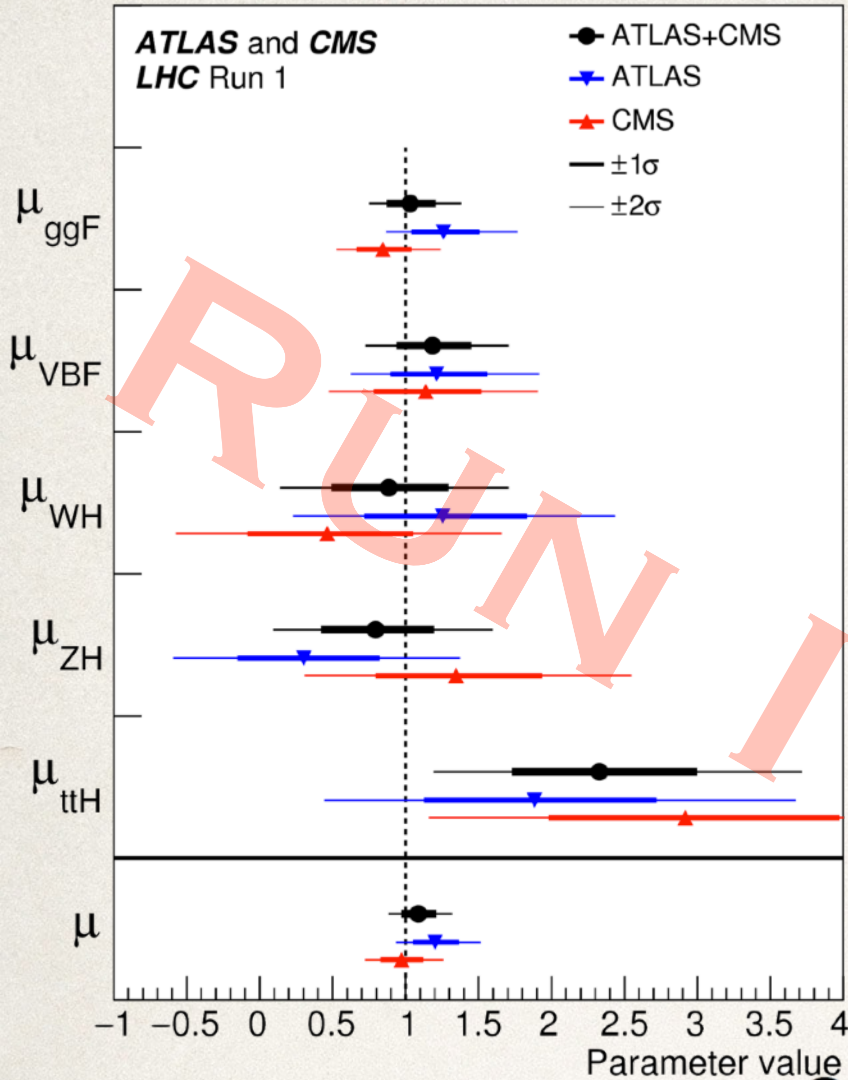
QCD predictions for Higgs phenomenology at the LHC

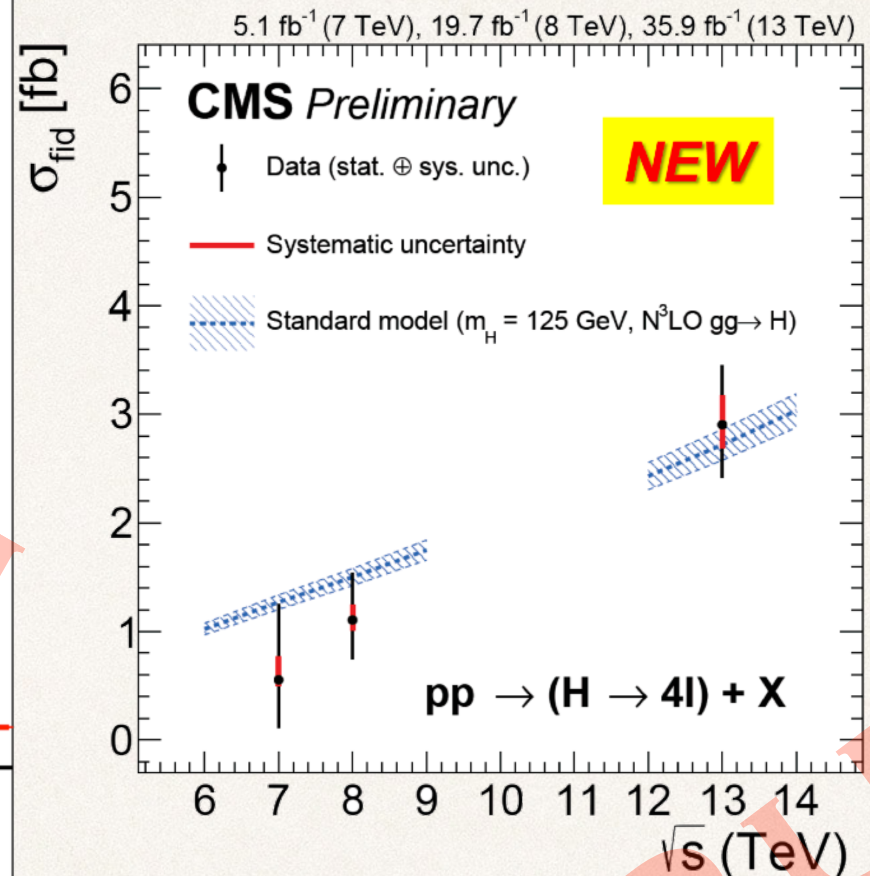
Fabrizio Caola, CERN & IPPP Durham

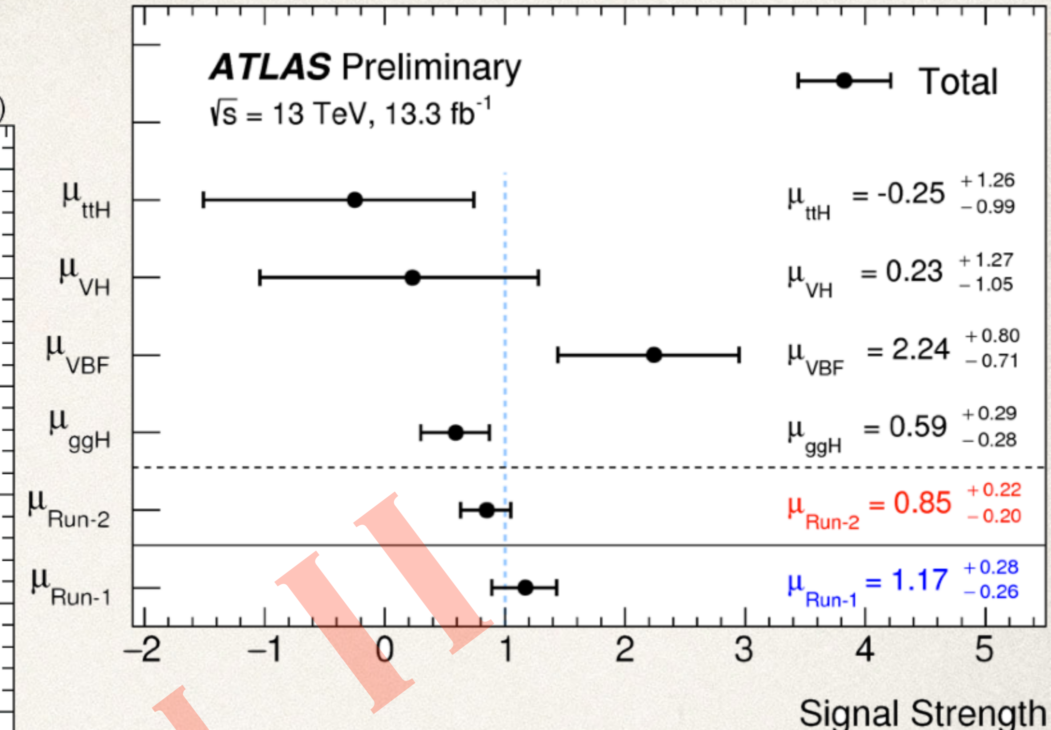
University of Durham

Università degli Studi Roma Tre, 31 March 2017

Higgs physics circa 2017

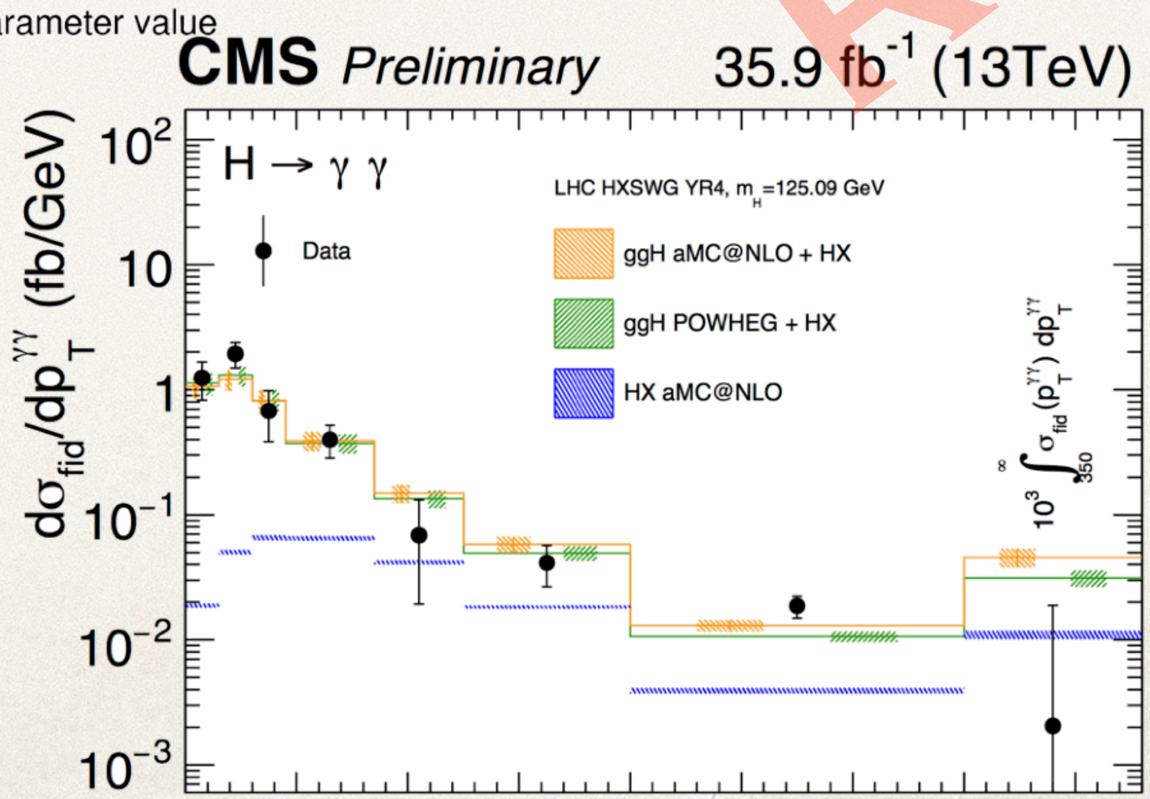


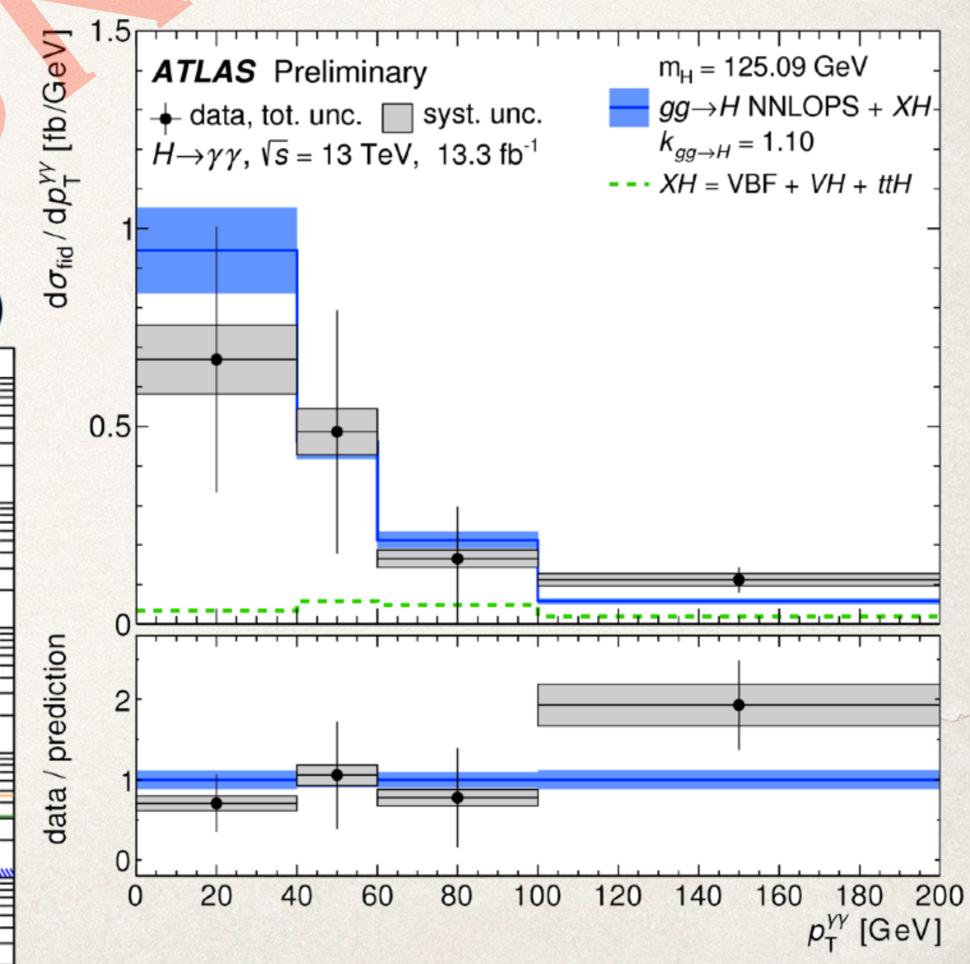




RUN I

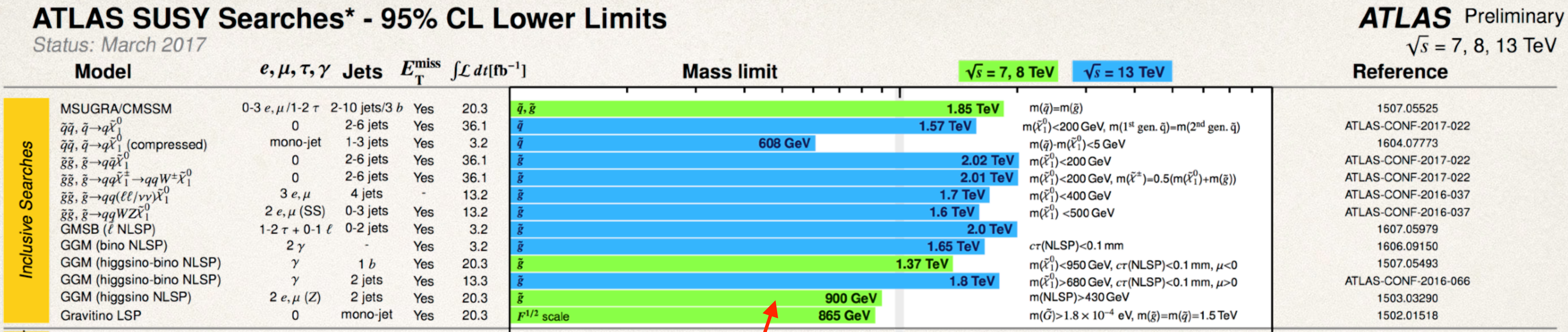
RUN II





A SM-LIKE HIGGS BOSON

Searches circa 2017

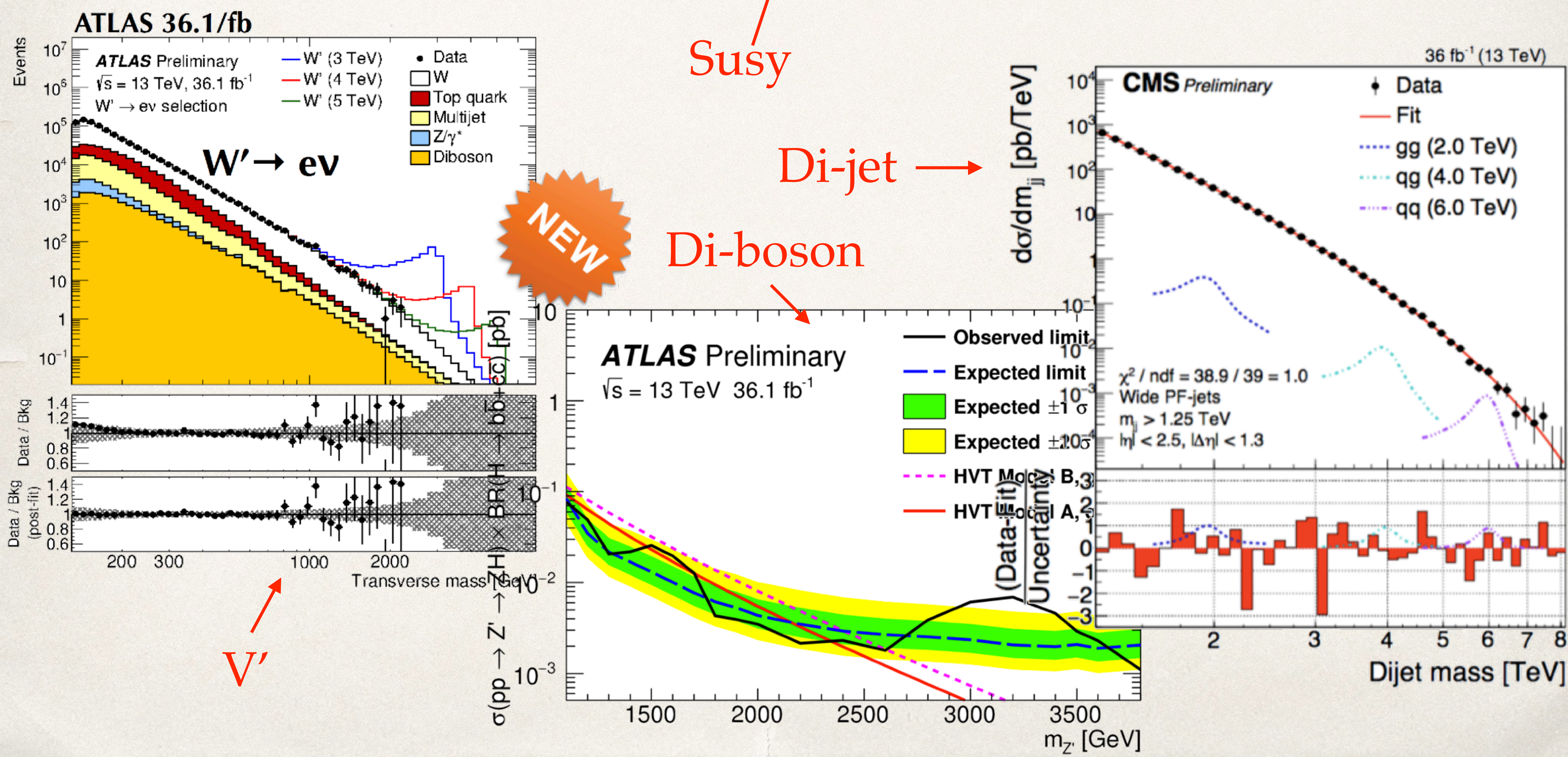


ATLAS SUSY Searches* - 95% CL Lower Limits
Status: March 2017

ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV

$\sqrt{s}$ = 7, 8 TeV | $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	1.57 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$	608 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	1604.07773
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.02 TeV	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.01 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	13.2	$\tilde{g}$	1.7 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 jets	Yes	13.2	$\tilde{g}$	1.6 TeV	m($\tilde{\chi}_1^0$) <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$	2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$	1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	1.37 TeV	m($\tilde{\chi}_1^0$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$	1.8 TeV	m($\tilde{\chi}_1^0$)>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	m($\tilde{G}$)>1.8 × 10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518



