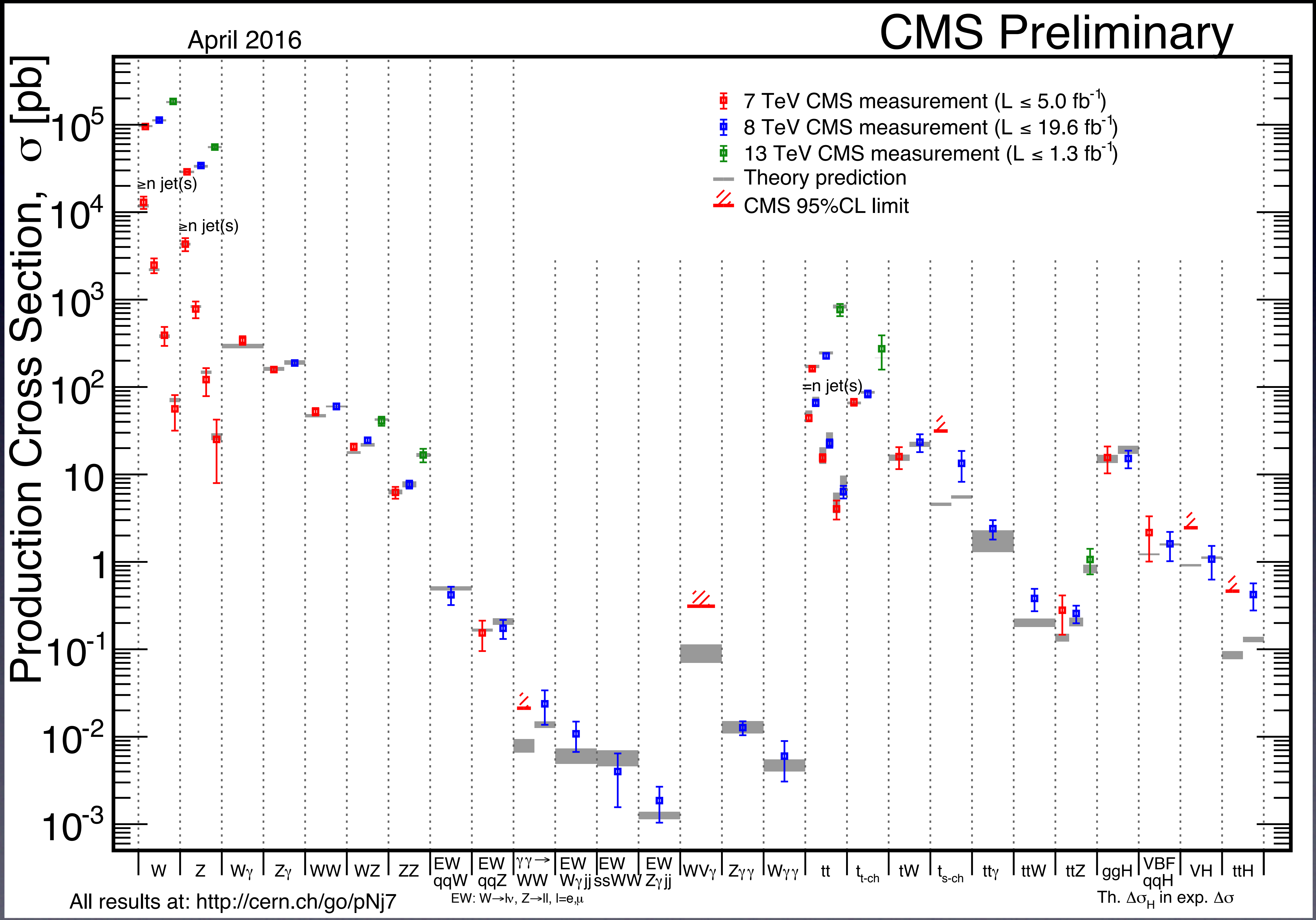
Precision Higgs studies at the LHC

Stress testing the Standard Model at the LHC

KITP, 27th May 2016

G. Zanderighi - CERN & Oxford University

Production cross sections at the LHC



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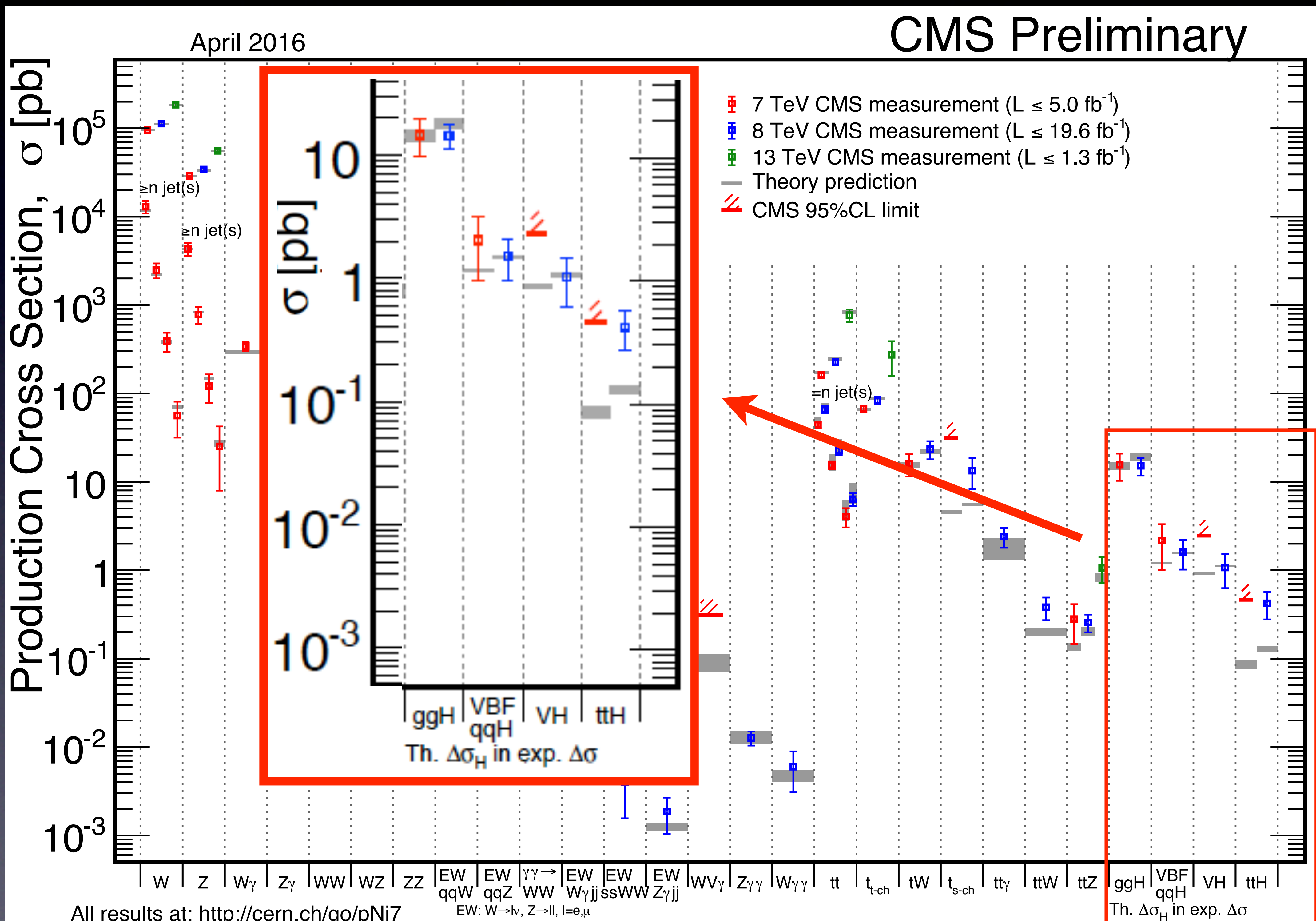
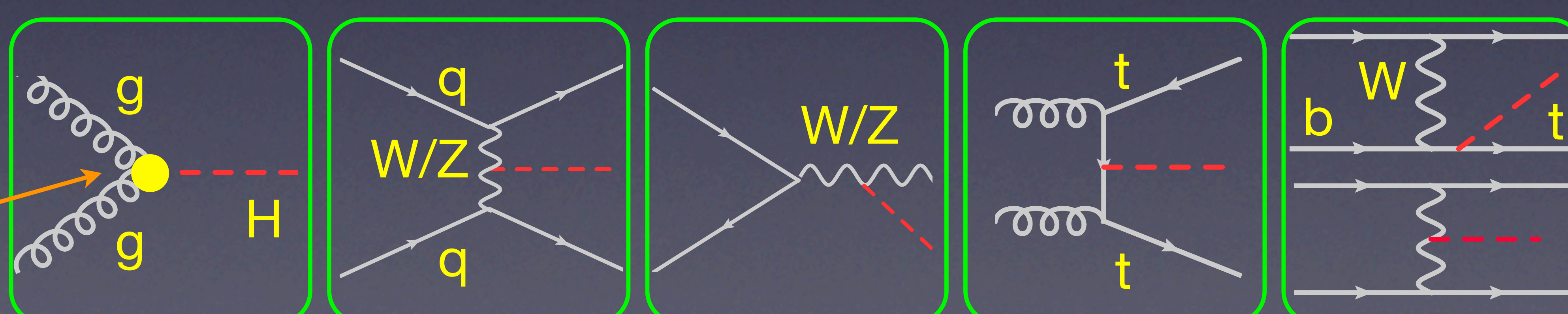


Main Higgs production at the LHC

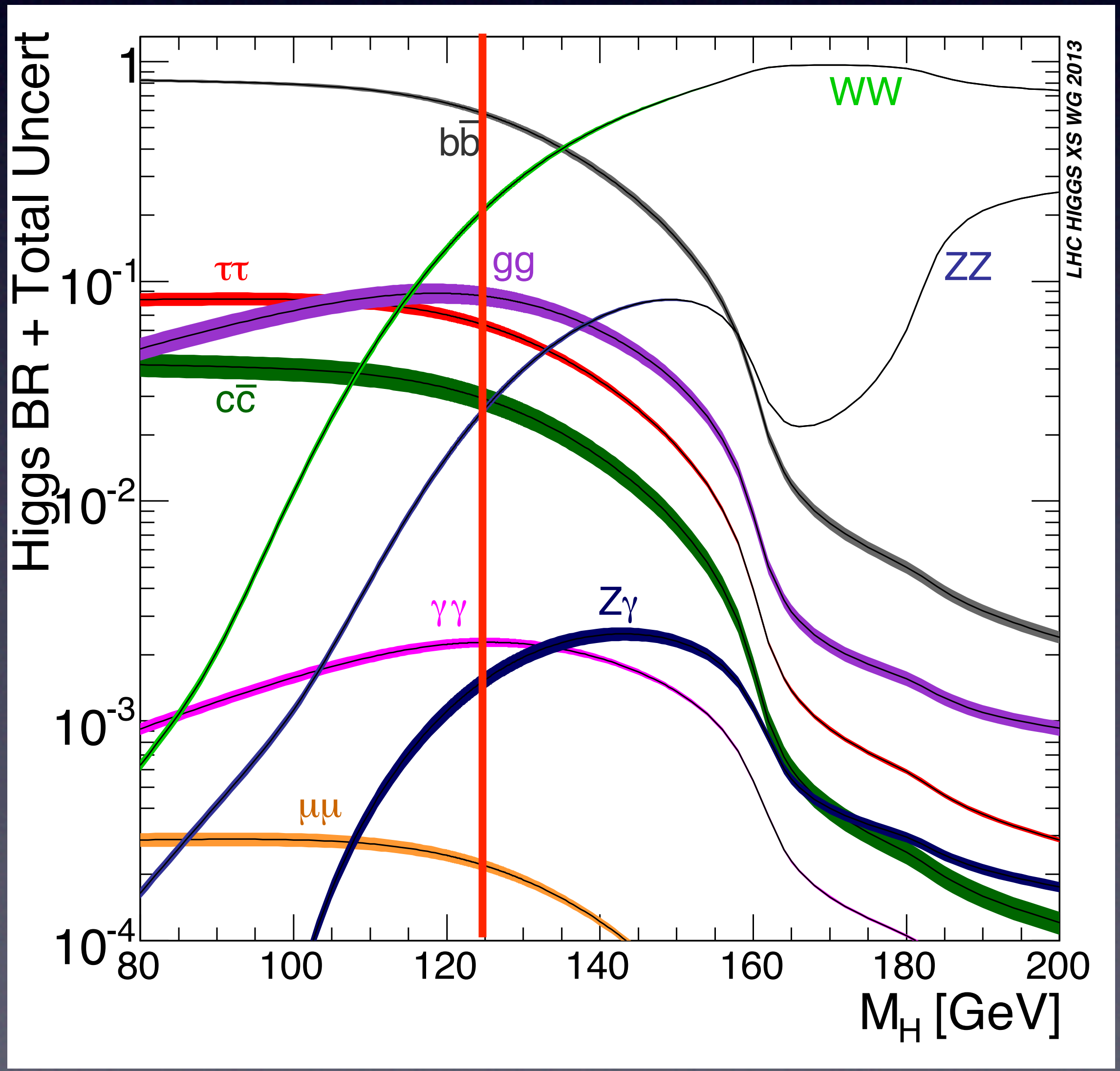
	ggH	VBF	WH/ZH	ttH	tH
8 TeV ~ 25 fb^{-1} (2012)	19 pb	1.6 pb	1.1 pb	0.13 pb	20 fb
13 TeV ~ 4 fb^{-1} (2015)	48 pb	3.7 pb	2.2 pb	0.51 pb	90 fb

heavy-quark loop ⇒ effective Lagrangian



Higgs decay modes

Higgs mass (m_H=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



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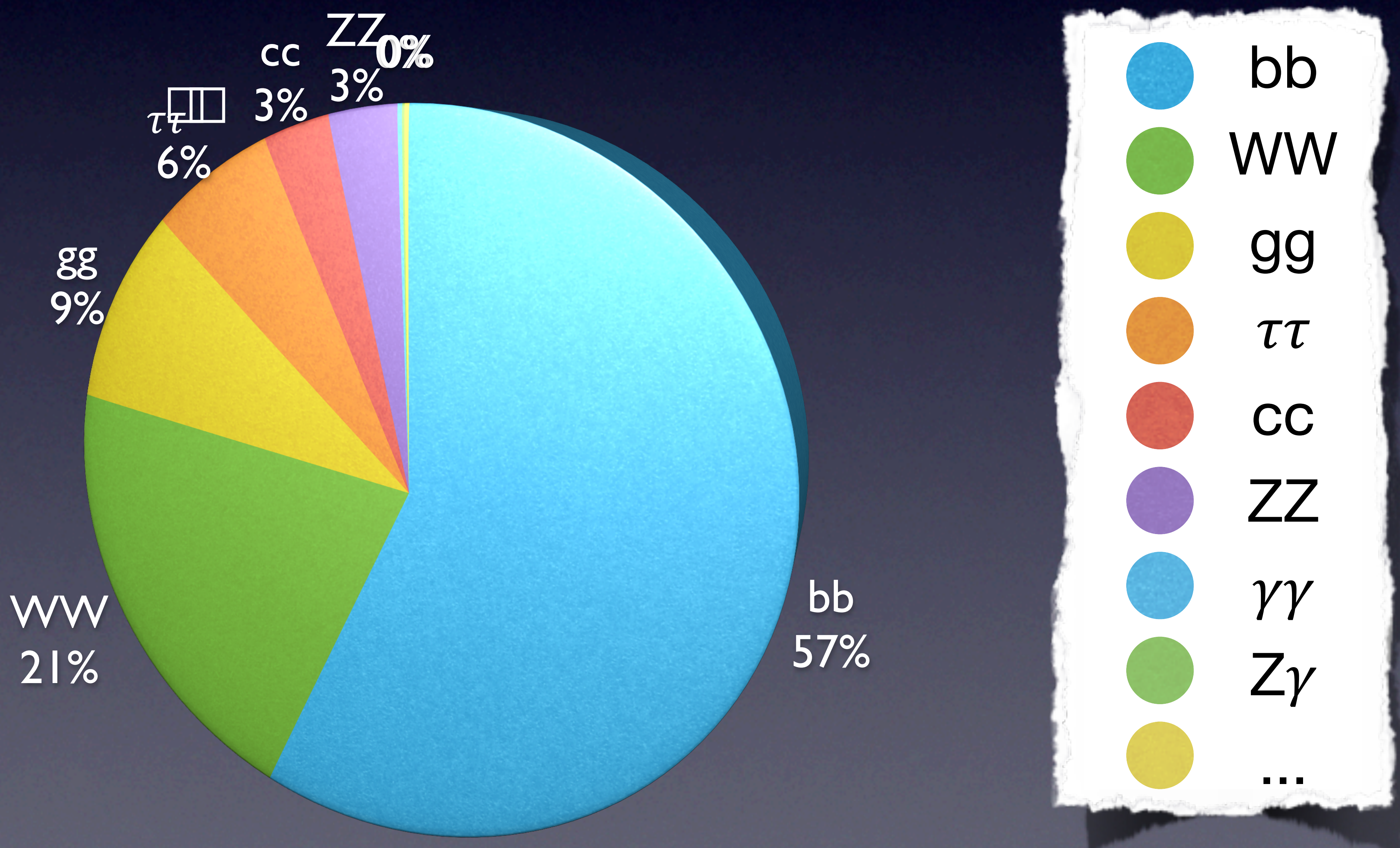
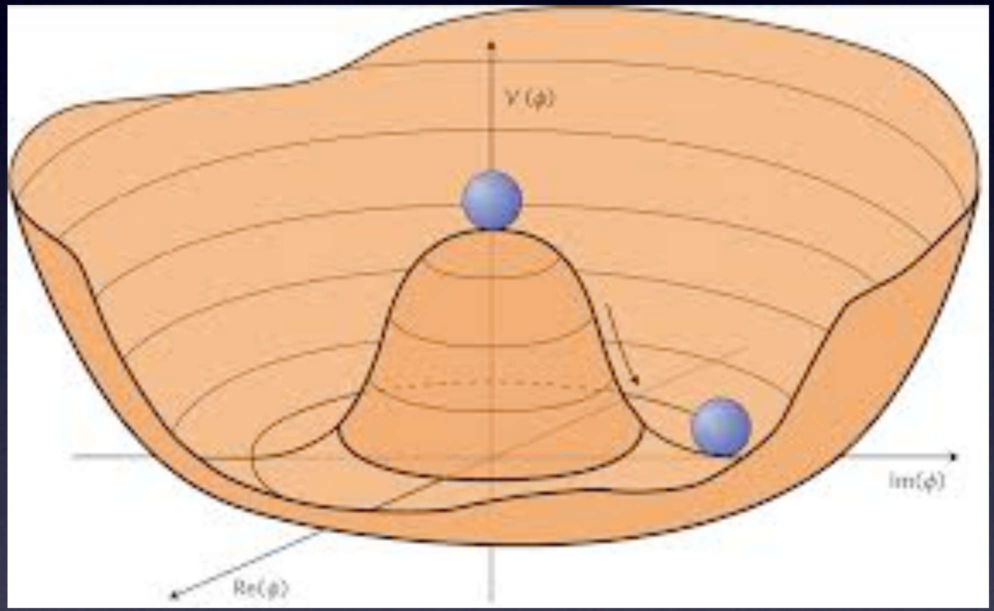


The Standard Model Higgs

- it is a fundamental, CP even scalar particle
- 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

