Higgs studies at the LHC: what's the ultimate precision?

GGI Institute on

"Understanding the TeV scale through LHC data,

DM and other experiments"

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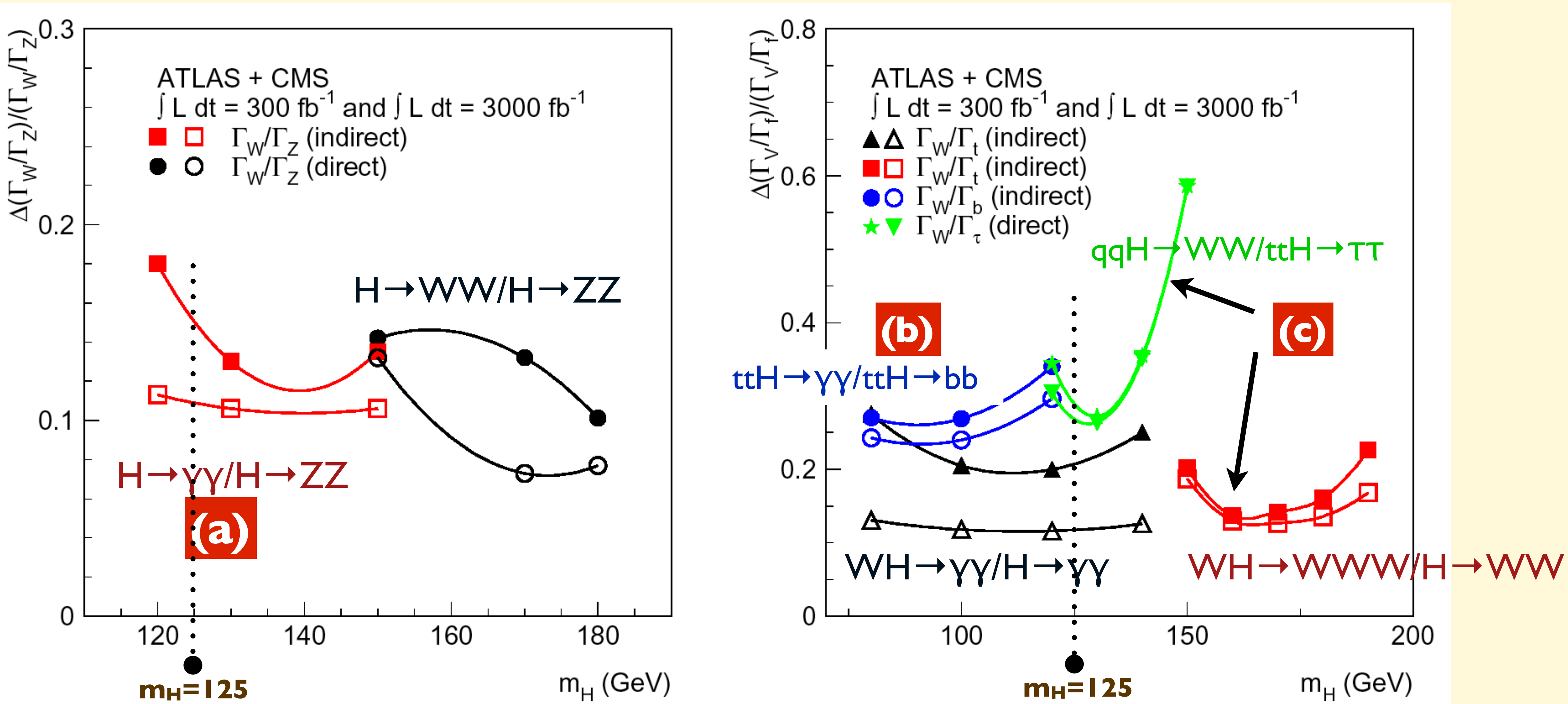
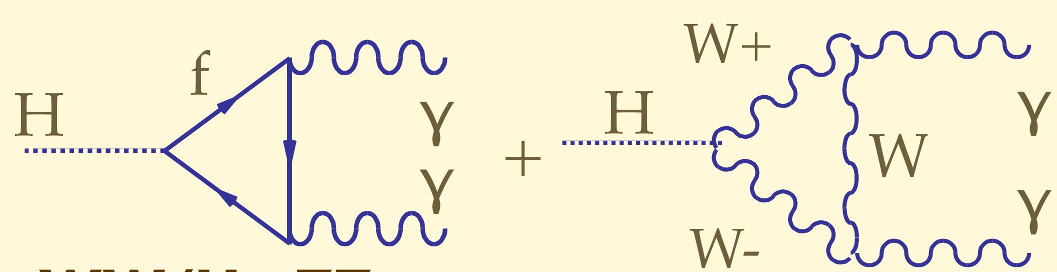
From the 2002 SLHC study *(Gianotti, Mangano, Virdee et al, EPJC, hep-ph/0204087)*



(a) Indirect. Extracts HWW from H→γγ:



No estimate of precision for direct H→WW/H→ZZ

(b) Need to reassess tt+H→bb

(c) Assumed to be TH-systematics limited (in particular, no improvement at SLHC). Review $syst_{TH}$, also in view of forthcoming LHC data

More recent assessments

M.Peskin, http://arxiv.org/abs/1207.2516v1

Using Duhrssen, ATLAS report ATL-PHYS-2003-030

Observable	Expected Error (experiment $\oplus$ theory)
LHC at 14 TeV with 300 fb^{-1}	
$\sigma(gg) \cdot BR(\gamma\gamma)$	$0.20 \oplus 0.15$
$\sigma(WW) \cdot BR(\gamma\gamma)$	$0.55 \oplus 0.10$
$\sigma(gg) \cdot BR(ZZ)$	$0.21 \oplus 0.15$
$\sigma(WW) \cdot BR(WW)$	$0.27 \oplus 0.10$
$\sigma(WW) \cdot BR(\tau^+\tau^-)$	$0.22 \oplus 0.10$
$BR(\tau^+\tau^-)/BR(ZZ)$	0.38
$BR(\gamma\gamma)/BR(ZZ)$	0.21
$BR(\gamma\gamma)/BR(WW)$	0.21
$\sigma(Wh) \cdot BR(b\bar{b})$	$0.25 \oplus 0.20$
$\sigma(Wh) \cdot BR(\gamma\gamma)$	$0.24 \oplus 0.10$
$\sigma(Zh) \cdot BR(b\bar{b})$	$0.25 \oplus 0.20$
$\sigma(Zh) \cdot BR(\gamma\gamma)$	$0.24 \oplus 0.10$
$\sigma(t\bar{t}h) \cdot BR(b\bar{b})$	$0.25 \oplus 0.30$
$\sigma(t\bar{t}h) \cdot BR(\gamma\gamma)$	$0.27 \oplus 0.20$
$\sigma(WW) \cdot BR(\text{invisible})$	$0.2 \oplus 0.24$

Table 1: Input data for the fits to Higgs couplings from LHC measurements.

with d(A) defined by

$$\frac{g(hAA)}{g(hAA)|_{SM}} = 1 + d(A)$$

Program	1σ Confidence interval for $d(X)$
LHC at 14 TeV with 300 fb^{-1}	
$h \to WW$	(-0.075 , 0.000)
$h \to ZZ$	(-0.087 , 0.000)
$h \to b\bar{b}$	(-0.221 , 0.067)
$h \to gg$	(-0.129 , 0.137)
$h \to \gamma\gamma$	(-0.098 , 0.052)
$h \to \tau^+\tau^-$	(-0.120 , 0.151)
$h \to c\bar{c}$	—
$h \to t\bar{t}$	(-0.164 , 0.139)
$h \to$ invisible	(-0.000 , 0.232)

ILC at 250 GeV with 250 fb^{-1}	
$h \to WW$	(-0.051 , 0.000)
$h \to ZZ$	(-0.009 , 0.000)
$h \to b\bar{b}$	(-0.048 , 0.026)
$h \to gg$	(-0.076 , 0.037)
$h \to \gamma\gamma$	(-0.059 , 0.044)
$h \to \tau^+\tau^-$	(-0.056 , 0.033)
$h \to c\bar{c}$	(-0.064 , 0.038)
$h \to t\bar{t}$	(-0.178 , 0.096)
$h \to$ invisible	(-0.000 , 0.058)

