LHC physics: present and future

XL International Meeting on Fundamental Physics

Centro de Ciencias de Benasque Pedro Pascual

May 31 2012

Michelangelo L. Mangano

TH Unit, Physics Department, CERN

michelangelo.mangano@cern.ch

Introduction

Introduction

- Most of the interest from the HEP community goes to a couple of basic questions:

Introduction

- Most of the interest from the HEP community goes to a couple of basic questions:
  - what's the status of the Higgs search?

Introduction

- Most of the interest from the HEP community goes to a couple of basic questions:
  - what's the status of the Higgs search?
  - is there any sign of SUSY or other BSM phenomena?

Introduction

- Most of the interest from the HEP community goes to a couple of basic questions:
  - what's the status of the Higgs search?
  - is there any sign of SUSY or other BSM phenomena?
- The LHC is much more than this, and we are only slowly coming to appreciate its true potential and the multitude of possible handles we have available to optimize its exploitation

Introduction

- Most of the interest from the HEP community goes to a couple of basic questions:
  - what's the status of the Higgs search?
  - is there any sign of SUSY or other BSM phenomena?
- The LHC is much more than this, and we are only slowly coming to appreciate its true potential and the multitude of possible handles we have available to optimize its exploitation
- I'll try to cover complementary aspects of LHC physics

Introduction

- Most of the interest from the HEP community goes to a couple of basic questions:
  - what's the status of the Higgs search?
  - is there any sign of SUSY or other BSM phenomena?
- The LHC is much more than this, and we are only slowly coming to appreciate its true potential and the multitude of possible handles we have available to optimize its exploitation
- I'll try to cover complementary aspects of LHC physics
  - Highlight the new elements that make physics at the LHC so special

Introduction

- Most of the interest from the HEP community goes to a couple of basic questions:
  - what's the status of the Higgs search?
  - is there any sign of SUSY or other BSM phenomena?
- The LHC is much more than this, and we are only slowly coming to appreciate its true potential and the multitude of possible handles we have available to optimize its exploitation
- I'll try to cover complementary aspects of LHC physics
  - Highlight the new elements that make physics at the LHC so special
- Several topics, have been/will be reviewed in specific talks at this meeting (flavour at LHC, Higgs, BSM, top, EW, etc)

Introduction

- Most of the interest from the HEP community goes to a couple of basic questions:
  - what's the status of the Higgs search?
  - is there any sign of SUSY or other BSM phenomena?
- The LHC is much more than this, and we are only slowly coming to appreciate its true potential and the multitude of possible handles we have available to optimize its exploitation
- I'll try to cover complementary aspects of LHC physics
  - Highlight the new elements that make physics at the LHC so special
- Several topics, have been/will be reviewed in specific talks at this meeting (flavour at LHC, Higgs, BSM, top, EW, etc)
- I'll focus on SM dynamics, for several reasons:

- SM physics is interesting since we have today almost 10fb-1 of it, and, so far, nothing much else (except tantalizing evidence of a – possibly SM – Higgs and CPV in D decays)

- SM physics is interesting since we have today almost 10fb-1 of it, and, so far, nothing much else (except tantalizing evidence of a – possibly SM – Higgs and CPV in D decays)
- The precision or our predictions for SM dynamics will have a great impact on the potential of LHC operations to fully exploit the immense statistics of possible BSM phenomena to be uncovered in the future

- SM physics is interesting since we have today almost 10fb-1 of it, and, so far, nothing much else (except tantalizing evidence of a – possibly SM – Higgs and CPV in D decays)
- The precision or our predictions for SM dynamics will have a great impact on the potential of LHC operations to fully exploit the immense statistics of possible BSM phenomena to be uncovered in the future
  - the value of future initiatives (flavour factories, LCs, etc) must be gauged against what we can and cannot extract from LHC data

- SM physics is interesting since we have today almost 10fb-1 of it, and, so far, nothing much else (except tantalizing evidence of a – possibly SM – Higgs and CPV in D decays)
- The precision or our predictions for SM dynamics will have a great impact on the potential of LHC operations to fully exploit the immense statistics of possible BSM phenomena to be uncovered in the future
  - the value of future initiatives (flavour factories, LCs, etc) must be gauged against what we can and cannot extract from LHC data
- While there is no doubt that searching new physics must be the primary task of this phase of the analyses, detailed studies of SM phenomena lay the foundations on which to build the future phase of the LHC adventure

- The most spectacular surprise from the LHC, in my view, is the accuracy and precision of the results.

- The most spectacular surprise from the LHC, in my view, is the accuracy and precision of the results.
  - exptl systematics, including ability to perform multiple and independent cross-checks of detector performance (detector simulation, test beam data, real data with multiple control samples or trigger streams, ...)

- The most spectacular surprise from the LHC, in my view, is the accuracy and precision of the results.
  - exptl systematics, including ability to perform multiple and independent cross-checks of detector performance (detector simulation, test beam data, real data with multiple control samples or trigger streams, ...)
  - MC modeling of SM processes

- The most spectacular surprise from the LHC, in my view, is the accuracy and precision of the results.
  - exptl systematics, including ability to perform multiple and independent cross-checks of detector performance (detector simulation, test beam data, real data with multiple control samples or trigger streams, ...)
  - MC modeling of SM processes
  - LHC absolute luminosity measurement

- The most spectacular surprise from the LHC, in my view, is the accuracy and precision of the results.
  - exptl systematics, including ability to perform multiple and independent cross-checks of detector performance (detector simulation, test beam data, real data with multiple control samples or trigger streams, ...)
  - MC modeling of SM processes
  - LHC absolute luminosity measurement
- The synergy of all these elements offers an immense potential for further improvement. E.g.

- The most spectacular surprise from the LHC, in my view, is the accuracy and precision of the results.
  - exptl systematics, including ability to perform multiple and independent cross-checks of detector performance (detector simulation, test beam data, real data with multiple control samples or trigger streams, ...)
  - MC modeling of SM processes
  - LHC absolute luminosity measurement
- The synergy of all these elements offers an immense potential for further improvement. E.g.
  - better MC modeling (e.g. of acceptances) allows for more precise measurements (e.g. of event rates); better luminosity monitoring turns these into more precise cross-sections, so that the TH modeling itself can be further improved (e.g. by extracting more precise PDFs), and so on ....

- The most spectacular surprise from the LHC, in my view, is the accuracy and precision of the results.
  - exptl systematics, including ability to perform multiple and independent cross-checks of detector performance (detector simulation, test beam data, real data with multiple control samples or trigger streams, ...)
  - MC modeling of SM processes
  - LHC absolute luminosity measurement
- The synergy of all these elements offers an immense potential for further improvement. E.g.
  - better MC modeling (e.g. of acceptances) allows for more precise measurements (e.g. of event rates); better luminosity monitoring turns these into more precise cross-sections, so that the TH modeling itself can be further improved (e.g. by extracting more precise PDFs), and so on ....
- Let's not forget that the heritage of LEP is mostly based on its ability to perform very precise measurements, and match them to precise theoretical calculations

The basic themes of this presentation will be:

- what are the challenges that precision measurements pose to the LHC ?
- how far can we push the LHC as a precision tool ?
- which new territories of exploration, in the context of SM dynamics, can the LHC open ?

Describing the dynamics of LHC collisions: a renewed theoretical challenge

Describing the dynamics of LHC collisions: a renewed theoretical challenge

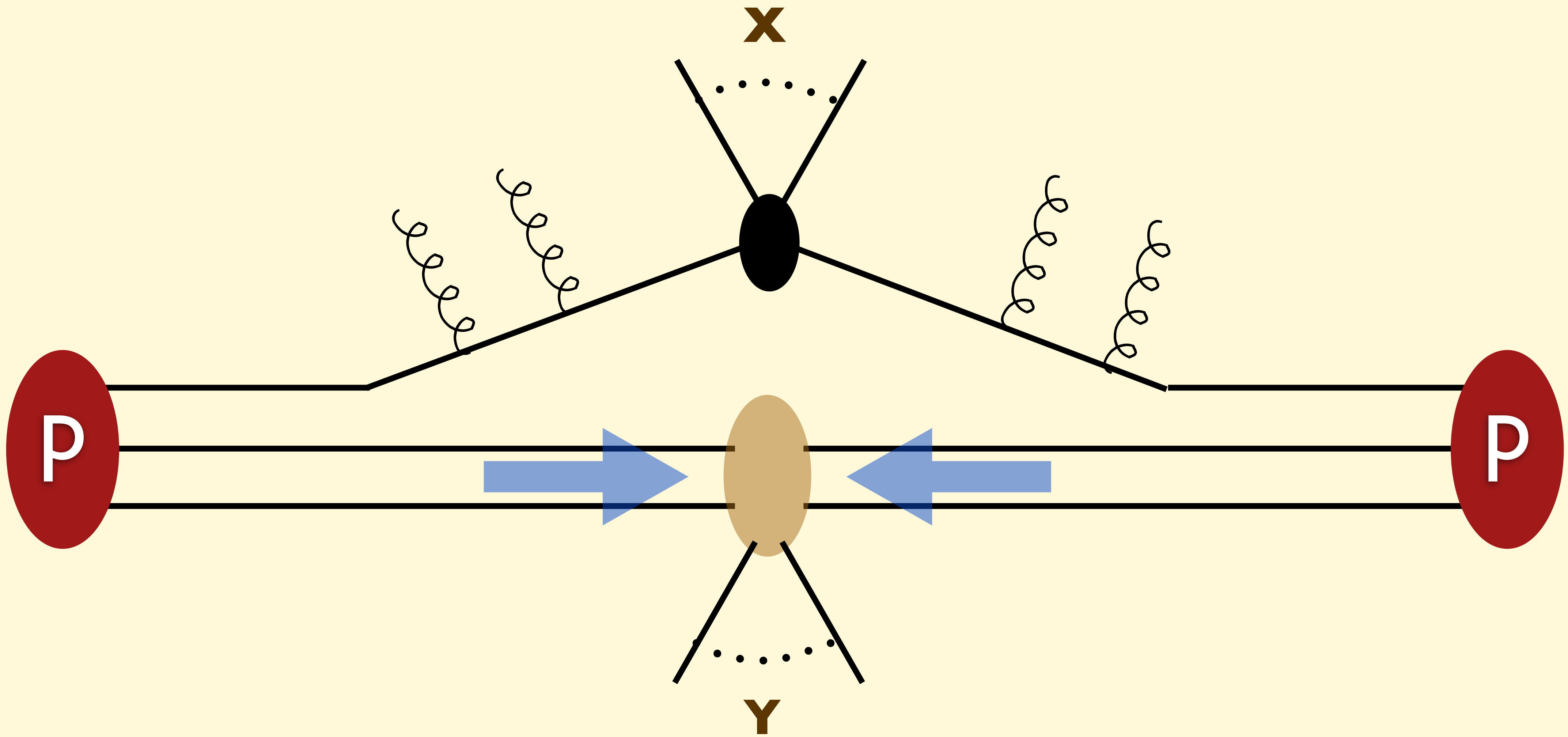
- Primary goal: description of dynamics from first principles (a "theory", not a "model")
  - interesting "per sè"
  - important to model backgrounds to searches of new phenomena

Describing the dynamics of LHC collisions: a renewed theoretical challenge

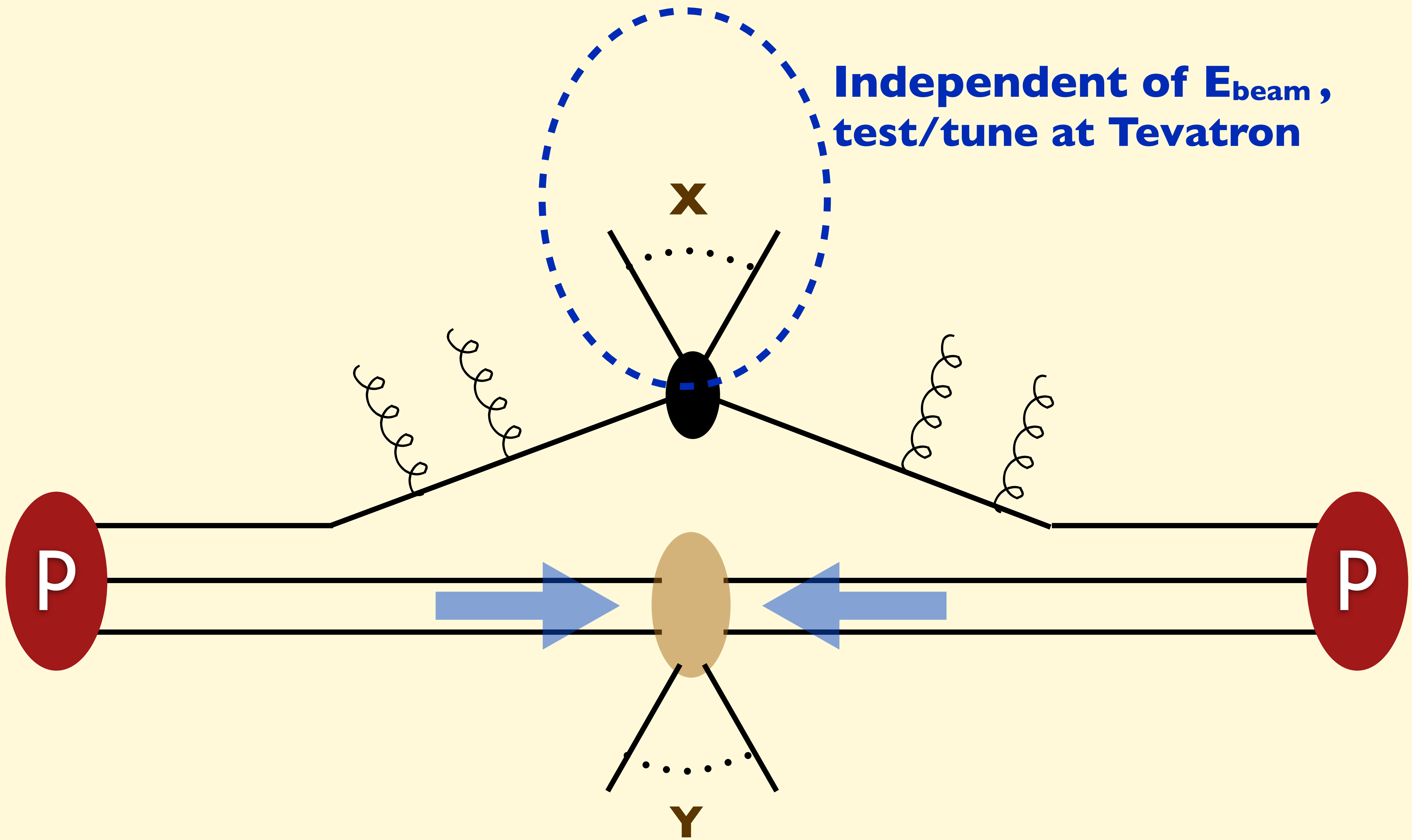
- Primary goal: description of dynamics from first principles (a "theory", not a "model")
  - interesting "per sè"
  - important to model backgrounds to searches of new phenomena
- Tools:
  - mixture of perturbative and non-perturbative techniques
  - perturbation theory describes the dynamics at short-distances, techniques developed to calculate beyond Born approximation, up to (next-to-)next-to-leading order
  - long-distance, non-perturbative elements, mapped into a few parameters, independent of the short-distance process, measurable once and for all

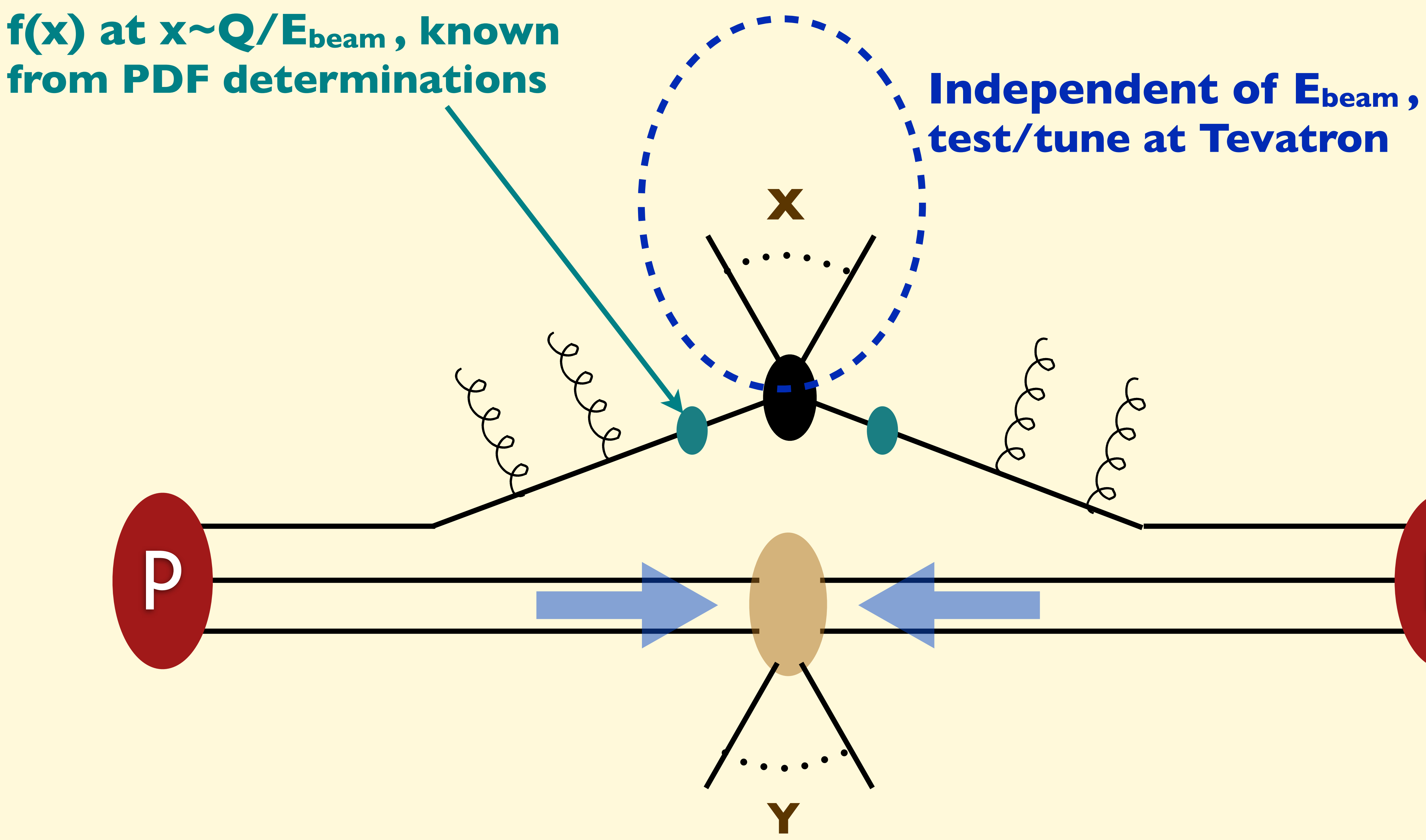
Describing the dynamics of LHC collisions: a renewed theoretical challenge

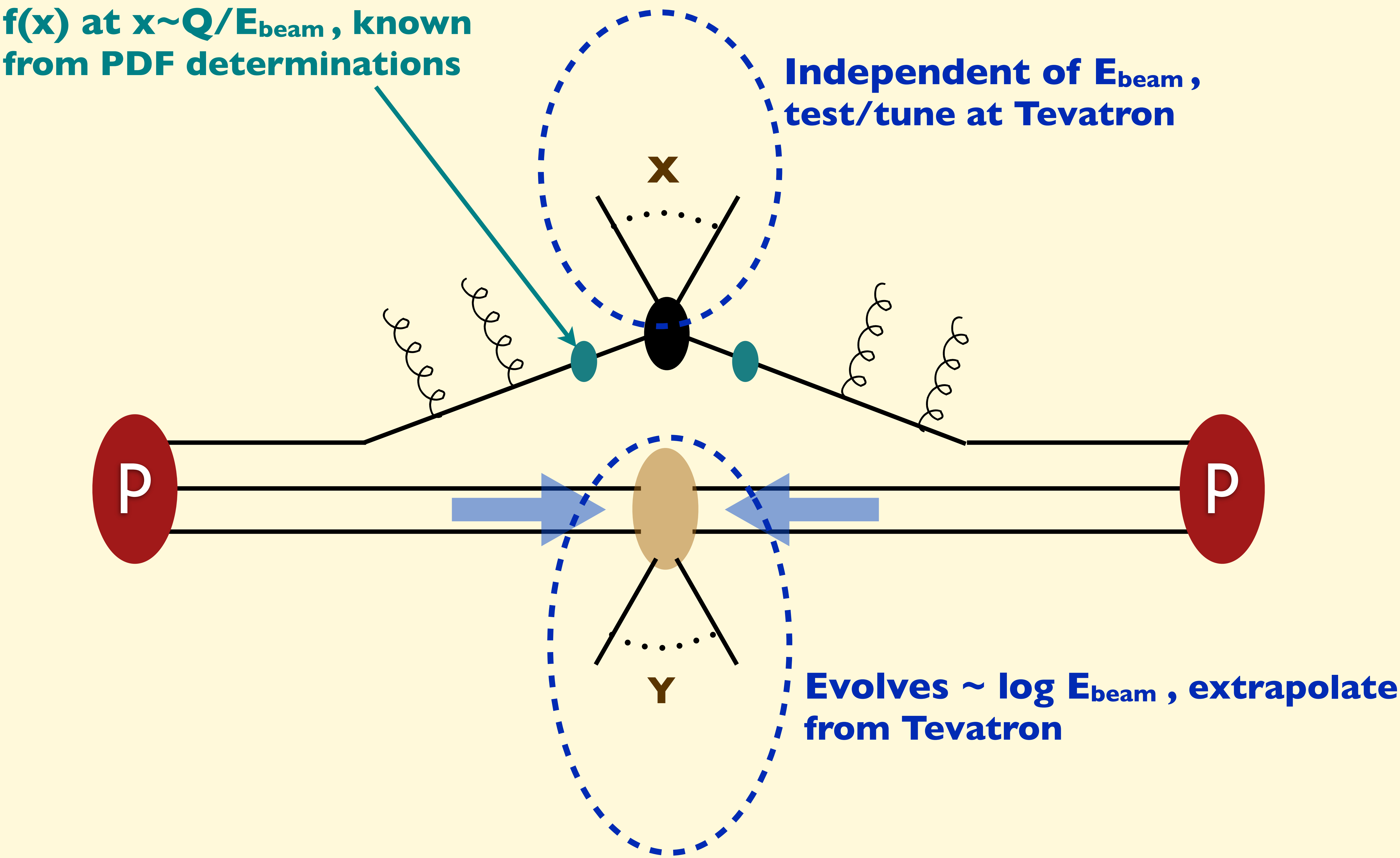
- Primary goal: description of dynamics from first principles (a "theory", not a "model")
  - interesting "per sè"
  - important to model backgrounds to searches of new phenomena
- Tools:
  - mixture of perturbative and non-perturbative techniques
  - perturbation theory describes the dynamics at short-distances, techniques developed to calculate beyond Born approximation, up to (next-to-)next-to-leading order
  - long-distance, non-perturbative elements, mapped into a few parameters, independent of the short-distance process, measurable once and for all
- Validation: comparison of predictions against a huge body of LHC experimental data

