Recent results in Higgs theory

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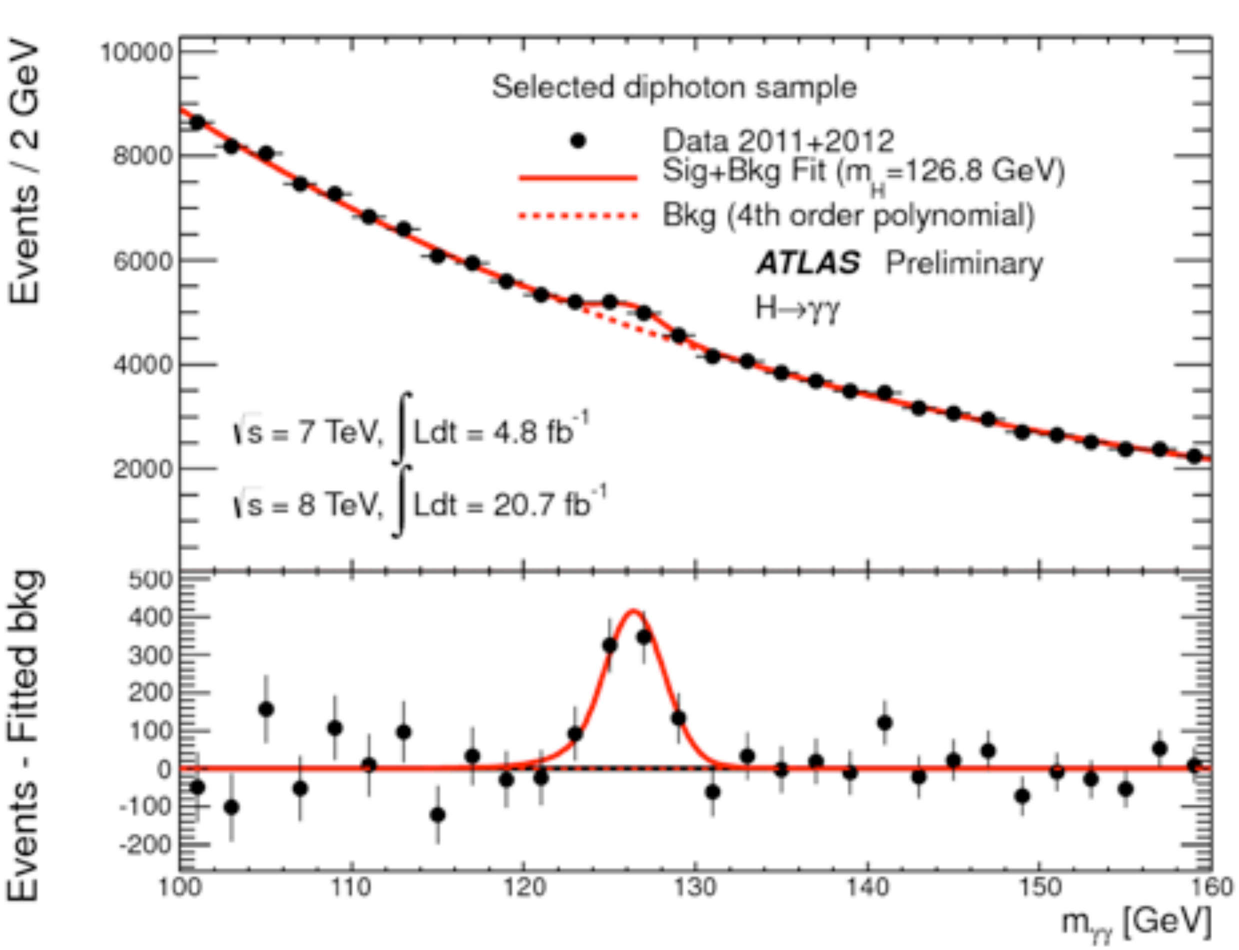
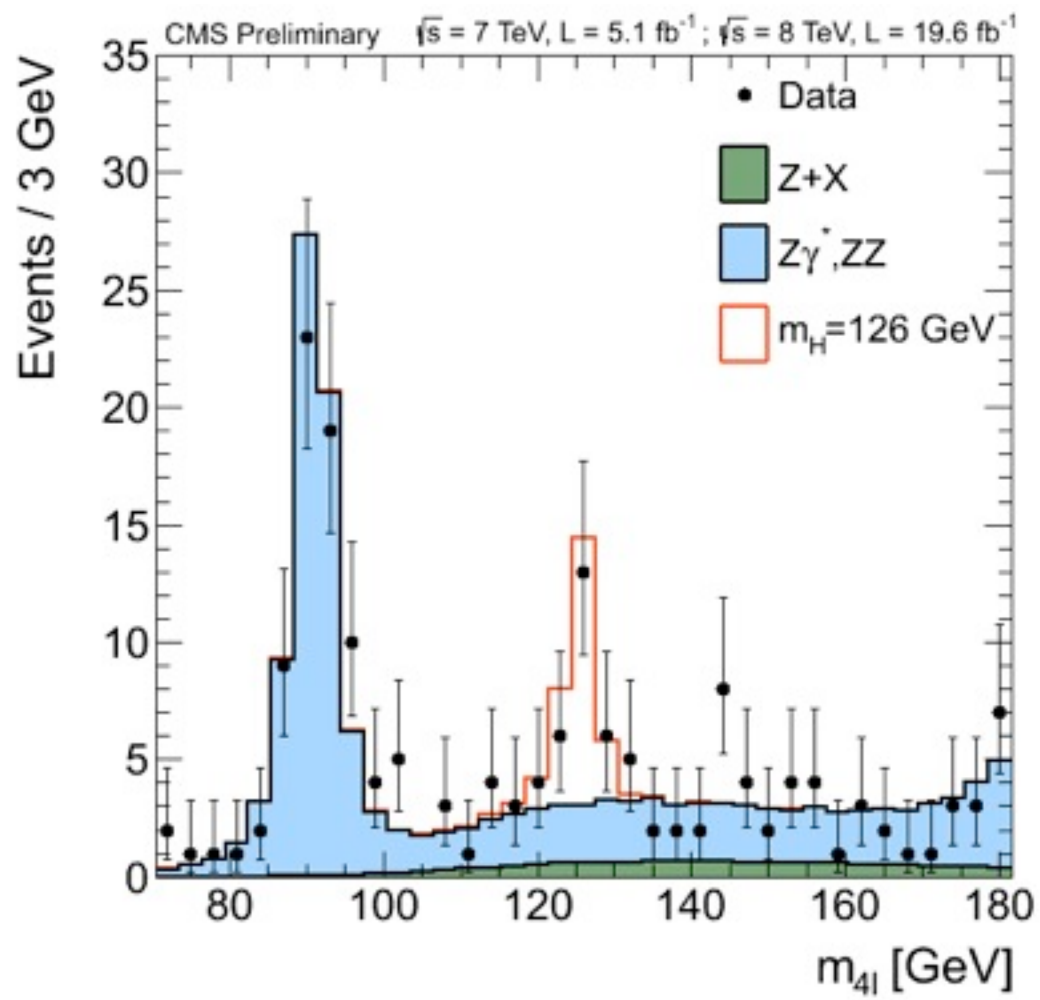
Argonne National Laboratory

US ATLAS meeting, July 15, Argonne

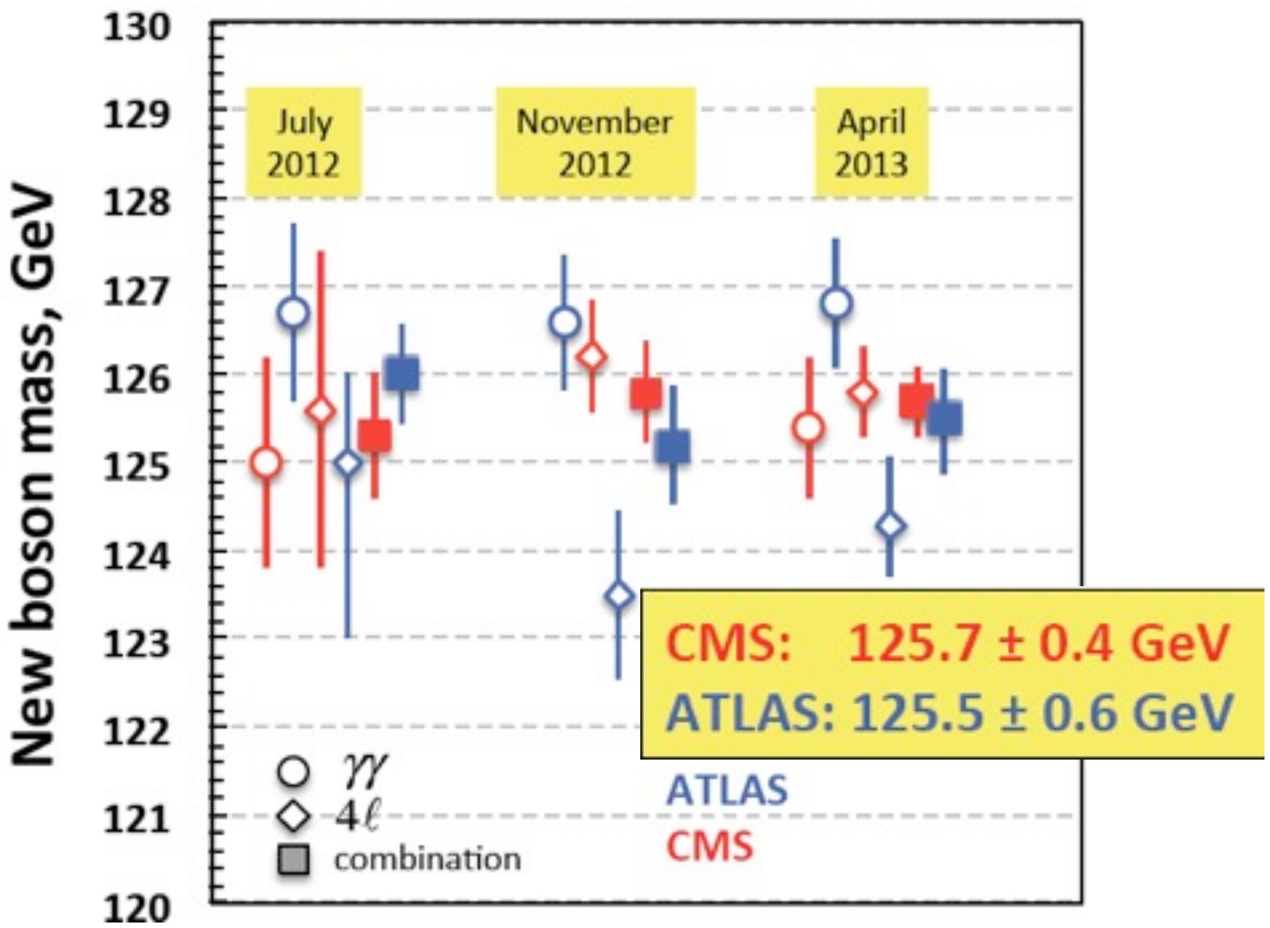
The Higgs discovery

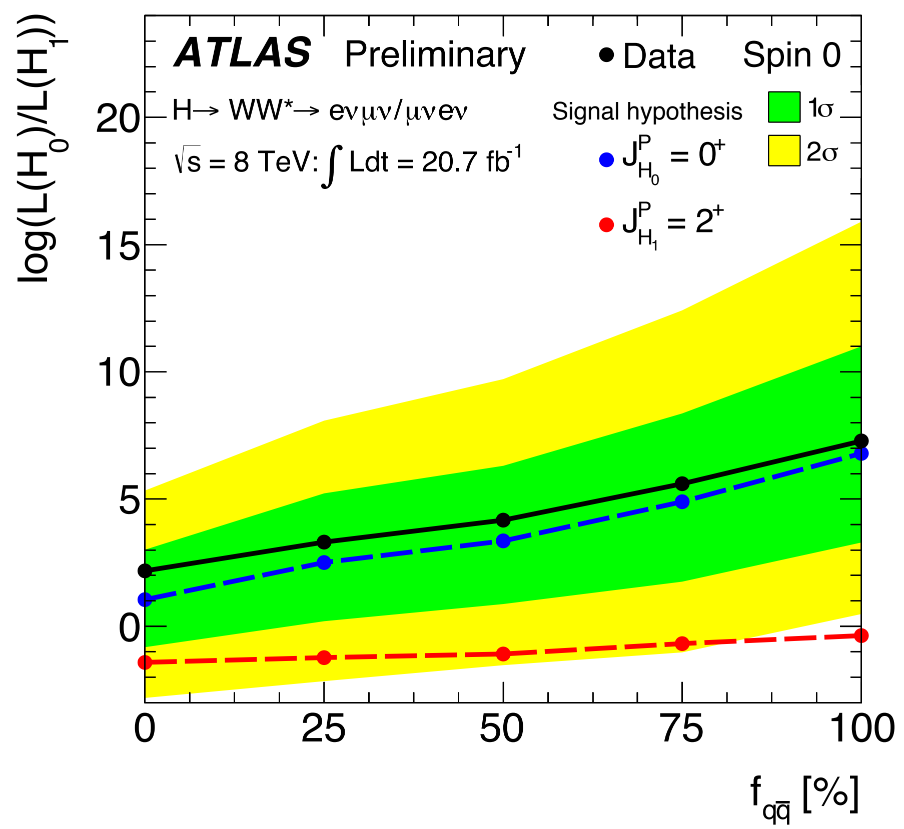
- A year ago (July 4th, 2012): ATLAS and CMS discovered a bump at 125.5 GeV

