Theoretical Standard Model Predictions

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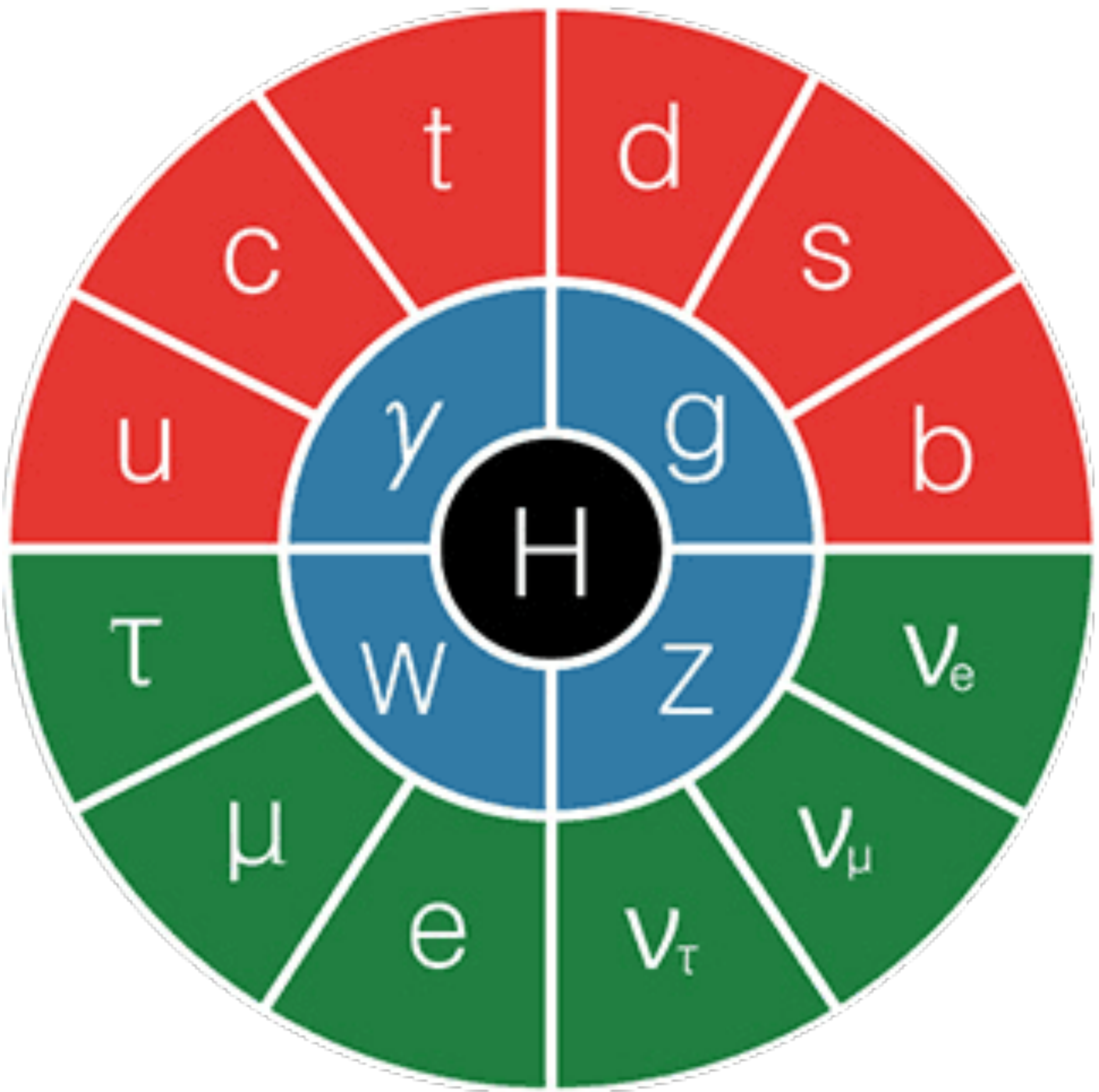
Pushing the Frontiers of Particle Physics During the LHC Run II Era,

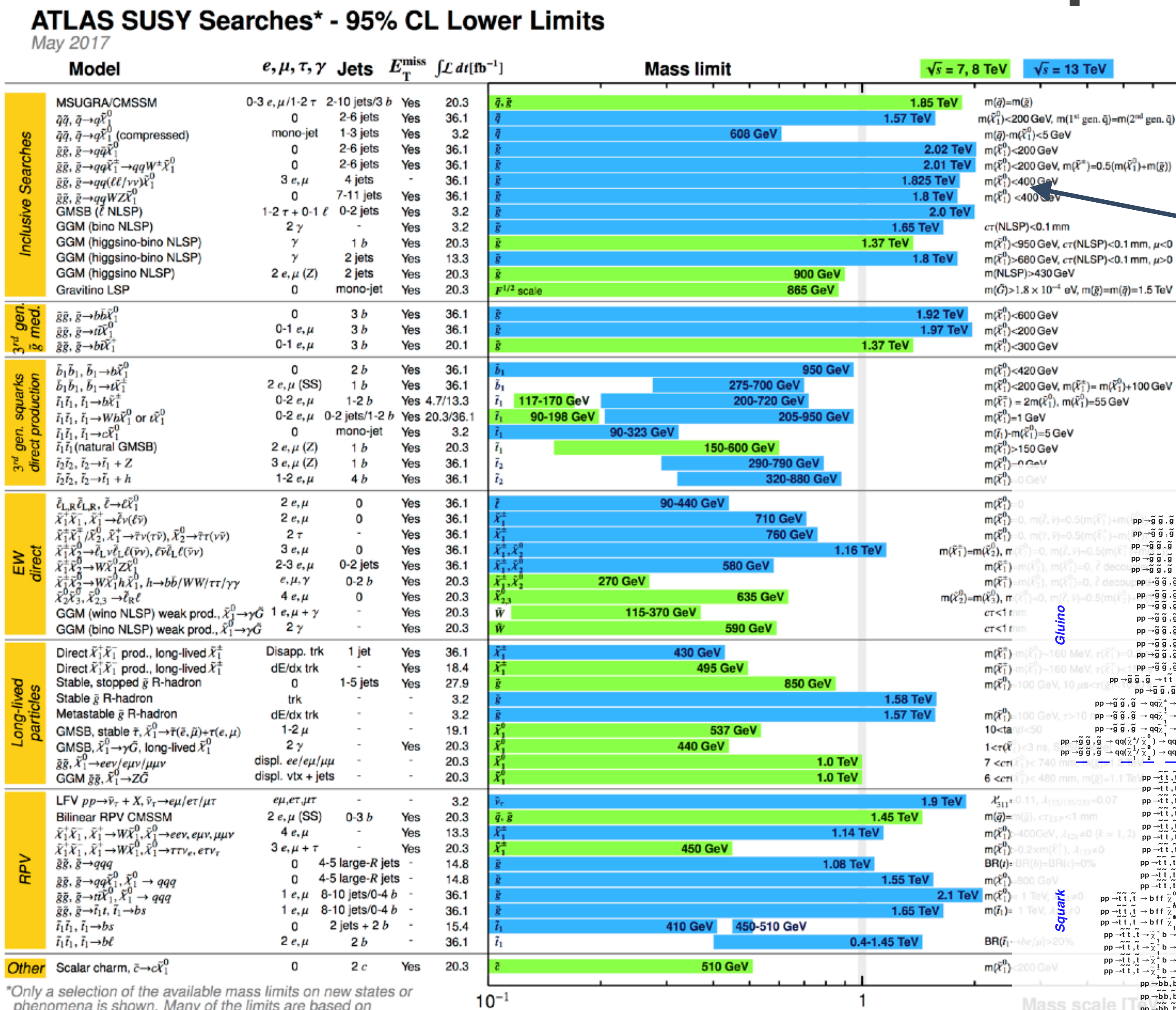
Gordon Research Conference, Hong Kong, 25 Jun. 2017

Particle physics circa 2017



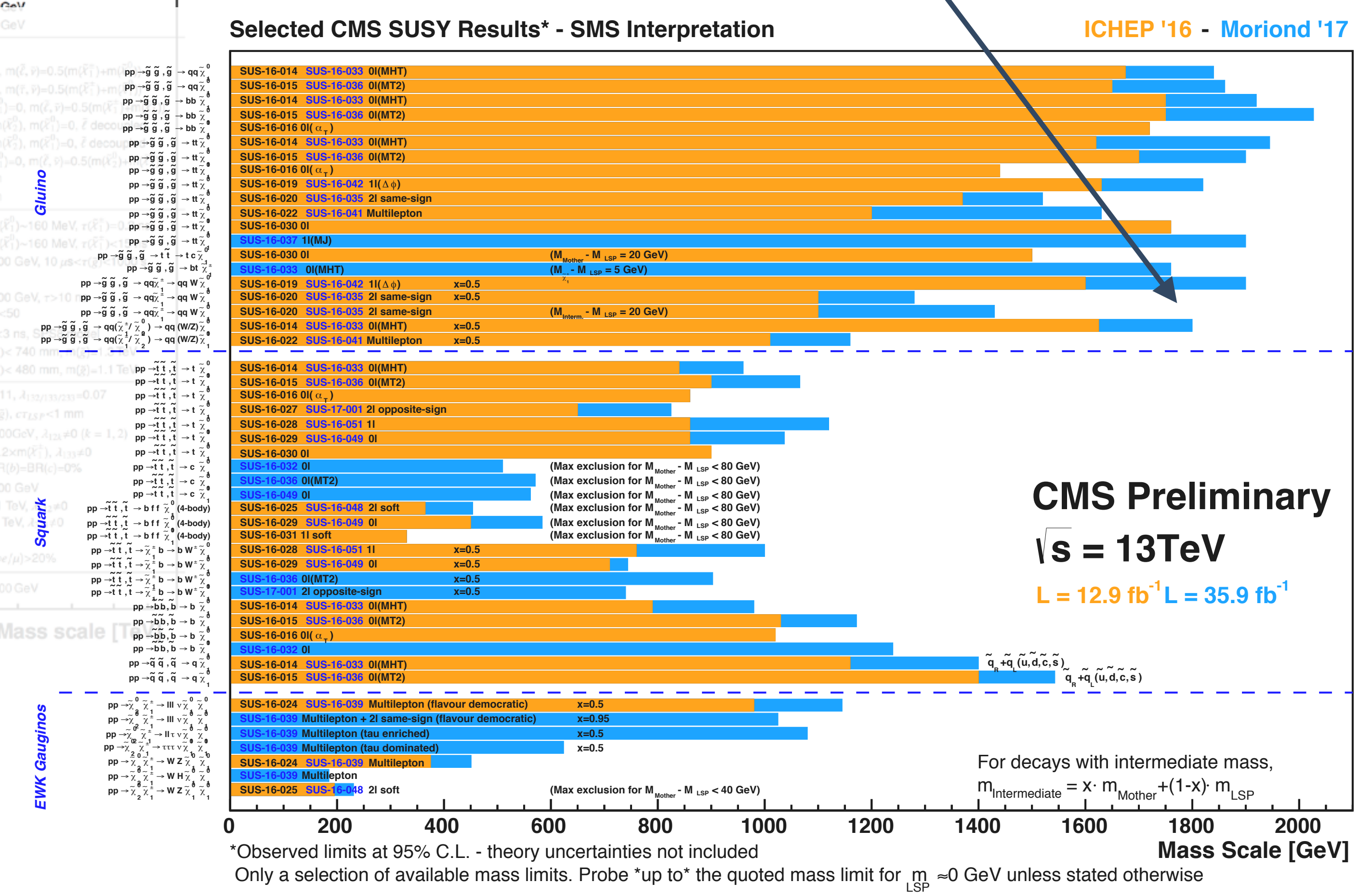
- With the discovery of the Higgs, for the first time we have a ``complete'' theory of fundamental interactions
- The world beyond colliders: strong strong indications of BSM (dark matter/energy, baryon asymmetry…)
- At least some of these new physics phenomena have a simple particle explanation
- The new information: $m_H = 125$ GeV. *NATURALNESS: a light Higgs comes with new extra light d.o.f. (see tomorrow's discussion). NP behind the corner? (also the WIPM miracle…)*

Not quite…



SUSY exclusion limits as of May 2017

m ~ 2 TeV

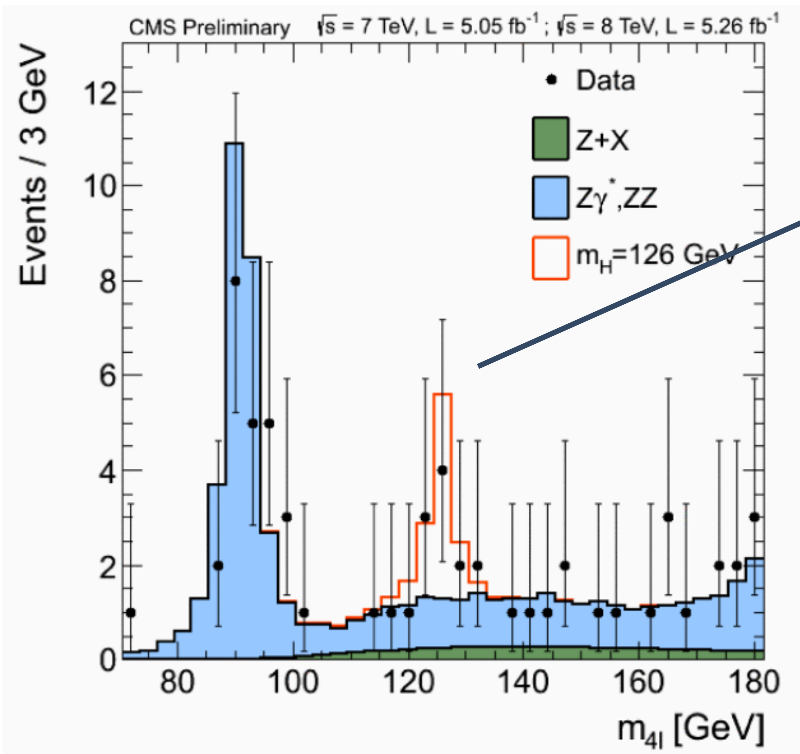


+ many other negative results.