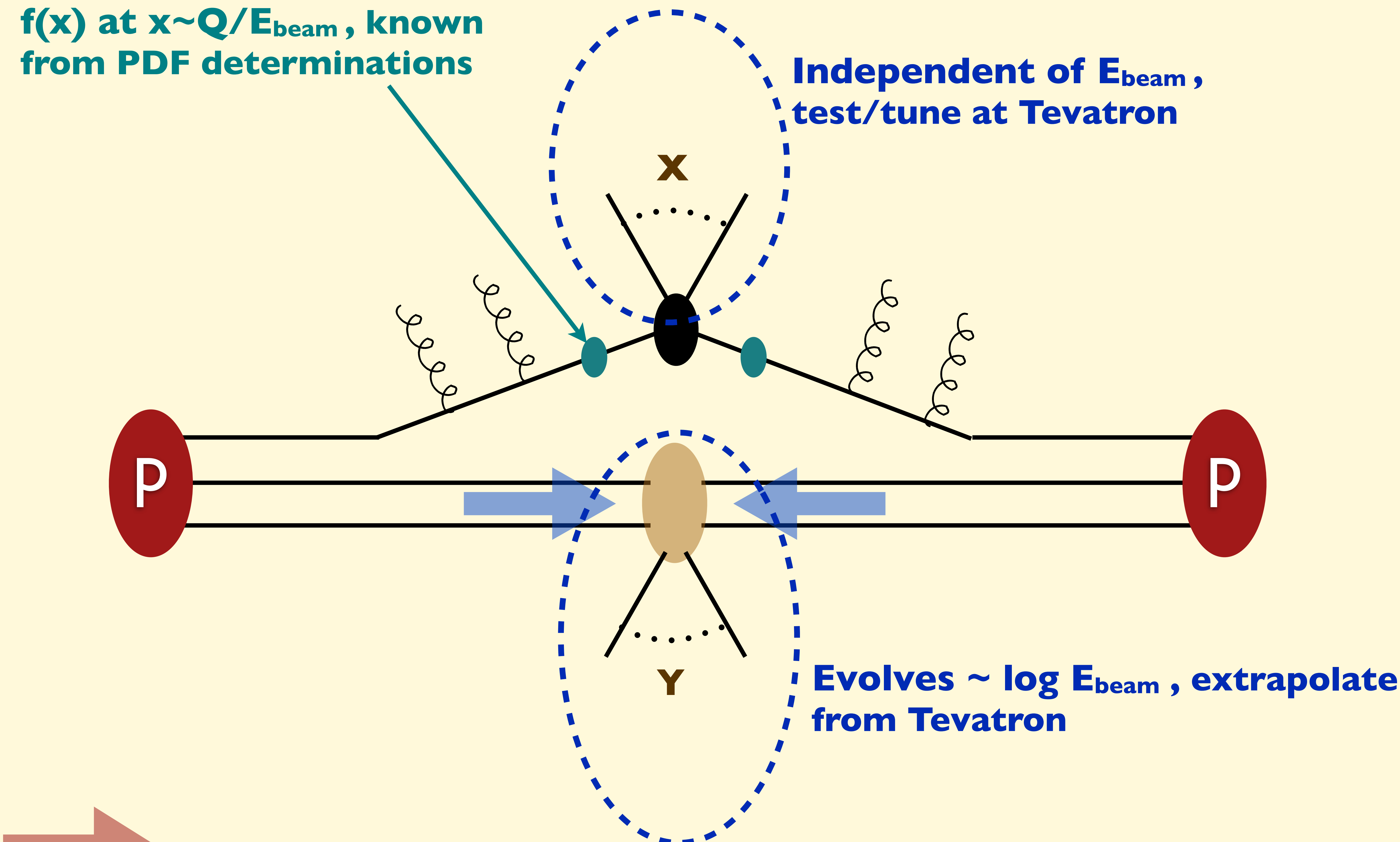


X
p
p
Y


Independent of E beam ,
test/tune at Tevatron
X
P
P
Y


f(x) at x~Q/Ebeam , known
from PDF determinations
Independent of Ebeam ,
test/tune at Tevatron
X
p
p
Y


f(x) at x~Q/Ebeam , known
from PDF determinations
Independent of Ebeam ,
test/tune at Tevatron
X
p
p
Y
Evolves ~ log Ebeam , extrapolate
from Tevatron



all seems to be under control and easily predictable at the LHC

... on the other hand ...

- the energy reach at the LHC is such that in many instances we are exploring kinematical regions never probed before
- cross sections for many processes of interest at the LHC are too small at the Tevatron to give significant tests of our dynamical understanding
- this is particularly true of
  - final states with many jets, especially if produced in association with gauge bosons and/or heavy quarks (such as bottom and top)
  - vector-boson fusion configurations
  - etc.
- Last but not least:
  - **the experimental accuracy of LHC measurements sets new standards of precision for the theoretical calculations**

Example of PDF uncertainties: impact on the gg->H cross section

G.Watt, http://arXiv.org/pdf/1106.5788

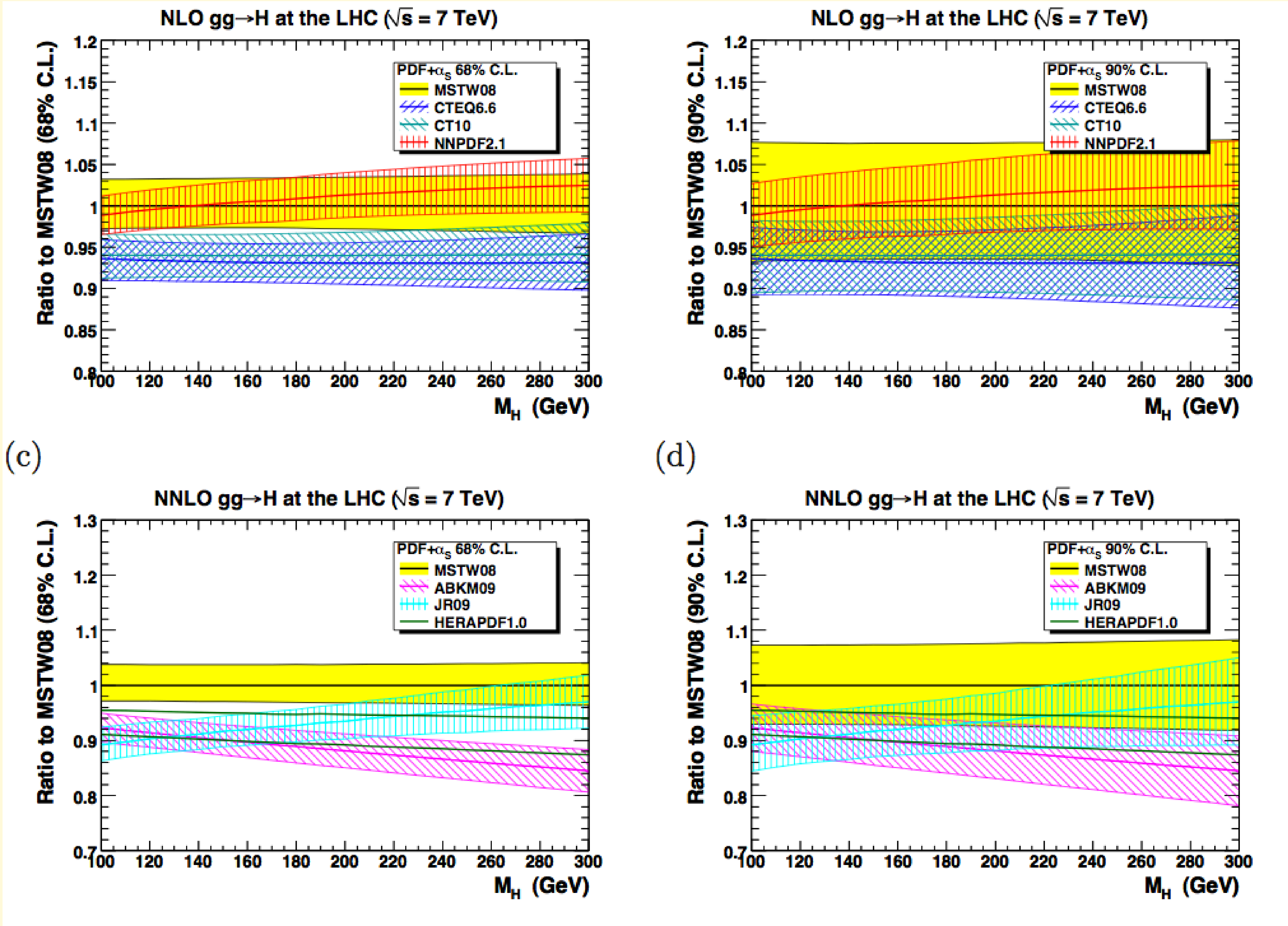
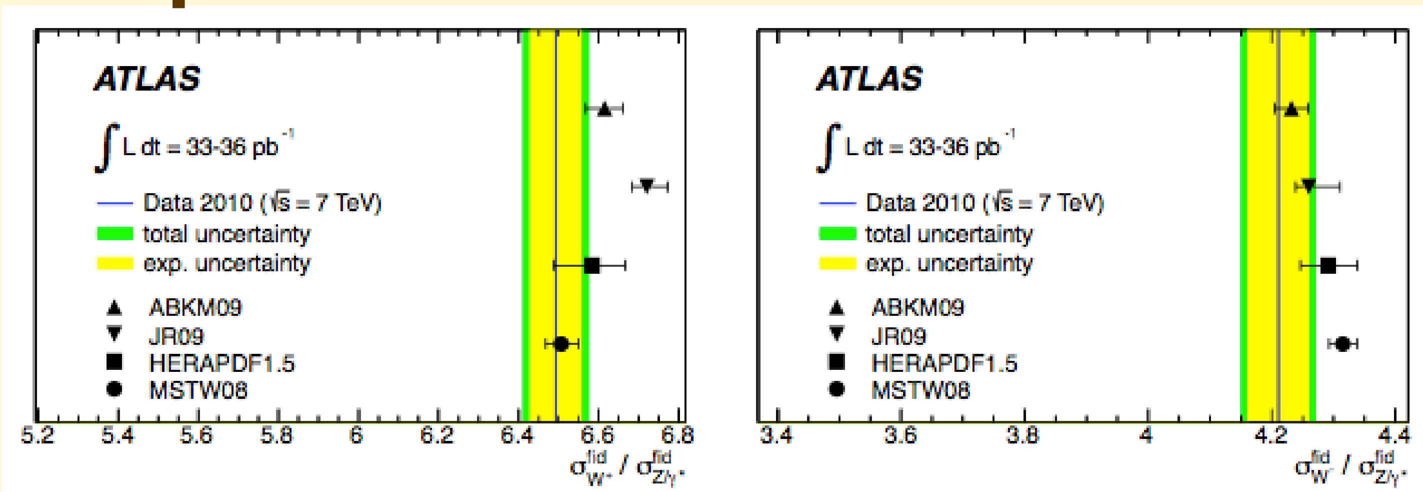
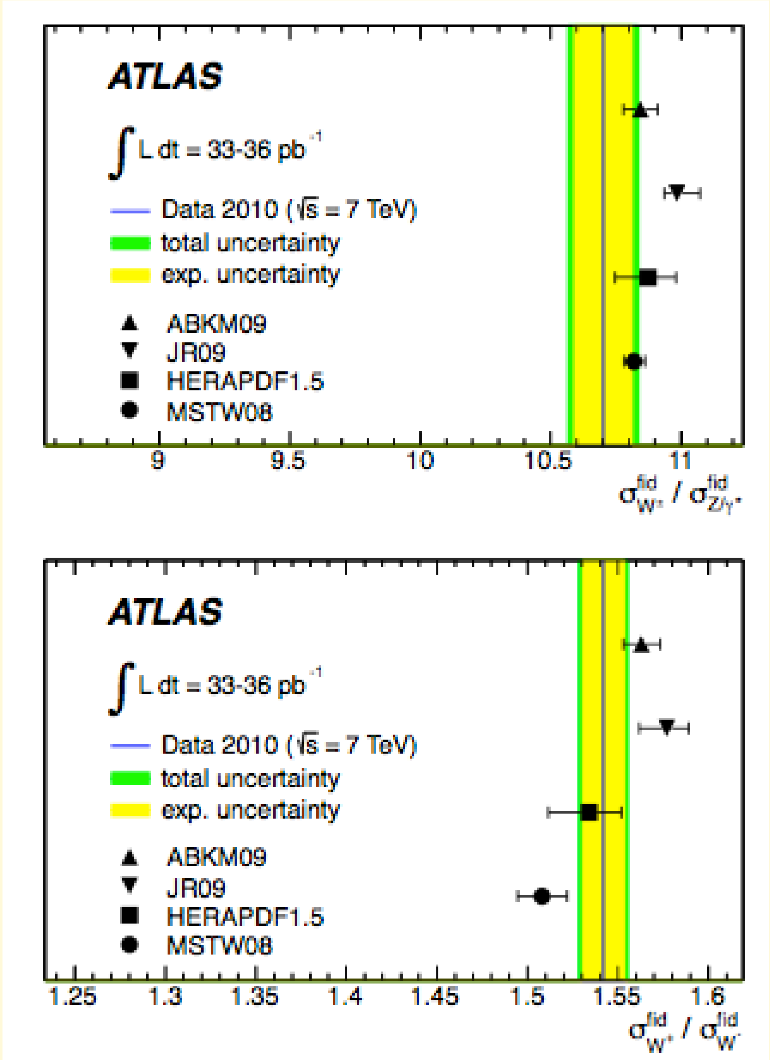
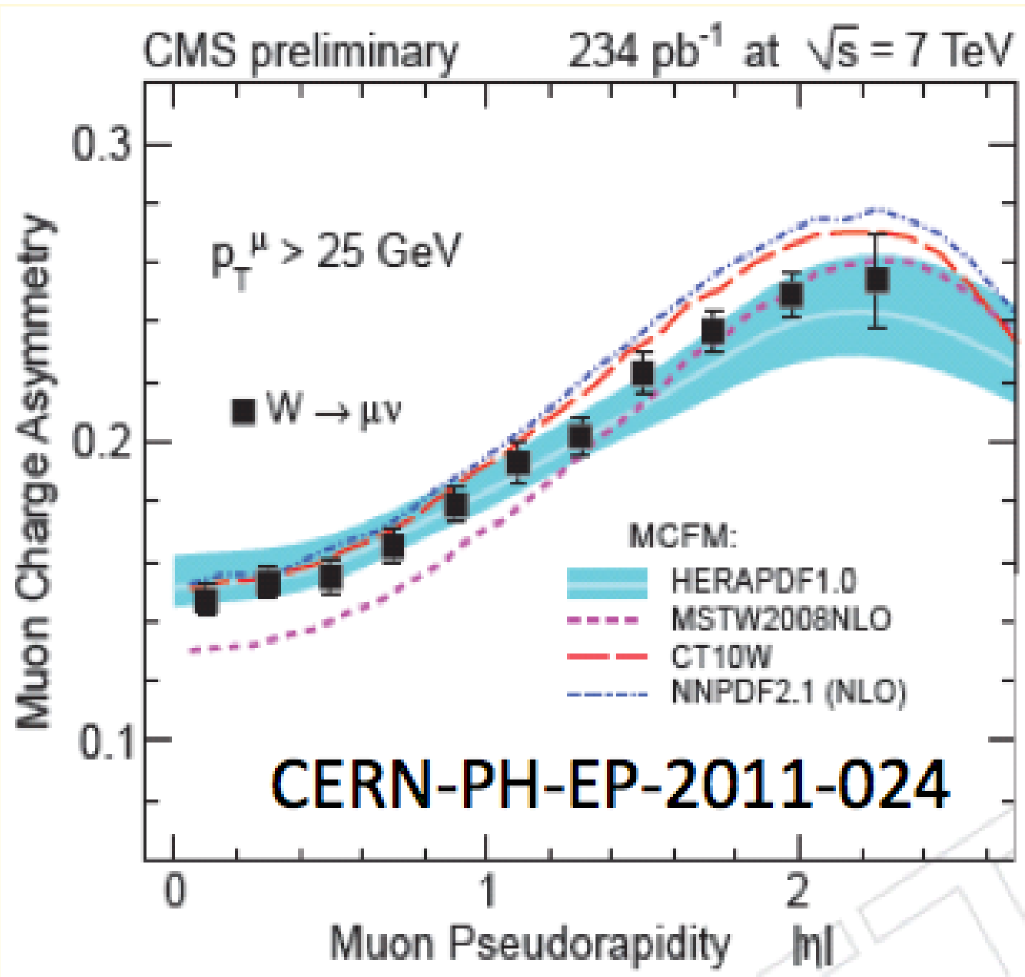


Figure 15. Ratio to the MSTW08 prediction for $gg \to H$ with PDF+α_S uncertainties for (a) NLO at 68% C.L., (b) NLO at 90% C.L., (c) NNLO at 68% C.L., (d) NNLO at 90% C.L.

