New results for Higgs production in association with a jet

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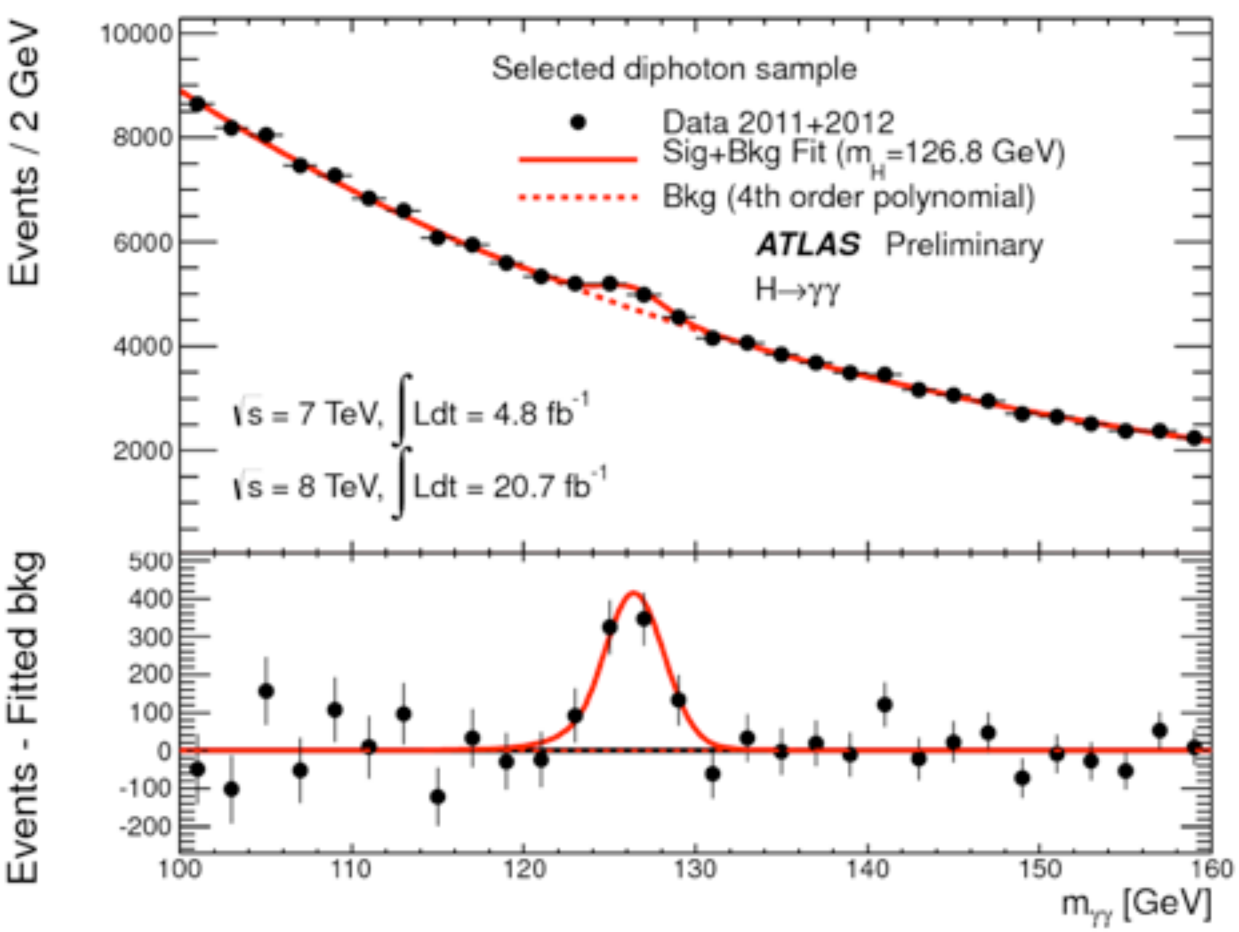
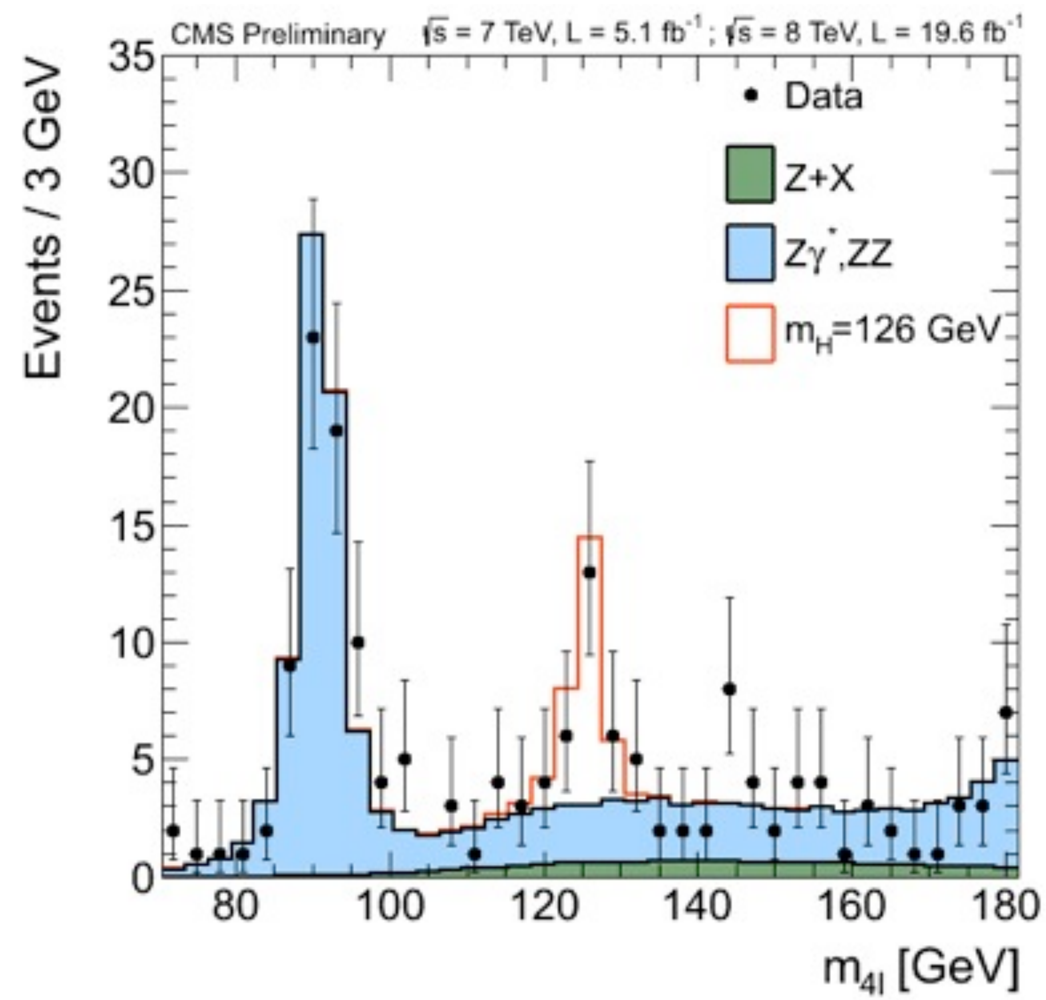
The Higgs discovery

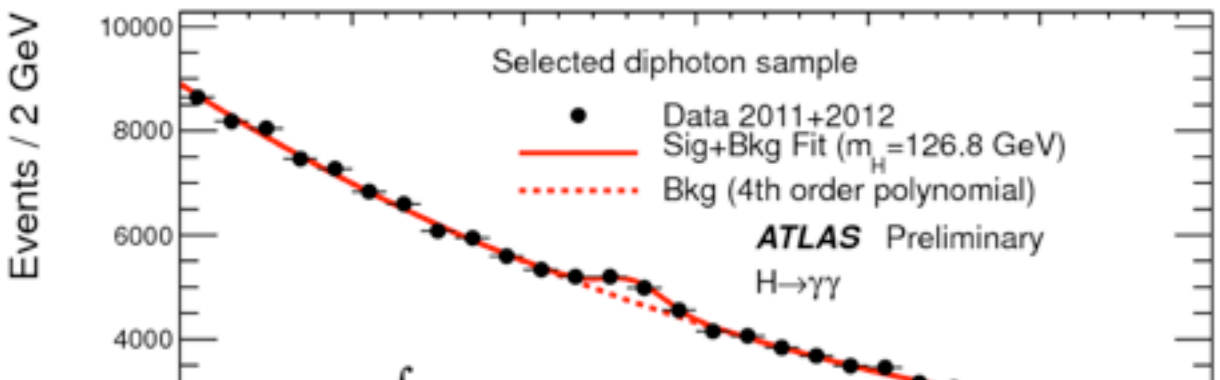
- Roughly a year ago (July 4th, 2012): ATLAS and CMS discovered a bump at 125.5 GeV

