Taming QCD issues in gluon fusion with gg->VV

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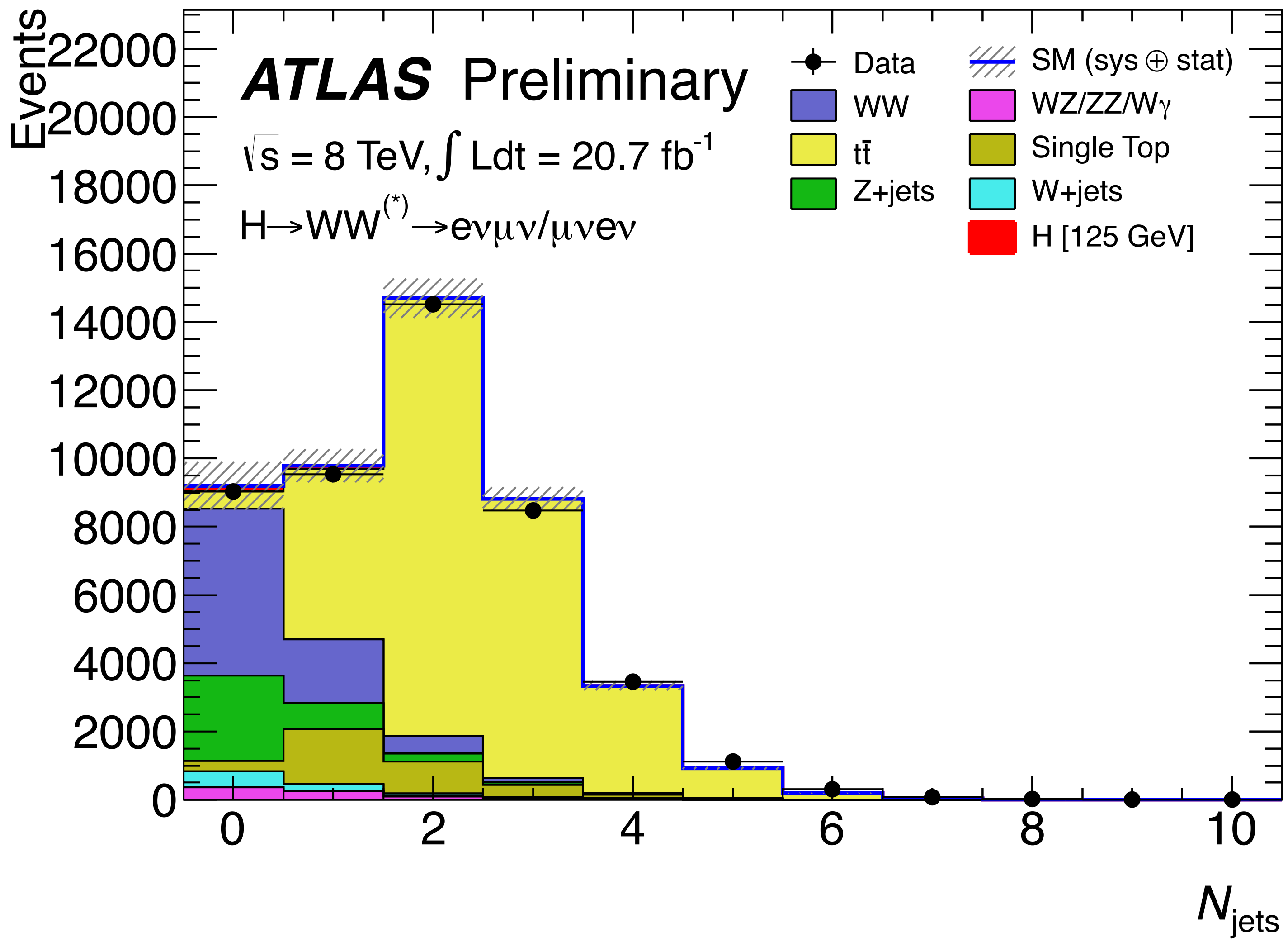
QCD Tools for LHC Physics: From 8 to 14 TeV - What's needed and why?

Fermilab, Nov. 15th 2013

VV production and Higgs searches: why it is interesting

VV production and Higgs physics: vector bosons as a background



Inclusive searches, coupling measurements, channel separation… mostly qq->VV (~ 90%)

VV production and Higgs physics: vector bosons as probes for Higgs properties

[Martin; Dixon, Li; Passarino, Kauer; Kauer; FC, Melnikov]

Use off-shell effects to probe the Higgs nature

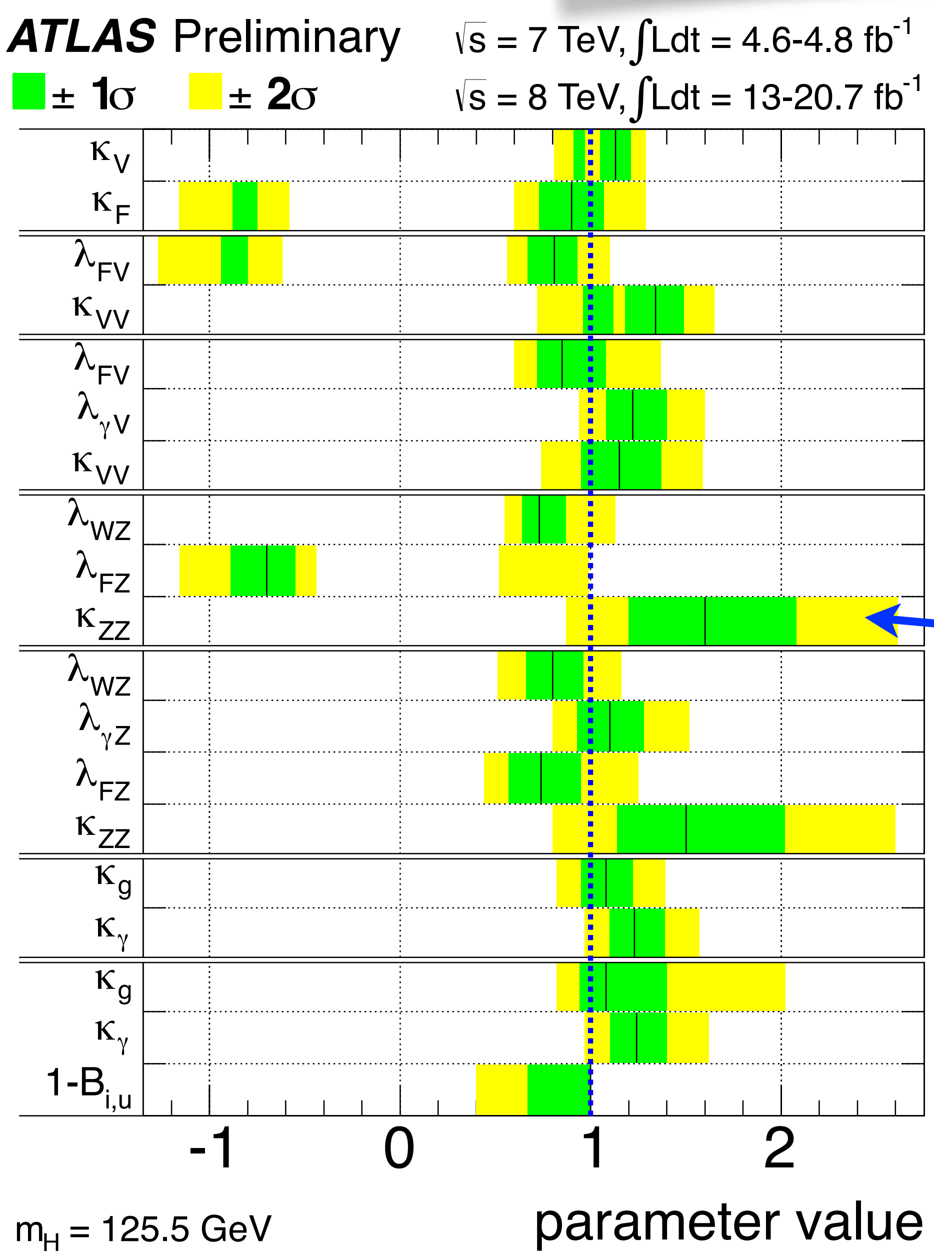
Off-shell effects:

- negligible for the fiducial rate for m_H ~ 126 GeV SM Higgs
  [Ellis, Campbell, Williams (2011); Kauer, Passarino (2012); Kauer (2013)]
- can provide complementary information wrt traditional on-shell measurements -> model-independent Higgs properties
- may become large for non standard Higgs (e.g. high-mass SM-like Higgs)

SENSITIVE TO GG -> VV PROCESSES

Two examples: Higgs coupling determination

$$\sigma_{i\to H\to f} \approx \frac{\sigma_{i\to H}\Gamma_{H\to f}}{\Gamma_H} \approx \frac{g_i^2 g_f^2}{\Gamma_H}$$



Naively, we only have access to coupling ratios

A pragmatic approach:

1. take cross-section rations to isolate desired production/ decay mode
2. fit assuming SM-like behavior

[see e.g. Giardino et al.; Djouadi, Moreau (2013)]

Ideally:

MODEL-INDEPENDENT results

Higgs couplings: the problem

$$\sigma_{i\to H\to f} \approx \frac{\sigma_{i\to H}\Gamma_{H\to f}}{\Gamma_H} \approx \frac{g_i^2 g_f^2}{\Gamma_H}$$

σ is invariant under $g \to \xi g,\ \Gamma_H \to \xi^4 \Gamma_H$

For a model-independent determination,
we must break this degeneracy

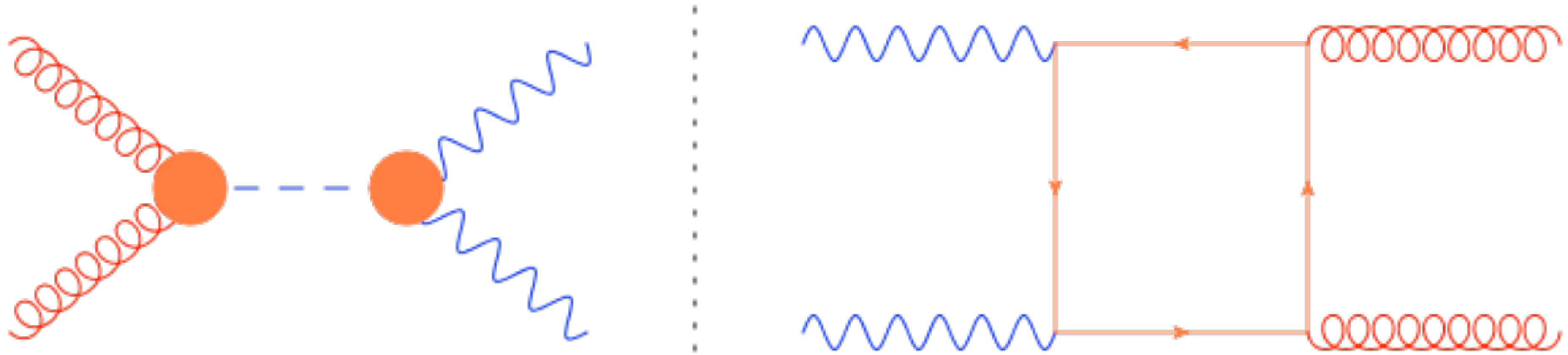
Direct Measurement of the Higgs Width?

