Precise predictions for Higgs physics at the LHC

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Outline

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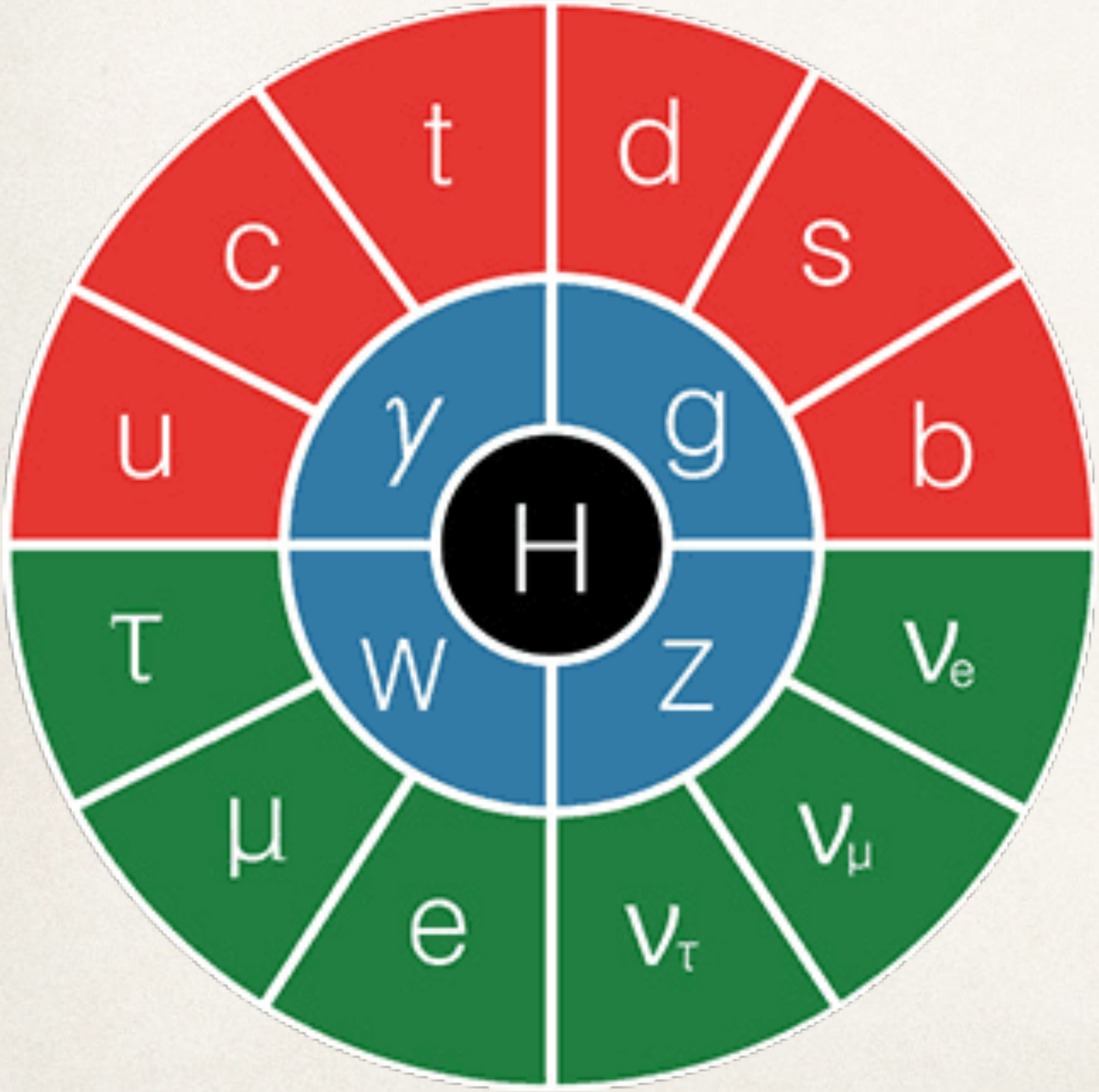
  - Why precision
  - Precision goals and how to achieve them
- A first example: H+J @ NNLO
  - Integrating out the top
  - NNLO computations: anatomy
  - LHC phenomenology: fiducial results, jet veto, Higgs p_t
- A second example: the off-shell Higgs and gg→VV
  - The off-shell region and the Higgs width/couplings
  - NLO predictions for gg→VV and `amplitude’ progress
  - LHC phenomenology: signal, background and interference *K*-factors
- Conclusions

Particle physics circa 2016

Higgs boson discovery: one of the most important experimental results of the last 20 years



An apparent contradiction:

- The SM seems to describe all collider measurements to arbitrary precision
- \`Complete theory' up to any scale to be probed in the foreseeable future
- Still, STRONG INDICATIONS that the SM is not the end of the story (dark matter, dark energy, baryogenesis…)

Moving forward: the need for precision

- Strong cosmological indications for physics beyond the SM
- Before the LHC, some expectation of new physics beyond the corner (naturalness, fine tuning, WIMP miracle…): SUSY, extra dimensions… So far, this has not happened
- Already now, the LHC points toward a SM-like Higgs sector (~no matter what would happen at 750 GeV)
- Discovering new physics turned out to be more challenging. No spectacular new signatures ⇒ new physics can be hiding in small deviations from SM behavior, or in unusual places. Very good control on SM predictions is required to single them out

PRECISION IS NOW A PRIVILEGED TOOL FOR DISCOVERY AT THE LHC

Hunting down small deviations: the Higgs sector

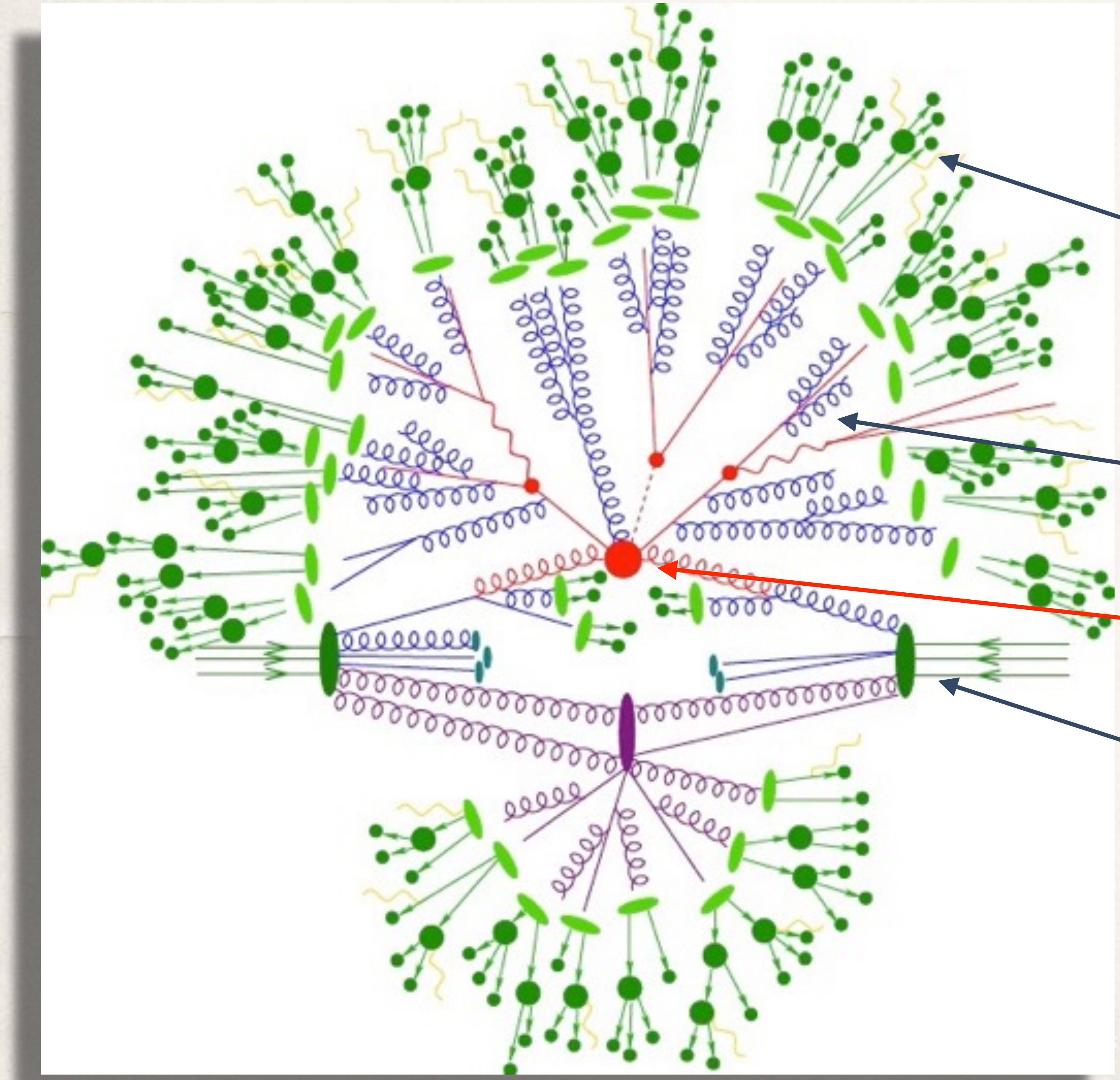
To pursue our quest for new physics at the LHC, we can envision at least two strategies

- Pushing collider phenomenology to the boundary:
  N^3LO 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

Precise predictions: requirements

THE GOAL:
precise modeling of the actual experimental setup



Many different ingredients

- Non perturbative models (hadronization…)
- Parton shower evolution
- HARD SCATTERING
- Parton distributions
- Input parameters (α_s…)

The hard scattering cross-section

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f(x_1) f(x_2) \mathrm{d}\sigma_{\mathrm{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q))$$

Require precise input parameters (α_s, PDFs…)

HIGH-Q^2 PHYSICS → PART WE HAVE MOST CONTROL ON, AND SENSITIVE TO SHORT DISTANCE PHYSICS (BSM)

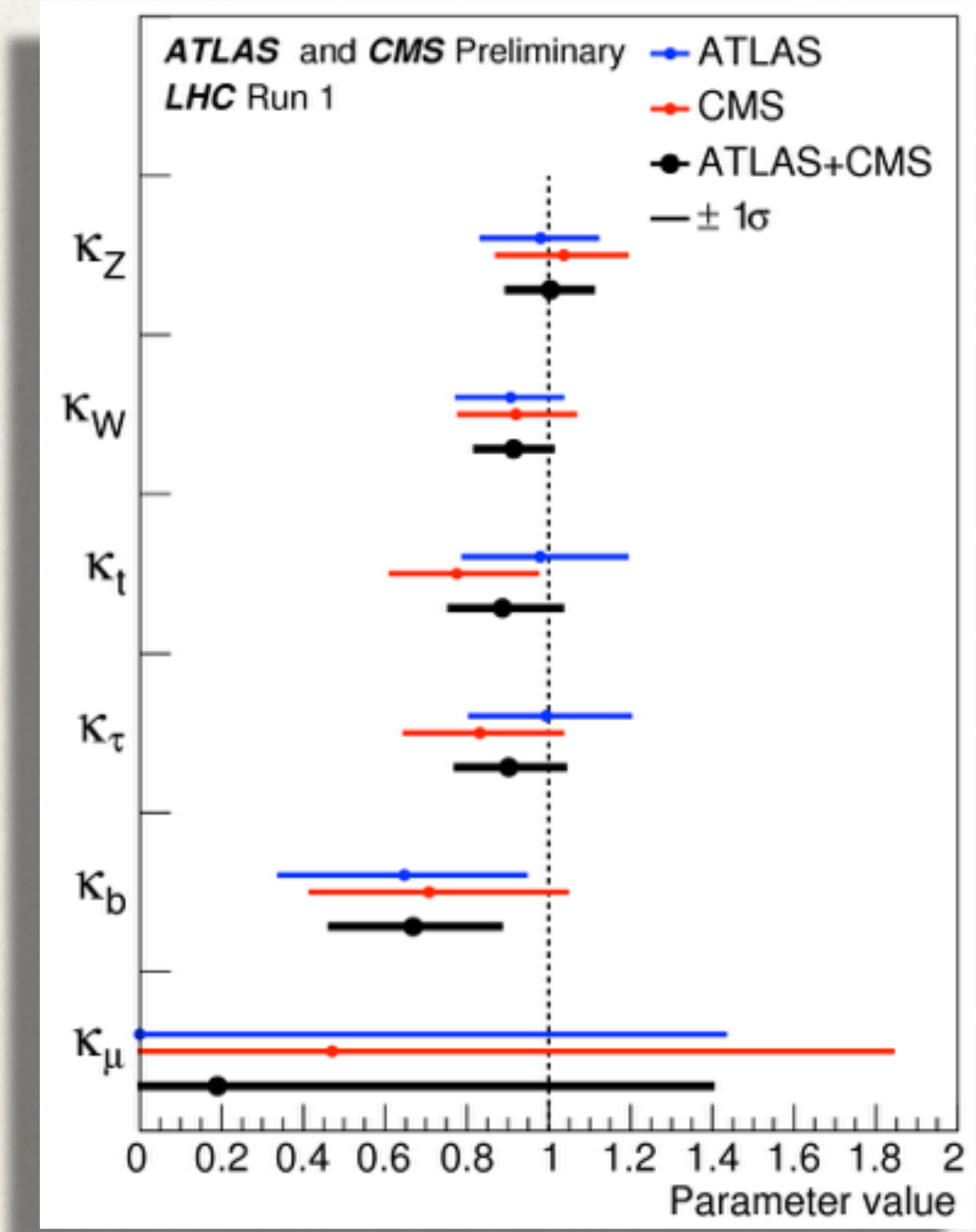
Must describe realistic conditions (fiducial cuts, arbitrary differential observables…) → fully differential

Ultimate limitation: non-perturbative corrections

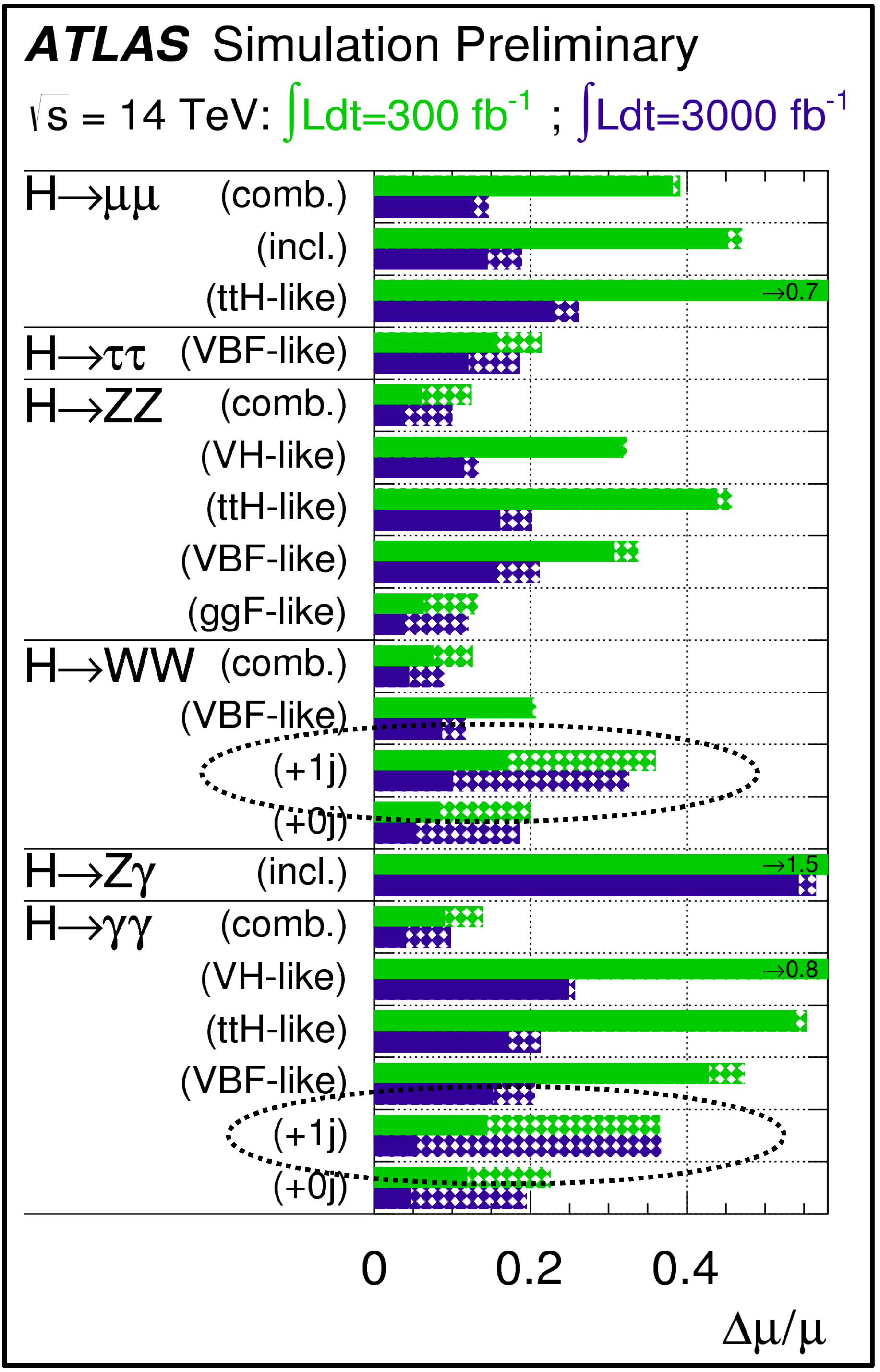
For typical electro-weak scale: ~ percent

Precision goals: the Higgs sector

LHC Run I



Run II and HL



Percent-level accuracy achievable experimentally → OUR TARGET

The path towards precision

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f(x_1) f(x_2) \mathrm{d}\sigma_{\mathrm{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q))$$

Input parameters: ~few percent.

In principle improvable

HARD SCATTERING MATRIX ELEMENT

- $\alpha_s \sim 0.1 \rightarrow$ percent-level accuracy requires second order (NNLO) computations
- For Higgs production: large gluon charges, $C_A \alpha_s \sim 0.3 \rightarrow$ third order (N^3LO) is desirable

NP effects: ~ few percent

No good control/understanding of them at this level

The hard matrix element

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f(x_1) f(x_2) \mathrm{d}\sigma_{\mathrm{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q))$$

Many different way to obtain more or less accurate estimations of the partonic cross section (soft/collinear approximations and resummation, PS merging…)

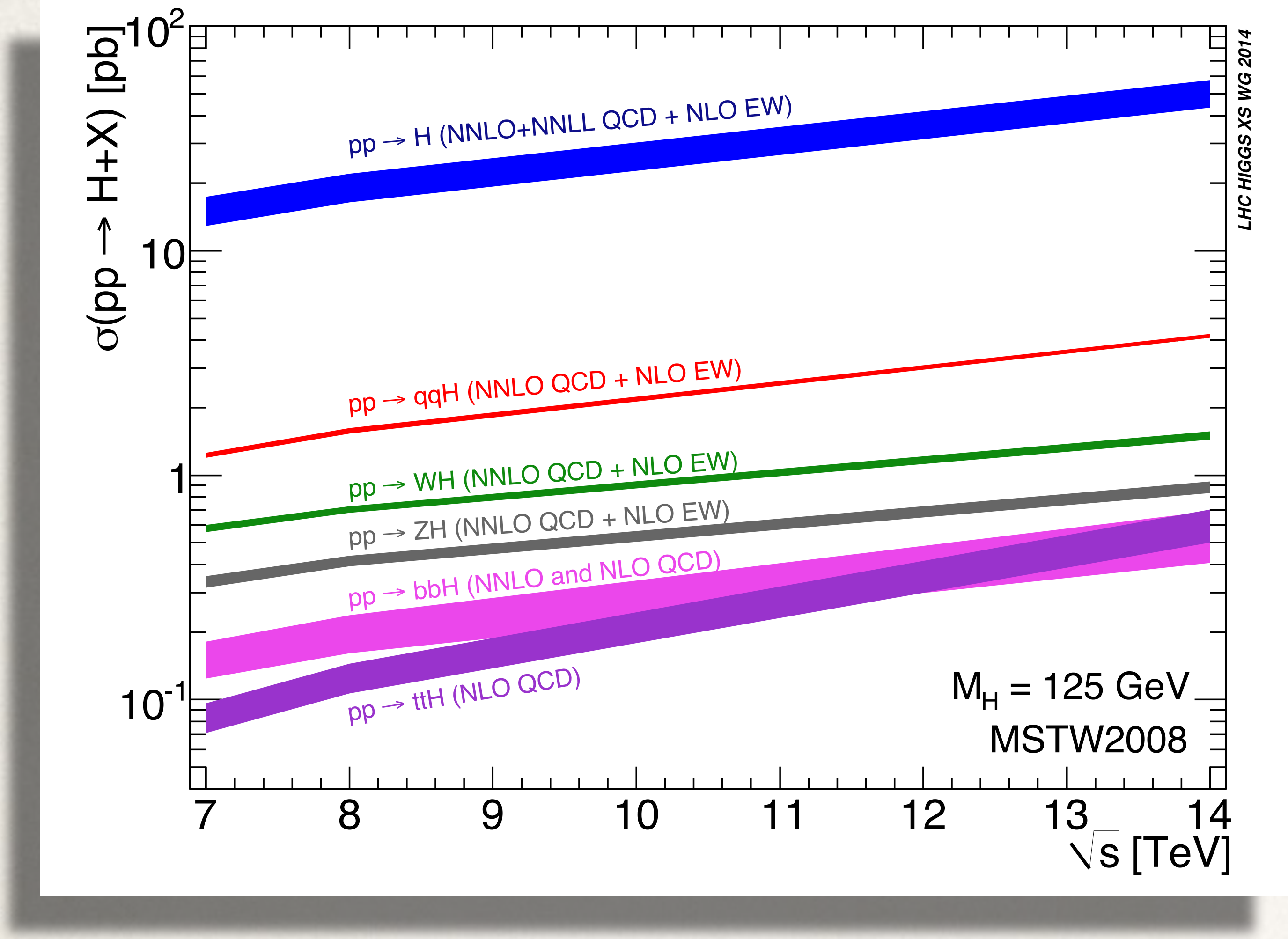
If HIGH PRECISION is sought however, PERTURBATIVE (FIXED ORDER) COMPUTATIONS are a very important instrument

