SM physics at the LHC: relevance, challenges and prospects

Wine and Cheese Seminar

Fermilab

November 15, 2013

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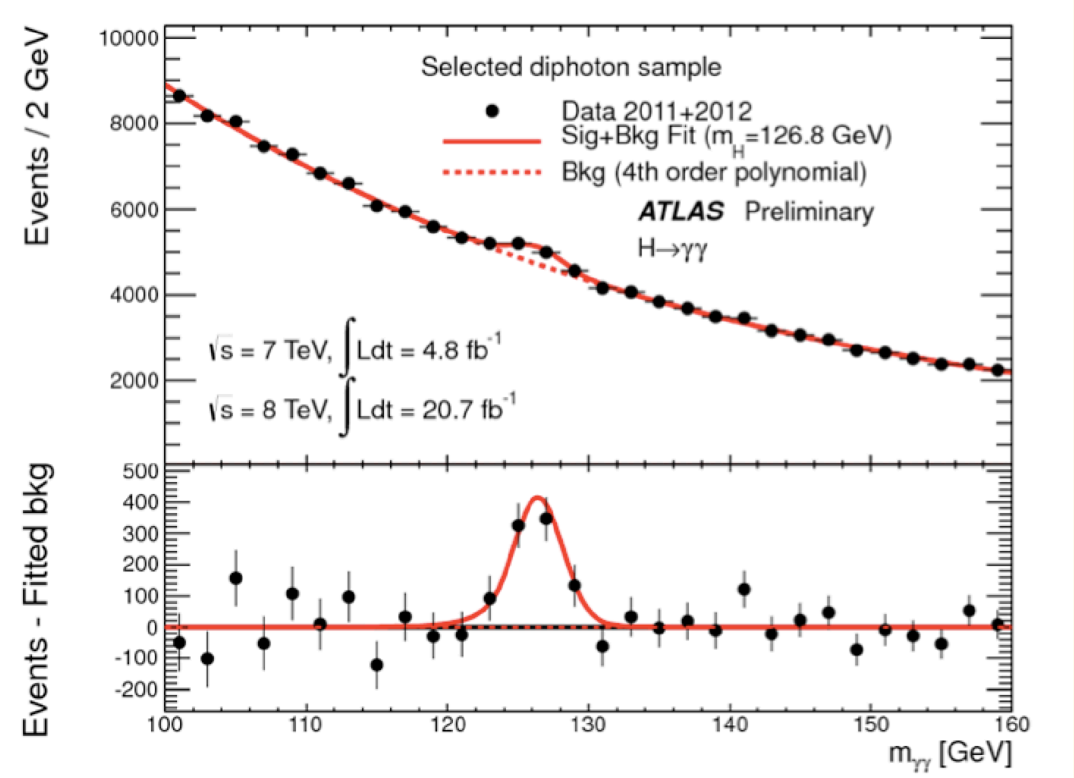
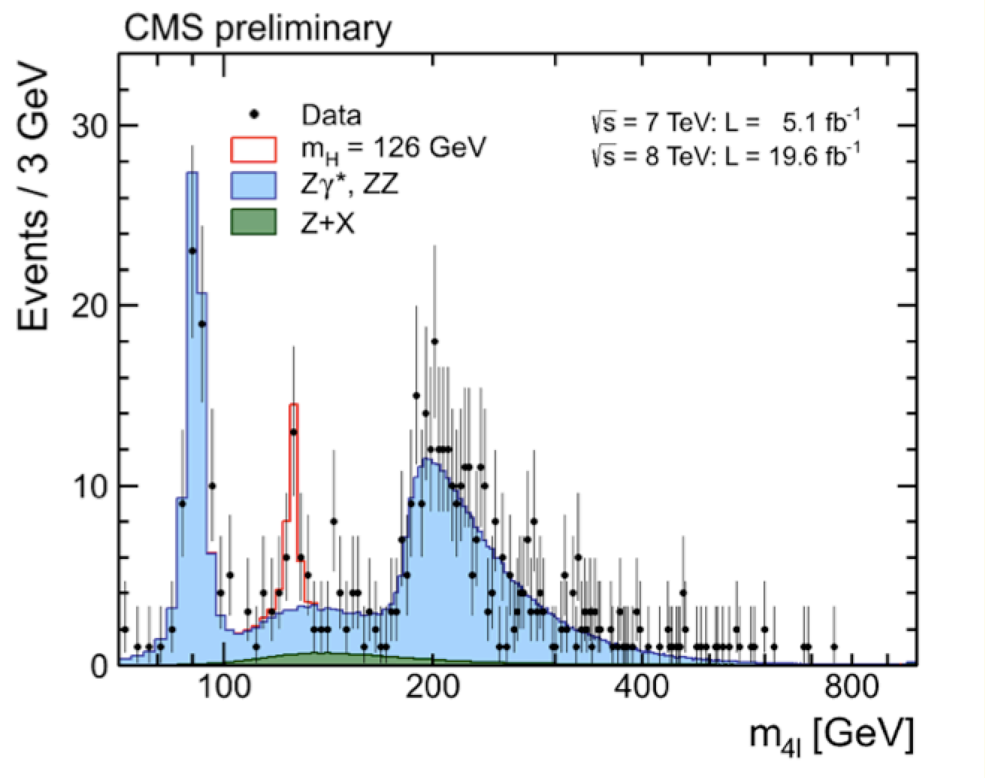
Key outcomes of 3 yrs at the LHC: I

I: The Higgs signal has been detected through sharp mass peaks in several channels

II: Its production and decay rates are consistent with the SM expectation, at the +/– 20% level .....

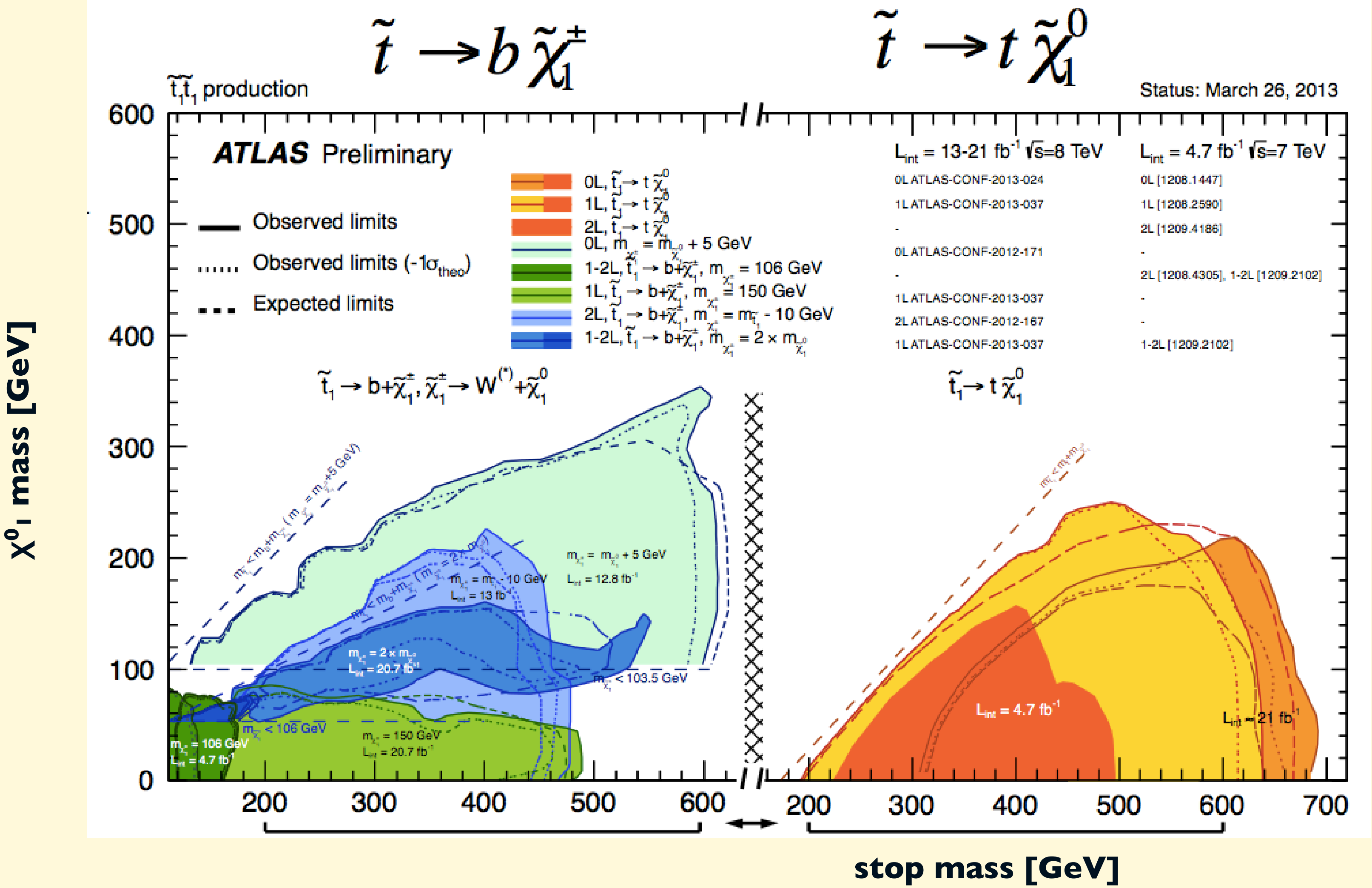




.... how far can we push the accuracy of these tests, and probe the mechanism of EWSB ?

Key outcomes of 3 yrs at the LHC: 2

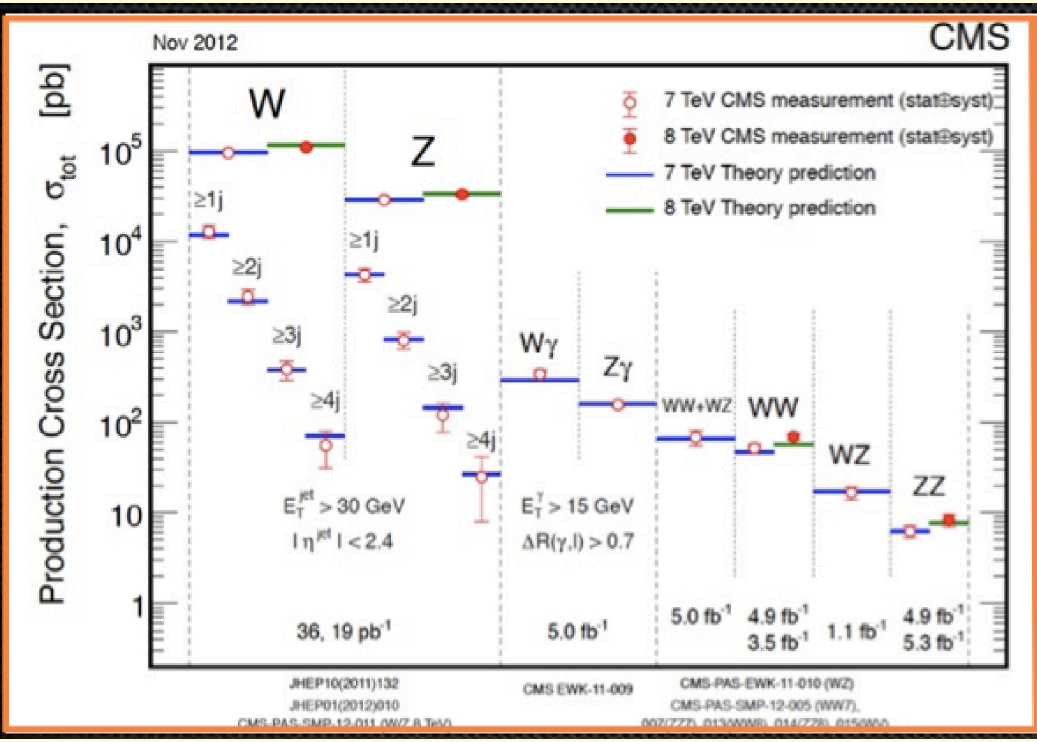
No sign of BSM, in all places the experiments have looked .....

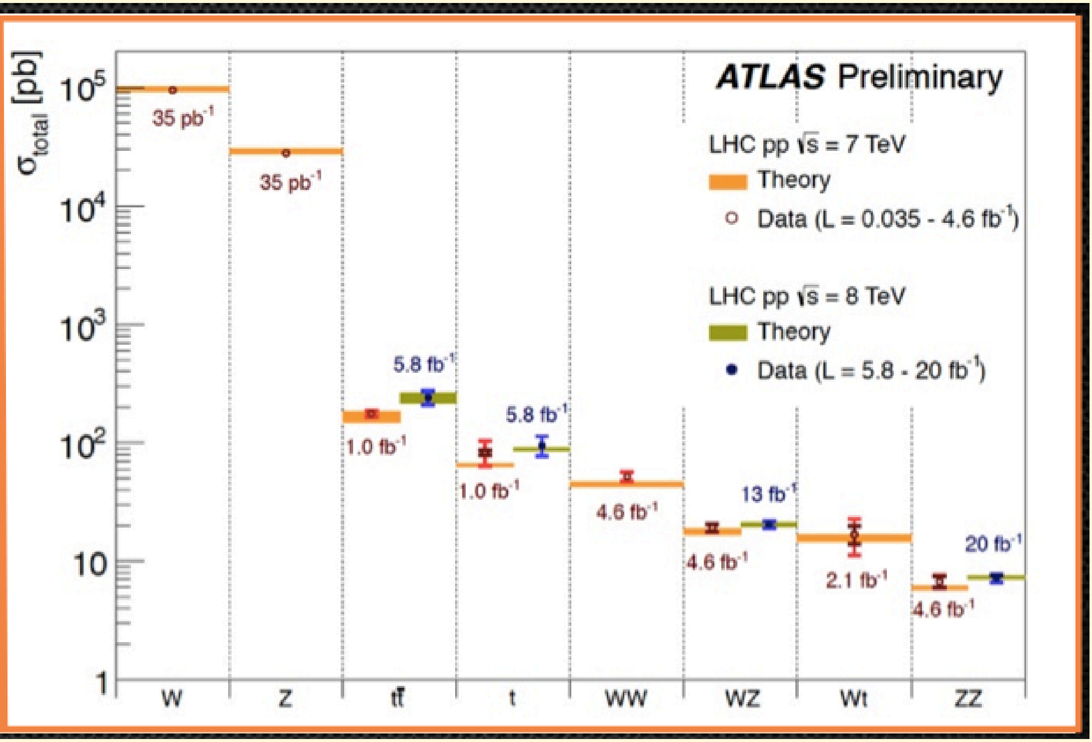


.... how to access regions of parameters of BSM models where the sensitivity is low?

Key outcomes of 3 yrs at the LHC: 3

The theoretical description of high-Q^2 processes at the LHC is very good ....





.... but must and can be improved

SM studies at the LHC:

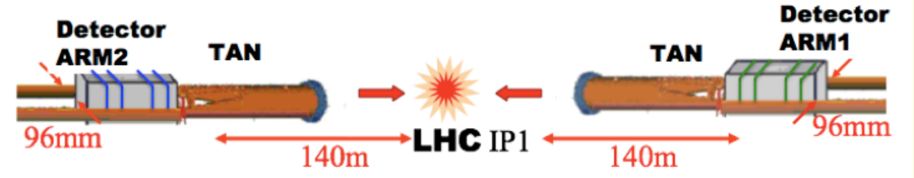
- improve and validate our ability to model final states and make predictions, increasing the potential for precise measurements and for more sensitive BSM searches
- provide opportunities for the exploration of new and complex dynamical regimes of the SM, both in the QCD and EW sectors
- feed back into the HEP community valuable and often unique knowledge

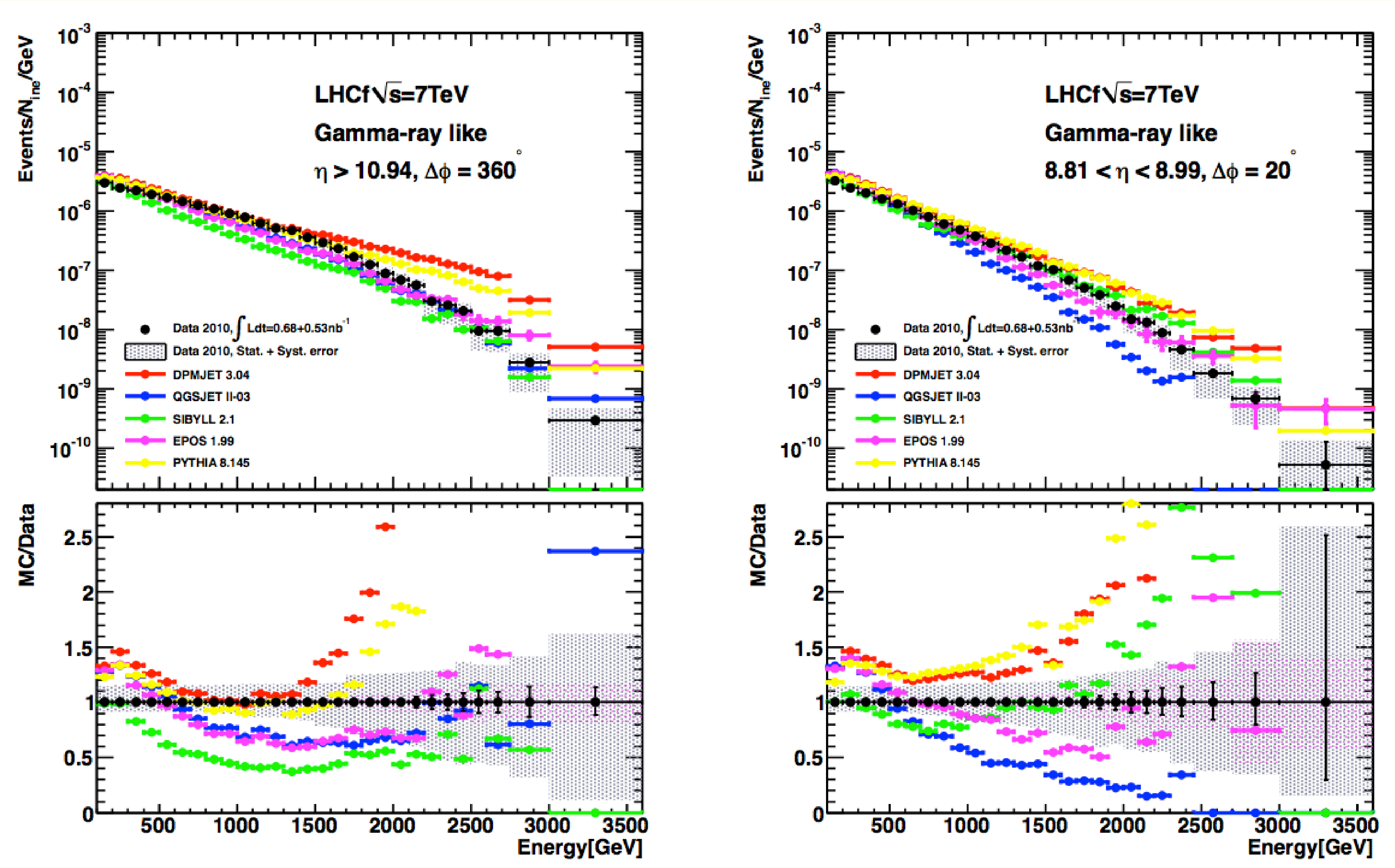
LHCf: Very forward energy flow

See also K.Noda, MPI 2011

“Measurement of zero degree single photon energy spectra for $\sqrt{s}$ = 7 TeV proton-proton collisions at LHC“

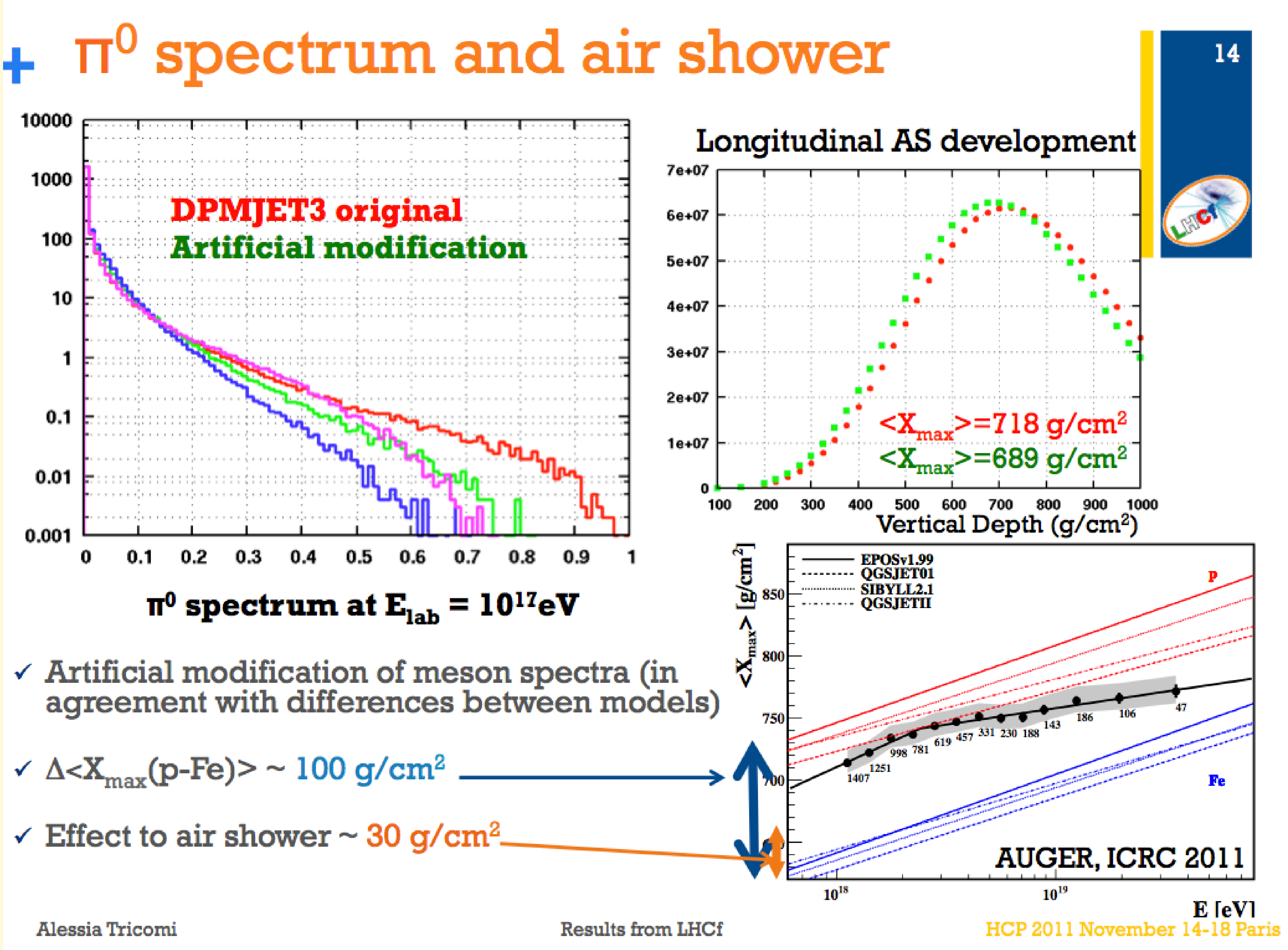
PLB 703 (2011) 128





Impact on modeling of HECR showers: first assessment

A.Tricomi, HCP 2011

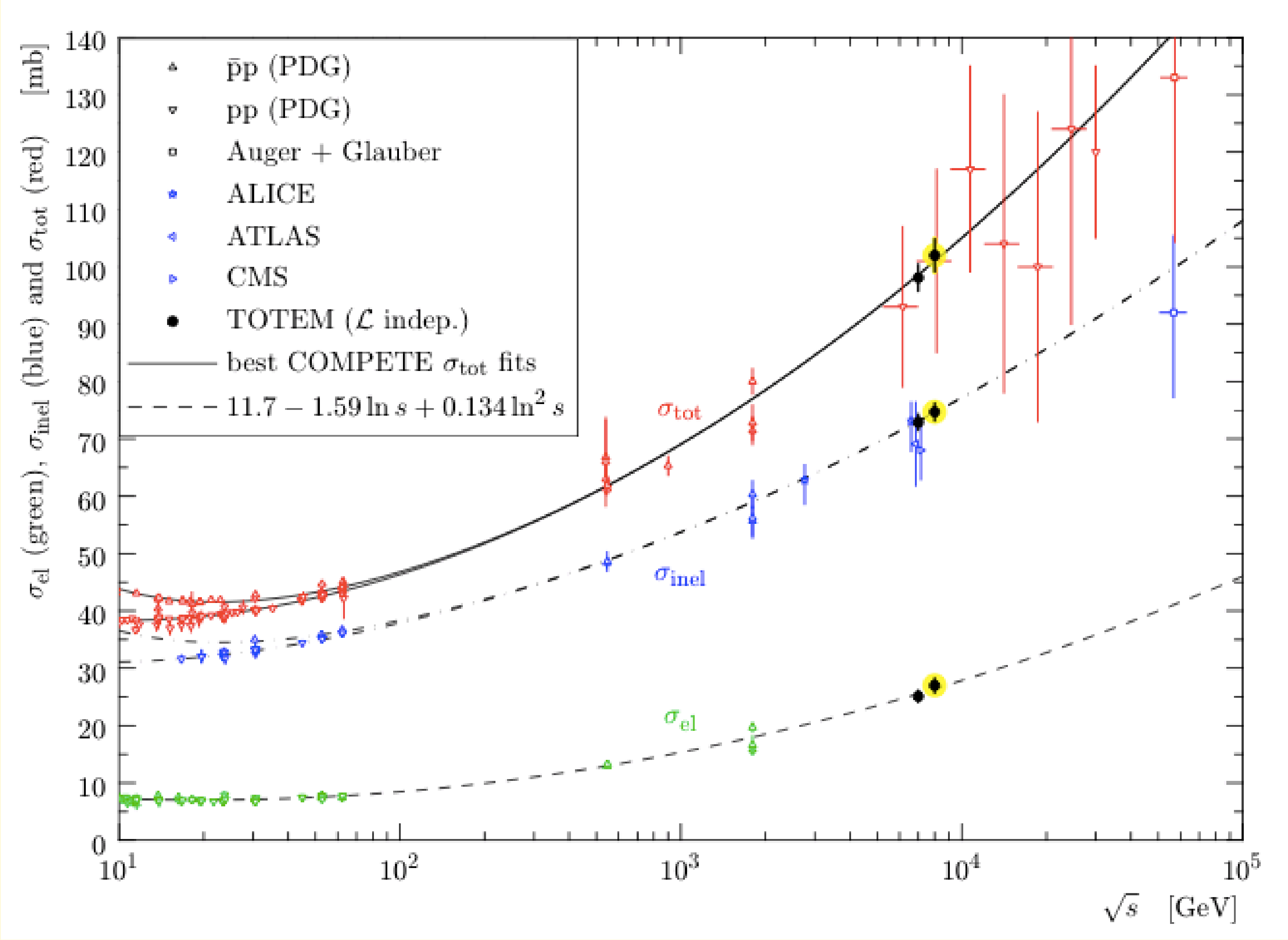


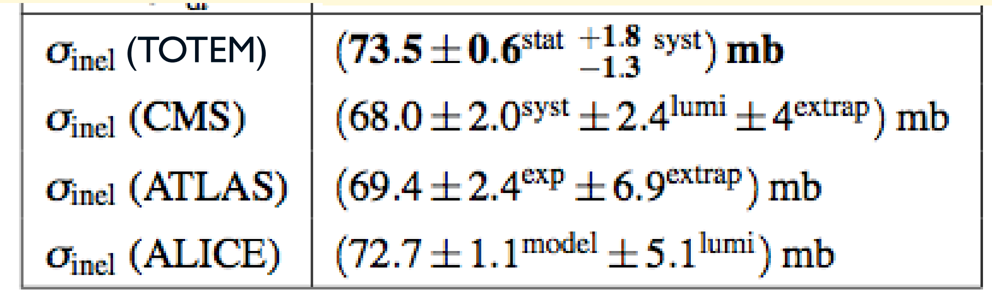
π^0 spectrum and air shower

π^0 spectrum at $E_{lab} = 10^{17}$eV

- ✓ Artificial modification of meson spectra (in agreement with differences between models)
- ✓ $\Delta\langle X_{max}(p\text{-}Fe)\rangle \sim 100\ g/cm^2$
- ✓ Effect to air shower ~ 30 g/cm^2

