Off-shell effects in Higgs processes at a linear collider and the LHC

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EPS-HEP 2015,
Vienna, 07 / 2015

Outline

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Based on collaboration with:
N. Greiner, S. Liebler, G. Moortgat-Pick

Introduction: Higgs coupling determination at the LHC

Problem: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields combinations of Higgs couplings ($\Gamma_{\text{prod, decay}} \sim g^2_{\text{prod, decay}}$):

$$\sigma(H) \times \text{BR}(H \to a + b) \sim \frac{\Gamma_{\text{prod}}\Gamma_{\text{decay}}}{\Gamma_{\text{tot}}},$$

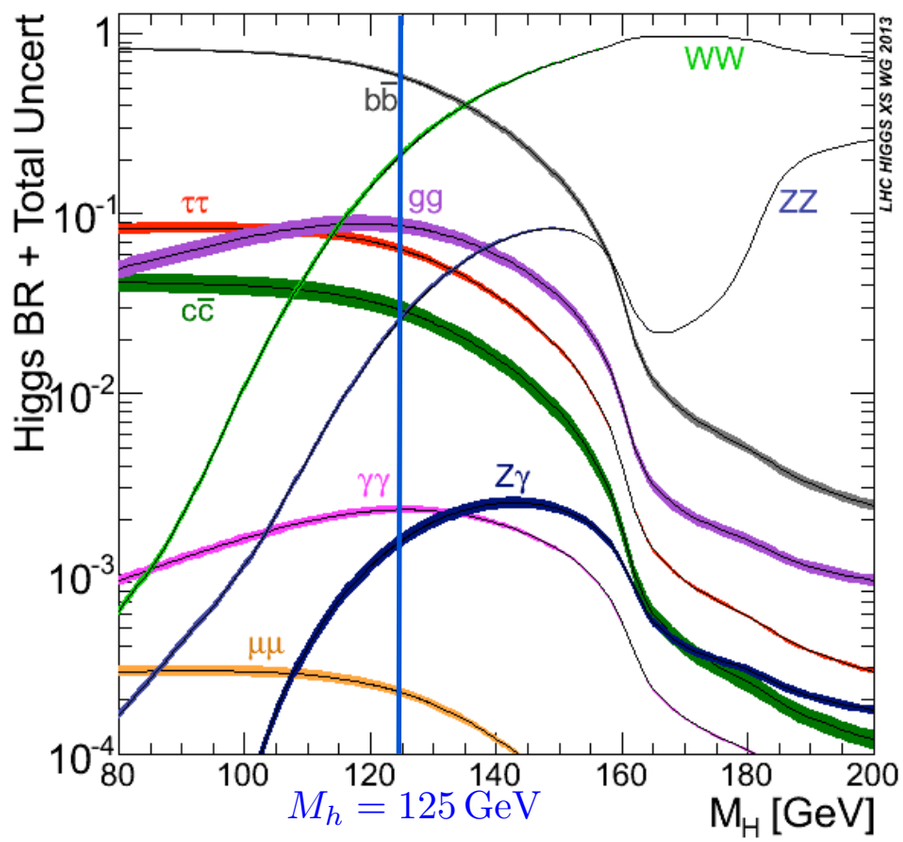
Total Higgs width cannot be determined without further assumptions

$\Rightarrow$ LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$

Additional source of information: off-shell effects

Reason for importance of off-shell effects (and high sensitivity to Higgs mass value) for BR(H → ZZ*), BR(H → WW*):

SM Higgs branching fractions:



[LHC Higgs XS WG '14]

For a 125 GeV Higgs boson the branching ratios into BR(H → ZZ*), BR(H → WW*) are far below threshold

⇒ Strong phase-space suppression, steep rise with M_H

⇒ Sensitive dependence on M_H, off-shell effects are important

Total Higgs width: recent analyses from CMS and ATLAS

- Exploit different dependence of on-peak and off-peak contributions on the total width in Higgs decays to $ZZ^{(*)}$

- CMS quote an upper bound of $\Gamma/\Gamma_{\text{SM}} < 5.4$ at 95% C.L., where 8.0 was expected, ATLAS: $\Gamma/\Gamma_{\text{SM}} < 5.7$ at 95% C.L., 8.5 expect.
  [CMS Collaboration '14] *[ATLAS Collaboration '14]*

- Problem: equality of on-shell and far off-shell couplings assumed; relation can be severely affected by new physics contributions, in particular via threshold effects (note: effects of this kind may be needed to give rise to a Higgs-boson width that differs from the SM one by the currently probed amount)
  [C. Englert, M. Spannowsky '14]

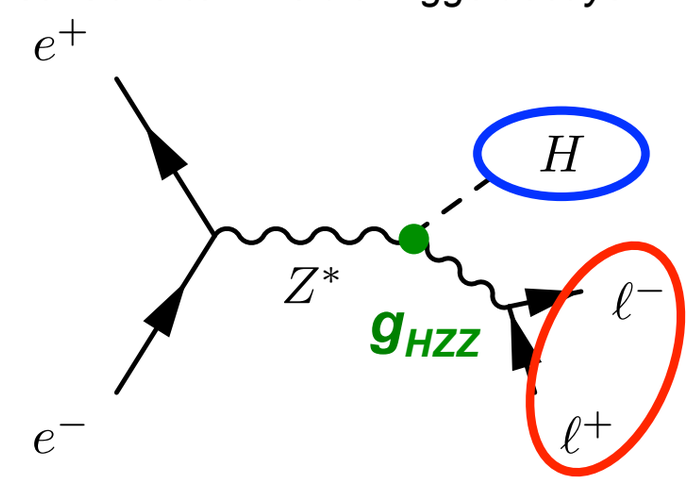
$\Rightarrow$ SM consistency test rather than model-independent bound

