Status of Precision SM Higgs Cross Sections and Branching Ratio Calculations

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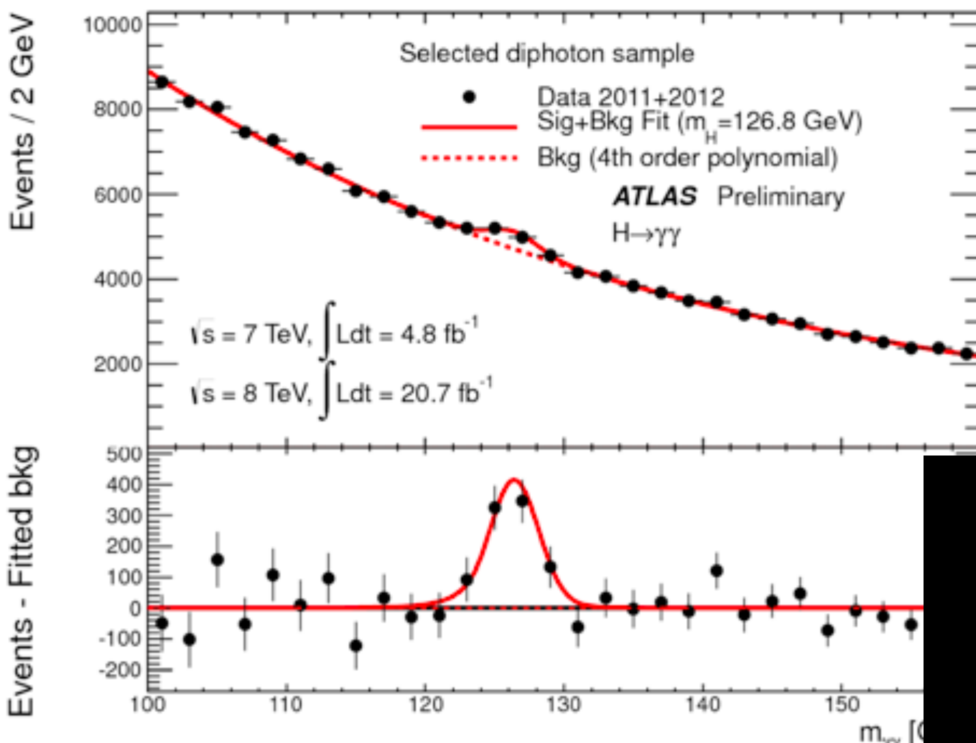
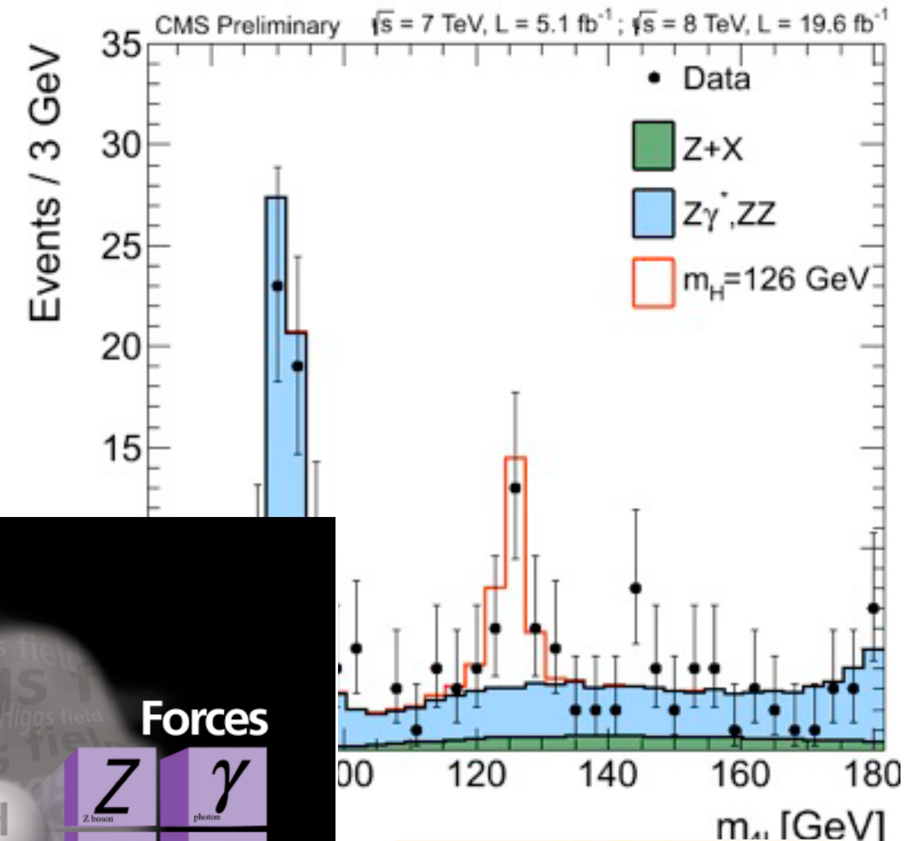
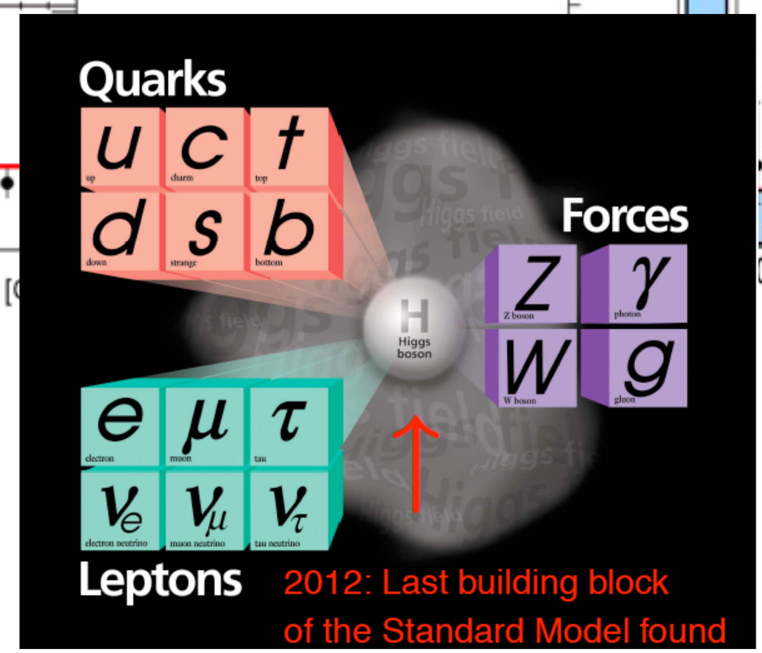
SUSY 2015, August 23-29, Lake Tahoe, California

The LHC circa 2012



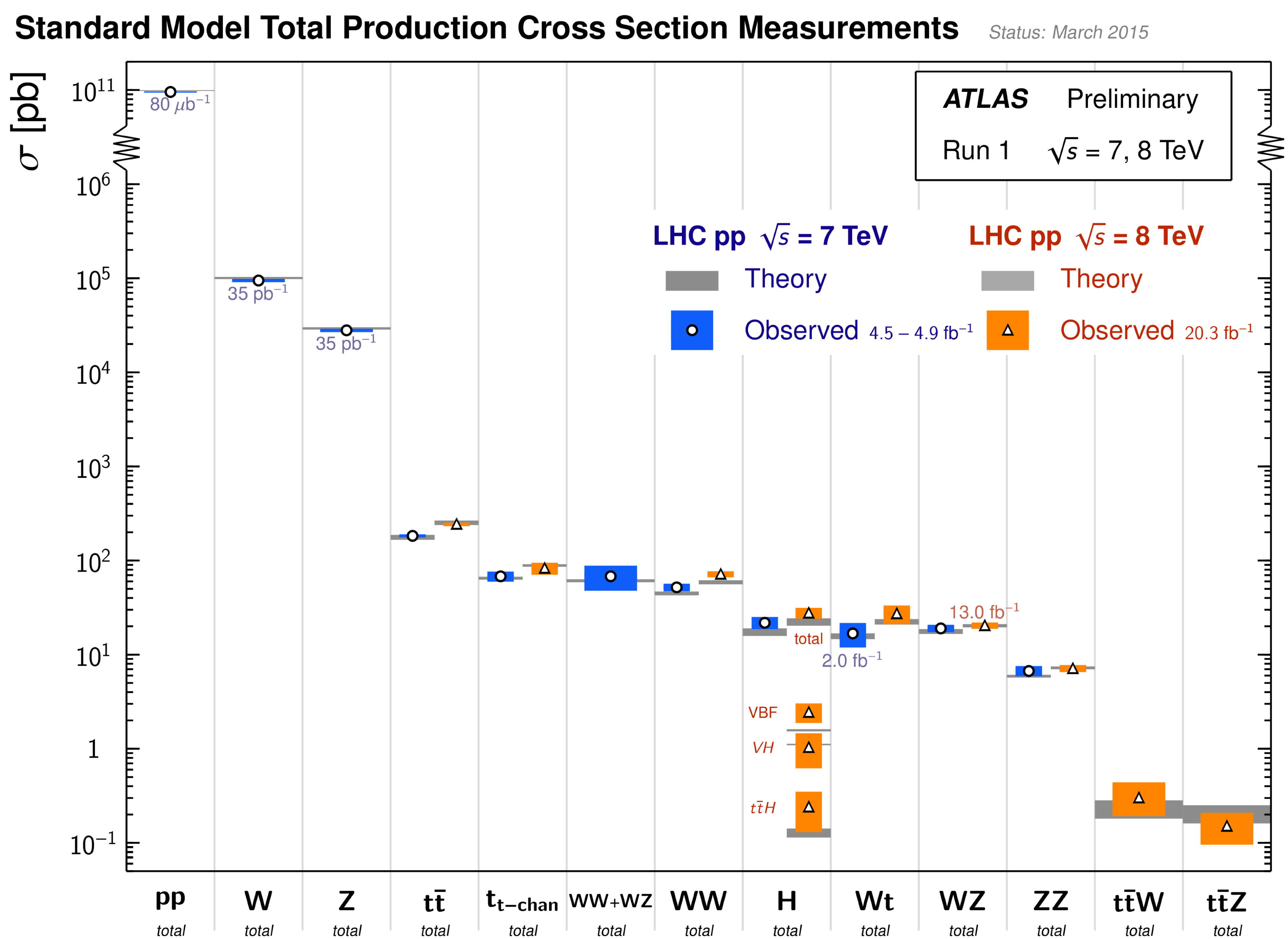




2013

July 4, 2012: a new member was added to the SM family !

