Higgs TH Tools

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Outline

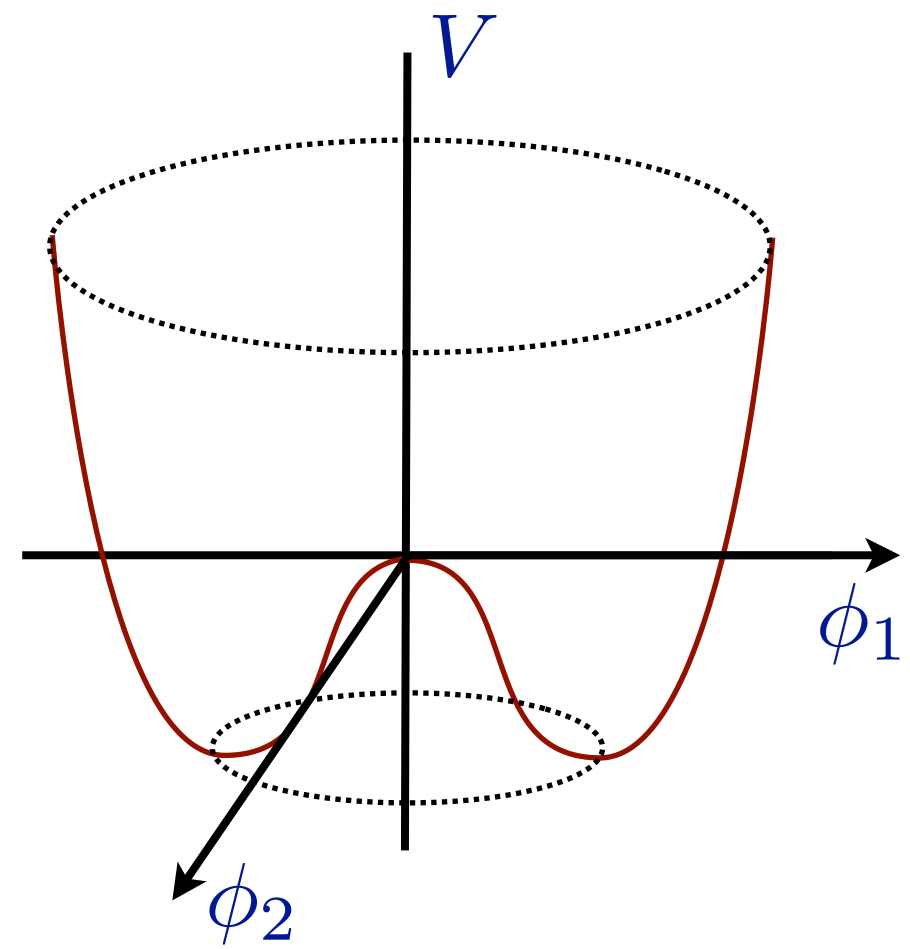
- The shortest introduction about Higgs Boson Physics
- Summary of production cross-sections

  where is room/possibility/need for improvements

- Decay and Interferences

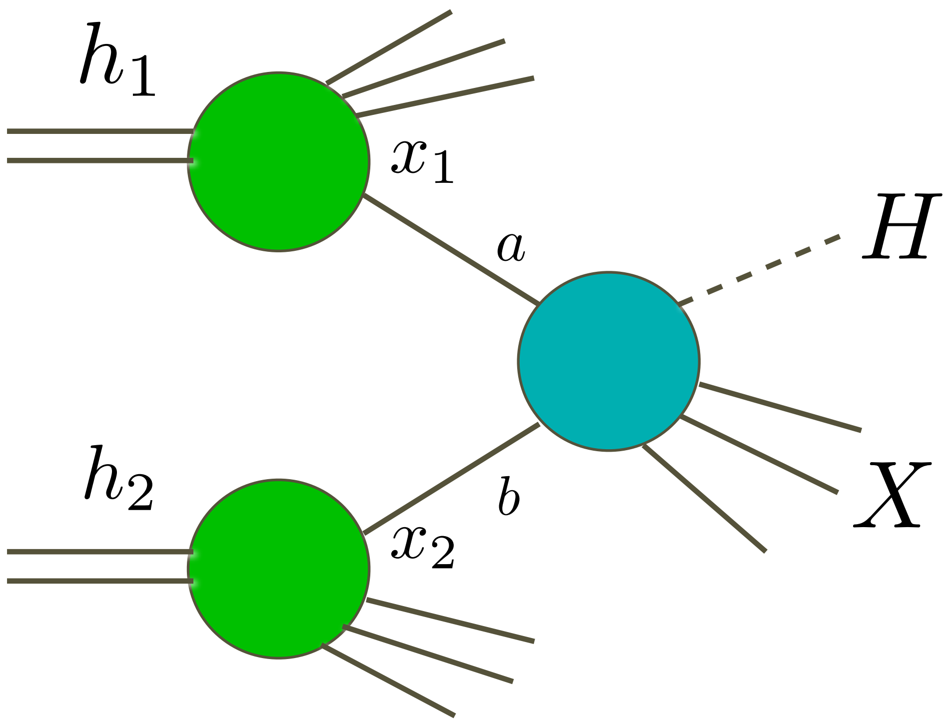
- The shortest introduction about Higgs Boson Physics

The SM Higgs boson is responsible for EW symmetry breaking



End of introduction

Higgs at Hadronic Colliders



non-perturbative parton distributions

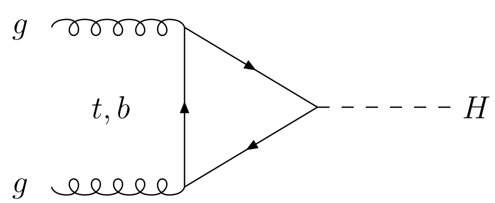
$$d\sigma = \sum_{ab} \int dx_a \int dx_b \, f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \times d\hat{\sigma}_{ab}(x_a, x_b, Q^2, \alpha_s(\mu_R^2))$$

perturbative partonic cross-section

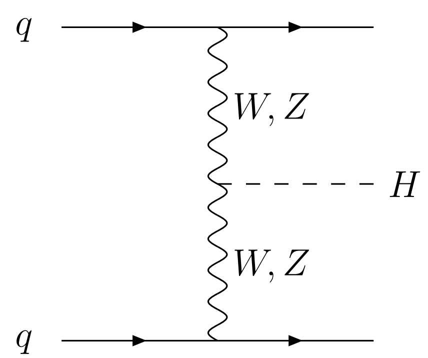
Partonic cross-section: expansion in $\alpha_s(\mu_R^2) \ll 1$ $\quad d\hat{\sigma} = \alpha_s^n \, d\hat{\sigma}^{(0)} + \alpha_s^{n+1} \, d\hat{\sigma}^{(1)} + \ldots$

- Need precision for both PDFs and partonic cross sections

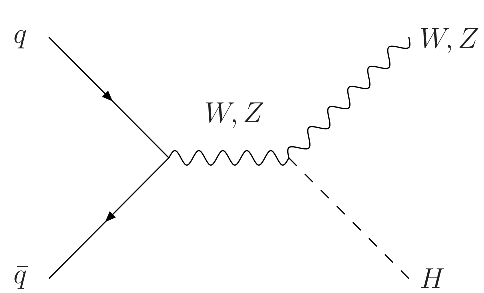
Production Channels at the LHC



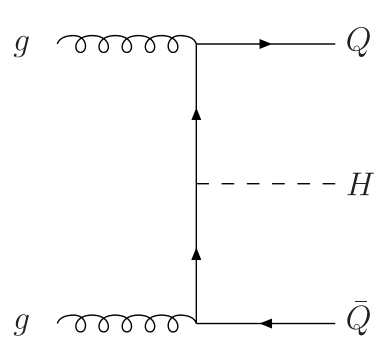
gg fusion



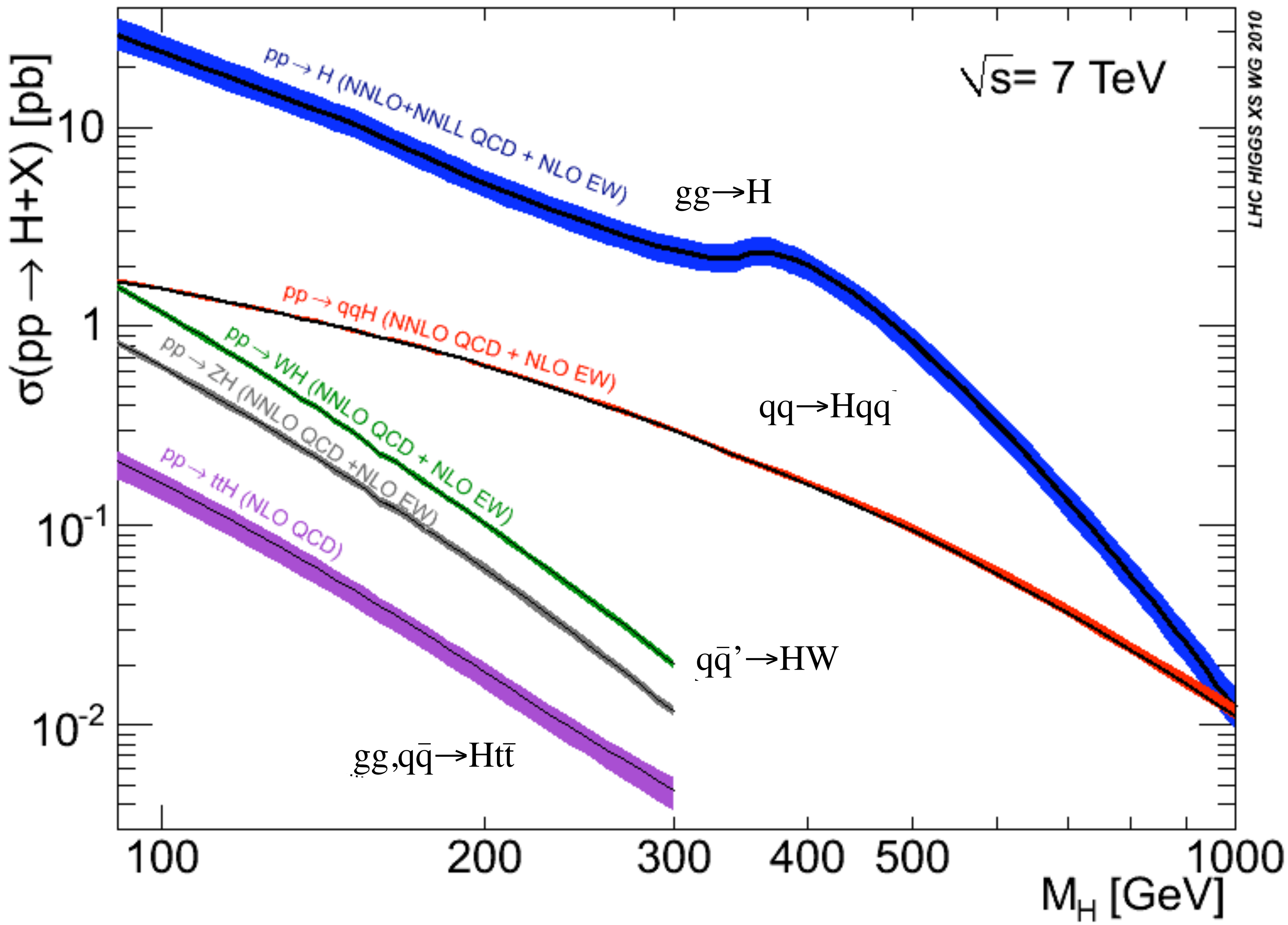
vector boson fusion



associated production with W,Z

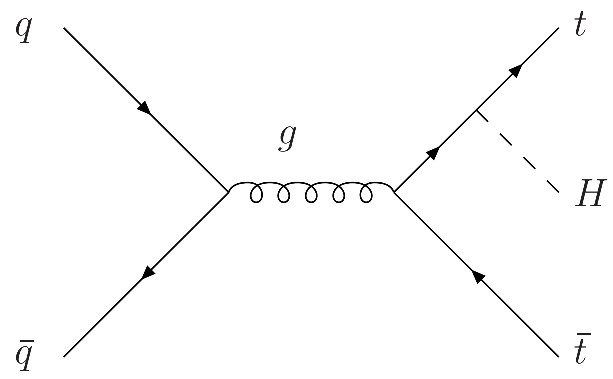


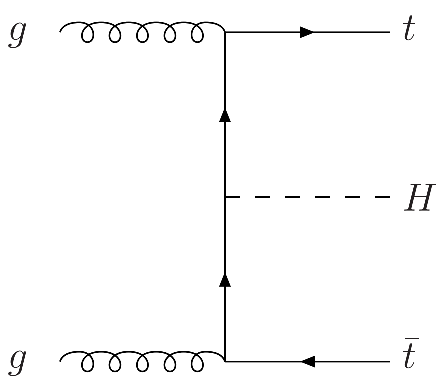
associated production with heavy quarks



- Gluon-gluon fusion dominates due to large gluon luminosity

Heavy Quark Associated production





$t\bar{t}H$

Yukawa coupling

- It was considered an important discovery channel in low mass region
- Not an easy channel because of background and signature

→ boosted analysis   Plehn, Salam, Spannowsky (2009)

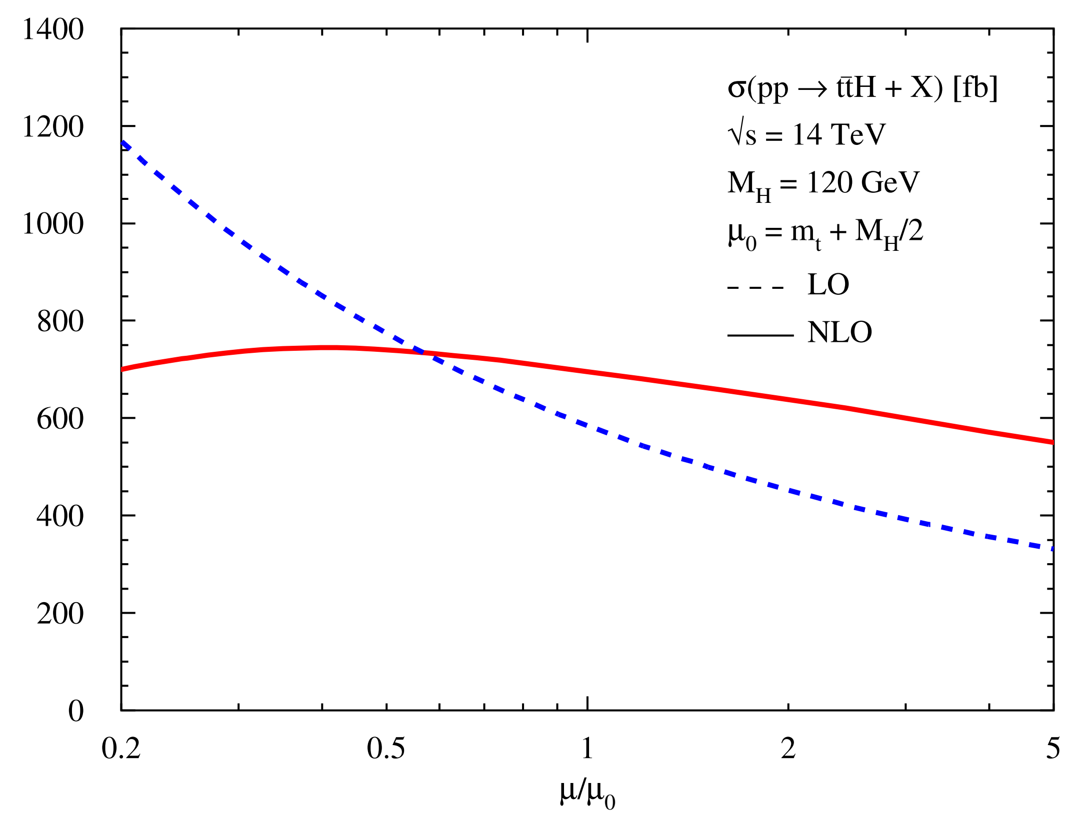
LO known for a long time

Kunszt (1984); Gunion (1991), Marciano, Paige (1991)

