\text{Higgs}}$	$K_{gg\to\gamma\gamma}$
98	2.92	2.43	1.82
118	2.54	2.12	1.61
138	2.39	1.99	1.55

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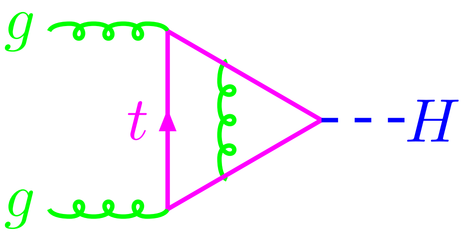


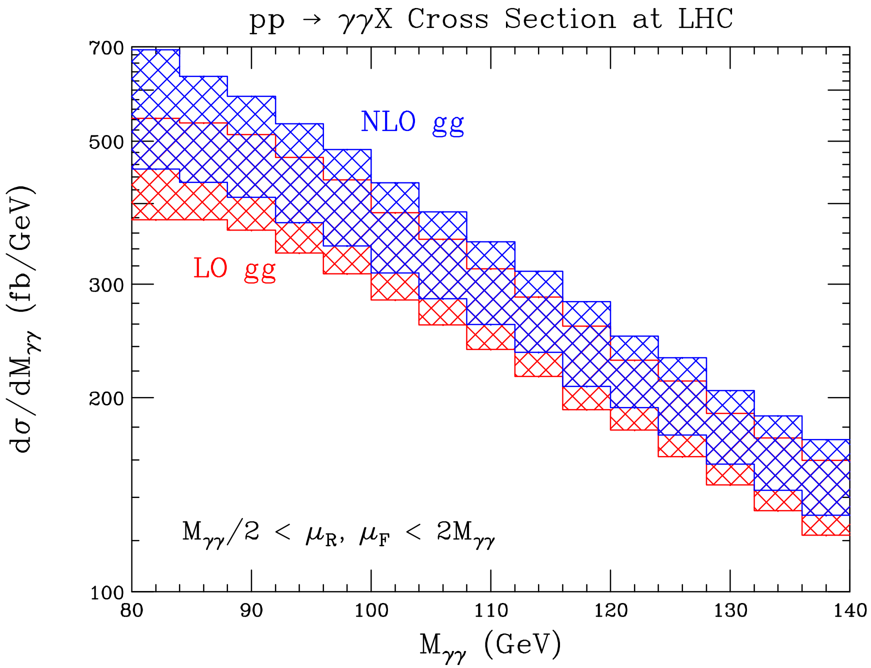
$$\Rightarrow \quad K^{\rm s.d.}_{\rm Higgs} = 1 + \frac{11}{2}\frac{\alpha_s}{\pi} \approx 1.2$$

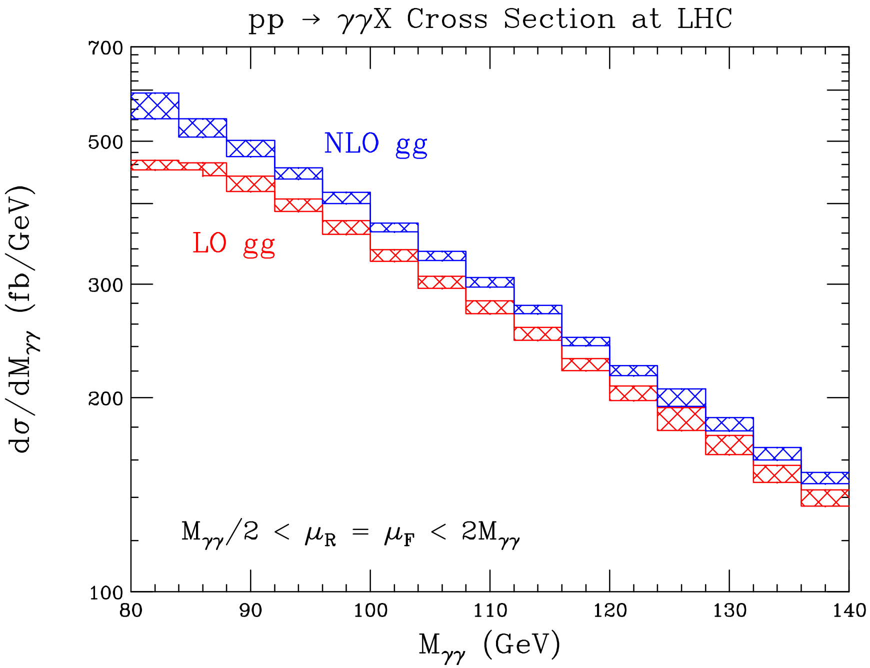
- "Removing" $K^{\rm s.d.}_{\rm Higgs}$, $K_{gg\to\gamma\gamma}$ still significantly less than $K_{\rm Higgs}$:

