The Precision Higgs Frontier

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ICAS

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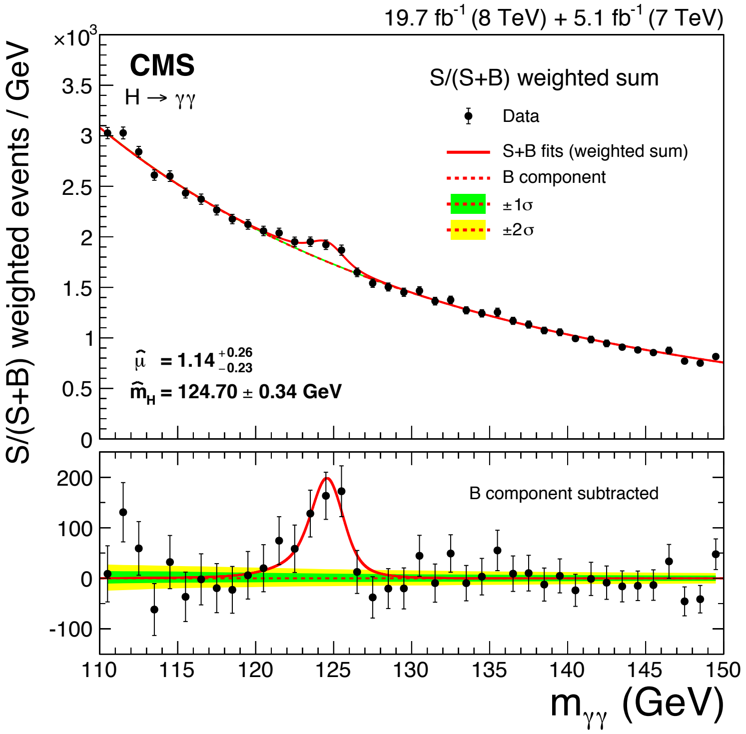
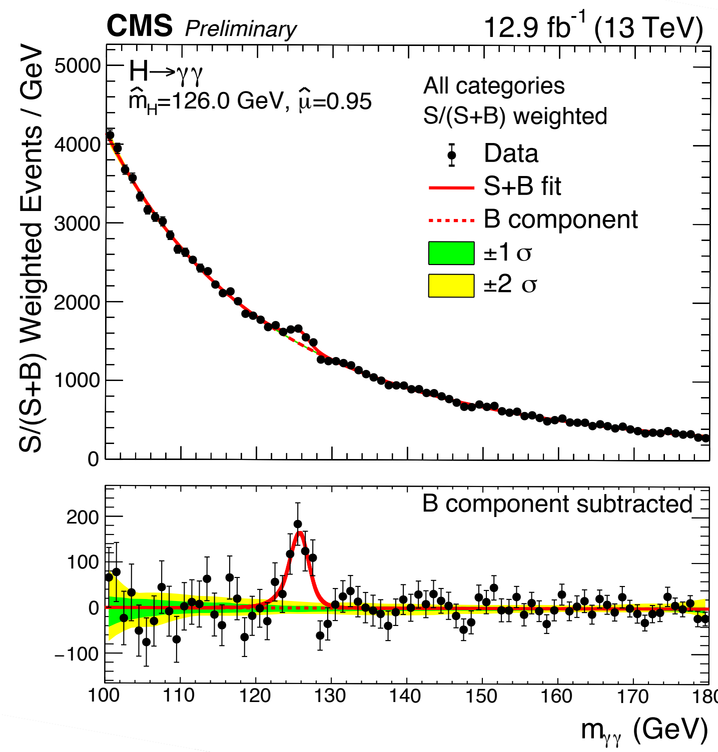
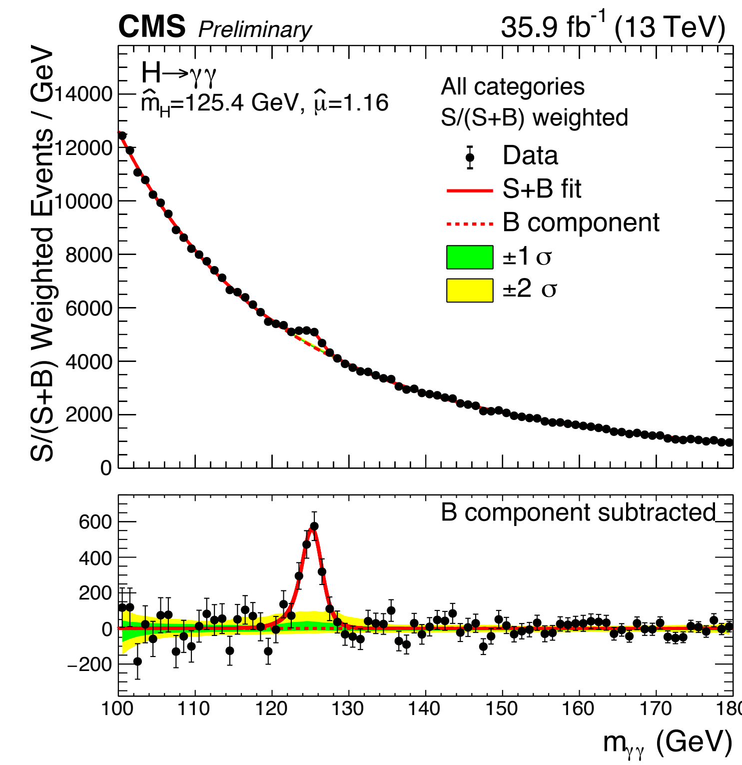
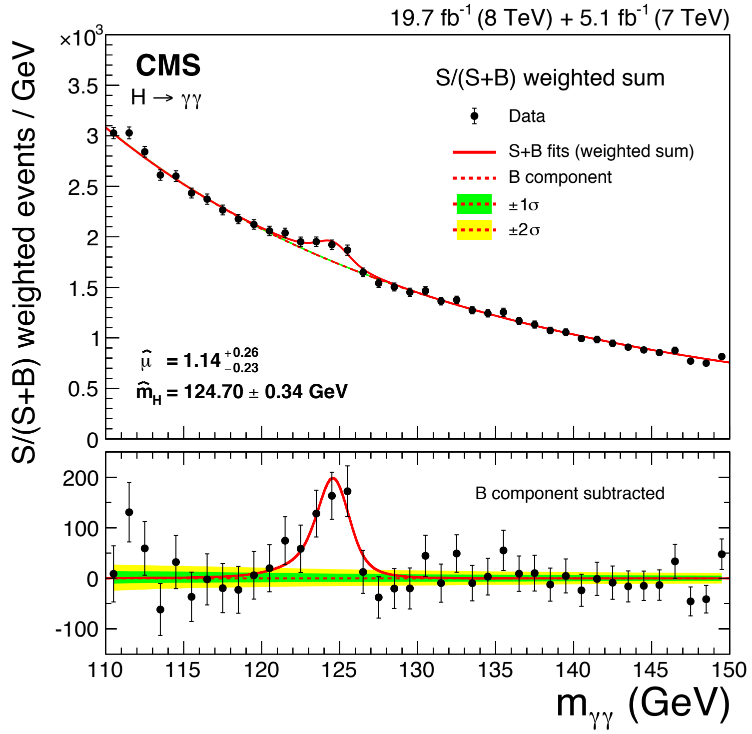
Higgs discovered, re-discovered and re-re-discovered

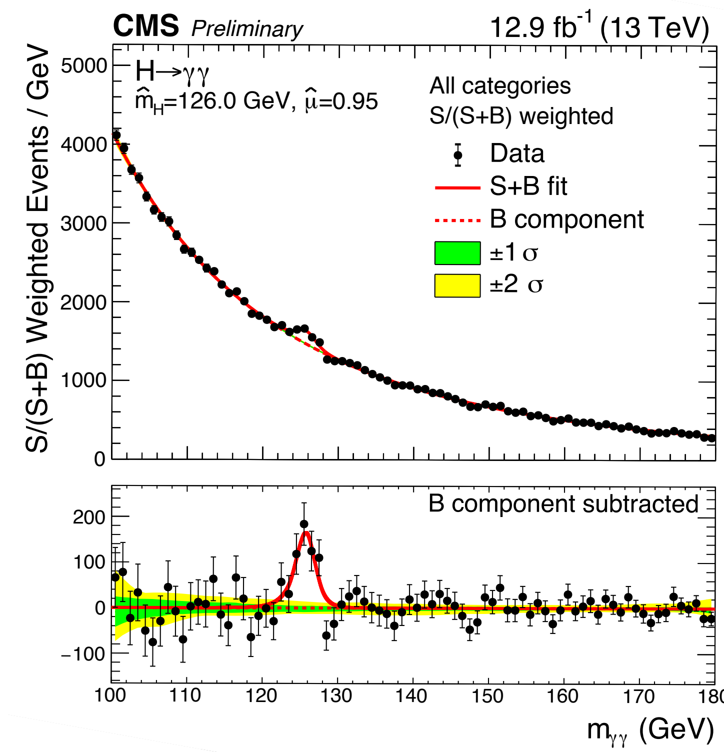


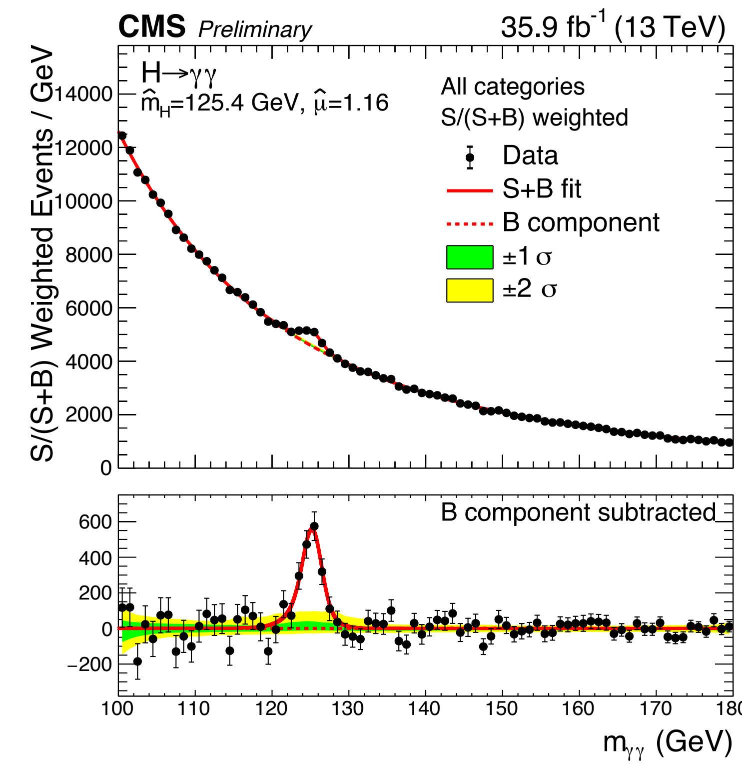




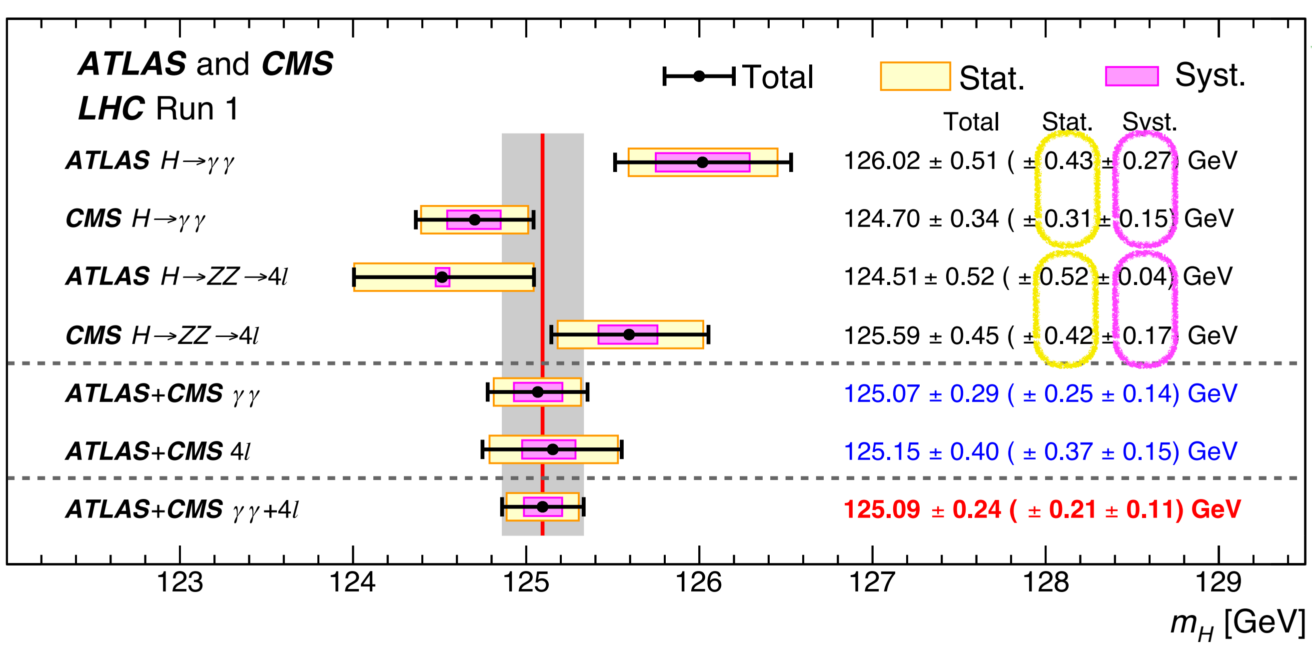
Higgs discovered, re-discovered and re-re-discovered





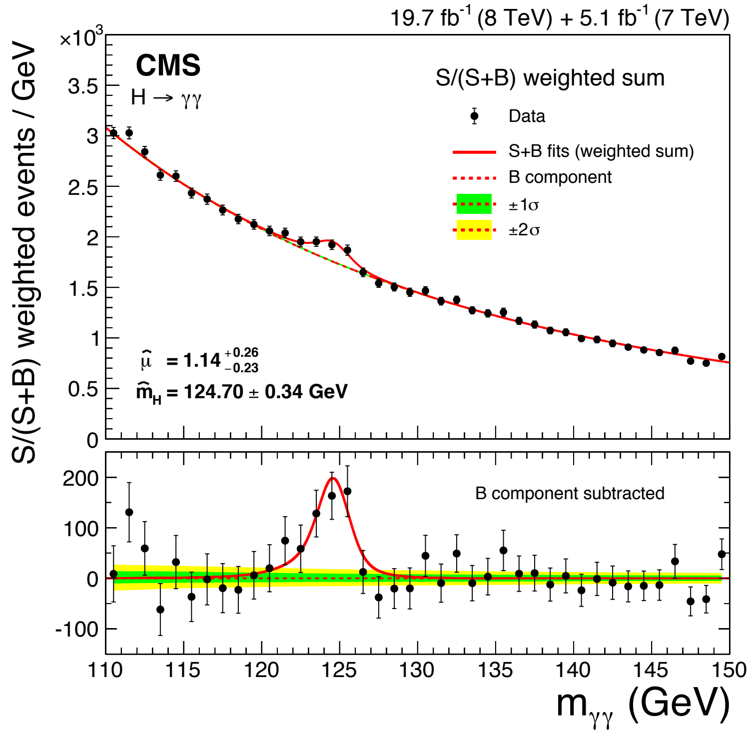


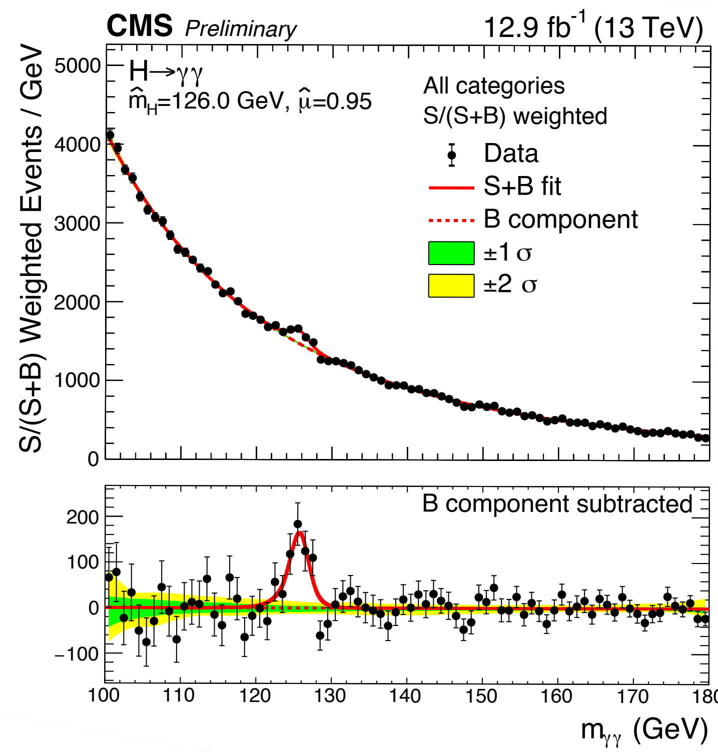
- Run 1 mass combination: ATLAS and CMS (2015) 125.09 GeV

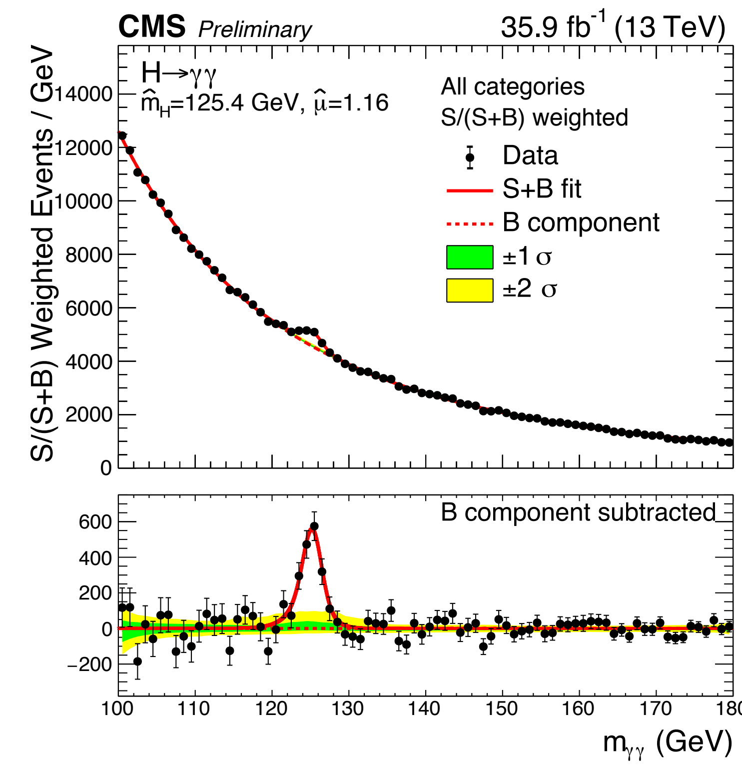


- Uncertainty in mass ~ 0.2% , better than for top (~0.5%)!

Higgs discovered, re-discovered and re-re-discovered







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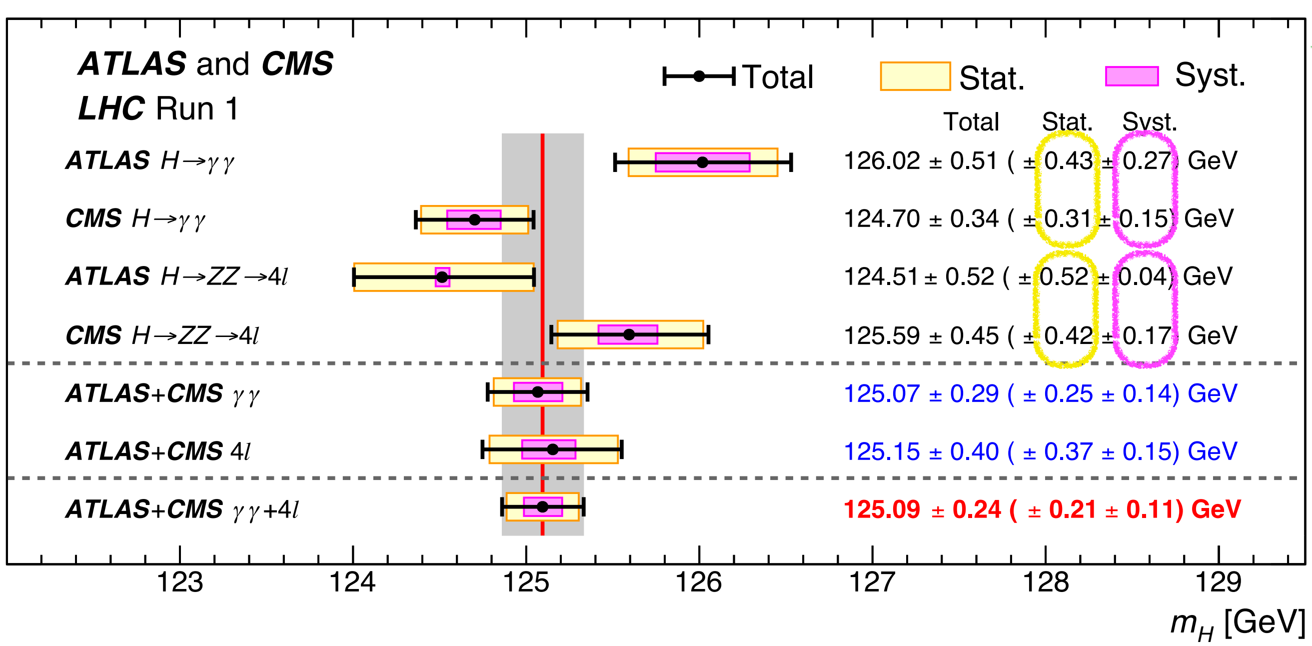
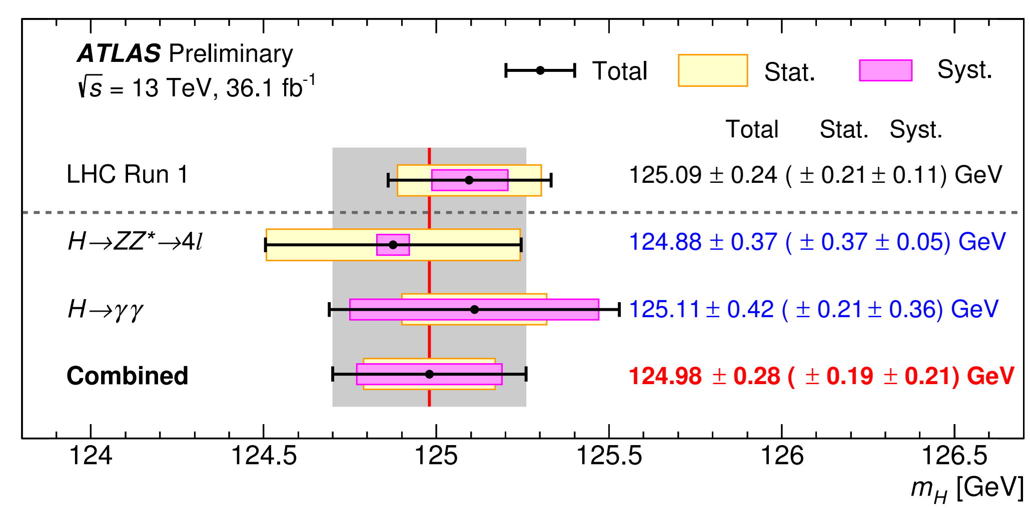


now similar precision in one exp



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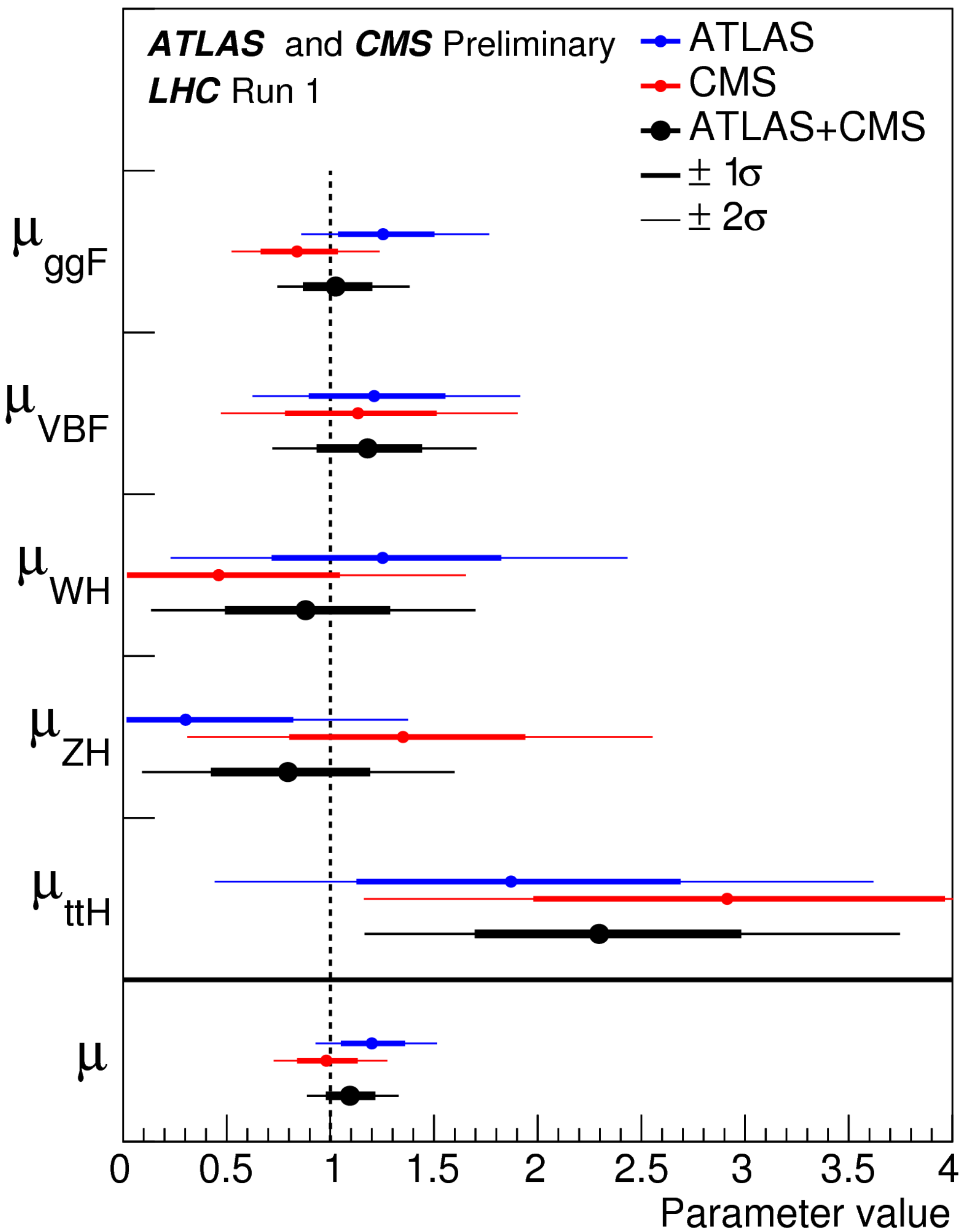
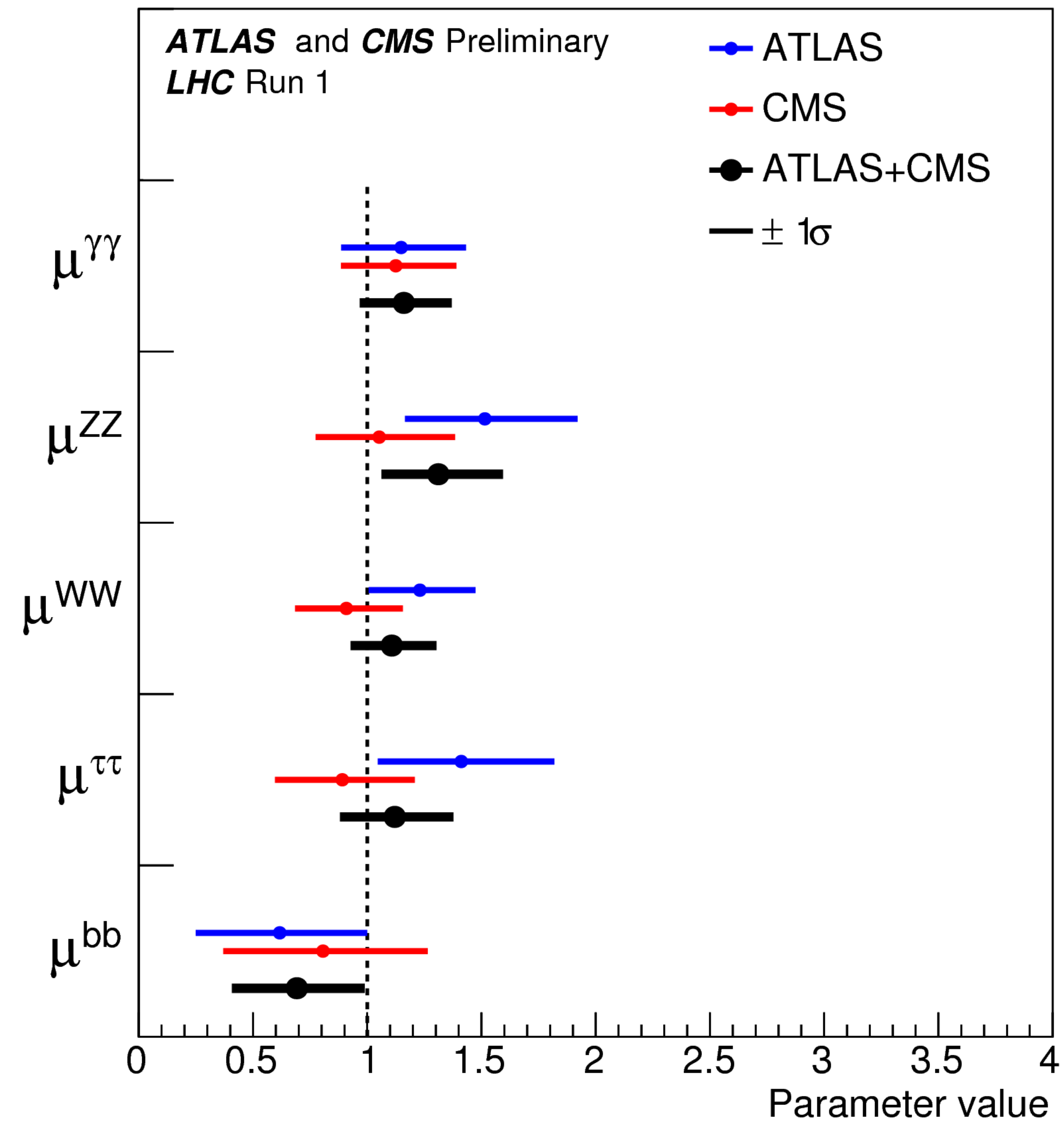
Cross sections in "agreement" with SM in all channels (large errors yet)

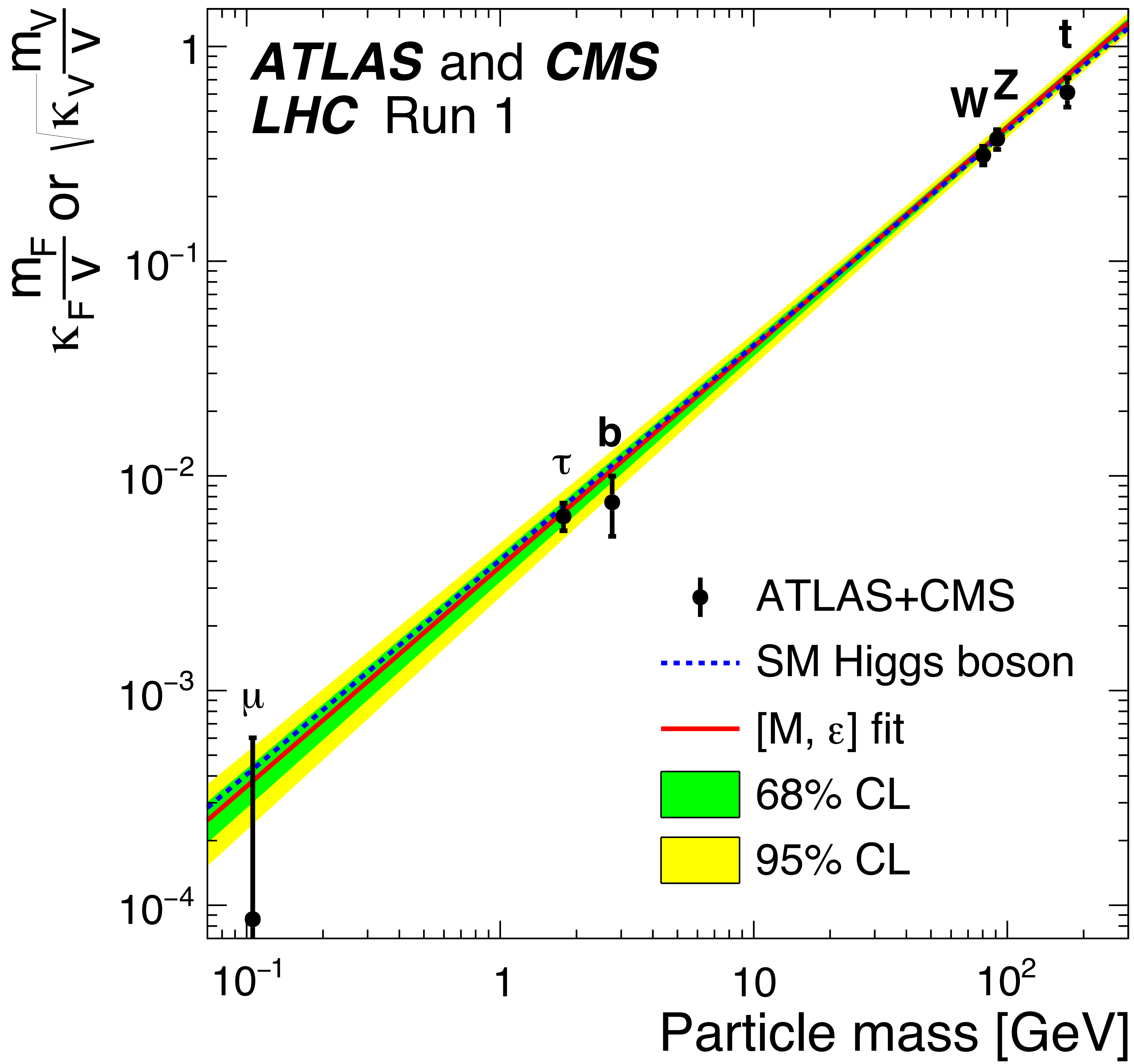
Signal strength $\mu = \dfrac{\sigma}{\sigma_{SM}}$ similar for Run 2





$$\frac{\sigma}{\sigma_{SM}} \equiv \mu = 1.09 \pm 0.07(stat) \pm .04(syst) \pm .03(th\ bckd)^{+.07}_{-.06}(th\ signal)$$

