Cross section computations for Higgs production

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The Higgs: what do we know today

- it is a very narrow resonance, 99.9% CL spin 0, parity+
- its mass is already known to about 0.2% precision
  $m_H = 125.09 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})$ GeV
- it is produced in gluon-fusion (top loop), vector boson fusion, production in association with a W or Z boson
- it decays to fermions (τ lepton, bottom quarks), but couplings to first and second generation barely probed
- it decays to bosons (photons, W, Z)
- couplings agree with SM predictions within large errors (10-50%) for observed modes, but several modes not observed yet
- only very loose limits on Higgs self coupling
- signal strength $\mu = 1.09^{+0.11}_{-0.10}$

While precise theory was not crucial for the Higgs discovery, it is for precision measurements and tests of the SM in the Higgs sector

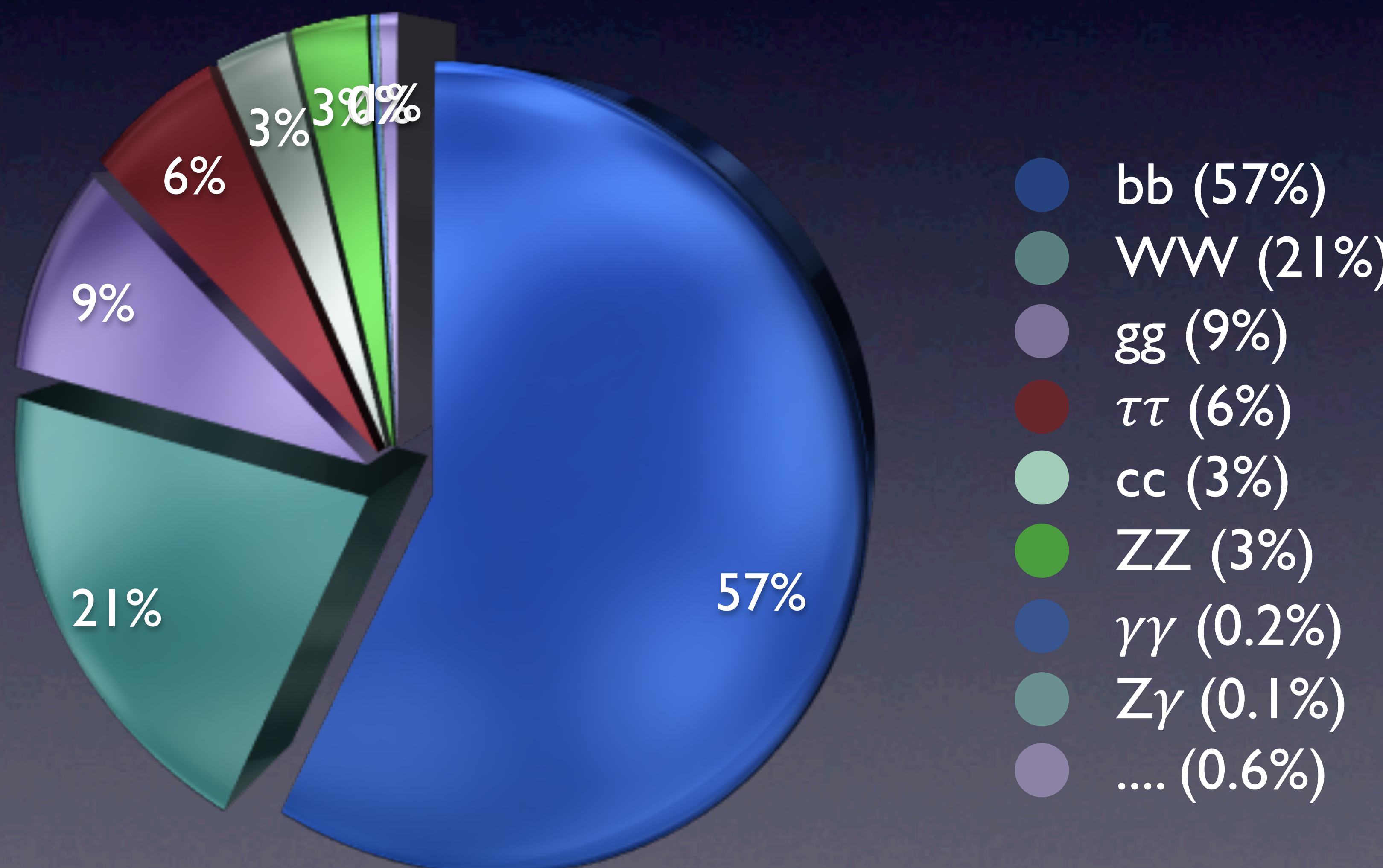
Higgs production at the LHC

	8 TeV	13 TeV	
ggH	19 pb	48 pb	✓
VBF	1.6 pb	3.7 pb	✓
WH/ZH	1.1 pb	2.2 pb	✓
ttH	0.13 pb	0.51 pb	✗
tH	20 fb	90 fb	✗

~25 fb^{-1} (2012) ~4 fb^{-1} (2015)

Higgs decay modes

Higgs mass (mH=125 GeV) lies in a nice spot where many decay modes are available. However dominant decay mode is to b-quarks (overwhelming QCD background), leptonic modes suppressed by branching ratios



Some spectacular achievements

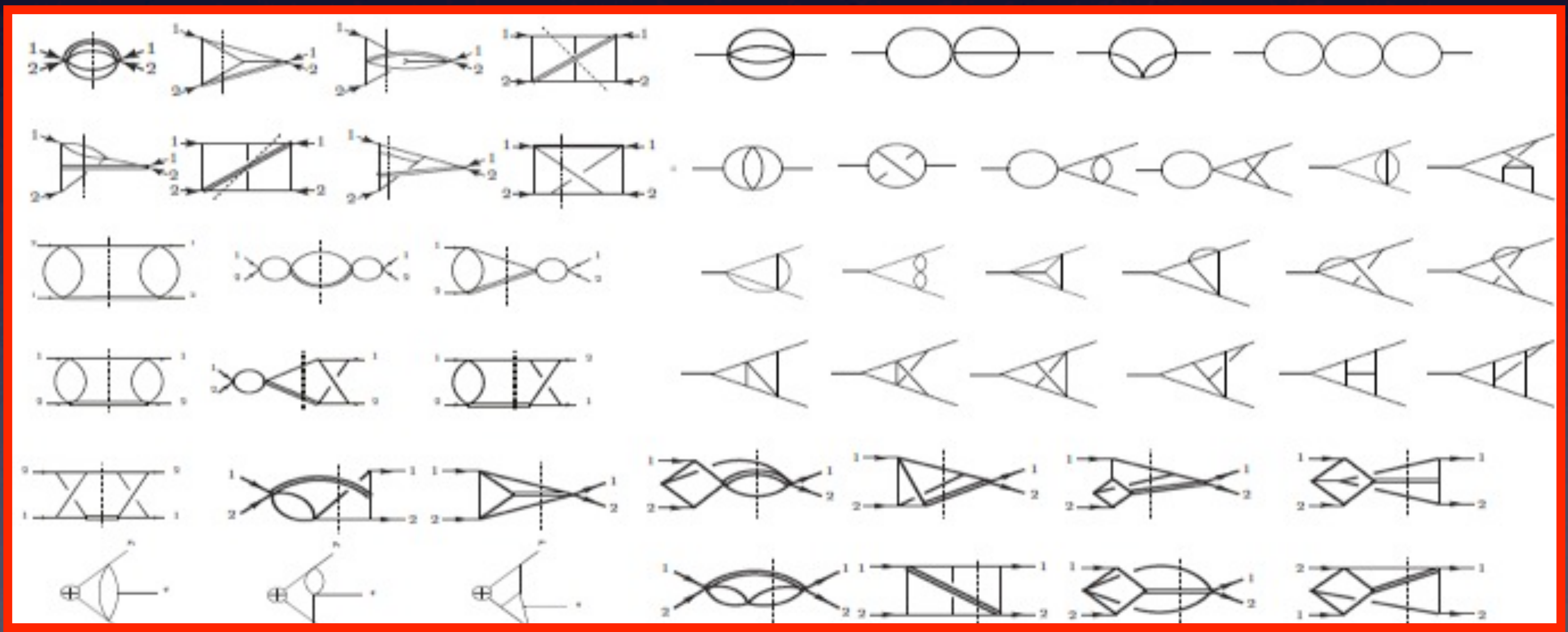
Some spectacular achievements

Generic reaction: *WOW! How did they do it?*

N^3LO Higgs production

Only collider process known to this accuracy: $O(10^7)$ phase space integrals, $O(10^5)$ interference diagrams, $O(10^3)$ three-loop master integrals. A truly amazing technical achievement

And a result that *really* matters for future Higgs physics



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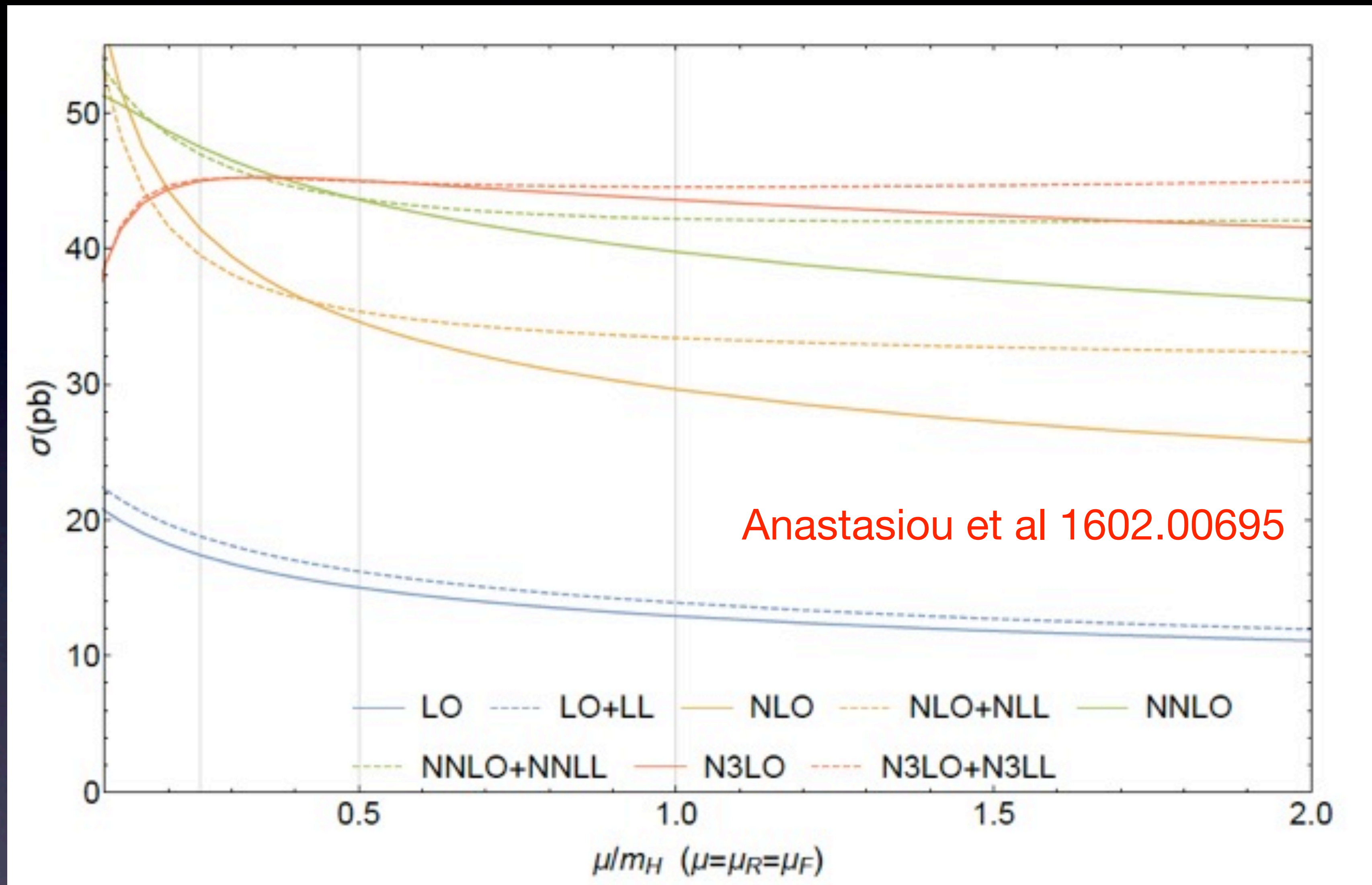
N^{3}LO Higgs production



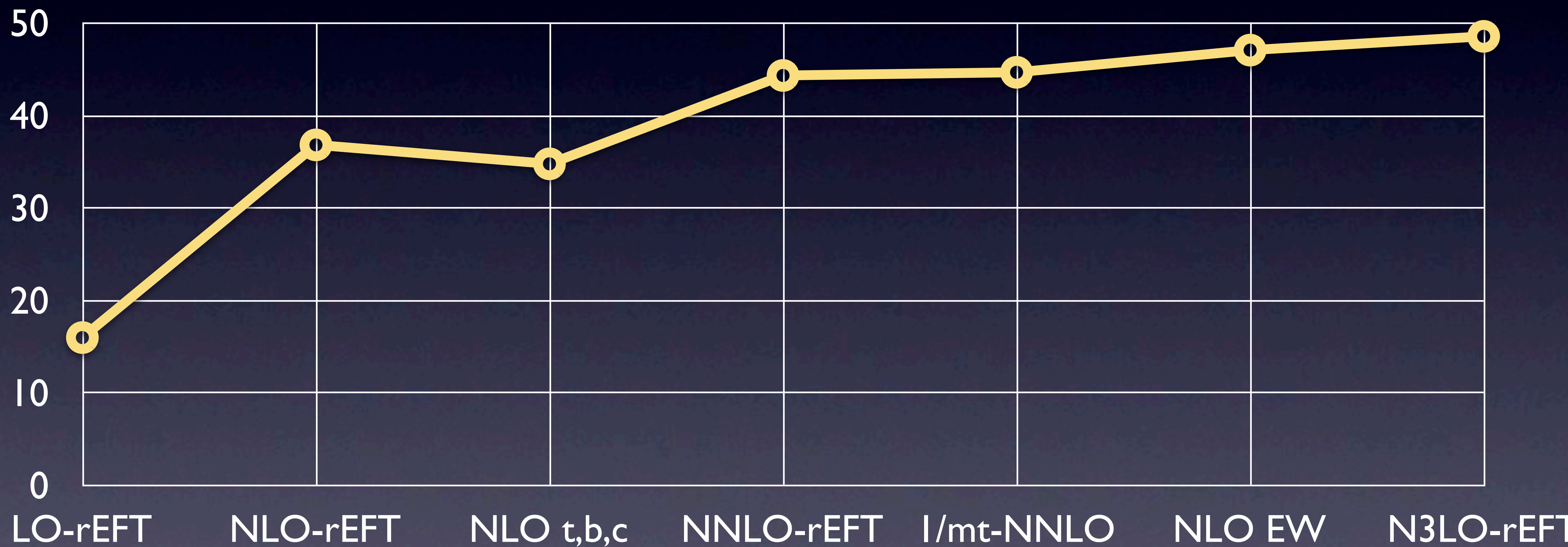
- also matching to resummed calculations available (essentially no impact on central value at preferred scale $m_H/2$)
- N^{3}LO finally stabilizes the perturbative expansion

Inclusive Higgs production

Anastasiou et al 1602.00695

At this level of accuracy, many other effects must be accounted for

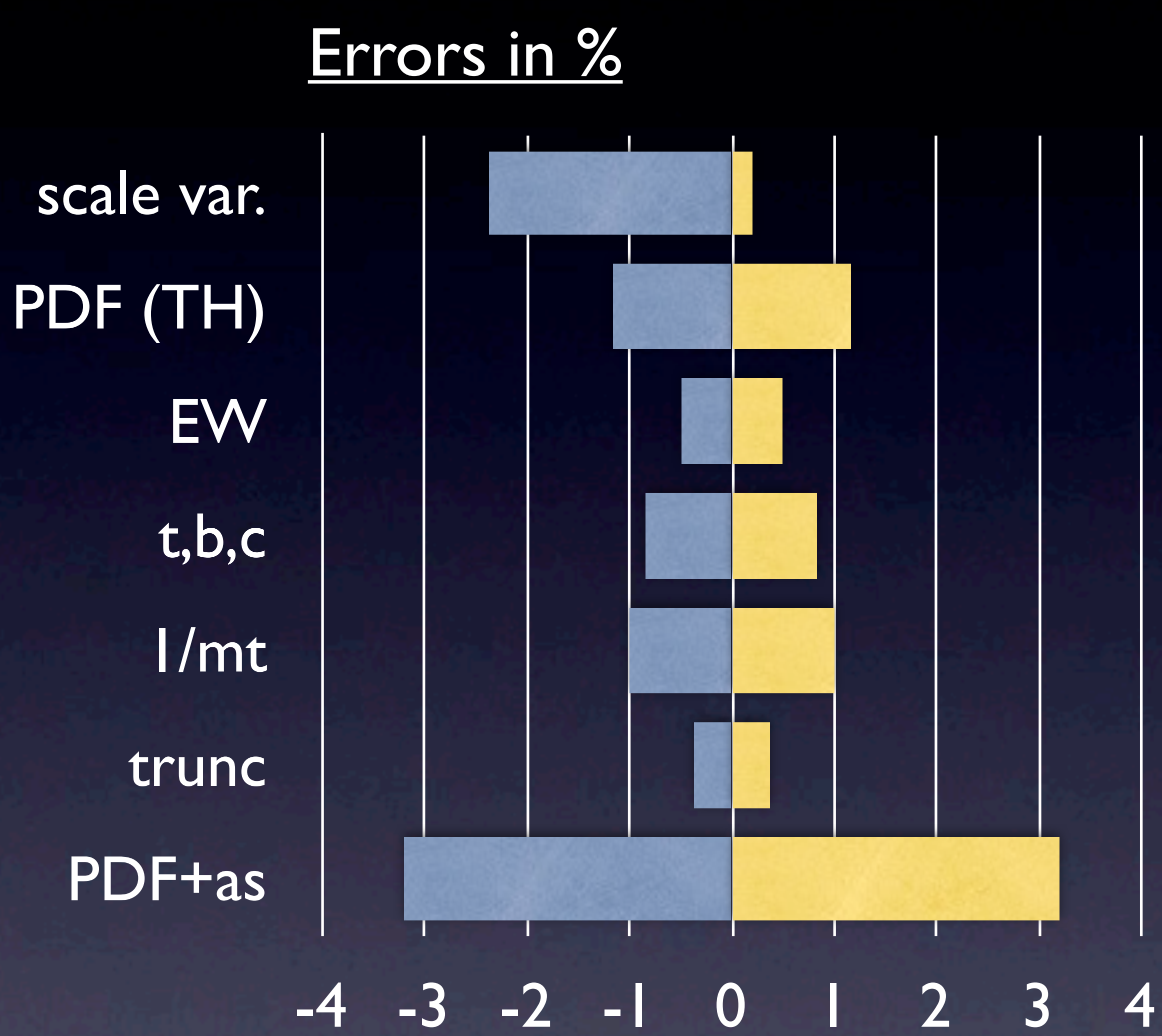
LHC 13 TeV: cross section in [pb] = 48.58 pb



16.00 20.84 -2.05 9.56 0.34 2.40 1.49

rEFT = EFT (i.e. heavy top approximation) but rescaled by (exact Born) / (EFT Born)

