

# **What will be the evolution until 2017 after three years of running of LHC at 14TeV?**

***Expected MC precision from Theory***

**9th Franco-Italian Meeting on B Physics,  
LAPP, Annecy, Febr 18-19 2013**

**Michelangelo L. Mangano**

TH Unit, Physics Department, CERN

[michelangelo.mangano@cern.ch](mailto:michelangelo.mangano@cern.ch)

# Introduction

# Introduction

- **Goal of MC generators**

- bring together the most accurate knowledge on both perturbative and non-perturbative aspects of LHC final states:
  - Perturbative aspects: NLO, NNLO
    - absolute rates
    - jet structure and distributions: Njet rates, correlations, jet spectra
  - Non-perturbative: hadronization, modeling of proton fragments, multiple parton interactions
    - contribution to individual jet energies (efficiency of jet  $E_T$  cuts, smearing of mass resolution in jet spectroscopy, overall Njet count, definition of mtop, ....)

# Introduction

- **Goal of MC generators**

- bring together the most accurate knowledge on both perturbative and non-perturbative aspects of LHC final states:
  - Perturbative aspects: NLO, NNLO
    - absolute rates
    - jet structure and distributions: Njet rates, correlations, jet spectra
  - Non-perturbative: hadronization, modeling of proton fragments, multiple parton interactions
    - contribution to individual jet energies (efficiency of jet  $E_T$  cuts, smearing of mass resolution in jet spectroscopy, overall Njet count, definition of mtop, ....)

- **Progress driven by:**

- theoretical improvements:
  - higher-order calculations (NLO, NNLO, ....)
  - resummation, merging with shower MCs, ...
- better inputs (e.g. PDF), and validation (comparisons with data)

# Recent progress in NLO, two examples

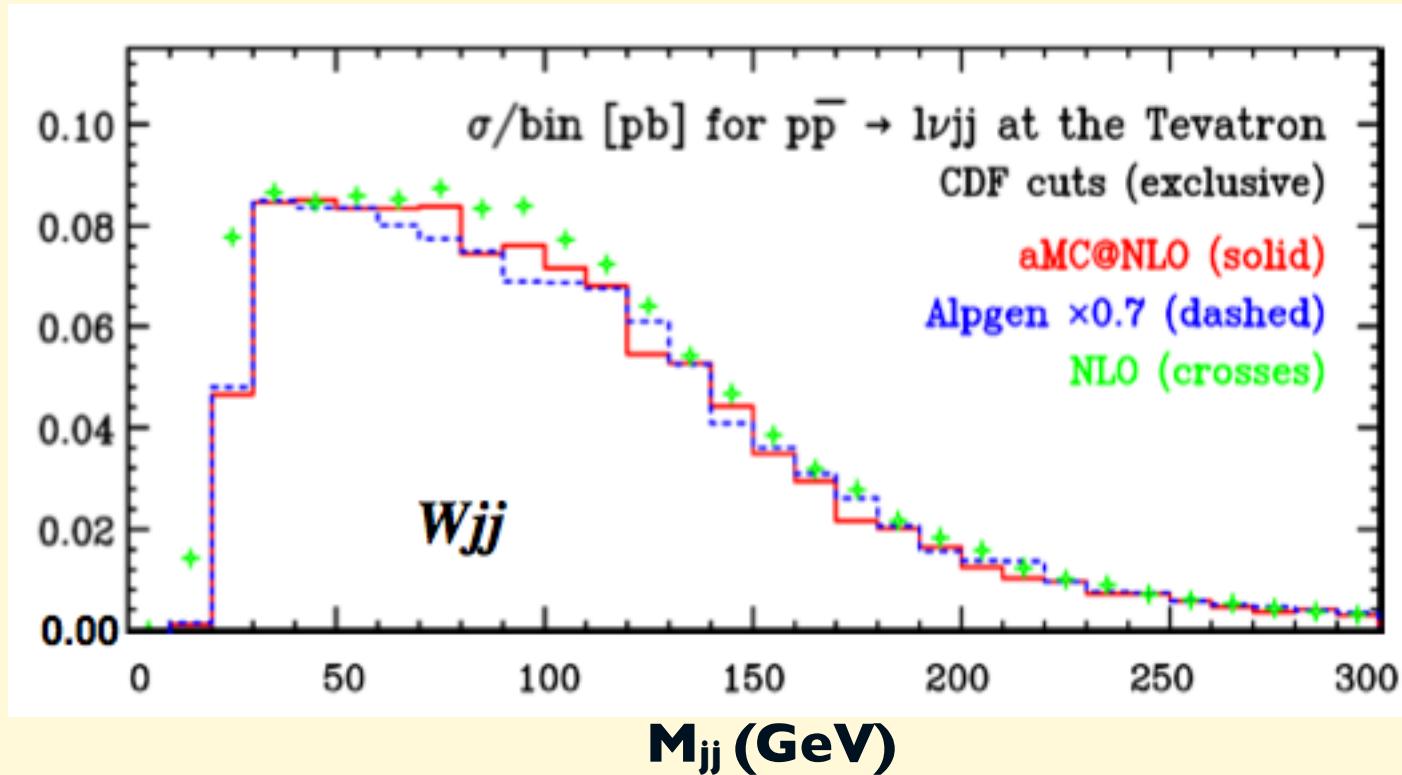
- Dedicated calculations for multijet final states
  - $W+n$  jets,  $n$  up to 5 !! (e.g. Z.Bern et al, arXiv:1210.6684)
- Fully automatic framework for NLO calculations and shower evolution
  - **aMC@NLO** (<http://amcatnlo.cern.ch>, Alwall, Artoisenet, Conte, Degrade, Frederix, Frixione, Fuchs, Hirschi, Lauwers, Maltoni, Mattelaer, Pittau, Stelzer, Torrielli, Zaro)

# Importance of the inclusion of shower effects at NLO

## Example:

### Dijet mass spectrum in $Wjj$ events at the Tevatron (cfr. the CDF anomaly)

R.Frederix et al, arXiv:1110.5502v1

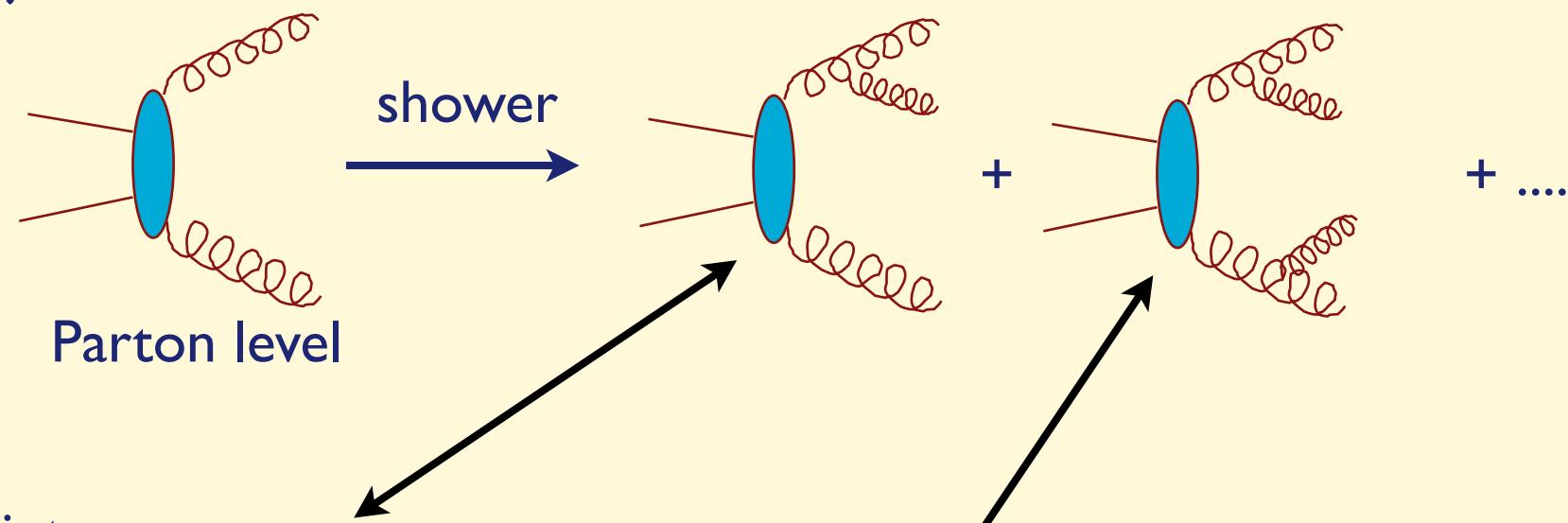


- Parton level NLO quite different from Alpgen (LO + shower + matching)
- However NLO+shower closer to Alpgen than to PL NLO ...  
⇒ inclusion of shower is essential

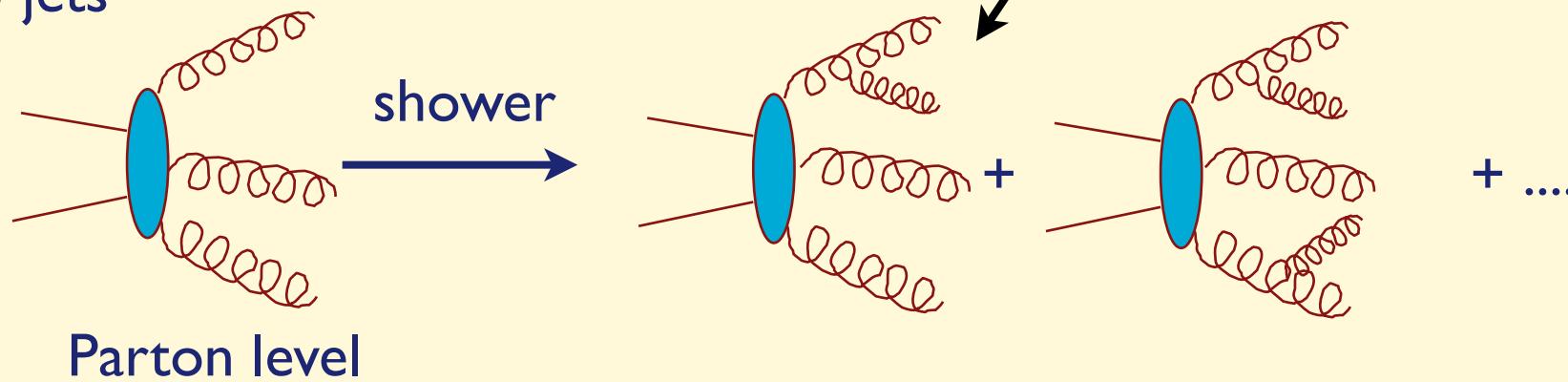
# Problems met in merging higher-order calculations w. shower evolution