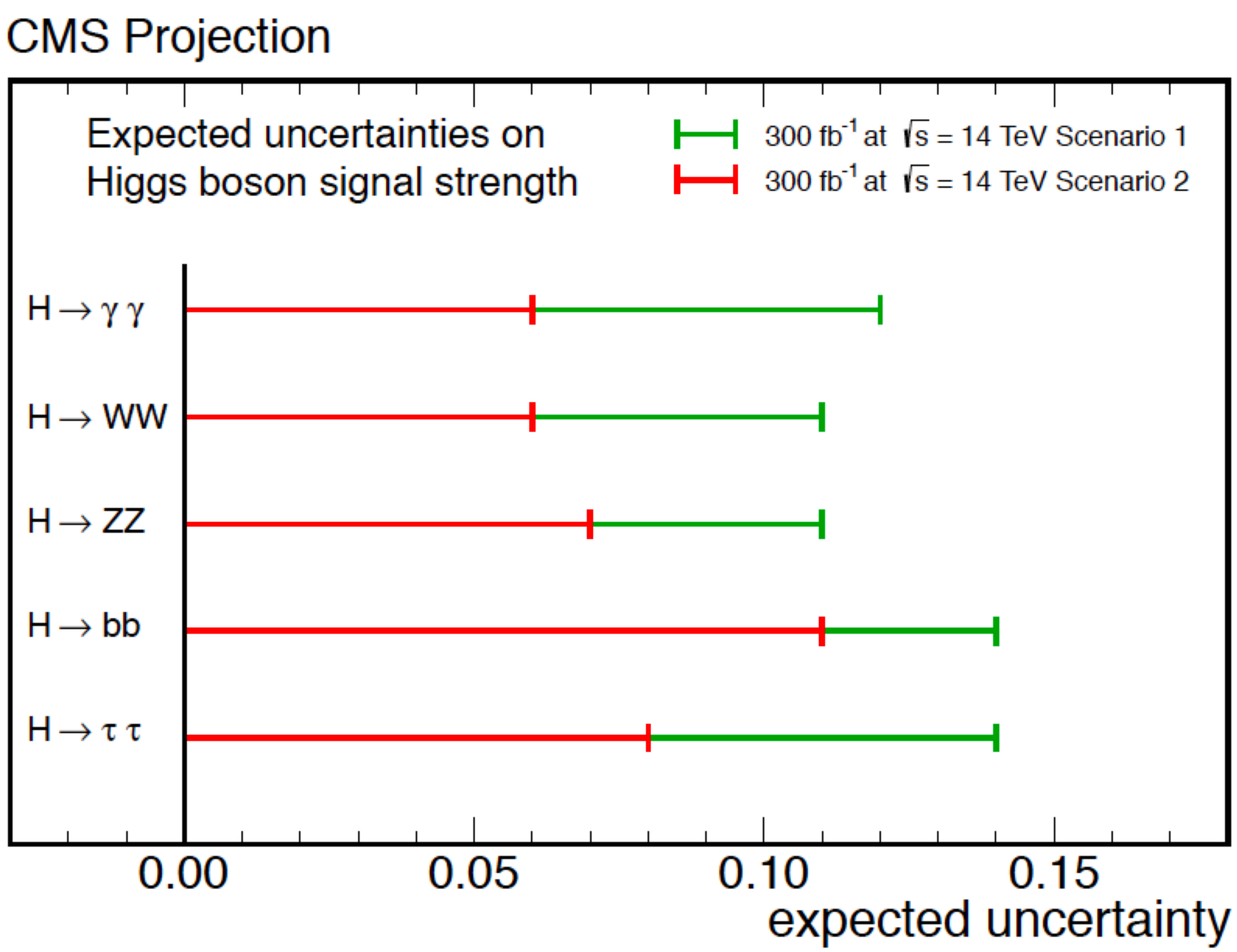
The LHC circa 2015



Very good overall agreement between theory and experiment

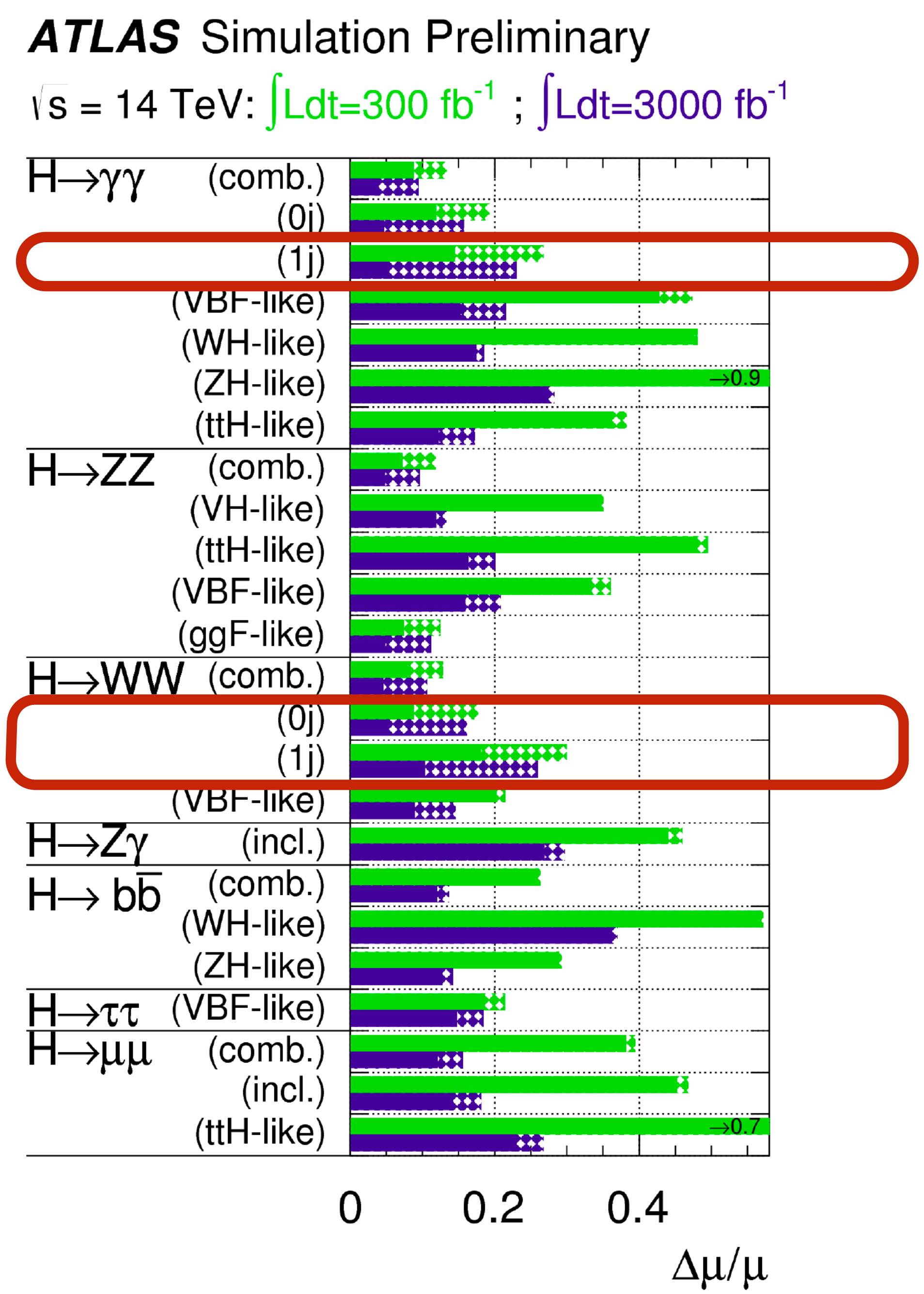
LHC Run 2: prospects

- High expectations from the higher energy (13-14 TeV) and luminosity (~300fb^{-1})



Scenario 1: all systematic uncertainties same as now

Scenario 2: scale theory unc. by 1/2, experimental sys. by 1/sqrt(L)



Large impact from theory uncertainties (dashed) coming from QCD scale, jet binning, PDF+α_s

LHC Run 2 & theory

$H \rightarrow ZZ^*$

ATLAS

Source of uncertainty	4μ	$2e2\mu$	$2\mu 2e$	$4e$	combined
Electron reconstruction and identification efficiencies	–	1.7%	3.3%	4.4%	1.6%
Electron isolation and impact parameter selection	–	0.07%	1.1%	1.2%	0.5%
Electron trigger efficiency	–	0.21%	0.05%	0.21%	<0.2%
$\ell\ell + ee$ backgrounds	–	–	3.4%	3.4%	1.3%
Muon reconstruction and identification efficiencies	1.9%	1.1%	0.8%	–	1.5%
Muon trigger efficiency	0.6%	0.03%	0.6%	–	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.6%	1.6%	–	–	1.2%
QCD scale uncertainty					6.5%
PDF, α_s uncertainty					6.0%
$H \rightarrow ZZ^*$ branching ratio uncertainty					4.0%

LHC Run 2 & theory

ATLAS

$H \to ZZ^*$

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Electron reconstruction and	%	4.4%	1.6%
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$H \to ZZ^*$ branching ratio u			4.0%

$H \to WW^*$

Source	Observed $\mu = 1.09$ Error +	Error −	Plot of error (scaled by 100)
Data statistics	0.16	0.15	
Signal regions	0.12	0.12	
Profiled control regions	0.10	0.10	
Profiled signal regions	-	-	-
MC statistics	0.04	0.04	
Theoretical systematics	0.15	0.12	
Signal $H \to WW^*$ $\mathcal{B}$	0.05	0.04	
Signal ggF cross section	0.09	0.07	
Signal ggF acceptance	0.05	0.04	
Signal VBF cross section	0.01	0.01	
Signal VBF acceptance	0.02	0.01	
Background WW	0.06	0.06	
Background top quark	0.03	0.03	
Background misid. factor	0.05	0.05	
Others	0.02	0.02	
Experimental systematics	0.07	0.06	
Background misid. factor	0.03	0.03	
Bkg. $Z/\gamma^* \to ee$, $\mu\mu$	0.02	0.02	
Muons and electrons	0.04	0.04	
Missing transv. momentum	0.02	0.02	
Jets	0.03	0.02	
Others	0.03	0.02	
Integrated luminosity	0.03	0.03	
Total	0.23	0.21	
			-30 -15 0 15 30

LHC Run 2 & theory

ATLAS

$H \to ZZ^*$

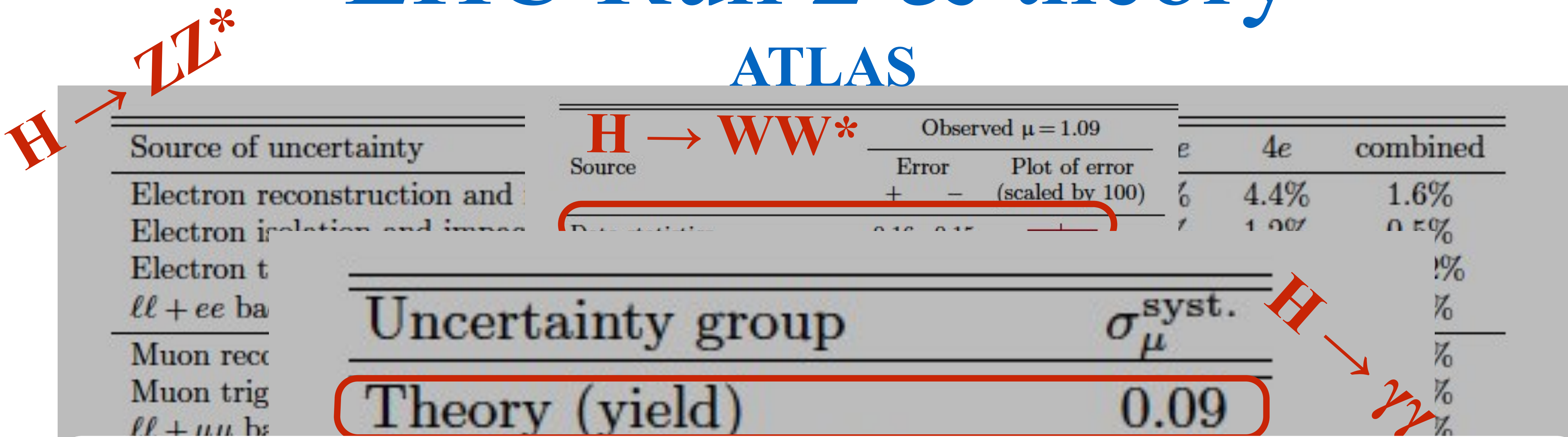
$H \to WW^*$

$H \to \gamma\gamma$

Uncertainty group	$\sigma_{\mu}^{\text{syst.}}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02

LHC Run 2 & theory

ATLAS



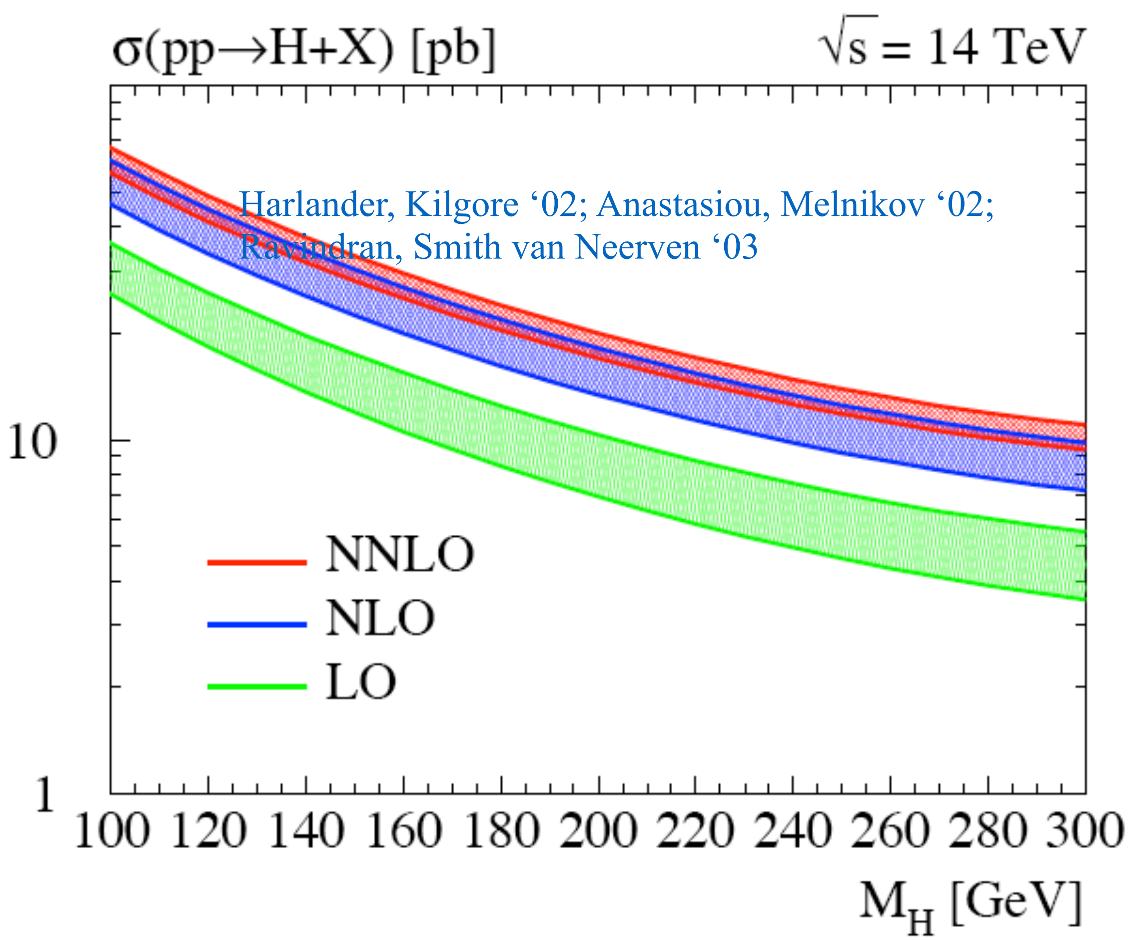
For the three 'precision' channels, theory uncertainty is the dominant source of systematic uncertainty !

Outline

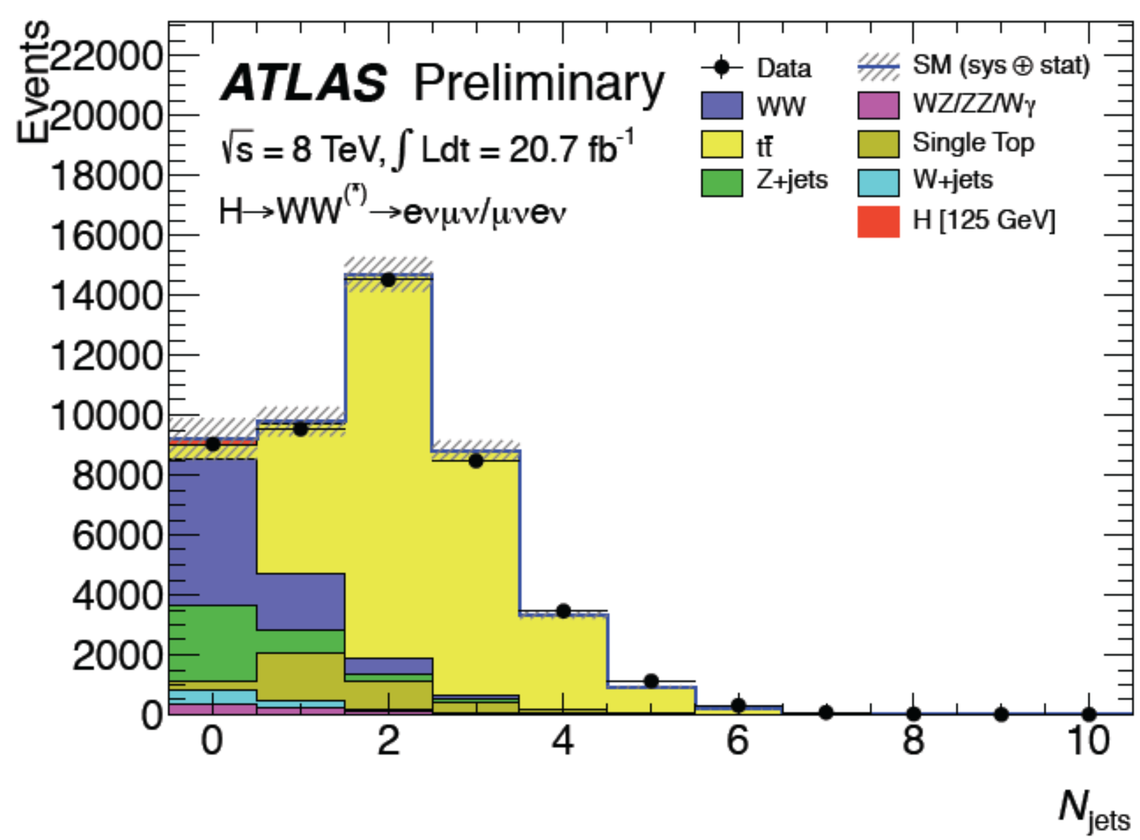
- Theory uncertainties: overall signal normalization and differential distributions
- Resummation of jet veto logarithms
- PDF and parametric uncertainties
- Summary

Theory uncertainties: double trouble

- Two reasons for the dominance of theory uncertainties in Higgs physics



How well do we understand the overall signal normalization? There are famously large higher-order corrections!