ILC at 500 GeV with 500 fb^{-1}	
$h \to WW$	(-0.006 , 0.000)
$h \to ZZ$	(-0.007 , 0.000)
$h \to b\bar{b}$	(-0.002 , 0.020)
$h \to gg$	(-0.025 , 0.025)
$h \to \gamma\gamma$	(-0.040 , 0.049)
$h \to \tau^+\tau^-$	(-0.015 , 0.026)
$h \to c\bar{c}$	(-0.013 , 0.028)
$h \to t\bar{t}$	(-0.096 , 0.066)
$h \to$ invisible	(-0.000 , 0.047)

More recent assessments

ATLAS submission to Strategy Group,
https://indico.cern.ch/contributionDisplay.py?contribId=174&confId=175067

	with theory systematics	without theory systematics
$H \to \mu\mu$	0.525	0.505
$ttH, H \to \mu\mu$	0.733	0.719
$VBF, H \to \tau\tau$	0.227	0.189
$VBF, H \to \tau\tau$ (extrap)	0.146	0.114
$H \to ZZ$	0.156	0.093
$VBF, H \to WW$	0.668	0.662
$H \to WW$	0.289	0.259
$VH, H \to \gamma\gamma$	0.769	0.768
$ttH, H \to \gamma\gamma$	0.551	0.537
$VBF, H \to \gamma\gamma$	0.336	0.309
$H \to \gamma\gamma(+j)$	0.160	0.120
$H \to \gamma\gamma$	0.145	0.081

Uncertainties on the signal strength, **300 fb^{-1}**

	with theory systematics	without theory systematics
$H \to \mu\mu$	0.207	0.164
$ttH, H \to \mu\mu$	0.260	0.230
$VBF, H \to \tau\tau$	0.202	0.160
$H \to ZZ$	0.134	0.047
$VBF, H \to WW$	0.581	0.574
$H \to WW$	0.289	0.259
$VH, H \to \gamma\gamma$	0.253	0.251
$ttH, H \to \gamma\gamma$	0.206	0.174
$VBF, H \to \gamma\gamma$	0.160	0.105
$H \to \gamma\gamma(+j)$	0.119	0.054
$H \to \gamma\gamma$	0.126	0.040

Uncertainties on the signal strength, **3000 fb^{-1}**

	with theory systematics	without theory systematics
Γ_Z/Γ_g	0.523	0.479
Γ_t/Γ_g	0.519	0.485
Γ_τ/Γ_μ	0.669	0.659
Γ_τ/Γ_μ (extrap)	0.591	0.576
Γ_μ/Γ_Z	0.448	0.448
Γ_τ/Γ_Z	0.417	0.404
Γ_τ/Γ_Z (extrap)	0.283	0.255
Γ_W/Γ_Z	0.254	0.254
Γ_γ/Γ_Z	0.110	0.110
$\Gamma_g \bullet \Gamma_Z/\Gamma_H$	0.156	0.093

Relative uncertainties, **300 fb^{-1}**

	with theory systematics	without theory systematics
Γ_Z/Γ_g	0.284	0.220
Γ_t/Γ_g	0.230	0.153
Γ_τ/Γ_μ	0.251	0.230
Γ_μ/Γ_Z	0.142	0.142
Γ_τ/Γ_Z	0.206	0.181
Γ_W/Γ_Z	0.225	0.225
Γ_γ/Γ_Z	0.029	0.029
$\Gamma_g \bullet \Gamma_Z/\Gamma_H$	0.132	0.047

Relative uncertainties, **3000 fb^{-1}**

	300 fb^{-1}	3000 fb^{-1}
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)

In ( ):
with TH syst

Also **HH→bbγγ:** 260 events/3000fb^{-1} , 3σ evidence/expt
Expect 30% uncertainty on λ_{HHH}, adding also other decay channels, and combining ATLAS+CMS

More recent assessments

CMS submission to Strategy Group,
https://indico.cern.ch/contributionDisplay.py?contribId=177&confId=175067

Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Plus Hμμ coupling to better than 5% at 3000fb^{-1}

Scenario 1: same systematics as 2012 (TH and EXP)
Scenario 2: half the TH syst, and scale with 1/sqrt(L) the EXP syst

Note: assume no invisible Higgs decay contributing to the Higgs width

Note: results of scenario 1 @ 300/fb are ~ consistent with Peskin's estimates

Note: results of scenario 2 @ 3000/fb are almost as powerful as ILC@500GeV !!

TGC's precision: any significant probe of Higgs anomalous couplings?

coupling	LHC	HL-LHC	HE-LHC
g_1^Z	0.0030	0.0019	0.0013
λ_γ	0.0009	0.0004	0.0004
λ_Z	0.0023	0.0014	0.0014
κ_γ	0.026	0.016	0.019
κ_Z	0.037	0.031	0.022

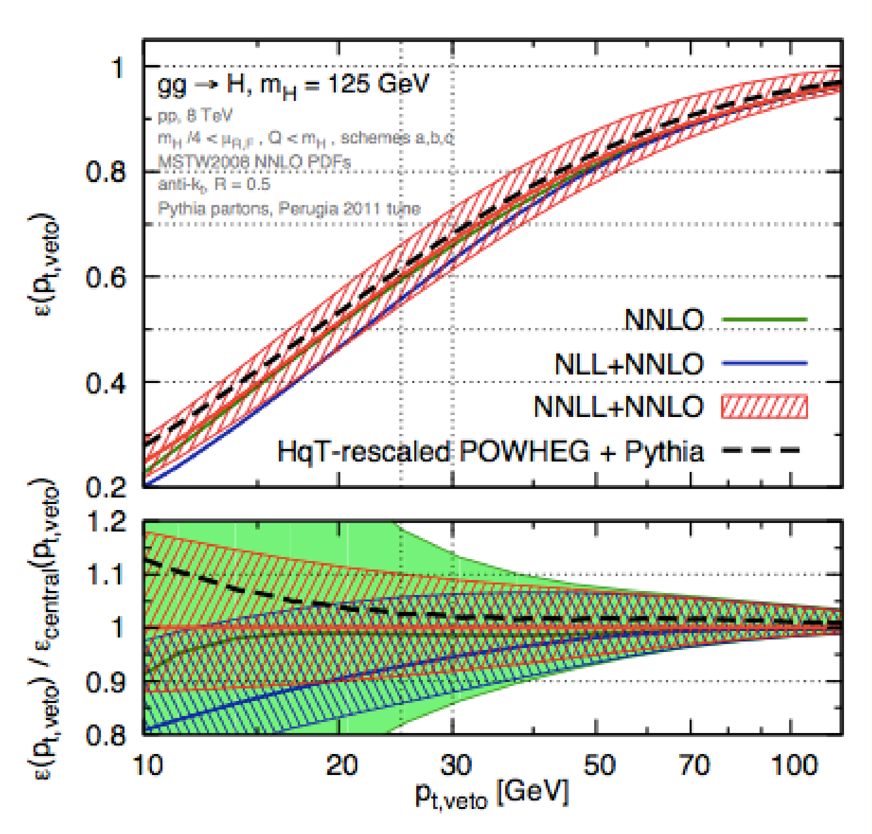
H coupling ~ N(events) / [Lum x σ_{TH}(coupling=1) x efficiency (selection cuts)]

Theoretical uncertainties on production rates

14 TeV	δ(pert. theory)	δ(PDF, α_S)
gg→H	± 10 %	± 7%
VBF (WW→H)	± 1 %	± 2%
qq→WH	± 0.5 %	± 4%
(qq,gg)→ZH	± 2 %	± 4%
(qq,gg)→ttH	± 8 %	± 9%

Theoretical uncertainties on modeling of selection cuts.