- LHC sensitivity: ~ 1-5 GeV
- SM width: ~ 4 MeV !!!

We need an indirect way of measuring Γ_H

The key point: search for an observable with different dependence on $g_{i,f}$ and Γ_H

First example: use the mass-shift coming from H-> γγ interference [Dixon, Li (2013)]



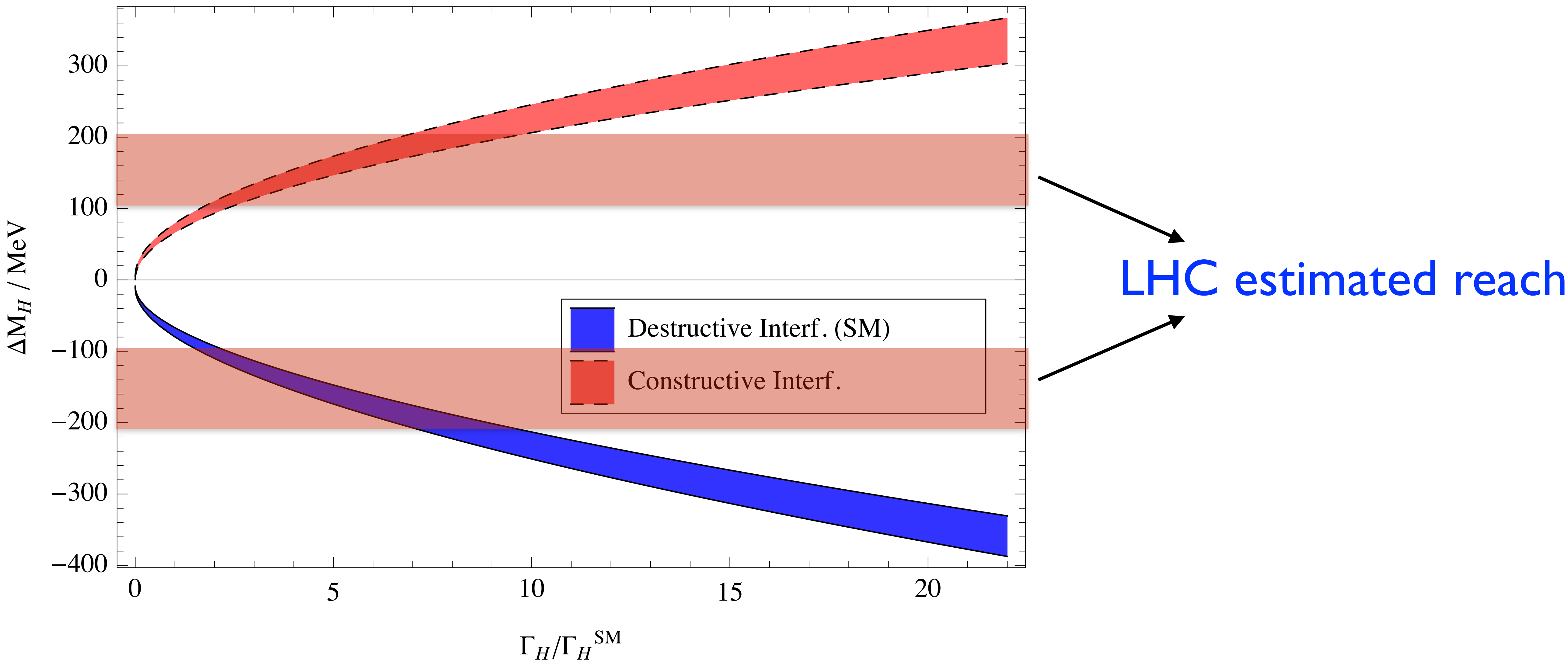
$$\sigma_{gg\to H\to\gamma\gamma} \sim \frac{g_{Hgg}^2 g_{H\gamma\gamma}^2}{\Gamma_H}$$

$$\sigma_{gg\to H\to\gamma\gamma}^{int} \sim g_{Hgg}g_{H\gamma\gamma}$$

Observable effect from the interference: $\Delta M_{ZZ,\gamma\gamma}$

[Martin (2012)]

Measurement of $\Delta M_{ZZ,\gamma\gamma}$: model-independent determination of Γ_H



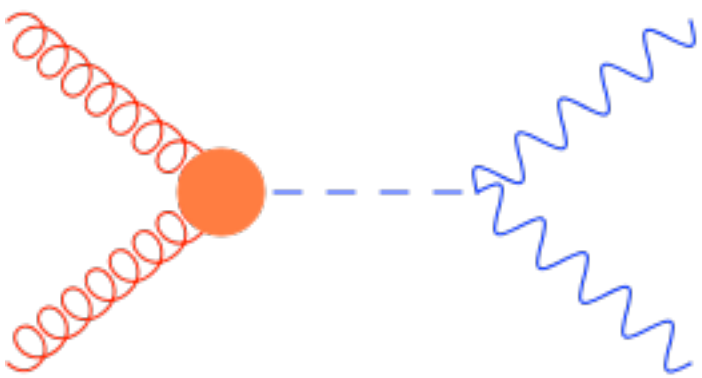
PROMISING, UNDER EXPERIMENTAL STUDY

Similar effects can be used to determine J^{+-} properties

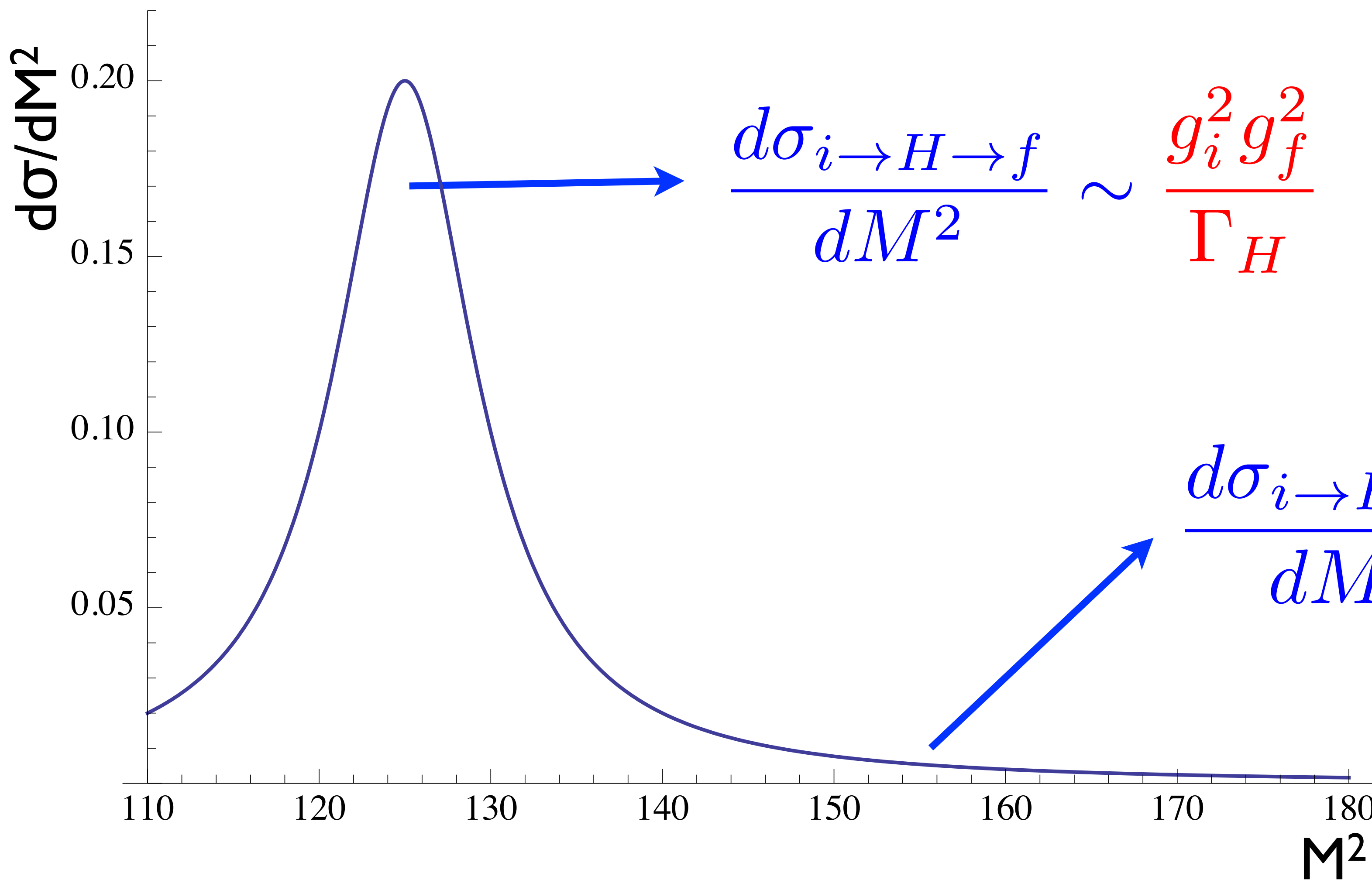
[Dixon, talk at Radcor 2013]

Second example: use the cross-section itself

[FC, Melnikov (2013)]



$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{(M^2-m_H^2)^2+m_H^2\Gamma_H^2}$$



$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{(M^2-m_H^2)^2}$$

OFF THE MASS SHELL, σ DOES NOT DEPEND ON Γ_H

LHC results: on the Higgs peak, the number of events is compatible with the SM expectation

$$\frac{g_i^2 g_f^2}{\Gamma_H} = \frac{g_{i,\mathrm{SM}}^2 g_{f,\mathrm{SM}}^2}{\Gamma_{H,\mathrm{SM}}} \longrightarrow g = \xi g_{\mathrm{SM}}, \;\; \Gamma_H = \xi^4 \Gamma_{H,\mathrm{SM}}$$