Error budget from 1602.00695

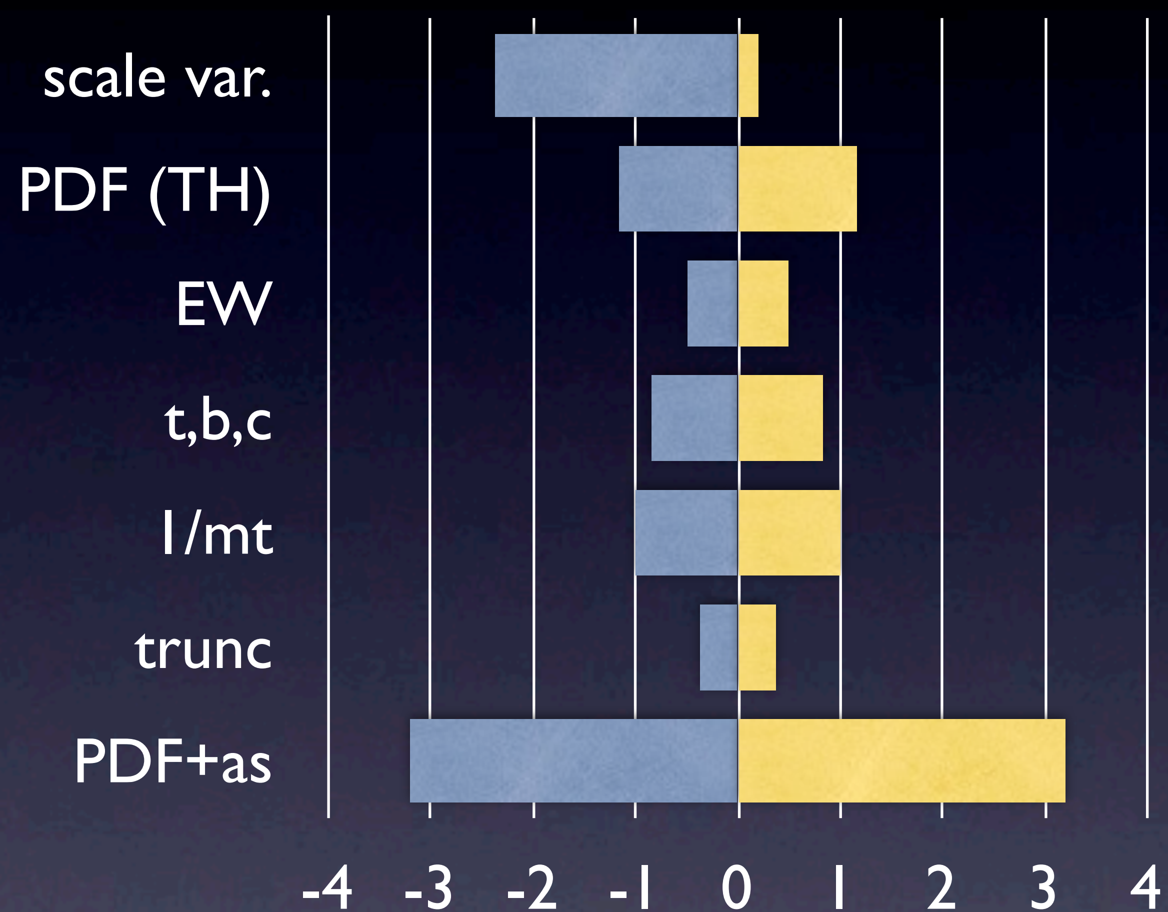


Combined error estimate: add all 6 theory errors linearly and keep the (PDF+α_s) error separate (add quadratically). Gives

$$\sigma = 48.58\text{pb}^{+2.22\text{pb}(4.56\%)}_{-3.27\text{pb}(-6.72\%)}\,\text{theory} \pm 1.56\text{pb}(3.2\%)(\text{PDF} + \alpha_s)$$

Error budget from 1602.00695

Errors in %



Currently under discussion in the Higgs Cross Section working group (HXSWG)

- include or not some resummation?
- 3 or 7 point scale variation? symmetrize scale var. error?
- alternative estimate of (b,c) effects
- quadratic vs linear combination of errors

Will result in a new HSXWG recommendation for 4th Yellow Report

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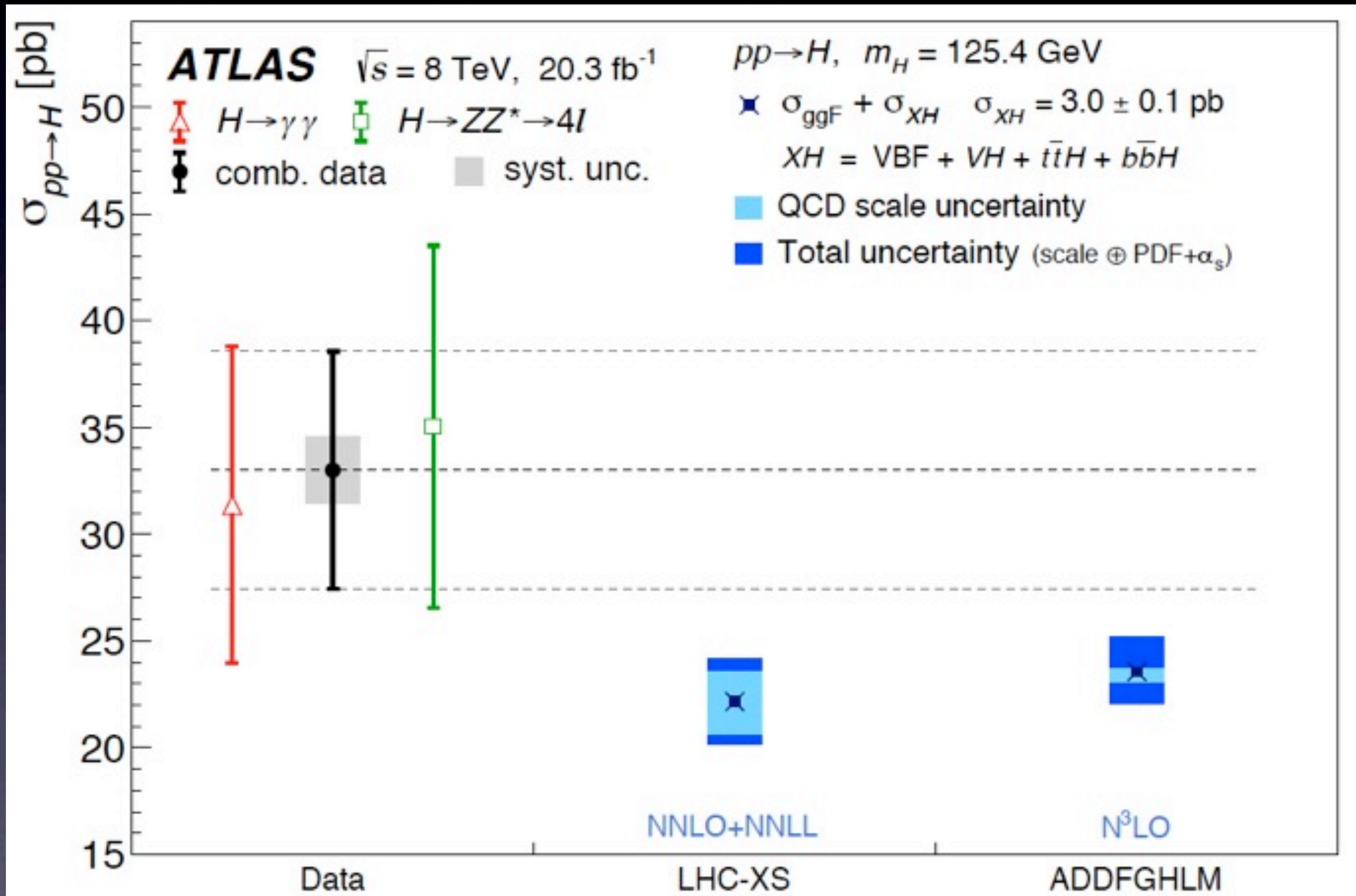
8 TeV data vs theory



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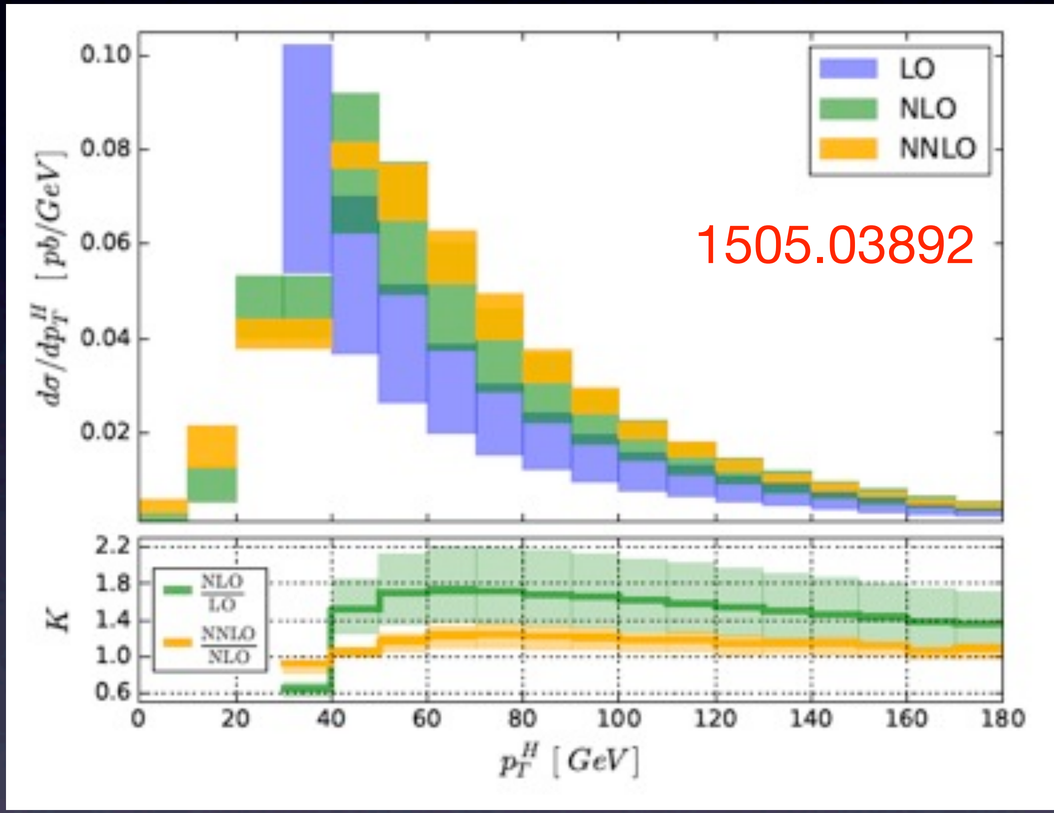
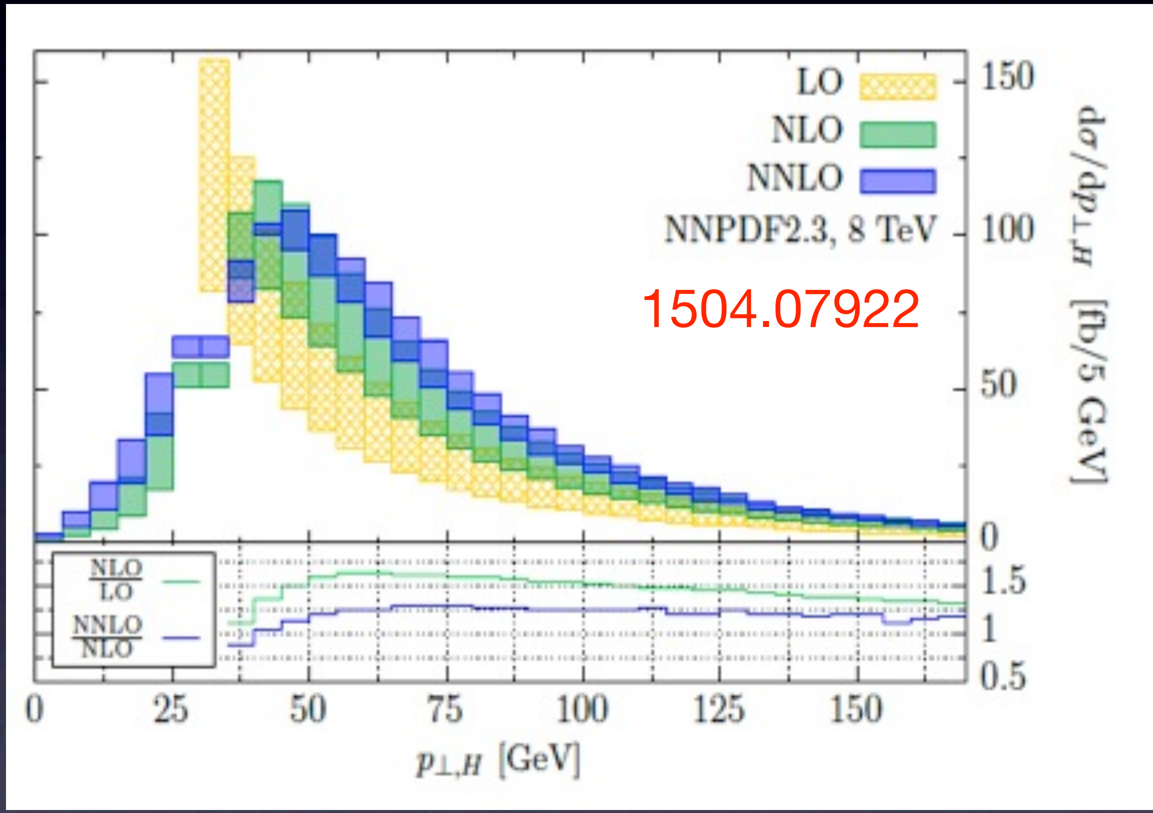
Another amazing achievement

H + 1 jet at NNLO

Boughezal, Caola, Melnikov, Petriello, Schulze ’15
Boughezal, Focke, Giele, Liu, Petriello ’15
Chen, Gehrmann, Glover, Jacquier ’15



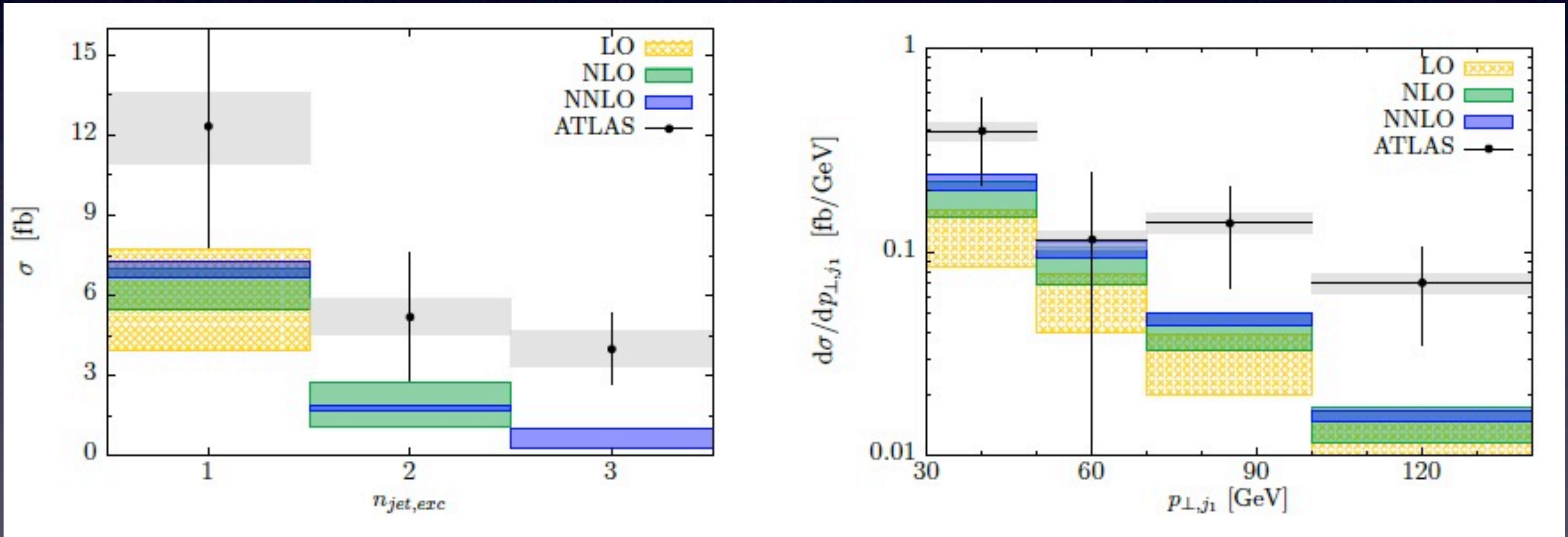


- new techniques developed to achieve cancellations of intermediate divergences
- large K-factor (≈1.15-1.20)
- useful comparison between independent calculations

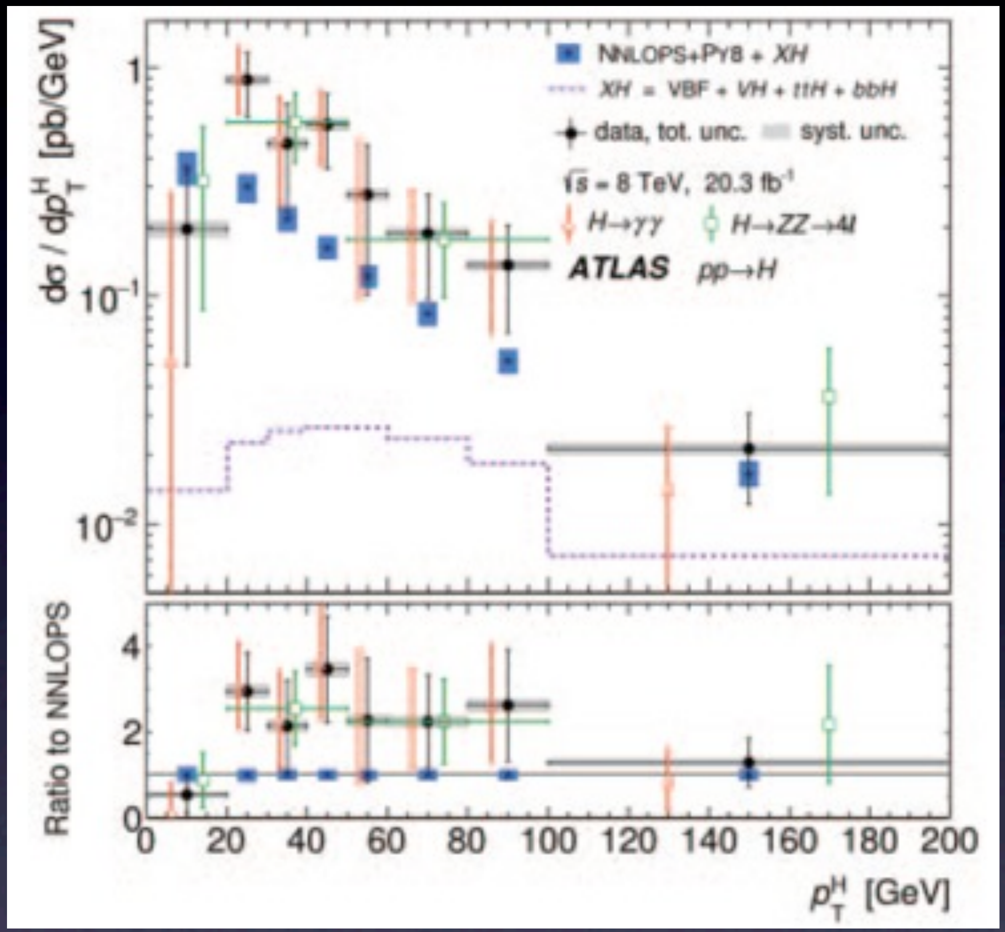
H+1jet at NNLO

Decays of Higgs to bosons also included. Fiducial cross-sections compared to ATLAS and CMS data

Caola, Melnikov, Schulze 1508.02684



Measurement of Higgs pt



Currently compared to NNLO+parton shower (NNLOPS). i.e. NLO (rather than NNLO) description at high transverse momentum.

b-mass effects: suppressed by the b-Yukawa, but enhanced by $\log(m_h^2/m_b^2)$ & $\log(p_t^2/m_b^2)$. Abelian logarithms resummed to all-orders.