Elastic, inelastic, total cross sections

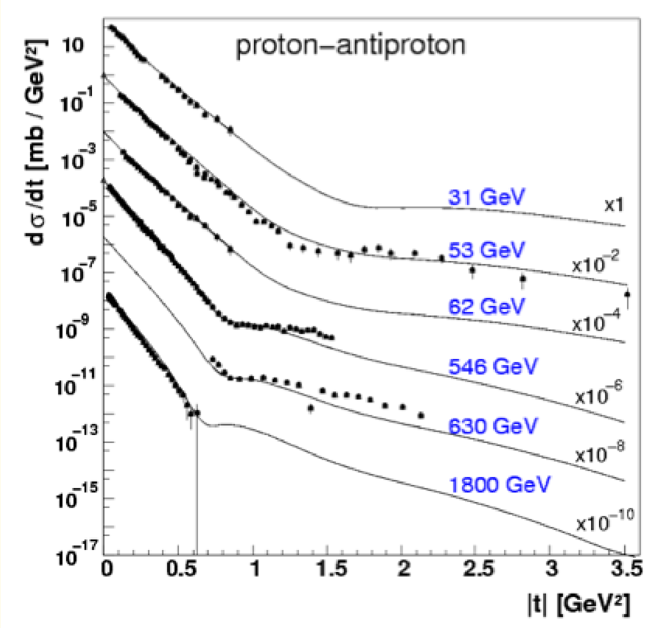


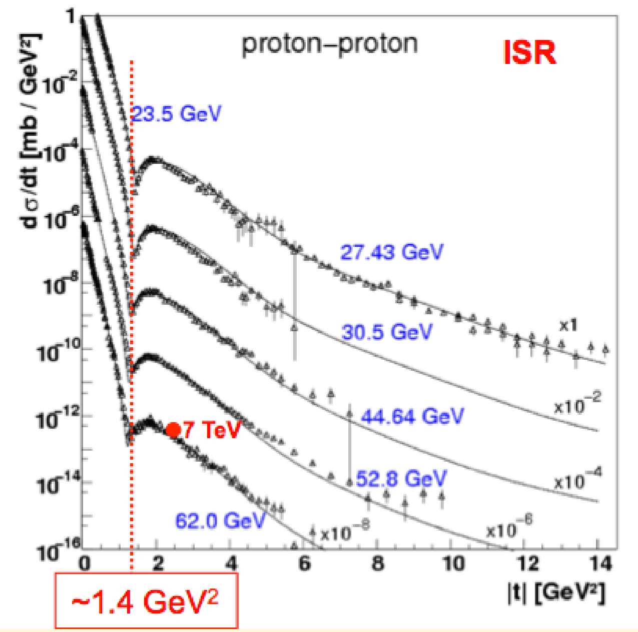


$\sigma_{\rm inel}$ (TOTEM)	$(\mathbf{73.5 \pm 0.6^{stat}\ {}^{+1.8}_{-1.3}\ syst})$ **mb**
$\sigma_{\rm inel}$ (CMS)	$(68.0 \pm 2.0^{\rm syst} \pm 2.4^{\rm lumi} \pm 4^{\rm extrap})$ mb
$\sigma_{\rm inel}$ (ATLAS)	$(69.4 \pm 2.4^{\rm exp} \pm 6.9^{\rm extrap})$ mb
$\sigma_{\rm inel}$ (ALICE)	$(72.7 \pm 1.1^{\rm model} \pm 5.1^{\rm lumi})$ mb

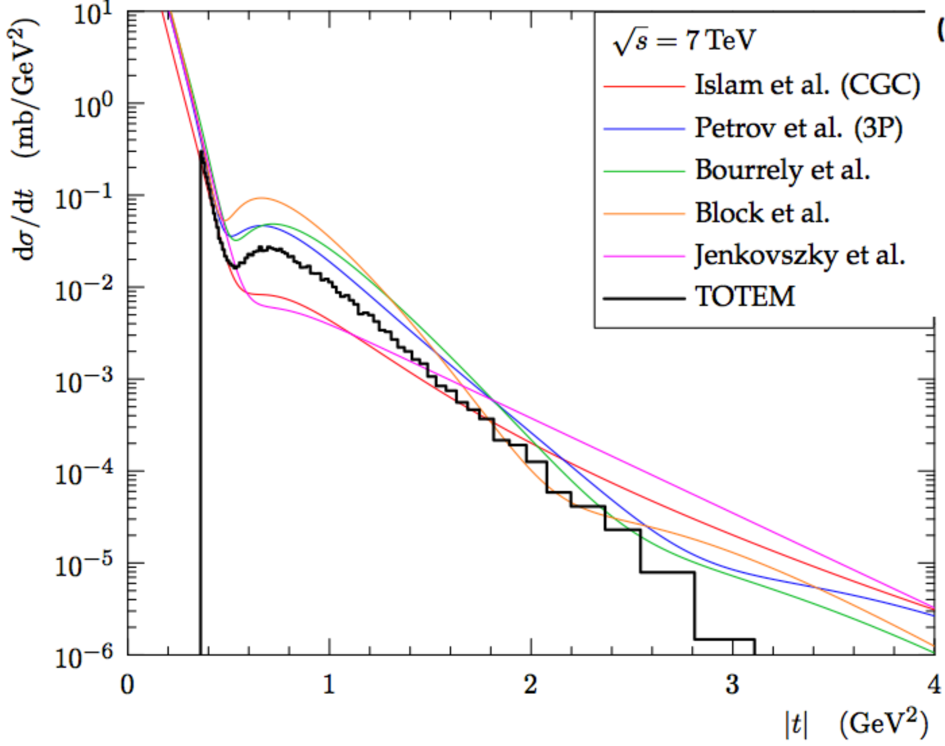
Valuable input for modeling of low-mass diffractive events

TOTEM: elastic cross section





TOTEM: EPL 95 (2011) 41001

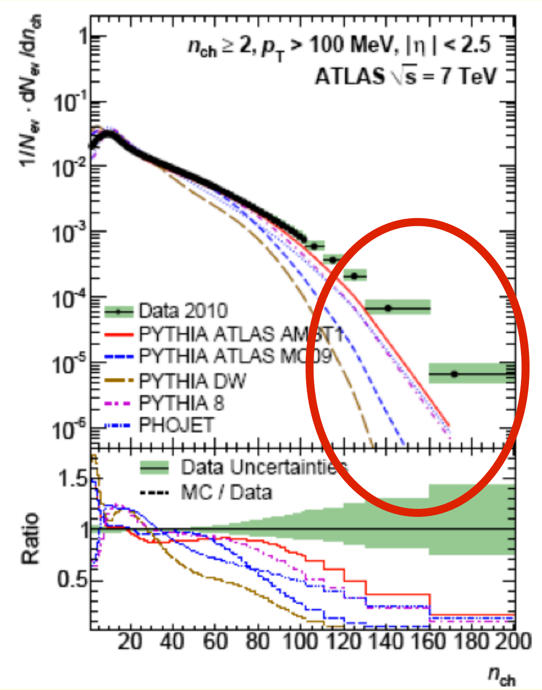


	B (t=-0.4 GeV²)	**t_{DIP}**	**t^{-n} [1.5–2.5 GeV²]**
Islam et al. (CGC)	20.2	0.60	5.0
Petrov et al. (3P)	**23.3**	**0.51**	**7.0**
Bourrely et al.	**22.0**	**0.54**	**8.4**
Block et al.	25.3	0.48	10.4
Jenkovszky et al.	20.1	0.72	4.2
TOTEM	**23.6 ± 0.5**	**0.53 ± 0.01**	**7.8 ± 0.3**

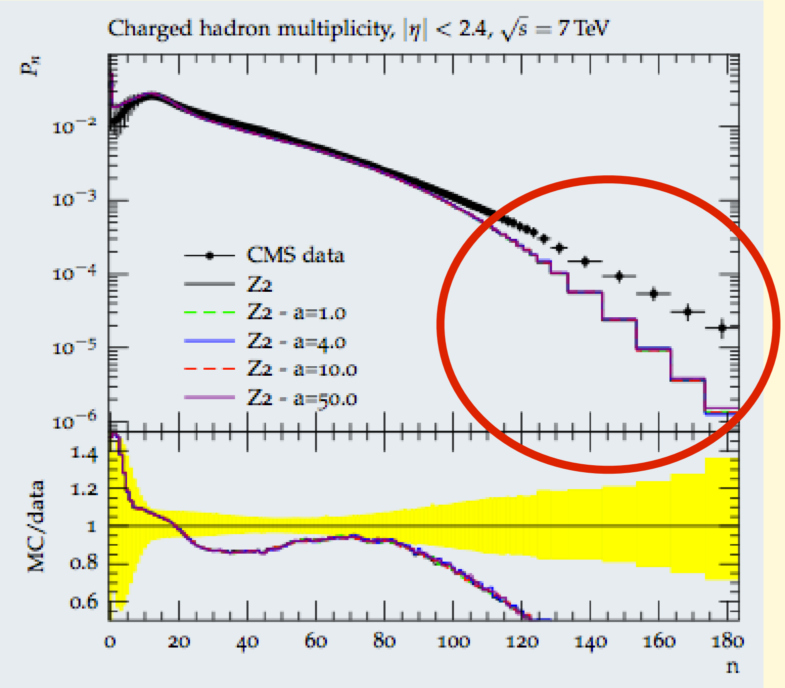
More, available, data will allow to extend the measurement up to O(4-5 GeV^2)

Properties of final states in “0-bias” events

Large multiplicity final states



ATLAS, http://arxiv.org/pdf/1012.5104v2



S.Alderweireldt, MPI-2011

Need a detailed characterization of the structure of large-multiplicity final states:

- are they dominated by 2-jets back to back?
- are they dominated by many soft jets (e.g. multiple semi-hard collisions)
- do they look “fireball”-like (spherically symmetric)?
- does the track-pt spectrum of high-Nch events agree with MCs?
- y-distribution of very soft tracks in high-Nch events?
- .....

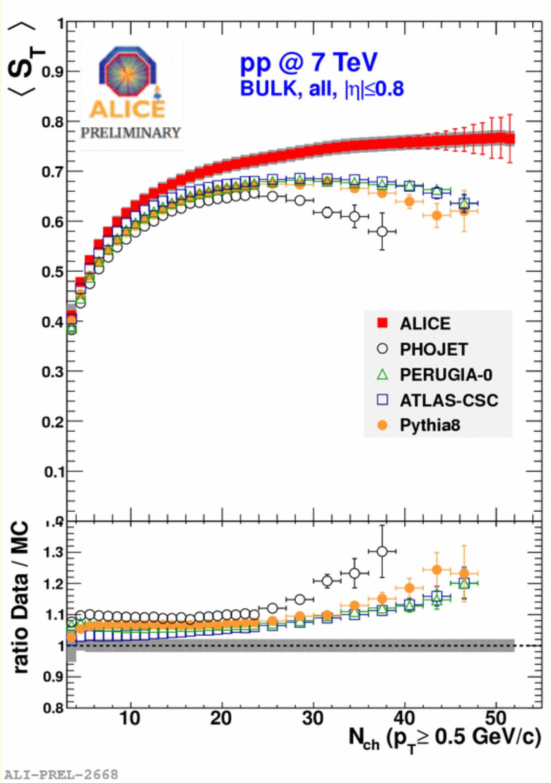
Are we staring at something *fundamental*, or is this just QCD chemistry and MC-tuning?

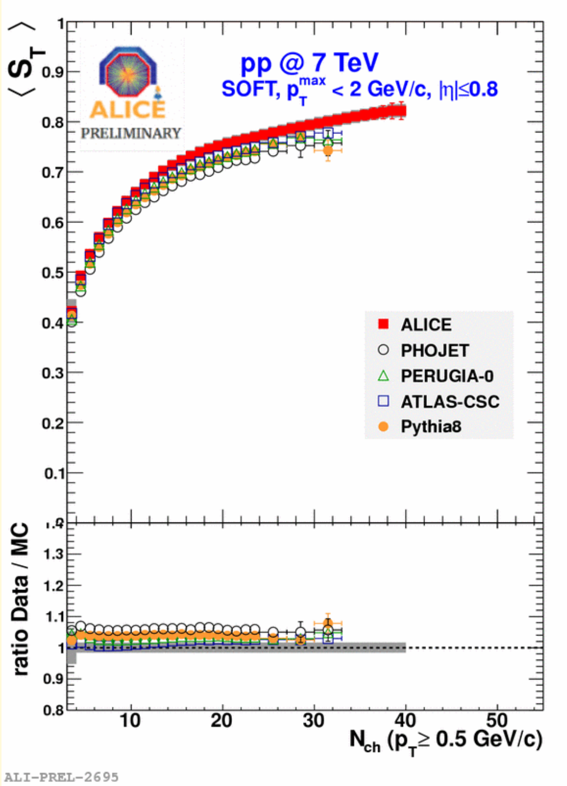
.... see also the CMS ridge effect

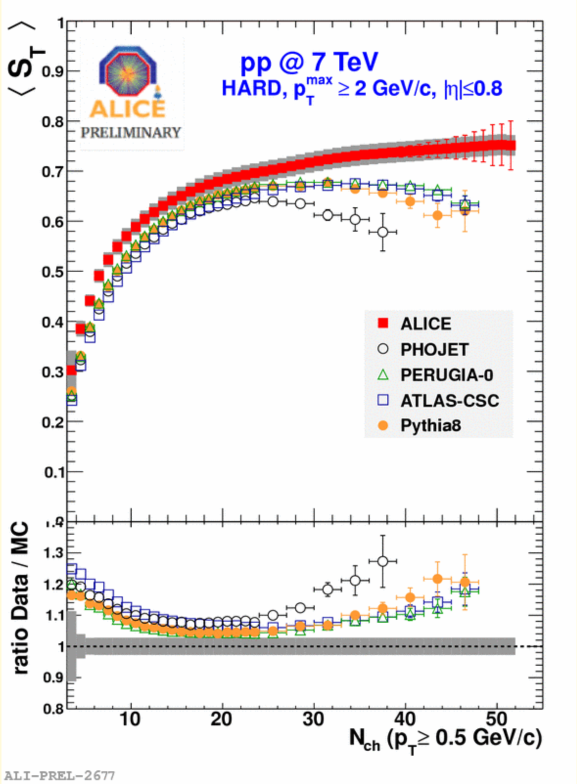
Further insight and puzzles on large-N_{ch} events

ALICE study of transverse sphericity vs N_{ch} arXiv:1110.2278

J.F. Grosse-Oetringhaus, MPI-2011







Events are generically more spherical, less jetty, than MC.

Most of the discrepancy comes however from hard events, not soft ones

Given the smaller rapidity coverage of ALICE, the multiplicities used in this study, with N_{ch} up to ~50, probe final state consistent with those of extreme N_{ch} (>100) measured by ATLAS/CMS in a larger rapidity volume

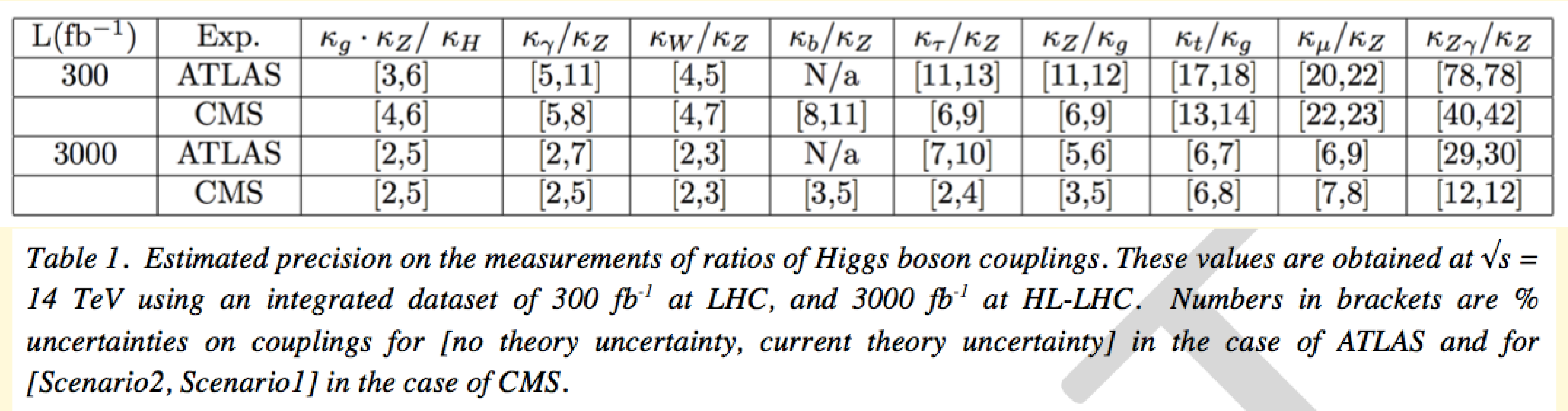
Open challenge:

To prove that the underlying mechanisms of multiparticle production at high energy are *understood*, in addition to being simply *properly modeled*

Back to large Q^2 ....

Current challenges for the field: precision

Ex: Future precision in the determination of Higgs coupling ratios



$L(fb^{-1})$	Exp.	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ/κ_Z	κ_W/κ_Z	κ_b/κ_Z	κ_τ/κ_Z	κ_Z/κ_g	κ_t/κ_g	κ_μ/κ_Z	$\kappa_{Z\gamma}/\kappa_Z$
300	ATLAS	[3,6]	[5,11]	[4,5]	N/a	[11,13]	[11,12]	[17,18]	[20,22]	[78,78]
	CMS	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	ATLAS	[2,5]	[2,7]	[2,3]	N/a	[7,10]	[5,6]	[6,7]	[6,9]	[29,30]
	CMS	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

Table 1. Estimated precision on the measurements of ratios of Higgs boson couplings. These values are obtained at $\sqrt{s}$ = 14 TeV using an integrated dataset of 300 fb^{-1} at LHC, and 3000 fb^{-1} at HL-LHC. Numbers in brackets are % uncertainties on couplings for [no theory uncertainty, current theory uncertainty] in the case of ATLAS and for [Scenario2, Scenario1] in the case of CMS.

CMS Scenario 1: same systematics as 2012 (TH and EXP)
CMS 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 2 @ 3000/fb are overall as powerful as LC@500GeV !!

Current challenges for the field: precision

Theoretical uncertainties on production rates (Higgs XS WG, arXiv:1101.0593)

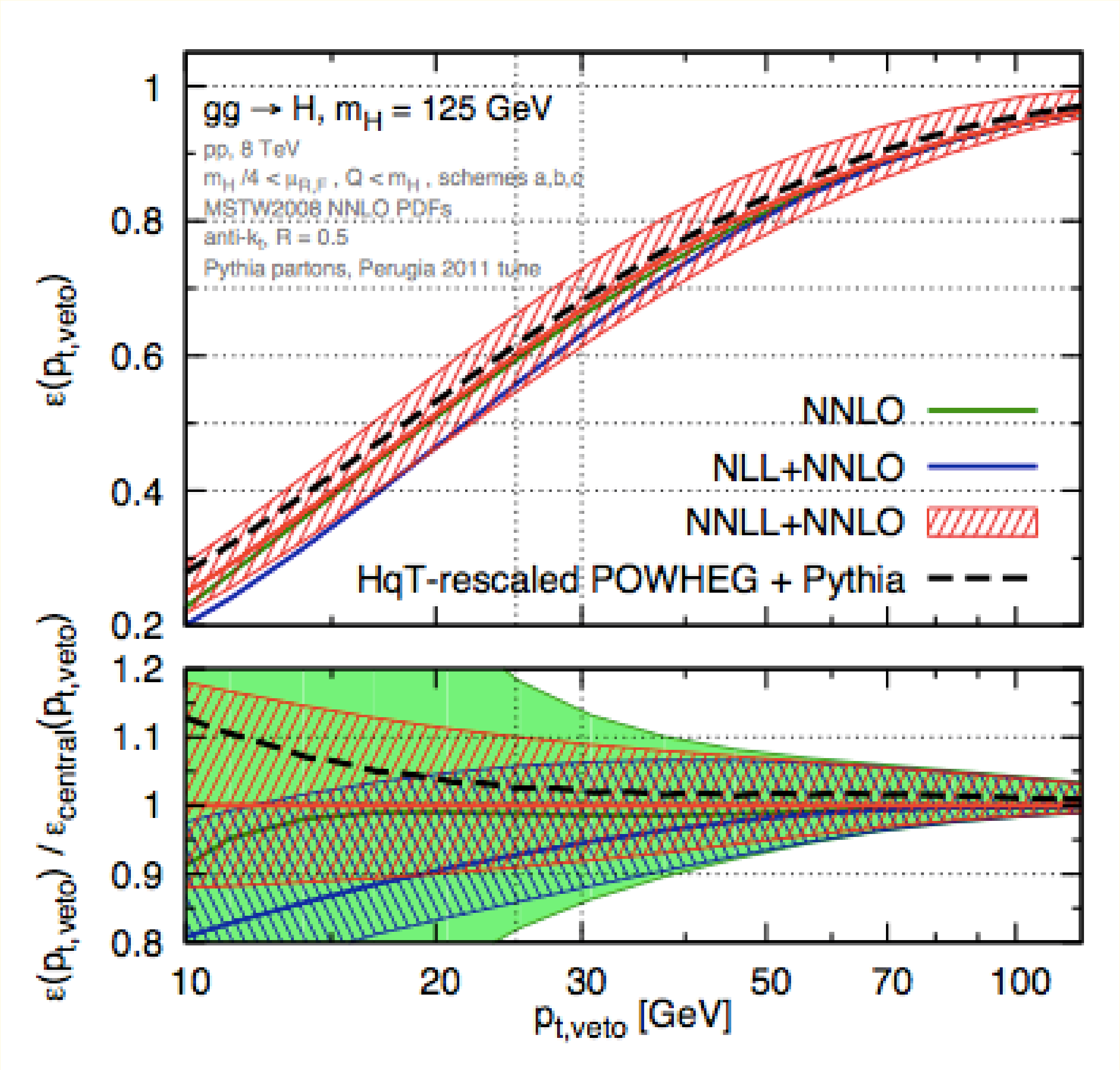
14 TeV	δ(pert. theory)	δ(PDF, α_S)
gg→H	± 10 %	± 7%
VBF (WW→H)	± 1 %	± 2%
qq→WH	± 0.5 %	± 4%
(qq,gg)→ZH	± 2 %	± 4%
(qq,gg)→ttH	± 8 %	± 9%

Improve with higher-loop calculations:
gg->H @ NNNLO
ttH @ NNLO

Improve with dedicated QCD measurements, and appropriate calculations

Current challenges for the field: accurate description of final states

- to properly model experimental selection cuts
- to properly model the separation between signals and background
- to improve the sensitivity to rare and “stealthy” final states in BSM searches



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

Banfi, Monni, Salam, Zanderighi, arXiv:1206.4998

Goals of the SM LHC programme

- Precise determination of fundamental SM parameters:
  - m(top), m(W), α_S, $\sin^2\theta_W$, CKM
  - Higgs properties
- Determination of the PDFs
- Validation of the reliability/precision/uncertainties of the modeling of SM dynamics (QCD and EW), for applications to:
  - the measurements above
  - the search for new phenomena, through deviations from established SM behaviour