New physics and where to find it…

Imagine to have new physics at a scale Λ

- if Λ small → should see it directly, bump hunting
- if Λ large, typical modification to observable w.r.t. standard model prediction: $\delta O \sim Q^2/\Lambda^2$
- standard observables at the EW scale: to be sensitive to ~ TeV new physics, we need to control δO to few percent
- high scale processes (large p_T, large invariant masses…): sensitive to ~TeV if we control δO to 10-20%

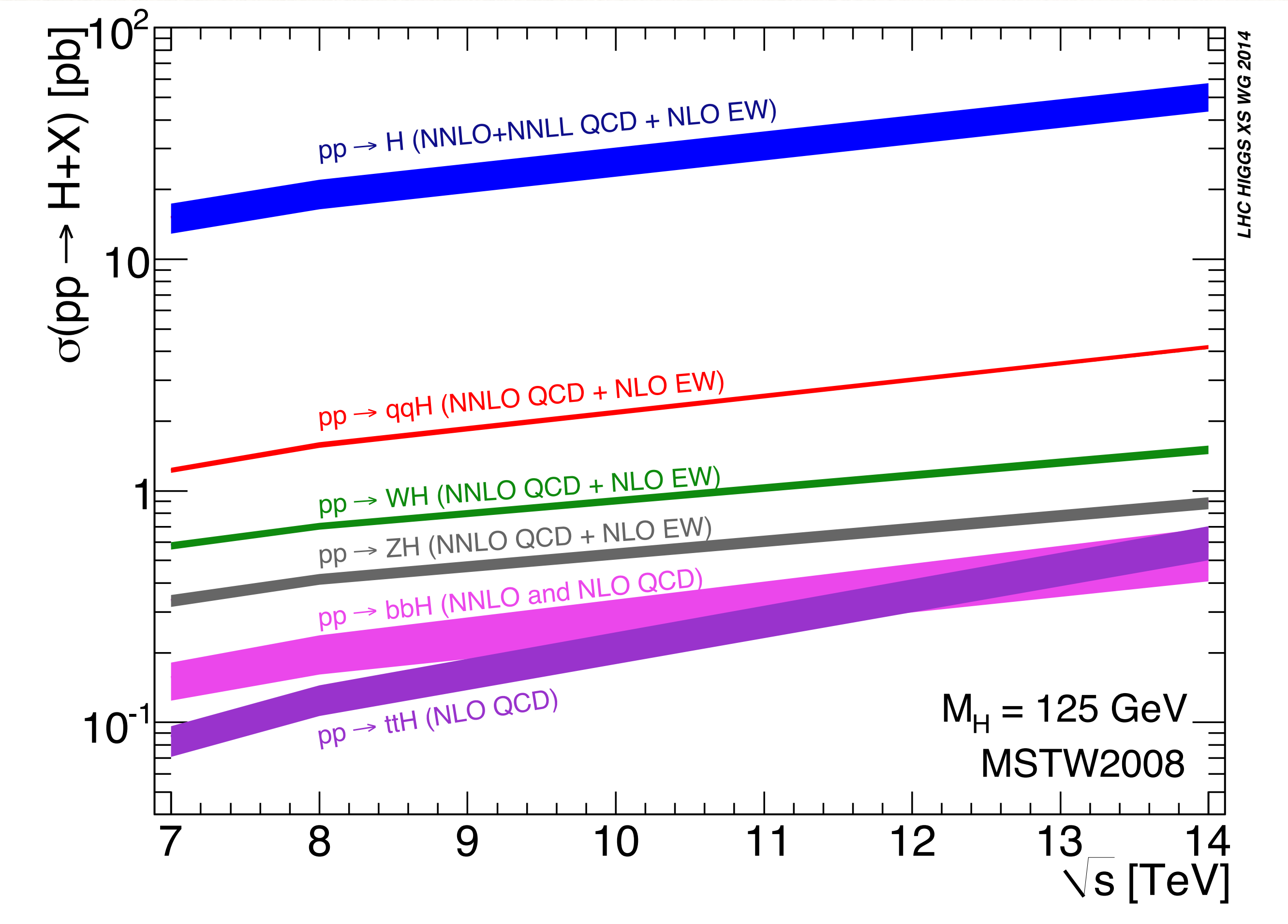
THESE KINDS OF ACCURACIES ARE WITHIN REACH OF LHC EXPERIMENT CAPABILITIES

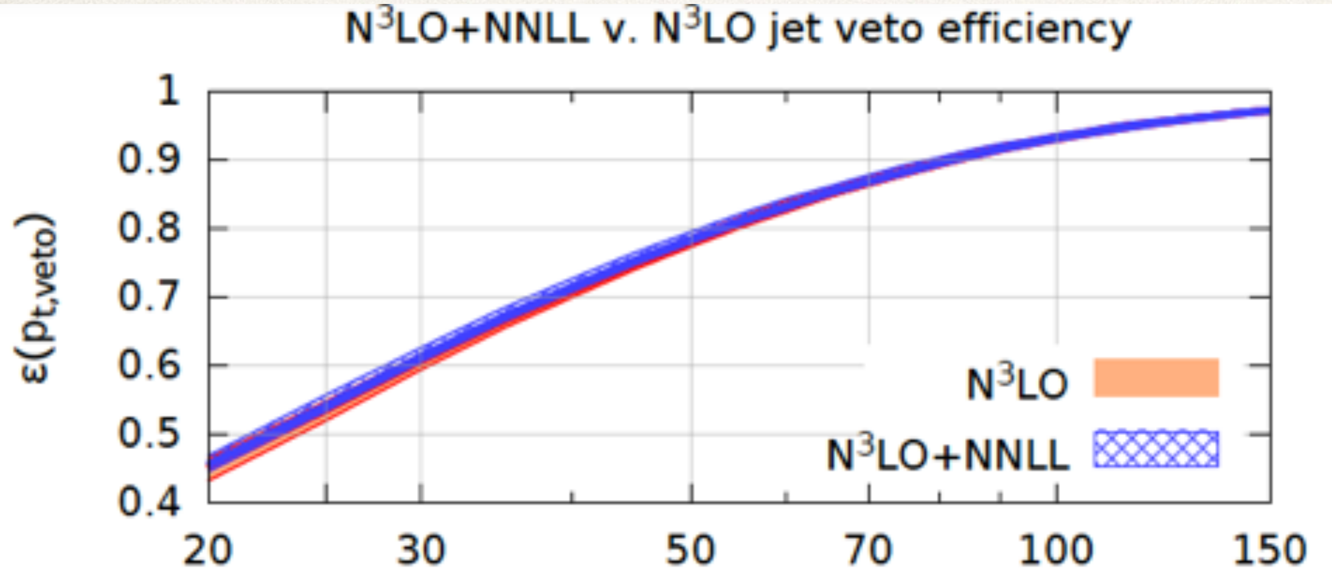
TO FULLY EXPLORE THE LHC POTENTIAL FOR NP, WE MUST CONTROL THEORY PREDICTIONS AT THIS LEVEL

QCD at a few percent-level:

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 ($H \to WW, H \to \tau\tau$) jet veto to suppress background

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^{3}LO) is desirable

NP effects: ~ few percent
No good control/understanding of them at this level

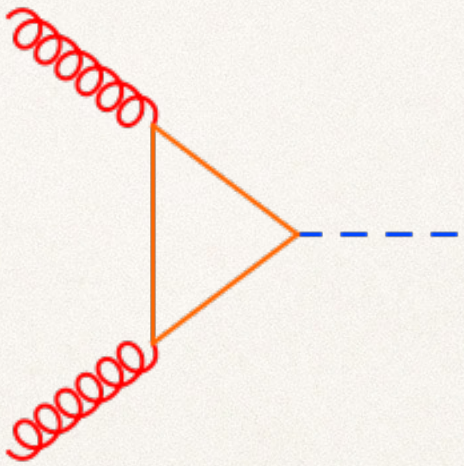
Higgs: status of theoretical predictions

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

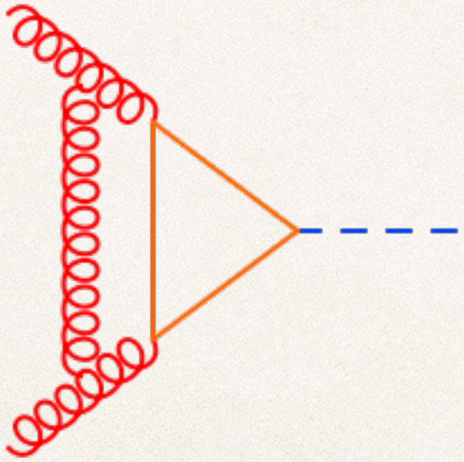
HIGGS INCLUSIVE

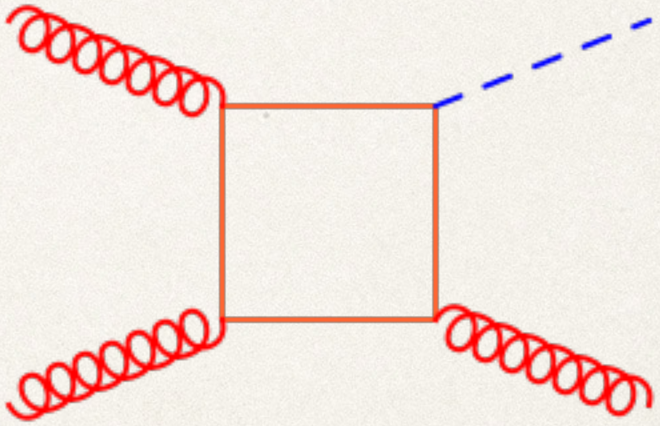
H+J / HIGGS p_T

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



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





NLO: ~100% corrections, clearly unsatisfactory result

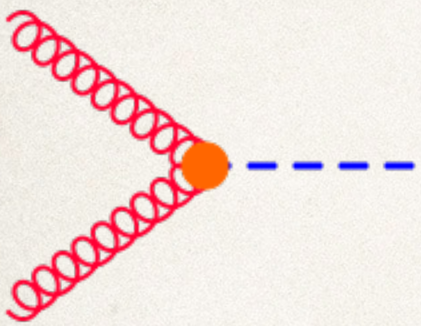
Integrating out the top

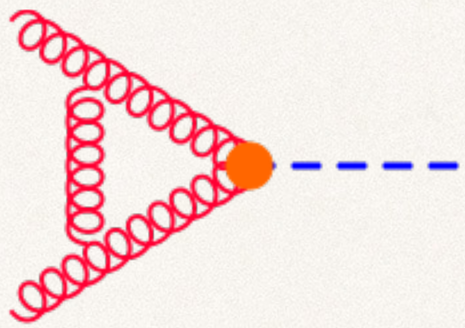
As long as the typical scale of the process is $Q \lessapprox m_t$: short distance (i.e. top mass) physics is not resolved → effective point-like interaction

- 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 → have to consider them.* t/b mass effects recently computed [Lindert, Melnikov, Tancredi, Wever (2016)]

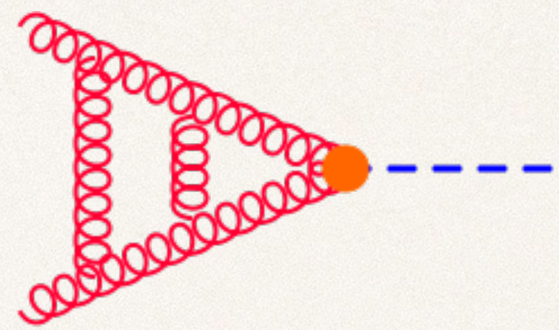
Integrating out the top: results

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

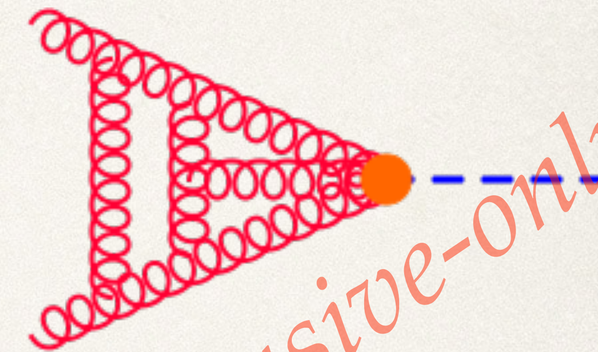




K~2, ~100% uncertainty



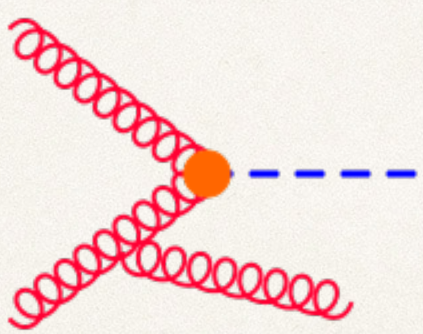
K~1.2, ~10% uncertainty

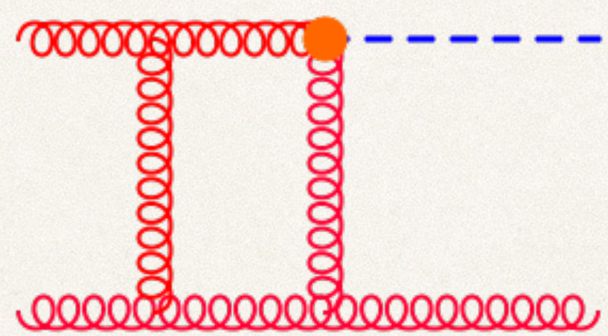


K~1.02, ~percent - level uncertainty

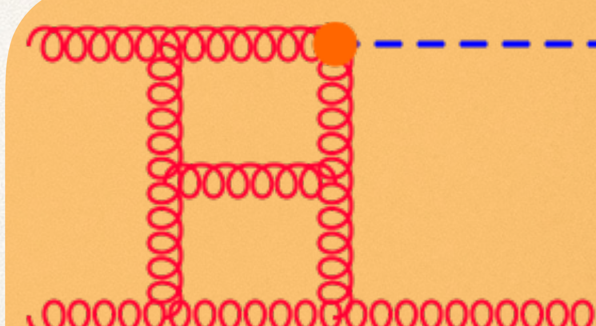
[Anastasiou et al., PRL (2015)]

fully inclusive-only





K~1.5, ~50% uncertainty

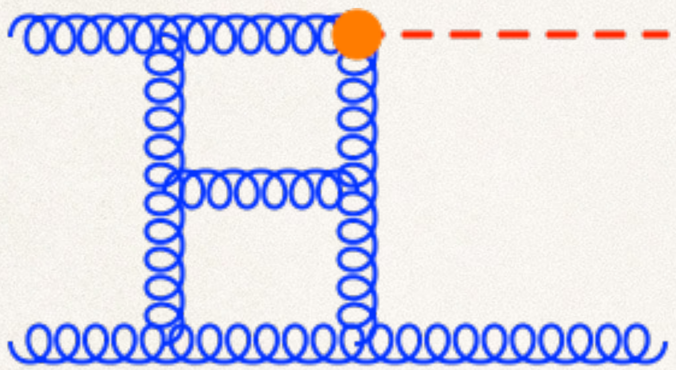


NNLO, fully exclusive

Anatomy of a NNLO computation

All required amplitudes known since long time

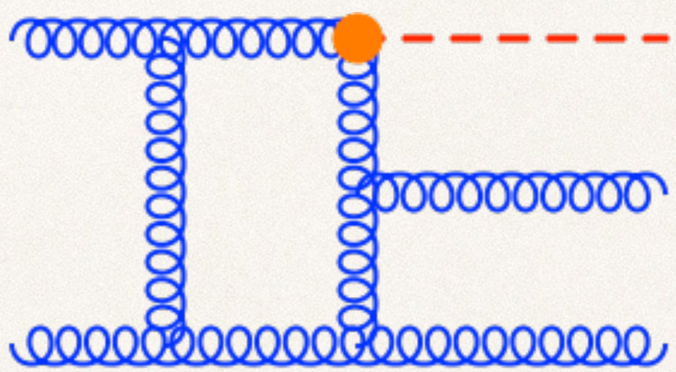
VV



Two-loop Amplitudes for H+J

Computed in 2011 [Gehrmann et al.]

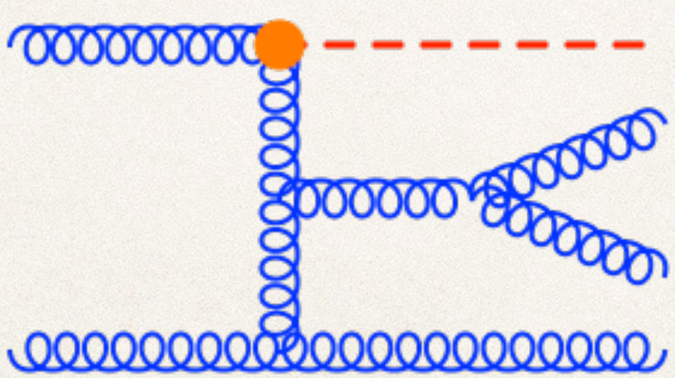
RV



One-loop Amplitudes for H+JJ

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

RR



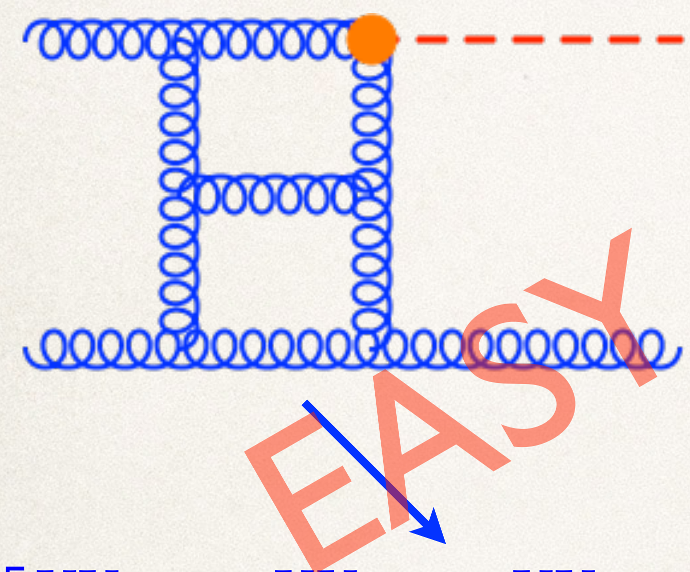
Tree-Level Amplitudes for H+JJJ

What prevented from doing the computation for so long?