Crucial to reach percent accuracy on Higgs p_t spectrum and theoretical very interesting result (resummation of non-Sudakov logs)

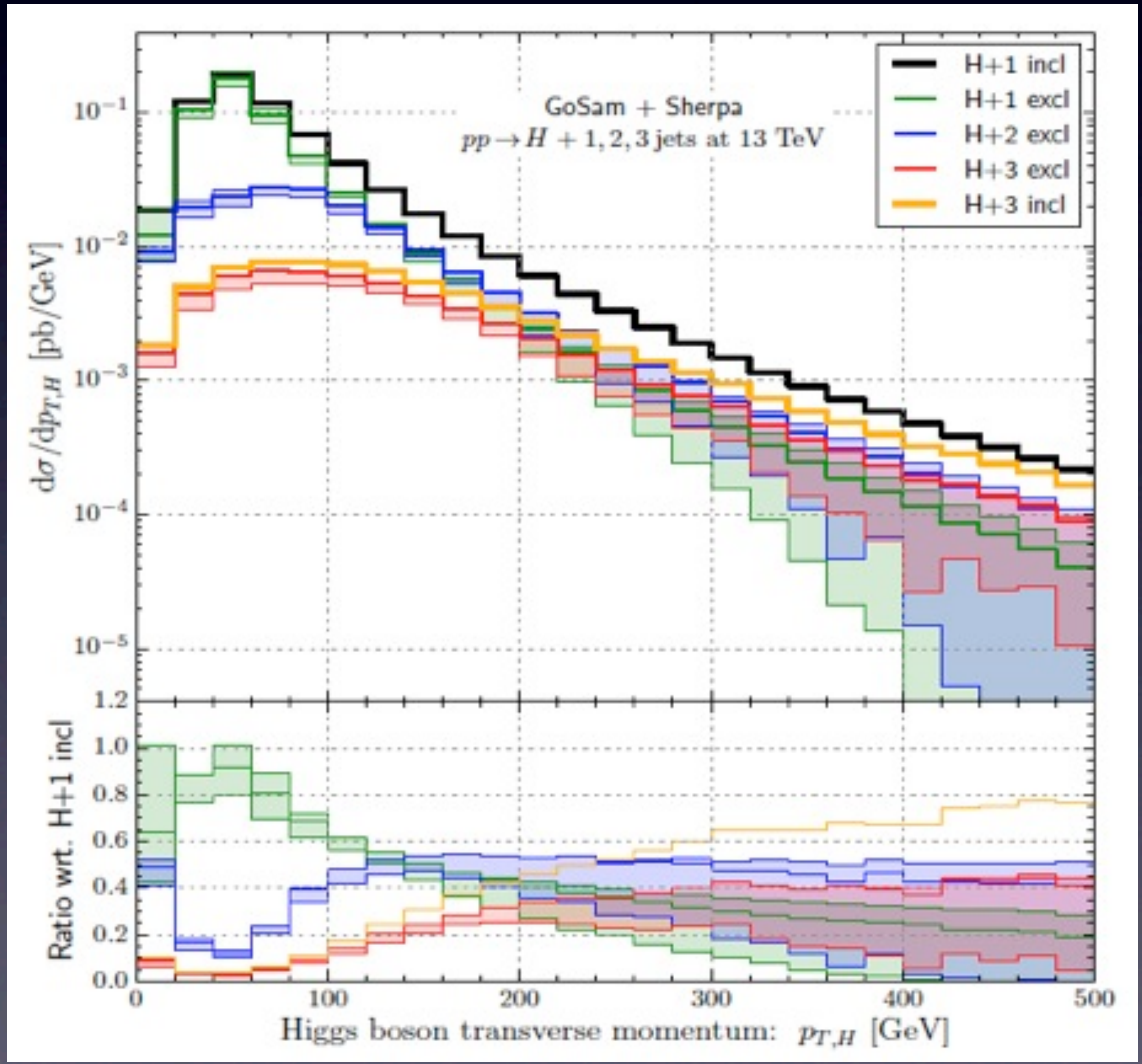
Melnikov, Penin 1602.09020

H + multi-jets at NLO

How much is the Higgs transverse momentum affected by additional QCD radiation?

NLO calculation of H+1,2,3 allows to study the question

- high $p_{t,H}$ region dominated by multi (soft) jet production
- but remember calculations performed in large m_t limit. Approximation breaks down at high $p_{t,H}$ (EFT overestimates)
- good control on 3[rd] jet important for VBF studies (jetveto)



Greiner et al 1307.4737, 1506.01016

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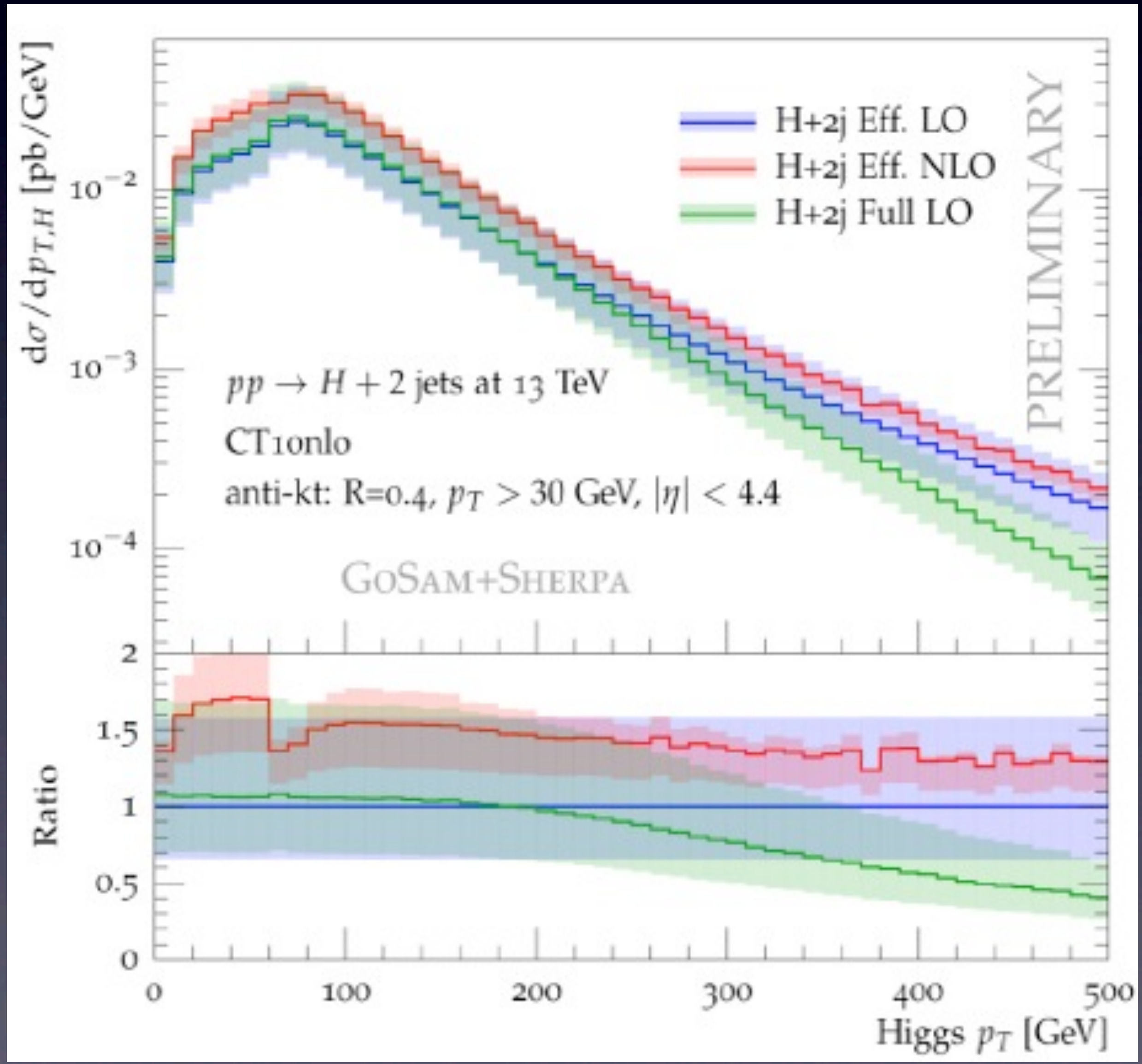
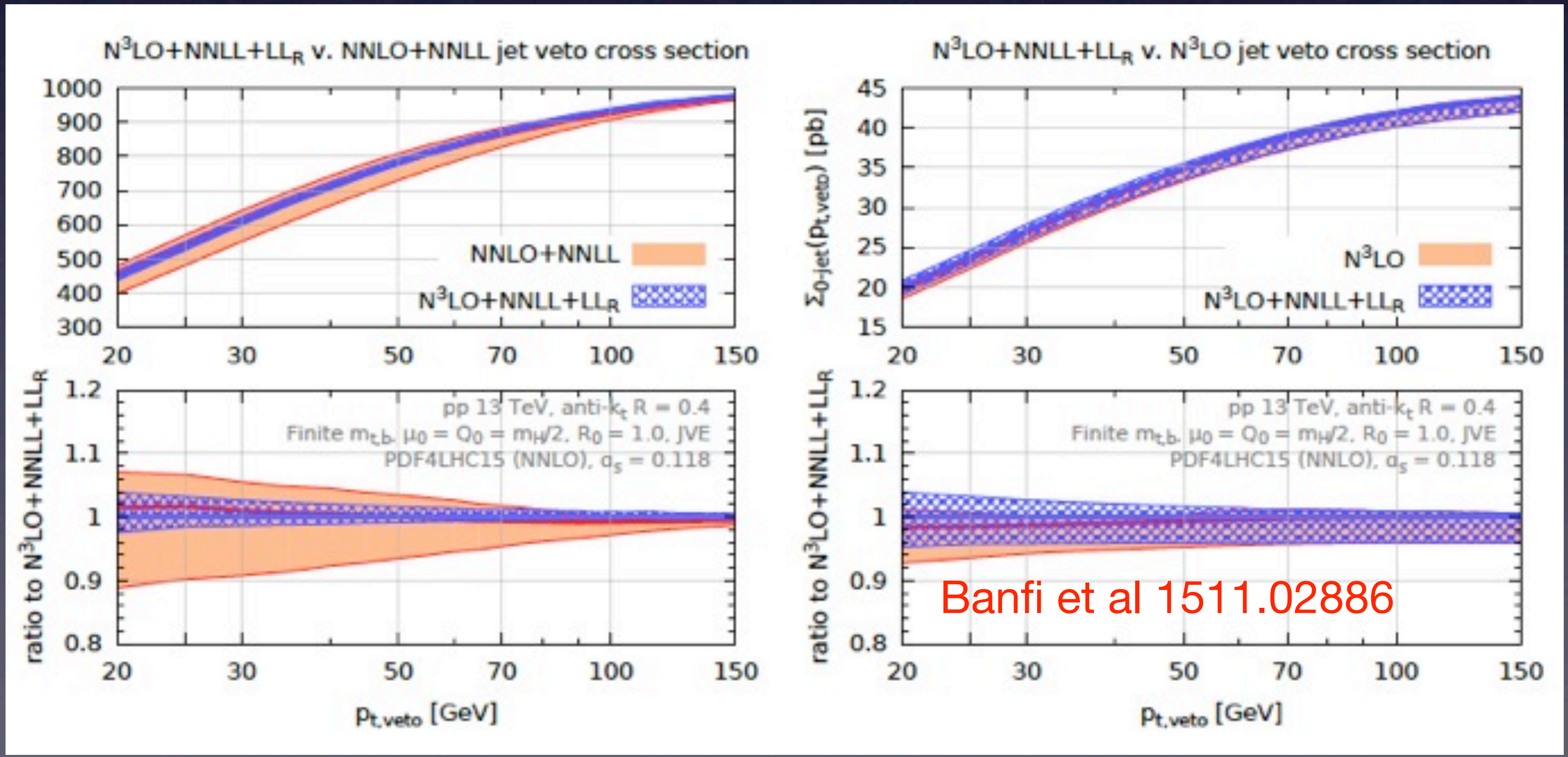


Greiner et al 1307.4737, 1506.01016

Improved jet-veto

Recently jet-veto predictions updated to include

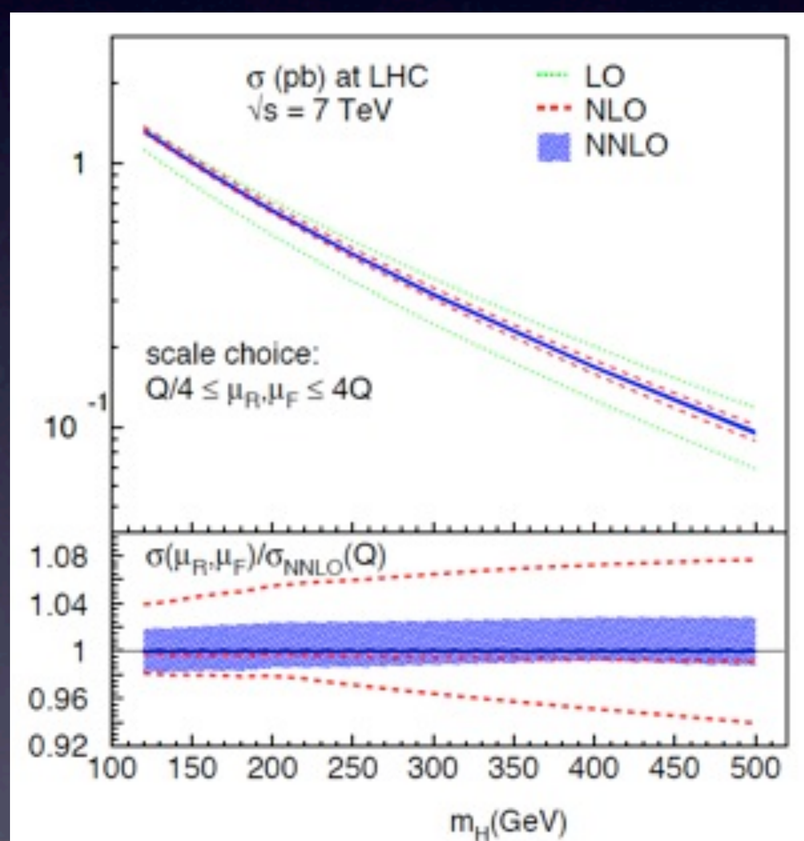
- N^3LO corrections to inclusive cross-section Anastasiou et al 1602.00695
- NNLO corrections to H + 1 jet Caola et al 1504.07922
- mass corrections Banfi et al 1308.4634
- resummation of logarithms of (small) jet-radius Dreyer et al 1411.5182

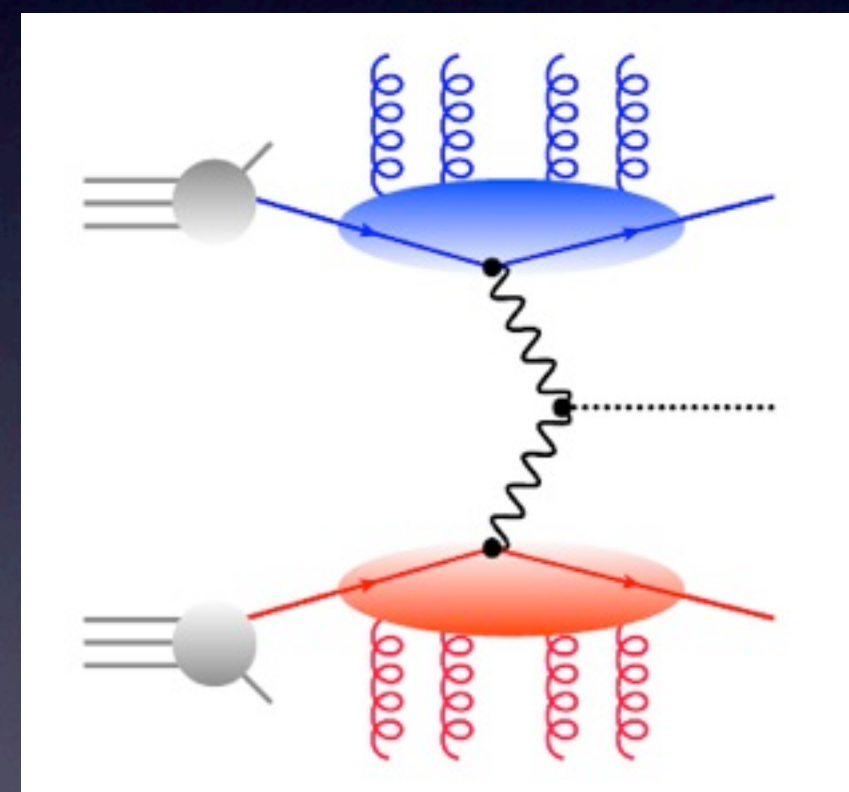


Differential VBFH at NNLO

Fully inclusive VBF Higgs production was known at NNLO in the structure function approach.