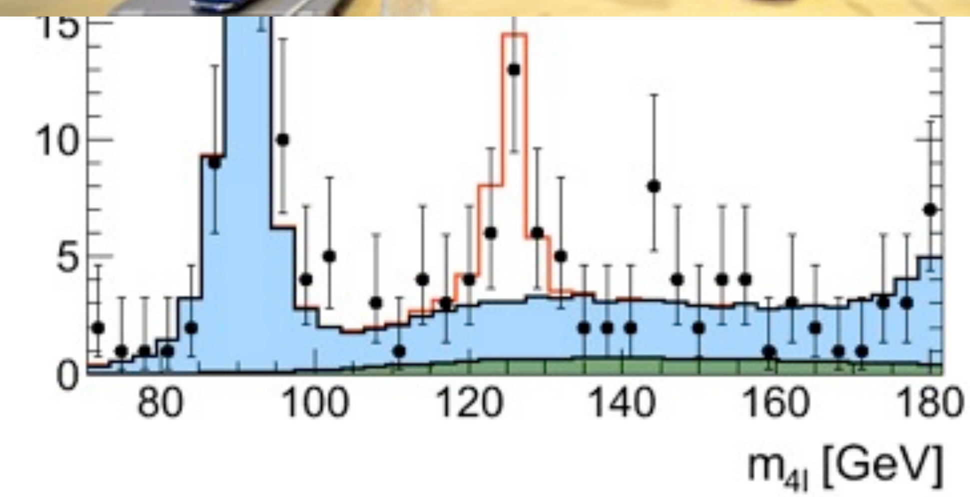




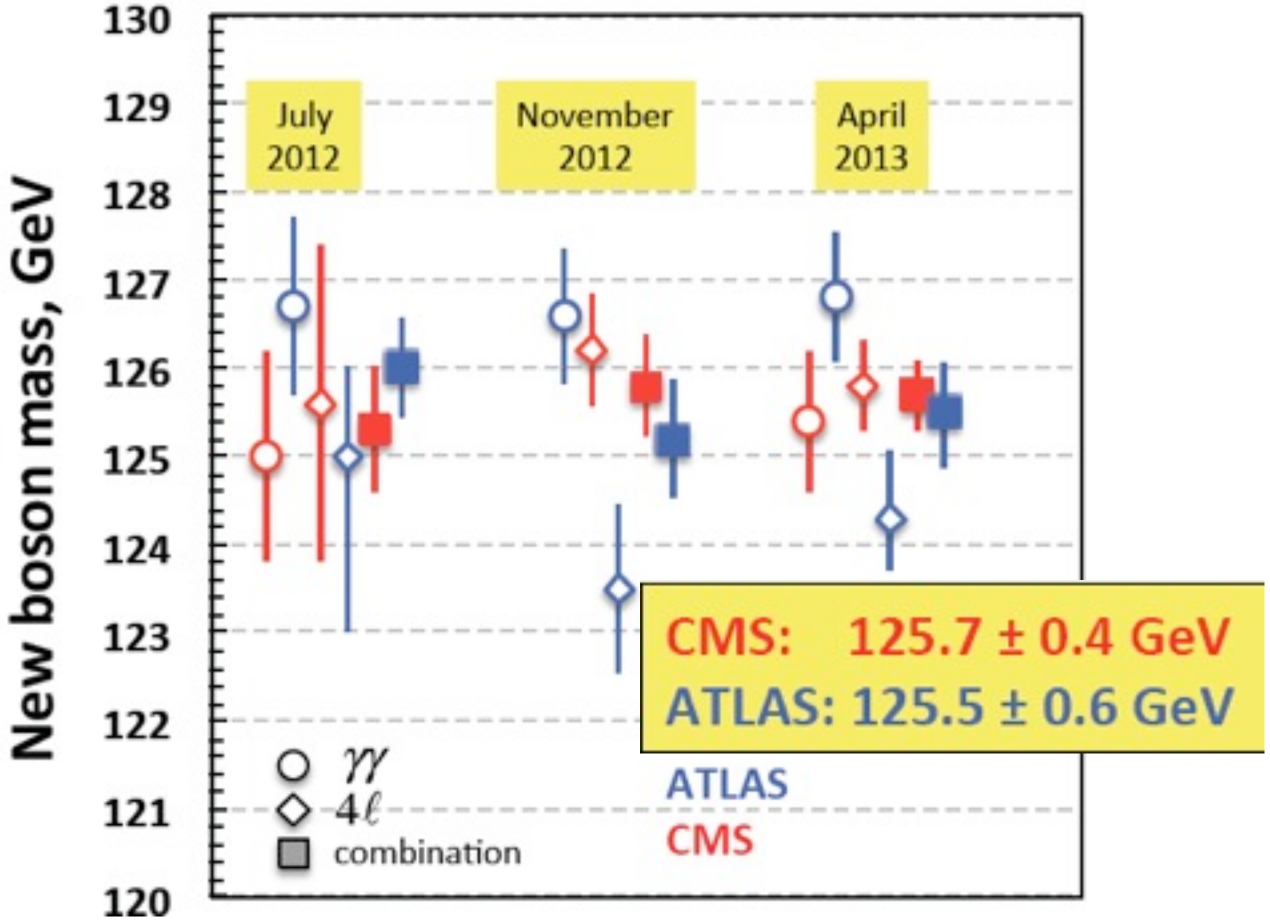
The Higgs discovery

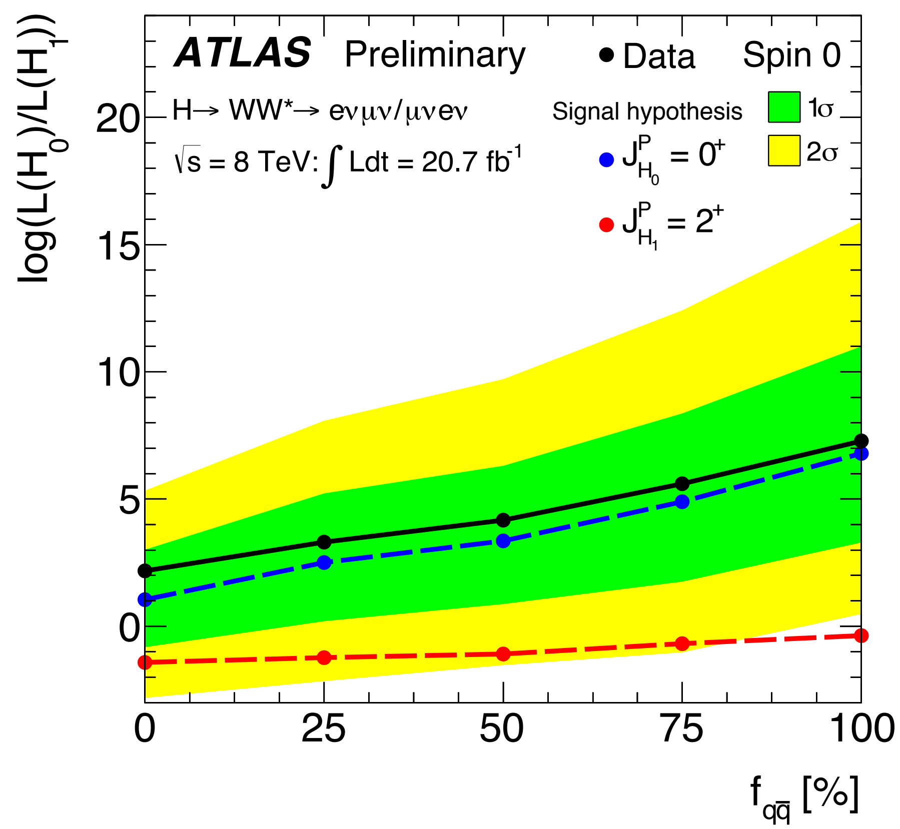
- Roughly a year ago (July 4th, 2012): ATLAS and CMS discovered a bump at 12

