Precision QCD as a tool for discovery

Fabrizio Caola, CERN

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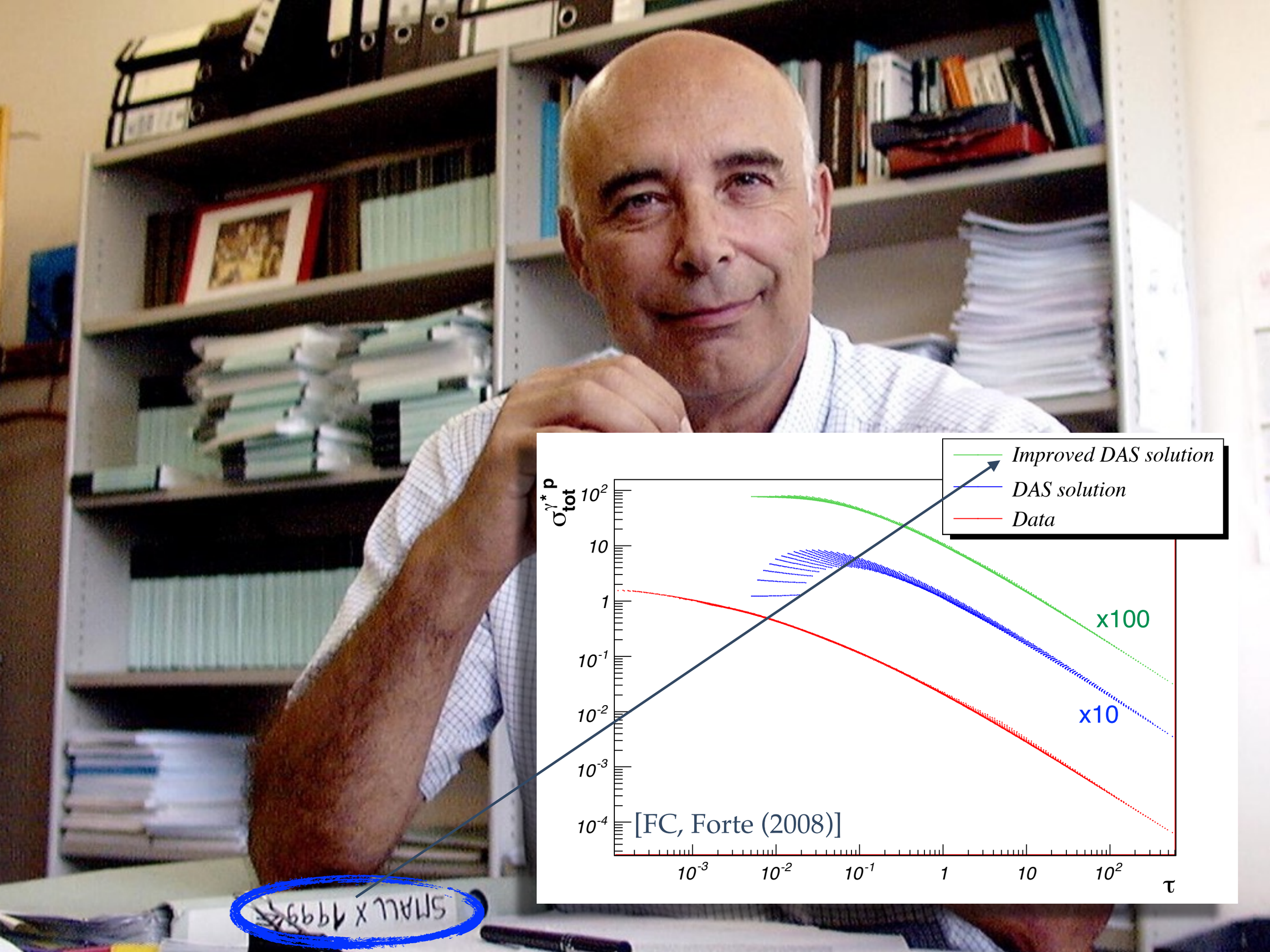
Improved DAS solution
DAS solution
Data
x100
x10
[FC, Forte (2008)]
$\sigma^{\gamma^* p}_{tot}$
τ
10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
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1
10
10^{2}

SU(3)xSU(2)xU(1): victims of our own success?

- With the discovery of the Higgs boson, the standard model is now complete

- For the first time, a coherent framework able to successfully describe fundamental interactions to the limits of current testability

- The EWSB mechanism seems to be triggered in the simplest possible way (~irrespective of what happens at 750 GeV…)

IS THIS AMAZING SUCCESS THE BEGINNING OF THE END OF PARTICLE PHYSICS?

Is the SM the end of the story? Not quite

- Indirect indications that the SM is not complete (dark matter/energy, baryon asymmetry…)
- Before the LHC, some expectation of new physics beyond the corner (naturalness…): SUSY, extra dimensions…
  So far, this has not happened
- Discovering new physics turned out to be more challenging. No spectacular new signatures ⇒ new physics can be hiding in small deviations from SM behavior. Very good control on the latter is required to single them out

PRECISION IS NOW A PRIVILEGED TOOL FOR DISCOVERY AT COLLIDERS

Some quotes from Guido…

The Higgs and the excessive success of the Standard Model (2014)

possibly there is no FT with no new threshold up to M_{Pl} and invoking some miracle within the theory of quantum gravity (at the price of giving up Grand Unification and heavy RH neutrinos below the Planck scale). Clearly we are experiencing a very puzzling situation but, to some extent, this is good because big steps forward in fundamental physics have often originated from paradoxes. We highly hope that the continuation of the LHC experiments will bring new light on these problems.