Bolzoni, Maltoni, Moch, Zaro '11



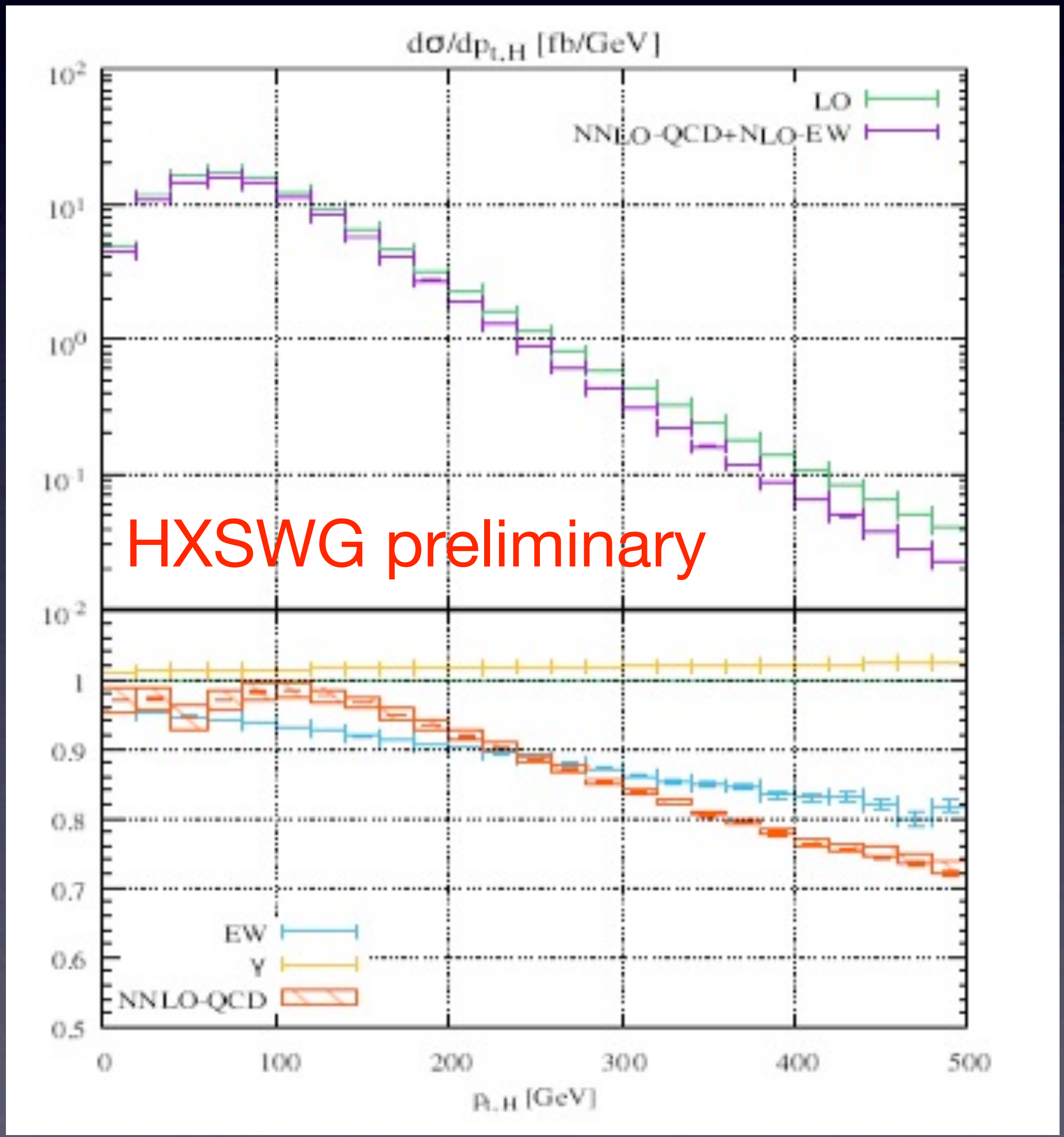


Inclusive calculation: tiny correction (~1%), tiny uncertainty (1-2%). Implies possibility to perform very accurate coupling measurements

Differential VBFH at NNLO

Fully differential calculation completed recently using projection to Born (P2B) method

Dreyer et al ’15



- Allows to study realistic observables, with realistic cuts
- NNLO corrections much larger (10%) than previously thought!
- NNLO QCD merged to NLO EW within the HXSWG
- Nice example of HXSWG activity
  - ✓ obtain best predictions by combining different ones
  - ✓ assign overall theoretical error

Associated HV production

HV production known to NNLO since a few years (small effects)

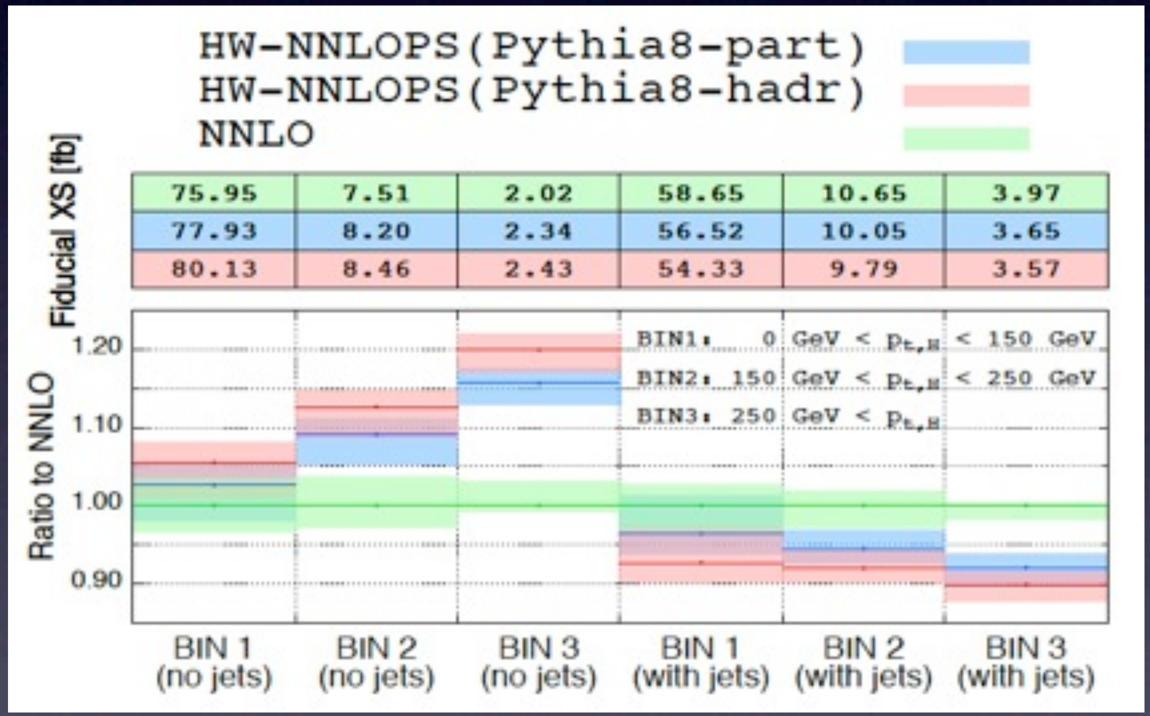
Ferrera, Grazzini, Tramontano '11-'14

Recently NNLO calculation matched to parton shower for HW

Bizon et al 1603.01620

Parton shower and hadronization cause migration between jet-bins.

Effects strongly depend on kinematical cuts



HV now in MCFM. Includes decays of the Higgs, includes $O(\alpha_s^2)$ corrections neglected previously (Higgs coupling to a fermion loop)

Campbell, Ellis, Williams 1601.00658

H+ photon production

Gabrielli et al. 1601.03656

	No γ	With γ	No γ	With γ	No γ	With γ
$\sigma_{(p_T^{\gamma,j}>30\text{GeV})}$	$(H)_{14\text{TeV}}$	$(H\gamma)_{14\text{TeV}}$	$(H)_{33\text{TeV}}$	$(H\gamma)_{33\text{TeV}}$	$(H)_{100\text{TeV}}$	$(H\gamma)_{100\text{TeV}}$
$gg, gq, q\bar{q}$	30.8 pb	3.05 fb	137. pb	12.9 fb	745. pb	65.8 fb
VBF	2.37	22.0	8.64	87.3	31.0	325.
WH	1.17	1.88	3.39	5.20	12.1	16.6
ZH	0.625	1.35	1.82	3.49	6.52	10.3
$t\bar{t}H$	0.585	2.55	4.08	17.8	34.3	158.
$tH + \bar{t}H$	0.056	0.536	0.428	4.17	2.18	29.7

Hierarchy of Higgs production modes strongly affected by photon

- ➡ VBF becomes dominant production mode
- ➡ at 100 TeV ttH dominates over gluon fusion
- ➡ at 100 TeV tH is of the same order of magnitude as gluon fusion (compare to O(1/1000) at 14 TeV without photon)

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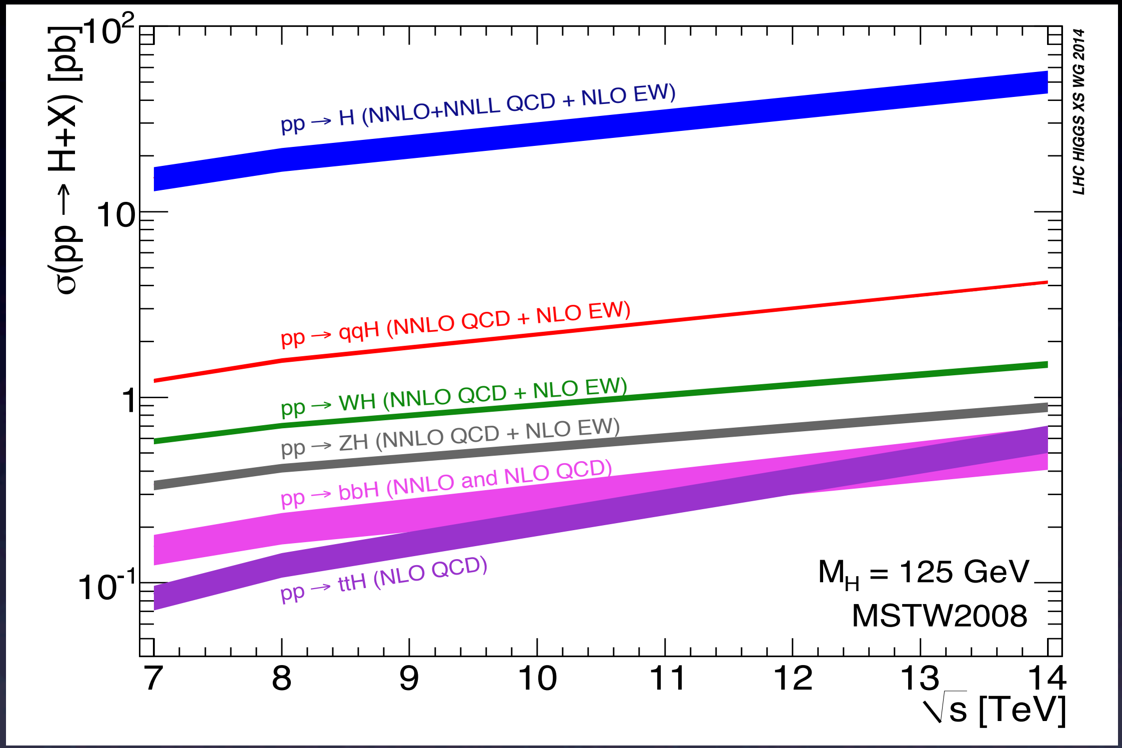
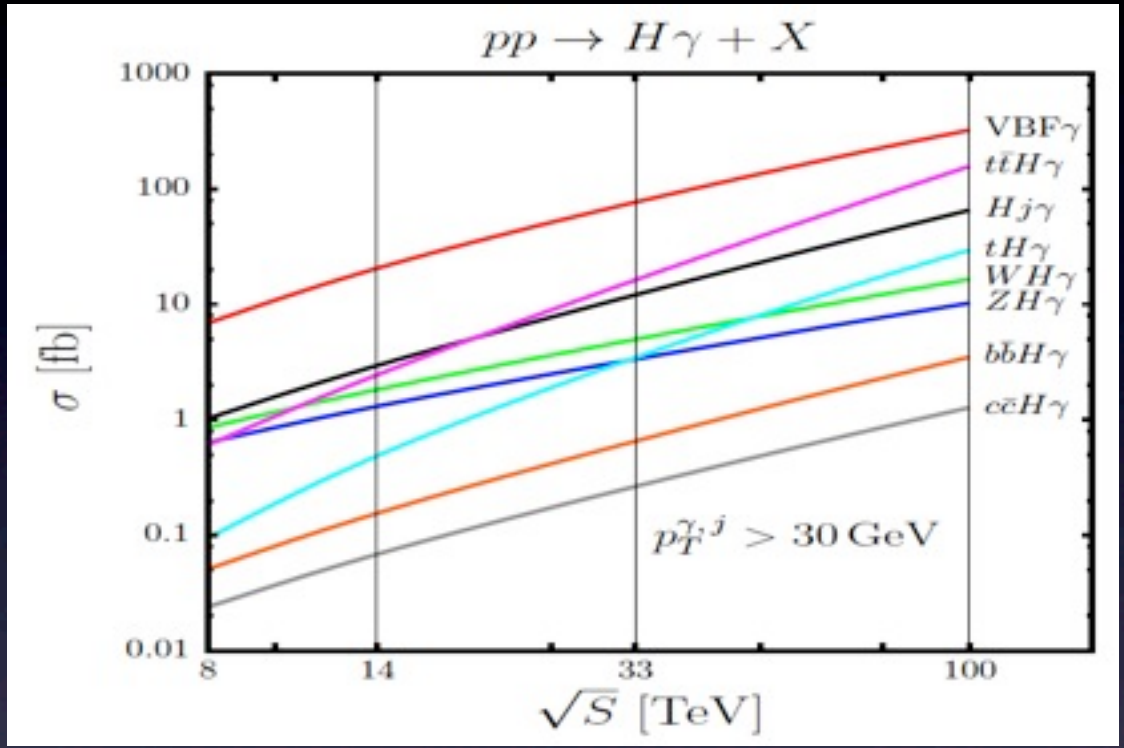


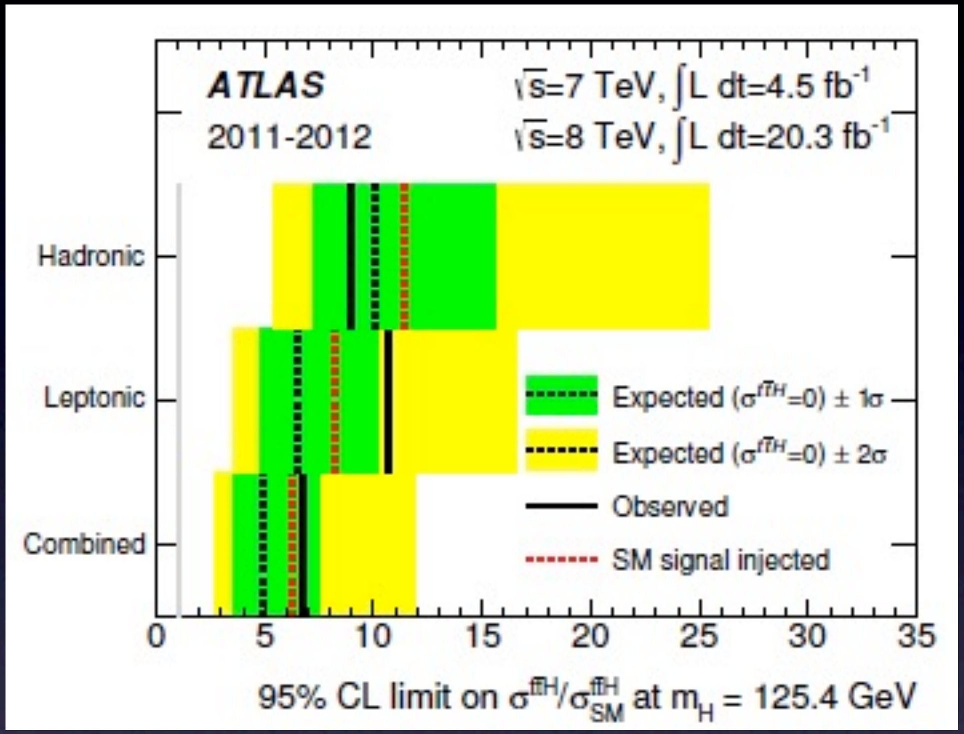


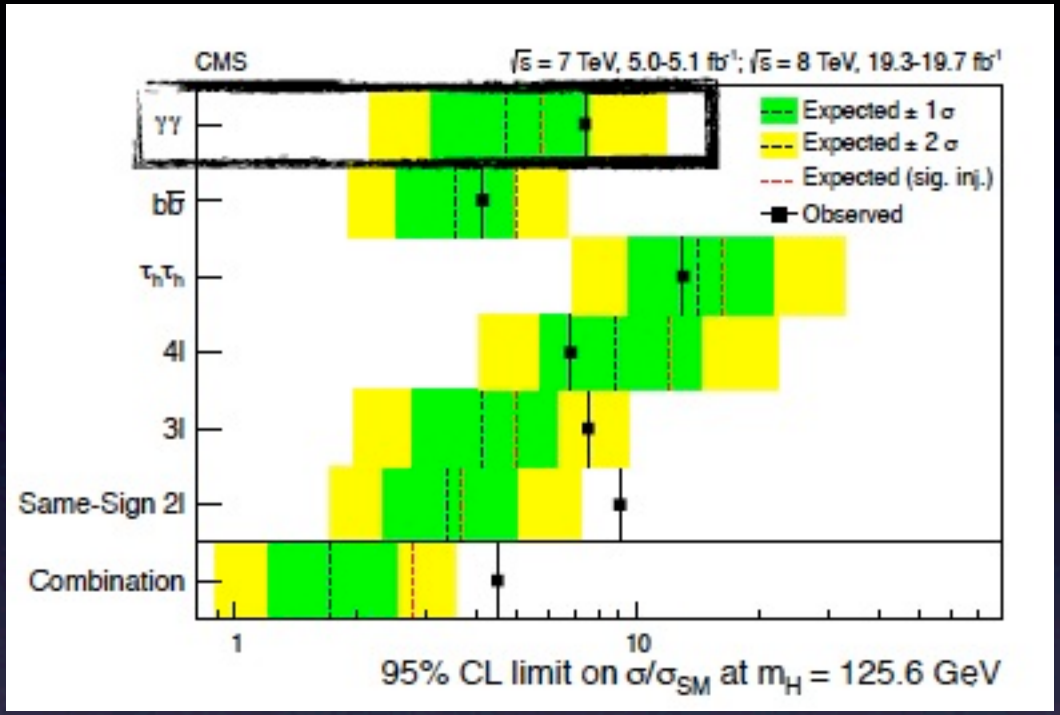
➡ tests of H-γ interactions

➡ probes of new physics effects in associated production of new scalar particles and photons

➡ searches for resonant three-photon final states

ttH production

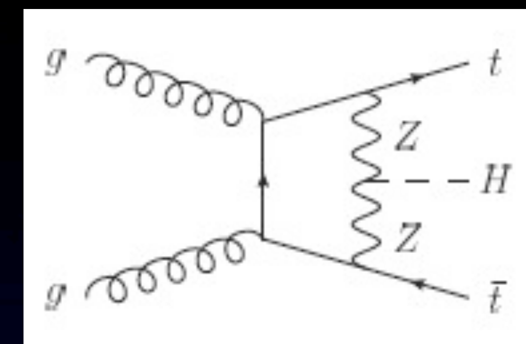


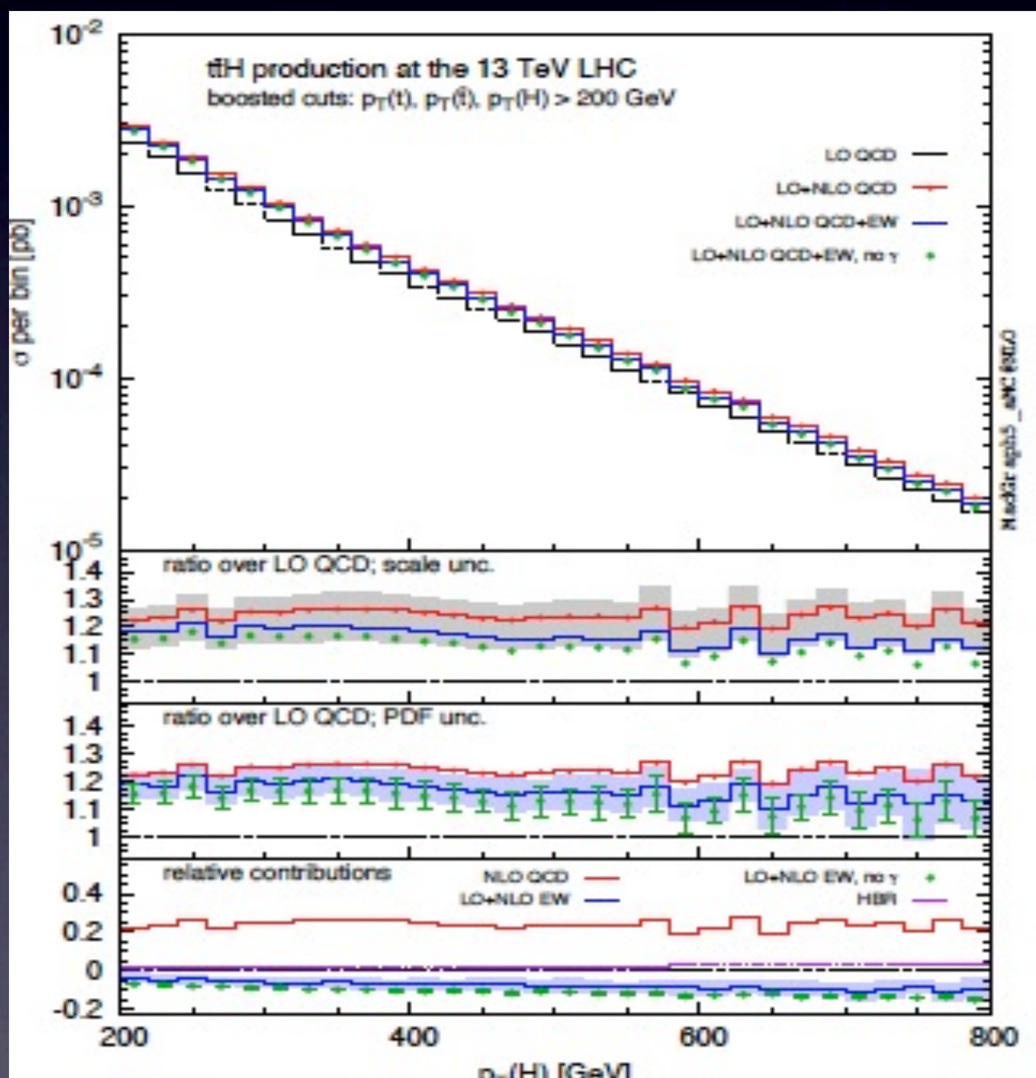


- ttH is the largest production mode not observed yet at the LHC (mostly limited by statistics)
- sensitive to top-Yukawa coupling