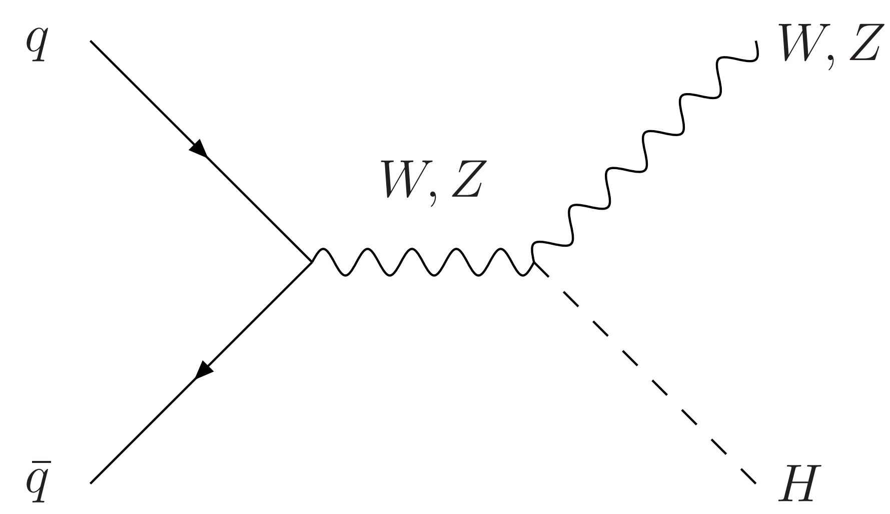
NLO provides more stable results (~10% scale) and 20% increase

Beenakker et al (2002), Dawson, Reina (2001), Wackeroth et al (2003)

Recent work includes spin correlations in top decay, exclusive distributions



Associated VH production



- Main channel for low mass at Tevatron

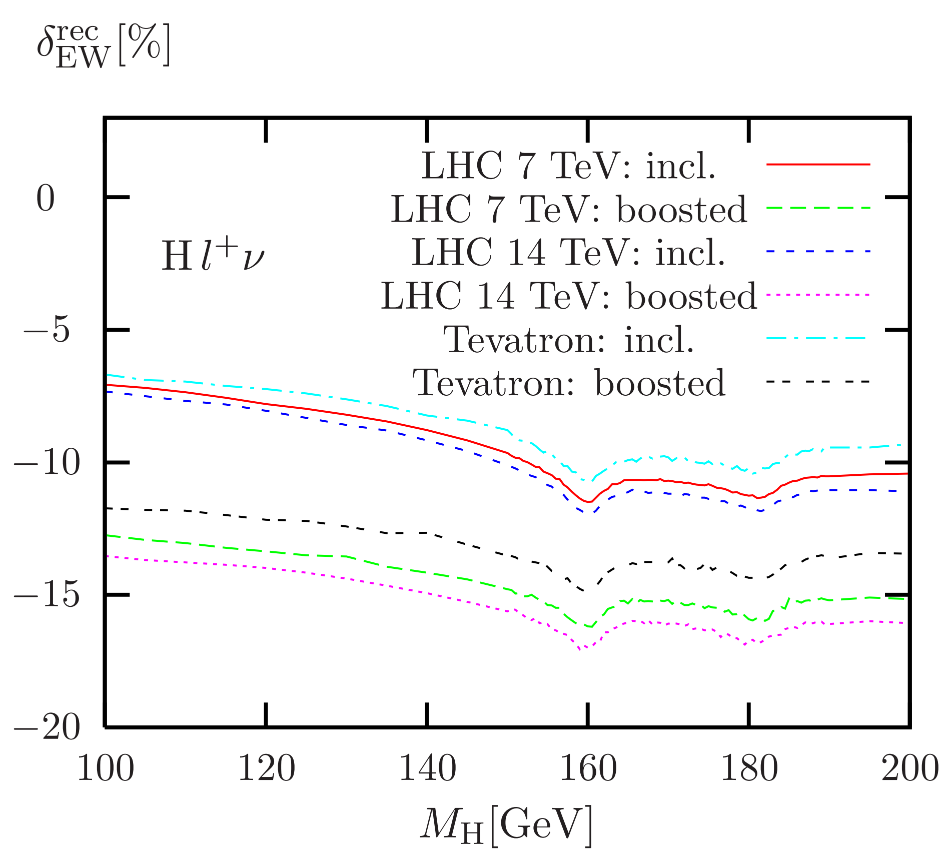
Possible at the LHC with boosted analysis
→ $b\bar{b}$ decay Butterworth et al (2007)

- From QCD point of view very similar to Drell-Yan (NNLO) van Neerven et al (1991)

- @ NLO exactly DY : ~30% corrections Han, Willenbrock (1990)

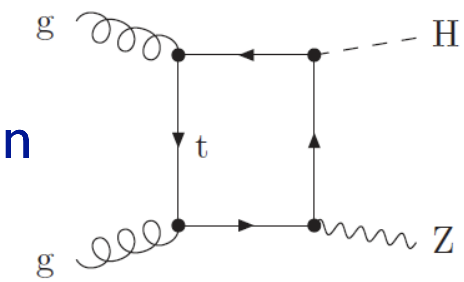
- EW corrections known : -(5/10) %
  more in distributions

Ciccolini, Dittmaier, Kramer (2003)
HAWK: Denner, Dittmaier, Kallweit, Mück (2011)



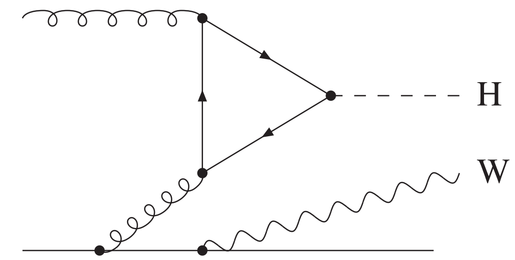
@ NNLO extra contributions involving a heavy quark loop

~2-6% contribution



Brein, Harlander, Djouadi (2003)

~1% contribution

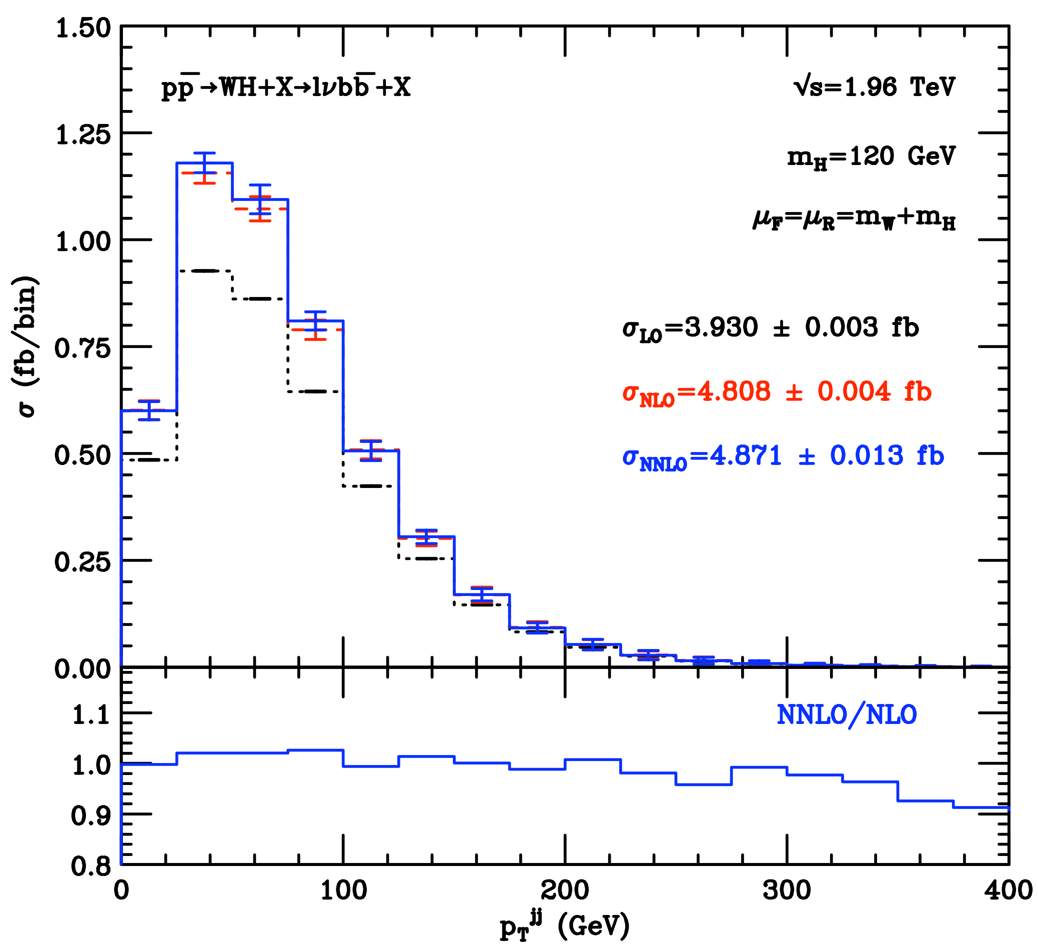


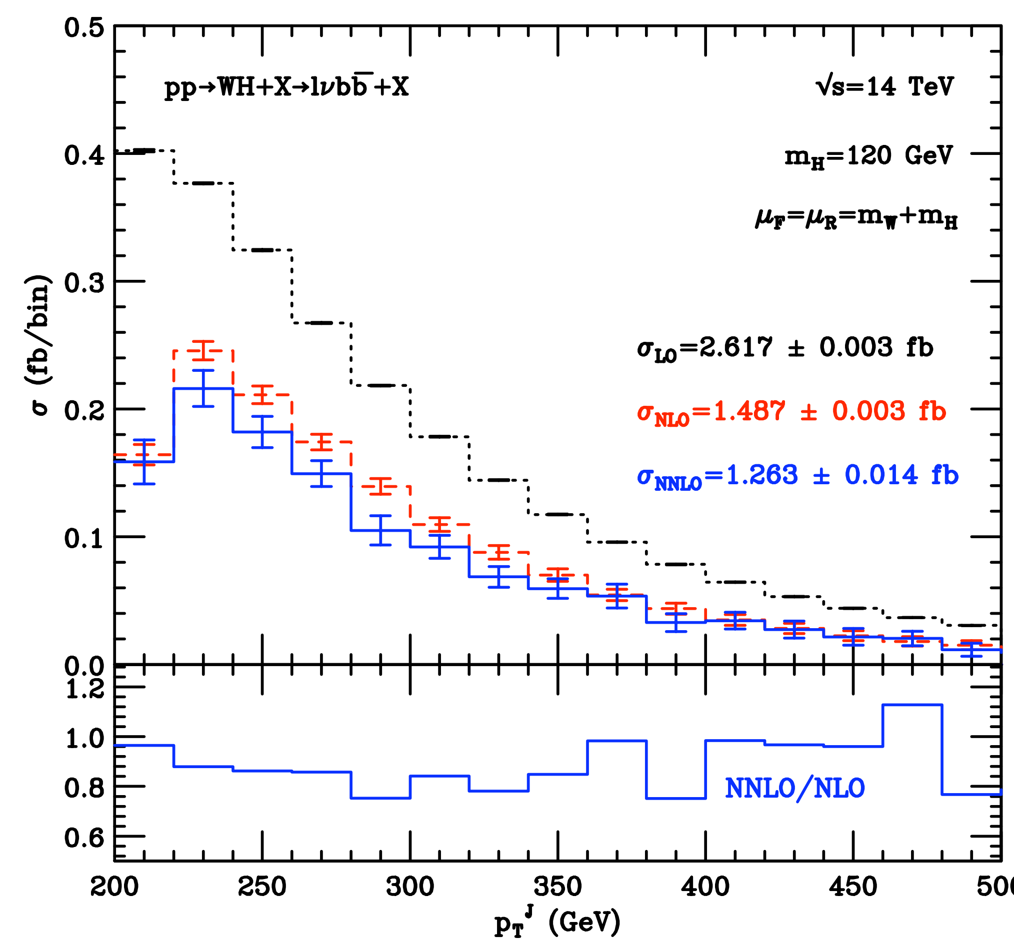
Brein, Wiesemann, Harlander, Zirke (2011)

QCD corrections (N3LO) Altenkamp et al (2012)

DY approach : fully exclusive NNLO calculation

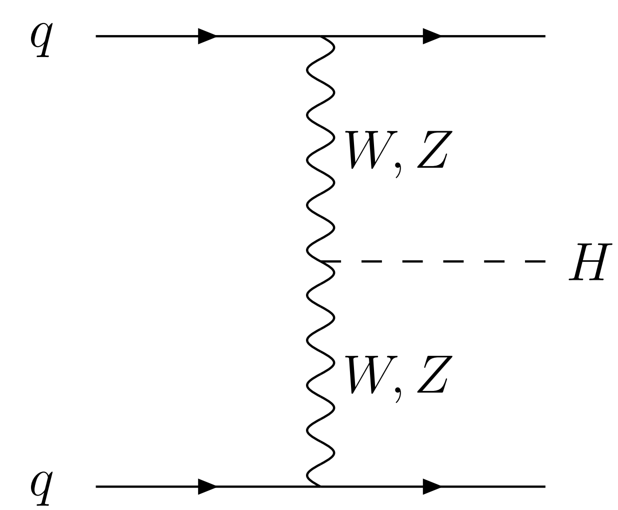
Ferrera, Grazzini, Tramontano (2011)





- Very stable results at Tevatron
- Fixed order challenged at LHC (boosted analysis with jet veto)

Vector Boson Fusion



- Almost one order of magnitude smaller than gg fusion but still very interesting

Signature : 2 highly energetic jets without hadronic activity in a large rapidity interval

- Moderate NLO corrections ~5-10%

Total rate: Han, Willenbrock(1991)
Distributions: Figy, Oleari, Zeppenfeld (2003)
J.Campbel, K.Ellis (2003)

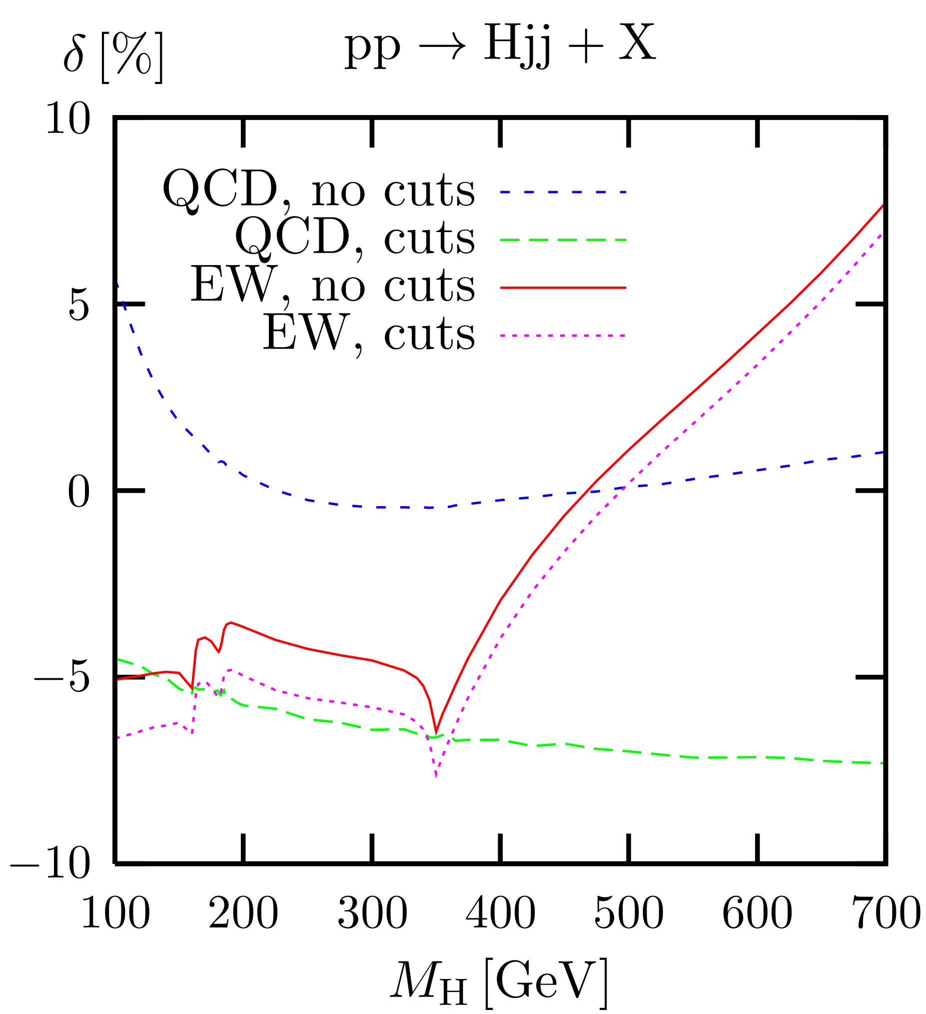
- EW+QCD corrections computed

Ciccolini, Denner, Dittmaier (2008) HAWK

- QCD NNLO within structure function approach

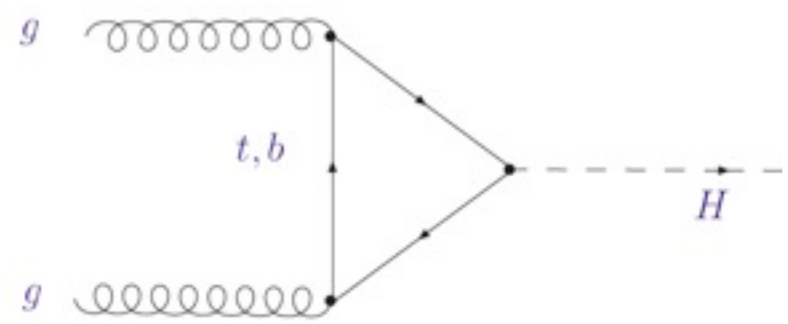
Bolzoni, Maltoni, Moch, Zaro (2011)

