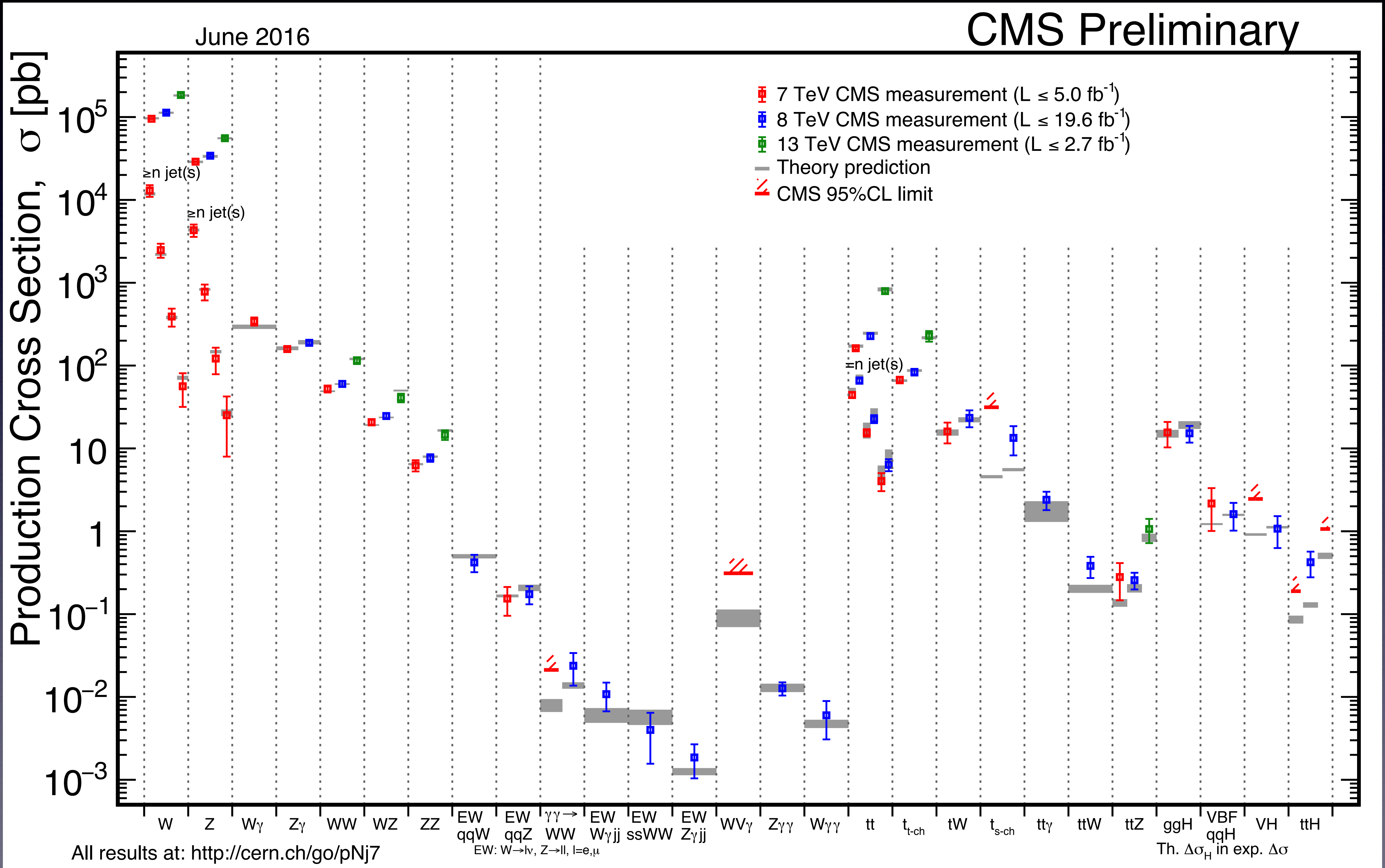
Precision Higgs studies at the LHC

A first glance beyond the energy frontier

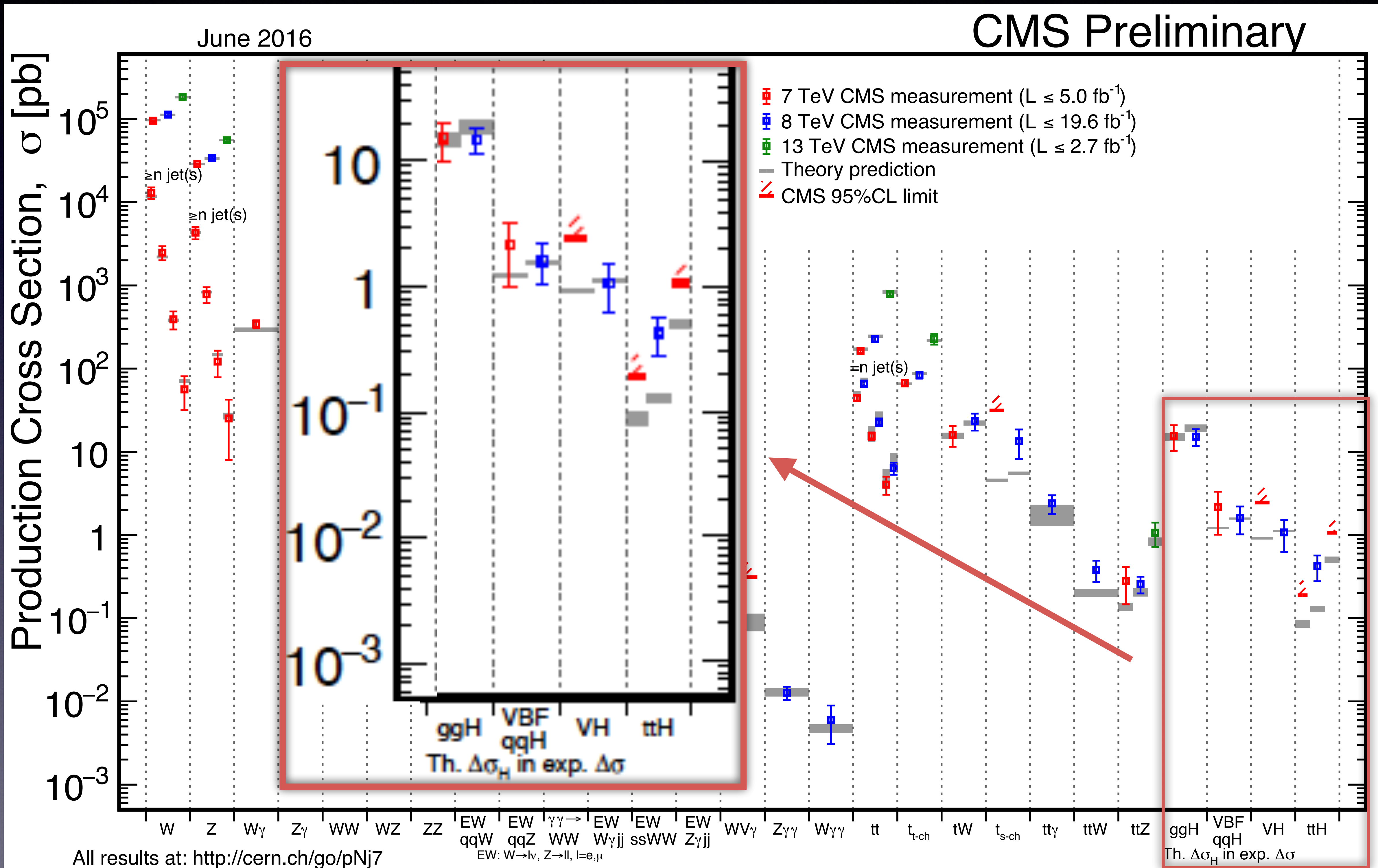
ICTP, 8th September 2016

G. Zanderighi - CERN & Oxford University

Production cross sections at the LHC



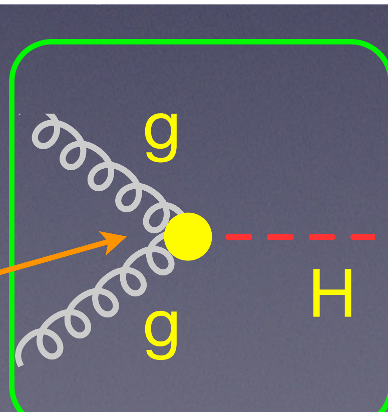
Production cross sections at the LHC

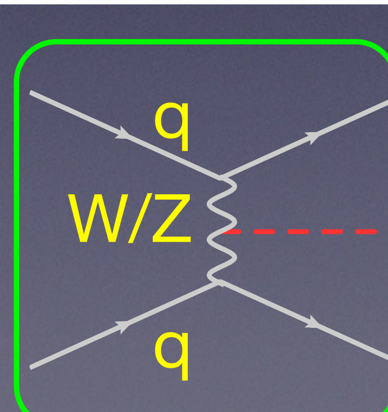


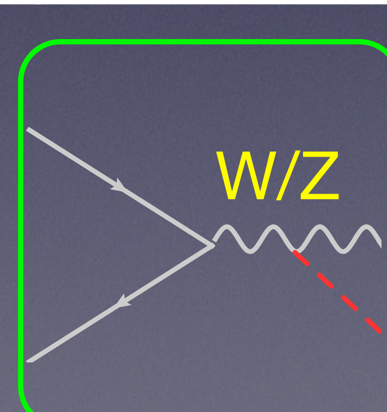
Main Higgs production at the LHC

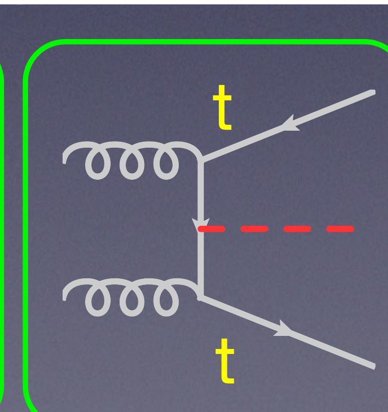
	ggH	VBF	WH/ZH	ttH	tH
8 TeV ~ 25 fb^{-1} (2012)	19 pb	1.6 pb	1.1 pb	0.13 pb	20 fb
13 TeV ~ 4+13 fb^{-1} ('15 &'Jul16)	48 pb	3.7 pb	2.2 pb	0.51 pb	90 fb

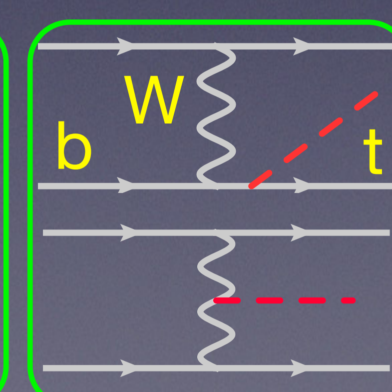
heavy-quark loop ⇒ effective Lagrangian





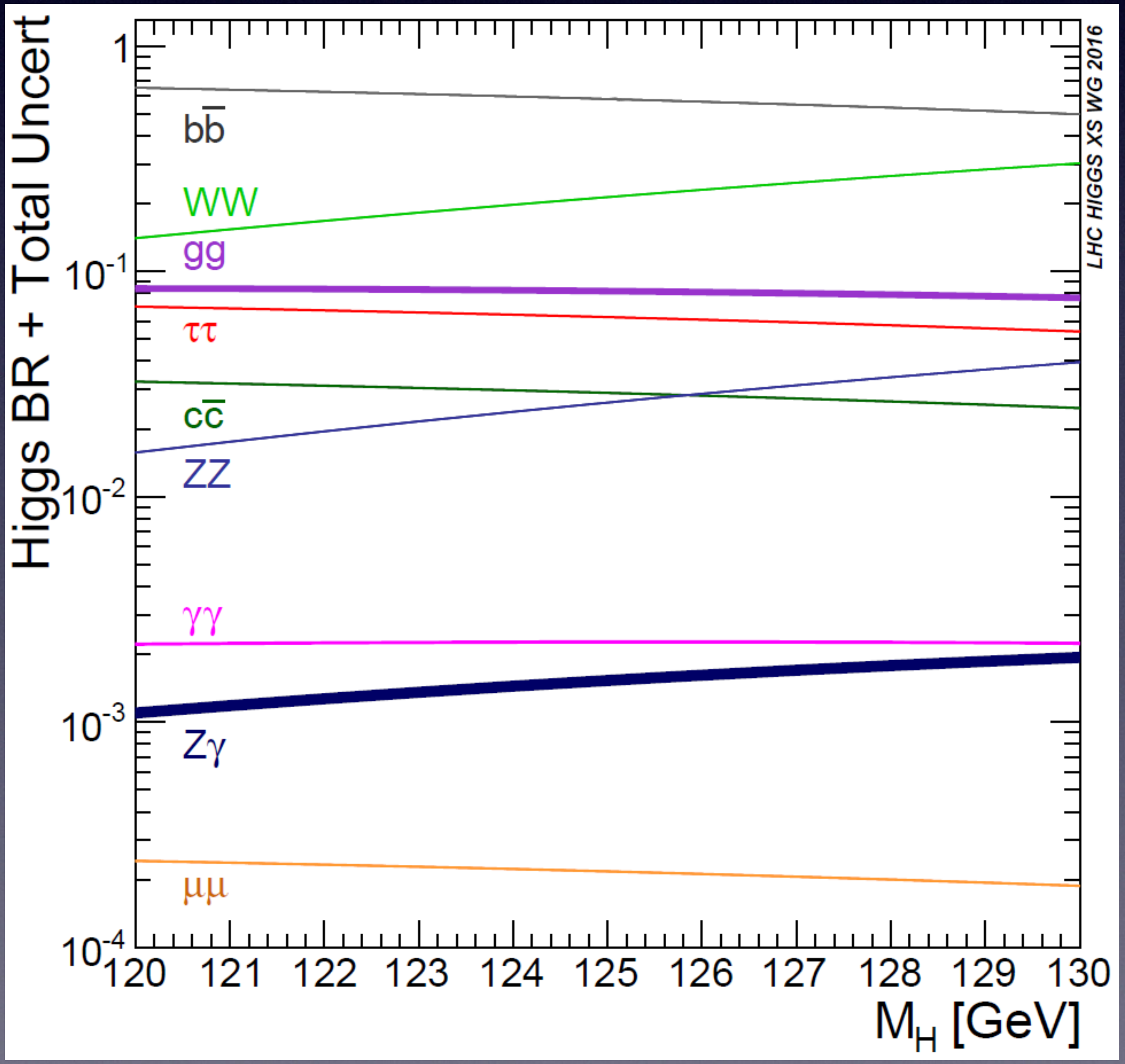






Higgs decay modes

The Higgs mass (m_H=125 GeV) lies in fantastic place to study Higgs couplings



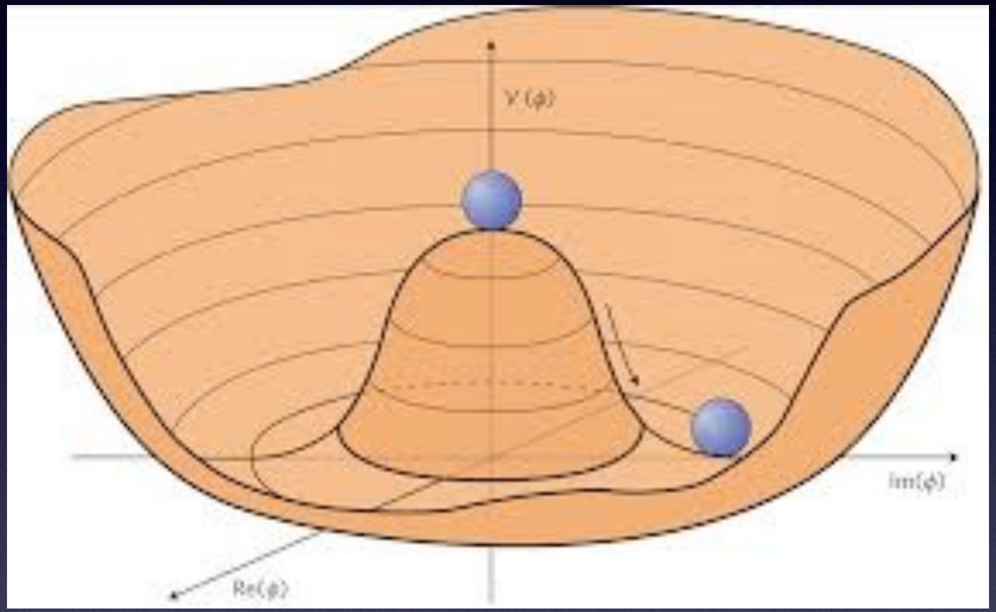
Channel	BR in %	
bb	58.1	✓
WW*	21.5	✓
gg	8.2	✗
ττ	6.3	✓
cc	2.9	✗
ZZ*	2.6	✓
γγ	0.23	✓
Zγ	0.15	✗
μμ	0.02	✗

The Higgs: what do we know today

- it is a very narrow resonance (Γ_H < 25 MeV), 99.9% CL spin 0, P+
- its mass is already known to about 0.2% precision
  $m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$ GeV
- it is produced in gluon-fusion (top loop), vector boson fusion, production in association with a W or Z boson and top quarks
- 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 $\mu = 1.09^{+0.11}_{-0.10}$

The Standard Model Higgs

- it is a fundamental, CP even scalar
- φ^4 potential
- responsible for masses of fermions and bosons in the SM
- mass generation mechanism very predictive: given the Higgs mass, all couplings fixed
- it completes the SM



But it also opens many questions, in particular it leaves us with a hierarchy problem. Many explanations exist to protect the Higgs mass that typically result in modifications of couplings, cross-sections, distribution

Precision, precision, precision …

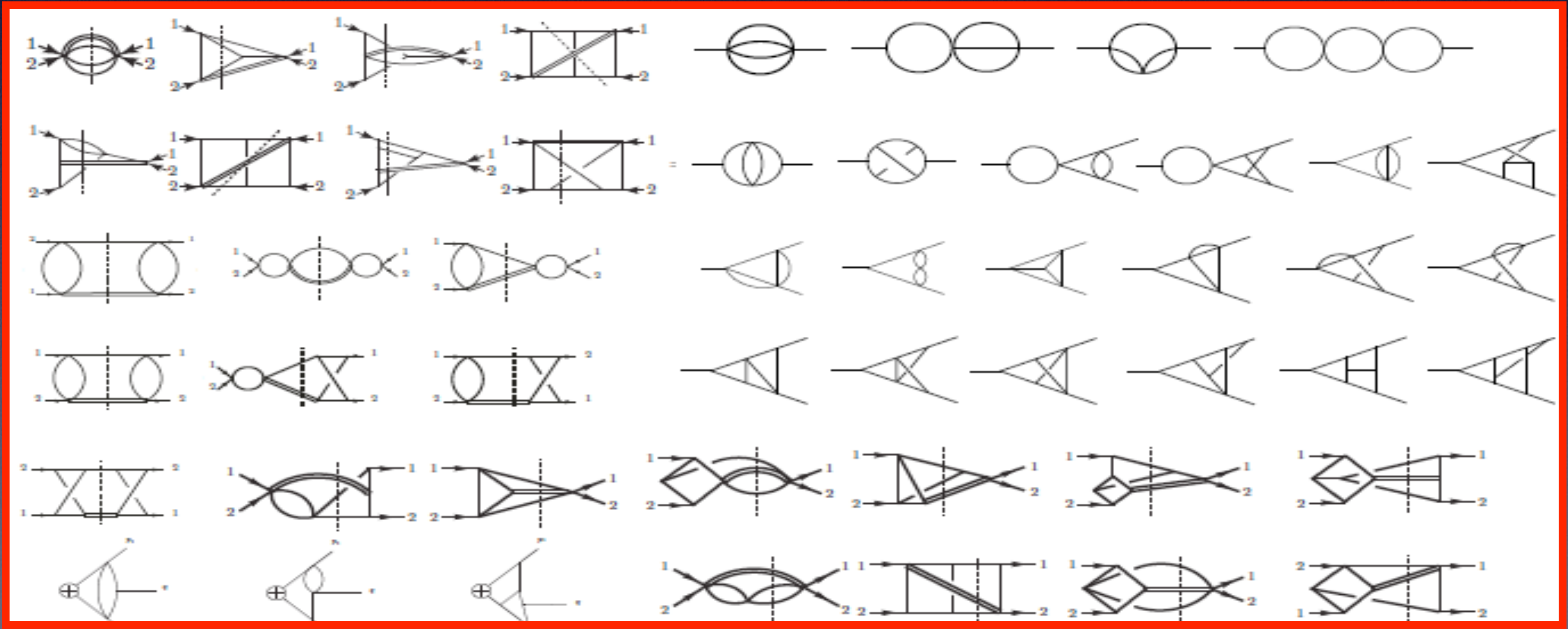
- This is why it is crucial to stress-test the Higgs sector as much as possible and establish possible deviations from SM pattern
- Also, after a first glance at Run II data, it is clear that indirect searches will play a prominent role

In these tasks, precision is crucial to maximise sensitivity

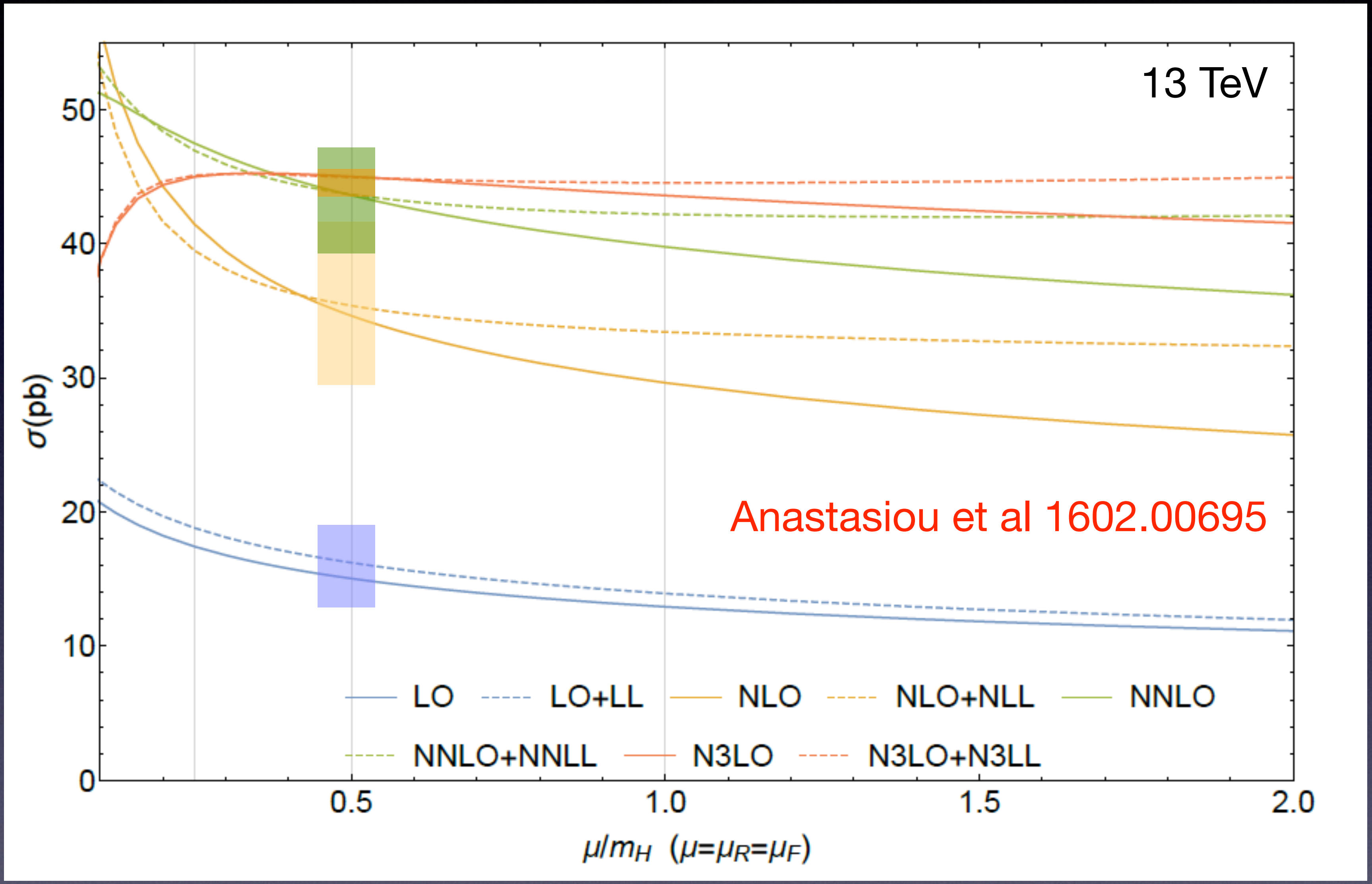
N^{3}LO Higgs production

Gluon-fusion Higgs production recently computed to N^{3}LO in the large m_t EFT: O(10^7) phase space integrals, O(10^5) interference diagrams, O(10^3) three-loop master integrals. A truly amazing technical achievement

