Cross Section ratios between different CM energies at the LHC: opportunities for precision measurements and BSM sensitivity

Juan Rojo
CERN, TH Unit, PH Division
PDF4LHC, CERN, 23/05/2012

Based on M. Mangano and J. R, in preparation

Outline

- ☑ Theoretical systematics in cross section ratios
- ☑ Sensitivity to New Physics contributions

Theoretical systematics in cross section ratios

Why cross section ratios?

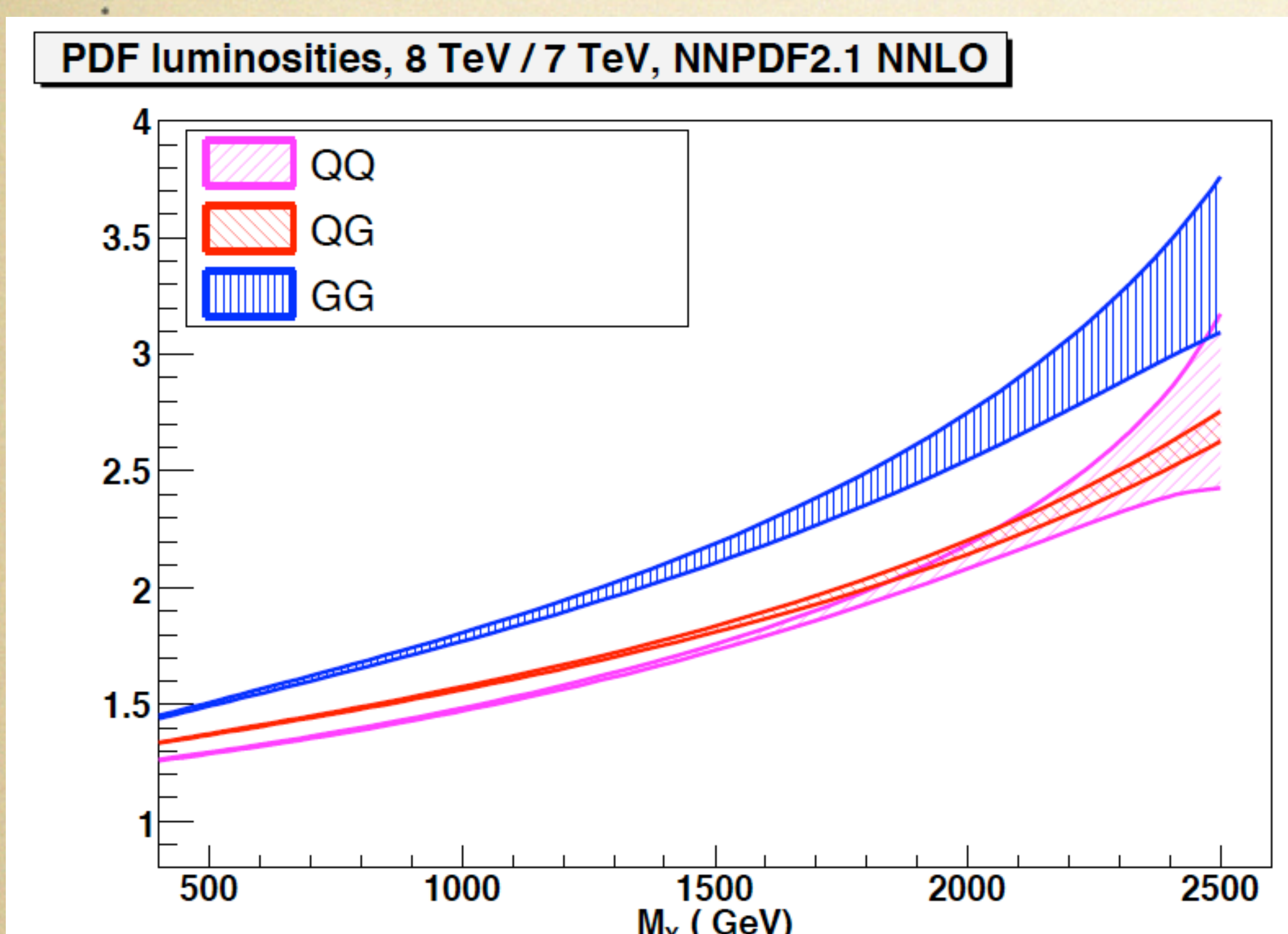
- The **staged increase of the LHC beam energy** provides a new class of interesting observables: **cross section ratios** and **double ratios** of **hard processes**

