QCD at the LHC: theoretical results

Giulia Zanderighi (CERN, Oxford, ERC)

Physics at the LHC and beyond
DESY Theory Workshop, 30^{th} September 2015

a personal selection of recent

QCD at the LHC: theoretical results

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Apologies for the important theoretical work that I will not have time to cover

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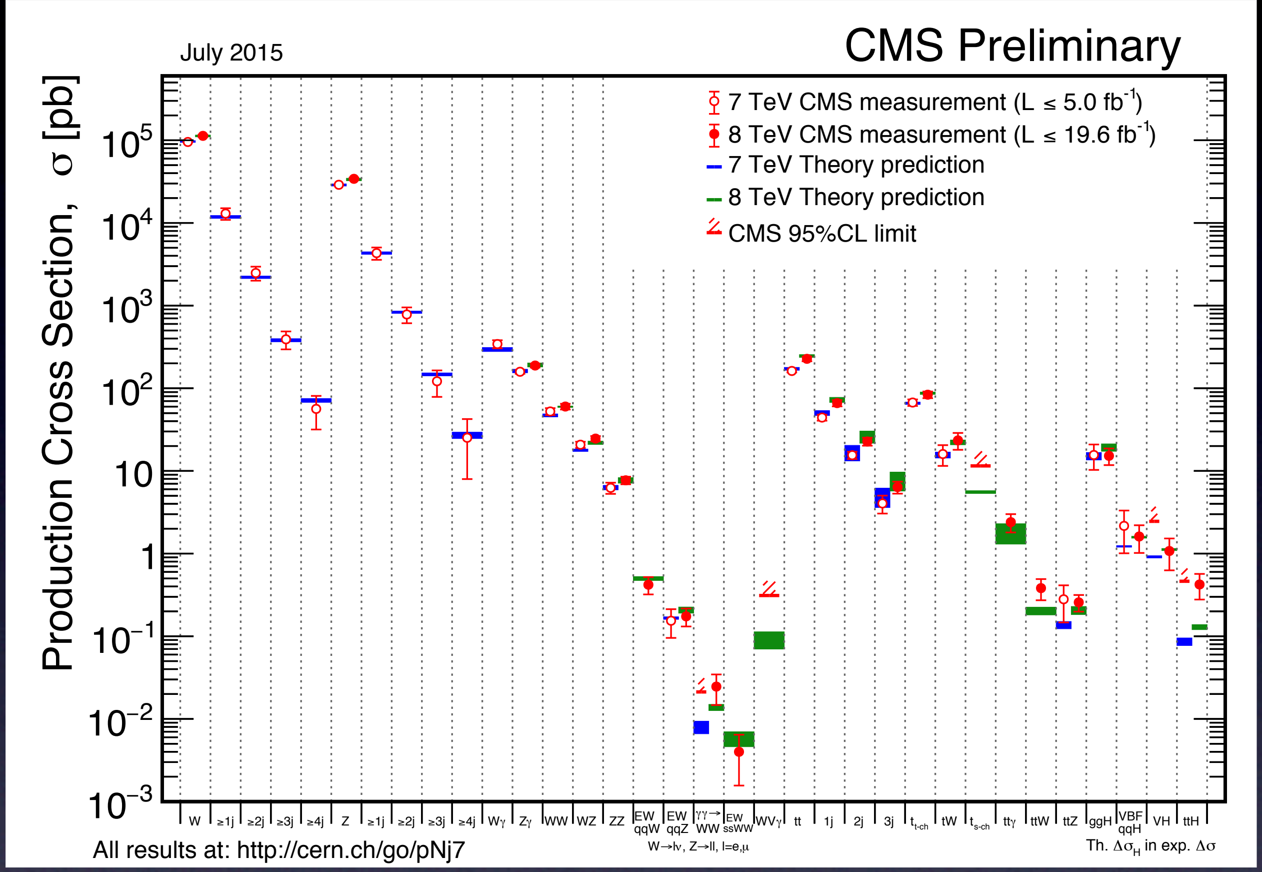
Tribute to LHC Run I

Standard Model fully re-discovered in Run I at the LHC e.g. Stairway to Heaven plots



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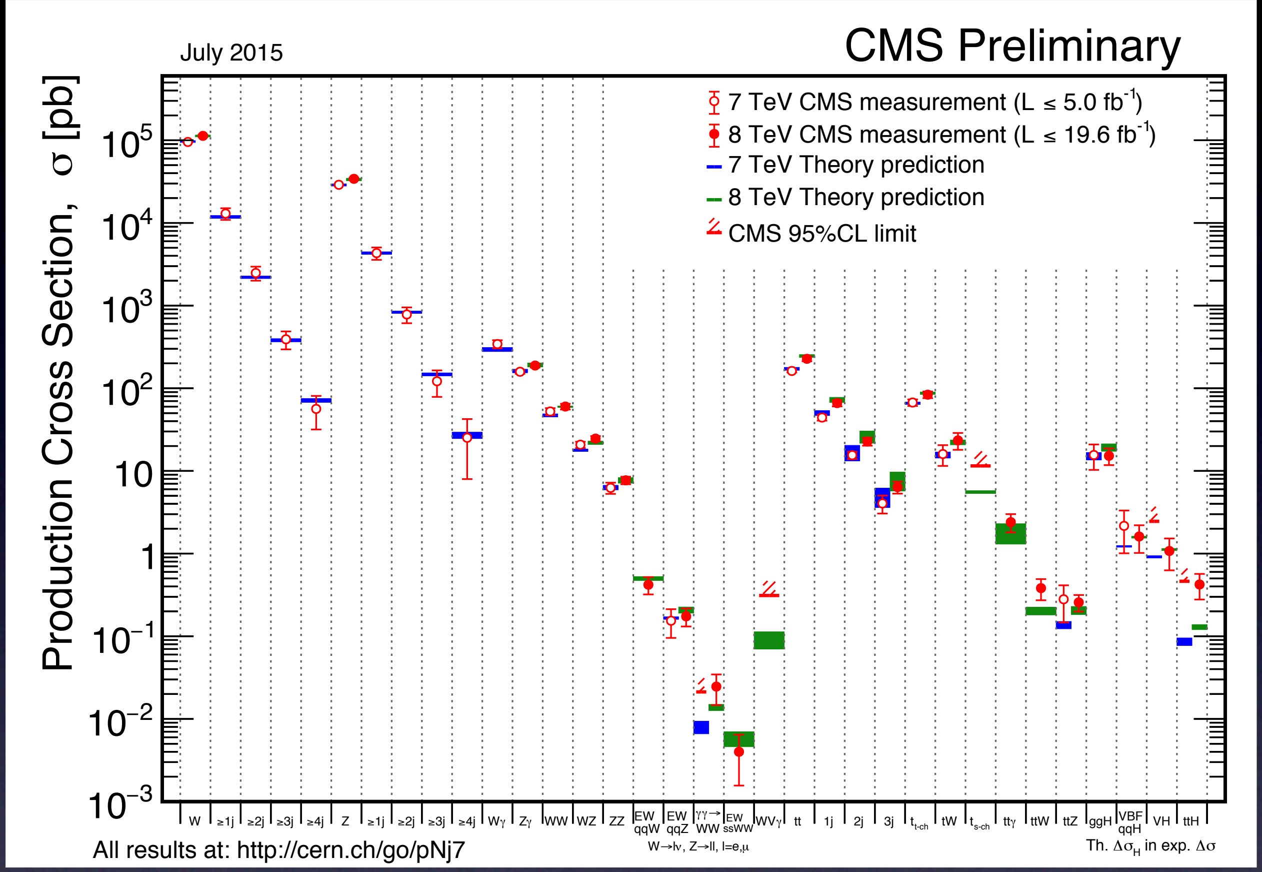
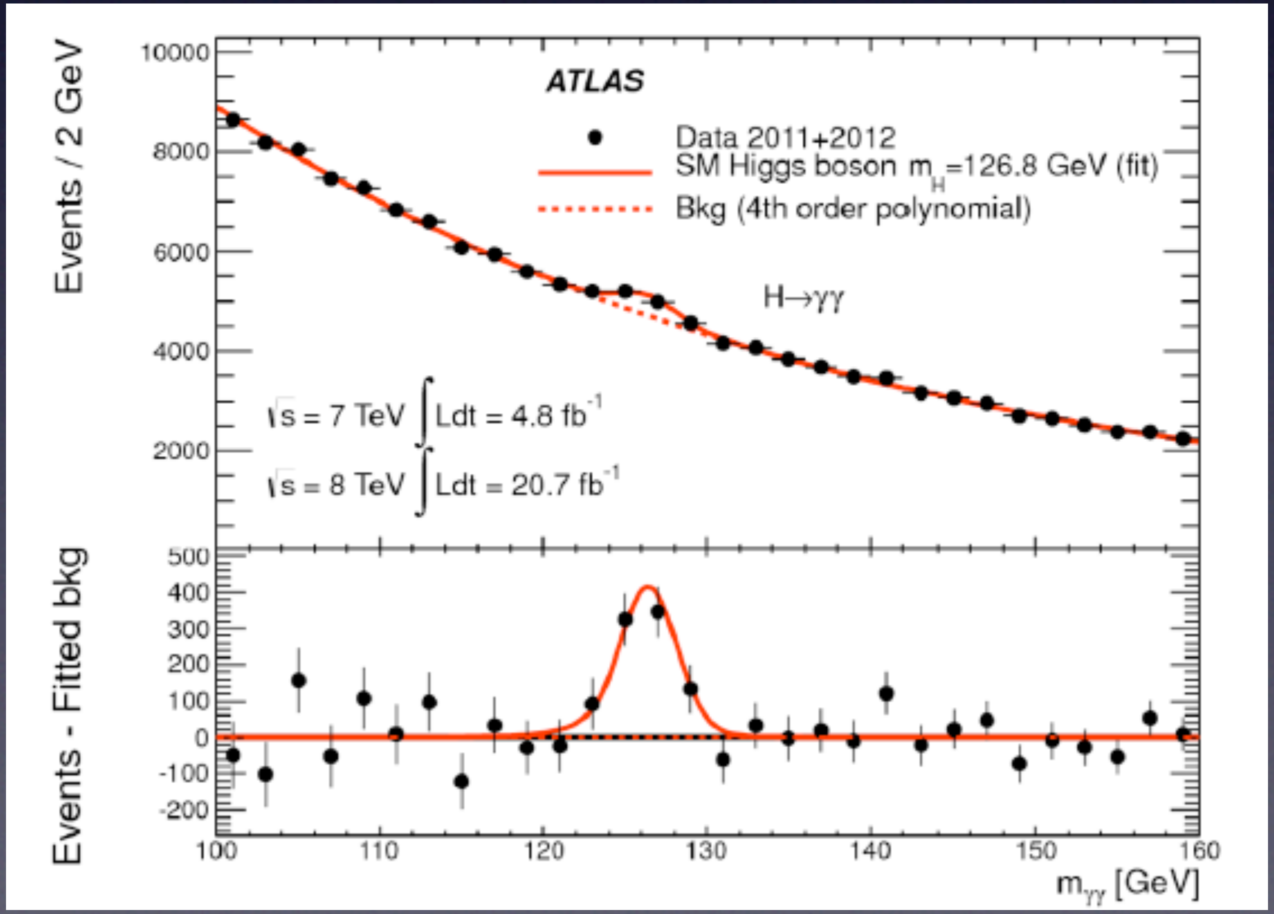




Higgs discovered even earlier than expected

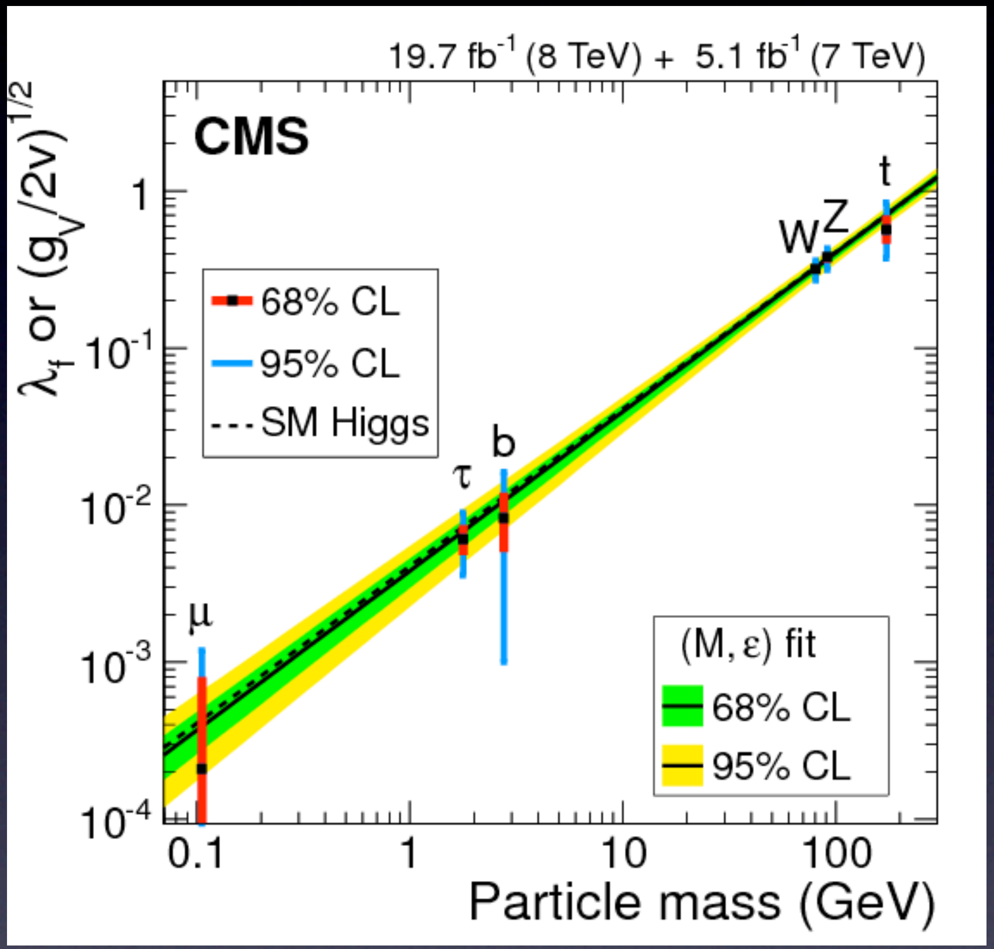
Tribute to LHC Run I

First studies of Higgs properties:

- consistent with $J^{CP}=0^{++}$
- SM Yukawa couplings
- m_H=125.09±0.21(stat.)±0.11(syst.) GeV

ATLAS & CMS 1503.07589

Looks very much like SM Higgs



Era of high-precision Higgs physics is about to start

While precise theoretical predictions were not crucial for the Higgs discovery, they are for precision measurements

New Physics in Run I?

Are there tensions between SM predictions and Run I LHC measurements (a.k.a. hints for New Physics)?

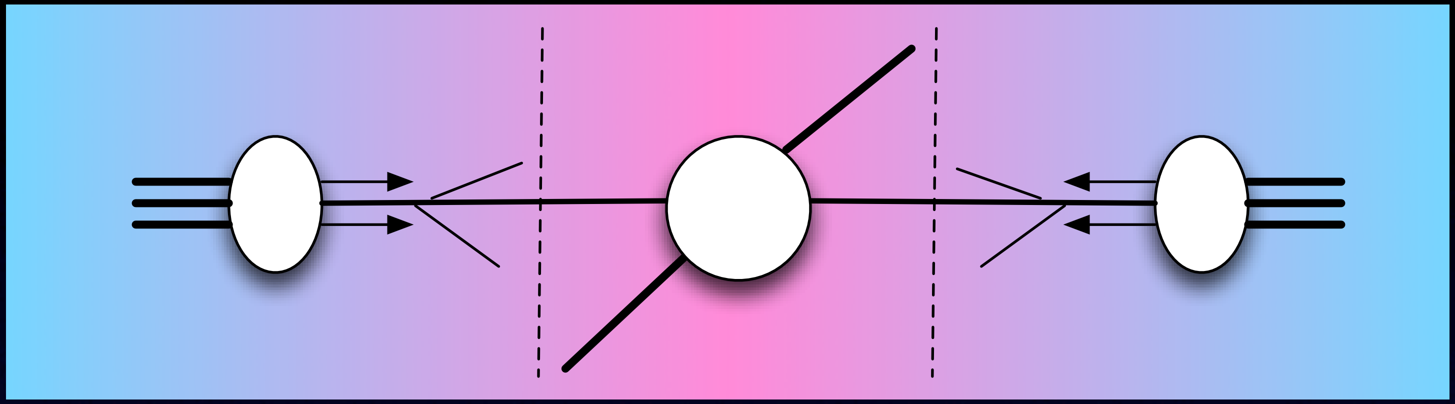
Thanks to superb signal and background modeling only few ones and not easy to accommodate in NP scenarios, e.g.

