Interference effects for Higgs-mediated ZZ+jet production

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Motivation

* a large fraction of the cross section for events where the Higgs decays to vector bosons,

$$pp \to H(\to VV) + X$$

lies in the high mass tail $M_{VV} > 2\, m_V$ Kauer, Passarino, JHEP 1208, 116 (2012)

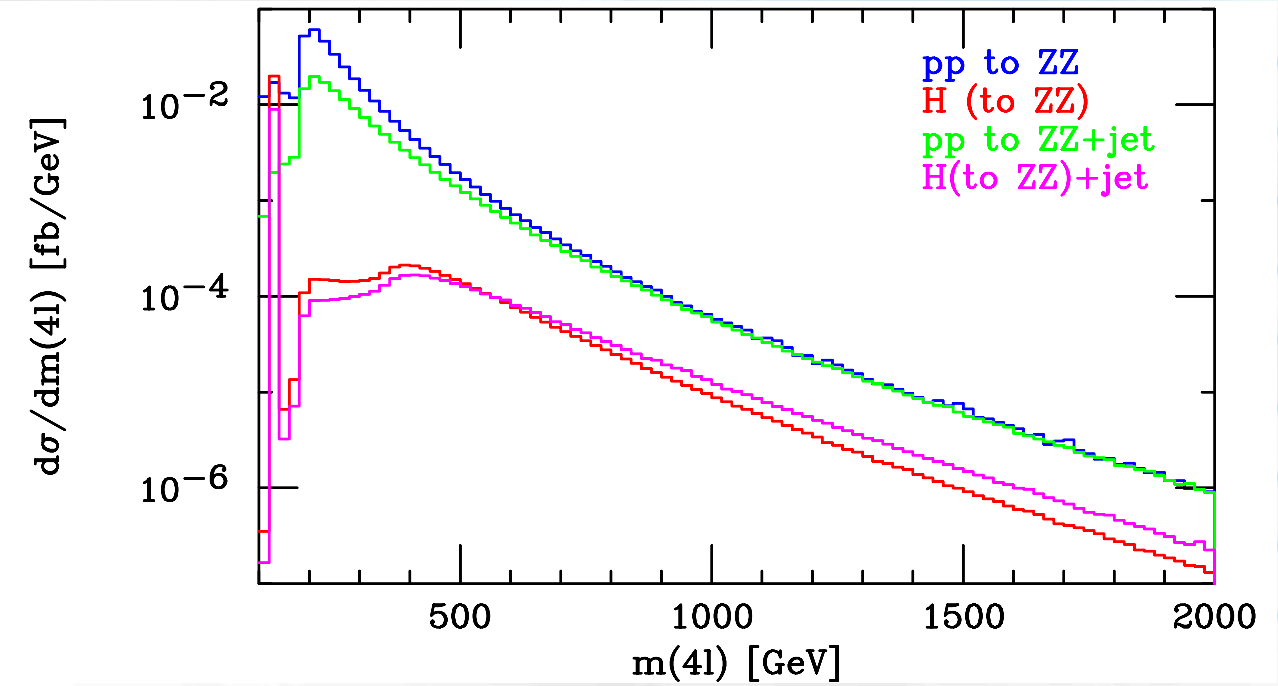
* this tail is independent of the Higgs boson width Γ_H

➡ use it to
- bound Γ_H — Caola, Melnikov, PRD88, 054024 (2013); Campbell et al., JHEP 1404, 060 (2014), PRD89,053011 (2014); Khachatryan et al. (CMS Collab.), PLB 736, 64 (2014); Tech. Rep. ATLAS-CONF-2014-042.
- study the effective gluon-Higgs coupling — Cacciapaglia et al., 1406.1757; Azatov et al., 1406.6338.

Motivation

why the extra jet?

* radiation in gluon-fusion Higgs production is large
  - ➡ large k-factors in gg -> H — Dawson, NPB 359, 283 (1991); Djouadi et al., PLB 264, 440 (1991); Graudenz et al., PRL 70, 1372 (1993); ...
  - ➡ large cross section for gg -> H + 1 jet — Ellis et al., NPB297, 221 (1998)
    - ➔ production xsec in H + 1 jet and H + 0 jet comparable



Motivation

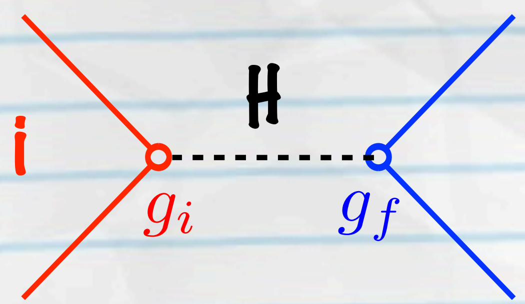
* the one-loop amplitudes entering ZZ + jet are part of the missing higher-order corrections to inclusive loop-mediated Z pair production relevant to the Higgs-continuum interference
* these corrections are expected to be large -> having them under control would allow for a more reliable bound on Γ_H from ZZ interference
* our results are analytical -> easier to integrate over singular regions
* virtual corrections are still missing ..

Introduction

Bounding the Higgs width using interference effects in ZZ

Caola, Melnikov, PRD88, 054024 (2013); Campbell et al., JHEP 1404, 060 (2014), PRD89,053011 (2014); Kauer, Passarino, JHEP 1208, 116 (2012)

* consider an Higgs-mediated process i -> H -> f



$$\frac{d\sigma}{dq^2} \sim \frac{g_i^2 g_f^2}{(q^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

➡ in the on-shell region
(integrate around $q^2 \sim m_H^2$)

$$\sigma^{peak} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

➡ in the off-shell region
(above the resonance,
$q^2 \gg m_H^2$)

