Recent theory issues in SM Higgs results

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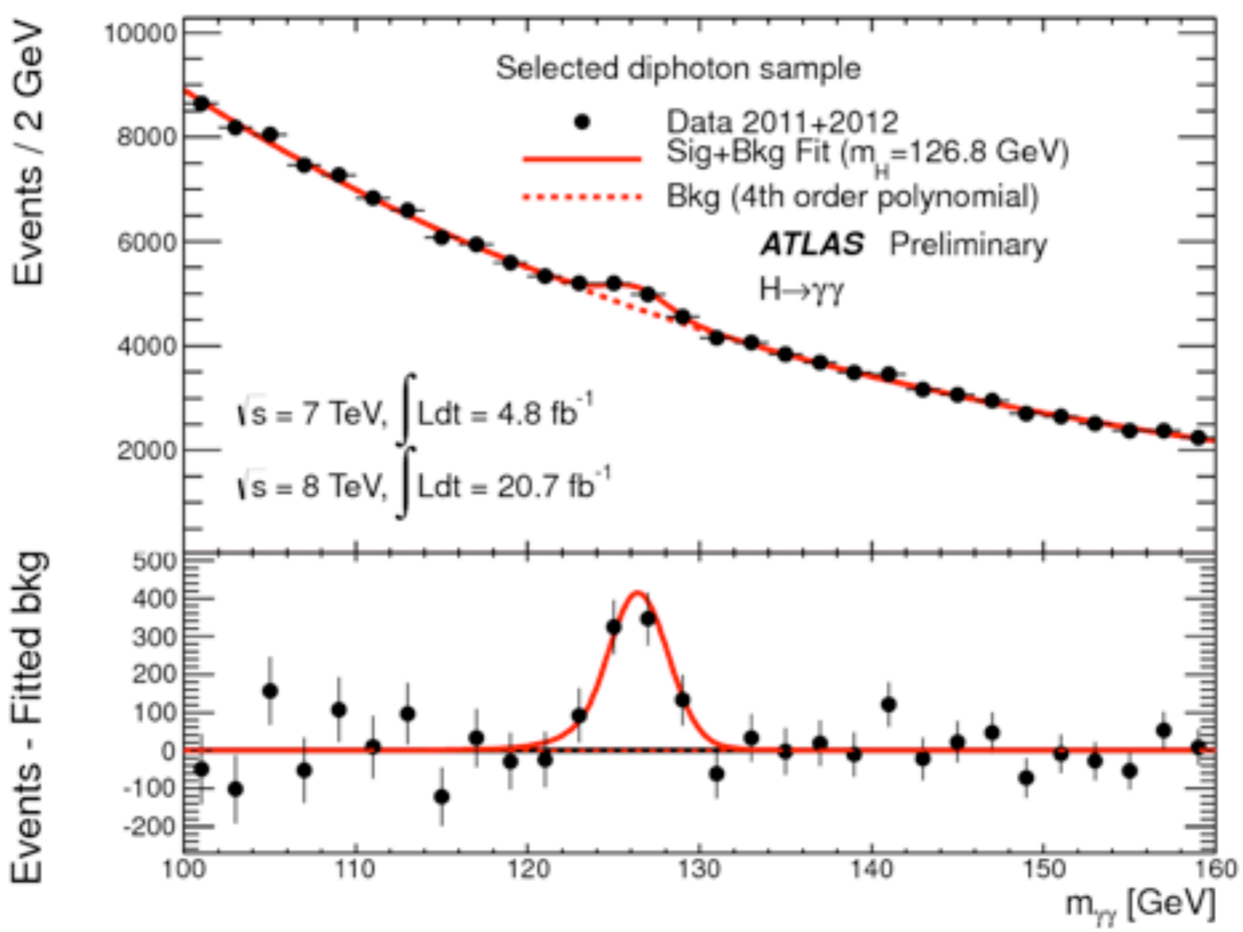
Argonne NATIONAL LABORATORY

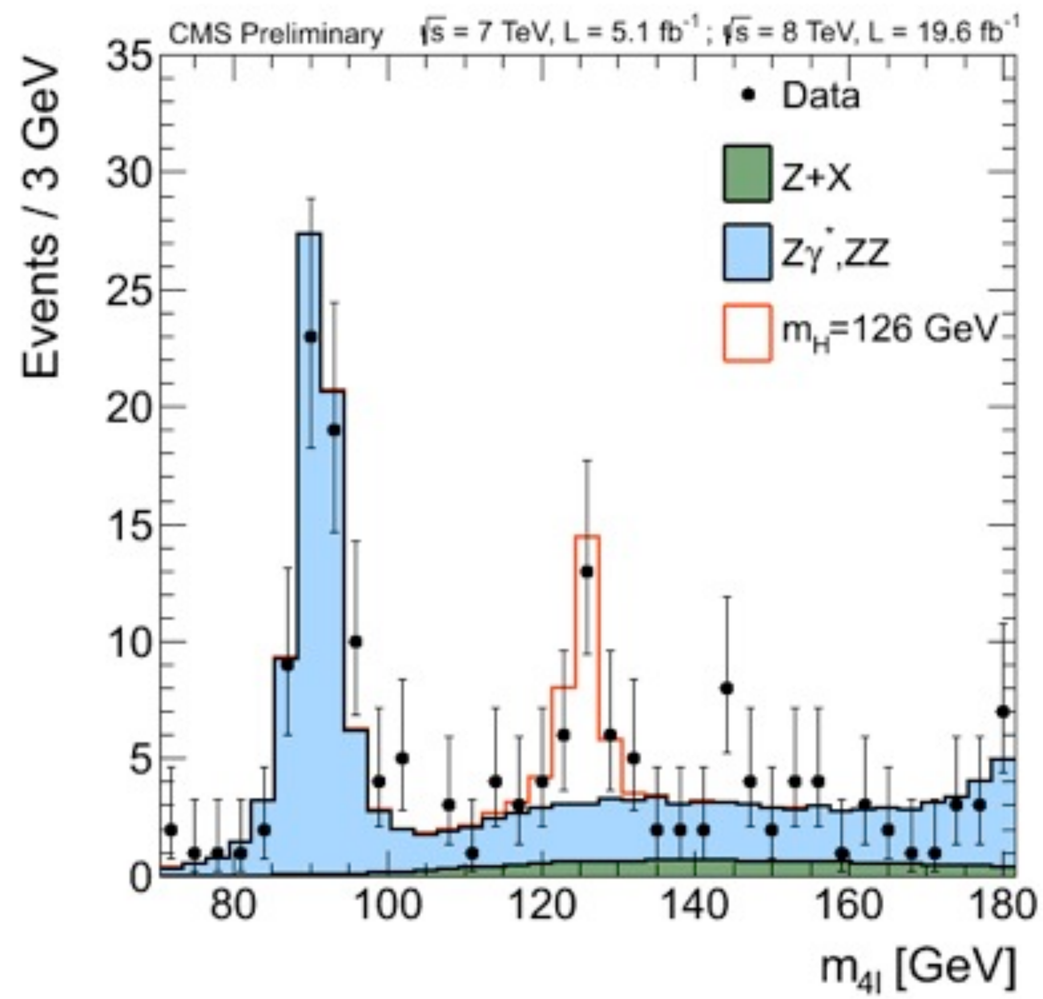
Outline

- A survey of Higgs measurements at the LHC
- The role of theory in unraveling the origin of EWSB
- Two issues for the future LHC program: theory predictions for exclusive jet bins and second-generation couplings
    - Theory for jet vetoes in the WW channel
    - Higgs+jet @NNLO
    - Measuring the Hccbar coupling at a luminosity-upgraded LHC

The Higgs discovery

- We've come a long way since July 2012:





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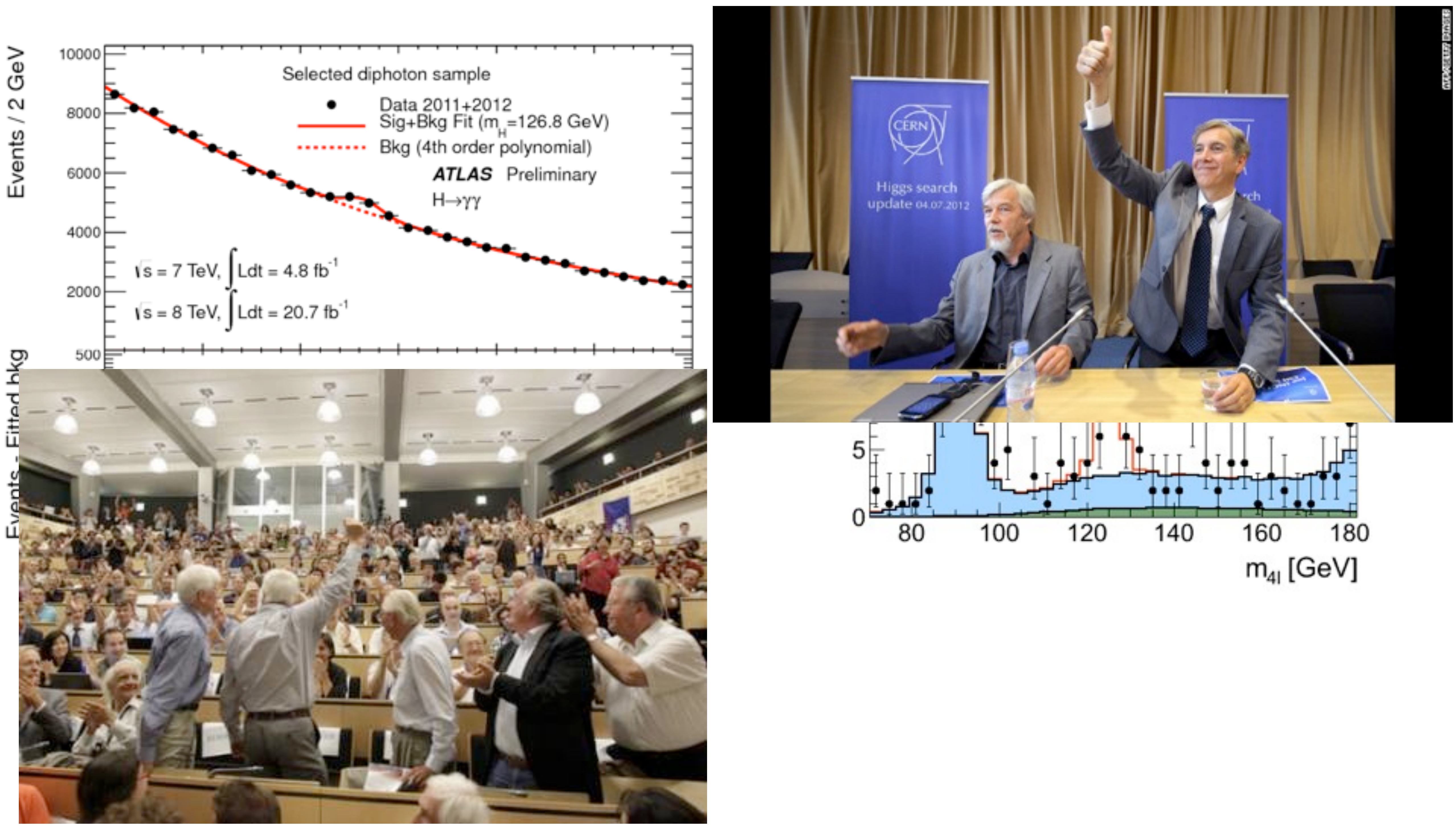
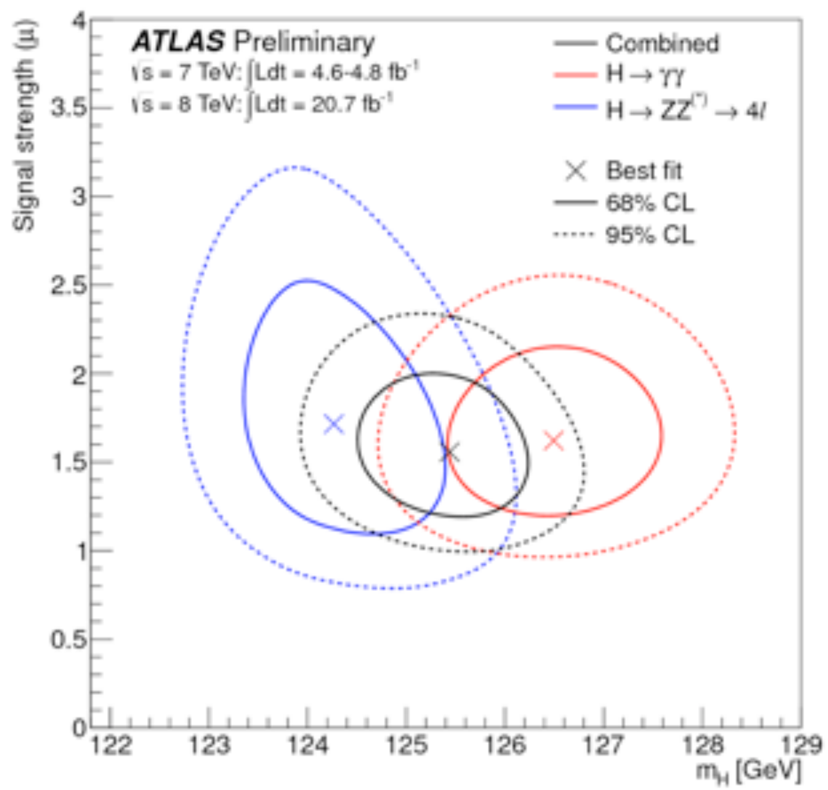
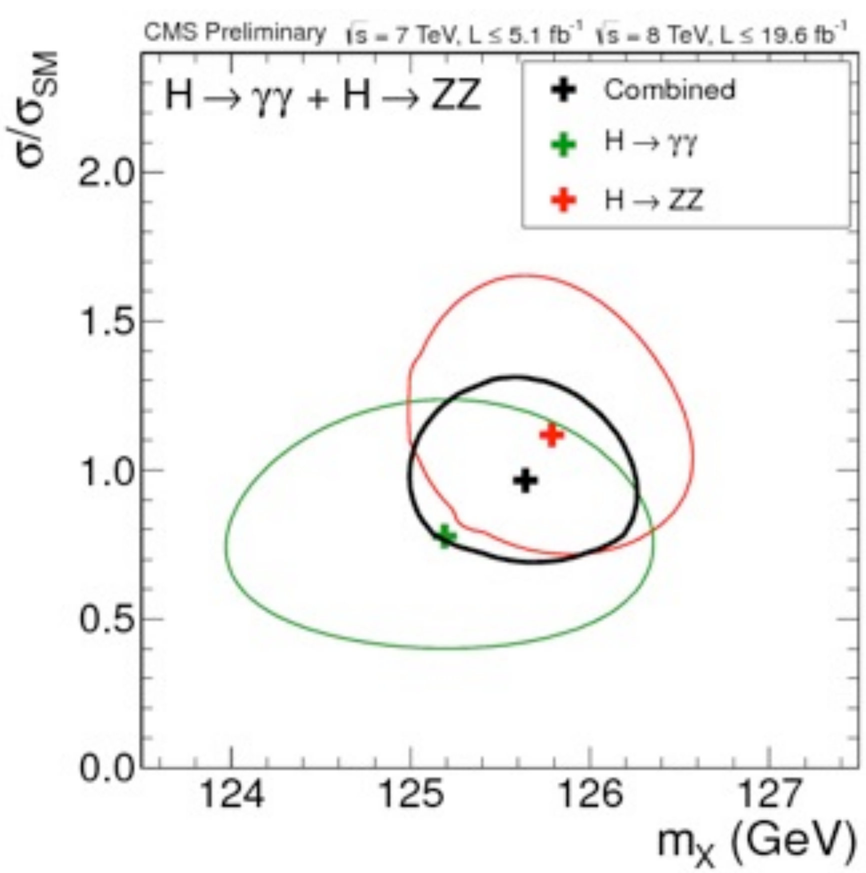
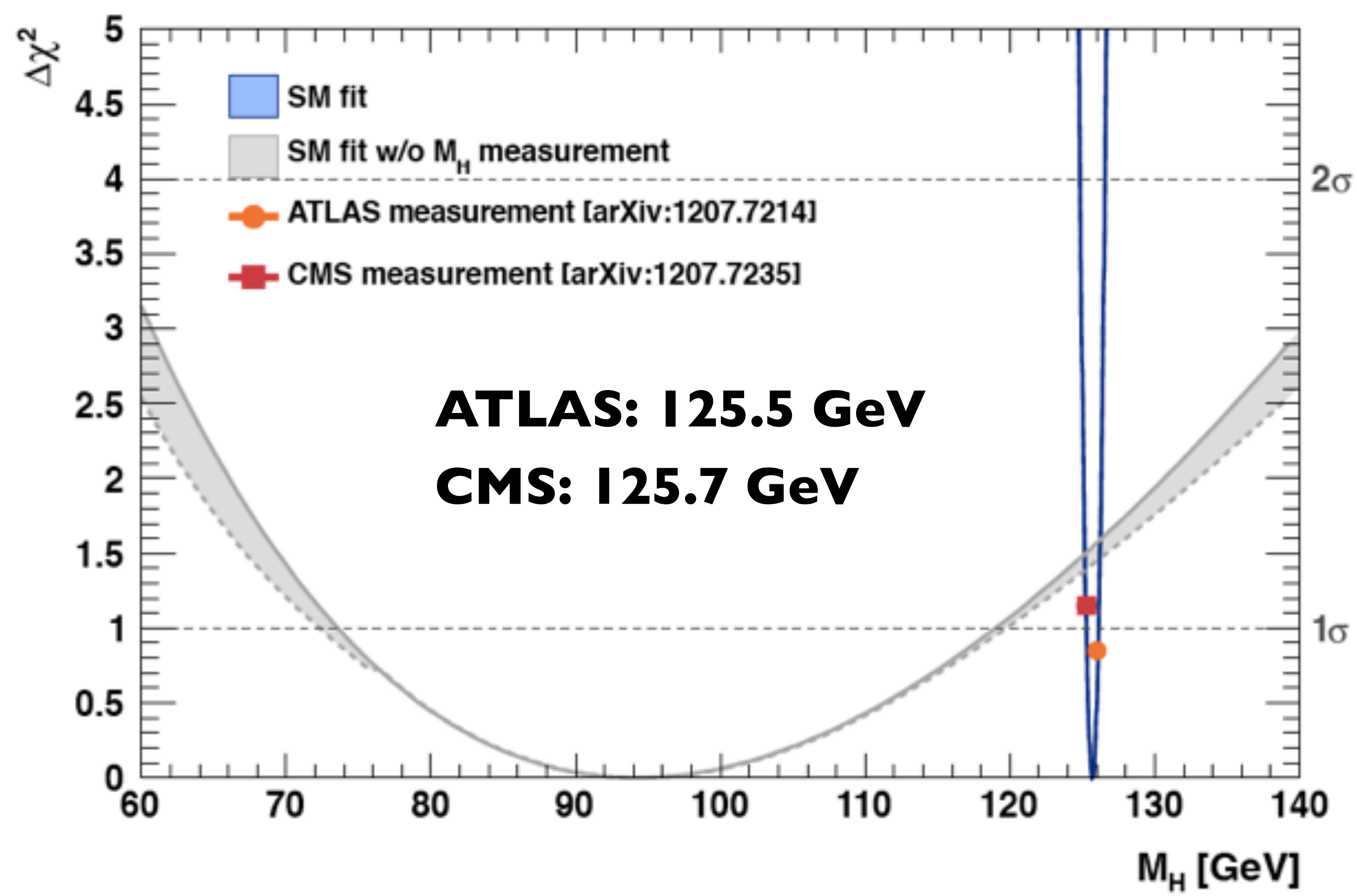