$M_{\gamma\gamma}$ (GeV)	$K_{\rm Higgs}$	$K_{\rm Higgs}/K^{\rm s.d.}_{\rm Higgs}$	$K_{gg\to\gamma\gamma}$
98	2.92	2.43	1.82
118	2.54	2.12	1.61
138	2.39	1.99	1.55

- $K_{gg\to\gamma\gamma} < K_{\rm Higgs}$ probably due to softness of $gg \to \gamma\gamma g$ at large g $p_{\rm T}$.

$\mathrm{pp} \to \gamma\gamma X$ scale variation

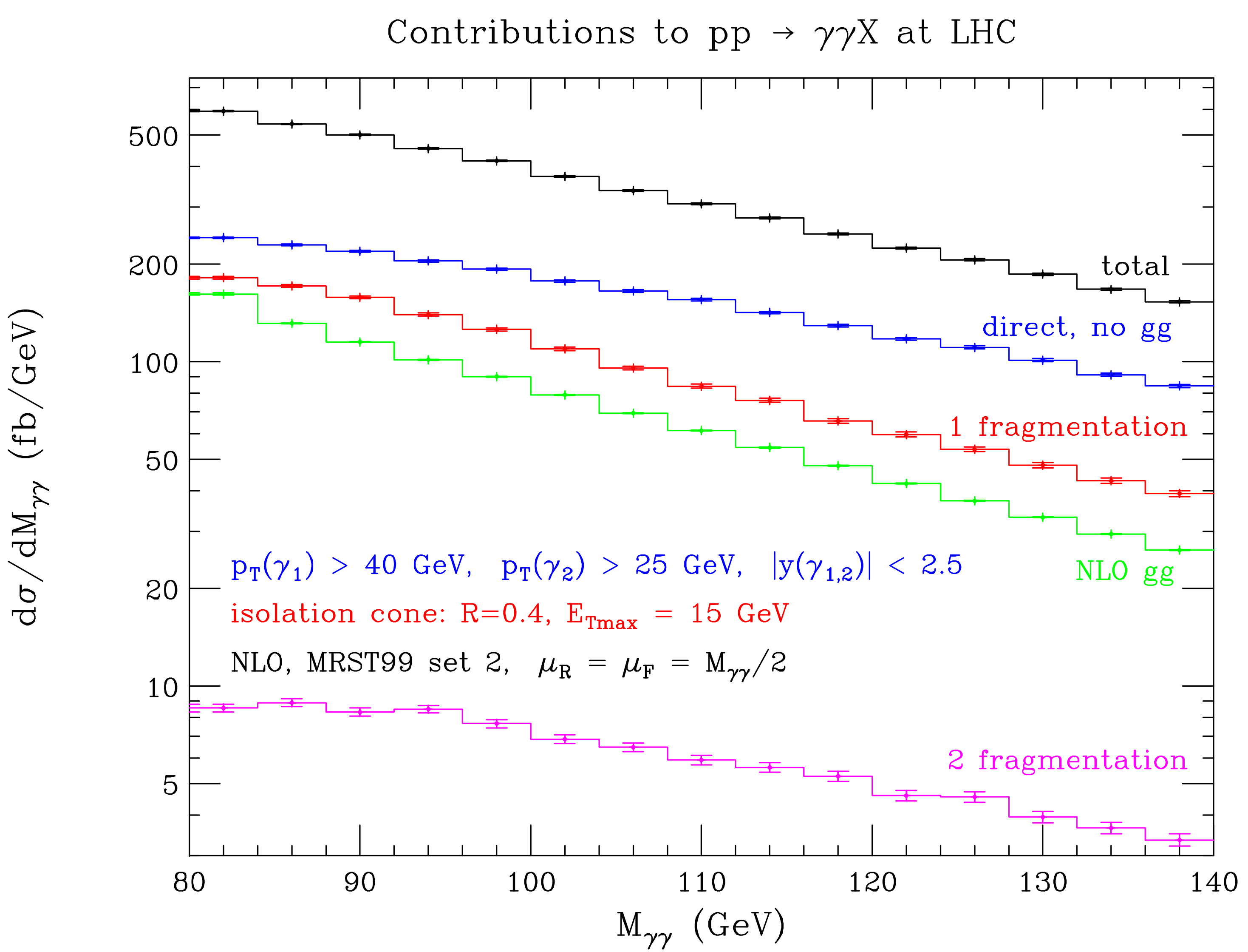




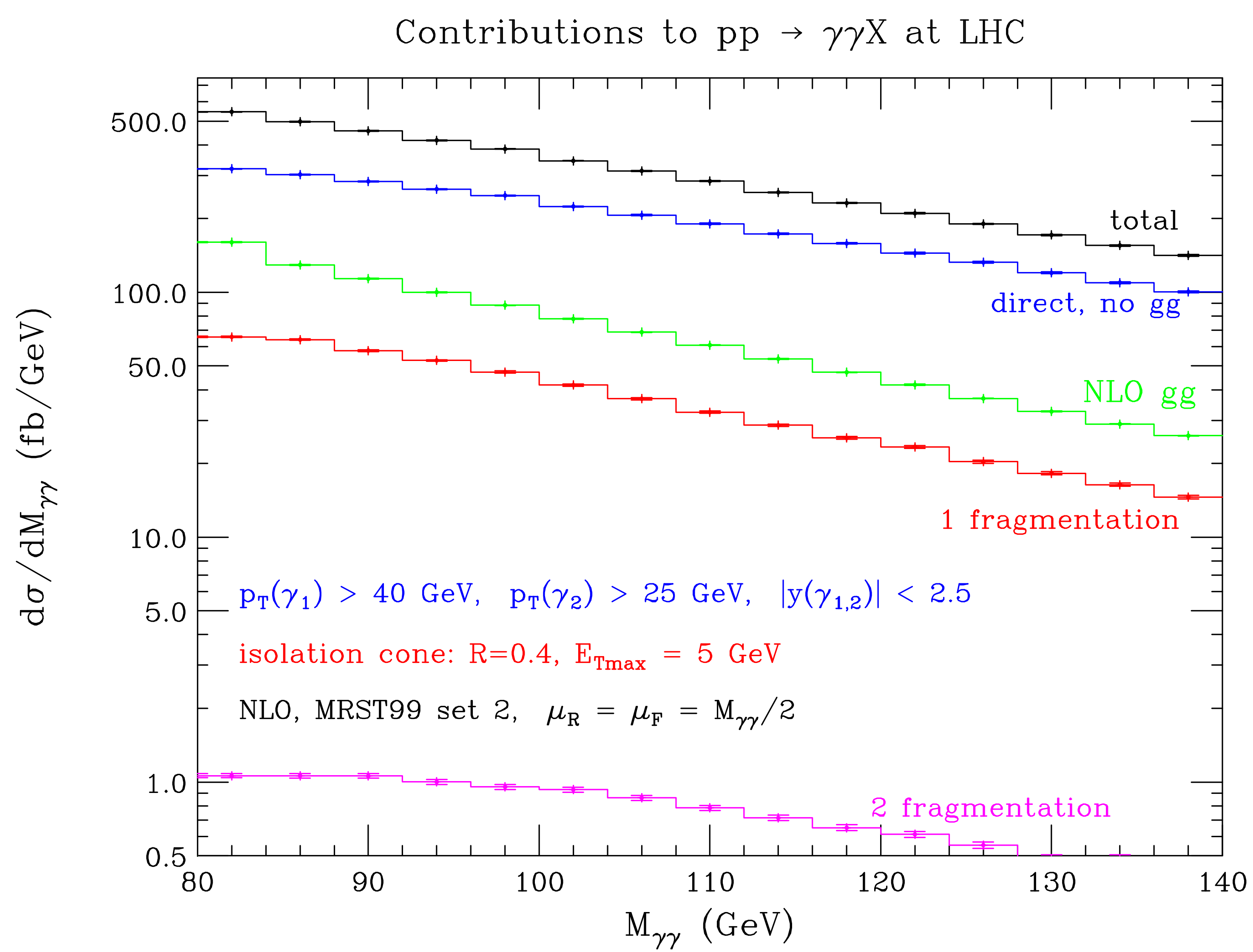
μ_R, μ_F independent

$\mu_R = \mu_F$

Irreducible background components



Irreducible components ($E_{T\,max} = 5$ GeV)



Interference

- General issue when extracting couplings $g^2_{Hii} \propto \Gamma_i$ from expt. signals for various production/decay channels:

$$\text{Is} \qquad \text{Signal} = \sigma_{ii \to H} \times \text{Br}(H \to ff) = \frac{\Gamma_i \Gamma_f}{\Gamma} \qquad ?$$