How well can we describe the Higgs kinematics (differential distributions)? Need cuts to remove the sometimes overwhelming backgrounds.

Theory uncertainties: double trouble

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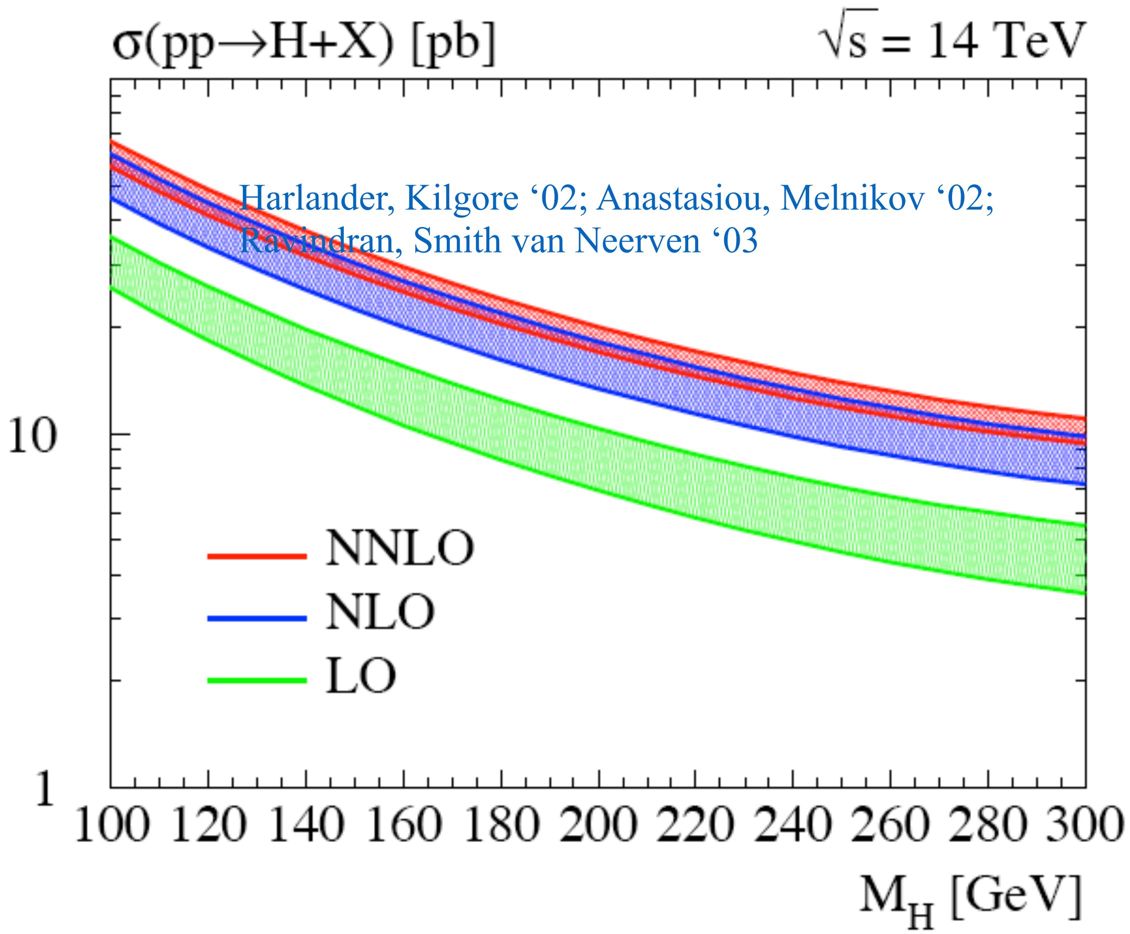

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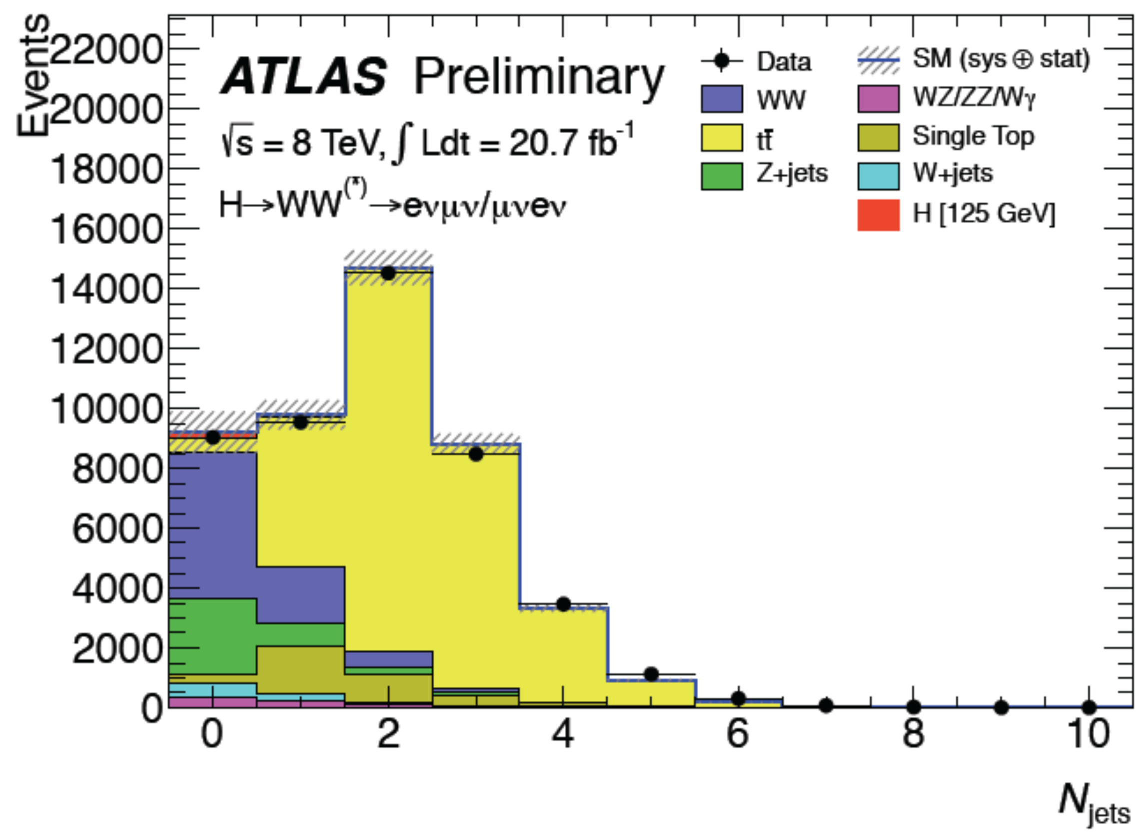


How well can we describe the Higgs kinematics (differential distributions)? Need cuts to remove the sometimes overwhelming backgrounds.

Progress on both fronts needed to improve Higgs-signal modeling for Run II of the LHC, in addition to better control over PDFs and parametric uncertainties.

Overall Signal Normalization

Higgs production in gluon fusion at N^{3}LO in QCD

- Calculation based on threshold expansion in $z = m_H^2/\hat{s}$

$$\hat{\sigma}_{ij}^{(3,N)} = \underbrace{\delta_{ig}\,\delta_{jg}\,\hat{\sigma}_{\rm SV}^{(3)}}_{\text{soft gluons + virtual corrections}} + \sum_{n=0}^{N} \underbrace{c_{ij}^{(n)}\,(1-z)^n}_{\text{hard gluons + collinear radiation}}$$

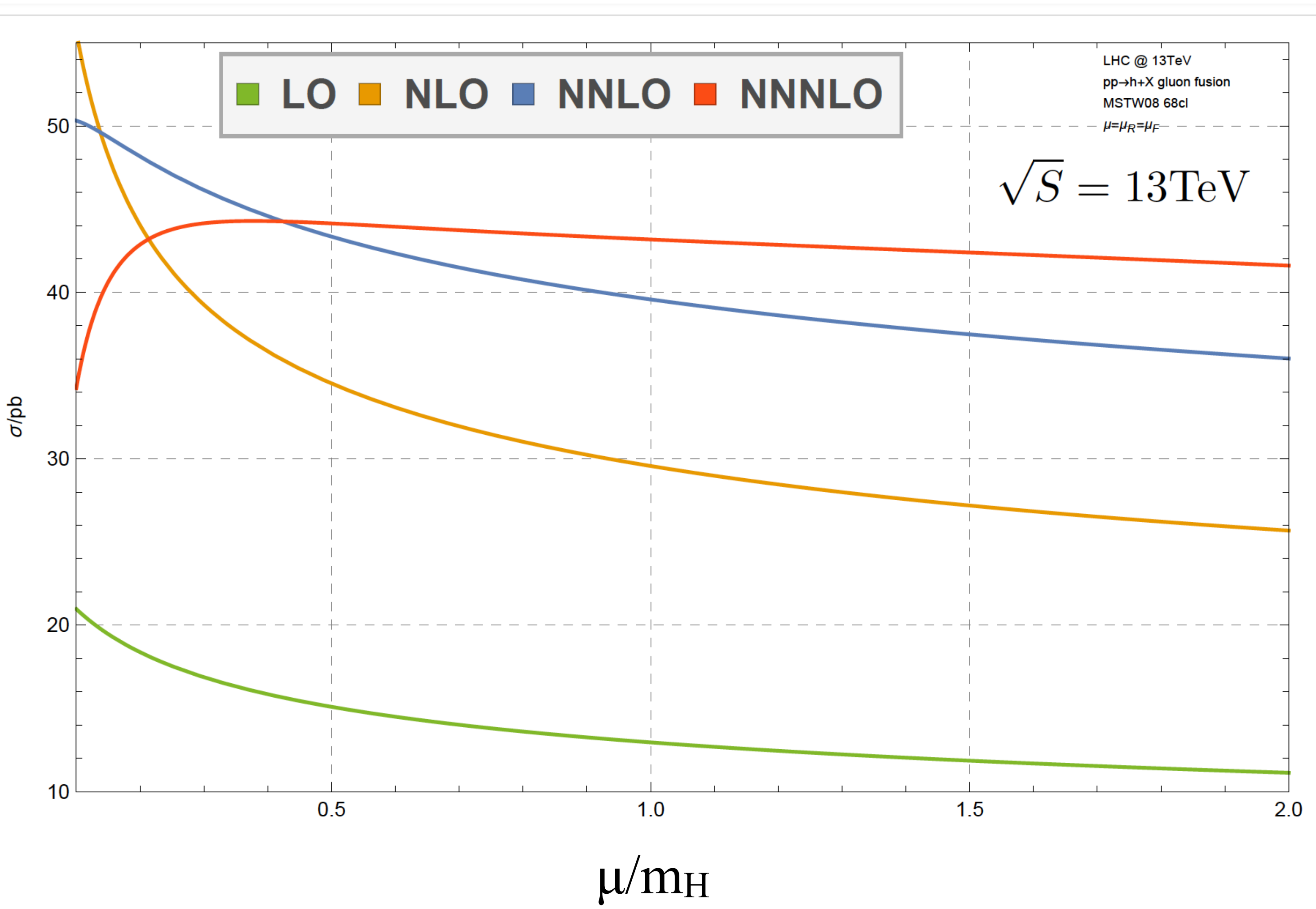
- Threshold expansion stabilizes starting from N=4 (up to n=30 terms were included).

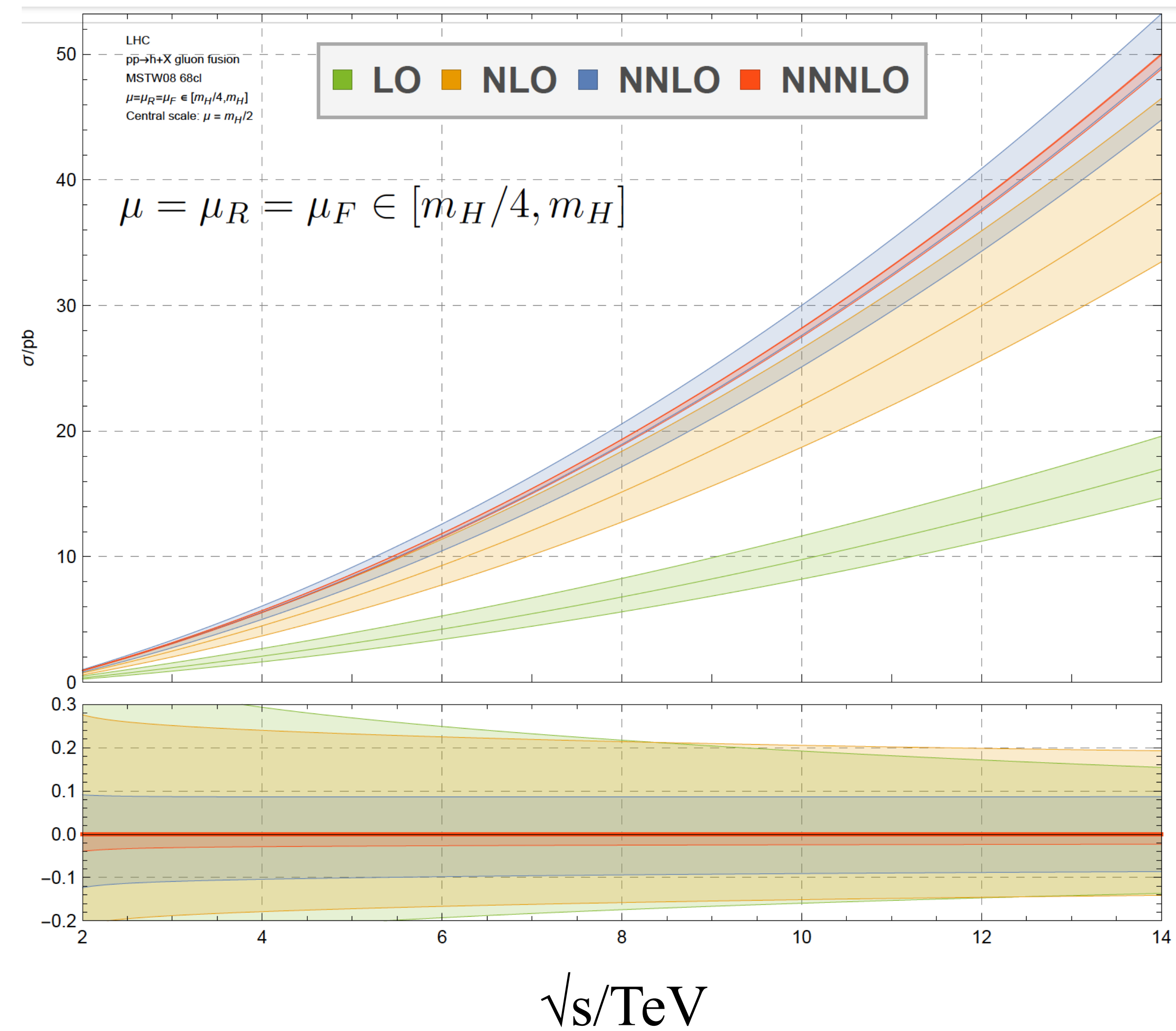
σ/pb	2 TeV	7 TeV	8 TeV	13 TeV	14 TeV
$\mu = \frac{m_H}{2}$	$0.99^{+0.43\%}_{-4.65\%}$	$15.31^{+0.31\%}_{-3.08\%}$	$19.47^{+0.32\%}_{-2.99\%}$	$44.31^{+0.31\%}_{-2.64\%}$	$49.87^{+0.32\%}_{-2.61\%}$
$\mu = m_H$	$0.94^{+4.87\%}_{-7.35\%}$	$14.84^{+3.18\%}_{-5.27\%}$	$18.90^{+3.08\%}_{-5.02\%}$	$43.14^{+2.71\%}_{-4.45\%}$	$48.57^{+2.68\%}_{-4.24\%}$

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

Higgs production in gluon fusion at N^{3}LO in QCD

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





- An additional 2.2% correction for $\mu_F = \mu_R = m_H/2$ w.r.t. NNLO
- Uncertainties from missing higher order corrections reduced down to ~ 3%.