The Higgs: so simple yet so unnatural (2013)

From the first LHC phase we have learnt very important facts. A Higgs particle has been discovered which is compatible with the elementary, weakly coupled Higgs boson of the minimal SM version of the EW symmetry breaking sector. No clear signal of new physics has been found by ATLAS, CMS and LHCb. On the basis of naturalness one was expecting a more complicated reality. Nature appears to disregard our notion of naturalness and rather indicates an alternative picture where the SM, with a few additional ingredients, is valid up to large energies. It is crucial for future experiments at the LHC and elsewhere to confirm the properties of the Higgs and the absence of new physics.

Hunting down small deviations: the Higgs sector

To pursue our quest for new physics at the LHC, we can envision at least two strategies

- Pushing collider phenomenology to the boundary:
  N^{3}LO predictions for the total cross-section, *fully differential NNLO predictions for H+jet/Higgs p_T spectrum and precise predictions in the experimental fiducial region…*

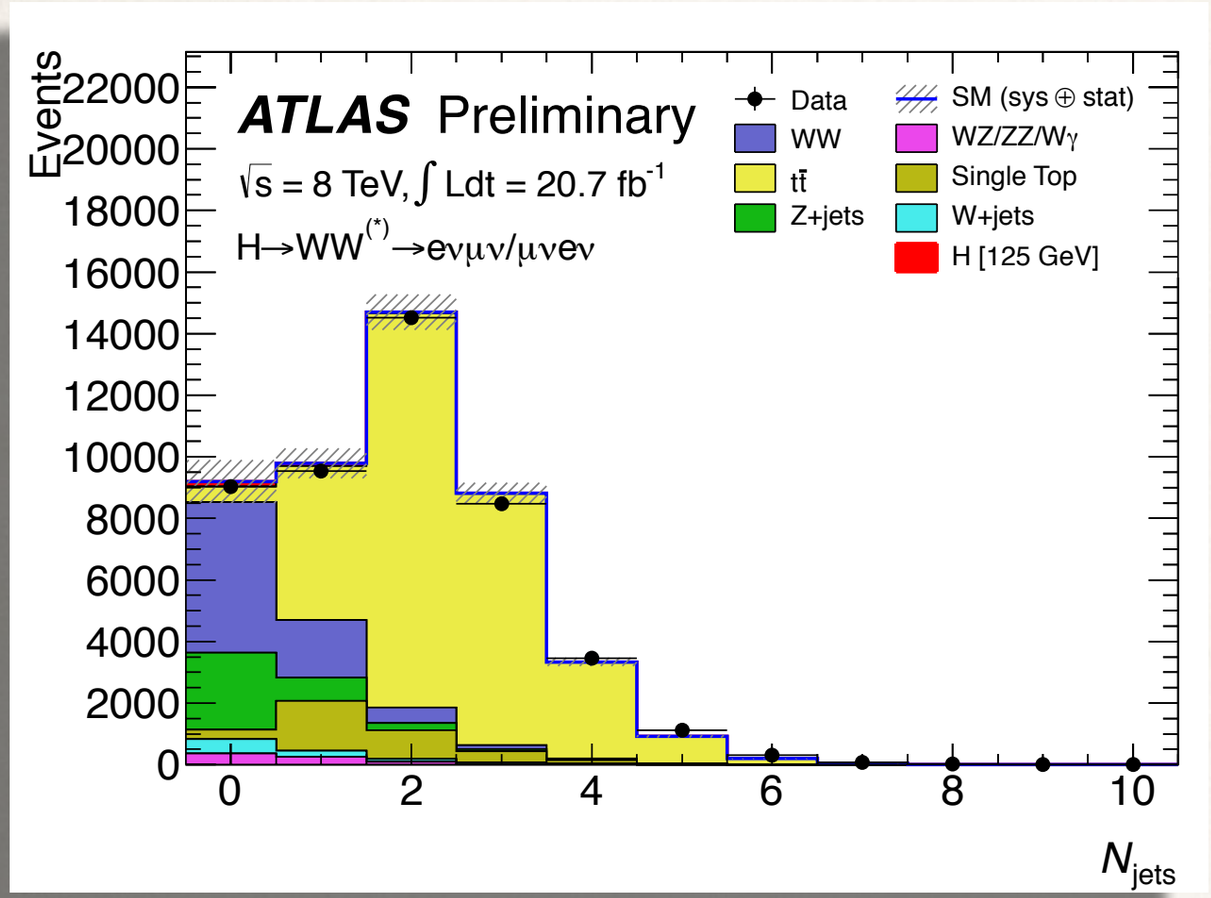
- Looking closer at small effects:
  Higgs interferometry, *the off-shell Higgs and the Higgs width/couplings*, boosted Higgs and the ggH coupling…

In the following, I will give two examples to illustrate both of these venues

Pushing collider phenomenology to the boundary:

Higgs plus jet at NNLO

Why H+J and why NNLO



- Large rate (H+J ~ 35% of σ_H)
- In important channels (H→WW,H→ττ) jet veto to suppress background
- Can give important information about Higgs properties (proxy for $p_{t,H}$)