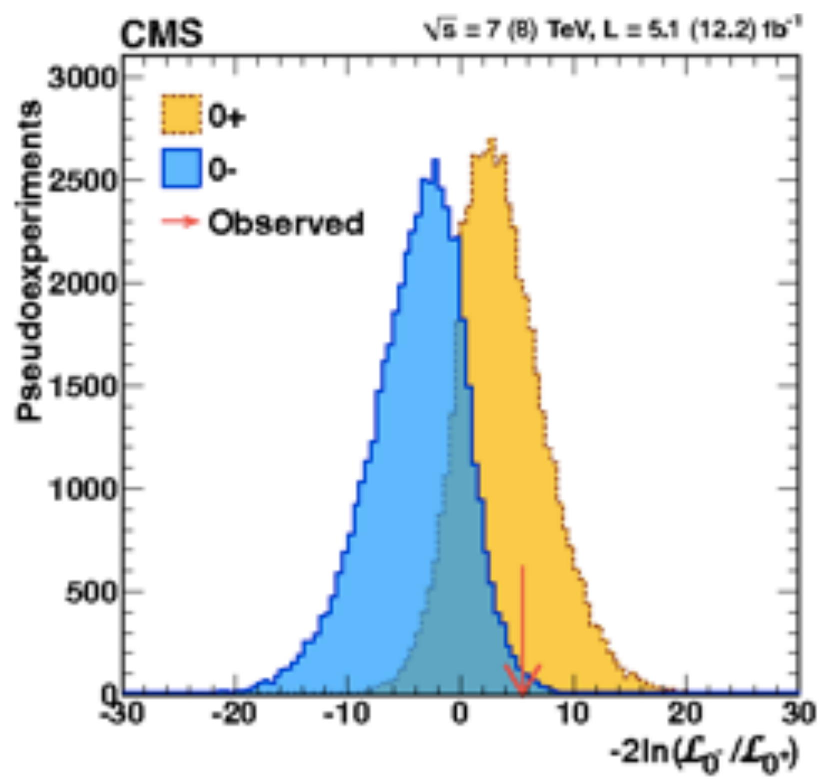




How fast things change





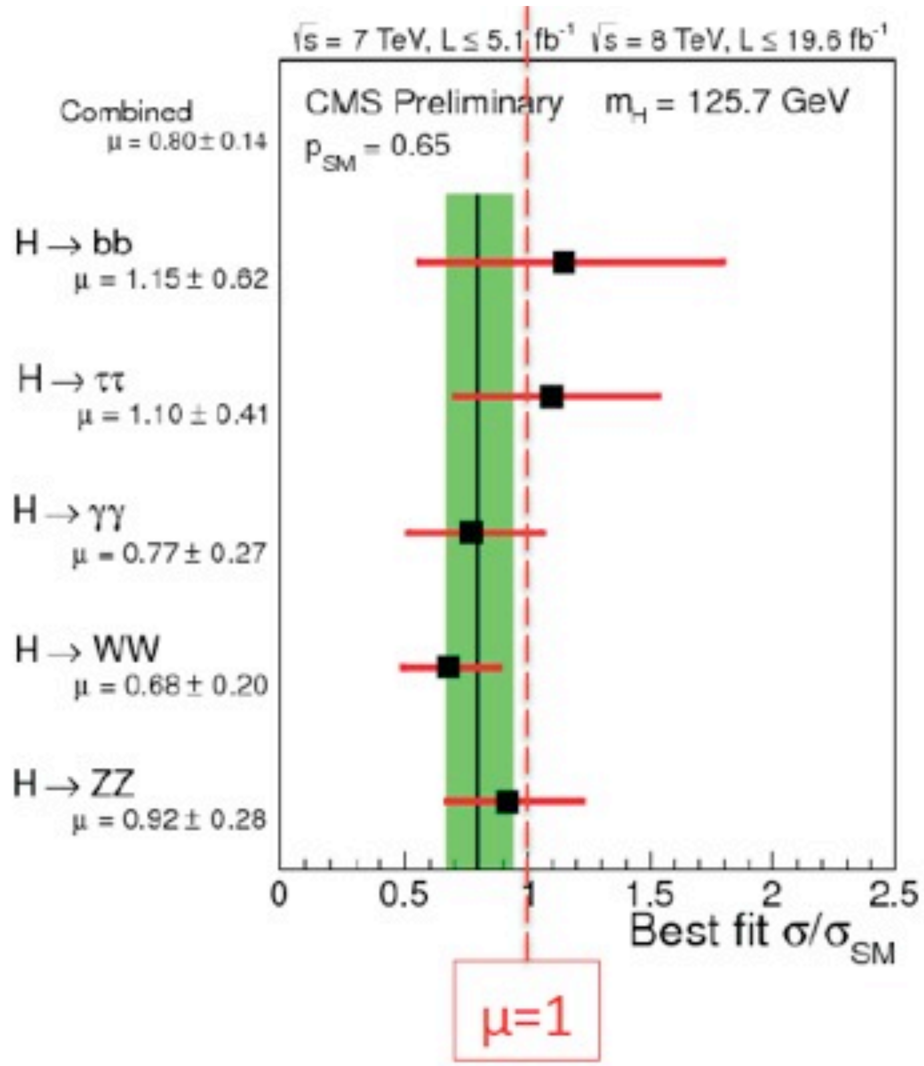


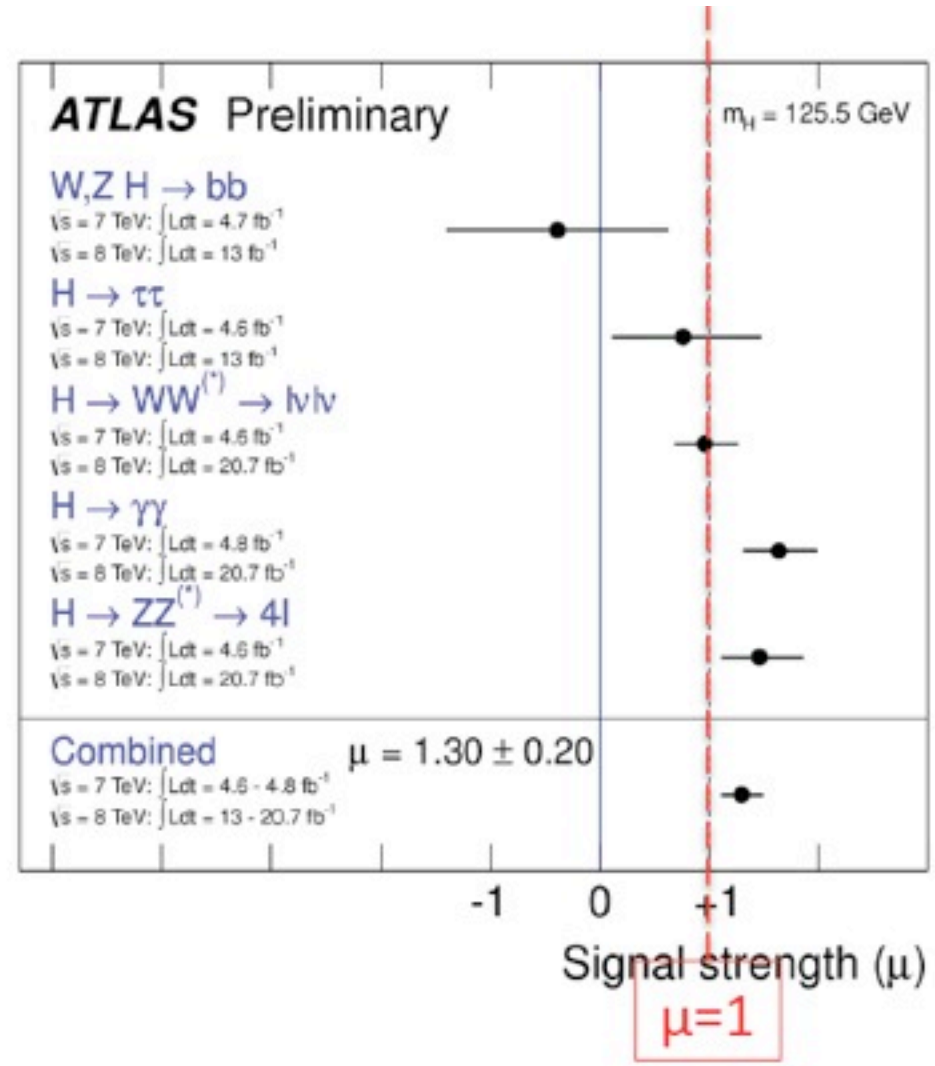
Higgs mass: a new precision parameter of SM

Spin-0 is favored, and it is a CP-even state

How fast things change

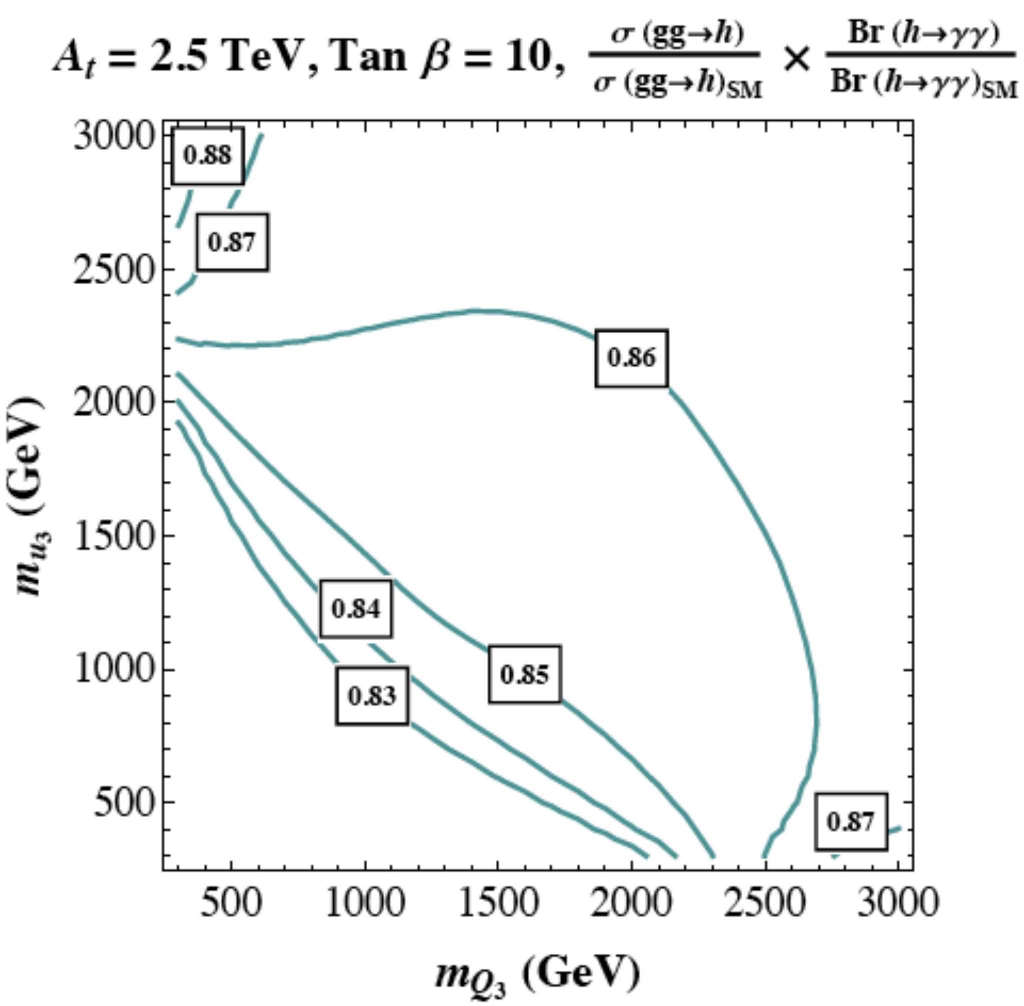
- Great progress on signal strength



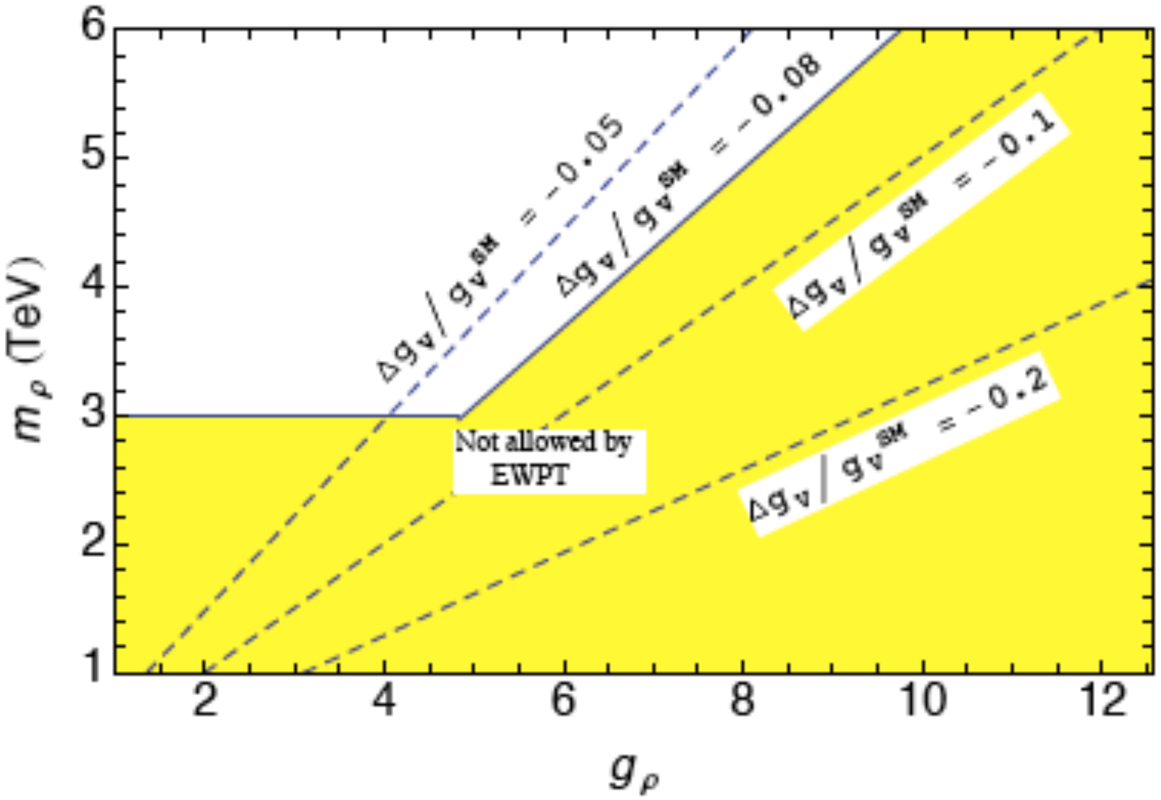


Denominator = σ_{SM} x Br_{SM} needed precise theory already, eg. σ_{NNLO}; more needed for LHC Run II

More precision needed for LHC Run II



Carena et al



Gupta et al

Want to control the SM predictions at the 5-10%. Still a chance for BSM effects to appear

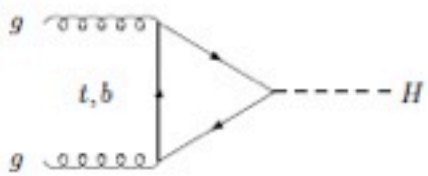
Outline

- H+jet @ NNLO
- Associated VH production
- Resummation of jet veto logarithms
- The approximate N^3LO results for the inclusive cross section
- The Hcc coupling measurement

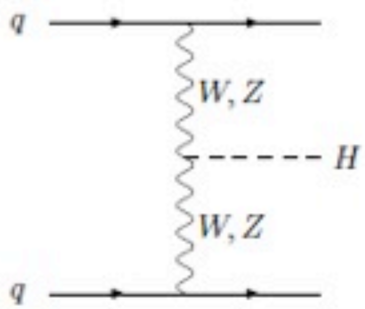
This is just a selection of some recent highlights, apologies in advance for possible omissions!

