Precision QCD in the LHC era

Daniel de Florian
Dpto. de Física - FCEyN- UBA
Argentina

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Warsaw, April 28

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- Everything SM like (including Higgs)

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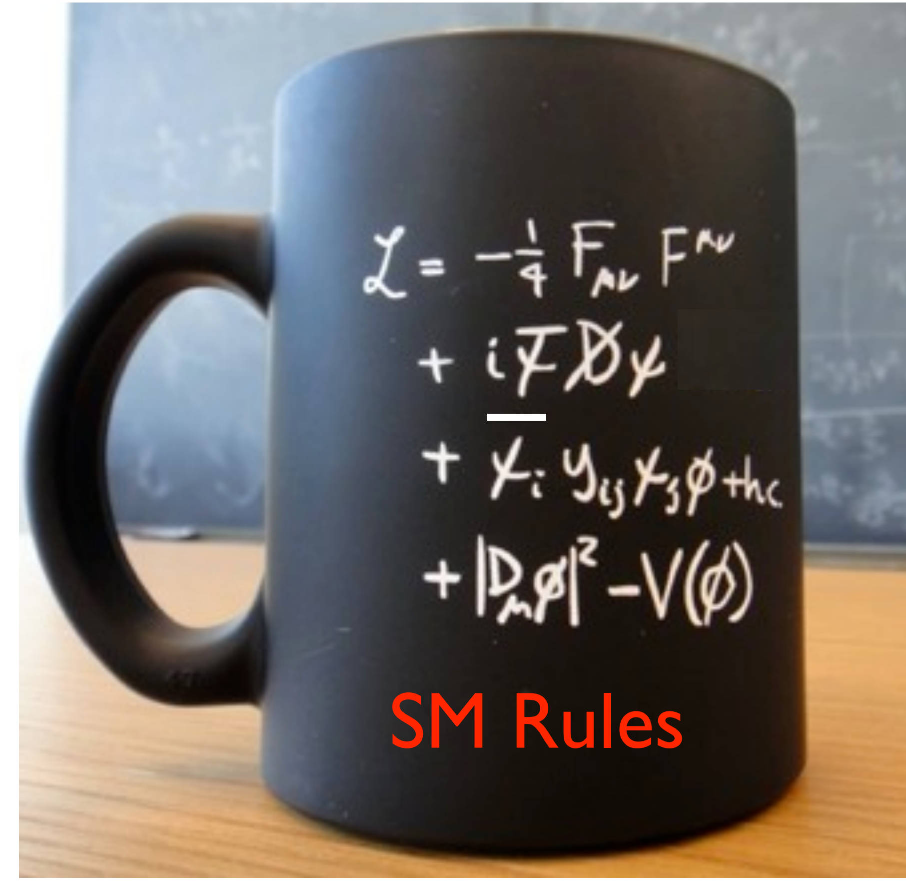

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- Everything SM like (including Higgs)

- New physics might be in the detail

- Need to be precise on cross-sections and SM parameters

$$m_H,\ m_t,\ \alpha_s,\ \ldots$$

Vacuum stability in the SM at NNLO requires

Degrassi et al; Bezrukov et al; Alekhin, Djouadi, Moch; Masina (2012)

$$m_H \geq 129.2 + 1.8 \times \left(\frac{m_t^{\rm pole} - 173.2\,{\rm GeV}}{0.9\,{\rm GeV}}\right) - 0.5 \times \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0\,{\rm GeV}$$

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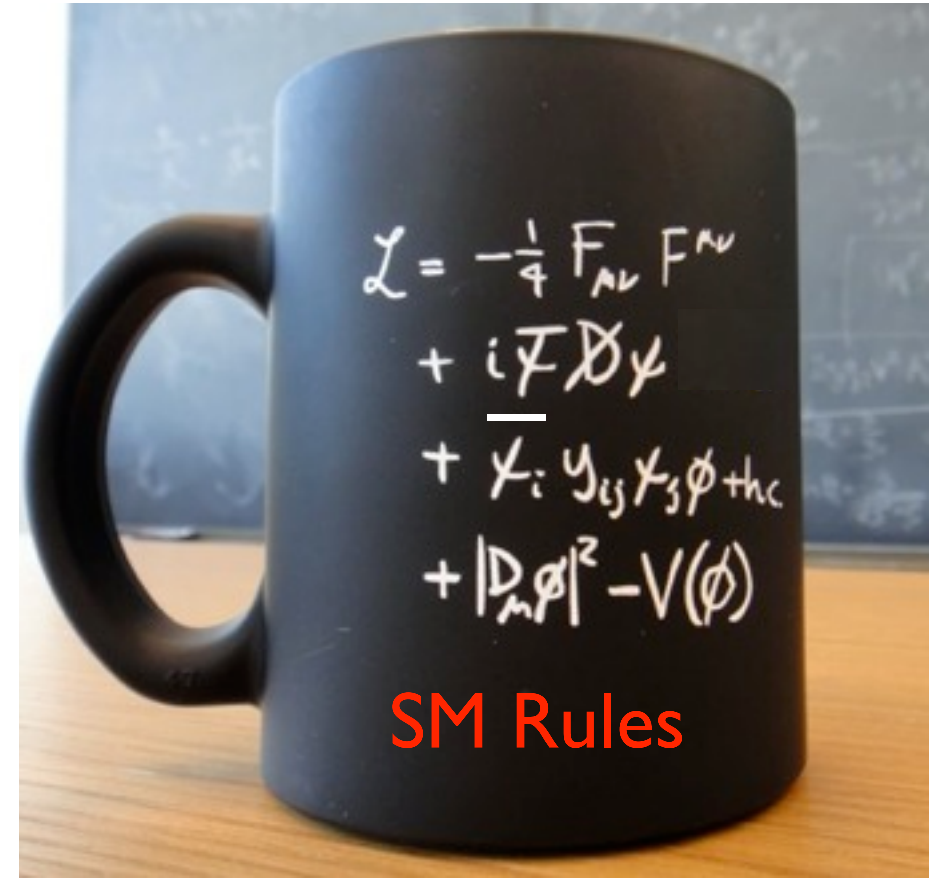

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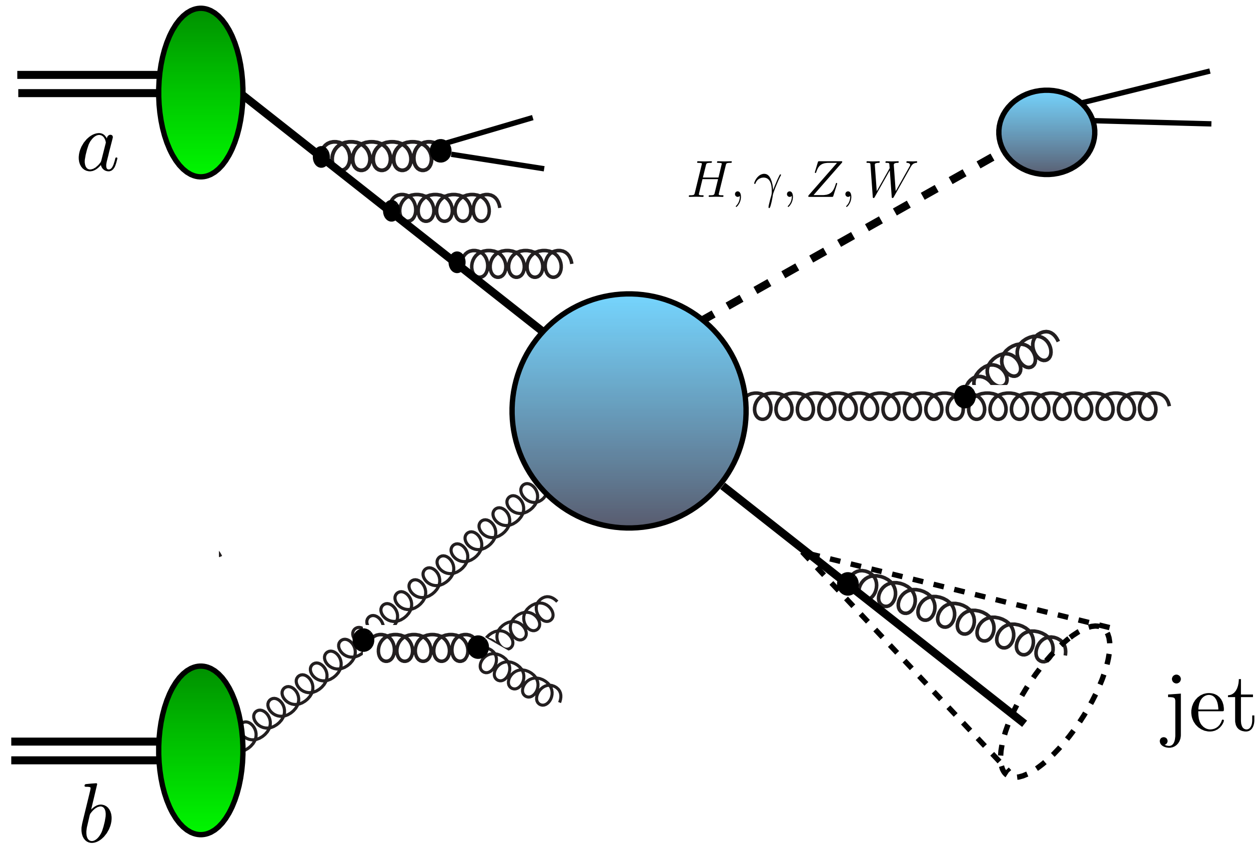
This Talk
Toolkit for precise TH predictions at the LHC

- In the LHC era, QCD is everywhere!



non-perturbative parton distributions

$$d\sigma = \sum_{ab} \int dx_a \int dx_b \, f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \times d\hat{\sigma}_{ab}(x_a, x_b, Q^2, \alpha_s(\mu_R^2)) + \mathcal{O}\left(\left(\frac{\Lambda}{Q} \right)^m \right)$$

perturbative partonic cross-section

Partonic cross-section: expansion in $\alpha_s(\mu_R^2) \ll 1$ $\quad d\hat{\sigma} = \alpha_s^n \, d\hat{\sigma}^{(0)} + \alpha_s^{n+1} \, d\hat{\sigma}^{(1)} + ...$

- Require precision for perturbative and non-perturbative contribution

PDFs

- Several groups provide pdf fits + uncertainties
- Differ by: data input, TH/bias, HQ treatment, coupling, etc

set	H.O.	data	$\alpha_s(M_Z)@NNLO$	uncertainty	HQ	Comments
MSTW 2008	NNLO	DIS+DY+Jets	0.1171	Hessian (dynamical tolerance)	GM-VFN (ACOT+TR')	old HERA DIS
CT10	NNLO	DIS+DY+Jets	0.118	Hessian (dynamical tolerance)	GM-VFN (SACOT-X)	New HERA DIS
NNPDF	NNLO	DIS+DY+Jets +LHC	0.1174	Monte Carlo	GM-VFN (FONLL)	New HERA DIS
ABKM	NNLO	DIS+DY(f.t.) +DY-tT(LHC)	0.1132	Hessian	FFN BMSN	New HERA DIS
(G)JR	NNLO	DIS+DY(f.t.)+ some jet	0.1124	Hessian	FFN (VFN massless)	valence like input pdfs
HERA PDF	NNLO	only DIS HERA	0.1176	Hessian	GM-VFN (ACOT+TR')	Latest HERA DIS

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up to 5% ! >15% in Higgs cross section

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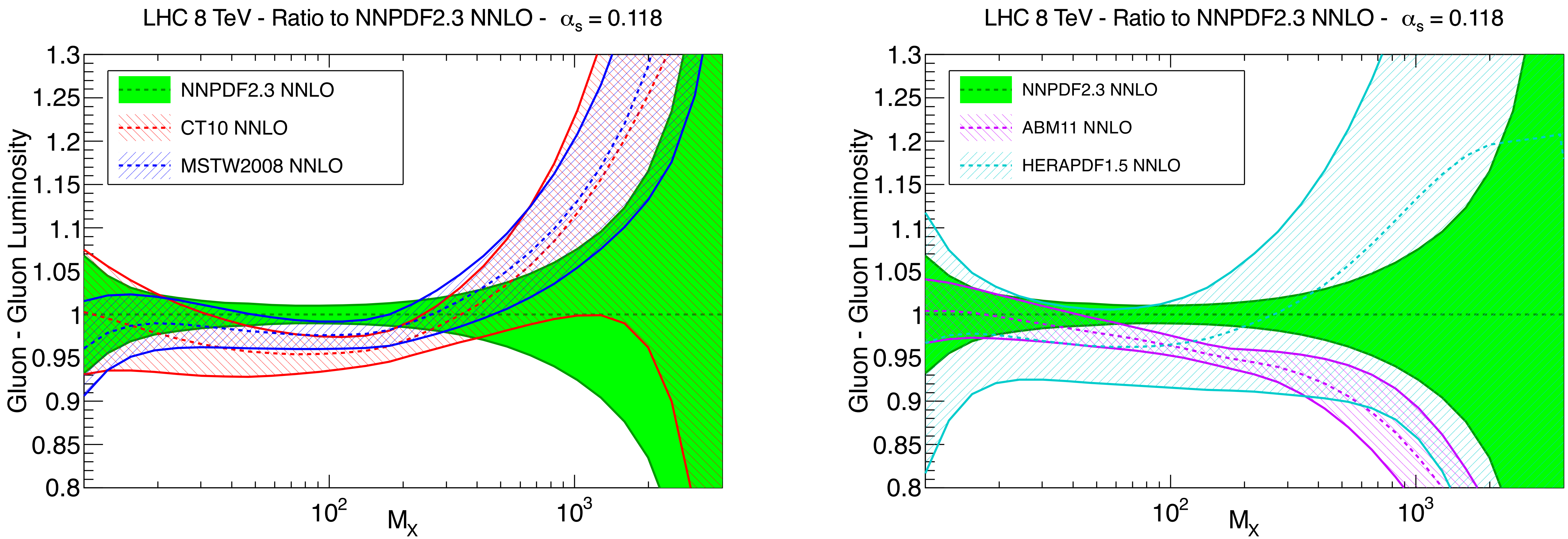
Luminosities with common $\alpha_s = 0.118$

R. Ball et al (2013)

$$\mathcal{L}_{ij}(\tau \equiv M_X^2/S) = \frac{1}{S}\int_\tau^1 \frac{dx}{x} f_i(x, M_X^2) f_j(\tau/x, M_X^2)$$

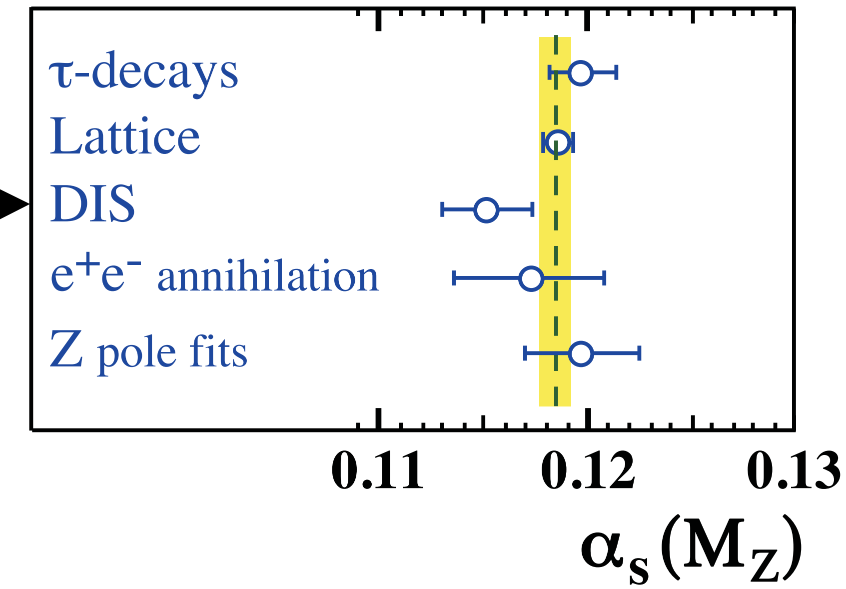
gluon-gluon



- Good agreement for global fits but deviations as large as uncertainties
- Larger differences with “non-global” results
- 2x larger uncertainties for gluon