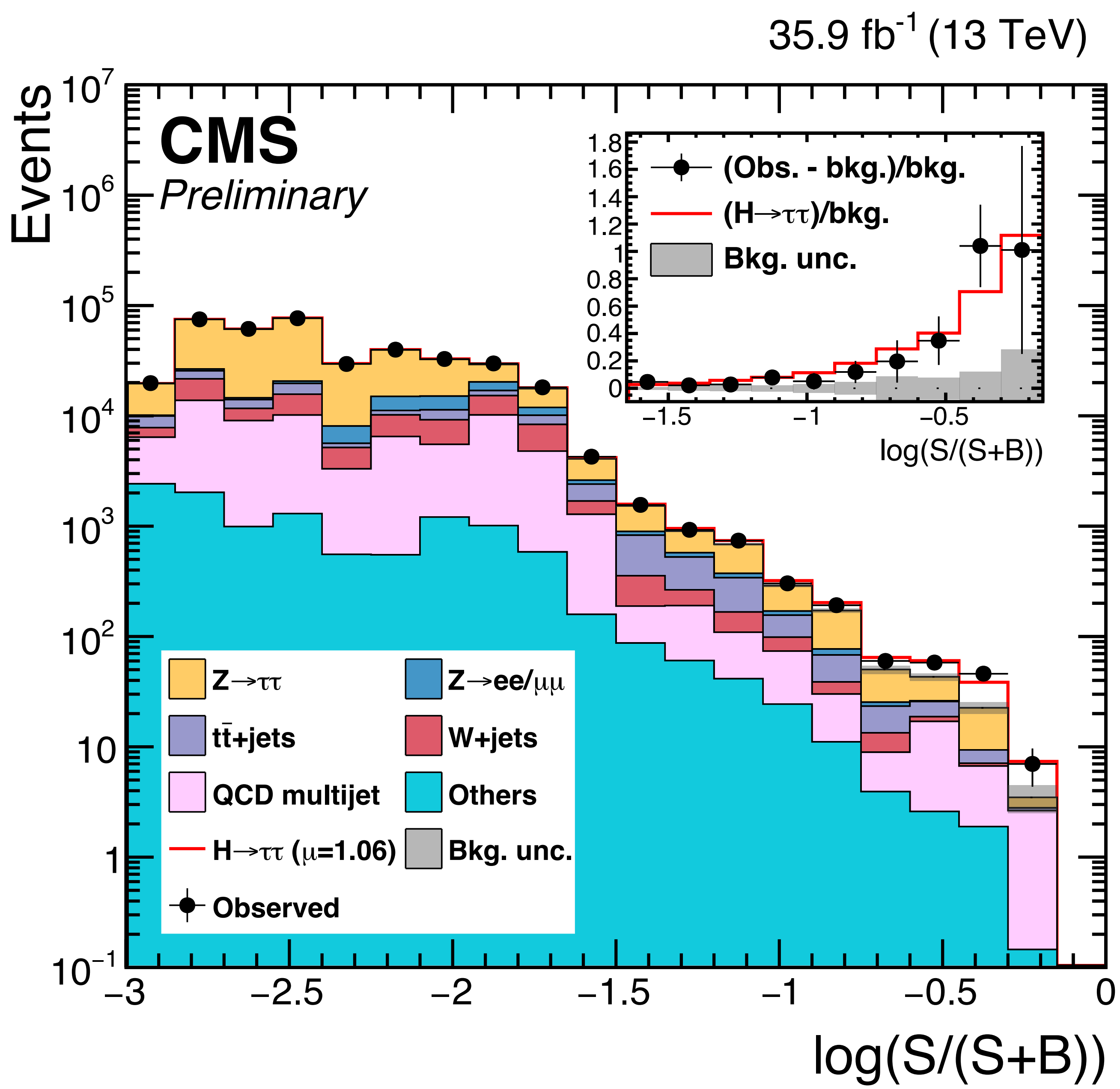
Couplings

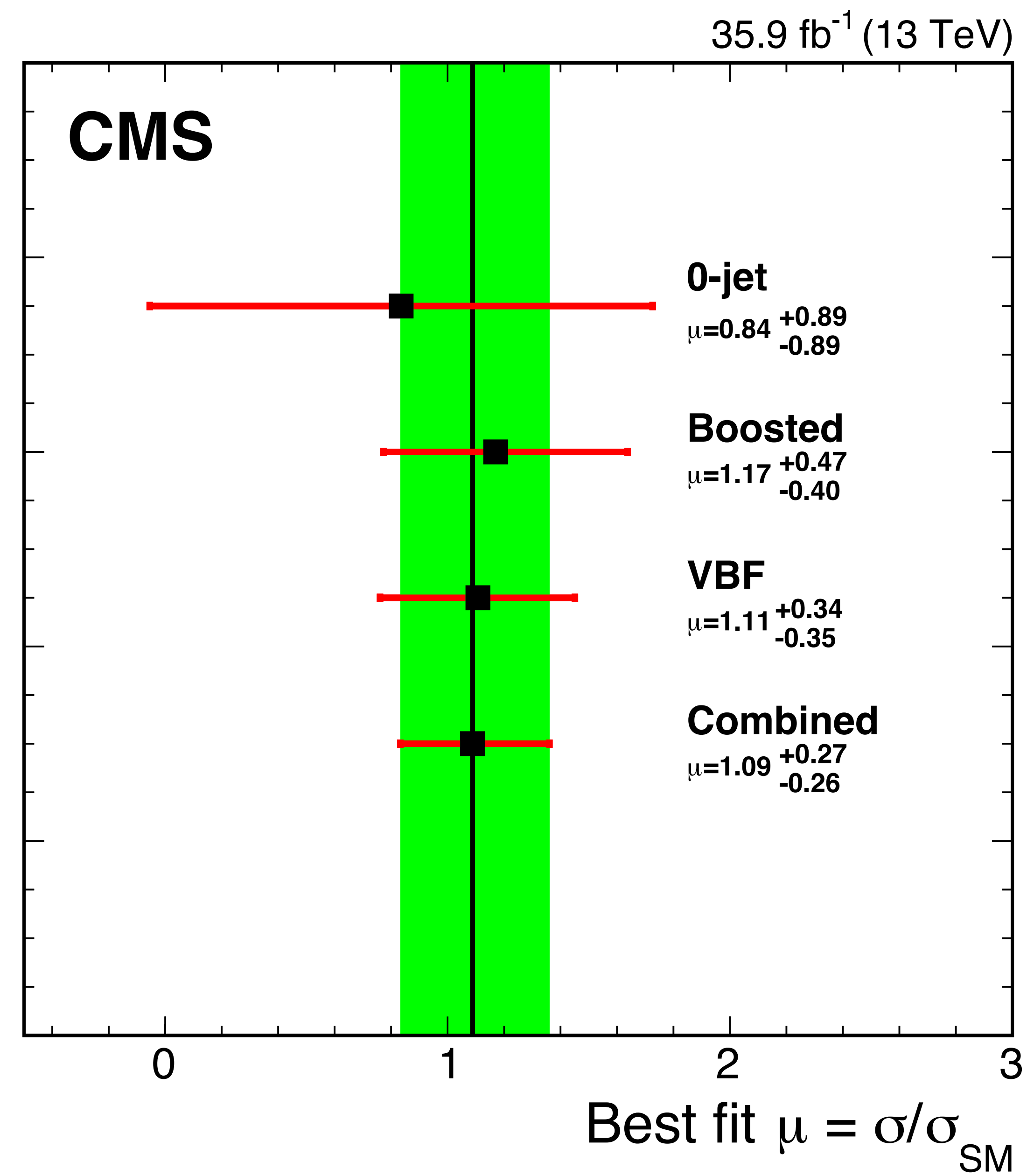


ATLAS and CMS
LHC Run 1
t
W
Z
τ
b
μ
ATLAS+CMS
SM Higgs boson
[M, ε] fit
68% CL
95% CL
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-1}
1
10
10^{2}
Particle mass [GeV]
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$

$H \to \tau\bar{\tau}$ observation!

~36 fb^{-1}





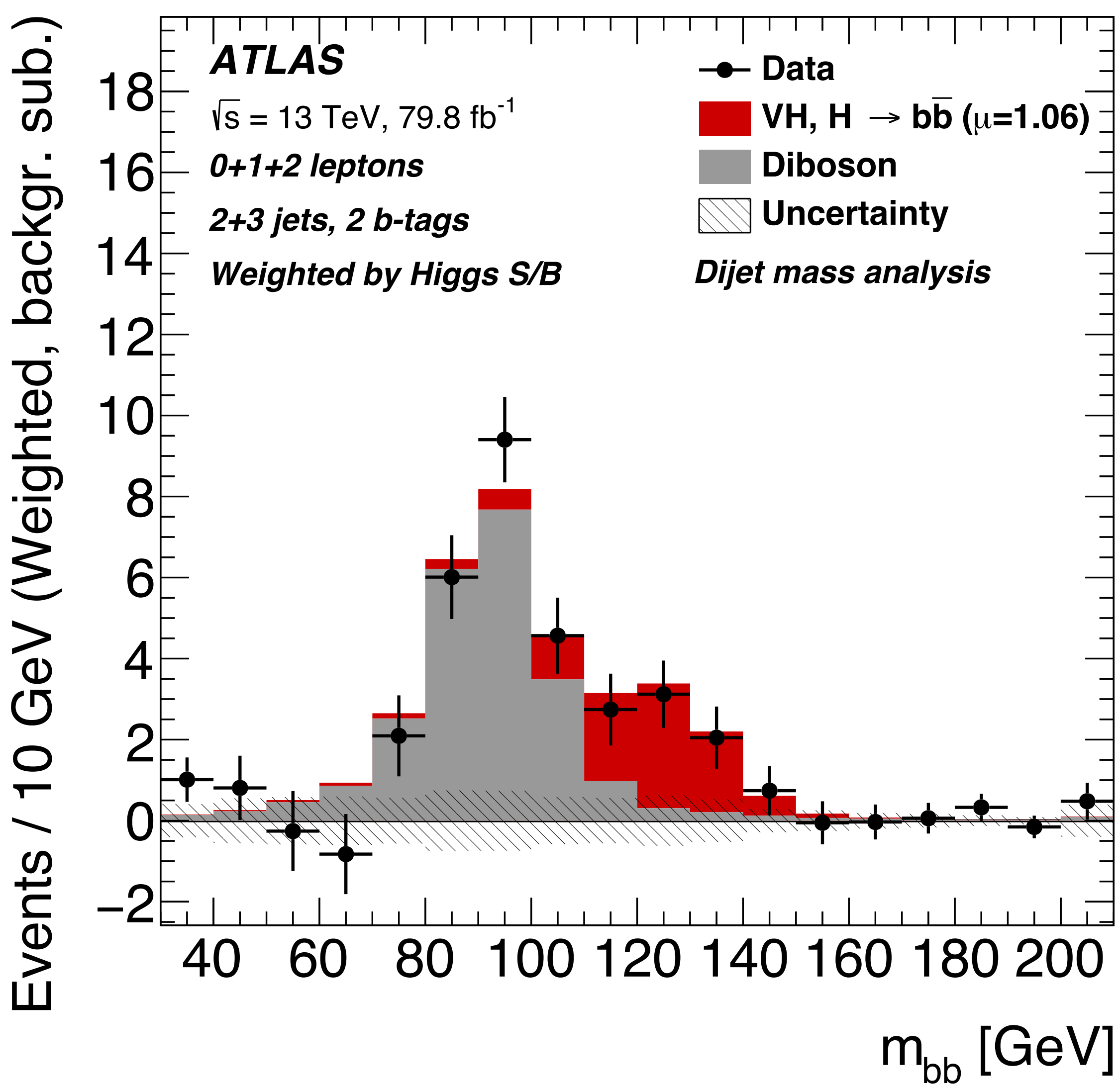
Observed significance is 4.9 σ

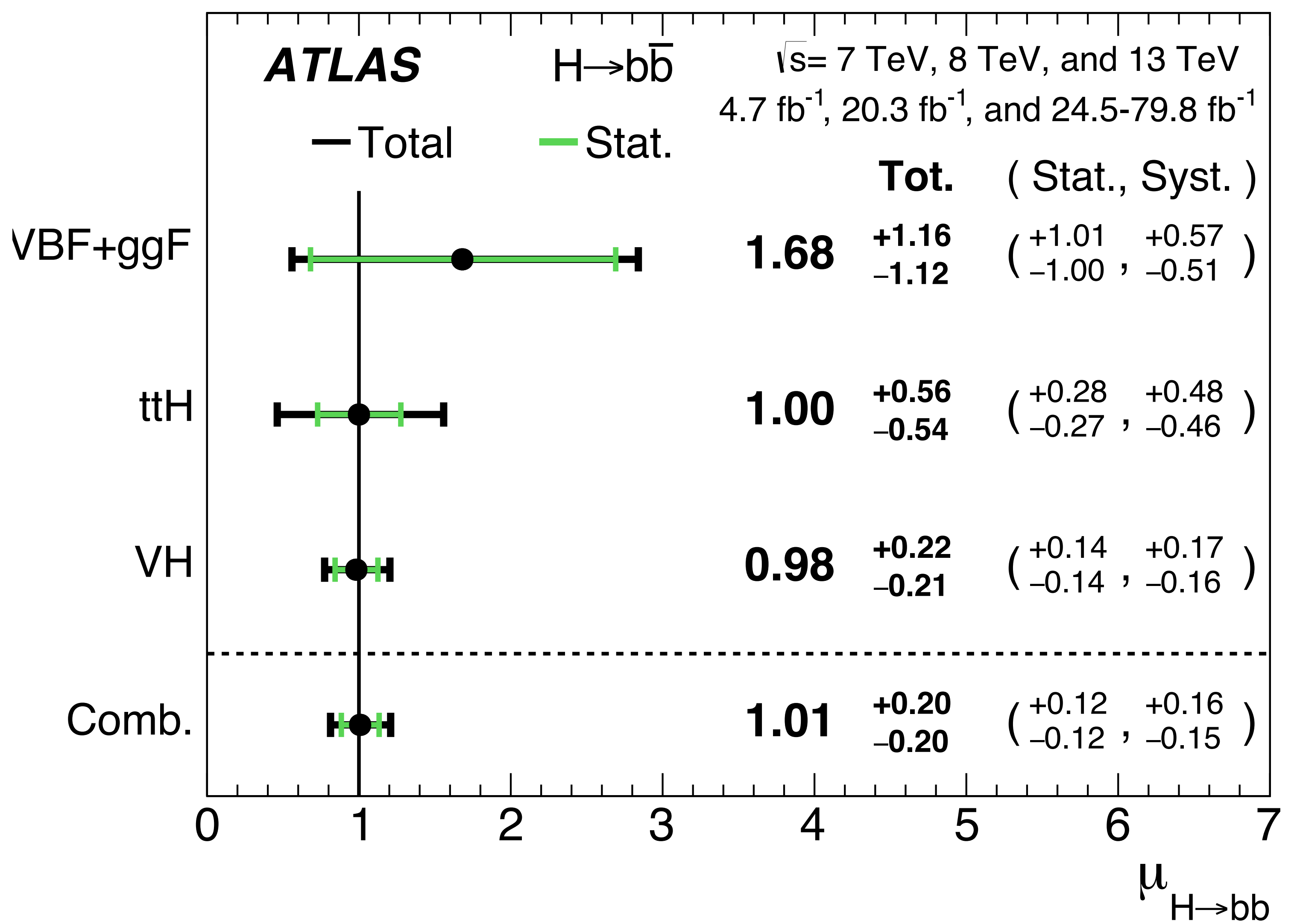
5.9 when combined with CMS Run1

Best Fit signal strength : 1.06 ± 0.25

$H \to b\bar{b}$ observation!

~80 fb^{-1}





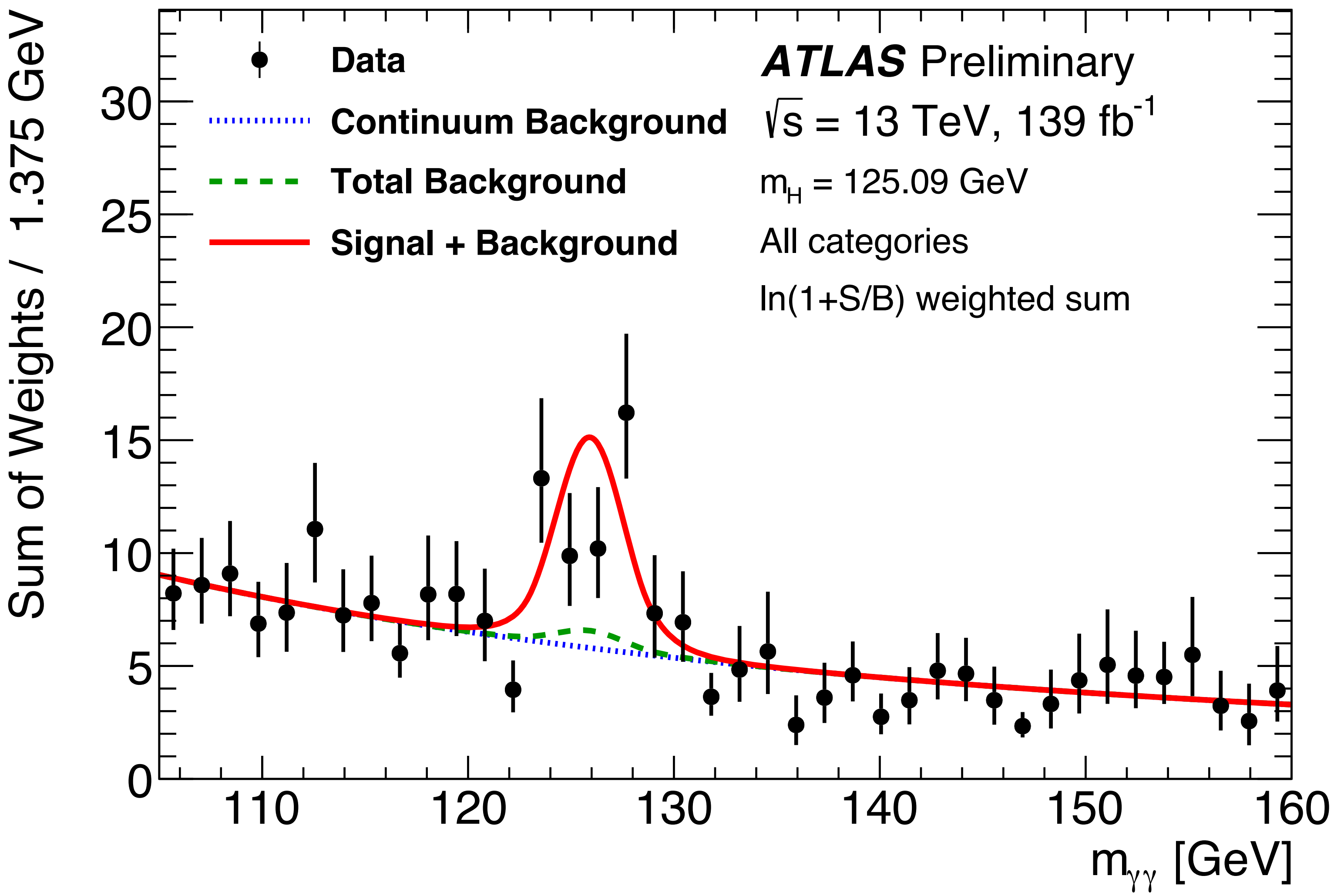
observed significance

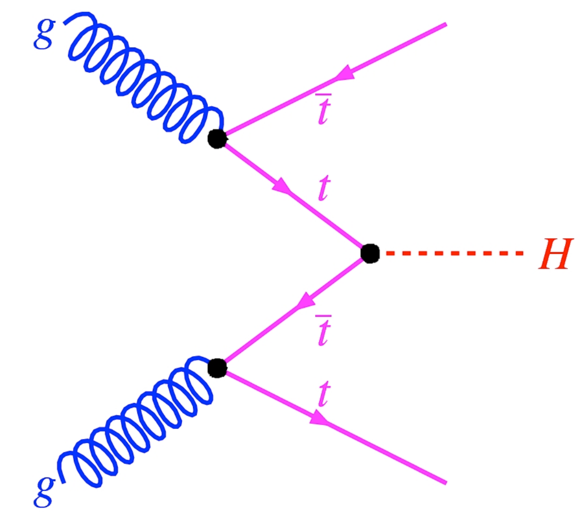
5.4σ

signal strength : $1.01 \pm 0.12(\mathrm{stat.})^{+0.16}_{-0.15}(\mathrm{syst.})$

$t\bar{t}H$ observation!

~139 fb^{-1}





direct access to H-top coupling

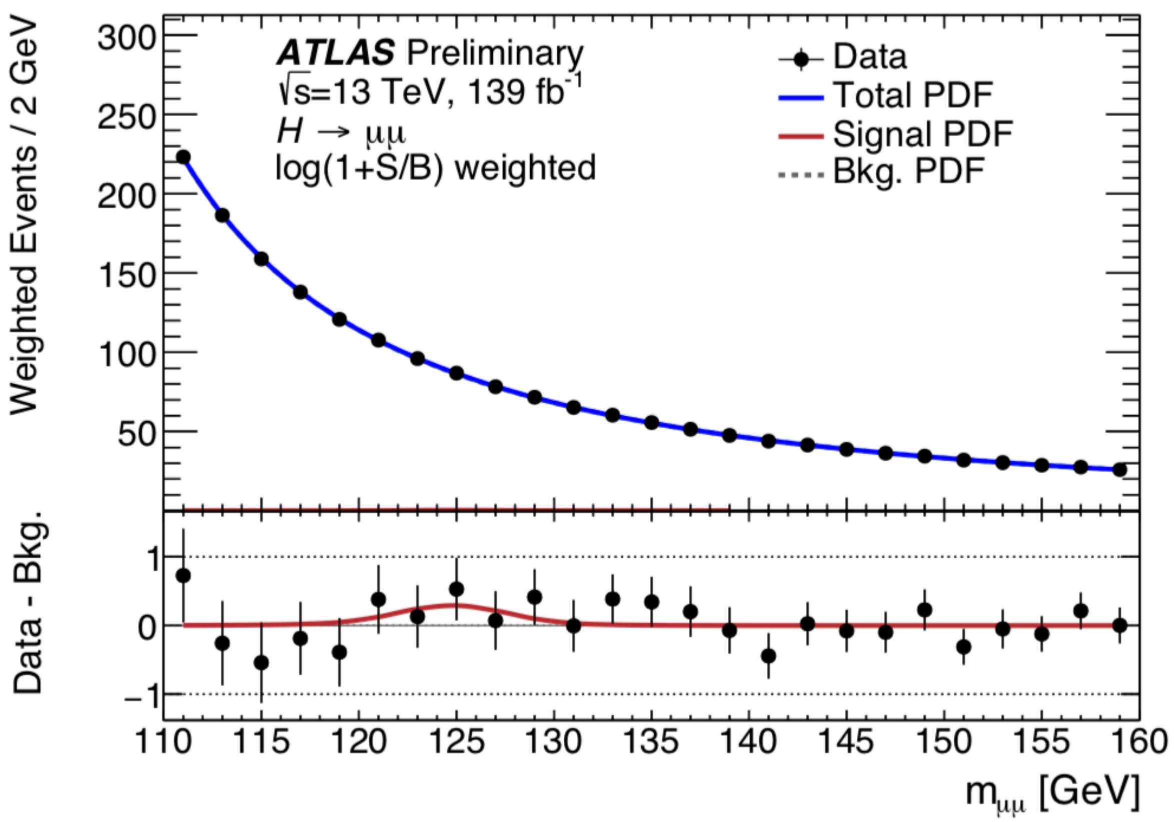
$$\sigma_{t\bar{t}H} \times B_{\gamma\gamma} = 1.59^{+0.43}_{-0.39}\ \text{fb} = 1.59^{+0.38}_{-0.36}\ \text{(stat.)}\ ^{+0.15}_{-0.12}\ \text{(exp.)}\ ^{+0.15}_{-0.11}\ \text{(theo.) fb.}$$

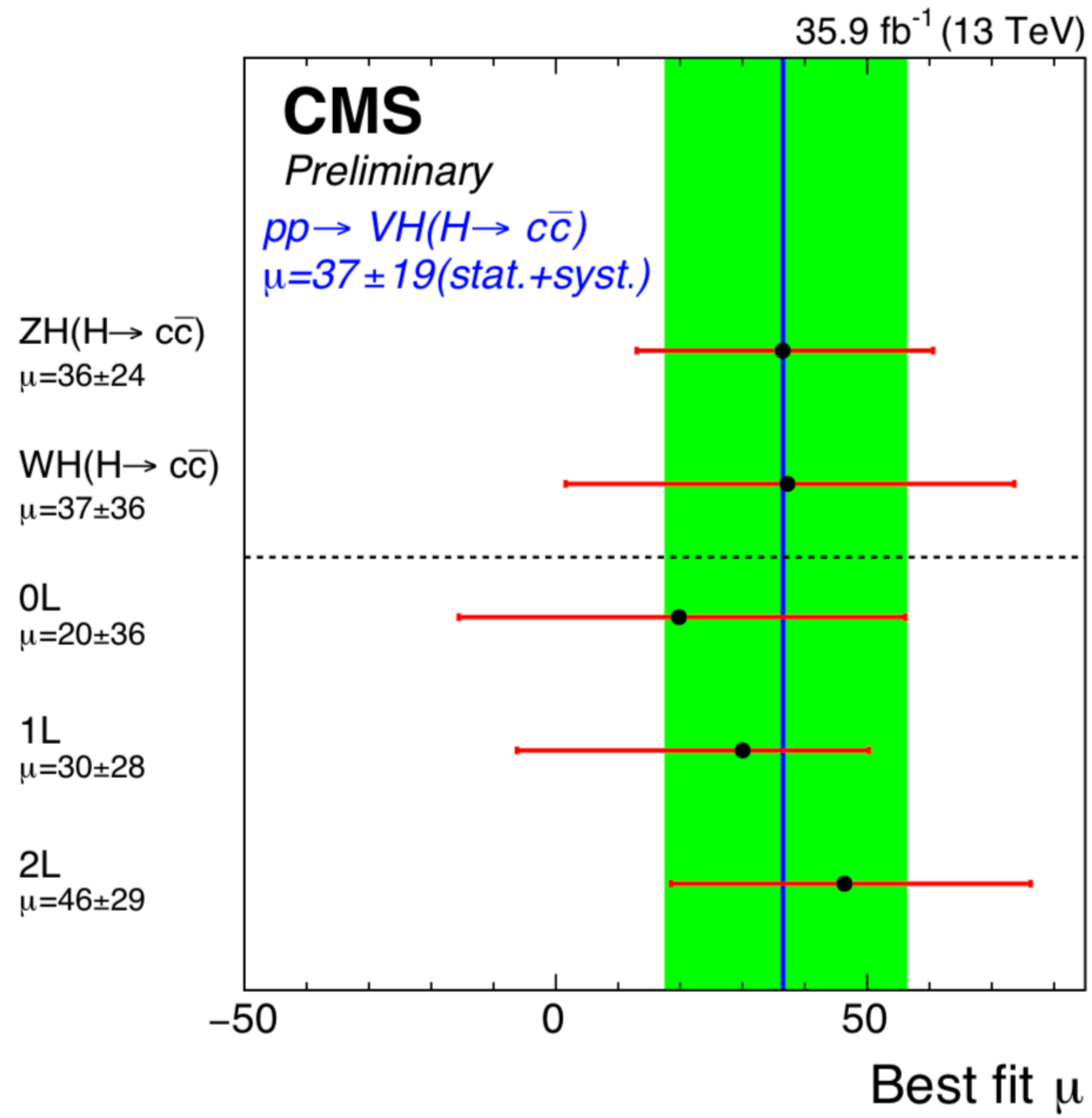
4.9σ signal strength : 1.38 ± 0.41

even Searching for

$$H \to \mu^+\mu^-$$

$$H \to c\bar{c}$$





upper limit of 1.7x SM-BR (95% cl)

$\mu = 0.5 \pm 0.7$

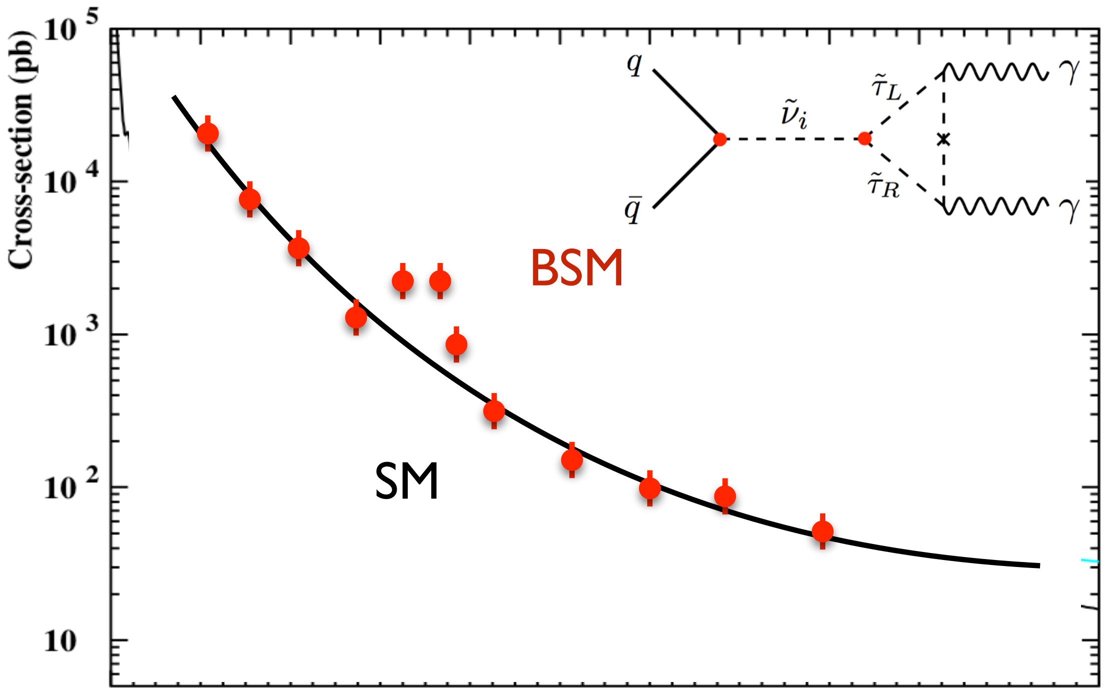
- second generation much more difficult

Everything looks SM-like within (large) uncertainties

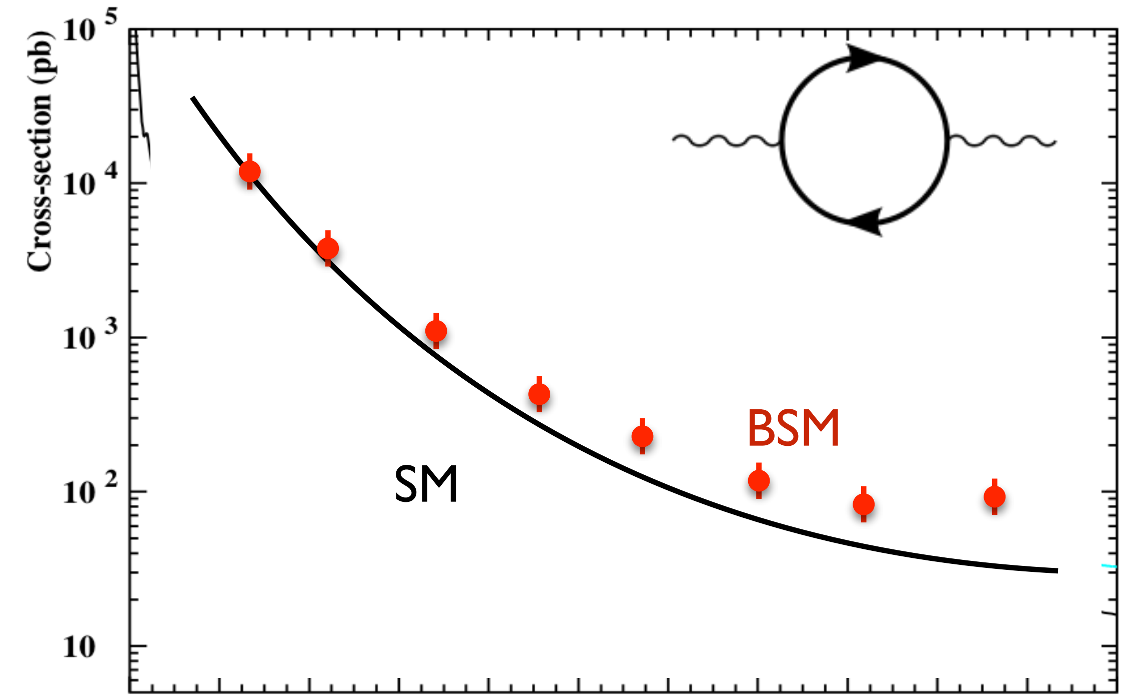
- There is plenty of room for discoveries yet

Everything looks SM-like within (large) uncertainties

▸ There is plenty of room for discoveries yet



Search for new *states*
Resonances: "Descriptive TH"

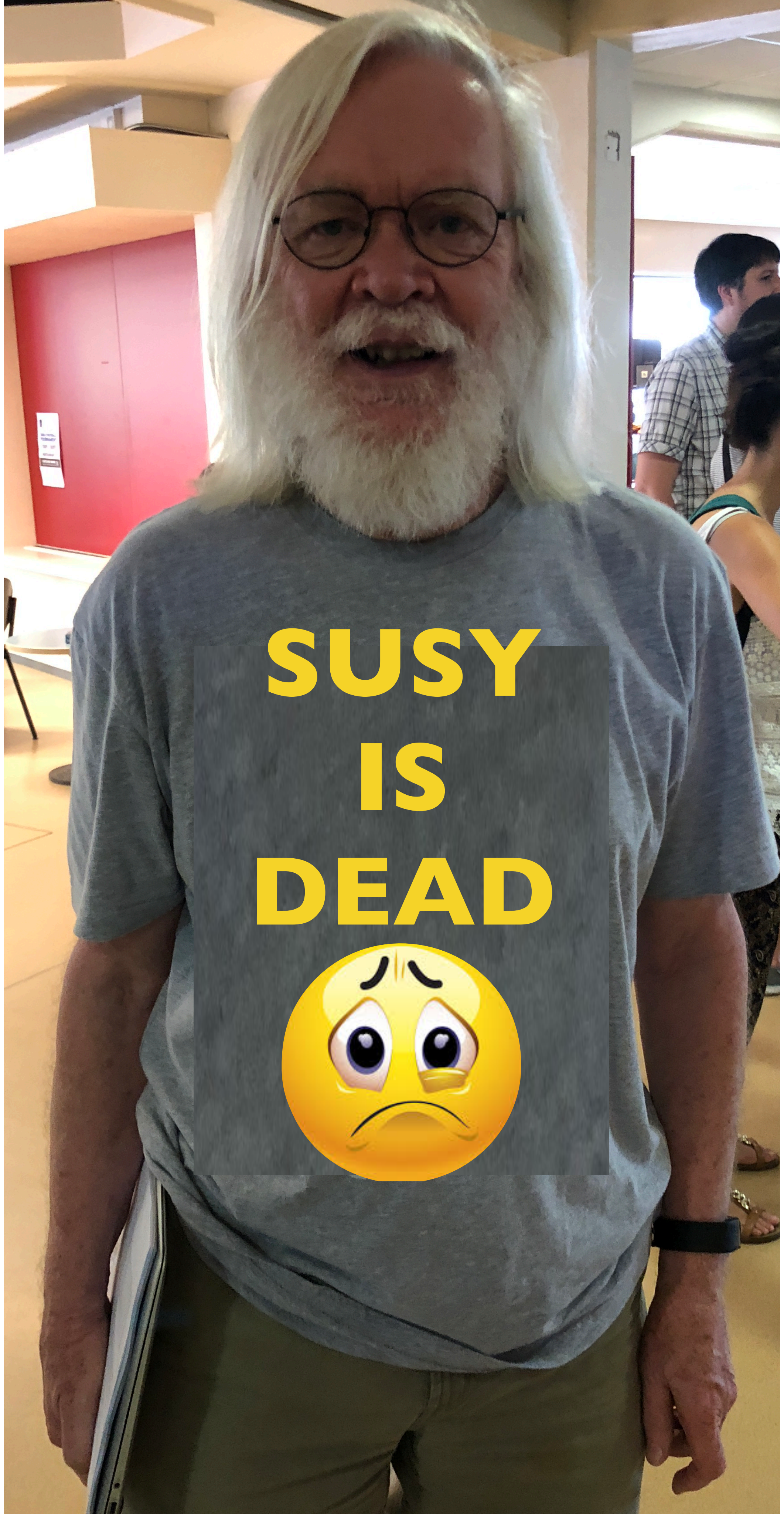


Search for new *interactions*
Deviations: "Precision TH"

