Theory Uncertainties in Higgs Production and Decays

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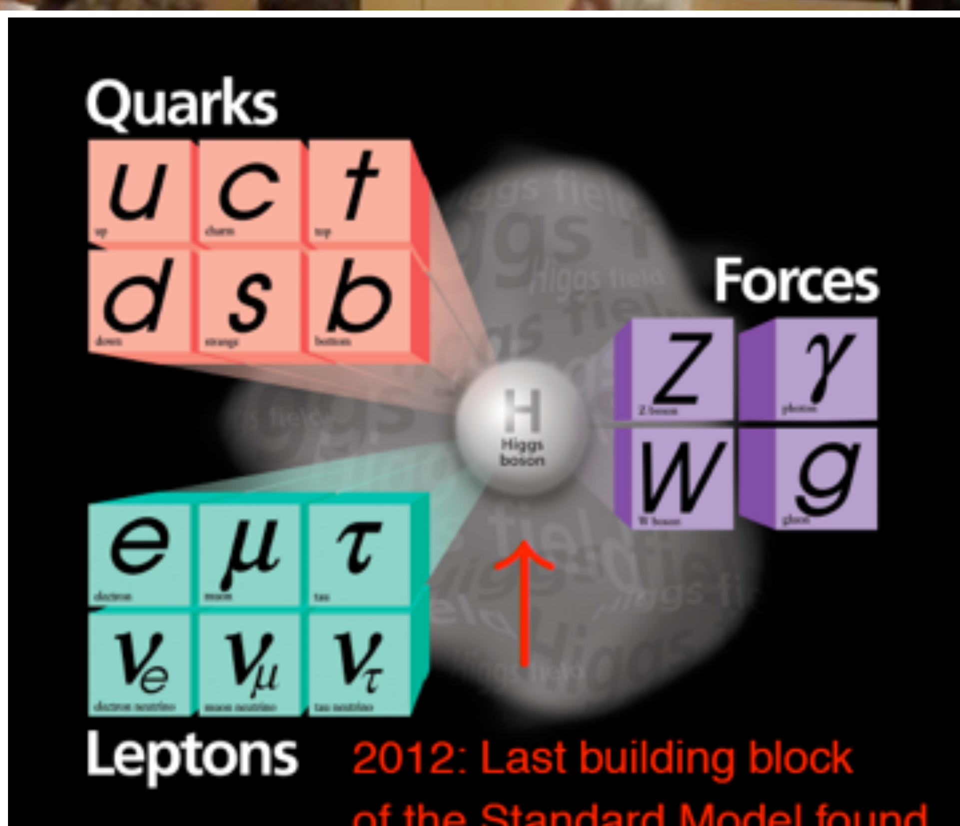
Physics at LHC and beyond, August 14, Quy-Nhon, Vietnam

History in the making

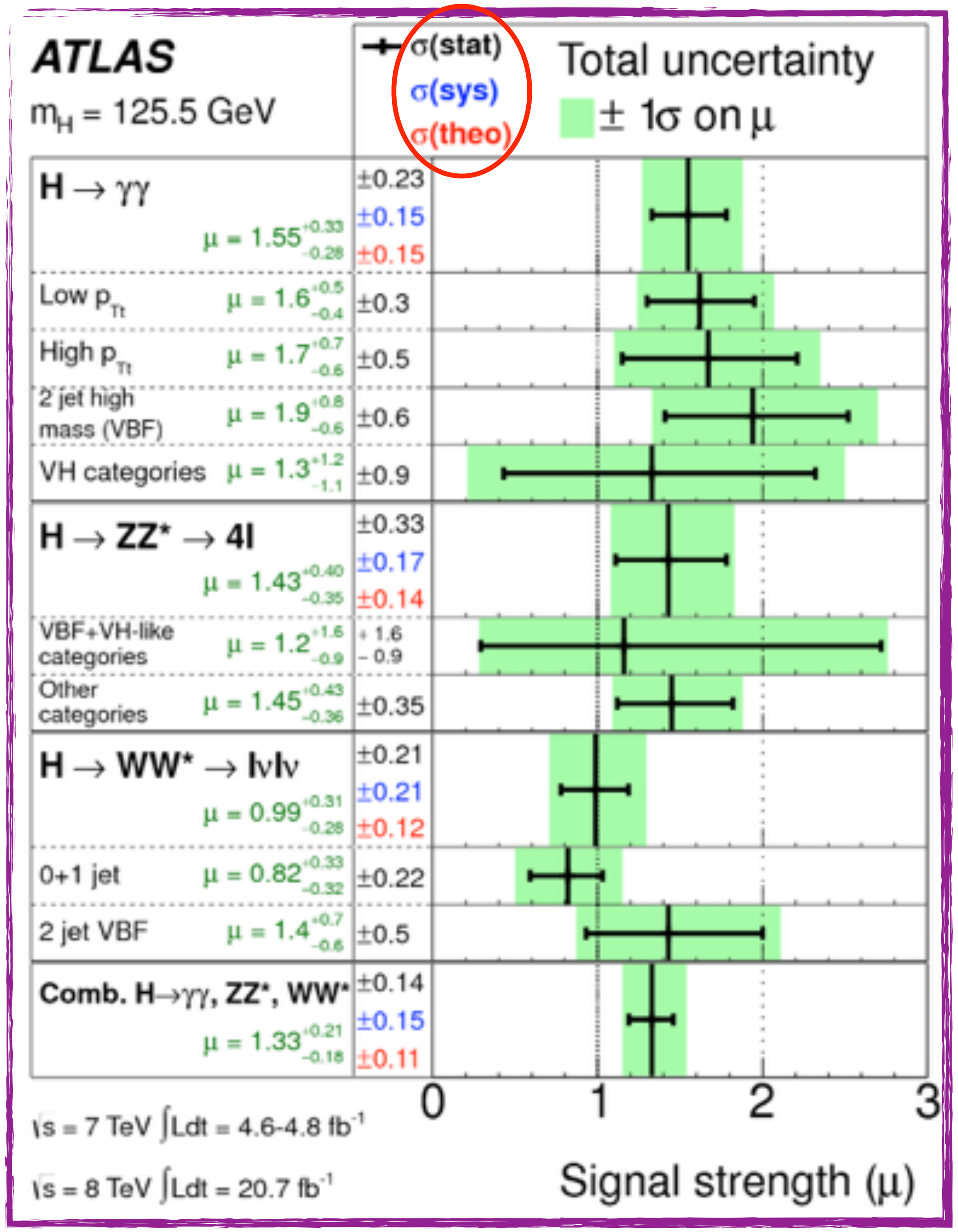
- July 2012: a Higgs boson was discovered!

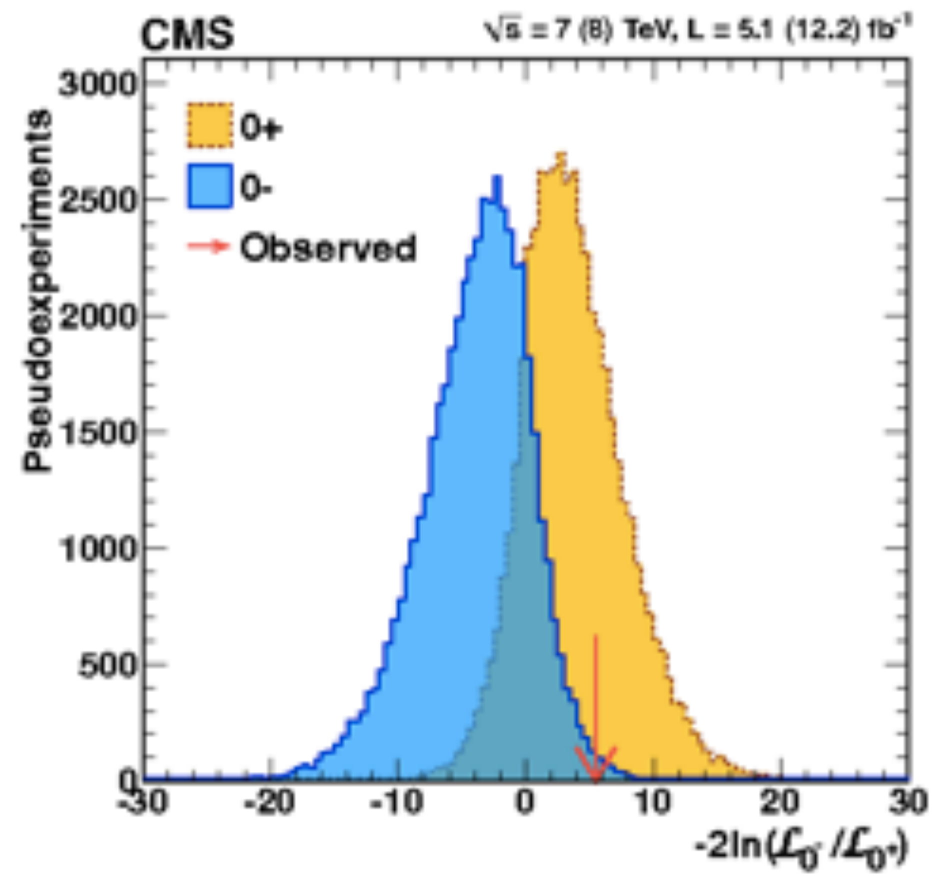


2013

What we know so far

- Gross properties of the new state roughly indicate SM-like couplings





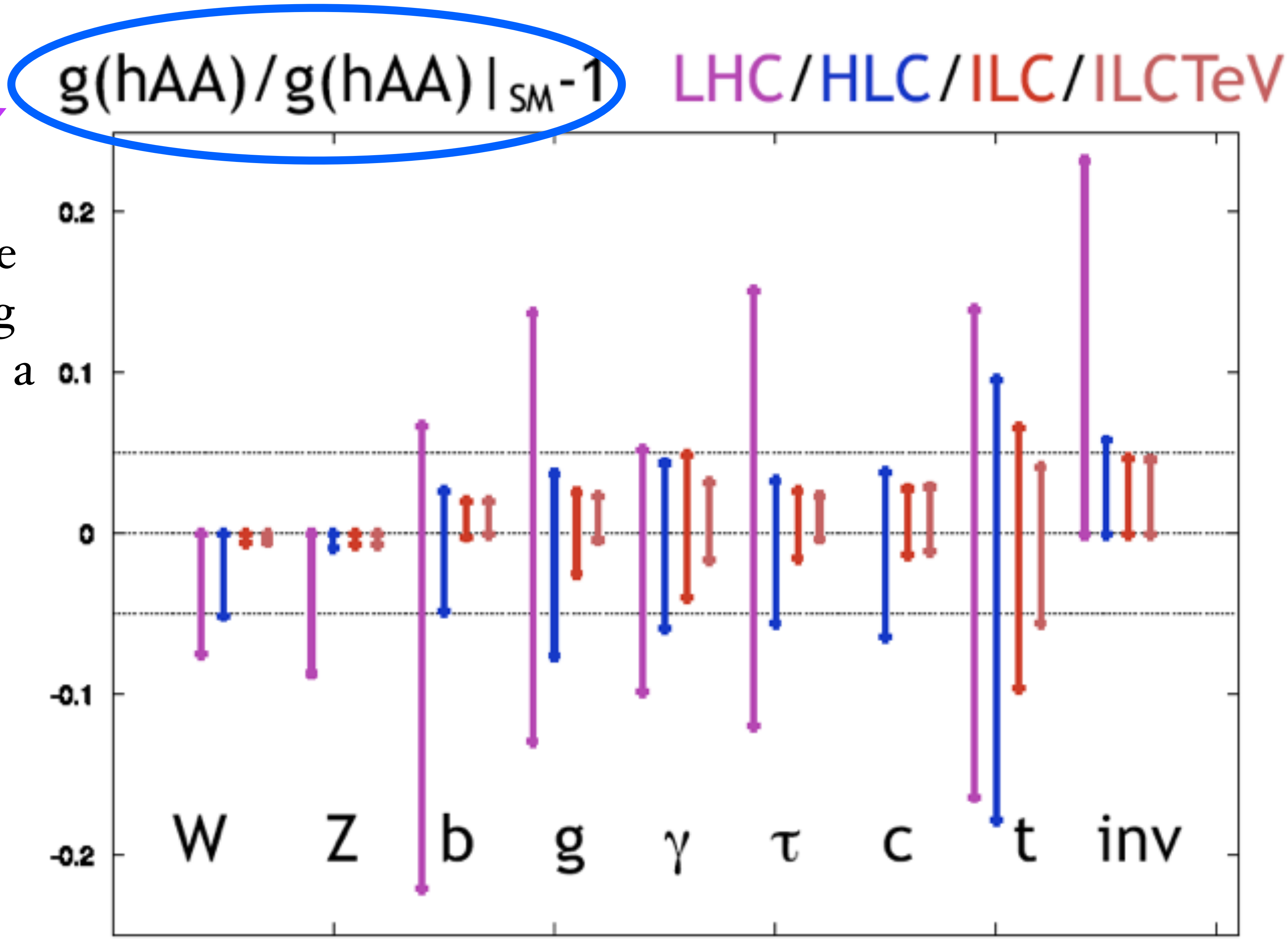
- Higgs mass: a new precision parameter of the SM
- Spin-0 is favored, and it is primarily a CP-even state

Underlying identity of the Higgs
is being slowly revealed

The Future

- LHC Run II will deliver more data, and will have more precise measurements
- The Higgs discovery motivates future experiments to definitively determine the properties of this state. Theory needs to match the experimental accuracy.