Comparisons of various PDF sets to W/Z production data at the LHC







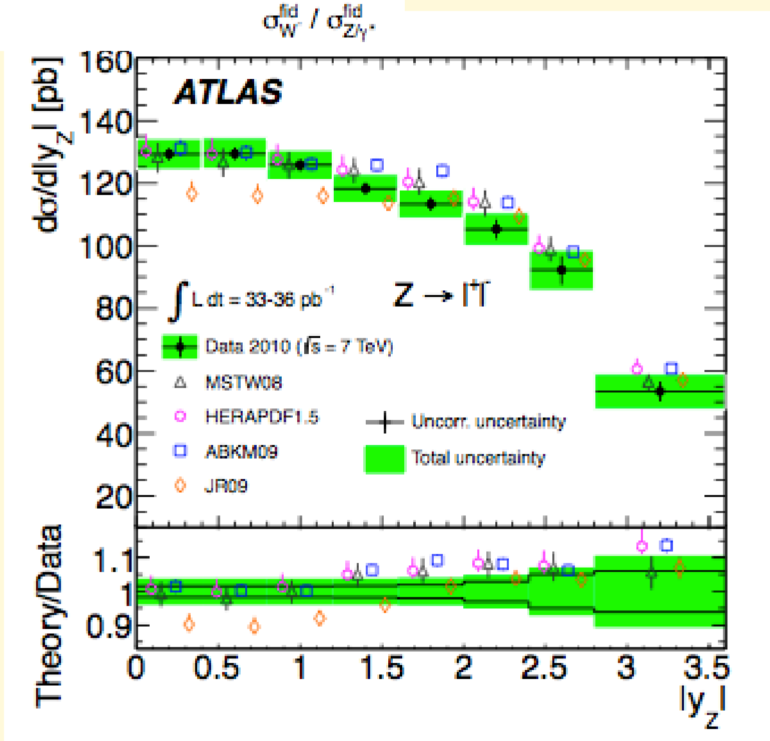
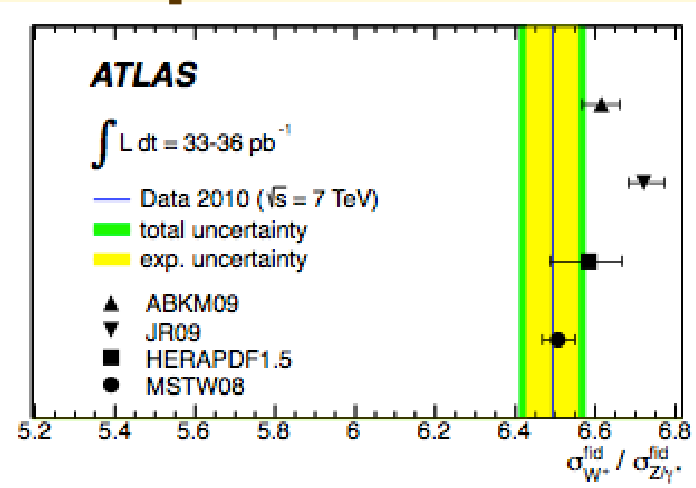
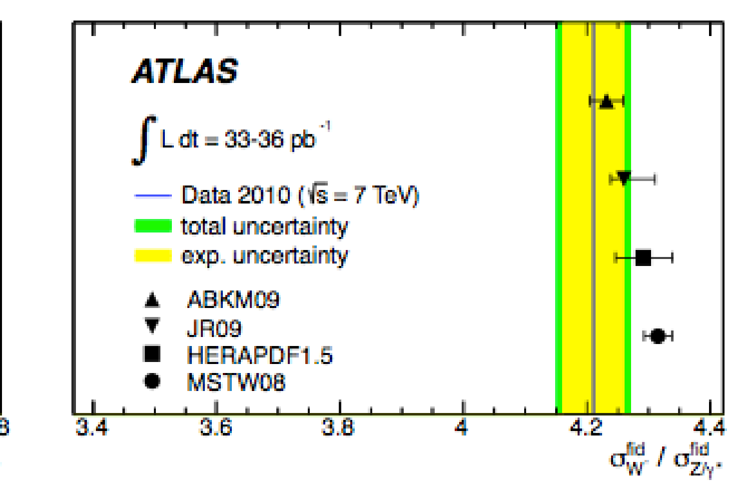


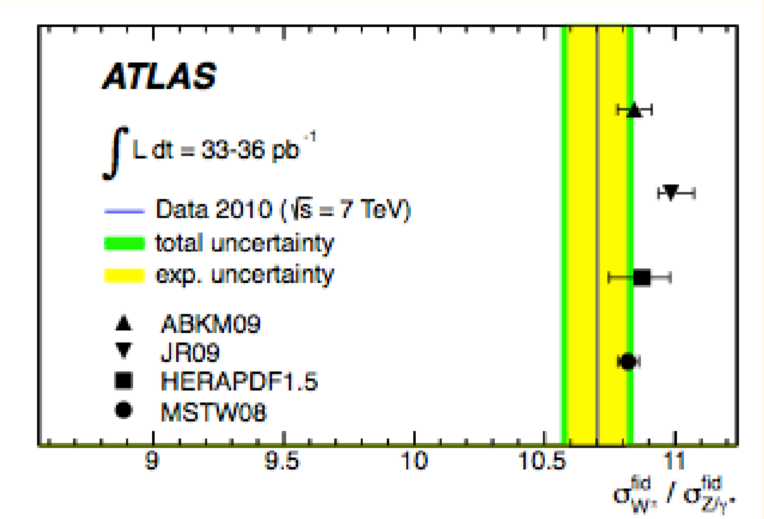
table entries NOT to be taken at face value!

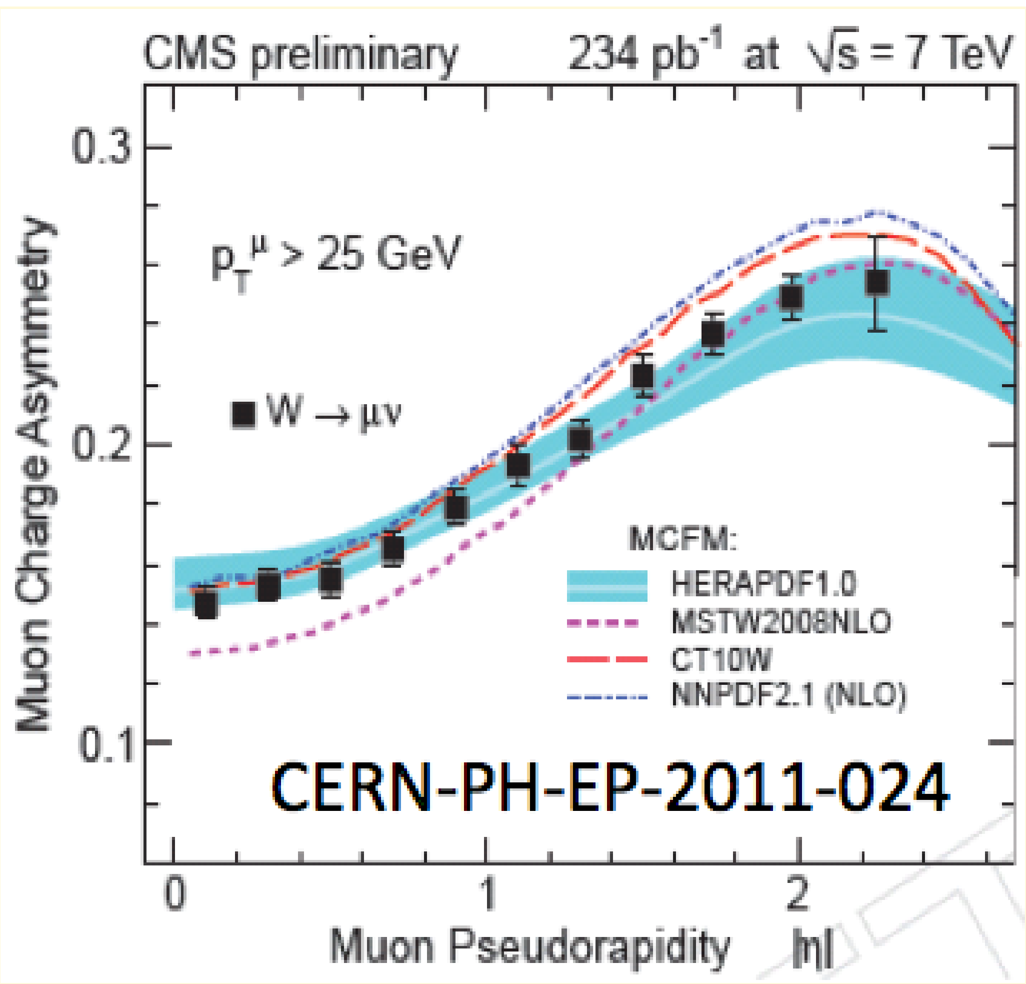
	ABKM	JR	HERA	MSTW
W+/Z	☹	☹	☺	☺
W−/Z	☺	☺	☹	☹
W/Z	☺	☹	☹	☺
W+/W−	☹	☹	☺	☹
y(Z)	☹	☹	☹	☺
y(μ←W)			☺	☹

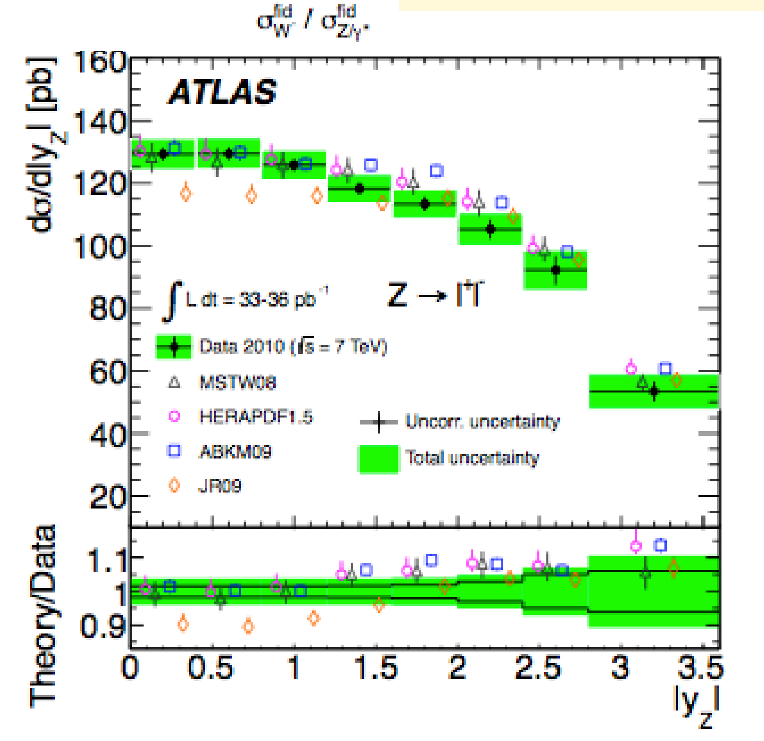
Comparisons of various PDF sets to W/Z production data at the LHC











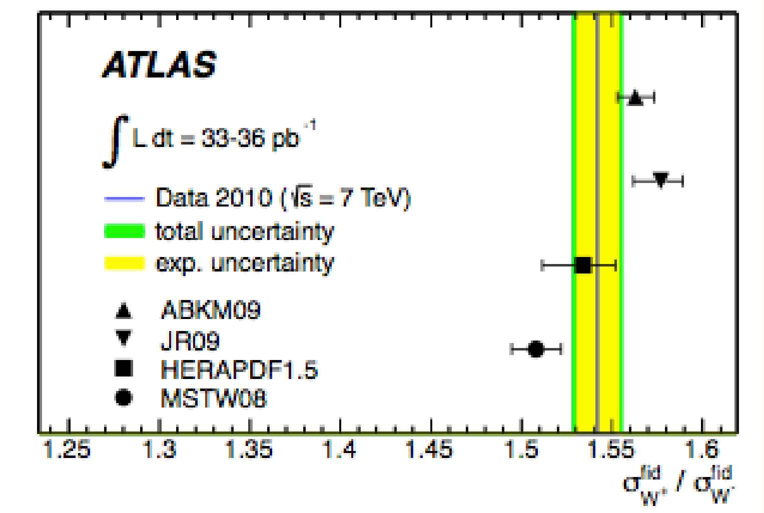
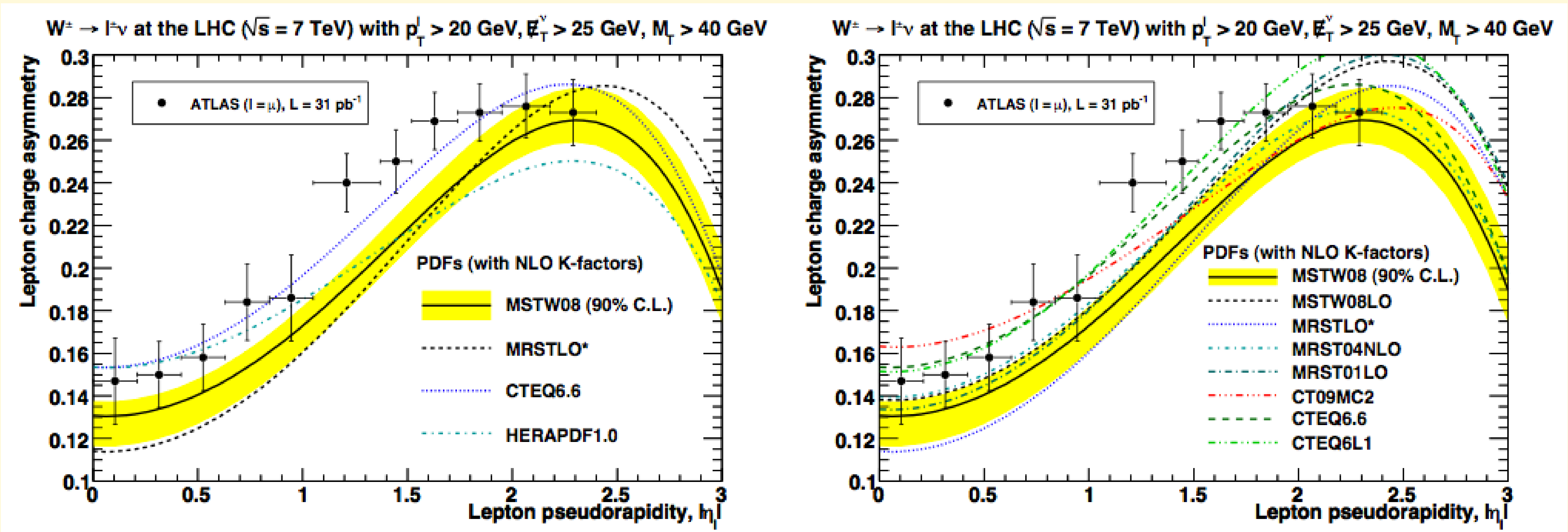


table entries NOT to be taken at face value!

	ABKM	JR	HERA	MSTW
W+/Z	☹	☹	☺	☺
W–/Z	☺	☺	☹	☹
W/Z	☺	☹	☹	☺
W+/W–	☹	☹	☺	☹
y(Z)	☹	☹	☹	☺
y(μ←W)			☺	☹

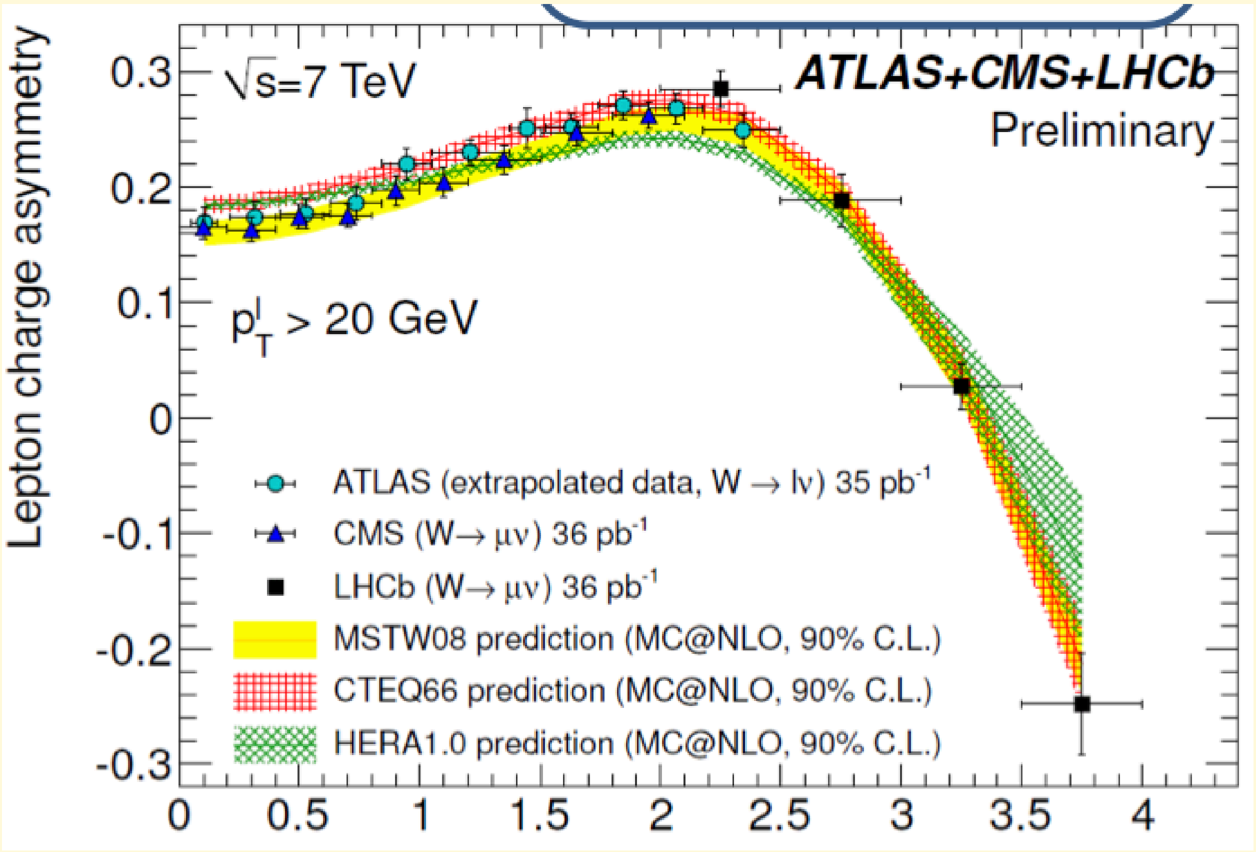
Need global fits of rates and distributions to judge which PDF set is best

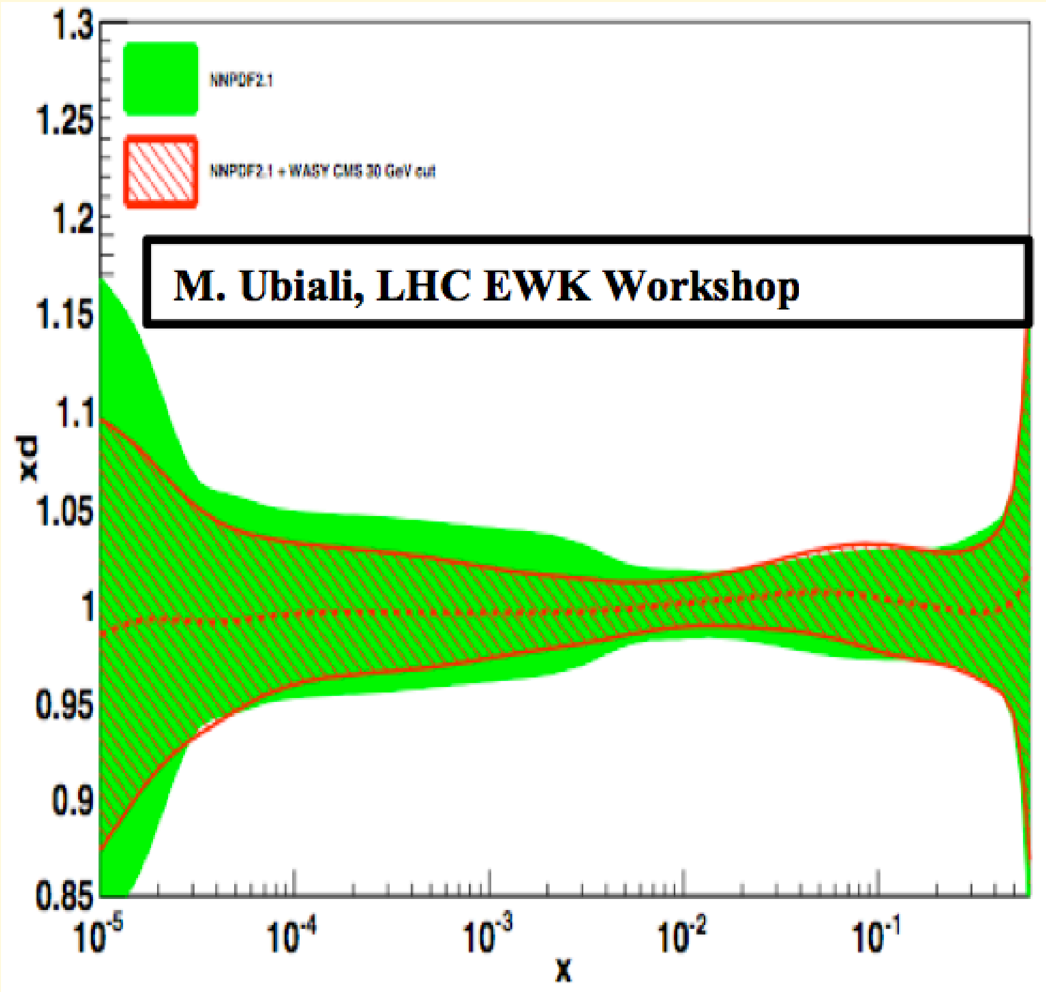
Lepton charge asymmetry in W production



G. Watt, http://arXiv.org/pdf/1106.5788

⇒ **push the measurement to large pt**
⇒ **also consider large-pt and large-MET, to probe large x values**
⇒ **fully exploit rapidity coverage**





... all of the above, and more ....