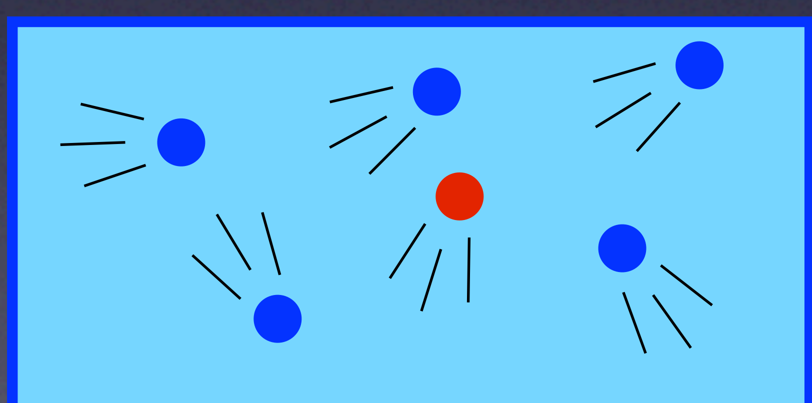


The hierarchy problem

- the Higgs mass receives corrections from vacuum fluctuations
- the size of the correction should be proportional to the maximum allowed energy (M_{Planck} , M_{GUT} ...)
- $M_H \ll M_{Planck}$ in the SM requires fine-tuning up to 17 digits

<u>Analogy with thermal fluctuations</u>

t = 0



thermalisation

At large t expect to have

$$E_{\color{red}\bullet} \sim E_{\color{blue}\bullet}$$

While the observation is

$$E_{\color{red}\bullet} \sim 10^{-17} E_{\color{blue}\bullet}$$

While it is not inconsistent, it seems hard to believe that it happens without a reason

The hierarchy problem

- ☛ In the analogy: natural explanation could be that red does not really interact with blue because the interaction is screened
- ☛ In the Higgs case: similarly, the interaction could be screened by new forces/particles

A variety of possible explanations exist to protect the Higgs mass from having a sensitivity to high-energy scales

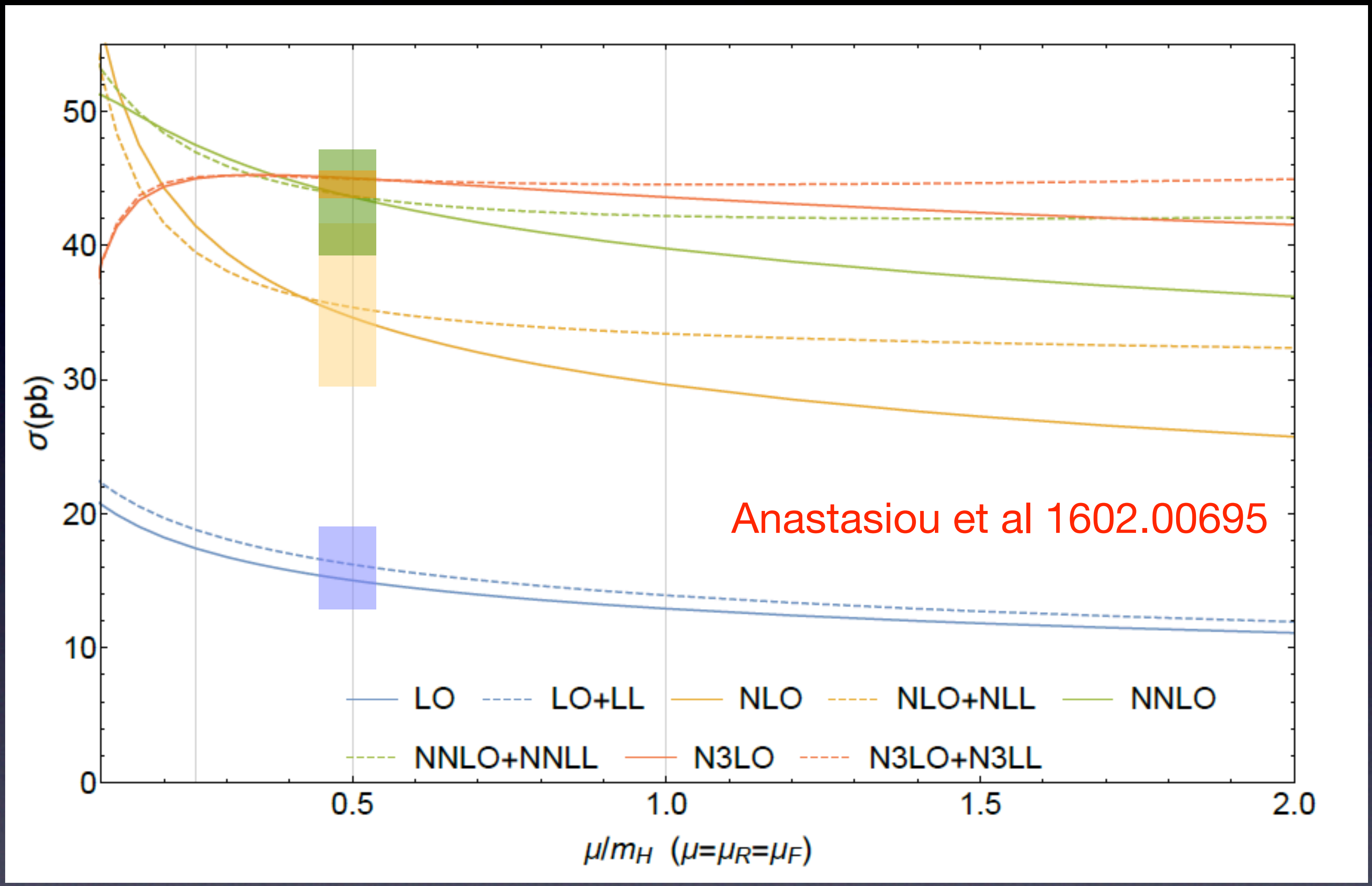
All these New Physics models typically result in modifications of the couplings, cross-sections, distributions

This is why it is crucial to stress-test the Higgs sector as much as possible and establish possible deviations from SM pattern

The Higgs: what do we know today

- it is a very narrow resonance ($\Gamma_H < 25$ 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 $\mu = 1.09^{+0.11}_{-0.10}$

N^3LO Higgs production



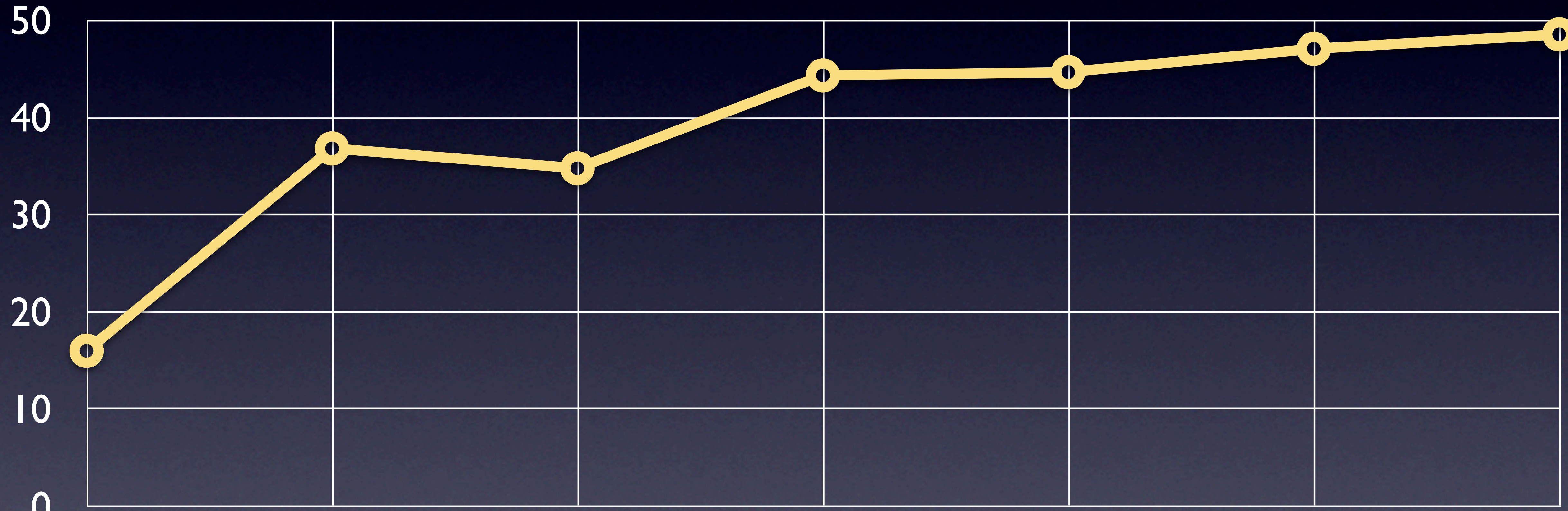
- also matched to resummed calculation (essentially no impact on central value at preferred scale $m_H/2$)
- N^3LO finally stabilizes the perturbative expansion

Inclusive Higgs production

Anastasiou et al 1602.00695

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

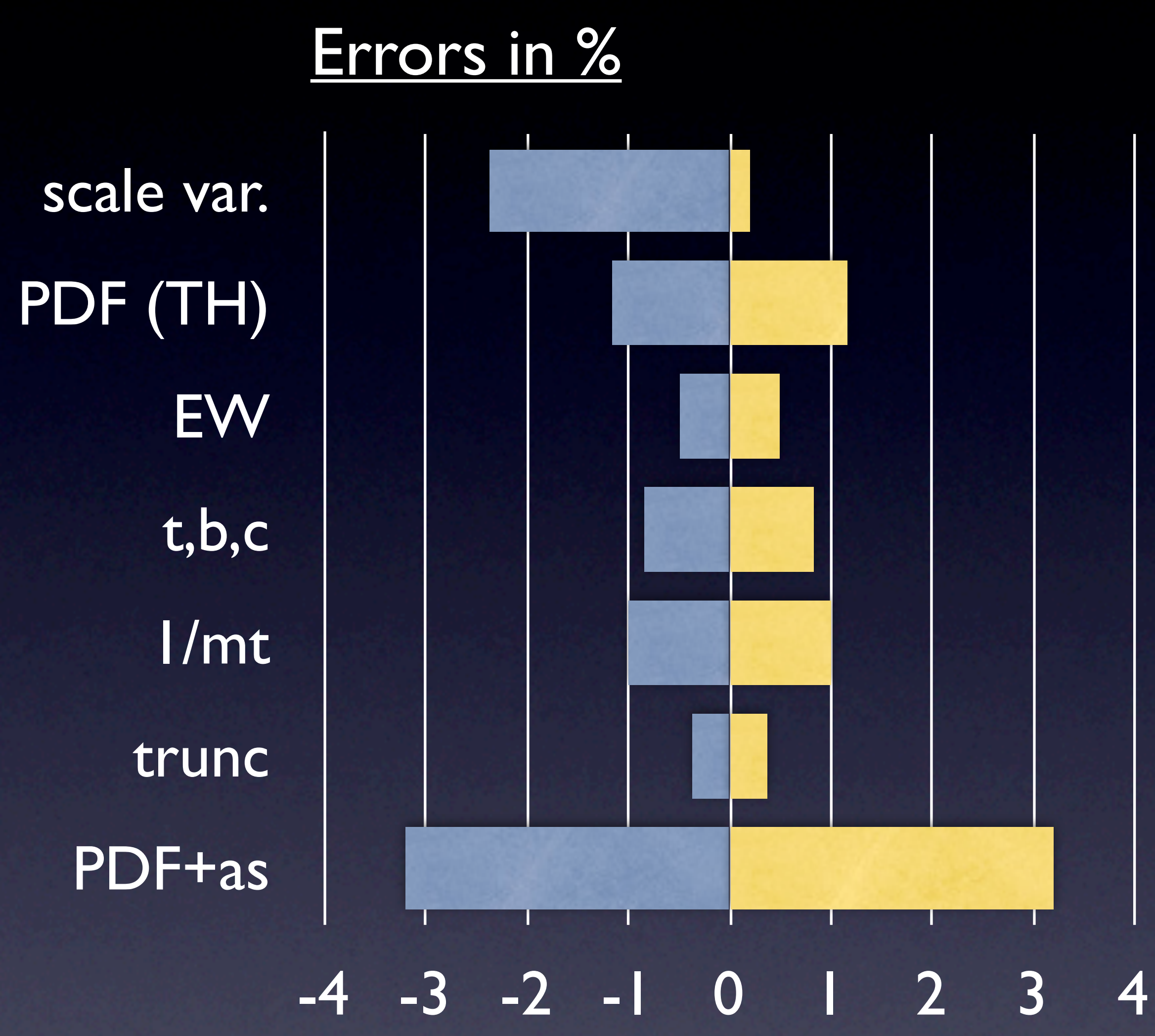
LHC 13 TeV: cross section in [pb] = 48.58 pb



LO-rEFT	NLO-rEFT	NLO t,b,c	NNLO-rEFT	1/mt-NNLO	NLO EW	N3LO-rEFT
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) ≈ 1.07

Error budget from 1602.00695



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

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

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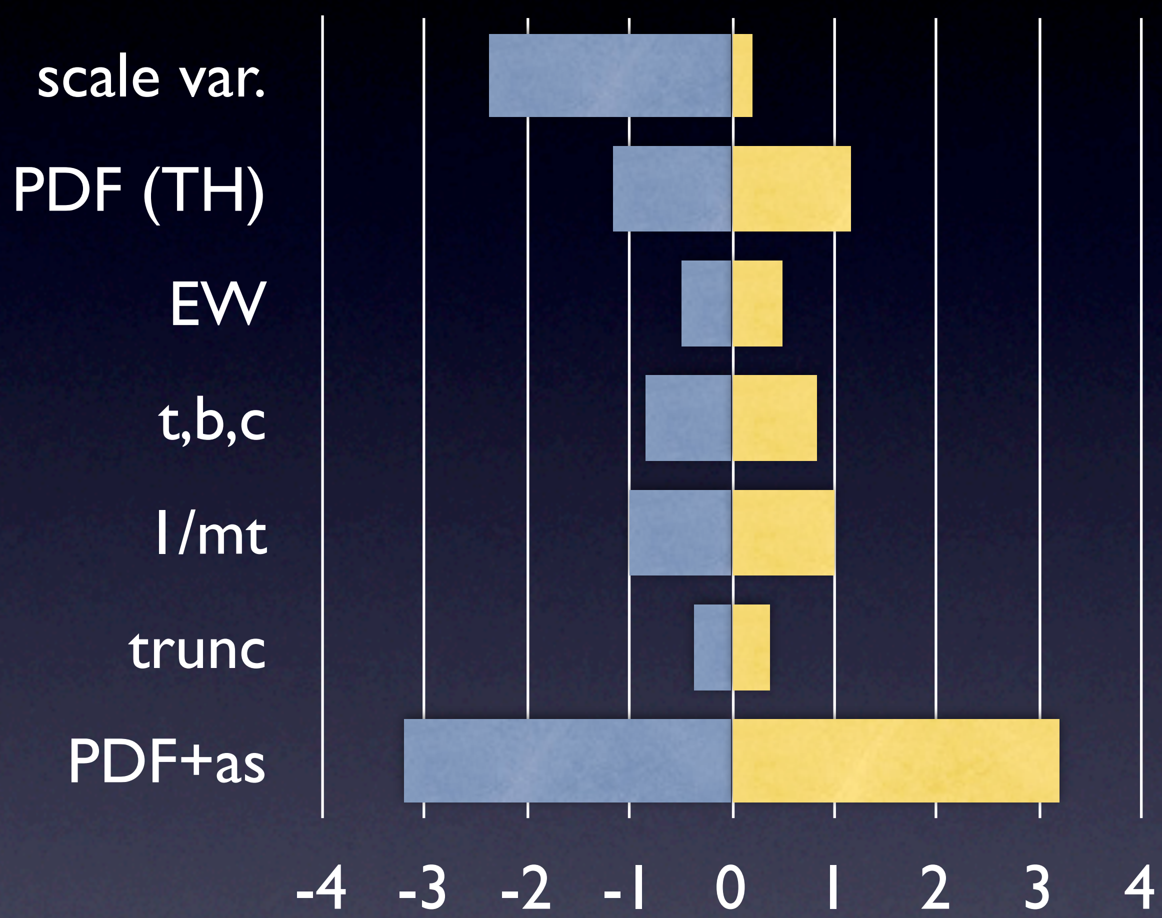
Errors in %



Under discussion 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 (b,c) effects
- quadratic vs linear combination of errors

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

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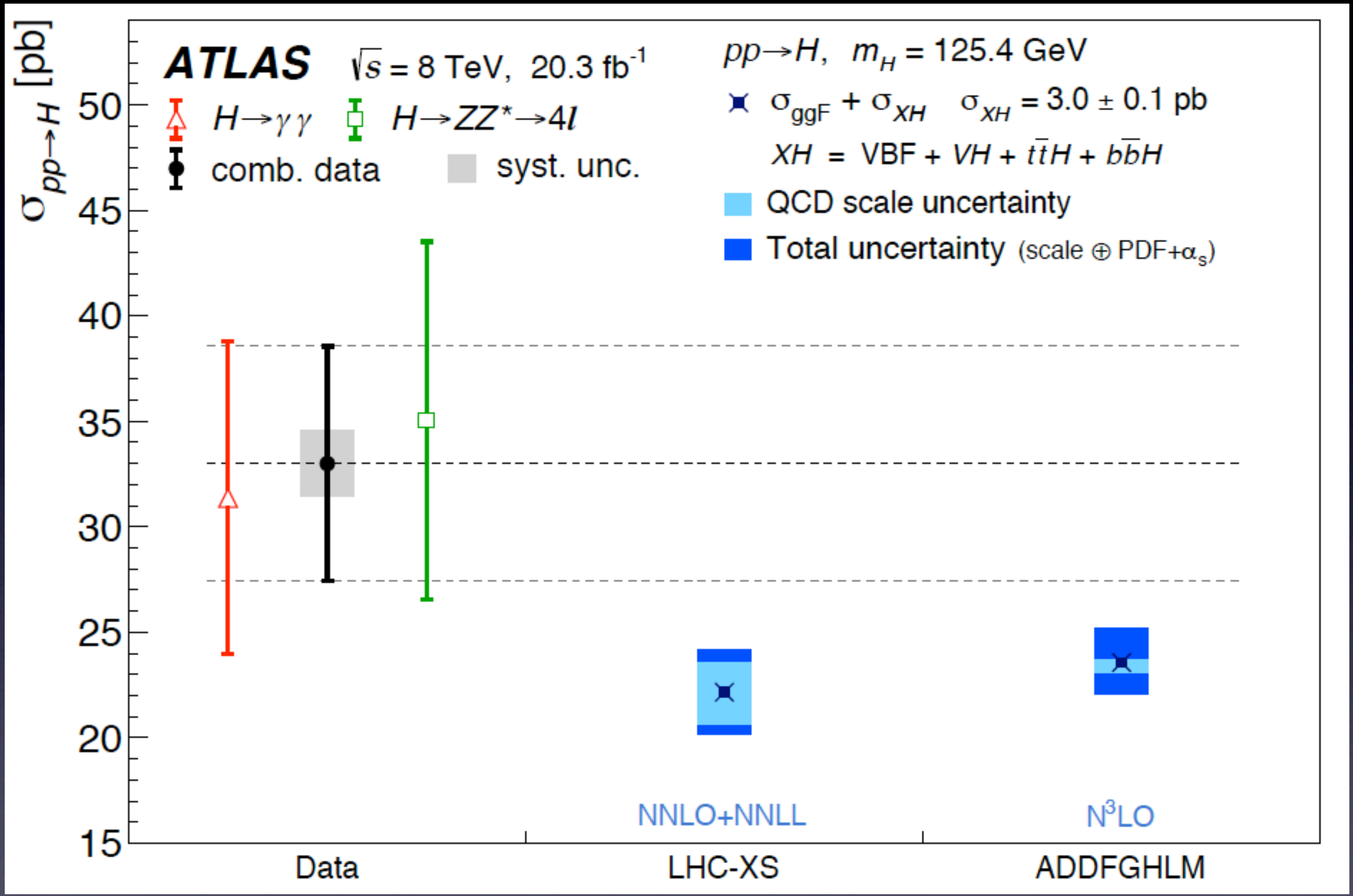
8 TeV data vs theory