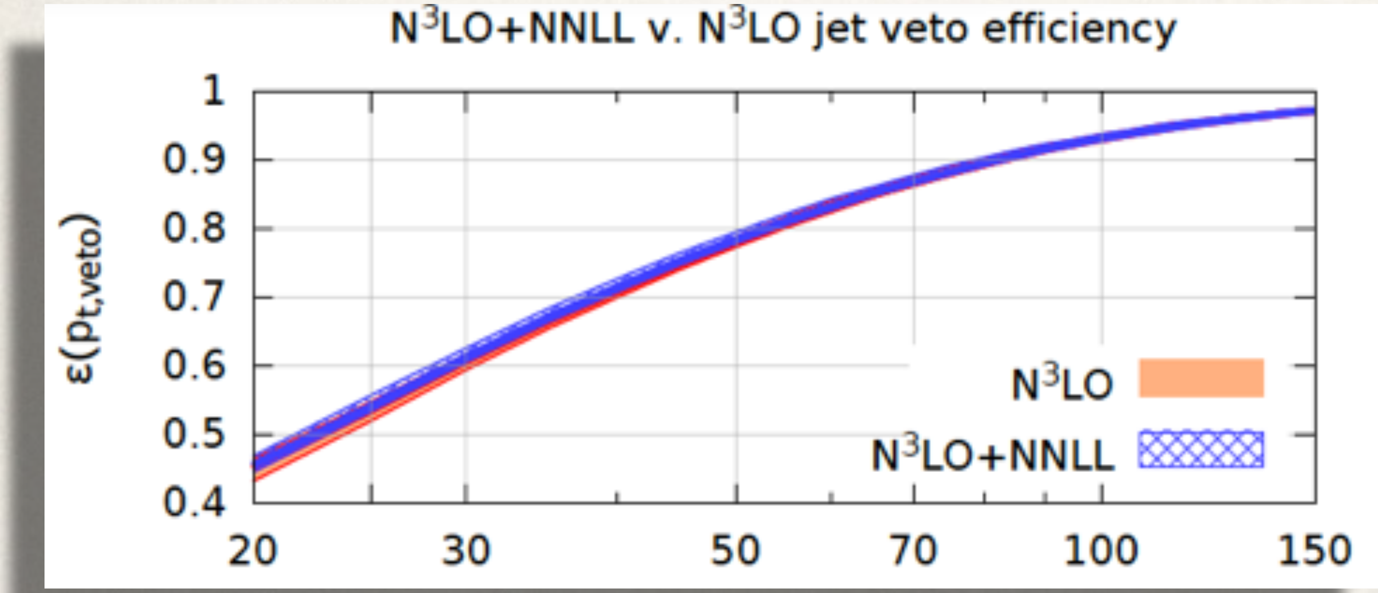
- controlled environment
- at the LHC, logs are often (≠ always) not so large → captured by fixed (high enough) order computations
- at high enough order, reasonable control on rates, shapes and uncertainties
- fiducial cuts, reliable modeling of experimental setup
- input for resummation

Pushing collider phenomenology to the boundary:

Higgs plus jet at NNLO in gluon fusion

Why Higgs plus Jet in gluon fusion





- Gluon fusion: bulk of the cross-section → precision
- Gluon have large color charges → easy to radiate extra jet. H+J: ~ 35% of σ_H
- Can give important information about Higgs properties (proxy for $p_{t,H}$, probe of the ggH coupling)
- In important channels (H→WW,H→ττ) jet veto to suppress background

Higgs: status of theoretical predictions

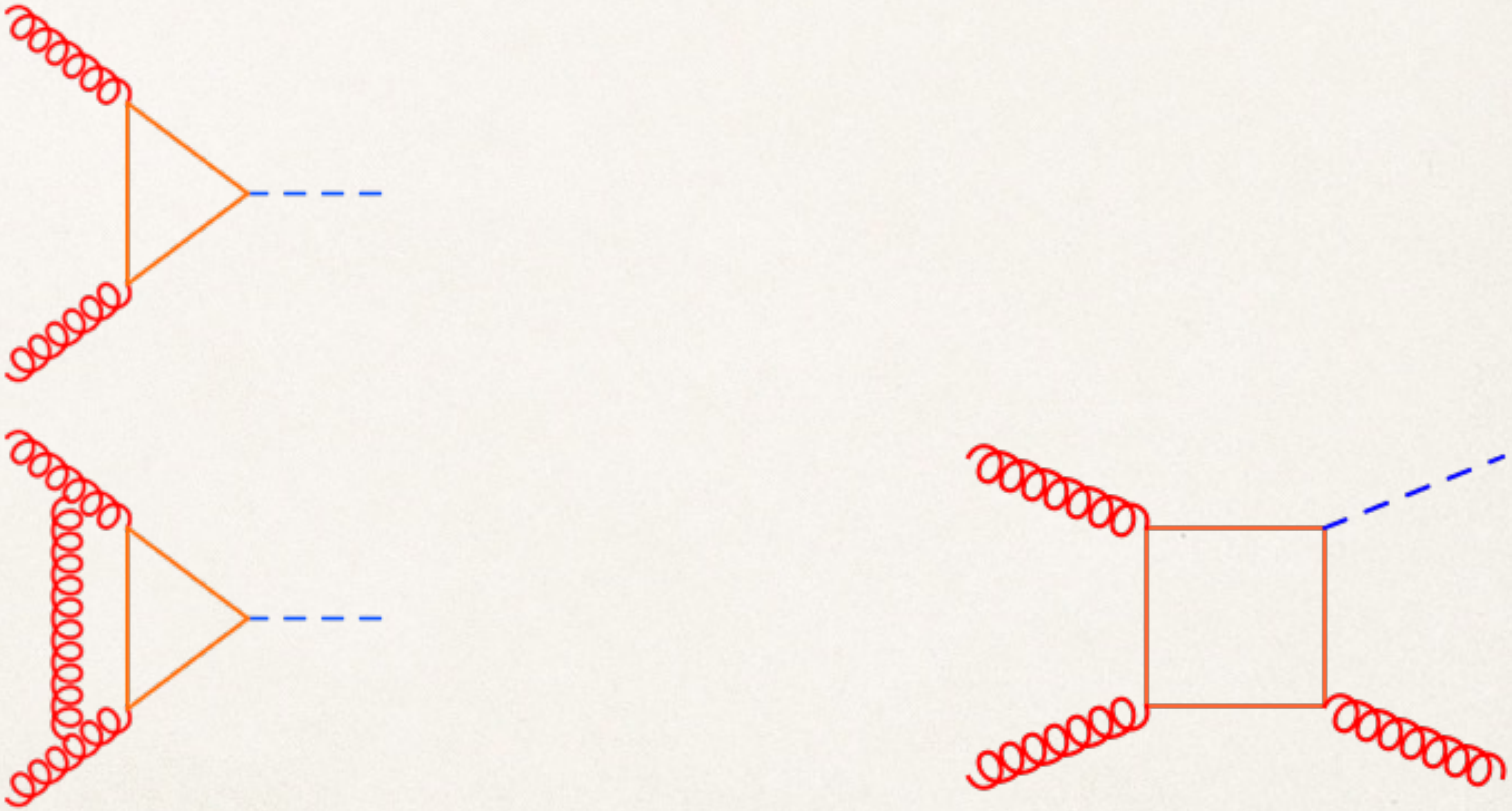
Higgs production in gluon fusion is a loop induced process → computing corrections involve complicated multi-loop amplitudes

HIGGS INCLUSIVE

H+J / HIGGS P_T

$\mathcal{O}(\alpha_s^2)$

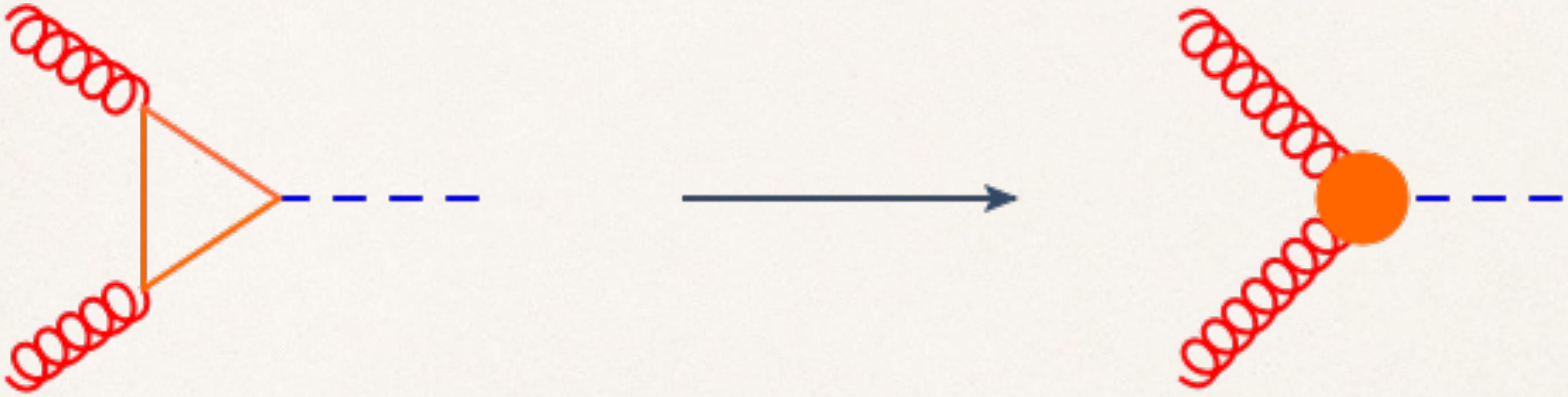
$\mathcal{O}(\alpha_s^3)$



NLO: ~100% corrections, clearly unsatisfactory result

Integrating out the top

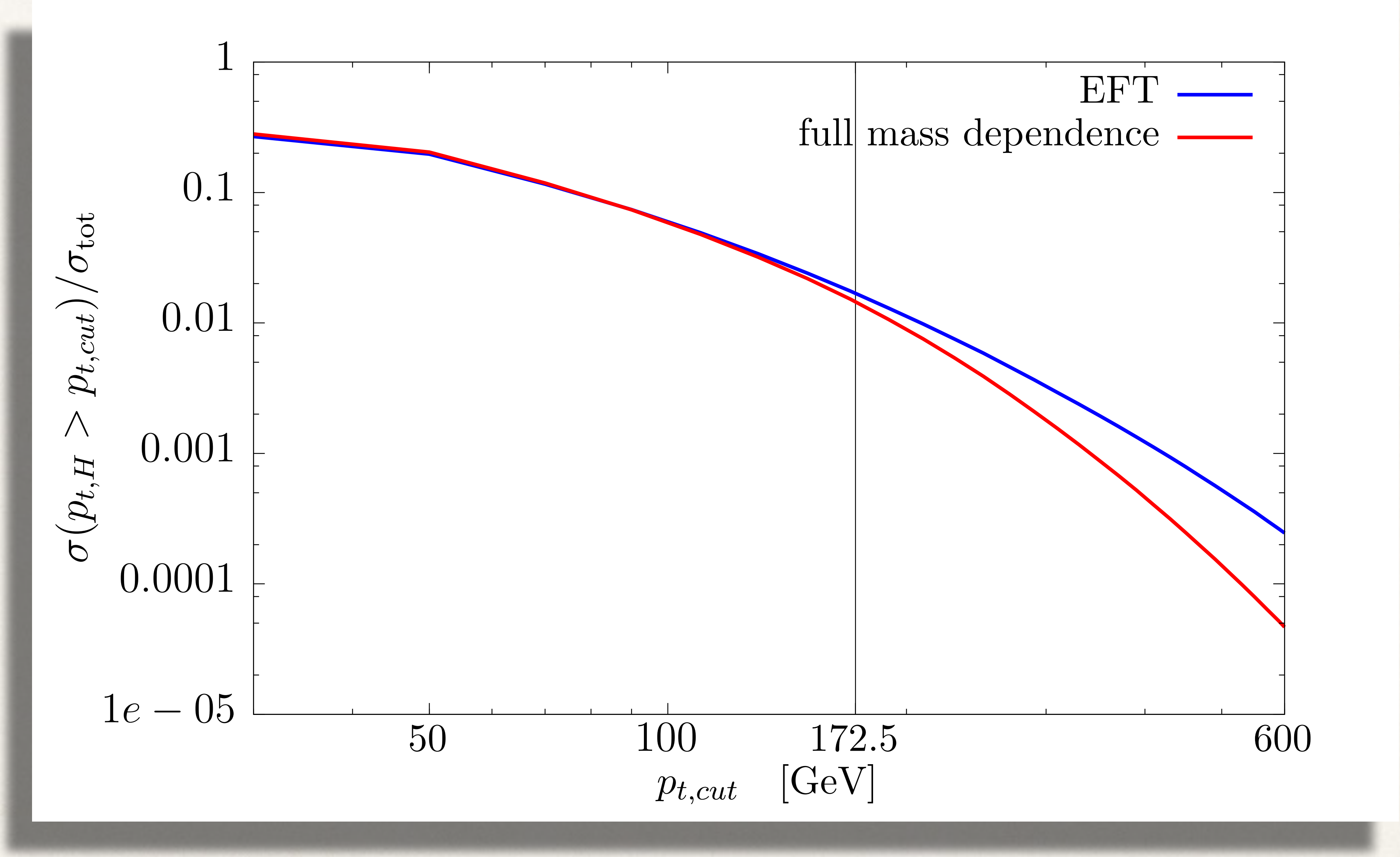
As long as the typical scale of the process is $Q \lesssim m_t$: short distance (i.e. top mass) physics is not resolved → effective point-like interaction



- This observation significantly simplifies computations (no internal structure). All advanced computations so far make use of this simplification
- In most cases, the typical scale of Higgs physics is $Q \sim m_H < m_t$, so this effective approximation is justified
- *Nevertheless, mass effects at the percent-level to be expected → we will have to improve on current technology to cope with them*

Integrating out the top

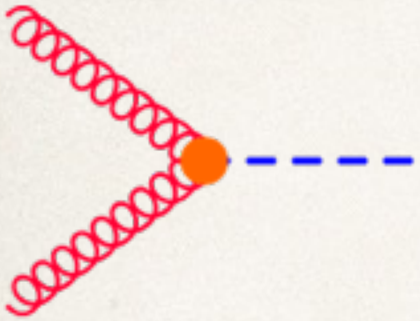
If the Higgs is produced in association with extra jet, the situation is potentially more dangerous: high-p_t jets can resolve the top loop

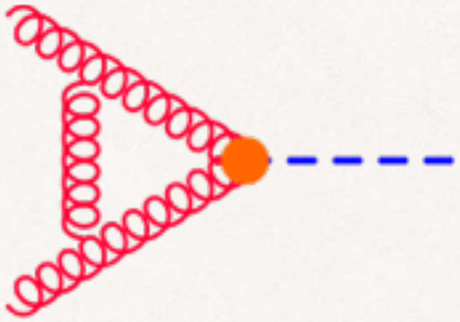


- Nevertheless, $d\sigma/dp_t^2 \sim 1/p_t^2$ so most of the events are in a region where the effective theory is reliable
- Only small fraction of events in the extreme high p_t region

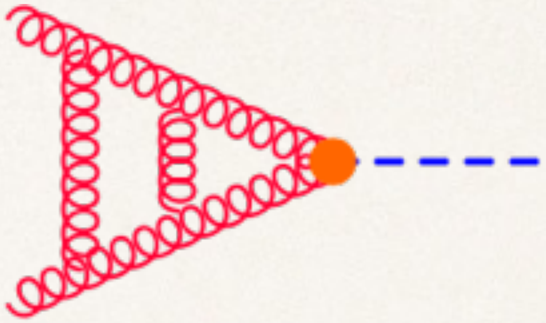
Integrating out the top: results

$\mathcal{O}(\alpha_s^2)$ $\mathcal{O}(\alpha_s^3)$ $\mathcal{O}(\alpha_s^4)$ $\mathcal{O}(\alpha_s^5)$

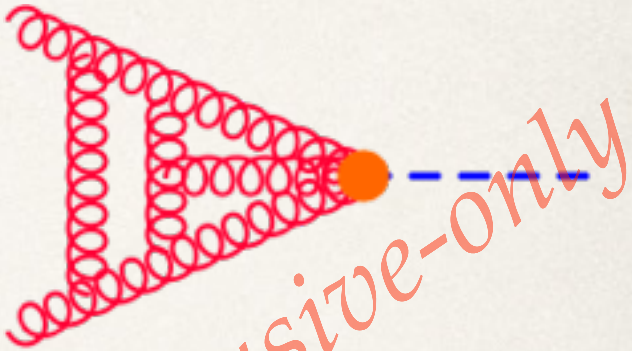




K~2, ~100% uncertainty



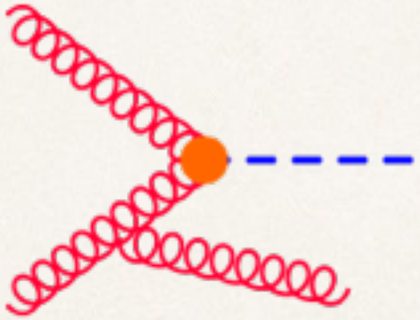
K~1.2, ~10% uncertainty

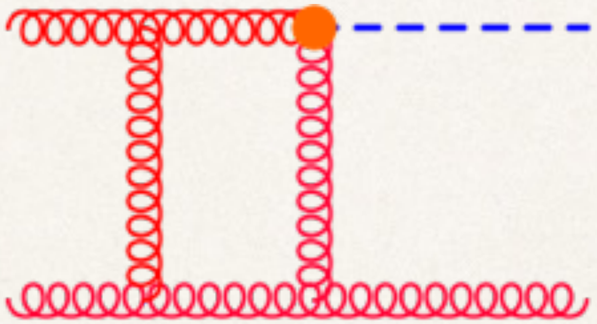


K~1.02, ~percent - level uncertainty

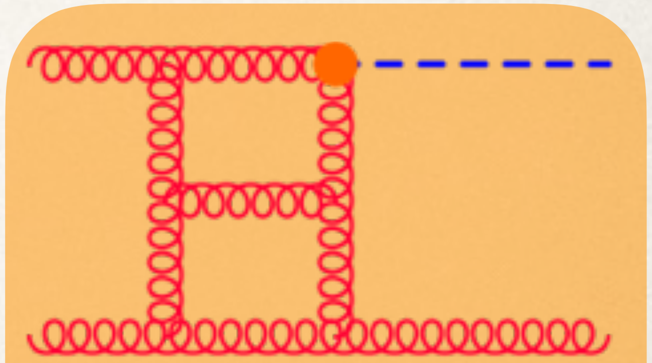
[Anastasiou et al., PRL (2015)]

fully inclusive-only





K~1.5, ~50% uncertainty

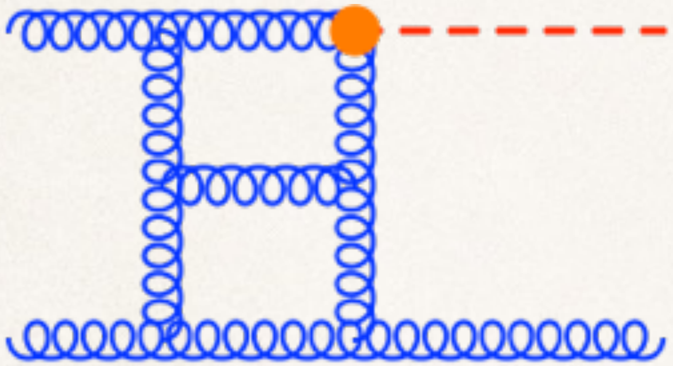


NNLO, fully exclusive

Anatomy of a NNLO computation

All required amplitudes known since long time

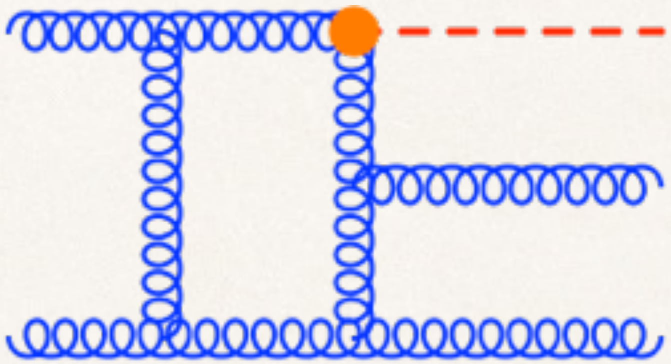
VV



Two-loop Amplitudes for H+J

Computed in 2011 [Gehrmann et al.]