EW corrections to ttH

Electroweak corrections spoil the y_t^2 dependence: crucial for extraction of y_t





Bottom line: EW corrections small for total cross-section, but become more important in tails (usual story)

Frixione, Hirschi, Pagani, Shao, Zaro '15

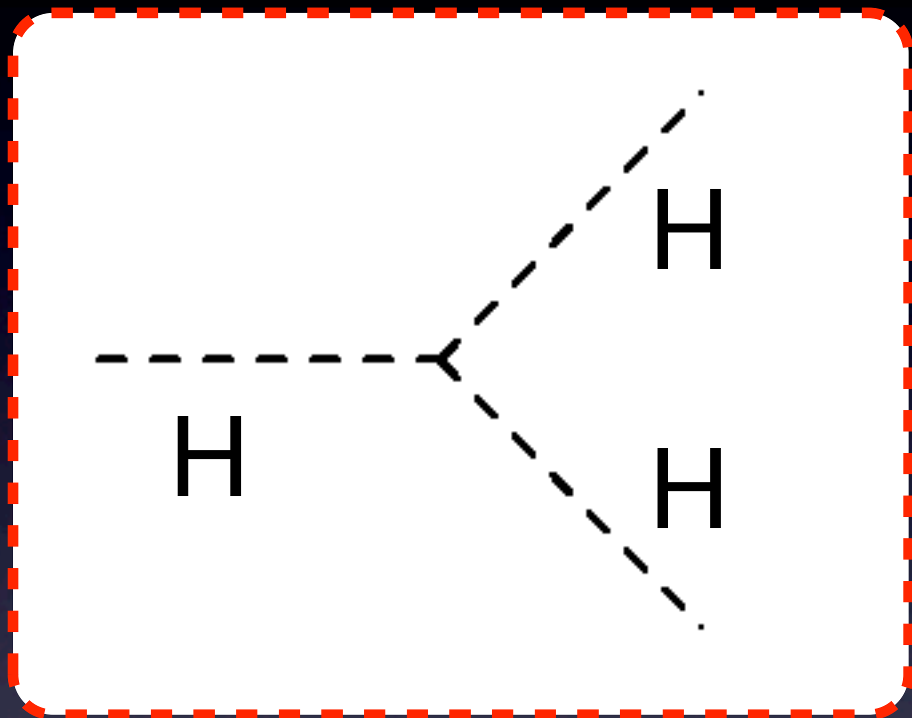
EW corrections also computed for irreducible background ttbb

Denner, Feger, Scharf '14

Smallest errors in ratio ttH/ttZ. Use it for extraction of y_t?

Mangano, Plehn, Reimitz, Schell, Shao '15

The Higgs self-coupling



Self-couplings fixed by the Higgs potential:

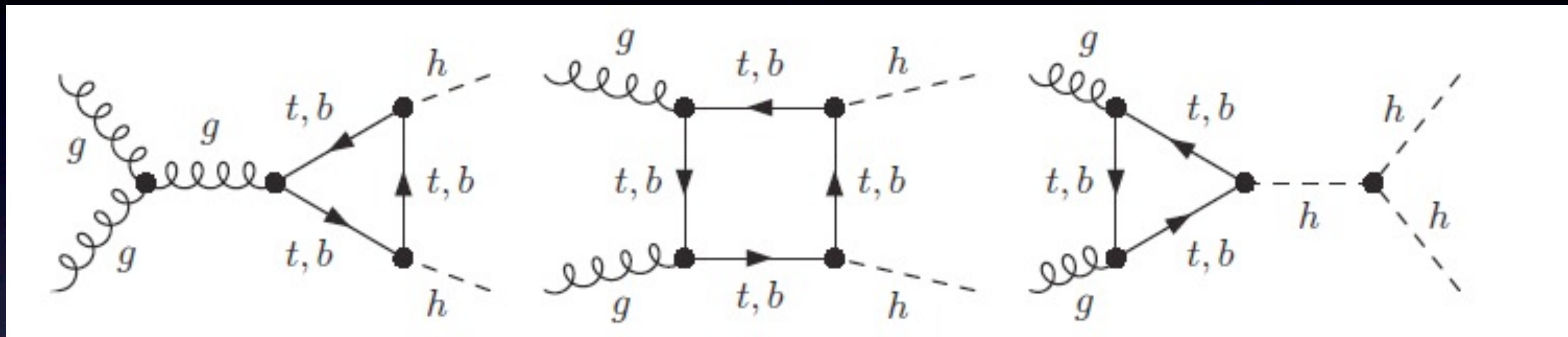
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$

In the SM: $\lambda_3 = \lambda_4 = \dfrac{m_H^2}{2v^2}$

- nothing like this (the self-interaction of a spin-zero particle) has ever been observed before
- crucial to pin down electroweak symmetry breaking
- can one measure this coupling at the LHC?

The Higgs self-coupling

Suitable process: Higgs pair production

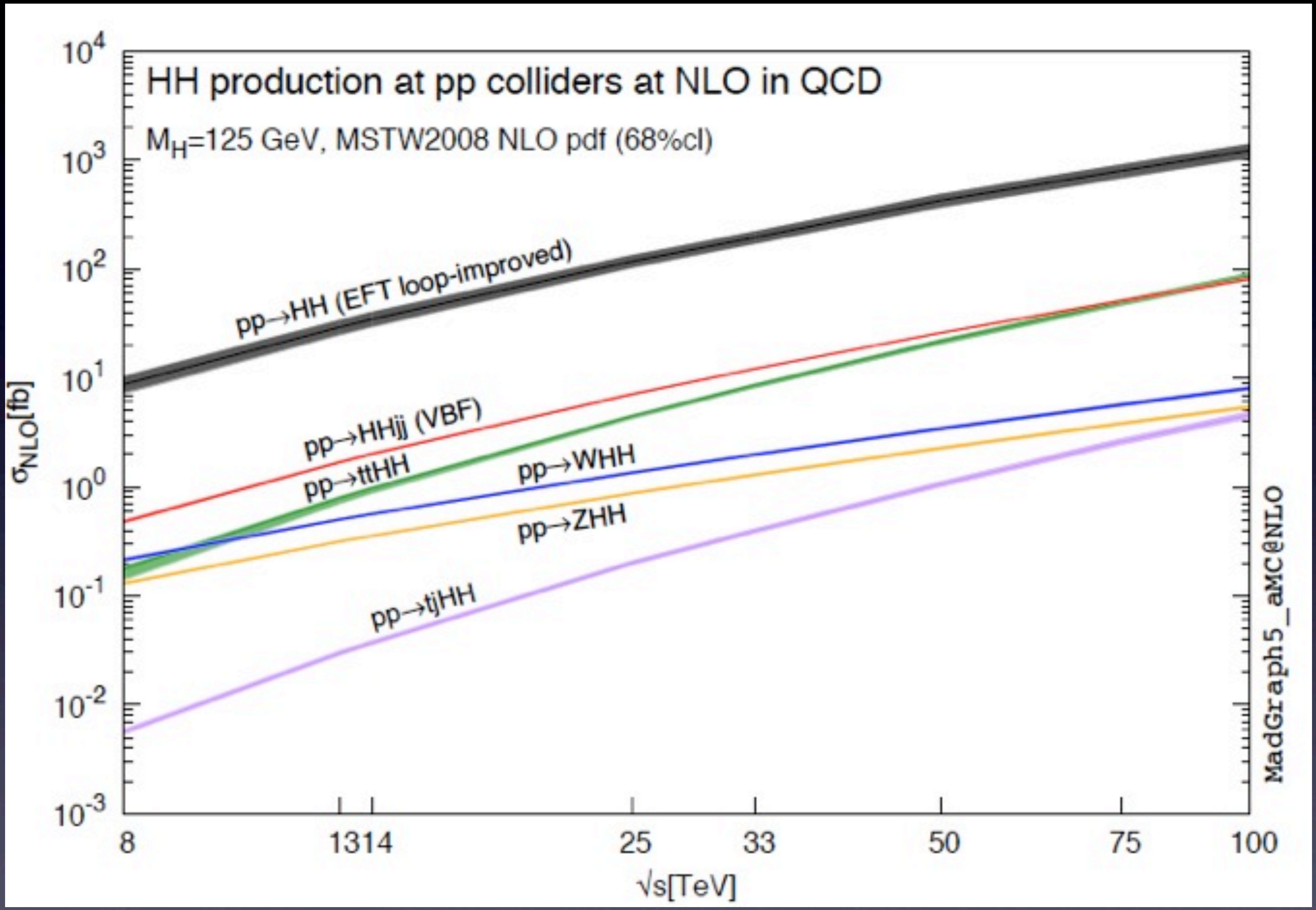


$m_h = 125.09$ GeV	NNLL (fb)	scale unc. (%)	PDF unc. (%)	PDF+α_S unc. (%)
7 TeV	7.71	$+4.0 - 5.7$	± 3.4	± 4.4
8 TeV	11.2	$+4.1 - 5.7$	± 3.1	± 4.0
13 TeV	37.9	$+4.3 - 6.0$	± 2.1	± 3.1
14 TeV	45.0	$+4.4 - 6.0$	± 2.1	± 3.0
100 TeV	1748	$+5.0 - 6.5$	± 1.7	± 2.6

(compare to O(pb) for single Higgs production)

E.g. at 13 TeV with 100 fb^{-1} of data can expect 3790 events, but high price paid for both Higgs bosons to decay (hence hadronic decays also studied)

HH: production channels



Double Higgs production at the LHC can be studied in the dominant gg → HH channel (subleading production channels too small)

Current LHC bounds

CMS: $bb\gamma\gamma$, bbbb

1503.04114, CMS-PAS-HIG-13-032

ATLAS: $bb\tau\tau$, $\gamma\gamma WW^*$, $bb\gamma\gamma$, bbbb

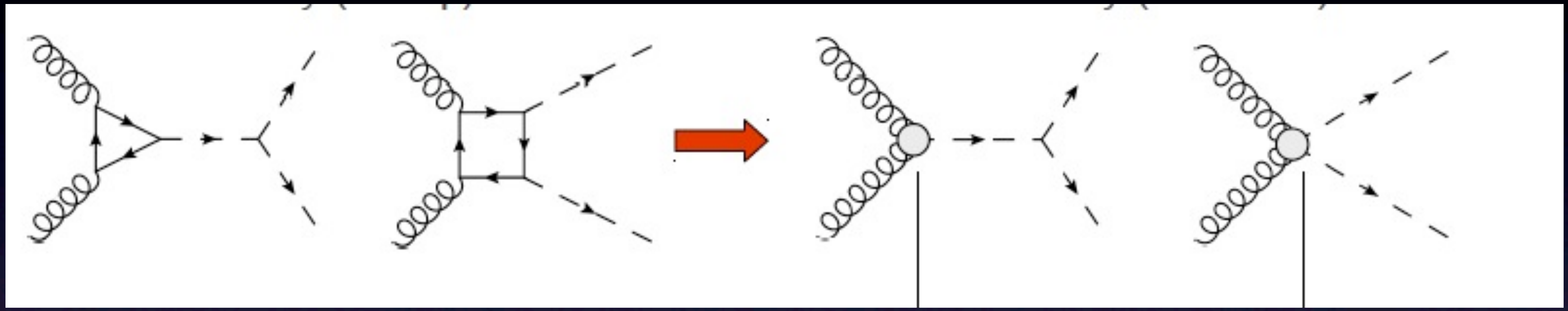
1506.00285, 1406.5053, 1509.04670

Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
	Upper limit on the cross section [pb]				
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
	Upper limit on the cross section relative to the SM prediction				
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

Current LHC bounds imply that trilinear Higgs coupling can deviate from SM value by a factor of about 17

State-of-the-art predictions for HH

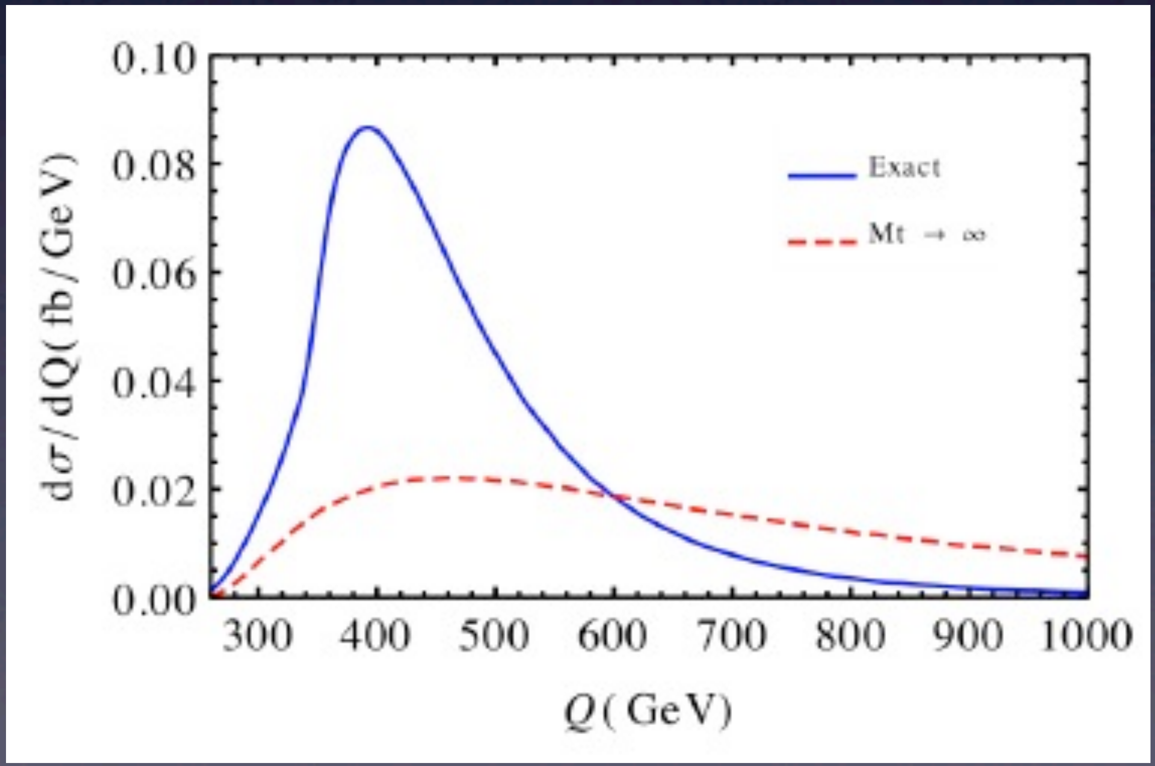
As for single Higgs production use effective theory:



Does it work at leading order?

EFT approximation works less well than for single Higgs (no surprise)

Adopt usual strategy: compute higher-order corrections in the EFT and normalize by the exact Born (validated with approx NLO)



Q: invariant mass of HH

State-of-the-art predictions for HH

- LO cross-section

Eboli et al ’87; Glover, van de Bij ’88

- NLO cross-section in EFT (~50-100%)

Dawson, Dittmaier, Spira ’98

- NNLO cross-section in EFT (~20-30%)

De Florian, Mazzitelli ’13; Grigo et al ’14

- Top mass as expansion in $1/m_t$ at NLO (~10%) and NNLO (~5%)

Grigo et al ’13-’15; Maltoni et al ’14

- Matrix element matching, NLO + parton shower

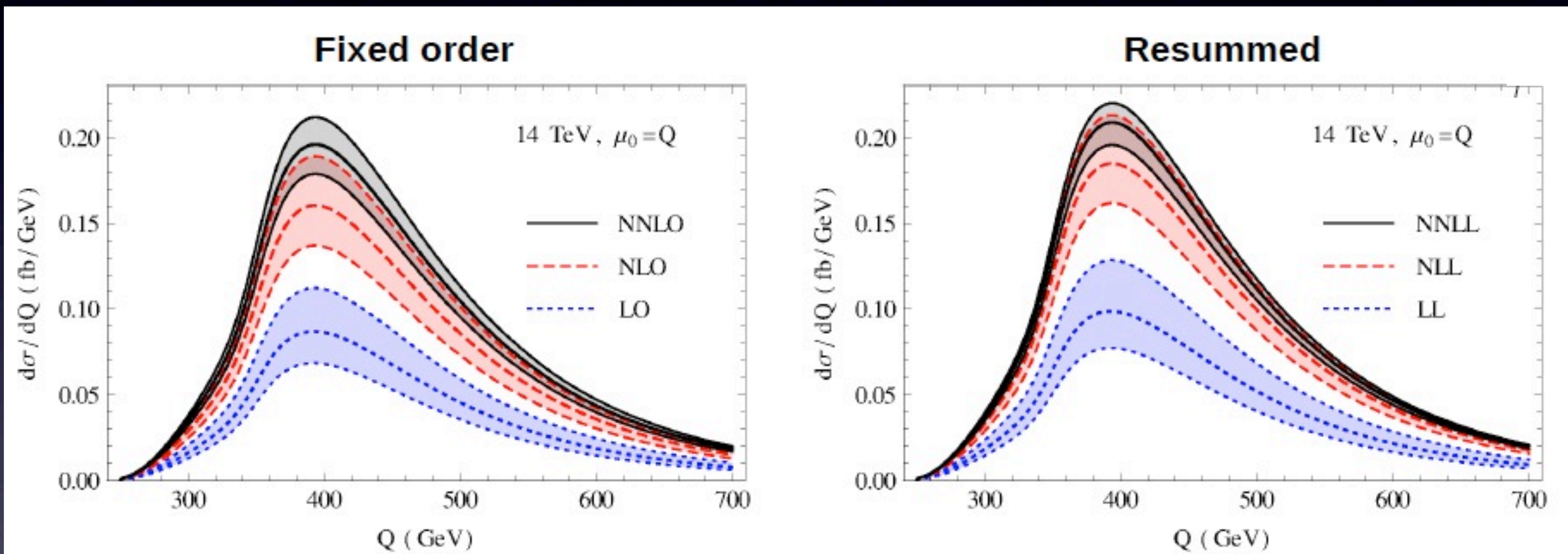
Li, Yan, Zhao ’13; Maierhoefer et al ’14; Frederix et al ’14

- Resummation of threshold logs (~5-10%)

