Recent progress in higher-order perturbative calculations

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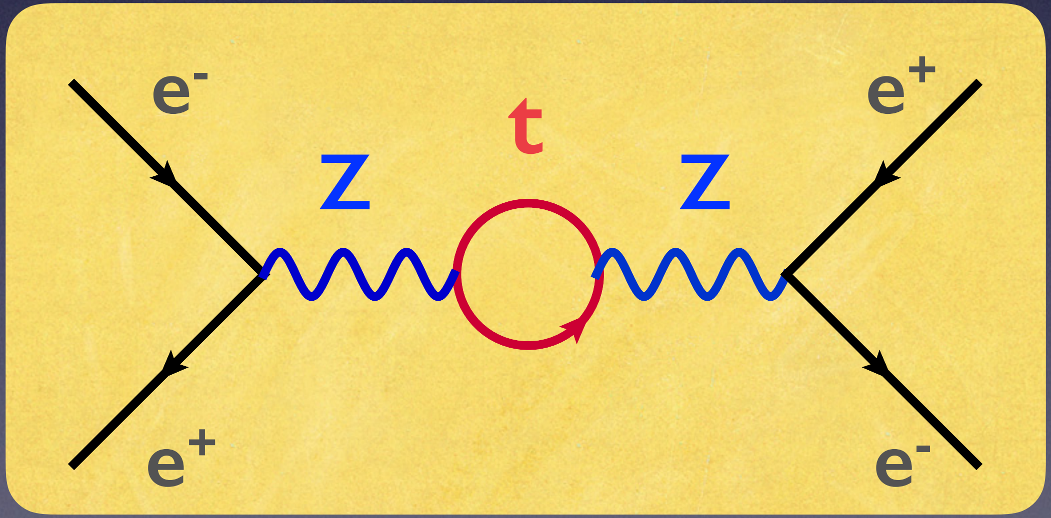
Why care about higher-orders/ precision?

Lep and the top quark

Example: precision calculations of e^+e^- collisions, together with the most precise measurements at LEP allowed us to estimate the top mass precisely before it was directly discovered at the Tevatron



- Mass of the top quark from ***indirect*** determinations at LEPI and SLC in 1993: $m_{top} = (177 \pm 10)$ GeV
- First ***direct*** production at the Tevatron in 1994: $m_{top} = (174 \pm 16)$ GeV

LHC as a precision machine

e^+e^- collider	proton-proton collider
elementary	composite
weakly interacting	strongly interacting
light	heavy
clean environment	reach higher energies
precision machines	**discovery machines**

Change of perspective with the Tevatron and **revolution with the LHC: hadron collider as a precision machine**

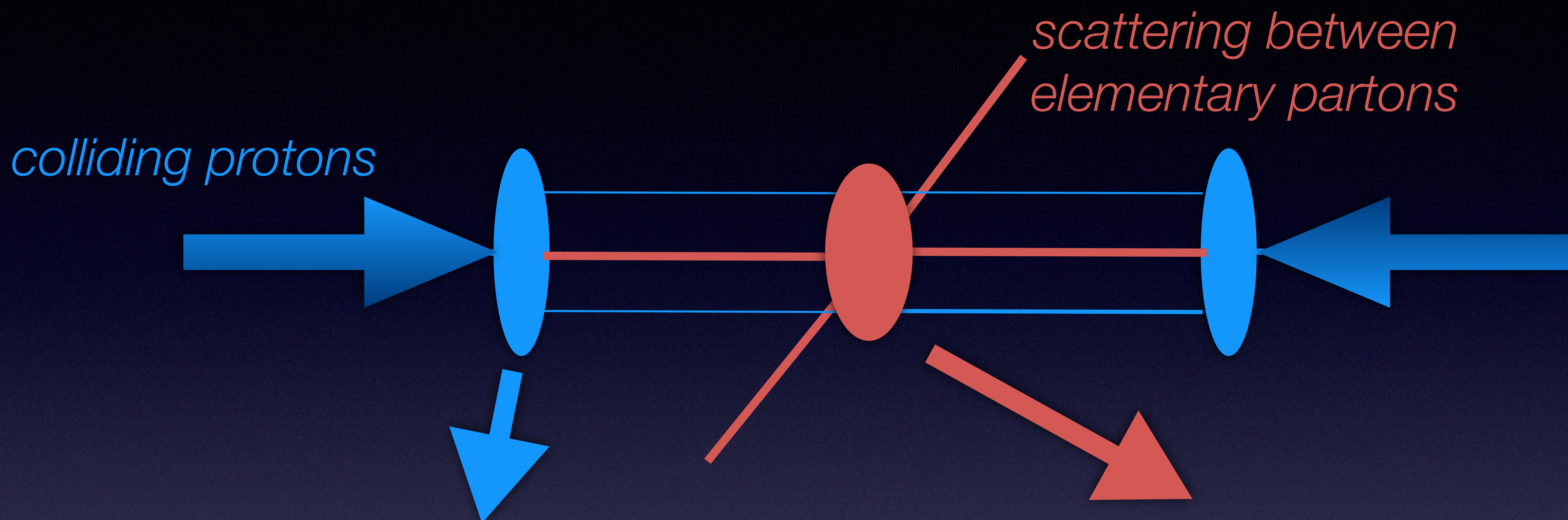
[e.g. W-boson mass measured with 20 MeV precision (0.02%), Higgs mass measured to 250 MeV (0.2%), Z-boson kinematic distributions to below a percent, …]

Precision: key to data

- Thanks to accelerator, experiments and computers, **precision measurements at the LHC are a reality now**
- This is a game changer which doubles the potential of the LHC physics programme
  - when new particles are found directly precision measurements of properties, which are needed to understand the new underlying theory (this is happening now with the Higgs sector of the SM)
  - but also precision tests bring in new possibilities, complementary to direct searches (like for the top quark)

Precise theory: key to exploit data

Precision via perturbative expansions



Parton distribution functions (PDFs): extracted from data at one scale, evolution is perturbative

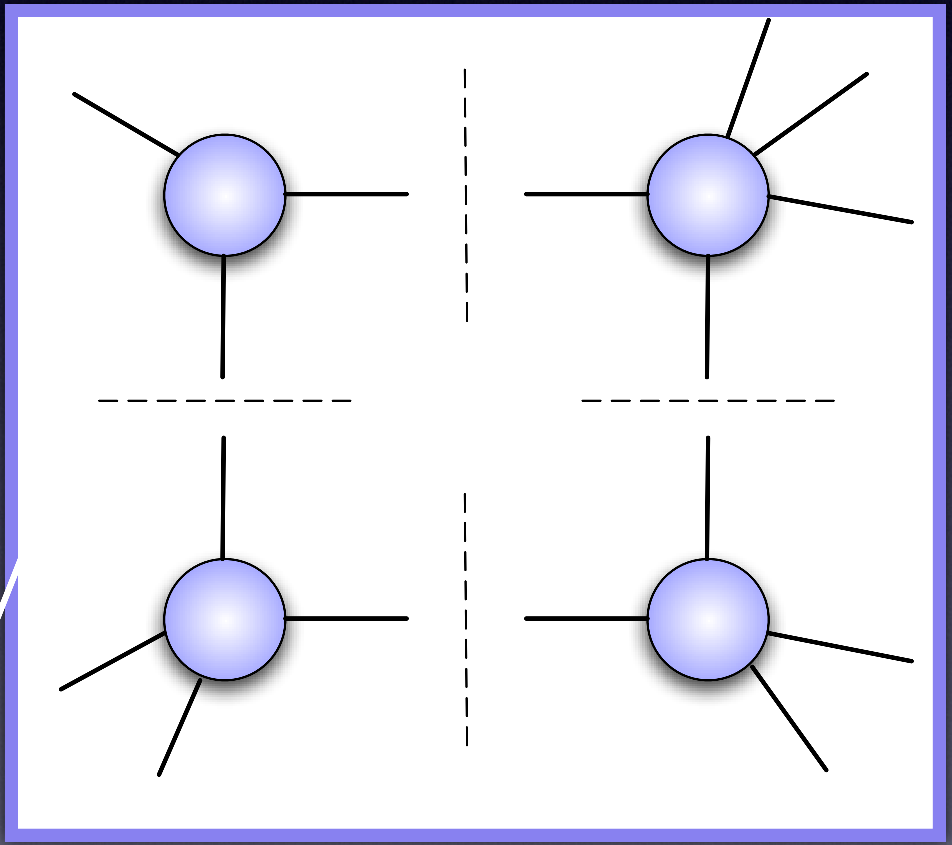
Perturbative cross section: Expansion in the coupling constant (LO, NLO, NNLO ...)

$$\frac{d\sigma_{\mathrm{pp}\to\mathrm{hadrons}}}{d\mathrm{O}} = \sum_{i,j=q,g} \int dx_1 dx_2 \boxed{f_i(x_1,\mu_F) f_j(x_2,\mu_F)} \times \boxed{\frac{d\sigma_{\mathrm{pp}\to\mathrm{partons}}}{d\mathrm{O}}} + \mathcal{O}\left(\frac{\Lambda^n_{\mathrm{QCD}}}{Q^n}\right)$$

The NLO revolution

For a long time, the NLO calculation for each process required a separate non-trivial, manual calculation. Suddenly, **thanks to theoretical conceptual breakthrough ideas**

- input from supersymmetry/string theory
- connection between NLO amplitudes and LO ones
- sophisticated algebraic methods / OPP
- generalised unitarity



the problem of computing NLO QCD corrections is now solved

Automated NLO

An example: single Higgs production processes

Alwall et al ’14

Process		Syntax	Cross section (pb)					
Single Higgs production			LO 13 TeV			NLO 13 TeV		
g.1	$pp \to H$ (HEFT)	`p p > h`	$1.593 \pm 0.003 \cdot 10^{1}$	$^{+34.8\%}_{-26.0\%}$	$^{+1.2\%}_{-1.7\%}$	$3.261 \pm 0.010 \cdot 10^{1}$	$^{+20.2\%}_{-17.9\%}$	$^{+1.1\%}_{-1.6\%}$
g.2	$pp \to Hj$ (HEFT)	`p p > h j`	$8.367 \pm 0.003 \cdot 10^{0}$	$^{+39.4\%}_{-26.4\%}$	$^{+1.2\%}_{-1.4\%}$	$1.422 \pm 0.006 \cdot 10^{1}$	$^{+18.5\%}_{-16.6\%}$	$^{+1.1\%}_{-1.4\%}$
g.3	$pp \to Hjj$ (HEFT)	`p p > h j j`	$3.020 \pm 0.002 \cdot 10^{0}$	$^{+59.1\%}_{-34.7\%}$	$^{+1.4\%}_{-1.7\%}$	$5.124 \pm 0.020 \cdot 10^{0}$	$^{+20.7\%}_{-21.0\%}$	$^{+1.3\%}_{-1.5\%}$
g.4	$pp \to Hjj$ (VBF)	`p p > h j j $$ w+ w- z`	$1.987 \pm 0.002 \cdot 10^{0}$	$^{+1.7\%}_{-2.0\%}$	$^{+1.9\%}_{-1.4\%}$	$1.900 \pm 0.006 \cdot 10^{0}$	$^{+0.8\%}_{-0.9\%}$	$^{+2.0\%}_{-1.5\%}$
g.5	$pp \to Hjjj$ (VBF)	`p p > h j j j $$ w+ w- z`	$2.824 \pm 0.005 \cdot 10^{-1}$	$^{+15.7\%}_{-12.7\%}$	$^{+1.5\%}_{-1.0\%}$	$3.085 \pm 0.010 \cdot 10^{-1}$	$^{+2.0\%}_{-3.0\%}$	$^{+1.5\%}_{-1.1\%}$
g.6	$pp \to HW^{\pm}$	`p p > h wpm`	$1.195 \pm 0.002 \cdot 10^{0}$	$^{+3.5\%}_{-4.5\%}$	$^{+1.9\%}_{-1.5\%}$	$1.419 \pm 0.005 \cdot 10^{0}$	$^{+2.1\%}_{-2.6\%}$	$^{+1.9\%}_{-1.4\%}$
g.7	$pp \to HW^{\pm}j$	`p p > h wpm j`	$4.018 \pm 0.003 \cdot 10^{-1}$	$^{+10.7\%}_{-9.3\%}$	$^{+1.2\%}_{-0.9\%}$	$4.842 \pm 0.017 \cdot 10^{-1}$	$^{+3.6\%}_{-3.7\%}$	$^{+1.2\%}_{-1.0\%}$
g.8*	$pp \to HW^{\pm}jj$	`p p > h wpm j j`	$1.198 \pm 0.016 \cdot 10^{-1}$	$^{+26.1\%}_{-19.4\%}$	$^{+0.8\%}_{-0.6\%}$	$1.574 \pm 0.014 \cdot 10^{-1}$	$^{+5.0\%}_{-6.5\%}$	$^{+0.9\%}_{-0.6\%}$
g.9	$pp \to HZ$	`p p > h z`	$6.468 \pm 0.008 \cdot 10^{-1}$	$^{+3.5\%}_{-4.5\%}$	$^{+1.9\%}_{-1.4\%}$	$7.674 \pm 0.027 \cdot 10^{-1}$	$^{+2.0\%}_{-2.5\%}$	$^{+1.9\%}_{-1.4\%}$
g.10	$pp \to HZj$	`p p > h z j`	$2.225 \pm 0.001 \cdot 10^{-1}$	$^{+10.6\%}_{-9.2\%}$	$^{+1.1\%}_{-0.8\%}$	$2.667 \pm 0.010 \cdot 10^{-1}$	$^{+3.5\%}_{-3.6\%}$	$^{+1.1\%}_{-0.9\%}$
g.11*	$pp \to HZjj$	`p p > h z j j`	$7.262 \pm 0.012 \cdot 10^{-2}$	$^{+26.2\%}_{-19.4\%}$	$^{+0.7\%}_{-0.6\%}$	$8.753 \pm 0.037 \cdot 10^{-2}$	$^{+4.8\%}_{-6.3\%}$	$^{+0.7\%}_{-0.6\%}$
g.12*	$pp \to HW^{+}W^{-}$ (4f)	`p p > h w+ w-`	$8.325 \pm 0.139 \cdot 10^{-3}$	$^{+0.0\%}_{-0.3\%}$	$^{+2.0\%}_{-1.6\%}$	$1.065 \pm 0.003 \cdot 10^{-2}$	$^{+2.5\%}_{-1.9\%}$	$^{+2.0\%}_{-1.5\%}$
g.13*	$pp \to HW^{\pm}\gamma$	`p p > h wpm a`	$2.518 \pm 0.006 \cdot 10^{-3}$	$^{+0.7\%}_{-1.4\%}$	$^{+1.9\%}_{-1.5\%}$	$3.309 \pm 0.011 \cdot 10^{-3}$	$^{+2.7\%}_{-2.0\%}$	$^{+1.7\%}_{-1.4\%}$
g.14*	$pp \to HZW^{\pm}$	`p p > h z wpm`	$3.763 \pm 0.007 \cdot 10^{-3}$	$^{+1.1\%}_{-1.5\%}$	$^{+2.0\%}_{-1.6\%}$	$5.292 \pm 0.015 \cdot 10^{-3}$	$^{+3.9\%}_{-3.1\%}$	$^{+1.8\%}_{-1.4\%}$
g.15*	$pp \to HZZ$	`p p > h z z`	$2.093 \pm 0.003 \cdot 10^{-3}$	$^{+0.1\%}_{-0.6\%}$	$^{+1.9\%}_{-1.5\%}$	$2.538 \pm 0.007 \cdot 10^{-3}$	$^{+1.9\%}_{-1.4\%}$	$^{+2.0\%}_{-1.5\%}$
g.16	$pp \to Ht\bar{t}$	`p p > h t t~`	$3.579 \pm 0.003 \cdot 10^{-1}$	$^{+30.0\%}_{-21.5\%}$	$^{+1.7\%}_{-2.0\%}$	$4.608 \pm 0.016 \cdot 10^{-1}$	$^{+5.7\%}_{-9.0\%}$	$^{+2.0\%}_{-2.3\%}$
g.17	$pp \to Htj$	`p p > h tt j`	$4.994 \pm 0.005 \cdot 10^{-2}$	$^{+2.4\%}_{-4.2\%}$	$^{+1.2\%}_{-1.3\%}$	$6.328 \pm 0.022 \cdot 10^{-2}$	$^{+2.9\%}_{-1.8\%}$	$^{+1.5\%}_{-1.6\%}$
g.18	$pp \to Hb\bar{b}$ (4f)	`p p > h b b~`	$4.983 \pm 0.002 \cdot 10^{-1}$	$^{+28.1\%}_{-21.0\%}$	$^{+1.5\%}_{-1.8\%}$	$6.085 \pm 0.026 \cdot 10^{-1}$	$^{+7.3\%}_{-9.6\%}$	$^{+1.6\%}_{-2.0\%}$
g.19	$pp \to Ht\bar{t}j$	`p p > h t t~ j`	$2.674 \pm 0.041 \cdot 10^{-1}$	$^{+45.6\%}_{-29.2\%}$	$^{+2.6\%}_{-2.9\%}$	$3.244 \pm 0.025 \cdot 10^{-1}$	$^{+3.5\%}_{-8.7\%}$	$^{+2.5\%}_{-2.9\%}$
g.20*	$pp \to Hb\bar{b}j$ (4f)	`p p > h b b~ j`	$7.367 \pm 0.002 \cdot 10^{-2}$	$^{+45.6\%}_{-29.1\%}$	$^{+1.8\%}_{-2.1\%}$	$9.034 \pm 0.032 \cdot 10^{-2}$	$^{+7.9\%}_{-11.0\%}$	$^{+1.8\%}_{-2.2\%}$

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Similar results available for all SM processes of similar complexity

NLO calculations

Various (public) tools developed: Blackhat+Sherpa, GoSam+Sherpa, Helac-NLO, Madgraph5_aMC@NLO, NJet+Sherpa, OpenLoops+Sherpa, Samurai, Recola ...