Many `vanilla' models excluded

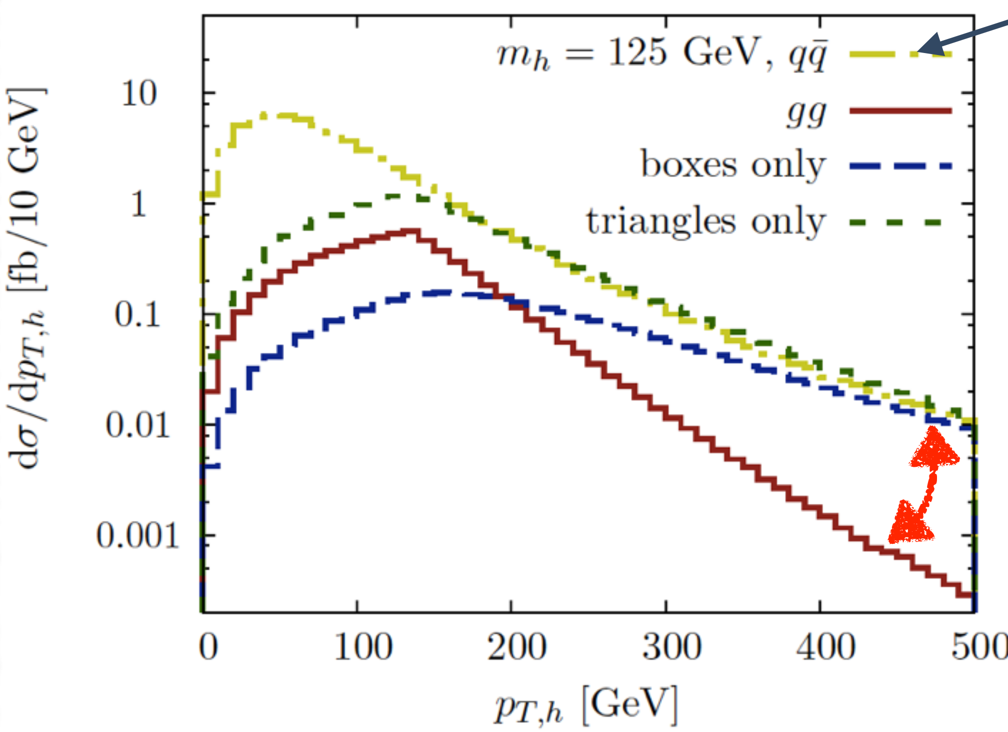
For many `standard' searches, the LHC is already reaching its asymptotic potential (energy reach)

NP and where to find it



BUMP HUNTING: little to no theoretical input needed. So far: Higgs

REQUIRE VERY GOOD CONTROL ON SM PREDICTIONS FOR SIGNALS / BACKGROUNDS



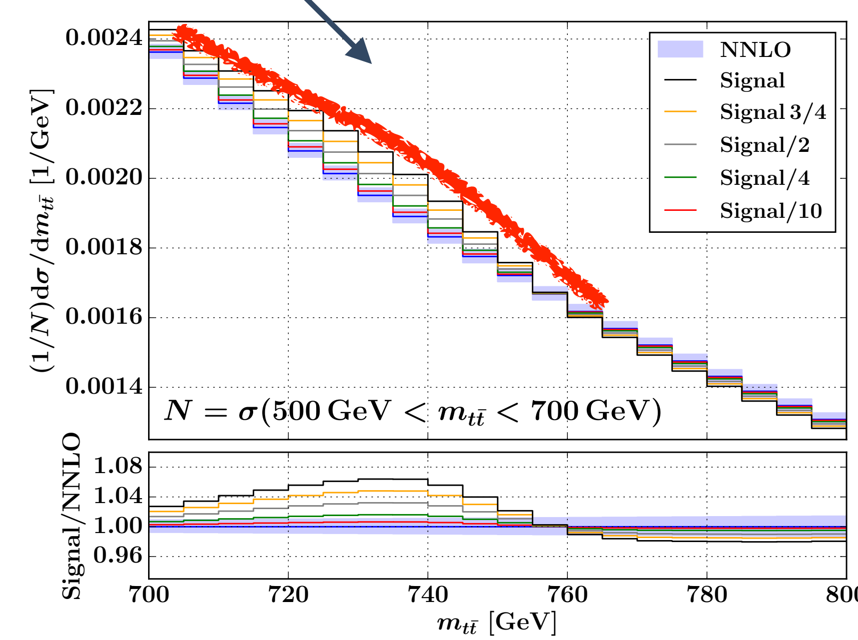
Shape distortions from high-scale NP

``Stealth scenarios''

$$\tilde{t} \to t + \mathrm{LSP}$$

$$m_{\tilde{t}} \approx m_t \gg m_{\mathrm{LSP}}$$

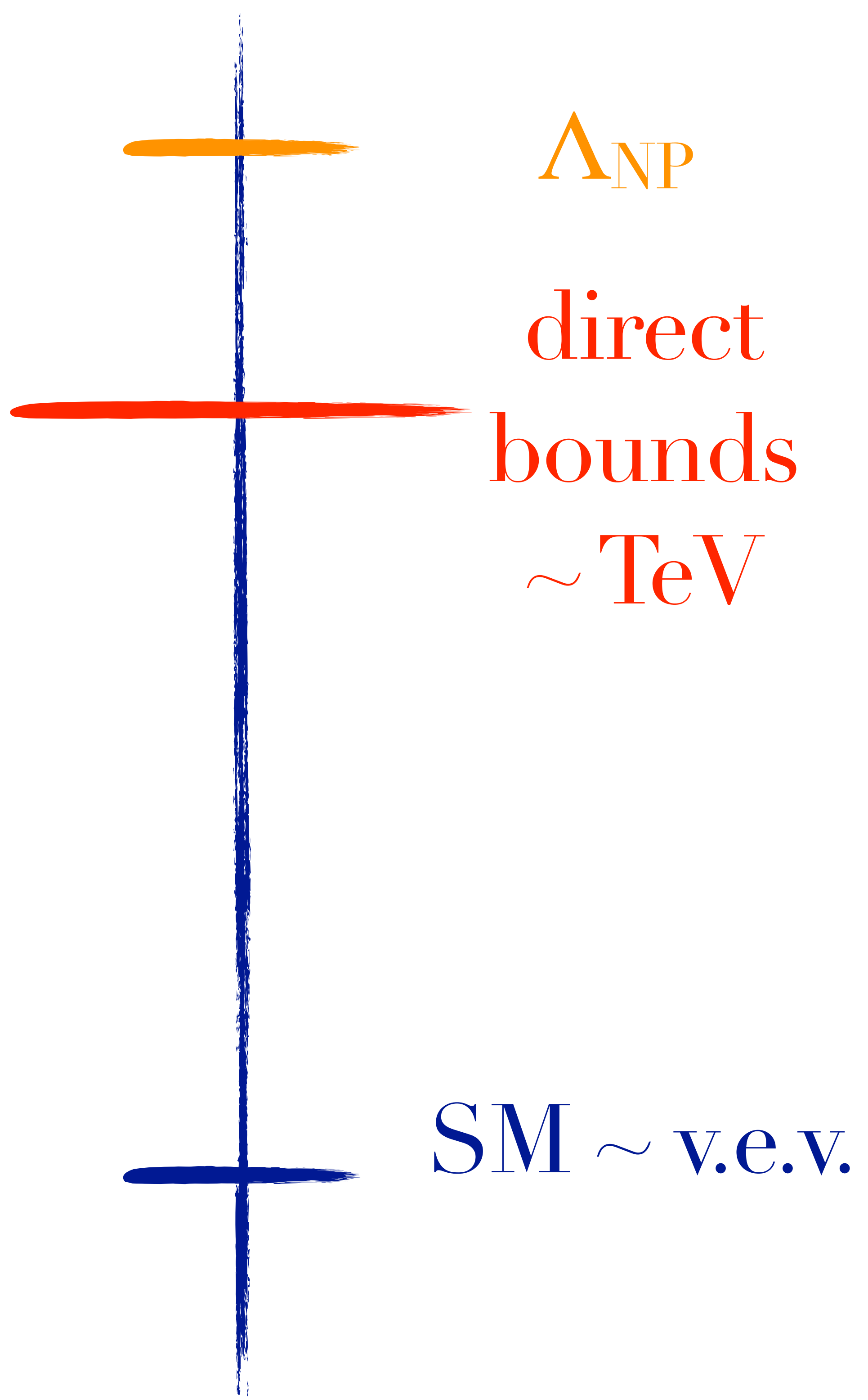
Tricky signatures



Wide resonances

+…

… `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

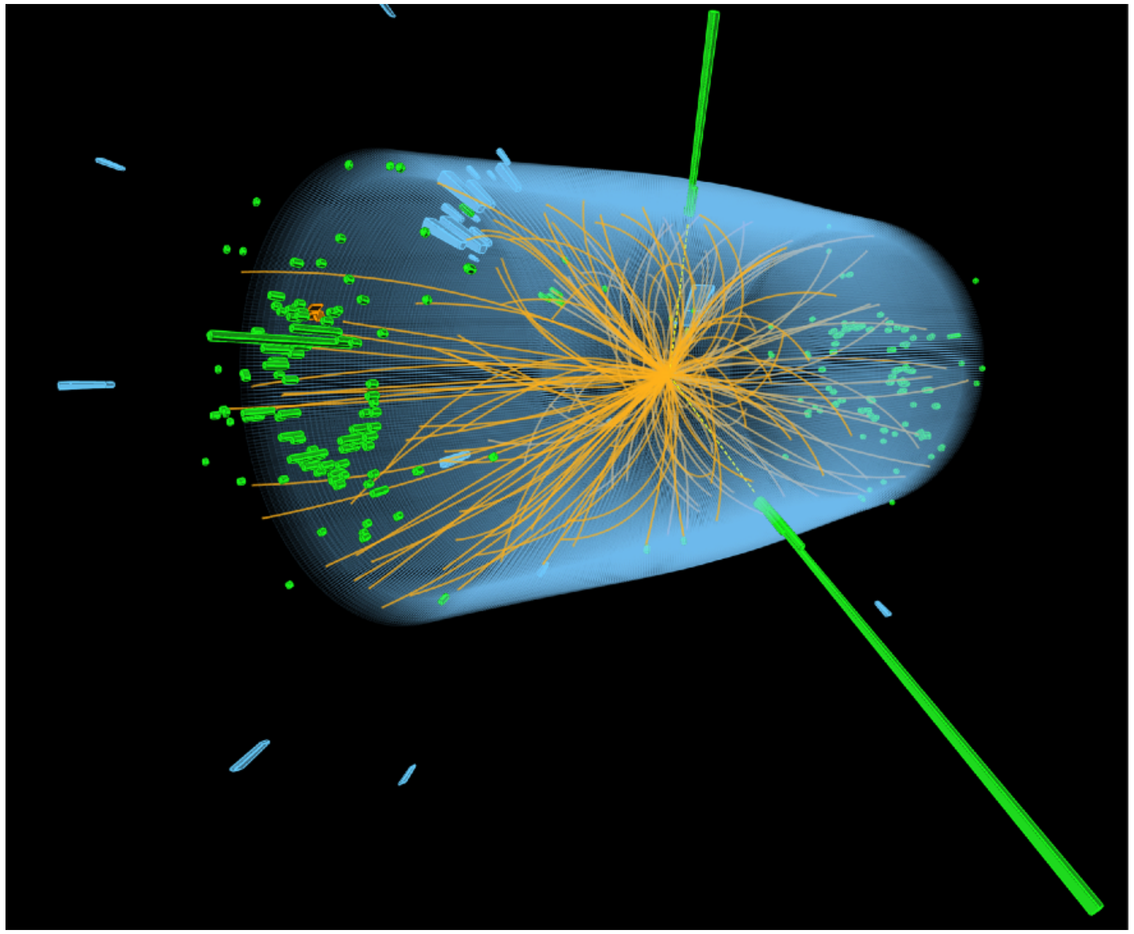
Theoretically, highly non trivial…

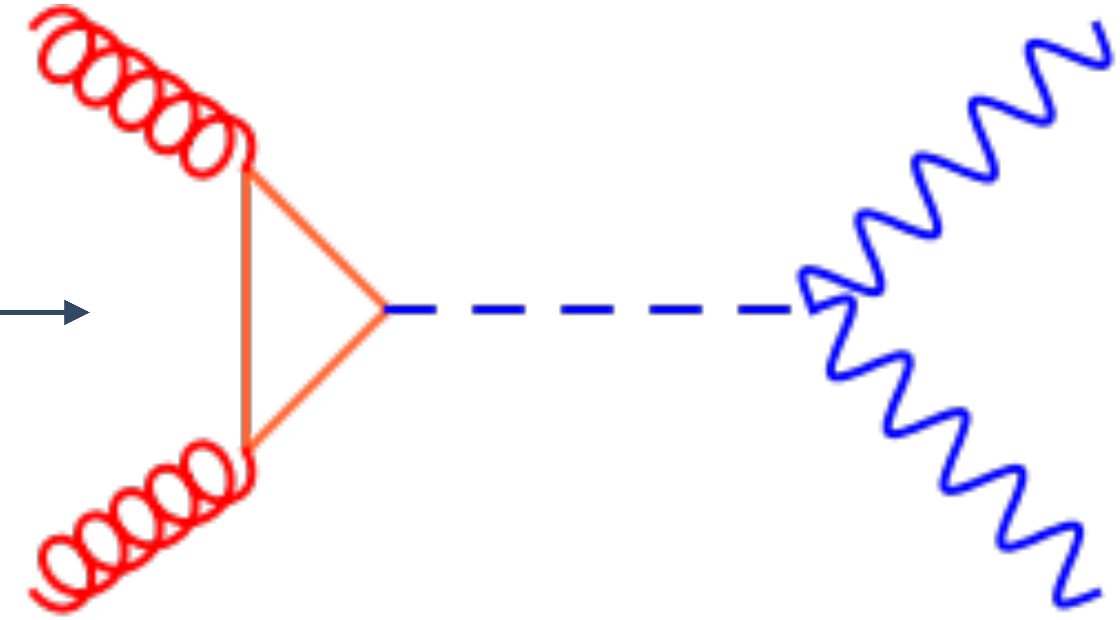
SM $\sim$ (v.e.v.)^2

IN THE BULK:
Q~M_H → few percent

Q≳ 500 GEV →
~10-20%

The path to precision: theory





- Precision physics in hadronic environment challenging
- The goal: accurate and reliable predictions for clean high momentum transfer processes
- As close as possible to actual experimental setup (fiducial cuts, unnecessary extrapolations kept to a minimum)…

This is for real: the (in)famous WW story

(Early) Experimental result,
extrapolated to the total cross-section

$\sigma_{ATLAS,8} = 71.4^{+1.2}_{-1.2}\,(\mathrm{stat})^{+5.0}_{-4.4}\,(\mathrm{syst})^{+2.2}_{-2.1}\,(\mathrm{lumi})\ \mathrm{pb}$

$\sigma_{CMS,8} = 69.9 \pm 2.8\,(\mathrm{stat}) \pm 5.6\,(\mathrm{syst}) \pm 3.1\,(\mathrm{lumi})\ \mathrm{pb}$

The theoretical prediction

$\sigma_{NLO} = 56.5^{+1.5}_{-1.1}\ \mathrm{pb}$

New physics? Electrow gauginos
hiding in plain sight?

? ? ?