- Higgs cross-section is notoriously badly convergent. For H+J: NLO *K*-factor ~ 40%, scale uncertainty ~ 30%
- Largish logs can further spoil perturbative convergence

The problems with fully exclusive NNLO

The GOAL: we are looking for precise predictions → as close as possible to experimental reality (fully differential, fiducial region)

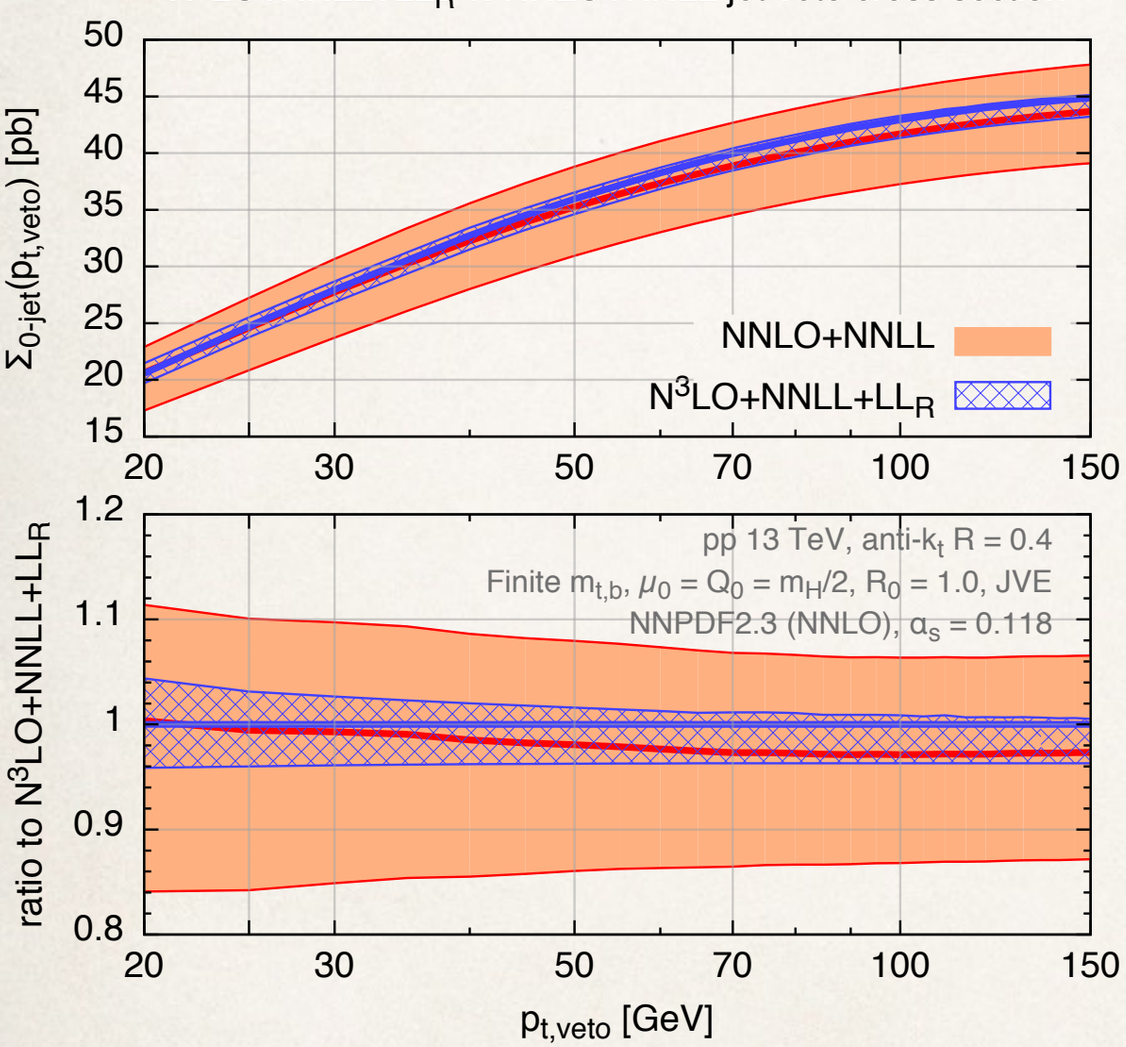
- Especially for processes with non trivial color flow, these computations pose significant conceptual challenges (consistent treatment of IR singularities)

- Thanks to a big effort in the community, we now see first glimpses towards solutions: antenna, sector decomposition +FKS/STRIPPER, colorful NNLO, N-jettines/q_T slicing…