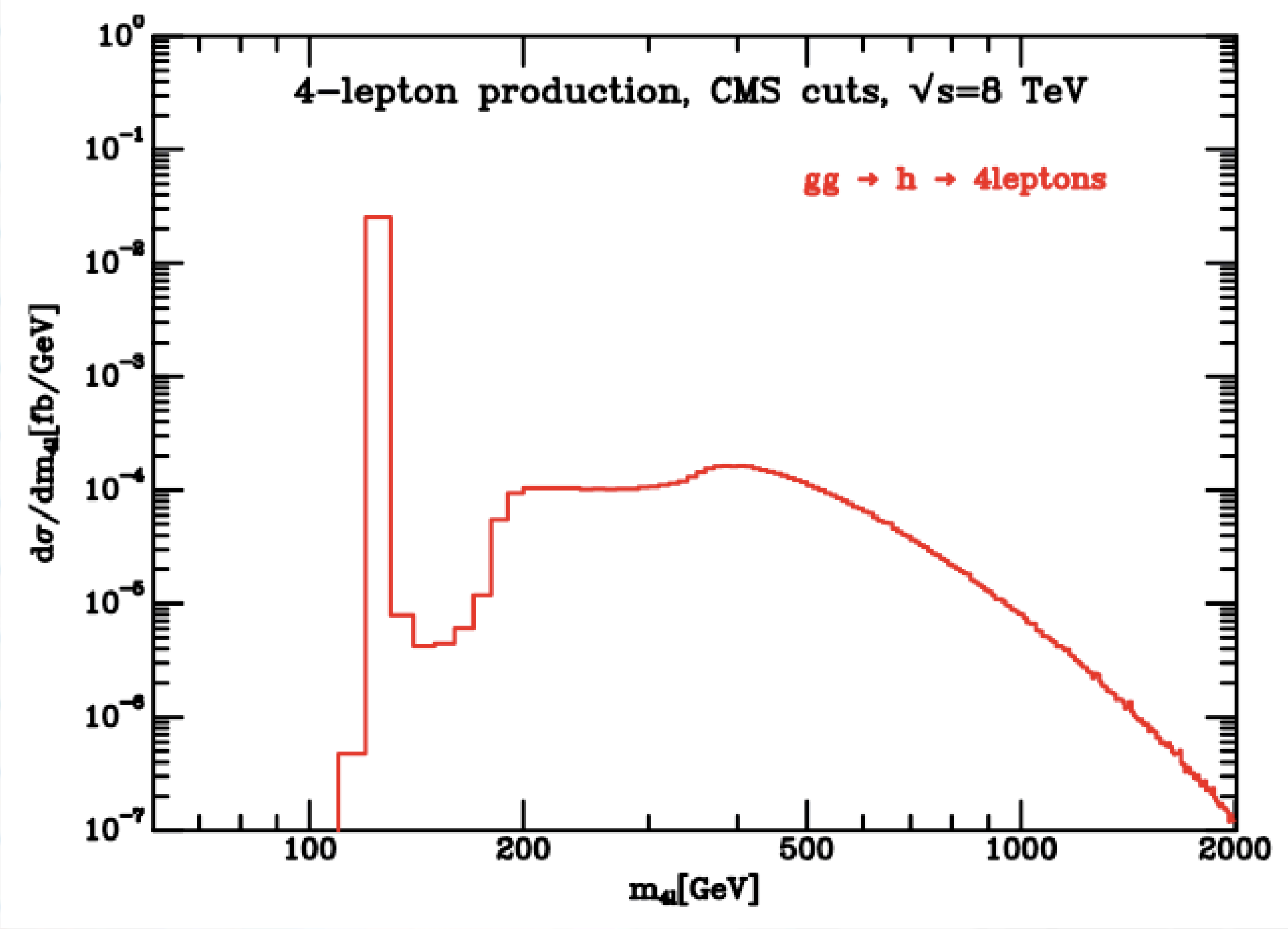
$$\sigma^{tail} \sim g_i^2 g_f^2$$

$$\Gamma_H \propto \frac{\sigma^{tail}}{\sigma^{peak}}$$

Introduction

* for pp -> H -> ZZ -> 4l, about 15% of the total cross section is in the region with m_{4l} > 130 GeV

Kauer, Passarino

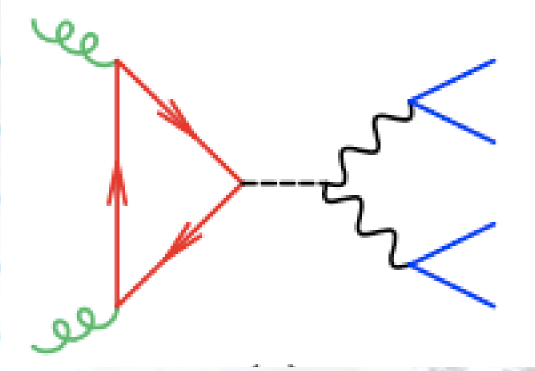


➡ use current measurements of the pp -> ZZ cross section to constrain Γ_H

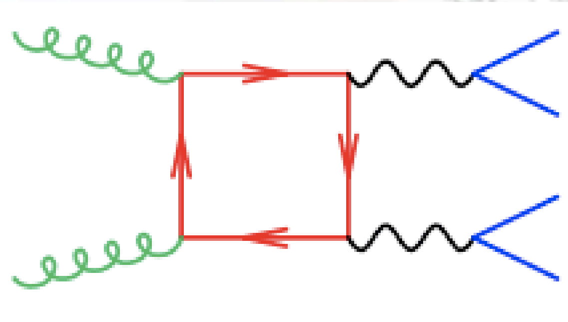
Caola, Melnikov,

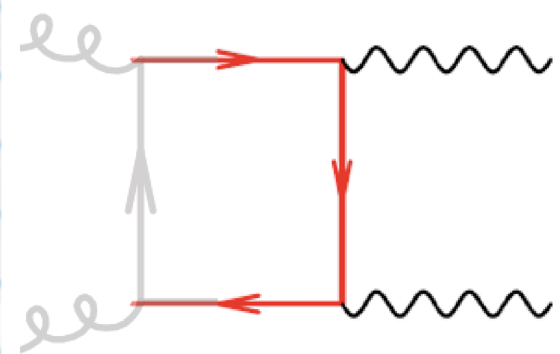
Introduction

* look at Higgs-mediated
  Z pair production
  gg -> H -> ZZ

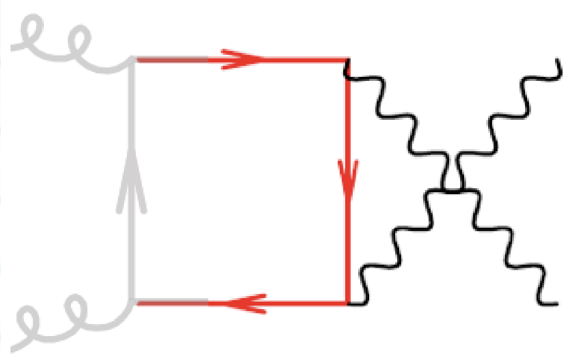


* interference effects with
  the background process
  gg -> ZZ
  are large in the high invariant mass region due to
  unitarity requirements for the $t\bar{t}$ -> ZZ scattering