Use LHC data to better constrain PDFs

The “tools”: recent progress and state of the art

Parton-level, fixed order calculations

- DY: NNLO predictions available for both total rates and lepton differential distributions. Intrinsic TH precision ±1-2% (excl PDF)
- Jets: automatic tools for calculation of NLO rates and distributions for multijet final states (δ_{TH}~10-20%) :
  - pp → 2,3,4 jets
  - pp → W/Z + 1,2,3,4,(5) jets
  - associated production of heavy quarks and 1,2 jets
  - ....
- Top quark pairs: full NNLO for qqbar→ttbar completed, gg→ttbar forthcoming, resummation of NNLL (δ_{TH}~3-4%)
- Inclusion of EW corrections (typically effects of O(few %))
- Work in progress towards jet cross-sections at NNLO

The "tools": recent progress and state of the art

Full shower MCs, with hadronization and UE

- NLO parton level + shower
  - MC@NLO
  - POWHEG
  - aMC@NLO (automatic generation of NLO partonic cross sections, and merging with shower MC)

PDF extraction

- NNLO analyses, including quark mass effects
- Consistent frameworks for rigorous handling of experimental and theoretical systematics
- Several approaches, allowing for robust cross-checks
  - MSTW, CTEQ, NNPDF, HERApdf, JR, ABKM
  - Future use of full NLO+shower MCs for analysis of input data

Hadronization, jet structure, underlying event, etc

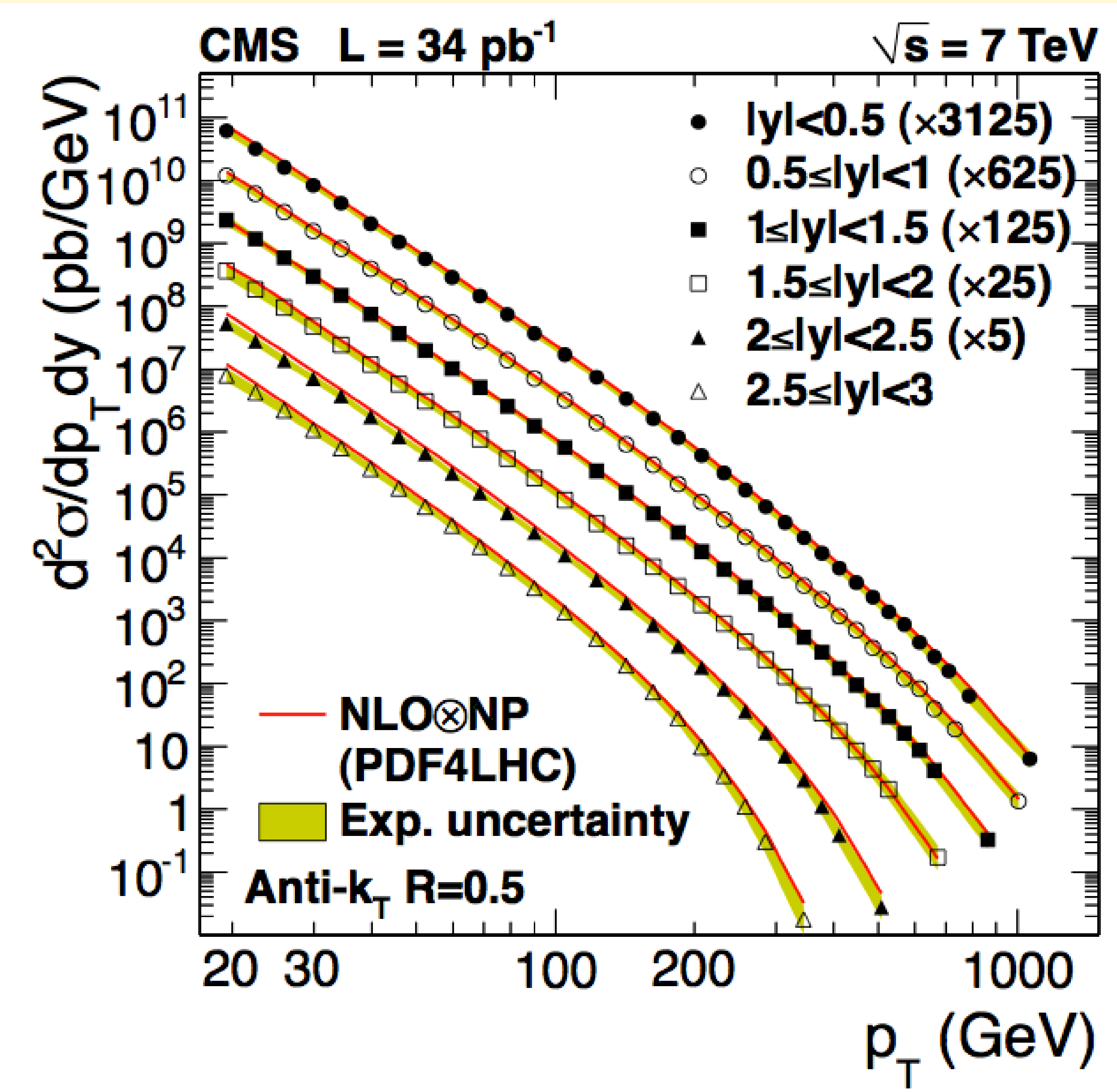
- New frameworks for shower evolution (Herwig++, Pythia8, Sherpa, Geneva, Vincia, KRKMC, ...)
- New phenomenological models for multiparticle interactions
- Global fits of event properties

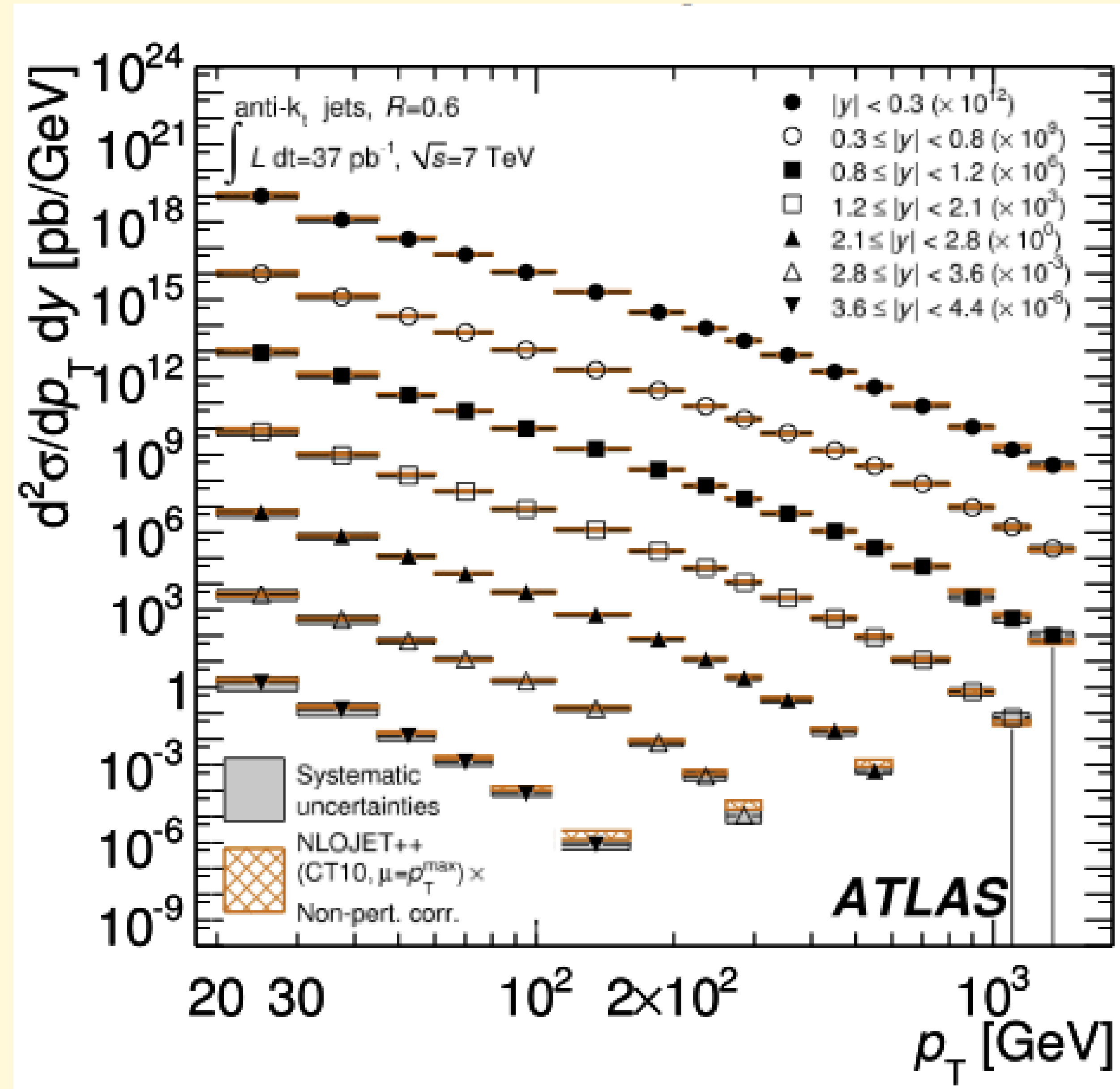
Theory calculations for hard hadronic collisions are getting mature to be challenged at the few % level

Examples

- Inclusive jet production
  - tests of quark substructure, PDF constraints, ...
- multijet final states
  - tests of higher-order calculations, search for new massive objects, ...
- associated production of W/Z+jets
  - bg to top studies, BSM searches

Jet cross section

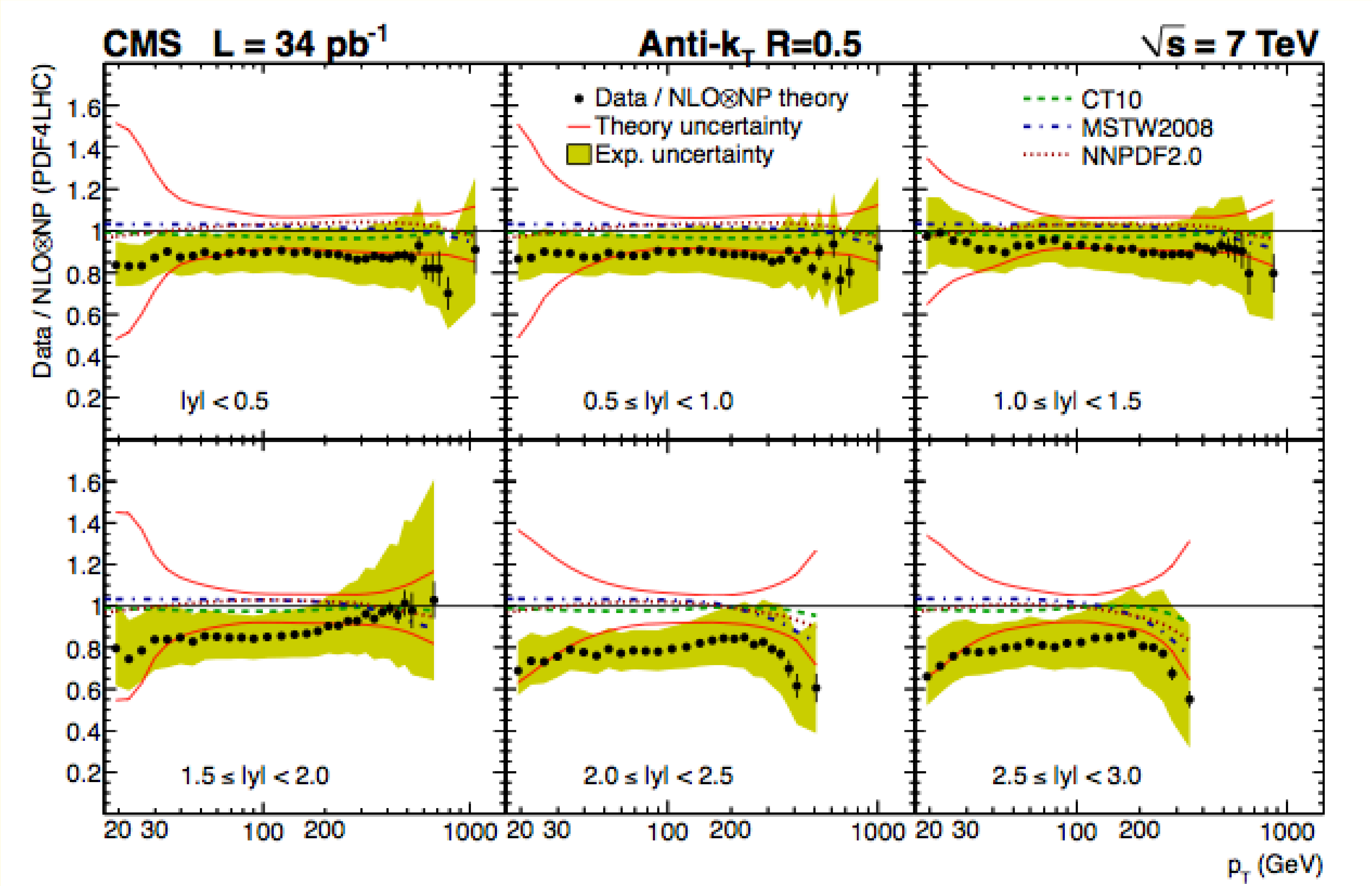




Rates span 10 orders of magnitude!

Jet cross section: data vs NLO

Theory: absolute prediction for both shape and normalization

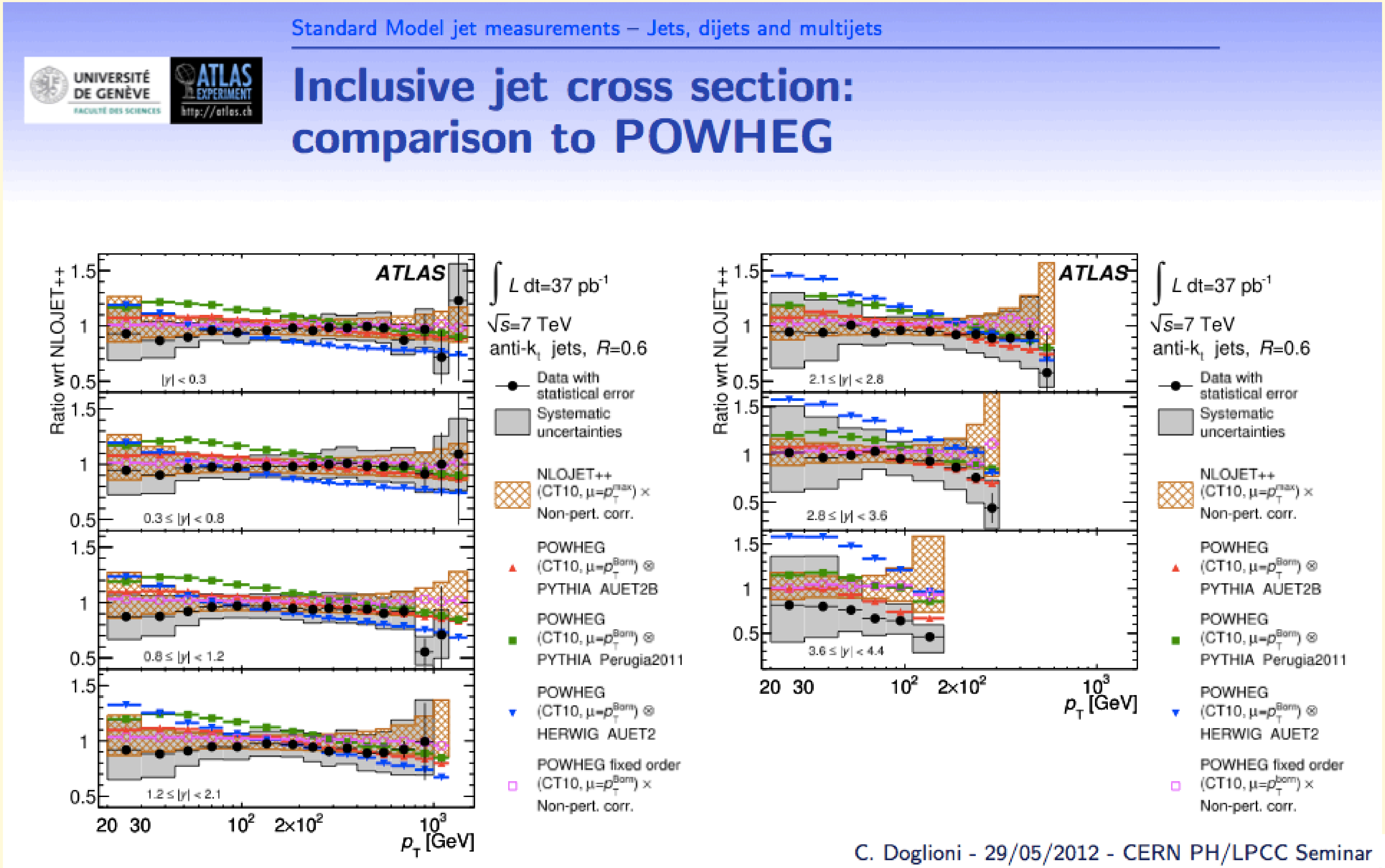


Agreement to within 20% (over 10 orders of magnitude!)

Residual discrepancy consistent with PDF and perturbative NLO uncertainties

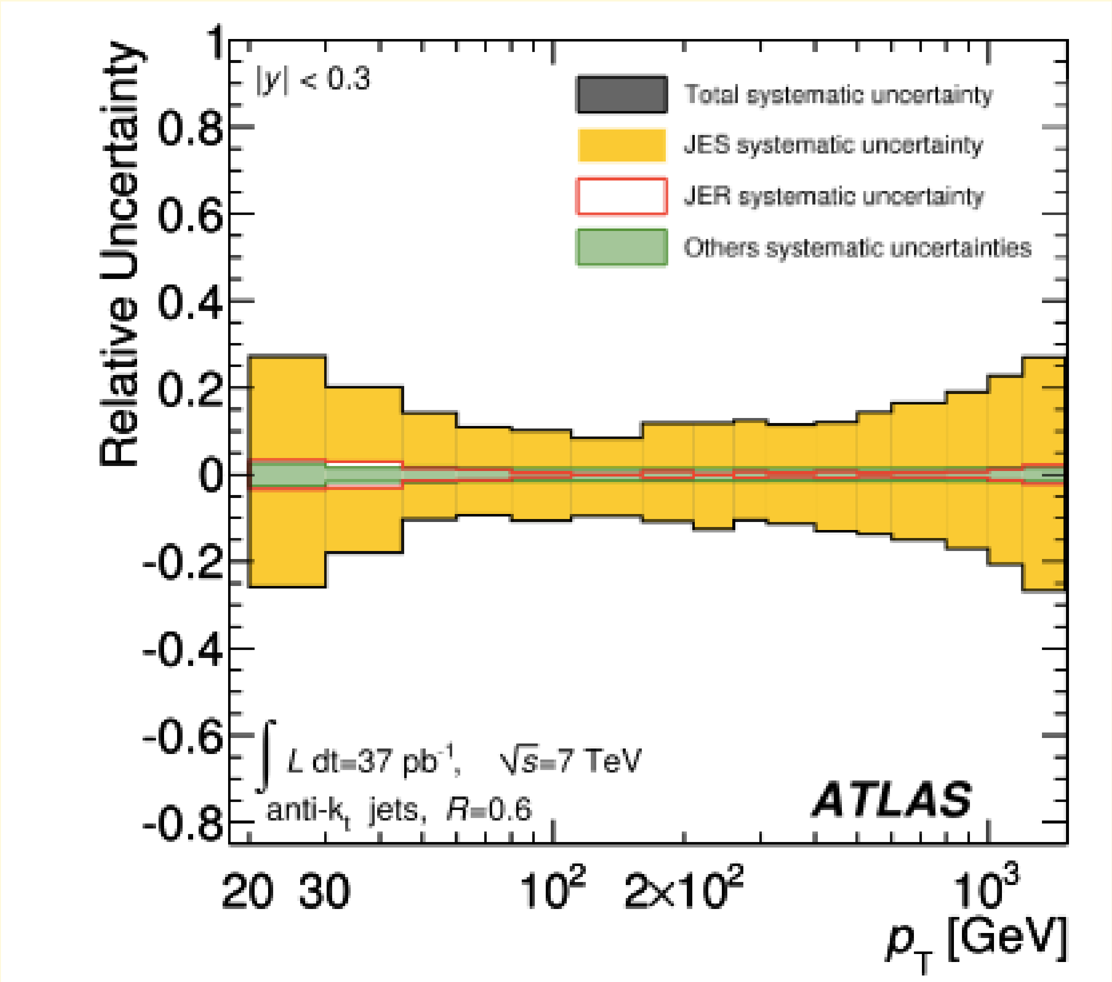
Jet cross section: data vs NLO vs NLO+shower