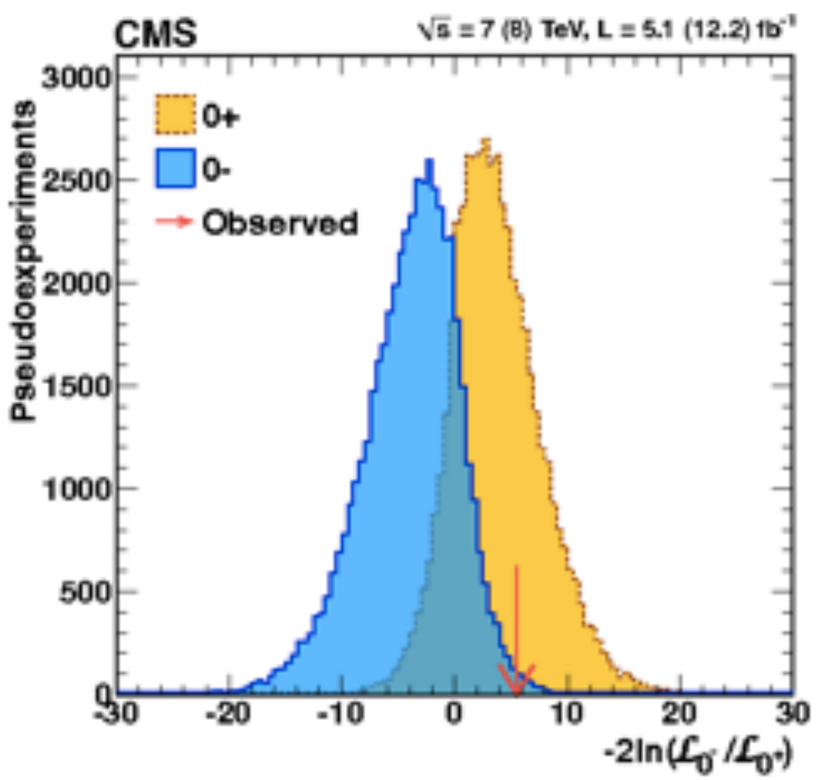




How fast things change





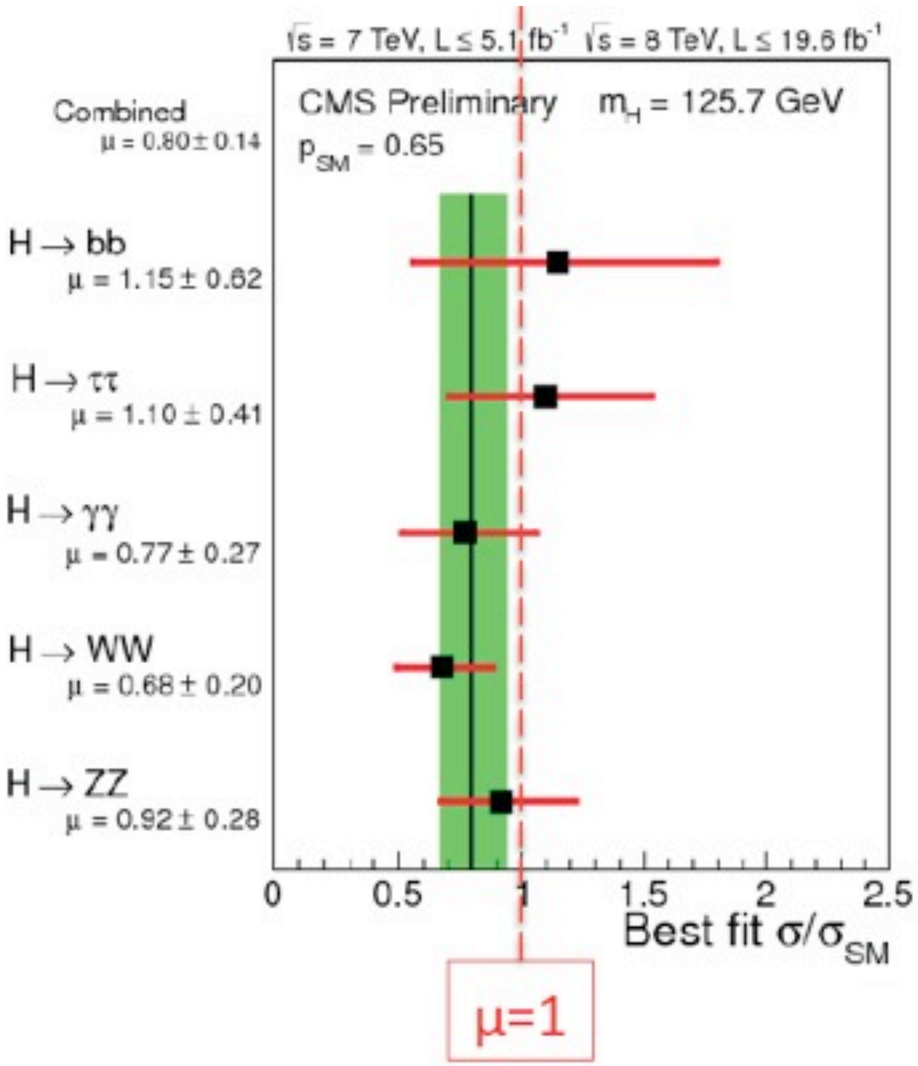


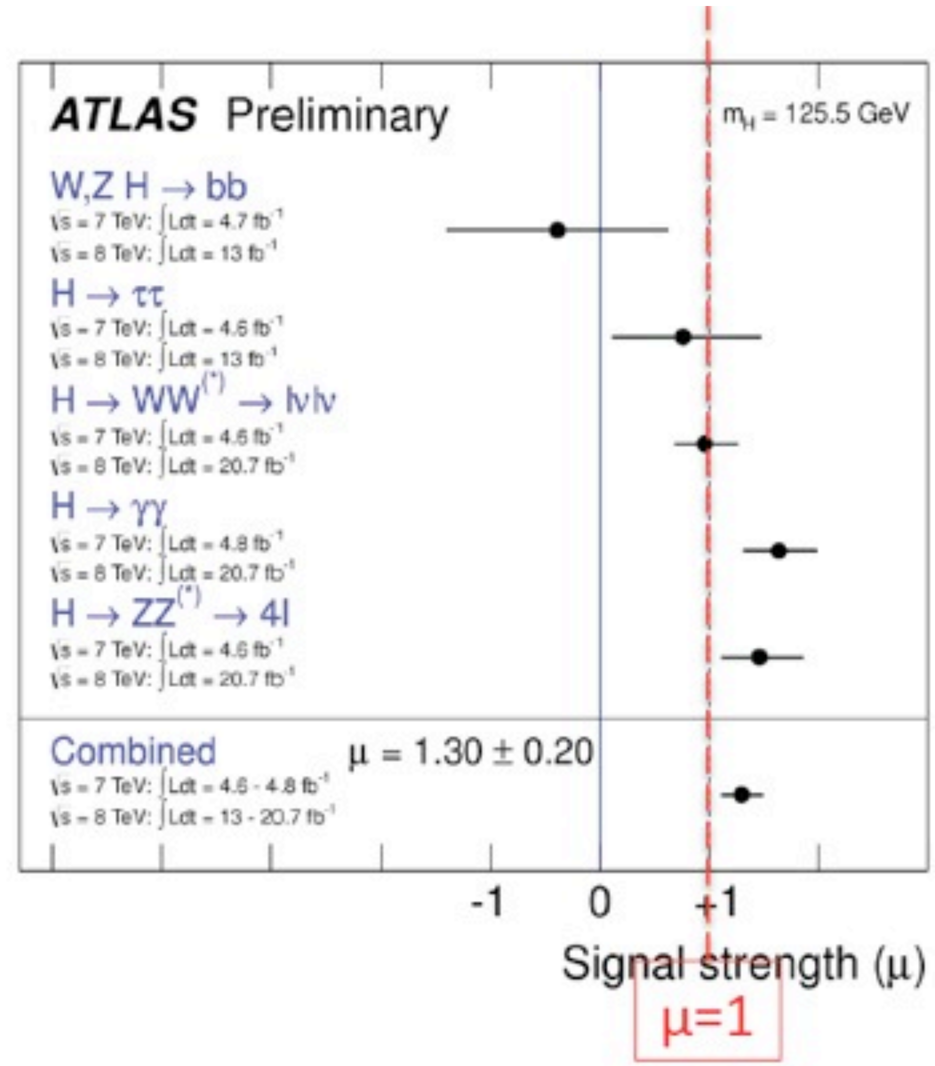
Higgs mass: a new precision parameter of SM

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

How fast things change

- Great progress on signal strength





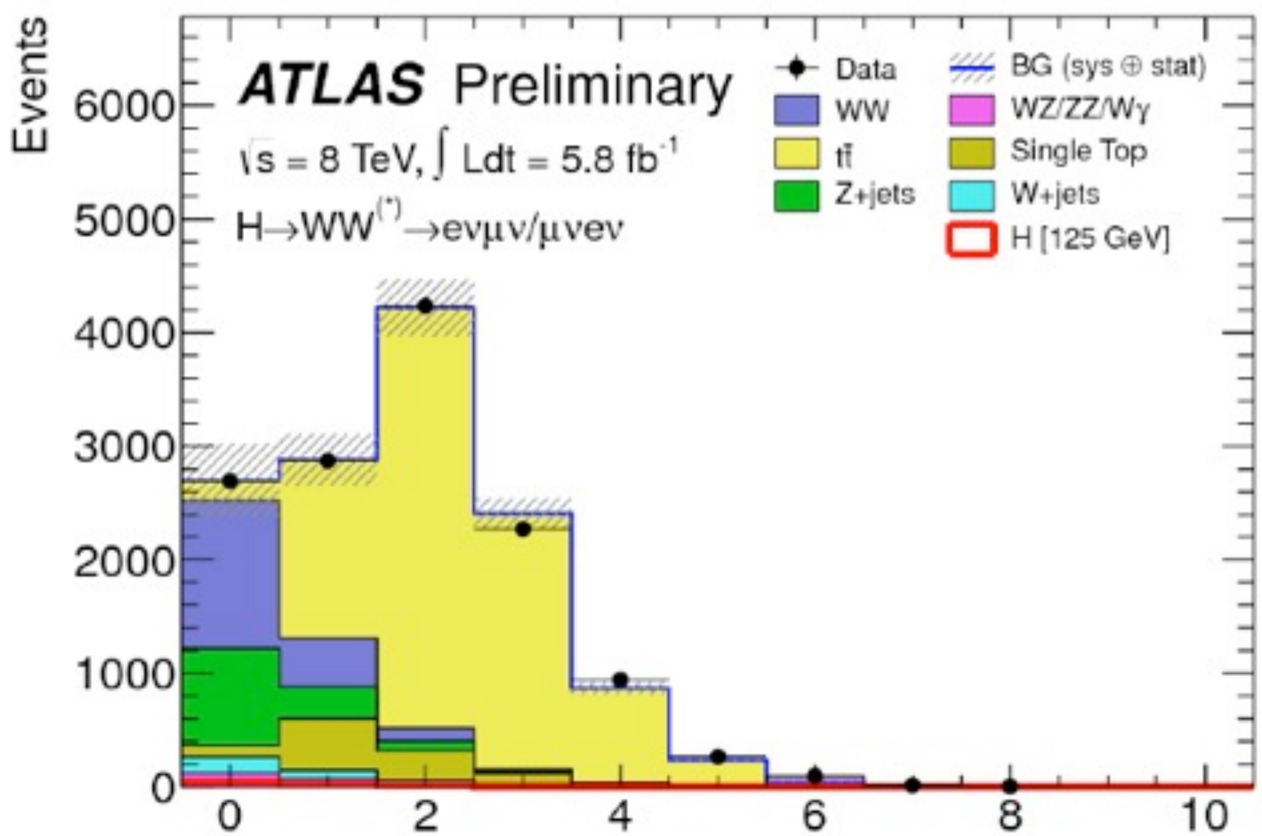
Denominator = σ_{SM} x Br_{SM} needed precise theory already, eg. σ_{NNLO}; more needed for LHC Run II