All results will be interpreted using the SM Higgs as a benchmark



Peskin, 1207.2516

Outline

- Introduction
- Overview of current theoretical and parametric uncertainties in Higgs production and decays
- Higgs production in gluon fusion:
  - Overall signal normalization
  - Higgs kinematics and differential distributions
- Summary

Higgs Decays

- Precise calculations for various SM Higgs-boson decay modes are known:

$H \to f\bar{f}$

Bardin et al '91; Dabelstein, Hollik '92; Kniehl '92; ...

Total decay dominated by $H \to b\bar{b}$, known in QCD up to NNNNLO,

Baikov et al ('97-'05)

$H \to \gamma\gamma/gg$

Full two-loop result known + higher order improvements

Spira et al '95; Actis, Passarino et al '07, '08

$H \to WW/ZZ \to 4f$

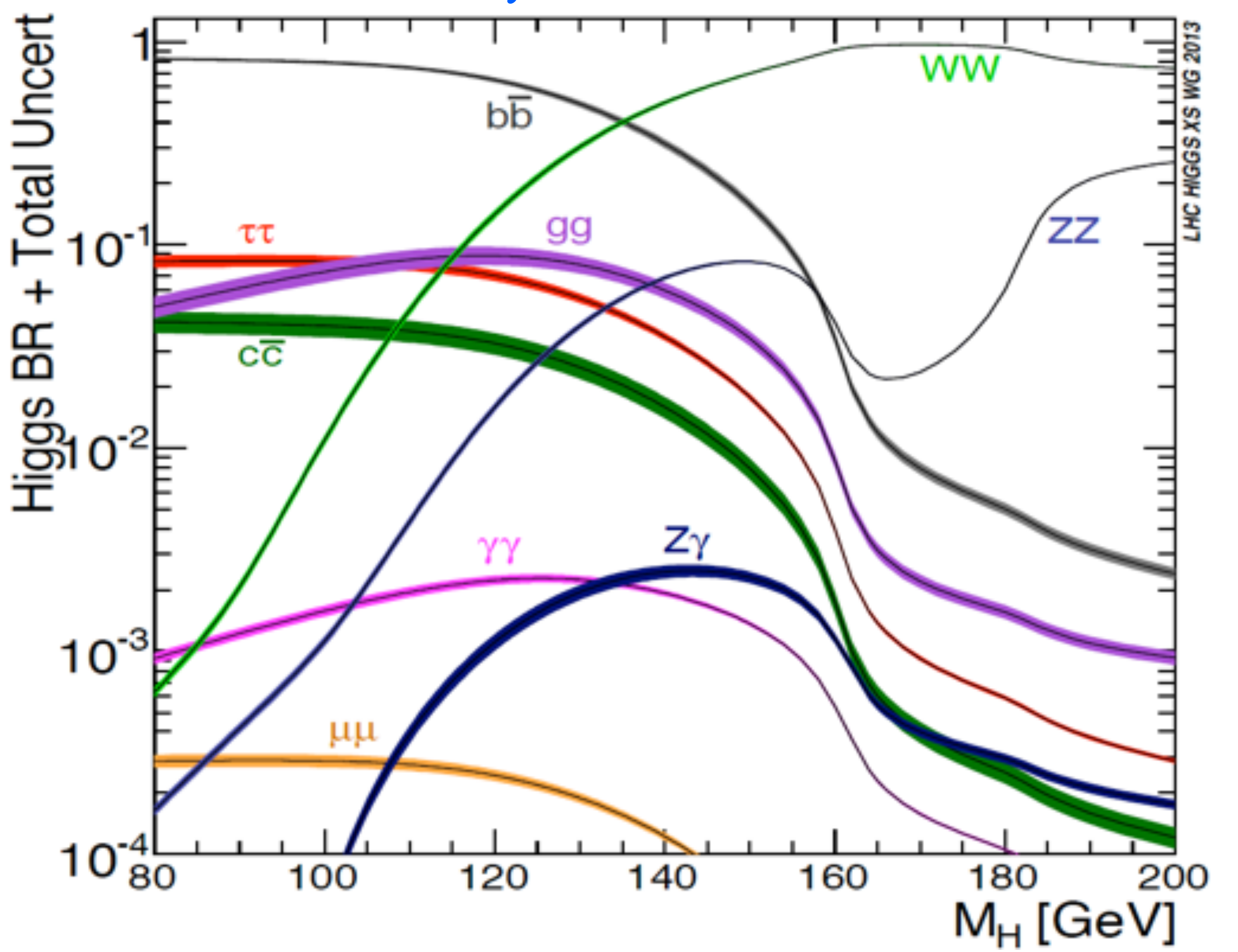
NLO for stable W/Z:

Fleischer, Jegerlehner '81; Kniehl '91;Bardin et al '91

NLO for off-shell/decaying W/Z:

Bredenstein,Denner, Dittmaier, Webber '06

Hdecay+PROPHECY4f



M_H[GeV]	H →	$b\bar{b}$	$\tau^+\tau^-$	$c\bar{c}$	gg	$\gamma\gamma$	WW	ZZ
120		3%	6%	12%	10%	5%	5%	5%
150		4%	3%	10%	8%	2%	1%	1%
200		5%	3%	10%	8%	2%	$< 0.1\%$	$< 0.1\%$

parametric + theoretical uncertainty of BRs:
LHC Higgs XS WG '10 -'13

Parametric Uncertainties

Channel	M_H [GeV]	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
H → bb	122	2.30	−2.3% / +2.3%	+3.2% / −3.2%	+0.0% / −0.0%	+0.0% / −0.0%	+2.0% / −2.0%
	126	2.36	−2.3% / +2.3%	+3.3% / −3.2%	+0.0% / −0.0%	+0.0% / −0.0%	+2.0% / −2.0%
	130	2.42	−2.4% / +2.3%	+3.2% / −3.2%	+0.0% / −0.0%	+0.0% / −0.0%	+2.0% / −2.0%
$H \to \tau^+\tau^-$	122	$2.51 \cdot 10^{-1}$	+0.0% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.1%	+2.0% / −2.0%
	126	$2.59 \cdot 10^{-1}$	+0.0% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.1% / −0.1%	+2.0% / −2.0%
	130	$2.67 \cdot 10^{-1}$	+0.0% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.1% / −0.1%	+2.0% / −2.0%
$H \to \mu^+\mu^-$	122	$8.71 \cdot 10^{-4}$	+0.0% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.1% / −0.1%	+2.0% / −2.0%
	126	$8.99 \cdot 10^{-4}$	+0.0% / +0.0%	+0.0% / −0.0%	−0.1% / −0.0%	+0.0% / −0.1%	+2.0% / −2.0%
	130	$9.27 \cdot 10^{-4}$	+0.1% / +0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.1% / −0.0%	+2.0% / −2.0%
$H \to c\bar{c}$	122	$1.16 \cdot 10^{-1}$	−7.1% / +7.0%	−0.1% / −0.1%	+6.2% / −6.0%	+0.0% / −0.1%	+2.0% / −2.0%
	126	$1.19 \cdot 10^{-1}$	−7.1% / +7.0%	−0.1% / −0.1%	+6.2% / −6.1%	+0.0% / −0.1%	+2.0% / −2.0%
	130	$1.22 \cdot 10^{-1}$	−7.1% / +7.0%	−0.1% / −0.1%	+6.3% / −6.0%	+0.1% / −0.1%	+2.0% / −2.0%
H → gg	122	$3.25 \cdot 10^{-1}$	+4.2% / −4.1%	−0.1% / −0.1%	+0.0% / −0.0%	−0.2% / +0.2%	+3.0% / −3.0%
	126	$3.57 \cdot 10^{-1}$	+4.2% / −4.1%	−0.1% / −0.1%	+0.0% / −0.0%	−0.2% / +0.2%	+3.0% / −3.0%
	130	$3.91 \cdot 10^{-1}$	+4.2% / −4.1%	−0.1% / −0.2%	+0.0% / −0.0%	−0.2% / +0.2%	+3.0% / −3.0%
$H \to \gamma\gamma$	122	$8.37 \cdot 10^{-3}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+1.0% / −1.0%
	126	$9.59 \cdot 10^{-3}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+1.0% / −1.0%
	130	$1.10 \cdot 10^{-2}$	+0.1% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+1.0% / −1.0%
$H \to Z\gamma$	122	$4.74 \cdot 10^{-3}$	+0.0% / −0.1%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.1%	+5.0% / −5.0%
	126	$6.84 \cdot 10^{-3}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.1%	+0.0% / −0.1%	+5.0% / −5.0%
	130	$9.55 \cdot 10^{-3}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+5.0% / −5.0%
H → WW	122	$6.25 \cdot 10^{-1}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
	126	$9.73 \cdot 10^{-1}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
	130	1.49	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
H → ZZ	122	$7.30 \cdot 10^{-2}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
	126	$1.22 \cdot 10^{-1}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%
	130	$1.95 \cdot 10^{-1}$	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.0% / −0.0%	+0.5% / −0.5%

Partial widths

LHC Higgs CS WG, arXiv:1307.1347

Parametric uncertainties are the largest source of uncertainty for the partial widths into $b\bar{b}$, $c\bar{c}$, gg

Such uncertainties limit the precision of the SM predictions and hinder the observation of possible deviations from the SM. They need to be improved.

Parametric Uncertainties: possible future improvements from lattice

What to expect

Lepage, Mackenzie, and Peskin, arXiv:1404.0319, "Expected Precision of Higgs Boson Partial Widths within the Standard Model"

Talk by Mackenzie at the Americas workshop on Linear Colliders, Fermilab, May 2014

Results:

$$\delta_A = \frac{1}{2}\frac{\Delta\Gamma(h \to A\overline{A})}{\Gamma(h \to A\overline{A})}$$

	$\delta m_b(10)$	$\delta\alpha_s(m_Z)$	$\delta m_c(3)$	δ_b	δ_c	δ_g
current errors [10]	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

Expected improvements in α_s and m_q.

Resulting improvements in δ_A.

Table 1: Projected fractional errors, in percent, for the $\overline{\text{MS}}$ QCD coupling and heavy quark masses under different scenarios for improved analyses. The improvements considered are: PT - addition of 4$^{\text{th}}$ order QCD perturbation theory, LS, LS^2 - reduction of the lattice spacing to 0.03 fm and to 0.023 fm; ST - increasing the statistics of the simulation by a factor of 100. The last three columns convert the errors in input parameters into errors on Higgs couplings, taking account of correlations. The bottom line gives the target values of these errors suggested by the projections for the ILC measurement accuracies.