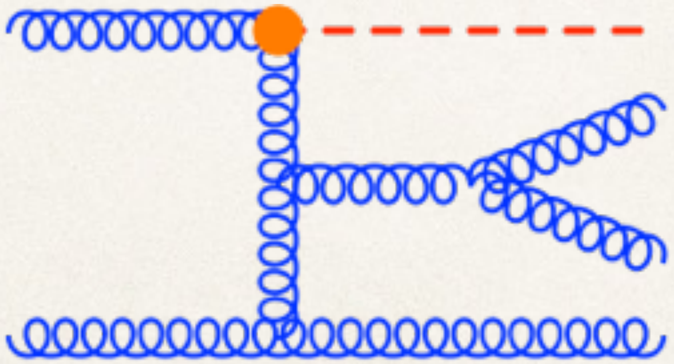
RV



One-loop Amplitudes for H+JJ

Compact analytical expressions known and implemented in MC programs [MCFM]

RR

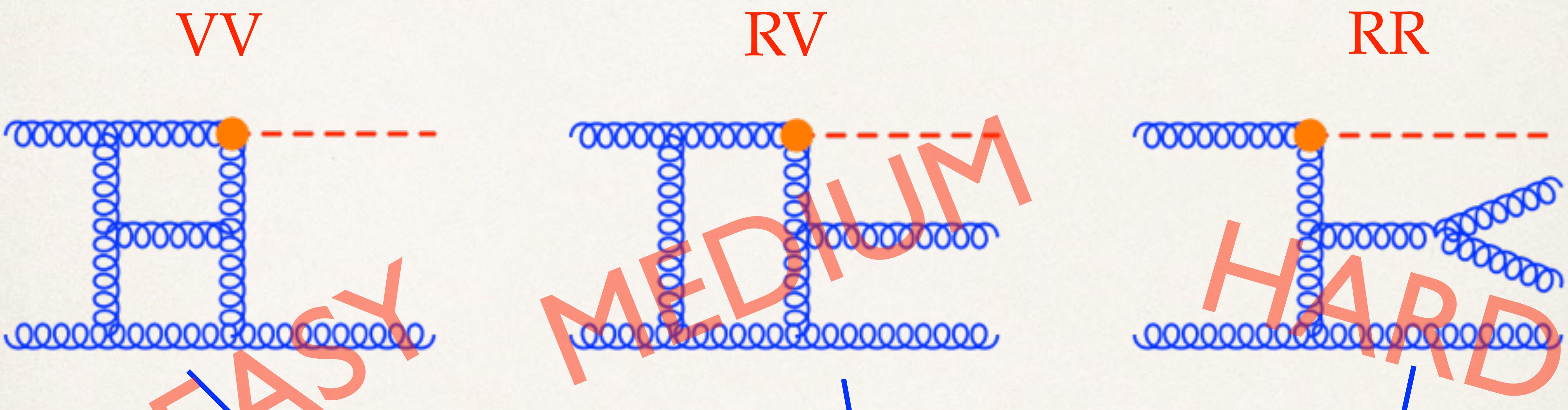


Tree-Level Amplitudes for H+JJJ

What prevented from doing the computation for so long?

Anatomy of a NNLO computation

The actual bottleneck for the computation was not the availability of two-loop amplitudes but how to consistently handle IR singularities



$$\int \left[\frac{\mathrm{vv}_4}{\epsilon^4} + \frac{\mathrm{vv}_3}{\epsilon^3} + \frac{\mathrm{vv}_2}{\epsilon^2} + \frac{\mathrm{vv}_1}{\epsilon} + \mathrm{vv}_0\right] d\phi_2$$

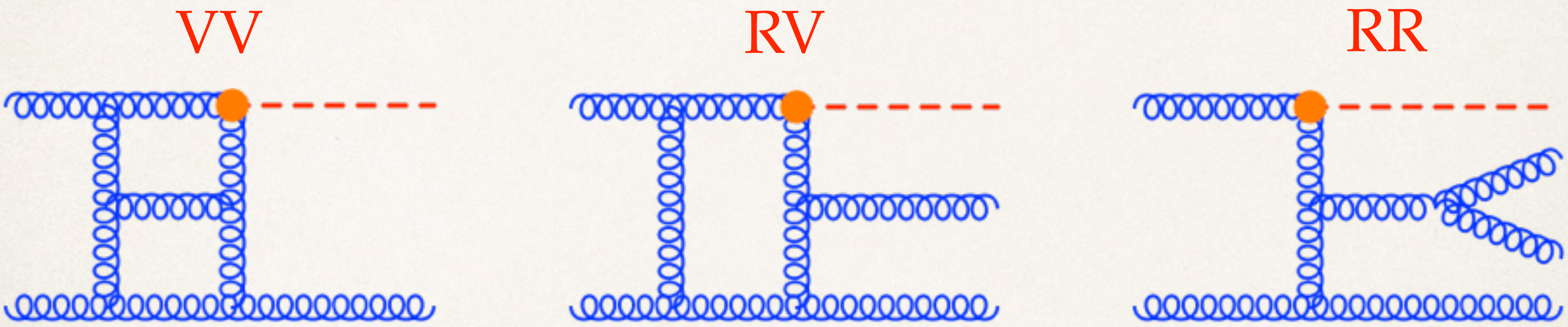
$$\int [\mathrm{rr}_0]\, d\phi_4$$

$$\int \left[\frac{\mathrm{rv}_2}{\epsilon^2} + \frac{\mathrm{rv}_1}{\epsilon} + \mathrm{rv}_0\right] d\phi_3$$

COMPLICATED IR STRUCTURE HIDDEN IN THE PHASE SPACE INTEGRATION

Anatomy of a NNLO computation

The actual bottleneck for the computation was not the availability of two-loop amplitudes but how to consistently handle IR singularities



- IR singularities (long-distance physics) hidden in PS integration
- After integration, all singularities are manifest and cancel (KLN)
- We are interested in FULLY DIFFERENTIAL results (arbitrary cuts, arbitrary observables) → we are not allowed to integrate over the PS
- The challenge: extract PS-integration singularities without actually performing any integration. Highly non trivial

The problem 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)

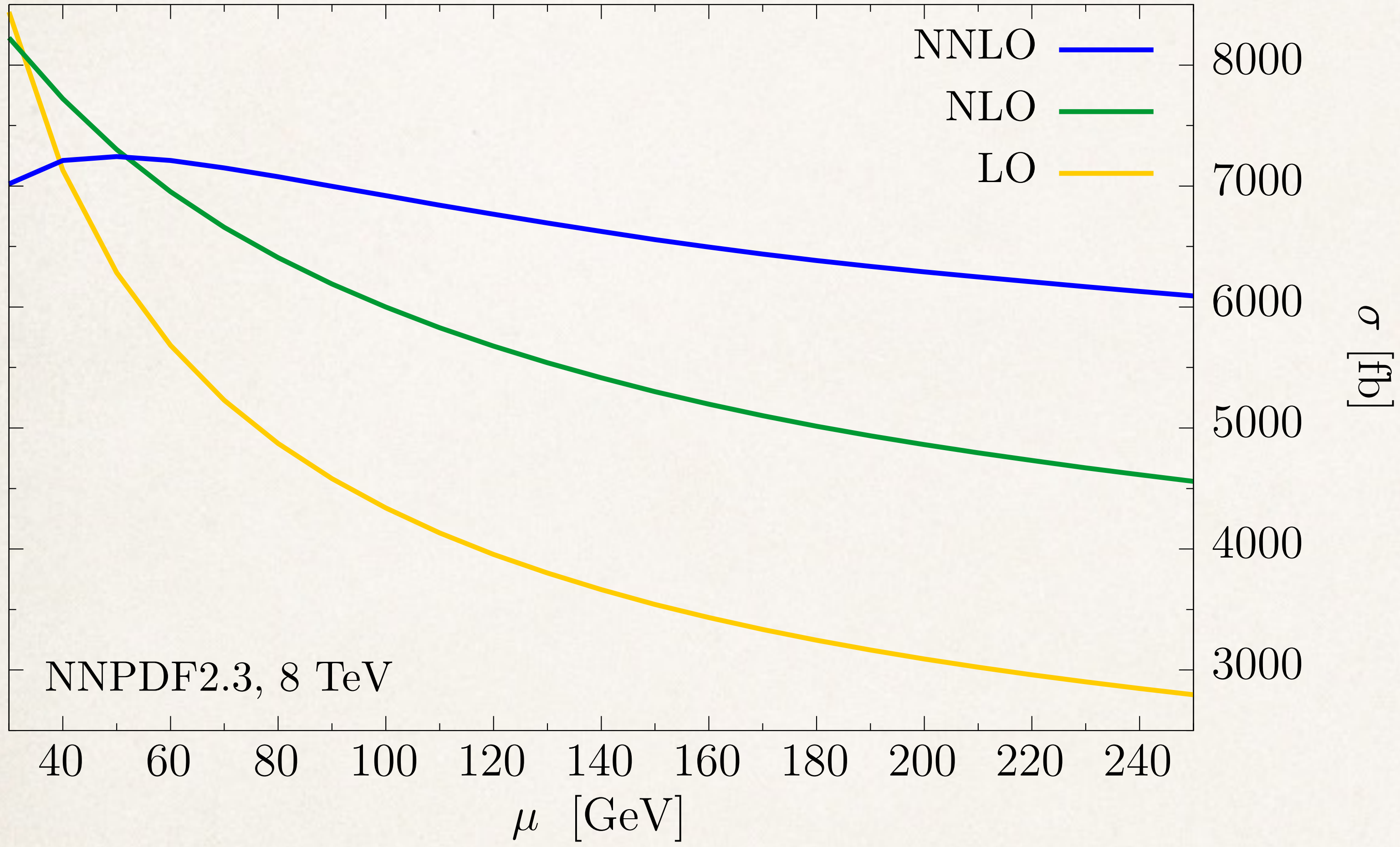
- Thanks to a big effort in the community, we now see first glimpses towards solutions: antenna, sector decomposition +FKS/STRIPPER, colorful NNLO, N-jettines/q_T slicing…

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

Higgs plus Jet@NNLO: results

[Boughezal, FC, Melnikov, Petriello, Schulze, PRL (2015)]

THE SETUP: LHC8, anti-k_t R=0.5, $p_{t,jet} > 30$ GeV, $\mu = m_H$.
Only approximation: EFT ($m_t \to \infty$)



$$\sigma_{\rm LO} = 3.9^{+1.7}_{-1.1}\ {\rm pb}$$

$$\sigma_{\rm NLO} = 5.6^{+1.3}_{-1.1}\ {\rm pb}$$

$$\sigma_{\rm NNLO} = 6.7^{+0.5}_{-0.6}\ {\rm pb}$$

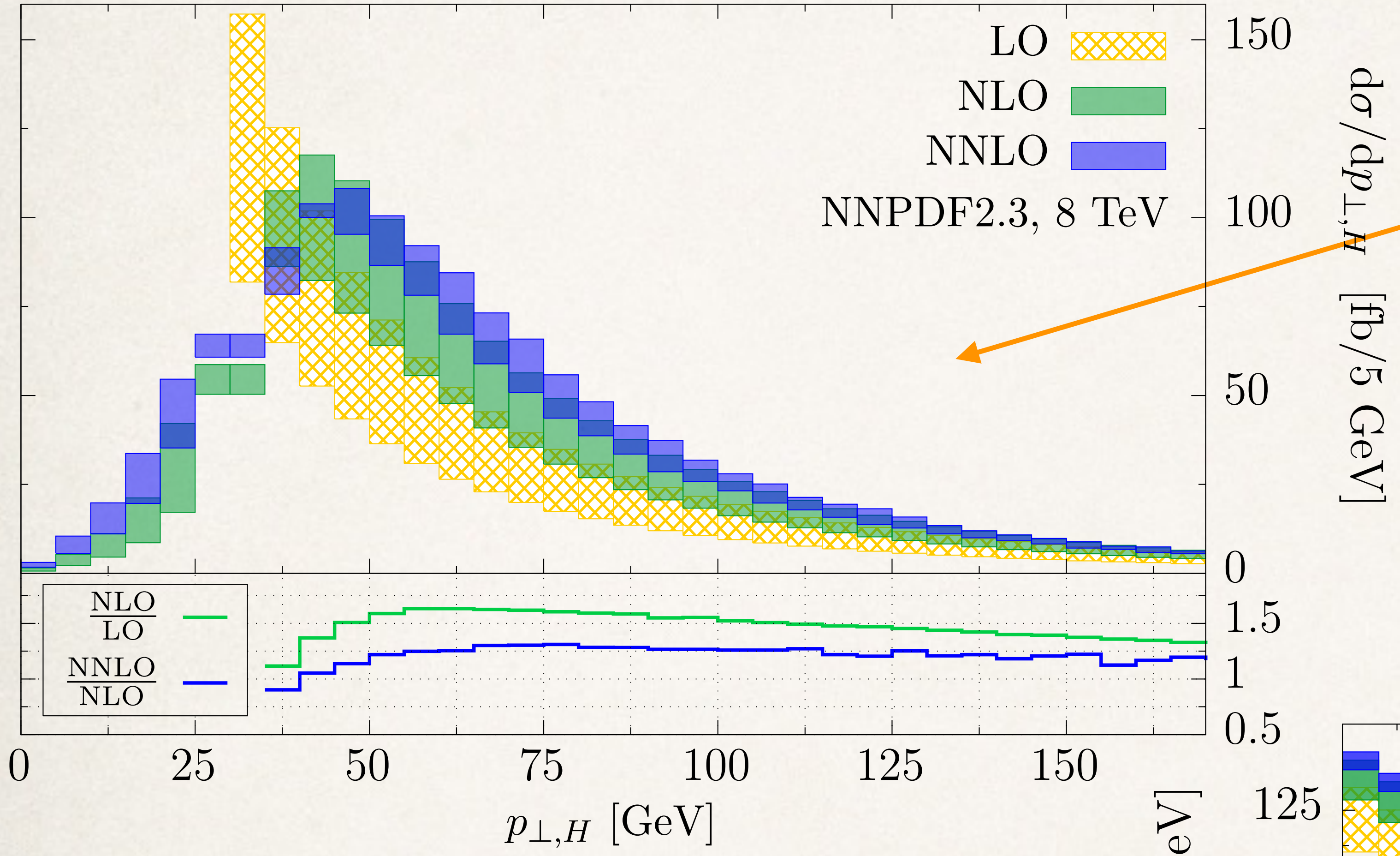
$$K_{\rm NNLO} \sim 20\%$$

$$\delta_{\rm PDF} \sim 5\%$$

- Significantly improved scale uncertainty (makes discussion of dynamical scale largely irrelevant)
- Still sizable correction for $\mu = m_H$, smaller for $\mu = m_H/2$ [$K_{\rm NNLO}$=4%].
  First sign of perturbative convergence

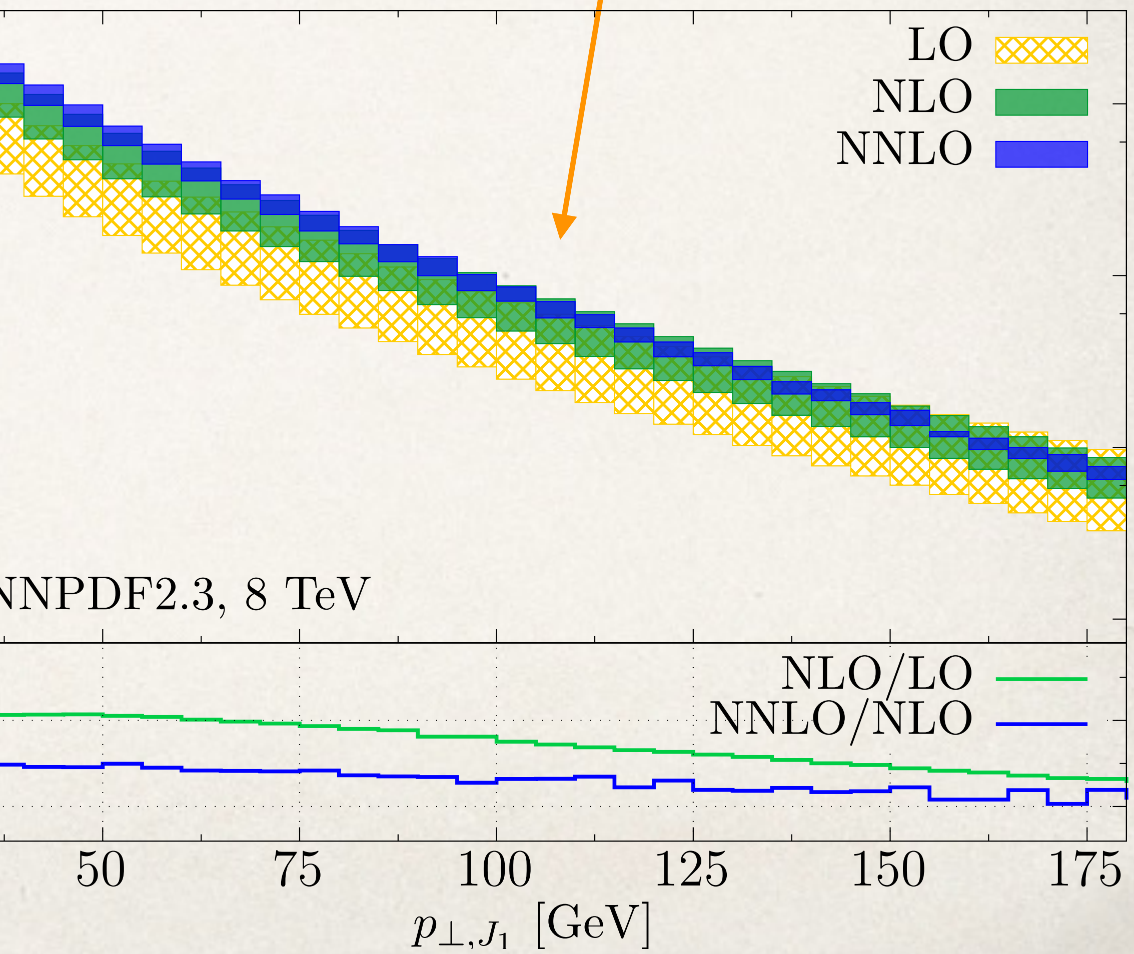
Differential distributions

[Boughezal, FC, Melnikov, Petriello, Schulze, PRL (2015)]



Higgs p_T, LHC8

Leading jet p_T, LHC8



- NNLO greatly stabilizes results
- Non-trivial K-factor shape
- Reasonable convergence
- No sign of perturbation theory breakdown for $p_{t,j} \gtrsim 30$ GeV

A step closer to reality: fiducial analysis

- If very high precision is sought, it becomes important to reduce to a minimum unnecessary extrapolations from uncontrolled sources (e.g. PS acceptance corrections)

- Fully exclusive computations are able to deal with arbitrary cuts on final state partons

- For Higgs plus jet: can exactly reproduce experimental analysis in terms of cuts on photons ($H \to \gamma\gamma$)/leptons ($H \to WW/ZZ$) and jets