- Practical limitation: high-multiplicity processes still difficult because of numerical instabilities, need long run-time on clusters to obtain stable results (edge: 5-6 particles in the final state, depending on the process)
- Today focus on
  - ➡ automation of NLO for BSM signals
  - ➡ loop-induced processes: formally higher-order, but enhanced by gluon PDF
  - ➡ automation of NLO electroweak corrections (necessary to match accuracy of NNLO)

NNLO

NNLO is one of the most active areas in QCD now

After pioneering calculations for Higgs and Drell-Yan more than 15 years ago, recently many $2 \to 2$ processes computed at NNLO

NNLO most important in three different situations

Benchmark processes measured with highest accuracy
- $Z \to ll$
- $W \to l\nu$
- Z + jet
- …

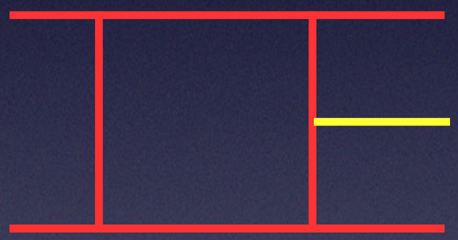
Input to PDF fits + background to Higgs studies
- diboson
- boson + jet
- top-pairs
- dijets, …

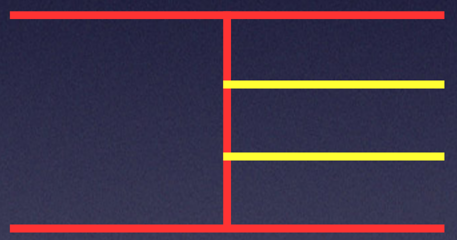
Very large NLO corrections (moderate precision requires NNLO)
- Higgs
- Higgs + jet
- …

Two main difficulties at NNLO

calculation of two-loop amplitudes/ master integrals

methods to cancel (overlapping) divergences before integration





$$\int d\Phi_n 2\mathrm{Re}|\mathcal{M}^{2-loop}\mathcal{M}^{tree}| \qquad \int d\Phi_n d\Phi_1 2Re|\mathcal{M}^{\mathrm{one-loop}}_{n+1}\mathcal{M}^{\mathrm{tree}}_{n+1}| \qquad \int d\Phi_n d\Phi_2|\mathcal{M}^{\mathrm{tree}}|^2_{n+2}$$

$$\int d\Phi_n \left\{ \left(a_4 \frac{1}{\epsilon^4} + a_3 \frac{1}{\epsilon^3} + \ldots + a_0 \right) - \left(a_4 \frac{1}{\epsilon^4} + a_3 \frac{1}{\epsilon^3} + \ldots + b_0) \right) \right\}$$

Cancelation manifest after phase space integration, but to have fully differential results must achieve cancelation before integration

1. Cancelation of divergences

Two strategies

<u>Slicing methods:</u>

partition the phase space with a (small) slicing parameter so that divergences are all below the slicing cut. In the divergent region use an approximate expression, neglecting finite terms, above use the exact (finite) integrand

(need to test independent of slicing parameter)

<u>Subtraction methods:</u>

since IR singularities of amplitudes are knows, add and subtract counterterms so as to make integrals finite. “Easy” at NLO, but complicated at NNLO due to the more intricate structure of (overlapping) singularities

(possible to use local subtraction terms)

Practical realisations

Slicing methods:

- q_T subtraction Catani, Grazzini
- N-jettiness subtraction Boughezal, Focke, Liu, Petriello; Gaunt, Stahlhofen, Tackmann, Walsh

Subtraction methods:

- Sector decomposition Anastasiou, Melnikov, Petriello; Binoth, Heinrich
- Antenna subtraction Kosower; Gehrmann, Gehrmann De Ridder, Glover
- Sector Improved residue subtraction Czakon; Boughezal, Melnikov, Petriello; Czakon Heymes; Caola, Melnikov, Rontsch
- Colourful subtraction Del Duca, Duhr, Kardos, Somogyi, Trocsanyi
- Projection to Born Cacciari, Dreyer, Karlberg, Salam, GZ

Practical realisations

In principle, the problem of cancelation of singularities solved in theory in a generic way
In practise, methods applied to $2 \to 2$ processes. Require long runs on large computer farms (plus, possibly, a way to deal with outliers/spikes)

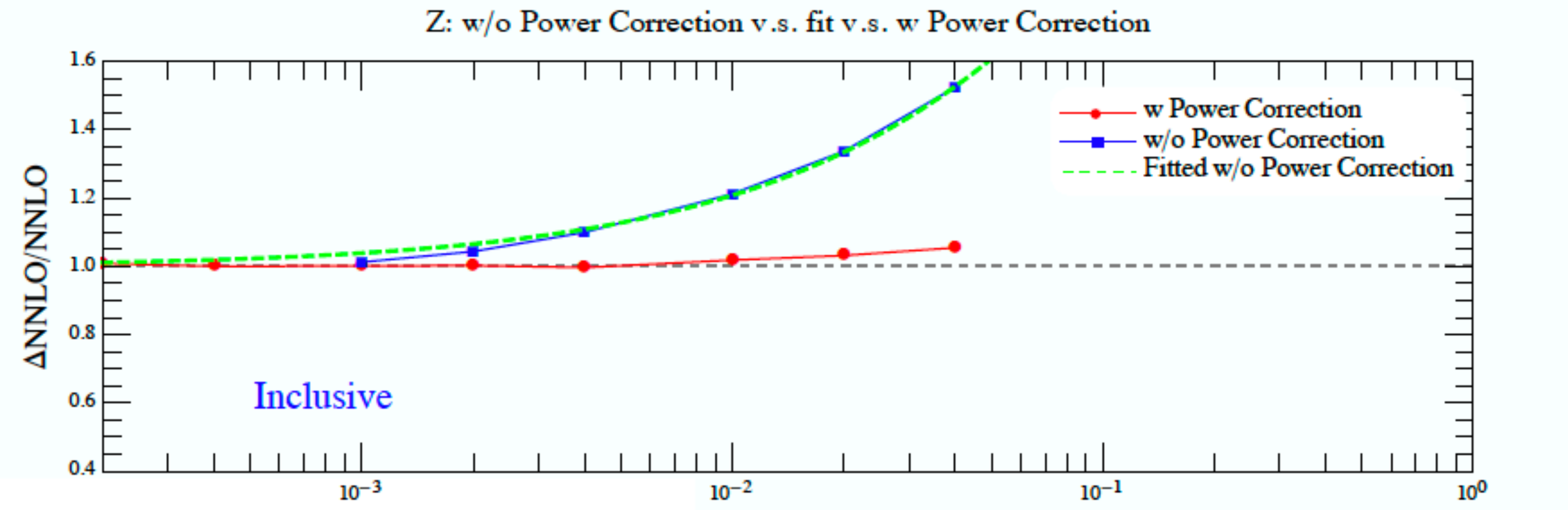
NB: the attitude "Today we have big farms, so why care?" is not acceptable. The phenomenology that one gets out of a calculation scales as inverse power of the computation time

Lots of progress still to come …

Slicing: one improvement

- A spurious dependence on the slicing parameter δ is power suppressed, but logarithmically enhanced
- Hence, a very low value of δ is required
- However small choices of δ require longer and longer runs

Recently: leading power-corrections for colour-singlet production using N-jettiness slicing (allows to relax value of δ)



Boughezal, Petriello, Liu '17
see also Moult, Rothen, Stewart, Tackman, Zhu et al '17

Progress/optimization also in sector-improved subtraction methods exploiting knowledge of singularity structure of the full amplitude

Caola,Melnikov, Rontsch '17

Two-loop amplitudes

- A number of massless amplitudes computed long time ago (e.g. gg $\to\ \gamma\gamma$)

Bern, De Freitas, Dixon 2002

- 2 to 2 amplitudes with internal or external masses are the state-of-the-art today, computed either analytically or numerically (e.g. pp $\to$ VV, pp $\to$ tt, pp $\to$ HH …)

Caola,Henn, Melnikov, Smirvov,Smirnov (2014-2015); Gehrmann, Mantueffel,Tancredi (2014-2015)
Czakon, Birowks, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert,Zirke (2016)

The calculation of the amplitude requires

- a reduction from tensor to scalar (master) integrals
- the calculation of the master integrals

Unlike at one loop, both steps are still not well-understood/ automated (many MI, choice of basis not clear, integrals not all known, no connection to tree level …)

Two-loop integrals

- Rather than brute-force calculation, master integrals in many cases computed solving differential equations

Kotikov 1991; Remiddi 1997; Henn 2013; Papadopoulos 2014

- Method well-understood when only generalised polylogarithmic functions (GPL) are involved

e.g. method pushed to 3-loop 4-point functions in N=4 SYM Henn & Mistlberger 1608.00850
or to 2-loop planar 5-point functions Gehrmann, Henn, Lo Presti 1511.05409 …

- Internal masses complicate the problem considerably: elliptic functions appear
- Steady progress with internal masses, but no complete understanding yet

Tancredi, Remiddi (2016),Adams,Bogner, Weinzierl (2015-2016), Abreu, Britto, Duhr, Gardi (2017)

- One case-study involving elliptic functions: two-loop planar results for Higgs p_t with full mass dependence

Bonciani et al. 1609.06685

Two upcoming challenges

1. Fully mastering conceptual challenges related to internal masses (internal masses necessary for Higgs physics at high p_t)
2. Extension of NNLO to 2 to 3 processes

A few encouraging results for going to higher multiplicity from generalised unitarity methods

- 5/6 all-plus gluon amplitudes computed analytically at two loops

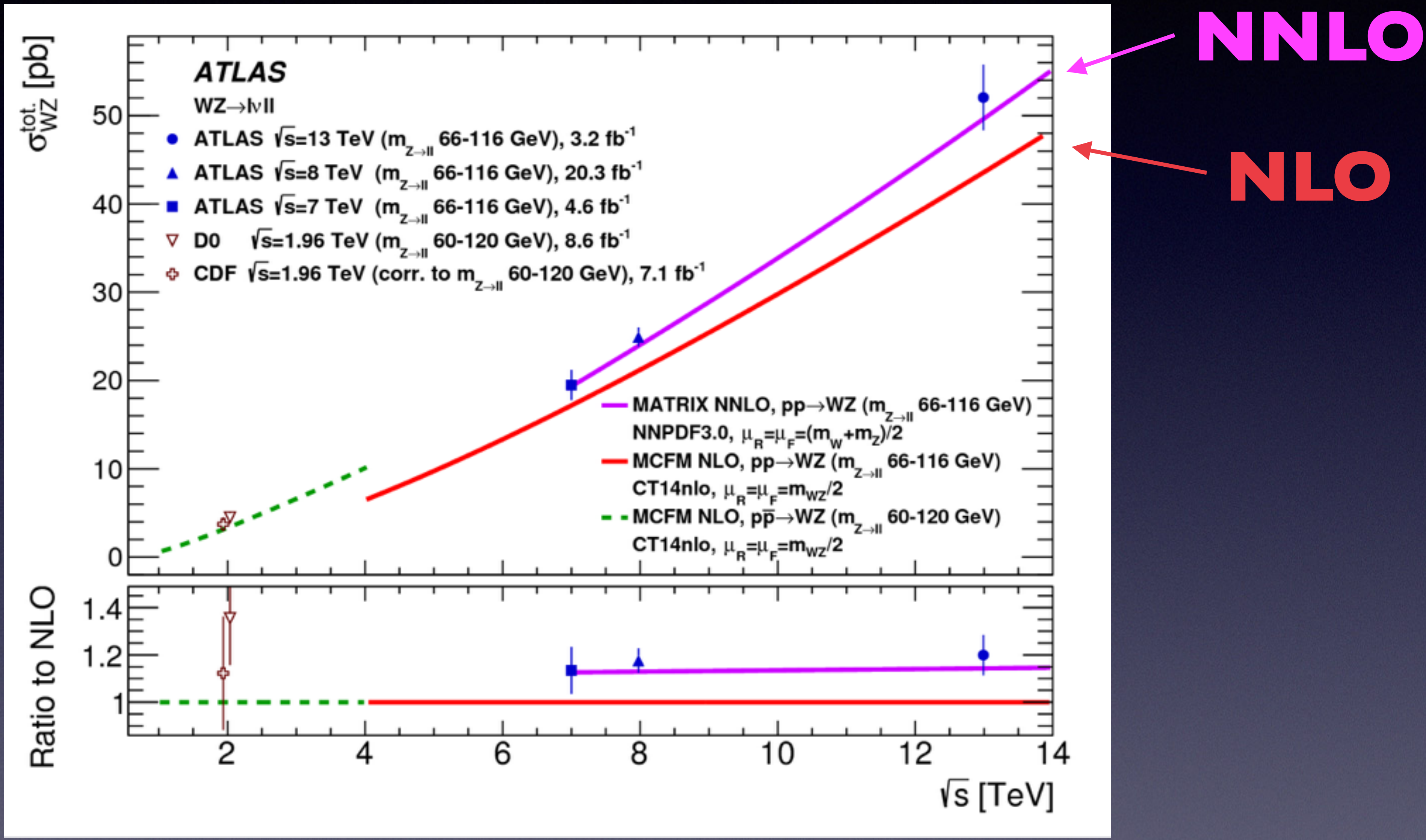
Badger, Frellesvig, Zhang (2013); Badger, Modull,Ochiruv, O'Connel (2015); Badger, Scabinger (2015); Dunbar, Perkins (2016)

- numerical unitarity at two-loops: full numerical results of pp → 2j

Abreu, Febres-Cordero, Ita, Jaquier, Page,Zeng (2017)

Is NNLO really needed?