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$$\delta_A = \frac{1}{2}\frac{\Delta\Gamma(h\to A\overline{A})}{\Gamma(h\to A\overline{A})}$$

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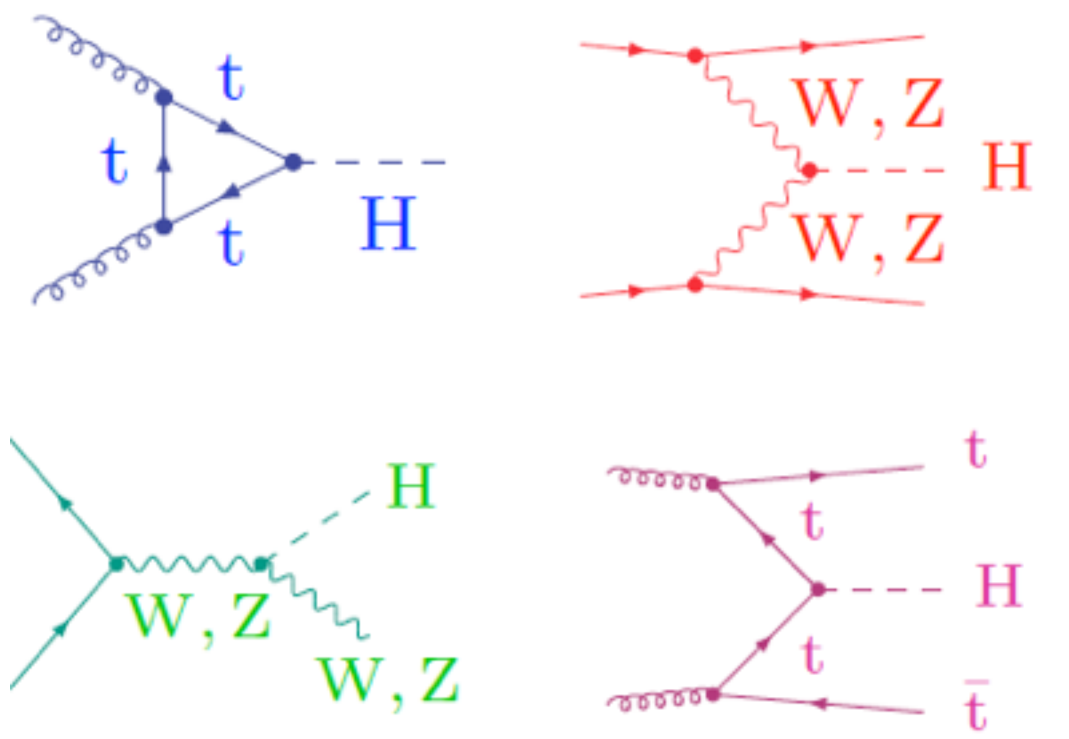
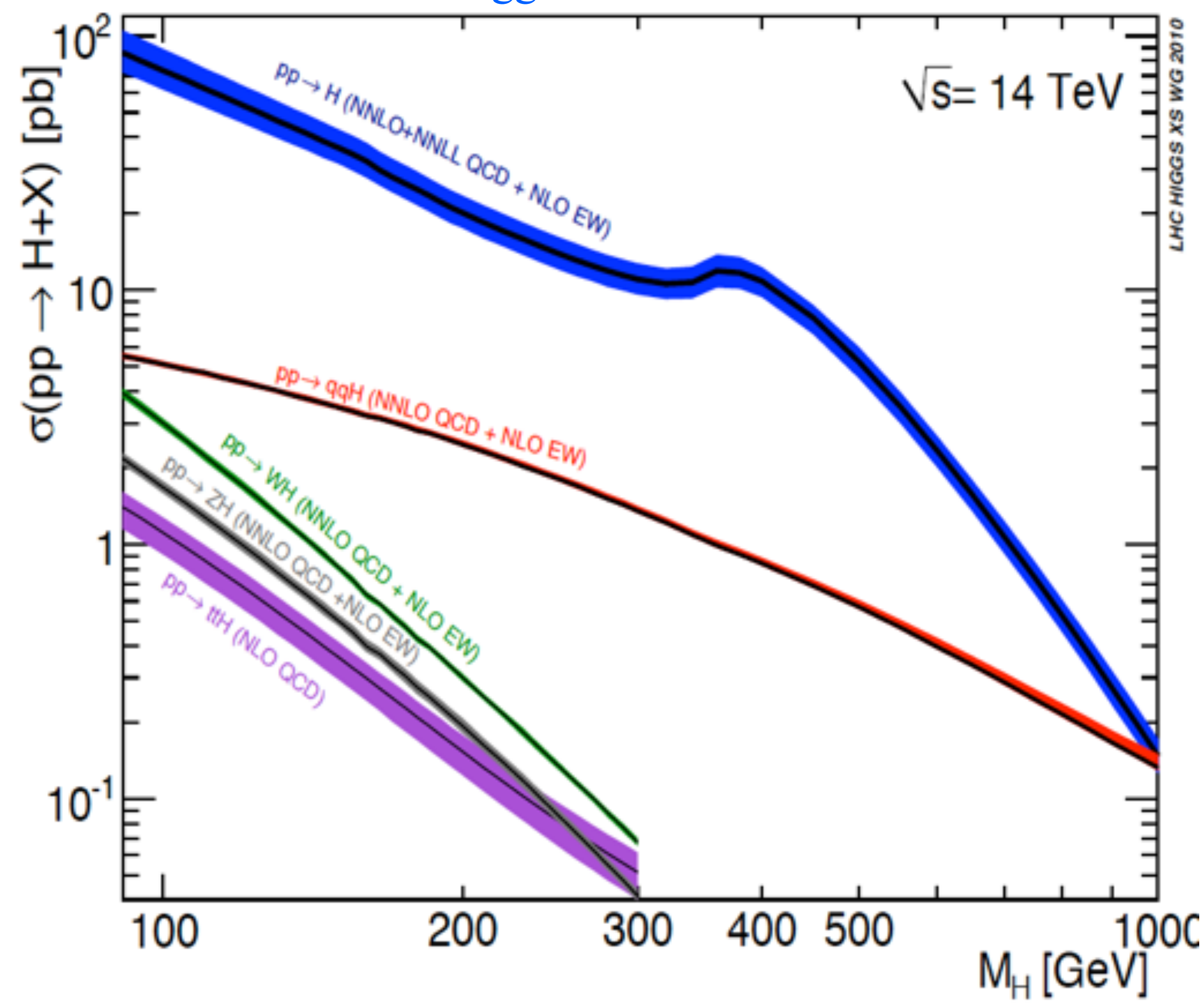
Possibility for a factor of few reduction in the parametric uncertainties affecting Higgs branching fractions in the SM!

Higgs Production at the LHC

Dominated by the gluon fusion mode



LHC Higgs XS WG '10 -'13



Quantum corrections are large, significantly affecting the various predictions:

QCD: $\mathcal{O}(\alpha_s) \sim 10\text{–}100\%$

EW: $\mathcal{O}(\alpha) \sim 10\%$

They must be calculated to reduce the theoretical uncertainties to the level of PDF uncertainties $(q\bar{q} \sim 5\%, gg \sim 5-10\%)$ and experimental measurements.

	Uncertainties		NLO/NNLO/NNLO+	
$M_H = 126\,\mathrm{GeV}$	scale	PDF4LHC	QCD	EW
ggF	8–11%	7%	>100%	5%
VBF	1%	2–3%	5%	5%
WH	1%	4%	20%	7%
ZH	3%	4%	30%	5%
ttH	9%	9%	15–20%	?

- Significant progress for the total Higgs cross section in gluon fusion, results improved the theory uncertainty significantly over the years:

  - Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about 6-15%) — Catani, De Florian, Nason, Grazzini '03

  - Partial N^3LO corrections (soft gluon approximation) — Moch, Vogt '05

  - Partial N^3LO corrections (soft + virtual exact corrections) — Anastasiou et al '14

  - Approximate N^3LO in QCD by matching two limits: soft gluons and highly energetic gluons — Ball et al '13; Bonvini, Marzani '14

  - Resummation of π^2 factors through appropriate matching condition — Ahrens, Becher, Neubert, Yang '08

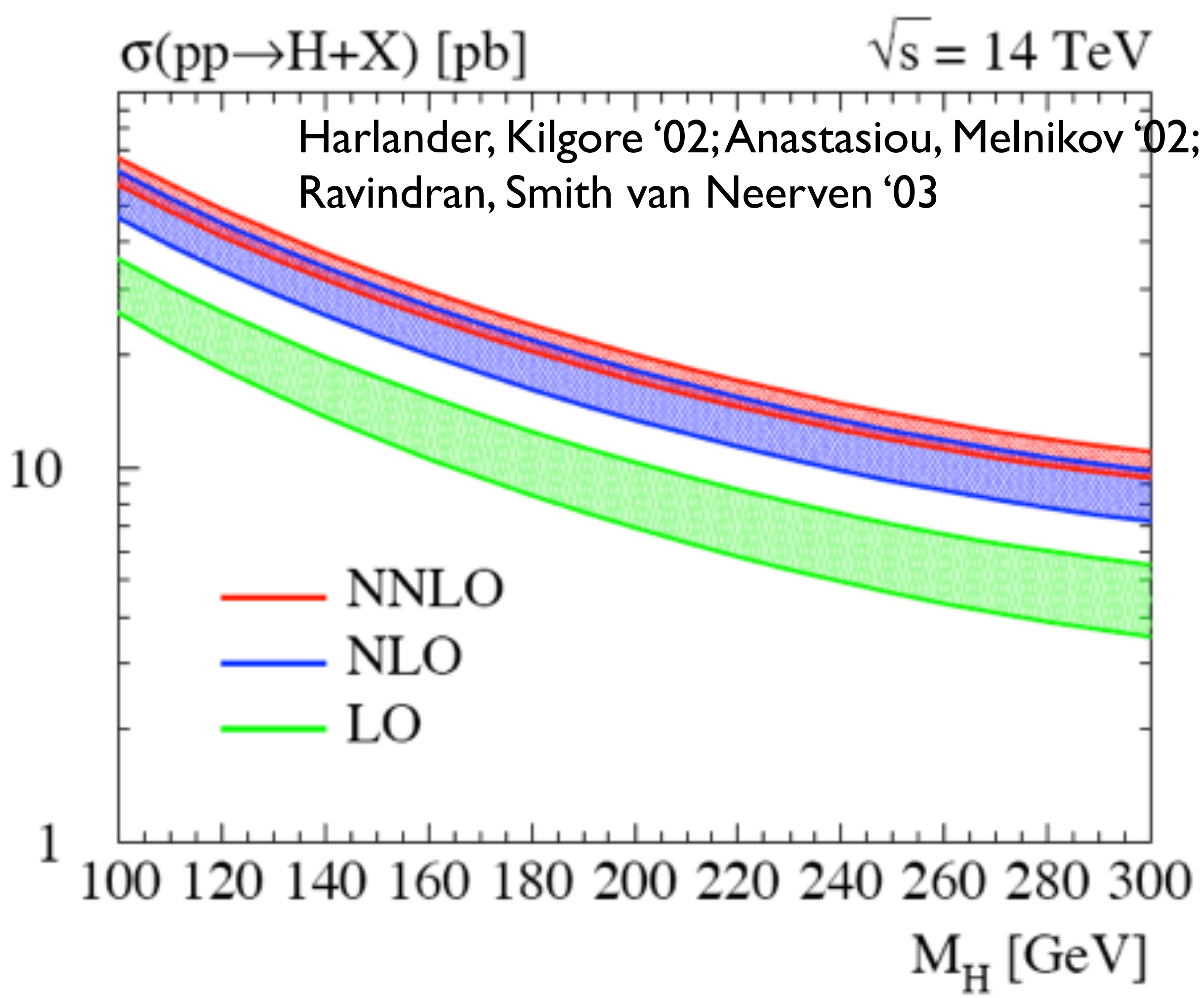
  - Two-loop EW corrections are also known (effect is O(5%)) — Aglietti et al '04; Degrassi, Maltoni '04; Passarino et al '08

  - Mixed QCD-EW effects evaluated in EFT approach — Anastasiou, R.B., Petriello '08

