Higgs Hunting 2014
Results and prospects in the electroweak symmetry breaking sector

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www.higgshunting.fr

Higgs Production Theory

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Argentina

Higgs Boson

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BEH Boson ICHEP'14

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BEGHHK Boson

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"The" scalar Boson of the Standard Model responsible for ElectroWeak symmetry breaking

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Outline

▸Latest results on Higgs boson production

✓ ggF at N^{3}LO

✓ Uncertainties

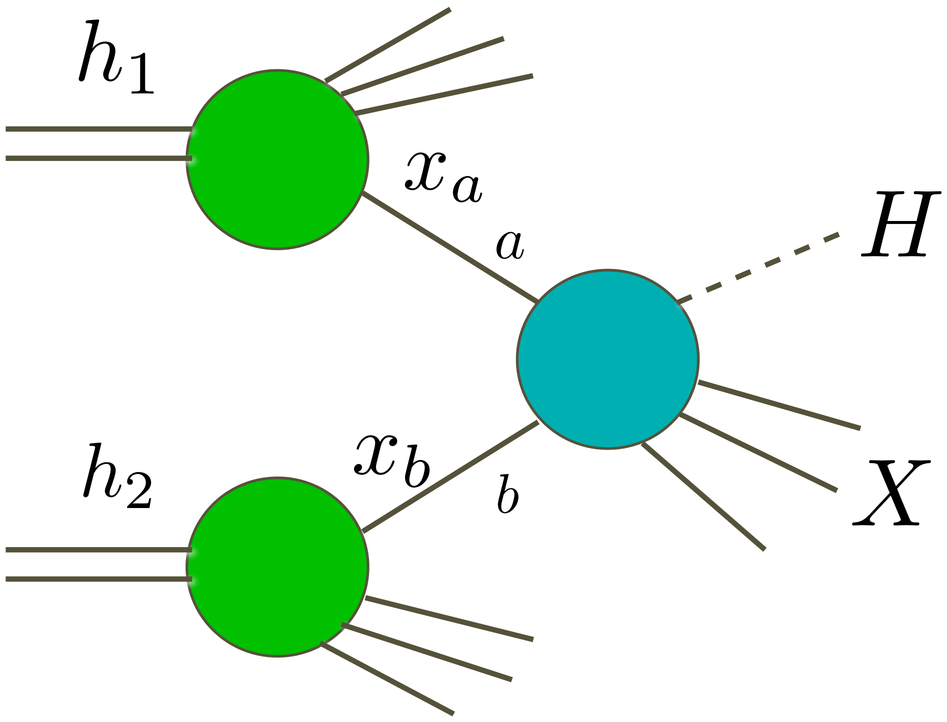
✓ H + jet

✓ (N)NLOPS

✓ Interferences and Higgs width

✓Higgs pair production at NNLO

Higgs at Hadronic Colliders



non-perturbative parton distributions

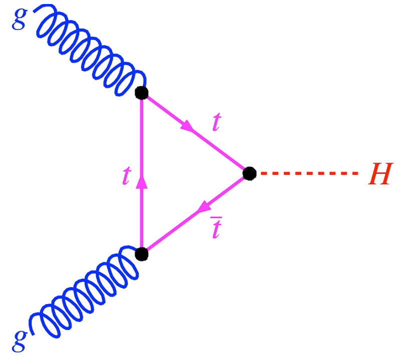
$$d\sigma = \sum_{ab} \int dx_a \int dx_b \, f_a(x_a,\mu_F^2) f_b(x_b,\mu_F^2) \times d\hat{\sigma}_{ab}(x_a, x_b, Q^2, \alpha_s(\mu_R^2)) \; + \mathcal{O}(1/Q^2)$$

perturbative partonic cross-section

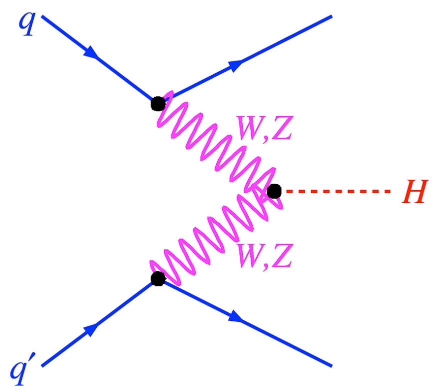
Partonic cross-section: expansion in $\alpha_s(\mu_R^2) \ll 1$ $\quad d\hat{\sigma} = \alpha_s^n \, d\hat{\sigma}^{(0)} + \alpha_s^{n+1} \, d\hat{\sigma}^{(1)} + \ldots$

- Need precision for both PDFs and partonic cross sections

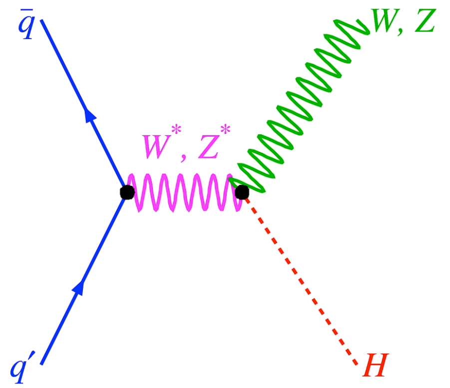
Production Channels at the LHC



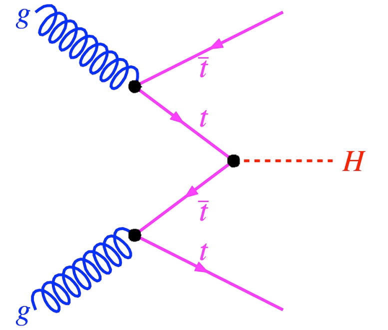
gg fusion



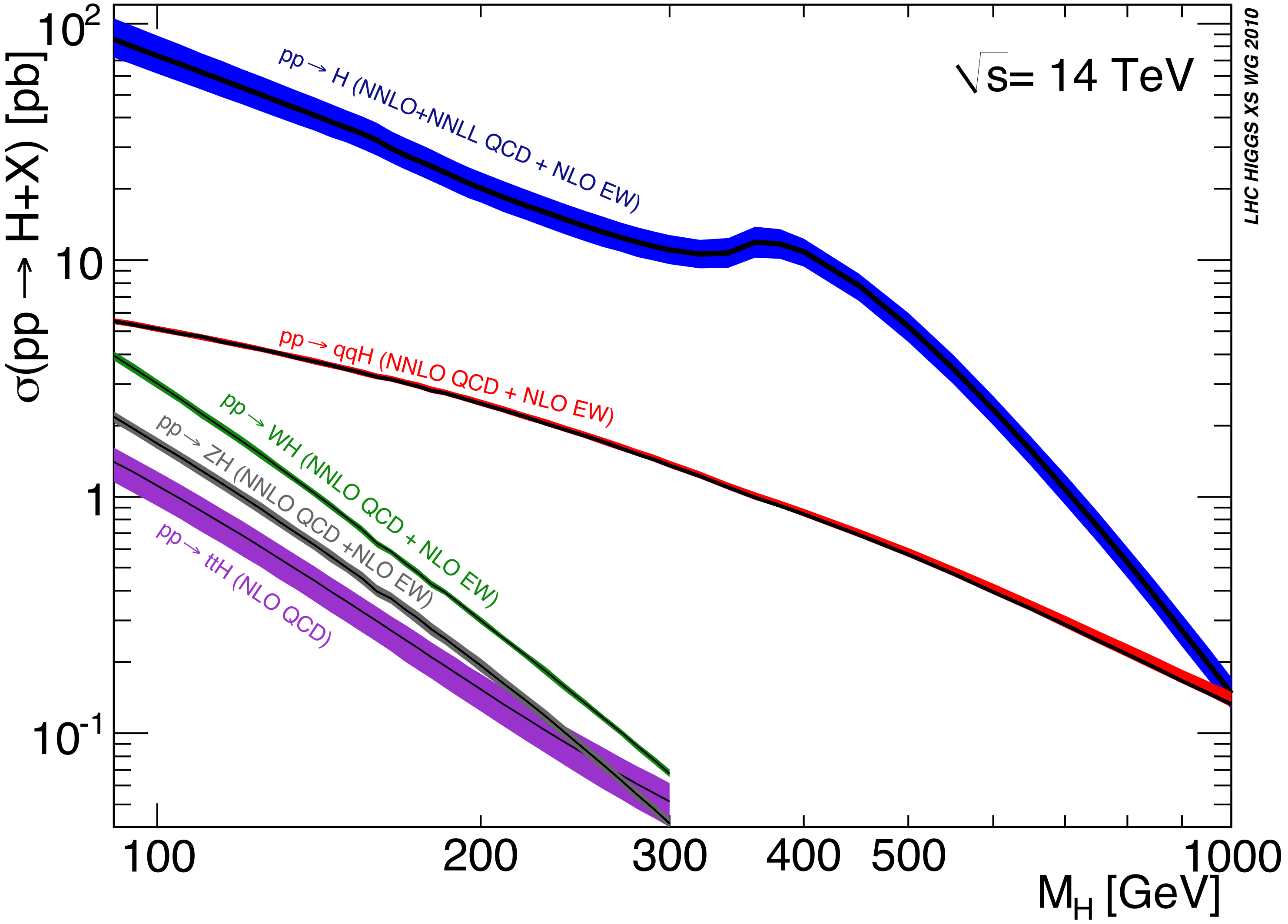
vector boson fusion



associated production with W,Z



associated production with heavy quarks



- Gluon-gluon fusion dominates due to large gluon luminosity

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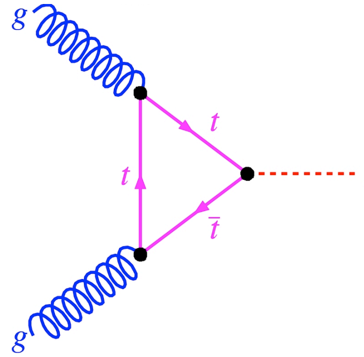

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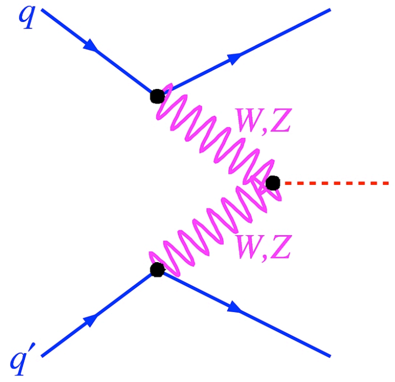

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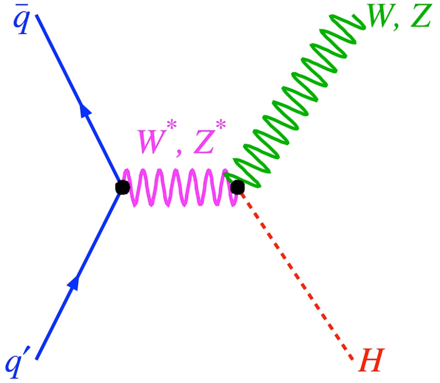

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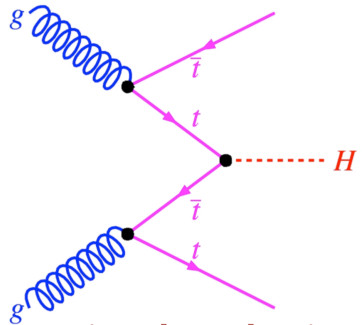

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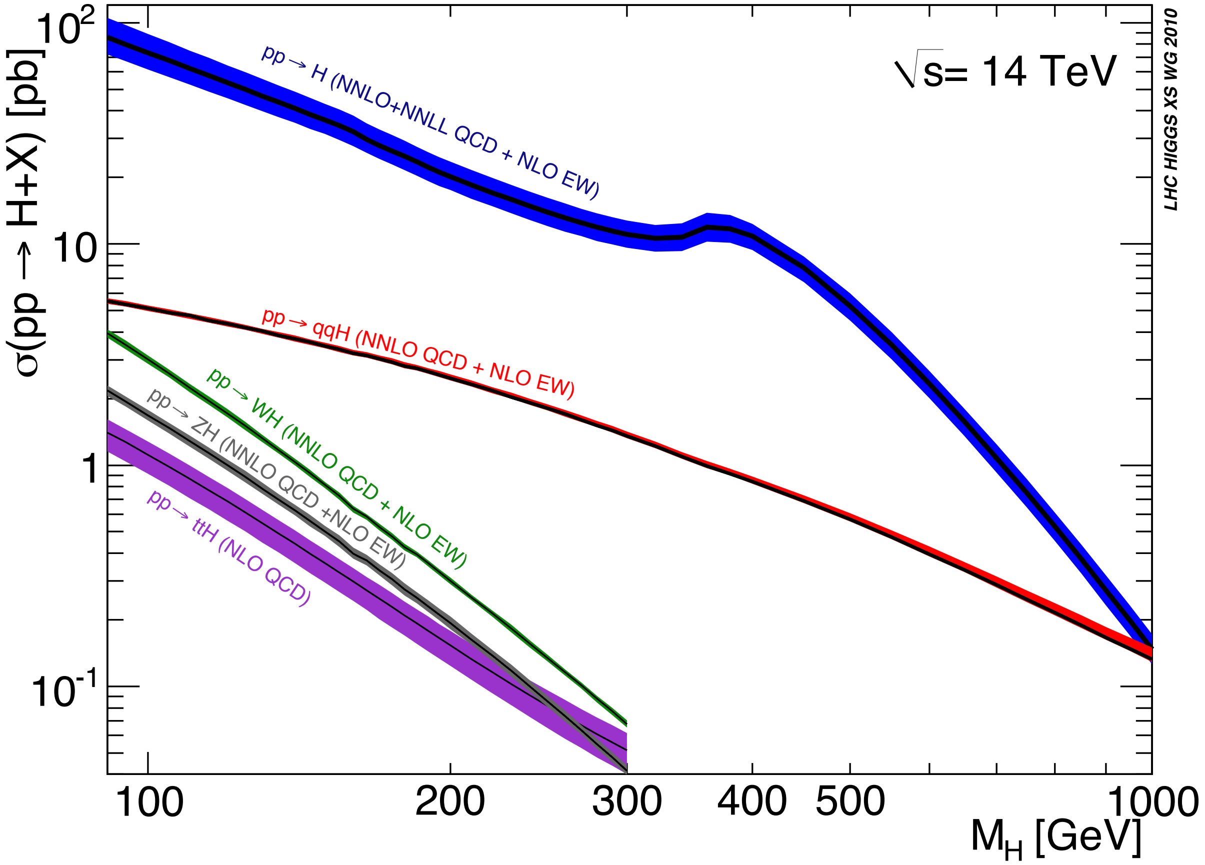

Uncertainties @ LHC

14 TeV

	TH	PDF4LHC	QCD	EW
ggF	8%	7%	> 100%	5%
VBF	1%	3%	5%	5%
WF	1%	3%	25%	7%
ZH	4%	4%	30%	5%
ttH	9%	9%	5%	?

ggF Higgs Cross-section @ LHC

- NNLO

Harlander, Kilgore (2002)
Anastasiou, Melnikov (2002)
Ravindran, Smith, van Neerven (2003)

- NNLL Resummation (9% at 7 TeV) Catani, deF., Grazzini, Nason (2003)

- Two loop EW corrections not negligible ~ 5%

Aglietti, Bonciani, Degrassi, Vicini (2004)
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Djouadi, Gambino (1994)

- Mixed EW-QCD effects evaluated in EFT approach Anastasiou et al (2008)

- + Mass effects, Line-shape, interferences, ...

Goria, Passarino, Rosco (2012)
Higgs Cross-Section WG

$$\sigma(\mathrm{m_H} = 125\,\mathrm{GeV}) = 19.27\overset{\text{scale}}{{}^{+7.2\%}_{-7.8\%}}\ \overset{\text{pdf}+\alpha_S}{{}^{+7.5\%}_{-6.9\%}}\ \mathrm{pb}$$

deF, Grazzini

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ATLAS signal significance

$$\boxed{\mu = 1.30 \pm 0.12\ (\mathrm{stat})\ \pm 0.10\ (\mathrm{th})\ \pm 0.09\ (\mathrm{syst})}$$

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For RUN 2 higher TH accuracy needed

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Higher orders

LHC data and more observables

For RUN 2 higher TH accuracy needed

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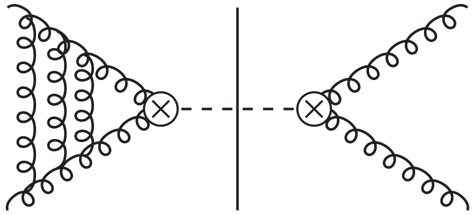
Even Higher orders : N^{3}LO

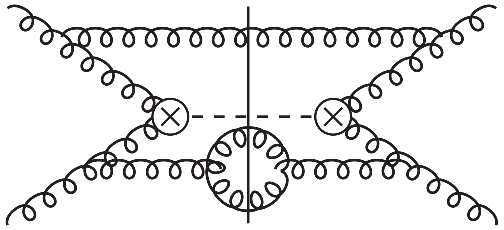
- 3 loop form factor

Baikov et al (2009)
Gehrmann et al (2010)
Lee, Smirnov, Smirnov (2010)



- Triple real emission

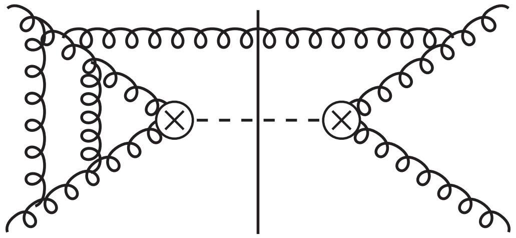
Anastasiou, Duhr, Dulat, Mistlberger (2013)



threshold expansion

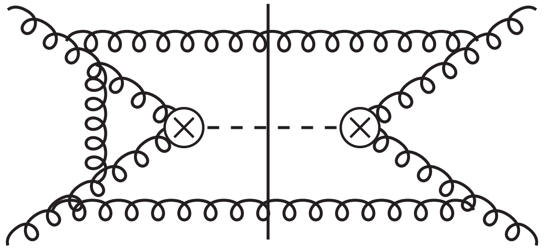
- 2 loop + single emission

Duhr, Gehrmann (2013); Li, Zu (2013);
Gehrmann, Jaquier, Glover, Koukoutsakis (2012);
Anastasiou, Duhr, Dulat, Herzog, Mistlberger; Kilgore (2013)



- 1 loop + double emission

Anastasiou, Duhr, Dulat, Herzog, Mistlberger, Furlan (2013);
Li, Manteuffel, Schabinger, Zhu (2013)



- Subtraction terms

Höschele, Hoff, Pak, Steinhauser, Ueda (2013)
Buehler, Lazopoulos (2013)

NEW

N^3LO in the Soft-Virtual approximation

$$
\begin{aligned}
c_{gg}^{(3)}(z) \simeq\; & \delta(1-z)\, 1124.308887\ldots && (\to 5.1\%) \\
& + \left[\frac{1}{1-z}\right]_+ 1466.478272\ldots && (\to -5.85\%) \\
& - \left[\frac{\log(1-z)}{1-z}\right]_+ 6062.086738\ldots && (\to -22.88\%) \\
& + \left[\frac{\log^2(1-z)}{1-z}\right]_+ 7116.015302\ldots && (\to -52.45\%) \\
& - \left[\frac{\log^3(1-z)}{1-z}\right]_+ 1824.362531\ldots && (\to -39.90\%) \\
& - \left[\frac{\log^4(1-z)}{1-z}\right]_+ 230 && (\to 20.01\%) \\
& + \left[\frac{\log^5(1-z)}{1-z}\right]_+ 216\,. && (\to 93.72\%)
\end{aligned}
$$

Anastasiou, Duhr, Dulat, Furlan, Gehrmann,
Herzog, Mistlberger (2014)