- excess in total WW cross-section, both ALTAS and CMS
- ATLAS excess in diboson production at 2 TeV (3.4σ), CMS also see anomalies, but below 2 TeV
- CMS anomaly in W_R search
- CMS two anomalies in di-leptoquark search
- top transverse momentum (high p_t)
- LHCb: B-meson anomalies (R_K, P_5', ...)
- branching of $H \to \tau\ \mu$
- ...

[...]

If deviations from SM are to be seen “indirectly” we need very solid theoretical predictions

Prerequisite: factorization



$$\frac{d\sigma_{\mathrm{pp}\to\mathrm{hadrons}}}{dX} = \sum_{a,b}\int dx_1 dx_2 f_a(x_1,\mu_F) f_b(x_2,\mu_F) \times \frac{d\hat{\sigma}_{\mathrm{ab}\to\mathrm{partons}}(\alpha_s(\mu_R),\mu_R,\mu_F)}{dX} + \mathcal{O}\left(\frac{\Lambda^n_{\mathrm{QCD}}}{Q^n}\right)$$

PDFs: extracted from data, but evolution is perturbative

Partonic cross-sections: expansion in the coupling constant

Ingredients for precision

According to this master formula, accurate predictions for hadronic cross-section require precise input for:

1. parton distribution functions (PDFs)
2. the strong coupling constant α_s
3. partonic cross-sections, mostly computed via
   - fixed order, perturbative calculations (LO, NLO, NNLO ...)
   - all-order resummed perturbative calculations (NLL, NNLL ...)
   - Monte Carlo event generators (includes hadronization and Underlying Event modeling)

Parton distribution functions

PDFs are an essential ingredient for the LHC program

Recent progress includes

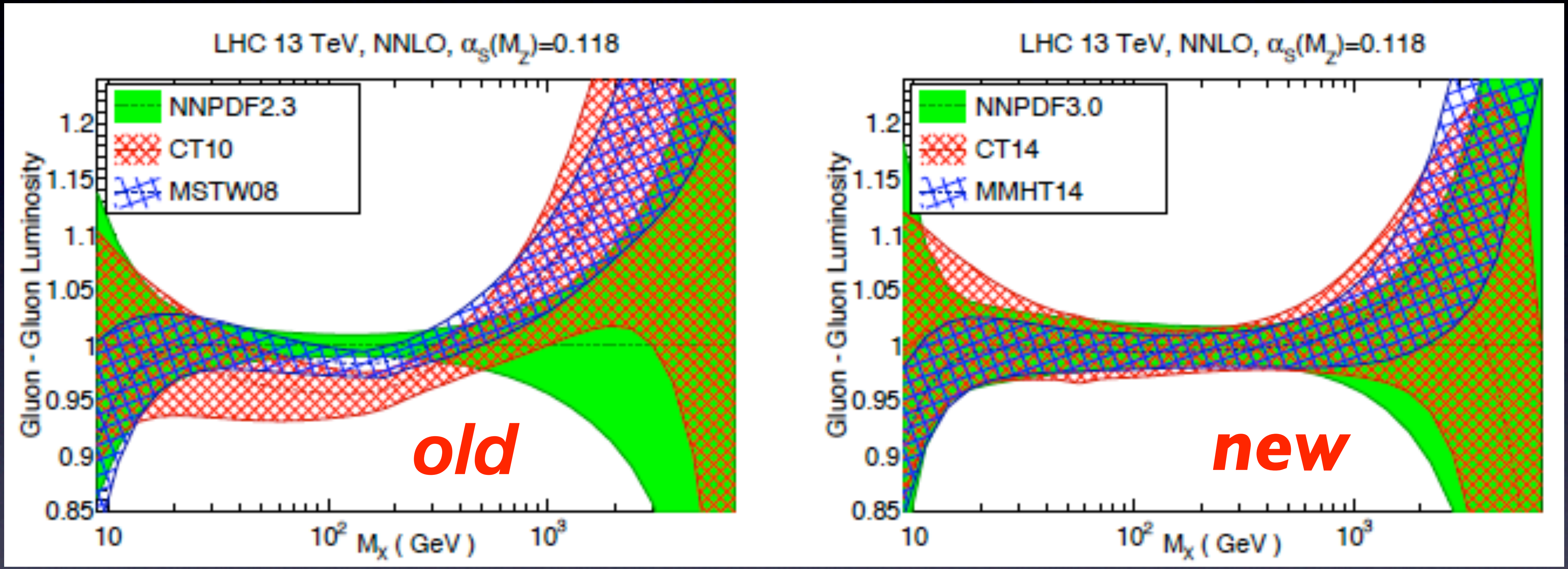
- better assessment of uncertainties (e.g. different groups now agree at the 1σ level where data is available)
- exploit wealth of new information from LHC Run I measurements
- progress in tools and methods to include these data in the fits

Collaborations regularly provide updated fits. Recent releases include ABM12, CT14, CJ12m GR14, HERAPDF2.0, MMHT14, NNPDF3.0

Important to always use up-to-date PDFs as recent PDFs include latest date, latest theoretical understanding and implementation (bugs in earlier PDFs corrected)

Parton distribution functions

Example: gluon-gluon luminosity as needed for Higgs measurements



- obvious improvement from older sets to newer ones
- agreement at 1σ between different PDFs for the gluon luminosity in the intermediate mass region relevant for Higgs studies (but larger differences at large M, key-region for NP searches)

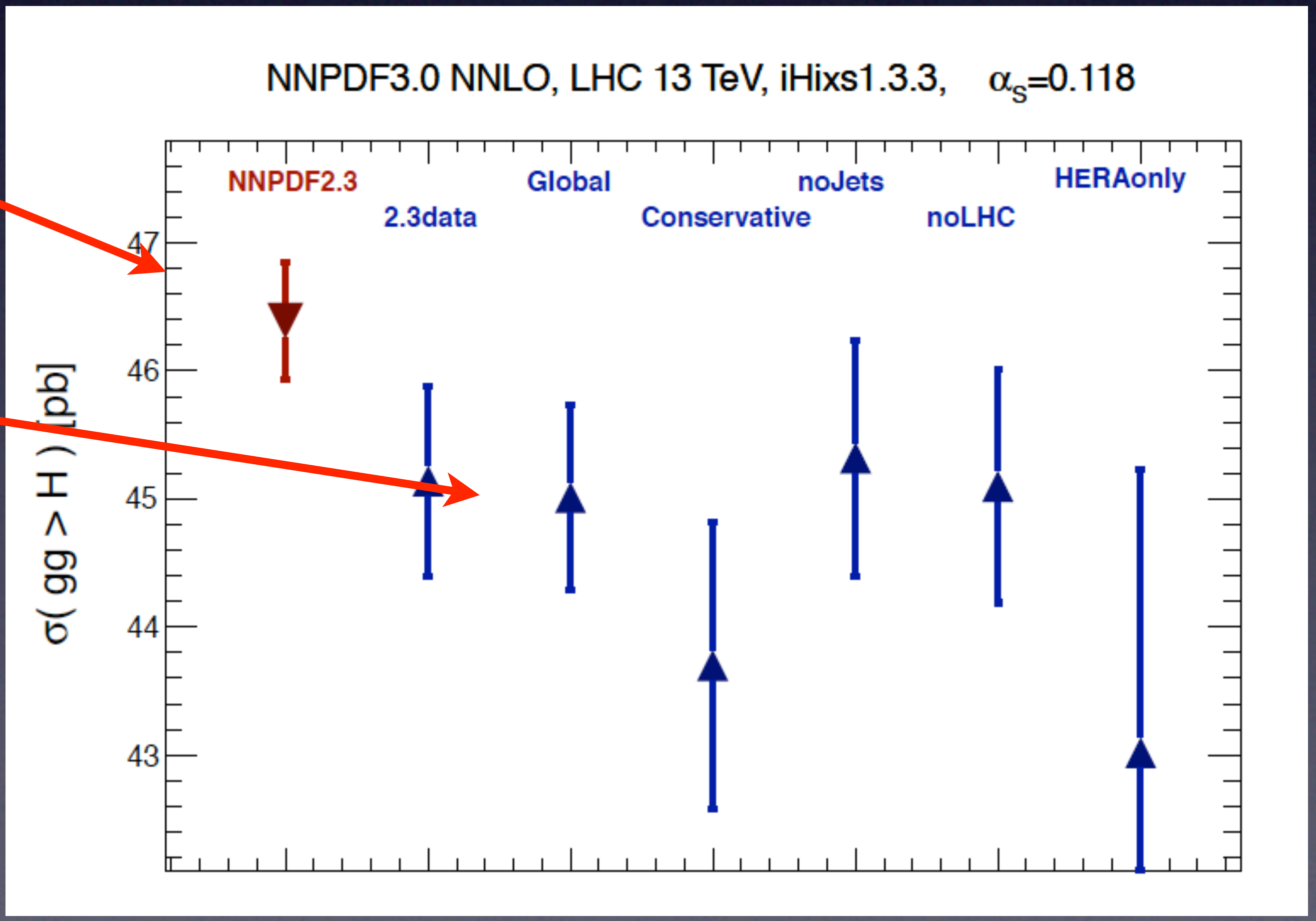
Parton distribution functions

Q: which PDF result changed mostly and why?
A: largest change is in the NNPDF result

NNPDF2.3

NNPDF3.0

3% difference in Higgs cross section



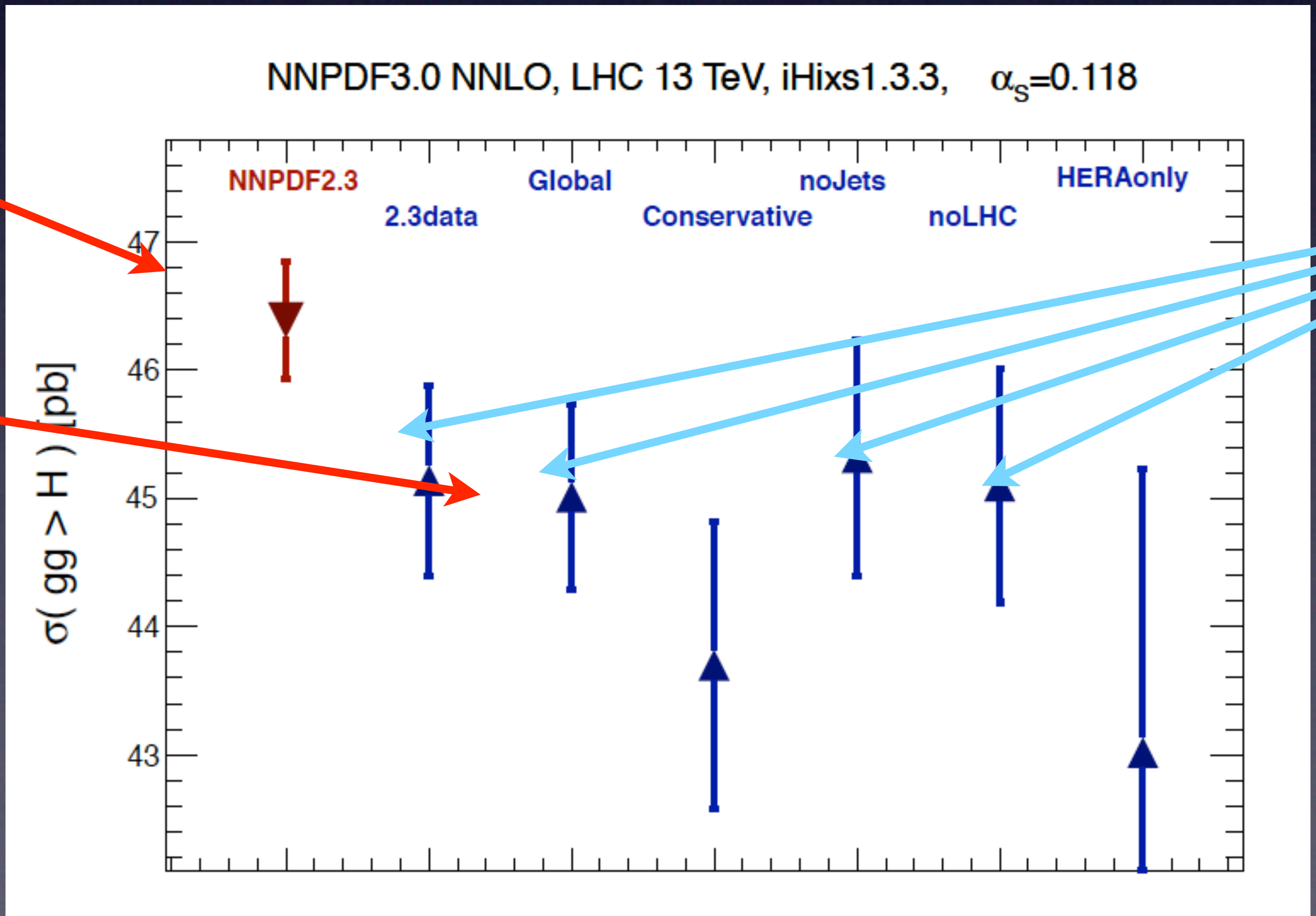
Parton distribution functions

Q: which PDF result changed mostly and why?
A: largest change is in the NNPDF result

Q: is it due to new data or to theoretical treatment?
A: Not due to inclusion of new data

NNPDF2.3

NNPDF3.0

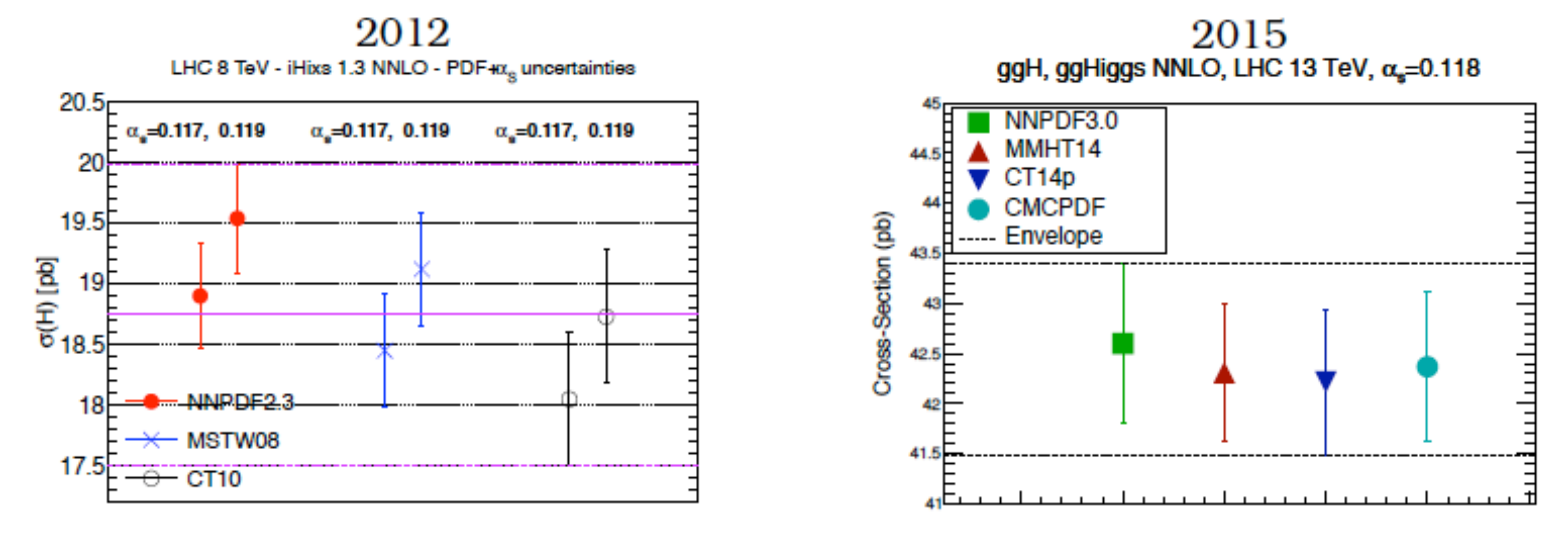


choice of data in the fit has little-to-no impact

3% difference in Higgs cross section

Parton distribution functions

Improved control on gluon distributions results in more consistent Higgs production cross-sections