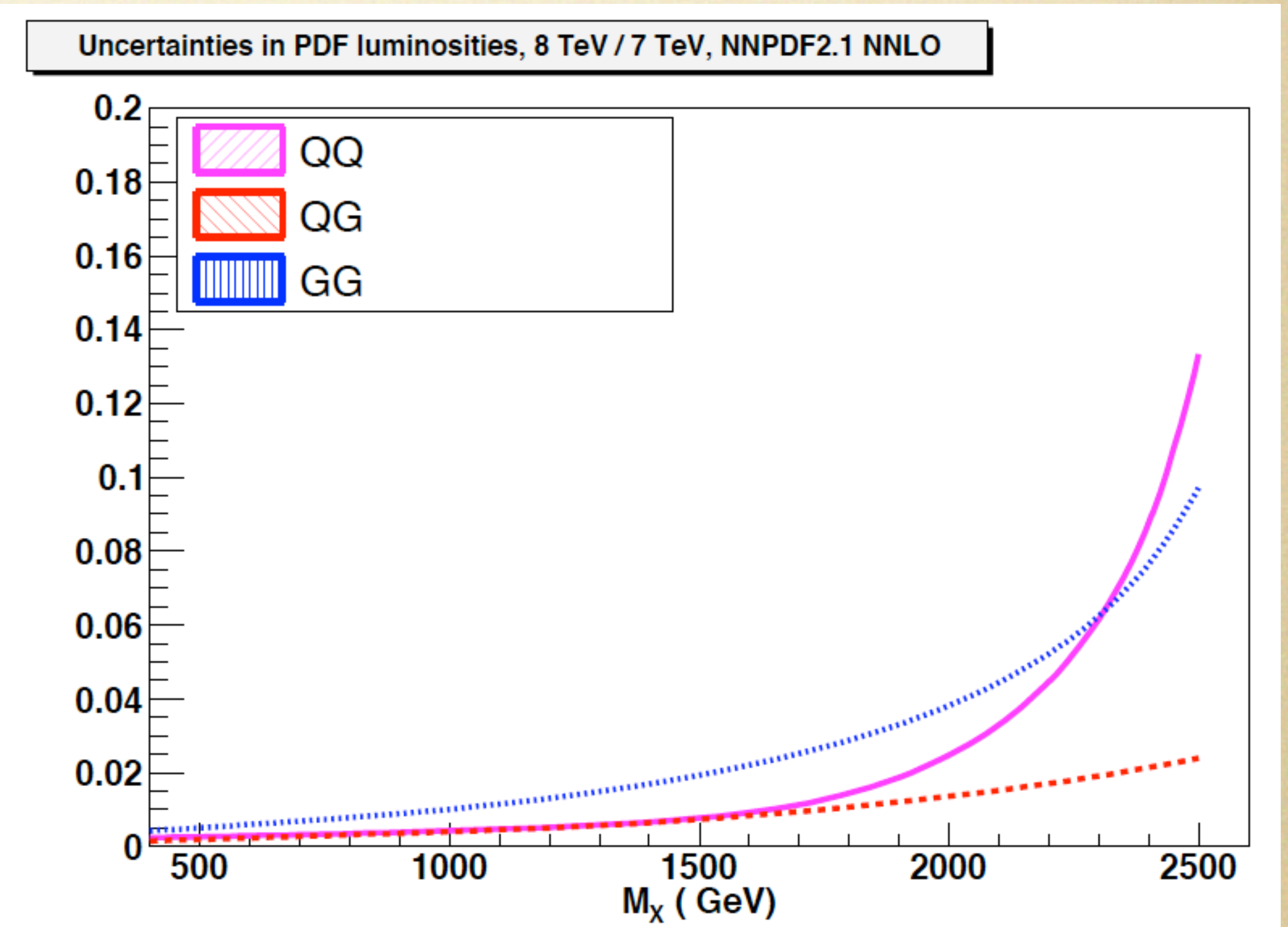
$$R_{E_2/E_1}(X) \equiv \frac{\sigma(X,E_2)}{\sigma(X,E_1)} \qquad R_{E_2/E_1}(X,Y) \equiv \frac{\sigma(X,E_2)/\sigma(Y,E_2)}{\sigma(X,E_1)/\sigma(Y,E_1)}$$