Mass measurement

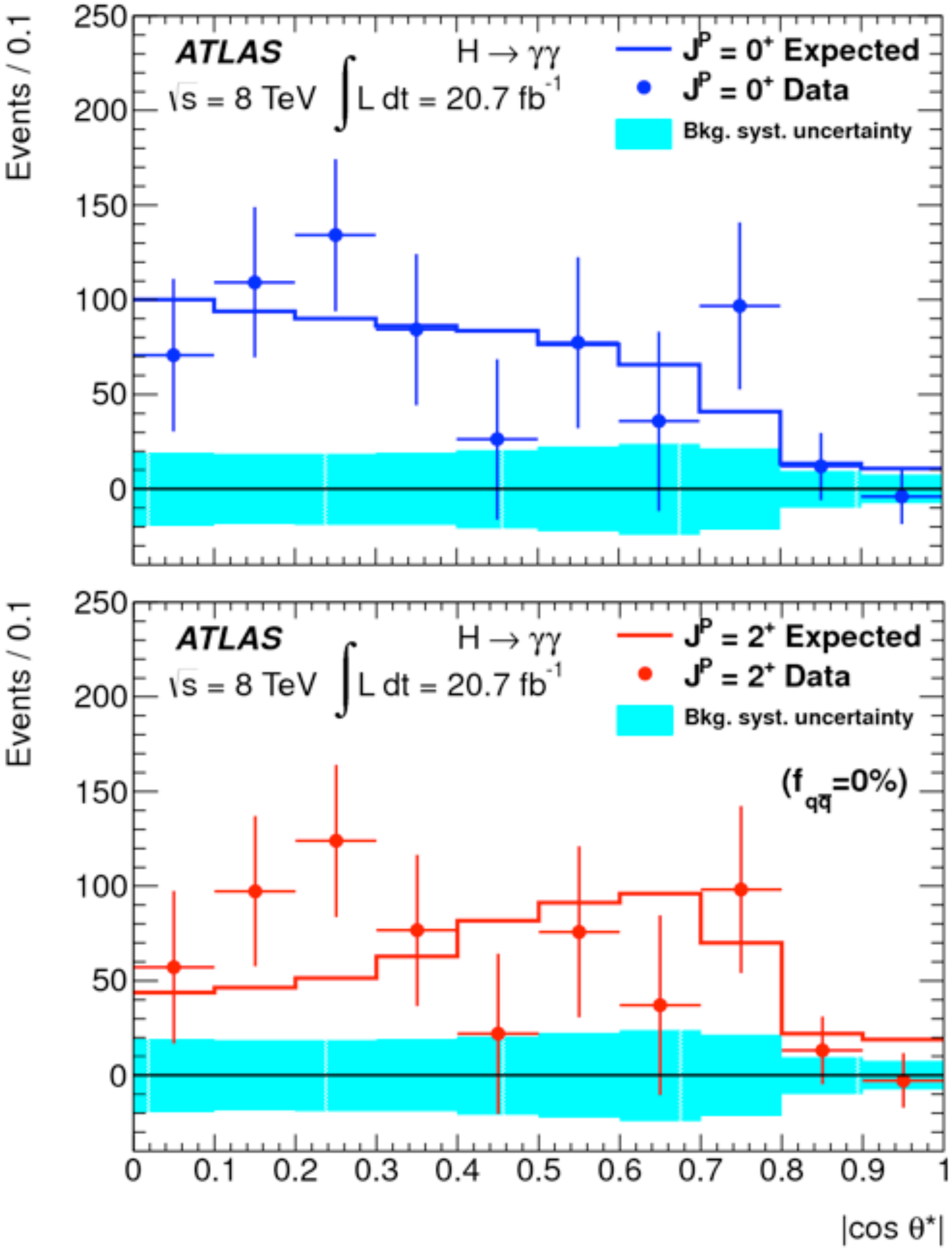
- Consistent with the global EW fit without the LHC measurement to better than 2σ
- Measurement errors are sub-GeV, and are becoming systematic-dominated