Destructive interference between Higgs- and gauge-boson contributions (unitarity cancellations) $\Rightarrow$ difficult to reach $\Gamma/\Gamma_{\text{SM}} \approx 1$ even for high statistics

Impact of off-shell Higgs contributions on Linear Collider physics

Linear Collider (LC): absolute measurements of *ZH* cross section and Higgs branching ratios possible

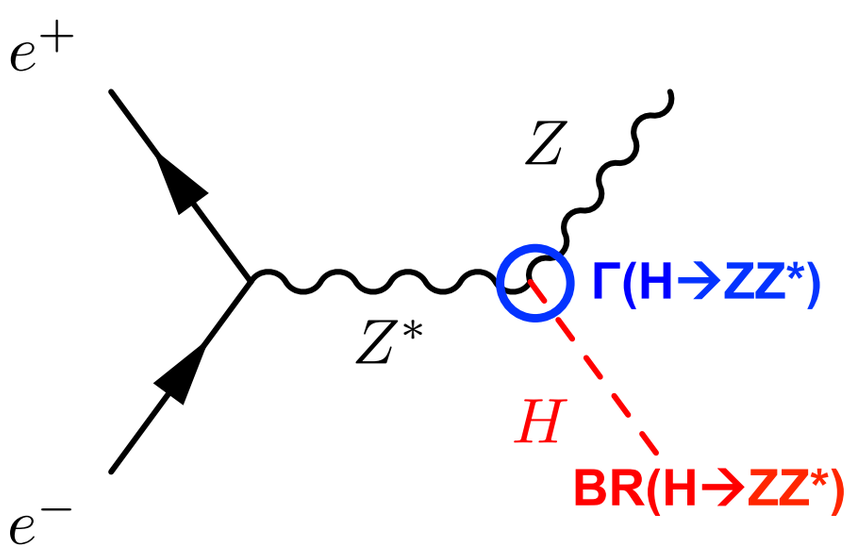
Reconstruct $Z \to l^+l^-$
independent of Higgs decay
sensitive to invisible Higgs decays