Good Theoretical accuracy (2% scale dependence)



gg fusion

- Top quark dominates

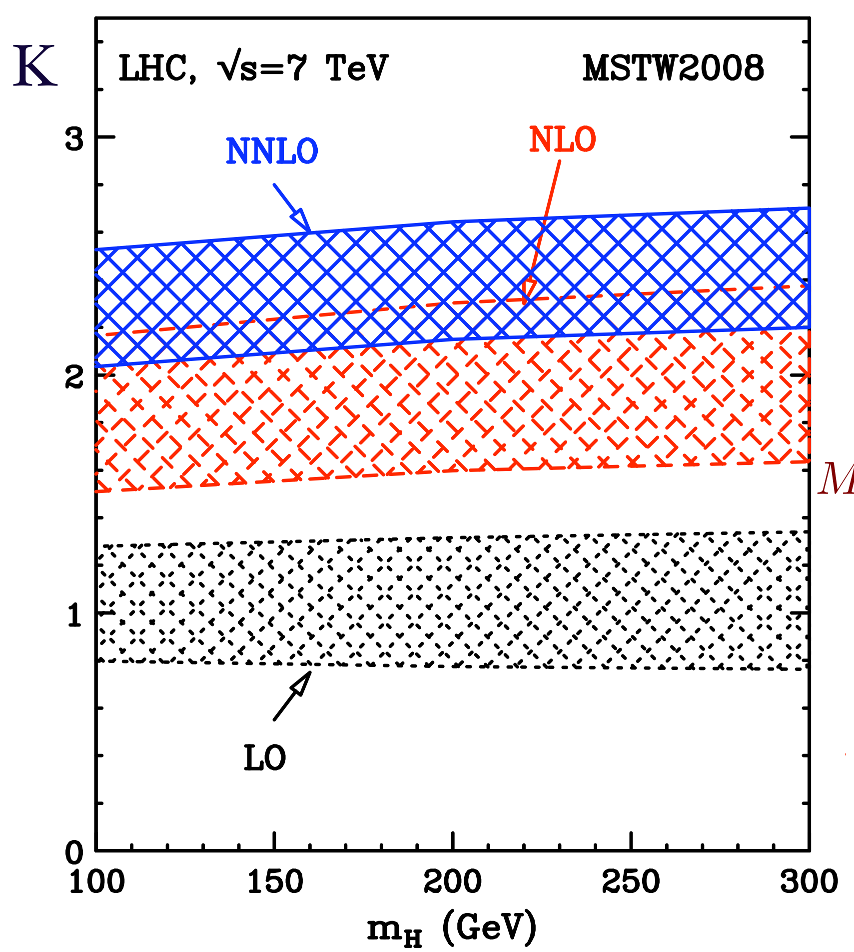


- Higher order corrections very large: $\mathcal{O}(100\%)$ at NLO

  Large top mass limit — Dawson (1991); Djouadi, Spira, Zerwas (1991)

  exact — Graudenz, Spira, Zerwas (1993)

- Still sizable at NNLO: +25% at LHC and +30% at Tevatron

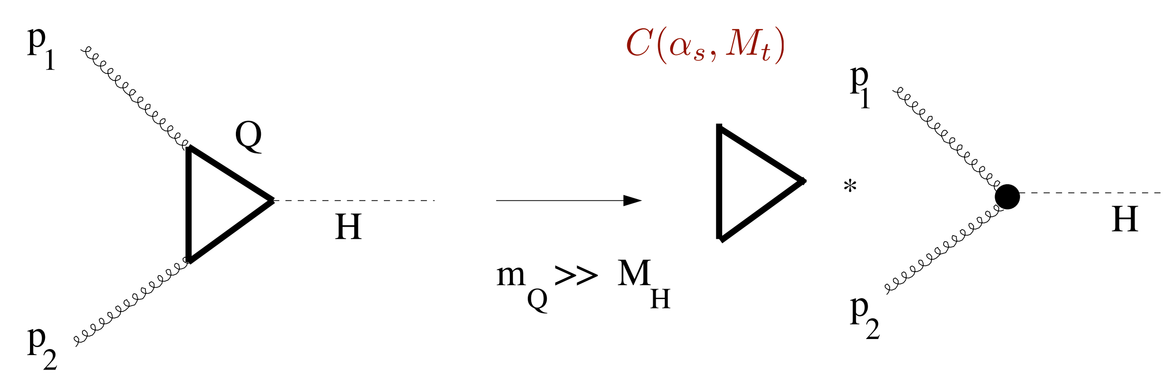


Within large M_t limit — Harlander, Kilgore (2002); Anastasiou, Melnikov (2002); Ravindran, Smith, van Neerven (2003)

Scale band

$M_H/2 < \mu_F, \mu_R < 2\,M_H$

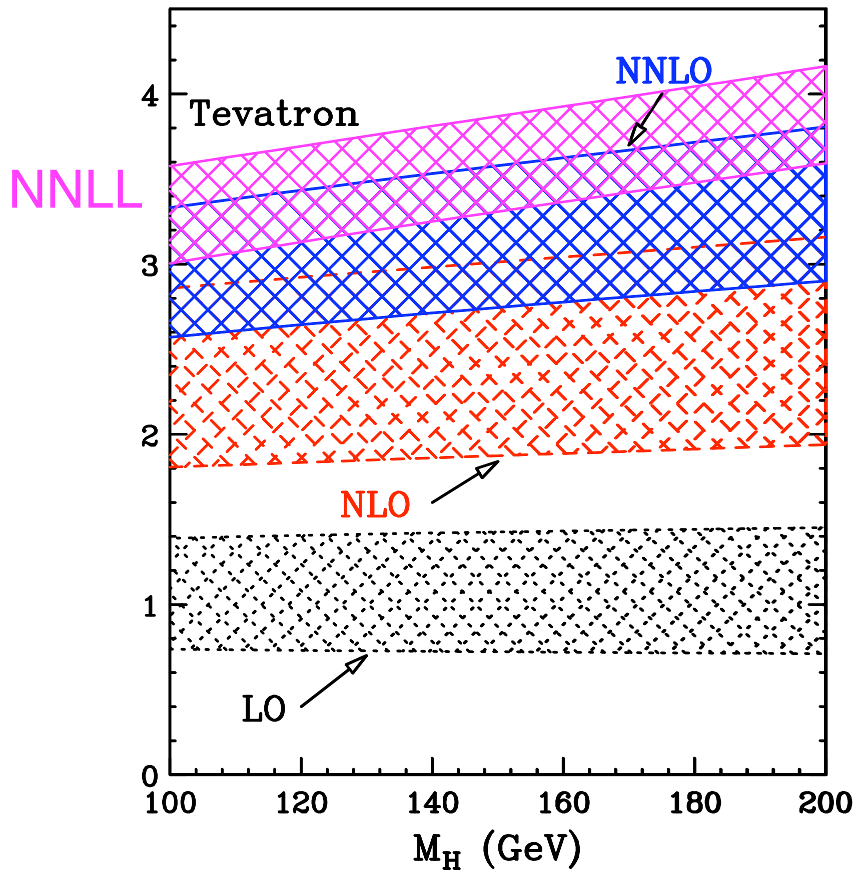
$1/2 < \mu_F/\mu_R < 2$



Start to observe some overlap at NNLO/NLO

Improvements over NNLO

- QCD corrections completely dominated by soft and virtual gluon radiation

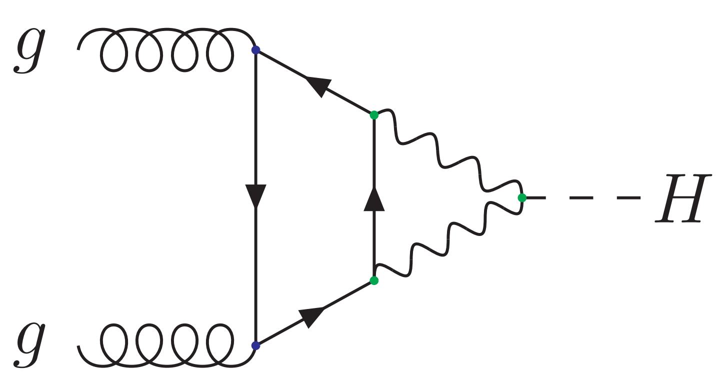


Threshold NNLL (+NNLO) Resummation

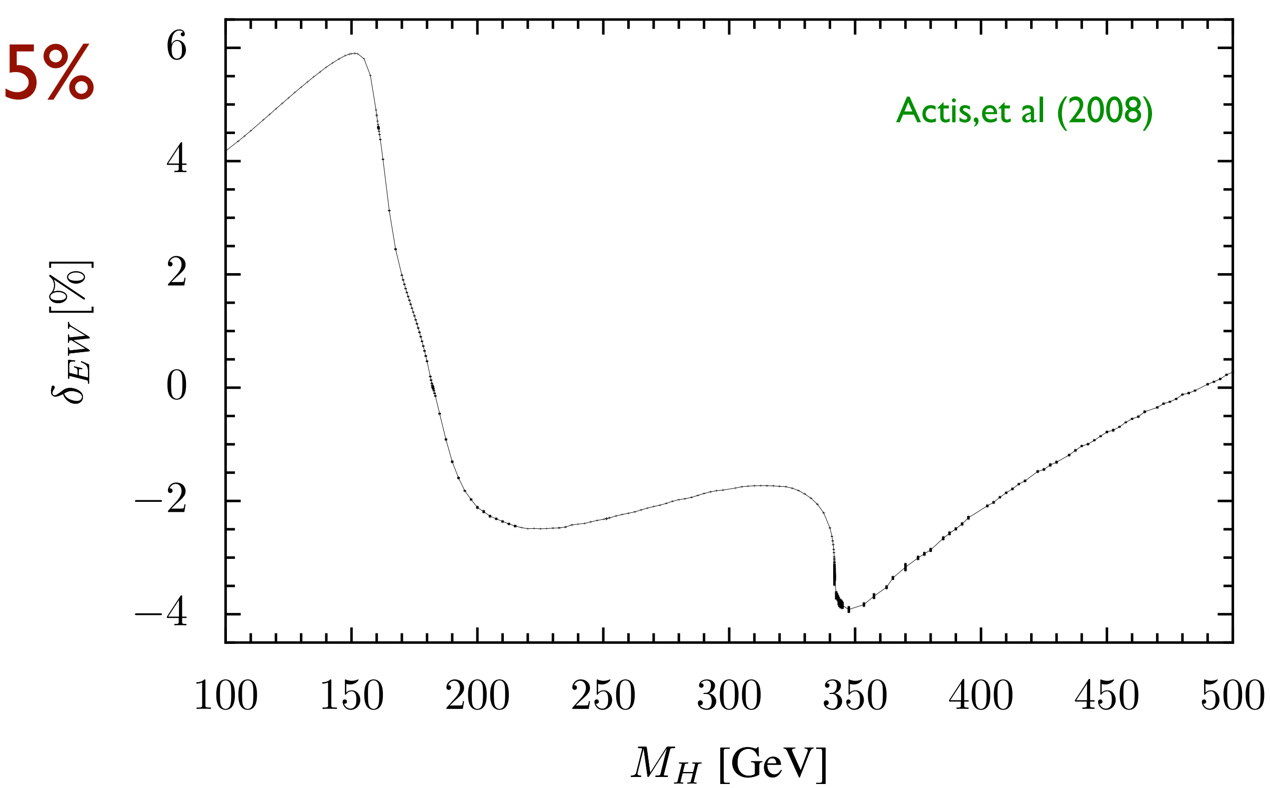
9% at 7 TeV, 13% at Tevatron

Catani, deF, Grazzini, Nason (2003)

- Two loop EW corrections not negligible ~ 5%



Aglietti, Bonciani, Degrassi, Vicini (2004)
Degrassi, Maltoni (2004)
Actis, Passarino, Sturm, Uccirati (2008)



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

→ supports "complete factorization" of EW effects

- EW effects from real radiation < 1% — Keung, Petriello(2009); Brein (2010) Anastasiou et al (2011)

- Higgs Line-shape

$$\sigma_{H\to X}(m_H) = \int dQ^2 \frac{Q\,\Gamma_{H\to X}(Q)}{\pi} \frac{\sigma_H(Q)}{(Q^2-m_H^2)^2+m_H^2\Gamma_H^2}$$

complex pole

Goria, Passarino, Rosco (2011)

- Better understanding of (loop) mass effects — Schreck, Steinhauser (2007); Marzani et al (2008); Harlander et al (2009,2010)

Improved Higgs Cross-section @ LHC

- dFG: deF, Grazzini

- Use full result at NLL+NLO and effective Lagrangian for top quark contribution (normalized to Born) for NNLL+NNLO

$$\sigma^{QCD} = \sigma_{top}^{NNLL+NNLO} + \sigma_{bottom}^{NLO}$$

- Include EW effects assuming complete factorization

$$\sigma^{best} = (1+\delta_{EW})\,\sigma^{QCD}$$

Actis, Passarino, Sturm, Uccirati (2008)

Other calculations

- Baglio, Djouadi, Ferrag, Godbole (2011)
- more conservative estimate of uncertainties

- SCET resummation — Ahrens, Becher, Neubert, Yang (2010)
- Exponentiates π^2 terms (concern about consistency)
- ✓ Central value agrees with others
- Scale dependence 3% or less → underestimates TH uncertainty

- iHixs — Anastasiou, Buehler, Herzog, Lazopoulos (2012)
- Based on ABPS + Breit-Wigner line-shape + EW effects from real radiation

Agreement within uncertainties with LHC-HXS numbers for light Higgs

Fully Exclusive:

FEHIP — Anastasiou, Melnikov, Petriello (2005)

FEHIPRO — Anastasiou, Lazopoulos, Stoeckli

HNNLO — Catani, Grazzini (2007); Grazzini (2008)

'now' including HQ mass dependence exactly up to NLO

$$\sigma(m_H = 125\,\text{GeV}) = 19.52^{+7.2\%\;+7.5\%}_{-7.8\%\;-6.9\%}\ \text{pb}$$

(scale, pdf + α_S)

Uncertainties in inclusive cross-sections

Dittmaier and Schumacher (2012)

		LHC @ $\sqrt{s} = 7$ TeV				LHC @ $\sqrt{s} = 14$ TeV			
		uncertainties		corrections		uncertainties		corrections	
	M_H[GeV]	THU	PU	QCD	EW	THU	PU	QCD	EW
ggF	< 500	6–10%	8–10%	$\gtrsim$100%	5%	6–14%	7%	$\gtrsim$100%	5%
VBF	< 500	1%	2–7%	5%	5%	1%	3–4%	5%	5%
HW	< 200	1%	3–4%	30%	5–10%	1%	3–4%	30%	5–10%
HZ	< 200	1–2%	3–4%	40%	5%	2–4%	3–4%	45%	5%
ttH	< 200	10%	9%	5%	?	10%	9%	15–20%	?