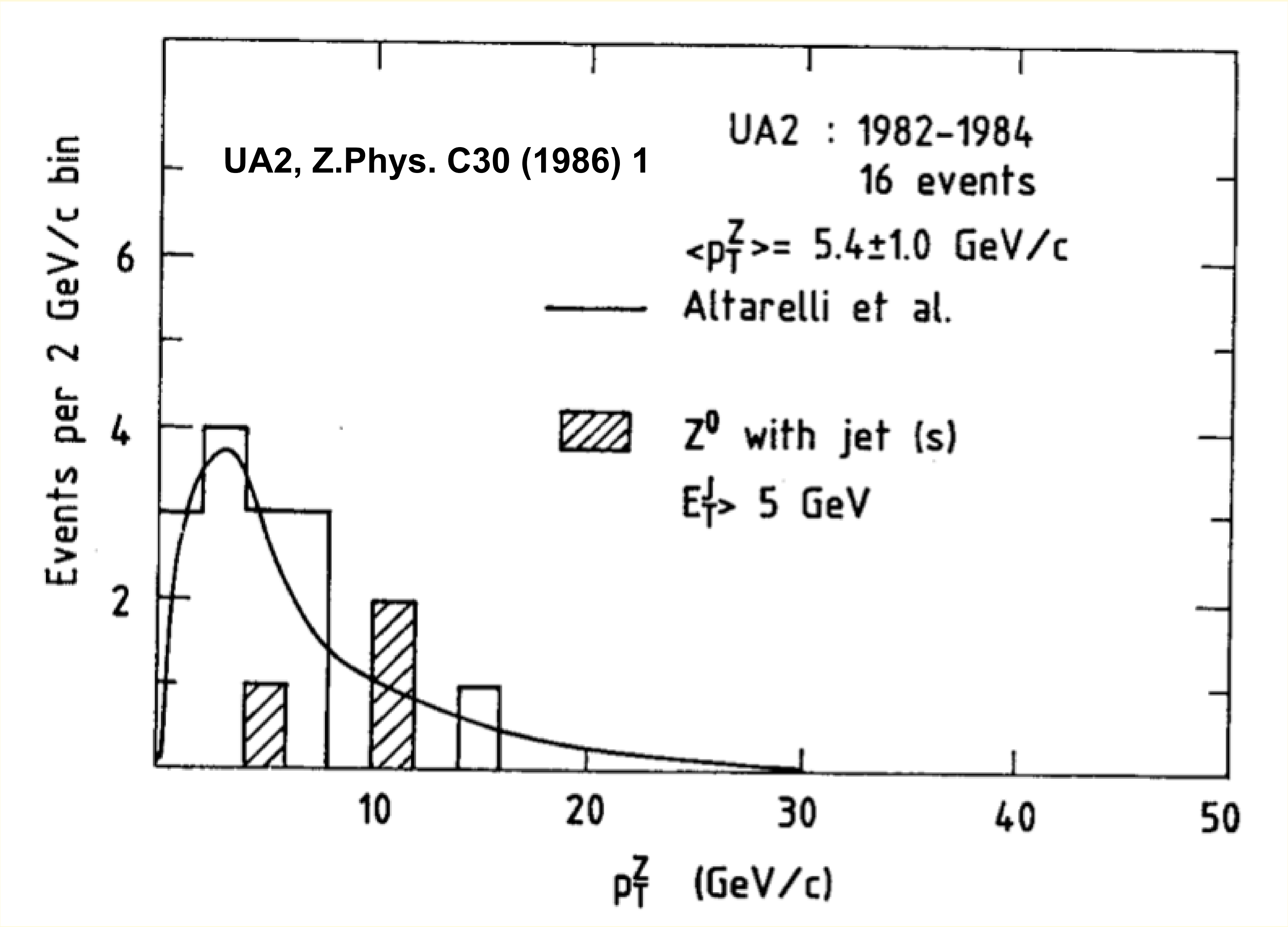
Ex. jet veto efficiency, required to reduce bg's to H→WW*



Banfi, Monni, Salam, Zanderighi, arXiv:1206.4998

Why is it reasonable to expect progress?

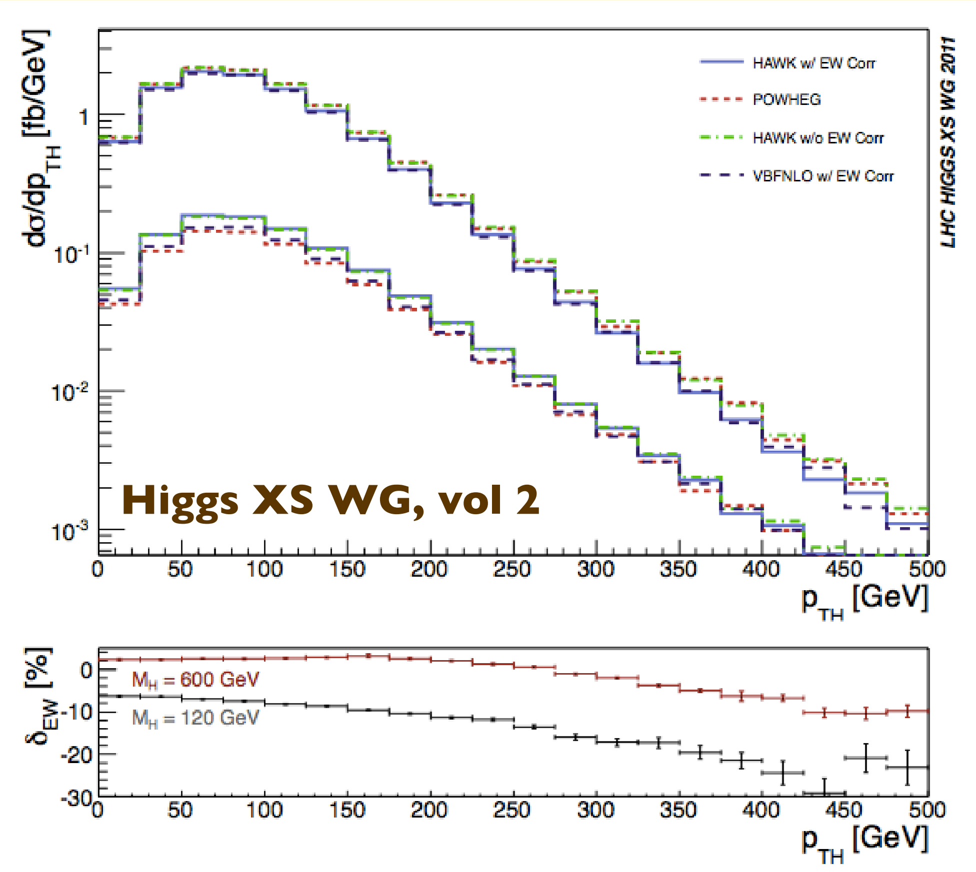
To put it in perspective, W/Z physics started like this ....., from a score of events:



Looking forward to the first measurement of $p_T(gg \to H \to ZZ^*)$ with the 15-20 events that you will have by the end of 2012!

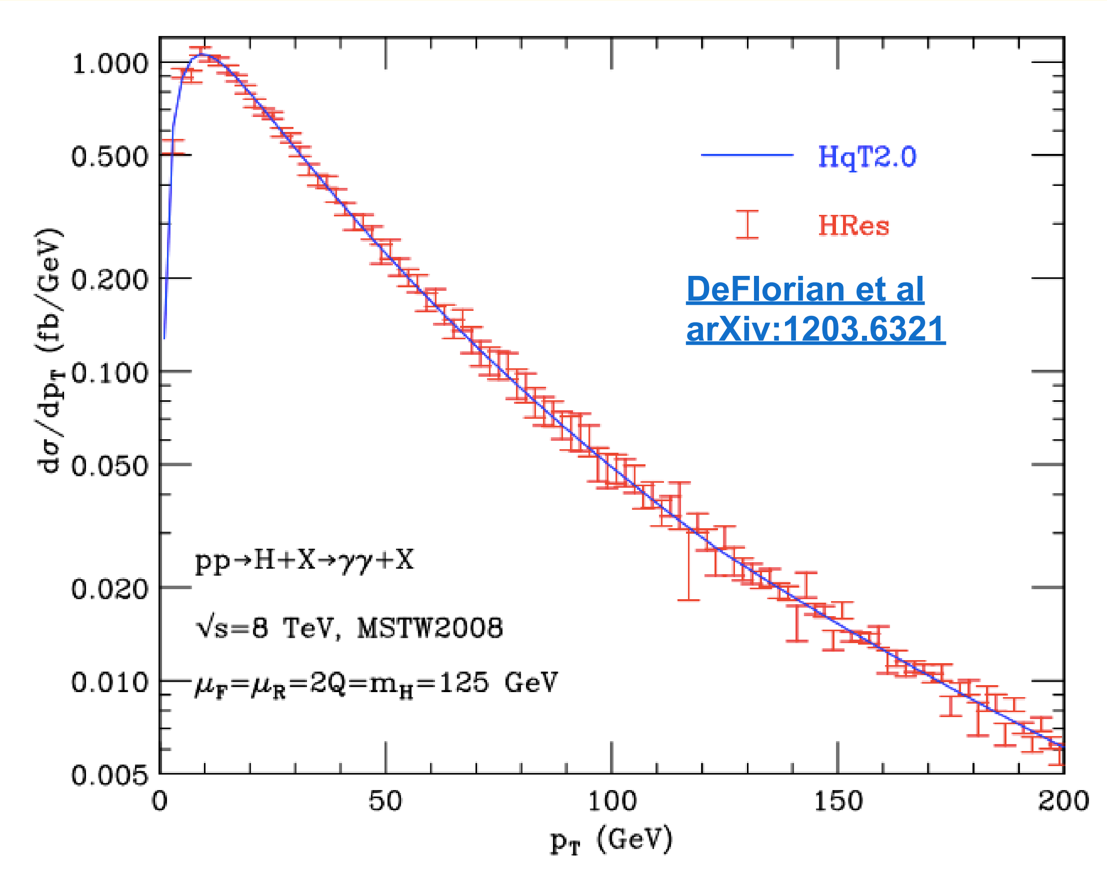
Much will be learned to improve our QCD modeling of Higgs production, form the thousands of ($gg \to H \to ZZ^*$) events that will become available in the future