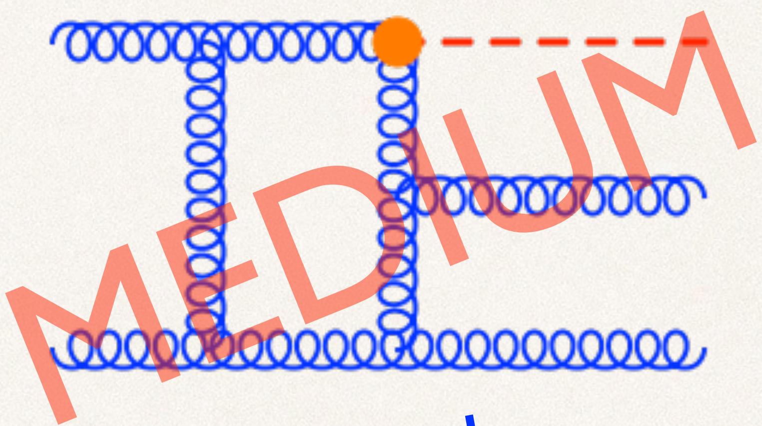
Anatomy of a NNLO computation

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

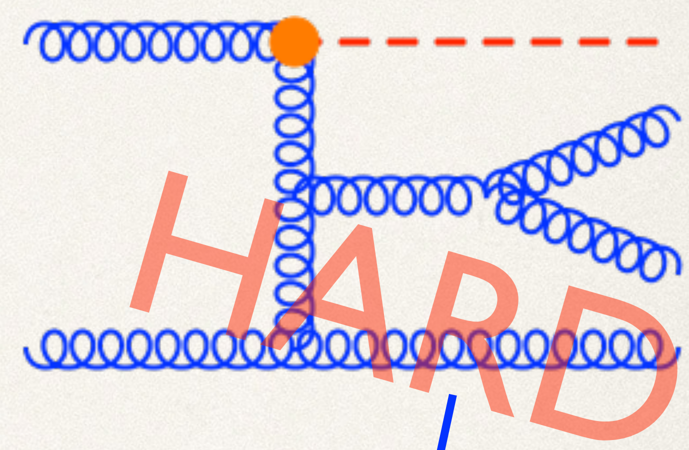
VV



RV



RR



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

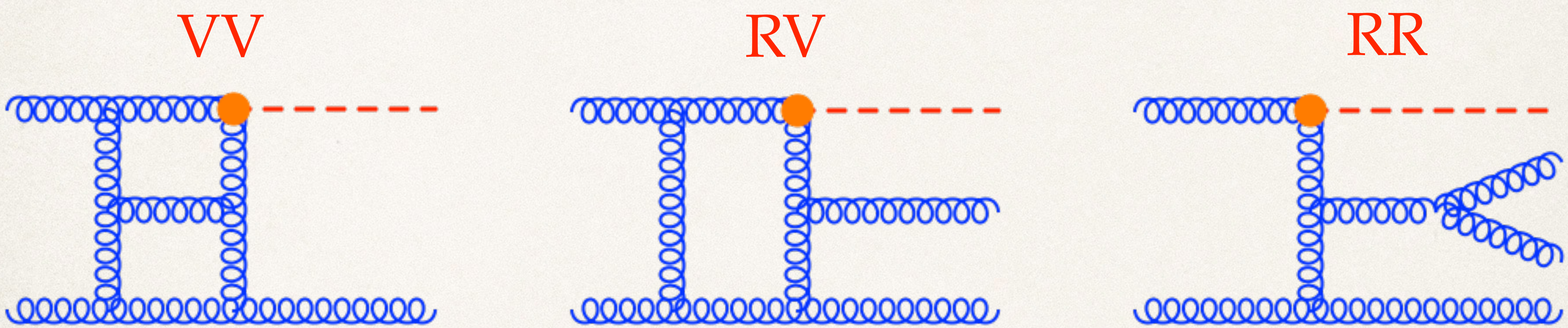
$$\int \left[\mathrm{rr}_0\right] d\phi_4$$

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

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

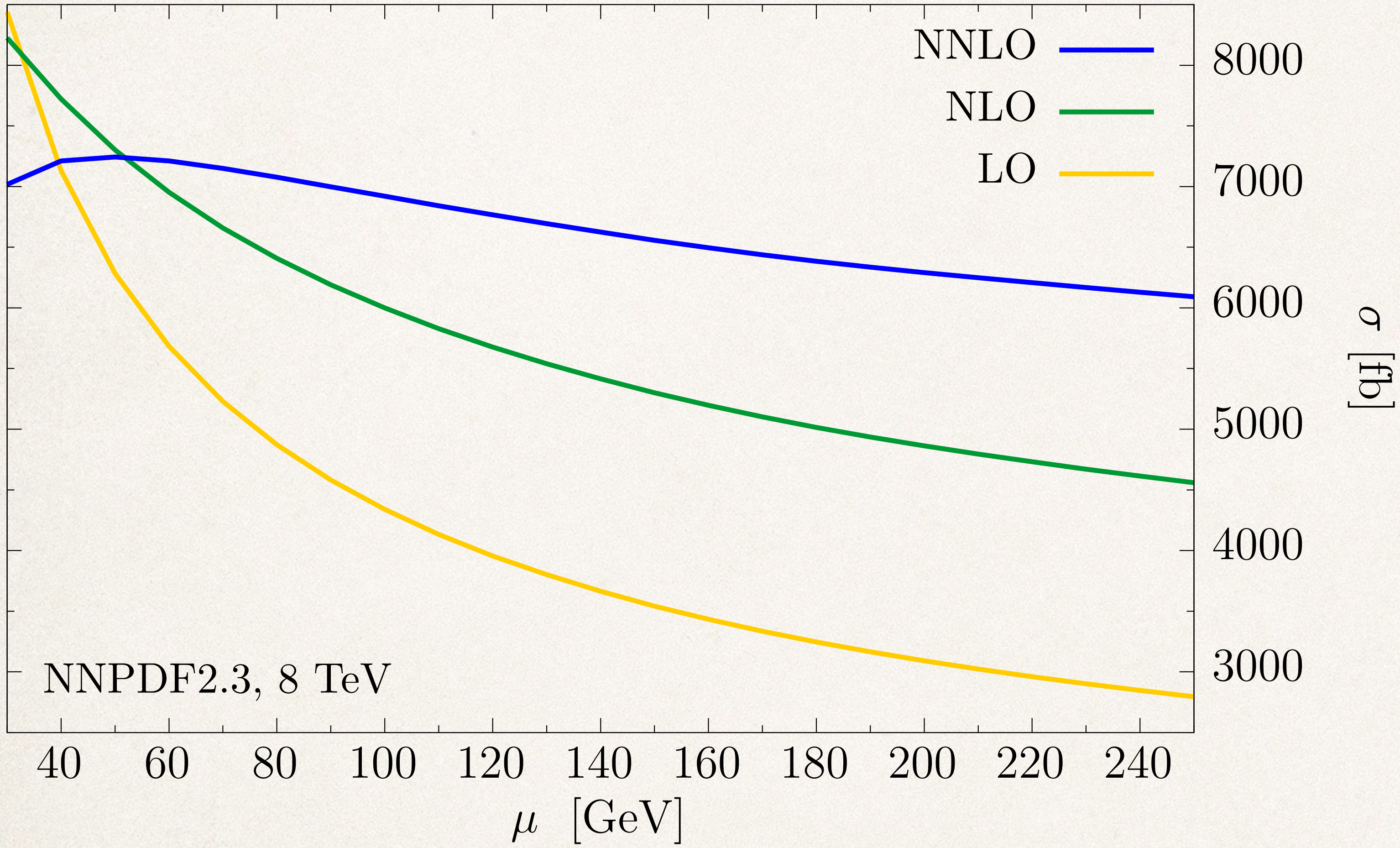
The GOAL: we are looking for precise predictions →
as close as possible to experimental reality
(fully differential, fiducial region)

- 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 now possible, with large computing power (typical result: ~ 100.000 CPU hours)

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 ($m_t \to \infty$)



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

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

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

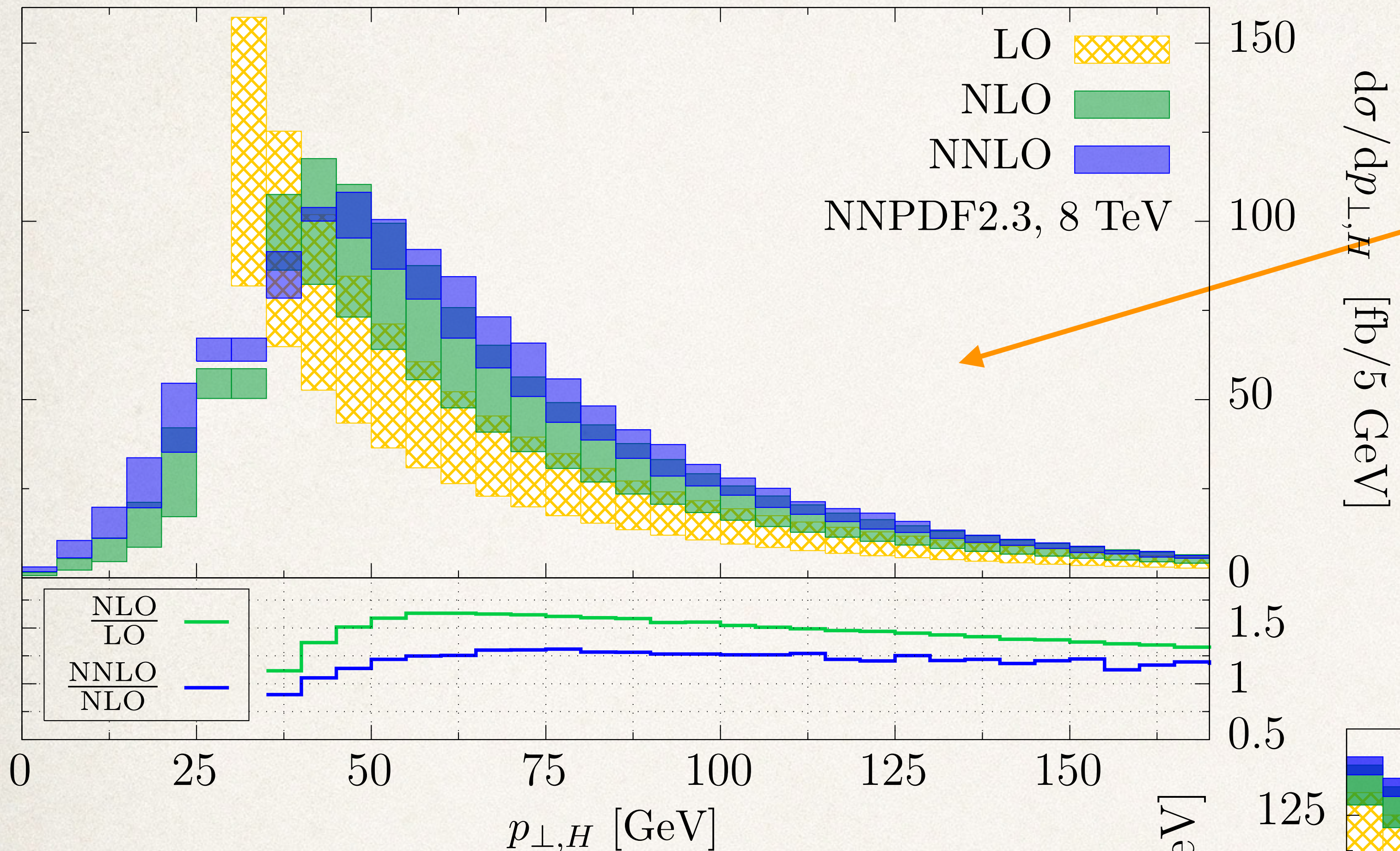
$$K_{\mathrm{NNLO}} \sim 20\%$$

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

- 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_{NNLO}=4%]. First sign of perturbative convergence

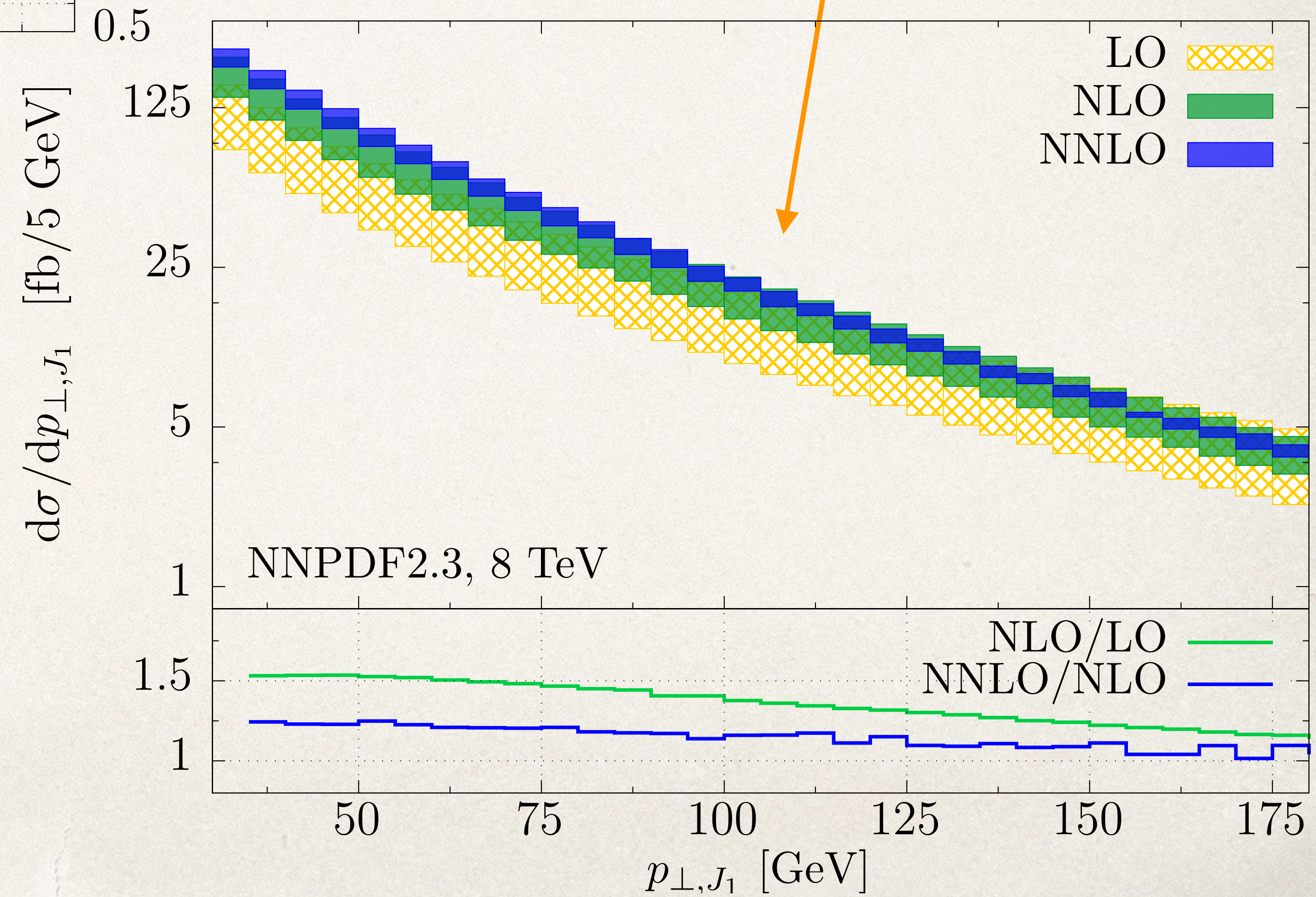
Differential distributions

[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

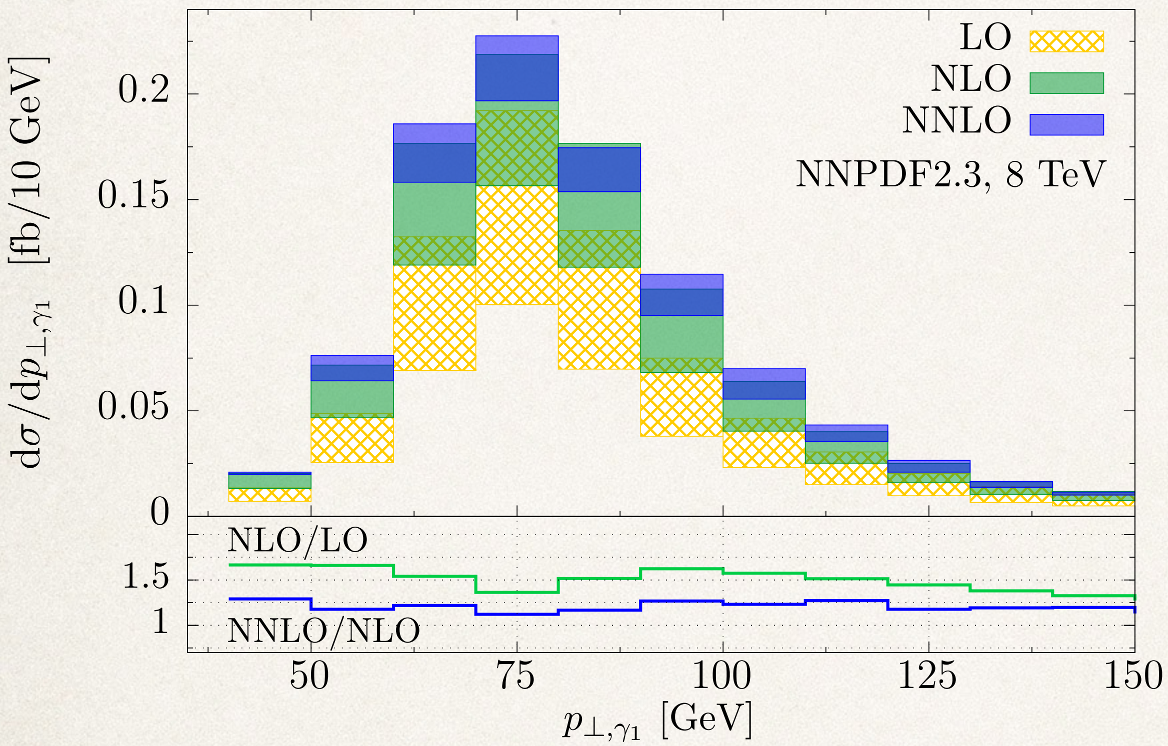
- \`Nice' experimental cuts: no need for extrapolations after this → insensitive to soft physics (*interesting topic for precision frontier, e.g. symmetric cuts…*)