- PDF uncertainty in the Higgs cross-section down to about 2-3%
- envelope of 3 PDFs (previous recommendation) no longer needed

PDFs from LHC data

Key PDF sensitive measurements at the LHC include

- jet production (inclusive, dijet, three jet, multi jet, ...)
  quark and gluons at medium/large x
- inclusive W/Z production and asymmetries
  handle on quark flavour separation and strangess, increase range in x wrt to Tevatron
- high- and low-mass Drell Yan production
  constraints at low and high x, increased sensitivity to photon PDF
- W+charm
  as a probe of strange-quark (besides neutrino data)
- top-quark pair production
  gluon PDF at large x from total cross-section, more to come from distributions
- ratio and double ratios at different collider energies
  PDFs probed at different x, but many theory and systematics cancel

A lot of information to improve PDFs is available.
To exploit it need highest theoretical precision for these processes

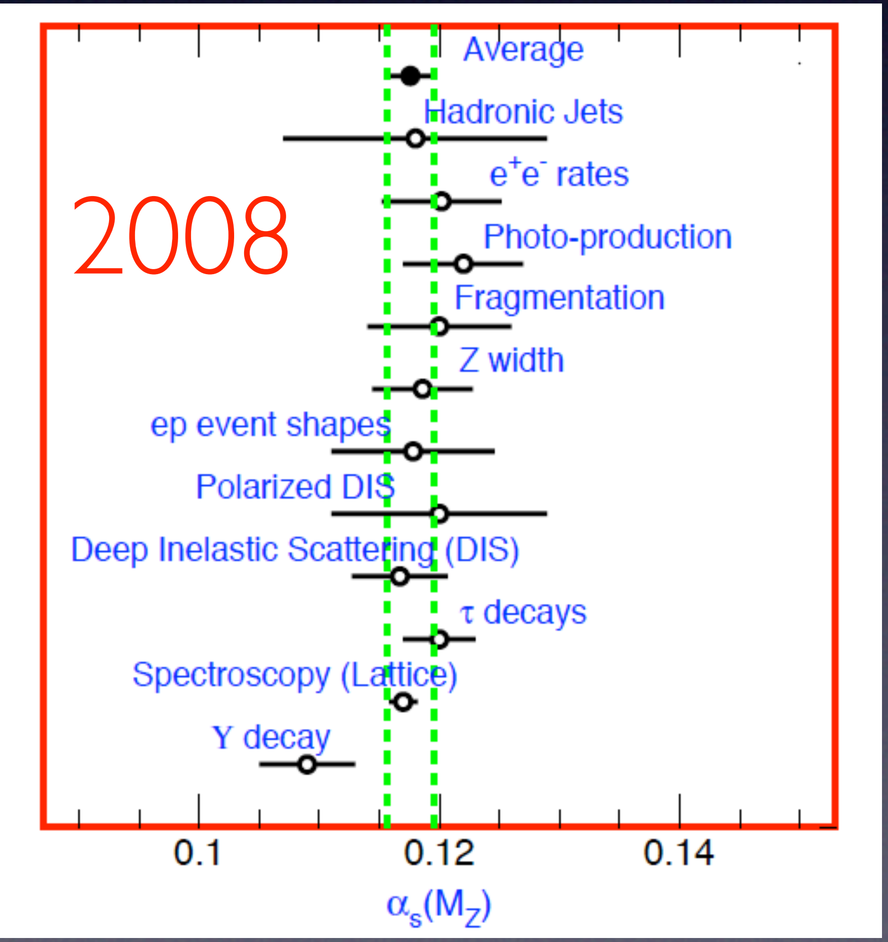
The coupling constant

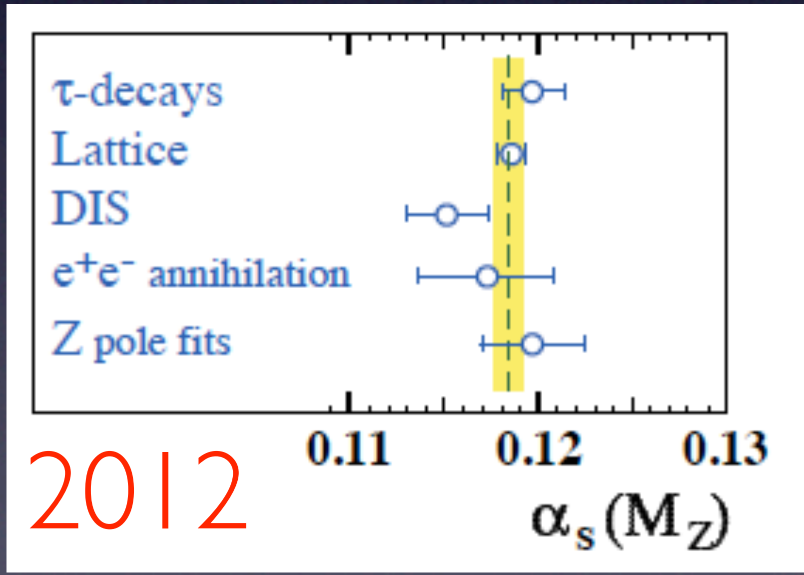
The PDG value of α_s stable in the last years

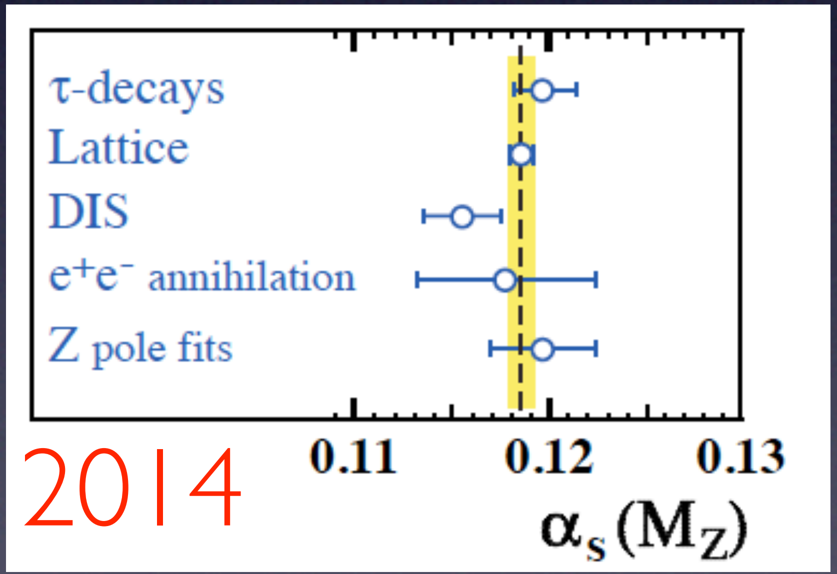
$$\alpha_s(M_Z) = 0.1176 \pm 0.0009 \quad \boxed{(2008)} \quad [0.1185 \text{ w.o. lattice result}]$$

$$\alpha_s(M_Z) = 0.1184 \pm 0.0007 \quad \boxed{(2012)}$$

$$\alpha_s(M_Z) = 0.1185 \pm 0.0006 \quad \boxed{(2014)}$$







Recently computed as average of averages (some of which contain inconsistent results)

The coupling constant

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$$\alpha_s(M_Z^2) = 0.1184 \pm 0.0006 \quad (\text{w/o } \tau \text{ results; } \chi_0^2/\text{d.o.f.} = 2.3/3),$$
$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0012 \quad (\text{w/o lattice results; } \chi_0^2/\text{d.o.f.} = 2.9/3),$$
$$\alpha_s(M_Z^2) = 0.1187 \pm 0.0007 \quad (\text{w/o DIS results; } \chi_0^2/\text{d.o.f.} = 0.6/3),$$
$$\alpha_s(M_Z^2) = 0.1185 \pm 0.0005 \quad (\text{w/o } e^+e^- \text{ results; } \chi_0^2/\text{d.o.f.} = 2.9/3), \text{ and}$$
$$\alpha_s(M_Z^2) = 0.1185 \pm 0.0005 \quad (\text{w/o e.w. precision fit; } \chi_0^2/\text{d.o.f.} = 2.7/3).$$

Also stable against elimination of classes of results used in the fit

But a number of outlier results exist

$$\alpha_s(M_Z) = 0.1135 \pm 0.0010$$

Thrust [Abbate et al '10; also Thrust cumulants '12]

$$\alpha_s(M_Z) = 0.1134 \pm 0.0011$$

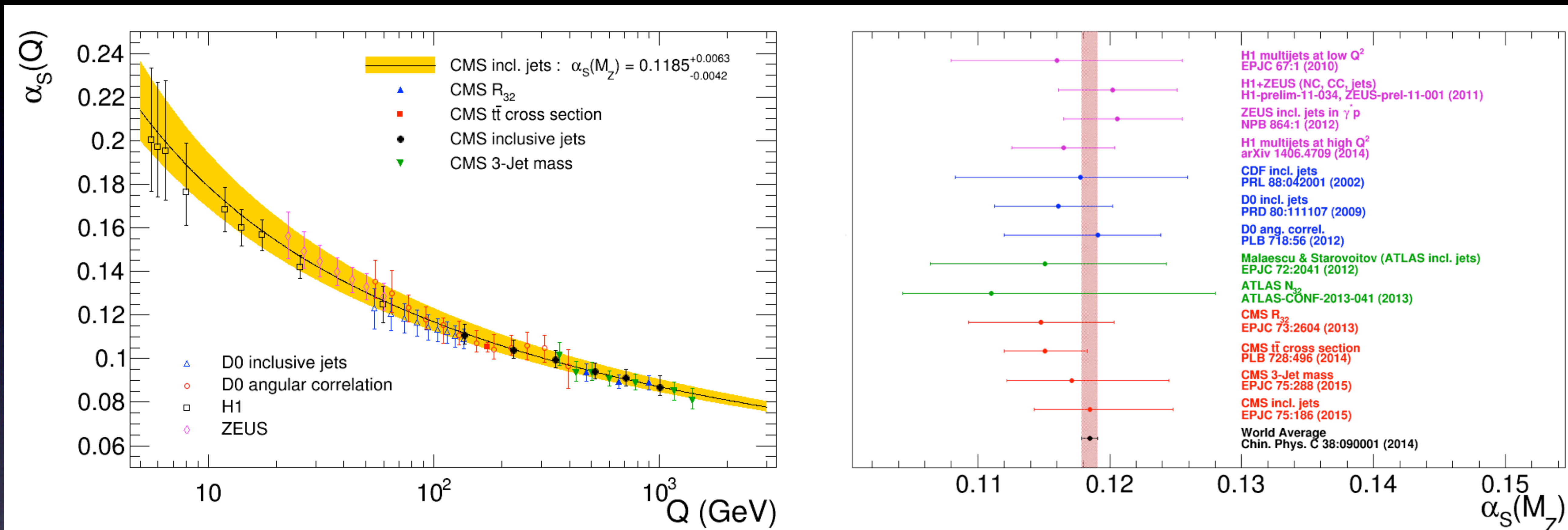
Fit with PDFs [Alekhin et al '13]

$$\alpha_s(M_Z) = 0.1112 \pm 0.0015$$

C-parameter [Hoang et al '15]

...

α_s at the LHC



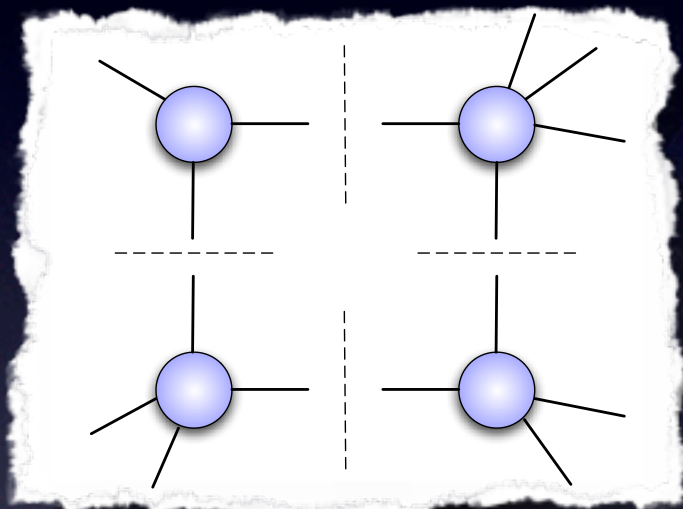
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined#Summary_of_alphaS_running

- already fantastic proof of α_s running up to TeV region
- more to come with Run II

NLO calculations

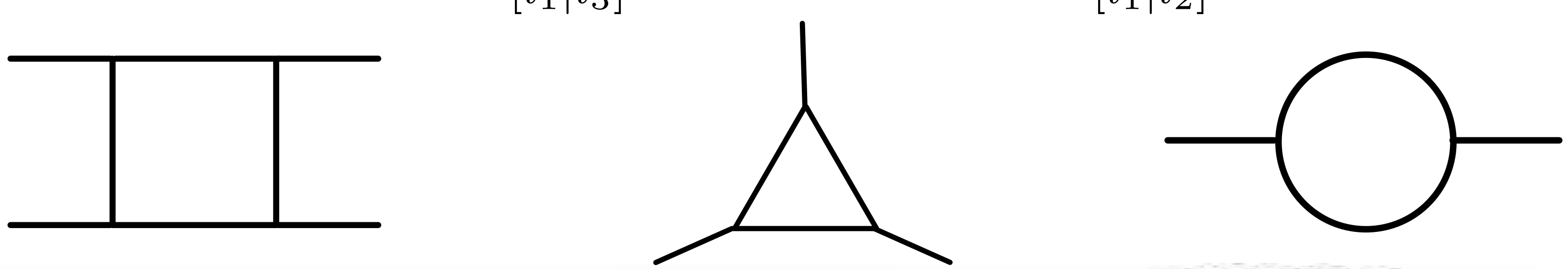
A number of breakthrough ideas developed in the last 10 years, most notably

- sew together tree level amplitudes to compute loop amplitudes [on-shell intermediate states, cuts, generalized unitarity ...]



- OPP: extract coefficients of master integrals by evaluating the amplitudes at specific values of the loop momentum [algebraic method]

$$\mathcal{A}_N = \sum_{[i_1|i_4]} \left(d_{i_1 i_2 i_3 i_4} \; I^{(D)}_{i_1 i_2 i_3 i_4} \right) + \sum_{[i_1|i_3]} \left(c_{i_1 i_2 i_3} \; I^{(D)}_{i_1 i_2 i_3} \right) + \sum_{[i_1|i_2]} \left(b_{i_1 i_2} \; I^{(D)}_{i_1 i_2} \right) + \mathcal{R}$$



Bern, Dixon, Kosower; Britto, Cachazo, Feng; Ossola, Pittau, Papadopoulos; Ellis, Giele, Kunszt, Melnikov; ....