NNLO vs data



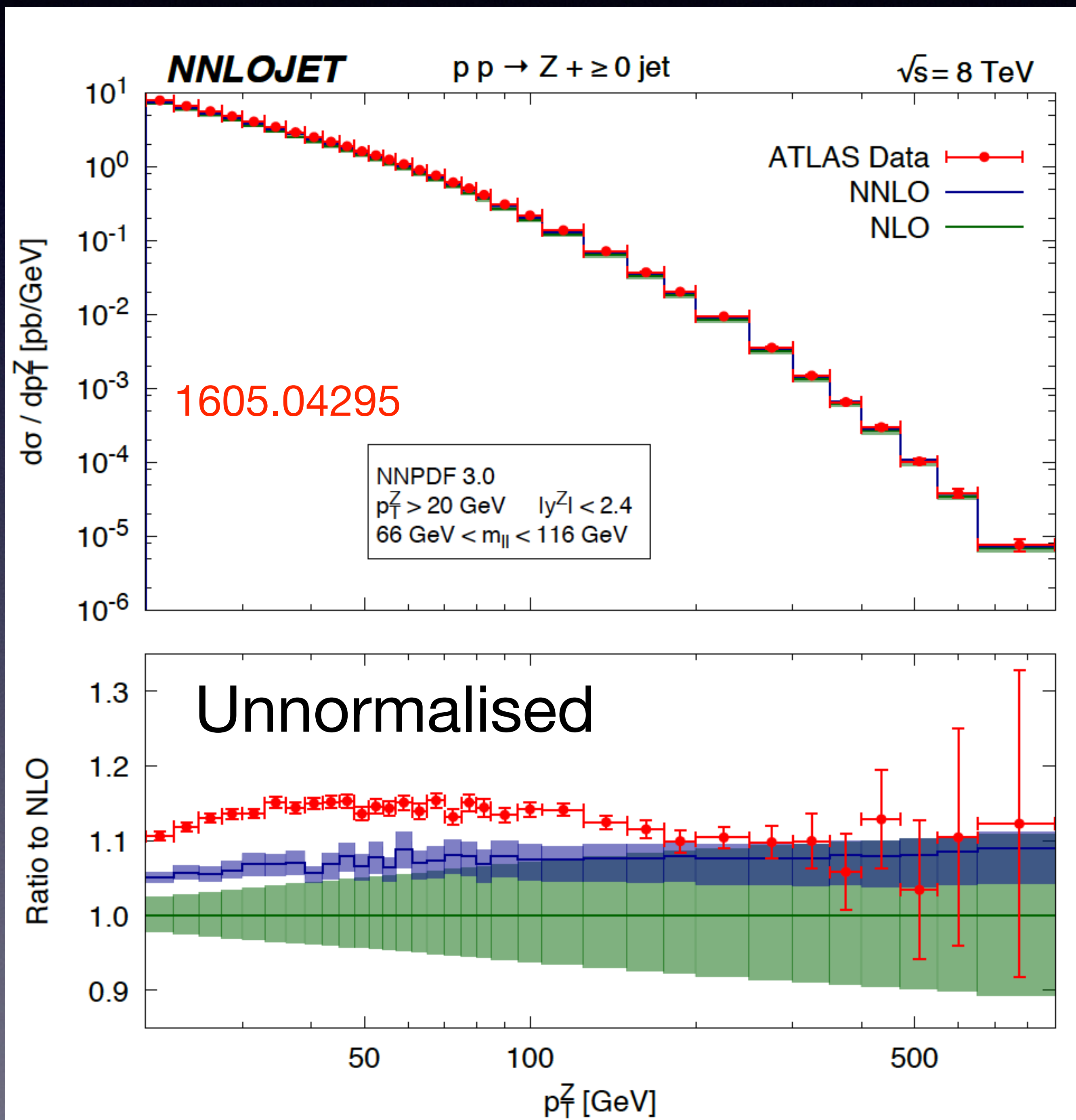
LHC data clearly prefers NNLO

Same conclusion in all measurements examined so far

With more data NLO likely to be insufficient

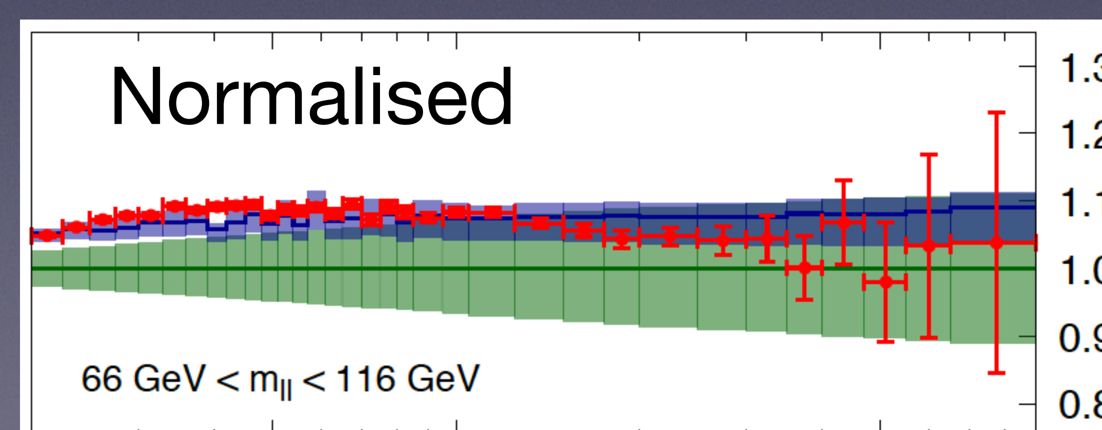
Comparison to NNLO for Z + jet

Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan ’16
Boughezal, Liu, Petriello ’16
Boughezal, Ellis, Focke, Giele, Liu, Petriello ’15

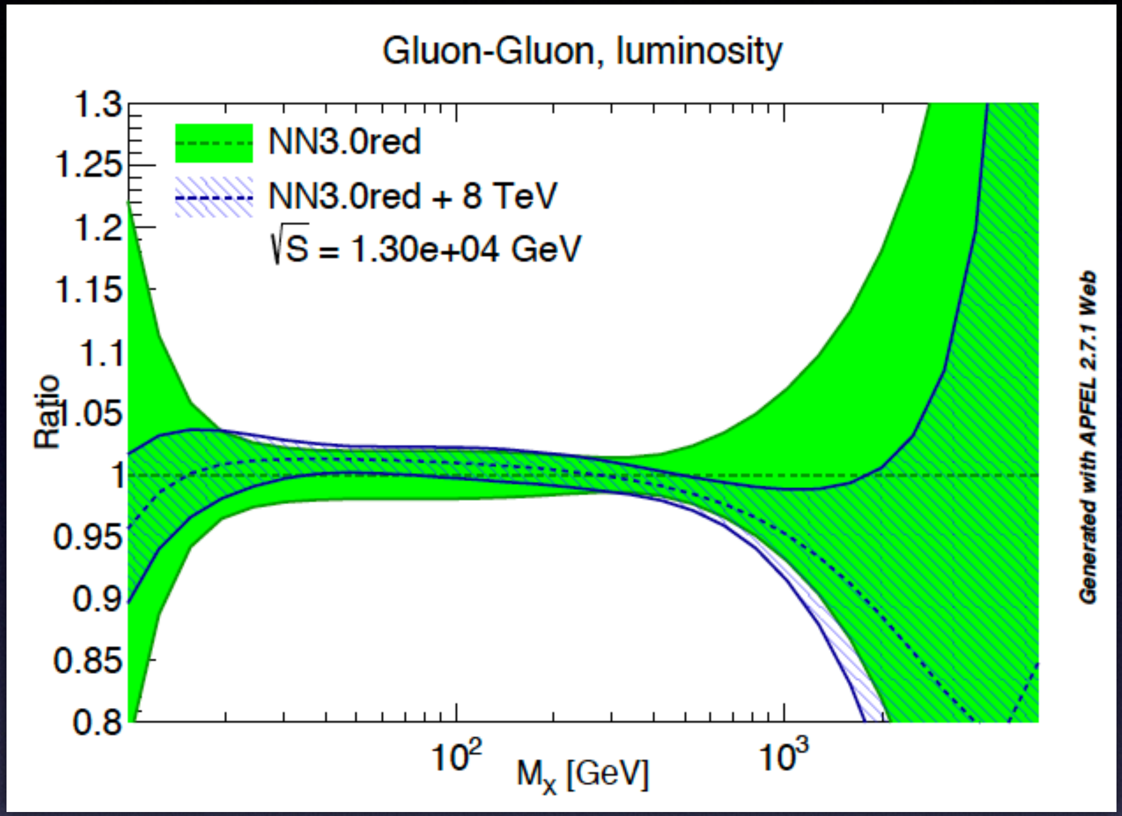


- NNLO and EW alleviate tension between data and theory
- better agreement in normalised distribution
- remember 2-3% luminosity error on data

⇒ see talk of A. Huss

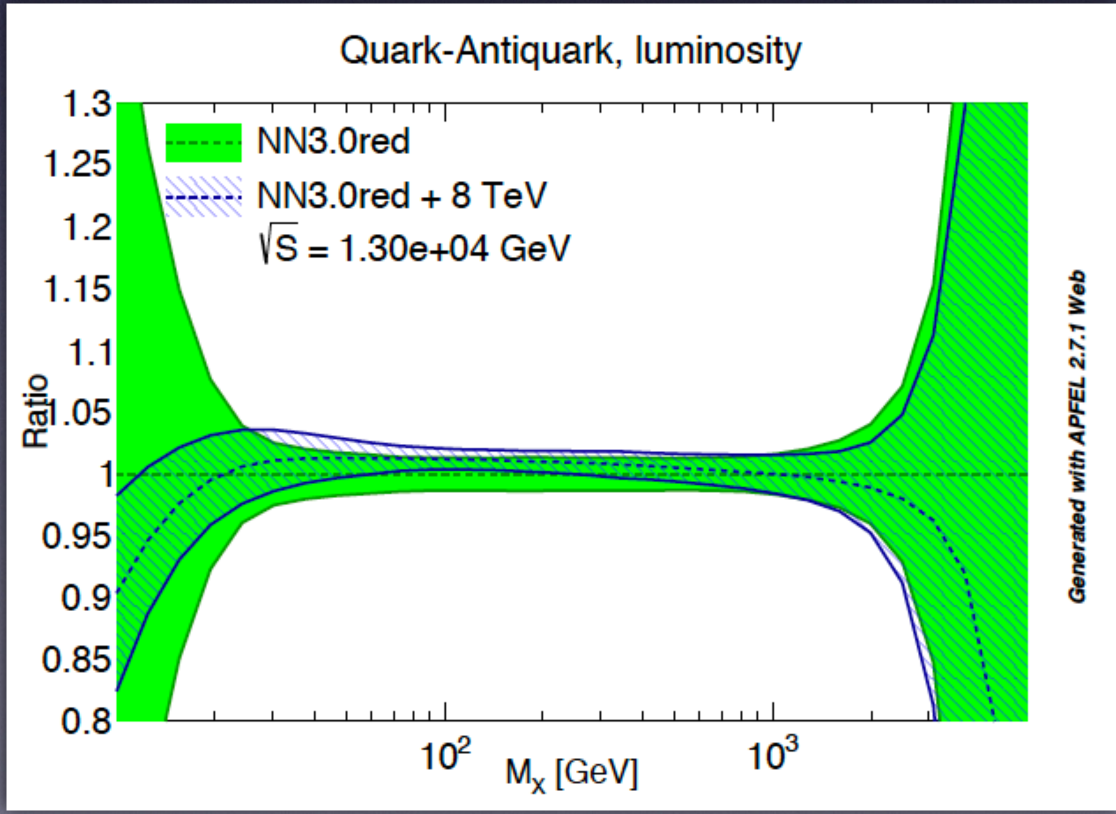


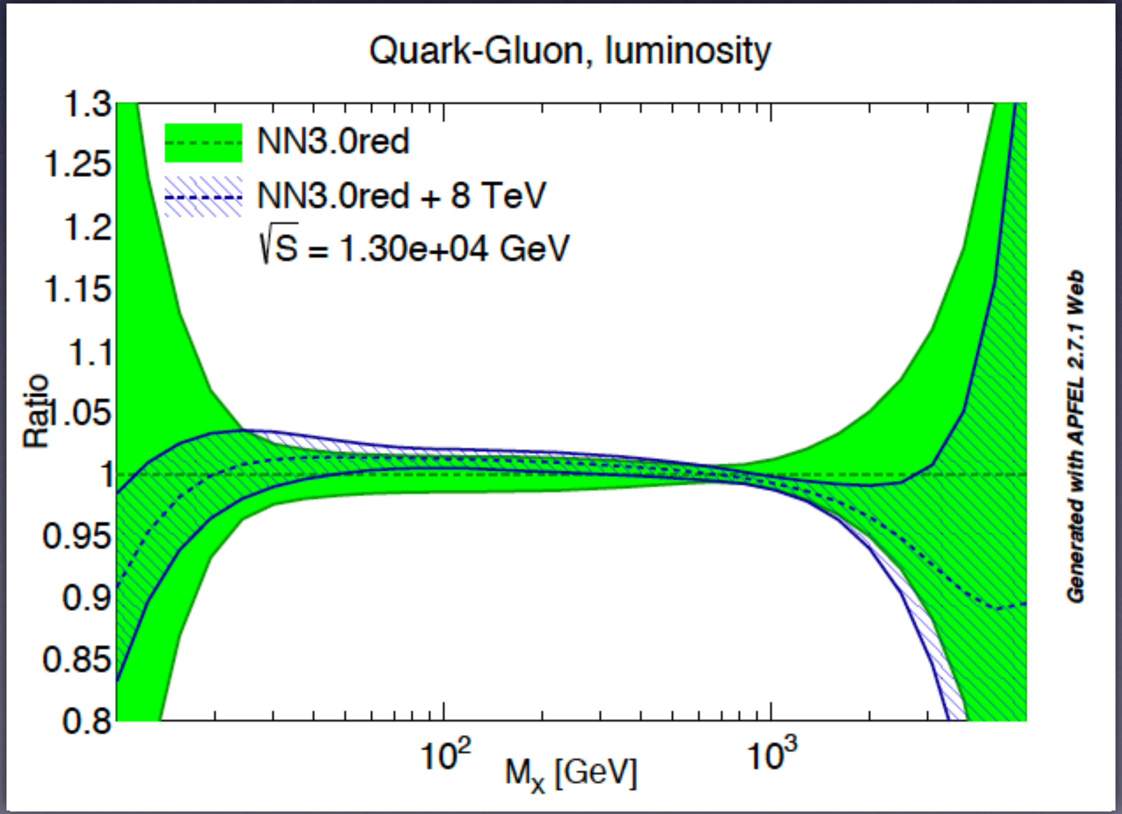
Impact of Z + jet on luminosities



Boughezal, Guffanti, Petriello, Ubiali 1705.00343

Significant reduction of uncertainty in all luminosities (e.g. 30% impact on PDF uncertainty of Higgs cross-section)





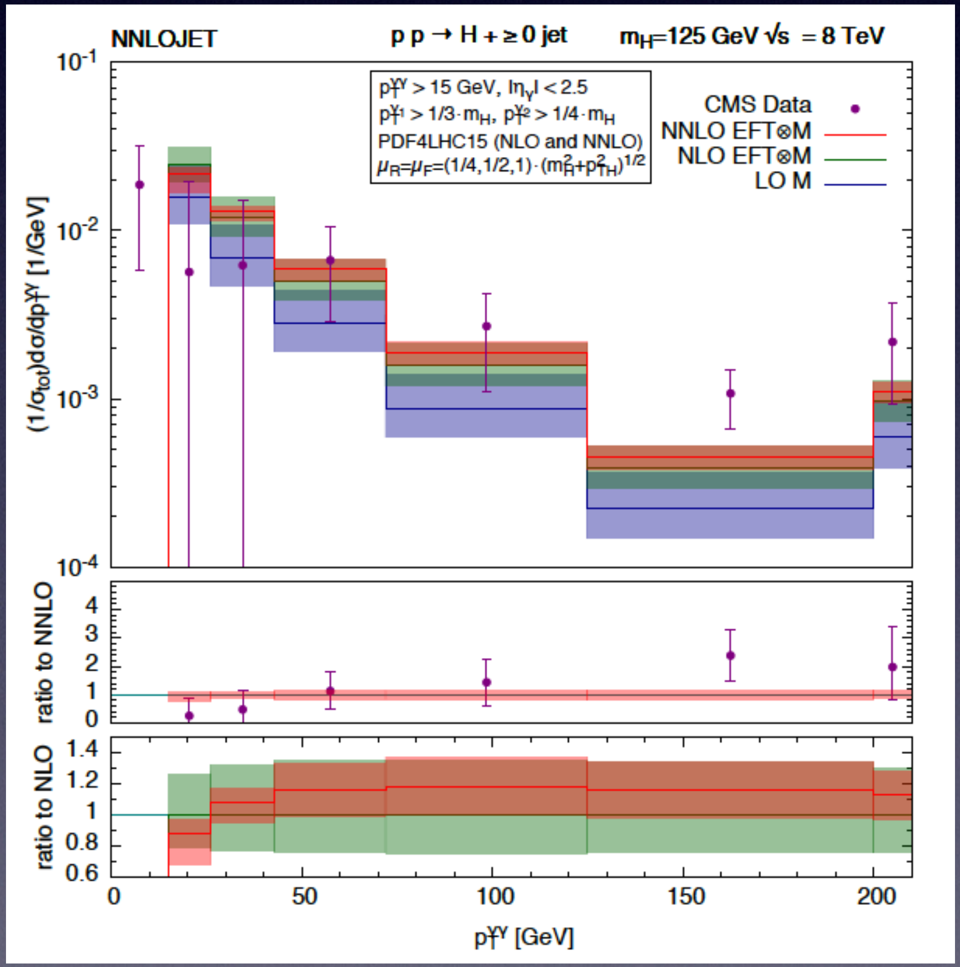
H + one jet at NNLO

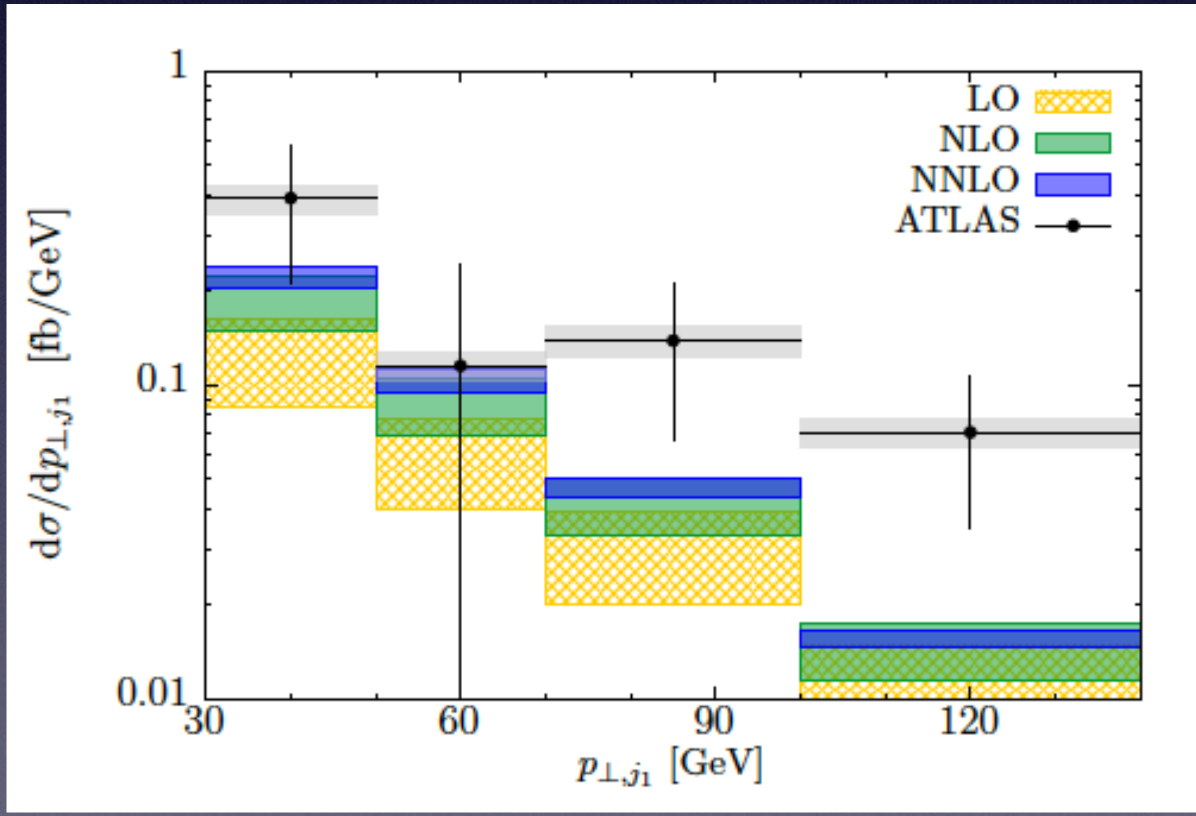
3 calculations with 3 methods. Cross-checks and validation. Decays of Higgs to bosons also included. Fiducial cross-sections compared to ATLAS and CMS data