Cross section depends on one variable $z = \frac{M_H^2}{s}$

$< 1 - z >$ not the most appropriate measure of distance to threshold

Affected by factorially-growing subleading terms (kinematic mistreat of energy conservation)

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Natural space for threshold effects : Mellin

$z \to 1 \quad \Rightarrow \quad N \to \infty$

$$c_{ab}(N) = \int_0^1 dz\, z^{N-1}\, c_{ab}(z)$$

$$\left[\frac{1}{1-z}\right]_+ \to -\ln N - \gamma_E + \mathcal{O}\left(\frac{1}{N}\right)$$

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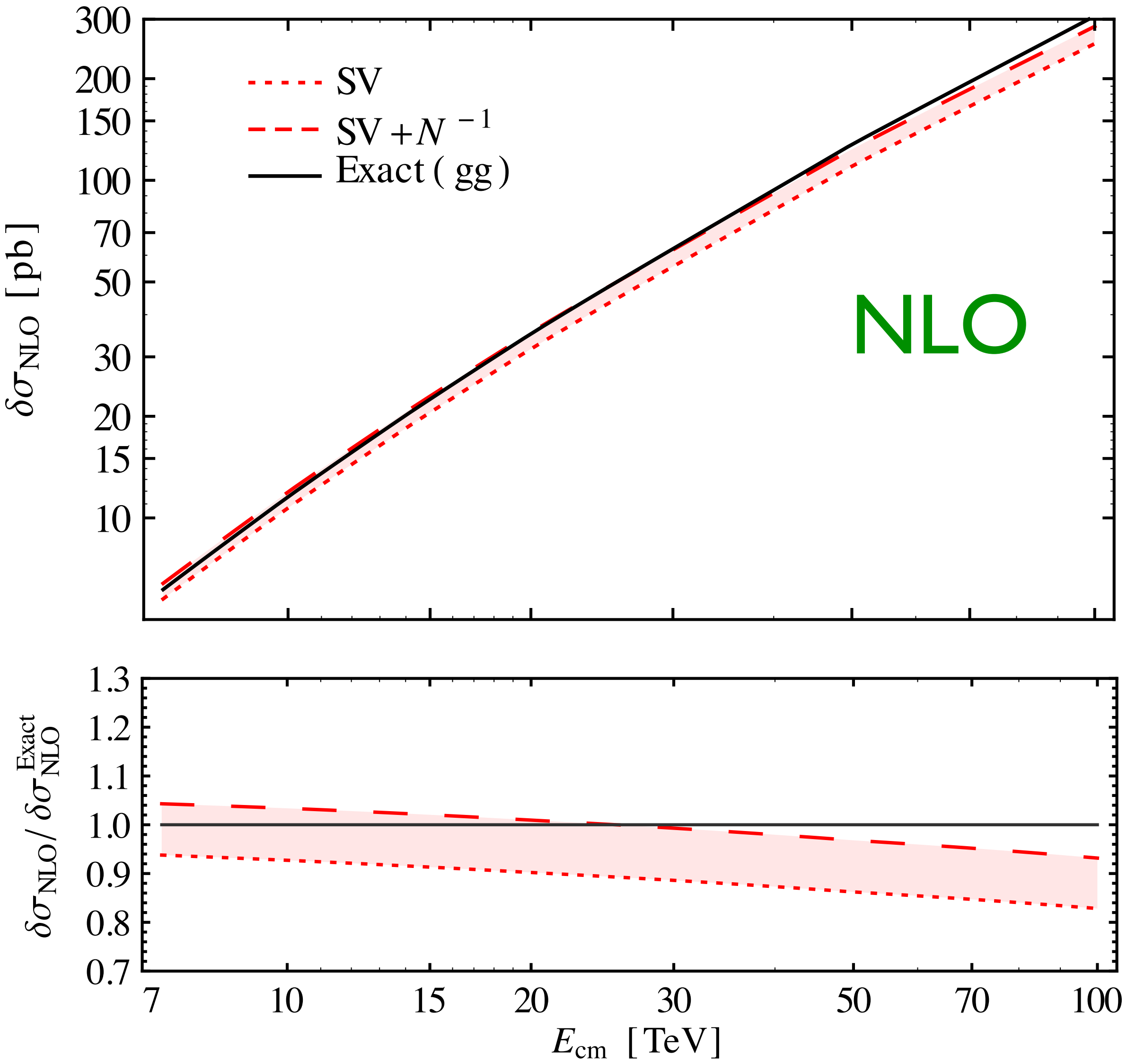
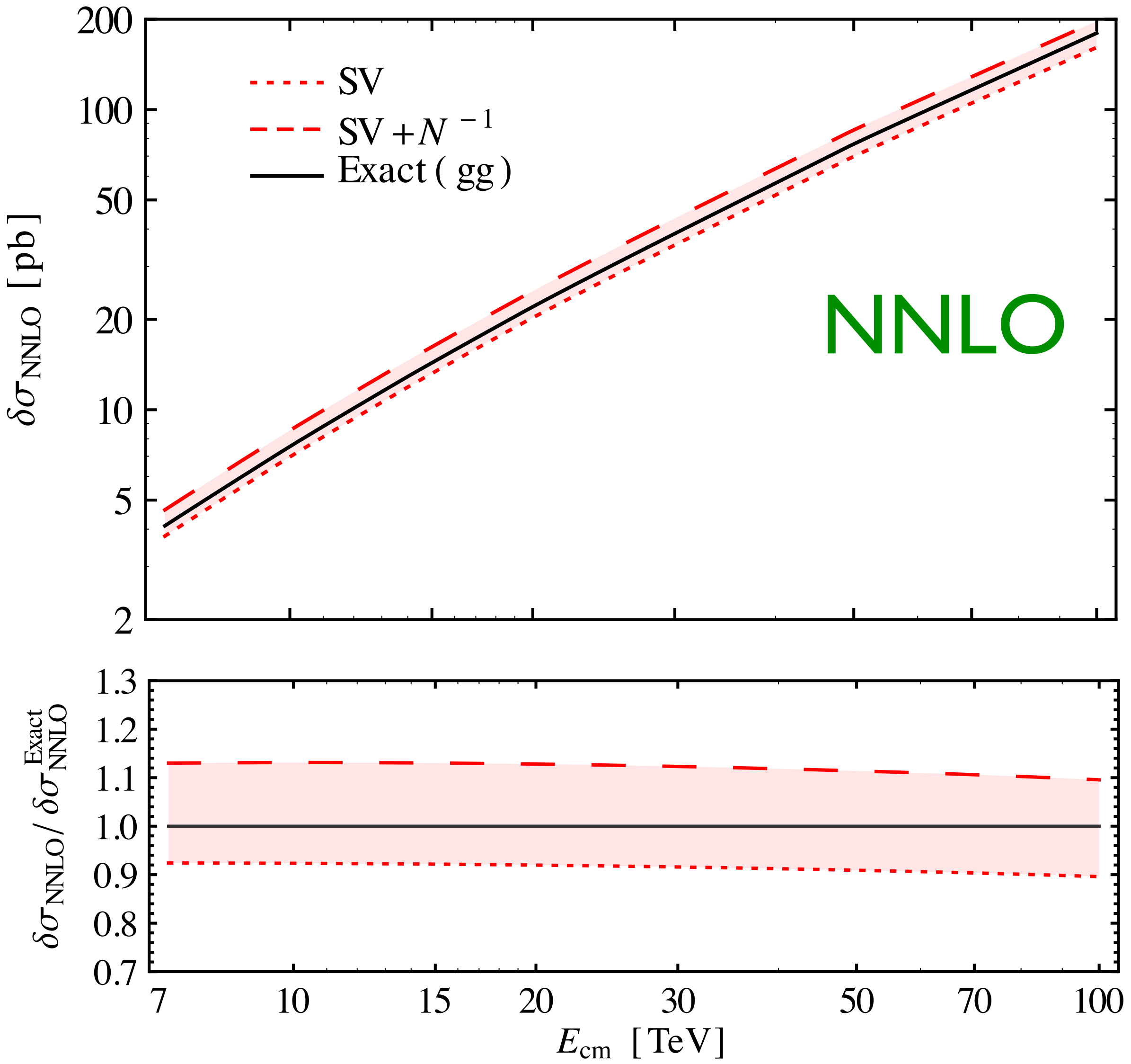
$$c_{gg}^{(3)}(N) = 36\ln^6 N + 170.7\ln^5 N + 744.8\ln^4 N + 1405.2\ln^3 N + 2676\ln^2 N + 1897\ln N + 1783.7$$

- all coefficients positive
- automatically impose energy conservation
- better phenomenological approx. at NLO and NNLO

- Soft Virtual + sub-leading terms $\ln^k N, \quad \frac{\ln^k N}{N}$

Provides very good approximation for full result at NLO and NNLO





Use differences between SV and SV+sl to estimate error in approx.

deF, Mazzitelli, Moch, Vogt (2014)

N^3LO approximation

deF, Mazzitelli, Moch, Vogt (2014)

NEW

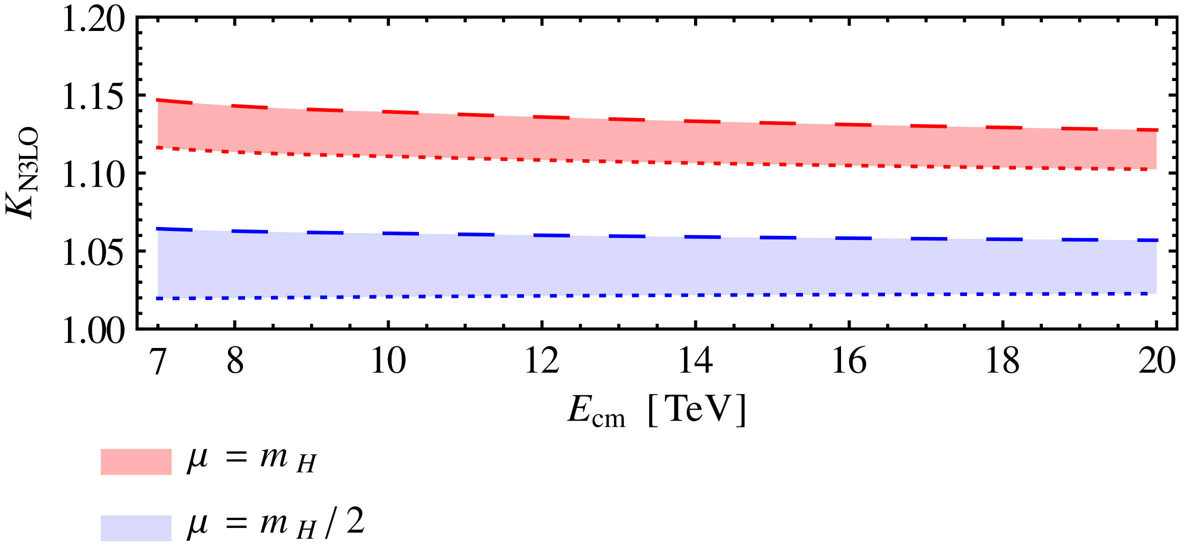
SV+ sub-leading terms computed with physical kernel

$$\frac{\ln^k N}{N}$$

k=5,4,3 computed

2,1,0 estimated

Correction ~within the expectation from scale dependence at NNLO



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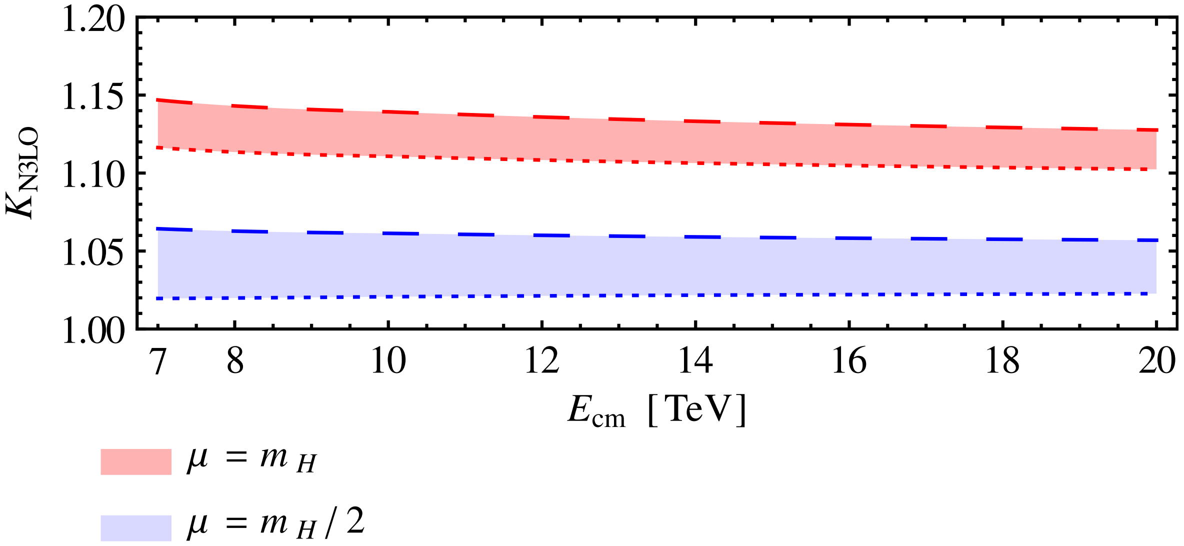

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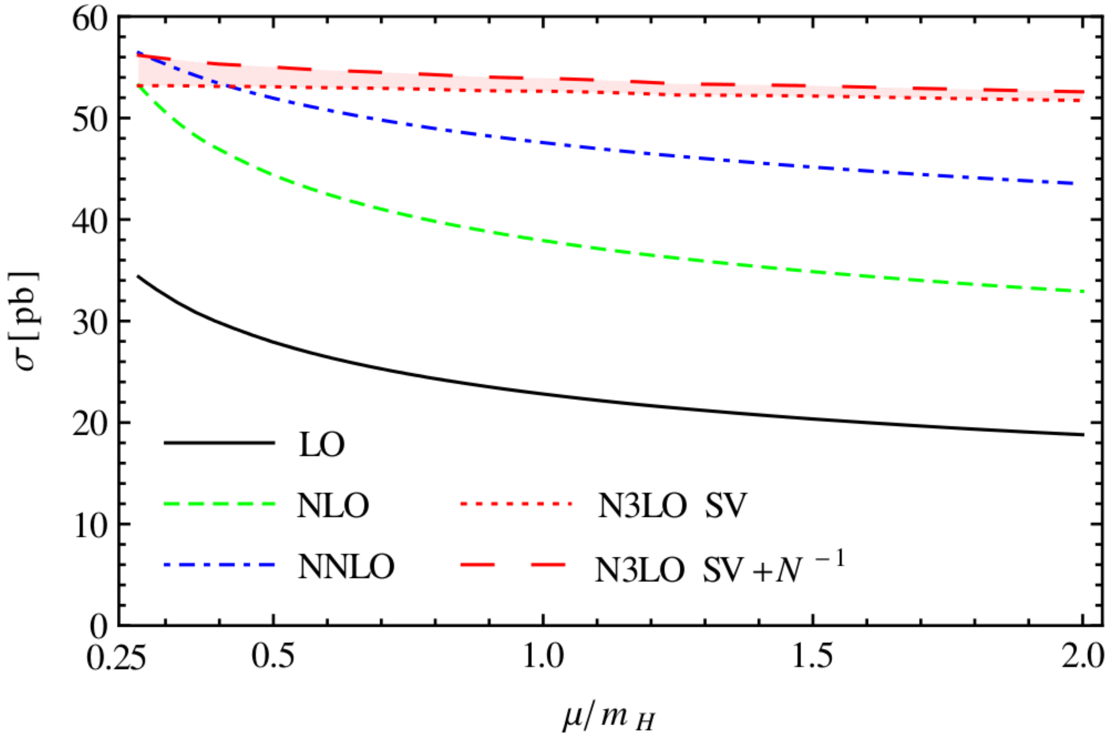


Reduction in scale dependence

Estimate of N^4LO SV contribution

TH uncertainty below 5%

Can be improved by adding more terms when computed

Improved Soft approximation

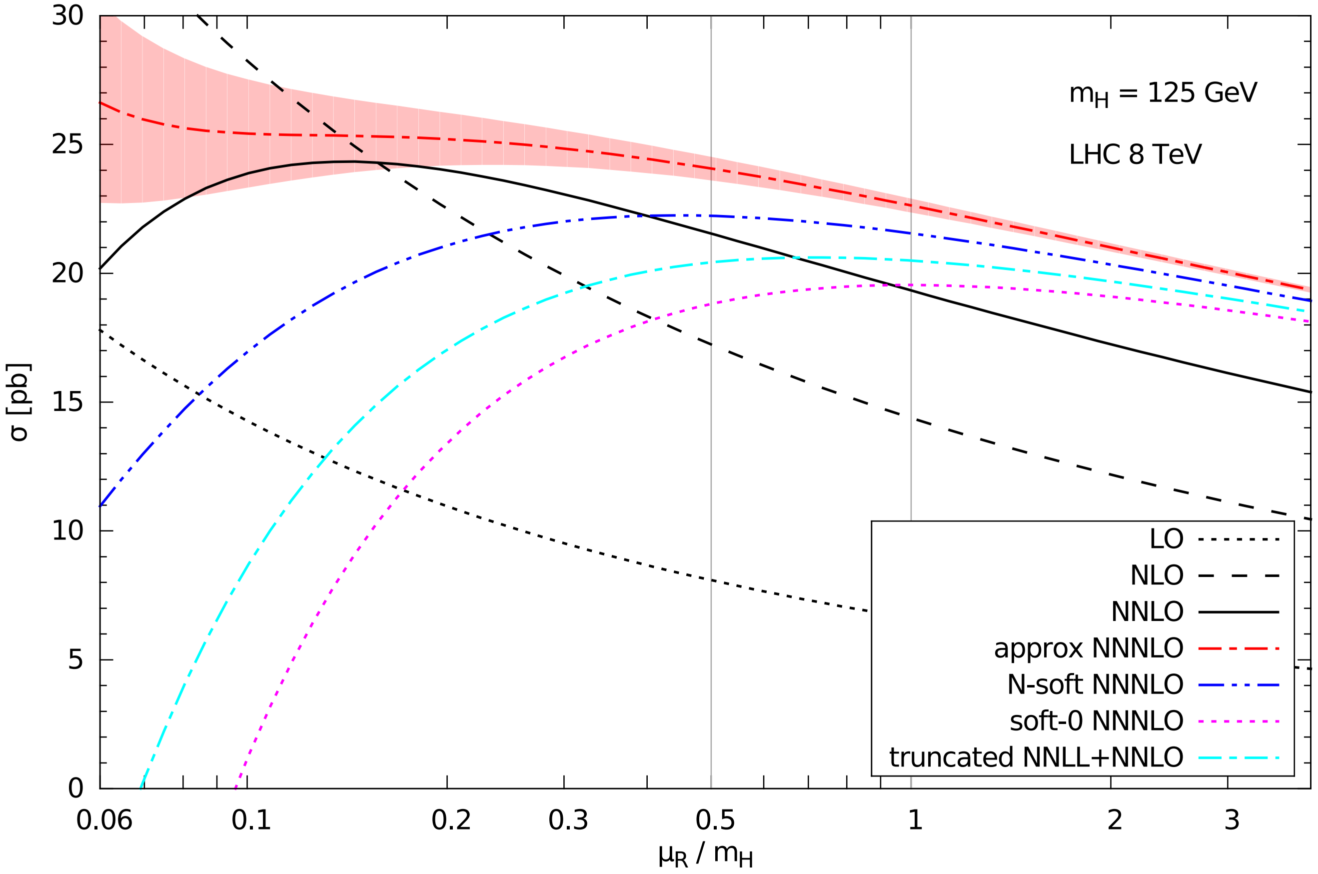
Ball, Bonvini, Forte, Marzani, Ridolfi (2012)