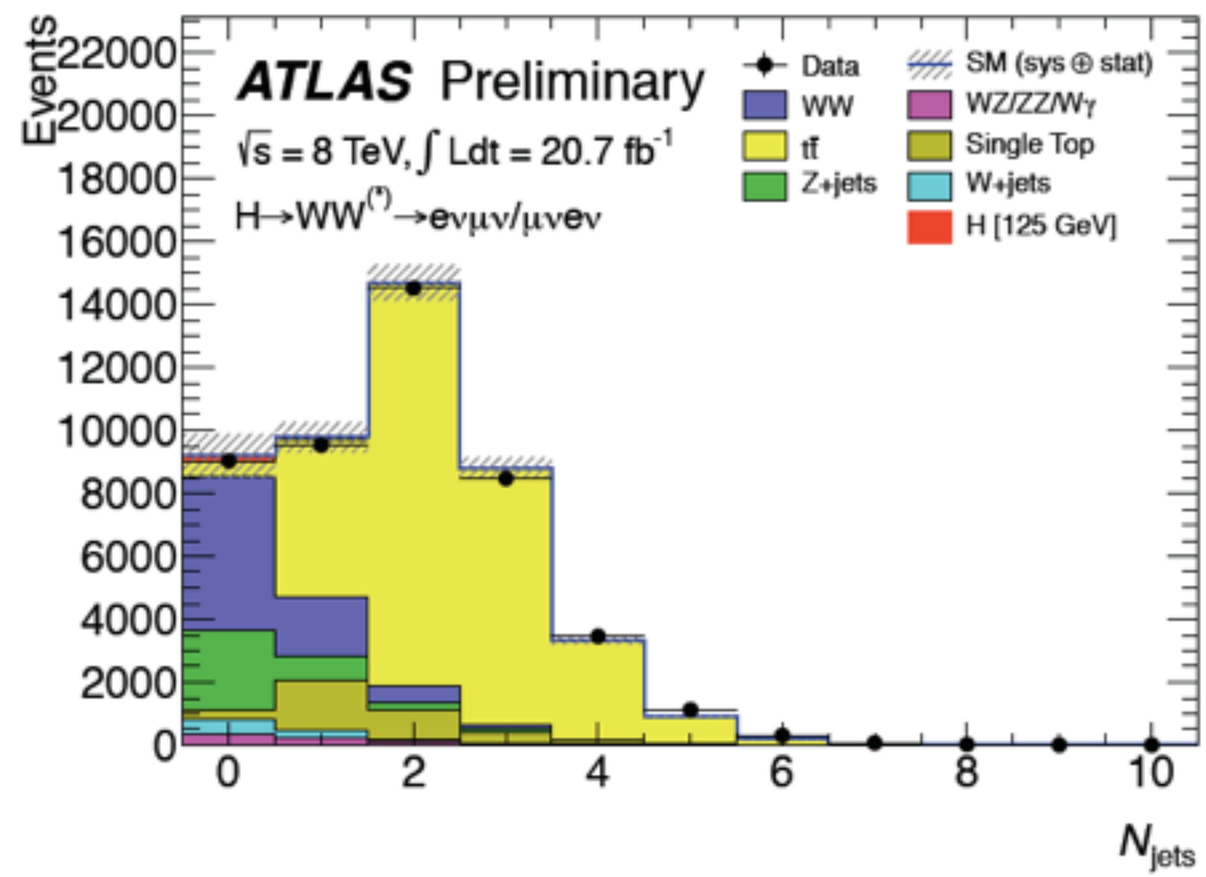
  - EW effects for real radiation — Keung, Petriello '09; O. Brein '10

Theory uncertainties: double trouble

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



How well do we understand the overall signal normalization



How well can we describe the Higgs kinematics: differential distributions

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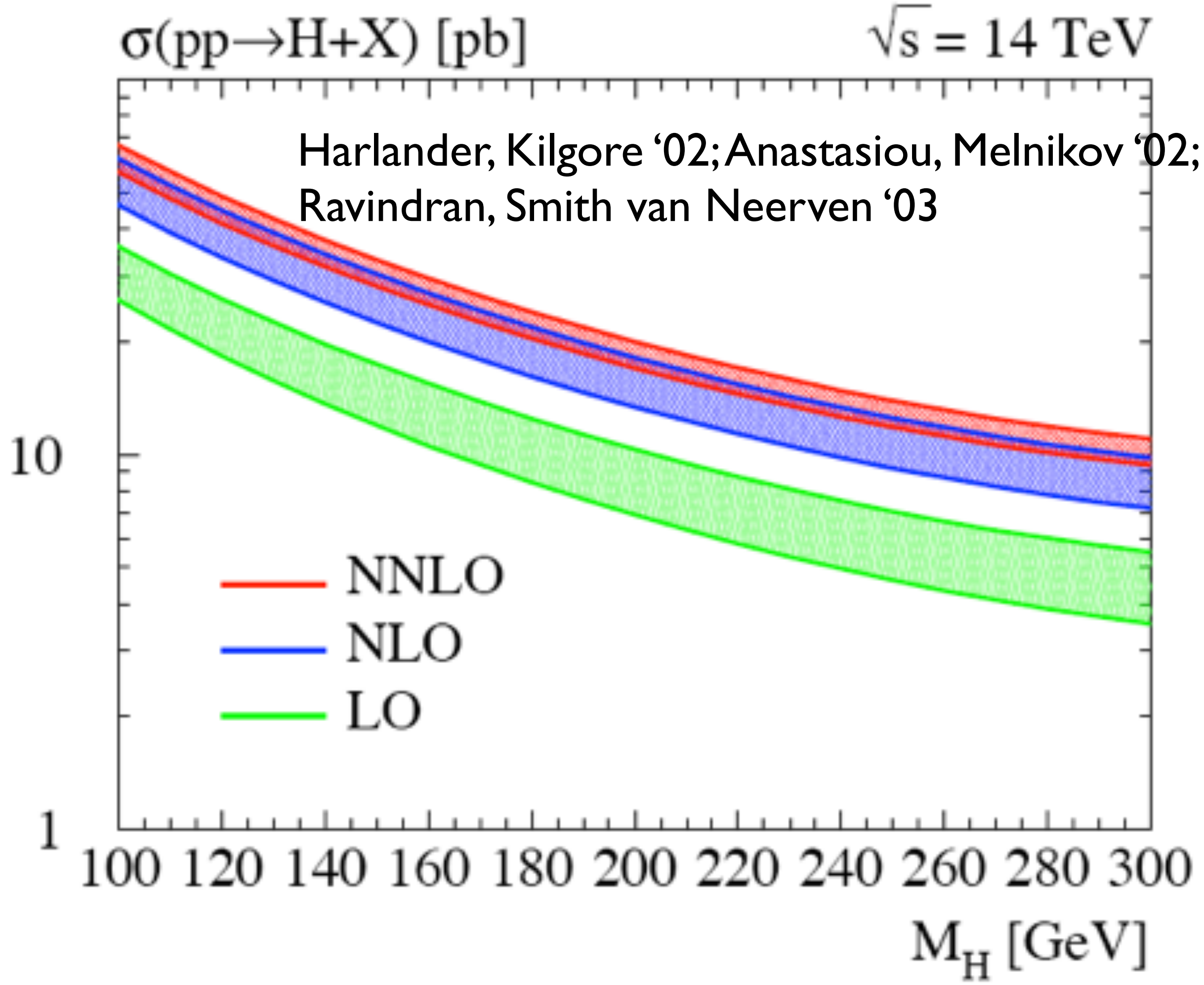

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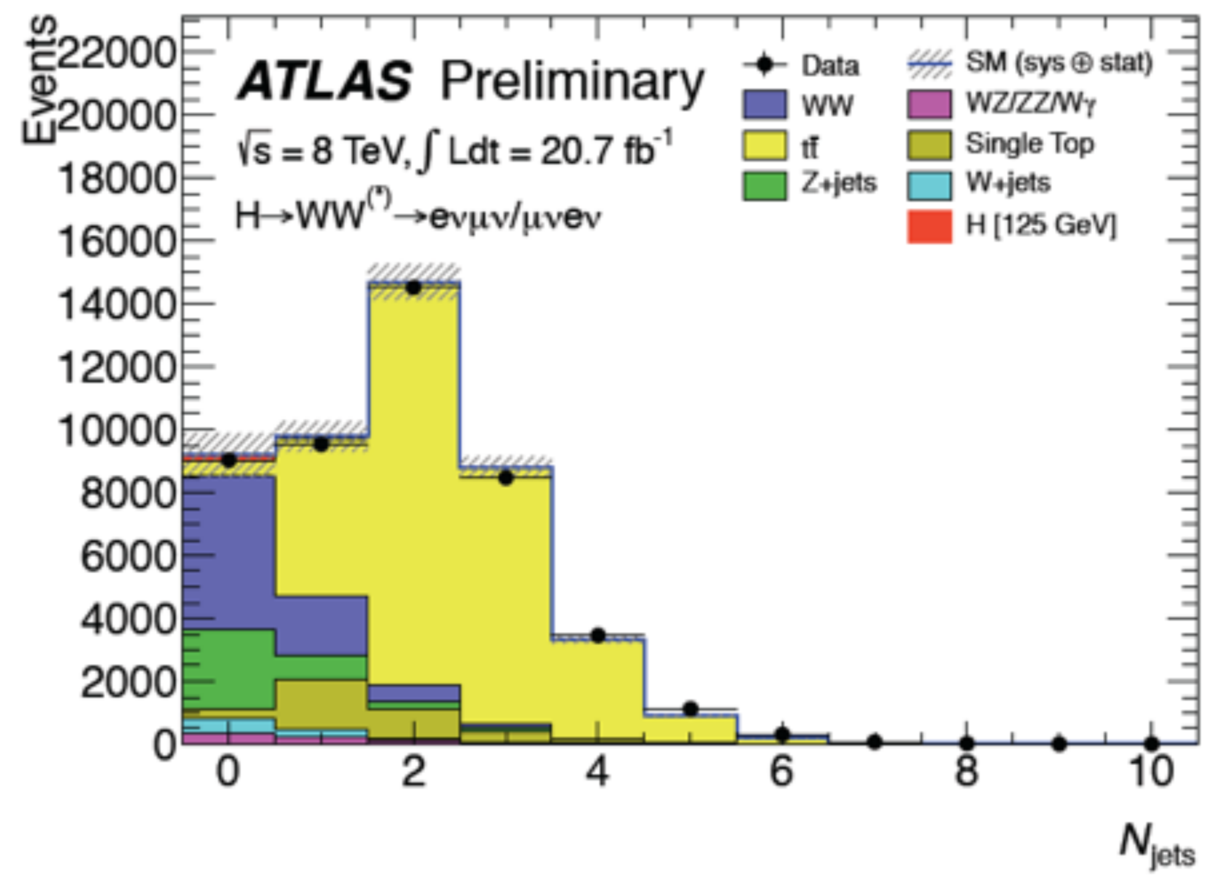


How well can we describe the Higgs kinematics: differential distributions

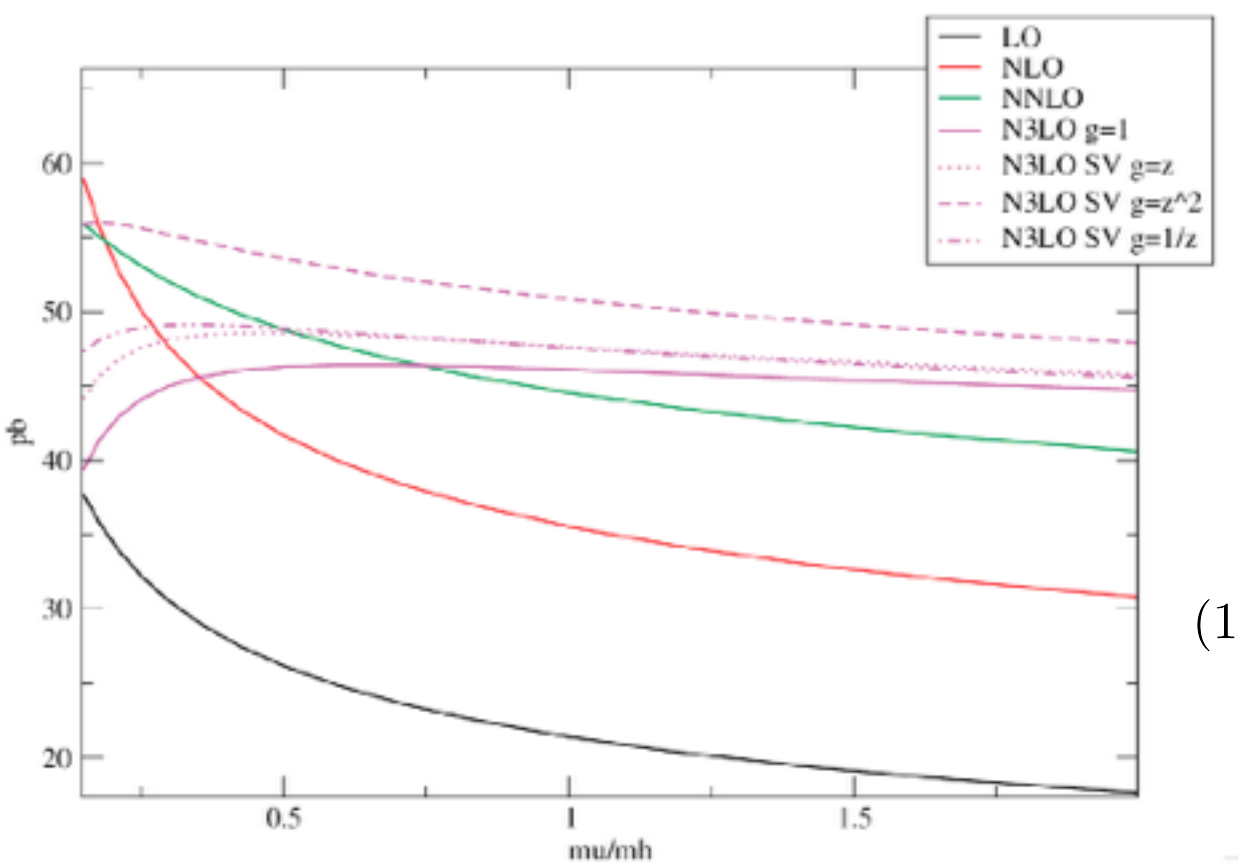
Progress on both fronts needed to improve Higgs-signal modeling for Run II of the LHC, in addition to better control over PDFs and parametric uncertainties.