NLO calculations

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

- the automation of NLO QCD corrections is mostly considered a solved problem
- high-multiplicity processes still difficult (long run-time on clusters to obtain stable distributions, numerical instabilities).
  Edge: 4 to 6 particles in the final state, depends on the process
- also loop-induced processes automated (enhanced by gluon PDF) Hirschi, Mattelaer '15
- comparison to NLO is now the standard in most physics analysis

NLO automation

Hirschi, Frederix, Garzelli, Maltoni, Pittau 1103.0621

Example: heavy quarks and jets at NLO

	Process	Syntax	Cross section (pb)			
Heavy quarks+vector bosons			LO 13 TeV		NLO 13 TeV	
e.1	$pp \to W^\pm b\bar{b}$ (4f)	`p p > wpm b b~`	$3.074 \pm 0.002 \cdot 10^{2}$	${}^{+42.3\%}_{-29.2\%}\ {}^{+2.0\%}_{-1.6\%}$	$8.162 \pm 0.034 \cdot 10^{2}$	${}^{+29.8\%}_{-23.6\%}\ {}^{+1.5\%}_{-1.2\%}$
e.2	$pp \to Z b\bar{b}$ (4f)	`p p > z b b~`	$6.993 \pm 0.003 \cdot 10^{2}$	${}^{+33.5\%}_{-24.4\%}\ {}^{+1.0\%}_{-1.4\%}$	$1.235 \pm 0.004 \cdot 10^{3}$	${}^{+19.9\%}_{-17.4\%}\ {}^{+1.0\%}_{-1.4\%}$
e.3	$pp \to \gamma b\bar{b}$ (4f)	`p p > a b b~`	$1.731 \pm 0.001 \cdot 10^{3}$	${}^{+51.9\%}_{-34.8\%}\ {}^{+1.6\%}_{-2.1\%}$	$4.171 \pm 0.015 \cdot 10^{3}$	${}^{+33.7\%}_{-27.1\%}\ {}^{+1.4\%}_{-1.9\%}$
e.4*	$pp \to W^\pm b\bar{b} j$ (4f)	`p p > wpm b b~ j`	$1.861 \pm 0.003 \cdot 10^{2}$	${}^{+42.5\%}_{-27.7\%}\ {}^{+0.7\%}_{-0.7\%}$	$3.957 \pm 0.013 \cdot 10^{2}$	${}^{+27.0\%}_{-21.0\%}\ {}^{+0.7\%}_{-0.6\%}$
e.5*	$pp \to Z b\bar{b} j$ (4f)	`p p > z b b~ j`	$1.604 \pm 0.001 \cdot 10^{2}$	${}^{+42.4\%}_{-27.6\%}\ {}^{+0.9\%}_{-1.1\%}$	$2.805 \pm 0.009 \cdot 10^{2}$	${}^{+21.0\%}_{-17.6\%}\ {}^{+0.8\%}_{-1.0\%}$
e.6*	$pp \to \gamma b\bar{b} j$ (4f)	`p p > a b b~ j`	$7.812 \pm 0.017 \cdot 10^{2}$	${}^{+51.2\%}_{-32.0\%}\ {}^{+1.0\%}_{-1.5\%}$	$1.233 \pm 0.004 \cdot 10^{3}$	${}^{+18.9\%}_{-19.9\%}\ {}^{+1.0\%}_{-1.5\%}$
e.7	$pp \to t\bar{t} W^\pm$	`p p > t t~ wpm`	$3.777 \pm 0.003 \cdot 10^{-1}$	${}^{+23.9\%}_{-18.0\%}\ {}^{+2.1\%}_{-1.6\%}$	$5.662 \pm 0.021 \cdot 10^{-1}$	${}^{+11.2\%}_{-10.6\%}\ {}^{+1.7\%}_{-1.3\%}$
e.8	$pp \to t\bar{t} Z$	`p p > t t~ z`	$5.273 \pm 0.004 \cdot 10^{-1}$	${}^{+30.5\%}_{-21.8\%}\ {}^{+1.8\%}_{-2.1\%}$	$7.598 \pm 0.026 \cdot 10^{-1}$	${}^{+9.7\%}_{-11.1\%}\ {}^{+1.9\%}_{-2.2\%}$
e.9	$pp \to t\bar{t} \gamma$	`p p > t t~ a`	$1.204 \pm 0.001 \cdot 10^{0}$	${}^{+29.6\%}_{-21.3\%}\ {}^{+1.6\%}_{-1.8\%}$	$1.744 \pm 0.005 \cdot 10^{0}$	${}^{+9.8\%}_{-11.0\%}\ {}^{+1.7\%}_{-2.0\%}$
e.10*	$pp \to t\bar{t} W^\pm j$	`p p > t t~ wpm j`	$2.352 \pm 0.002 \cdot 10^{-1}$	${}^{+40.9\%}_{-27.1\%}\ {}^{+1.3\%}_{-1.0\%}$	$3.404 \pm 0.011 \cdot 10^{-1}$	${}^{+11.2\%}_{-14.0\%}\ {}^{+1.2\%}_{-0.9\%}$
e.11*	$pp \to t\bar{t} Z j$	`p p > t t~ z j`	$3.953 \pm 0.004 \cdot 10^{-1}$	${}^{+46.2\%}_{-29.5\%}\ {}^{+2.7\%}_{-3.0\%}$	$5.074 \pm 0.016 \cdot 10^{-1}$	${}^{+7.0\%}_{-12.3\%}\ {}^{+2.5\%}_{-2.9\%}$
e.12*	$pp \to t\bar{t} \gamma j$	`p p > t t~ a j`	$8.726 \pm 0.010 \cdot 10^{-1}$	${}^{+45.4\%}_{-29.1\%}\ {}^{+2.3\%}_{-2.6\%}$	$1.135 \pm 0.004 \cdot 10^{0}$	${}^{+7.5\%}_{-12.2\%}\ {}^{+2.2\%}_{-2.5\%}$
e.13*	$pp \to t\bar{t} W^- W^+$ (4f)	`p p > t t~ w+ w-`	$6.675 \pm 0.006 \cdot 10^{-3}$	${}^{+30.9\%}_{-21.9\%}\ {}^{+2.1\%}_{-2.0\%}$	$9.904 \pm 0.026 \cdot 10^{-3}$	${}^{+10.9\%}_{-11.8\%}\ {}^{+2.1\%}_{-2.1\%}$
e.14*	$pp \to t\bar{t} W^\pm Z$	`p p > t t~ wpm z`	$2.404 \pm 0.002 \cdot 10^{-3}$	${}^{+26.6\%}_{-19.6\%}\ {}^{+2.5\%}_{-1.8\%}$	$3.525 \pm 0.010 \cdot 10^{-3}$	${}^{+10.6\%}_{-10.8\%}\ {}^{+2.3\%}_{-1.6\%}$
e.15*	$pp \to t\bar{t} W^\pm \gamma$	`p p > t t~ wpm a`	$2.718 \pm 0.003 \cdot 10^{-3}$	${}^{+25.4\%}_{-18.9\%}\ {}^{+2.3\%}_{-1.8\%}$	$3.927 \pm 0.013 \cdot 10^{-3}$	${}^{+10.3\%}_{-10.4\%}\ {}^{+2.0\%}_{-1.5\%}$
e.16*	$pp \to t\bar{t} ZZ$	`p p > t t~ z z`	$1.349 \pm 0.014 \cdot 10^{-3}$	${}^{+29.3\%}_{-21.1\%}\ {}^{+1.7\%}_{-1.5\%}$	$1.840 \pm 0.007 \cdot 10^{-3}$	${}^{+7.9\%}_{-9.9\%}\ {}^{+1.7\%}_{-1.5\%}$
e.17*	$pp \to t\bar{t} Z\gamma$	`p p > t t~ z a`	$2.548 \pm 0.003 \cdot 10^{-3}$	${}^{+30.1\%}_{-21.5\%}\ {}^{+1.7\%}_{-1.6\%}$	$3.656 \pm 0.012 \cdot 10^{-3}$	${}^{+9.7\%}_{-11.0\%}\ {}^{+1.8\%}_{-1.9\%}$
e.18*	$pp \to t\bar{t} \gamma\gamma$	`p p > t t~ a a`	$3.272 \pm 0.006 \cdot 10^{-3}$	${}^{+28.4\%}_{-20.6\%}\ {}^{+1.3\%}_{-1.1\%}$	$4.402 \pm 0.015 \cdot 10^{-3}$	${}^{+7.8\%}_{-9.7\%}\ {}^{+1.4\%}_{-1.4\%}$

Similar tables for
- boson+jets
- diboson+jets
- triboson+jets
- four bosons
- heavy quarks + jets
- heavy quarks + bosons
- single top
- single Higgs
- Higgs pair
- ...

Attention shifted towards NLO electro-weak corrections

First automated approaches to NLO EW Chiesa, Greiner, Tramontano 1507.08579

NLO EW corrections

NLO EW corrections more important for Run II:

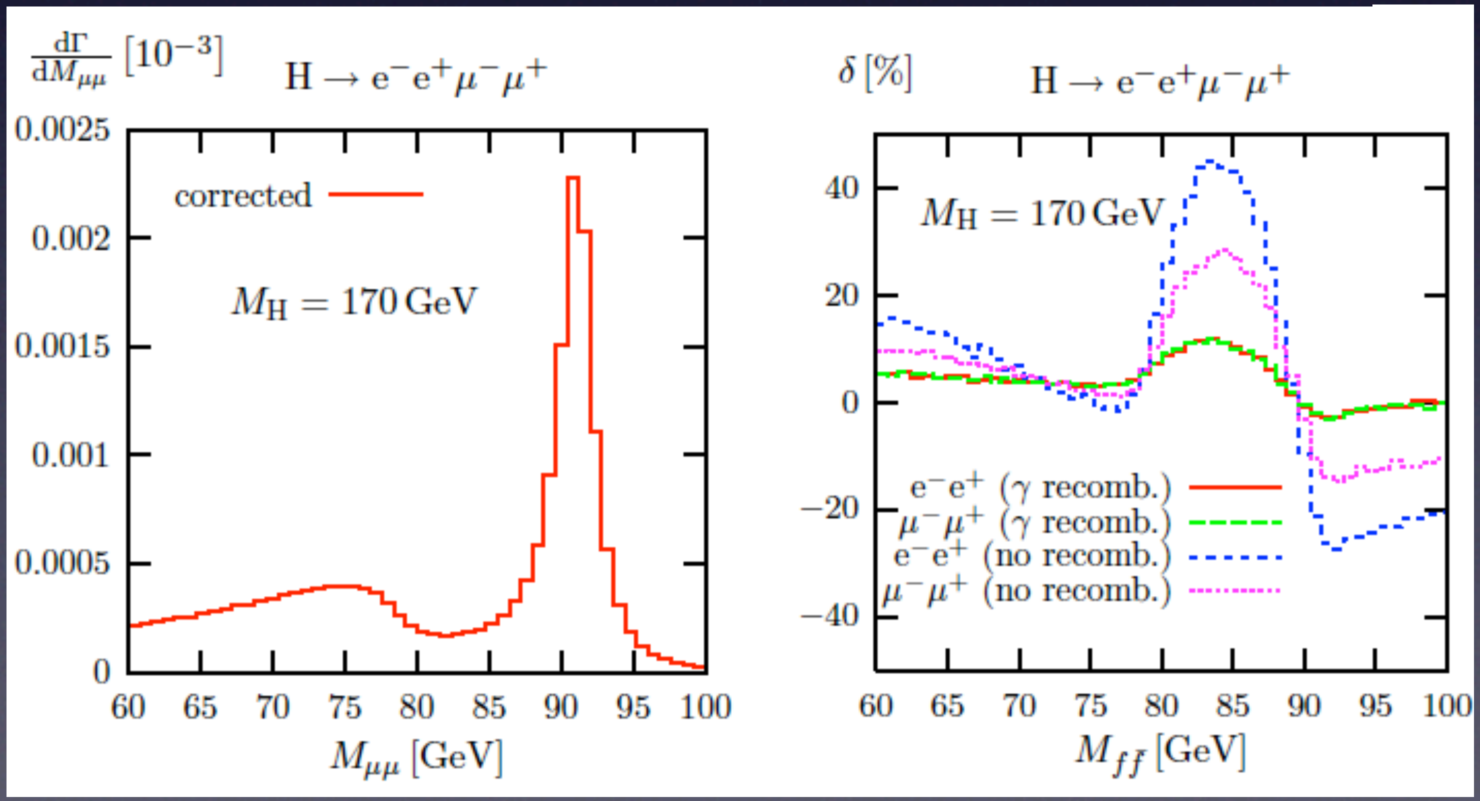
- Run II energy extends more in the TeV region where EW corrections are enhanced by large EW Sudakov logarithms
- enhancement by photon emissions (mass-singulars logs, photon PDF)
- high-precision measurements at the LHC (most notably M_W)
- with higher luminosity many cross-sections will reach few percent precision
- naively, NNLO QCD “counts” as NLO EW, $\mathcal{O}(\alpha_s^2) \sim \mathcal{O}(\alpha_{em})$, hence to increase precision both must be included
- expertise on NLO QCD corrections can be exploited, but theoretically more rich, non-Abelian charge of W/Z are open, so Bloch Nordsieck theorem can not be applied

NLO EW corrections

NLO EW corrections are

- most important close to peaks of invariant mass distributions and in high-p_t tails
- often dominant EW corrections from QED

Example: NLO EW correction to Z invariant mass in $H \to ZZ \to e^+e^-\mu^+\mu^-$



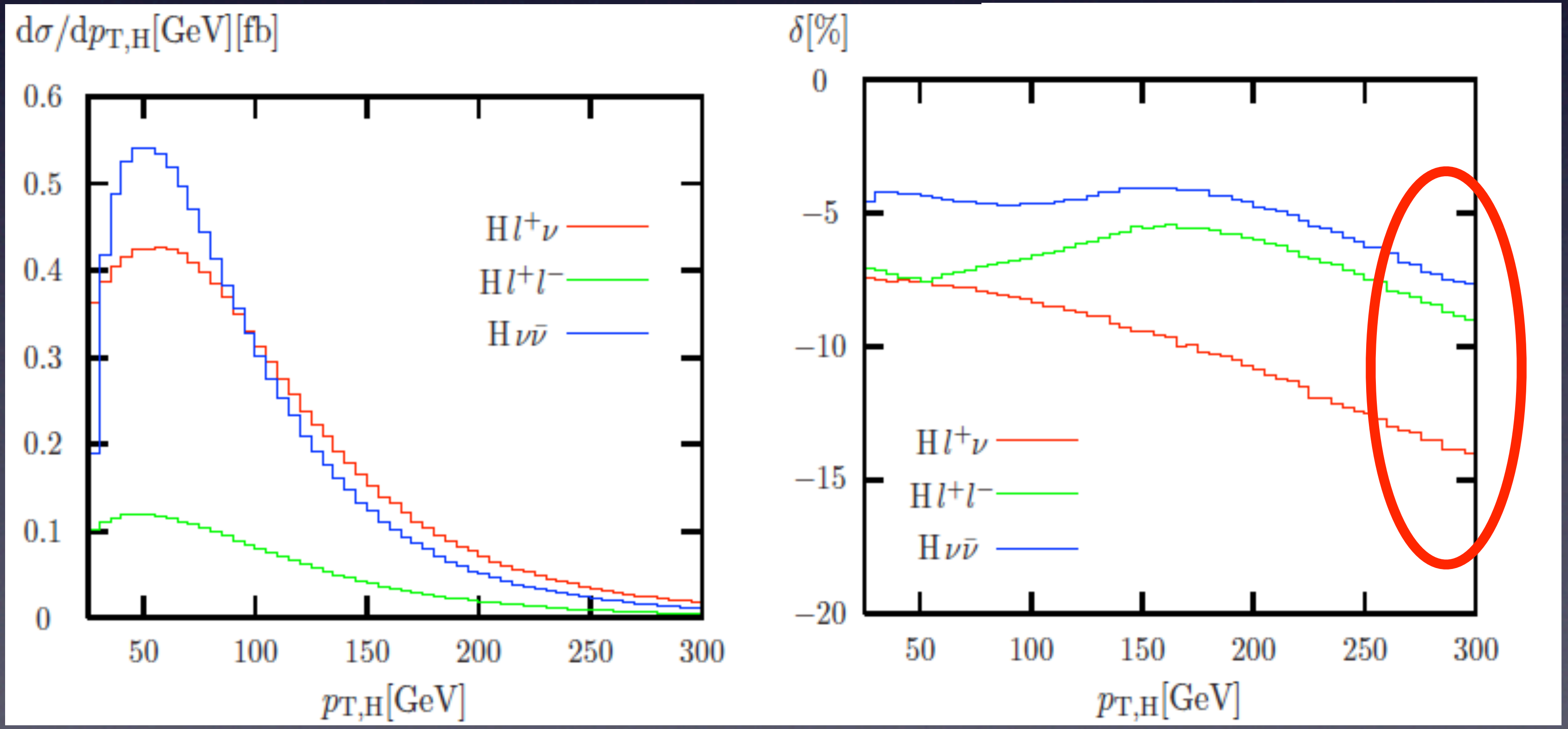
Bredenstein, Denner, Dittmeier, Weber '06

NLO EW corrections

NLO EW corrections are

- most important close to peaks of invariant mass distributions and in high-p_t tails
- often dominant EW corrections from QED

Example: NLO EW corrections to $p_{t,H}$ distributions



Denner, Dittmeier, Kallweit, Muck ’11

NLO EW corrections

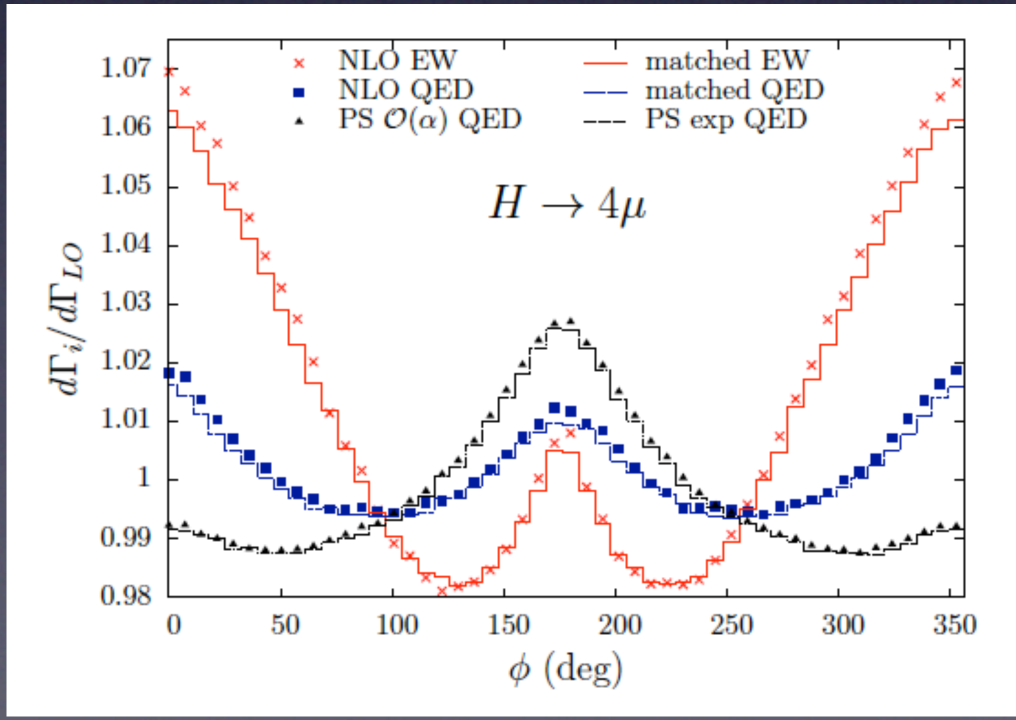
NLO EW corrections are

- most important close to peaks of invariant mass distributions and in high-p_t tails
- often dominant EW corrections from QED

but not always the case

Example: angle between Higgs Z-decay planes in the H-rest frame (probe of HZZ coupling, small CP-odd component ...)