- NNLO predictions for colorful 2→2 processes are a reality

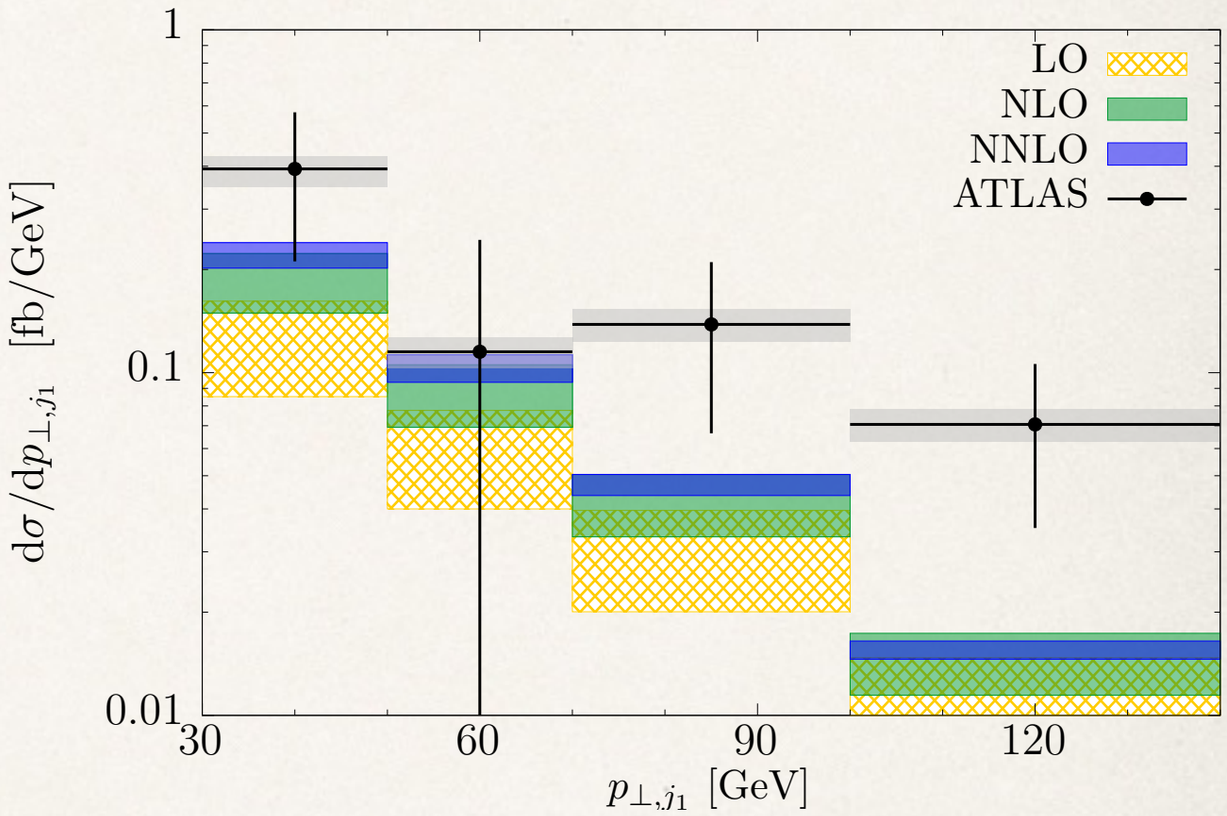
H+J at NNLO: some results

Full control on jet veto logs



[Banfi, FC, Dreyer, Monni, Salam, Zanderighi, Dulat (2016)]

High precision comparison in the actual fiducial region possible



[FC, Melnikov, Schulze (2015)]

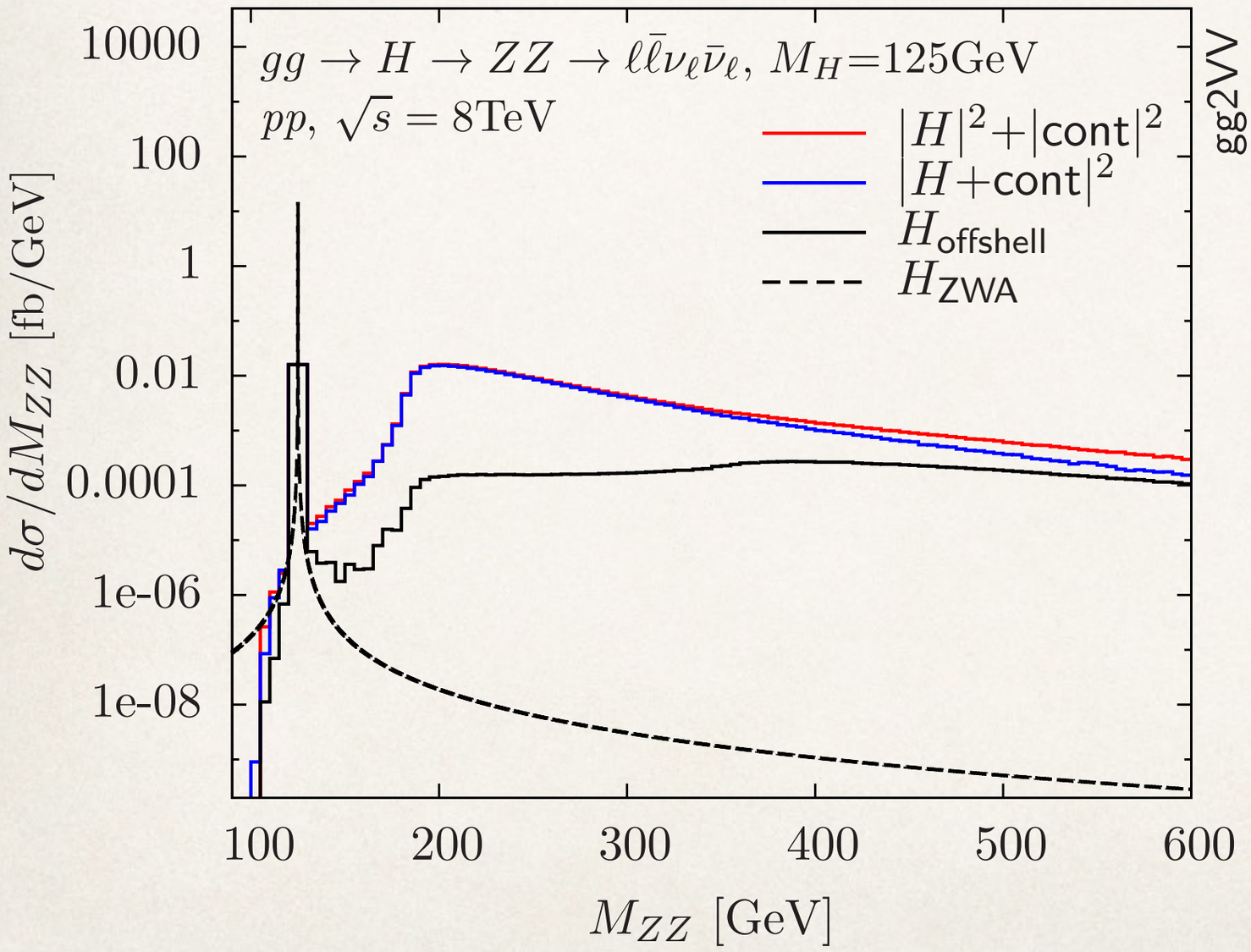
NNLO: good perturbative convergence, significantly reduced uncertainties