Shao et al ’13; De Florian, Mazzitelli ’15

NNLO+NNLL predictions

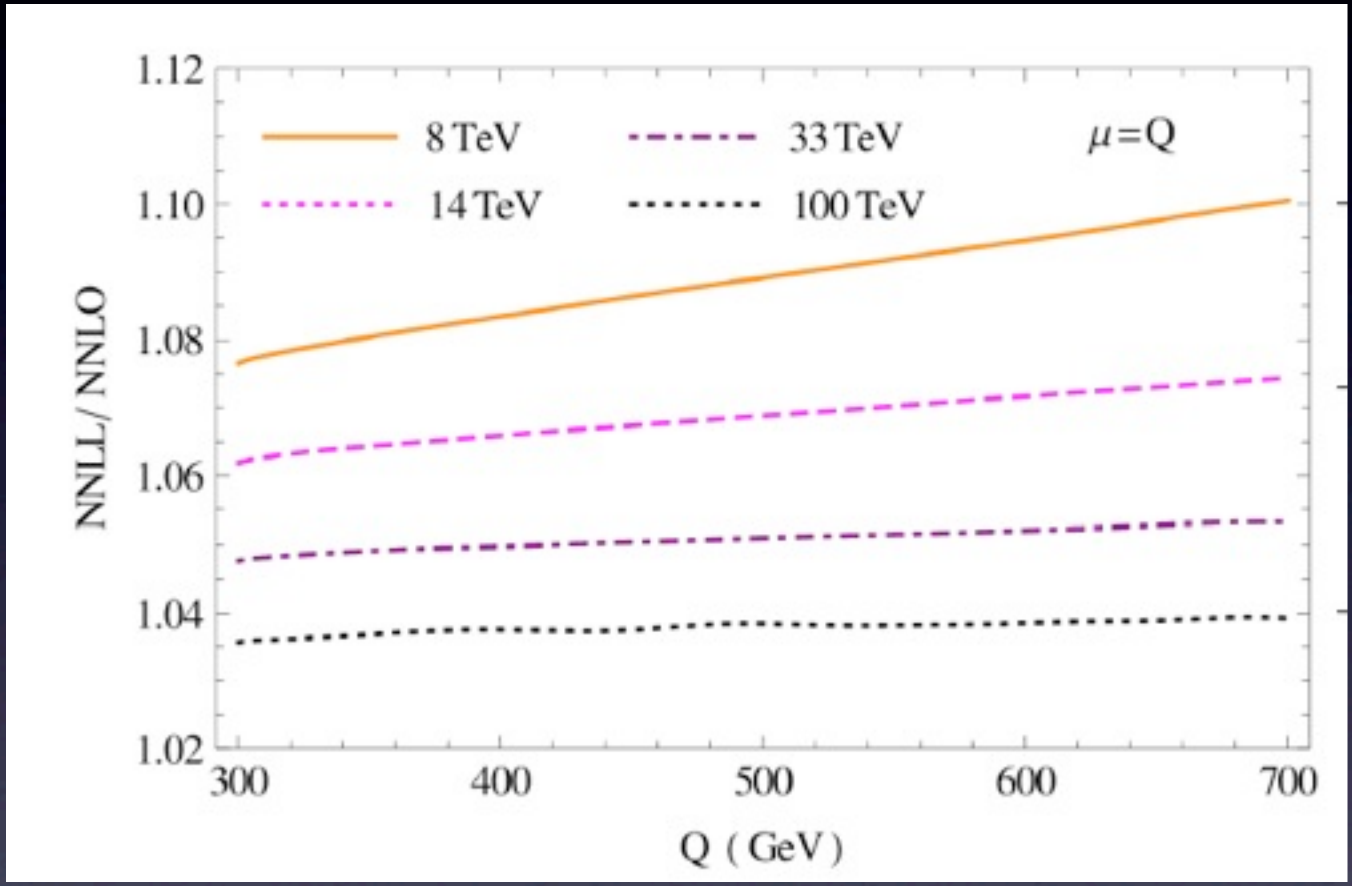
De Florian, Mazzatelli 1505.07122



As for inclusive Higgs production, NNLL resummation has a modest impact (increase), stabilizes the perturbative expansion

NNLO+NNLL predictions

Impact of NNLL as a function of the di-Higgs invariant mass



De Florian, Mazzatelli
1505.07122

- impact of NNLL resummation reduced at higher energies (further away from threshold)
- resummation more important for large invariant masses (close to threshold)

Prospects for HH

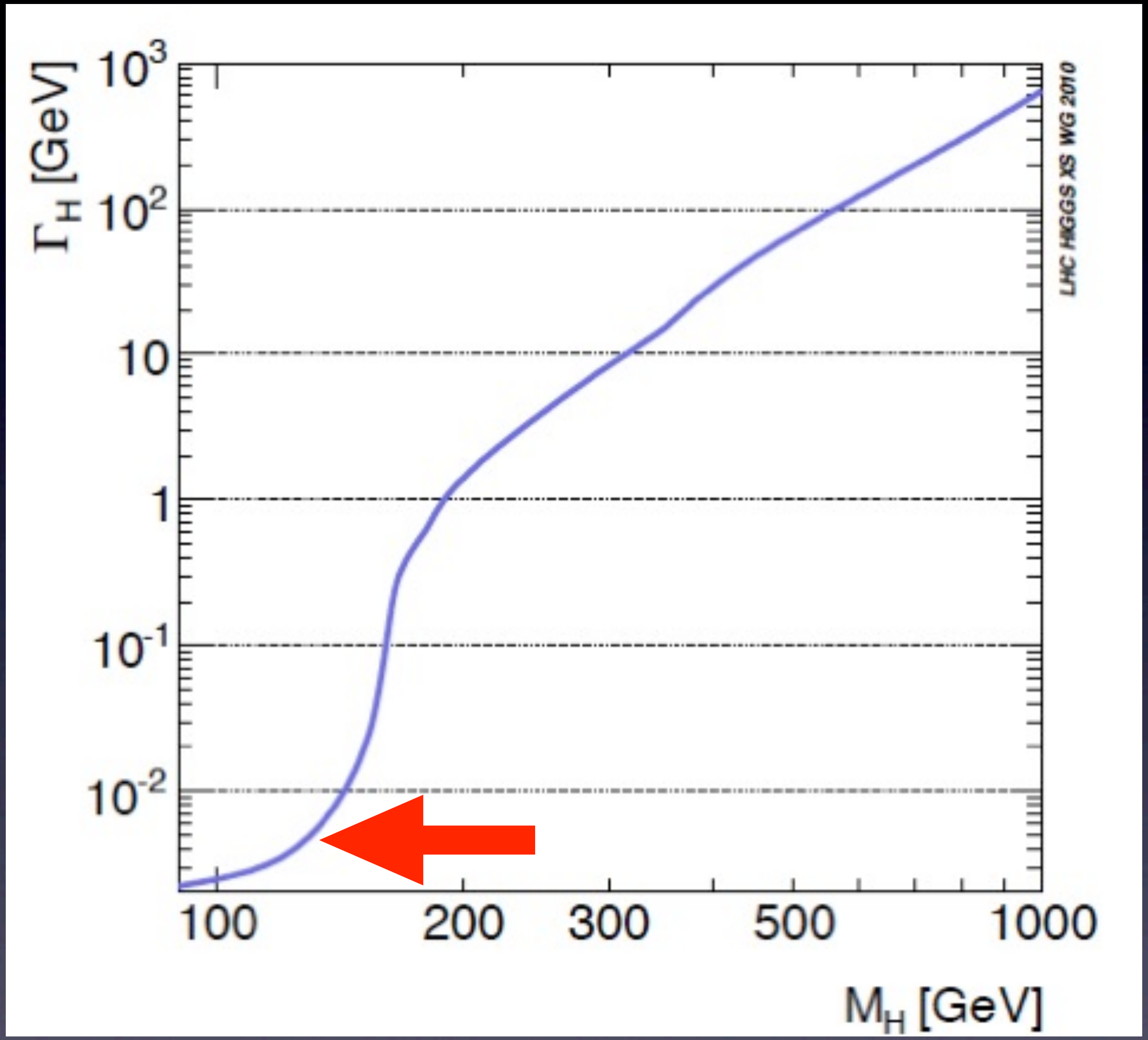
Studies performed so far suggest that

- promising $S/\sqrt{B}$ only at the price of very small event rates
- double Higgs can be observed in HL-LHC only (3000 fb^{-1})
- a sensitivity to the Higgs self-coupling at the LHC (to about 20-50%) possibly achieved by combining as many channels as possible / exploit ideas to study ratio of double-to-single Higgs production / boosted searches
- percent accuracy can be achieved with a Future 100 TeV Circular Collider (FCC) and luminosity of several ab^{-1} (NB: quartic coupling remains very difficult there too)

⇒ strong motivation for a 100 TeV pp collider (FCC)

Baur et al hep-ph/0310056, hep-ph/0304015; Dolan et al 1206.5001; Papaefstathiou et al 1209.1489; Baglio et al 1212.5581; Dolan et al 1310.1084; Barger et al 1311.2931; Barr et al 1309.6318; Ferrera de Lima et al 1404.7139; Wardrope et al 1410.2794; Behr et al 1512.08928 ....

Higgs width: extremely small



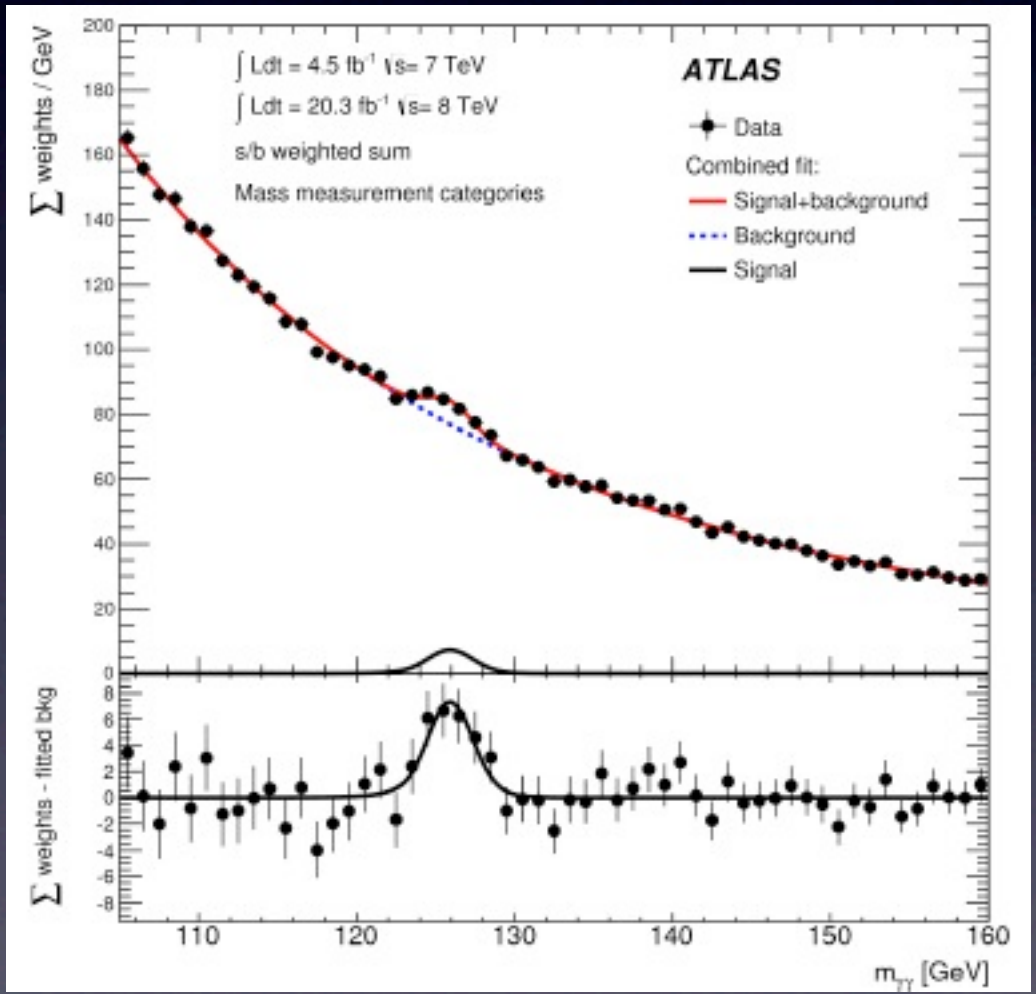
In the SM for M_H = 125 GeV
Γ_H = 4 MeV (very very narrow!)

Almost impossible to measure it directly (possible exception at a muon collider)

Direct measurement of the width

Width measured directly by profiling the Breit-Wigner resonance

Measurement limited by detector resolution



<u>Current direct bounds</u>

✓$\Gamma_H < 5$ GeV (ATLAS, $\gamma\gamma$)

✓$\Gamma_H < 2.6$ GeV (ATLAS, ZZ)

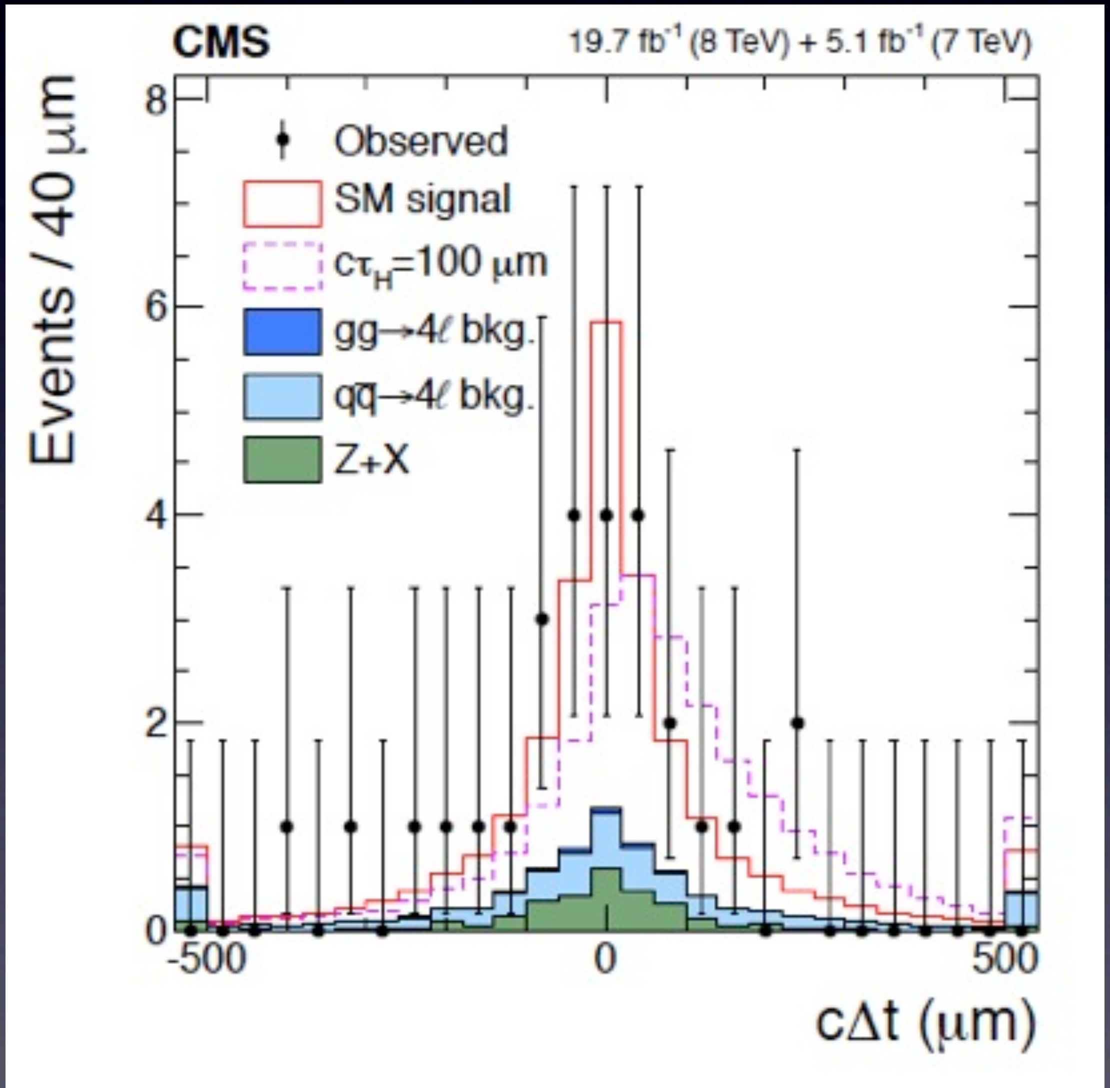
✓$\Gamma_H < 1.7$ GeV (CMS)

<u>Estimated LHC reach: 1 GeV</u>

To be sensitive to SM width must be improved by a factor 250

Lower bound from lifetime?

In the Higgs rest frame: $\langle \Delta t \rangle = \tau_H = \dfrac{1}{\Gamma_H}$



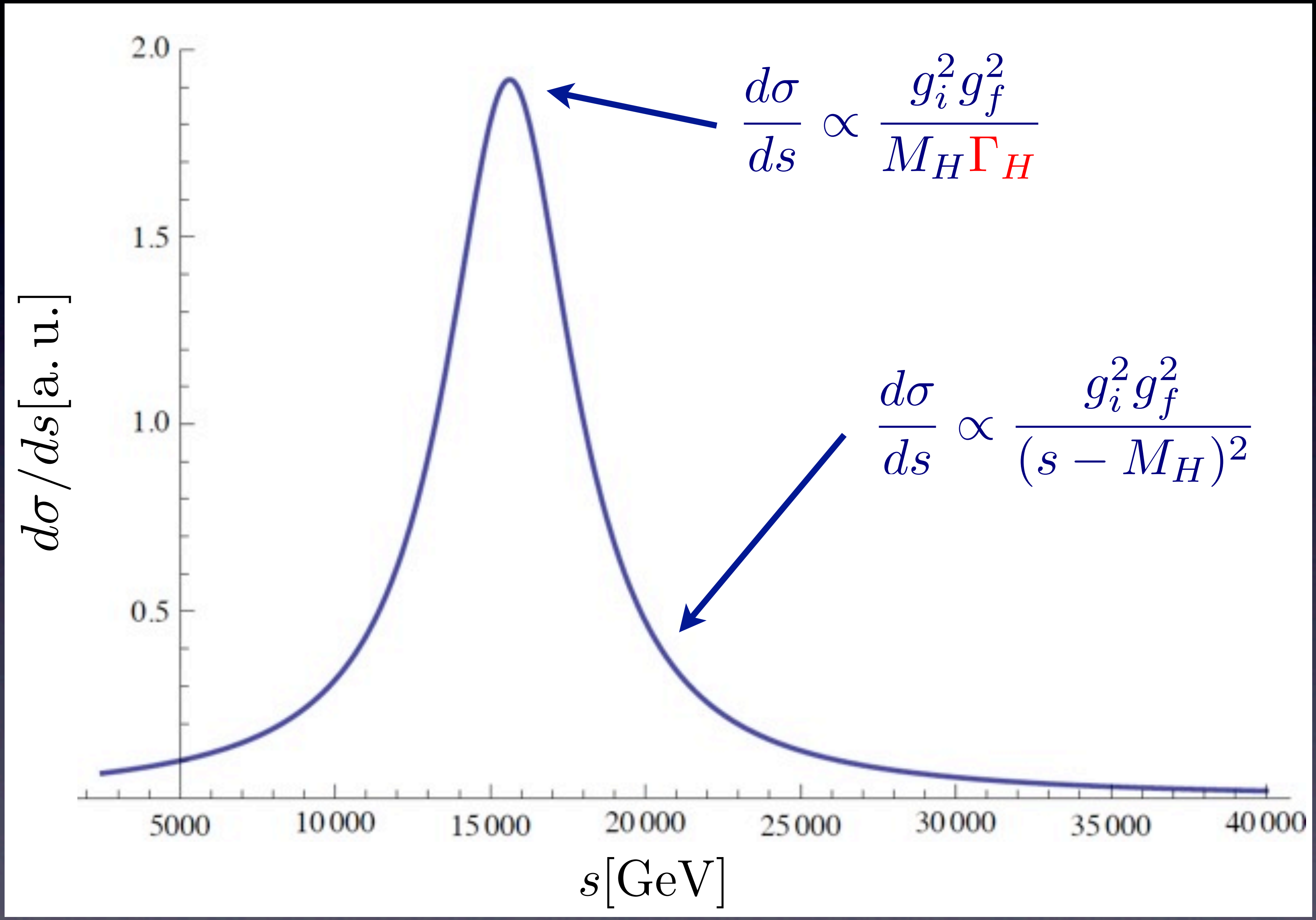
From H → 4 leptons:

$$c\tau_H < 57\mu\mathrm{m} \Rightarrow \Gamma_H > 3.5 \cdot 10^{-9}\mathrm{MeV}$$

In the SM: $c\tau_H \sim 4.8 \cdot 10^{-8} \mu\mathrm{m}$

LHC sensitivity from direct measurements: $10^{-9}\mathrm{MeV} < \Gamma_H < 1\mathrm{GeV}$