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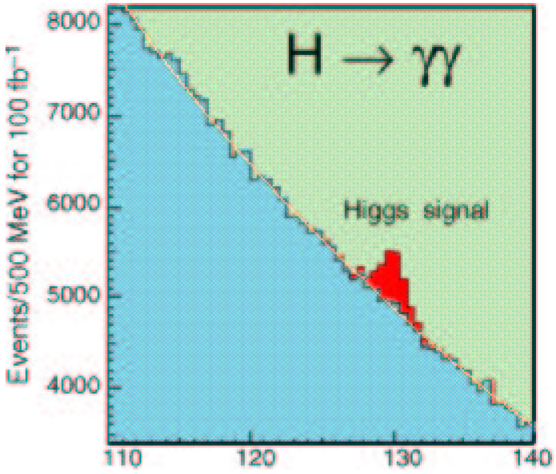
- Normally interf. effects small for a narrow resonance: If expt'l resolution $\gg$ intrinsic linewidth Γ, and if you can see it at all, it must be that the intrinsic $S/B \gg 1$, right?

Back-of-envelope calculation

- Recall $S/B \approx 1/20$



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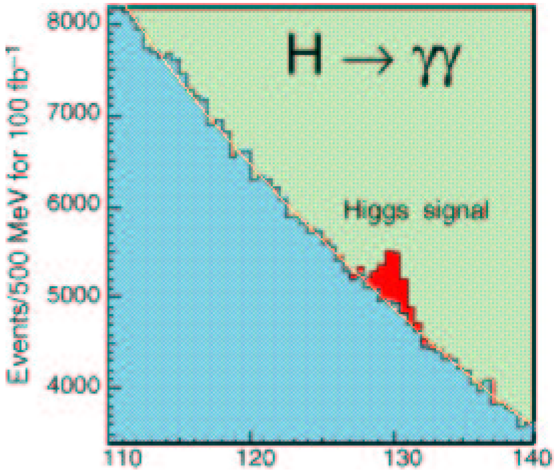

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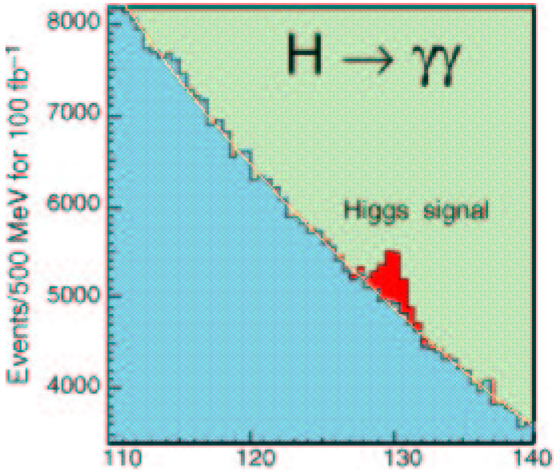

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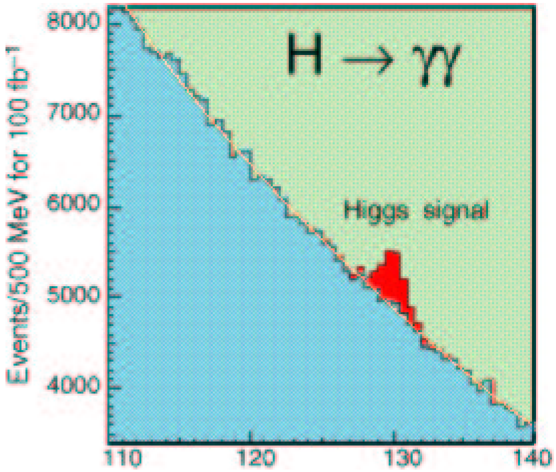

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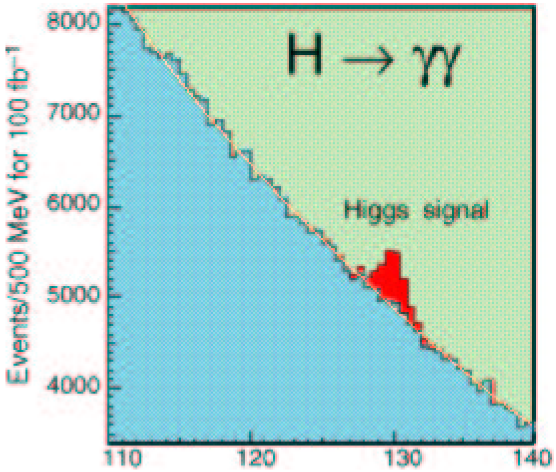