"... 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 send yesterday by Reisaburo Tanaka to the ggF conveners]

Going differential

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

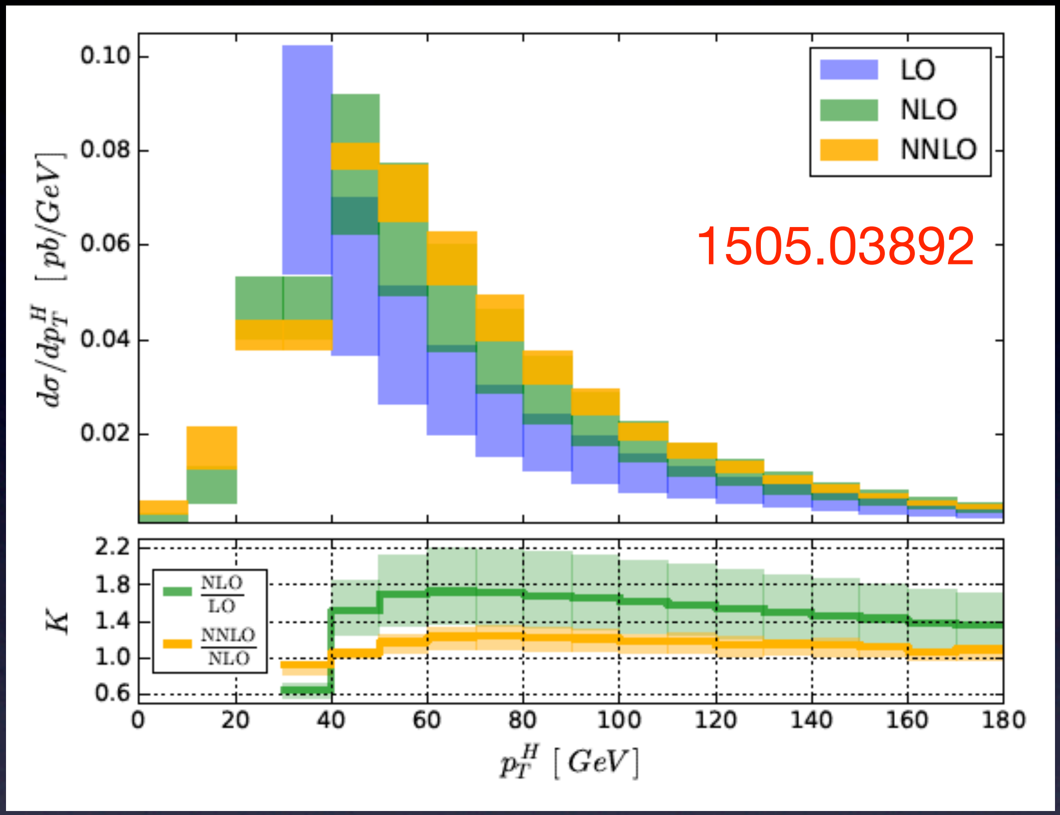
- ➡ signal significance optimized by categorizing events according to kinematic properties (e.g. jet bins, Higgs p_t ...)
- ➡ a large fraction (30-40%) of Higgs events come with at least one jet
- ➡ kinematical distributions used to extract/constraint couplings and quantum numbers

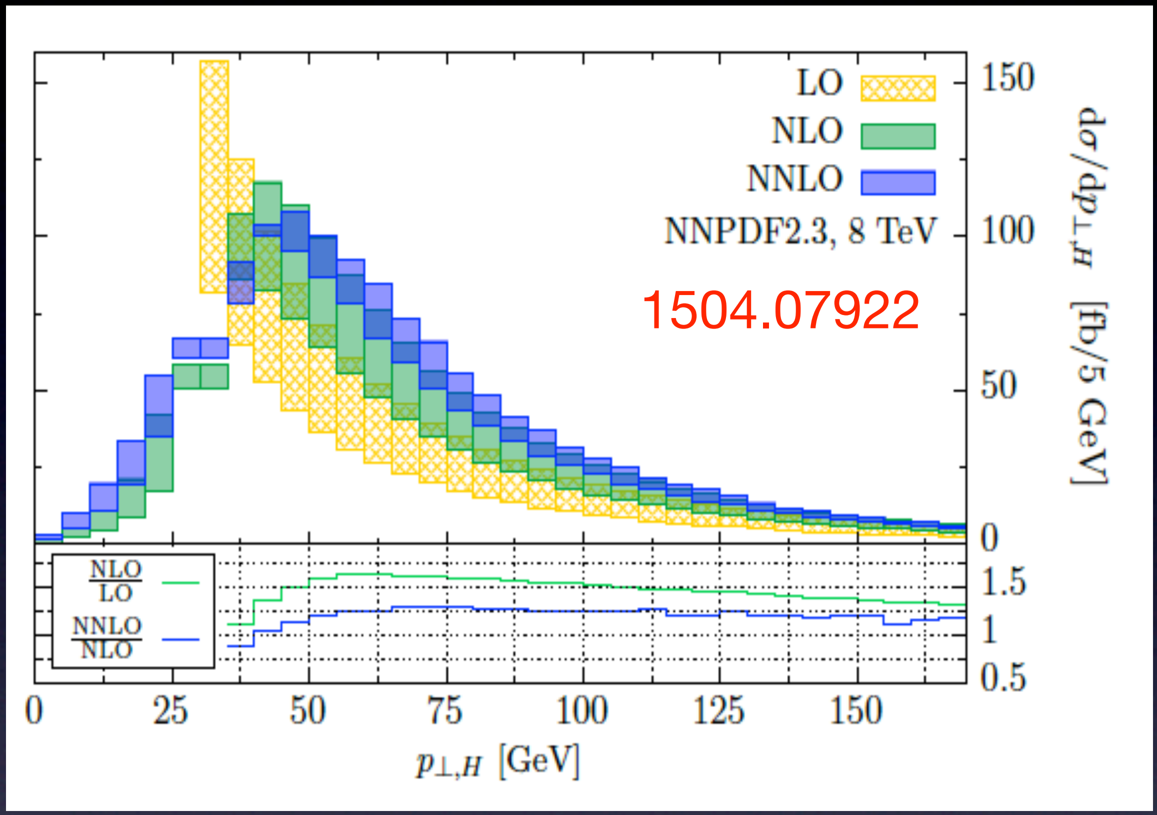
The most basic distribution: transverse momentum of the Higgs boson

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%)

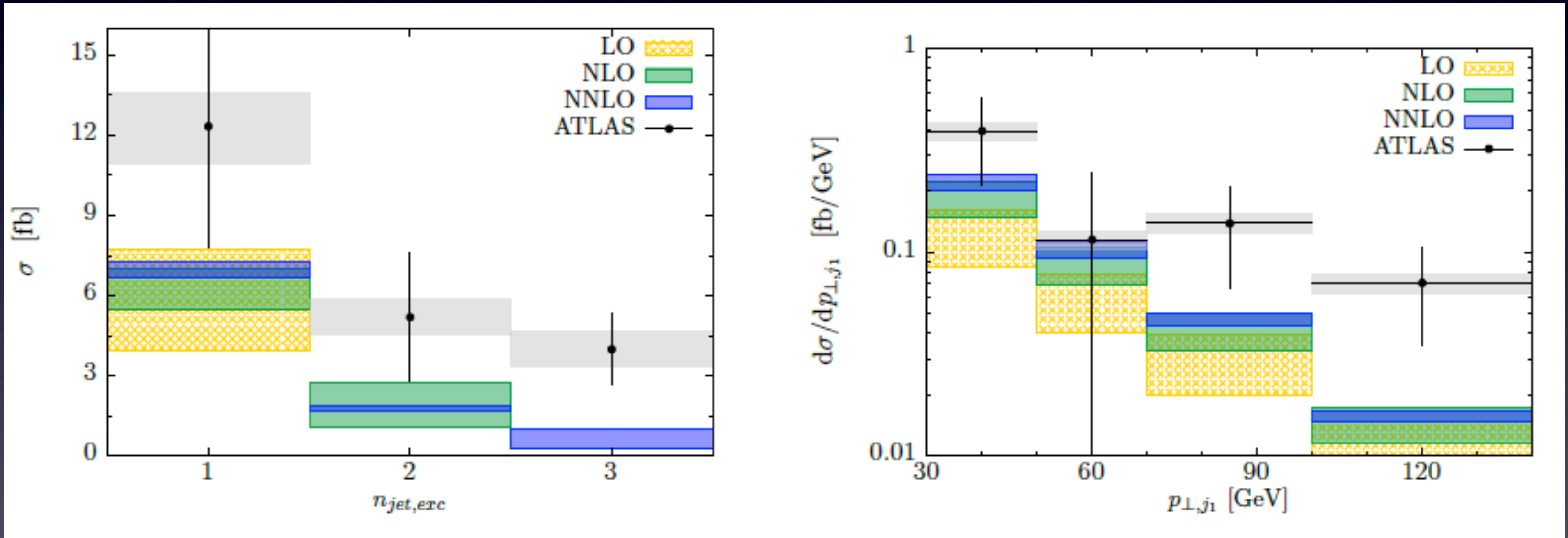
[see talk of R. Boughezal]

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

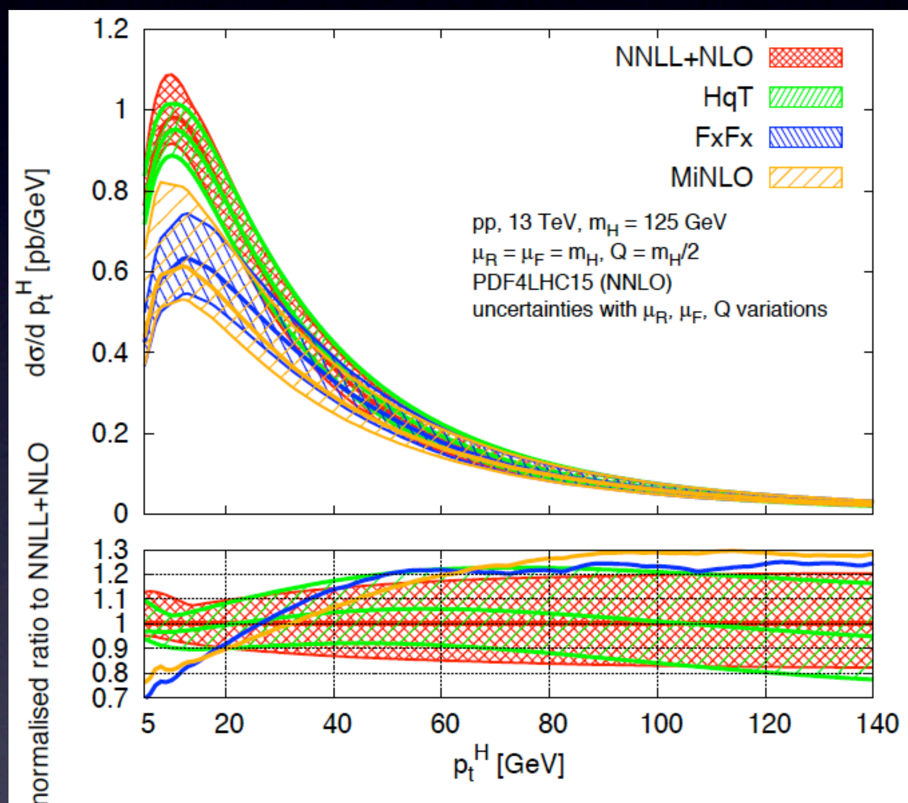
Caola, Melnikov, Schulze 1508.02684

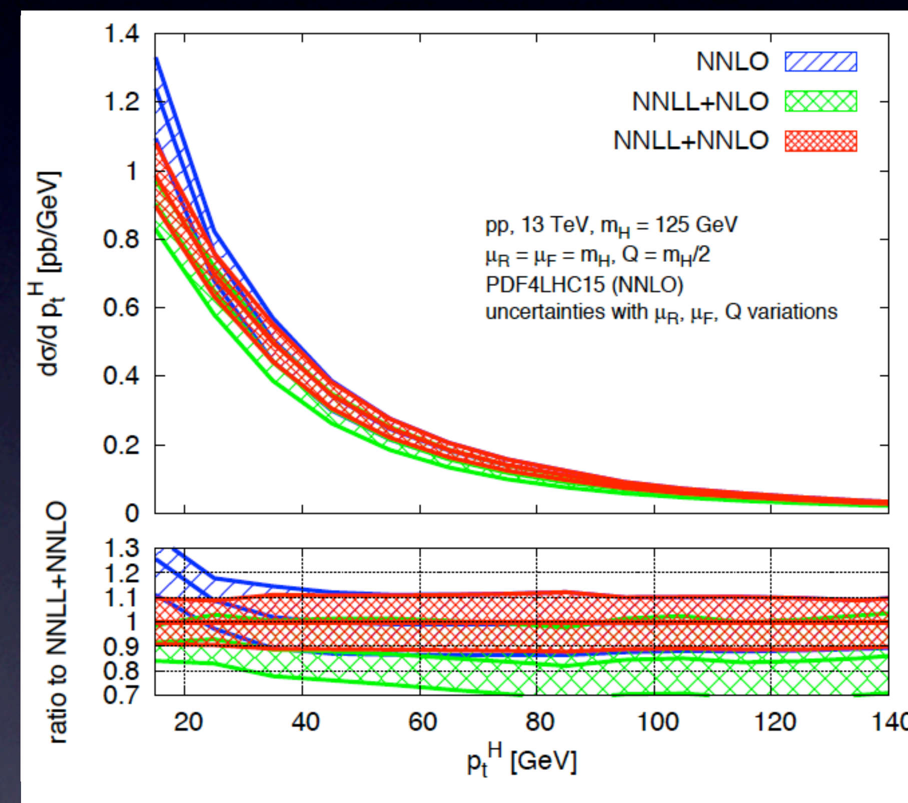


Agreement with data within large errors, but corrections beyond large top-mass effective theory could be sizable

NNLO + NNLL Higgs p_t spectrum

New method to resum Higgs transverse momentum directly in momentum space (rather than in impact parameter space)





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

- NNLO corrections: about 10%
- resummation: sizable impact below 25 GeV

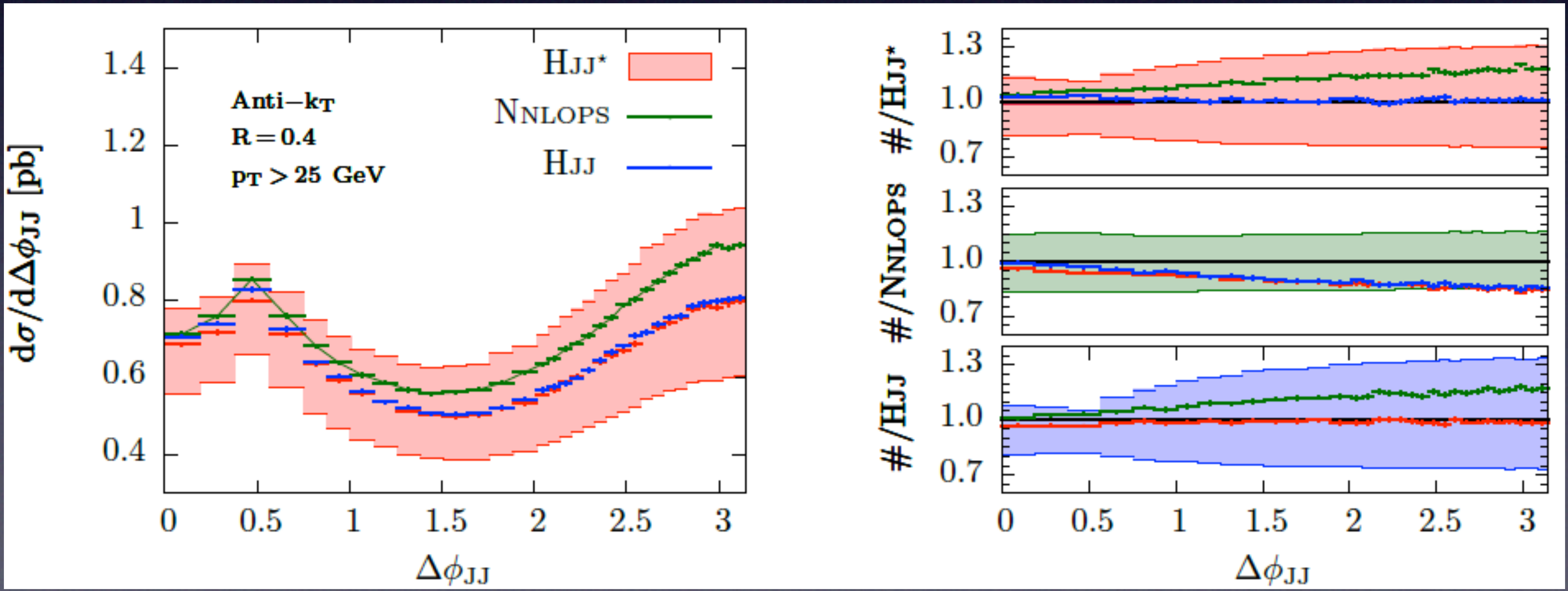
Monni, Re, Torrielli 1604.02191

MiNLO merging for H plus jets

Merging with no merging scale achieved recently for H(NNLOPS), H+1jet (NLOPS) and H+2jets (NLOPS) using extension of MiNLO method

Basic idea: impose that missing higher-order terms in the MiNLO Sudakov in X+n are such that one recovers (n-1)-jet (N)NLO distributions