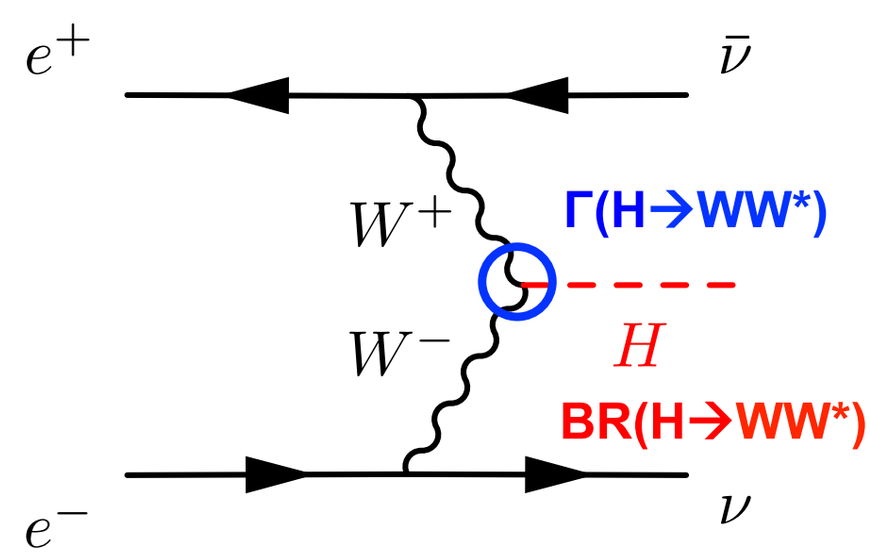


$\Rightarrow$ Model-independent determination of the total Higgs width

$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

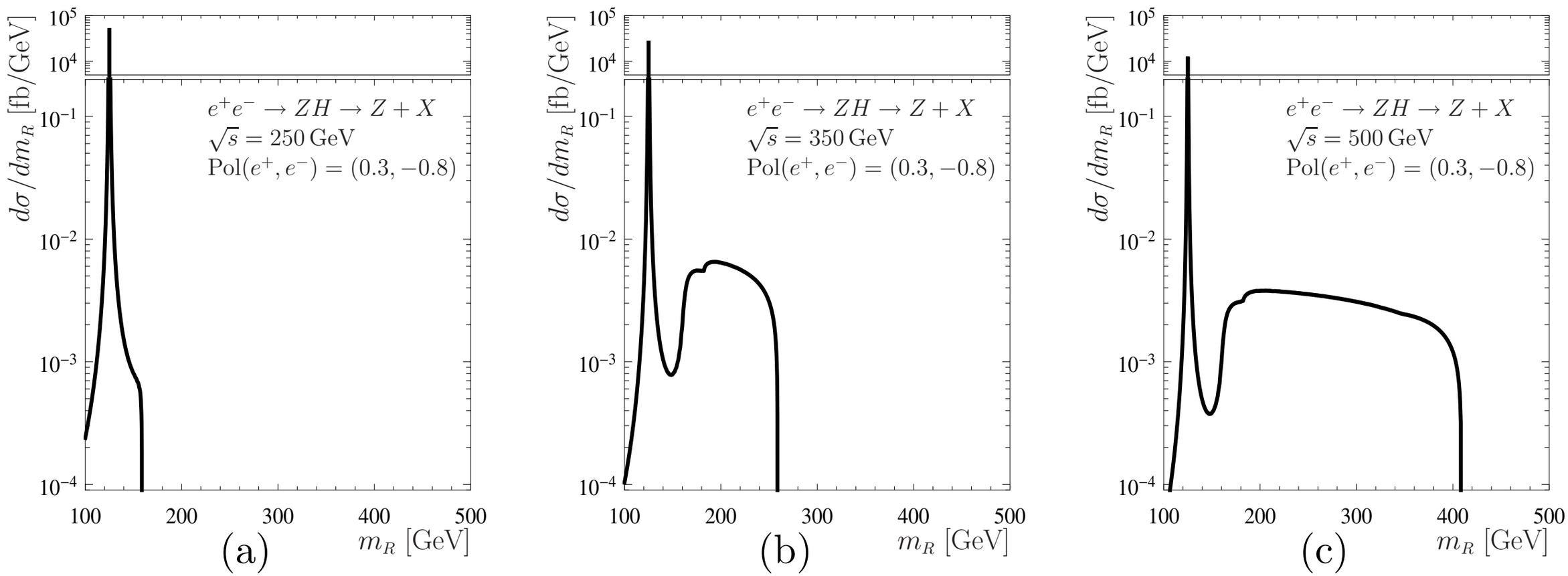
$$\Gamma_H = \Gamma(H \to XX)/\text{BR}(H \to XX)$$





Recoil method: impact of off-shell effects

[S. Liebler, G. Moortgat-Pick, G. W. '15]



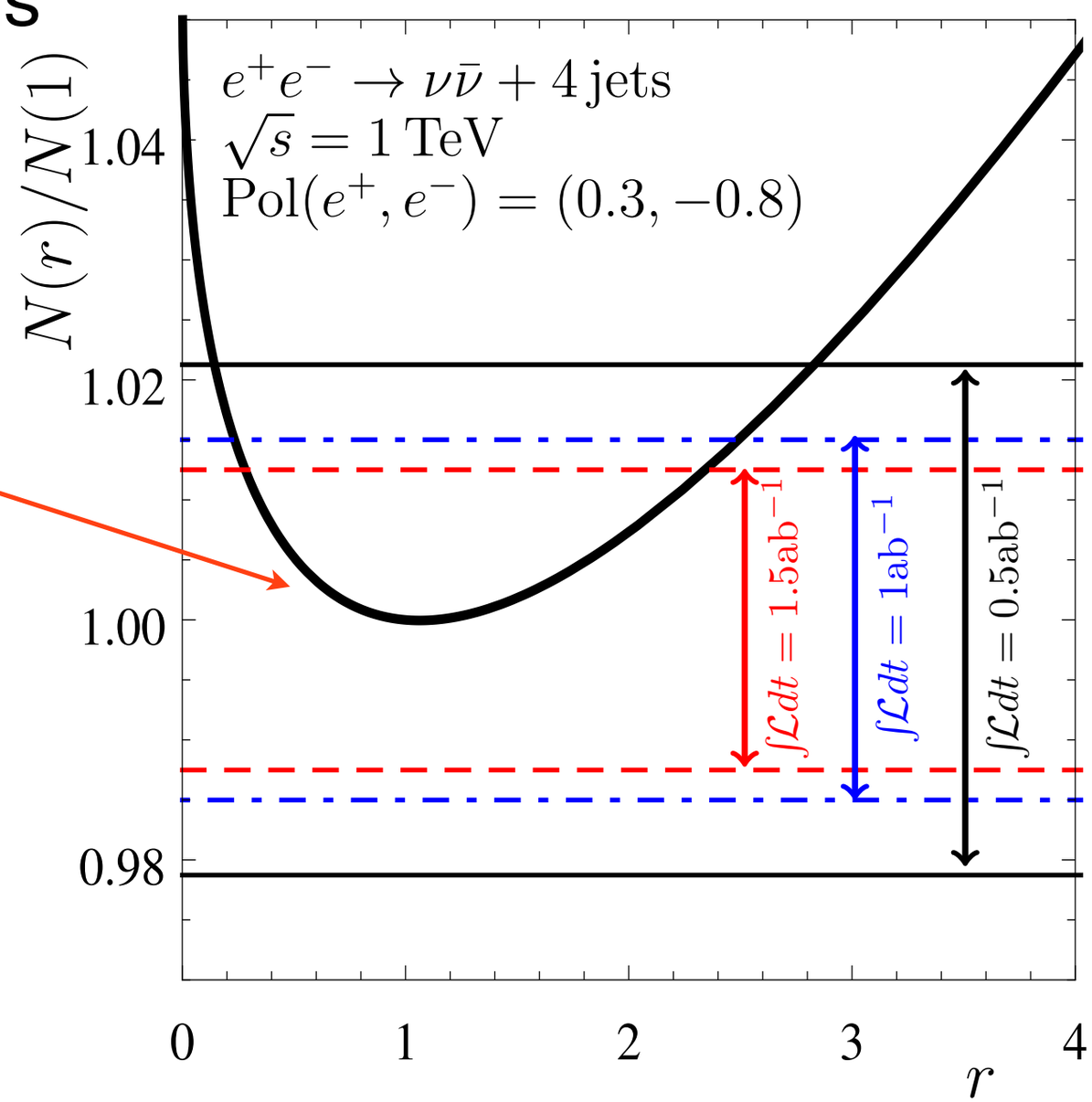
$\sqrt{s}$	250 GeV	300 GeV	350 GeV	500 GeV	1 TeV
Δ_{off}	0.02 %	0.12 %	0.30 %	0.91 %	1.84 %