Higgs production in gluon fusion at N^3LO in QCD

- Things observed from the N^3LO result for $\mu = m_H/2$:
  - Reduced scale uncertainty compared to $\mu = m_H$
  - Better convergence of the perturbative series
  - Negligible impact of soft-gluon resummation
- Other sources of uncertainties of a comparable size to N^3LO:
  - $1/m_{top}$ corrections @ NNLO: small, agree within 1% with EFT (Harlander, Mantler, Marzani, Ozeren)
  - Bottom quark effects: unknown beyond NLO, could be few percent
  - PDF + α_s: ~ 2-3% with the latest PDF sets (2015)
  - NLO EW corrections: leads to 5% if we assume complete factorization

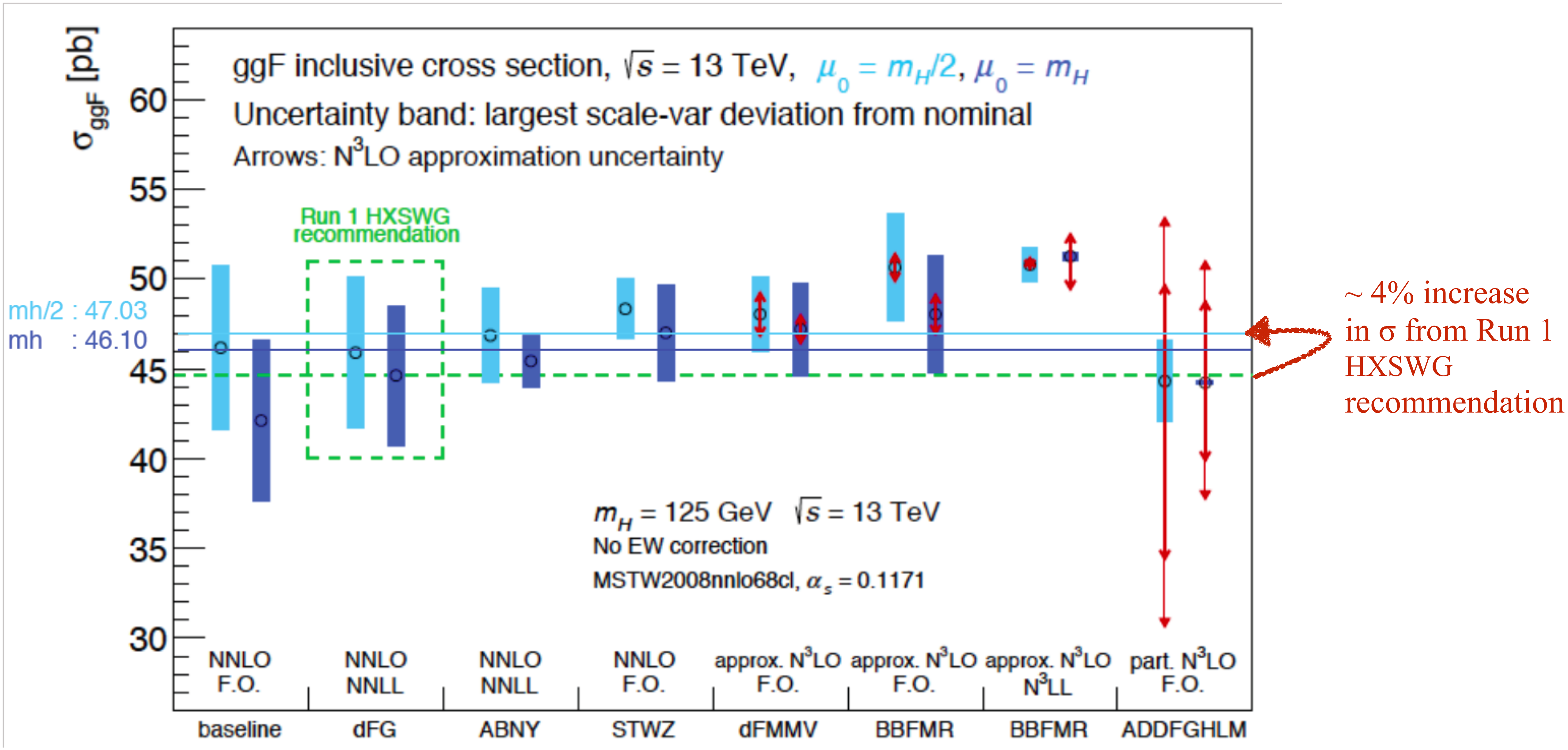
    (Djouadi, Gambino, Kniehl; Aglietti, Bonciani, Degrassi; Degrassi, Maltoni; Anastasiou, RB, Petriello; Actis, Passarion, Sturm, Uccirati)

$$\sigma_0\left(1+\delta_{QCD}+\delta_{EW}\right) \quad vs \quad \sigma_0\left(1+\delta_{QCD}\right)\left(1+\delta_{EW}\right)$$

  - Missing higher order QCD

Comparison to approximate N^3LO

Duhr, Higgs Hunting 2015

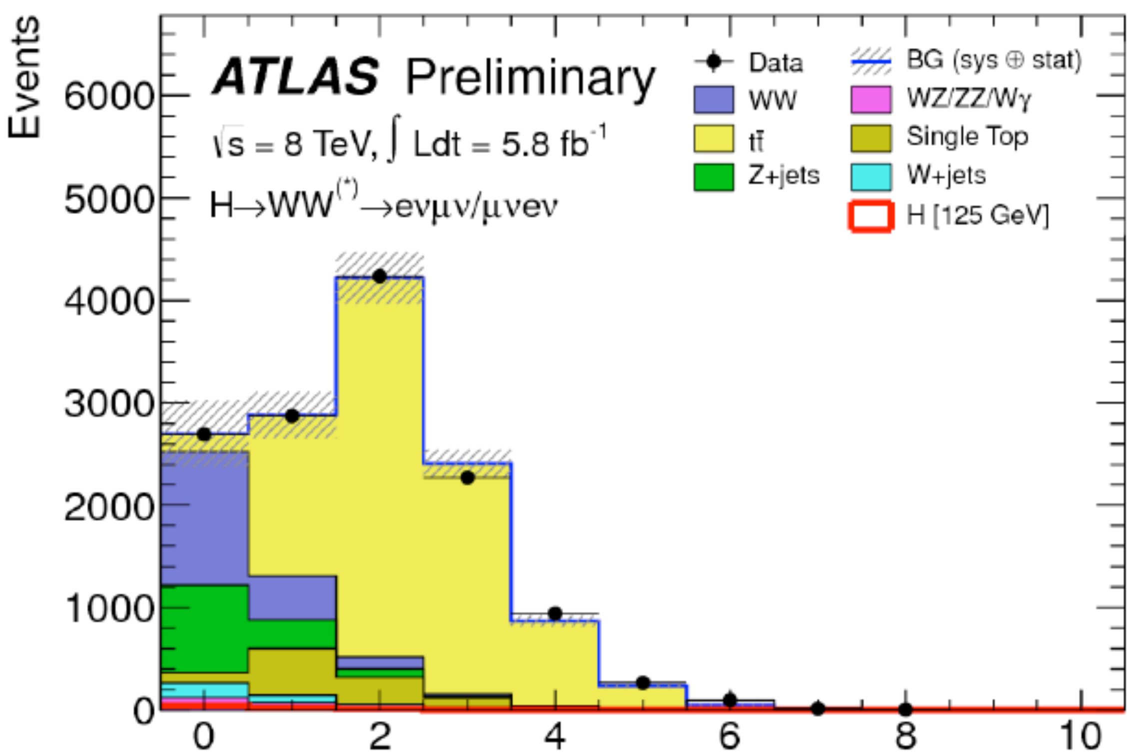


$\sigma_{N3LO}/\sigma_{NNLO} =$
- 8.9% for $\mu = m_H$
- 2.2% for $\mu = m_H/2$

no resummation included

Higgs Kinematics and Differential Distributions

Higgs in association with jets



$\sigma_1 = \sigma_{>=1} - \sigma_{>=2}$

Source (1-jet)	Signal (%)	Bkg. (%)
1-jet incl. ggF signal ren./fact. scale	27	0
2-jet incl. ggF signal ren./fact. scale	15	0
Missing transverse momentum	8	3
W+jets fake factor	0	7
b-tagging efficiency	0	7
Parton distribution functions	7	1

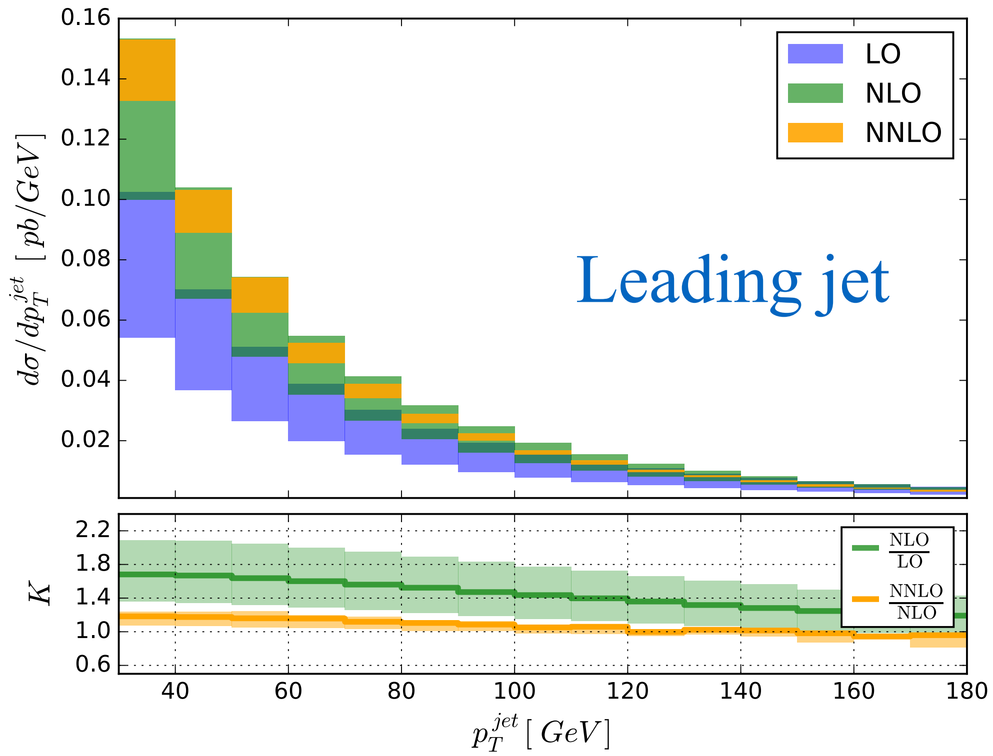
ATLAS

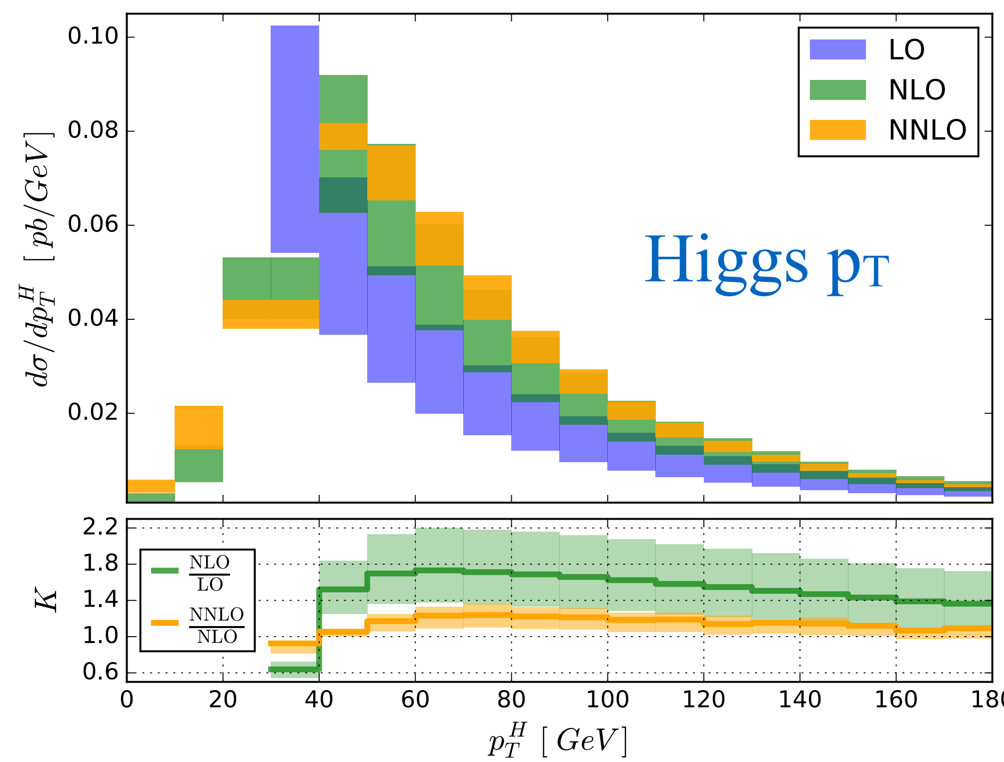
Theory uncertainty as estimated by ATLAS is large

