Theory status of Diboson Production and Energy Ratios

Juan Rojo
CERN, TH Unit, PH Division

Based on M. Mangano and J. Rojo
arXiv1206.3557 + work in progress

LPCC Electroweak Working Group
CERN, 10/10/2012

Diboson production at the LHC

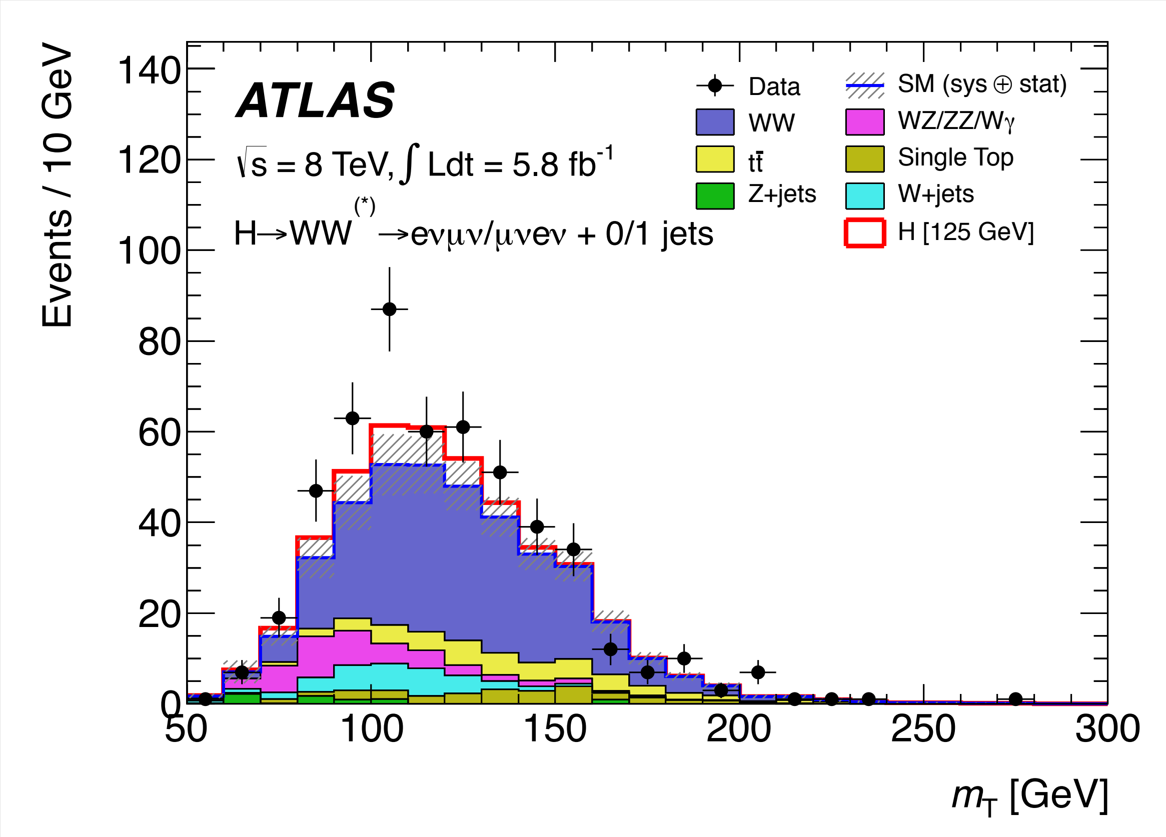
Diboson Production at the LHC

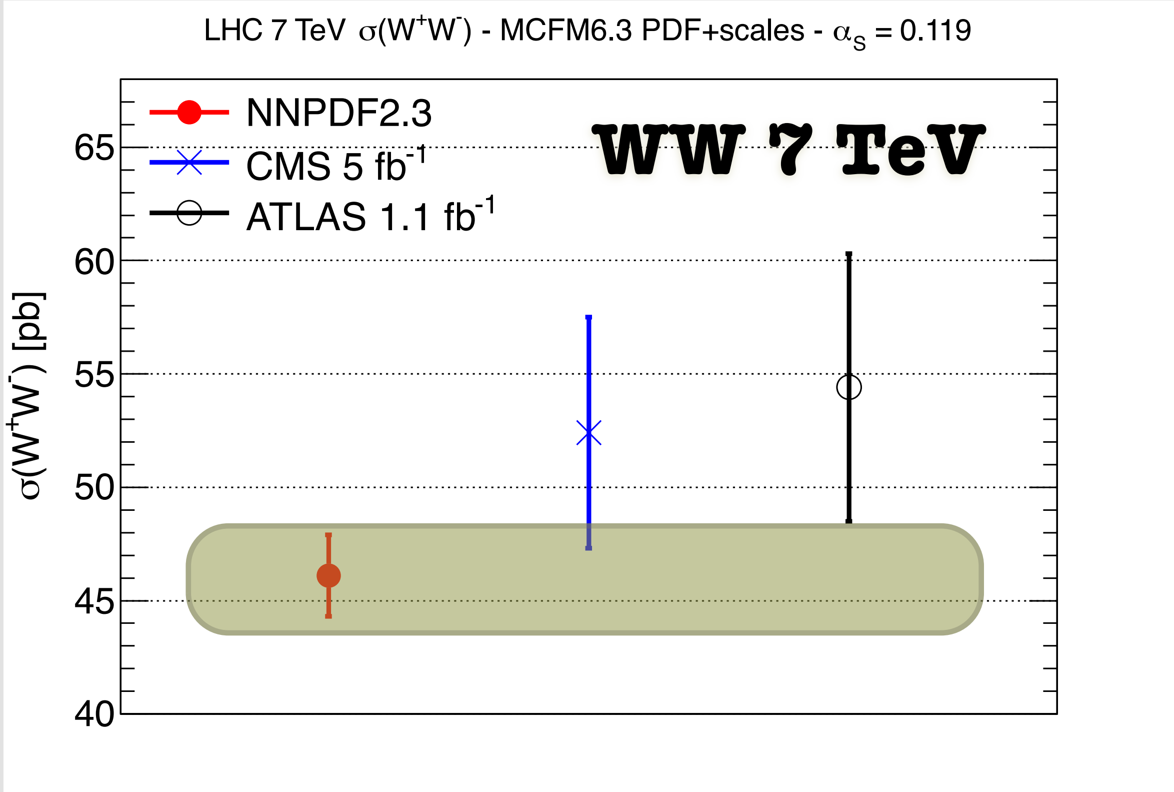
- **Precision tests of QCD/EW dynamic**s of the Standard Model

- Measurement of the triple gauge couplings, **search for anomalous gauge couplings**

- Background to Higgs production decaying to Vector Boson pairs, **H->WW** and **H->ZZ.** Also relevant **QCD continuum-signal interference** for Higgs production

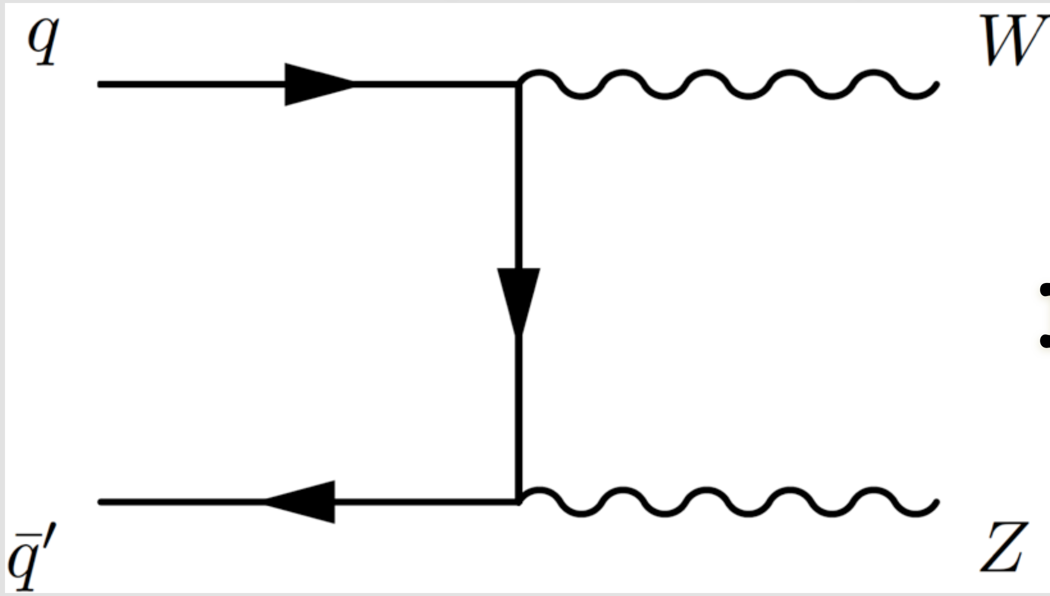
- Some diboson (specially *WW)* cross sections show an **excess over the SM predictions**. **Not statistically significant** but consistent between **ATLAS and CMS** and between **7 and 8 TeV**. Possibly **SM explanation**, but also **BSM supersymmetric** scenarios proposed