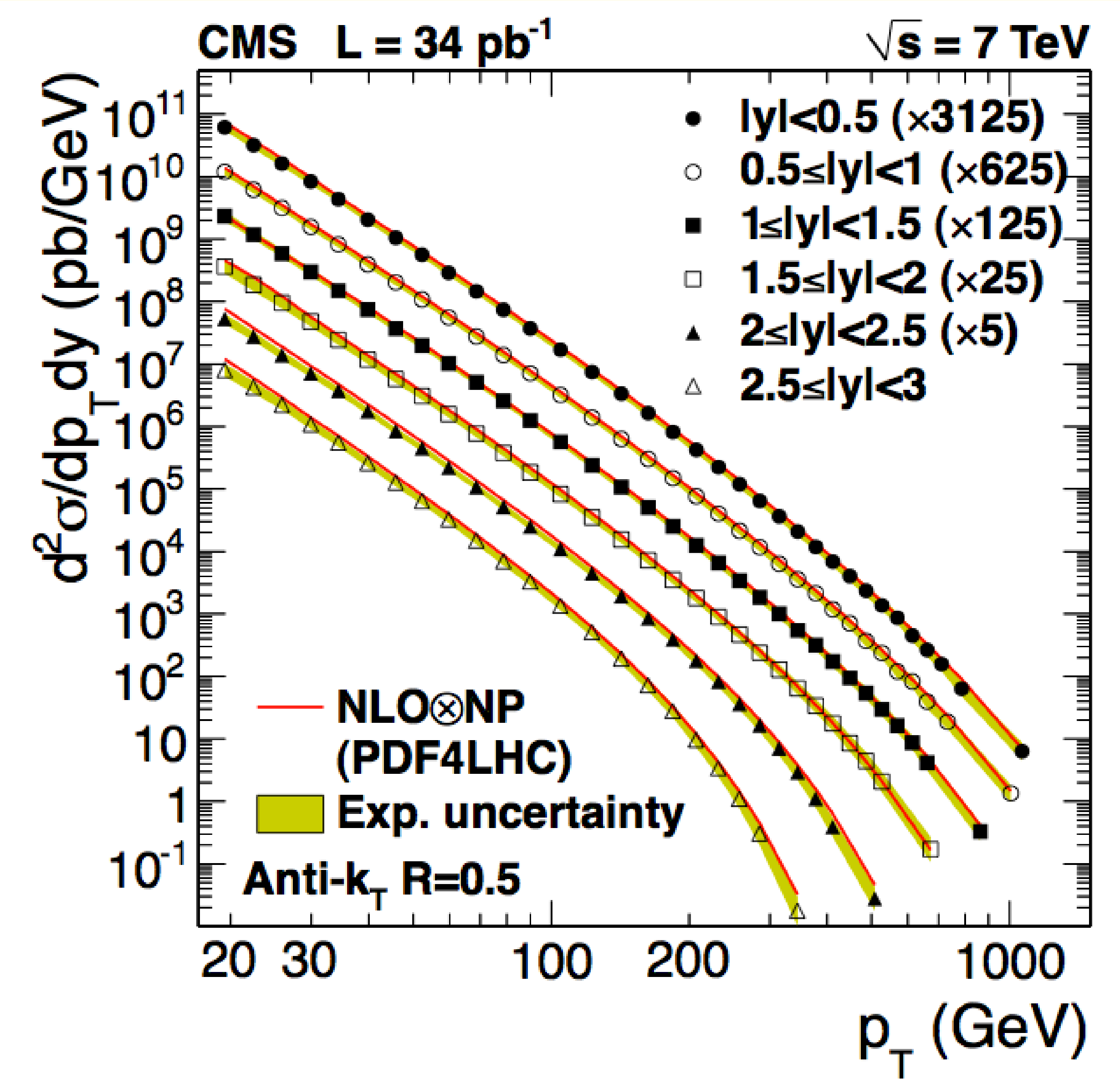
Means:

- Precise measurement of ancillary quantities, necessary to
  - improve the inputs of theory calculations
  - validate the theoretical precision and systematics
- This includes what may otherwise be considered as **“and now what?”** measurements, whose key purpose is to build confidence in the theoretical modeling, for applications to the precision physics programme and to the searches

Opportunities opened by LHC data

- High statistics and superior experimental precision
- Access to small rates:
  - rare final states (multijets, associated production of multiple EW and QCD objects)
  - high-energy final states (highest pt jets, highest mass DY, ...)
  - VBF final states
- EW radiative corrections:
  - impact on EW observables (V, VV production - V=W,Z)
  - impact on QCD observables (jet cross sections)
- New probes of PDFs:
  - large-x gluons (jet, top production)
  - heavy quarks (γQ, ZQ, WQ associated production)
- Correlations:
  - ratios of cross sections for different processes
  - ratios of cross sections at 7 vs 8 vs 14 TeV

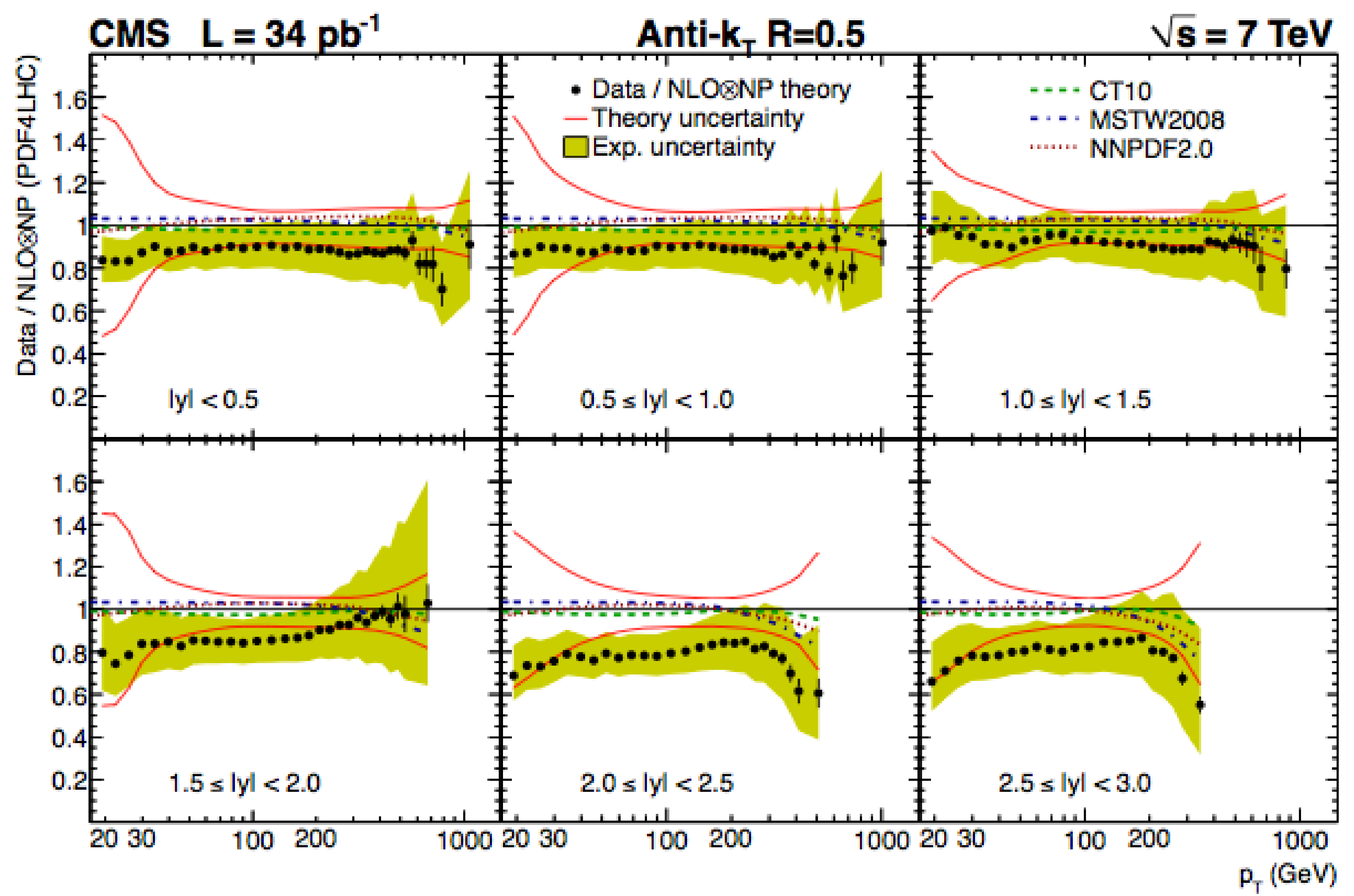
Example: Jet cross section



Rates span 10 orders of magnitude!

Example: Jet cross section

Theory: absolute prediction for both shape and normalization

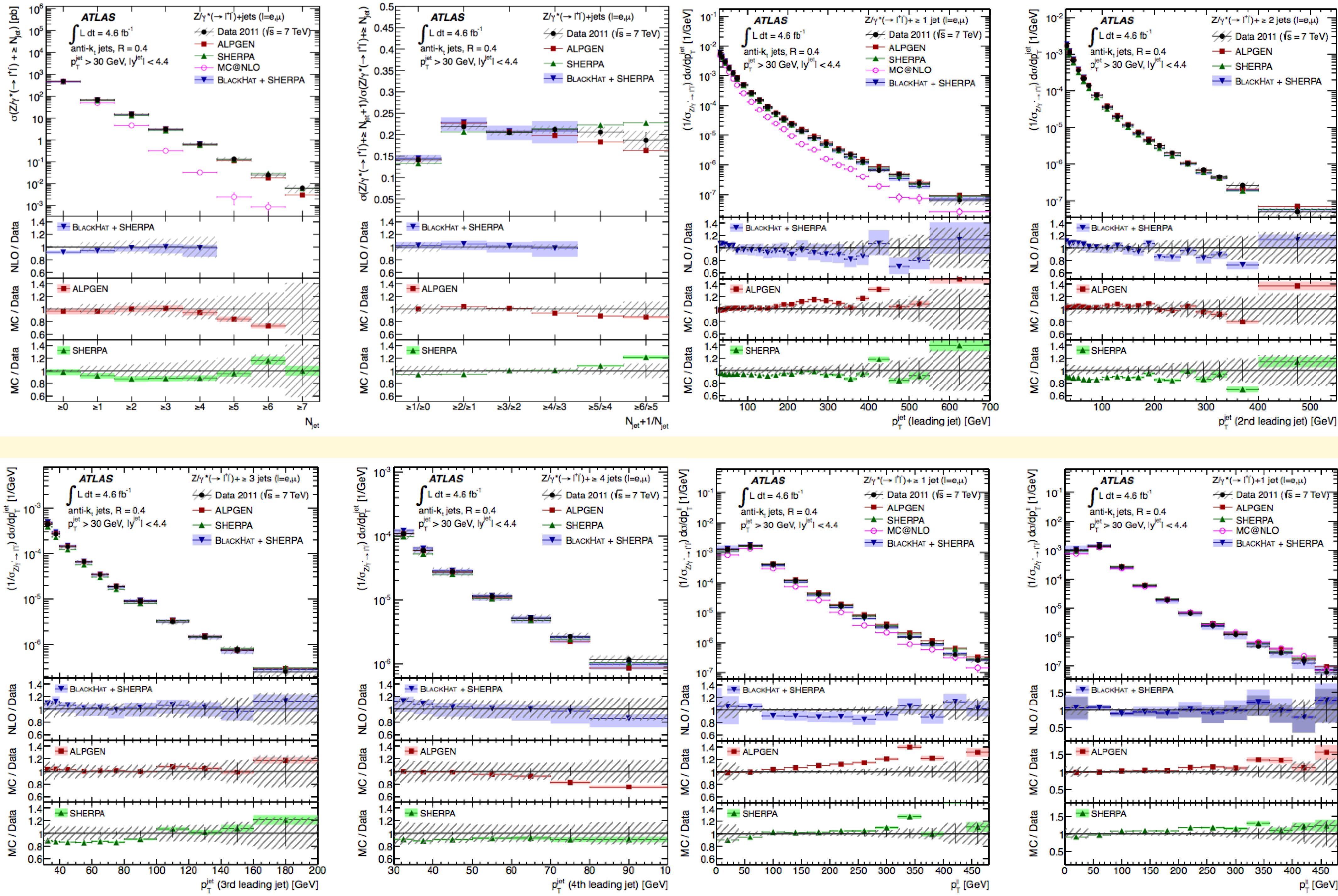


Agreement to within 20% (over 10 orders of magnitude!)

Residual discrepancy consistent with PDF and perturbative NLO uncertainties

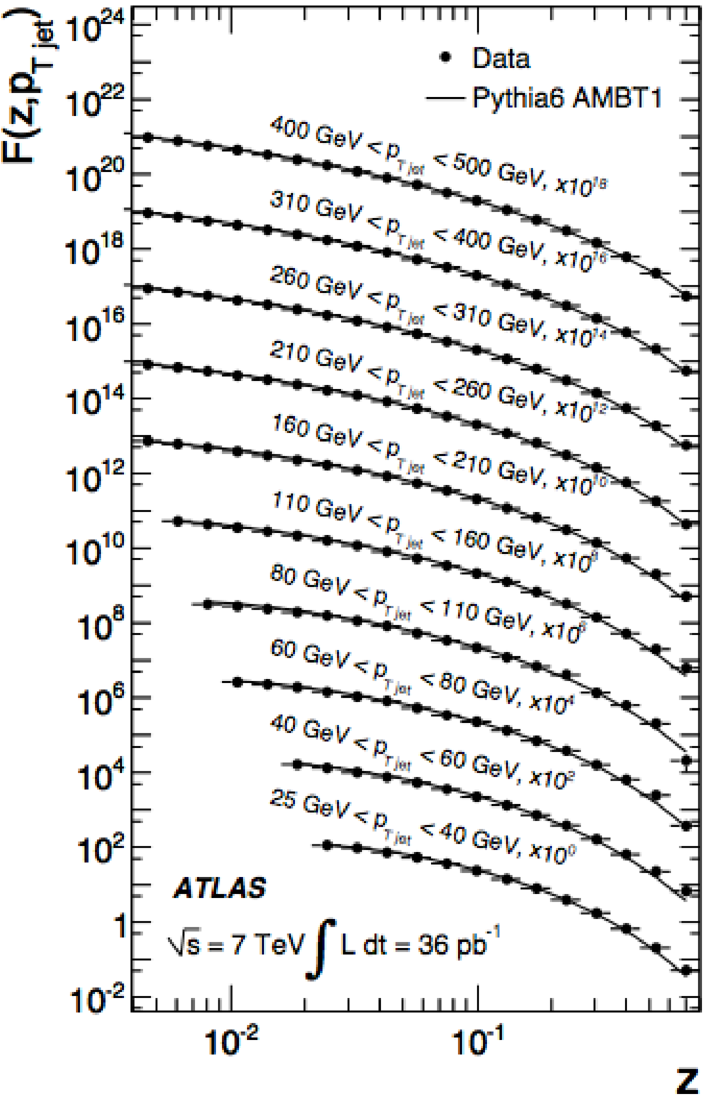
4.6/fb

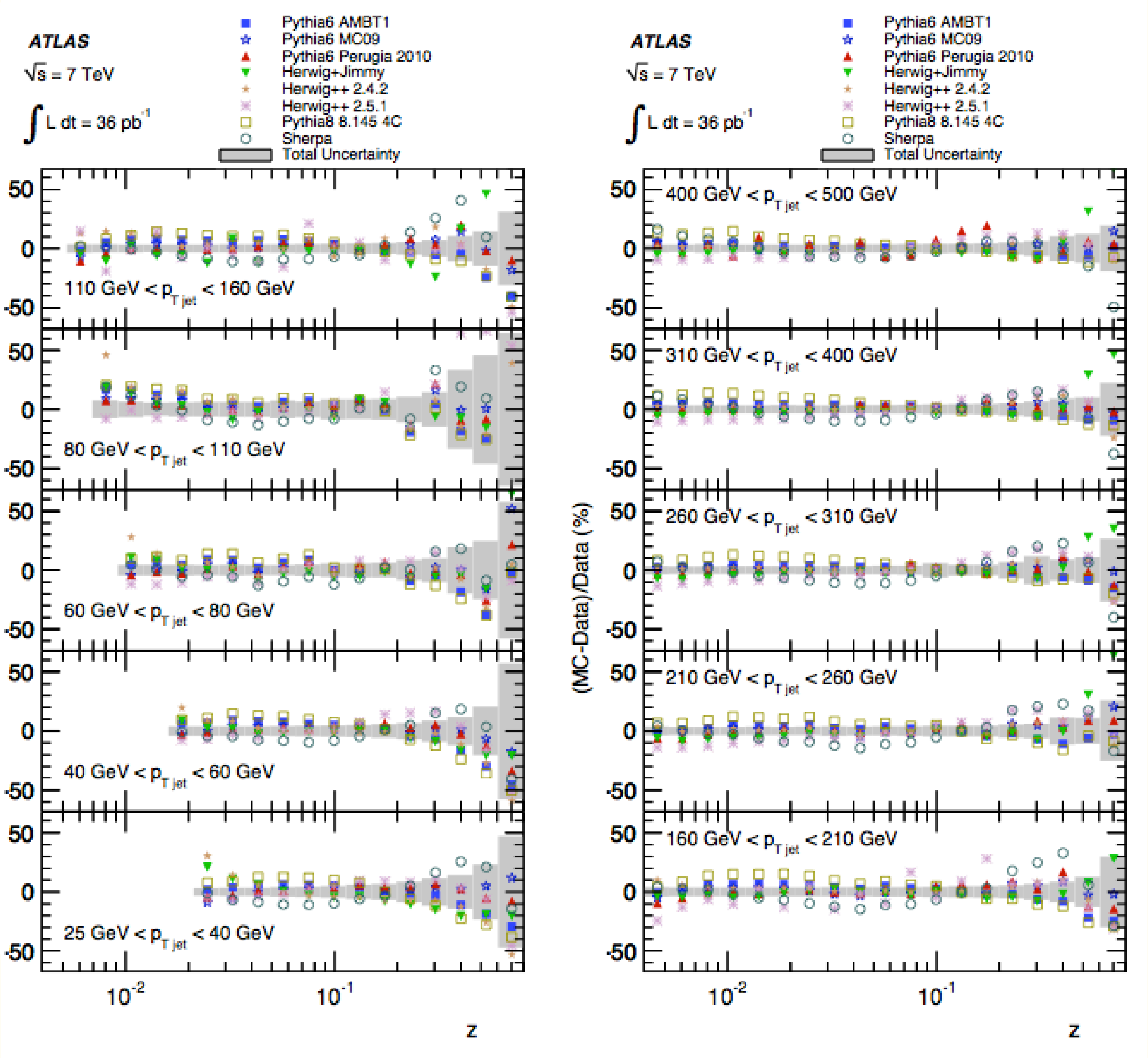
Example: Z+jets



Example: Jet fragmentation function

ATLAS, arXiv:1109.5816



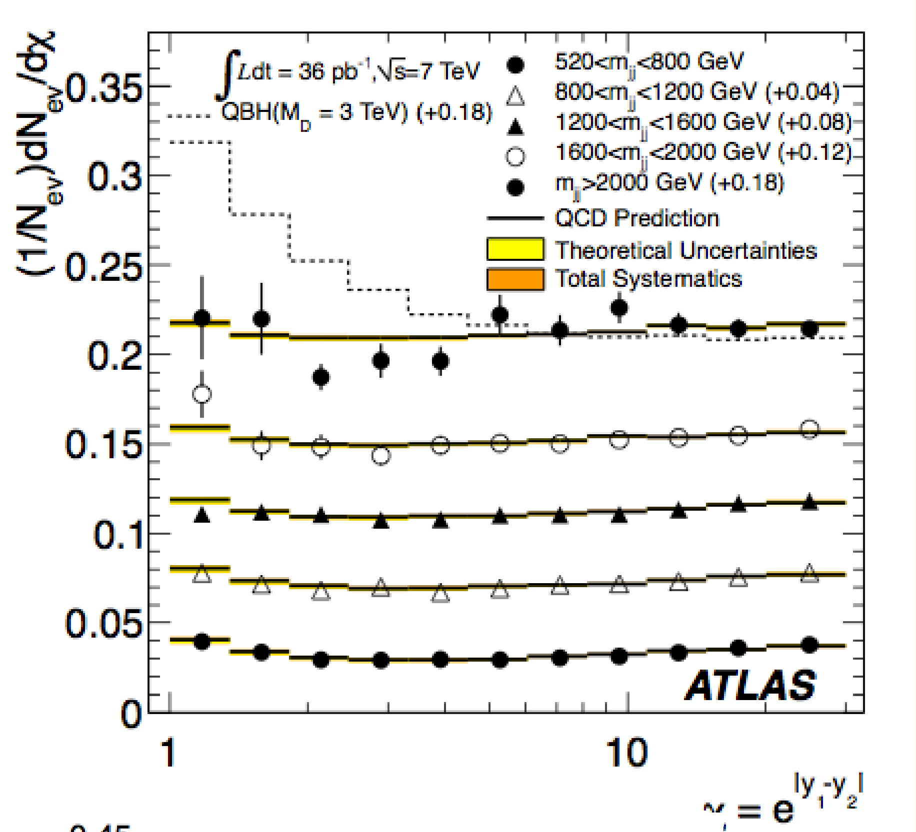


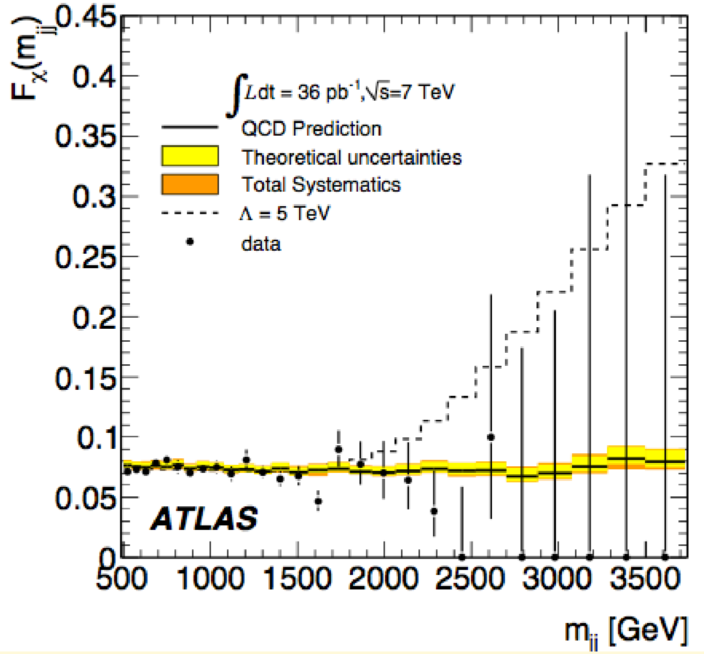
plus

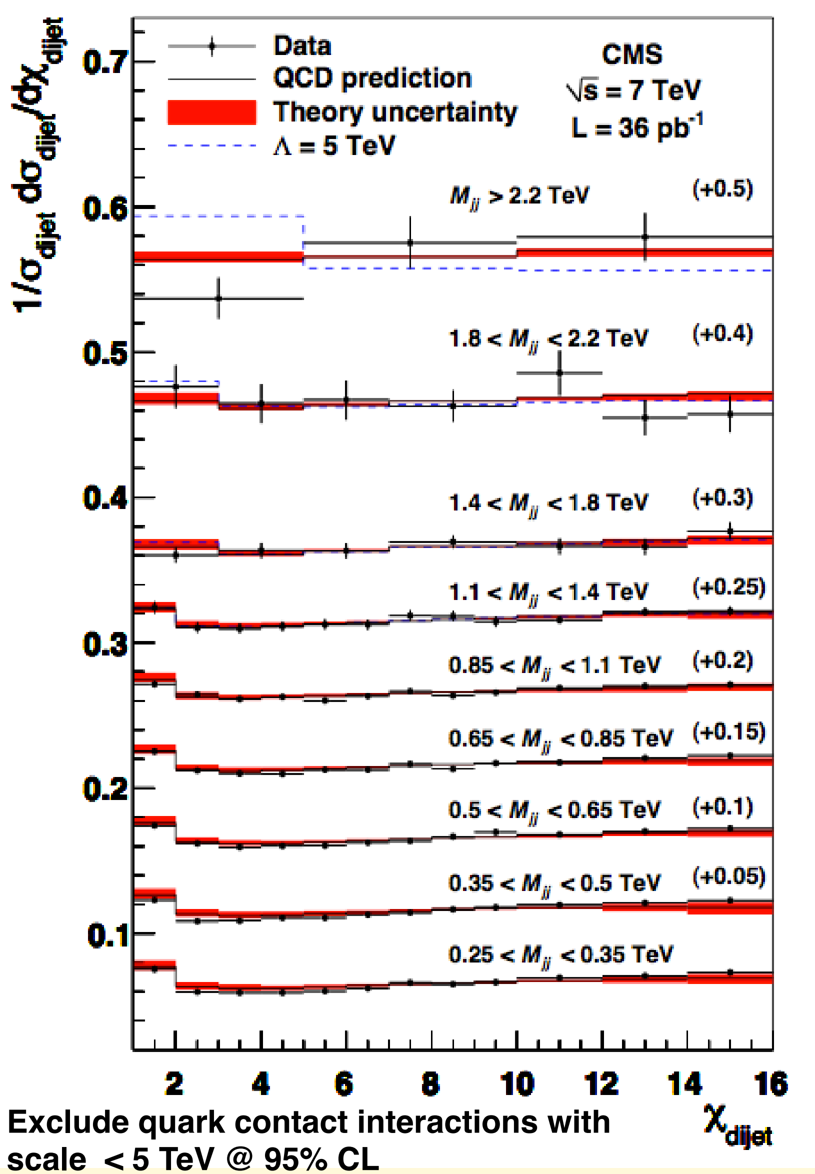
- **jet shapes**
- **ptrel spectra**
- **$\langle N_{ch} \rangle$ and $\langle z \rangle$ distributions,**
- **....**