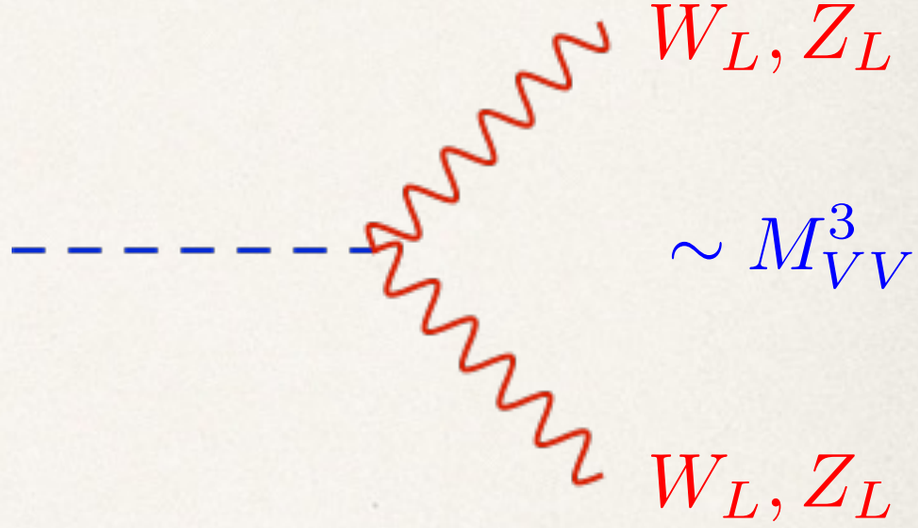
Looking closer at small effects:

the off-shell Higgs and gg→VV

The off-shell Higgs

Despite being a narrow resonance, in the H→VV channels
the SM Higgs develops a sizable high-invariant mass tail
(enhanced decay to real longitudinal W/Z)