- improved by analyticity

$$\ln^k N \to (\psi(N) + \gamma_E)^k$$

- and high energy asymptotic behavior (small N)

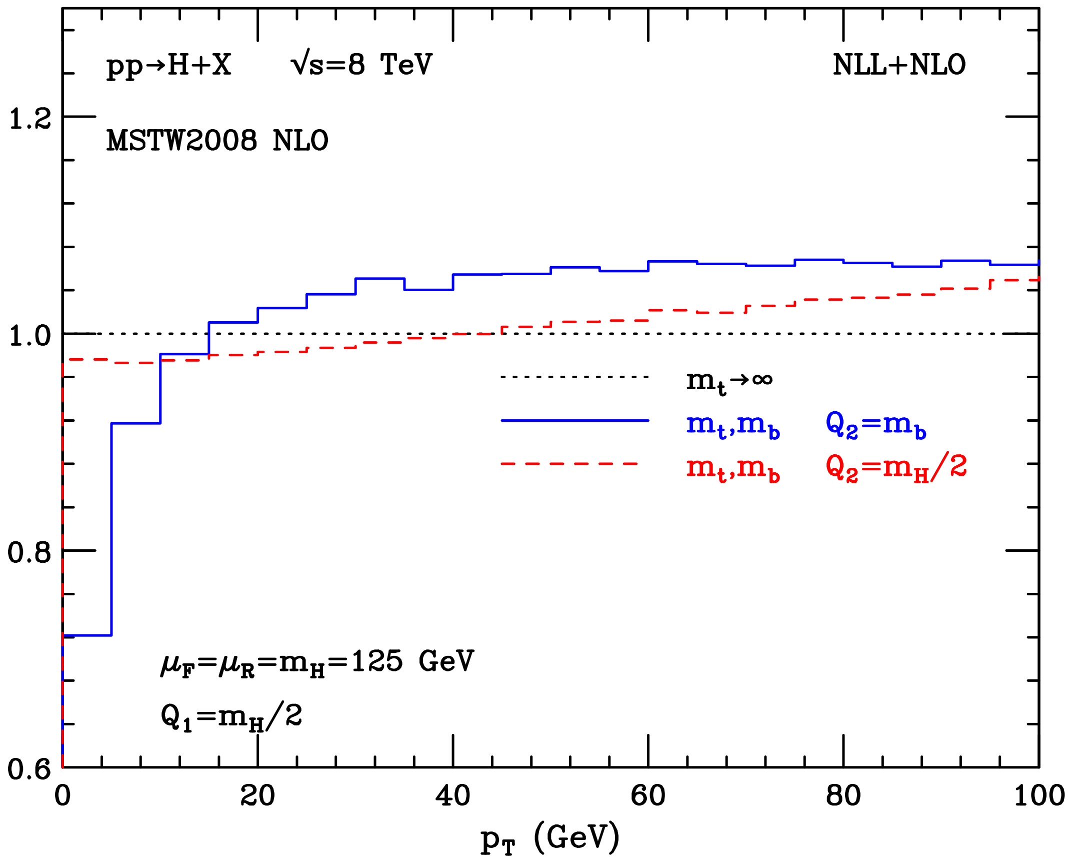
$$C_{\mathrm{h.e.}}(N, \alpha_s) = \sum_{n=1}^{\infty} c_n(m_t, m_H, \mu_F)\left(\frac{\alpha_s}{N-1}\right)^n + O\left(\alpha_s\left(\frac{\alpha_s}{N-1}\right)^n\right)$$



~10-15% at 14 TeV

Core of both approximations is Soft-Virtual (TH agreement)
Differences in Sub-leading logs (only log^5 correct)

- ✓ Full N^{3}LO on the way (more terms in threshold expansion first)
- ✓ 4-5% accuracy calls for attention to other corrections
  - To be improved by resummation, EW, etc
  - (Bottom) mass effects in distributions (and inclusive at NNLO?)



Grazzini, Sargsyan (2013)

Need matching precision in non-perturbative component!

PDFs

- Several groups provide pdf fits + uncertainties
- Differ by: data input, TH/bias, HQ treatment, coupling, etc
- Deviations larger than uncertainties : "global" vs "non-global"

set	H.O.	data	$\alpha_s(M_Z)@NNLO$	uncertainty	HQ
MSTW 2008	NNLO	DIS+DY+Jets	0.1171	Hessian (dynamical tolerance)	GM-VFN (ACOT+TR')
CT10	NNLO	DIS+DY+Jets	0.118	Hessian (dynamical tolerance)	GM-VFN (SACOT-X)
NNPDF	NNLO	DIS+DY+Jets +LHC	0.1174	Monte Carlo	GM-VFN (FONLL)
ABM	NNLO	DIS+DY(f.t.) +DY-tT(LHC)	0.1132	Hessian	FFN BMSN
(G)JR	NNLO	DIS+DY(f.t.)+ some jet	0.1124	Hessian	FFN (VFN massless)
HERA PDF	NNLO	only DIS HERA	0.1176	Hessian	GM-VFN (ACOT+TR')

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up to 5% ! >15% in Higgs cross section

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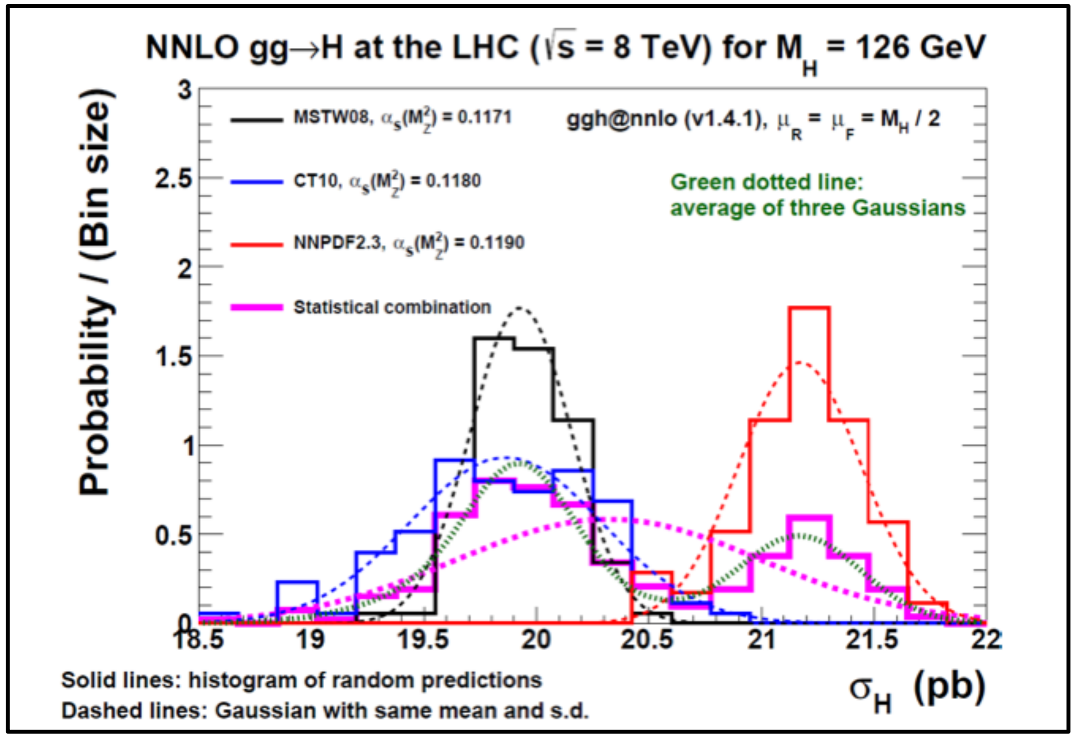
PDF4LHC recommendation

- Envelope of MSTW & CT & NNPDF (68%cl) $\Delta\alpha_s(M_Z) = \pm 0.0012$

- No discovery/lack of discovery hurt by this choice (HH'11)



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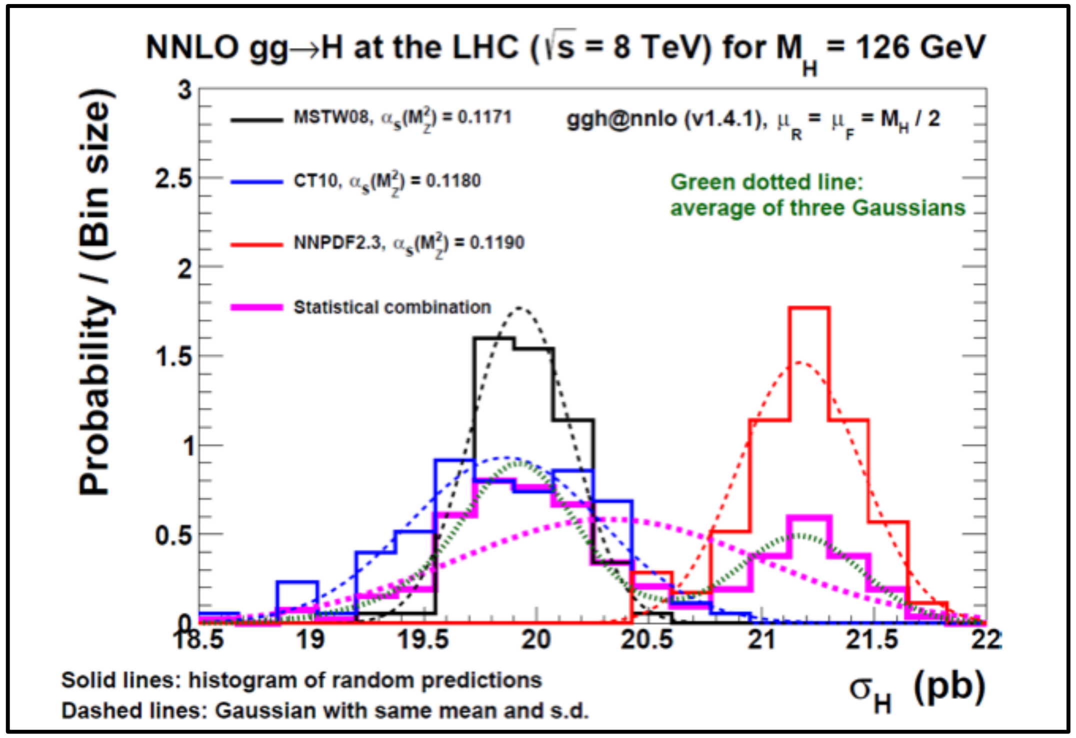

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Need to match perturbative accuracy

- •Some sets out of the recommendation
- •Increased uncertainty due to different central values

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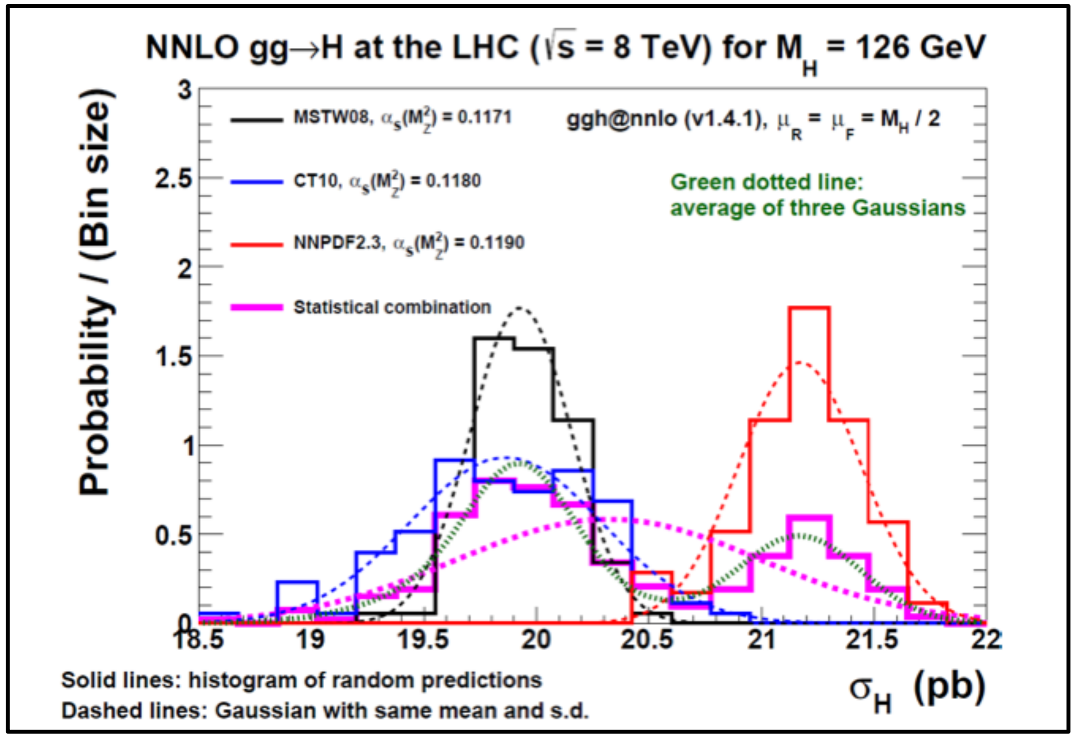

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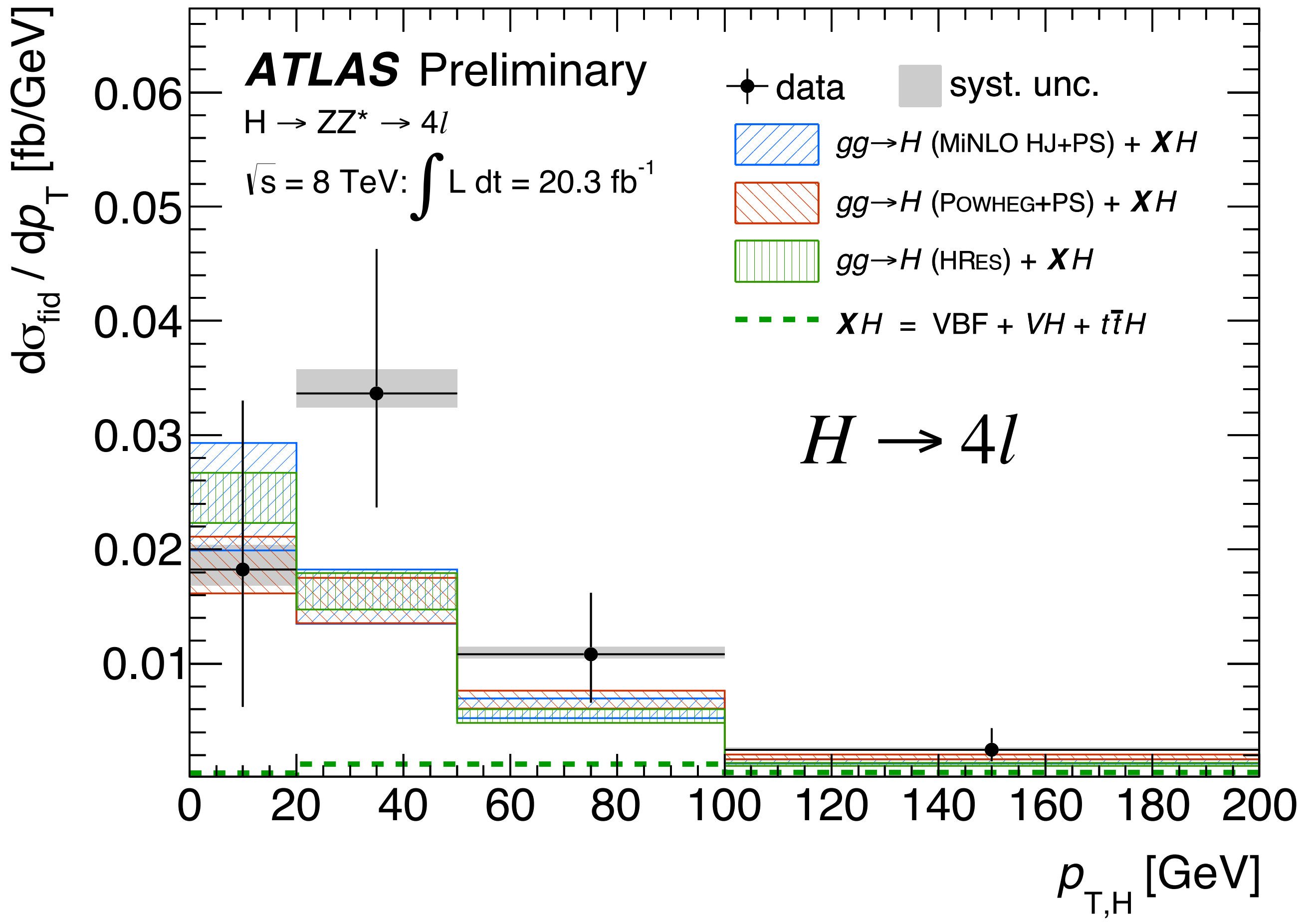
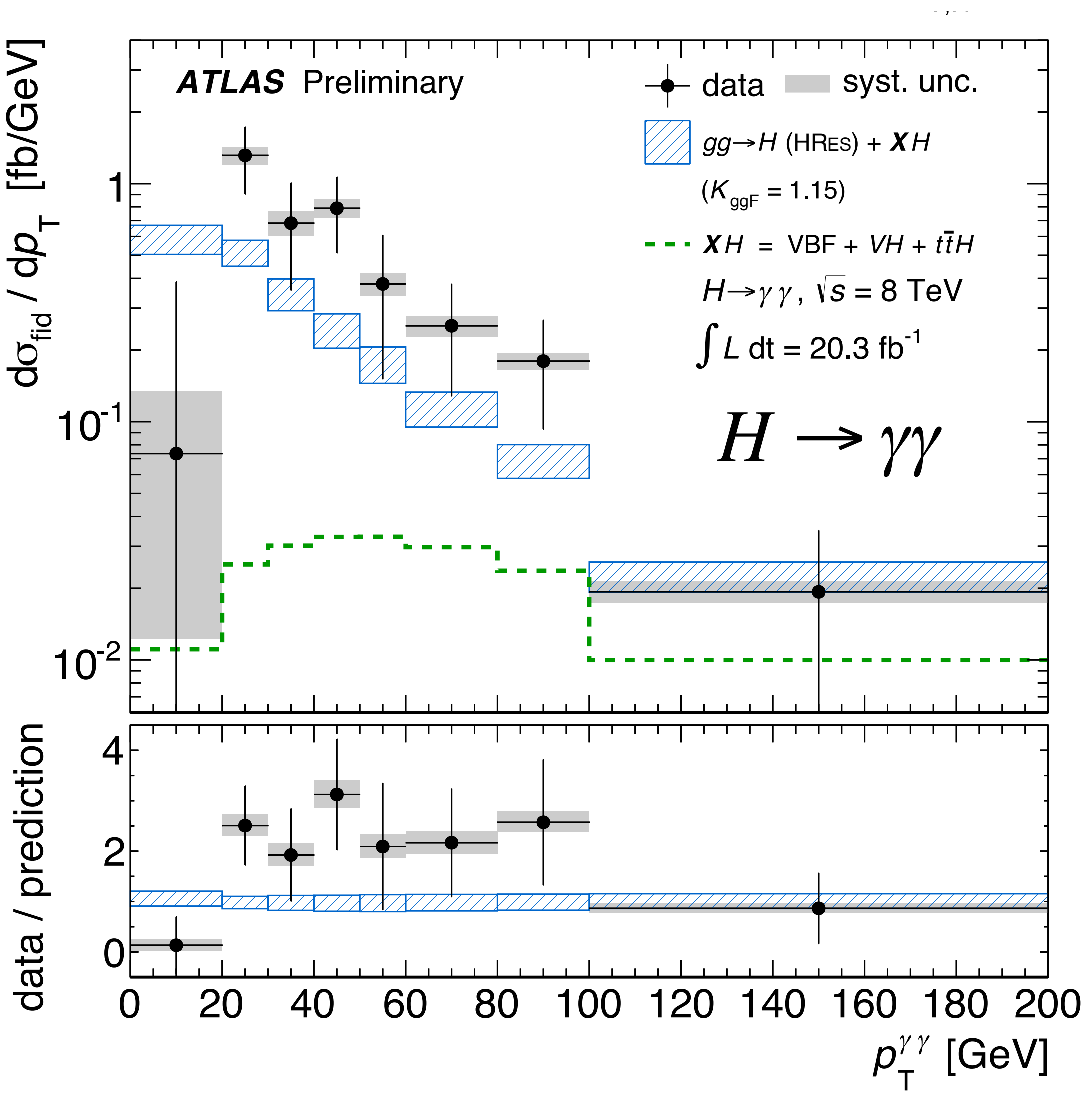
- Precise LHC data needed for validation & improvement

Jets might no be enough? (NNLO on the way)
Transverse momentum of V (qg) (NNLO needed)
Find the origin of differences between sets!!!

will take some time...