Look for off-peak events: $\sigma_{off} \sim g_i^2 g_f^2$

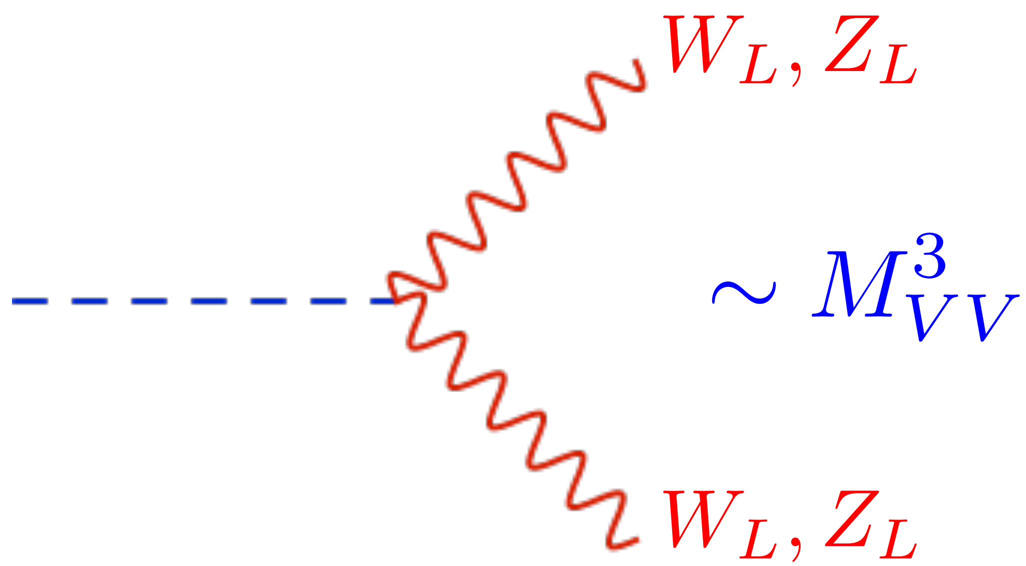
$$N_{obs}^{off} \propto g_i^2 g_f^2 = \xi^4 g_{i,\mathrm{SM}}^2 g_{f,\mathrm{SM}}^2 \propto \xi^4 N_{\mathrm{SM}}^{off} = \frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}} N_{\mathrm{SM}}^{off}$$

Direct Access to the Width

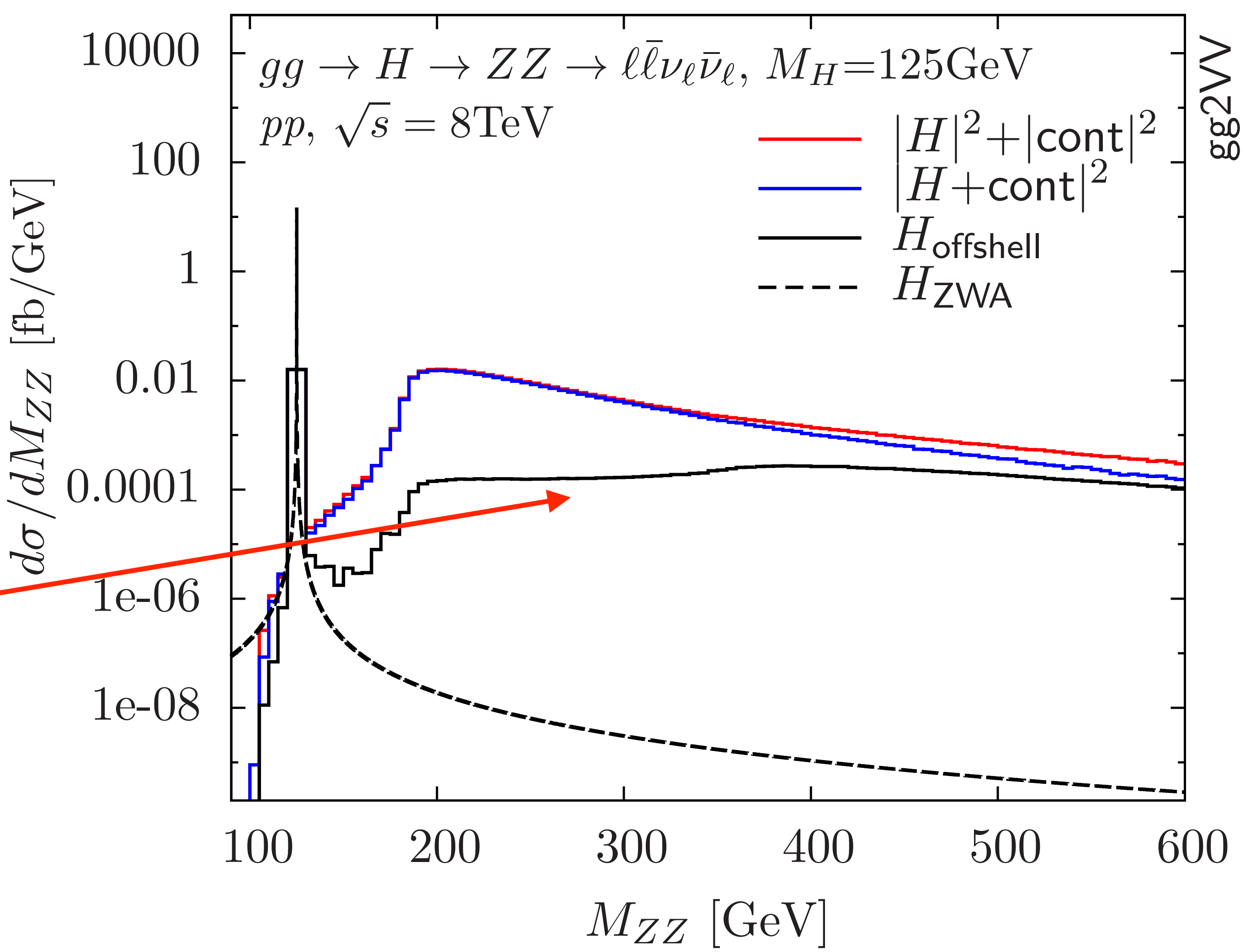
$$\Gamma_H = \frac{N_{obs}^{off}}{N_{\mathrm{SM}}^{off}} \Gamma_{H,\mathrm{SM}}$$

The role of vector bosons: enhanced off-shell tail of the cross section

[Kauer, Passarino (2012)]



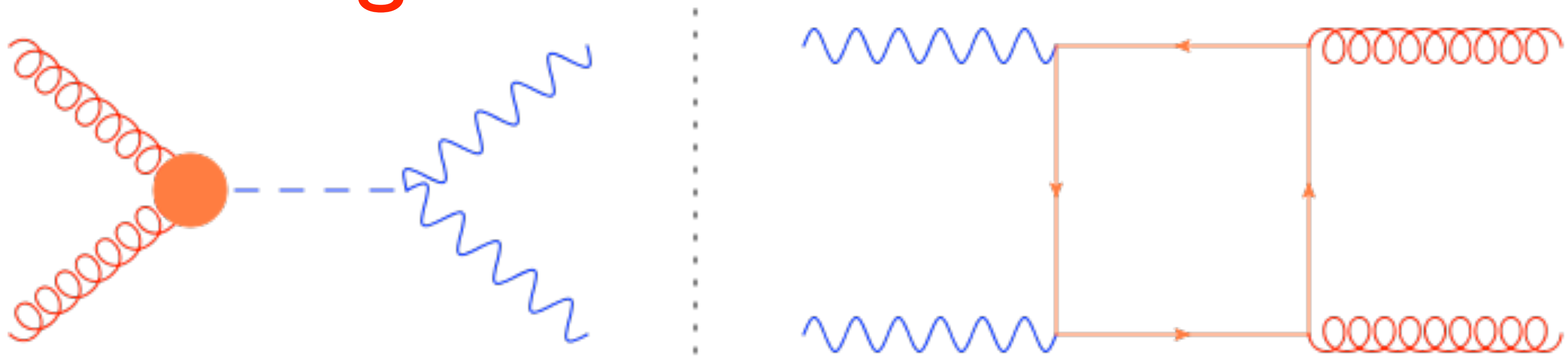
Above the VV threshold:
enhanced decay into longitudinal gauge bosons



Large plateau, eventually washed away by parton luminosities

Large O(10%) effect

The role of vector bosons: large interference effects



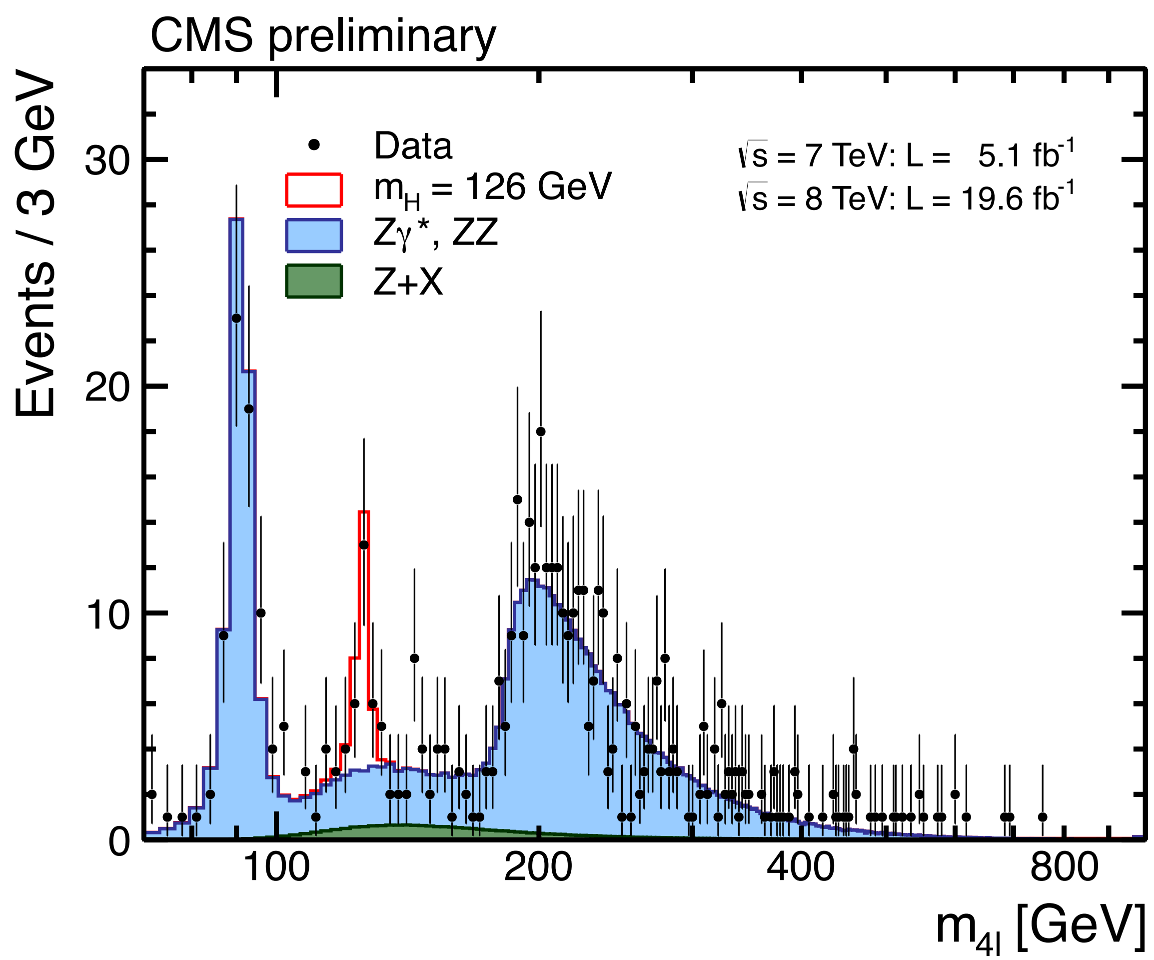
In the SM: σ^{int} ~ - 50% off peak [Kauer, Passarino (2012)]