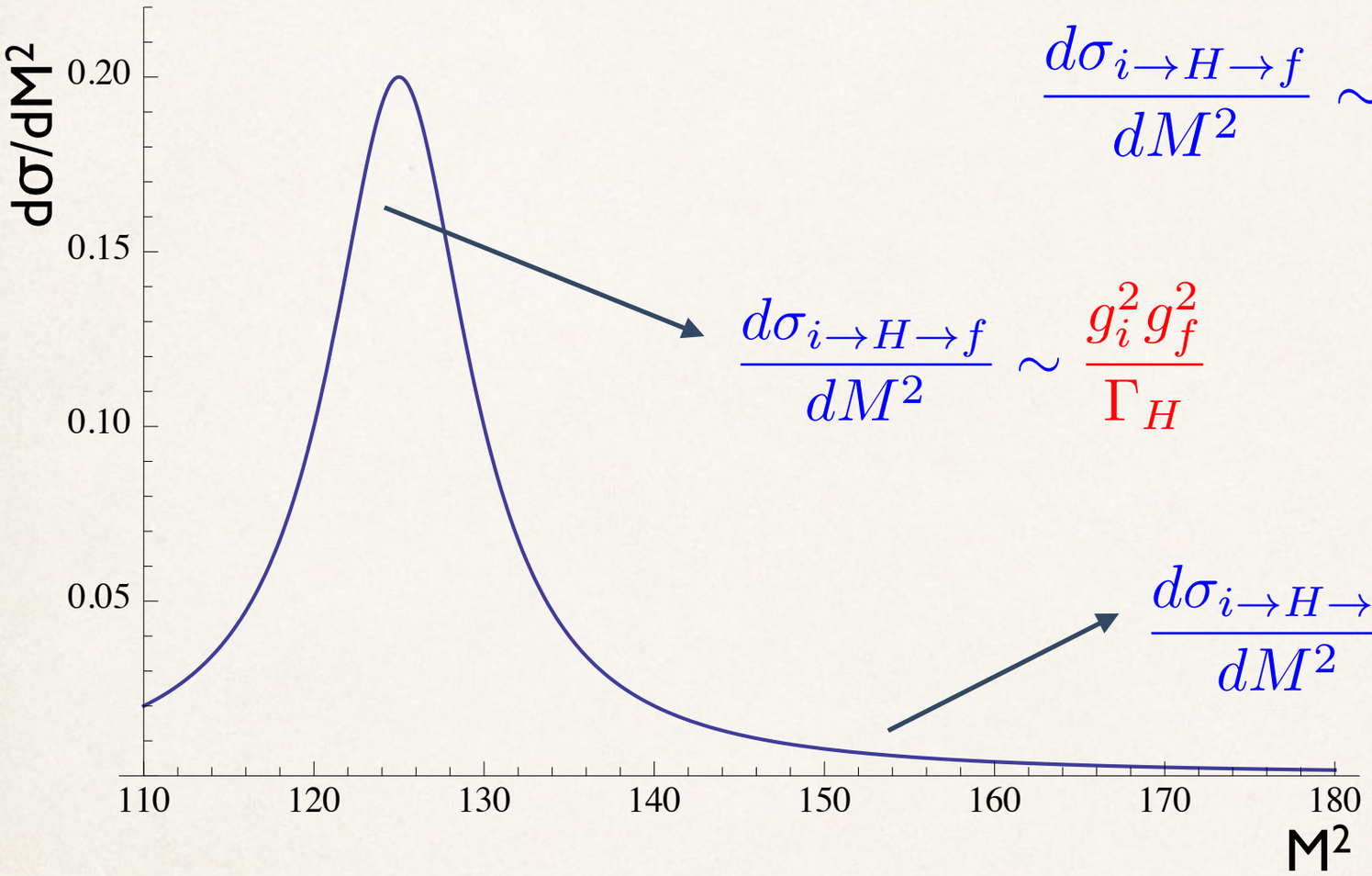




[Kauer, Passarino (2012)]

The off-shell Higgs

Contrary to the peak region, in the off-shell tail the (SM) cross-section only depends on the couplings, and not on the width



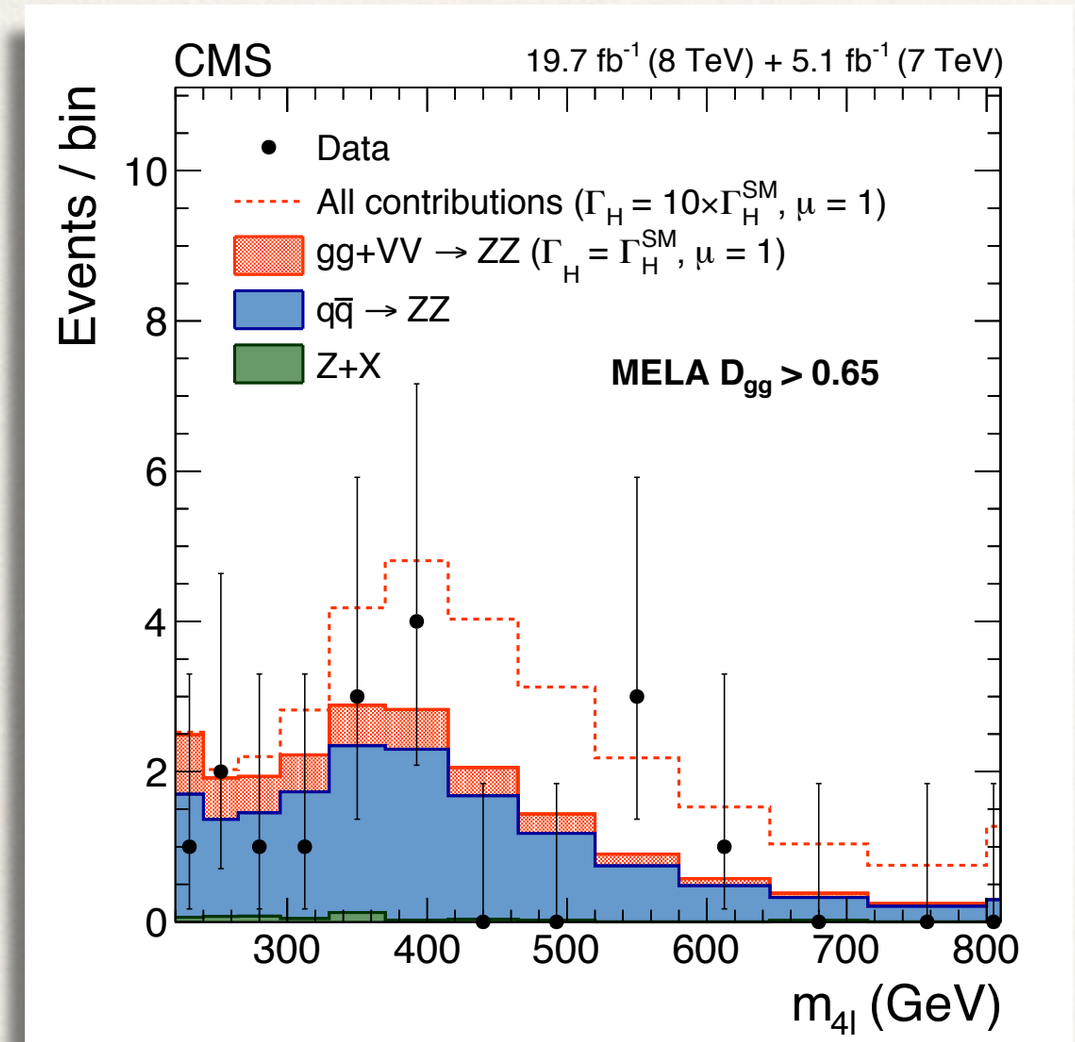
$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{(M^2-m_H^2)^2+m_H^2\Gamma_H^2}$$