More exclusive





- Transverse momentum distributions

- Jet vetoes

Still large Experimental uncertainties → Run 2

NEW

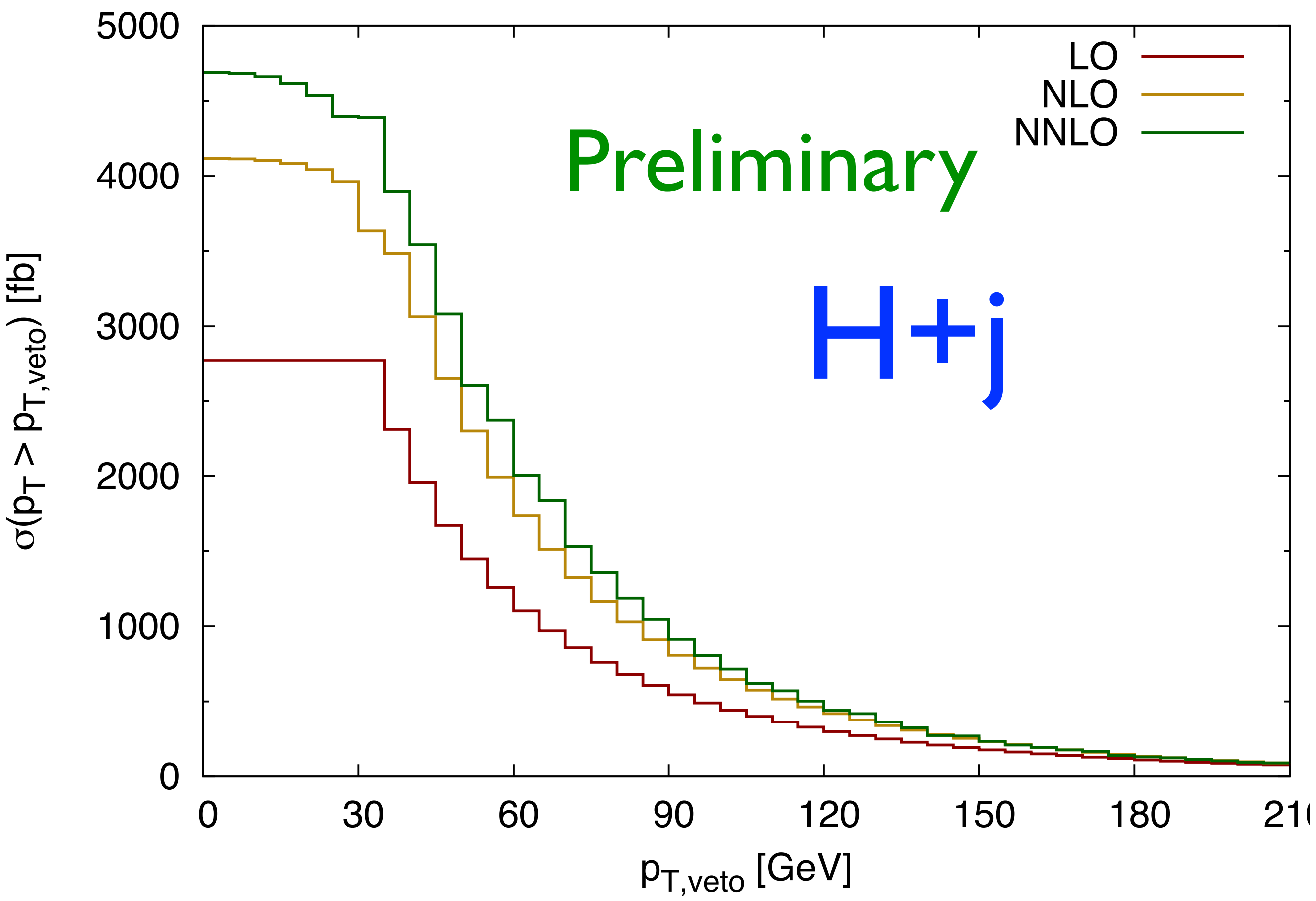
$pp \to H + \text{jet}$

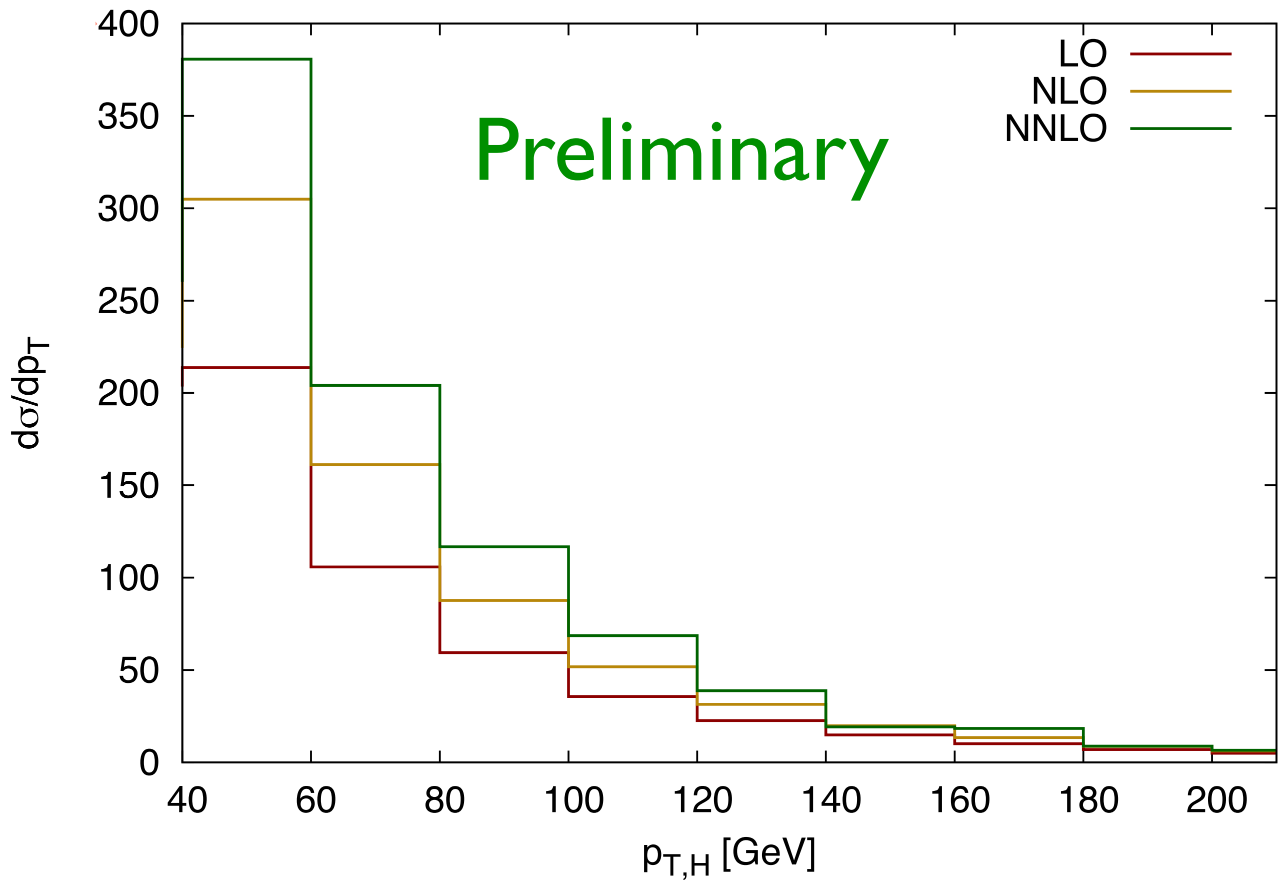
R.Boughezal, F.Caola, K.Melnikov, F.Petriello, M.Schulze (2013)

- NOW: gg and qg channels (>98% of total result)
- Full NNLO with exclusive distributions
- Preliminary results F.Caola (LoopFest 2014)

+60% NLO
+30-40% NNLO

scale dep. ~4%





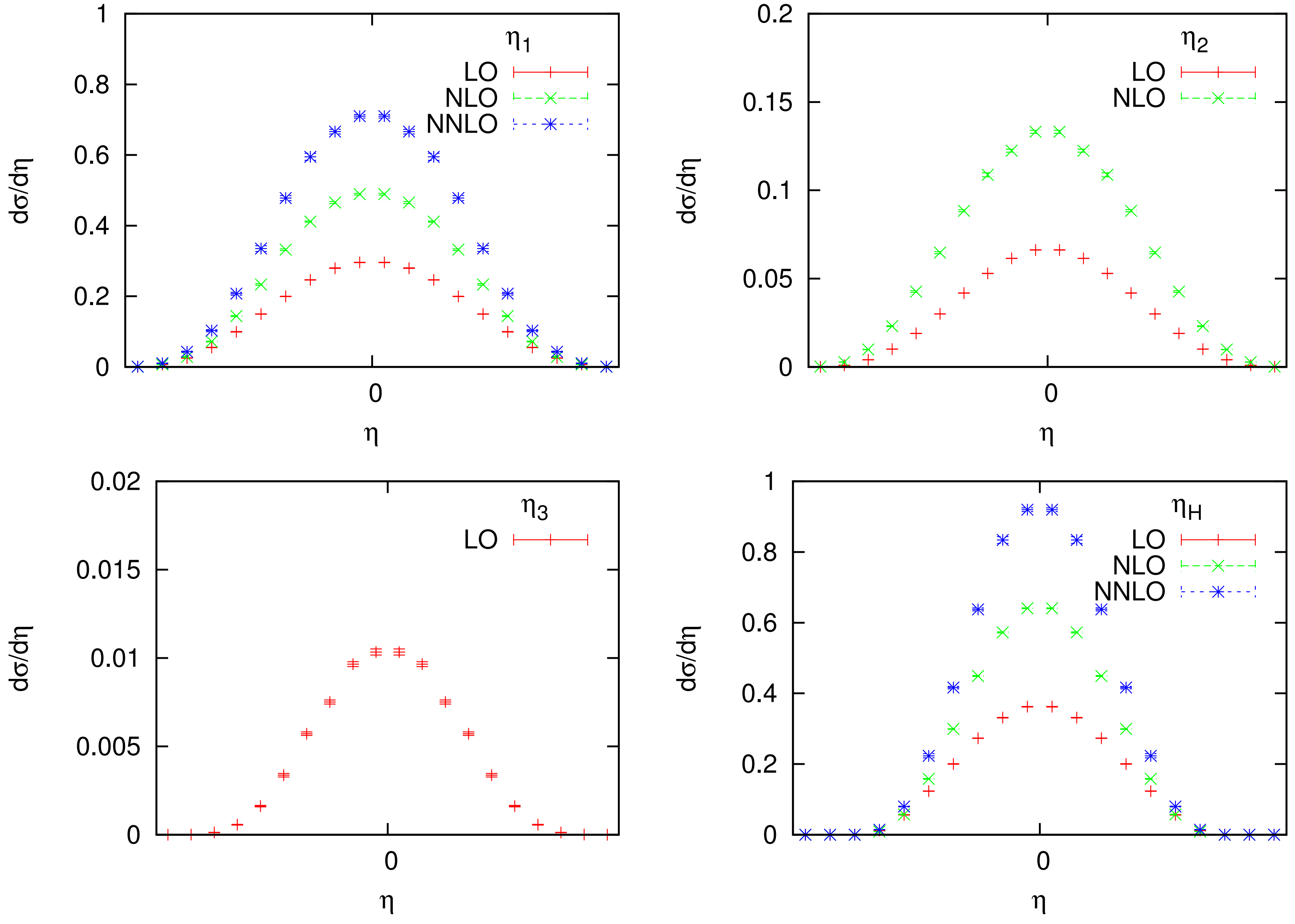
NEW

$pp \to H + \text{jet}$

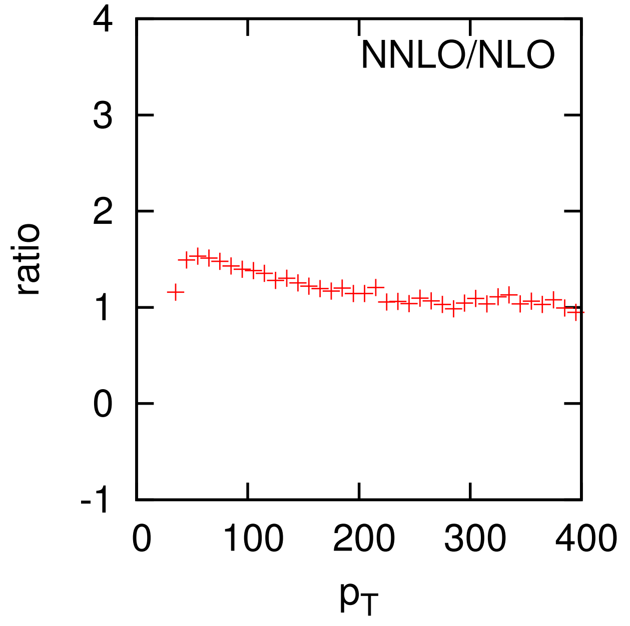
X. Chen, T. Gehrmann, M. Jaquier, N. Glover

- gg channel : agrees with previous calculation (2 NNLO calculations!)
- Differential : Rapidity and transverse momentum

M. Jaquier (LoopFest 2014)



K-factor



Merging NLO with Parton Showers

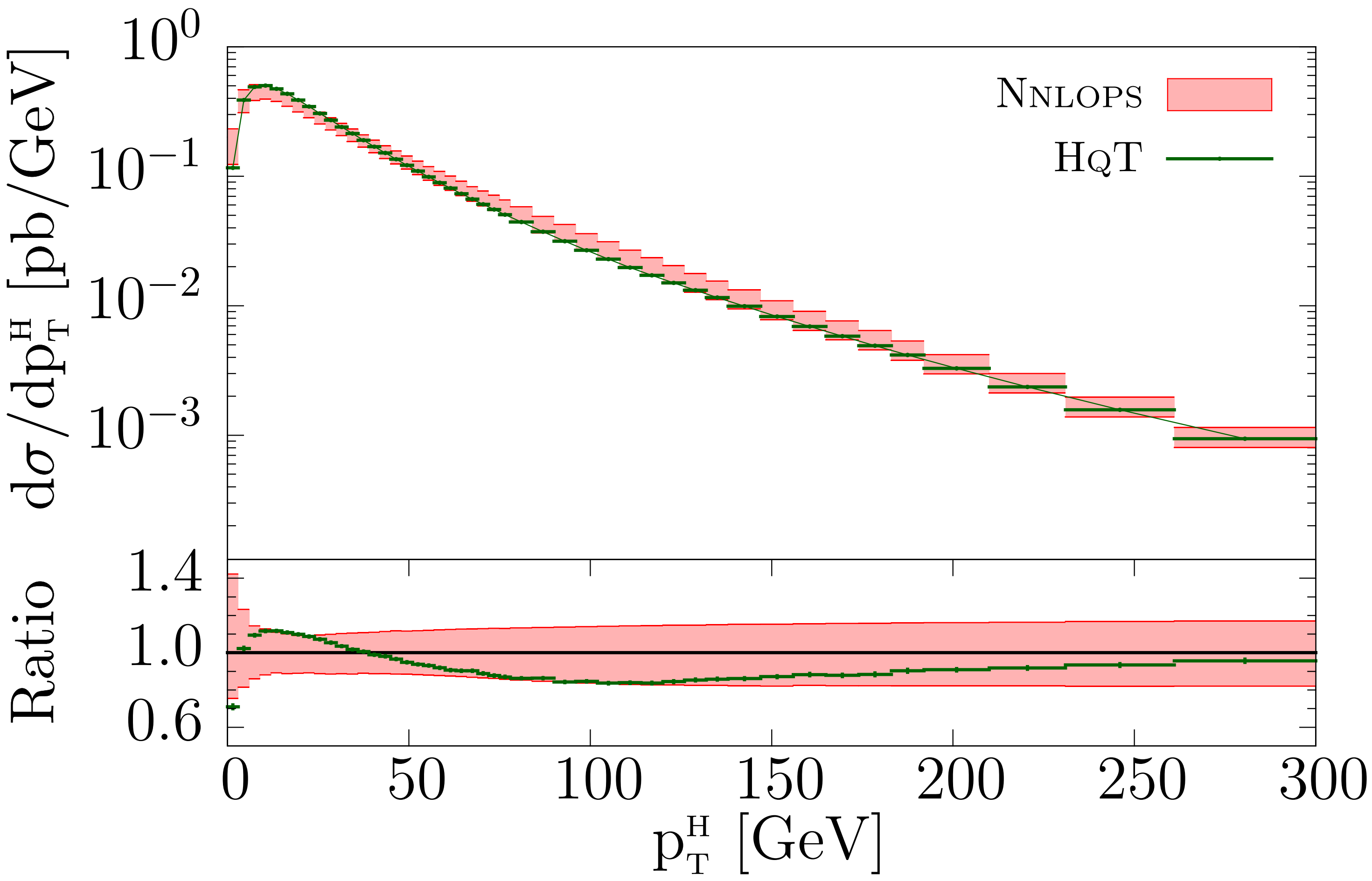
- Resummation to NLL accuracy + realistic final states
- Carry (N)NLO precision to all aspects of experimental analysis

talk by S. Frixione

NEW

- NNLOPS (Higgs)

Hamilton, Nason, Re, Zanderighi



•POWHEG+MINLO

•H+jet at NLO (+PS)

