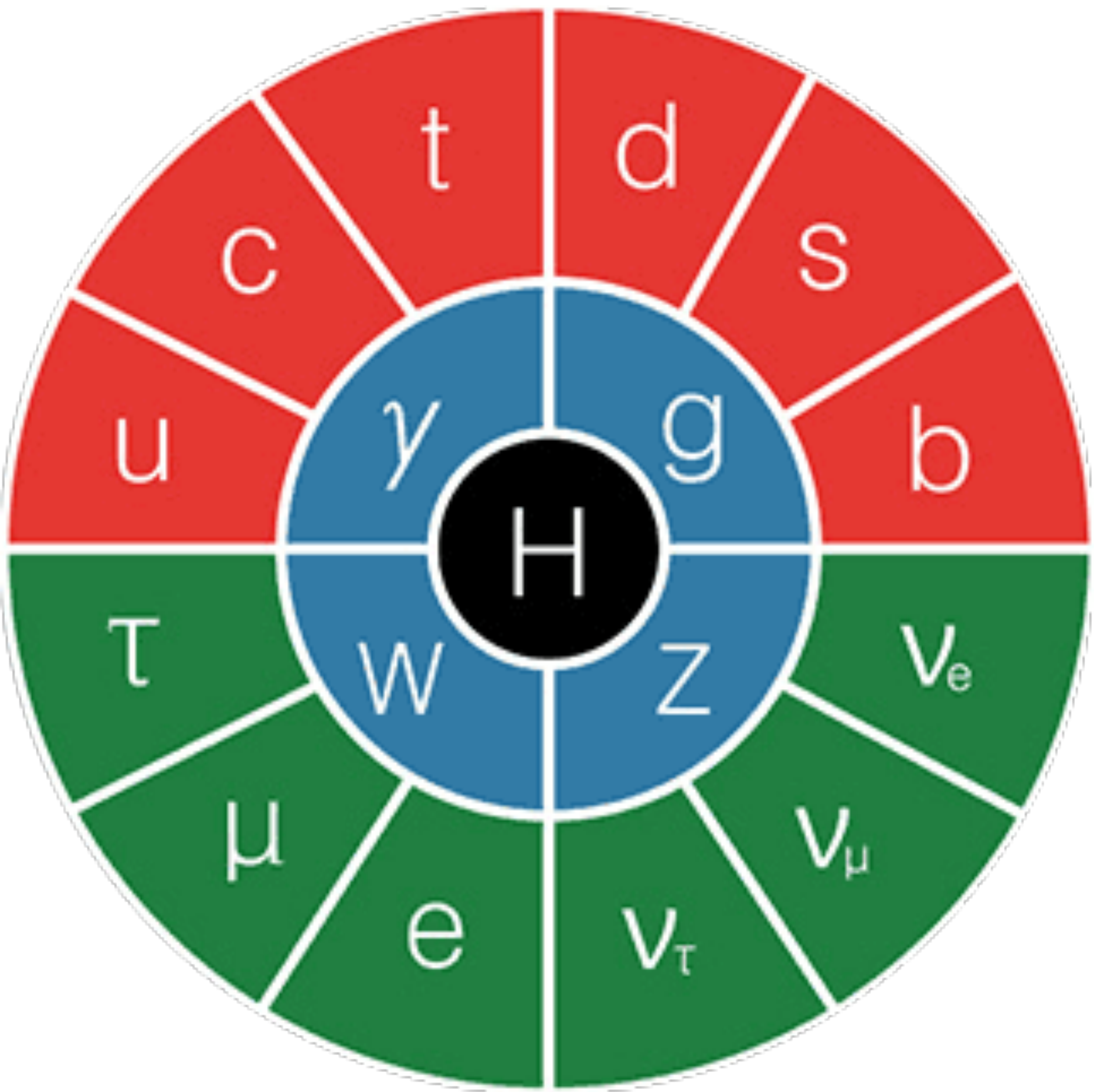
Higgs Boson Production and Decay

Fabrizio Caola, IPPP Durham

Higgs Maxwell Workshop — ``Higgs and Einstein"

Edinburgh, 14 February 2018

Particle physics circa 2018



- With the discovery of the Higgs, for the first time we have a ``complete'' theory of fundamental interactions
- If we lived inside a collider: found the ``ultimate'' theory?
- The world beyond colliders: strong strong indications of BSM (dark matter/energy, baryon asymmetry…)
- At least some of these new physics phenomena have a simple particle explanation → look for them!
- Searching for new physics (at colliders): Higgs plays a central role

Particle physics circa 2018

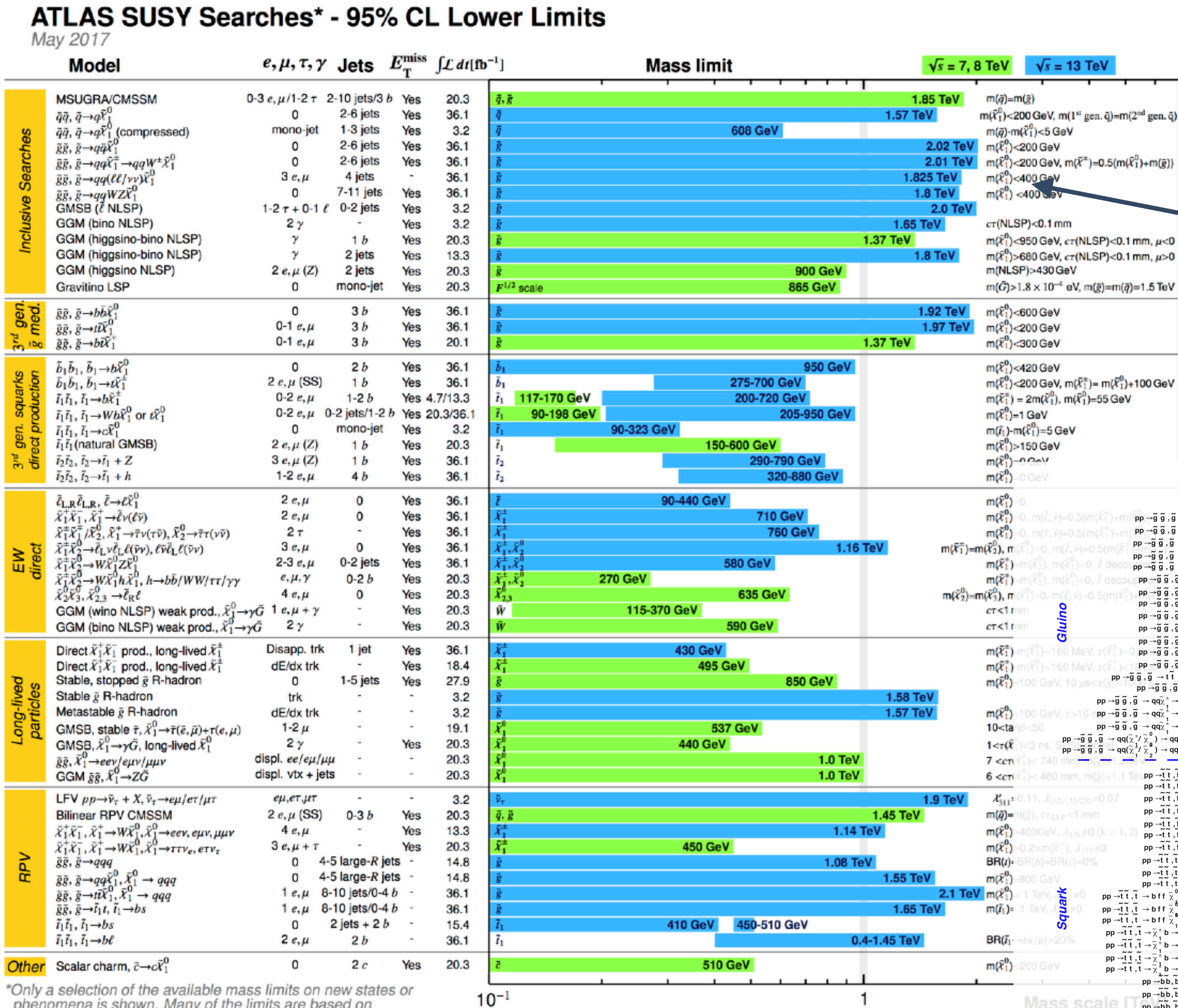
Why the Higgs?

- New kid on the block → you want to know it better
- Crucial connection to unitarization of the SM
- Crucial connection to the EW scale and nature of the EW vacuum (EW phase transition…)
- Γ_H difficult to measure → decay to new particles
- $H^\dagger H$ only relevant gauge singlet operator → natural portal to new sectors
- …

The New Information: $m_H = 125$ GeV.

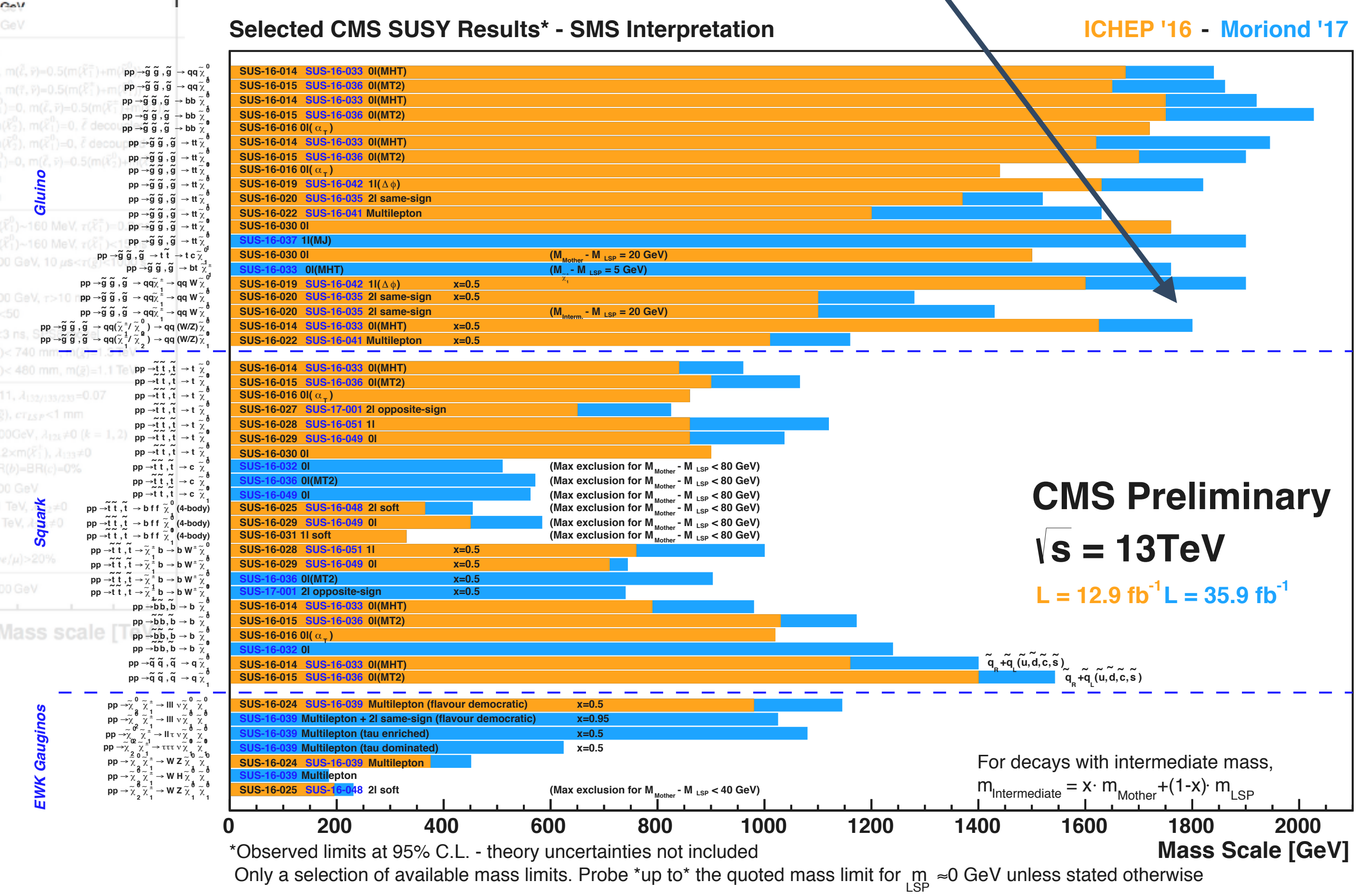
The *Naturalness Problem:* *``In any [reasonable] theory we know where the Higgs mass is computable, a low mass Higgs implies NP at low scales"* [~N. Arkani-Hamed]

NP at low scales… not quite



SUSY exclusion limits as of May 2017

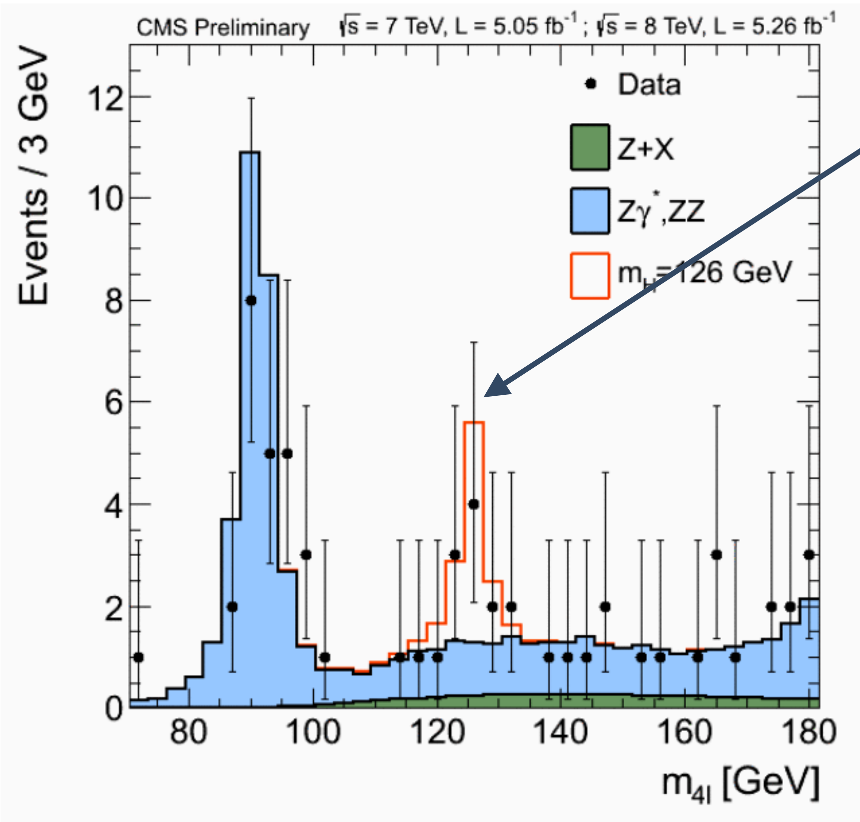
m ~ 2 TeV



+ many other negative results.
Many `vanilla' models excluded

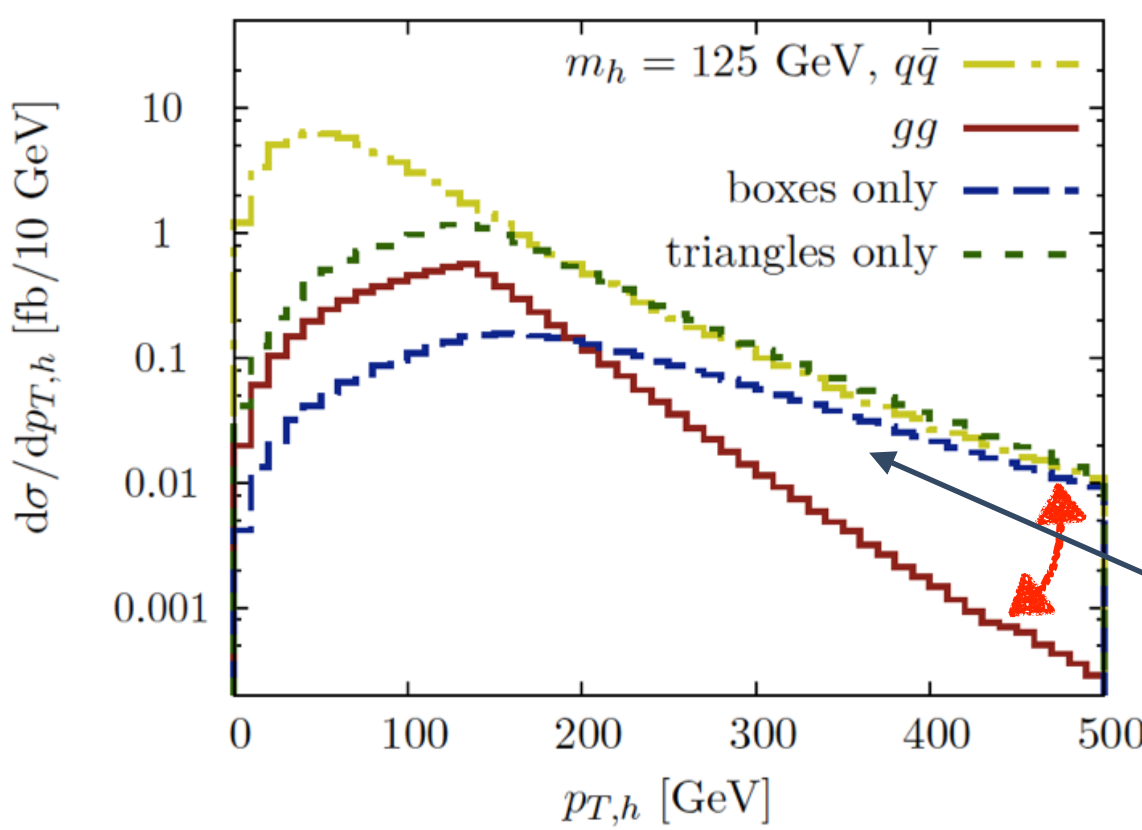
For many `standard' searches, the LHC is already reaching its asymptotic potential (energy reach)