This is for real: the (in)famous WW story

Unfortunately, much more mundane explanation

- Analysis requires quite harsh cut on extra hadronic activity to limit the top background
- Notoriously difficult to describe theoretically
- In the fiducial → total cross section extrapolation, this effect was theoretical mis-modeled by not accurate enough tools

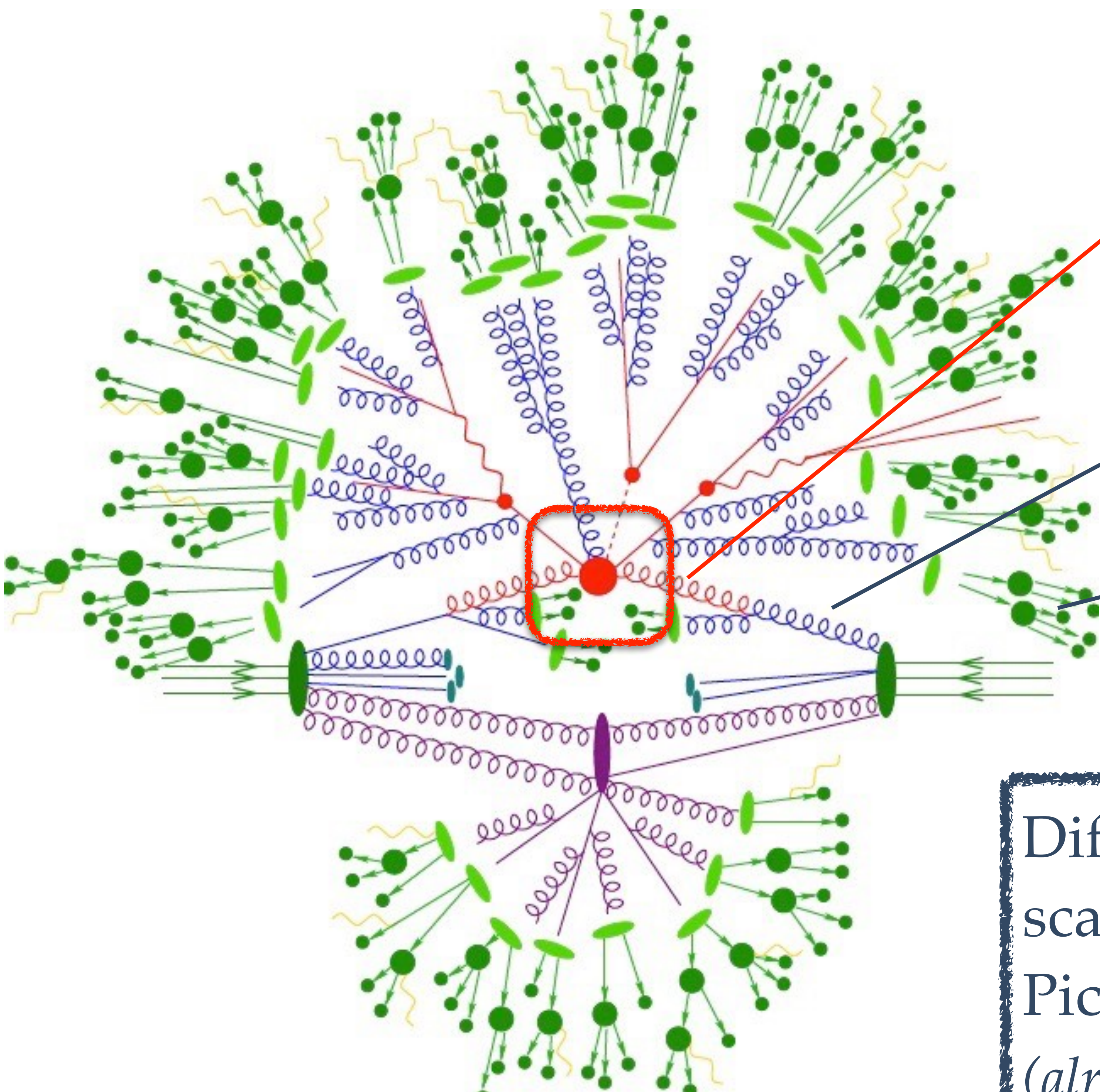
The same data/theory comparison performed in the region of the *actual experimental analysis*

	ATLAS	Theory (NLO)
e^+e^-	$68.5^{+4.2}_{-4.1}(\text{stat.})^{+7.7}_{-6.6}(\text{syst.})^{+2.1}_{-2.0}(\text{lumi.})$	$63.7^{+0.8}_{-0.4}$
$\mu^+\mu^-$	$74.4^{+3.3}_{-3.2}(\text{stat.})^{+7.0}_{-6.0}(\text{syst.})^{+2.3}_{-2.1}(\text{lumi.})$	$69.3^{+0.9}_{-0.4}$

[Monni, Zanderighi (2013)]

QCD at the LHC: factorization

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



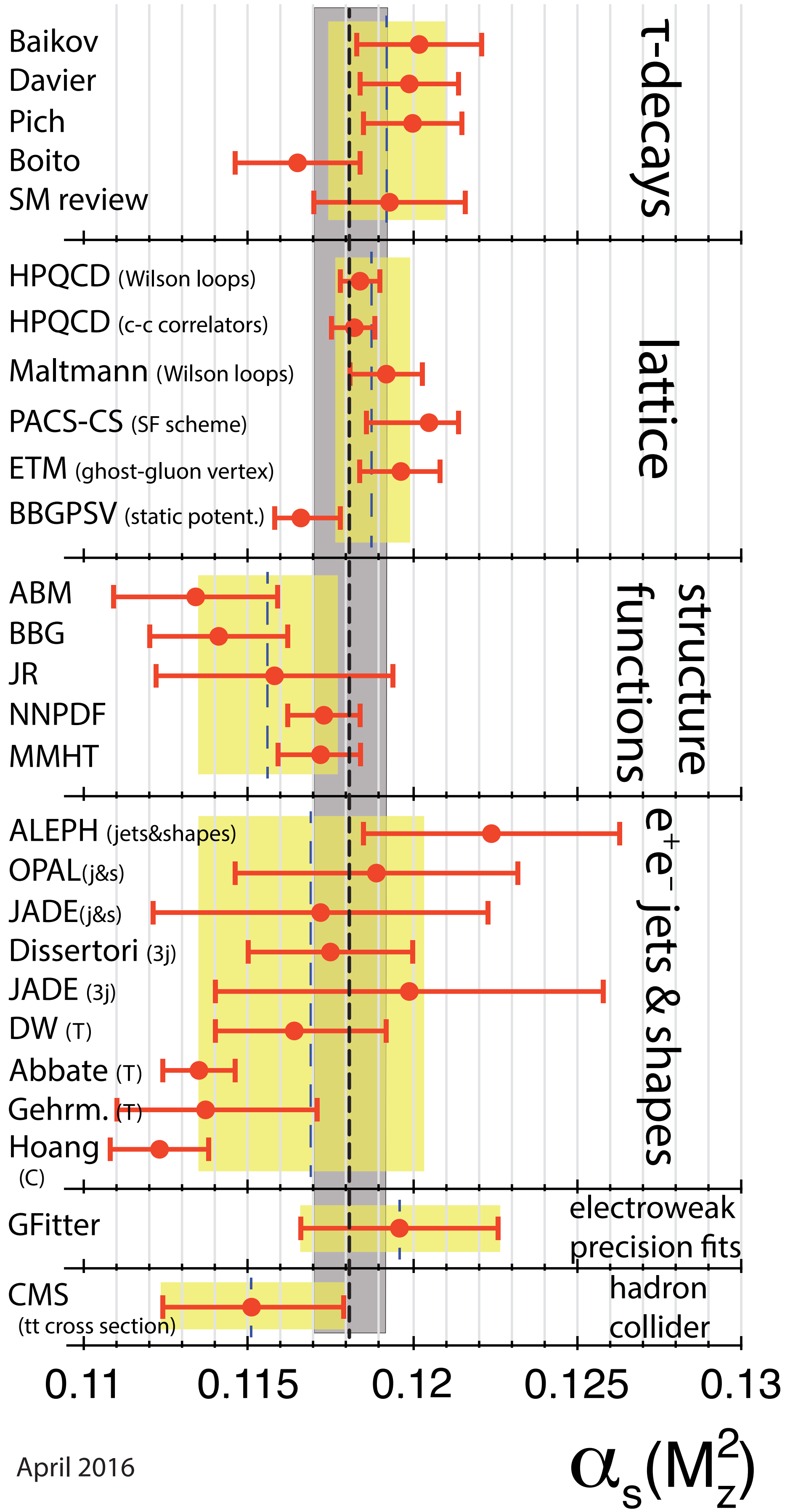
The ``interesting'' short distance cross-section

Extracting partons from protons: *Parton Distribution Functions*

The experimental world: hadrons / jets in the detector

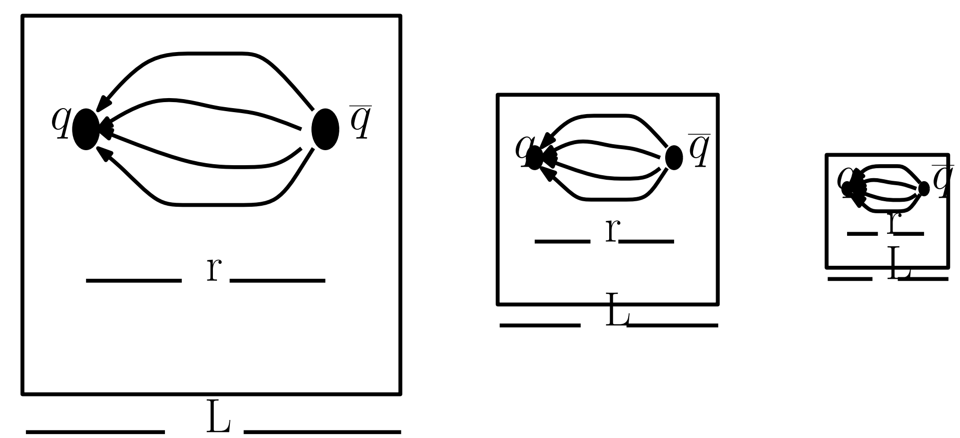
Different physics at different scales, can be ***Treated Separately***. Picture valid up to few percent *(already a limiting factor for $m_{t,W}$)*

The precision on input parameters: α_S



$$\boxed{\alpha_s(m_Z) = 0.118 \pm 1\%}$$

- Many different determinations, (more or less) consistent
- Lattice: the best hope for improvement?
- A lot of recent developments to properly connect the non-perturbative to the perturbative regime (finite size scaling…)



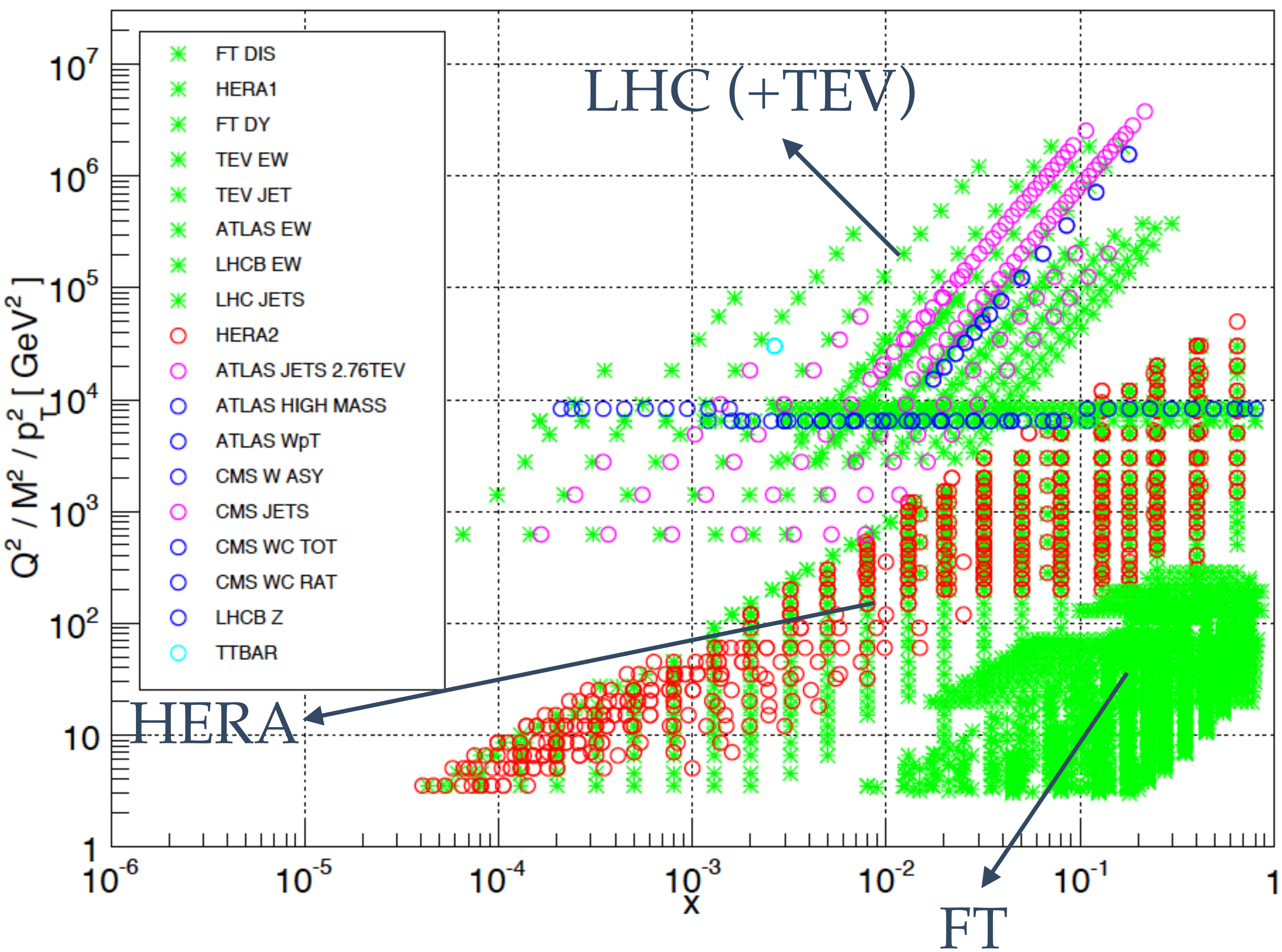
[Lüscher et al (1991), ALPHA (2017)]

0.5% precision may be possible?