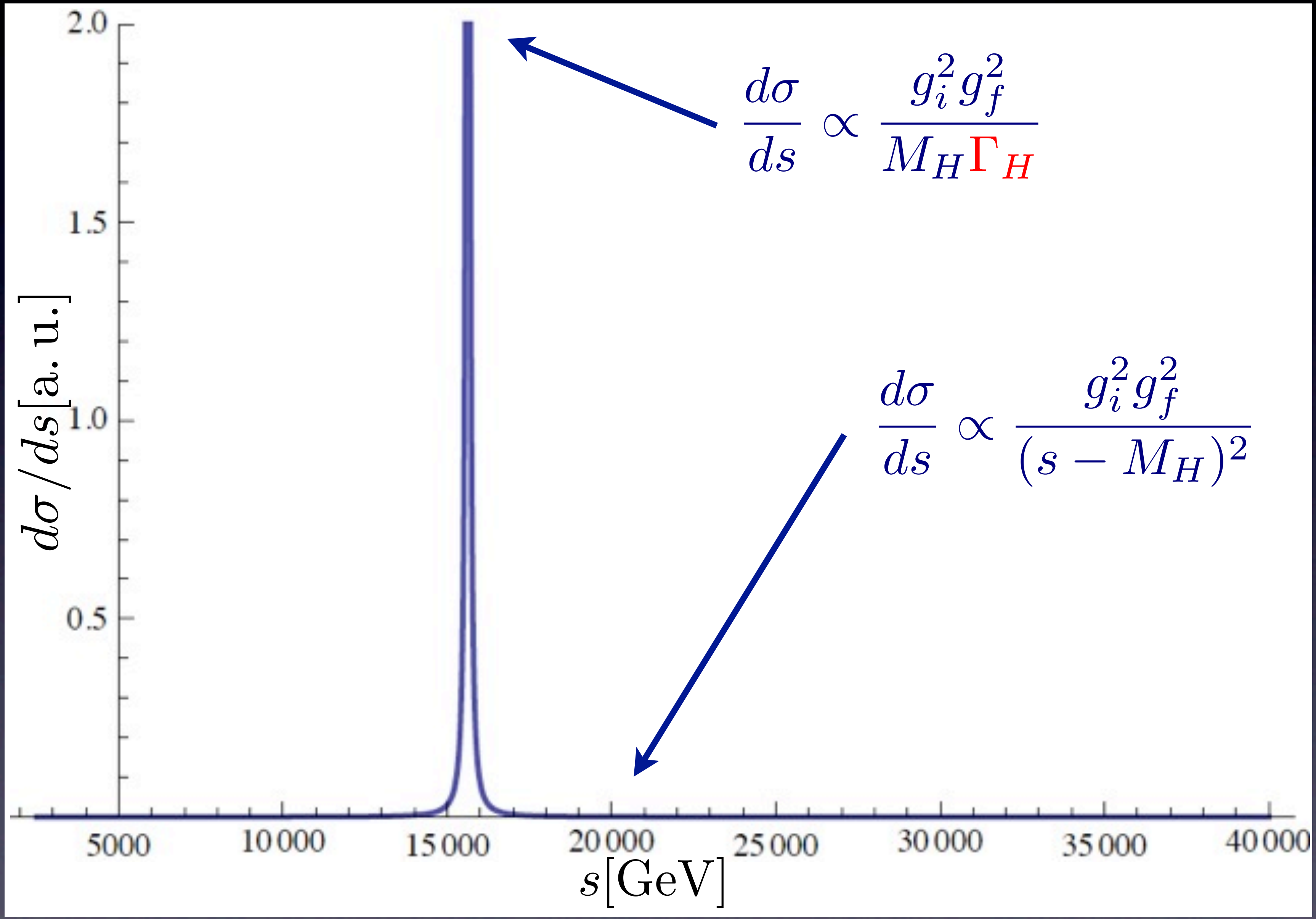
Breakthrough idea



Caola, Melnikov ’13
Campbell, Ellis, Ciaran ’14

Ratio of on-shell to off-shell cross-section sensitive to Higgs width

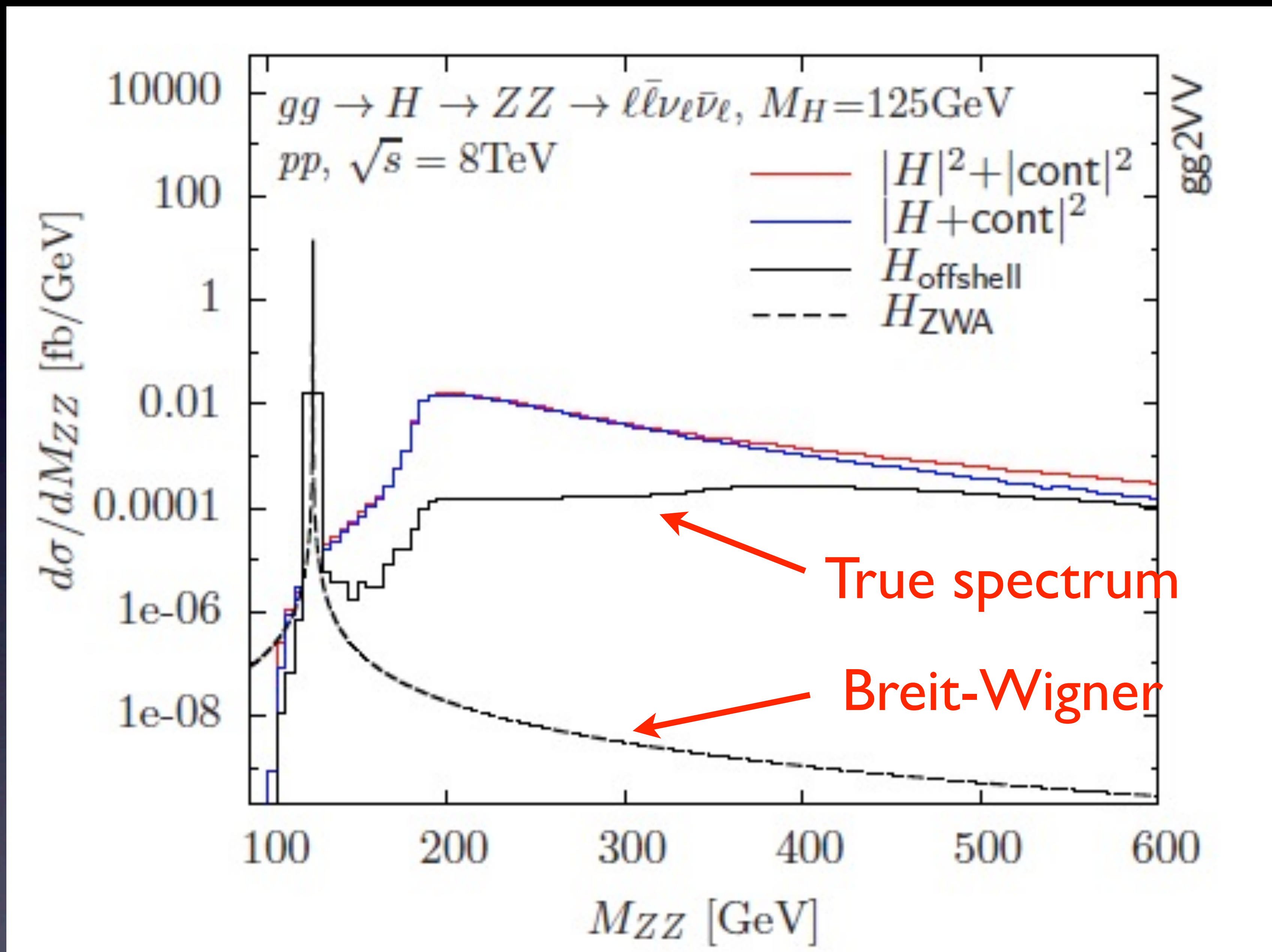
Breakthrough idea



Caola, Melnikov ’13
Campbell, Ellis, Ciaran ’14

But the Higgs resonance is narrow! Is there anything in the tail?

YES!

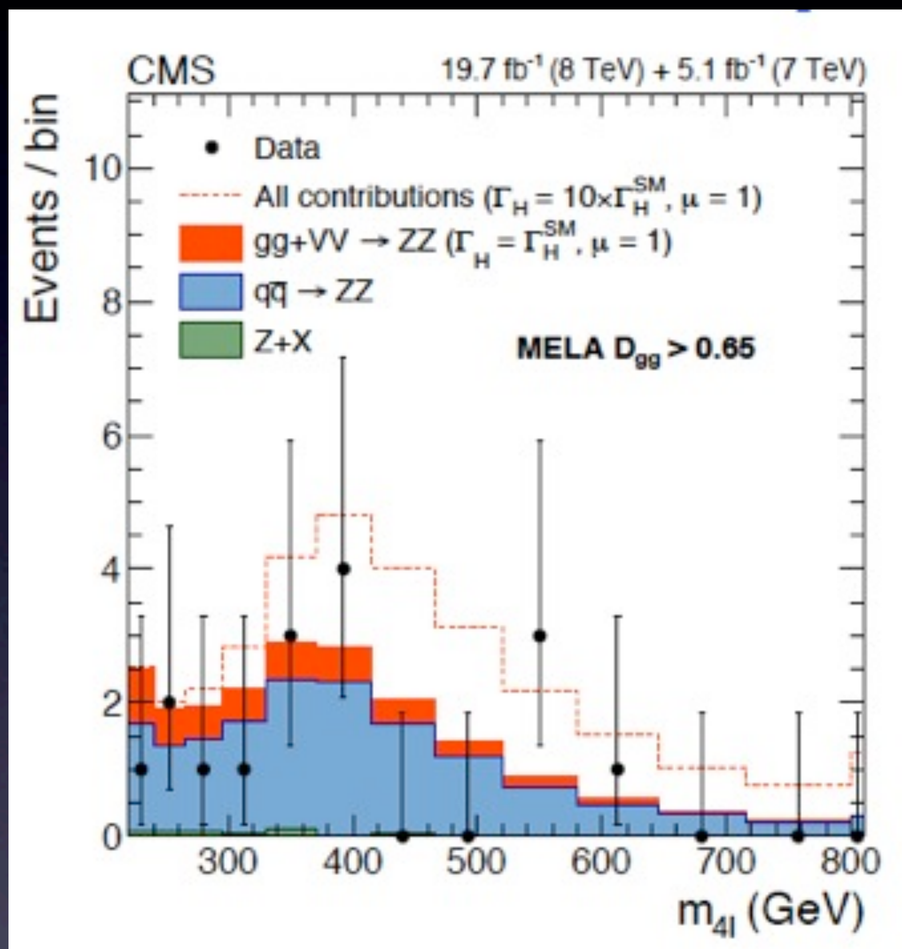


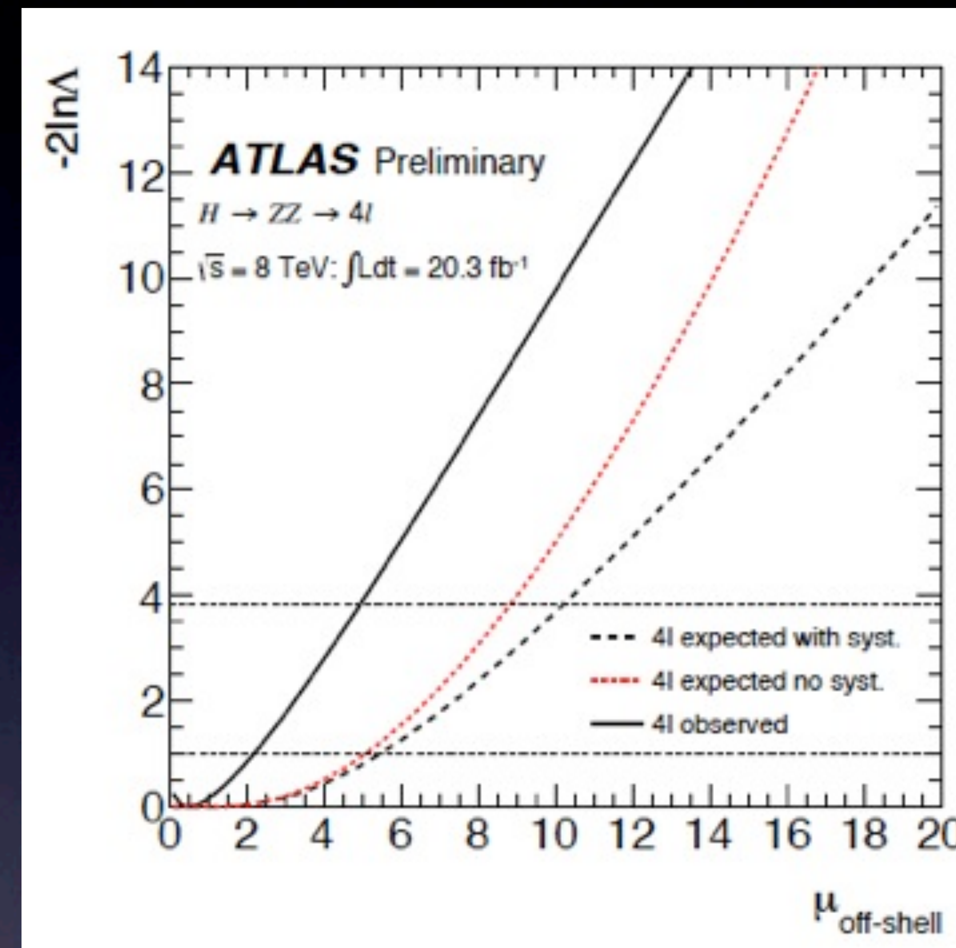
Kauer, Passarino

Large off-shell tail of the cross-section (10%) (because of enhancement due to decay of Higgs to longitudinal modes)

Today's bounds: 5 times SM value

CMS: $\Gamma_{\rm H} < 22\,{\rm MeV}\ @\ 95\% C.L.$





ATLAS: $\Gamma_{\rm H} < 20 - 32\,{\rm MeV}\ @\ 95\% C.L.$

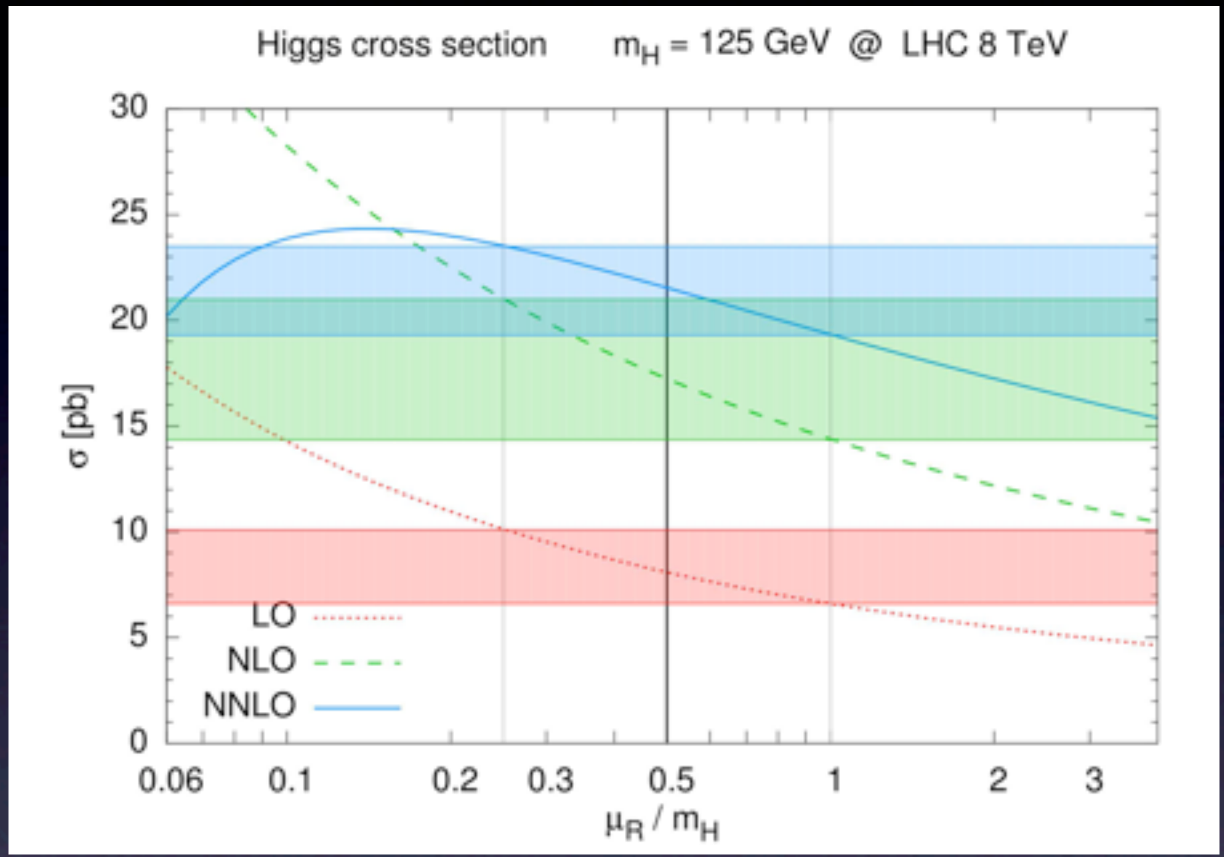
- assumes that the difference between on-shell and off-shell couplings is negligible
- important to control of off-shell cross-sections/backgrounds

Conclusions

- I presented only a personal selection of recent calculations relevant for Higgs physics (apologies for what I left out...)
- Higgs discovery was a true milestone for particle physics, it is the only fundamental spin-0 scalar ever observed. Suggesting its existence in the '60 was a remarkably brave proposal!
- But the Higgs leaves also many open questions for the LHC Run II to explore (hierarchy problem, naturalness, ...)
- Precision calculations are making giant steps: new techniques, new ideas, better measurements
- Progress in theory and experiment go truly hand in hand (in fact, often theory is ahead☺)

Stay tuned!