Constraints on quark contact interactions

$$\chi = \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$





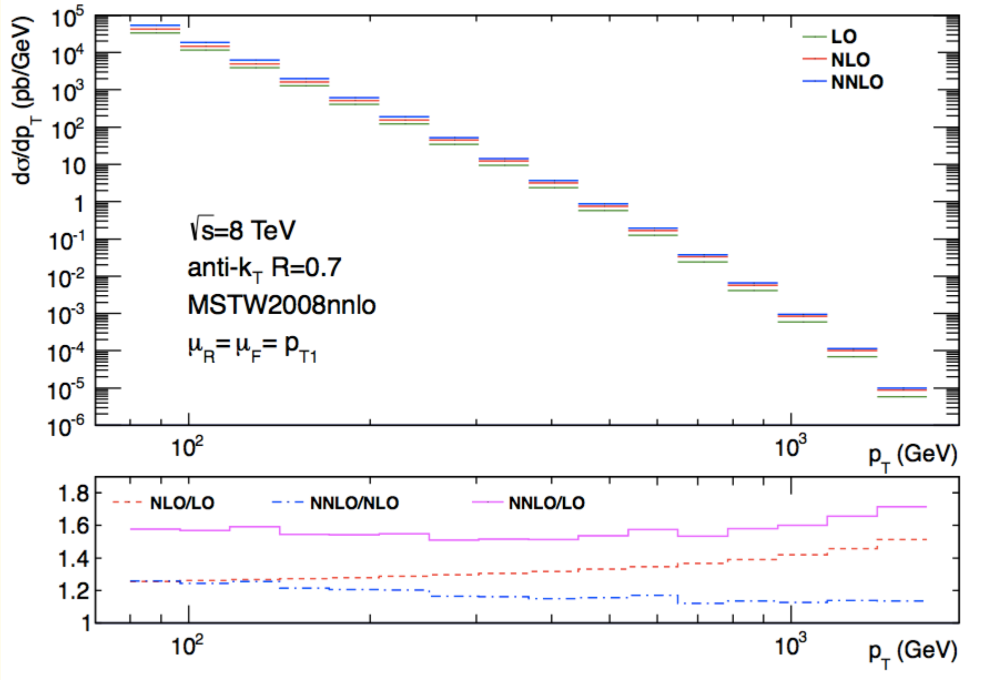


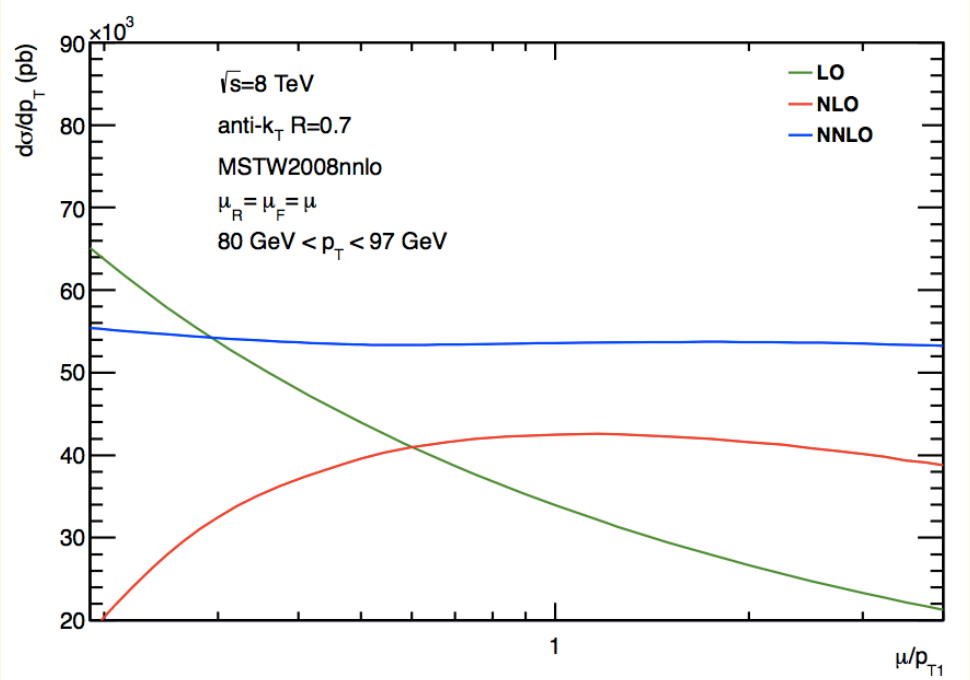
Exclude quark contact interactions with scale < 5 TeV @ 95% CL

Quarks appear pointlike even at the distances probed by the LHC

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 ~ 1.2

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

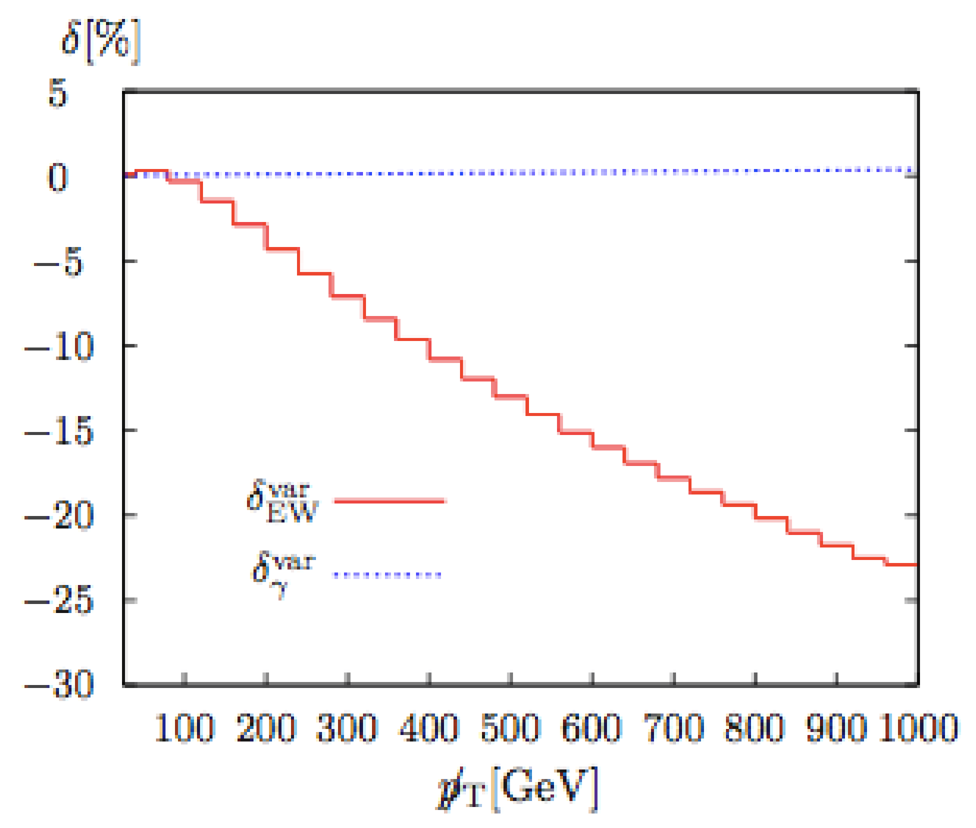
Notice that NNLO outside the NLO scale-variation band

At this level of precision, there are other things one should start considering. E.g. non-perturbative systematics and EW corrections

Impact of EW radiative corrections, example:

Jet+MET spectrum from (Z→νν)+jet: corrections due to pure EW and pure EM corrections

Denner, Dittmaier, Kasprzik, Mück, arxiv:1211.5078v2

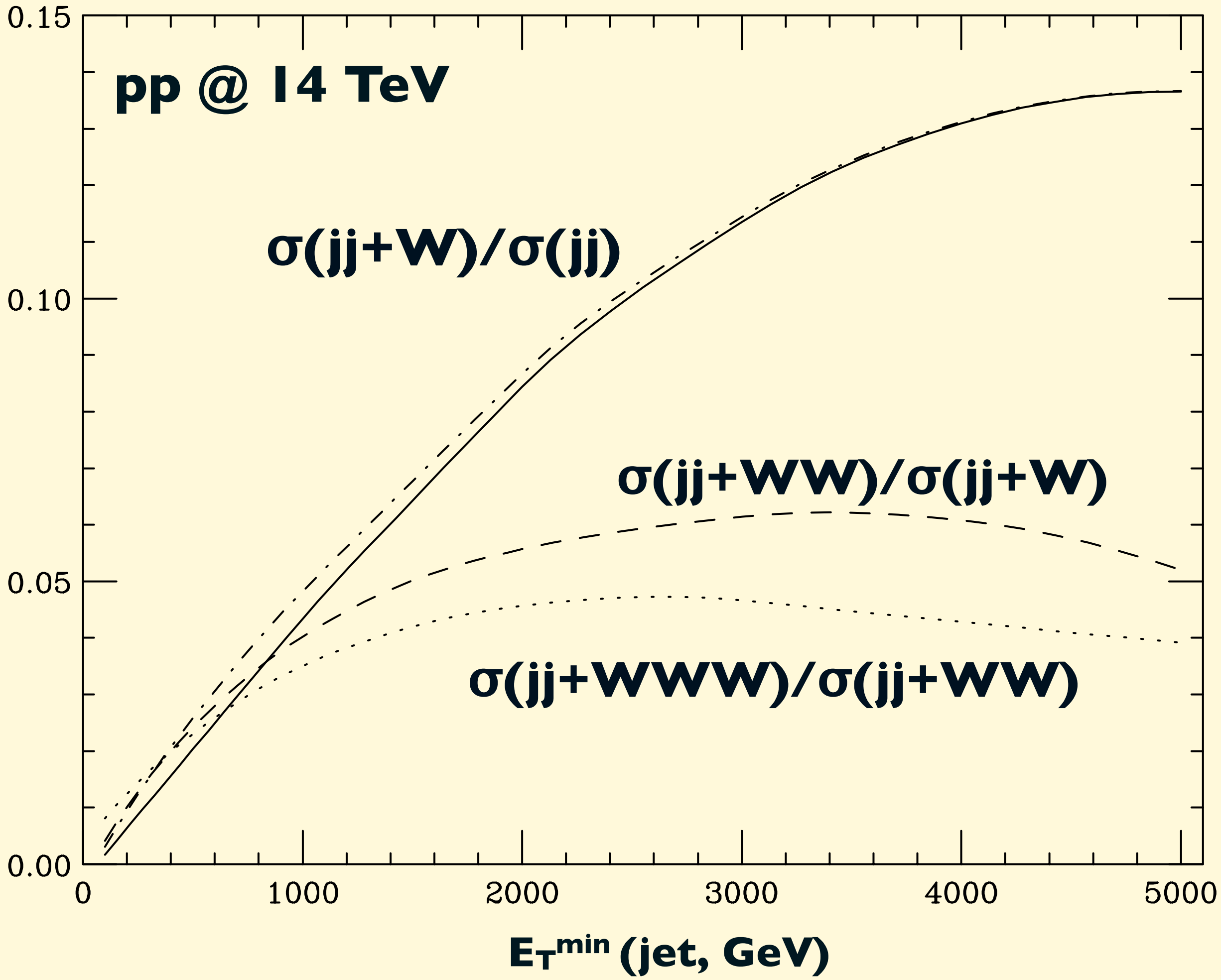


Unless EW corrections are included in the calculations, we might end up removing possible differences between data and QCD predictions for the Z pt spectrum by retuning the QCD MCs!

Very-high pt data on the Z pt spectrum are crucial to assess that the effect is indeed so large!

How does one convince himself that possible deviations of this size from the QCD expectation are indeed the result of EW corrections ?

W production, in events with high-E_T jets



Dotdashes: σ(jj) in the denominator replaced by σ(jj, no gg→gg)

- **Substantial increase of W production at large energy: over 10% of high-ET events have a W or Z in them!**
- **It would be interesting to go after these W and Zs, and verify their production properties**

Multi-gauge boson production:

WWW → 3lept's

$\sigma(W) = 100$ nb

$\sigma(WW) = 50$ pb $\qquad \sigma(WW) / \sigma(W) = 0.5 \times 10^{-3}$

$\sigma(WWW) = 60$ fb $\qquad \sigma(WWW) / \sigma(WW) = 10^{-3}$

$\sigma(WWW \to 3\ \ell) = 0.7$ fb ⇒ **20 events/30 fb^{-1}** $\qquad \ell = e, \mu$

ZWW → 4lept's

$\sigma(Z) = 30$ nb

$\sigma(ZW) = 20$ pb $\qquad \sigma(ZW) / \sigma(Z) \sim 10^{-3}$

$\sigma(ZWW) = 50$ fb $\qquad \sigma(ZWW) / \sigma(ZW) \sim 2 \times 10^{-3}$

$\sigma(ZWW \to 4\ \ell) = 0.15$ fb ⇒ **5 events/30 fb^{-1}** $\qquad \ell = e, \mu$

$\sigma(W) / \sigma(Z) \sim 3$

$\sigma(WW) / \sigma(ZW) \sim 2.5$

$\sigma(WWW) / \sigma(ZWW) \sim 1.2$

Ratio determined by couplings to quarks, u/d PDF

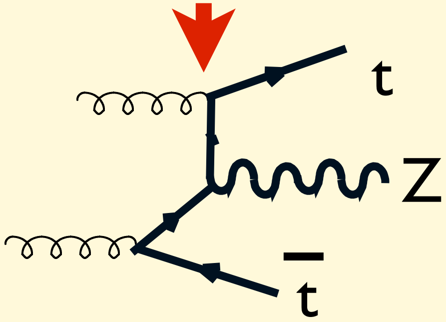
↓

Ratio determined by couplings among W/Z, SU(2) invariance

Multi-gauge boson production:

ttZ → WWZ → 4lept's

$\sigma(Ztt) = 100\ \mathrm{fb} = 40_{(uubar+ddbar)}\ \mathrm{fb} + 60_{(gg)}\ \mathrm{fb} = 100\ \mathrm{fb}$



The gg part is directly proportional to the ttZ coupling. **First** "direct" measurement (indirect: virtual corrections to Z self-energy)

$\sigma(Ztt) \times B(Z\to\ell\ell) \times B(tt\to\ell'\ell'') = 0.3\ \mathrm{fb} \Rightarrow$ 10 events/30 fb^{-1} $\ell = e,\mu$

ttW → 3 W →3lept's

$\sigma(Wtt)=110\ \mathrm{fb}$

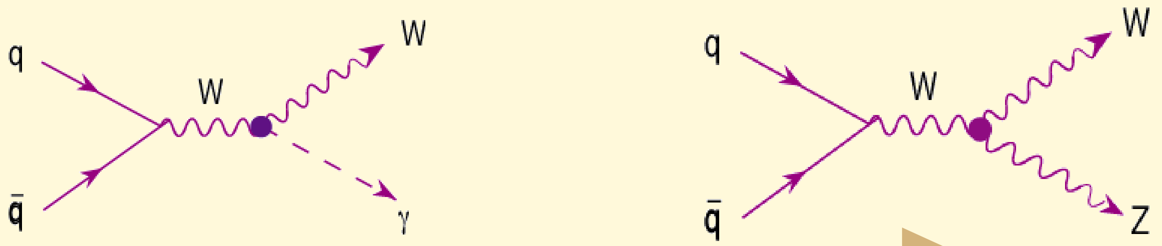
Notice $\sigma(Wtt) \sim \sigma(Ztt)$, while typically $\sigma(W) \sim 3\ \sigma(Z)$. The reason is that Wtt cannot have a gg production channel!!

$\sigma(Wtt) \times B(W\to\ell) \times B(tt\to\ell'\ell'') = 1.2\ \mathrm{fb} \Rightarrow$ 40 events/30 fb^{-1} $\ell = e,\mu$

$\sigma(Wtt) / \sigma(tt) = 0.7 \times 10^{-3}$

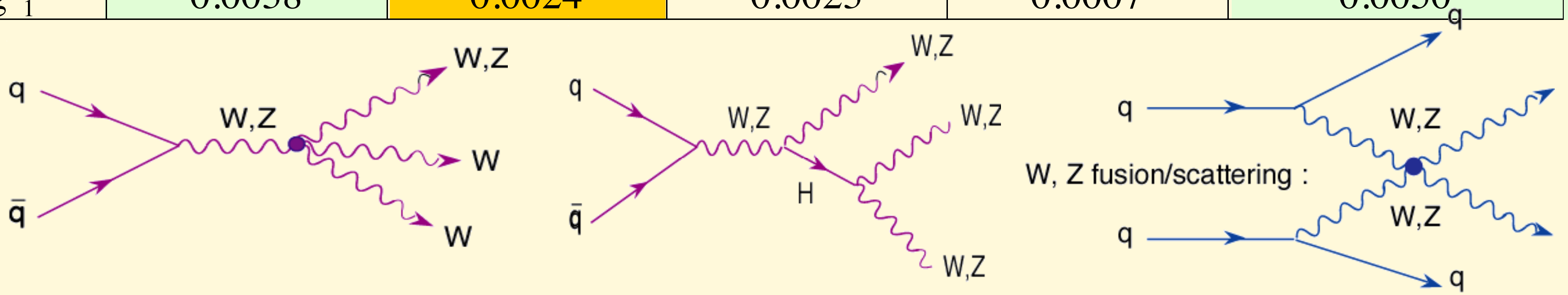
Precise determinations of the self-couplings of EW gauge bosons

5 parameters describing weak and EM dipole and quadrupole moments of gauge bosons. The SM predicts their value with accuracies at the level of **10^{-3}**, which is therefore the goal of the required experimental precision



LHC options

Coupling	14 TeV 100 fb^{-1}	14 TeV 1000 fb^{-1}	28 TeV 100 fb^{-1}	28 TeV 1000 fb^{-1}	LC 500 fb^{-1}, 500 GeV
λ_γ	0.0014	0.0006	0.0008	0.0002	0.0014
λ_Z	0.0028	0.0018	0.0023	0.009	0.0013
$\Delta\kappa_\gamma$	0.034	0.020	0.027	0.013	0.0010
$\Delta\kappa_Z$	0.040	0.034	0.036	0.013	0.0016
g^Z_1	0.0038	0.0024	0.0023	0.0007	0.0050

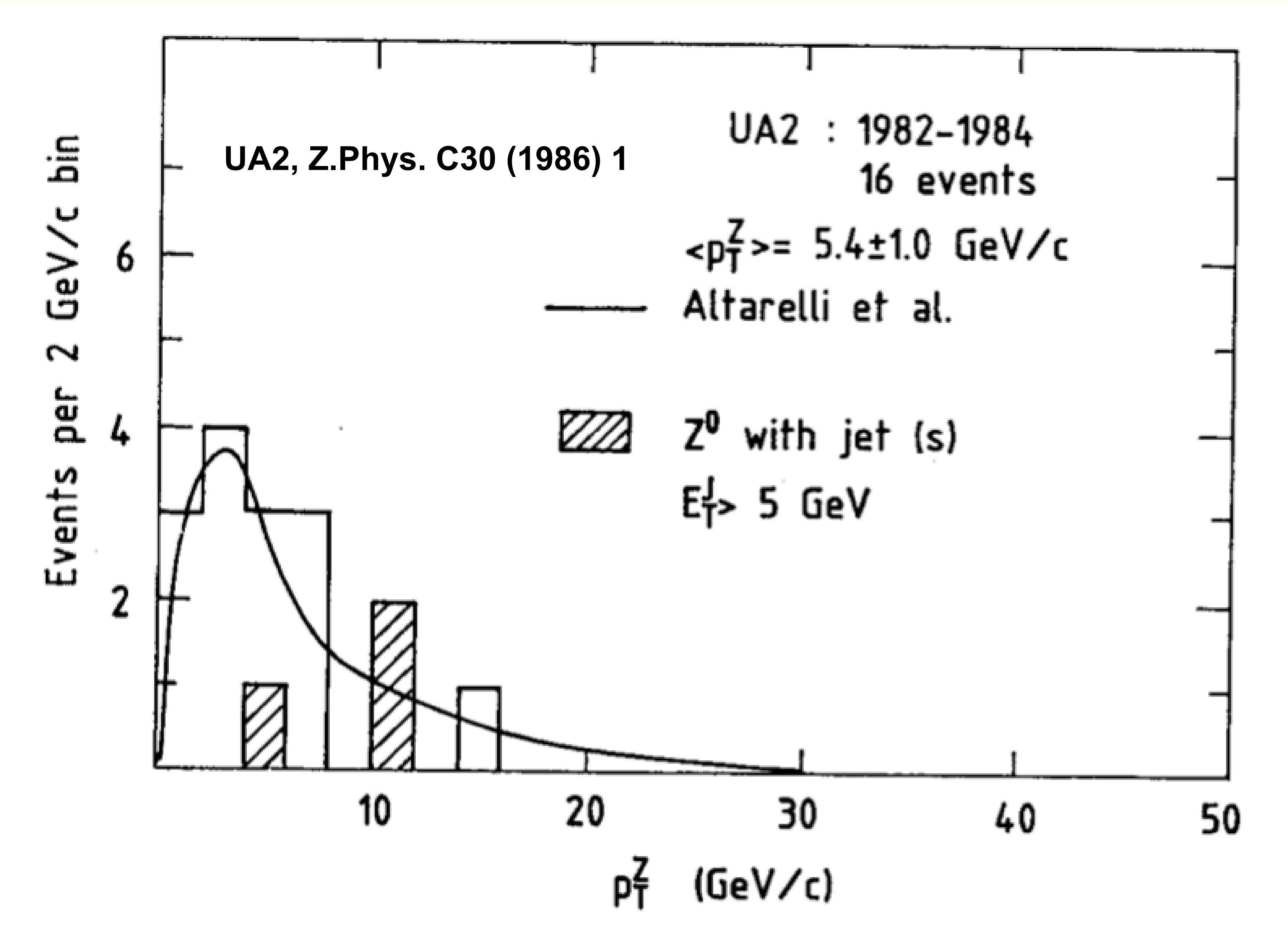


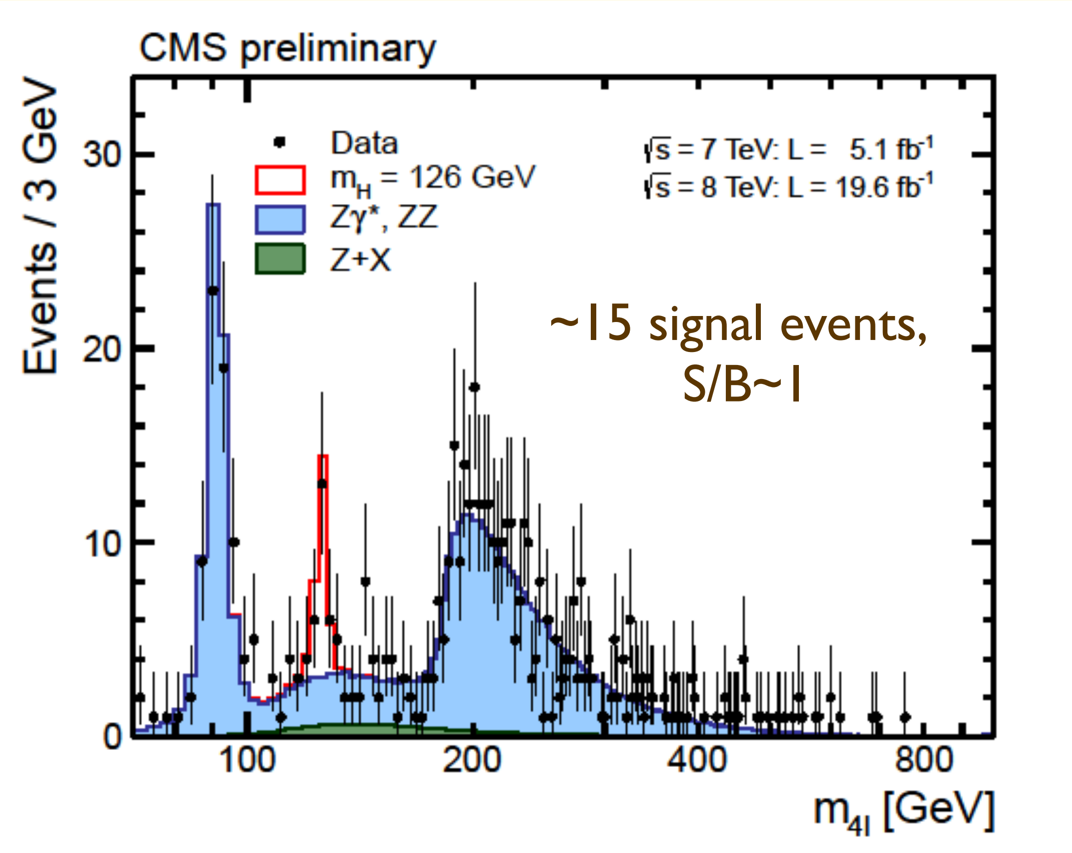
(LO rates, CTEQ5M, k ~ 1.5 expected for these final states)

Process	WWW	WWZ	ZZW	ZZZ	WWWW	WWWZ
N(m_H = 120 GeV)	2600	1100	36	7	5	0.8
N(m_H = 200GeV)	7100	2000	130	33	20	1.6

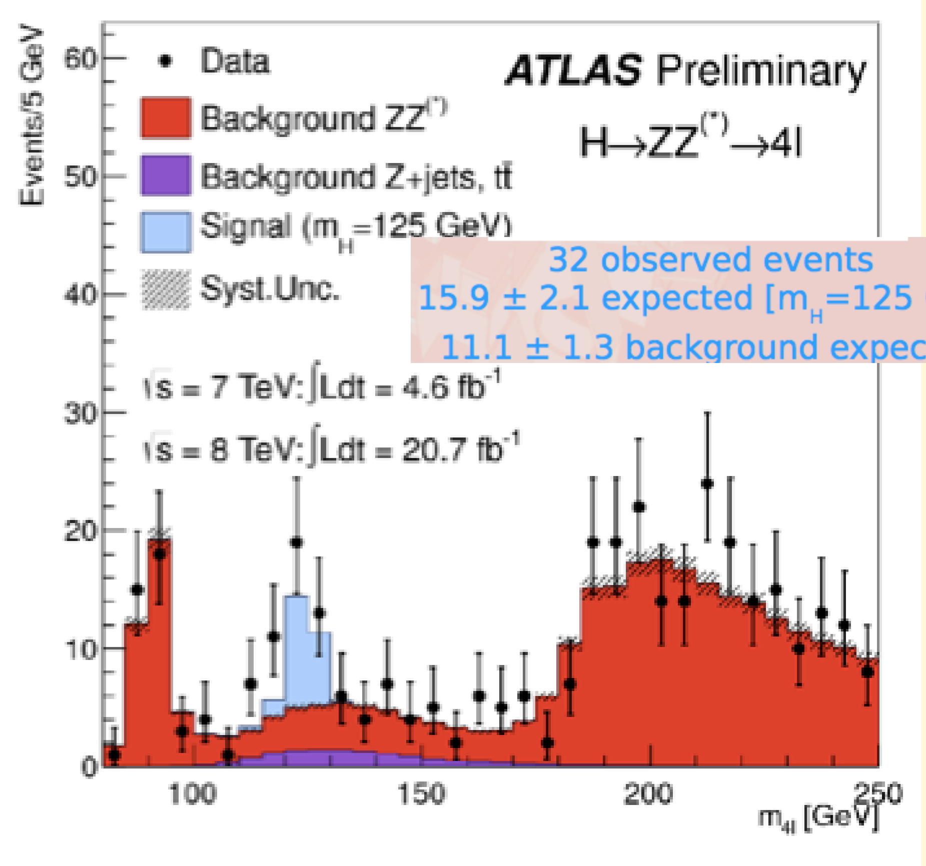
Towards experimental constraints on Higgs production dynamics ....