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



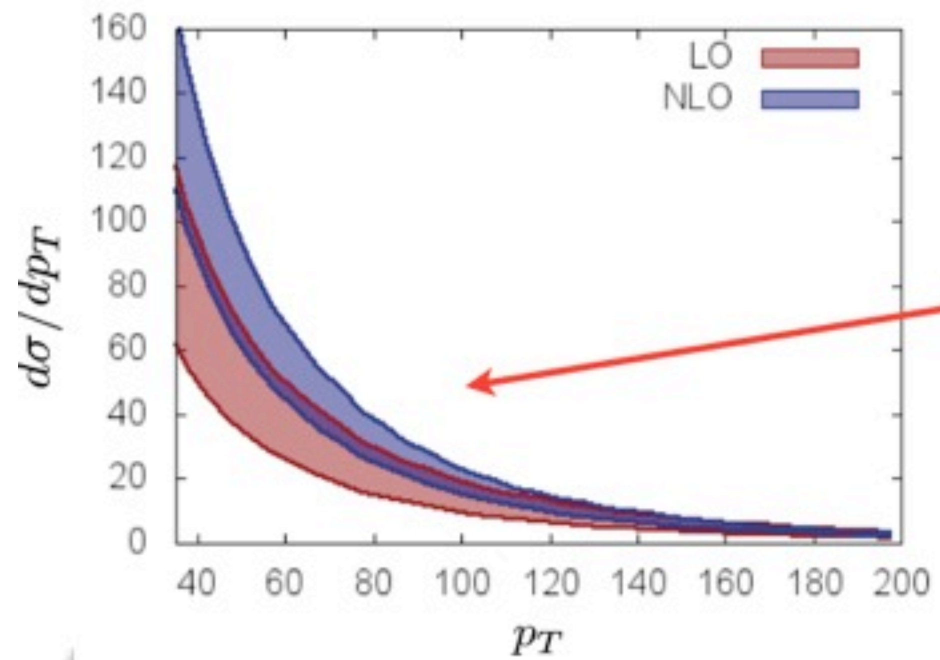
Higgs in association with jets

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

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



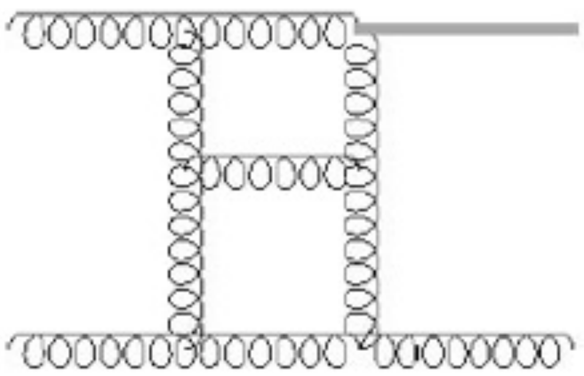
Need for higher orders!

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

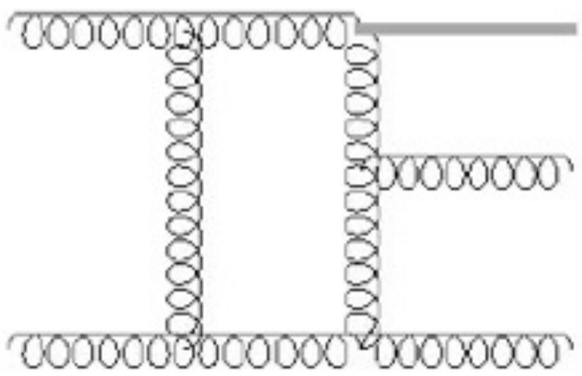
Urgently need NNLO for H+jets to resolve these issues!

Structure of NNLO cross sections

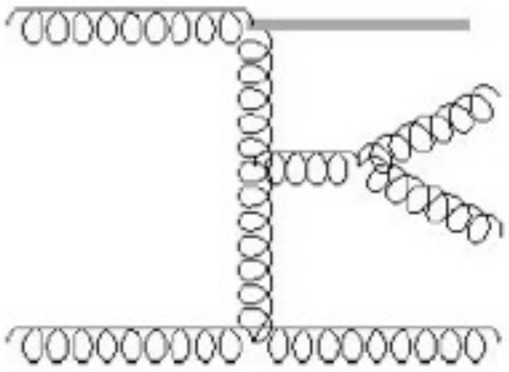
- Need the following ingredients for H+1j @ NNLO cross section



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

Sector decomposition

- One method successfully used in the past to obtain NNLO cross sections is sector decomposition   Binoth, Heinrich; Anastasiou, Melnikov, Petriello (2003)
- Basic idea: introduce explicit parameterizations of phase space in which the poles in ε can be easily extracted via a plus-distribution expansion

$$\int |M|^2 d\Phi \rightarrow$$

$$\int [|M|^2 x]\{dy\} \frac{dx}{x^{1+\epsilon}} = -\frac{1}{\epsilon} F(0) + \int dx \frac{F(x) - F(0)}{x} + \ldots$$

$$F(x) = \int [|M|^2 x]\{dy\}$$

Remap singular denominators on the hypercube

Singularities are extracted before integration

Sector decomposition for simpler processes

$$\int |M|^2 d\phi = -\frac{F(0)}{\epsilon} + \int dx \frac{F(x) - F(0)}{x} + \ldots$$

Subtraction and integrated subtraction terms are for free

(no need for analytic PS integrations)

Successfully applied for NNLO differential cross sections, but for "special" processes

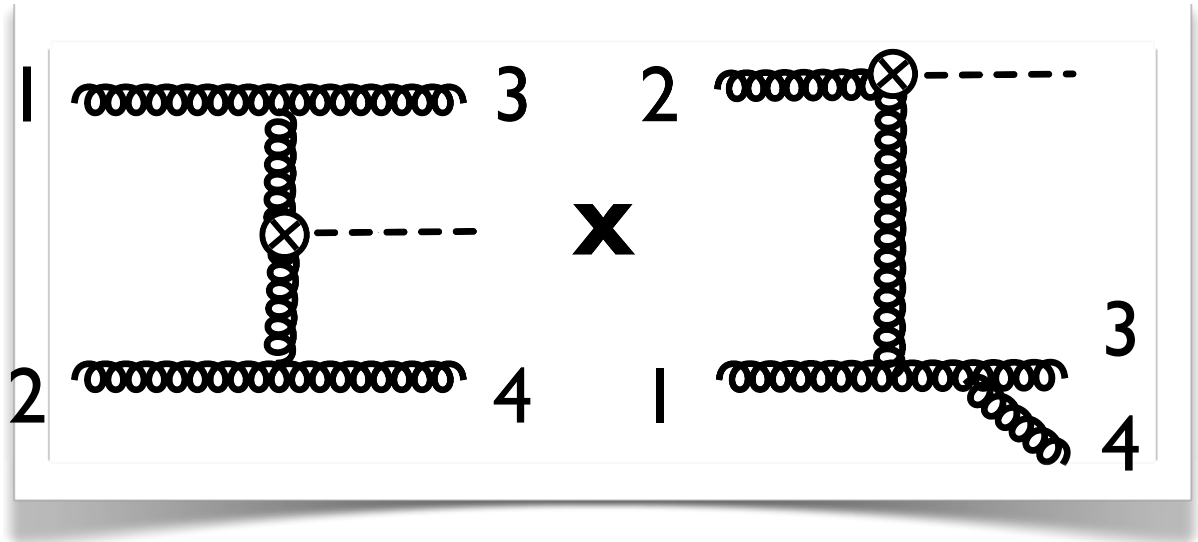
- $e^+e^- \to 2$ jets
- Higgs production at hadron colliders
- Electroweak gauge boson production

Note that:

- Parametrization known only for one collinear direction
- In its original version, sector decomposition is a highly process-dependent framework

The downside

- To illustrate the drawbacks, use Higgs production as an example



- Invariants that occur in this topology : $s_{13}, s_{24}, s_{134}, s_{34}$. These contain the collinear singularities $p_1||p_3, p_2||p_4, p_3||p_4, p_1||p_3||p_4$

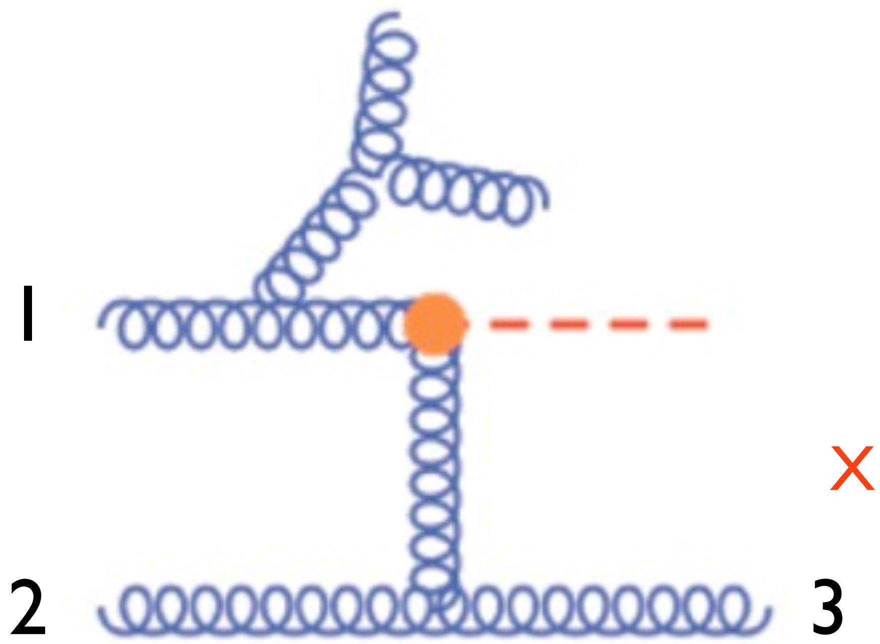
- Initial uses of sector decomposition attempted to find a ***global*** parameterization of phase space to handle all of these singularities at once