Focus of the rest of my talk: Higgs production in gluon fusion - overall signal normalization and differential distributions

Overall signal normalization

Soft+Virtual exact N³LO results for the inclusive cross section

- gg → H at N^3LO: needed to reduce the theoretical uncertainty to help extract the Higgs properties (Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger)



- Uses threshold expansion in z

$\mathbf{z} = \mathbf{m^2}/\mathbf{s}$ where $\mathbf{z} \sim \mathbf{1}$ near threshold

$$\hat{\sigma}(z) = \sigma_{-1} + \sigma_0 + (1-z)\sigma_1 + \mathcal{O}(1-z)^2$$

- The soft-virtual term receives contribution from a 'pole' at z~1

$$(1-z)^{-1+n\,\epsilon} = \frac{\delta(1-z)}{n\epsilon} + \left[\frac{1}{1-z}\right]_+ + n\,\epsilon\left[\frac{\ln(1-z)}{1-z}\right]_+ + \mathcal{O}(\epsilon^2)$$

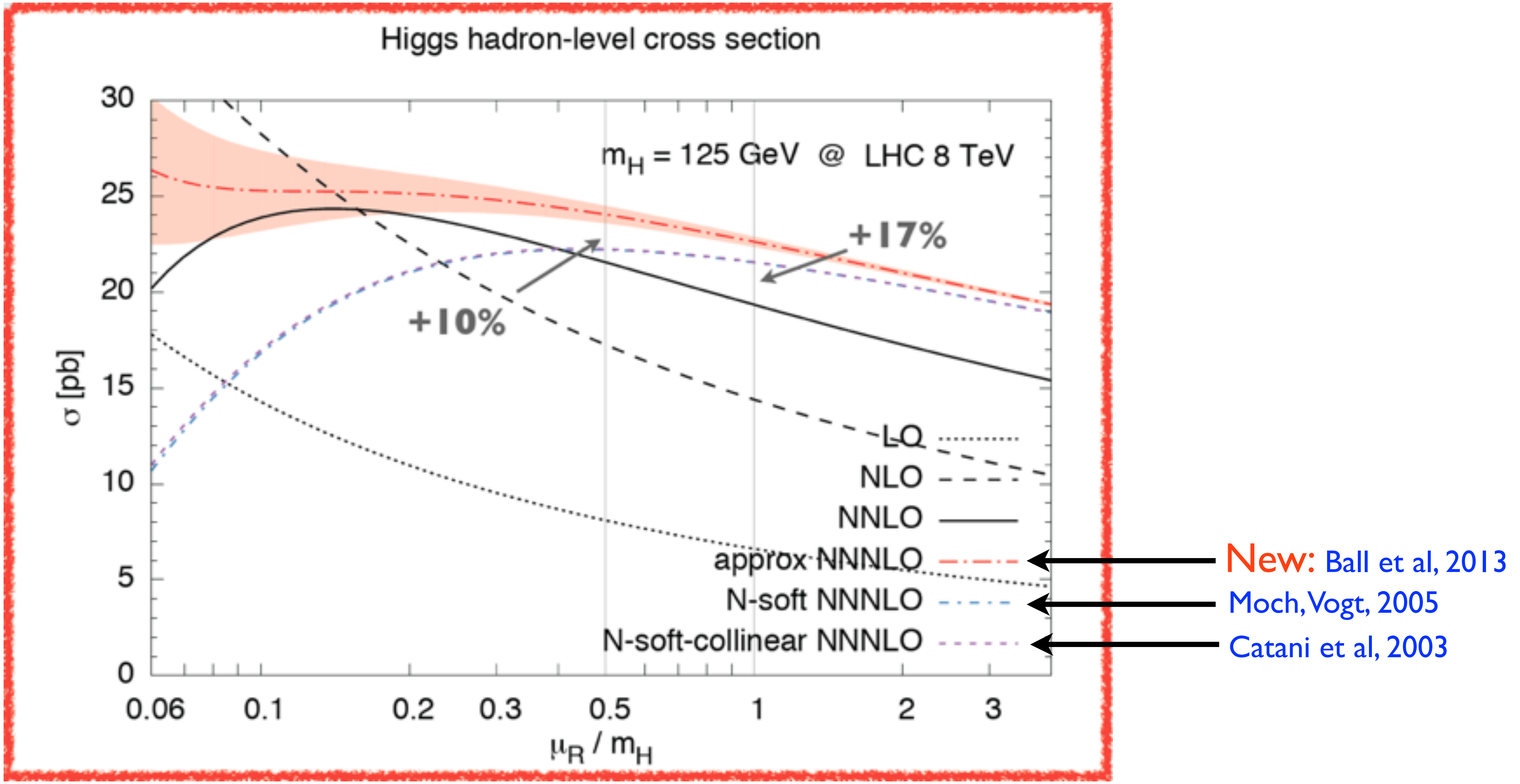
New

Moch, Vogt

- Work in progress to determine the subleading terms at threshold

Other partial and approximate results are available: Li, von Manteuffel, Schabinger, Xing Zhu; Kilgore; Bonvini, Forte, Marzani, Ridolfi; Buehler, Lazopoulos; Hoeschele, Hoff, Ball, Pak, Steinhauser, Ueda

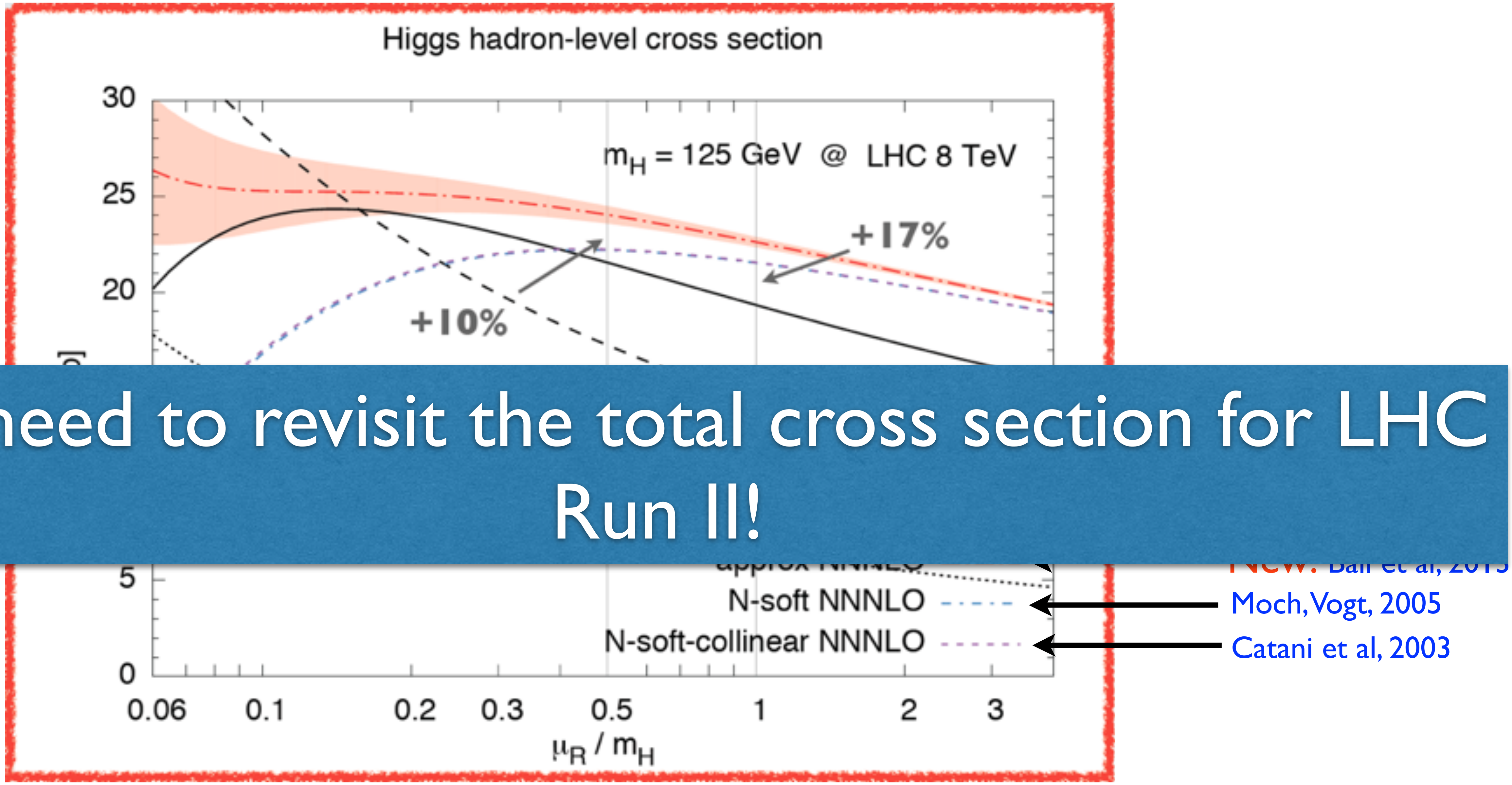
Approximate N^3LO results for the inclusive cross section



10% corrections for mu = $m_H/2$

Updates of this result in arXiv:1404.3204 lead to the same numerical shift

Approximate N^{3}LO results for the inclusive cross section



May need to revisit the total cross section for LHC Run II!

10% corrections for mu = $m_H/2$

Higgs kinematics and differential distributions

Higgs in association with jets

- Higgs cross-sections in pp →H →WW are binned by jet multiplicity to reduce the background
- The measured value of pp→H→WW production cross section results from combining 0-jet, 1-jet and 2-jet cross sections. Each of them has its own uncertainty
- What we knew so far: H+0j @ NNLO, H+1j, H+2j and H+3j @ NLO

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

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

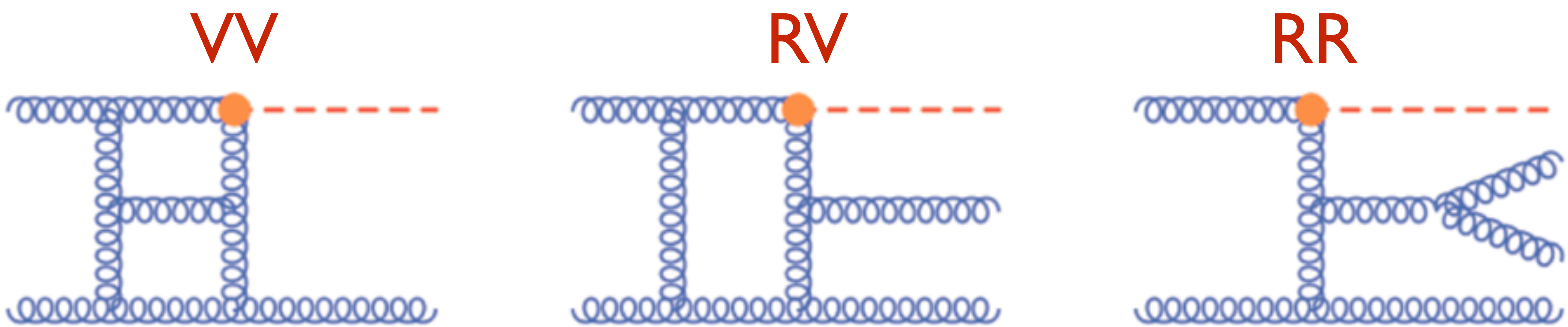
ATLAS

Large K-factors, error dominated by missing higher orders

- Theory uncertainties becoming a limiting factor in many analyses, especially H→WW
- Precise exclusive results are needed, also to separate between gg and VBF...