Anastasiou et al 1602.00695



N^{3}LO Higgs production



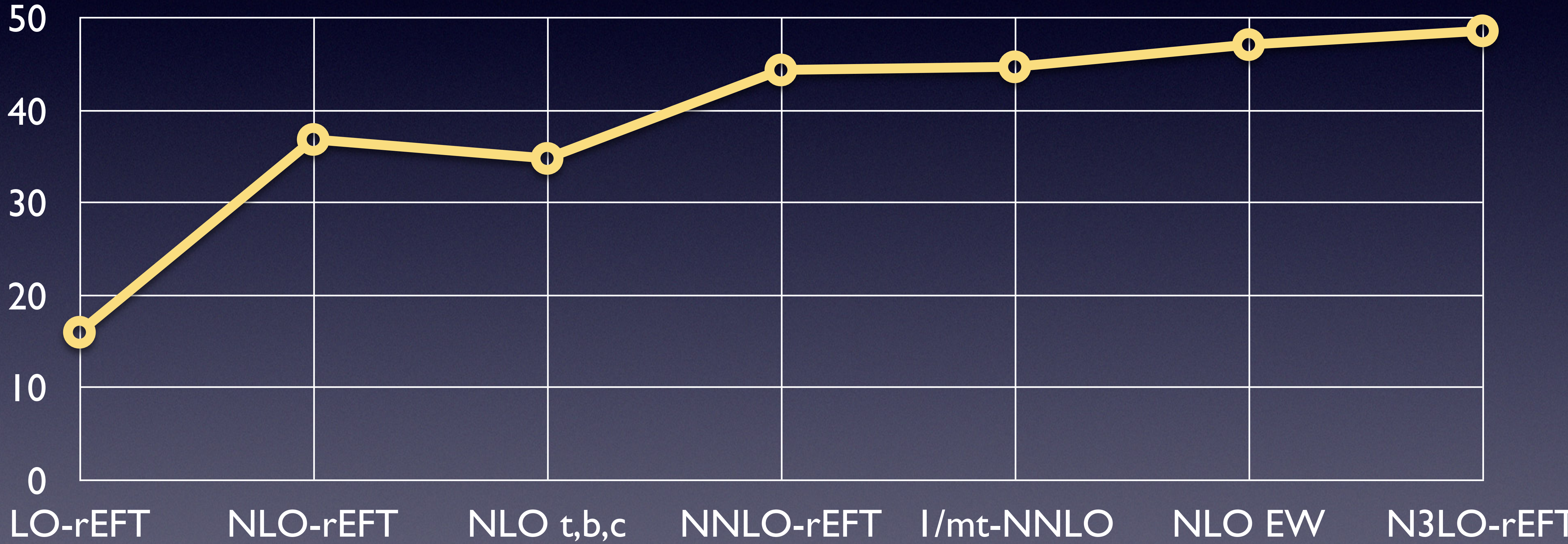
- also matched to resummed calculation (essentially no impact on central value at preferred scale $m_H/2$)
- N^{3}LO finally stabilizes the perturbative expansion

Inclusive Higgs production

Anastasiou et al 1602.00695

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

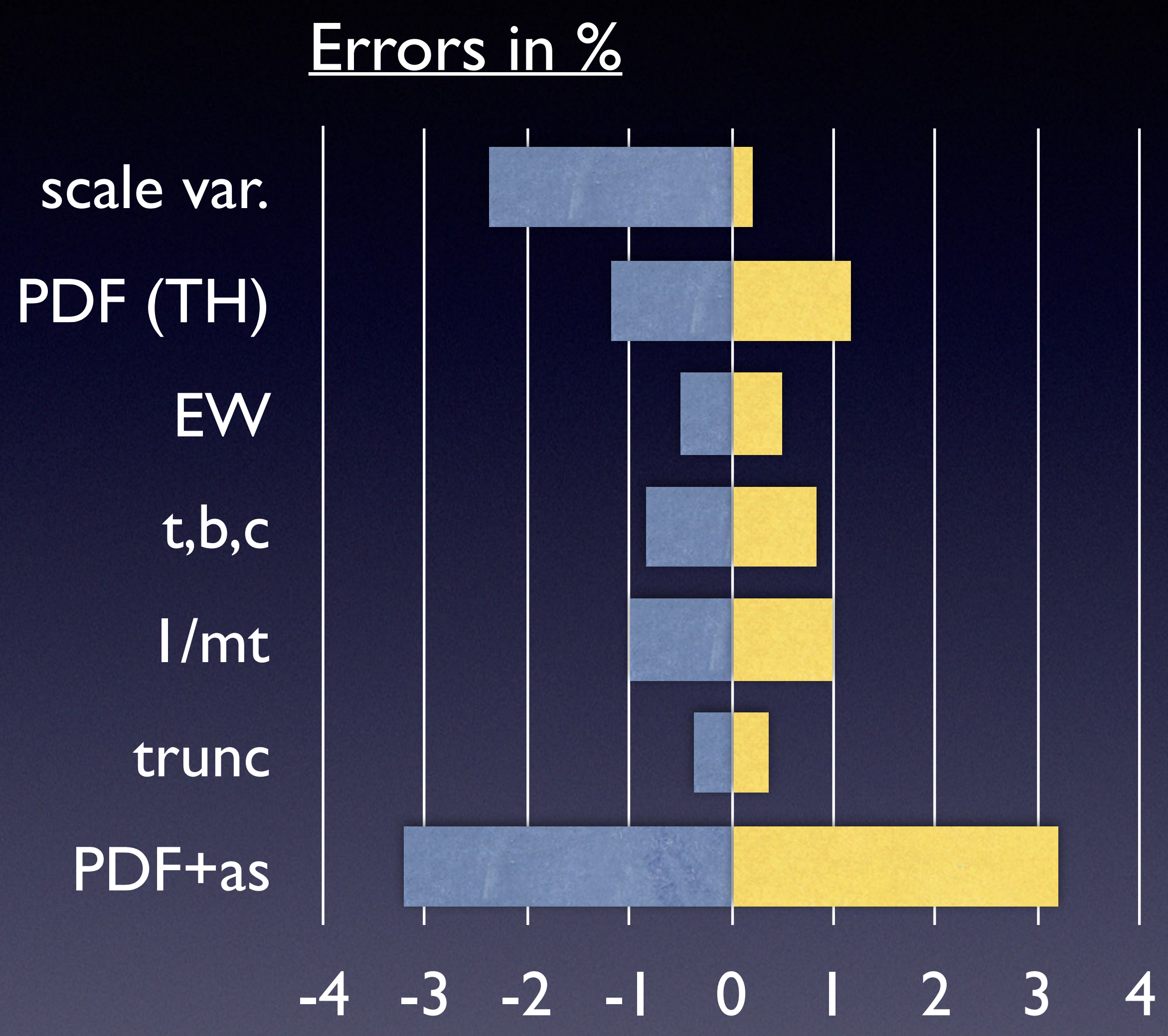
LHC 13 TeV: cross section in [pb] = 48.58 pb



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) $\approx$ 1.07

Error budget from 1602.00695



Most debated points in the Higgs Cross Section working group (HXSWG)

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

Total theory error: add all 6 theory errors linearly and keep the (PDF+α_s) error separate (to be added quadratically)

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

The new HXSWG recommendation

Discussion resulted in a new recommendation of the HSXWG for 4th Yellow Report: use the pure fixed order result from 1602.00695 for the central value, and take it's uncertainty interpreted as

100% flat

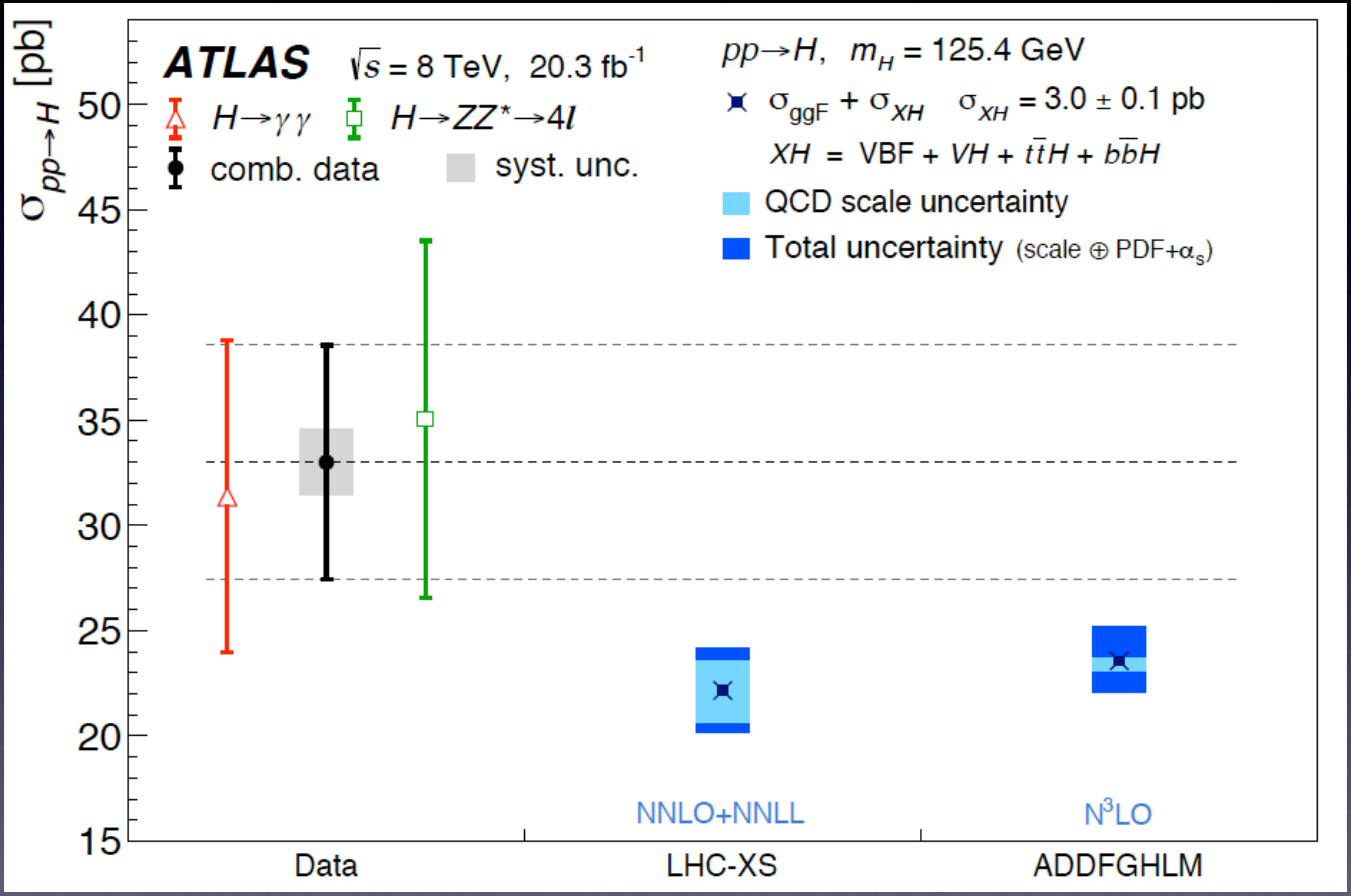
68% gaussian

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

$$\Delta_{\mathrm{th}} = 3.9\%$$

If it is highly preferred to have only gaussian theory uncertainties then transform to gaussian one (symmetrize and divide by $\sqrt{3}$)

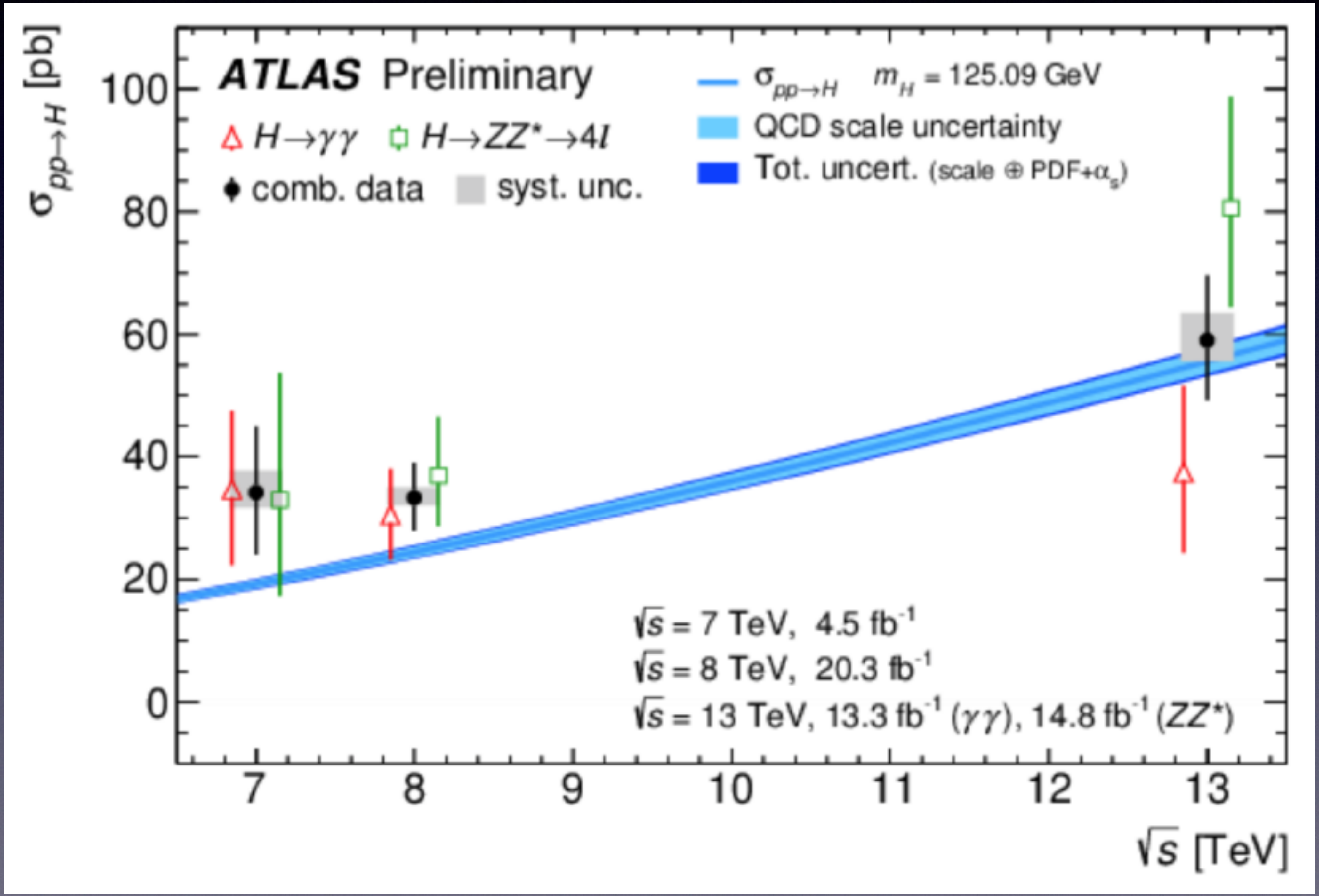
8 TeV data vs theory



"... EXP precision is very far away (TH went ahead 15 years of EXP?), but it would be better to have numbers with best precision."

[email by Reisaburo Tanaka to the ggF conveners]

13 TeV data vs theory



Going differential

Beyond inclusive cross-sections, accurate predictions for differential distributions crucial for Run II

➡ signal significance optimized by categorizing events according to kinematic properties (e.g. jet bins, Higgs p_t ...)

➡ a large fraction (30-40%) of Higgs events come with at least one jet

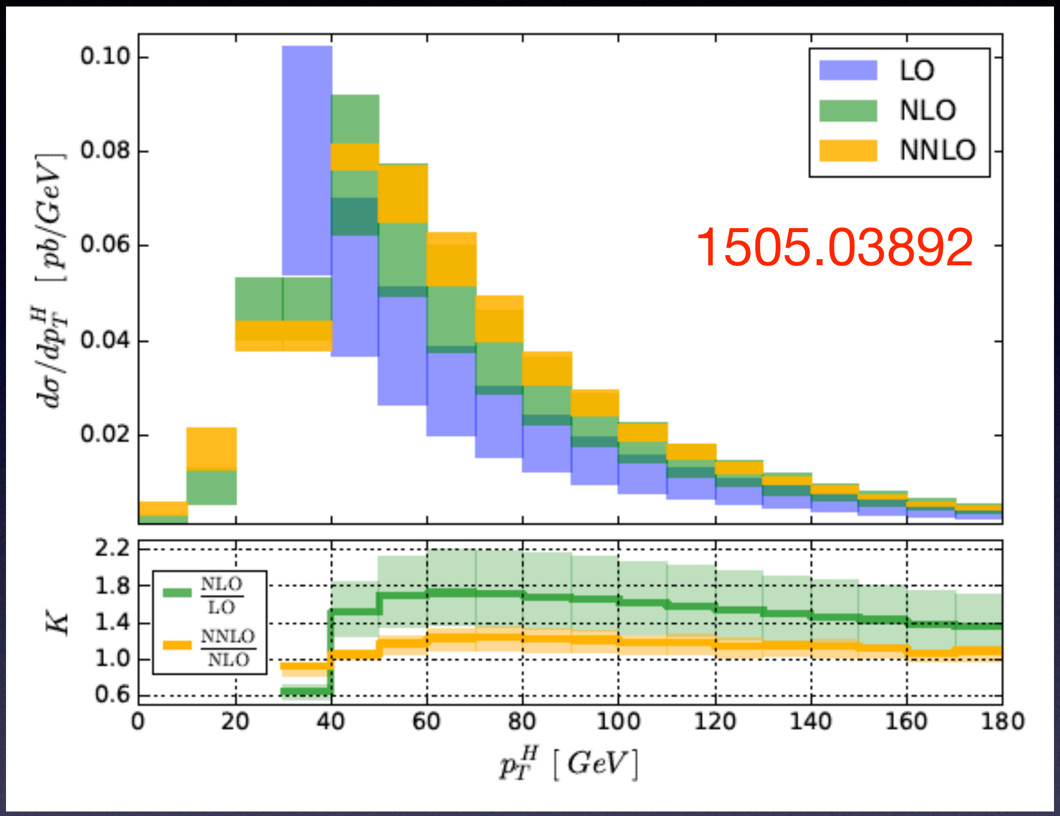
➡ kinematical distributions used to extract/constraint couplings and quantum numbers

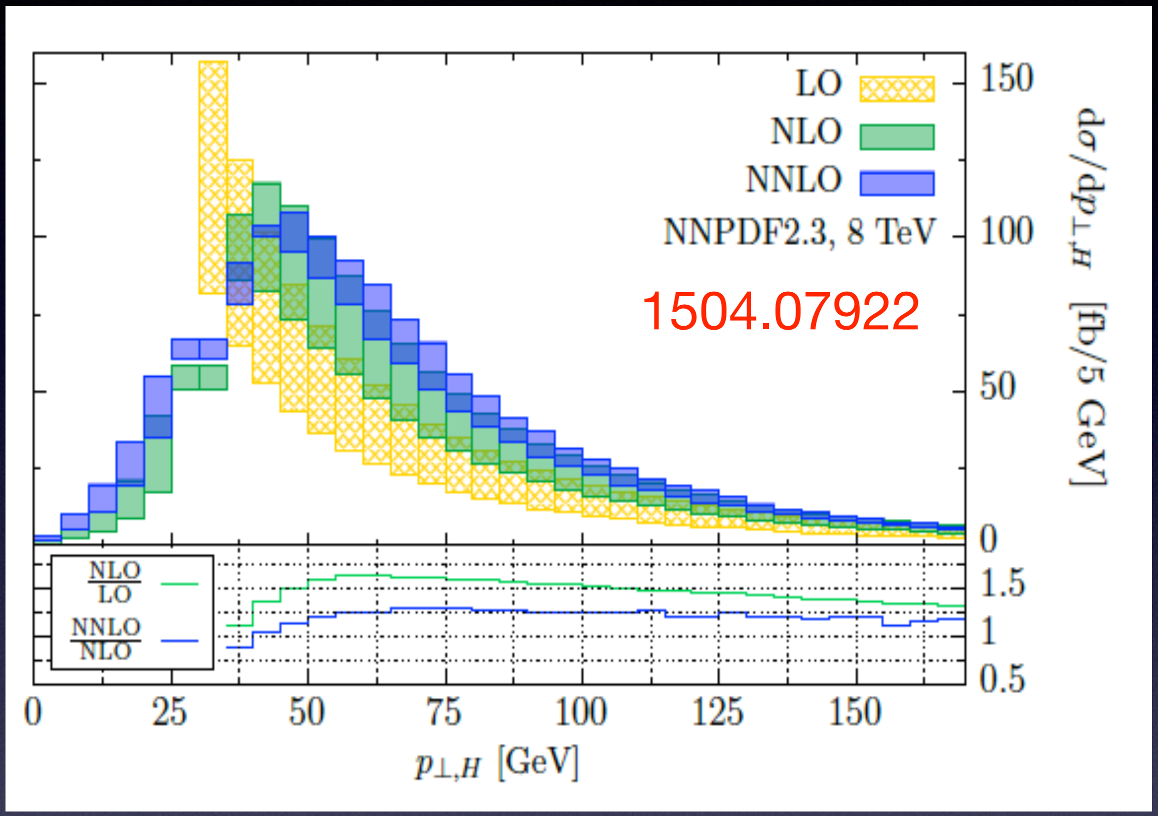
The most basic distribution: transverse momentum of the Higgs boson

It is inclusive on radiation, not sensitive to definition of jets or hadronization effects

Precision at high p_t requires H+1jet production at NNLO

H + 1jet at NNLO





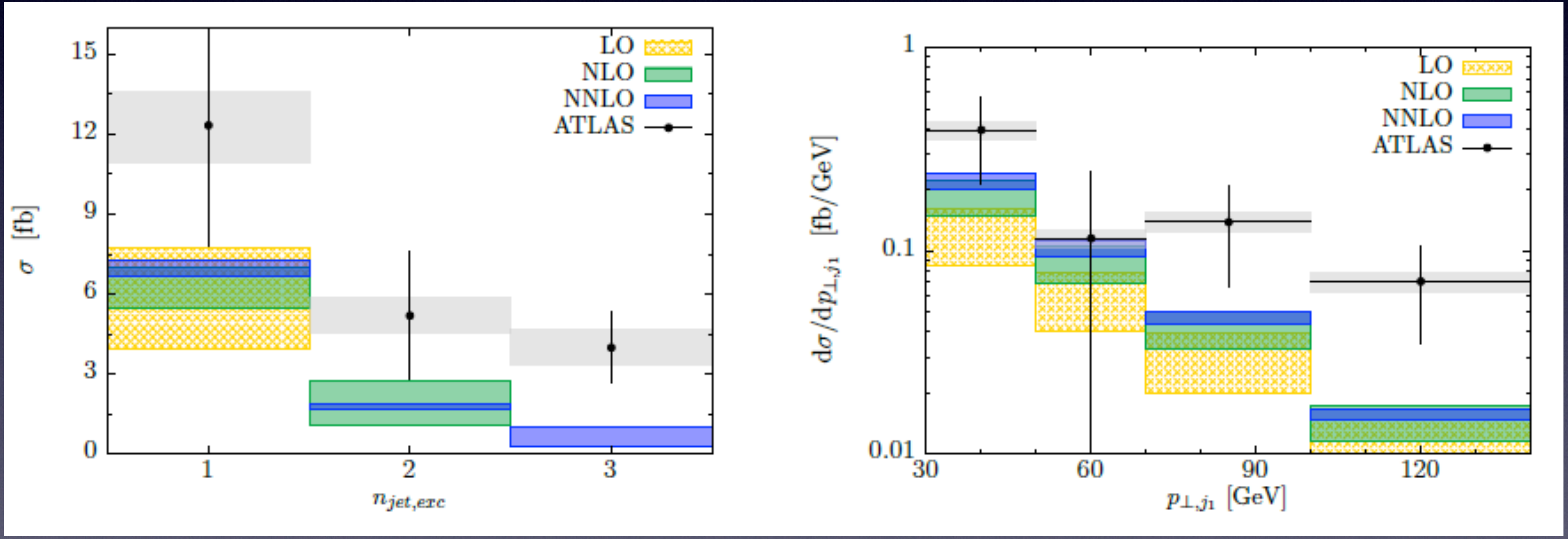
- useful comparison between independent calculations
- sizable K-factor (≈1.15-1.20)
- reduction of theory error (still about 10-15%)