- E_i can be **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**

Parton Luminosities

- When increasing the LHC beam energy, the **PDF luminosity increase, specially for high final state masses**





- PDF uncertainties **in the ratio** cancel to very good extent for not too large final state masses, then **PDF error blow up** because **very high-x PDFs** (with large errors) being probed
- Depending on the analysis, we might want to **maximize** (PDF constraints) or **minimize** (luminosity monitoring, BSM searches) the **PDF sensitivity of ratios**

Settings

- Several processes considered (just a small sample of possible observables)
  - **Electroweak gauge boson** production computed at NNLO with **Vrap**
  - **Top quark pair** production at NLO+NNLL with **Top++**
  - **Higgs boson production** at NNLO with **iHixs**
  - Top quark pair production with **invariant mass** above 1 and 2 TeV at NLO with **MCFM6.2**, cross-checked with **HVQMNR**
  - **Inclusive jet production** for pT above 1 and 2 TeV at NLO with **ModifiedEKS** (Thanks to J. Gao for pre-release version)

- Theoretical systematics considered are **PDFs** (both intrinsic PDF errors and differences between PDF sets), **scale variations**, **strong coupling variations** and **top mass** variations

$$0.5 \le \mu_R/Q, \mu_F/Q \le 2, \qquad 0.5 \le \mu_R/\mu_F \le 2$$

- We consider **NNPDF2.1**, **MSTW08** and **ABKM09** NNLO PDFs in all processes

Cross section Ratios - 8 over 7 TeV

CrossSection	$r^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	δ_{α_s} (%)	δ_{scales} (%)
$t\bar{t}/Z$	1.231	0.28	$-0.23 - 0.24$	$0.17 - 0.33$
$t\bar{t}$	1.432	0.25	$-0.15 - 0.20$	$0.14 - 0.33$
Z	1.163	0.08	$-0.04 - 0.08$	$0.05 - 0.09$
W^+	1.148	0.08	$-0.01 - 0.06$	$0.06 - 0.08$
W^-	1.167	0.09	$-0.03 - 0.06$	$0.06 - 0.07$
W^+/W^-	0.983	0.08	$0.00 - 0.02$	$0.00 - 0.02$
W/Z	0.994	0.03	$-0.02 - 0.02$	$0.02 - 0.00$
ggH	1.273	0.11	$-0.04 - 0.06$	$0.24 - 0.16$
$ggH/t\bar{t}$	0.889	0.22	$-0.15 - 0.11$	$0.41 - 0.22$
$t\bar{t}(M_{tt} \geq 1\mathrm{TeV})$	1.807	0.73	$0.00 - 0.00$	$0.61 - 0.54$
$t\bar{t}(M_{\mathrm{tt}} \geq 2\mathrm{TeV})$	2.734	3.60	$0.00 - 0.00$	$0.00 - 1.45$
$\sigma\mathrm{jet}(p_T \geq 1\mathrm{TeV})$	2.283	1.02	$0.00 - 0.00$	$5.89 - 0.91$
$\sigma\mathrm{jet}(p_T \geq 2\mathrm{TeV})$	7.386	4.70	$0.00 - 0.00$	$2.33 - 1.08$