- Allow for an unbiased data/theory comparison

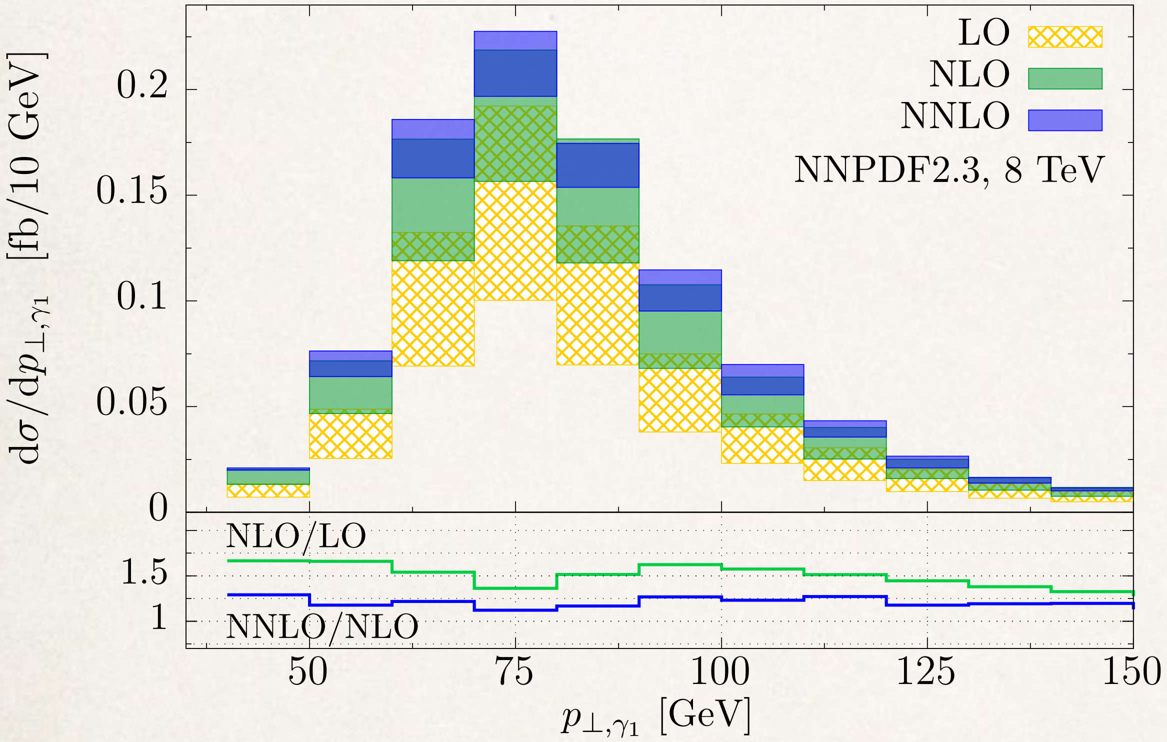
- `Nice' experimental cuts: no need for extrapolations after this → insensitive to soft physics (*interesting topic for precision frontier, e.g. symmetric cuts…*)

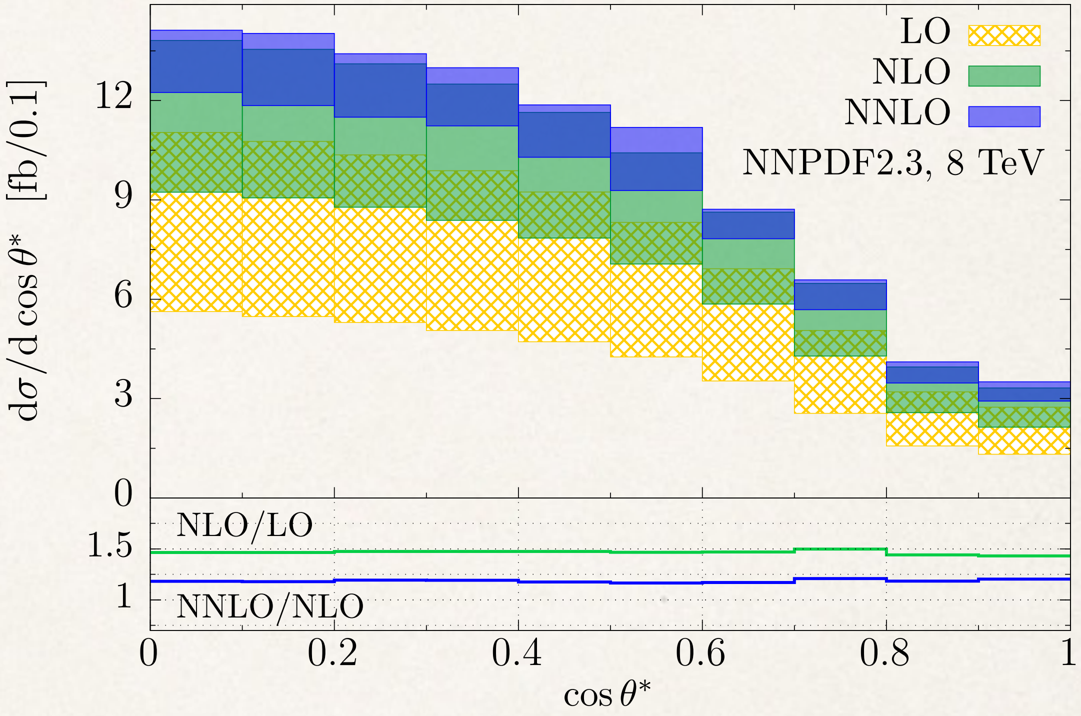
Fiducial analysis: $H \to \gamma\gamma$

[FC, Melnikov, Schulze (2015)]

SETUP: ATLAS 8 TEV ANALYSIS

Anti-k_t with R=0.4, $p_{t,j} > 30$ GeV, $|y_j| < 4.4$, $p_{t,\gamma} > \max(25\text{ GeV}, 0.35/0.25\, m_{\gamma\gamma})$, $|y_\gamma| < 2.37$, no photons with $1.37 < |y_\gamma| < 1.56$, $\Delta R_{\gamma j} > 0.4$

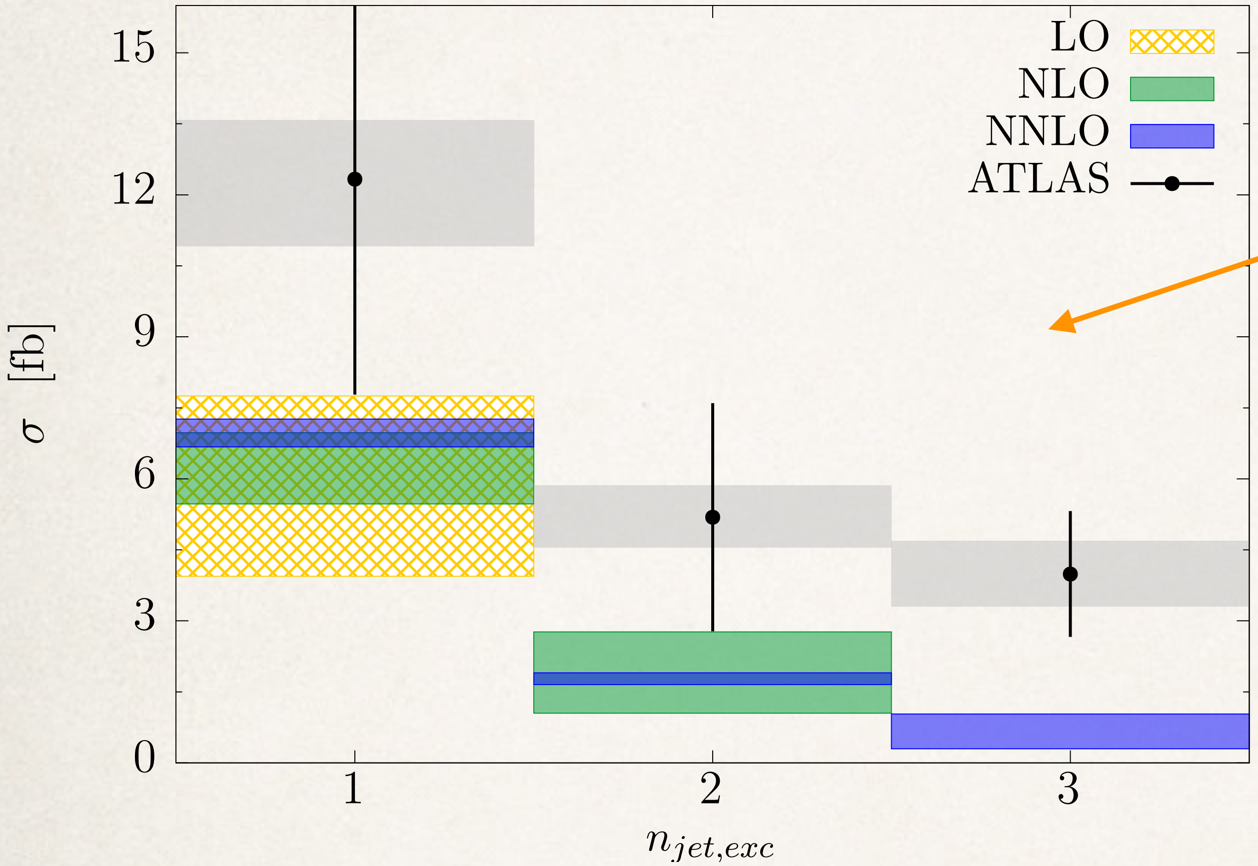




- Reduced uncertainties
- Stable shapes
- Virtually no shape correction for $\cos(\theta^*)$ → Higgs characterization

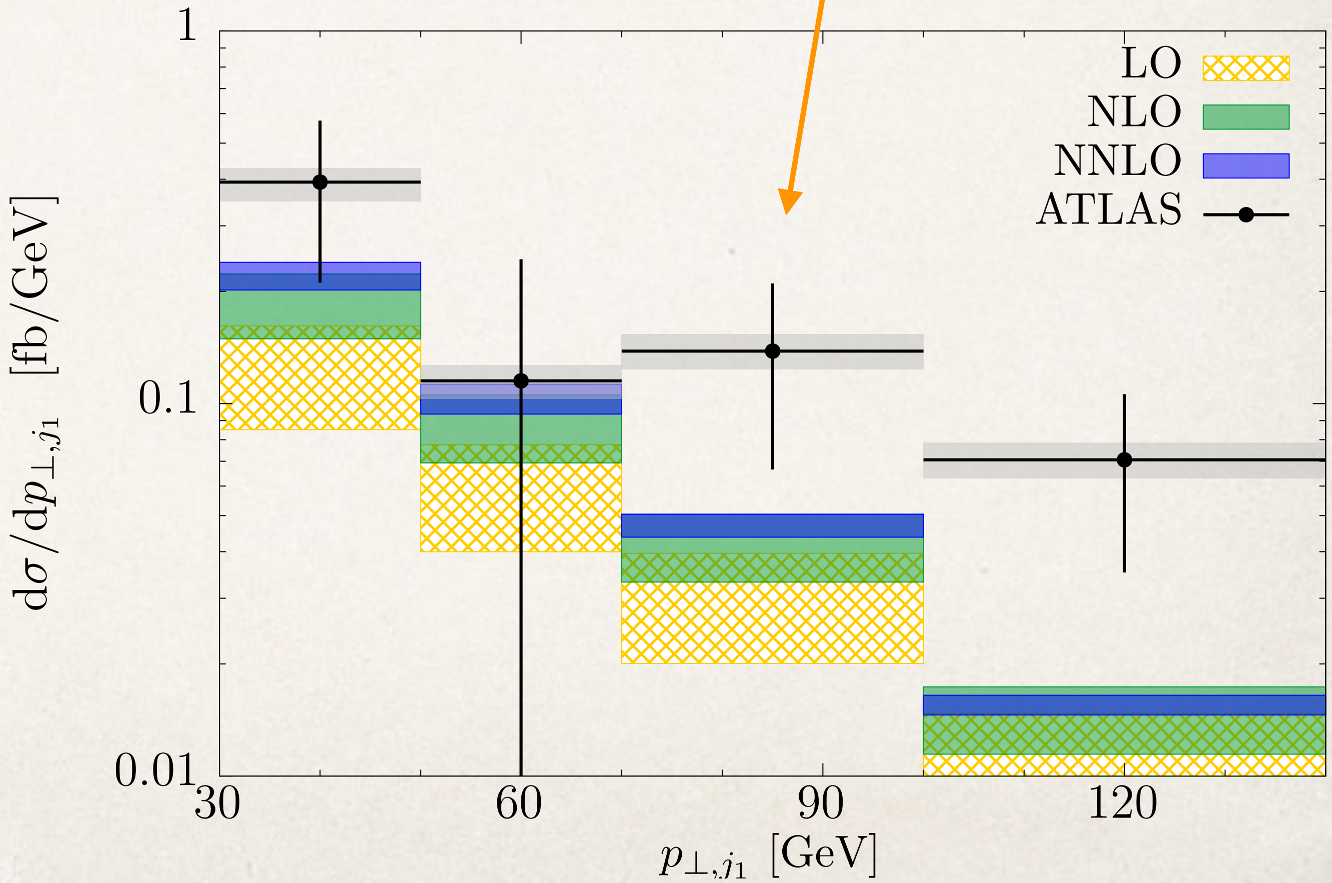
Fiducial analysis: $H \to \gamma\gamma$

[FC, Melnikov, Schulze (2015)]



Exclusive Jet bins, ATLAS8

Leading jet p_T, ATLAS8



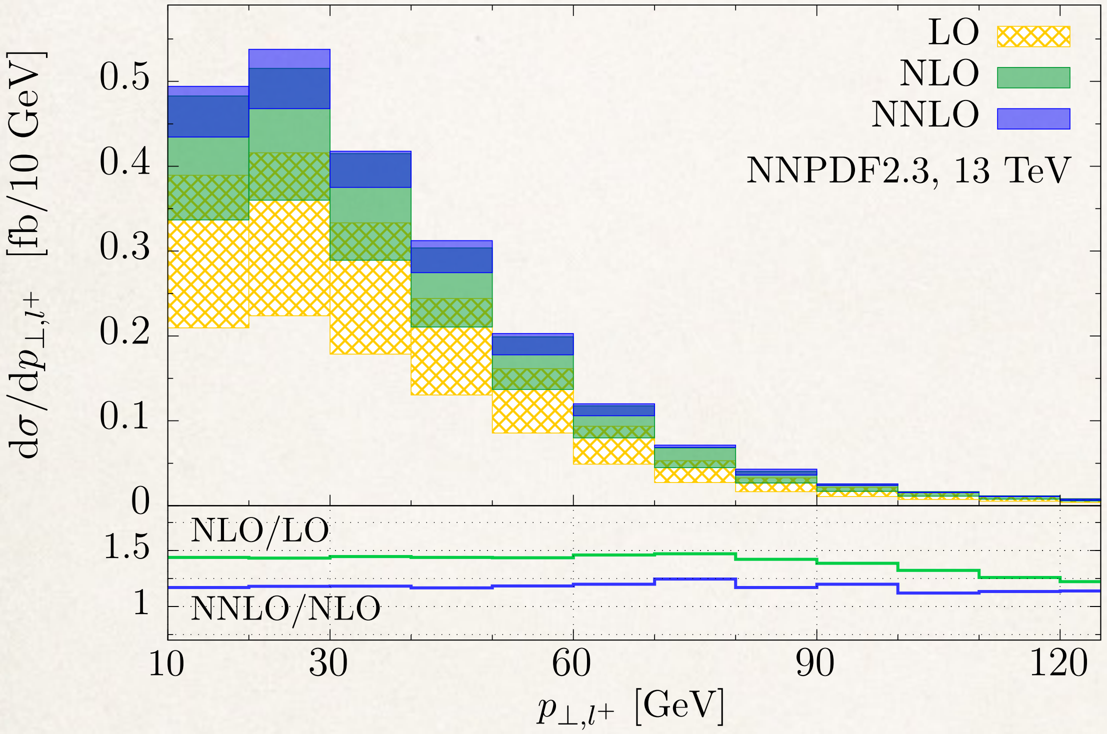
Still very large statistical fluctuations for these analysis to mean much, but NNLO theory error ~ systematic error

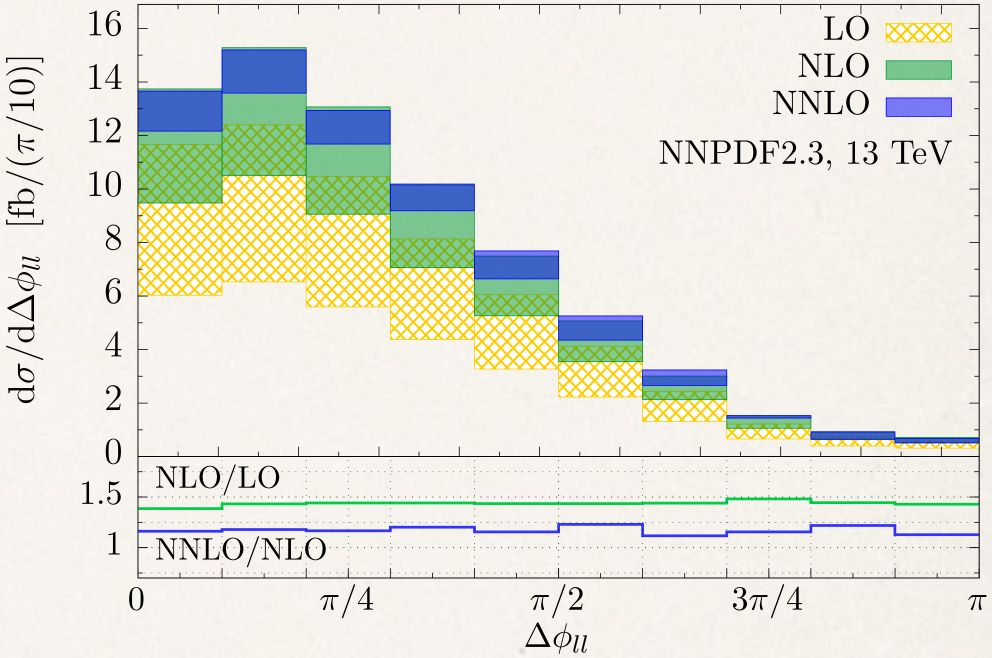
Fiducial analysis: $H \rightarrow 2l2\nu$

[FC, Melnikov, Schulze (2015)]

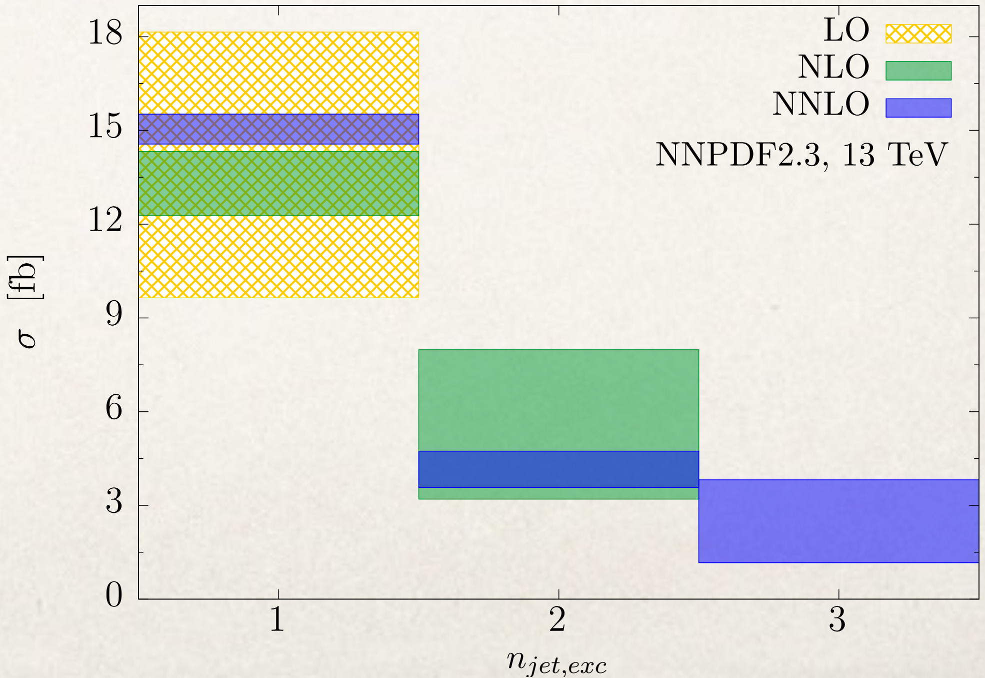
SETUP: CMS-LIKE ANALYSIS, 13 TEV

Anti-k_t with R=0.4, $p_{t,j} > 30$ GeV, $|y_j| < 4.7$, $p_{t,l} > 20/10$ GeV, $E_{t,miss} > 20$ GeV, $m_{ll} > 12$ GeV, $p_{t,ll} > 30$ GeV, $m_{t,WW} > 30$ GeV