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

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

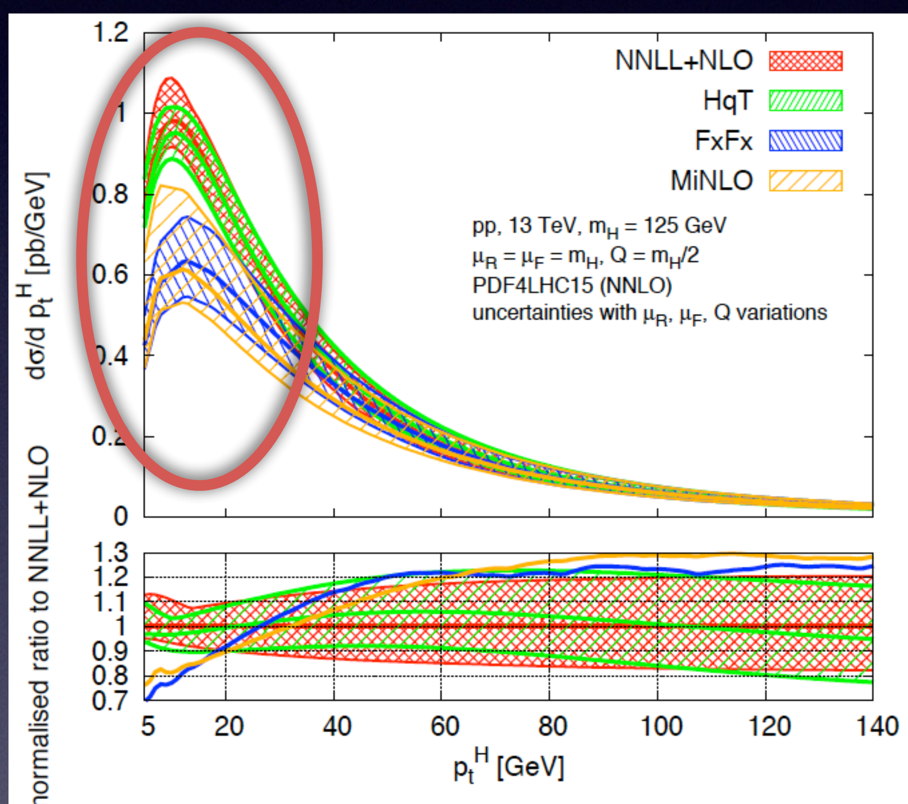


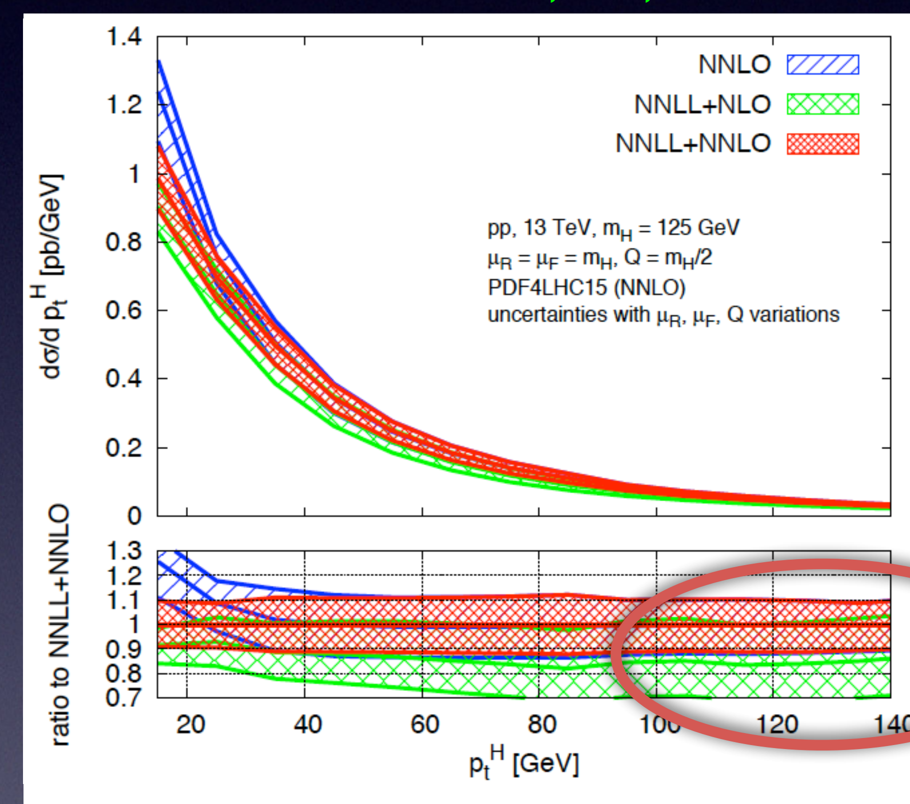
Agreement with data within large errors, but corrections beyond large top-mass effective theory could be sizable

NNLO + NNLL Higgs p_t spectrum

Best accuracy at low p_t (NNLL) but matched to best fixed order at high p_t (NNLO) (improvement over HqT predictions)

Monni, Re, Torrielli 1604.02191





- good agreement with previous NNLL+NLO (HqT)
- less good agreement with other NLO+PS simulations

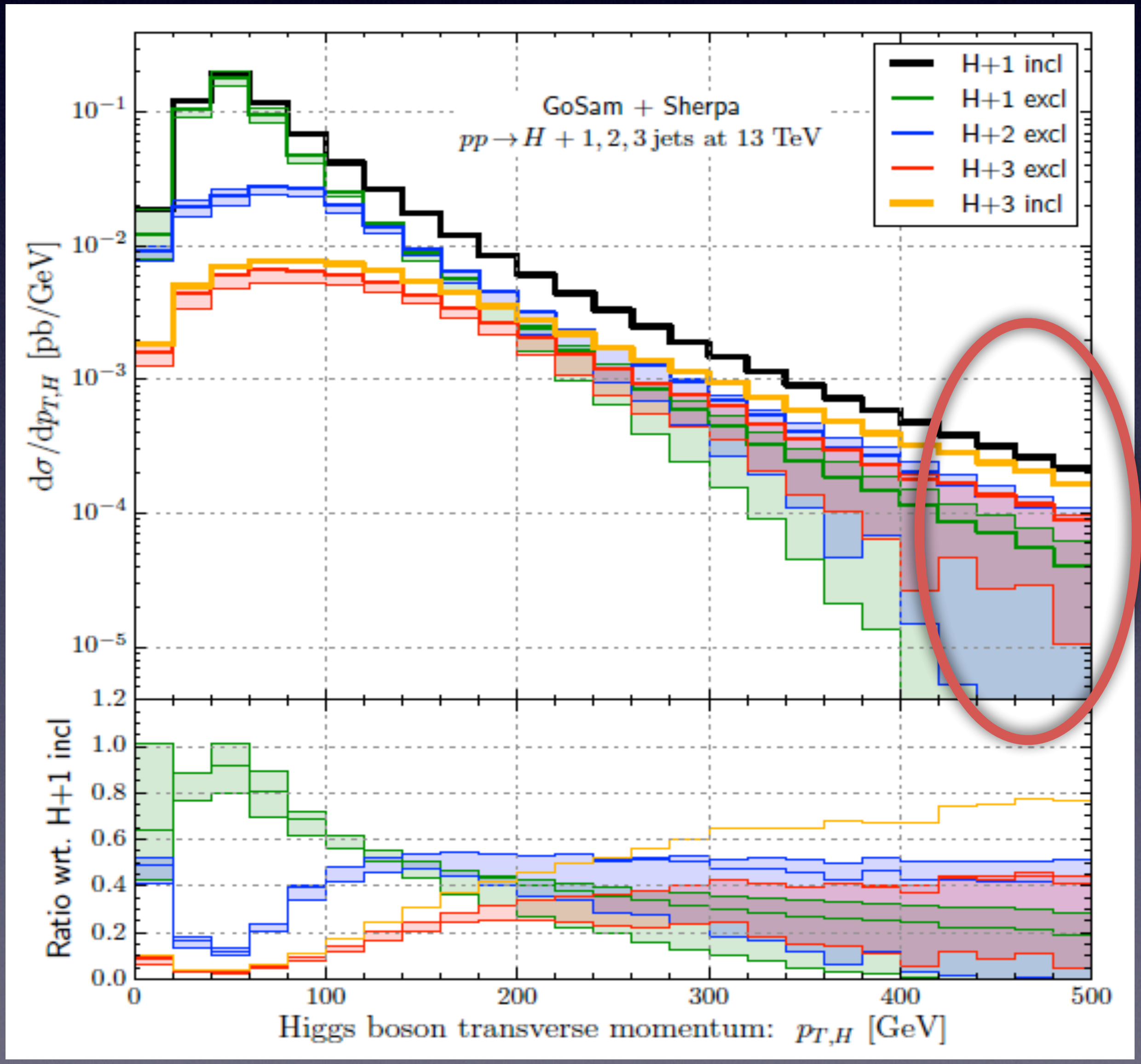
- improvement over HqT with NNLO corrections at high p_t
- resummation: sizable impact below 25 GeV

H + multi-jets at NLO

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

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

- high $p_{t,H}$ region dominated by multi (soft) jet production
- but calculations performed in large m_t limit. Approximation breaks down at high $p_{t,H}$ (EFT overestimates true answer)



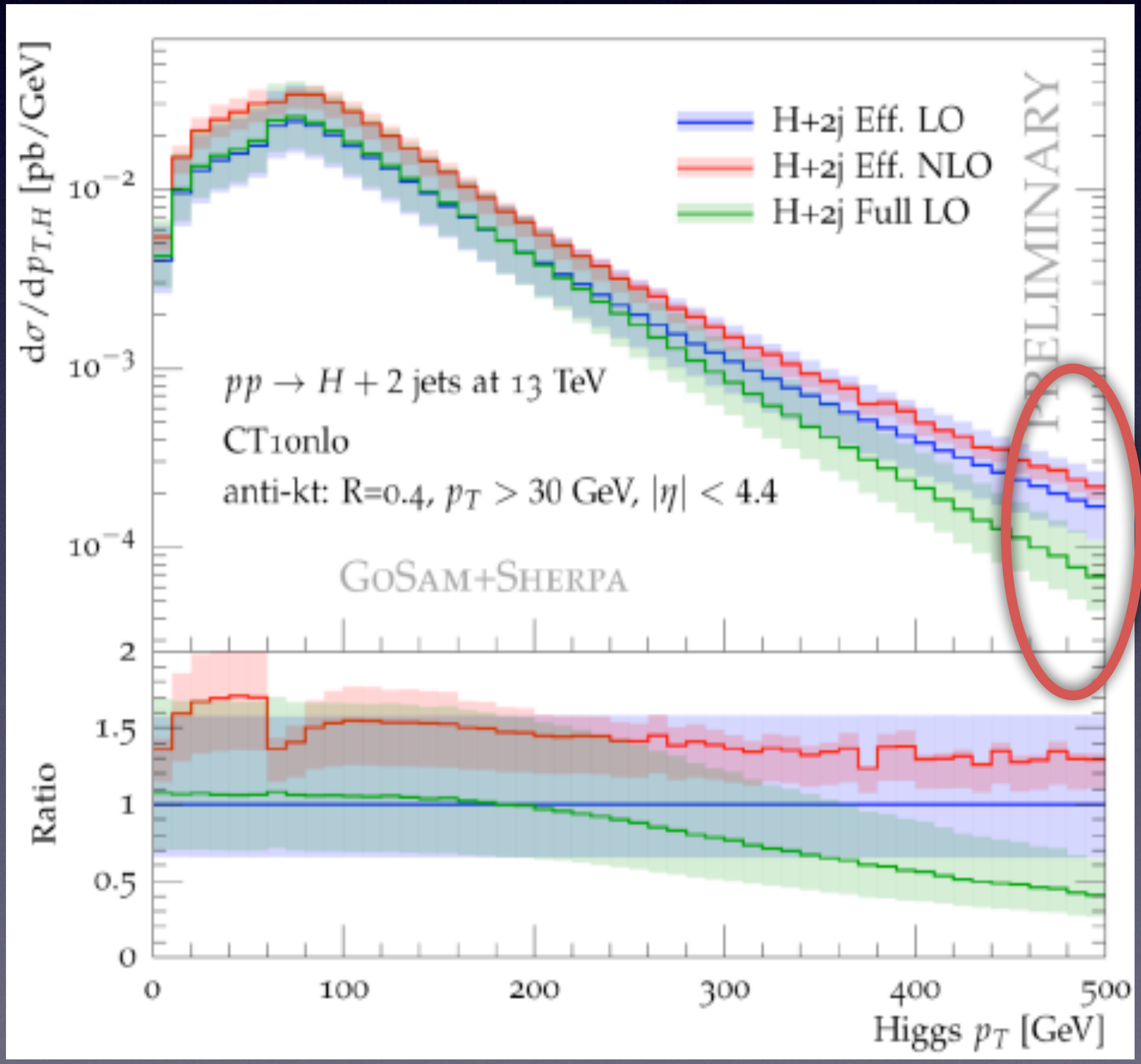
Greiner et al 1307.4737, 1506.01016

H + multi-jets at NLO

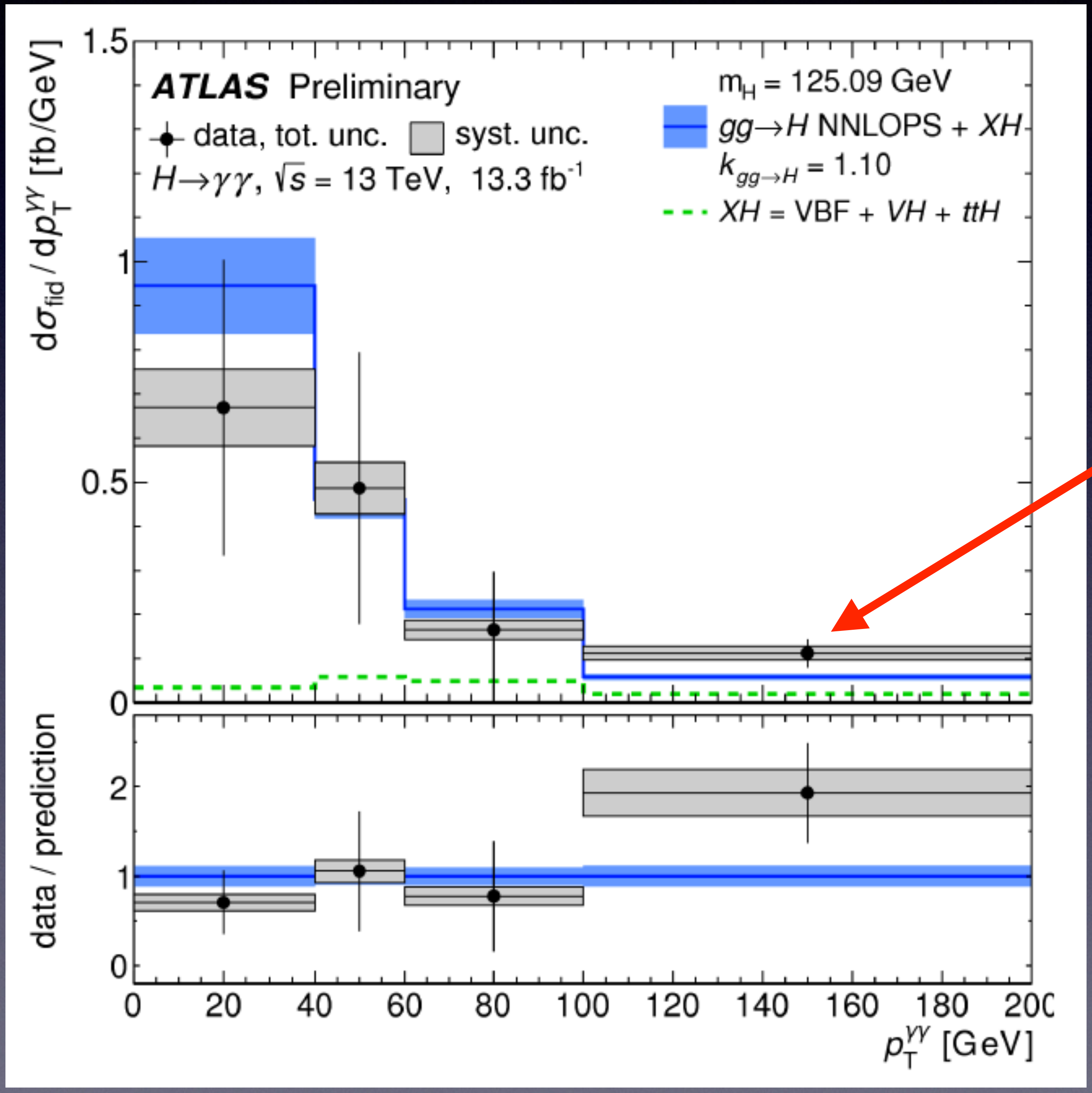
How much is the Higgs transverse momentum affected by additional QCD radiation?

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

- high $p_{t,H}$ region dominated by multi (soft) jet production
- but calculations performed in large m_t limit. Approximation breaks down at high $p_{t,H}$ (EFT overestimates true answer)



Measurement of Higgs pt



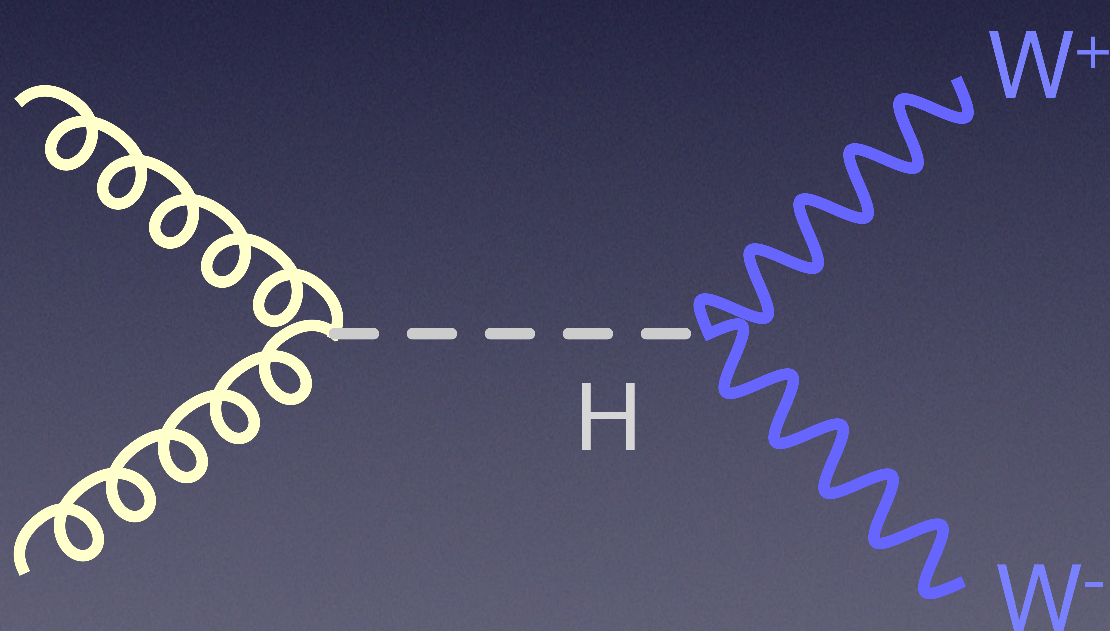
Harder spectrum (as in Run I), but compared to NNLOPS, misses NNLO correction at high transverse momentum

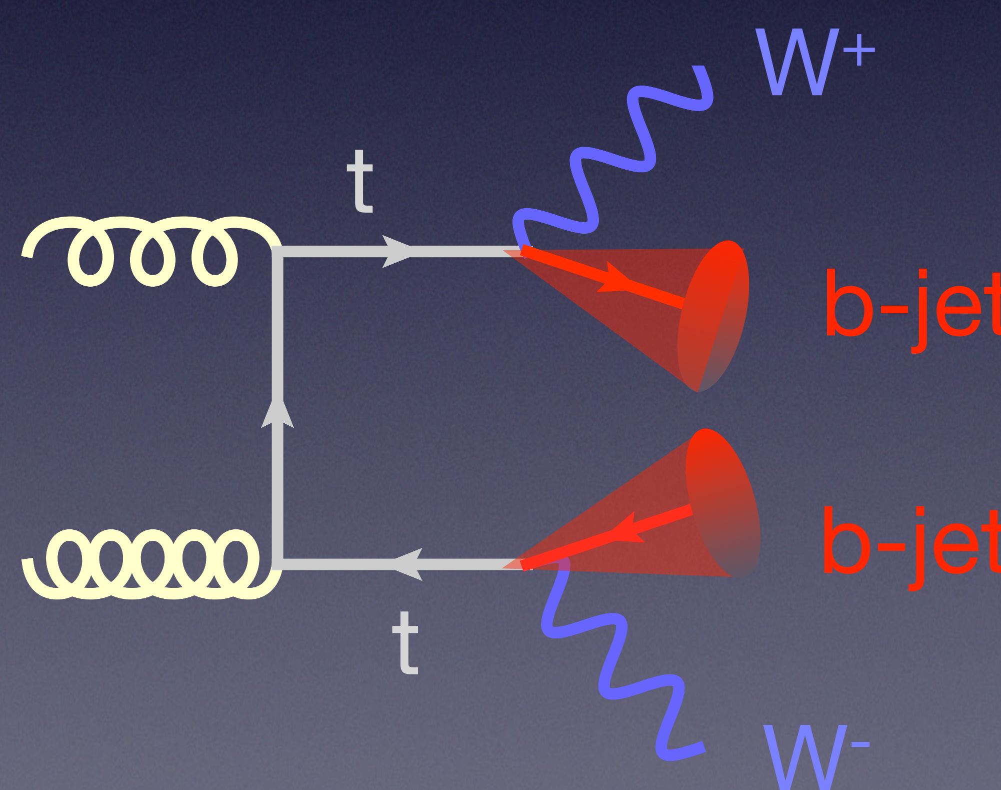
Room for improvement

The zero-jet cross-section

In H $\rightarrow$ WW and H $\rightarrow \tau\tau$, zero-jet cross section particularly important as it is nearly free of (difficult) top-antitop background

(aim is accurate extraction of HWW and H$\tau\tau$ couplings)

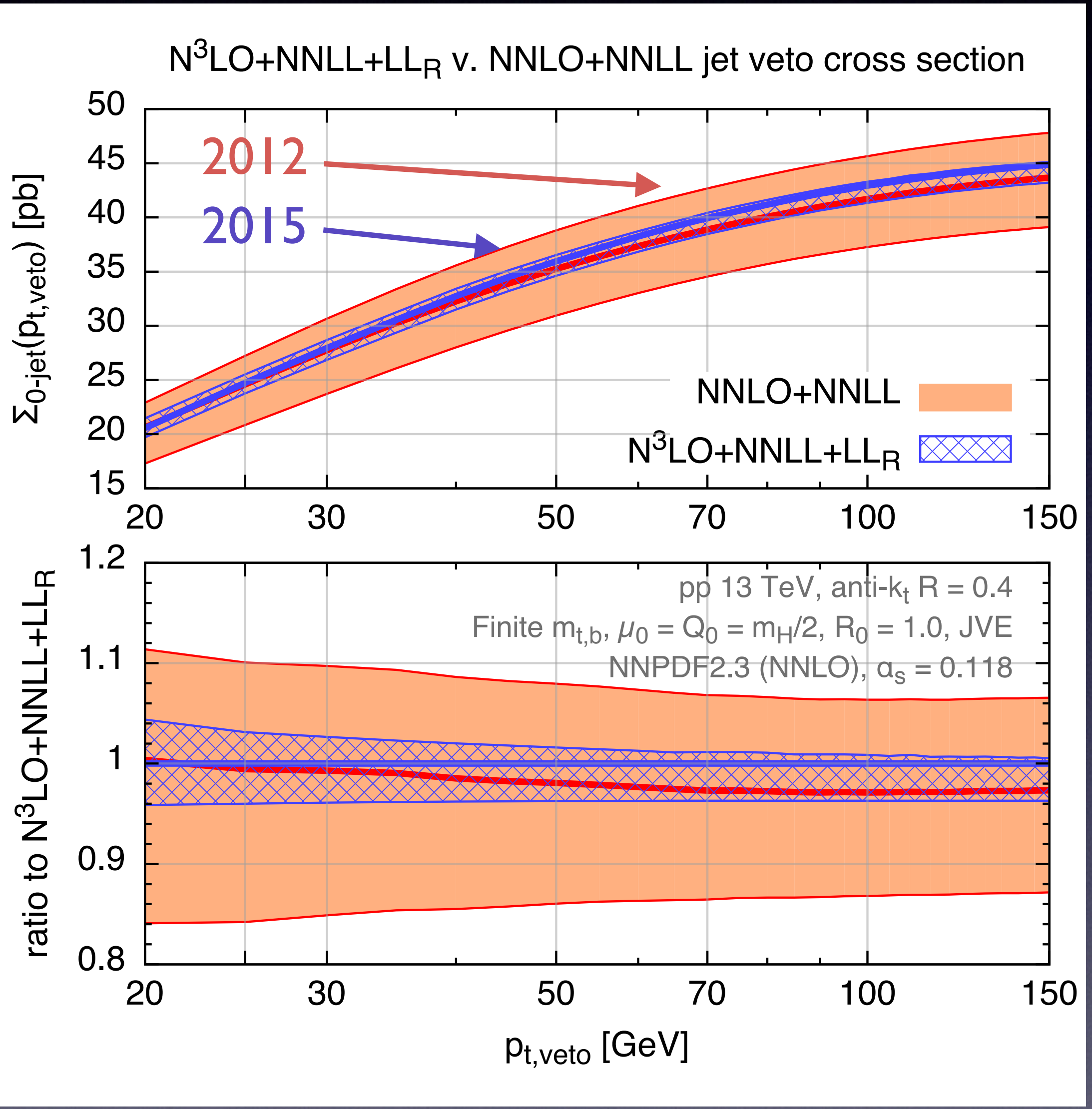




Improved jet-veto

Recently jet-veto predictions updated to include

- ✓ N^3LO corrections to inclusive cross-section
  Anastasiou et al 1503.06056
- ✓ 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