Sample results



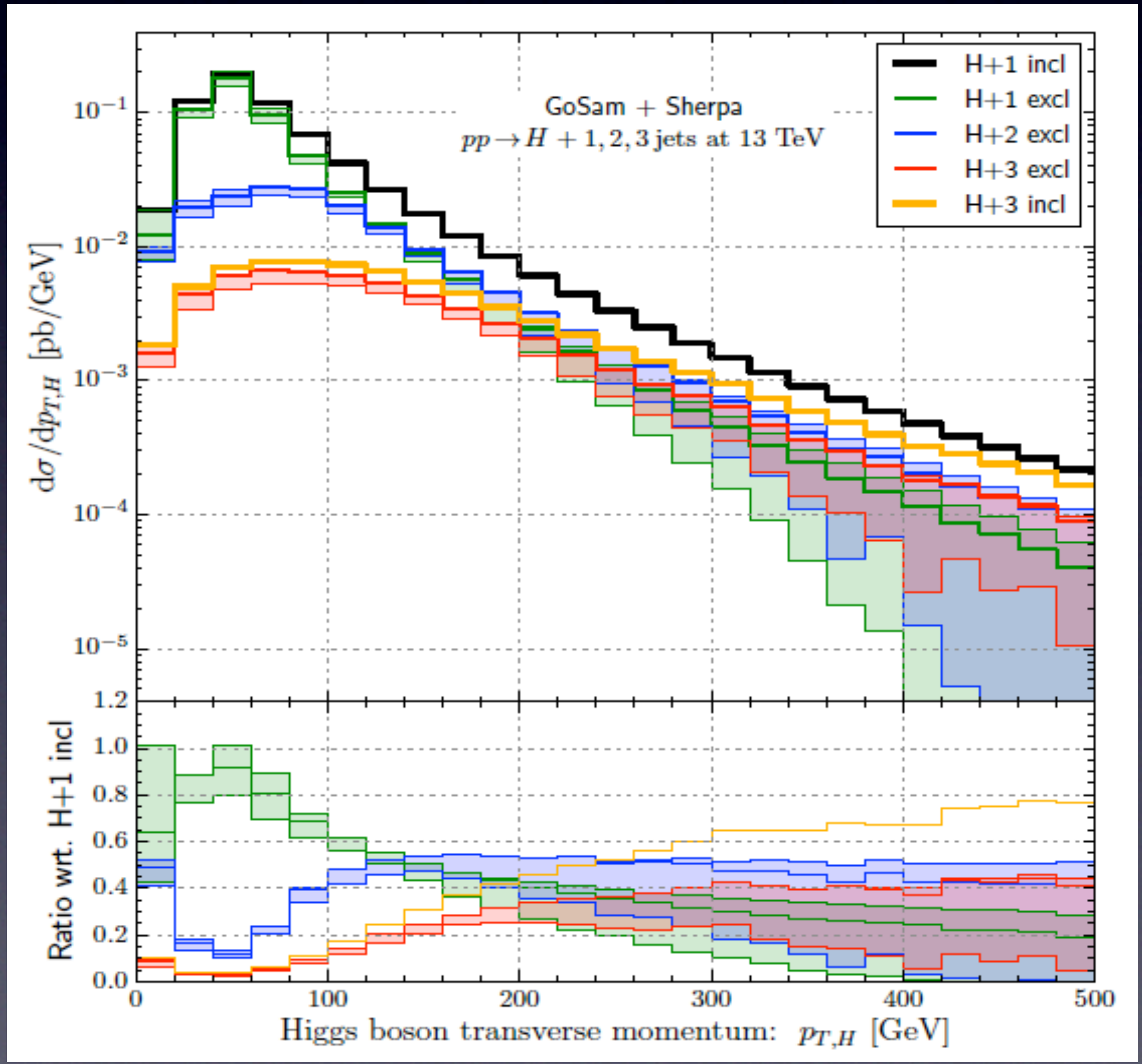
Hamilton & Frederix 1512.02663

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

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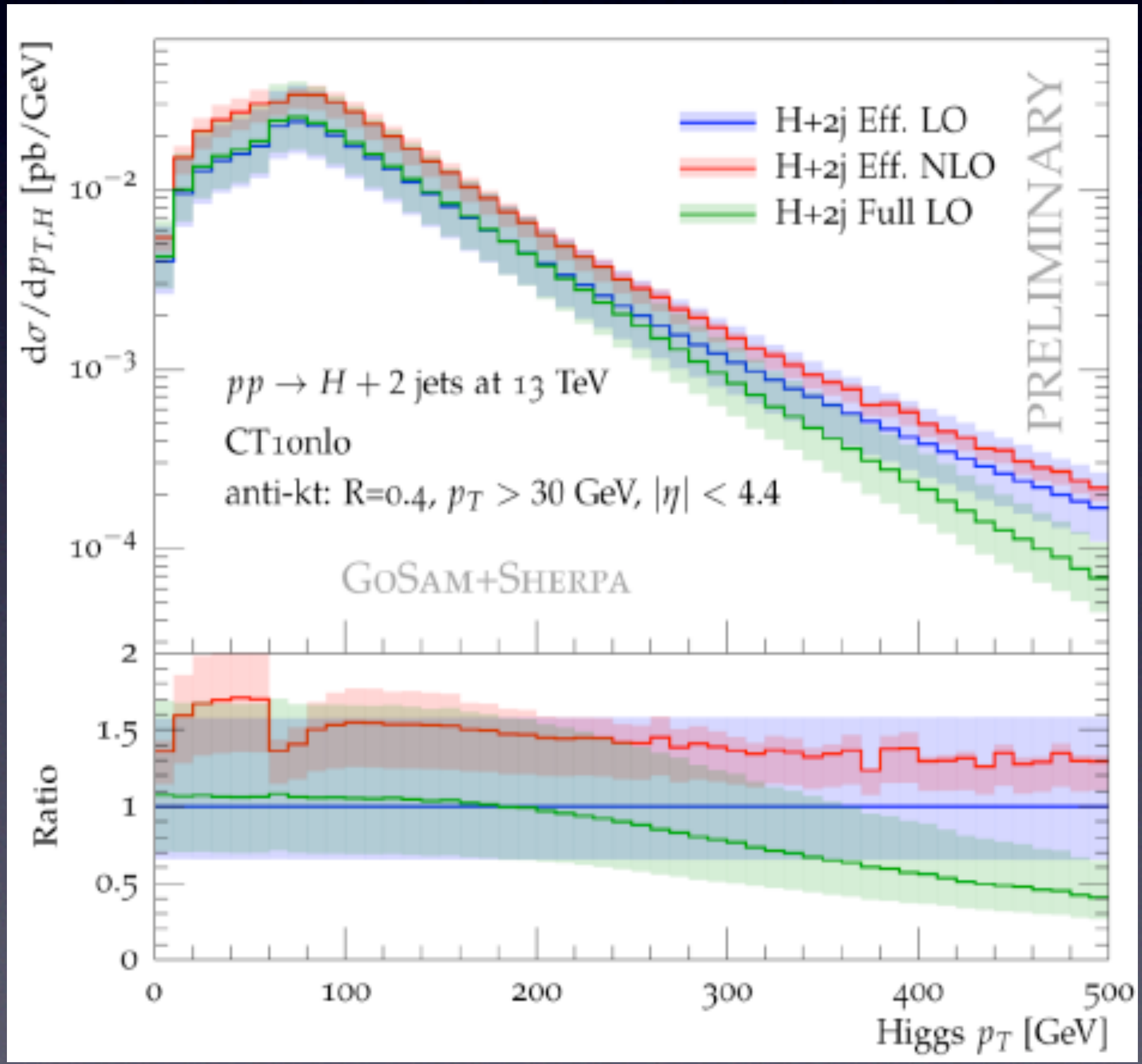
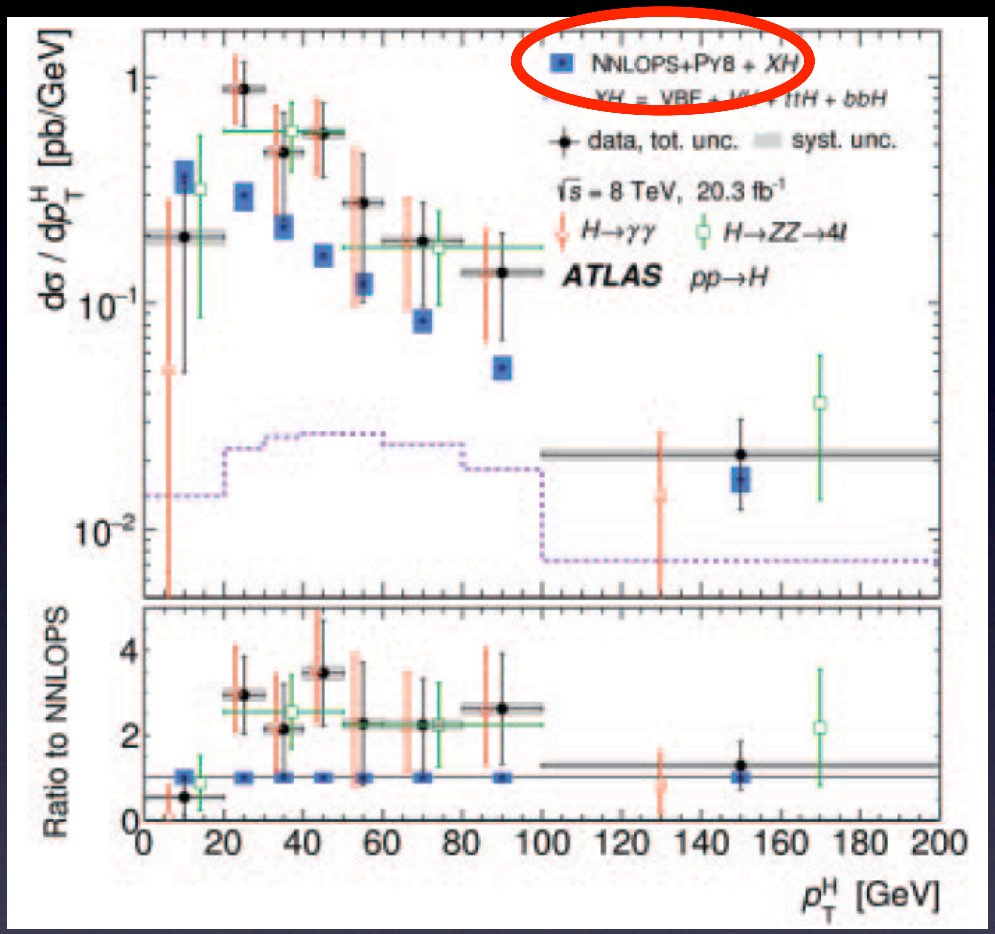


Measurement of Higgs pt



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

Room for improvement

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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.

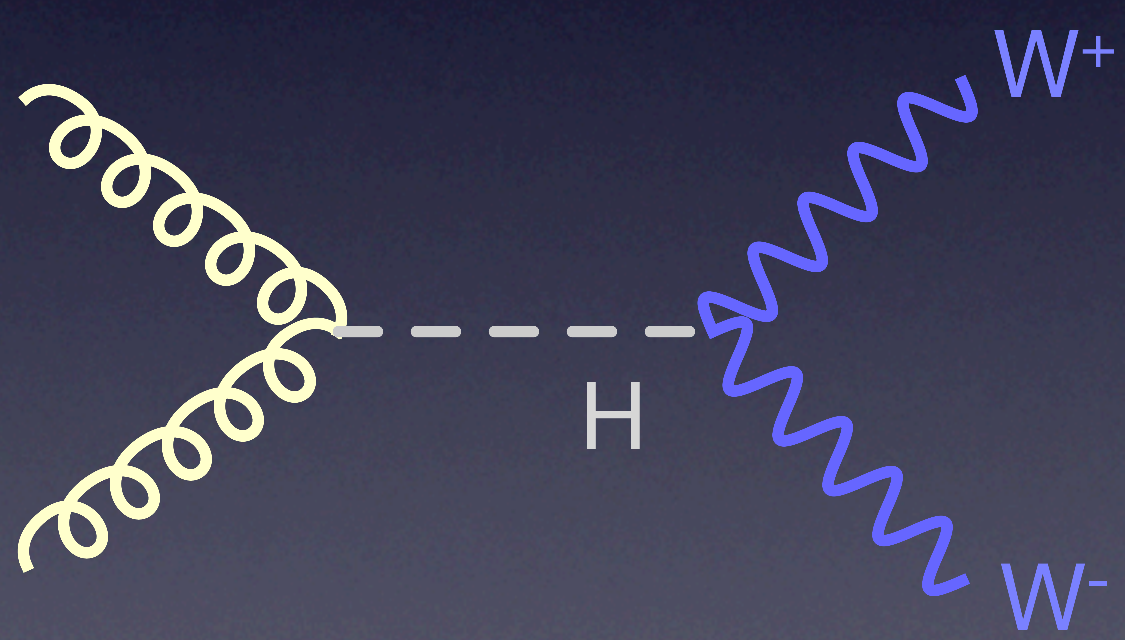
Crucial to reach percent accuracy on Higgs p_t spectrum and theoretical very interesting result (resummation of non-Sudakov logs)

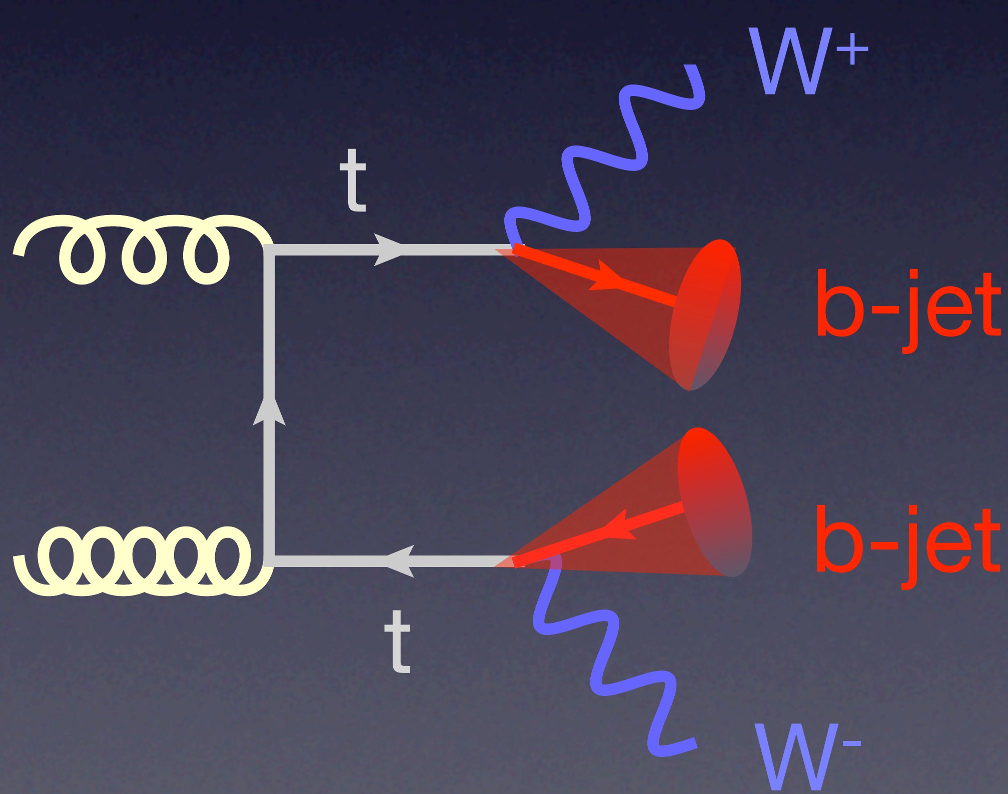
Melnikov, Penin 1602.09020

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)

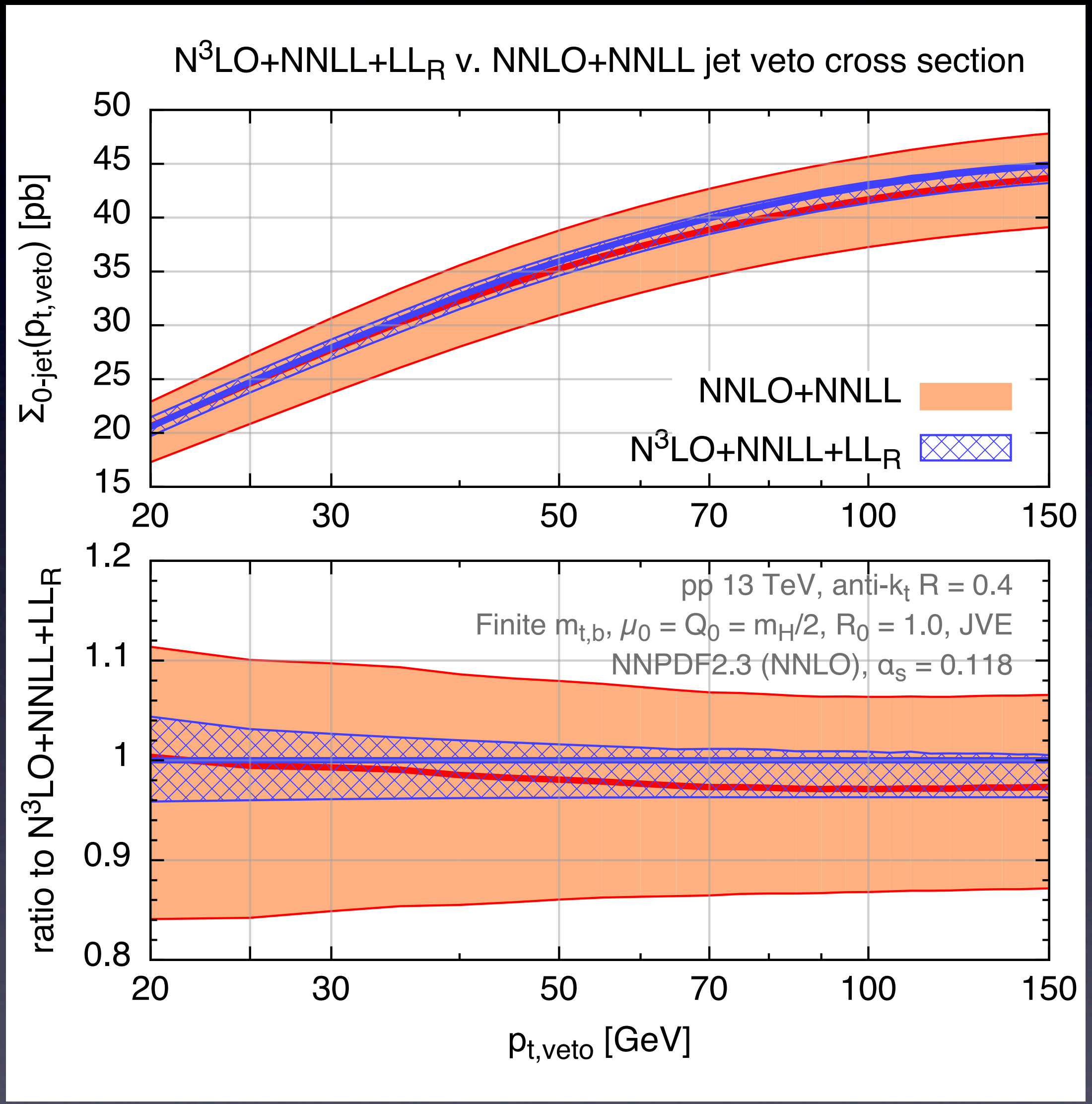




Improved jet-veto

Recently jet-veto predictions updated to include

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



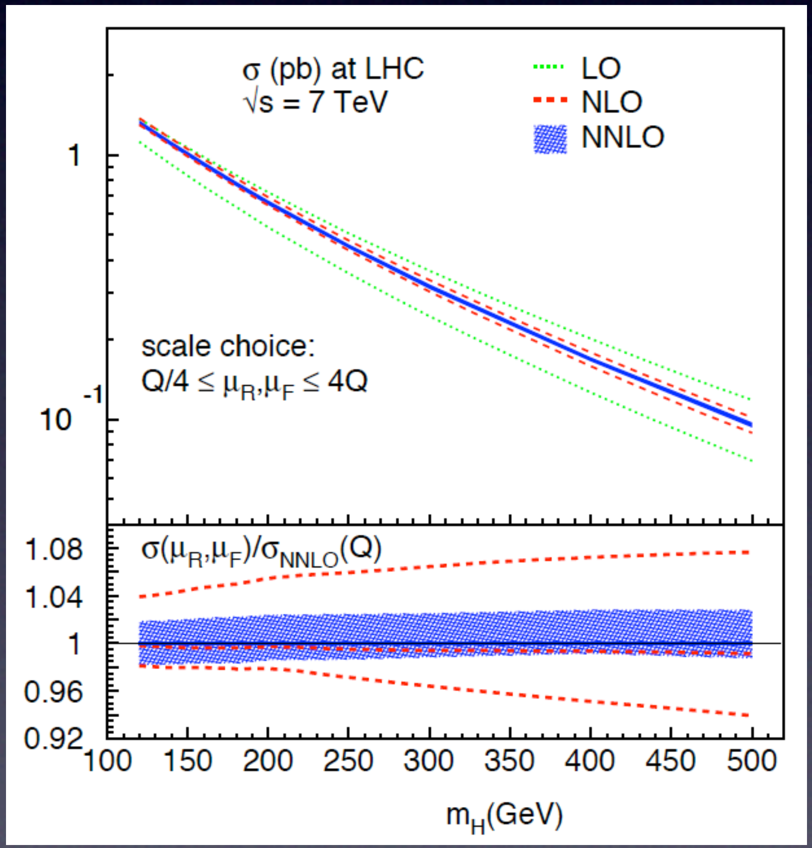
Few percent theory error (considerable reduction in the last years)