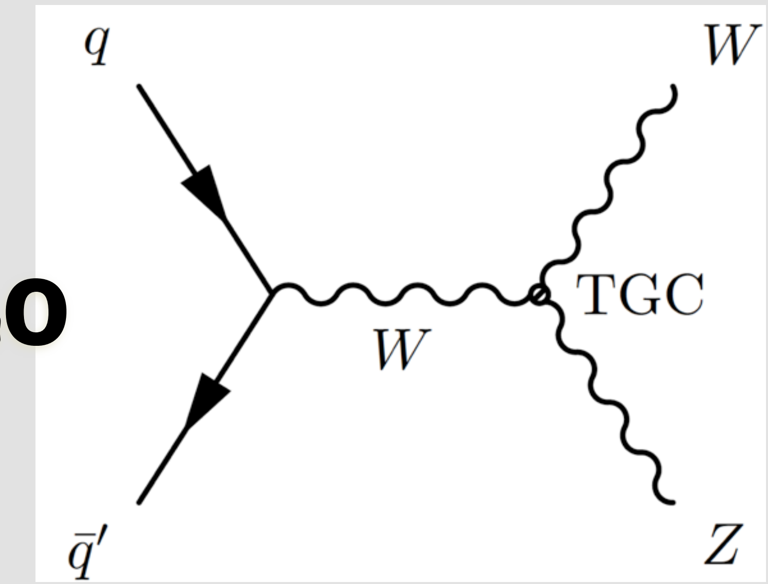


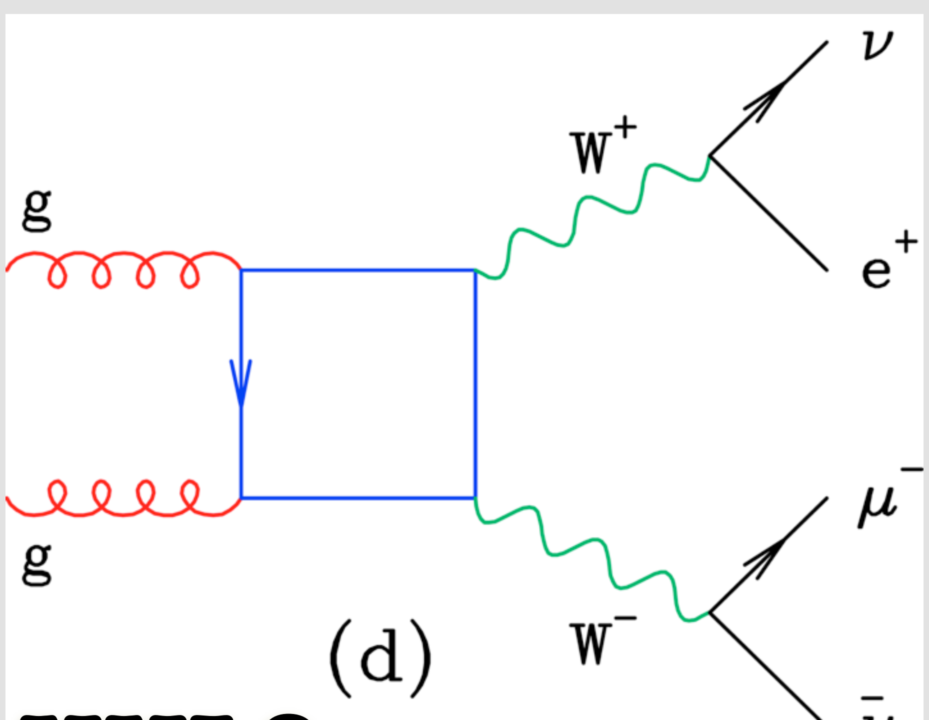
Diboson Production

- Diboson production proceeds though **quark-quark** scattering **at LO**.



LO





NNLO

- Cross section available at **NLO QCD**. Full **NNLO** calculation not available, only **gluon gluon initiated piece.** Full NNLO could be sizable (S. Sapeta's talk)

- Implemented in codes like **MCFM, VBFNLO** and **gg2VV**.

- Contribution from **Higgs production small**, perhaps not negligible? Also available in MCFM. For Higgs searches **WW off shell.**

- **Electroweak** corrections also available (< 1-2% in total cross sections, larger in tails of distributions from **Sudakov enhancement**). See J. Huston Monday talk.

Diboson Production

- We have computed with **MCFM6.3** all relevant **diboson cross sections and related ratios** (Higgs contribution not yet, in the pipeline).
- Computation at **NLO QCD + NNLO for gg** piece (with massive quarks in loop)
- **NNPDF2.3** as input PDF set, with **theory uncertainties** from **scales and PDF variations**

7 TeV	$\sigma^{\rm th,nnpdf}$	$\delta_{\rm PDF}(\%)$	$\delta_{\rm scales}\ (\%)$
WW	46.1 pb	$\pm$ 1.2	-3.2 – 4.3
$gg \to WW$	1.25 pb	$\pm$ 1.8	-0.0 – 0.0
WW/W	$4.8\,10^{-4}$	$\pm$ 0.8	-3.8 – 4.7
WZ	21.0 pb	$\pm$ 1.1	-2.1 – 3.2
ZZ	52.1 pb	$\pm$ 1.4	-3.8 – 3.0
$gg \to ZZ$	2.30 pb	$\pm$ 1.3	-0.0 – 0.0
ZZ/Z	$1.8\,10^{-3}$	$\pm$ 0.8	-3.0 – 3.2

(scale errors missing, probably large!)

(scale errors missing)

	WW 7	WZ 7	ZZ 7	WW 8	WZ 8	ZZ 8	WW 14	WZ 14	ZZ 14
QQ+QG	97.3%	100%	95.7%	97.0%	0%	95.5%	96.0%	100%	94.5%
GG	2.7 %	0%	4.4%	3.0%	0%	4.6%	4.0%	0%	5.6%

Preliminary

Diboson Production

- We have computed with **MCFM6.3** all relevant diboson cross sections and related ratios.
- **NNPDF2.3** as input PDF set, with theory uncertainties from scales and PDF variations.

8 TeV	$\sigma^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	$\delta_{\mathrm{scales}}\ (\%)$
WW (abs)	56.4 pb	$\pm\,1.2$	$-3.2 - 4.2$
$gg \to WW$	1.67 pb	$\pm\,1.6$	$-0.0 - 0.0$
WW/W	$5.1\,10^{-4}$	$\pm\,0.8$	$-3.7 - 4.5$
WZ	25.4 pb	$\pm\,1.2$	$-3.0 - 3.2$
ZZ	60.7 pb	$\pm\,1.4$	$-4.0 - 2.5$
$gg \to ZZ$	2.81 pb	$\pm\,1.3$	$-0.0 - 0.0$
ZZ/Z	$1.8\,10^{-3}$	$\pm\,0.8$	$-3.2 - 2.7$

(scale errors missing, probably large!)