Caola, Melnikov, Schulze 1508.02684

Boughezal, Melnikov, Petriello, Schulze 1504.07922

Chen, Gehrmann, Glover, Jaquier 1607.08817



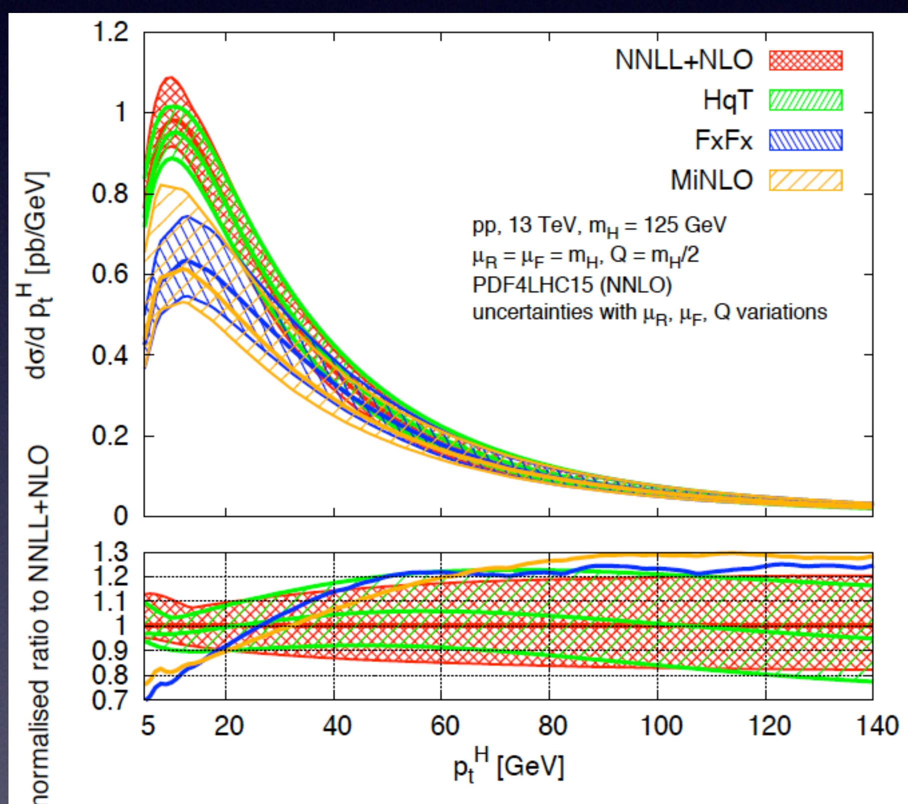


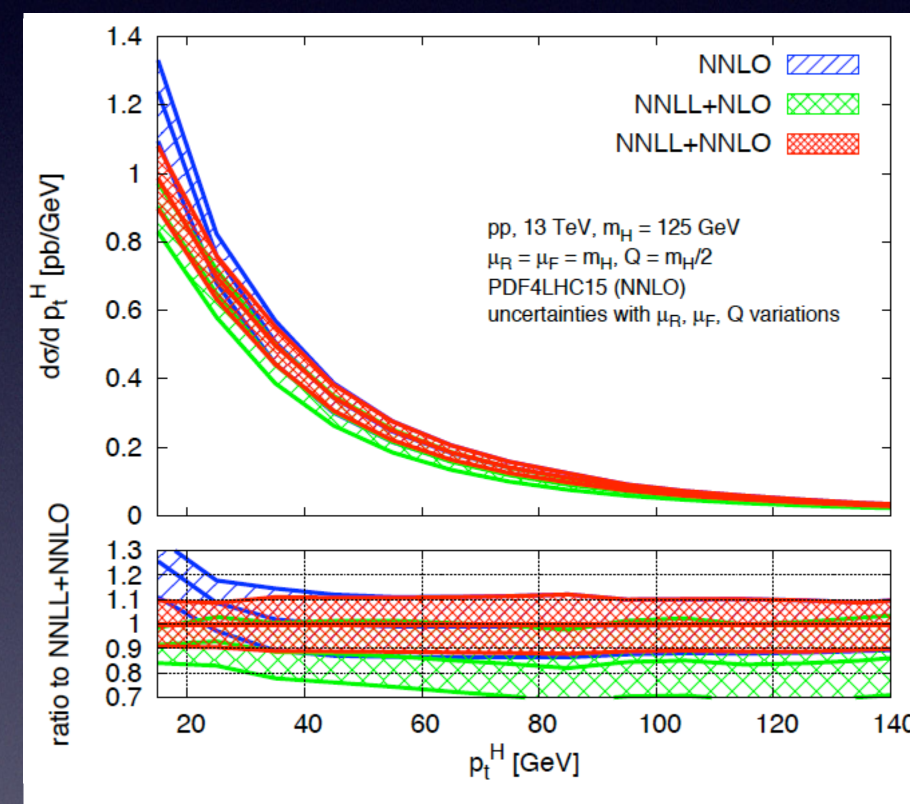
Good agreement on normalised distributions, less good agreement on unnormalised ones (but current data have large errors)

NNLO + NNLL Higgs p_t

New method to resum Higgs p_t directly in momentum space (rather than in impact parameter space) + matching to NNLO

Monni, Re, Torrielli 1604.02191



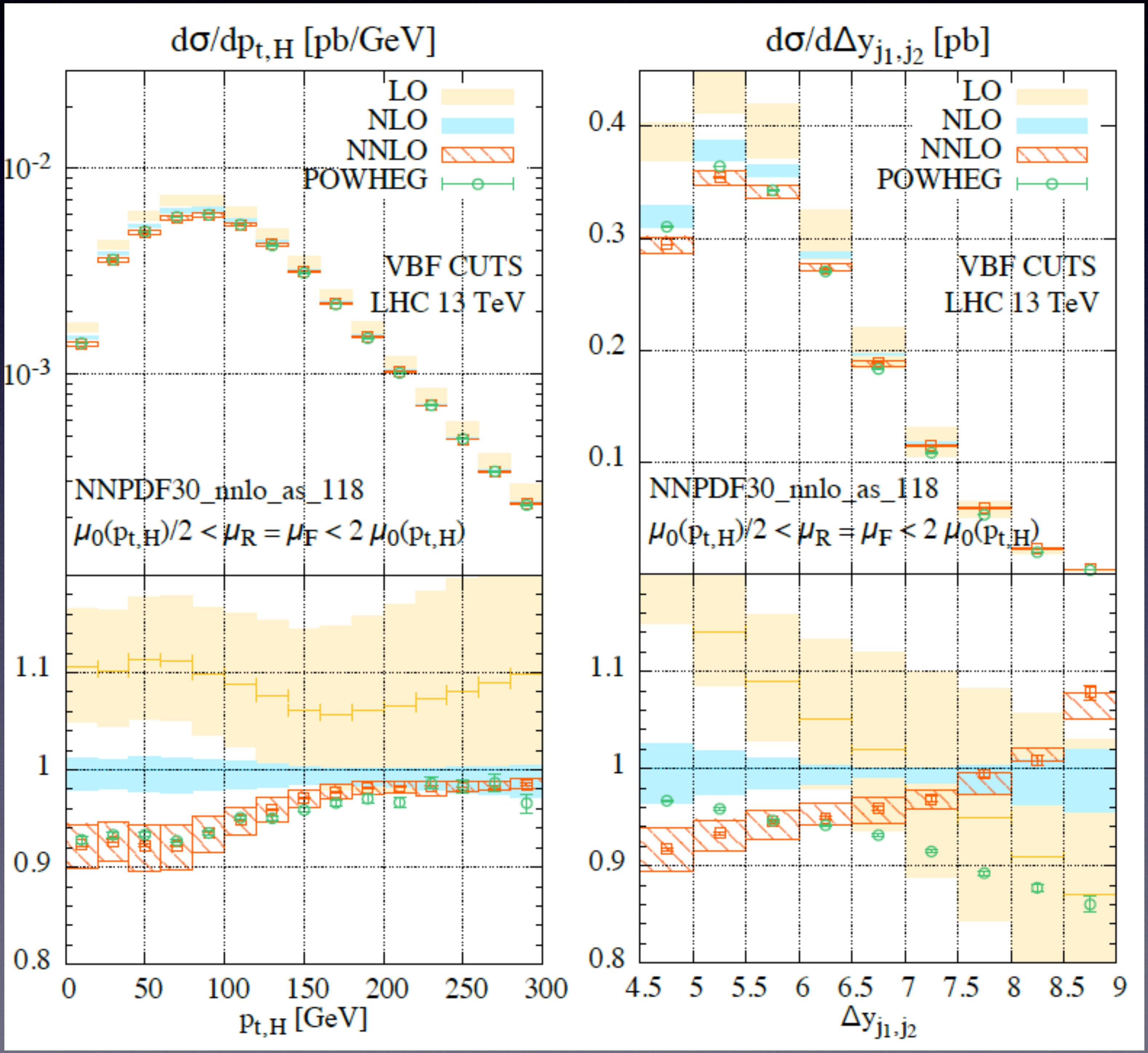


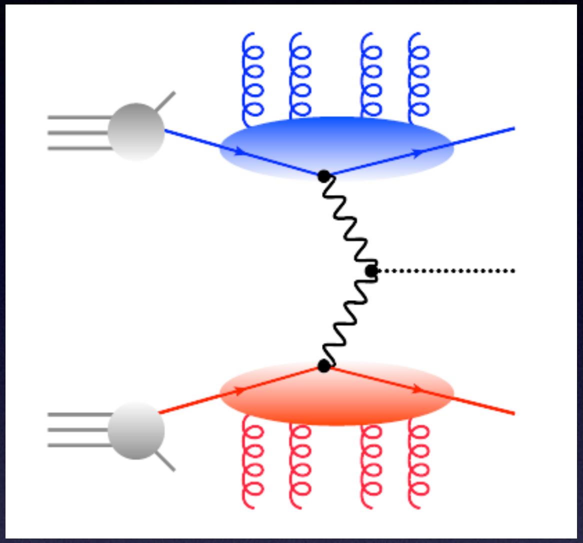
- good agreement with previous NNLL+NLO (HqT)
- less good agreement with other NLO+PS simulations

- NNLO corrections: about 10%
- resummation: sizeable impact below 25 GeV (or: fixed order works down to 25 GeV…)

Fully differential VBFH at NNLO

Cacciari, Dreyer, Karlberg, Salam, GZ 1506.02660

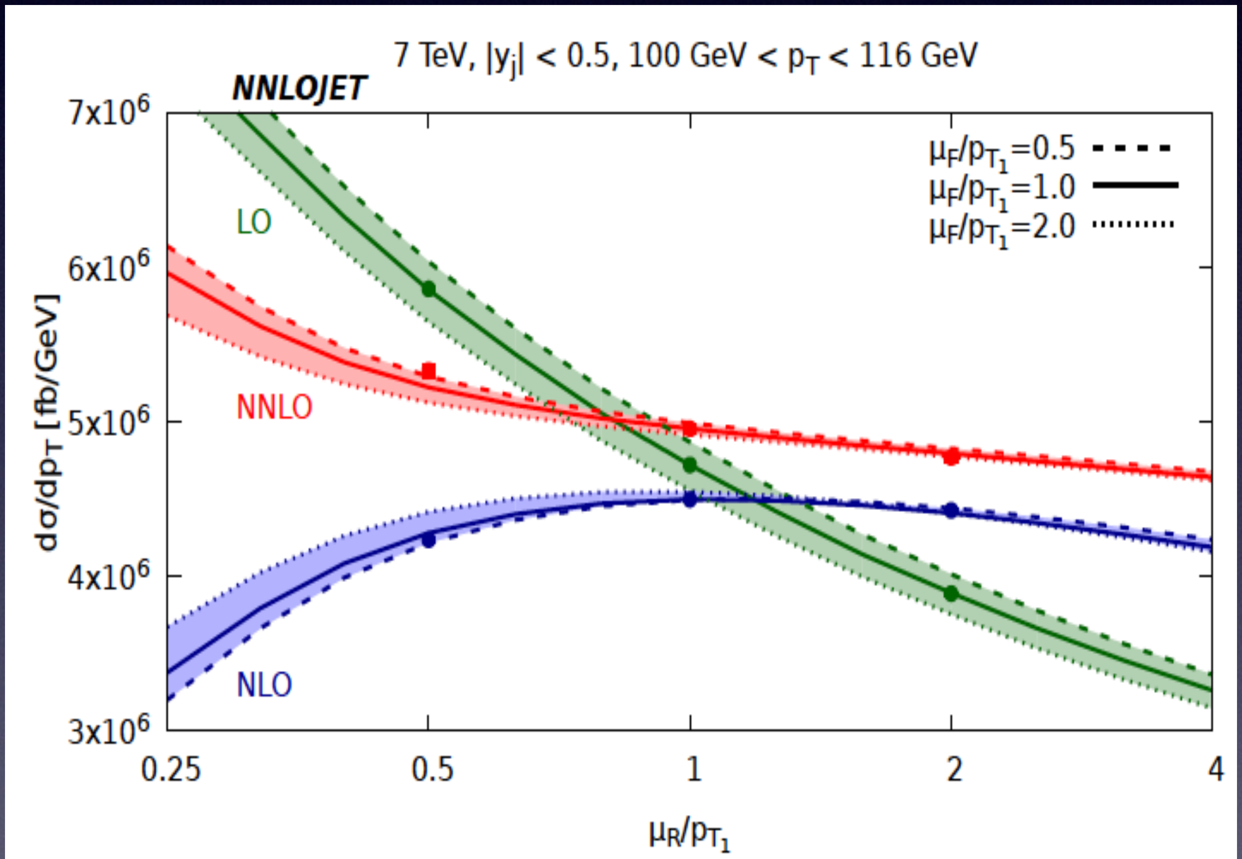




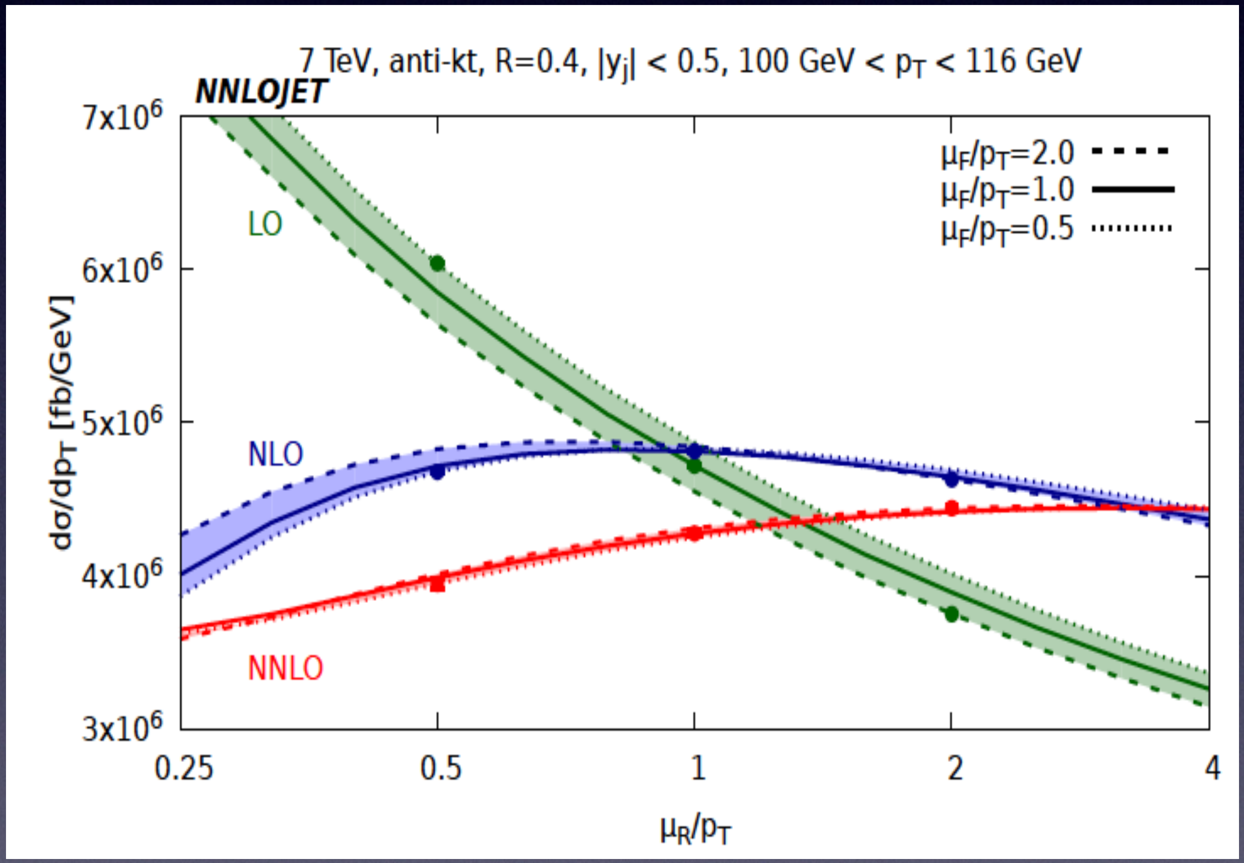
- Allows to study realistic observables, with realistic cuts
- NNLO corrections much larger (10%) than expected (1%)
- Important for coupling measurements