Current status of theoretical predictions

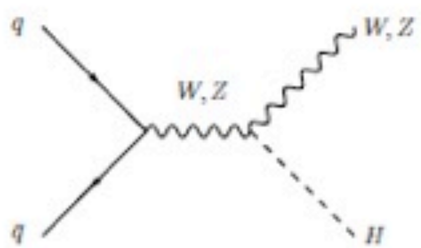
Higgs production at the LHC



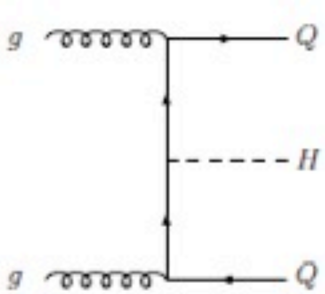
gg fusion



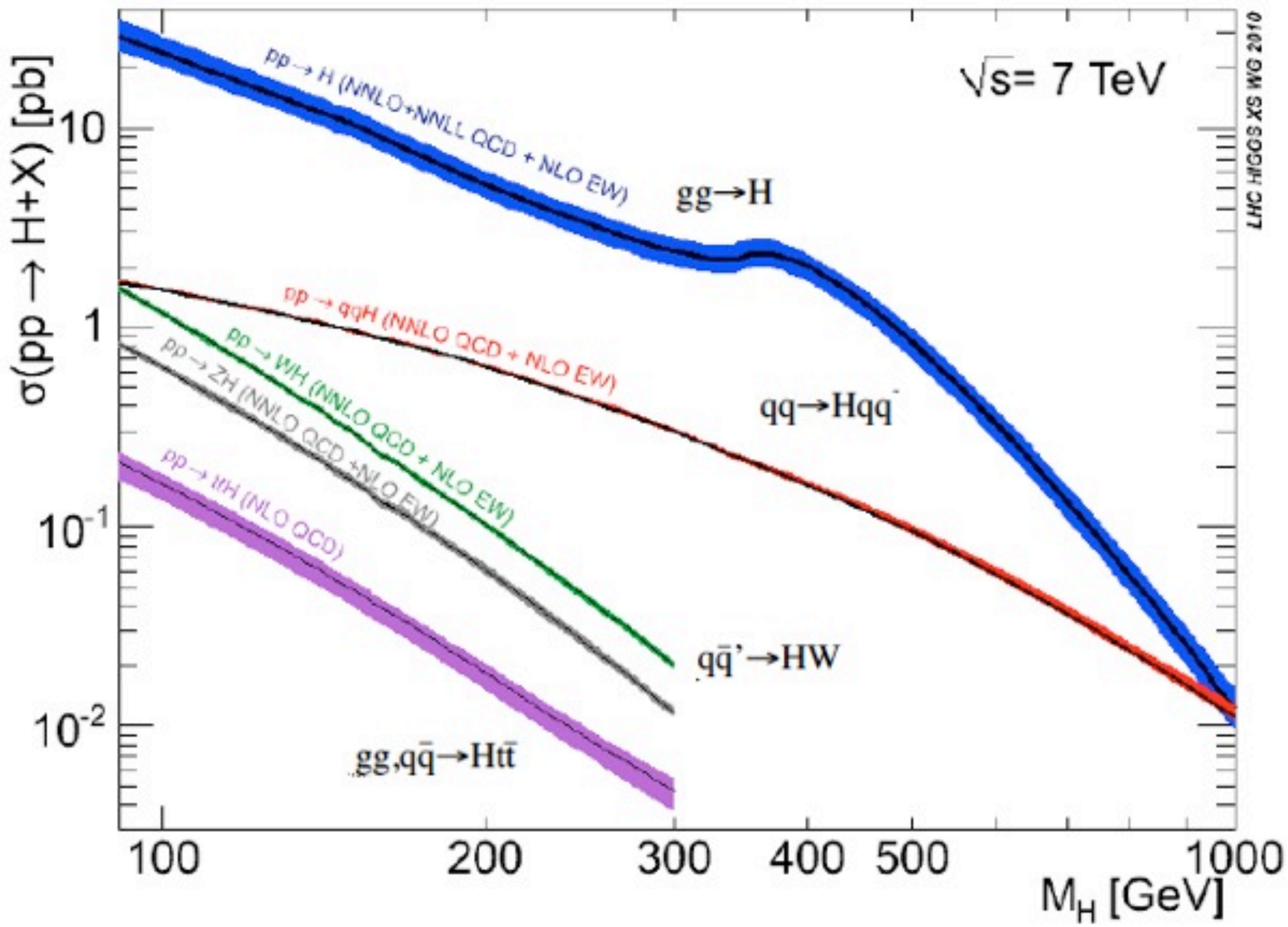
vector boson fusion



associated production with W,Z



associated production with heavy quarks



- Gluon-gluon fusion dominates due to large gluon luminosity

Higgs production at the LHC

- Current status of the theoretical uncertainties on the inclusive cross sections

Uncertainties in inclusive cross-sections

Dittmaier and Schumacher (2012)

		LHC @ $\sqrt{s} = 7\,\mathrm{TeV}$				LHC @ $\sqrt{s} = 14\,\mathrm{TeV}$			
		uncertainties		corrections		uncertainties		corrections	
	M_H[GeV]	THU	PU	QCD	EW	THU	PU	QCD	EW
ggF	< 500	6–10%	8–10%	$\gtrsim$100%	5%	6–14%	7%	$\gtrsim$100%	5%
VBF	< 500	1%	2–7%	5%	5%	1%	3–4%	5%	5%
HW	< 200	1%	3–4%	30%	5–10%	1%	3–4%	30%	5–10%
HZ	< 200	1–2%	3–4%	40%	5%	2–4%	3–4%	45%	5%
ttH	< 200	10%	9%	5%	?	10%	9%	15–20%	?

PDF4LHC recommendation for Higgs

- Compute uncertainties using global MSTW & CT & NNPDF
- Obtain the envelope of all 68% c.l. bands : uncertainty

supplemented with $\Delta\alpha_s(M_Z) = \pm 0.0012\,(\pm 0.002)$ at 68% (90%) c.l.

Higgs production at the LHC

- Current status of the theoretical uncertainties on the inclusive cross sections

Uncertainties in inclusive cross-sections — Dittmaier and Schumacher (2012)

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ttH	< 200	10%	9%	5%	?	10%	9%	15–20%	?

The uncertainties for the exclusive cross sections are still large and require significant work to improve

Selected recent results

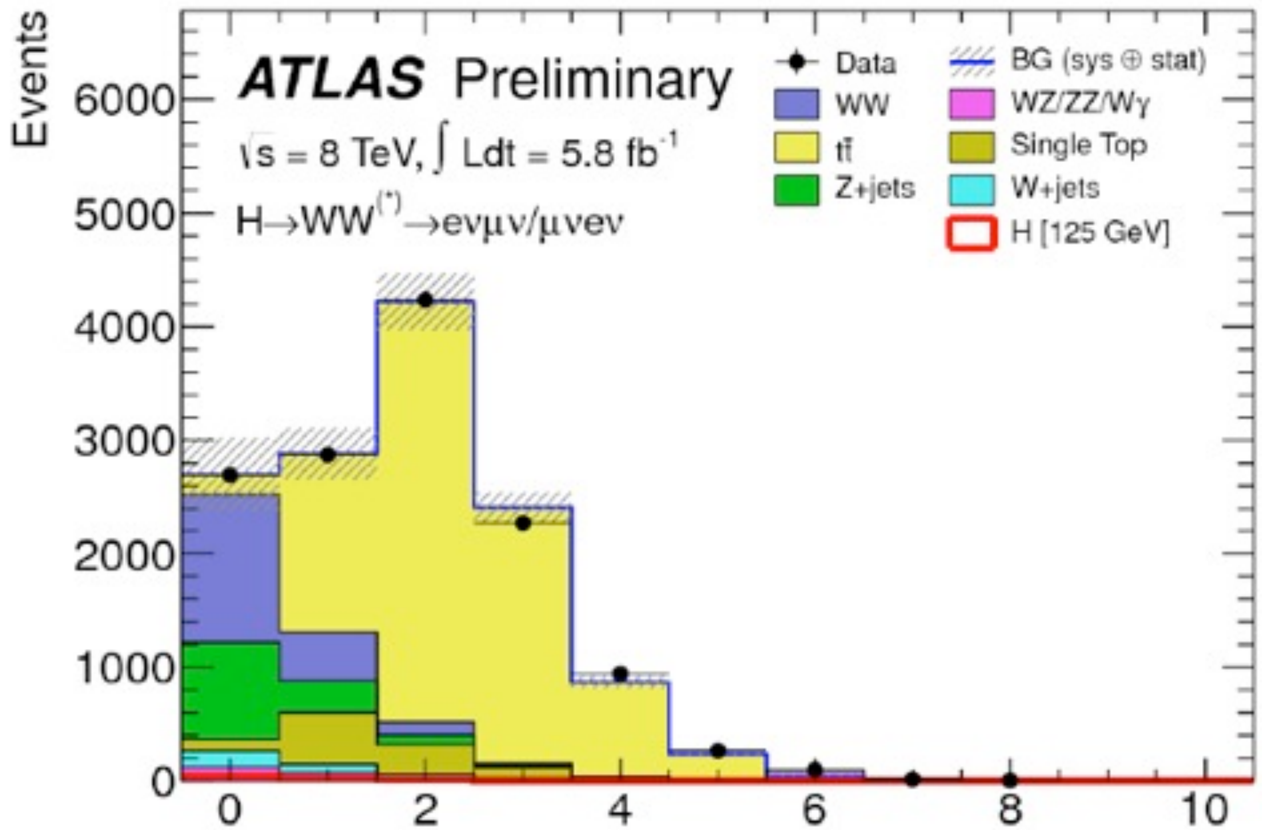
I. Higgs + jet @ NNLO

Higgs in association with jets

- Higgs cross-sections in pp→H→WW are binned according to the jet multiplicity to beat 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 and H+2j @ NLO



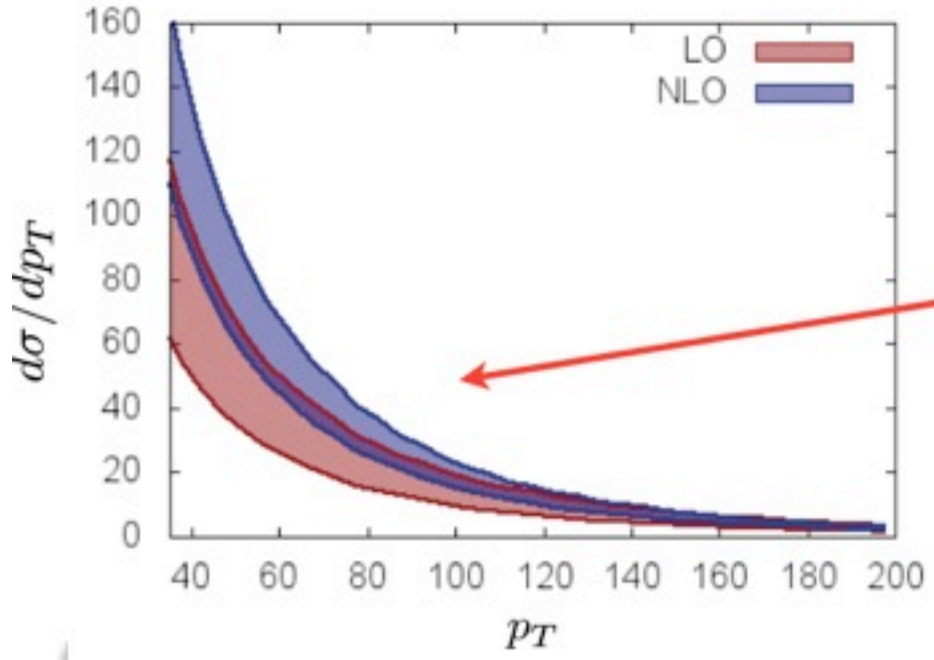
Higgs in association with jets

The H+1 jet bin: large NLO K-factor and large theoretical uncertainty

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

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



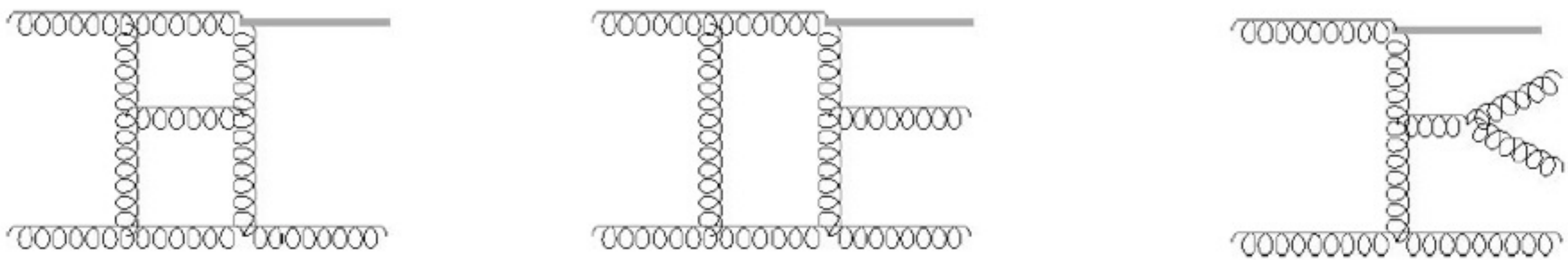
Need for higher orders!

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

Urgently need NNLO for H+jets to resolve these issues!

Higgs + jet @ NNLO

- Need the following ingredients for H+1j @ NNLO cross section

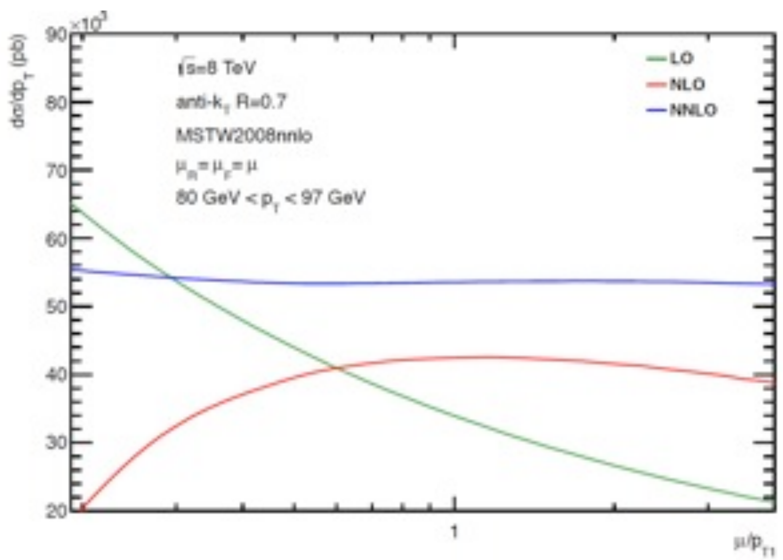


Gehrmann, Jaquier, Glover, Koukoutsakis (2011) — Badger, Glover, Mastrolia, Williams (2009) — Del Duca, Frizzo, Maltoni; Dixon, Glover, Khoze (2004)

- All ingredients were available, some even for a while, what stopped us from having this calculation done before now?
  - 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.
  - A generic procedure to extract IR singularities from RR and RV was unknown until very recently

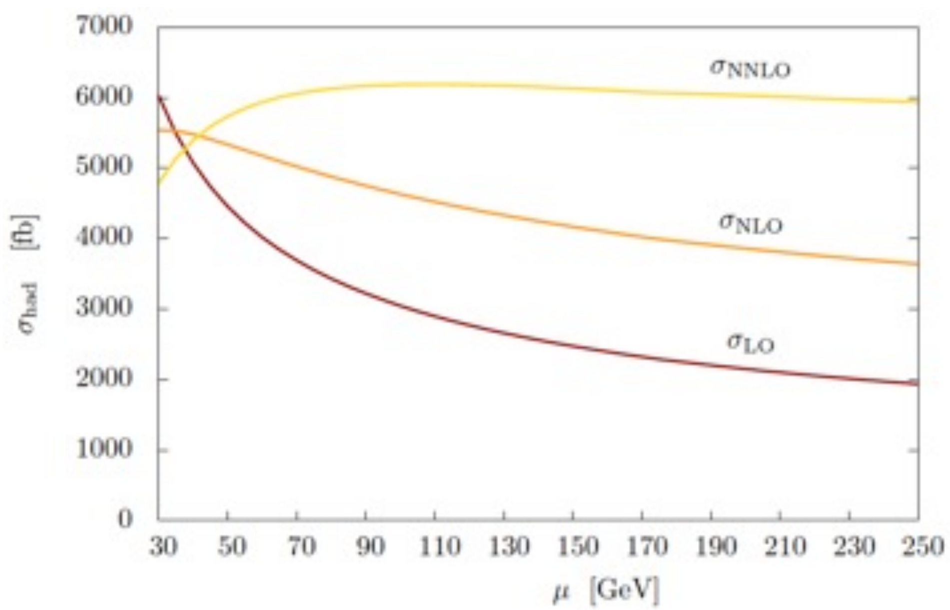
First NNLO QCD results to processes with both colored initial and final states