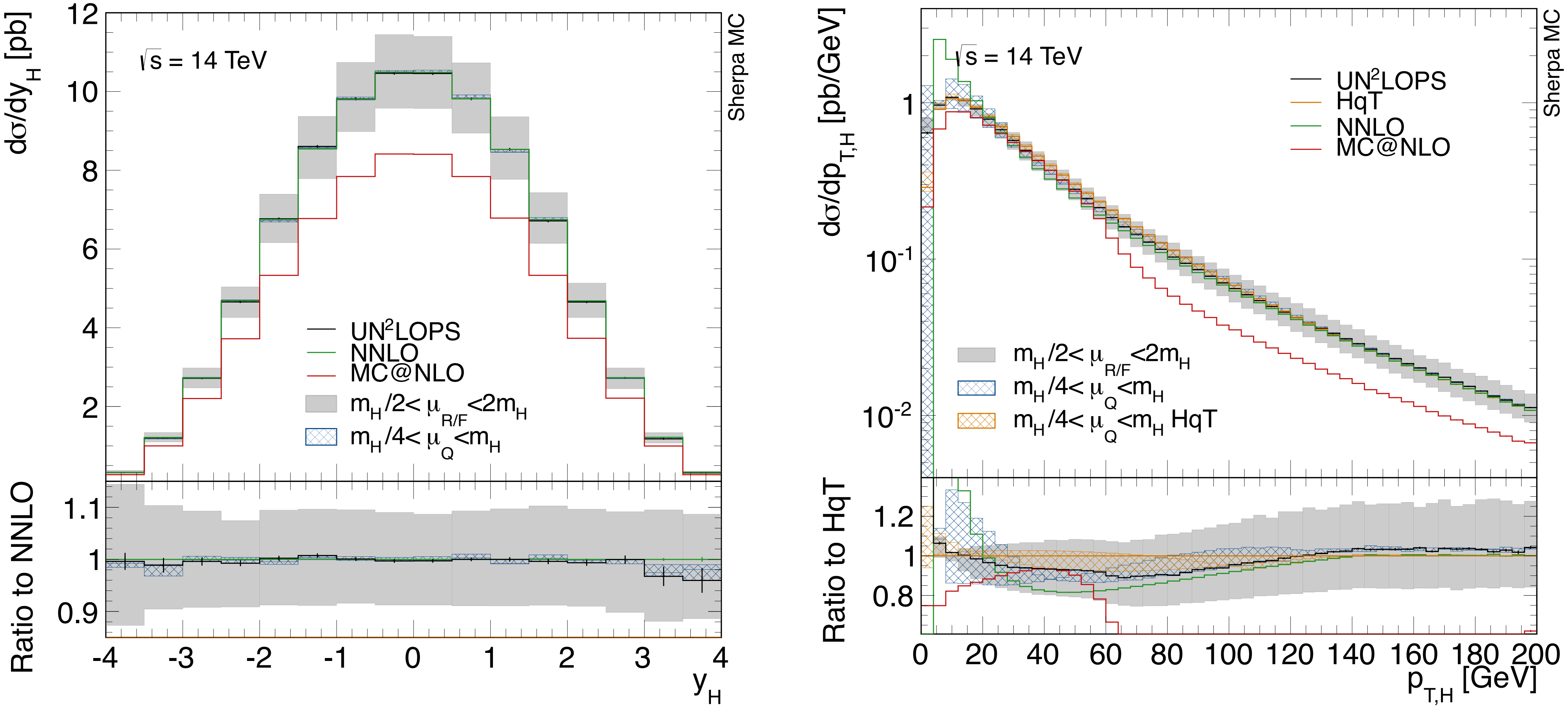
•Inclusive reweigthed to NNLO

•Can not reach NNLL but good overall agreement with HqT

NEW ▸ UN^{2}LOPS (Higgs)

Höche, Li, Prestel (2014)

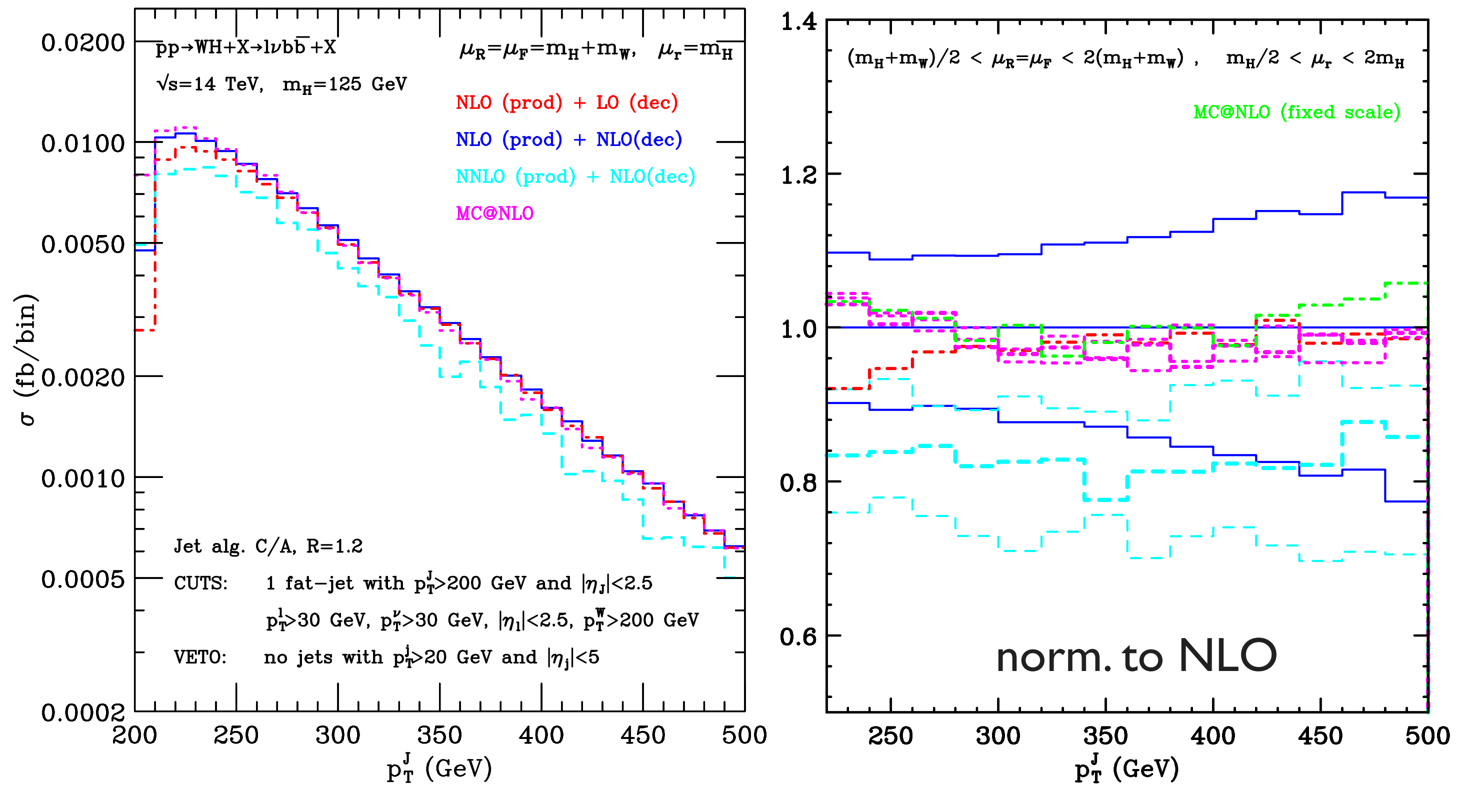
- UN^{2}LOPS method to match H+0 jet and H+1 jet at NLO+PS
- Implement NNLO with q_T subtraction in SHERPA



- Excellent agreement with HNNLO
- Very good agreement with HqT (still not NNLL)

VH production

- Fully differential NNLO calculation for VH including NLO $H \to bb$ and $V \to ll$ decays with spin correlations



LHC14 fat-jet analysis

HVNNLO

Ferrera, Grazzini, Tramontano (2013,2014)
WH ZH

- NLO decay effects relevant but well accounted by MC
- NNLO corrections at 14 TeV sizable (~16% due to jet veto) beyond MC@NLO uncertainties

σ (fb)	NLO (with LO dec.)	NLO (full)	NNLO (with NLO dec.)	MC@NLO
w/o jet veto	$2.54^{+1\%}_{-1\%}$	$2.63^{+1\%}_{-1\%}$	$2.52^{+2\%}_{-2\%}$	$2.82^{+1\%}_{-1\%}$
w jet veto	$1.22^{+11\%}_{-14\%}$	$1.29^{+12\%}_{-13\%}$	$1.07^{+8\%}_{-6\%}$	$1.33^{+1\%}_{-1\%}$

Off-shell effects and interference

signal

background

$$\mathcal{A}_{ij\to X} = \mathcal{A}_{ij\to H} \, \Delta_{\mathrm{H}} \, \mathcal{A}_{H\to X} + \mathcal{A}_{continuum}$$

Propagator

$$\Delta^2_H(q^2) \sim \frac{1}{(q^2 - M_H^2)^2 + \Gamma_H^2 M_H^2} \sim \frac{\pi}{M_H \Gamma_H} \delta(q^2 - M_H^2) + \mathcal{O}\left(\frac{\Gamma_H}{M_H}\right)$$

ZWA

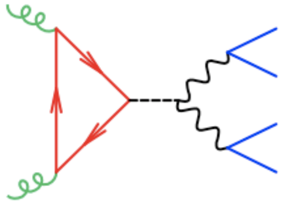
Off-shell effects and interference

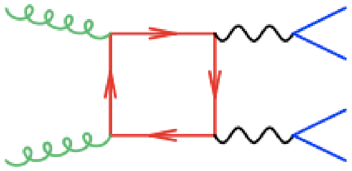
signal

background

$$\mathcal{A}_{ij\to X} = \mathcal{A}_{ij\to H}\ \Delta_{\rm H}\ \mathcal{A}_{H\to X} + \mathcal{A}_{continuum}$$

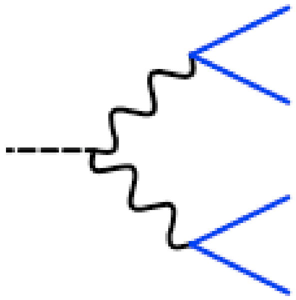
Propagator





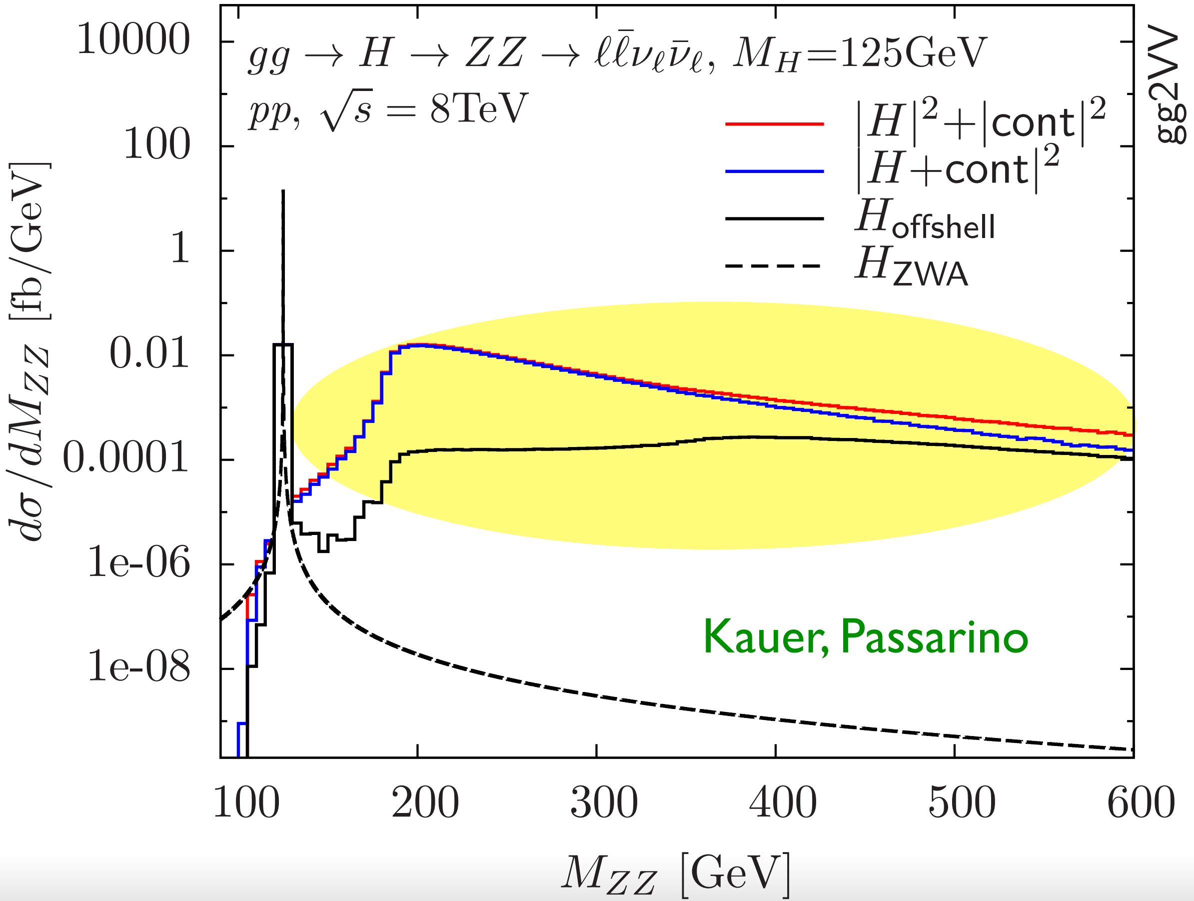
$$\Delta_H^2(q^2) \sim \frac{1}{(q^2-M_H^2)^2+\Gamma_H^2 M_H^2} \sim \frac{\pi}{M_H\Gamma_H}\delta(q^2-M_H^2)+\mathcal{O}\left(\frac{\Gamma_H}{M_H}\right)$$ ZWA

But above threshold decay amplitude compensates $1/(q^2)^2$



$$|\mathcal{A}_{H\to VV}|^2 \sim (q^2)^2$$

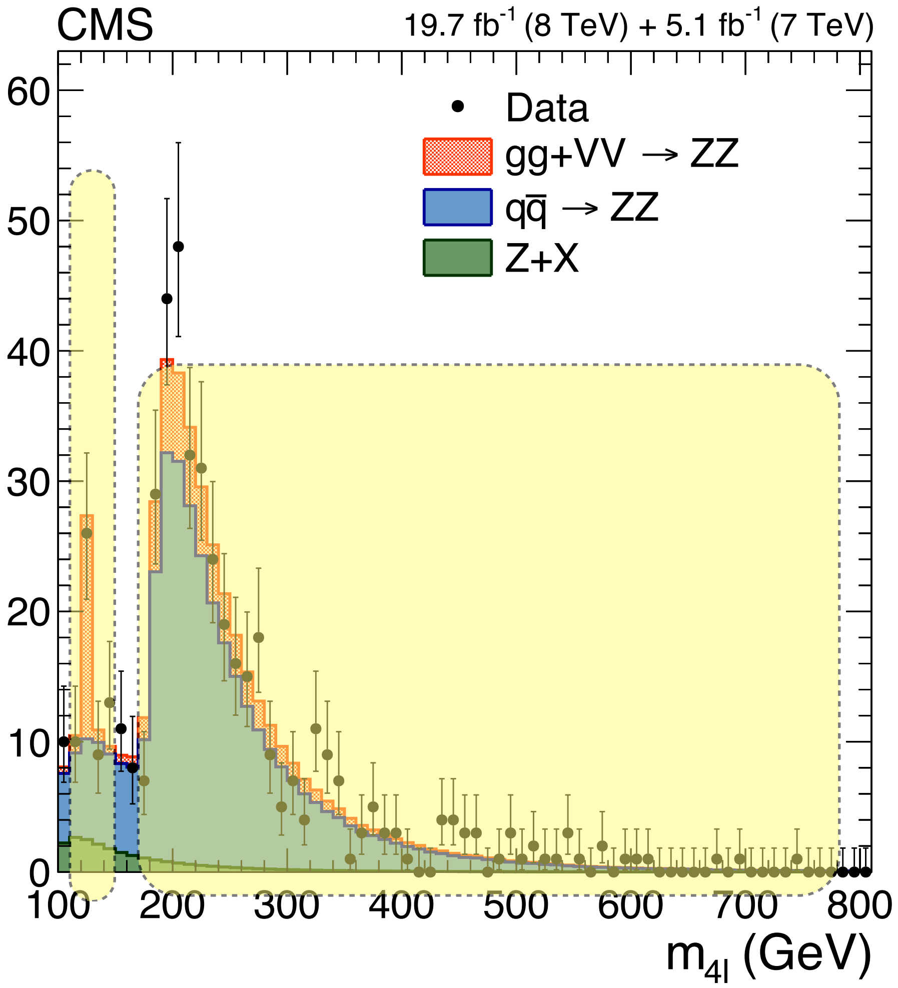
- Sizable contribution from off-shell
- Enhances effect of interference



Kauer, Passarino

Width measurement from off-shell

Caola, Melnikov



$$\sigma^{\text{on}} \quad \int_{M_H^2-\Delta^2}^{M_H^2-\Delta^2} dq^2 \frac{|A_{gg\to H\to VV}|^2}{(q^2-M_H^2)+\Gamma_H^2 M_H^2} \sim \frac{g_{ggH}^2(M_H^2)\, g_{HVV}^2(M_H^2)}{\Gamma_H}$$

$$g = \xi\, g^{SM}$$
$$\Gamma_H = \xi^4\, \Gamma_H^{SM}$$

$$\sigma^{\text{off}} \int_{q^2 \gg M_H^2} dq^2 \frac{|A_{gg\to H\to VV}|^2}{(q^2-M_H^2)+\cancel{\Gamma_H^2} M_H^2} \sim \int dq^2 g_{ggH}^2(q^2)\, g_{HVV}^2(q^2)$$

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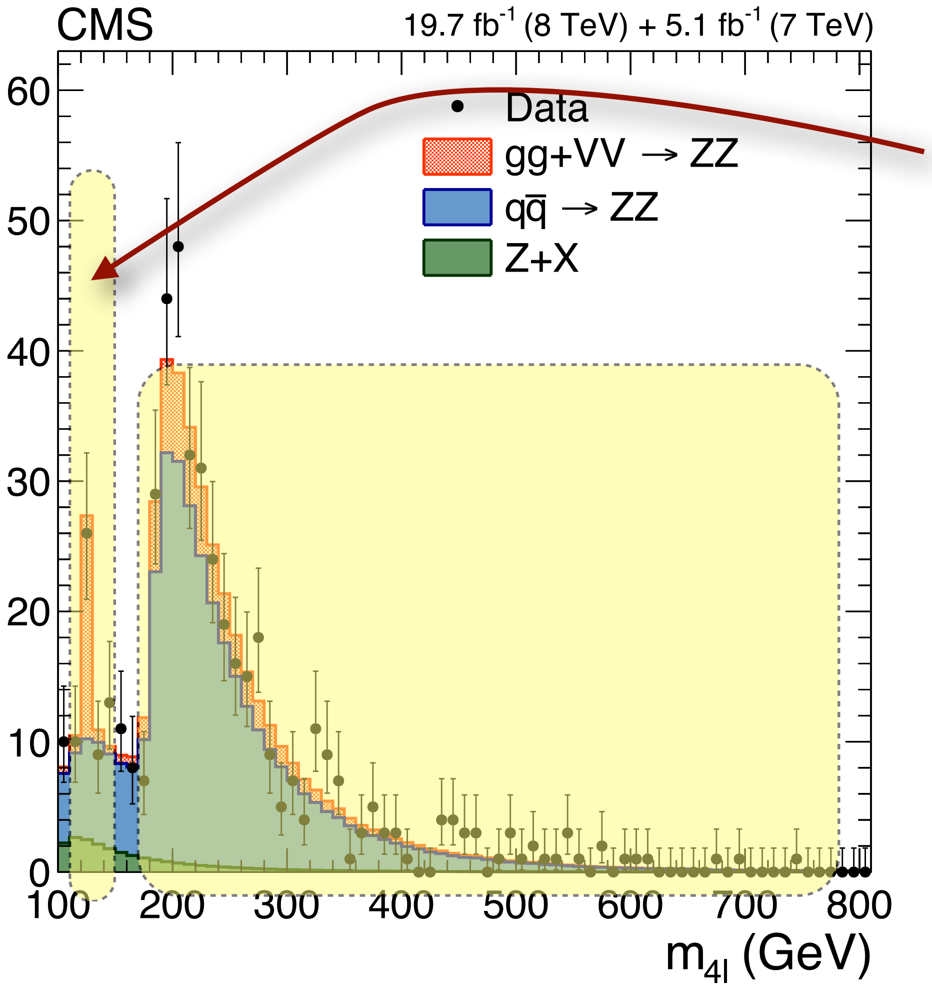