Inclusive jet spectrum

Scale (μ_R,μ_F) : p_t of leading jet



Scale (μ_R,μ_F) : p_t of jet

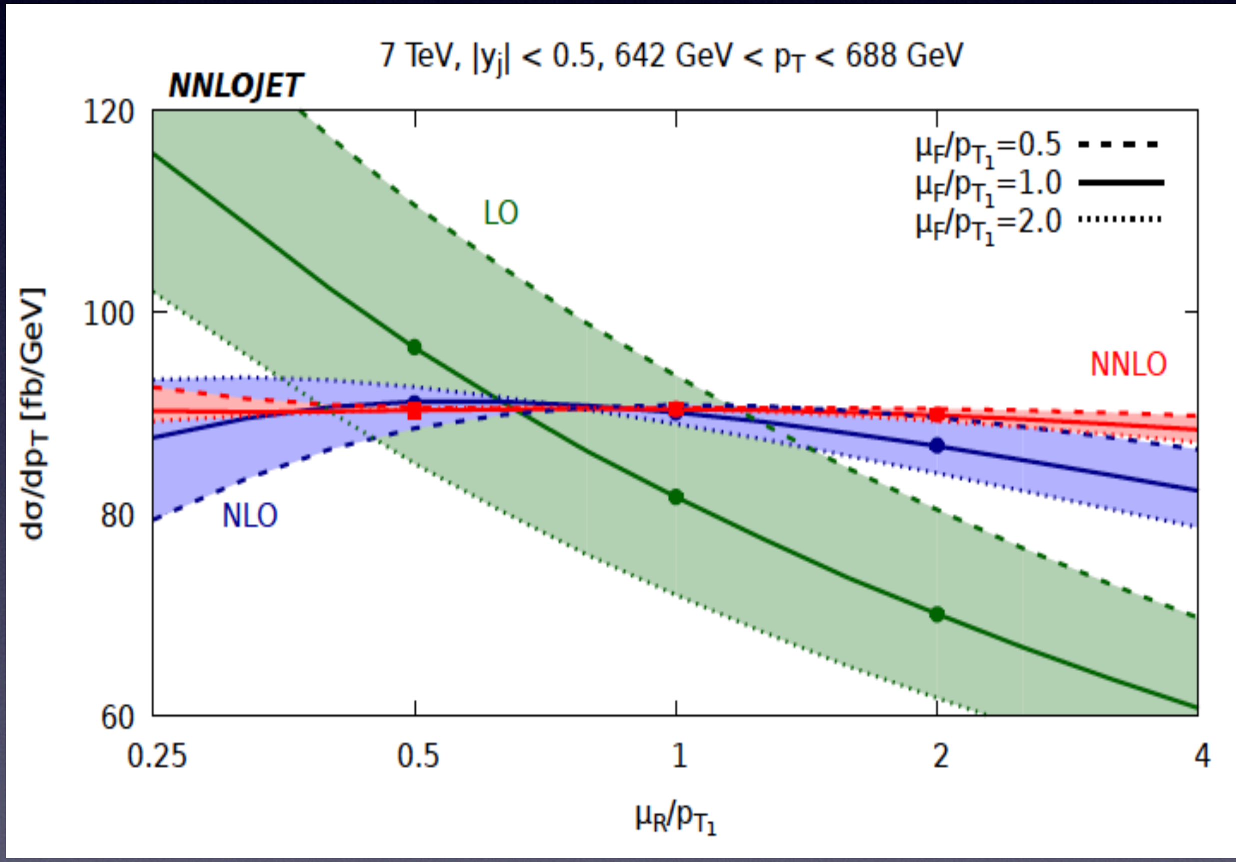


Currie,, Glover, Pires 1611.01460

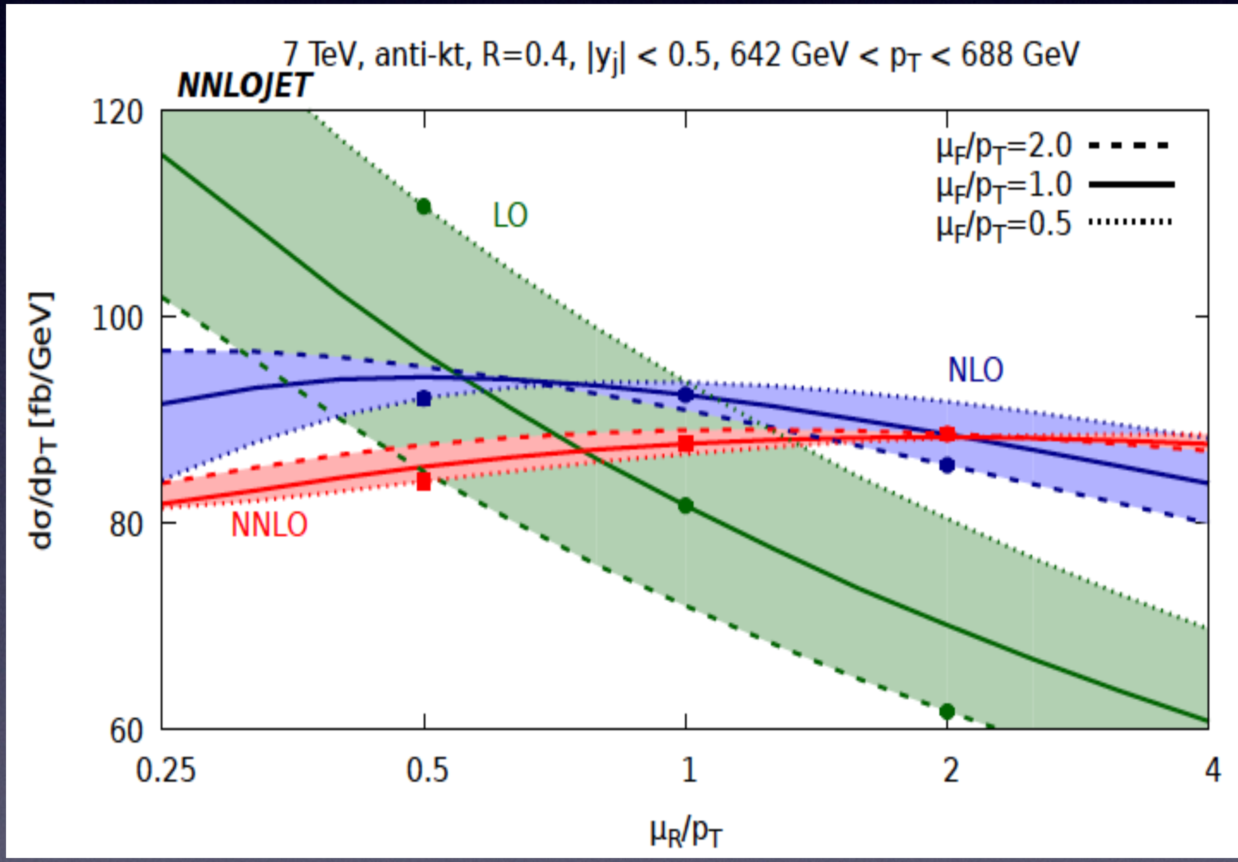
Low transverse momentum region

Inclusive jet spectrum

Scale (μ_R,μ_F) : p_t of leading jet



Scale (μ_R,μ_F) : p_t of jet

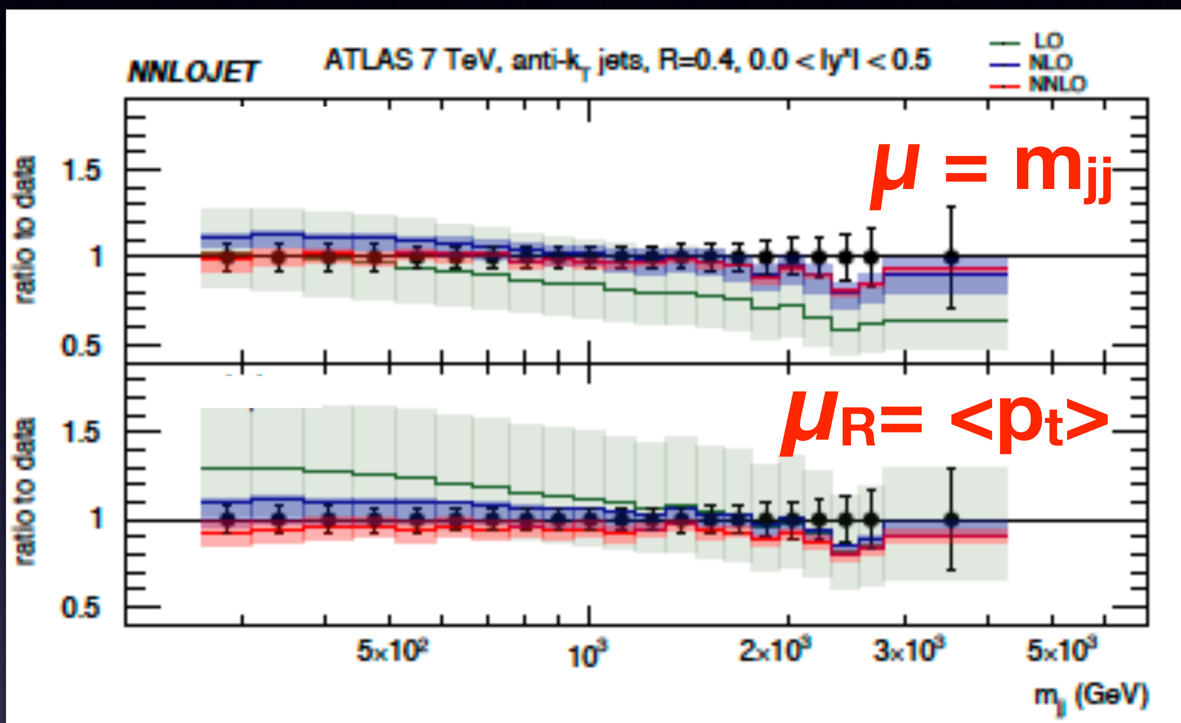


Currie,, Glover, Pires 1611.01460

High transverse momentum region

Di-jet invariant mass

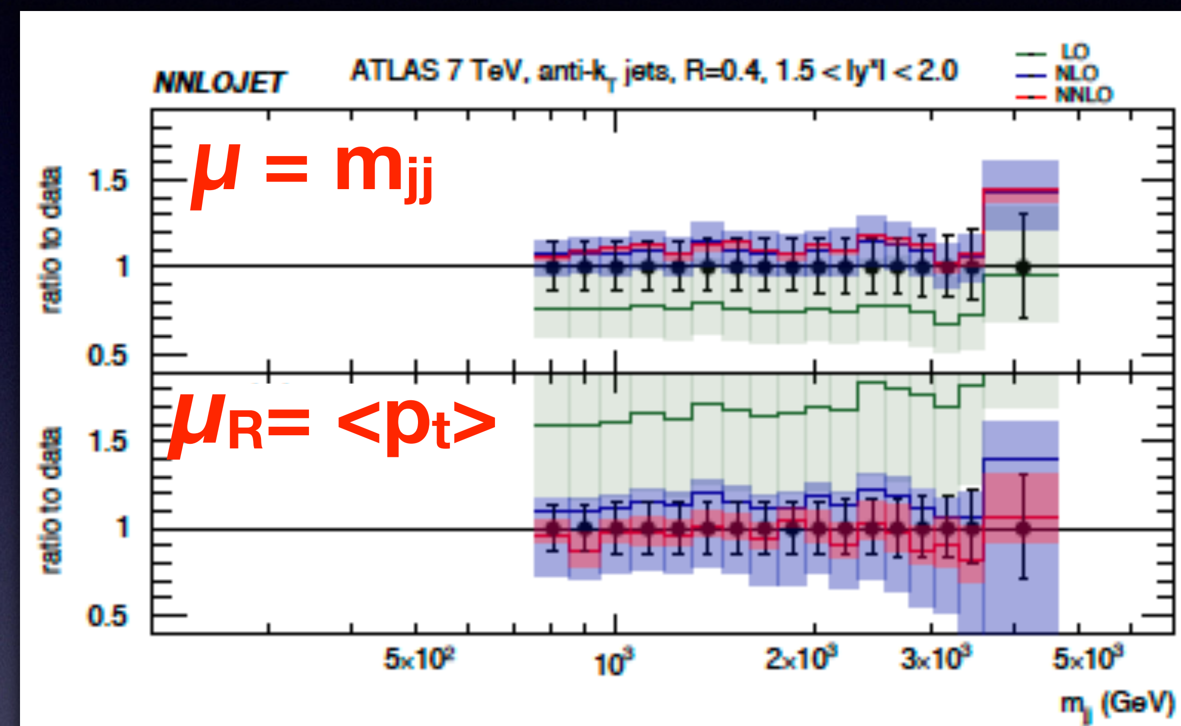
Small y_1-y_2



$$2p_t \lesssim m_{jj} \lesssim 3p_t \text{ (LO)}$$

$\Rightarrow$ p_t and m_{jj} scales similar

Larger y_1-y_2



$$9p_t \lesssim m_{jj} \lesssim 15p_t \text{ (LO)}$$

$\Rightarrow$ p_t and m_{jj} very different

"We choose the diet invariant mass as the theoretical scale on the grounds of perturbative convergence and residual scale variation …"

Currie, A. Gehrmann-De Ridder, Gehrmann, Glover, Huss, Pires 1705.10271

Scale: the usual questions

- *How should one set the renormalization and factorization scale in a given process? It is fair to set the scale a posteriori …?*
- *Can one trust the scale uncertainty band, i.e.the factor two variation around central scale [in particular if set a posteriori]?*
- *How should the scale uncertainty be interpreted? as a flat 100% interval* or as a 1σ (3σ?,5σ?) gaussian …?*

Mostly, there are no good answers. A few approaches:

- dynamical, a priori procedure to set the scales based on clustering scales (CKKW, MiNLO) [typically yields larger bands]
- uncertainty extracted from convergence of the PT series [but needs a few orders…]
- Cacciari-Houdeau Bayesian approach [suggests scale band is less then 1σ]

(*) Scale uncertainty interpreted as a 100% flat interval e.g. in the N3LO Higgs cross-section in the HXSWG and in the first extraction of α_s from ttbar at the LHC

Scale setting

Some (obvious) considerations are:

- The question is not what is the right scale (BLM? PCM?) but rather what is the theoretical uncertainty, and what is its interpretation
- The more orders one computes, the less relevant the question is — however the more data is collected the more important the question is again, so the question likely to remain important
- In all cases examined, when the scale uncertainty band fails miserably to estimate size of the next order there is a reason (e.g. new channels, Born zeros, large logarithms …). Still scale variation has serious limitations and should never to overrated
- In the only two cases for which the N^3LO result is available, it does lie in the NNLO scale band (but inclusive results only)