Input parameters: PDFs in the LHC era

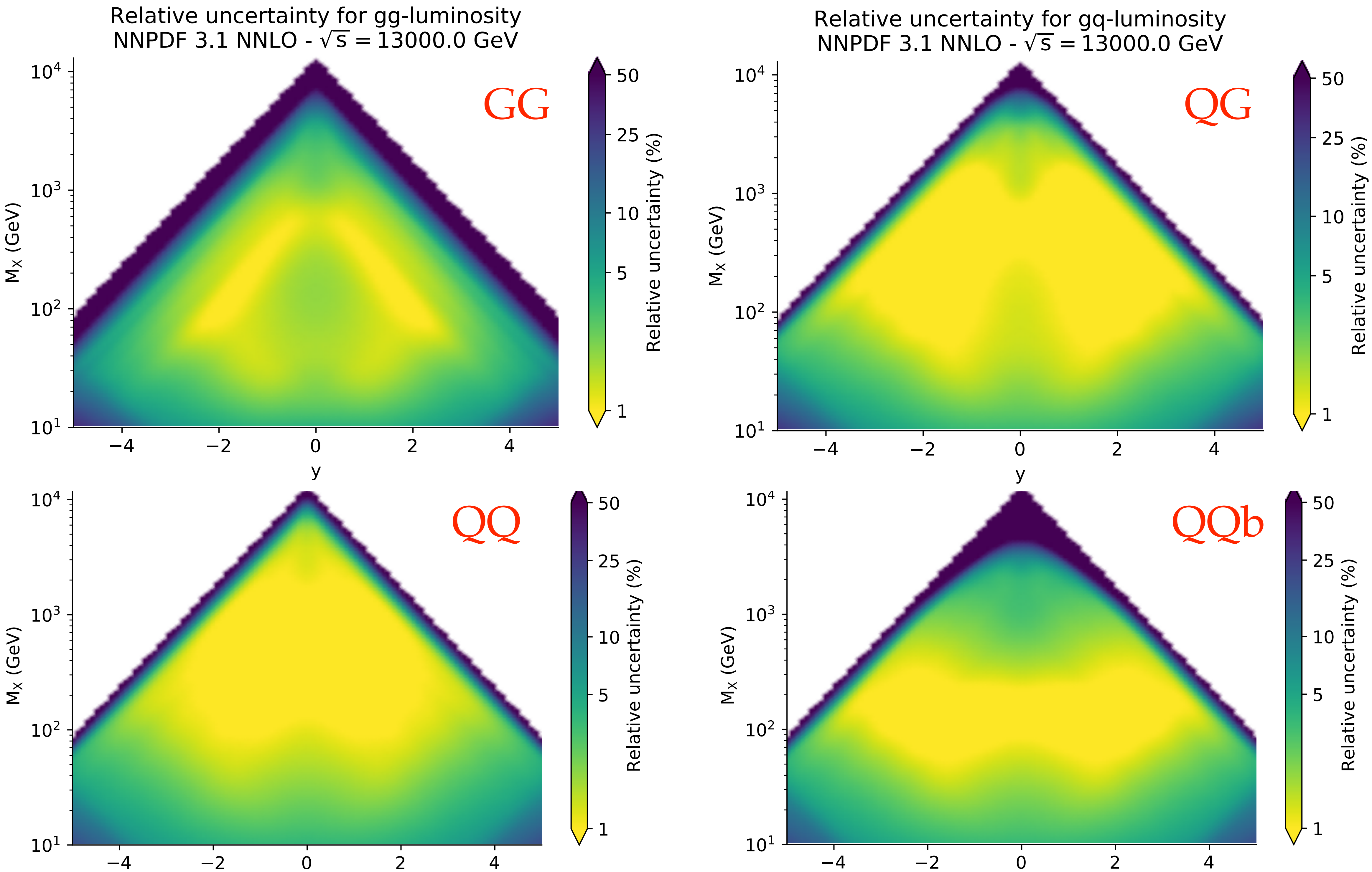
- Parton content of the proton non pert → fitted to data
- Data at different scales related by first-principle computable AP evolution → universality

$$\frac{\partial f(x,Q^2)}{\partial \log Q^2} = \alpha_s \int_x^1 \frac{dy}{y} P\left(\frac{x}{y}\right) f(y,Q^2) + \mathcal{O}(\alpha_s^2)$$



- Results consistent over many orders of magnitude → great test of pQCD
- A lot of precise data from the LHC are already now having great impact (tt, jj, Z/W…)
- We may soon discard `old' low-Q data with limited theoretical control (*nuclear corrections*…)
- SOLID, ROBUST AND `CLEAN' DETERMINATIONS

PDFs: the overall precision

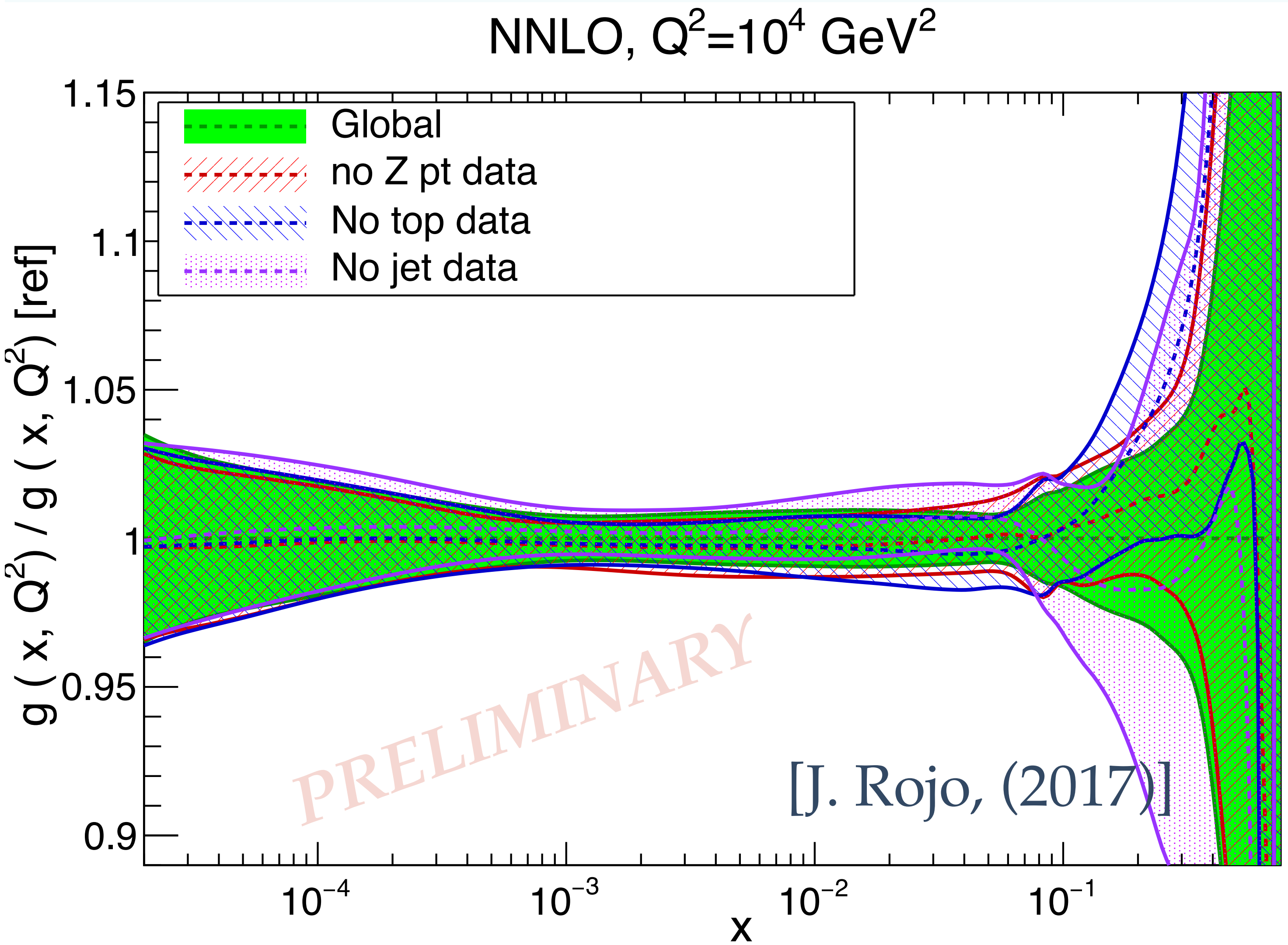


[NNPDF31, Jun. 2017]

- Big improvement w.r.t. few years ago
- For Central EW Production: percent precision
- *Although be careful to take these uncertainties at face value*

PDFs: sanity checks

or how do we make sure we are not fitting new physics away…

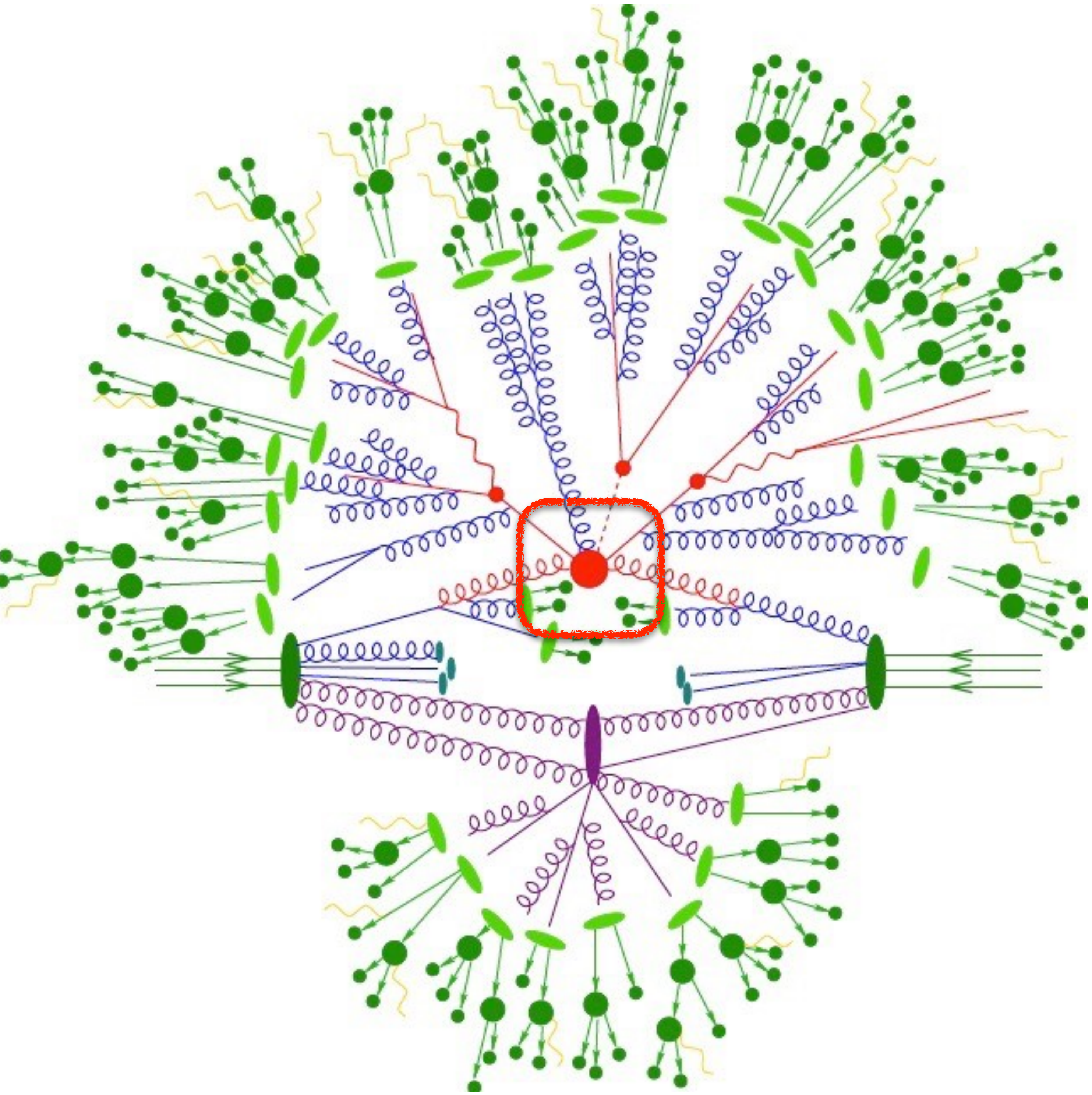


- Fits are stable under inclusion/exclusion of extra data-set
- Effect of new data: mostly reduction in uncertainty, small change in the central value

- With more and more data, can also try to fit ``safest'' PDF from PS regions which should be free from NP contaminations (e.g. forward jets…)…

The hard process: precise computations

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



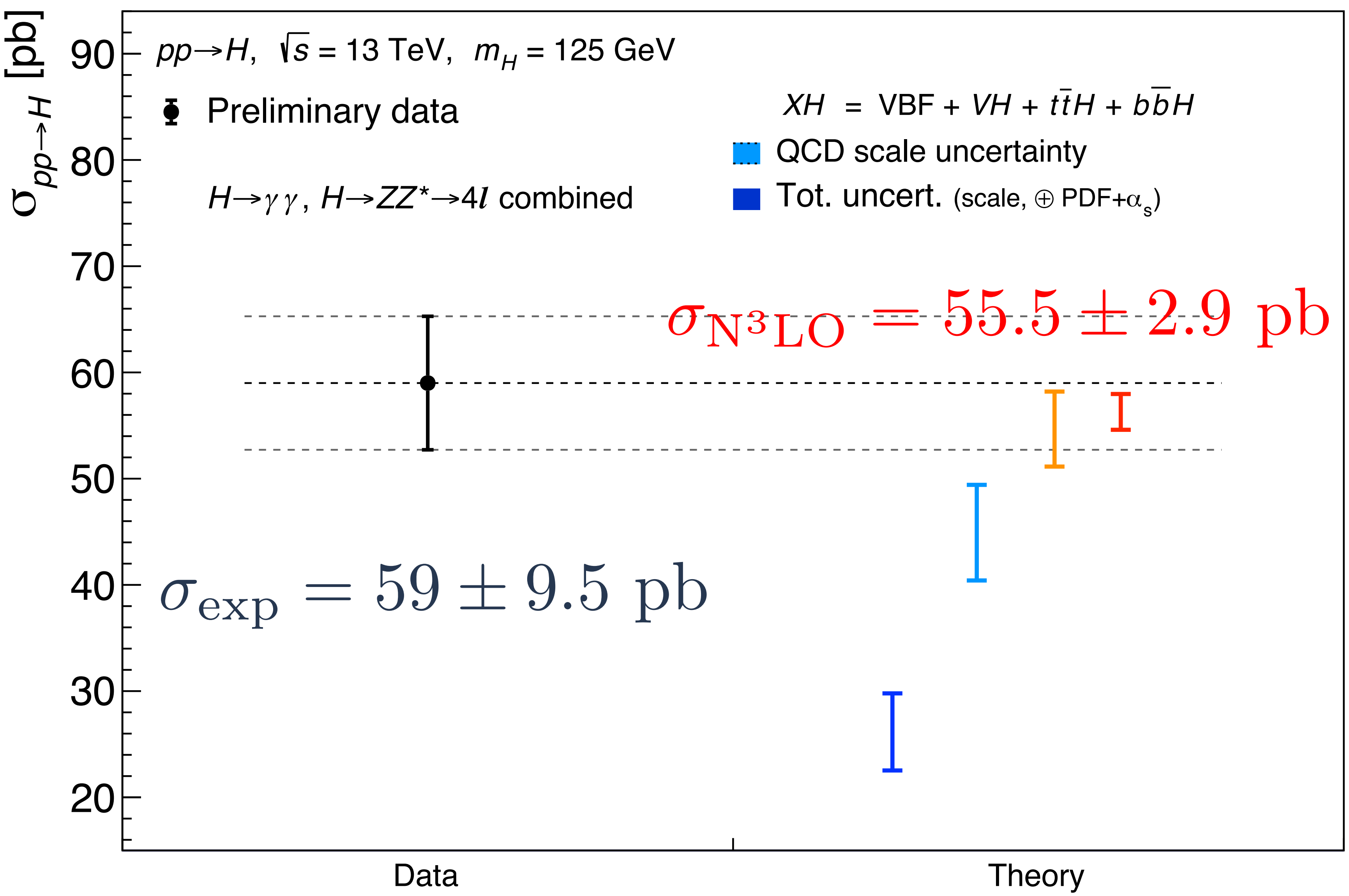
THE ``INTERESTING'' SHORT DISTANCE CROSS-SECTION