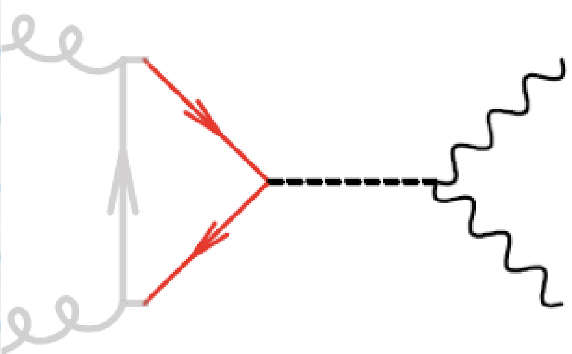




$-aE^2 + (d - c)m_t E$



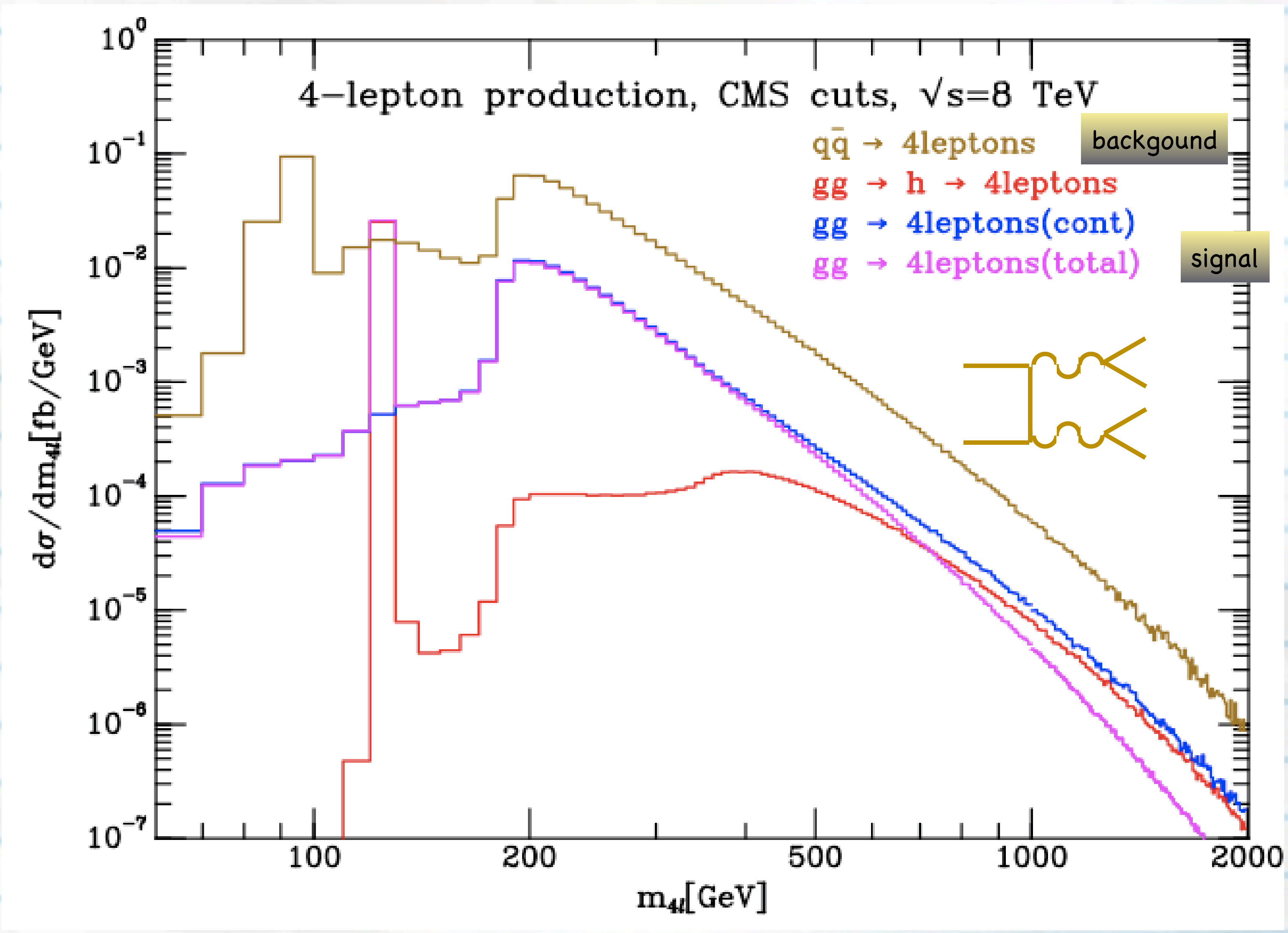
$aE^2 + (b + c)m_t E$



$-(b + d)m_t E$

Introduction

- this yields large destructive interference between
  gg -> H(->ZZ) -> 4l and gg -> ZZ -> 4l



➡ the qq background is 1-2 orders of magnitude larger than the signal

➡ situation improves at higher center of mass energies

Campbell et al., JHEP 1404, 060 (2014)

Introduction

* constraint on the Higgs width: assume that

$$\sigma_H^{peak} = \sigma_H^{peak,SM} \quad , \quad g_{i,f}^{peak} = g_{i,f}^{off}$$

but allow for $\Gamma_H \neq \Gamma_H^{SM}$, i.e., $g_{i,f} = \alpha g_{i,f}^{SM}$,

$$\Gamma_H = \alpha^4 \Gamma_H^{SM} .$$

* the ratio of peak and off-peak cross sections at 8TeV yields

$$\frac{\sigma_{off}^{H+I}(m_{4l} > 300 \text{ GeV})}{\sigma_{peak}^{H}} = 0.098 \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 0.141 \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