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





~15 signal events,
S/B~1

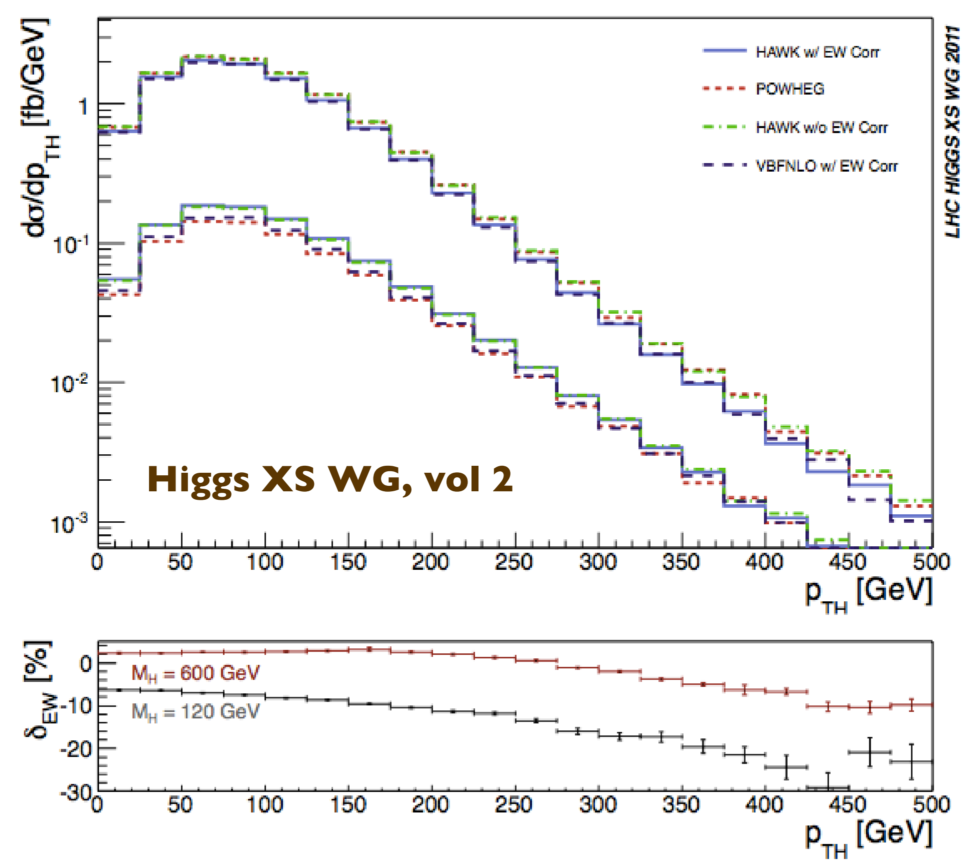


32 observed events
15.9 ± 2.1 expected [m_H=125 GeV]
11.1 ± 1.3 background expected

There is enough to start plotting pt(H), N_{jet} distribution in H production, etc.

p_T(H): qq → qq H vs gg → H

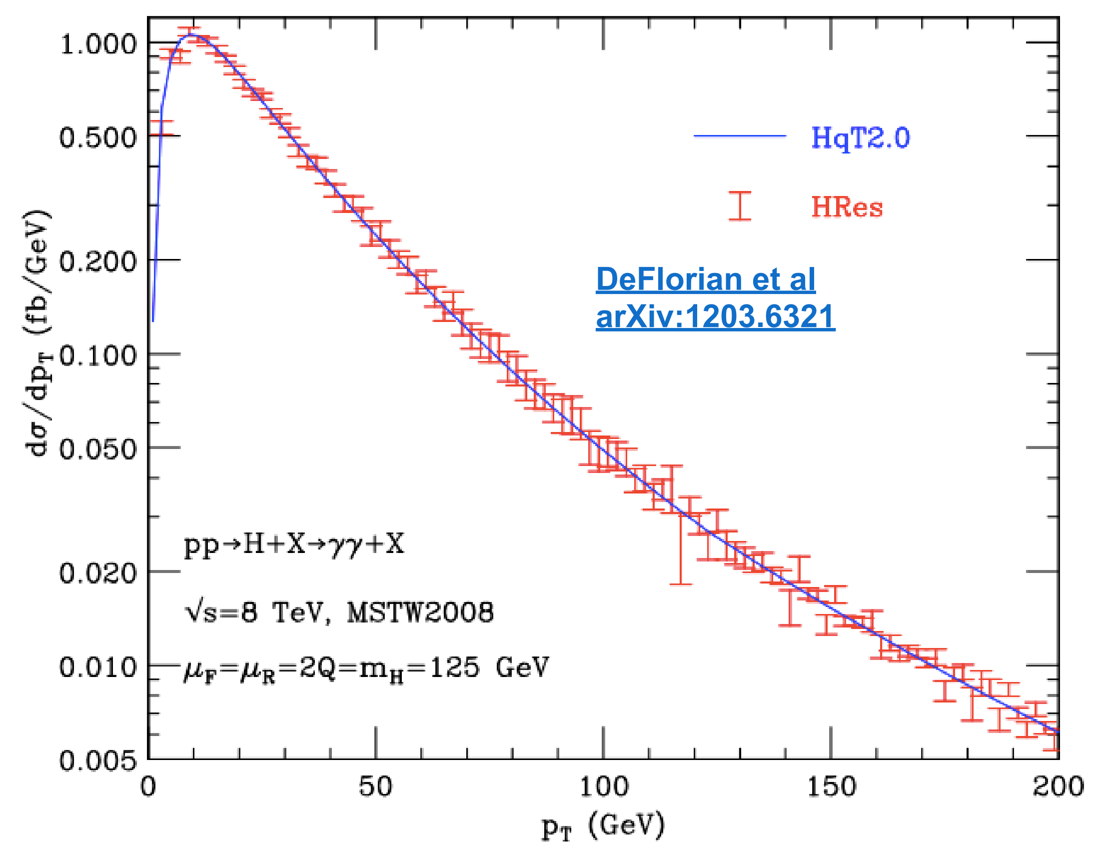
qq → qq H



Higgs XS WG, vol 2

- p_T(peak)~60 GeV
- Large size of EW corrections

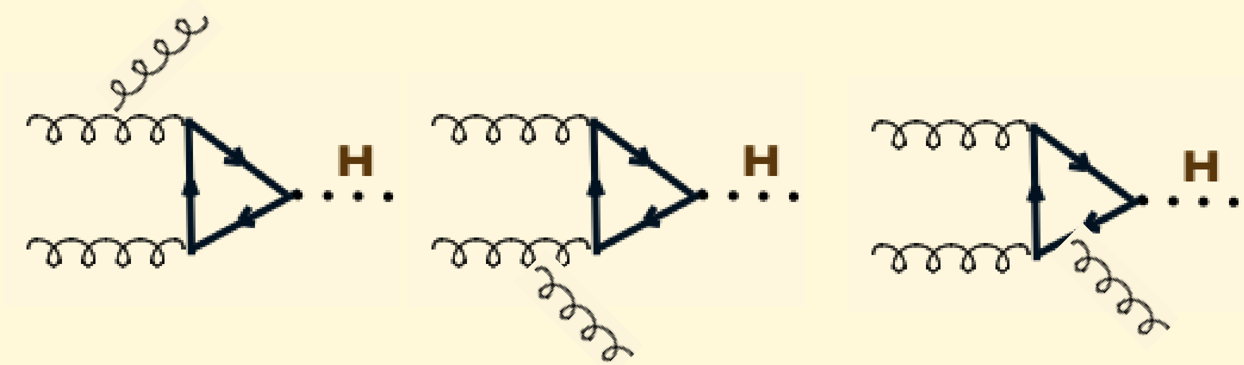
gg → H



DeFlorian et al
arXiv:1203.6321

- p_T(peak)~10 GeV

gg→H at $p_T > m_{top}$ resolves the inside of the production triangle, an alternative probe to its components

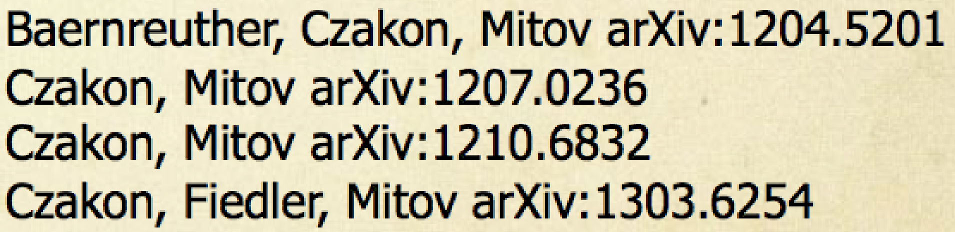


Recent progress in NNLO

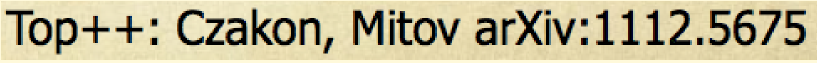
- **Two long-awaited milestone calculations in progress, delivering first results:**

  - **Jet production**. Completed so far:
    - gg initial state: A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover, J. Pires, **arXiv:1301.7310**

  - **$\sigma(tt)$** (Czakon, Mitov et al): full results available for total cross section, at NNLO+NNLL


Baernreuther, Czakon, Mitov arXiv:1204.5201
Czakon, Mitov arXiv:1207.0236
Czakon, Mitov arXiv:1210.6832
Czakon, Fiedler, Mitov arXiv:1303.6254

    - implemented in a numerical code

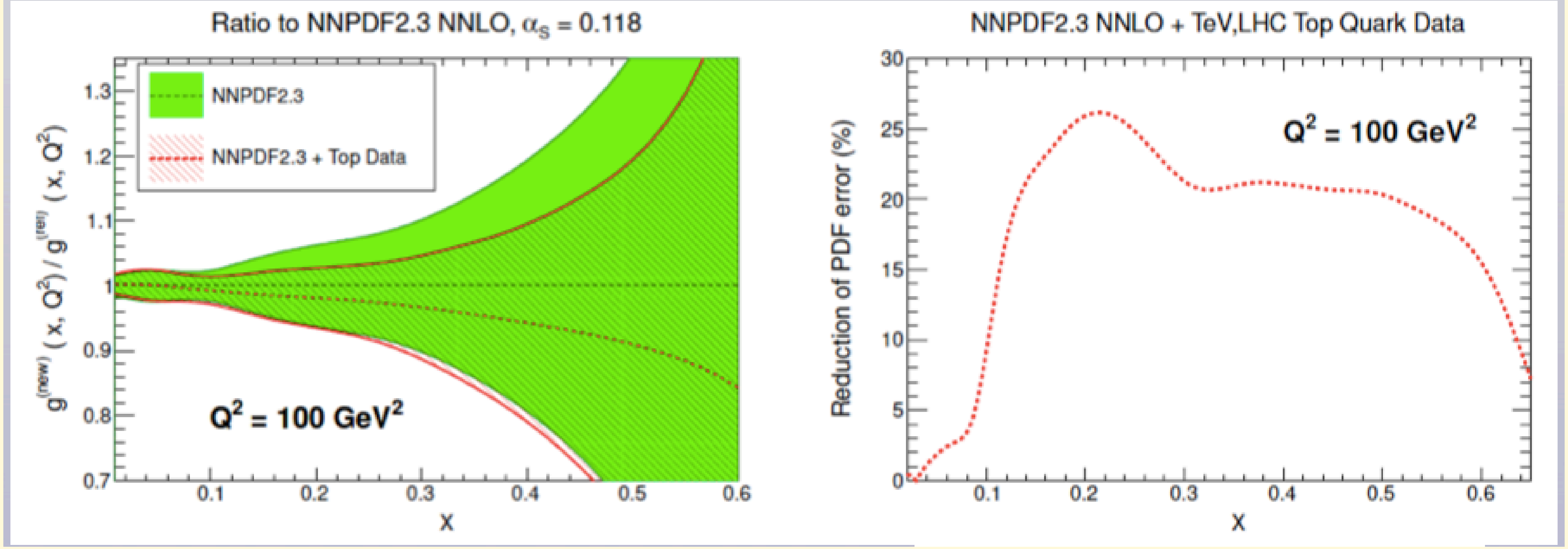

Top++: Czakon, Mitov arXiv:1112.5675

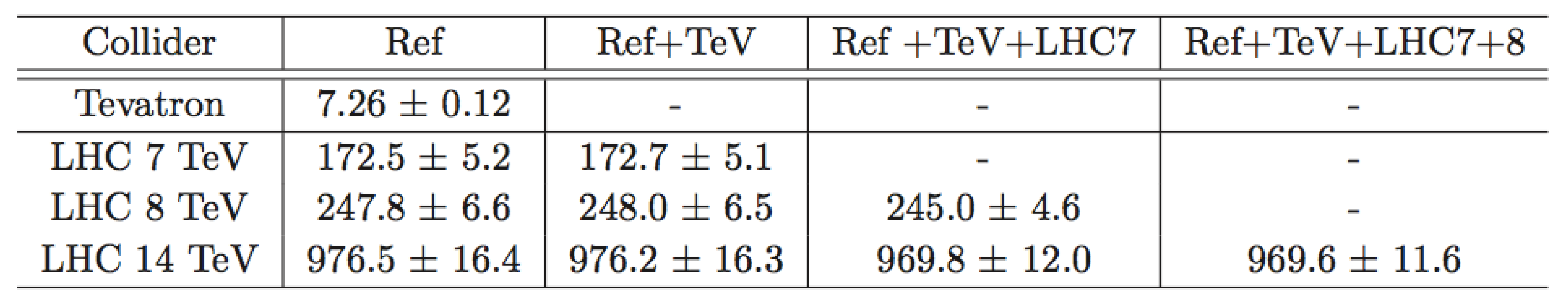
    - first NNLO result for production of coloured final state in hadron collisions, first direct probe of gluon PDF known to NNLO

Constraining the gluon PDF with σ(tt)

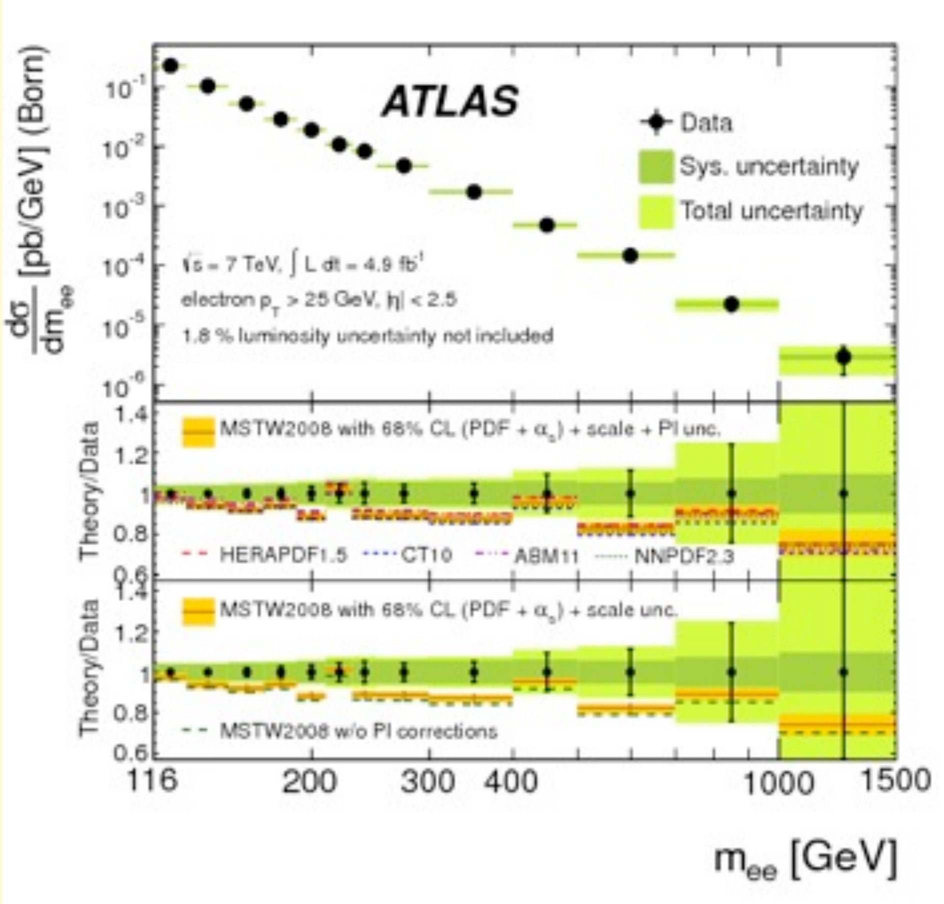
M. Czakon et al arXiv:1303.7215

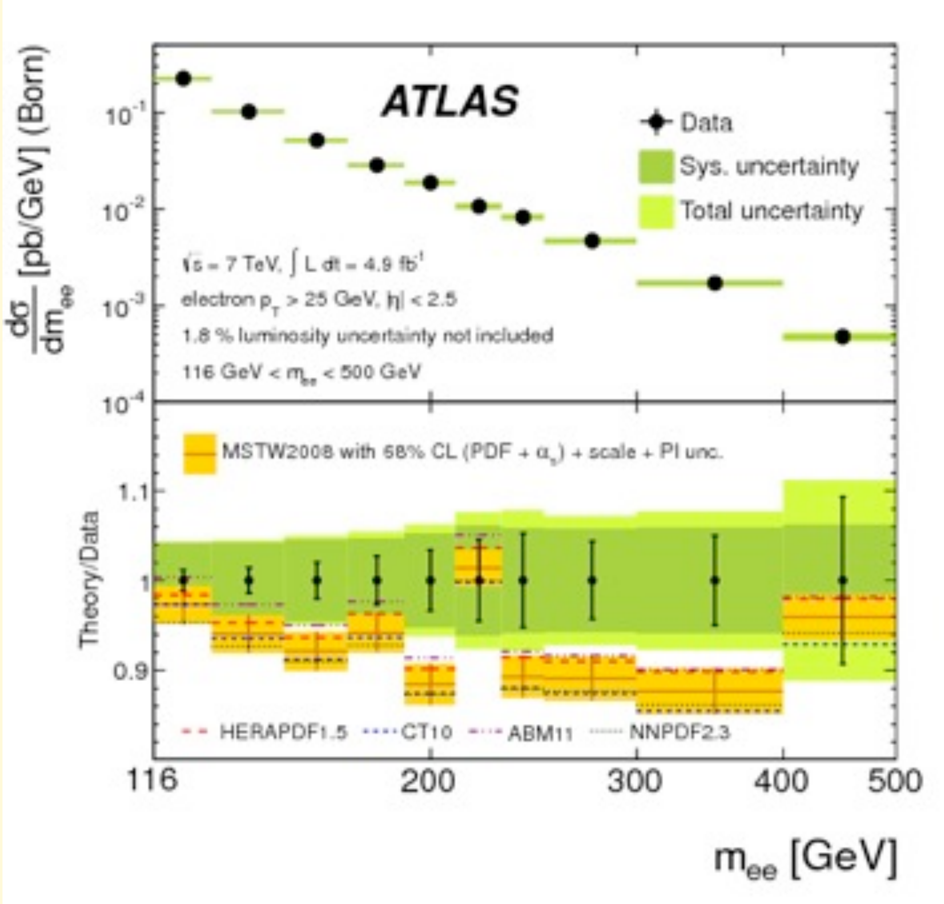
- Top quark cross-section data **discriminates between PDF sets**
- In addition, it can also be used to **reduce the PDF uncertainties** within a single PDF set
- We included the most precise top quark data into the **NNPDF2.3** global PDF analysis





Collider	Ref	Ref+TeV	Ref +TeV+LHC7	Ref+TeV+LHC7+8
Tevatron	7.26 ± 0.12	-	-	-
LHC 7 TeV	172.5 ± 5.2	172.7 ± 5.1	-	-
LHC 8 TeV	247.8 ± 6.6	248.0 ± 6.5	245.0 ± 4.6	-
LHC 14 TeV	976.5 ± 16.4	976.2 ± 16.3	969.8 ± 12.0	969.6 ± 11.6

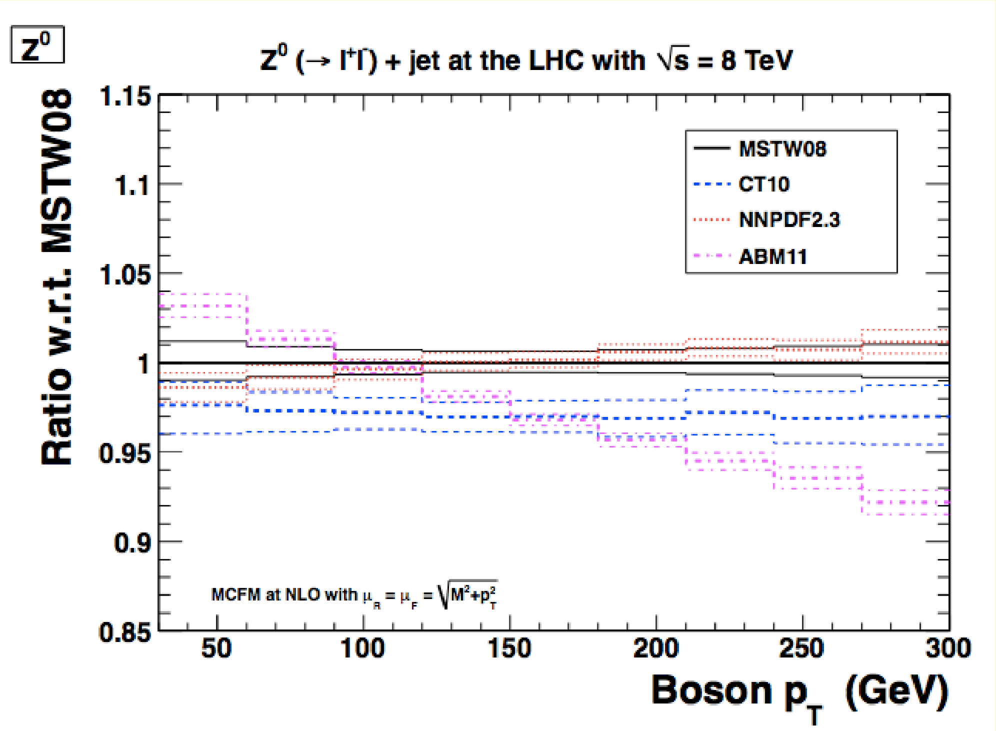


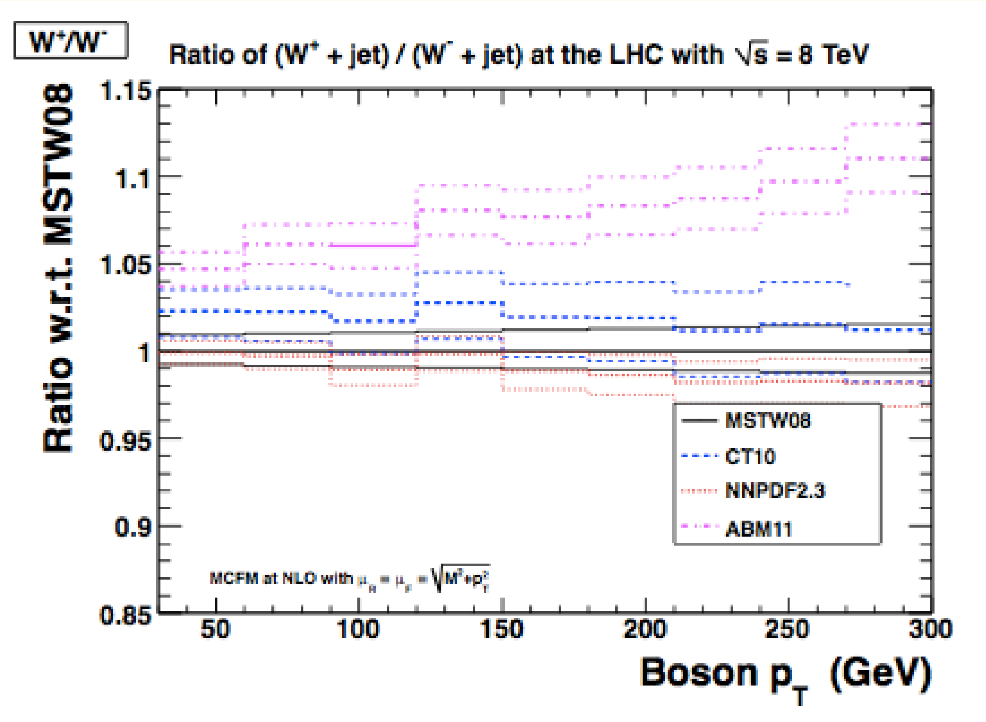


ATLAS, Phys.Lett. B725 (2013) 223-242 arXiv:1305.4192

Large-pt production of gauge bosons as a probe of gluon PDF in the region of relevance to gg→H production

S.Malik and G.Watt, arXiv:1304.2424





⇒ **excellent motivation to undertake the calculation of $d\sigma/dp_T(V)$ at NNLO !!**

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

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

→

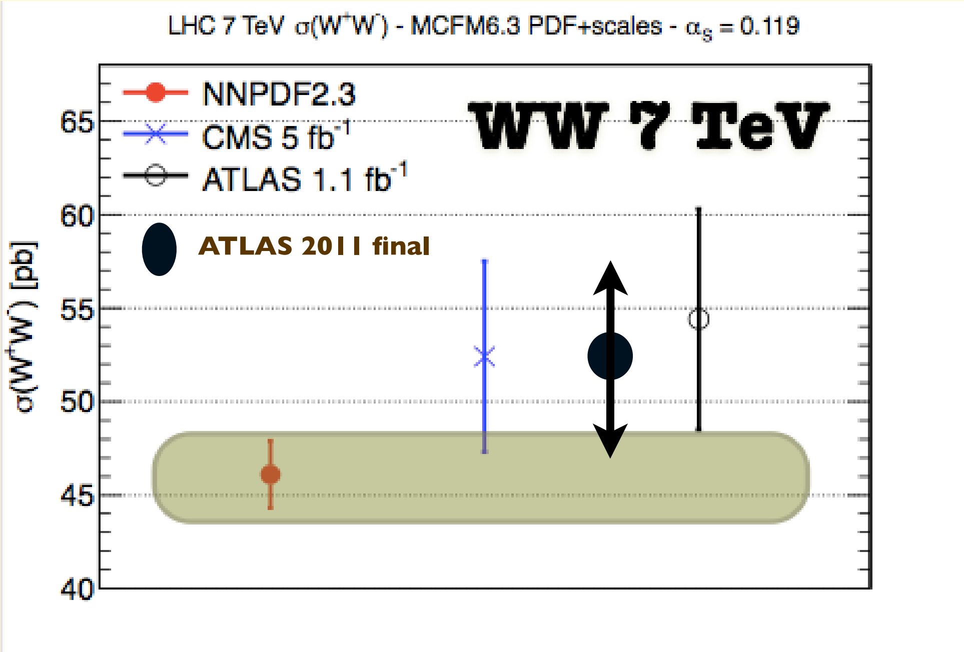
- TH: reduce "scale uncertainties"
- TH: reduce parameters' systematics: PDF, m_{top}, α_S, ... at E_1 and E_2 are fully correlated
- TH: reduce MC modeling uncertainties
- EXP: reduce syst's from acceptance, efficiency, JES, ...