**At Leading Order:**

LO, 2 jets



LO, 3 jets



⇒ double counting of the same phase-space points

⇒ solved by CKKW-L and MLM matching algorithms

# Example of recent progress: multi jet rates

Generation:

$p_{\text{T}}^{\text{min}}=40 \text{ GeV}$   $\eta^{\text{max}}=5$   $R^{\text{min}}=0.7$

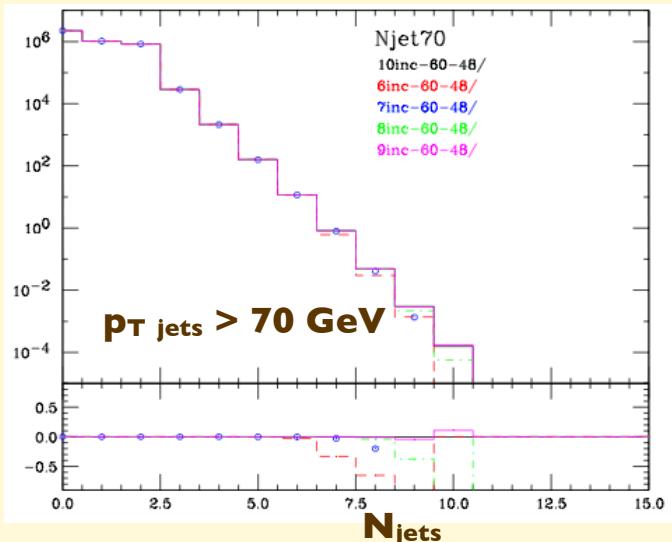
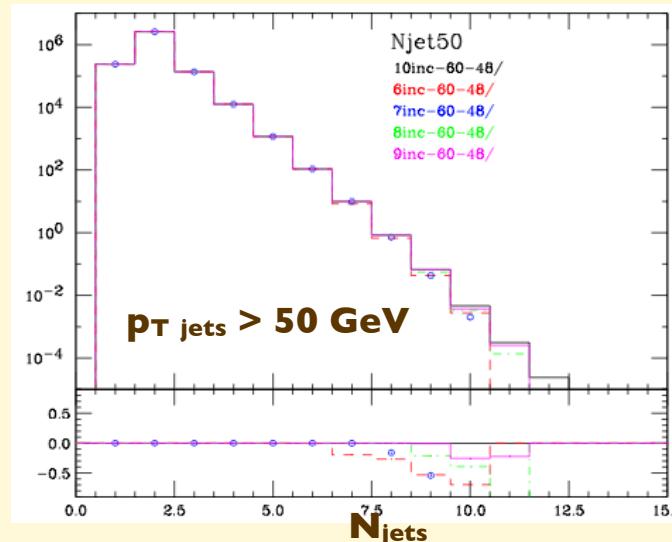
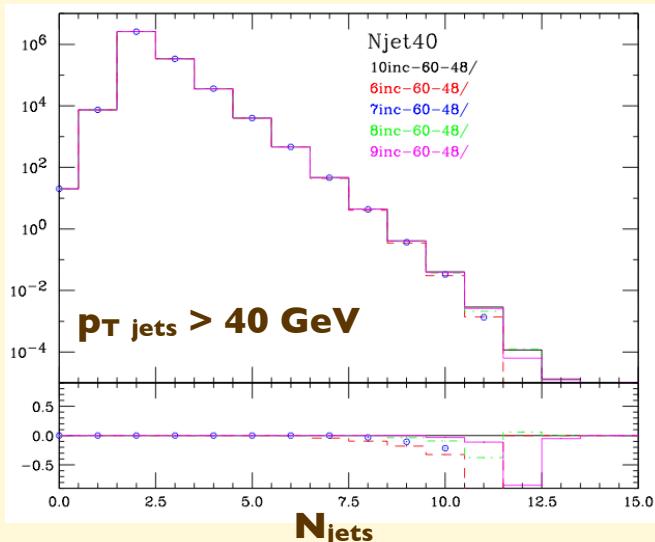
Matching:

$\text{etclus}=48 \text{ GeV}$

Analysis:

1 jet  $> 60 \text{ GeV}$

**Ninc in the plots means: used matrix elements up to N partons**

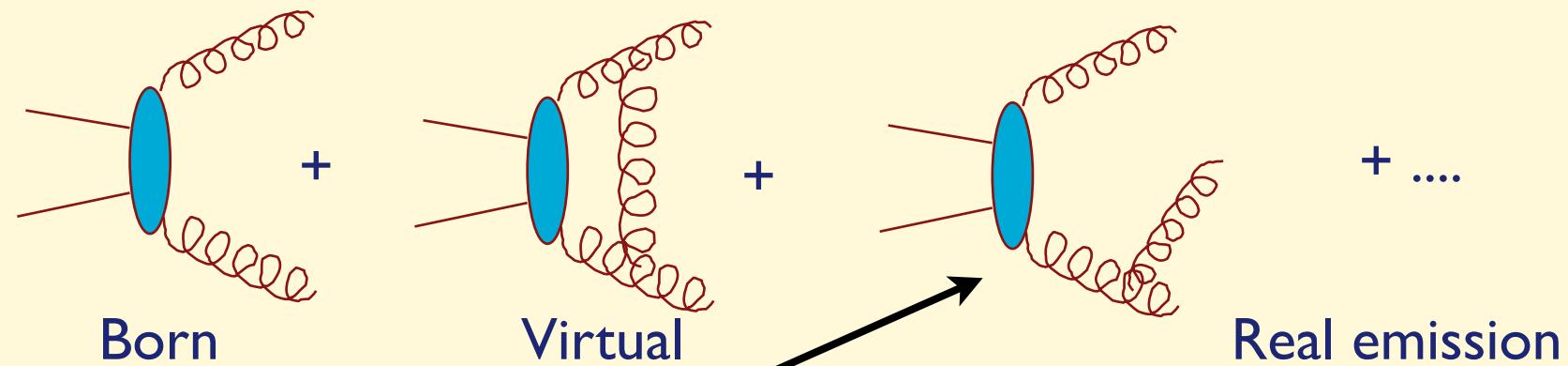


Alpgen, October 2012

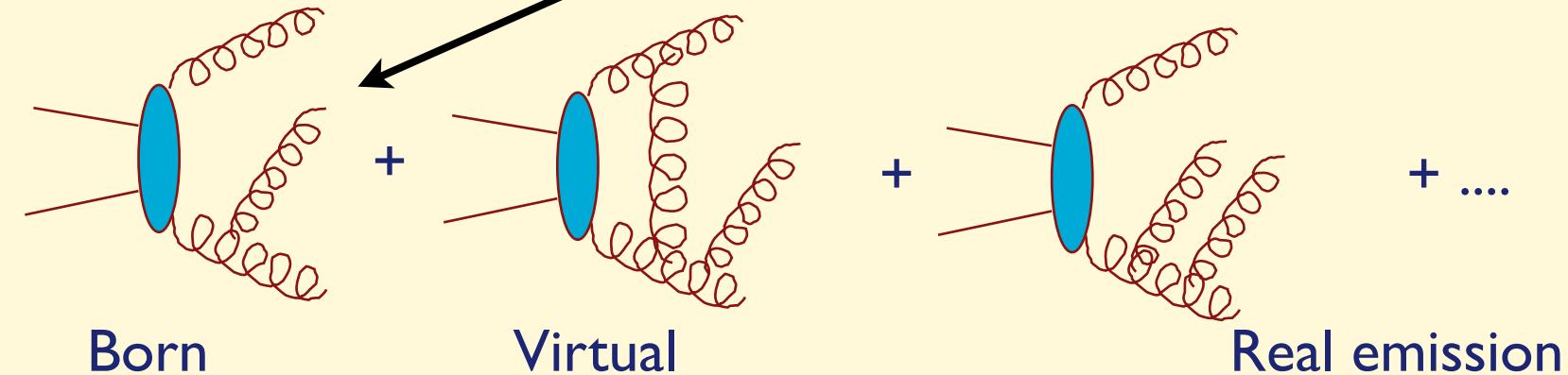
<b>p<sub>T</sub>&gt;40 GeV</b>	<b>N<sub>max</sub>=6</b>	<b>N<sub>max</sub>=7</b>	<b>N<sub>max</sub>=8</b>	<b>N<sub>max</sub>=9</b>	<b>N<sub>max</sub>=10</b>
<b>Njets=6</b>	<b>465</b>	<b>465</b>	<b>465</b>	<b>465</b>	<b>465</b>
<b>N<sub>max</sub>=7</b>	<b>44</b>	<b>46</b>	<b>46</b>	<b>46</b>	<b>46</b>
<b>N<sub>max</sub>=8</b>	<b>4.1</b>	<b>4.3</b>	<b>4.5</b>	<b>4.5</b>	<b>4.5</b>
<b>N<sub>max</sub>=9</b>	<b>0.35</b>	<b>0.37</b>	<b>0.40</b>	<b>0.41</b>	<b>0.41</b>
<b>N<sub>max</sub>=10</b>	<b>0.030</b>	<b>0.033</b>	<b>0.037</b>	<b>0.039</b>	<b>0.04</b>
<b>N<sub>max</sub>=11</b>	no stat	no stat	0.0021	0.0026	0.029

**At NLO there is also double counting among parton-level contributions, even before one attaches the shower development:**