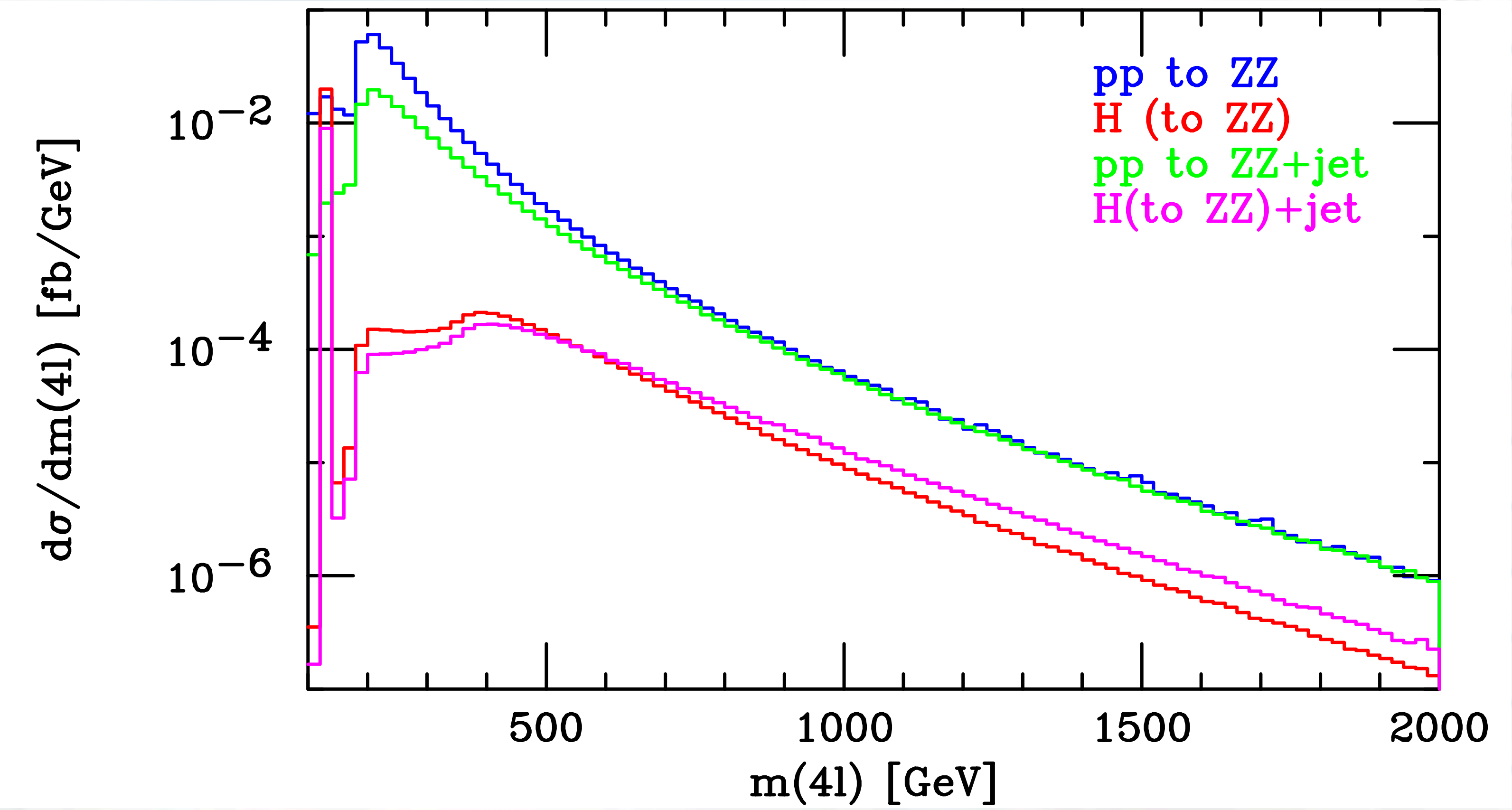
➡ $\Gamma_H \lesssim 25.2 \Gamma_H^{SM}$ Campbell et al., JHEP 1404, 060 (2014)

$$\Gamma_H < 5.4 \Gamma_H^{SM} \quad \text{(CMS)}$$

$$\Gamma_H < (4.8 - 7.7) \Gamma_H^{SM} \quad \text{(ATLAS)}$$

Introduction

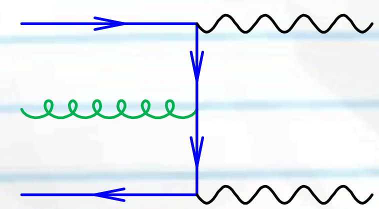
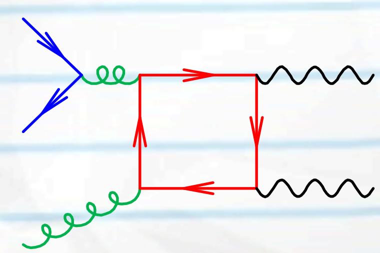
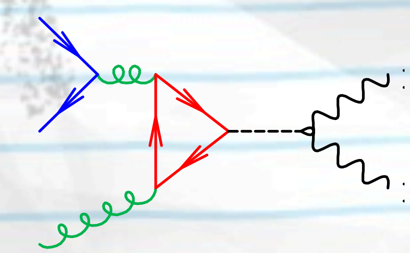
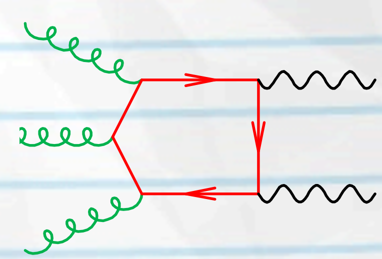
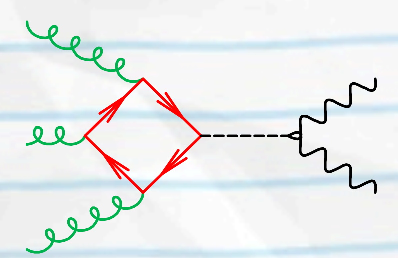
* similar ideas for interference effects in pp -> ZZ+1 jet
    - ➡ in the tail, the ratio of Higgs signal to LO background even (slightly) better than for pp -> ZZ