Boselli et al. 1503.07394



- 2-7% effects
- EW effects not dominated by QED
- parton shower approximation off

↪ **percent precision requires knowledge of full EW corrections**

NNLO revolution

NNLO is one of the most active areas in QCD now

After pioneering calculations for Higgs and Drell Yan more than 10 years ago, only recently many 2 → 2 processes computed at NNLO

NNLO most important in three different situations

Benchmark processes (measured with highest accuracy)	Input to PDFs fits + backgrounds to Higgs studies	Very large NLO corrections (moderate precision needs NNLO)
- $Z \to l^+l^-$ - $W \to l\nu$ - ...	- Diboson - Boson + jet - top-pairs - ...	- Higgs - Higgs + jet - ...

Plus more reliable estimate of theory uncertainty

Still early days, but in the few cases examined (e.g. Higgs and Drell Yan, VV, Vγ, top ...), better agreement with data at NNLO

NNLO

While at NLO the bottleneck has been for a long time the calculation of virtual (one-loop) amplitudes, at NNLO the bottleneck comes mostly from finding a method to cancel divergences before numerical integration.

Two main approaches

Slicing:
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.

Subtraction:
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

NNLO

Different practical realizations:

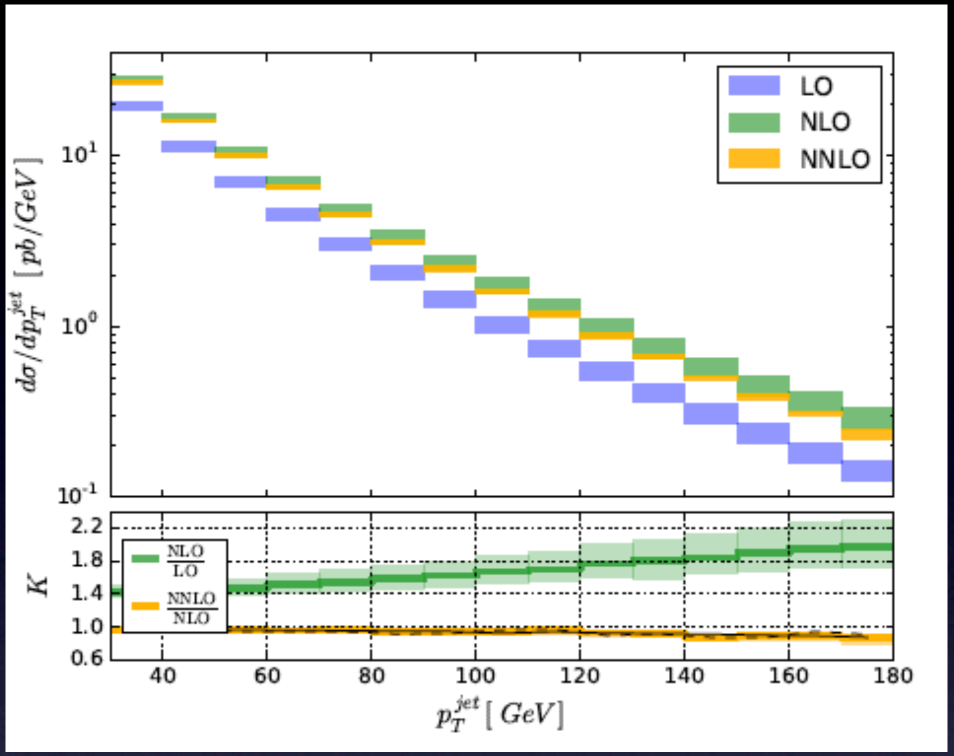
- antenna subtraction
- q_T subtraction (slicing)
- colorful subtraction
- sector improved residue subtraction scheme
- projection to Born (P2B) method
- N-jettiness subtraction/slicing

Obviously, two-loop integrals are also needed. Lots of progress here too. I will not discuss this here, only mention Henn's conjecture to compute integrals using differential equations

NNLO V plus one jet

W+1jet

1504.02131



$p_T^{jet} > 30$ GeV, $\lvert\eta_{jet}\rvert < 2.4$	
Leading order:	533^{+39}_{-38} pb
Next-to-leading order:	797^{+63}_{-49} pb
Next-to-next-to-leading order:	787^{+0}_{-8} pb

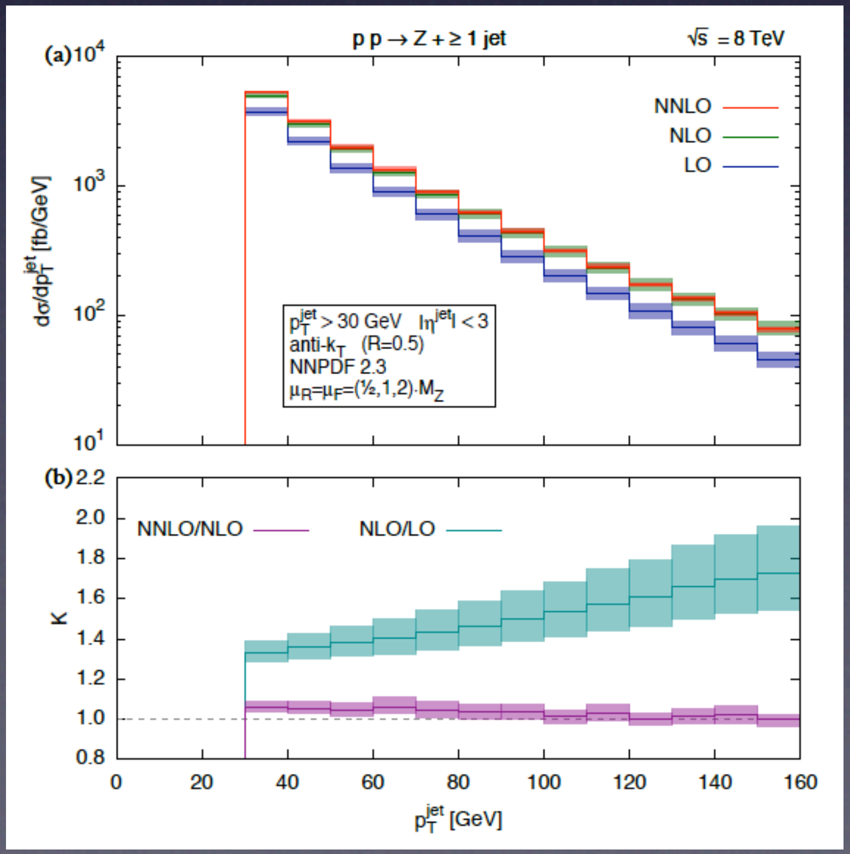
- flat K-factor (≈1)
- huge reduction of theory error

Z+1jet

1507.02850

$$\sigma_{LO} = 103.6^{+7.7}_{-7.5} \text{ pb}$$
$$\sigma_{NLO} = 144.4^{+9.0}_{-7.2} \text{ pb}$$
$$\sigma_{NNLO} = 151.0^{+4.9}_{-3.6} \text{ pb}$$

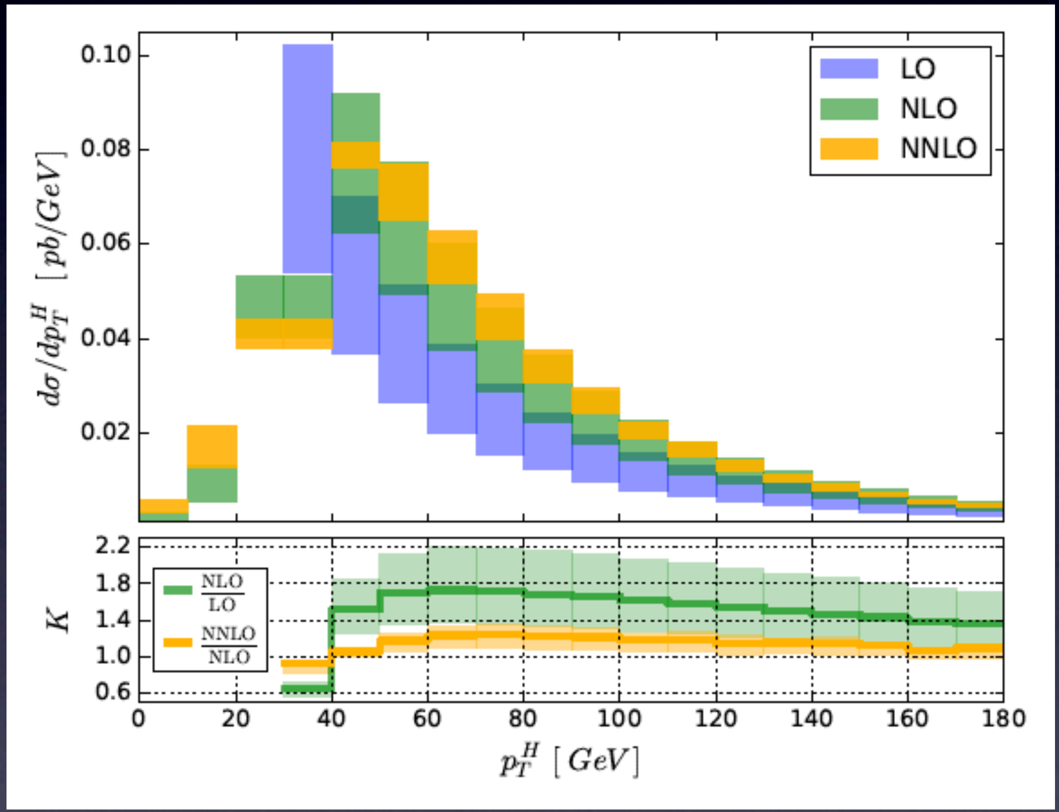
- similar features in Z+jet
- other observables ($p_{t,Z}$, y_Z, ...) non-trivial K-factor



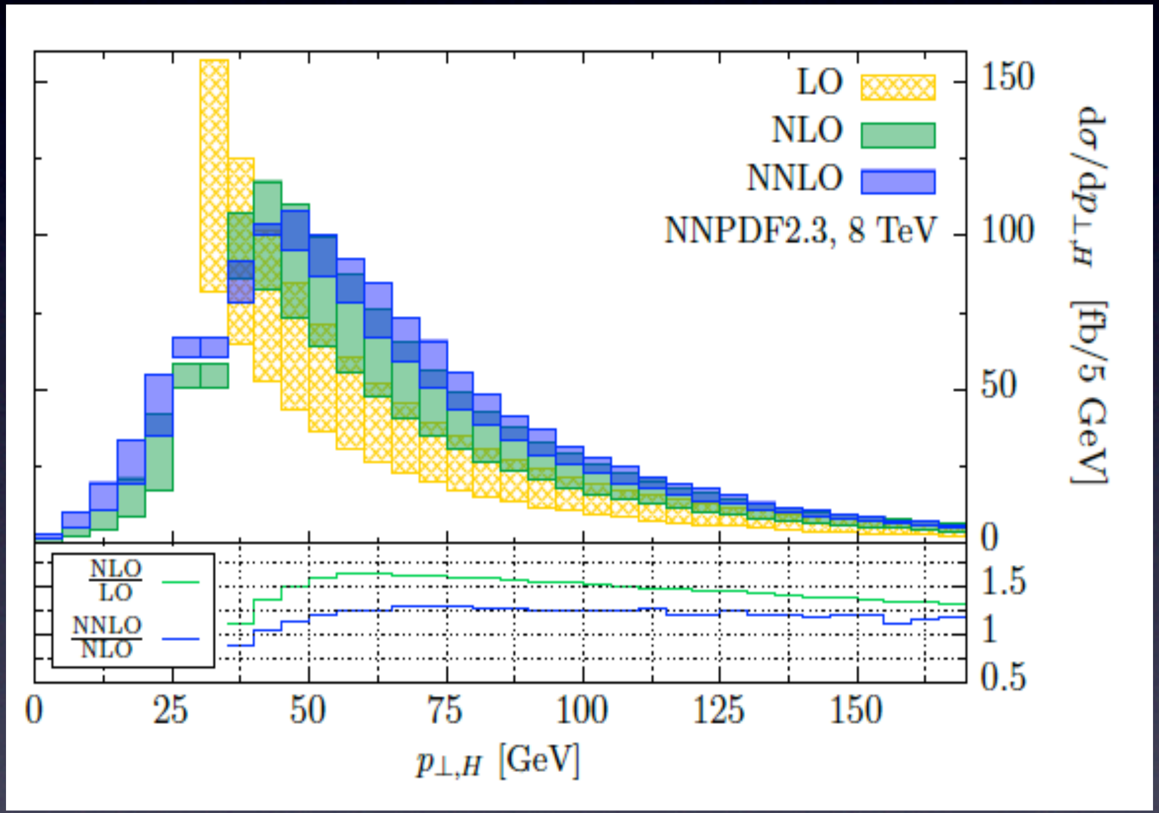
NNLO Higgs plus one jet

Higgs transverse momentum:

1505.03892



1504.07922



- larger K-factor (≈1.15-1.20) for H+1jet
- useful comparison between independent calculations