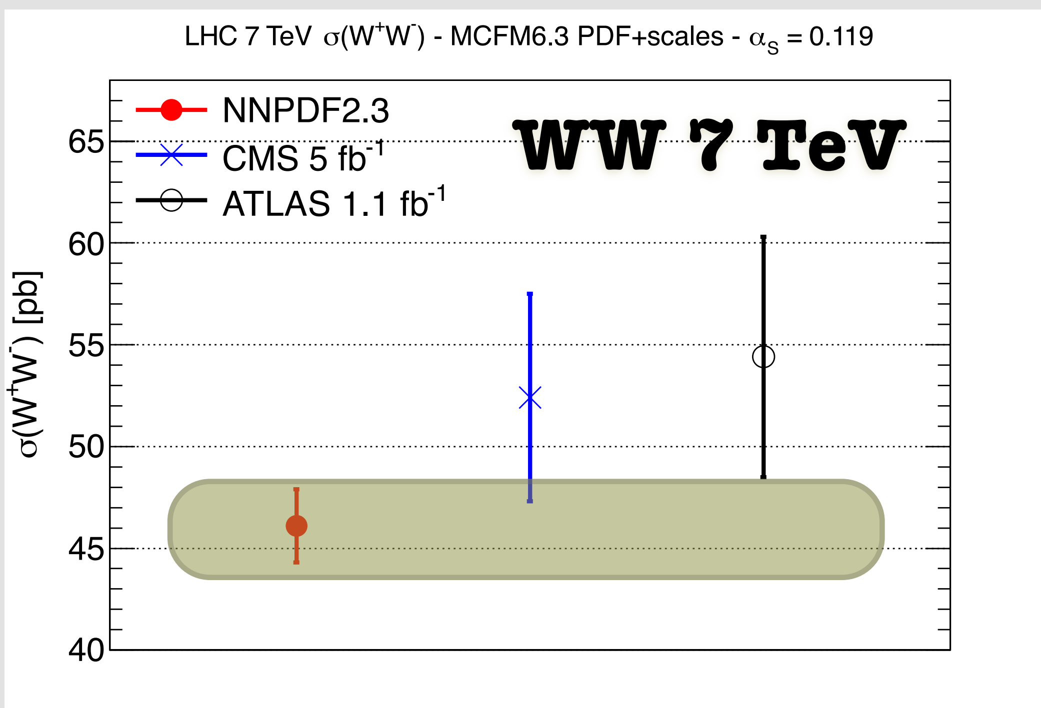
(scale errors missing)

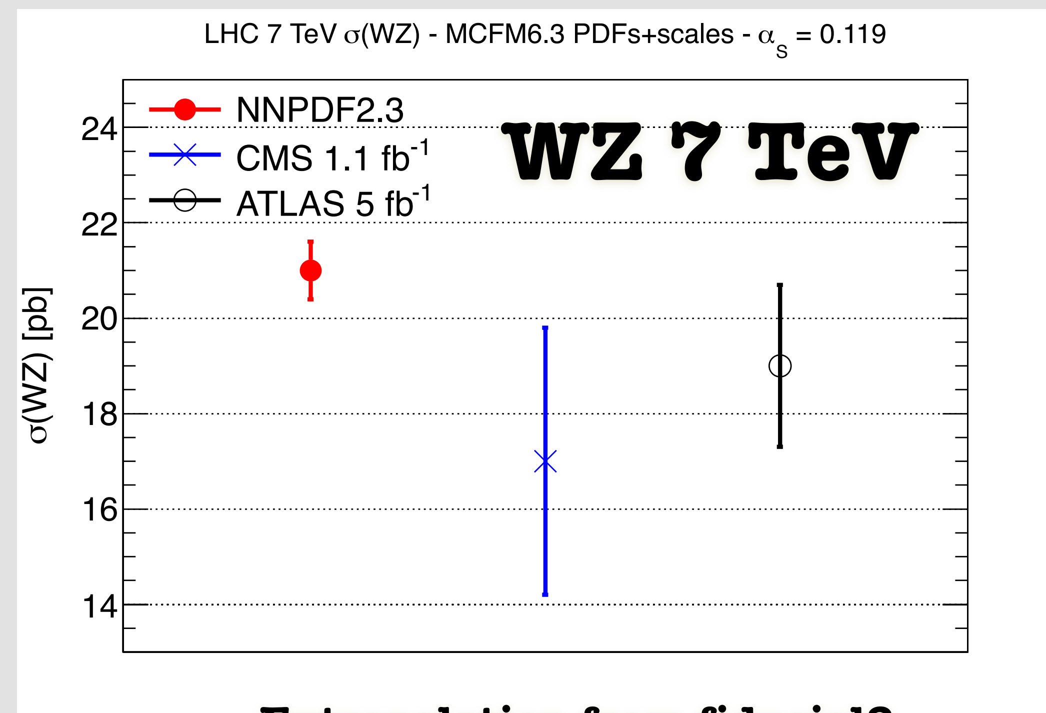
	WW 7	WZ 7	ZZ 7	WW 8	WZ 8	ZZ 8	WW 14	WZ 14	ZZ 14
QQ+QG	97.3%	100%	95.7%	97.0%	0%	95.5%	96.0%	100%	94.5%
GG	2.7 %	0%	4.4%	3.0%	0%	4.6%	4.0%	0%	5.6%

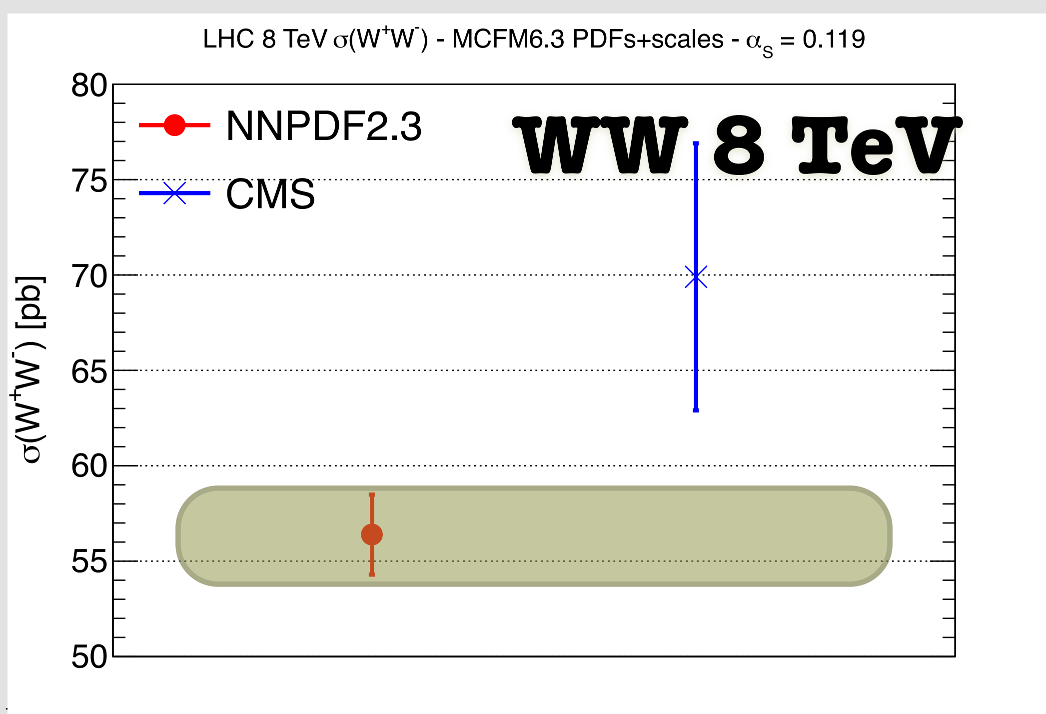
Preliminary

Diboson Production vs LHC data

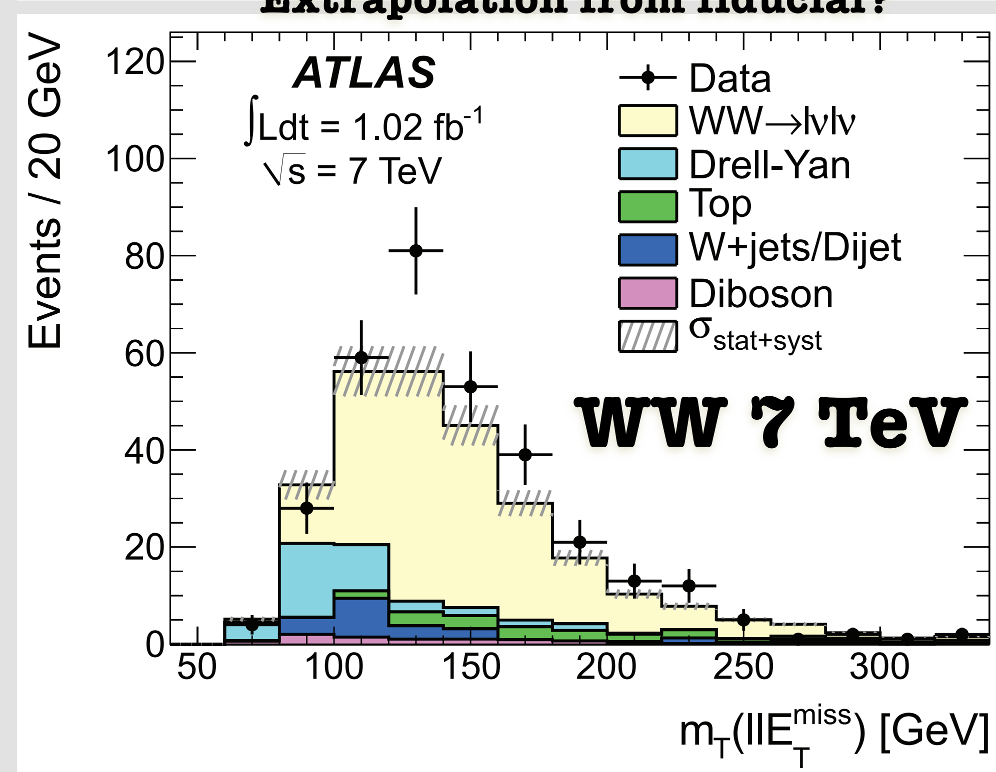
- CMS and ATLAS have measured **WW**, **WZ** and **ZZ** cross sections at 7 and 8 TeV
- In general good agreement with SM, except for **WW**, where **data overshoots theory**, for **ATLAS and CMS**, at **7 and 8 TeV**. Not **statistically significant** but perhaps not a fluctuation?