PDF4LHC recommendation for Higgs

- Compute uncertainties using global MSTW & CT & NNPDF
- Obtain the envelope of all 68% c.l. bands : uncertainty

  supplemented with $\Delta\alpha_s(M_Z) = \pm 0.0012\,(\pm 0.002)$ at 68% (90%) c.l.

Even Higher orders N^3LO

- Towards N^3LO and N^3LL $g^{(4)} \to \alpha_s^2(\alpha_s \ln N)^n$

Soft corrections at N3LO Moch, Vermaseren, Vogt (2005)

combination of small x and threshold to estimate N3LO Ball et al (2013)

Possible to reach Soft+Virtual approximation (and even beyond that) in near future

- 3 loop form factor
  Baikov et al (2009)
  Gehrmann et al (2010)
  Lee, Smirnov, Smirnov (2010)

- Triple real emission: expansion in (1-z) Anastasiou, Duhr, Dulat, Mistlberger (2013)

- 2 loop + single emission : SV approximation

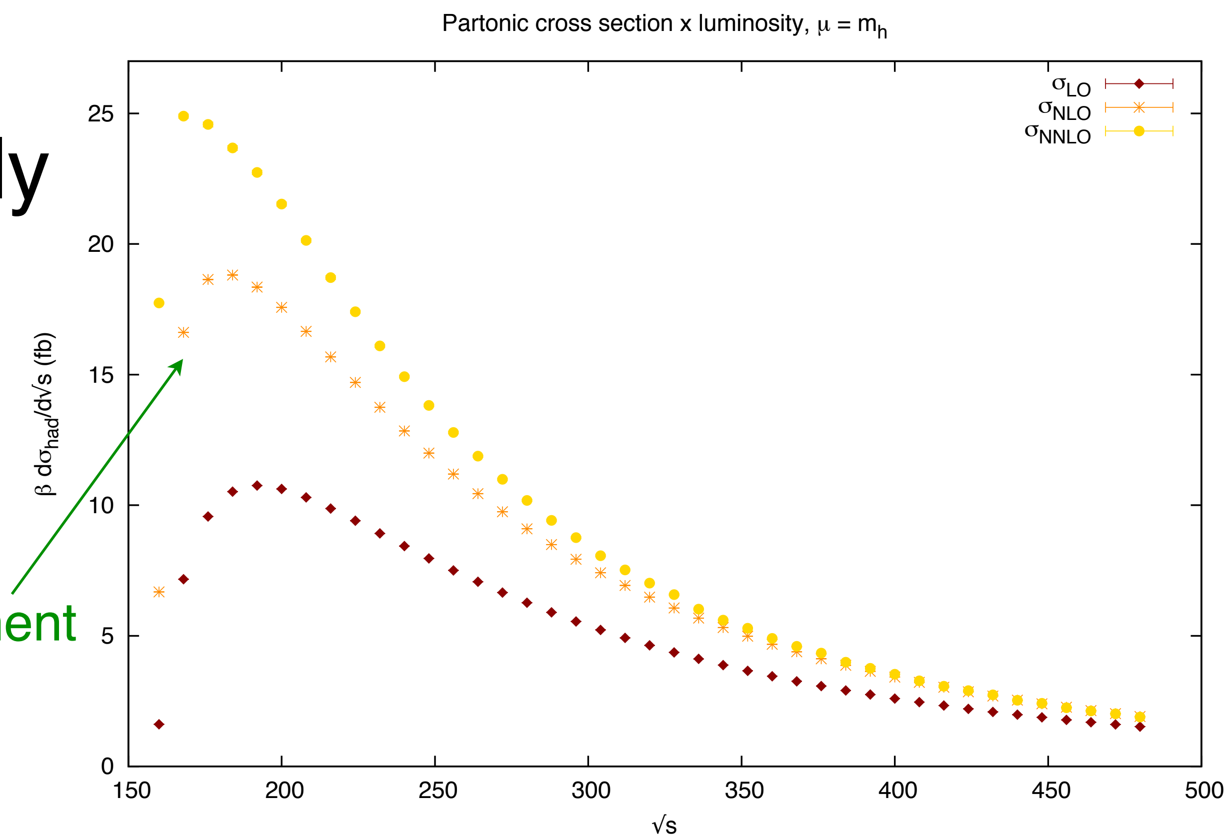
- 1 loop + double emission : needs soft current for SV approximation
  or explicit calculation (expansion in (1-z))

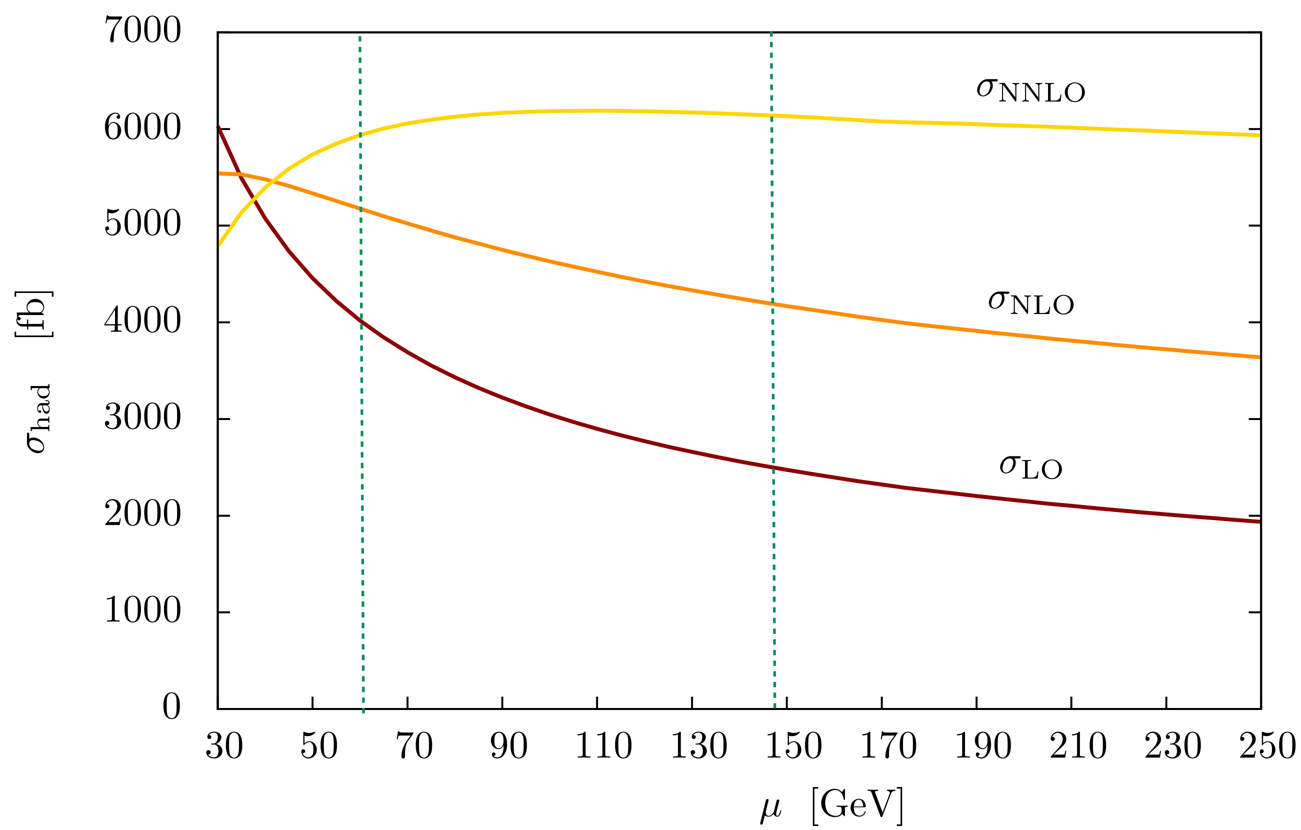
H+jet at NNLO

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

pure gluon only

Threshold enhancement





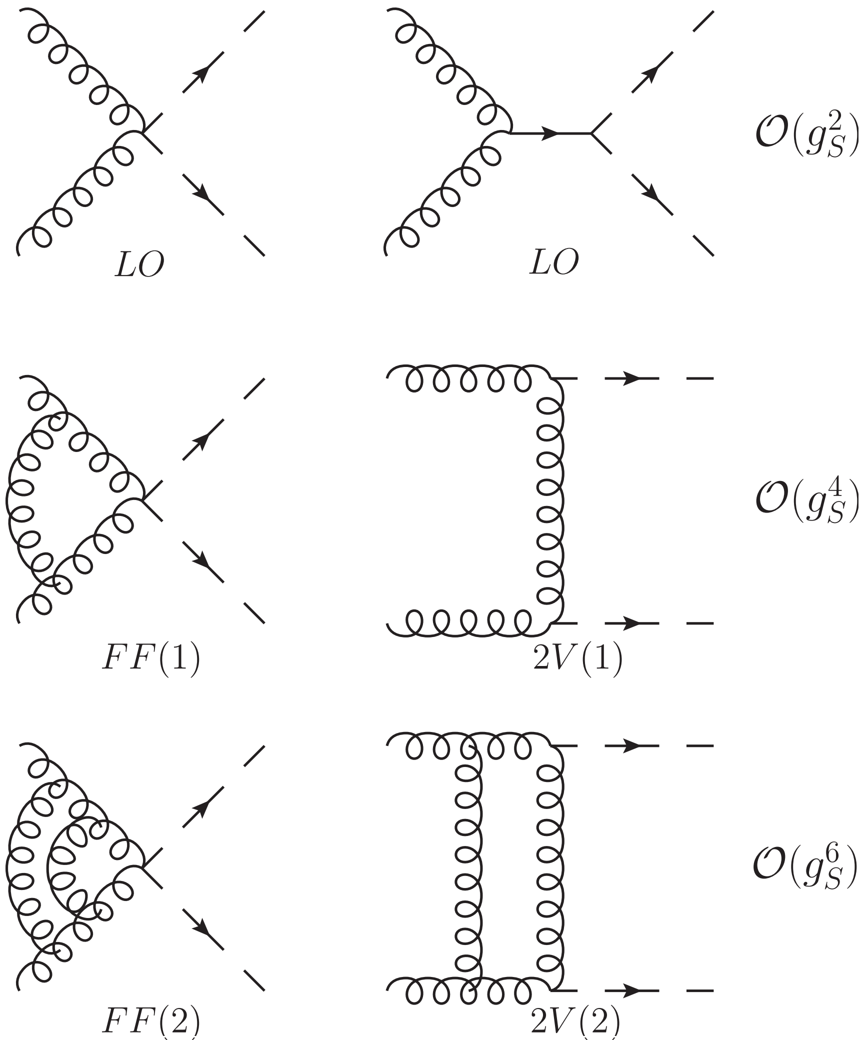
$p_T^{jet} > 30\text{GeV}$

$$\sigma_{\rm LO}(pp \to Hj) = 2713^{+1216}_{-776}\ \text{fb},$$
$$\sigma_{\rm NLO}(pp \to Hj) = 4377^{+760}_{-738}\ \text{fb},$$
$$\sigma_{\rm NNLO}(pp \to Hj) = 6177^{-204}_{+242}\ \text{fb}.$$

+60% NLO
+40% NNLO

more stable results for
$\mu = M_H/2$

Double Higgs production



Direct access to Higgs self-coupling

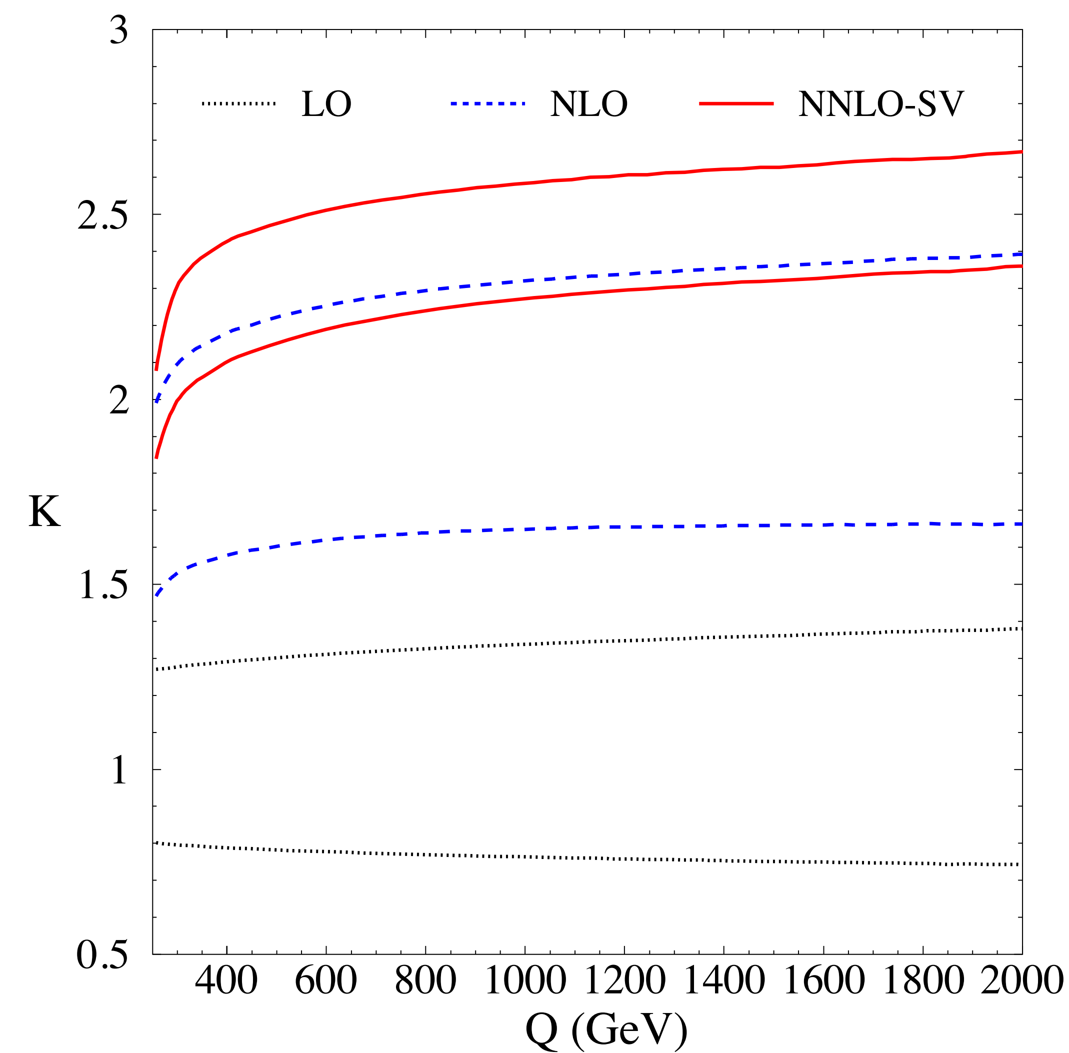
$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda' H^4$$

in SM

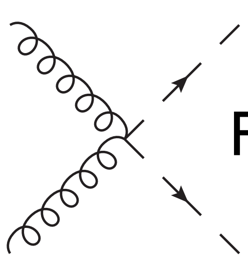
$$\lambda = \lambda' = M_H^2/(2v^2)$$

NLO computed within effective Lagrangian (large K)

Dawson, Dittmaier, Spira (1998)



New : two-loop corrections and NNLO-SV approximation deF, Mazzitelli (2013)