- After more than a decade of research we finally know how to generically handle NNLO QCD corrections to processes with both colored initial and final states



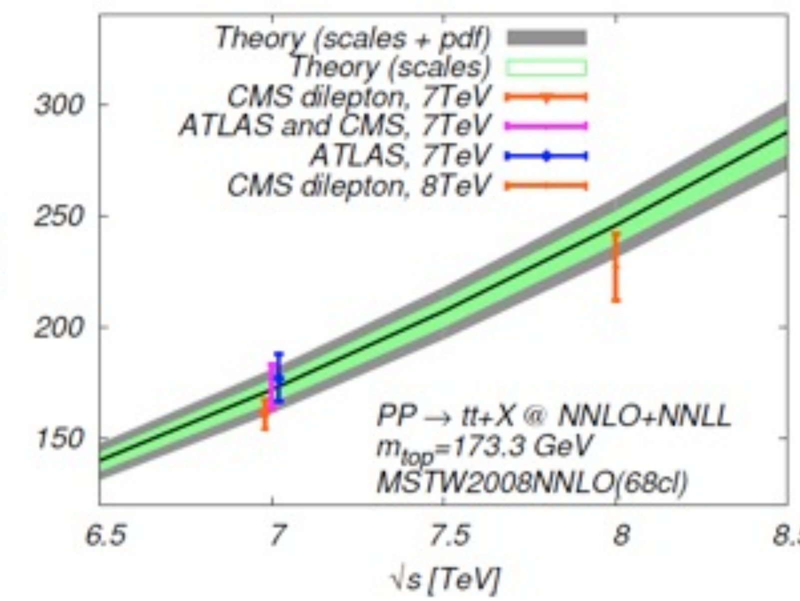
Gehrmann-de Ridder, Gehrmann, Glover, Pires (2013)

dijet: gg-channel



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

H+1j:gg-channel



Czakon, Fiedler, Mitov (2013)

ttbar: all-channels

Based on Antenna subtraction scheme

Based on sector-improved subtraction scheme

First NNLO QCD results to processes with both colored initial and final states

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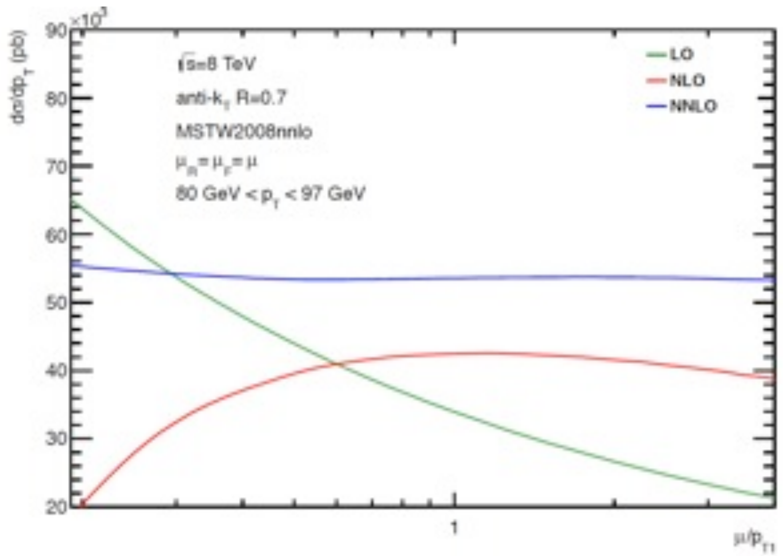

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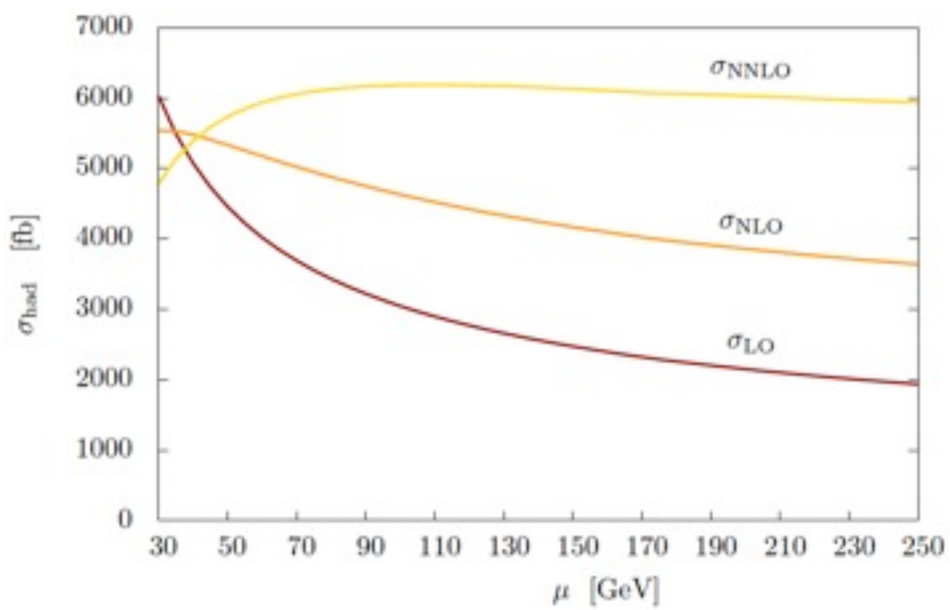

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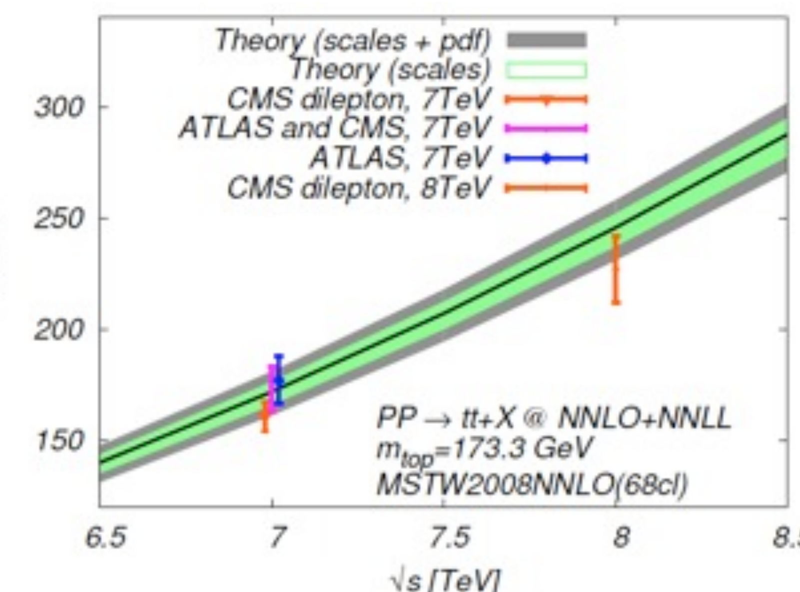


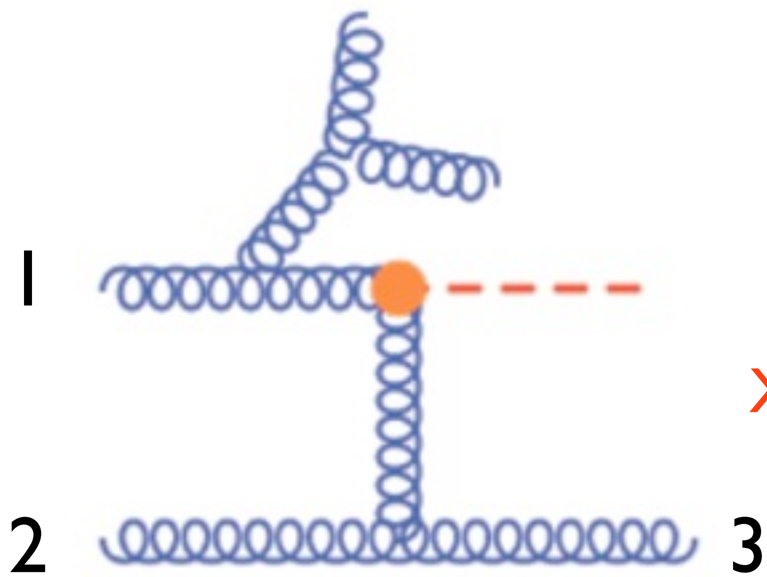
Czakon, Fiedler, Mitov (2013)

- For a long time, only color singlet final states available at full NNLO, mostly 2 → 1 at Born level: H, W, Z, $\gamma\gamma$
- 2013 will be remembered as the year of 2 → 2 at NNLO

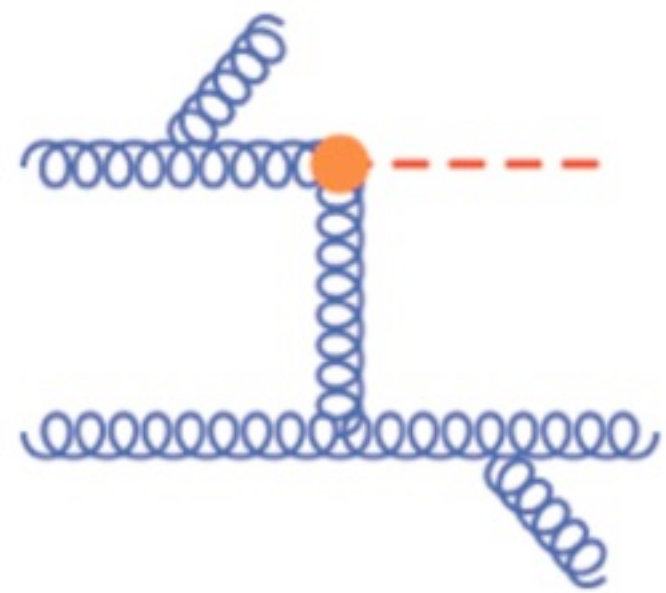
Lance Dixon, LoopFest 2013

Higgs + jet @ NNLO

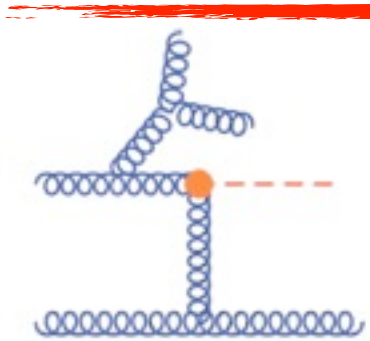
- Complicated singularity structure, in particular three collinear directions:



x 3



x 6



$$\sim \frac{P_{ggg}\otimes|M_j|^2}{s_{igg}}, \quad \frac{P_{gg}\otimes|M_{jj}|^2}{s_{gg}}$$

Subtraction terms made out of splitting functions or eikonal factors and matrix elements with lower multiplicities

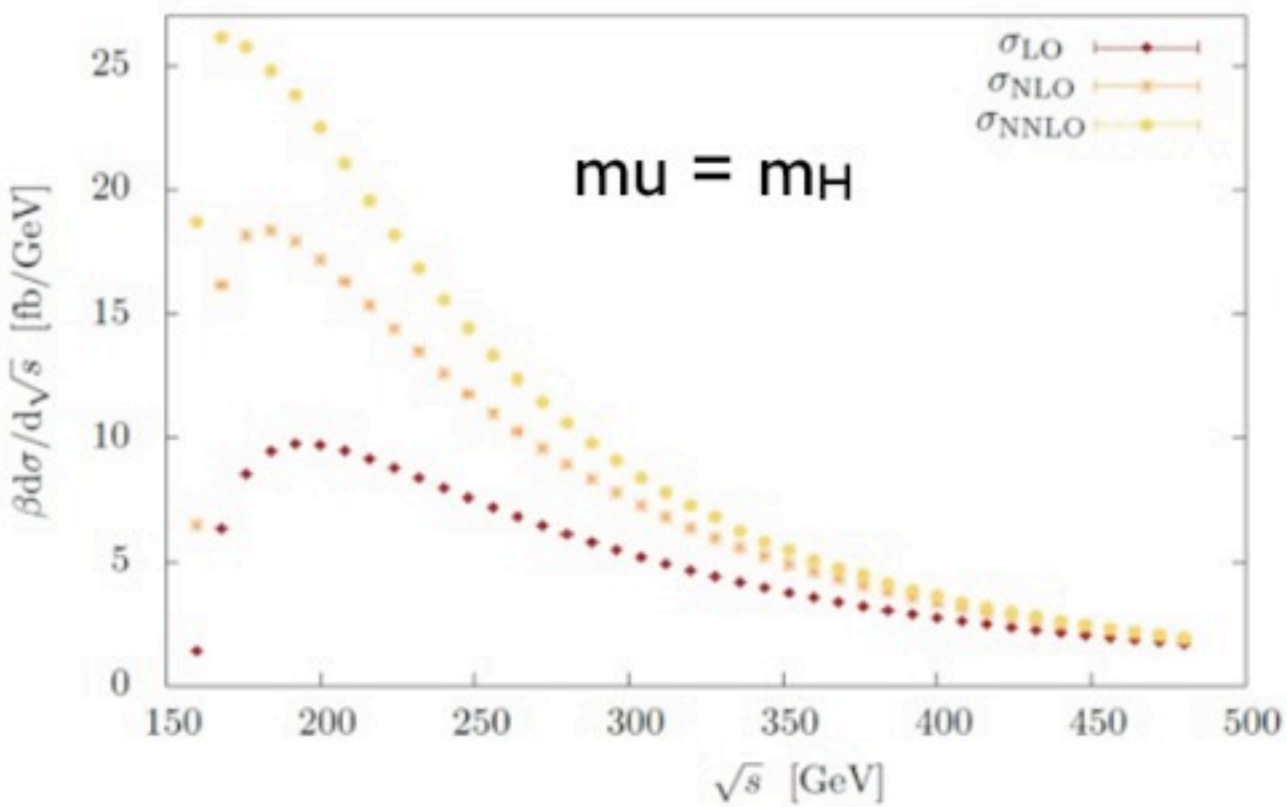
170 different subtraction terms had to be implemented for gg →H g!