- **Explore Higgs sector with precision**
  - less known (room for surprises!)
  - more sensitive (Portal) to new physics
  - ***Potential*** : look at multiple Higgs production

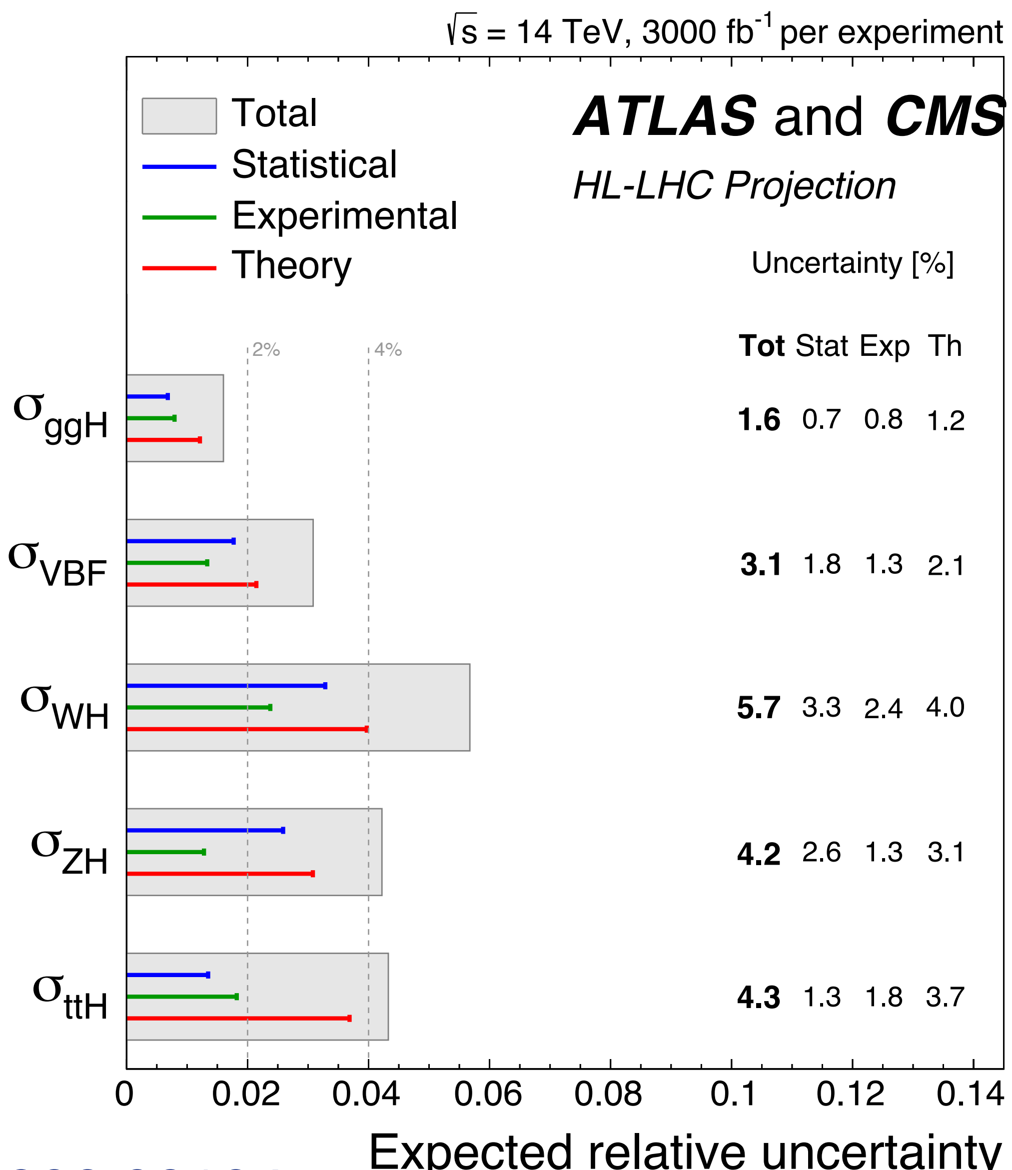
- EXP and TH : (for Higgs) Precision is the name of the game

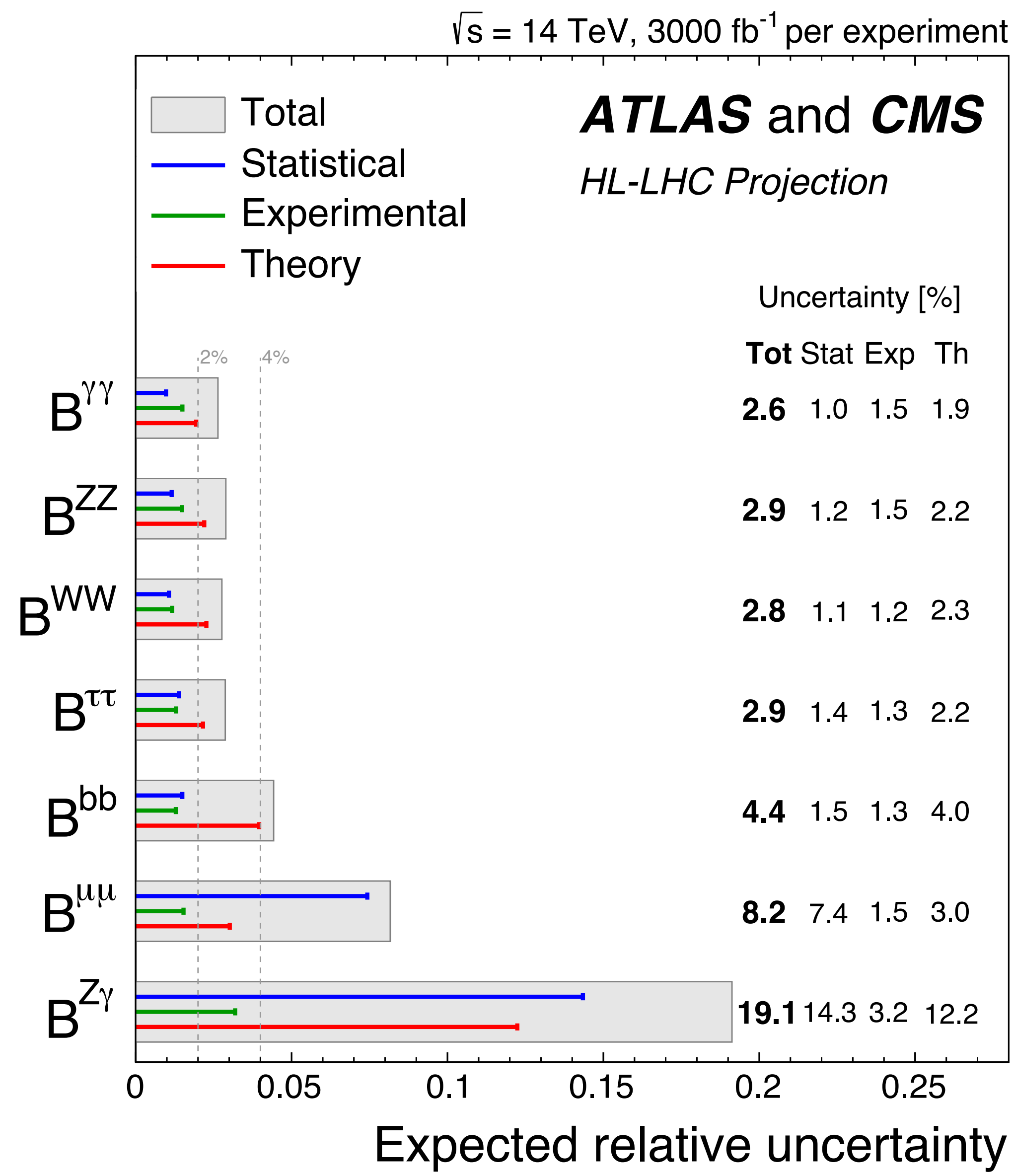

LEAVE NO STONE
UNTURNED


SUSY
IS
DEAD

HL-LHC projections ~20 years from now!

(S2) TH uncertainties scaled down by factor 2, EXP scaled according to $\sqrt{\mathscr{L}}$





1902.00134

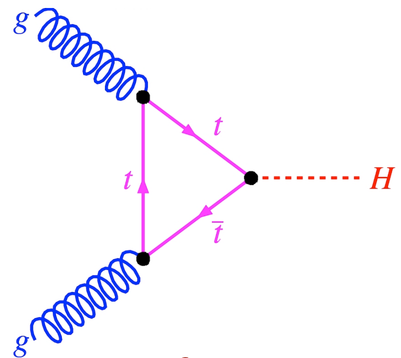
TH errors may dominate

- Precision becomes critical

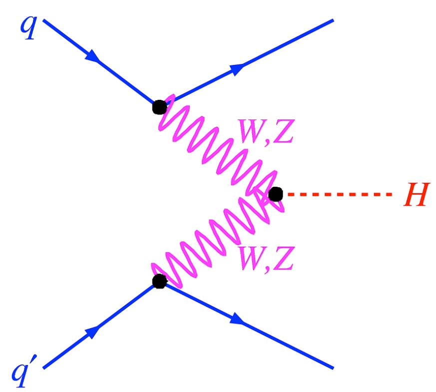
- TH: can we improve calculations? are we missing sources of uncertainty?
- EXP: using the most accurate results?

TH Precision in Higgs Production

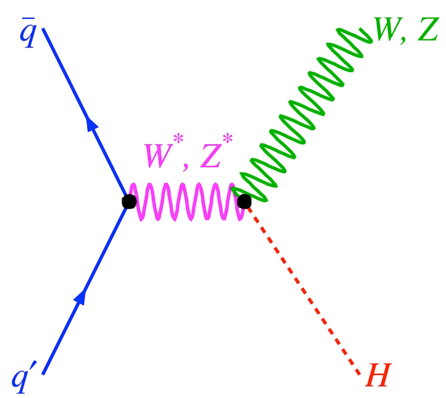
Production Channels at the LHC



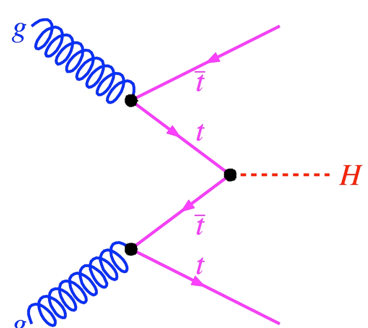
gg fusion



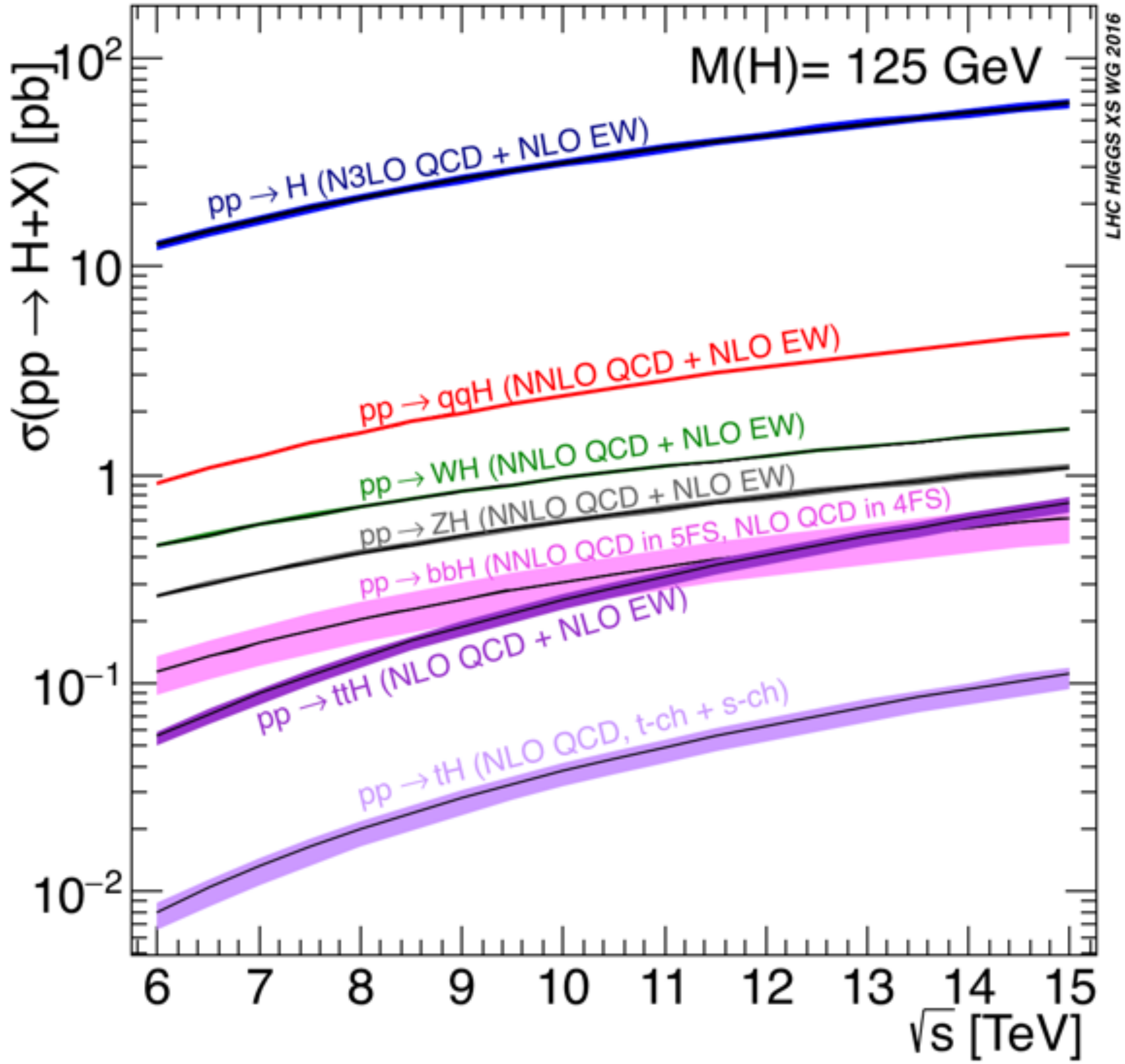
vector boson fusion



associated production with W,Z



associated production with heavy quarks

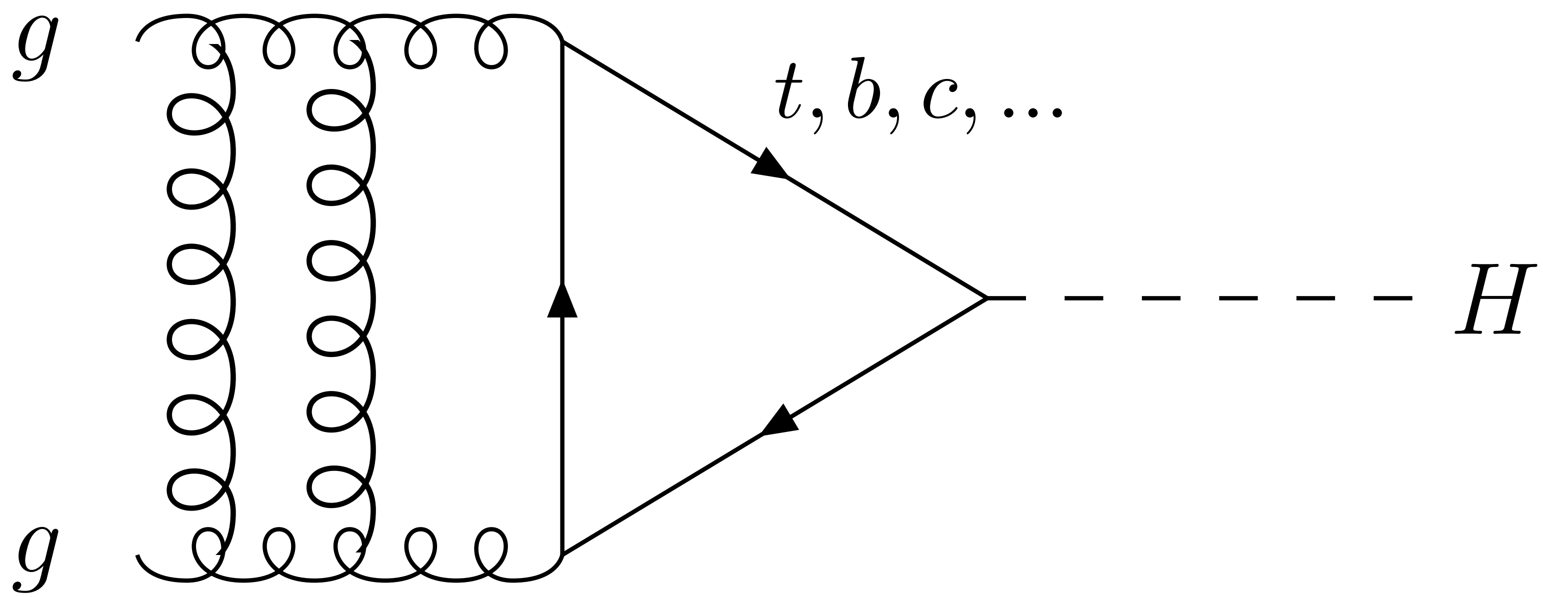


- Gluon-gluon fusion dominates due to large gluon luminosity

- Higgs boson production: how to achieve high precision in ggF

- Perturbative expansion in QCD $\alpha_s \sim 0.11$

$$C_0\alpha_s^0 + C_1\alpha_s^1 + C_2\alpha_s^2 + C_3\alpha_s^3 + \ldots$$



$$\sigma = \sigma^{(0)}(1 + 0.89 + 0.55 + 0.3 + \ldots)$$

$$\alpha_s^0 + \alpha_s^1 + \alpha_s^2 + \alpha_s^3$$

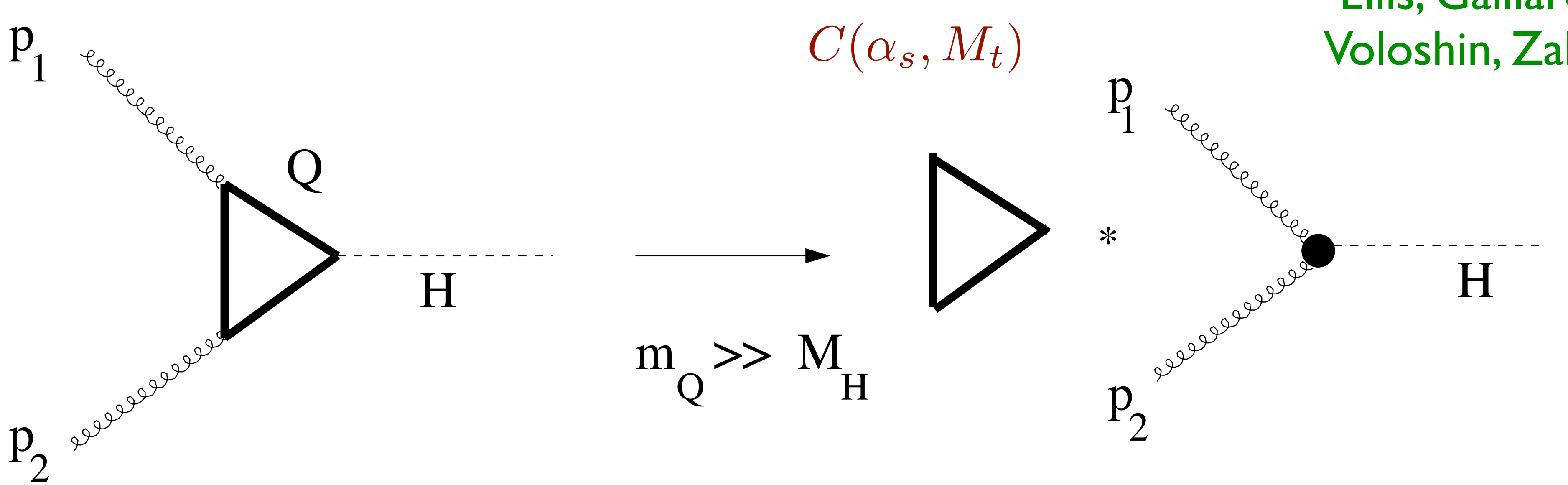
Slow convergence : requires high orders → Complicated by loop at the lowest order...

$m_{\text{top}} \to \infty$ approximation

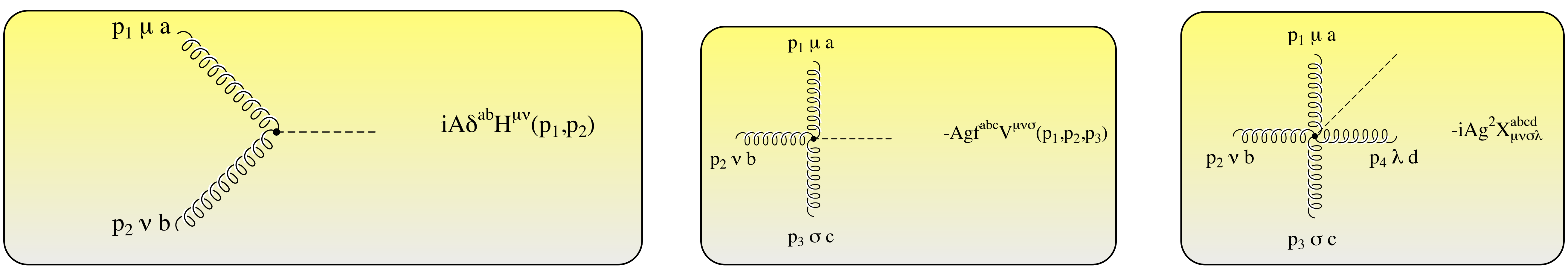
For light Higgs can use effective Lagrangian : one loop less!

- **Effective Lagrangian** $$\mathcal{L}_{eff} = -\frac{1}{4}\left[1 - \frac{\alpha_S}{3\pi}\frac{H}{v}(1+\Delta)\right] \mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu}$$

Ellis, Gaillard, Nanopoulos (1976)
Voloshin, Zakharov, Shifman (1979)



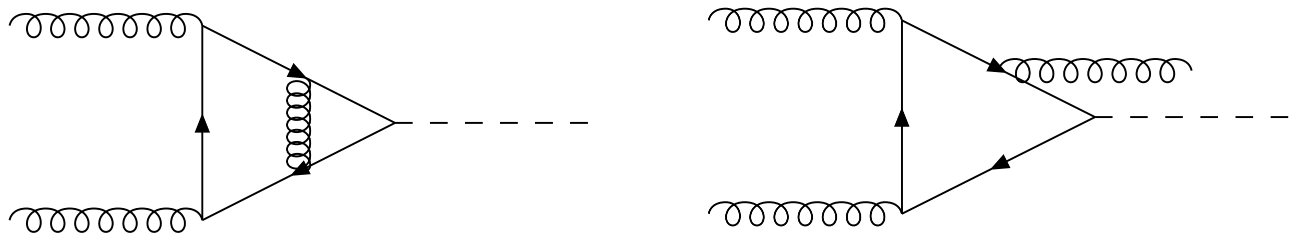
$H^{\mu\nu}(p_1,p_2) = g^{\mu\nu} p_1 \cdot p_2 - p_1^\nu p_2^\mu$



- Approximation works at the percent level for ‘top’

NLO exact

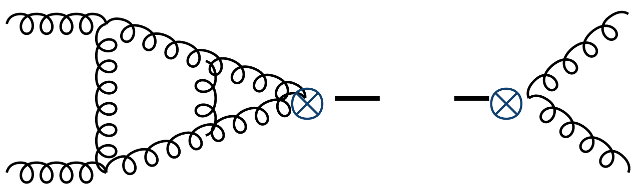
Dawson (1991); Djouadi, Spira, Zerwas (1991)   Graudenz, Spira, Zerwas (1993)



NNLO computed using effective

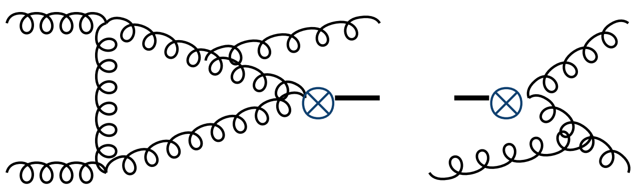
Harlander, Kilgore (2002)
Anastasiou, Melnikov (2002)
Ravindran, Smith, van Neerven (2003)

Double Virtual:



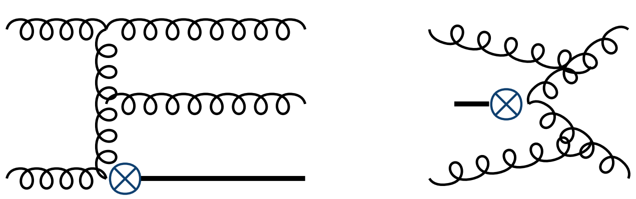
+ 148 terms;

Real Virtual:



+ 635 terms;

Double Real:



+ 594 terms.

In addition:

$q + g \to h + X(q, \overline{q}, g)$ $q_i + q_j(\overline{q}_j) \to h + X(q, \overline{q}, g)$

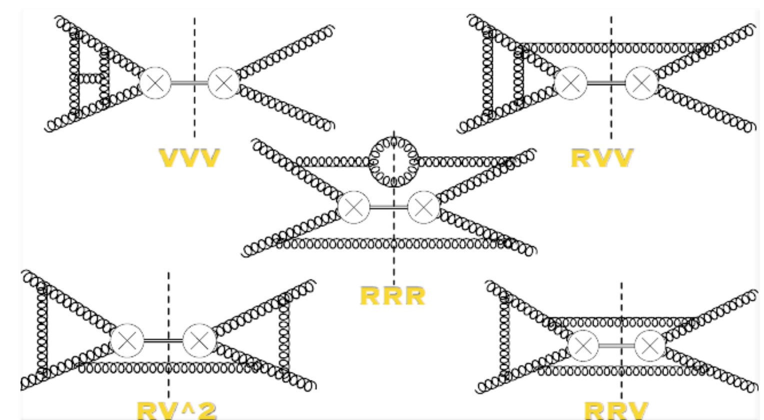
Improved by Threshold Resummation

Catani, deF., Grazzini, Nason (2003)

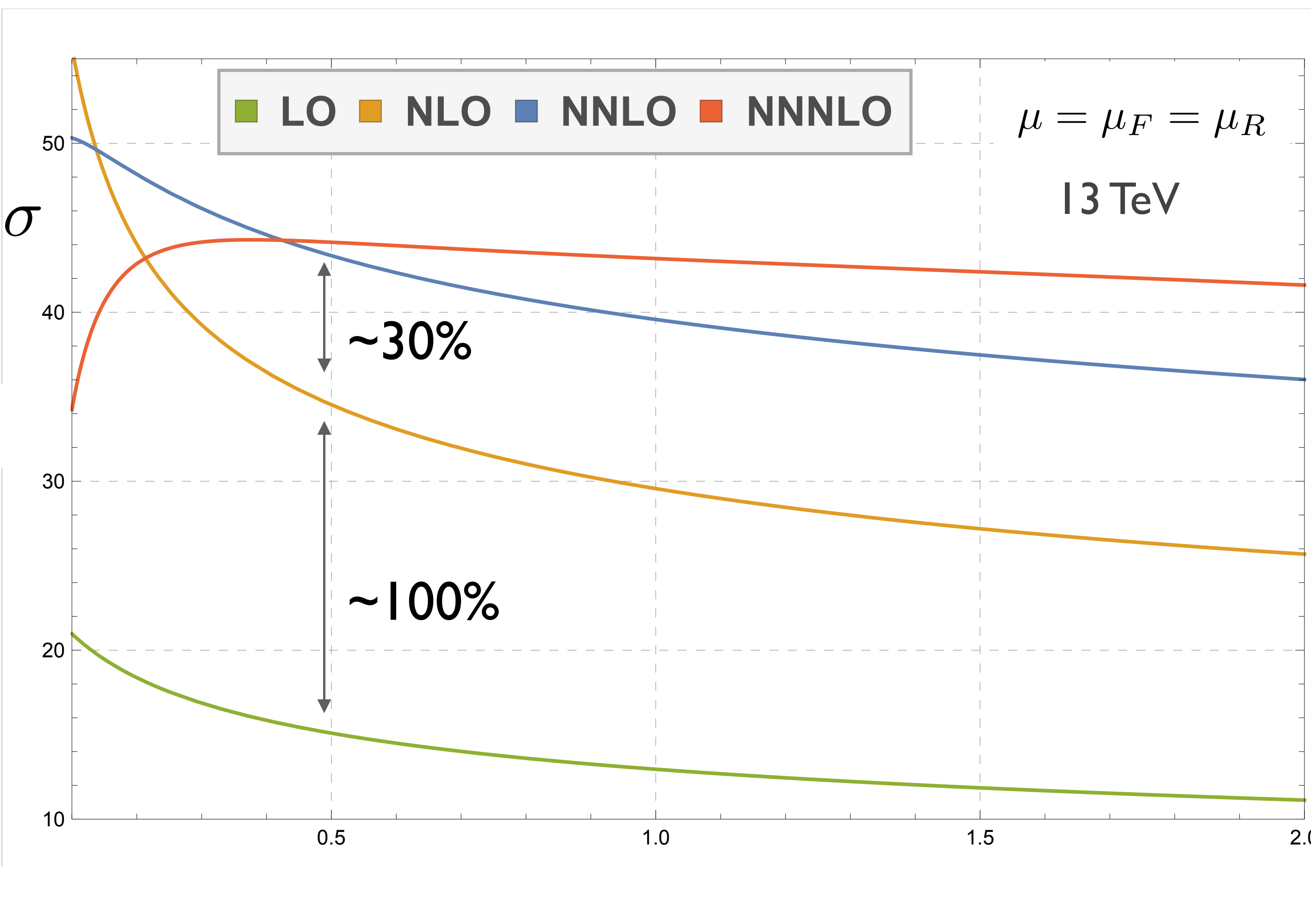
Higgs at N3LO

Anastasiou, Duhr, Dulat, Herzog, Mistlberger (2015)

- Very relevant observable called for higher orders (slow convergence)
- Impressive calculation : new techniques
  - Threshold expansion (very high order)
  - Now full calculation Mistlberger (2018)
  - Within heavy top approximation



68273802 loop and phase space integrals



- Inclusive over parton radiation
- Observe stabilization
- Small correction (2% at $M_H/2$)
- Scale variation at N3LO ~2%

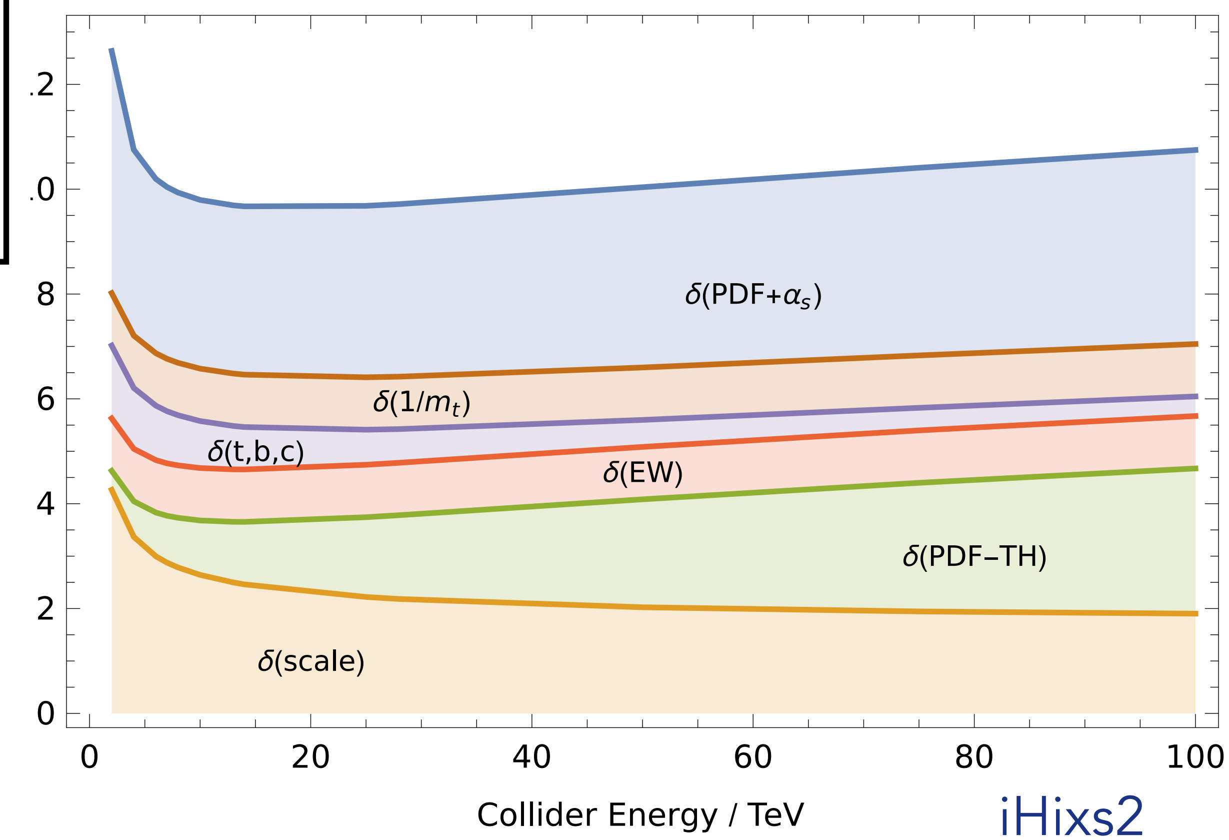
Improved Higgs Cross-section @ LHC

✓at 13 TeV   Higgs Cross-Section WG

$$
\begin{aligned}
\sigma_{PP\to H+X} &= 16.00\text{ pb} \quad (+32.87\%) \quad \text{LO, rEFT}\\
&+ 20.84\text{ pb} \quad (+42.82\%) \quad \text{NLO, rEFT}\\
&+ 9.56\text{ pb} \quad (+19.64\%) \quad \text{NNLO, rEFT}\\
&+ 1.62\text{ pb} \quad (+3.32\%) \quad \text{N}^3\text{LO, rEFT}\\
&- 2.07\text{ pb} \quad (-4.25\%) \quad \text{(t,b,c) corr. to exact NLO}\\
&+ 0.34\text{ pb} \quad (+0.70\%) \quad 1/m_t \text{ corr. to NNLO}\\
&+ 2.37\text{ pb} \quad (+4.87\%) \quad \text{EWK corr.}\\
&= 48.67\text{ pb}\,.
\end{aligned}
$$

$$
\begin{aligned}
\delta(\text{theory}) &= {}^{+0.13pb}_{-1.20pb} \quad \left({}^{+0.28\%}_{-2.50\%}\right) \quad \delta(\text{scale})\\
&+ \pm 0.56pb \quad (\pm 1.16\%) \quad \delta(\text{PDF-TH})\\
&+ \pm 0.49pb \quad (\pm 1.00\%) \quad \delta(\text{EWK})\\
&+ \pm 0.41pb \quad (\pm 0.85\%) \quad \delta(\text{t,b,c})\\
&+ \pm 0.49pb \quad (\pm 1.00\%) \quad \delta(1/m_t)\\
&= {}^{+2.08pb}_{-3.16pb} \quad \left({}^{+4.28\%}_{-6.5\%}\right),\\
\delta(\text{PDF}) &= \pm 0.89\text{pb} \quad (\pm 1.85\%)\,,\\
\delta(\alpha_S) &= {}^{+1.25pb}_{-1.26pb} \quad \left({}^{+2.59\%}_{-2.62\%}\right).
\end{aligned}
$$

uncertainties



- Great improvement over the last years
- Without QCD corrections : fail by more than a factor of 2
- Need to attack in many fronts to further improve: pdf, top mass, EW