Introduction

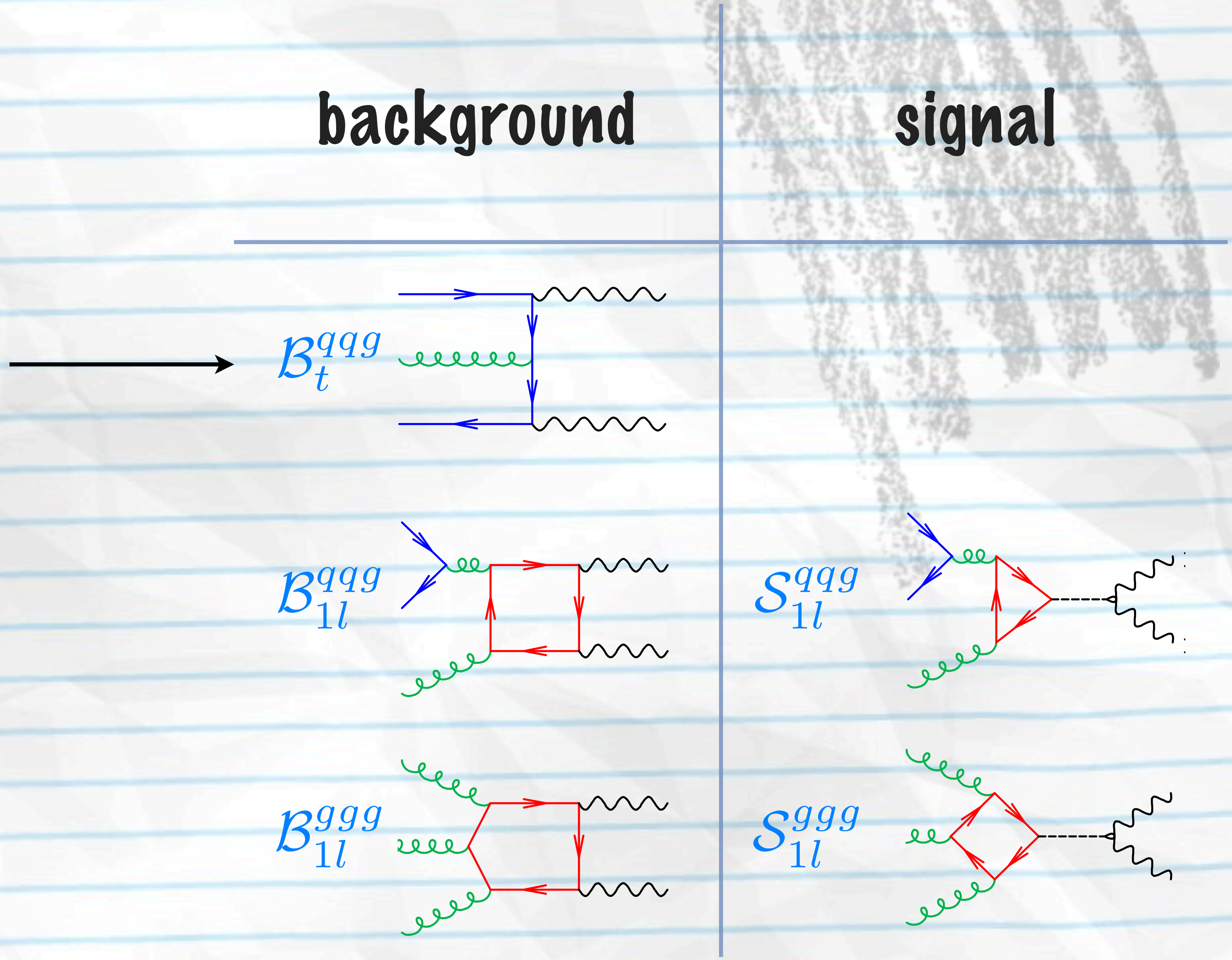
* similar ideas for interference effects in pp -> ZZ+1 jet
  - ➡ in the tail, the ratio of Higgs signal to LO background even better than for pp -> ZZ!
  - ➡ also in this case the interference between pp -> H(->ZZ) + 1 jet and pp -> ZZ + 1 jet in the high energy region is large and needs to be taken into account

Ingredients

order	process	background	signal
$g_w^2 g_s$	$q\bar{q} \to ZZ + g$ $qg \to ZZ + q$	$\mathcal{B}_t^{qqg}$ 	
$g_w^2 g_s^3$	$q\bar{q} \to ZZ + g$ $qg \to ZZ + q$	$\mathcal{B}_{1l}^{qqg}$ 	$\mathcal{S}_{1l}^{qqg}$ 
	$gg \to ZZ + g$	$\mathcal{B}_{1l}^{ggg}$ 	$\mathcal{S}_{1l}^{ggg}$ 