p_T(H) in qq → qq H



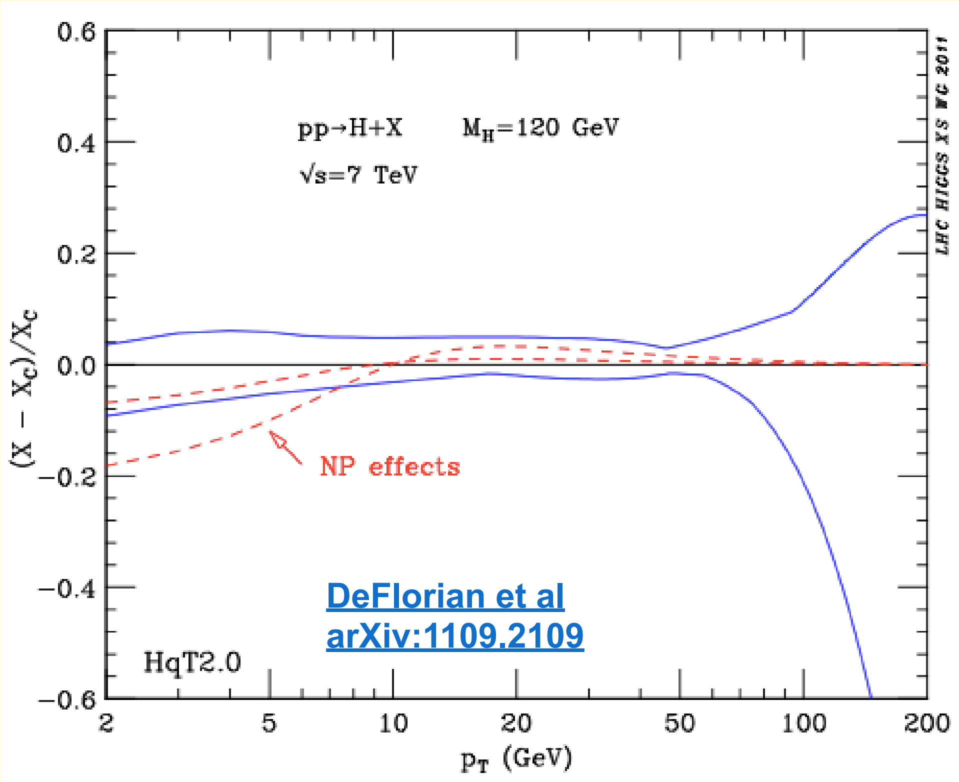
p_T(peak)~60 GeV

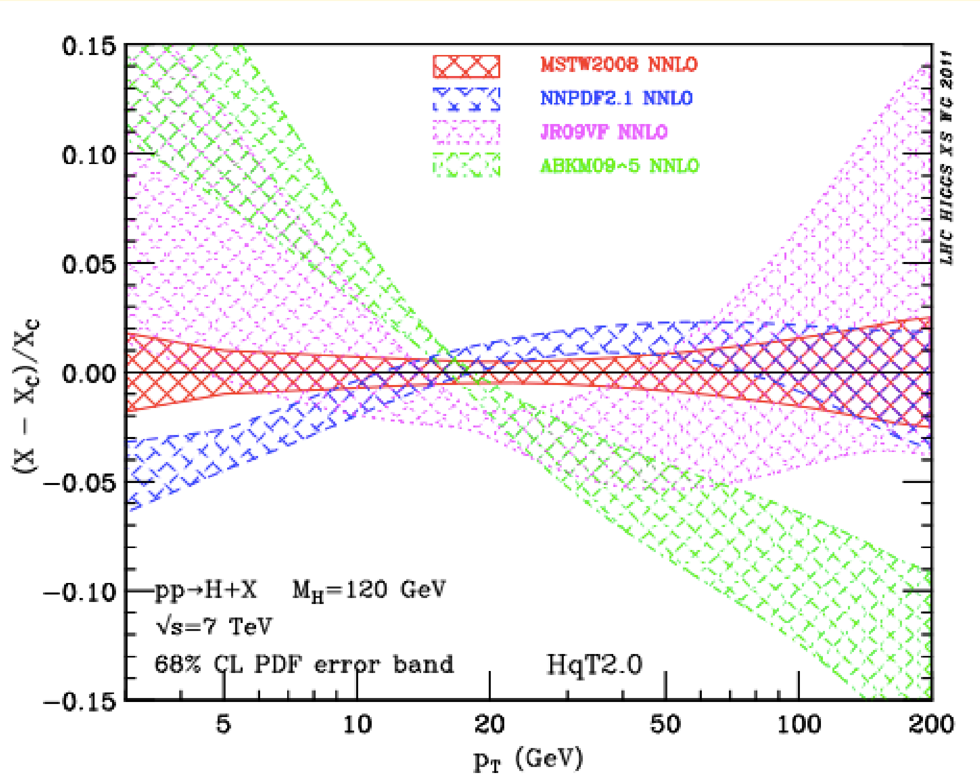
p_T(H) in gg → H



p_T(peak)~10 GeV

TH systematics for p_T(H) in gg → H





Studies of jet activity in final states with dijets at large Δy

ATLAS, JHEP 1109 (2011) 053

indirect validation of jet-veto suppression efficiency for bgs

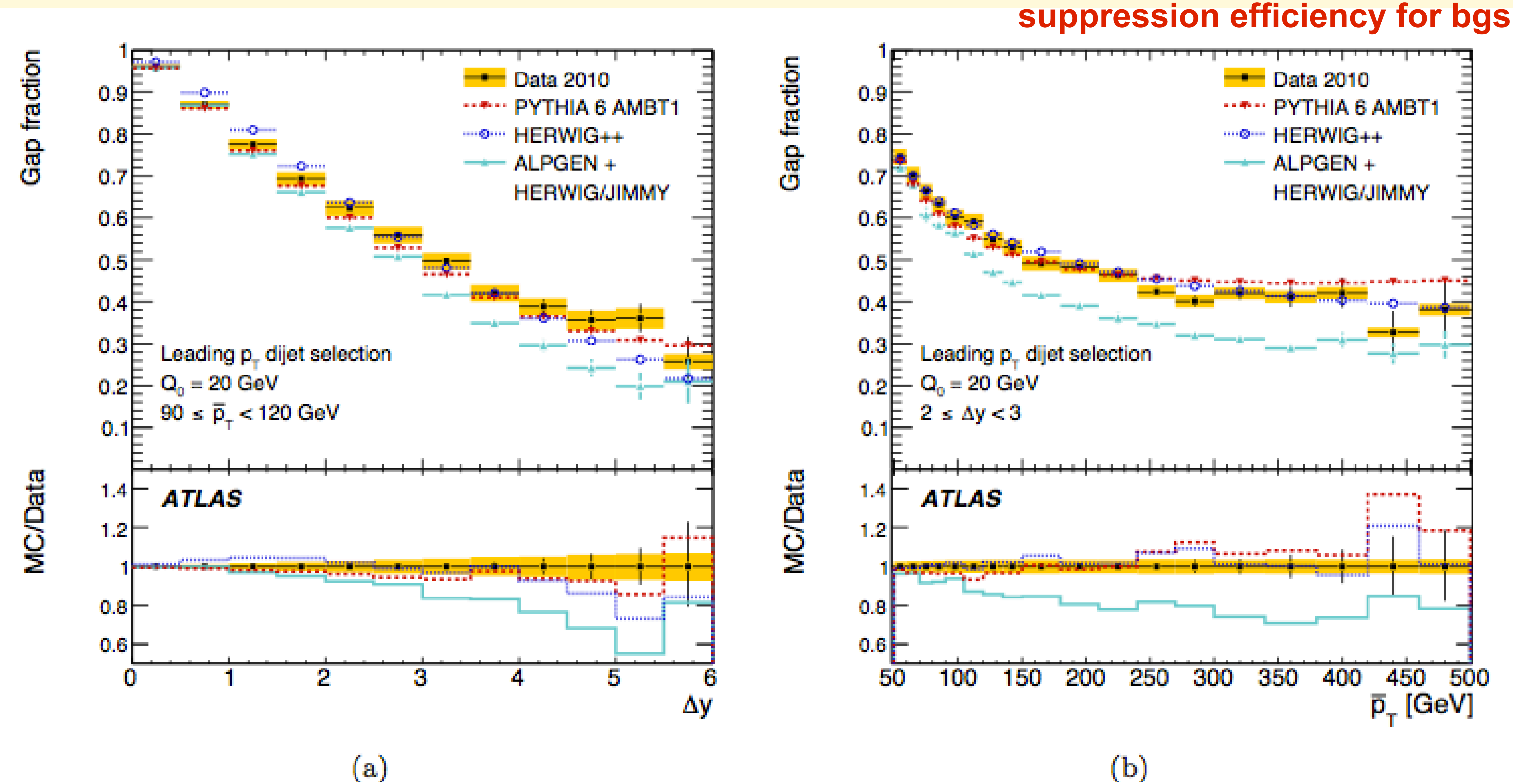
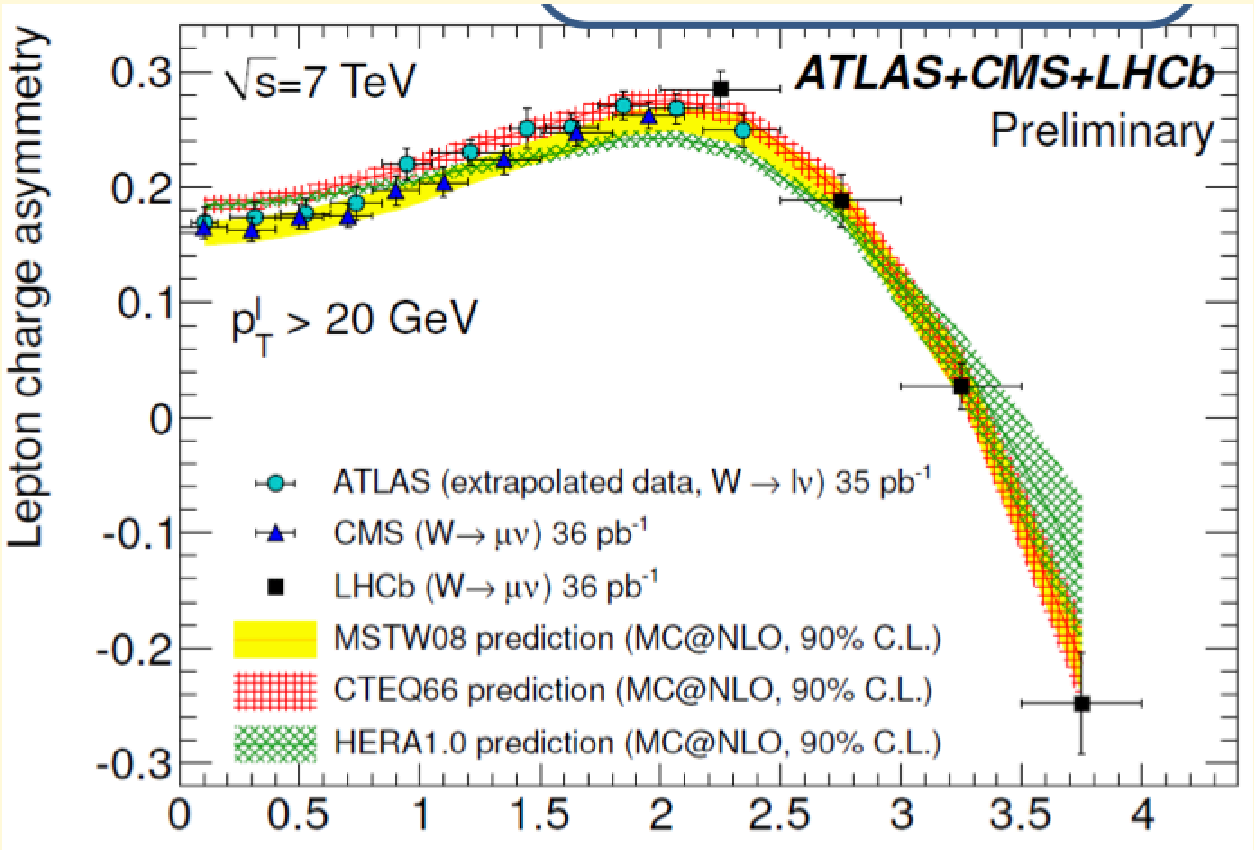
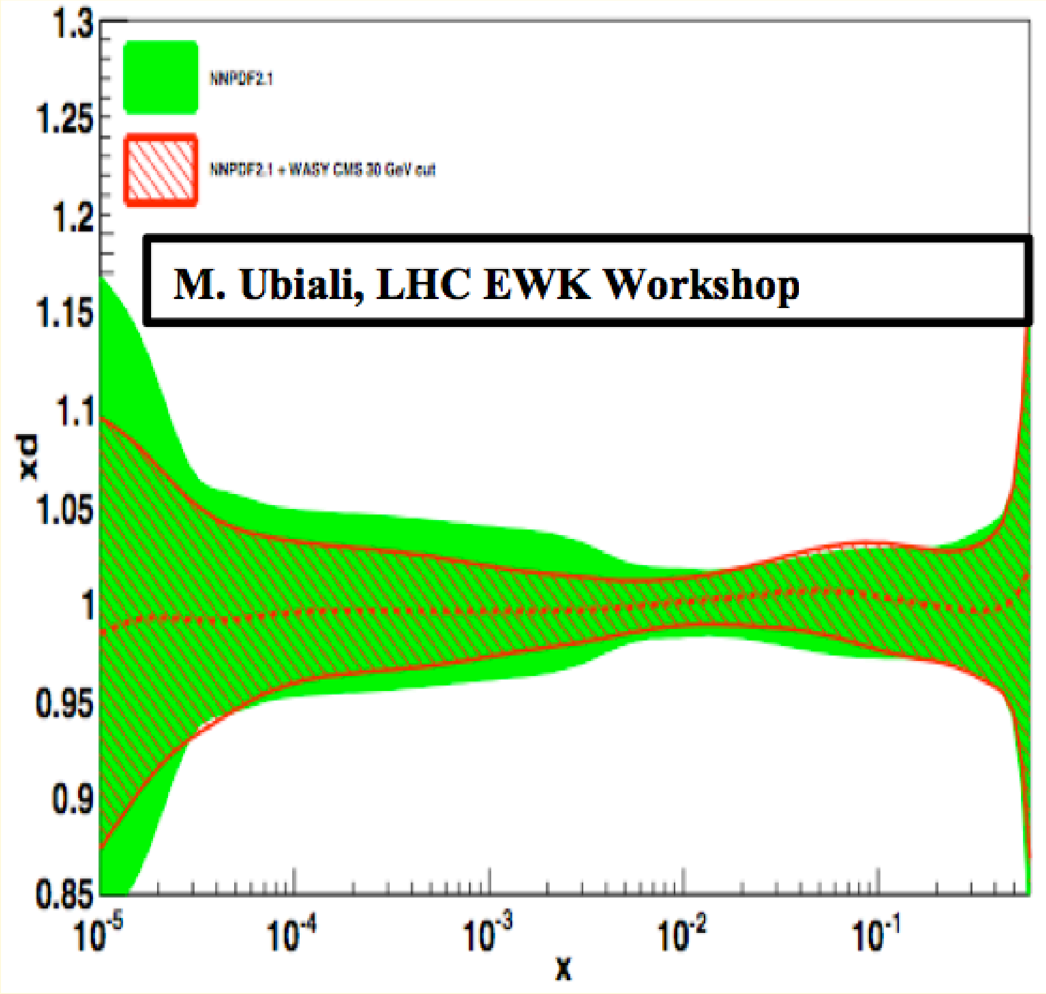


Figure 2. Gap fraction as a function of Δy, given that the dijet system is defined as the leading-p_T jets in the event and satisfies $90 \leq \bar{p}_T < 120$ GeV (a). Gap fraction as a function of $\bar{p}_T$ given that the rapidity interval is $2 \leq \Delta y < 3$ (b). The (corrected) data are the black points, with error bars representing the statistical uncertainty. The total systematic uncertainty on the measurement is represented by the solid (yellow) band. The dashed (red) points represents the PYTHIA prediction (tune AMBT1), the dot-dashed (blue) points represents the HERWIG++ prediction (tune LHC-UE7-1) and the solid (cyan) points represents the ALPGEN prediction (tune AUET1).