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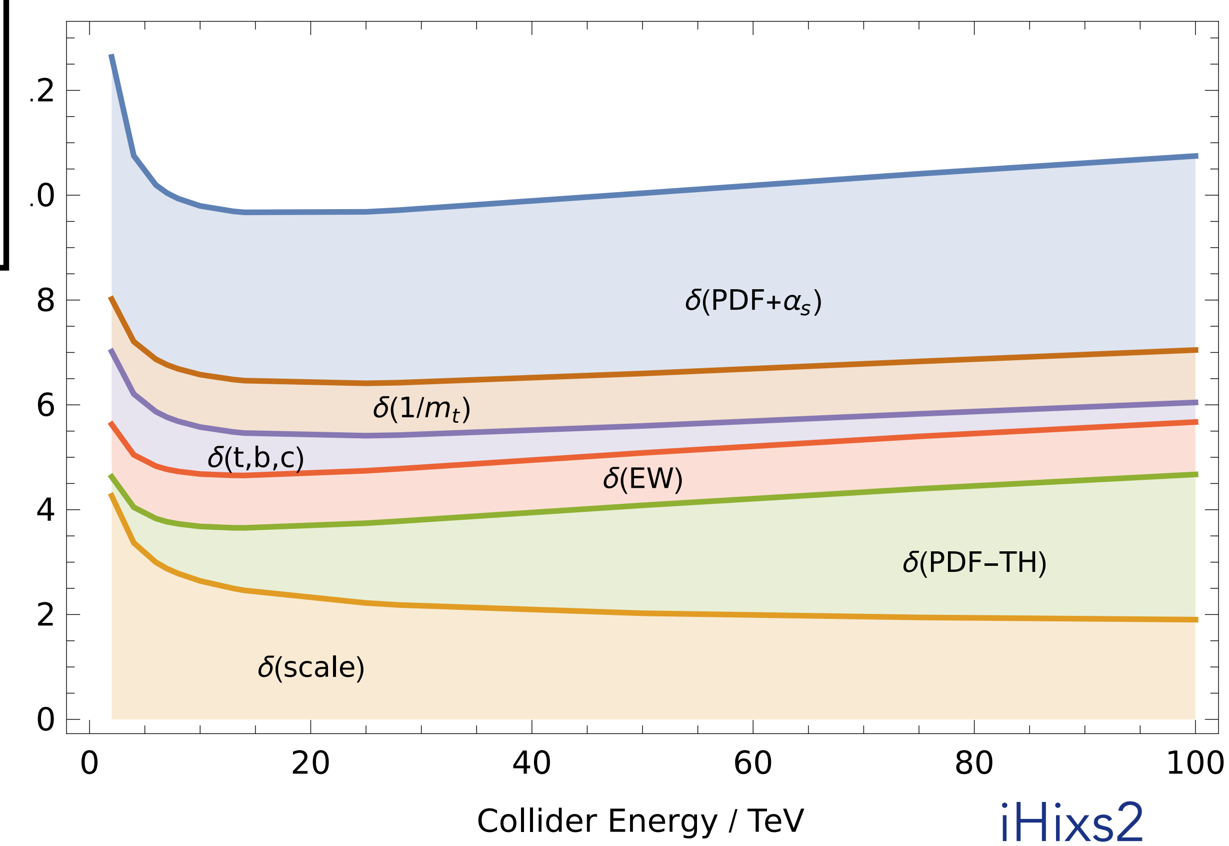
uncertainties



iHixs2

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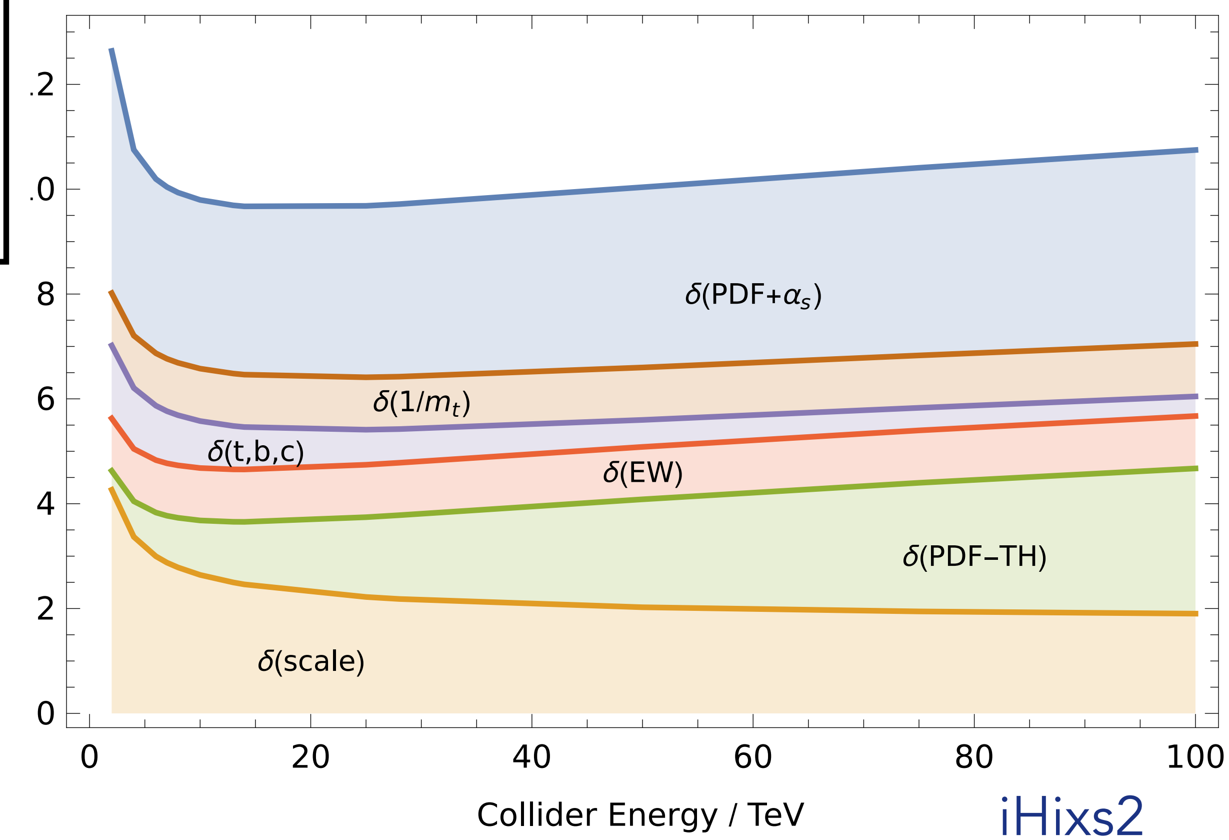
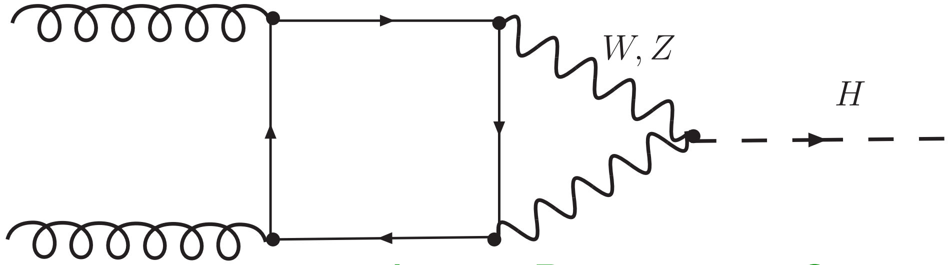
 & + & \pm 0.56pb & (\pm 1.16\%) & \delta(\text{PDF-TH}) \\
 & + & \pm 0.49pb & (\pm 1.00\%) & \delta(\text{EWK}) \\
 & + & \pm 0.41pb & (\pm 0.85\%) & \delta(\text{t,b,c}) \\
 & + & \pm 0.49pb & (\pm 1.00\%) & \delta(1/m_t) \\
 & = & {}^{+2.08pb}_{-3.16pb} & \left({}^{+4.28\%}_{-6.5\%}\right), & \\
\delta(\text{PDF}) & = & \pm 0.89\text{pb} & (\pm 1.85\%)\,, & \\
\delta(\alpha_S) & = & {}^{+1.25pb}_{-1.26pb} & \left({}^{+2.59\%}_{-2.62\%}\right). &
\end{array}
$$

uncertainties



- Great improvement over the last years
- Without QCD corrections : fail by more than a factor of 2
- Need to attack in many fronts to further improve: pdf, top mass, EW

EW corrections



~5% at LO

- Add them to QCD result, how?

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

additive EW $\sigma = \sigma^{(QCD)} + \delta_{EW}$ ~2% effect

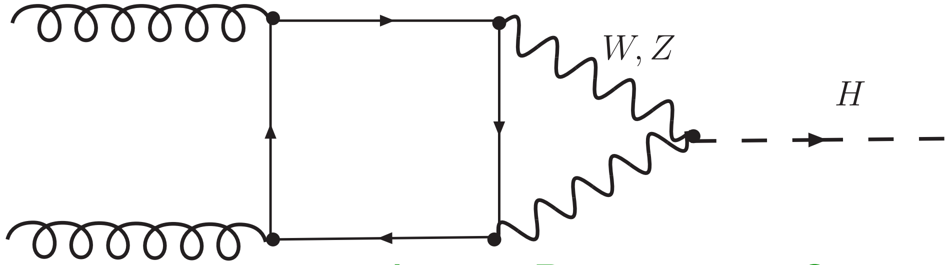
total factorization EW including HQ $\sigma = \sigma^{(QCD)}(1 + \delta_{EW}/\sigma^{(LO)})$ ~5% effect

differ by mixed QCD-EW effects: estimated in $M_V \gg M_H$ EFT limit

Anastasiou, Boughezal, Petriello (2009) support total factorization

but one source of uncertainty

EW corrections



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including HQ

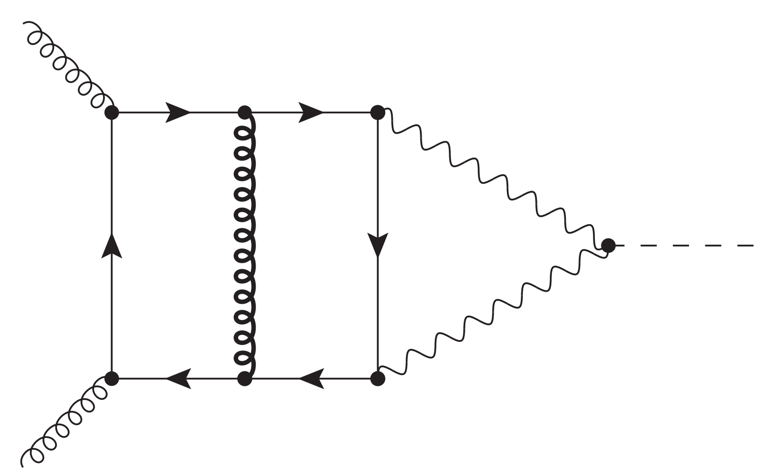
differ by mixed QCD-EW effects: estimated in $M_V \gg M_H$ EFT limit

Anastasiou, Boughezal, Petriello (2009) support total factorization

but one source of uncertainty

- NEW: 3-loop QCD-EW corrections computed

Bonetti, Melnikov, Tancredi (2018-2019)



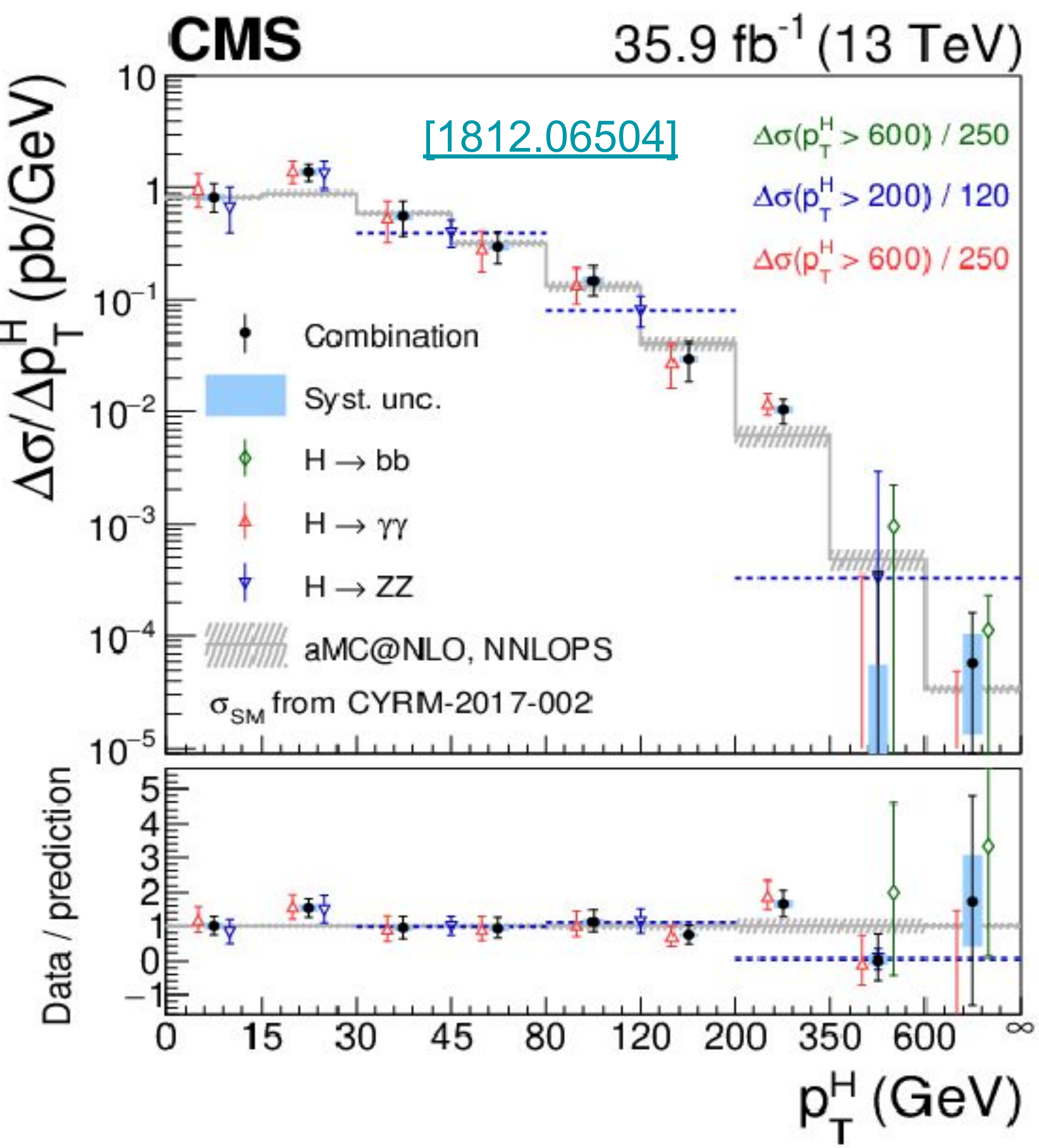
combined with real using soft approximation

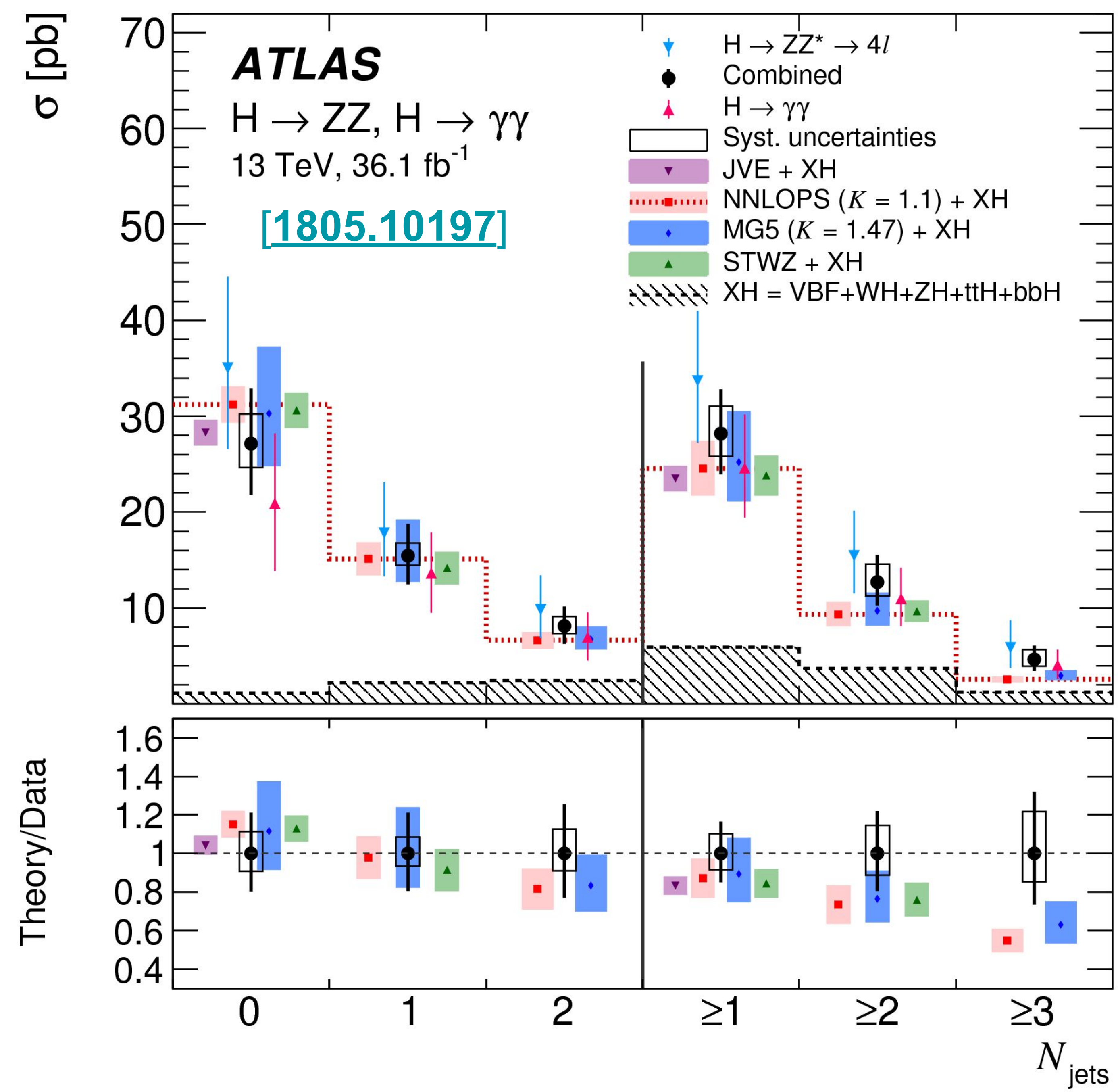
$\sigma^{\mathrm{LO}}_{\mathrm{QCD}} = 20.6$ pb, $\sigma^{\mathrm{LO}}_{\mathrm{QCD/EW}} = 21.7$ pb, +5.3% at LO

$\sigma^{\mathrm{NLO}}_{\mathrm{QCD}} = 32.66$ pb, $\sigma^{\mathrm{NLO}}_{\mathrm{QCD/EW}} = 34.41$ pb +5.3% at NLO

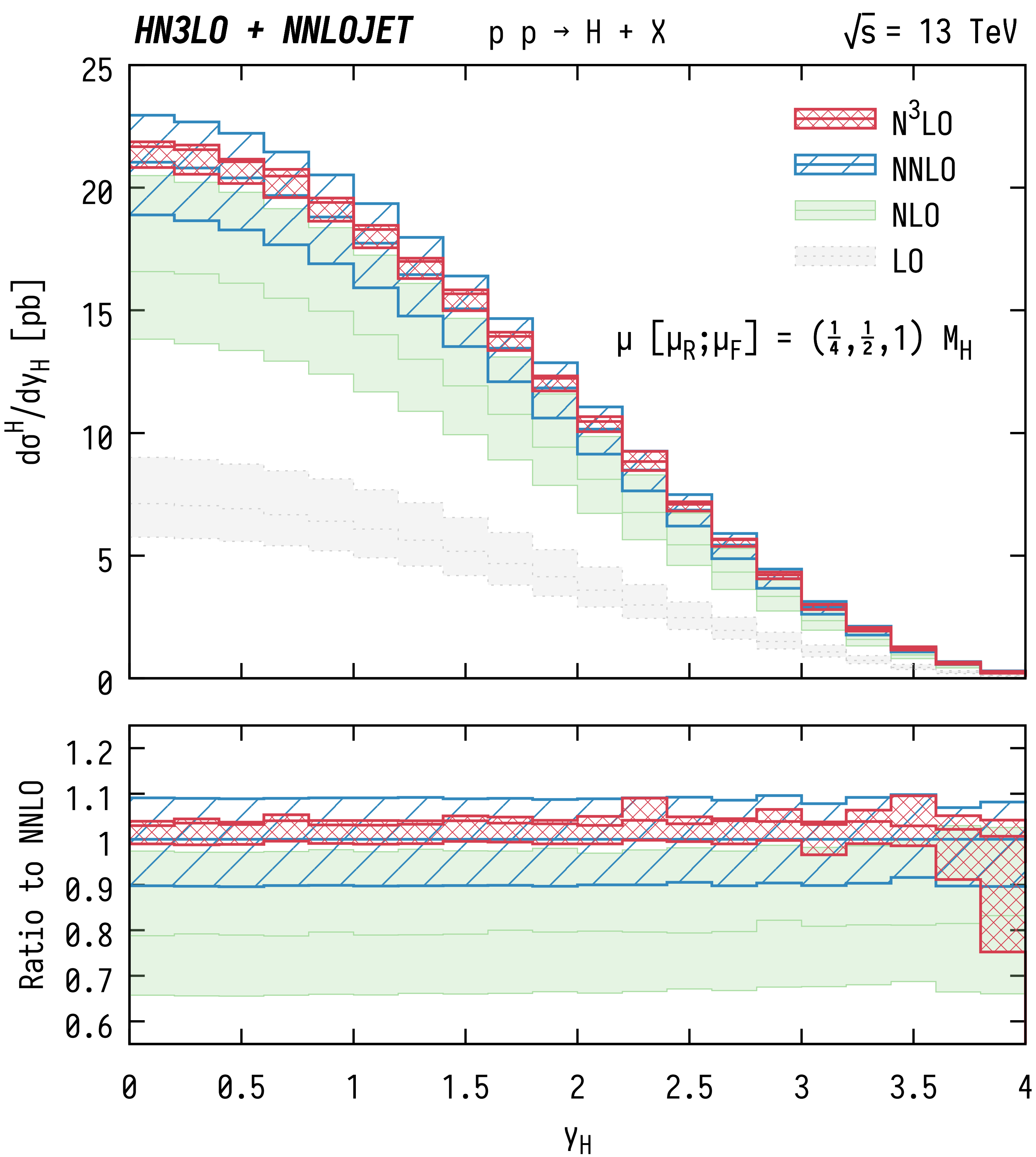
total factorization at NLO

Higgs Precision Era : DISTRIBUTIONS





Rapidity @ N3LO

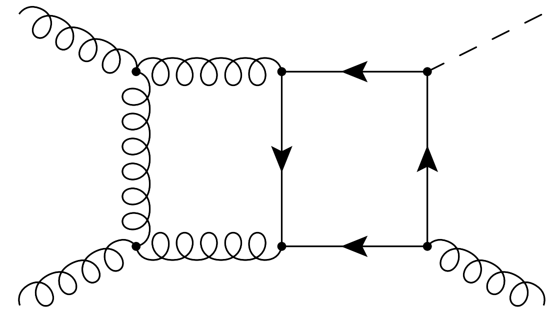


Cieri, Chen, Gehrmann, Glover, Huss (2018)

- relies on qT subtraction method (assumption on 3rd order coeff.)
- will include decay and fiducial
- Flat K-factor (expected)
- similar features as inclusive convergence, scale dependence

agrees with Dulat, Mistlberger, Pelloni (2018) Threshold expansion

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

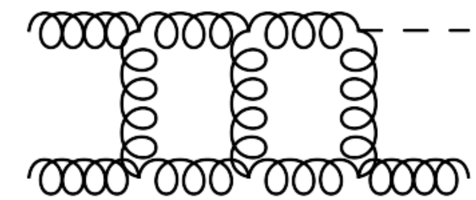


sensitivity to loop structure

- 3 NNLO calculations
  large mt approximation

R.Boughezal, C. Focke, W. Giele, X. Liu, F. Petriello
R.Boughezal, F.Caola, K.Melnikov, F.Petriello, M.Schulze
X. Chen, T. Gehrmann, M. Jaquier, N. Glover

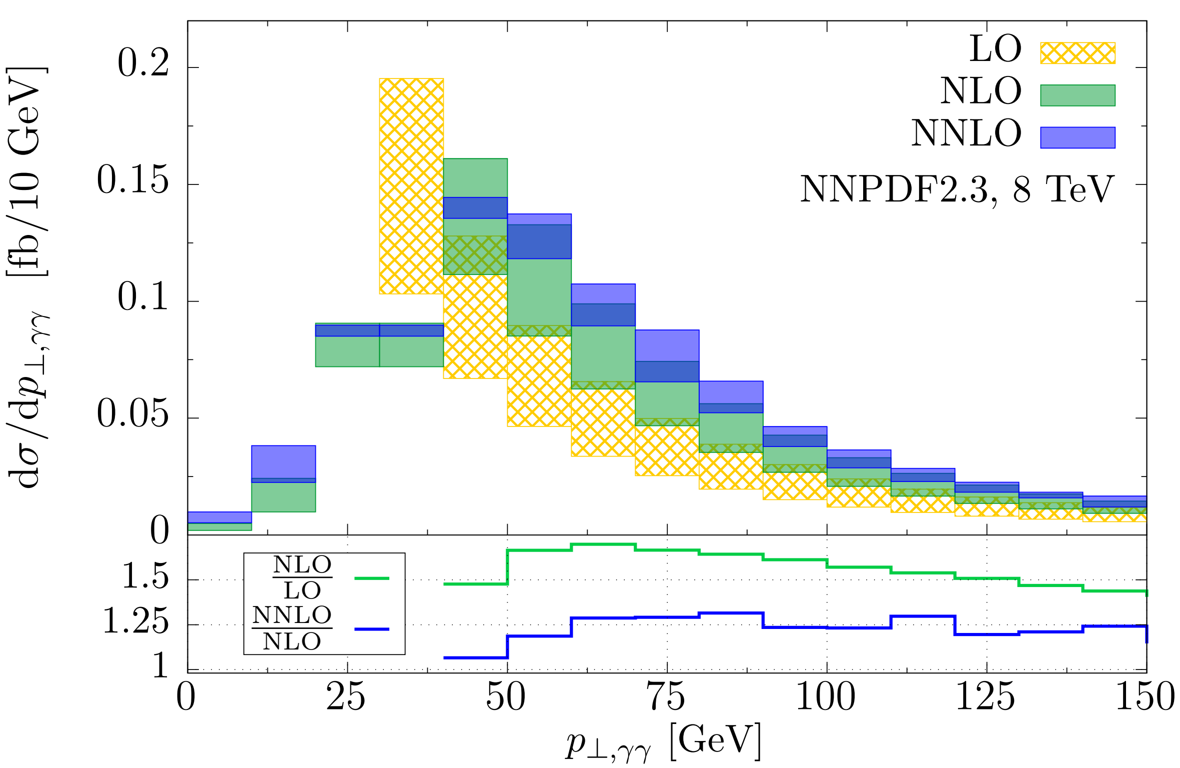
- 3 now in agreement (numerical accuracy far from trivial)



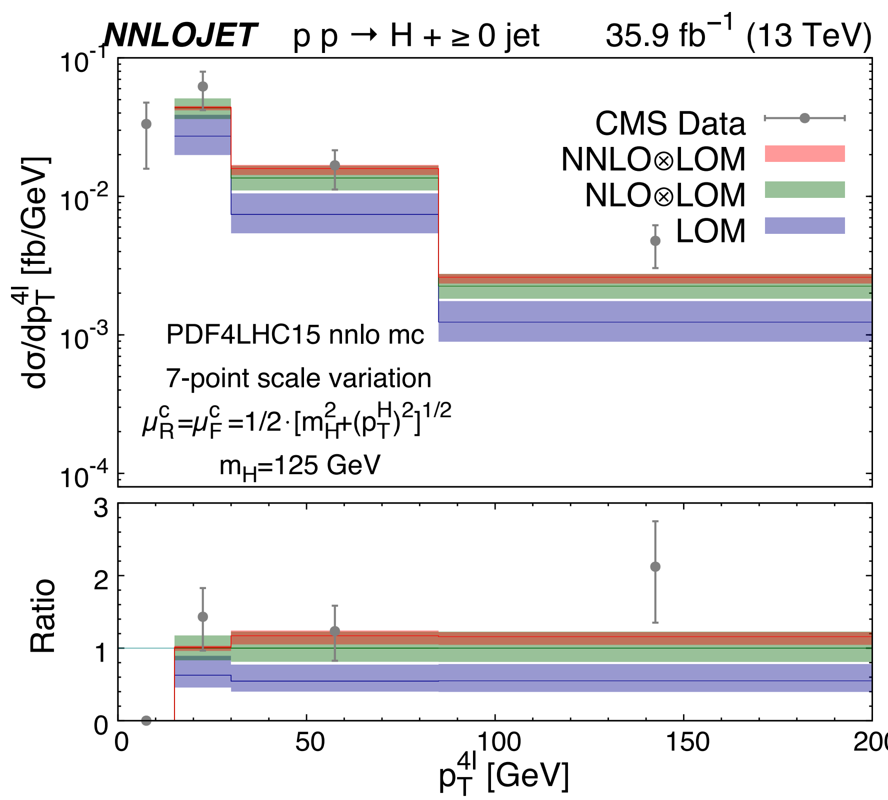
- Most recently including H decays

- $H \to \gamma\gamma$
- $H \to WW^* \to (2l, 2\nu)$
- $H \to ZZ^* \to 4l$

- Fiducial cross sections

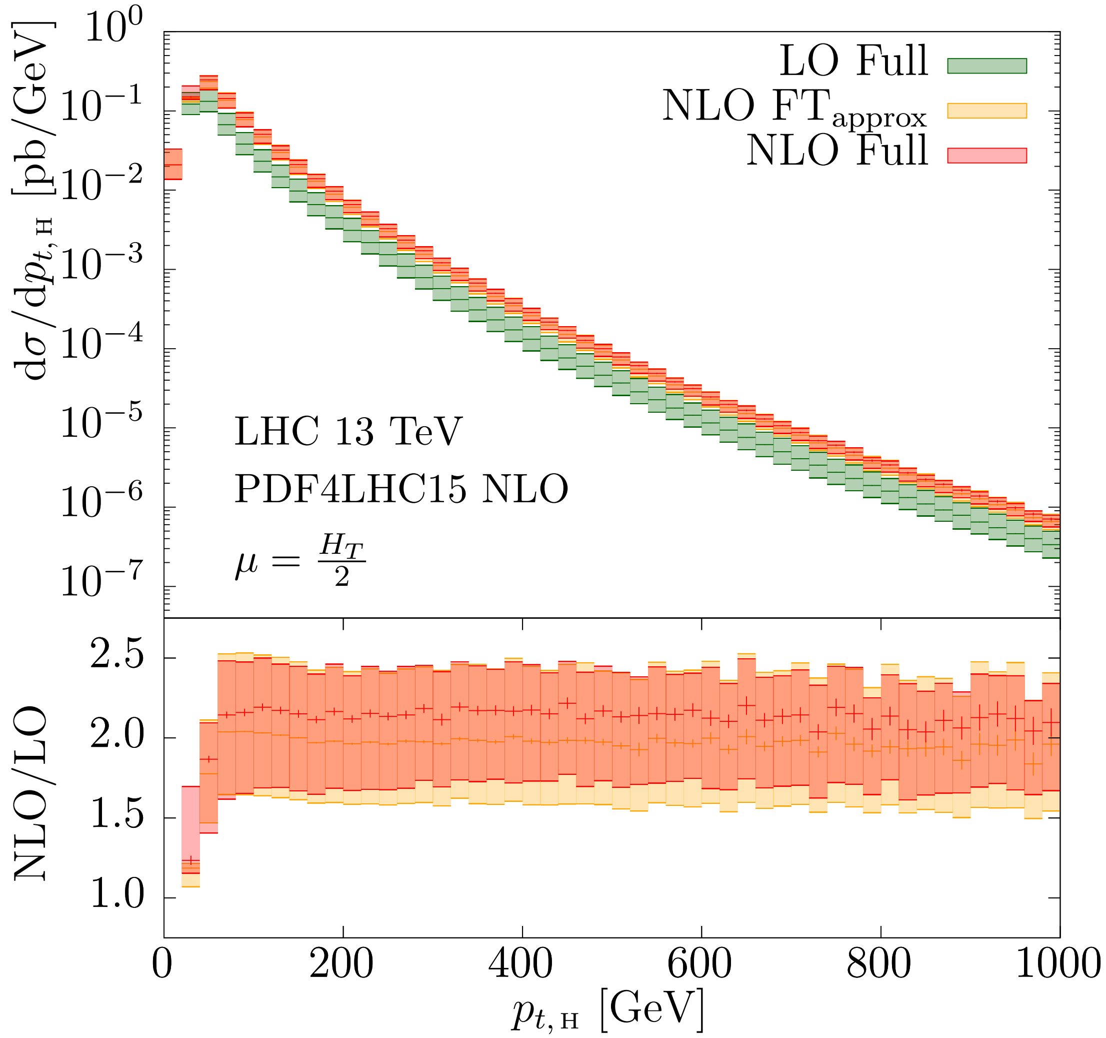


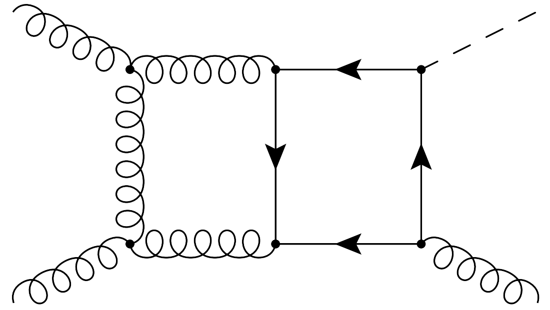
F.Caola, K.Melnikov, M.Schulze



Chen, Gehrmann, Glover, Huss

Beyond the large top mass approximation: full NLO





Jones, Kerner, Luisoni (2018)