- Single W and Z ratios have a total systematic of 0.1%: could be used to **correlate luminosities of 8 and 7 TeV runs with high precision**
- **tt Mtt distributions and** jets provide TeV scale observables with few % theory systematics

Cross section Ratios - 8 over 7 TeV

Ratio	$r^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	$r^{\mathrm{th,mstw}}$	$\delta_{\mathrm{PDF}}(\%)$	$\Delta^{mstw}(\%)$	$r^{\mathrm{th,abkm}}$	$\delta_{\mathrm{ABKM}}(\%)$	Δ^{abkm} (%)
$t\bar{t}/Z$	1.231	0.28	1.227	0.24	0.37	1.247	0.55	-1.20
$t\bar{t}$	1.432	0.25	1.428	0.24	0.34	1.452	0.55	-1.35
Z	1.163	0.08	1.163	0.09	-0.02	1.165	0.08	-0.15
W^+	1.148	0.08	1.149	0.10	-0.06	1.150	0.07	-0.18
W^-	1.167	0.09	1.167	0.09	0.02	1.170	0.08	-0.23
W^+/W^-	0.983	0.08	0.984	0.05	-0.08	0.983	0.04	0.05
W/Z	0.994	0.03	0.994	0.02	-0.02	0.994	0.03	-0.04
ggH	1.273	0.11	1.274	0.17	-0.05	1.240	0.16	2.65
$ggH/t\bar{t}$	0.889	0.22	0.000	0.00	0.00	0.000	0.00	0.00
$t\bar{t}(M_{tt} \geq 1\mathrm{TeV})$	1.807	0.73	1.791	0.66	0.95	1.855	1.02	-2.61
$t\bar{t}(M_{tt} \geq 2\mathrm{TeV})$	2.734	3.60	2.645	2.84	3.61	2.645	4.04	3.61
$\sigma\mathrm{jet}(p_T \geq 1\mathrm{TeV})$	2.283	1.02	2.290	1.99	0.13	2.268	2.03	1.08
$\sigma\mathrm{jet}(p_T \geq 2\mathrm{TeV})$	7.386	4.70	7.915	4.29	-7.59	7.695	4.92	-4.59

- **tT ratios** (inclusive and invariant mass distributions) potentially **useful to distinguish between PDF sets**: NNPDF/MSTW vs ABKM
- **Inclusive jets with p_T > 1 TeV** instead very close for all PDFs, small overall PDF errors
- **W and Z ratios** also robust agains changing the PDF set: possibly **one of the most precise standard candles** at the LHC

Cross section Ratios - 14 over 8 TeV

CrossSection	$r^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	δ_{α_s} (%)	δ_{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
$t\bar{t}(M_{tt} \geq 1\mathrm{TeV})$	8.215	2.09	0.00 – 0.00	1.61 – 2.06
$t\bar{t}(M_{\mathrm{tt}} \geq 2\mathrm{TeV})$	24.776	6.07	0.00 – 0.00	3.05 – 1.07
$\sigma\mathrm{jet}(p_T \geq 1\mathrm{TeV})$	15.235	1.72	0.00 – 0.00	2.31 – 2.19
$\sigma\mathrm{jet}(p_T \geq 2\mathrm{TeV})$	181.193	6.75	0.00 – 0.00	3.66 – 5.76

- Single W and Z ratios have a total systematic of 0.5%: could be used **to correlate luminosities of 14 and 8 TeV runs** with high precision
- Ratios of **Higgs cross section** have **1% theory accuracy**: stringent test of **SM vs BSM Higgs**
- **Inclusive tT ratios** also 1% accuracy, more precise that absolute cross sections

SENSITIVITY TO NEW PHYSICS CONTRIBUTIONS

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**

$$R^X_{E_1/E_2} \sim \frac{\sigma_X^{SM}(E_1)}{\sigma_X^{SM}(E_2)} \times \left\{ 1 + \frac{\sigma_X^{BSM}(E_1)}{\sigma_X^{SM}(E_1)} \Delta_{E_1/E_2}\left[\frac{\sigma_X^{BSM}}{\sigma_X^{SM}}\right]\right\}$$