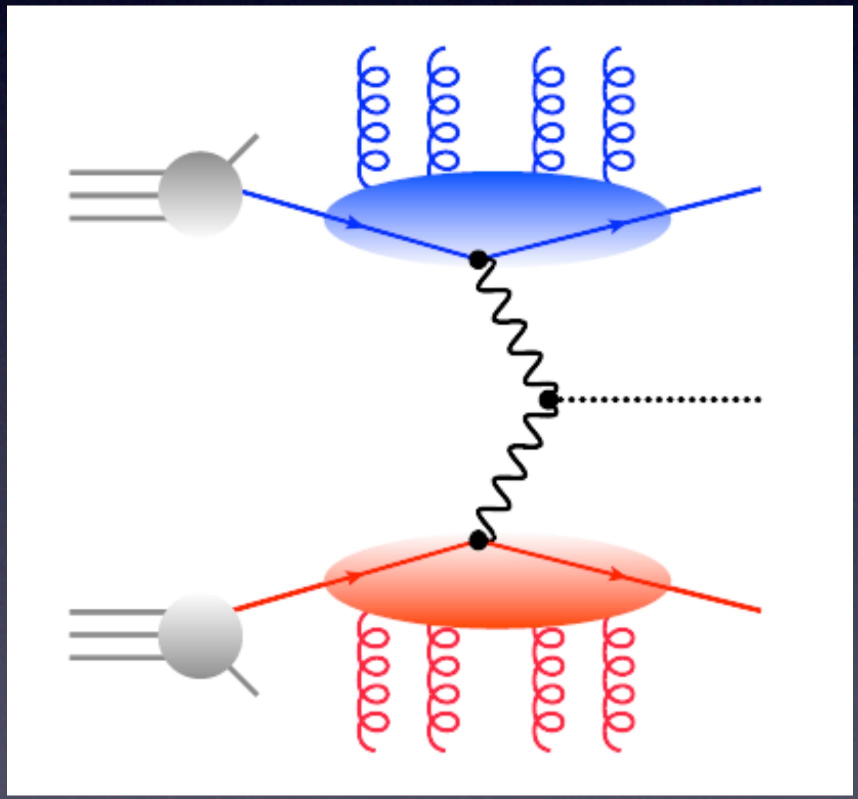
Banfi, Caola, Dryer, Monni, Salam, GZ, Dulat 1511.02886

Differential VBFH at NNLO

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

Bolzoni, Maltoni, Moch, Zaro '11





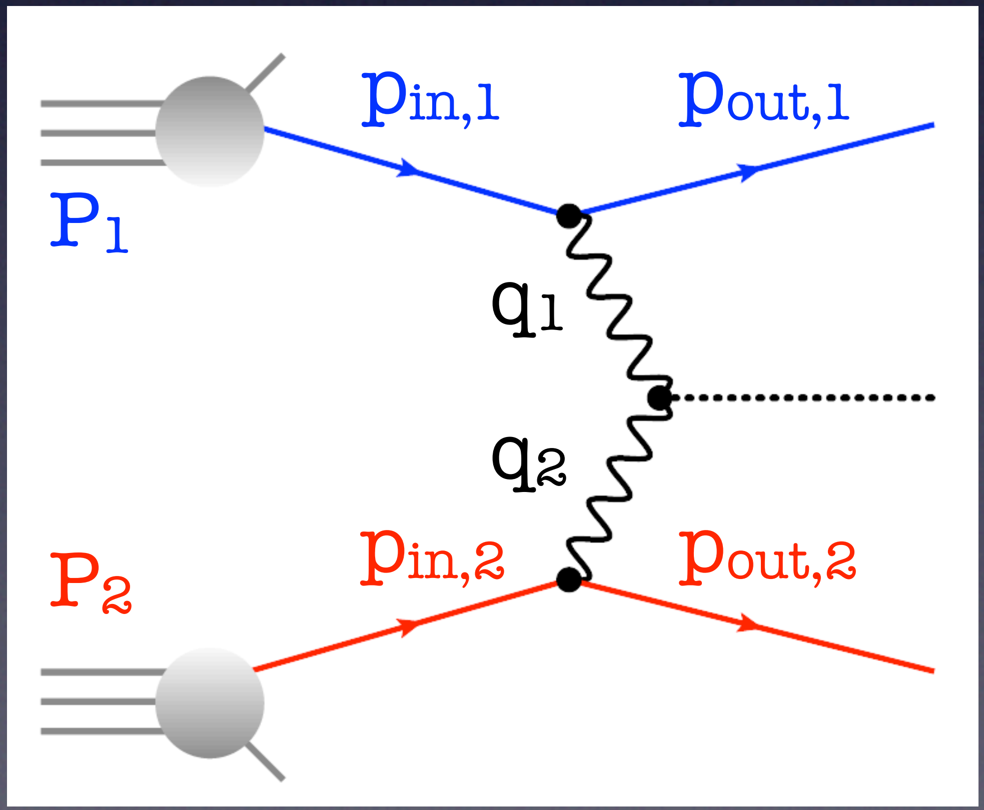
Inclusive calculation: tiny correction (~1%), tiny uncertainty (1-2%). Implies possibility to perform very accurate coupling measurements

Differential VBFH at NNLO

<u>Key observation:</u>

If the scattering is Born like, then the vector boson-momenta q_i, and on-shell conditions, fix the incoming and outgoing parton momenta:

$$p_{\rm in,i} = x_i P_i \qquad p_{\rm out,i} = x_i P_i - q_i \qquad x_i = \frac{q_i^2}{2 q_i P_i}$$



Differential VBFH at NNLO

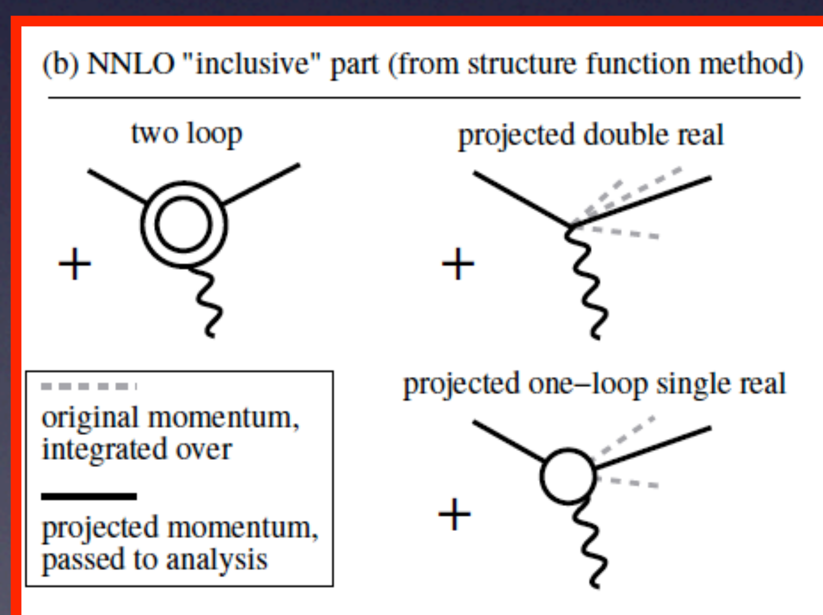
<u>Schematically:</u>

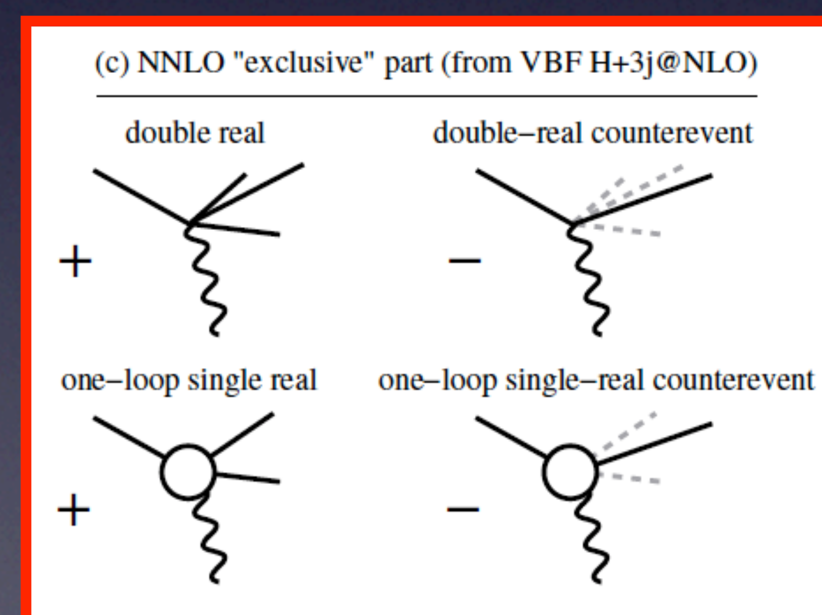
P2B = Projection to Born

[redacted]

$$\sigma = \int d\Phi_B (B + V) + \int d\Phi_R R$$

$$= \underbrace{\int d\Phi_B (B + V) + \int d\Phi_R R_{P2B}}_{\text{From inclusive contribution}} + \underbrace{\int d\Phi_R R - \int d\Phi_R R_{P2B}}_{\text{Finite, from exclusive contribution}}$$



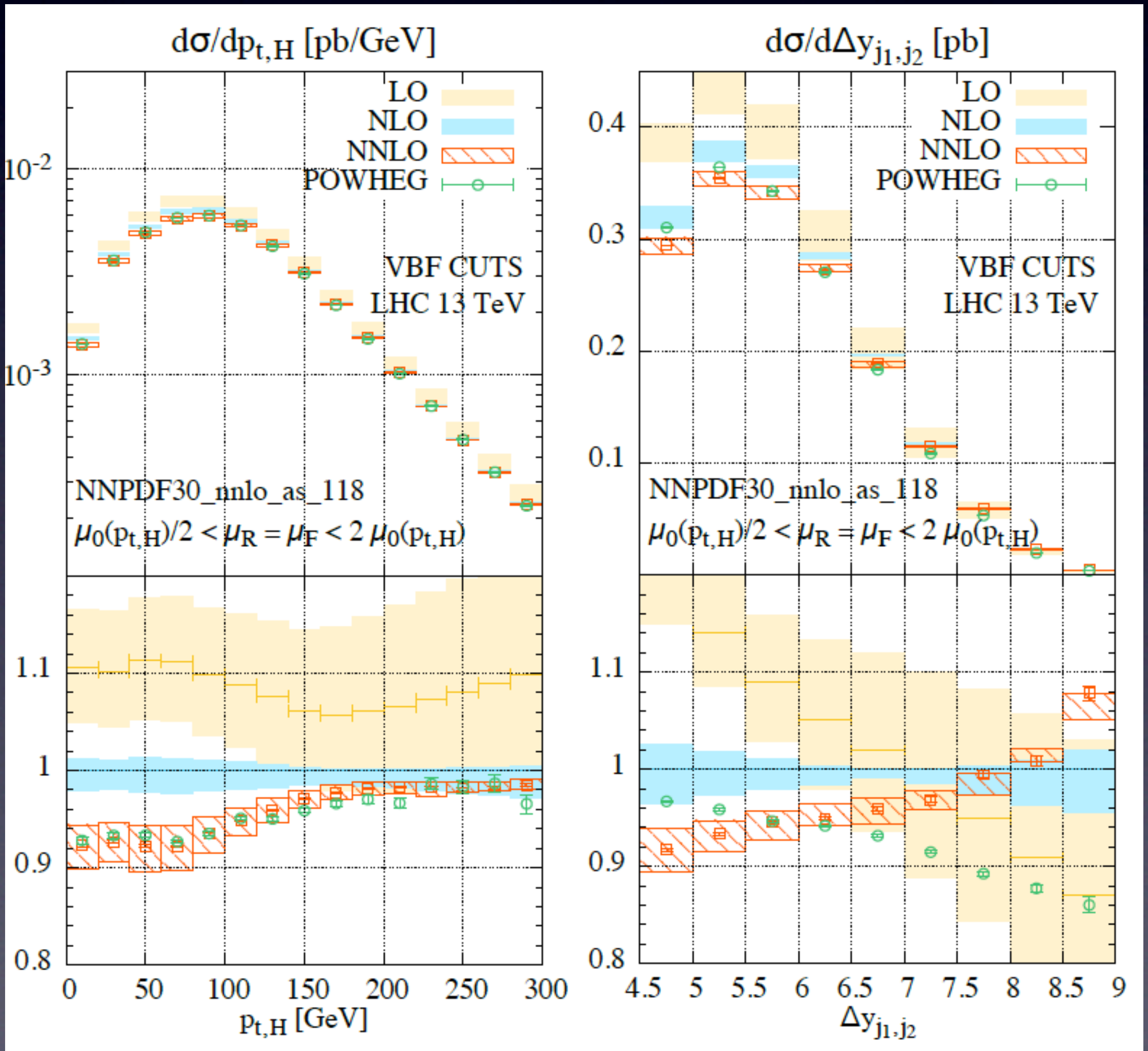


The sum gives thus the complete, fully differential NNLO result

Differential VBFH at NNLO

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

Cacciari, Dreyer, Karlberg, Salam, GZ 1506.02660



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

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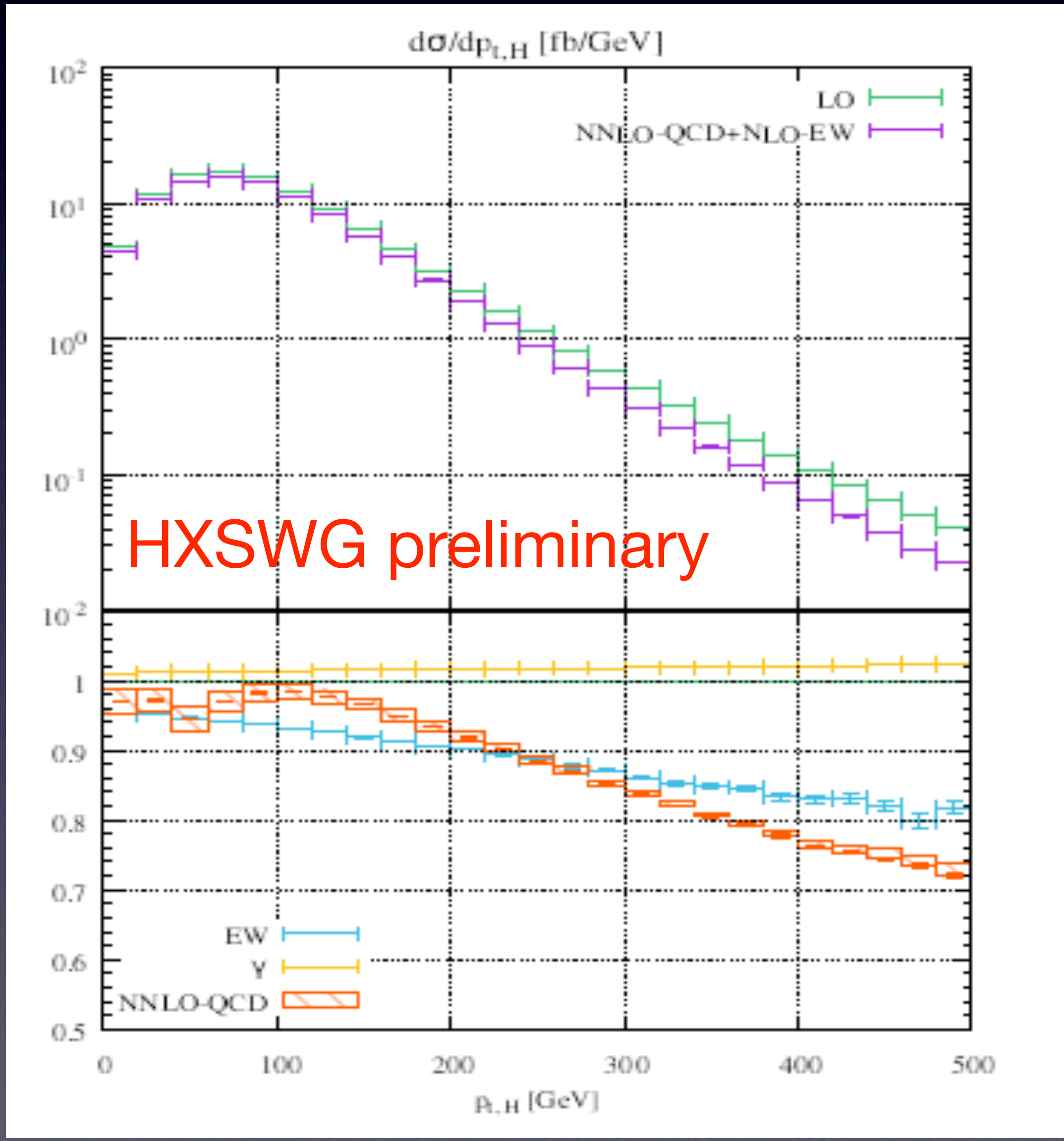


- Allows to study realistic observables, with realistic cuts
- NNLO corrections much larger (10%) than previously thought
- NNLO QCD merged to NLO EW within the HXSWG
- Nice example of HXSWG activity
  - ✓ obtain best predictions by combining different ones
  - ✓ assign overall theoretical error