Inclusive production (Jan. 2015)



- perturbative series for gg → H converges very slowly
- renormalization scale variation (commonly used to estimate theory uncertainty) underestimates the shift to the next order
- control on this cross-section has a direct impact on New Physics searches and precision measurements in the Higgs sector

Backgrounds: ZZ @ NNLO

Fiducial cross sections

Grazzini, Kallweit, Rathlev 1507.06257

Channel	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NNLO} (fb)	σ_{exp} (fb)
$e^+e^-e^+e^-$	$3.547(1)^{+2.9\%}_{-3.9\%}$	$5.047(1)^{+2.8\%}_{-2.3\%}$	$5.79(2)^{+3.4\%}_{-2.6\%}$	$4.6^{+0.8}_{-0.7}(\mathrm{stat})^{+0.4}_{-0.4}(\mathrm{syst.})^{+0.1}_{-0.1}(\mathrm{lumi.})$
$\mu^+\mu^-\mu^+\mu^-$				$5.0^{+0.6}_{-0.5}(\mathrm{stat})^{+0.2}_{-0.2}(\mathrm{syst.})^{+0.2}_{-0.2}(\mathrm{lumi.})$
$e^+e^-\mu^+\mu^-$	$6.950(1)^{+2.9\%}_{-3.9\%}$	$9.864(2)^{+2.8\%}_{-2.3\%}$	$11.31(2)^{+3.2\%}_{-2.5\%}$	$11.1^{+1.0}_{-0.9}(\mathrm{stat})^{+0.5}_{-0.5}(\mathrm{syst.})^{+0.3}_{-0.3}(\mathrm{lumi.})$

- contains LO only gg → ZZ (expected large K-factor like Higgs)
- residual uncertainty estimated to be ~3%
- NNLO higher than data

Tension with

- For region m(4l) > 180 GeV, extract gg → ZZ rate by subtracting other contributions.
- Measure $\mu_{gg} = \sigma(\mathrm{data})/\sigma_{MC}(\mathrm{LO})$. Theory expectation for gg continuum/interference K ~2-3.
- μ_{gg} = 2.4 ± 1.0 (stat) ± 0.5 (exp) ± 0.8 (theo)

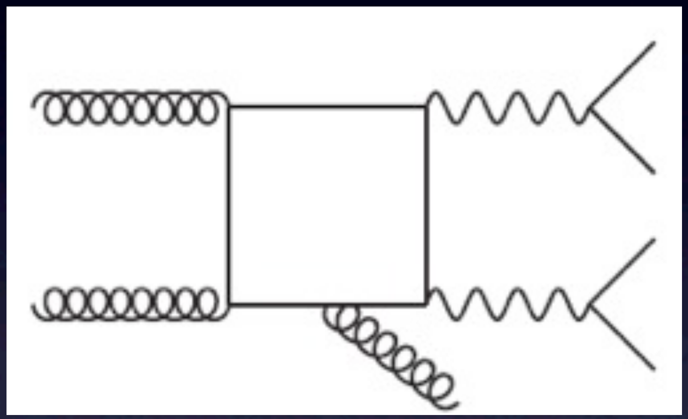
From Lepton Photon '15 talk of Einsweiler

ATLAS 1509.07844

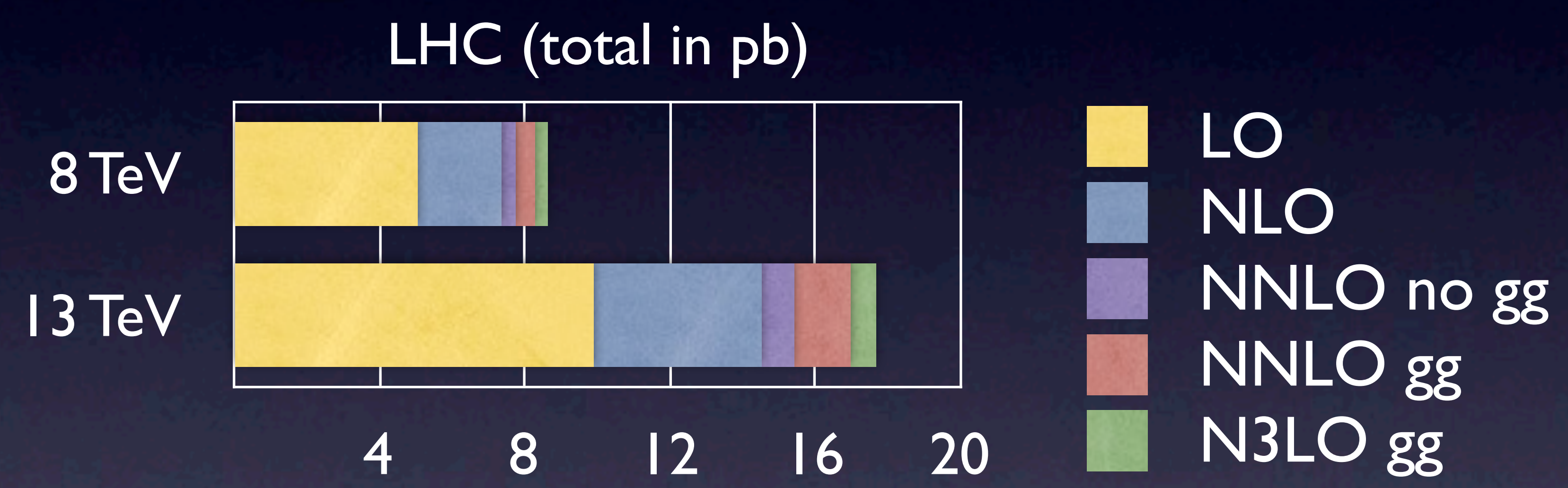
Background: gg → ZZ @NLO

Caola, Melnikov, Roentsch, Tancredi 1509.06734

NLO correction to gg loop-induced process computed recently.
N^{3}LO contribution to pp → ZZ, but enhanced by large gluon flux



+ two-loop diagrams



Calculation confirms extraction of K-factor by ATLAS and moves the total pp → ZZ result outside the (previous) NNLO uncertainty band

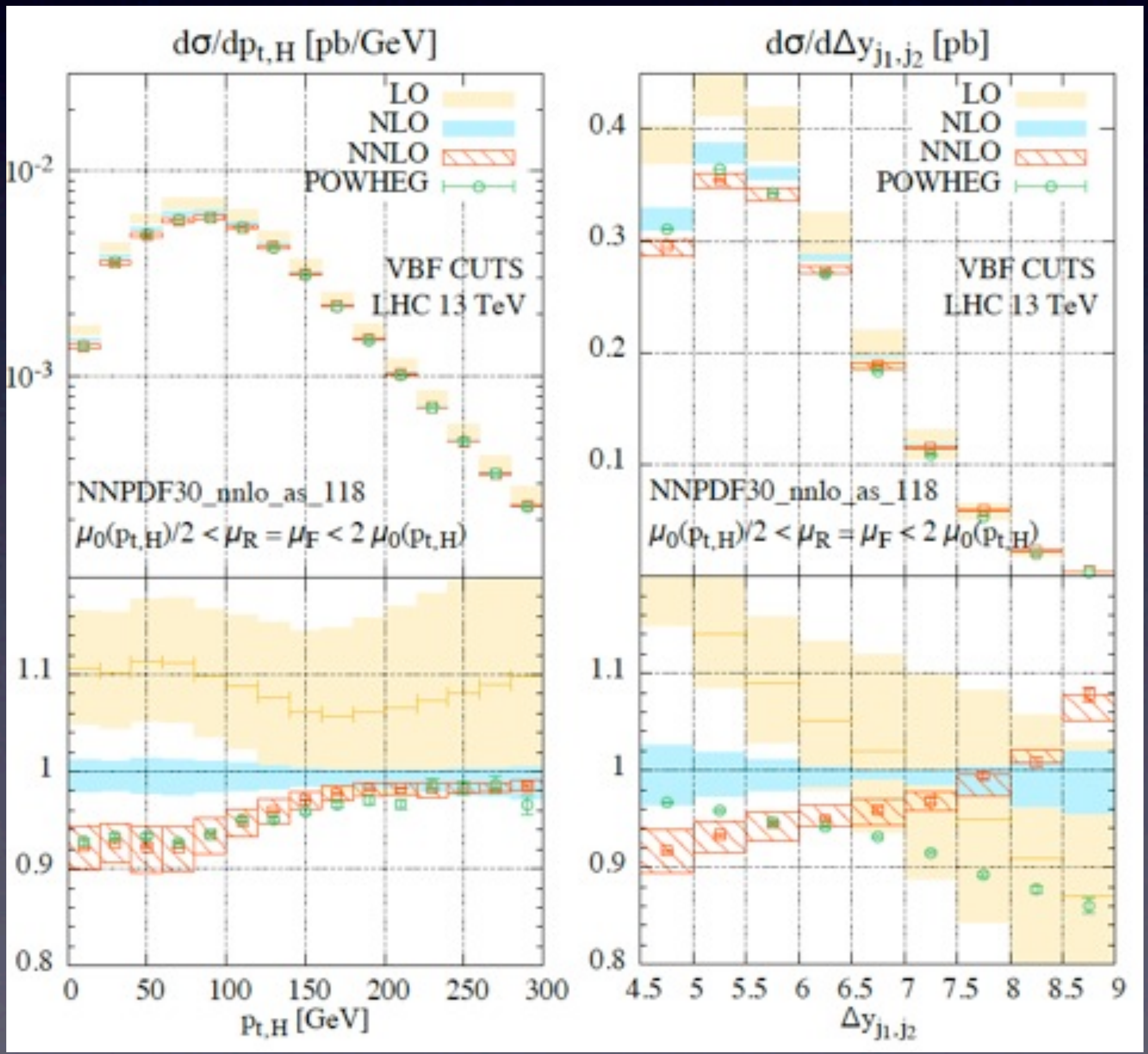
total (pb)	w. LO gg	w. NLO gg
LHC8	8.28 ± 0.2	8.63 ± 0.2
LHC13	16.9 ± 0.5	17.6 ± 0.5

Impact on:
- ongoing comparisons of TH/data
- off-shell studies of Higgs (width)
- other cases (WW, ...)

Differential VBFH at NNLO

Dreyer et al ’15

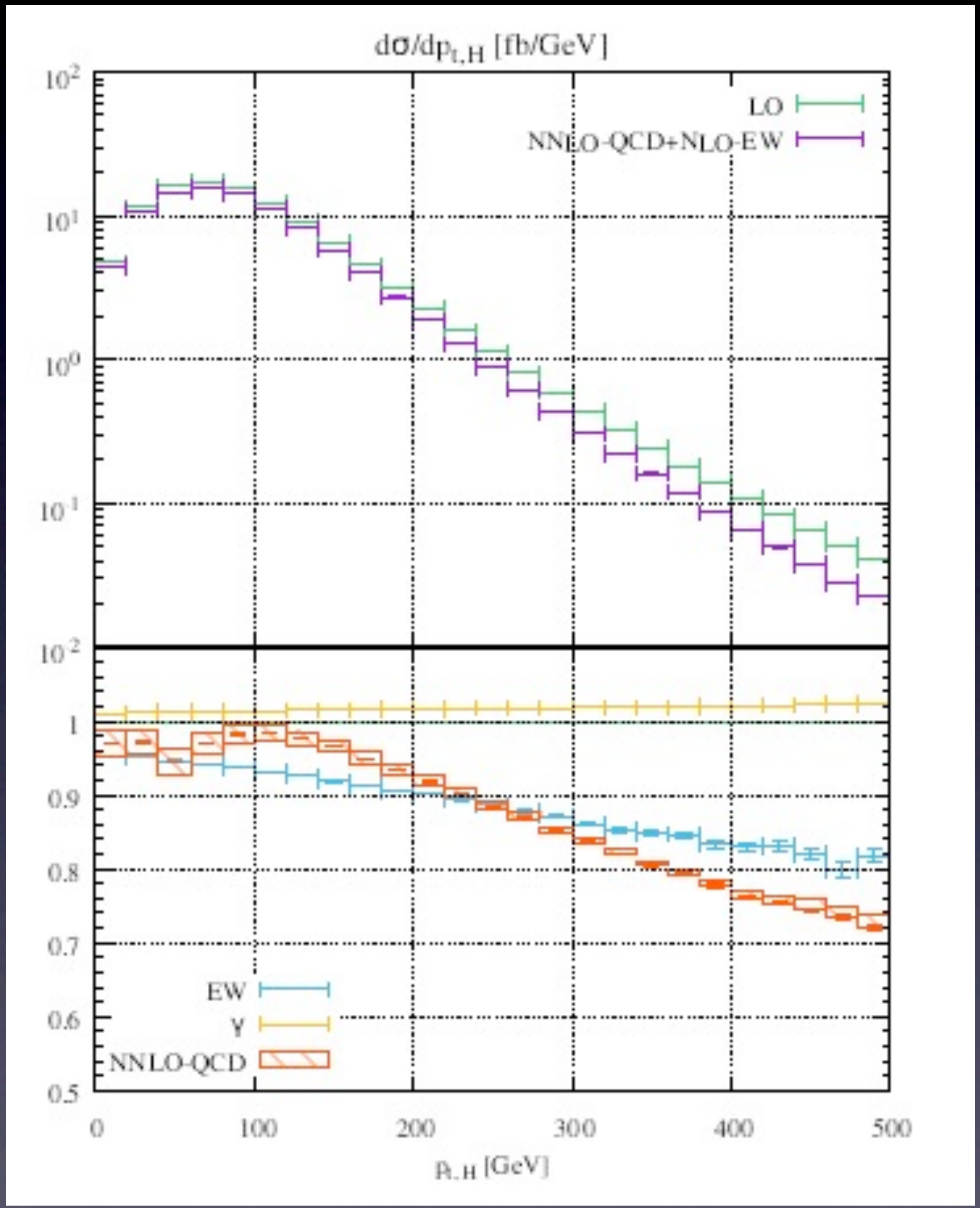
Fully differential calculation completed recently using projection to Born (P2B) methods



- Allows to study realistic observables, with realistic cuts
- NNLO corrections and uncertainties much larger (10%) than previously thought!
- Precision measurements require differential NNLO

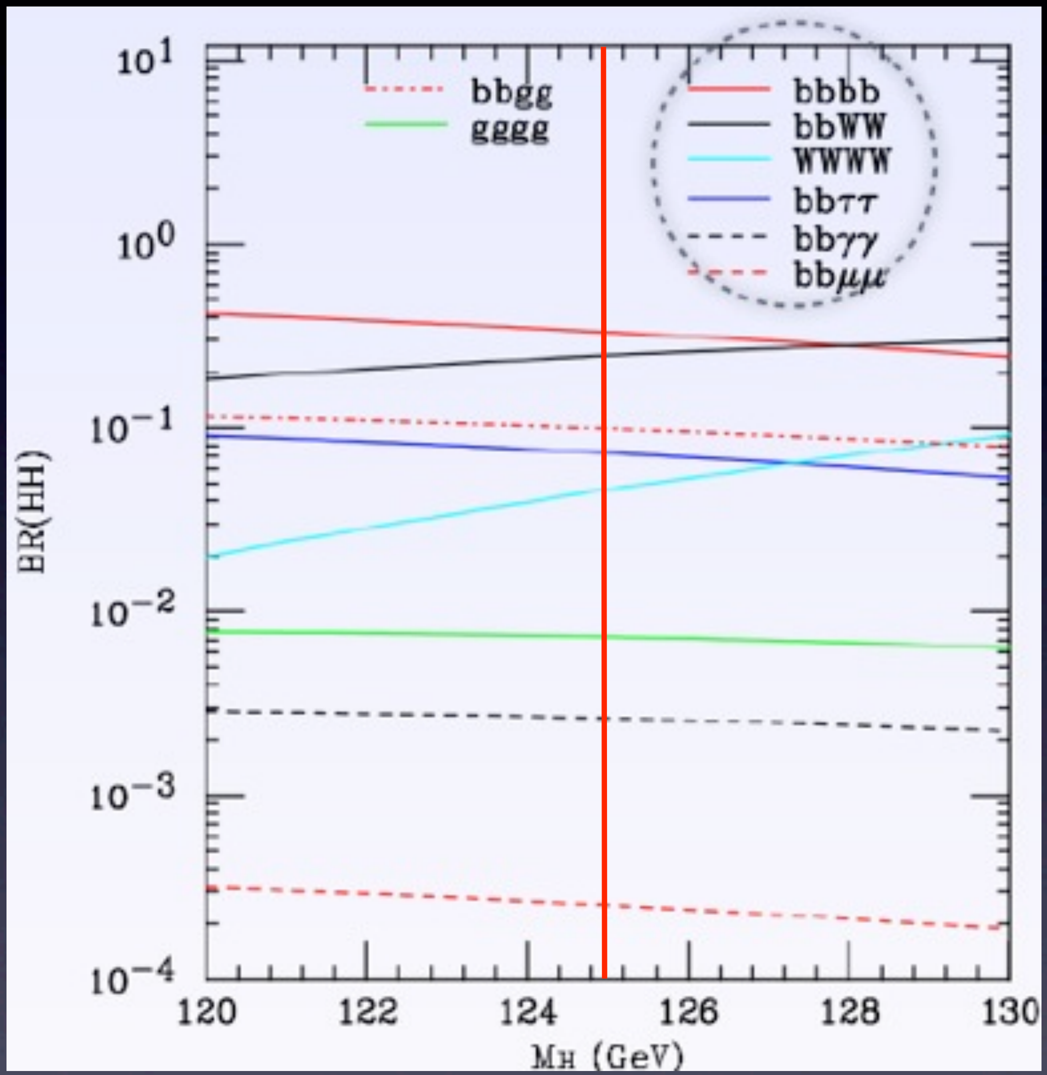
Differential VBFH at NNLO + NLO EW

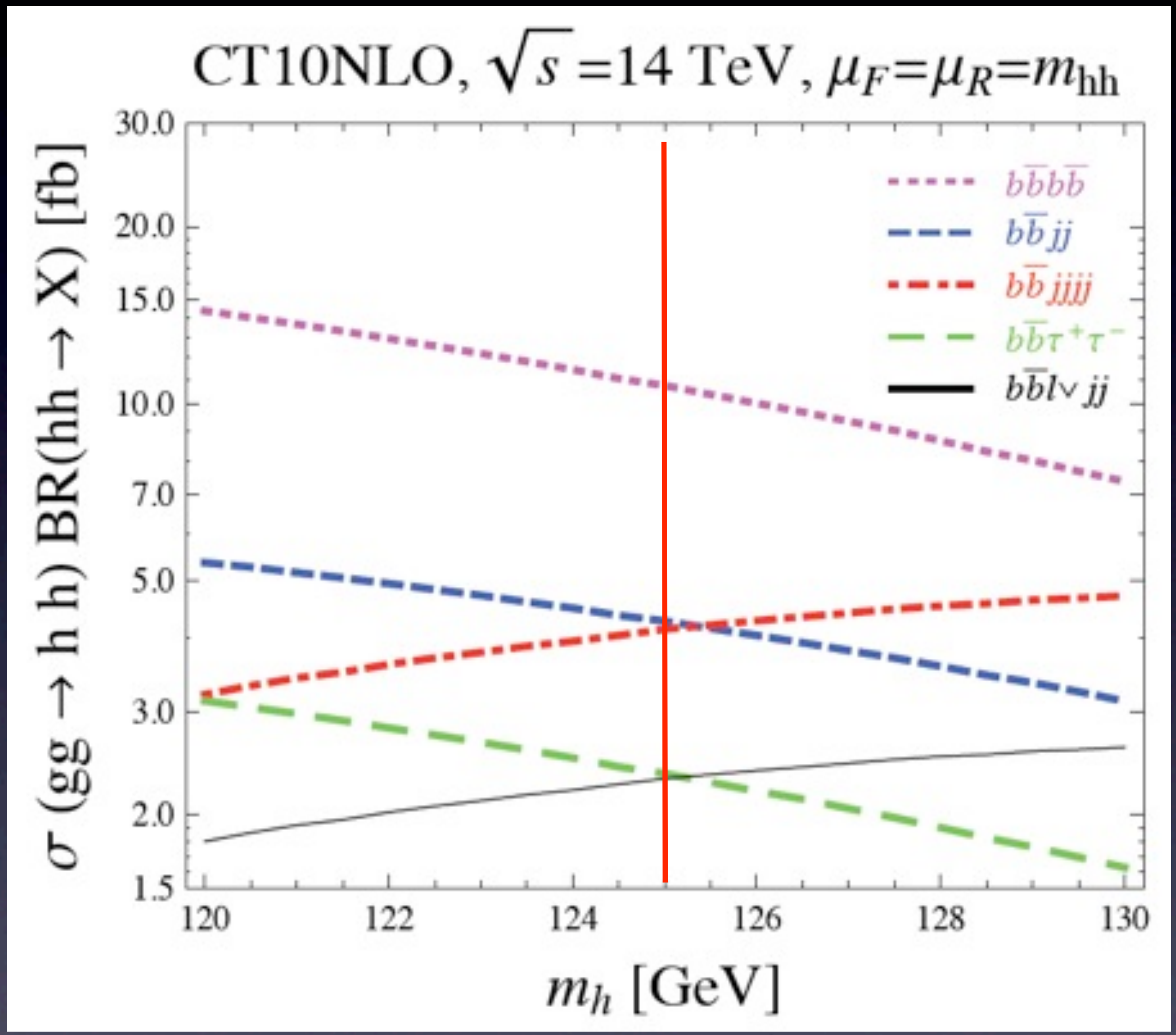
- NNLO QCD calculation merged to NLO EW one within the Higgs Cross Section Working Group
- Nice example of activity of the HXSWG towards
  - ✓ obtaining best predictions by combining different calculations
  - ✓ assigning overall theoretical error



HXSWG preliminary

HH: decays channels





High price to be paid for the two decays compared to single Higgs production. Also hadronic modes studied.

HH: sensitivity to selfcoupling