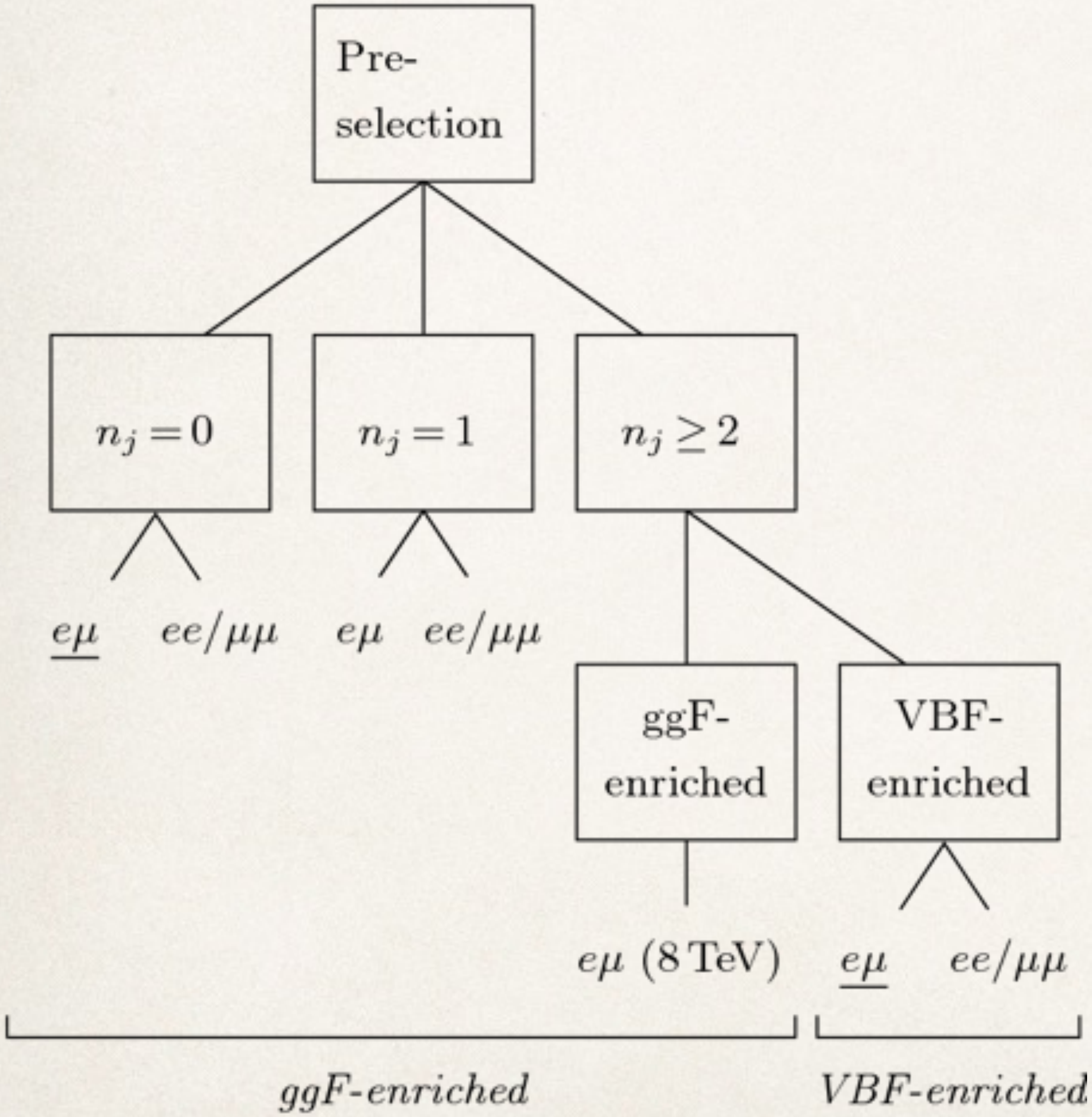


NNLO able to cope with complicated final states (up to 7 particles)



Further applications: Jet Veto analysis

Experimental analysis for $pp \rightarrow H \rightarrow WW$ (similar for $\tau\tau$)
binned according to jet multiplicity (different systematics)



Pre-selection

$n_j = 0$

$n_j = 1$

$n_j \geq 2$

$e\mu$ $ee/\mu\mu$

$e\mu$ $ee/\mu\mu$

ggF-enriched

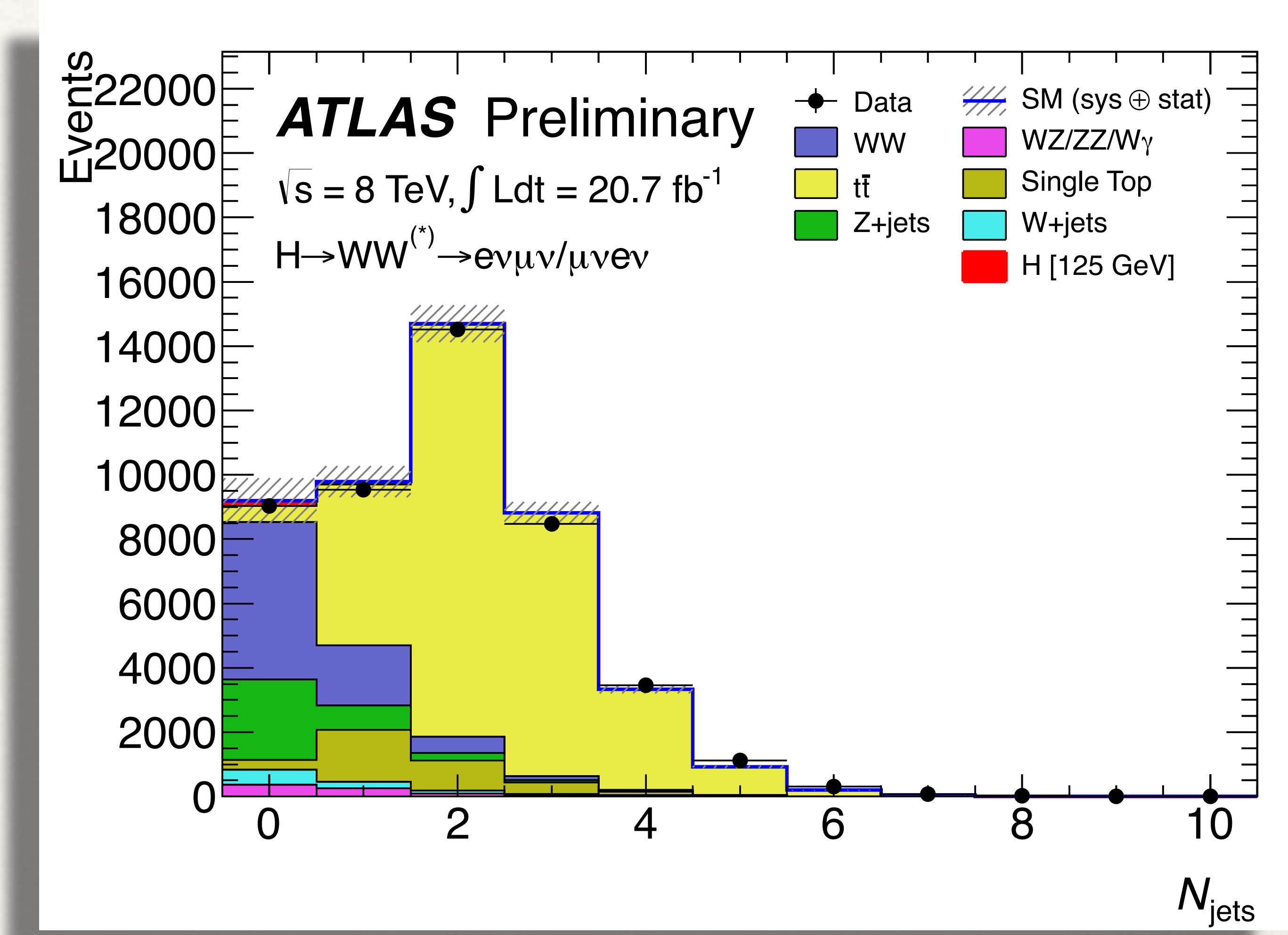
VBF-enriched

$e\mu$ (8 TeV)

$e\mu$ $ee/\mu\mu$

ggF-enriched

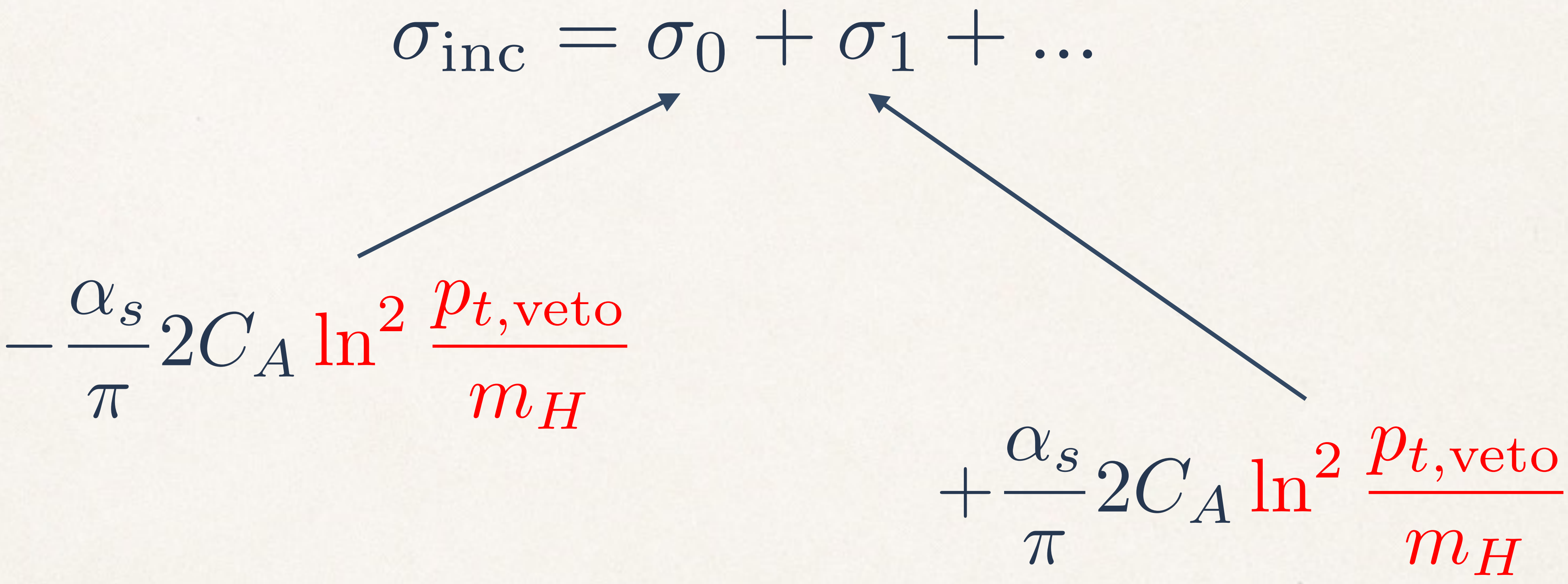
VBF-enriched



Experimentally required to increase sensitivity and S/B discrimination

The problem of jet binning: veto log

In general, putting sharp constraints on the phase space (e.g. veto emission) leads to logarithmically enhanced contributions



$$\sigma_{\rm inc} = \sigma_0 + \sigma_1 + \ldots$$

$$-\frac{\alpha_s}{\pi} 2C_A \ln^2 \frac{p_{t,\rm veto}}{m_H}$$

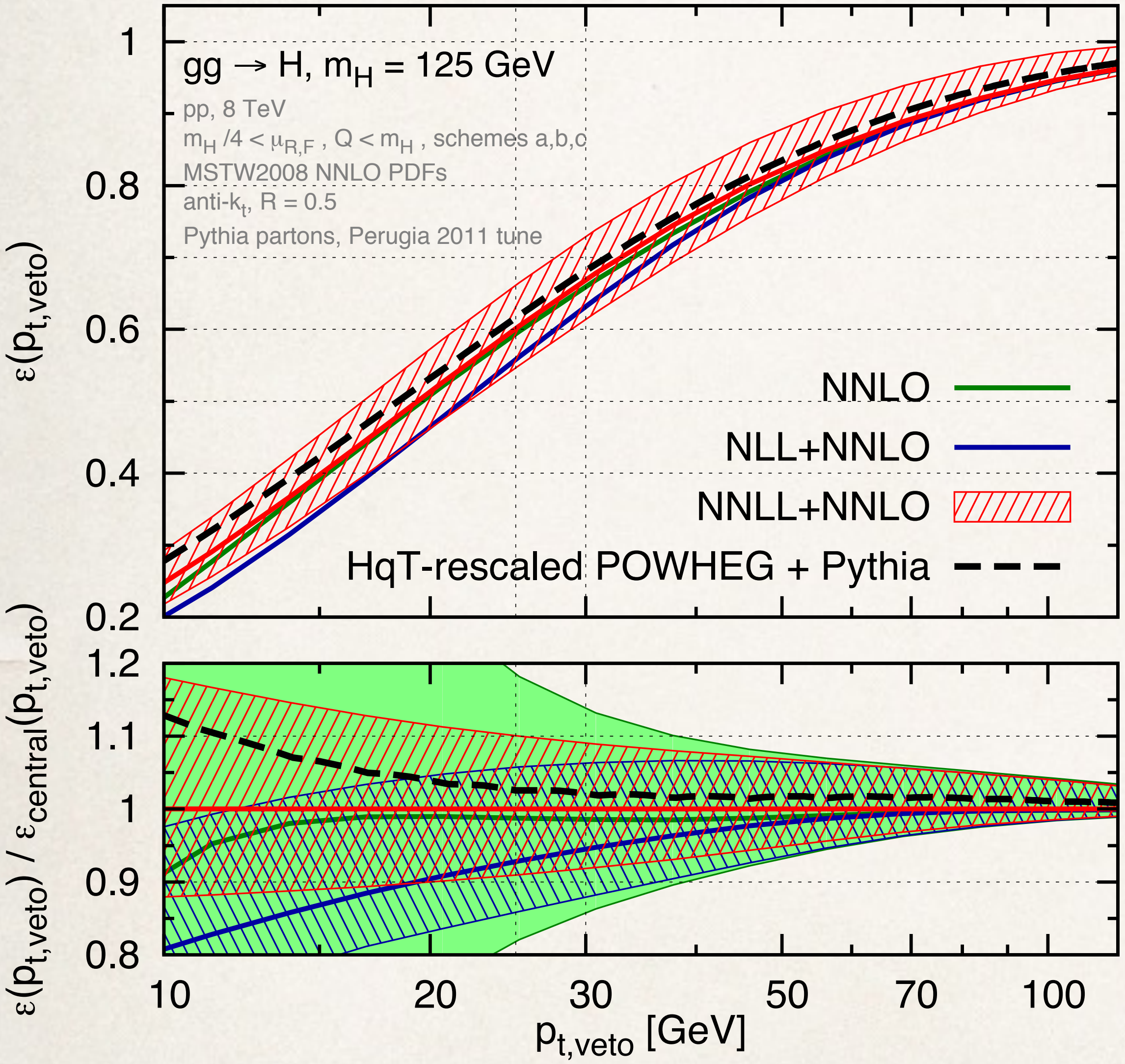
$$+\frac{\alpha_s}{\pi} 2C_A \ln^2 \frac{p_{t,\rm veto}}{m_H}$$

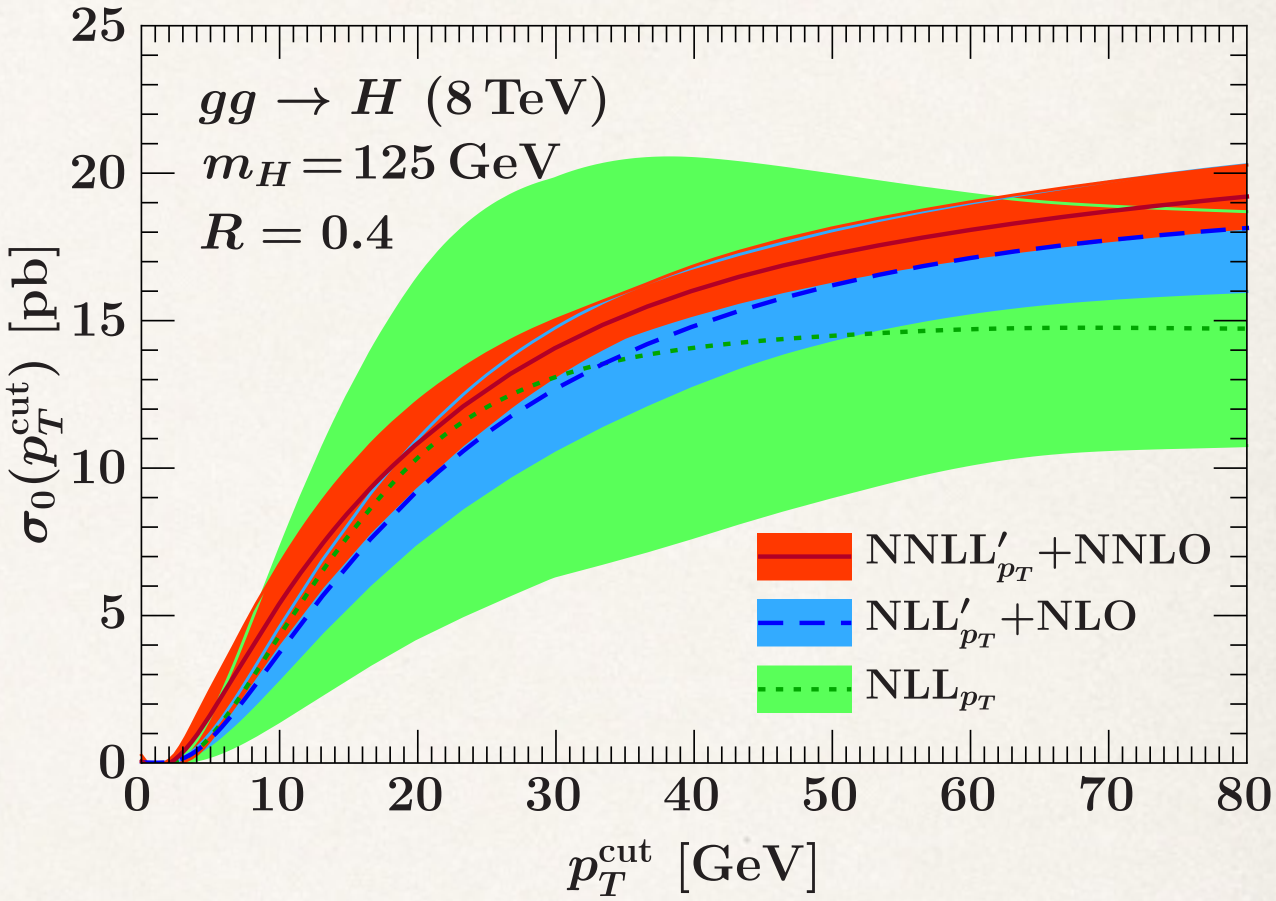
- For $p_{\rm t,veto}$ = 30 GeV: ~40% effect, on top of already large perturbative corrections
- Can spoil perturbative convergence, and give rise to spurious cancellations (→ accidentally small scale variation uncertainties)

Resummation at NNLO+NNLL

Resummation program in good shape

[Banfi et al, Stewart, Tackmann et al (2013); Liu, Petriello (2013); Boughezal et al (2014); Becher et al (2014)]





- Logs under control
- Still large uncertainties, driven by fixed order (large p_t). Potentially large h.o.
- $p_t \sim 40$ GeV: onset of perturbative breakdown

Jet veto: N^{3}LO+NNLL

[Banfi, FC, Dreyer, Monni, Salam, Zanderighi and Dulat (2015)]

$$\sigma_{\rm inc} = \sigma_0 + \sigma_1 + \ldots$$

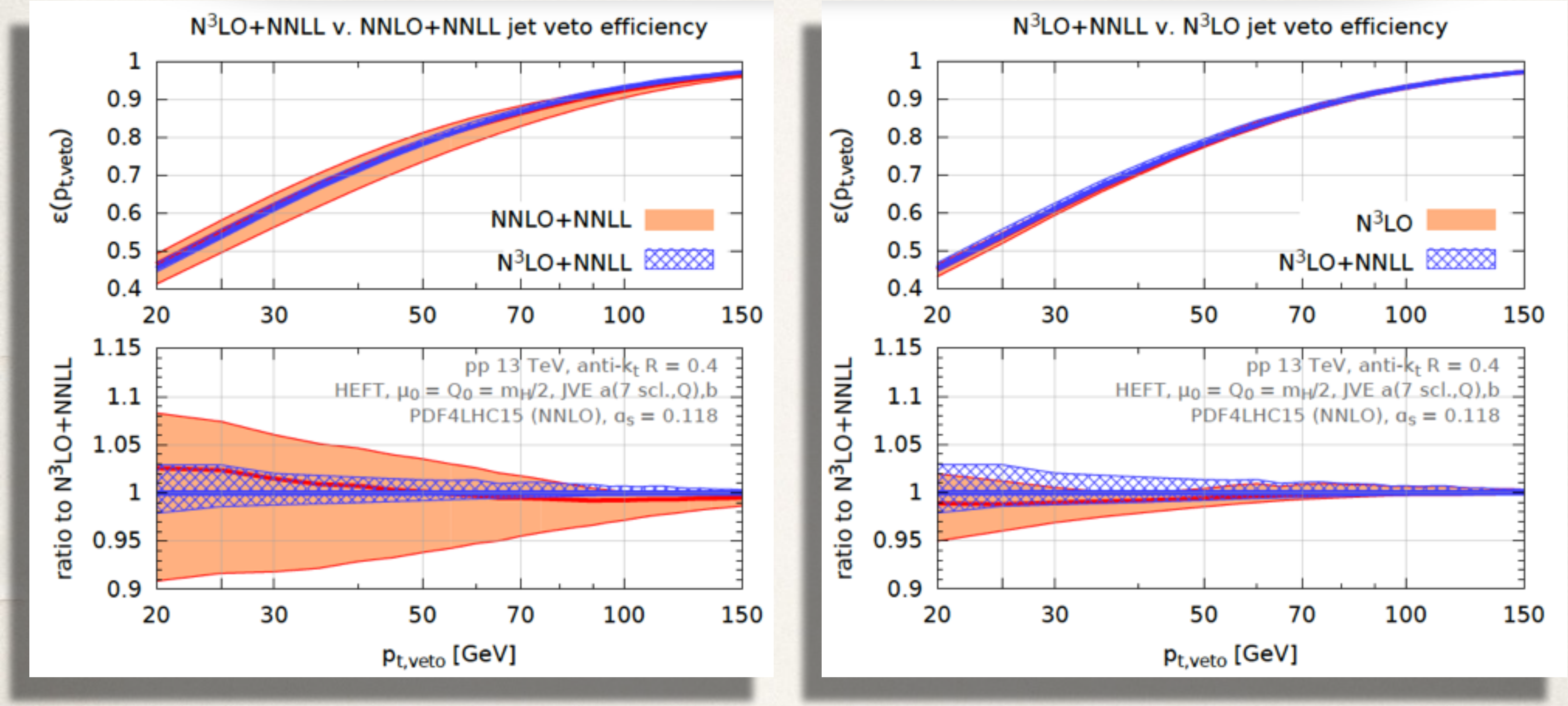
Fully inclusive N^{3}LO cross-section

Fully differential NNLO H+J

- Combining inclusive N^{3}LO results for the total cross section and the NNLO H+J computation described above allows to compute σ_0 at $O(\alpha_s^5)$, i.e. N^{3}LO
- Can be matched to resummation to study jet veto physics to a new level of accuracy
- Allow for reliable error estimates for vetoed cross-sections and efficiencies ($\varepsilon=\sigma_0/\sigma_{\rm inc}$)