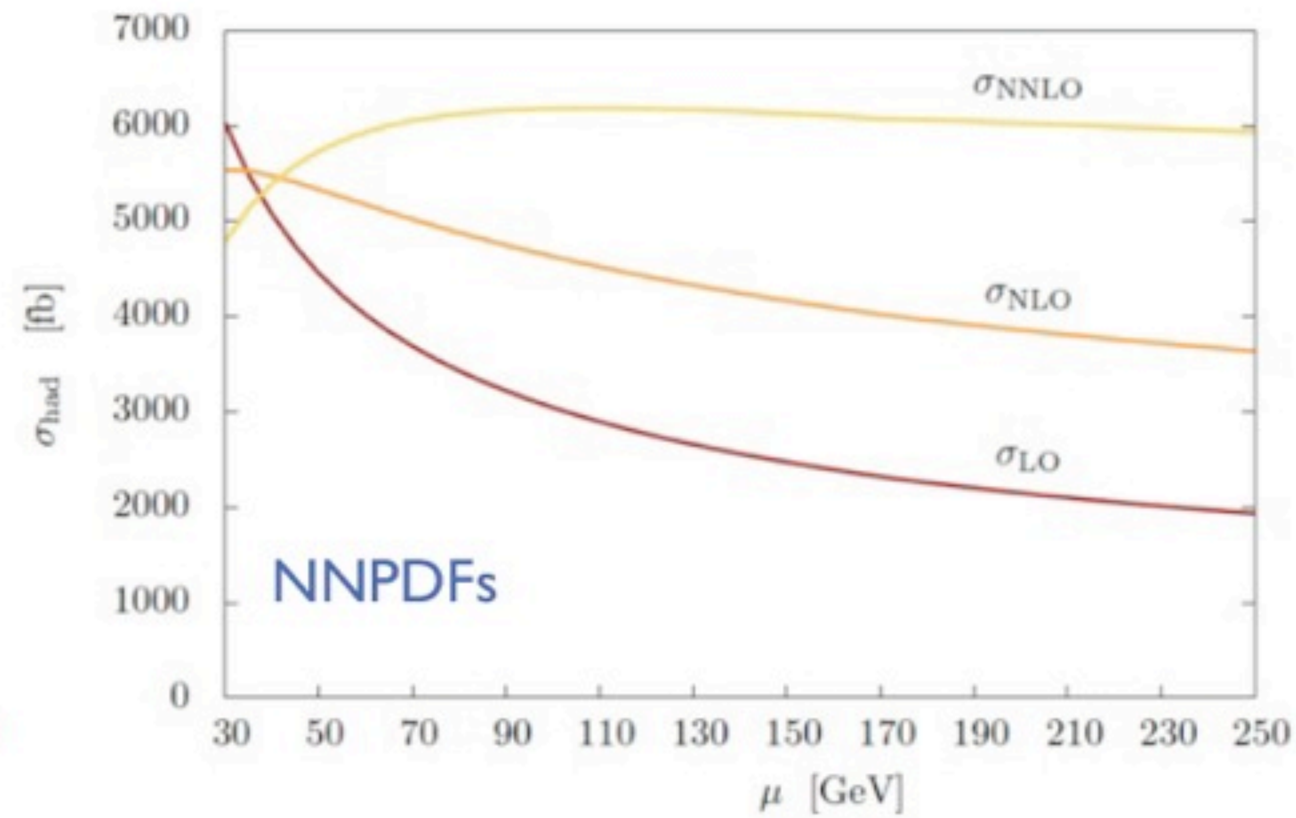
Higgs + jet @ NNLO: building blocks

- tree-level H+3j
- tree-level H+2j up to $O(\varepsilon^2)$
- tree-level H+1j up to $O(\varepsilon)$
- one-loop H+2j (Badger et al (2011))
- one-loop H+1j up to $O(\varepsilon^2)$
- two-loop H+1j (Gehrmann et al. (2011))
- renormalization, collinear subtraction

Since the amplitudes have to be evaluated near singular configurations, numerical stability of all the above amplitudes is very important

Higgs + jet @ NNLO (gg only)



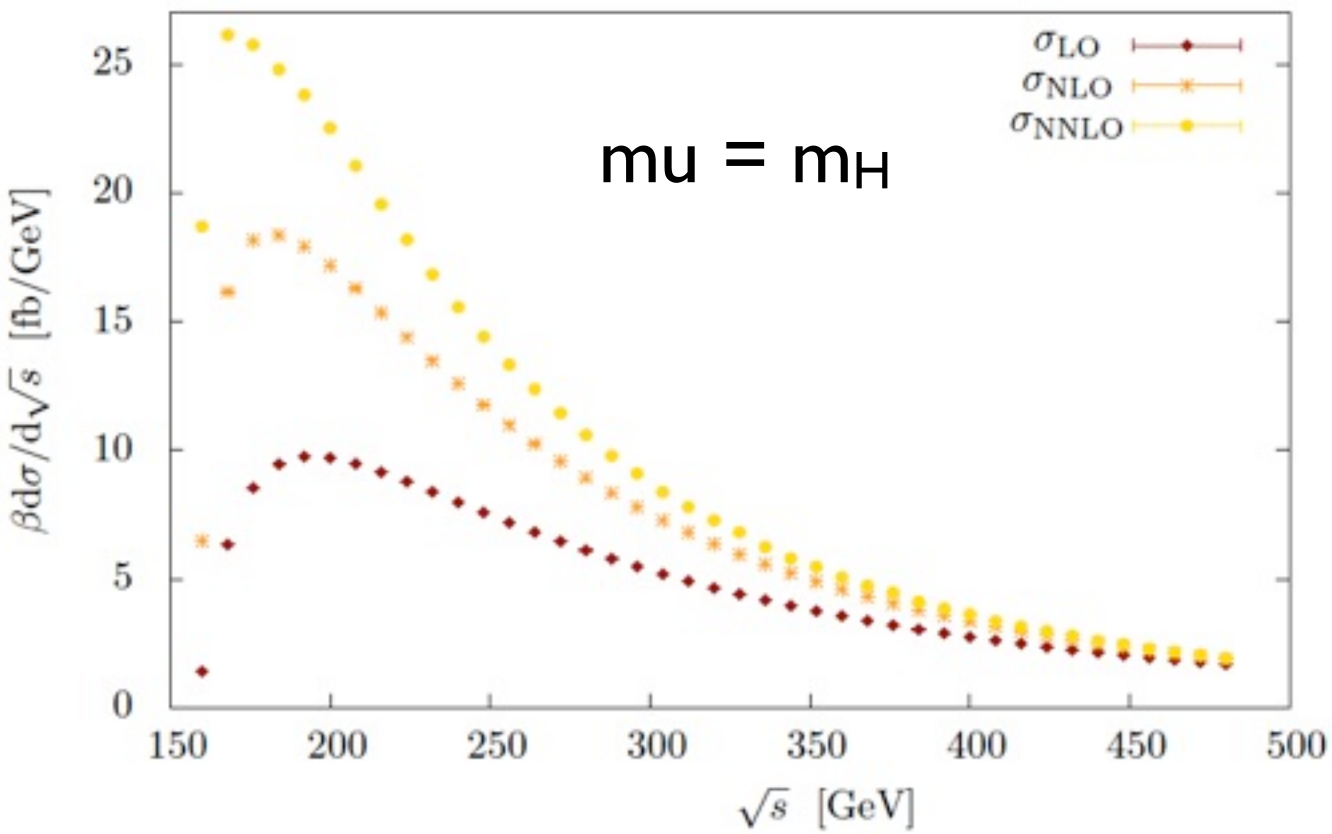


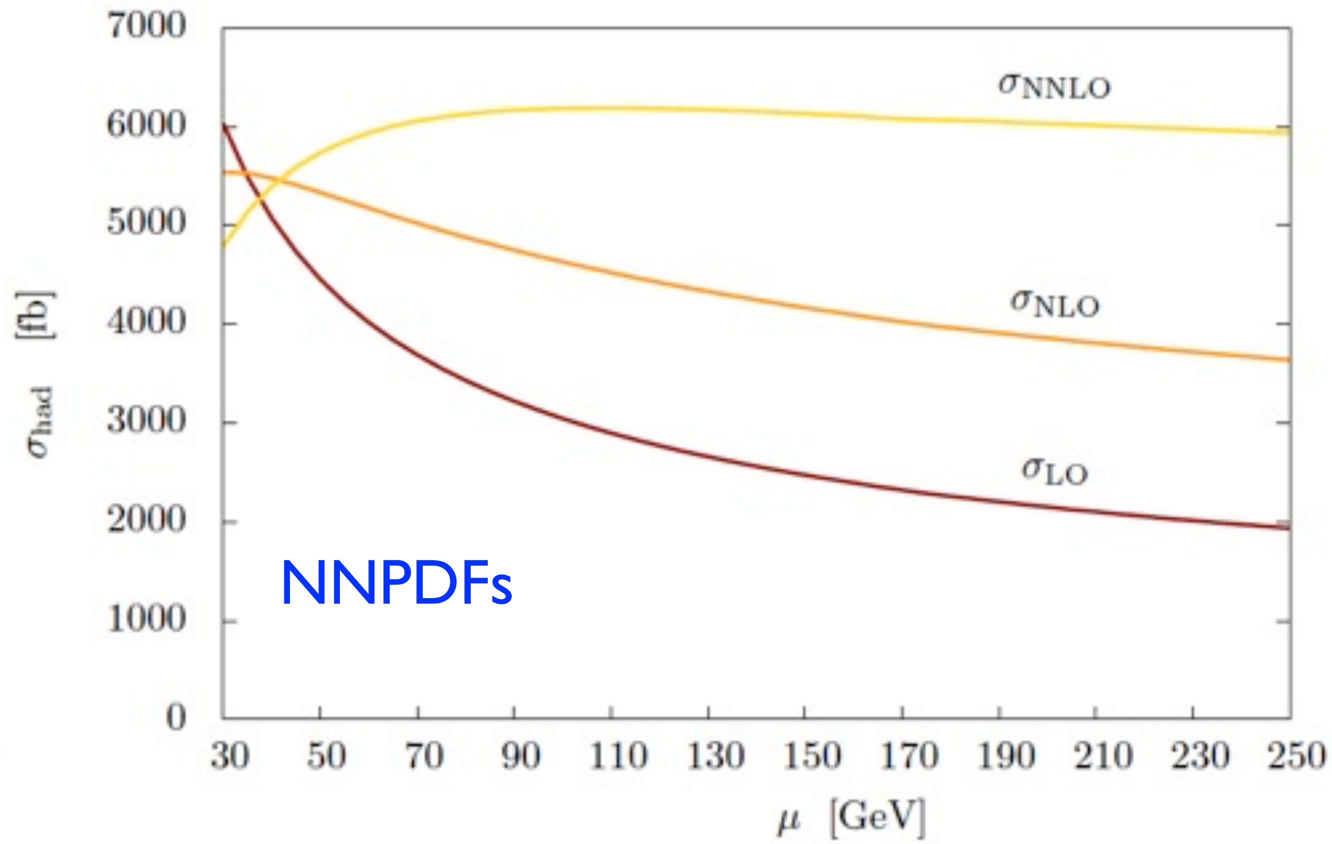
R.B., Caola, Melnikov, Petriello, Schulze (2013)

- Partonic cross section for $gg \to Hj$ @ LO, NLO, NNLO
- Realistic jet algorithm, k_T with $R=0.5$, $p_T > 30$ GeV
- Hadronic cross-section $pp \to Hj$ using latest NNPDF sets
- Scale variation in the range $m_H/2 < \mu < 2\,m_H$, $m_H = 125$ GeV

Higgs + jet @ NNLO (gg only)

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





$$\sigma_{LO}(pp \to Hj) = 2713^{+1216}_{-776} \text{ fb},$$
$$\sigma_{NLO}(pp \to Hj) = 4377^{+760}_{-738} \text{ fb},$$
$$\sigma_{NNLO}(pp \to Hj) = 6177^{-204}_{+242} \text{ fb}.$$

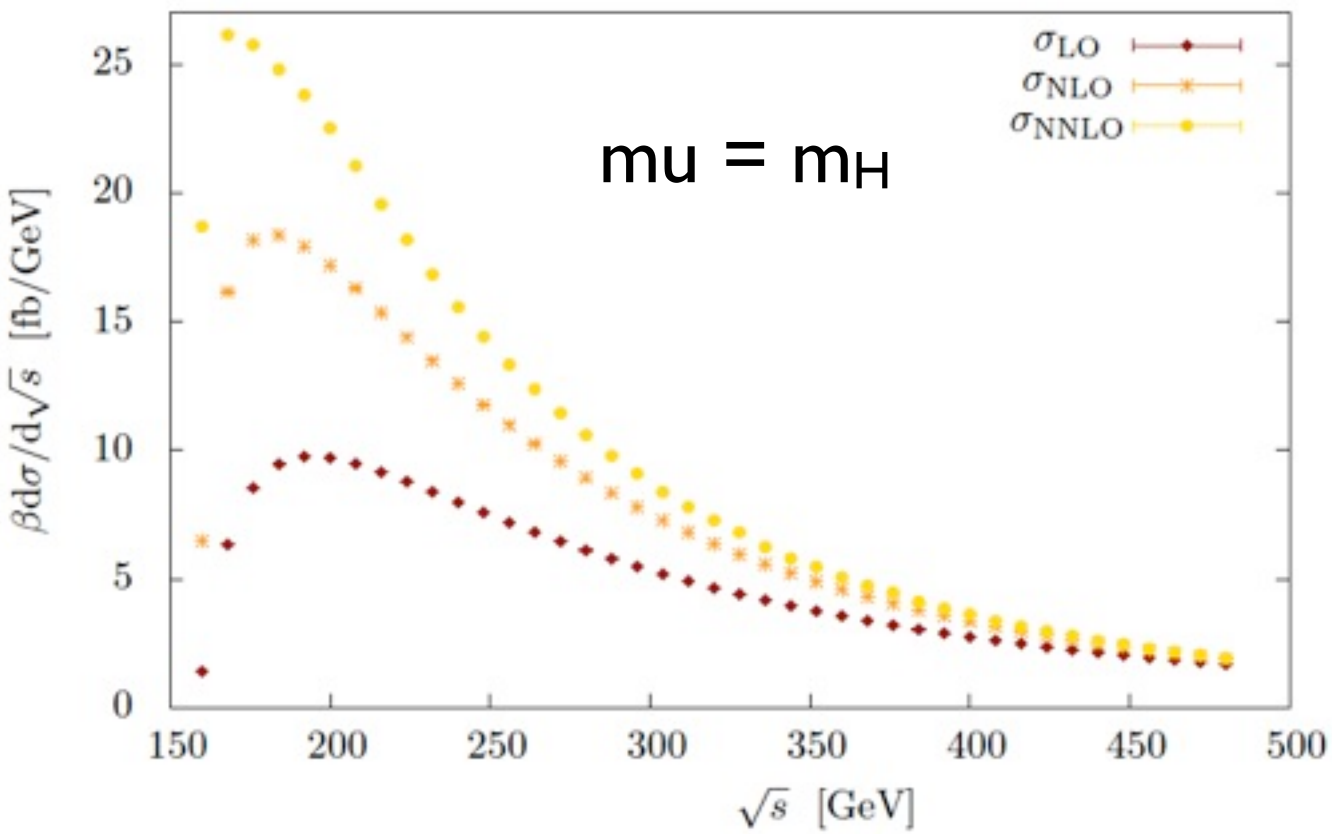
Significantly reduced scale dependence O(4%)