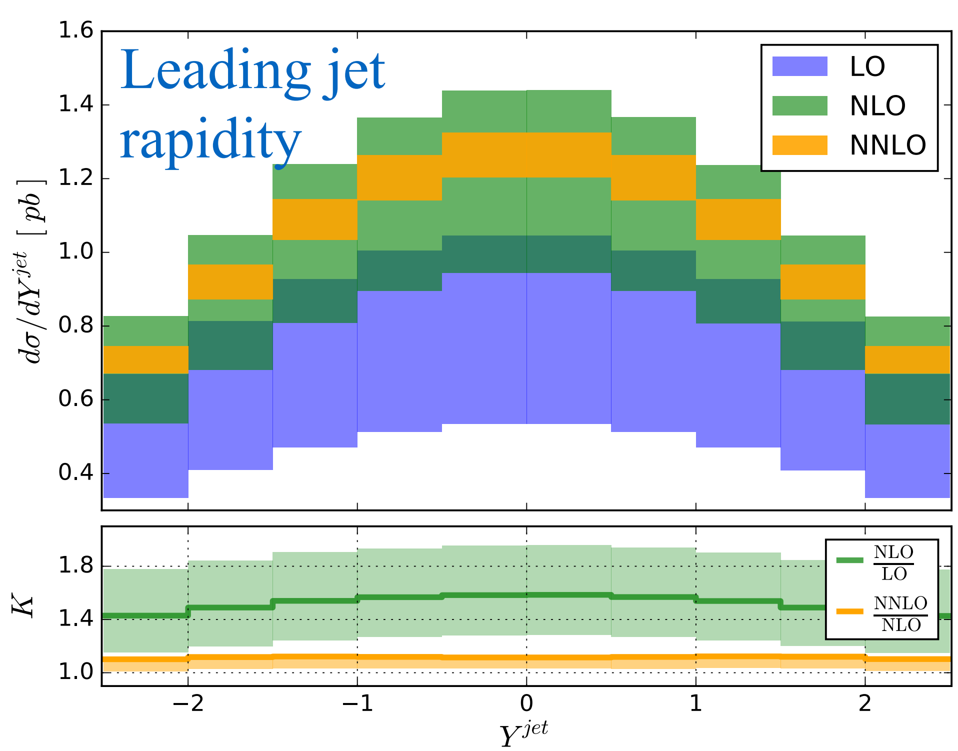
- Selection of experimental events in H → WW uses jet binning to reduce the background.
- Theory uncertainties in the 1-jet and 2-jet bins are currently a limiting factor.
- Looking for BSM effects would benefit from a better precision control of the differential distributions, eg. Higgs p_T (Banfi, Martin, Sanz, 2013; Azatov, Paul 2013)
- Precise exclusive results are also needed to separate between gluon fusion and vector boson fusion

Higgs+jet @ NNLO in QCD using jettiness

R.B., Giele, Focke, Liu, Petriello, 2015





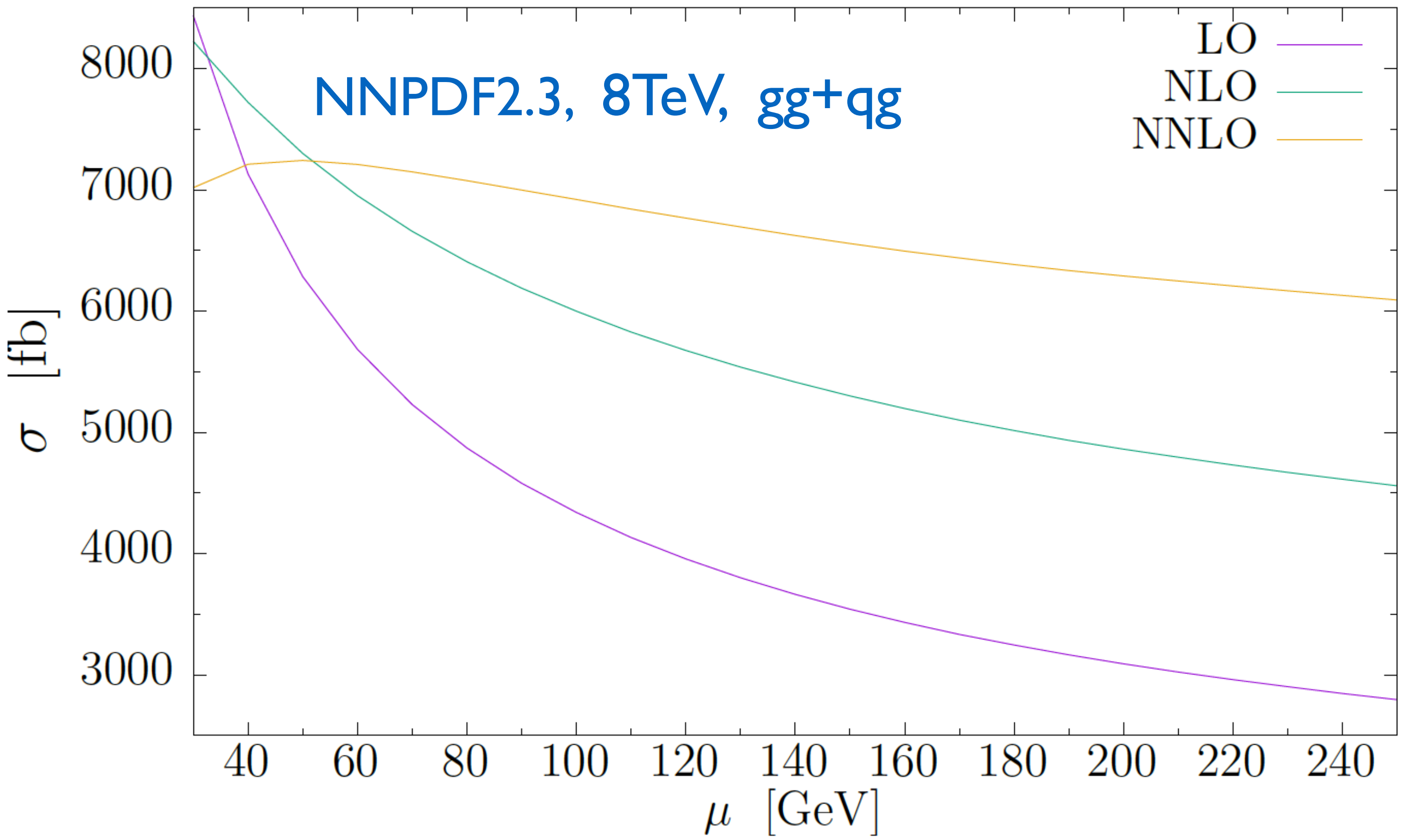


- First complete NNLO result. Uses jettiness subtraction method
- Non-trivial K-factor shape as a function of p_{Tj} and p_{TH} while flat as a function of Y^{jet}
- Good perturbative behavior and smaller uncertainties for all differential distributions
- Ready to compare with 13 TeV data!

Higgs + 1 jet @ NNLO using sector-improved residue subtraction

- Greatly reduced theoretical errors for the inclusive cross section

R.B., Caola, Melnikov, Petriello, Schulze, 2015



anti-kT jet algorithm

$R = 0.5$, $p_{T,cut} = 30$ GeV

Corrections:

LO $\xrightarrow{+44\%}$ NLO $\xrightarrow{+20\%}$ NNLO for $\mu = m_H$

LO $\xrightarrow{+23\%}$ NLO $\xrightarrow{+4\%}$ NNLO for $\mu = m_H/2$

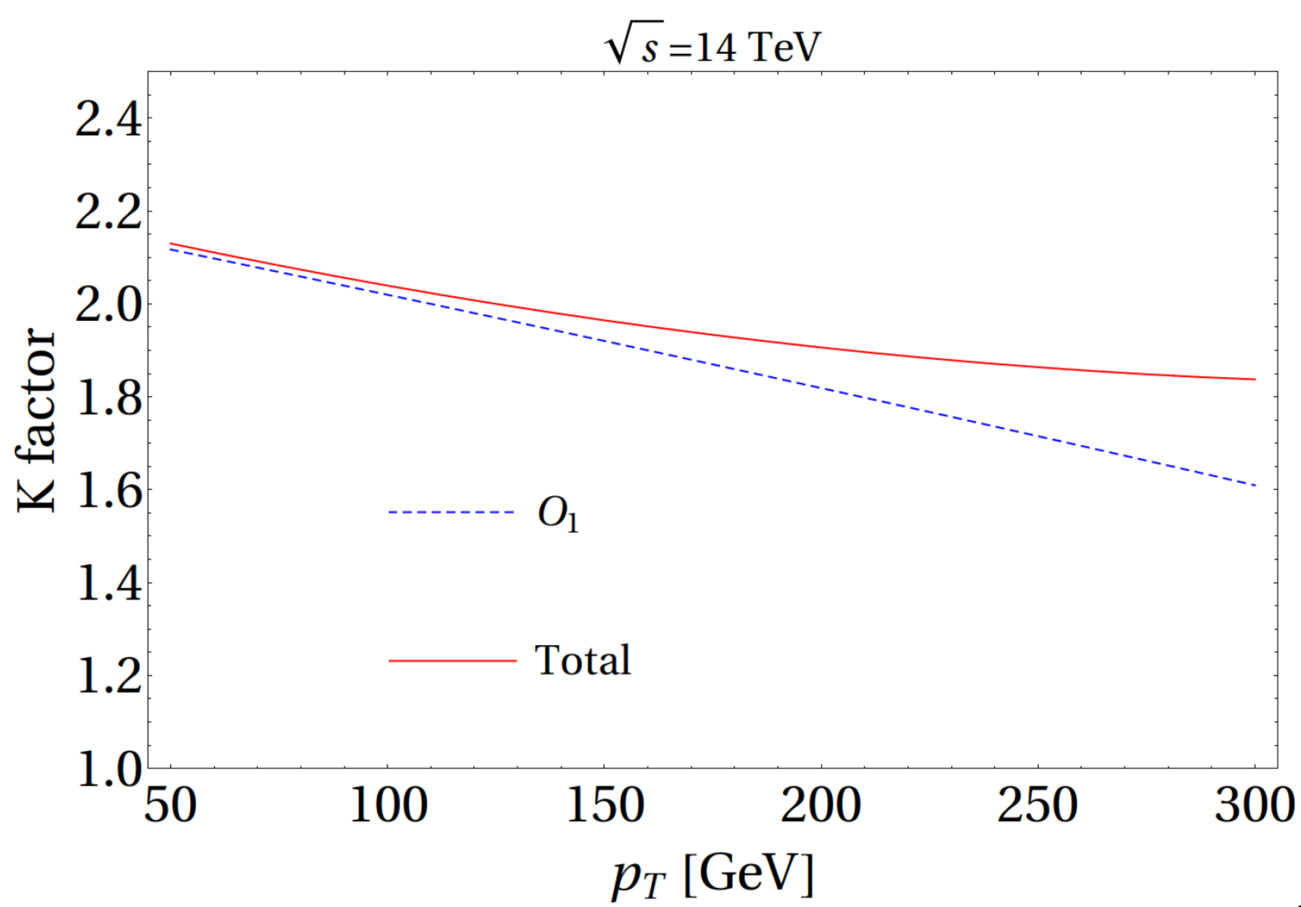
Scale uncertainties: 36% LO 21% NLO 8% NNLO

Finite top mass effects in H+1j @ NLO

- The infinite top-mass limit was shown to work well up to $p_{TH} \leq 150$GeV (Harlander, Neumann, 2013).
- Can go beyond the infinite top-mass limit @ NLO to get improved SM prediction for $p_{TH} \geq 150$GeV

$$\mathcal{L}_{\rm eff} = \hat{C}_1 O_1 + \frac{1}{\Lambda^2} \Sigma_{i=2,3,4,5} \hat{C}_i O_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$ (in SM, $\Lambda = m_{top}$)

Dawson, Lewis, Zeng, 2014



$$O_1 = G^A_{\mu\nu} G^{\mu\nu,A} h$$ dim. 5, SM operator

$$O_2 = D_\sigma G^A_{\mu\nu} D^\sigma G^{A,\mu\nu}\, h$$
$$O_3 = f_{ABC} G^{A,\mu}_{\nu} G^{B,\nu}_{\sigma} G^{C,\sigma}_{\mu}\, h$$
$$O_4 = g_s^2\, \Sigma^{n_{lf}}_{i,j=1} \overline{\psi}_i \gamma_\mu T^A \psi_i\, \overline{\psi}_j \gamma^\mu T^A \psi_j\, h$$
$$O_5 = g_s \Sigma^{n_{lf}}_{i=1} G^A_{\mu\nu} D^\mu\, \overline{\psi}_i \gamma^\nu T^A \psi_i\, h\,,$$