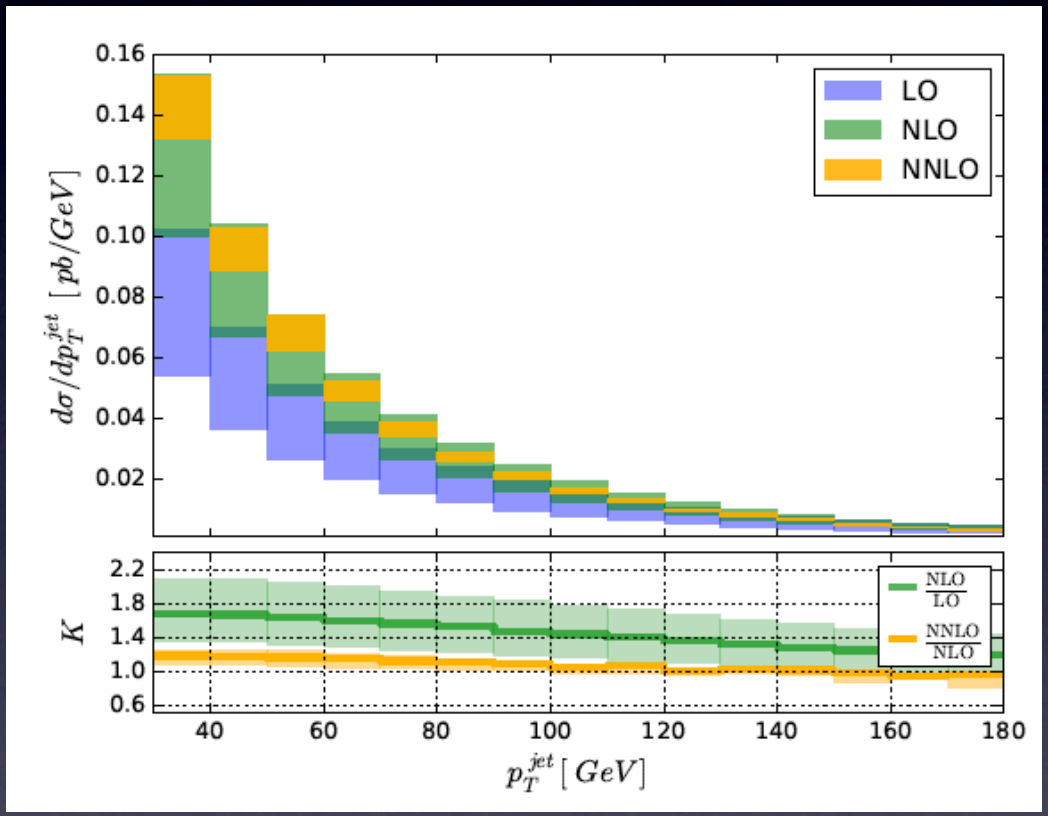
Decays of Higgs to bosons also included. Fiducial cross-sections compared to ATLAS and CMS data

Caola, Melnikov, Schulze 1508.02684

NNLO Higgs plus one jet

Leading jet transverse momentum:

1505.03892



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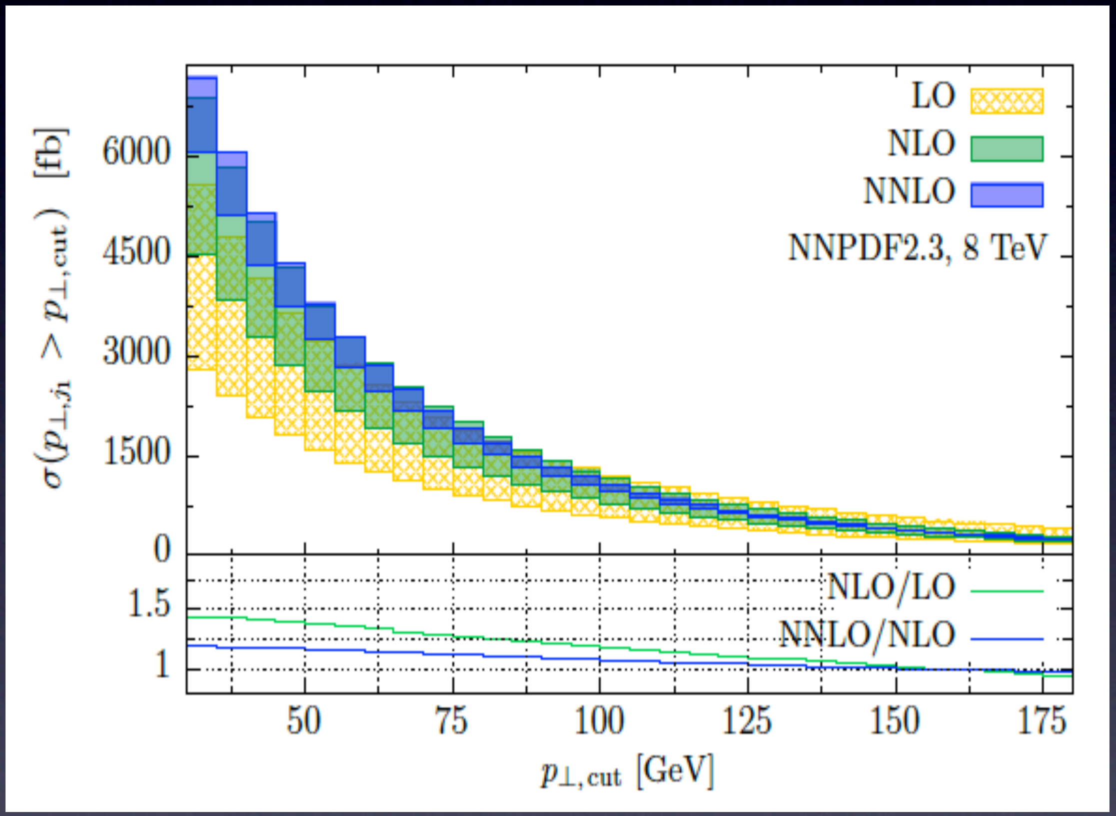

- larger K-factor (≈1.15-1.20) for H+1jet
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Decays of Higgs to bosons also included. Fiducial cross-sections compared to ATLAS and CMS data Caola, Melnikov, Schulze 1508.02684

NNLO ZZ vs data

Fiducial cross sections

Grazzini, Kallweit, Rathlev 1507.06257

Channel	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NNLO} (fb)	σ_{exp} (fb)
$e^+e^-e^+e^-$	$3.547(1)^{+2.9\%}_{-3.9\%}$	$5.047(1)^{+2.8\%}_{-2.3\%}$	$5.79(2)^{+3.4\%}_{-2.6\%}$	$4.6^{+0.8}_{-0.7}(\mathrm{stat})^{+0.4}_{-0.4}(\mathrm{syst.})^{+0.1}_{-0.1}(\mathrm{lumi.})$
$\mu^+\mu^-\mu^+\mu^-$				$5.0^{+0.6}_{-0.5}(\mathrm{stat})^{+0.2}_{-0.2}(\mathrm{syst.})^{+0.2}_{-0.2}(\mathrm{lumi.})$
$e^+e^-\mu^+\mu^-$	$6.950(1)^{+2.9\%}_{-3.9\%}$	$9.864(2)^{+2.8\%}_{-2.3\%}$	$11.31(2)^{+3.2\%}_{-2.5\%}$	$11.1^{+1.0}_{-0.9}(\mathrm{stat})^{+0.5}_{-0.5}(\mathrm{syst.})^{+0.3}_{-0.3}(\mathrm{lumi.})$

- contains LO only gg → ZZ (expected large K-factor like Higgs)
- residual uncertainty estimated to be ~3%
- NNLO higher than data

Tension with

- For region m(4l) > 180 GeV, extract gg → ZZ rate by subtracting other contributions.
- Measure $\mu_{gg} = \sigma(\mathrm{data})/\sigma_{MC}(\mathrm{LO})$. Theory expectation for gg continuum/interference K ~2-3.
- $\mu_{gg} = 2.4 \pm 1.0$ (stat) ± 0.5 (exp) ± 0.8 (theo)

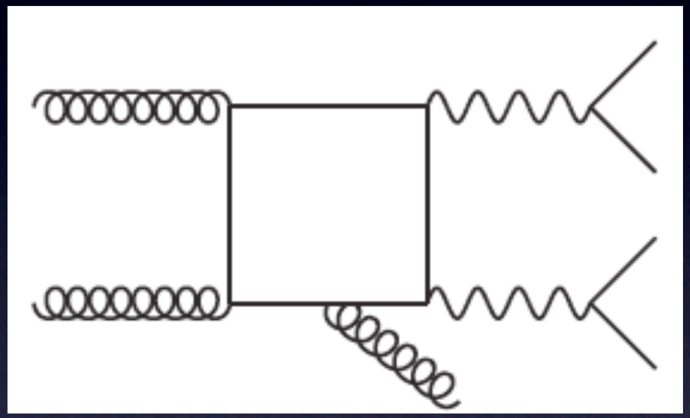
From Lepton Photon ’15 talk of Einsweiler

ATLAS 1509.07844

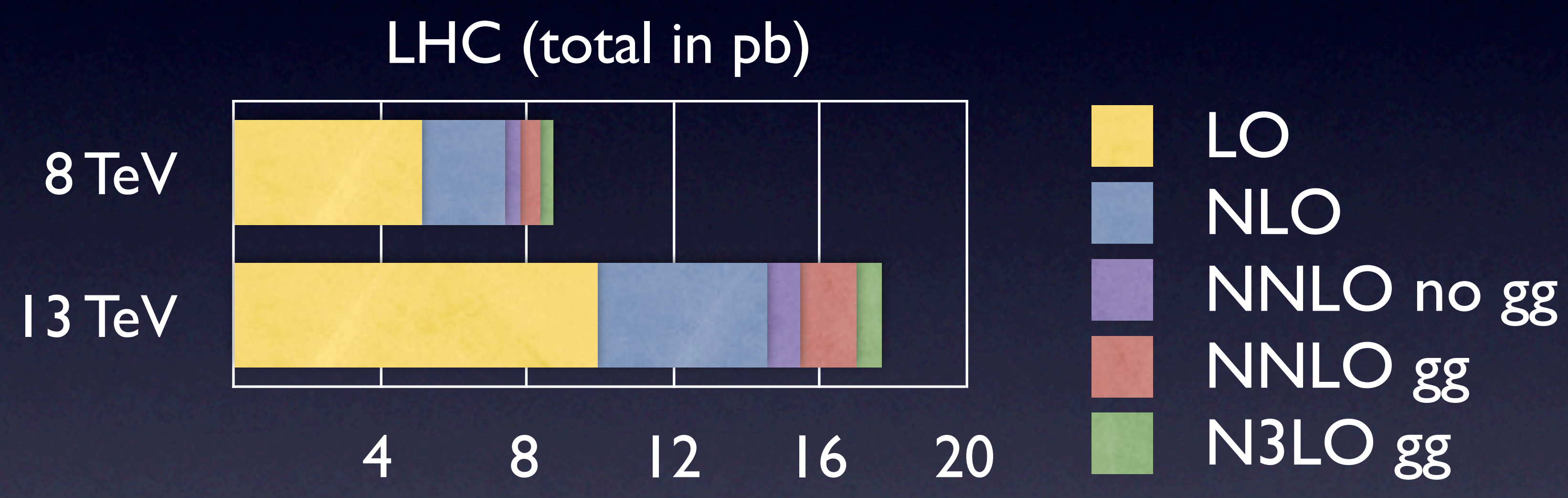
NNLO ZZ vs data

Caola, Melnikov, Roentsch, Tancredi 1509.06734

NLO correction to gg loop-induced process computed recently.
N^3LO contribution to pp → ZZ, but enhanced by large gluon flux



+ two-loop diagrams



Calculation confirms extraction of K-factor by ATLAS and moves the total pp → ZZ result outside the (previous) NNLO uncertainty band

total (pb)	w. LO gg	w. NLO gg
LHC8	8.28 ± 0.2	8.63 ± 0.2
LHC13	16.9 ± 0.5	17.6 ± 0.5

Impact on:
- ongoing comparisons of TH/data
- off-shell studies of Higgs (width)
- other cases (WW, ...)

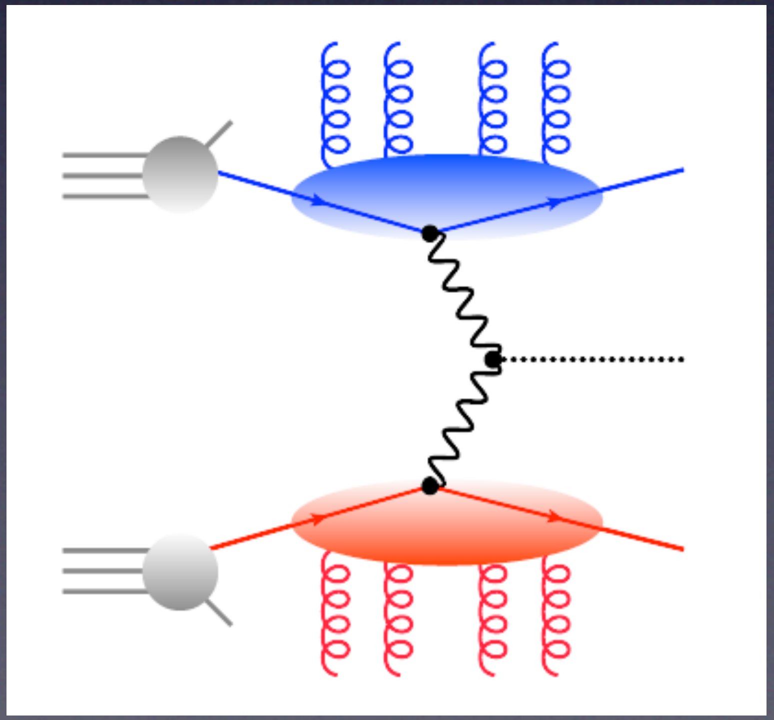
VBF Higgs at NNLO

Fully inclusive VBF Higgs production was known at NNLO in the structure function approach. Calculation suggests NNLO is correction is ~1%, with 1-2% residual uncertainty

Bolzoni, Maltoni, Moch, Zaro ’11

Fully differential calculation recently performed using “Projection to Born” (P2B) method

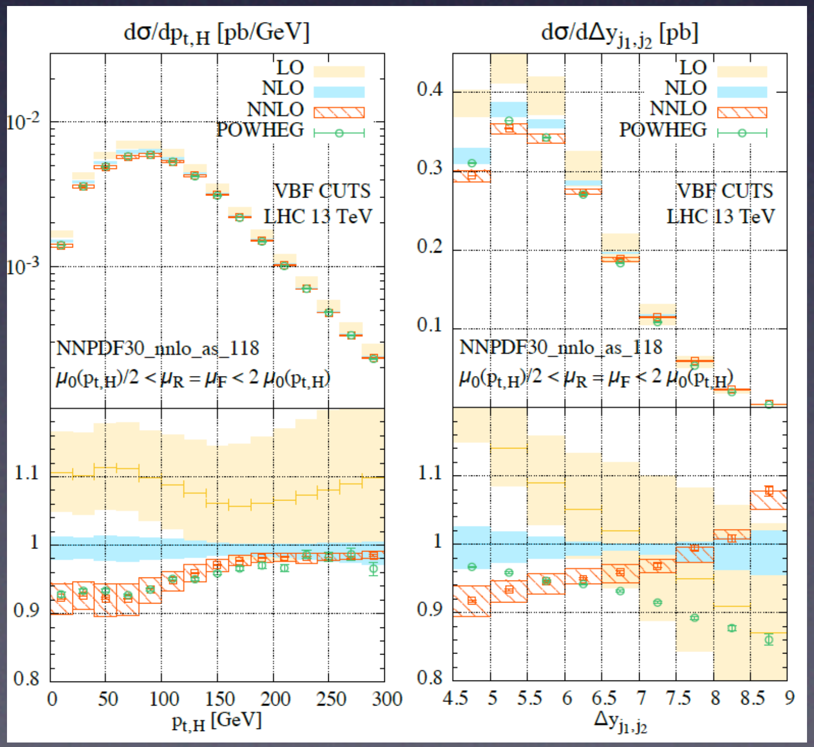
Cacciari, Karlberg, Dreyer, Salam, GZ ’15



	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

1% 6%

Non trivial (10%) effects in distributions.
Precision measurements require differential NNLO



NLO + parton shower

- status of NNLO today similar to that of NLO about 15-20 ys ago
- NLO+PS: for a long time not know how to do it (difficult to avoid double counting). Then two new ideas caused a leap in the field

1. MC@NLO (aMC@NLO)

   Frixione and Webber '02 and later refs.

   - explicitly subtract double counting

2. POWHEG (POWHEG-BOX)

   Nason '04 and later refs.