Fixed Order Cross Sections @ NNLO

- Need the following ingredients for NNLO cross sections



- IR singularities cancel in the sum of real and virtual corrections and mass factorization counterterms but only after phase space integration for real radiations

- Virtual corrections have explicit IR poles, whereas real corrections have implicit IR poles that need to be extracted.

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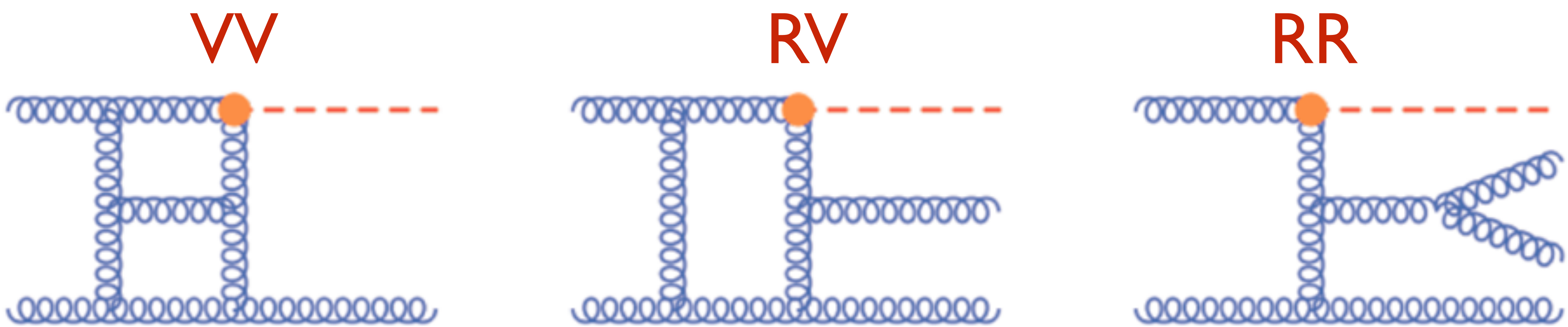

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$$\int \left[\frac{vv_4}{\epsilon^4} + \frac{vv_3}{\epsilon^3} + \frac{vv_2}{\epsilon^2} + \frac{vv_1}{\epsilon} + vv_0\right] \, d\Phi_2$$

$$\int \left[\frac{rv_2}{\epsilon^2} + \frac{rv_1}{\epsilon} + rv_0\right] \, d\Phi_3$$

$$\int [rr_0] \, d\Phi_4$$

Fixed Order Cross Sections @ NNLO

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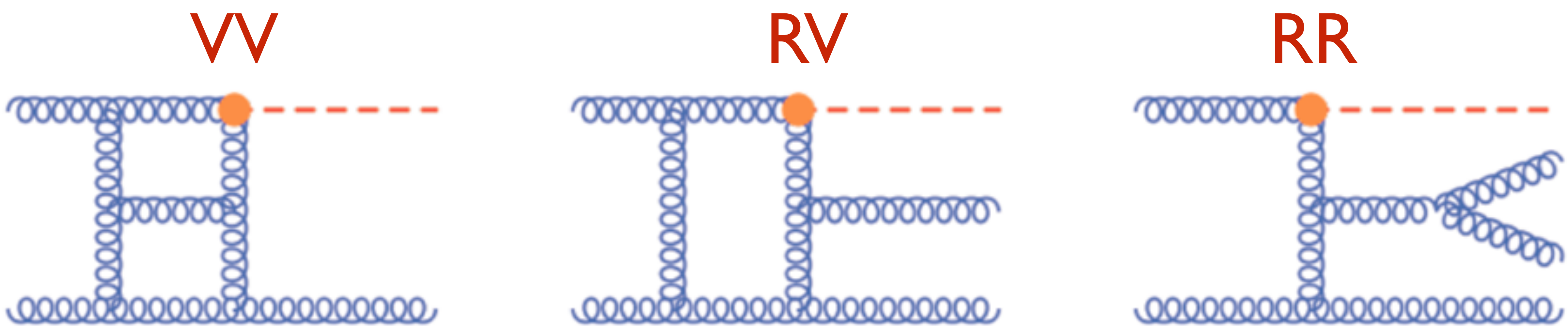

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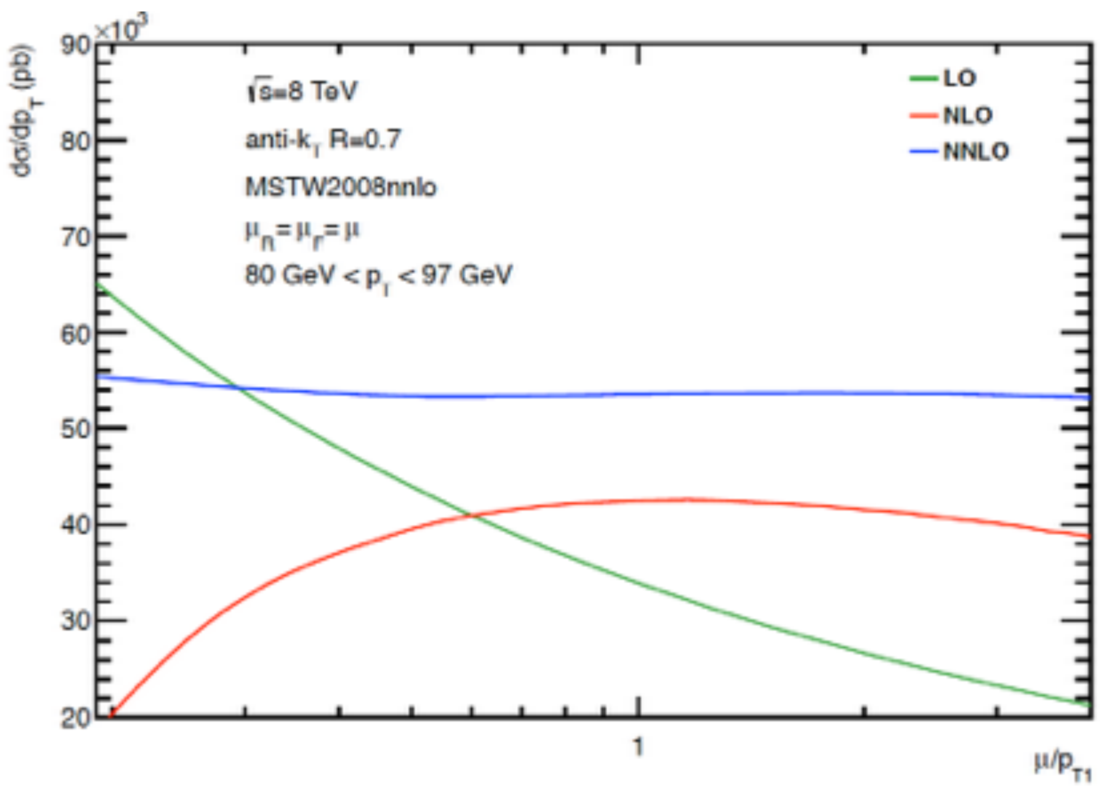
- Virtual corrections have explicit IR poles, whereas real corrections have implicit IR poles that need to be extracted.

- A generic procedure to extract IR singularities from RR and RV was unknown when jets in the final state are involved, until very recently

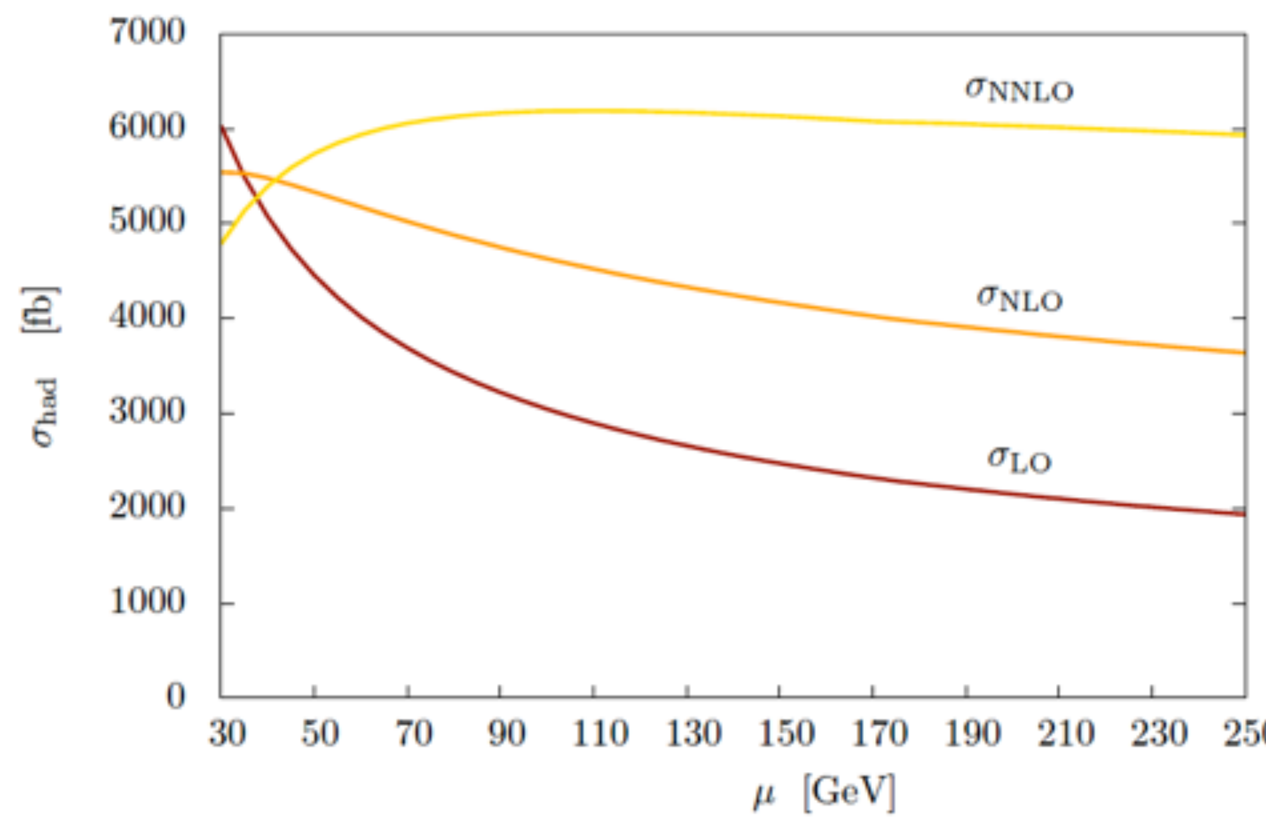
First NNLO Results with final state jets

- First NNLO QCD corrections to processes with final state jets (2013)