$$\sigma^{int} \sim g_{Hgg} g_{HVV} = [e^{i\theta}] \sqrt{\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}} \sigma^{int}_{\mathrm{SM}}$$

PUTTING EVERYTHING TOGETHER:

$$N^{off} = \frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}} N^{off}_{\mathrm{SM}} - [e^{i\theta}] \sqrt{\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}} N^{int}_{\mathrm{SM}}$$

Phenomenological results: Γ_H from H-> ZZ decays



Very crude analysis, current CMS dataset:

$$\Gamma_H \leq 21\ \Gamma_{H,sm}$$

$$\Gamma_H \leq 88\ \mathrm{MeV}$$

[FC, Melnikov (2013)]

More refined analysis, matrix element method:

$$\Gamma_H \leq (15.7^{-2.9}_{+3.9}) \cdot \Gamma_{H,sm} \text{ at } 95\%\ \mathrm{CL}$$

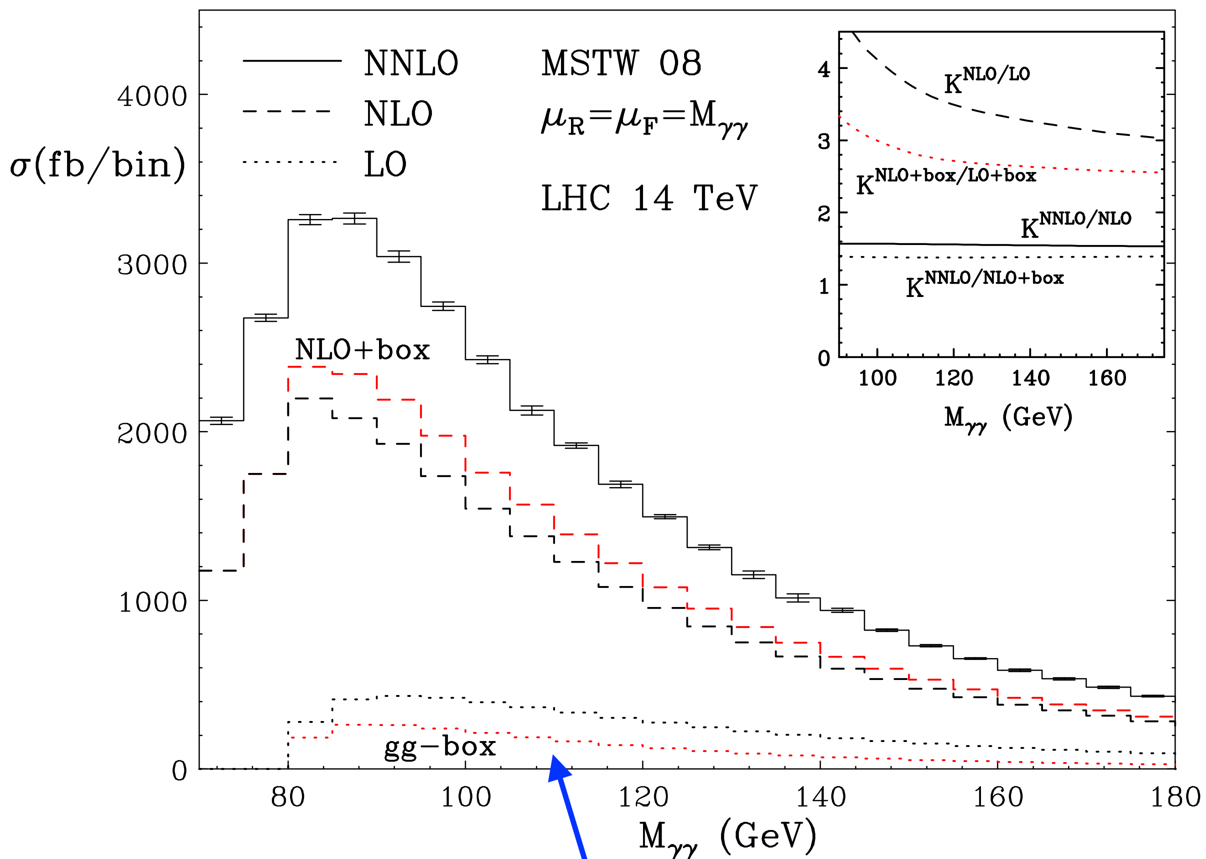
[Campbell, Ellis, Williams arXiv:1311.3589]

Estimated reach of this method at the LHC:

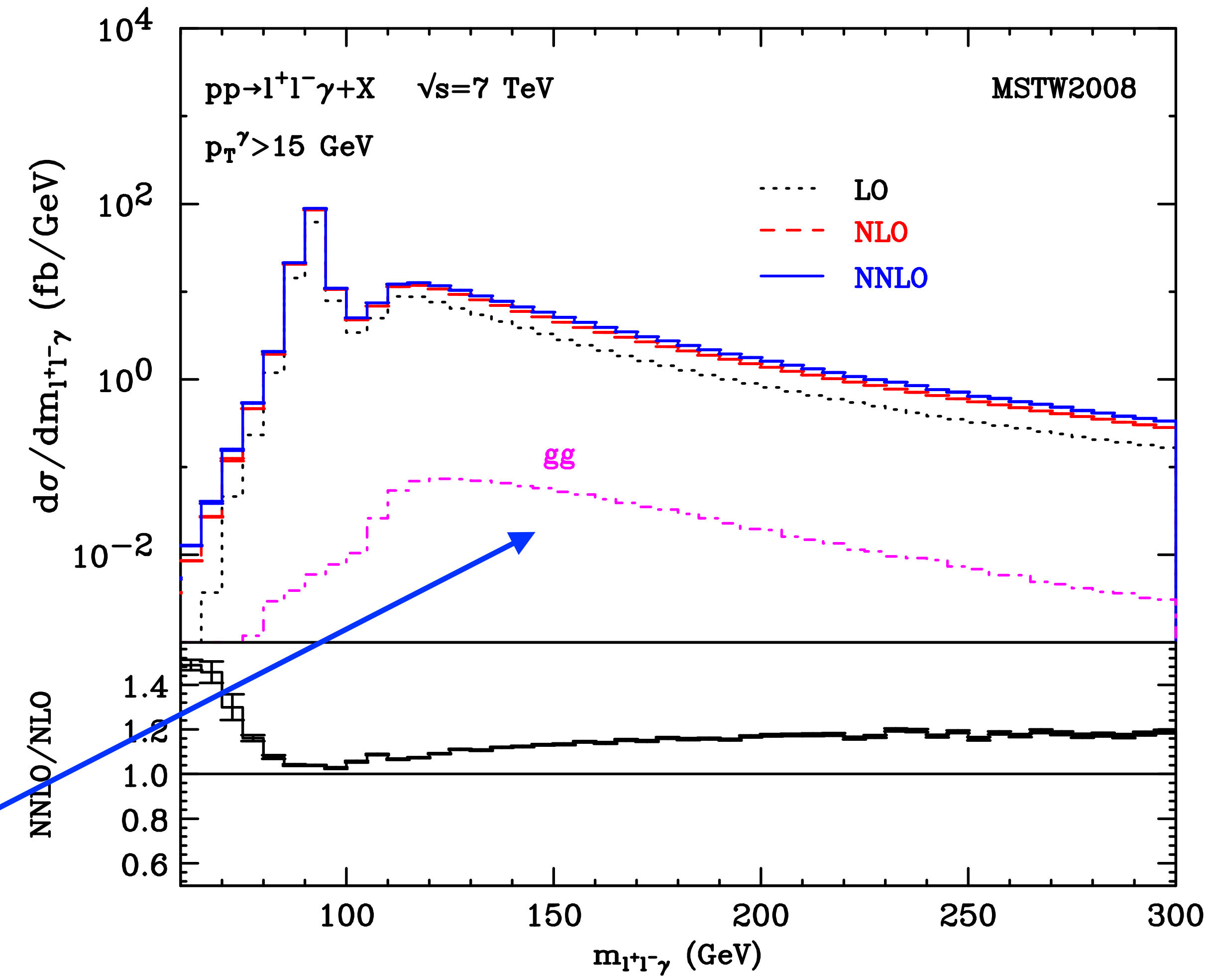
$$\Gamma_H \leq 5 - 10\ \mathrm{MeV}$$

VV production and Higgs searches: where do we stand

qq->γγ, qq->Zγ is known @ NNLO



[Catani et al (2011)]