NP and where to find it



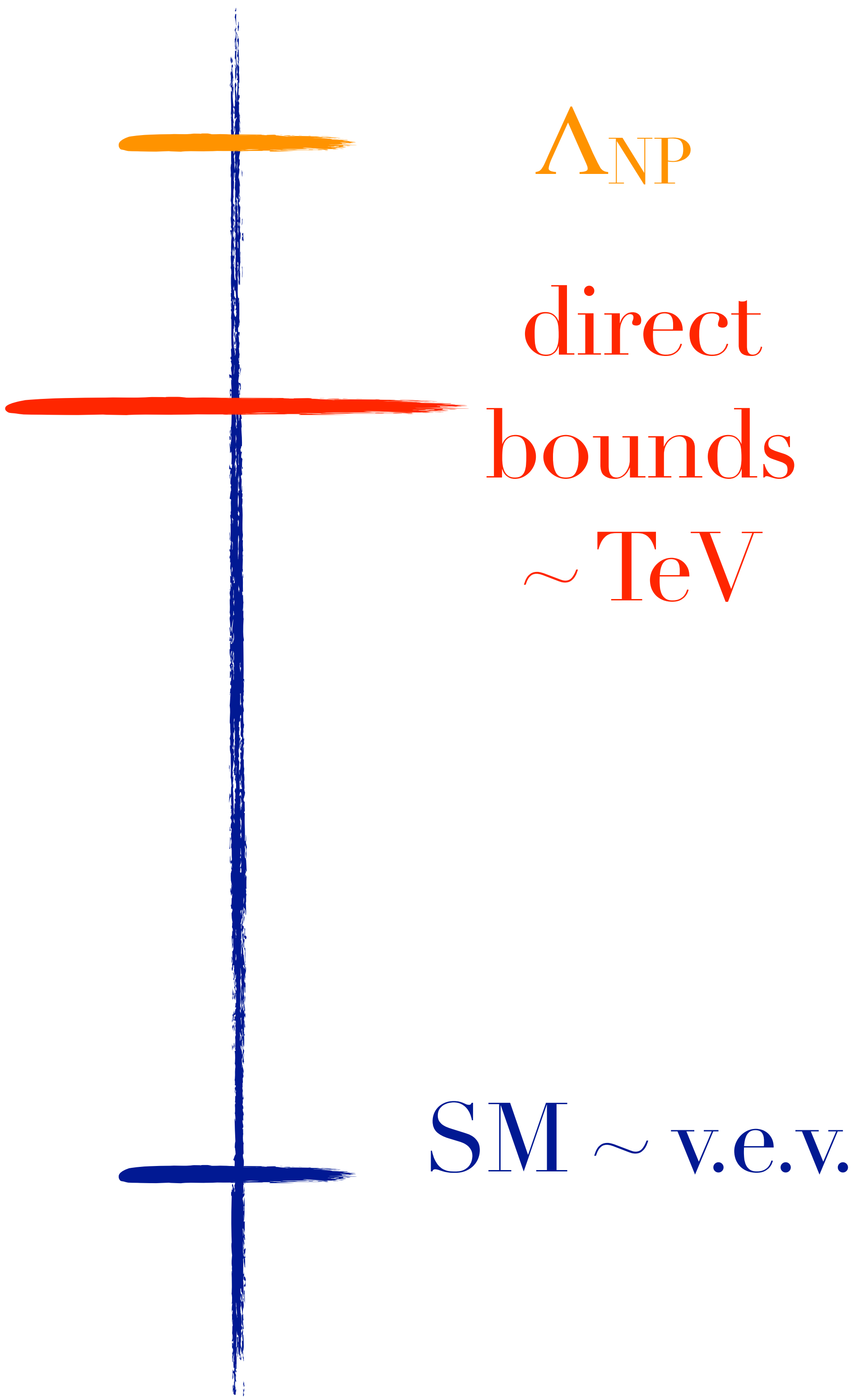
The traditional way: BUMP HUNTING. Little to no theoretical input needed.

So far: only Higgs. Already running out of steam at the LHC…



- In the SM, structure of Higgs interactions completely fixed if we know m_H
- NP would modify this
- Careful scrutiny of Higgs interaction may eviscerate deviations from SM predictions, pointing towards NP
- LOOK FOR (SMALL) DEVIATIONS FROM SM BEHAVIOR → good control on theory predictions!

… ``good control”: a (rough) estimate



Imagine to have new physics at a (heavish) scale Λ_{NP}

Typical modification to observable w.r.t. standard model prediction:

$$\delta O \sim Q^2 / \Lambda_{NP}{}^2$$

To gain over direct bounds:

IN THE BULK:

$Q \sim M_H \rightarrow$ few percent

IN THE TAIL:

$Q \gtrsim 500$ GEV $\rightarrow$

~10-20%

… ``good control”: a (rough) estimate

Λ_{NP}

Imagine to have new physics at a (heavish) scale Λ_{NP}

Typical modification to observable

THIS LEVEL OF PRECISION: WITHIN EXPERIMENTAL REACH OF THE (HL-)LHC

Theoretically, highly non trivial…

SM $\sim$ (v.e.v.)^2

IN THE BULK:

Q~M_H → few percent

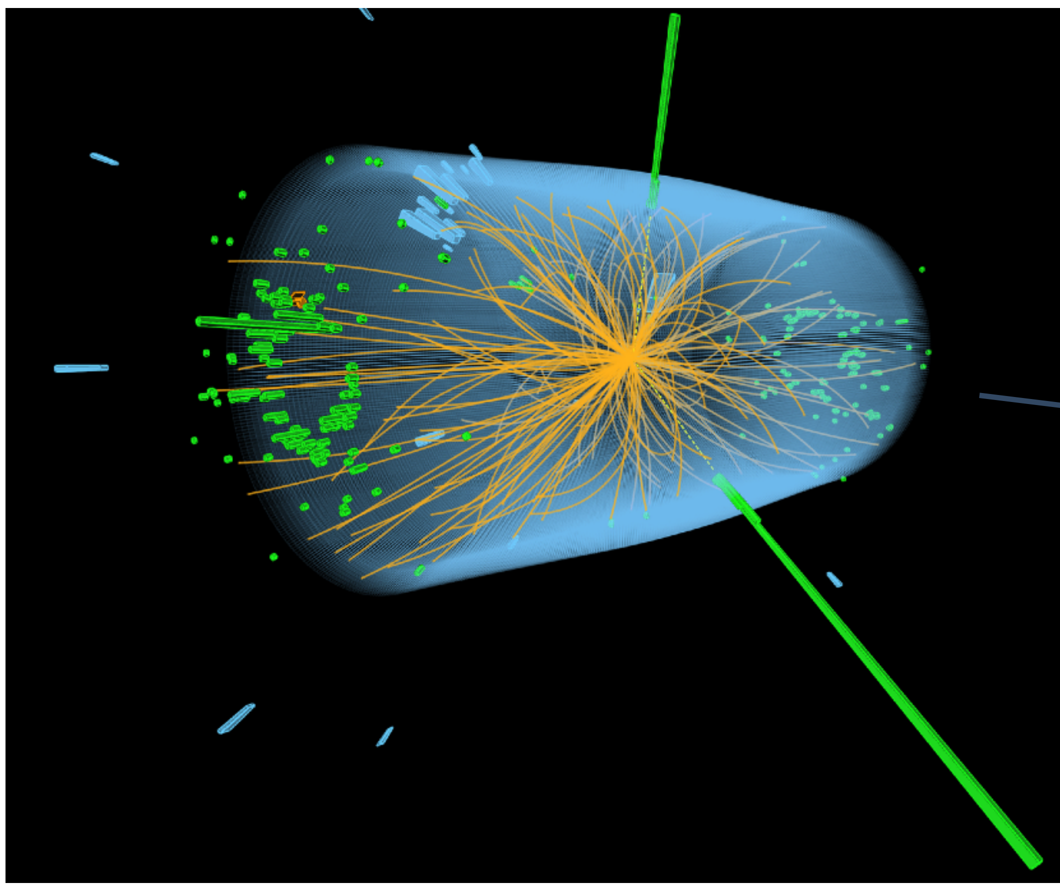
Q≳ 500 GEV →

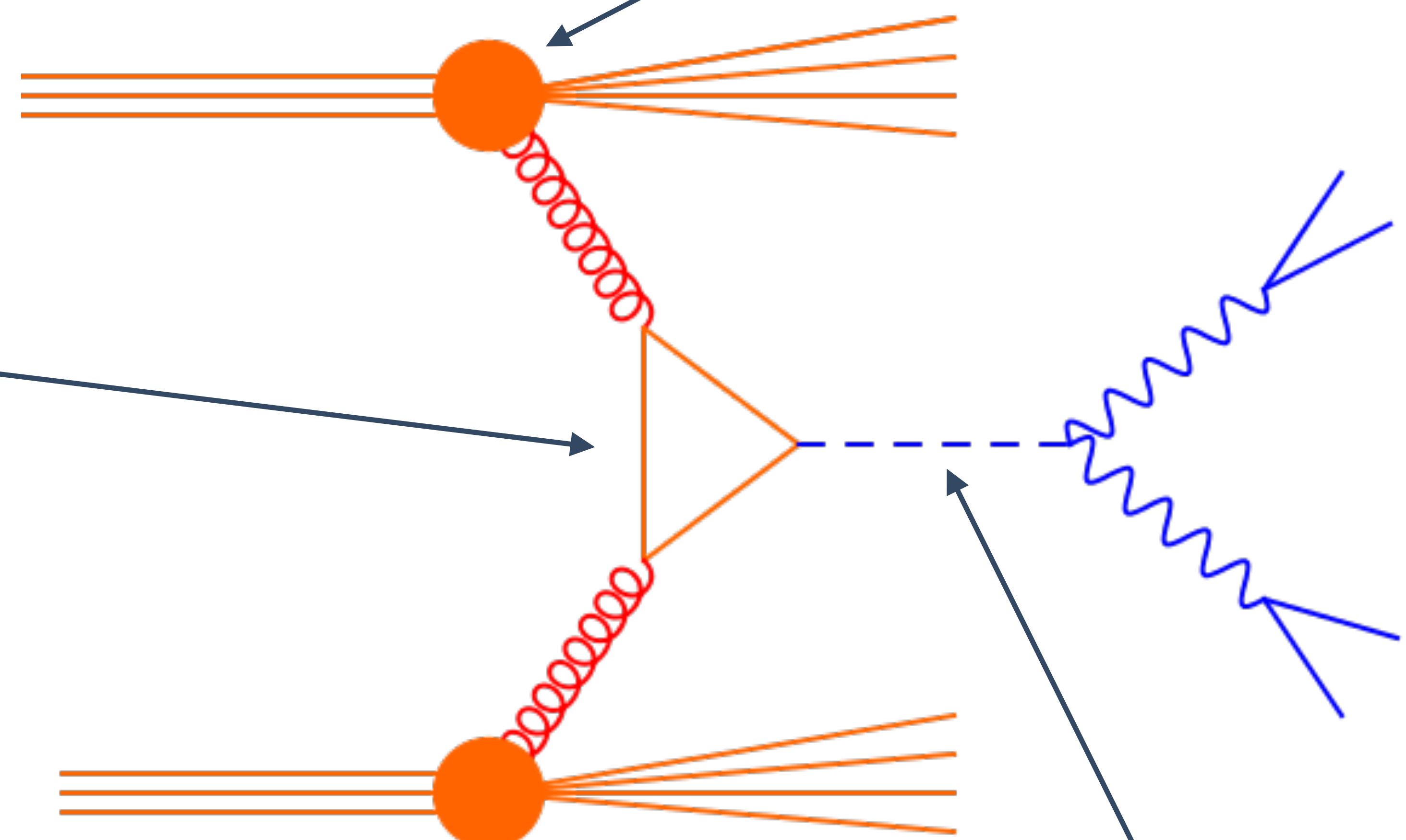
~10-20%

The path to precision: theory

- Precision physics at hadron colliders is very challenging.
- Key: QCD FACTORIZATION

Short distance non perturbative effects (PDFs)





Interesting high-Q phenomena

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

The path to precision: theory

$$d\sigma = \int dx_1 dx_2 f(x_1) f(x_2) d\sigma_{\text{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\text{QCD}}/Q))$$

Input parameters (α_s, PDFs…): ~few percent. Remarkable control, in principle improvable

NP effects: No good control / understanding of them. Fortunately, ≲ percent

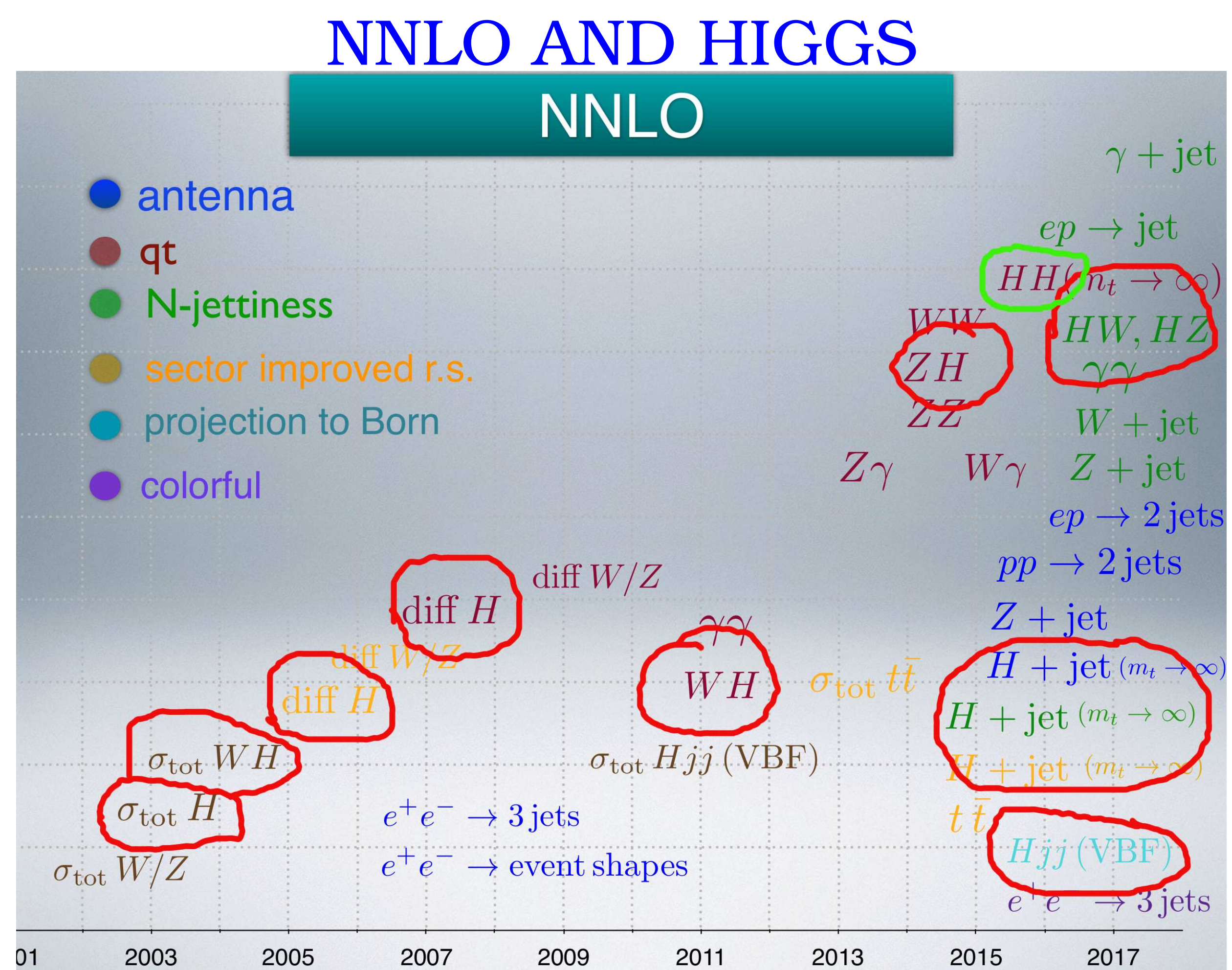
HARD SCATTERING MATRIX ELEMENT

- large Q → most ``fundamental'' part
- α_s ~ 0.1 → For TYPICAL PROCESSES, we need NLO for ~ 10% and NNLO for ~ 1 % accuracy. Processes with large color charges (Higgs): $\alpha_s C_A$~ 0.3 → N^3LO

The path to precision: theory

HIGHLY NON-TRIVIAL QCD / QFT PROBLEM!