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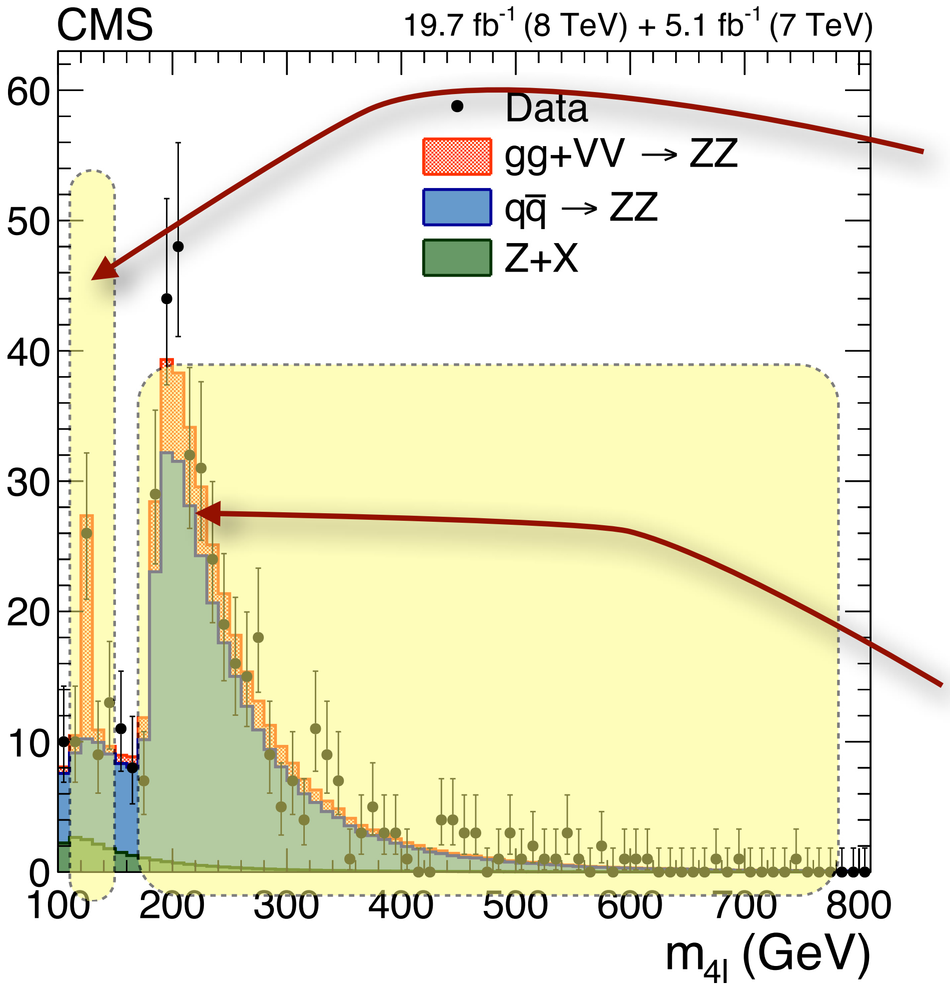

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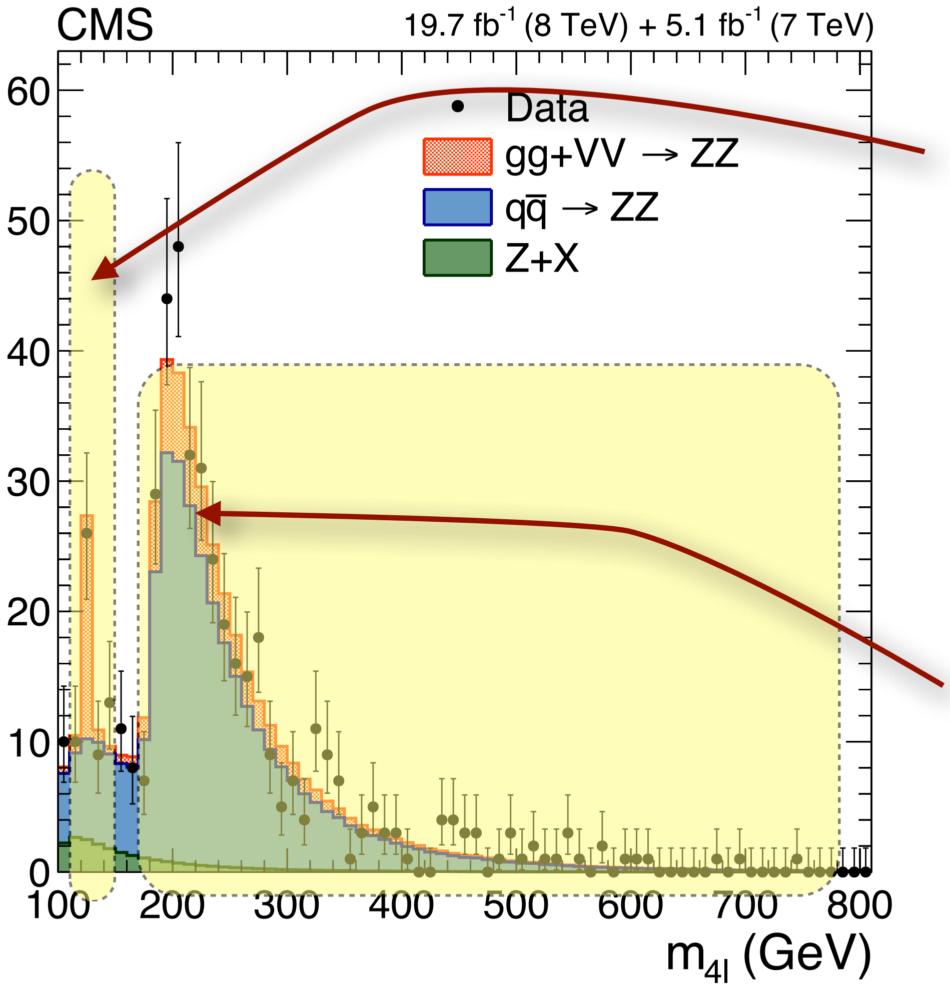

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SM assumptions on couplings (running)

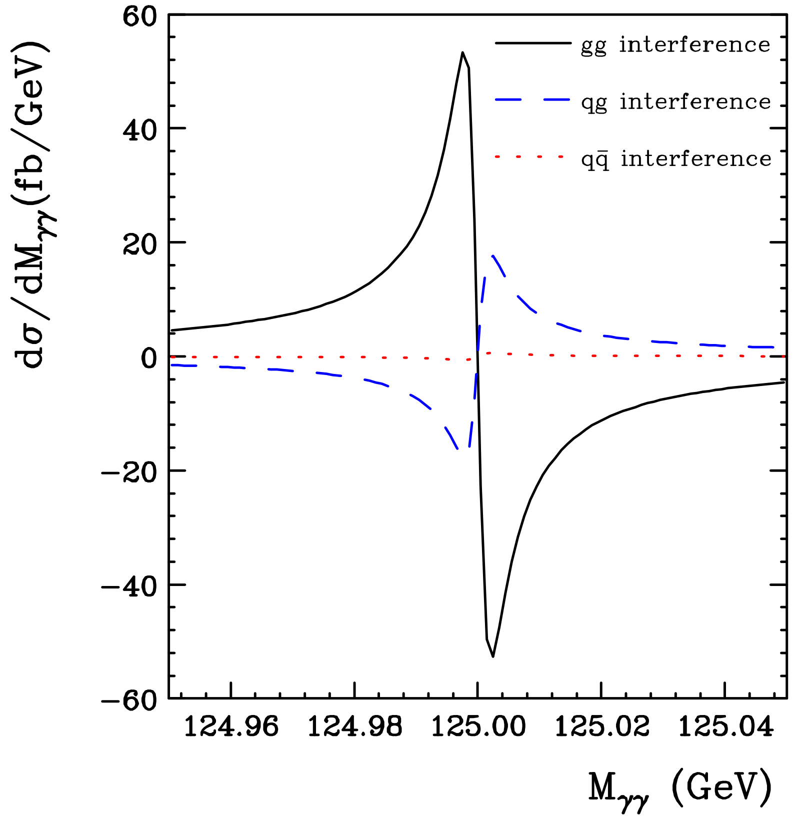
$$\sigma^{\text{exp}} = \sigma^{\text{back}} + \sigma^{\text{on}} + \sigma^{\text{off}} \times \frac{\Gamma_H}{\Gamma_H^{SM}} + \sigma^{\text{int}} \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

CMS $\Gamma_H < 22\,\text{MeV}$ (5.4 SM)

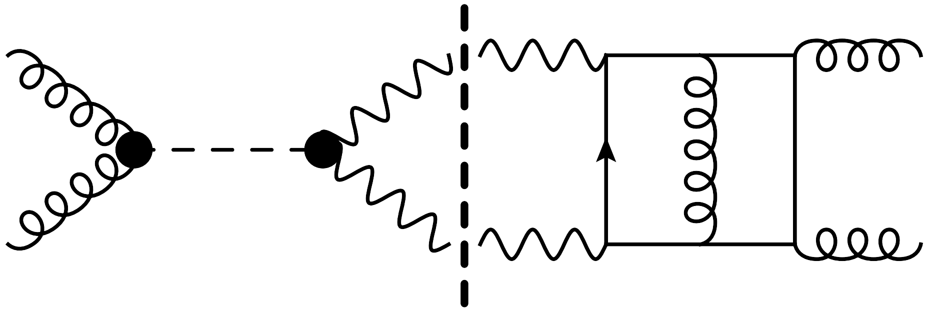
ATLAS $\Gamma_H < 24\,\text{MeV}$ (5.7 SM)

Width measurement from interference

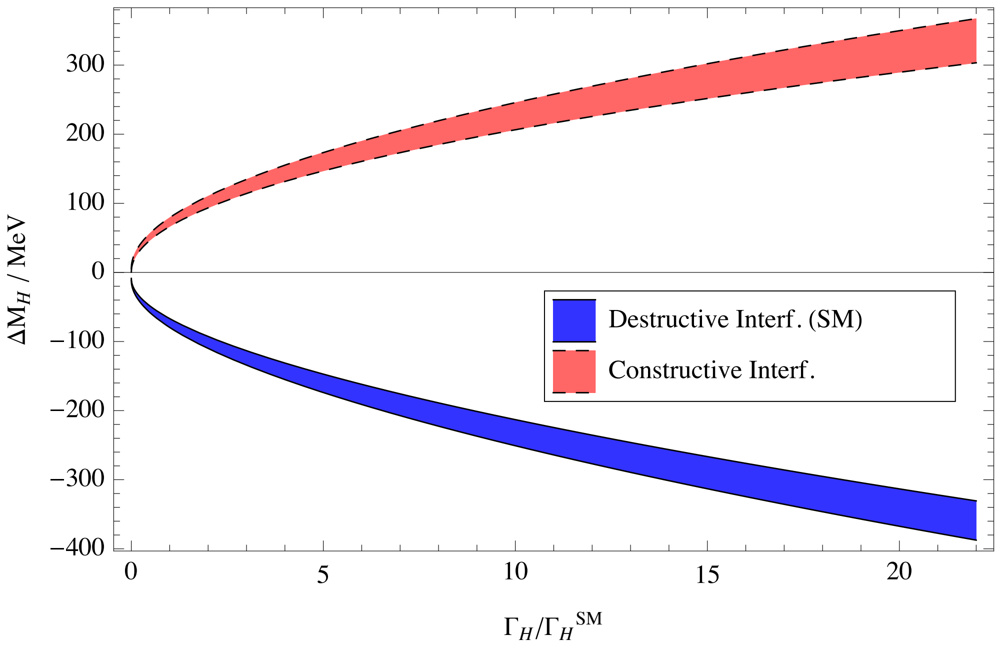
In diphoton channel, interference small for total cross section but asymmetry produces shift in invariant mass : enhanced by detector resolution



Dicus, Willenbrock (1986)
Dixon, Siu (2003)
Martin (2012,2013)
deF et al (2013)
Dixon, Li (2013)



Known to $\mathcal{O}(\alpha_s^3)$



Look at $\Delta M_{\mathrm{H}} = M_{\mathrm{H}}^{\gamma\gamma} - M_{\mathrm{H}}^{\mathrm{ZZ}}$

$\Delta M_{\mathrm{H}} \sim 1\,\mathrm{GeV}$ implies $\Gamma_H \sim 200\,\Gamma_H^{\mathrm{SM}}$

$$\Delta M_{\mathrm{H}} = \begin{cases} -0.90 \pm 0.75\,\mathrm{GeV}\ \ (\mathrm{CMS}) \\ +1.47 \pm 0.72\ \mathrm{GeV}\ \ (\mathrm{ATLAS}) \end{cases}$$

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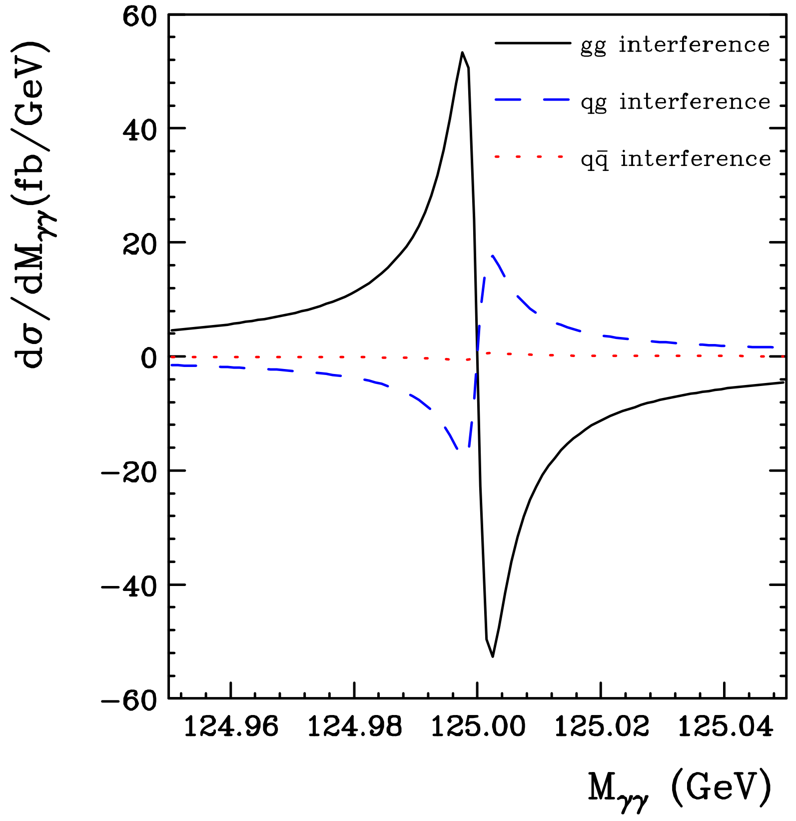
In diphoton channel, interference small for total cross section but asymmetry produces shift in invariant mass : enhanced by detector resolution



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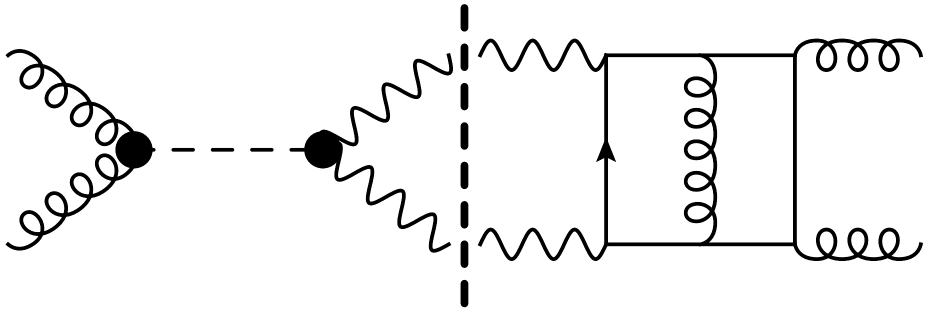

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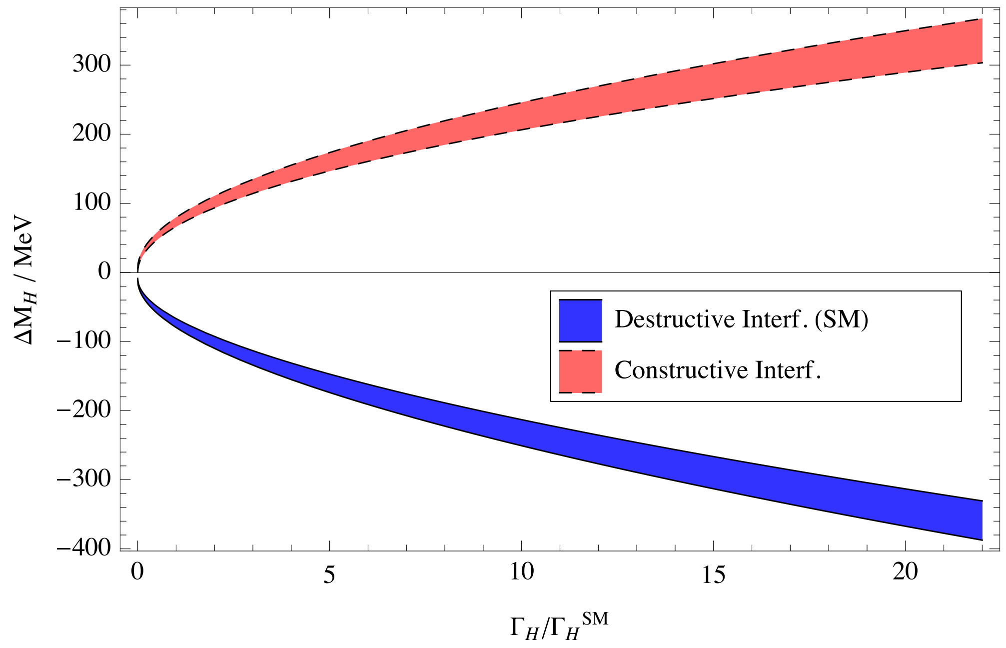

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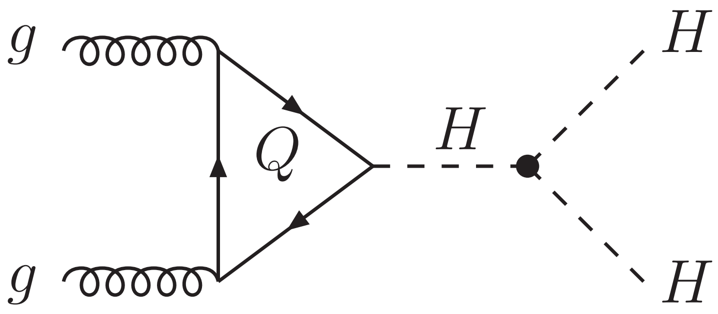
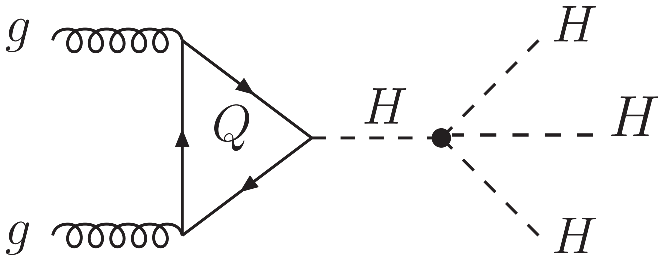
$$\Delta M_{\rm H} = \begin{cases} -0.90 \pm 0.75\,{\rm GeV}\ \ ({\rm CMS}) \\ +1.47 \pm 0.72\ {\rm GeV}\ \ ({\rm ATLAS}) \end{cases}$$

QCD corrections needed for Interference in general talk by K. Ellis

Higgs self couplings: Fundamental to test Higgs potential

$$V = \frac{\lambda}{4}\left(2vH + H^2\right)^2 = \frac{1}{2}(2\lambda v^2)H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$