- However, can only have: p1||p3 & p2||p4 or p1||p3||p4. Not all invariants above can have collinear singularities simultaneously

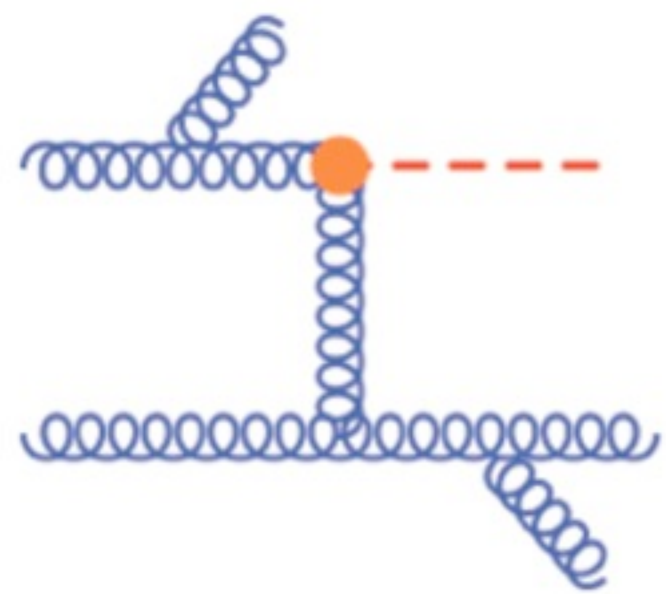
- The attempt to find suitable global parameterizations meant that one would need to find an entirely new parameterization for Higgs+jet, since the additional final-state parton leads to new singularities; can't recycle information from differential Higgs production

Higgs plus jet: singularity structure

- Much more complicated singularity structure, in particular three collinear directions:



x 3



x 6

Potential troubles: $s_{1g}, s_{2g}, s_{3g}, s_{gg}, s_{1gg}, s_{2gg}, s_{3gg}$ and combinations

Finding a 'good' global parametrization is (very) hard

Sector-improved subtraction scheme

- A combination of sector decomposition and FKS (Frixione,Kunszt,Signer) ideas makes the extraction of singularities more systematic Czakon (2010)

  - @ NNLO the elementary building block is the double unresolved phase space where two unresolved particles can become soft or collinear to one or two hard directions

  - partition the phase space such that in each partition only a subset of particles leads to singularities: only two soft singularities can occur, and only one triple collinear or one double collinear singularity can occur.

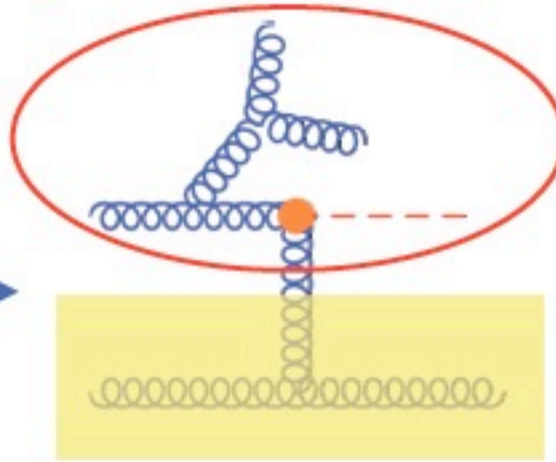
  - we can now pick a ***local*** parametrization for each partition

  - the partitioning is done using energies and angles of the unresolved particles w.r.t. the hard parton(s) emitting them

Sector-improved subtraction scheme

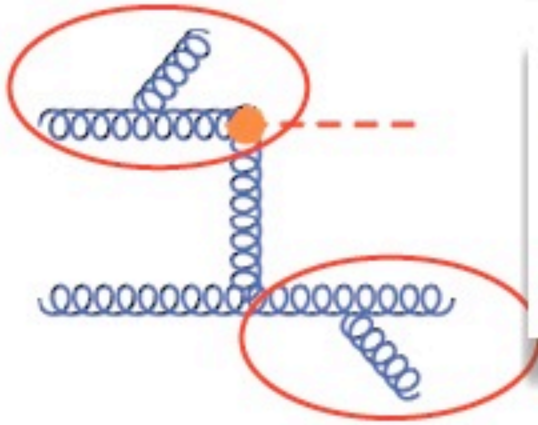
$$\int |M|^2 d\phi = \sum_s \int |M|^2 d\phi \Delta_s^{g_1||i,g_2||j}$$

$$\int |M|^2 d\phi \Delta^{g_1||1,g_2||1} \longrightarrow$$



Single collinear direction
~ parametrization of
ggH, DY, $e^+e^- \to$ dijets

$$\int |M|^2 d\phi \Delta^{g_1||1,g_2||3} \longrightarrow$$

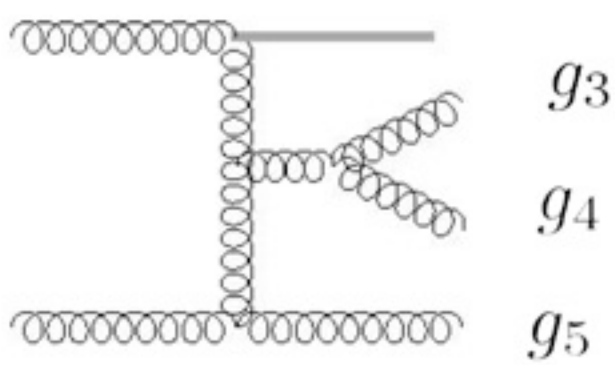


Two (~uncorrelated) dir.
~ NLO^2

No matter how complicated the process is,
it can be reduced to the sum of individual contributions. For each of them, we know a sector decomposition-friendly PS parametrization

Sector-improved subtraction scheme

- disentangling singularities as energies and angles vanish leads to a tree of sectors.



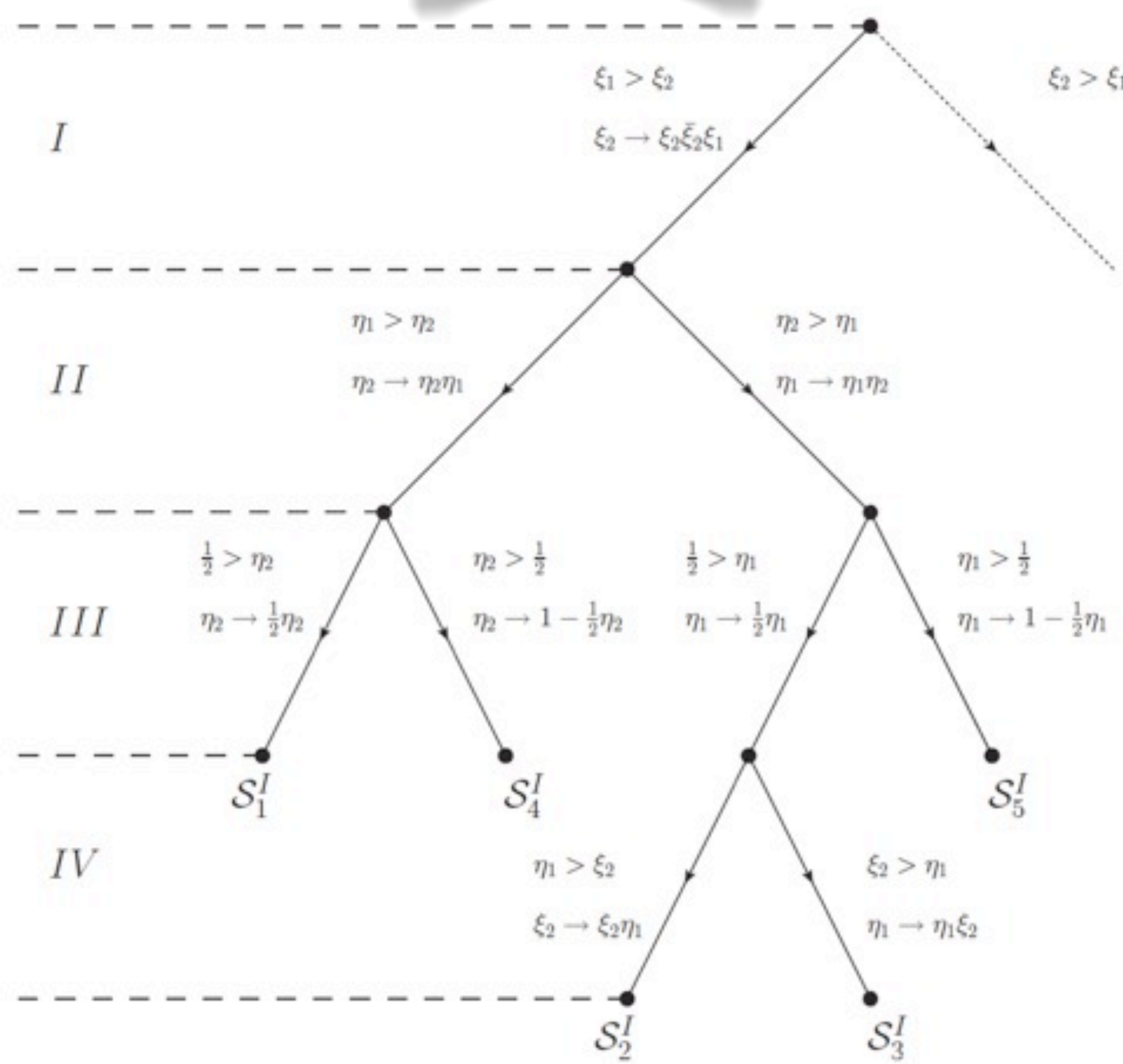
- Need to consider the following partitions for H+1j:

  - triple collinear partitions:
    (5||4||1), (5||4||2) , (5||4||3) ;

  - double collinear partitions:
    (5||1,4||2), (5||1,4||3), (5||3,4||1), (5||3,4||2),(5||2,4||1),(5||2,4||3)

$\eta \sim$ angles

$\xi \sim$ energies

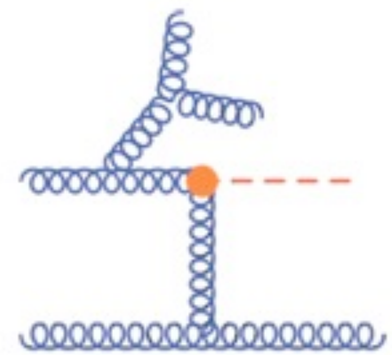


Building blocks for H+j

Recall the general structure: $F(x) = \int [|M|^2 x]\{dy\}$

$$\int |M|^2 d\phi = \frac{F(0)}{\epsilon} + \int dx \frac{F(x) - F(0)}{x} + \ldots$$

The Subtraction terms are constructed from reduced matrix elements using QCD factorization of soft and collinear singularities



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

We need to provide

- $F(\vec{x}; \{y\})$: fully-resolved matrix element (RR and RV)
- $\lim_{x_i \to 0} F(\vec{x}; \{y\})$: matrix element in a singular configuration

↓

$\lim_{x_i \to 0} F(\vec{x}; \{y\})$: reduced (=lower multiplicity) matrix element times universal eikonals / splitting functions

[Catani, Grazzini (1998, 2000); Kosower, Uwer (1999)]

Building blocks for H+j

Because of gluon spin correlations, we are forced to work in full CDR

- 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, Glover, Mastrolia, Williams (2009)
- one-loop H+1j up to $O(\varepsilon^2)$
- two-loop H+1j Gehrmann, Jaquier, Glover, Koukoutsakis (2011)
- renormalization, collinear subtraction

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

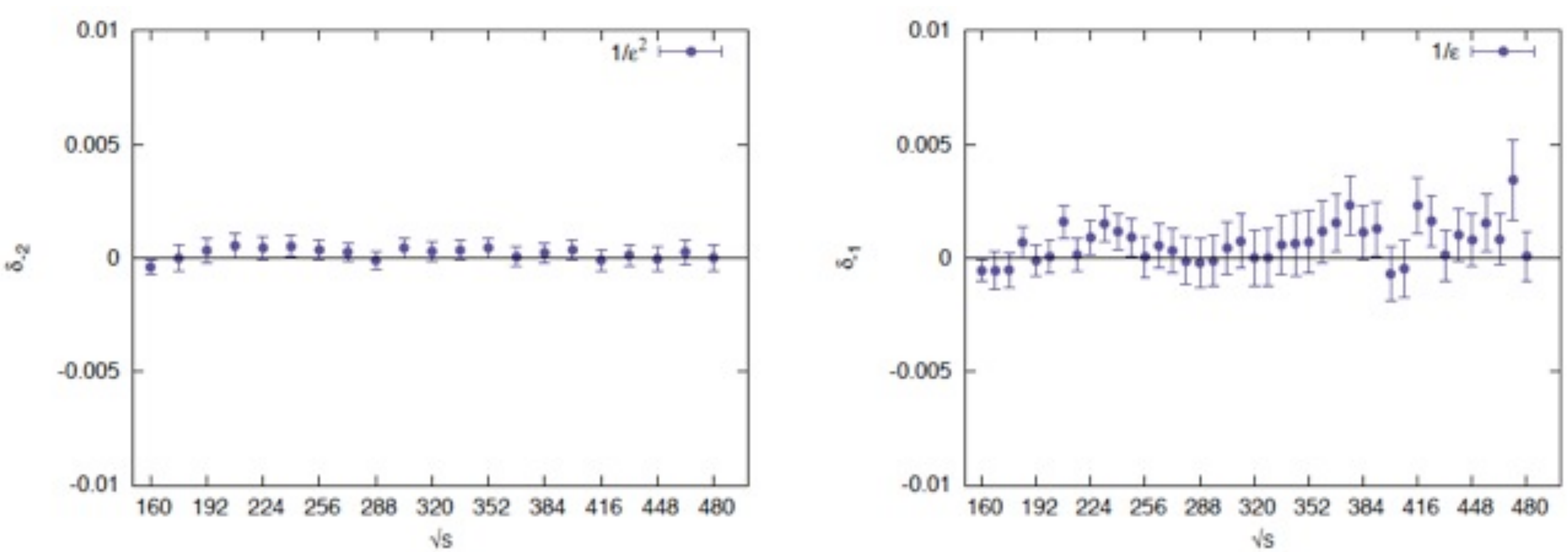
H+jet @ NNLO: gg-channel

Checks:

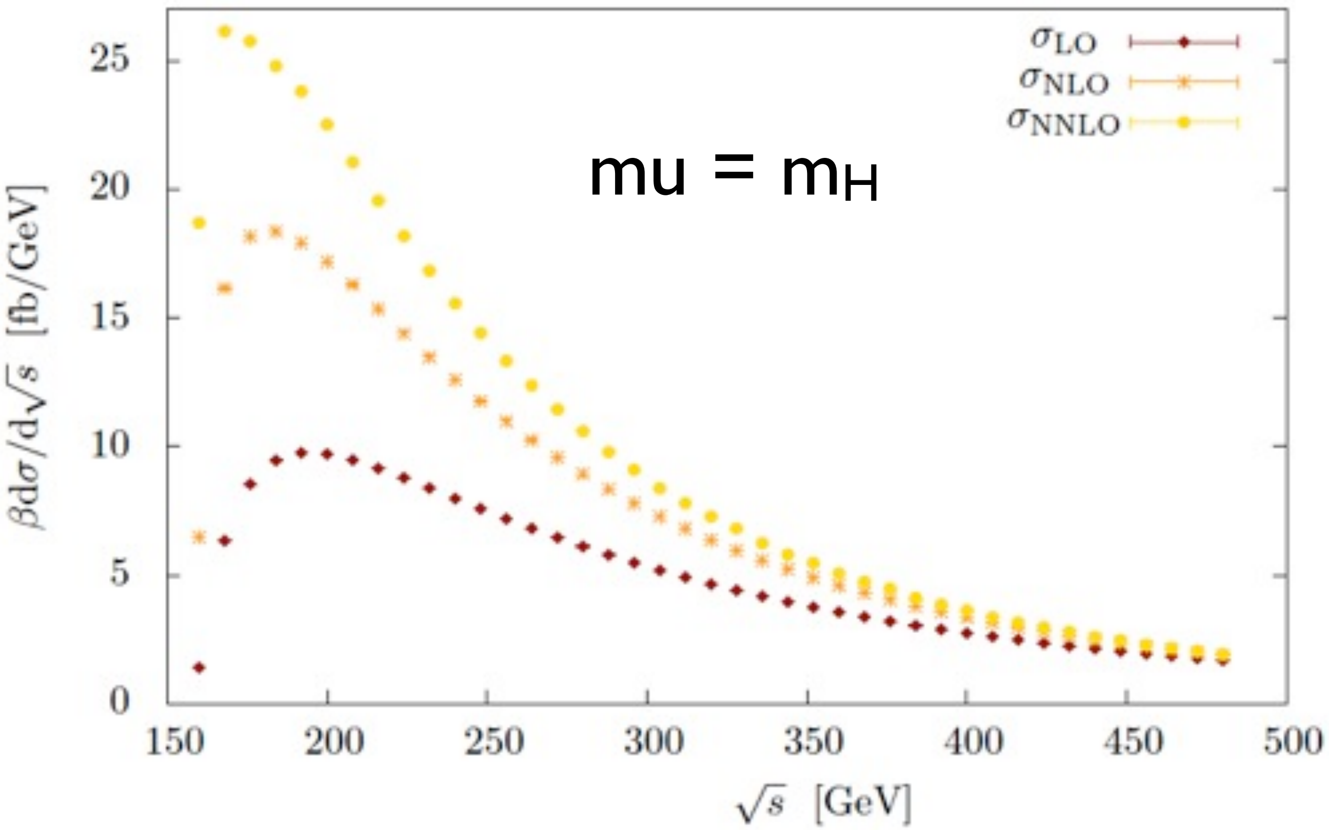
- Two separate calculations were performed and agreement was found on all the steps