⇒ Relatively small overall effect, grows with increasing c.m. energy
Absolute det. of σ_{tot} at low energies not affected by off-shell effects

Constraints on the Higgs width via off-shell effects

Same theoretical assumptions as in LHC analyses

[S. Liebler, G. Moortgat-Pick, G. Weiglein '15]



Large negative signal - background interference (reason: unitarity cancellations)

$$N(r) = N_0(1 + R_1\sqrt{r} + R_2 r)$$

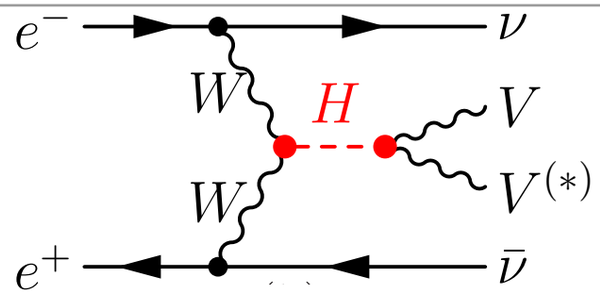
$r = \Gamma/\Gamma_{\text{SM}}$

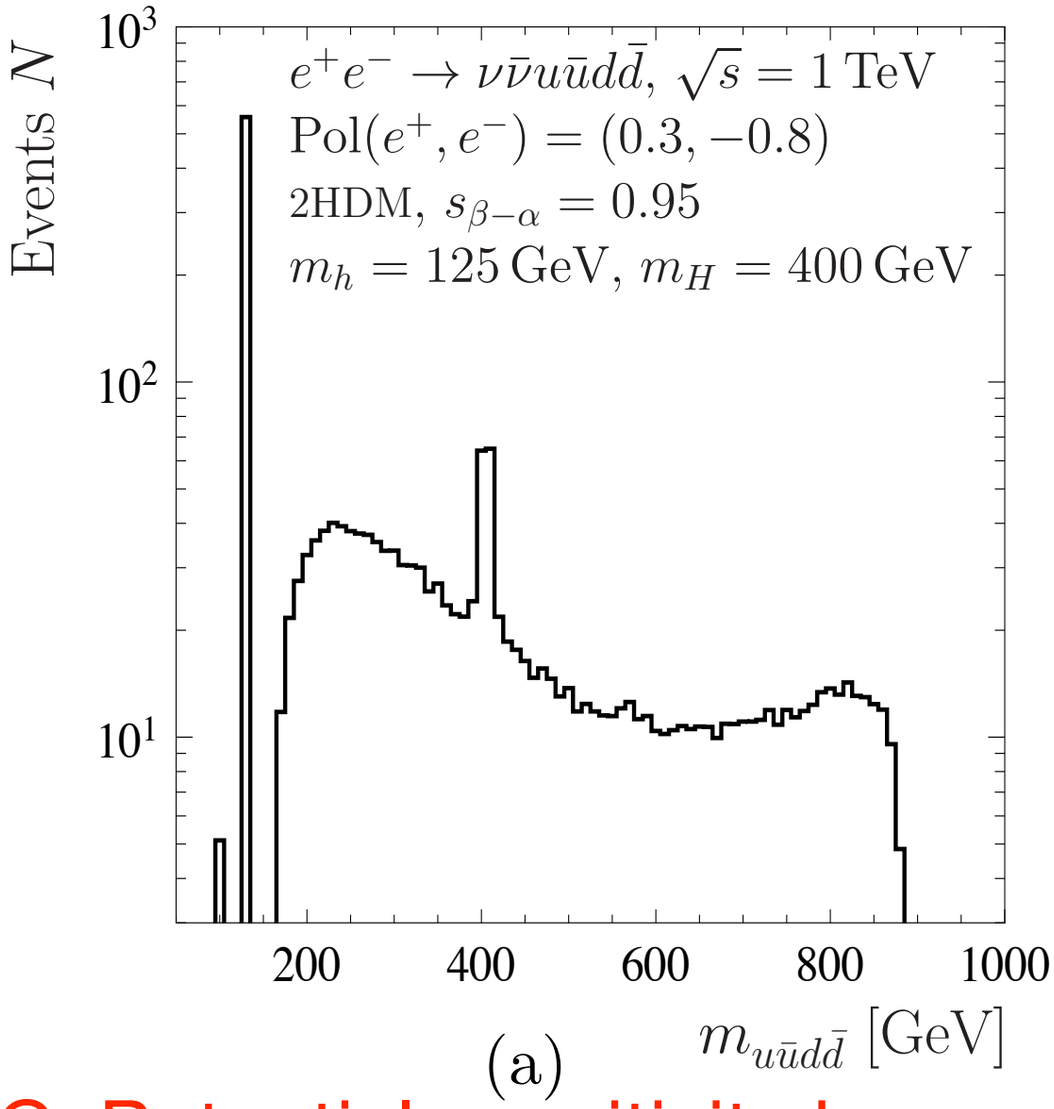
⇒ Limited sensitivity even with high integrated luminosity

Qualitative behaviour at the LHC is the same!