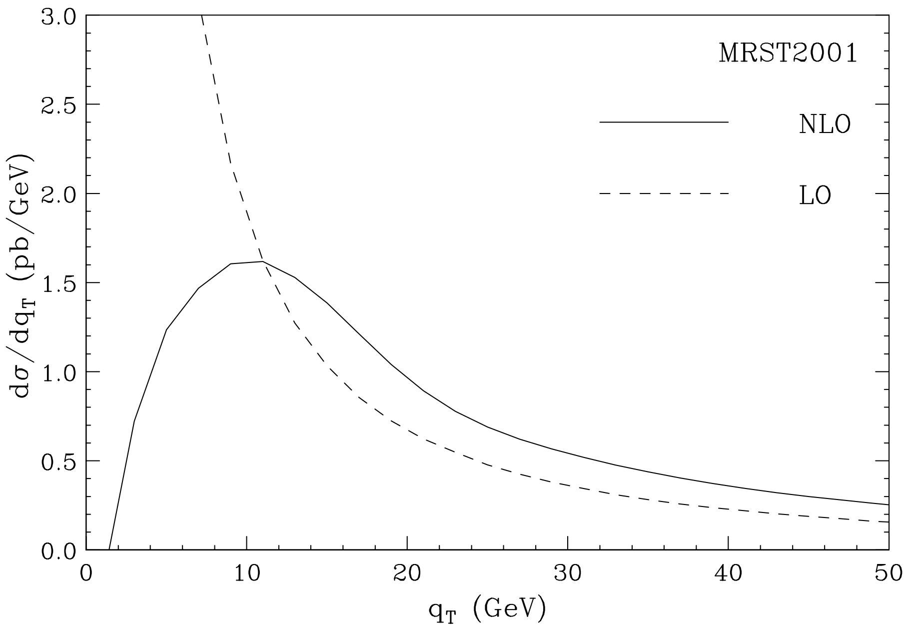


Full NNLO soon : still missing two-loop correction to effective vertex

$$C_{HH} = -\frac{1}{3}\frac{\alpha_S}{\pi}\left\{1 + \frac{11}{4}\frac{\alpha_S}{\pi} + \left(\frac{\alpha_S}{\pi}\right)^2 C_{HH}^{(2)} + \mathcal{O}(\alpha_S^3)\right\}$$

Higgs Transverse momentum distribution

Fixed order not reliable at small transverse momentum

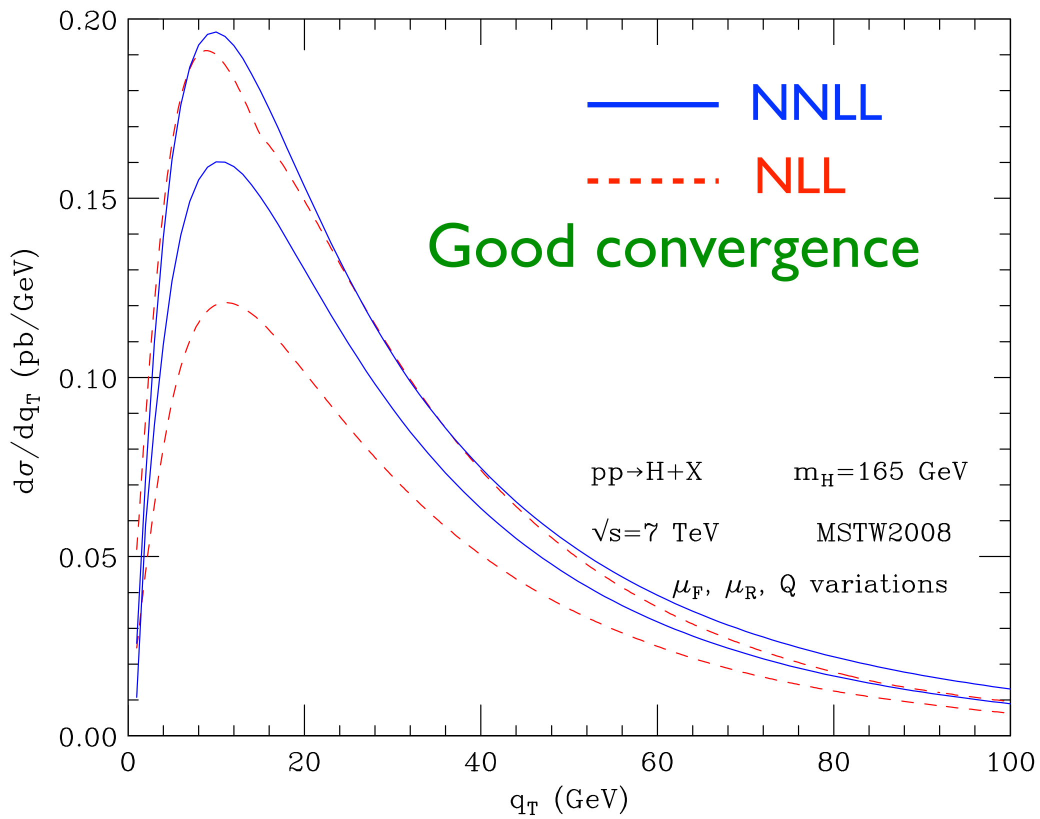


- Convergence spoiled when two scales are very different (small q_T)

$$\alpha_s^n \mathcal{C}_n \sim \frac{\alpha_s^n}{q_T^2} \log^{2n-1} \frac{M_H^2}{q_T^2}$$

Logs originated by soft and collinear gluon radiation

- Large logs need to be resummed! : analytical calculations allow to reach NNLL



HqT 2.0 deF, Ferrera, Grazzini, Tommasini (2011)

HRes deF, Ferrera, Grazzini, Tommasini (2012)

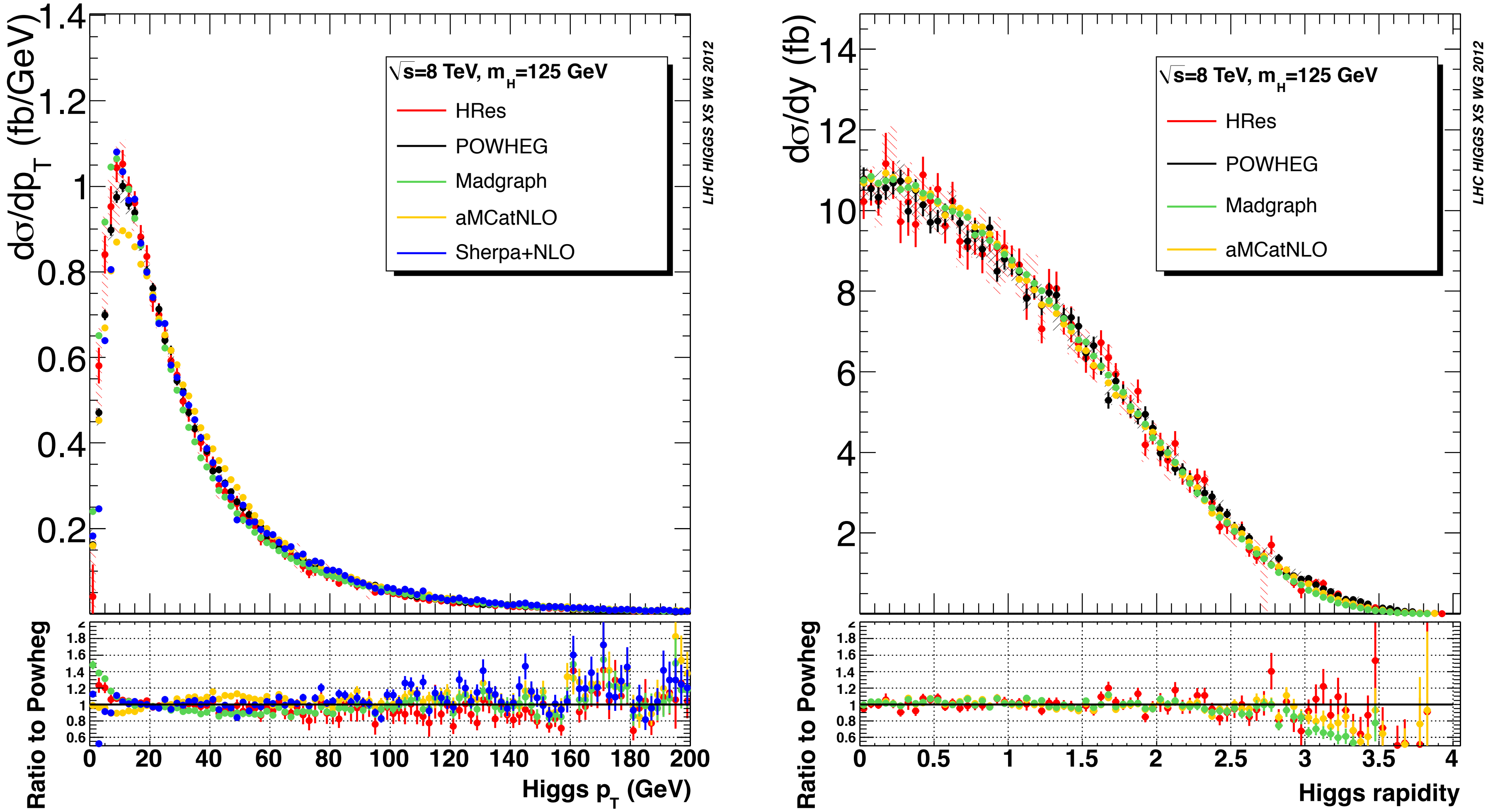
Include full description of Higgs decay products → $\gamma\gamma$, $WW \to l\nu l\nu$, $ZZ \to 4l$

Effect from Higgs small transverse momentum propagates into more exclusive distributions

But analytical calculations are too inclusive (final state partons are integrated)

Merging NLO with Parton Showers

- Resummation to NLL accuracy + realistic final states
- Allow to carry NLO precision to all aspects of experimental analysis
- (Formally) Same Logarithmic accuracy but numerical differences



N.Chanon

no HQ masses

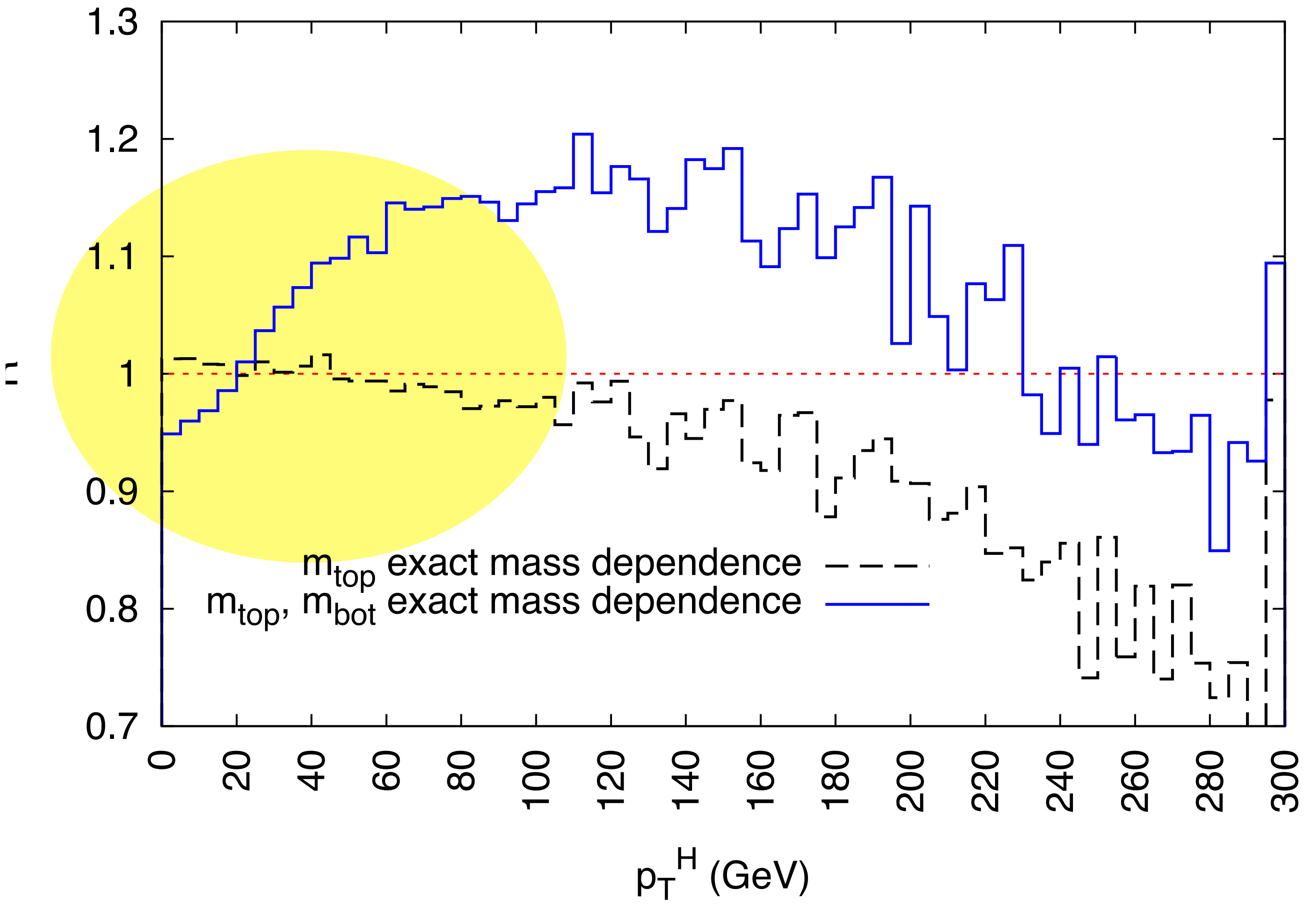
Reasonable agreement, but non-negligible differences in the spectrum

POWHEG with hfact=m_H/1.2 to match Hqt/HRes

How to include effect of HQ masses?