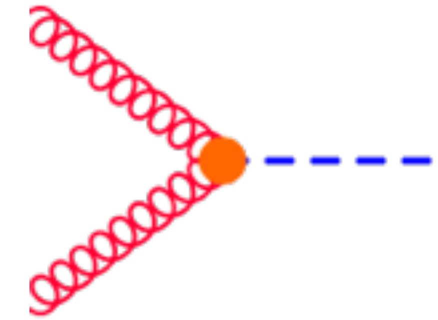
- Asymptotic freedom → at high scale QCD is perturbative
- Still, for typical EW scales $\alpha_S \sim 0.1$
- The path to precision: NLO ~ 10%, NNLO ~ 1%. Gluonic processes (e.g. Higgs): large color charges $\alpha_S C_A \sim 0.3$. Even higher orders may be required (N^3LO…)

The hard process: an ideal world

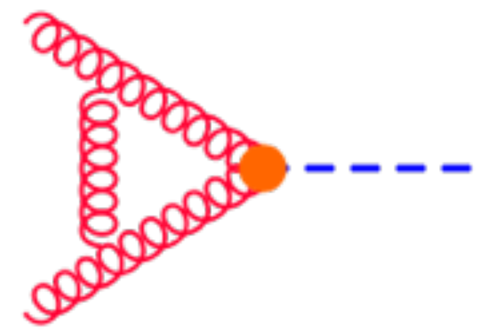
- In a perfect world (= large luminosities, good S/B control, large energy coverages):
  - find simple high-Q observables, where contamination by non-perturbative effects is minimal
  - ``cut-and-count'' like analysis, in the fiducial region → very clean data / theory comparison
- Whenever this is possible: very good theoretical control on our predictions. If the process is simple enough, we can obtain very accurate reliable results via *HIGHER ORDER PERTURBATIVE COMPUTATIONS* → *see T. Gehrmann's talk*
- Fixed order (differential) computations:
  - very solid framework
  - they give direct access to the actual fiducial region (i.e. we can put cuts on the final state)

The need for higher orders: Higgs

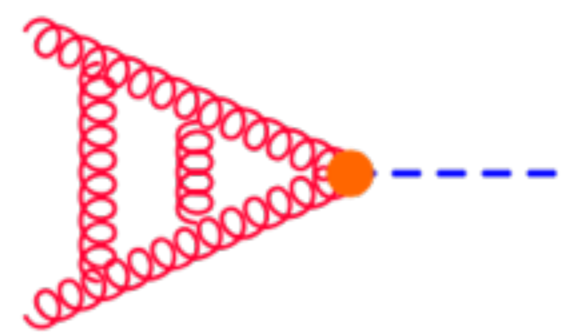




$\alpha_S{}^2$

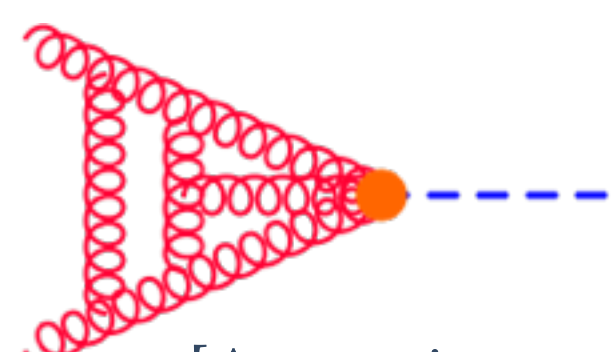


$\alpha_S{}^3$



$\alpha_S{}^4$

[Anastasiou, Melnikov; Harlander, Kilgore]



$\alpha_S{}^5$

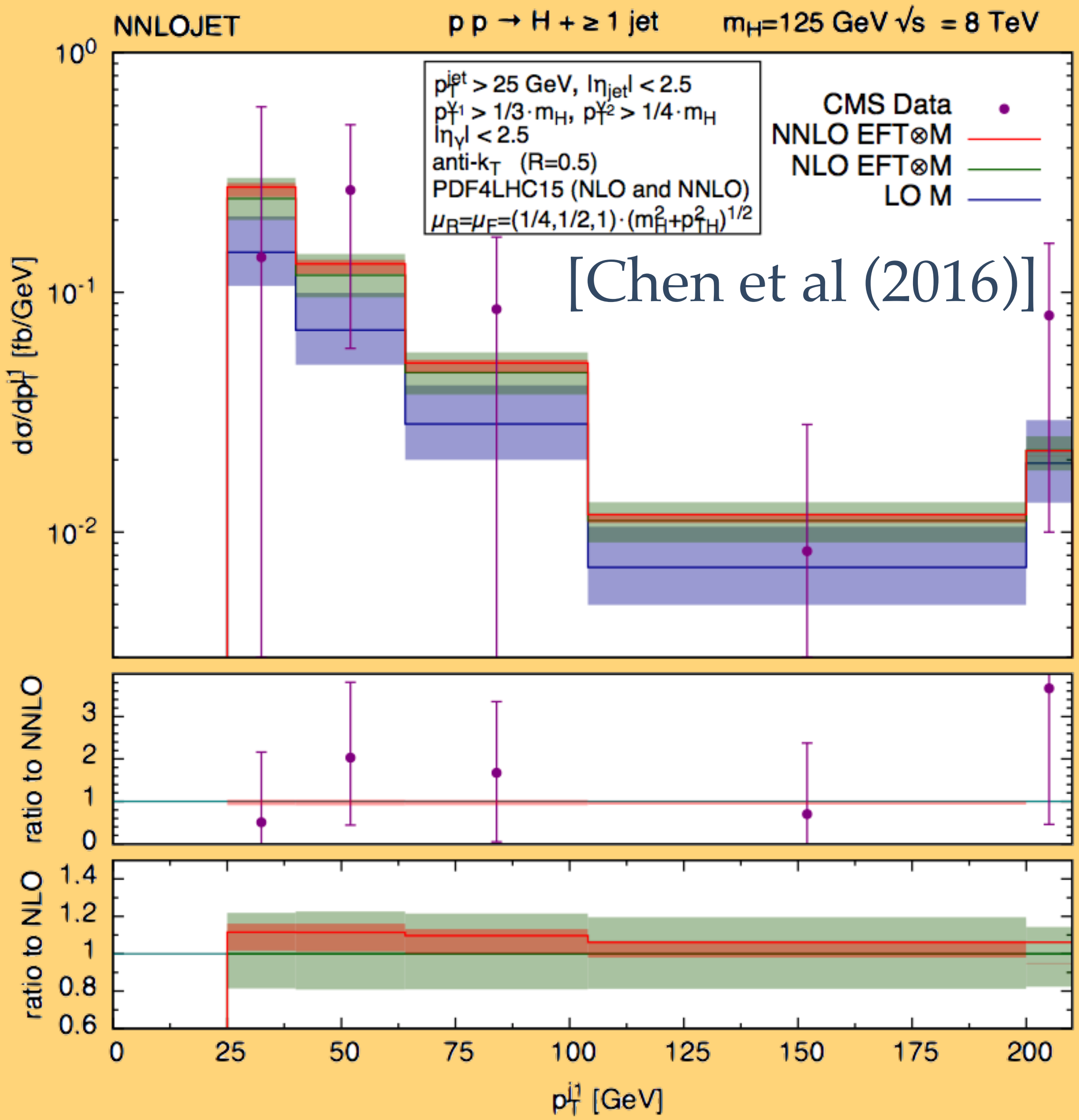
[Anastasiou et al]

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

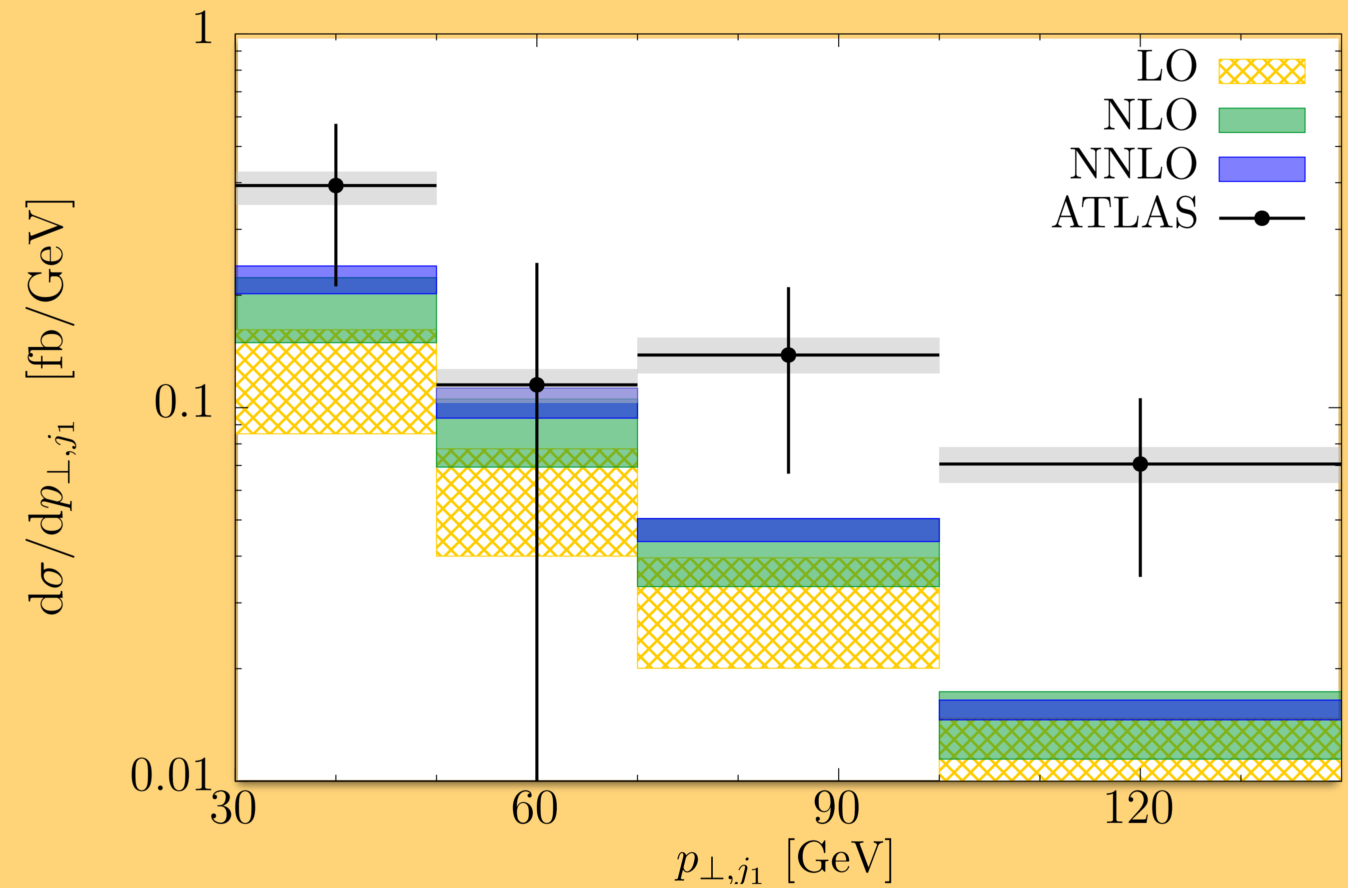
The need for higher orders: Higgs

Similar picture at the differential level:

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



[Chen et al (2016)]

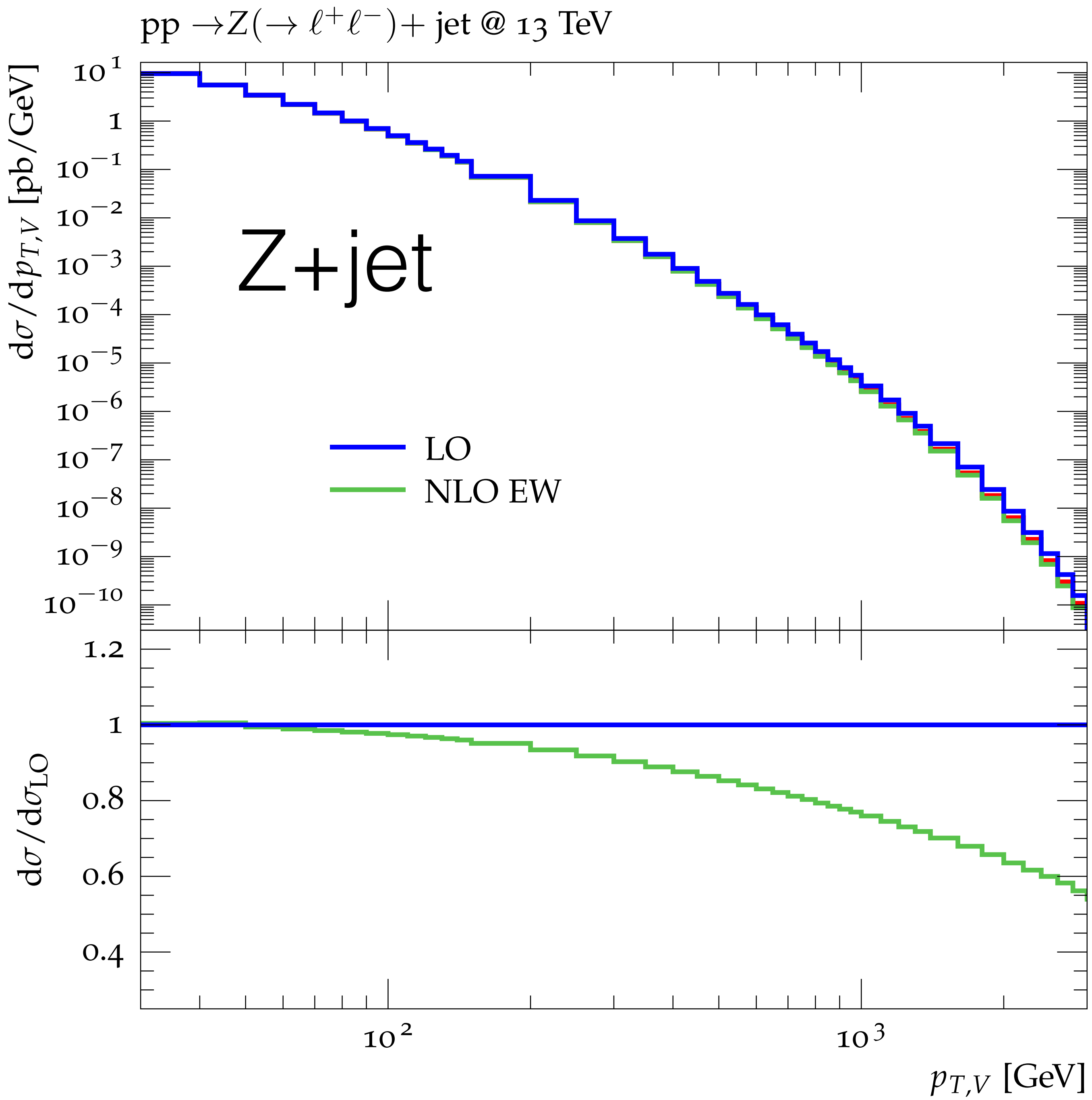


[FC, Melnikov, Schulze]