NLO 2-jet+X



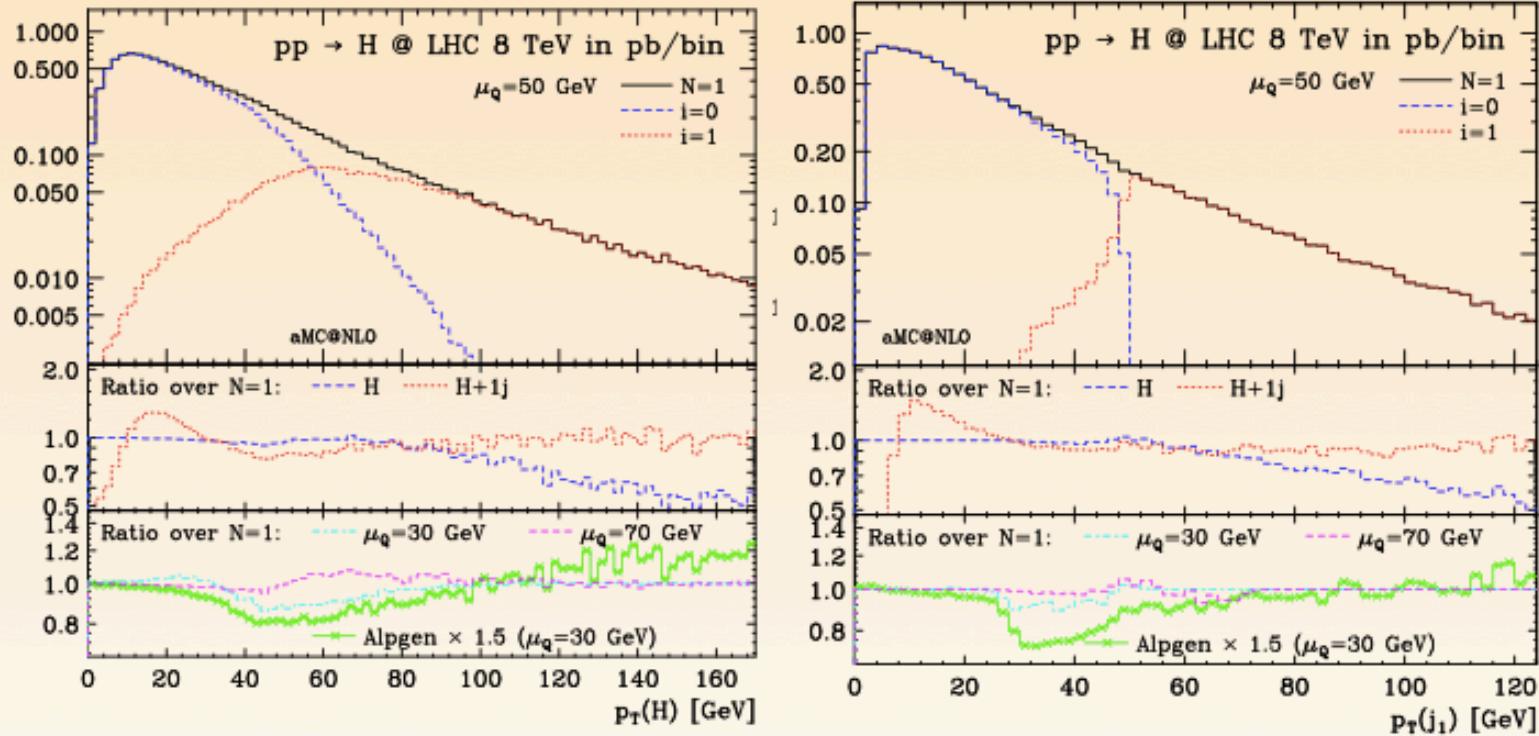
NLO 3-jet+X



**Various proposals to address merging at NLO+shower:**

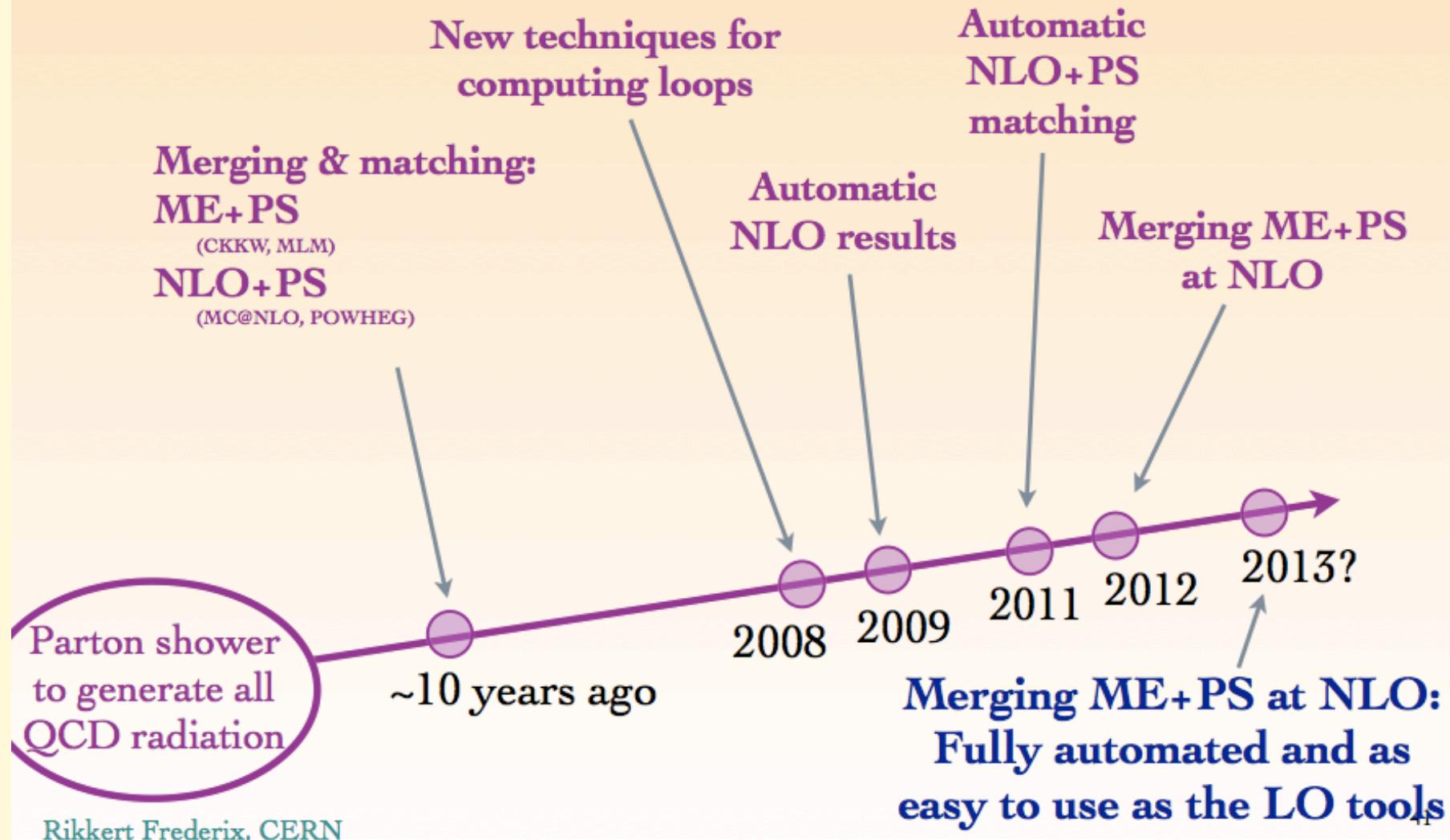
- K.Hamilton, P.Nason, G.Zanderighi, arXiv:1206.3572
- S.Hoeche, F.Krauss, M.Schoenherr, F.Siegert, arXiv:1207.5030
- R.Frederix and S.Frixione, arXiv:1209.6215

# HIGGS BOSON



- Transverse momentum of the Higgs and of the 1st jet.
- Agreement with  $H+0j$  at MC@NLO and  $H+1j$  at MC@NLO in their respective regions of phase-space; Smooth matching in between; Small dependence on matching scale
- Alpgen (LO matching) shows larger kinks

# QCD AND MC PROGRESS



# Recent progress in NNLO

- **Two long-awaited milestone calculations in progress, delivering first results:**
- $\sigma(t\bar{t})$  (Mitov and Czakon). Completed so far:
  - qqbar initial state [arXiv:1207.0236](#)
  - qg initial state [arXiv:1210.6832](#)
- Jet production. Completed so far:
  - gg initial state: A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, J. Pires, [arXiv:1301.7310](#)

# $\sigma(t\bar{t})$ NNLO results

NLO + NNLL resummation:

M.Cacciari et al, arXiv:1111.5869

$$\begin{aligned}\sigma_{\text{tot}}^{\text{NLO+NNLL}}(\text{Tevatron}; m_t = 173.3 \text{ GeV}) &= 6.722 {}^{+0.238(3.5\%)}_{-0.410(6.1\%)} [\text{scales}] {}^{+0.160(2.4\%)}_{-0.115(1.7\%)} [\text{PDF}] \text{ pb}, \\ \sigma_{\text{tot}}^{\text{NLO+NNLL}}(\text{LHC}_{8\text{TeV}}; m_t = 173.3 \text{ GeV}) &= 226.6 {}^{+17.8(7.8\%)}_{-19.4(8.6\%)} [\text{scales}] {}^{+5.6(2.5\%)}_{-5.8(2.6\%)} [\text{PDF}] \text{ pb}.\end{aligned}$$

PDF set: MSTW2008nnlo68cl

NNLO + NNLL resummation for  $q\bar{q}$  and  $qg$ , NLO+NNLL for  $gg$ :