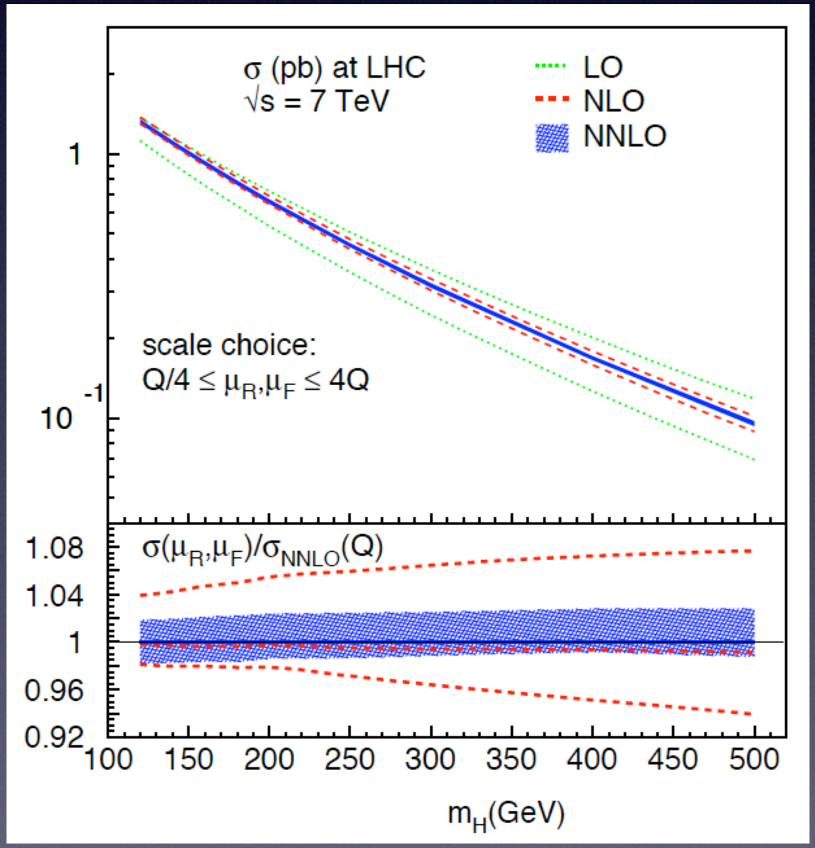
Few percent theory error (considerable reduction in the last years)

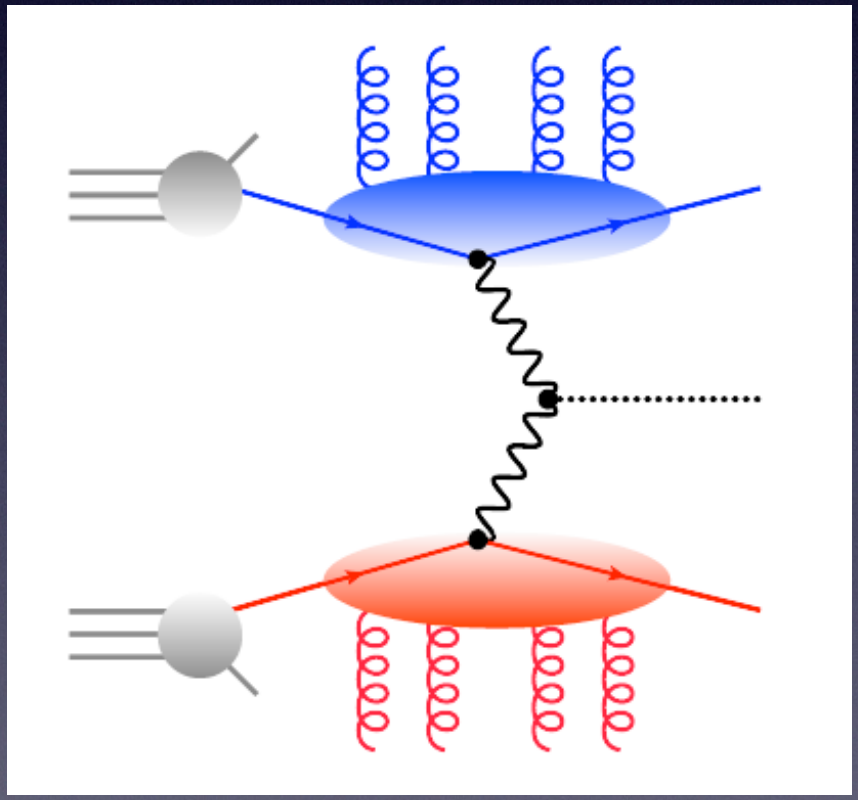
Banfi, Caola, Dreyer, Monni, Salam, GZ, Dulat 1511.02886

Inclusive VBFH at NNLO

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

Bolzoni, Maltoni, Moch, Zaro ’11

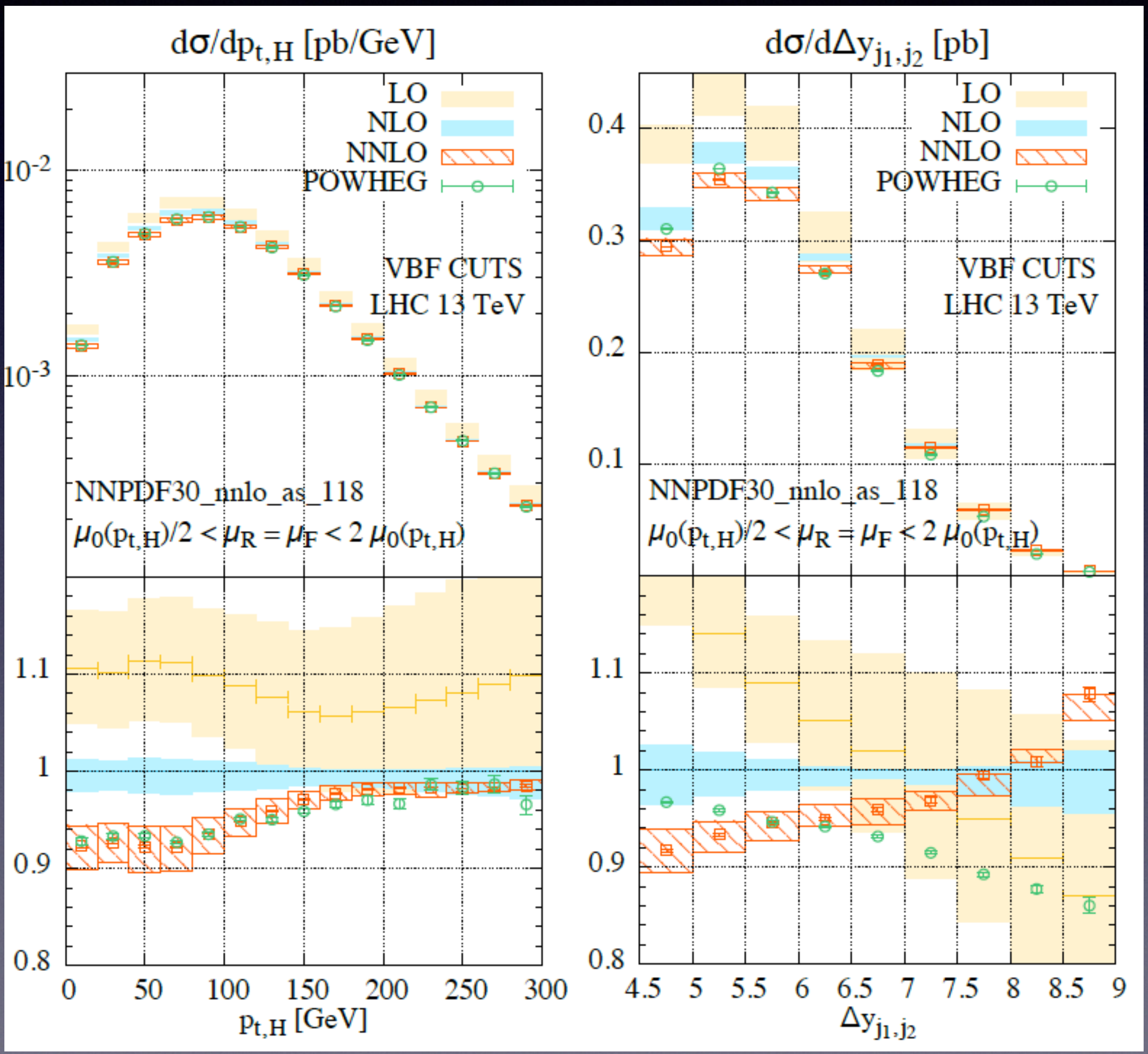




Inclusive calculation: tiny correction (~1%), tiny uncertainty (1-2%). Implies possibility to perform very accurate coupling measurements

Fully differential VBFH at NNLO

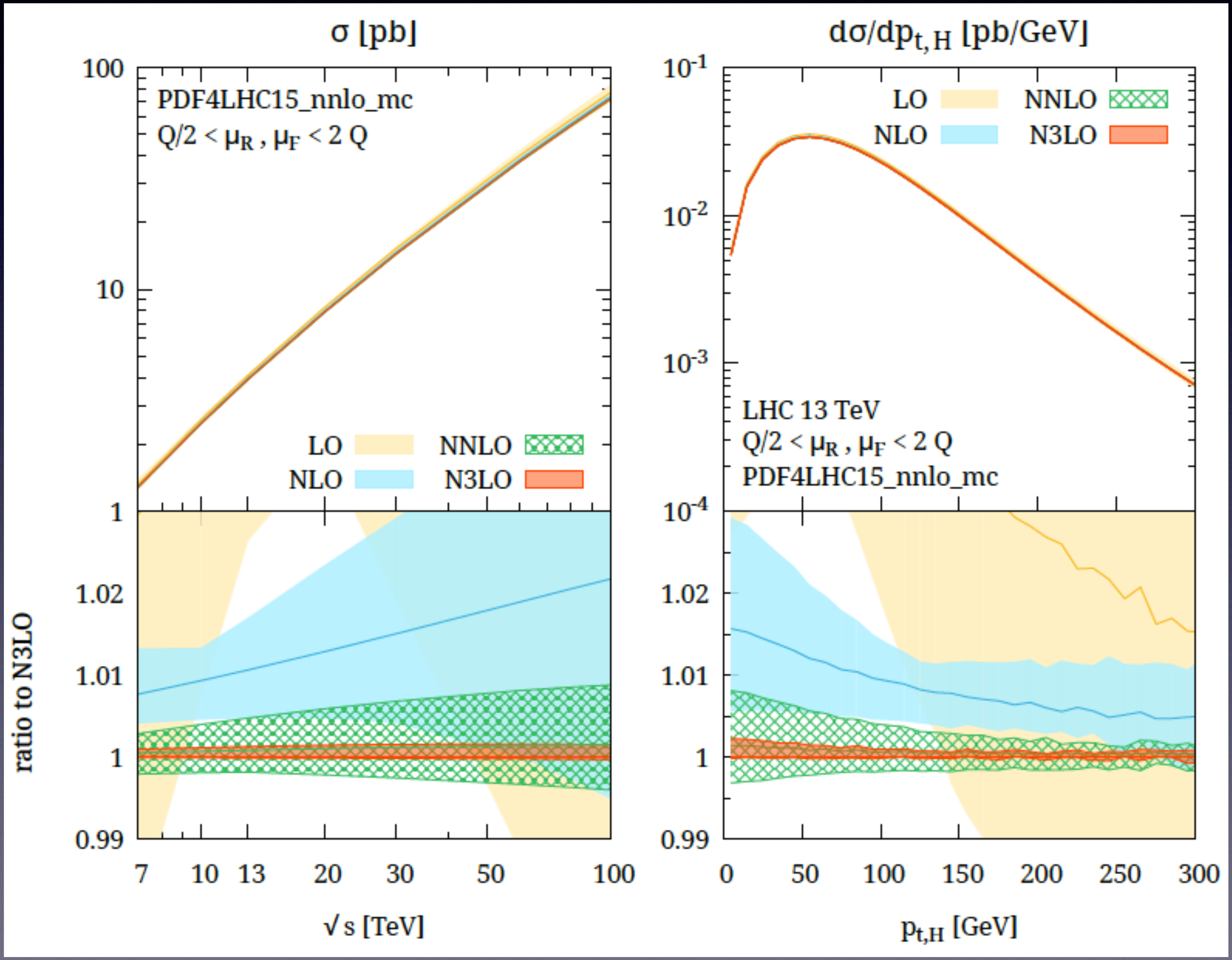
Cacciari, Dreyer, Karlberg, Salam, GZ 1506.02660



- Allows to study realistic observables, with realistic cuts
- NNLO corrections much larger (10%) than expected

… and inclusive VBFH at N³LO

Dreyer & Karlberg 1606.00840



Associated HV production

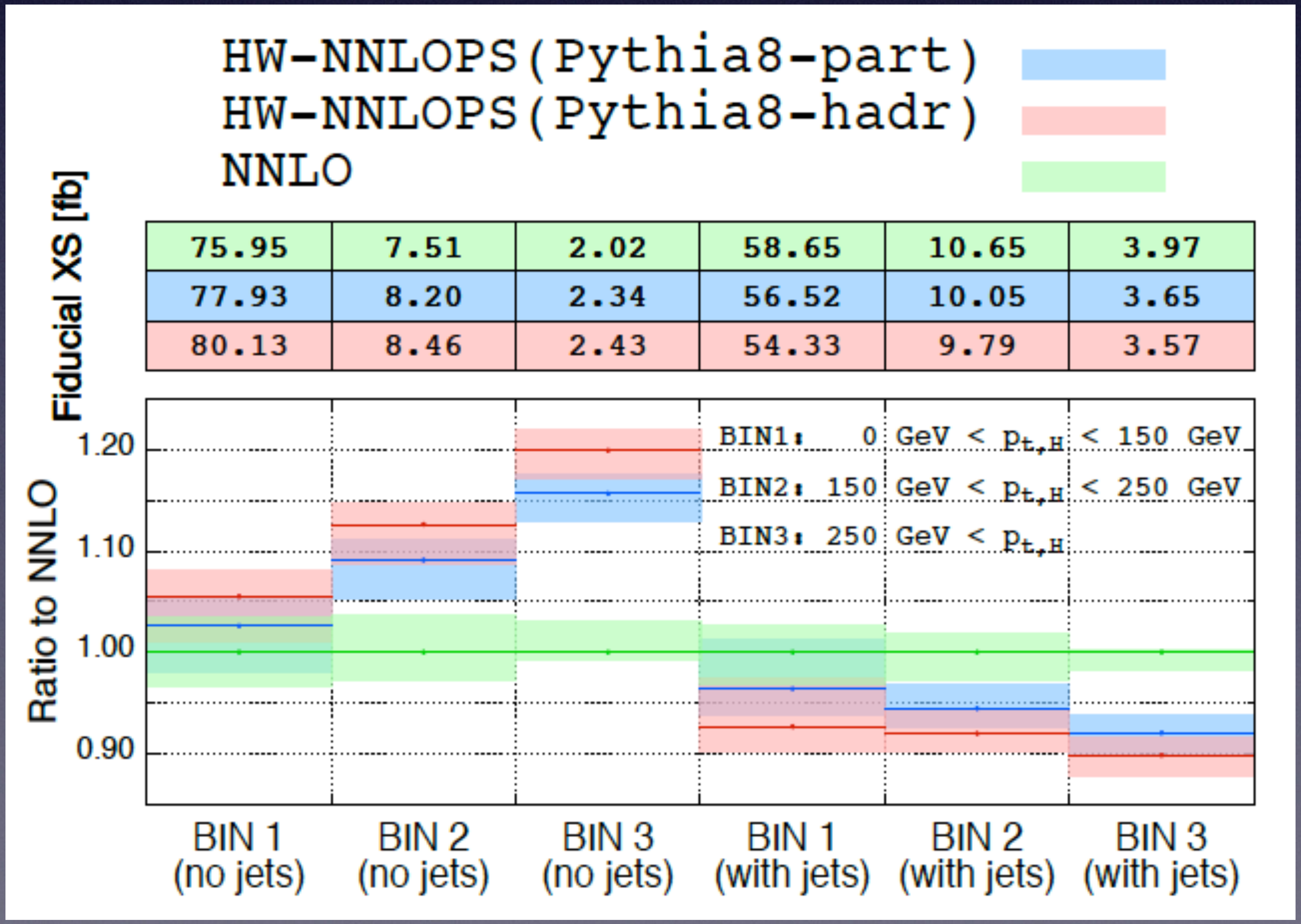
HV production known to NNLO since a few years. Gives small (1-2%) NNLO effects, even on most distributions

Ferrera, Grazzini, Tramontano ’11-’14

Recently NNLO calculation matched to parton shower for HW

Astill, Bizon, Re, GZ 1603.01620

- parton shower and hadronization cause migration between jet-bins
- difficult to reach high accuracy in jet-binned observables



(

The photon PDF

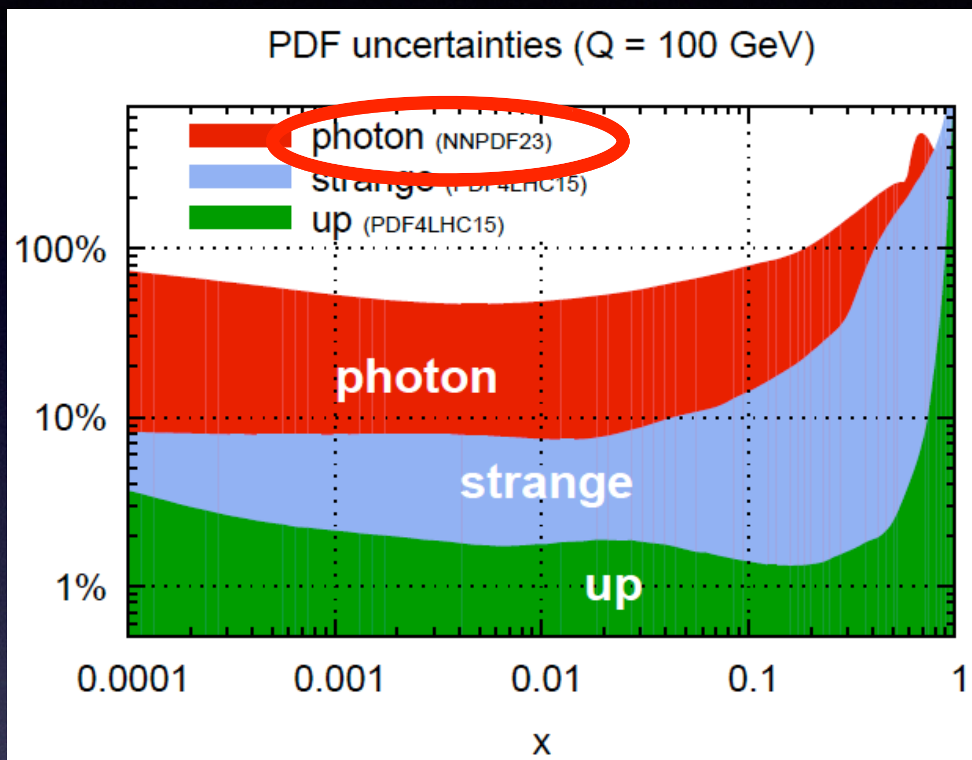
Interest in photon PDF spurred by 750 GeV di-photon resonance, but also important for precision physics in general (electro-weak corrections) and Higgs physics in particular, e.g.:

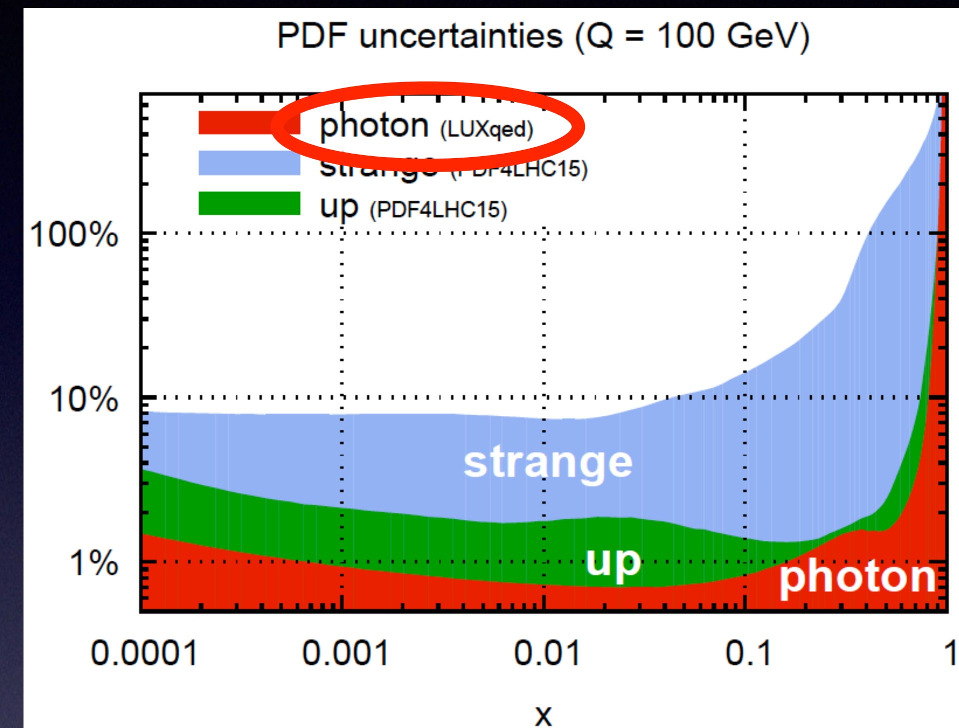
Cross section for associated HW($\to l\,\nu$) production at 13 TeV

Cross section without photon induced	91.2 ±1.8 fb
Photon induced with NNPDF2.3	$6.0^{+4.4}_{-2.9}$ fb

Dominant uncertainty from photons in the initial state

How well do we know partons?