Theory: absolute prediction for both shape and normalization

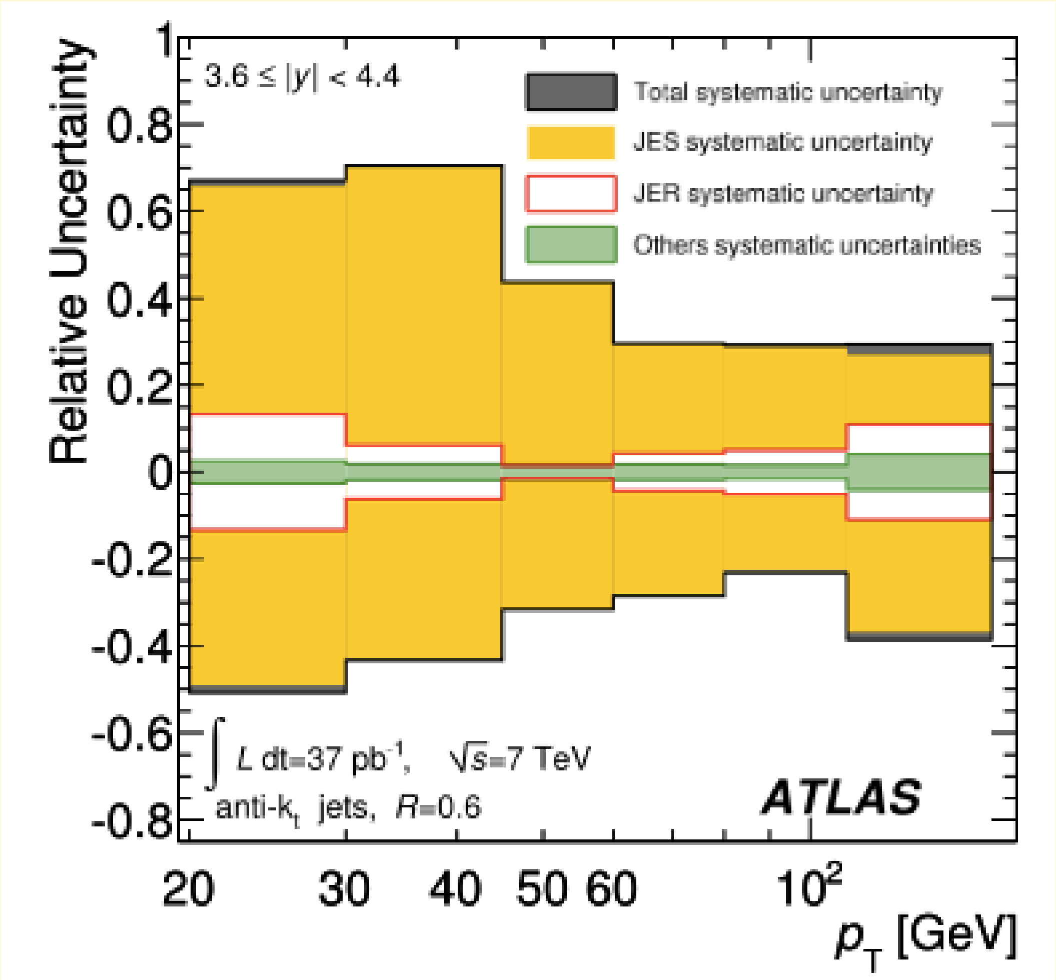


Important systematic differences in the NLO vs NLO+shower description

Experimental systematics

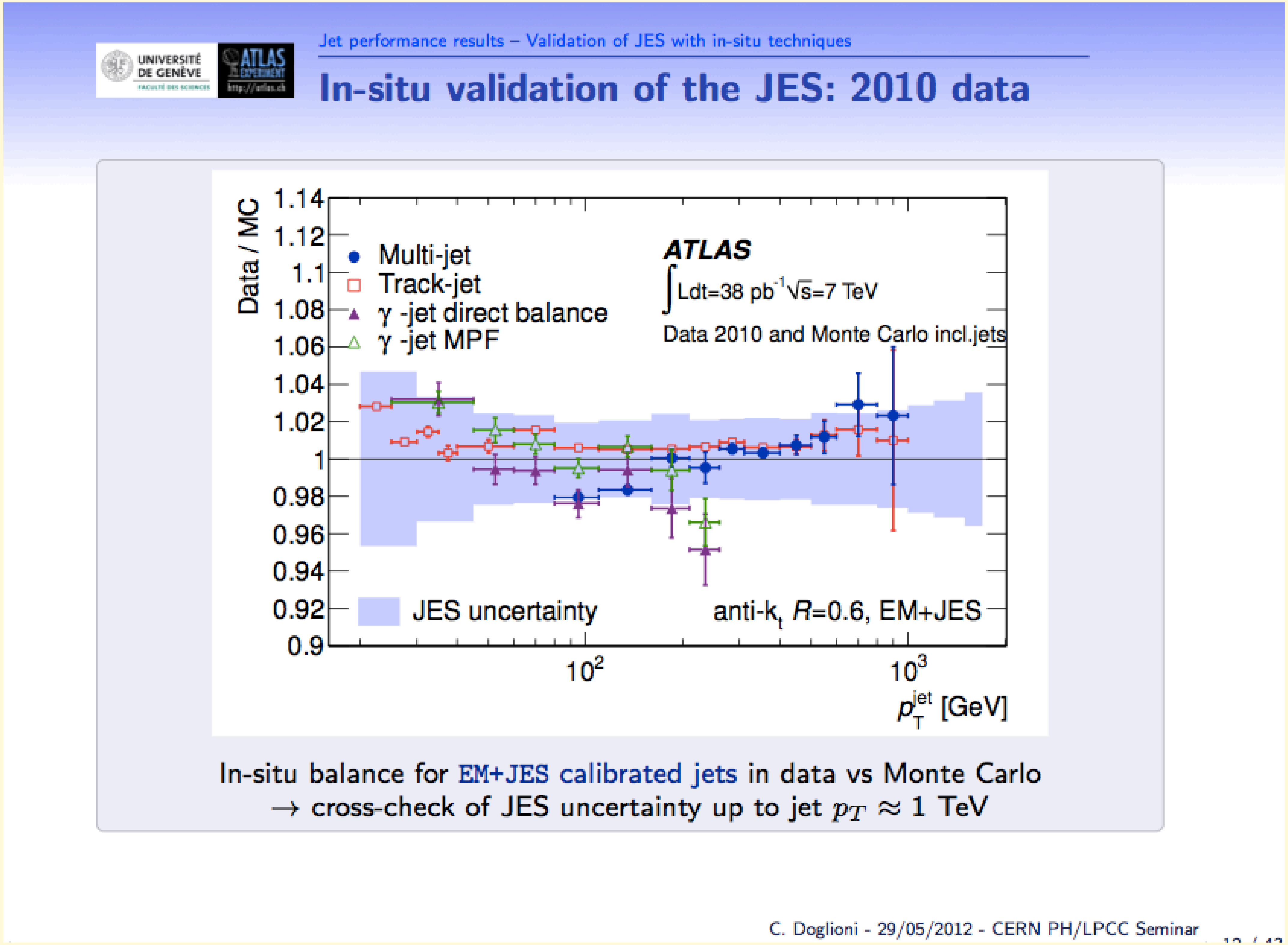


Central jets



Forward jets

What is the ultimate attainable precision in the determination of the jet energy scale?



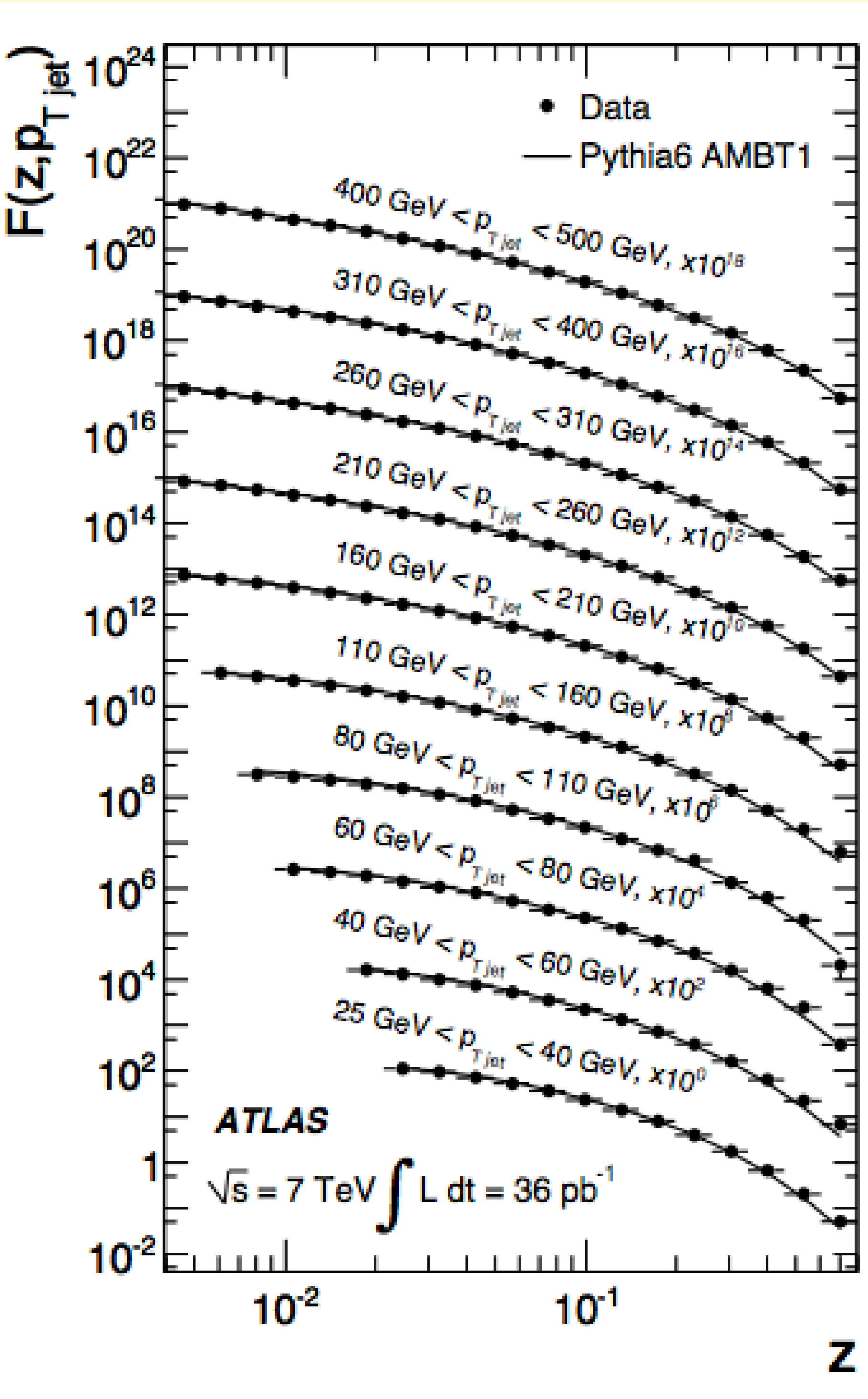
TH systematics biases the exptl measurement of JES:

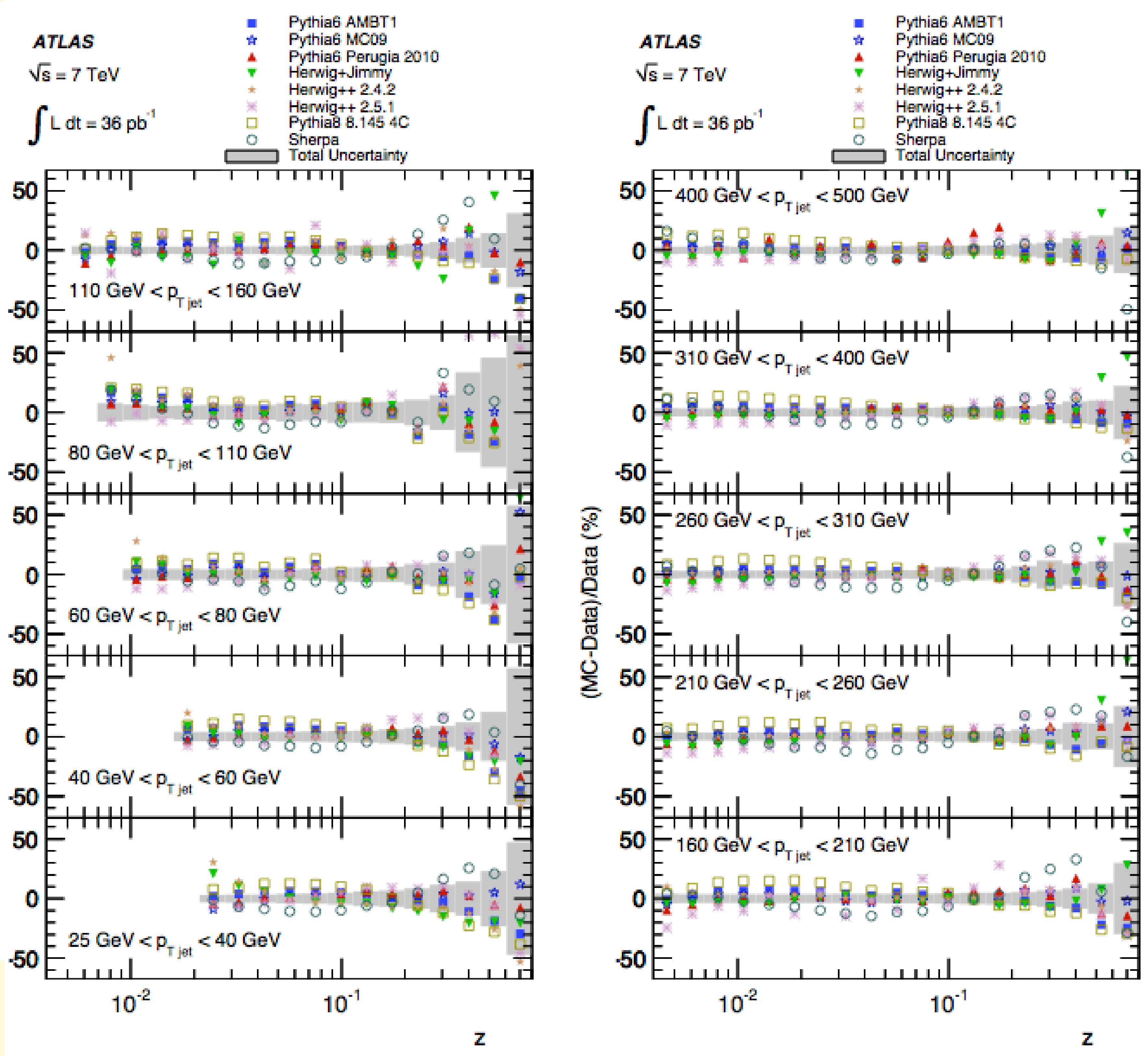
jet flavour composition, structure of the recoil hadronic system, multijet structure of the event, ...

Can be reduced with detailed studies of jet structure, and improvement of jet models

Jet fragmentation function

ATLAS, arXiv:1109.5816

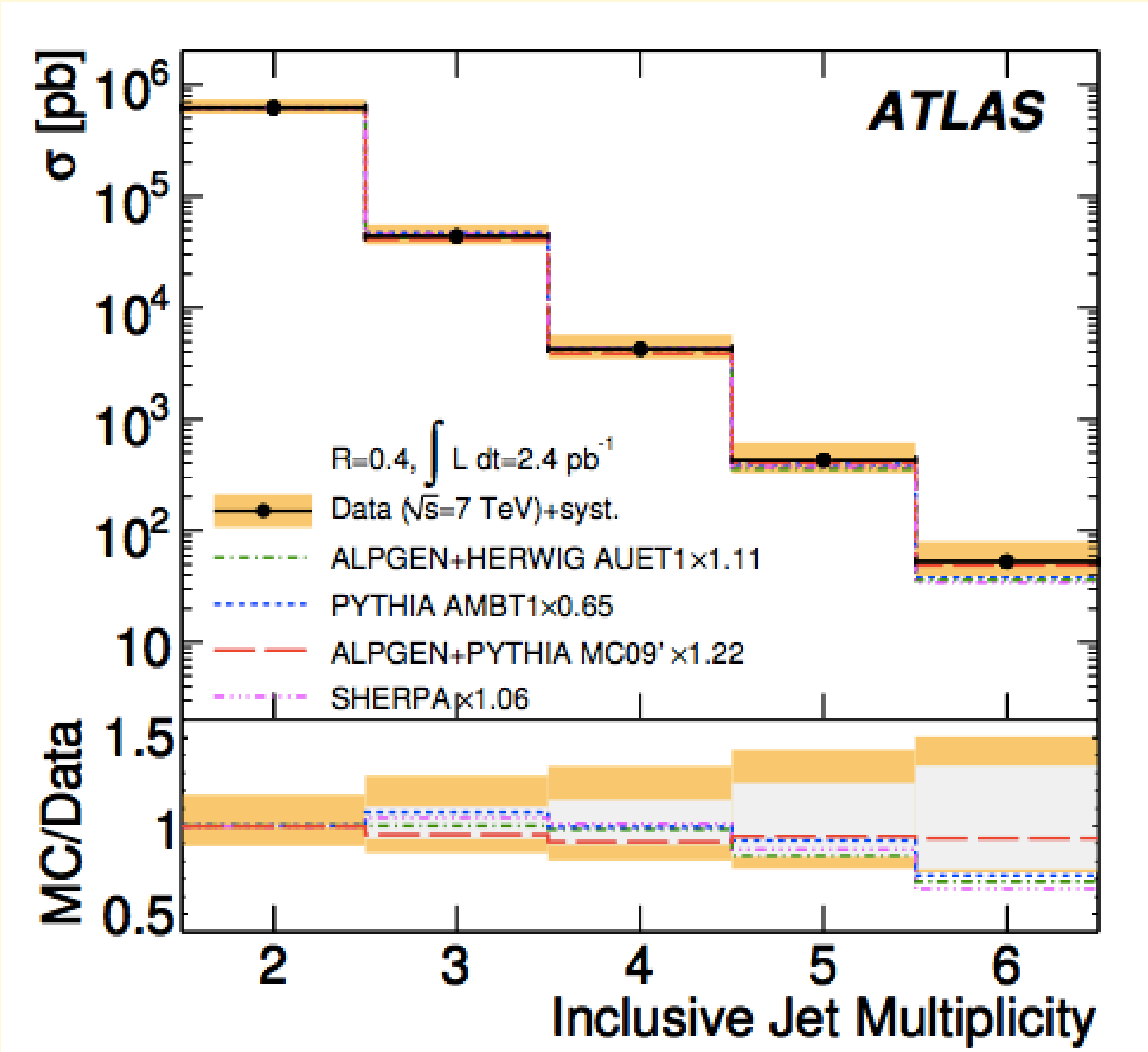


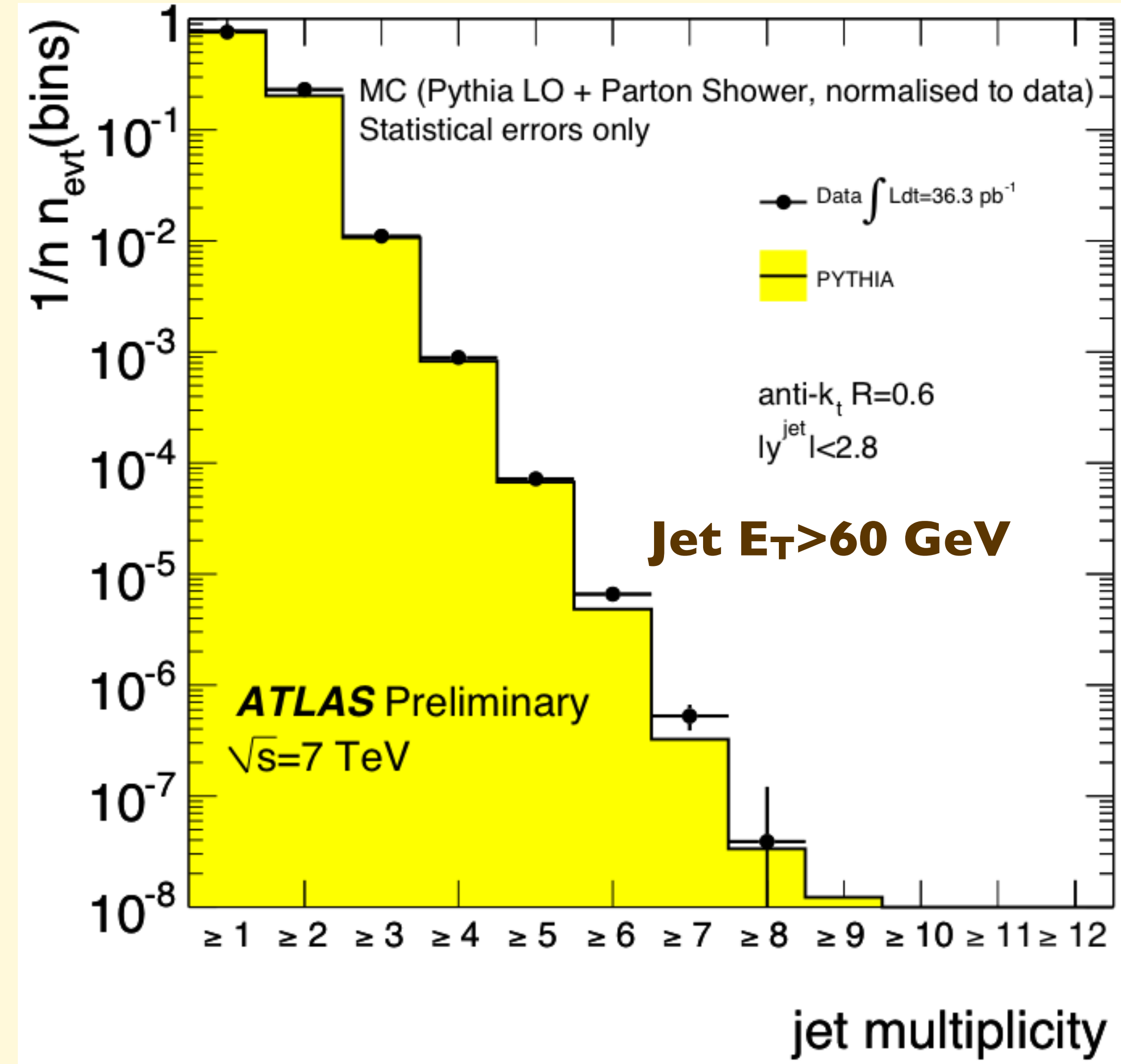


plus
- **jet shapes**
- **ptrel spectra**
- **<N_{ch}> and <z> distributions,**
- **....**

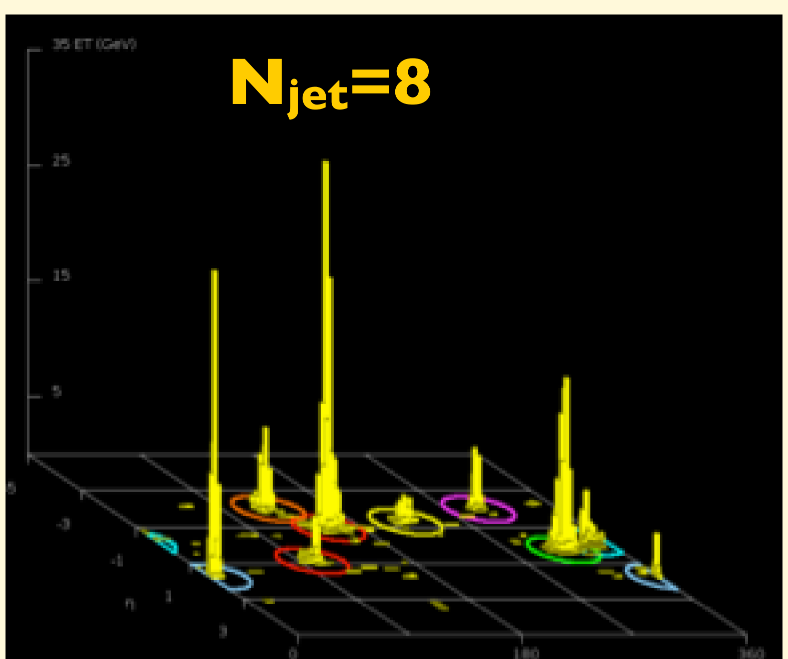
Data are much more precise than theory predictions, and can be used to improve them!