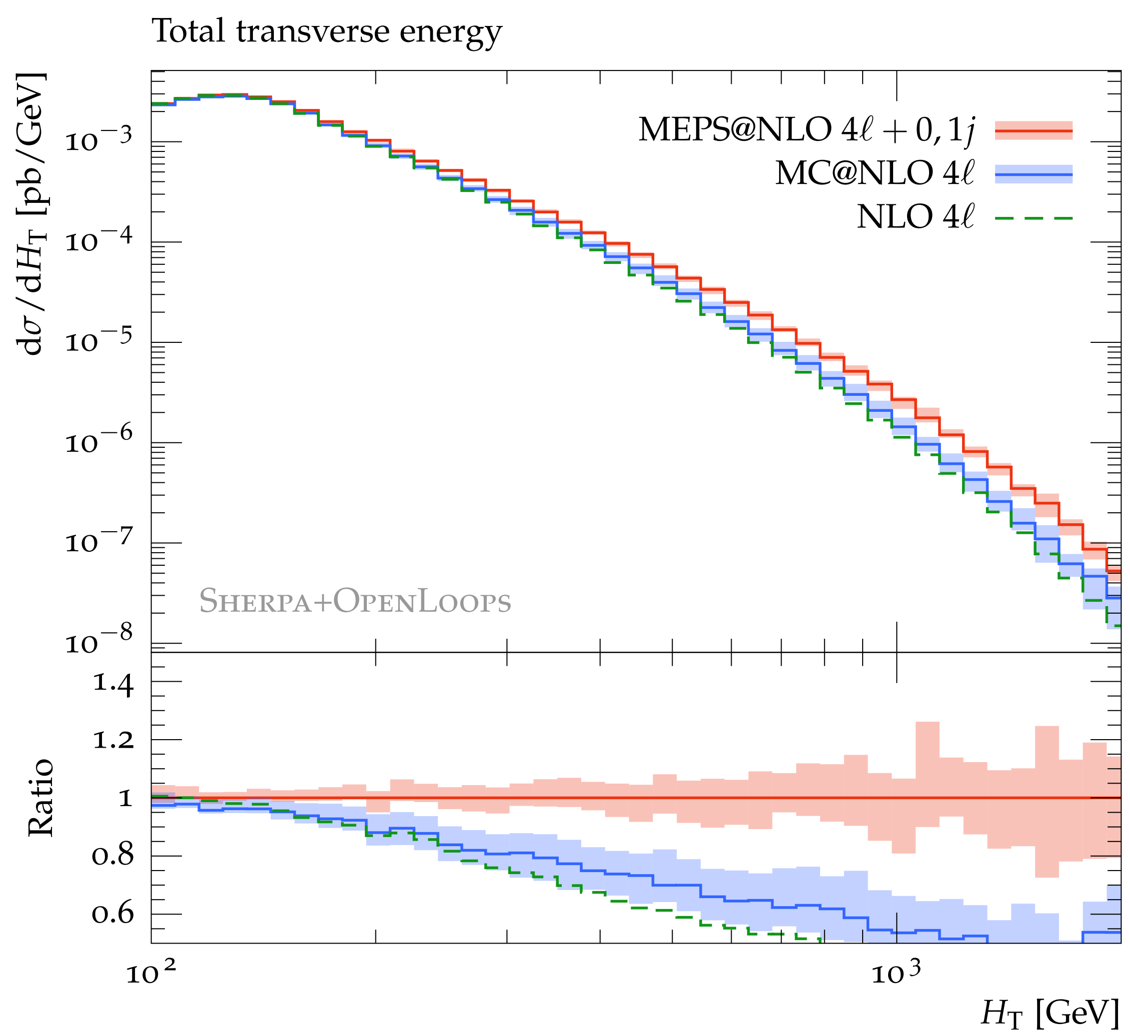


[Grazzini et al (2013)]

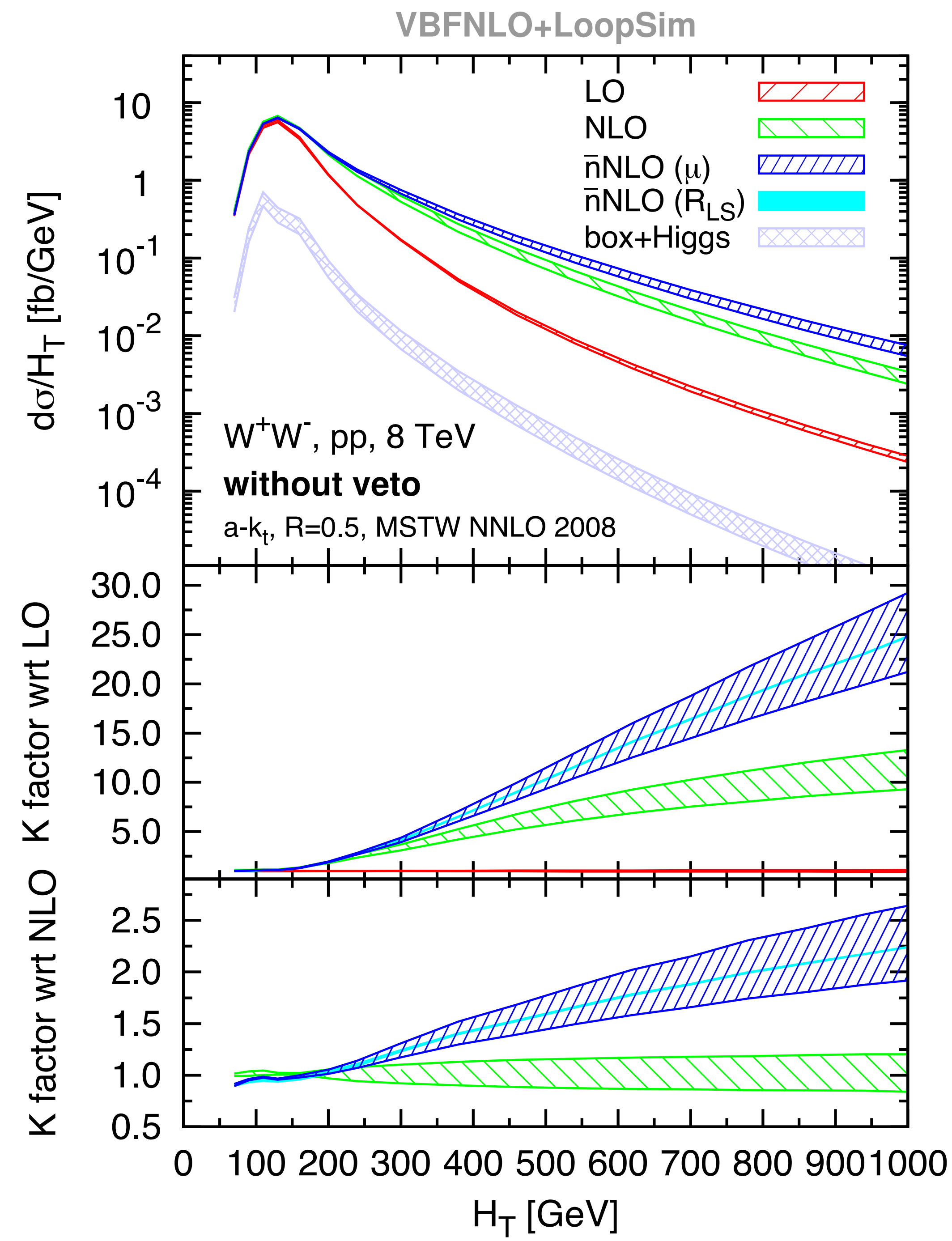
- contains LO gg->γγ/Zγ
- expect NNLO qq-> Wγ soon?

A lot of recent developments for qq->VV

Matching/merging: sizable part of NNLO corrections



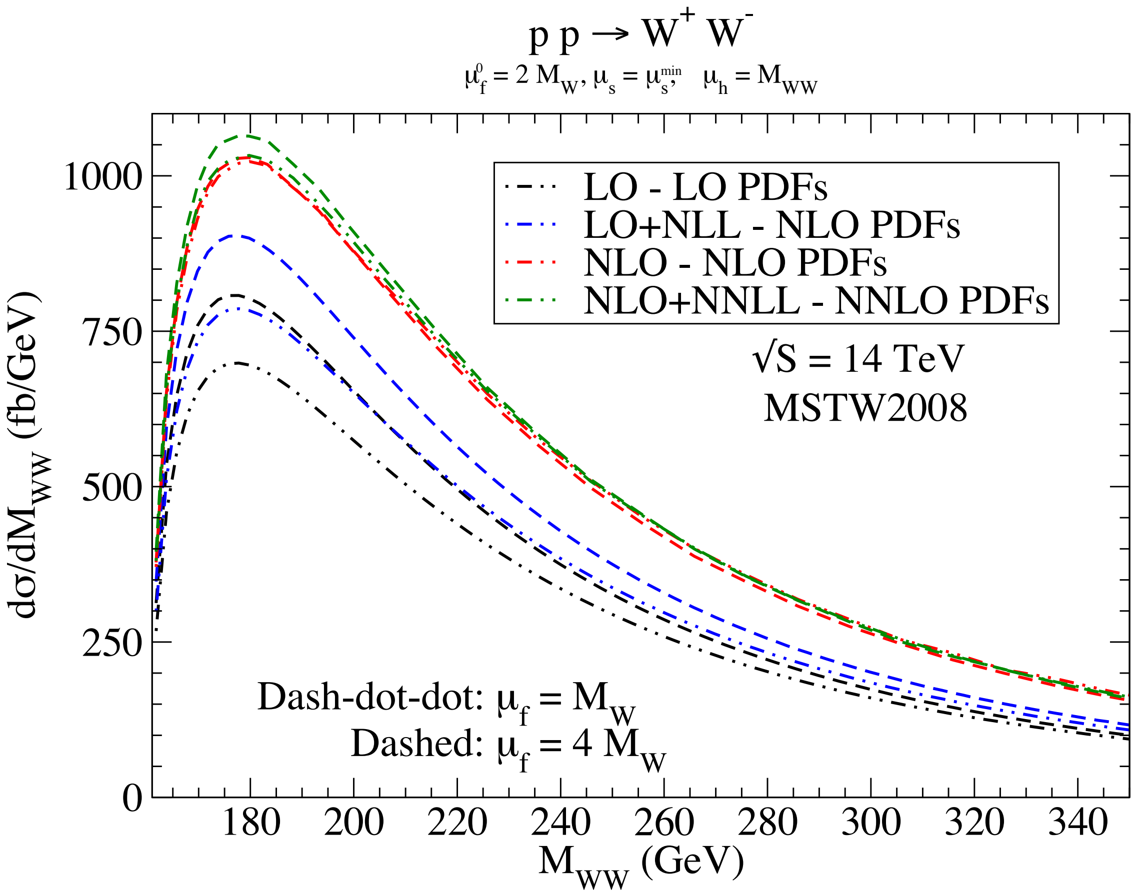
[Cascioli et al (2013), SHERPA+OPENLOOPS]