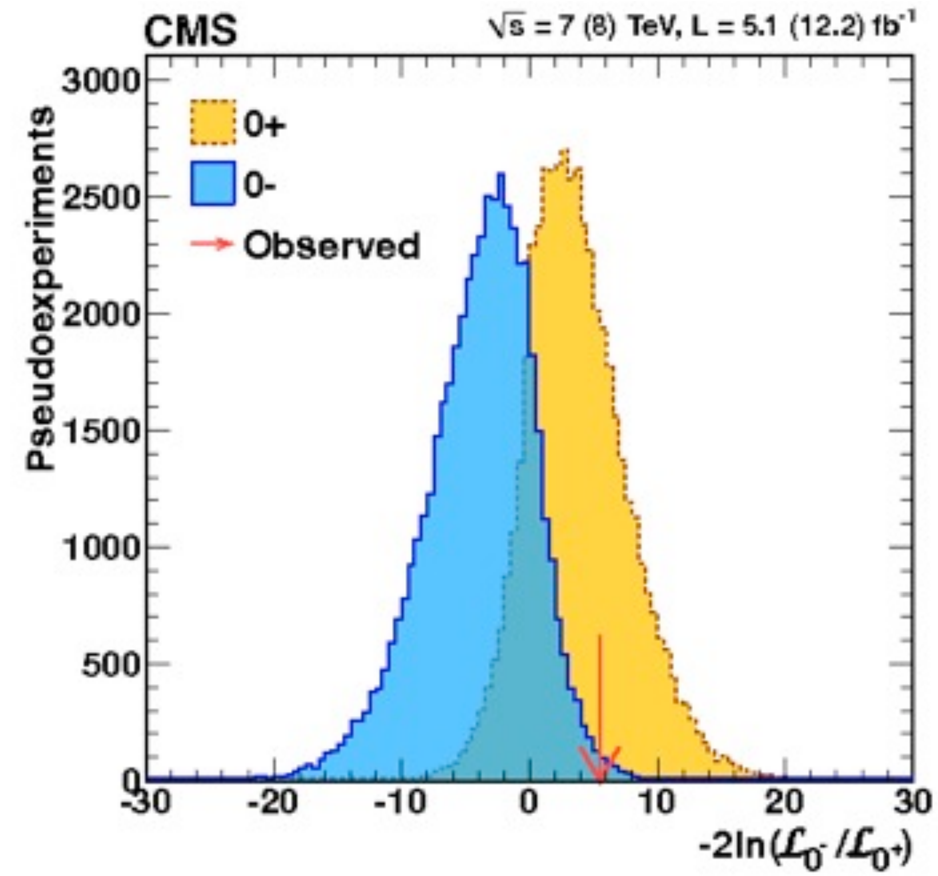






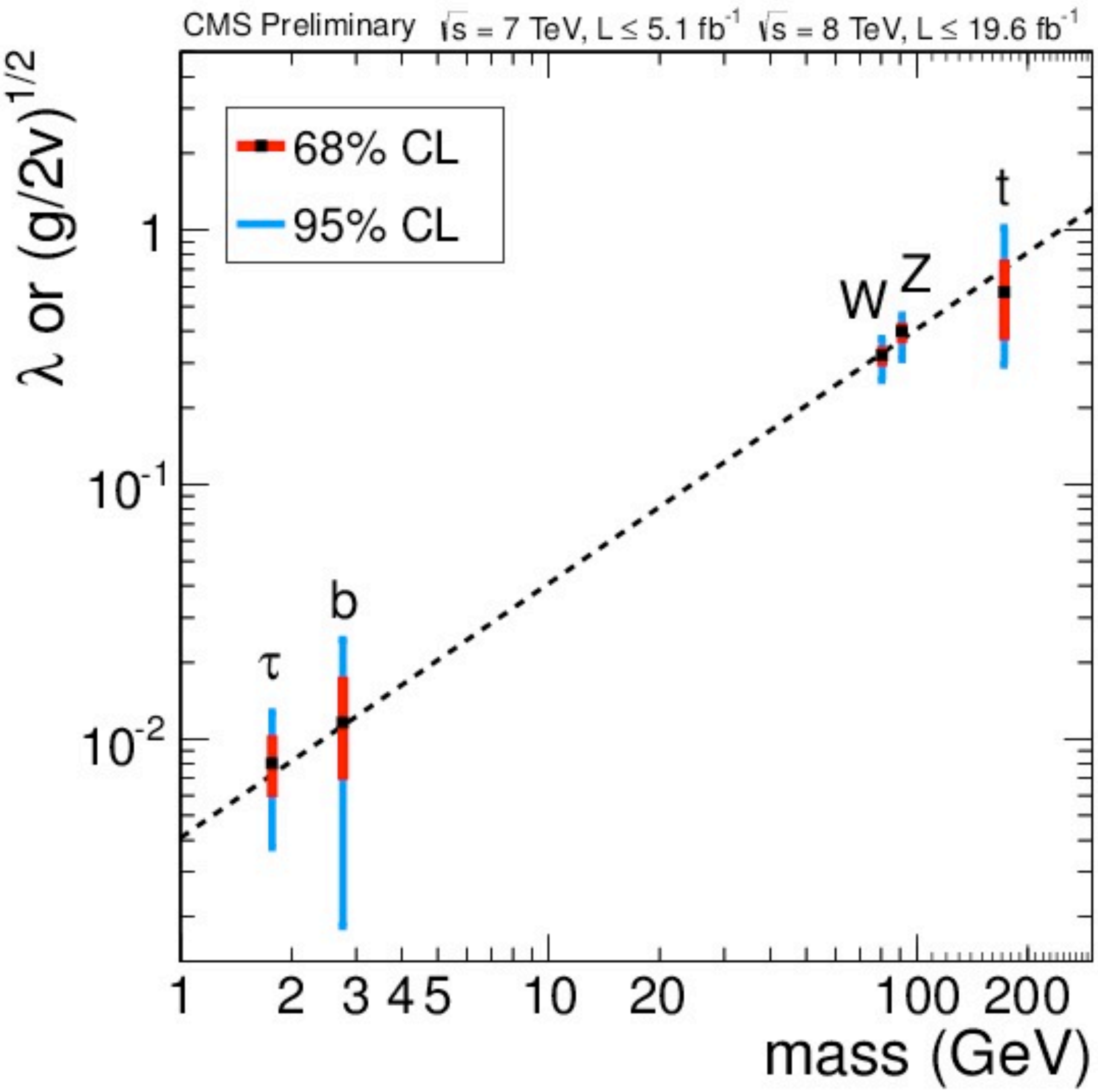
Spin-parity analysis



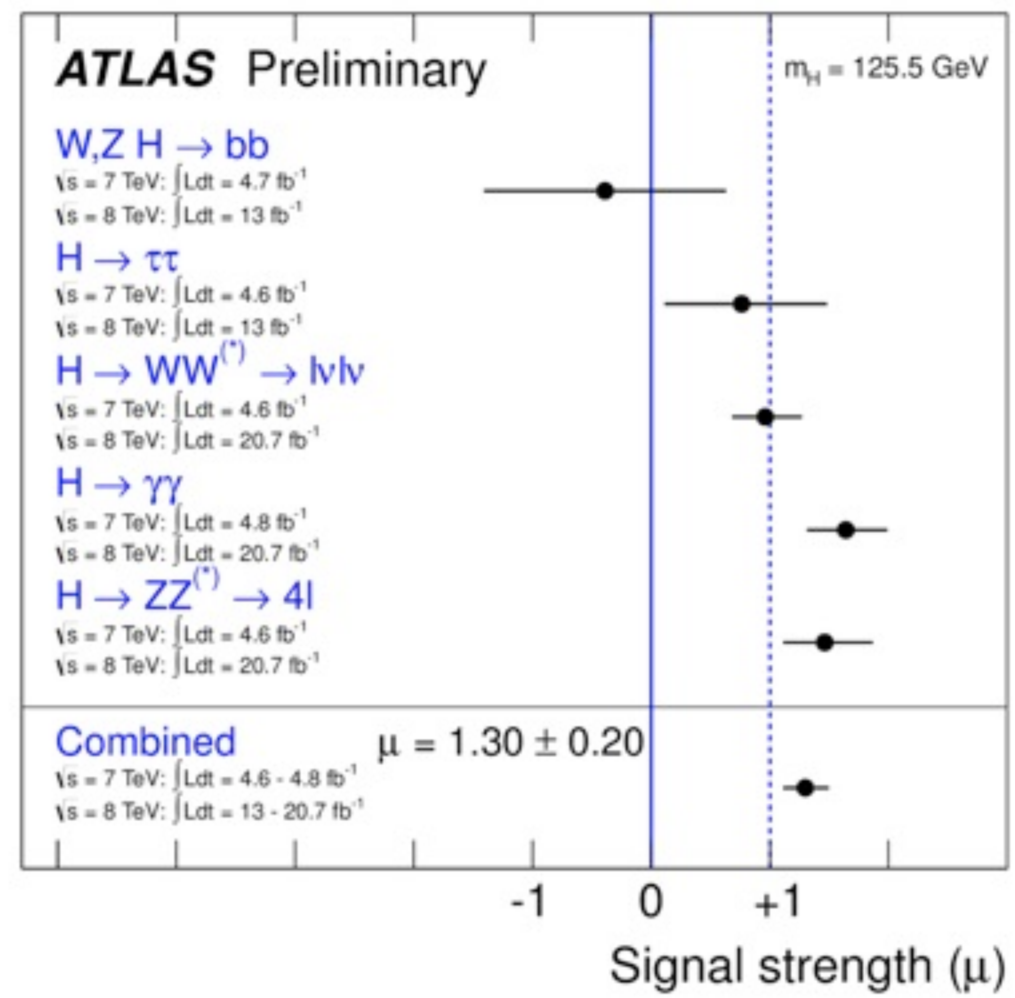


- Kinematic distributions in γγ, ZZ, and WW final states prefer a 0^+ state
- ATLAS example: 0^-, 1^+, 1^-, and 2^+ excluded at or above 97.8% C.L.

Coupling measurement

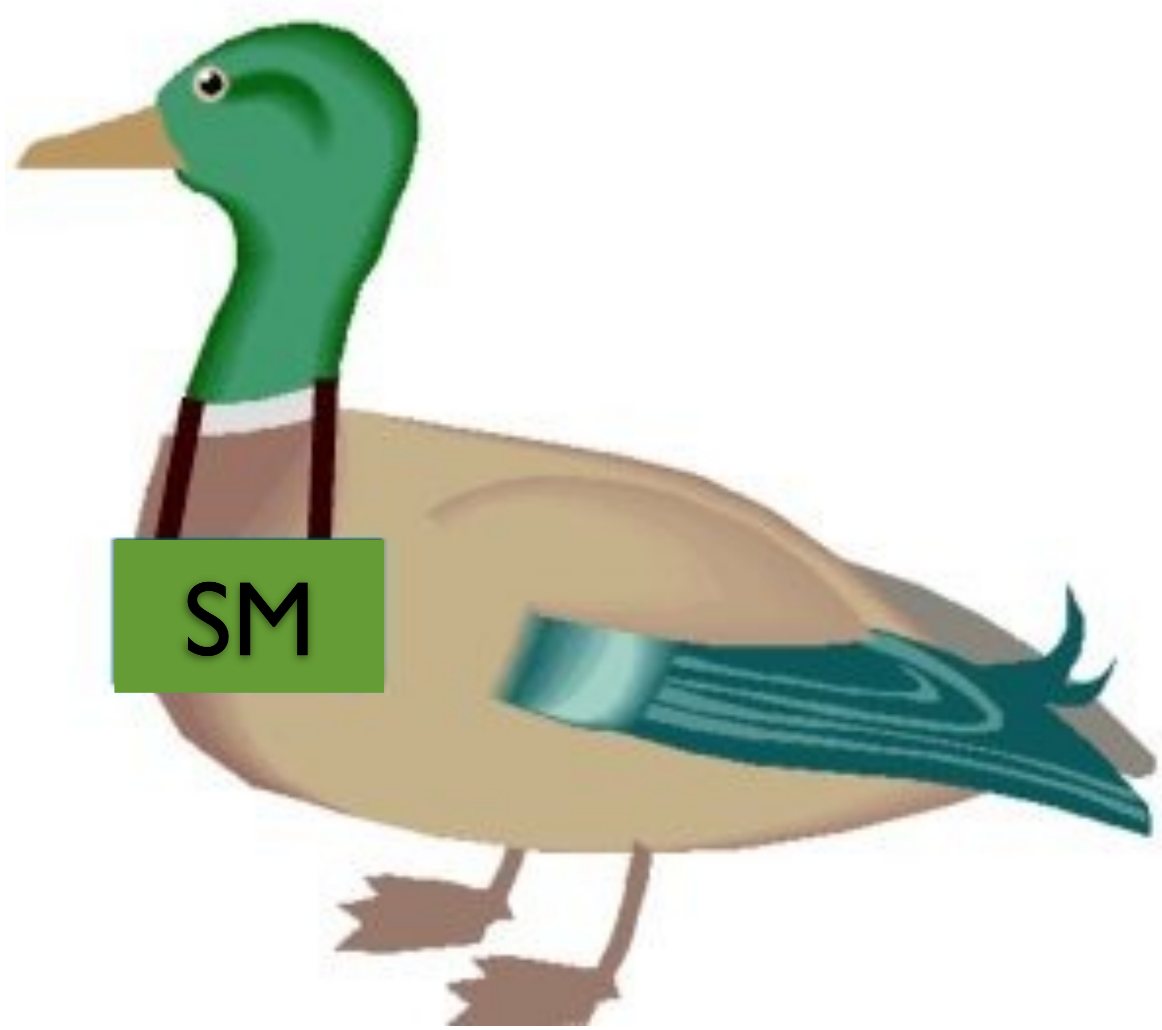


- Couplings proportional to mass, as predicted in the SM



Summary of measured properties

``If it walks like a duck and talks like a duck...''



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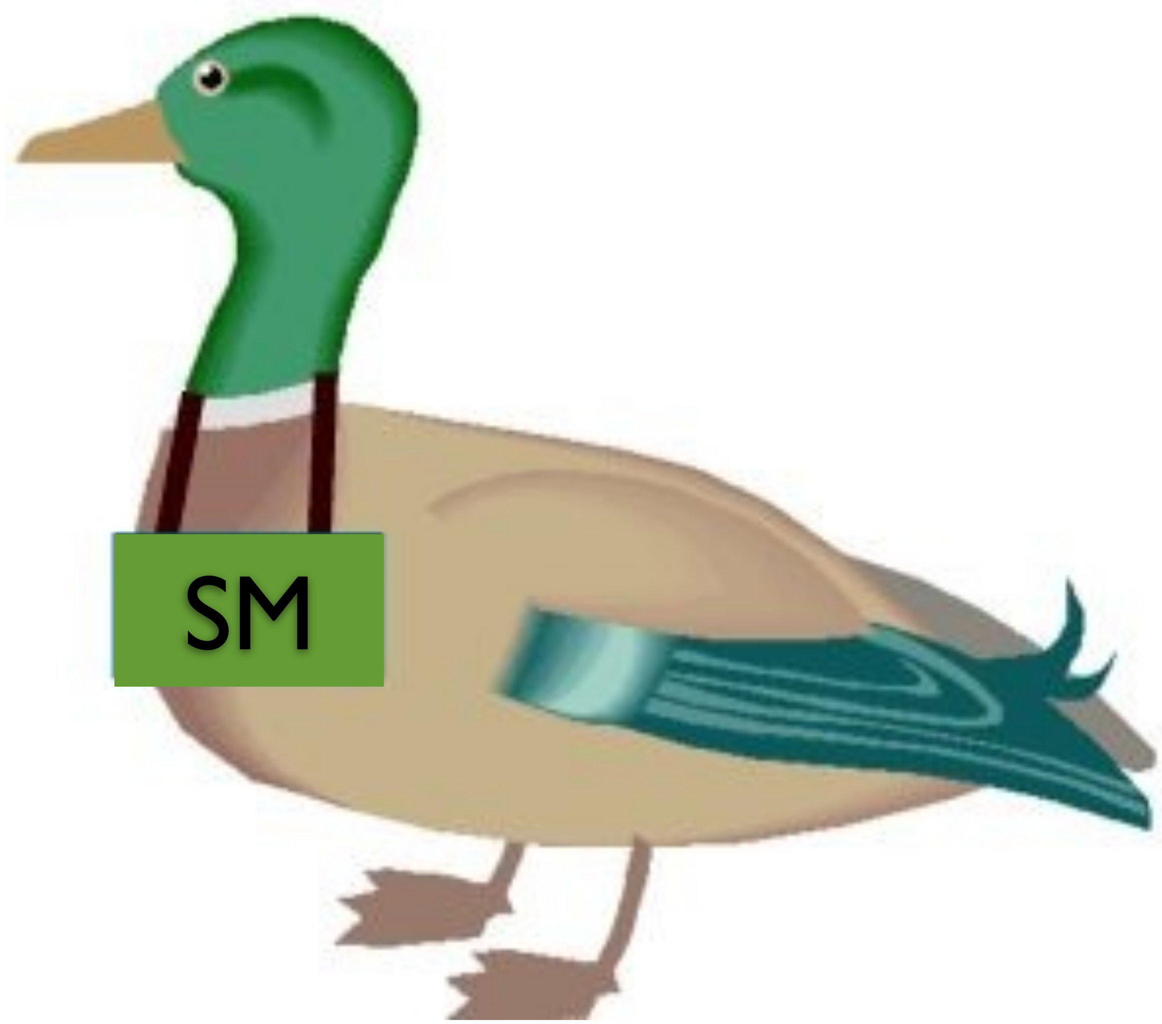
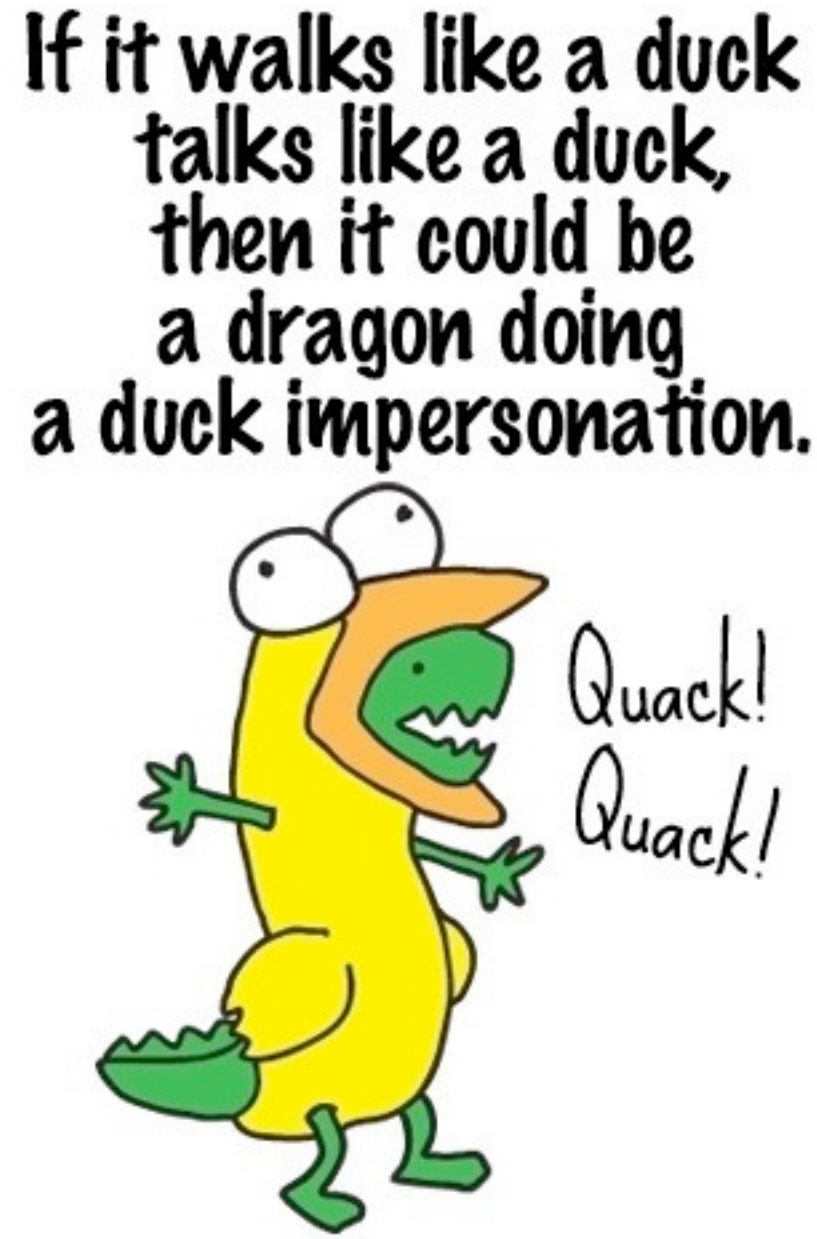