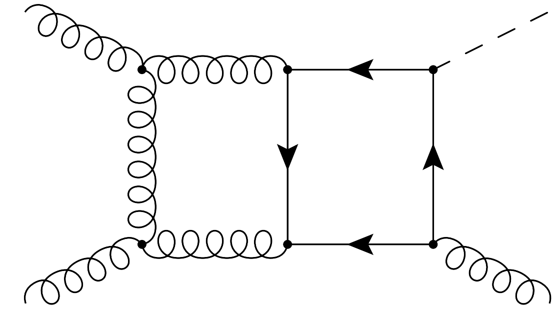
Large K-factor ~ 2

For the scale choice $\mu = H_T/2$:

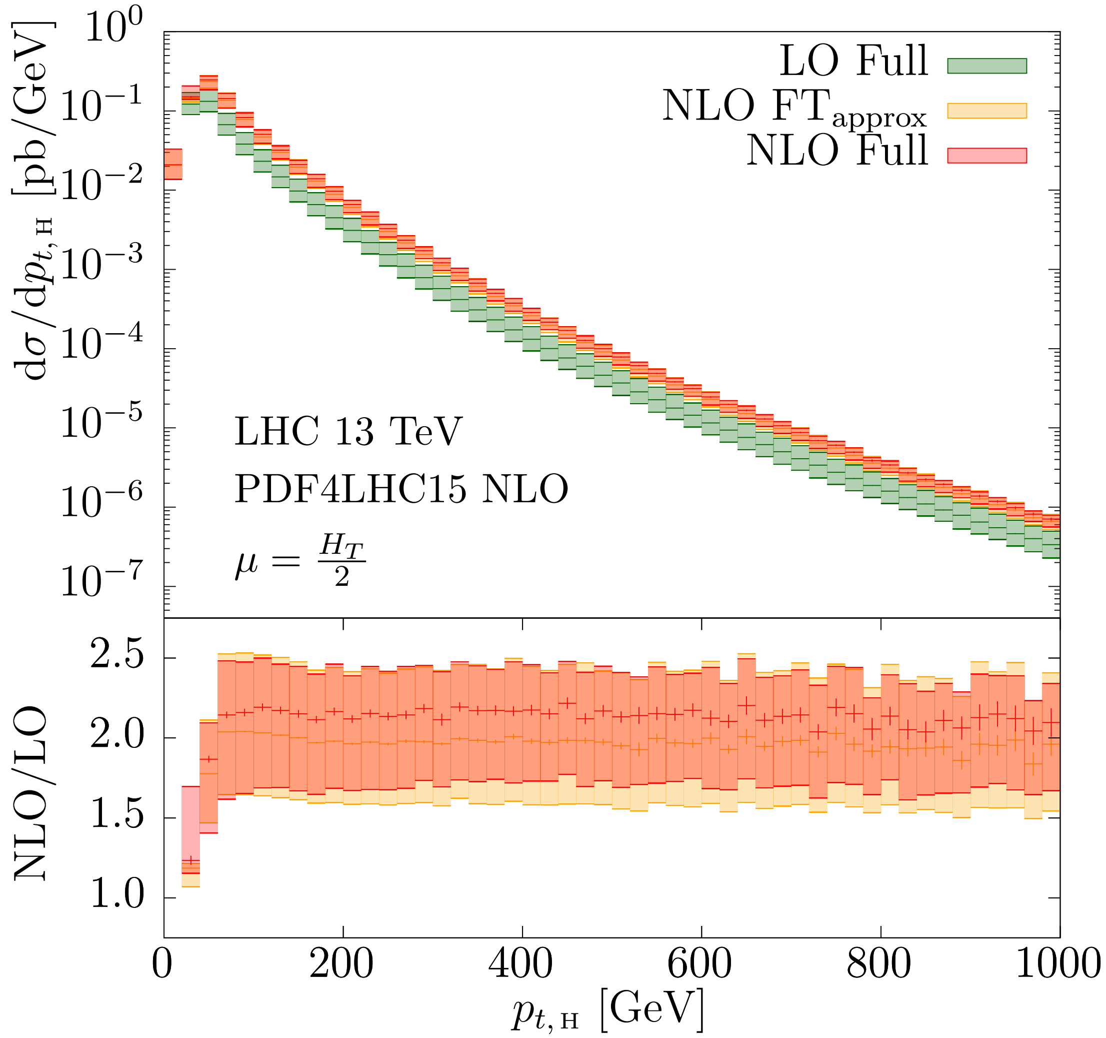
- K-factor very similar to HTL
- K-factor nearly flat at large p_T
- ~8% increase from including m_T in virtuals

top quark mass scheme uncertainty

Beyond the large top mass approximation: full NLO



Jones, Kerner, Luisoni (2018)



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For the scale choice $\mu = H_T/2$:

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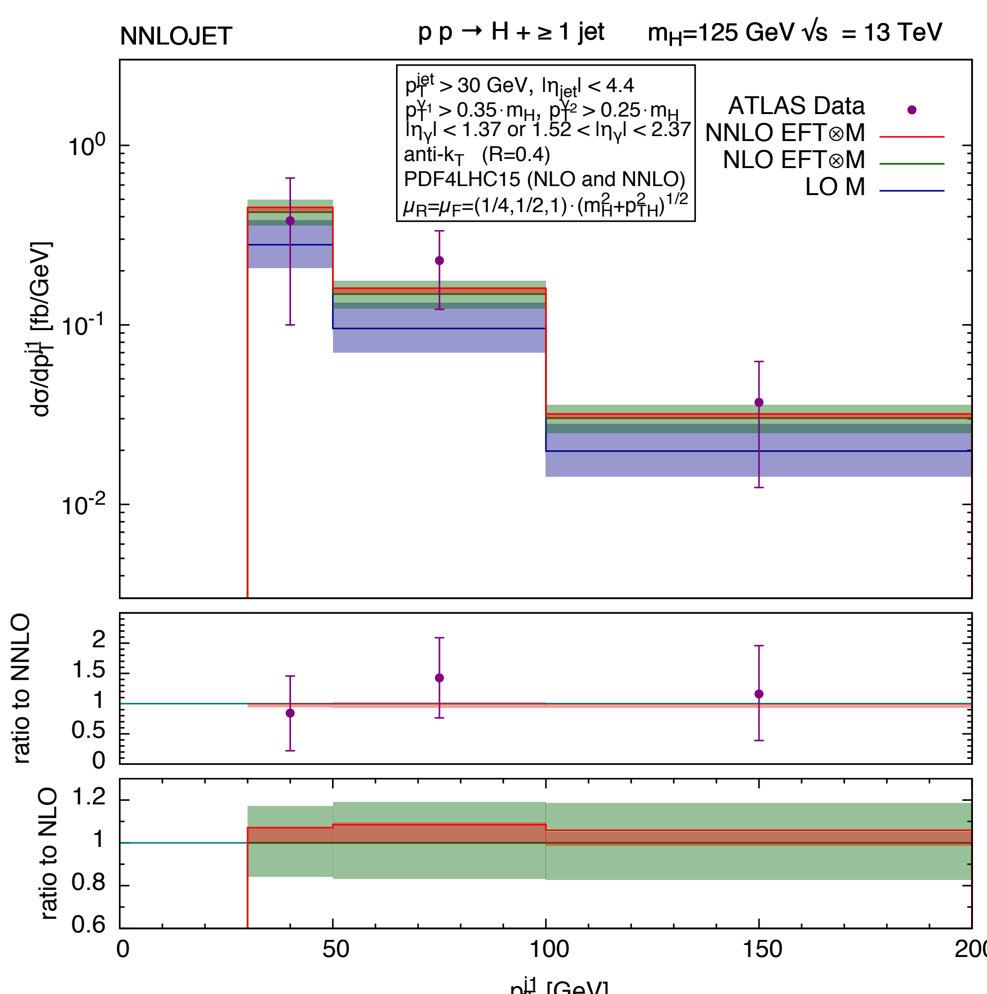
top quark mass scheme uncertainty

At large p_T the $m_T \to \infty$ approx fails:
Rescale NLO by $K_{NNLO} = NNLO_{HTL}/NLO_{HTL}$

Produce NLO improved NNLO predictions for $H \to \gamma\gamma$ with fiducial cuts,

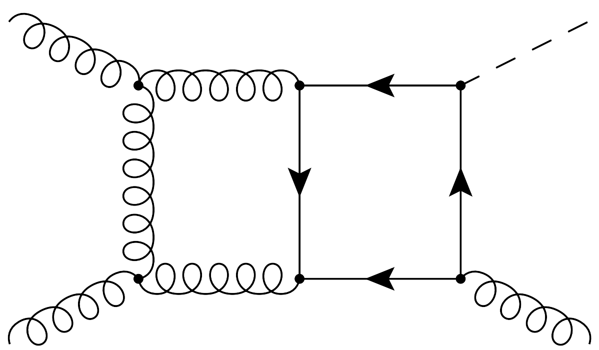
Jones, Chen, Les Houches 2019



bottom-top quark interference in $pp \to H + \text{jet}$

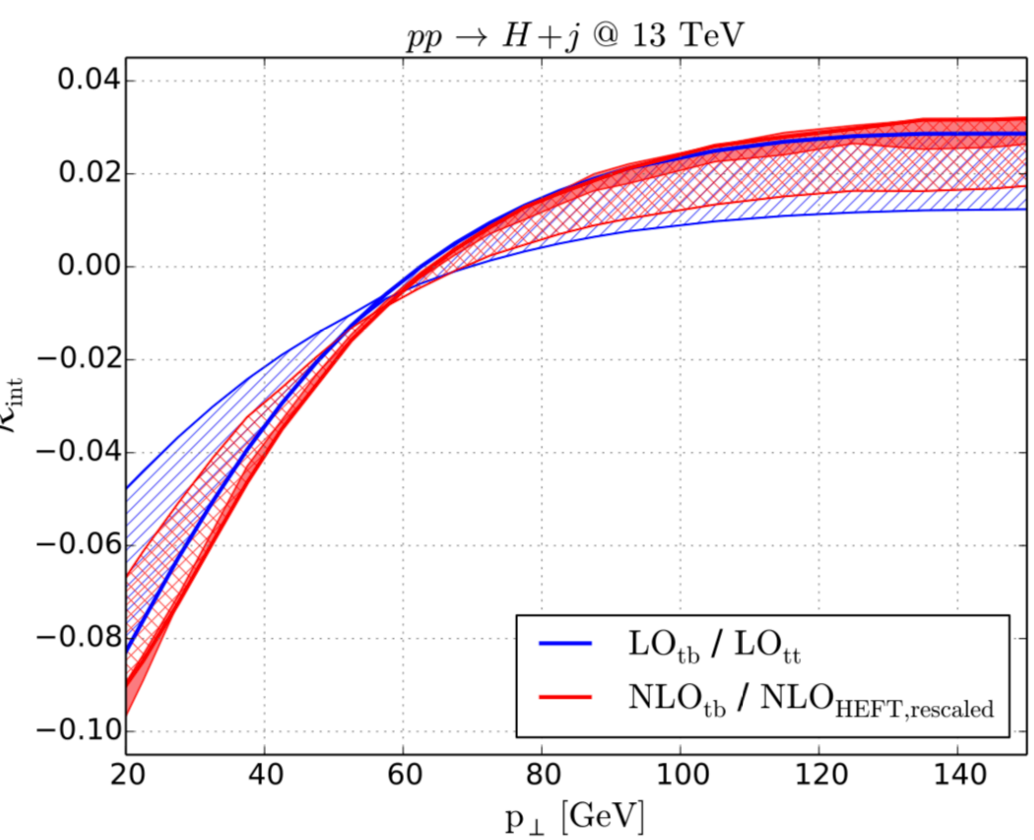
Interference studied at NLO+NNLL (for $m_B < p_T < m_T$)

$$\sigma_{tb}^{\text{virt}} \sim \text{Re}\left[A_t^{\text{LO}} A_b^{\text{LO}*} + \frac{\alpha_s}{2\pi}(A_t^{\text{NLO}} A_b^{\text{LO}*} + A_t^{\text{LO}} A_b^{\text{NLO}*})\right]$$



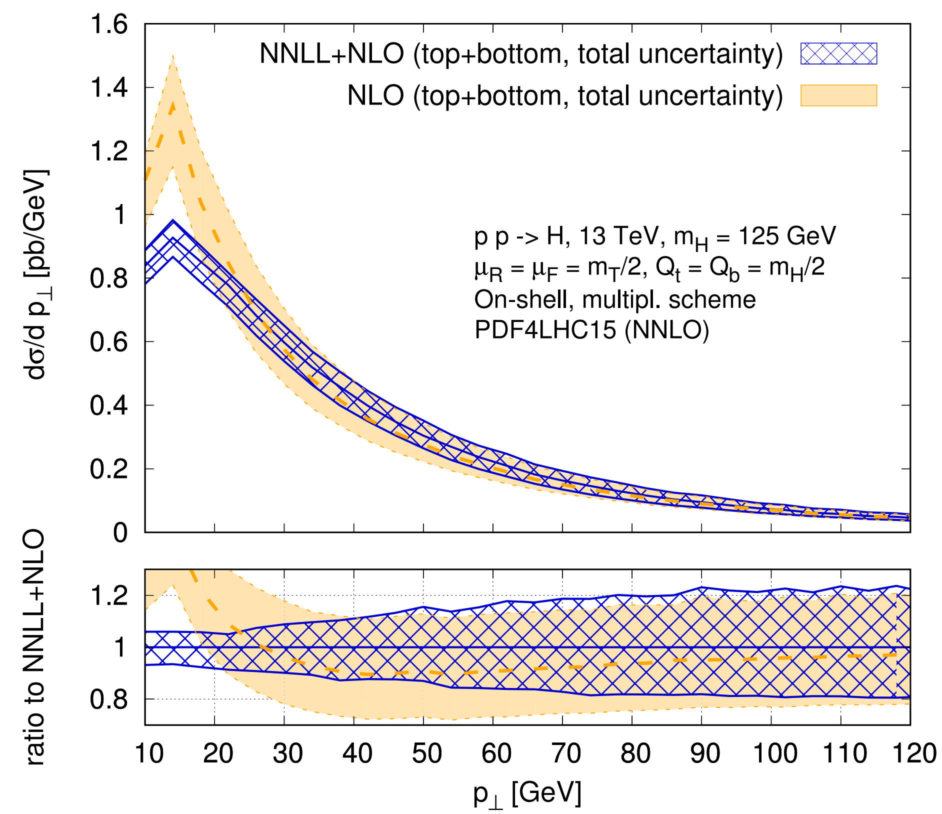
Can combine $m_B^2 \ll |s|,|t|,|u|,m_H^2$ with $m_T \to \infty$ approximation for NLO pieces to compute this effect

Lindert, Melnikov, Tancredi, Weber (2017)



similar NLO to top-mediated in HTL

Caola, Lindert, Melnikov, Monni, Tancredi, Weber (2018)

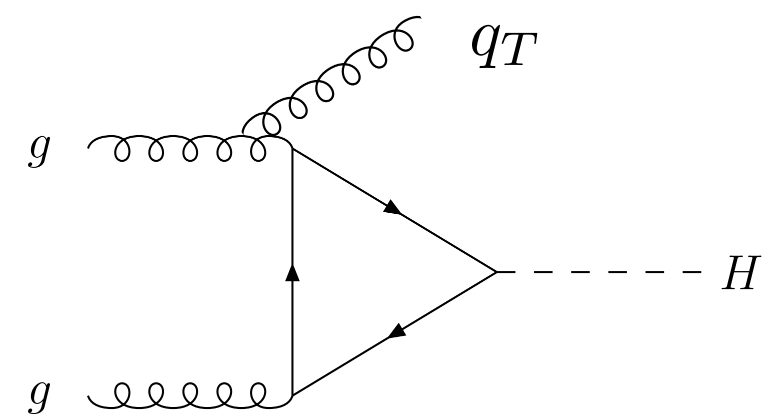


q_T resummation performed :uncertainties O(20%) from bottom quark mass scheme

Transverse momentum distribution M_H^2, q_T^2 Two scales problem

- QCD based on convergence of perturbative expansion $\alpha_s \ll 1 \;\; , \;\; \mathcal{C}_n \sim \mathcal{O}(1)$

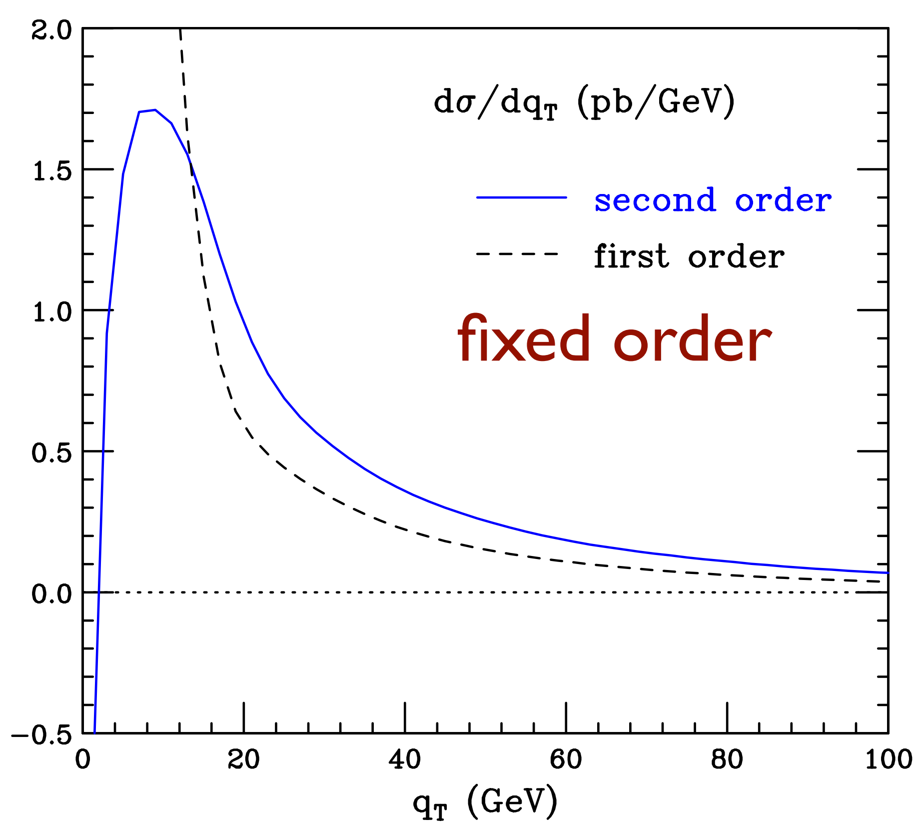
$$C_0\alpha_s^0 + C_1\alpha_s^1 + C_2\alpha_s^2 + C_3\alpha_s^3 + \ldots$$

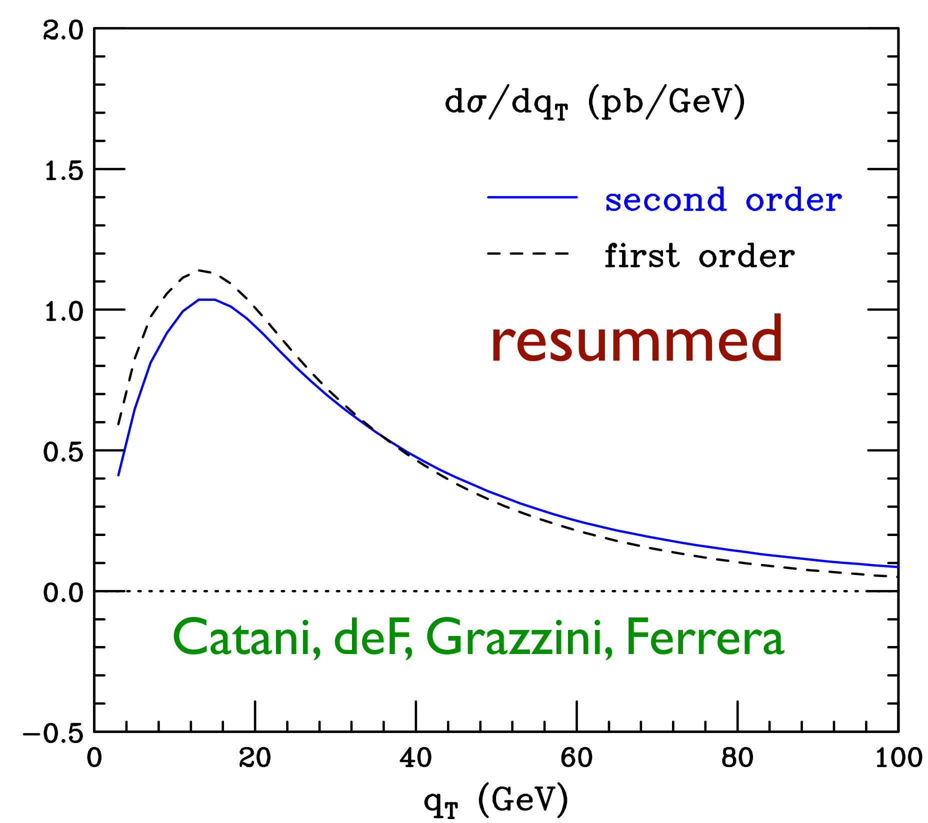


$$\alpha_s^n \log^{2n} \frac{M_H^2}{q_T^2}$$ soft and collinear origin

- Convergence spoiled when two scales are very different (small qT)
- Converge of perturbative expansion restored after ***resummation***

sum "dominant logarithms" to all orders in coupling constant

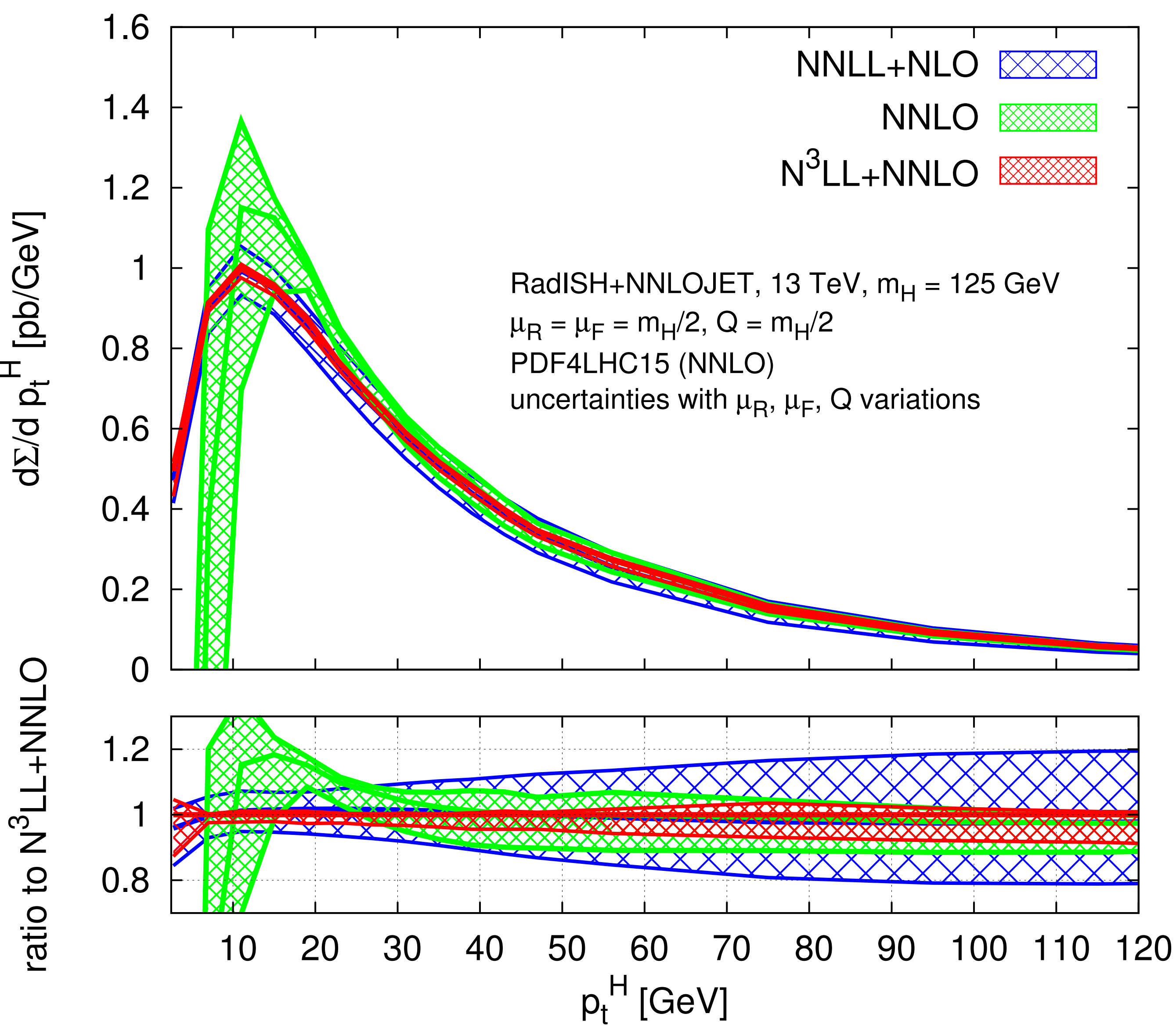




- H known at N3LO
- H+jet known at N2LO
- resummation functions known at N3LL

‣ qT resummation performed at (~)N3LL

Bizon et al (2018)
RadISH



$$\sigma^{N^aLL} \sim H(\alpha_s)^{N^aLO} \times e^{S(\log M_H/q_T)^{N^aLL}}$$

+ matching with f.o. distribution O(a-1)

‣ very good convergence N2LL to N3LL

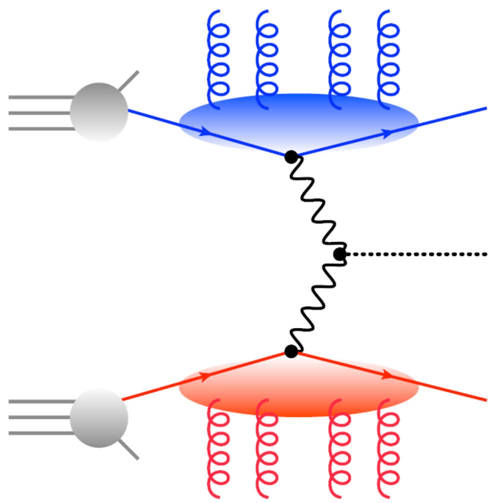
$\mu_F = \mu_R = m_H/2$

‣ reduction in scale dependence (accidentally small in some cases)

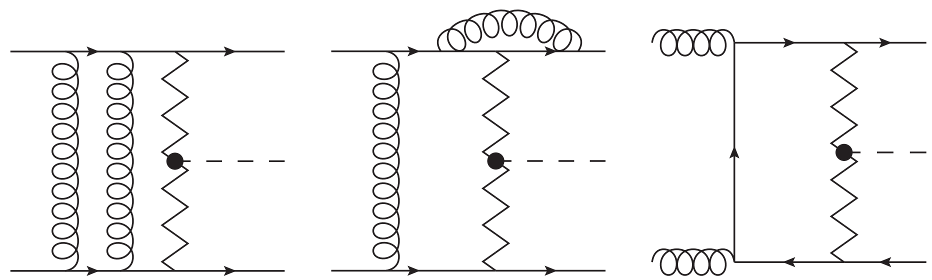
‣ perturbative uncertainties around 6% for 5<q_T<35 GeV

‣ similar results for fiducial case $H \to \gamma\gamma$

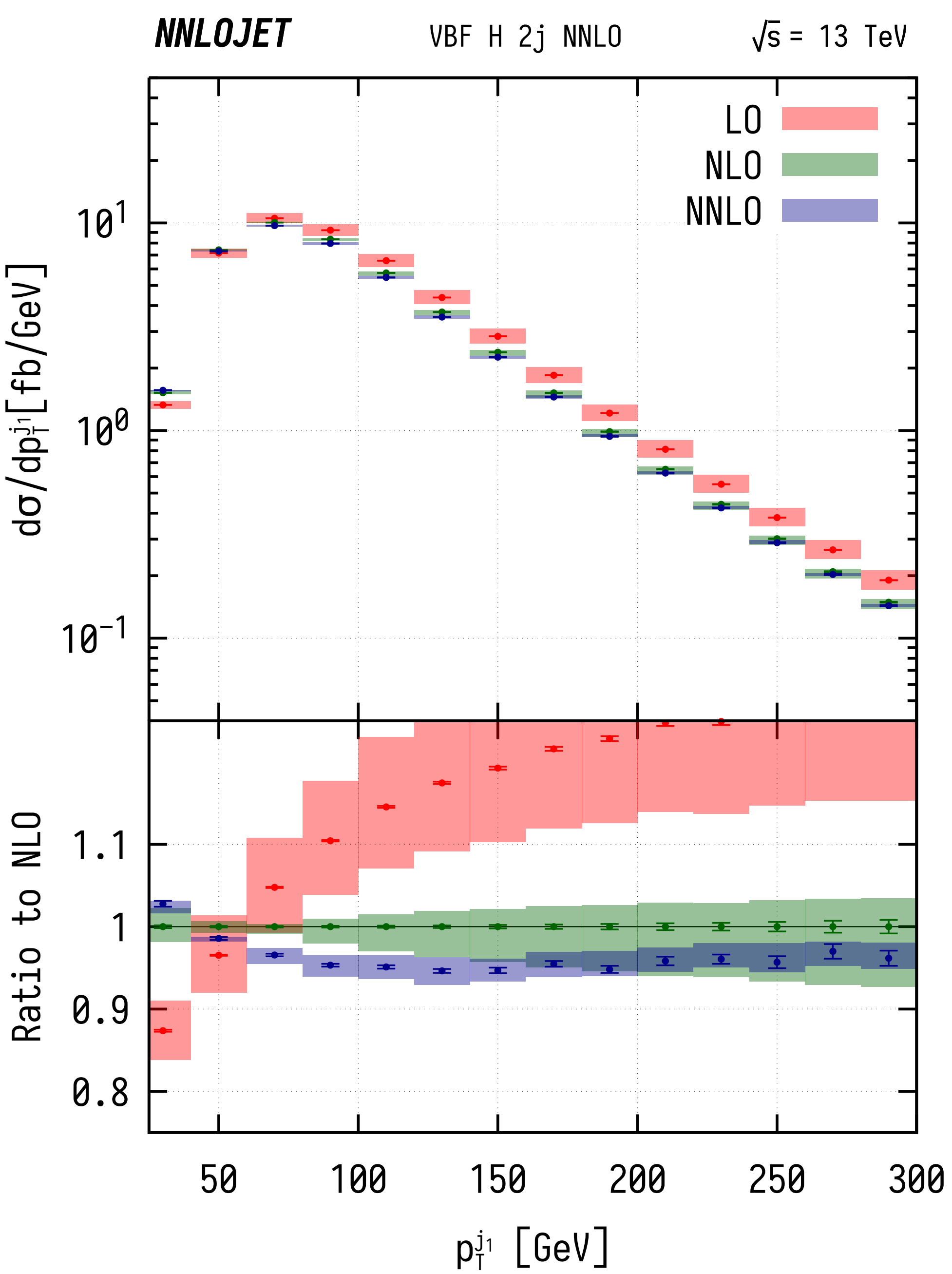
VBF at NNLO



- (SF) DISxDIS like approach ~1% accurate picture



neglect color exchange between lower and upper legs



Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2015)
Cruz-Martinez, Gehrmann, Glover, Huss (2018)

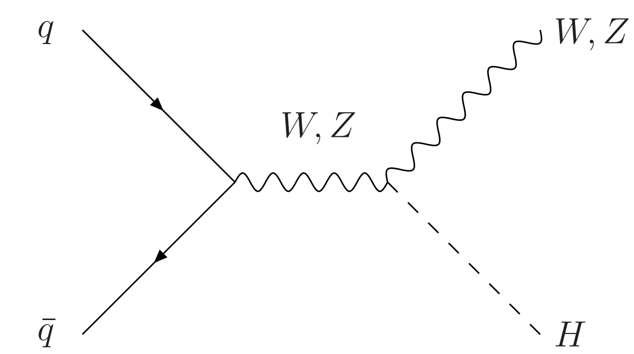
Uncovered error in earlier calculation stemming from (NLO) VBF-3j piece

- NNLO differential corrections larger (5-10%) than for inclusive (1%)
- NNLO beyond NLO band
- -4% correction from NNLO to NLO with VBF cuts
- Known at N3LO for inclusive case

F. Dreyer, A. Karlberg (2016)

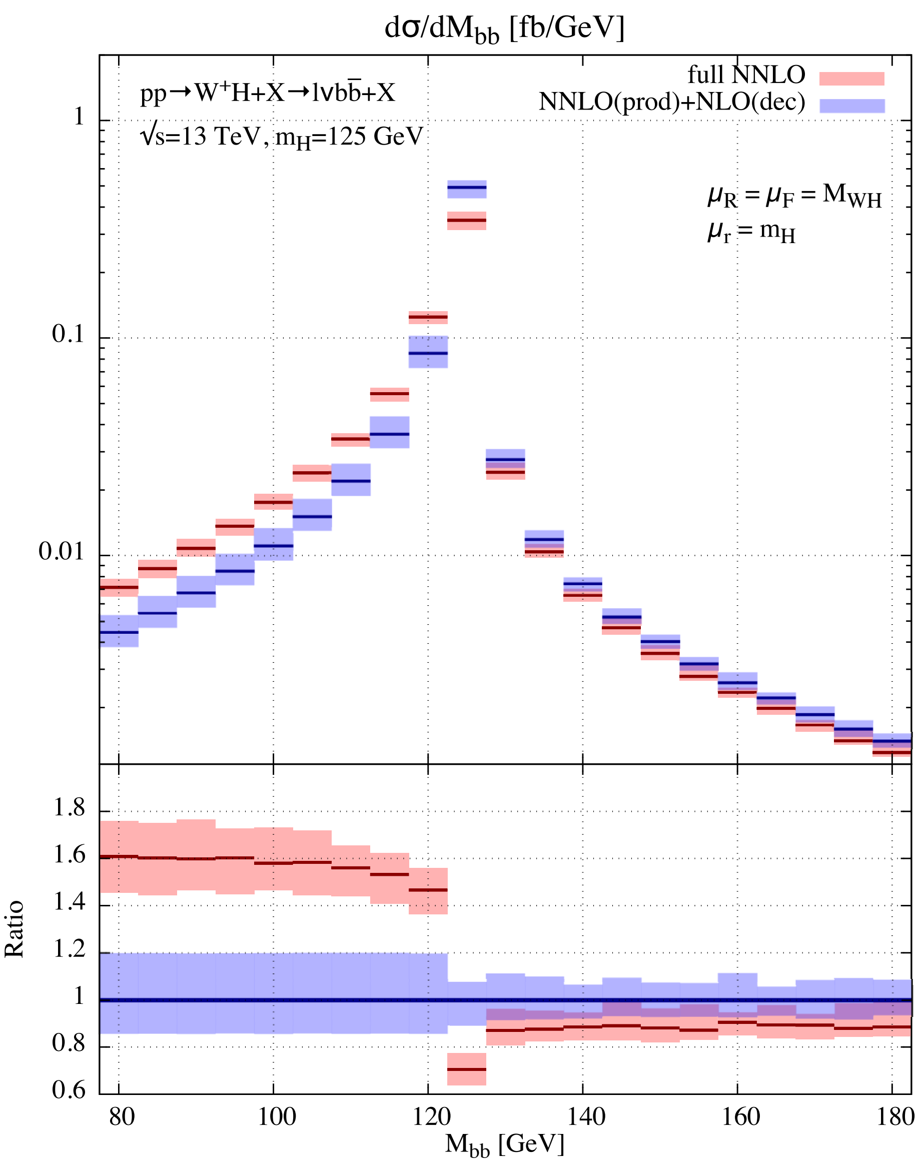
$H \to b\bar{b}$

VH at NNLO



- Full NNLO production and decay (narrow width)
  - previously NNLO production and NLO decay