Higgs key motivation in pushing forward collider pheno



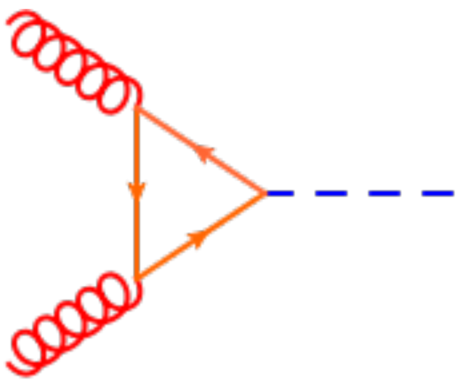
(G. Heinrich, LHCP, May 2017)

[slide from S. Forte, Blois 2017]

Since January: at least 5 *state of the art QCD papers involving the Higgs*

[Lindert et al.: NLO Higgs at large p_t; Bonetti et al: mixed QCD-EW; Mistlberger: analytic ggF@N^{3}LO; Cruz-Martinez et al: differential VBF@NNLO; Jones et al: NLO ggF with full m_t dependence

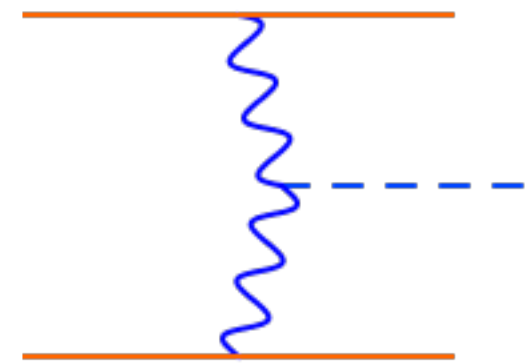
Higgs production at the LHC: overview



``gluon fusion''

[large rate, Htt/Hbb/ Hgg couplings…]

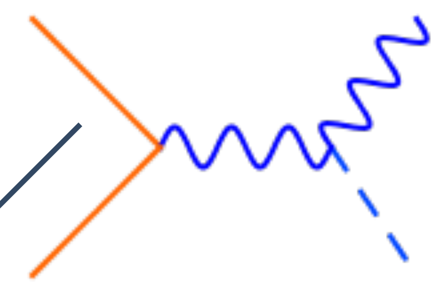
$\Delta_{TH} \sim 4\%$



``VBF''

[g_{HVV} coupling]

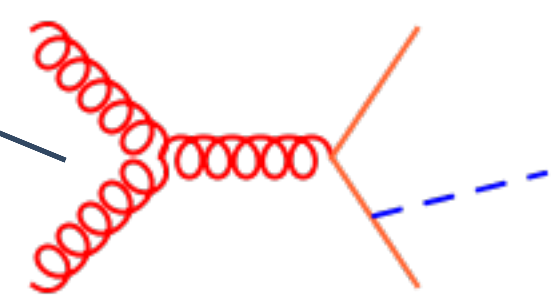
$\Delta_{TH} \sim 0.5\%$



``VH''

[g_{HWW} vs g_{HZZ}]

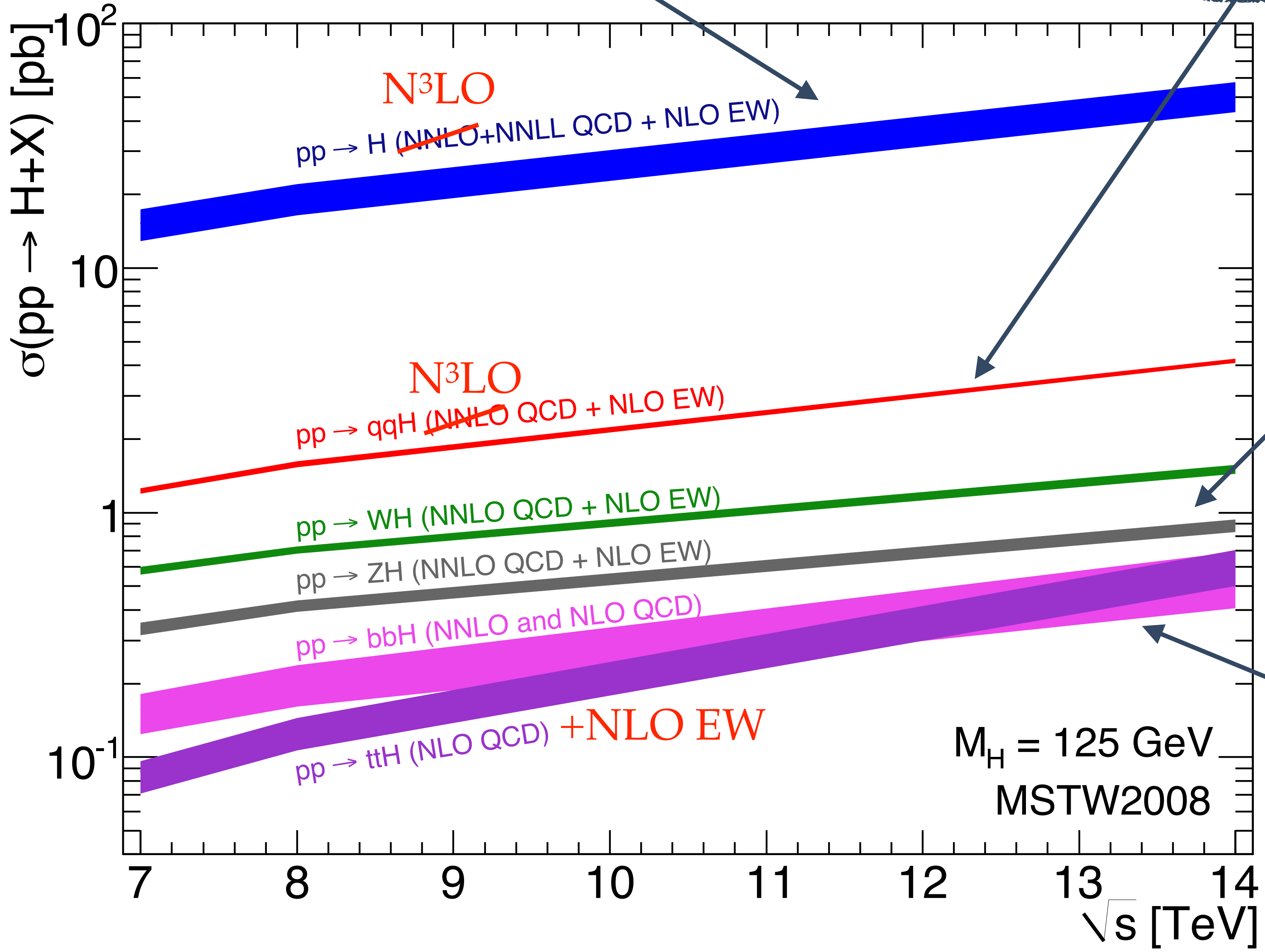
$\Delta_{TH} \sim 1/2\%$



``ttH''

[g_{Hff}]

$\Delta_{TH} \sim 5\%$



CAREFUL: $\Delta_{TH} \rightarrow$ QCD uncertainty on the TOTAL (=unobservable) cross-section

Higgs production at the LHC: overview

``gluon fusion''

``VBF''

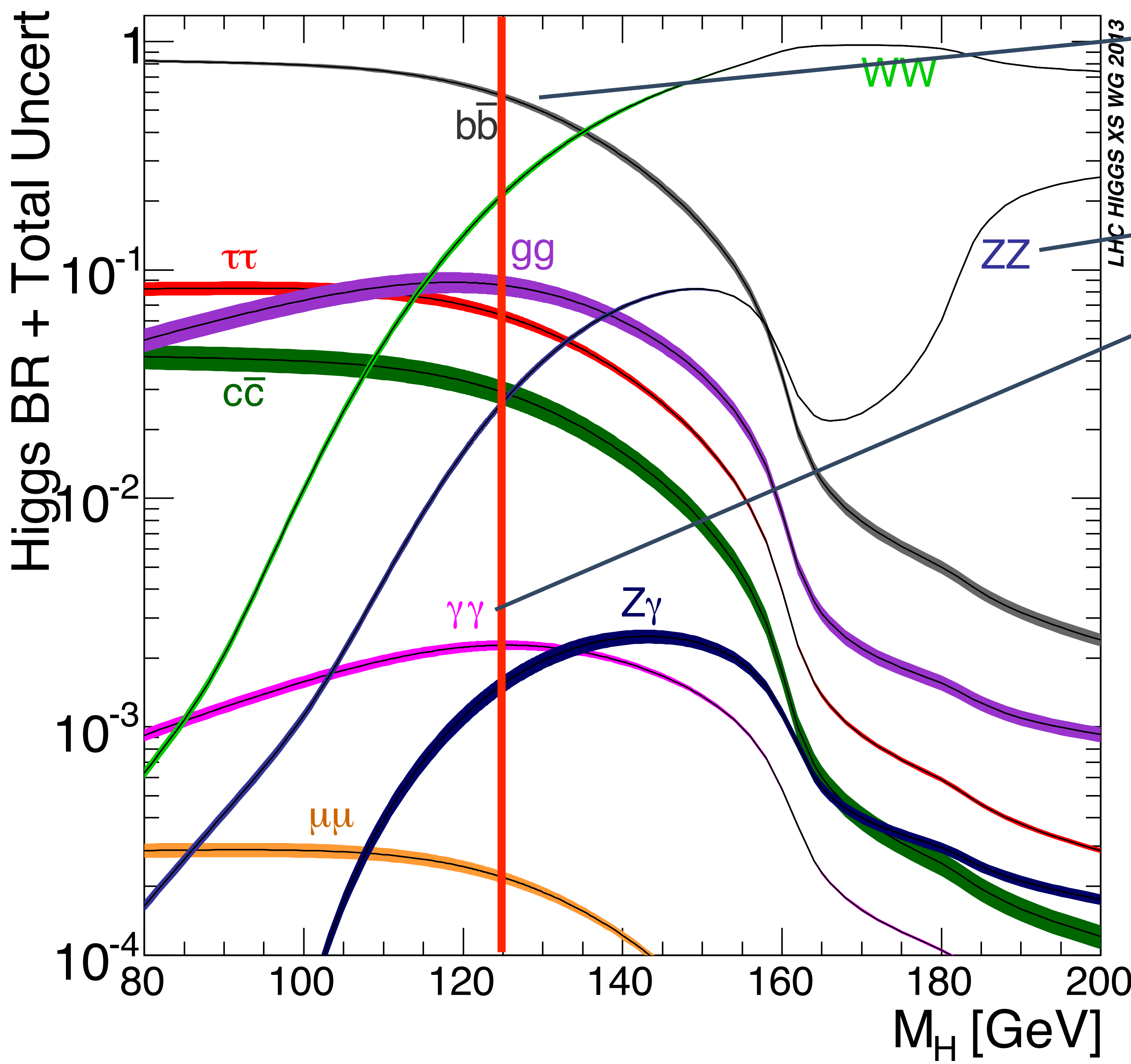
σ(pp → H+X) [pb]

- Although actual error (much) larger than for the (unobservable) σ_{TOT}, situation under good control
- Higgs production in association with many jets is known to (at least) NLO QCD as well → probe interesting dynamics
- By and large, currently theory error are not the main show-stopper for LHC analysis
- In many cases, backgrounds or poorly understood QCD effects are the most problematic part (ttH, VBF…)
- Experimentally: at least evidence for all the main channels!
- First results for differential distributions!

CAREFUL: Δ_{TH} → QCD uncertainty on the TOTAL (=unobservable) cross-section

Higgs decays: overview

For $m_H \sim 125$ GeV: many channels accessible →
THOROUGH INVESTIGATION POSSIBLE