The documentation frontier (C. Brock)

arXiv:1101.0593v3 [hep-ph] 20 May 2011

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
1. Inclusive observables

Report of the LHC Higgs Cross Section Working Group

arXiv:1201.3084v1 [hep-ph] 15 Jan 2012

Handbook of LHC Higgs cross sections:
2. Differential Distributions

Report of the LHC Higgs Cross Section Working Group

arXiv:1307.1347v1 [hep-ph] 4 Jul 2013

~830 pages

Handbook of LHC Higgs cross sections:
3. Higgs properties

Report of the LHC Higgs Cross Section Working Group

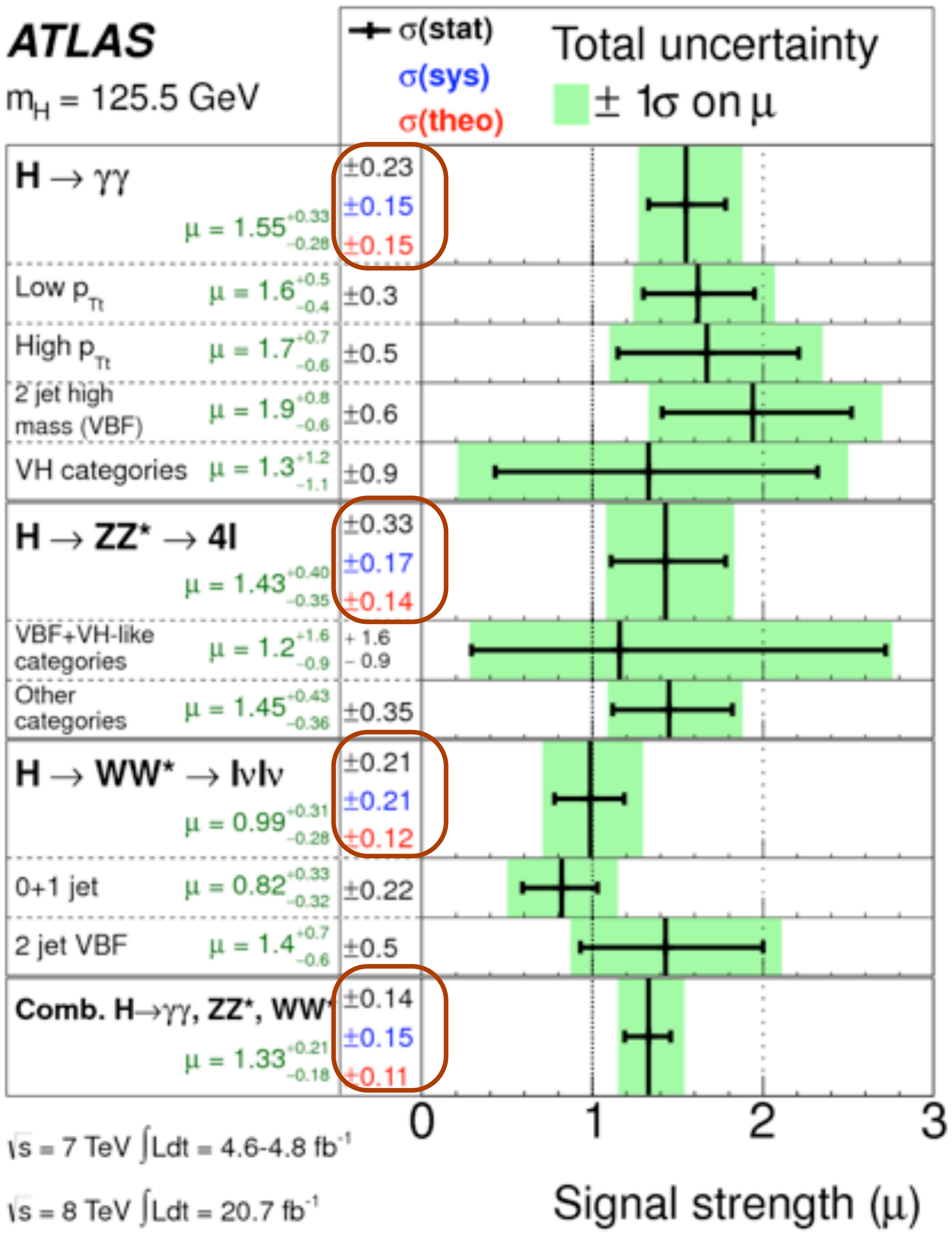
Uncertainties in inclusive cross-sections

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%	?

And yet...

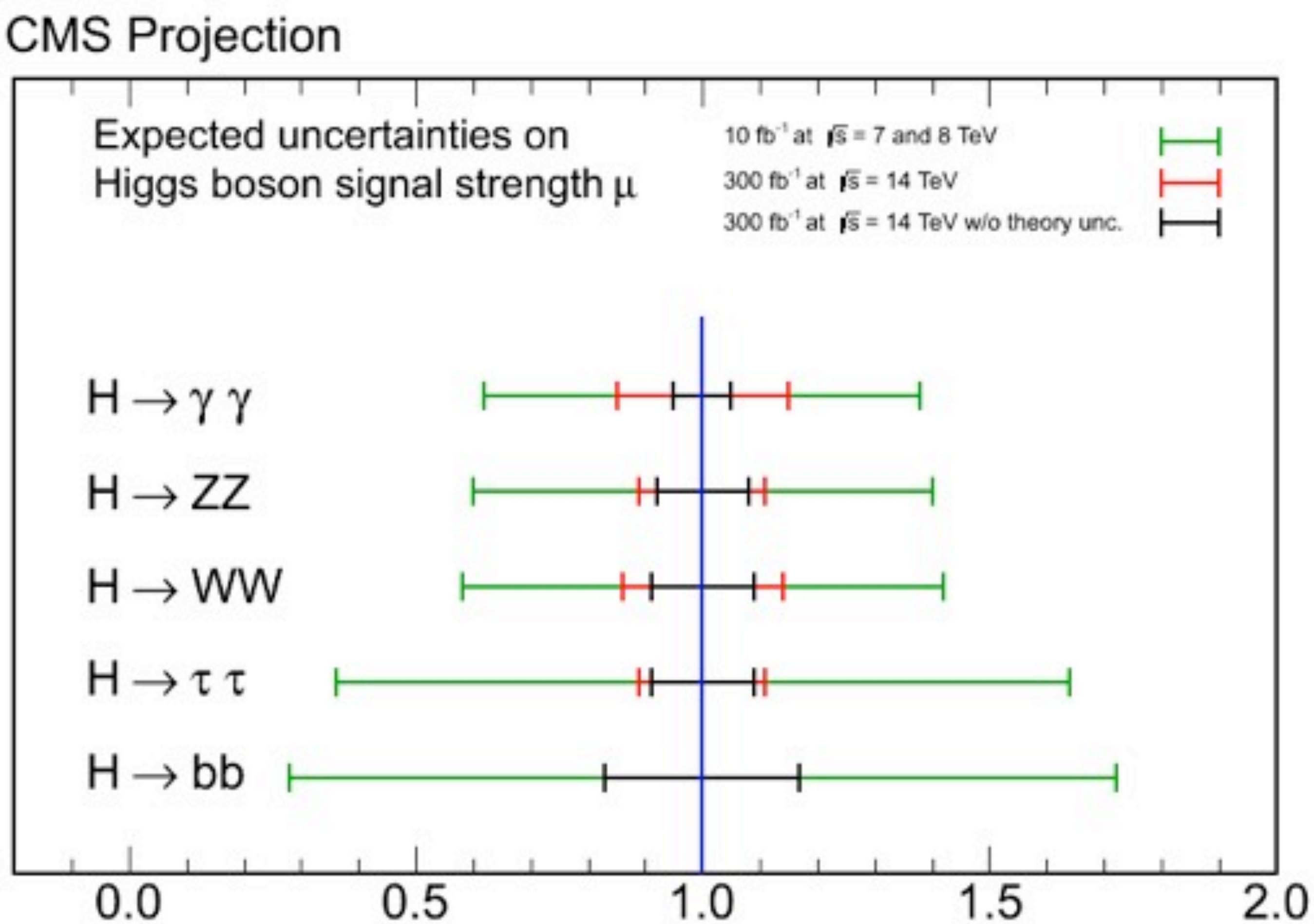
Sharpening our image

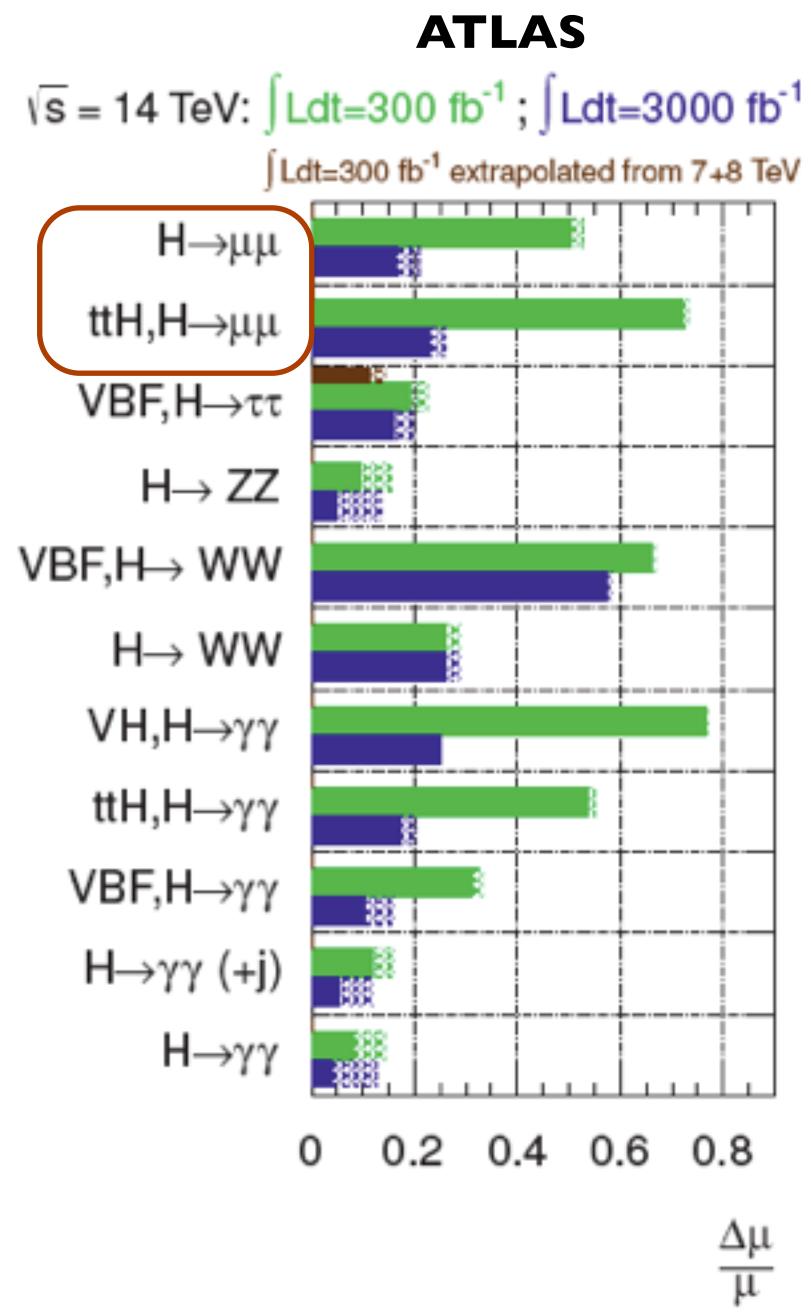


- Systematic errors already approaching statistical ones; will overtake with 14 TeV data
- Systematic error shown is the combination of experimental and theoretical systematics; theory is already the dominant systematic error
- A particular issue is the division into bins of exclusive jet multiplicity

Source	$N_{jet}=0$	$N_{jet}=1$	$N_{jet}\geq 2$
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	-

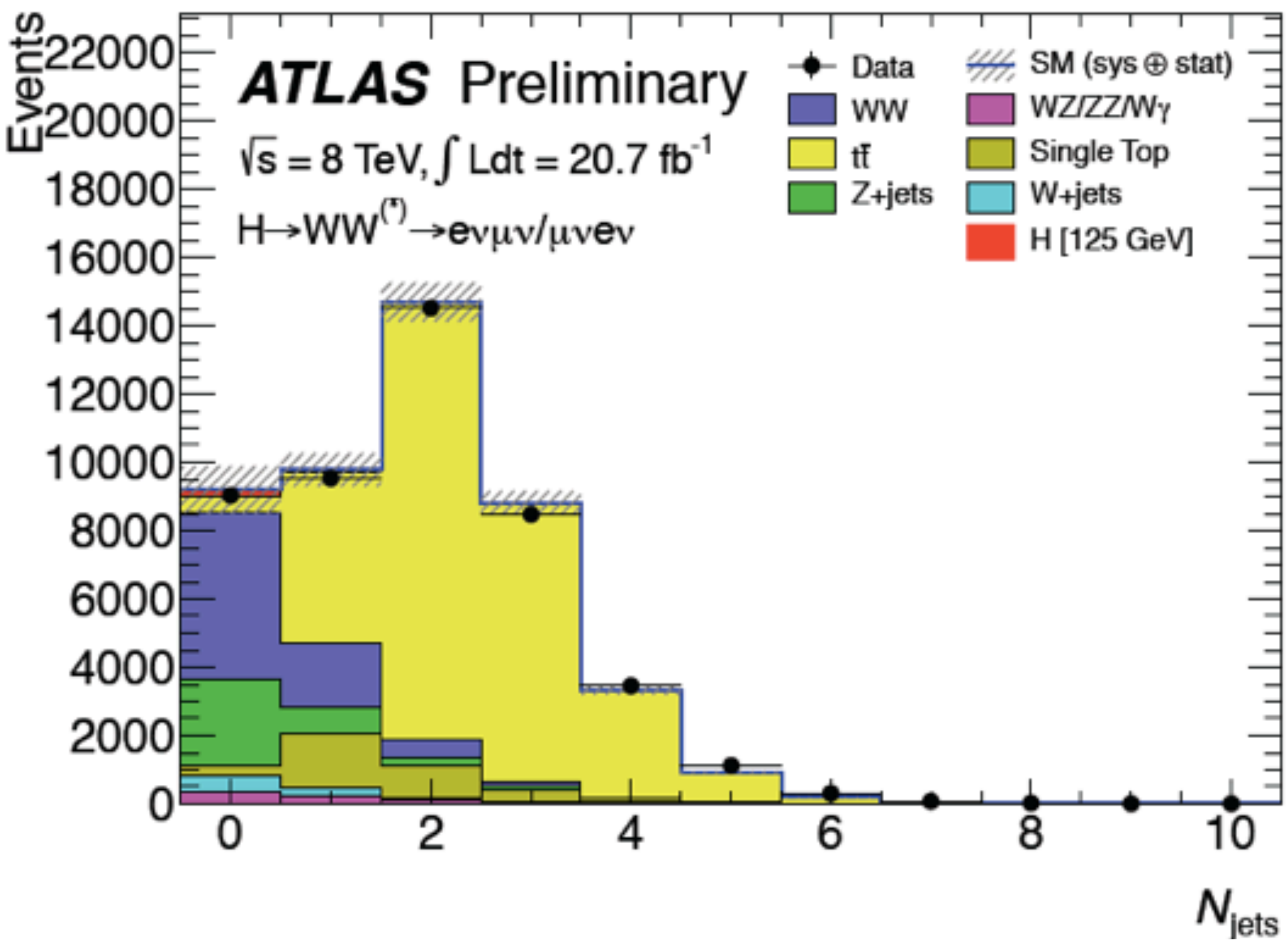
The lost generation





- Extremely difficult to access second-generation couplings at the LHC
- Only possible with high luminosity; only muon final-state considered by ATLAS/CMS so far
- Is an e^+e^- Higgs factory needed to access 2nd-generation quark couplings?