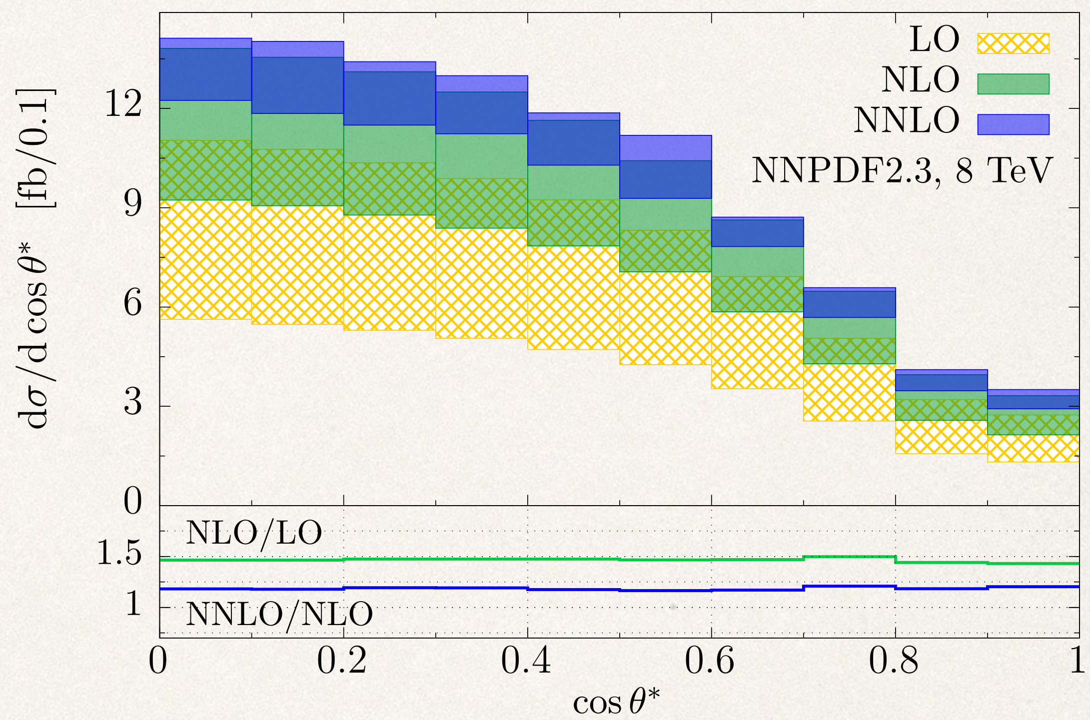
Fiducial analysis: H→γγ

[FC, Melnikov, Schulze (2015), Chen, Martinez, Gehrmann, Glover, Jaquier (2016)]

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 GeV,0.35/0.25 $m_{\gamma\gamma}$), $|y_\gamma|<2.37$, no photons with $1.37<|y_\gamma|<1.56$, $\Delta R_{\gamma j} > 0.4$

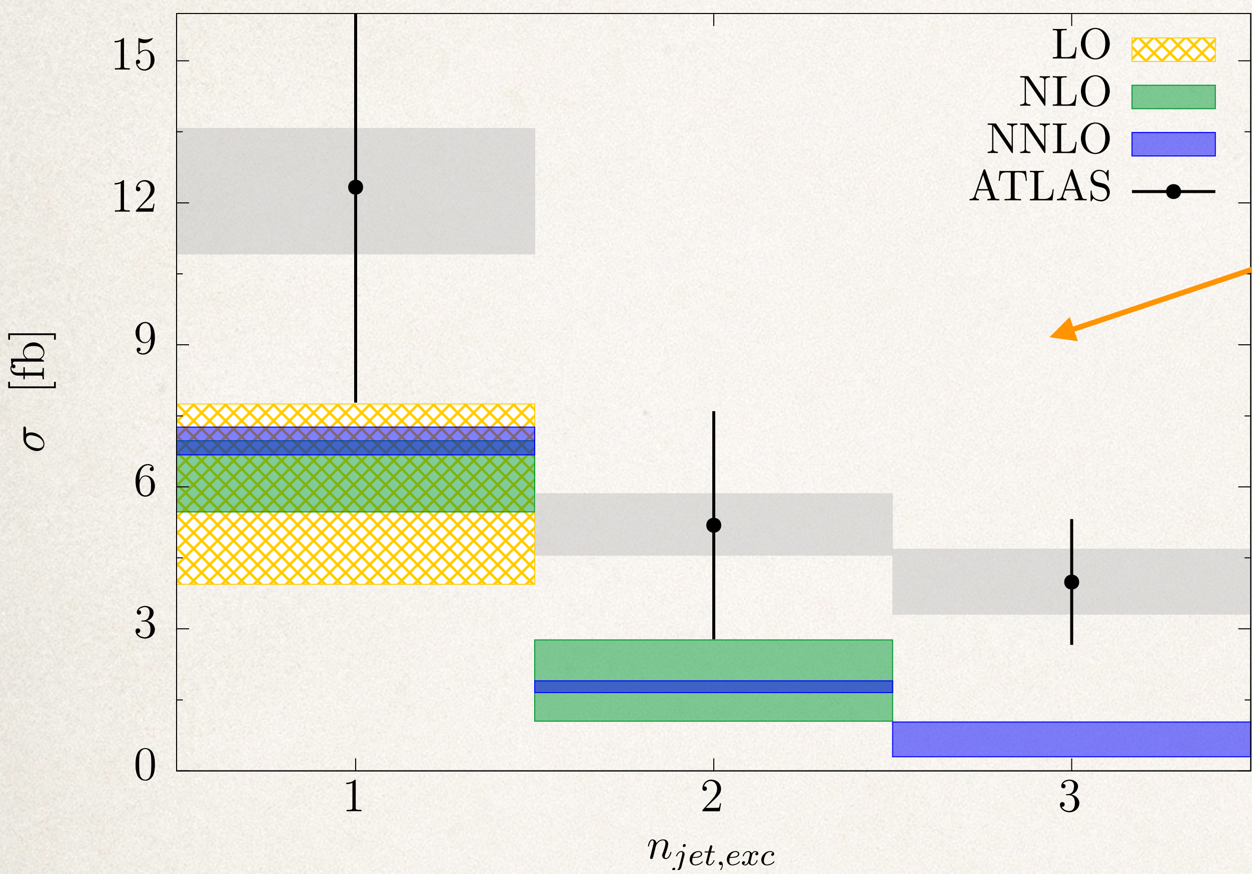




- Reduced uncertainties
- Stable shapes
- Virtually no shape correction for cos(θ^*) → Higgs characterization

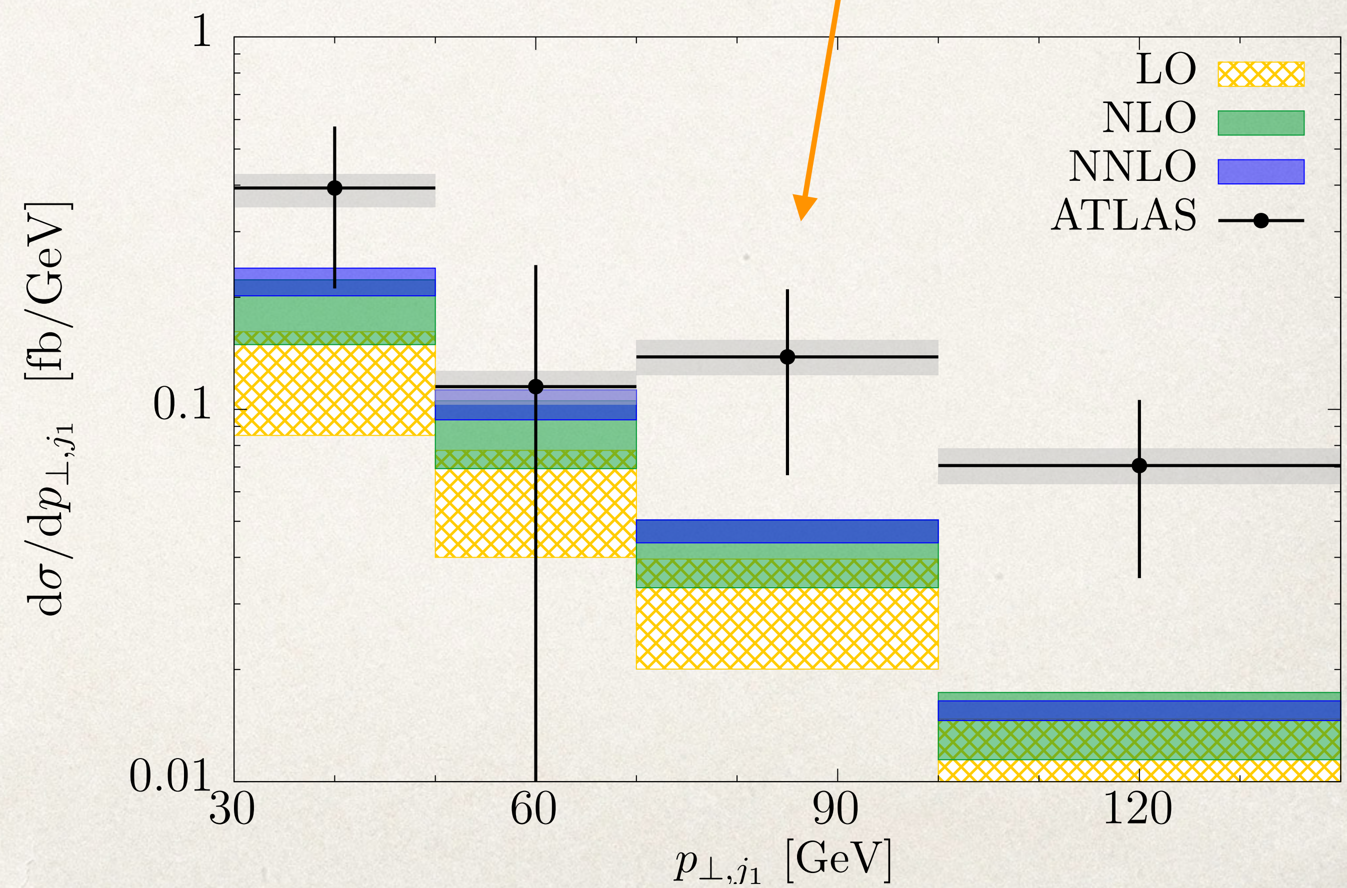
Fiducial analysis: H→γγ

[FC, Melnikov, Schulze (2015), Chen, Martinez, Gehrmann, Glover, Jaquier (2016)]



Exclusive Jet bins, ATLAS8

Leading jet p_T, ATLAS8



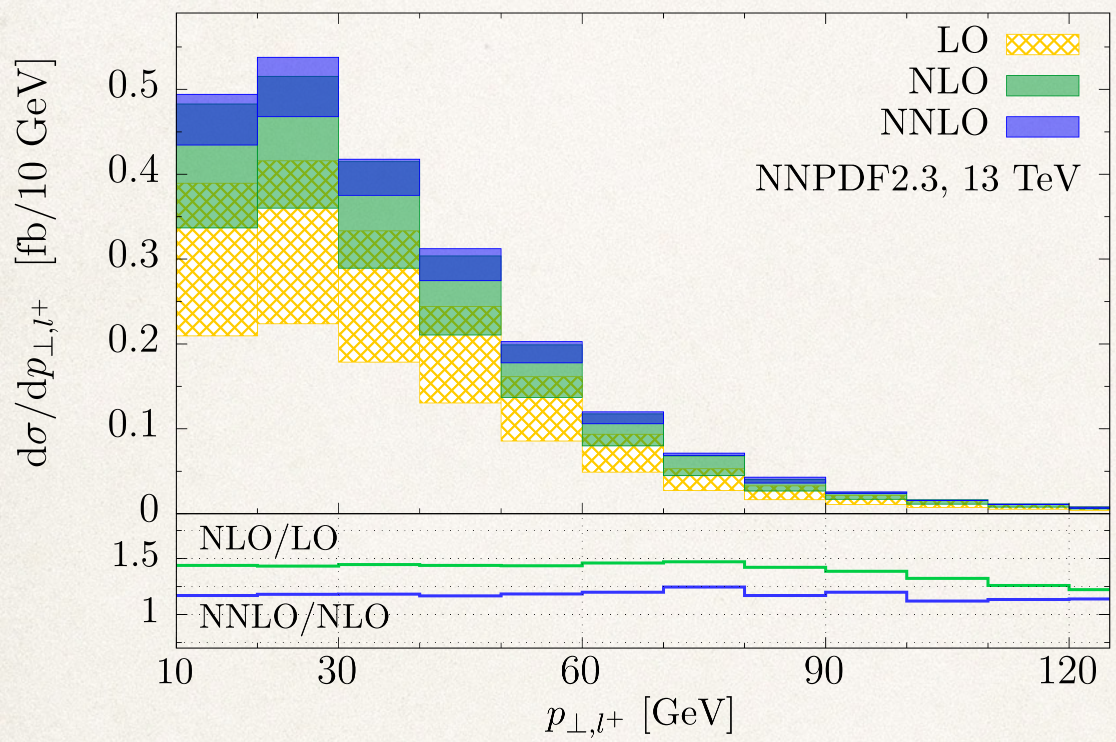
Still very large statistical fluctuations for these analysis to mean much, but NNLO theory error ~ systematic error

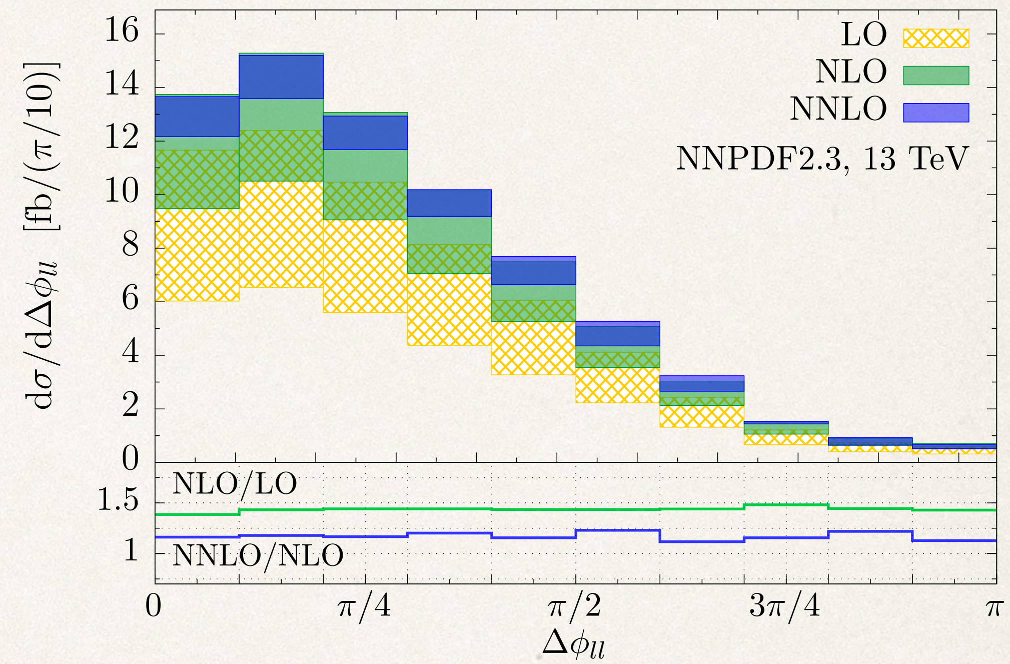
Fiducial analysis: $H \to 2l2\nu$

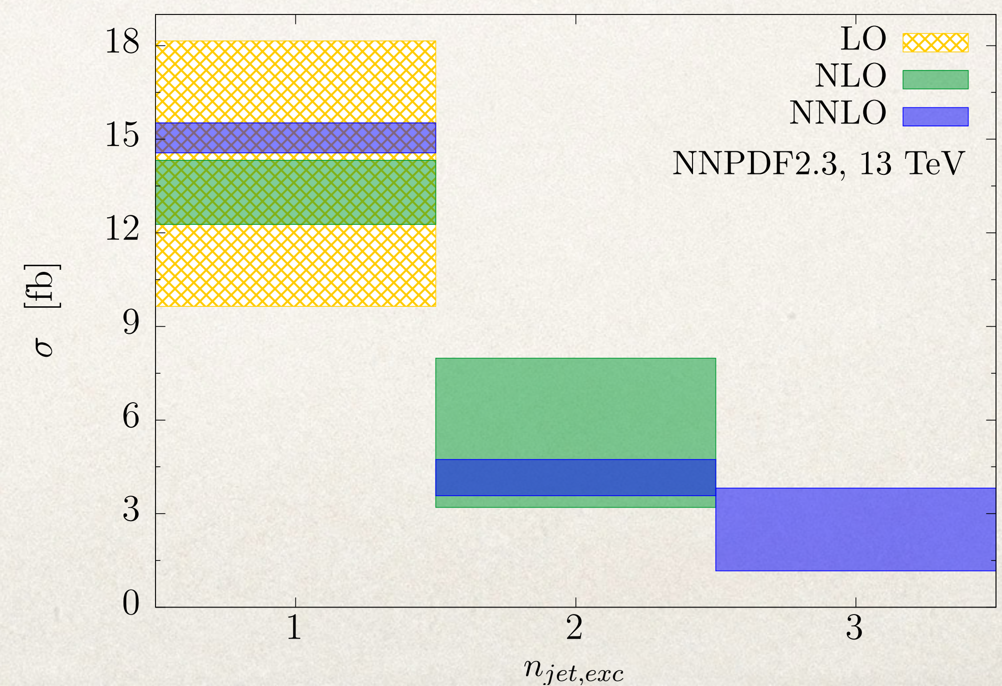
[FC, Melnikov, Schulze (2015)]