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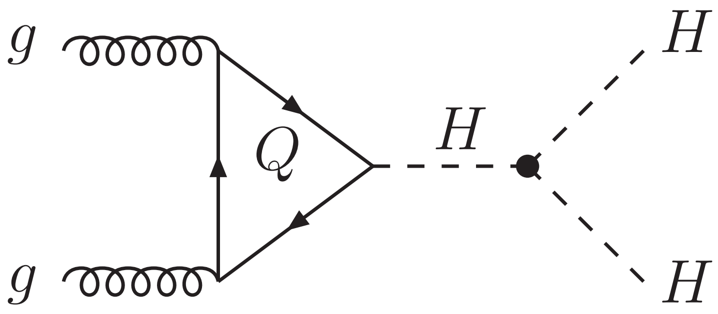
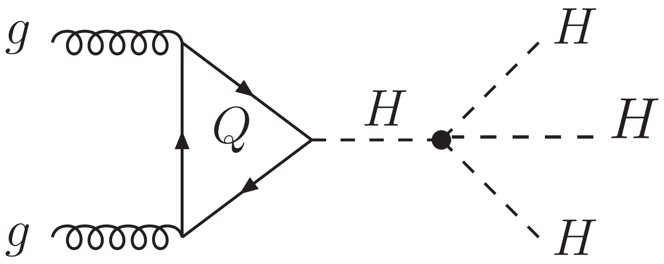


~ 40 fb very challenging



~ 0.05 fb impossible

@ 14 TeV

Compared to ~50 pb for single Higgs production

Higgs self couplings: Fundamental to test Higgs potential

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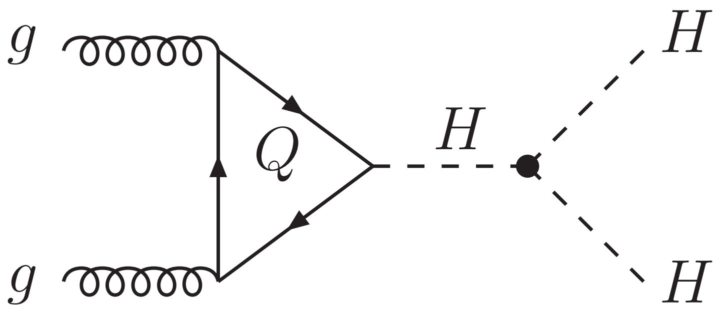

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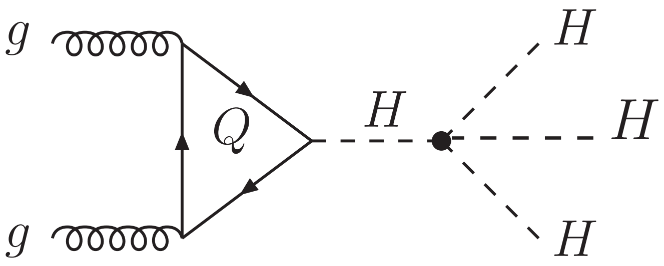


~ 0.05 fb impossible

Compared to ~50 pb for single Higgs production

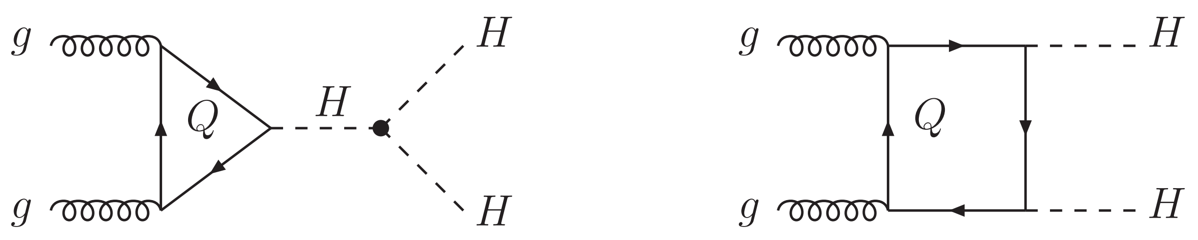
- Several recent phenomenological studies
  - In general need very large luminosities 600-3000 fb^{-1}

Baur, Plehn, Rainwater (2003)
Dolan, Englert, Spannowsky (2012)
Baglio et al (2012)
Papaefstathiou, Yang, Zurita (2012)

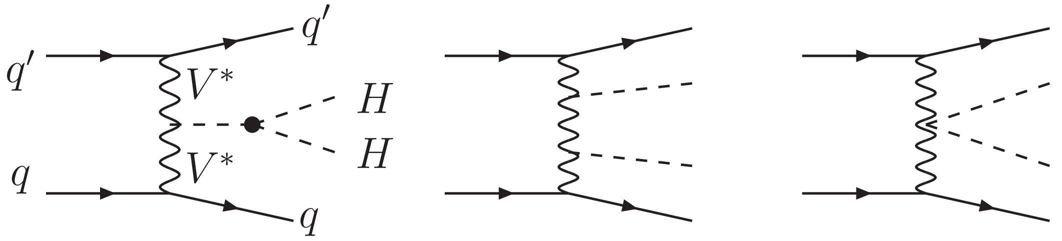
20%-30% uncertainty in triple Higgs coupling ?

HH production channels

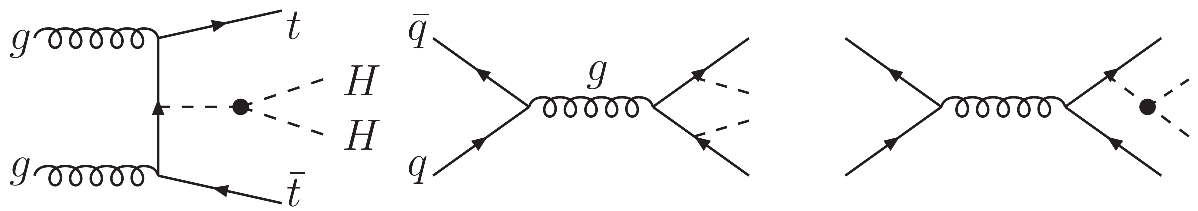
gg fusion



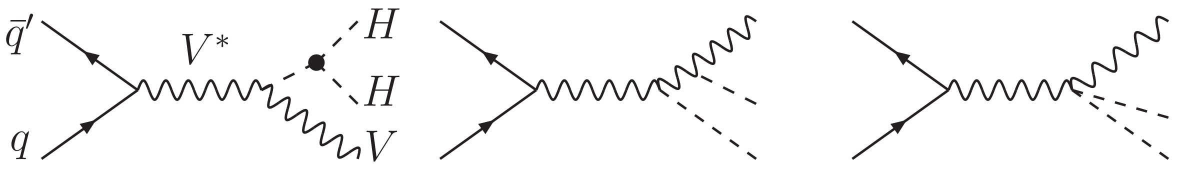
VV fusion

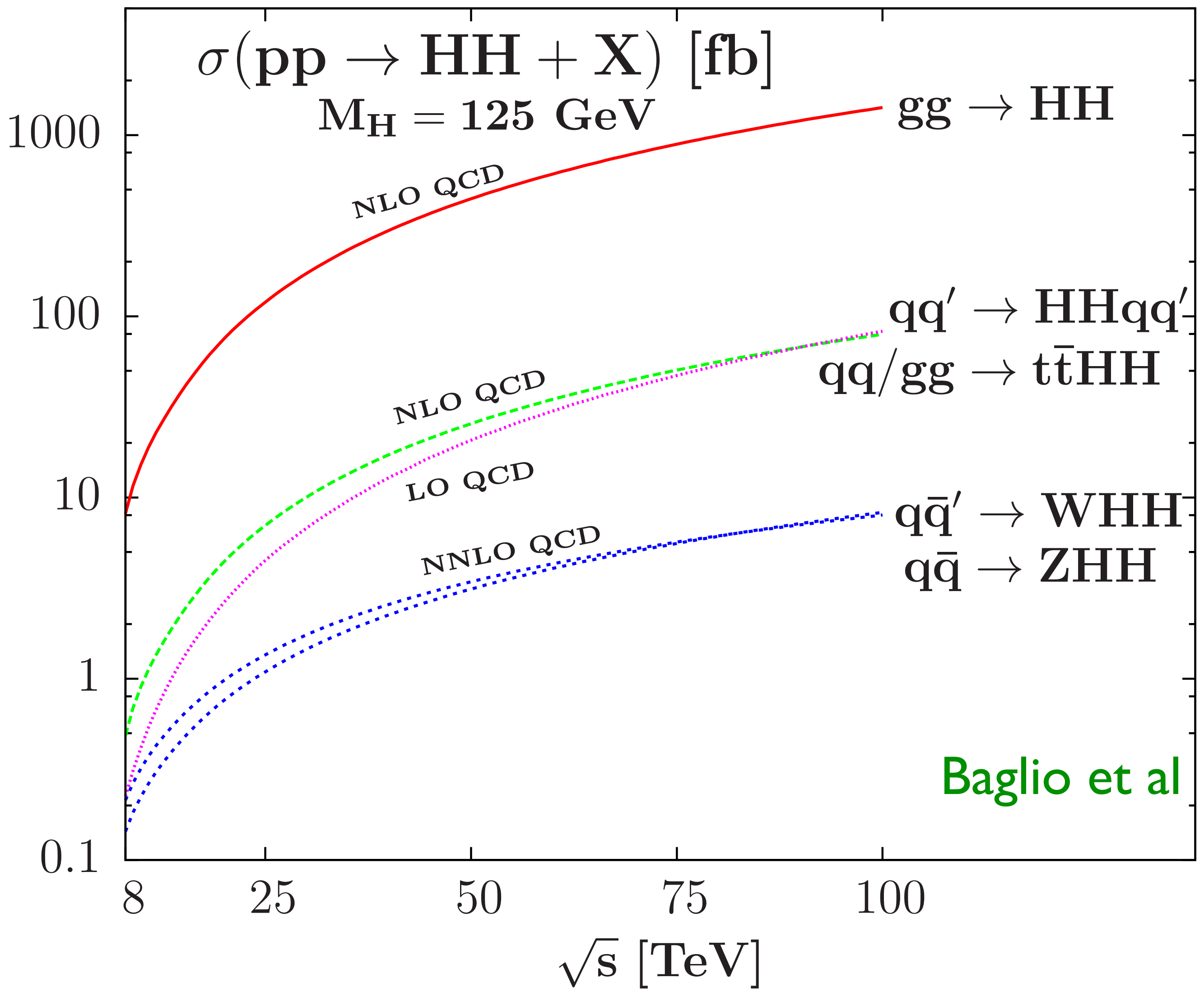


Associated production with top



Higgs-strahlung



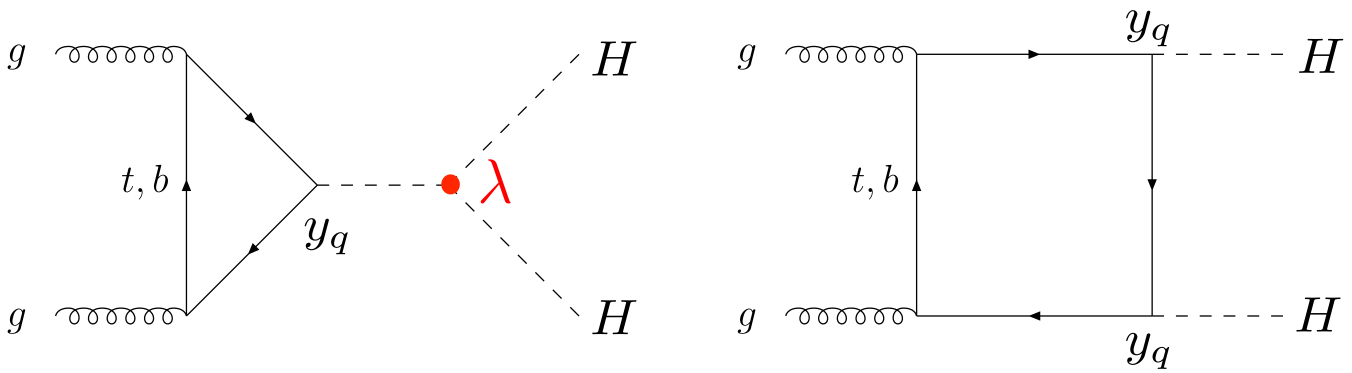


Gluon-gluon fusion dominates

Only some contribute with HHH

HH production in gg fusion

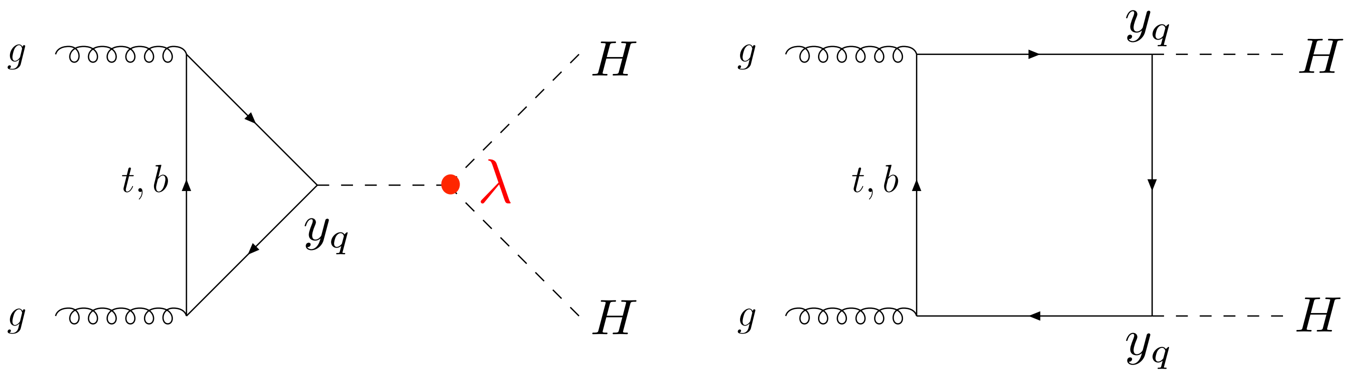
LO : Triangle and Box contributions



Very difficult to reach higher orders ⇨ Use effective Lagrangian

HH production in gg fusion

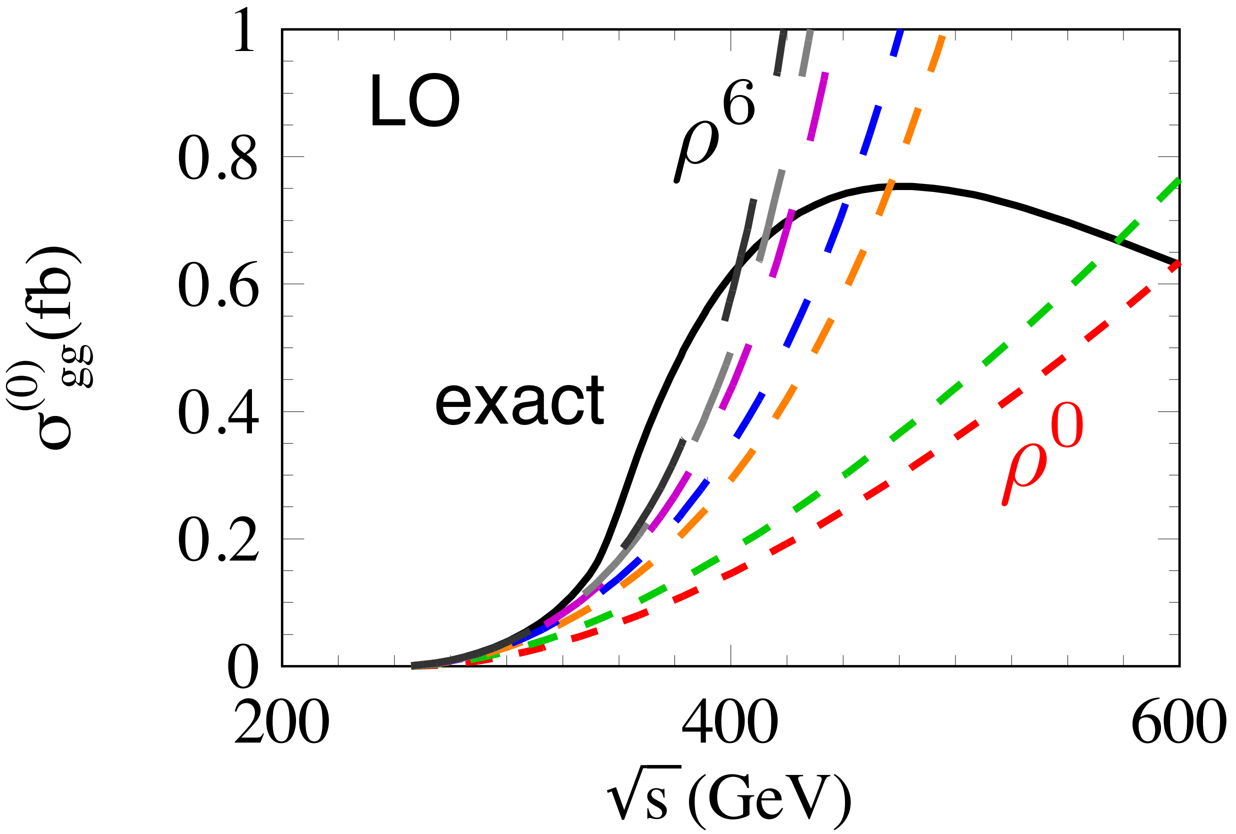
LO : Triangle and Box contributions



Very difficult to reach higher orders → Use effective Lagrangian

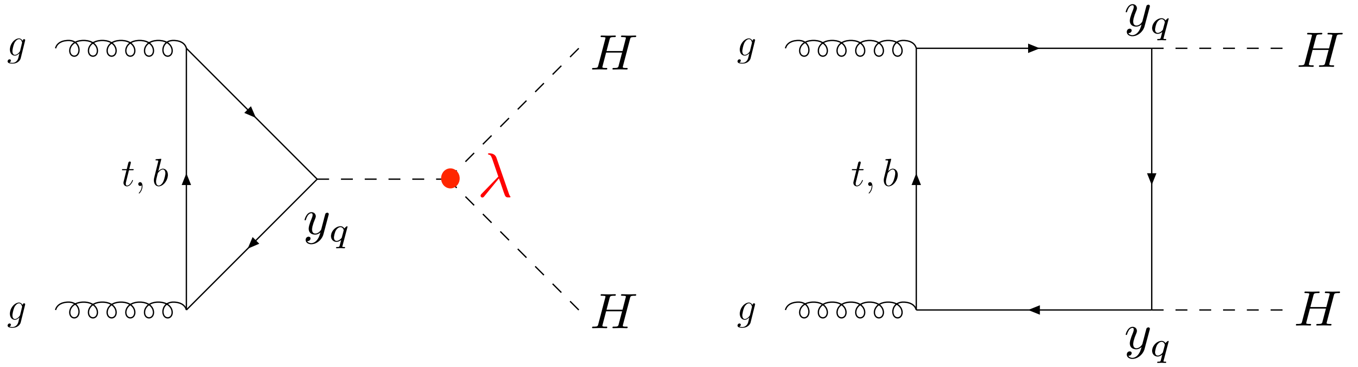
Pretty bad approximation at LO

expansion in $\rho = \frac{m_H^2}{m_t^2}$ Grigo, Hoff, Melnikov, Steinhauser (2013)