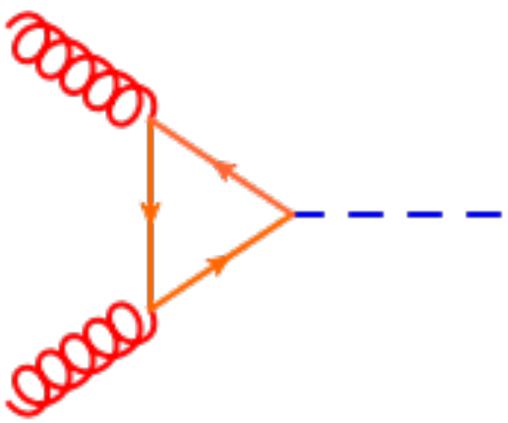


Largest BR, but very tough at the LHC

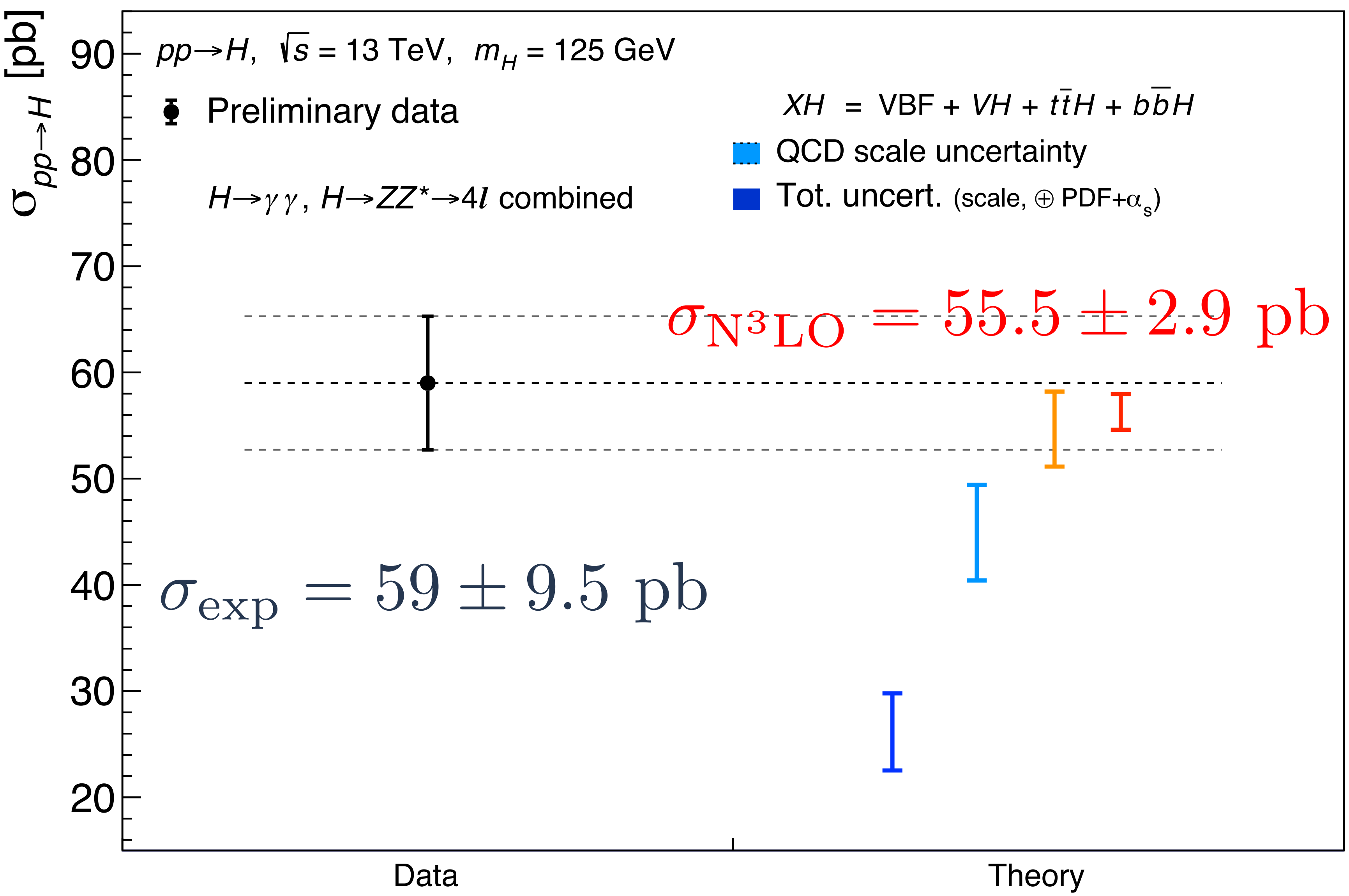
Golden channels, low BR but very clean

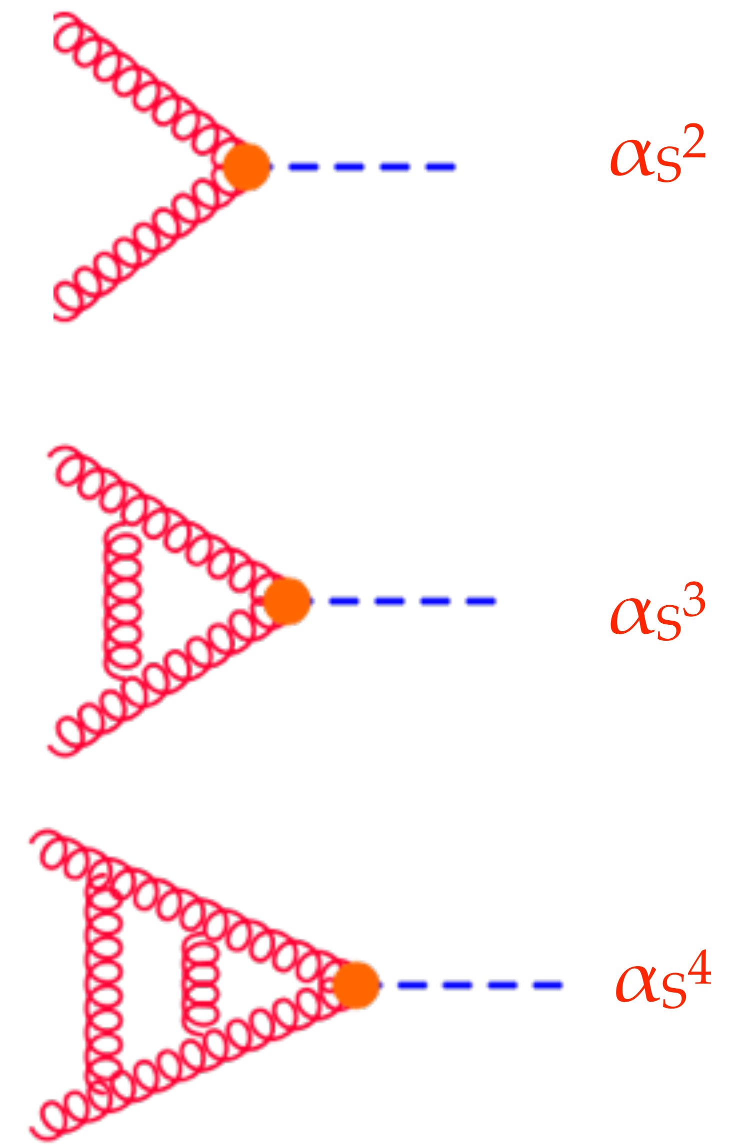
- All important decay channels known to (at least) NNLO QCD+NLO EW
- In many cases, *parametric* uncertainty significant

Gluon Fusion

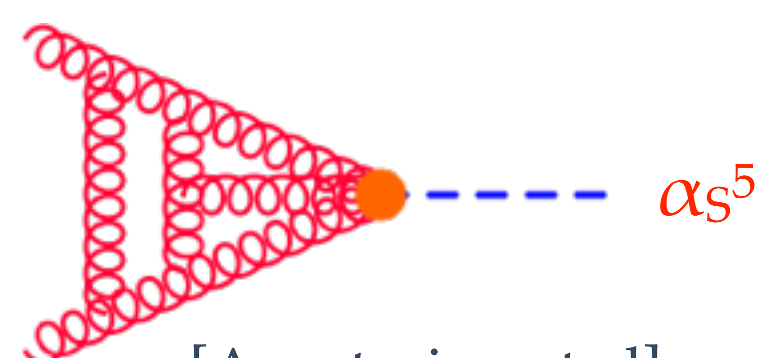


The need for higher orders





[Anastasiou, Melnikov; Harlander, Kilgore]



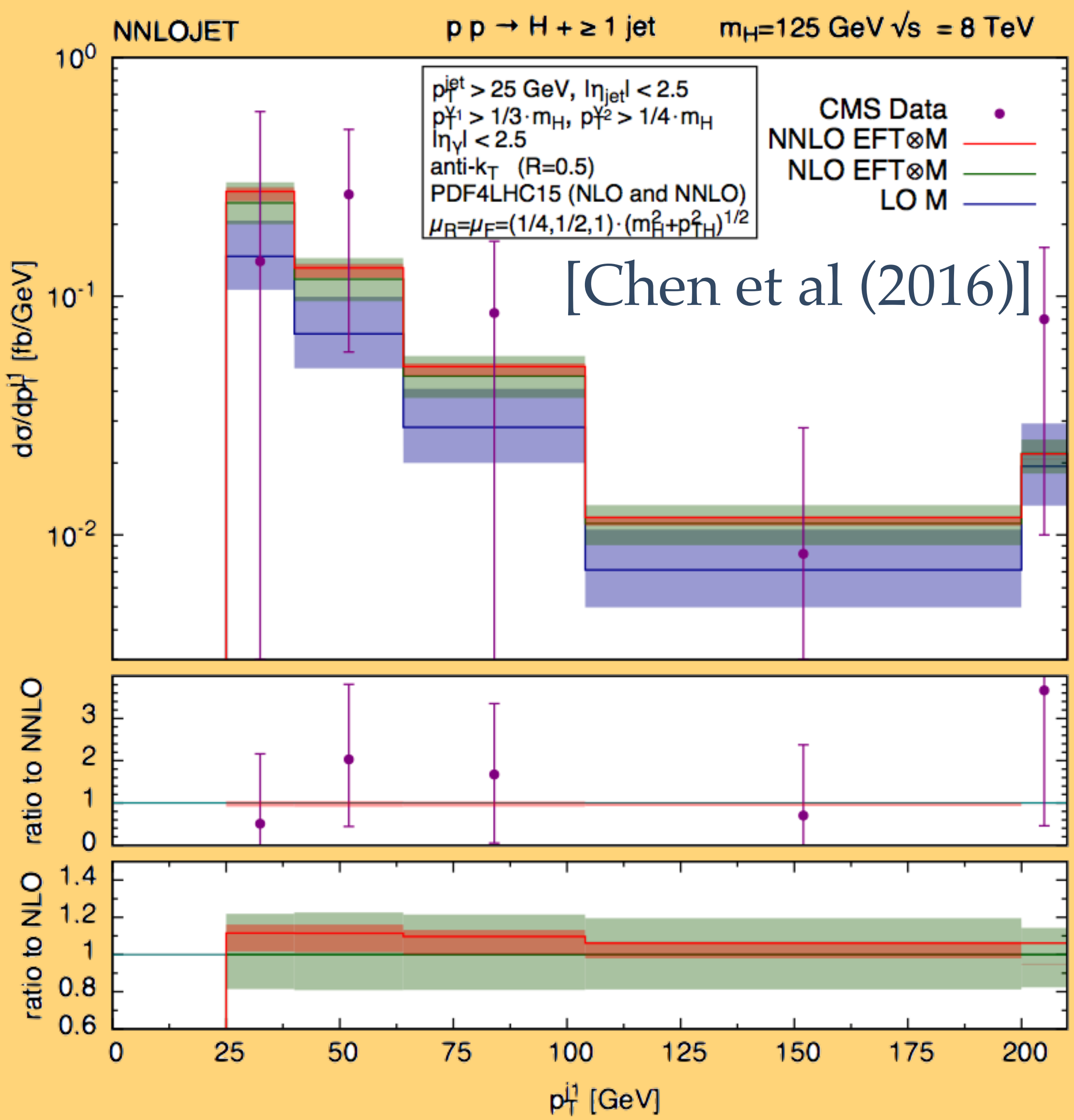
[Anastasiou et al]

N^{3}LO results needed to establish perturbative convergence / reduce residual theoretical uncertainty

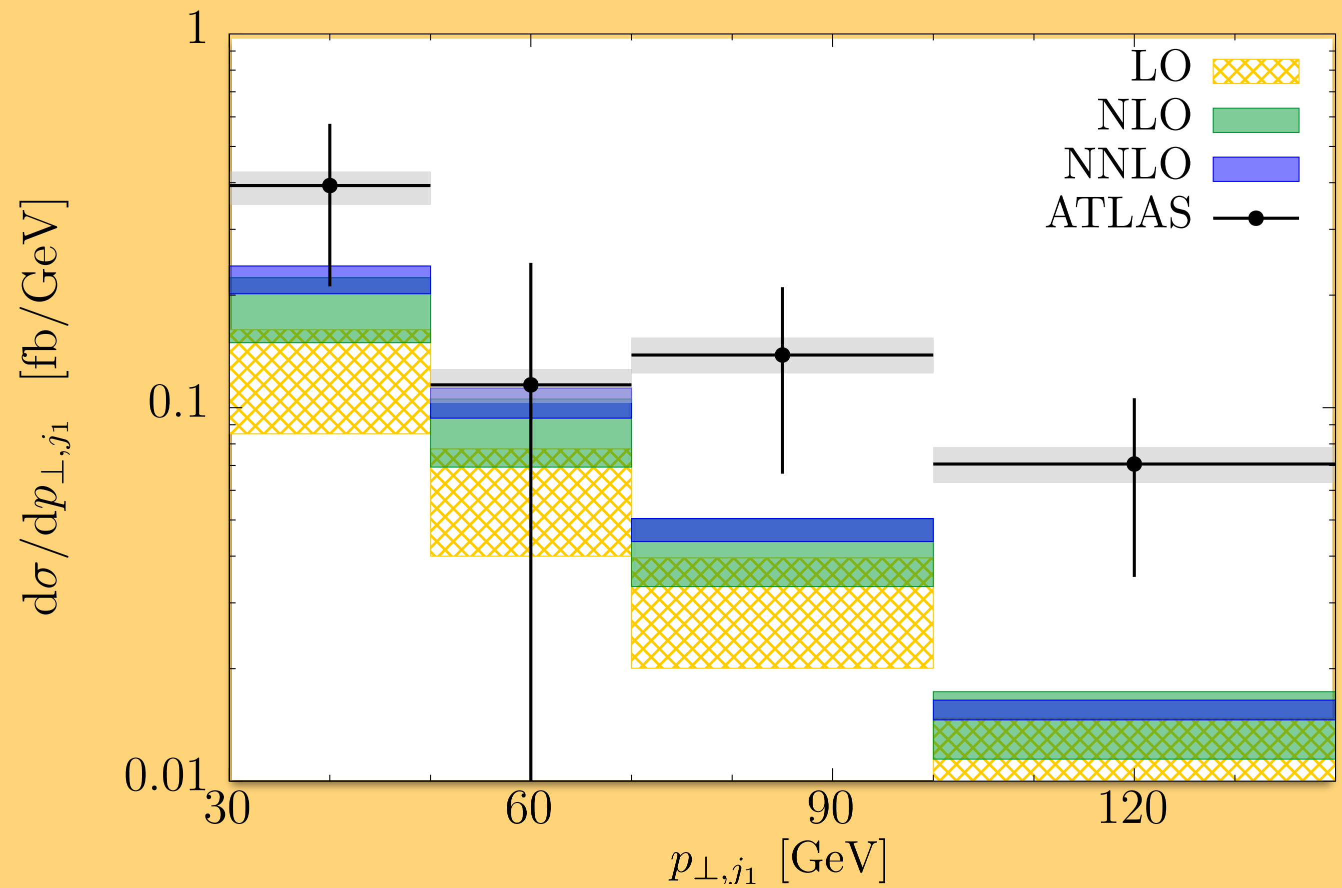
The need for higher orders: Higgs

Similar picture at the differential level:

$O(\alpha_s^5)$ [NNLO] needed to match exp. systematics



[Chen et al (2016)]



[FC, Melnikov, Schulze]

13 TeV data are there!

Gluon fusion: the fine prints

- At this level of precision, basically everything becomes relevant

[Mistlberger, QCD@LHC2016]

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)\,.$$

$48.58\,\text{pb} =$	$16.00\,\text{pb}$	$(+32.9\%)$	(LO, rEFT)
	$+\,20.84\,\text{pb}$	$(+42.9\%)$	(NLO, rEFT)
	$-\ \ 2.05\,\text{pb}$	(-4.2%)	$((t,b,c)$, exact NLO)
	$+\ \ 9.56\,\text{pb}$	$(+19.7\%)$	(NNLO, rEFT)
	$+\ \ 0.34\,\text{pb}$	$(+0.7\%)$	(NNLO, $1/m_t$)
	$+\ \ 2.40\,\text{pb}$	$(+4.9\%)$	(EW, QCD-EW)
	$+\ \ 1.49\,\text{pb}$	$(+3.1\%)$	(N^3LO, rEFT)

perturbative uncertainty

- Todo List:
  - Full mass dependent NNLO
  - Mixed $\mathcal{O}(\alpha\alpha_S)$ corrections
  - N3LO PDFs
  - ….

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm0.37\%$	$\pm1.16\%$	$\pm1\%$	$\pm0.83\%$	$\pm1\%$

[Bonetti, Melnikov, Tancredi (2018)]

A step back: how we do computations…

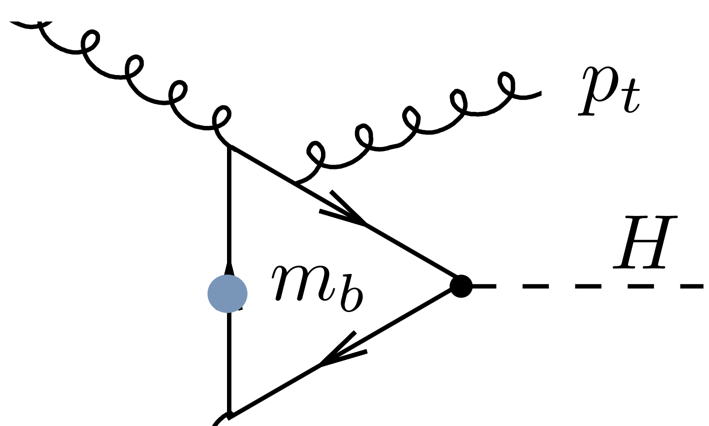
- At LO, gg → H mediated by virtual heavy quark loop → already at NLO, complicated 2-loop amplitudes. At NNLO: prohibitively complicated!
- HOWEVER: $m_H \sim 125$ GeV ≪ $m_t \sim 173$ GeV → Higgs wavelength not enough to resolve the structure of the loop → effective ggH description, much simpler!