- One main issue is the coupling constant

PDG S. Bethke $\alpha_s(M_Z) = 0.1184 \pm 0.0007$



- Optimistic value for the uncertainty at the LHC

- DIS (PDFS) not well covered : some experiments pull value down

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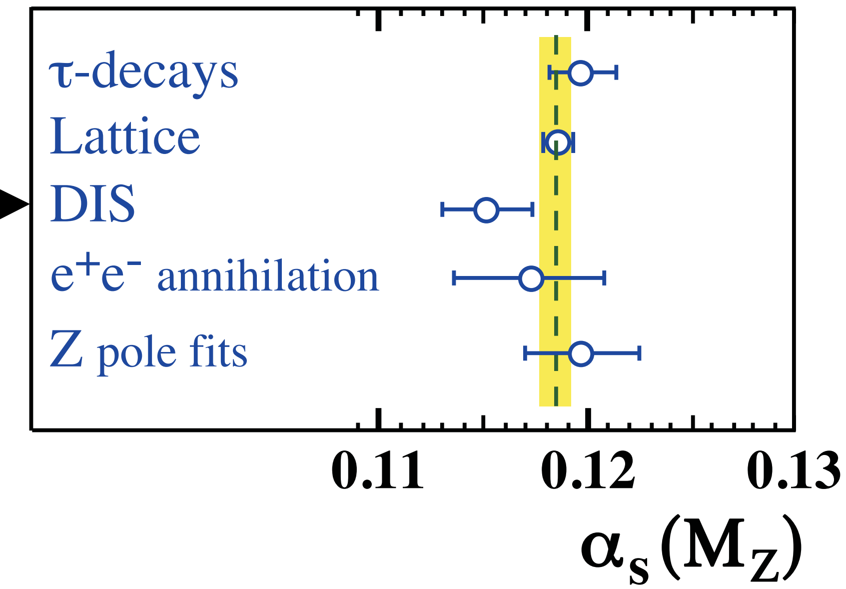

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- DIS (PDFS) not well covered : some experiments pull value down

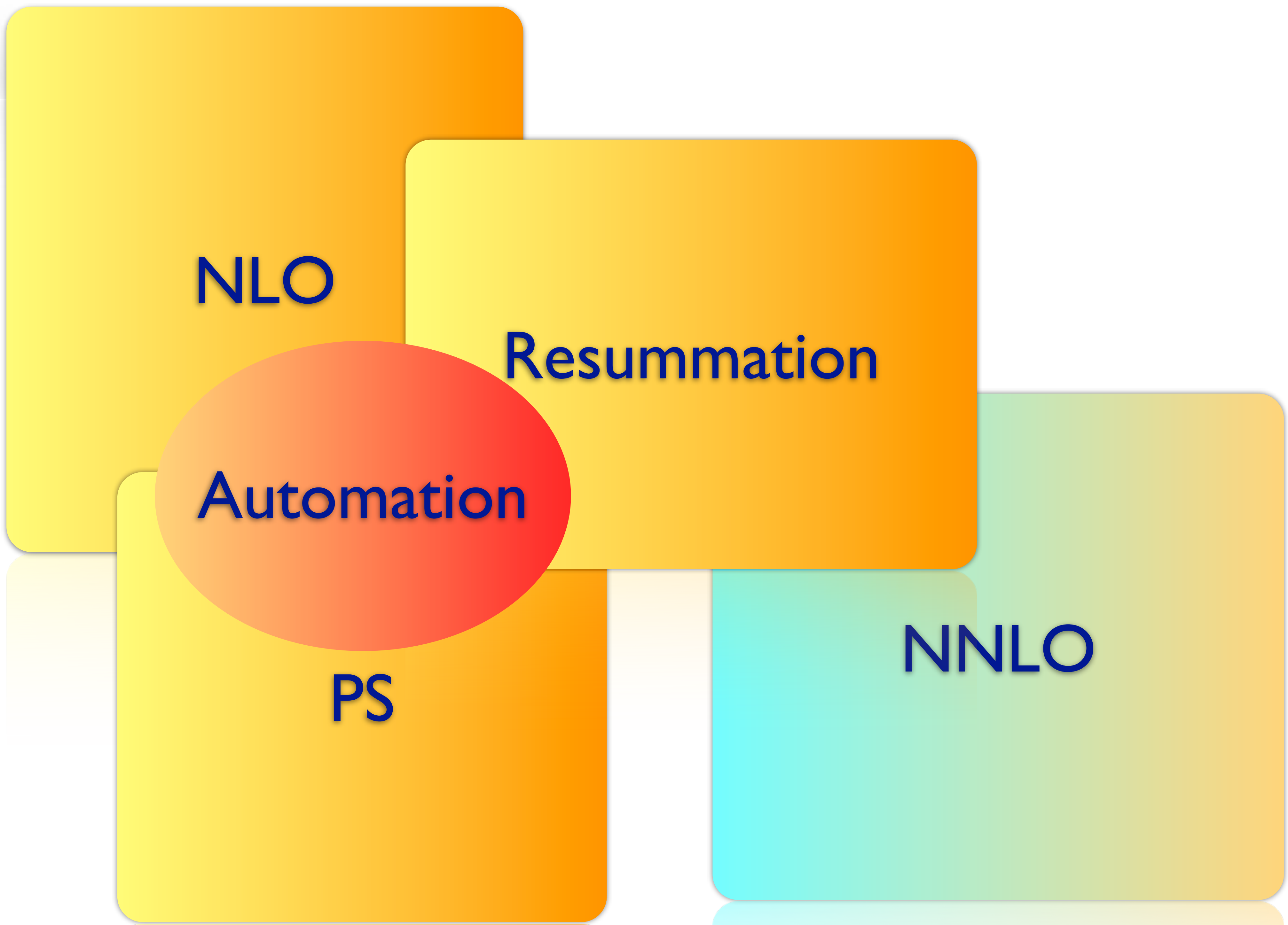
PDF4LHC recommendation

- Compute pdfs uncertainties using MSTW & CT & NNPDF (68%cl)
- Obtain the envelope of all bands and use

$$\Delta\alpha_s(M_Z) = \pm 0.0012\,(\pm 0.002)\ \text{at}\ 68\%\,(90\%)\,\text{c.l.}$$

- Precise LHC data will have important effect on validation & improvement

The perturbative toolkit for precision at colliders



The NLO revolution

Why NLO?

- Accurate Theoretical Predictions
  - shape and normalization
  - first error estimate
- Large Corrections : check PT   Higgs
- Opening of new channels
- Effect of extra radiation
  - jet algorithm dependence

Amazing progress in the last few years

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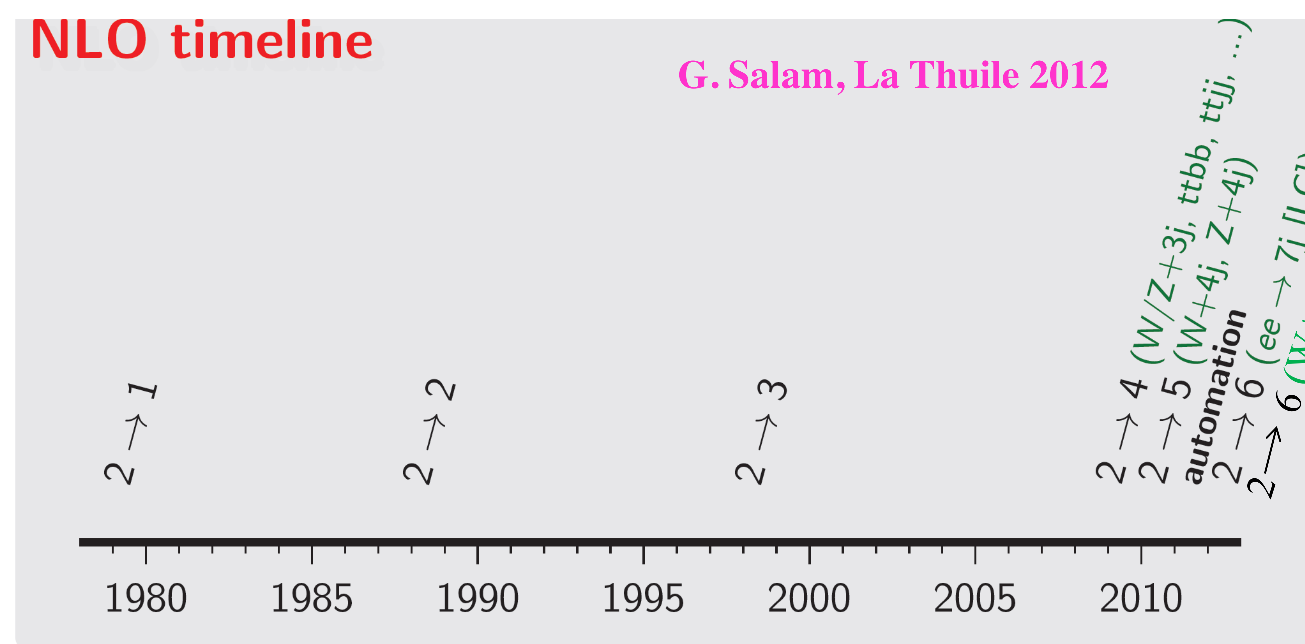
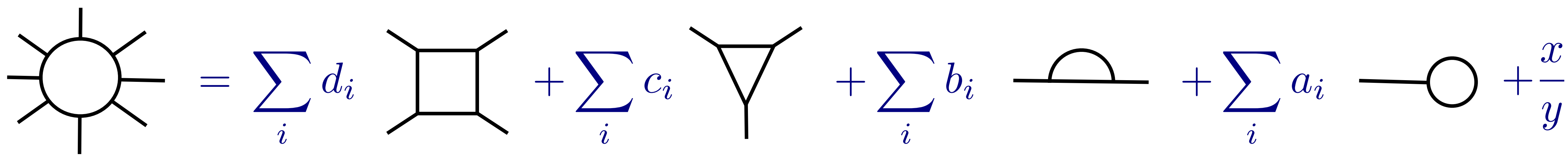
Large multiplicities relevant for LHC



Revolution in calculation of 1-loop amplitudes

Bottleneck in the virtual contribution : large multiplicities



Feynmanian approach

- Improvements in decomposition and reduction

Denner, Dittmaier; Pozzorini; Binoth, Guillet, Heinrich, Pilon, Schubert + many others

Unitarian approach

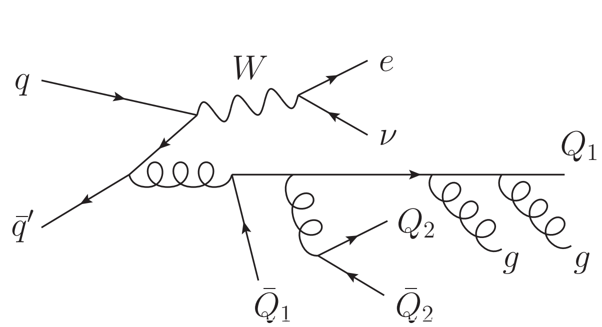
- Use multi-particle cuts from generalized unitarity

Bern, Dixon, Dunbar, Kosower; Britto, Cachazo, Feng; Mastrolia; Forde; Badger; Ellis, Giele, Kunszt, Melnikov + many others

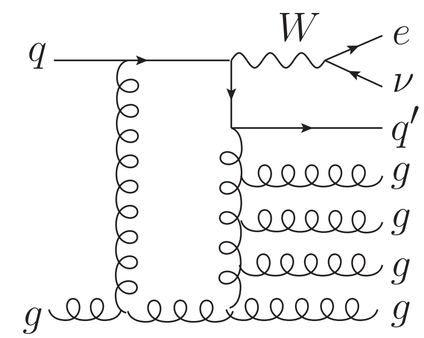
OPP Ossola, Papadopoulos, Pittau — decomposition at the *integrand* level

A very recent example : W+5 jets !!

BlackHat Collaboration, Z.Bern et al

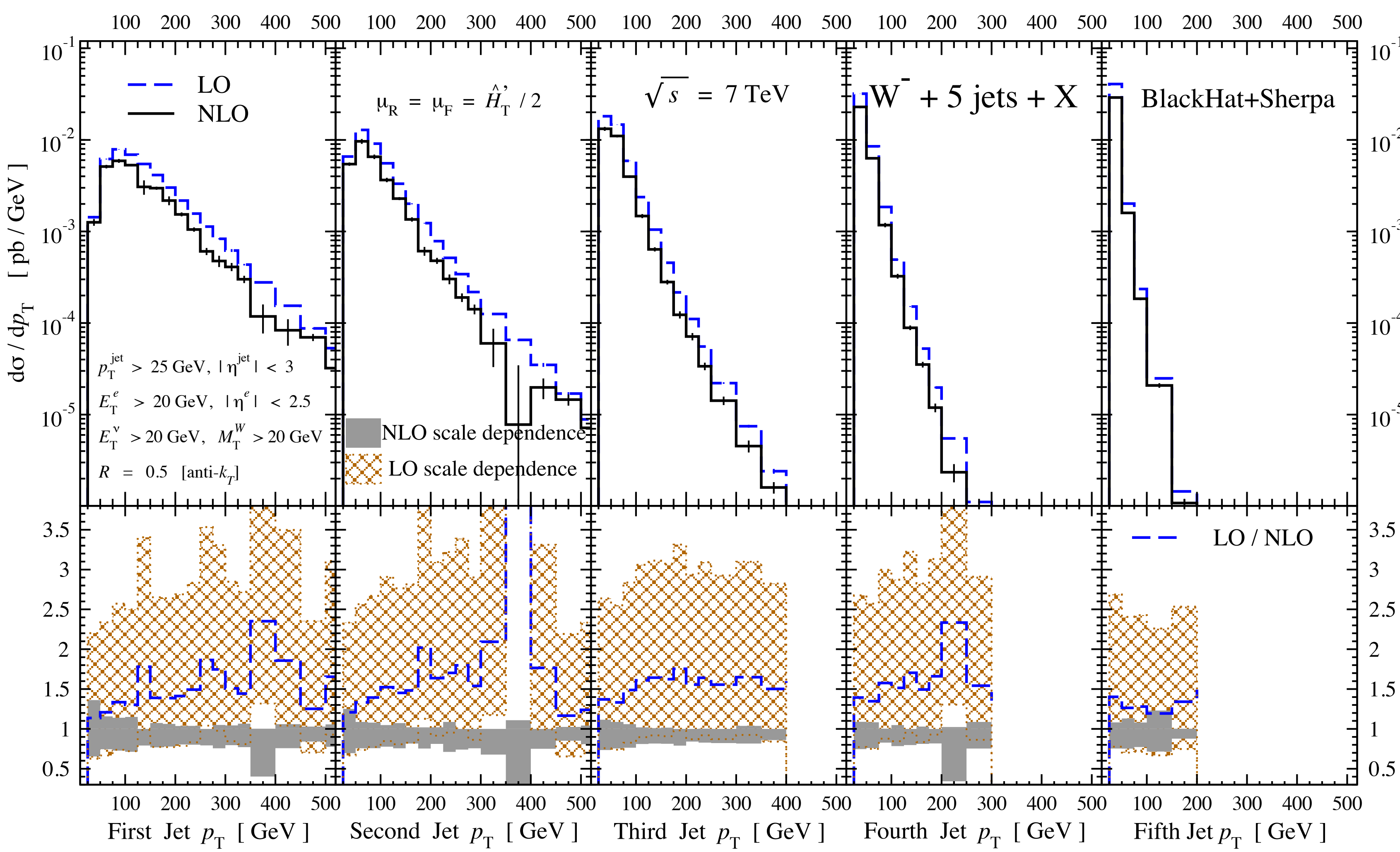


Real $2 \to 8$ SHERPA



Virtual $2 \to 7$ BlackHat

Dynamical Scale choice $\mu_R = \mu_F = \frac{\hat{H}'_T}{2} \equiv \frac{1}{2}\sum_m p_T^m + E_T^W$