POWHEG with HQ (t,b,c) masses

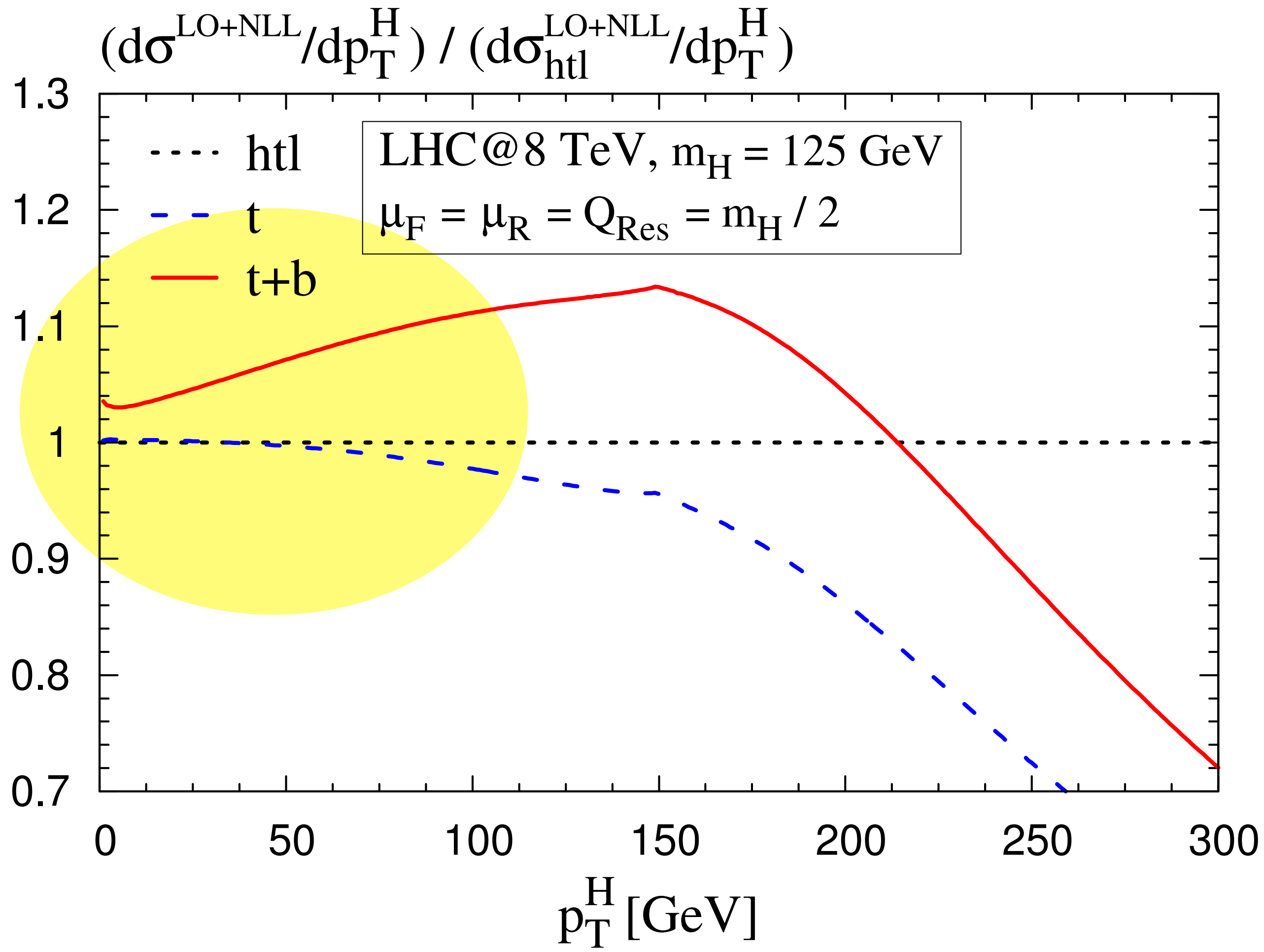
Bagnaschi, Degrassi, Slavich, Vicini



NLL with HQ (t,b,c) masses

Mantler, Wiesemann

similar MC@NLO
and Grazzini,Sargsyan



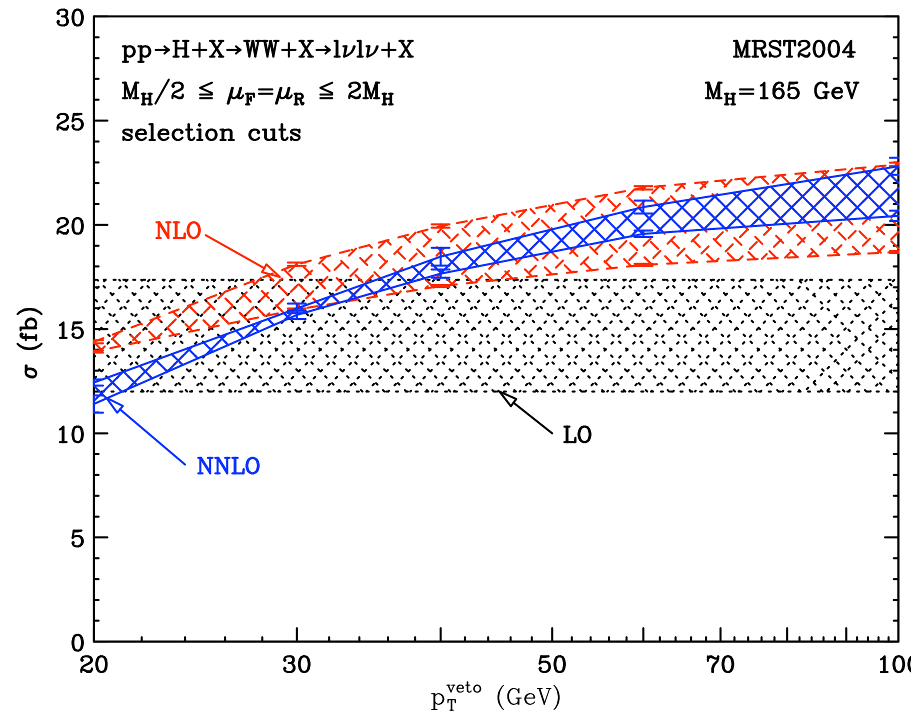
visible effects (depend on implementation)~ TH uncertainty

ongoing work within this workshop

Jet-veto

Use of fixed order calculations dangerous for jet-veto cross section

→ underestimate uncertainties



- Better estimate of uncertainties using f.o.

  Stewart, Tackmann

Consider *inclusive* jet cross section uncertainties → Transform to *exclusive* jet cross sections

$$\Delta_0^2 = \Delta_{\mathrm{total}}^2 + \Delta_{\geq 1}^2$$

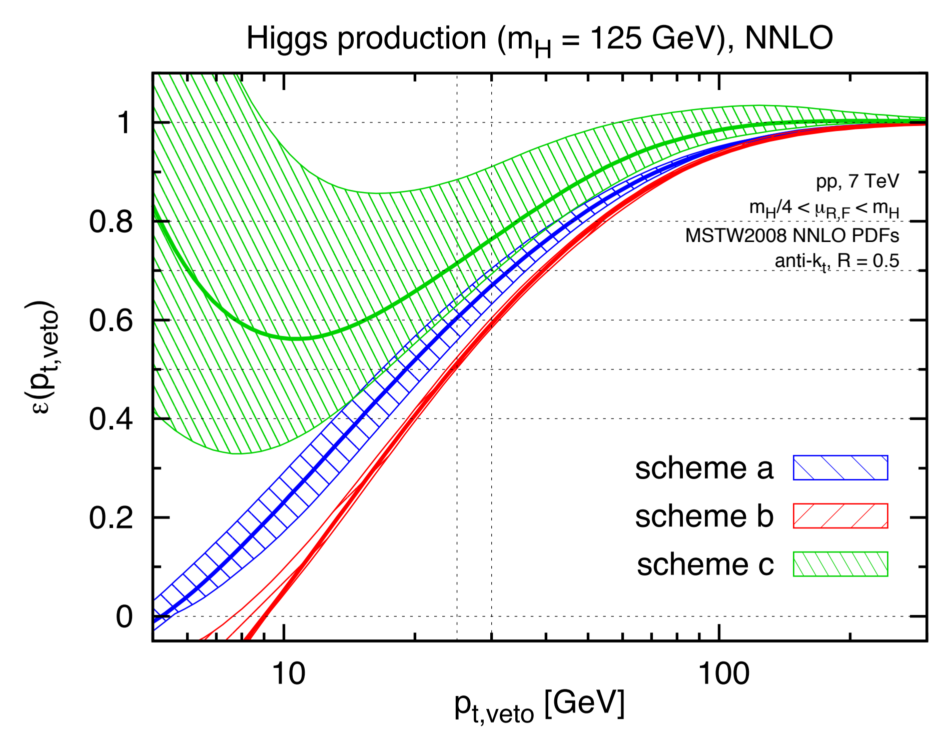
cut	$\frac{\Delta\sigma_{\rm total}}{\sigma_{\rm total}}$	$\frac{\Delta\sigma_{\geq 1}}{\sigma_{\geq 1}}$	$\frac{\Delta\sigma_{\geq 2}}{\sigma_{\geq 2}}$	$\frac{\Delta\sigma_0}{\sigma_0}$	$\frac{\Delta\sigma_1}{\sigma_1}$
$p_T^{\rm cut} = 30\,{\rm GeV},\ \eta^{\rm cut} = 3$	10%	21%	45%	17%	29%

- Alternative: study uncertainties in efficiencies

  Banfi, Salam, Zanderighi

$$\epsilon(p_{T,veto}) \equiv \frac{\sigma_0(p_{T,veto})}{\sigma}$$

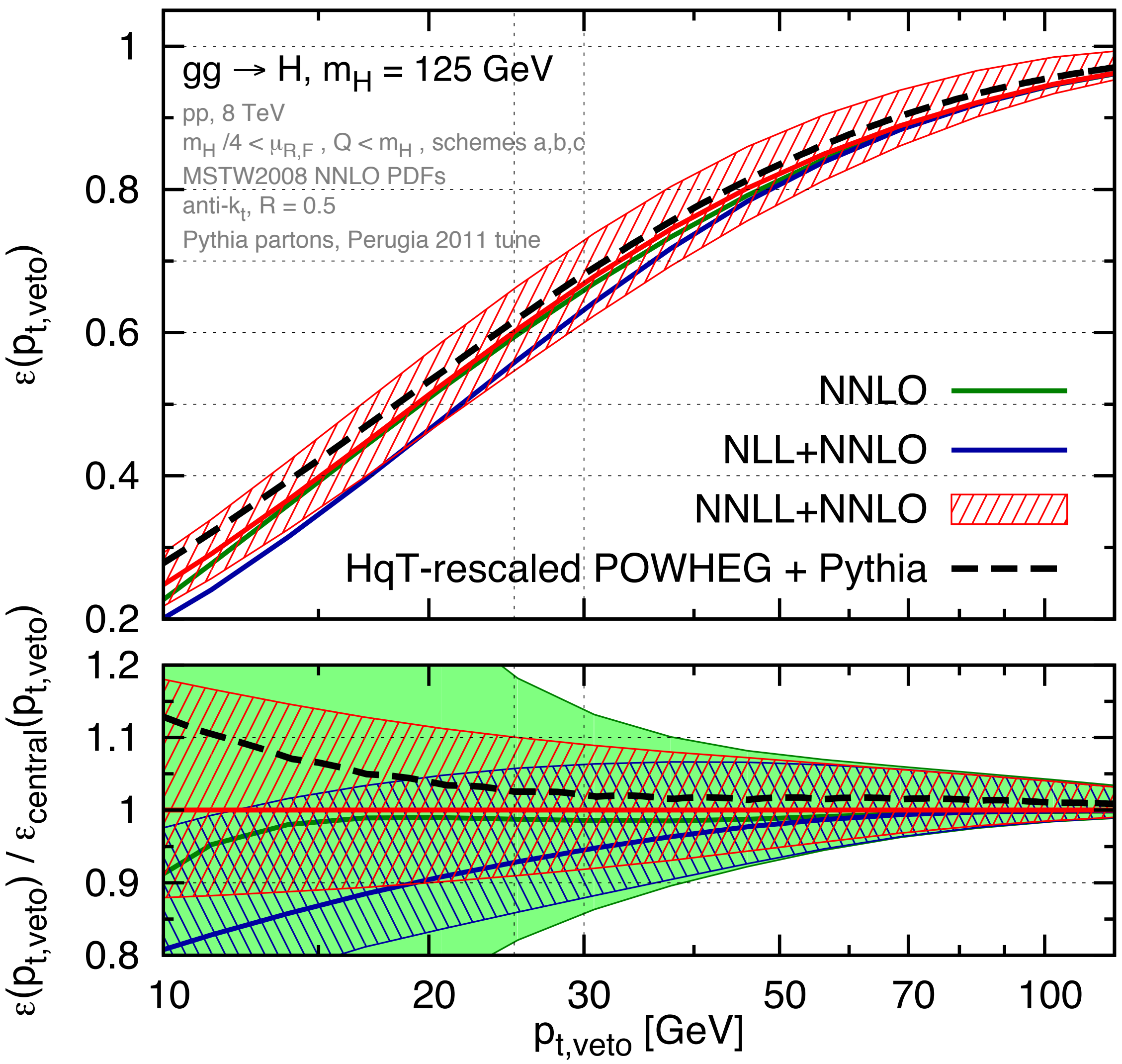
Different schemes (formally equivalent definitions at NNLO) :
Envelope from spread in central values agrees with ST



Recent progress on resummation for jet veto (H+ 0jet, H+1jet, H+ n jets)

Berger, Marcantonni, Stewart, Tackmann, Waalewijn
Liu, Petriello
Becher, Neubert
Tackmann, Walsh, Zuberi
Bernlochner, Gangal, Gillbert, Tackmann

- NNLL+NNLO jet veto efficiencies   Banfi, Monni, Salam, Zanderighi (2012)

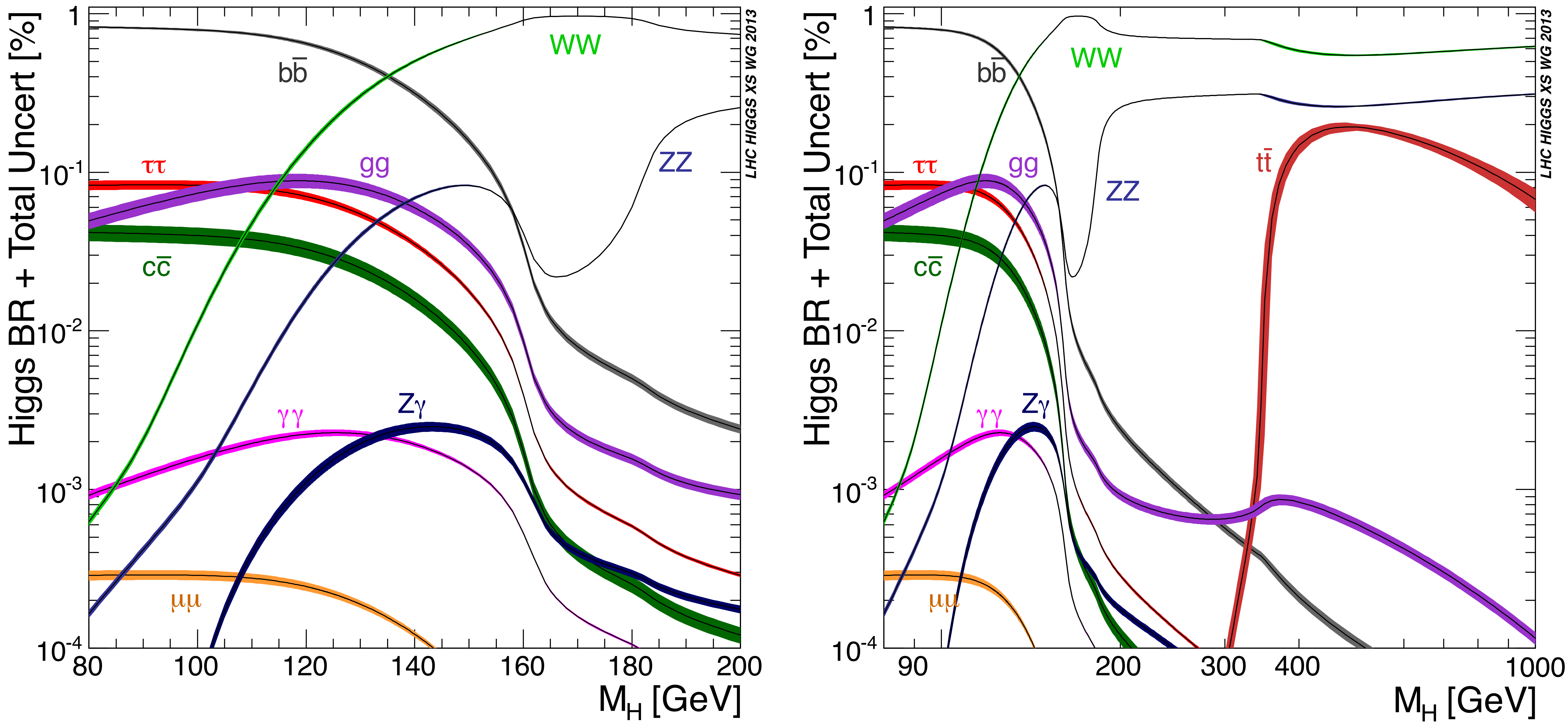


R	$p_{t,\mathrm{veto}}$	$\epsilon^{(7\ \mathrm{TeV})}$	$\sigma^{(7\ \mathrm{TeV})}_{0\text{-jet}}$	$\epsilon^{(8\ \mathrm{TeV})}$	$\sigma^{(8\ \mathrm{TeV})}_{0\text{-jet}}$
0.4	25	$0.63^{+0.07}_{-0.05}$	$9.6^{+1.3}_{-1.1}$	$0.61^{+0.07}_{-0.06}$	$12.0^{+1.6}_{-1.4}$
0.5	30	$0.68^{+0.06}_{-0.05}$	$10.4^{+1.2}_{-1.1}$	$0.67^{+0.06}_{-0.05}$	$13.0^{+1.5}_{-1.5}$
1.0	30	$0.64^{+0.03}_{-0.05}$	$9.8^{+0.8}_{-1.1}$	$0.63^{+0.04}_{-0.05}$	$12.2^{+1.1}_{-1.4}$

~10-13%

- reduction in efficiency uncertainty
- HqT-Reweighted POWHEG agrees with central value (might not be reliable for uncertainty)

Decay : Branching ratios (and partial widths)



$$\Gamma_{\mathrm{H}} = \Gamma^{\mathrm{HD}} - \Gamma^{\mathrm{HD}}_{\mathrm{ZZ}} - \Gamma^{\mathrm{HD}}_{\mathrm{WW}} + \Gamma^{\mathrm{Proph.}}_{\mathrm{4f}}$$