Multijets





Should probe N_{jet}~11-12 by end of 2012 !



Number of Feynman diagrams, at Born level, in the quantum mechanical amplitude for:

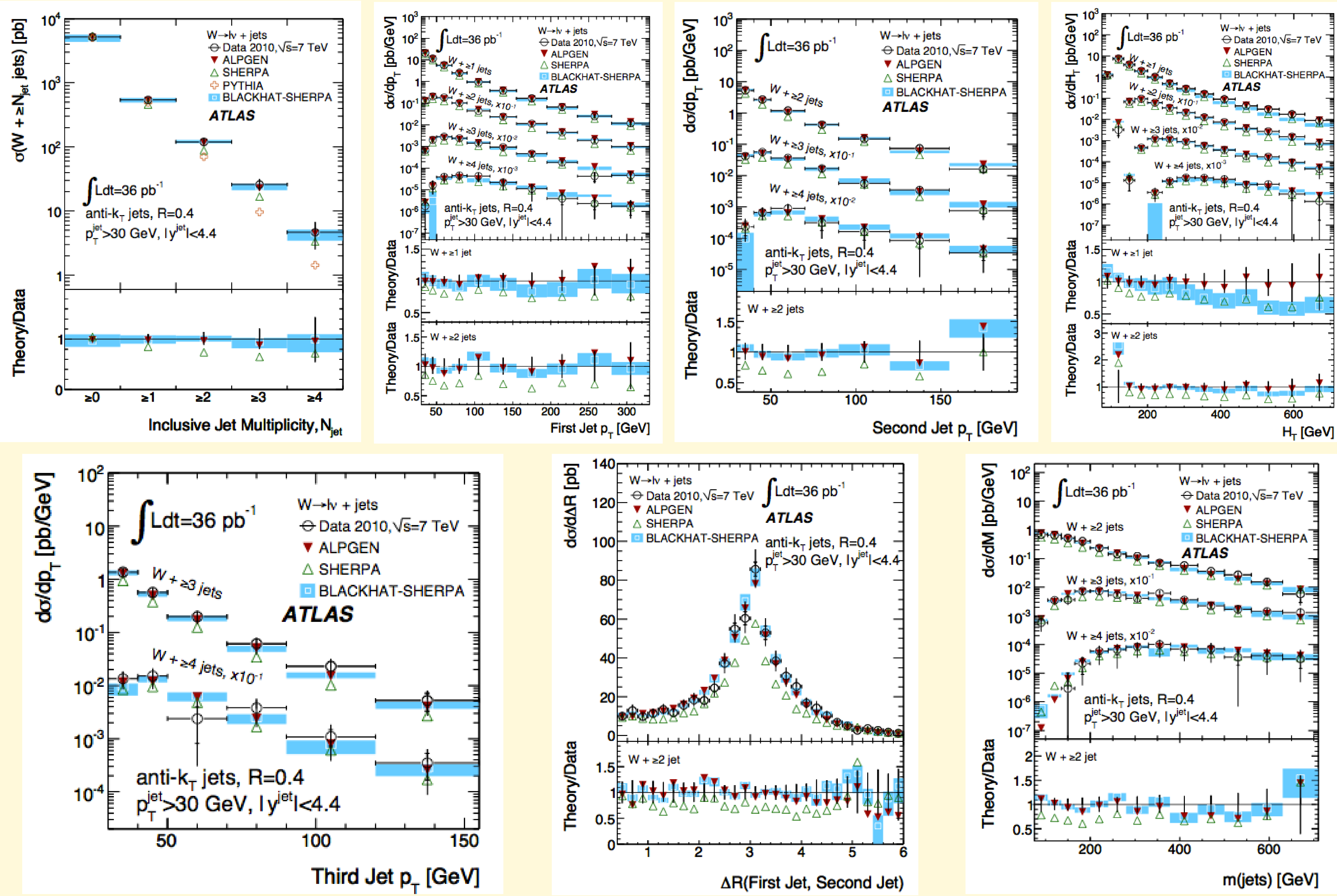
$gg \rightarrow g_1\ g_2\ ....\ g_{nj}$

n_j	2	3	4	5	6	7	8
# diag's	4	25	220	2485	34300	5×10^5	10^7

W+jets

ATLAS, arXiv:1201.1276

Alpgen Sherpa and Pythia σ_{tot} normalized to $\sigma_{NNLO}(W)$

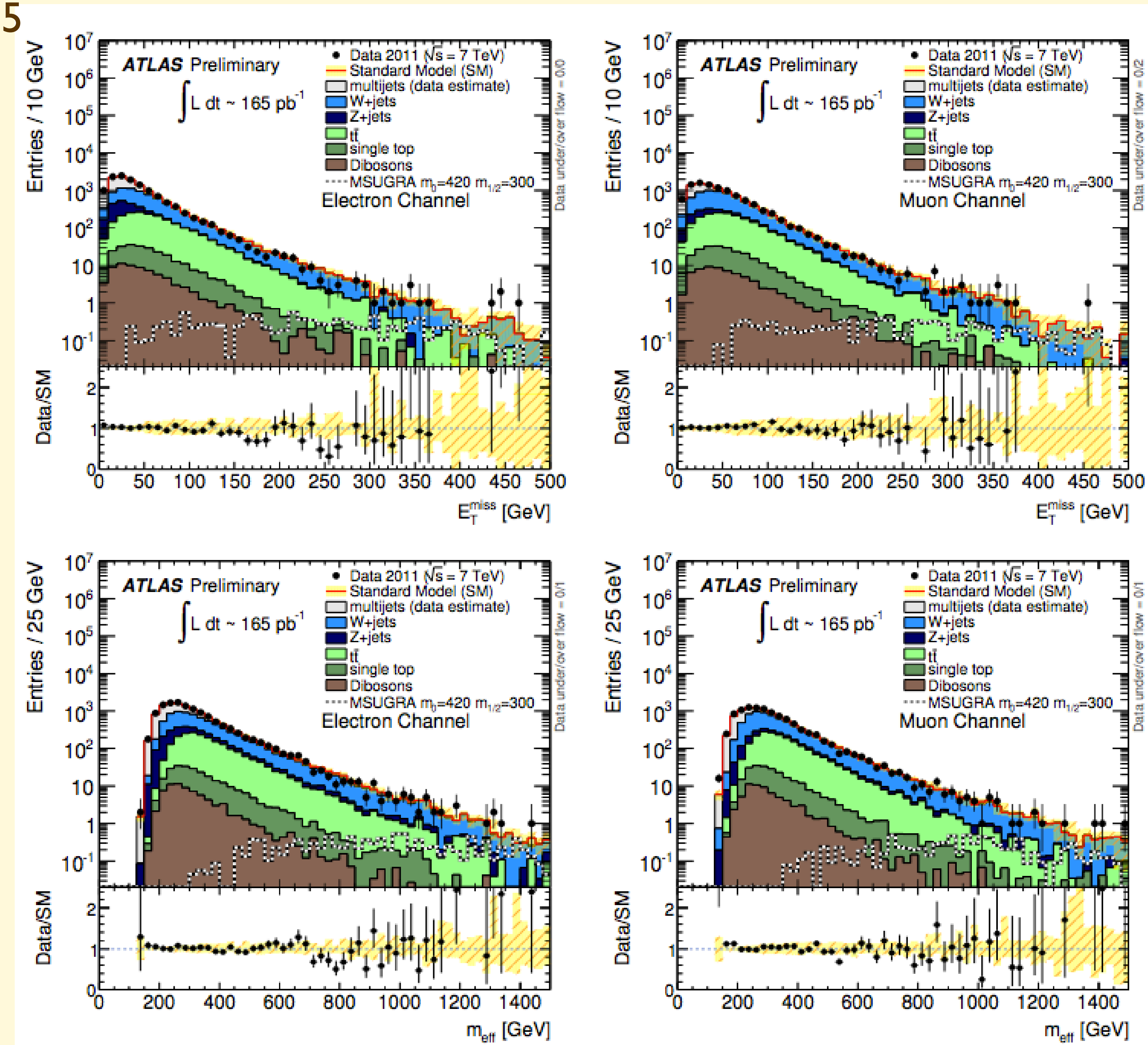


ATLAS 0.16fb^{-1}: SUSY search in ℓ+jets+MET

ATLAS-CONF-2011-090

Signal region:

- ≥3 jets w. E_T>25 GeV, $|\eta|$<2.8, E_{T1}>60 GeV
- M_{TW}>100 GeV ⇒ **typically this is a far off-shell W**
- MET>125 GeV, MET/M_{eff}>0.25



W+jets MC normalized to control region, defined by same jet and lepton cuts, but

- 30<MET<80 GeV
- 40<M_{TW}<80 GeV

Bg MC tools:

- W/Z+jets: Alpgen+Herwig/Jimmy(AUE1 tune)
- top (single and pair): MC@NLO +Herwig
- WW/WZ: Herwig, scaled to σ_{NLO}

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

MLM and J.Rojo, work in progress

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

X,Y: different hard processes

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

- 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, ...

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

- 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	$r^{th,nnpdf}$	$\delta_{PDF}(\%)$	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
- $\delta_{scale} < \delta_{PDF}$ at large p_T^{jet} and M_{tt}: constraints on PDFs

8 TeV / 7 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} (%)
$t\bar{t}/Z$	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

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
$\sigma\text{jet}(p_T \geq 1\text{TeV})$	15.235	1.72	0.00 – 0.00	2.31 – 2.19
$\sigma\text{jet}(p_T \geq 2\text{TeV})$	181.193	6.75	0.00 – 0.00	3.66 – 5.76

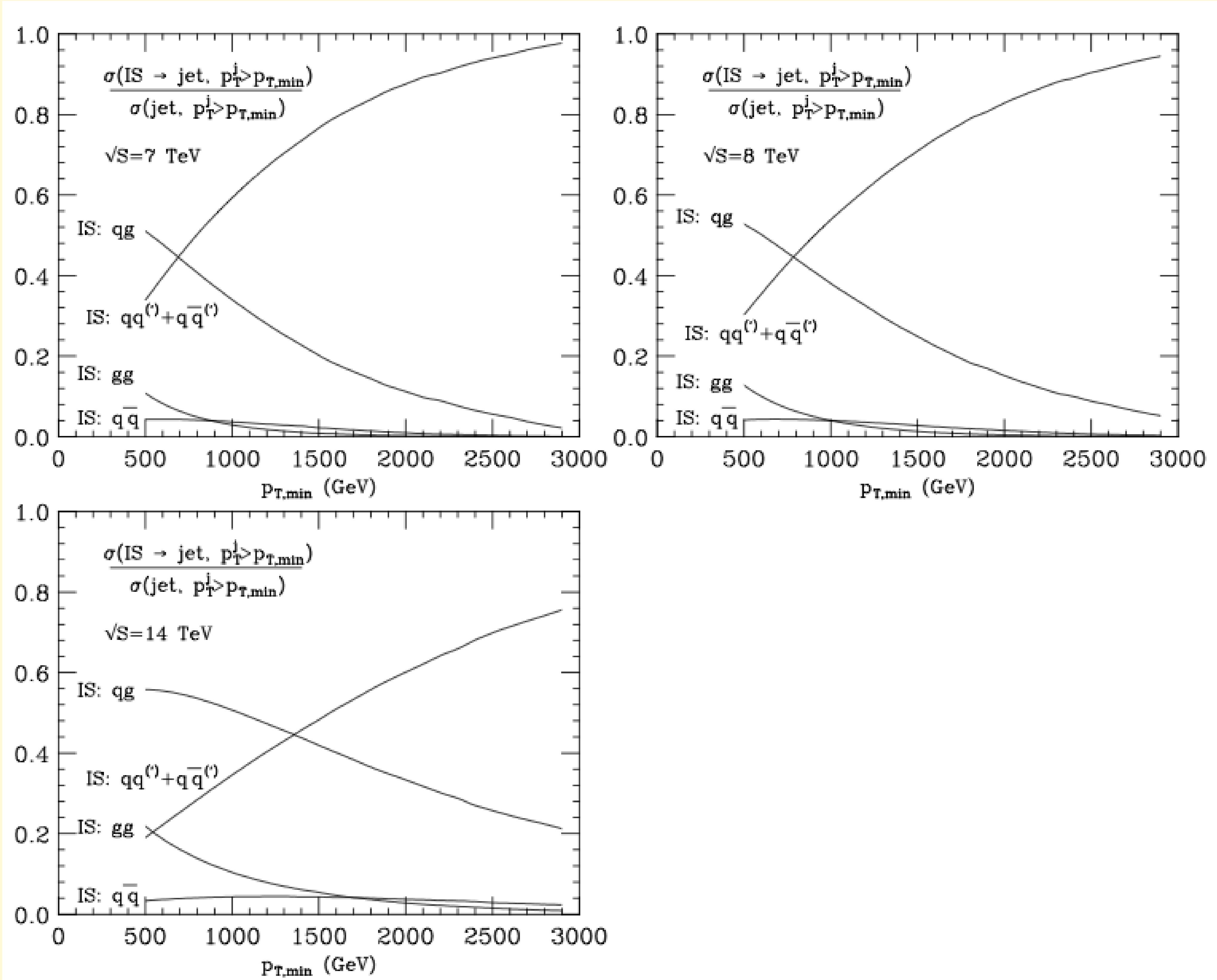
- $\delta < 10^{-2}$ in $W^\pm$ ratios: absolute calibration of 14 vs 8 TeV lumi
- $\delta \sim 10^{-2}$ in $\sigma(tt)$ ratios
- $\delta_{scale} < \delta_{PDF}$ at large p_T^{jet} and M_{tt}: constraints on PDFs

14 TeV / 8 TeV: NNPDF vs MSTW vs ABKM

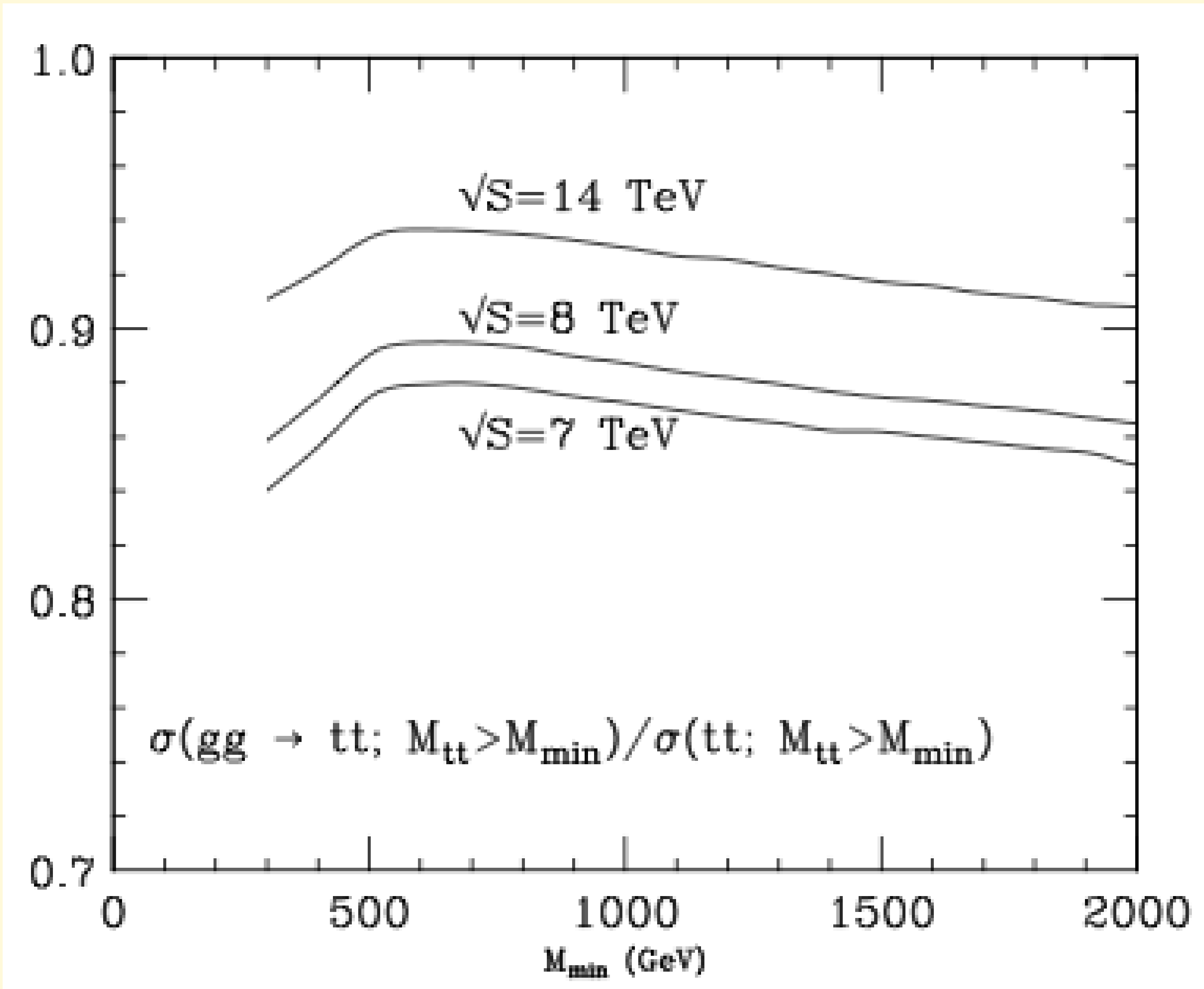
Ratio	$r^{th,nnpdf}$	$\delta_{PDF}(\%)$	$r^{th,mstw}$	$\delta_{PDF}(\%)$	$\Delta^{mstw}(\%)$	$r^{th,abkm}$	$\delta_{ABKM}(\%)$	Δ^{abkm} (%)
$t\bar{t}/Z$	2.121	1.01	2.108	0.95	0.93	2.213	1.87	-3.99
$t\bar{t}$	3.901	0.84	3.874	0.91	0.97	4.103	1.87	-4.90
Z	1.839	0.37	1.838	0.41	0.04	1.855	0.34	-0.87
W^+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

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

Initial state composition of inclusive jet events



Initial state gg fraction in t-tbar events



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:

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

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

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

theory systematics in 7→8 TeV extrapolation

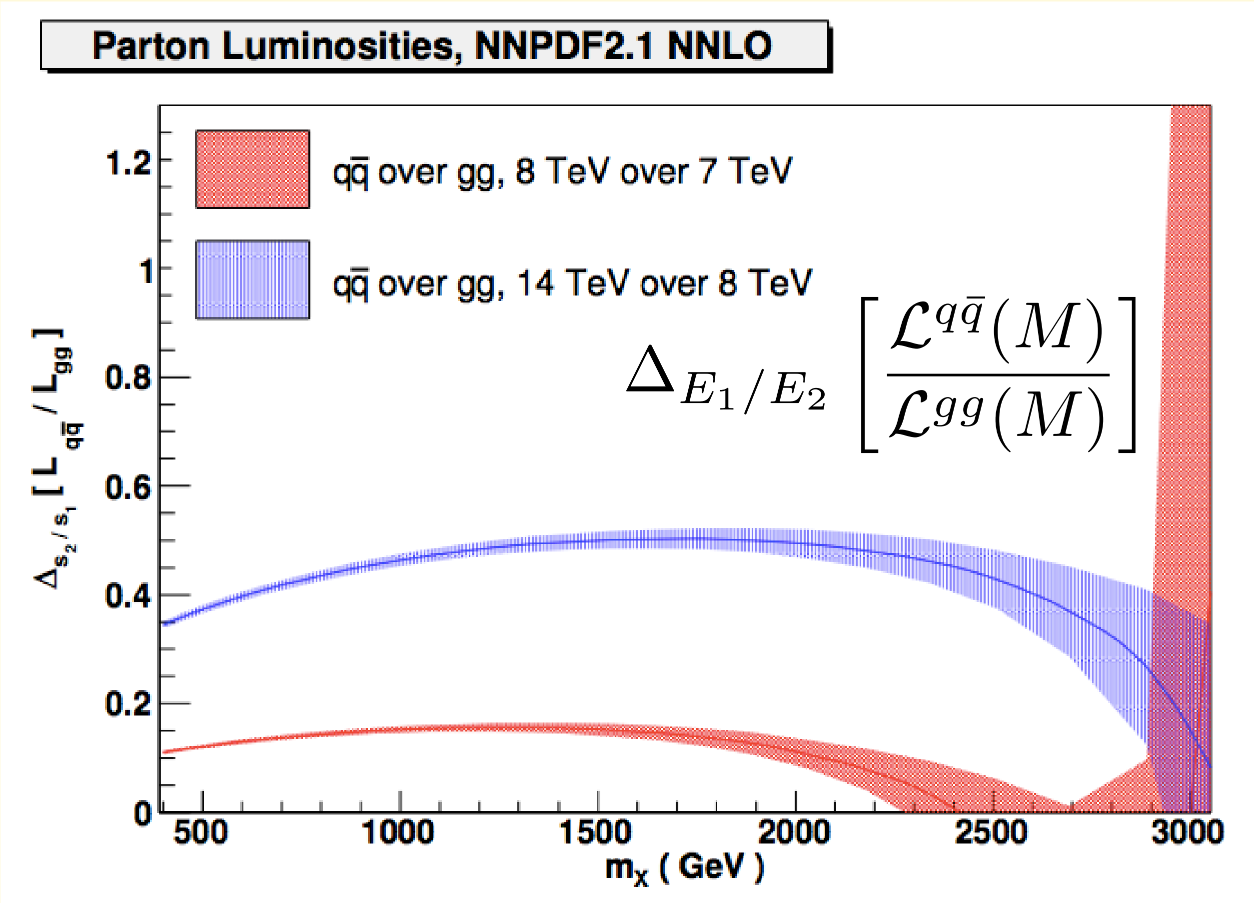
Energy dependence of the relative BSM contamination