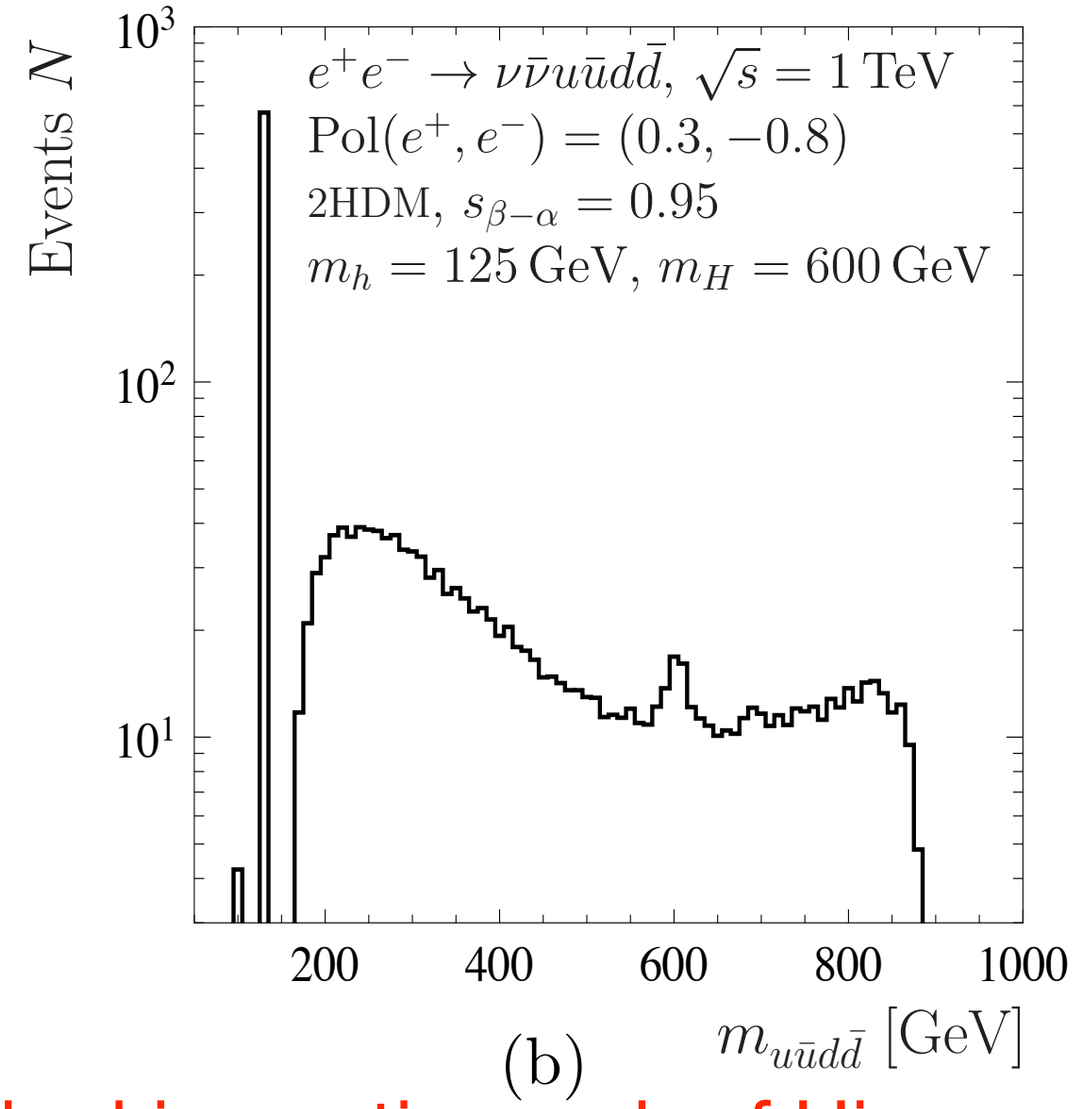
Sensitivity to the small signal of an additional heavy Higgs boson in a Two-Higgs-Doublet model (2HDM)

[S. Liebler, G. Moortgat-Pick, G. W. '15]





(a)



(b)

⇒ ILC: Potential sensitivity beyond the kinematic reach of Higgs pair production

LHC: sensitivity to an additional heavy Higgs boson of a Two-Higgs-Doublet model (2HDM)

Assume: M_h = 125 GeV, M_H = 400 GeV, couplings to gauge bosons are sin(β−α), cos(β−α) rel. to SM, three scenarios:

Scen. 1: tanβ = 1, sin(β−α) = 0.99, Γ_H = 3.6 GeV

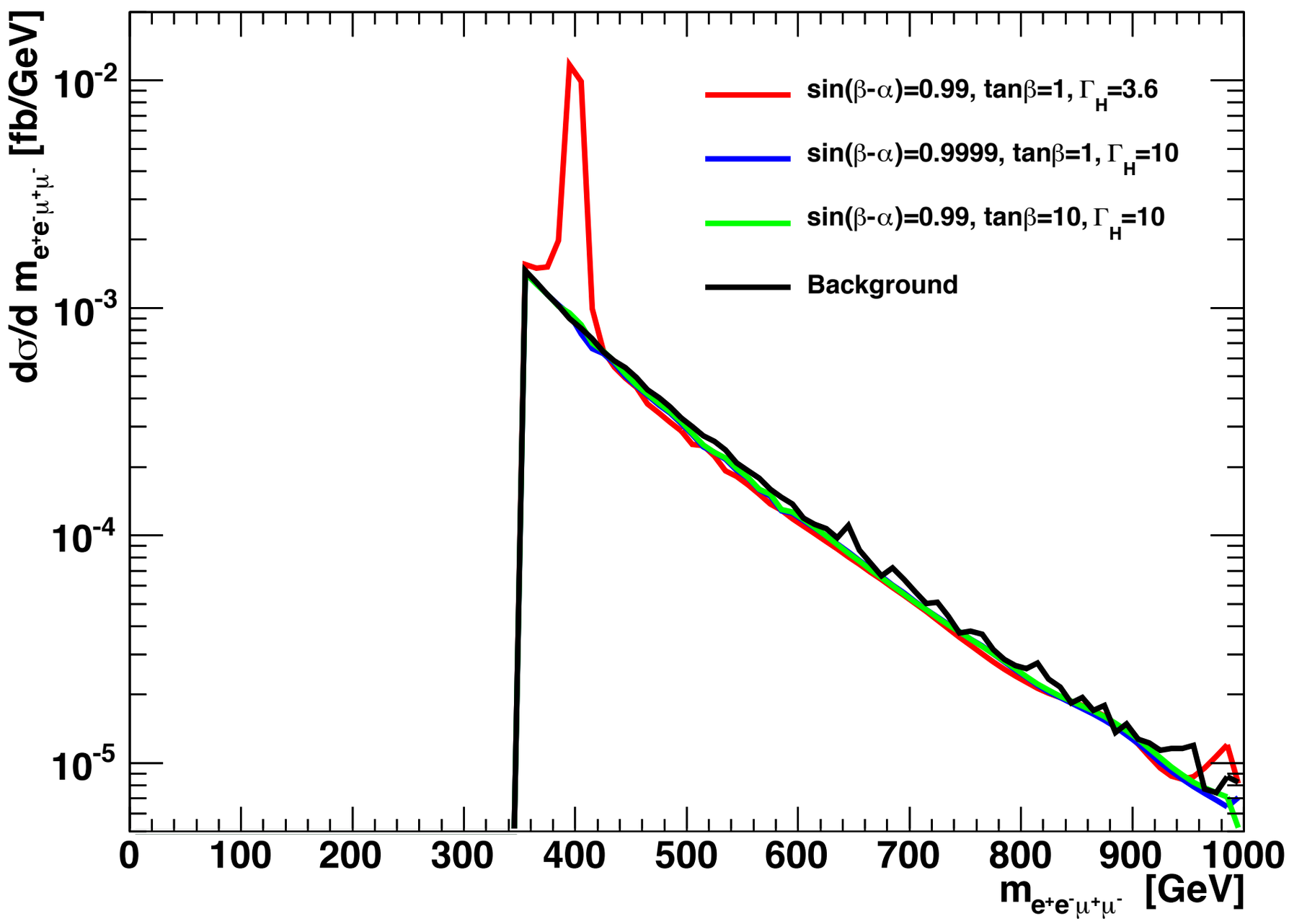
Scen. 2: tanβ = 1, sin(β−α) = 0.9999, Γ_H = 10 GeV

Scen. 3: tanβ = 10, sin(β−α) = 0.99, Γ_H = 10 GeV

Analysis of gg → $e^+e^-\mu^+\mu^-$ including signal, background and H-h, H-background interference contributions using *GoSam* *[G. Cullen et al. '14]* and *MadEvent* *[F. Maltoni, T. Stelzer '02]*