dim. 7 operators

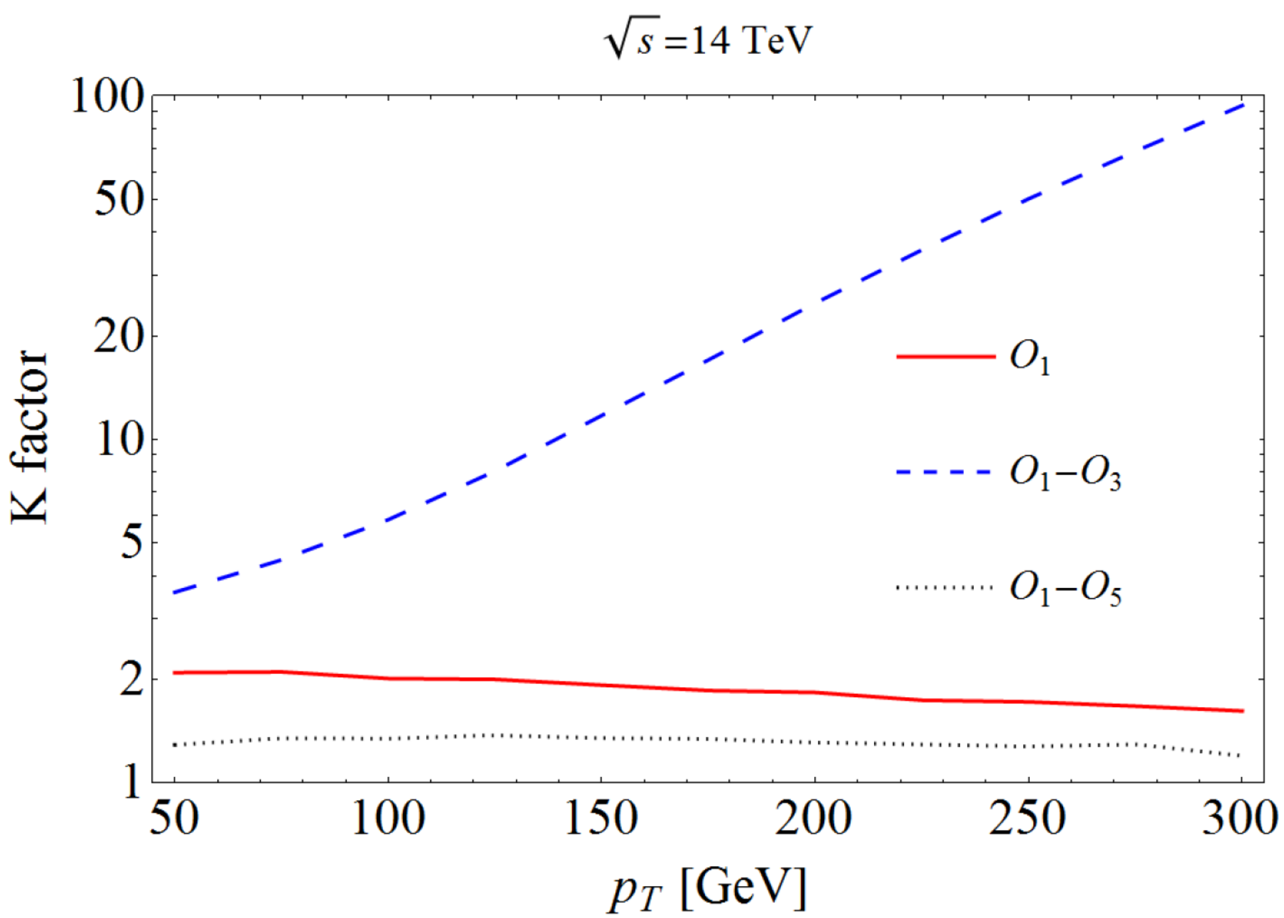
Finite top mass effects in H+1j @ NLO

- Some higher dimensional operators can have large QCD corrections. If enhanced by BSM effects, can dramatically shift the SM prediction.

$$\mathcal{L}_{\text{eff}} = \hat{C}_1 O_1 + \frac{1}{\Lambda^2}\Sigma_{i=2,3,4,5}\hat{C}_i O_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

(in BSM, Λ is the scale at which contributions to Ci are generated)

Dawson, Lewis, Zeng, 2014



operators with the largest effect:

$$O_1 = G^A_{\mu\nu} G^{\mu\nu,A} h$$ dim. 5, SM operator

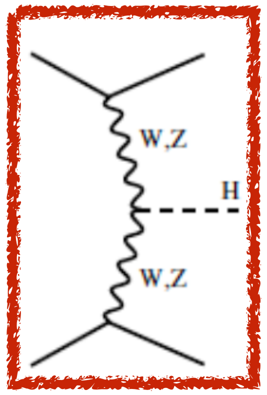
$$O_3 = f_{ABC} G^{A,\mu}_{\nu} G^{B,\nu}_{\sigma} G^{C,\sigma}_{\mu}\, h$$

$$O_5 = g_s \Sigma^{n_{lf}}_{i=1} G^A_{\mu\nu} D^\mu\, \overline{\psi}_i \gamma^\nu T^A \psi_i\, h$$

dim. 7 operators

VBF @ NNLO in QCD

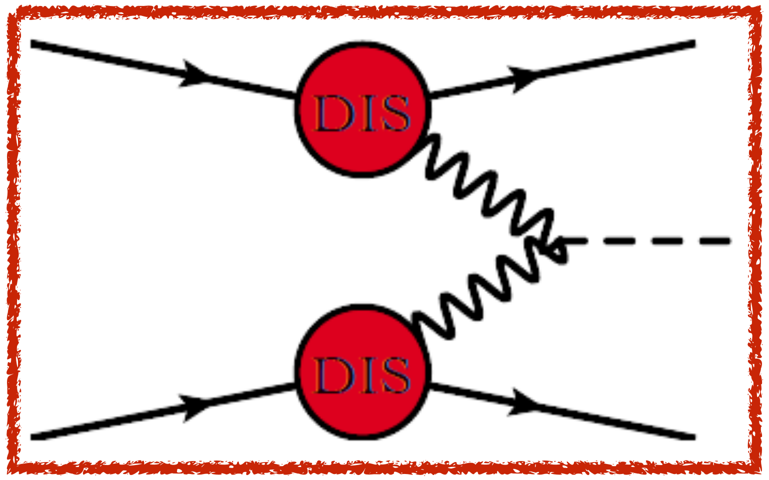
- VBF: second largest production mode at the LHC
  - ✦ Offers direct access to VVH
  - ✦ Possibility to disentangle ggH from VBF through VBF radiation pattern (VBF cuts)



- Inclusive VBF@NNLO known in the structure function approach (2loop virtuals unknown for the $2 \rightarrow 3$ process)

Bolzoni, Maltoni, Moch, Zaro

  - ✦ Structure function approach: no color exchange between the two quark lines
    - Exact at NLO
    - VBF = $(\mathrm{DIS})^2$
  - ✦ Small Corrections for the inclusive case: 1-2%



VBF @ NNLO in QCD

- Inclusive cross section insufficient: need differential distributions to impose VBF cuts
- NNLO differential VBF became available recently using the structure function approach (Cacciari, Dreyer, Karlberg, Salam, Zanderighi)

Central scale choice:

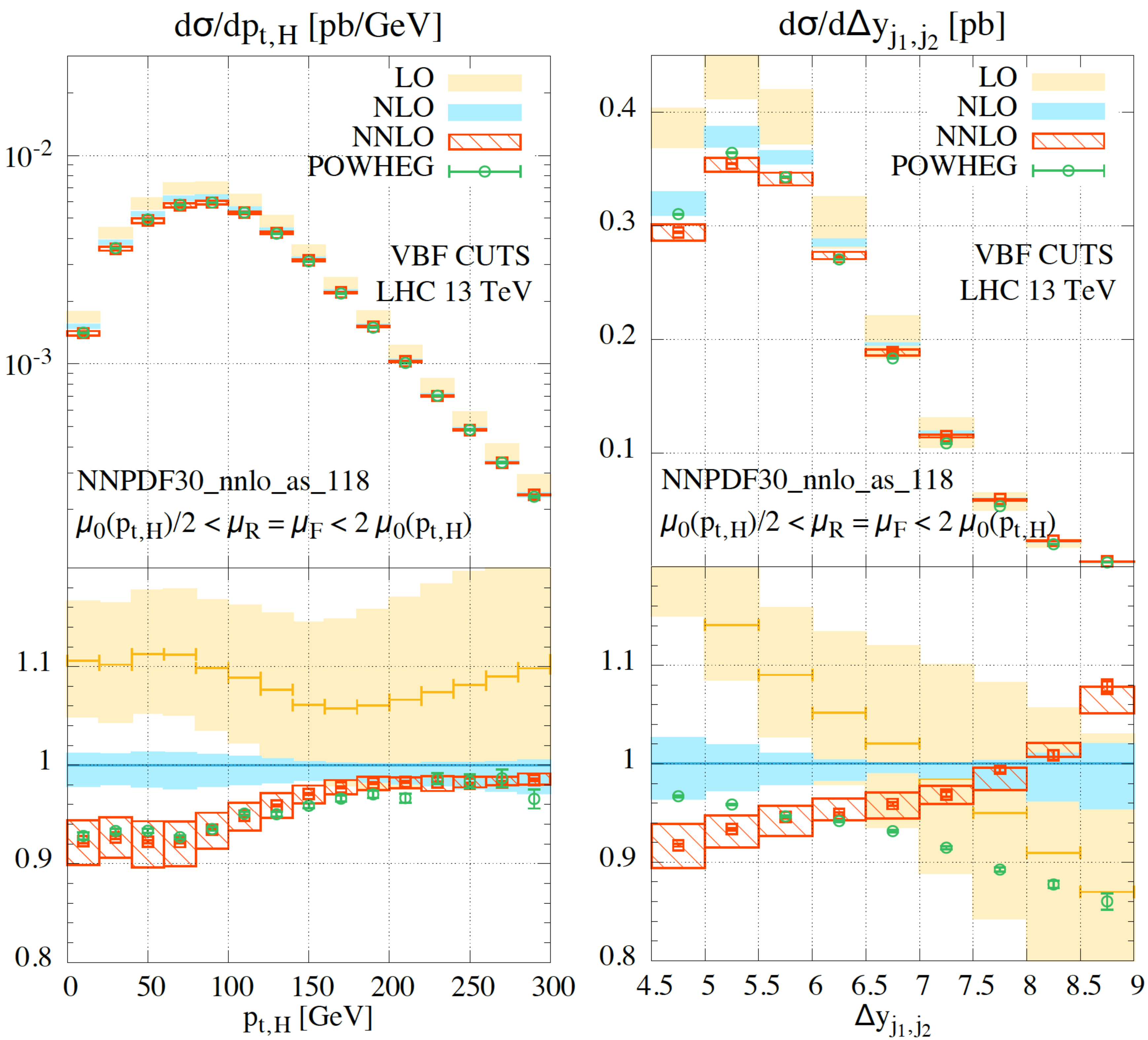
$$\mu_0^2(p_{t,H}) = \frac{M_H}{2}\sqrt{\left(\frac{M_H}{2}\right)^2 + p_{t,H}^2}$$

- NNLO corrections outside the NLO band after VBF cuts

13TeV, anti-KT, R=0.4, NNPDF

	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$
	~ -1%	~ -5%

VBF @ NNLO in QCD



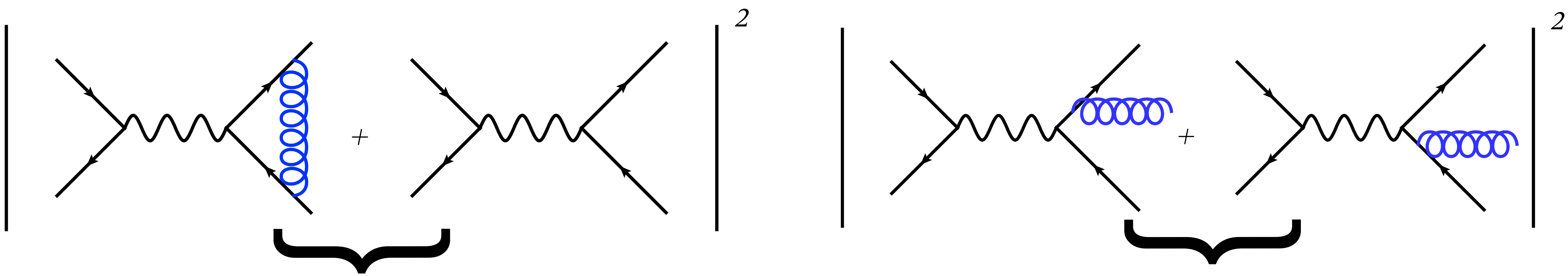
NLO+parton shower agrees well with NNLO for P_{TH} but not for $\Delta y_{j1,j2}$

Non trivial kinematic dependence of the K-factors

Jet binning and the Higgs

- For many important processes we require resummation to NNLL and beyond matched to high-precision fixed-order.
- Important example: jet vetoes for Higgs in the WW channel.

illustrate with a simple $e^+e^- \rightarrow$ jets example



Virtual corrections: $-1/\varepsilon_{IR}^2$

Real corrections: $1/\varepsilon_{IR}^2 - a\times\ln^2(Q/p_{T,cut})$

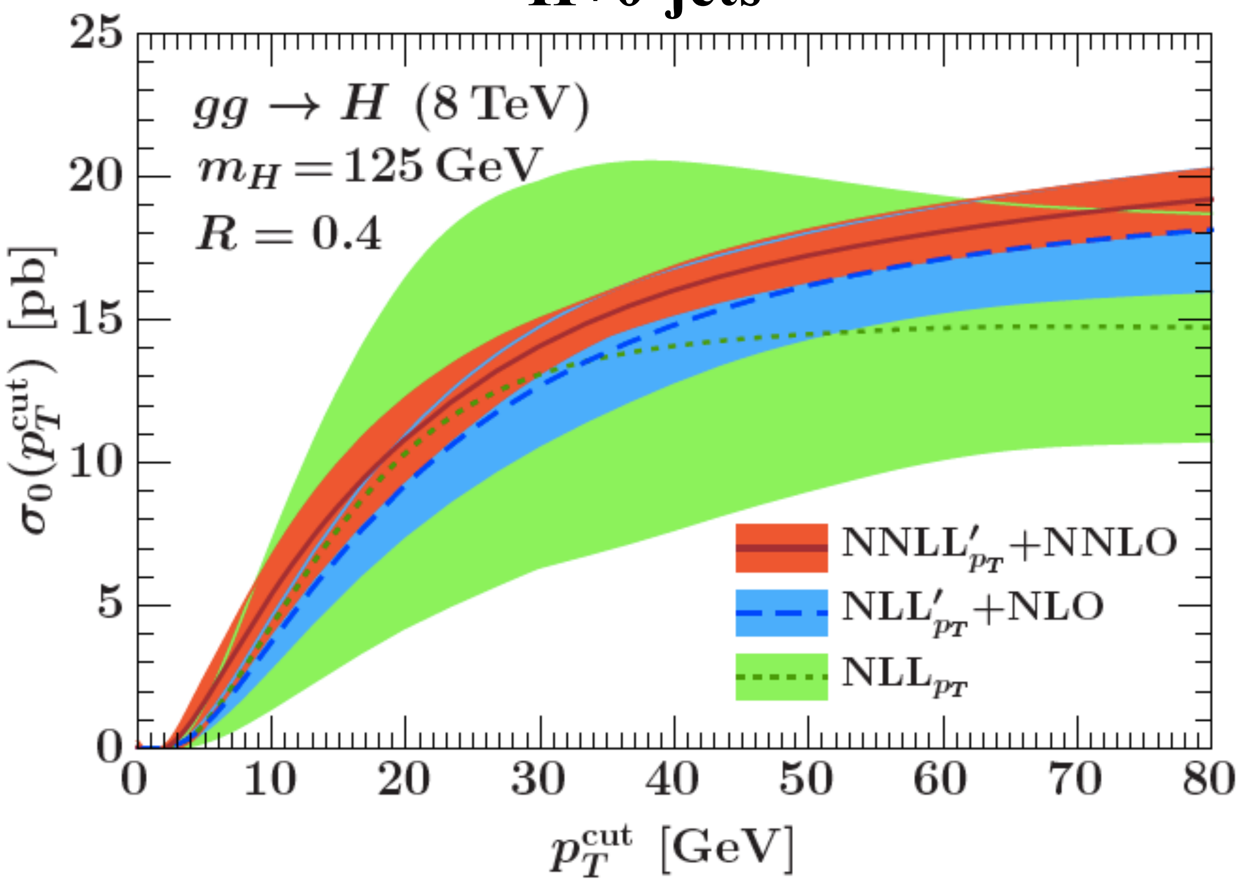
- Incomplete cancellation of IR divergences in presence of final state restrictions gives large logarithms of restricted kinematic variable
- Relevant log term for gluon-fusion Higgs searches: $6(\alpha_S/\pi)\ln^2(M_H/p_{T,veto})\sim 1/2$
- We need to resum these terms; they are a large source of systematic uncertainty in this channel!