More experience with NNLO and N3LO will guide us further

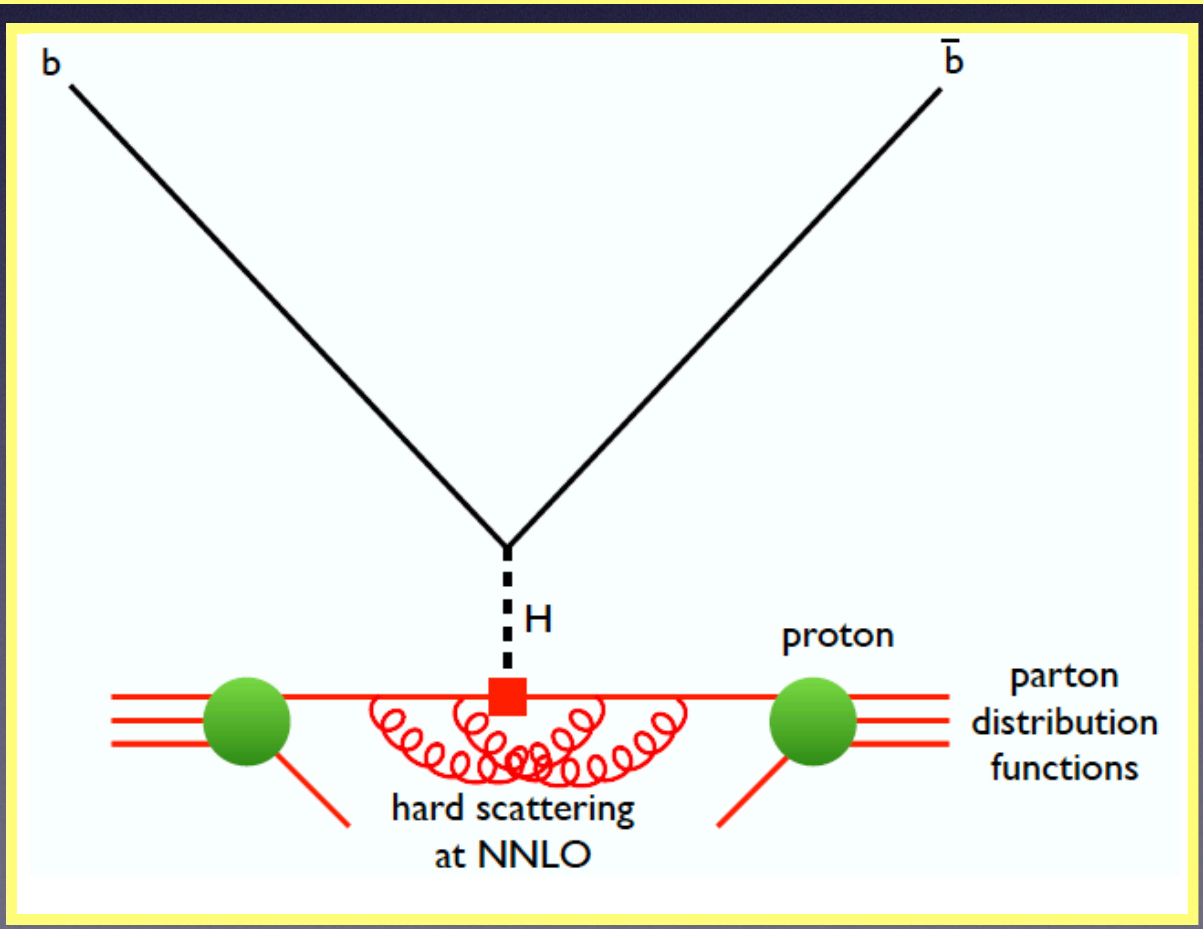
NNLO+PS

<u>NNLO</u>:

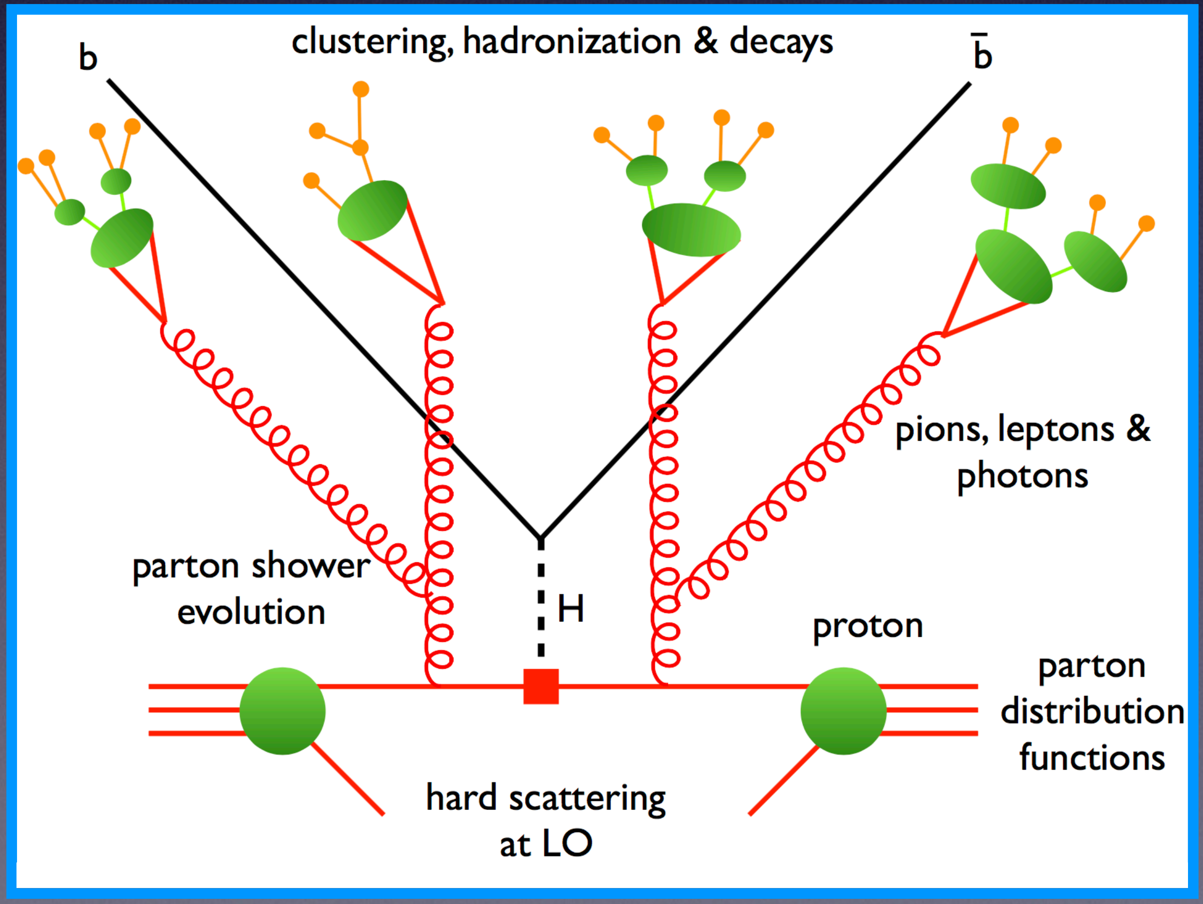
good perturbative accuracy, accurate inclusive cross-sections, but limited to low multiplicity and parton level only

<u>Parton shower</u>:

less accurate, but realistic description, including multi-parton interactions, resummation, hadronization effects

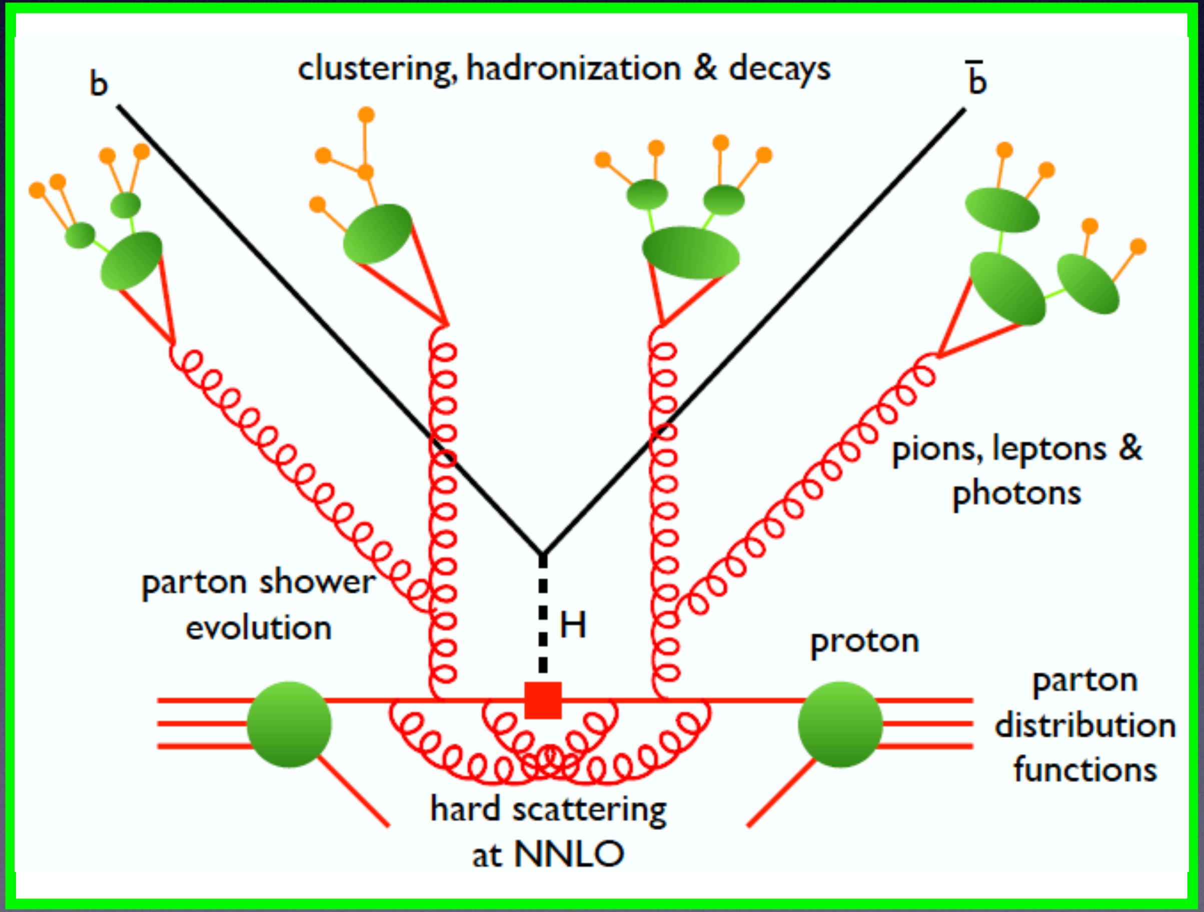


?



NNLO+PS

Merging NNLO and parton shower (NNLOPS) is a must to have the best perturbative accuracy with a realistic description of final state



- First NNLOPS codes: Higgs, Drell-Yan & associated Higgs production
- currently, three different methods: MiNLO, UNNLOPS, Geneva

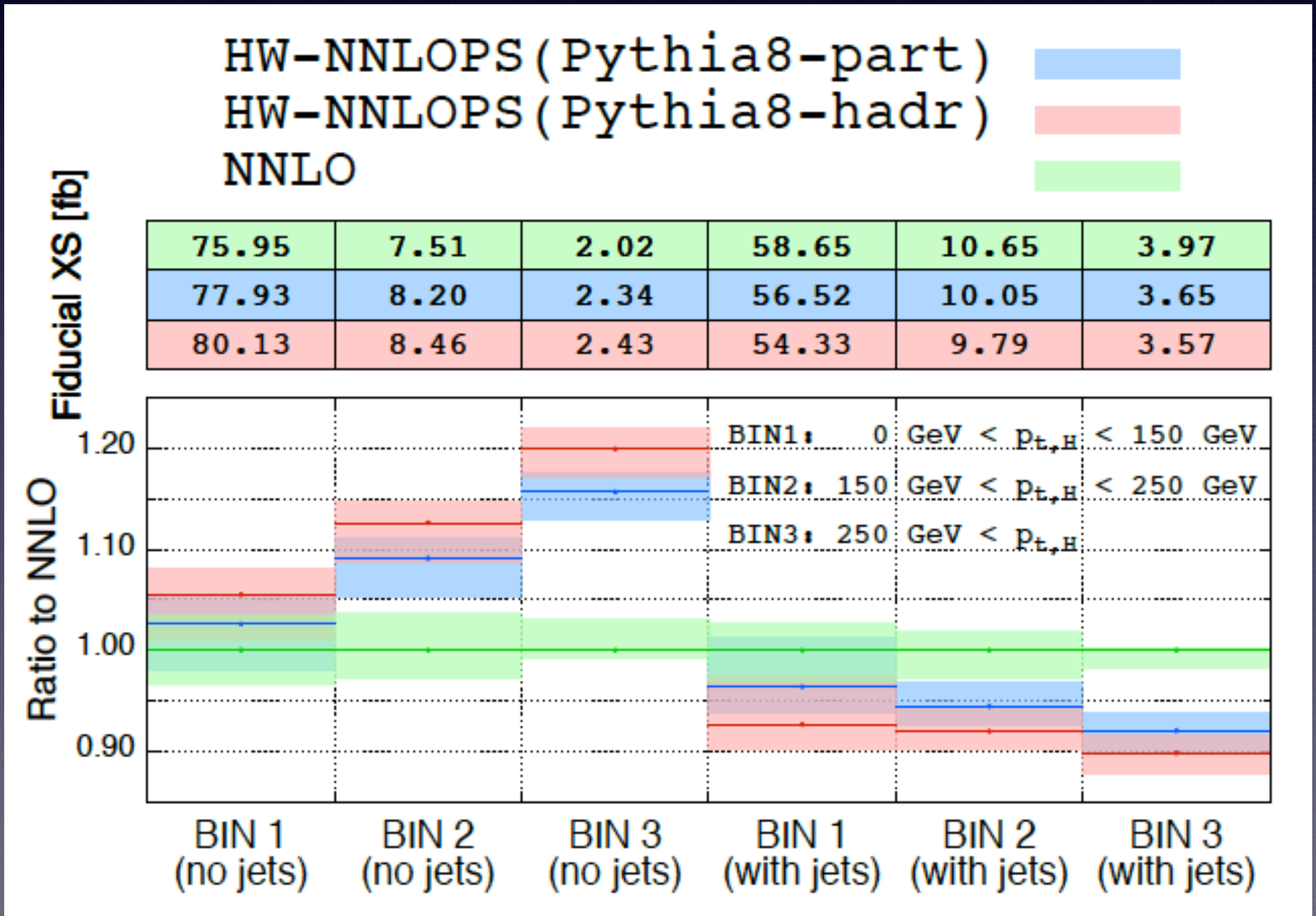
Hoeche, Li,Prestel '14-'15 [UNNLOPS]
Astill, Bizon, Hamilton, Karlberg, Nason, Re, GZ '13-'16 [MiNLO]
Alioli, Bauer, Berggren, Guns, Tackmann, Walsh '15-'16 [Geneva]

NNLO+PS for HW

One sample NNLOPS result: HW with cuts suggests by HXSWG

Astill, Bizon, Re, GZ 1603.01620

- Parton shower and hadronization cause migration between jet-bins
- Difficult to reach high accuracy in jet-binned observables



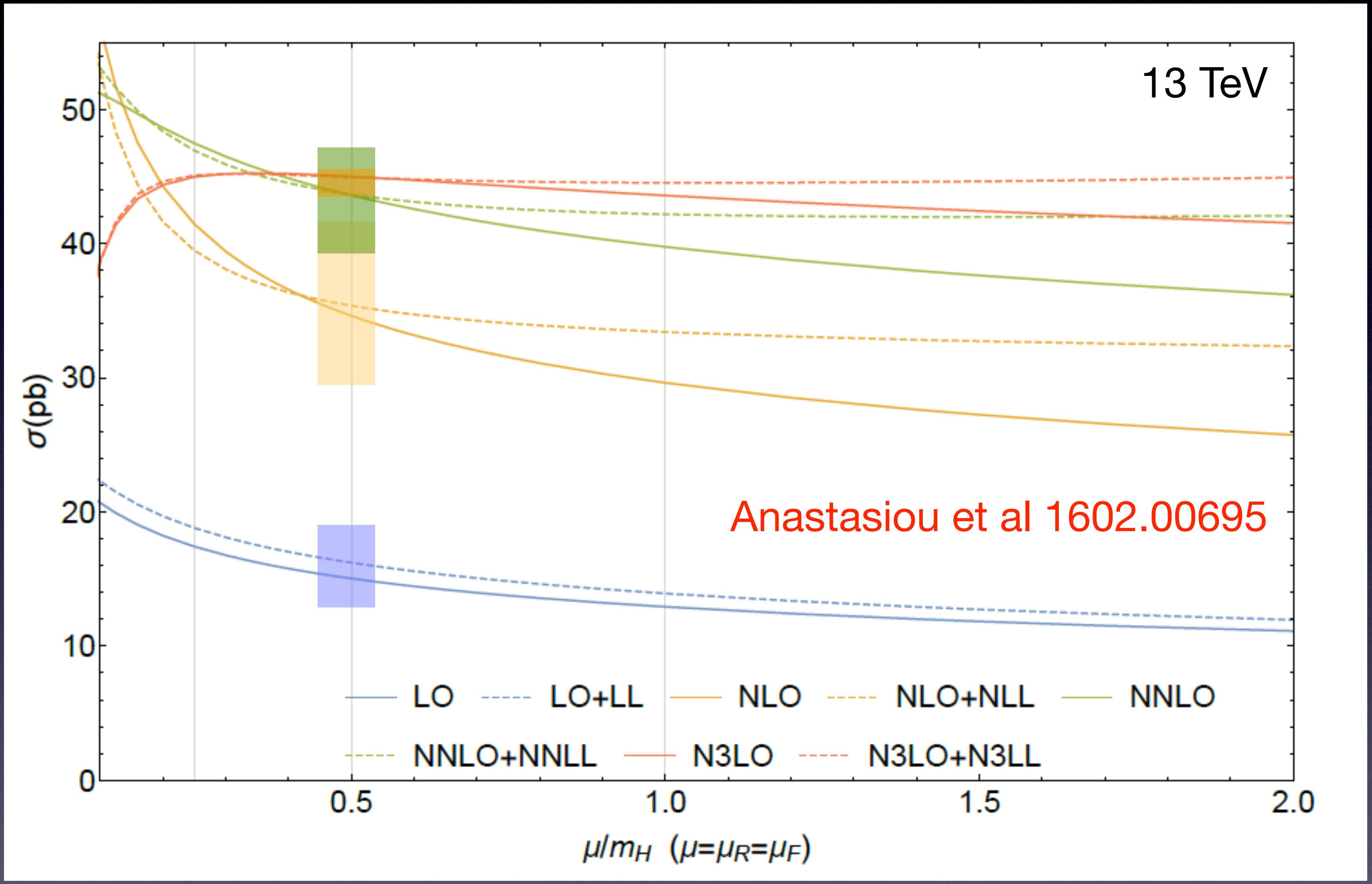
N^3LO

Two LHC processes known at N^3LO

Gluon fusion Higgs production (in the limit of infinite top-quark mass)