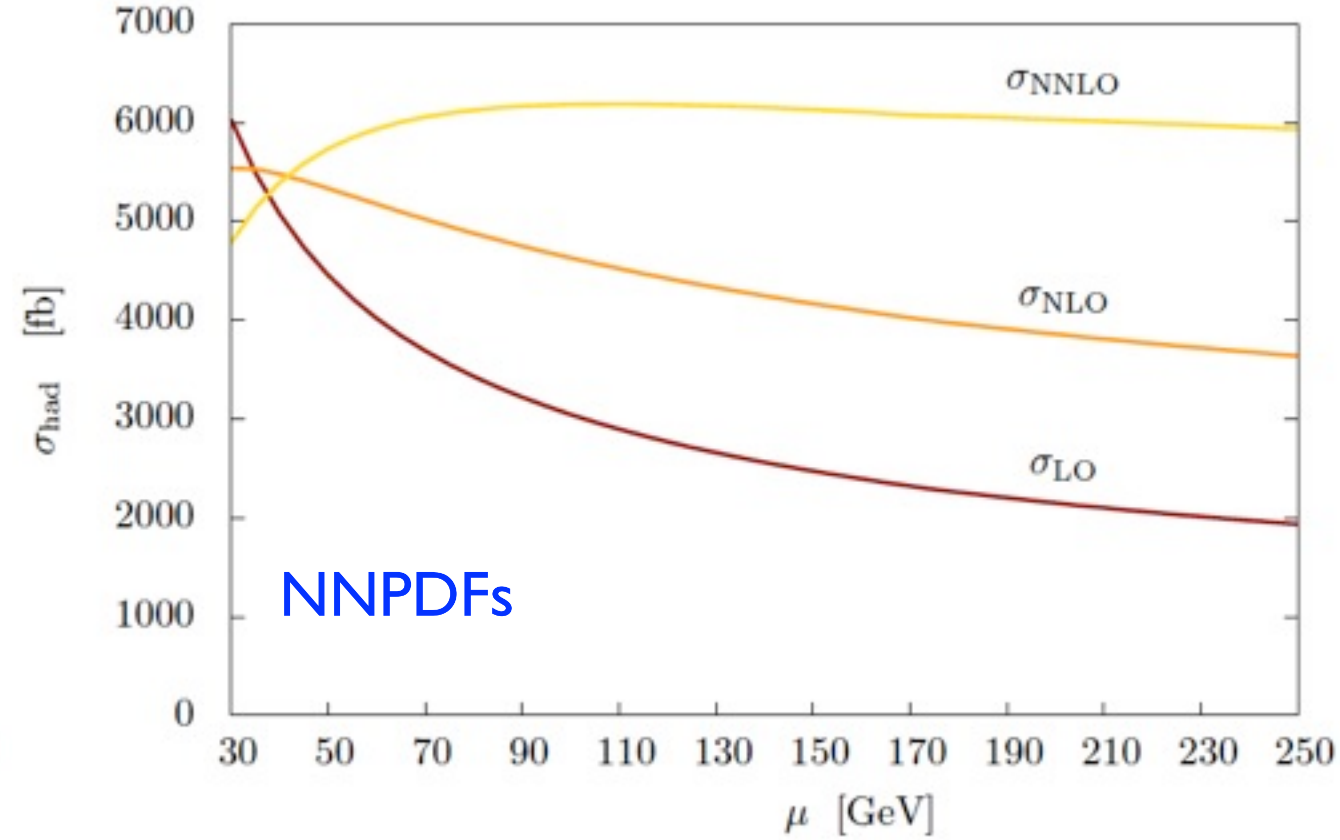
- Correctness of the limits: the subtraction terms should approach the full amplitudes in the singular limit. This is a non-trivial check since the two contributions are calculated independently from each other.

- Numerical cancellation of poles. This is another non-trivial check since all the ingredients including renormalization and collinear subtraction contribute. A typical cancellation of poles is 10^{-4} for ep^{-2} and 10^{-3} for ep^{-1}.



H+jet @ NNLO: gg-channel

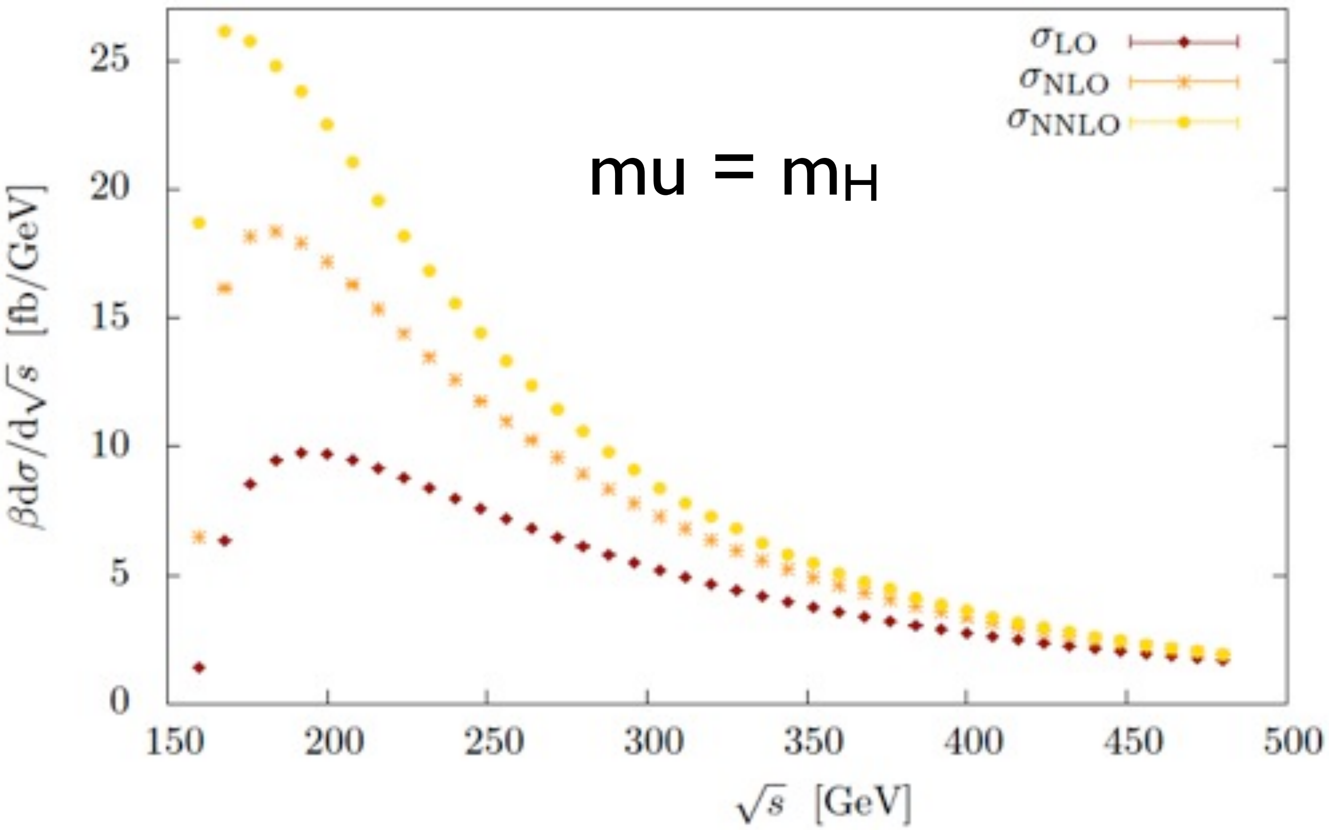


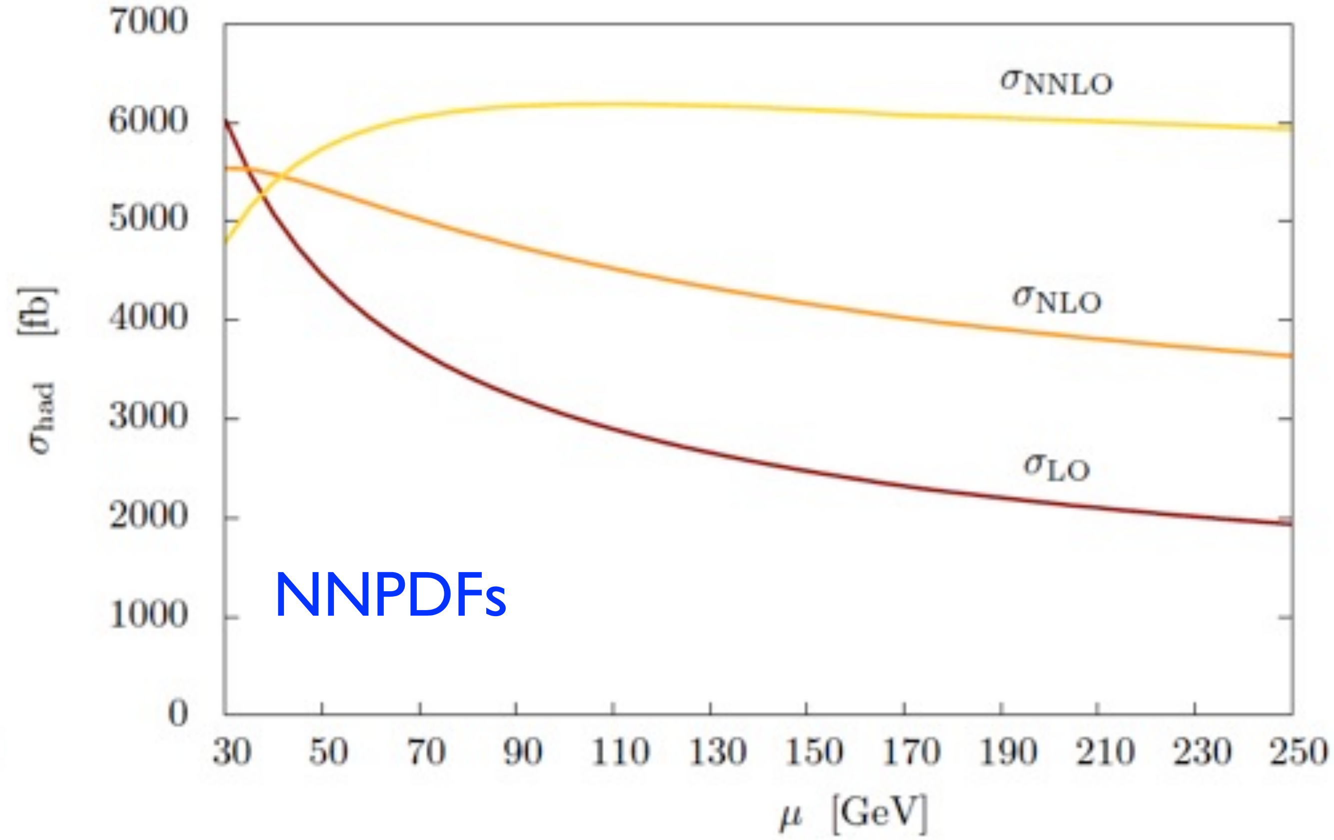


R.B., Caola, Melnikov, Petriello, Schulze (2013)