Exclusive jet bins

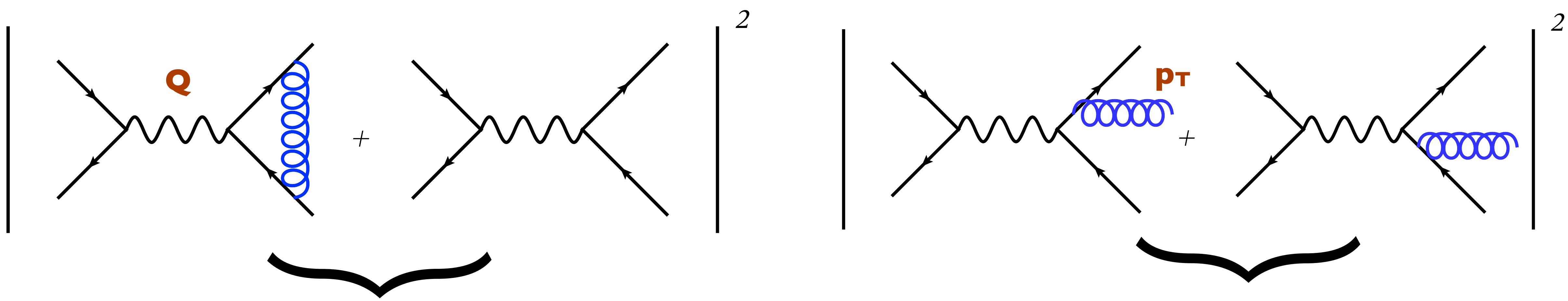


Category	$N_{jet}=0$	$N_{jet}=1$	$N_{jet}\geq 2$
Pre-selection	Two isolated leptons ($\ell = e, \mu$) with opposite charge Leptons with $p_T^{lead} > 25$ and $p_T^{sublead} > 15$ $e\mu + \mu e$: $m_{\ell\ell} > 10$ $ee + \mu\mu$: $m_{\ell\ell} > 12$, $\lvert m_{\ell\ell} - m_Z \rvert > 15$		
Missing transverse momentum and hadronic recoil	$e\mu + \mu e$: $E_{T,rel}^{miss} > 25$ $ee + \mu\mu$: $E_{T,rel}^{miss} > 45$ $ee + \mu\mu$: $p_{T,rel}^{miss} > 45$ $ee + \mu\mu$: $f_{recoil} < 0.05$	$e\mu + \mu e$: $E_{T,rel}^{miss} > 25$ $ee + \mu\mu$: $E_{T,rel}^{miss} > 45$ $ee + \mu\mu$: $p_{T,rel}^{miss} > 45$ $ee + \mu\mu$: $f_{recoil} < 0.2$	$e\mu + \mu e$: $E_{T}^{miss} > 20$ $ee + \mu\mu$: $E_{T}^{miss} > 45$ $ee + \mu\mu$: $E_{T,STVF}^{miss} > 35$ -
General selection	- $\lvert\Delta\phi_{\ell\ell,MET}\rvert > \pi/2$ $p_T^{\ell\ell} > 30$	$N_{b\text{-}jet} = 0$ - $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto	$N_{b\text{-}jet} = 0$ $p_T^{tot} < 45$ $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto

- Required experimentally in the WW channel due to the background composition
- Continuum WW production in the 0-jet bins; both WW and ttbar in the 1-jet bin; ttbar in the 2-jet bin
- Need different cuts as a function of jet multiplicity
- Typical jet-p_T choices: 25-30 GeV
- Similar divisions used in some ττ analyses

Why are jet vetoes dangerous?

- Imposing a jet veto leads to an interesting two-scale problem in QFT. Illustrate with simple example of $e^+e^- \to$ jets
- Infrared safety: must sum both virtual and real corrections



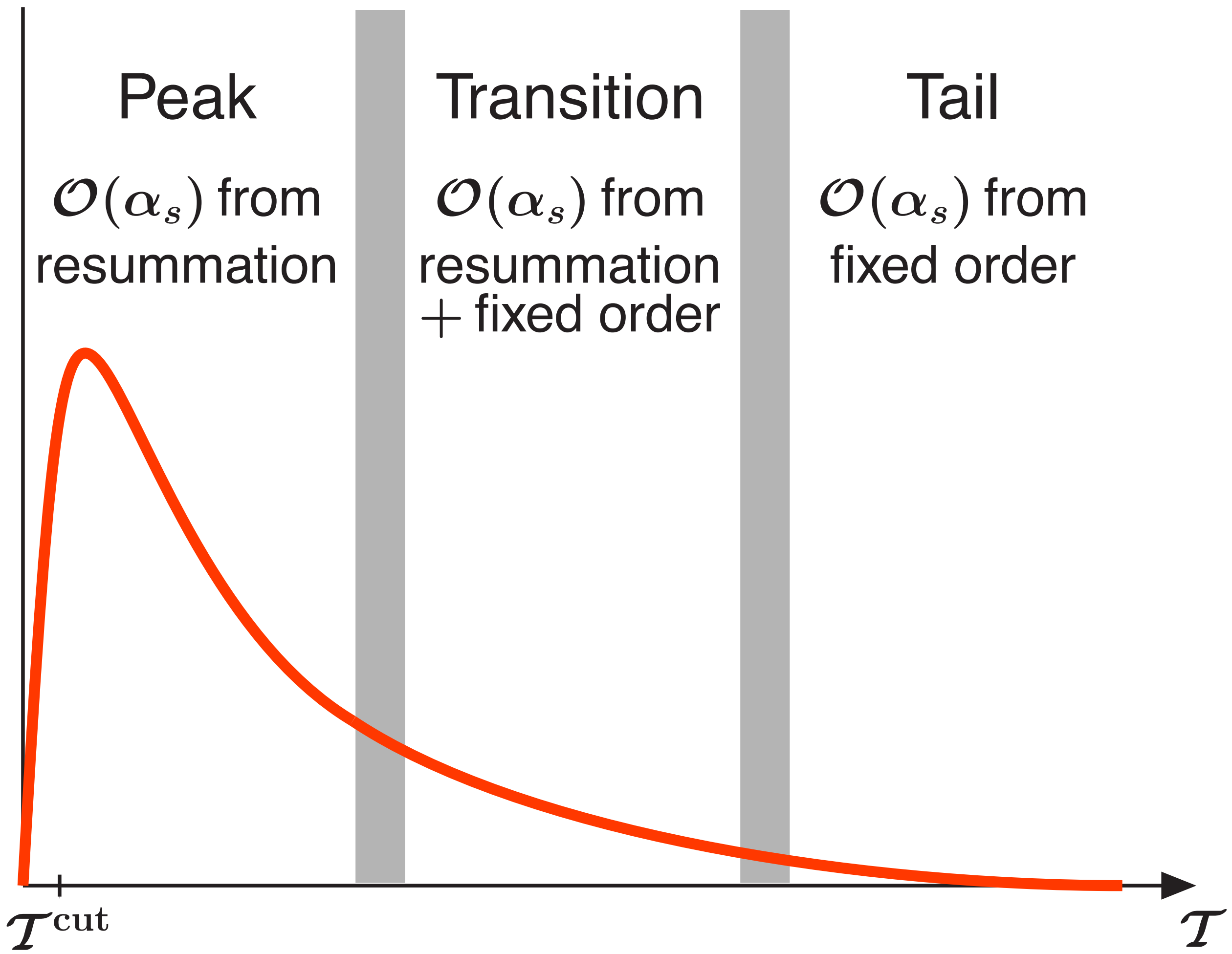
Virtual corrections: $-1/\varepsilon_{IR}^2$ Real corrections: $1/\varepsilon_{IR}^2 - a \times \ln^2(Q/p_{T,veto})$

- Incomplete cancellation of IR divergences in presence of final state restrictions gives logarithms of the restricted kinematic variable
- Relevant term for gluon-fusion Higgs searches:

$2C_A(\alpha_S/\pi)\ln^2(M_H/p_{T,veto}) \sim 1/2 \Rightarrow$ potentially a large correction

- $\alpha_S^n \ln^{2n}(M_H/p_{T,veto})$ appears at each order *n* in perturbation theory

The structure of the Higgs cross section



from arXiv:1211.7049

- Can identify three kinematic regions for a QCD prediction when a (dimensionless) variable τ is restricted
- Peak region: $\alpha_S \ln^2(\tau_{cut}) \gg 1$; perturbative expansion dominated by logarithms, predict using resummation
- Tail region: $\alpha_S \ln^2(\tau_{cut}) \ll 1$; logarithms not large, predict using standard fixed-order perturbation theory
- Transition region: $\alpha_S \ln^2(\tau_{cut}) \lesssim 1$; need progress on both resummation and fixed-order

- Higgs production at the LHC is in the most-difficult transition region; must consider both resummation and fixed-order results to describe this process
- Nature (or at least experimentalists) is unkind...

Zero-jet resummation

- Begin in the zero-jet bin. 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^3LL+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

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

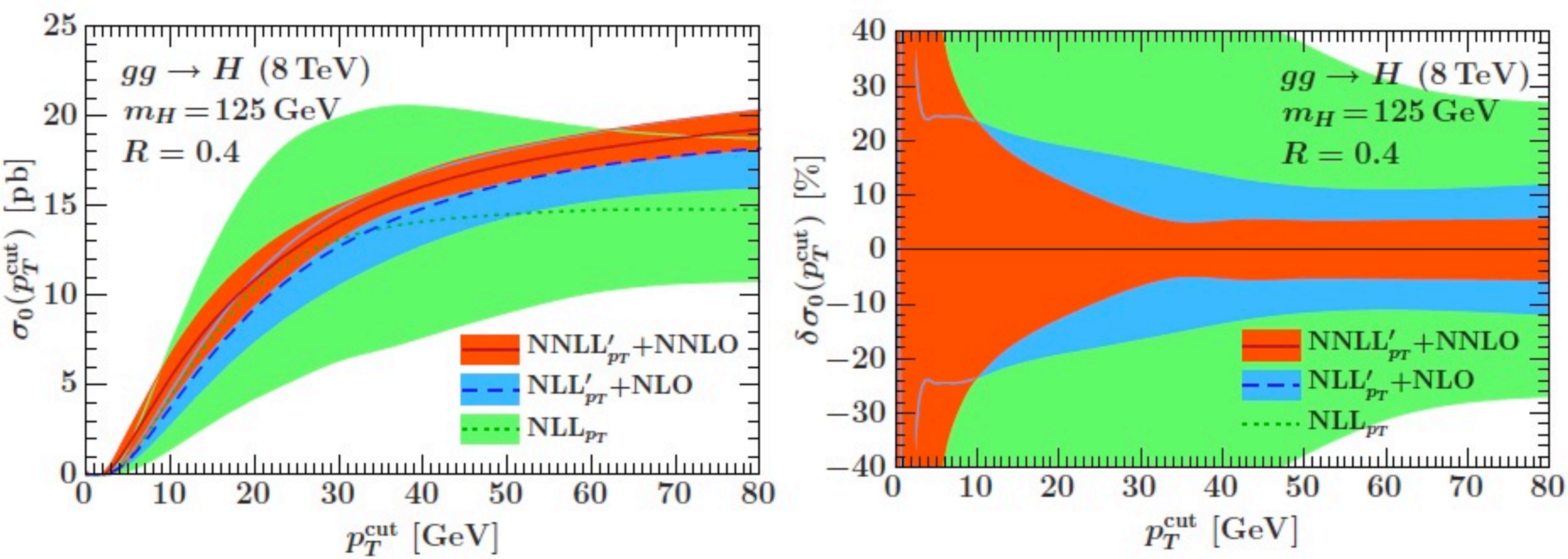
Global veto log structure

NNLL'+NNLO resummation

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

- Uses soft-collinear effective theory
- Significant improvement in prediction from including higher-order resummation and fixed-order
- Has not yet propagated into experimental studies

Including resummation and fixed-order uncertainties



Stewart, Tackmann, Walsh, Zuberi 1307.1808

NNLL+NNLO resummation

- 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.

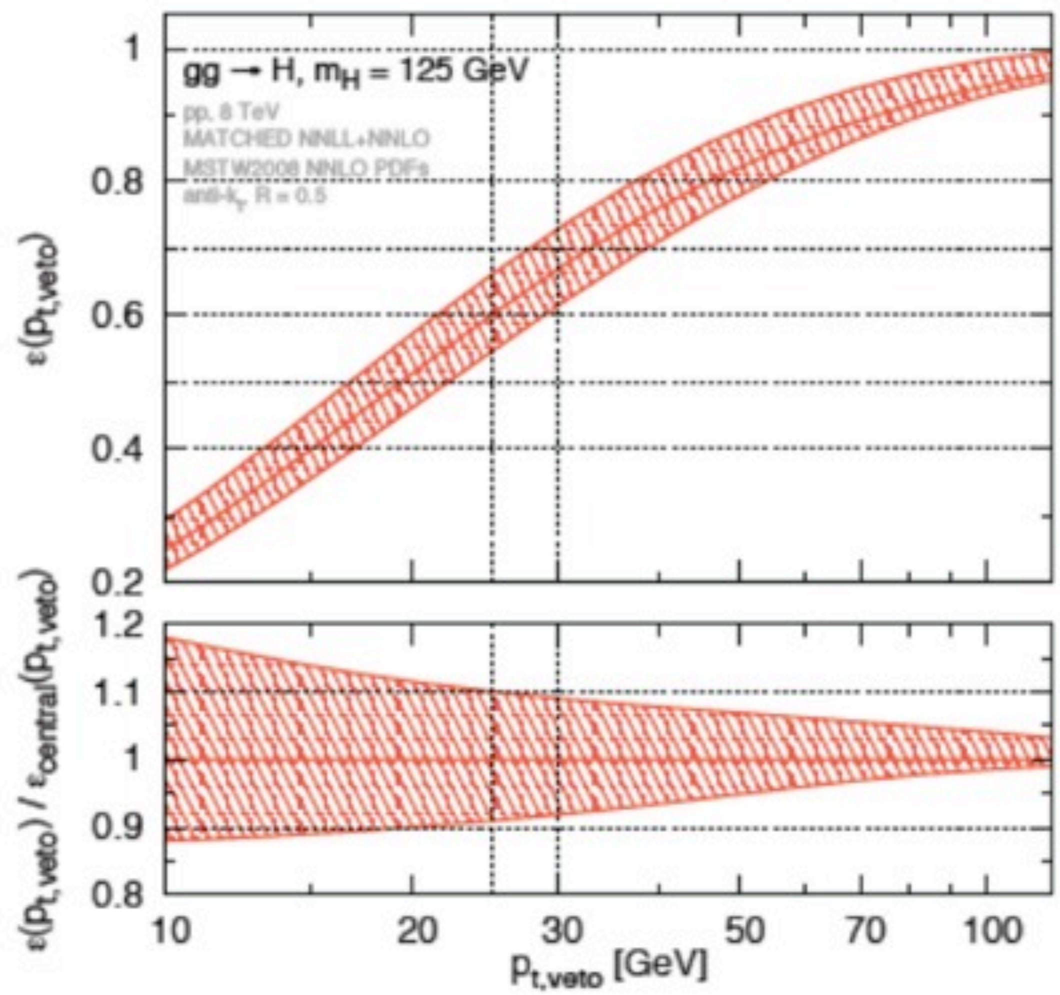
$$\ln \frac{M}{p_{t,\mathrm{veto}}} \to \ln \frac{Q}{p_{t,\mathrm{veto}}}$$