- All higher order computations use this trick.
- EXCELLENT APPROXIMATION, but there are cases when it is inadequate

1) b-quark effects at low p_T

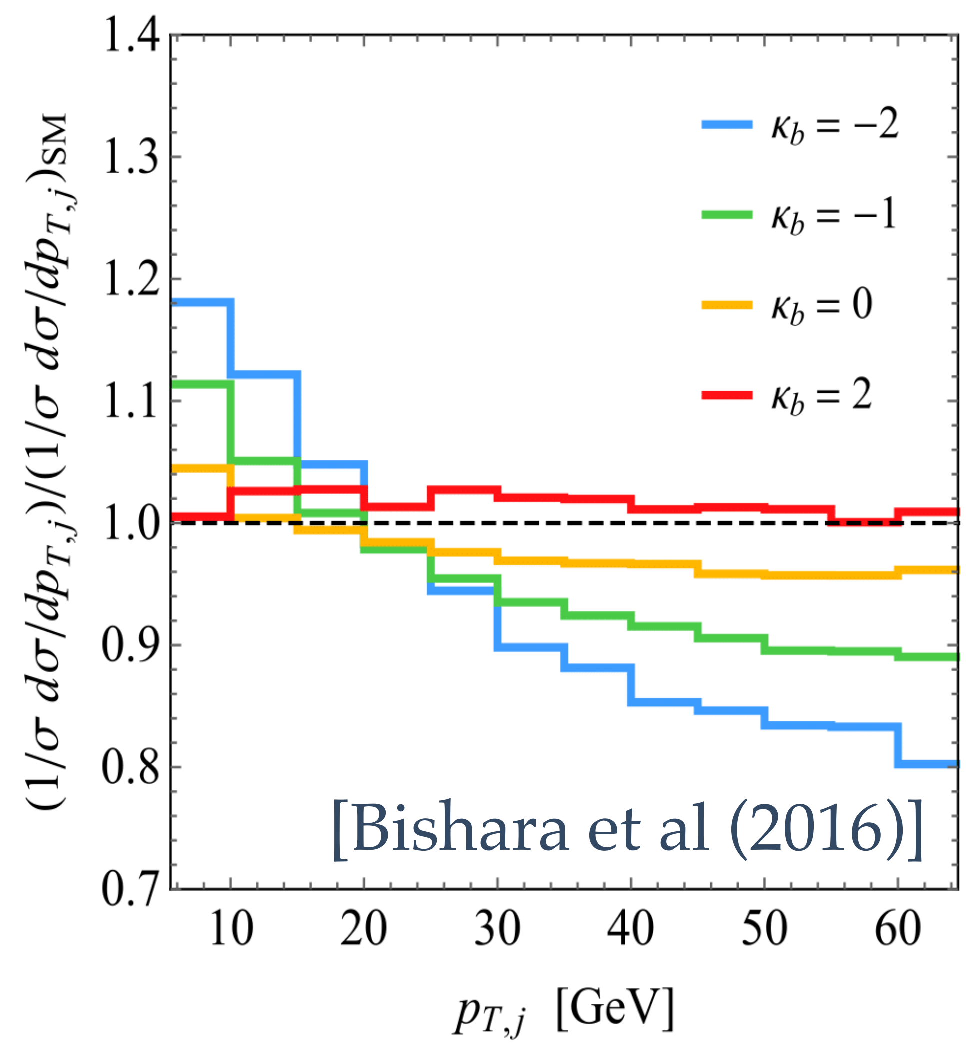
- Point-like approximation clearly not valid for bottom quark
- Although $y_b \ll y_t$, top/bottom interferences non-negligible
- In particular: in the Higgs transverse momentum distribution, Sudakov-like double logarithmic enhancement. Very interesting theoretically: emission from *virtual SOFT QUARKS*, related to angular momentum conservation ``helicity flip'' on the quark line

ENHANCEMENT IN THE SPECTRUM → CAN BE USED TO INVESTIGATE HBB COUPLING



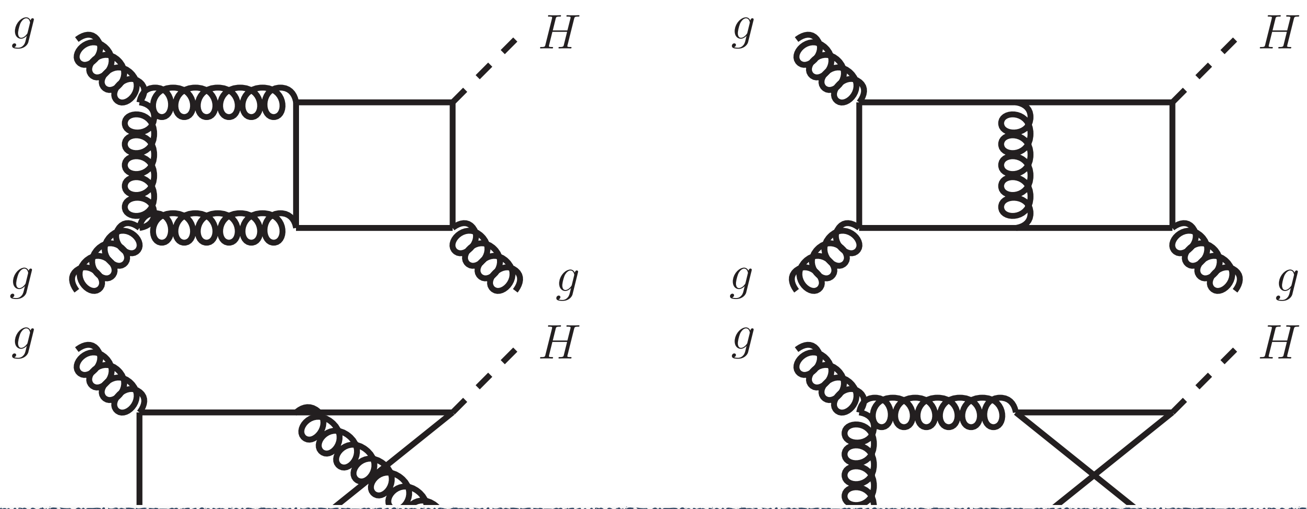
$m_b/p_\perp \ll 1$

$$\alpha_s \ln^2 \frac{p_\perp}{m_b} \gg 1$$

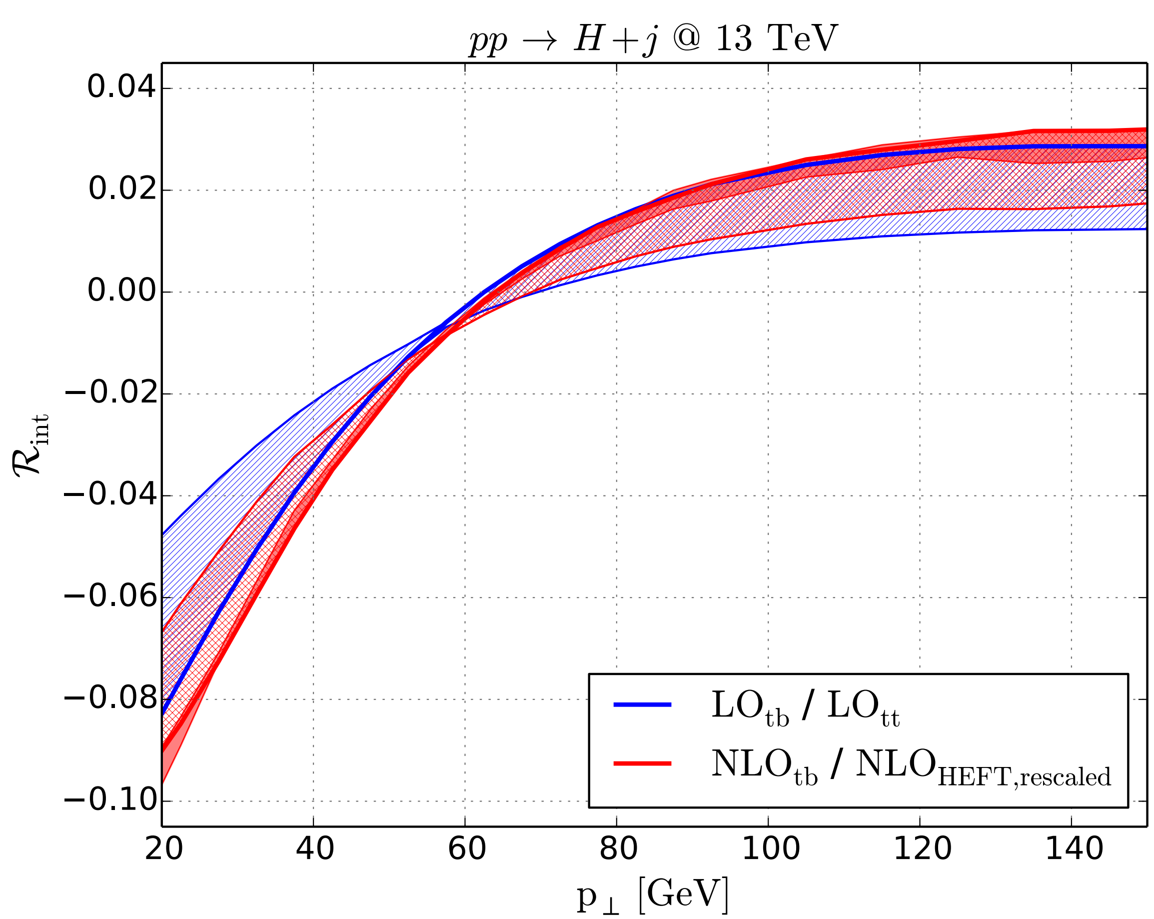


1) b-quark effects at low p_T

Logarithmic enhancement delicate → important to consider *impact of (large) QCD corrections*



Requires understanding of highly non-trivial multi-loop amplitudes involving *virtual massive particles*



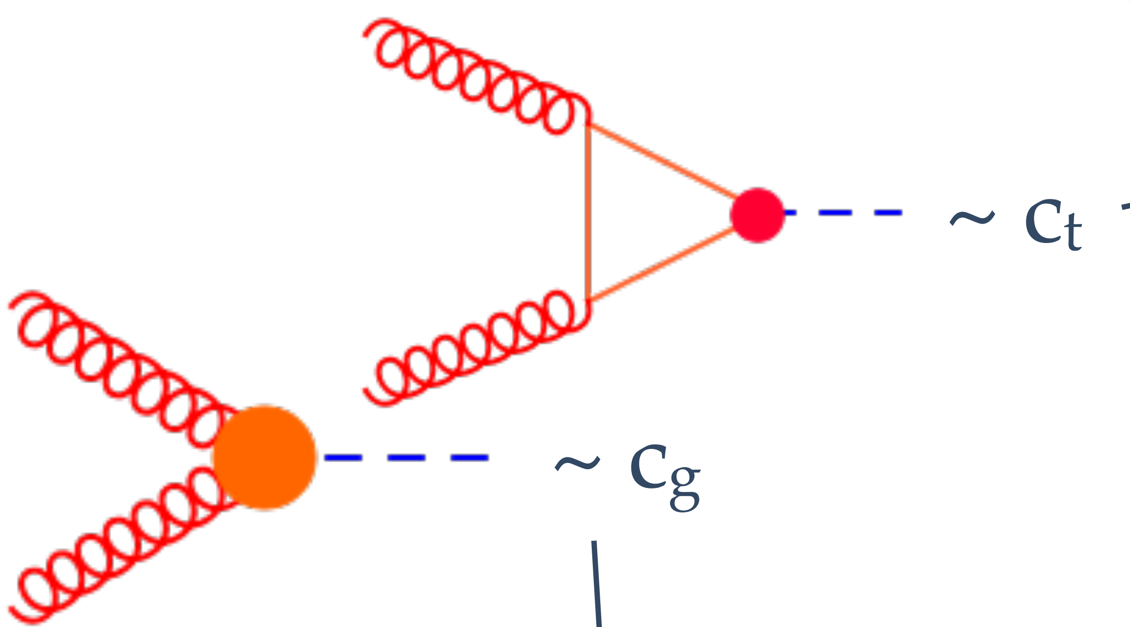
RECENTLY COMPUTED!

[Lindert, Melnikov, Tancredi, Wever (2017)]

Despite (large) corrections, the interference shape stable under QCD corrections → solid observable

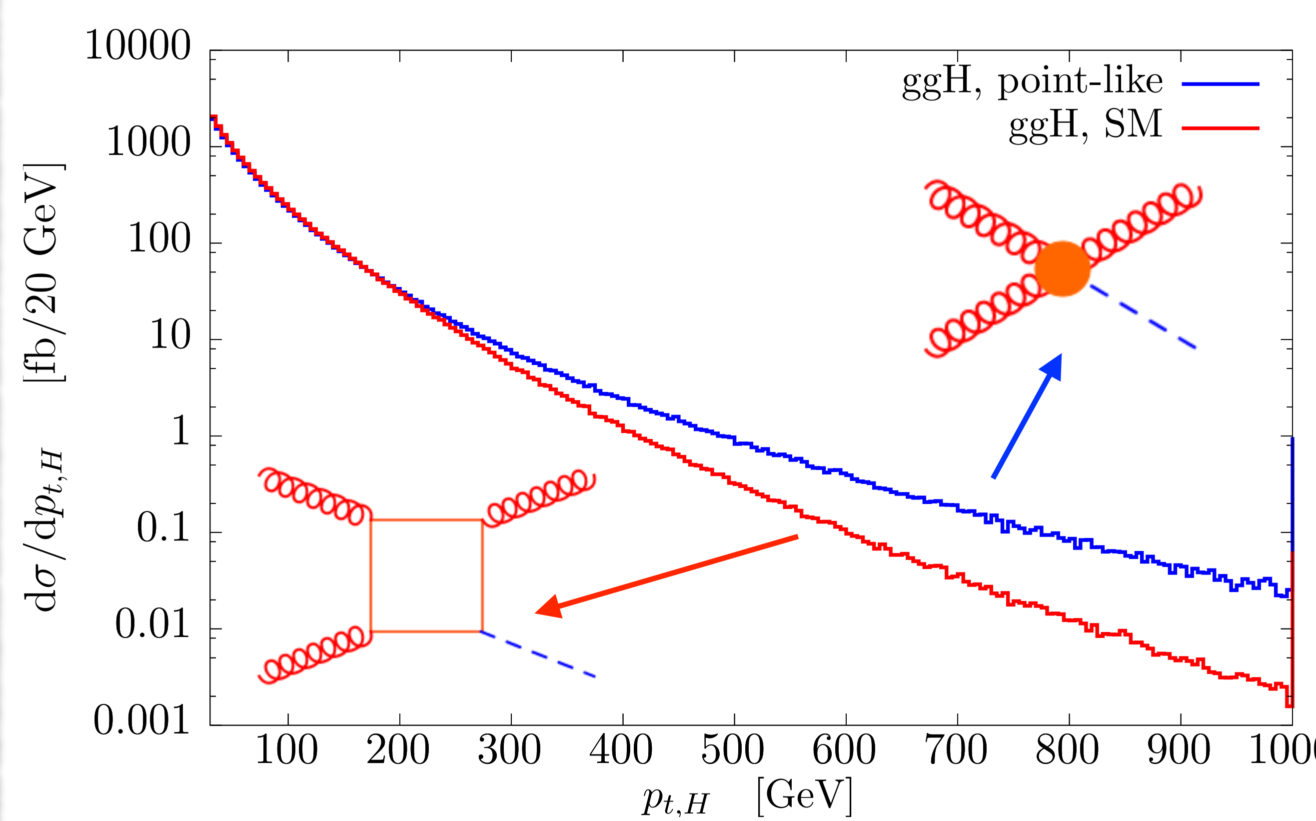
2-) the boosted region

- If the Higgs recoils against a high transverse momentum jet → high Q process, can resolve the top loop
- Crucial process to disentangle anomalous ggH and ttH couplings!