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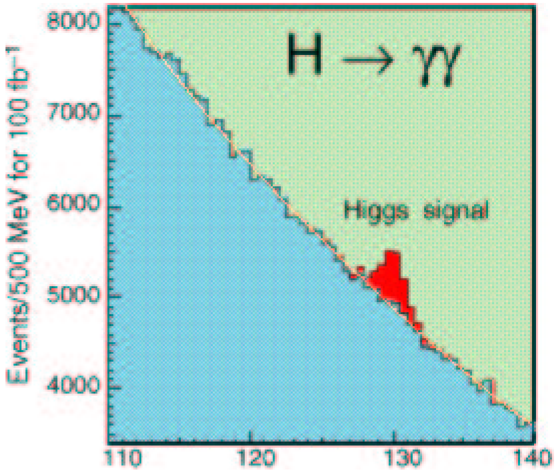

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- $\Rightarrow$ Better check it out!

In search of a phase

- Total $gg \to \gamma\gamma$ amplitude

$$\mathcal{A}_{gg\to\gamma\gamma} = \frac{-\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}}{\hat{s} - m_H^2 + im_H\Gamma_H} + \mathcal{A}_{\mathrm{cont}}$$

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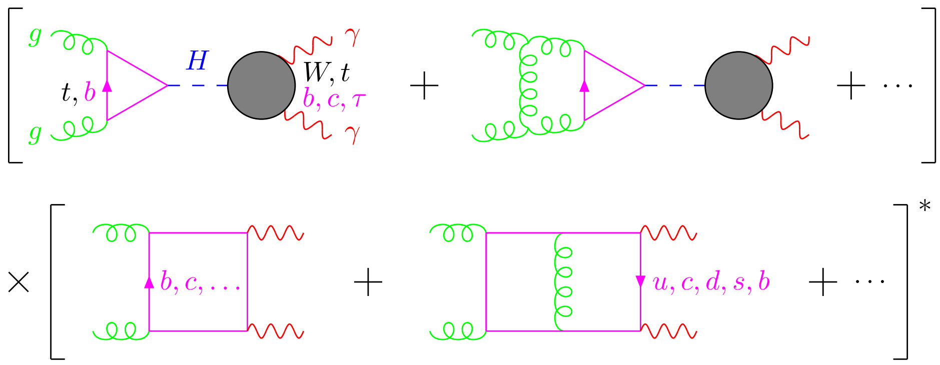
- "Im" term needs relative phase, resonance *vs.* continuum.

Source of the phase?

- Interference in diagrams:



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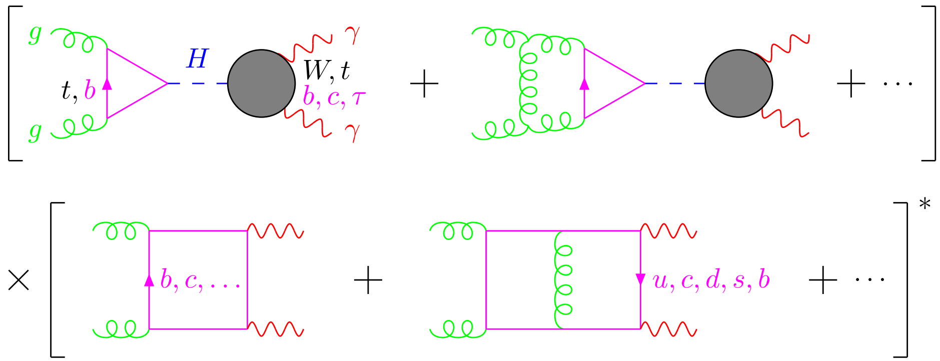

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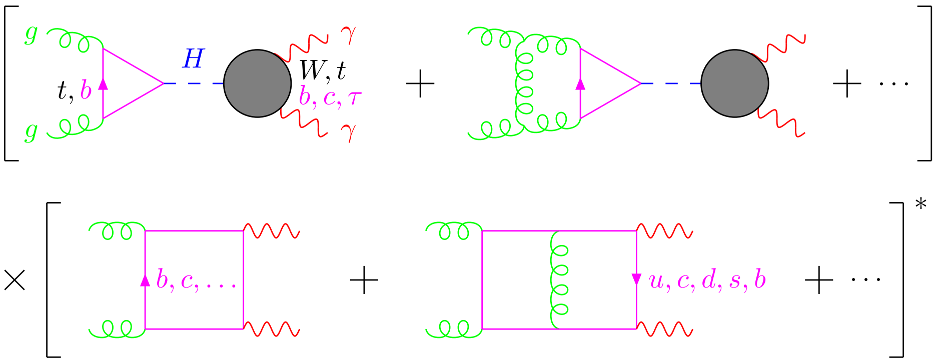