Czakon and Mitov, arXiv:1210.6832

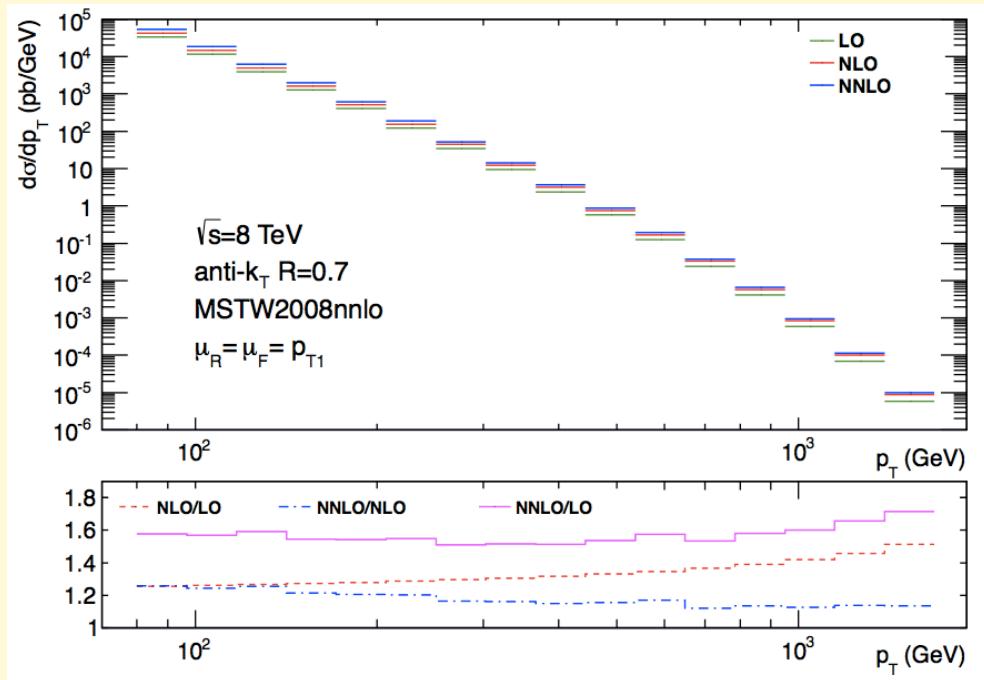
$$\begin{aligned}\sigma_{\text{tot}}^{\text{NNLO+NNLL}}(\text{Tevatron}) &= 7.010 {}^{+0.143(2.0\%)}_{-0.228(3.2\%)} [\text{scales}] {}^{+0.186(2.7\%)}_{-0.122(1.7\%)} [\text{pdf}], \\ \sigma_{\text{tot}}^{(\text{N})\text{NLO+NNLL}}(\text{LHC}_{8\text{TeV}}) &= 220.4 {}^{+12.7(5.7\%)}_{-10.8(4.9\%)} [\text{scales}] {}^{+5.4(2.5\%)}_{-5.6(2.5\%)} [\text{pdf}].\end{aligned}$$

PDF set: MSTW2008nnlo68cl

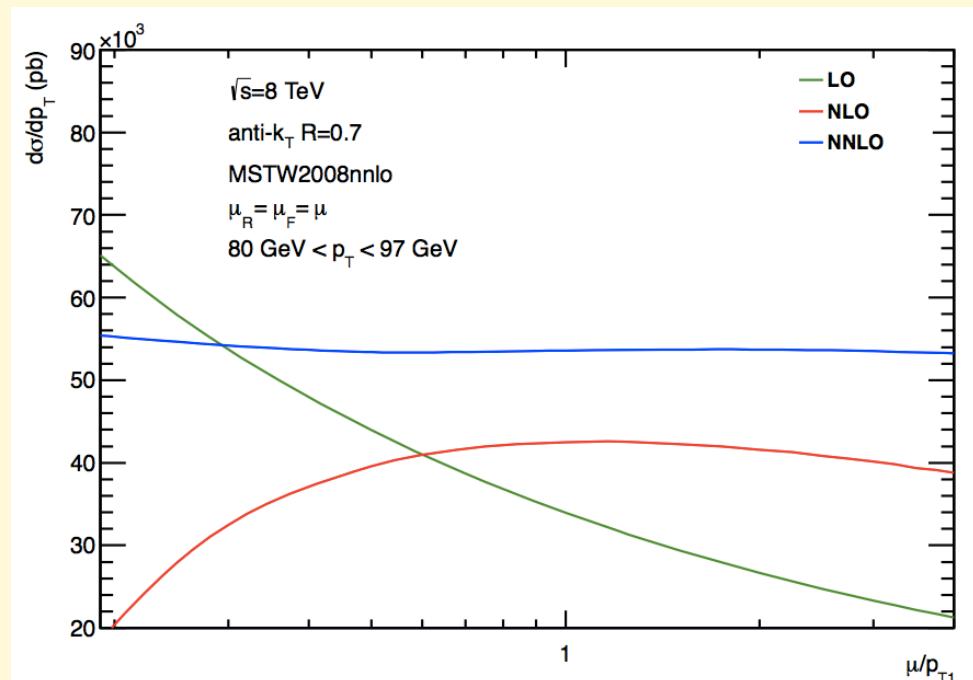
- NNLO at the Tevatron within the NLO uncertainty band
- Completion, with NNLO  $gg$ , to be published soon by Czakon&Mitov

# Inclusive jet cross section at NNLO

“Second order QCD corrections to jet production at hadron colliders: the all-gluon contribution”, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, J. Pires, arXiv:1301.7310



**NNLO/NLO  $\sim 1.2$**



**NNLO scale systematics  $\sim$  few % ...**  
**- does this survive if  $\mu_F \neq \mu_R$  ?**

**Notice that NNLO outside the NLO scale-variation band**

# Directions for future progress at N<sup>n</sup>LO

- Fully differential distributions
  - e.g. calculate  $A_{FB}(\text{top})$  at the Tevatron at NNLO
- Implementation of NNLO matrix elements in shower MCs
  - at least for simplest processes like W/Z and H production
- “Automatic NNLO”: similarly to automatic NLO, develop algorithms to automatize the calculation of ME’s, renormalization, cancellation of IR and collinear singularities in physical cross sections, possibly using a mixture of analytic and numerical tools
- First NNNLO results: Drell-Yan, Higgs

# PDF inputs

- Precise PDFs needed for precise applications. E.g.:
  - $\sigma(t\bar{t})$  data vs theory: check production mechanism, measure  $m_{top}$ , ...
  - Higgs properties extractions
  - $M_W$  measurement
  - BSM limits

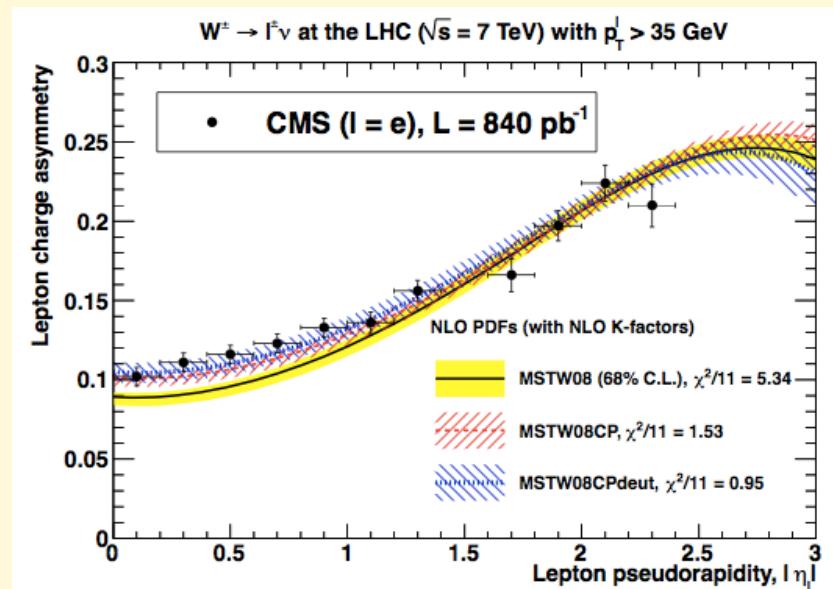
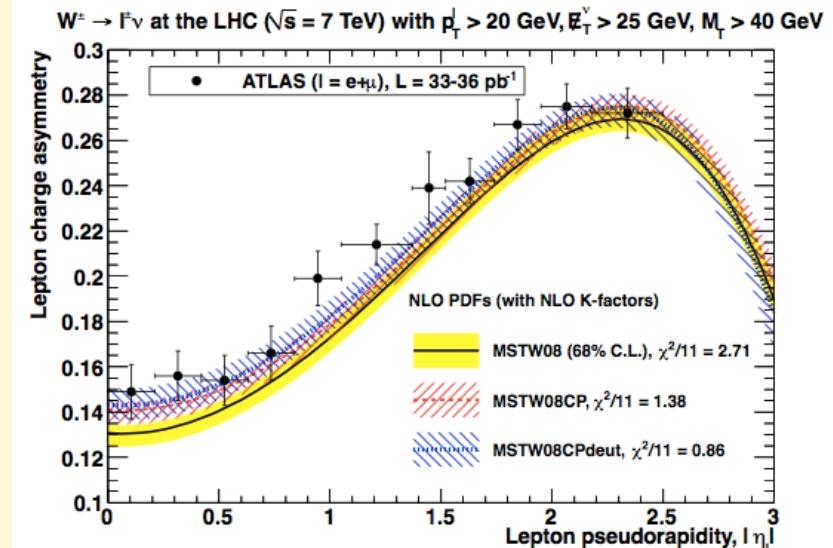
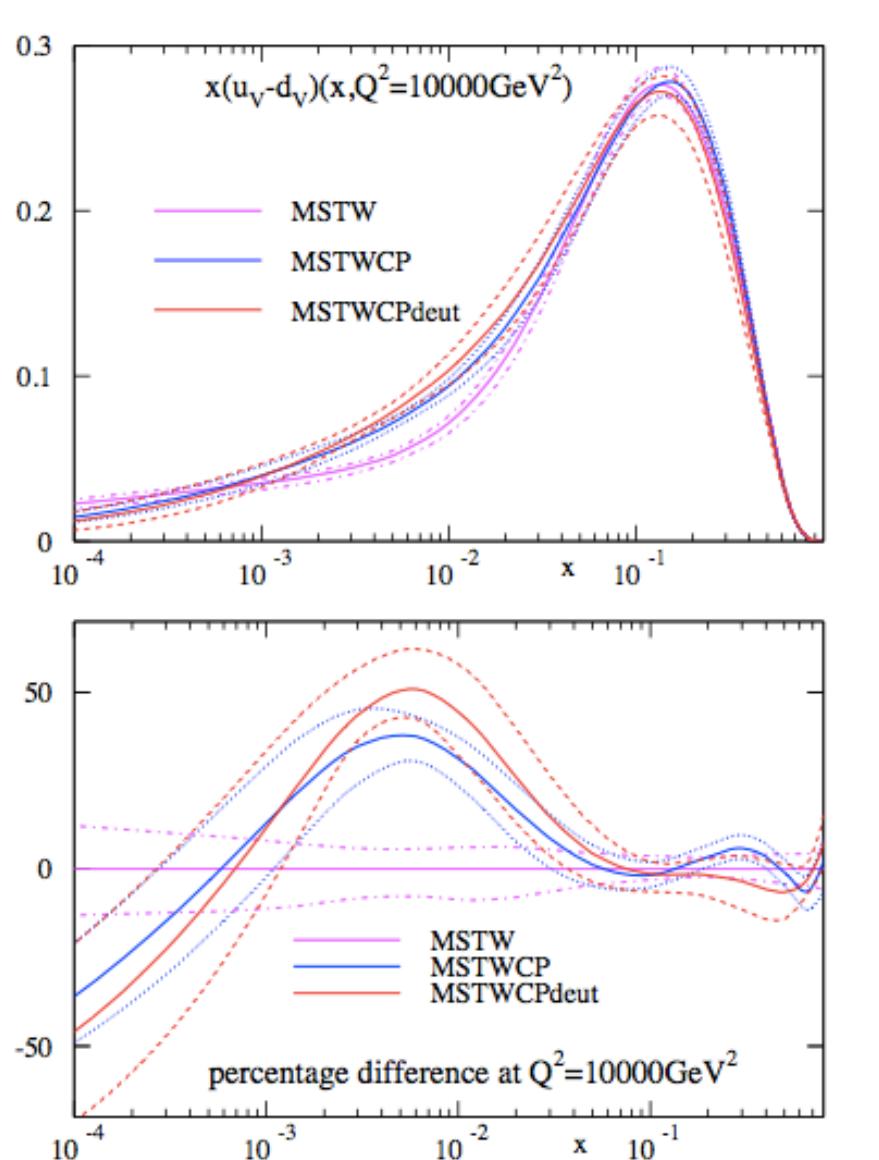
## Example: Theoretical uncertainties on Higgs production rates