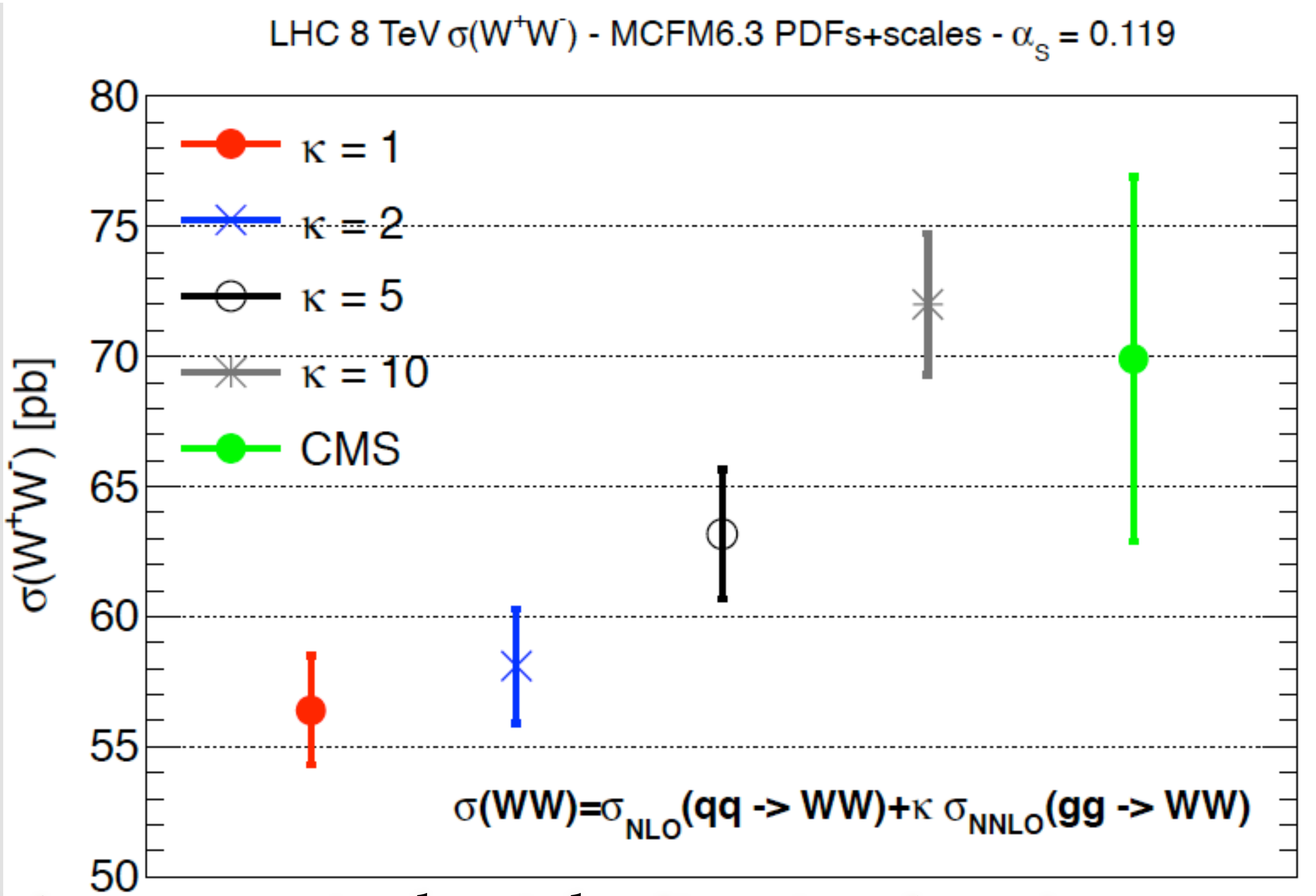
Extrapolation from fiducial?



Excess from large gg K-factor?

- **Gluon-gluon initiated cross sections** are affected in some cases by large K-factors (*ie* Higgs)
- Could a **large K-factor in the gg contribution** lead to observed excess? Note that **gg-> H** also contributes to the experimental yields
- **gg initiated BSM contribution**s could mimic effectively a large K-factor

$$\sigma(W^+W^-,\kappa) = \sigma(qq(g)\to W^+W^-) + \kappa\sigma(gg\to W^+W^-)$$



- A large gg K-factor goes in the right direction, but **size unnaturally large** ....
- Higgs contribution (inclusive) **not negligible** $\sigma_{8\ \mathrm{TeV}}(gg\to H)\mathrm{BR}(H\to WW)\sim 4\ \mathrm{pb}$

Cross Section Ratios for LHC Diboson production

Why cross section ratios?

- The **staged increase of the LHC beam energy** provides a new class of interesting observables: **cross section ratios** for different beam energies

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

- E_i can be **2.76, 7, 8 or 14 TeV** (*ex* Recent ATLAS jet measurement of 7 over 2.76 ratio)
- These ratios can be computed with **very high precision** due to the large degree of **correlation of theoretical uncertainties** at different energies
- **Experimentally** these ratios can also be measured accurately since many systematics, like luminosity or jet energy scale, **cancel partially in the ratios**
- These ratios allow **stringent precision tests of the SM**, and can be used for example as **standard candles to measure/correlate luminosities** between different energies....
- .... but also could provide **new strategies for new physics searches,** exploiting the fact that **BSM physics** typically **scale different with CM energy** than **SM processes**