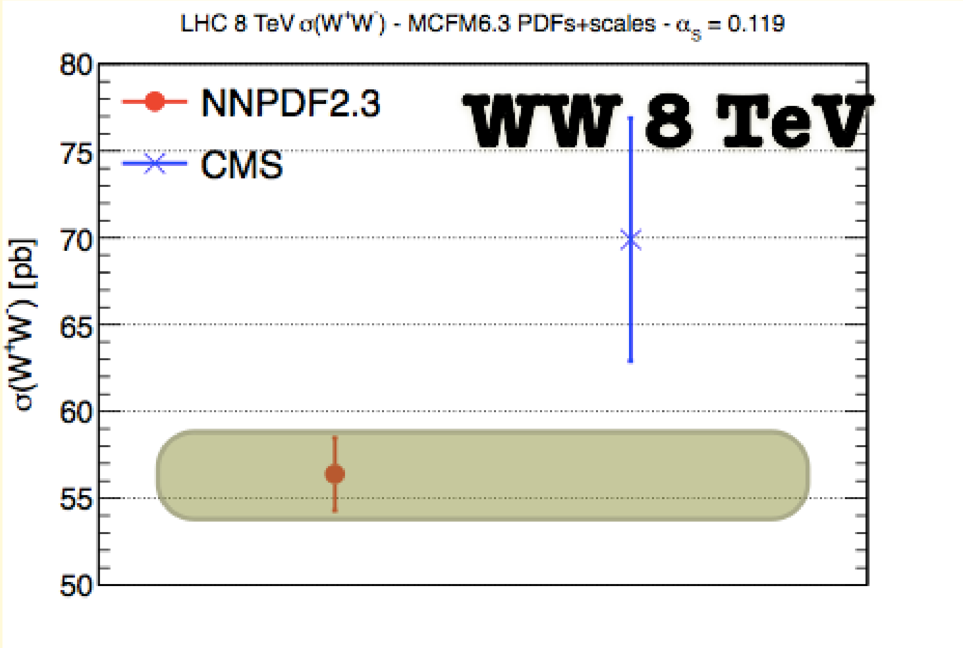
$$R_{E_2/E_1}(X,Y) \equiv \frac{\sigma(X,E_2)/\sigma(Y,E_2)}{\sigma(X,E_1)/\sigma(Y,E_1)} \equiv \frac{R_{E_2/E_1}(X)}{R_{E_2/E_1}(Y)}$$

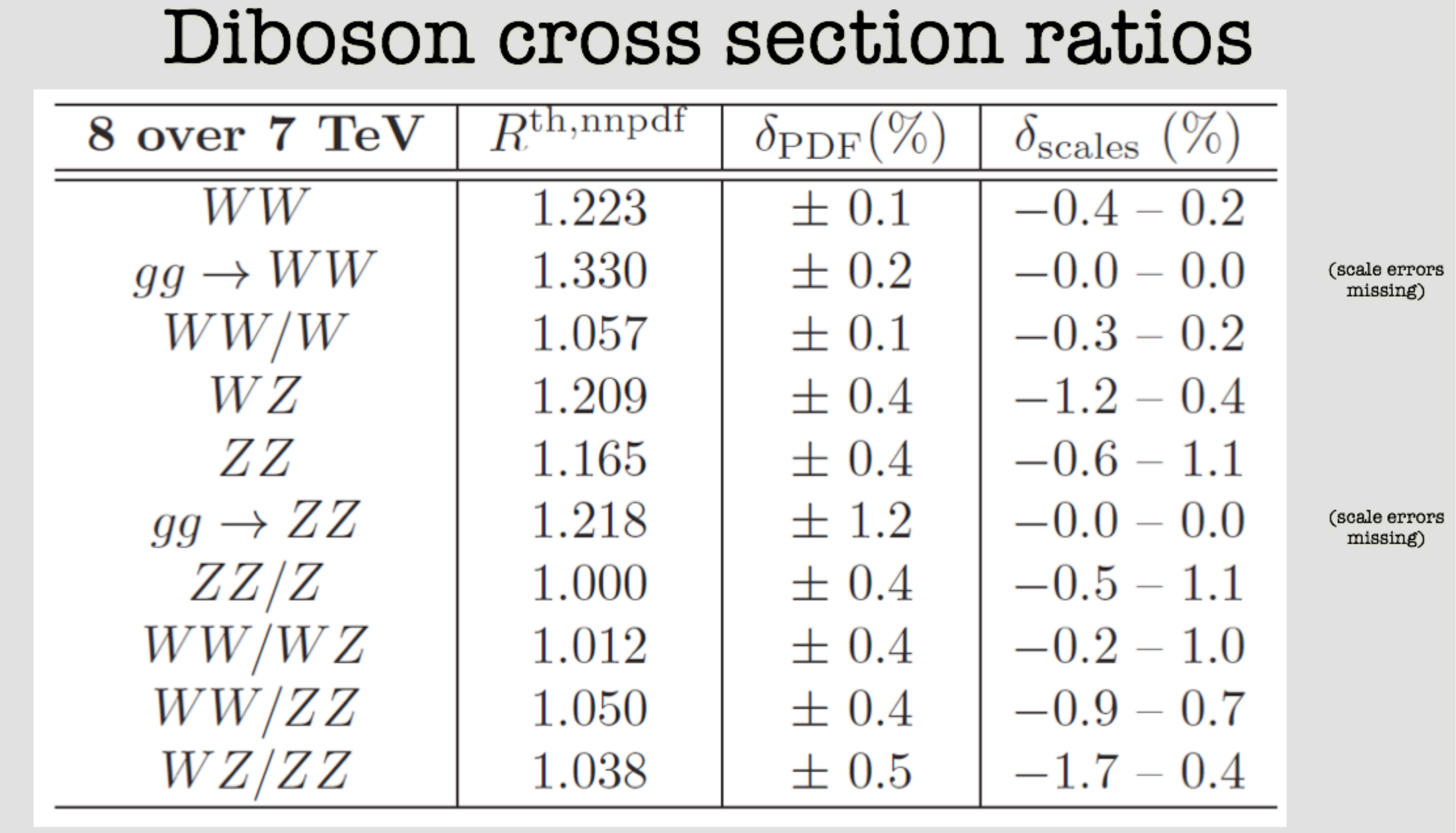
→

- 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







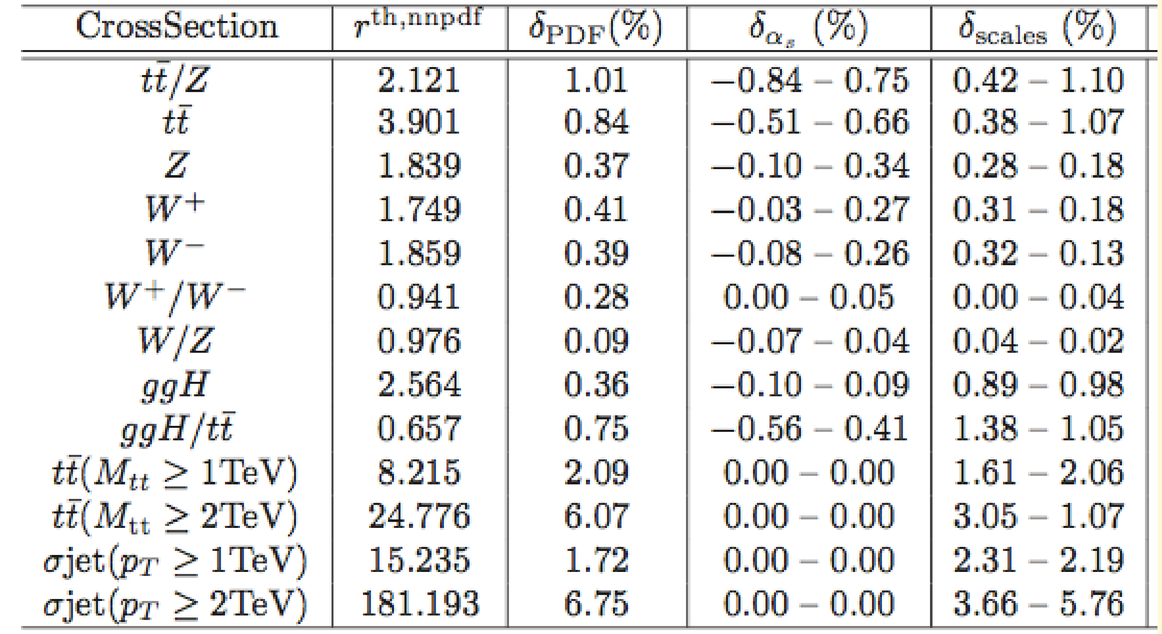
Diboson cross section ratios

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

(scale errors missing)

(scale errors missing)

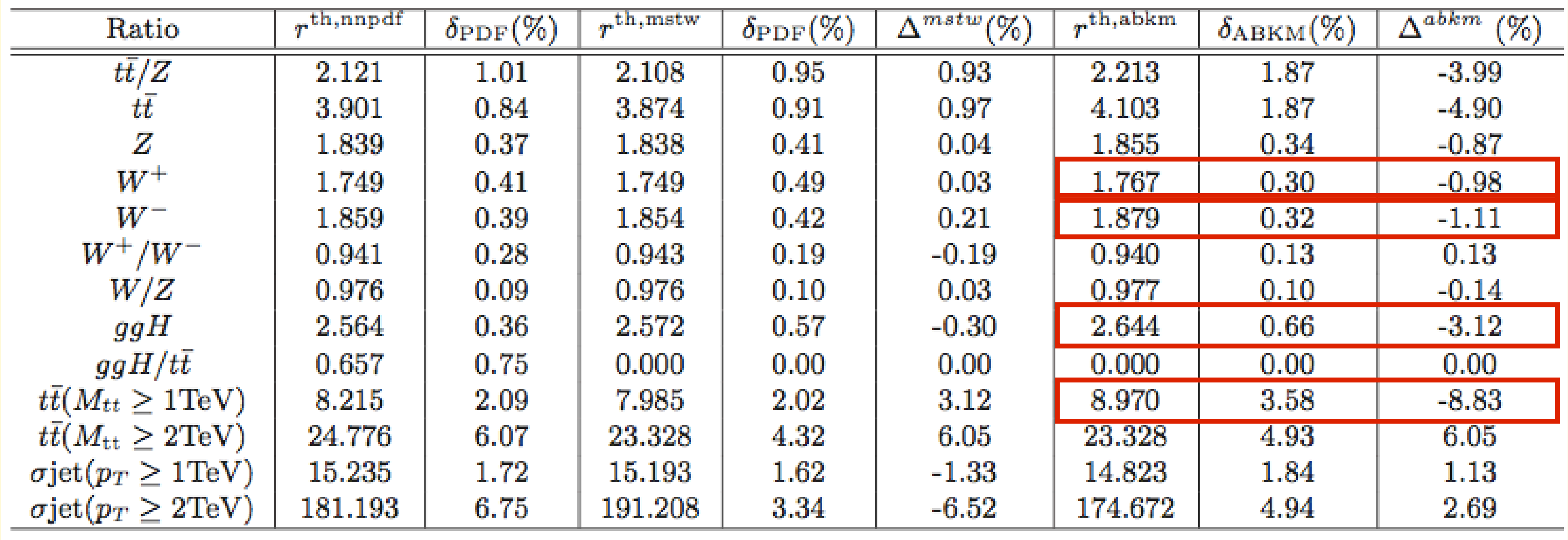
14 TeV / 8 TeV: NNPDF results



CrossSection	$r^{th,nnpdf}$	$\delta_{PDF}(\%)$	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
$t\bar{t}(M_{tt} \geq 1\text{TeV})$	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
σjet($p_T \geq 1\text{TeV}$)	15.235	1.72	0.00 – 0.00	2.31 – 2.19
σjet($p_T \geq 2\text{TeV}$)	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
- $\delta\sim10^{-2}$ 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

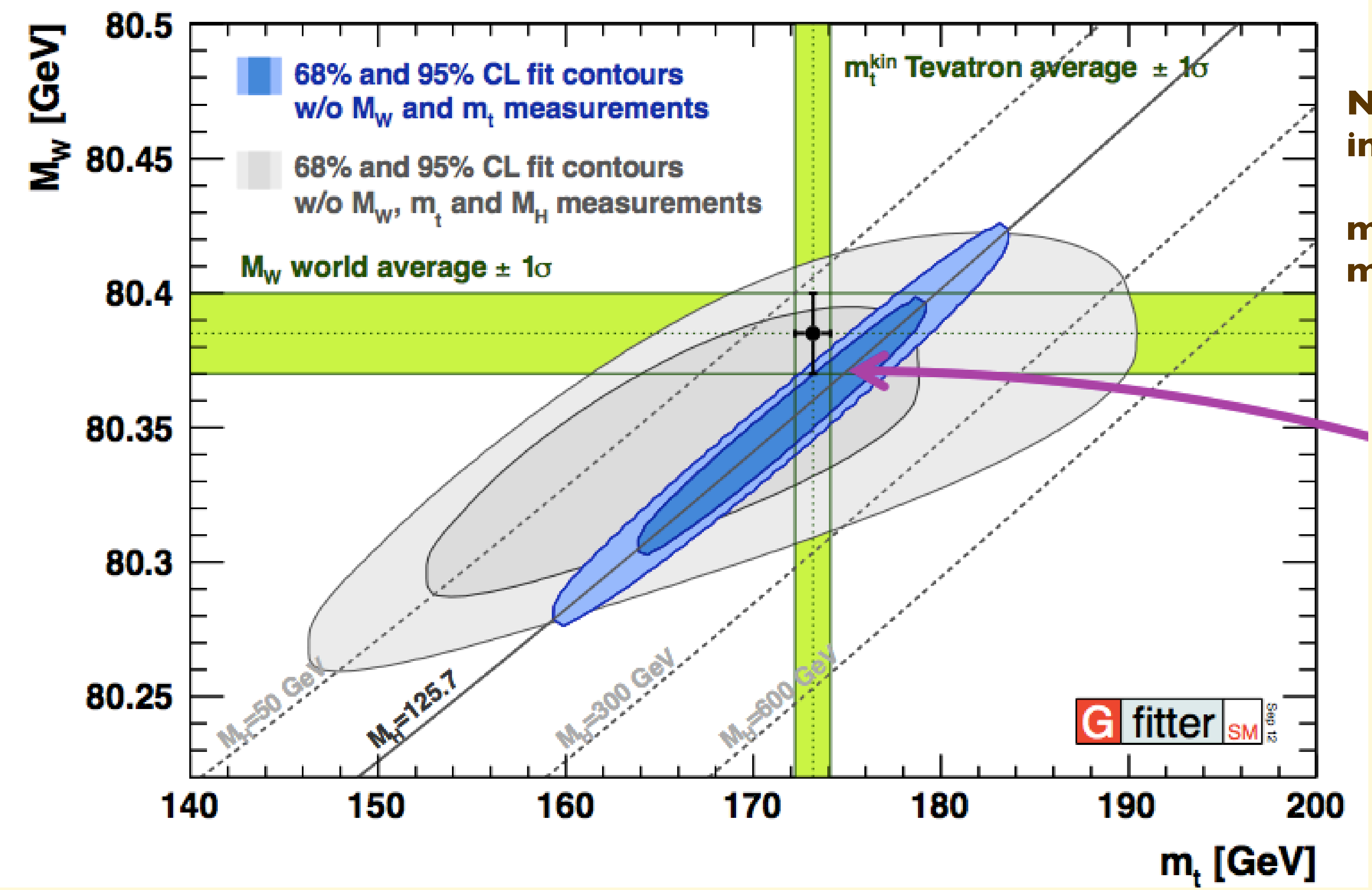


Ratio	$r^{th,nnpdf}$	$\delta_{PDF}(\%)$	$r^{th,mstw}$	$\delta_{PDF}(\%)$	$\Delta^{mstw}(\%)$	$r^{th,abkm}$	$\delta_{ABKM}(\%)$	Δ^{abkm} (%)
$t\bar{t}/Z$	2.121	1.01	2.108	0.95	0.93	2.213	1.87	-3.99
$t\bar{t}$	3.901	0.84	3.874	0.91	0.97	4.103	1.87	-4.90
Z	1.839	0.37	1.838	0.41	0.04	1.855	0.34	-0.87
W^+	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
$t\bar{t}(M_{tt} \geq 1\text{TeV})$	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
σjet($p_T \geq 1\text{TeV}$)	15.235	1.72	15.193	1.62	-1.33	14.823	1.84	1.13
σjet($p_T \geq 2\text{TeV}$)	181.193	6.75	191.208	3.34	-6.52	174.672	4.94	2.69

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

Top quark and W mass

Inclusion of m_H in EW fits greatly tightens correlation between m_W and m_{top}
introducing perhaps a slight tension ?

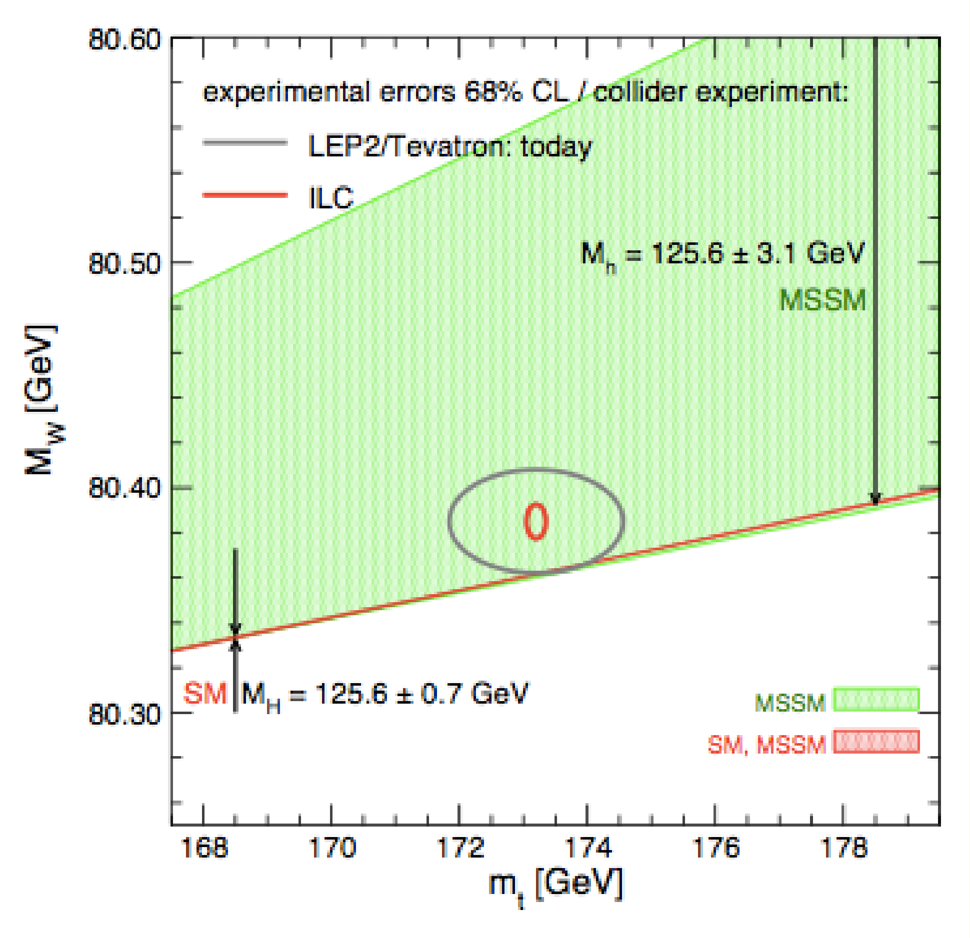


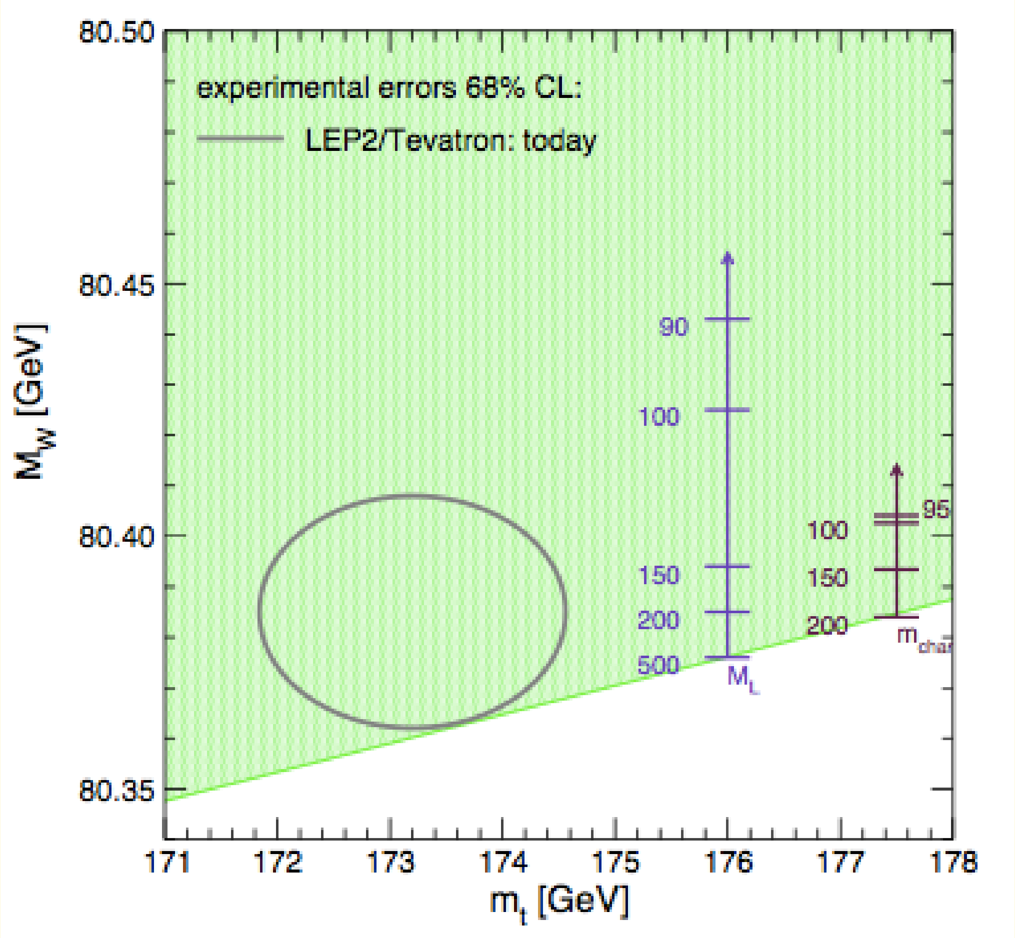
New EW fit results, including m_{Higgs} :

m_{top} = 175.8$^{+2.7}_{-2.4}$ GeV
m_W = 80359 ± 11 MeV

Continued improvement in the direct determination of m_W and m_{top} remains a high priority

Tension released in the MSSM:

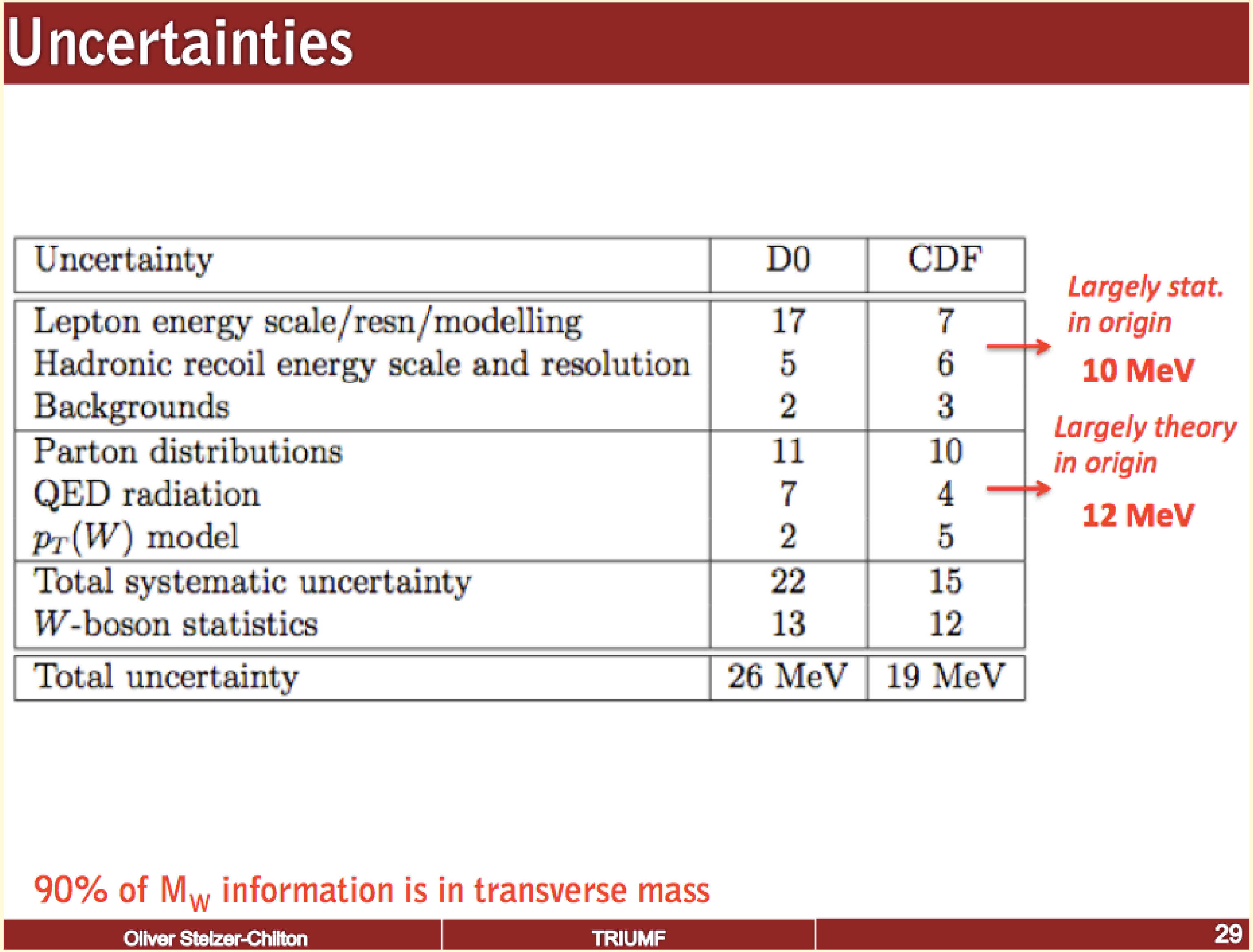




S.Heinemeyer et al, arXiv:1311.1663v1

Tevatron combined W mass: M_W =80387±16 MeV

Tevatron+LEP2 combined W mass: M_W =80385±15 MeV



Uncertainties

Uncertainty	D0	CDF
Lepton energy scale/resn/modelling	17	7
Hadronic recoil energy scale and resolution	5	6
Backgrounds	2	3
Parton distributions	11	10
QED radiation	7	4
$p_T(W)$ model	2	5
Total systematic uncertainty	22	15
W-boson statistics	13	12
Total uncertainty	26 MeV	19 MeV