Ferrera, Somogyi, Tramontano (2017)
Caola, Luisoni, Melnikov, Röntsch (2017)

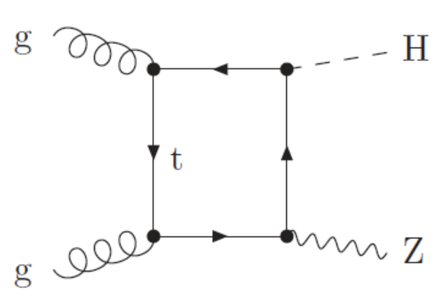


- cross section with usual boosted cuts

σ (fb)	NNLO(prod)+NLO(dec)	full NNLO
$pp \to W^+H + X \to l\nu_l b\bar{b} + X$	$3.94^{+1\%}_{-1.5\%}$	$3.70^{+1.5\%}_{-1.5\%}$
$pp \to ZH + X \to \nu\nu b\bar{b} + X$	$8.65^{+4.5\%}_{-3.5\%}$	$8.24^{+4.5\%}_{-3.5\%}$

- accepted xsection reduced by full NNLO (6%) ~ O(EW) corrections
- substantial impact on distributions trivial at LO
- some effects accounted by PS (NNLOPS)

Astil, Bizon, Re, Zanderighi (2018)

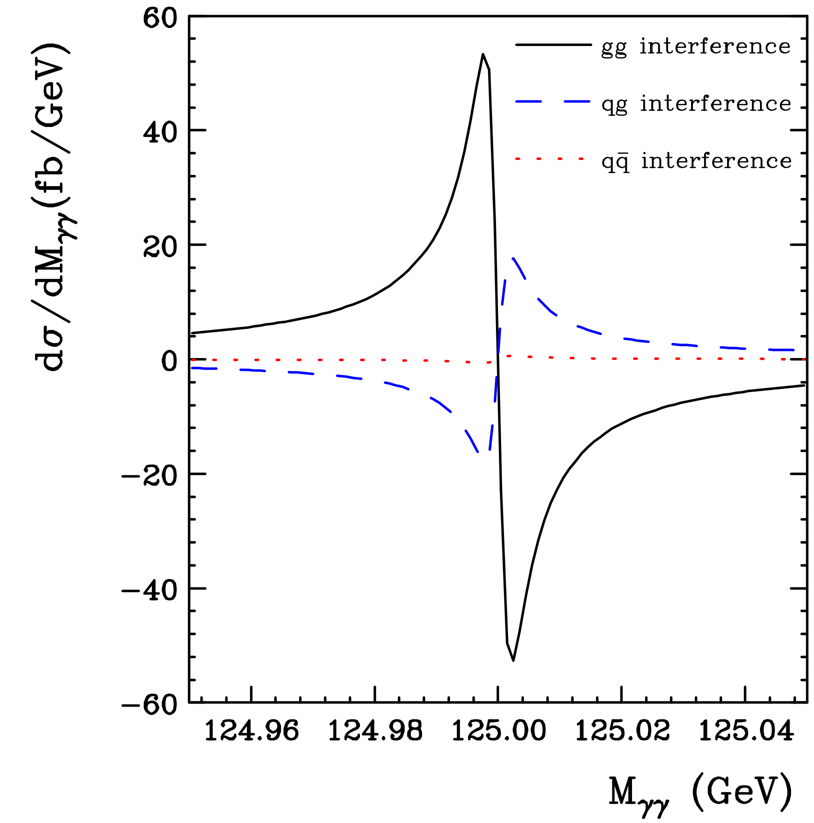


- sizeable $gg \to HV$ above top threshold

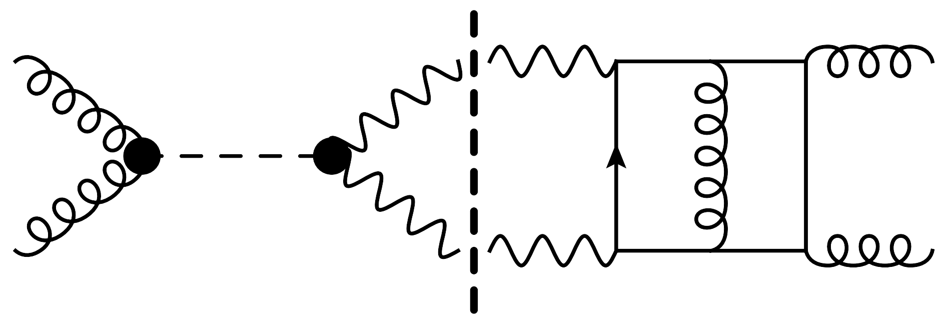
Higgs Width

Width from interference $H \to \gamma\gamma$

- 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)

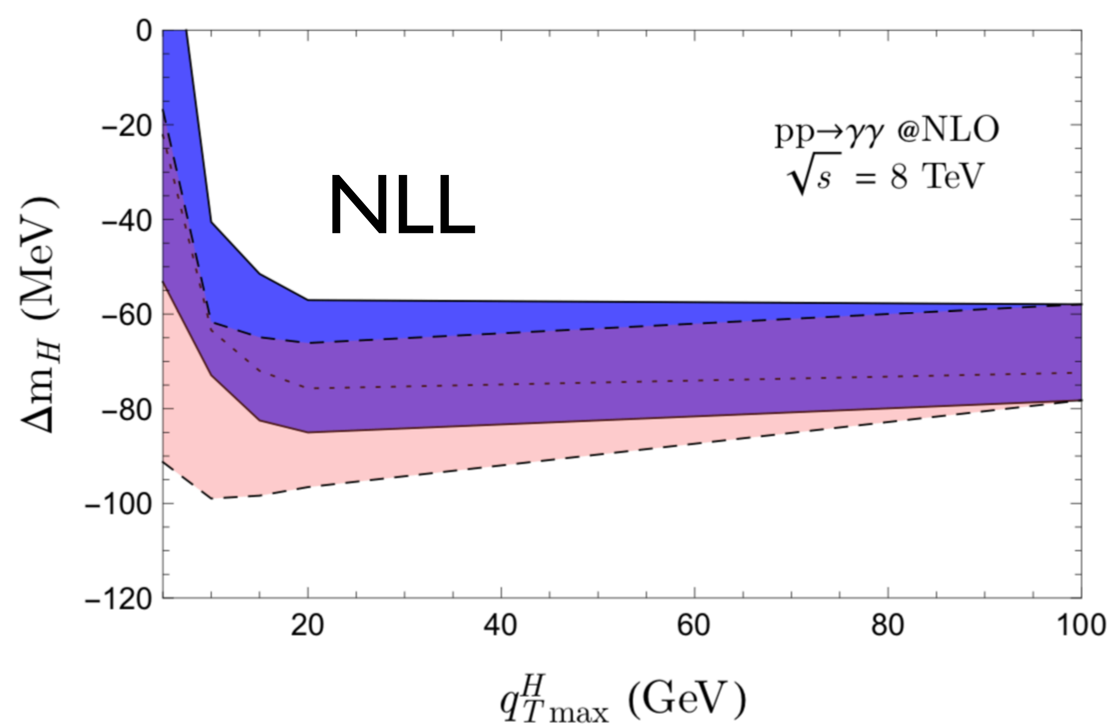


Known to $\mathcal{O}(\alpha_\varepsilon^3)$

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

  or precise mass measurements in different H q_T bins in $\gamma\gamma$

  Cieri, Coradeschi, deF, Fidanza (2017)



- Search for -2% effect of interference in cross section

Campbell, Carena, Harnik, Liu (2017)

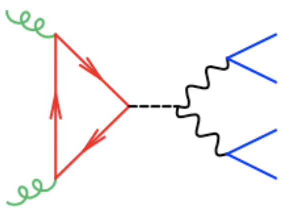
- All effects might be enhanced by BSM

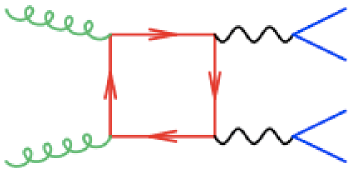
Off-shell effects and interference

signal | background

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

Propagator





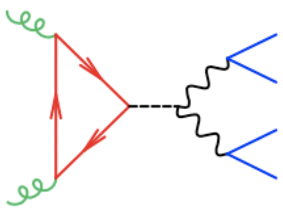
$$\Delta_H^2(q^2) \sim \frac{1}{(q^2 - M_H^2)^2 + \Gamma_H^2 M_H^2} \sim \frac{\pi}{M_H \Gamma_H}\delta(q^2 - M_H^2) + \mathcal{O}\left(\frac{\Gamma_H}{M_H}\right)$$ ZWA

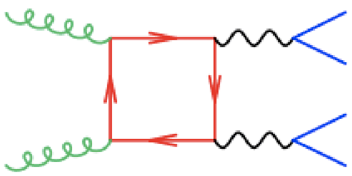
Off-shell effects and interference

signal   background

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

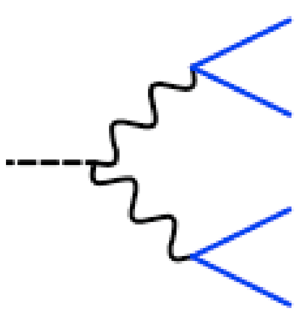
Propagator





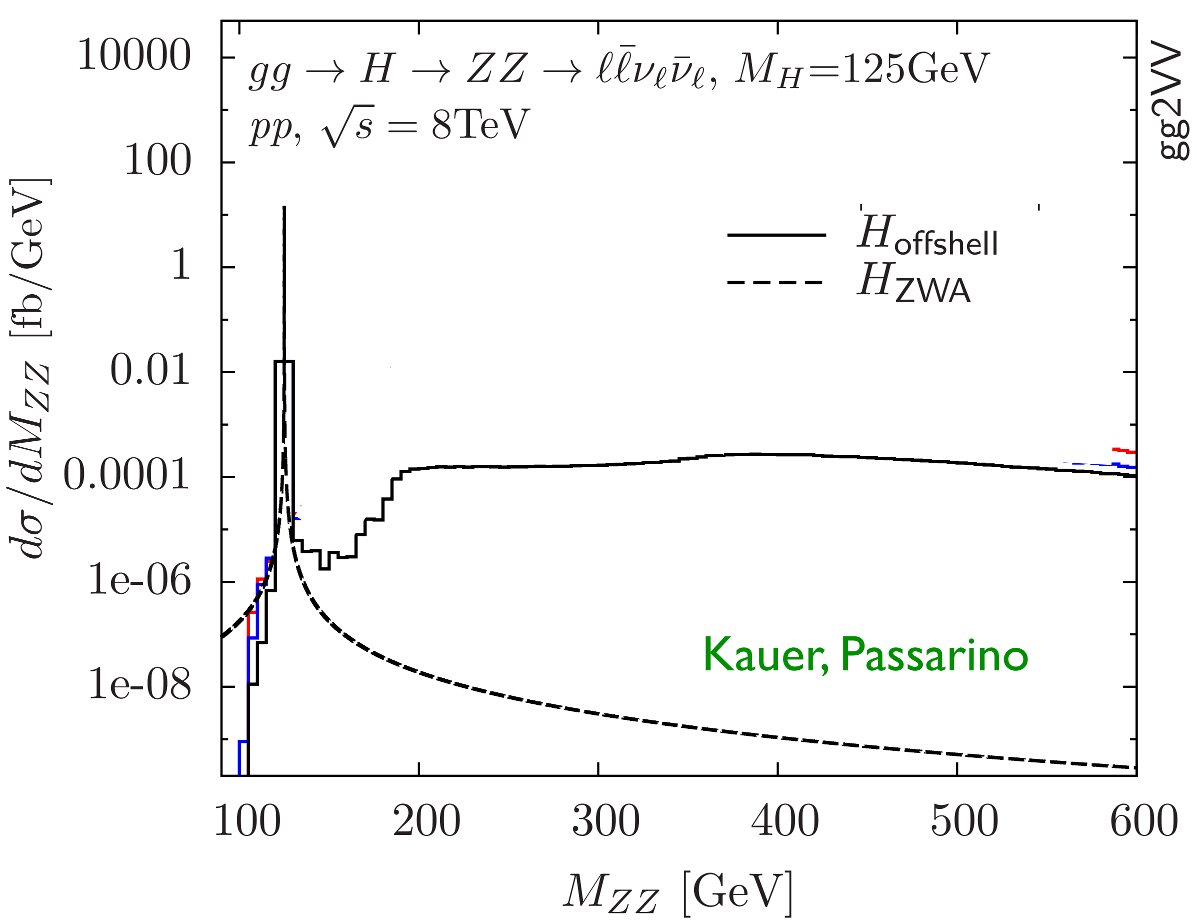
$$\Delta^2_H(q^2) \sim \frac{1}{(q^2-M_H^2)^2+\Gamma_H^2 M_H^2} \sim \frac{\pi}{M_H\Gamma_H}\delta(q^2-M_H^2) + \mathcal{O}\left(\frac{\Gamma_H}{M_H}\right)$$ ZWA

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

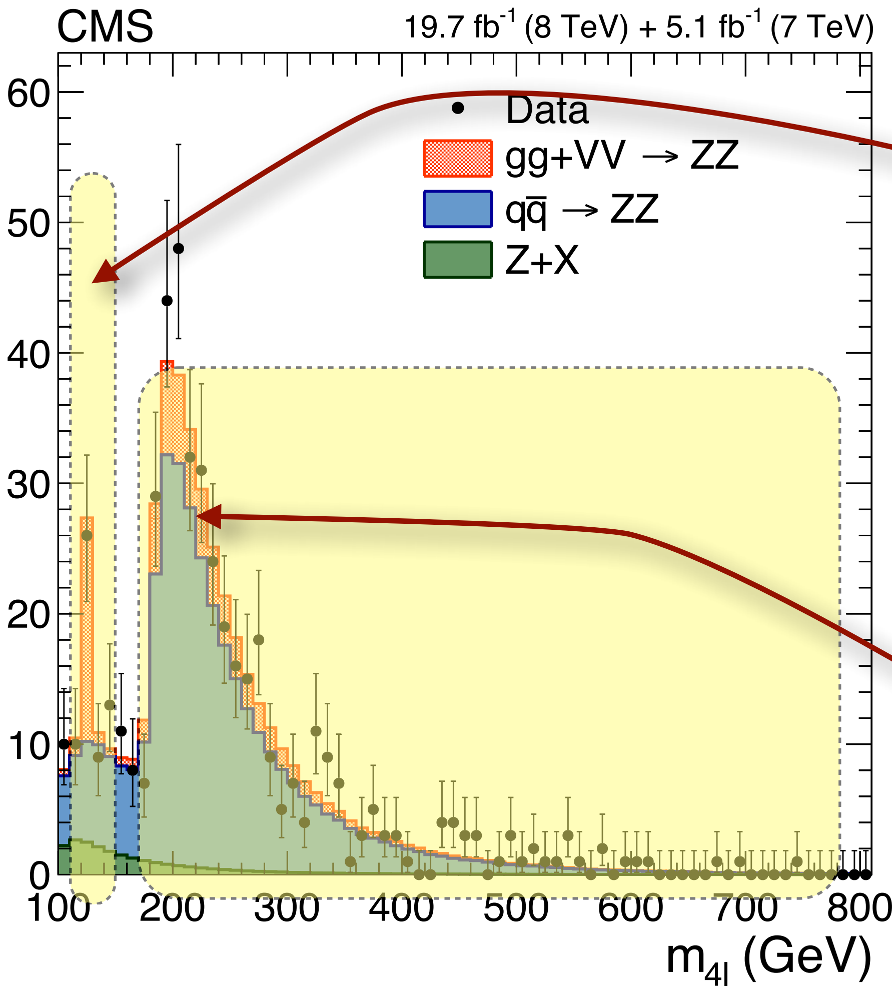


$$|\mathcal{A}_{H\to VV}|^2 \sim (q^2)^2$$

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



Width measurement from off-shell $gg \to H \to VV$



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

SM assumptions on couplings (running)

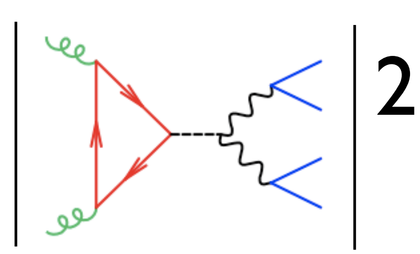
$$g = \xi\, g^{SM}$$
$$\Gamma_H = \xi^4\, \Gamma_H^{SM}$$

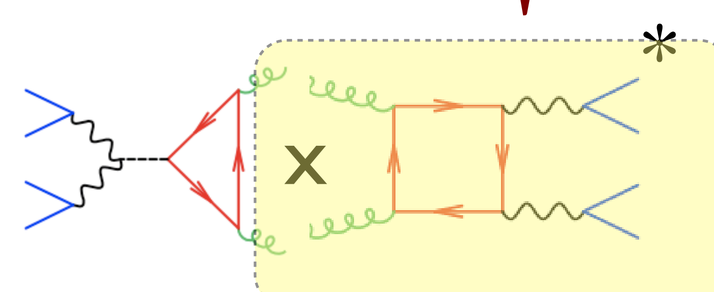
$$\sigma^{\text{off}} \int_{q^2 \gg M_H^2} dq^2 \frac{|A_{gg\to H\to VV}|^2}{(q^2-M_H^2)+\Gamma_H^2 M_H^2} \sim \int dq^2 g_{ggH}^2(q^2)\, g_{HVV}^2(q^2)$$

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

CMS

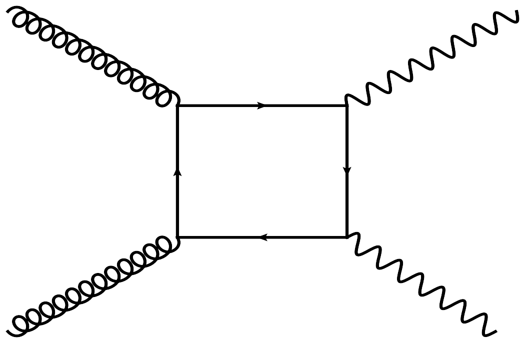
$3.2^{+2.8}_{-2.2}$ MeV





potential problem: top mass scheme uncertainty ~ 20%

need precision on $gg \to VV$ NNLO for background but sizeable

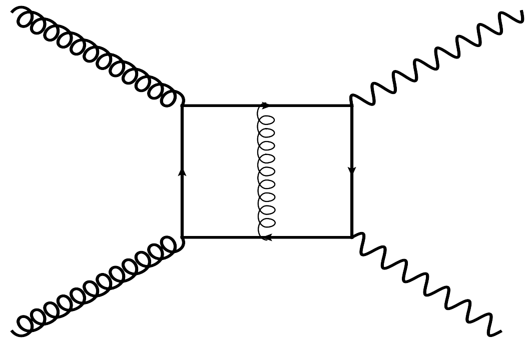


$$gg \to VV$$

H background

$$gg \to (H) \to VV$$

signal-background interference

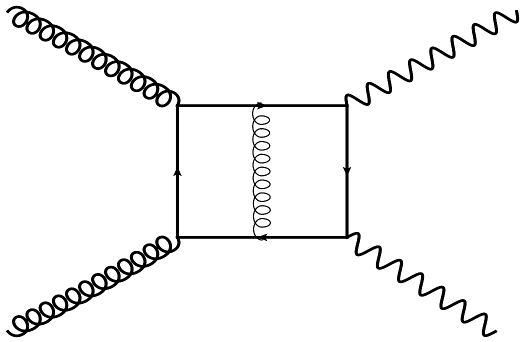


$$gg \to VV$$

H background

$$gg \to (H) \to VV$$

signal-background interference



$$gg \to VV$$

H background

$$gg \to (H) \to VV$$

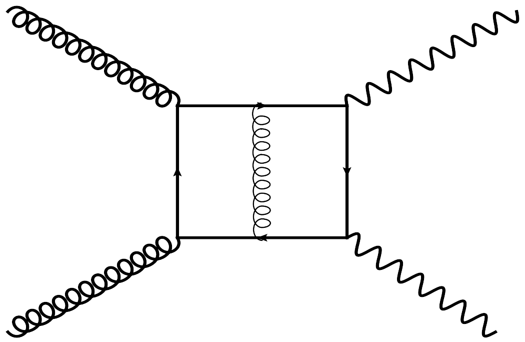
signal-background interference

Caola, Dowling, Melnikov, Röntsch, Tancredi (2016)
Campbell, Ellis, Czakon, Kirchner (2016)

- Available for massless partons @NLO (+$1/m_T$ expansion below threshold)
- But mass effects not-negligible (helicity flip in interference)

$$K_{\rm intf} = 1.65 \simeq \sqrt{K_{\rm sigl} K_{\rm bkgd}}$$

- K-factor for ZZ interference about geometric mean for signal and bckg
- Larger for WW



$gg \to VV$
H background

$gg \to (H) \to VV$
signal-background interference

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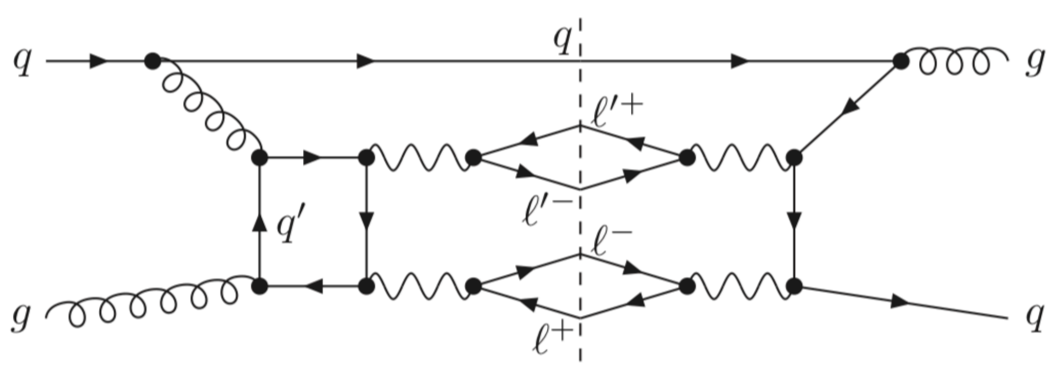
$$K_{\text{intf}} = 1.65 \simeq \sqrt{K_{\text{sigl}} K_{\text{bkgd}}}$$

- K-factor for ZZ interference about geometric mean for signal and bckg
- Larger for WW

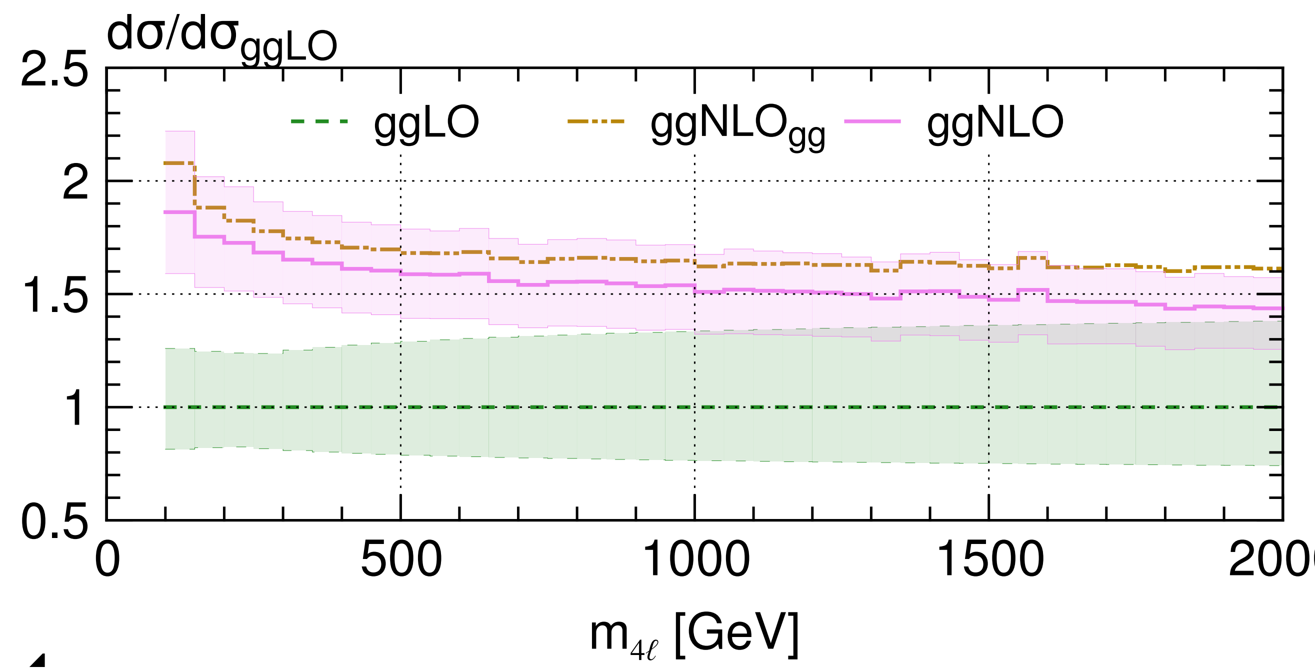
- Inclusion of leptonic decay, H interference and all channels

$gg \to ZZ \to 4\ell$

top exact in real, reweight on 2-loop



Grazzini, Kallweit, Wiesemann, Yook (2019)
MATRIX @NNLO

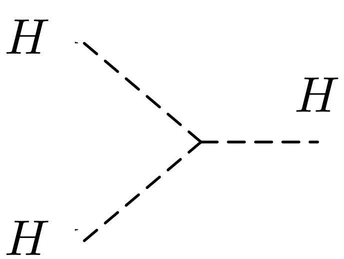


- Large, non-flat, no overlap

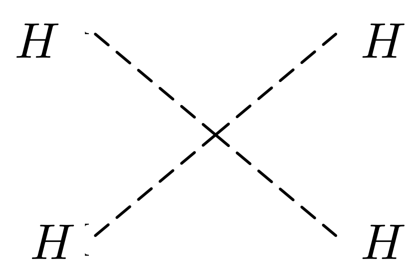
Higgs pair production

Higgs pair production

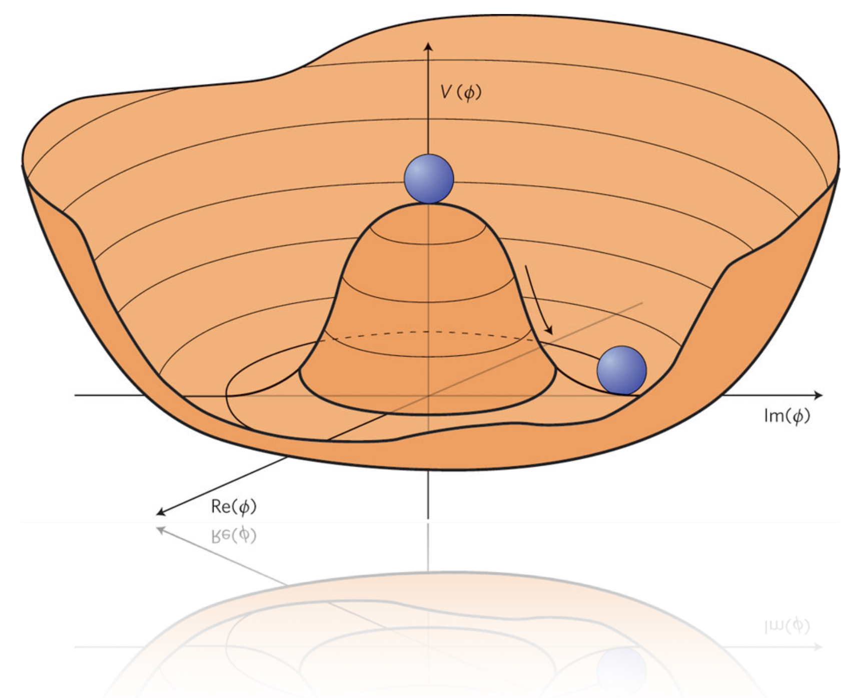
- Need to measure HHH and HHHH couplings to explore the details of SSB mechanism



$$-3i\frac{m_H^2}{v}$$



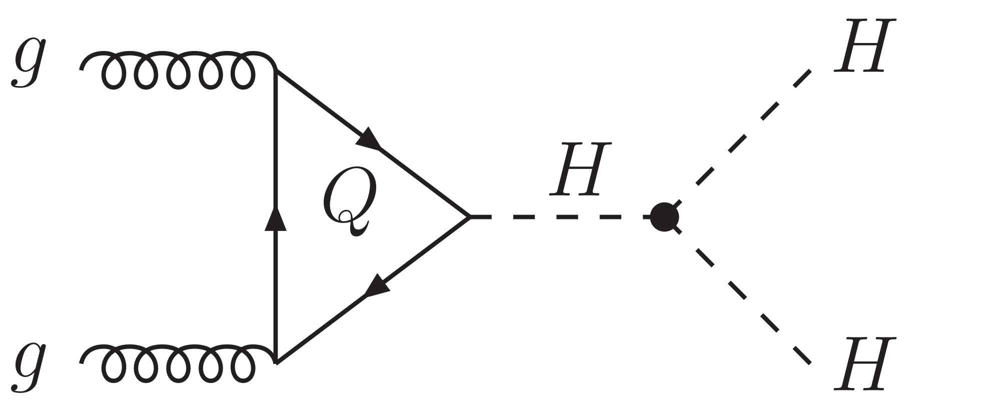
$$-3i\frac{m_H^2}{v^2}$$



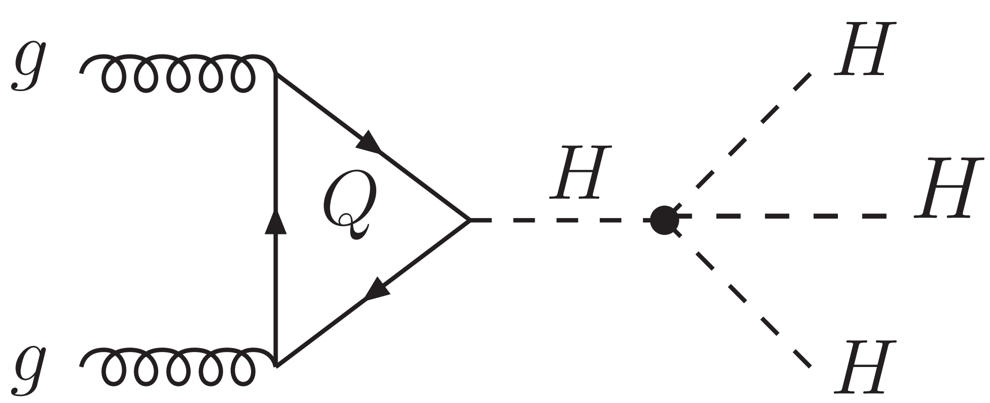
$$V = \frac{\lambda}{4}\left(2vH + H^2\right)^2 = \frac{1}{2}(2\lambda v^2)H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$

Problem: to measure *n*H coupling need to measure (*n*-1)H production

Much smaller cross sections @ 13 TeV



~ 30 fb challenging

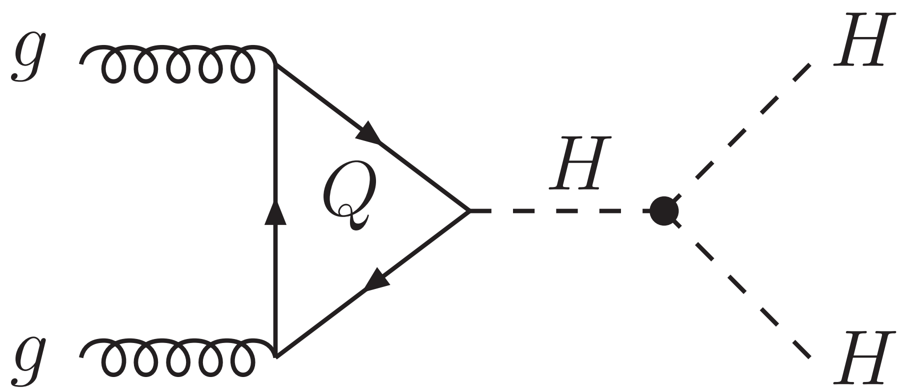


~ 0.05 fb impossible

Compared to ~50 pb for single Higgs(3 orders per extra H)

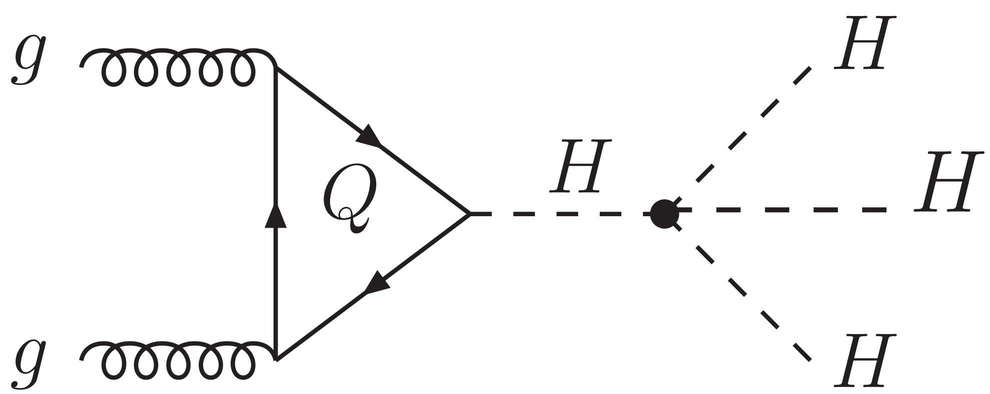
Problem: to measure *n*H coupling need to measure (*n*-1)H production

Much smaller cross sections @ 13 TeV



~ 30 fb challenging

4500 events/exp at 150 fb^{-1}
HH next discovery at the LHC??