Resummation of jet veto logarithms

- Resummation of jet-veto logarithms in Higgs physics is a very active area

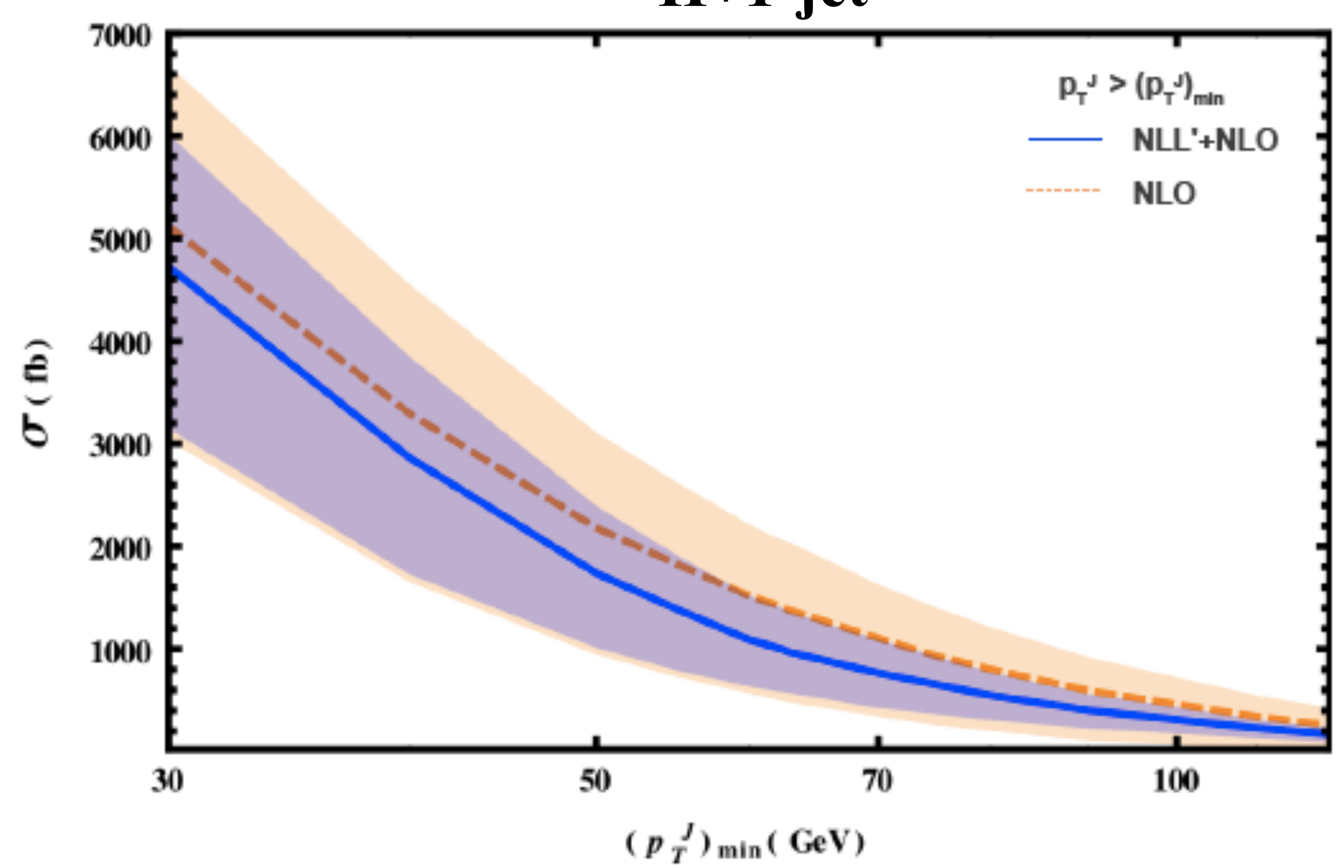
- H+0-jets in gluon fusion (Banfi, Monni, Salam, Zanderighi; Becher, Neubert; Stewart, Tackmann, Walsh, Zuberi)
- H+1-jet in gluon fusion (Liu, Petriello)
- Combination of the 0+1-jet bins (R.B., Liu, Petriello, Tackmann, Walsh)
- Associated VH production with a jet veto (Li,Liu)

H+0-jets



Stewart, Tackmann, Walsh, Zuberi (2013)

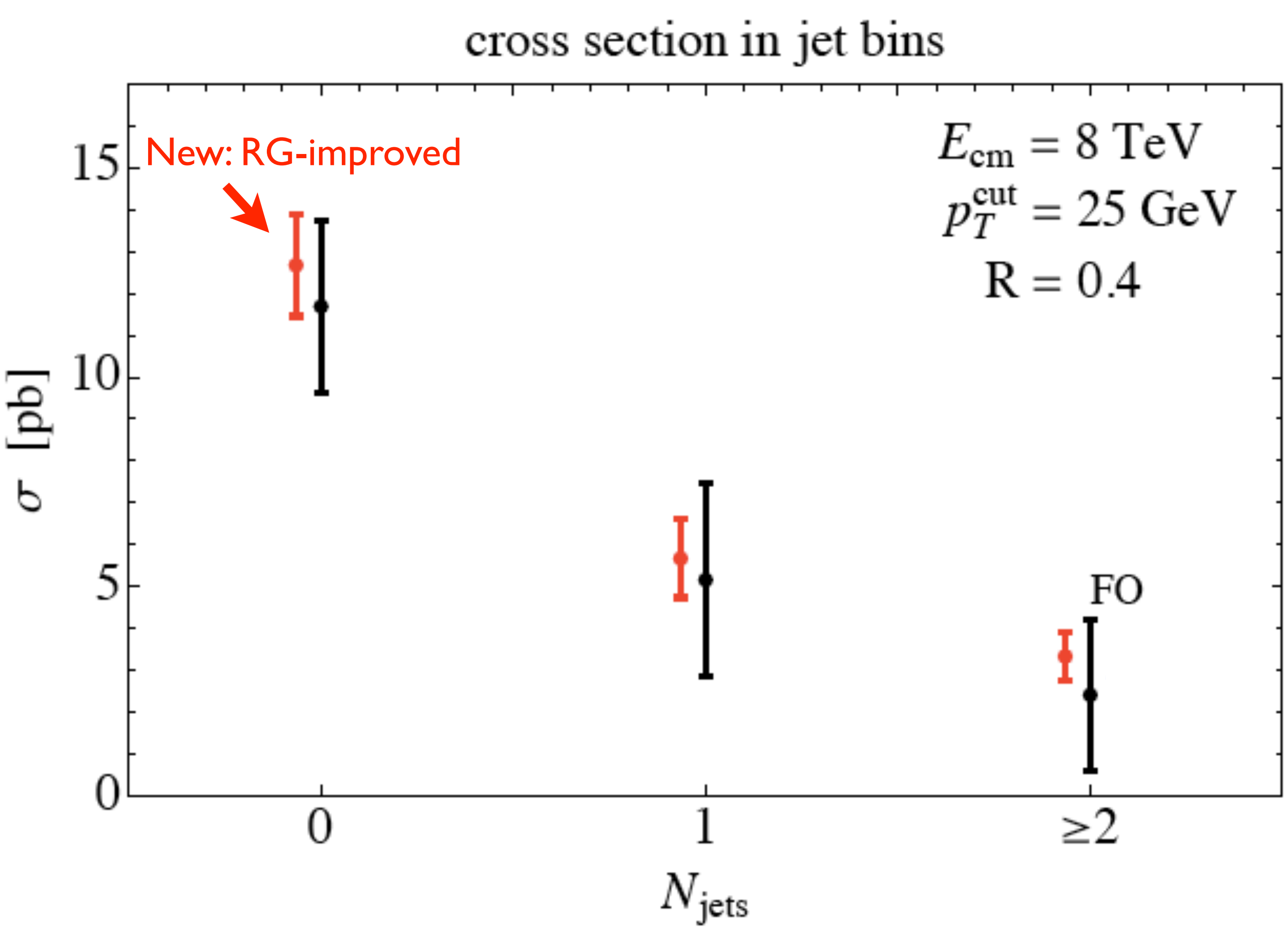
H+1-jet



Liu, Petriello (2013)

Resummation of jet veto logarithms

- Can combine the resummation of the zero-jet and one-jet bins into a complete resummation of the global logarithms affecting the Higgs signal in gluon fusion R.B., Liu, Petriello, Tackmann, Walsh (2014)



- Greatly reduced uncertainties in all three bins used in the analysis
- Leads to a complete covariance matrix for experimental use
- Can translate into a reduced uncertainty in the signal-strength extraction:

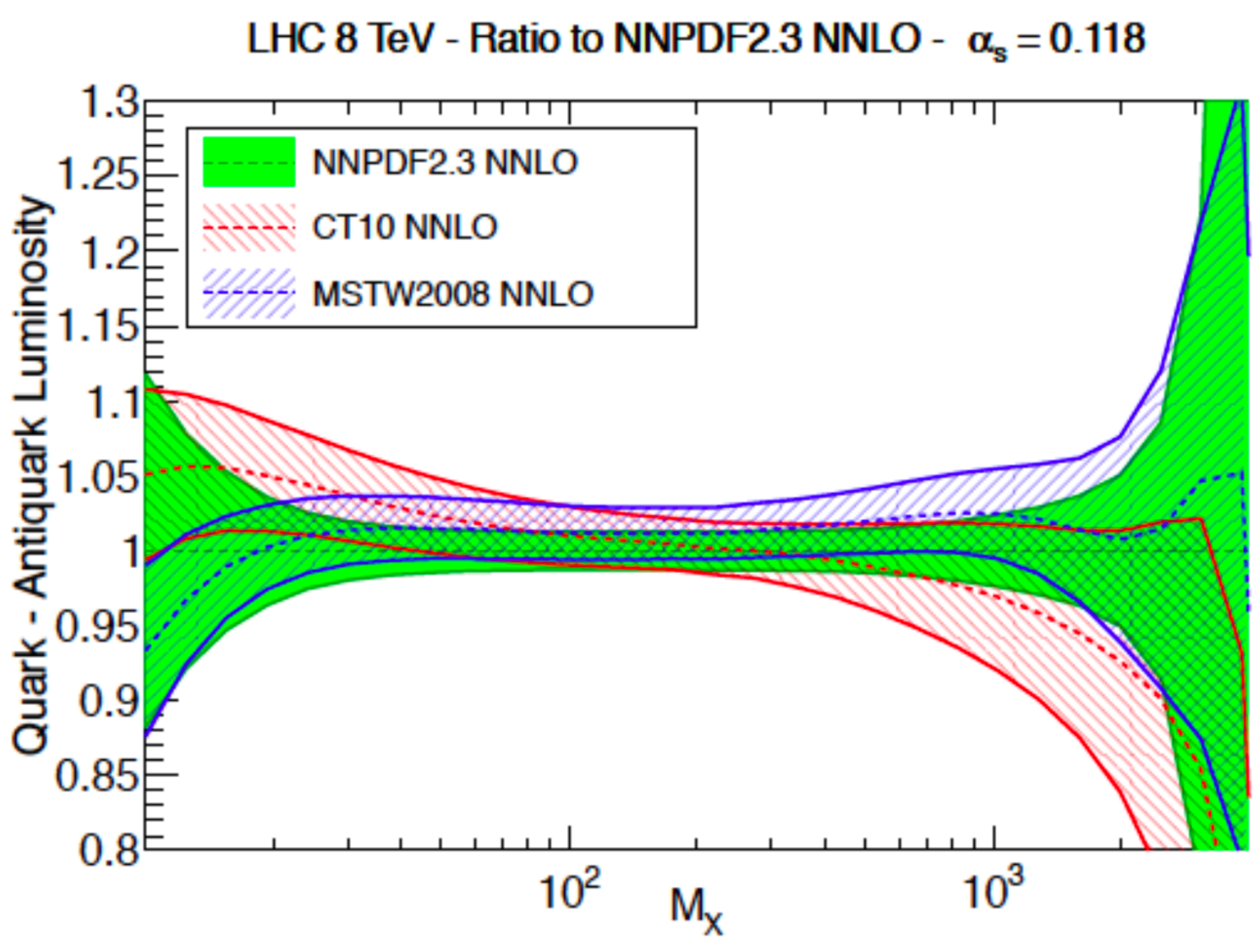
$$(\Delta\mu/\mu)_{old} = 13.3\%$$
$$(\Delta\mu/\mu)_{new} = 6.9\%$$