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



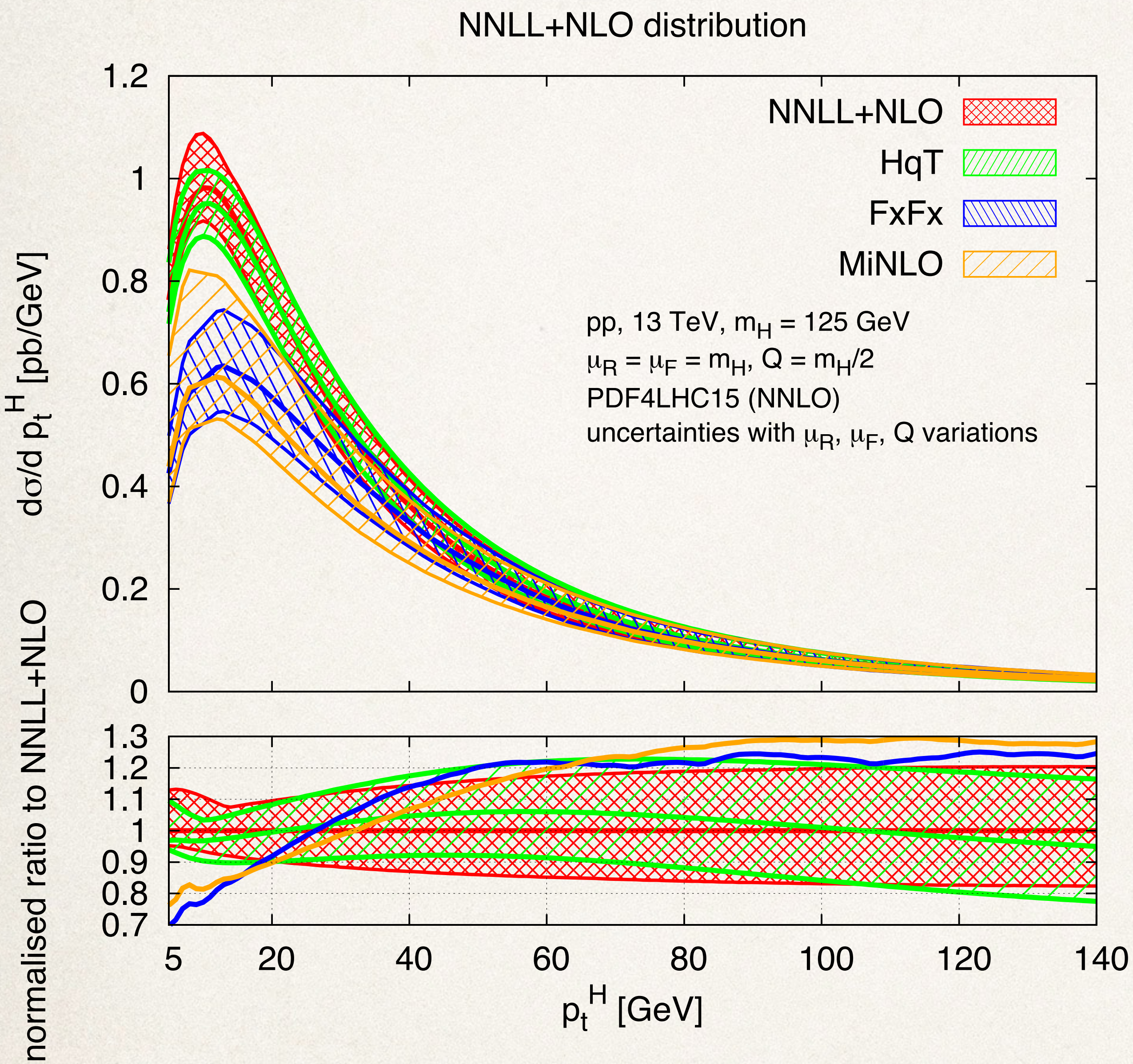


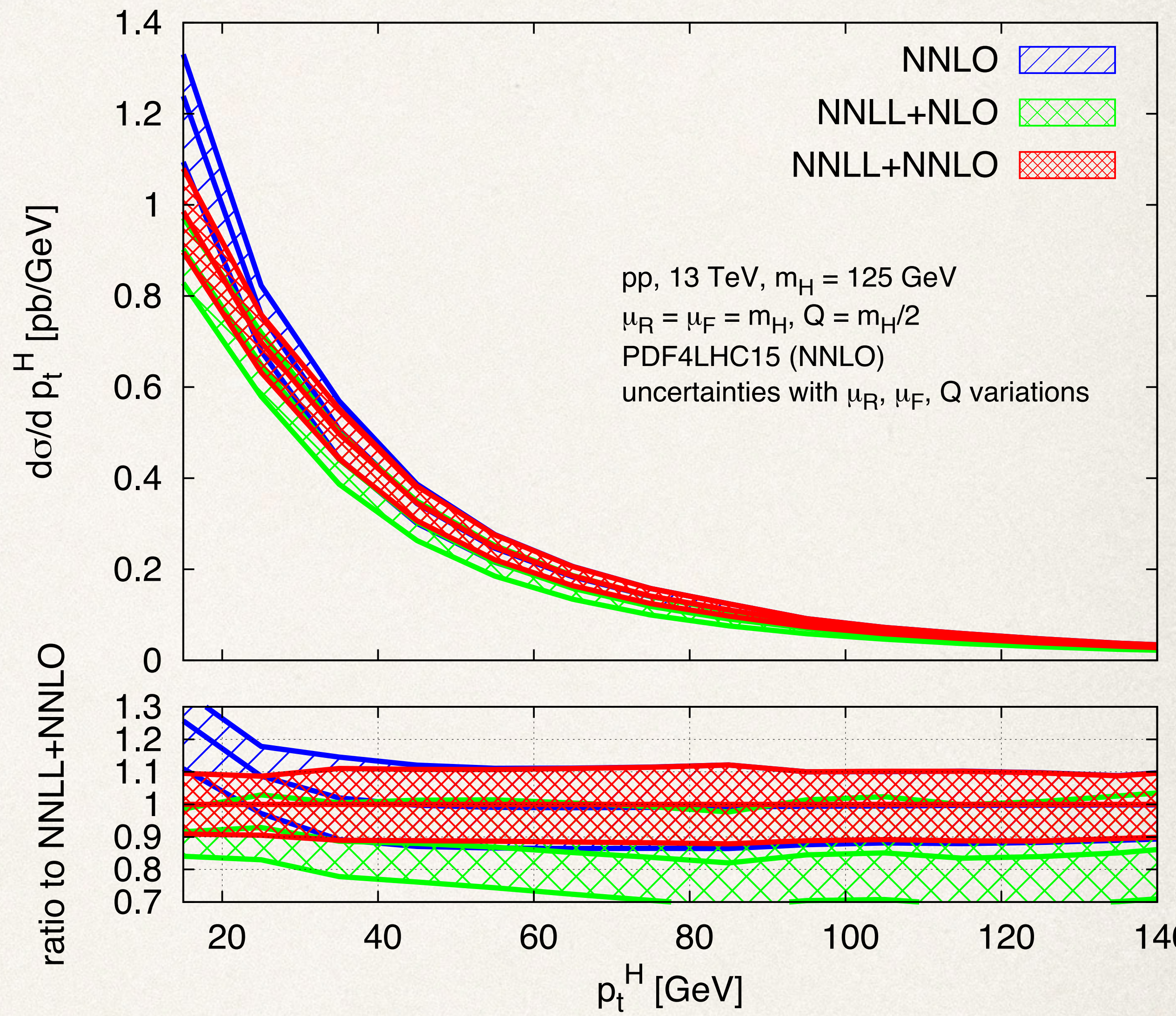


NNLO able to cope with complicated final states (up to 7 particles)

Higgs p_t spectrum at NNLO (for real)+NNLL

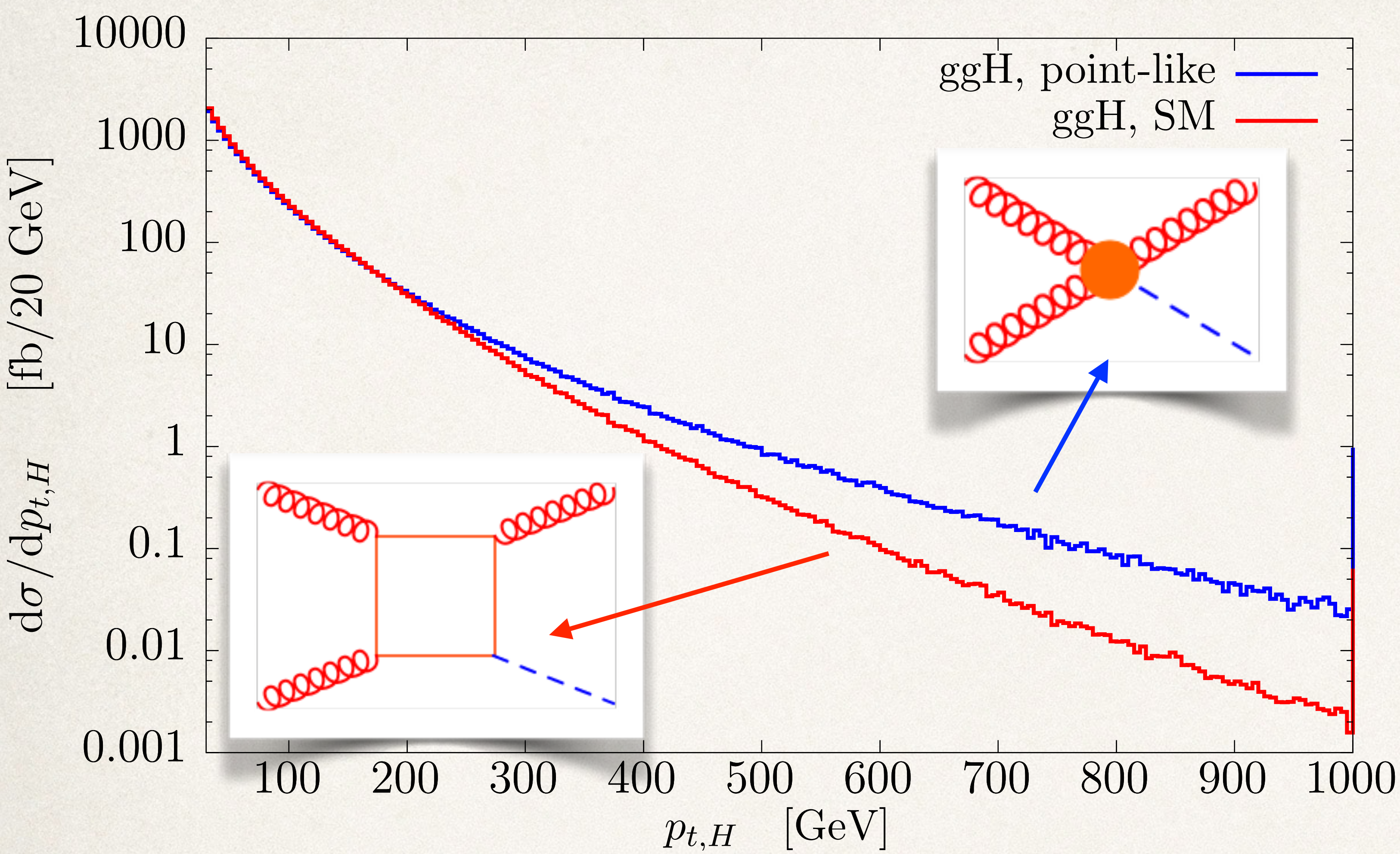
[Monni, Re, Torrielli (2016). In `usual' name coding: N^3LO+NNLL]





- 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

Moving towards the tail: top mass effects



σ_{gg} (p_t>$p_{t,cut}$) =	1 fb	1 ab
bb	$p_{t,cut}$ ~ 600 GeV	$p_{t,cut}$ ~ 1.5 TeV
ττ	~ 400 GeV	~ 1.2 TeV
2l2ν	~ 300 GeV	~ 1 TeV
γγ	~ 200 GeV	~ 750 GeV
4l	~ 50 GeV	~ 450 GeV

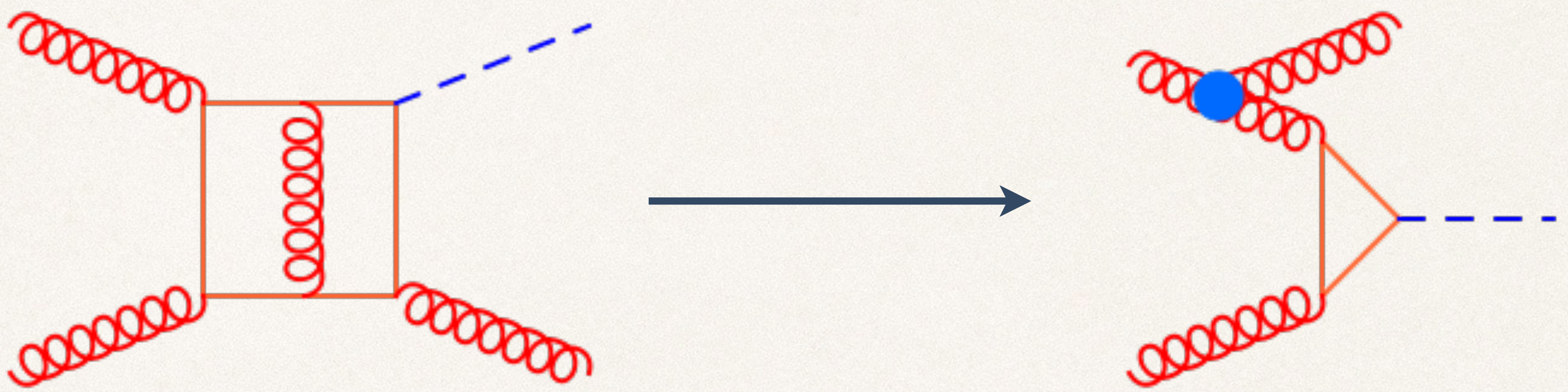
- Rates are low
- It would be very interesting to investigate *sub-structure potential for bb*
- Not unreasonable sensitivity expectation at high p_t ~ 10%
- DOES NOT REQUIRE PERFECT THEORETICAL CONTROL
- UNFORTUNATELY, WE ONLY KNOW IT AT LO

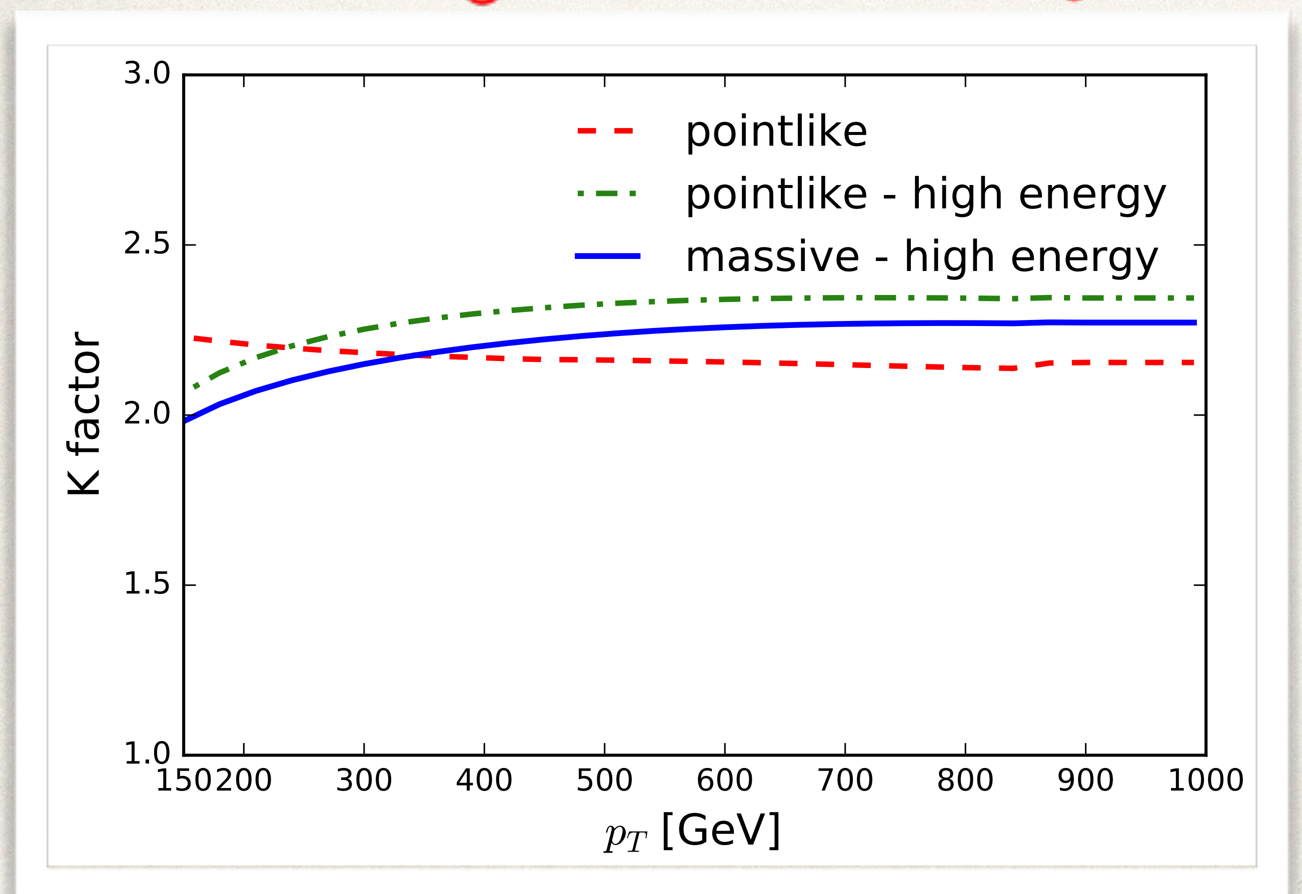
  (Although significant progress towards NLO [Bonciani et al (2016)])

Mass effects from BFKL physics

[FC, Forte, Marzani, Muselli, Vita (2016)]

- HEFT has wrong asymptotic behavior at large p_t: $1/p_t^2$ vs $1/p_t^4$
- Full SM contribution can be computed e.g. in the high energy limit. Factorization





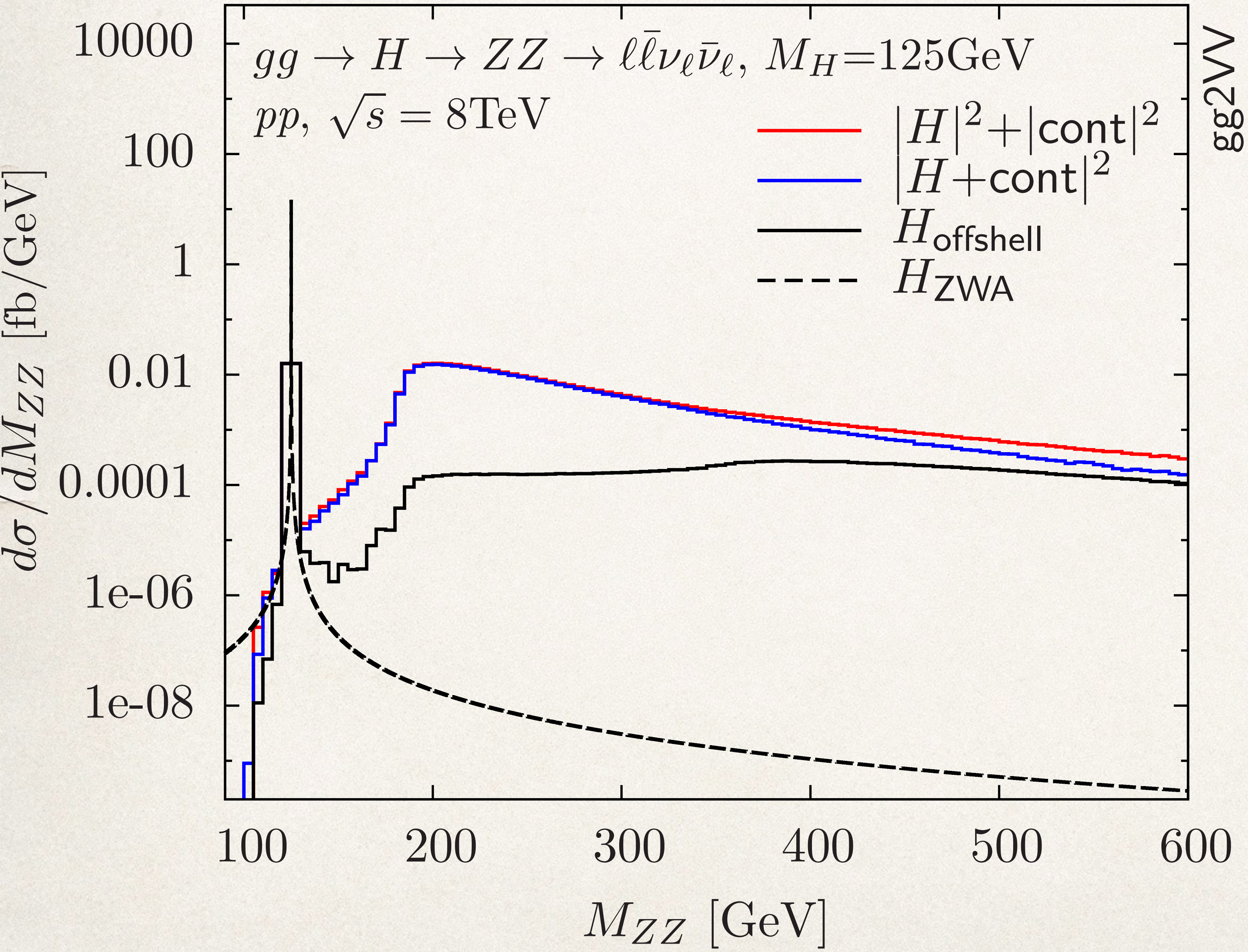
- Within ~20-30% accuracy: massive/massless K-factor the same
- Same conclusion from other approaches (jet merging, approx. NLO) [Frederix et al, Greiner et al, Neunmann and Williams (2016)]
- Waiting for the full NLO…