Use LHC data to improve knowledge of PDFs





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}, α_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

8 TeV / 7 TeV: NNPDF results

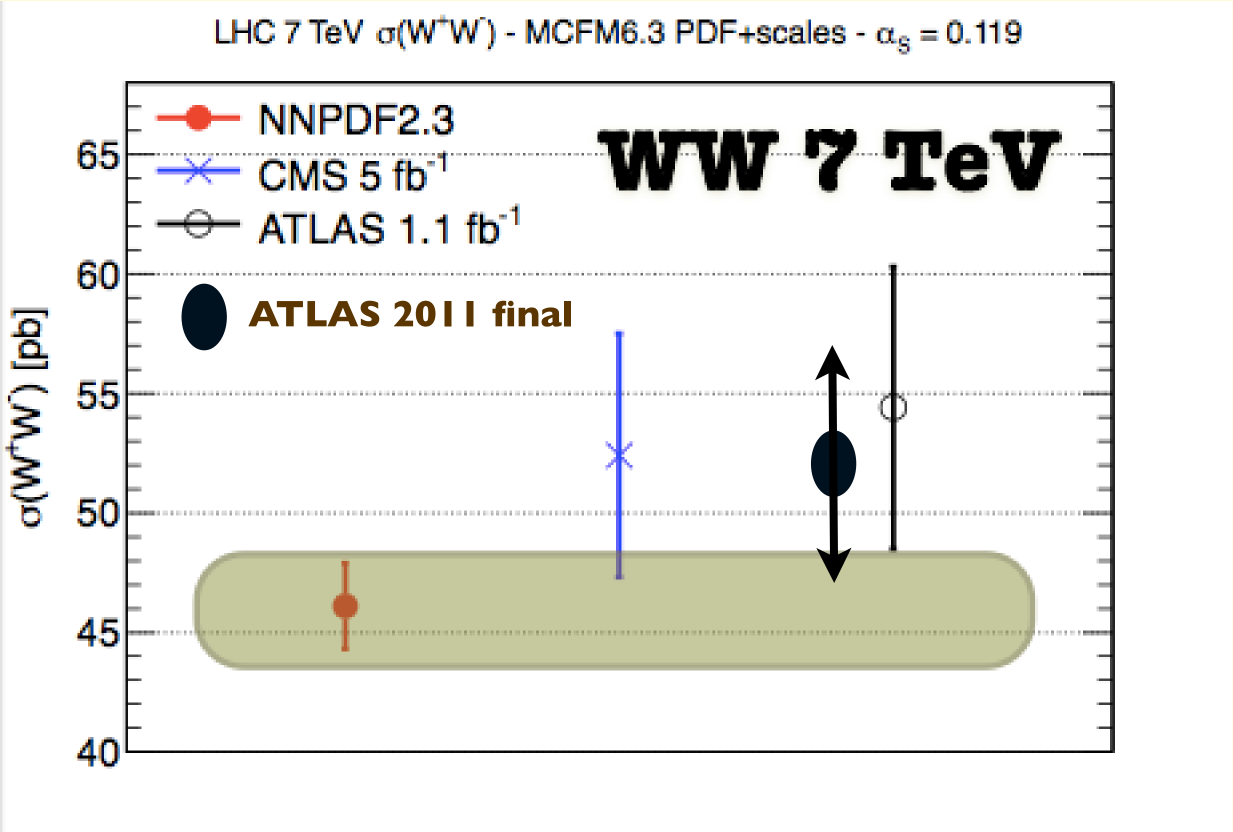
CrossSection	$r^{\text{th,nnpdf}}$	$\delta_{\text{PDF}}(\%)$	δ_{α_s} (%)	δ_{scales} (%)
$t\bar{t}/Z$	1.231	0.28	−0.23 − 0.24	0.17 − 0.33
$t\bar{t}$	1.432	0.25	−0.15 − 0.20	0.14 − 0.33
Z	1.163	0.08	−0.04 − 0.08	0.05 − 0.09
W^+	1.148	0.08	−0.01 − 0.06	0.06 − 0.08
W^-	1.167	0.09	−0.03 − 0.06	0.06 − 0.07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

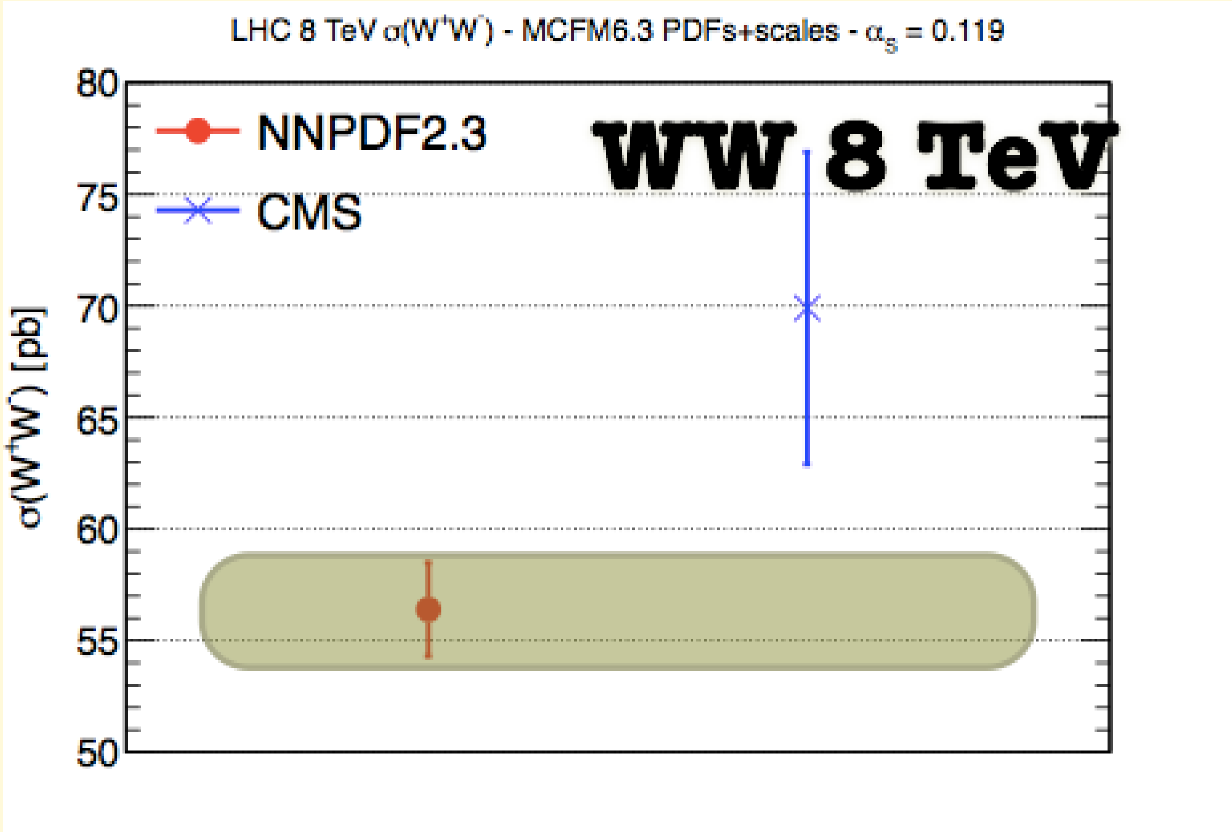
- $\delta < 10^{-3}$ in $W^\pm$ ratios: absolute calibration of 7 vs 8 TeV lumi
- $\delta < 10^{-2}$ in $\sigma(tt)$ ratios
- $\delta_{\text{scale}} < \delta_{\text{PDF}}$ at large p_T^{jet} and M_{tt}: constraints on PDFs