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

- Scheme (b) and (c) with

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

- Total uncertainty $\longleftrightarrow$ envelope



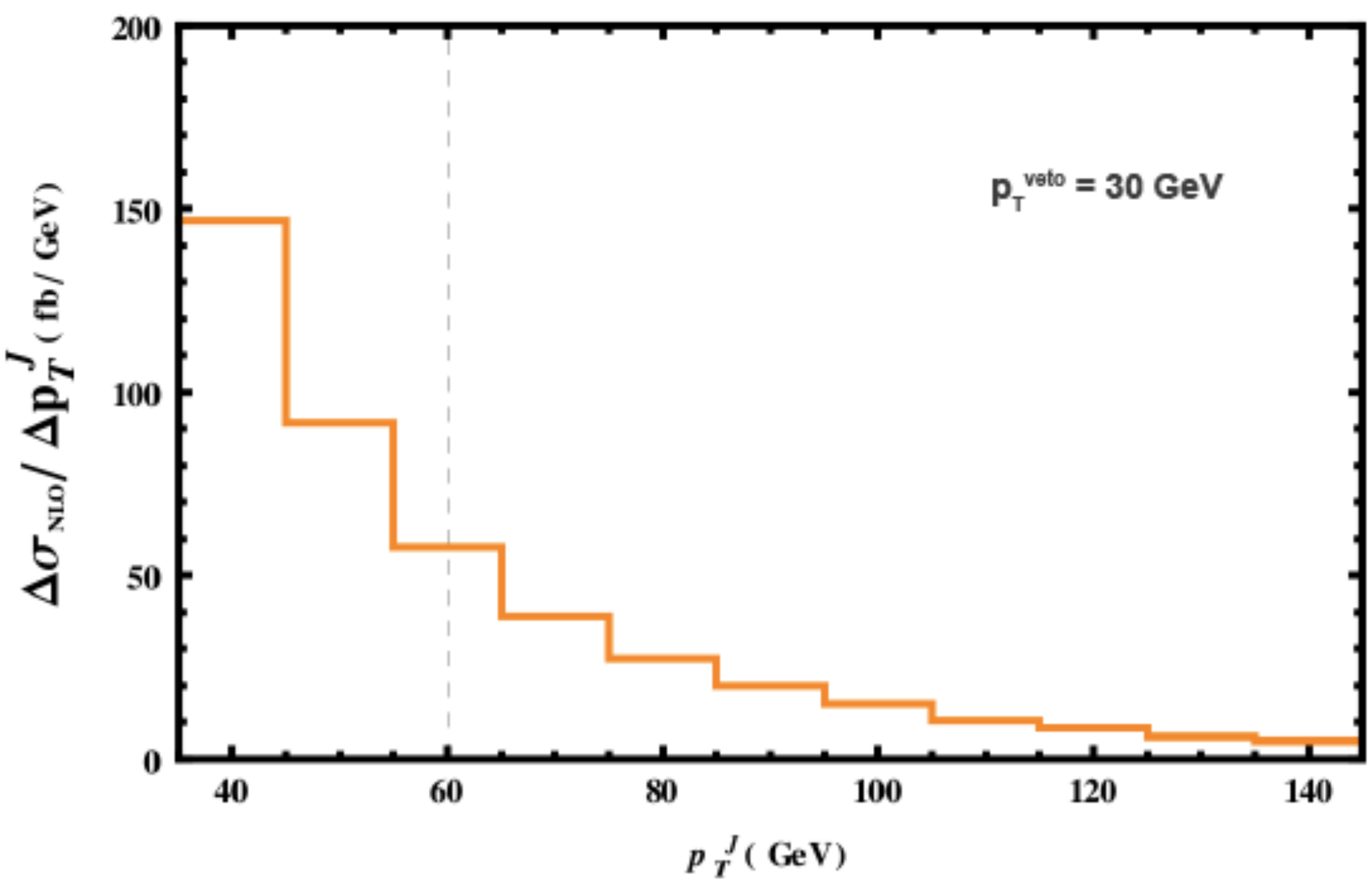
From P. Monni

Banfi, Monni, Salam, Zanderighi 1206.4998

•Very different theoretical approach, but similar results for uncertainty; reduced error estimates coming from the resummation program are robust

One-jet resummation

- Two relevant regions of jet p_T: $p_T \sim m_H >> p_{T,veto}$, $m_H >> p_T \sim p_{T,veto}$
- Currently can resum the first region at NLL'+NLO X. Liu, FP 1210.1906, 1303.4405

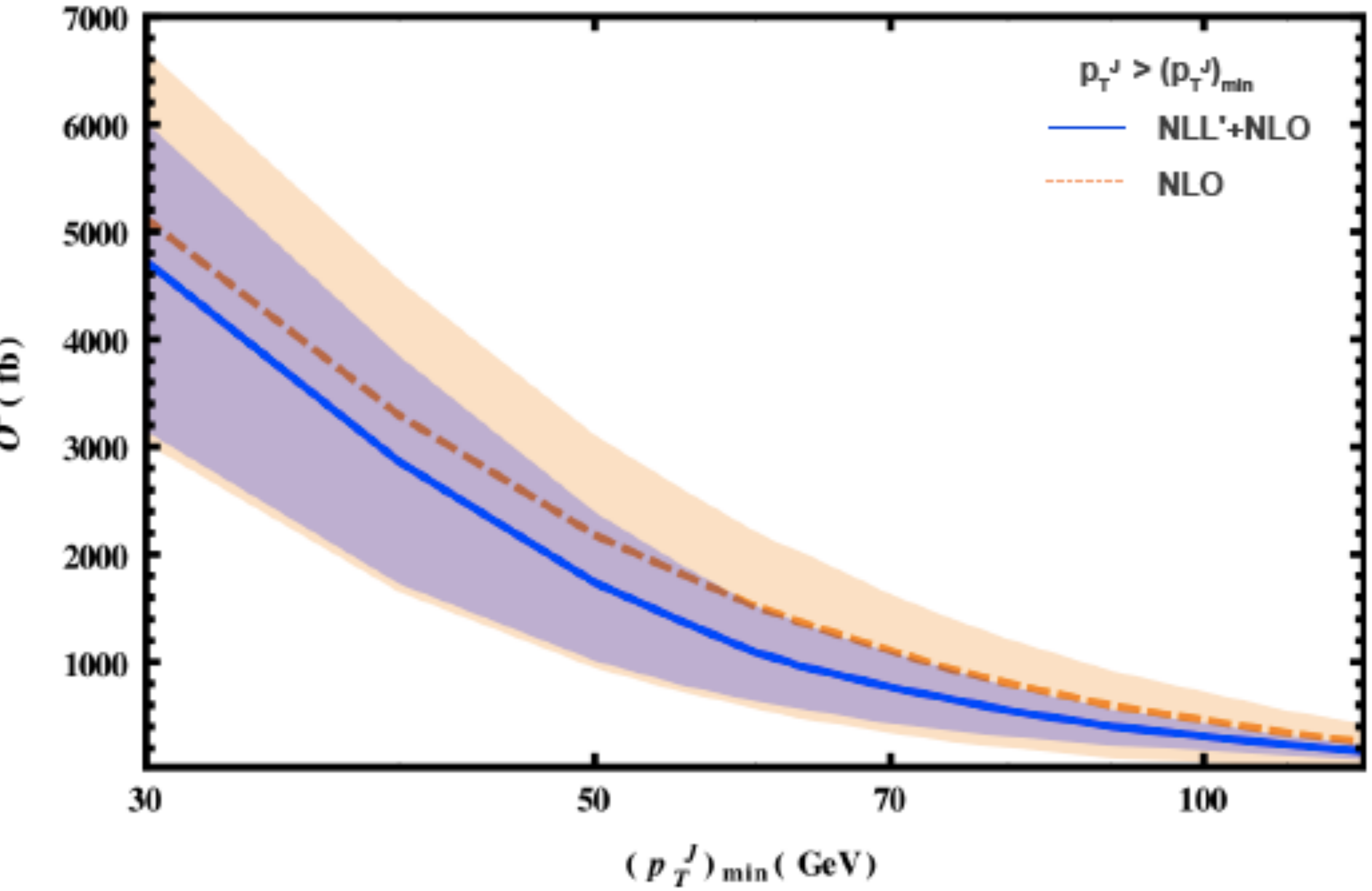


- Comprises roughly 30% of the event rate at the LHC, but roughly 50% of the error
- An improved treatment of this region can significantly reduce relevant errors in LHC analyses

NLO:	$\sigma(p_T^J > 30)(\text{pb})$	$\sigma(63 > p_T^J > 30)(\text{pb})$	$\sigma(p_T^J > 63)(\text{pb})$
$\mu = m_H/2$	$5.2^{+1.65}_{-2.12}$	$3.9^{+1.01}_{-0.95}$	$1.3^{+0.75}_{-1.30}$

Numerical results for the one-jet bin

- Integrate over entire p_T range used in the ATLAS measurement



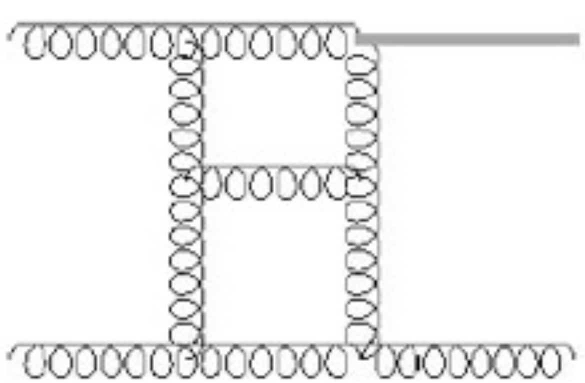
m_H (GeV)	p_T^{veto} (GeV)	$\sigma_{\rm NLO}$ (pb)	$\sigma_{\rm NLL'+NLO}$ (pb)	$f^{1j}_{\rm NLO}$	$f^{1j}_{\rm NLL'+NLO}$
124	25	$5.92^{+35\%}_{-46\%}$	$5.62^{+29\%}_{-30\%}$	$0.299^{+38\%}_{-49\%}$	$0.283^{+33\%}_{-34\%}$
125	25	$5.85^{+34\%}_{-46\%}$	$5.55^{+29\%}_{-30\%}$	$0.300^{+37\%}_{-49\%}$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

- Large uncertainty from the high-p_T region makes this resummation very effective in reducing errors in the one-jet bin
- Very conservatively (turn off resummation at $p_{T,J}=m_H/2$), error on 1-jet bin result is decreased by 25% relative to fixed-order
- Has not yet propagated into the experimental studies

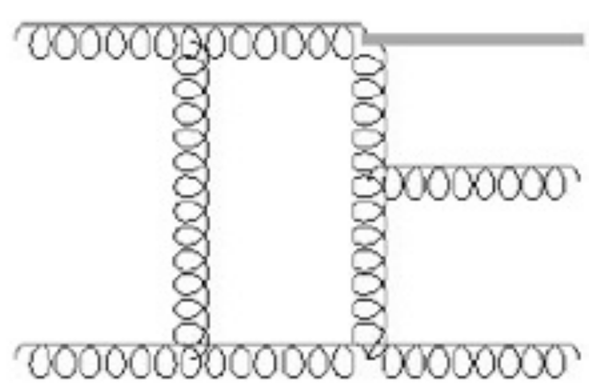
X. Liu, FP 1210.1906, 1303.4405

Higgs plus one-jet @NNLO

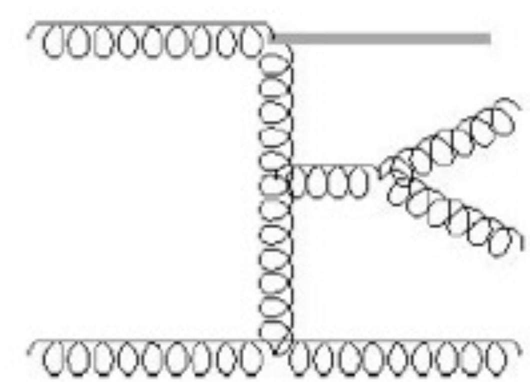
- Higgs plus zero-jets known in fixed-order through NNLO
- Until recently, Higgs plus one-jet known only through NLO
- The following ingredients are needed for H+1-jet @NNLO:



Gehrmann, Jaquier, Glover, Koukoutsakis (2011)



Badger, Glover, Mastrolia, Williams (2009)

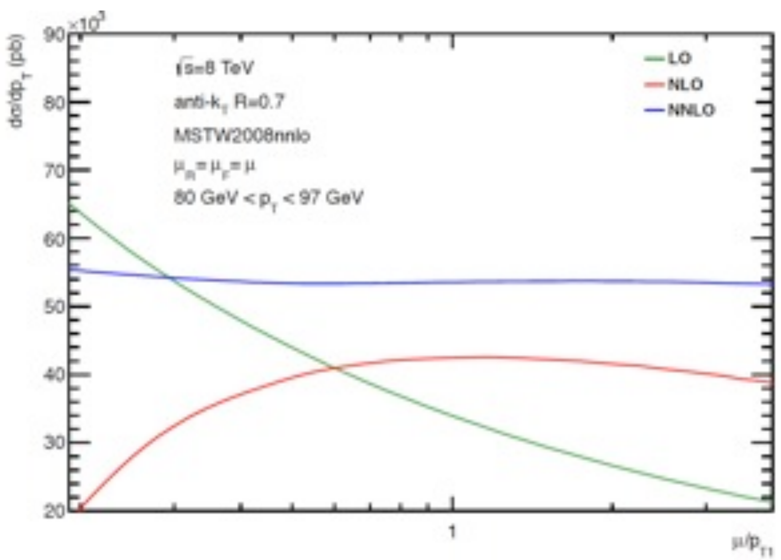


Del Duca, Frizzo, Maltoni;
Dixon, Glover, Khoze (2004)

- All ingredients were available, some even for a while; what prevented 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 radiation
- A generic procedure to extract IR singularities from RR and RV before phase-space integration was unknown until very recently

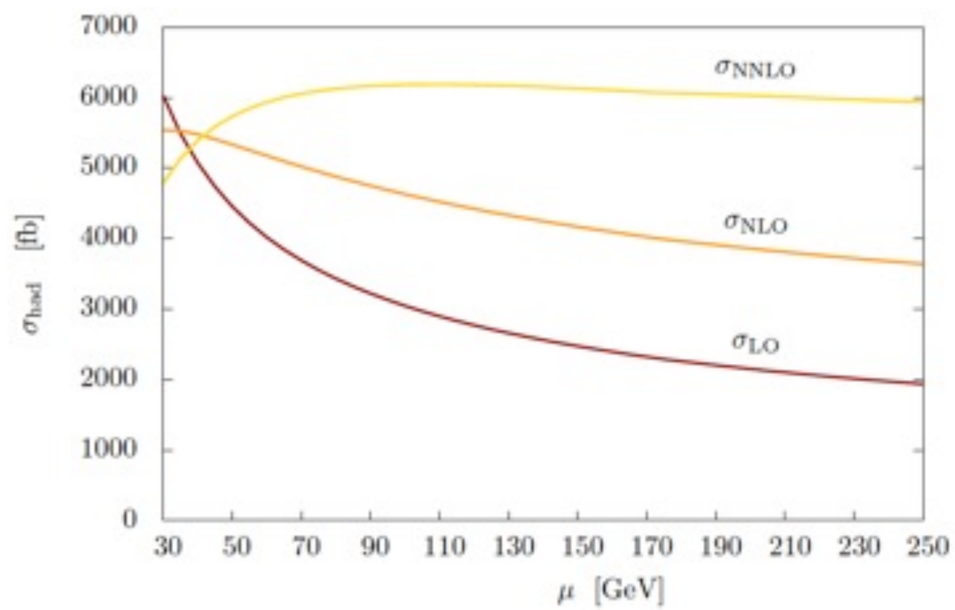
NNLO QCD at the LHC

- 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



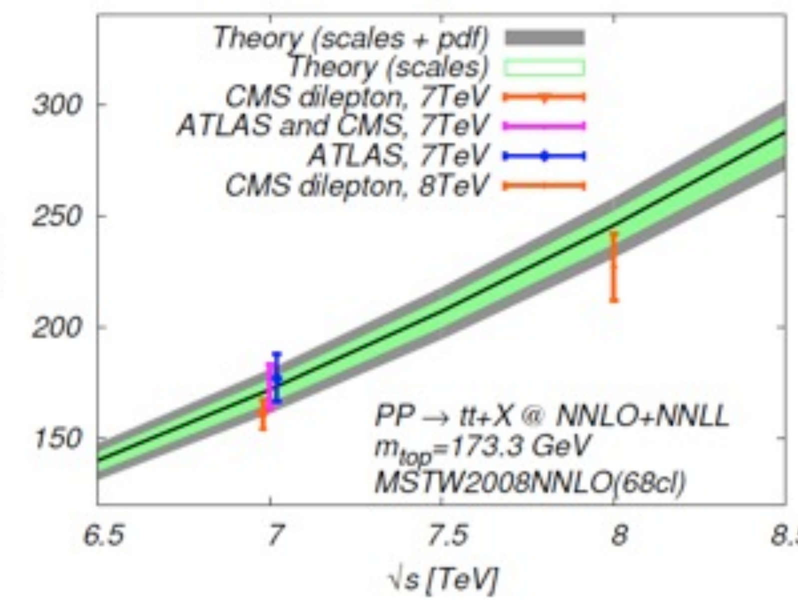
Gehrmann-de Ridder, Gehrmann, Glover, Pires (2013)

dijet: gg-channel



Boughezal, Caola, Melnikov, FP, Schulze (2013)