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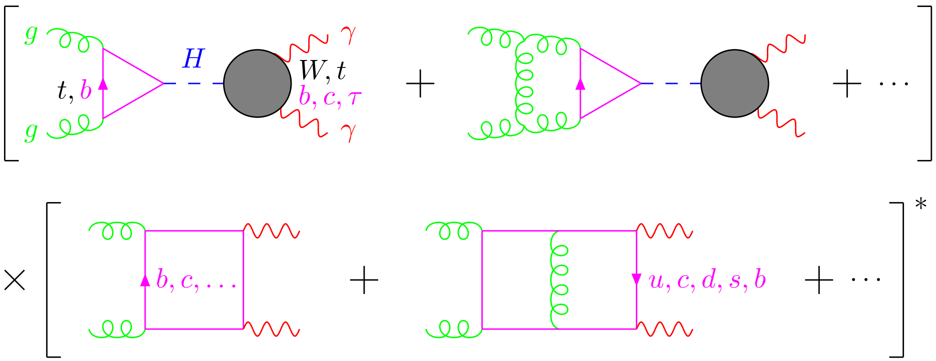

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- Dominant phase is from $\mathcal{A}^{2-\text{loop}}_{gg\to\gamma\gamma}$, in particular $\text{Im}\, F^{\text{L}}_{--++}$.

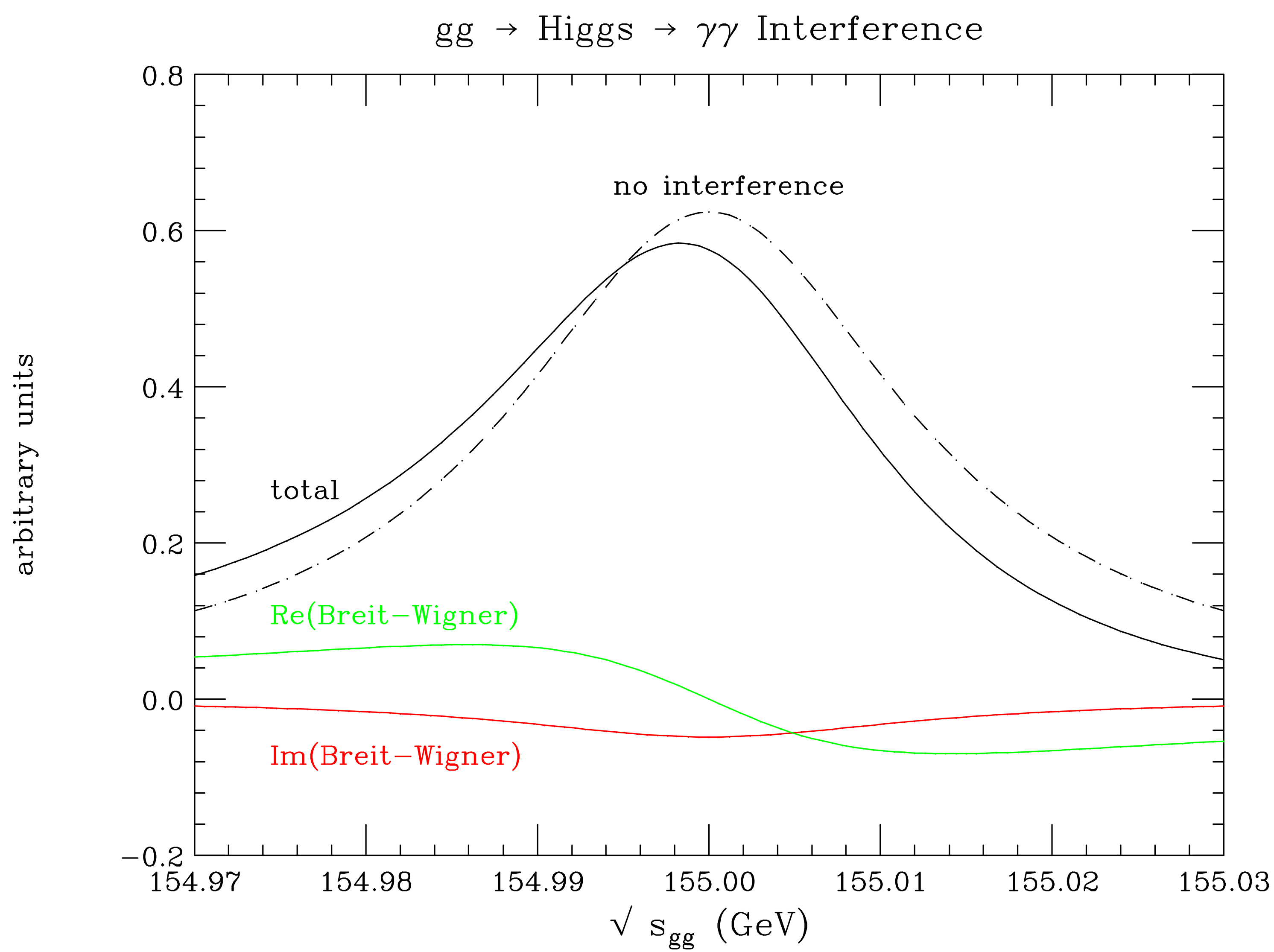
Some finite terms in $\mathcal{A}^{2-\text{loop}}_{gg\to\gamma\gamma}$