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

- 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

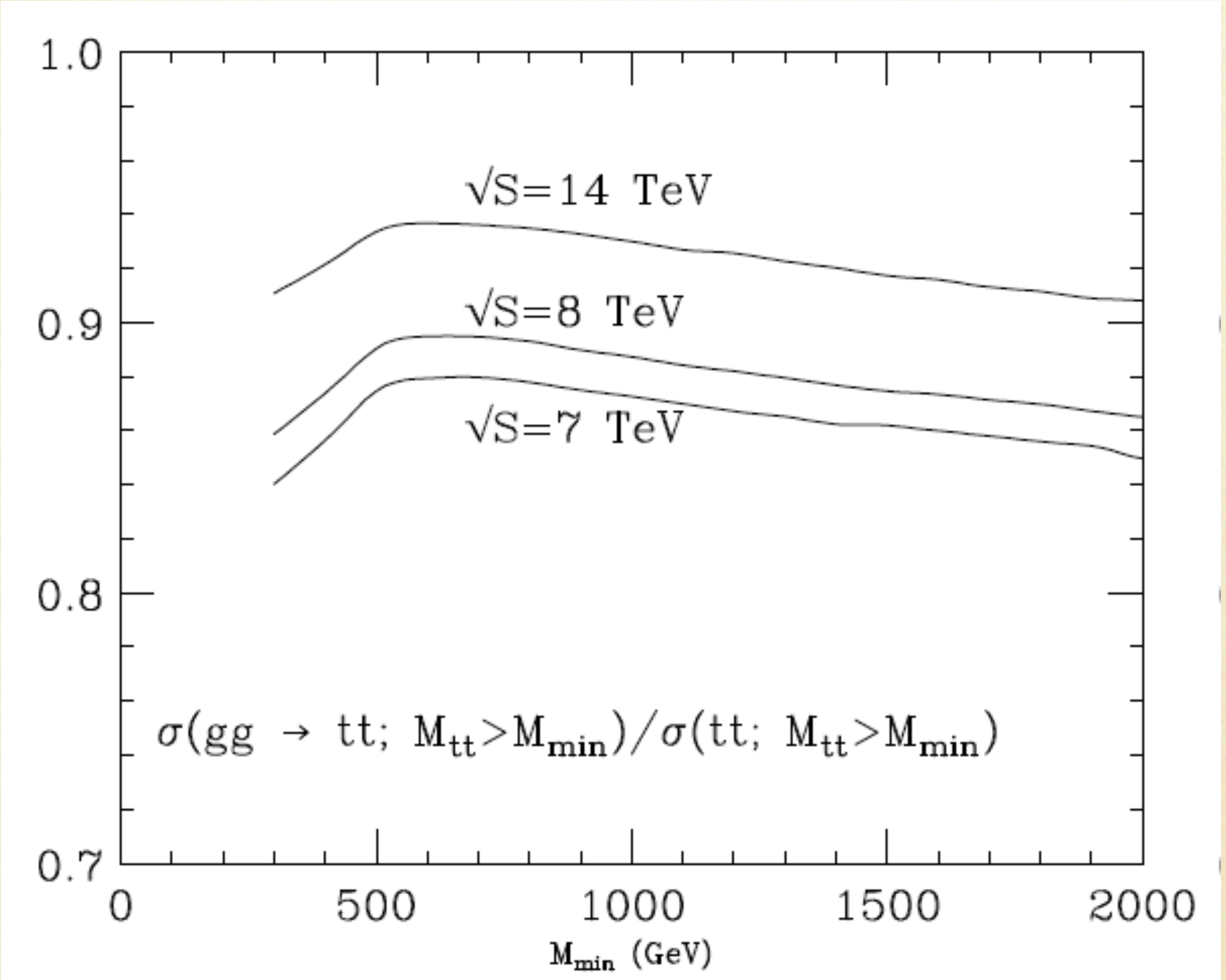
$$\frac{\sigma_X^{BSM}(E_1)}{\sigma_X^{SM}(E_1)} \times \Delta_{E_1/E_2}\left[\frac{\sigma_X^{BSM}}{\sigma_X^{SM}}\right] > \delta_{TH} \equiv \frac{\delta R^{SM}_{E_1/E_2}}{R^{SM}_{E_1/E_2}}$$