H+1j:gg-channel



Czakon, Fiedler, Mitov (2013)

ttbar: all-channels

Based on Antenna subtraction scheme

Based on sector-improved subtraction scheme

NNLO QCD at the LHC

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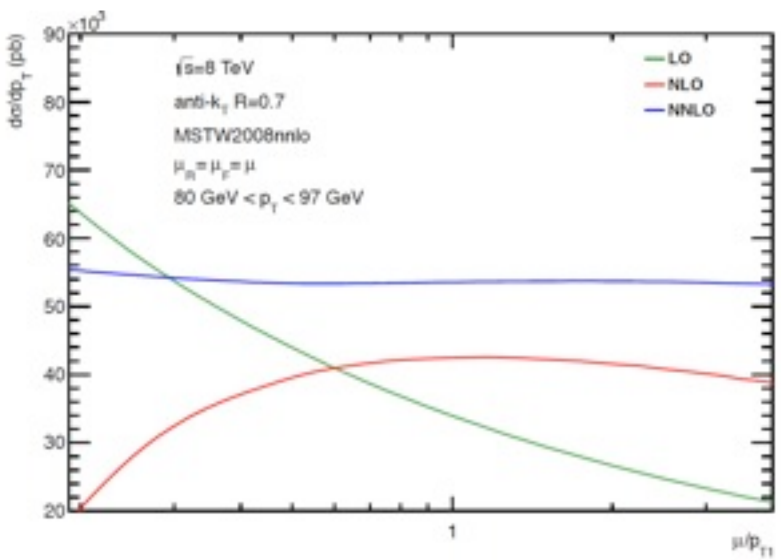

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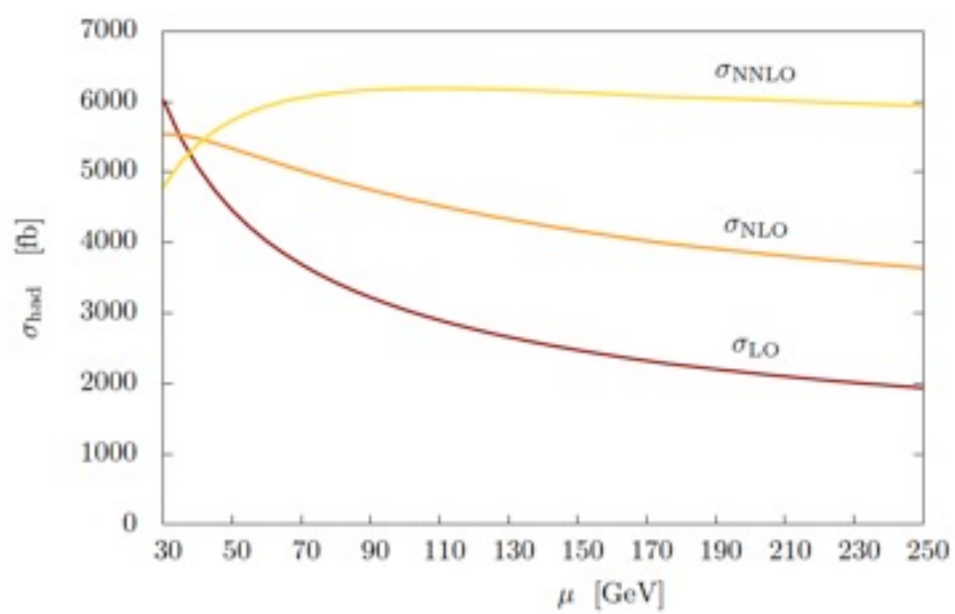
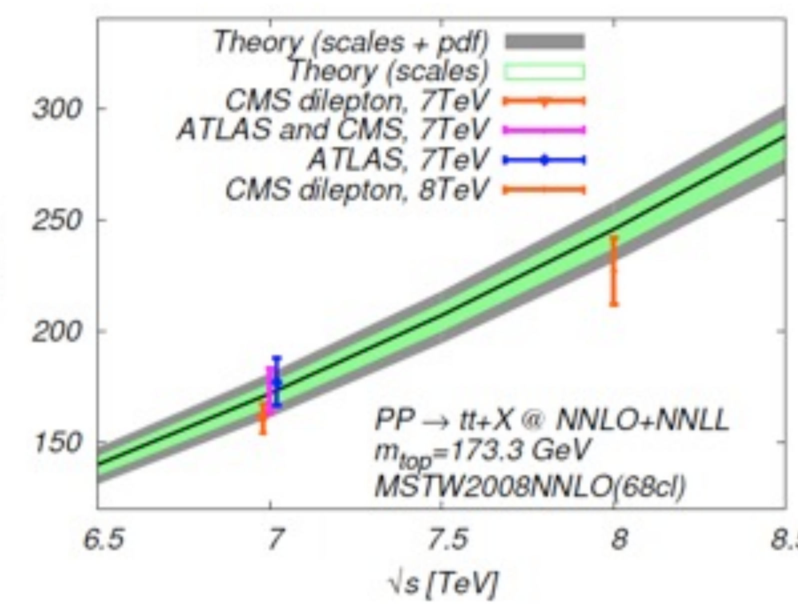


Boughezal, Caola, Melnikov, FP, Schulze (2013)

H+1j:gg-channel



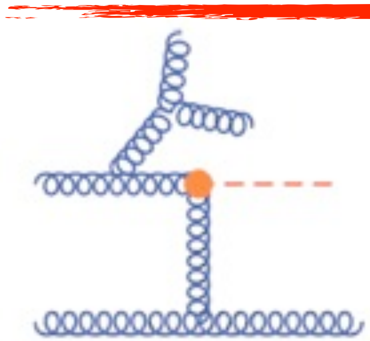
Czakon, Fiedler, Mitov (2013)

ttbar: all-channels

- 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

Singularity structure of H+jet

- Complicated singularity structure, in particular **three collinear directions:**



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

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

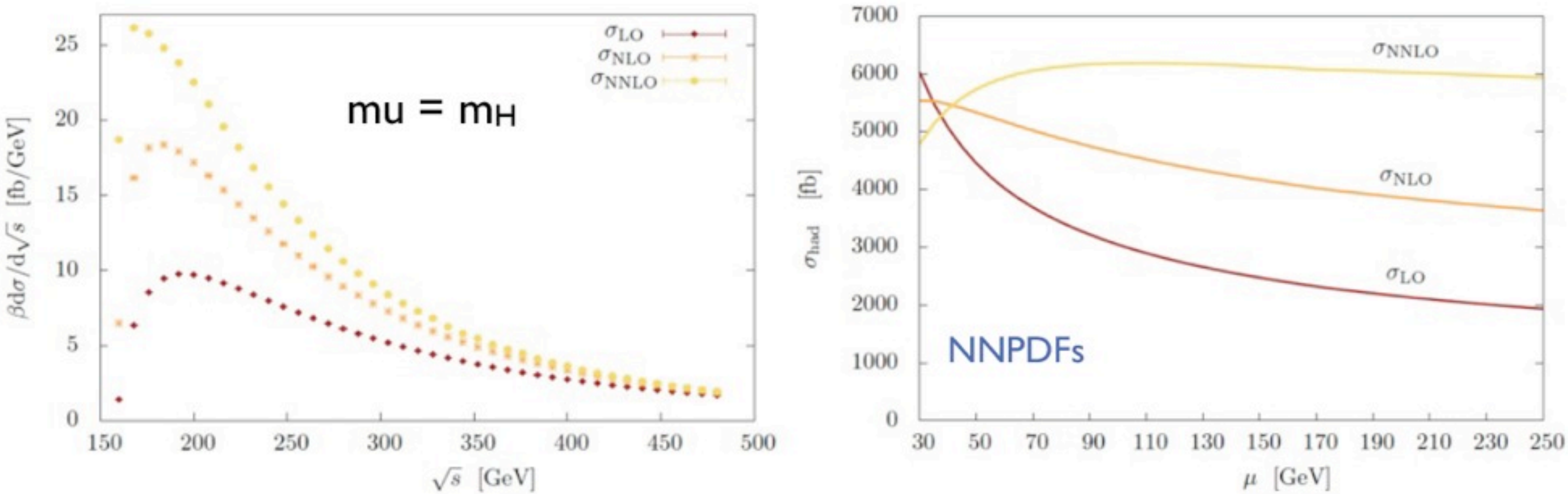
170 different subtraction terms had to be implemented for gg →H g!

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

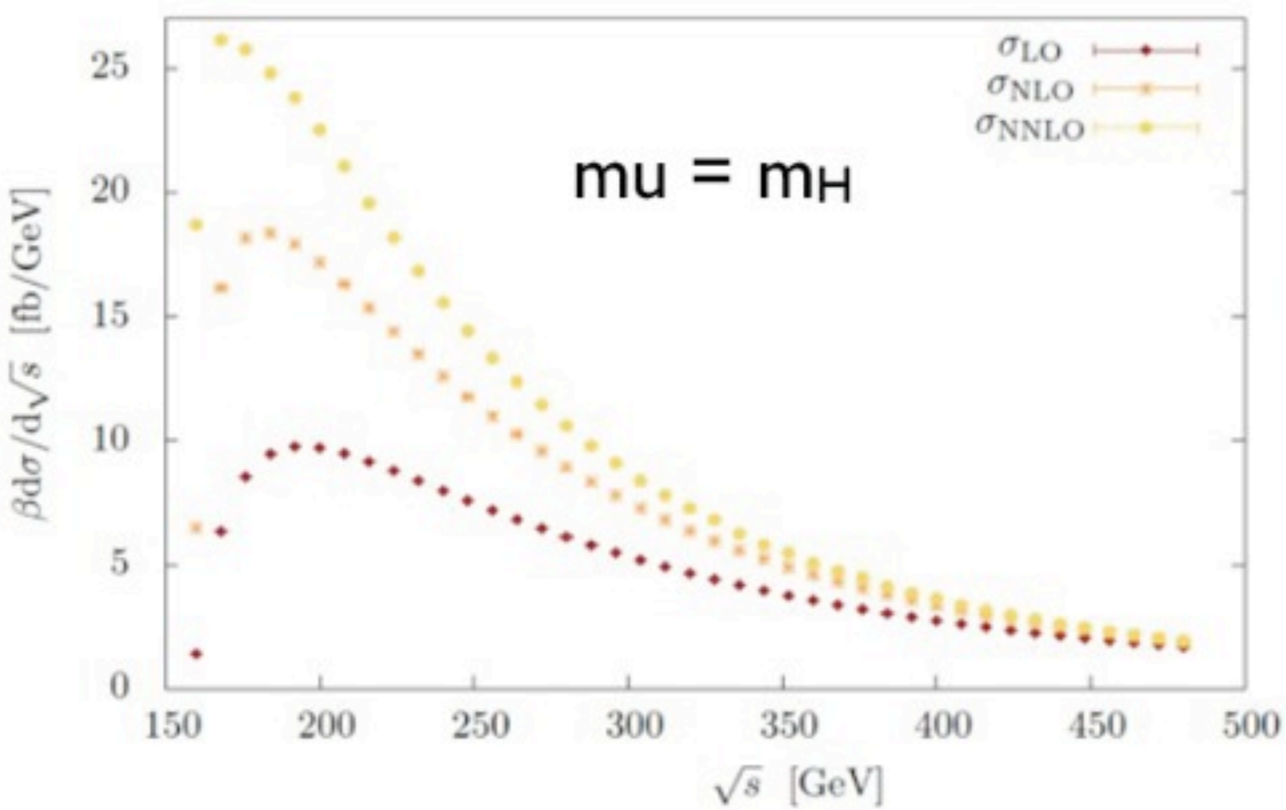
Numerical results (gg only)

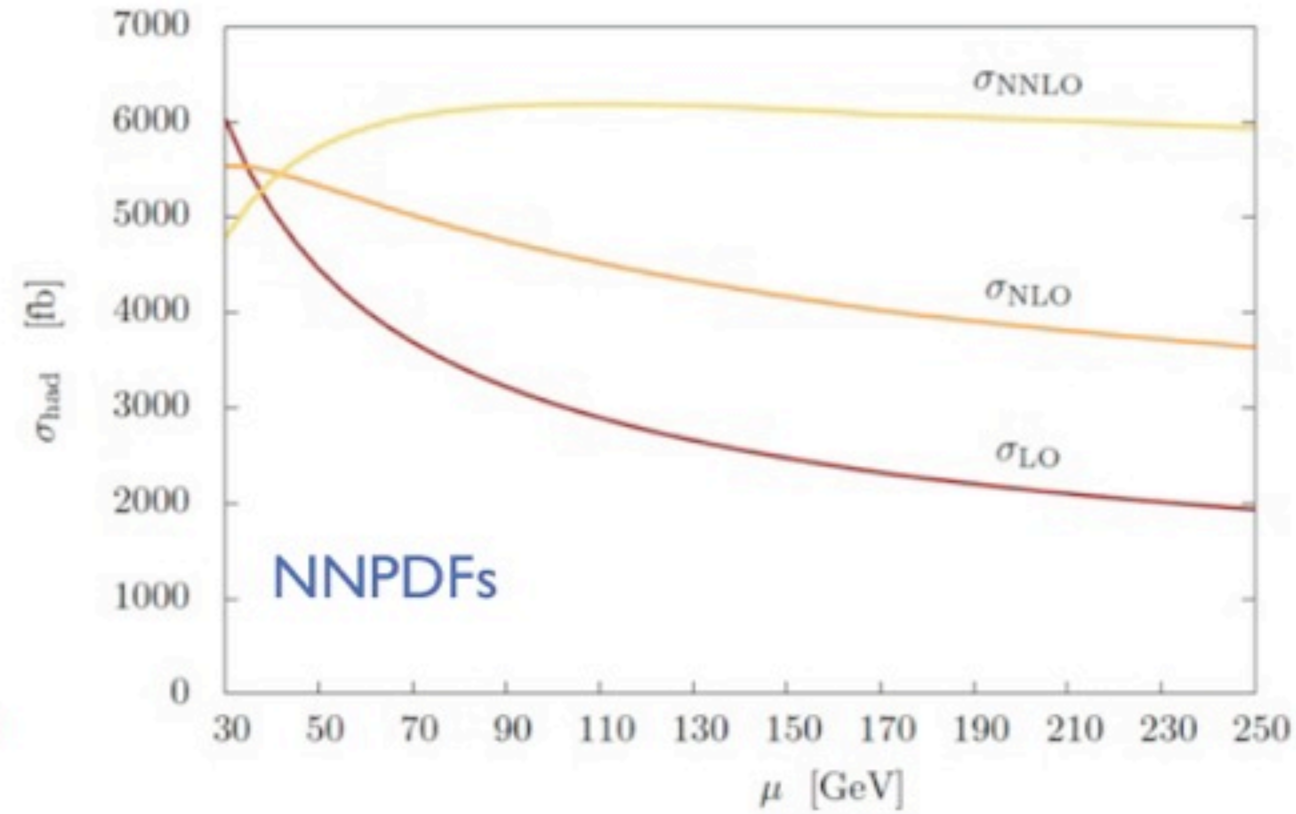


Boughezal, Caola, Melnikov, FP, Schulze 1302.6216

- 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

Numerical results (gg only)