M. Mangano and J. Rojo, arXiv1206.3557

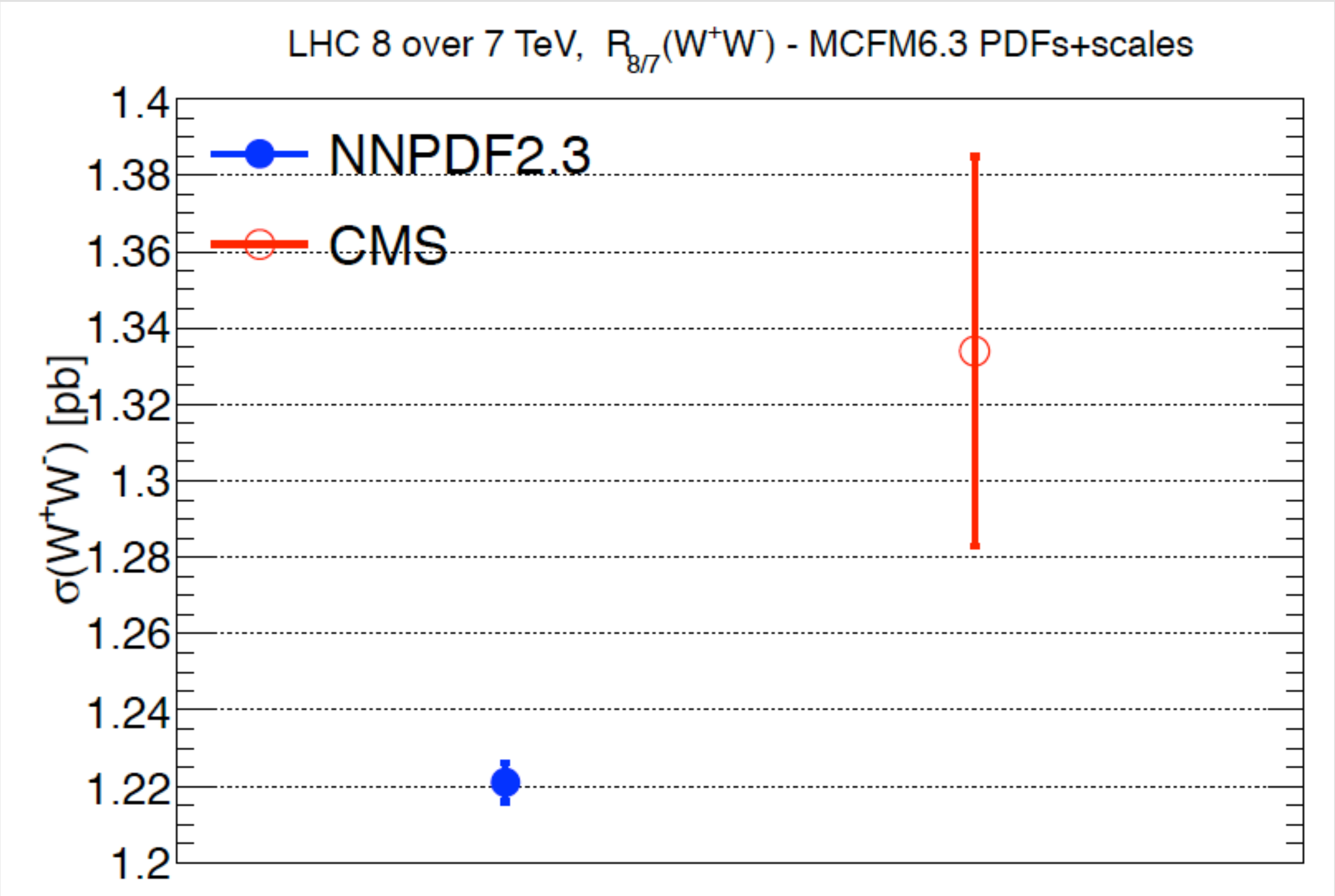
Diboson cross section ratios

- Estimate **8/7** cross section ratio in **WW cross sections** from CMS data. Assume experimental uncertainties in the ratio limited by 7 TeV statistics

- If central values at 8 TeV unchanged, discrepancy with theory predictions above the **2-sigma** level

- Clear potential to **better understand the origin of WW excess** in absolute cross sections

- A **fully dedicated measurement** would be required



$$R_{8\ \mathrm{TeV}/7\ \mathrm{TeV}}(W^+W^-)\Big|_{\mathrm{exp}} = 1.334 \pm 0.051 \quad (3.8\%)$$

$$R_{8\ \mathrm{TeV}/7\ \mathrm{TeV}}(W^+W^-)\Big|_{\mathrm{th}} = 1.221 \pm 0.005 \quad (0.4\%)$$

$$\boxed{R^{\mathrm{exp}}_{8/7}/R^{\mathrm{th}}_{8/7} = 1.093 \pm 0.042}$$

Diboson cross section ratios

8 over 7 TeV	$R^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	$\delta_{\mathrm{scales}}\ (\%)$
WW	1.223	$\pm\ 0.1$	$-0.4 - 0.2$
$gg \to WW$	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	$\pm\ 0.4$	$-0.6 - 1.1$
$gg \to ZZ$	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)

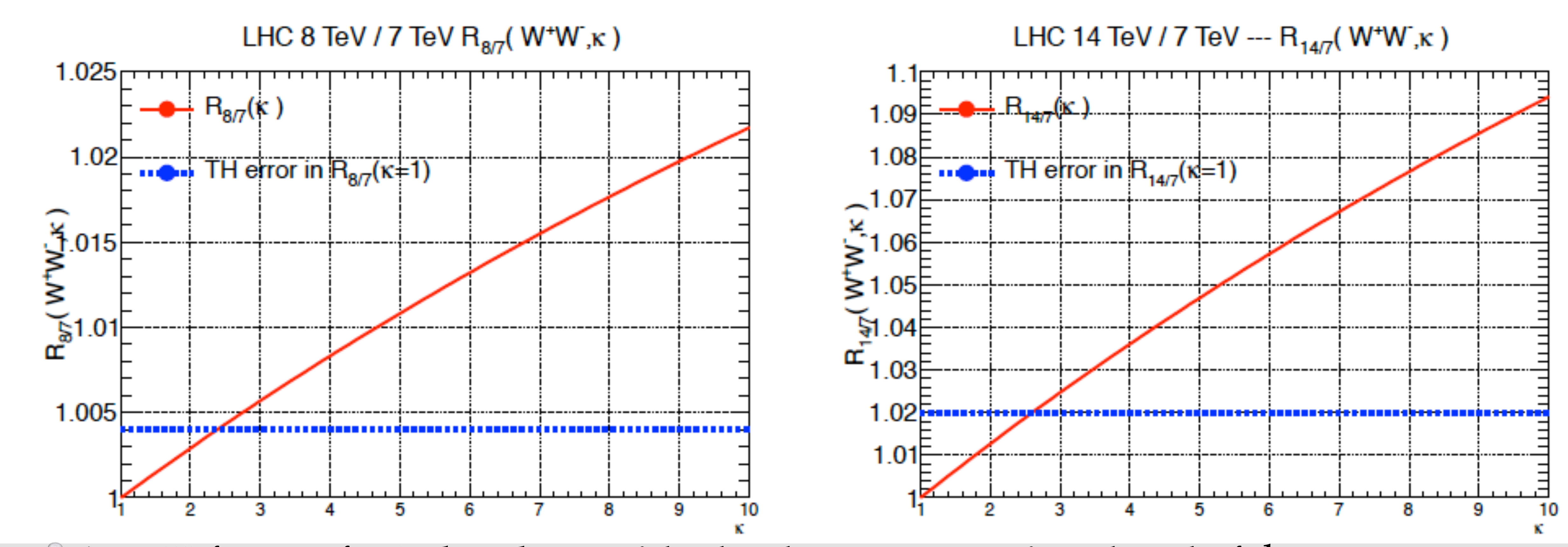
- Theory systematics at the **subpercent level**. Residual scale variations dominate
- The **gg** contribution grows faster with the CM energy from the increased luminosity
- Opportunity to understand the **excess in the WW cross section:** if there is a physical origin (SM or BSM) it will be **enhanced** in the ratio, if it is a fluctuation it will be **diluted**

Preliminary

Diboson cross section ratios

- Determine how a **large gg K-factor** (SM or BSM) affects the cross section ratios

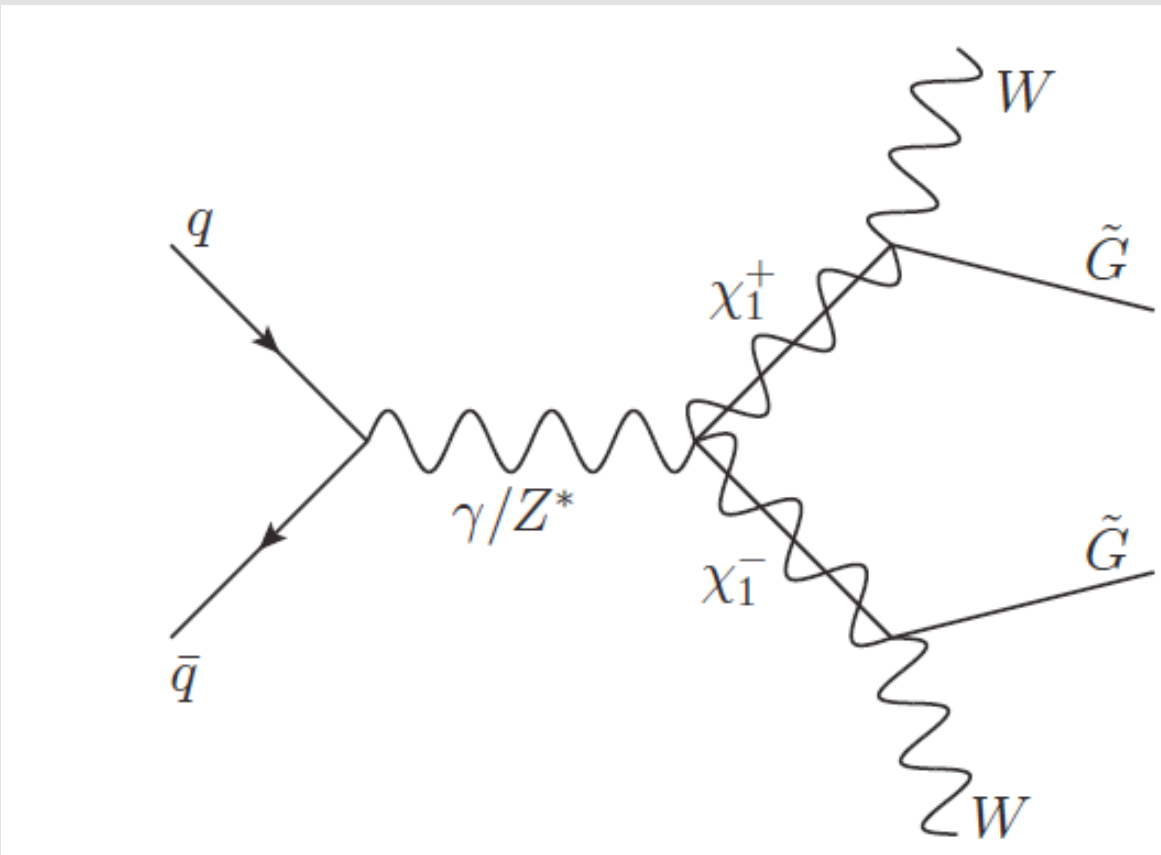
$$R_{E_2/E_1}(W^+W^-,\kappa) \equiv \frac{\left[\sigma(qq(g)\to W^+W^-) + \kappa\sigma(gg\to W^+W^-)\right]\Big|_{E_2}}{\left[\sigma(qq(g)\to W^+W^-) + \kappa\sigma(gg\to W^+W^-)\right]\Big|_{E_1}}$$