HDECAY Prophecy4F

$$\Gamma^{\mathrm{Proph.}}_{\mathrm{4f}} = \Gamma_{\mathrm{H}\to\mathrm{W}^*\mathrm{W}^*\to 4\mathrm{f}} + \Gamma_{\mathrm{H}\to\mathrm{Z}^*\mathrm{Z}^*\to 4\mathrm{f}} + \Gamma_{\mathrm{WW/ZZ-int.}}$$

most complicated channel (EW corrections)

$$\mathcal{A}_{ij\to H\to X} = \mathcal{A}_{ij\to H} \frac{-1}{Q^2 - m_H^2 + i m_H \Gamma_H} \mathcal{A}_{H\to X}$$

$$\sigma_{H\to X}(m_H) = \int dQ^2 \frac{Q\,\Gamma_{H\to X}(Q)}{\pi} \frac{\sigma_H(Q)}{(Q^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

$$\xrightarrow[\Gamma_H \ll m_H]{} \frac{\pi}{m_H \Gamma_H} \delta(Q^2 - m_H^2)$$

zero (narrow) width approximation

$$\sigma_{H\to X}(m_H) = \sigma_H(m_H) \frac{\Gamma_{H\to X}}{\Gamma_H} = \sigma_H(m_H) \times Br(H \to X)$$

Proper calculation requires

- Implementation of Higgs Boson Lineshape

  complex pole
  Goria, Passarino, Rosco (2011)

- Computation of Signal-Background Interferences

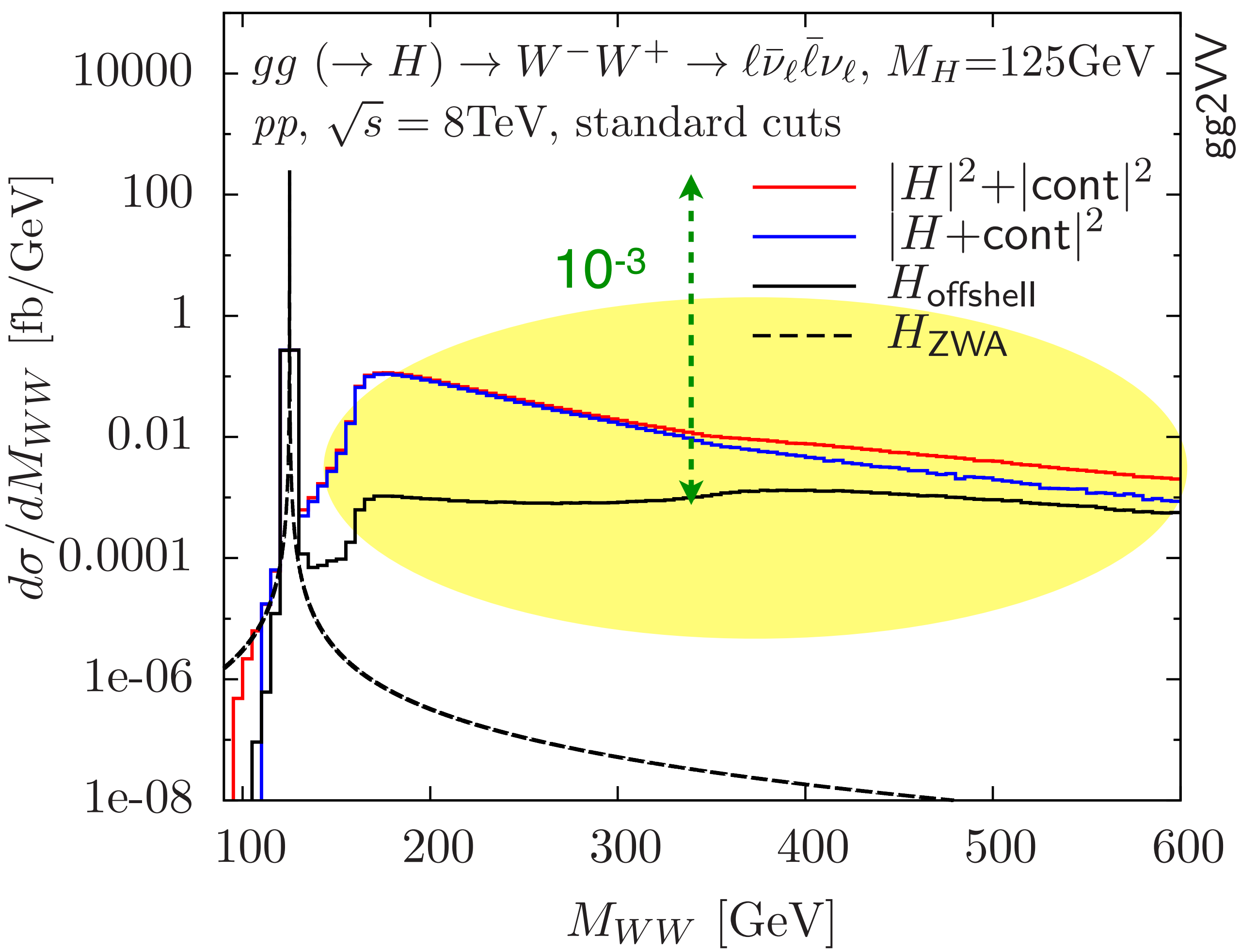
$$\mathcal{A}_{ij\to X} = \mathcal{A}_{ij\to H} \frac{-1}{Q^2 - m_H^2 + i m_H \Gamma_H} \mathcal{A}_{H\to X} + \mathcal{A}_{continuum}$$

• Finite width effects can be sizable in some decay channels even for a light Higgs

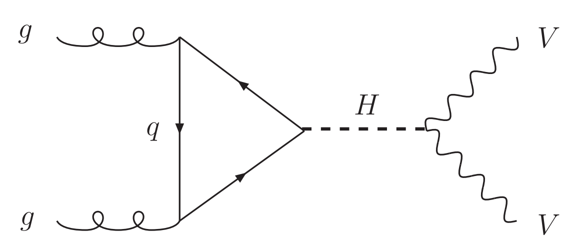
N. Kauer

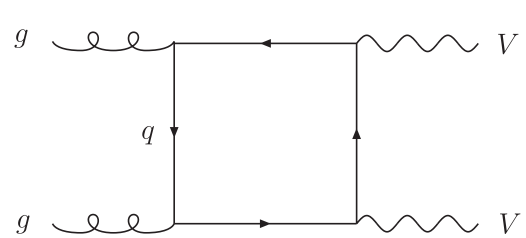
e.g., Breit-Wigner lineshape deformed by decay amplitude above threshold

$$|\mathcal{M}_d(H \to VV)|^2 \sim (q^2)^2 \quad \text{for } \sqrt{q^2} \gtrsim 2\,M_V$$



$gg\ (\to H) \to W^-W^+ \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$, σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 125$ GeV					
selection cuts	H_{ZWA}	H_{offshell}	cont	$\lvert H_{\text{ofs}}+\text{cont}\rvert^2$	R
standard cuts	2.707(3)	3.225(3)	10.493(5)	12.241(8)	0.839(2)
Higgs search cuts	1.950(1)	1.980(1)	2.705(2)	4.497(3)	0.9850(7)
$0.75M_H < M_T < M_H$	1.7726(9)	1.779(1)	0.644(1)	2.383(2)	0.9966(8)





Integration over large kinematical range enhances off-shell effects and interference with background

How to include interference (QCD recommendations)

G.Passarino

Additive

$$\frac{d\sigma^{\rm NNLO}_{eff}}{dx} = \frac{d\sigma^{\rm NNLO}}{dx}(S) + \frac{d\sigma^{\rm LO}}{dx}(I) + \frac{d\sigma^{\rm LO}}{dx}(B)$$

Multiplicative

$$\frac{d\sigma^{\rm NNLO}_{eff}}{dx} = K_{\rm D}\left[\frac{d\sigma^{\rm LO}}{dx}(S) + \frac{d\sigma^{\rm LO}}{dx}(I)\right] + \frac{d\sigma^{\rm LO}}{dx}(B), \qquad K_{\rm D} = \frac{\frac{d\sigma^{\rm NNLO}}{dx}(S)}{\frac{d\sigma^{\rm LO}}{dx}(S)},$$

Intermediate

$$\frac{d\sigma^{\rm NNLO}_{eff}}{dx} = K_{\rm D}\,\frac{d\sigma^{\rm LO}}{dx}(S) + \left(K_{\rm D}^{\rm gg}\right)^{1/2}\frac{d\sigma^{\rm LO}}{dx}(I) + \frac{d\sigma^{\rm LO}}{dx}(B)$$

"Central value"

Signal-background interference effects for $gg \to H \to W^+W^-$ beyond leading order

M.Bonvini, F.Caola, S.Forte, K.Melnikov, G.Ridolfi

Use soft-virtual approximation at NNLO (assuming two-loop Higgs coefficient for background)

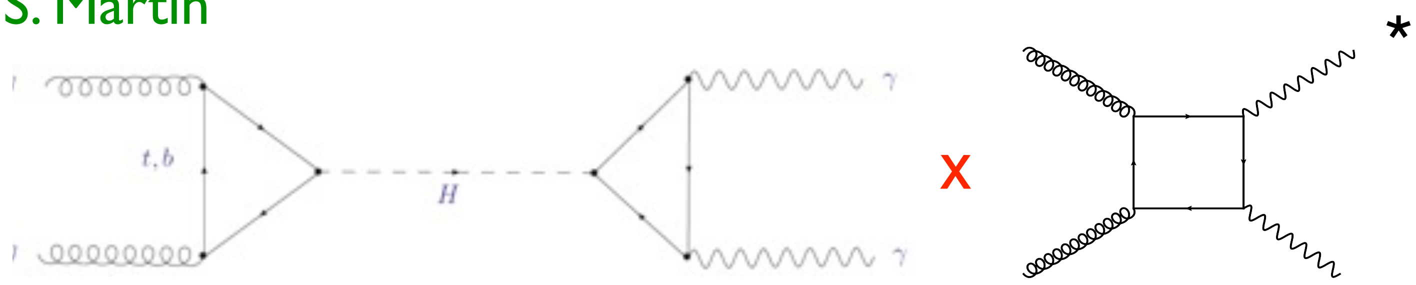
QCD corrections enhance interference, similar to enhancement for signal

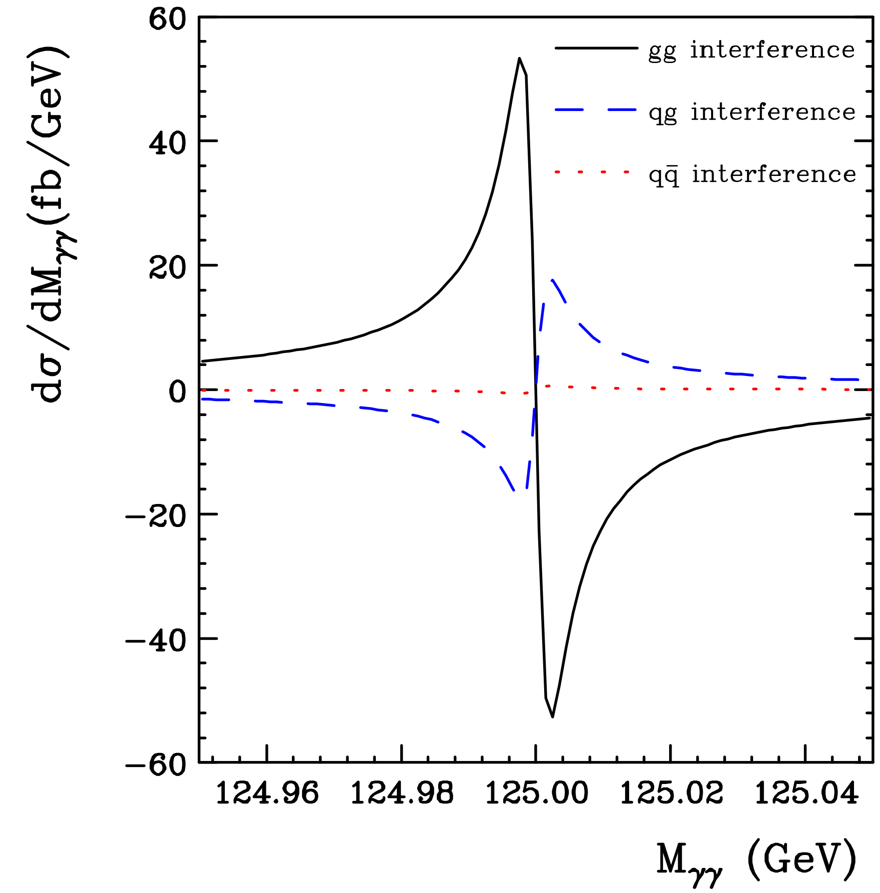
$$K_{signal} \sim K_{interf}$$

$m_h = 600$ GeV.	$\sqrt{s} = 8$ 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)
$\sigma_H/\sigma_H^{\rm LO}$	—	2.19(5)	2.8(1)	—	2.13(5)	2.7(1)
$\sigma_{Hi}/\sigma_{Hi}^{\rm LO}$	—	2.19(7)	2.8(2)	—	2.12(6)	2.7(1)

Interference in diphoton production

•S. Martin



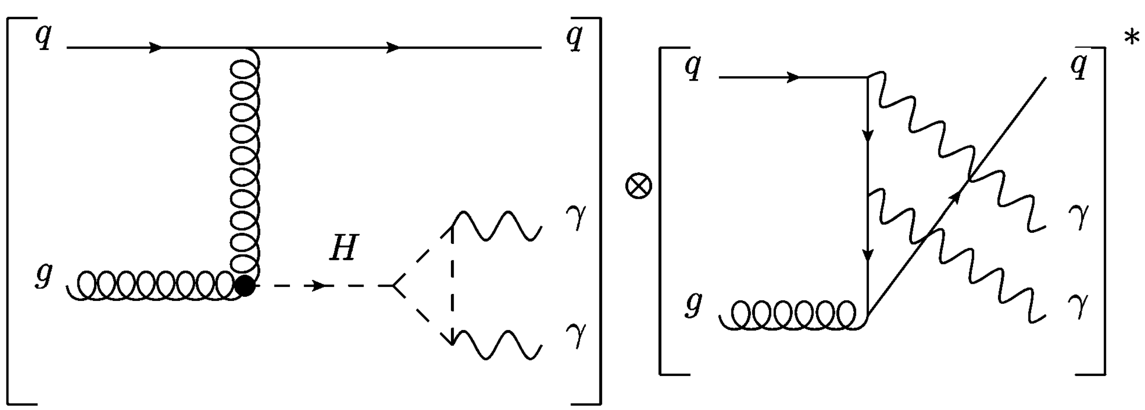


- small asymmetry in the interference
- at this level shift is O(MeV) as expected

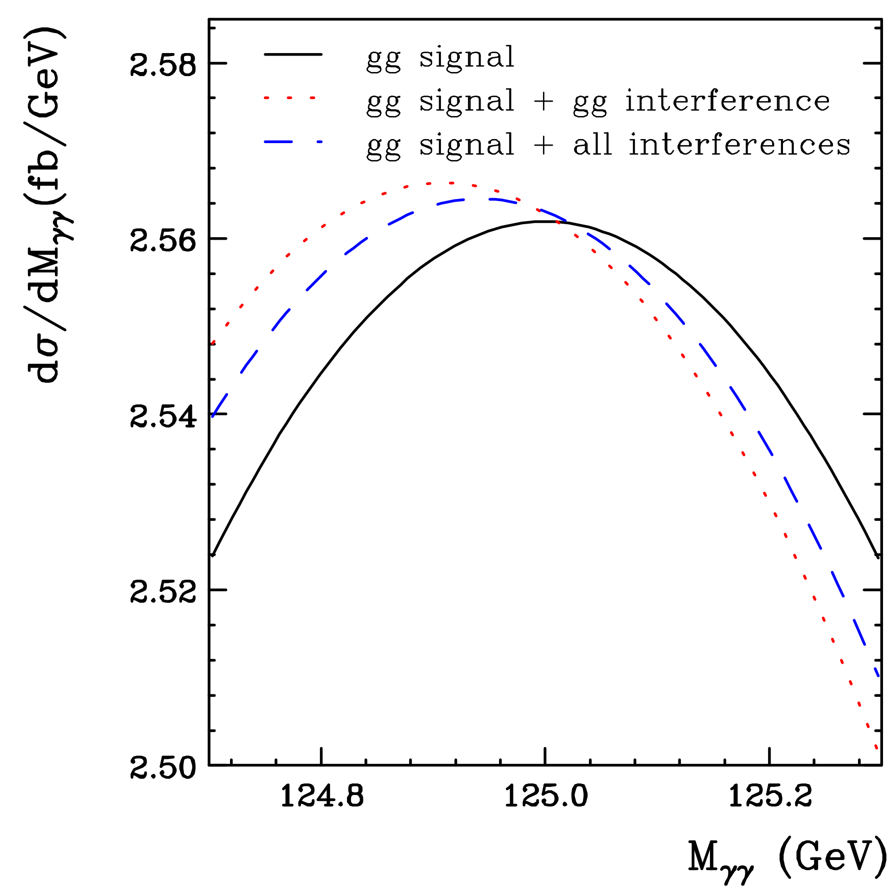
Asymmetry enhanced by detector resolution can reach 100 MeV effect