[Campanario et al (2013), LOOPSIM+VBF@NLO]

Approximate NNLO from resummation

[S. Dawson et al (2013)]



σ(pb)	$\sqrt{S}=7$ TeV	$\sqrt{S}=8$ TeV	$\sqrt{S}=13$ TeV	$\sqrt{S}=14$ TeV
σ^{NLO}	$45.7^{+1.5}_{-1.1}$	$55.7^{+1.7}_{-1.2}$	$110.6^{+2.5}_{-1.6}$	$122.2^{+2.5}_{-1.8}$
σ^{gg}	$1.0^{+0.3}_{-0.2}$	$1.3^{+0.4}_{-0.3}$	$3.5^{+0.9}_{-0.7}$	$4.1^{+0.9}_{-0.7}$
$\sigma^{NLO+NNLL}$	$44.9^{+0.6}_{-0.6}$	$54.8^{+0.7}_{-0.8}$	$108.2^{+1.3}_{-1.5}$	$119.5^{+1.5}_{-1.6}$
$\sigma'^{NLO+NNLL}$	$45.9^{+0.5}_{-0.6}$	$56.1^{+0.7}_{-0.8}$	$111.7^{+1.8}_{-1.6}$	$123.6^{+2.0}_{-1.8}$
σ^{NNLO}_{approx}	$45.0^{+0.4}_{-0.1}$	$54.9^{+0.5}_{-0.05}$	$108.3^{+1.0}_{-0.4}$	$119.6^{+1.2}_{-0.5}$
σ'^{NNLO}_{approx}	$46.0^{+0.4}_{-0.047}$	$56.2^{+0.6}_{-0.1}$	$111.8^{+1.7}_{-1.1}$	$123.7^{+1.8}_{-1.2}$

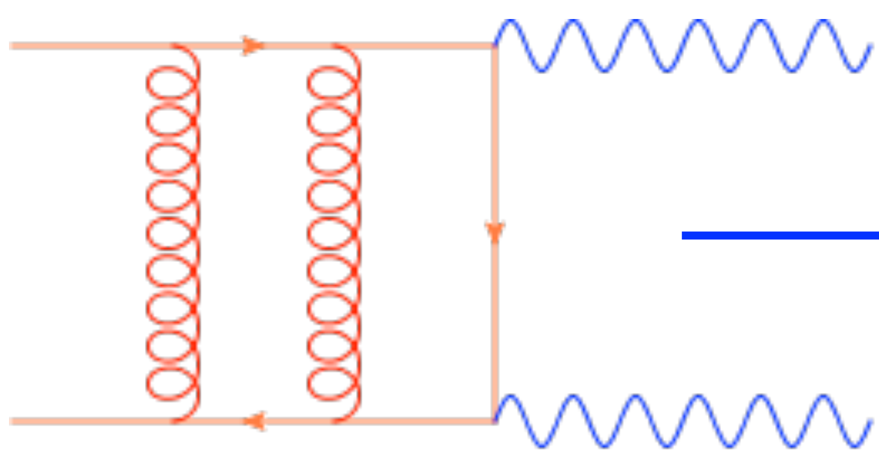
- approximate NNLO: few percent effect
- beyond NNLO, tiny resummation effect (~ Higgs N^{3}LO)

Towards the exact NNLO for qq->VV

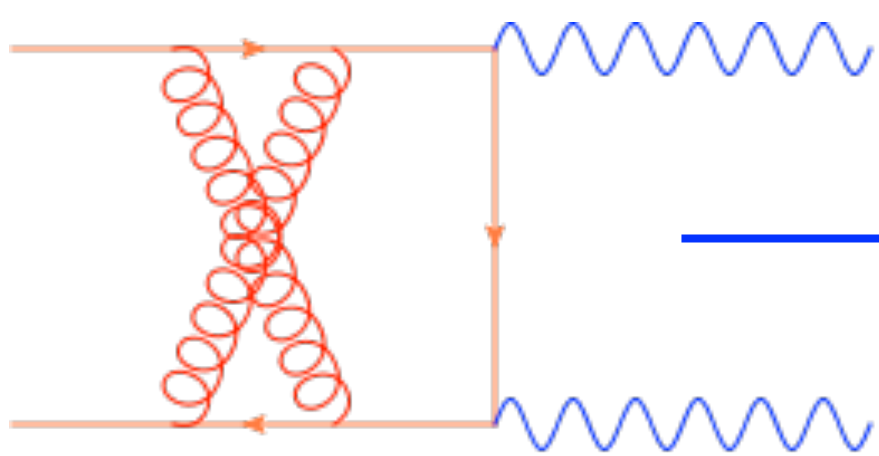
All qq->VV loop amplitudes known numerically

[Chachamis, talk at EPS-HEP 2013]

Analytical results:



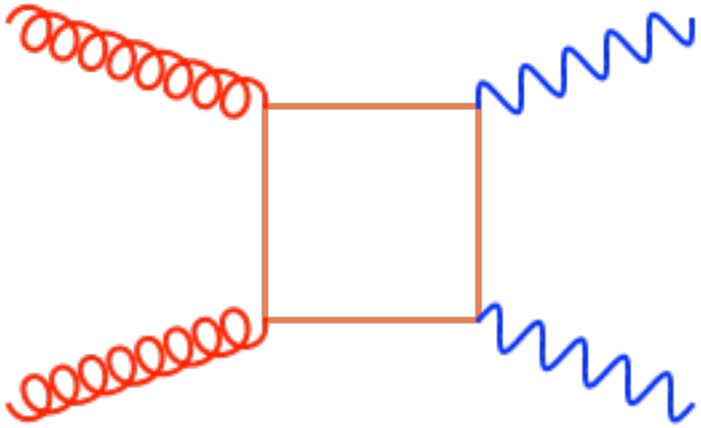
VV: [Gehrmann et al (2013)]
VV*: [Henn, Smirnov, to appear]



more complicated

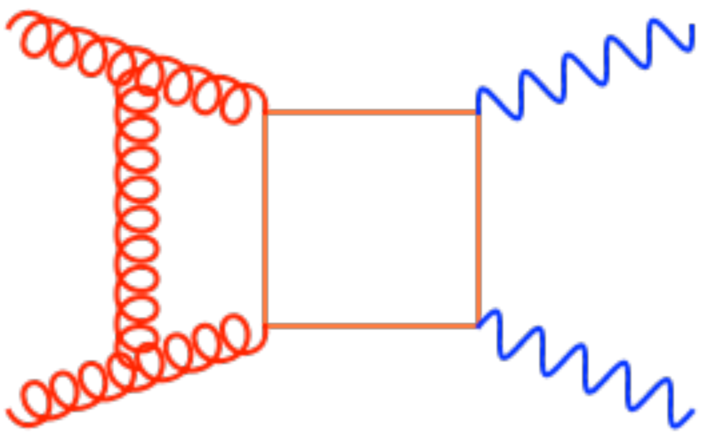
REASONABLE TO EXPECT RESULTS IN THE NOT TOO FAR FUTURE

gg->VV: worse situation



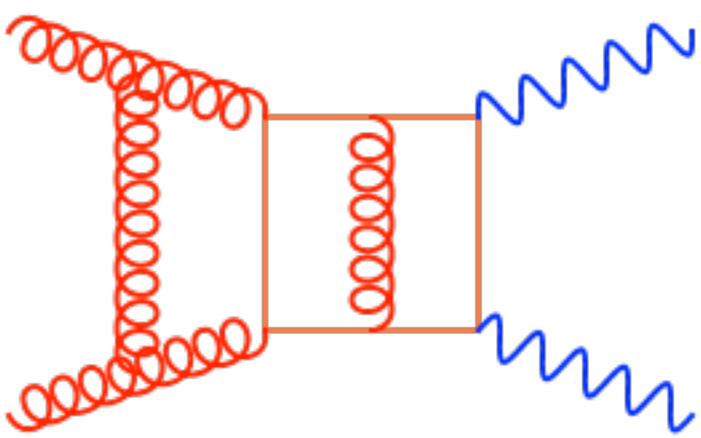
LO: Known

[Glover, van der Bij (1989); Binoth et al (2006,2008); Campbell et al (2011)...]



NLO: Unknown

Apart from γγ [Bern et al (2002)]



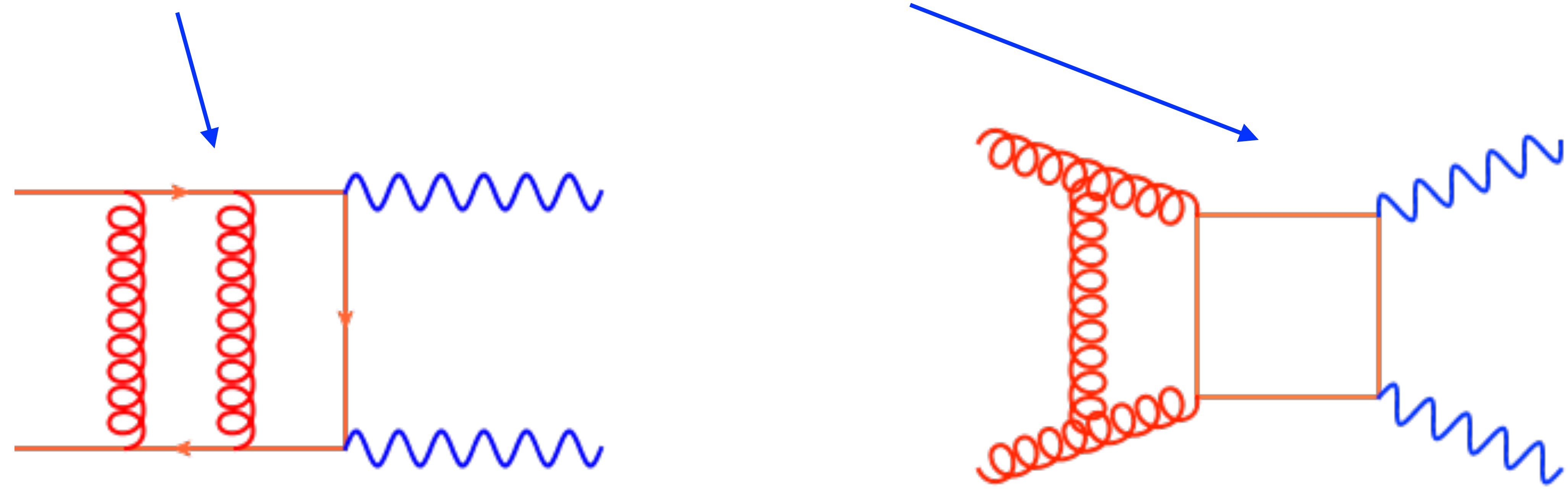
NNLO: Unknown

Gluon-Induced Process -> Expect Large Corrections

gg->VV: can we compute at least NLO?