$$F^{\rm L}_{++++} = \frac{1}{2}$$

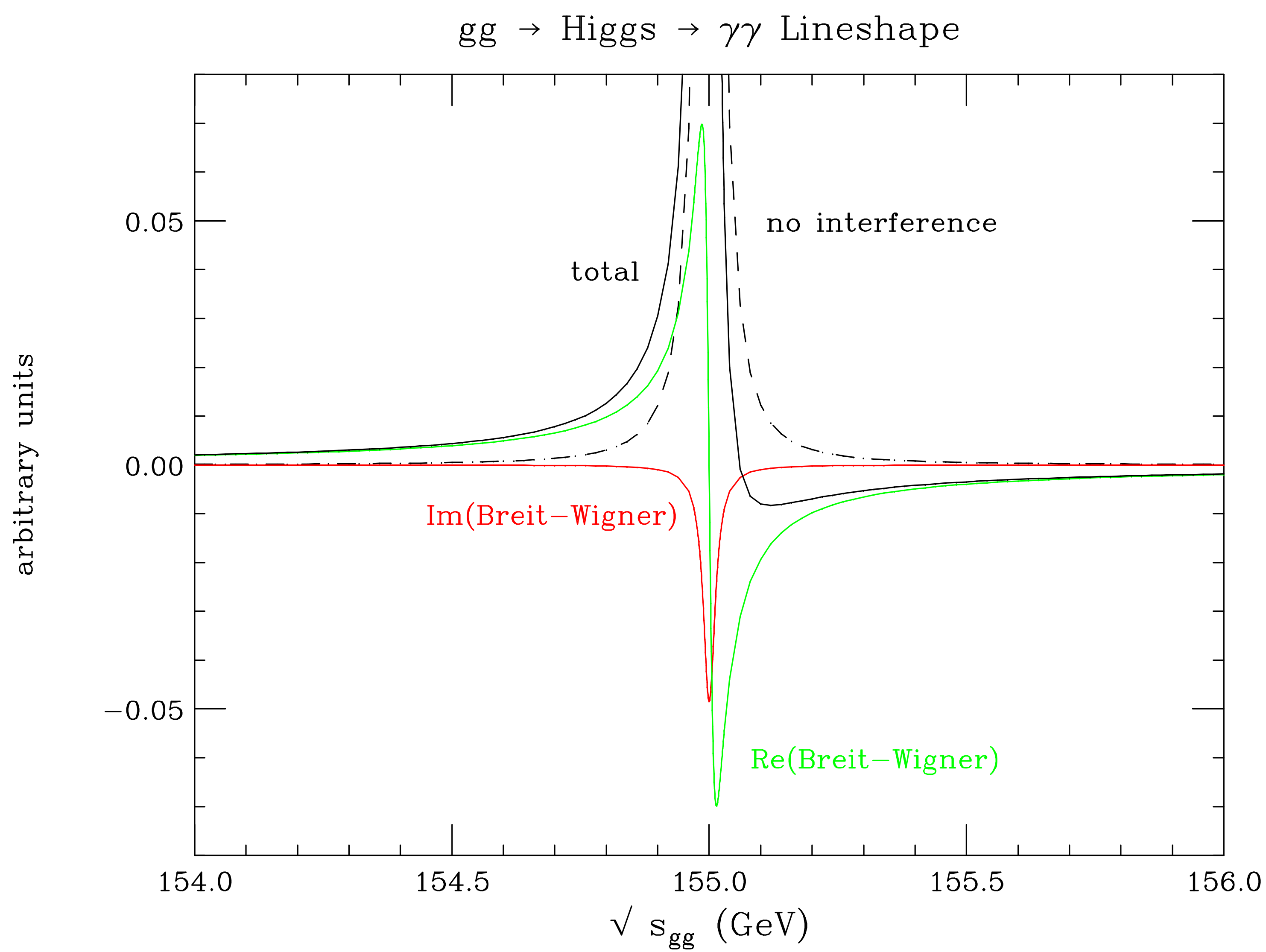
$$\begin{aligned}
F^{\rm L}_{--++} = & -(x^2+y^2)\Big[4{\rm Li}_4(-x) + (Y-3X-2i\pi){\rm Li}_3(-x) \\
& + ((X+i\pi)^2+\pi^2){\rm Li}_2(-x) + \frac{1}{48}(X+Y)^4 \\
& + i\frac{\pi}{12}(X+Y)^3 + i\frac{\pi^3}{2}X - \frac{\pi^2}{12}X^2 - \frac{109}{720}\pi^4\Big] \\
& + \frac{1}{2}x(1-3y)\Big[{\rm Li}_3(-x/y) - (X-Y){\rm Li}_2(-x/y) - \zeta_3 + \frac{1}{2}Y((X-Y)^2+\pi^2)\Big] \\
& + \frac{1}{4}x^2\Big[(X-Y)^3 + 3(Y+i\pi)((X-Y)^2+\pi^2)\Big] \\
& + \frac{1}{8}\left(14(x-y) - \frac{8}{y} + \frac{9}{y^2}\right)((X+i\pi)^2+\pi^2) \\
& + \frac{1}{16}(38xy-13)((X-Y)^2+\pi^2) - \frac{\pi^2}{12} - \frac{9}{4}\left(\frac{1}{y}+2x\right)(X+i\pi) + \frac{1}{4} \\
& + \Big\{t \leftrightarrow u\Big\}
\end{aligned}$$