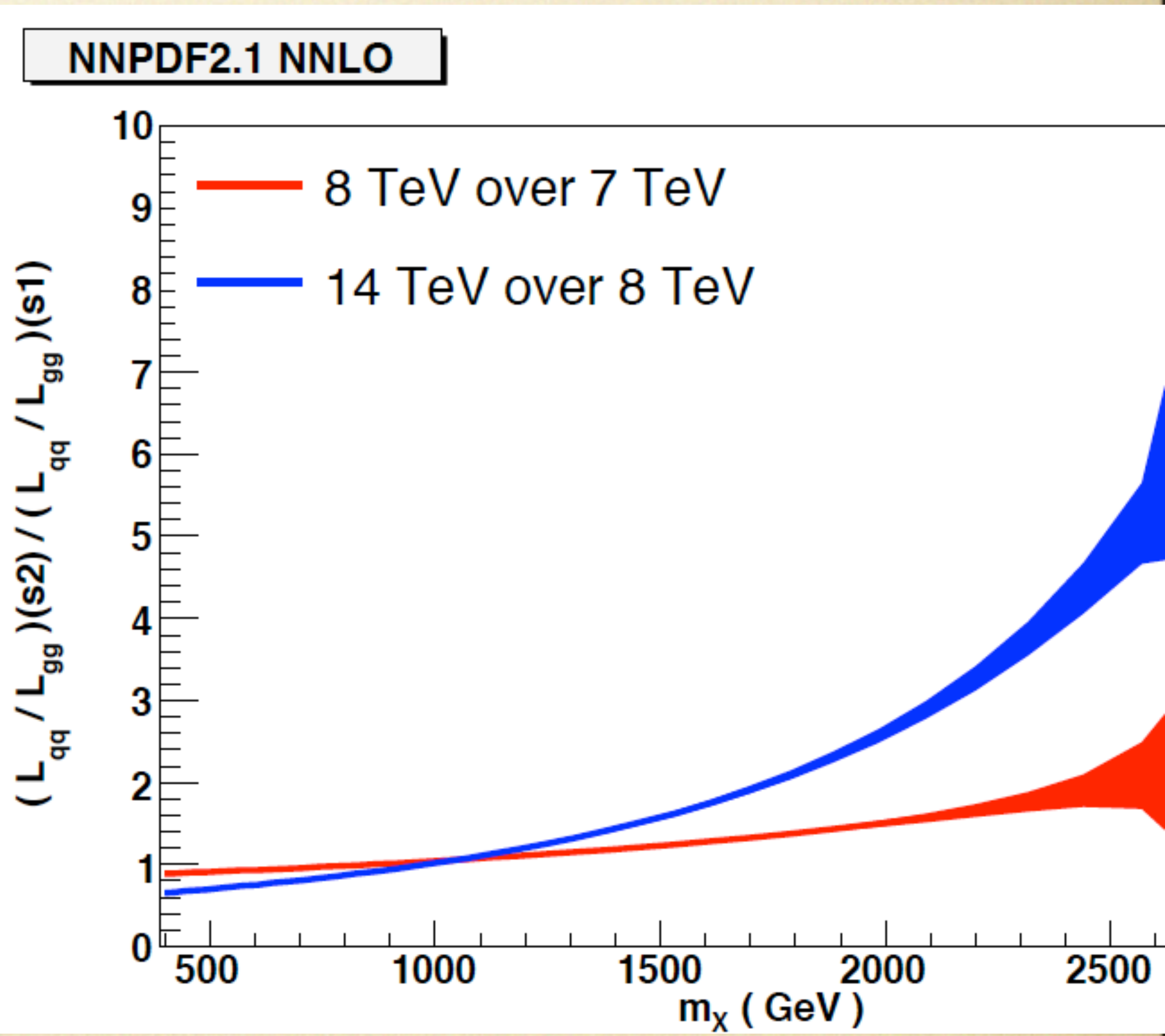
- This also defined the **goals for the precision of the experimental measurement**
- Since the theory systematics are at the % **level or even smaller**, BSM contributions of few % could be detected if the SM and BSM cross sections **scale differently enough in energy**
- This scaling with energy is 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: tT at large M_{tT}