Associated HV production

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

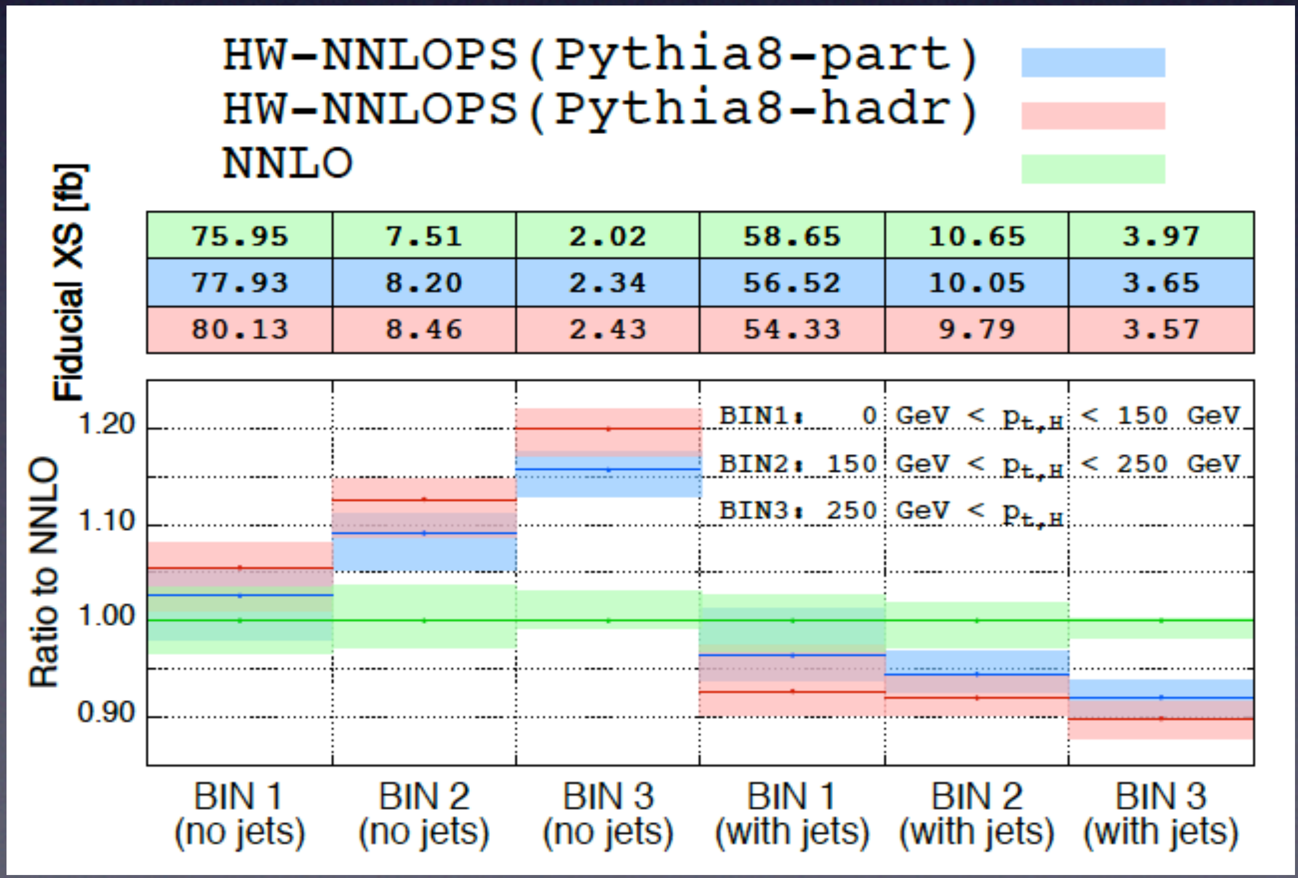
Ferrera, Grazzini, Tramontano ’11-’14

Recently NNLO calculation matched to parton shower for HW

Astill, Bizon, Re, GZ 1603.01620

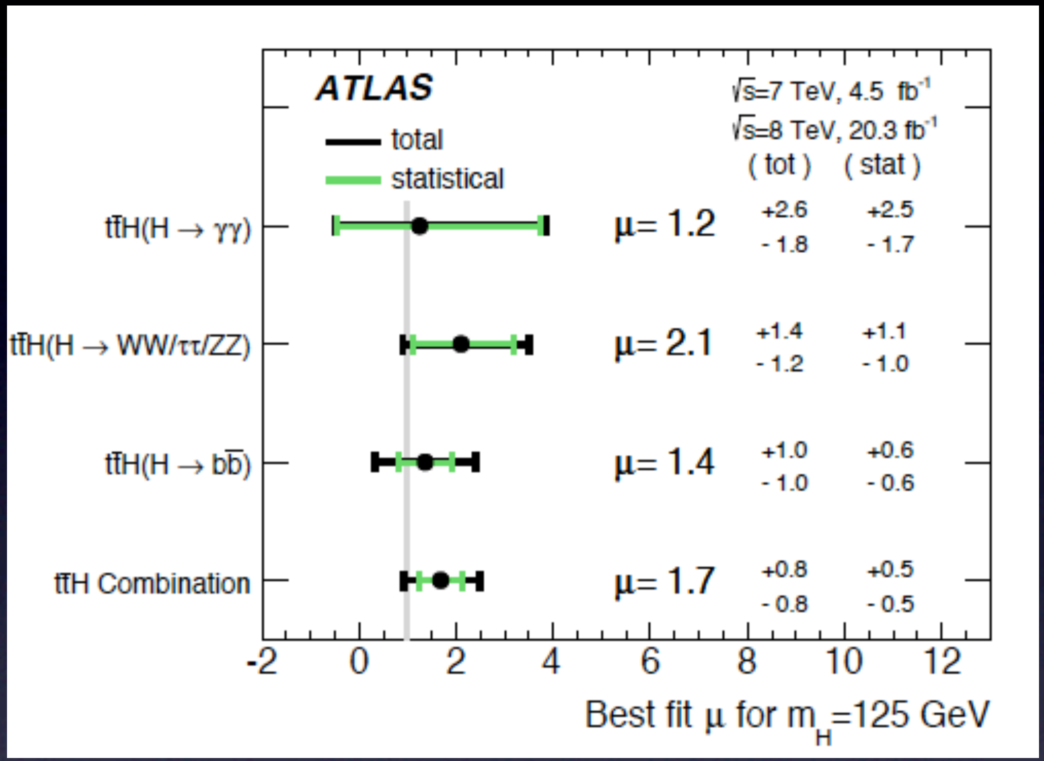
Parton shower and hadronization cause migration between jet-bins

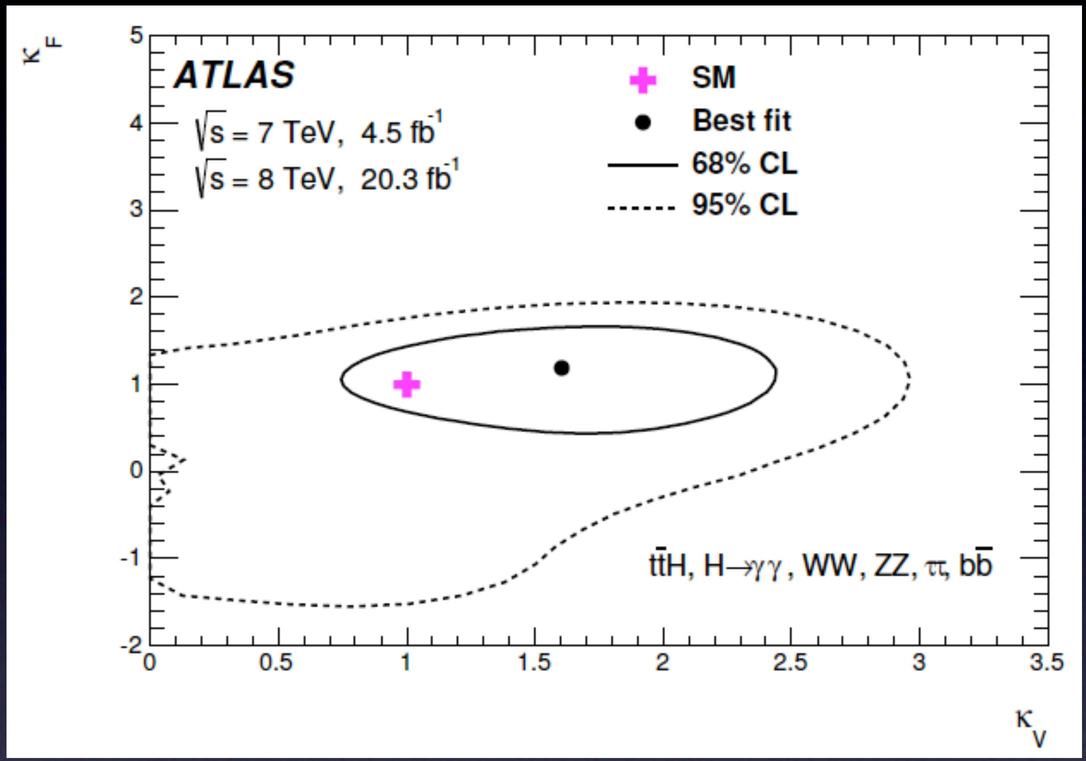
Difficult to reach high accuracy in jet-binned observables



ttH production

ATLAS 1604.03812 [similar results from CMS]

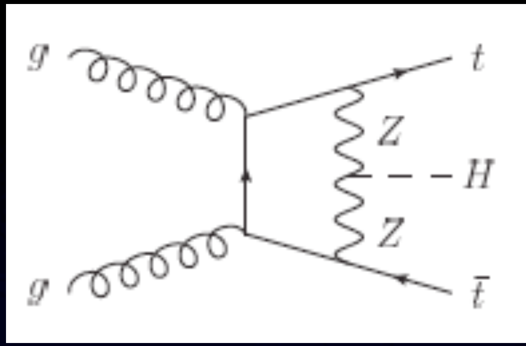


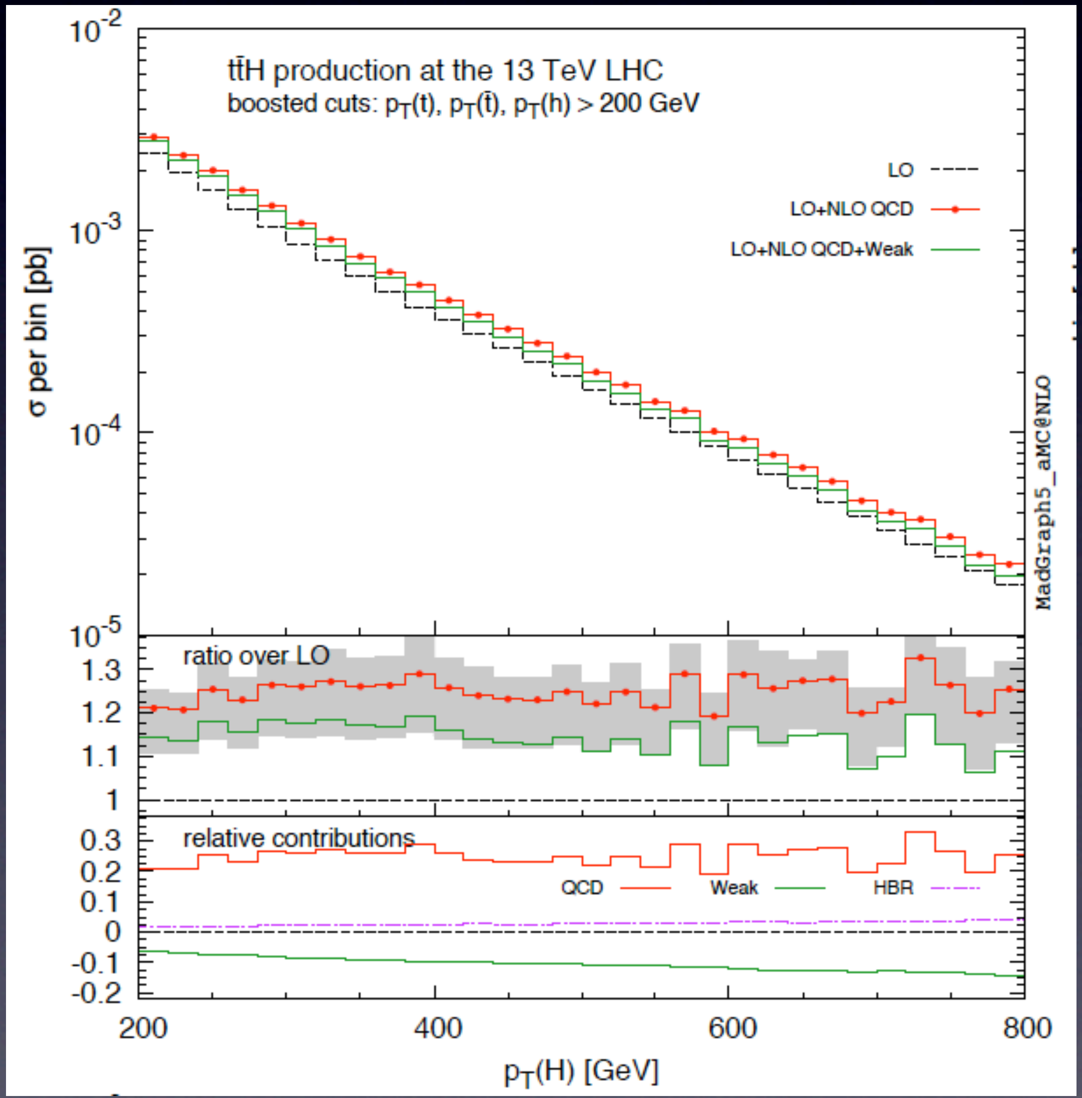


- ttH difficult at the LHC (limited by statistics and difficult backgrounds)
- current limits (7+8 TeV): about 3 times the SM expectation
- sensitive to top-Yukawa coupling. Fits done using the κ framework

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

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

H+ photon production

Gabrielli et al. 1601.03656

$\sigma_{(p_T^{\gamma,j}>30\text{GeV})}$	No γ $(H)_{14\text{TeV}}$	With γ $(H\gamma)_{14\text{TeV}}$	No γ $(H)_{33\text{TeV}}$	With γ $(H\gamma)_{33\text{TeV}}$	No γ $(H)_{100\text{TeV}}$	With γ $(H\gamma)_{100\text{TeV}}$
$gg, gq, q\bar{q}$	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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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

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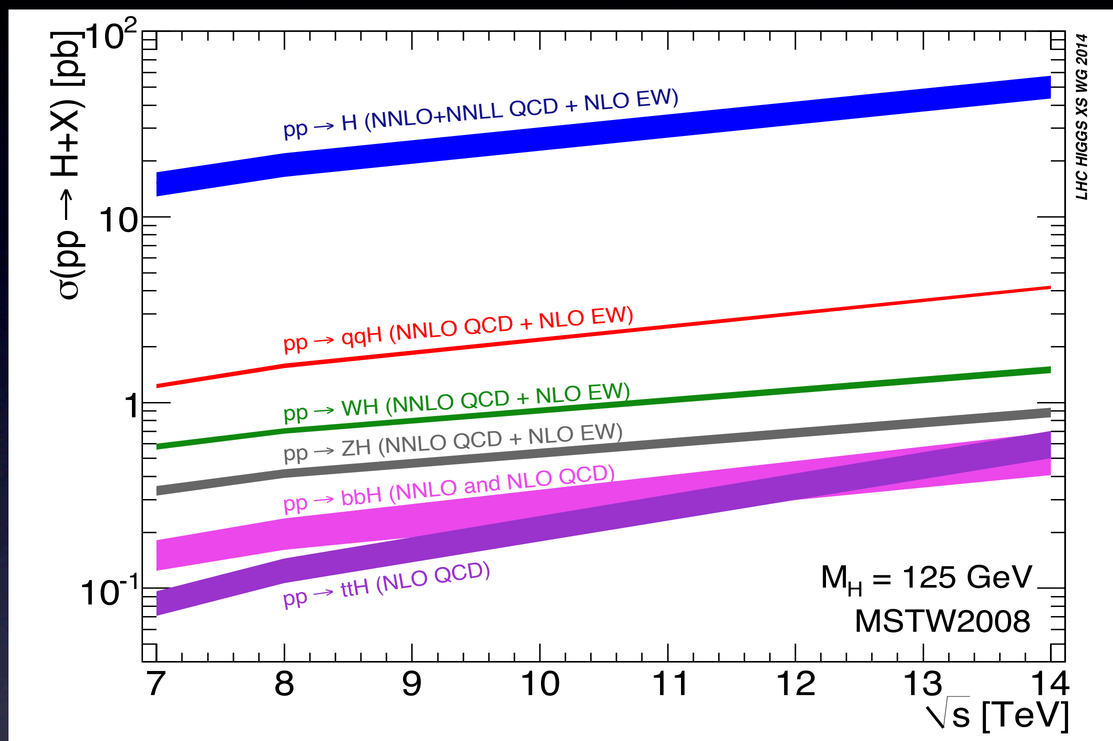
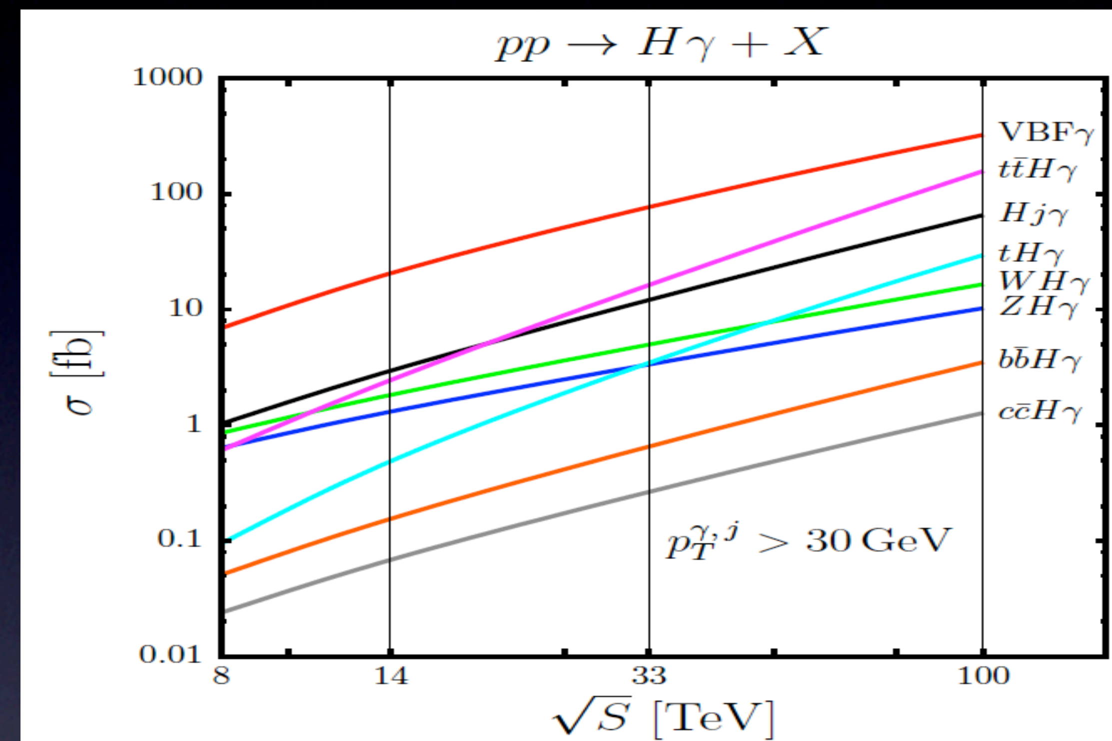


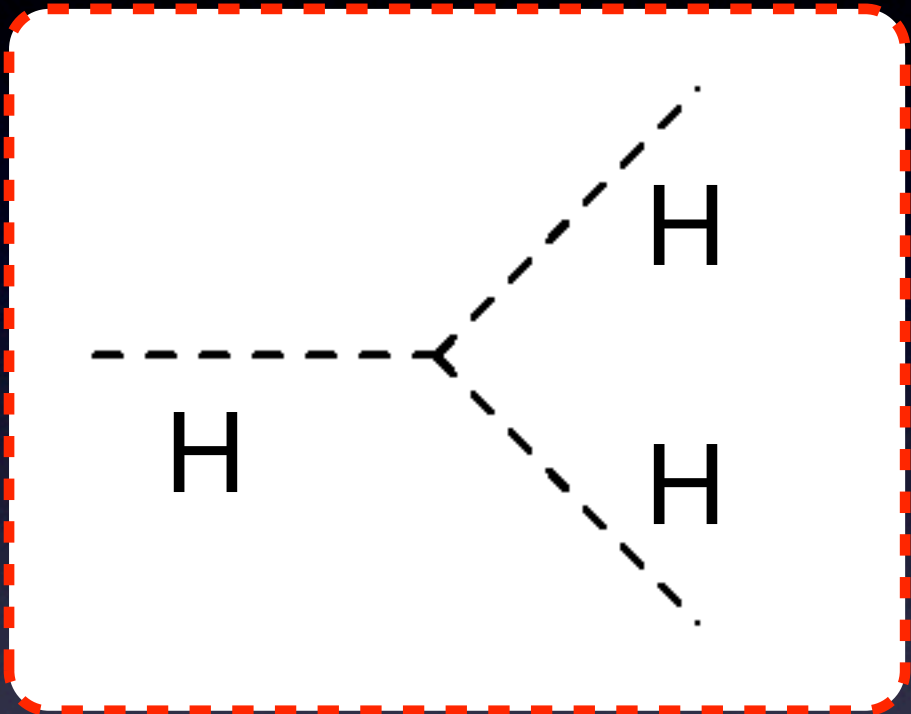


➡ tests of H-γ interactions

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

➡ searches for resonant three-photon final states

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: $\lambda_3 = \lambda_4 = \frac{m_H^2}{2v^2}$

- 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?