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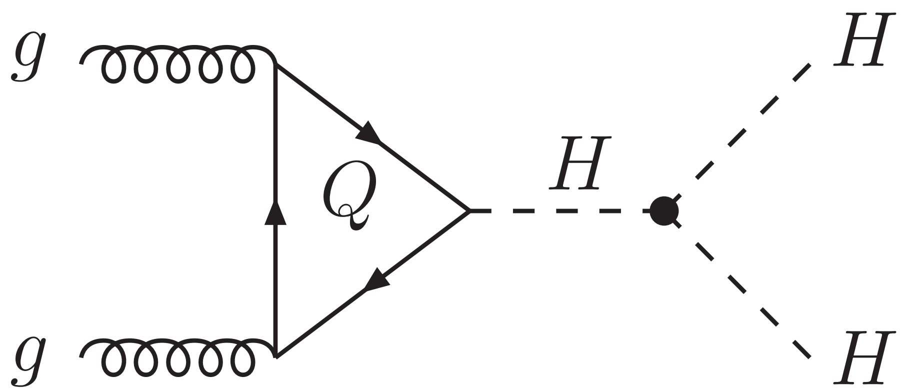

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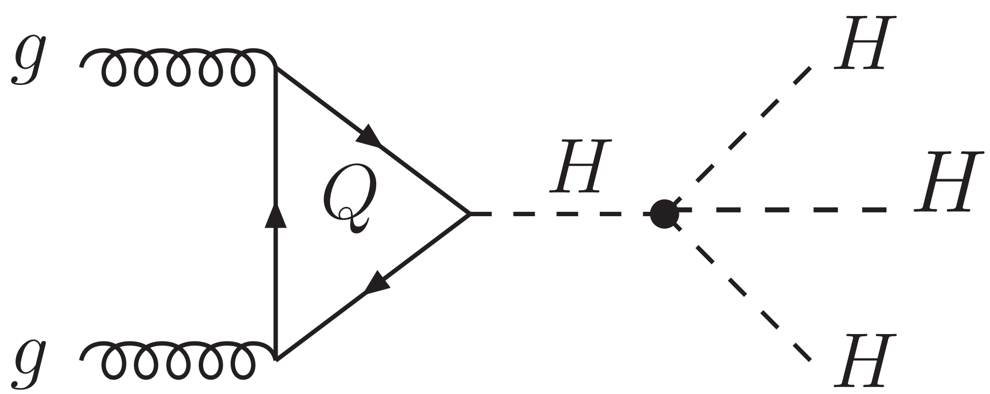


~ 0.05 fb impossible

Compared to ~50 pb for single Higgs(3 orders per extra H)

- Several recent phenomenological studies

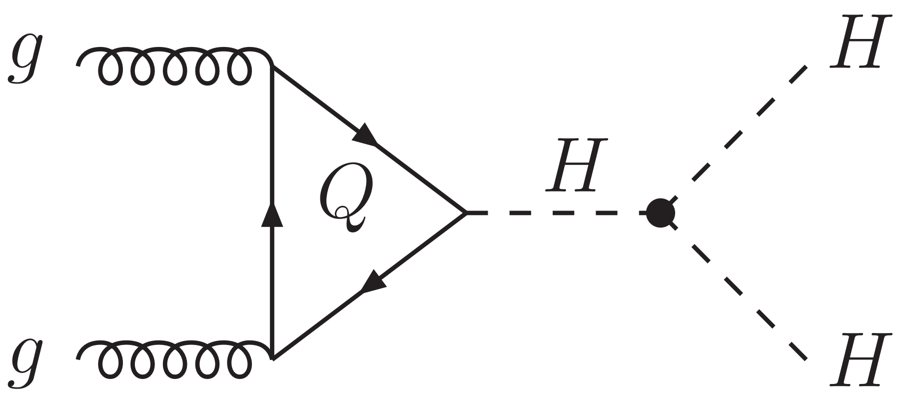
20%-30% uncertainty in triple Higgs coupling ?

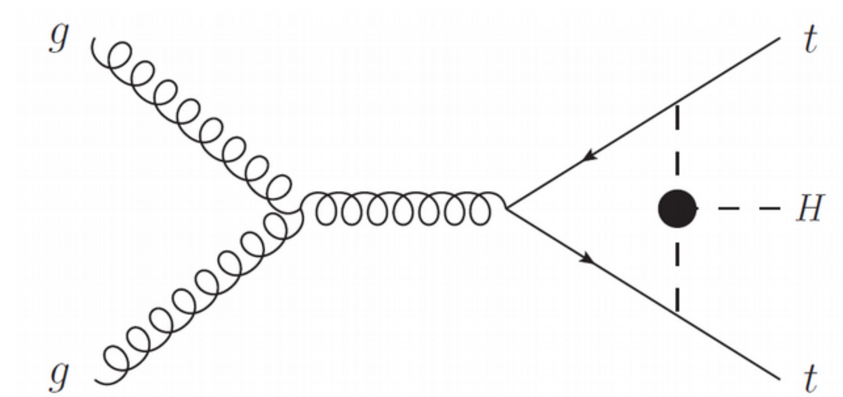
Baur, Plehn, Rainwater (2003)
Dolan, Englert, Spannowsky (2012)
Baglio et al (2012)
Papaefstathiou, Yang, Zurita (2012)

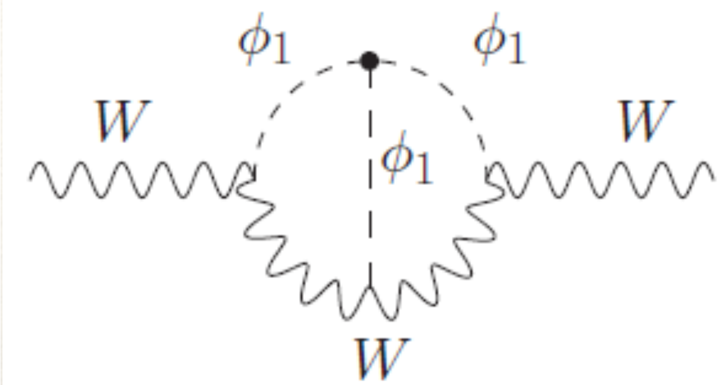
More pessimistic ~ 100% call for 100 TeV Collider with 3000 fb^{-1}

Azatov, Contino, Panico, Son (2015)

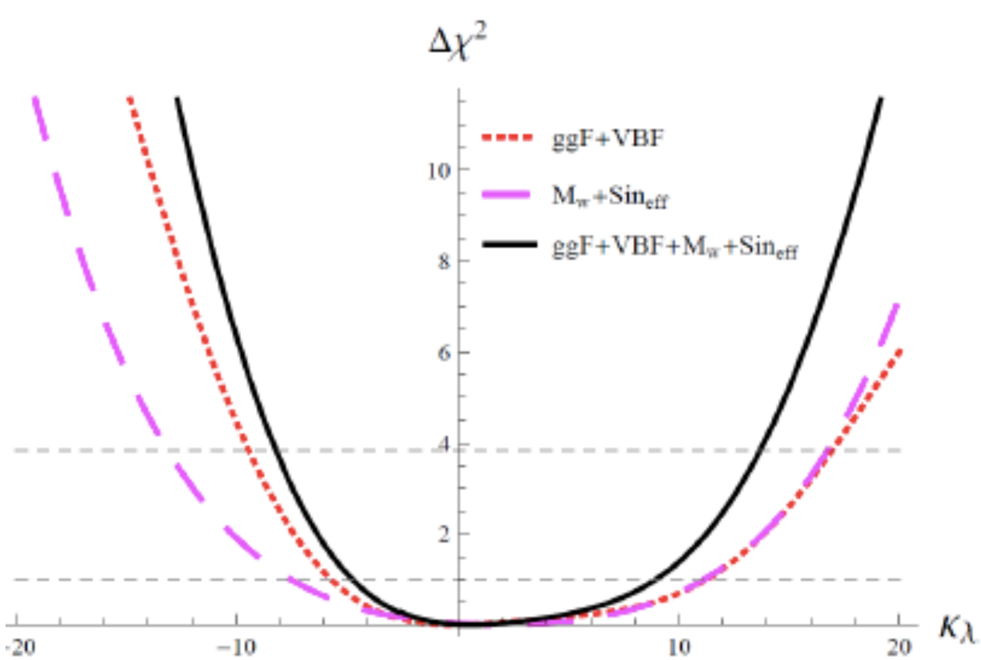
Other ways to probe the HHH coupling (indirectly)

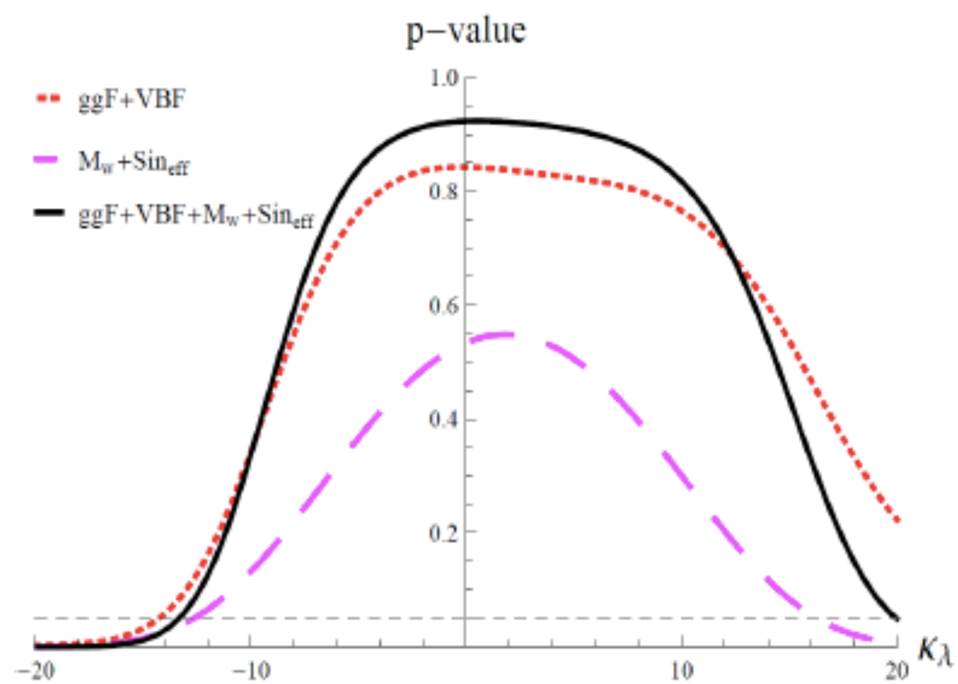


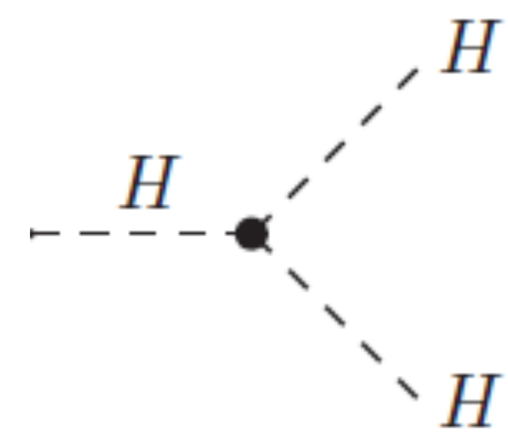




tree level	1 loop	2 loop
Direct	Indirect	Indirect[2]
2H fs	1H fs	0H fs (PO)







$\kappa_\lambda^{\rm SM} = 1$

P.O. + ggF +VBF $\quad \kappa_\lambda^{\rm best} = 0.5\,, \qquad \kappa_\lambda^{1\sigma} = [-4.7, 8.9]$

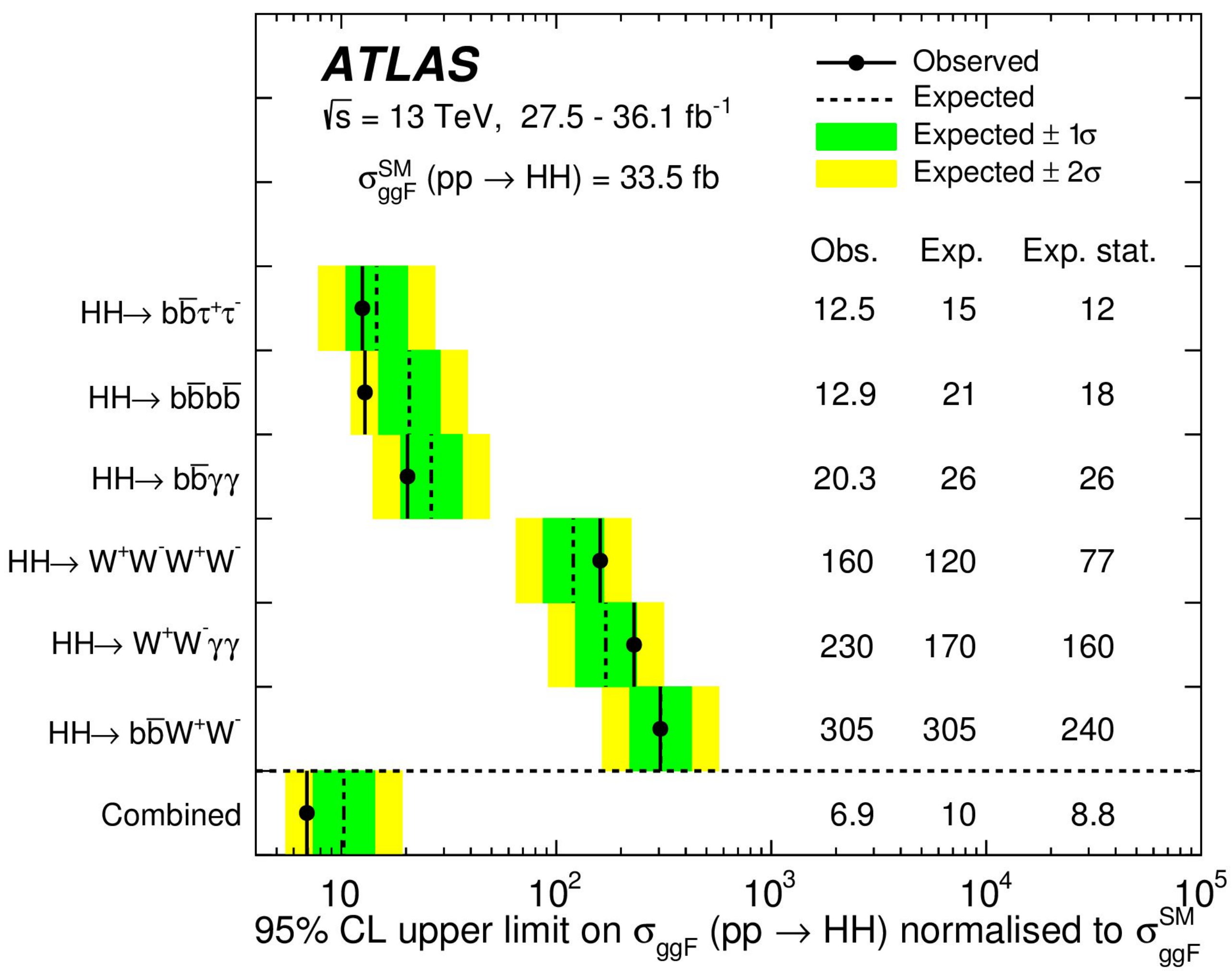
Degrassi, Giardino, Maltoni, Pagani (2016)

"CMS-HL-II" (3000 fb^{-1}) $\kappa_\lambda^{1\sigma} = [-0.7, 4.2]$

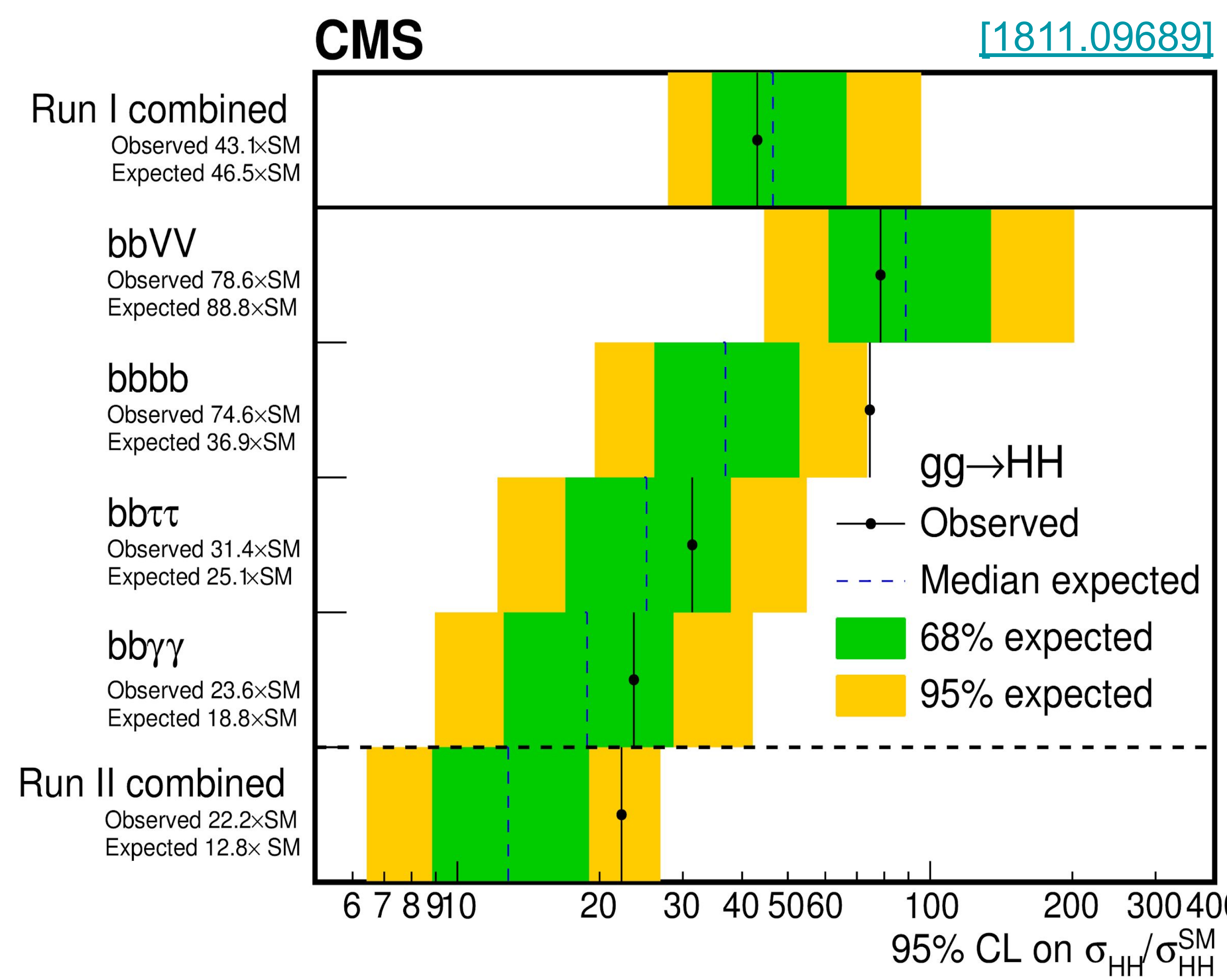
HH upper limits

- Combined upper limits on Higgs pair production
- Experiments have different sensitivities on the different channels, but similar when combined

[1906.02025]



[1811.09689]

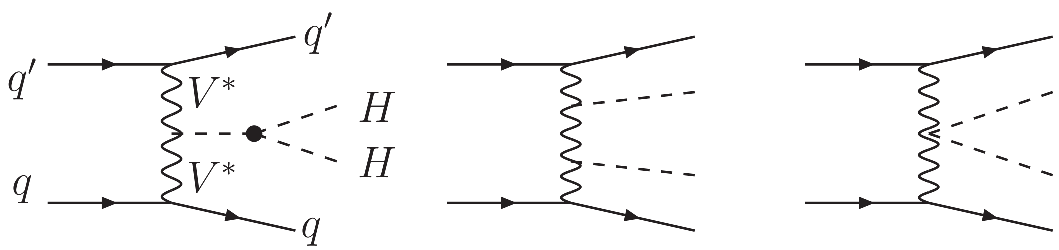


Reaching ~ O(10) xSM sensitivity

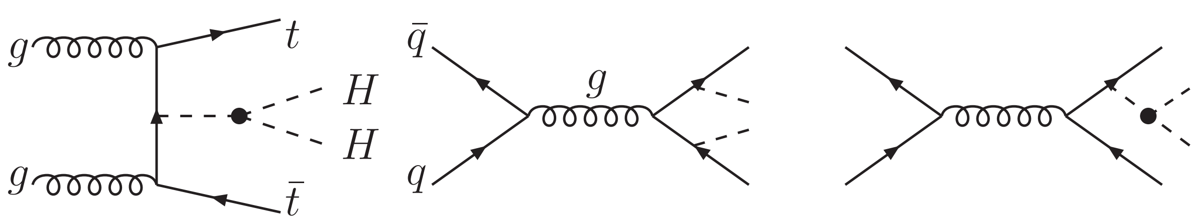
HH production channels

gg fusion

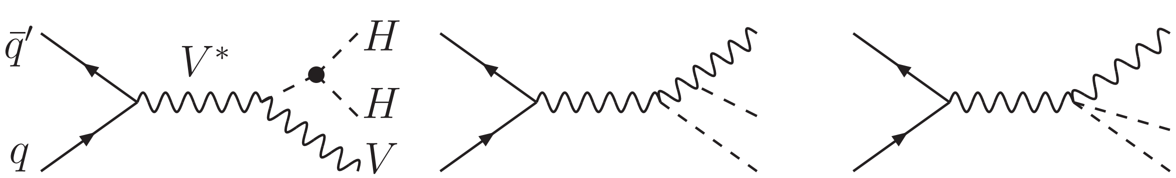
VV fusion

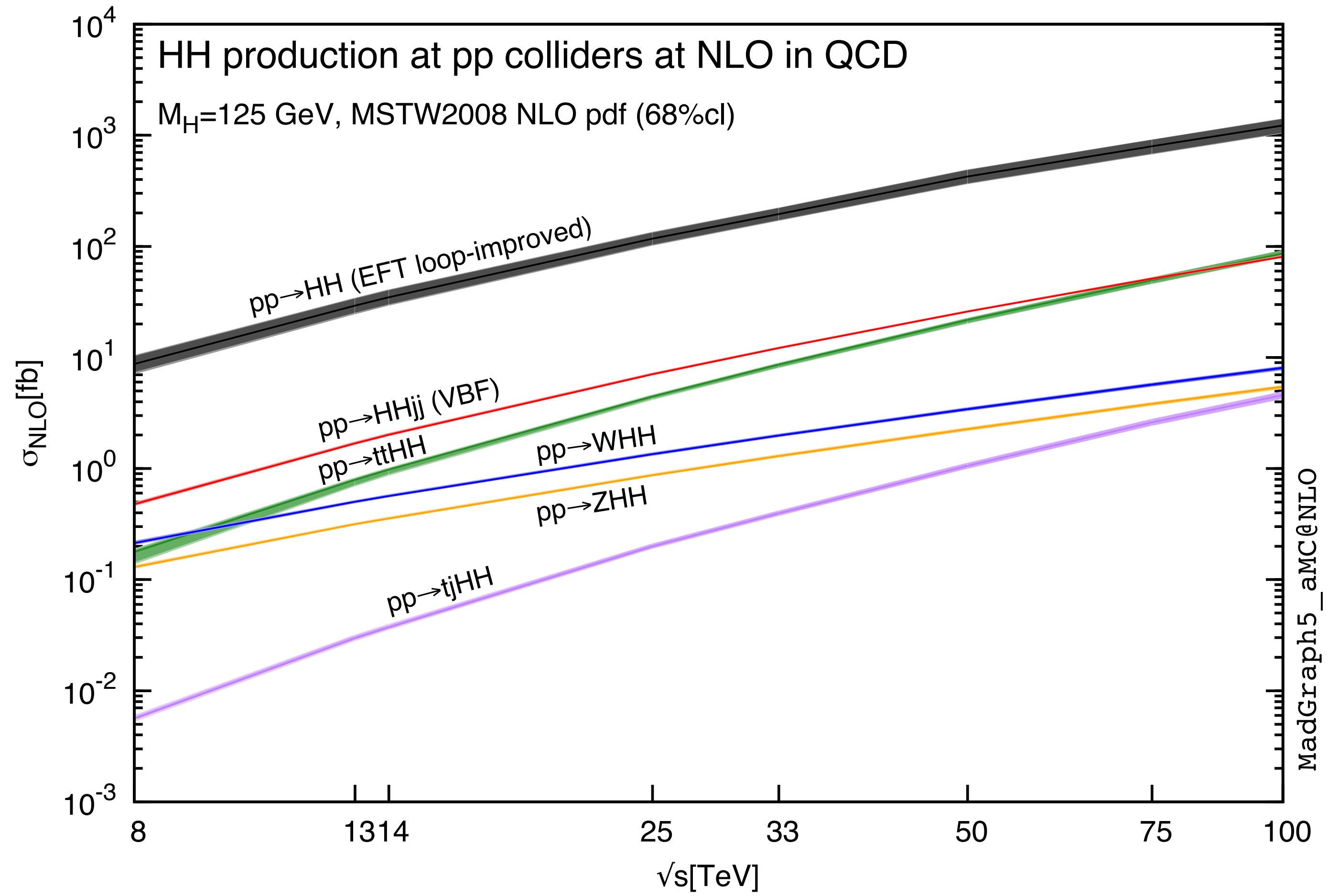


Associated production with top



Higgs-strahlung



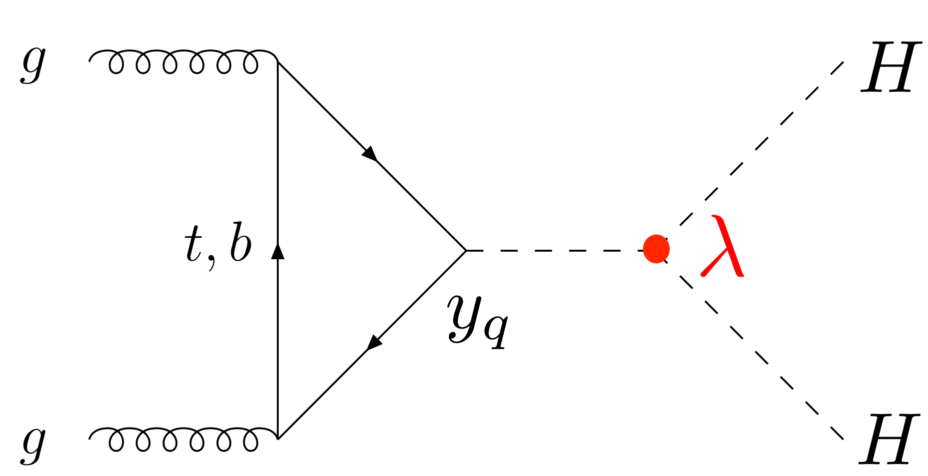


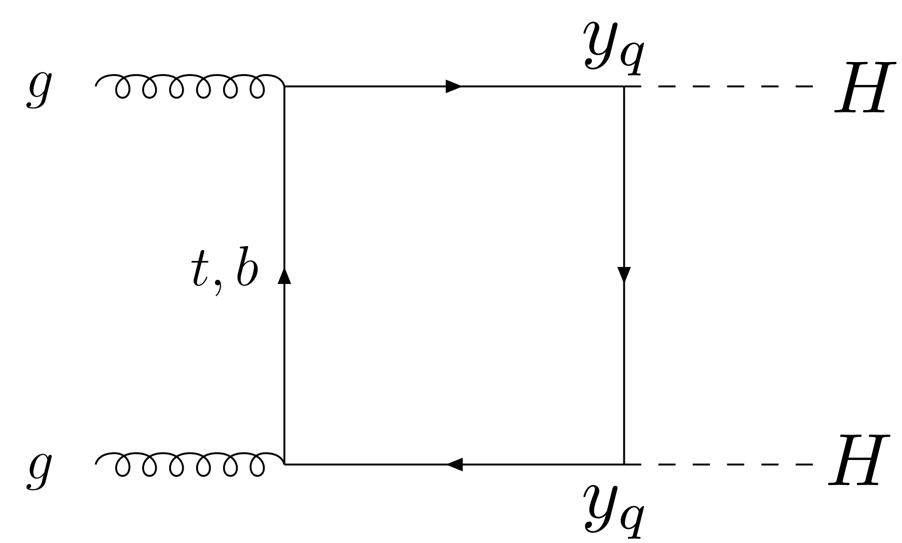
$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}_{gg\to HH}$ [fb]	$\sigma^{\rm NLO}_{qq'\to HHqq'}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\rm LO}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05	1.99	1.68	7.91
100	1417.83	79.55	8.00	8.27	77.82

Gluon-gluon fusion dominates
Only some contribute with HHH

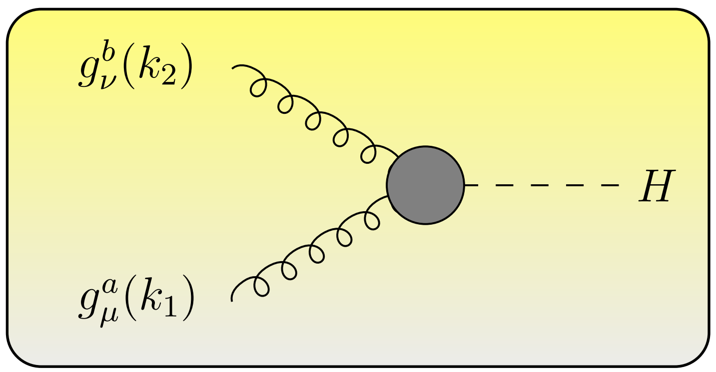
LO production of HH in gg fusion

LO : Triangle and Box contributions

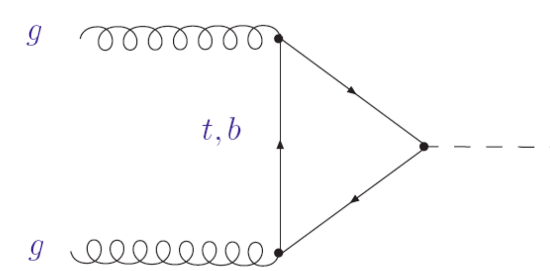


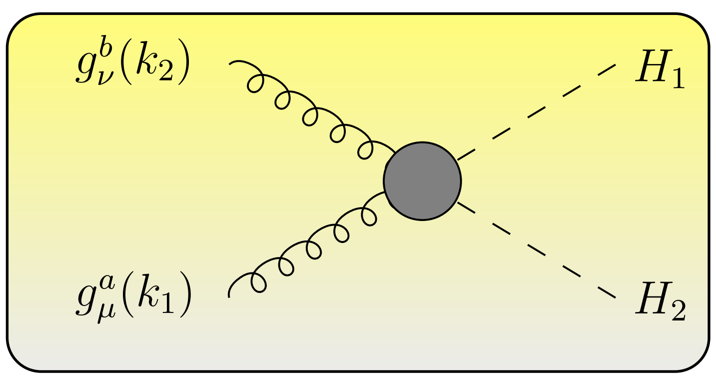


Very difficult to reach higher orders → Use HTL Lagrangian

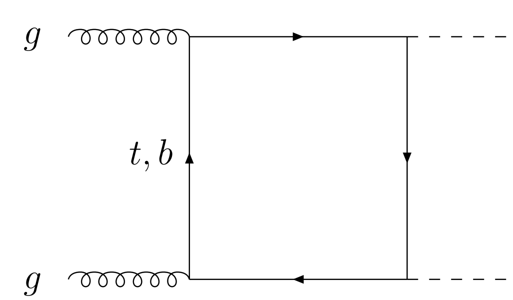


$$i\delta_{ab}\frac{\alpha_s}{3\pi v}g_t^H\left\{-g^{\mu\nu}(k_1\cdot k_2)+k_1^\nu k_2^\mu\right\}$$





$$-i\delta_{ab}\frac{\alpha_s}{3\pi v^2}g_t^{H_1}g_t^{H_2}\left\{-g^{\mu\nu}(k_1\cdot k_2)+k_1^\nu k_2^\mu\right\}$$



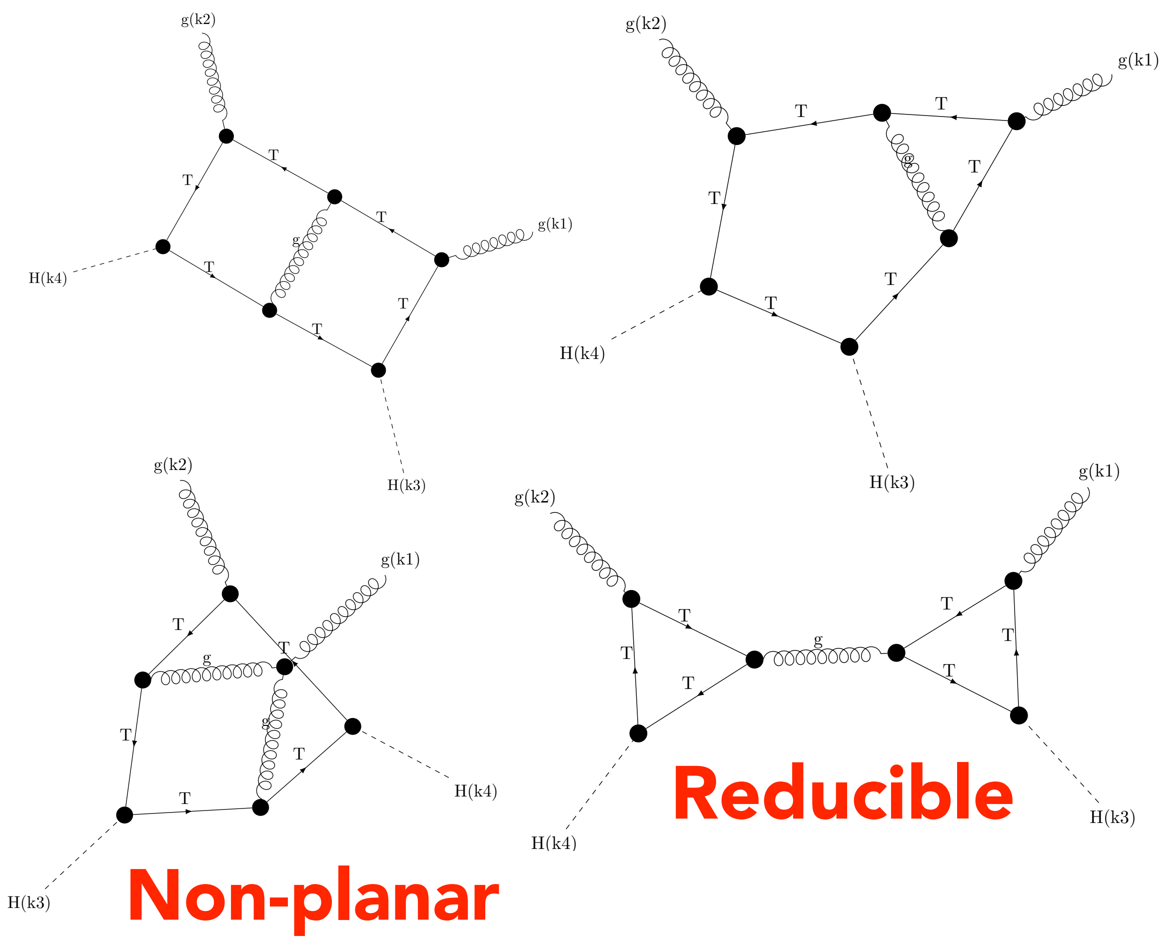
Pretty bad approximation at LO → But OK (~10%?) for K-factors!