- A gg K-factor of 2-3 already **outside the theory uncertainty band** of the ratio.
- A **large qq K-factor** (from full NNLO) should **affect much less the ratio**
- Which would be the precision of a **dedicated ratio measurement**?
- NNLO corrections outside NLO uncertainty band?

SUSY scenarios for WW excess

- **Supersymmetric scenarios** have been suggested to explain the **WW excess,** in terms of light **charginos/sleptons** that mimic the WW final state, arXiv:1206.6888, 1205.3468



- Certain SUSY models allow sizable cross sections for **light chargino and slepton production for 100 GeV**
- Consistent with direct searches and precision electroweak data
- Cross sections of **O(1-10) pb** not excluded: allow better fit of LHC WW data

- Currently investigating the **sensitivity of the 8/7 ratio to supersymmetric contributions**.
- Chargino production scales with CM energy different than WW production because

i) **Charginos χ heavier than W** (different, larger Bjorken-x probed)
ii) The relative rate **(qqbar -> χ χ)/(qqbar->WW)** grows with energy

$$R\left(m_\chi\right) \equiv \frac{\left[\sigma_{WW} + \sigma_{\chi\chi}(m_\chi)\right]_8}{\left[\sigma_{WW} + \sigma_{\chi\chi}(m_\chi)\right]_7}$$

Summary and outlook

- **Diboson production** is a very important processes at the LHC, both for **precision physics**, **Higgs production** and **direct/indirect BSM sensitivity**

- **LHC data** generally in agreement with SM, but **WW cross sections** (and others) seem to be consistently larger that the SM predictions.

- **Precision measurements of single and double cross section ratios** of hard processes at **different LHC energies** are new interesting observables, both for precision measurements and in terms of BSM discrimination

- **The 8 over 7 TeV WW ratio** has the potential to enhance/dilute the observed excess, and thus help to ascertain its origin: **SM vs BSM, qq vs gg**, ...). Also for other **diboson** xsecs. **Combination** between ATLAS and CMS?

- Currently studying various possibilities, in the **SM and in BSM scenarios**, to **explain the diboson excess** and formulate ratio observables to test them. Also fiducial distributions.

Extra Material

Why cross section ratios?

- The **staged increase of the LHC beam energy** provides a new class of interesting observables: **cross section ratios** and **double ratios** of **hard processes**

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

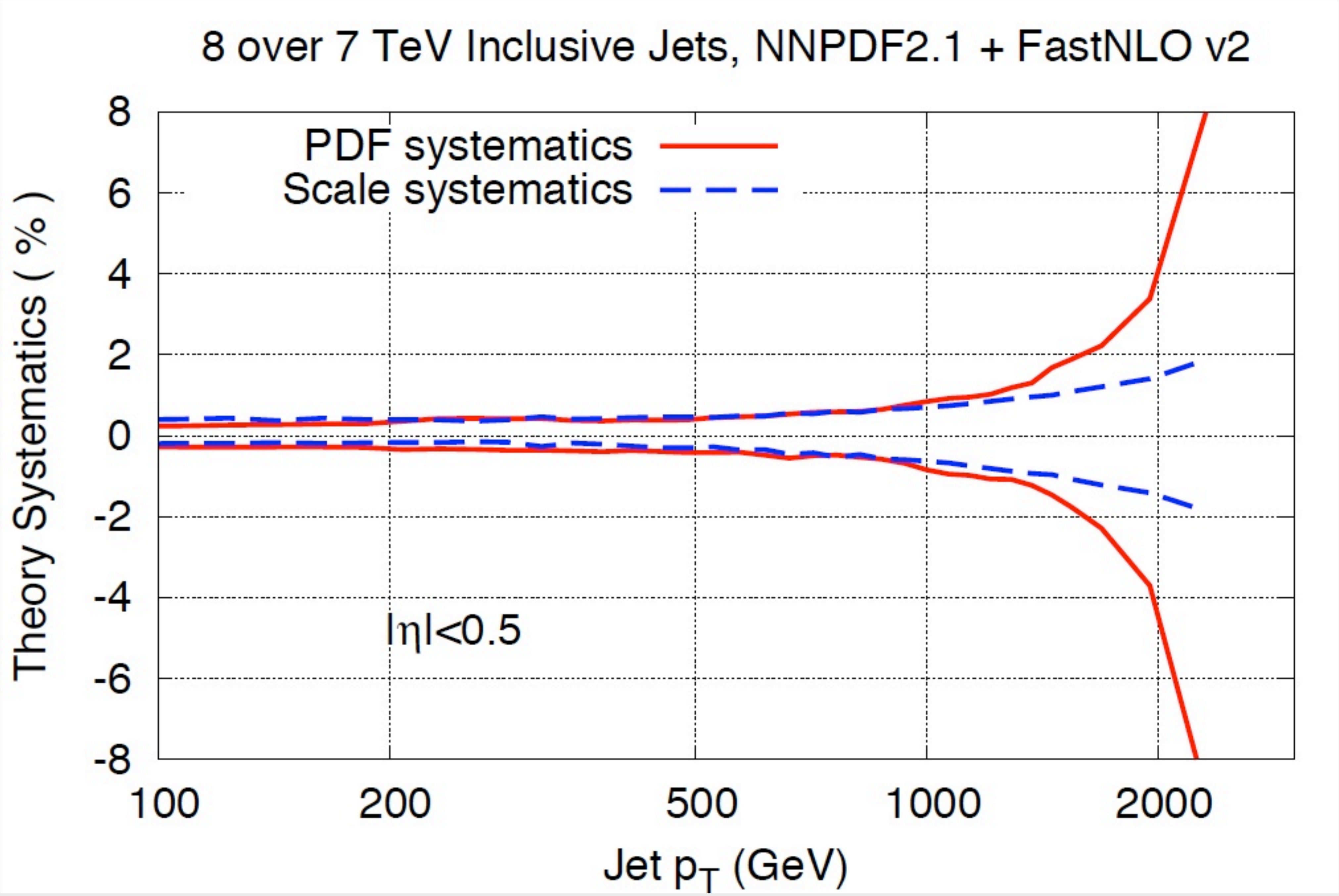
- E_i can be **2.76, 7, 8 or 14 TeV**
- These ratios can be computed with **very high precision** due to the large degree of **correlation of theoretical uncertainties** at different energies
- **Experimentally** these ratios can also be measured accurately since many systematics, like luminosity or jet energy scale, **cancel partially in the ratio**s
- These ratios allow **stringent precision tests of the SM**, and can be used for example as **standard candles to measure/correlate luminosities** between different energies....
- .... but also could provide **new strategies for new physics searches**