Largely stat. in origin → **10 MeV**

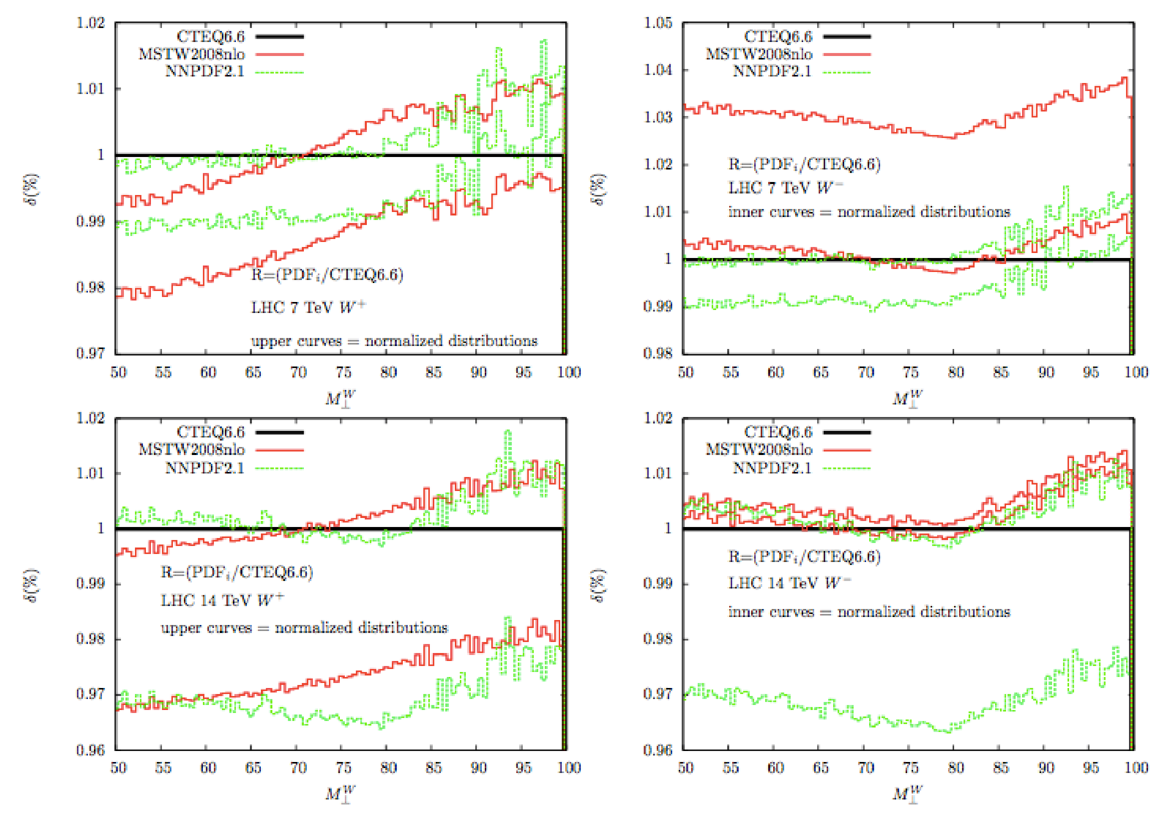
Largely theory in origin → **12 MeV**

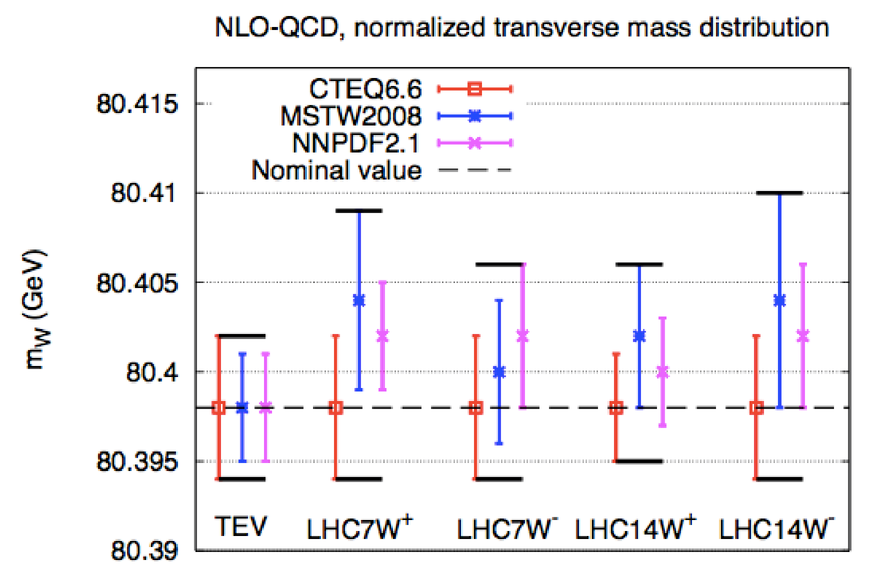
90% of M_W information is in transverse mass

Oliver Stelzer-Chilton | TRIUMF | 29

Predictions for PDF-induced TH syst at the LHC

Bozzi, Rojo, Vicini, arXiv:1104.2056, updated in arXiv:1309.1311





Theory syst:
$\Delta m_W \simeq \pm 8$ MeV

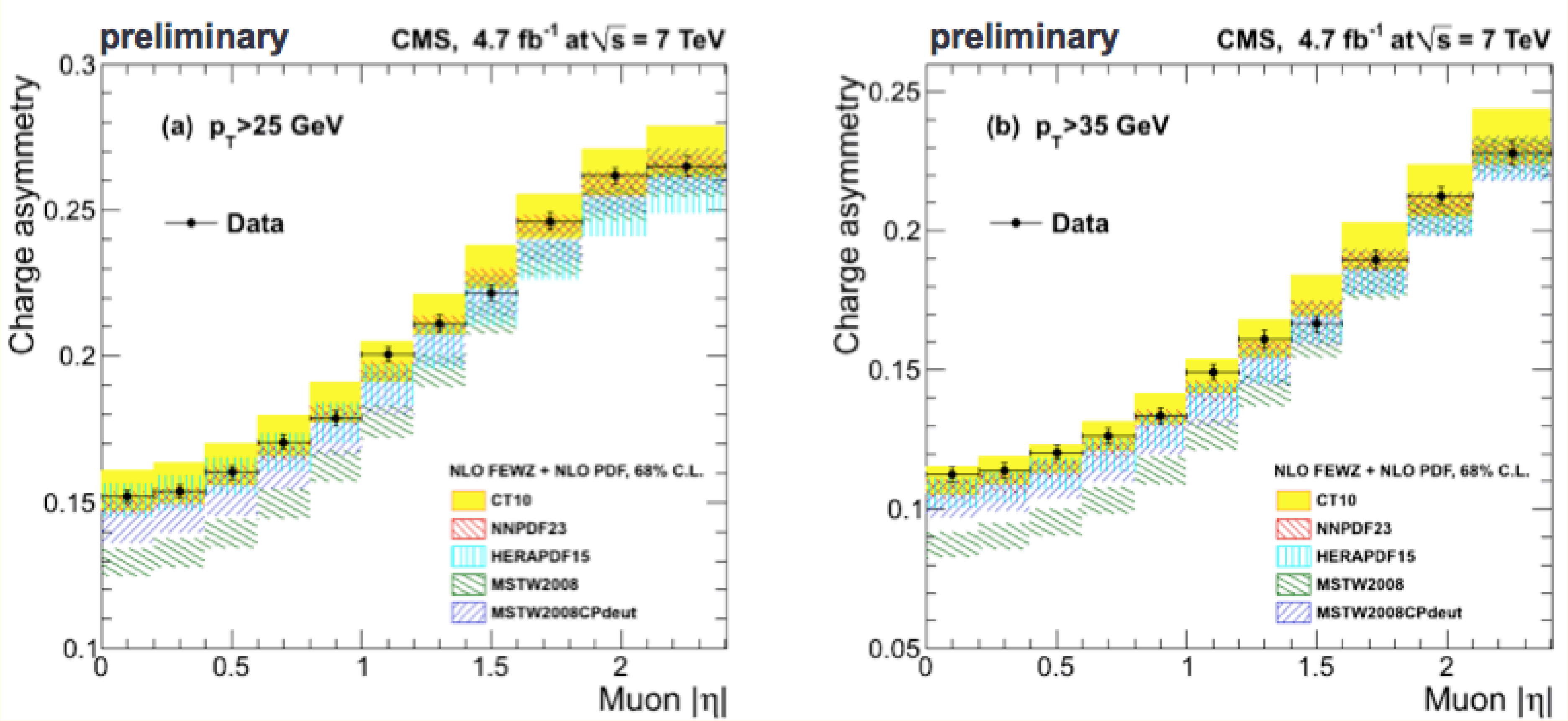
- This uncertainty should be further reduced, to be confident that it's negligible in the context of a measurement with a total systematics of less than ± 20 MeV

- These systematics should be validated through dedicated measurements: can one extract at the same time PDF and m_W from the fit of the relevant distributions (e.g. pt(e))?

- there remain issues raised by Krasny et al, Eur. Phys. J. C 69, 379 (2010) which are not fully addressed by this study (e.g. the impact of the charm mass in using pt(Z) to model pt(W)

There is still room to further constrain PDF distributions relevant for W/Z production properties.

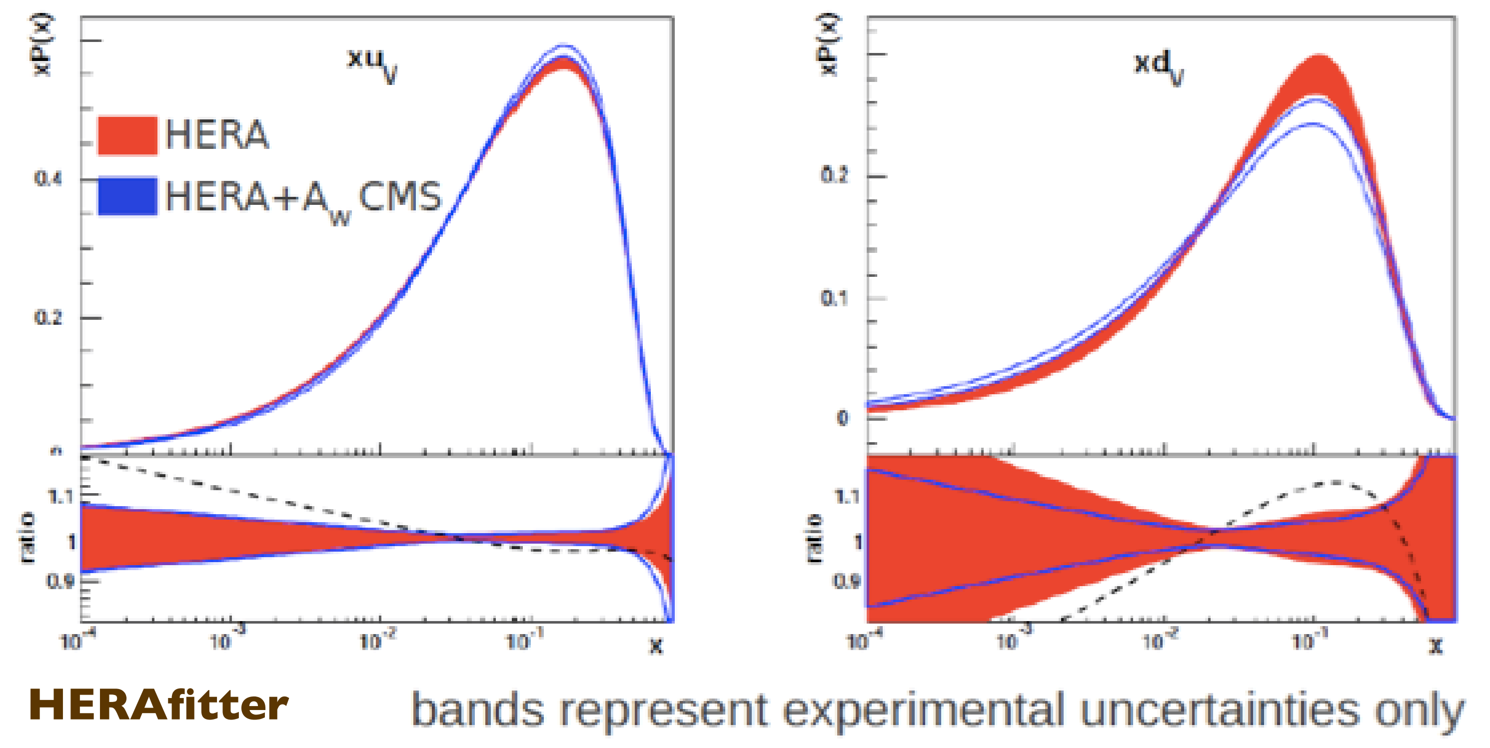
CMS-PAS-SMP-12-021



Questions:

- How do we convince ourselves that we are actually fitting the PDFs, and not missing higher-order QCD or EW effects in the matrix elements?
- Would this have an impact in the extraction of m_W ?

Impact of CMS W-asymmetry data on the fit of u,d(x) using HERA data only



bands represent experimental uncertainties only

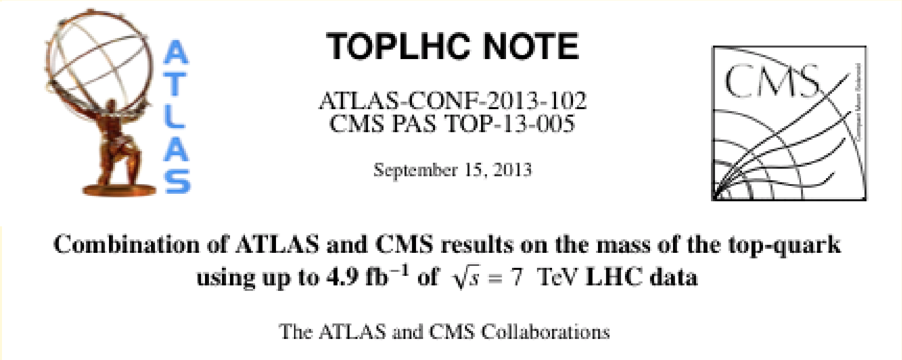
R. Placakyte, A. Vargas, http://indico.cern.ch/getFile.py/access?contribId=4&resId=0&materialId=slides&confId=238762
A.Khukhunaishvili, CCT Sept 12, http://indico.cern.ch/conferenceDisplay.py?confId=270169

Top quark mass

Tevatron combination:

m_{top} = 173.20 ± 0.51 (stat) ± 0.71 (syst) = 173.20 ± 0.87 GeV

LHC combination:



TOPLHC NOTE

ATLAS-CONF-2013-102
CMS PAS TOP-13-005

September 15, 2013

Combination of ATLAS and CMS results on the mass of the top-quark using up to 4.9 fb^{-1} of $\sqrt{s} = 7$ TeV LHC data

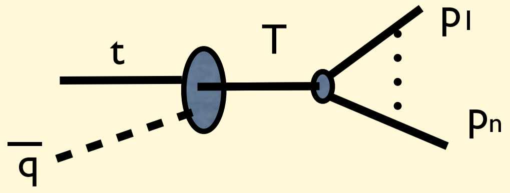
The ATLAS and CMS Collaborations

m_{top} = 173.29 ± 0.23 (stat) ± 0.92 (syst) = 173.29 ± 0.95 GeV

!!!!!!!!!!!!!!!!!!!!!!!!

Definition of m_{top}

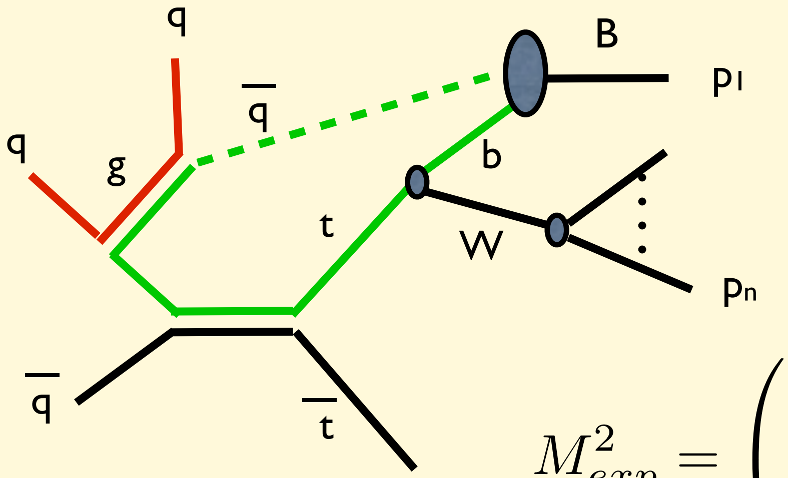
If Γ_{top} were < 1 GeV, top would hadronize before decaying. Same as b-quark



$$m_T^2 = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

$m_t = F_{\text{lattice/potential models}}\,(m_T, \alpha_{QCD})$

But Γ_{top} is > 1 GeV, top decays before hadronizing. Extra antiquarks must be added to the top-quark decay final state in order to produce the physical state whose mass will be measured



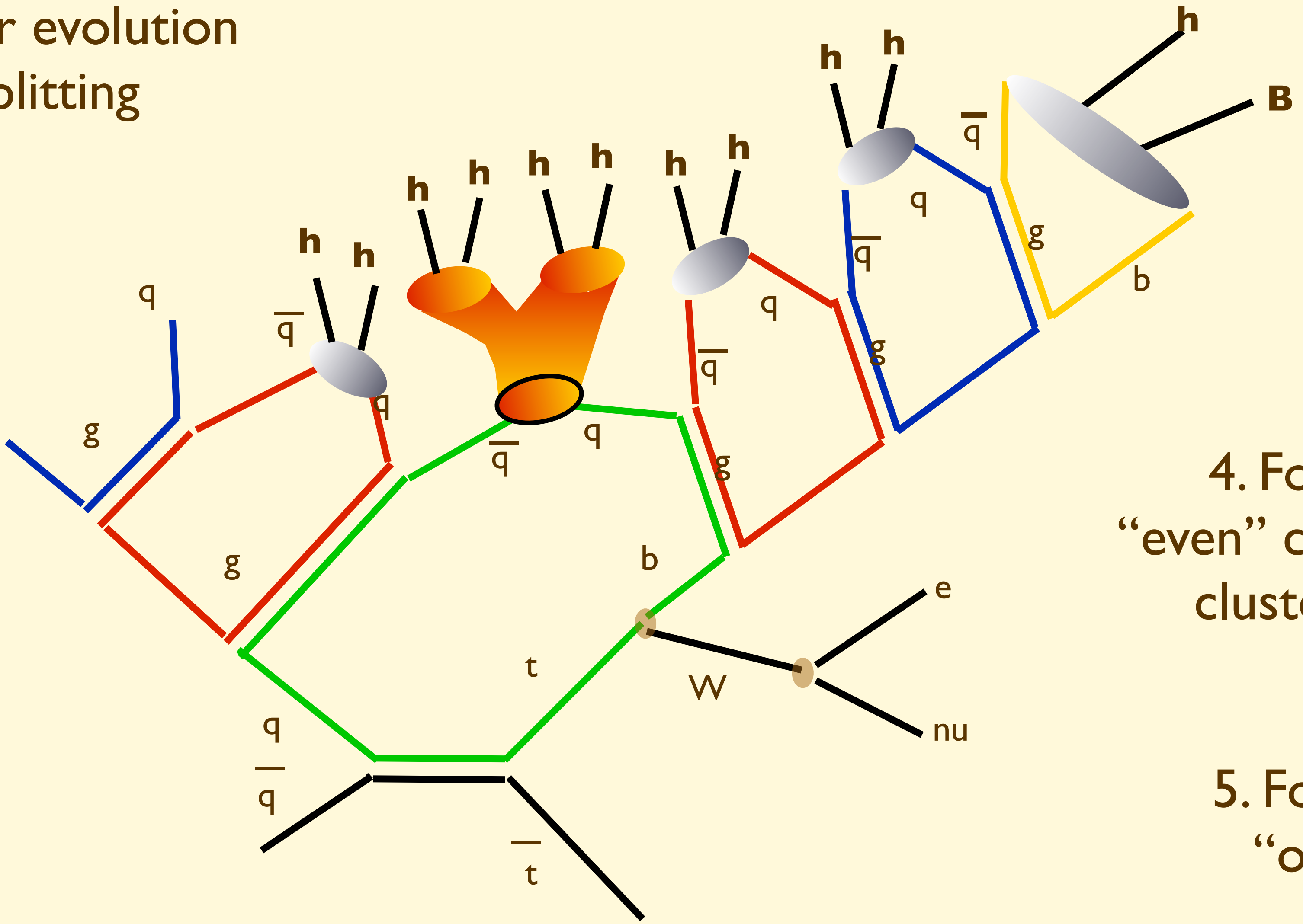
$$M_{exp}^2 = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

As a result, M_{exp} is not equal to m^{pole}_{top}, and will vary in each event, depending on the way the event has evolved.

The top mass extracted in hadron collisions is not well defined below a precision of $O(\Gamma_{top})\sim 1$ GeV

Goal:
- correctly quantify the systematic uncertainty
- identify observables that allow to validate the theoretical modeling of hadronization in top decays
- identify observables less sensitive to these effects

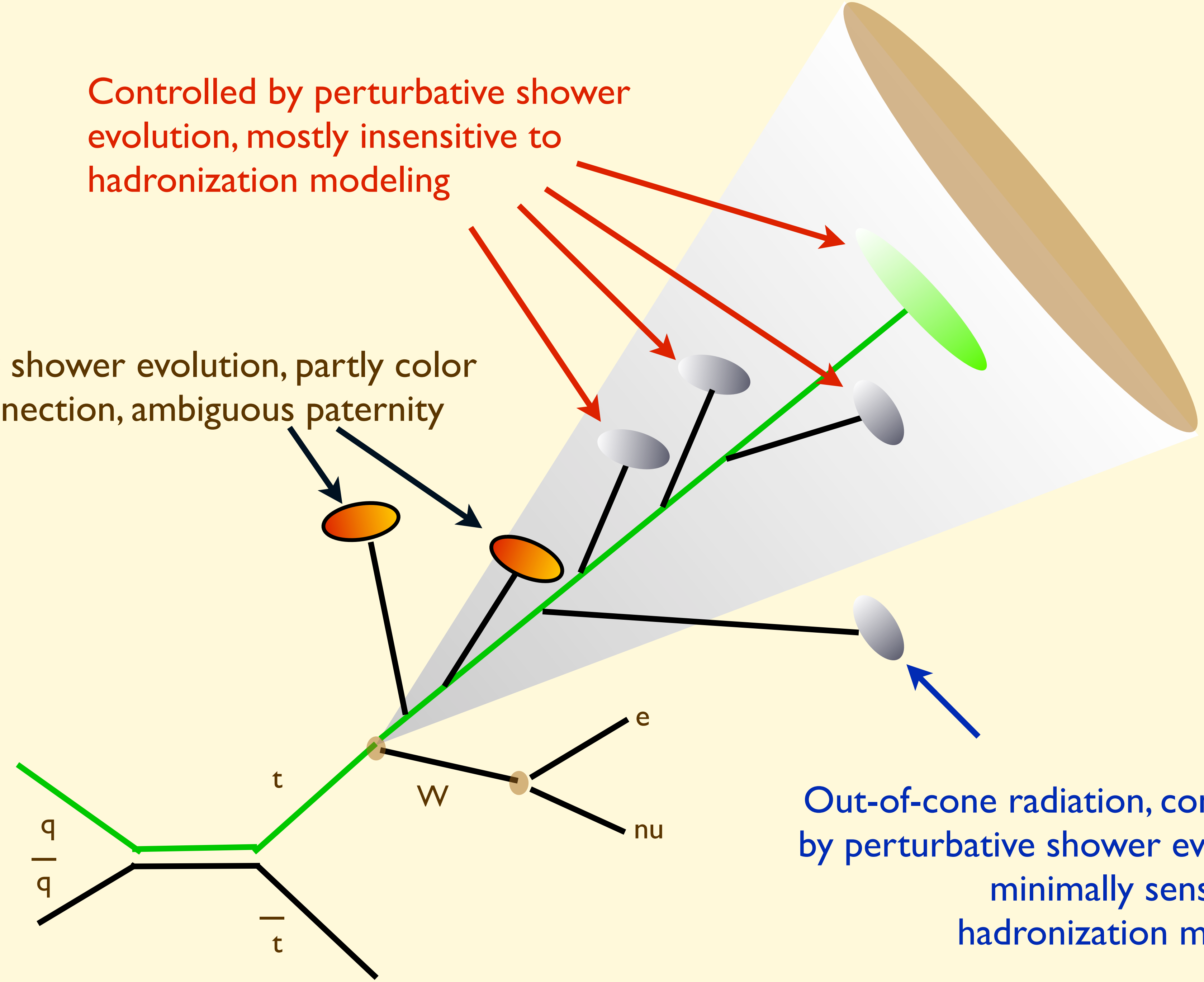
1. Hard Process
2. Shower evolution
3. Gluon splitting



4. Formation of “even” clusters and cluster decay to hadrons

5. Formation of “odd” cluster

6. Decay of “odd” clusters, if large cluster mass, and decays to hadrons



Controlled by perturbative shower evolution, mostly insensitive to hadronization modeling

Partly shower evolution, partly color reconnection, ambiguous paternity

Out-of-cone radiation, controlled by perturbative shower evolution, minimally sensitive to hadronization modeling

A good way to assess the relevance of these effects and the reliability of the MC modeling is to monitor the dependence of the reconstructed m_{top} on the production environment. E.g.