14 TeV	$\delta(\text{pert. theory})$	$\delta(\text{PDF}, \alpha_S)$
$gg \rightarrow H$	$\pm 10\%$	$\pm 7\%$
VBF ( $WW \rightarrow H$ )	$\pm 1\%$	$\pm 2\%$
$qq \rightarrow WH$	$\pm 0.5\%$	$\pm 4\%$
$(qq, gg) \rightarrow ZH$	$\pm 2\%$	$\pm 4\%$
$(qq, gg) \rightarrow ttH$	$\pm 8\%$	$\pm 9\%$

- Needed for precise benchmarking, validation and/or tuning of theoretical calculations of SM processes.

# Examples of impact of PDF inputs on LHC data interpretation

“Extended Parameterisations for MSTW PDFs and their effect on Lepton Charge Asymmetry from W Decays”, A.D. Martin et al, arXiv:1211.1215v1



MSTWCP\*: fits to same input data as MSTW, but using Chebyshev polynomial expansion, rather than default parameterization

Big improvement in the description of LHC W charge asymmetry data (only observable strongly dependent on u/d valence asymmetry)<sup>15</sup>

# **Directions for future PDF improvements**

# **Directions for future PDF improvements**

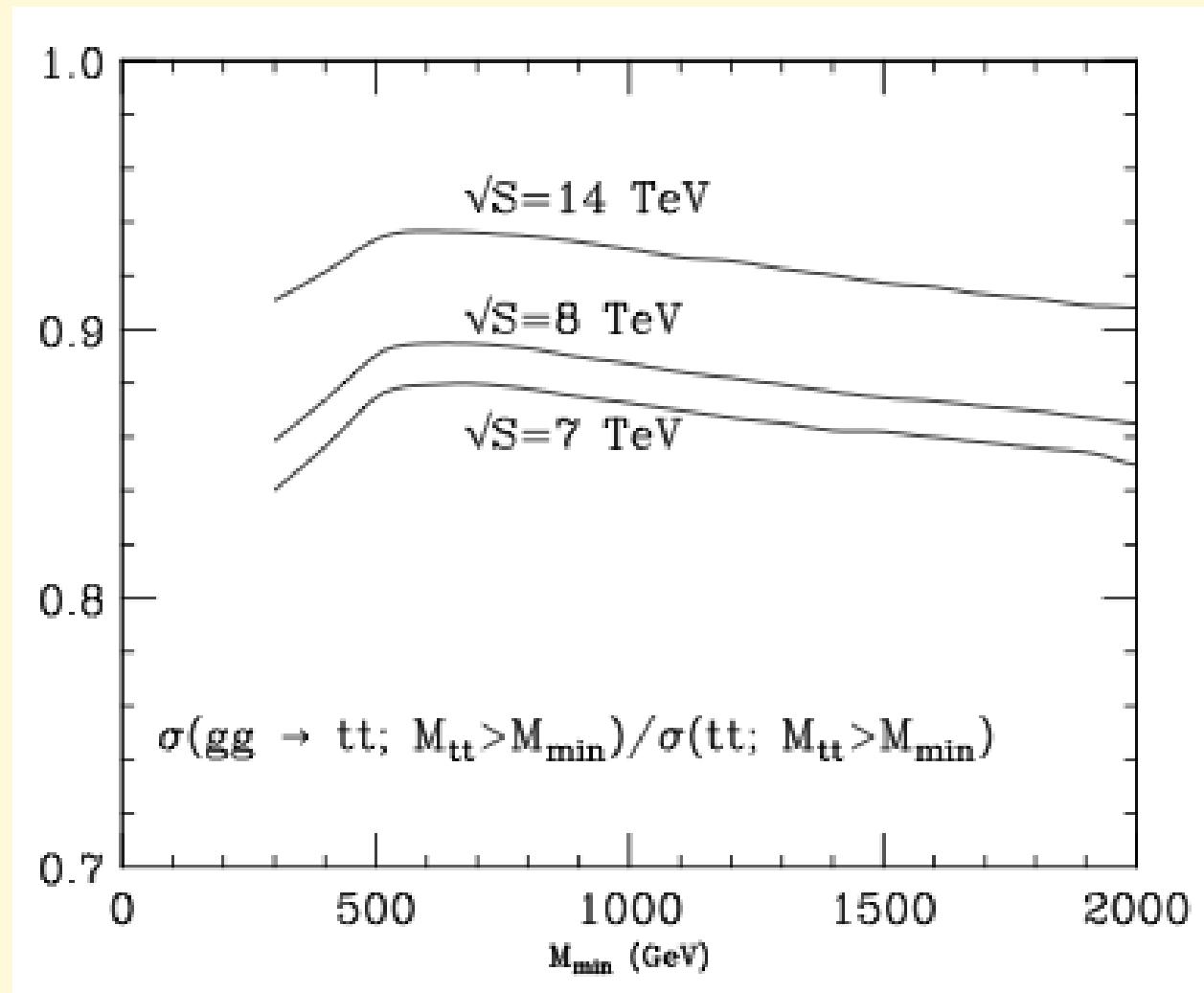
- Full use of NLO and NNLO, where possible, and inclusion of new observables:

# Directions for future PDF improvements

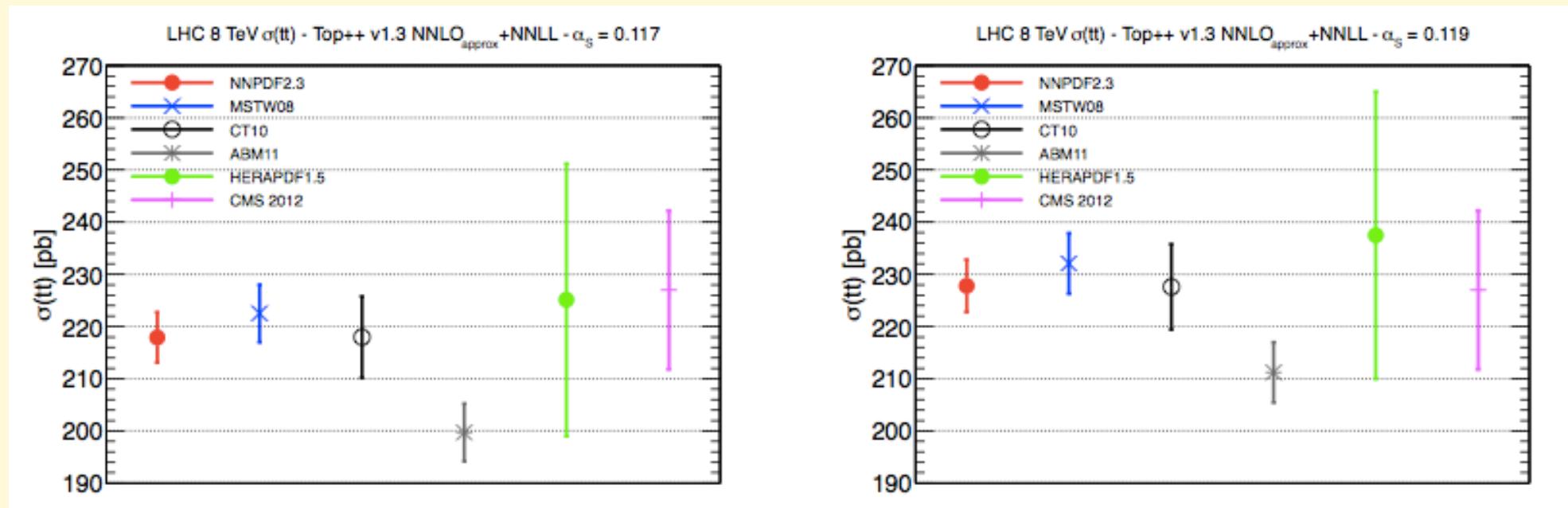
- Full use of NLO and NNLO, where possible, and inclusion of new observables:
  - top final states (e.g. ttbar at large  $M \Rightarrow$  unique probe of  $g(x)$ )

# Directions for future PDF improvements

- Full use of NLO and NNLO, where possible, and inclusion of new observables:
  - top final states (e.g. ttbar at large M => unique probe of g(x) )