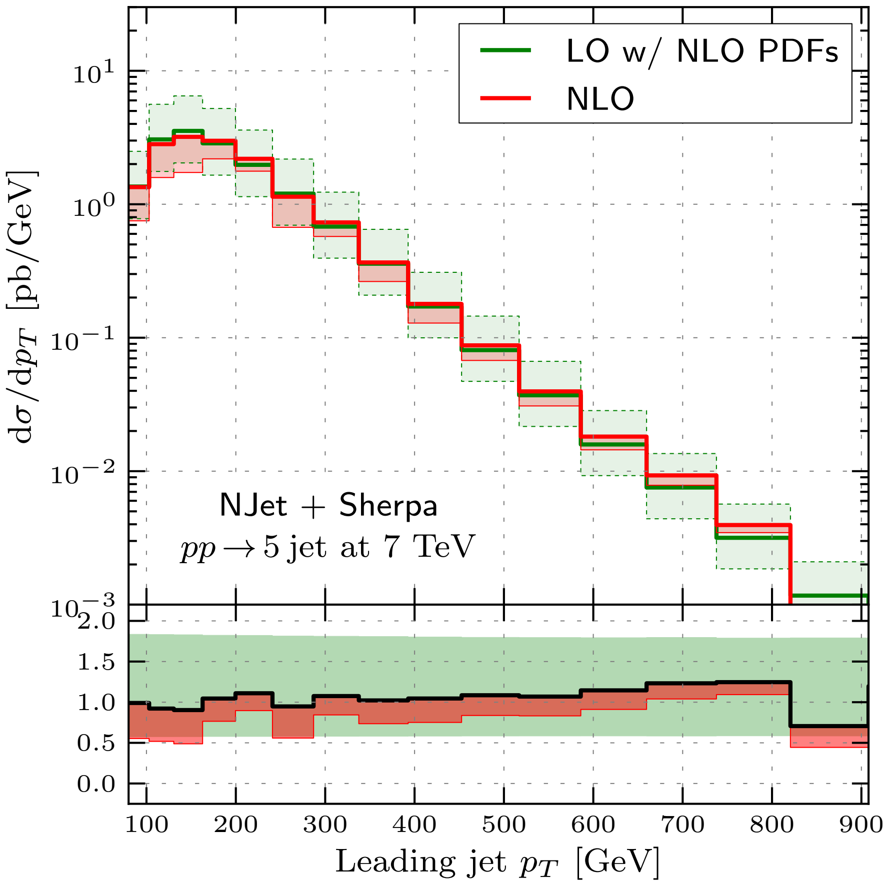


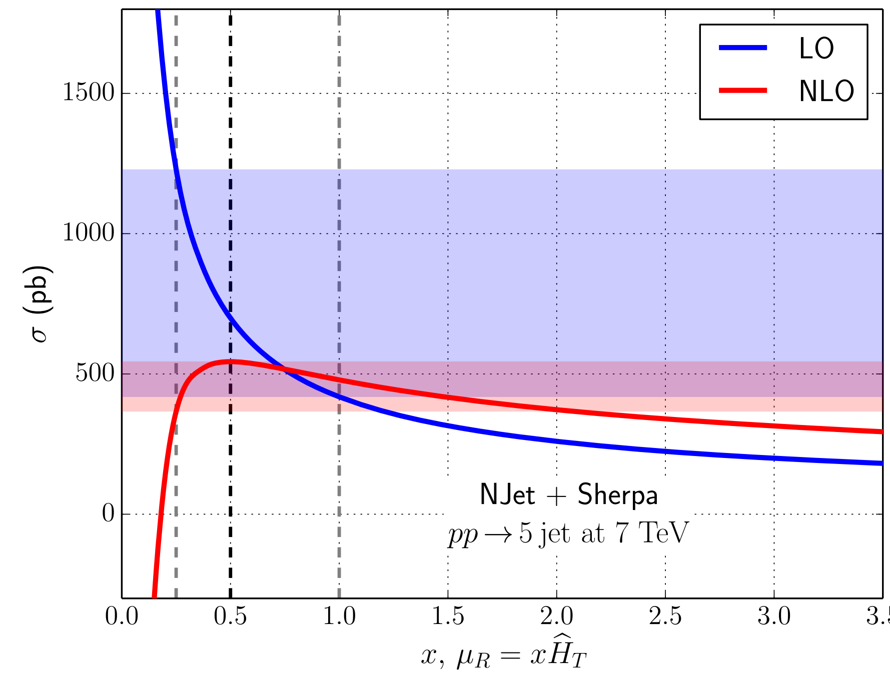
- Dramatic reduction in scale dependence (~20%)
- Up to 50% correction (non-trivial in shape)

Multi-jet production

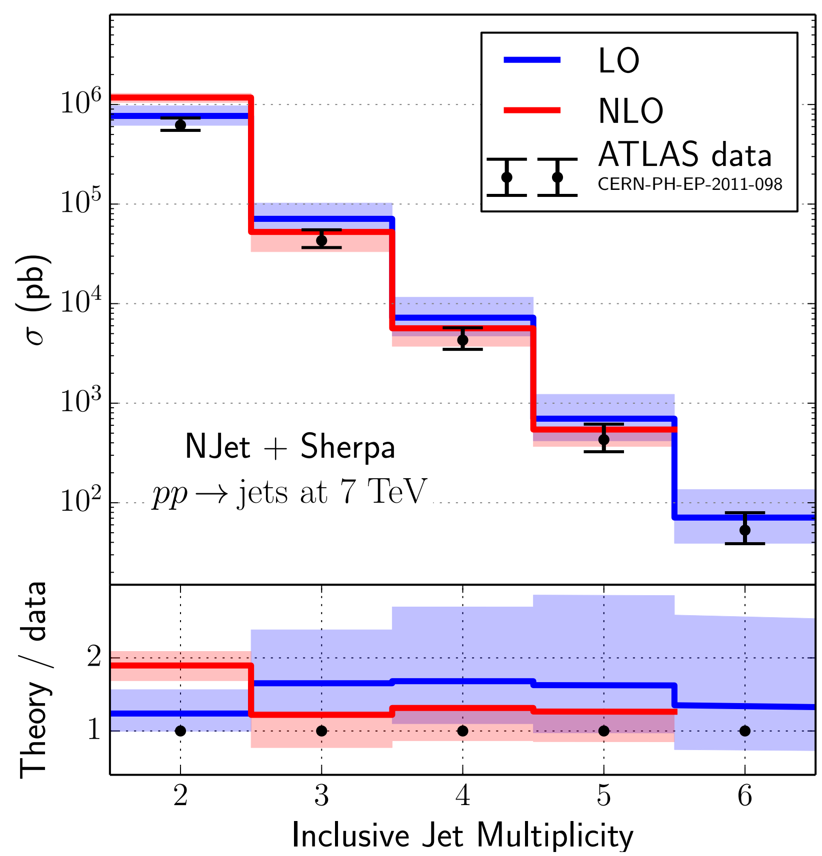
$pp \to 5\,\text{jets at NLO}$

Njet+Sherpa (Badger, Biedermann, Uwer, Yundin)





$$\widehat{H}_T = \sum_{i=1}^{N_{\text{parton}}} p_{T,i}^{\text{parton}}$$



- Better stability
- NLO in very good agreement with data!

Experimenter's wish-list

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [4,5]; Campbell/Ellis/Zanderighi [6]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [8]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [9,10]
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14,15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
7. $pp \to VV\,b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
8. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [20–22]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration [23]
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10. $pp \to V$+4 jets	top pair production, various new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \to W^*W^*$ $\mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
14. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
15. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
16. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

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CLOSED

- Final goal: Really automatic NLO calculations

zero cost for humans

  - Specify the process (input card)
  - Input parameters
  - Define final cuts

- Automatic NLO calculation "conceptually" solved

  - in a few years a number of codes (among others)

Blackhat+Sherpa   GoSam + Sherpa/MadGraph
MadLoop+MadFKS   CutTools   OpenLoops+Sherpa

✓ compete on precision, flexibility, speed, stability, ...
✓ many features : uncertainties, ...

Best solution still to emerge, but not more NLO wish-list, do it yourself!

- Individual calculations still relevant!   ✓ open the way to new methods

Resummation

- QCD based on convergence of perturbative expansion

$$\sigma = \mathcal{C}_0 + \alpha_s \mathcal{C}_1 + \alpha_s^2 \mathcal{C}_2 + \alpha_s^3 \mathcal{C}_3 + \ldots$$

requires $\alpha_s \ll 1 \ , \ \mathcal{C}_n \sim \mathcal{O}(1)$

In the boundaries of phase space → soft and collinear emission

unbalance cancellation of infrared singularities between real and virtual contributions

- Convergence spoiled when two scales are very different $L = |\log \frac{E_1}{E_2}| \gg 1$

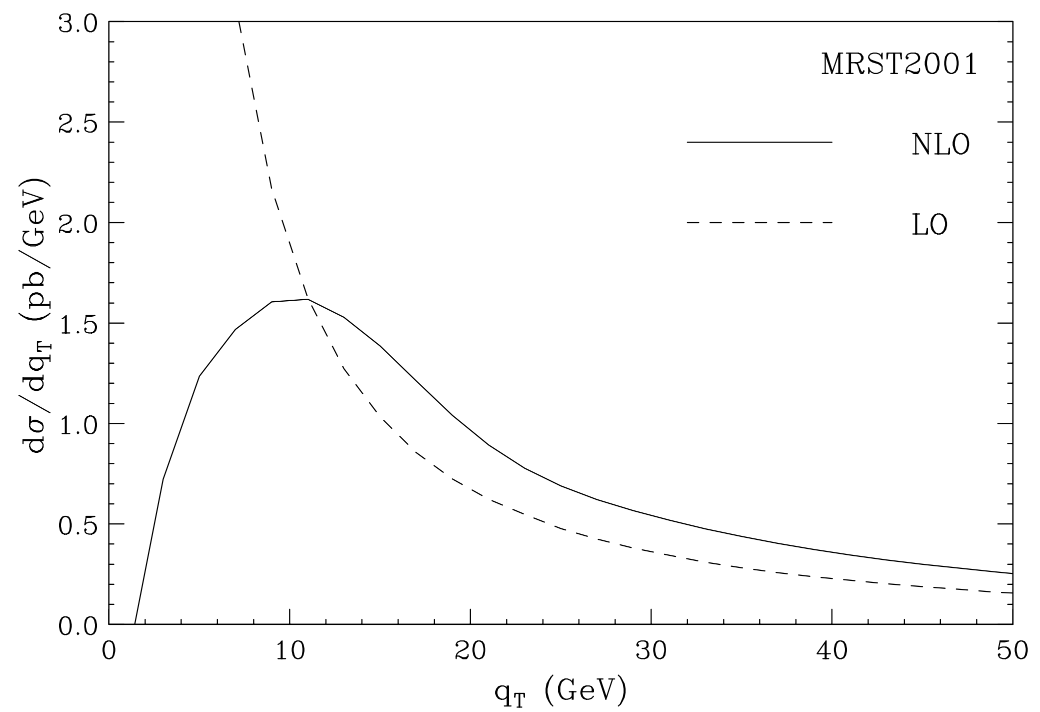
$$\mathcal{C}_m \sim L^n \quad n \leq 2m$$

low transverse momentum $\log \frac{q_T}{Q}$

Higgs

LO: $\frac{d\sigma}{dq_T} \to +\infty$ as $q_T \to 0$

NLO: $\frac{d\sigma}{dq_T} \to -\infty$ as $q_T \to 0$



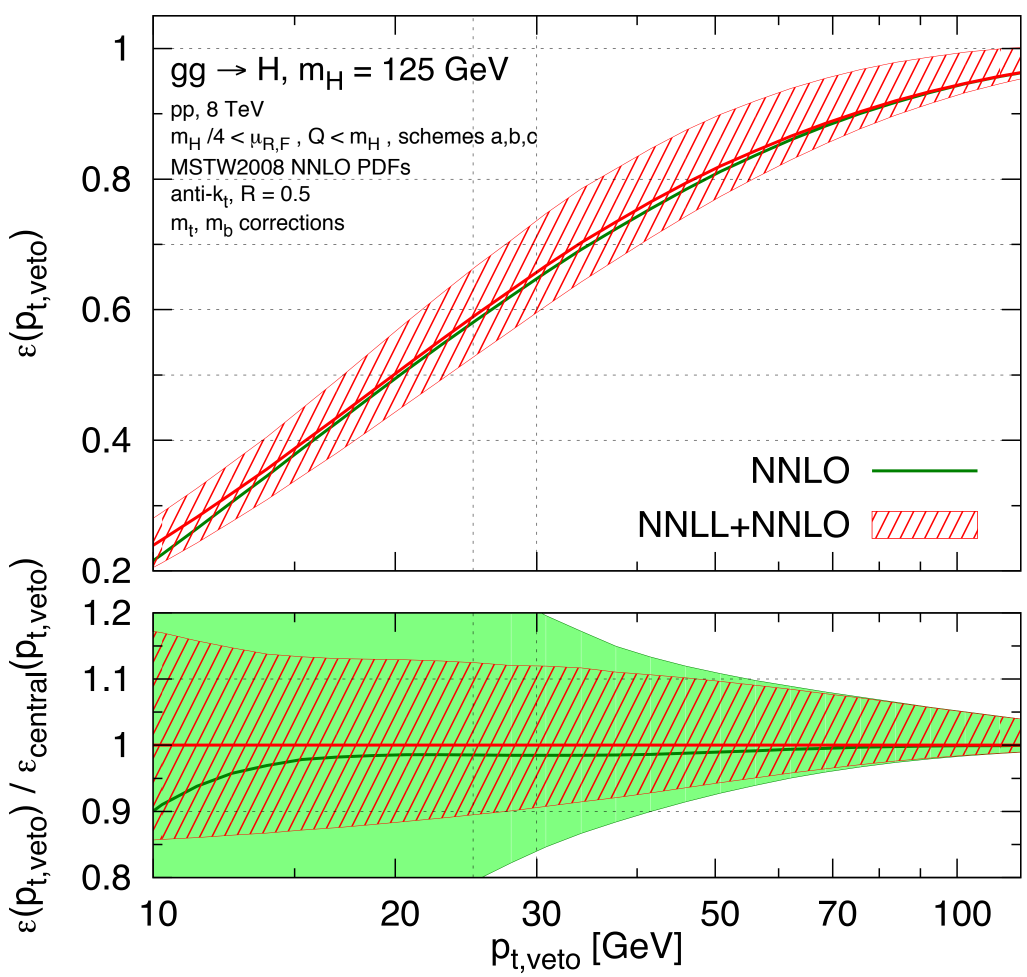
- Resummation achieved by exponentiation of large logs in Sudakov factor

Most recently: jet vetos

Jet veto in Higgs @ NNLL

Banfi, Monni, Salam, Zanderighi (2012)

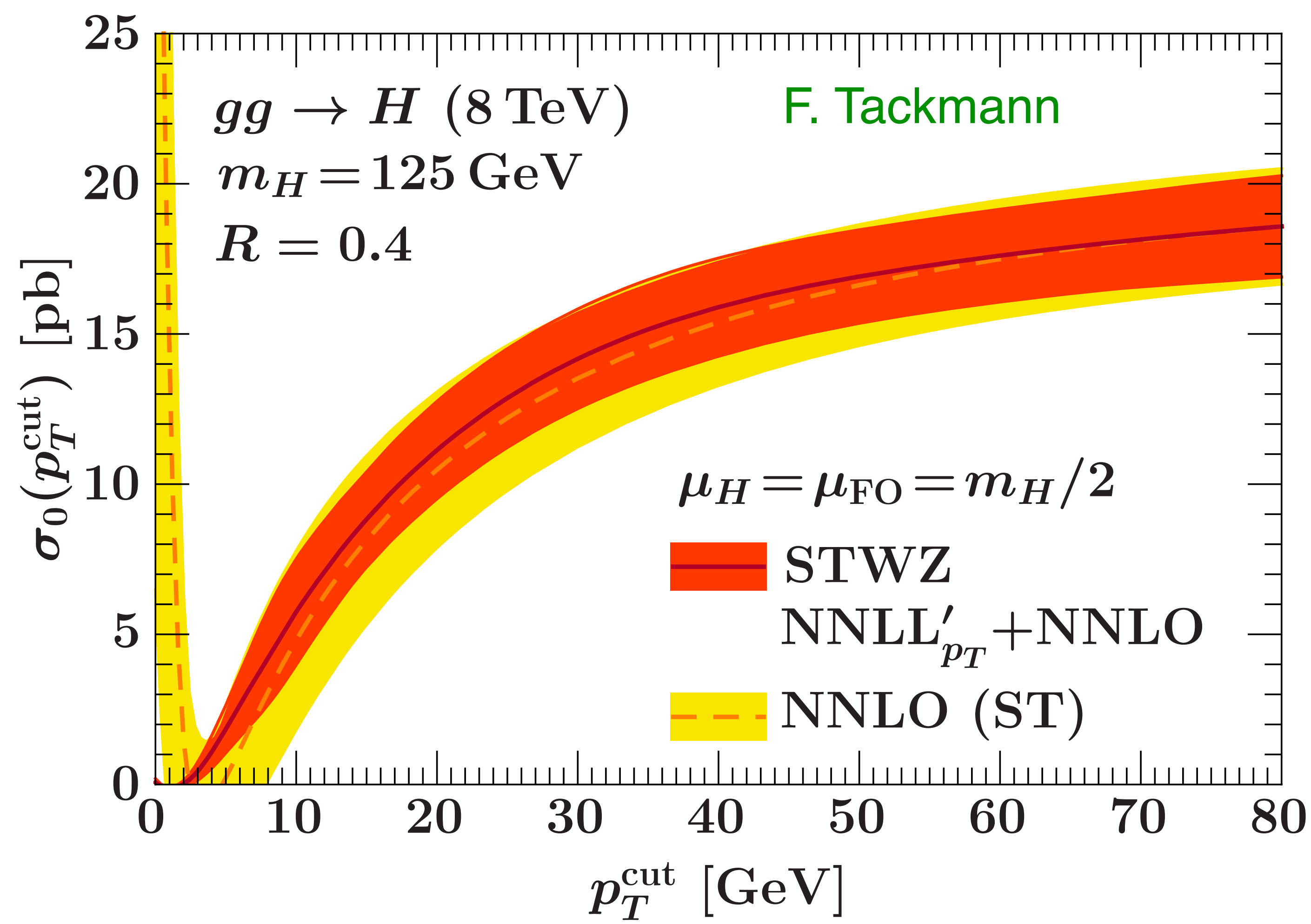
Banfi, Monni, Zanderighi (2013)



efficiency 0-jet "QCD"

- Reduction in uncertainty
- Validation of tools

Stewart, Tackmann, Walsh, Zuberi (2013)



cross section 0-jet "SCET"