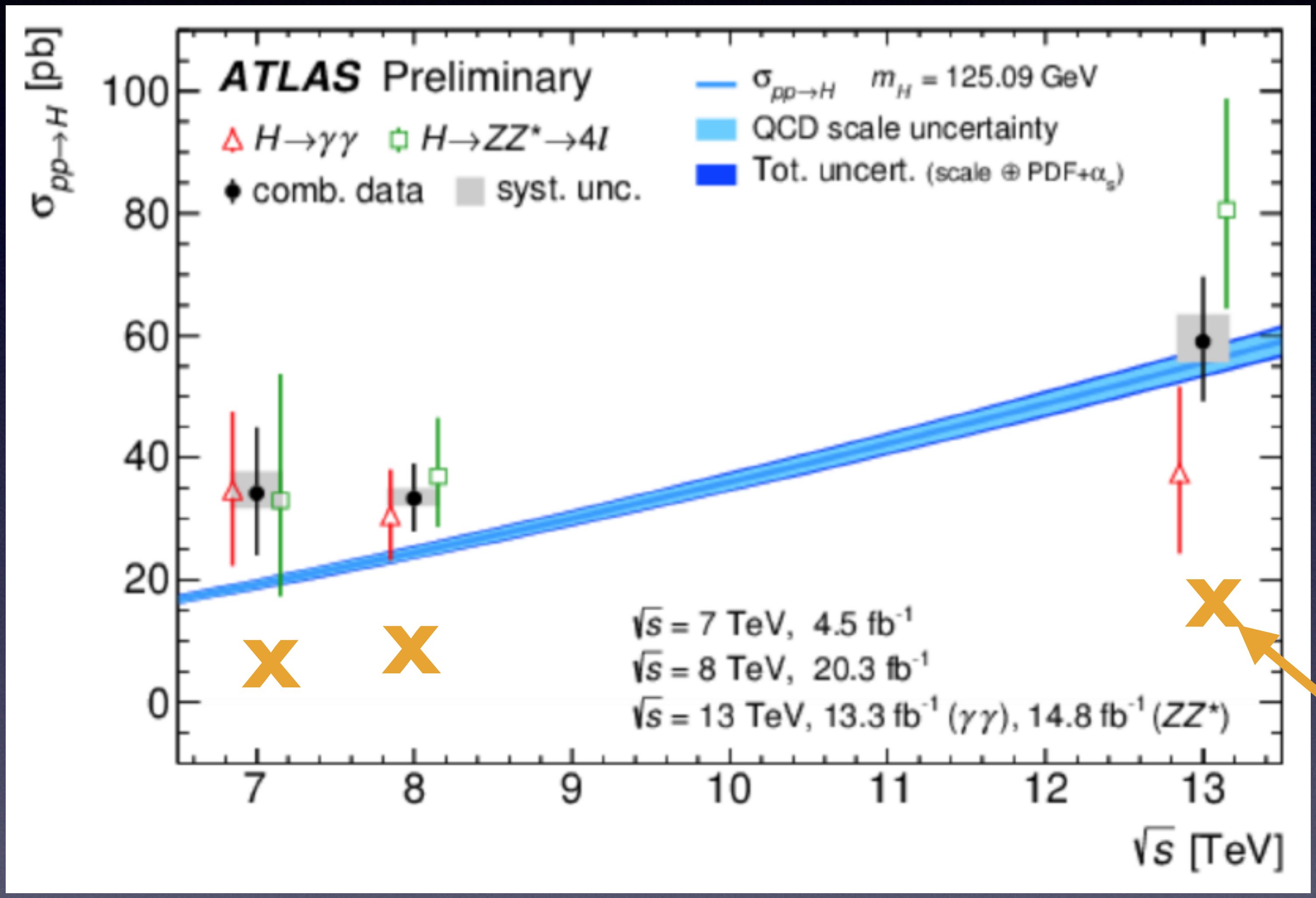
Vector boson fusion Higgs production (in the structure function approximation, i.e. double DIS process)

N^3LO Higgs production



- dashed lines include resummation of even higher orders (essentially no impact on central value at preferred renormalisation scale $m_H/2$)
- N^3LO stabilises the perturbative expansion (N^3LO band contained in NNLO band, while NNLO was not in the NLO band)

Data vs theory



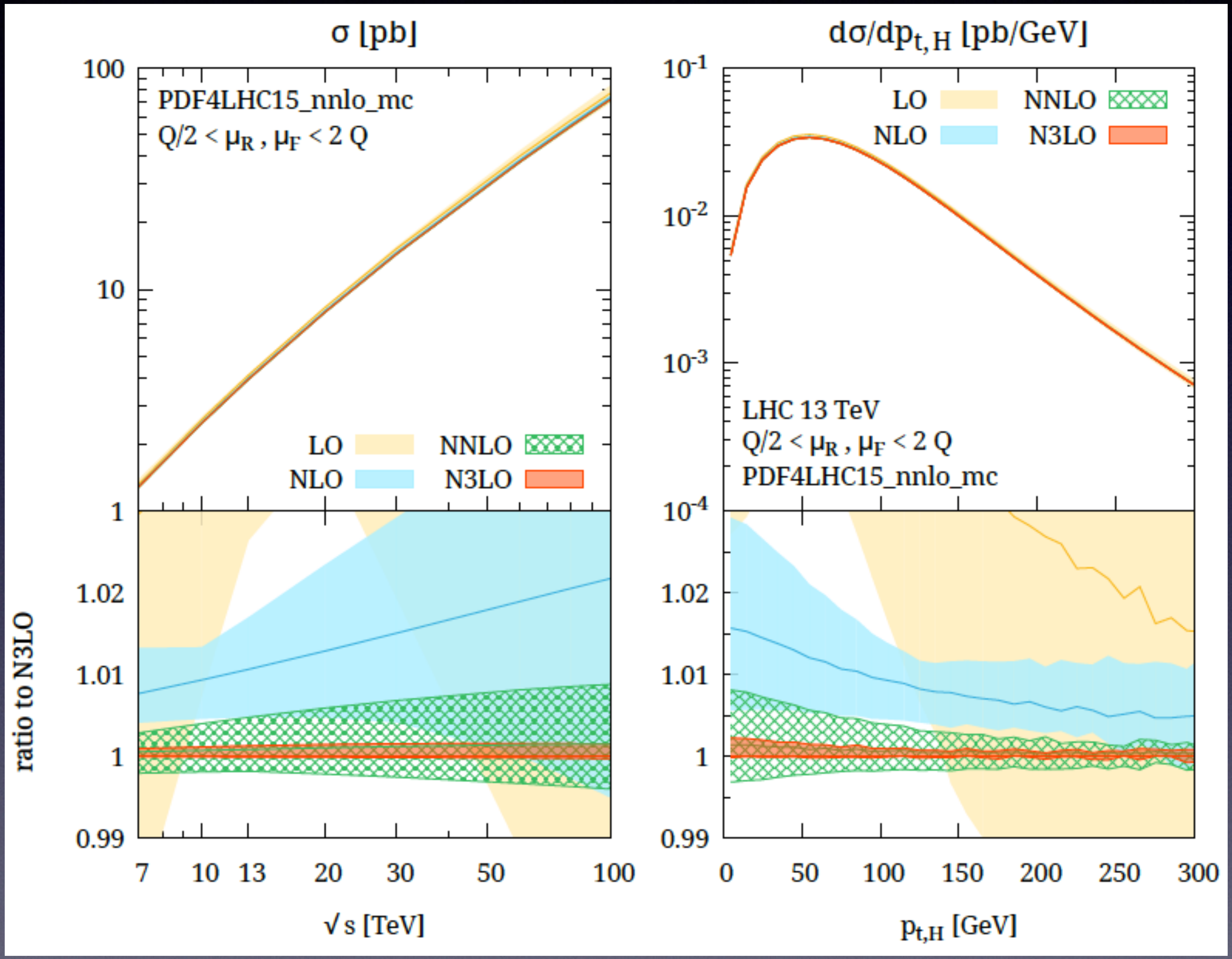
Theory 15 years ahead of experiment!

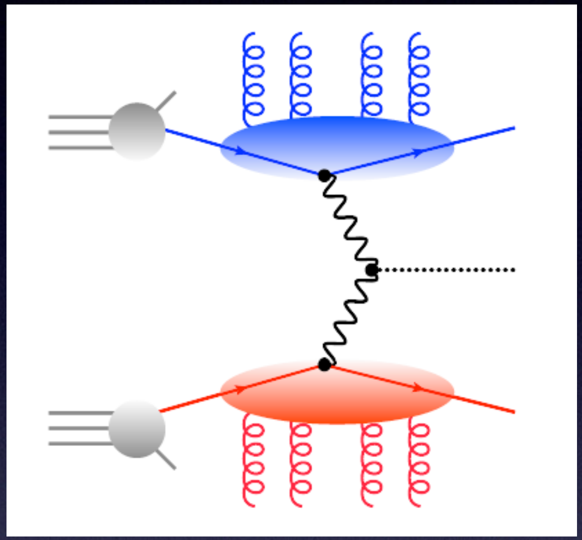
Theory predictions without higher orders

Next challenge: extend N^3LO accuracy to differential distributions (hard but within reach?)

… and inclusive VBFH at N³LO

Dreyer & Karlberg 1606.00840

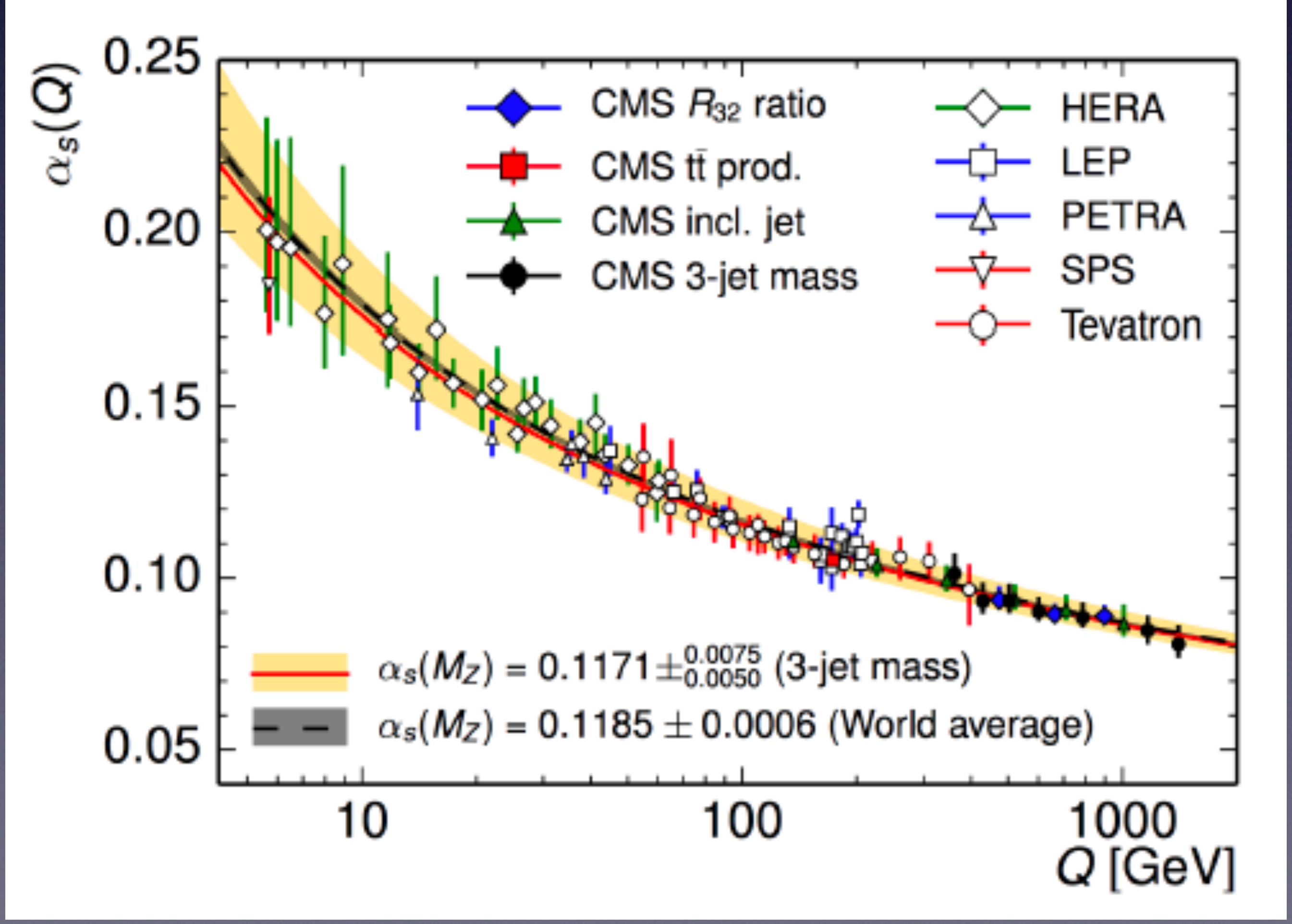




Again, NNLO was outside the NLO uncertainty band, while N^{3}LO band (with sensible scale) is fully contained in the NNLO band

The strong coupling

The strong coupling is the fundamental parameter of QCD. It is not an observable, but observables depend on it, hence $\alpha_s(Q)$ extracted by comparing calculations and data. Four key considerations: sensitivity, accuracy, control of non-perturbative, scale Q probing α_s



Summary of extractions from e^+e^-, DIS and hadron collider experiments

- ➡ running probed to TeV scales
- ➡ good agreement between various fits (but the devil is in the details)

The strong coupling

Tevatron + LHC average (NLO, not contributing to world average)

$$\alpha_s(M_Z) = 0.1172 \pm 0.0059$$

agrees well with the world average*

$$\alpha_s(M_Z) = 0.1181 \pm 0.0011$$

PDG 2016

(*) world average obtained as average of sub-averages. Removing each sub-average changes the average by less than its quoted error

Further improvements likely to come from lattice (but one never knows)

Two examples where precision brings in new opportunities

1. Pinning down the Higgs potential

Single Higgs
done
O(45pb)

Triple Higgs
out of reach at LHC
O(0.1fb)

$$V_{\rm SM} = \boxed{\frac{m_h}{2} h^2} + \boxed{\lambda_{\rm SM} v h^3} + \boxed{\frac{\kappa_{\rm SM}}{4} h^4}$$

Double Higgs
very hard
O(45fb)

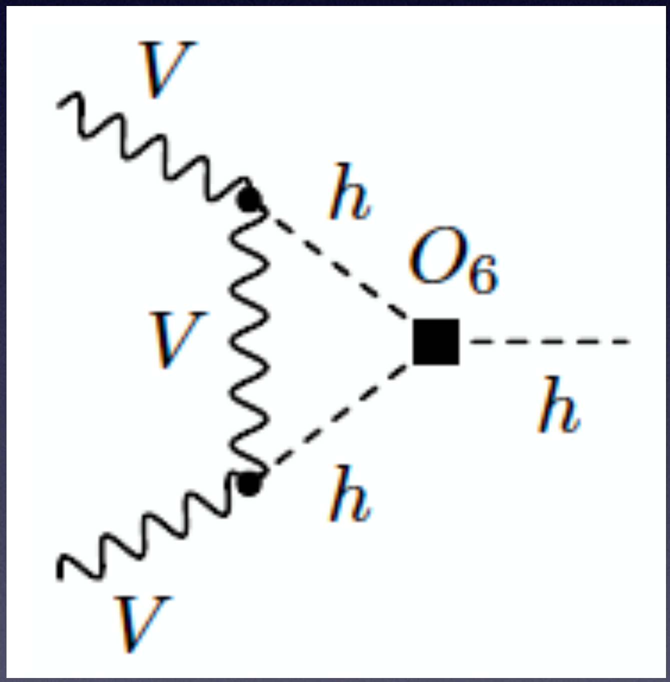
Bounds on λ today:

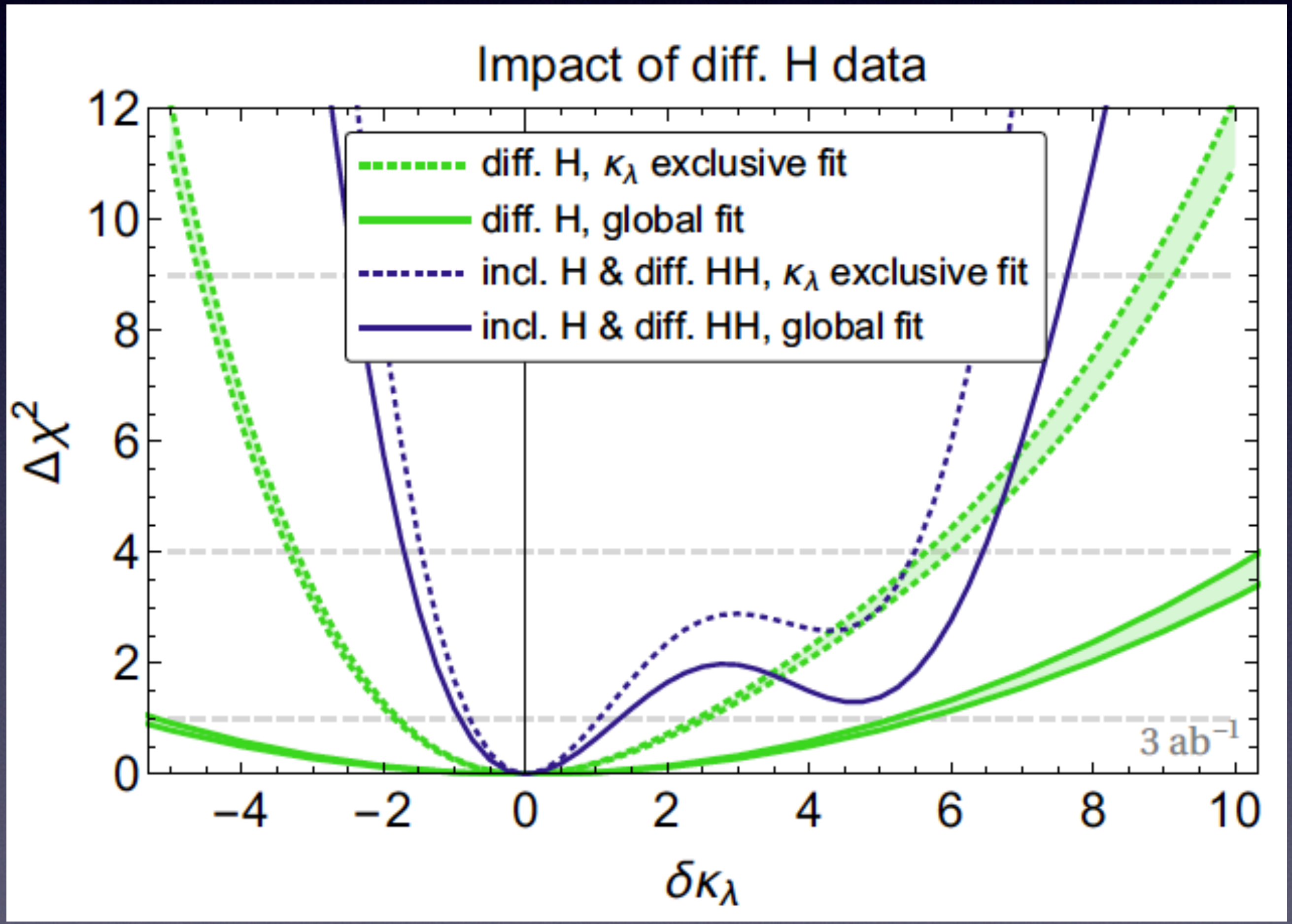
$$-14.5\lambda_{\rm SM} \leq \lambda \leq 19.1\lambda_{\rm SM}$$ Run I (20fb^{-1})

$$-8.4\lambda_{\rm SM} \leq \lambda \leq 13.4\lambda_{\rm SM}$$ Run II (13fb^{-1})

1. Pinning down the Higgs potential

Alternative: exploit indirect sensitivity to λ of single Higgs production



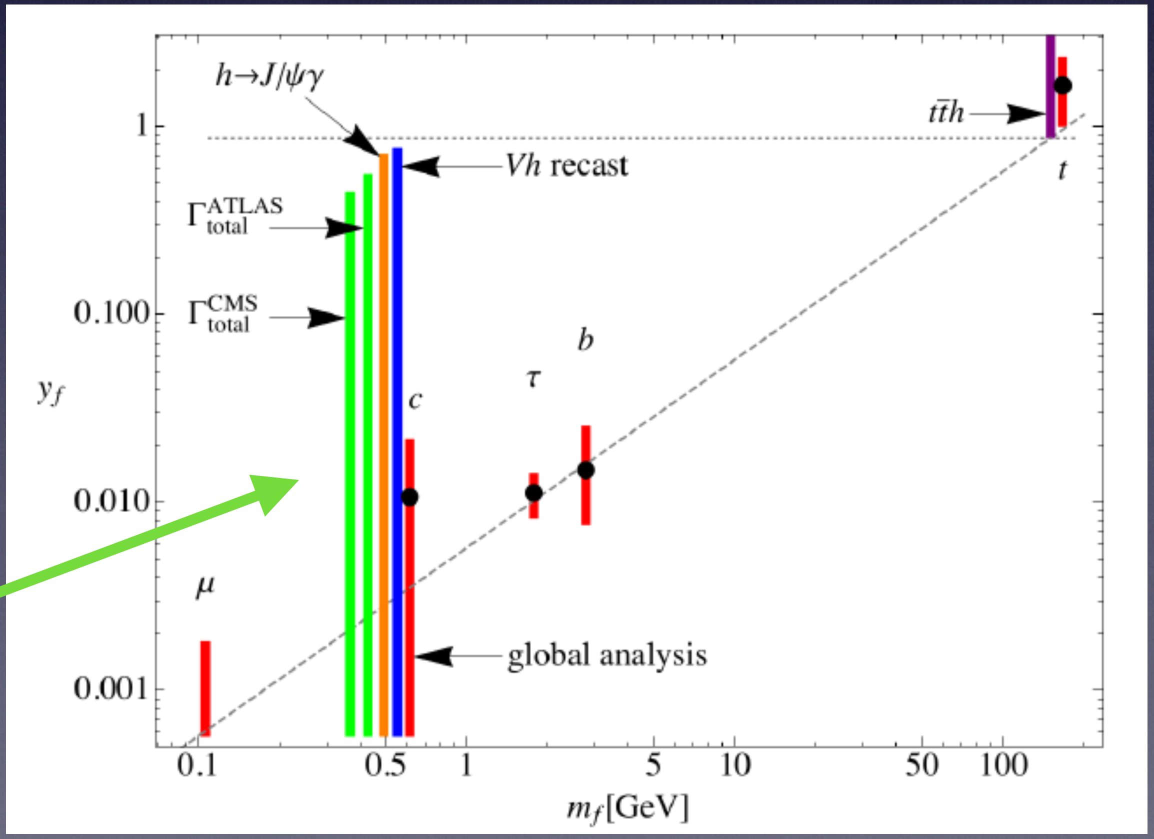


Bizon, Gorbahn, Haisch, GZ '16
Degrassi, Maltoni, Giardino, Pagani '16
Degrassi, Fedele, Giardino '17
Di Vita, Grojean, Panico, Riembau, Vantalon '17

2. Higgs coupling to 2nd generation

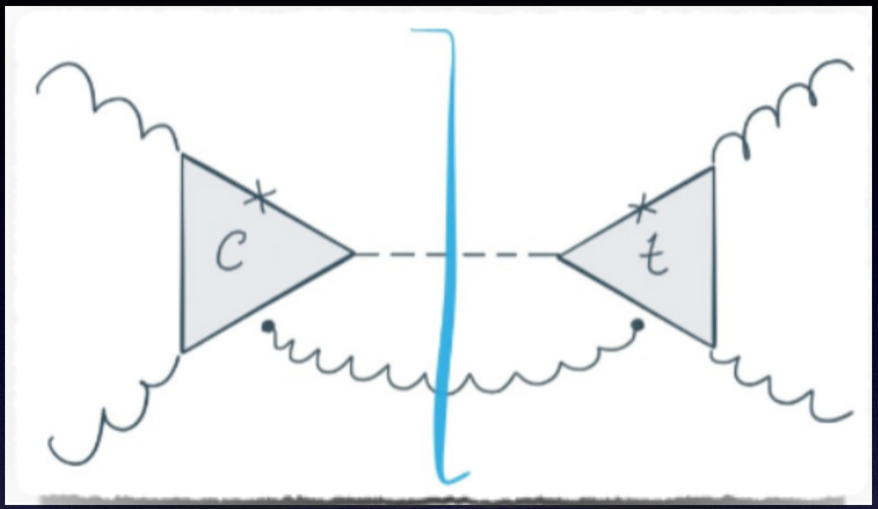
- we know quite well that the Higgs couples to vector bosons and to 3rd generation (heavy) quarks as predicted in the SM
- couplings to 2nd (and 1st) generation notoriously more difficult
- a number of ways to constraint the coupling of Higgs to charm:
  - rare exclusive Higgs decays
  - Higgs + charm production
  - constraint from VH (H →bb) including charm mis-tagging
  - constraint from Higgs width

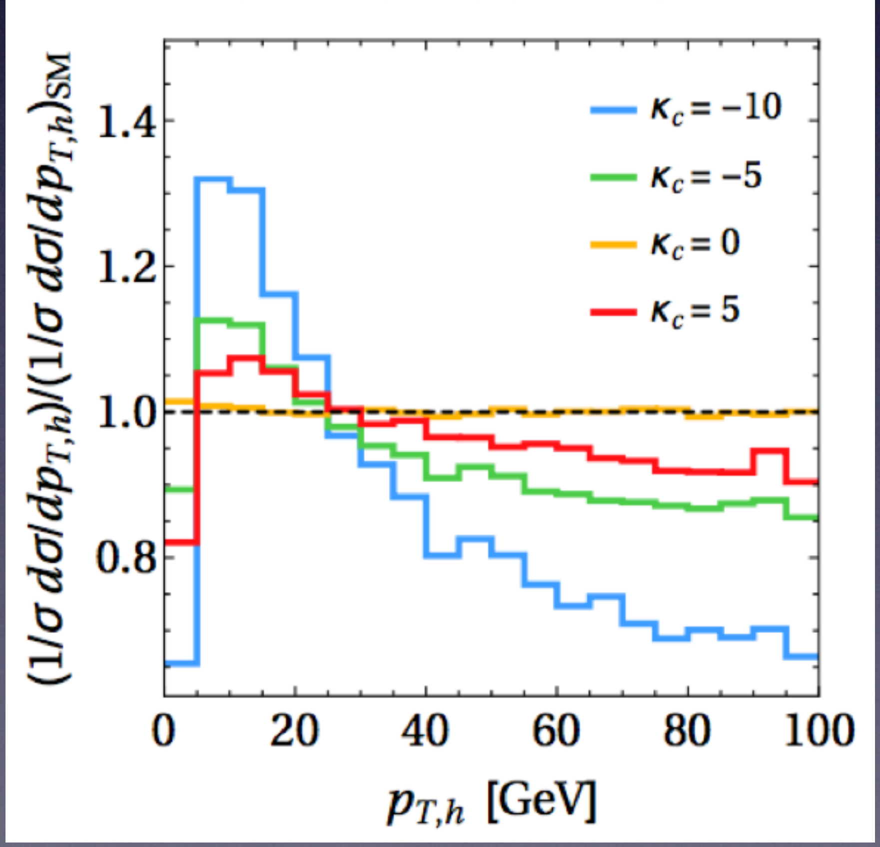
still largely unconstraint



2. Higgs coupling to 2^{nd} generation

- Higgs produced dominantly via top-quark loop (largest coupling)
- but interference effects with light quarks are not negligible
- provided theoretical predictions are accurate enough, constraint on charm (and possible strange) Yukawa can be significantly improved





Bishara, Haisch, Monni, Re ’16
[similar ideas in Soreq, Zhu, Zupan ’16]

similar sensitivity in leading jet p_t

2. Higgs coupling to 2nd generation

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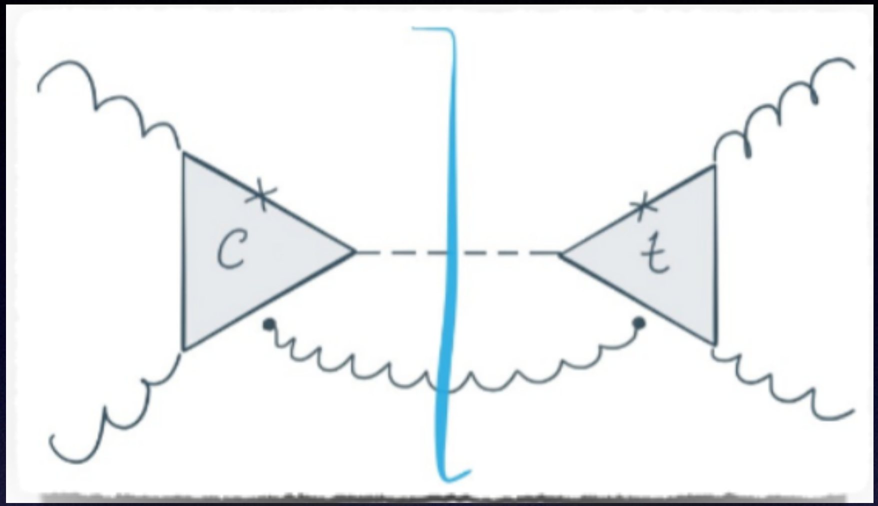

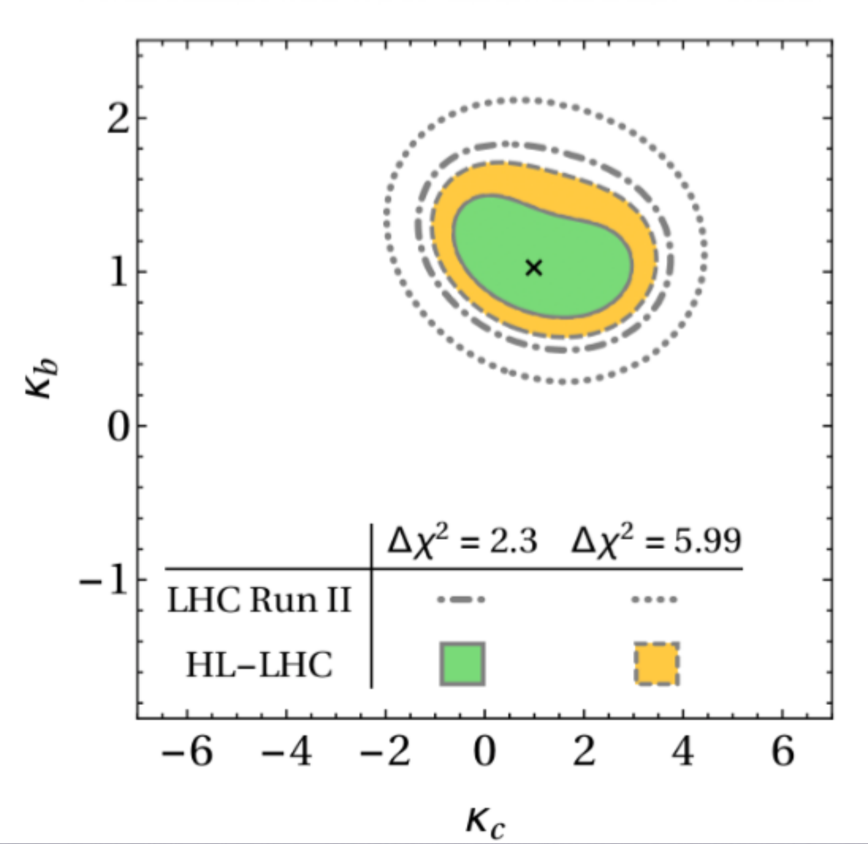

Bishara, Haisch, Monni, Re ’16
[similar ideas in Soreq, Zhu, Zupan ’16]

Conclusions

- The Higgs discovery leaves many open questions for the LHC Run II to explore
- Precision calculations, crucial to address those questions, are making giant steps: new techniques, new ideas, better observables
- Residual uncertainties at the level of the few percent for cross-sections (larger for distributions)
- Perturbative QCD uncertainty often already not the dominant theory uncertainty, other corrections must be included (EW corrections, PDF and α_s uncertainties, non-perturbative effects, corrections to large-m_t effective theory in gluon-fusion production ...)
- Progress in theory and experiment go truly hand in hand