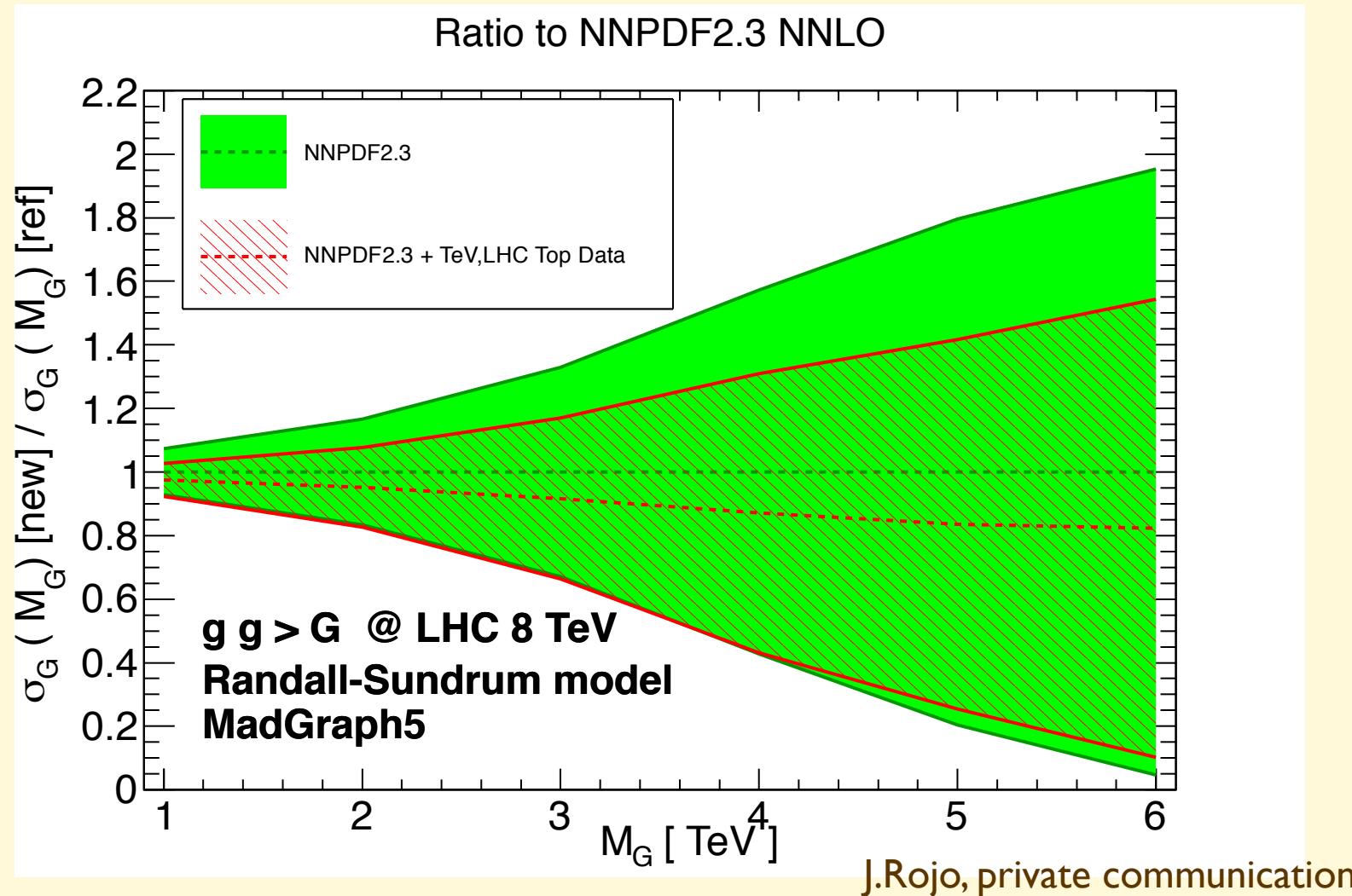
# Examples of impact of LHC data on PDF determinations



$\sigma(t\bar{t})$ : M. Czakon and A. Mitov, arxiv:1210.6832

PDF study: R. Ball et al, arXiv:1211.5142v1

# Examples of impact of LHC data on PDF determinations



Improvement in the PDF systematics on the production cross section of an s-channel gluon-gluon resonance, when adding to the PDF fits the ttbar cross sections data

# Directions for future PDF improvements

- Full use of NLO and NNLO, where possible, and inclusion of new observables:
  - top final states (e.g. ttbar at large  $M \Rightarrow$  unique probe of  $g(x)$ )
  - prompt photons
  - forward production (LHCb acceptance) to probe small/large- $x$ : W/Z, low-mass DY ( $g(x)$ ), ....
- Use of full MC final states for theory input in PDF fits
  - jets: more accurate modeling of jet structure, UE effects, ...
  - W production: effects of W  $p_T$  resummation
  - ttbar final states: avoid having to define “top” at parton level
- Cross section ratios at different energies

# 8TeV/7TeV and 14TeV/8TeV cross section ratios: the ultimate precision

MLM and J.Rojo, arXiv:1206.3557

$E_{1,2}$ : different beam energies

$X, Y$ : different hard processes

$$R_{E_2/E_1}(X) \equiv \frac{\sigma(X, E_2)}{\sigma(X, E_1)}$$



- TH: reduce “scale uncertainties”
- TH: reduce parameters’ systematics: PDF,  $m_{top}$ ,  $\alpha_s$ , .... at  $E_1$  and  $E_2$  are fully correlated
- TH: reduce MC modeling uncertainties
- EXP: reduce syst’s from acceptance, efficiency, JES, ....

$$R_{E_2/E_1}(X, Y) \equiv \frac{\sigma(X, E_2)/\sigma(Y, E_2)}{\sigma(X, E_1)/\sigma(Y, E_1)} \equiv \frac{R_{E_2/E_1}(X)}{R_{E_2/E_1}(Y)}$$



- TH: possible further reduction in scale and PDF syst’s
- EXP: no luminosity uncertainty
- EXP: possible further reduction in acc, eff, JES syst’s (e.g.  $X, Y = W^+, W^-$ )

Following results obtained using best available TH predictions: NLO, NNLO, NNLL  
resummation when available

## 14 TeV / 8 TeV: NNPDF results

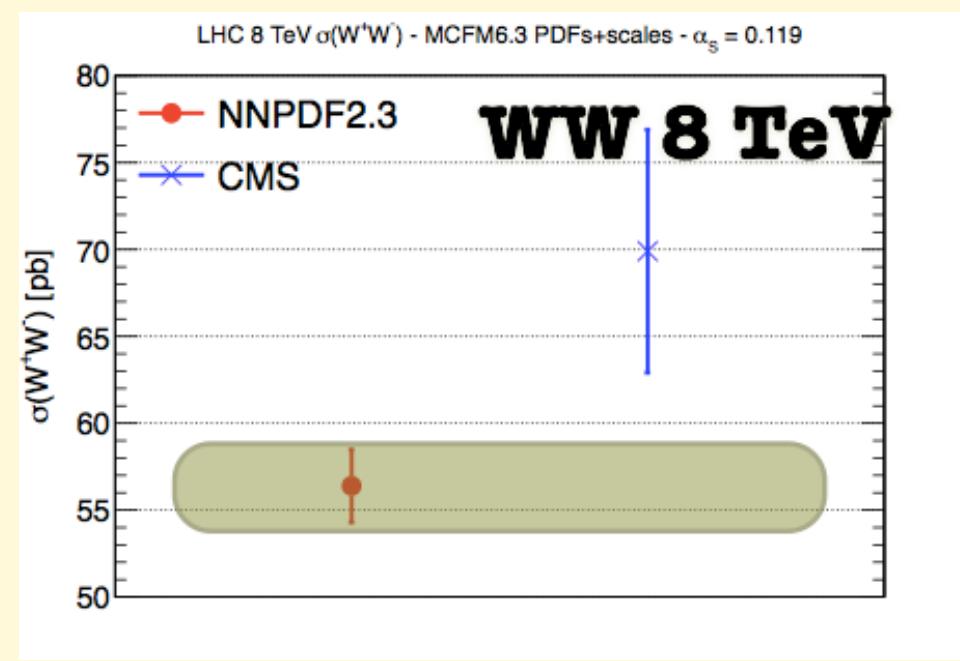
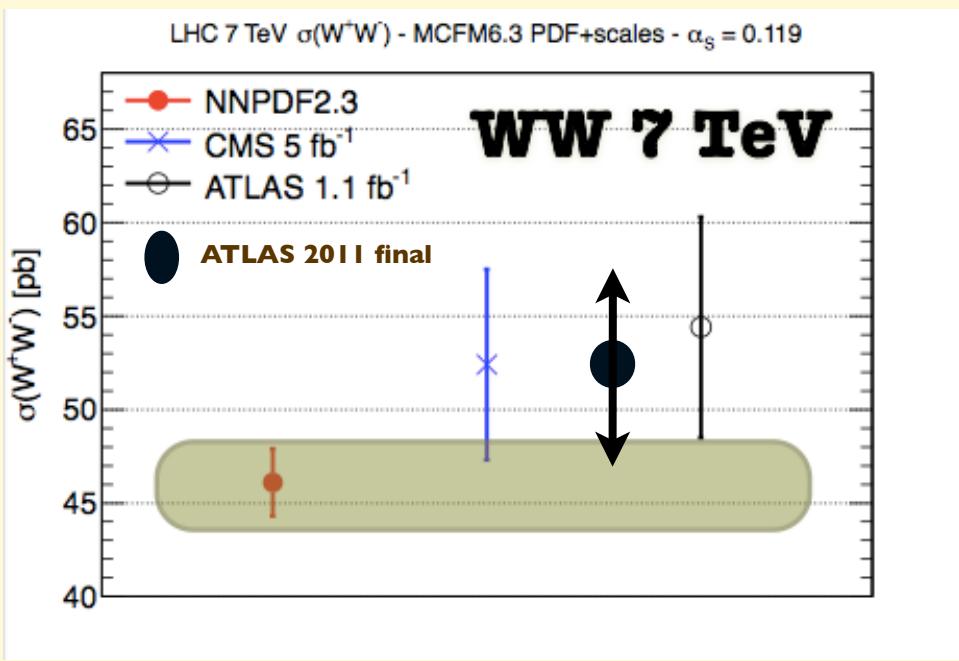
CrossSection	$r^{\text{th,nnpdf}}$	$\delta_{\text{PDF}}(\%)$	$\delta_{\alpha_s} (\%)$	$\delta_{\text{scales}} (\%)$
$t\bar{t}/Z$	2.121	1.01	-0.84 - 0.75	0.42 - 1.10
$t\bar{t}$	3.901	0.84	-0.51 - 0.66	0.38 - 1.07
$Z$	1.839	0.37	-0.10 - 0.34	0.28 - 0.18
$W^+$	1.749	0.41	-0.03 - 0.27	0.31 - 0.18
$W^-$	1.859	0.39	-0.08 - 0.26	0.32 - 0.13
$W^+/W^-$	0.941	0.28	0.00 - 0.05	0.00 - 0.04
$W/Z$	0.976	0.09	-0.07 - 0.04	0.04 - 0.02
$ggH$	2.564	0.36	-0.10 - 0.09	0.89 - 0.98
$ggH/t\bar{t}$	0.657	0.75	-0.56 - 0.41	1.38 - 1.05
$t\bar{t}(M_{tt} \geq 1\text{TeV})$	8.215	2.09	0.00 - 0.00	1.61 - 2.06
$t\bar{t}(M_{tt} \geq 2\text{TeV})$	24.776	6.07	0.00 - 0.00	3.05 - 1.07
$\sigma_{\text{jet}}(p_T \geq 1\text{TeV})$	15.235	1.72	0.00 - 0.00	2.31 - 2.19
$\sigma_{\text{jet}}(p_T \geq 2\text{TeV})$	181.193	6.75	0.00 - 0.00	3.66 - 5.76