Boughezal, Caola, Melnikov, FP, Schulze 1302.6216

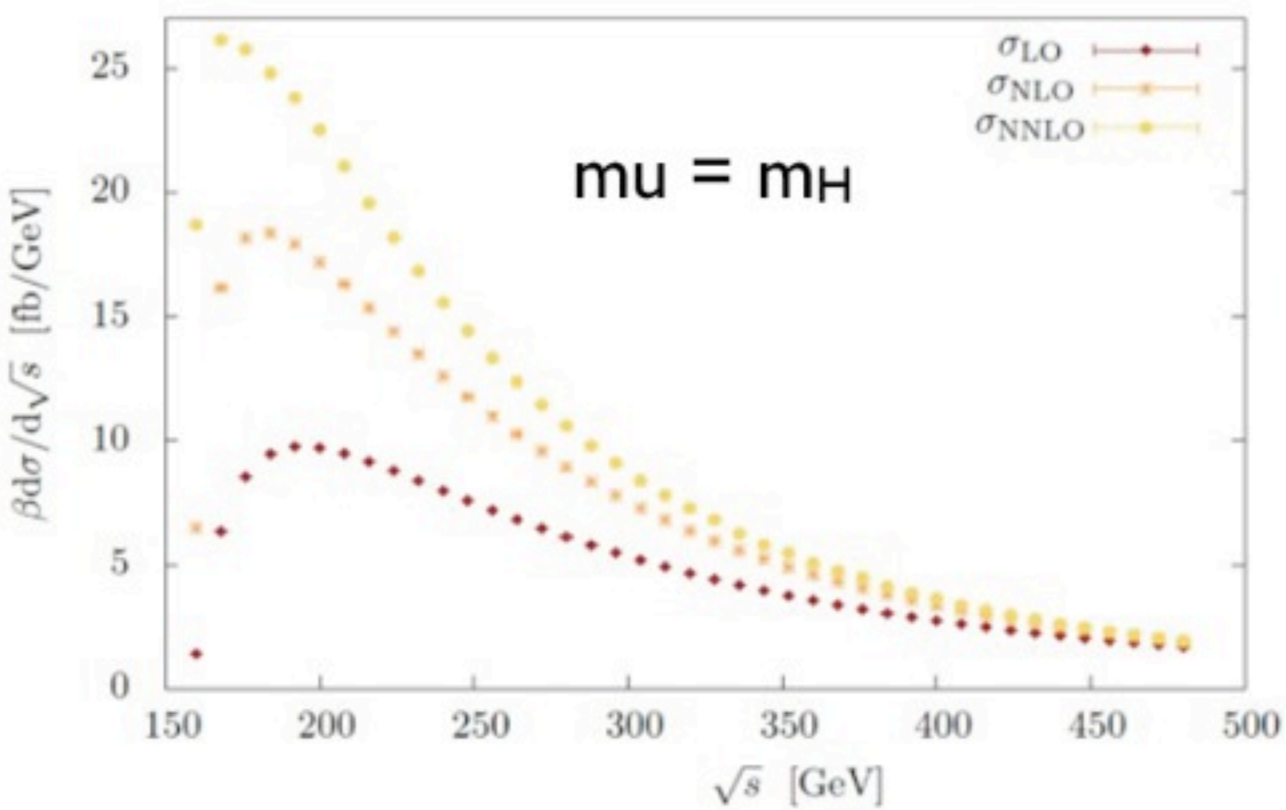
Significantly reduced scale dependence O(4%)

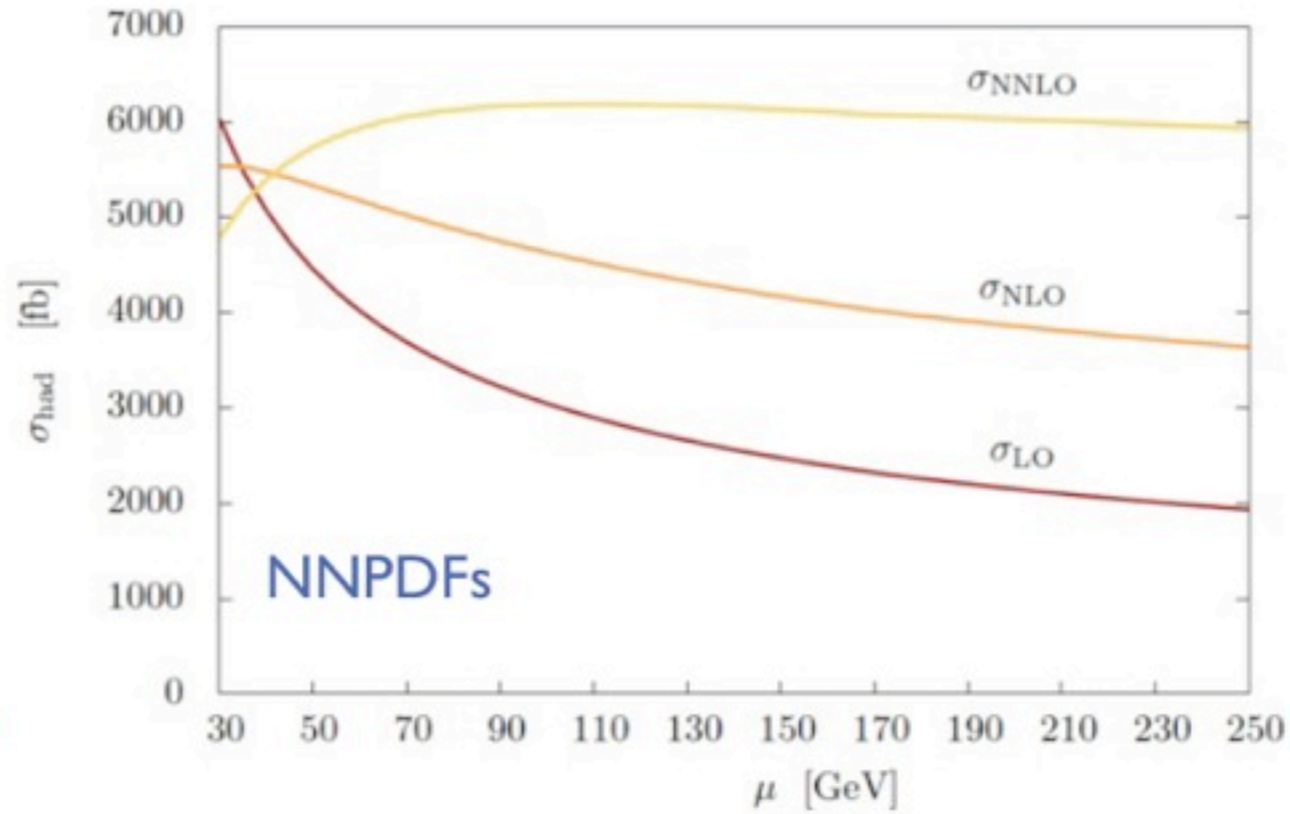
$\sigma_{NLO}/\sigma_{LO} = 1.6$

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

Large K-factor

Numerical results (gg only)



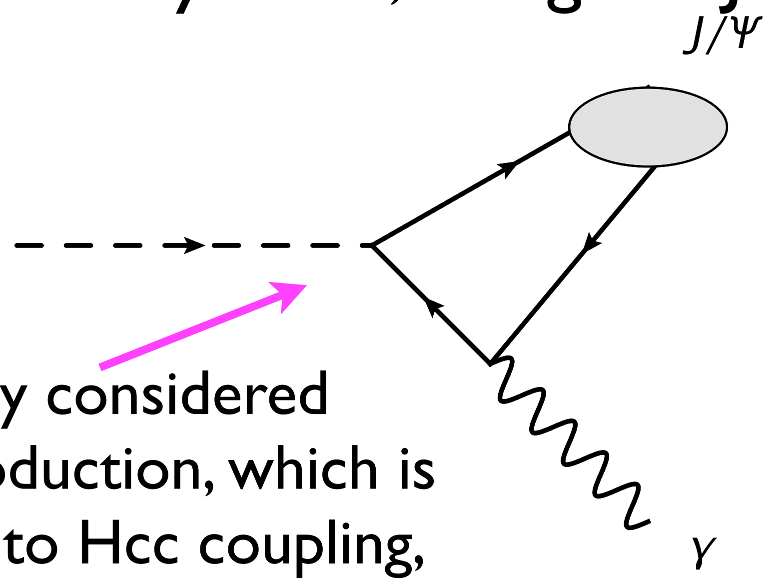


Boughezal, Caola, Melnikov, FP, Schulze 1302.6216

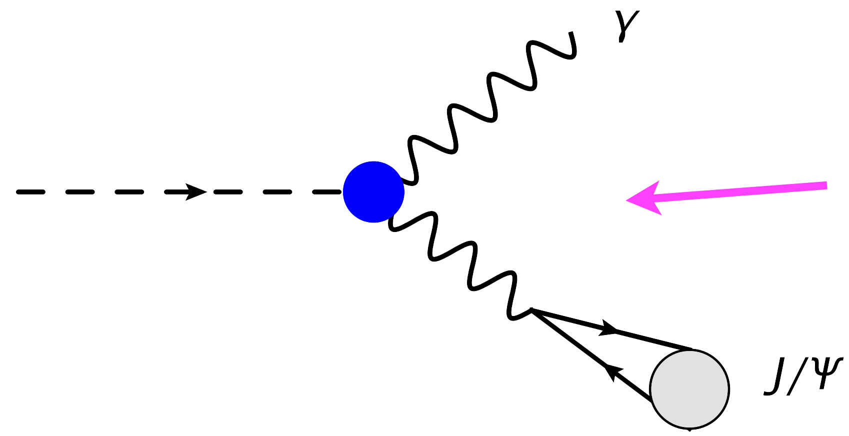
- gg-channel is the dominant one for phenomenological studies: at NLO gg (70%), qg(30%)
- quark channels necessary for achieving the relevant precision: ongoing work

Measuring the Hcc coupling

- Can we measure second-generation quark couplings at the LHC?
- Recent result: it may be possible to measure the hcc coupling at a high-luminosity LHC, using h→J/Ψ+γ Bodwin, FP, Stoynev, Velasco 1306.5770

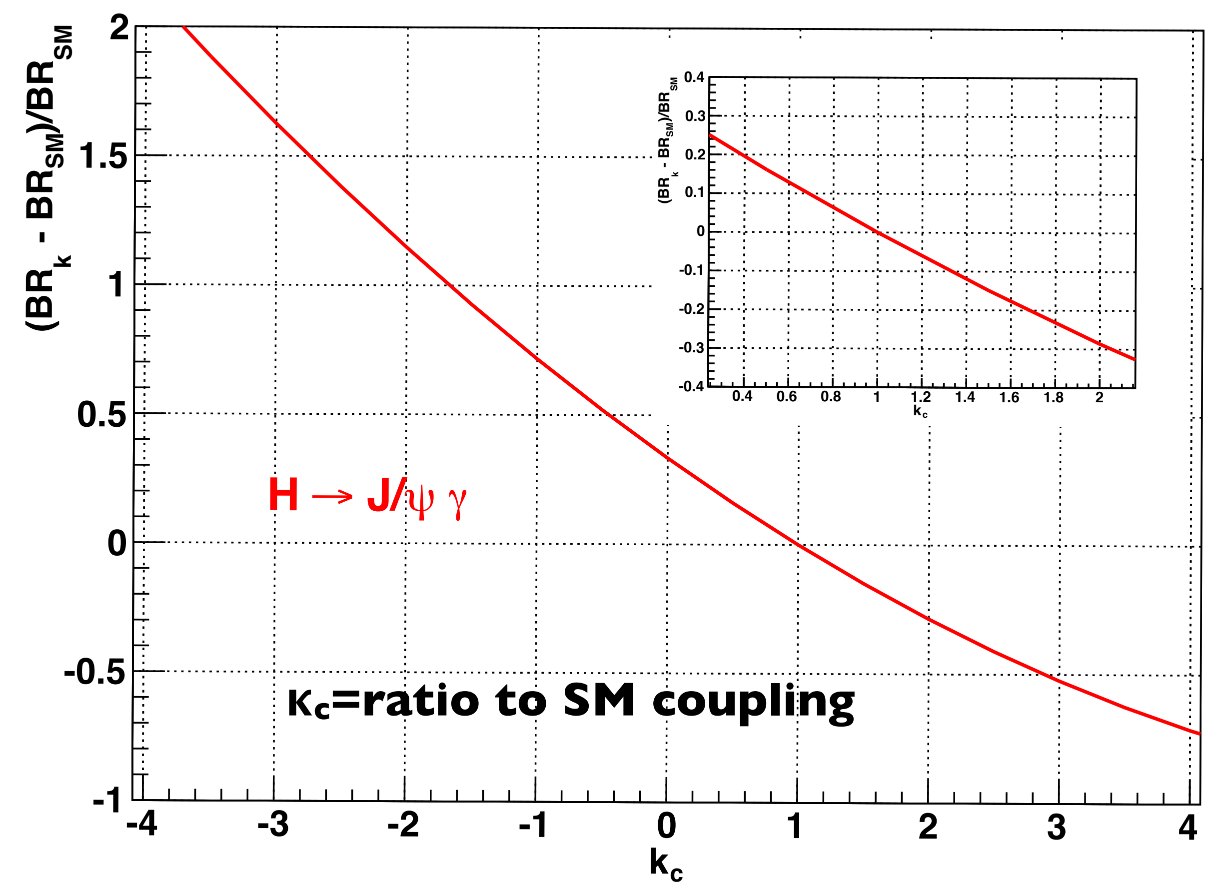


previously considered *direct* production, which is sensitive to Hcc coupling, is small



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
- Very sensitive to BSM deviations!
- Also have h→Υ(1S)+γ decay mode; sensitive to sign of hbb coupling, unlike other hbb measurements



Conclusions

- Theory errors are beginning to limit our understanding of the underlying theory describing the Higgs. This will become more urgent with the increased data from a 14 TeV run.
- Progress needed on two fronts to understand Higgs+jets
  - New resummations at NNLL'+NNLO (H+0-jets) and NLL'+NLO (H+1-jet) will improve predictions in the WW channel
  - Initial results available for H+1-jet @NNLO
- Notoriously difficult to measure 2nd-generation couplings at the LHC. New results indicate $H \rightarrow J/\Psi + \gamma$ might provide access to the Hccbar coupling.
- Looking forward to the 14 TeV data!