13 TeV data are coming in…

Precision in the tails: EW and all that

DM searches: jets + MET. *Need good control on V→νν in the TeV regime*



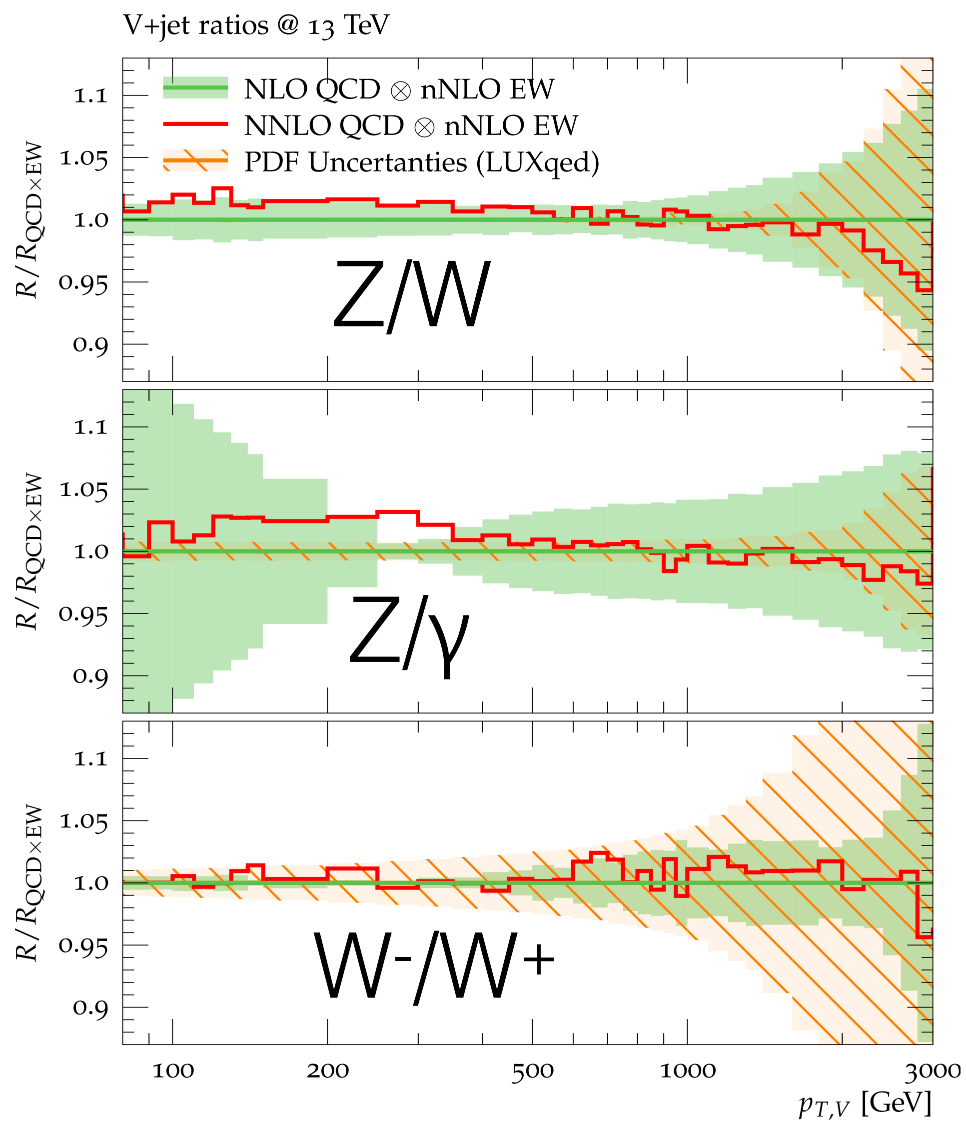
New player in the TeV regime:
EW logs

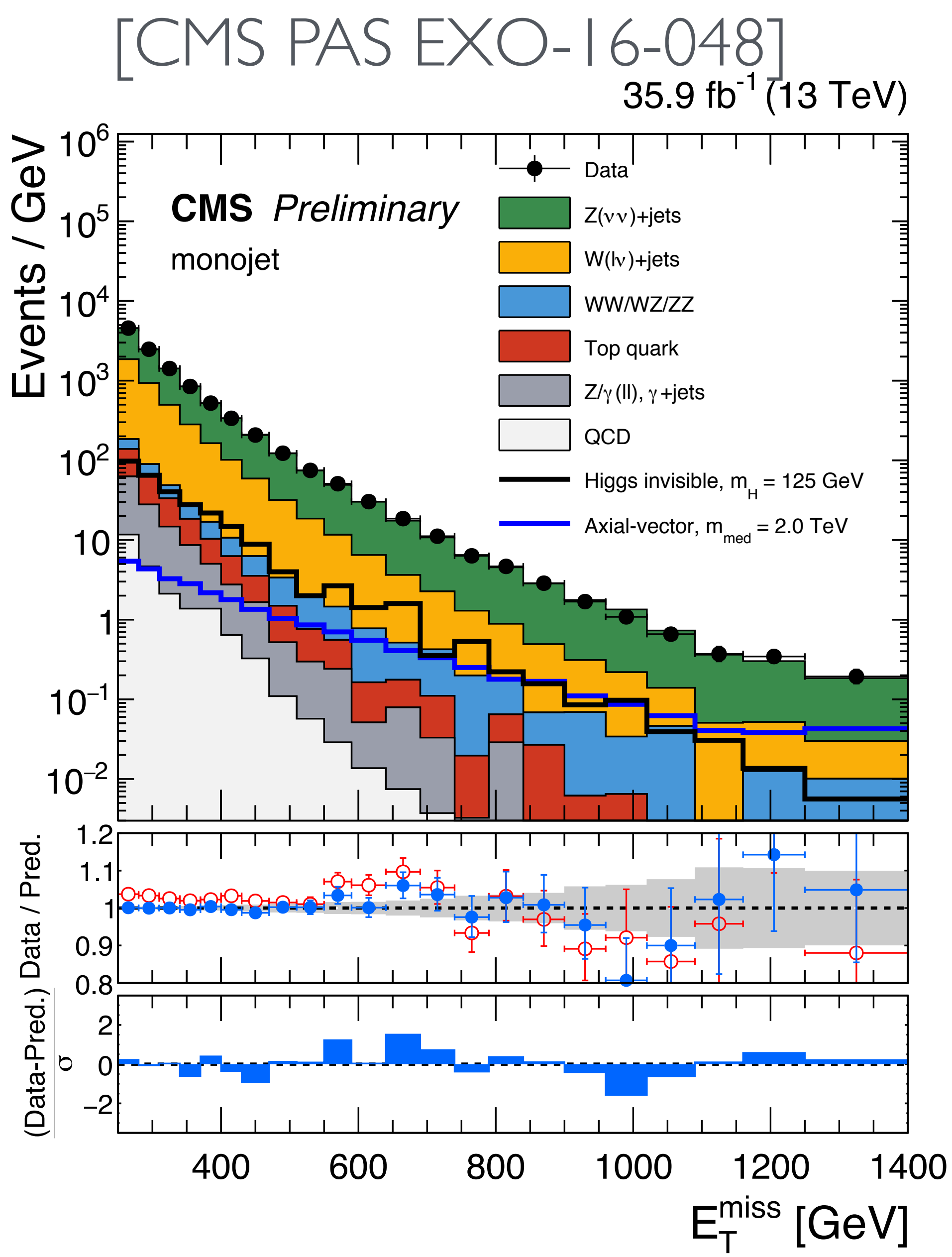
- $\alpha_s^2 \sim \alpha$
- Physical bosons are not EW singlet → large Sudakov (double) logs from real/virtual (non) cancellation
- Large effects at high scales, must properly taken into account

[plot from Boughezal et al (2017)]

$$d\sigma \sim 1 + \alpha \ln^2 \frac{Q^2}{M_V^2} + \alpha^2 \ln^4 \frac{Q^2}{M_V^2} + \ldots$$

Precision in the tails: EW and all that



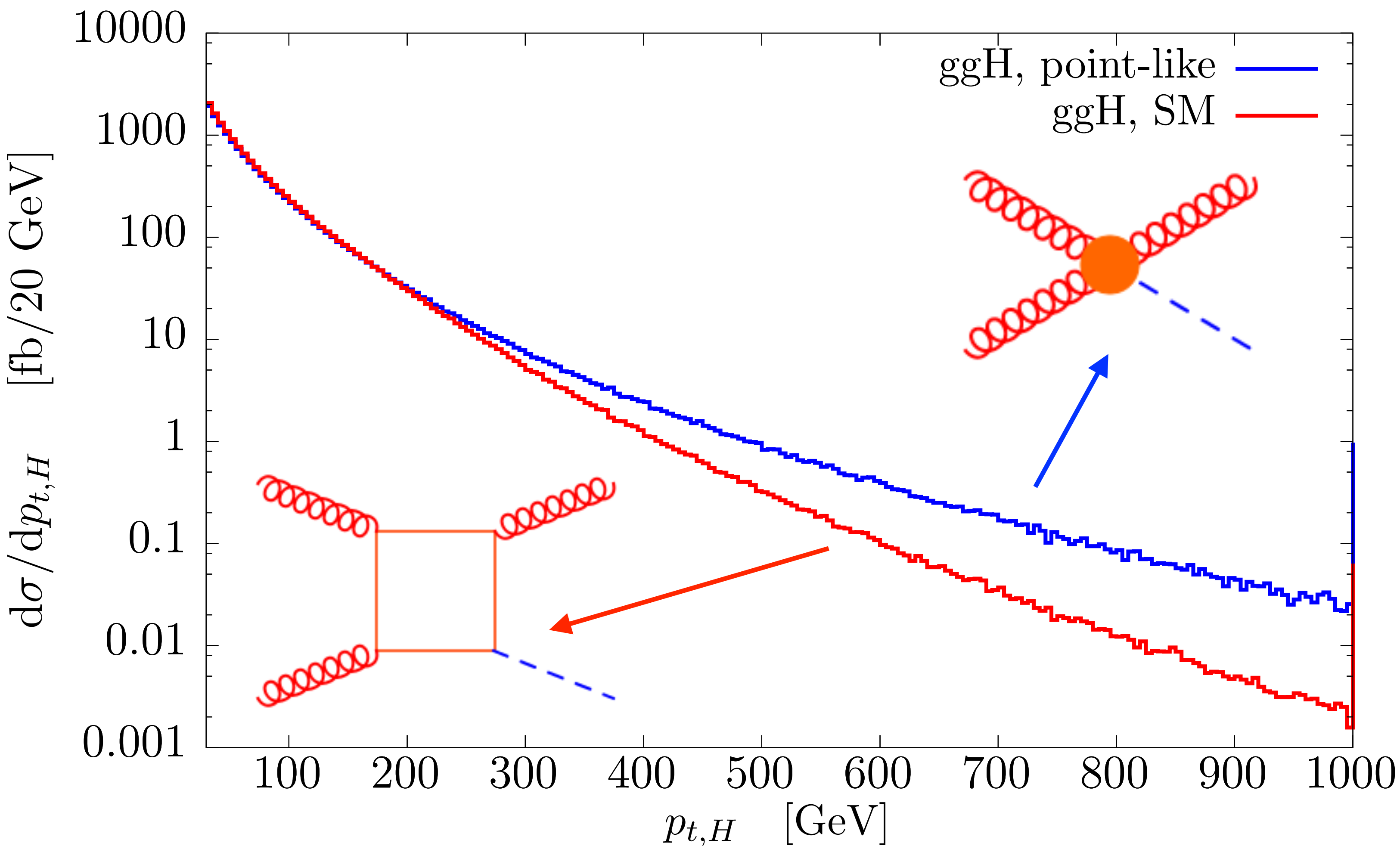


[J. Lindert, talk at "LHC and the Standard Model" CERN TH Institute]

few - 10% precision for DM searches bckgd achieved

further investigation: how to combine EW and QCD?