- $\delta < 10^{-2}$  in  $W^\pm$  ratios: absolute calibration of 14 vs 8 TeV lumi
- $\delta \sim 10^{-2}$  in  $\sigma(t\bar{t})$  ratios
- $\delta_{\text{scale}} < \delta_{\text{PDF}}$  at large  $p_T^{\text{jet}}$  and  $M_{tt}$ : constraints on PDFs

## 14 TeV / 8 TeV: NNPDF vs MSTW vs ABKM

Ratio	$r^{\text{th,nnpdf}}$	$\delta_{\text{PDF}}(\%)$	$r^{\text{th,mstw}}$	$\delta_{\text{PDF}}(\%)$	$\Delta^{\text{mstw}}(\%)$	$r^{\text{th,abkm}}$	$\delta_{\text{ABKM}}(\%)$	$\Delta^{\text{abkm}}(\%)$
$t\bar{t}/Z$	2.121	1.01	2.108	0.95	0.93	2.213	1.87	-3.99
$t\bar{t}$	3.901	0.84	3.874	0.91	0.97	4.103	1.87	-4.90
$Z$	1.839	0.37	1.838	0.41	0.04	1.855	0.34	-0.87
$W^+$	1.749	0.41	1.749	0.49	0.03	1.767	0.30	-0.98
$W^-$	1.859	0.39	1.854	0.42	0.21	1.879	0.32	-1.11
$W^+/W^-$	0.941	0.28	0.943	0.19	-0.19	0.940	0.13	0.13
$W/Z$	0.976	0.09	0.976	0.10	0.03	0.977	0.10	-0.14
$ggH$	2.564	0.36	2.572	0.57	-0.30	2.644	0.66	-3.12
$ggH/t\bar{t}$	0.657	0.75	0.000	0.00	0.00	0.000	0.00	0.00
$t\bar{t}(M_{tt} \geq 1\text{TeV})$	8.215	2.09	7.985	2.02	3.12	8.970	3.58	-8.83
$t\bar{t}(M_{tt} \geq 2\text{TeV})$	24.776	6.07	23.328	4.32	6.05	23.328	4.93	6.05
$\sigma_{\text{jet}}(p_T \geq 1\text{TeV})$	15.235	1.72	15.193	1.62	-1.33	14.823	1.84	1.13
$\sigma_{\text{jet}}(p_T \geq 2\text{TeV})$	181.193	6.75	191.208	3.34	-6.52	174.672	4.94	2.69

- Several examples of  $3-4\sigma$  discrepancies between predictions of different PDF sets, even in the case of  $W$  and  $Z$  rates



## Diboson cross section ratios

8 over 7 TeV	$R^{\text{th,nnpdf}}$	$\delta_{\text{PDF}} (\%)$	$\delta_{\text{scales}} (\%)$
$WW$	1.223	$\pm 0.1$	-0.4 – 0.2
$gg \rightarrow WW$	1.330	$\pm 0.2$	-0.0 – 0.0
$WW/W$	1.057	$\pm 0.1$	-0.3 – 0.2
$WZ$	1.209	$\pm 0.4$	-1.2 – 0.4
$ZZ$	1.165	$\pm 0.4$	-0.6 – 1.1
$gg \rightarrow ZZ$	1.218	$\pm 1.2$	-0.0 – 0.0
$ZZ/Z$	1.000	$\pm 0.4$	-0.5 – 1.1
$WW/WZ$	1.012	$\pm 0.4$	-0.2 – 1.0
$WW/ZZ$	1.050	$\pm 0.4$	-0.9 – 0.7
$WZ/ZZ$	1.038	$\pm 0.5$	-1.7 – 0.4

(scale errors missing)

(scale errors missing)

# **Other relevant elements, not covered**

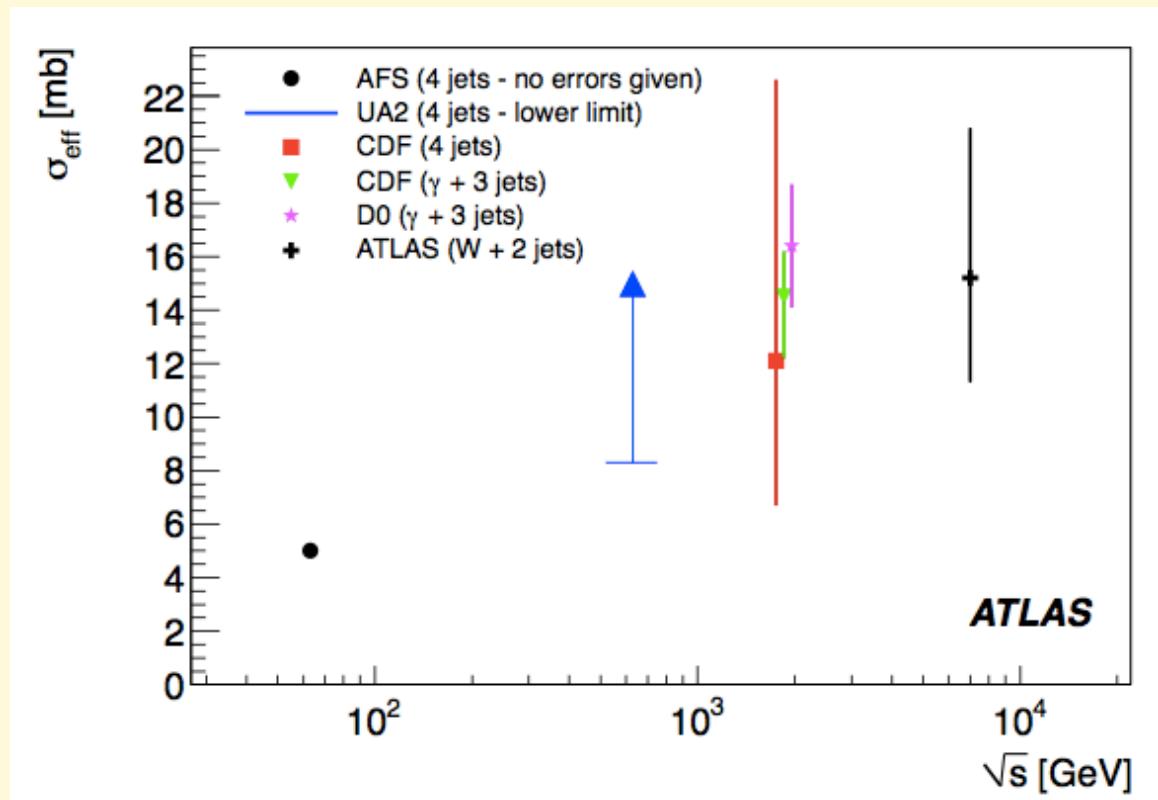
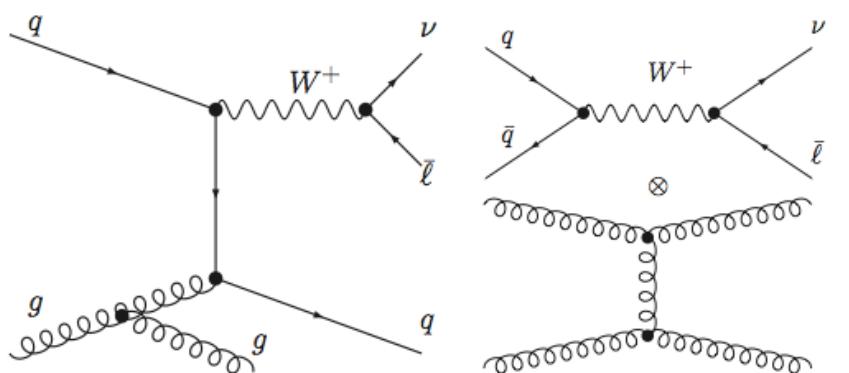
- Vast and diverse samples of data and analysis available for MC testing and validation
  - Multijet production
  - Associated production of vector bosons ( $W/Z$ ) with multijets, heavy quarks
  - Extreme kinematical configurations (large invariant masses, forward jets, boosted  $W/Z$  and tops, ....)
  - Properties of the underlying event, multiparton interactions
  - ....