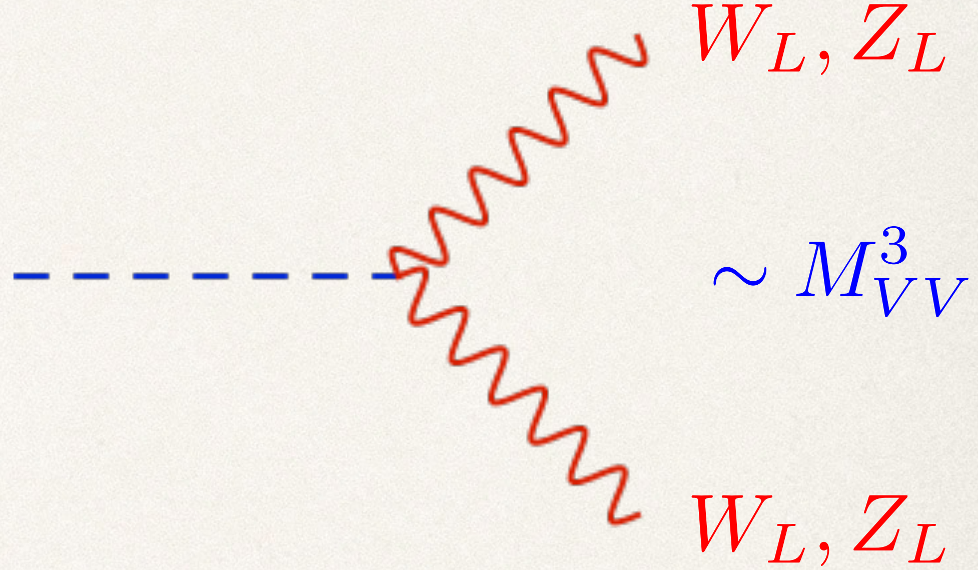
Tails of distributions:

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)]

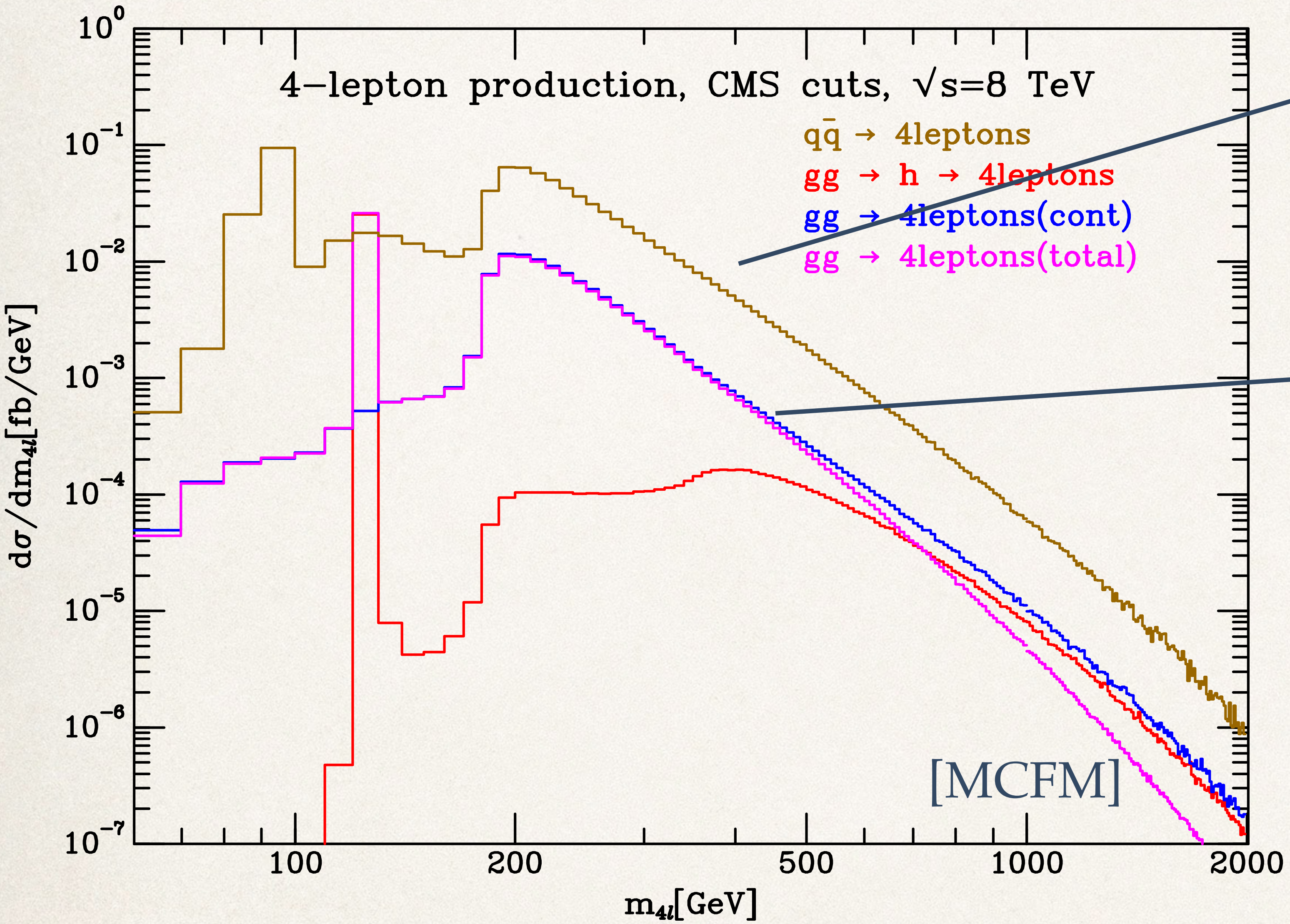




Can provide useful extra information w.r.t. on-shell cross section. E.g.: constraints on Γ_H [FC, Melnikov (2013)]

4l production at the LHC

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



Large qq background

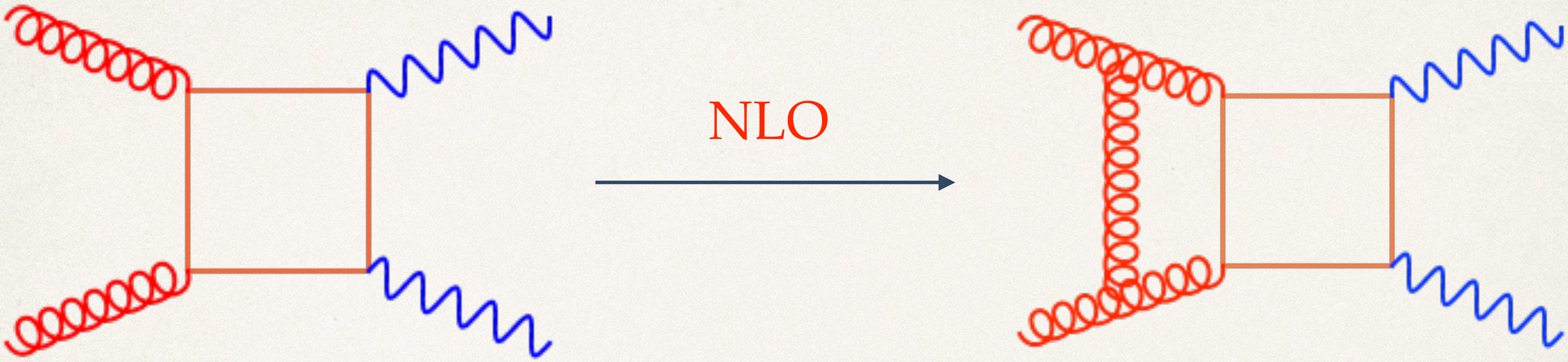
- recently computed at NNLO

Tricky gg background

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

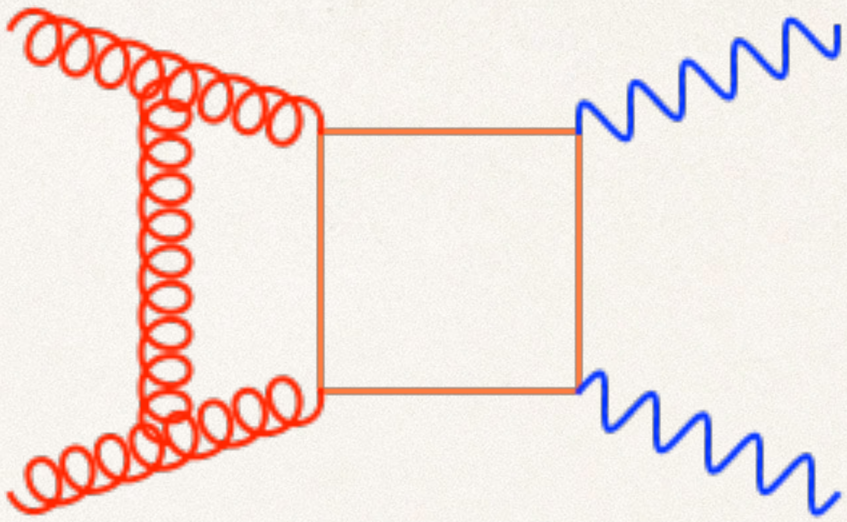
To have good control on width / coupling constraints: qq within 10%, gg within 50%

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

Loop amplitudes: general remarks

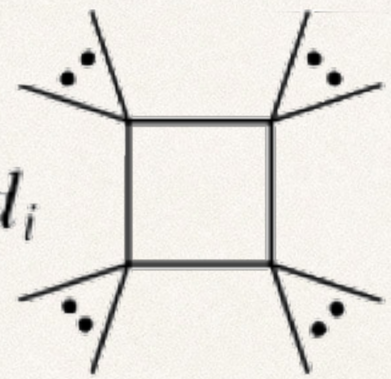
Computation of loop-amplitudes in two steps

1. reduce all the integrals of your amplitudes to a minimal set of independent `master' integrals
2. compute the independent integrals

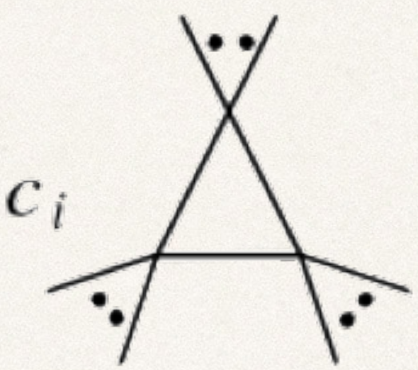
At one-loop:

- independent integrals are always the same (box, tri., bub., tadpoles)
- only (1) is an issue. Very well-understood (tensor reduction, unitarity…)

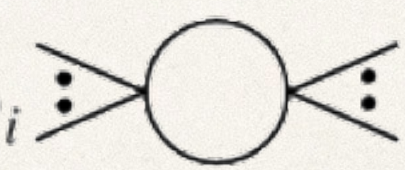
$$A_n^{1-\text{loop}} = \sum_i d_i$$



$$+ \sum_i c_i$$



$$+ \sum_i b_i$$



$$+ R_n + O(\varepsilon)$$

Beyond one-loop: reduction not well understood, MI many and process-dependent (and difficult to compute…)

Reduction to ``Master Integrals"

- This case: based on traditional IBP-LI RELATIONS [Tkachov; Chetyrkin and Tkachov (1981); Gehrmann and Remiddi (2000)] / LAPORTA ALGORITHM [Laporta (2000)]

$$\int d^d k F(k;\{p_j\}) = \int d^d(k+\alpha q) F(k+\alpha q;\{p_j\})$$

$$\downarrow$$

$$\alpha \int d^d k \frac{\partial}{\partial k}\cdot\left[q F(k,\{p_j\})\right] = 0$$

- Non-trivial relations between integrals with different numerator/ propagator structures. Can be systematically solved

- ``Brute force approach". Very solid, generates very large intermediate expressions
- For the case at hand, this was not a bottleneck. 75 Master Integrals

Computing MI: differential equations

[Kotikov (1991), Remiddi (1997)]

- Loop integrals in generic kinematics: very hard
- In general however, they simplify for specific kinematics configurations (threshold, high-energy…)
- If derivatives of MI are known, one can use the to transport simple kinematics to generic kinematics
- Taking derivatives of MI: ~ IBP procedure → DERIVATIVES OF MI ARE LINEAR COMBINATIONS OF MI

$$\partial_x \vec{f}(x) = A(\epsilon, x) \cdot \vec{f}(x)$$

- Naively: system of 75 coupled differential equations… impossible to solve. In reality
  - A is a sparse matrix (only small subsets really coupled)
  - f are Feynman Integrals, not generic functions. Expect simplifications in A

Differential equations made simple

[Henn (2013)]

$$\partial_x \vec{f}(x) = A(\epsilon, x) \cdot \vec{f}(x)$$

- We are dealing with a physical problem → constraints from singularity structure of Feynman integrals
- Near singular points (thresholds,...): $f(x) \sim (x - x_0)^{a\epsilon}$
- System can be put in a Fuchsian form (i.e. singularity structure can be made manifest)

$$\partial_x \vec{g}(x) = \sum_i \frac{A_i(\epsilon)}{(x - x_i)} \vec{g}(x) \qquad g(x) = T(x, \epsilon) f(x)$$

- Simplest possible case

$$\partial_x \vec{h}(x) = \epsilon \sum_i \frac{A_i}{(x - x_i)} \vec{h}(x) \text{ or } d\vec{h}(x) = \epsilon \sum_i A_i d\ln(x - x_i) \vec{h}(x)$$

- While the last step is not obvious, in many cases — including ours — it actually happens (*beware, not always the case…*)

Integrating the differential equations

$$\partial_x \vec{f}(x) = A(\epsilon, x) \cdot \vec{f}(x) \longrightarrow \partial_x \vec{h}(x) = \epsilon \sum_i \frac{A_i}{(x - x_i)} \vec{h}(x)$$

- While integrating the full system can still be hard, it is simple to obtain an expansion around ε = 0 in terms of well known iterated integrals
- All system can be integrated at once (modulo boundary conditions…) and expressed in terms of Goncharov PolyLogs

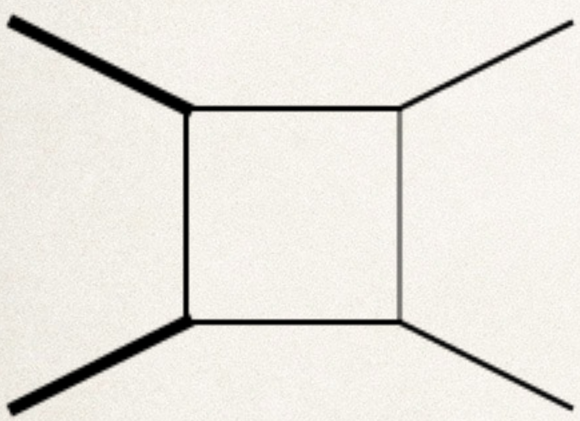
$$G(a_n, a_{n-1}, ..., a_1, t) = \int_0^t \frac{\mathrm{d}t}{t_n - a_n} G(a_{n-1}, ..., a_1, t_n) \qquad G(a_1; z) = \int_0^z \frac{dt}{t - a_1}$$

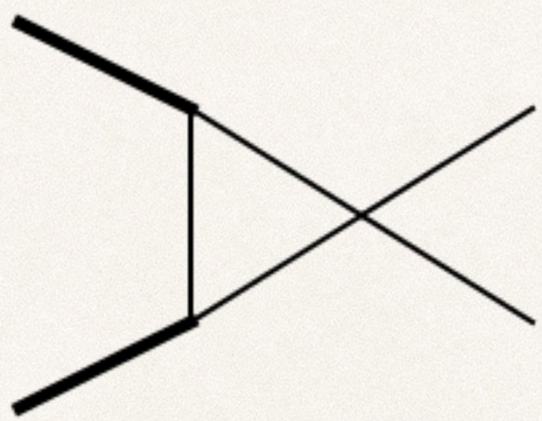
- Extremely well known functions, with a lot of structure to efficiently deal with them (shuffle, symbol, coproduct…)
- Can be efficiently numerically evaluated
- h: pure function of uniform weight

Finding the canonical basis

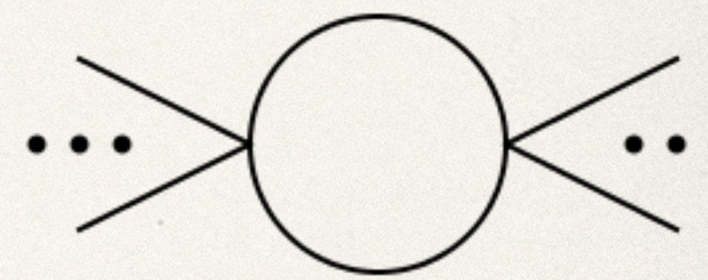
- The problem: finding the right basis h
- Algorithms for finding it exist, e.g. [Lee (2014), Meyer (2016)]
- Basis is not unique. ``Nice'' choice can simplify problem a lot (e.g. boundaries)
- In fact, can be found quite easily by bootstrapping the singularity structure of the integrals. Canonical basis: pure functions of uniform weight

ONE LOOP





x4 (s,t,M_3^2,M_4^2)

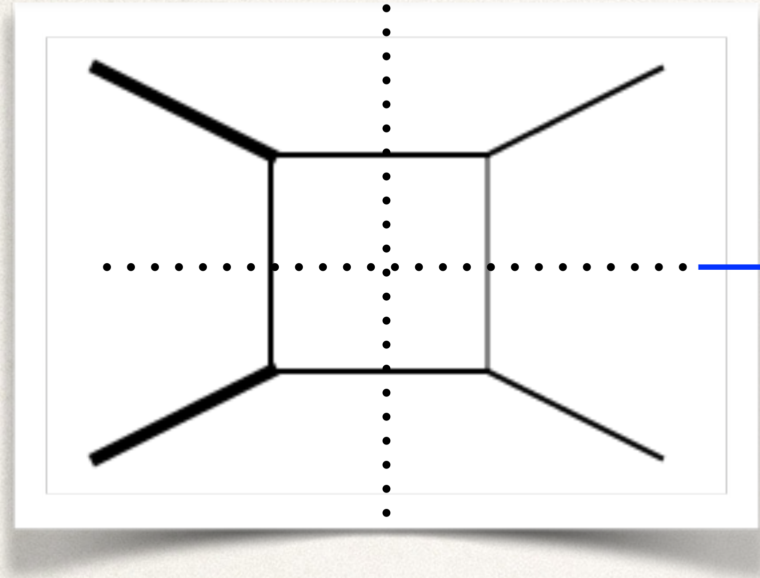


- Fix the simple integrals by hand

$$B \sim \frac{(p^2)^{-\epsilon}}{\epsilon(1-2\epsilon)} = \frac{1}{\epsilon}\left[1+\epsilon(-\ln p^2+2)+\ldots\right] \longrightarrow B \to (1-2\epsilon)B$$