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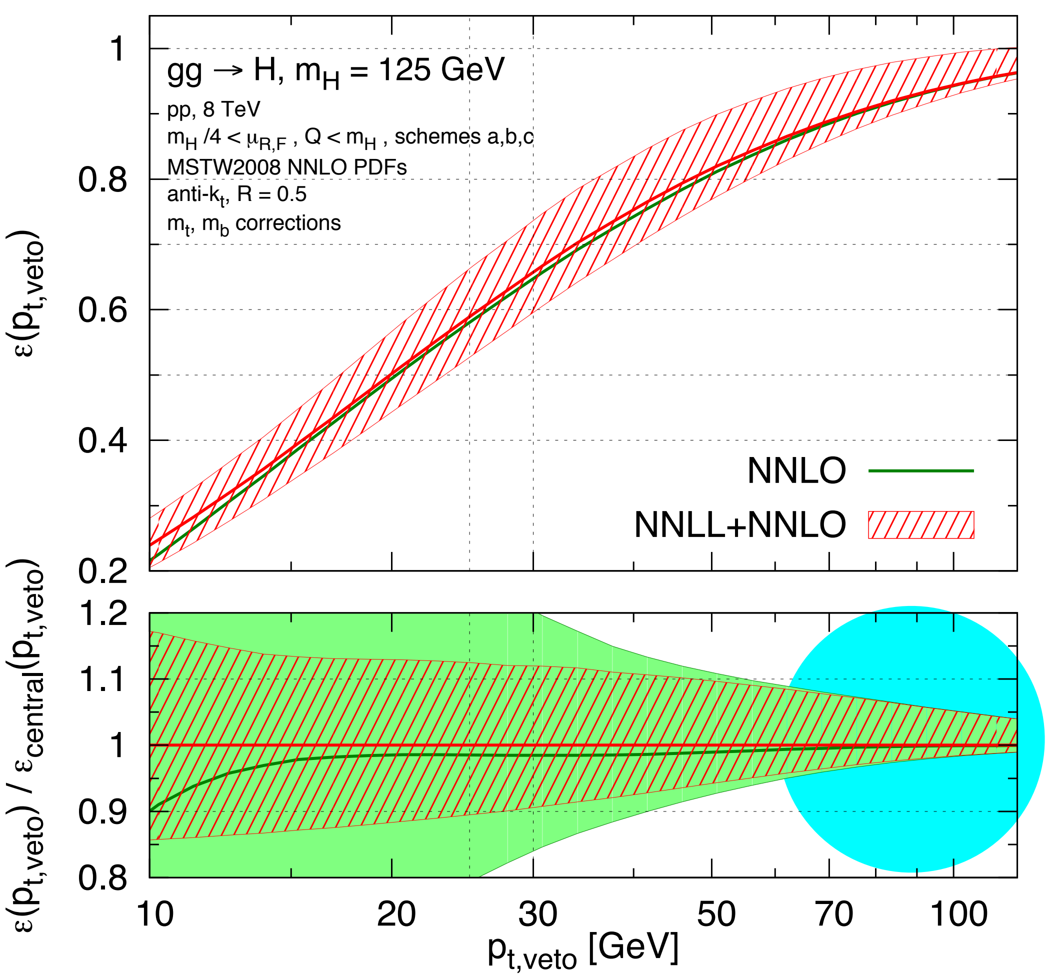

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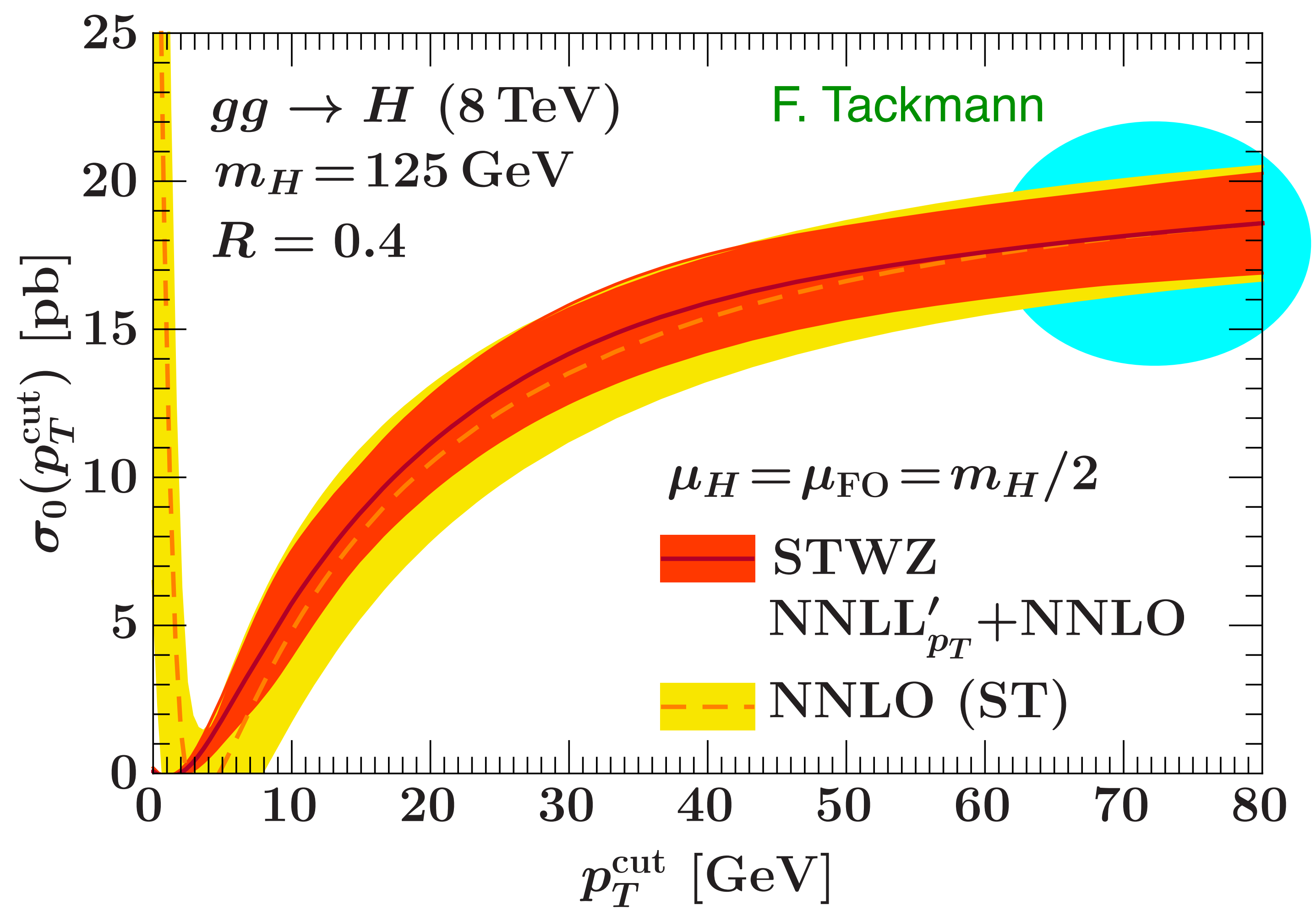

cross section 0-jet "SCET"

Recover fixed order at large transverse momentum

Merging NLO with Parton Showers

- Resummation to NLL accuracy + realistic final states
- Allow to carry NLO precision to all aspects of experimental analysis
  - MC@NLO Frixione, Webber
  - POWHEG Nason; Frixione, Nason, Oleari
- Can be interfaced to different tools : Herwig, Phytia,Sherpa
- Treat radiation differently but formally same NL accuracy

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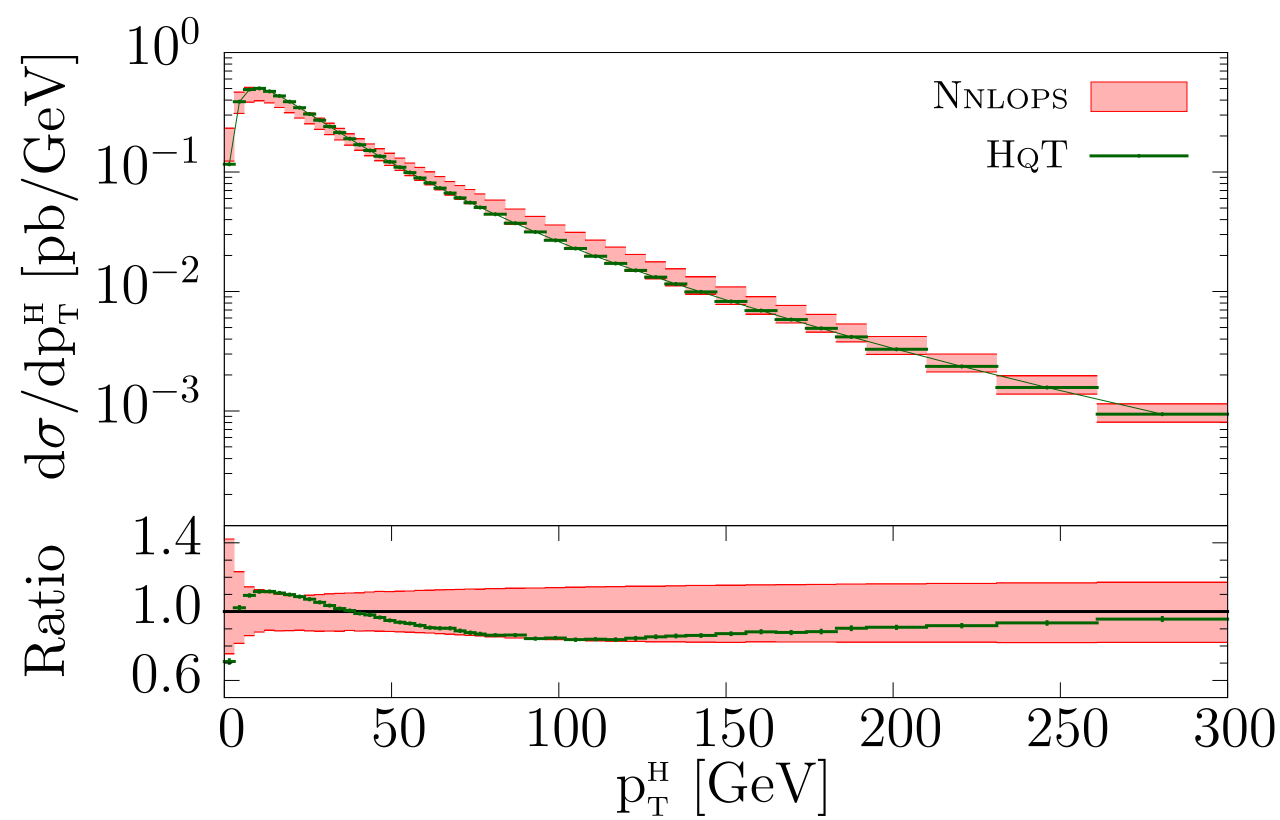
- NNLOPS (Higgs)

Hamilton, Nason, Re, Zanderighi

POWHEG+MINLO

H+jet at NLO

Inclusive H reweigthed to NNLO



Automation and more

- Provide large library of processes or different degree of automation
- aMC@NLO: full automation of NLO and PS in MC@NLO framework
  Frederix, Frixione, Hirschi, Pittau, Maltoni, Torrelli
- POWHEG-BOX framework Aioli, Nason, Oleari, re
- Sherpa : real matrix elements matching MC@NLO and POWHEG
  Krauss, Höche, Siegert, Schönher
- POWHEL: automation of ME from HELAC with POWHEG-Box
  Papadopoulos, Garzelli, Kardos, Trocsanyi
- POWHEG Box + Madgraph4 Campbell, Ellis, Frederix, Nason, Oleari, Williams
- MINLO Hamilton, Nason, Oleari, Zanderighi
- UNLOPS Lönnbland, Prestel
- GENEVA Aioli et al