Low invariant mass: neglect the top-loop contribution

qq->VV @ NNLO and gg->VV @ NLO same complexity

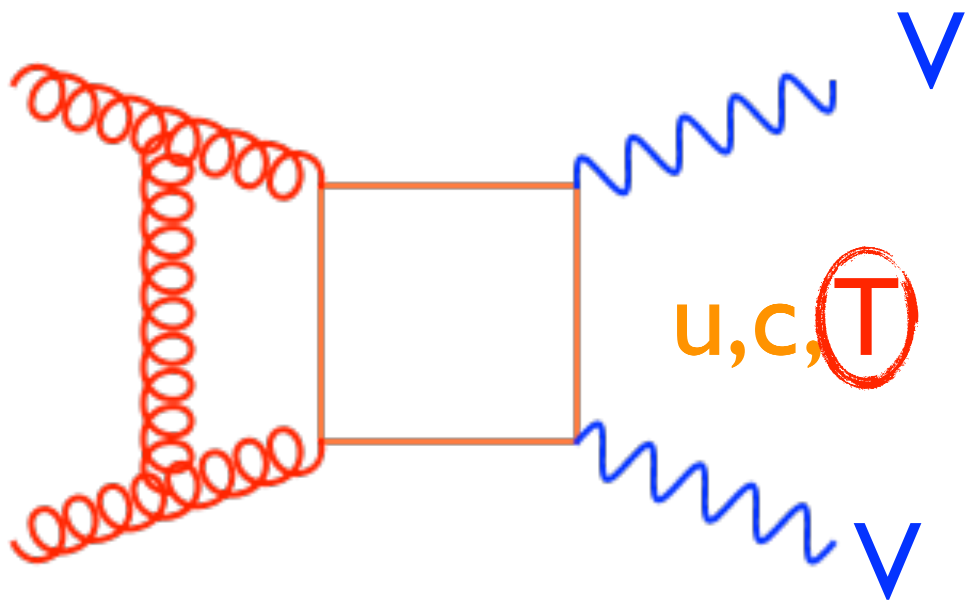


Profit from acquired knowledge for qq->VV @ NNLO

AFTER QQ->VV @ NNLO, NEXT NATURAL STEP

At high invariant mass, VV strongly couple to the

THIRD GENERATION



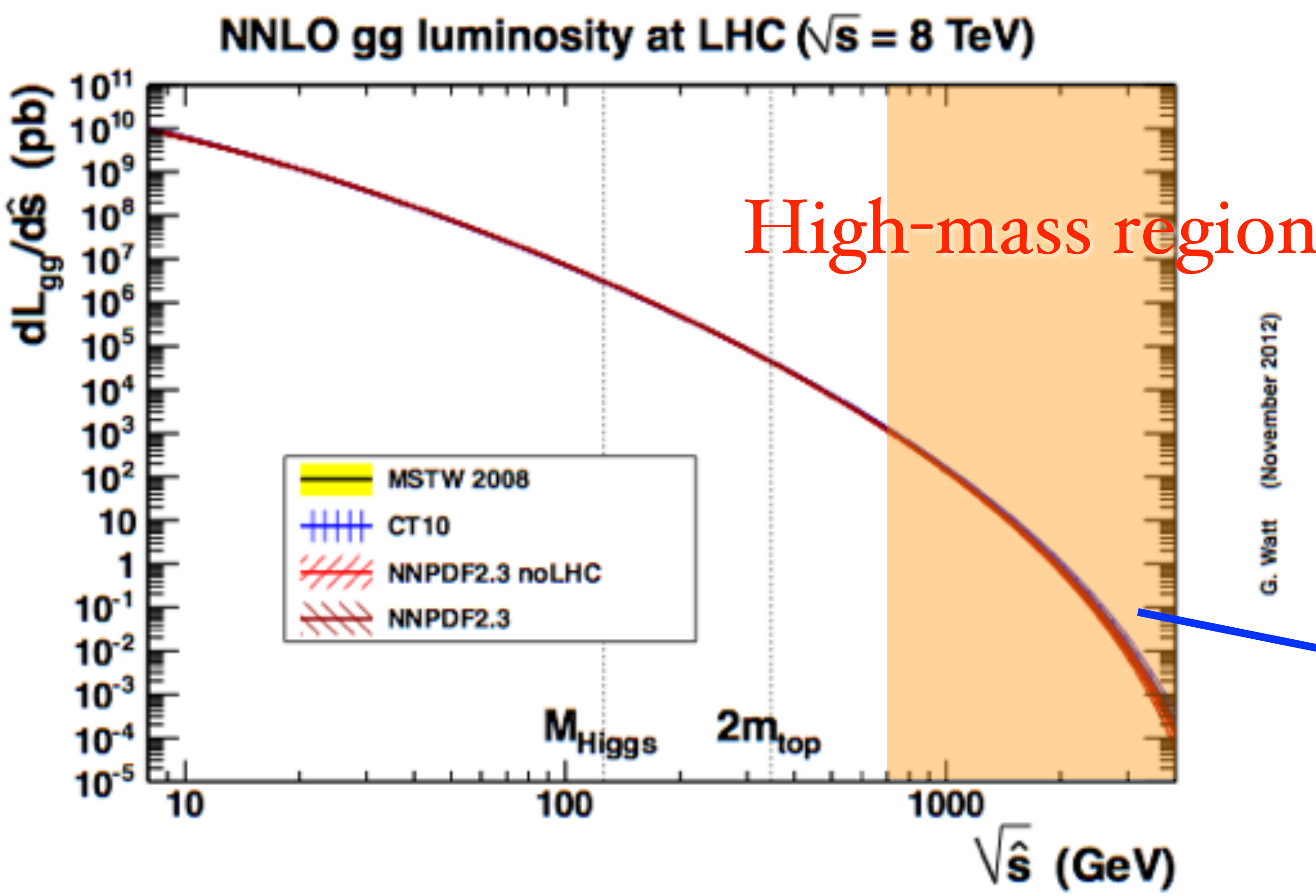
Multi-scale problem internal masses → (WELL) BEYOND OUR CURRENT COMPUTATIONAL TECHNOLOGY

Yet important:

- off-shell tail -> indirect measurement of the Higgs width
- large pT tails (coupling extraction, channel separation…)
- irreducible background for SM-like heavy Higgs
- high mass Higgs exclusion limits

(N)NLO in the soft approximation

We are interested in the production of a
high invariant-mass system in the gluon-gluon channel



$$\sigma = \int_\tau^1 \frac{dz}{z}\mathcal{L}\left(\frac{\tau}{z}\right)\hat{\sigma}(z)$$

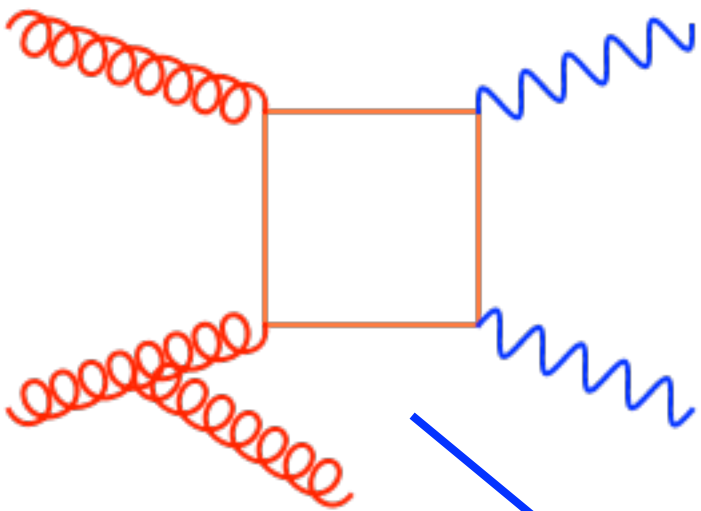
$$\tau = M^2/s$$

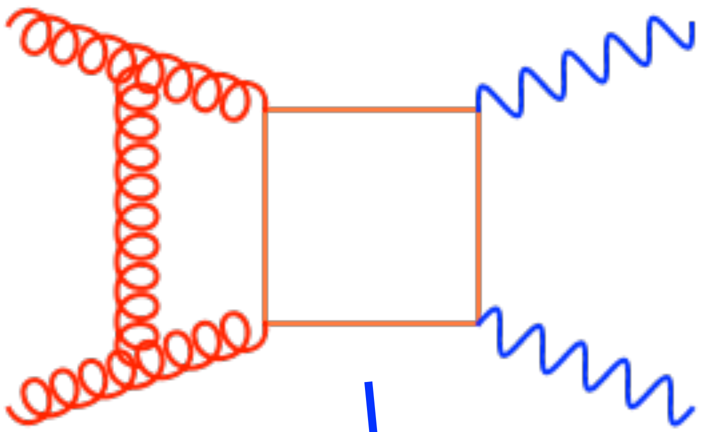
Rapidly falling gluon PDF

The cross section is dominated by the soft z ~1 region

(N)NLO in the soft approximation

Enhanced terms: emission of soft gluons





$$\hat{\sigma} = \sigma_0 + \sigma_0 \frac{\alpha_s}{2\pi} \left(8C_A \left[\frac{\ln(1-z)}{1-z} \right]_+ + c_1 \delta(1-z) + \text{reg} \right) + \text{h.o.}$$