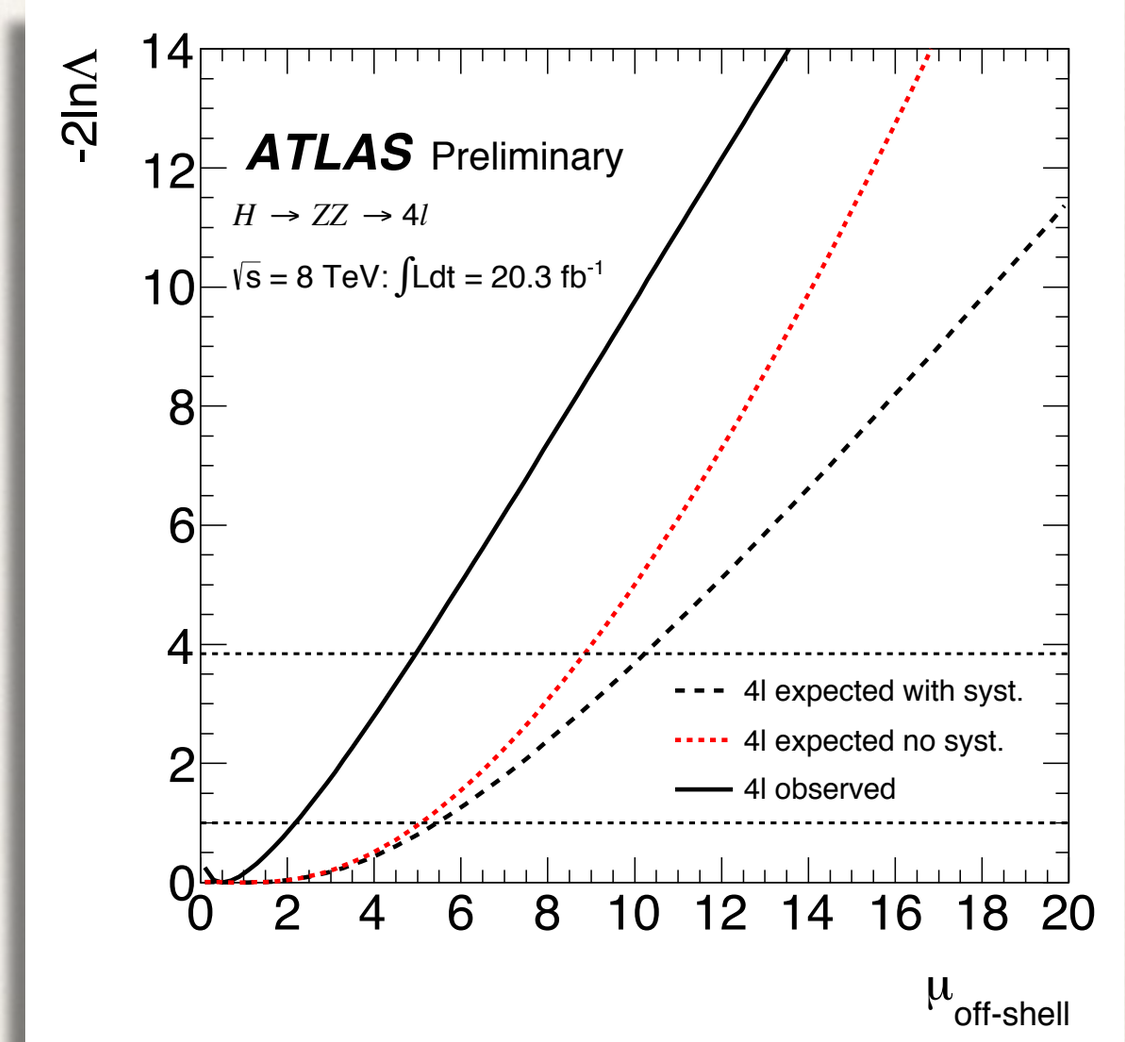
$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{(M^2-m_H^2)^2}$$

When combined with standard measurements, off-shell region helps in decorrelating couplings/width, thus giving additional information on them [FC, Melnikov (2013)]