   - hardest emission from NLO

First only processes with no light jets in the final state, now automated in the POWHEG BOX, MG5_aMC@NLO, Sherpa-MC@NLO, PowHel, Matchbox ... also with fast procedure to get uncertainties (change scales and PDFs)

Main advantaged of NLO+PS compared to pure Monte Carlo:
- meaningful theoretical uncertainty to predictions
- better extrapolation of backgrounds from control to signal region

Today used in all advanced LHC analyses

NNLO + parton shower

NNLO + parton shower: realistic exclusive description of the final state (including MPI, resummation effects, hadronisation, U.E.) with today's state-of-the-art perturbative accuracy

Clearly a must for the LHC physics program

NNLO + parton shower

NNLO+PS in it's infancy, currently three methods/approaches:

- MiNLO: upgrade NLO X+1jet calculations to be NLO accurate for X production (X=H,V), NNLO reweighing in the Born variables

  Hamilton, Nason, Re, GZ '13
  Karlberg, Re, GZ '14

- UNNLOPS: relies on NLO multi-jet merging, adds the precise difference between fixed-order real ME and PS approximation. Depends on merging scale. Virtual correction confined to lowest bin (not spread)

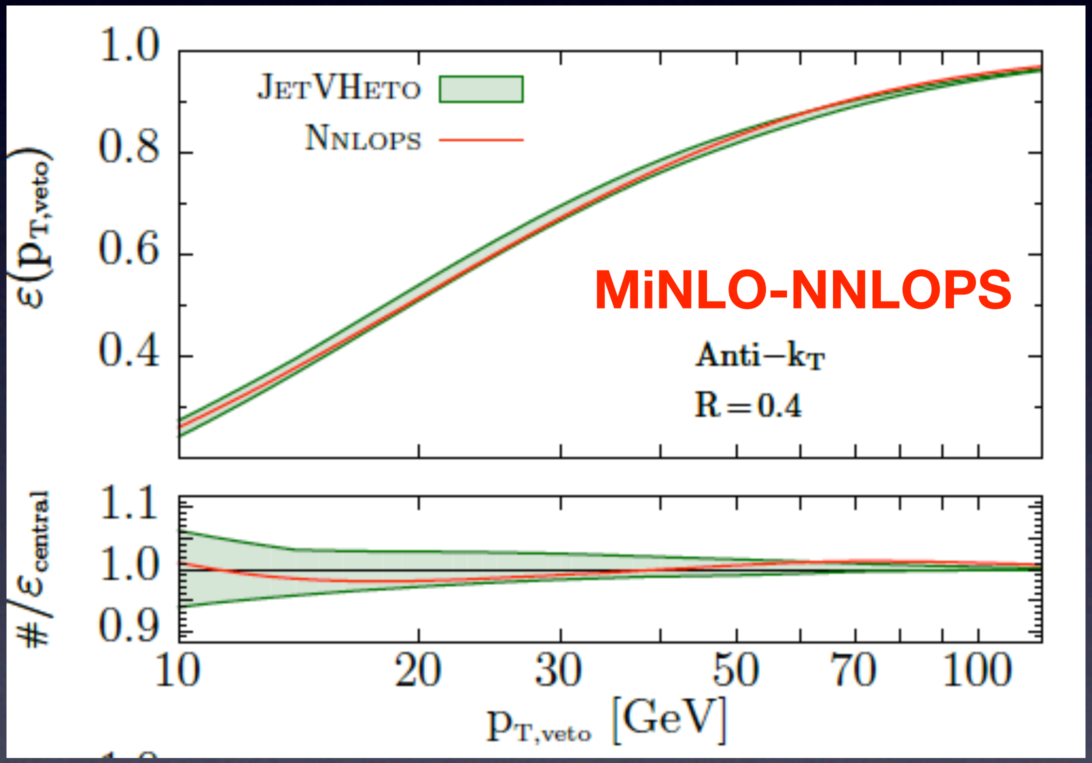
  Hoeche, Li, Prestel '14

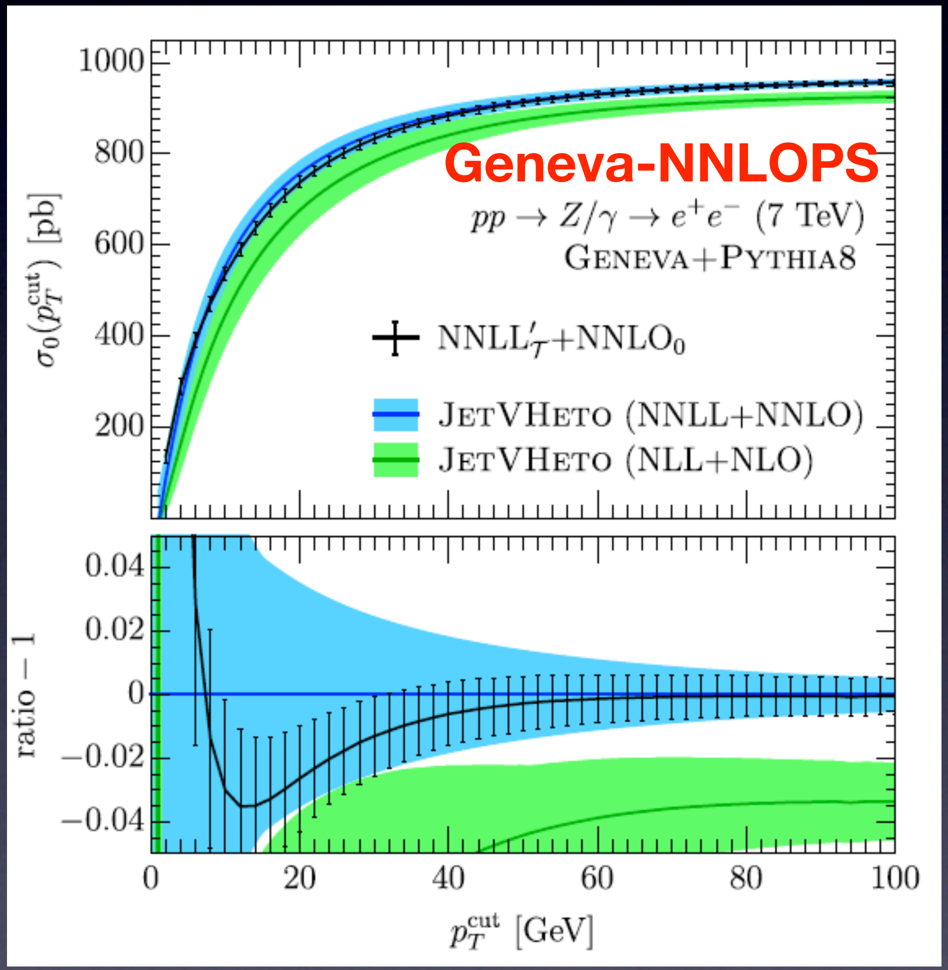
- Geneva: combine differential NNLO calculation for X with 0-jettiness $\mathcal{T}_0$ (aka beam thrust) NNLL' resummation. Perform first two shower emissions by hand, such that they don't split the $\mathcal{T}_0$ resummation

  Alioli, Bauer, Berggren, Tackmann, Walsh '15

NNLO + parton shower

Example: comparison of NNLOPS with NNLO+NNLL resummation of JetVHeto Banfi, Monni, Salam, GZ '12

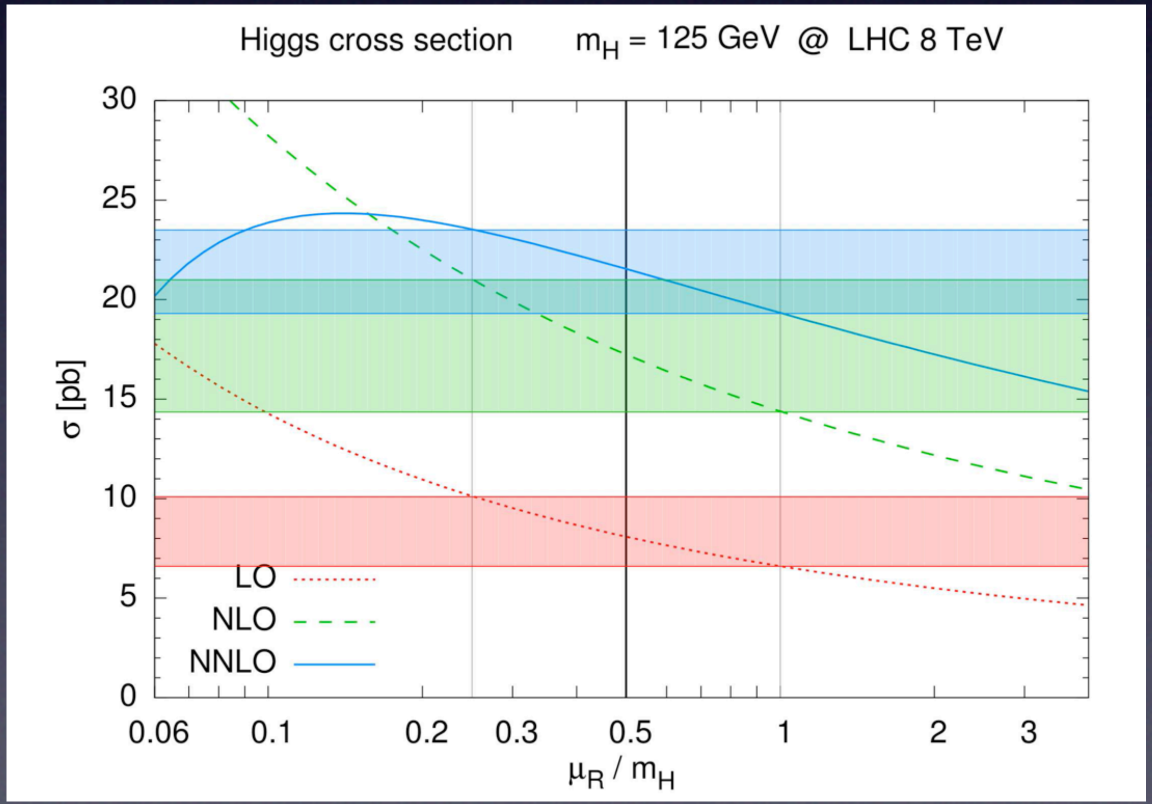




Comparison to high-order resummations very valuable to validate new calculations and tools (best analytic control, many handles on uncertainties)

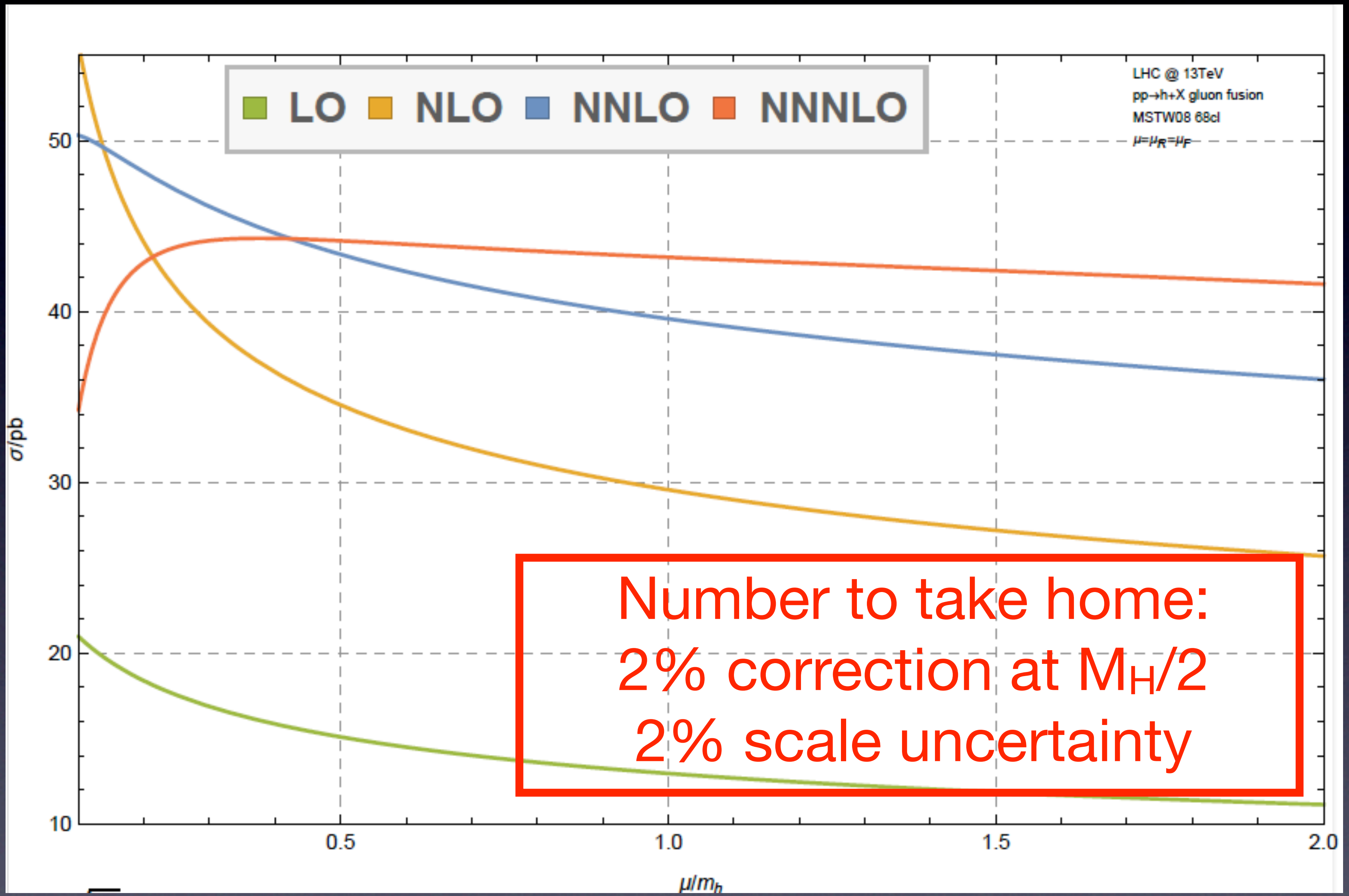
Beyond NNLO

- New in 2015: calculation of inclusive Higgs production via gluon-gluon fusion in the large m_t approximation at N^3LO
- first N^3LO calculation of a hadron collider production process
- calculation motivated by the slow perturbative convergence
- renormalization scale variation underestimates the shift to the next order
- amount of perturbative control on the cross-section has a direct impact on a range of NP searches in the Higgs sector



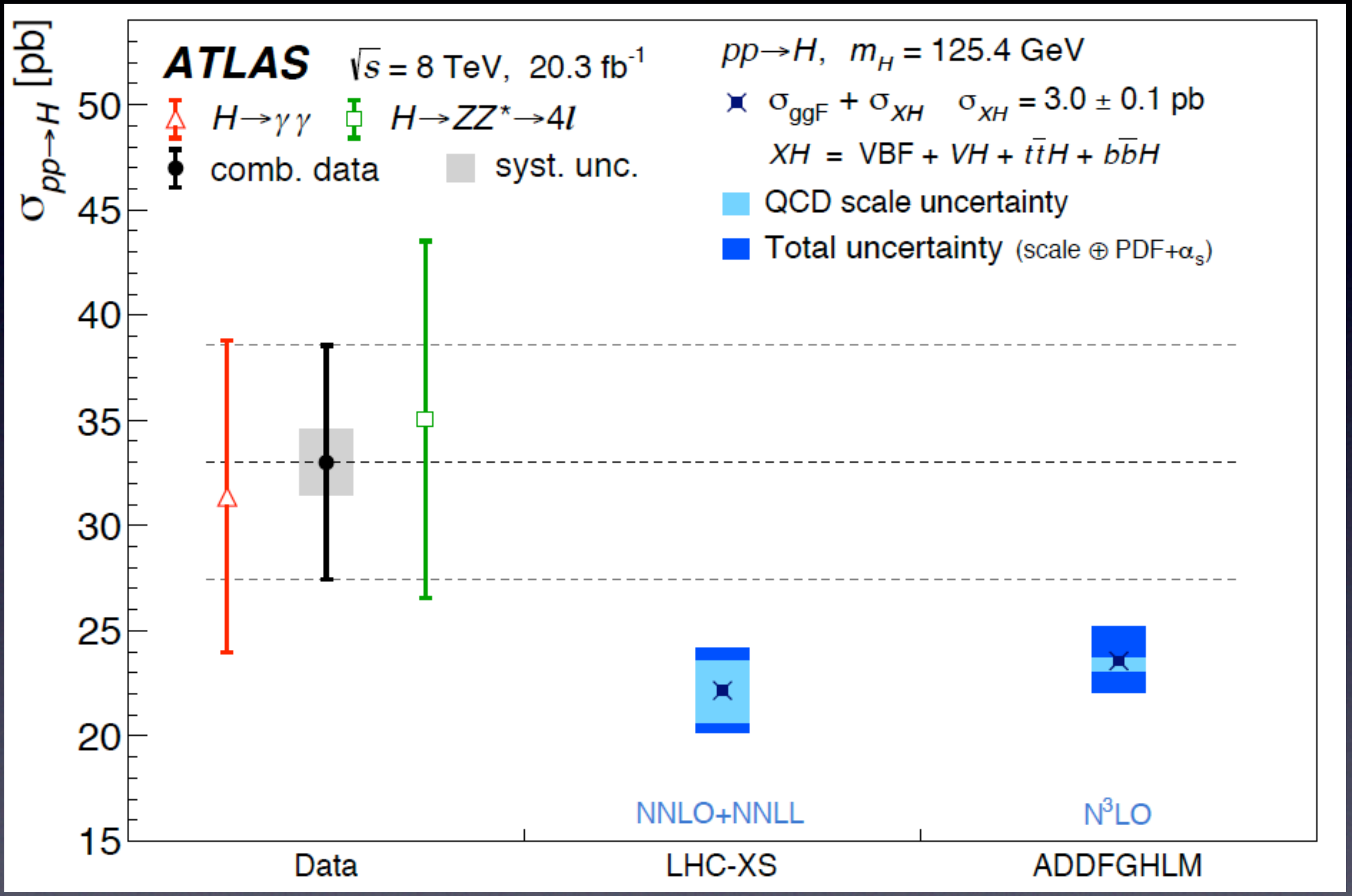
from General Assembly Higgs Cross Section Working Group Jan. 2015

N^3LO Higgs production



Other uncertainties now become all important (PDFs, treatment of EW, heavy-top approximation, top-bottom interference in loops...).