Ingredients

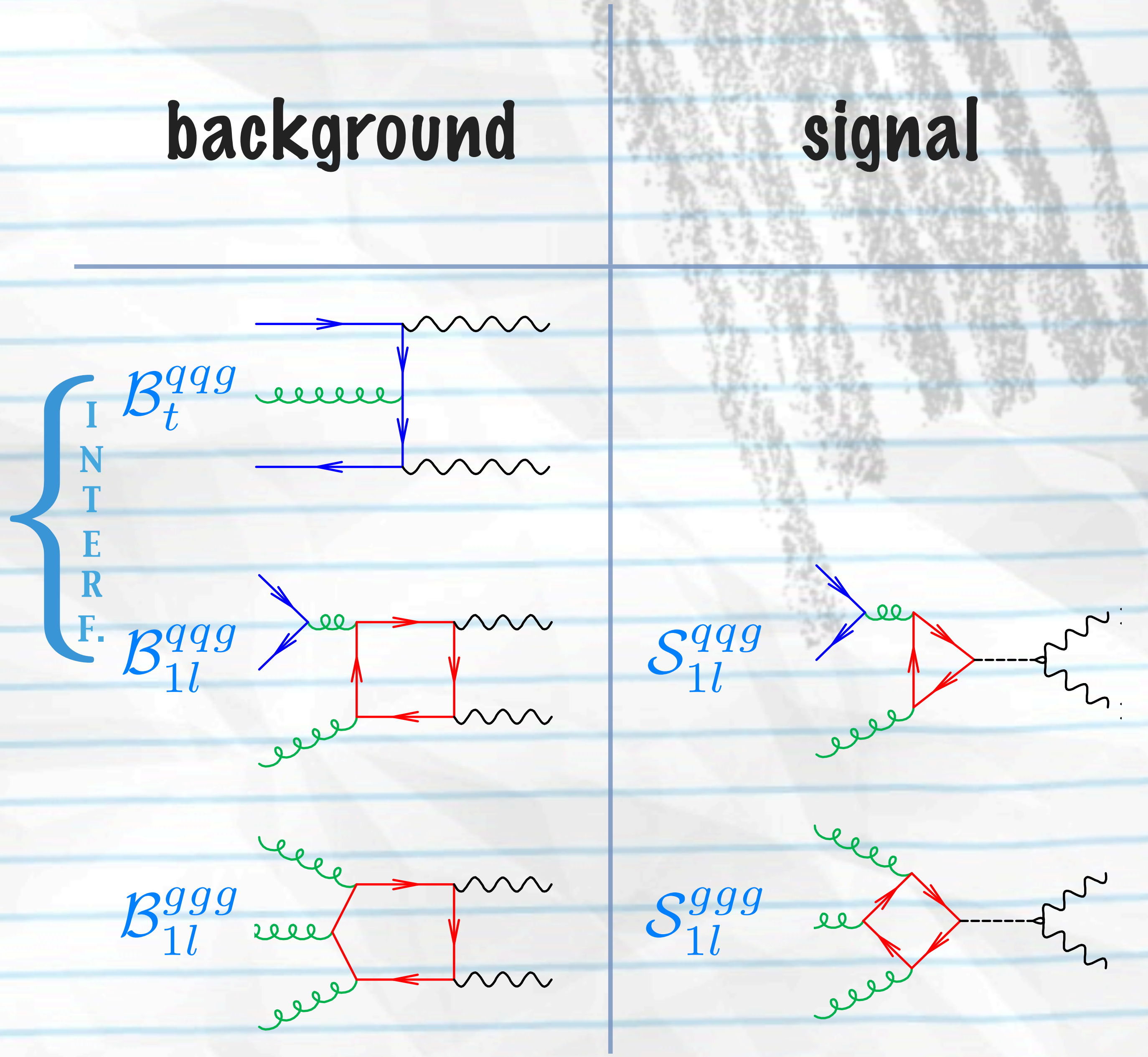
* LO cross section
* $O(g_W^4\, g_s^2)$



Ingredients

* NLO effects
* $O(g_W^4\, g_s^4)$
* interference is small both for S and B:
  -> $k_{NLO}^{ZZj,\,B} \sim 0.98$ Binoth et al., PLB 683, 154 (2010)

  and fermion loops yield ~ 1% of the contribution
  -> for S, expect the same due to unitarity