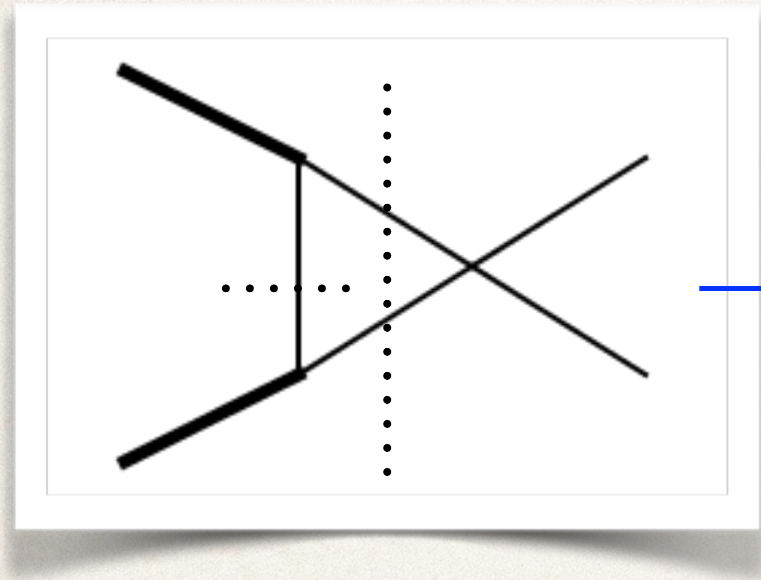
Finding the canonical basis

- Singularity structure must reflect ``pure and uniform'' properties → CUT



$$J = \frac{1}{st}$$

GOOD CANDIDATE
$D \to stD$



$$\int \frac{dt}{t} \frac{1}{\sqrt{\Delta}}$$

GOOD CANDIDATE
$C \to \sqrt{\Delta}C$

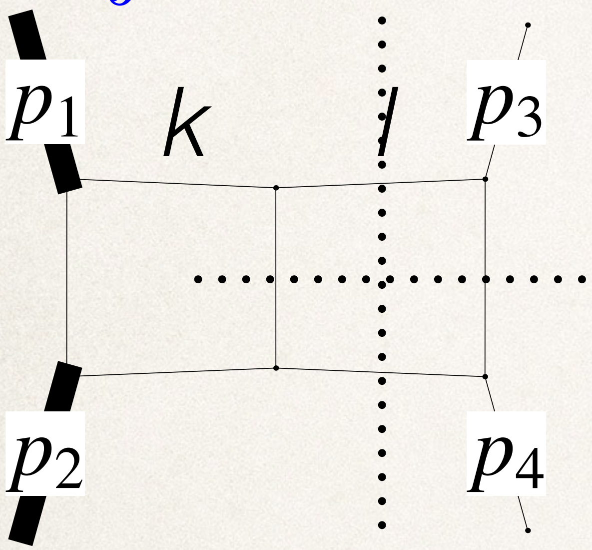
$$\Delta = s^2 + m_3^4 + m_4^4 - 2(sm_3^2 + sm_4^2 + m_3^2 m_4^2)$$

- These simple considerations are enough to find a canonical basis at one loop.

Finding the canonical basis: bootstrap

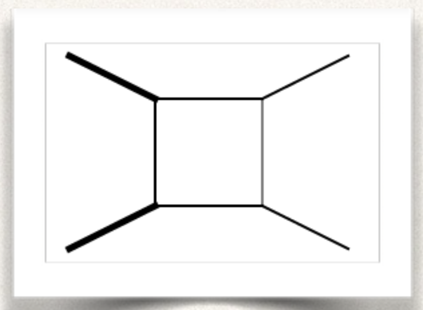
Example: COMPLICATED DOUBLE BOX INTEGRAL

$$I = \int d^dk d^dl \frac{N(k)}{k^2(k+p_1)^2(k+p_{12})^2 l^2 (l+p_1)^2 (l-p_3)^2 (k-l)^2}$$

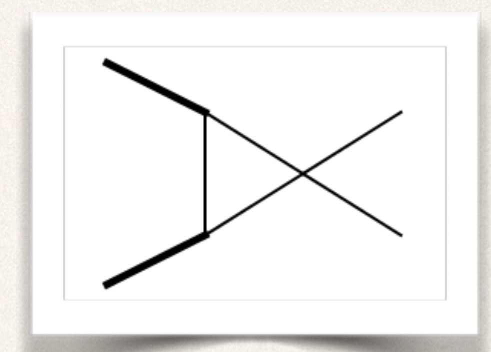


$$\longrightarrow \int d^dk \left[\frac{1}{s(k-p_3)^2}\right] \frac{N(k)}{k^2(k+p_1)^2(k+p_{12})^2}$$

GOOD CANDIDATES



$N(k) = s^2 t,$



$N(k) = s(k-p_3)^2\sqrt{\Delta}$

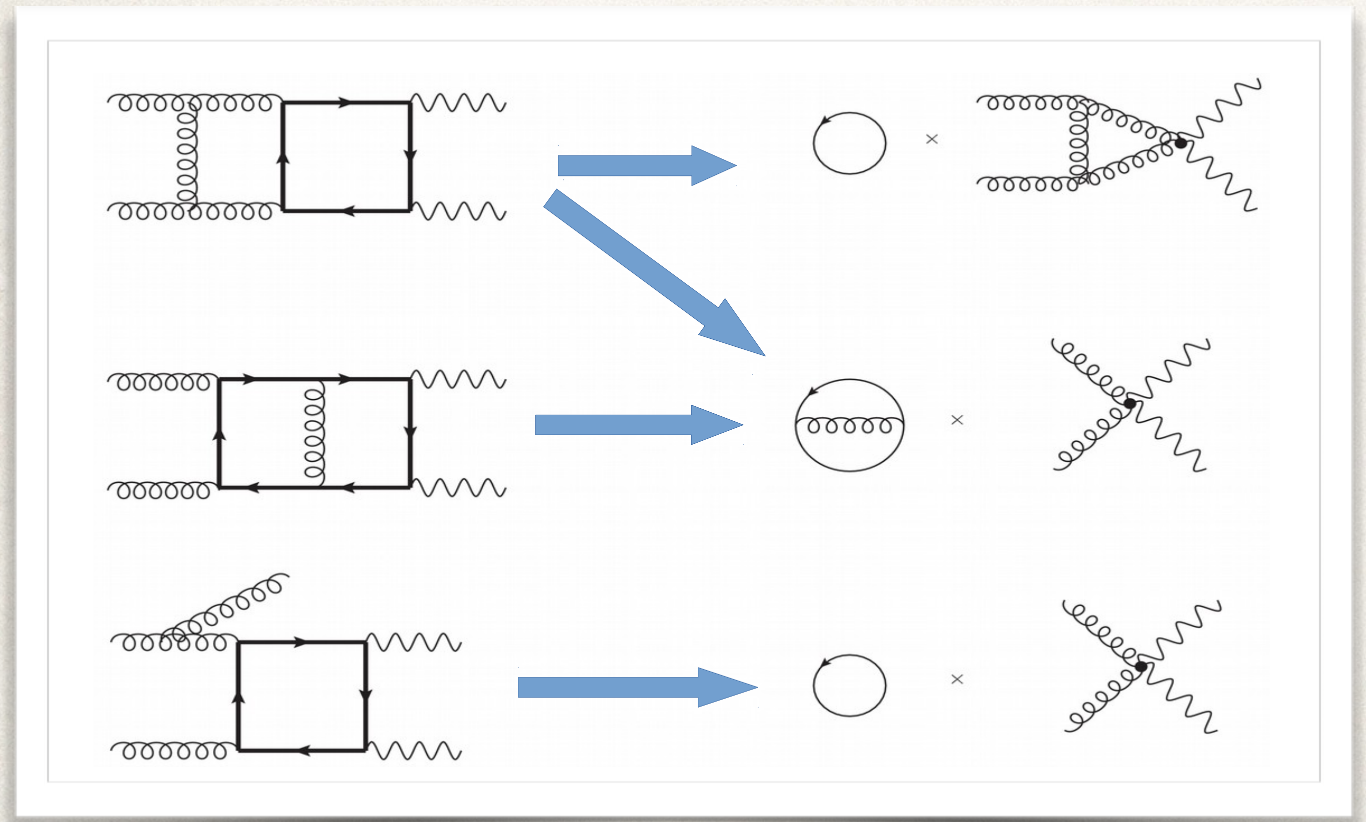
Using these ideas, FULL CANONICAL BASIS AT TWO LOOPS CAN BE EASILY FOUND

gg→VV 2-loop amplitudes: recap

- Thanks to new insight into the singularity structure of Feynman Integrals, very complicated 2-loop amplitudes could be computed for massless quarks circulating into the loops [FC, Henn, Melnikov, Smirnov, Smirnov (2014-15); Gehrmann, Manteuffel, Tancredi (2014-15)]

- Many subtle points not described here (linearization of the alphabet, boundary conditions, analytic continuations…)

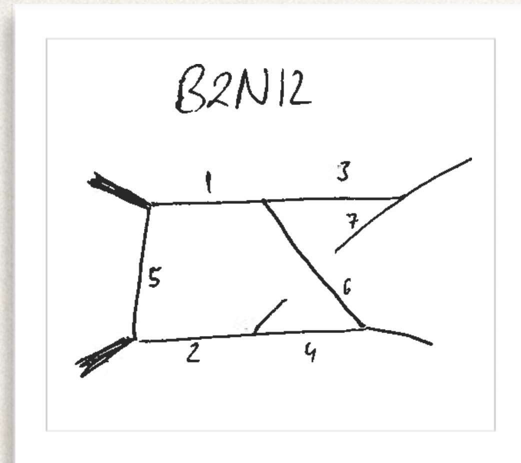
- Massive loops: still too complicated. If $m_{4l} < 2\, m_t$: Expand (~Higgs case)

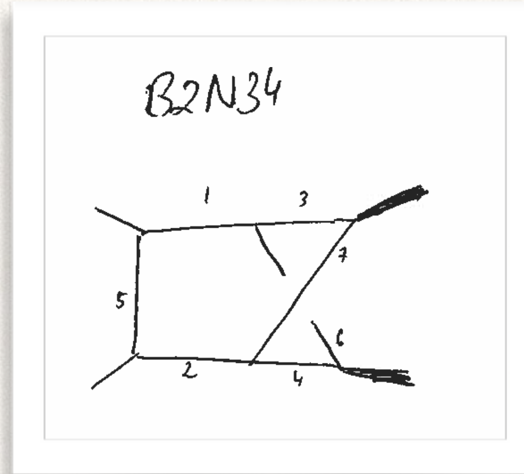


- Expand in s/m_t^2
- Amplitude known up to $(s/m_t)^4$ [Dowling, Melnikov (2015)]
- Beyond threshold: Padé approximations [Kirschner et al (2016)]
- Full result could be obtained numerically? (see HH [Borowka et al (2016)])

gg→VV @ NLO: massless quarks

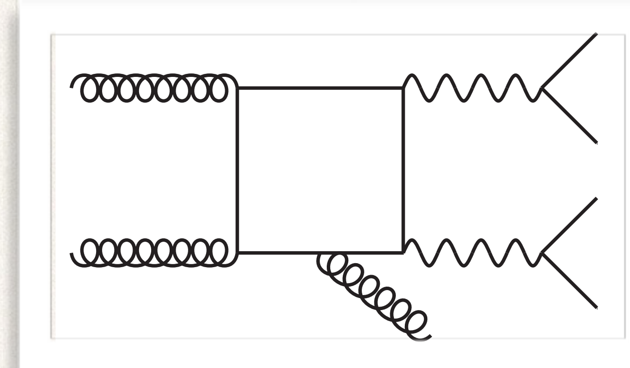
2-Loop Amplitudes





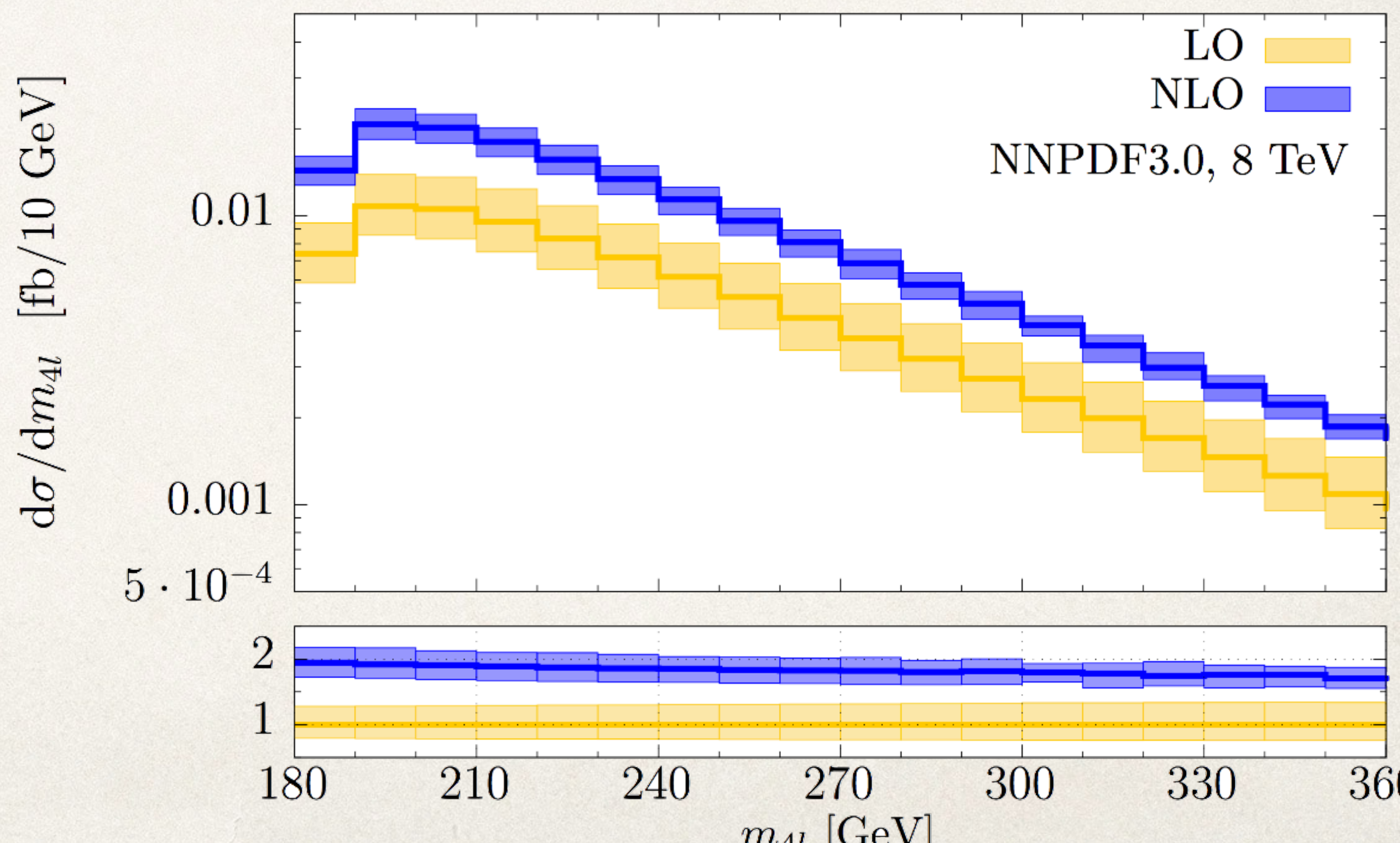
+

Real Emission



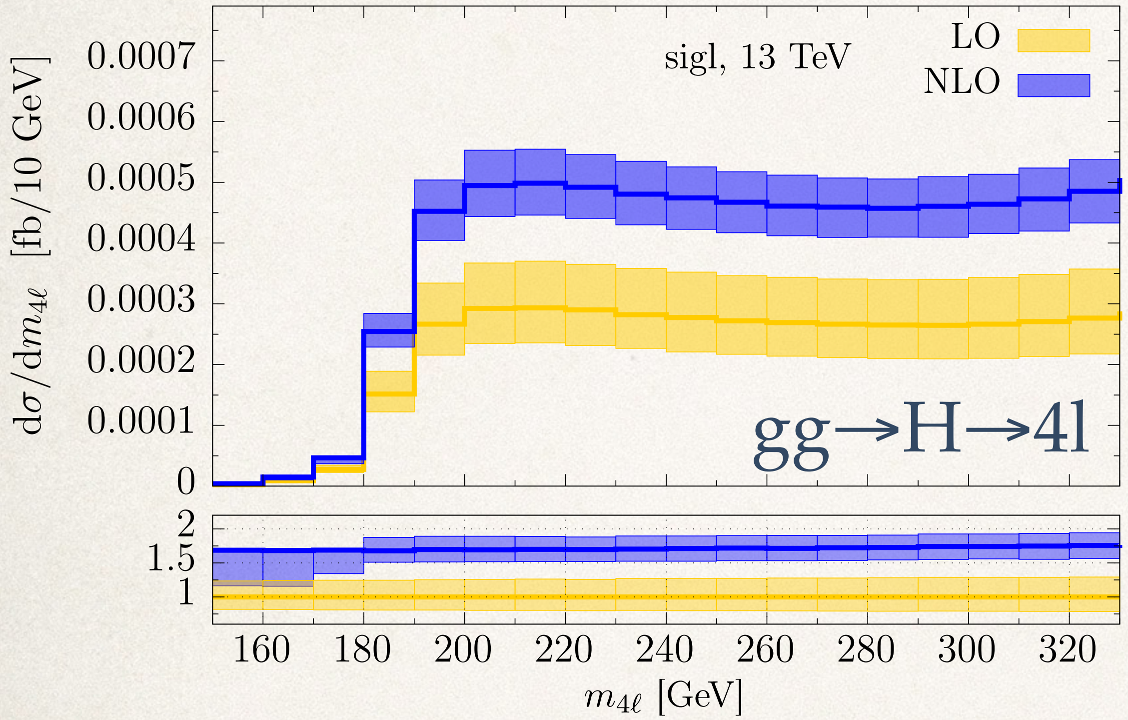
Mixed analytical + numerical unitarity
[FC, Melnikov, Röntsch, Tancredi (2015)]