recoiling against high p_T object: $Q \sim p_T \gg m_t$, resolve the top loop

REMOVE DEGENERACY

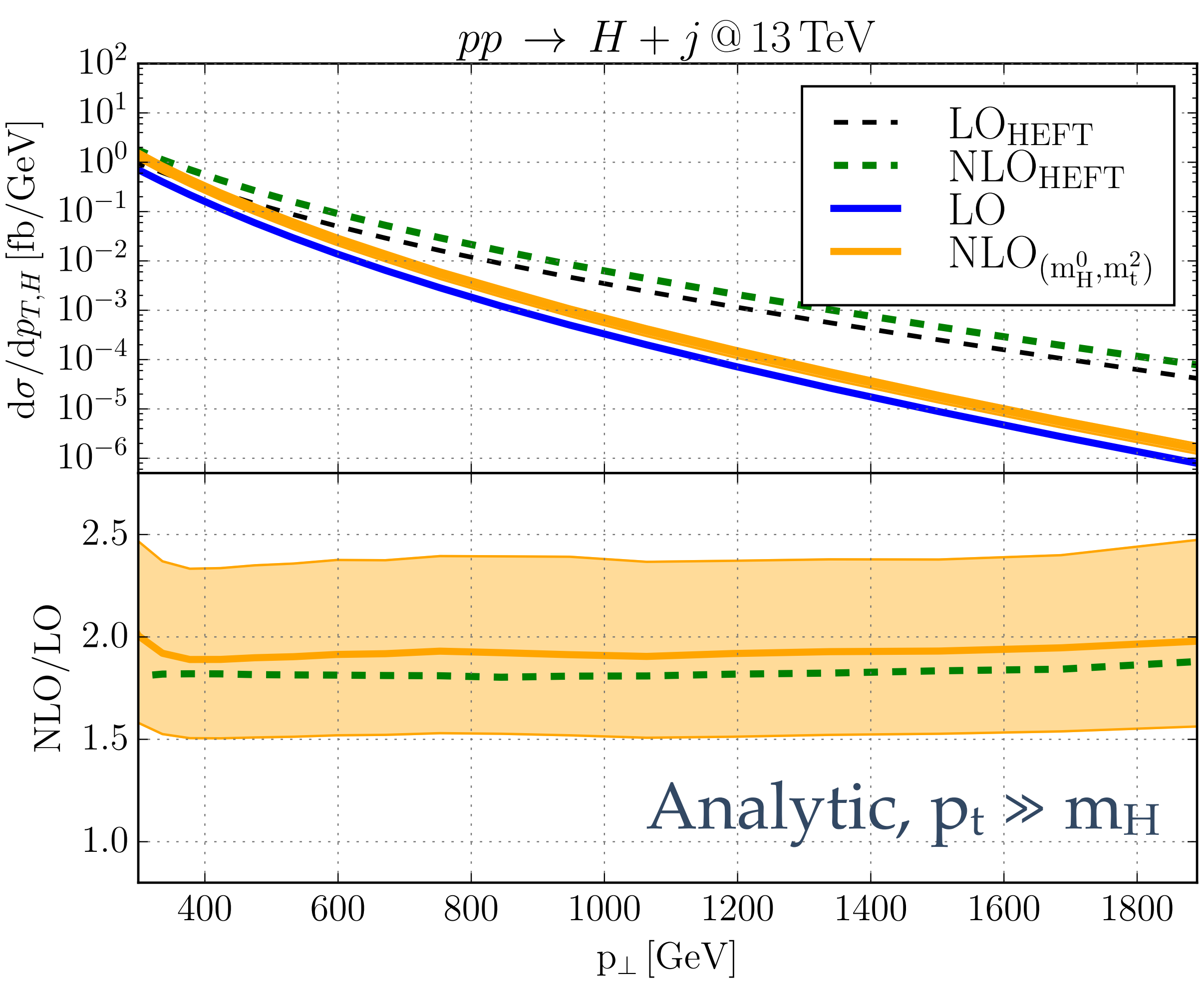


$\sim$ at rest: $Q \sim m_H \ll m_t$

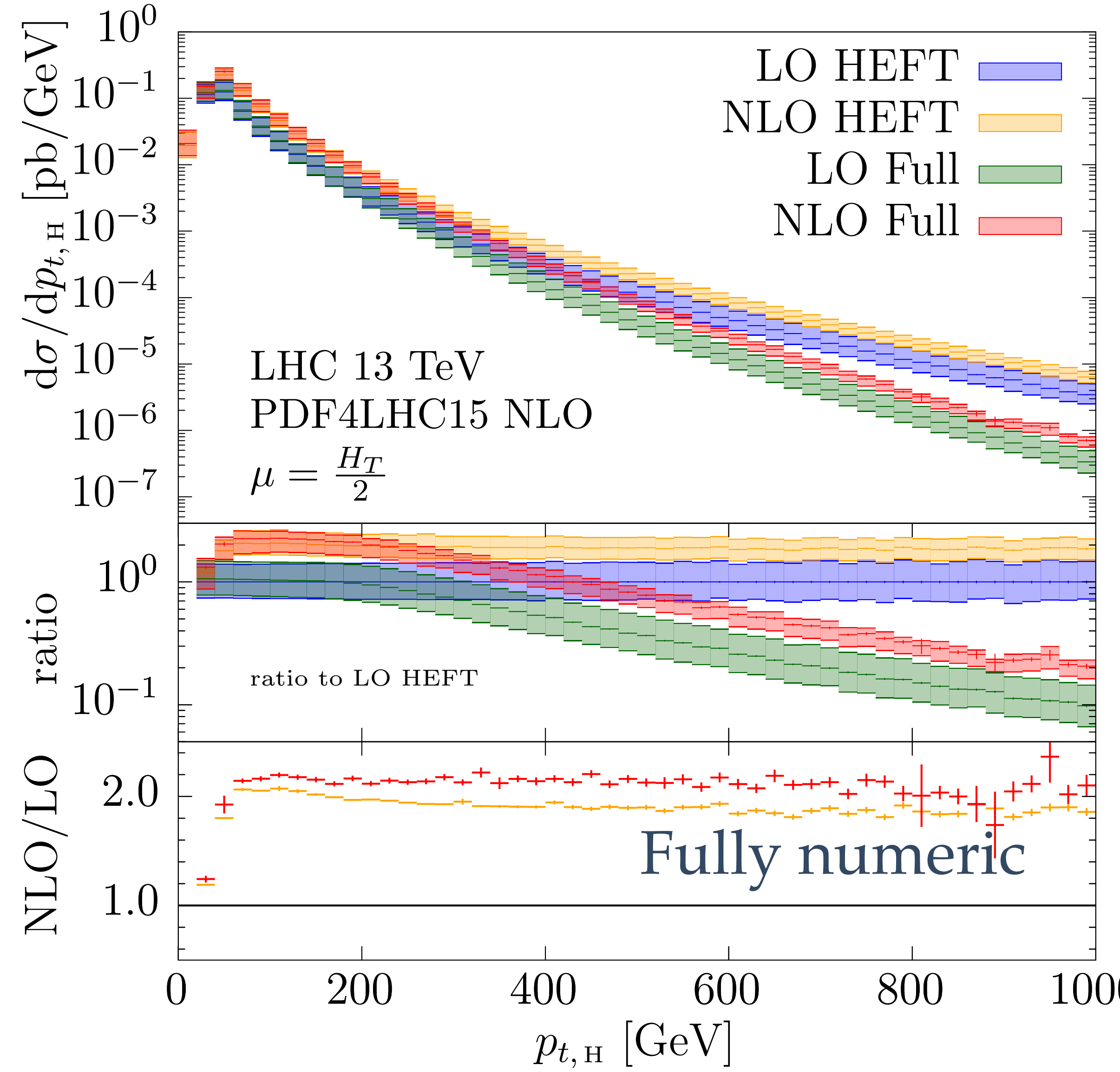
DEGENERACY

2-) the boosted region

- As for the *b* case, QCD corrections are expected to be large and require very complicated loop amplitudes → until recently only LO
- This year: TWO CALCULATIONS



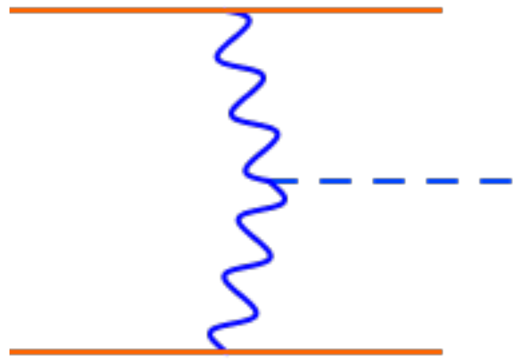
[Lindert, Kudashkin, Melnikov, Wever (2018)]



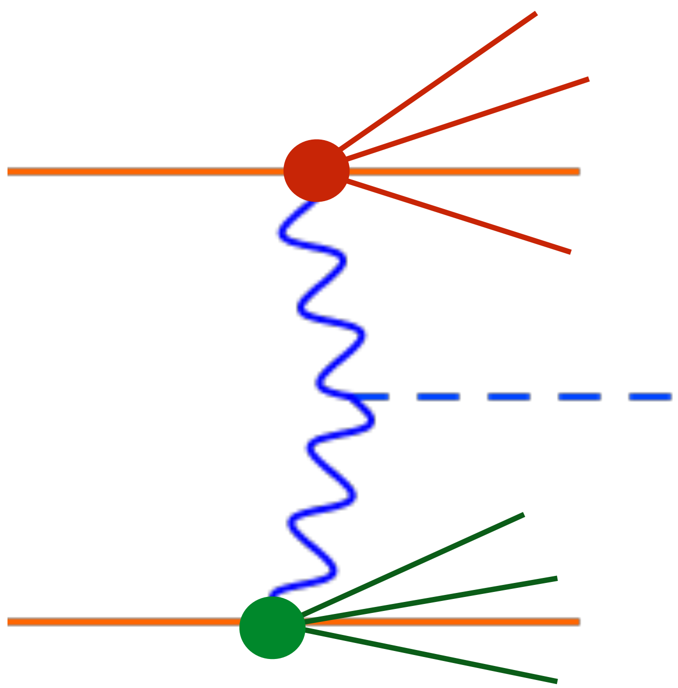
[Jones, Kerner, Luisoni (2018)]

As in the *b* case: very large corrections, but structure of QCD corrections largely insensitive to quark mass → solid distribution

VBF



VBF: inclusive corrections



- To a very good approximation: corrections to the two legs can be treated independently (*cross-talk starts at NNLO, and it is color and kinematic suppressed*)
- This observation makes the calculation much simpler → 3rd order QCD correction (N^3LO) known [Karlberg, Dreyer (2016)]

The perturbative expansion:

$$\sigma^{13\ \mathrm{TeV}}[\mathrm{pb}] = 4.099 - 0.129 - 0.038 - 0.004$$

Already NLO ~ 3%. Why compute higher orders?

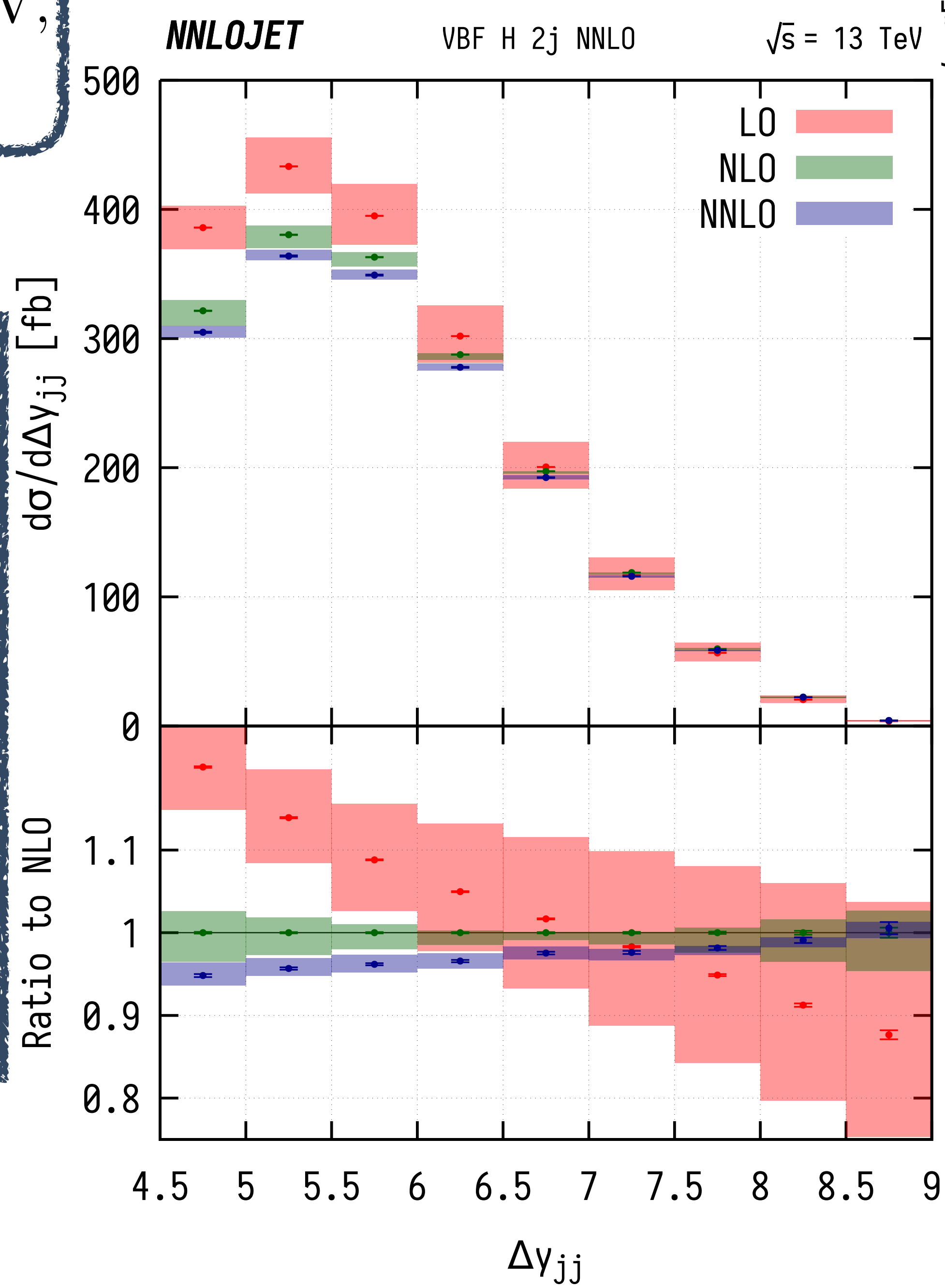
VBF: differential results

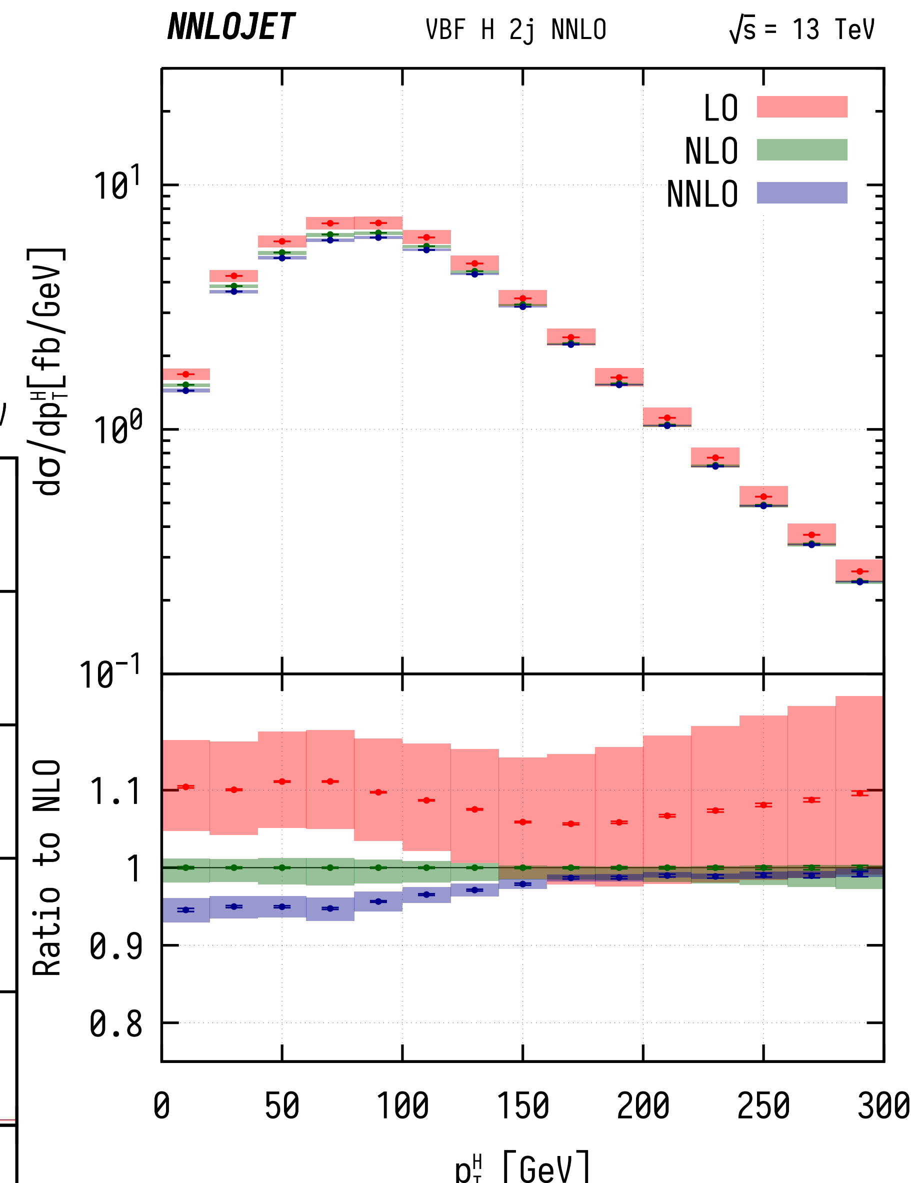
The total cross section is not measurable! In particular for VBF, tight cuts on the tagging jets