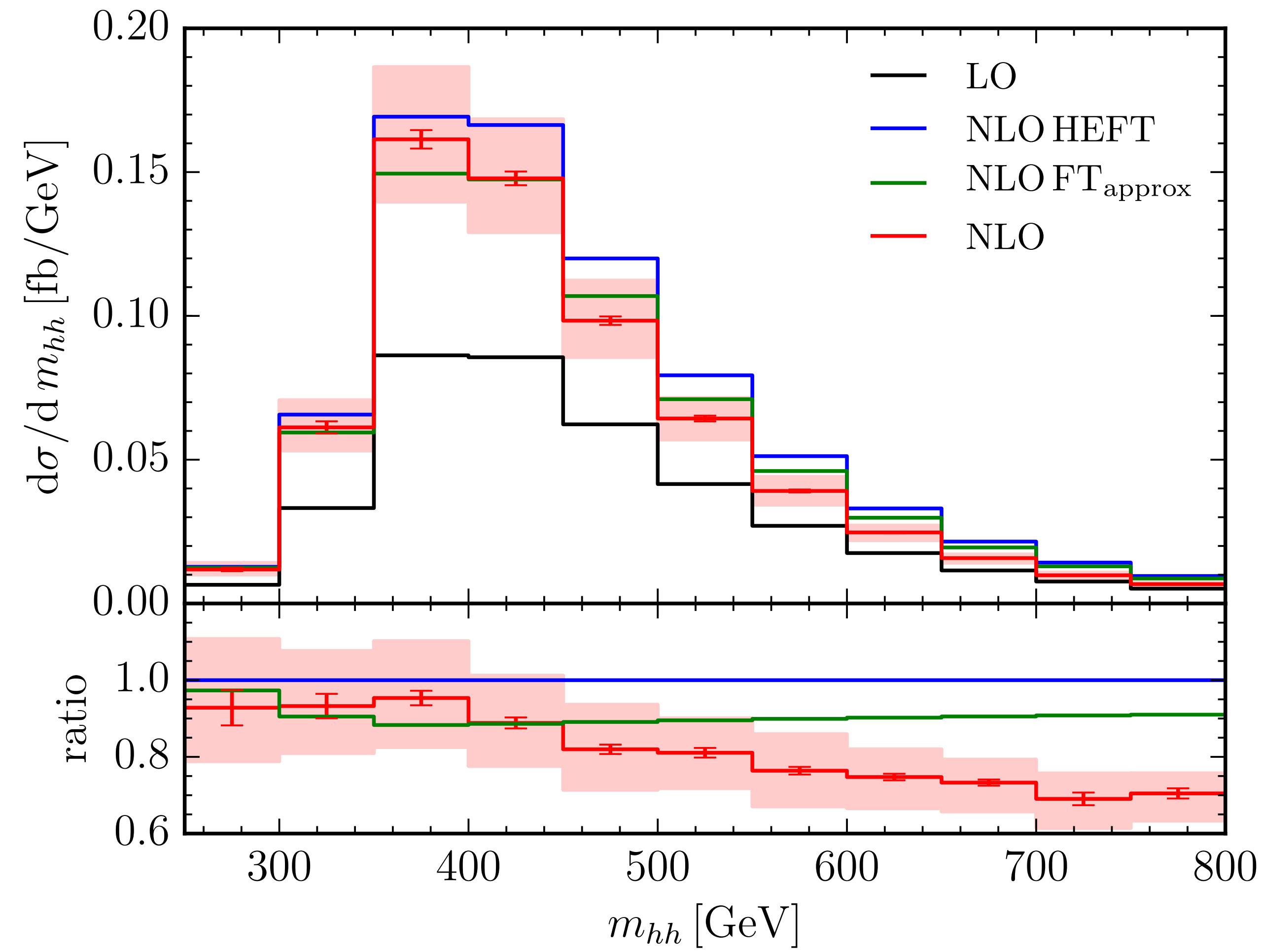
NLO first computed using HTL : large corrections Dawson, Dittmaier, Spira (1998)

Full NLO calculation (partially numerical)

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke (2016)

Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher (2018)





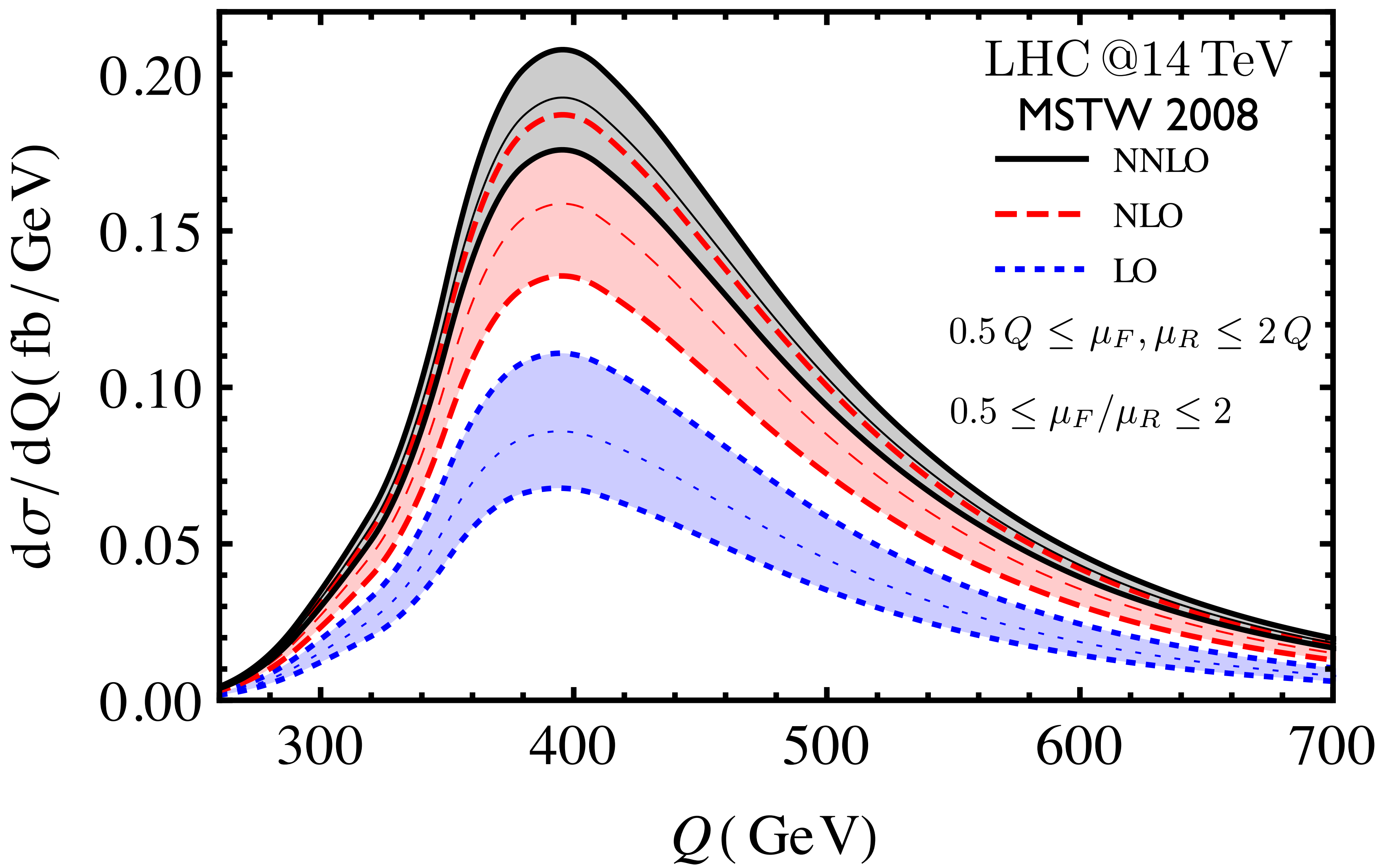
-14% wrt naive approx.

bigger for large invariant masses

- Provides solid results and distributions
- Understand approximations to be used at NNLO

NNLO corrections computed within HTL

deF, Mazzitelli (2013)



K

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

1.86

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

21%

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

2.26

$\pm 8\%$

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

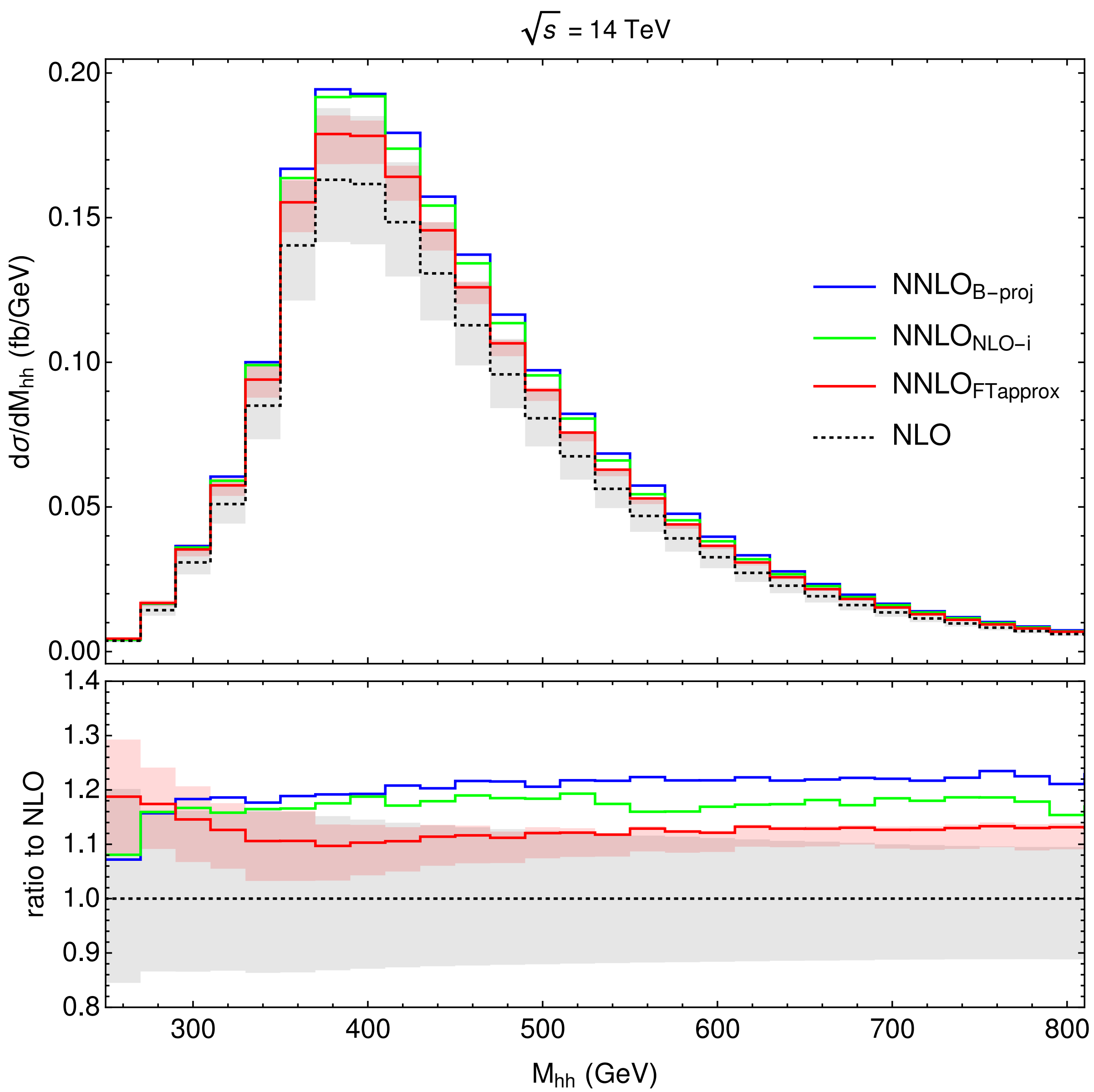
As expected, very similar pattern to single Higgs

- Large QCD corrections
- Scale band: overlap between NLO and NNLO
- Reduction in scale dependence
- Recently improved by NNLL threshold resummation deF, J. Mazzitelli (2018)

- Exclusive NNLO calculation available in HTL

deF, Grazzini, Hanga, Kallweit, Lindert, Maienrhöfer, Mazzitelli, Rathlev (2018)

- recently matched to full NLO in 3 different schemes (uncertainty estimate)



Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli (2018)

- estimate uncertainty on lack of top mass at NNLO about 3%

1) $\mathrm{NNLO_{NLO\text{-}i}}$

Rescale NLO by $K_{NNLO} = \mathrm{NNLO_{HTL}/NLO_{HTL}}$

2) $\mathrm{NNLO_{B\text{-}proj}}$

Project real radiation contributions to Born configurations, rescale by $\mathrm{LO/LO_{HTL}}$

3) $\mathrm{NNLO_{FTapprox}}$

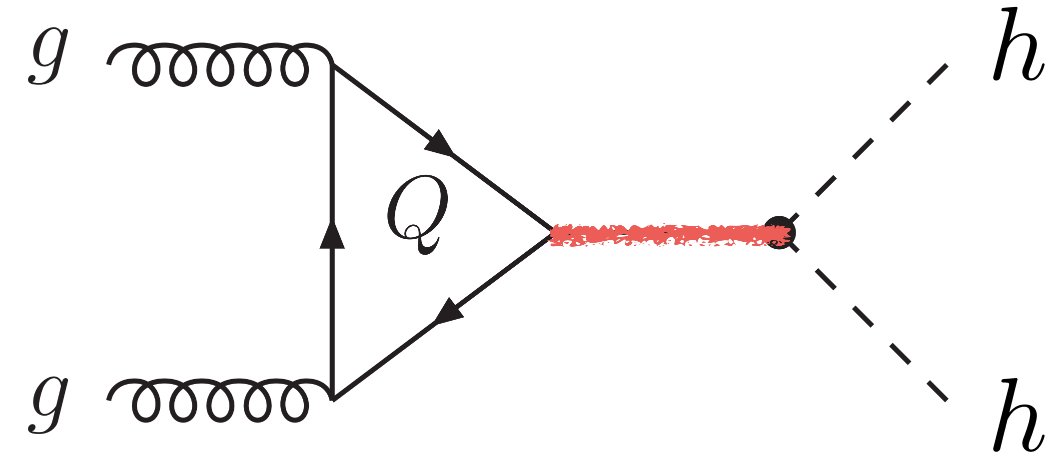
NNLO HTL correction rescaled for each multiplicity by:

$$\mathcal{R}(ij \to HH + X) = \frac{\mathcal{A}^{\mathrm{Born}}_{\mathrm{Full}}(ij \to HH + X)}{\mathcal{A}^{(0)}_{\mathrm{HEFT}}(ij \to HH + X)}$$

$\sqrt{s}$	13 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$
$\mathrm{NLO_{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$
$\mathrm{NNLO_{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$
$\mathrm{NNLO_{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$
$\mathrm{NNLO_{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$
M_t unc. $\mathrm{NNLO_{FTapprox}}$	$\pm 2.6\%$
$\mathrm{NNLO_{FTapprox}/NLO}$	1.118

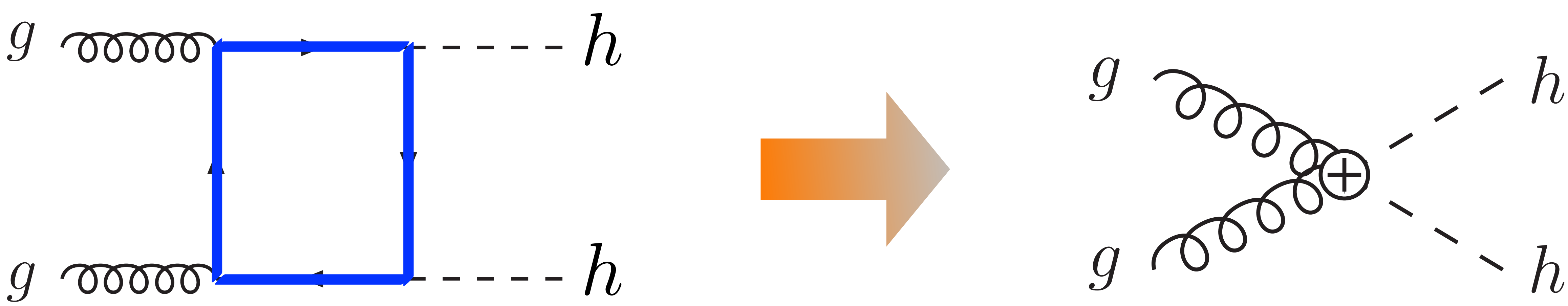
New Physics in HH

- **Resonant production**: new particle observed if light enough to appear in invariant mass distribution (peak)



- **Non-Resonant production**: if new particles are too heavy (TeV)

- Effect due to heavy object in loops integrate out to “new interaction”

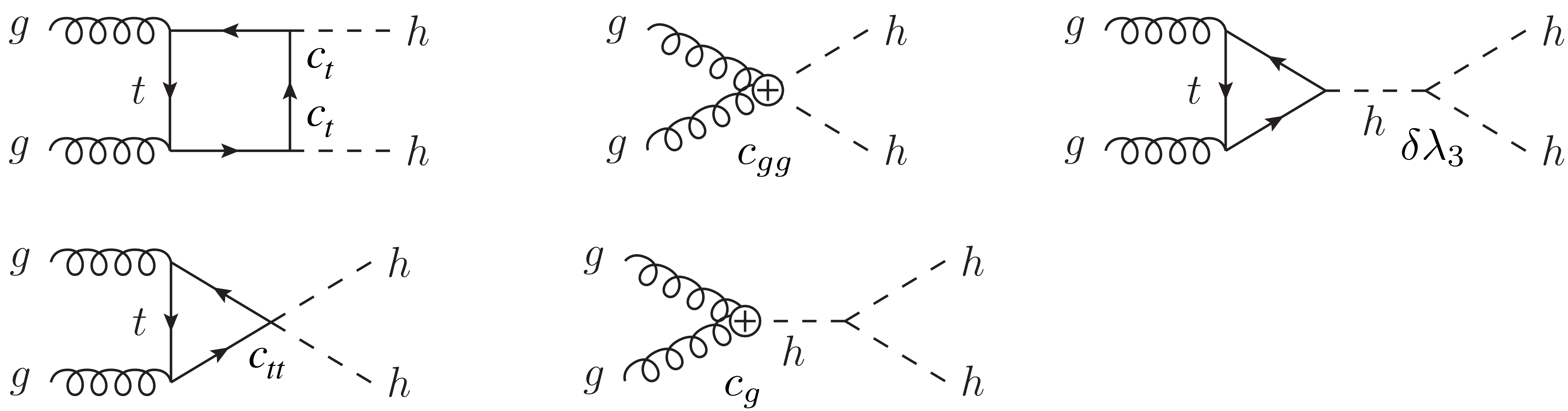


- Incorporated into Effective Lagrangian (higher dimensional operators)

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}_6 + \Delta\mathcal{L}_8 + \ldots$$

Dimension 6 operators for HH production

$$\mathcal{L} \supset -M_t\,\bar{t}t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{2v^2}\right)-c_3\frac{1}{6}\left(\frac{3M_h^3}{v}\right)h^3+\frac{\alpha_s}{\pi}G^{a\,\mu\nu}G^a_{\mu\nu}\left(c_g\frac{h}{v}+c_{gg}\frac{h^2}{2v^2}\right)$$

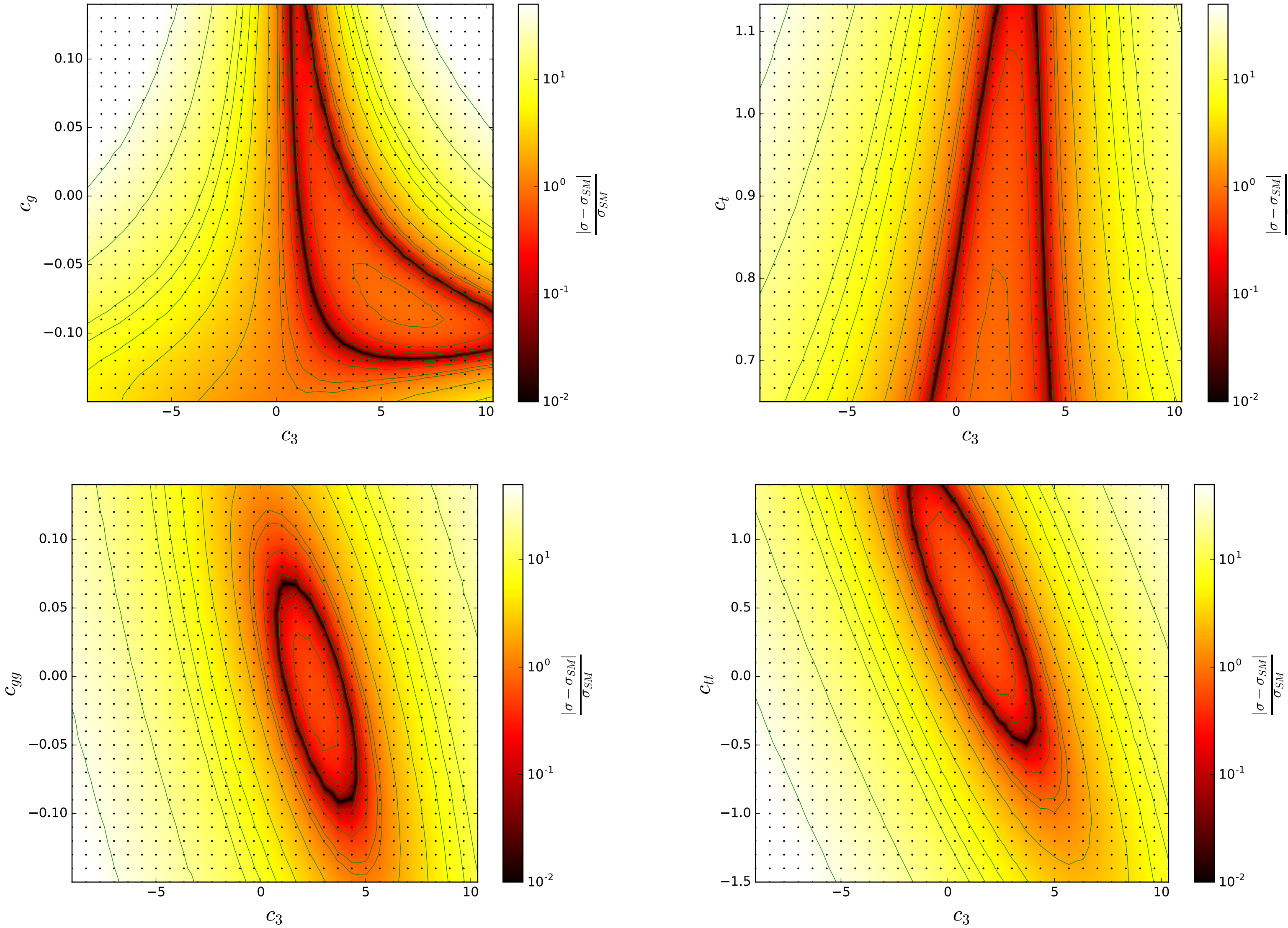


- EFT HH production

  - full m_T at NLO Buchalla, Capozi,Celis, Heinrich, Scyboz (2018)
  - HTL at NNLO deF, Fabre, Mazzitelli (2018)

Combination applying $K_{NNLO} = NNLO_{HTL}/NLO_{HTL}$ to full m_T at NLO

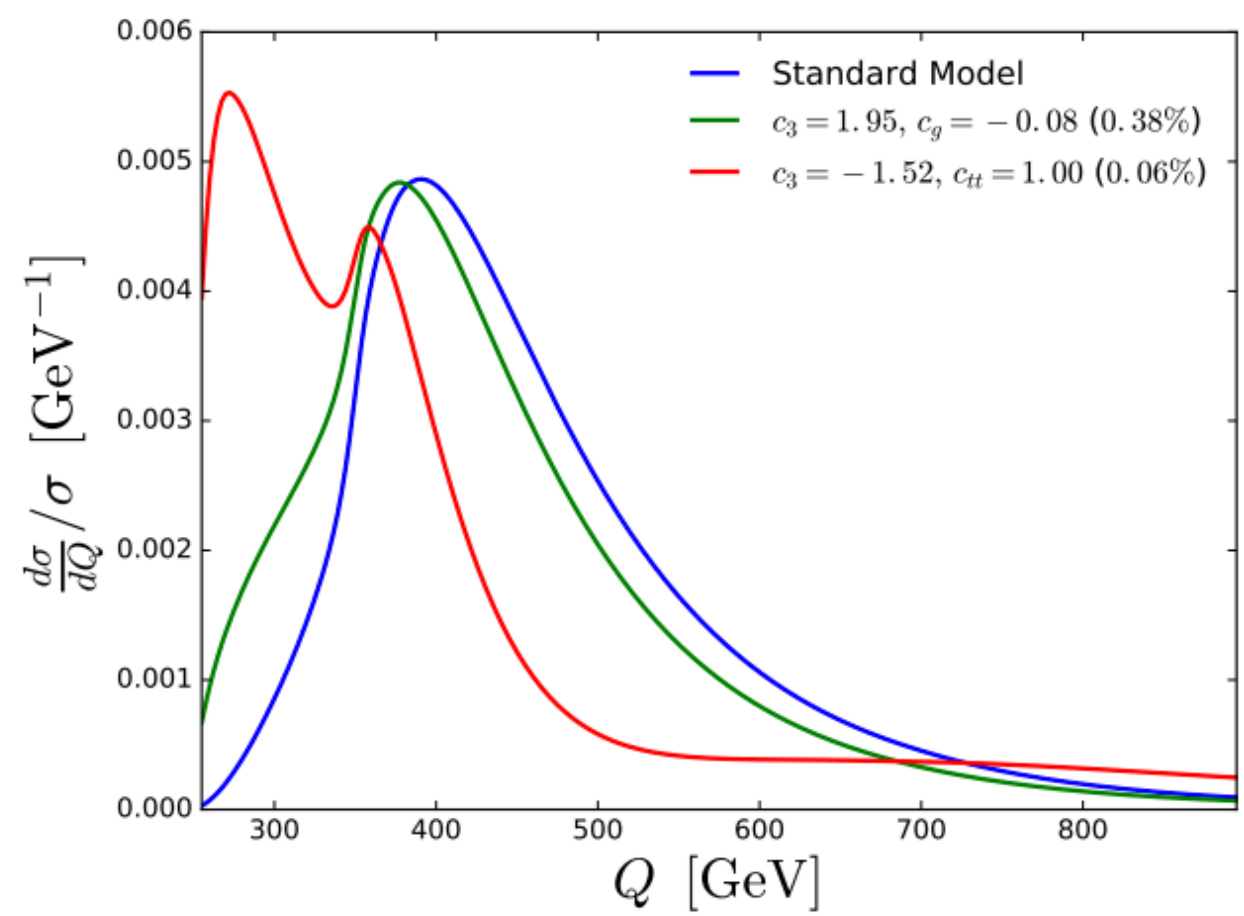
deF, Jones, Mazzitelli @ Les Houches (2019)



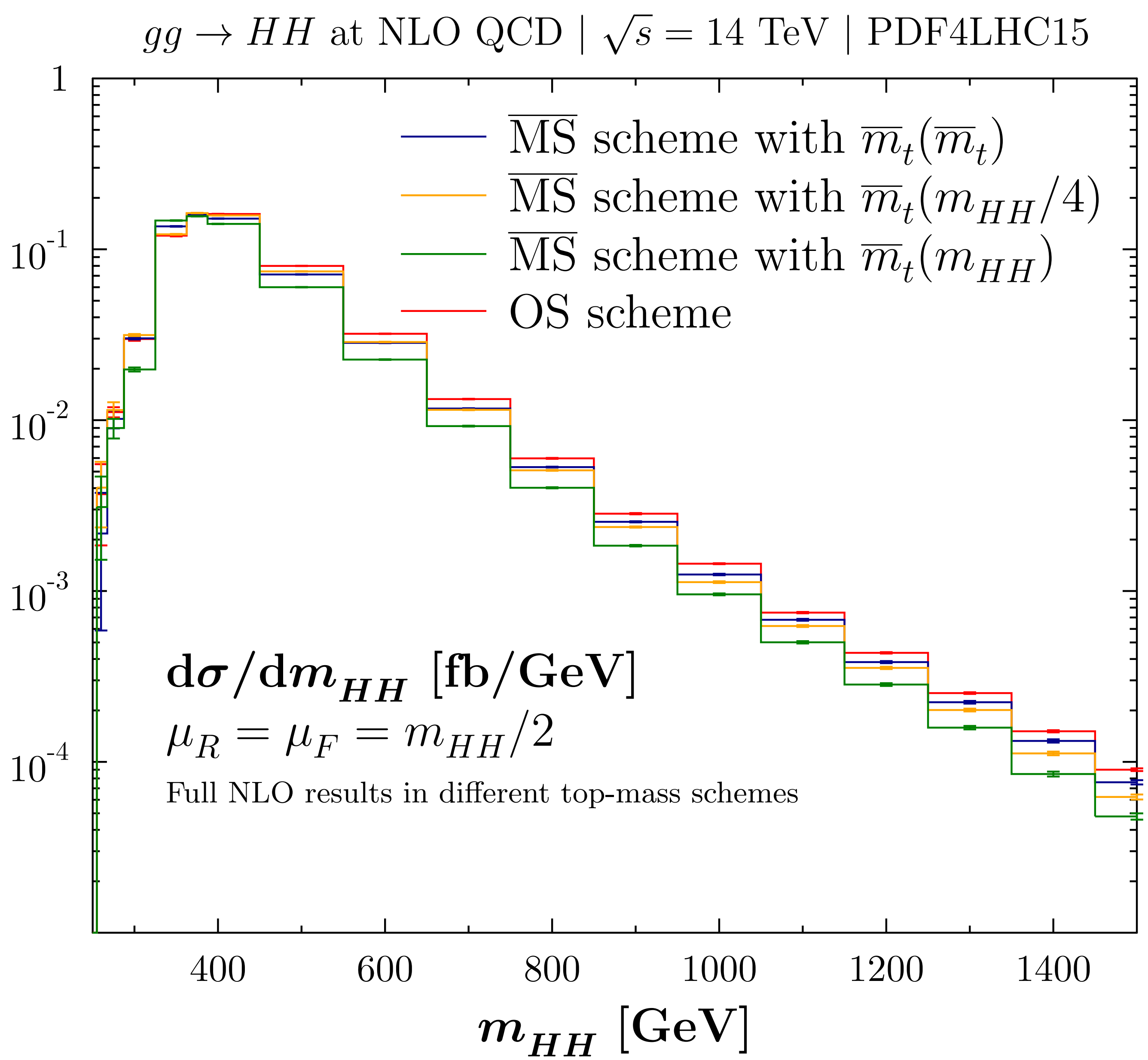
degeneracy in dim6 with SM
in total cross section

deF, Fabre, Mazzitelli (2018)

need differential distributions to
break degeneracy (and SM vs BSM)



One (big) issue: top mas scheme definition



M.Spira @ Les Houches

- transform $m_t \to \overline{m}_t(\mu)$ ($\overline{\text{MS}}$)

  $\to$ modification of mass CT

- use m_t, $\overline{m}_t(\overline{m}_t)$ and scan $Q/4 < \mu < Q$

  uncertainty = envelope

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=300\ \text{GeV}} = 0.031(1)^{+10\%}_{-22\%}\ \text{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=400\ \text{GeV}} = 0.1609(4)^{+7\%}_{-7\%}\ \text{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=600\ \text{GeV}} = 0.03204(9)^{+0\%}_{-26\%}\ \text{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=1200\ \text{GeV}} = 0.000435(4)^{+0\%}_{-30\%}\ \text{fb/GeV}$$

- Sizeable uncertainties (can reach 30%), hard to reduce

  higher order corrections (3-loop with top)
  resummation very complicated (several regions with diff. treatments)

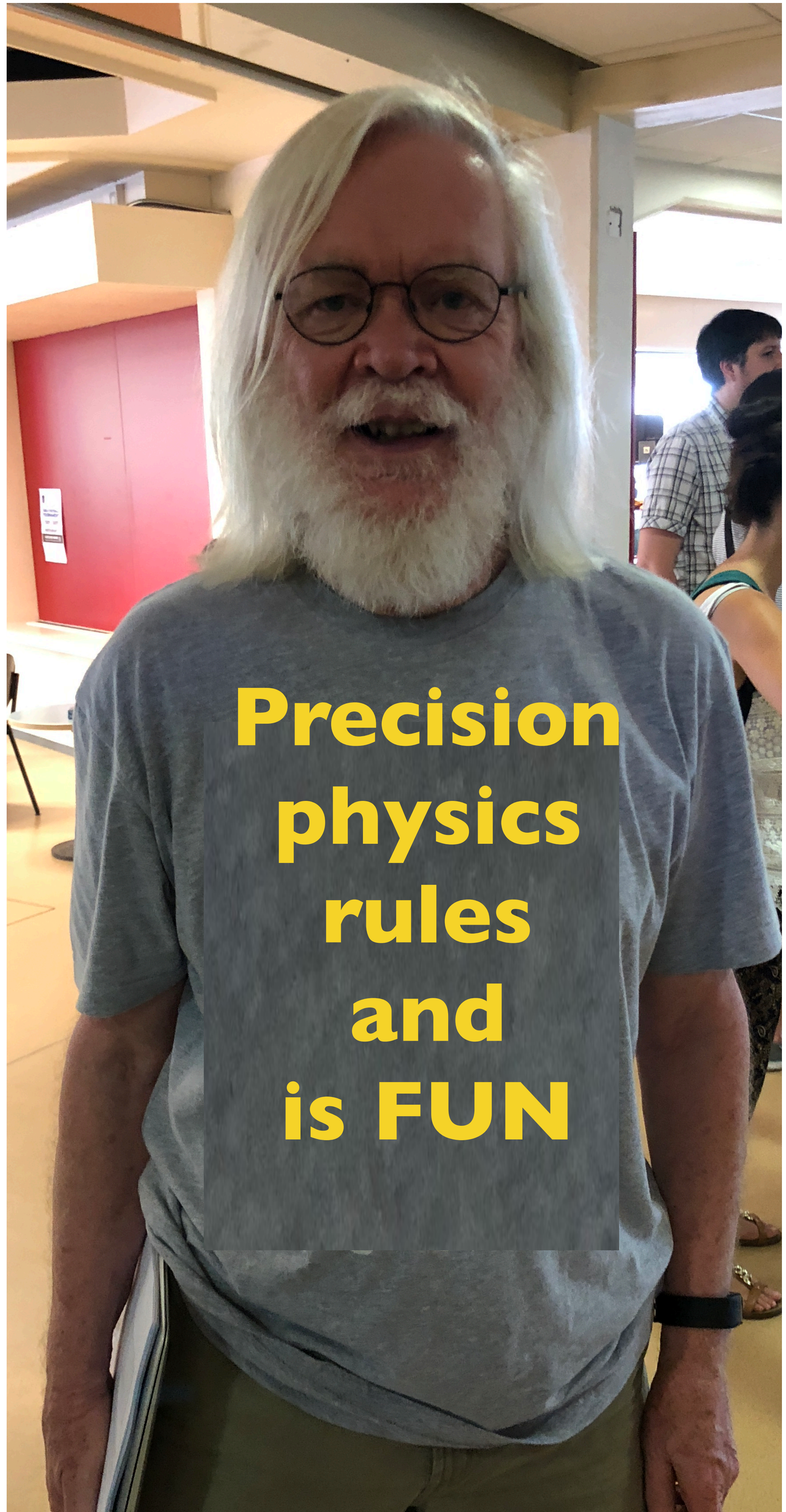
- Single Higgs off-shell production affected same way: width extraction…

~~Conclusions~~. ~~Prospects~~. Requirements

- Amazing progress in LHC calculations during the last 2 decades

- But to reach the TH accuracy required by the HL-LHC we will need:
    - Higher order pQCD calculations (move towards N3LO)
    - Resummation improvements
    - EW/QED corrections
    - Improvements in PS (>NL) and matching with fixed order
    - Higher Precision in pdfs (N3LO?)
    - More accurate extraction of coupling constant
    - More rigorous treatment of TH uncertainties
    - + many more

- Involve both signal and background
    - SM and SM+EFT tools (complete framework for global fits)


Precision
physics
rules
and
is FUN

рахмат
danke
謝謝
ngiyabonga
teşekkür ederim
Баярлалаа
спасибо
spas
mersi
kia ora
barka
welalin
tack
faafetai lava
vinaka
dank je
misaotra
paldies
grazzi
mahalo
kiitos
dankie
спасибі
blagodaram
matondo
tapadh leat
nanni
nandri
dhanyavad
thank you
gracias
хвала
asante
manana
bedankt
bayarlalaa
gracie
hvala
maururu
koszonom
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