Jet veto at N^{3}LO+NNLL: results

[Banfi, FC, Dreyer, Monni, Salam, Zanderighi and Dulat (2015)]



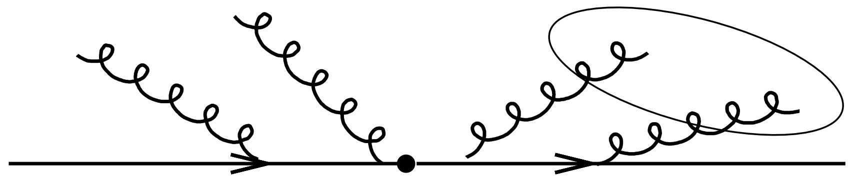
- Corrections moderate (previous uncertainty estimates over-conservative)
- No breakdown of perturbation theory for $p_t > 20$ GeV
- Fixed (high) order properly captures the logs at the 1-2% level

Jet veto: detailed analysis

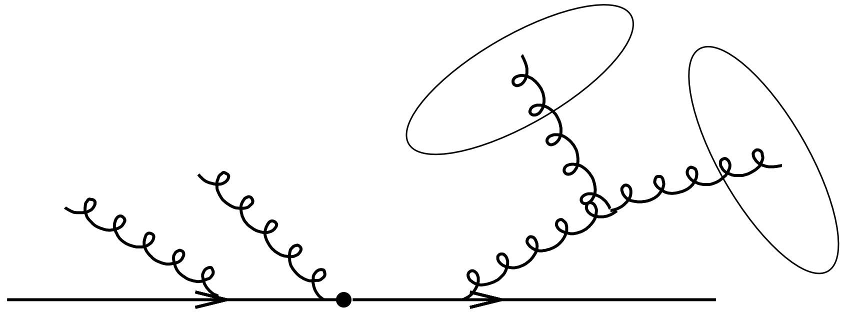
[Banfi, FC, Dreyer, Monni, Salam, Zanderighi and Dulat (2015)]

At the percent-level, one can imagine several contributions becoming relevant:

- Finite top/bottom mass effects → consider different prescriptions for their all-order behavior and compare
- Parton recombination and clustering: logR-enhanced terms appear → resum them [Dasgupta, Dreyer, Salam, Soyez (2014)]



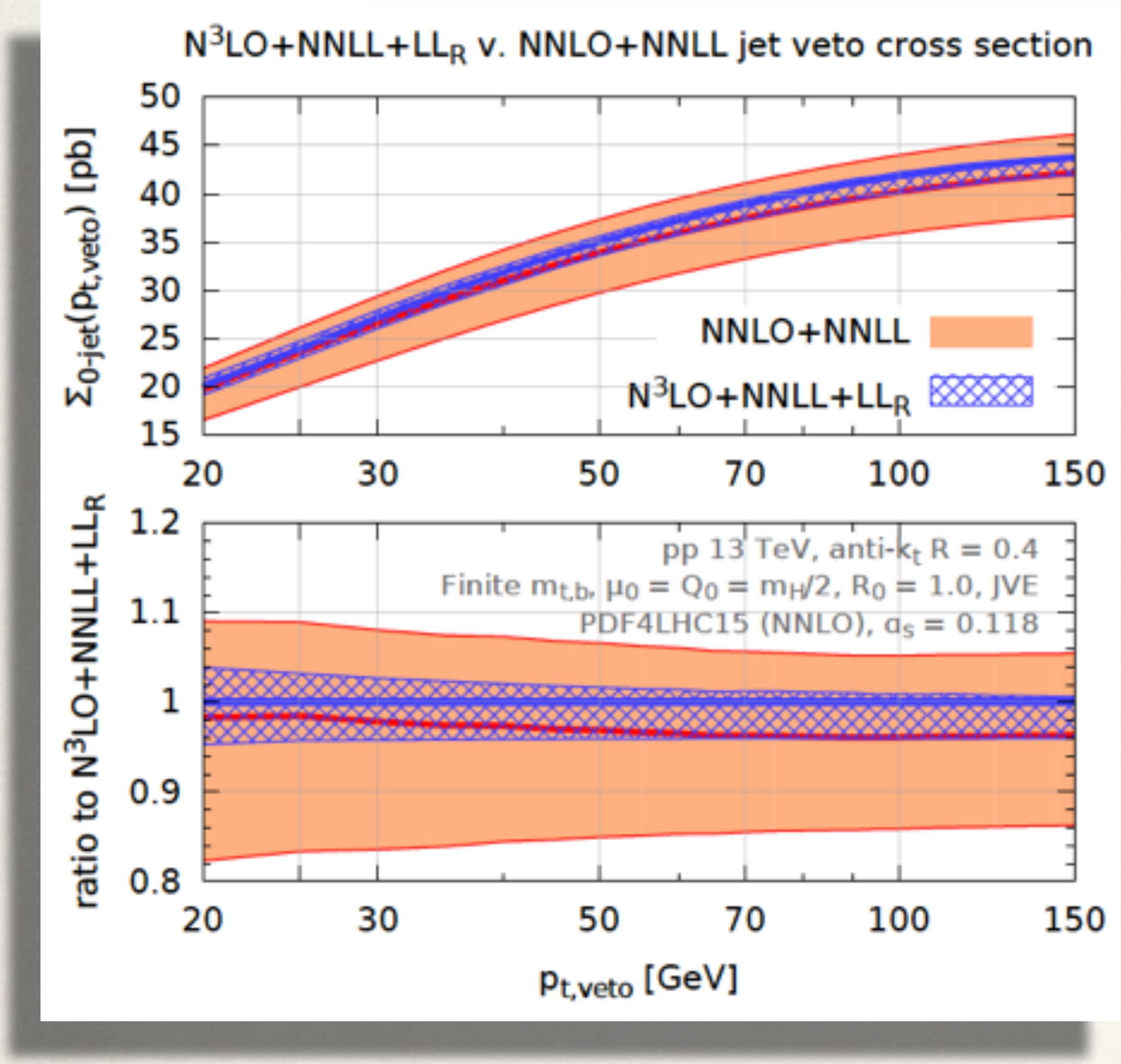
$$\mathcal{F}^{\rm clust}(R) = \frac{4\alpha_s^2(p_{\rm t,veto})C_A^2 L}{\pi^2}\left(-\frac{\pi^2R^2}{12}+\frac{R^4}{16}\right)$$

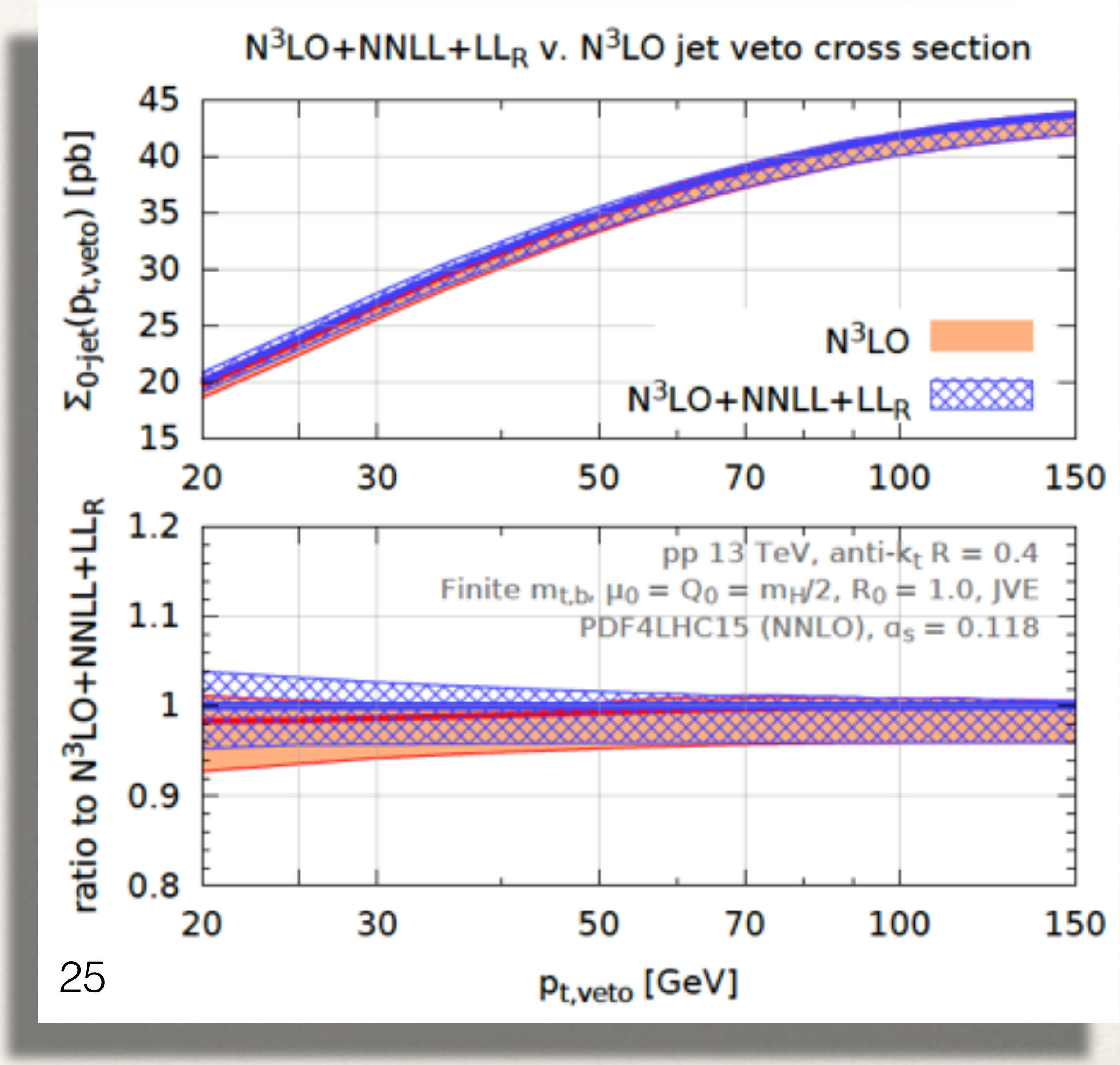


$$\mathcal{F}^{\rm correl}(R) = \frac{4\alpha_s^2(p_{\rm t,veto})C_A L}{\pi^2}\left(f_1\ln\frac{1}{R}+f_{\rm reg}(R)\right)$$

Jet veto: full results at $N^3LO+NNLL+LL_X$

[Banfi, FC, Dreyer, Monni, Salam, Zanderighi and Dulat (2015)]

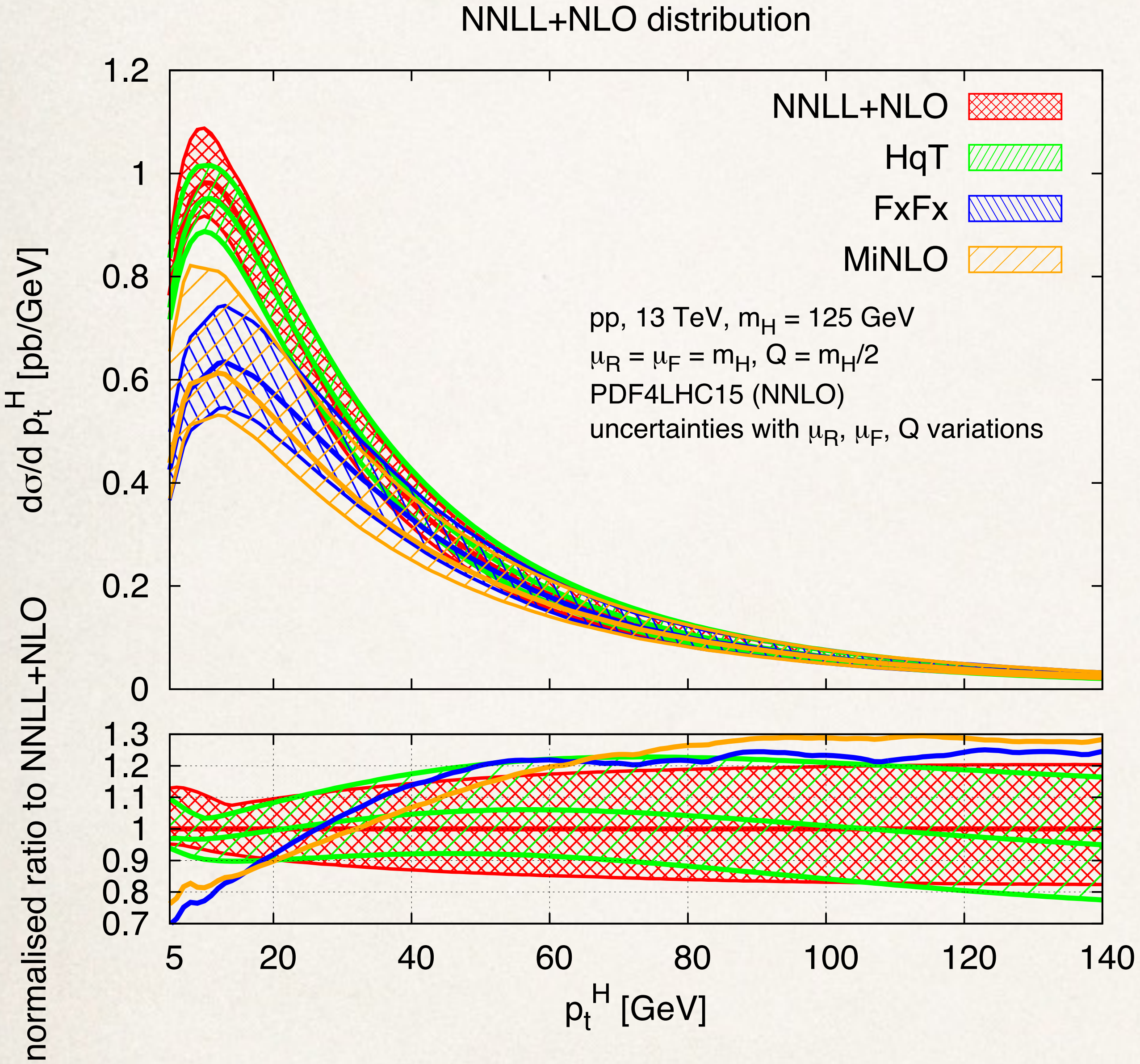


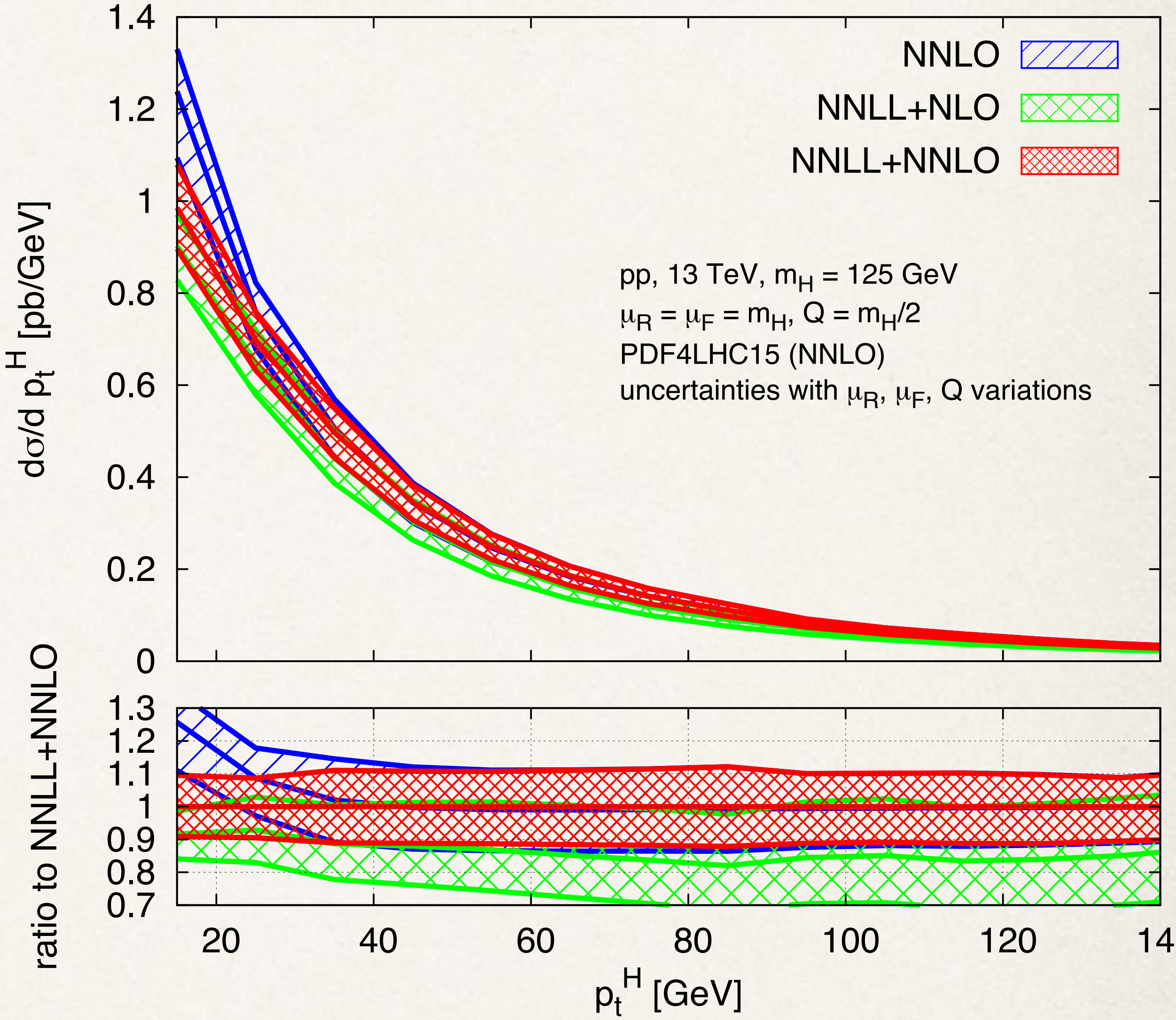


- Very small corrections, (conservative) uncertainty at the 4% level
- All logs effects properly described by fixed order, small impact of resummation, no breakdown of perturbation theory
- FIXED ORDER RELIABLE → FIDUCIAL REGION

One last application of H+J: Higgs p_t spectrum at NNLO (for real)+NNLL

[Monni, Re, Torrielli (2016). In `usual' name coding: N^{3}LO+NNLL]