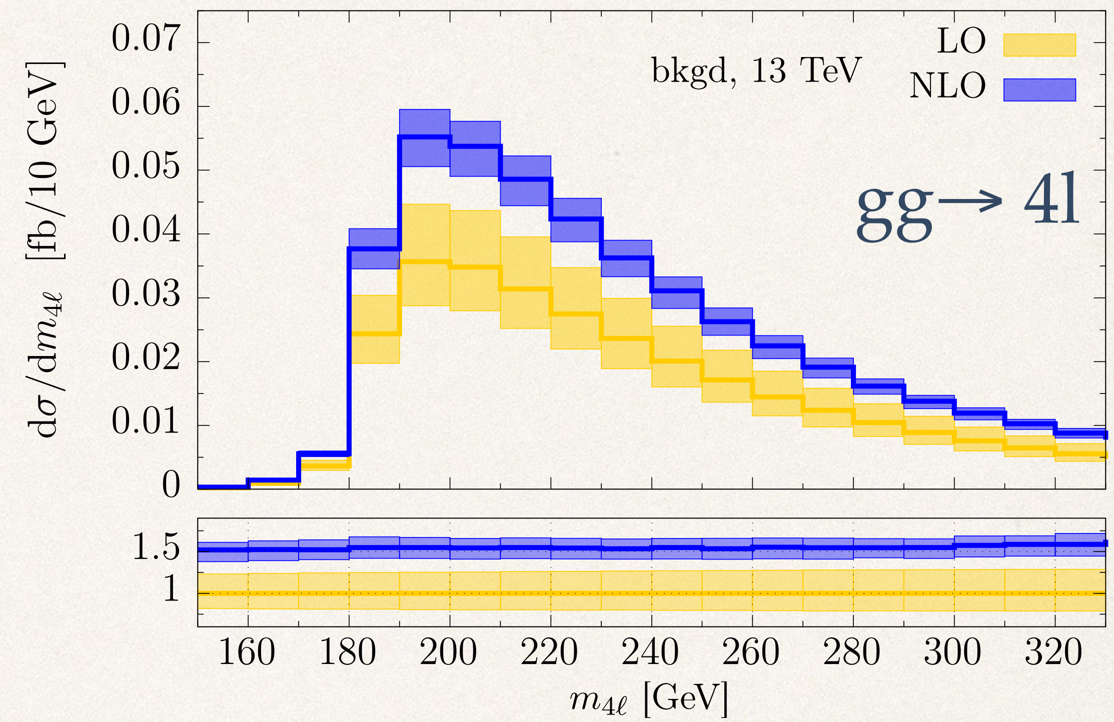
- Large corrections (as expected). Outside uncertainty estimate of NNLO qqb → ZZ
- behavior very similar to gg → H signal (expected)
- Confirms previous estimates based on soft-gluon resummation

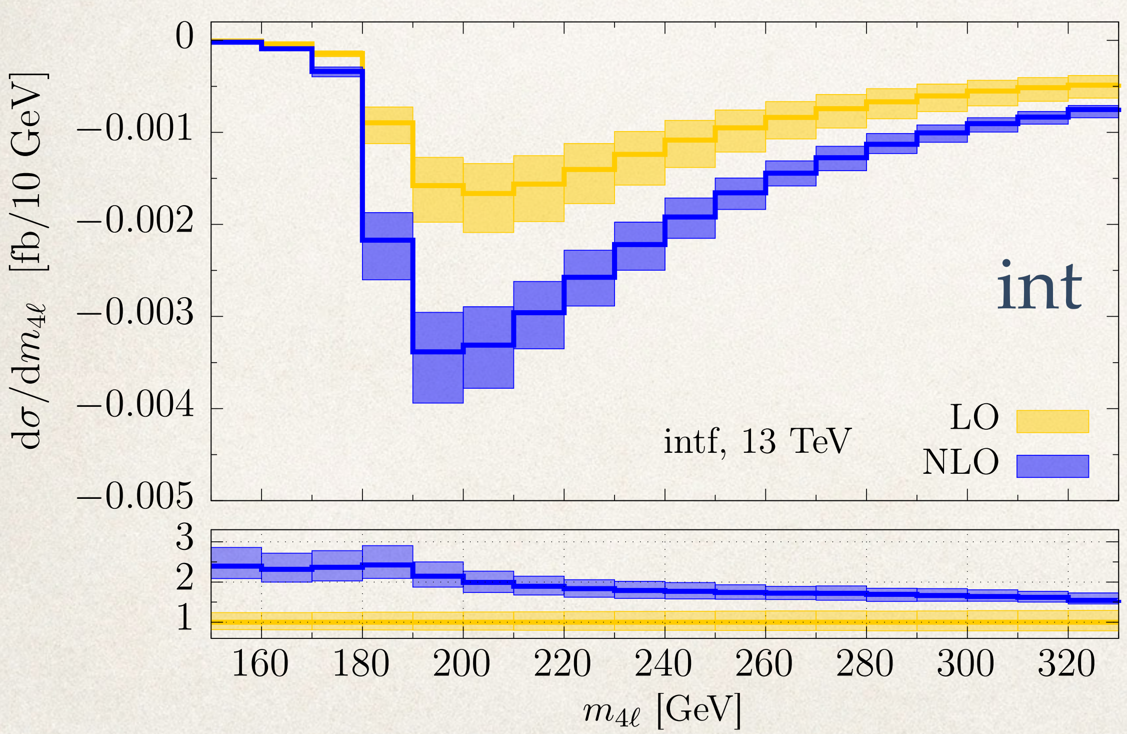


gg→4l: NLO results

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

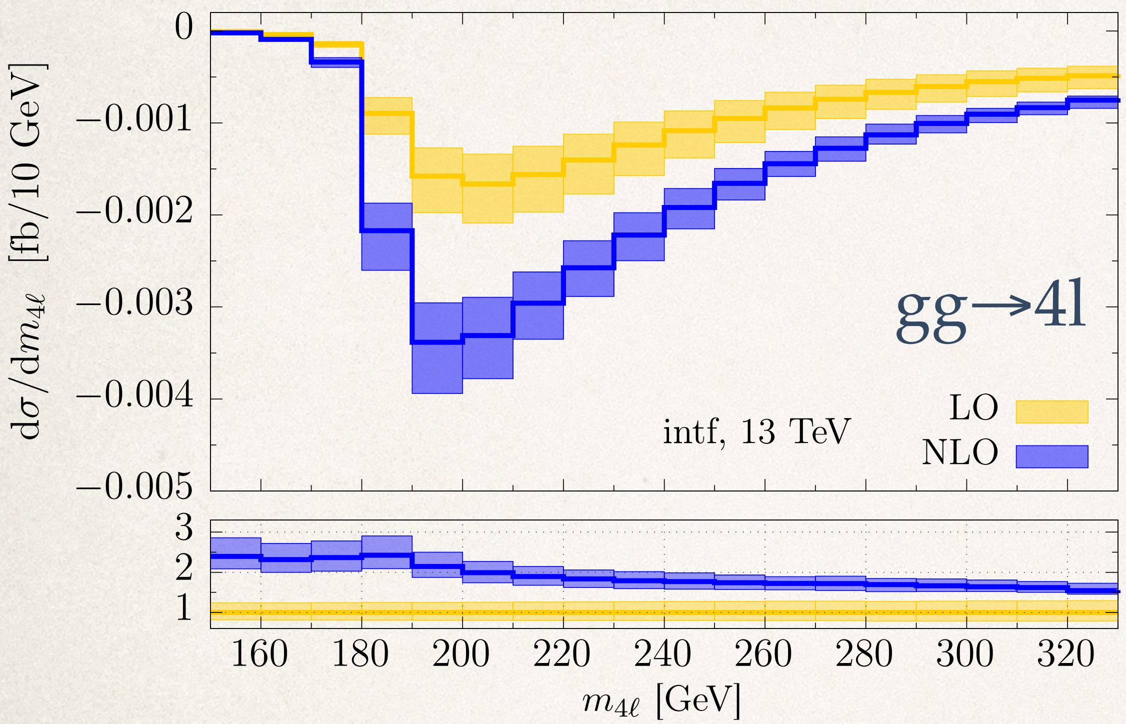


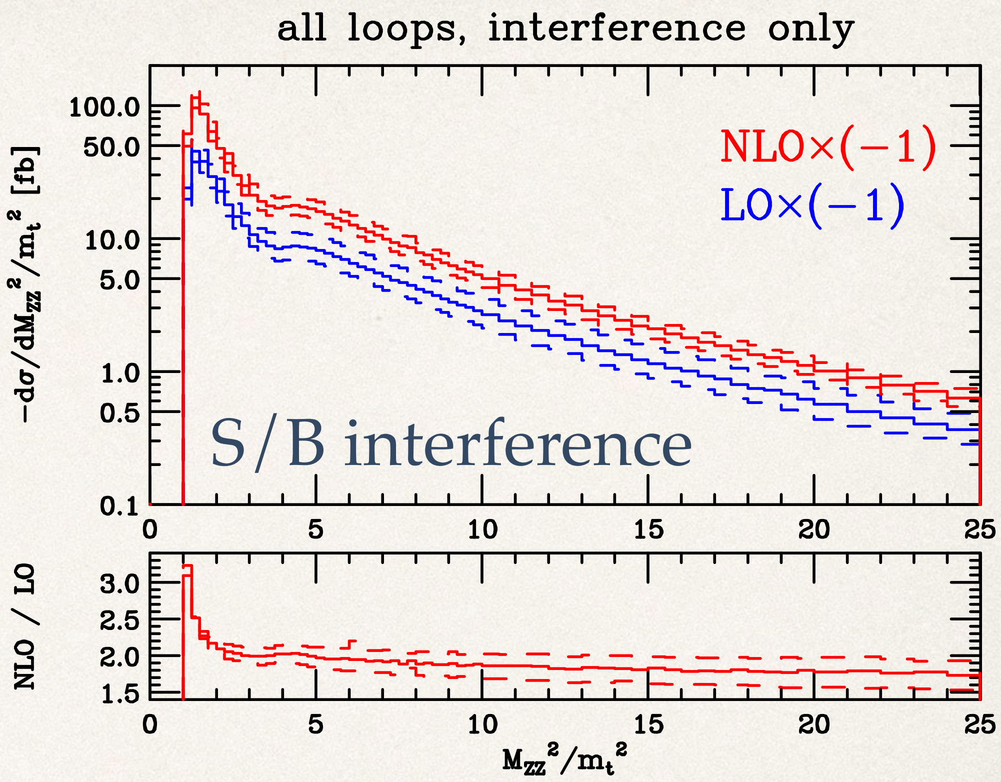




- RESULT VALIDATES $K_{sig} \sim K_{bck} \sim K_{int}$ [Bonvini, FC, Forte, Melnikov, Ridolfi (2013)]
- $K_{int} \sim K_{sig}$ seem to persist also at high m_{4l} ([Campbell et al] approximation)
- Interestingly, non trivial K_{int} *below* the Z threshold. Negligible overall effect

gg→ZZ: beyond threshold?





- [Campbell et al (2016)]: use a trick to make the $1/m_t^2$ expansion working beyond threshold. Conformal mapping + Padé

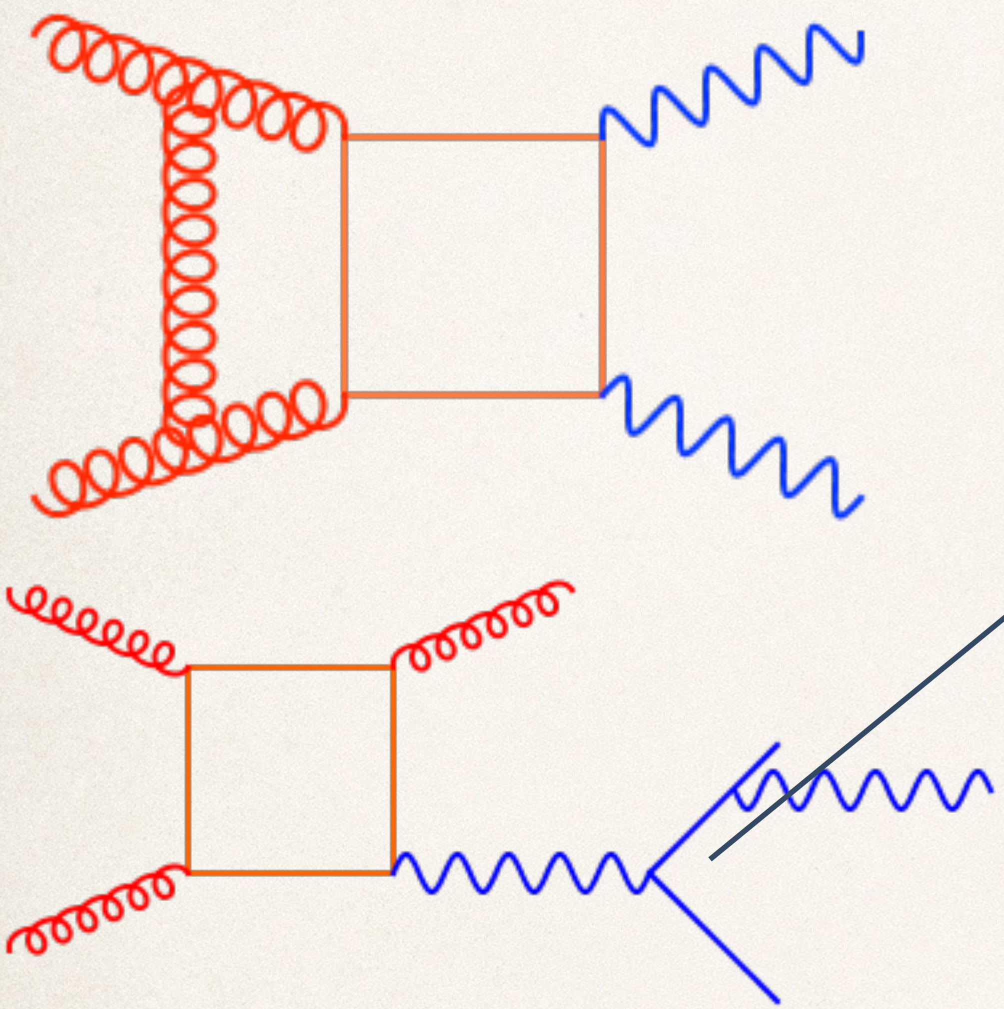
$$w(z) = \frac{1-\sqrt{1-s/(4m_t^2)}}{1+\sqrt{1-s/(4m_t^2)}}$$

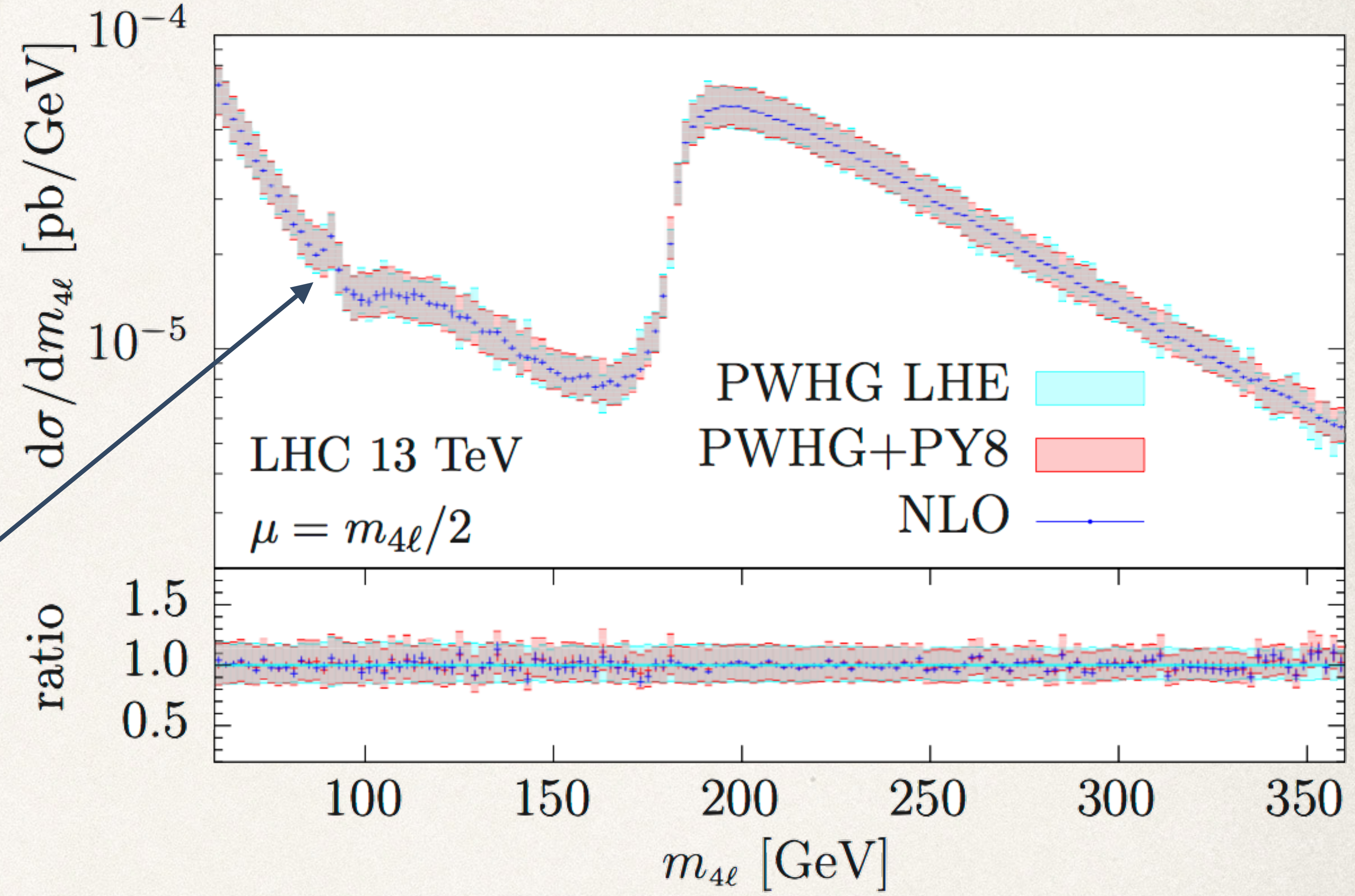
- Works very well for gg → H (although *much simpler threshold structure*)
- Give the expected qualitative behavior
- Would be interesting to check against (unknown) *exact computation. Fully numerical approach?*

One step closer to reality: PS matching

[Alioli, FC, Luisoni, Röntsch (2016)]

Powheg + Pythia8, background only, massless





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

Work in progress:

- Signal + bckd + interference, massive
- More exclusive quantities. Tricky part: qg initiated channels, not fully under control

Conclusions

- No obvious new physics at the LHC and SM-like EWSB sector calls for new scrutiny of SM predictions, hoping to spot deviations pointing to new physics
  - Bulk of distributions: new level of accuracy is needed. Sophisticated predictions, which required very interesting conceptual advancement in QCD (IR structures and exclusive NNLO, new ideas for multi-loop amplitudes)
  - Tails of distributions are interesting, but very hard to properly model (virtual massive quark effects, EW corrections…)
- Despite lot of progress, still a lot is missing
- The remarkable success of the experimental program at the LHC keeps providing exciting motivation to pursue these investigations

WE LOOK FORWARD FOR THE FUTURE…

Thank you for your attention!