1607.04266

A. Manohar, P. Nason, G. Salam, GZ

- valence quarks known to few percent
- others quarks to 10% over a large x-range
- The only data driven photon PDF determination has O(100%) uncertainty (other model dependent ones have much small uncertainties)

The LUX photon PDF determination

Take a hypothetical (BSM) flavour-changing heavy-neutral lepton production process, and calculate the cross section in two ways

- using proton structure functions (F_2 and F_L)
- using photon parton distribution function

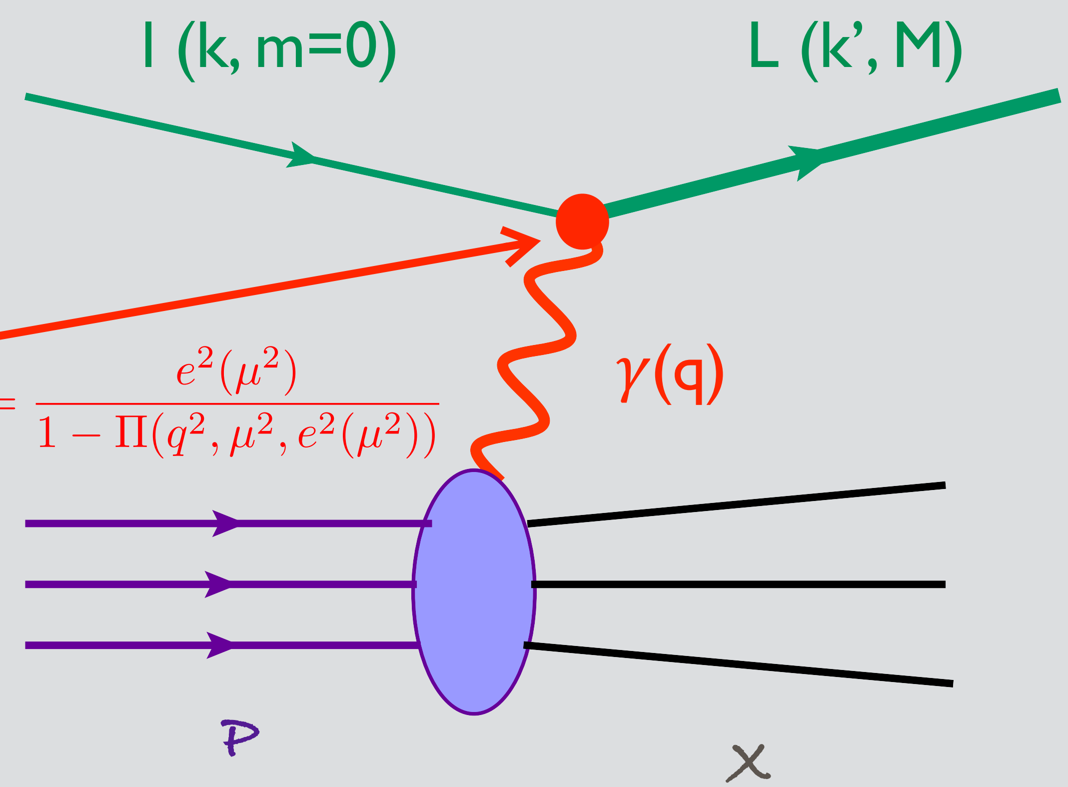
Imposing an equality between the two expression gives a model-independent, data driven determination on the photon PDF

Imaginary flavour changing process

TRANSITION MAGNETIC MOMENT

$$\mathcal{L}_{\rm int} = \frac{e}{\Lambda}\bar{L}\sigma^{\mu\nu}F_{\mu\nu}l$$

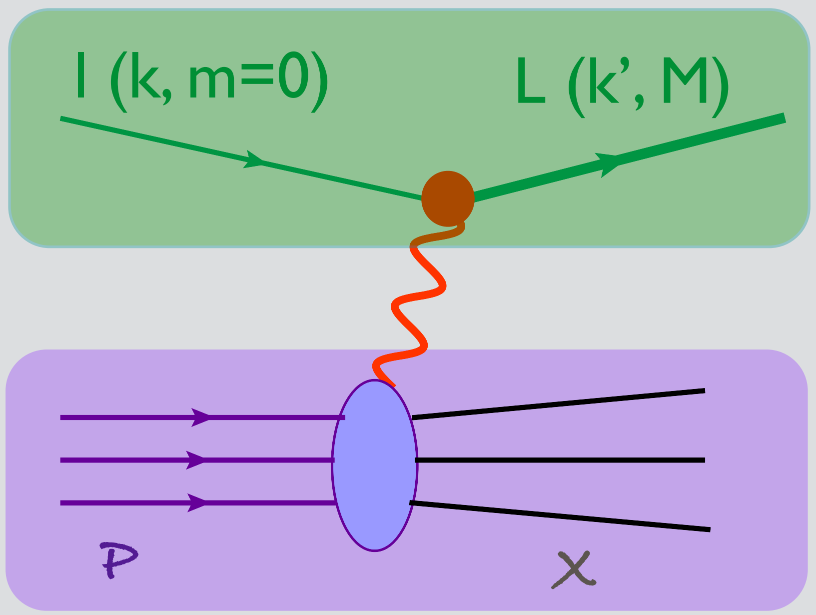
$$e^2_{\rm ph}(q^2) = \frac{e^2(\mu^2)}{1-\Pi(q^2,\mu^2,e^2(\mu^2))}$$



Λ NEEDED TO PRESERVE DIMENSIONS, TAKEN LARGER THAN ALL OTHER SCALES

Cross section in terms of form factors

$$L^{\mu\nu}(k,q) = \frac{1}{2}\frac{e^2_{\text{ph.}}(q^2)}{\Lambda^2}\,\mathrm{Tr}\left(\not{k}'[\not{q},\gamma^\mu](\not{k}'+M)[\gamma^\nu,\not{q}]\right)$$



$$W_{\mu\nu}(p,q) = -g_{\mu\nu}F_1(x_B,Q^2) + \frac{p_\mu p_\nu}{pq}F_2(x_B,Q^2) + \text{long. terms}$$

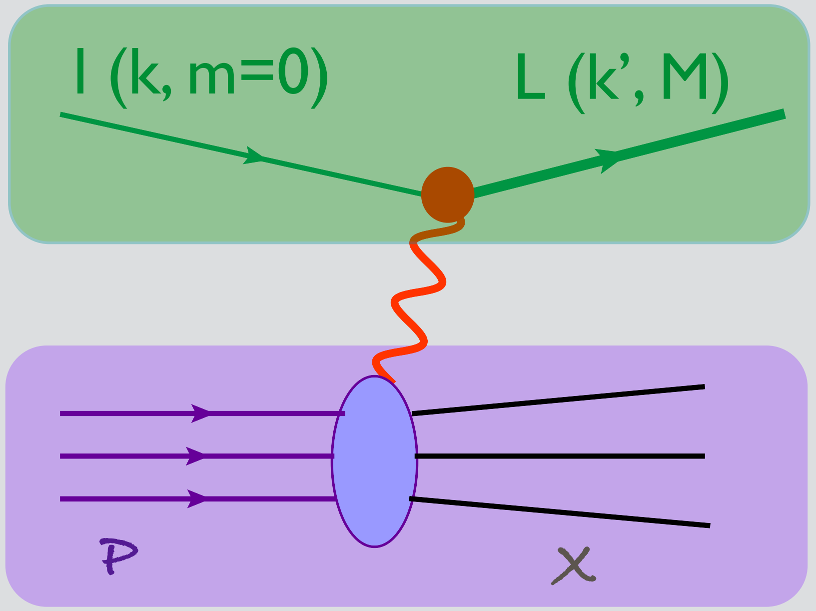
$$\sigma = \frac{1}{2s}\int d\Phi_q e^2_{\text{ph}}(q^2)\,W_{\mu\nu}(p,q)\,\frac{1}{q^4}\,L^{\mu\nu}(k,q)\,\delta((k-q)^2 - M^2)$$

NB:

1. the expression is exact in QCD
2. since the leptons are neutral, this result is accurate up to terms $O(s/\Lambda^2)$

Cross section in terms of PDF

$$\sigma = \frac{16\pi^2}{\Lambda^2} \sum_a \int_x^1 \frac{dz}{z} \hat{\sigma}_a(z,\mu^2) \frac{M^2}{zs} f_{a/p}\left(\frac{M^2}{zs}, \mu^2\right)$$



- compute partonic cross section in the MSbar scheme
- drop subleading terms

Finally

- equate the two expressions
- derive the photon PDF in terms of an integral over proton structure functions

NB: it is a purely model-independent data-driven determination, relies on high precision DIS data

The LUX Photon PDF

Main result of this work is the following expression of the photon PDF in terms of proton form factors and structure functions (measured accurately in DIS):

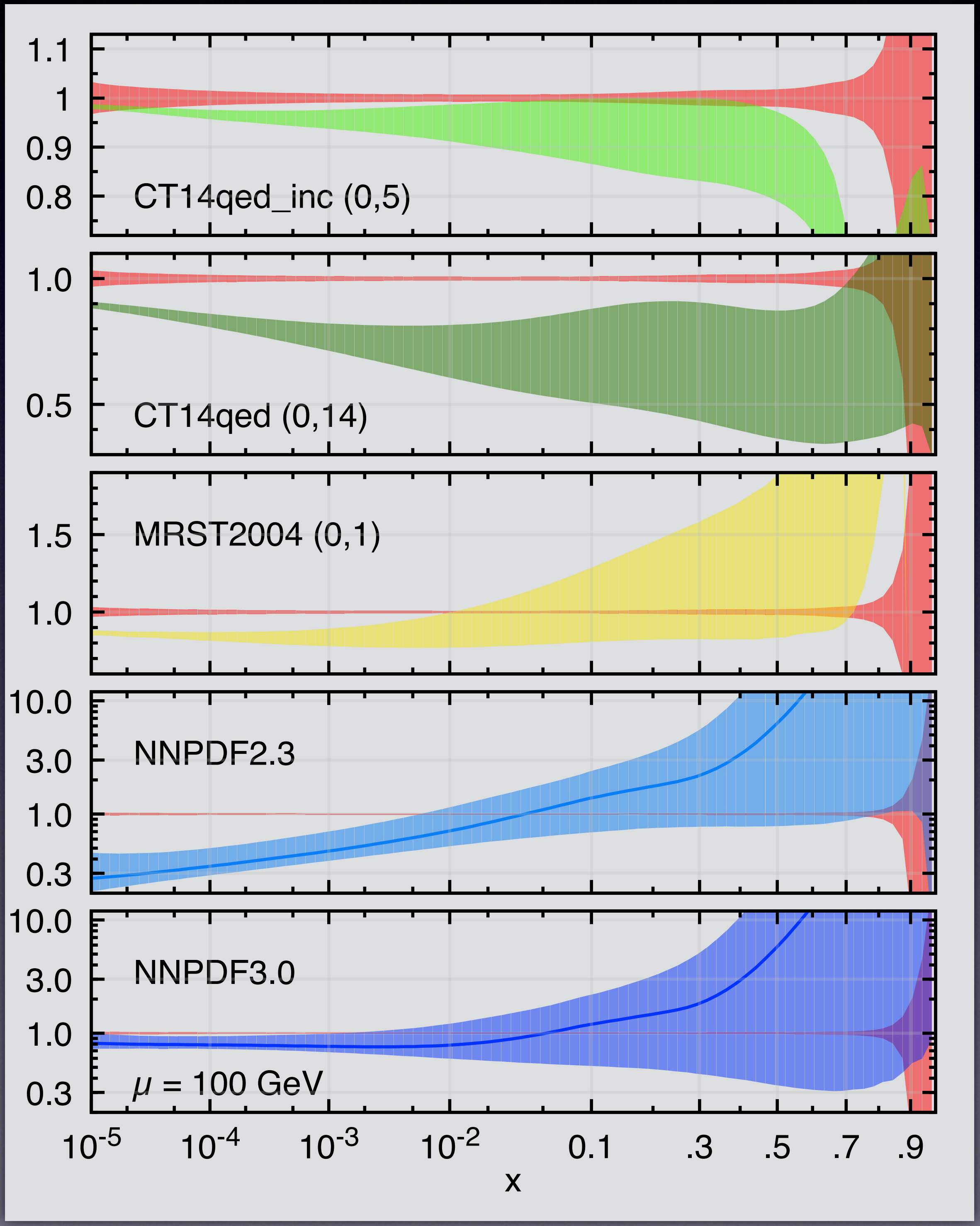
$$
\begin{aligned}
x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \Bigg\{ \int_{Q^2_{\mathrm{min}}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2) \\
\left[\left(2 - 2z + z^2 + \frac{2x^2 m_p^2}{Q^2}\right) F_2(x/z, Q^2) \right. \\
\left. - z^2 F_L\left(\frac{x}{z}, Q^2\right)\right] - \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z},\mu^2\right) \Bigg\}
\end{aligned}
$$

Comparison to other PDFs

Ratios of other PDFs to LUXqed PDF

Best agreement with

- CT14qed_inc (includes elastic component, but neglects magnetic component for neutron). But still no overlap of the bands in large regions
- NNPDF3.0 (extends NNPDF2.3 with treatment of $\alpha(\alpha_s L)^n$ terms in the evolution, but still about 20% differences at small x



Impact on associated production

Cross section for associated HW($\to l\nu$) production at 13 TeV

Cross section without photon induced	91.2 ±1.8 fb
Photon induced with NNPDF2.3	$6.0\ ^{+4.4}_{-2.9}$ fb
Photon induced with LUXqed	4.4 ± 0.1 fb

The photon induced contribution was the dominant source of error in HW, now associated error negligible

Included now in LHAPDF: (LUXqed_plus_PDF4LHC15_nnlo_100)
Play around with it!

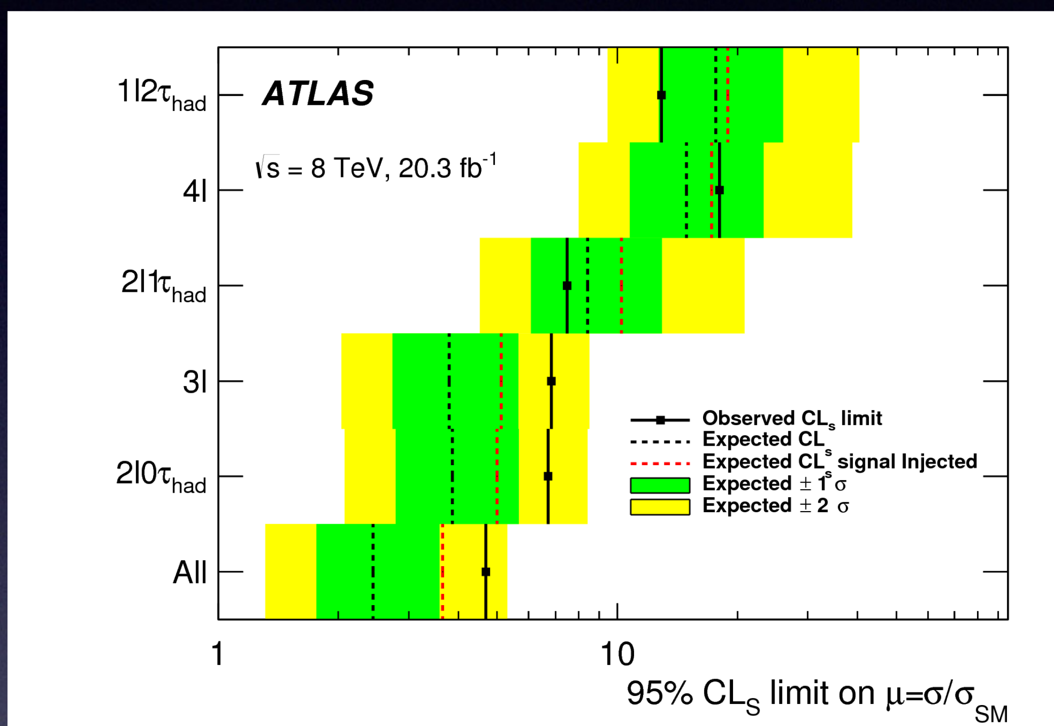
If you think about it, it's awesome: we are made of protons, and protons are, in some part, made of light... And now we know how much of it

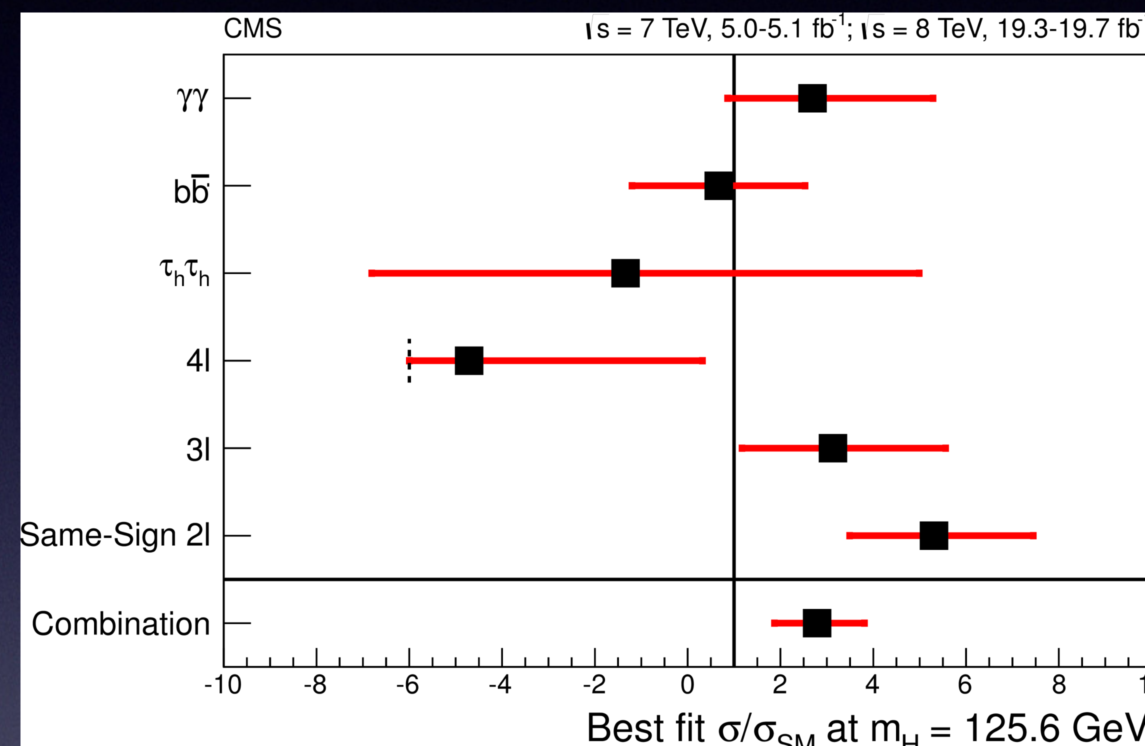
http://www.science20.com/a_quantum_diaries_survivor/how_much_light_does_a_proton_contain-176396

)

ttH production

ATLAS 1506.05988, 1604.03812
CMS 1408.1602, 1502.02485

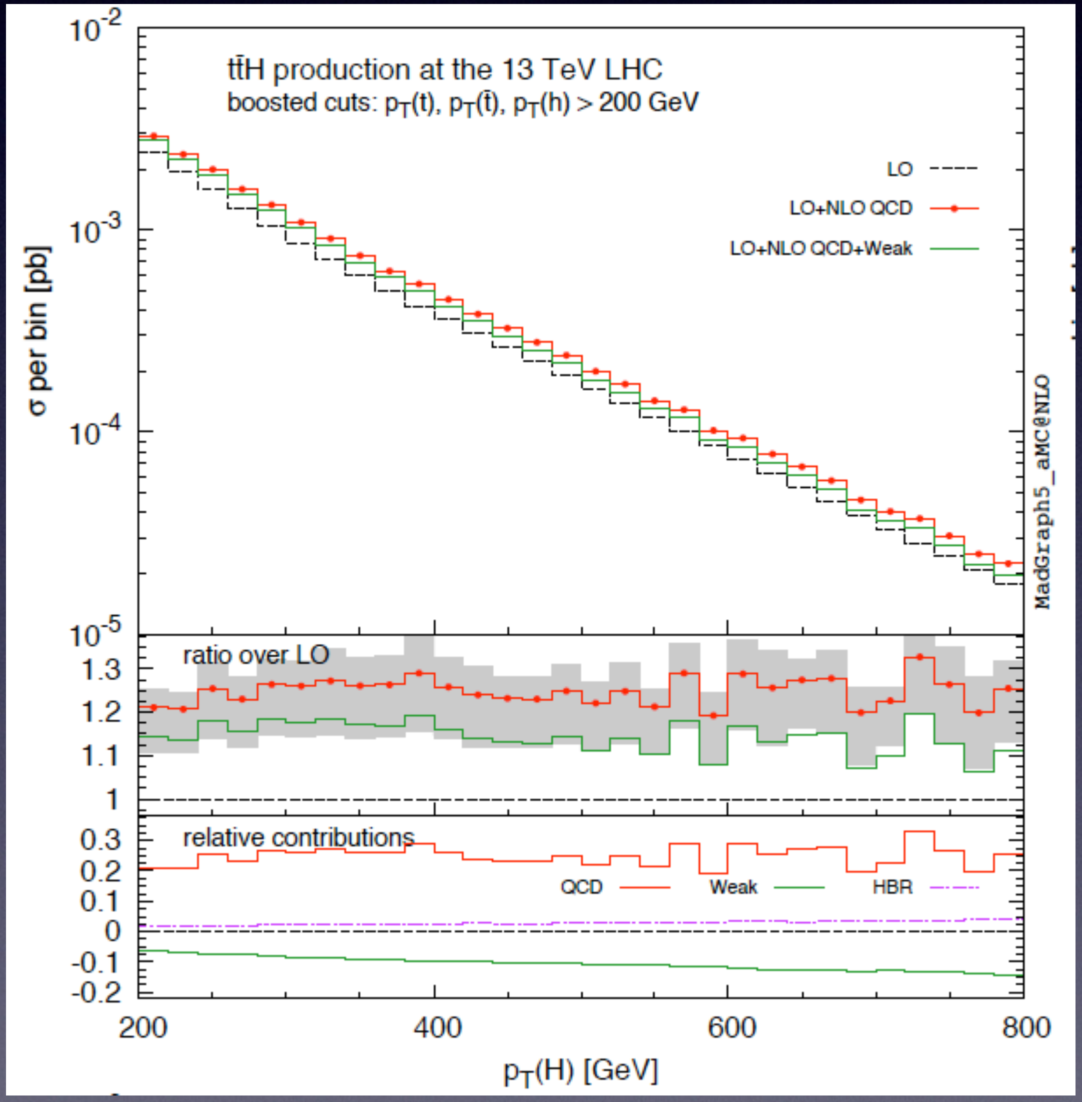


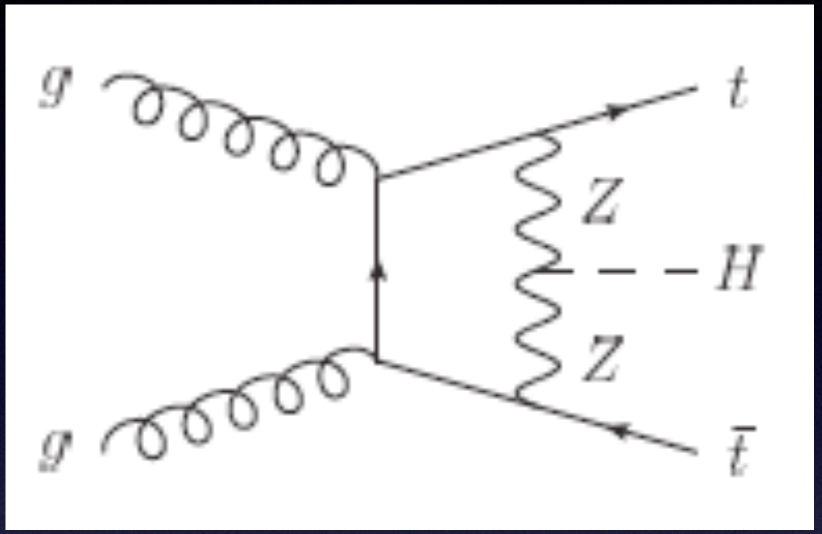


- direct probe of Yukawa coupling
- largest gain at 13 TeV (cross section increases by a factor 4 wrt 8 TeV)
- signal strength: $1.7^{+0.7}_{-0.8}$ [ATLAS] and $2.0^{+0.8}_{-0.7}$ [CMS]

EW corrections to ttH

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





Bottom line: EW corrections small for total cross-section (~1-2%), but become more important (~10%) in boosted kinematics