Gehrmann-de Ridder, Gehrmann, Glover, Pires

dijet: gg-channel



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

H+1j:gg-channel

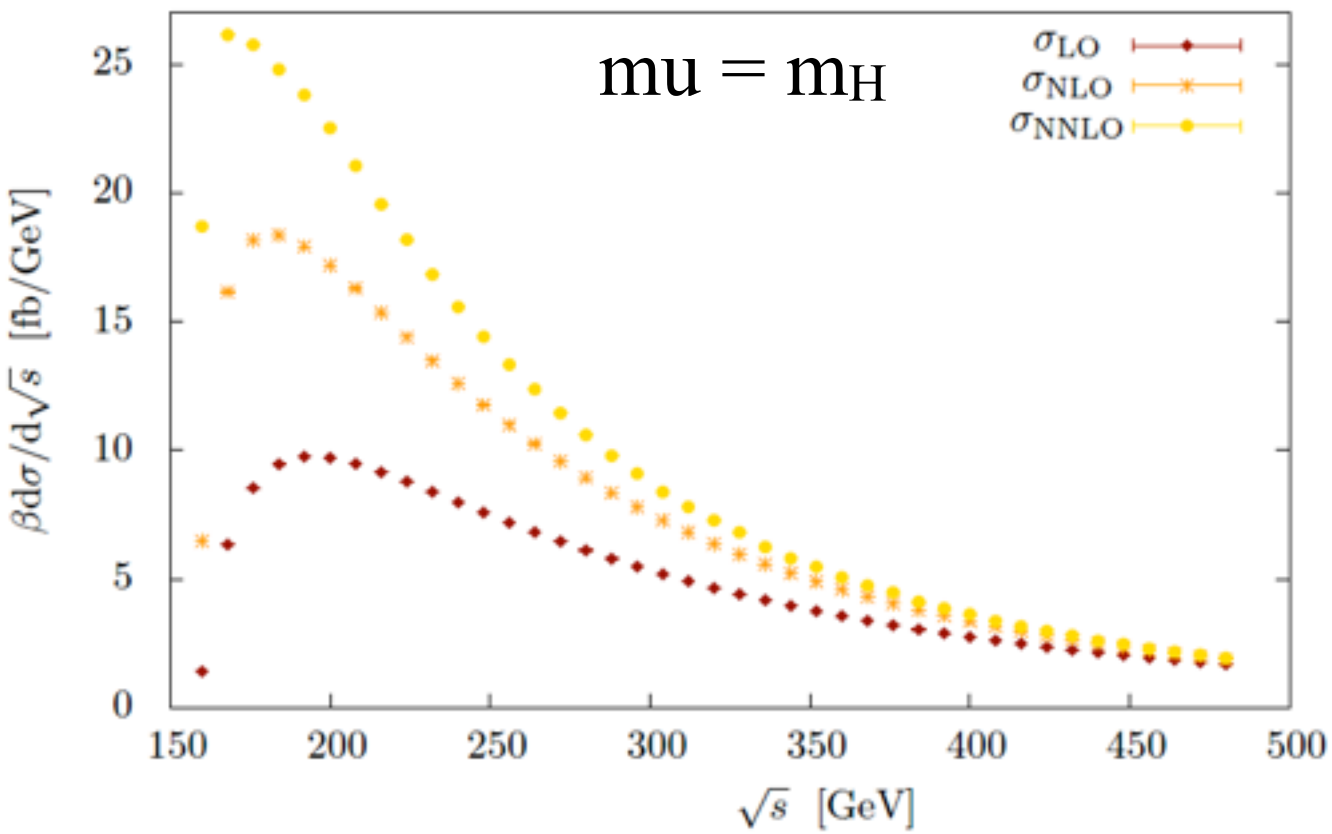
Based on Antenna subtraction scheme

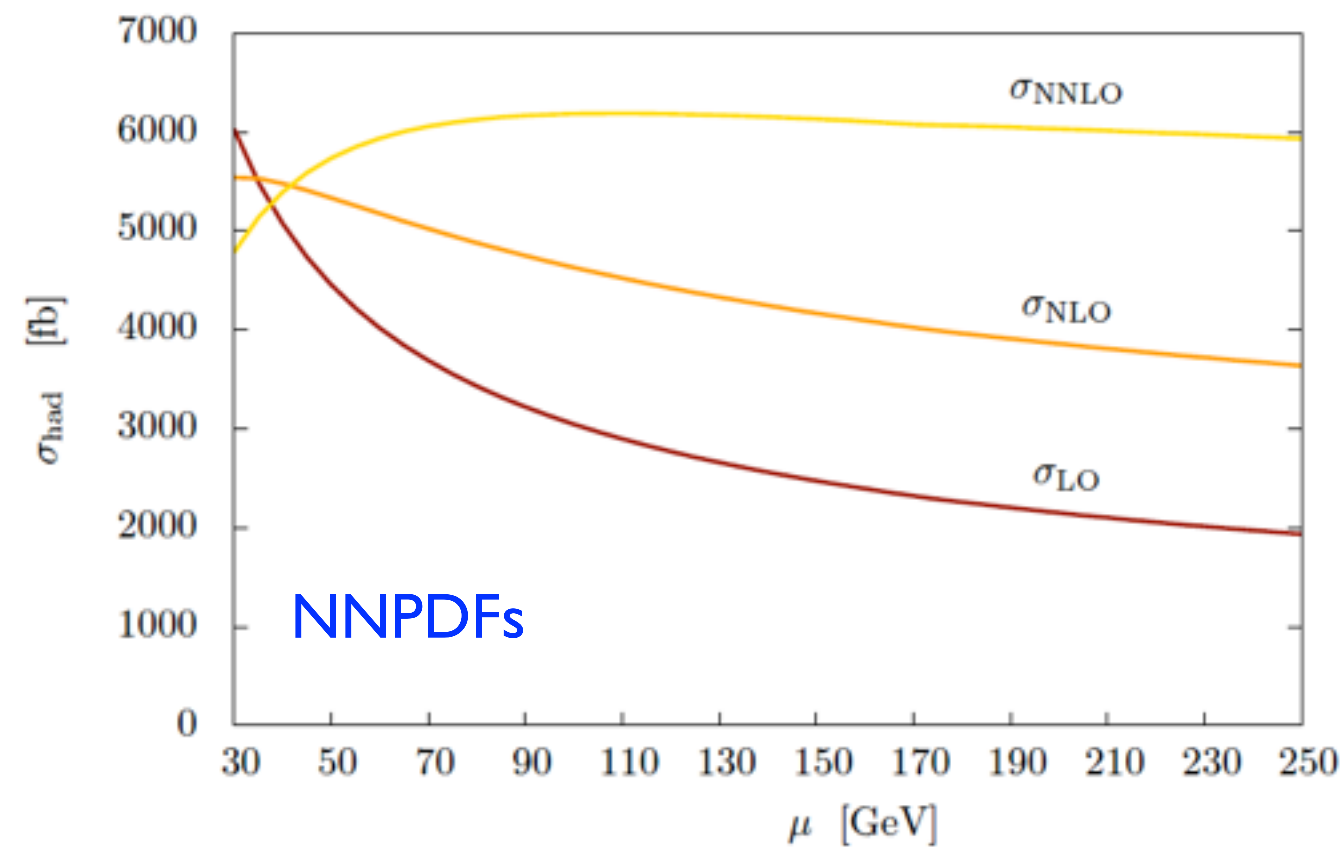
Based on sector-improved subtraction scheme

Higgs + jet @ NNLO (gg only)

- Large NNLO QCD corrections to Higgs+jet !

R.B., Caola, Melnikov, Petriello, Schulze (2013)





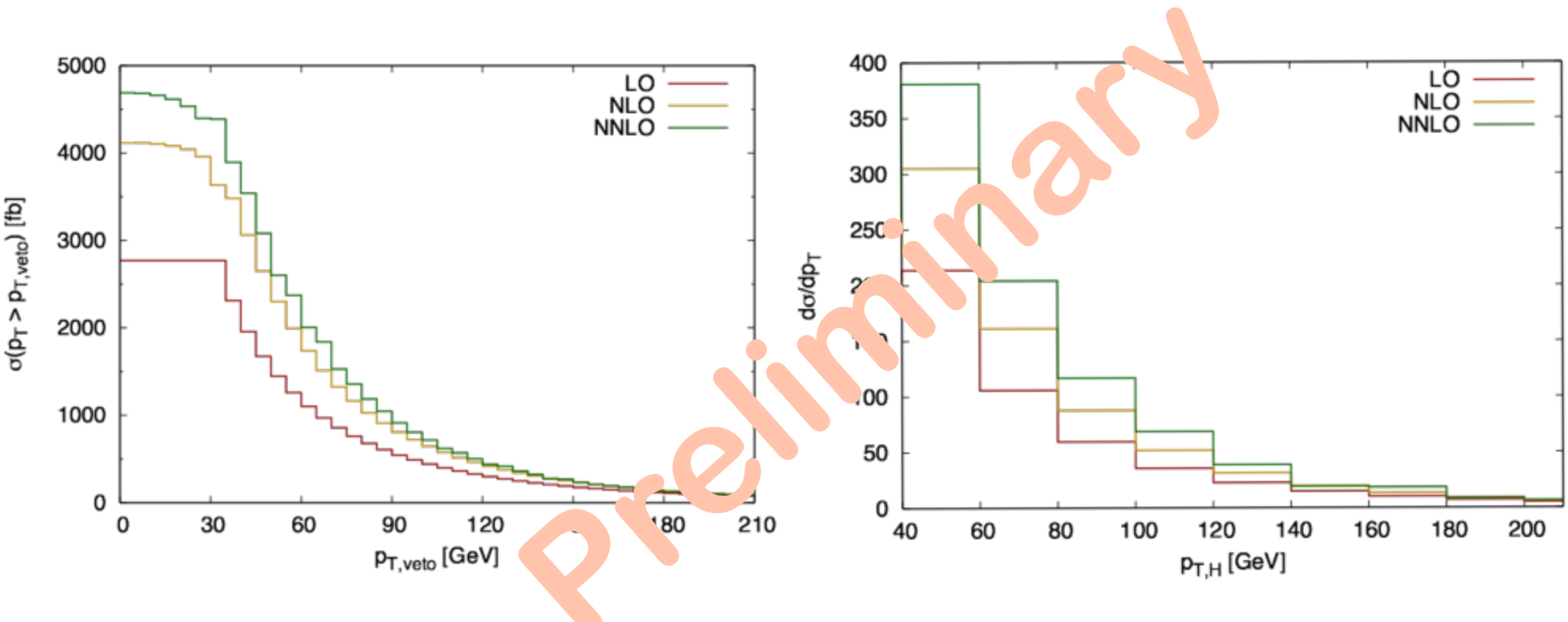
Corrections: LO $\xrightarrow{+60\%}$ NLO $\xrightarrow{+30\%}$ NNLO

Scale uncertainties: 50% LO 20% NLO 5% NNLO

- gg-channel is the dominant one for phenomenological studies: at NLO gg (70%), qg (30%)
- quark-gluon channel necessary for achieving the relevant precision

Higgs + jet @ NNLO: preliminary full result

R.B., Caola, Melnikov, Petriello, Schulze (2013)



- Computation completed for all the relevant channels (gg, qg), can now provide a differential description for the important kinematic observables!
- Will drastically improve the Higgs phenomenology for LHC Run II

Combining fixed-order and analytic resummation

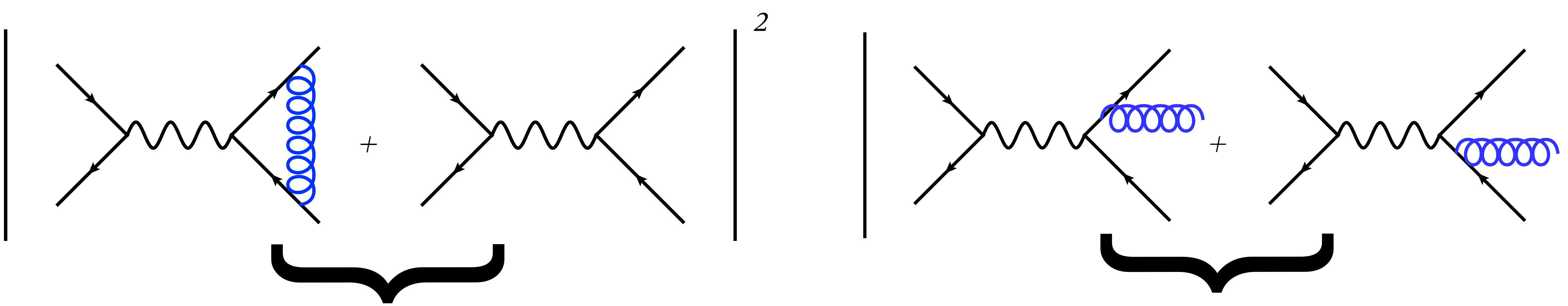
- Parton showers resum leading logarithms (LL) and partial next-to-leading logarithms (NLL) in phase-space regions dominated by soft+collinear radiation
- For many important processes we require resummation to NNLL and beyond matched to high-precision fixed-order

Source ATLAS	$N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} \geq 2$
Theoretical uncertainties on total signal yield (%)			
QCD scale for ggF, $N_{jet} \geq 0$	+13	-	-
QCD scale for ggF, $N_{jet} \geq 1$	+10	−27	-
QCD scale for ggF, $N_{jet} \geq 2$	-	−15	+4
QCD scale for ggF, $N_{jet} \geq 3$	-	-	+4
Parton shower and underlying event	+3	−10	±5
QCD scale (acceptance)	+4	+4	±3
Experimental uncertainties on total signal yield (%)			
Jet energy scale and resolution	5	2	6
Uncertainties on total background yield (%)			
WW transfer factors (theory)	±1	±2	±4
Jet energy scale and resolution	2	3	7
b-tagging efficiency	-	+7	+2
f_{recoil} efficiency	±4	±2	-

- An example of recent importance is the use of jet vetoes in Higgs measurements in the WW channel
- This introduces large uncertainties coming from large terms $\ln(m_H/p_{veto})$ in the perturbative expansion
- Uncertainties currently handled at fixed-order using the Stewart-Tackmann prescription (2011)
- We want to resum these terms; they are a large source of systematic uncertainty in this channel!

Why are jet vetoes dangerous?