VBF cuts:

$$p_\perp^{j_{1,2}} > 25 \text{ GeV}, \quad |y_{j_{1,2}}| < 4.5,$$
$$\Delta y_{j_1,j_2} = 4.5, \quad m_{j_1,j_2} > 600 \text{ GeV},$$
$$y_{j_1} y_{j_2} < 0, \quad \Delta R > 0.4$$

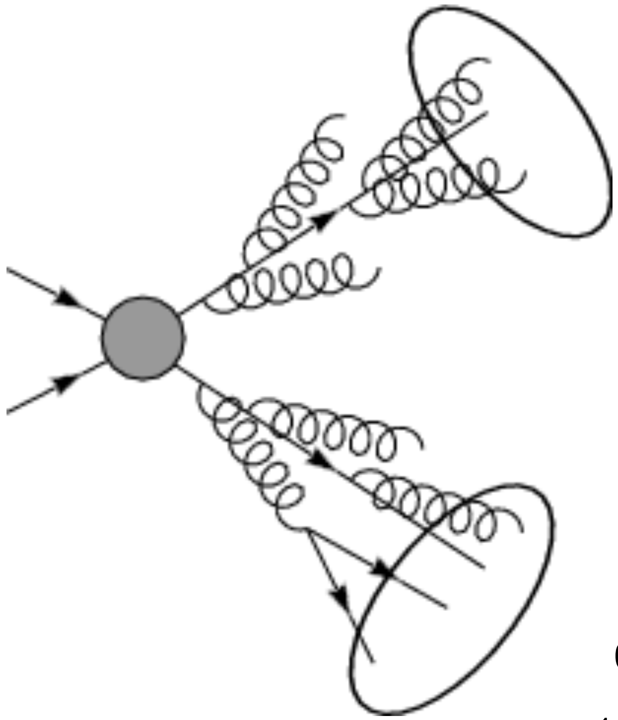
Much larger corrections on the measured xsec/ distributions! Only at NNLO stabilization (and still visible corrections)





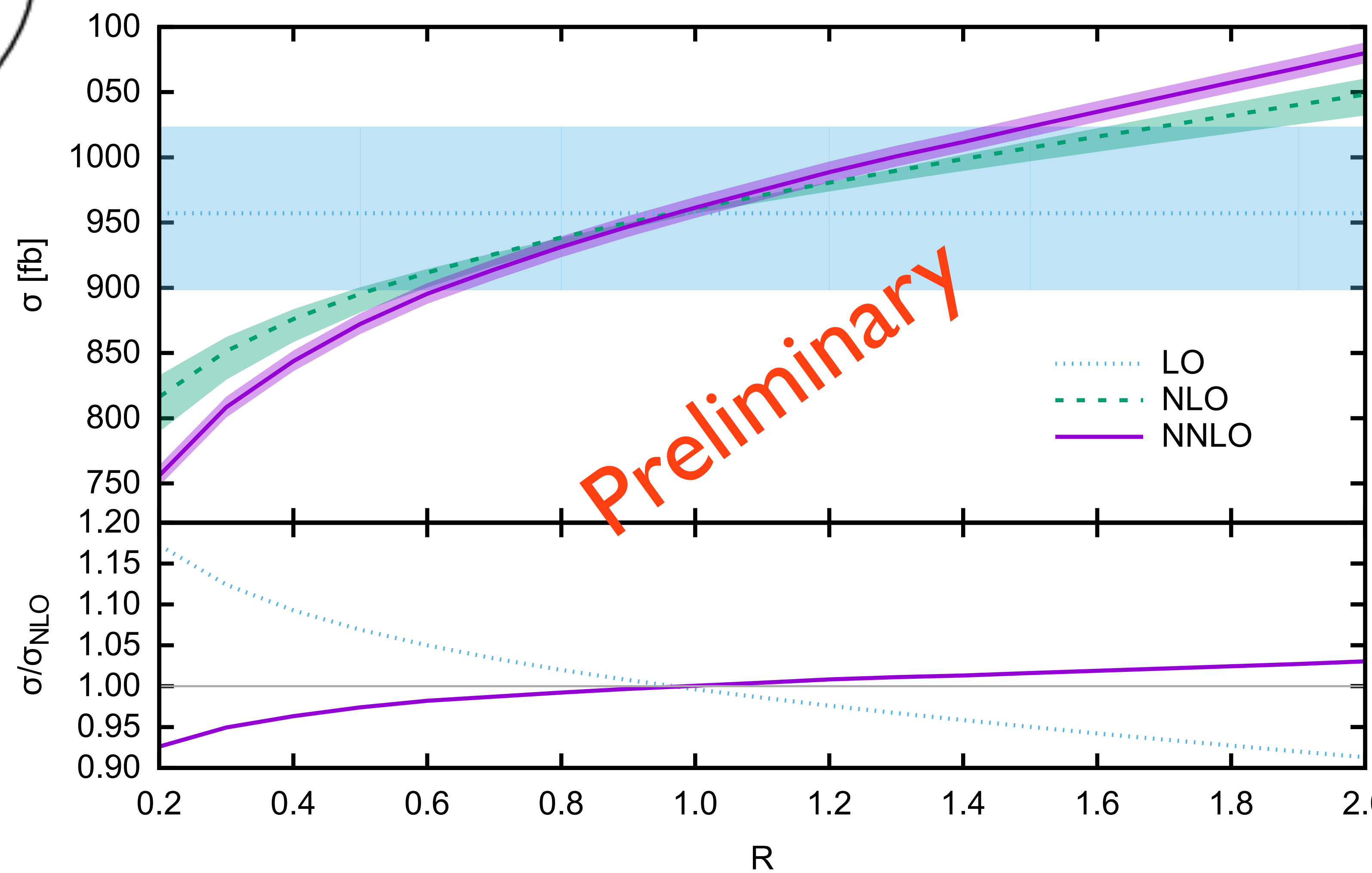
[Cruz-Martinez, Gehrmann, Glover, Huss (2018)]

VBF and large corrections: jet dynamics



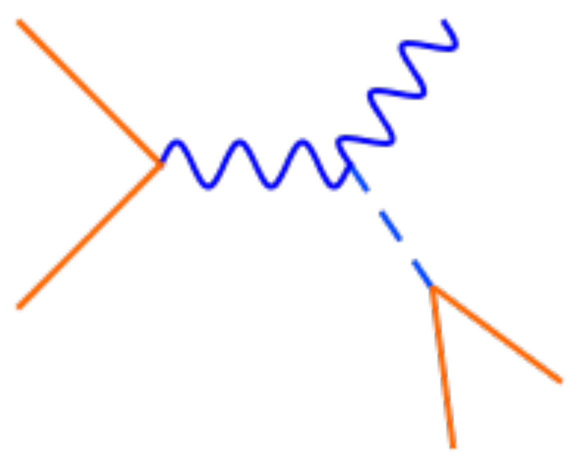
With experimental cuts: realistic requirement on hadronic activity → non trivial jet dynamics

Can explain at least partially why corrections larger than at the inclusive level



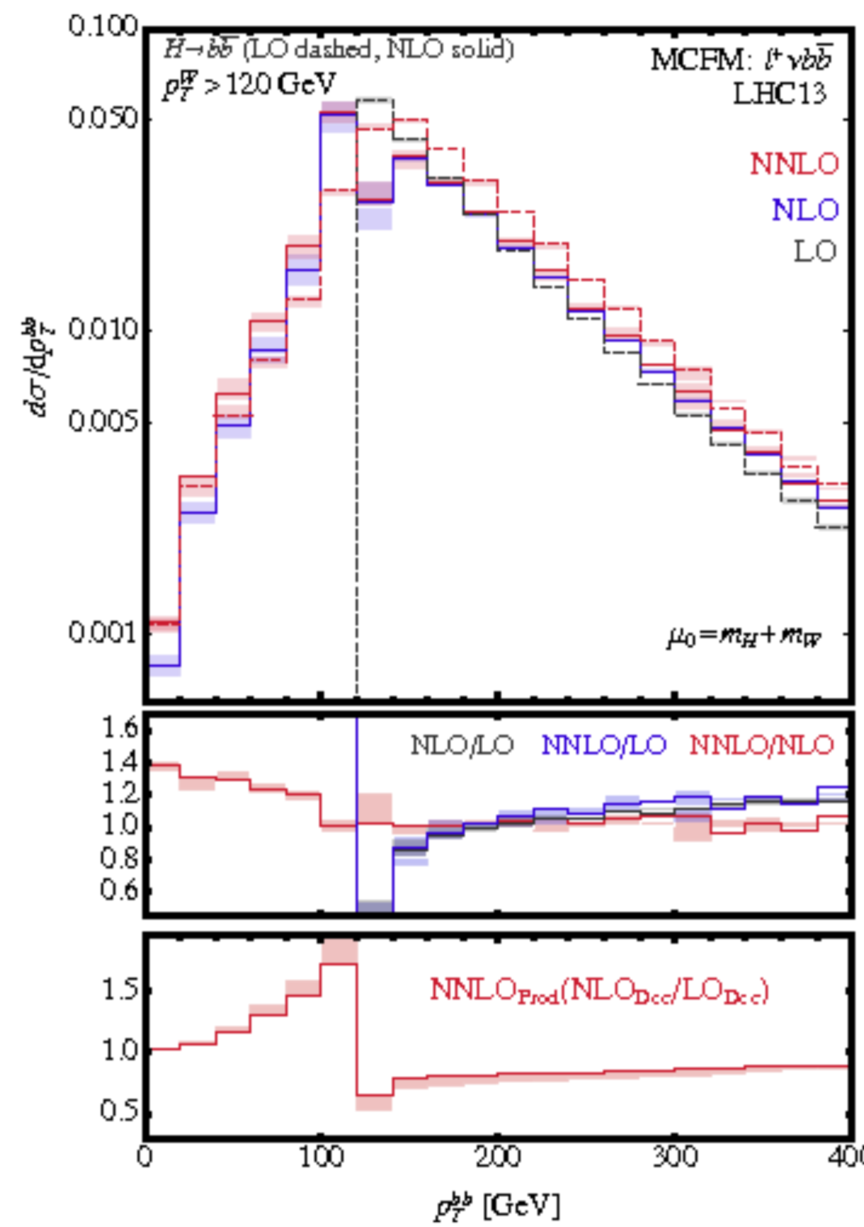
[M. Rauch, talk at VBF HXSWG meeting, 2018)

$$VH, H \rightarrow bb$$



The H→bb decay

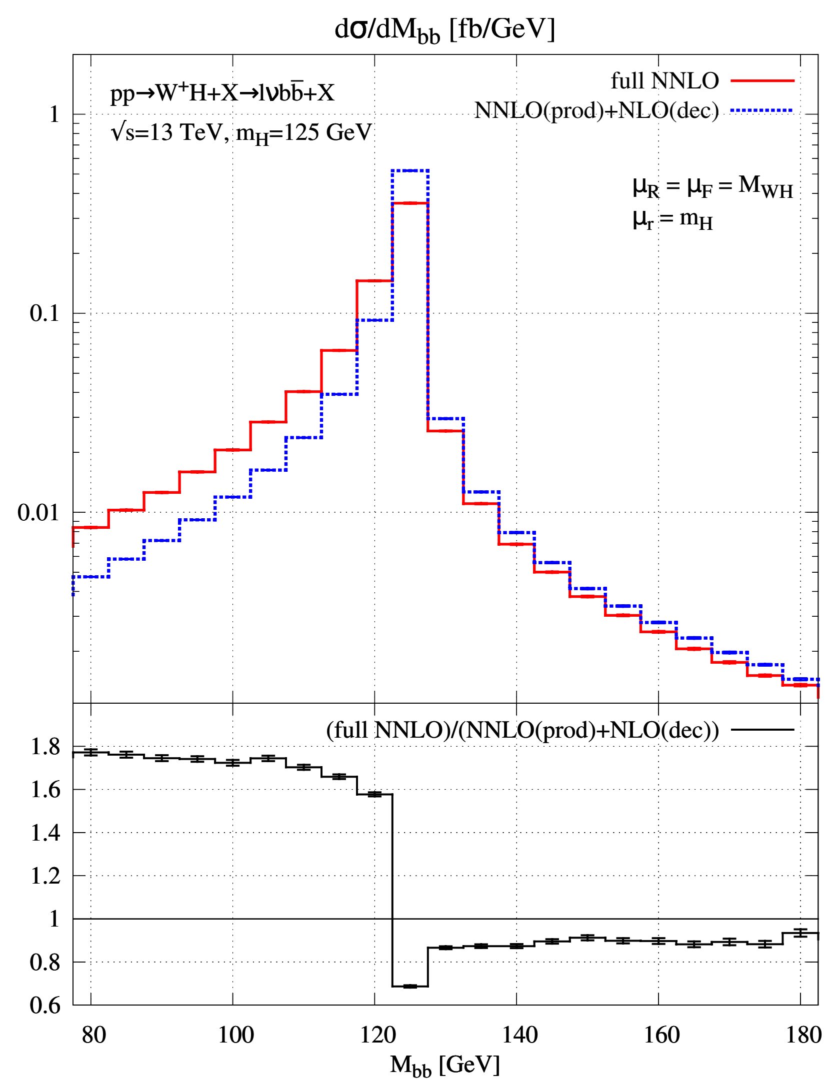
- H→bb decay extremely hard to observe, very large background. E.g.: tt → Wb Wb → bb l ν + unobserved, and E_b ~ 65 GeV ~ $m_H/2$…
- Still, it was possible to find significative evidence using VH production mode (tagging V)
- Analysis relies on the different features of signal and background → good control on predictions is important
- In particular, *b* quarks can radiate gluons → shape distortions due to corrections in the decay
- Until recently: $\mathrm{NNLO_{prod}}$ x $\mathrm{NLO_{dec}}$
- What happens at higher orders?