Frixione, Hirschi, Pagani, Shao, Zaro ’15

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

Mangano, Plehn, Reimitz, Schell, Shao ’15

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

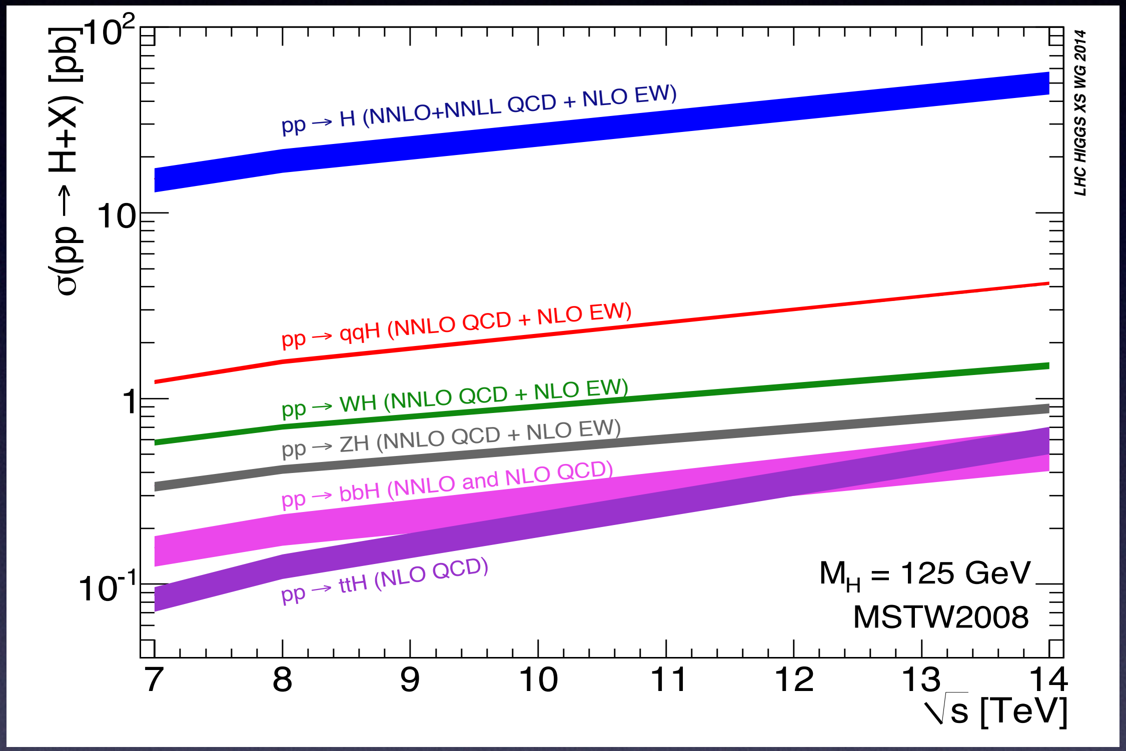
➡ VBF becomes dominant production mode

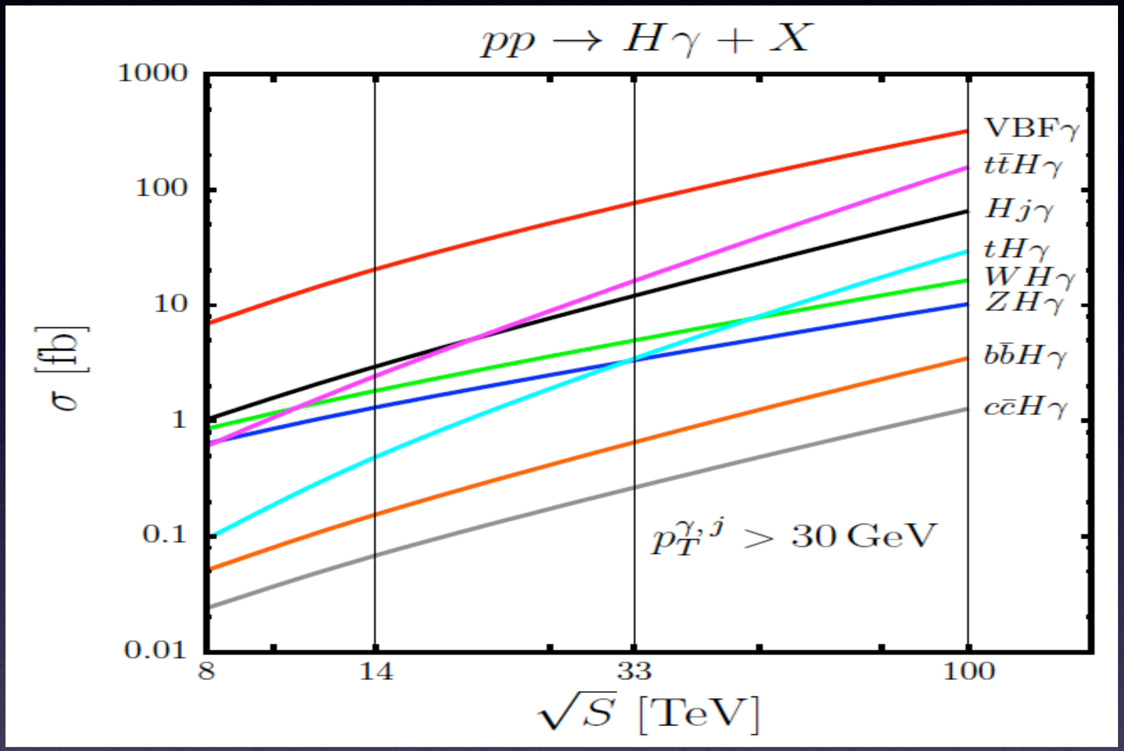
➡ at 100 TeV ttH dominates over gluon fusion

➡ at 100 TeV tH is of the same order of magnitude as gluon fusion (compare to O(1/1000) at 14 TeV without photon)

H+ photon production

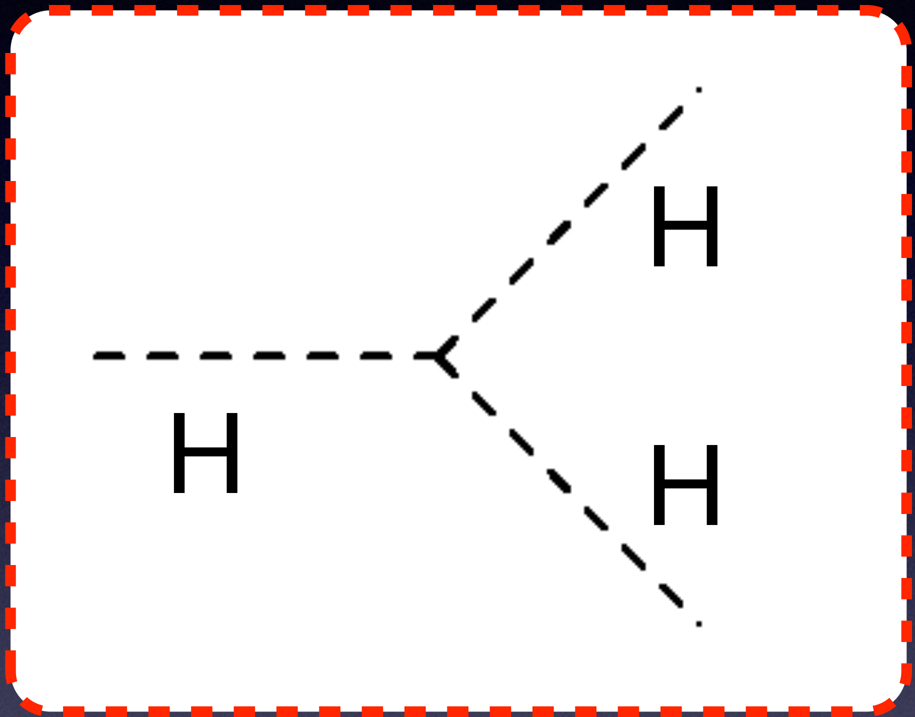
Gabrielli et al. 1601.03656





- ➡ 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

The Higgs self-coupling



Self-couplings fixed by the Higgs potential:

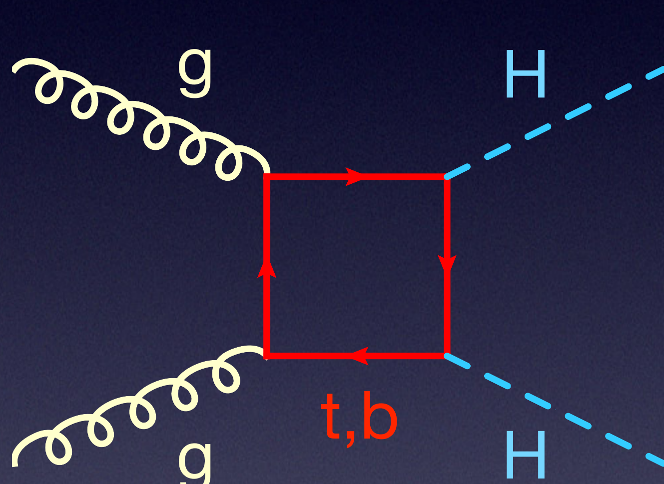
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$

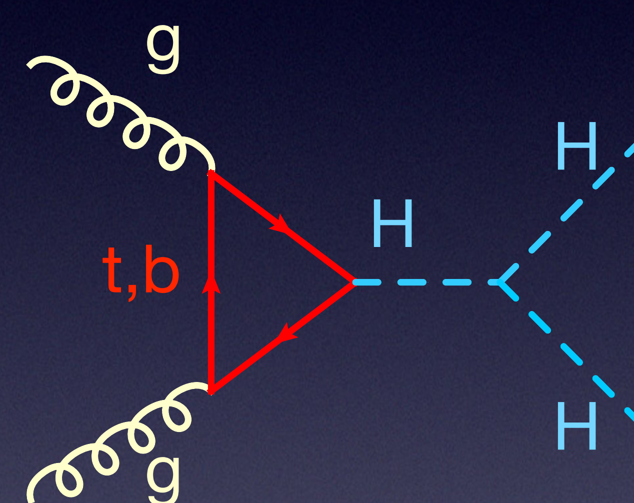
In the SM: $\lambda_3 = \lambda_4 = \dfrac{m_H^2}{2v^2}$

- 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 but sensitivity limited due to box terms

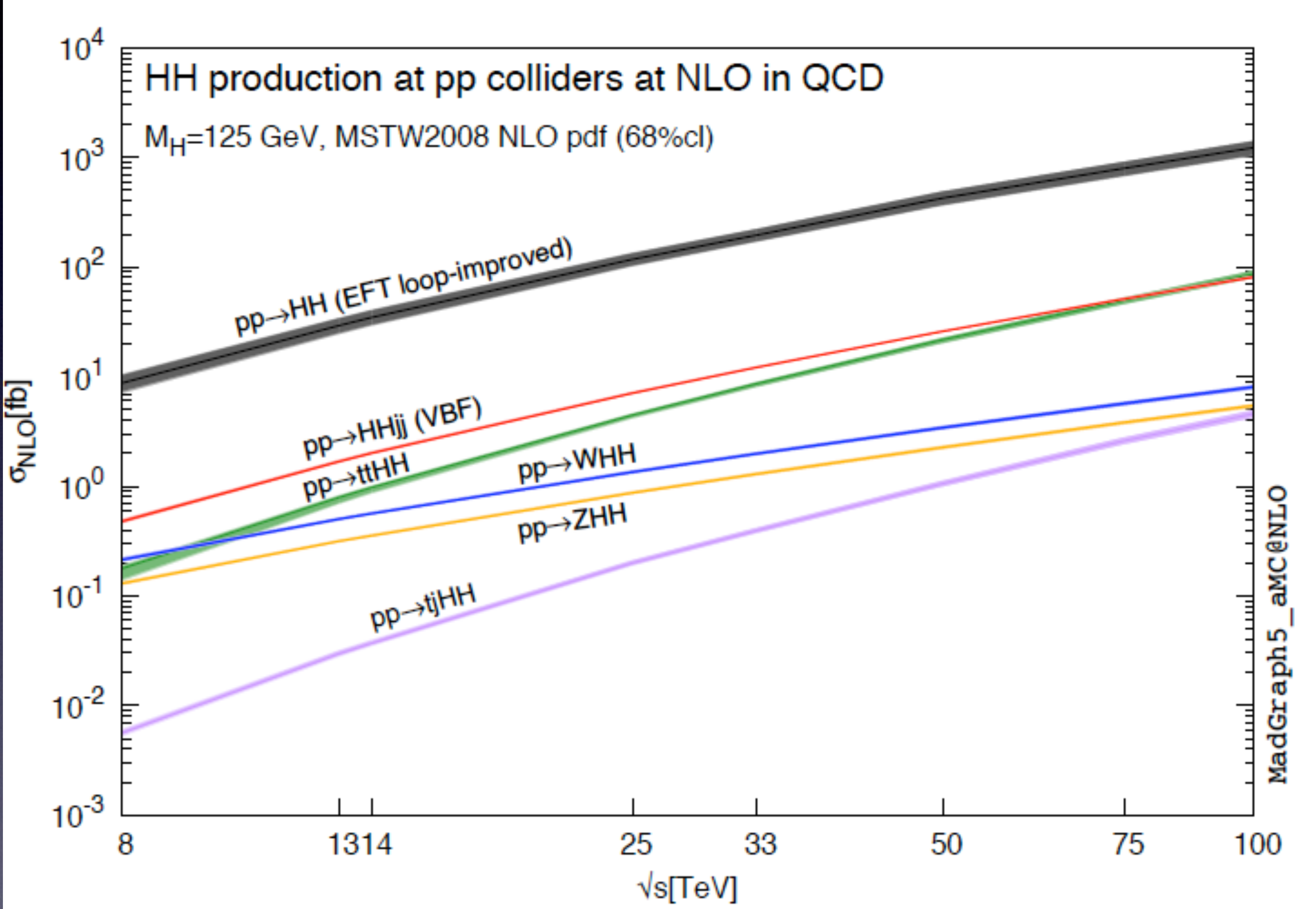




Cross-section at 13 TeV: ~ 40 fb)
(compare to ~ 40 pb for single Higgs production)

Additionally 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

ATLAS-CONF-2016-004, ATLAS-CONF-2016-049, ATLAS-CONF-2016-071
CMS-HIG-16-024, CMS-HIG-16-026, CMS-HIG-16-028

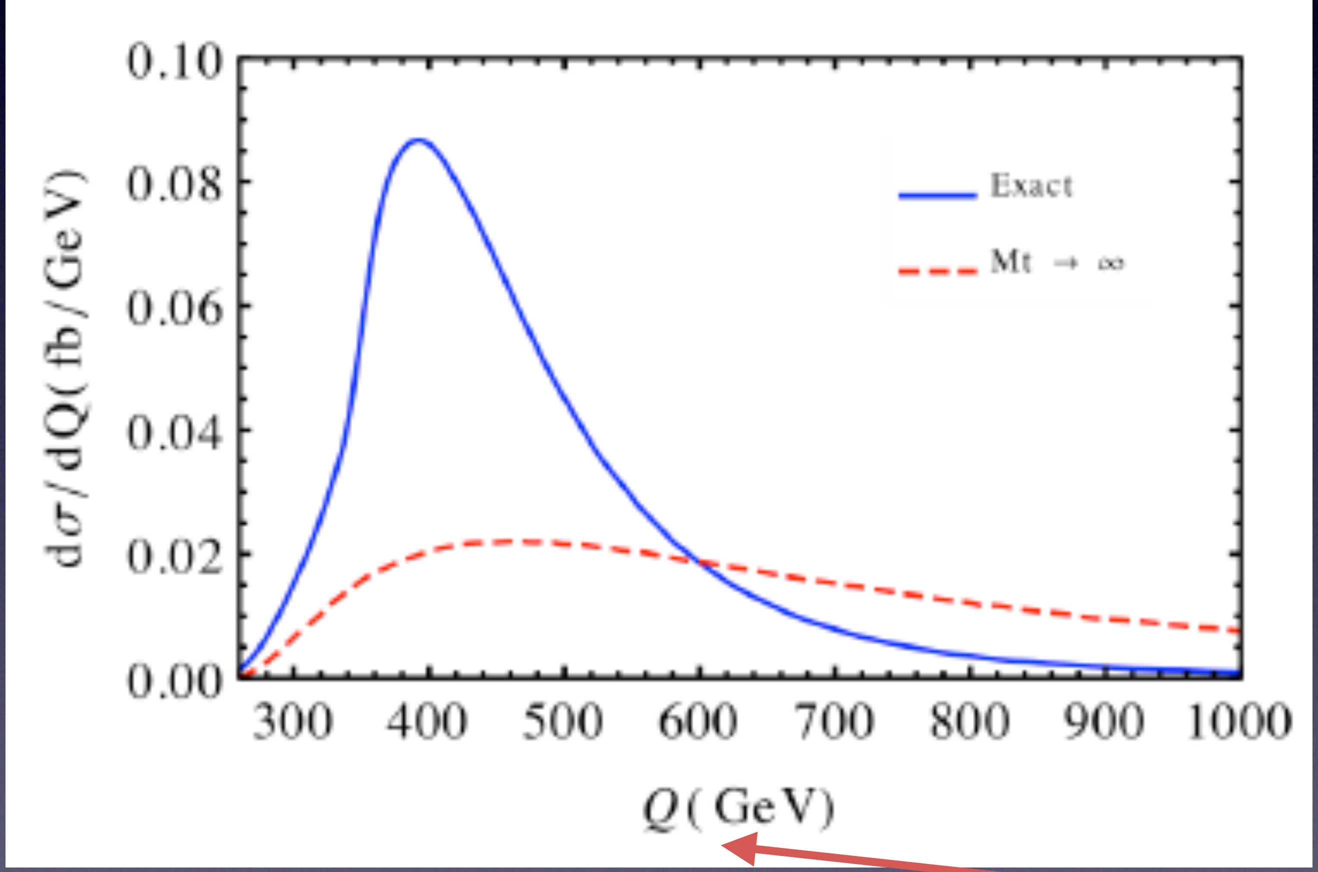
	Upper bound	Limit times SM
ATLAS 4b	1 pb	29
ATLAS 2W2γ	25 pb	1000
ATLAS 2b2γ	3.9 pb	100
CMS 2b2τ	508 fb	200
CMS 2b2W	167 fb	400
CMS 4b	3880 fb	342

Current Run 2 bound of 30 × SM (bound was 70 in Run 1) imply that trilinear Higgs coupling can deviate from SM value by a factor of about 11

State-of-the-art predictions for HH

As for single Higgs production use large m_t effective theory (EFT):

Does it work at leading order?



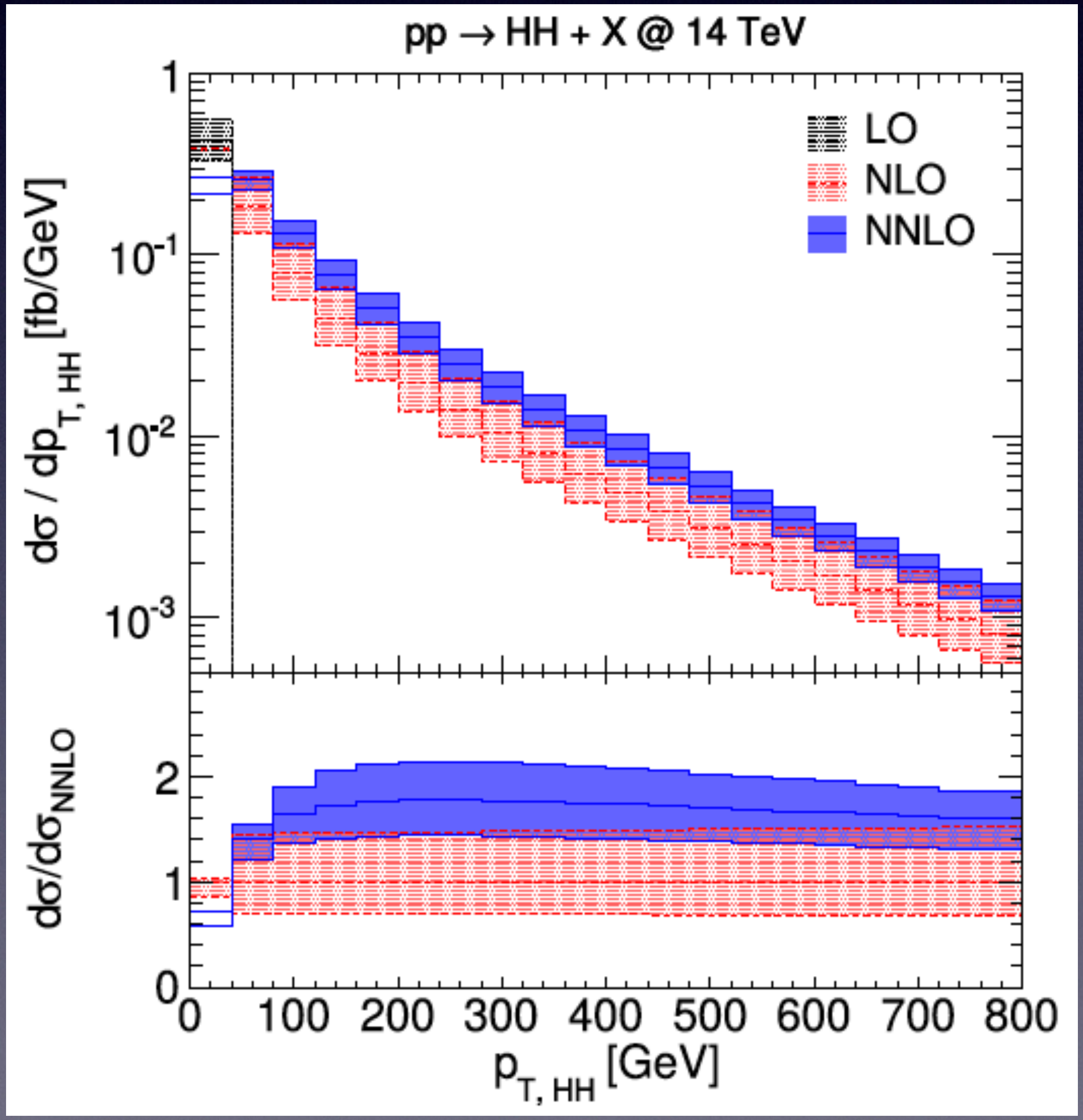
invariant mass of HH

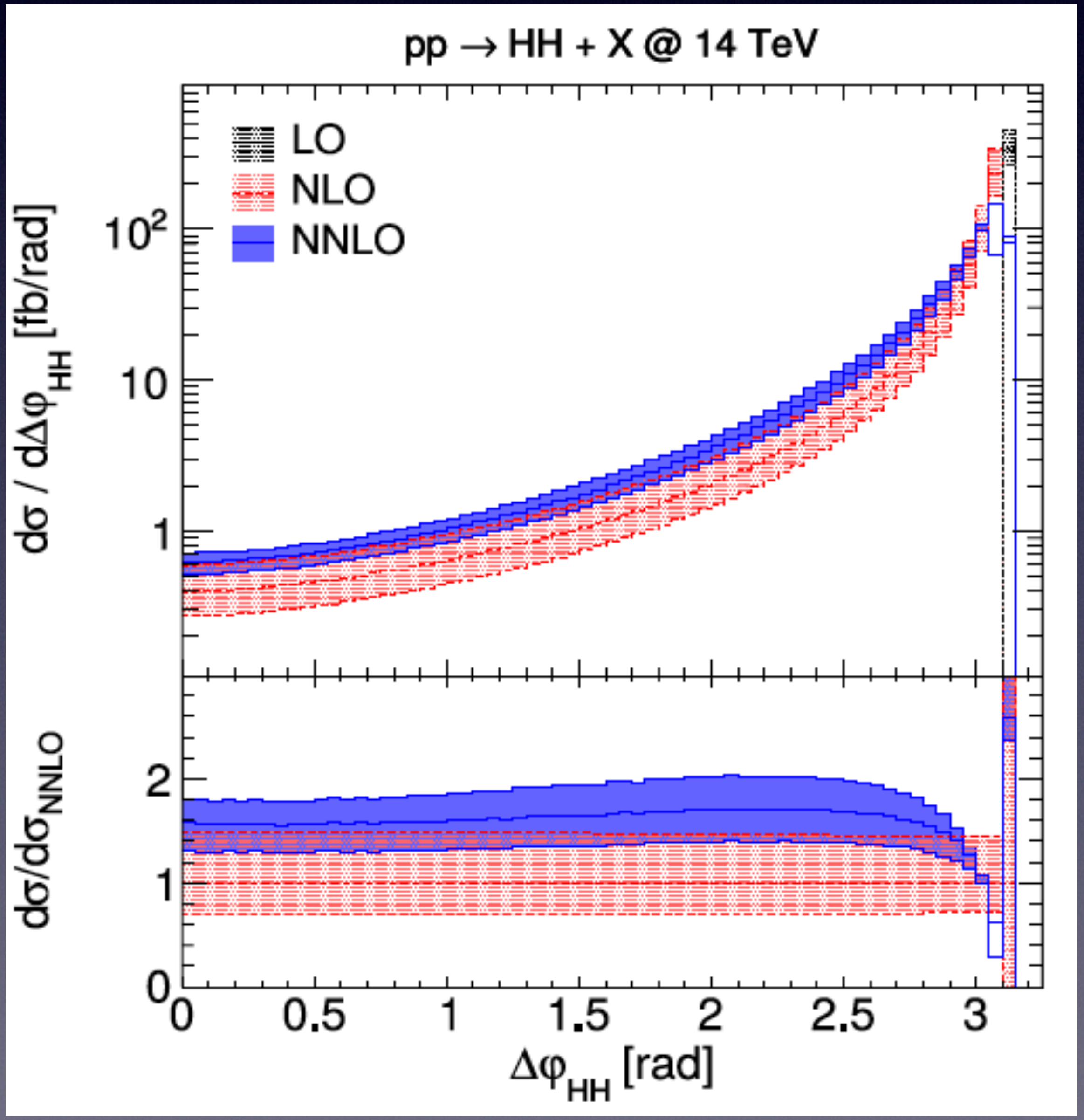
- EFT approximation works less well than for single Higgs (no surprise)
- still EFT widely used (after rescaling by the correct Born)