- We compute partonic cross sections for gg→H+jet at LO, NLO, NNLO in QCD
- We use the k_T-jet algorithm, P_{Tj} > 30GeV, R=0.4, mH=125GeV
- Hadronic cross sections for pp→H+jet at 8TeV LHC are produced by convoluting with PDFs. We present results using NNPDFs for the scale choices $m_H/2$, m_H, $2m_H$

H+jet @ NNLO: gg-channel





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

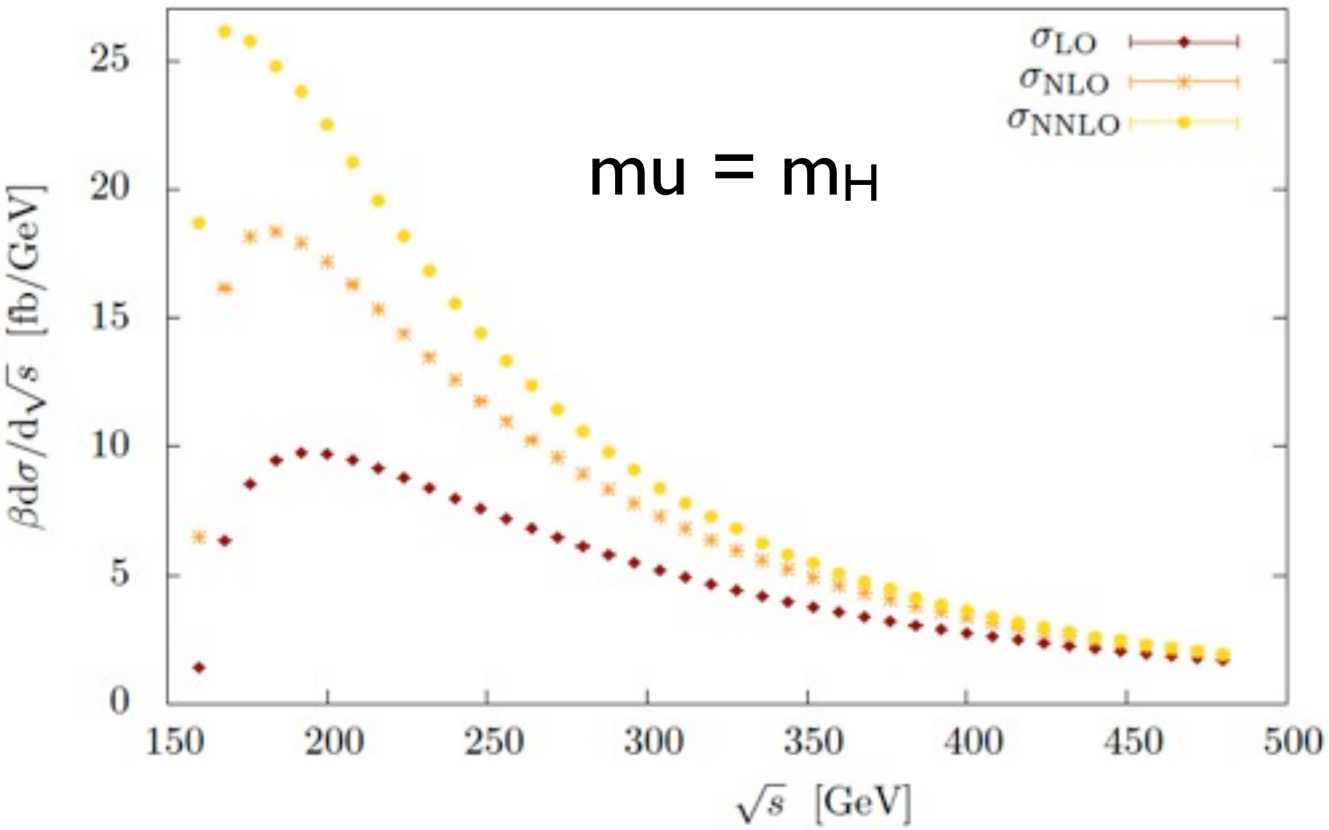
$$\sigma_{LO}(pp \to Hj) = 2713^{+1216}_{-776} \text{ fb},$$
$$\sigma_{NLO}(pp \to Hj) = 4377^{+760}_{-738} \text{ fb},$$
$$\sigma_{NNLO}(pp \to Hj) = 6177^{-204}_{+242} \text{ fb}.$$

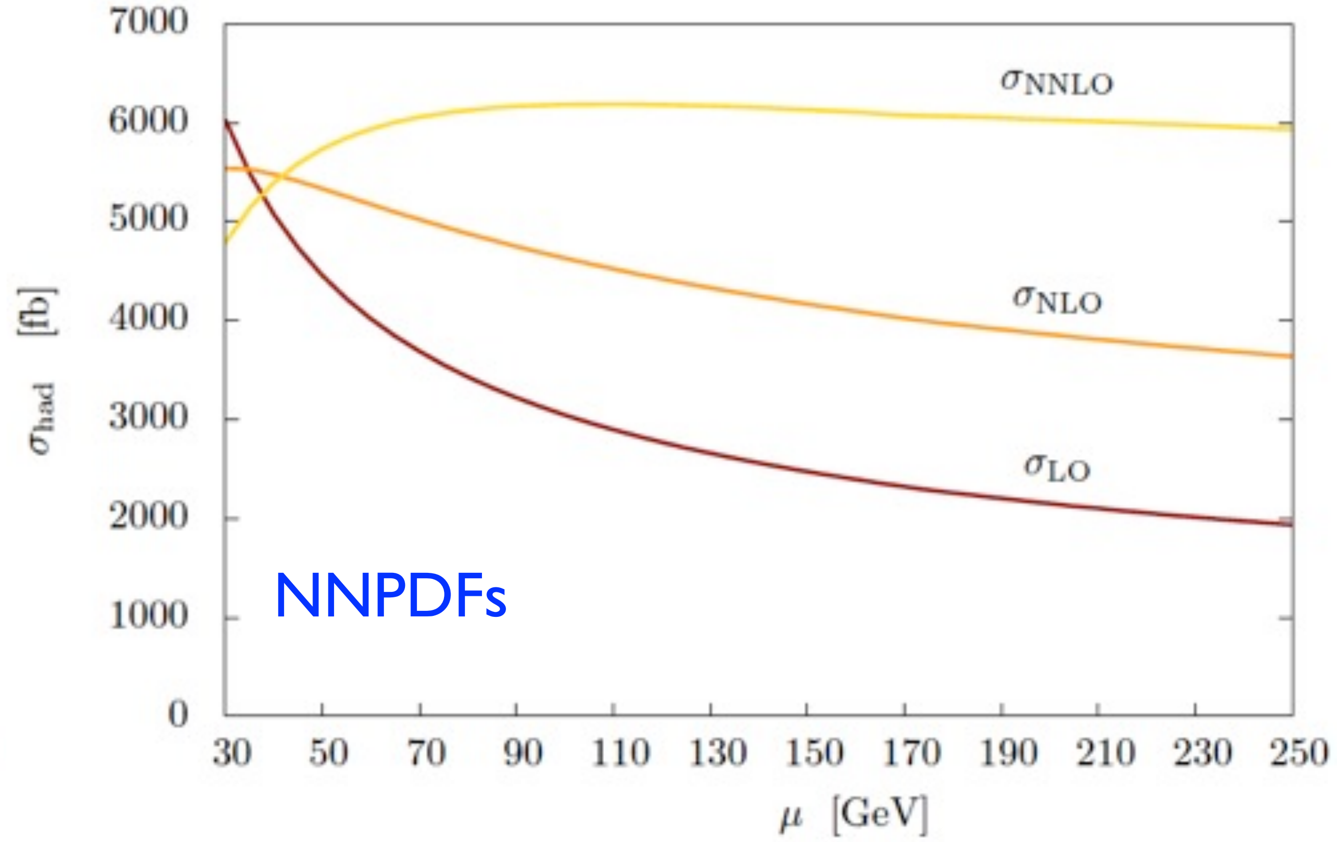
$\sigma_{NLO}/\sigma_{LO} = 1.6$

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

- Significant reduction of scale dependence from 50% at LO to 20% at NLO to less than 5% at NNLO.

H+jet @ NNLO: gg-channel





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

- 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

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 (gg-chanel), an extremely challenging calculation and one of the first NNLO QCD results for two-to-two scattering processes at LHC

- Quark channels are necessary for achieving the relevant precision for Higgs+jet: ongoing work R.B., Caola, Melnikov, Petriello, Schulze