N^3LO Higgs production



More accurate measurements awaited eagerly! …

Conclusions

QCD is a field very active

- NLO revolution belongs already to the past, NNLO the current hottest battlefield.
  Only in the last few months: H+1jet, Z+1jet, W+1jet, VBF Higgs, VV, dijets at NNLO and even Higgs at N3LO!
- many other important theoretical and phenomenological developments (NLO multi-jet merging, matching, inclusion of EW corrections, resummations ...)
- tools getting more and more refined: improvement in theory uncertainties and more attention paid towards a solid estimate

Very exciting to work on QCD as new ideas/calculations are promptly used in LHC analyses. Thrilling times ahead, but also time to start thinking beyond the LHC

Extra Slides

Antenna subtraction

Antenna subtraction

+ analytic cancelation of poles
- complicated/cumbersome?

A. Gehrmann, T. Gehrmann, Glover, Heinrich ’05

Applied to

✓ $e^+e^- \rightarrow 3$ jets A. Gehrmann, T. Gehrmann, Glover, Heinrich ’07

✓ dijet production (approx) A. Gehrmann, T. Gehrmann, Glover, Pires ’13; Currie, Gehrmann, Gehrmann, Glover, Pires ’13; Currie, A. Gehrmann, Glover, Pires ’13

✓ Z+jet (leading colour, dominant channels) A. Gehrmann, T. Gehrmann, Glover, Huss, Morgan ’15

✓ Higgs + jet (gluon only) Chen, Gehrmann, Glover, Jacquier ’14

✓ top-pair production (approx, quarks only) Abelof, A. Gehrmann, Majer ’14

q_T subtraction

q_T subtraction

Catani, Grazzini ’07

+ efficient, simple
- applied mostly to colourless final state

Originally based on transverse momentum resummation for single boson production (H, Drell Yan). Recently extended to di-bosons:

✓ $\gamma\gamma$ Catani, Cieri, De Florian, Ferrera, Grazzini ’11

✓ WH, ZH Ferrera, Grazzini, Tramontano ’11-’14

✓ $W\gamma$, $Z\gamma$ Grazzini, Kallweit, Rathlev, Torre ’13; Grazzini, Kallweit, Rathlev ’15

✓ ZZ Cascioli, Gehrmann, Grazzini, Kallweit, Maierhofer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs ’14; Grazzini, Kallweit, Rathlev ’15

✓ WW Gehrmann, Grazzini, Kallweit, Maierhofer, von Manteuffel, Pozzorini, Rathlev, Tancredi ’14

✓ extended to top-pair production Bonciani, Catani, Grazzini, Hargsyan, Torre ’15

Colorful subtraction and P2B

Colorful subtraction

Del Duca,Somogyi, Trocsanyi '05

+ local subtraction terms
- cumbersome? no application with initial state hadrons

First application to final state radiation

✓ $H \to bb$ Del Duca, Duhr, Tramontano, Trocsanyi '15

Projection to Born

Cacciari, Dreyer, Karlberg, Salam, GZ '15

+ simple
- limited scope

✓ Differential VBF Higgs productions Cacciari, Dreyer, Karlberg, Salam, GZ '15

Sector improved residue

Sector improved residue subtraction (4D formulation)

+ generic method, can be applied in principle to any process
- numerical cancelation of poles

Czakon '10
Czakon, Heymes '14

✓ $Z \to e^+e^-$ Boughezal, Melnikov, Petriello '11

✓ top-pair production (inclusive and differential) Berneuter, Czakon, Fiedler, Mitov '12-'13; Czakon, Fiedler, Mitov '14

✓ top decay Bruchseifer, Caola, Melnikov '13

✓ $b \to X_u\, e\, \nu$ Bruchseifer, Caola, Melnikov '13

✓ single top Bruchseifer, Caola, Melnikov '14

✓ muon decay spin asymmetry Caola, Czarnecki, Liang, Melnikov, Szafron '14

✓ Higgs + jet Boughezal, Caola, Melnikov, Petriello, Schulze '13-'15

N-jettiness slicing

Bouchezal, Focke, Liu, Petriello ’15
Gaunt, Stahlhofen, Tackmann, Walsh ’15

N-jettiness subtraction

+ promising: already very non-trivial applications
- dependence on slicing parameter needs to be checked accurately

✓ W+jet Boughezal, Focke, Liu, Petriello ’15

✓ H+jet Boughezal, Focke, Giele, Liu, Petriello ’15

Remarks:

- slicing not that successful at NLO (almost abandoned in favour of subtraction)
- why does this slicing method work so nicely at NNLO? is it because of today’s better computer facilities?
- the value of the slicing parameter used is higher than theoretical arguments would suggest (small parameter means higher instabilities). Th. arguments too conservatives?

More to learn in the next months ...

Resummations

- resummation relevant in multi-scale problems
- source of large logs: veto on real radiation spoils the KNL cancellation of singularities between real and virtual contributions
  $\Rightarrow$ large logs are left over

As a result fixed-order calculations have logarithmic divergences

- 0-jet bins: $\log(p_{t,\mathrm{veto}}/M)$
- 1-jet bins: $\log(p_{t,j1}/M)$, $\log(p_{t,\mathrm{veto}}/M)$, $\log(p_{t,j1}/p_{t,\mathrm{veto}})$
- event-shapes v=(T, C, M_H, B_T, B_W, beam thrust, N-jettiness): log(v)
- ...

Reliable predictions in exclusive regions obtained after resumming large logarithms to all orders in the strong coupling constant.

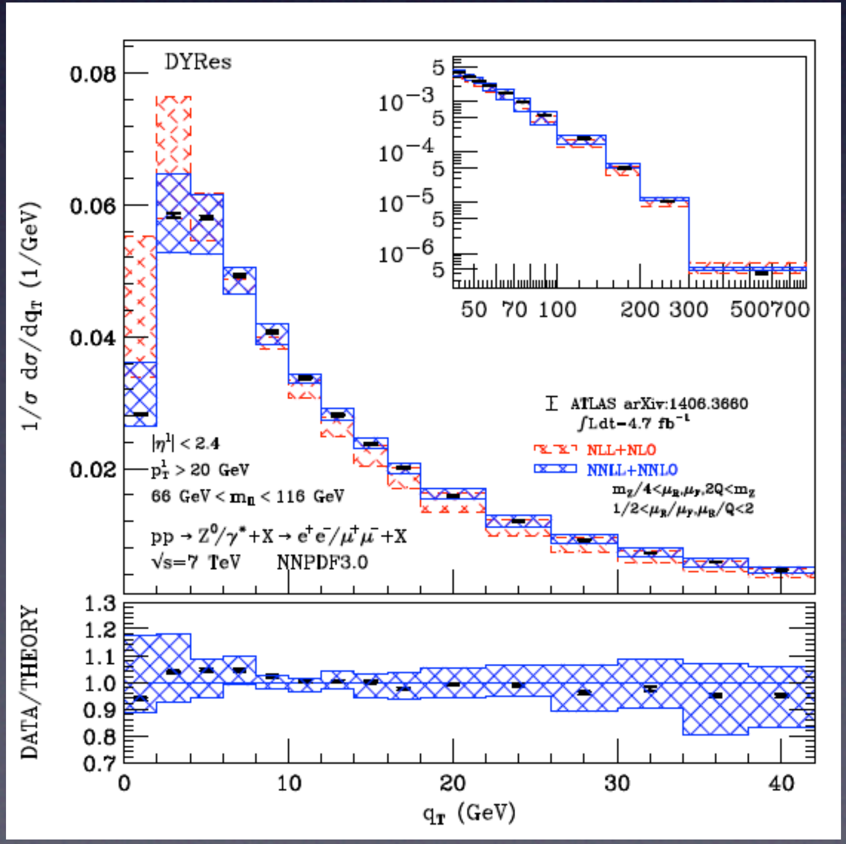
State-of-the-art: NNLL accuracy for two-scale problems

Resummations

Resummed calculations matched to fixed order play a key role in comparison to data and in validation of MC predictions

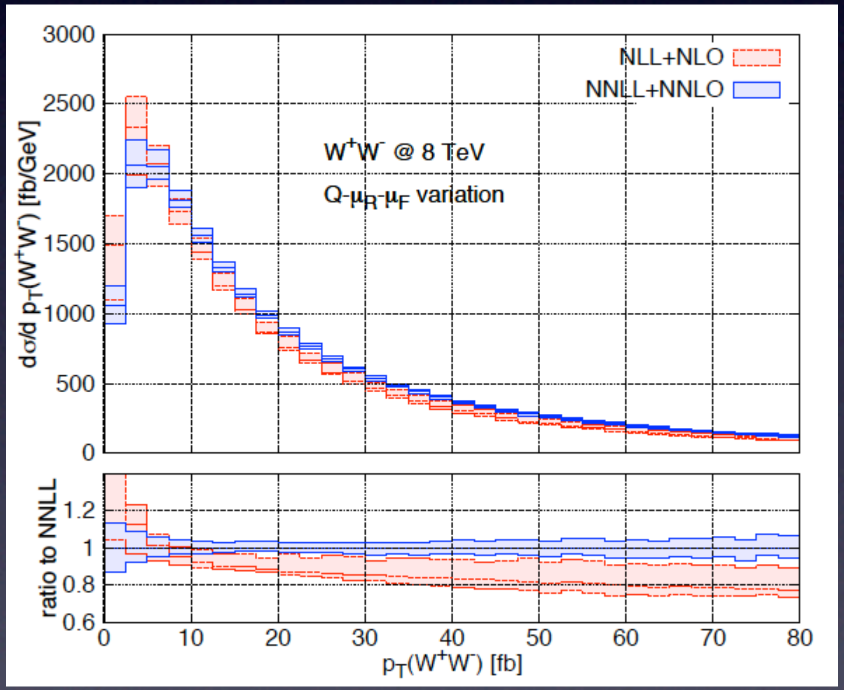
- best analytic control (NNLL+NNLO)
- many handles to estimate theory uncertainties (besides μ_R, μ_F)

Catani, De Florian, Ferrera, Grazzini '15



Transverse momentum resummation for vector boson pair production

DYRes extended to include decays of bosons (fiducial predictions possible)



Grazzini, Kallweit, Rathlev, Wiesemann '15

Automation of resummation

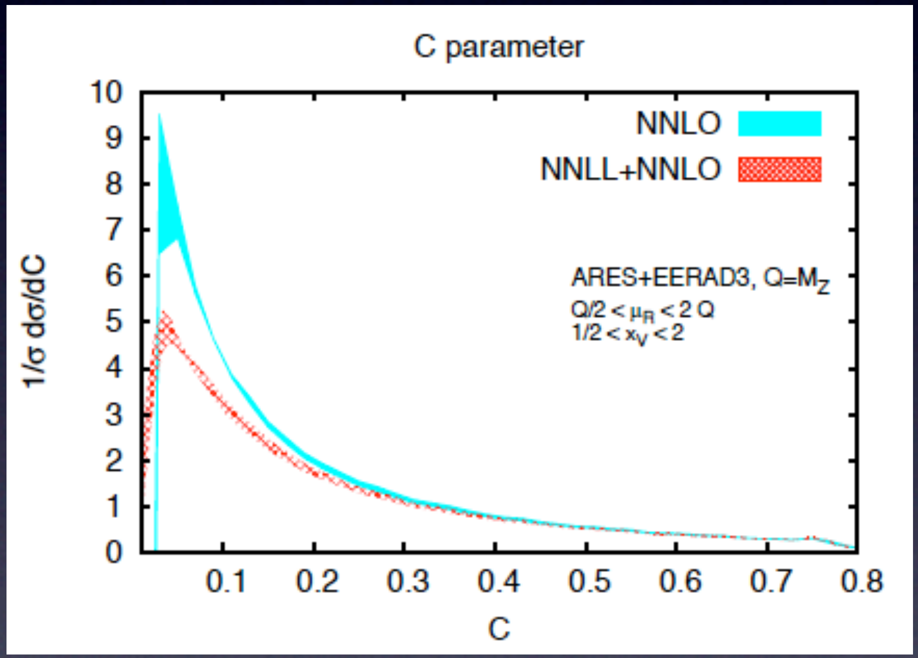
Resummation of large logarithms automated at NLL for a large class of QCD observables since a while

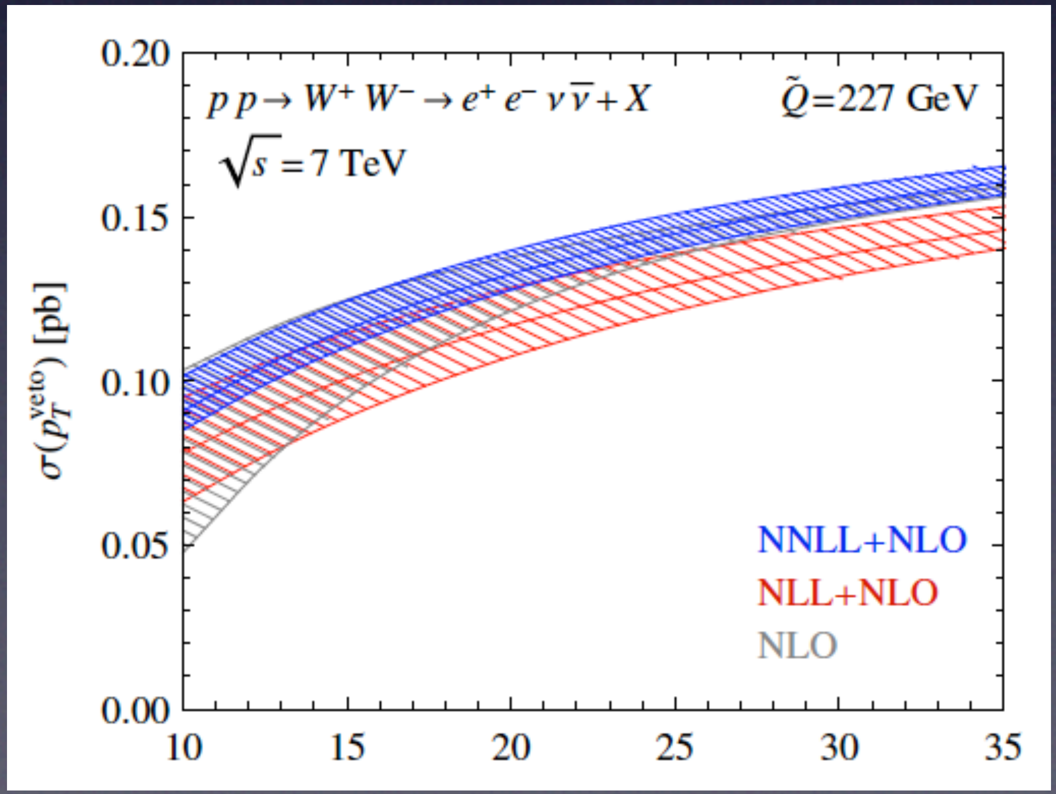
Banfi, Salam, GZ ’04

Recently, automation pushed to NNLL, e.g.

automated jet-veto resummation for event-shapes in e^+e^- at NNLL

Banfi, Monni, GZ ’14





automated jet-veto resummation for electro-weak boson production processes using MG5_aMC@NLO

Becher, Frederix, Neubert, Rothen ’14