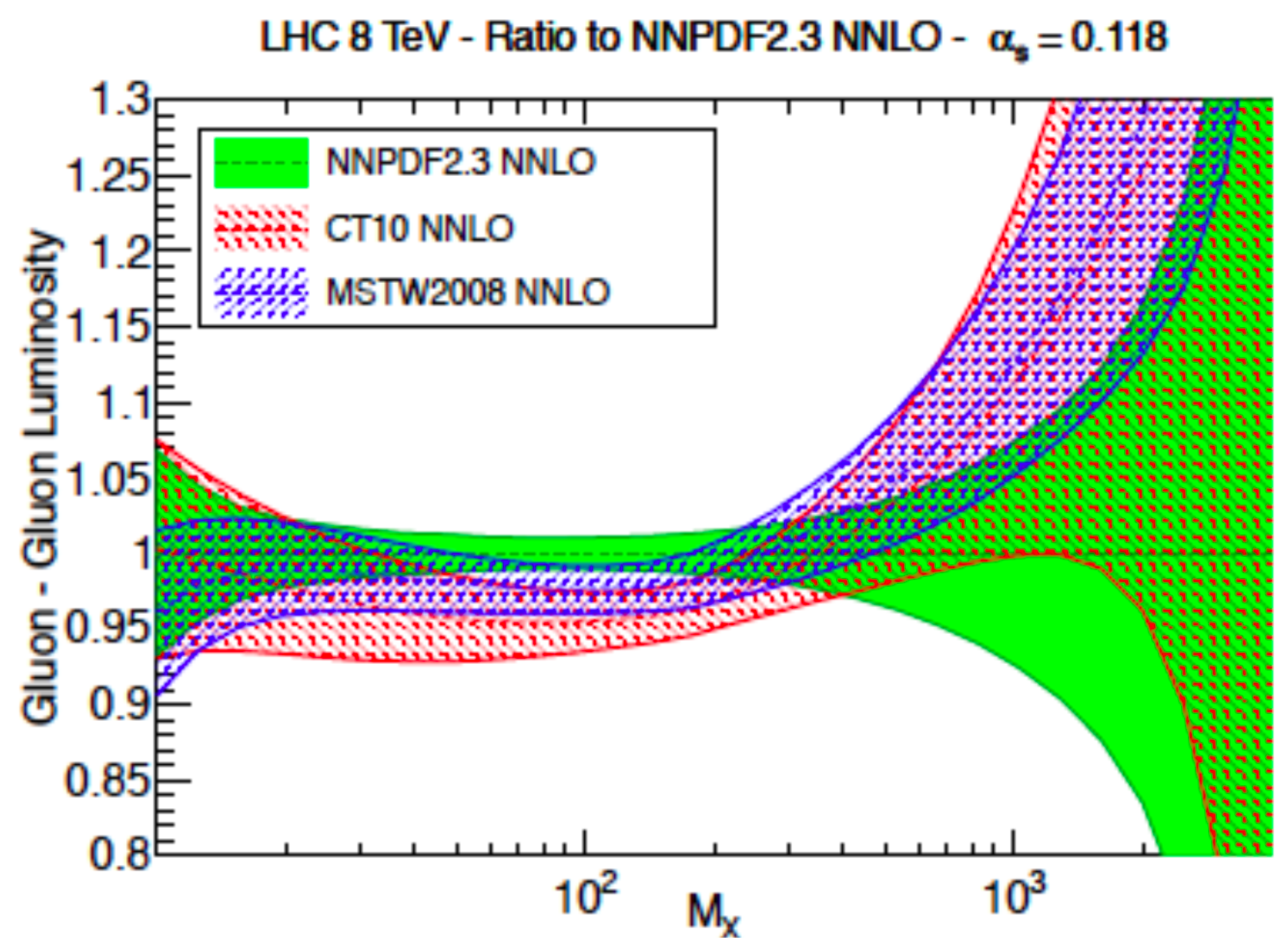
Nearly a factor of 2 reduction in the theory uncertainty affecting the WW channel!

Effect of PDFs and Parametric Uncertainties on Higgs Precision

NNLO PDF uncertainties

pre-2015



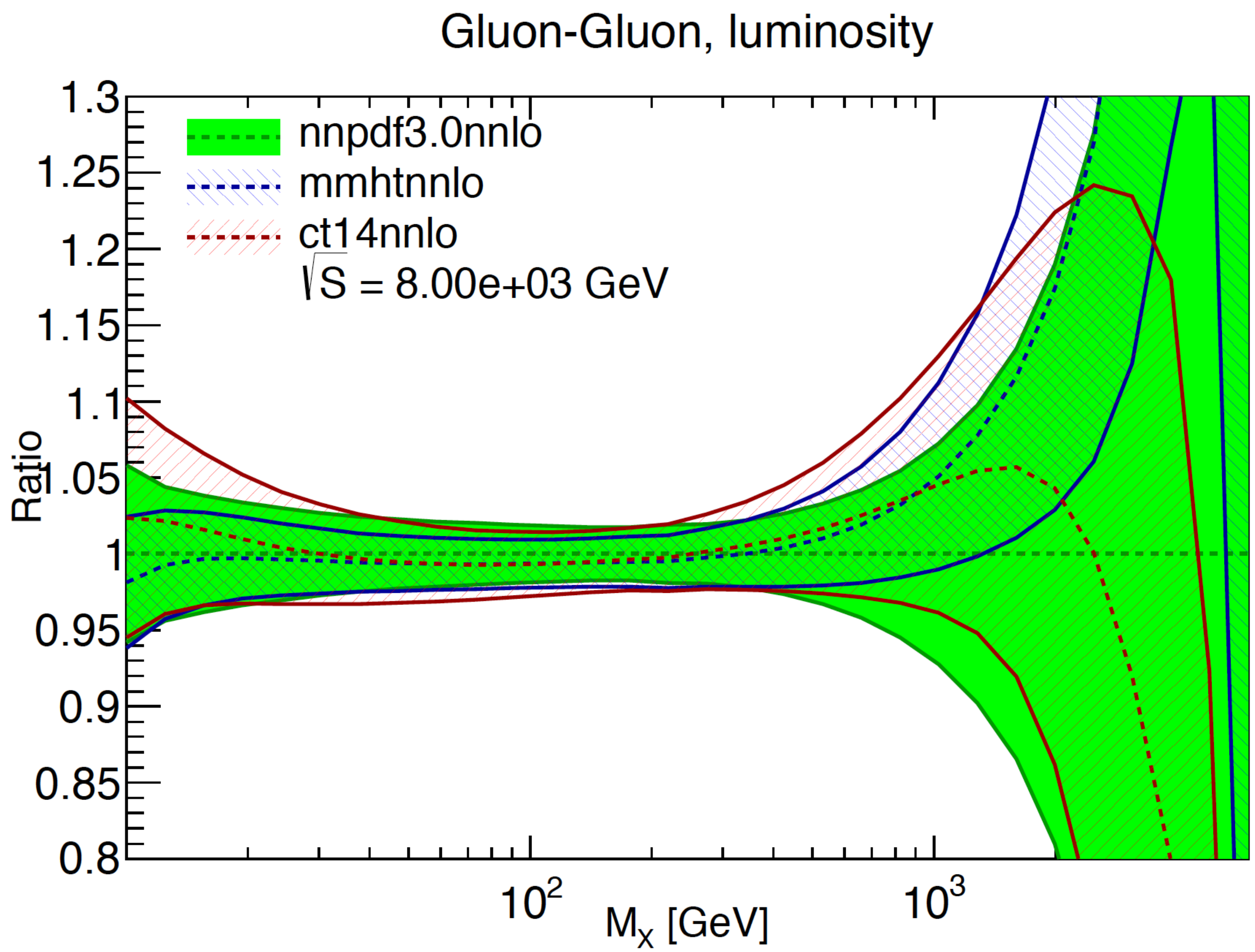


- Not so nice convergence of gg PDF luminosities around 125GeV at 8TeV
- PDF+α_s error dominate the theory uncertainty

±7% at a 13 TeV LHC

NNLO PDF uncertainties

NEW 2015



- Much nicer convergence for new generations of PDFs (updated HERA data included).
- PDF uncertainty on Higgs production down to about 2%
- New recommendations: conservative envelope no longer needed, PDF and α_s uncertainties to be kept separate (combine in quadrature if needed), PDFs delivered for each value of α_s.

Higgs branching ratios

Perturbative uncertainties, M. Spira, HXSWG meeting July 2015

Partial Width	QCD	Electroweak	Total	on-shell Higgs
$H \to b\bar{b}/c\bar{c}$	$\sim 0.1\%$	~ 1–2% for $M_H \lesssim 135$GeV	$\sim 2\%$	NNNNLO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$		~ 1–2% for $M_H \lesssim 135$GeV	$\sim 2\%$	NLO
$H \to t\bar{t}$	$\lesssim 5\%$	$\lesssim 2$–5% for $M_H < 500$GeV	$\sim 5\%$	(NNN)NLO / LO
		$\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 5–10%	
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	NNNLO approx. / NLO
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	(N)LO / LO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$GeV	$\sim 0.5\%$	(N)NLO
		$\sim 0.17(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 0.5–15%	

- Theory scale uncertainties under good control for most Higgs decays except H → Zγ (~5%)
- Parametric uncertainties also need improvements: current values adapted by the Higgs cross section working group

$$m_t = 172.5 \pm 2.5 \text{ GeV} \qquad \alpha_s(M_Z) = 0.119 \pm 0.002$$
$$m_b(m_b) = 4.16 \pm 0.06 \text{ GeV} \qquad m_c(m_c) = 1.28 \pm 0.03 \text{ GeV}$$

Parametric uncertainties

- Parametric and theory uncertainties are added linearly
- Current PDG uncertainty, in particular for α_s felt to be a bit aggressive. Suggested value: $\Delta\, \alpha_s = 0.001\text{-}0.0015$ (S. Forte, HXSWG meeting July 2015).
- It was suggested that lattice could help reduce the parametric uncertainties (Lepage, Mackenzie, Peskin)

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Table 1-4. *Uncertainties on $M_H = 126$ GeV Standard Model branching ratios arising from the parametric uncertainties on α_s, m_b, and m_c and from theory uncertainties [7, 6].*

Decay	Theory Uncertainty (%)	Parametric Uncertainty (%)	Total Uncertainty on Branching Ratios (%)	Central Value
$H \to \gamma\gamma$	±2.7	±2.2	±4.9	2.3×10^{-3}
$H \to b\bar{b}$	±1.5	±1.9	±3.4	5.6×10^{-1}
$H \to c\bar{c}$	±3.5	±8.7	±12.2	2.8×10^{-2}
$H \to gg$	±4.3	±5.8	±10.1	8.5×10^{-2}
$H \to \tau^+\tau^-$	±3.5	±2.1	±5.6	6.2×10^{-2}
$H \to WW^*$	±2.0	±2.1	±4.1	2.3×10^{-1}
$H \to ZZ^*$	±2.1	±2.1	±4.2	2.9×10^{-2}
$H \to Z\gamma$	±6.8	±2.2	±9.0	1.6×10^{-3}
$H \to \mu^+\mu^-$	±3.7	±2.2	±5.9	2.1×10^{-4}

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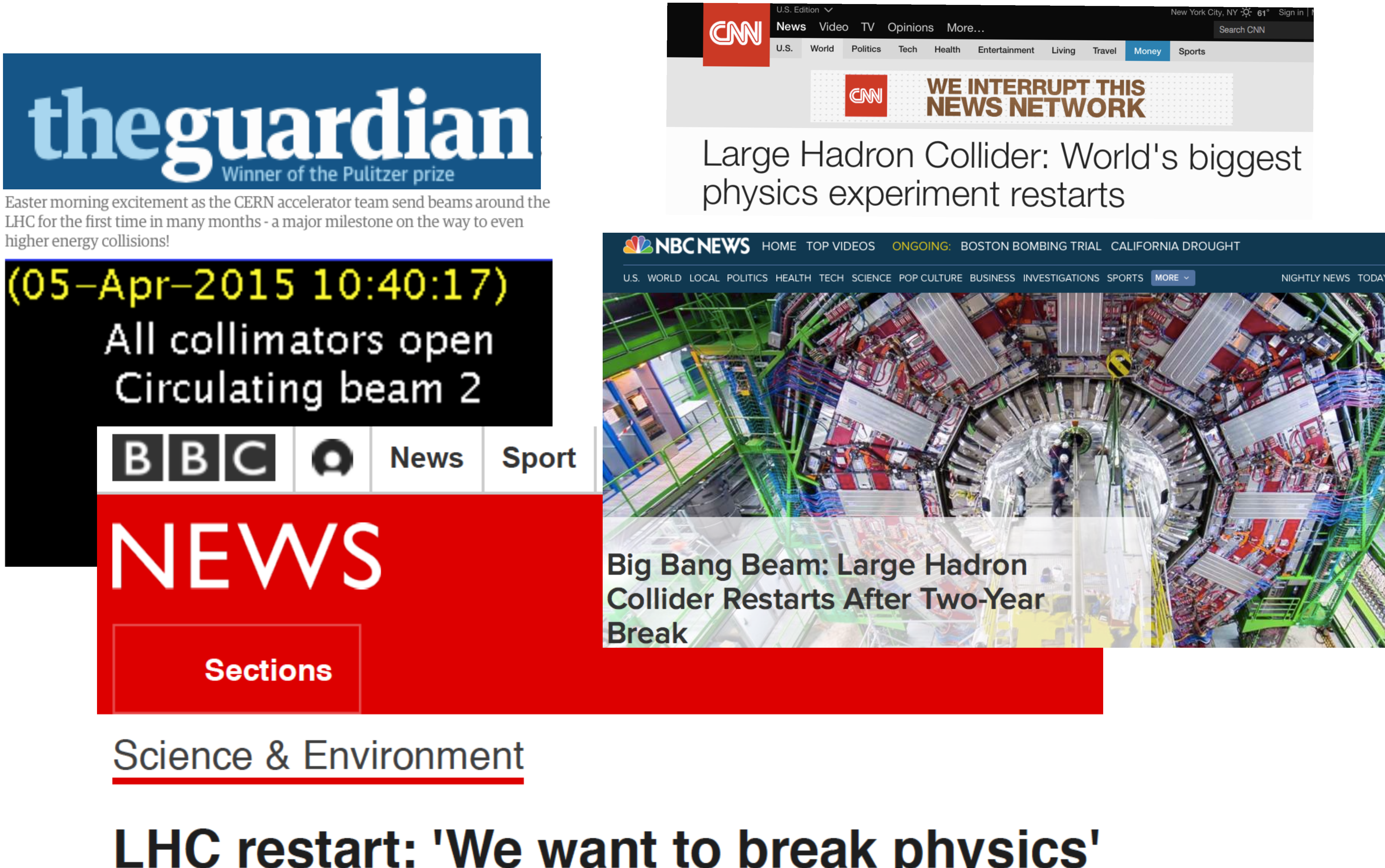
	Higgs X-section Working Group [26]	PDG [2]	Non-lattice	Lattice (2013)	Lattice (2018)	Targets of ILC/TLEP/LHeC
$\delta\alpha_s$	0.002	0.0007	0.0012 [2]	0.0006 [35]	0.0004	0.0001–0.0006 [10, 11, 23]
δm_c (GeV)	0.03	0.025	0.013 [39]	0.006 [35]	0.004	-
δm_b (GeV)	0.06	0.03	0.016 [39]	0.023 [35]	0.011	-

Summary

- We've observed what looks like a SM Higgs. More work needed to sharpen the Higgs picture and dig out possible new physics signals out of the overwhelming background.

- Significant improvements of theory uncertainties in the last couple of years; we've witnessed the completion of several important precision predictions in the last few months: ggH@N^3LO, and fully differential NNLO results: Higgs+jet, VBF.

Summary


theguardian
Winner of the Pulitzer prize
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Summary

Lets hope for more headlines soon !