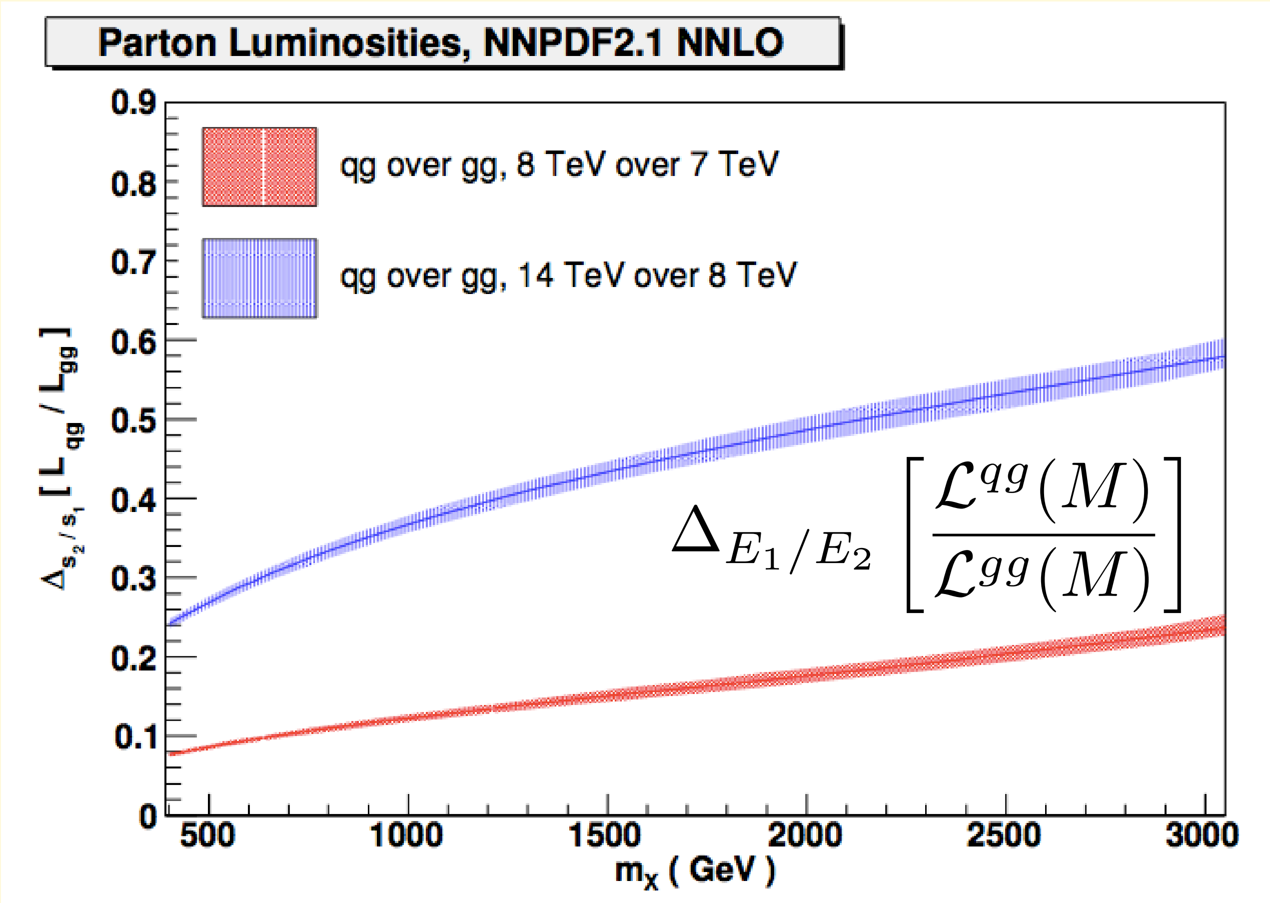
E.g., assuming $\sigma_{SM}(pp\to X)=\sigma(gg\to X)$ and $\sigma_{BSM}(pp\to X)=\sigma(qq\to X)$ (*)

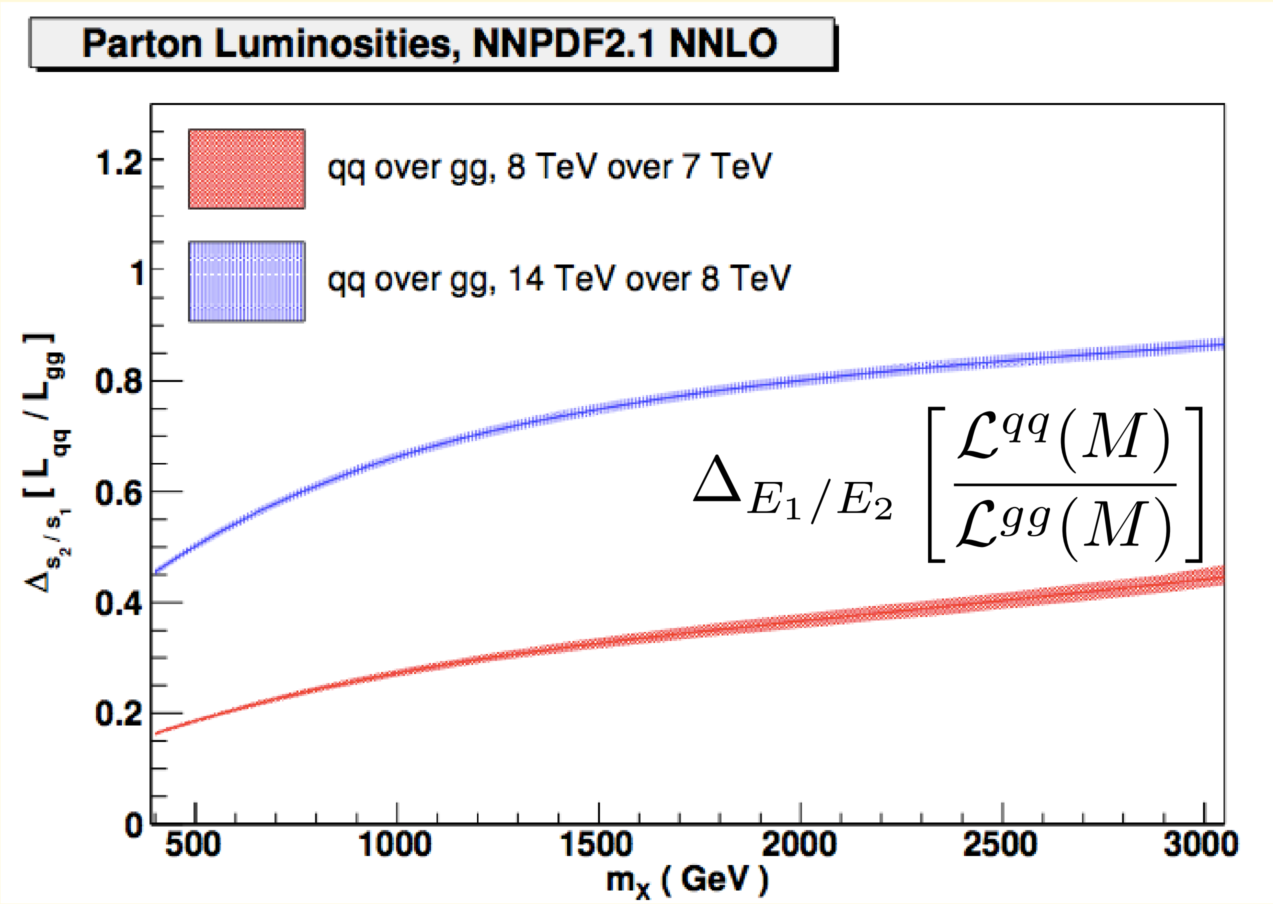
$$\Delta_{7/8}\left[\frac{\mathcal{L}^{BSM}_X}{\mathcal{L}^{SM}_X}\right] = \Delta_{7/8}\left[\frac{\mathcal{L}^{q\bar{q}}(M)}{\mathcal{L}^{gg}(M)}\right]$$

(*) 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)**

Need to explore in more detail the possible implications of precise measurements of energy (double-)ratios

E.g.

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

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

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

(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**

Finally, where PDF systematics are negligible, and if there is no new physics, Xsection (double)ratios provide excellent benchmarks for calibration, anaysis validation, etc.

Powerful diagnostic tool when coming back after 2 yrs of shut-down!

Experimental challenge to match this precision. Requires great degree of correlation in the systematics of the analyses at different energies (eff's, bg subtraction, JES, ...)

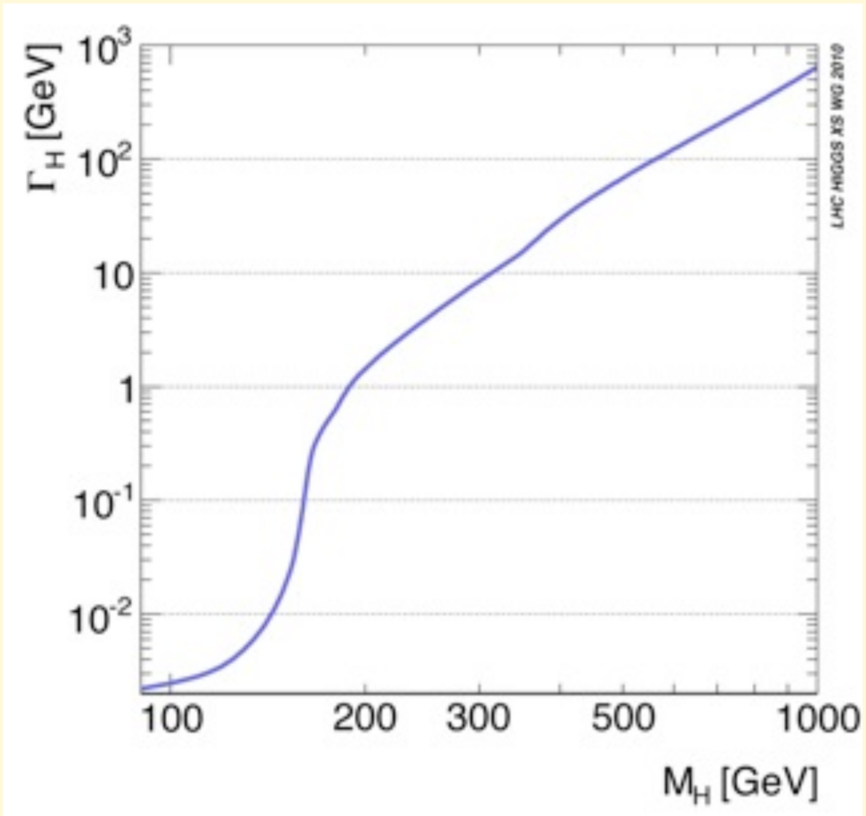
Coherent efforts to plan the analyses having in mind the needs of XS (double)ratios are worth consideration

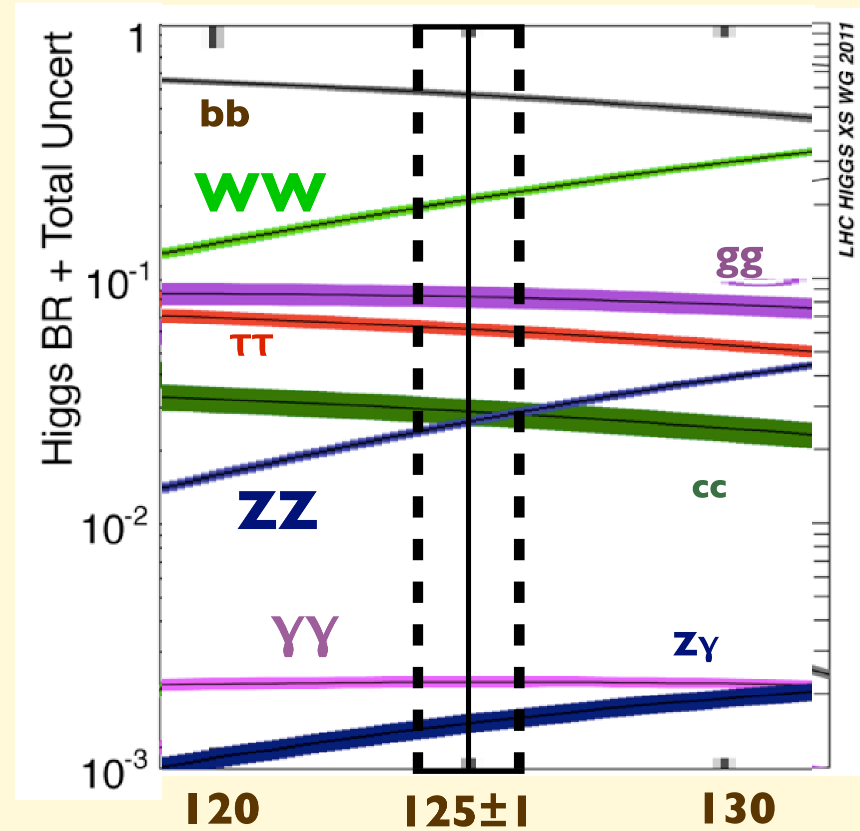
Many analyses of the (S)LHC potential are based on obsolete assumptions on the degree of either theoretical or experimental precision

Having established they it can meet, and exceed, the nominal performance promised in the TDRs and in the theory papers, the LHC programme should enhance its ambitions and reassess its ultimate limitations, reviewing the new potential of

- ***reliance on theory modeling***
- ***full exploitation of detectors' and triggers' capabilities, and of their modeing***
- ***new analysis probes and tools***
- ***....***

Higgs width and BRs





$(\Delta_{TH}$ BR(WW,ZZ) ~ 5%)

m_H(GeV)	124	125	126
B(WW) (%)	22	24	26
B(ZZ) (%)	2.8	3.0	3.3
B(γγ) (‰)	2.3	2.3	2.3
Γ_{TOT}(MeV)	4.0	4.1	4.3

} ΔBR ~ 10% Δm_H/GeV

→ $\Delta BR/\Delta m_H \sim 0$

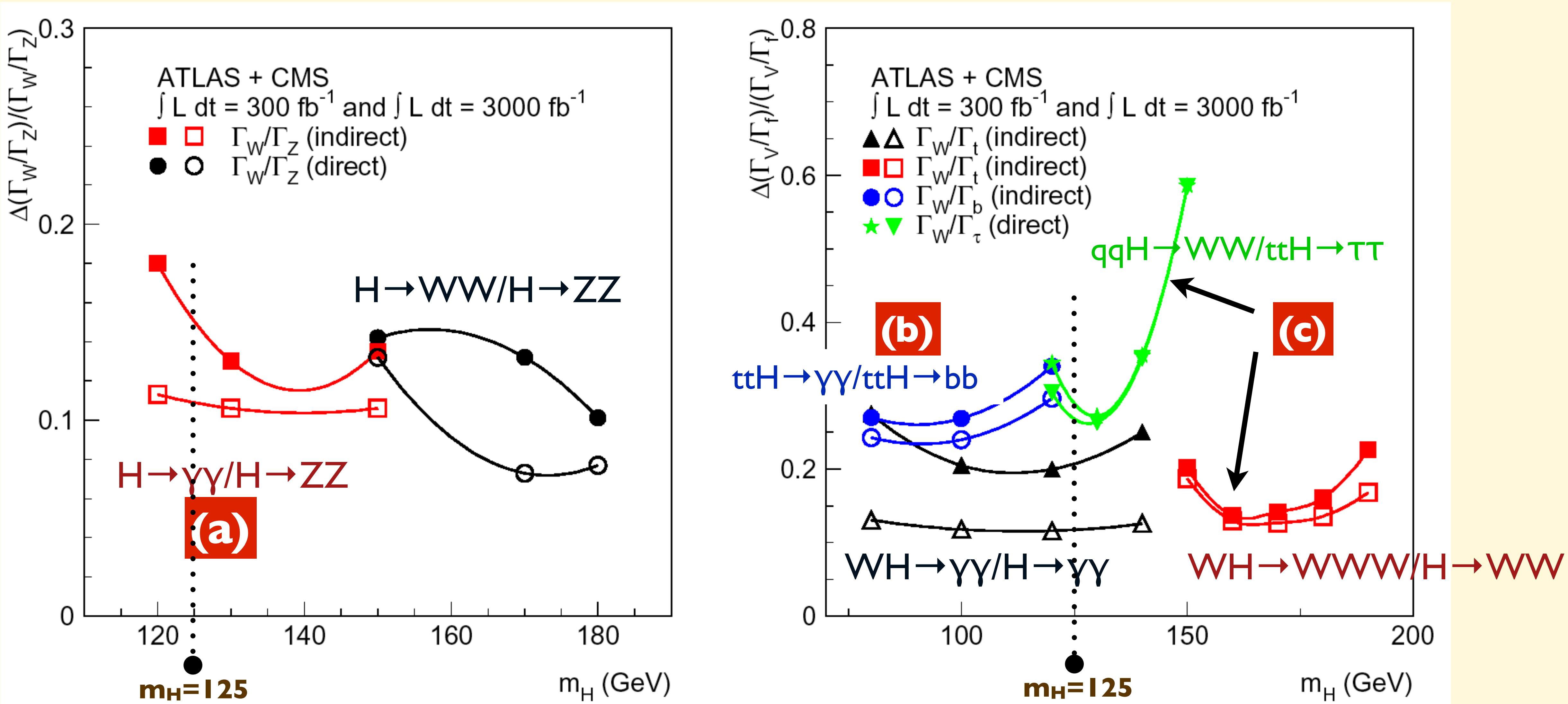
→ $\Delta\Gamma \sim 5\% \; \Delta m_H$ / GeV

- Γ_{SM} (m_H=125 GeV) ~ 4 MeV
- $\Gamma = \Sigma_i \Gamma_i$, $BR_i = \Gamma_i / \Gamma$

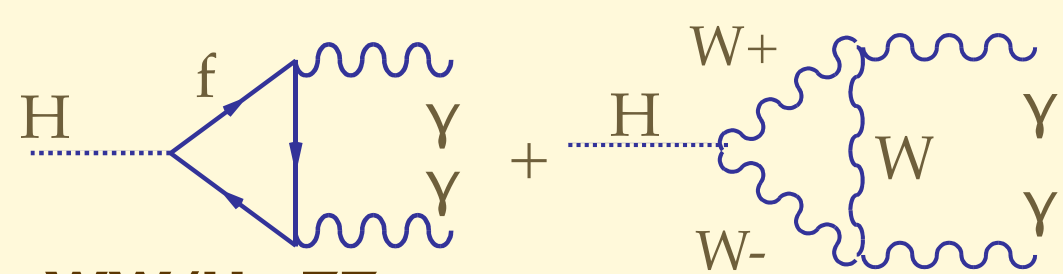
For a 125 GeV Higgs, a measurement of m_H to few x 100MeV will be enough to saturate the precision of the SM estimate of the Higgs BRs, at the ~5% level. This sets the goal for their experimental measurement, until further progress in the calculation of Γ(H→bb) is made

Example of projections to be reviewed:

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

New analysis probes: charge asymmetries

- So far mostly used in the context of W^+ vs W^- and PDF constraints

- With larger statistics, should monitor and use possible charge (a)symmetries in pretty much every measurement!

See also Kom and Stirling, arXiv:1010.2988

Example 1: BSM searches

- Most BSM processes lead to charge-symmetric final states (e.g. Z' , TT, gluino-gluino, ...)
- Many others are intrinsically charge-asymmetric. E.g.

q q' → ~q ~q' → lept + jets + MET

q g → ~q ~g → lept + jets + MET

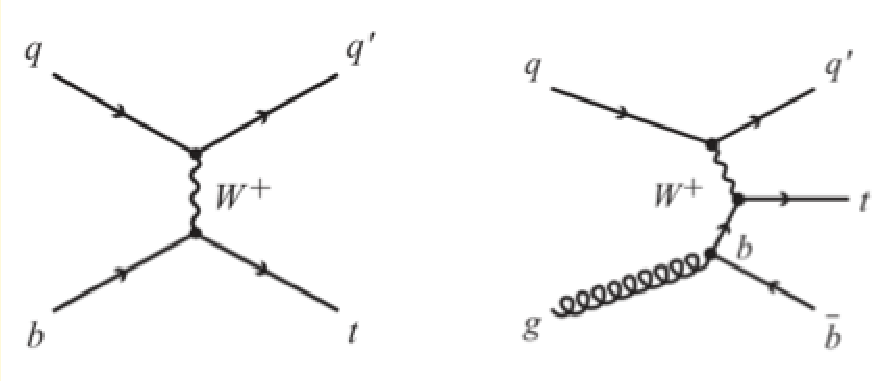
W' → lept + X

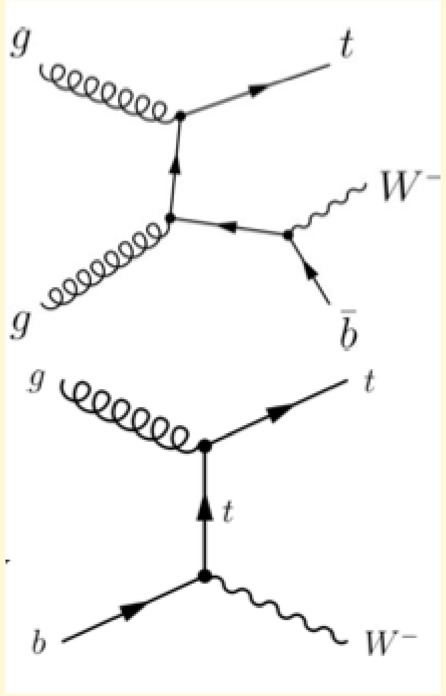
etc.