gg → $e^+e^-\mu^+\mu^-$, invariant mass distribution

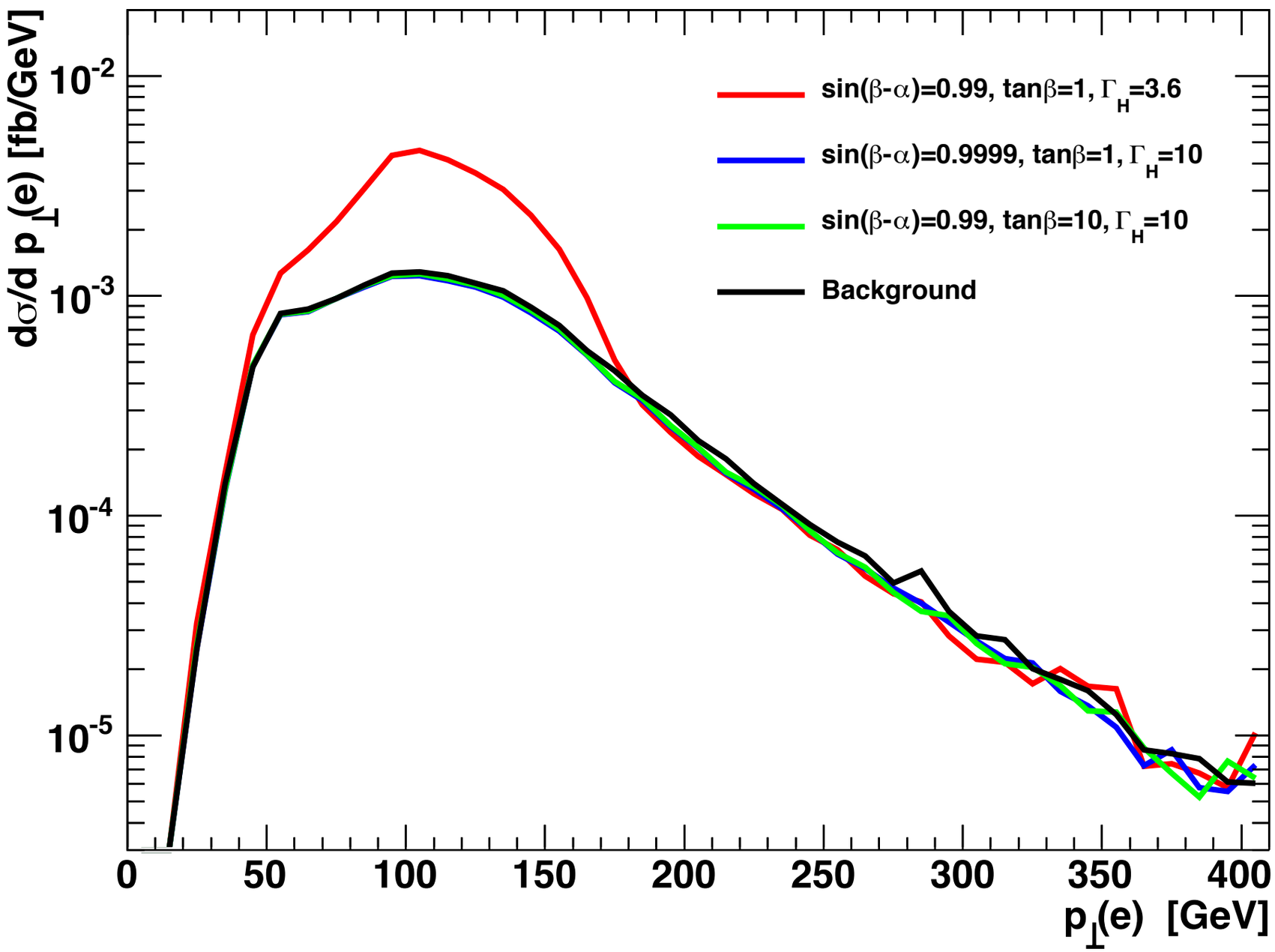
[N. Greiner, S. Liebler, G. W. '15]



⇒ H signal potentially separable from background for Scen. 1

gg → $e^+e^-\mu^+\mu^-$, p_T distribution

[N. Greiner, S. Liebler, G. W. '15]