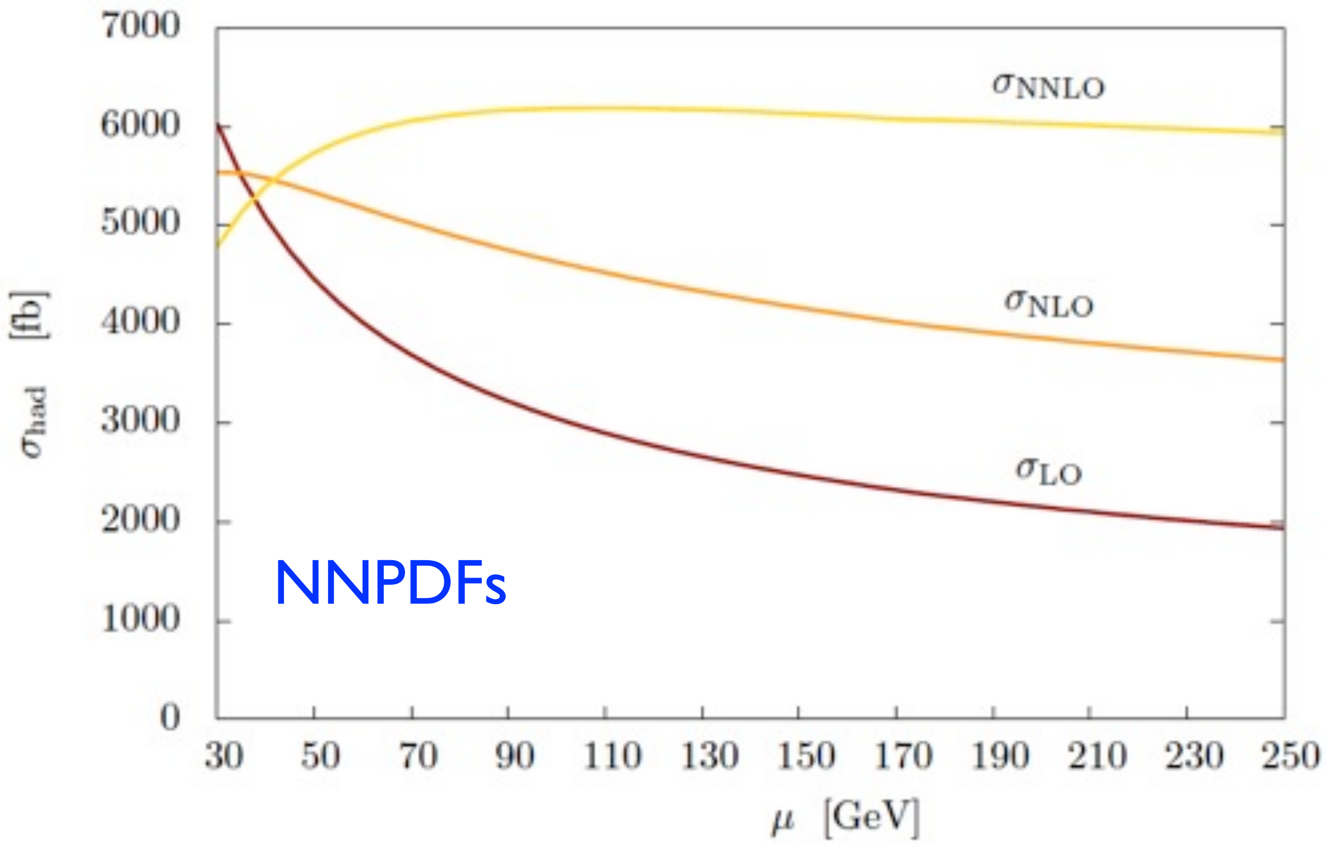
$\sigma_{NLO}/\sigma_{LO} = 1.6$

$\sigma_{NNLO}/\sigma_{NLO} = 1.3$

Large K-factor

Higgs + jet @ NNLO (gg only)



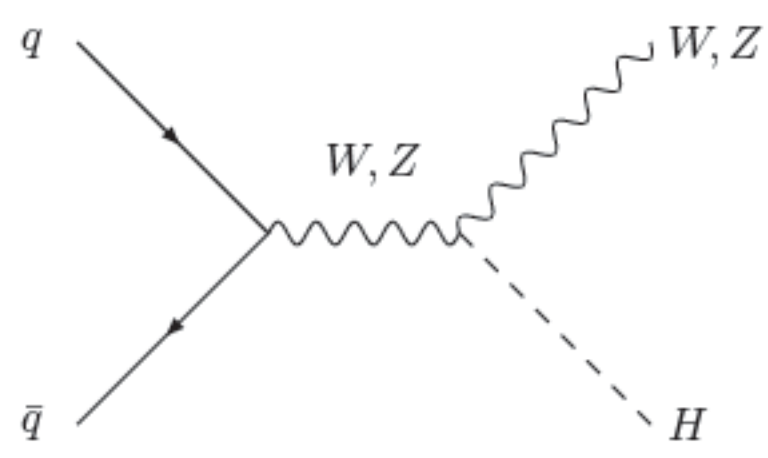


- gg-channel is the dominant one for phenomenological studies: at NLO gg (70%), qg(30%)
- quark channels necessary for achieving the relevant precision: ongoing work   R.B., Caola, Melnikov, Petriello, Schulze

Selected recent results

II. Associated VH production

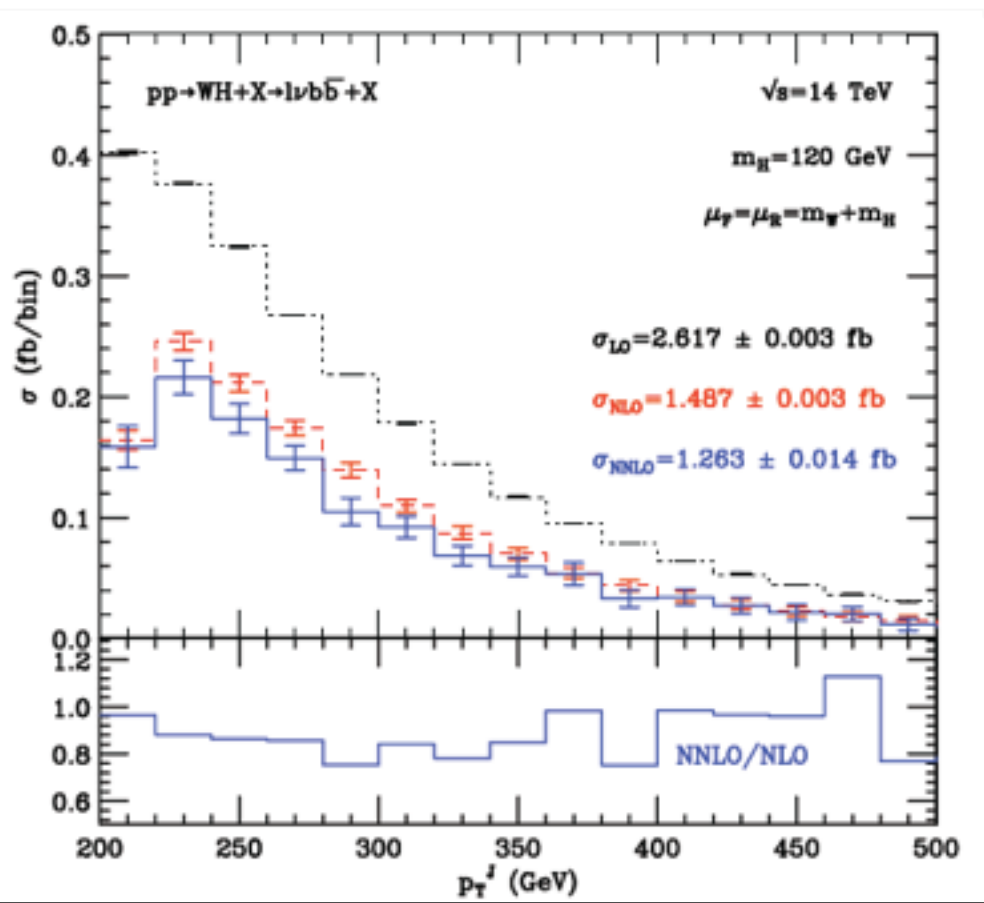
Associated VH production



- With bbar decay of Higgs, most important low-mass mode at Tevatron
- At LHC, boosted analysis possible

Butterworth, Davison, Rubin, Salam 2008

- Inclusive NLO QCD: +30% (Han, Wllenbrock 1990), NLO EW: +5-10% (Ciccolini, Dittmaier, Denner 2003)
- NNLO QCD: 1-2% in bulk of phase space (Ferrera, Grazzini, Tramontano 2011)

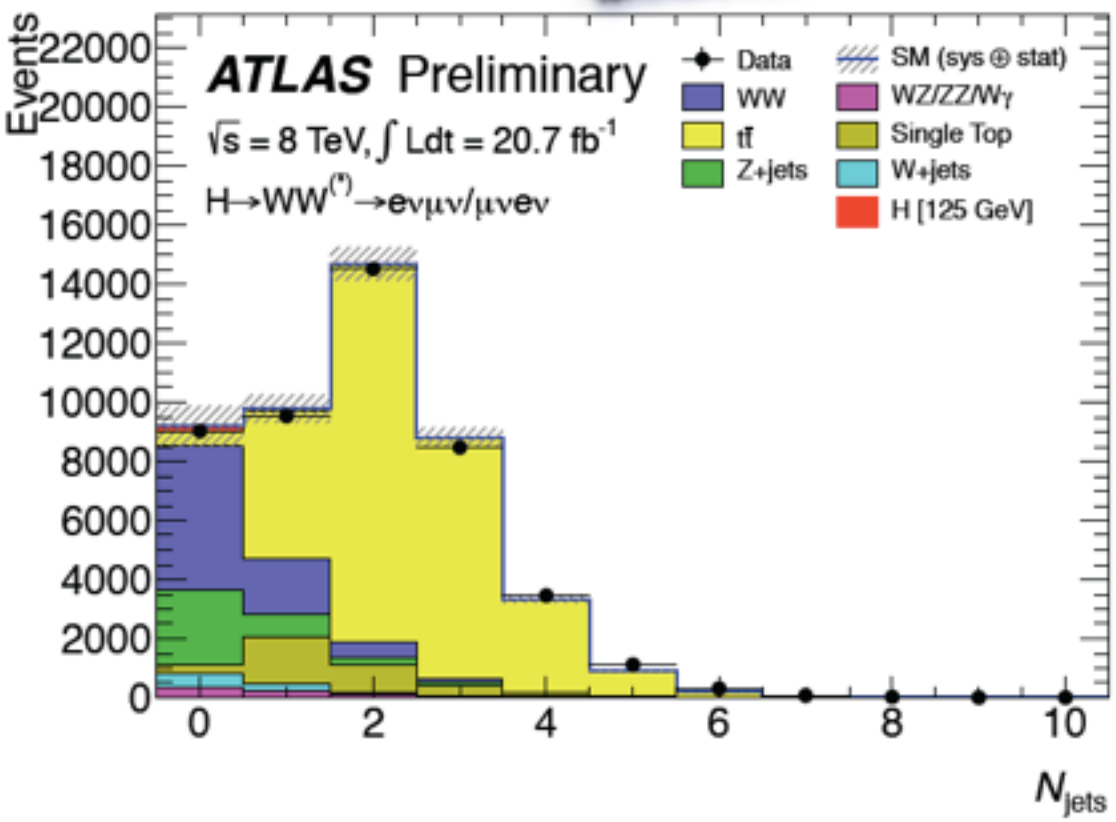


- Original boosted analysis vetoes additional jets to remove ttbar background
- Negative impact on stability of expansion (jet vetoes are theoretically dangerous!)

Selected recent results

III. Higgs production with a jet Veto

The jet veto in the WW channel



- Required in WW channel due to background composition
- 25-30 GeV jet cut used; restriction of radiation leads to large logs

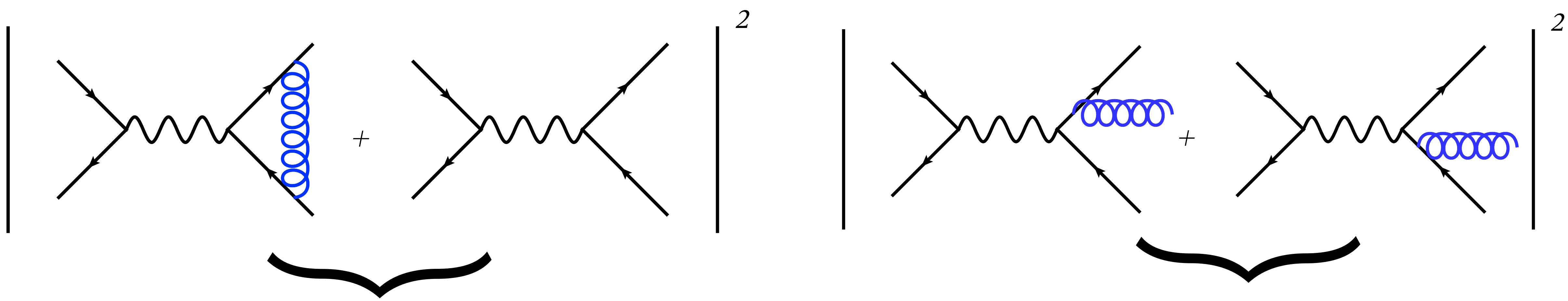
Source	Signal processes (%) $N_{jet}=0$	$N_{jet}=1$	$N_{jet}\geq 2$	Background processes (%) $N_{jet}=0$	$N_{jet}=1$	$N_{jet}\geq 2$
Theoretical uncertainties						
QCD scale for ggF signal for $N_{jet}\geq 0$	13	-	-	-	-	-
QCD scale for ggF signal for $N_{jet}\geq 1$	10	27	-	-	-	-
QCD scale for ggF signal for $N_{jet}\geq 2$	-	15	4	-	-	-
QCD scale for ggF signal for $N_{jet}\geq 3$	-	-	4	-	-	-
Parton shower and UE model (signal only)	3	10	5	-	-	-
PDF model	8	7	3	1	1	1
$H\to WW$ branching ratio	4	4	4	-	-	-
QCD scale (acceptance)	4	4	3	-	-	-
WW normalisation	-	-	-	1	2	4
Experimental uncertainties						
Jet energy scale and resolution	5	2	6	2	3	7
b-tagging efficiency	-	-	-	-	7	2
f_{recoil} efficiency	1	1	-	4	2	-

ATLAS

- Theory uncertainty becoming a limiting systematic in the 0-jet and 1-jet bins

Why are jet vetoes dangerous?