State-of-the-art predictions for HH

Recently fully differential NNLO calculation of HH in pure EFT

De Florian et al. 1606.09519

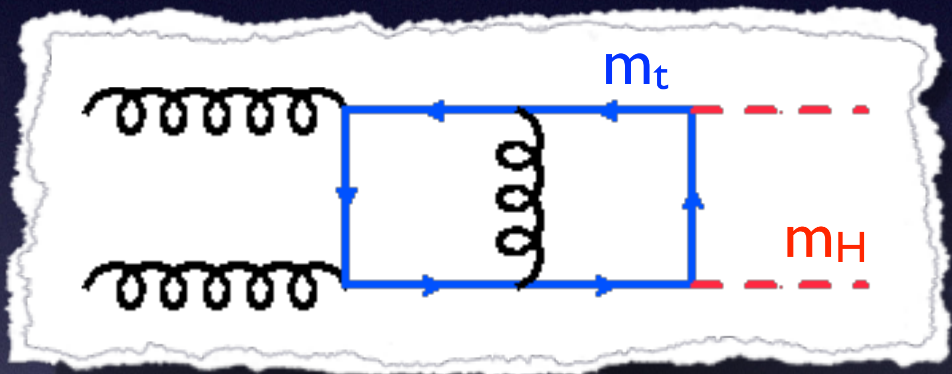




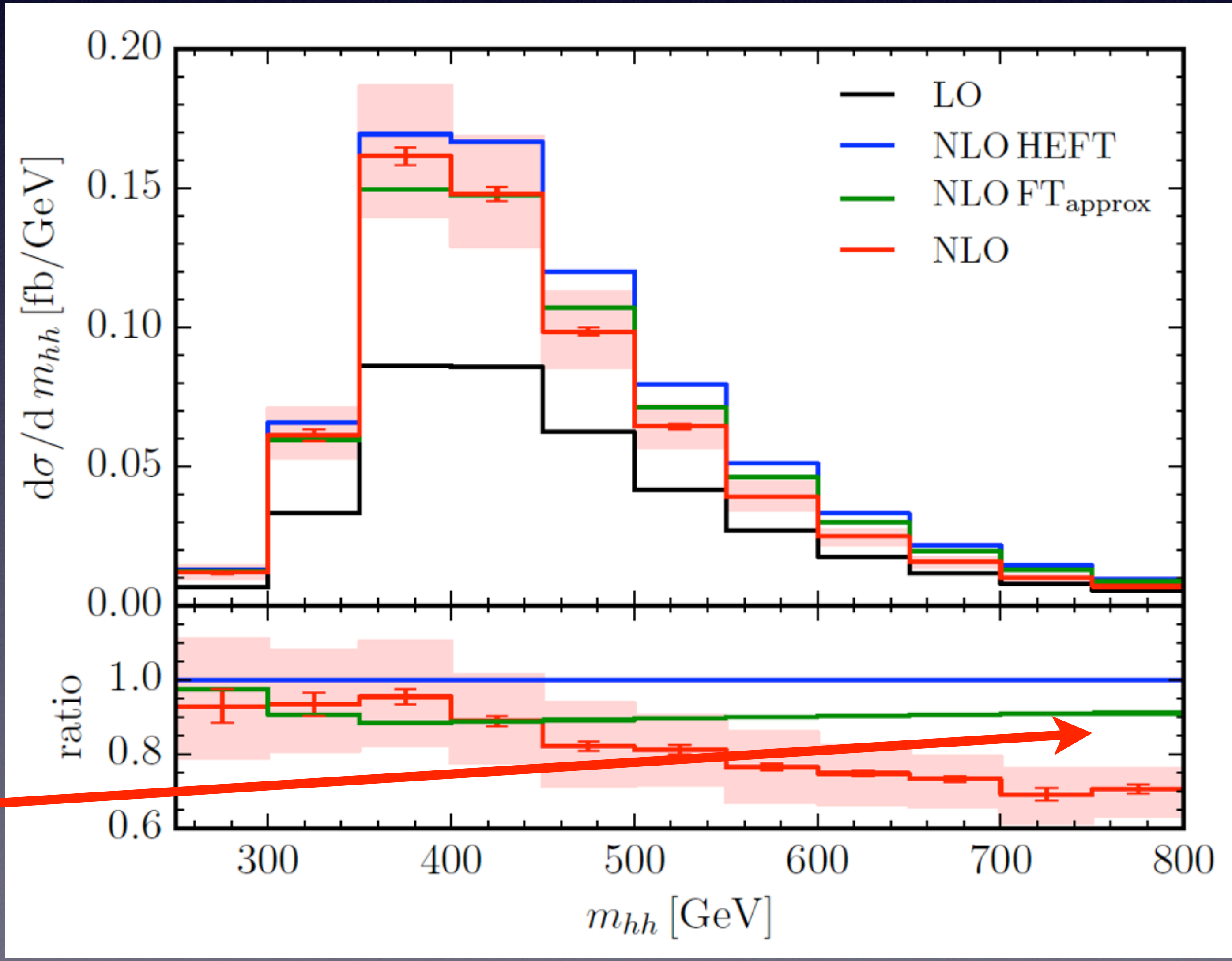
State-of-the-art predictions for HH

Exact NLO calculation of mass-effects performed recently

Borowka et al. 1604.06447



not known analytically, but computed numerically



Large effects at high m_{HH}

(not a real surprise)

Prospects for HH

Theoretical 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 self-coupling at the LHC (to about 20-50%) possibly achieved by combining many channels / exploit ratio of double-to-single Higgs production / boosted searches
- percent (10%?) 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; Contino et al 1606.09408 …

Prospects for HH

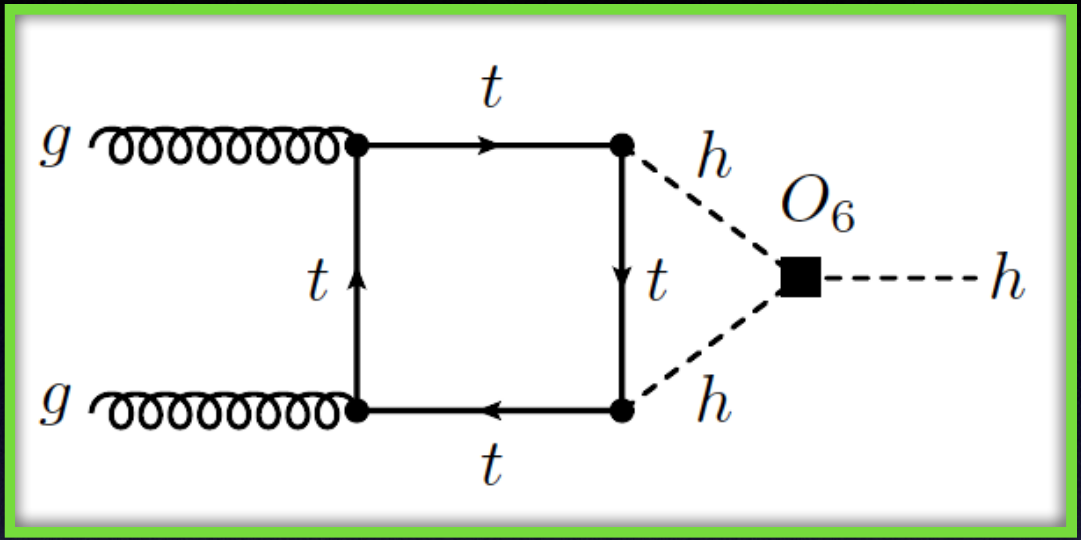
ATLAS study based on full Run 3 data set (3000 fb^{-1})

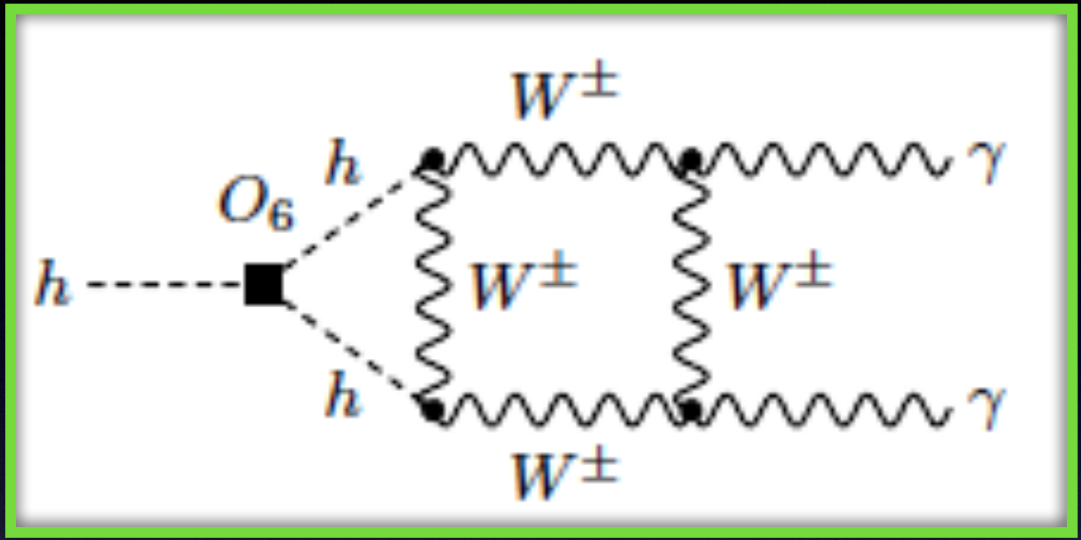
	λ/λ_{SM}
$2b2\gamma$	[-1.3;8.7]
$2b2\tau$	[-4;12]

ATLAS-PHYS-PUB-2014-019; ATLAS-PHYS-PUB-2015-046

Some room for improvement using MVA and other channels

Probing λ_3 in single Higgs production





Probe the Higgs coupling indirectly through gg → H and H → γγ

Work in EFT framework and assume that only non-vanishing coefficient is c_6

$$\mathcal{L}_{\mathrm{EFT}} = \sum_k \frac{c_k}{v^2} \mathcal{O}_k \qquad \mathcal{O}_6 = -\lambda (H^\dagger H)^3$$

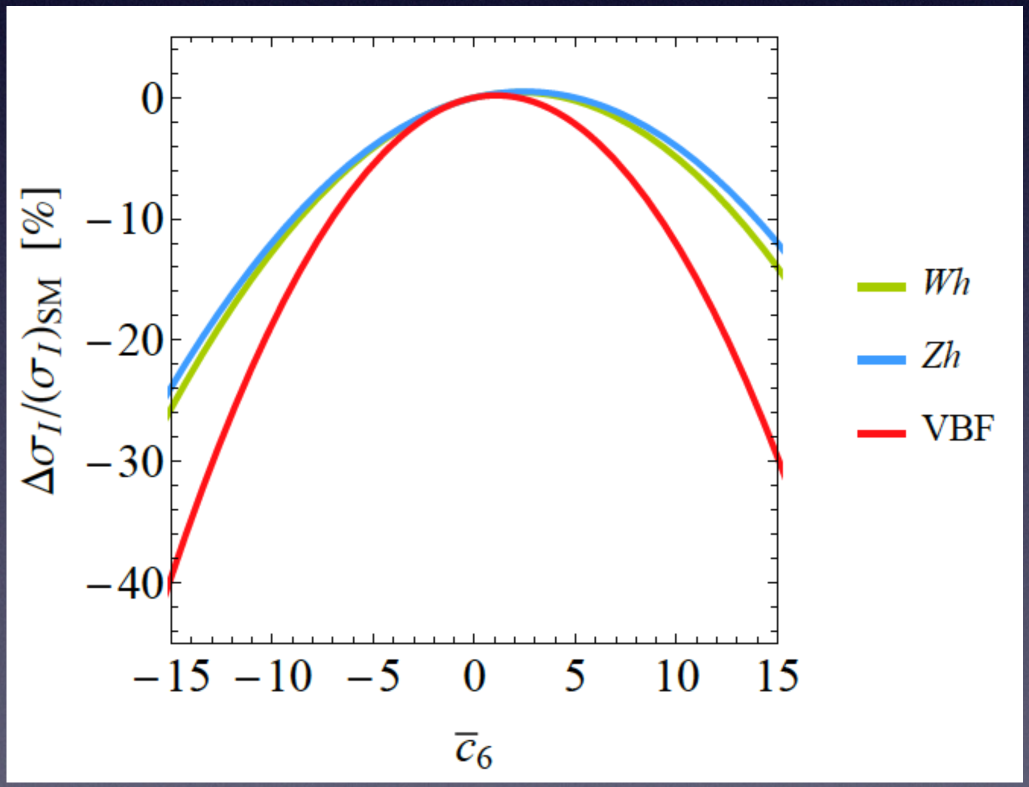
Combining current bounds on κ_g and κ_γ results in $c_6 \in [-12.7;9.9]$
(to be compared with $|c_6| < 10$ from double Higgs production)

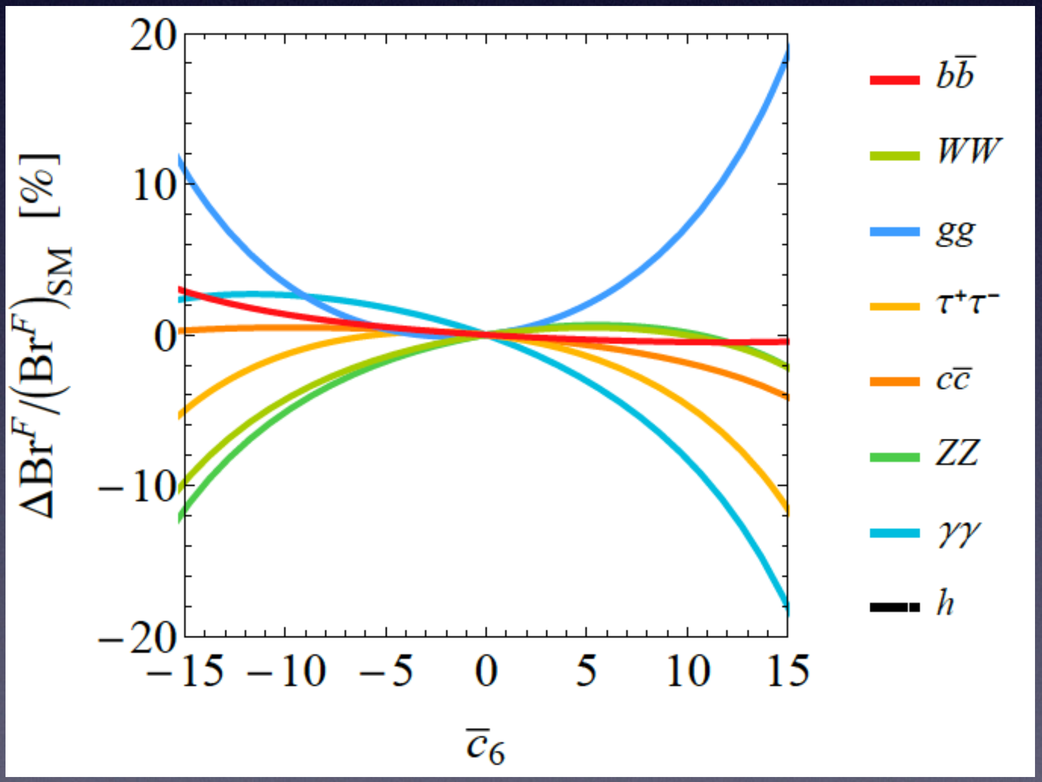
Gorbahn and Haisch 1607.03773

Probing λ_3 in single Higgs production

Bizon, Gorbahn, Haisch GZ 1609.xxxxx

Exploit accurate determination of VH and VBFH (including Higgs decays) to probe λ_3 indirectly (again work in EFT framework and assume that only non-vanishing coefficient is c_6)

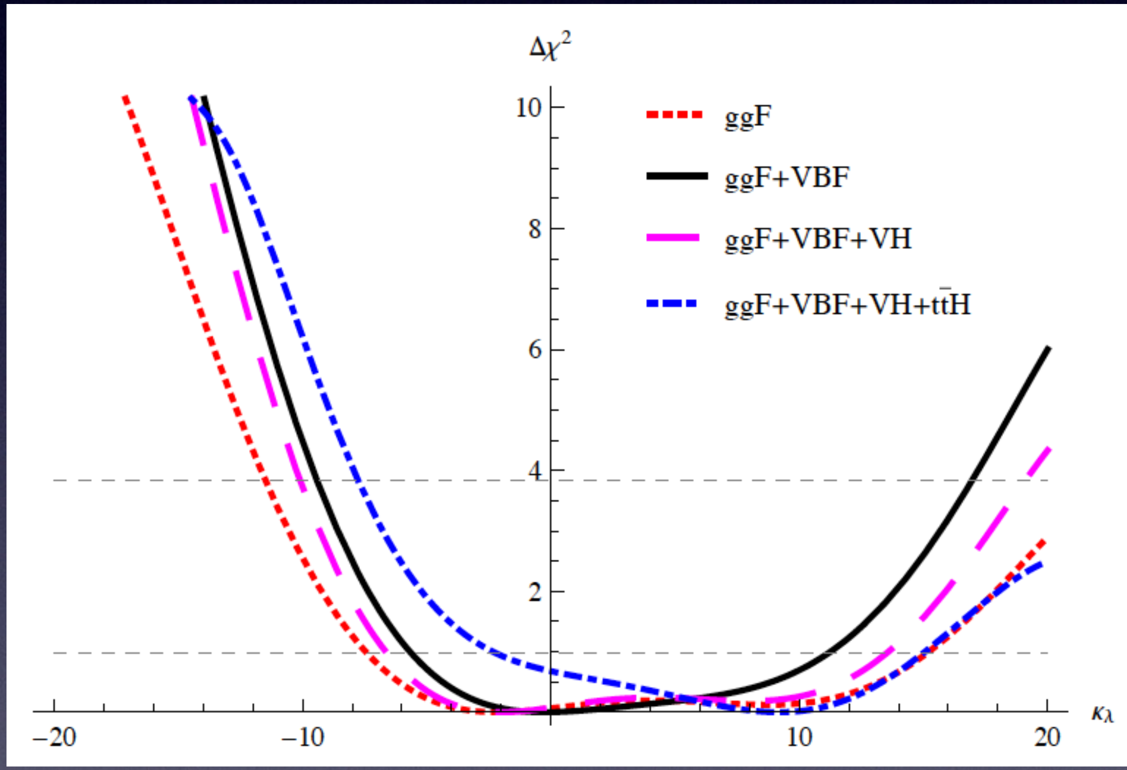




Using Run I combination of ATLAS and CMS measurements one obtains $c_6 \in [-14.7;16]$

Probing λ_3 in single Higgs production

Comprehensive study of sensitivity to λ_3 in main Higgs production (ggF, VBF, WH, ZH, tth) and decay modes (γγ, ZZ, WW, ff, gg) using a coupling modifier $\kappa_\lambda \sim (1+c_6)$



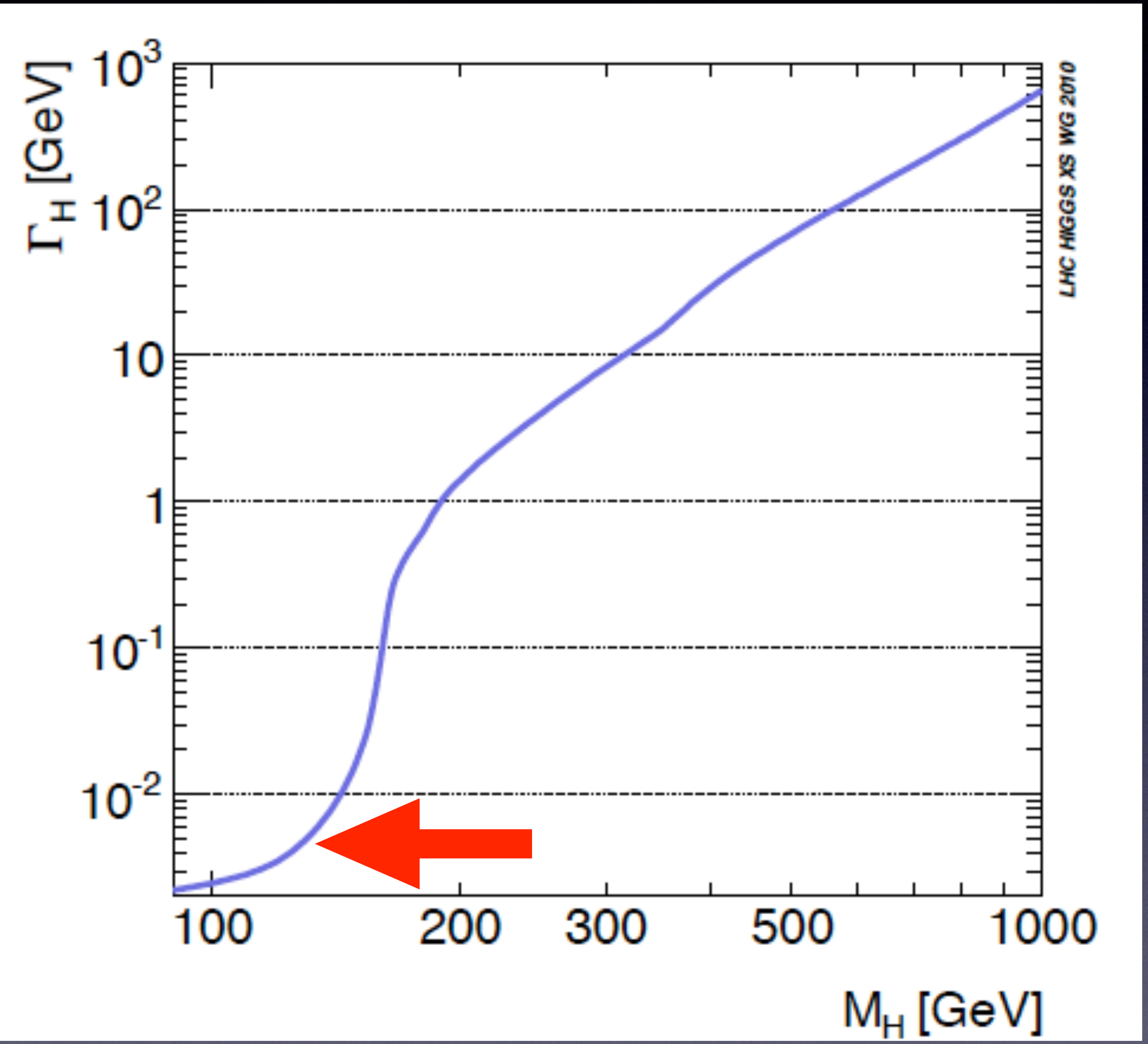
One parameter fit to the ggF and VBFH Higgs measurements at 8 TeV (NB: including ttH shifts best value to about 10)

$$\kappa_\lambda^{\text{best}} = -0.24\,, \qquad \kappa_\lambda^{1\sigma} = [-5.65, 11.21]\,, \qquad \kappa_\lambda^{2\sigma} = [-9.43, 16.97]\,,$$

Bounds competitive to current ones from di-Higgs production

De Grassi, Giardino, Maltoni, Pagani, 1607.04251

Higgs width: extremely small



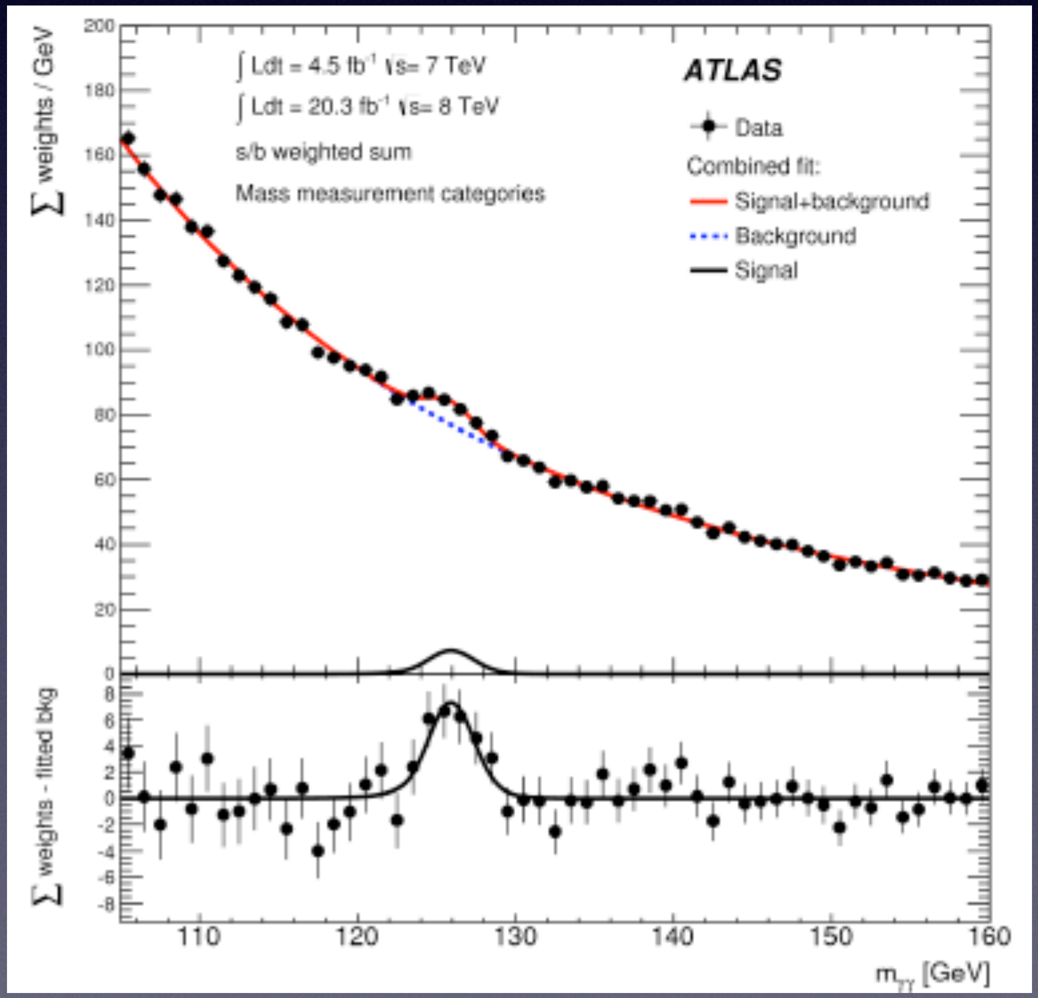
In the SM for M_H = 125 GeV
Γ_H = 4 MeV (very very narrow!)