8 TeV / 7 TeV: NNPDF vs MSTW vs ABKM

Ratio	$r^{\text{th,nnpdf}}$	$\delta_{\text{PDF}}(\%)$	$r^{\text{th,mstw}}$	$\delta_{\text{PDF}}(\%)$	$\Delta^{mstw}(\%)$	$r^{\text{th,abkm}}$	$\delta_{\text{ABKM}}(\%)$	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
$t\bar{t}(M_{tt} \geq 1\text{TeV})$	1.807	0.73	1.791	0.66	0.95	1.855	1.02	-2.61
$t\bar{t}(M_{tt} \geq 2\text{TeV})$	2.734	3.60	2.645	2.84	3.61	2.645	4.04	3.61
$\sigma\text{jet}(p_T \geq 1\text{TeV})$	2.283	1.02	2.290	1.99	0.13	2.268	2.03	1.08
$\sigma\text{jet}(p_T \geq 2\text{TeV})$	7.386	4.70	7.915	4.29	-7.59	7.695	4.92	-4.59

- Several examples of 2-2.5σ discrepancies between predictions of different PDF sets





Diboson cross section ratios

8 over 7 TeV	$R^{\rm th,nnpdf}$	$\delta_{\rm PDF}$(%)	$\delta_{\rm scales}$ (%)	
WW	1.223	$\pm$ 0.1	-0.4 – 0.2	
$gg \to WW$	1.330	$\pm$ 0.2	-0.0 – 0.0	(scale errors missing)
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	(scale errors missing)
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	

Xsection ratios as probes of BSM contributions

Assume the final state **X** receives both SM and BSM contributions:

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

Define the ratio:

$$R^X_{7/8} = \frac{\sigma^{exp}(pp \to X; 7\ \mathrm{TeV})}{\sigma^{exp}(pp \to X; 8\ \mathrm{TeV})} = \frac{\sigma^{exp}_X(7)}{\sigma^{exp}_X(8)}$$

We easily get:

$$R^X_{7/8} \sim \frac{\sigma^{SM}_X(7)}{\sigma^{SM}_X(8)} \times \left\{1 + \frac{\sigma^{BSM}_X(7)}{\sigma^{SM}_X(7)}\ \Delta_{7/8}\left[\frac{\sigma^{BSM}_X}{\sigma^{SM}_X}\right]\right\}$$

where:

$$\Delta_{7/8}\left[\frac{\sigma^{BSM}_X}{\sigma^{SM}_X}\right] = 1 - \frac{\sigma^{BSM}_X(8)/\sigma^{SM}_X(8)}{\sigma^{BSM}_X(7)/\sigma^{SM}_X(7)} \sim 1 - \frac{\mathcal{L}^{BSM}_X(8)/\mathcal{L}^{BSM}_X(7)}{\mathcal{L}^{SM}_X(8)/\mathcal{L}^{SM}_X(7)} = \Delta_{7/8}\left[\frac{\mathcal{L}^{BSM}_X}{\mathcal{L}^{SM}_X}\right]$$

Therefore:

relative BSM contamination

$$\frac{\delta R^X_{7/8}}{R^X_{7/8}} = \frac{\delta R^{SM}_{7/8}}{R^{SM}_{7/8}} + \frac{\sigma_X^{BSM}(7)}{\sigma_X^{SM}(7)} \times \Delta_{7/8}\left[\frac{\mathcal{L}_X^{BSM}}{\mathcal{L}_X^{SM}}\right]$$

theory systematics in 7→8 TeV extrapolation

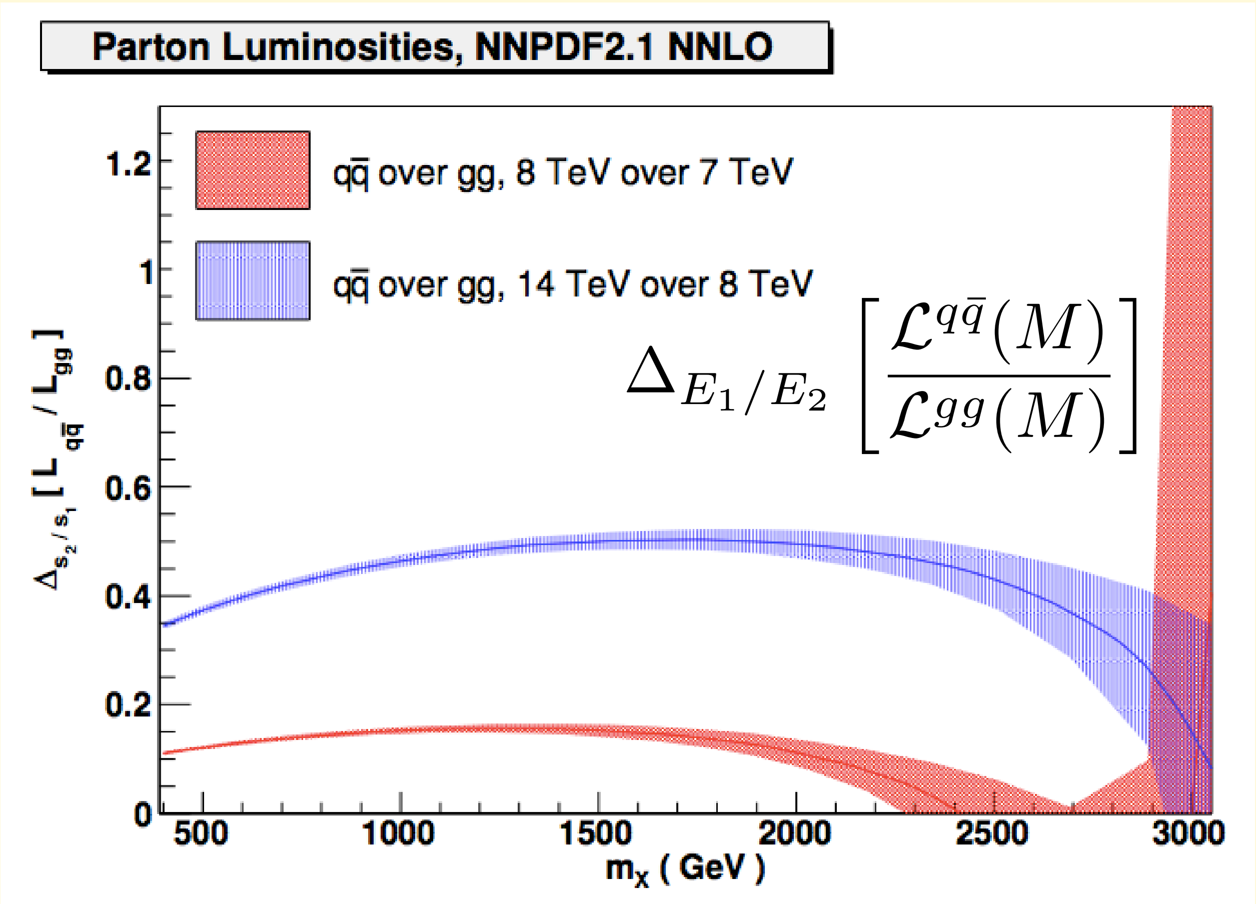
Energy dependence of the relative BSM contamination