note imaginary parts!

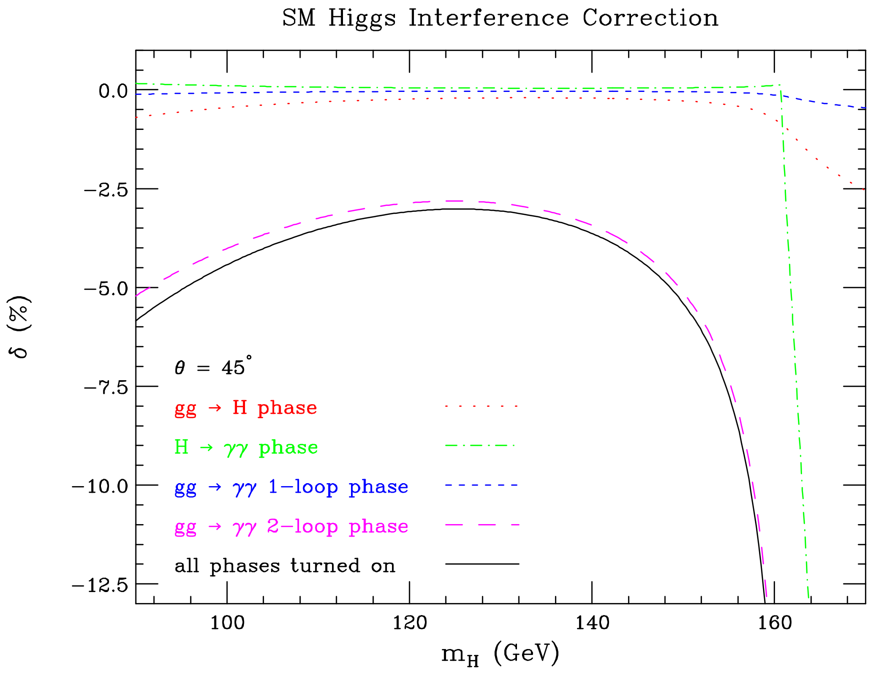
Close-up of Higgs resonance



Not-so-close-up of Higgs resonance



Percentage correction to signal



- Effect is $-(2-6)\%$ over region where $\gamma\gamma$ is visible.
- Gets very large near WW threshold.
- Interference effects in e.g. MSSM, selected other channels in (MS)SM, deserve further investigation.

Conclusions

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- Multi-loop amplitudes play an important role in
  - signal
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- All 3 quantities could use still further study!