- Illustrate with simple example of $e^+e^- \rightarrow$ 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

Fixed-order scale variation

- Use the H+0-jet cross section to illustrate the problem with estimating theory uncertainties on vetoed cross sections by direct scale variation in the exclusive 0-jet bin

$$\sigma_0 = \sigma_{\rm total} - \sigma_{\geq 1}$$

Large threshold corrections

$$\sigma_{\rm total} = (3.32\,{\rm pb})\big[1 + 9.5\,\alpha_s + 35\,\alpha_s^2 + \mathcal{O}(\alpha_s^3)\big]$$

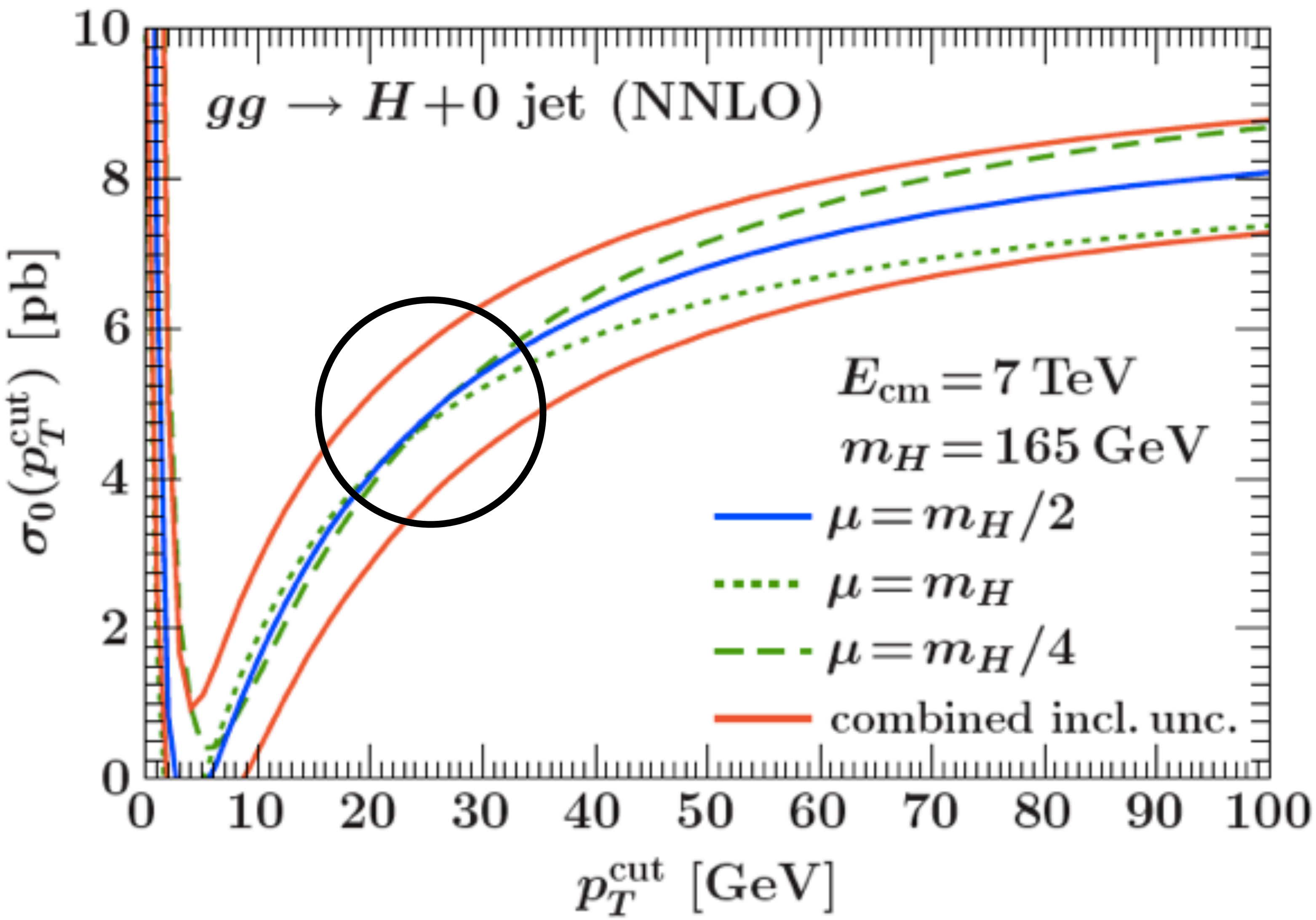
$$\sigma_{\geq 1}\big(p_T^{\rm jet} \geq 25\,{\rm GeV}\big) = (3.32\,{\rm pb})\big[6.0\,\alpha_s + 32\,\alpha_s^2 + \mathcal{O}(\alpha_s^3)\big]$$

Stewart, Tackmann 2011

Large jet-veto log corrections

- Strong cancellation between two independent series, which are sensitive to different scales. Uncertainty estimate sensitive to exactly how scales are varied.

Fixed-order scale variation



Stewart, Tackmann 2011

- The cancellation leads to a pinch point in the scale variation when σ_{total} and $\sigma_{\geq 1}$ are varied together
- Very likely an underestimate of higher-order corrections; why should the two independent series exhibit the same terms at each order?
- ST prescription: vary the scales separately then combine in quadrature $\Longrightarrow$ works well for Higgs but not other processes
- Best solution is to resum the large logarithms

Zero-jet resummation

- Current status with anti-k_T algorithm:
  - Banfi, Monni, Salam, Zanderighi: NNLL+NNLO 1203.5573, 1206.4998
  - Becher, Neubert NNLL+NNLO 1205.3806, partial N^{3}LL+NNLO 1307.0025
  - Stewart, Tackmann, Walsh, Zuberi NNLL'+NNLO 1307.1808

Counting in the log of the cross section

LL	NLL	NLL′ / NNLL	NNLL′ / NNNLL	
$\alpha_s L^2$	$\alpha_s L$	α_s		
$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2	
$\alpha_s^3 L^4$	$\alpha_s^3 L^3$	$\alpha_s^3 L^2$	$\alpha_s^3 L$	α_s^3

$$L = \ln \frac{p_T^{cut}}{m_H}$$

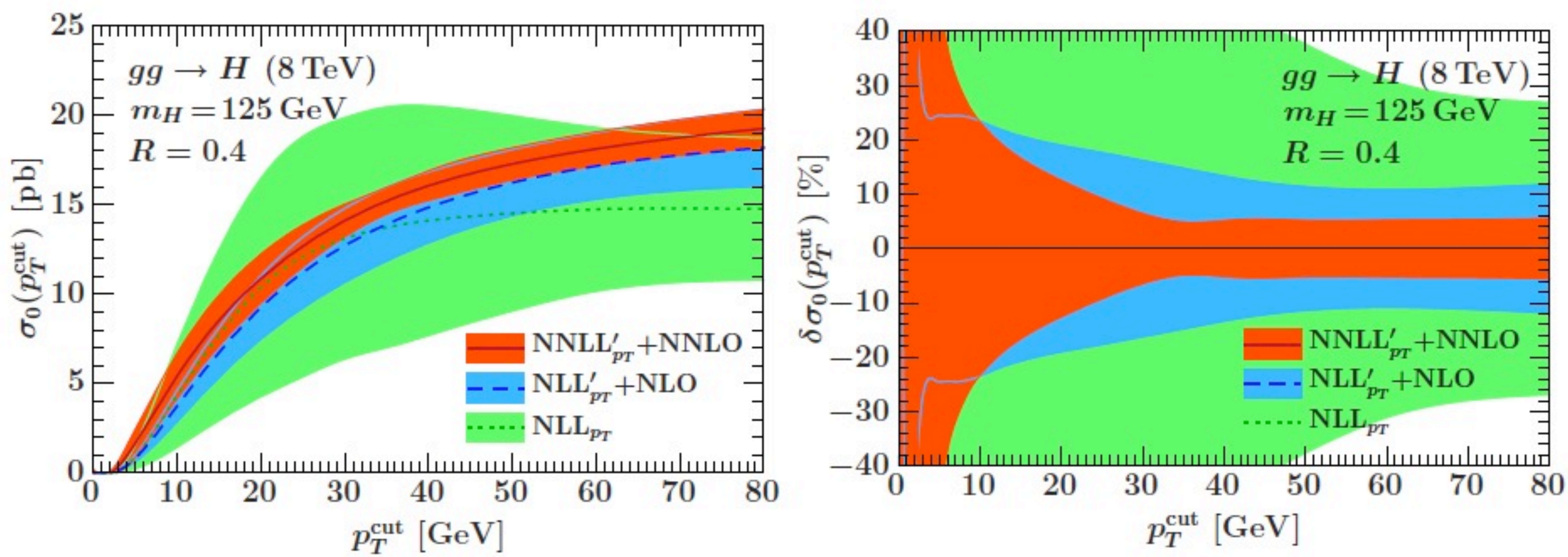
Global veto log structure

taken from J. Walsh

NNLL'+NNLO resummation for P_{Tj}

green: NLL_{p_T}
blue: NLL'_{p_T}+NLO
orange: NNLL'_{p_T}+NNLO

Including resummation and fixed-order uncertainties



Stewart, Tackmann, Walsh, Zuberi

Numerical results for zero jets

- Central value: scheme (a) with

$$\mu_R = \mu_F = Q = M/2$$

- μ_R and μ_F variations

$$\frac{M}{4} \leq \mu_R, \mu_F \leq M \qquad \frac{1}{2} \leq \frac{\mu_R}{\mu_F} \leq 2$$

- Resummation scale (Q) variation

i.e.

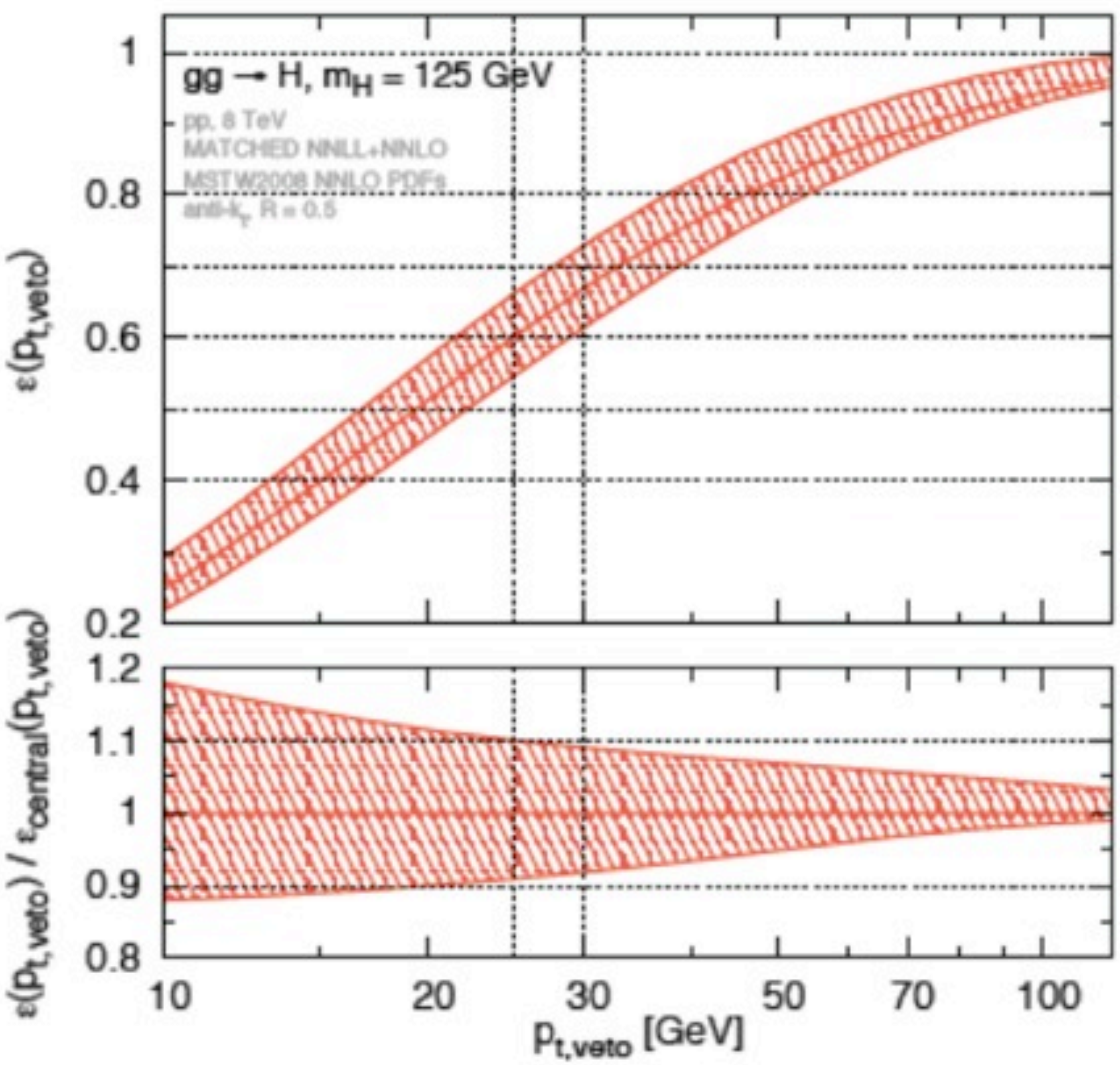
$$\ln \frac{M}{p_{t,veto}} \to \ln \frac{Q}{p_{t,veto}}$$

$$\frac{M}{4} \leq Q \leq M \qquad \mu_{R,F} = M/2$$

- Scheme (b) and (c) with

$$\mu_R = \mu_F = Q = M/2$$

- Total uncertainty $\longleftrightarrow$ envelope

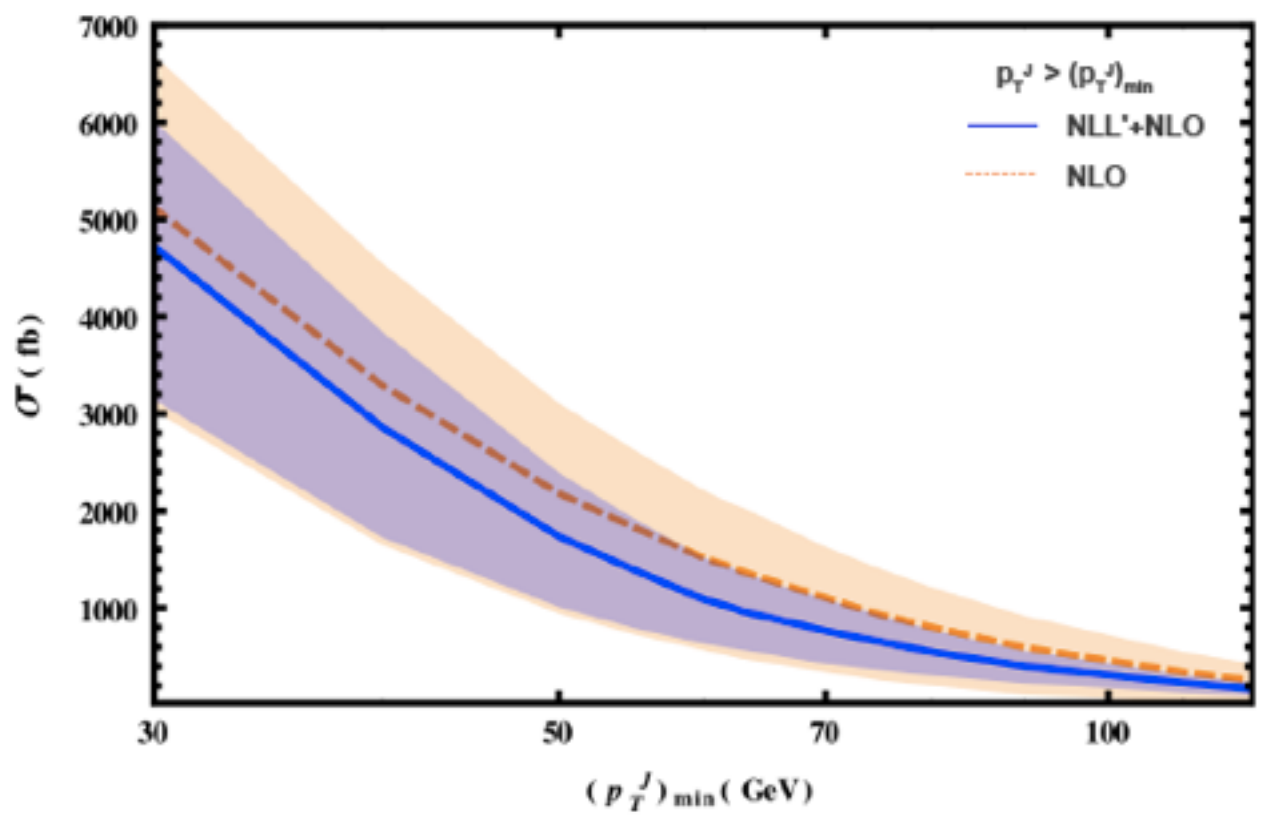


From P. Monni

Banfi, Monni, Salam, Zanderighi

One-jet resummation: numerical results

- Integration over entire p_T range used in the ATLAS measurement



- Large uncertainty from the high-p_T region makes this resummation very effective in reducing errors
- Very conservative (turn off resummation at $p_{T,J}=m_H/2$, use ST below this value). Error on 1-jet bin result is decreased by 25%