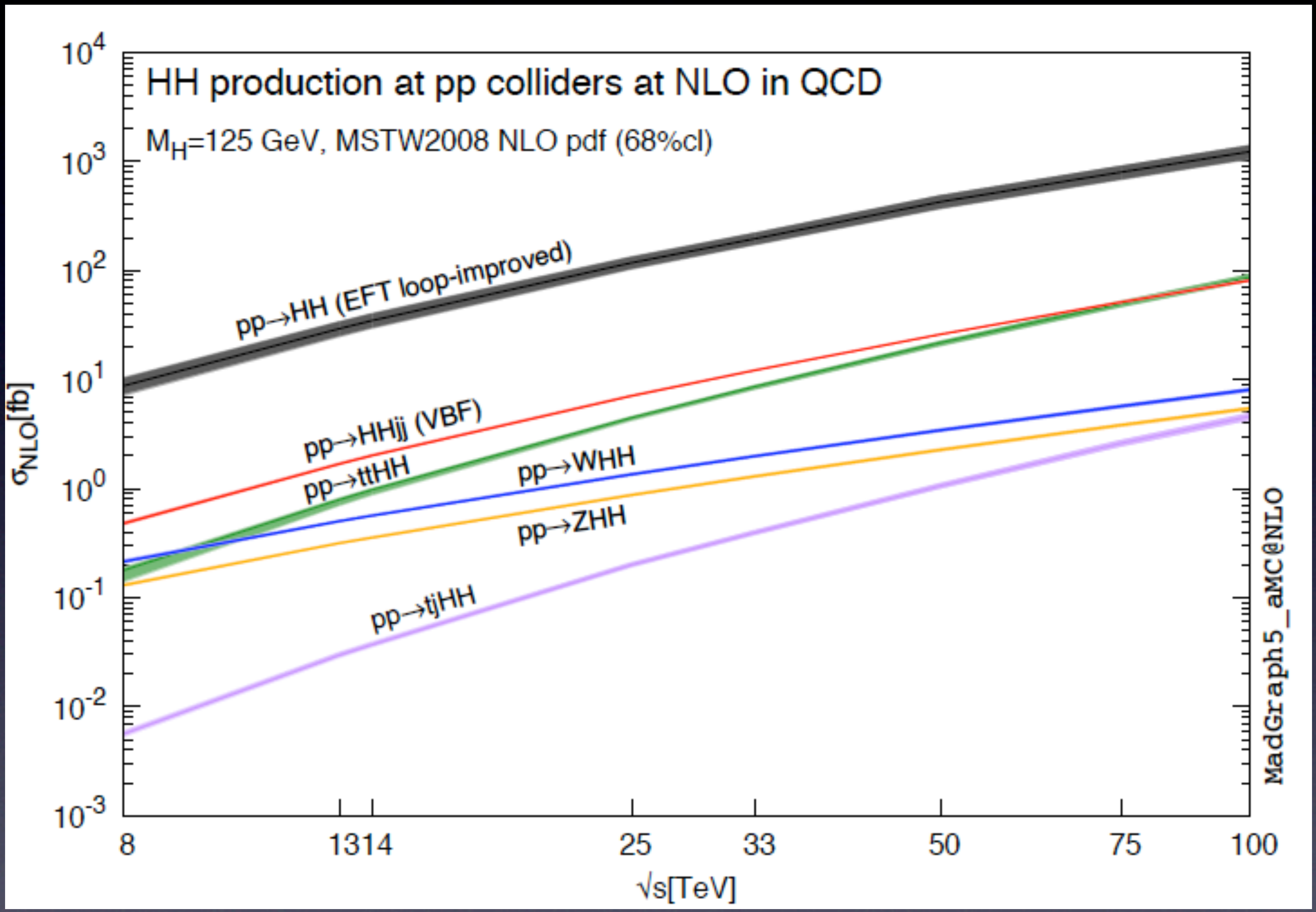
The Higgs self-coupling

Suitable process: Higgs pair production but sensitivity limited from box and interference 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

CMS: bb$\gamma\gamma$, bbbb 1503.04114, CMS-PAS-HIG-13-032

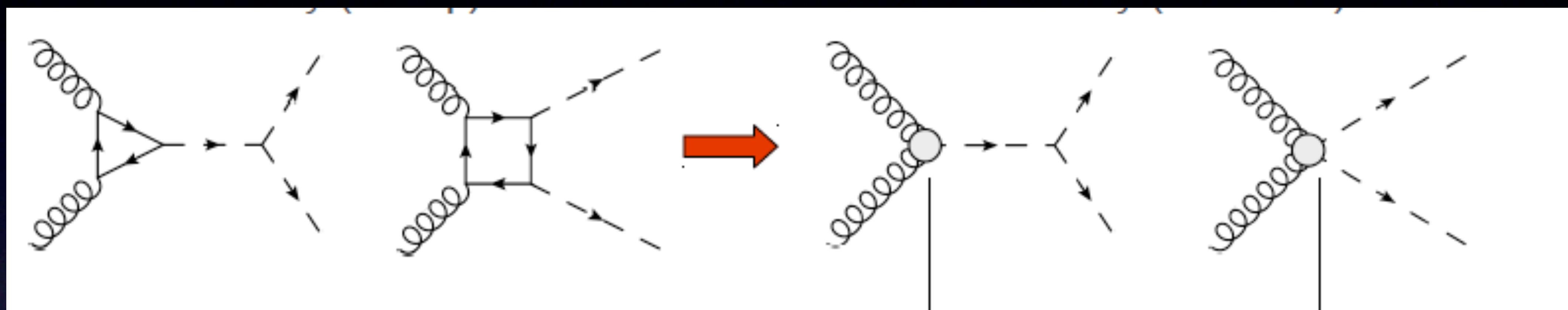
ATLAS: bb$\tau\tau$,$\gamma\gamma$WW*,bb$\gamma\gamma$,bbbb 1506.00285, 1406.5053, 1509.04670

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

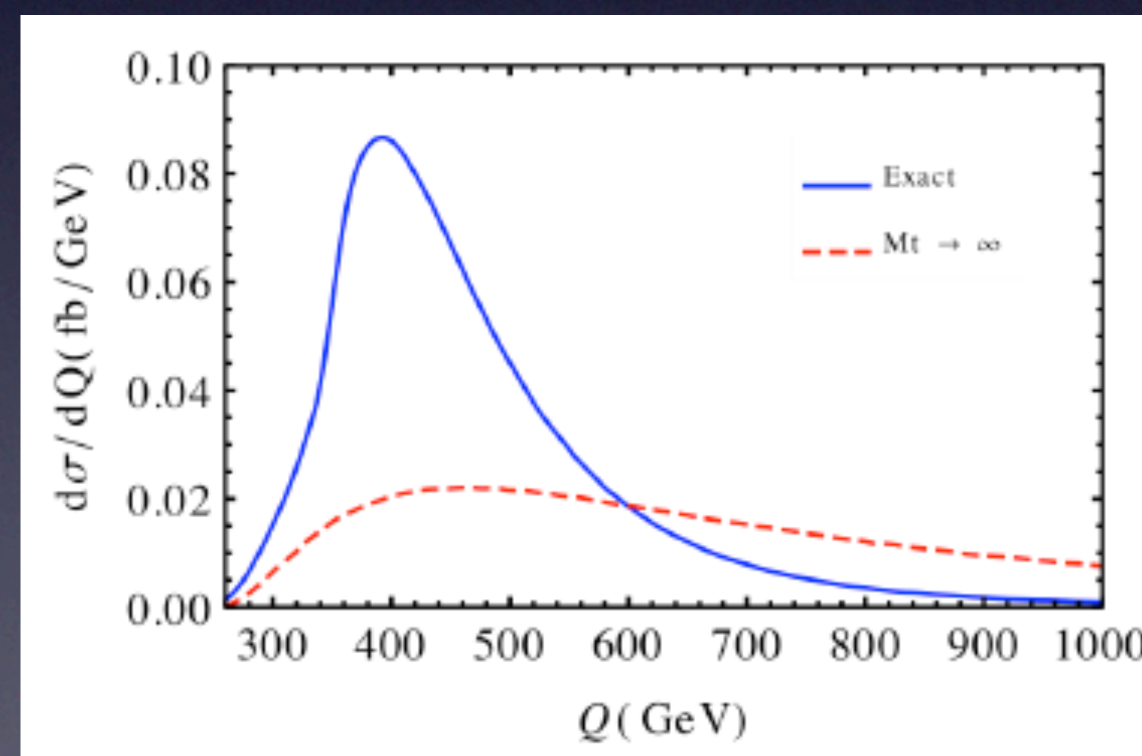
As for single Higgs production use effective theory (EFT):



Does it work at leading order?

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

Still, adopt same strategy as for single Higgs: compute higher-order corrections in the EFT and normalize by the exact Born



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

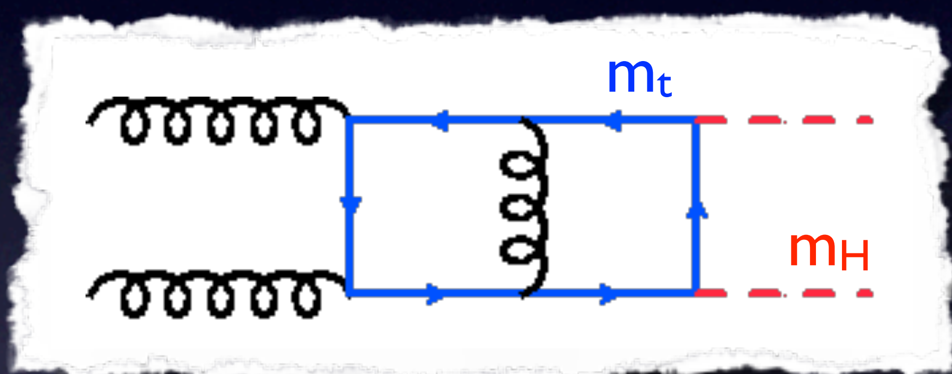
Li, Yan, Zhao ’13; Maierhoefer et al ’14; Frederix et al ’14

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

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

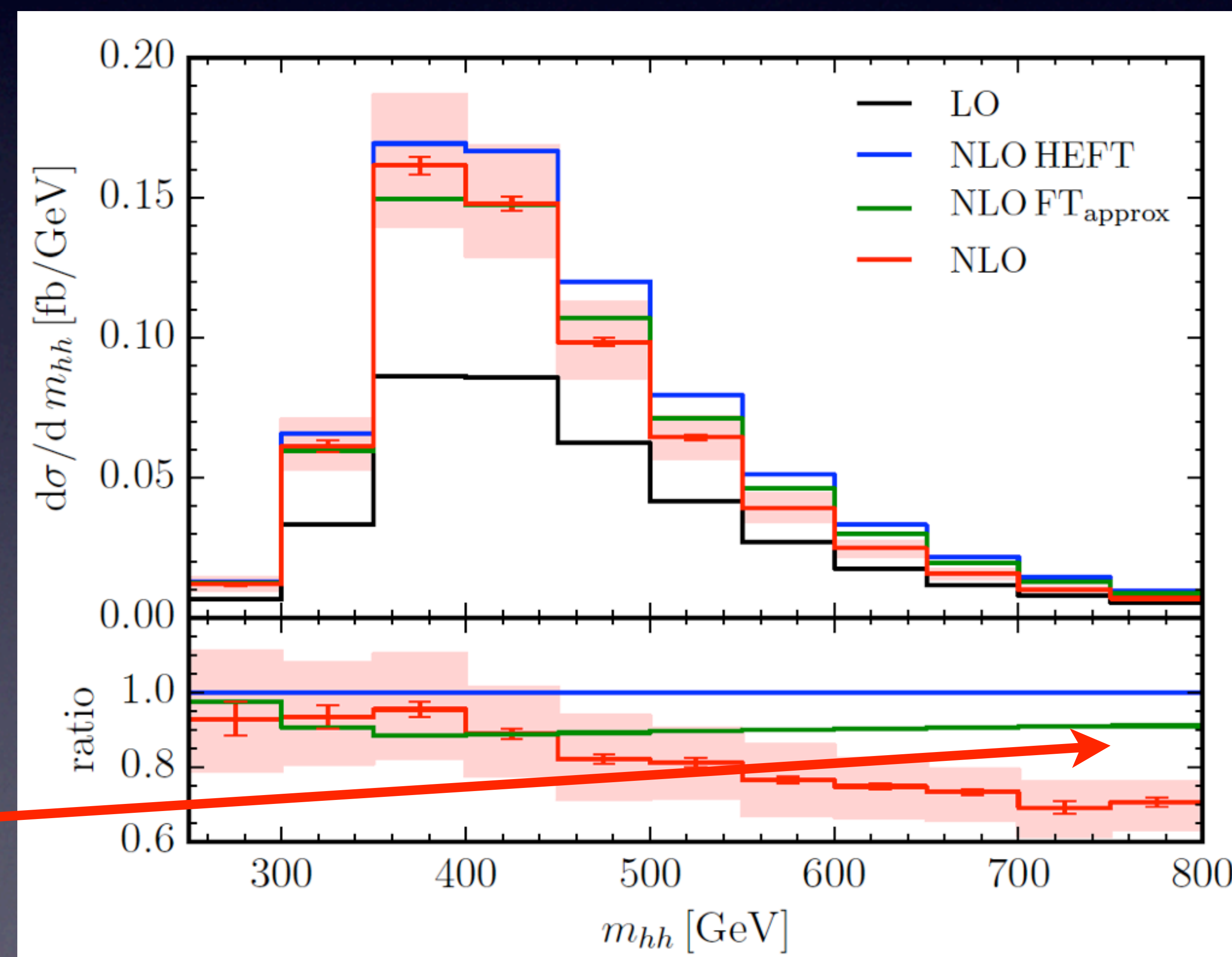
State-of-the-art predictions for HH

Exact NLO calculation of mass-effects requires (among other ingredients) two-loop box integrals with different internal and external masses



not known analytically

computed numerically only recently Borowka et al. 1604.06447



Previous approximations not that good at high m_{HH}!

[see talk of G. Heinrich]

Prospects for HH

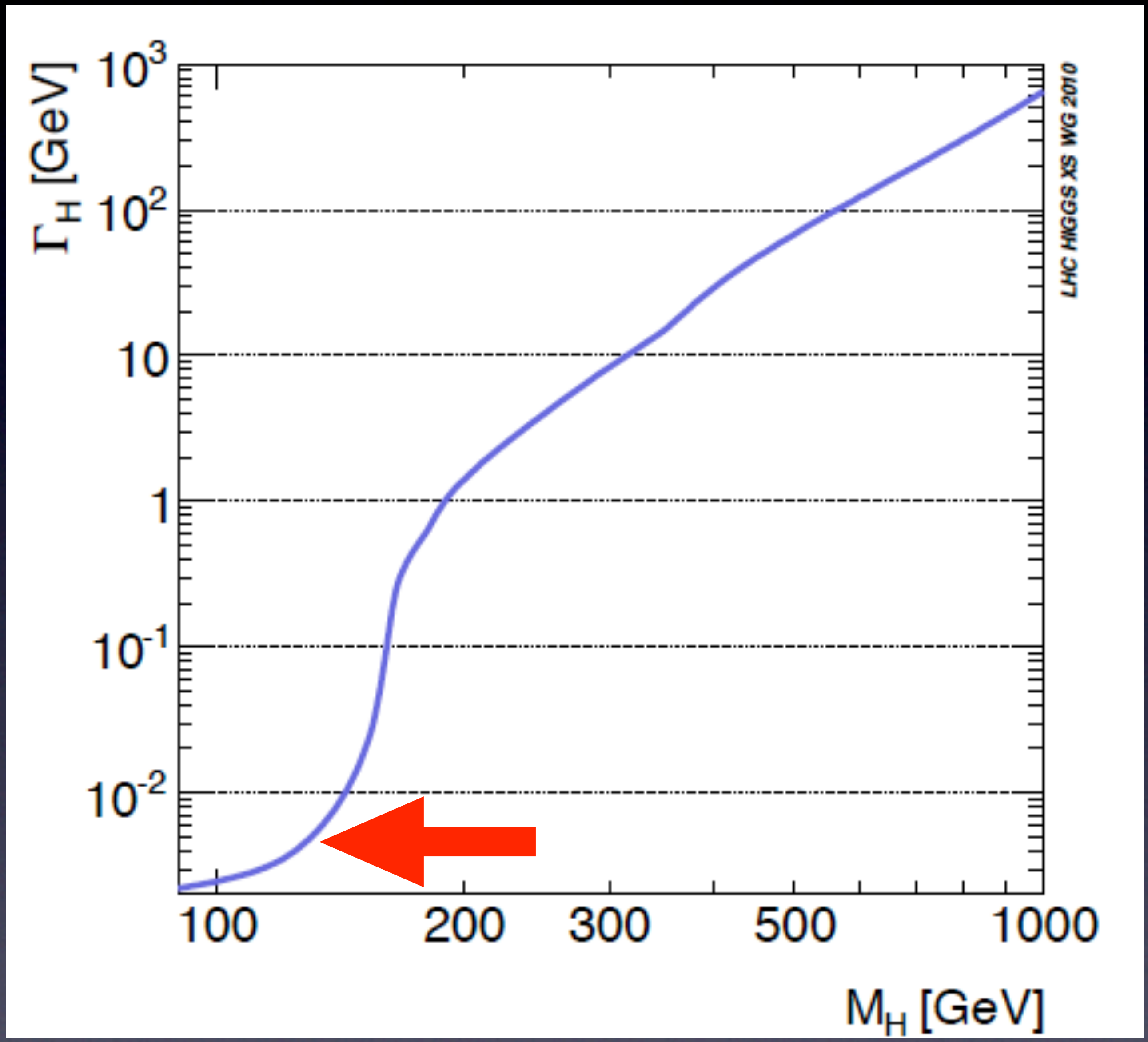
Studies performed so far suggest that

- 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



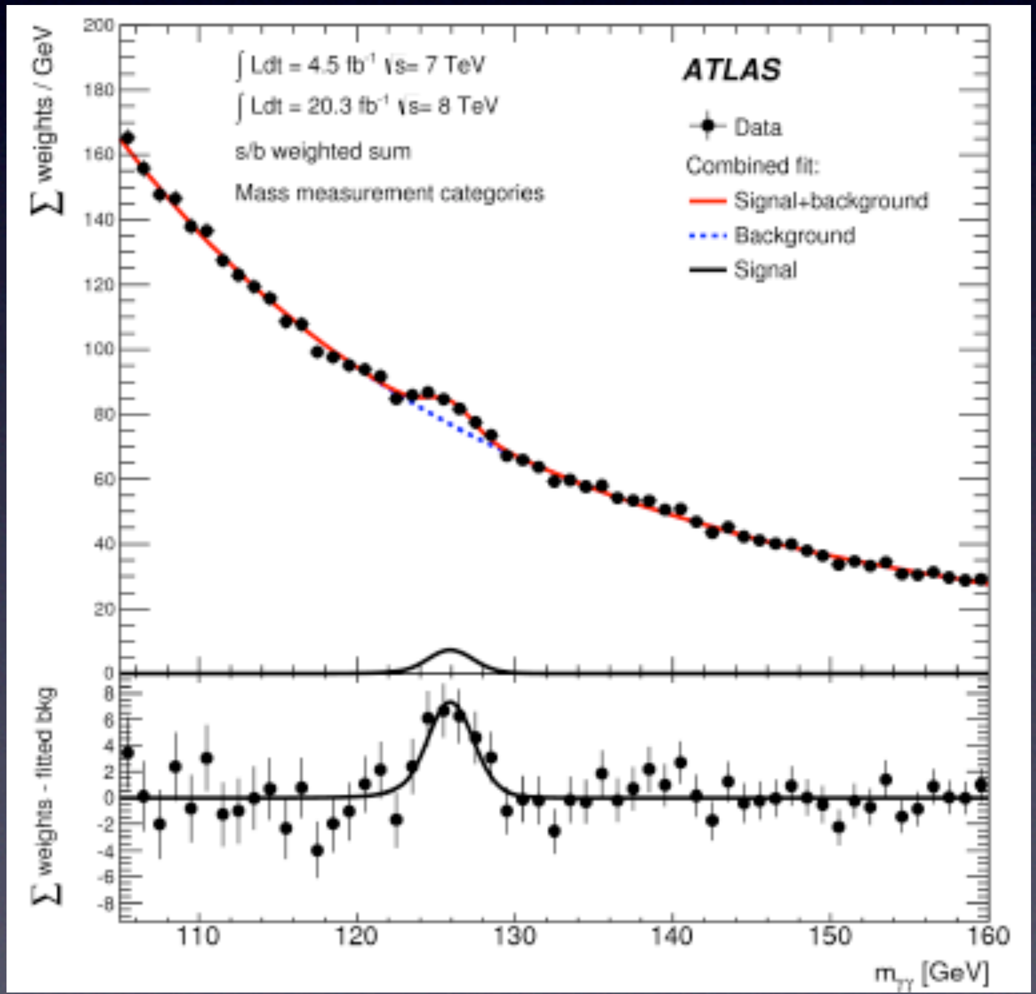
In the SM for M_H = 125 GeV
Γ_H = 4 MeV (very very narrow!)