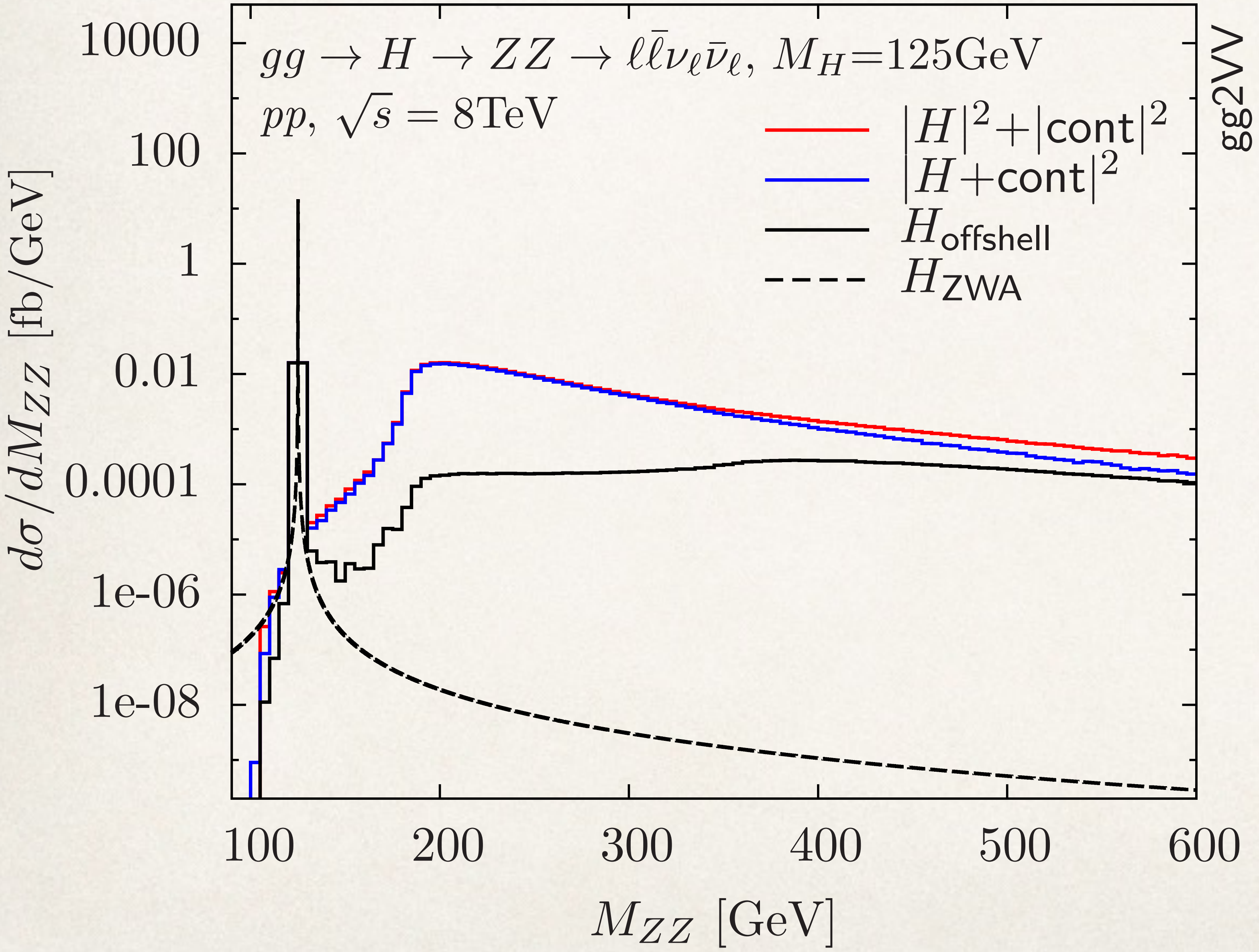
- Significant reduction of uncertainties
- No clear breakdown of p.t. to very low p_t
- Effect of NNLL at $p_T = 15$ GeV: 25%. No effects for $p_T > 40$ GeV

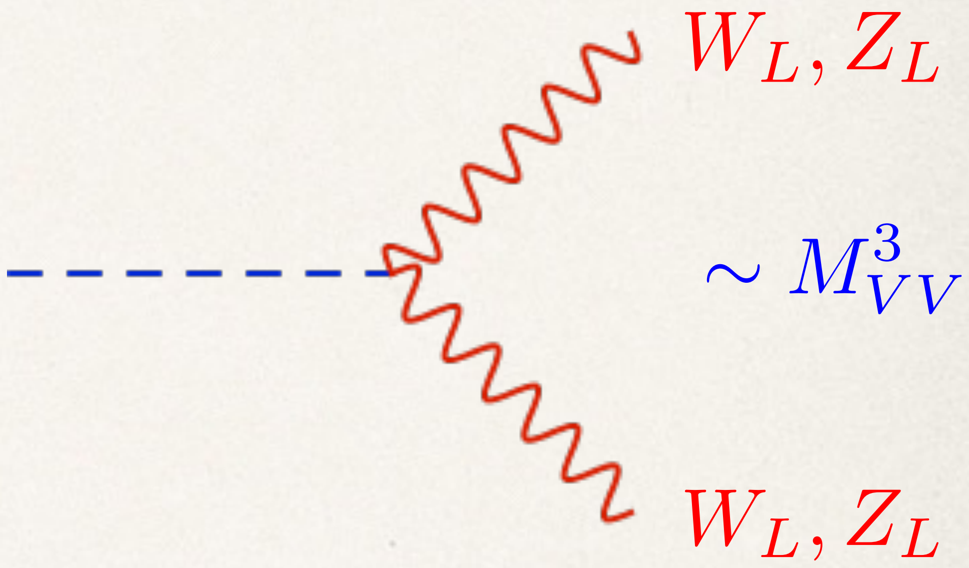
Looking closer at small effects:

Higgs in the off-shell region 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)

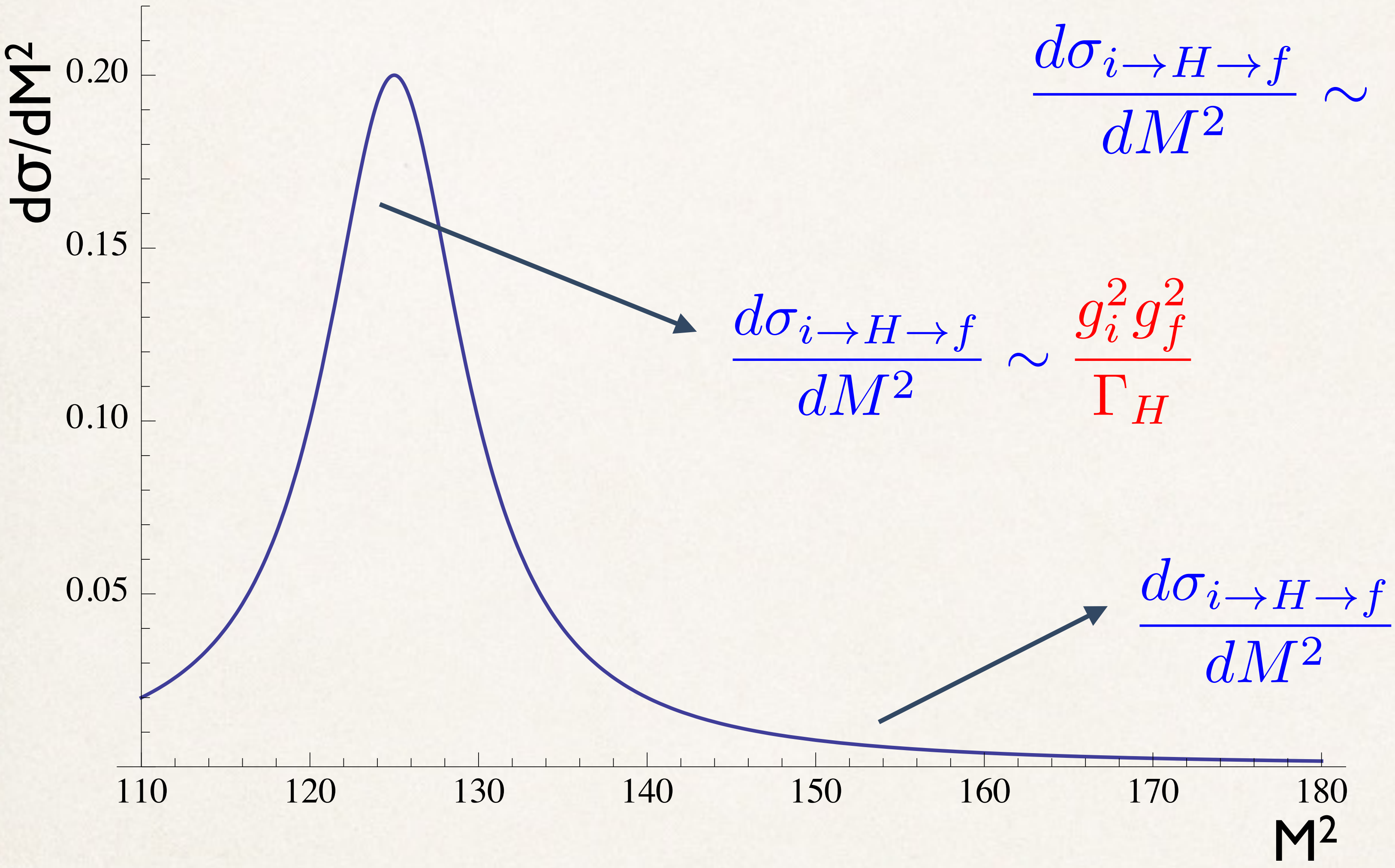




[Kauer, Passarino (2012)]

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



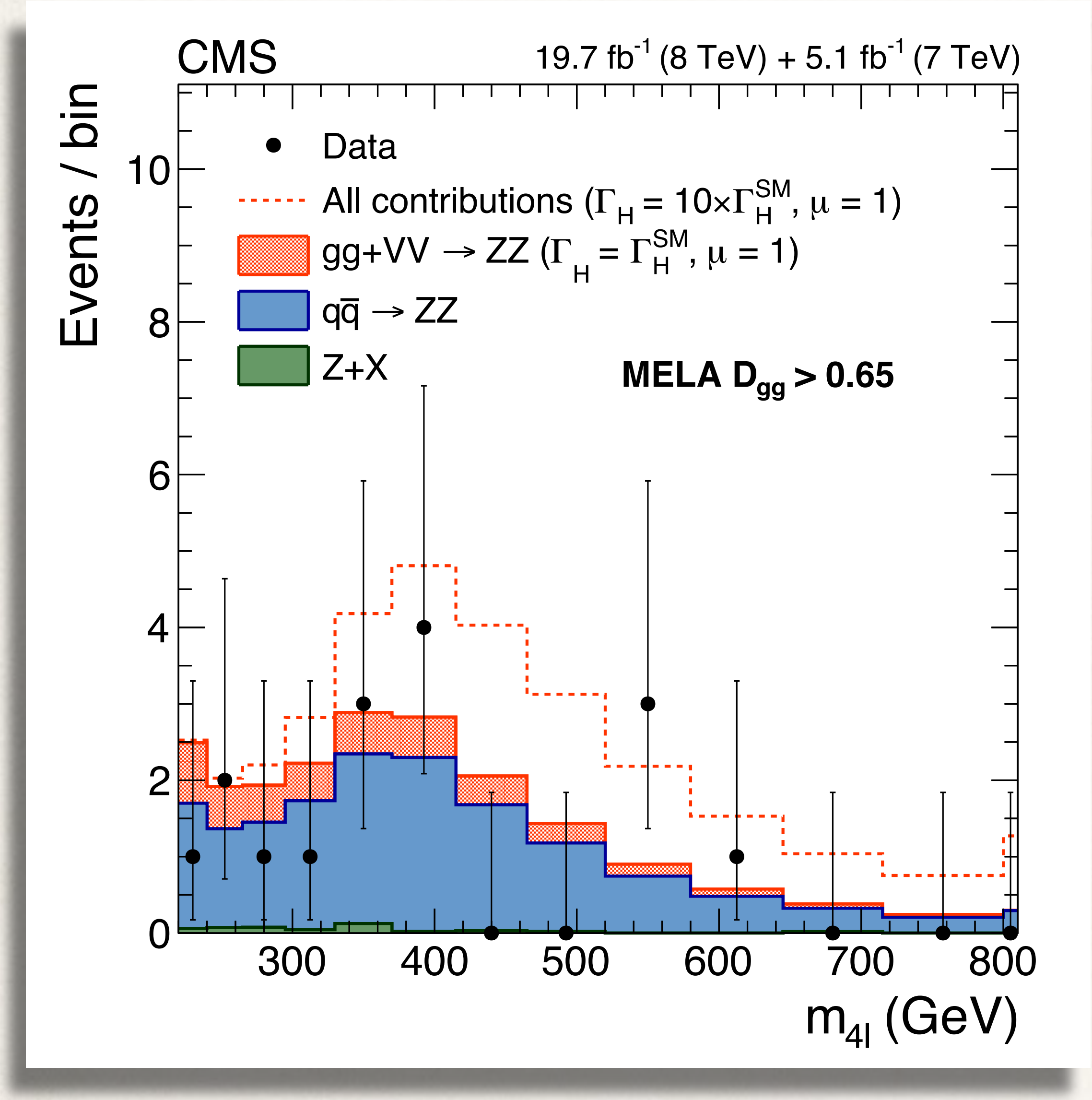
$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{(M^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

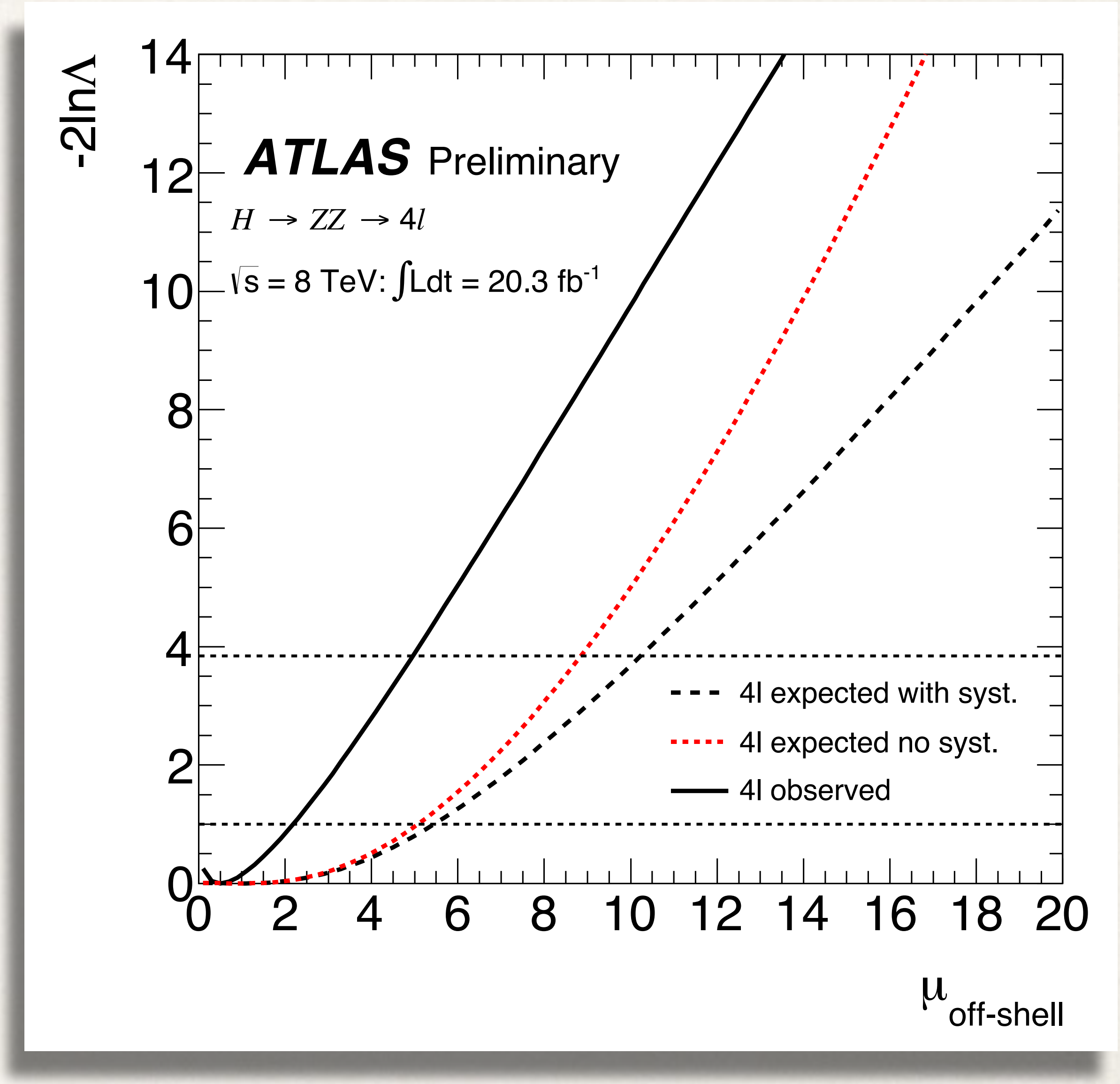
$$\frac{d\sigma_{i\to H\to f}}{dM^2} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

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

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





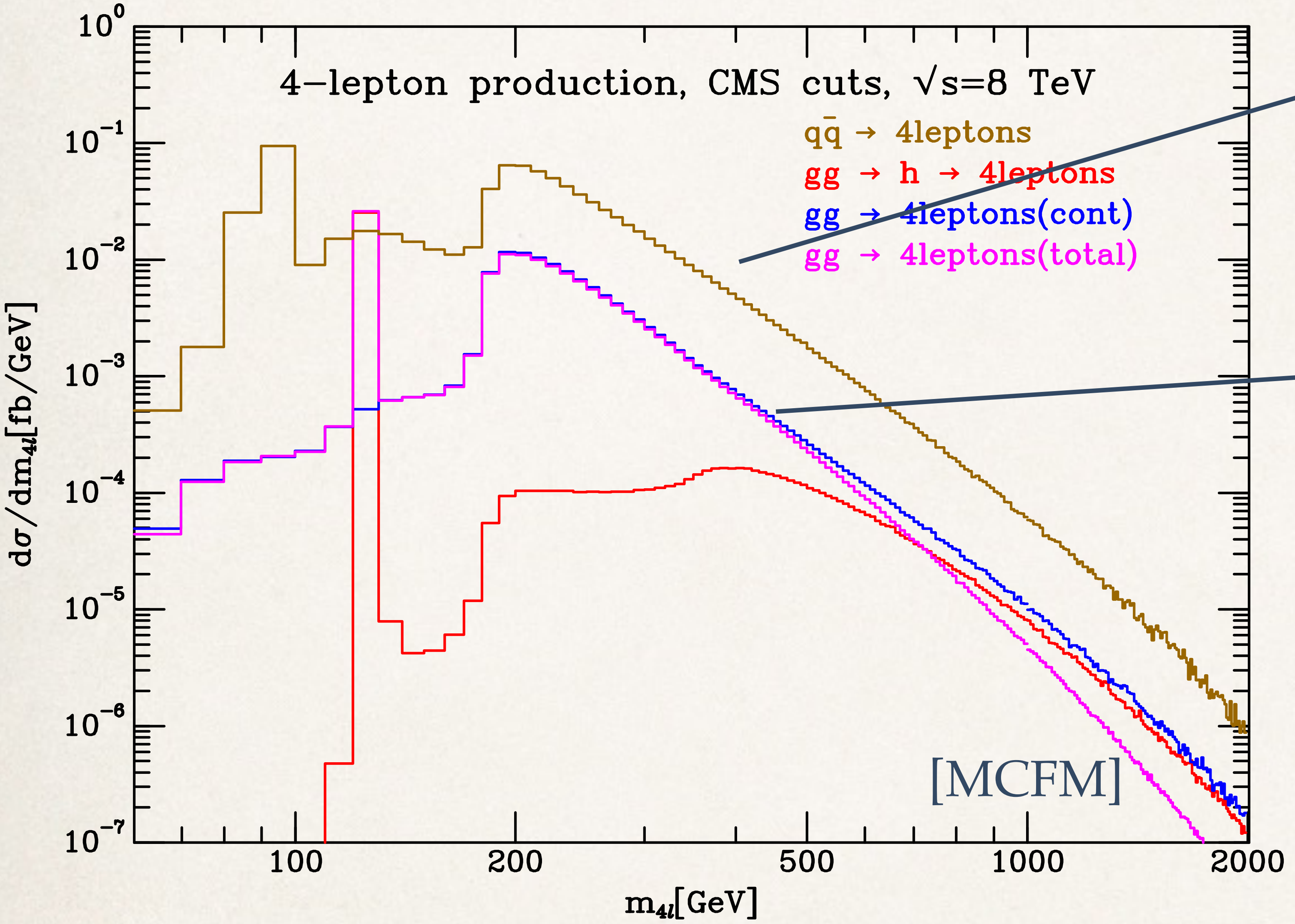
$\Gamma_H^{CMS} \leq 22$ MeV

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

4l production at the LHC

To fully profit from off-shell measurements: GOOD CONTROL ON PP→4L



Large qq background

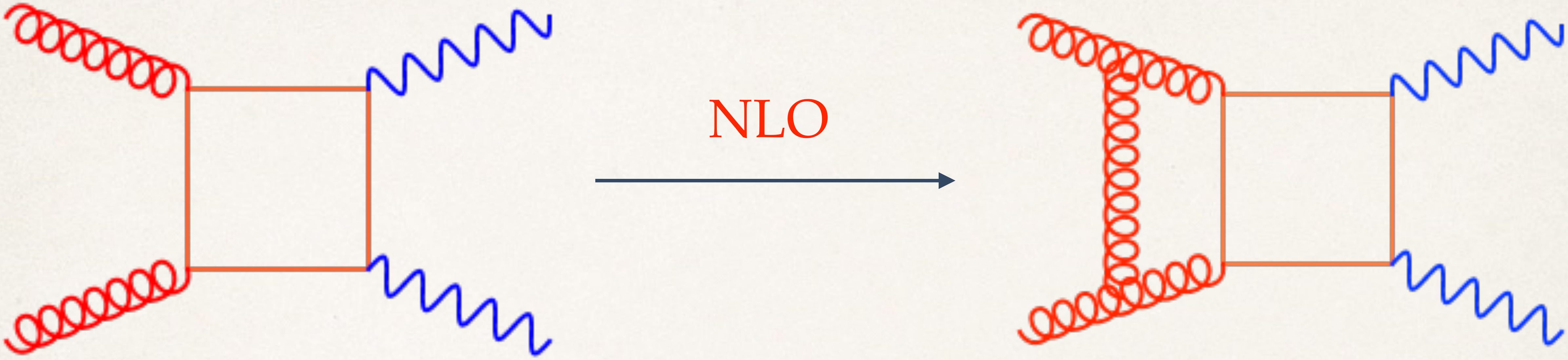
- recently computed at NNLO

Tricky gg background

- non trivial signal/background interference patterns
- gluon-induced → large corrections
- only known at LO until very recently