Cross section Ratios - 8 over 7 TeV

Cross Section	$r^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	δ_{α_s} (%)	δ_{scales} (%)
$t\bar{t}/Z$	1.23	$\pm$ 0.4	$-0.2 - 0.2$	$-0.2 - 0.3$
$t\bar{t}$	1.43	$\pm$ 0.3	$-0.2 - 0.2$	$-0.1 - 0.3$
Z	1.16	$\pm$ 0.1	$-0.0 - 0.1$	$-0.1 - 0.1$
W^+	1.15	$\pm$ 0.1	$-0.0 - 0.1$	$-0.1 - 0.1$
W^-	1.17	$\pm$ 0.1	$-0.0 - 0.1$	$-0.1 - 0.1$
W^+/W^-	0.98	$\pm$ 0.1	$0.0 - 0.0$	$-0.0 - 0.0$
W/Z	0.99	$\pm$ 0.0	$-0.0 - 0.0$	$-0.0 - 0.0$
ggH	1.27	$\pm$ 0.2	$-0.0 - 0.1$	$-0.2 - 0.2$
$ggH/t\bar{t}$	0.89	$\pm$ 0.3	$-0.1 - 0.1$	$-0.4 - 0.2$
$t\bar{t}(M_{tt} \geq 1$ TeV)	1.81	$\pm$ 0.8	$0.0 - 0.0$	$-0.6 - 0.5$
$t\bar{t}(M_{\mathrm{tt}} \geq 2$ TeV)	2.80	$\pm$ 3.2	$0.0 - 0.0$	$-0.0 - 1.4$
$\sigma_{\mathrm{jet}}(p_T \geq 1$ TeV)	2.30	$\pm$ 1.0	$0.0 - 0.0$	$-0.4 - 1.0$
$\sigma_{\mathrm{jet}}(p_T \geq 2$ TeV)	7.38	$\pm$ 5.2	$0.0 - 0.0$	$-2.5 - 2.3$

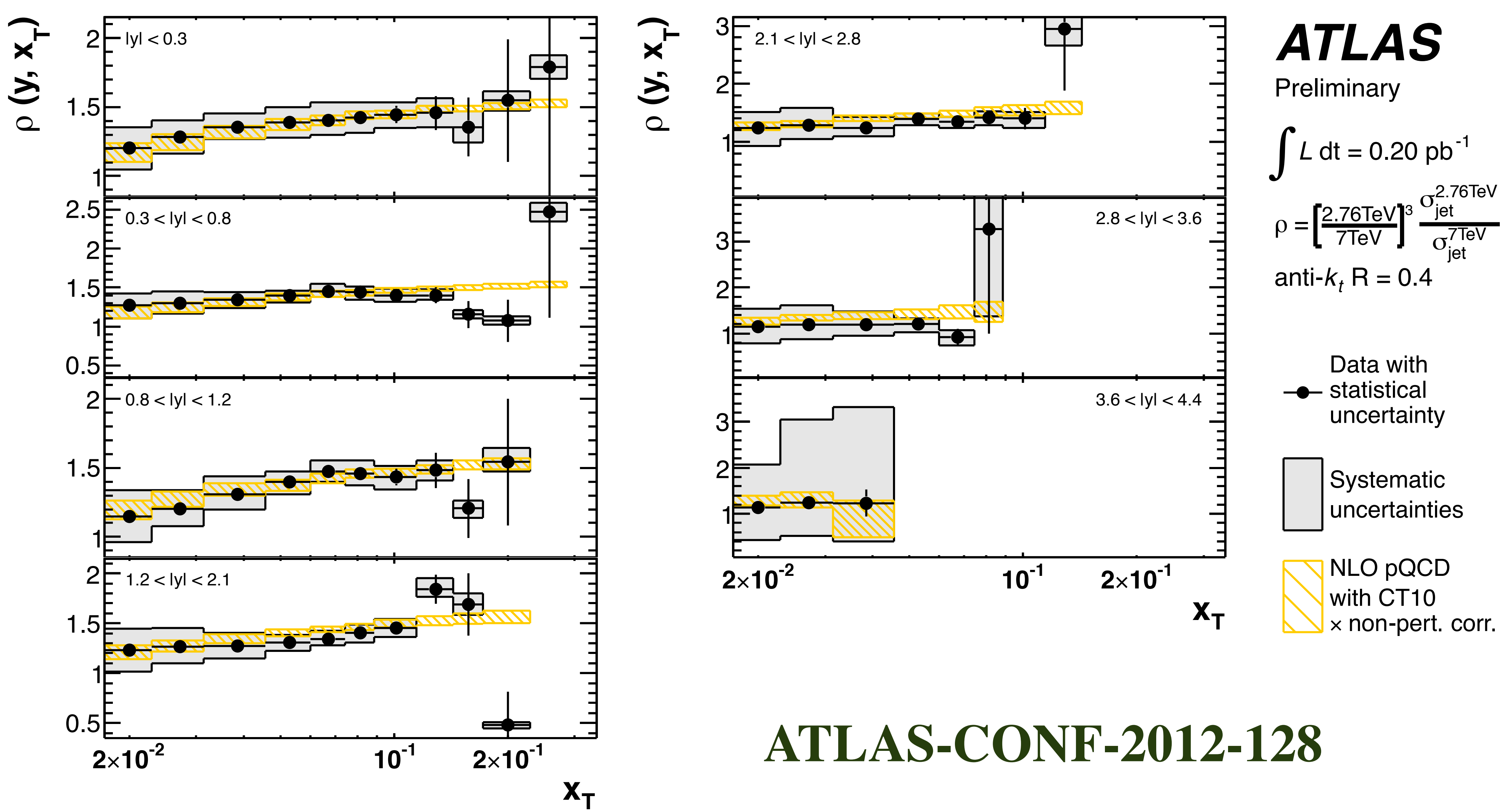
- **Inclusive cross sections** with theory systematics at the **permille** level
- Ratios of more exclusive distributions dominated by **PDF uncertainties**

Cross section Ratios - 8 over 7 TeV



- Theory systematics in **jet cross section ratios** between 8 and 7 TeV have been studied aslo with **FastNLO**, using the same pT and eta binning of the **2011 data**
- **PDF errors blowup**, much larger than scale errors **at large pT:** unique constrains on **very large-x PDFs**

Cross section Ratios - 2.76 over 7 TeV



ATLAS-CONF-2012-128

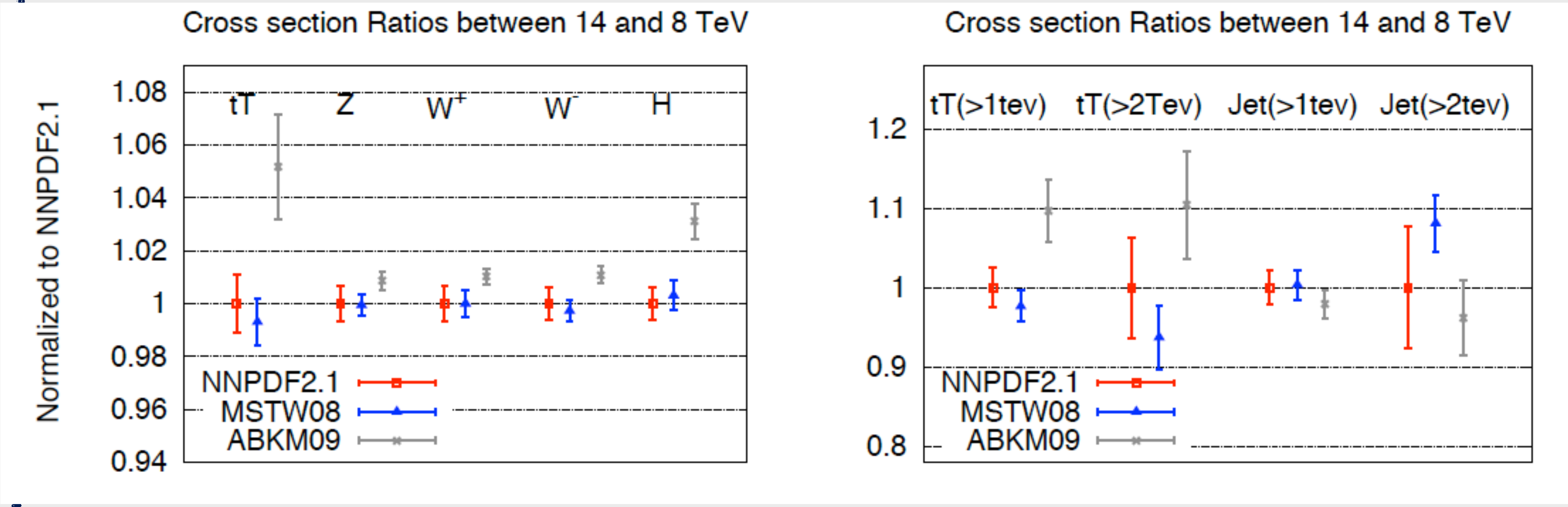
- Recent ATLAS measurement of the **inclusive jet cross section ratio** between **2.76** and **7 TeV**
- Full **correlation between most systematic errors** leads to reduced uncertainties in ratio
- Theory uncertainties in ratio **dominated by PDFs**: important input for global PDF fits