A (so far) less successful story: the Higgs tail

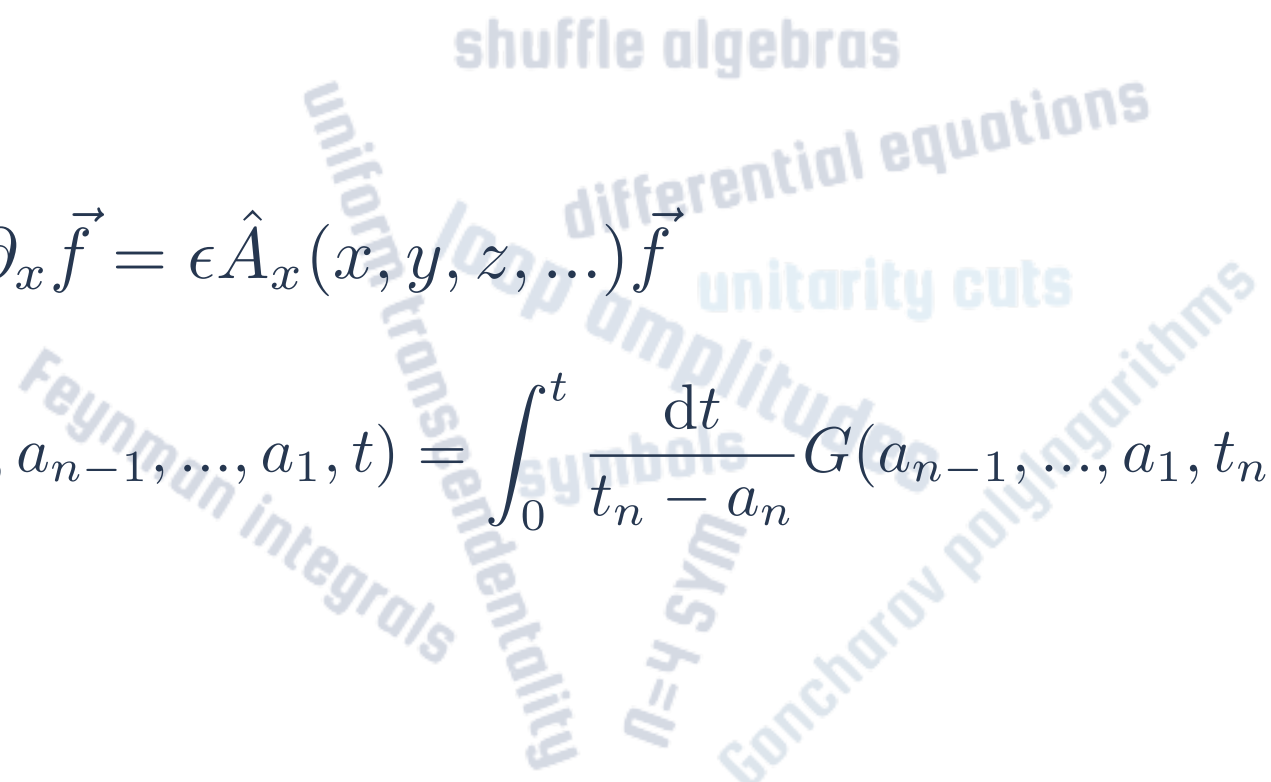


σ_{gg} ($p_t > p_{t,cut}$) =	1 fb	1 ab
bb	$p_{t,cut}$ ~ 600 GeV	$p_{t,cut}$ ~ 1.5 TeV
ττ	~ 400 GeV	~ 1.2 TeV
2l2ν	~ 300 GeV	~ 1 TeV
γγ	~ 200 GeV	~ 750 GeV
4l	~ 50 GeV	~ 450 GeV

- The LHC is starting to explore the boosted Higgs regime
- Crucial information on coupling structure, non accessible at low p_t
- TH input: ~20% would be fine
- Despite a lot of progress, [*see e.g. Bonciani et al.*] still only LO predictions there. Large p_T fully resolves the top loop, cannot neglect internal dynamics
- Similar for off-shell tail

An interlude: loop amplitudes in real life

- Amplitude COMPLEXITY GROWS VERY FAST with the number of scales: invariants (~# legs) and particle masses
- Despite a lot of recent progress, still pretty limited knowledge. State of the art:
  - Analytically: 2 -> 2, external masses (pp->VV*) [FC, Henn, Melnikov, Smirnov, Smirnov (2014-15); Gehrmann, Manteuffel, Tancredi (2014-15)]
  - Numerically: 2->2, internal/external masses (pp-> tt, pp->HH) [Czakon; Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke (2016)]



$$\partial_x \vec{f} = \epsilon \hat{A}_x(x, y, z, \ldots)\vec{f}$$

$$G(a_n, a_{n-1}, \ldots, a_1, t) = \int_0^t \frac{\mathrm{d}t}{t_n - a_n} G(a_{n-1}, \ldots, a_1, t_n)$$

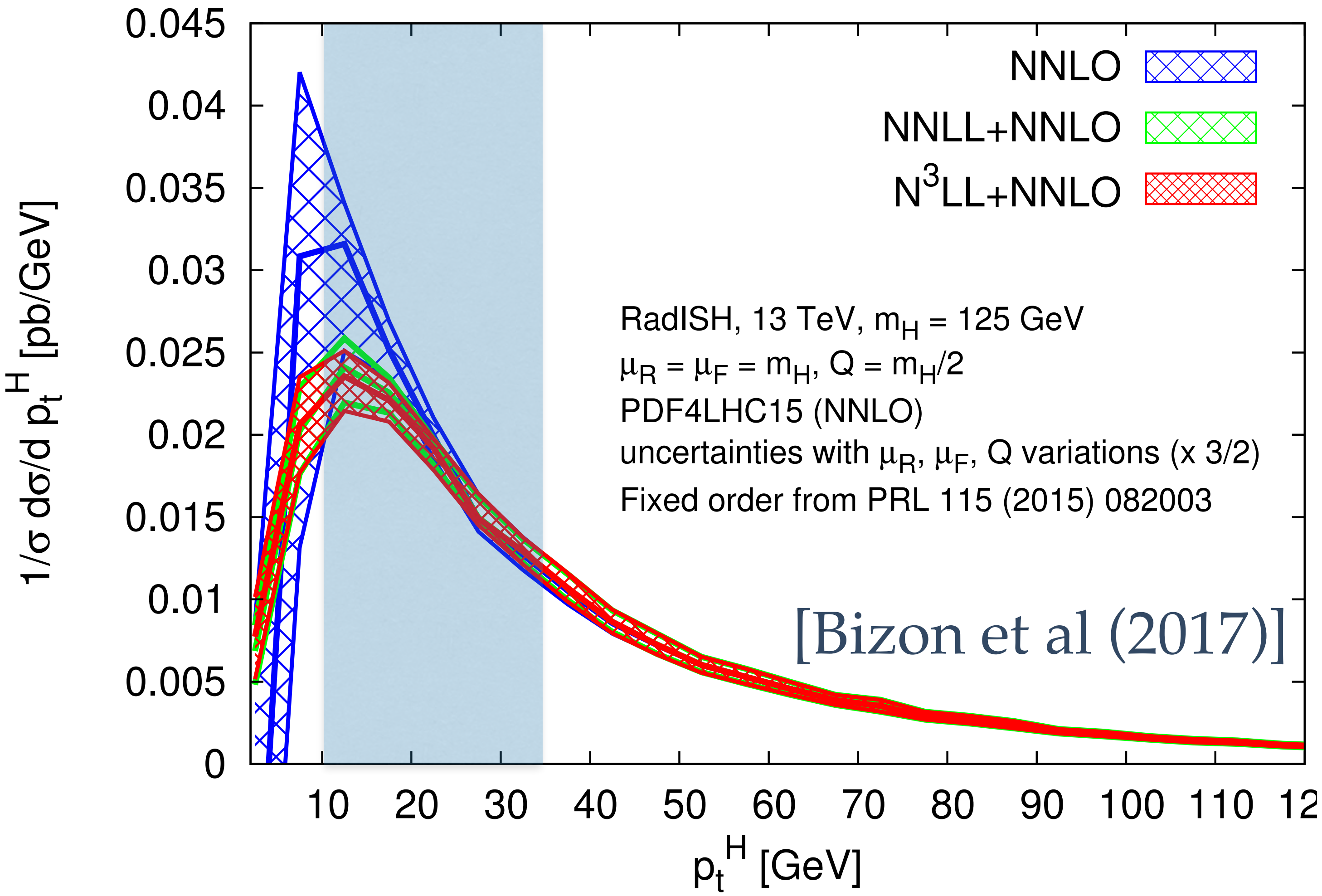
- Important steps towards 2->3 and structure of massive amplitudes [Badger et al., Bonciani et al., Papadopoulos et al., Gehrmann et al., Melnikov et al…]
- *AN INTERESTING OPEN FIELD, CURRENTLY (ONE OF THE) BOTTLENECKS FOR FURTHER PROGRESS*

When life is tricky: beyond f.o. computations

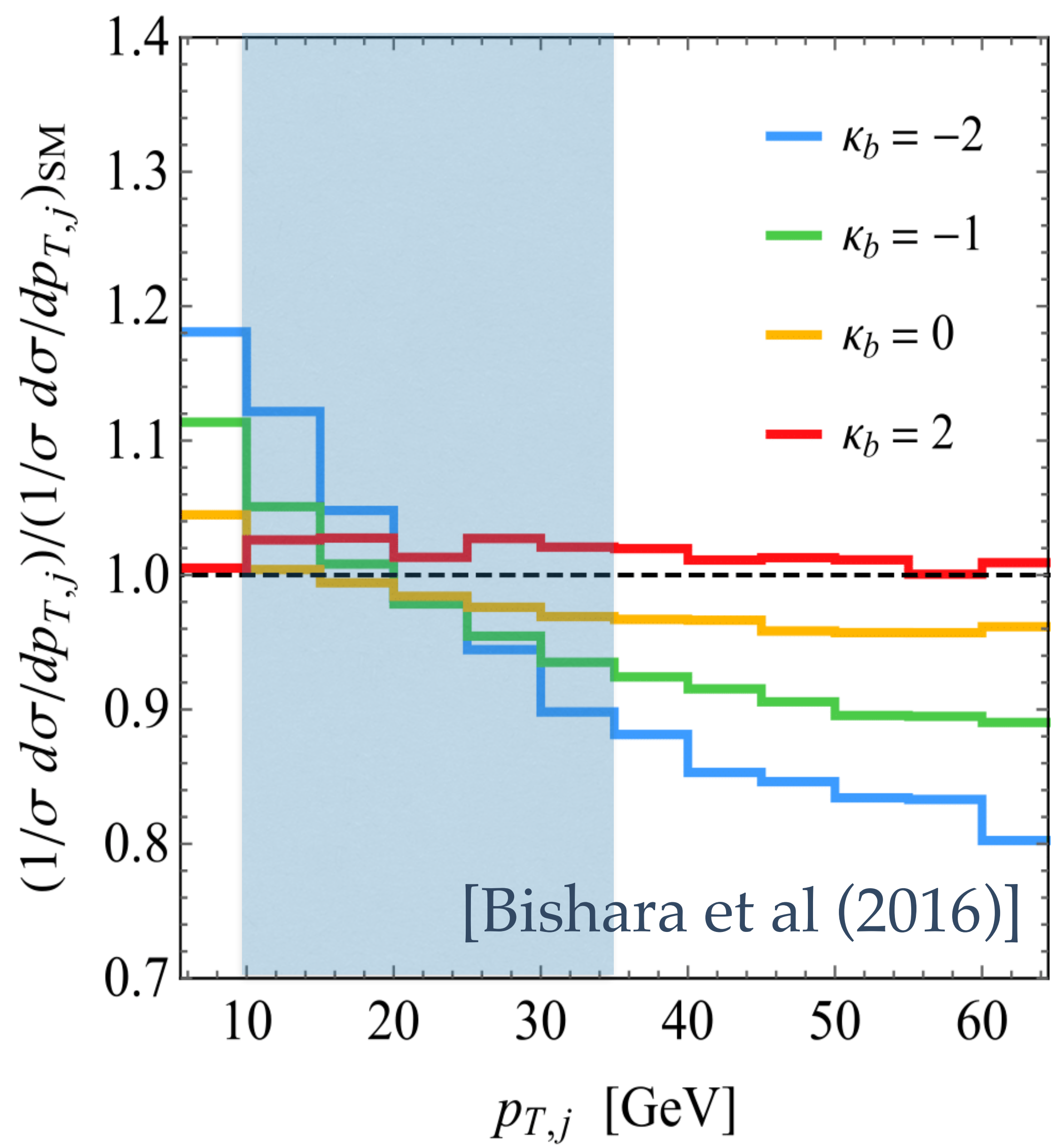
- In many important cases, the requirement of ``high-Q clean observable'' cannot be met
  - need harsh experimental cut to remove backgrounds (jet vetoes…) / collider reach is limited
  - harsh (more or less voluntary) restriction on QCD activity introduces large logarithmic corrections, that spoil the convergence of the perturbative series
- To deal with this issue, one should understand the dynamics of many parton emission. The leading contribution in these regions come from soft/collinear emission, that has a universal ~ process independent structure → *see H.X. Zhu's talk*
- Apart from curing the problem above, understanding of multi-particle dynamics in the soft/collinear limit can help understanding the interface of perturbative / non perturbative physics

Taming logs: the low-p_t Higgs spectrum

$$\alpha_s \ln^2 \frac{p_{t,H}}{M_H} \sim 0.5, \qquad p_t \sim 15 \text{ GeV}$$



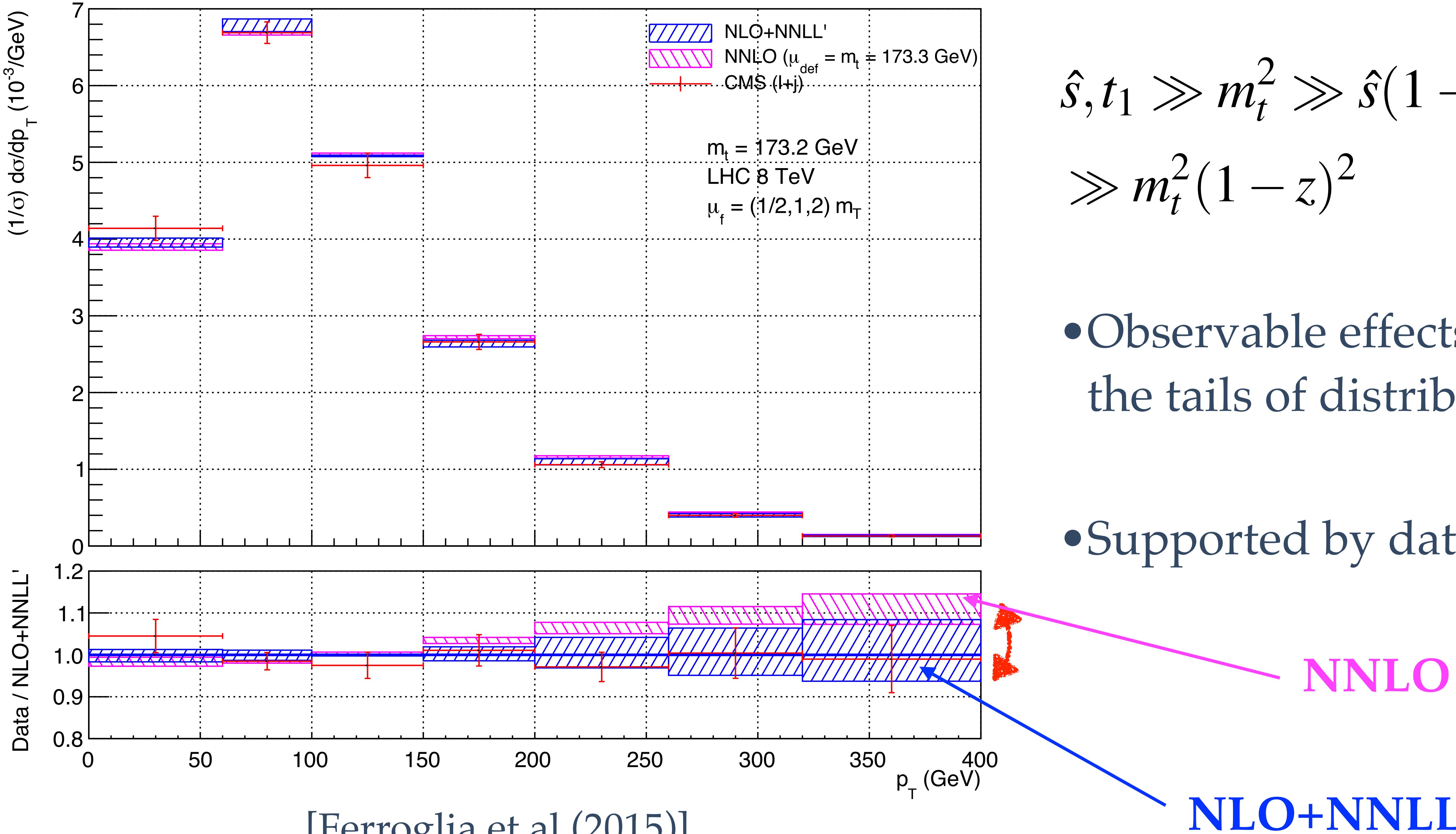
lowish p_t spectrum sensitive to non standard light Yukawa modifications