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



Current direct bounds

✓Γ_H < 5 GeV (ATLAS, $\gamma\gamma$)

✓Γ_H < 2.6 GeV (ATLAS, ZZ)

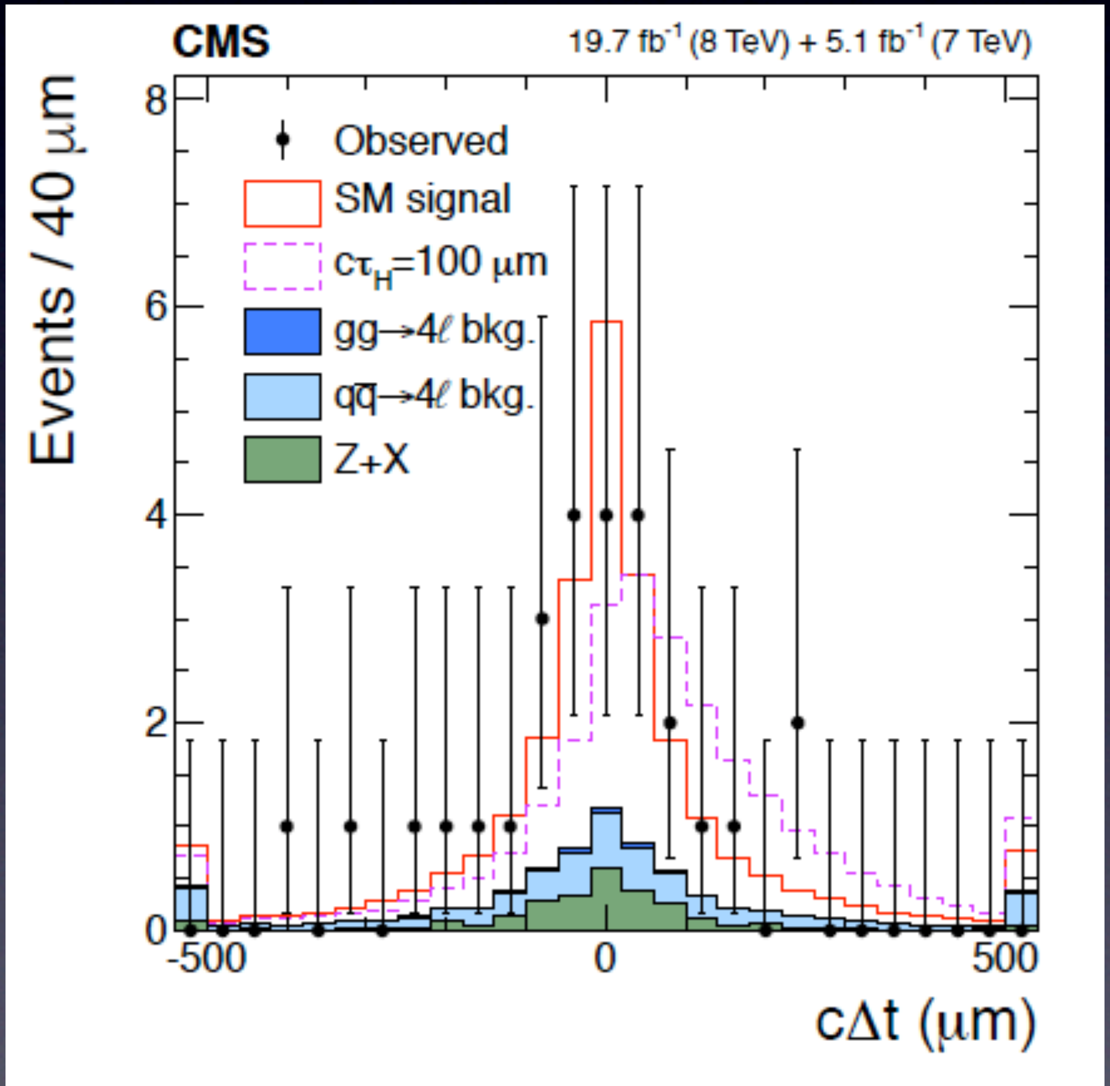
✓Γ_H < 1.7 GeV (CMS)

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:

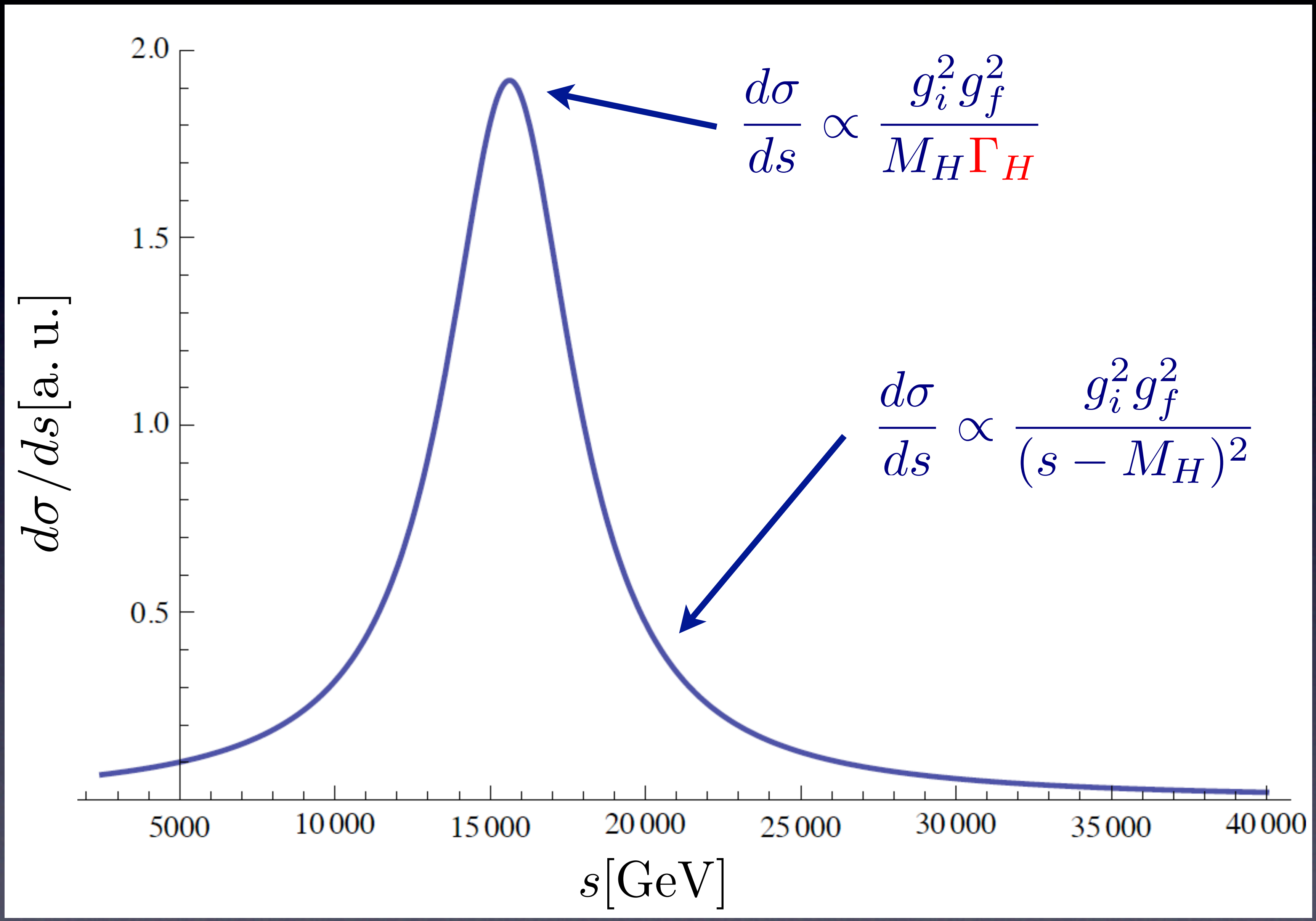
$$c\tau_H < 57\mu\text{m} \Rightarrow \Gamma_H > 3.5 \cdot 10^{-9}\text{MeV}$$

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

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

Breakthrough idea

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



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

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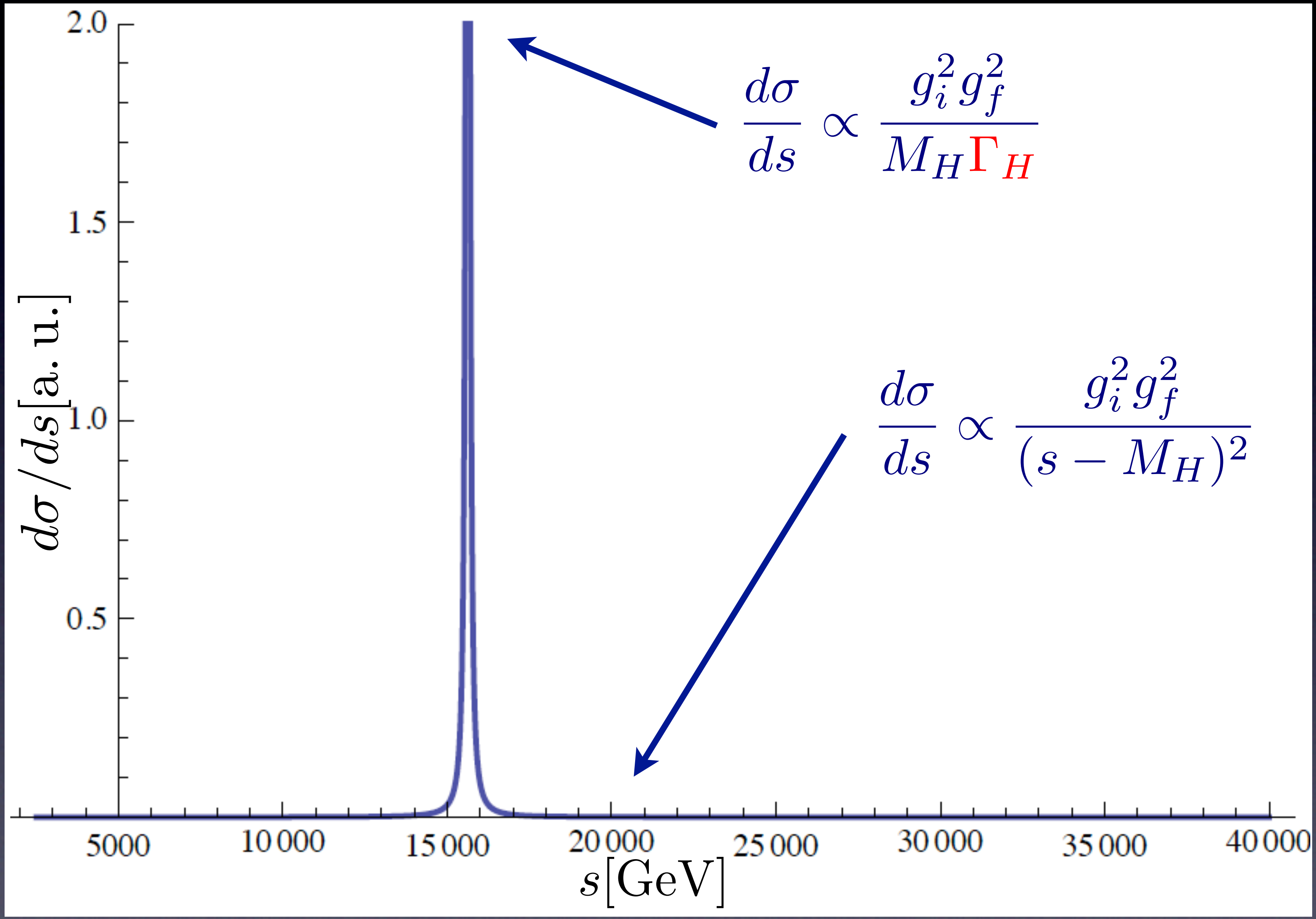
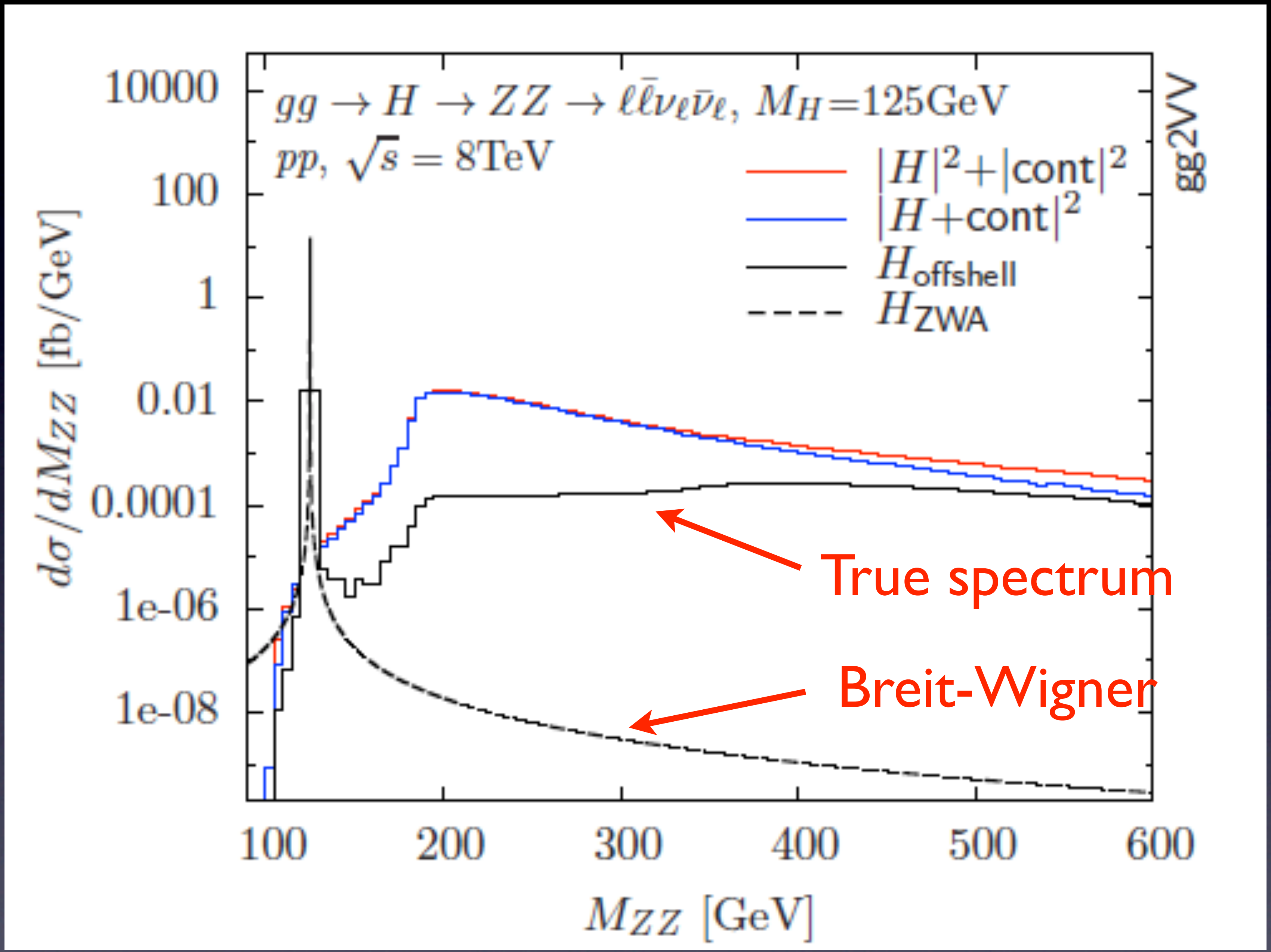


But the Higgs resonance is narrow! Is there anything in the tail?

YES!

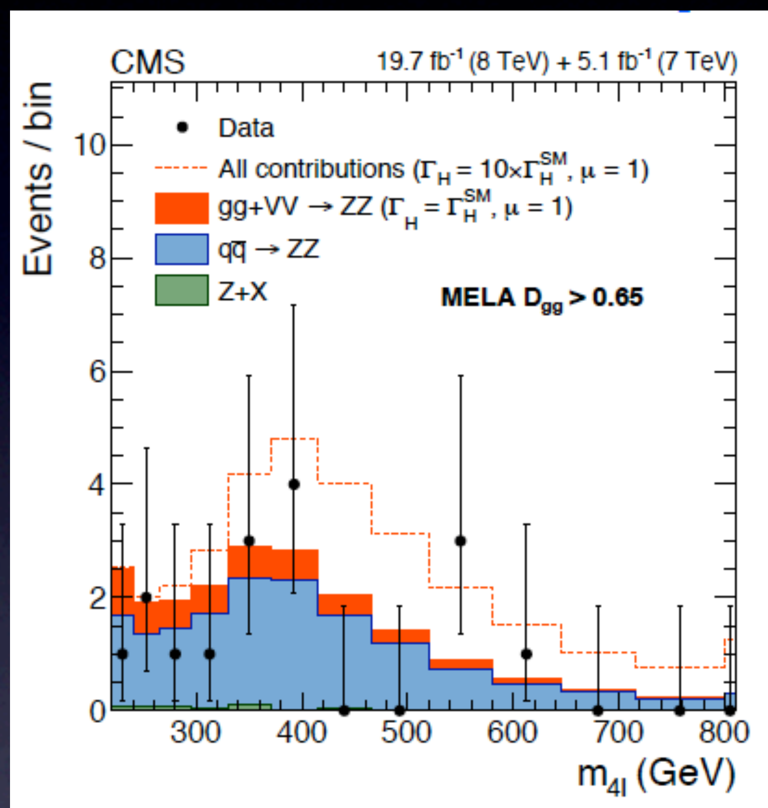


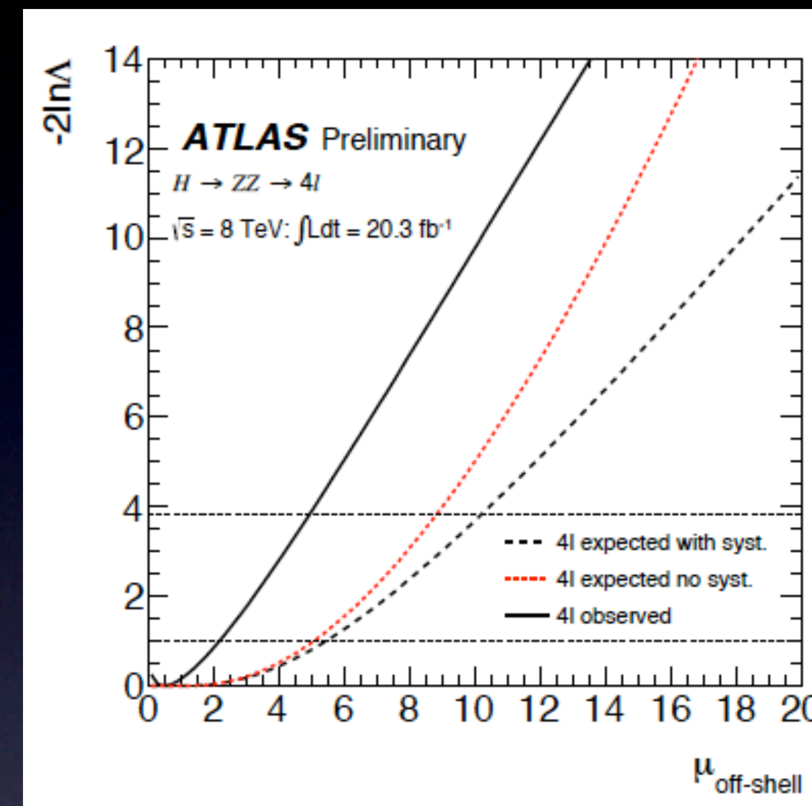
Kauer, Passarino

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





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

- assumes negligible difference between on-shell / off-shell couplings
- limits using other channels possible [see talk of J. Campbell]
- BUT important to control of off-shell cross-sections/backgrounds/ interference contributions (lots of work left to be done ...)

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☺)

Stay tuned!