+ many others

NNLO the new frontier

- Some measurements to few percent accuracy

✓ $e^+e^- \to 3\,\text{jets}$

$e^-p \to (2+1)\,\text{jets}$

✓ $pp \to V$

$pp \to \text{jets}$ partial

$pp \to V + \text{jets}$

✓ $pp \to t\bar{t}$

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

Match experimental accuracy
Extract accurate information

- Some processes with still (potentially) large NNLO corrections

✓ $pp \to H$ $\quad pp \to HH$

✓ $pp \to \gamma\gamma$ $\quad pp \to Z\gamma$ $\quad pp \to VH$

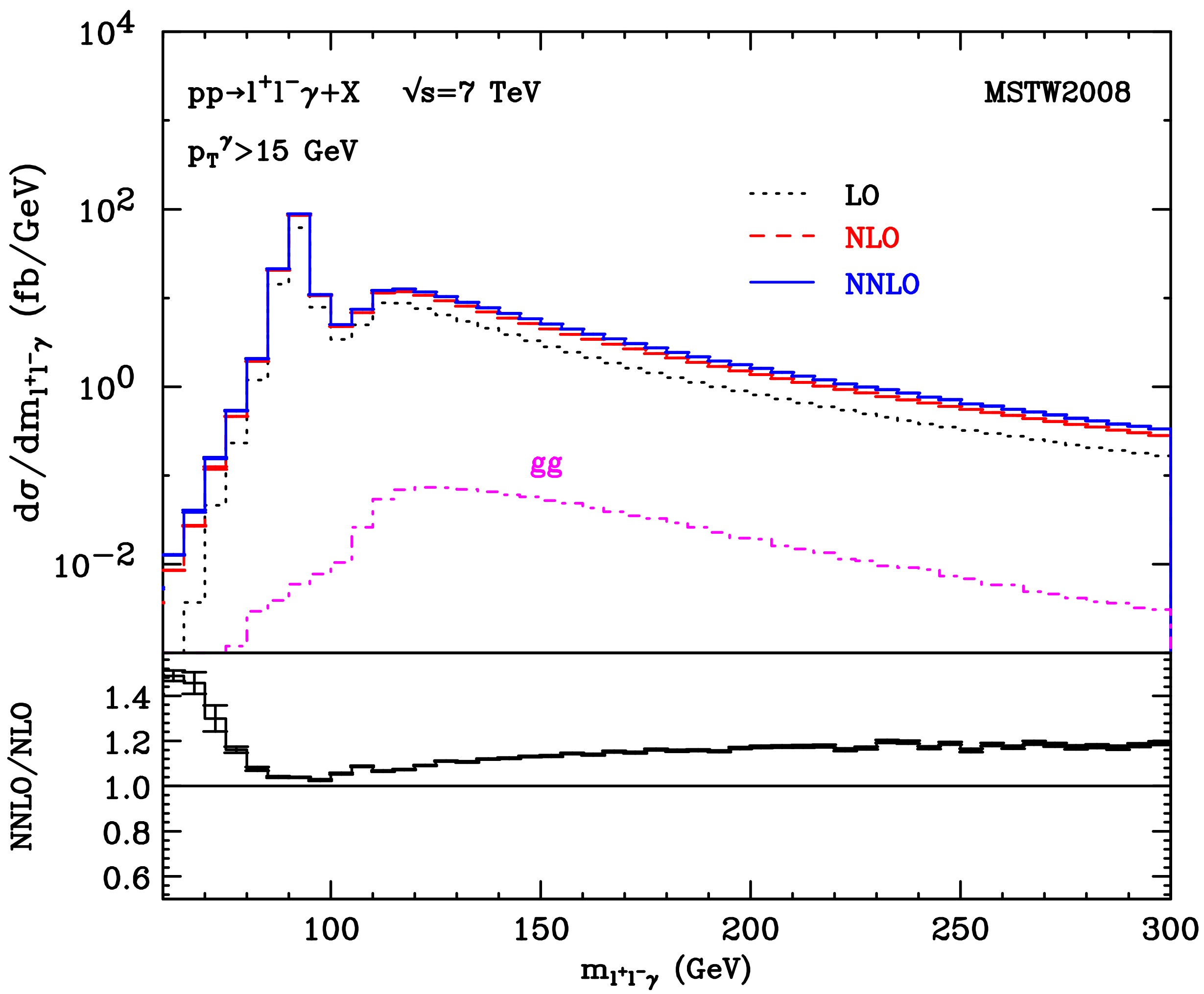
$pp \to VV$

$pp \to H + \text{jets}$ partial

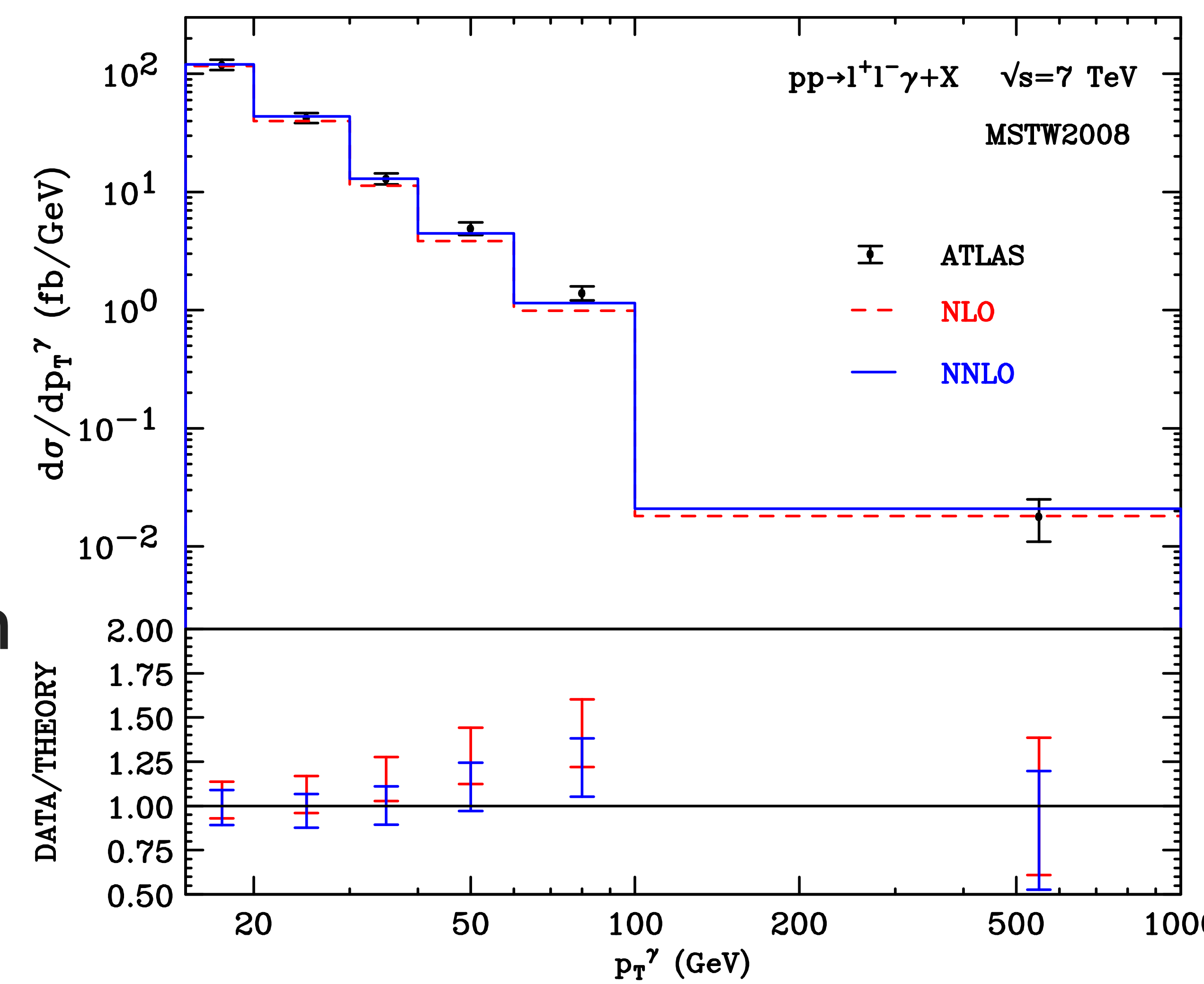
meaningful comparison
solid estimate of uncertainties

$pp \to Z\gamma$

M.Grazzini, S.Kallweit, D.Rathlev, A.Torre (2013)



- NNLO ~16% at LHC
- Improvement in data/TH



- Triple gauge boson couplings
- OpenLoops for amplitude generation
- First step towards automation

→ **VV** in general

$pp \to t\bar{t}$

- Very relevant observable at colliders
- LHC will reach better than 5% accuracy
- top mass, pdfs, new physics

(inclusive) Full NNLO available

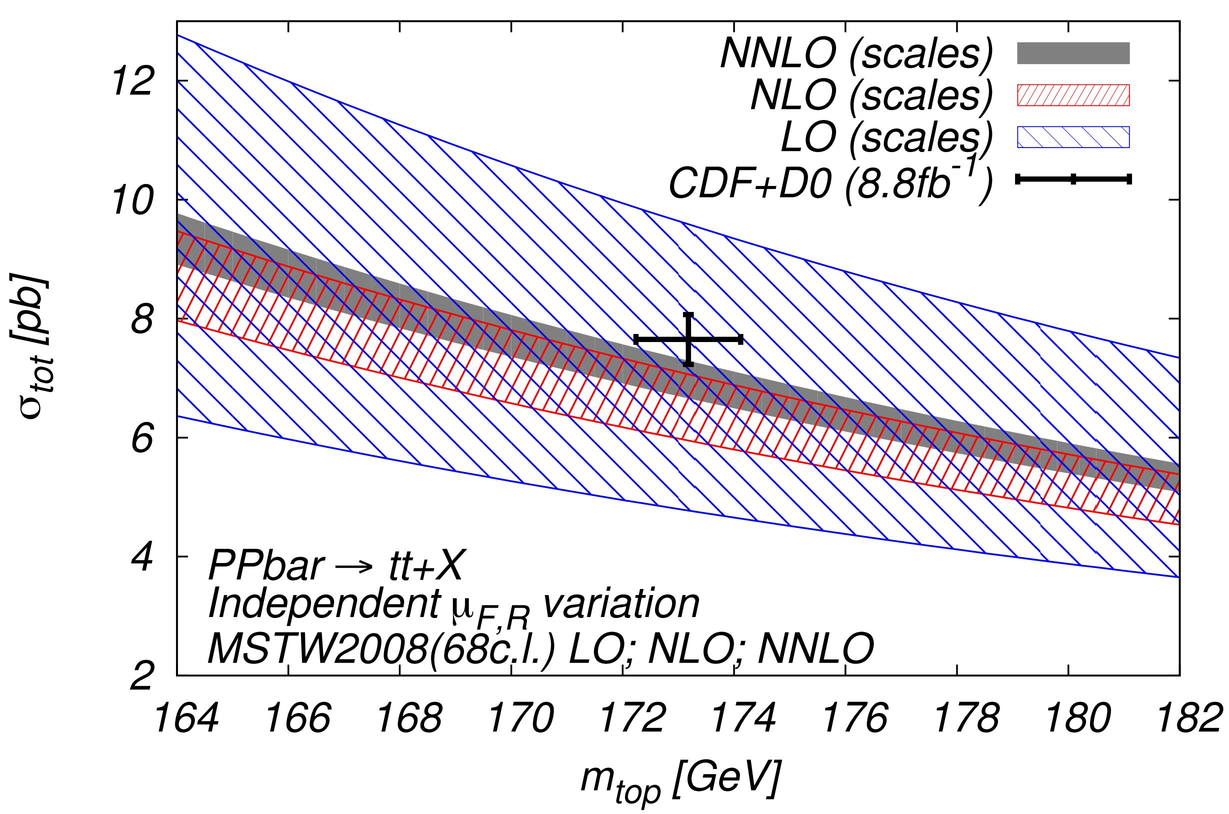
<5% TH uncertainties

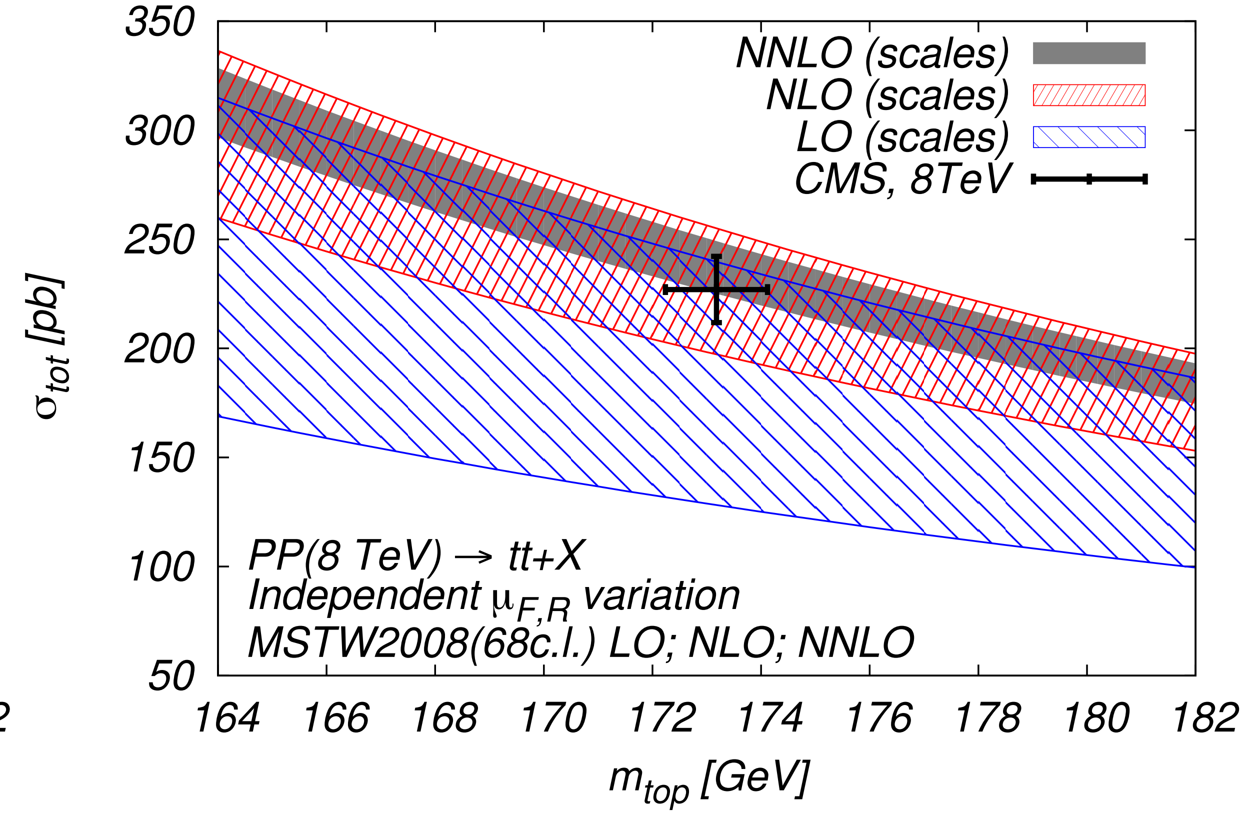
Czakon, Fiedler, Mitov (2013)

Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$^{+0.110(1.5\%)}_{-0.200(2.8\%)}$	$^{+0.169(2.4\%)}_{-0.122(1.7\%)}$
LHC 7 TeV	172.0	$^{+4.4(2.6\%)}_{-5.8(3.4\%)}$	$^{+4.7(2.7\%)}_{-4.8(2.8\%)}$
LHC 8 TeV	245.8	$^{+6.2(2.5\%)}_{-8.4(3.4\%)}$	$^{+6.2(2.5\%)}_{-6.4(2.6\%)}$
LHC 14 TeV	953.6	$^{+22.7(2.4\%)}_{-33.9(3.6\%)}$	$^{+16.2(1.7\%)}_{-17.8(1.9\%)}$

- Precision for mass

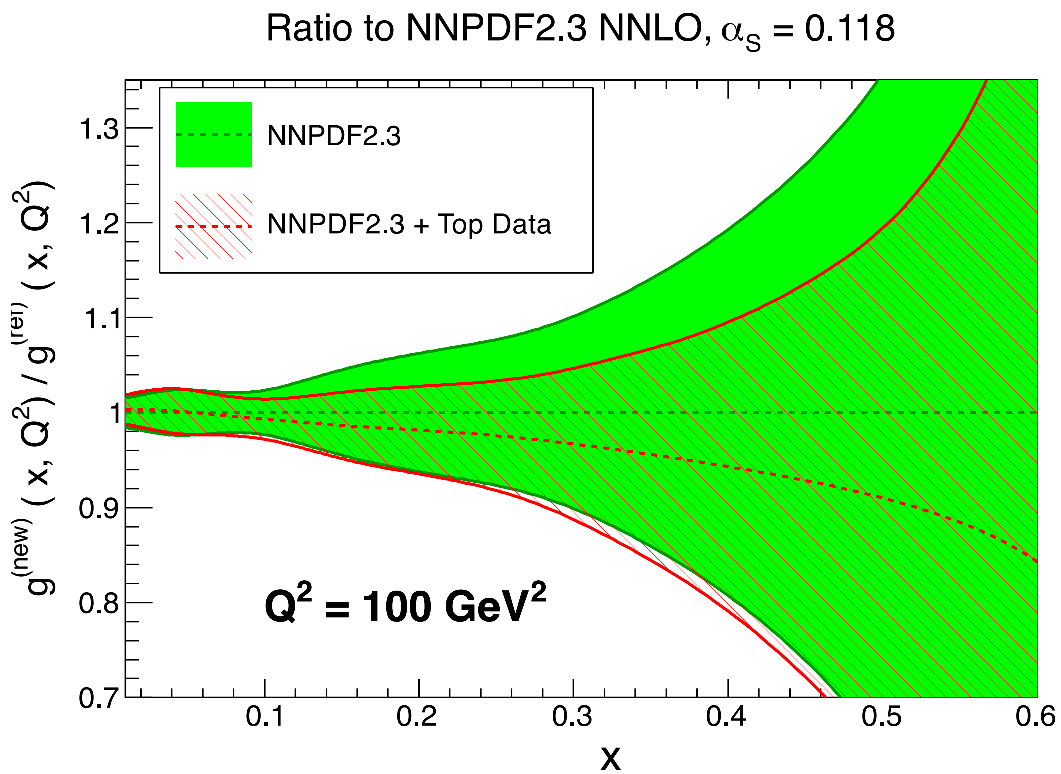
M. Czakon, P. Fiedler, A. Mitov, J. Rojo (2013)





$pp \to t\bar{t}$

- Precision for gluon pdf



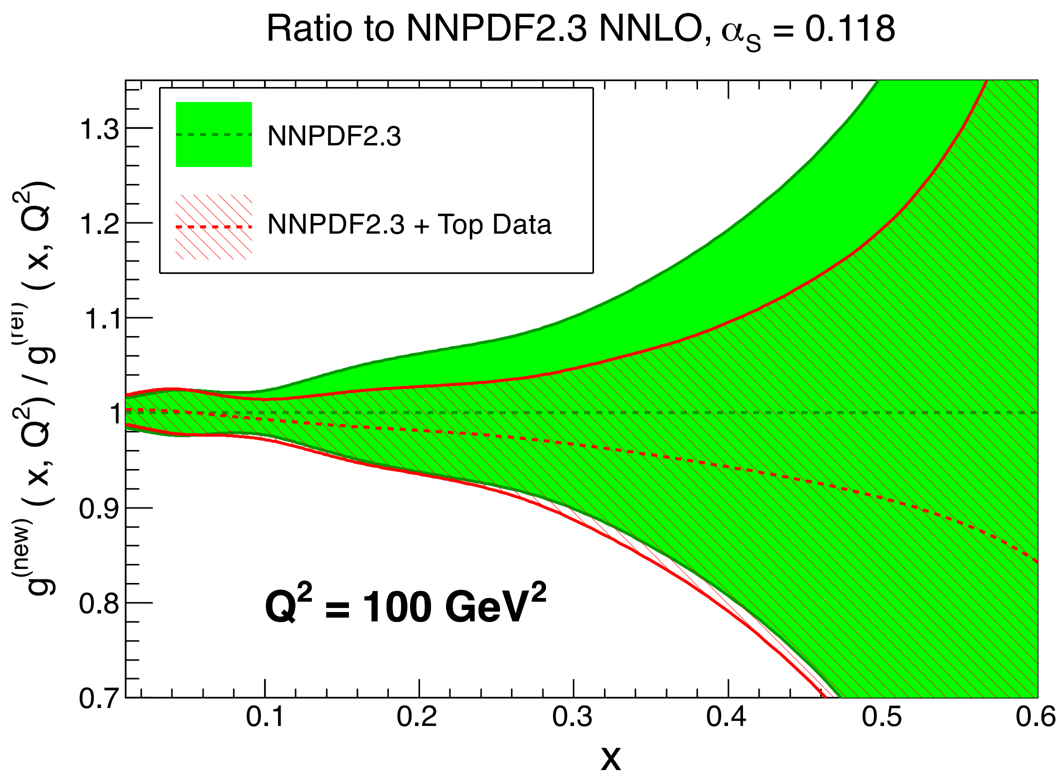
M. Czakon, M. Mangano, A. Mitov, J. Rojo (2013)