Effects from other channels go in opposite direction

•D.deF., N.Fidanza, R.Hernandez-Pinto, J.Mazzitelli, Y.Rotstein, G.Sborlini

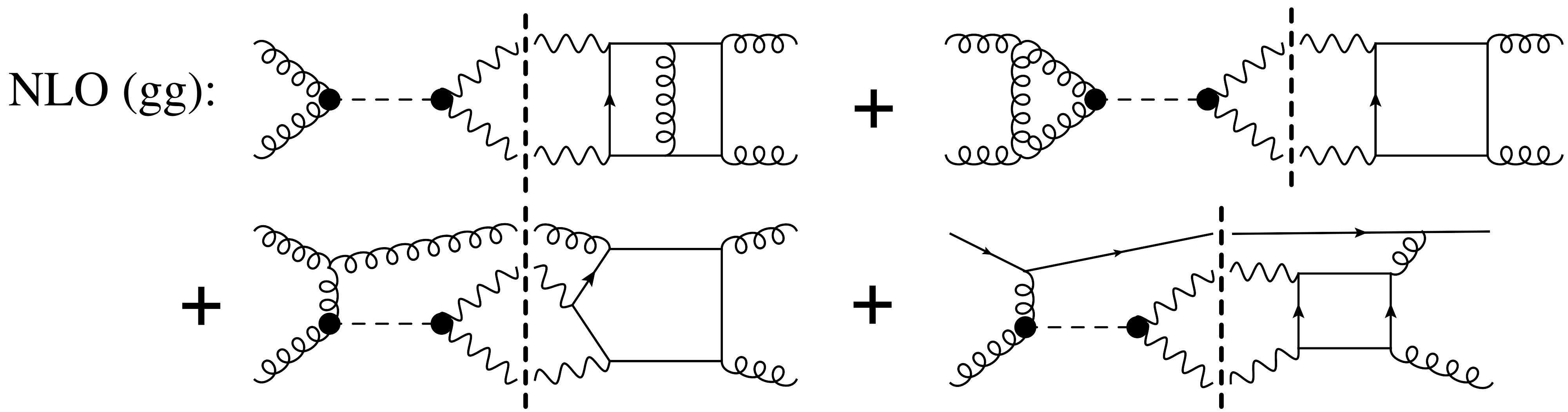


90 MeV ⟶ 60 MeV

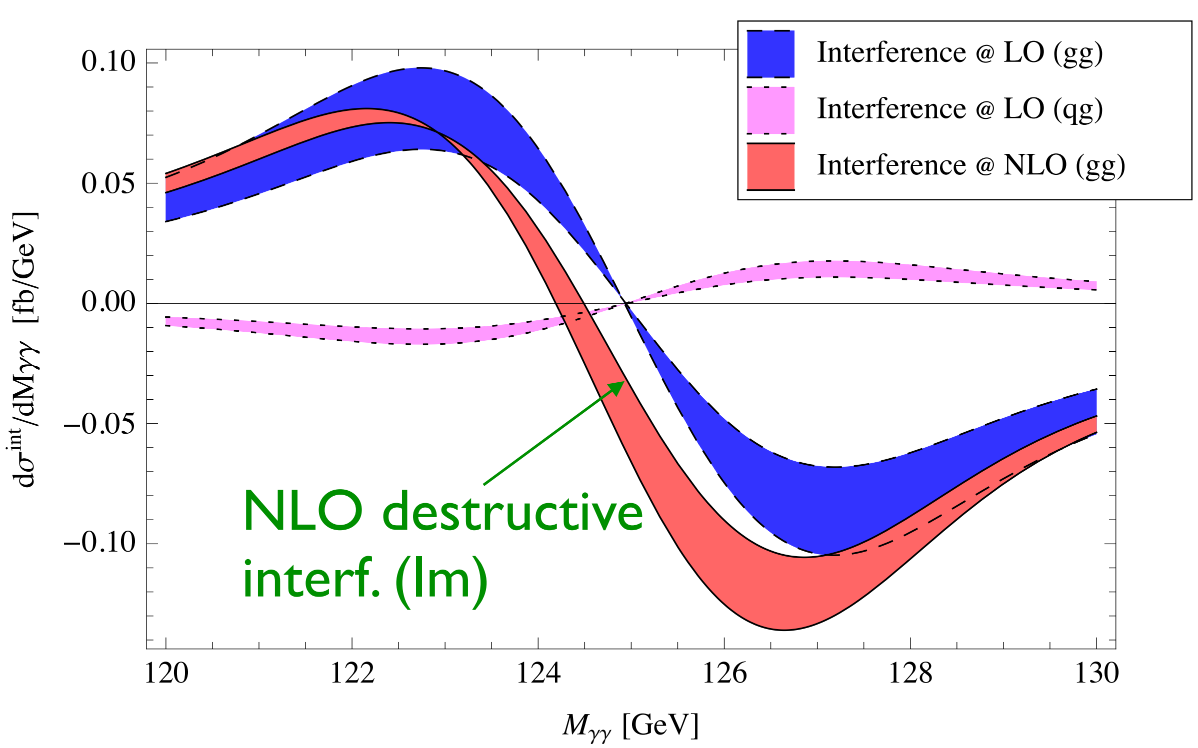


Interference at NLO

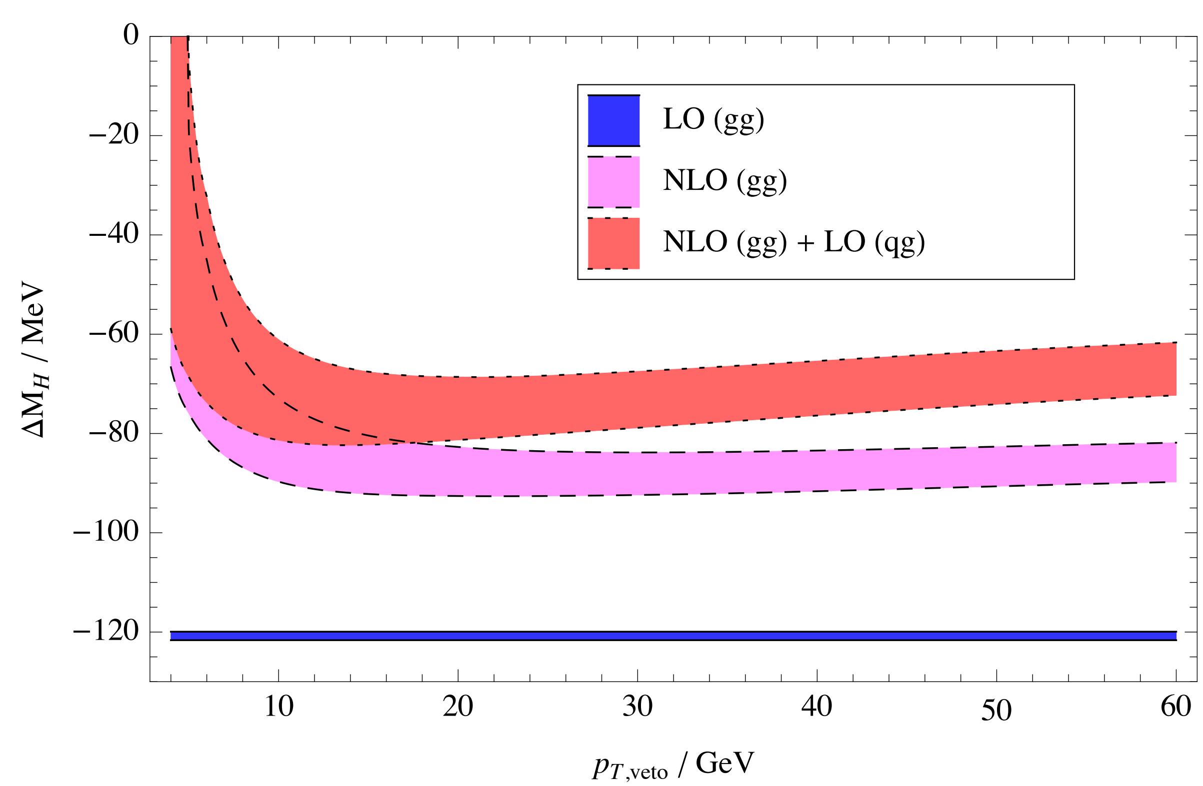
L.Dixon, Y.Li (2013)



Interferences



Mass shift

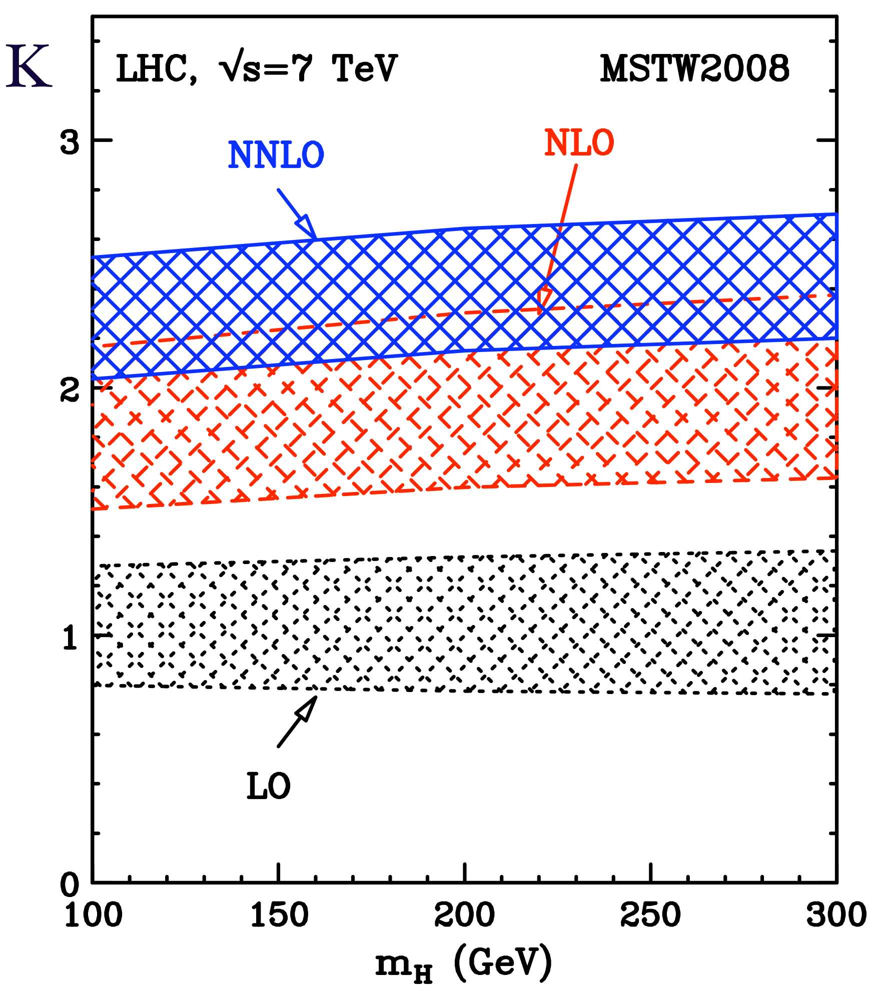


Reduction in mass shift but sensitive to width

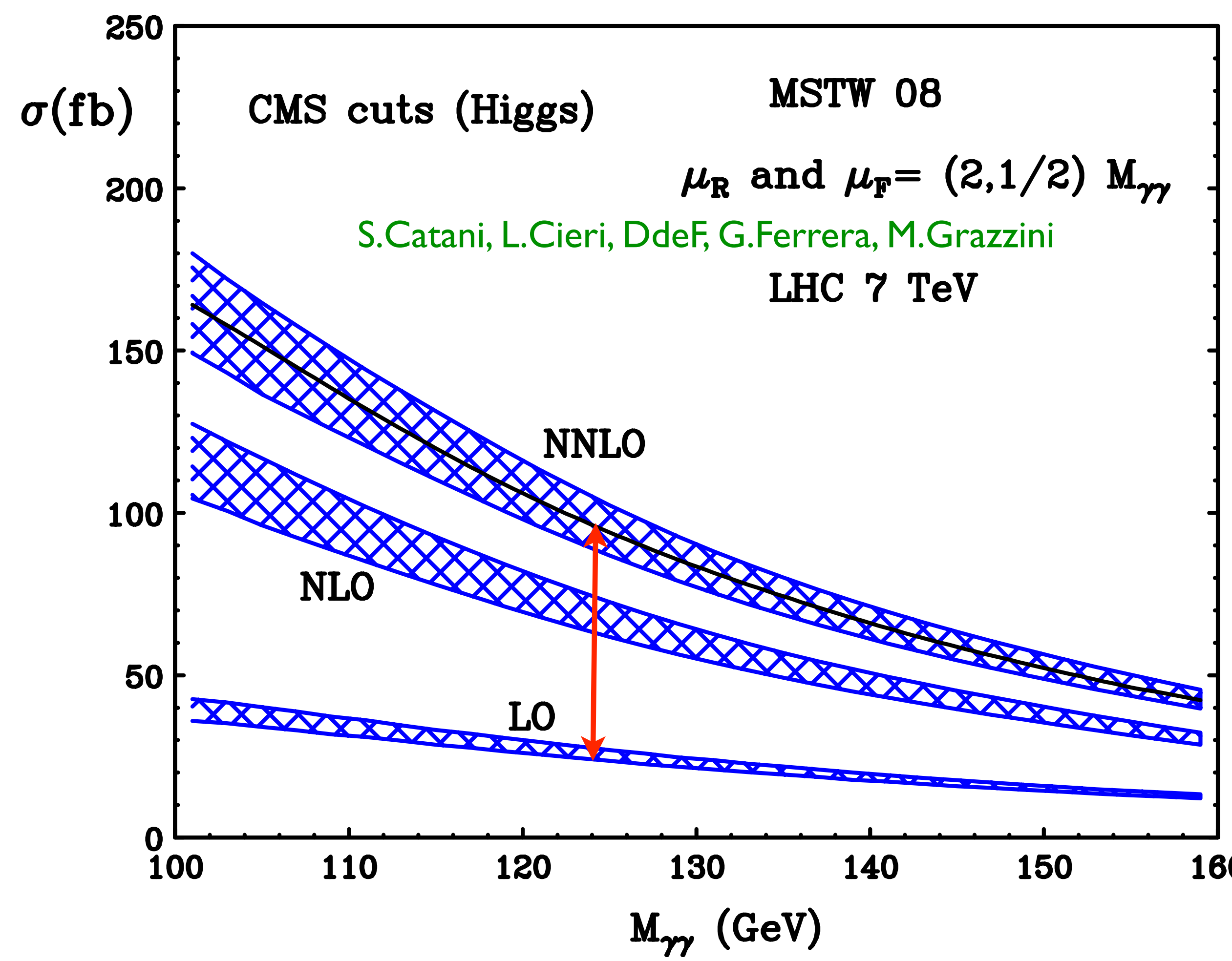
LH : Accords, Wish-list, Tools, Fondue, Joey Huston, Photons !

Signal NNLO

$\mathcal{O}(\alpha_s^4)$



Background NNLO



$K^{NNLO} \sim 3.5$