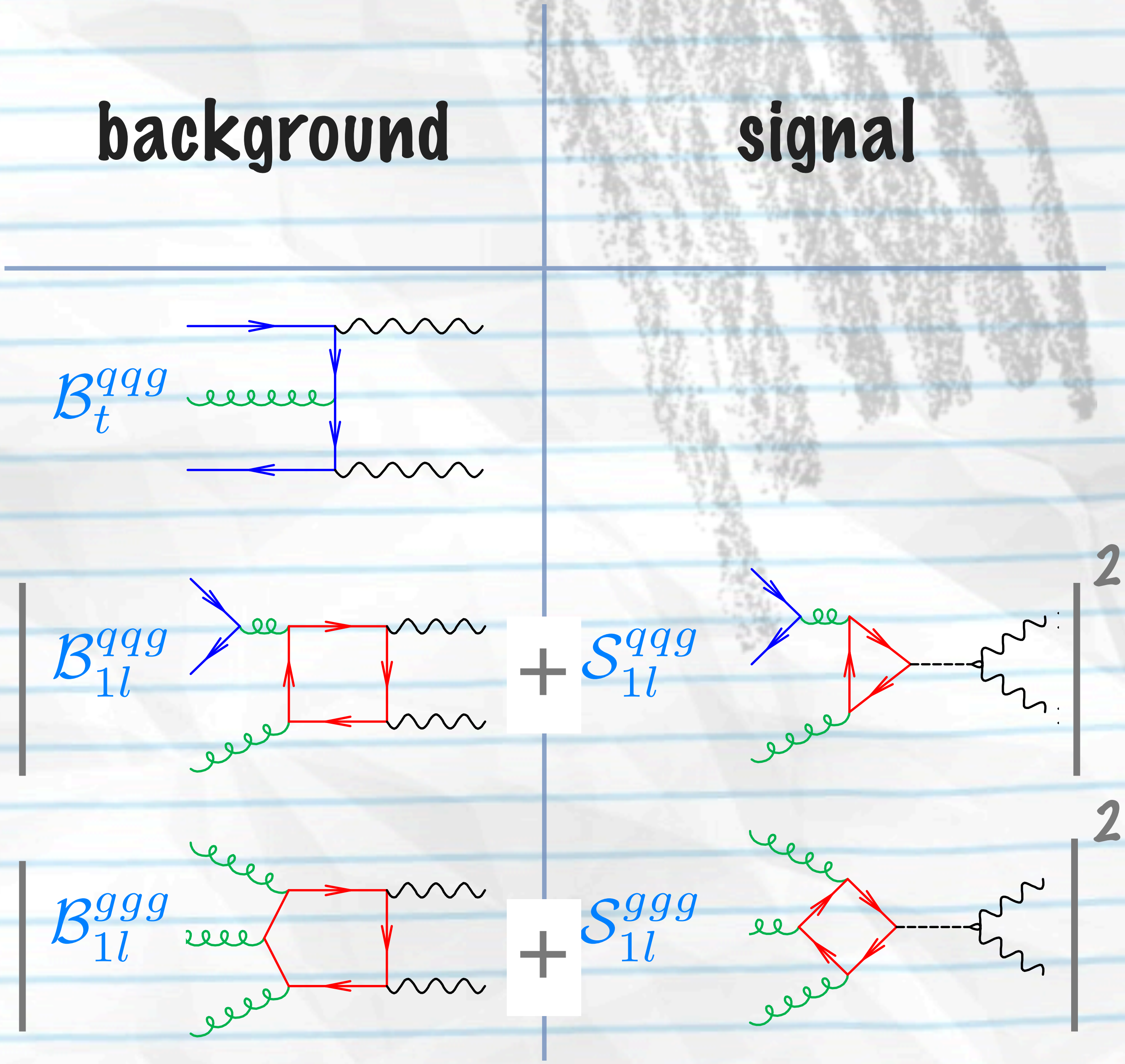


Ingredients

- NNLO effects
- $O(g_W^4\, g_s^6)$
- S-B interference in gg -> ZZg is large and negative in the high mass tail

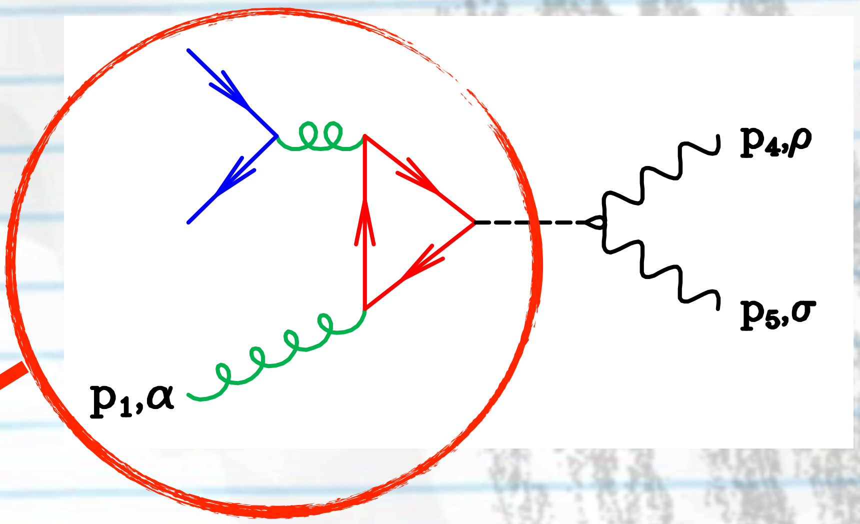
Campanario et al., JHEP 1306, 069 (2013)

- we add the interference in qqg -> ZZ -> 25 - 40% effect



Example

Amplitude for $gq \to H(\to ZZ)q$



$$-i\frac{g_s^2}{16\pi^2}\,\frac{g_W}{4m_W}\,\frac{1}{2}(t^A)_{32}\;g_s\frac{1}{s_{23}}\bar{u}(p_3)\gamma^\mu u(p_2)\left(g^{\alpha\mu}-\frac{p_1^\mu(p_2^\alpha+p_3^\alpha)}{p_1\cdot(p_2+p_3)}\right)F(s_{23},s_H)$$

scalar loop function for off-shell
Higgs production from g*g

Including also the Higgs decay into ZZ,

$$\mathcal{M}^{\alpha\rho\sigma}=\mathcal{N}\left(g_s(t^A)_{32}\frac{F(s_{23},s_H)}{s_H-M_H^2}\right)\frac{1}{s_{23}}\bar{u}(p_3)\gamma^\mu u(p_2)\left(g^{\alpha\mu}-\frac{p_1^\mu(p_2^\alpha+p_3^\alpha)}{p_1\cdot(p_2+p_3)}\right)g^{\rho\sigma}$$

$$\mathcal{S}_{gq\bar{q}}\;=\;\frac{V}{2}g_s^2|\mathcal{N}|^2\frac{1}{s_{23}}\frac{(p_1\cdot p_2^2+p_1\cdot p_3^2)}{p_1\cdot p_{23}^2}\frac{|F(s_{23},s_{123})|^2}{(s_{123}-M_H^2)^2}\left[8+\left(\frac{s_{123}-2m_Z^2}{m_Z^2}\right)^2\right]$$

Results for pp -> ZZ + jet

demand

- one single jet — $|\eta_j| < 3$, $p_{T,j} > p_{T,cut}$
- $m_{ZZ} > 300$ GeV **(high mass tail)**

$|\mathcal{S}_{1l}^{ggg}|^2$ $|\mathcal{S}_{1l}^{qqg}|^2$ $\mathcal{S}_{1l}^{qqg} \times \mathcal{B}_{1l}^{*,qqg}$

	$p_{T,\mathrm{cut}}$ [GeV]	σ_H^{gg} [fb]	$\sigma_H^{qg+q\bar{q}}$ [fb]	σ_I^{gg} [fb]	$\sigma_I^{qg+q\bar{q}}$ [fb]	σ_I^{tree} [fb]
$\sqrt{s} = 8$ TeV	30	0.0212	0.00679	-0.0299	-0.00929	0.00230
	50	0.0124	0.00522	-0.0173	-0.00706	0.00182
	100	0.00467	0.00279	-0.00632	-0.00369	0.00097
	200	0.00104	0.00086	-0.00133	-0.00111	0.00026

$\mathcal{S}_{1l}^{ggg} \times \mathcal{B}_{1l}^{*,ggg}$ $\mathcal{S}_{1l}^{qqg} \times \mathcal{B}_{t}^{*,qqg}$

Results for pp -> ZZ + jet

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* one single jet — * $|\eta_j| < 3$, $p_{T,j} > p_{T,cut}$
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✔ (σ_H^{gg}) ✔ (σ_I^{gg})

* agree with Campanario et al., JHEP 1306, 069 (2013)
* strong cancellation as required by unitarity

Results for pp -> ZZ + jet

demand

* one single jet * $|\eta_j| < 3$, $p_{T,j} > p_{T,cut}$
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* small, as expected from by unitarity arguments Dixon et al., PRD 60, 114037 (1999)