- **tT at large invariant masses** dominated by **gg**, **stable fraction for all energies**





- **qQ over gg luminosity** increases with the LHC energy
- For **8 over 7, enhancement factor up to 1.5** for M=2 TeV
- For 14 over 8, **enhancement factor up to 3** for M=2 TeV

Application: tT at large M_{tT}

- **tT at large invariant masses** dominated by **gg**, **stable fraction for all energies**
- **qQ over gg luminosity** increases with the LHC energy: **tT at large M_{tT}** useful to probe qQ iniated BSM processes that lead to the **same tT final state**

$$R^X_{E_1/E_2} \sim \frac{\sigma_X^{SM}(E_1)}{\sigma_X^{SM}(E_2)} \times \left\{ 1 + \frac{\sigma_X^{BSM}(E_1)}{\sigma_X^{SM}(E_1)} \Delta_{E_1/E_2}\left[\frac{\sigma_X^{BSM}}{\sigma_X^{SM}}\right]\right\}$$

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

- For **BSM contributions initiated by qQ processes** (Z', squarks, ...), one gets **improved sensitivity to deviations wrt the SM prediction** as compared to **naive σ^{BSM}/σ^{SM} ratio** in absolute cross sections
- Theory systematics now at the 5% level, should decrease (better PDFs + NNLO) down to the **1-2% level**
- **Explore BSM sensitivity** in particular scenarios (supersymmetry)
- Many other applications of this idea for **other processes** should be relevant and experimentally feasible

Summary and outlook

- **Precision measurements of single and double cross section ratios** of hard processes at **different LHC energies** are new interesting observables
- **Theoretical systematics** can be as small as **0.1%** for W and Z production, **below the 1%** for inclusive tT, and **few %** for TeV scale tT and jet observables
- Residual theoretical uncertainties dominated often by PDF systematics: ratios ratios can **constrain/discriminate PDF sets**
- Ratios can also be used to **accurately correlate the luminosity** between **different beam energies** and **between different experiments**
- Ratios enhance the **sensitivity to certain BSM contributions**, thanks to the **different evolution of SM and BSM signals** with the beam energy

EXTRA MATERIAL

Cross section Ratios - 14 over 8 TeV

Ratio	$r^{\mathrm{th,nnpdf}}$	$\delta_{\mathrm{PDF}}(\%)$	$r^{\mathrm{th,mstw}}$	$\delta_{\mathrm{PDF}}(\%)$	$\Delta^{mstw}(\%)$	$r^{\mathrm{th,abkm}}$	$\delta_{\mathrm{ABKM}}(\%)$	Δ^{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
$t\bar{t}(M_{tt} \geq 1\mathrm{TeV})$	8.215	2.09	7.985	2.02	3.12	8.970	3.58	-8.83
$t\bar{t}(M_{tt} \geq 2\mathrm{TeV})$	24.776	6.07	23.328	4.32	6.05	23.328	4.93	6.05
$\sigma\mathrm{jet}(p_T \geq 1\mathrm{TeV})$	15.235	1.72	15.193	1.62	-1.33	14.823	1.84	1.13
$\sigma\mathrm{jet}(p_T \geq 2\mathrm{TeV})$	181.193	6.75	191.208	3.34	-6.52	174.672	4.94	2.69

- tT ratios (inclusive and invariant mass distributions) potentially useful to distinguish between PDF sets: NNPDF/MSTW vs ABKM
- Inclusive jets with pT > 1 TeV instead very close for all PDFs, small overall PDF errors
- **W and Z ratios** also robust agains chaging the PDF set