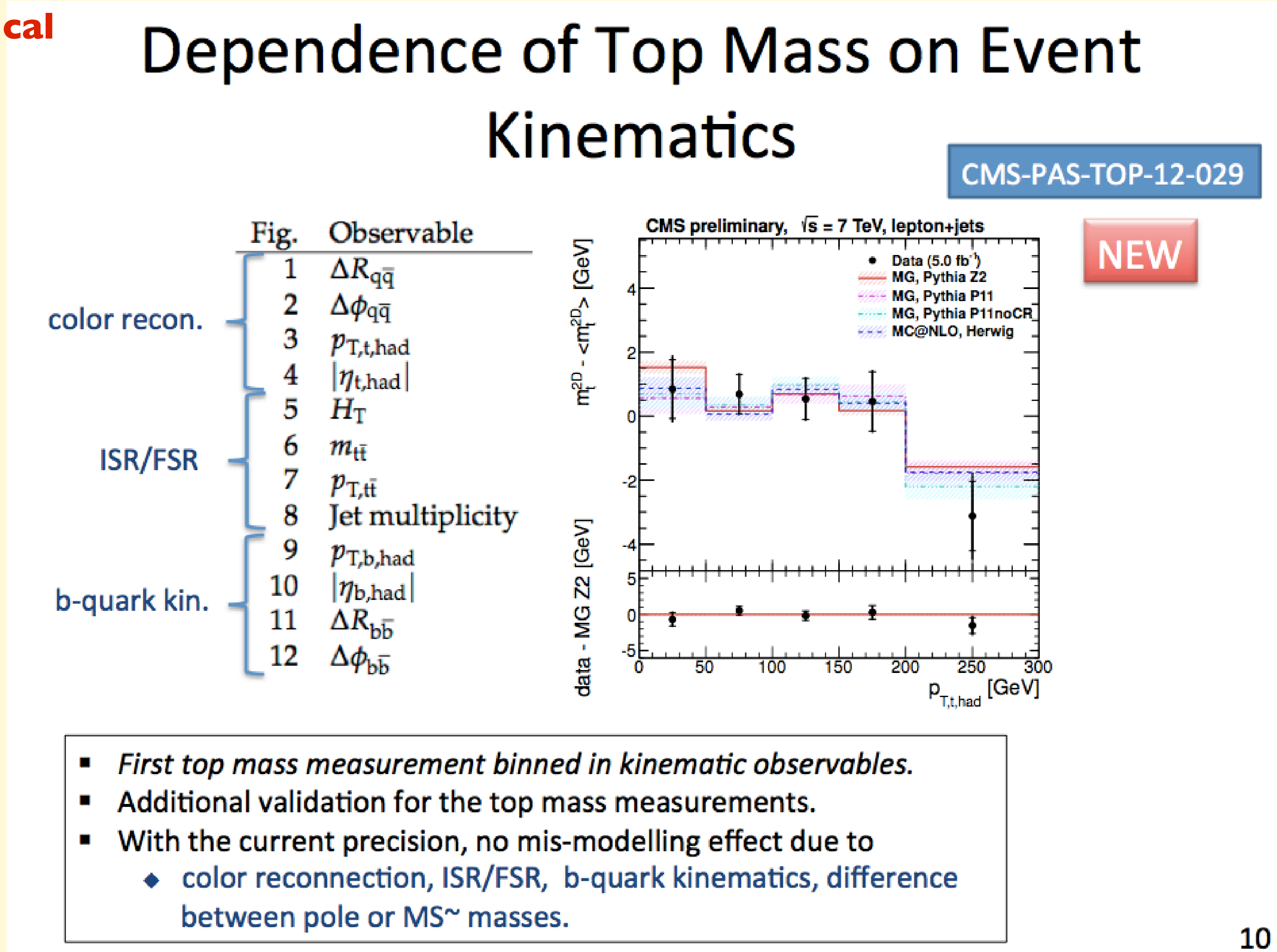
- m_{top} vs pt

- pp → t tbar implies that hadronization of top decay products differs from hadronization of tbar decay products ⇒ m_t vs m_{tbar} at the LHC probes possible hadronization systematics

- q qbar → t tbar vs gg → t tbar ⇒ m_{top}(Tevatron) vs m_{top}(LHC) is a probe of hadronization systematics

- ditto for m_{top} from single top events

First studies of kinematical dependence of top mass reconstruction, CMS



Dependence of Top Mass on Event Kinematics

CMS-PAS-TOP-12-029

NEW

	Fig.	Observable
color recon.	1	$\Delta R_{q\bar{q}}$
	2	$\Delta\phi_{q\bar{q}}$
	3	$p_{T,t,had}$
	4	$\lvert\eta_{t,had}\rvert$
ISR/FSR	5	H_T
	6	$m_{t\bar{t}}$
	7	$p_{T,t\bar{t}}$
	8	Jet multiplicity
b-quark kin.	9	$p_{T,b,had}$
	10	$\lvert\eta_{b,had}\rvert$
	11	$\Delta R_{b\bar{b}}$
	12	$\Delta\phi_{b\bar{b}}$

- *First top mass measurement binned in kinematic observables.*
- Additional validation for the top mass measurements.
- With the current precision, no mis-modelling effect due to
  - color reconnection, ISR/FSR, b-quark kinematics, difference between pole or MS~ masses.

CMS-PAS-TOP-12-031

$$\Delta m_t = m_t^{had} - m_{\bar{t}}^{had} = -272 \pm 196\ (stat) \pm \boxed{122\ (syst.)}\ MeV$$

Pole vs MSbar masses

$$m_{pole} = \overline{m} \times \left[1 + g_1 \frac{\bar{\alpha}}{\pi} + g_2 \left(\frac{\bar{\alpha}}{\pi} \right)^2 + g_3 \left(\frac{\bar{\alpha}}{\pi} \right)^3 \right]$$

where

$$\overline{m} = m_{MS}(m_{MS})$$

$$\bar{\alpha} = \alpha(\overline{m})$$

$$g_1 = \frac{4}{3}$$

$$g_2 = 13.4434 - 1.0414 \sum_k \left(1 - \frac{4}{3} \frac{\overline{m}_k}{\overline{m}} \right)$$

$$g_3 = 0.6527\, n_l^2 - 26.655\, n_l + 190.595$$

Melnikov, van Ritbergen, Phys.Lett. B482 (2000) 99

In the range m_{top} = 171 – 175 GeV, α_S is ~constant, and, using the 3-loop expression above,

$$m_{pole} = \overline{m} \times [1 + 0.047 + 0.010 + 0.003] = 1.060 \times \overline{m}$$

showing an excellent convergence. In comparison, the expansion for the bottom quark mass behaves very poorly:

$$m^b_{pole} = \overline{m}^b \times [1 + 0.09 + 0.05 + 0.04]$$

Assuming that after the 3rd order the perturbative expansion of m_{pole} vs m_{MS} start diverging, the smallest term of the series, which gives the size of the uncertainty in the resummation of the asymptotic series, is of O(0.003 * m), namely O(500 MeV), consistent with Λ_{QCD}

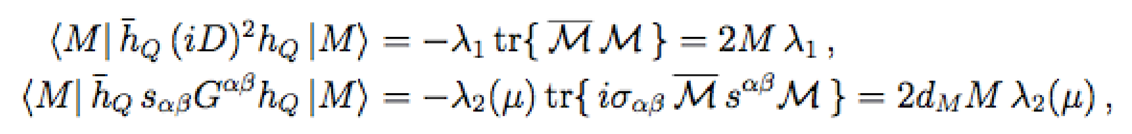
This same O(α_S^3) term gives also: $\overline{m}^{(3-loop)} - \overline{m}^{(2-loop)} = 0.49\,\mathrm{GeV}$

Meson vs hvy-Q masses

Heavy meson ⟹ (point-like color source) + (light antiquark cloud): properties of "light-quark" cloud are independent of mQ for mQ→∞

$$m_M = m_Q + \bar{\Lambda} - \frac{\lambda_1 + 3\lambda_2}{2m_Q}$$

$$m_{M^*} = m_Q + \bar{\Lambda} - \frac{\lambda_1 - \lambda_2}{2m_Q}$$



$$\langle M|\,\bar{h}_Q\,(iD)^2 h_Q\,|M\rangle = -\lambda_1\,\mathrm{tr}\{\,\overline{\mathcal{M}}\,\mathcal{M}\,\} = 2M\,\lambda_1\,,$$
$$\langle M|\,\bar{h}_Q\,s_{\alpha\beta}G^{\alpha\beta}h_Q\,|M\rangle = -\lambda_2(\mu)\,\mathrm{tr}\{\,i\sigma_{\alpha\beta}\,\overline{\mathcal{M}}\,s^{\alpha\beta}\mathcal{M}\,\} = 2d_M M\,\lambda_2(\mu)\,,$$

$d_{M^*} = -1$, $d_M = 3$

See e.g. Falk and Neubert, arXiv:hep-ph/9209268v1

where $\bar{\Lambda},\ \lambda_1,\ \lambda_2$ are independent of m_Q

From the spectroscopy of the B-meson system:

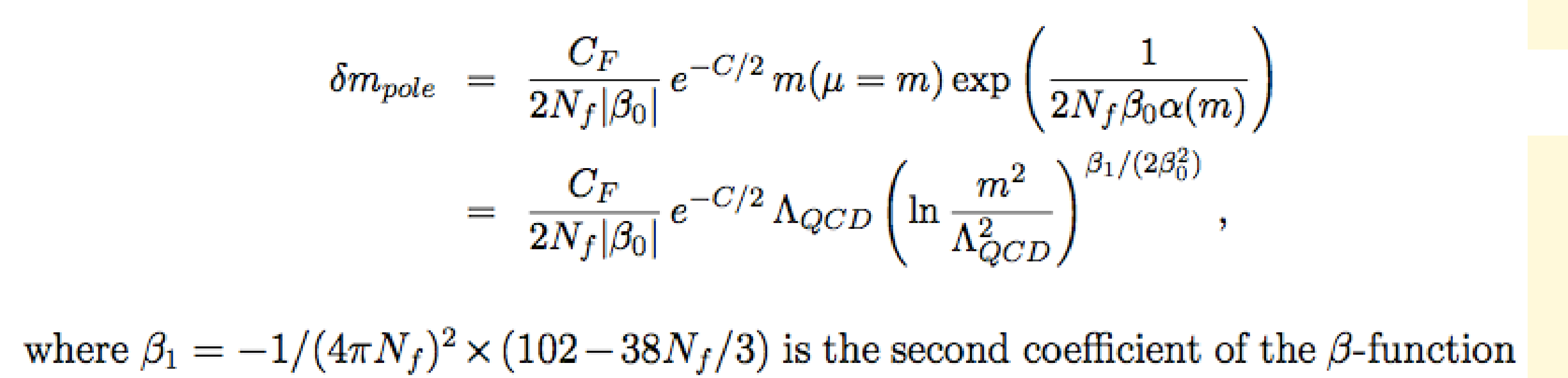
$m(B^*) - m(B) = 2\,\lambda_2/m_b \Rightarrow \lambda_2 \sim 0.15\ \mathrm{GeV}^2$

QCD sum rules: $\lambda_1 \sim 1\ \mathrm{GeV}^2$

QCD sum rules: $\Lambda = 0.5 \pm 0.07$ GeV

thus corrections of $O(\lambda_{1,2}/m_{top})$ are of O(few MeV) and totally negligible

Separation between mQ and Λ is however ambiguous:
renormalon ambiguity on the pole mass:



$$\begin{aligned}\delta m_{pole} &= \frac{C_F}{2N_f|\beta_0|}\, e^{-C/2}\, m(\mu=m)\exp\left(\frac{1}{2N_f\beta_0\alpha(m)}\right)\\ &= \frac{C_F}{2N_f|\beta_0|}\, e^{-C/2}\, \Lambda_{QCD}\left(\ln\frac{m^2}{\Lambda^2_{QCD}}\right)^{\beta_1/(2\beta_0^2)} ,\end{aligned}$$

where $\beta_1 = -1/(4\pi N_f)^2 \times (102-38N_f/3)$ is the second coefficient of the β-function

δm_{pole}=270 MeV for mtop.

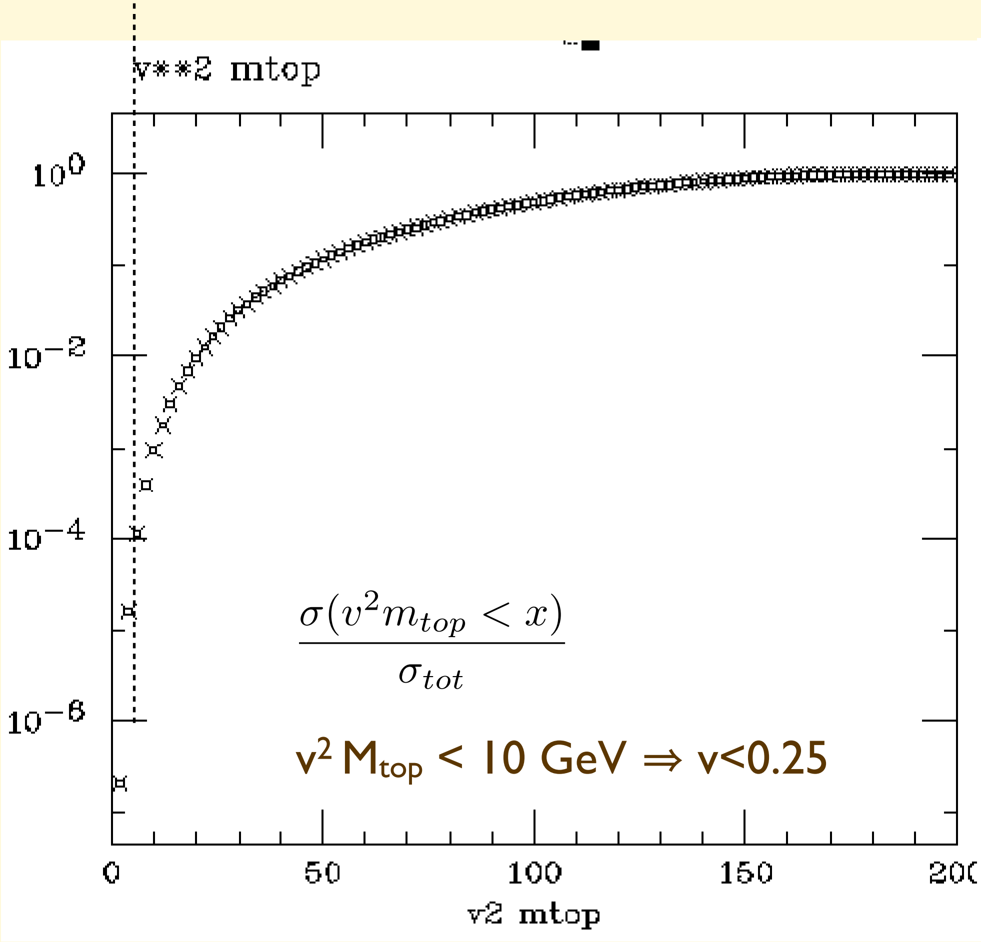
This is smaller than the difference between MSbar masses obtained using the 3-loop or 2-loop MSbar vs pole mass conversion.

It would be very interesting to have a 4-loop calculation of MSbar vs m_{pole}, to check the rate of convergence of the series, and improve the estimate of the m_{pole} ambiguity for the top

Beneke and Braun, Nucl. Phys. B426, 301 (1994)

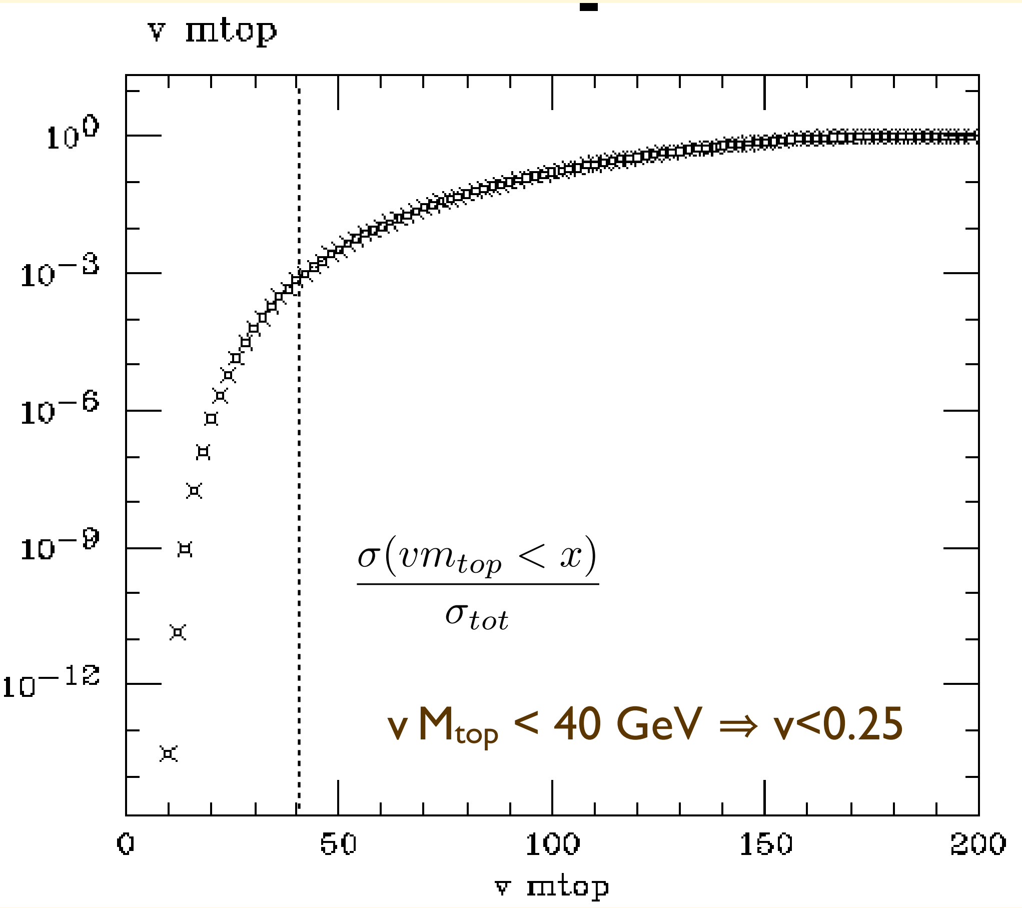
Bigi et al, 1994

Impact of IR sensitive phase-space regions on σ(tt)



$$\frac{\sigma(v^2 m_{top} < x)}{\sigma_{tot}}$$

$v^2\,M_{top} < 10$ GeV ⇒ $v<0.25$



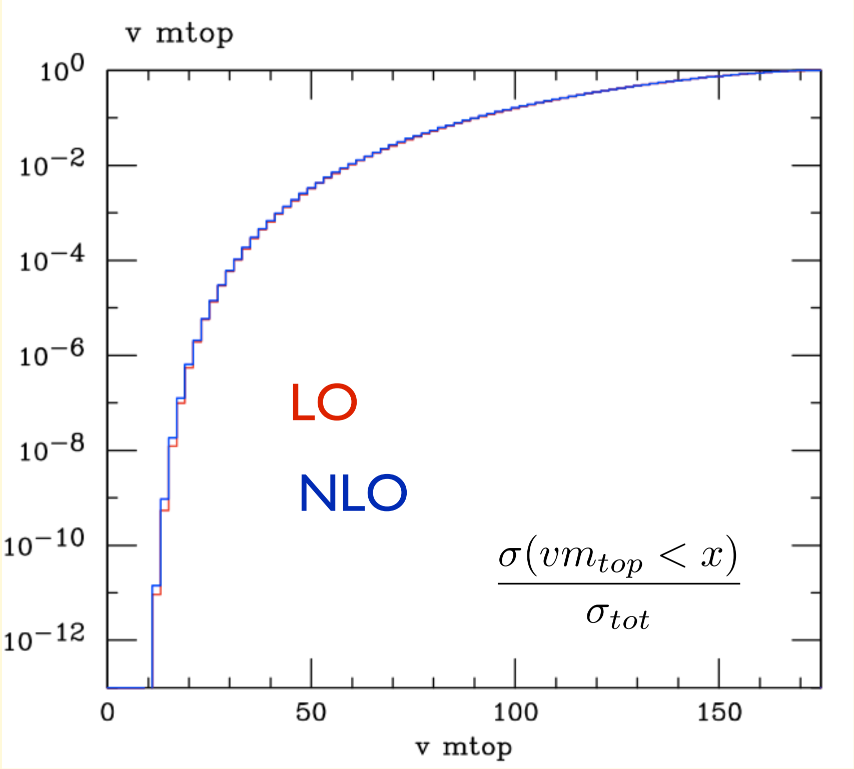
$$\frac{\sigma(v m_{top} < x)}{\sigma_{tot}}$$

$v\,M_{top} < 40$ GeV ⇒ $v<0.25$

$$\frac{1}{\sigma}\frac{\Delta\sigma}{\Delta m} \sim 0.03\,\mathrm{GeV}^{-1}$$

$v^2\,M_{top} < 10$ GeV

The region possibly sensitive to IR effects, $v^2M_{top}<10$ GeV, or $v<0.25$, contributes only 10^{-3} of the total rate.
Uncertainties of the order of 100% in the description of this region only change the extraction of M_{top} from the total rate at the level of 30 MeV



The impact of Coulomb corrections (which first appear at NLO) is confined to values of v that contribute very little to the total cross section

⇒ no evidence that the relation between m_{pole}(top) and total tt cross section in pp(bar) collisions is subject to the same IR problems that enter as main systematics in the extraction of m_{top} from the threshold scan in e^+e^-

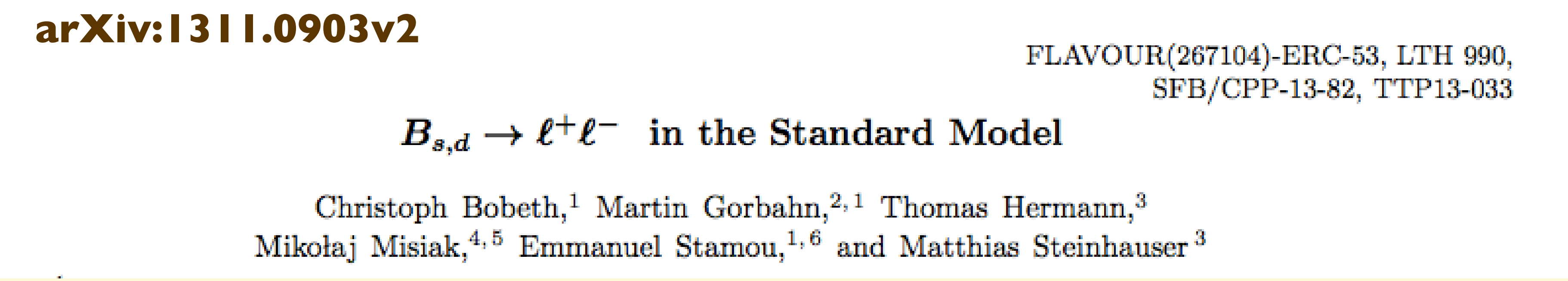
All in all I believe that it is correct to assume that MC mass parameter is interpreted as m_{pole}.

We are left with the ambiguity intrinsic in the definition of m_{pole}, thus at the level of ~250-500 MeV (uncertainty to be reduced by a future $O(\alpha_S^4)$ calculation of m_{pole} vs m_{MS}

$B_s \rightarrow \mu^+\mu^-$

(LHCb+CMS) : $B(Bs \rightarrow \mu+\mu-) = (2.9 \pm 0.7) \times 10^{-9}$

Instrinsic TH uncertainty **below 1%**, after recent calculation of
3-loop NNLO QCD and 2-loop NLO EW effects:



arXiv:1311.0903v2

FLAVOUR(267104)-ERC-53, LTH 990,
SFB/CPP-13-82, TTP13-033

$B_{s,d} \to \ell^+\ell^-$ in the Standard Model

Christoph Bobeth,[1] Martin Gorbahn,[2,1] Thomas Hermann,[3]
Mikołaj Misiak,[4,5] Emmanuel Stamou,[1,6] and Matthias Steinhauser[3]

Uncertainty dominated by f_{Bs} (lattice)

⇒ November 2013:

(Theory) : $B(Bs \rightarrow \mu+\mu-) = (3.65 \pm 0.23) \times 10^{-9}$

Concluding remarks

- **LHC measurements of SM phenomena moved to a new phase of quantitative and precision level**
- **It's a great reward for theorists to see the fruits of years of work developing tools**
  - theory/data agreement beyond expectations and hopes
  - thanks to the expt's for the thorough and incisive tests of theory
  - still, interesting open issues and problems to keep the challenge up
- **The Higgs is there ... but where is everyone else ??**

Concluding remarks

- Obvious priorities for the future include:
  - Precision studies of Higgs properties
  - Dig deeper in the search of well-hidden BSM processes:
    - extend mass reach going to higher energy
    - look for deviations from expected SM properties/distributions
- This will pose challenging demands on the accuracy of our predictions, which can only be met through further improvements in our understanding of SM physics
- These improvements will come not only from progress in theoretical calculations, but will need to rely on a robust programme of experimental validation
- SM measurements are thus a flagship component of the LHC physics, and in particular a crucial and indispensable part of a successful BSM programme.