~20% reduction x=0.1 to 0.5

- data used in ABM 2013

$pp \to t\bar{t}$

- Precision for gluon pdf

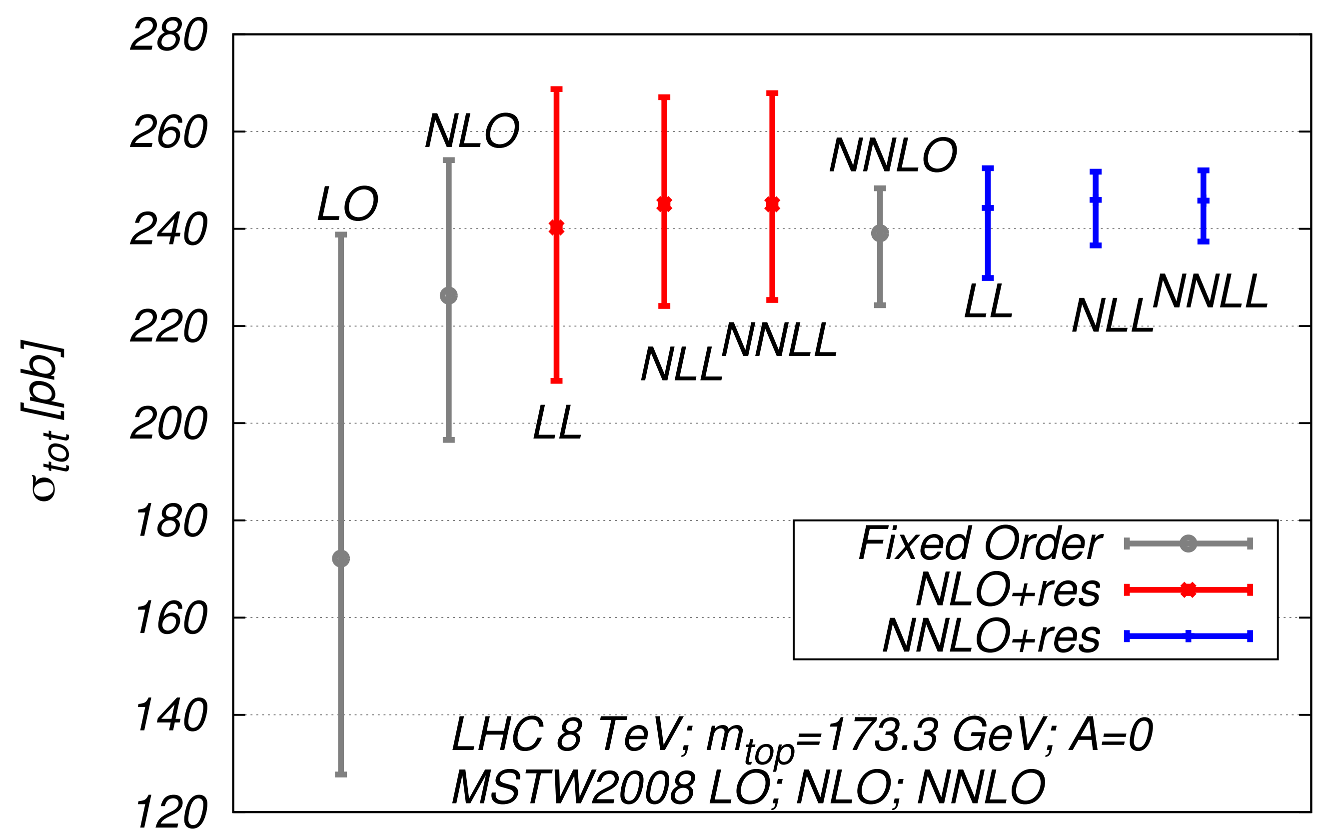


M. Czakon, M. Mangano, A. Mitov, J. Rojo (2013)

~20% reduction x=0.1 to 0.5

- data used in ABM 2013

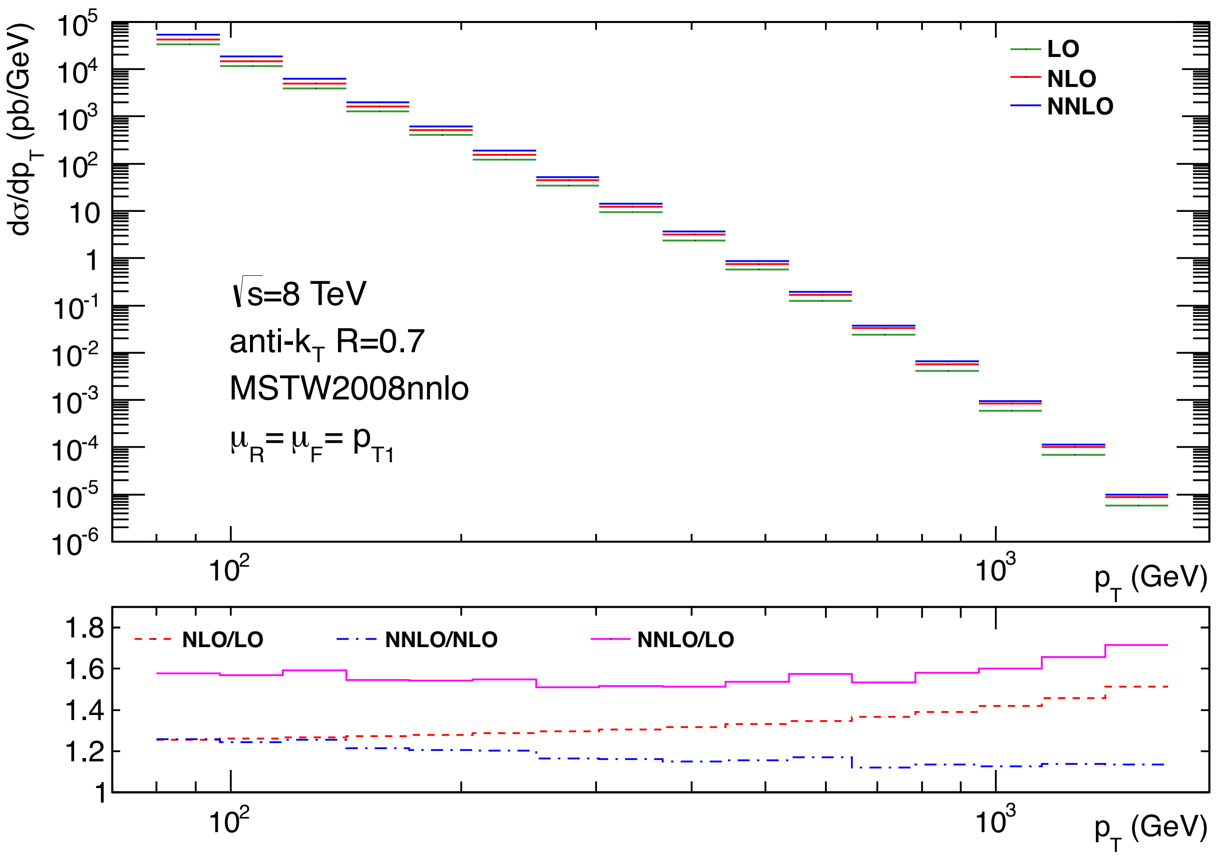
- Even higher precision: threshold resummation

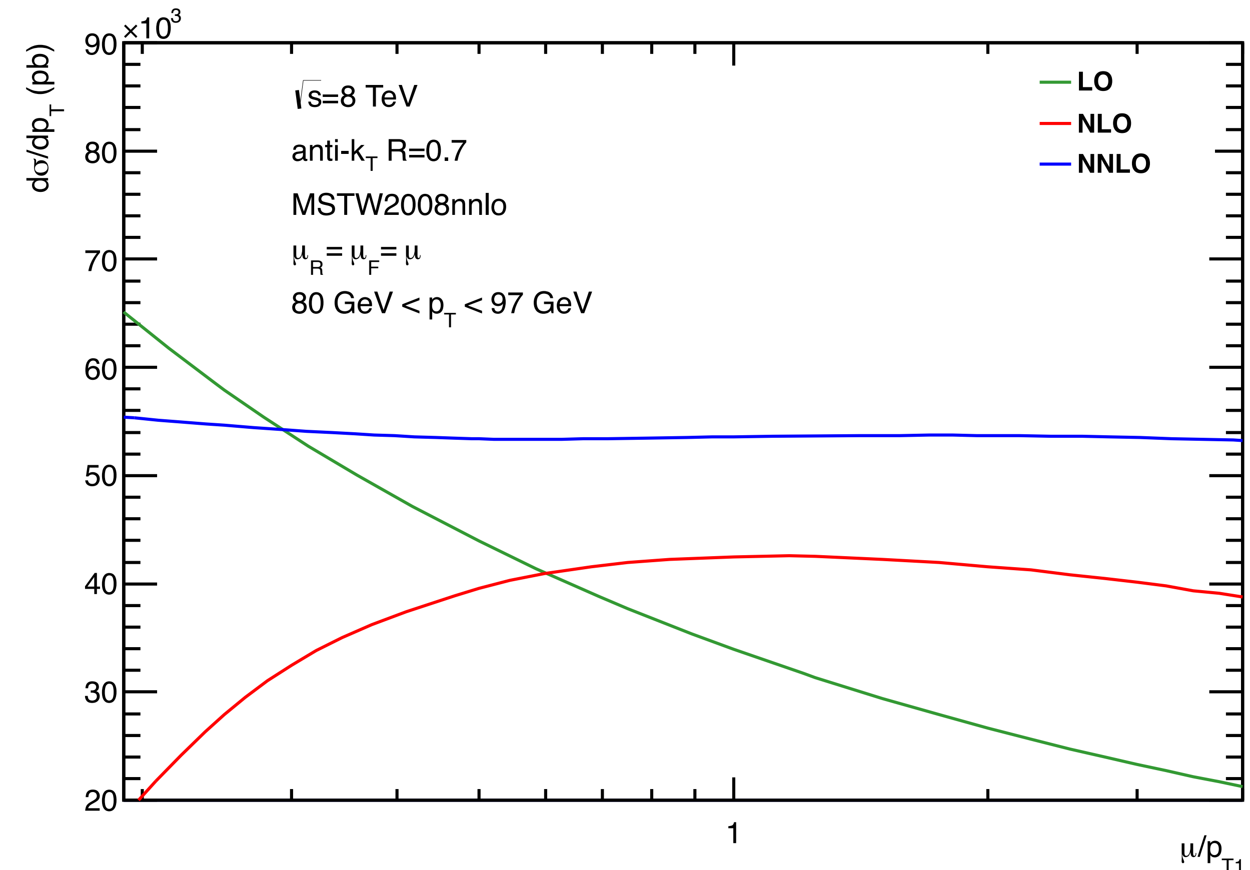


$pp \to 2\,\text{jets}$

A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, J.Pires (2013)
J.Curry, A. Gehrmann-De Ridder, E.W.N. Glover, J.Pires (2013)

- Pure gluon using antenna subtraction : NNLOJET





- 15-25% increase

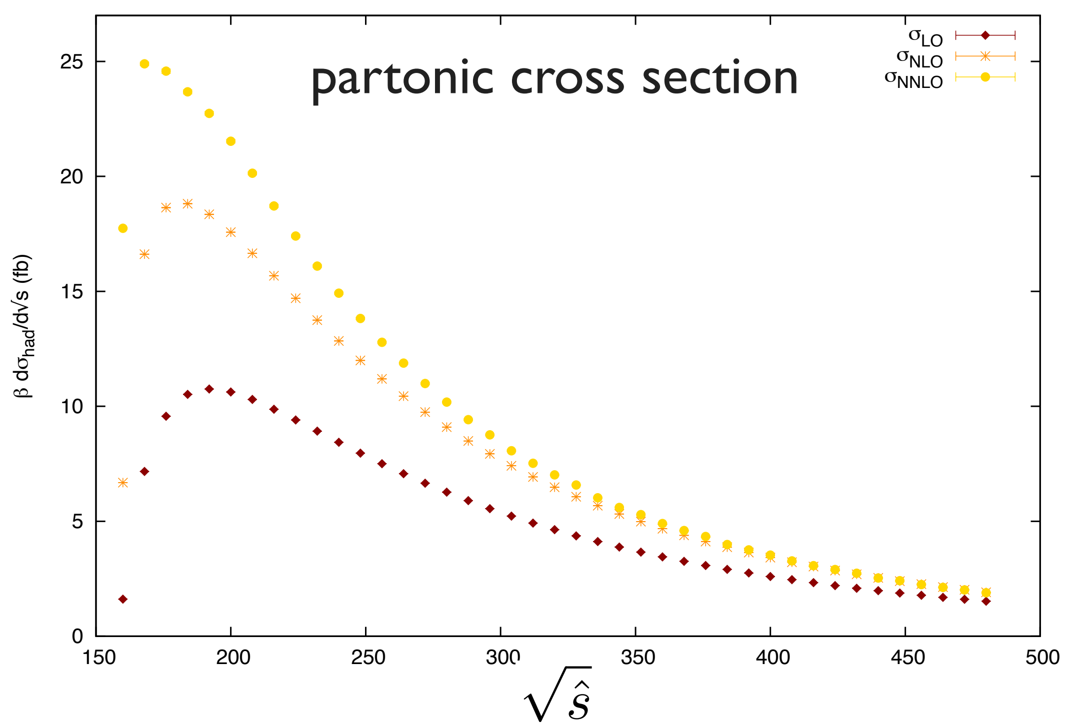
- Amazing reduction in scale dependence : precision for LHC

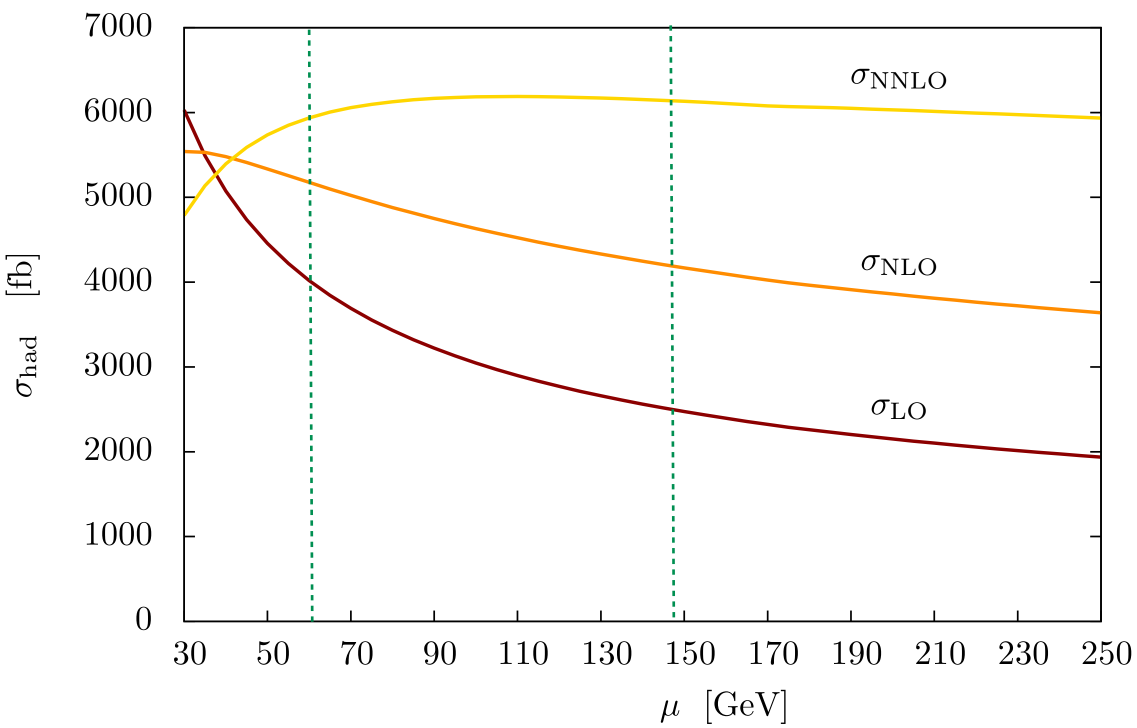
Similar results expected for other partonic channels (gg dominant at low p_T)

- But NNLO can not be predicted by NLO scale variations..