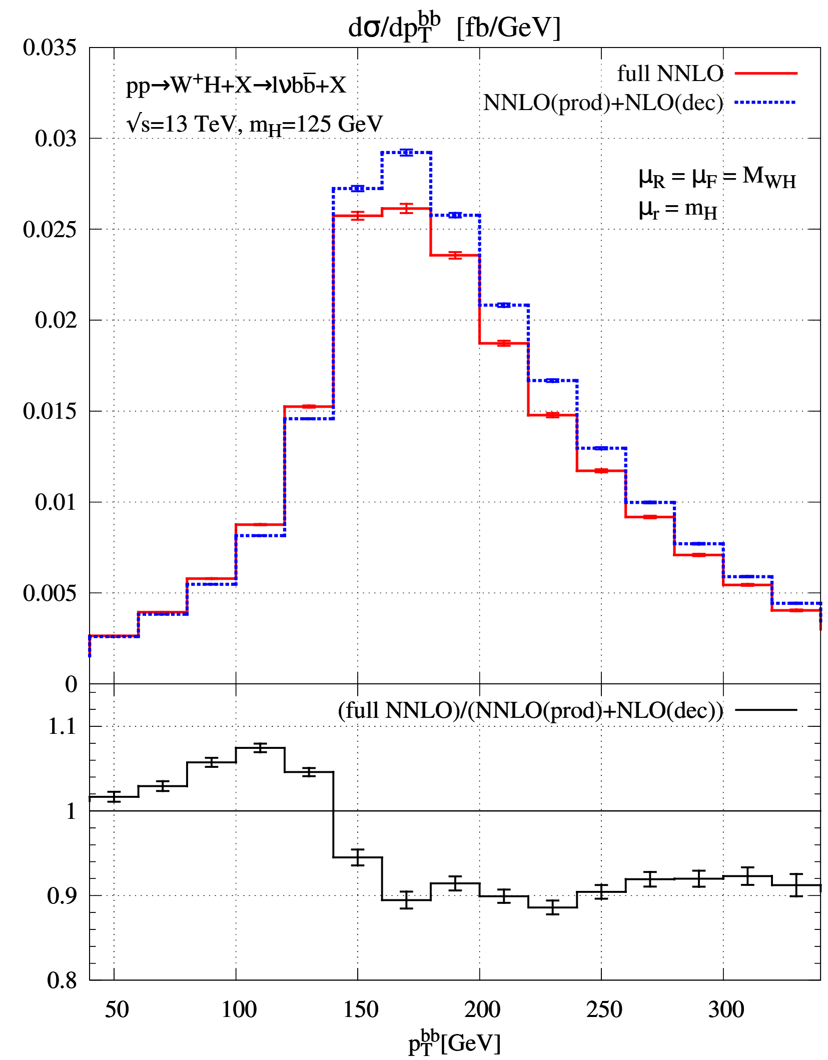


[Campbell, Ellis, Williams (2016)]

VH, H→bb decay@NNLO

- NNLO corrections for decay recently computed, neglecting the b-quark mass, i.e. $y_b \neq 0$ with $m_b = 0$ [Ferrera, Somogyi, Tramontano (2017)]
- Large deviations found, 5% corrections to the fiducial cross sections w.r.t. NLO



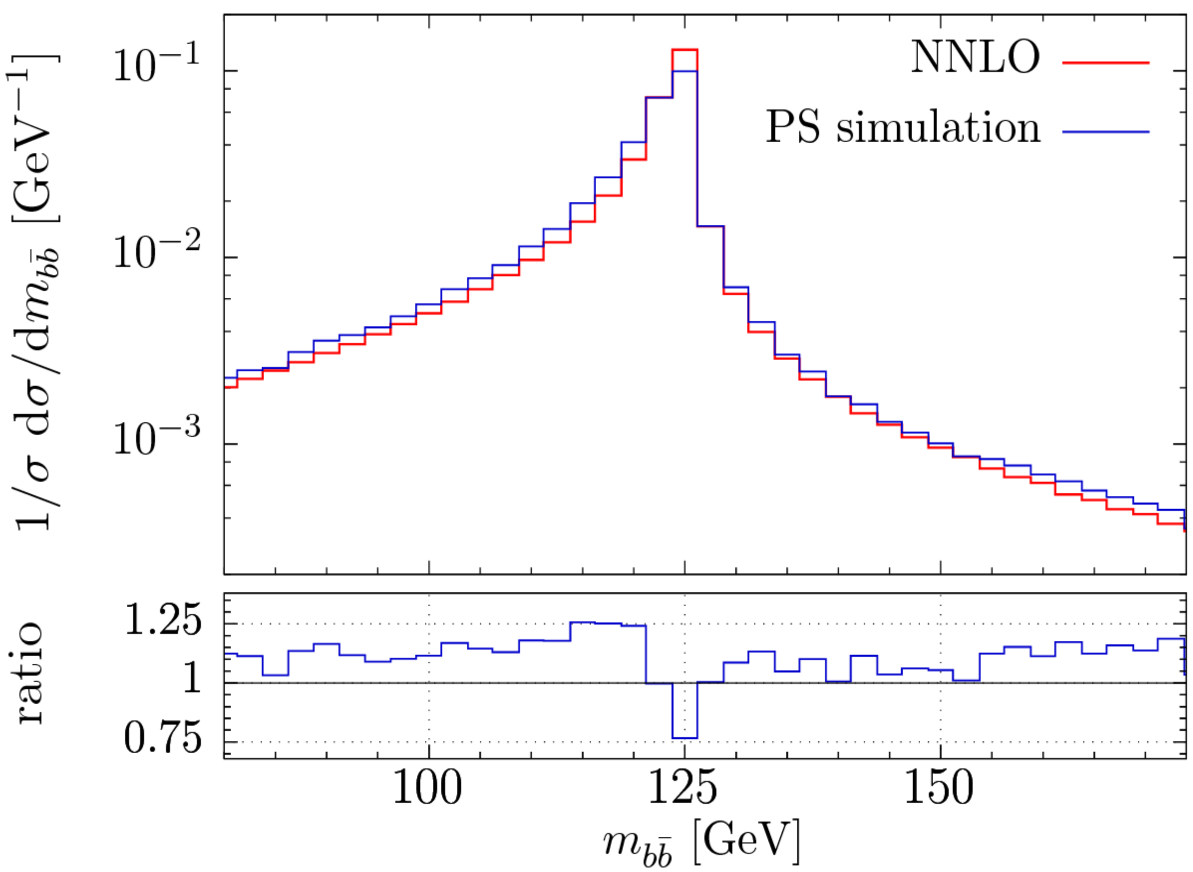


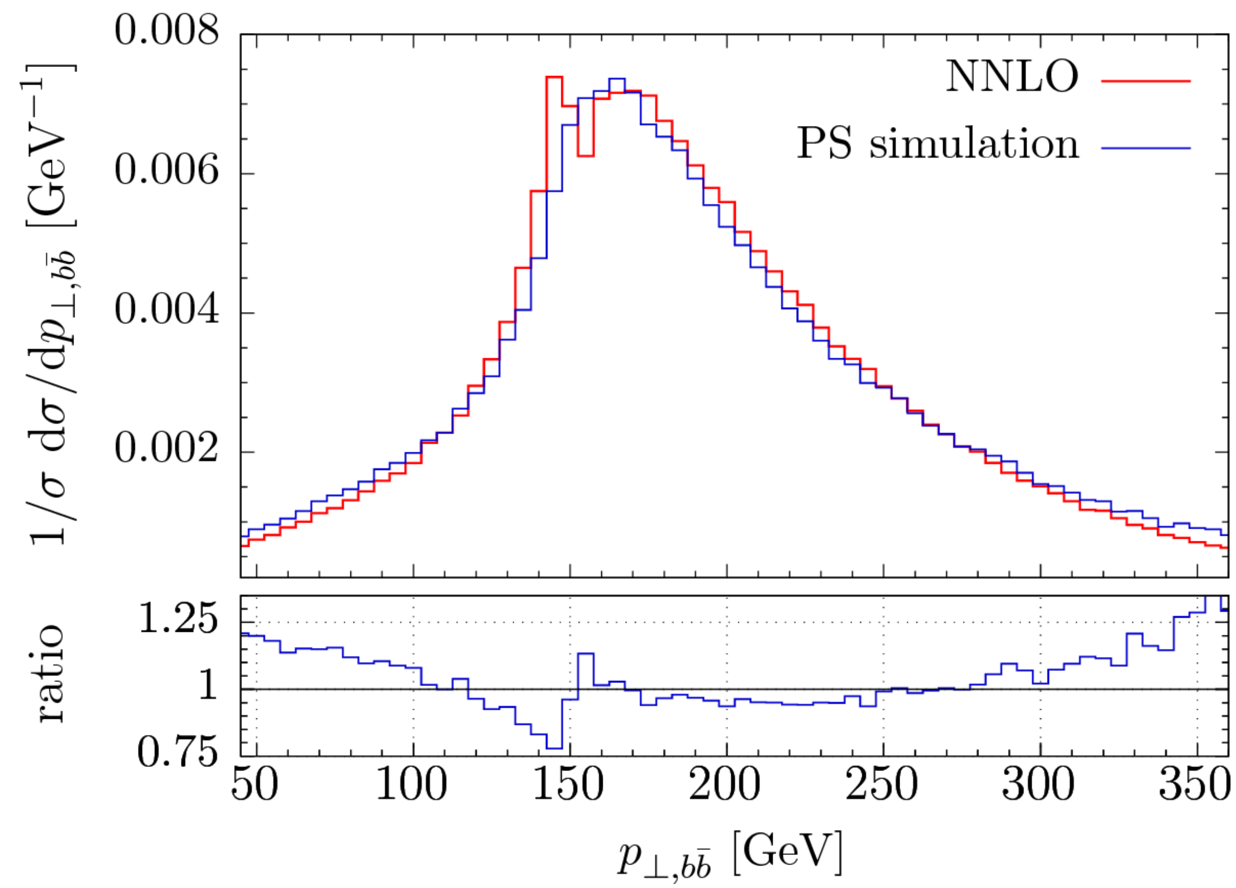
[Ferrera, Somogyi, Tramontano (2017)]

IN PRINCIPLE, PROBLEMATIC!

VH, H→bb decay@NNLO

- However: large corrections driven by extra parton emission → approximated in exp. simulations using parton shower. Could account for some of the correction…

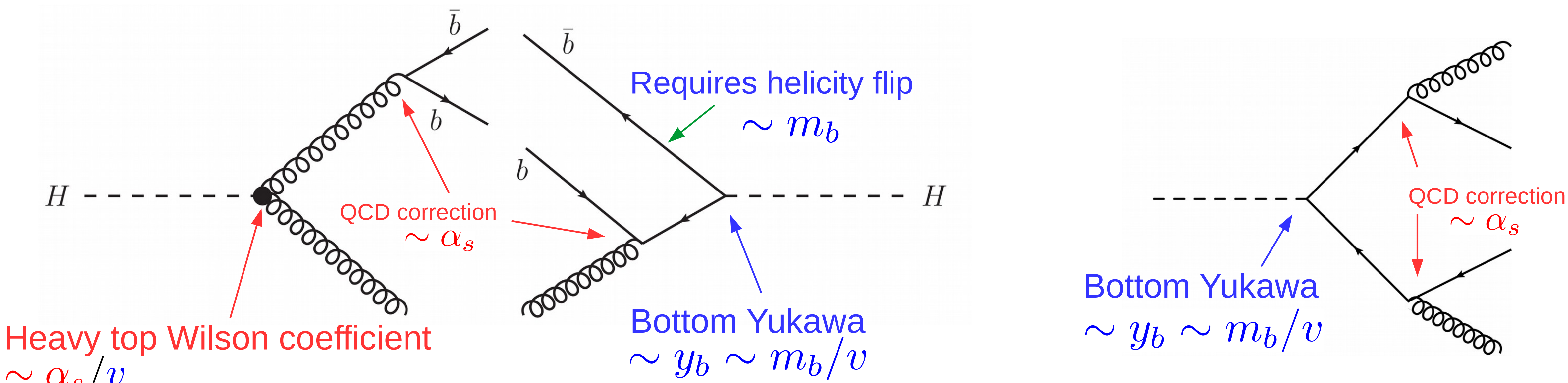




- Indeed: PS simulations capture the bulk of the NNLO correction [FC, Melnikov, Roentsch (2017)]

H→bb decay@NNLO: a theoretical issue

- To facilitate computations, decay computed with massless *b*-quarks: $m_b \ll m_H$
- Comparison with exp. [realistic final state]: use particular way of constructing *b*-jets, which uses from the fact that soft quarks don’t lead to any singularity
- This procedure is fine at LO/NLO, but problems arise at NNLO
- The problem: top/bottom interference

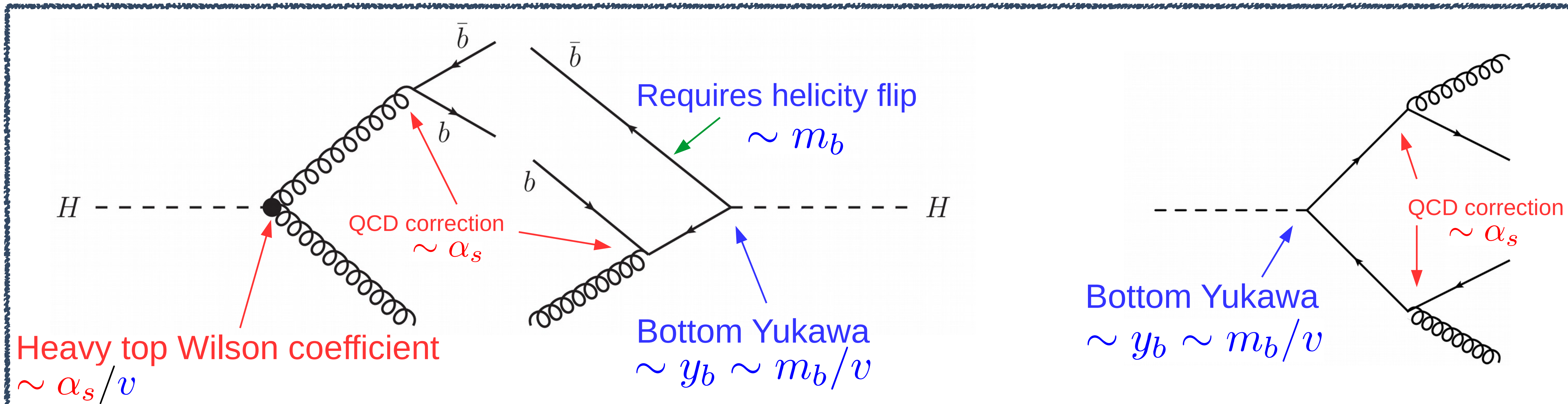


Top-loop interference contribution $\sim \alpha_s^2 m_b^2/v^2 \sim \alpha_s^2 y_b^2$

“Regular” contribution. Squared $\sim \alpha_s^2 m_b^2/v^2 \sim \alpha_s^2 y_b^2$

[Roentsch, talk at HXSWG VH meeting]

H→bb decay@NNLO: a theoretical issue



Top-loop interference contribution
$\sim \alpha_s^2 m_b^2/v^2 \sim \alpha_s^2 y_b^2$

"Regular" contribution.
Squared $\sim \alpha_s^2 m_b^2/v^2 \sim \alpha_s^2 y_b^2$

- In the SM, ''standard'' y_b^2 and interference non separable!
- Why is this a problem? We require helicity flip → after factoring out one power of m_b, amplitude acquires sub-leading power divergences when *the b quarks are collinear OR soft, regularization procedure of before does not work*
- In other words: amplitude develops logarithmic dependence $\ln(m_b)$, cannot set $m_b \to 0$

Higgs production at the LHC: overview

``gluon fusion''

``VBF''

- The interference contribution on the total decay rate can be estimated to be ~ 30% of the NNLO corrections → small, but not tiny [FC, Melnikov, Roentsch (2017)]
- It would be interesting to look at shape dependence
- … also because this term has different scaling with y_b → different behavior in BSM models [*although probably too small to be useful…*]
- To settle this: fully massive calculation is required…

$\sigma(pp \to H+X)$ [pb]

CAREFUL: Δ_{TH} → QCD uncertainty on the TOTAL (=unobservable) cross-section

Conclusions

- No obvious sign of NP at the LHC → crucial to perform detailed theory / experimental comparisons, to look for deviations from SM. Higgs is an obvious place to look…
- These studies are forcing us to keep improving our understanding of collider phenomenology → very good description of Higgs productions/decays
- The main goal are Higgs studies. However, in the process we keep learning important new information on a *real world quantum field theory.* Another (important) legacy of the LHC
- *The progress is huge and it is happening very fast, could not make justice to it in half an hour. Apologies if your favorite topic was missing.*
- Despite the progress, we are still very far from exploring the full potential of the (HL-)LHC (and future colliders). *A lot of interesting non trivial work still to be done*

Thank you very much for your attention