Cross section Ratios - 14 over 8 TeV

Cross Section	$r^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	δ_{α_s} (%)	δ_{scales} (%)
$t\bar{t}/Z$	2.12	$\pm$ 1.3	-0.8 – 0.8	-0.4 – 1.1
$t\bar{t}$	3.90	$\pm$ 1.1	-0.5 – 0.7	-0.4 – 1.1
Z	1.84	$\pm$ 0.7	-0.1 – 0.3	-0.3 – 0.2
W^+	1.75	$\pm$ 0.7	-0.0 – 0.3	-0.3 – 0.2
W^-	1.86	$\pm$ 0.6	-0.1 – 0.3	-0.3 – 0.1
W^+/W^-	0.94	$\pm$ 0.3	0.0 – 0.0	-0.0 – 0.0
W/Z	0.98	$\pm$ 0.1	-0.1 – 0.0	-0.0 – 0.0
ggH	2.56	$\pm$ 0.6	-0.1 – 0.1	-0.9 – 1.0
$ggH/t\bar{t}$	0.66	$\pm$ 1.0	-0.6 – 0.4	-1.4 – 1.1
$t\bar{t}(M_{tt} \geq 1$ TeV)	8.2	$\pm$ 2.5	0.0 – 0.0	-1.6 – 2.1
$t\bar{t}(M_{\mathrm{tt}} \geq 2$ TeV)	24.9	$\pm$ 6.3	0.0 – 0.0	-3.0 – 1.1
$\sigma_{\mathrm{jet}}(p_T \geq 1$ TeV)	15.1	$\pm$ 2.1	0.0 – 0.0	-1.9 – 2.4
$\sigma_{\mathrm{jet}}(p_T \geq 2$ TeV)	182.	$\pm$ 7.7	0.0 – 0.0	-5.7 – 4.0

- **Inclusive cross sections** with theory systematics at the **permille** level - Also for **Higgs production**
- Ratios of more exclusive distributions dominated by **PDF uncertainties**

Cross section Ratios - PDF dependence



- Cross section ratios provide opportunities for **PDF discrimination** in a **wide kinematical range.** In many cases the dominant systematic error
- **Spread** between different PDF set predictions larger than nominal PDF errors in many cases
- Complementary source of **PDF information**

Sensitivity to BSM contributions

- Consider that **final state X** receives contributions **both from SM and BSM processes**

$$\sigma(pp \to X) = \sigma^{SM}(pp \to X) + \sigma^{BSM}(pp \to X)$$

- Then one can write, assuming the **BSM contribution is small wrt SM one**

$$R^{X}_{E_1/E_2} \sim \frac{\sigma^{SM}_X(E_1)}{\sigma^{SM}_X(E_2)} \times \left\{ 1 + \frac{\sigma^{BSM}_X(E_1)}{\sigma^{SM}_X(E_1)} \, \Delta_{E_1/E_2}\left[\frac{\sigma^{BSM}_X}{\sigma^{SM}_X}\right]\right\}$$

$$\Delta_{E_1/E_2}(A) = 1 - \frac{A(E_2)}{A(E_1)}$$

- The **visibility of a BSM contribution** in the **evolution with energy** of the cross section requires that it evolves **differently from the SM contribution**

Sensitivity to BSM contributions

- The **threshold** to be **sensitive to BSM contributions** is given by the **precision of the SM prediction**, taken into account all theory systematics

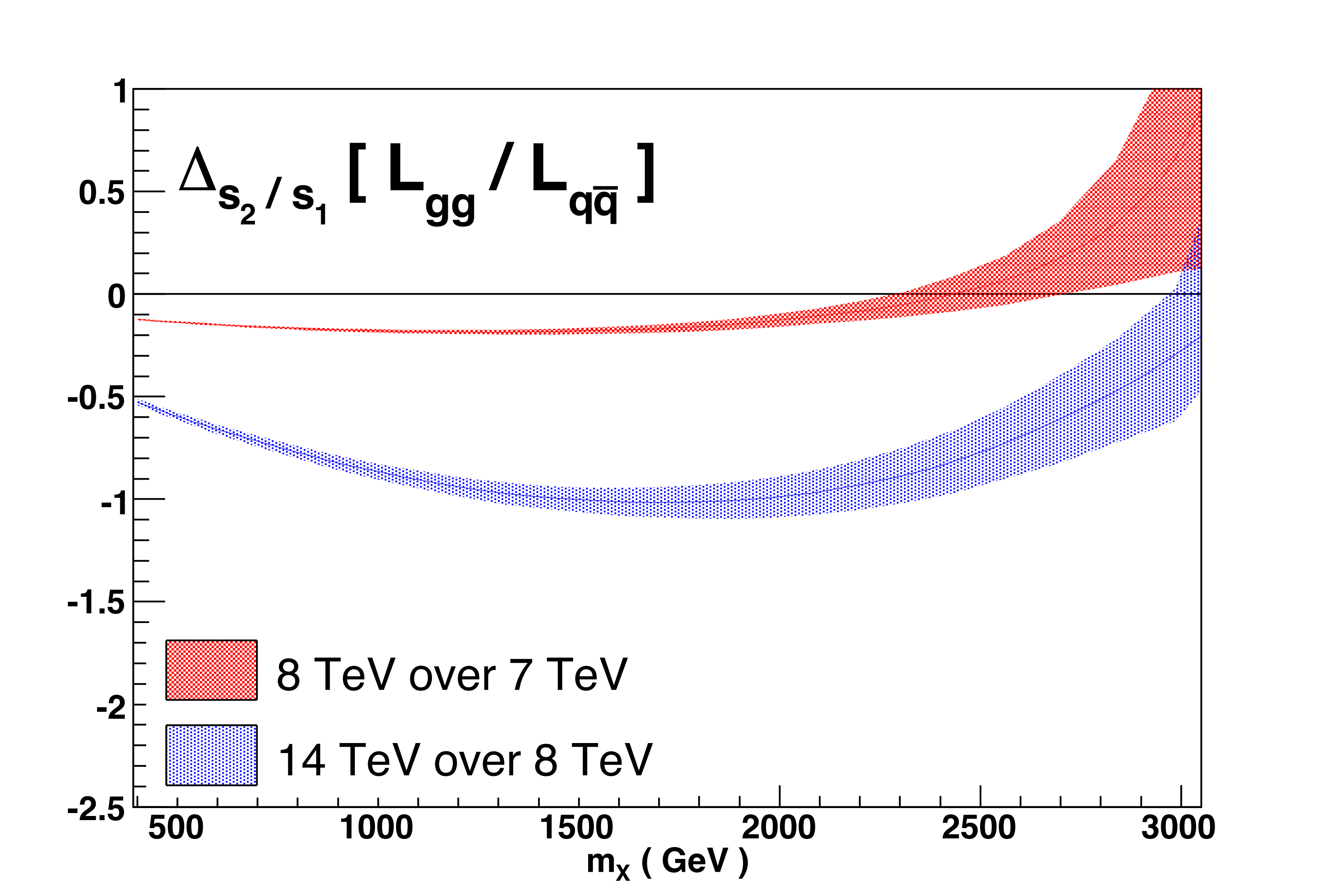
$$\frac{\sigma_X^{BSM}(E_1)}{\sigma_X^{SM}(E_1)} \times \Delta_{E_1/E_2}\left[\frac{\sigma_X^{BSM}}{\sigma_X^{SM}}\right] > \delta_{TH} \equiv \frac{\delta R^{SM}_{E_1/E_2}}{R^{SM}_{E_1/E_2}}$$

- This also defined the **goals for the precision of the experimental measurement**
- Since the theory systematics are at the % **level or even smaller**, BSM contributions of few % could be detected if the SM and BSM cross sections **scale differently enough in energy**
- This scaling with energy is driven by the **partonic luminosities**, for the production of a final state X with mass M

$$\Delta_{E_1/E_2}\left[\frac{\sigma_X^{BSM}}{\sigma_X^{SM}}\right] \sim \Delta_{E_1/E_2}\left[\frac{\mathcal{L}^{ij}(M)}{\mathcal{L}^{ab}(M)}\right]$$

Application: Off shell Z production

- **High mass Z production** dominated by **qqbar luminosity**
- Very different scaling with energy of **gg luminosity:** sensitivity to **BSM gluon initiated contributions** that lead to the same final state as of **Z production**



Relative deviation wrt SM scaling →

$$\frac{\sigma_Z^{\mathrm{BSM}}(m_X)}{\sigma_Z^{\mathrm{SM}}(m_X)} \Delta_{E_1/E_2}\left[\frac{\mathcal{L}_{gg}(m_X)}{\mathcal{L}_{q\bar{q}}(m_X)}\right]$$