Results for pp -> ZZ + jet

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	$p_{T,\text{cut}}$ [GeV]	σ_H^{gg} [fb]	$\sigma_H^{qg+q\bar{q}}$ [fb]	σ_I^{gg} [fb]	$\sigma_I^{qg+q\bar{q}}$ [fb]	σ_I^{tree} [fb]
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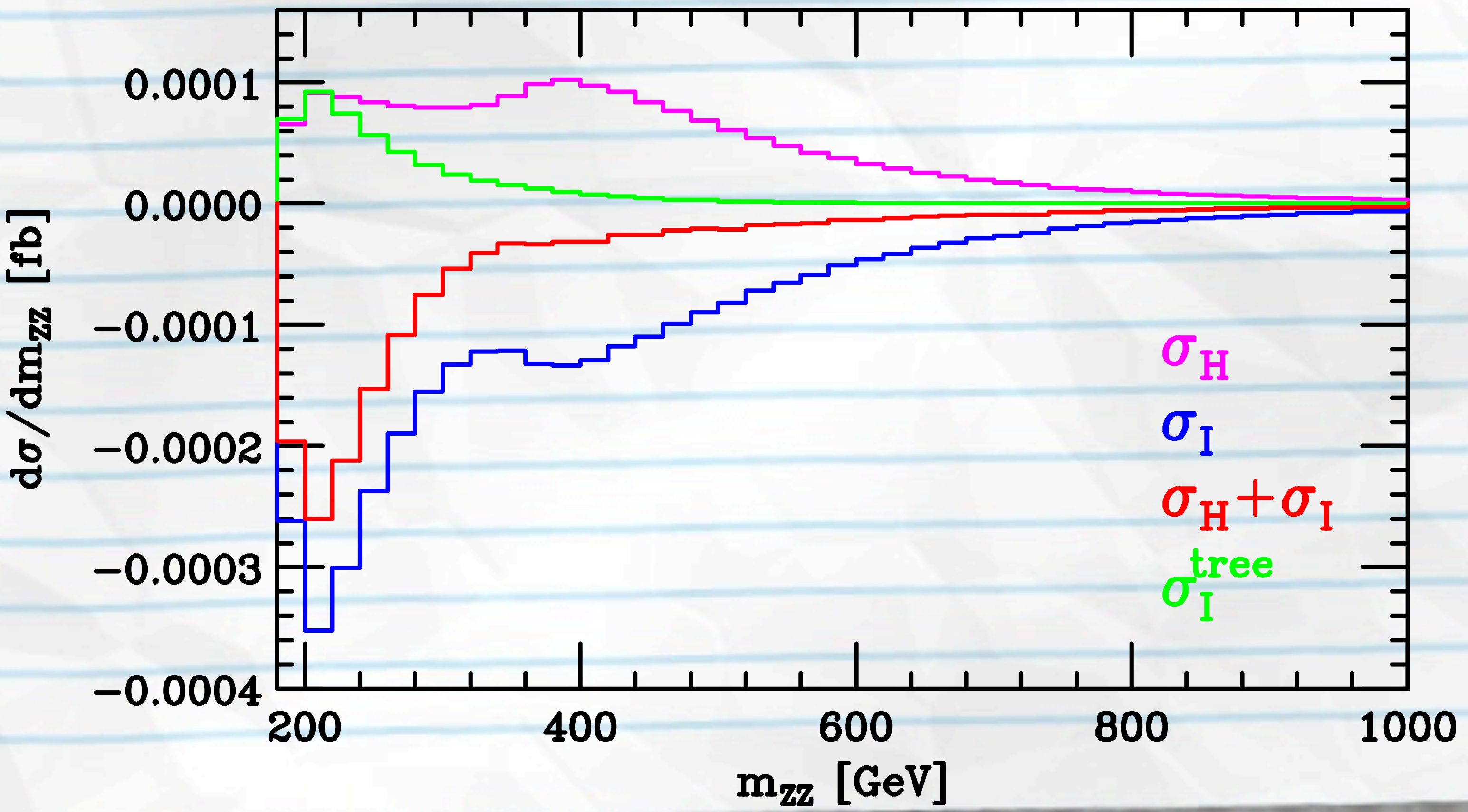
$$\frac{\sigma_H^{qg+q\bar{q}}}{\sigma_H} \sim \frac{\sigma_I^{qg+q\bar{q}}}{\sigma_I} \sim \begin{cases} 25\% & \text{for } p_{T,cut} = 30 \text{ GeV} \\ 50\% & \text{for } p_{T,cut} = 200 \text{ GeV} \end{cases}$$

➡ an harder cut probes regions of large x, where quark PDFs are relatively more important than gluon PDFs

Results for pp -> ZZ + jet

importance of the interference term:

* the Higgs-mediated contribution becomes negative
* its shape changes
* its magnitude is reduced in the high p_T tail



$p_{T,cut} = 30$ GeV

$\sqrt{s} = 8$ TeV

Results for pp -> ZZ + jet

* analogous to the ZZ case, the ratio of peak and off-peak cross sections at 8 TeV can be used to bound the Higgs width

$$\frac{\sigma^{H+I}_{off,ZZ+jet}(m_{ZZ} > 300 \text{ GeV})}{\sigma^{H}_{peak,ZZ+jet}} = 0.02890 \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 0.0391 \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

* in the next run of the LHC, expect about 100 events to be produced in the high mass tail

➡ alternative extraction of the Higgs width

Conclusions

* Higgs width already constrained from interference effects in ZZ production
* similar analysis in the ZZ + jet channel is viable: in the high invariant mass tail,
  - ➡ the Higgs production cross section in the zero and one jet bins are comparable
  - ➡ the ratio of the Higgs signal to the LO background is larger in the one-jet bin than in the zero-jet bin

Conclusions

* we performed a detailed analysis of the high invariant mass tail
  - ➡ interference effects between Higgs and QCD ZZ production:
    large and negative as required by unitarity
* as in the pp -> ZZ case, relate the ratio of peak and off-peak cross sections to the Higgs decay width relative to the Standard Model