$pp \to H + \text{jet}$

R.Boughezal, F.Caola, K.Melnikov, F.Petriello, M.Schulze (2013)





- Pure gluon only $\quad p_T^{\text{jet}} > 30\,\text{GeV}$

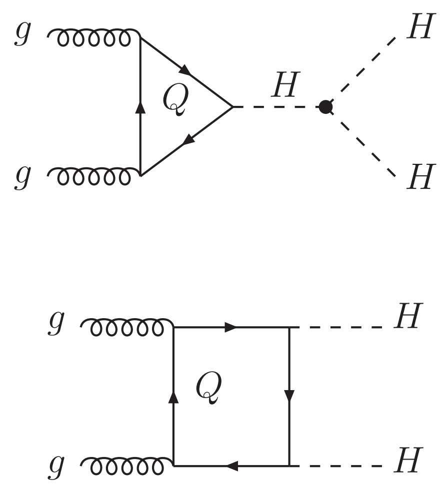
$$\sigma_{\text{LO}}(pp \to Hj) = 2713^{+1216}_{-776}\ \text{fb},$$
$$\sigma_{\text{NLO}}(pp \to Hj) = 4377^{+760}_{-738}\ \text{fb},$$
$$\sigma_{\text{NNLO}}(pp \to Hj) = 6177^{-204}_{+242}\ \text{fb}.$$

+60% NLO
+30-40% NNLO

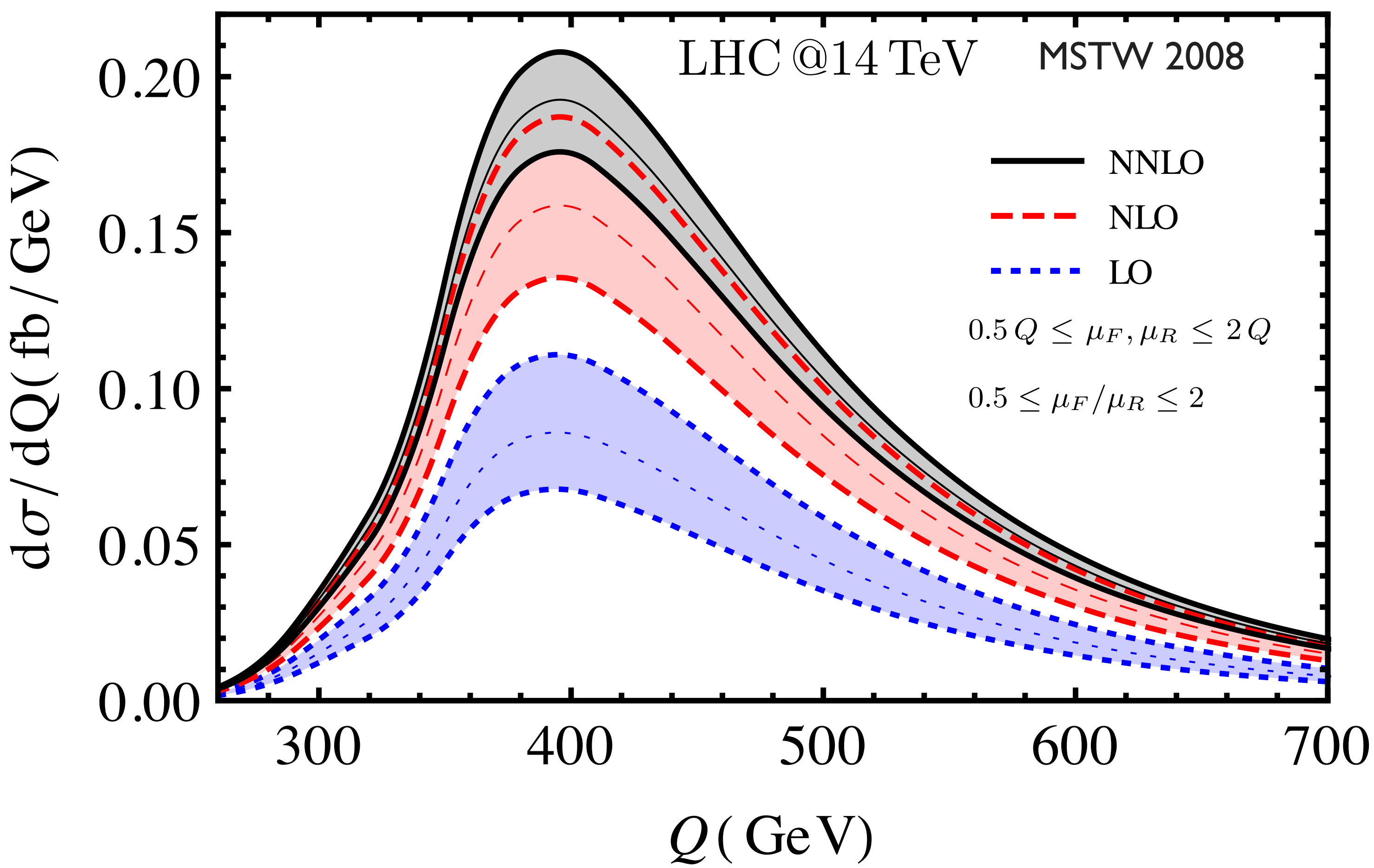
- Another case of significantly reduced scale dependence ~4%

$pp \to HH$

DdeF., J.Mazzitelli (2013)



- Triple Higgs coupling : Higgs potential
- Expect large corrections (single Higgs)
- Use large top mass limit



$$M_H = 126\,\text{GeV}$$

K

$$\sigma_{\text{LO}} = 17.8\,^{+5.3}_{-3.8}\,\text{fb}$$

$$\sigma_{\text{NLO}} = 33.2\,^{+5.9}_{-4.9}\,\text{fb} \quad 1.86$$

21%

$$\sigma_{\text{NNLO}} = 40.2\,^{+3.2}_{-3.5}\,\text{fb} \quad 2.26$$

$\pm 8\%$

$\mathcal{O}(\pm 20\%)$ at NLO.

Les Houches NNLO wish-list (2013)

- Many of them doable in the next few years
- More realistic final states (V, top with decays)
- Larger multiplicities not possible yet
- Automation far away
- Shower requires increase in accuracy
- NLO EW corrections needed

Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of H + jj final state
VV′	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
gg → VV	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
Vγ	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
Vb$\bar{\text{b}}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for VH → b$\bar{\text{b}}$
VV′γ	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs
VV′V″	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
VV′ + j	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
VV′ + jj	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	$d\sigma$ @ NNLO QCD		bkg to $H \to \gamma\gamma$

Process	known	desired	details
t$\bar{\text{t}}$	σ_{tot} @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW	precision top/QCD, gluon PDF, effect of extra radiation at high rapidity, top asymmetries
t$\bar{\text{t}}$ + j	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW	precision top/QCD top asymmetries
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD (t channel)	precision top/QCD, V_{tb}
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO weak	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: incl. jets, dijet mass → PDF fits (gluon at high x) → α_s CMS http://arxiv.org/abs/1212.6660
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: $R3/2$ or similar → α_s at high scales dom. uncertainty: scales CMS http://arxiv.org/abs/1304.7498
γ + j	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD +NLO EW	gluon PDF γ + b for bottom PDF

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
t$\bar{\text{t}}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Electroweak corrections at large energies

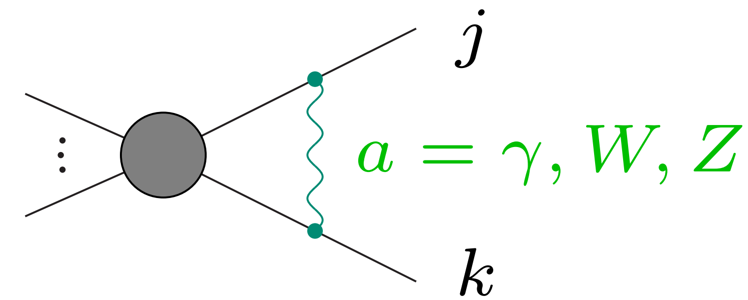
- Sudakov logarithms induced by soft gauge-boson exchange

at $\sqrt{s} \sim 1\,\text{TeV}$

S. Dittmaier

$$\delta_{\rm LL}^{1-\rm loop} \sim -\frac{\alpha}{\pi s_{\rm W}^2} \ln^2\left(\frac{s}{M_{\rm W}^2}\right) \simeq -26\%$$

$$\delta_{\rm LL}^{2-\rm loop} \sim +\frac{\alpha^2}{2\pi^2 s_{\rm W}^4} \ln^4\left(\frac{s}{M_{\rm W}^2}\right) \simeq 3.5\%$$



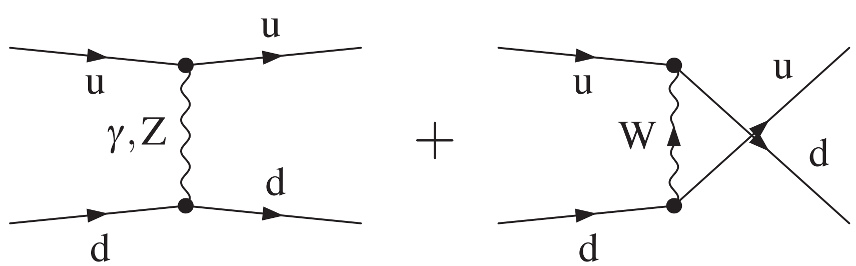
- still sizable at 2-loops

$s, |t|, |u| \gg M_W^2$

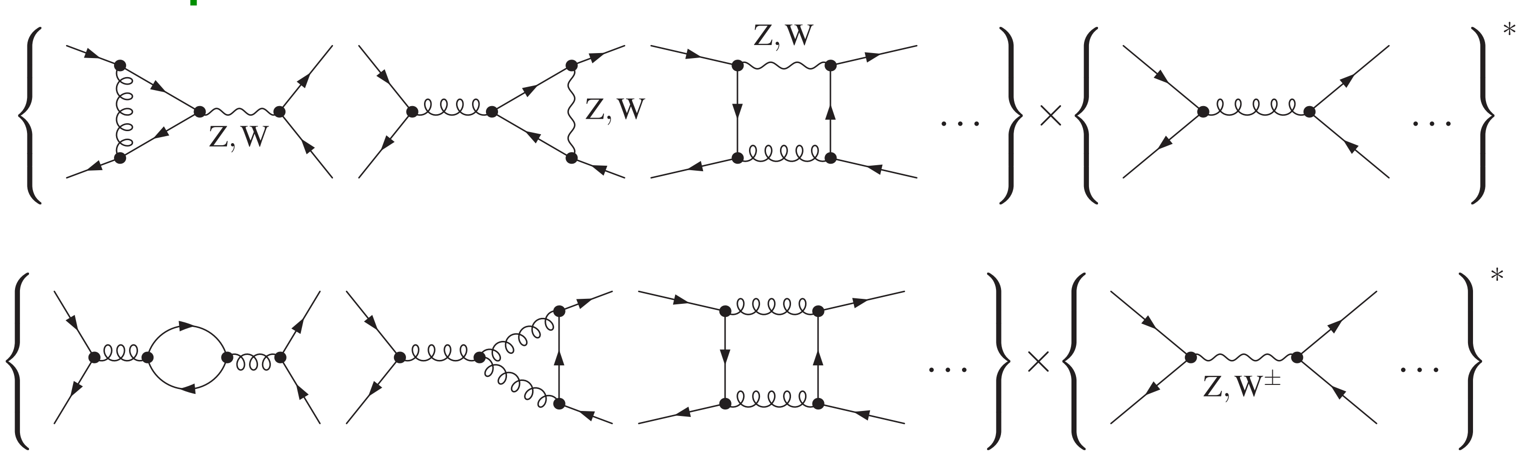
Dijet production

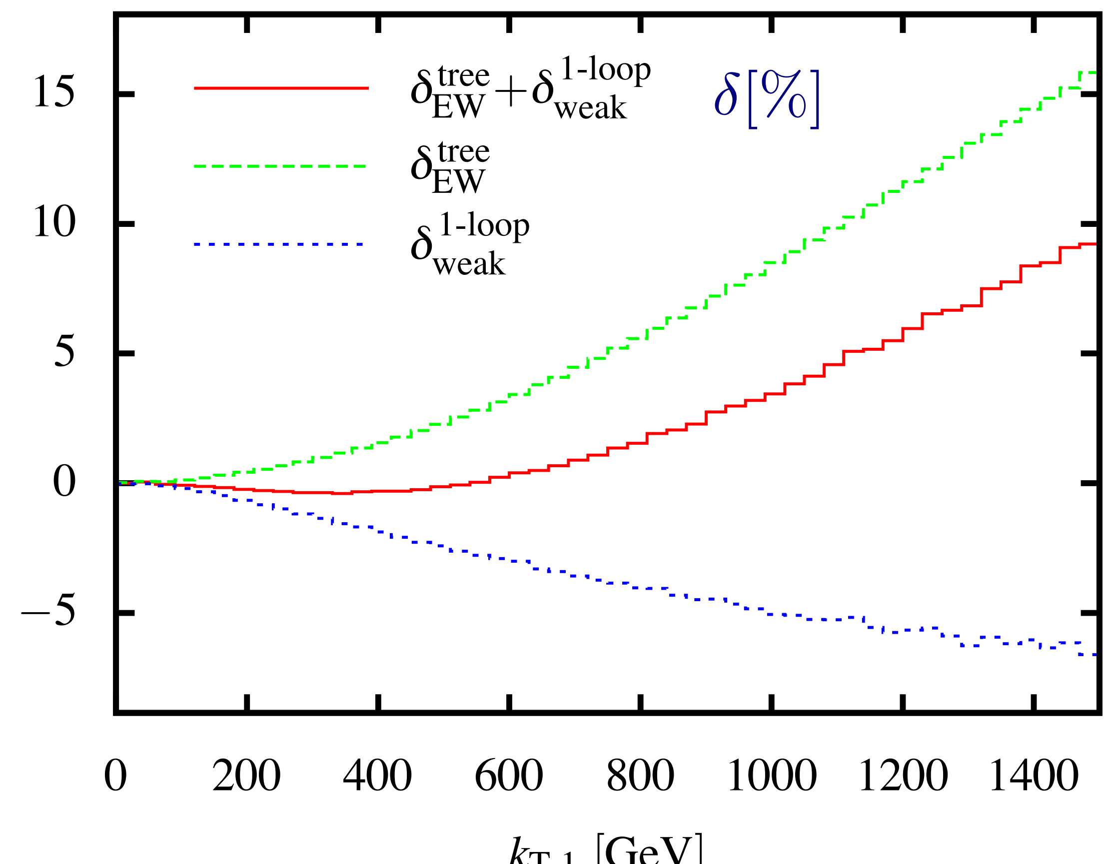
Dittmaier, Huss, Speckner

tree EW



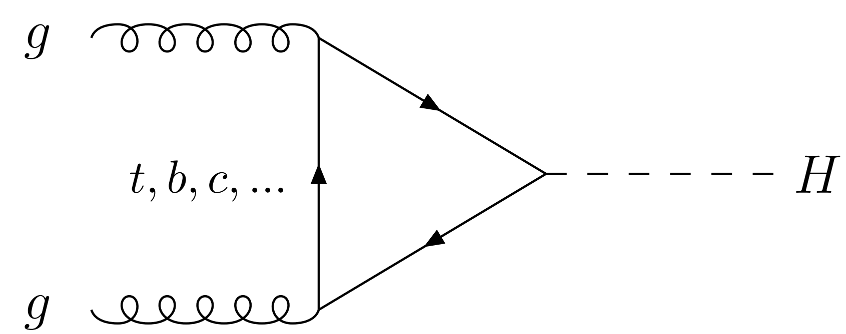
1-loop EW



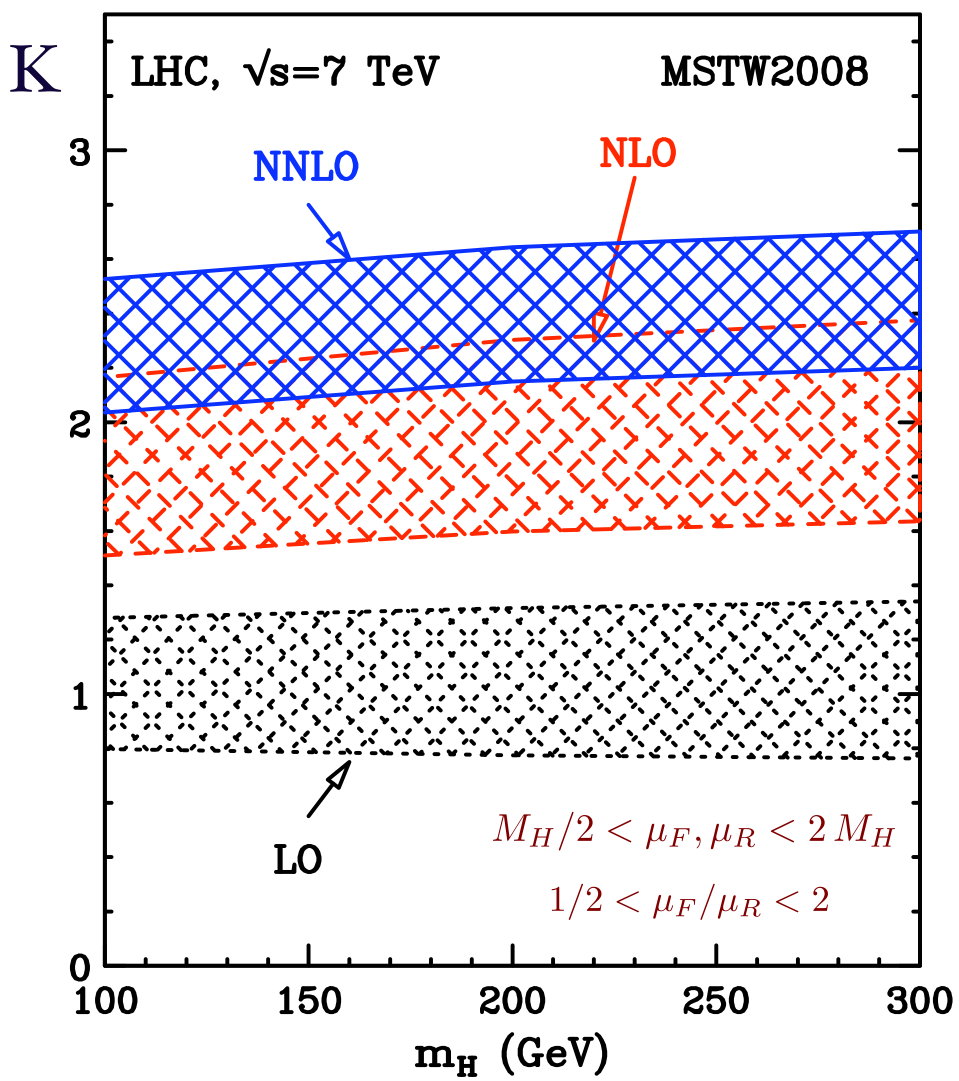


Higgs Boson

- Gluon-gluon fusion dominates due to large gluon luminosity



- QCD corrections are huge!



$$K = \frac{\sigma^{NNLO(NLO)}}{\sigma^{LO}}$$

NLO Dawson (1991); Djouadi, Spira, Zerwas (1991)
Graudenz, Spira, Zerwas (1993)

NNLO Harlander, Kilgore (2002)
Anastasiou, Melnikov (2002)
Ravindran, Smith, van Neerven (2003)

Improved Higgs Cross-section @ LHC

- NNLL Resummation 9% at 7 TeV — Catani, deF., Grazzini, Nason (2003)
- Two loop EW corrections not negligible ~ 5% — Aglietti, Bonciani, Degrassi, Vicini (2004); Degrassi, Maltoni (2004); Actis, Passarino, Sturm, Uccirati (2008)
- Mixed EW-QCD effects evaluated in EFT approach — Anastasiou et al (2008)
- + Mass effects, Line-shape, interferences, ... — Higgs Cross-Section WG

$$\sigma(\mathrm{m_H} = 125\,\mathrm{GeV}) = 19.27^{+7.2\%}_{-7.8\%}{}^{+7.5\%}_{-6.9\%}\ \mathrm{pb}$$

(scale, $\mathrm{pdf} + \alpha_S$) — deF, Grazzini

- Still sizable uncertainties but great improvement over the last years
- And more precise results just arriving!!