- Illustrate with a simple example of $e^+e^- \longrightarrow$ jets
- Infrared safety: must sum both virtual and real corrections



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: $6(\alpha_S/\pi)\ln^2(M_H/p_{T,veto}) \sim 1/2$

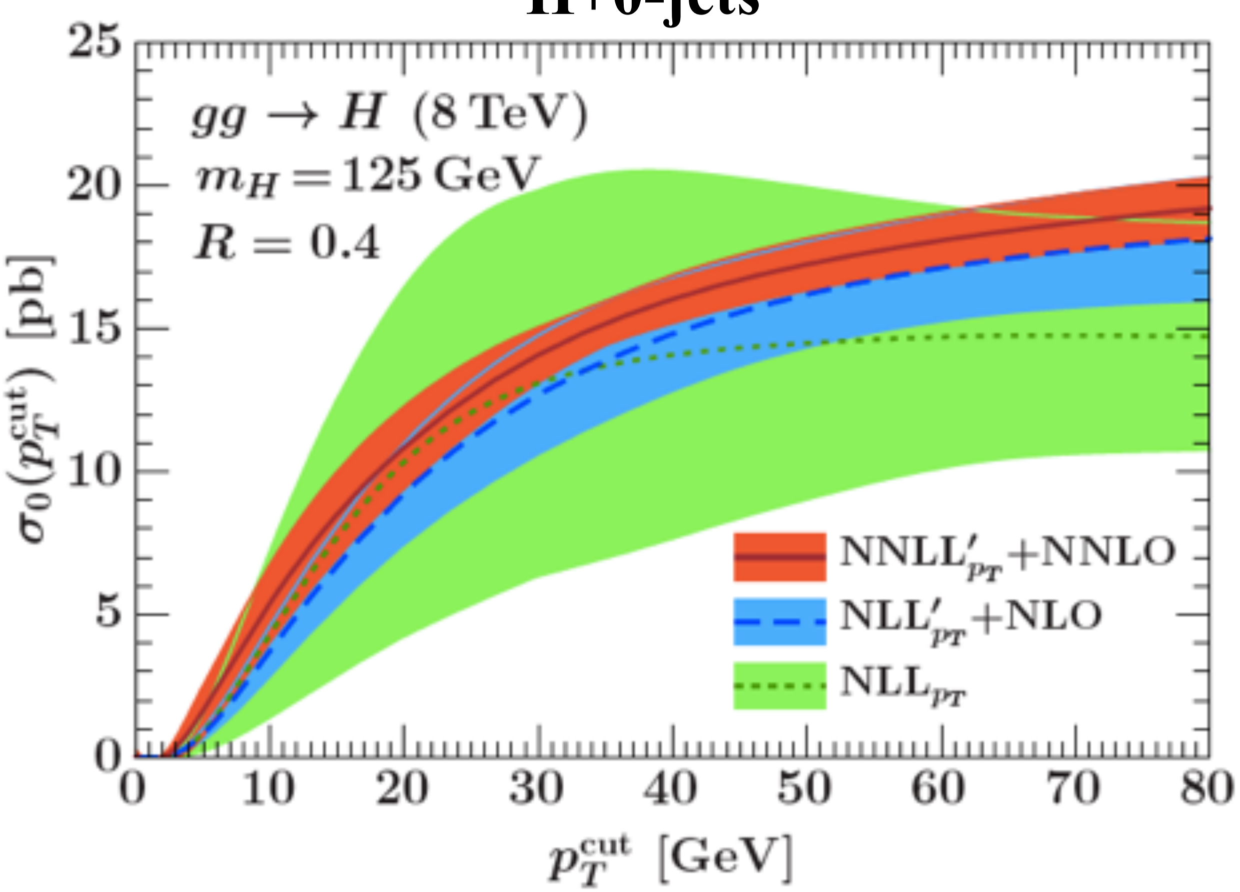
$\Rightarrow$ potentially a large correction

Resummation of jet-veto logarithms

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

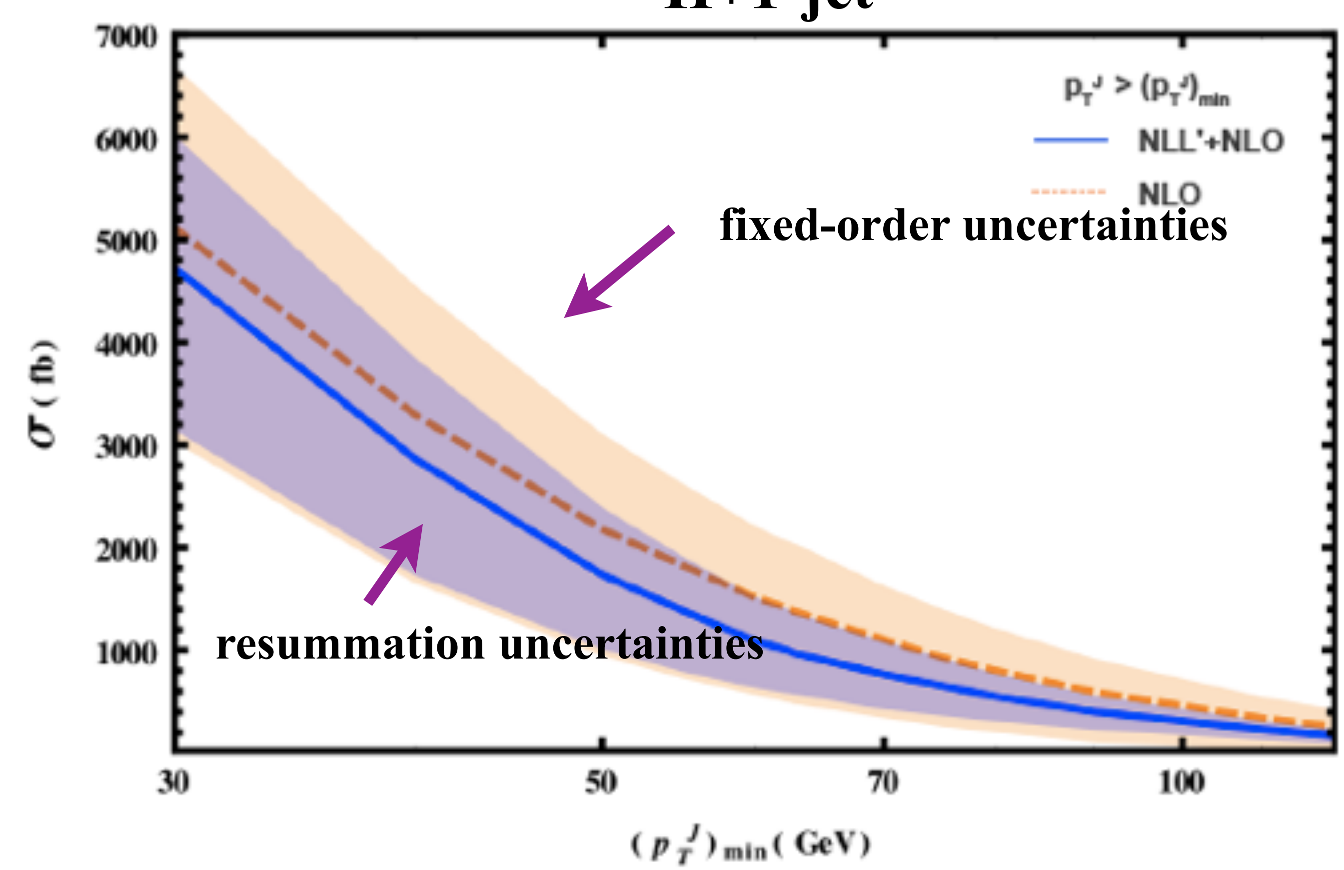
- H+0-jets in gluon fusion (Banfi, Monni, Salam, Zanderighi; Becher, Neubert; Stewart, Tackmann, Walsh, Zuberi)
- H+1-jet in gluon fusion (Liu, Petriello)
- Combination of the 0+1-jet bins (R.B., Liu, Petriello, Tackmann, Walsh)
- Associated VH production with a jet veto (Li,Liu)

H+0-jets



Stewart, Tackmann, Walsh, Zuberi (2013)

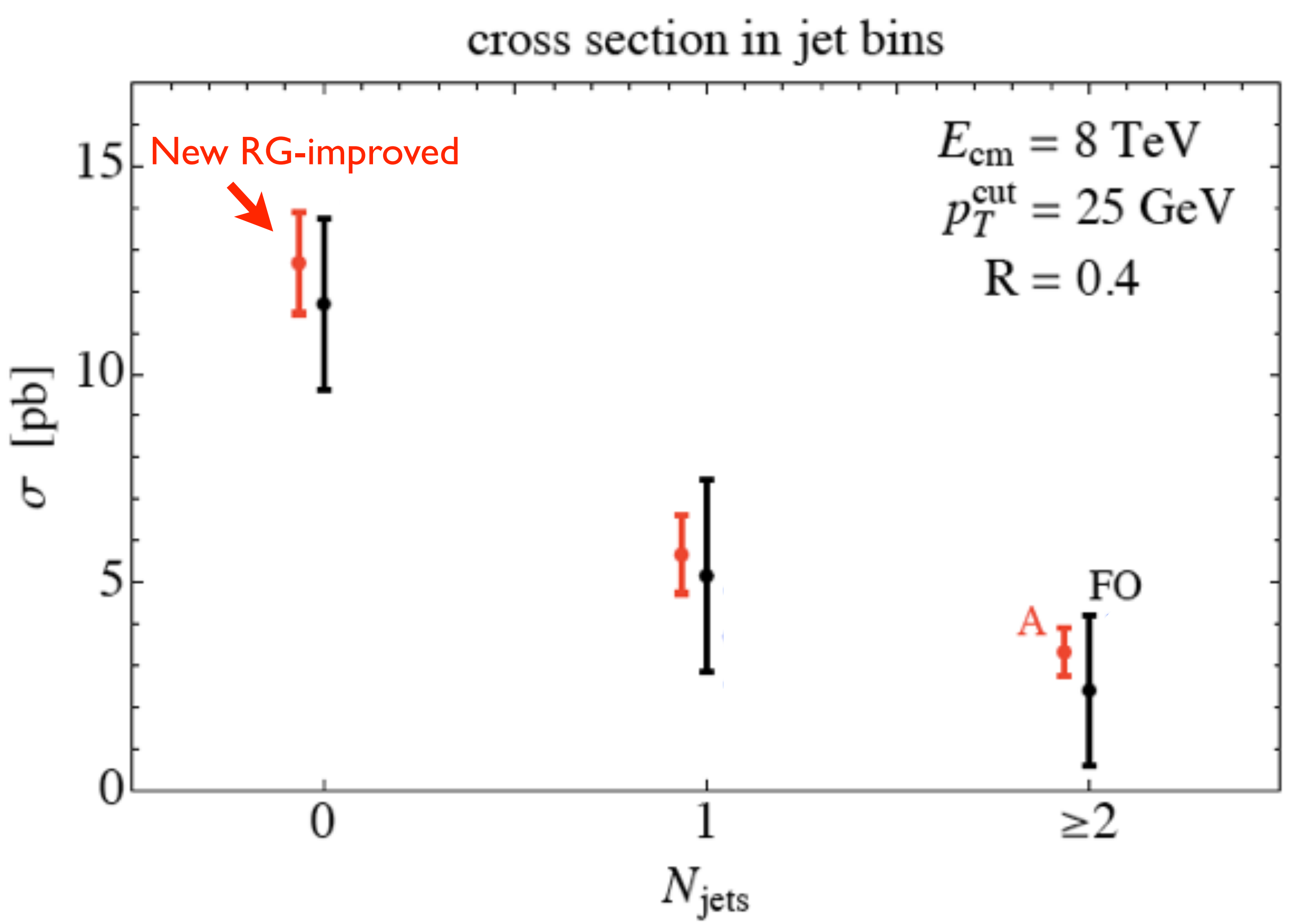
H+1-jet



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 (2013)



• Greatly reduced uncertainties in all three bins used in the analysis

• Provided 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!

Summary

- The need for precise and reliable description of signals and backgrounds for LHC Run II has led to several remarkable achievements.

- First results for Higgs production in gluon fusion at N3LO, with the goal of a precise understanding of the overall signal normalization.

- Preliminary complete results for the Higgs+jet @ NNLO in QCD are now available ! Result will significantly improve the Higgs phenomenology for LHC Run II.

- New understanding of analytic resummation in the presence of final-state jet algorithms, with important applications to Higgs predictions.