Process-dependent

Usually neglected in the soft approximation

Bulk of the result, universal

A soft-approximation for gg->VV @ (N)NLO

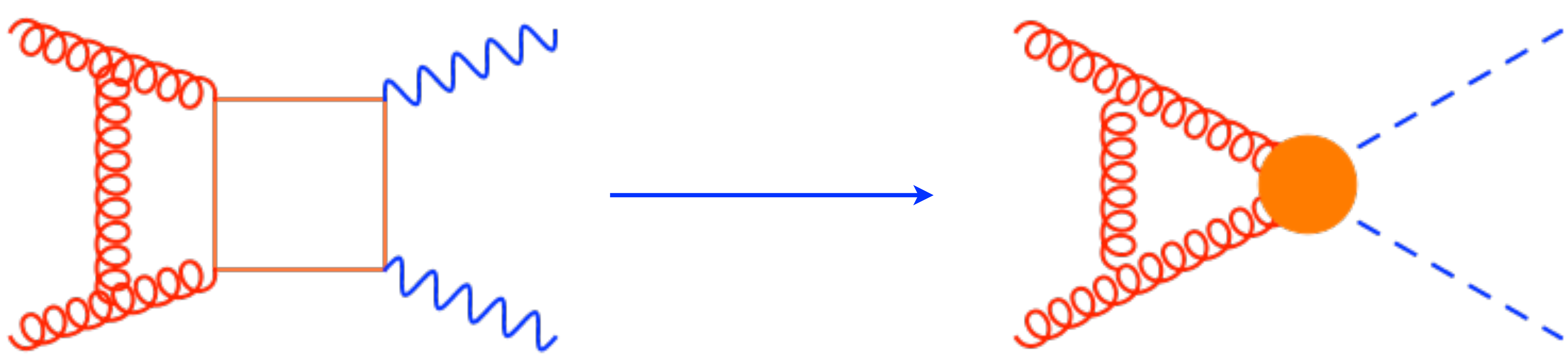
[Bonvini, FC et al (2013)]

Improvements w.r.t traditional soft approximation:

- correct kinematics information [R.D. Ball, Bonvini et al (2013)]
- correct leading collinear behavior [Catani et al (2013)]

$$\left[\frac{\ln^k 1-z}{1-z}\right]_+ \to A_{gg}(z)\left\{\left[\frac{\ln^k 1-z}{1-z}\right]_+ + \left(\frac{\ln^k \frac{1-z}{\sqrt{z}}}{1-z} - \frac{\ln^k 1-z}{1-z}\right)\right\}$$

- unknown loop amplitude estimated using EFT

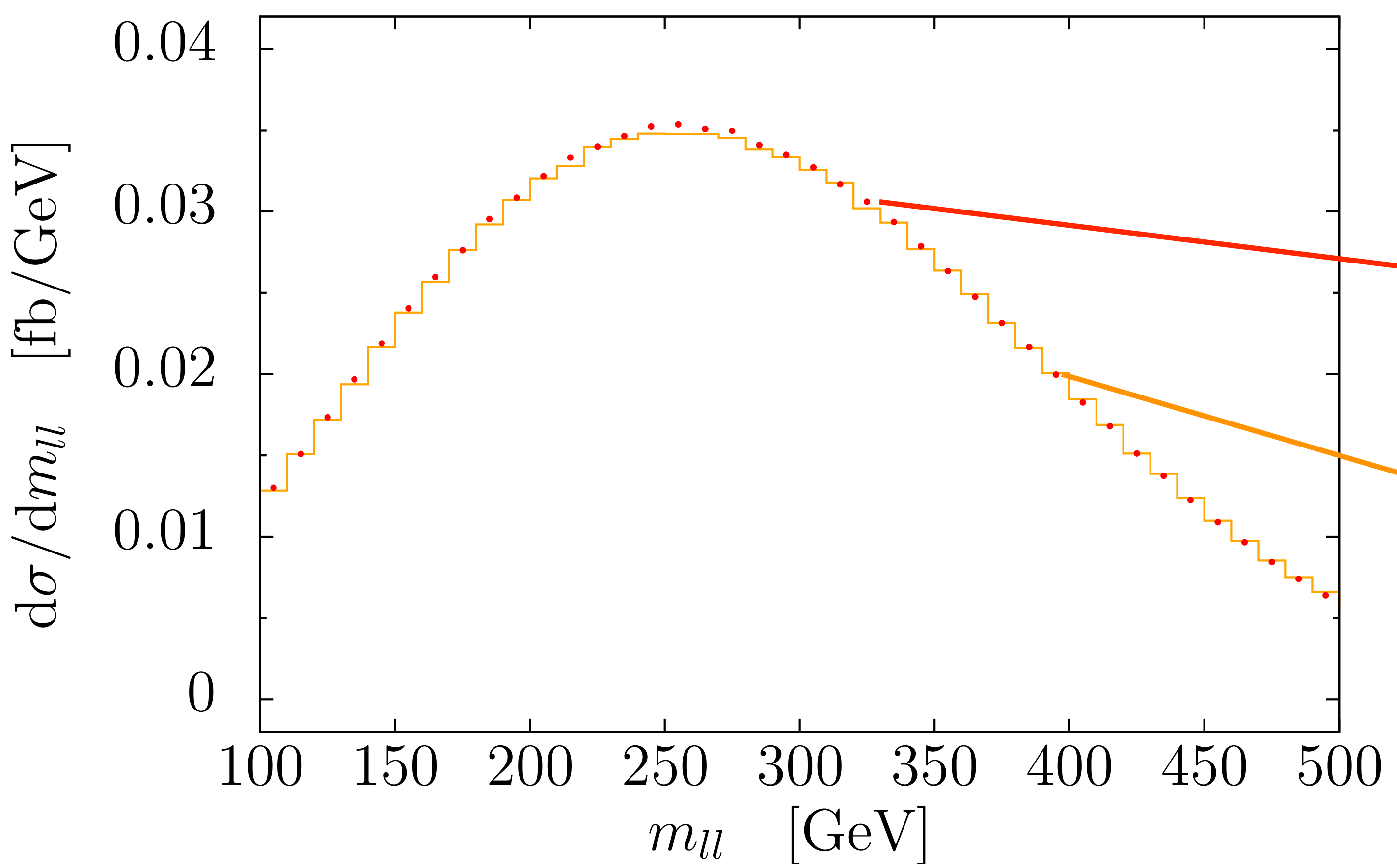


Validating the approximation: $gg \to H \to WW$

Inclusive K-factors, high-mass SM-like Higgs

	$\sqrt{s} = 8$ TeV		$\sqrt{s} = 13$ TeV	
	NLO	NNLO	NLO	NNLO
exact	2.150	2.78	2.074	2.67
soft-collinear	2.19±5	2.82±12	2.13±6	2.73±12

Differential distributions

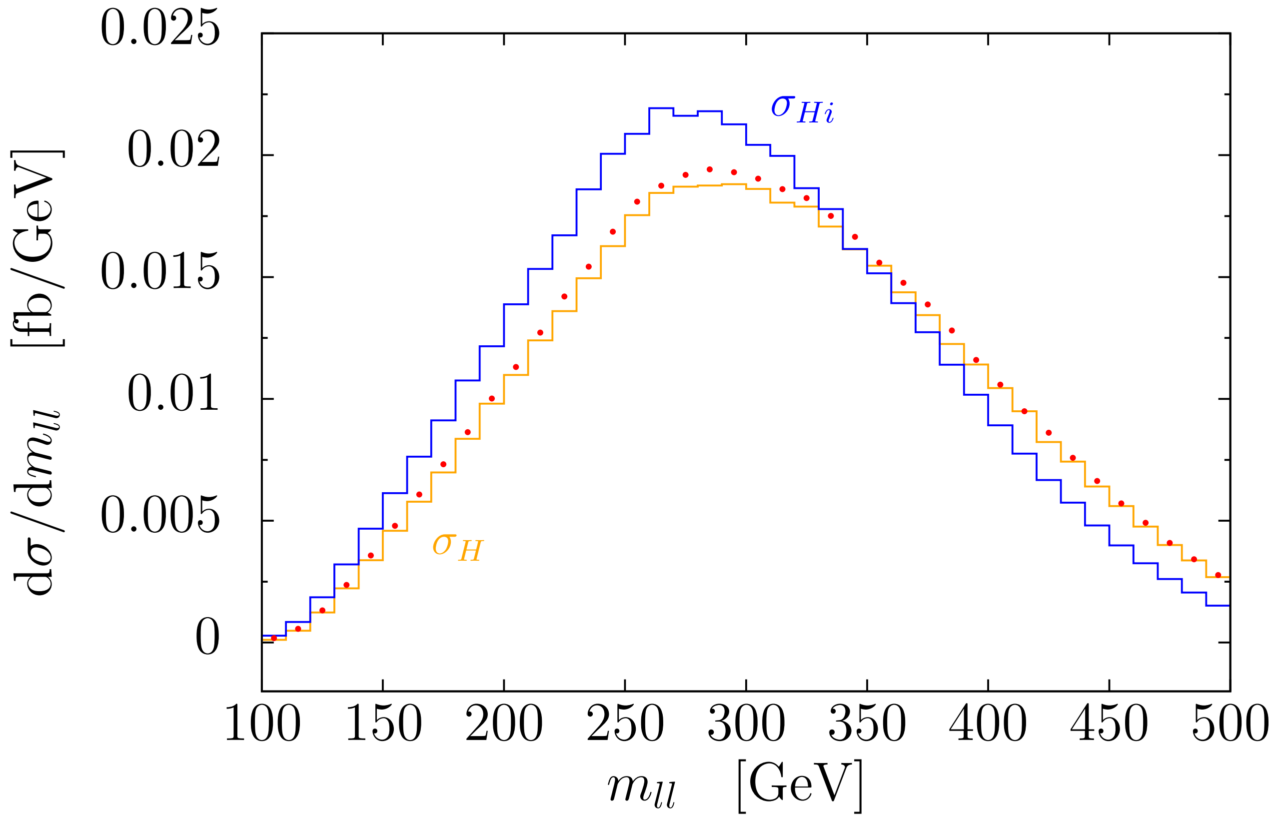


Exact

Approximate NNLO

An application: signal/background interference for heavy Higgs searches

	$\sqrt{s} = 8$ TeV			$\sqrt{s} = 13$ TeV		
	LO	NLO	NNLO	LO	NLO	NNLO
σ_H	0.379	0.83(2)	1.07(5)	1.55	3.29(8)	4.2(2)
σ_{Hi}	0.427	0.93(3)	1.20(7)	1.66	3.5(1)	4.5(2)
$\sigma_H/\sigma_H^{\mathrm{LO}}$	—	2.19(5)	2.8(1)	—	2.13(5)	2.7(1)
$\sigma_{Hi}/\sigma_{Hi}^{\mathrm{LO}}$	—	2.19(7)	2.8(2)	—	2.12(6)	2.7(1)



We believe that the interference K-factor can be estimated to $\mathcal{O}(10\%)$ accuracy

Conclusions and outlook

- gg->VV processes very interesting for Higgs physics
  - as a background
  - as a tool to probe Higgs properties (model independent determination of Higgs width/couplings)
- gg->VV currently known only at LO
  - but soft approximation is available, reliable in the high invariant mass region
  - can be used for instance for high-mass Higgs searches
- Expect improvements soon
  - full NNLO for qq->VV to be completed soon
  - profit from the acquired knowledge and compute NLO gg->VV in the low invariant mass region

Thank you for
your attention!