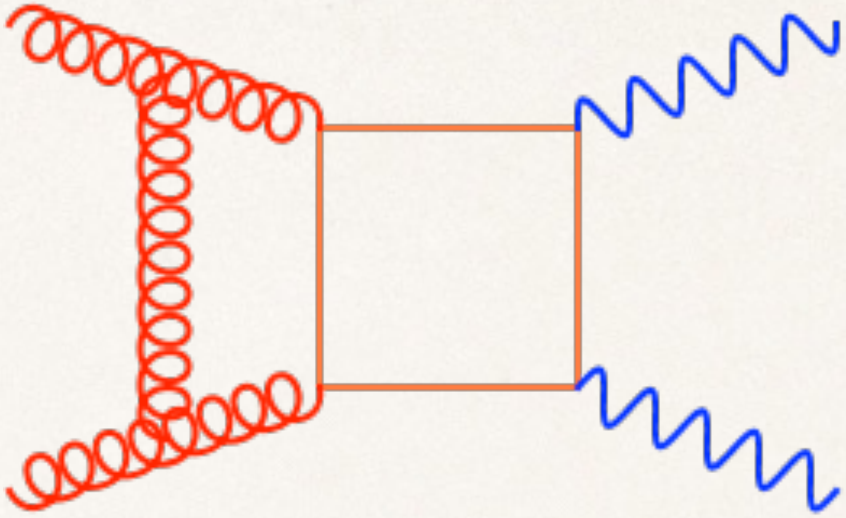
To improve width/coupling constraints by a factor of 2: qq within 10%, gg within 50%

gg→4l background and interference at NLO



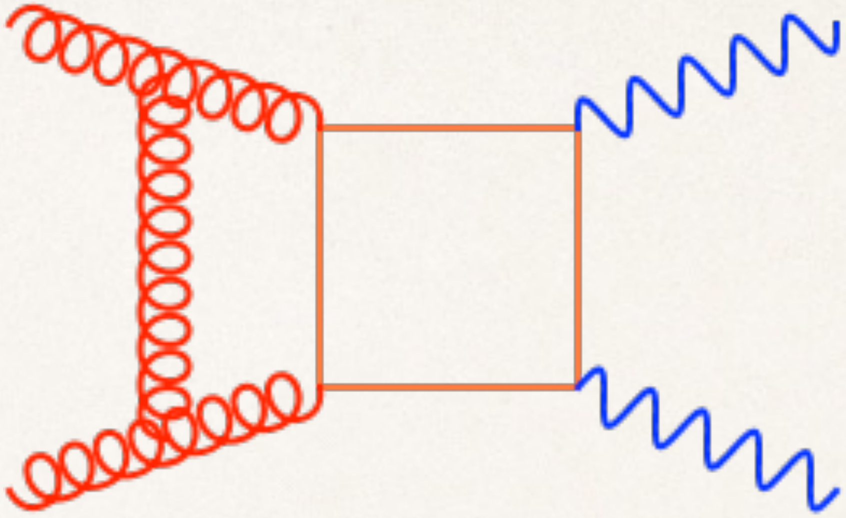
- Loop induced → NLO involves complicated two-loop amplitudes
- Light quark contribution → cannot integrate them out
- At high invariant mass → top effects non negligible
- In general, expect significant top effects for the interference also at small invariant mass (Higgs select transverse polarizations which strongly couple to the top)

The problem of (two) loop amplitudes



- As a rule of thumb, complexity of multi-loop amplitudes grows very rapidly
  - as we move away from the massless limit
  - as we increase the number of scales of the process
- Here: 4 scales ($s,t,m_{ee},m_{\mu\mu}$) → several orders of magnitude more complicated than di-jet, H+j,…
- With internal top masses: prohibitively complicated

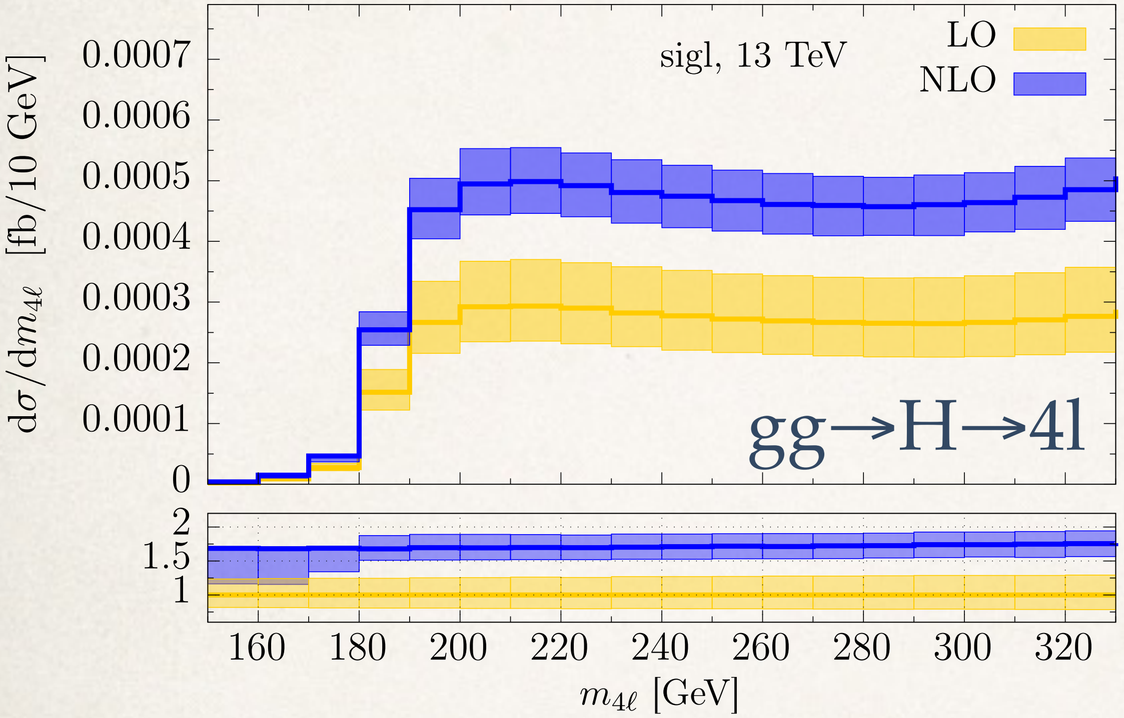
The problem of (two) loop amplitudes

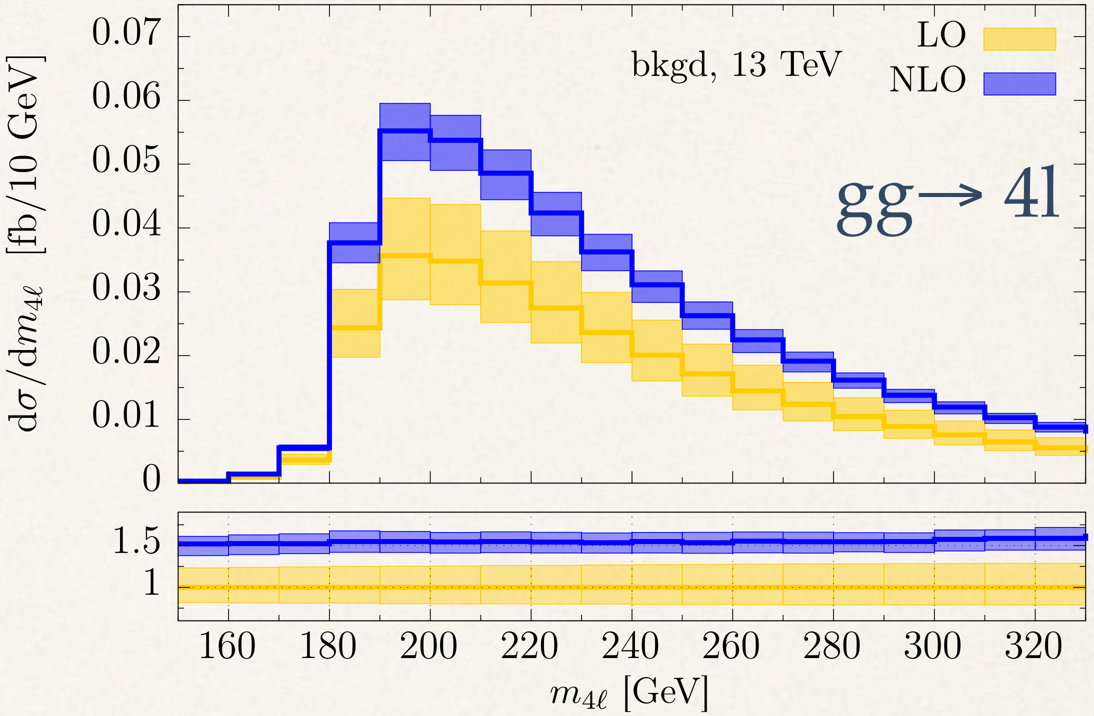


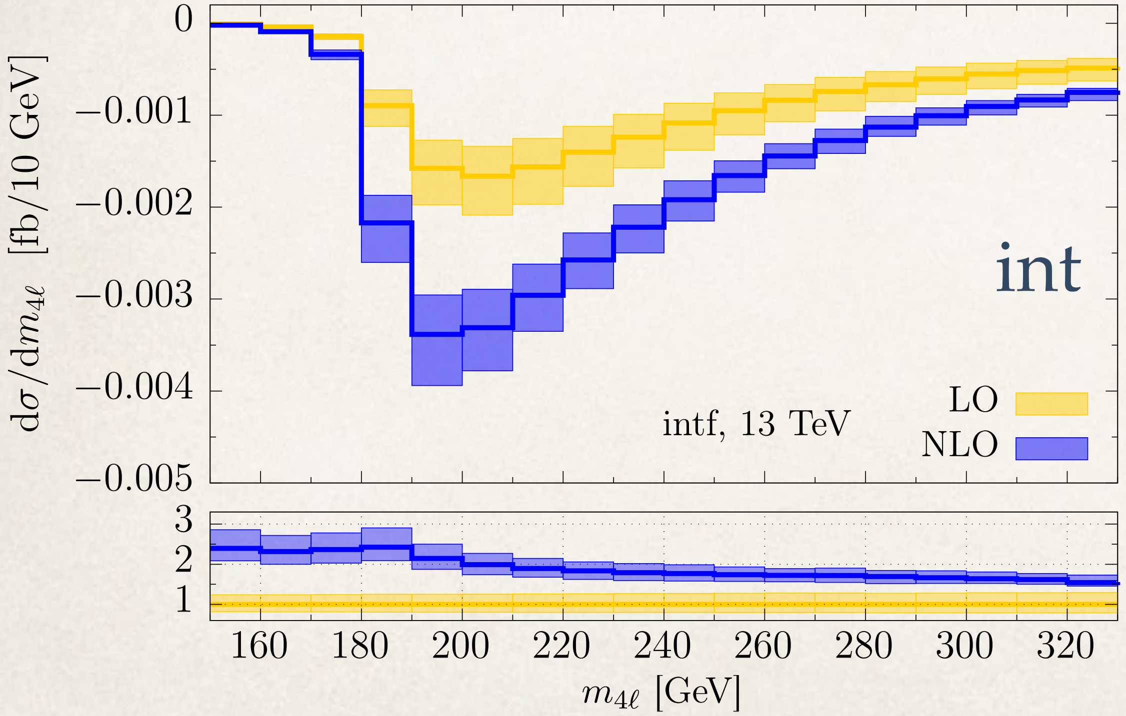
- Combining traditional techniques with new ideas inspired by more formal $\mathcal{N} = 4$ SYM studies, powerful new methods allowed to obtain amplitudes for massless quarks [FC, Henn, Melnikov, Smirnov, Smirnov (2015); Tancredi, v. Manteuffel, Gehrmann (2015); Tancredi, v. Manteuffel (2015); FC, Melnikov, Röntsch, Tancredi (2015)]
- For massive quarks: expand in the top mass below threshold (~ higher dim operators) [FC, Dowling, Melnikov, Röntsch, Tancredi (2016)]
- Results above top threshold still missing (although some approximations available [Campbell, Ellis, Czakon, Kirchner (2016)])
- *Full result could be obtained via brute force numerical methods?*

gg→4l: NLO results

[FC, Dowling, Melnikov, Röntsch, Tancredi (May 2016)]



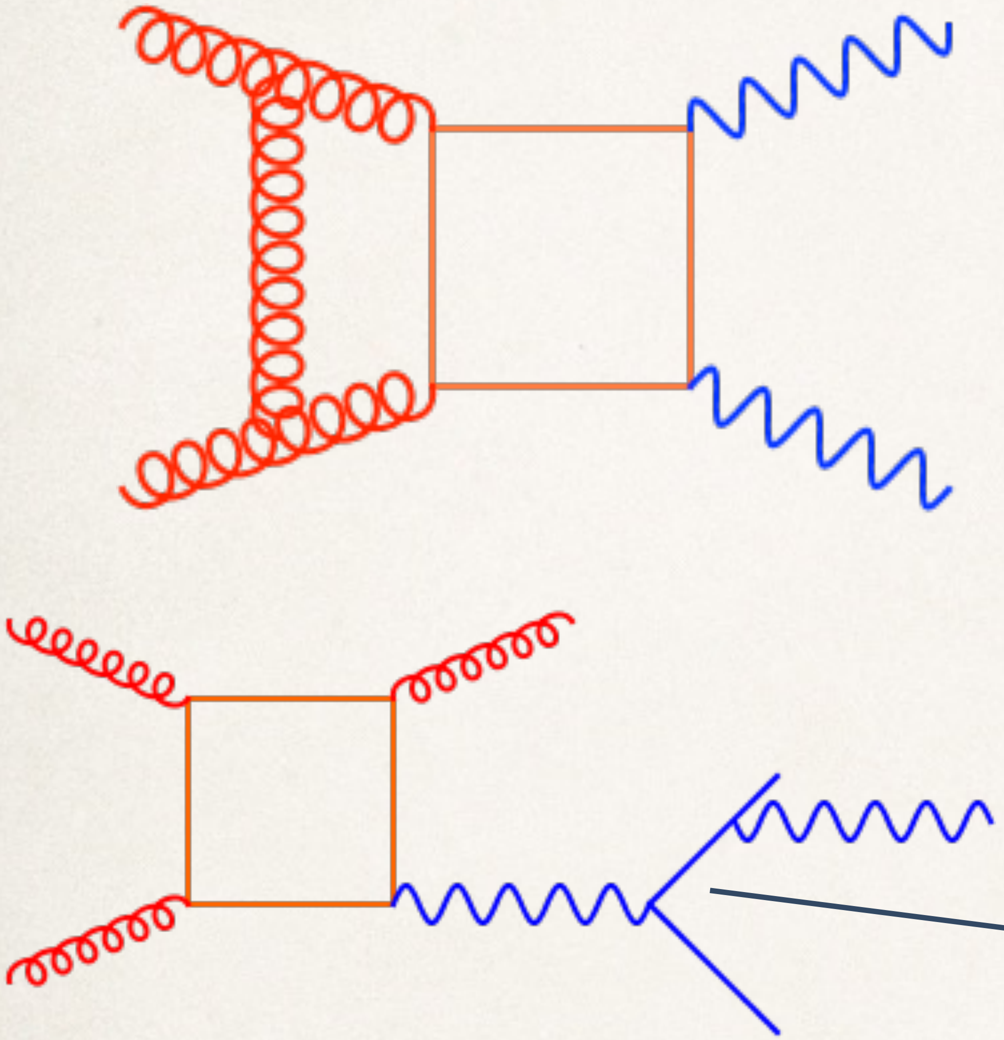




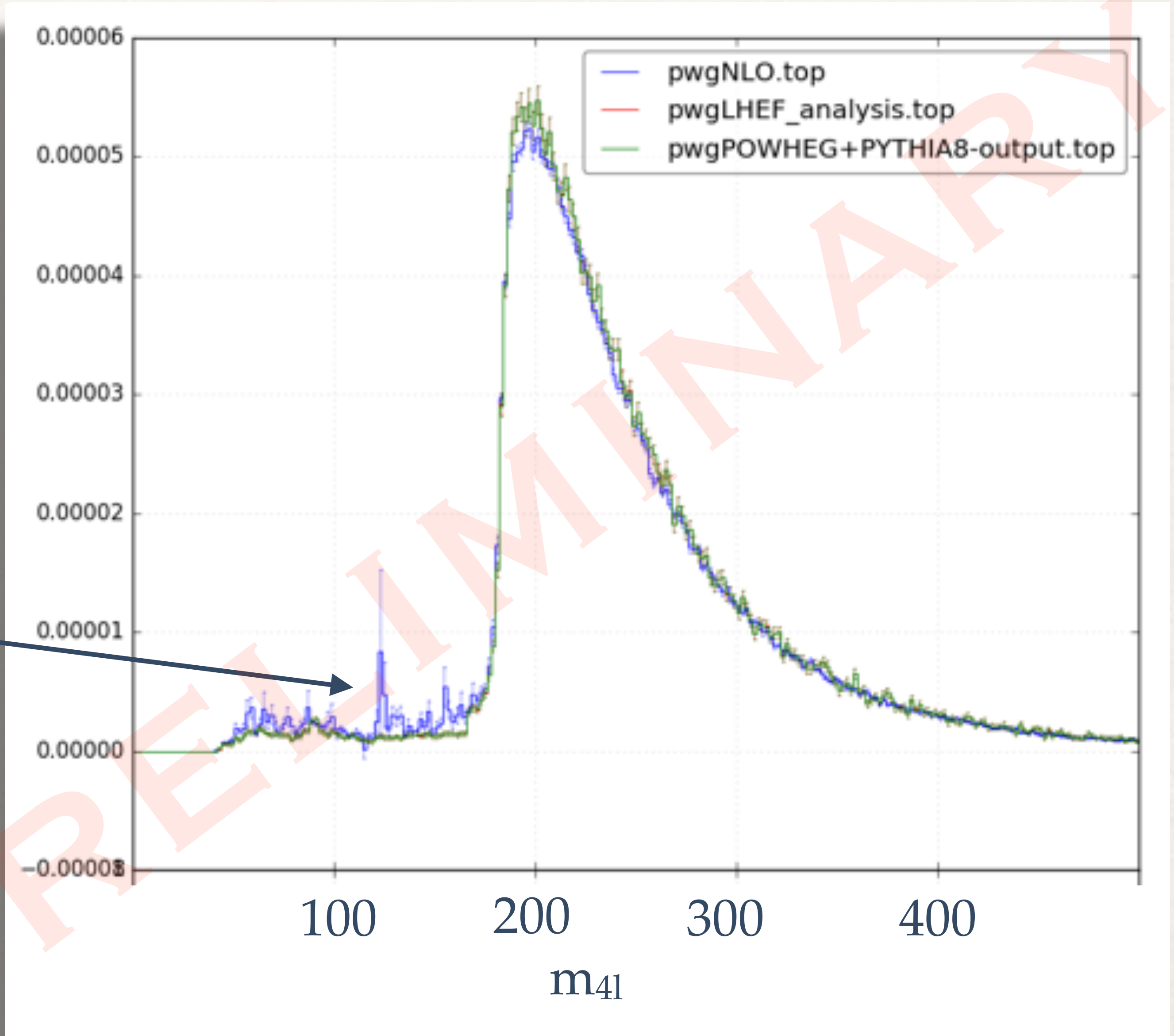
- RESULT VALIDATES K_{sig} ~ K_{bck} ~ K_{int} [Bonvini, FC, Forte, Melnikov, Ridolfi (2013)]
- K_{int} ~ K_{sig} seem to persist also at high m_{4l} ([Campbell et al] approximation)
- Interestingly, non trivial K_{int} the Z threshold. Negligible overall effect

One step closer to reality: PS matching

[Alioli, FC, Luisoni, Röntsch et al, work in progress]



Powheg + Pythia8, background only



Z off-shelness and $Z\gamma^*$ interference fully taken into account

Conclusions

- No obvious new physics at the LHC and SM-like EWSB sector calls for precise scrutiny of SM predictions, hoping to spot deviations pointing to new physics
- New level of accuracy is needed. Sophisticated predictions, which required very interesting conceptual advancement in QCD (soft/collinear singularities and fully exclusive NNLO, new ideas for multi-loop amplitudes)
- The processes I discussed today are only examples. Many precise predictions became available (top, V+J, VV, ~di-jet…)
- Despite lot of progress, still a lot is missing. IDEALLY: precision for a large class of processes / observables. This way: cross-correlate → find (and interpret) tensions
- The remarkable success of the experimental program at the LHC keeps providing exciting motivation for pursue these investigations. WE LOOK FORWARD FOR RUN II

Thank you for your attention!