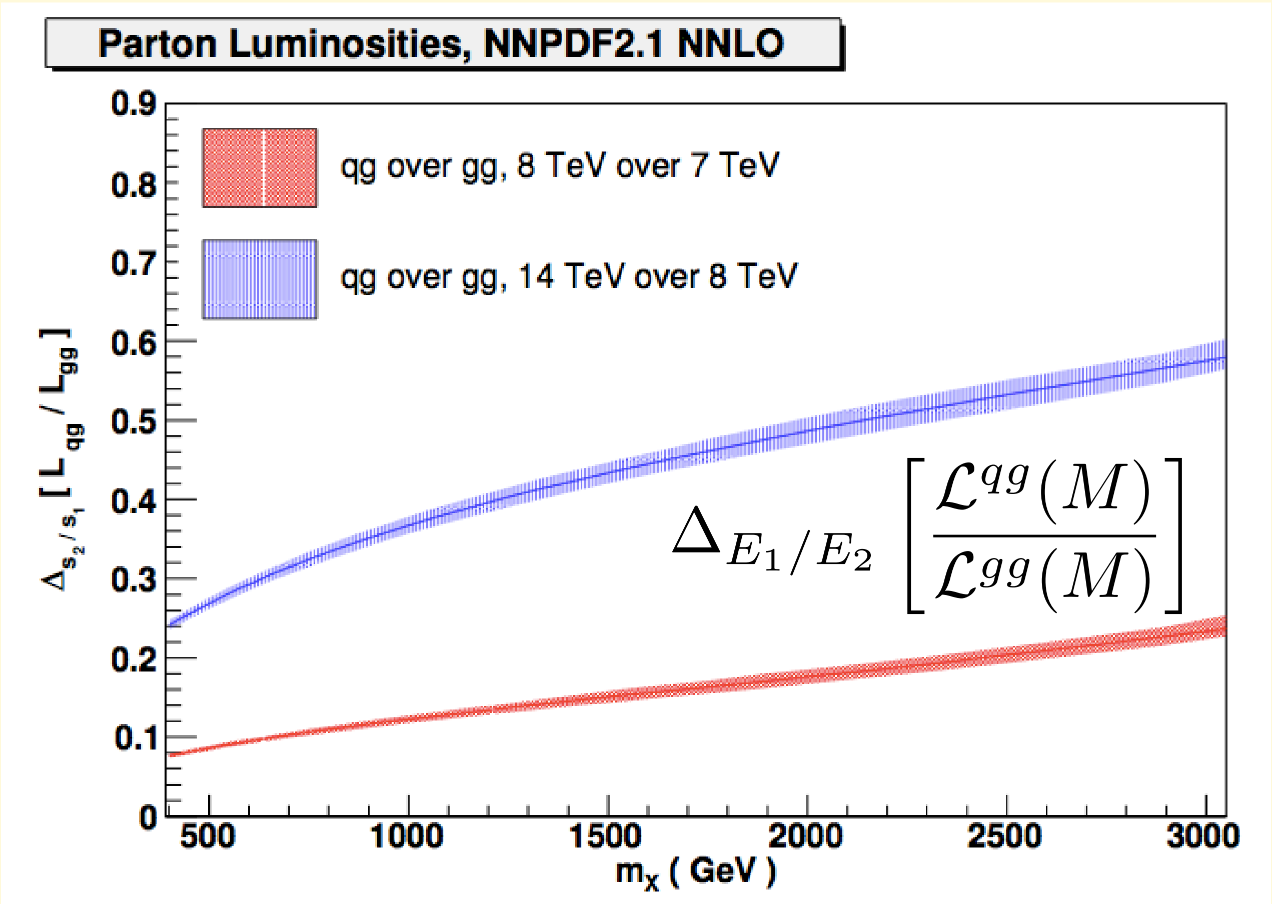
E.g., assuming $\sigma_{SM}(pp\to X)=\sigma(gg\to X)$ and $\sigma_{BSM}(pp\to X)=\sigma(qq\to X)$ (*)

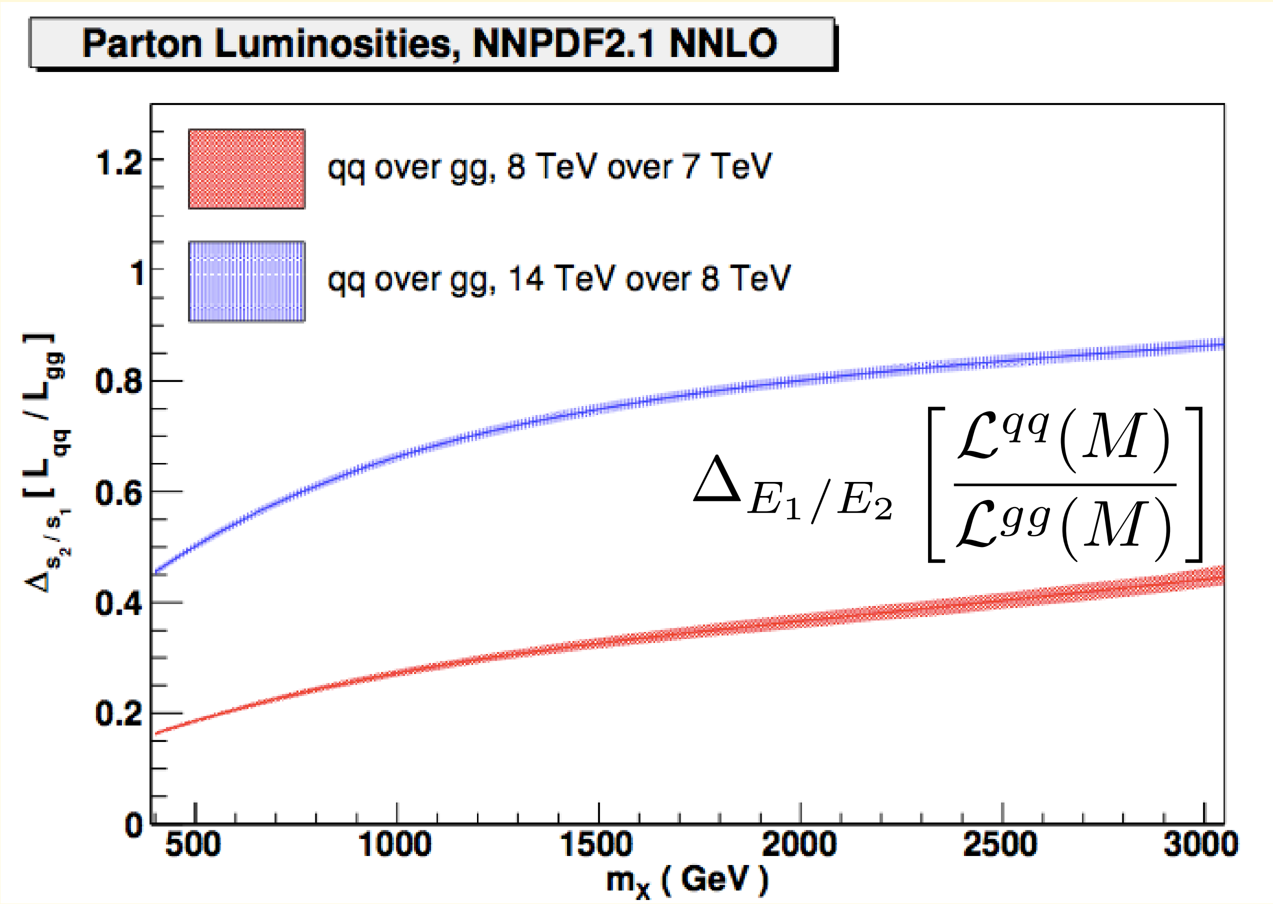
$$\Delta_{7/8}\left[\frac{\mathcal{L}_X^{BSM}}{\mathcal{L}_X^{SM}}\right] = \Delta_{7/8}\left[\frac{\mathcal{L}^{q\bar{q}}(M)}{\mathcal{L}^{gg}(M)}\right]$$

(*) e.g. SM: gg→tt and BSM: qqbar→Z'→tt

Examples of E-dependence of luminosity ratios







Given the sub-% precision of the SM ratio predictions, there is sensitivity to BSM rate contributions at the level of few% **(to be improved with better PDF constraints, especially for 8/14 ratios)**

14 TeV / 8 TeV: NNPDF results

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
$t\bar{t}(M_{tt} \geq 2\mathrm{TeV})$	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

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

14 TeV / 8 TeV: NNPDF vs MSTW vs ABKM

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

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

Worth exploring in more detail the possible implications of precise measurements of energy (double-)ratios

E.g.

(1) **$\sigma_{VBF}(H)$ grows with E differently than $\sigma_{gg}(gg\rightarrow H)$ or $\sigma_{qq}(VH)$: is there something to be learned from**

$$R_H(8)/R_H(14)$$

for $R_H = \sigma(gg\rightarrow H)/\sigma_{qq}(VH)$ or $\sigma(gg\rightarrow H)/\sigma_{VBF}(H)$?

(2) **Study ratios of asymmetries at different energies (lepton charge asym, t vs tbar asymm in single-top production, etc)**

(3) **Study ratios in different rapidity ranges, or with different kinematical cuts, to increase sensitivity to particular x-ranges of PDF, or to particular dynamical regimes**

Things to think through

- Estimates of precision on Higgs couplings are based on fully independent tree-level and loop-induced couplings.
  - What constraints among these, emerging from well motivated BSM scenarios, are worth considering? How does the precision of the measurements improve? (e.g. impact of no-invisible H decays)
- Explore in more detail the correlations between deviations from SM Higgs couplings and direct manifestations of the models causing them.
  - what is "typically" more effective at the LHC: looking for deviations of Higgs couplings or for more direct signatures (VBF scattering, resonances, TGC?)?
  - Define few benchmark scenarios for either situation, to explore in more detail
- Extrapolations to $3000 fb^{-1}$ typically assume tighter, less efficient, cuts, to reduce bg's due to pile-up.
  - How aggressive can one be, assuming important upgrades of detector/trigger technologies? Review in particular prospects for VBF and high mass WW scattering studies
  - Optimize luminosity vs detector performance?

Higgs rates at high energy

	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

$R(E) = \sigma(E\ \text{TeV})/\sigma(14\ \text{TeV})$