# Double-parton interactions

$$\sigma_{DPS}(X + Y) = \frac{\sigma(X) \times \sigma(Y)}{\sigma_{eff}}$$

- $\sigma_{eff} = O(\sigma_{inelastic})$
- $\sigma_{eff}$  universal: independent of process and  $E_{beam}$ , up to parton-parton correlations inside the nucleon

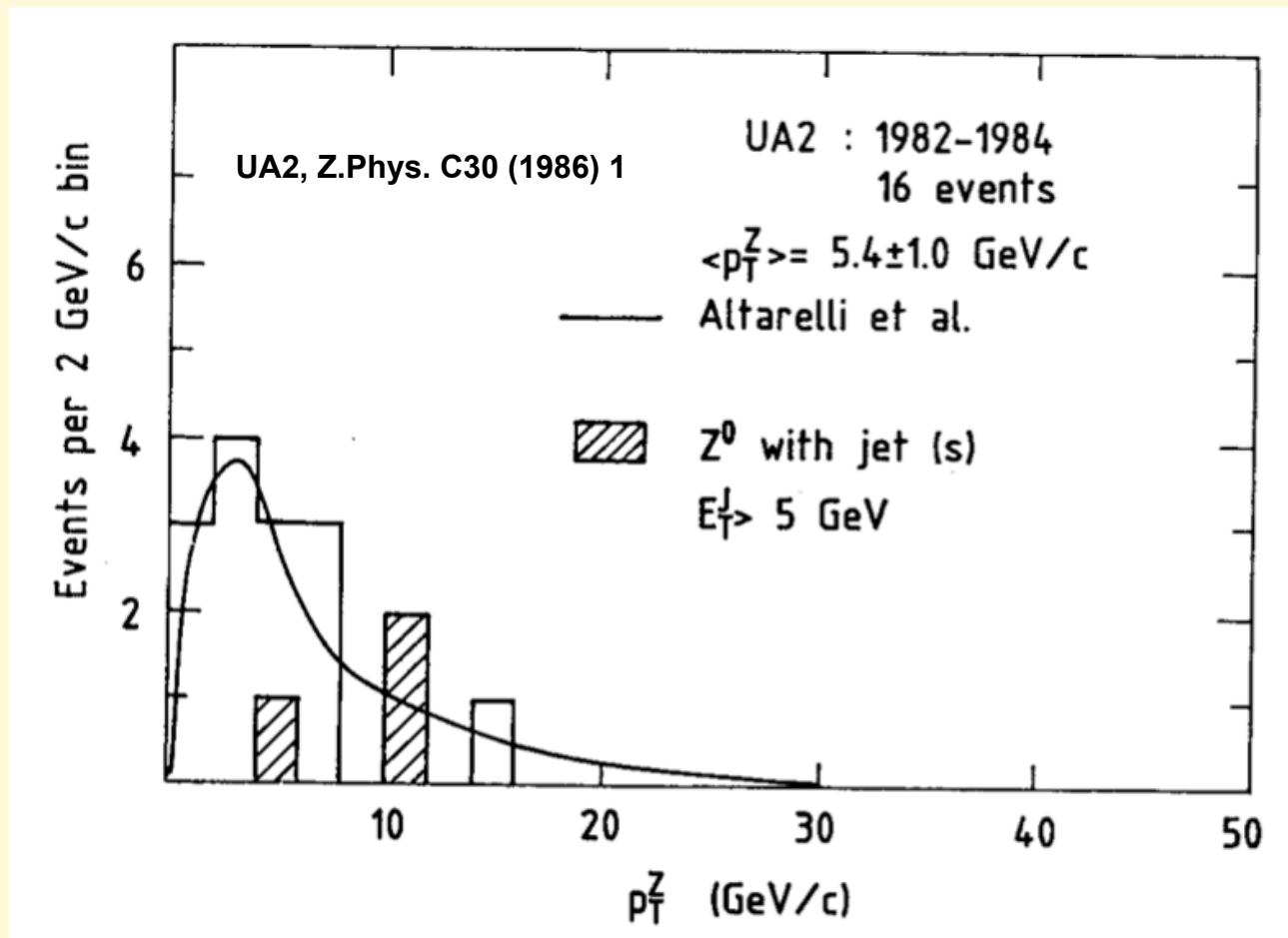
Measurement of hard double-parton interactions in  $W(\rightarrow l\nu) + 2$  jet events at 7 TeV with the **ATLAS** detector, arXiv:1301.6872v1



# **Towards experimental constraints on Higgs production dynamics ....**

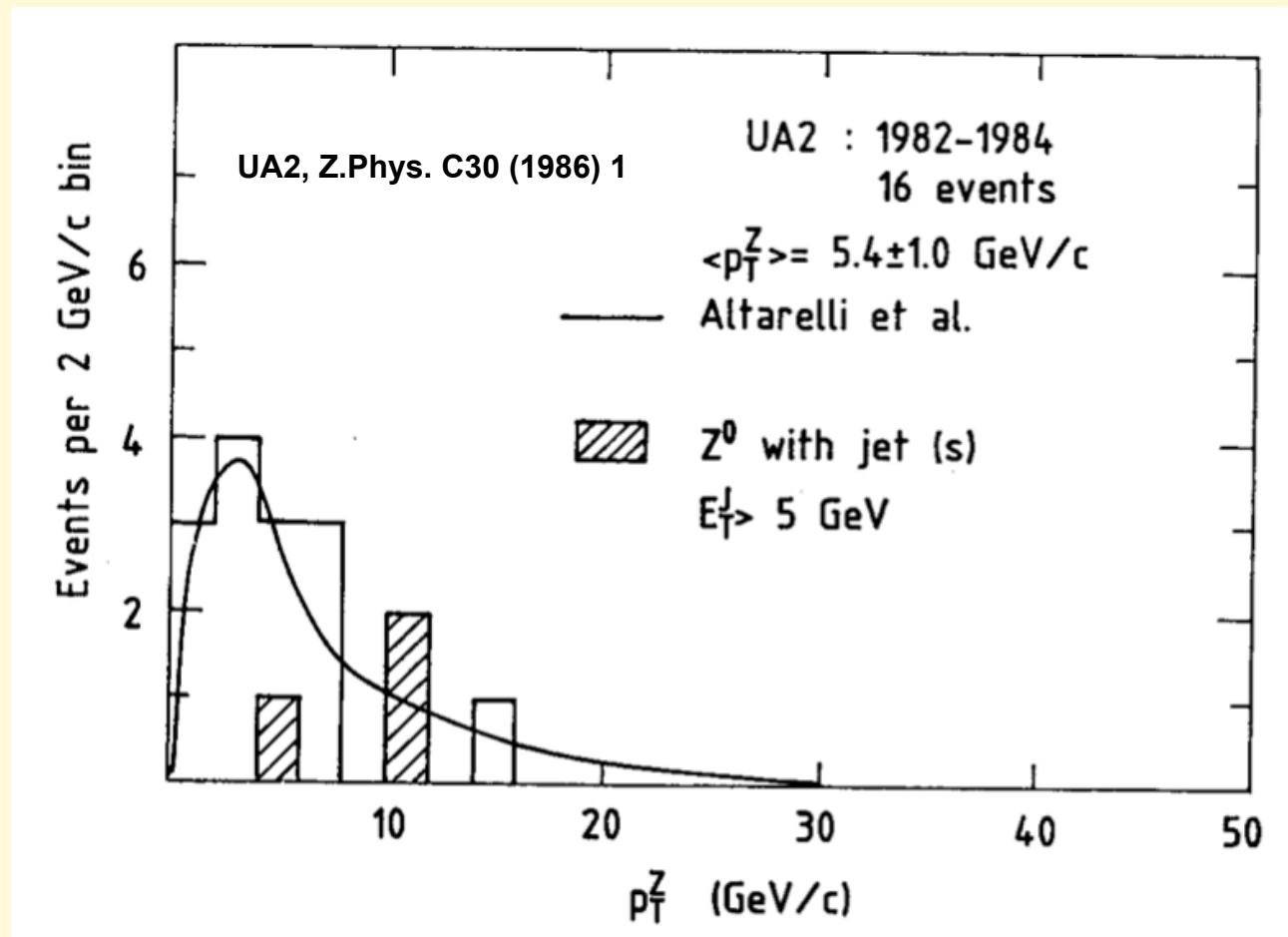
# Towards experimental constraints on Higgs production dynamics ....

To put it in perspective, W/Z physics started like this ..... from a score of events:



# Towards experimental constraints on Higgs production dynamics ....

To put it in perspective, W/Z physics started like this ....., from a score of events:



**Looking forward to the first measurement of  $p_T(gg \rightarrow H \rightarrow ZZ^*)$ ,  
 $\sigma(H + 1 \text{ jet})$ , .... with the 15-20 events that should now be on tape !**

**Will be O(200) events by 2017 !**

***What will be the evolution until 2017 after three years of running of LHC at 14TeV?***

# **Summary**

# **Summary**

- Very rapid progress is taking place:

# **Summary**

- Very rapid progress is taking place:
  - development of new perturbative techniques

# **Summary**

- Very rapid progress is taking place:
  - development of new perturbative techniques
  - completion of new calculations

# **Summary**

- Very rapid progress is taking place:
  - development of new perturbative techniques
  - completion of new calculations
  - development of more powerful MC tools

# Summary

- Very rapid progress is taking place:
  - development of new perturbative techniques
  - completion of new calculations
  - development of more powerful MC tools
  - better PDF constraints

# Summary

- Very rapid progress is taking place:
  - development of new perturbative techniques
  - completion of new calculations
  - development of more powerful MC tools
  - better PDF constraints
  - validation with LHC data

# Summary

- Very rapid progress is taking place:
  - development of new perturbative techniques
  - completion of new calculations
  - development of more powerful MC tools
  - better PDF constraints
  - validation with LHC data
- Most theory results shown here are no more than 6 months old!

# Summary

- Very rapid progress is taking place:
  - development of new perturbative techniques
  - completion of new calculations
  - development of more powerful MC tools
  - better PDF constraints
  - validation with LHC data
- Most theory results shown here are no more than 6 months old!
- Too early to say where we'll stand in 2017.

# Summary

- Very rapid progress is taking place:
  - development of new perturbative techniques
  - completion of new calculations
  - development of more powerful MC tools
  - better PDF constraints
  - validation with LHC data
- Most theory results shown here are no more than 6 months old!
- Too early to say where we'll stand in 2017.
- My bet is that, if anything, we're currently over-conservative in estimating the potential for improvements!