m_H (GeV)	p_T^{veto} (GeV)	$\sigma_{\rm NLO}$ (pb)	$\sigma_{\rm NLL'+NLO}$ (pb)	$f^{1j}_{\rm NLO}$	$f^{1j}_{\rm NLL'+NLO}$
124	25	$5.92^{+35\%}_{-46\%}$	$5.62^{+29\%}_{-30\%}$	$0.299^{+38\%}_{-49\%}$	$0.283^{+33\%}_{-34\%}$
125	25	$5.85^{+34\%}_{-46\%}$	$5.55^{+29\%}_{-30\%}$	$0.300^{+37\%}_{-49\%}$	$0.284^{+33\%}_{-33\%}$
126	25	$5.75^{+35\%}_{-46\%}$	$5.47^{+30\%}_{-30\%}$	$0.300^{+38\%}_{-49\%}$	$0.284^{+34\%}_{-33\%}$
124	30	$5.25^{+31\%}_{-41\%}$	$4.83^{+29\%}_{-29\%}$	$0.265^{+35\%}_{-43\%}$	$0.244^{+33\%}_{-33\%}$
125	30	$5.19^{+32\%}_{-41\%}$	$4.77^{+30\%}_{-29\%}$	$0.266^{+35\%}_{-43\%}$	$0.244^{+33\%}_{-33\%}$
126	30	$5.12^{+32\%}_{-41\%}$	$4.72^{+30\%}_{-29\%}$	$0.266^{+35\%}_{-43\%}$	$0.246^{+33\%}_{-32\%}$

Liu, Petriello 2013

Selected recent results

IV. Approximate N^3LO results for the inclusive cross section

V. Measuring the Hcc coupling

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

NLO in EFT:

$$\Delta\sigma = \sigma_0 \frac{\alpha_s}{\pi}\left\{\left(\frac{11}{2}+\pi^2\right)\delta(1-z)+12\left[\frac{\ln(1-z)}{1-z}\right]_+ - 12z(-z+z^2+2)\ln(1-z) -6\frac{(z^2+1-z)^2}{1-z}\ln(z)-\frac{11}{2}(1-z)^3\right\}$$

eikonal emission of soft gluons

collinear emission of gluons

$z = m_H^2/(x_1 x_2 s)$

- What we knew so far for approximate N^{3}LO: the soft gluon threshold (Moch, Vogt 2005)

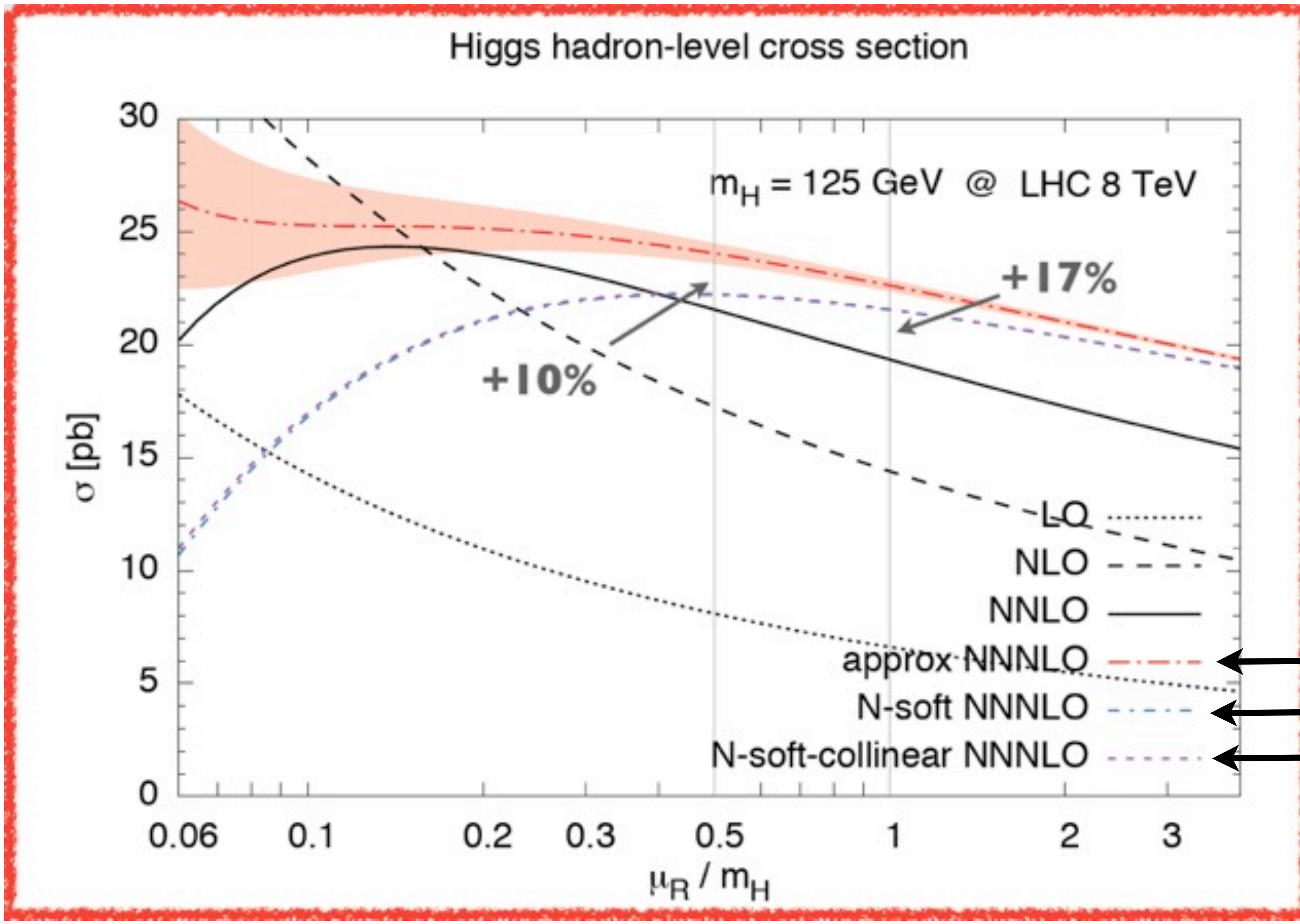
- New improvements by Ball, Bonvini, Forte, Marzani, Ridolfi, (2013) :

1. exact phase space limits for soft gluon emission in threshold logs: $\left(\frac{\ln(1-z)}{1-z}\right)_+ \rightarrow \left(\frac{\ln\frac{1-z}{\sqrt{z}}}{1-z}\right)_+$

2. they include the leading collinear gluon emissions, which are normally dropped

3. they make the perturbative expansion consistent with BFKL resummation

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



New: Ball et al, 2013

Moch, Vogt, 2005

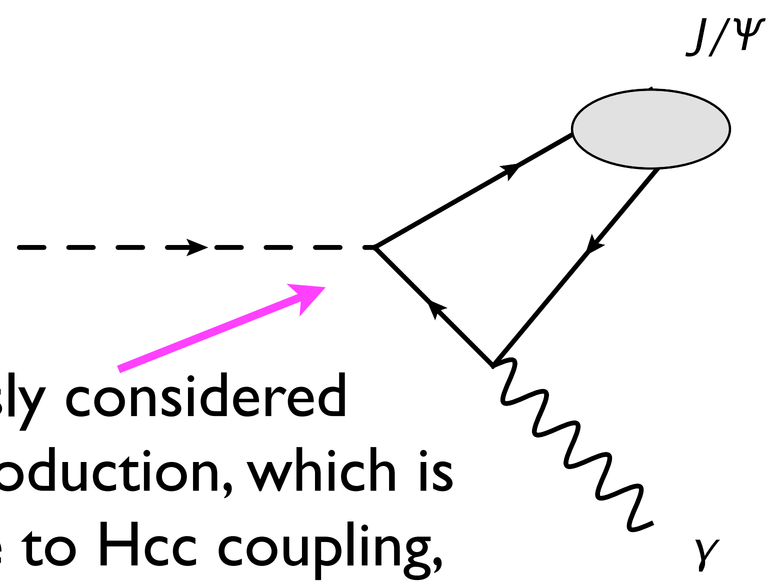
Catani et al, 2003

10% corrections for mu = $m_H/2$

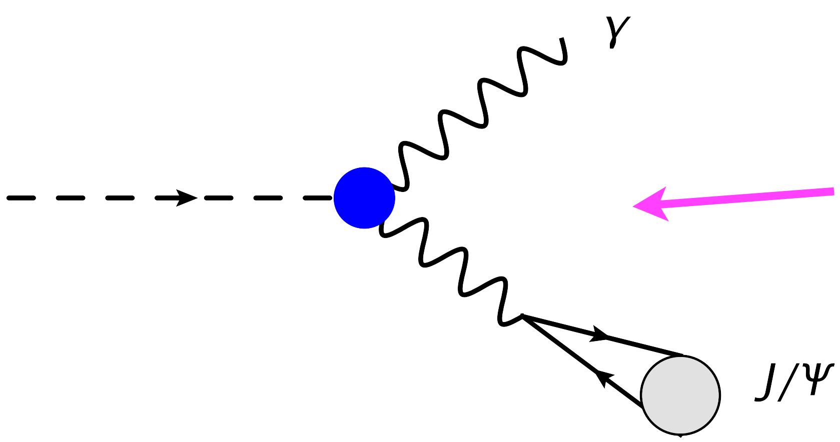
- First attempts for directly calculating N^{3}LO contributions (Hoeschele et al 2012; Anastasiou et al 2013)

Measuring the Hcc coupling

- Recent result: it may be possible to measure the hcc coupling at a high-luminosity LHC, using h→J/Ψ+γ Bodwin, Petriello, Stoynev, Velasco 1306.5770

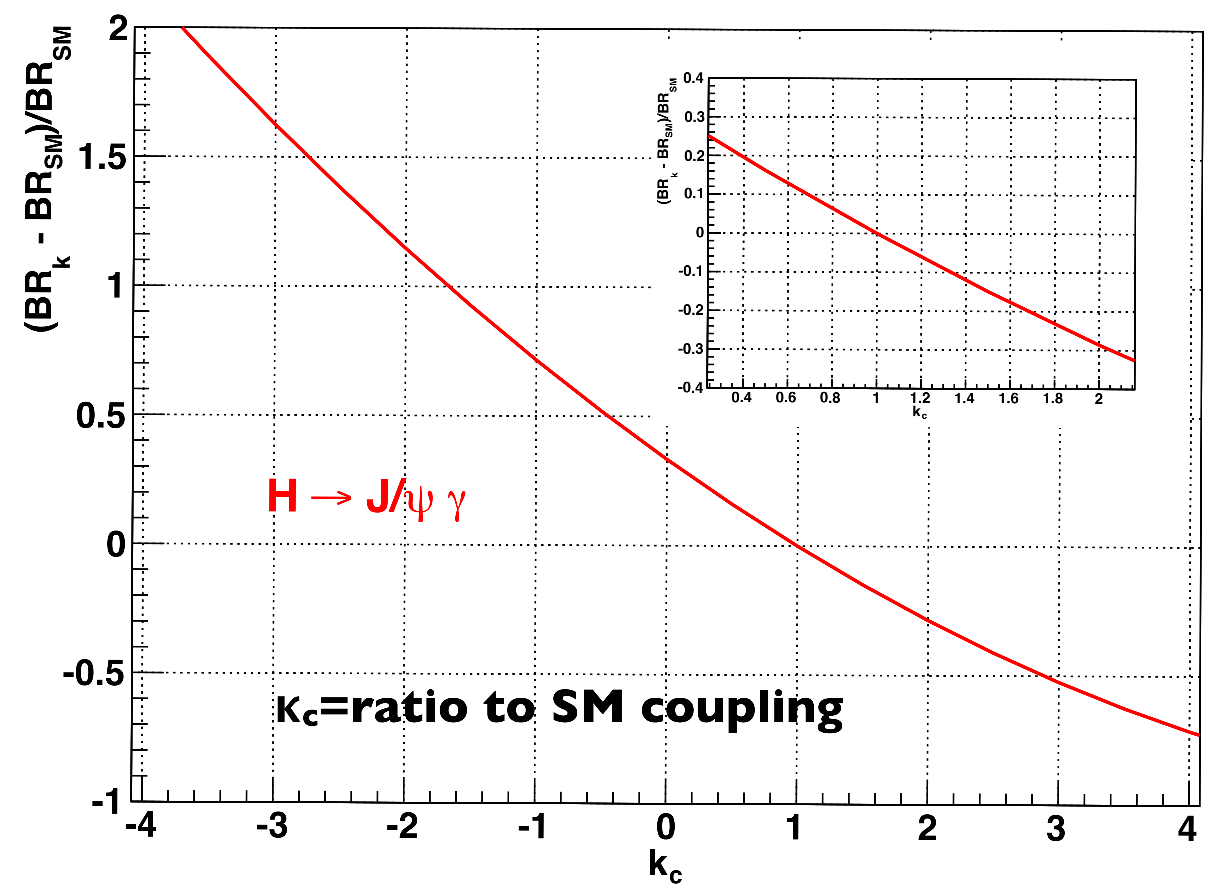


previously considered *direct* production, which is sensitive to Hcc coupling, is small



newly identified *indirect* production is larger; interferes quantum-mechanically with direct production

- Expect ~50 events after reconstruction with 3 ab^{-1}; very small theory errors
- ±20-30% coupling measurement in SM possible, depending on background reduction
- Removes sign degeneracies in hcc coupling determination. A similar h→ϒ+γ decay mode can remove sign degeneracies in hbb coupling determination
- Very sensitive to BSM deviations!



Summary

- We have moved very quickly from the discovery stage of the Higgs boson to precise measurements of its properties

- On the theory side the pace of progress in understanding SM Higgs production is remarkable

- New results for Higgs+jet at NNLO in QCD, an extremely challenging calculation and one of the first NNLO QCD results for two-to-two scattering processes at LHC

- Issues can appear in the interplay of experimental cuts with QCD. Significant progress has been made in resumming jet-veto logarithms, and these should propagate into the experimental analysis

- Estimated results for the inclusive N^3LO contribution exist and indications that explicit calculations are within reach

- New results indicate that measuring the hcc coupling at a high luminosity LHC, using $h \to J/\Psi + \gamma$, is possible