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



Current direct bounds

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

✓ $\Gamma_H < 2.6$ GeV (ATLAS, ZZ)

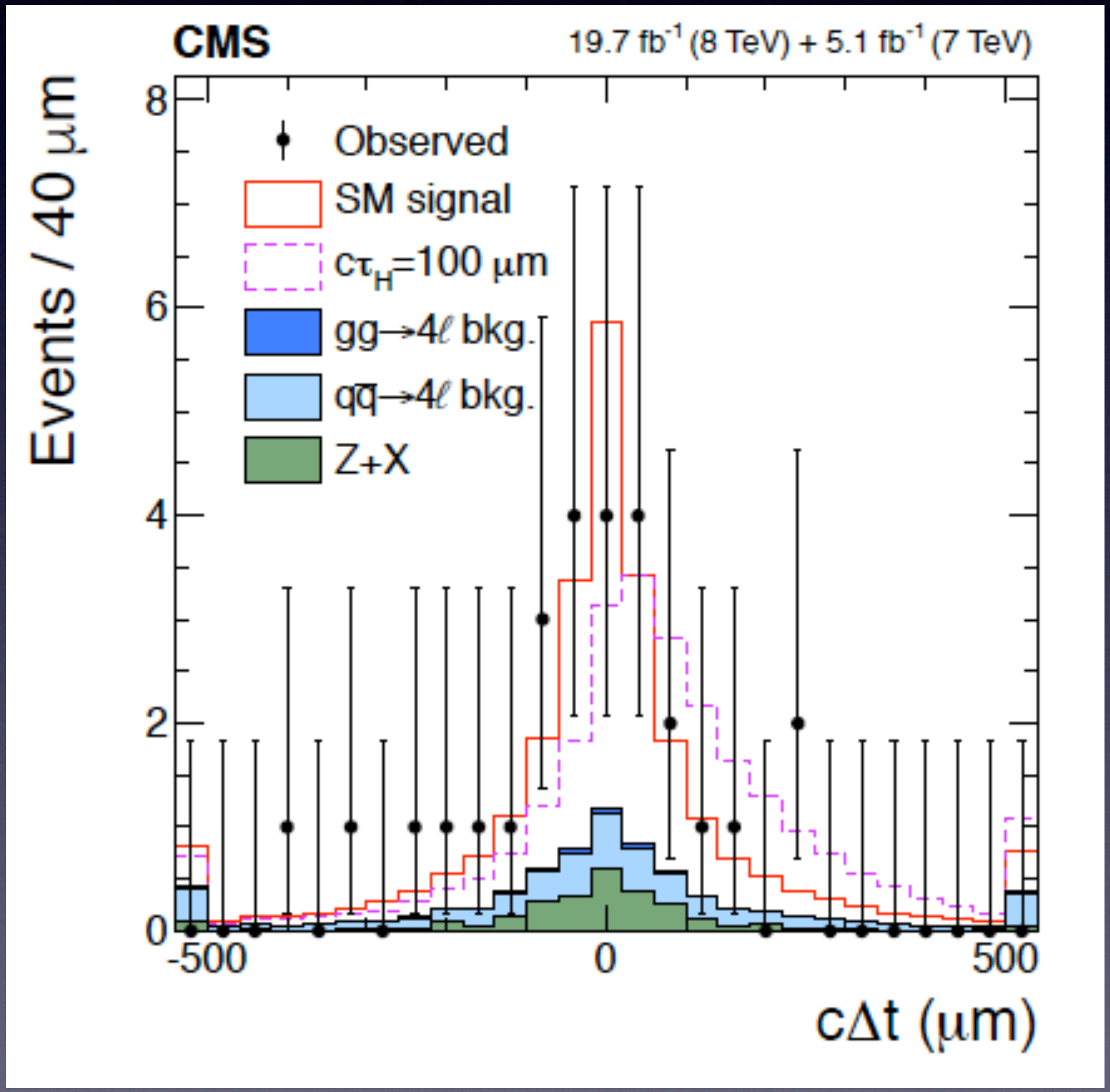
✓ $\Gamma_H < 1.7$ GeV (CMS)

Estimated LHC reach: 1 GeV

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:

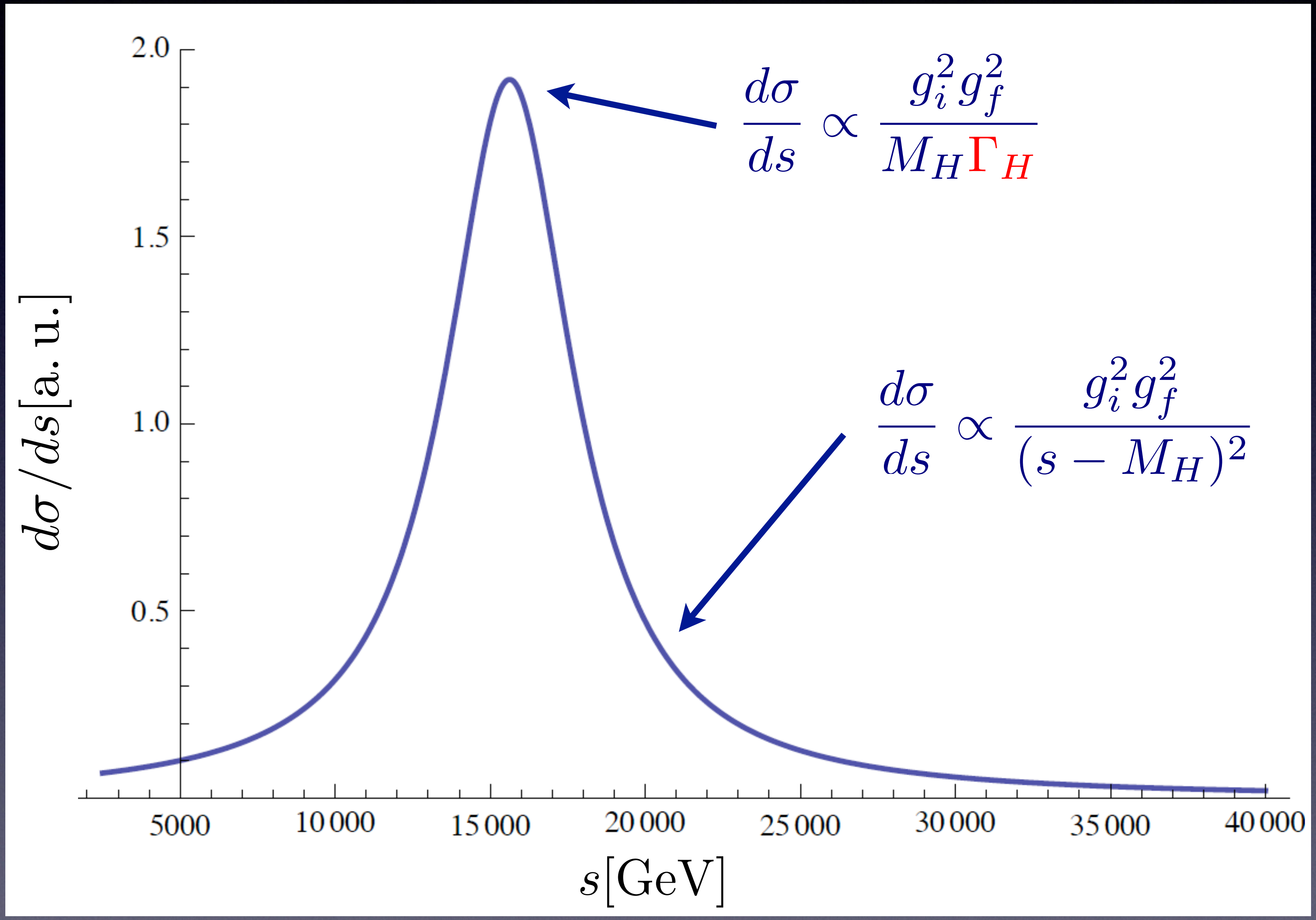
$$c\tau_H < 57\mu\mathrm{m} \Rightarrow \Gamma_H > 3.5 \cdot 10^{-9}\mathrm{MeV}$$

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

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

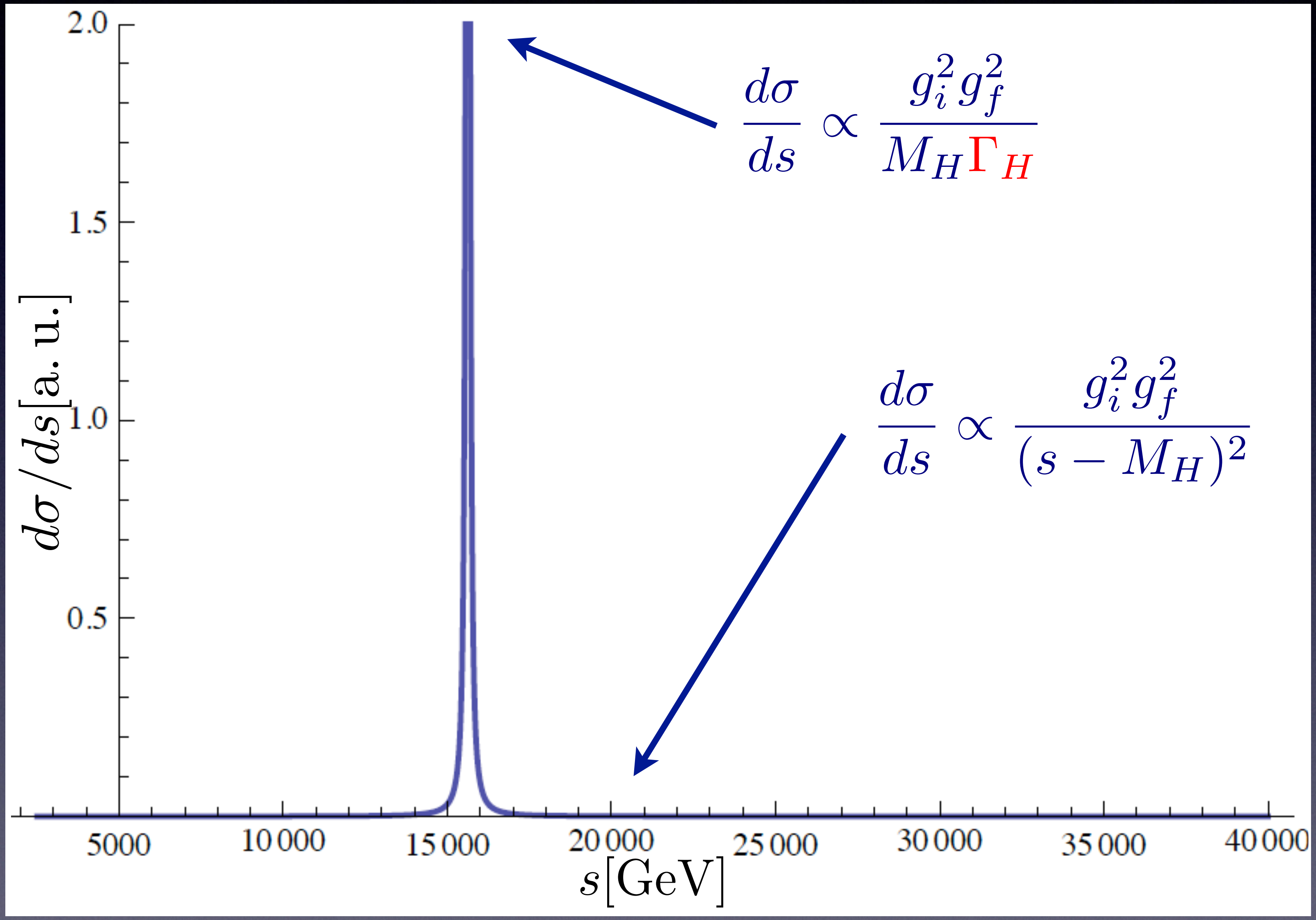
Breakthrough idea

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



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

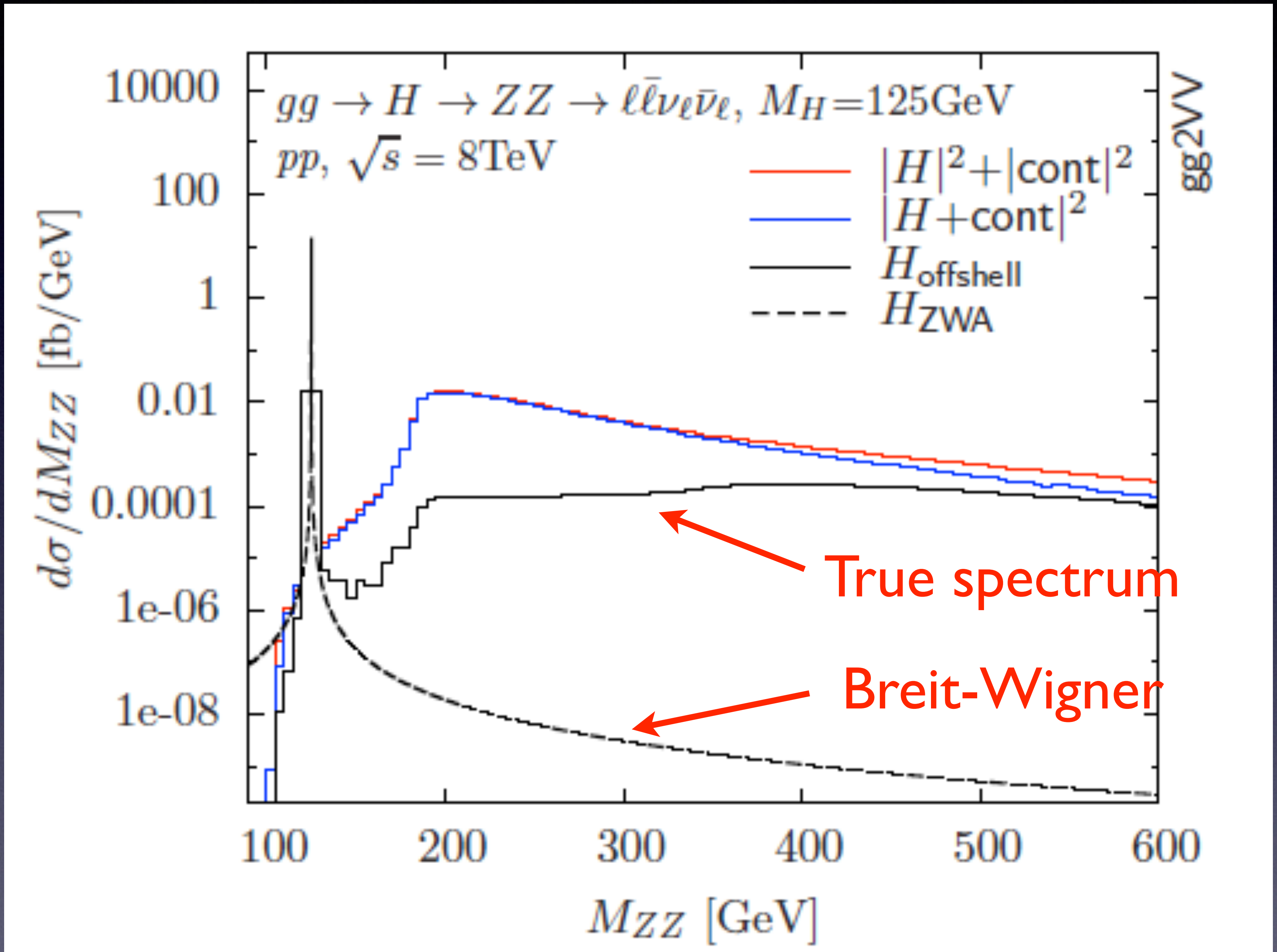
Breakthrough idea



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

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

YES!

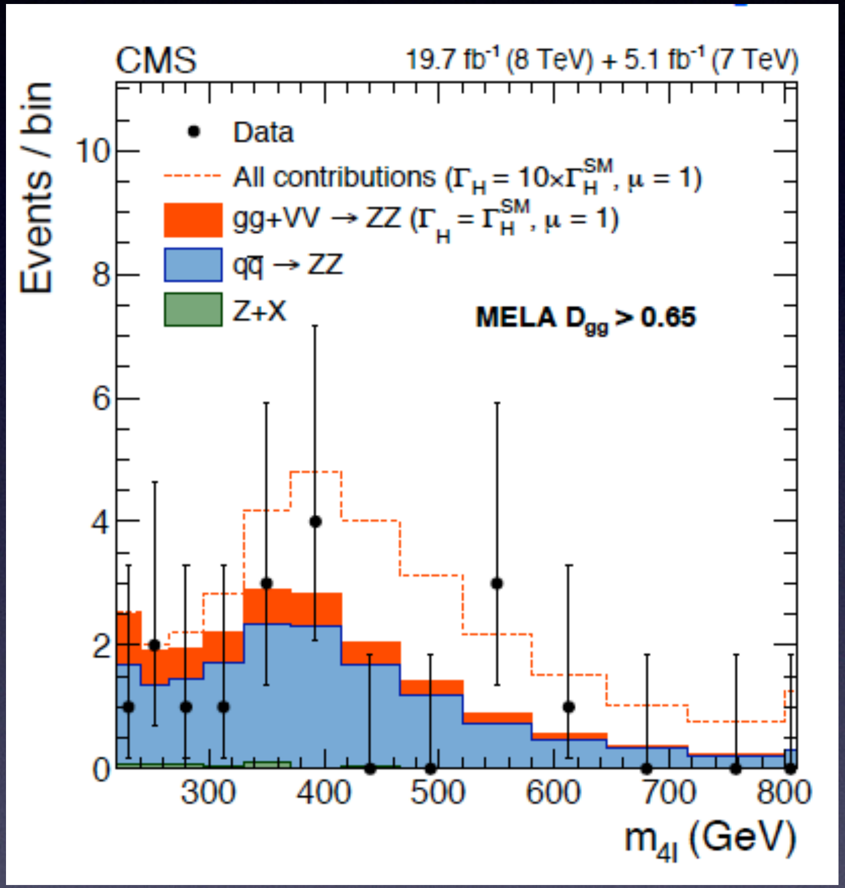


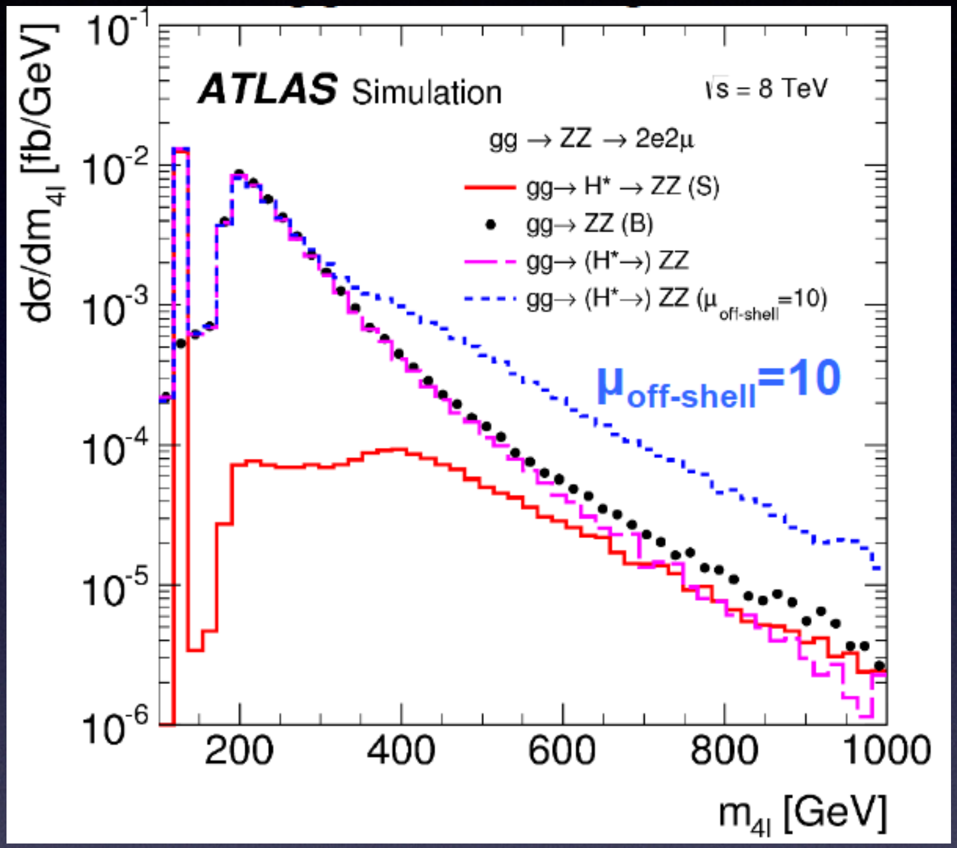
Kauer, Passarino

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





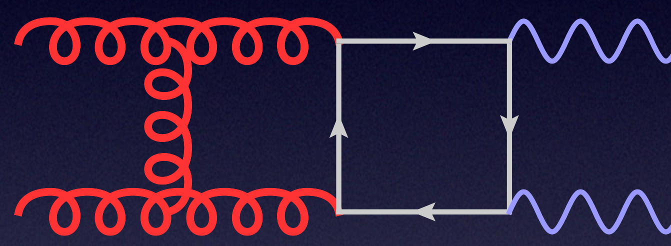
ATLAS: $\Gamma_H < 23{\rm MeV}\ @\ 95\% C.L.$

- assumes negligible difference between on-shell / off-shell couplings
- rely on ZZ* → 4l, ZZ* → 2l2ν, WW* →2l2ν. Limits using other channels possible
- BUT important to control of off-shell cross-sections/backgrounds/ interference contributions (need very precise control on VV)

Progress in VV

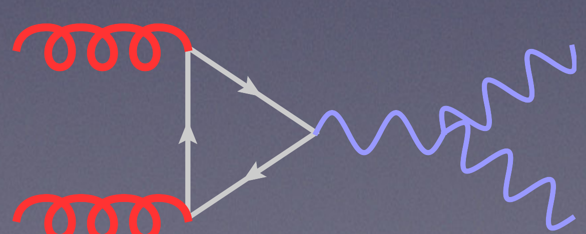
- all VV processes now known to NNLO
- important contribution from gg → VV
- recently NLO corrections to gg computed
  K ~ 1.6-1.8 (but treatment of 3rd generation incomplete)
- for ZZ the result lies outside the NNLO uncertainty bands quoted
- furthermore, interference between signal and background known to LO only (include geometric average of K-factors)

Catani et al ’11; Grazzini et al ’14; Cascioli et al ’15; Gehrmann et al. ’15; Grazzini et al ’15; Campbell et al ‘16

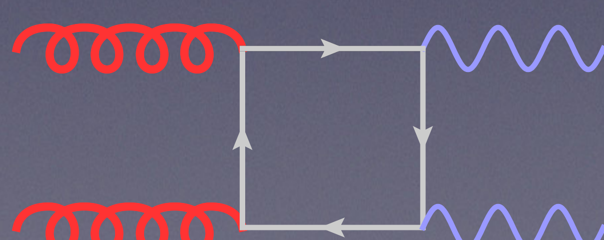


Caola et al ’15; Caola et al ’16;

expect more progress relevant for future constraints on the width



K_{signal}



$K_{\mathrm{back.}}$

$$\mathrm{Int.} \propto \sqrt{K_{\mathrm{signal}} K_{\mathrm{back.}}}$$

justified?

Conclusions

- The Higgs discovery leaves many open questions for the LHC Run II to explore
- Precision calculations, crucial to address those questions, are making giant steps: new techniques, new ideas, better observables
- Residual uncertainties at the level of the few percent for cross-sections (larger for distributions)
- Perturbative QCD uncertainty often already not the dominant theory uncertainty, other corrections must be included (EW corrections, PDF and α_s uncertainties, non-perturbative effects, corrections to large-m_t effective theory in gluon-fusion production ...)
- Progress in theory and experiment go truly hand in hand (in fact, often theory is ahead☺)