Good understanding of the transition between (recently computed) NLO and resummation would be beneficial

Taming logs: boosted tops

Because of finite energy / drop of PDFs, in the boosted regime extra radiation often forced to be soft



[Ferroglia et al (2015)]

$$\hat{s}, t_1 \gg m_t^2 \gg \hat{s}(1-z)^2$$
$$\gg m_t^2(1-z)^2$$

- Observable effects in the tails of distributions
- Supported by data

Learning from logs: jet dynamics

A better understanding of the soft/collinear structure of QCD can give interesting information on underlying dynamics. Especially true for jets

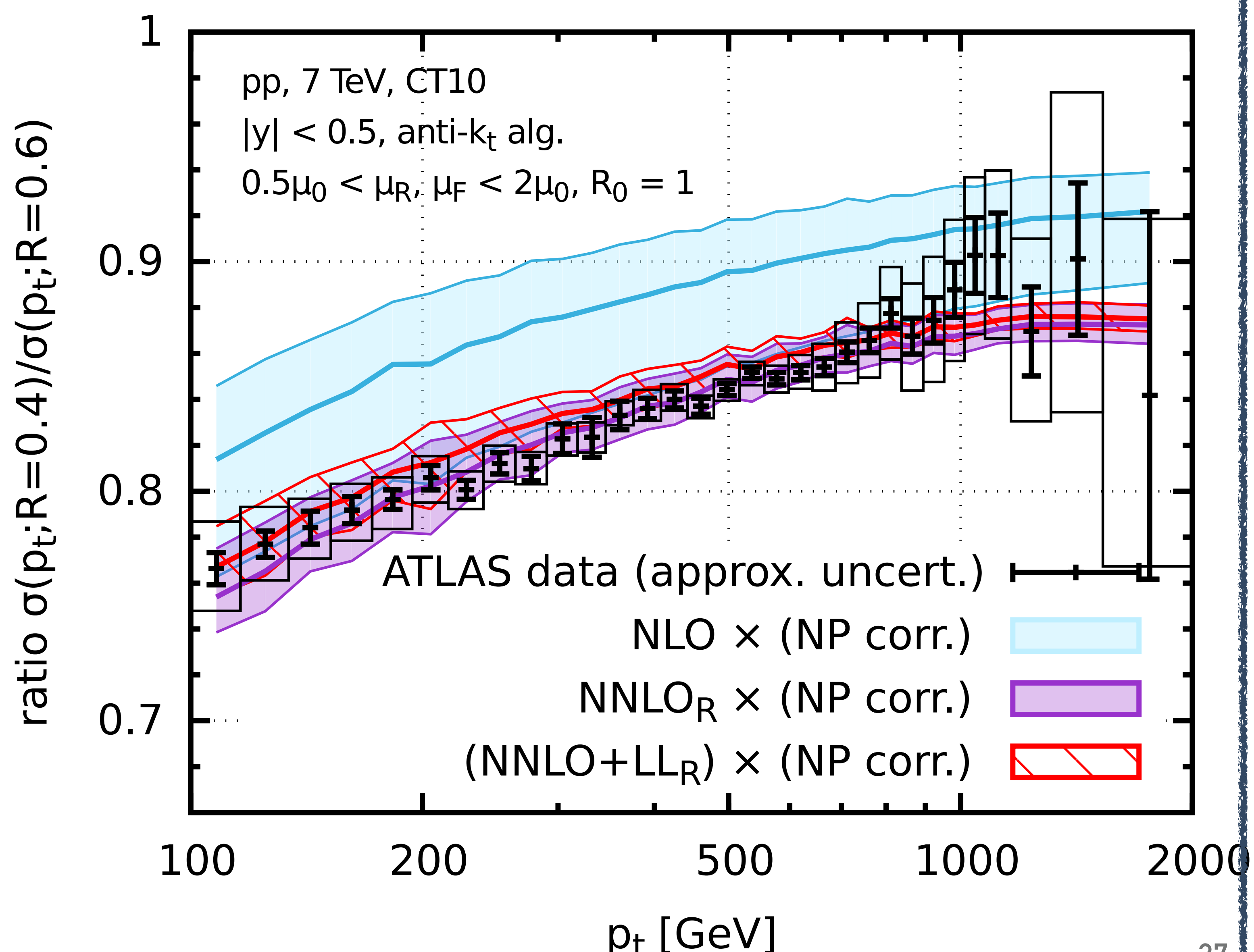
3 effects:

- perturbative (~ ln R)
- hadronisation (~ 1/R)
- MPI/UE (~ R^2)

To disentangle them, need ≥3 R values:

- 0.6–0.7: large MPI/UE
- 0.4: non-pert. effects cancel?
- 0.2–0.3: large hadronisation

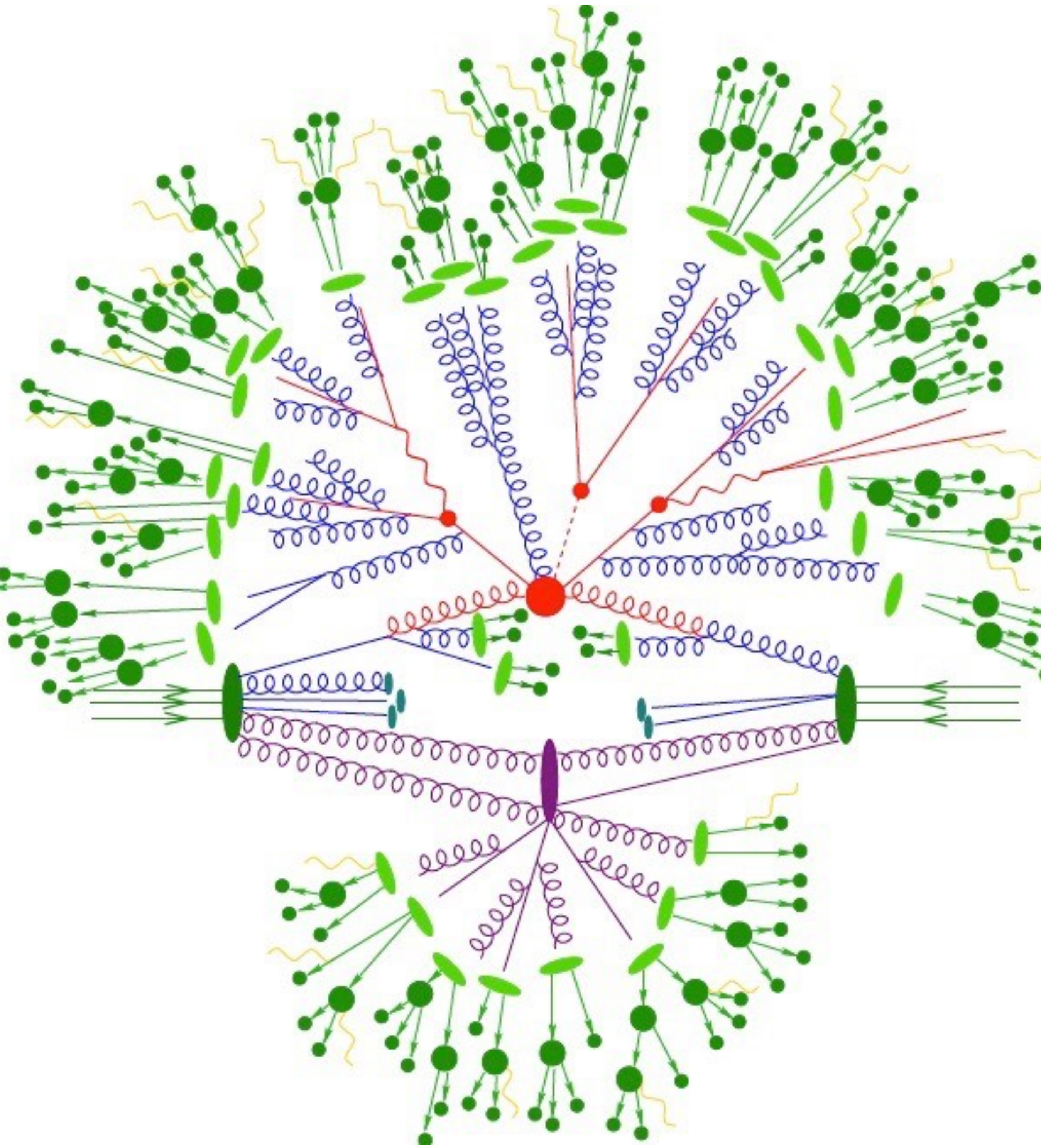
ratio of inclusive jet spectra at R=0.4 and 0.6



[*G.P. Salam, "Future challenges for perturbative QCD" 2016*]

other examples: new observables, jet substructure…

Connecting all of this with the real world: PS



one of the tricky parts: how to combine all this with state-of-the-art high Q predictions/resummations

PARTON SHOWER EVOLUTION

- Must degrade high-Q partons into mesons/hadrons…
- The first step: all order-emission of soft/collinear partons. Less accurate than dedicated resummation, but (much) more generic
- The second step: hadronization [*here we lost `first principle' approach*]
- CAN GENERATE FULL EVENTS → HADRONIZATION → DETECTOR SIMULATIONS
- *Some of the (many) bonuses added: multi-particle dynamics, merging…*

→ *see S. Alioli's talk*

Example: the mass of a quark…

At the LHC, top mass reconstructed from template fit to observables. Experimental reach ~ 500 MeV

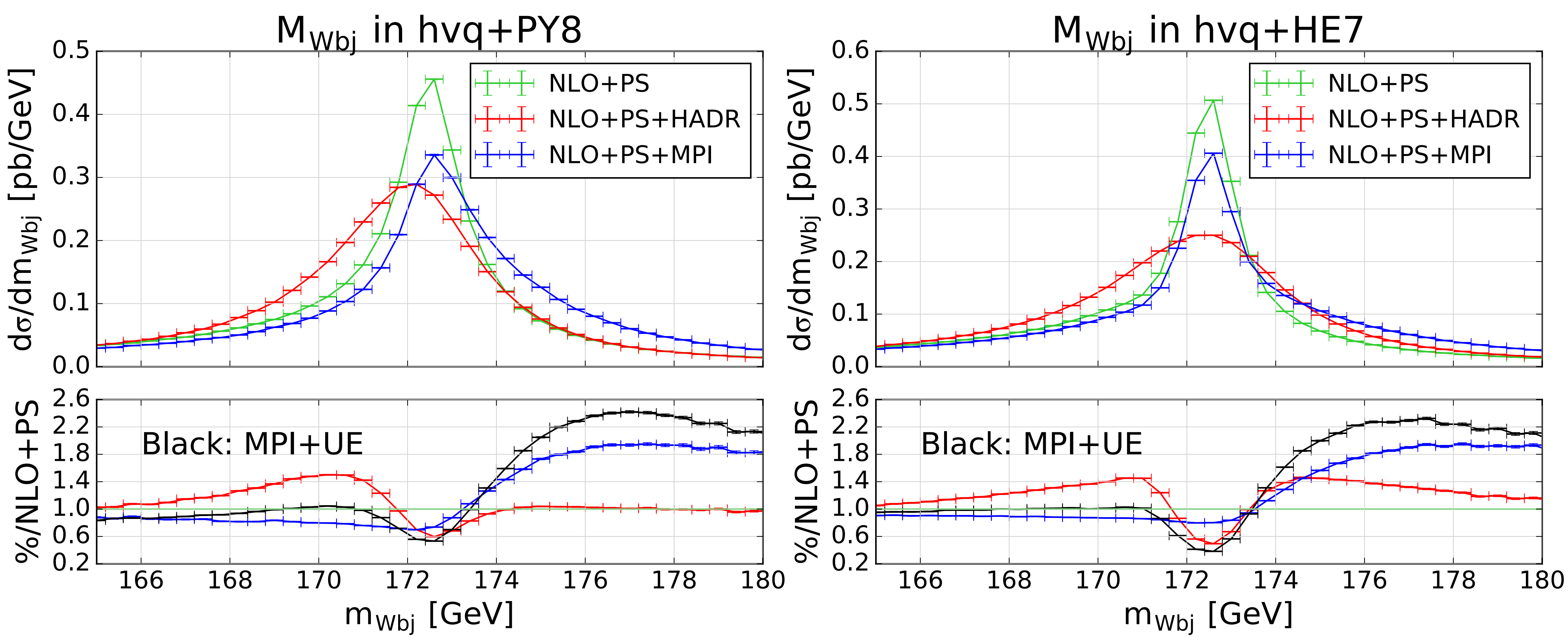
Quarks don't exist as asymptotic state. As such, the definition of their mass is subtle. Normal `pole of the propagator' definitions suffer from inherent theoretical ambiguities. Nevertheless, this ambiguity is estimated to be (much) less than 500 MeV

Still, tops are created in an hadronic environment. At this level of precision, our understanding of it is hampered by our lack of understanding of it from first principles → phenomenological models for hadronization, underlying event, MPI…

PS Monte Carlos are an ideal playground to test the robustness of top quark mass restrictions under known perturbative and (modeled) non perturbative effects

Example: the mass of a quark…

Hadronization and MPI



[P. Nason, talk at the TOP Working group (2017)]

- Hadronization: wider peak, raised tail below peak (Py8).
- MPI: raised tail above peak.

Some preliminary results…

		Extracted m_{Wbj} peak [GeV]			
		Full		Parton level (no MPI)	
		PY8	HE7	PY8	HE7
No smearing	$b\bar{b}4l$	172.828	172.935	172.527	172.497
	hvq	172.780	173.039	172.488	172.497
15 GeV smearing	$b\bar{b}4l$	173.052	172.355	171.803	171.102
	hvq	172.613	172.375	171.385	171.279

Conclusions

- The LHC is forcing us to push further the boundaries of our understanding of SM predictions at hadron colliders
- It is essential to spot small deviations: control signals / backgrounds
- While the main motivation is for searches/Higgs studies, 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 [but we'll have a week to discuss…]*

- 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*
- Right now: more in-depths analysis of some of the points I mentioned

Thank you very much
for your attention