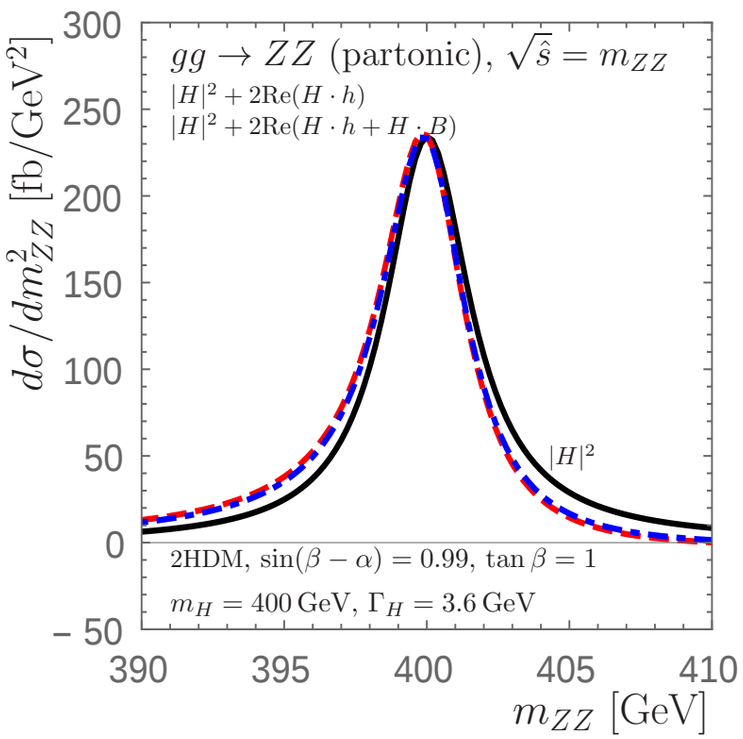


⇒ H signal potentially separable from background for Scen. 1

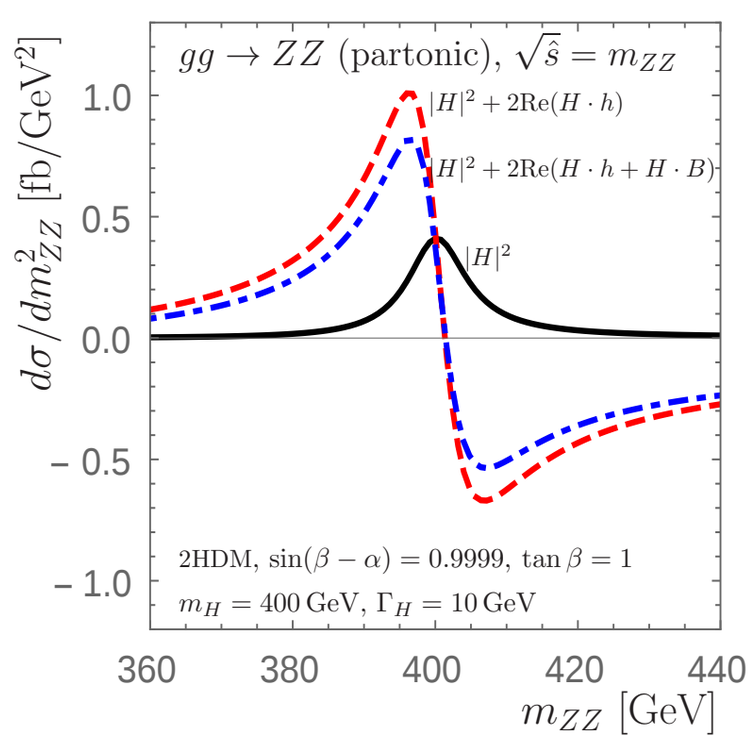
Partonic gg → ZZ cross sections, impact of interference contributions

[N. Greiner, S. Liebler, G. W. '15]

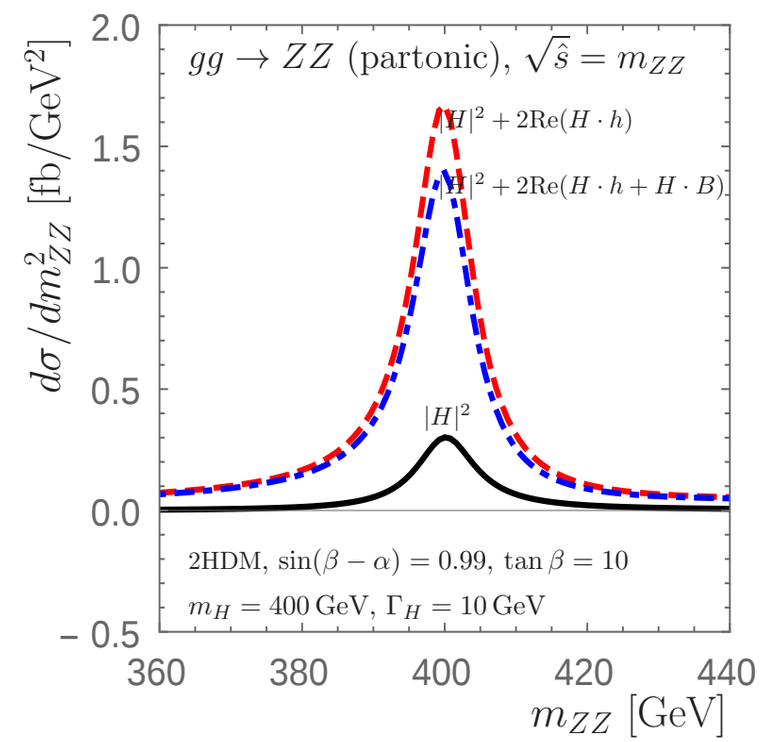
Scen. 1:



Scen. 2:



Scen. 3:



⇒ Interference effects of O(10%) for phenomenologically interesting cases

See also *[N. Kauer, C. O'Brien '15] [N. Kauer, C. O'Brien, E. Vryonidou '15]*

Conclusions

- Off-shell effects and interference contributions can be important for Higgs physics despite the small width of a SM-like Higgs at 125 GeV; very precise measurement of Higgs mass needed!

- Constraints on the total width from different dependence of on-peak and off-peak contributions in Higgs decays to $VV^{(*)}$: consistency test of the SM rather than model-independent bound

- Large signal-background interference reduces sensitivity of constraints on total width

- Absolute determination of total cross section at LC is not affected by off-shell contributions

- Interference effects can enhance sensitivity to small signal of additional heavy Higgs: O(10%) effects at the LHC, larger at the ILC

Backup

Higgs mass measurement: the need for high precision

Measuring the mass of the discovered signal with high precision is of interest in its own right

But a high-precision measurement has also direct implications for probing Higgs physics

M_H: crucial input parameter for Higgs physics

BR(H → ZZ*), BR(H → WW*): highly sensitive to precise numerical value of M_H

A change in M_H of 0.2 GeV shifts BR(H → ZZ*) by 2.5%!

⇒ Need high-precision determination of M_H to exploit the sensitivity of BR(H → ZZ*), ... for testing BSM physics