HH production in gg fusion

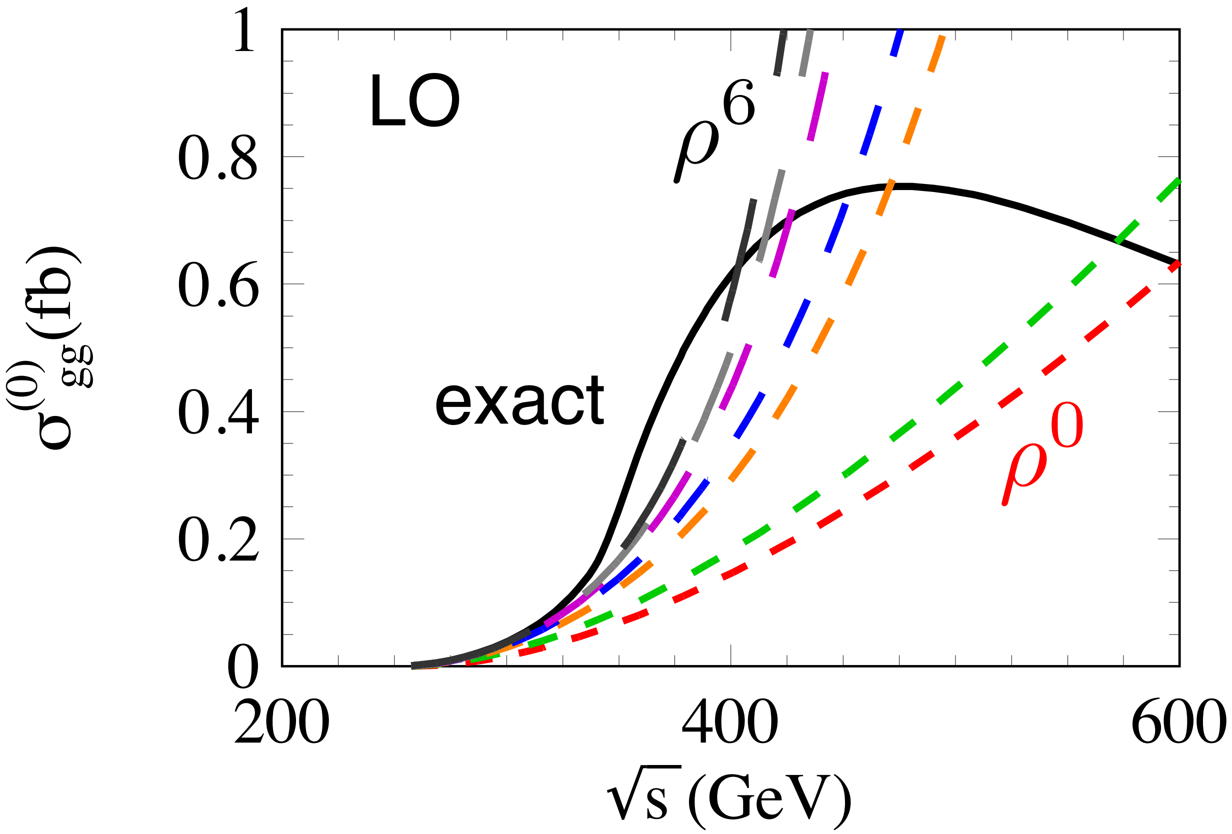
LO : Triangle and Box contributions

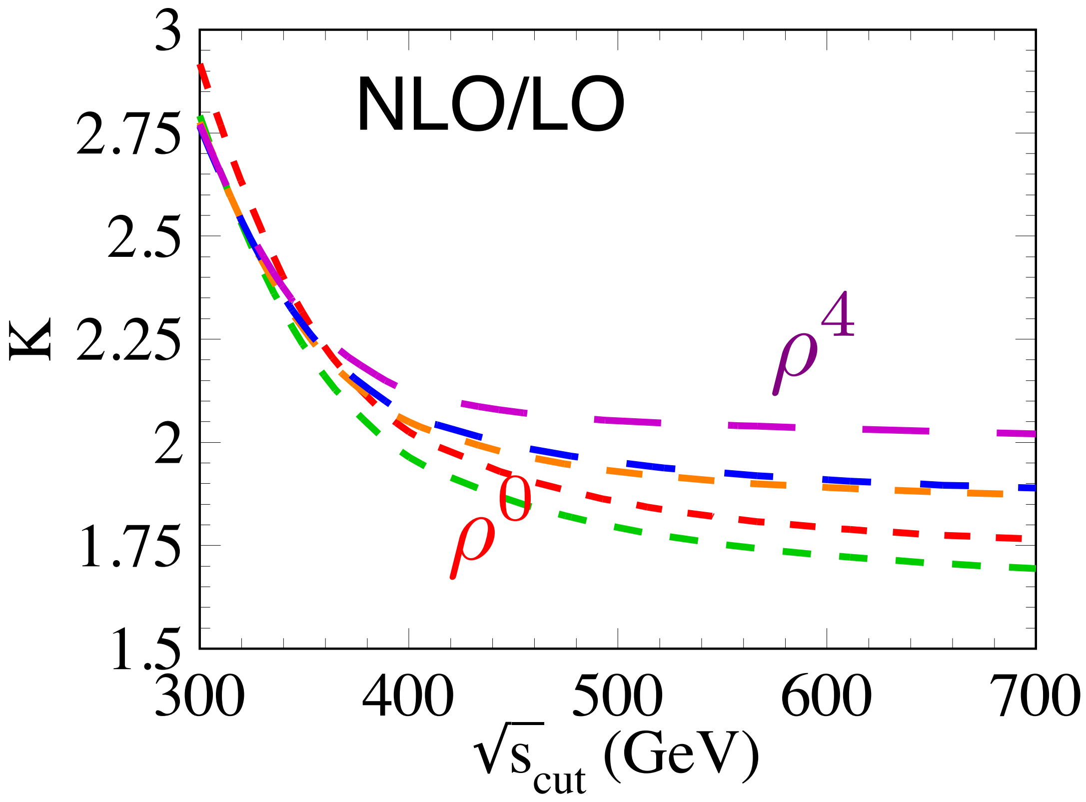


Very difficult to reach higher orders → Use effective Lagrangian

Pretty bad approximation at LO → But OK (~10%) for K-factors!

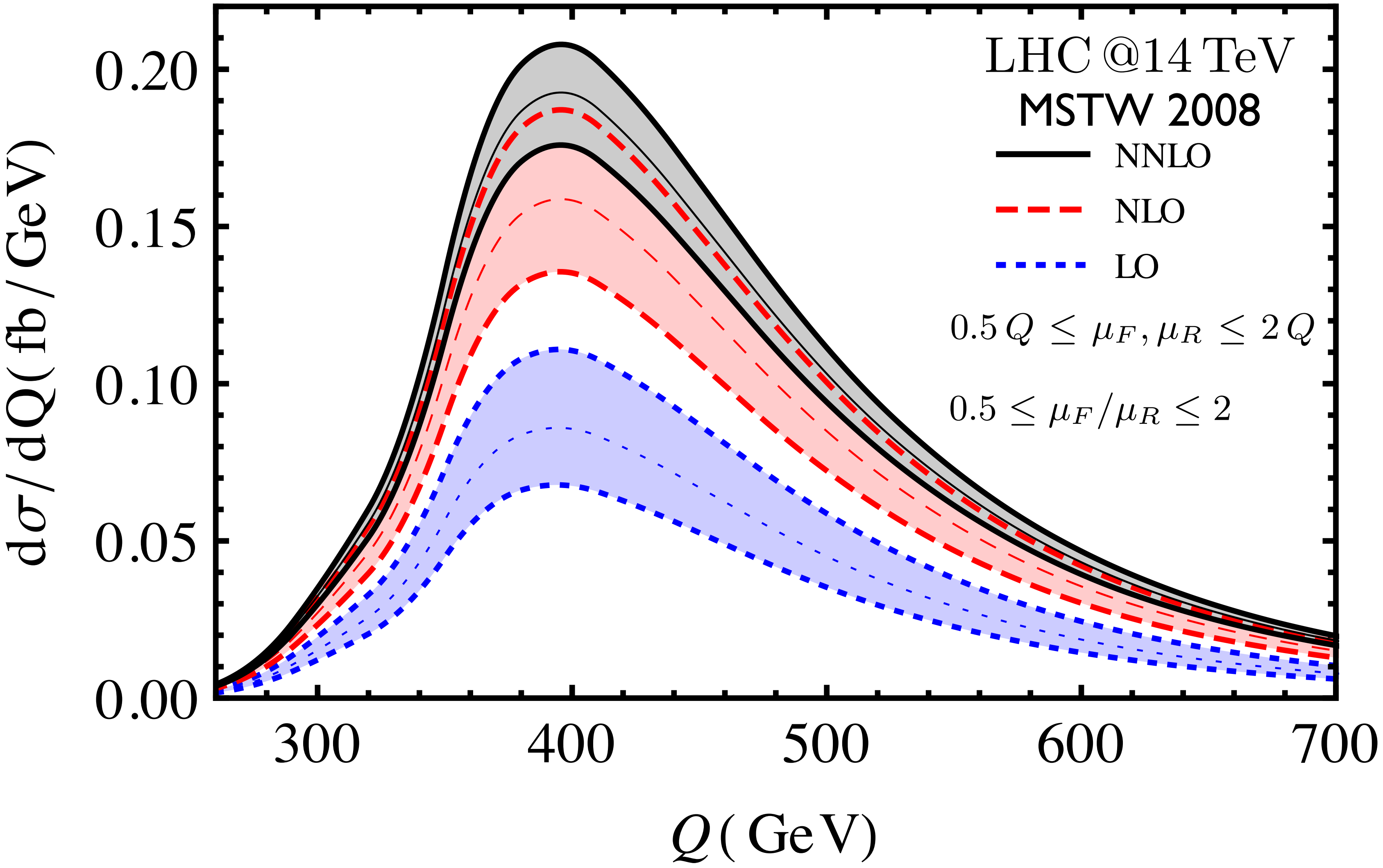
expansion in $\rho = \frac{m_H^2}{m_t^2}$ Grigo, Hoff, Melnikov, Steinhauser (2013)





NEW **NNLO** deF, J. Mazzitelli (2013)

NLO
Dawson, Dittmaier, Spira (1998)



$$M_H = 126\,\text{GeV}$$

K

$$\sigma_{\text{LO}} = 17.8\,^{+5.3}_{-3.8}\,\text{fb}$$

1.86

$$\sigma_{\text{NLO}} = 33.2\,^{+5.9}_{-4.9}\,\text{fb}$$

21%

$$\sigma_{\text{NNLO}} = 40.2\,^{+3.2}_{-3.5}\,\text{fb}$$

2.26

$\pm 8\%$

$\mathcal{O}(\pm 20\%)$ at NLO.

As expected, very similar pattern to single Higgs

- Large QCD corrections
- Scale band: overlap between NLO and NNLO
- Reduction in scale dependence

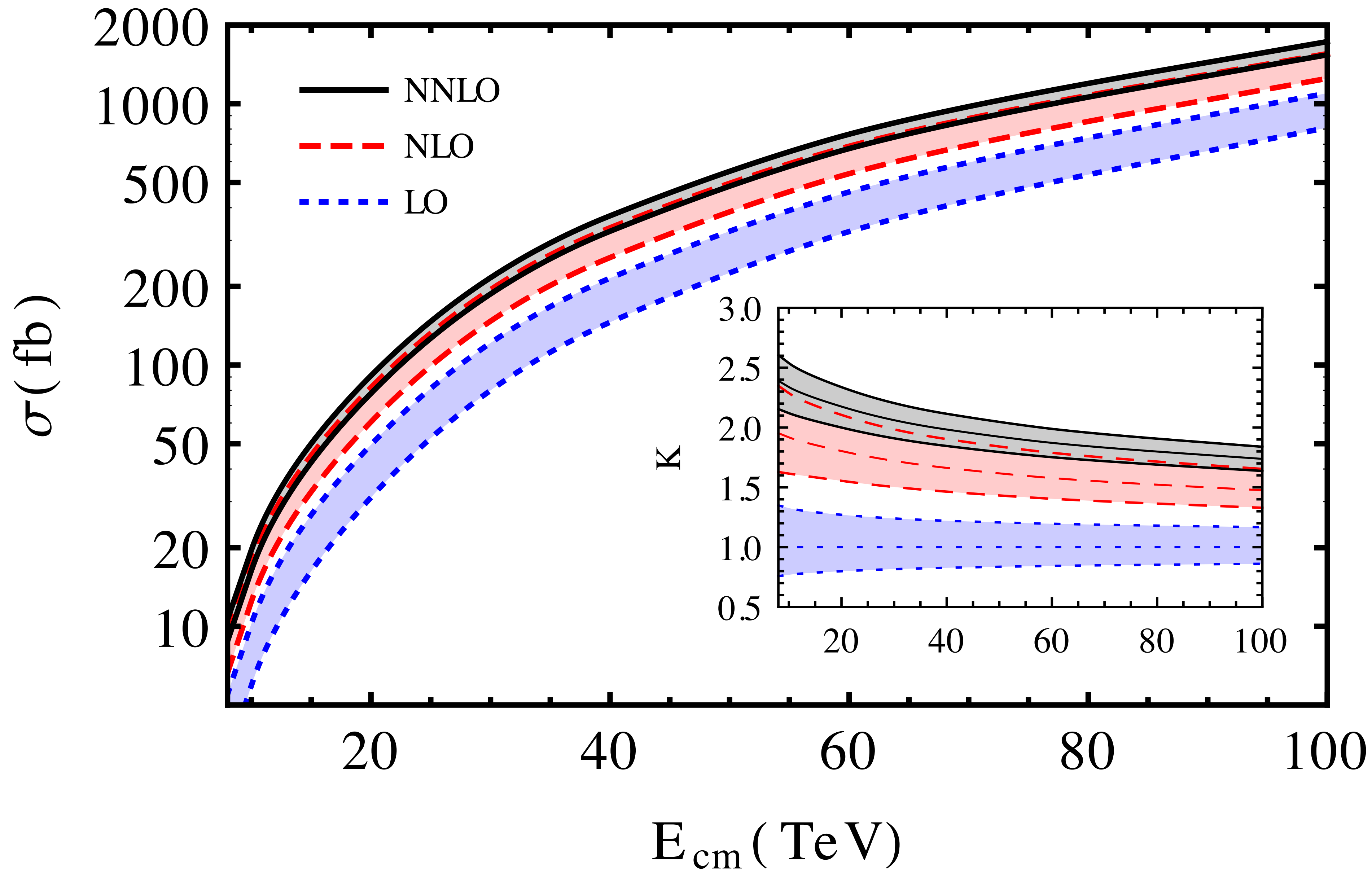
$$C_H^{(2)} = C_{HH}^{(2)}$$

< 2% effect

$$0 \le C_{HH}^{(2)} \le 2C_H^{(2)}$$

Dependence on collider Energy

E_{cm} [TeV]	8	14	33	100
$\sigma_{\rm NNLO}$ [fb]	$9.76^{+0.88}_{-0.96}$	$40.2^{+3.2}_{-3.5}$	243^{+17}_{-18}	1638^{+96}_{-95}



deF, J. Mazzitelli (2013)

- Soft-virtual emission ~98% of total correction (14 TeV)
- Explains increase of corrections at lower energies (closer to threshold)

Doable within EFT : reach status of single Higgs production

- Fully differential at NNLO, NNLL, SV@N^{3}LO, ...

Needed : go beyond EFT approximation and distributions !

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- Improve over EFT

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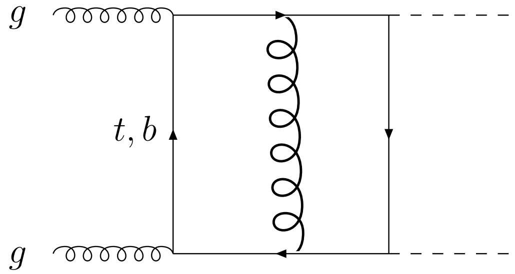

Doable within EFT : reach status of single Higgs production

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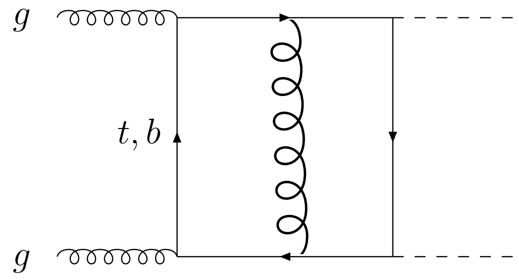
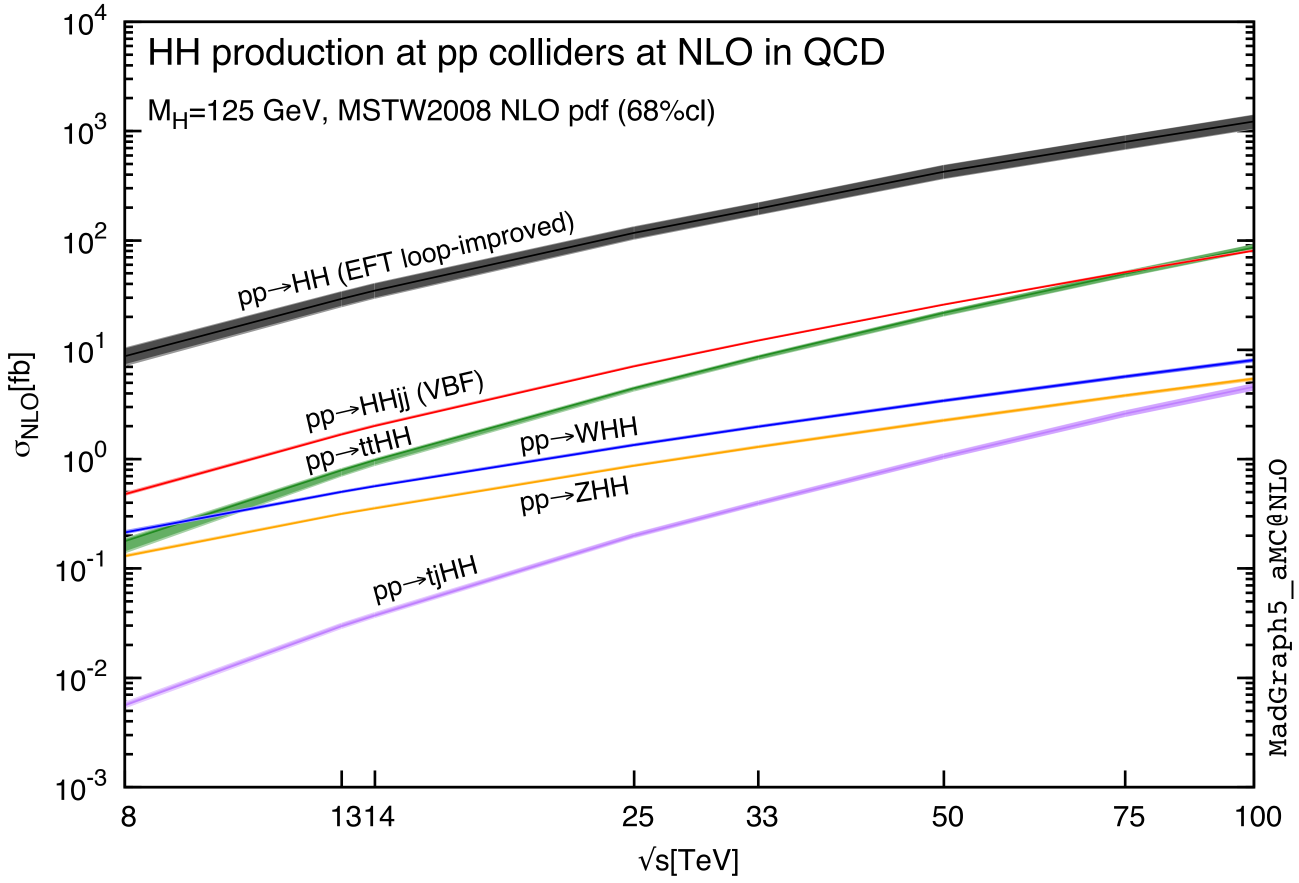


NEW



Frederix et al (2013) MadGraph5_aMC@NLO
Talk by Marco Zaro

All channels with full m_T dependence in real contributions

EFT for virtual

(short) Conclusions

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- Work triggered by experimental measurements

→ ***in the right path to Higgs precision!***

Thanks

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