Example: constraints on the Higgs width





$\Gamma_H^{CMS} \leq 22$ MeV

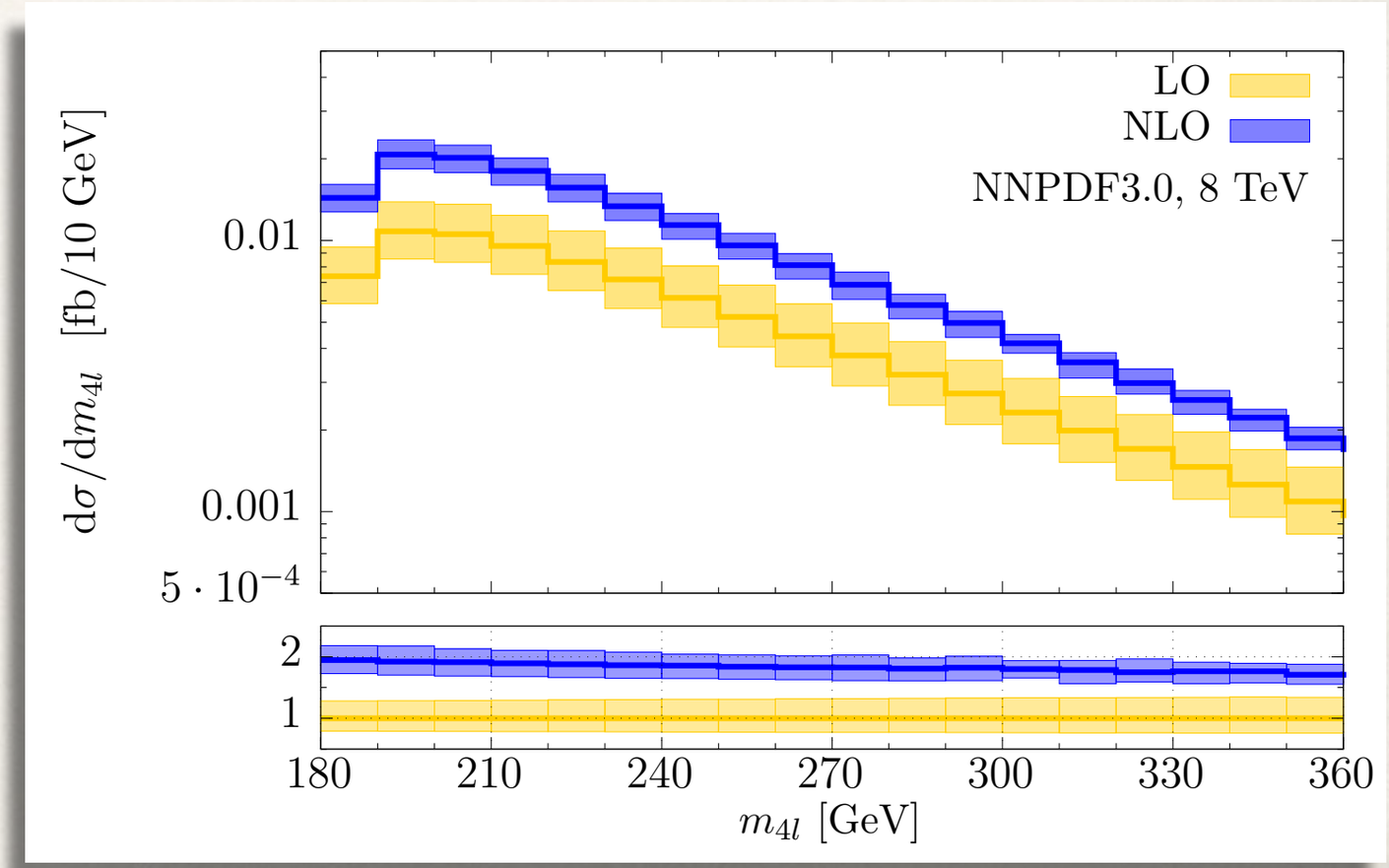
$\Gamma_H^{ATLAS} \leq 20\text{-}32$ MeV

To be compared with the ultimate LHC reach for
the direct measurement $\Gamma_H^{direct} \sim 1$ GeV
(although indirect constraints → some model dependence)

The off-shell Higgs: gg→VV

- To fully profit from off-shell data: good control on SM backgrounds, especially gg → VV(very delicate signal/ background interference patterns)
- This requires complicated two-loop amplitudes
- Combining traditional techniques with new ideas inspired by more formal $\mathcal{N}=4$ SYM studies, powerful new methods to tackle this problem

[FC, Henn, Melnikov, Smirnov, Smirnov (2015); Tancredi, v. Manteuffel, Gehrmann (2015); Tancredi, v. Manteuffel (2015); FC, Melnikov, Röntsch, Tancredi (2015); FC, Dowling, Melnikov, Röntsch, Tancredi, in progress]



Conclusion

- The pre-LHC expectation of easy-to-see new physics at the TeV scale did not come true: BSM physics more subtle than expected
- To investigate the structure of the EWSB, very precise predictions are required, to spot even the tiniest deviation
- Almost half a century after its early days — which Guido pioneered — QCD is still leading to conceptual advances in QFT and it is a privileged tool for new physics searches at colliders
- I presented only two examples of how precision QCD is relevant for this program, many other aspects are as important (PDF determination, α_s, resummation, non perturbative QCD…)

Conclusion

On behalf of the whole community, MANY THANKS TO GUIDO FOR HIS HUGE CONTRIBUTION TO QCD, COLLIDER PHENOMENOLOGY AND PARTICLE PHYSICS IN GENERAL

- Many thanks to the Search Committee and the International Advisory Committee of DIS — as well as NPB and VFFD — for this award

- Many thanks to all my collaborators, especially Kirill Melnikov and Stefano Forte. Without them I would not be here today

- … and many thanks to you all for your attention!