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scale: Higher orders; $\mathrm{pdf} + \alpha_\mathrm{S}$: LHC data and more observables — deF, Grazzini

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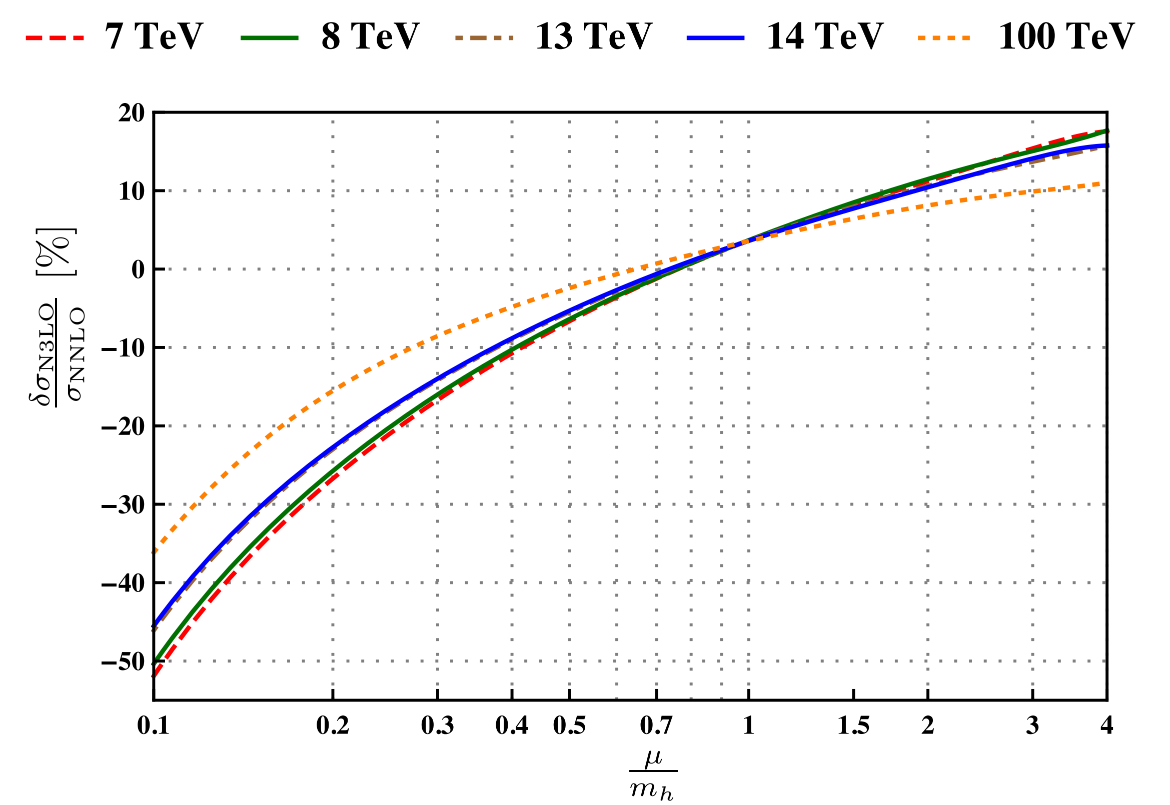
Even Higher orders : N^{3}LO

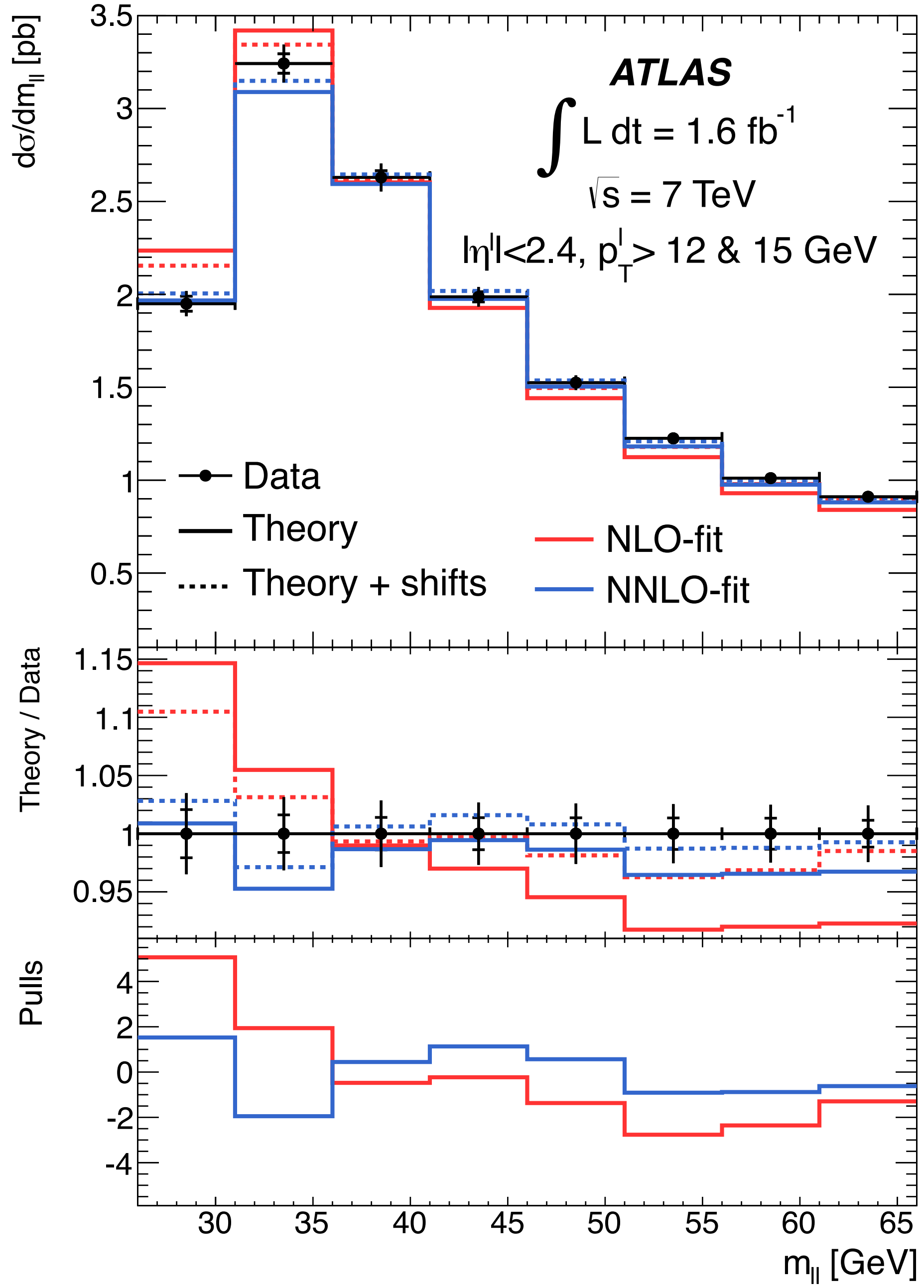
- 3 loop form factor — Baikov et al (2009); Gehrmann et al (2010); Lee, Smirnov, Smirnov (2010)
- Triple real emission : threshold expansion — Anastasiou, Duhr, Dulat, Mistlberger (2013)
- 2 loop + single emission — Duhr, Gehrmann (2013); Li, Zu (2013); Gehrmann, Jaquier, Glover, Koukoutsakis (2012)
- 1 loop + double emission — Anastasiou, Duhr, Dulat, Herzog, Mistlberger (2013)
- Subtraction terms — Höschele, Hoff, Pak, Steinhauser, Ueda (2013); Buehler, Lazopoulos (2013)
- NNNLO Soft-Virtual approximation

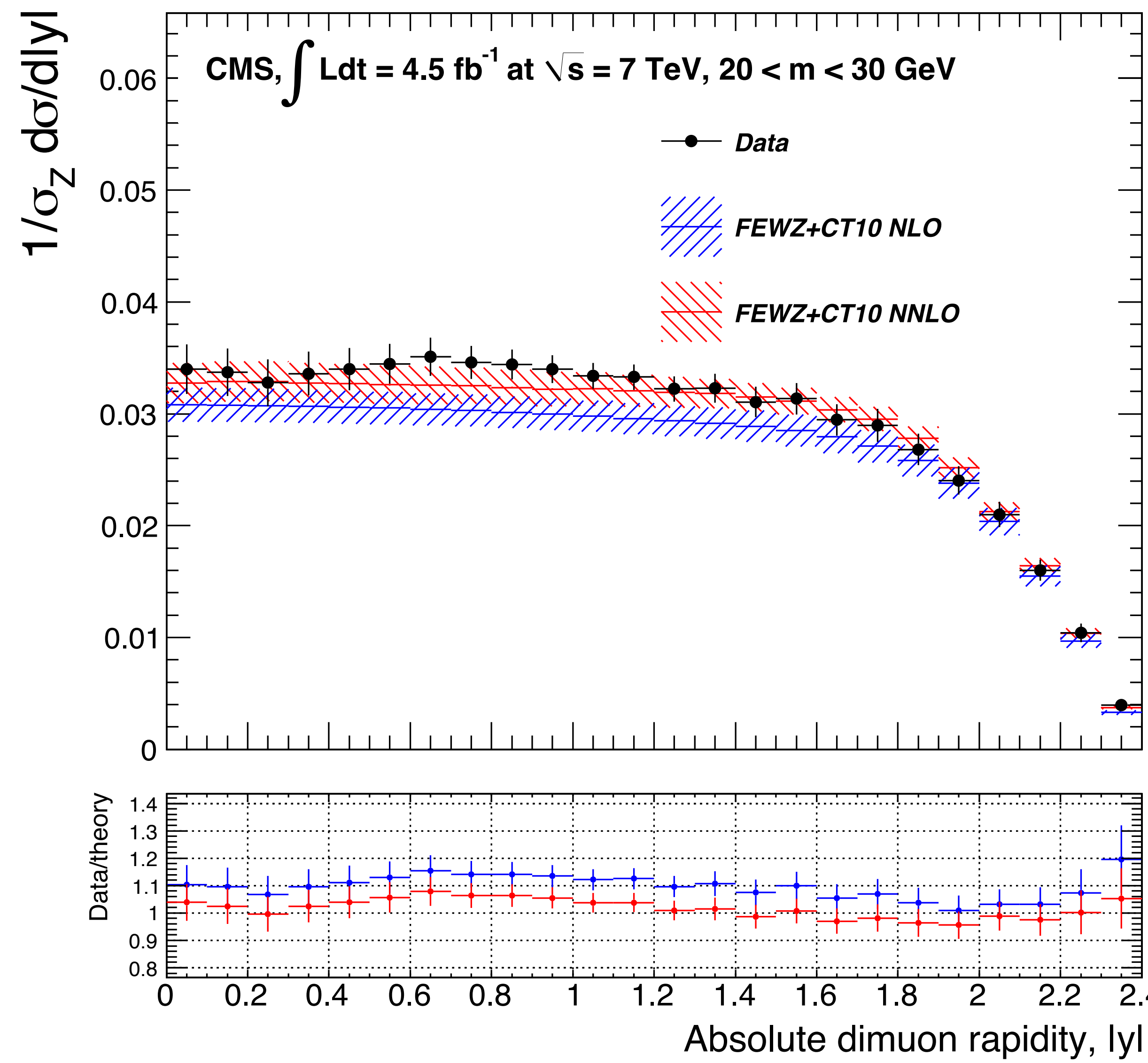
Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger (2014)



New era in precision
Further improvements expected

DATA vs TH : Drell-Yan

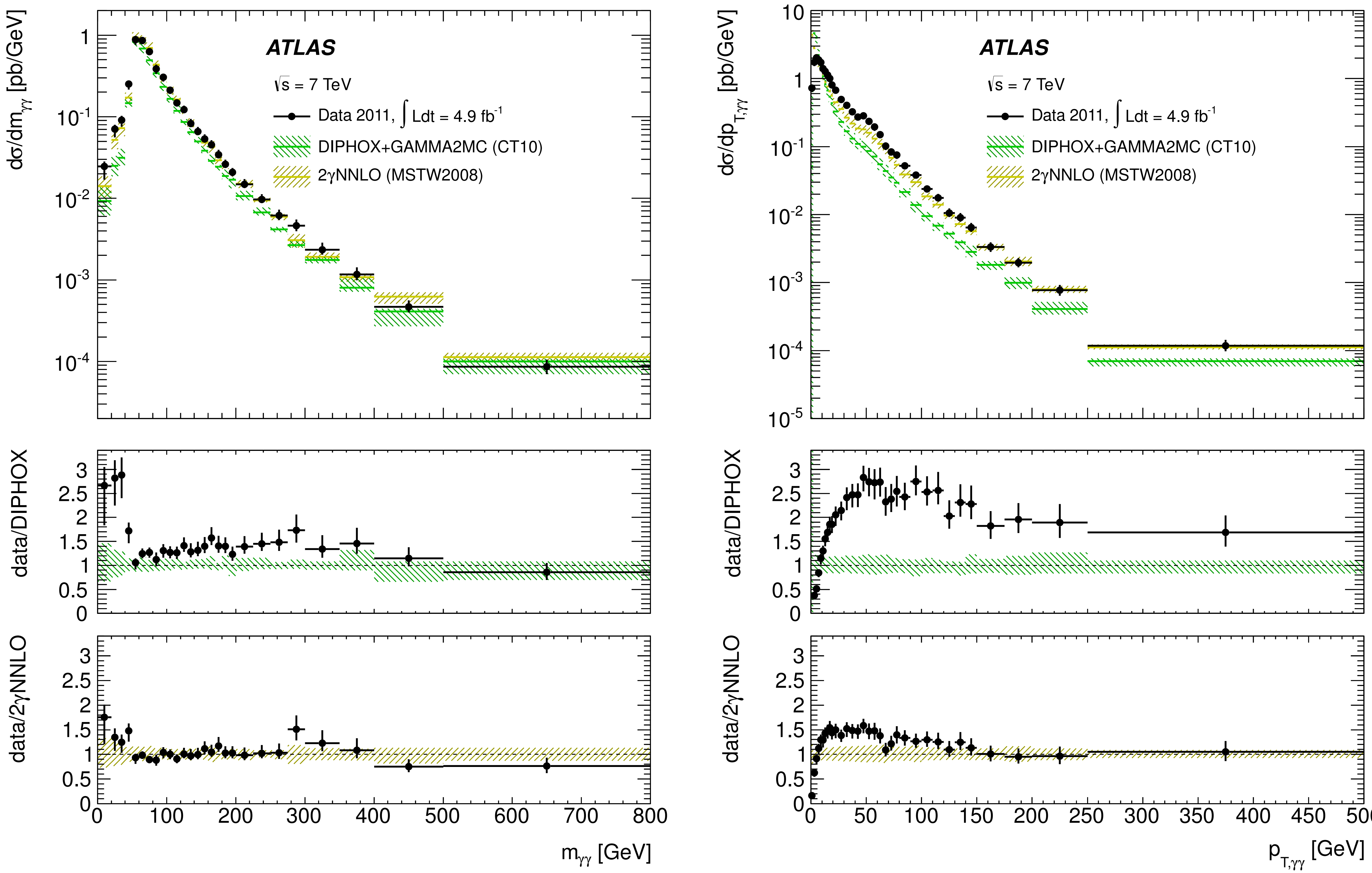




Precision in data sensitive to NNLO effects

TH vs EXP : detailed comparison just began at LHC

DATA vs TH : DiPhotons $pp \to \gamma\gamma$



Conclusions

Amazing work in the last few years → direct consequence of LHC

- PDFs: precision and uncertainties
- NLO : multileg processes and automatic!
- NNLO finally reaching $2 \to 2$ processes
- Resummation setting NNLL as new standard
- Improvements for NLO+PS and high degree of automation
- Higgs moving towards N3LO
- + many other issues not discussed (including jet structure)!

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Thanks to Sven Moch, Frank Tackmann, Stefan Dittmaier, Massimiliano Grazzini and Joey Huston for discussions

Thanks!