⇒ There could be a value in systematically monitoring and reporting BSM searches (e.g. ell+jets+met) in terms of possible charge (a)symmetries

Example 2: single top production

t-channel graphs, charge asymmetric (t>tbar)





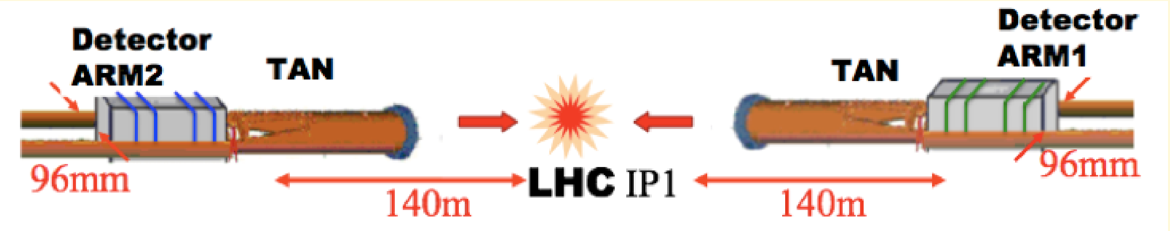
Wt-channel graphs, as well as t-tbar bgs, charge symmetric

Systematics of V_{tb} extraction from A(t)=[σ(t)–σ(tbar)] ?

There is more at the LHC than *just* high-Q^2 physics .....

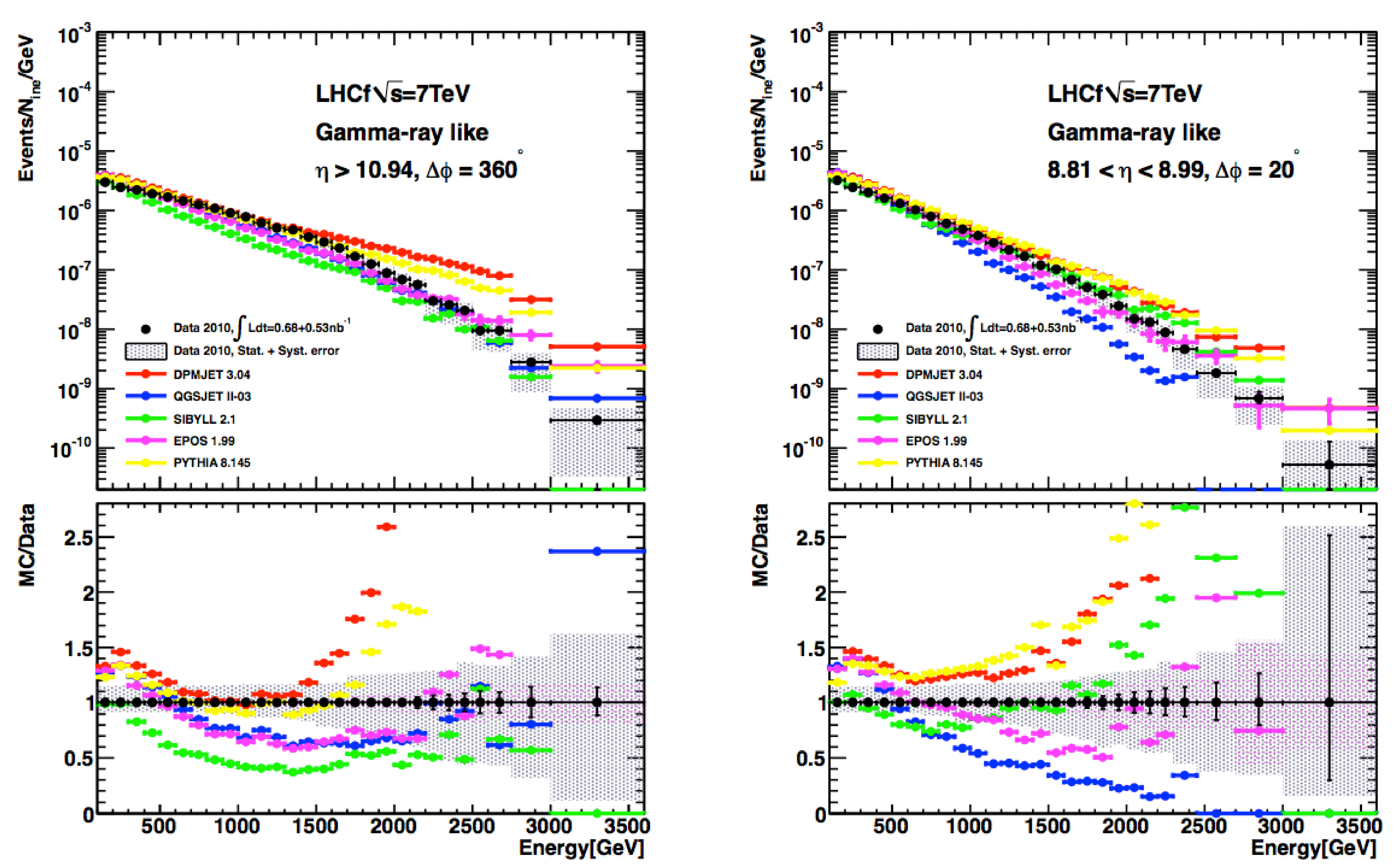
... and in addition to flavour physics, to be discussed later by Guy

LHCf: Very forward energy flow

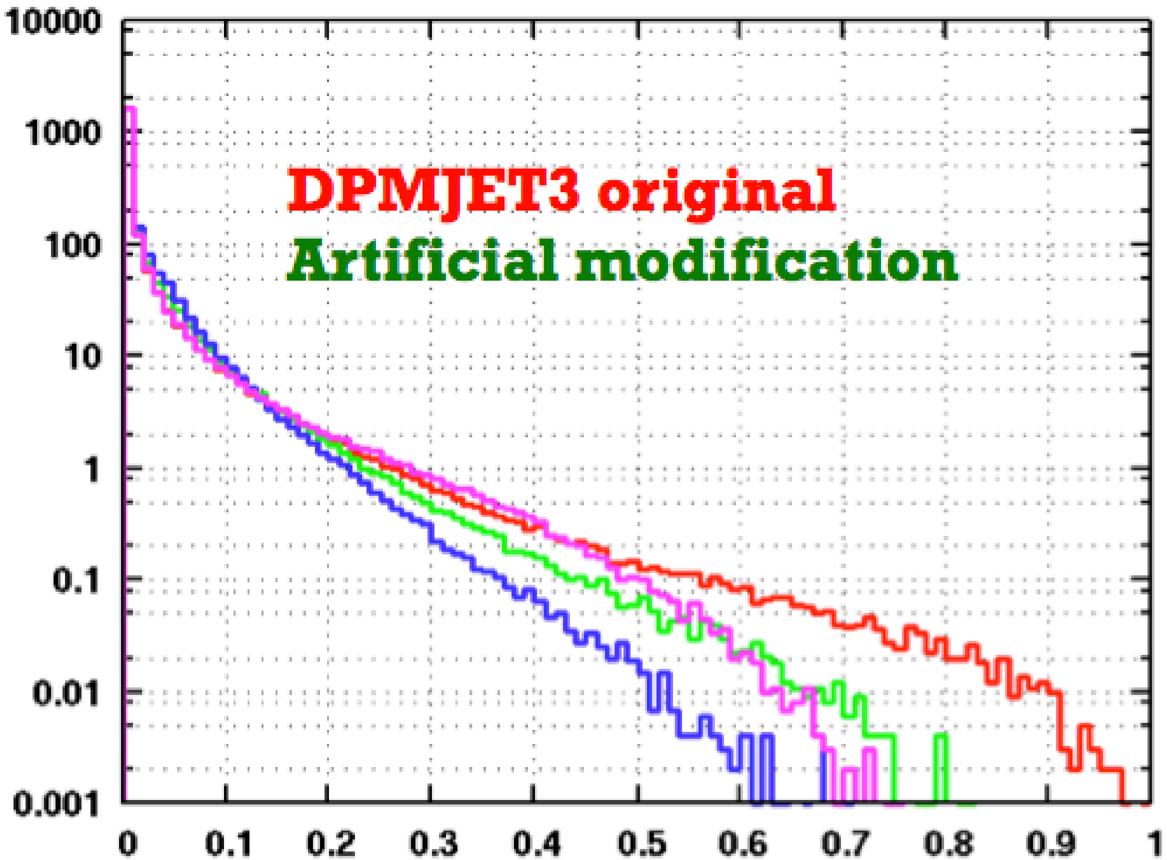


"Measurement of zero degree single photon energy spectra for $\sqrt{s}$ = 7 TeV proton-proton collisions at LHC"

PLB 703 (2011) 128

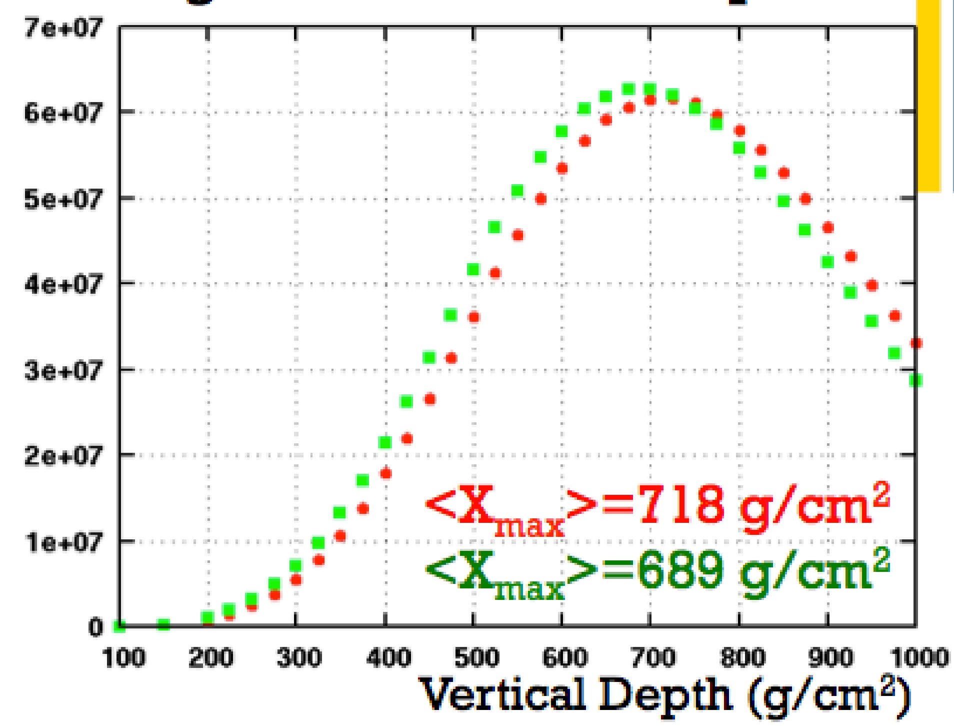


π^0 spectrum and air shower

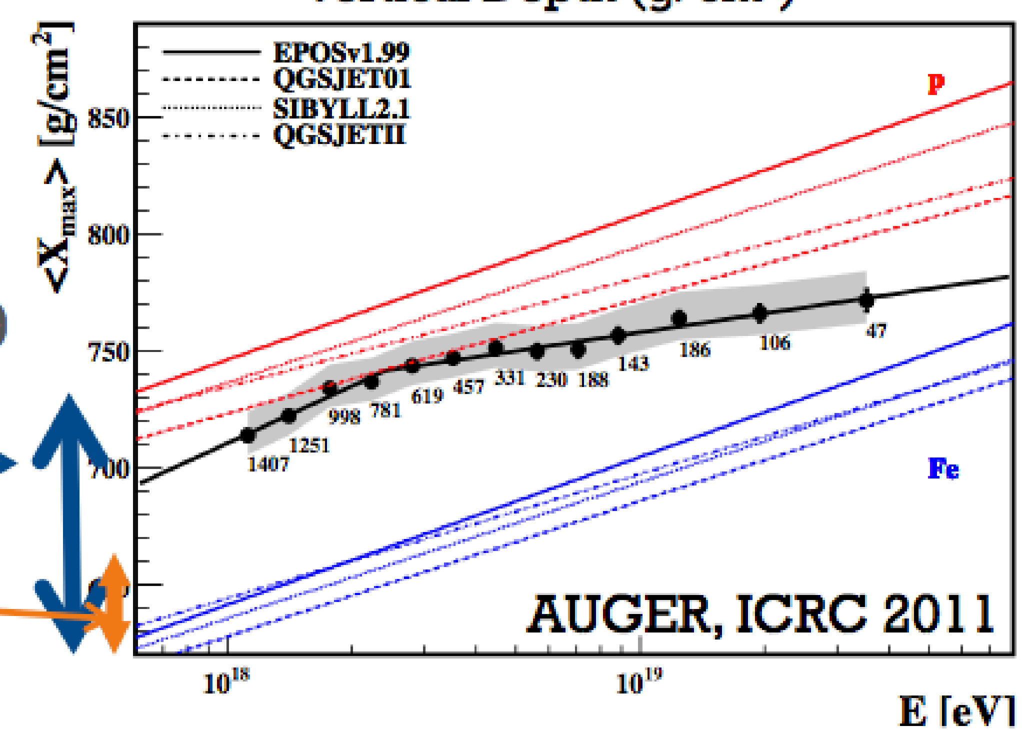


π^0 spectrum at $E_{lab} = 10^{17}$eV

Longitudinal AS development

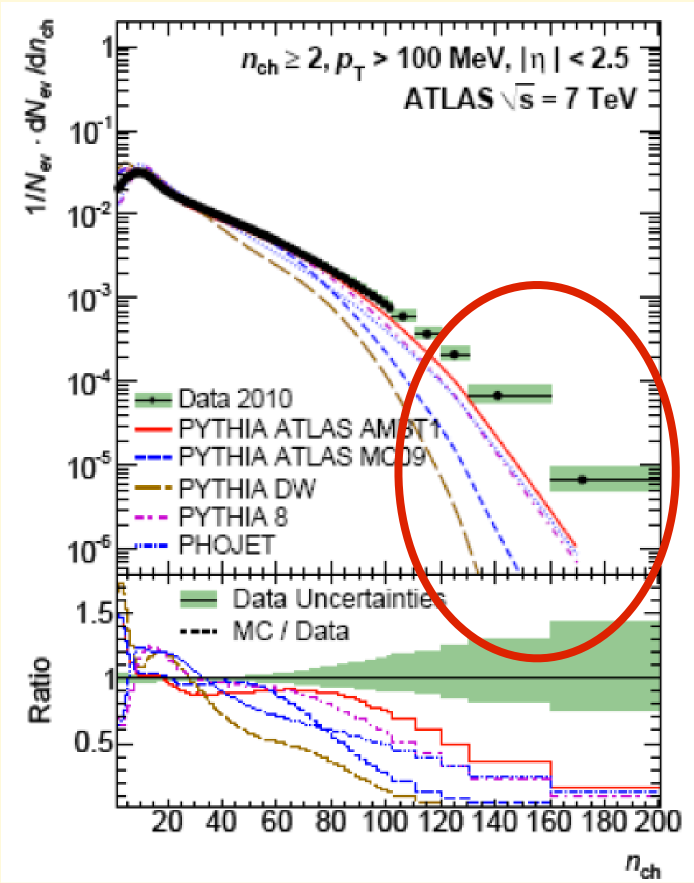


- ✓ Artificial modification of meson spectra (in agreement with differences between models)
- ✓ $\Delta\langle X_{max}(\text{p-Fe})\rangle \sim 100\ \text{g/cm}^2$
- ✓ Effect to air shower ~ 30 g/cm²

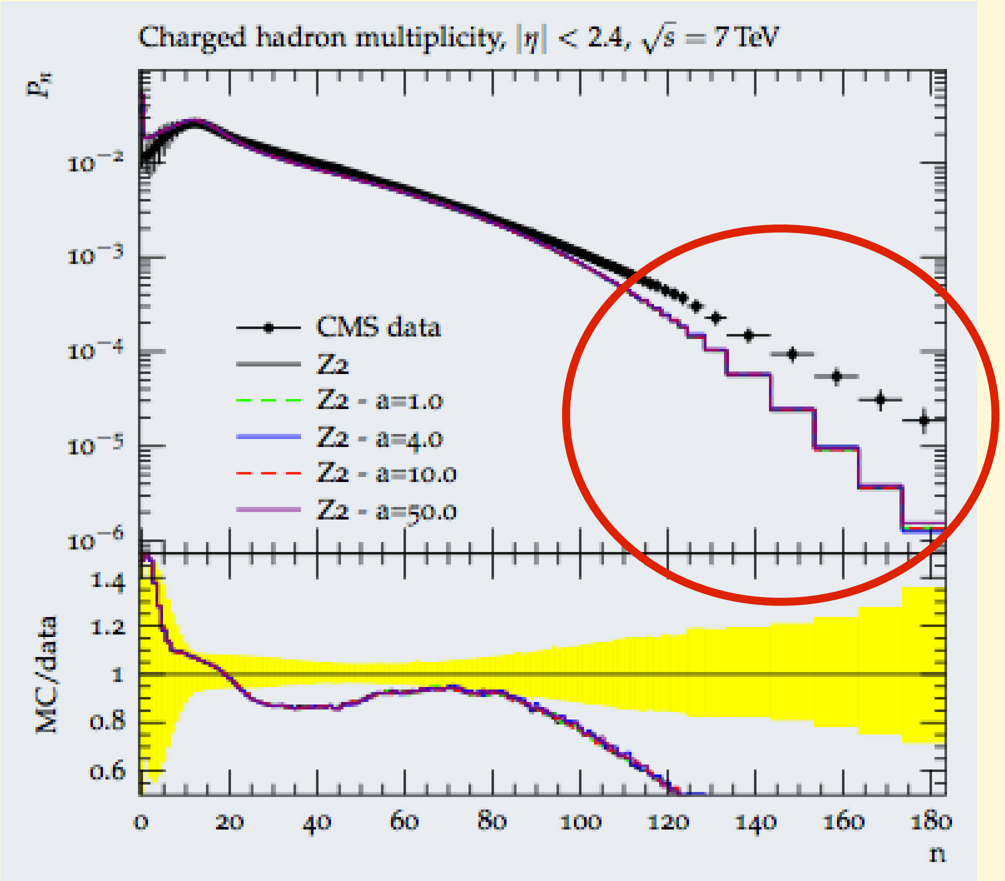


Properties of final states in “0-bias” events

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?**
- **.....**

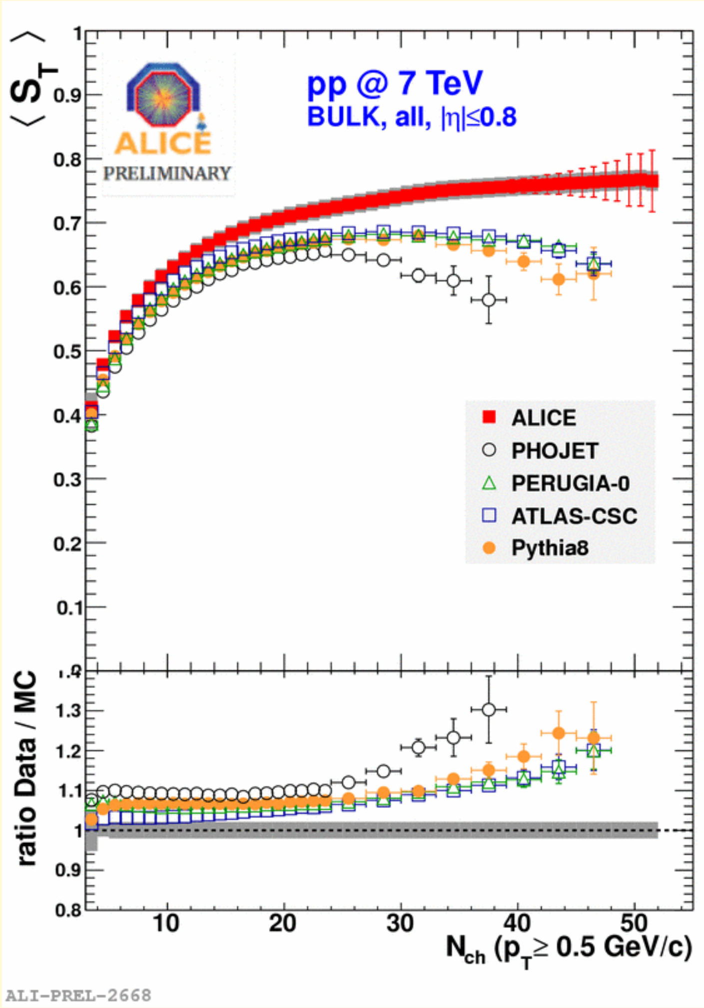
Are we staring at something *fundamental*, or is this just QCD chemistry and MC-tuning?

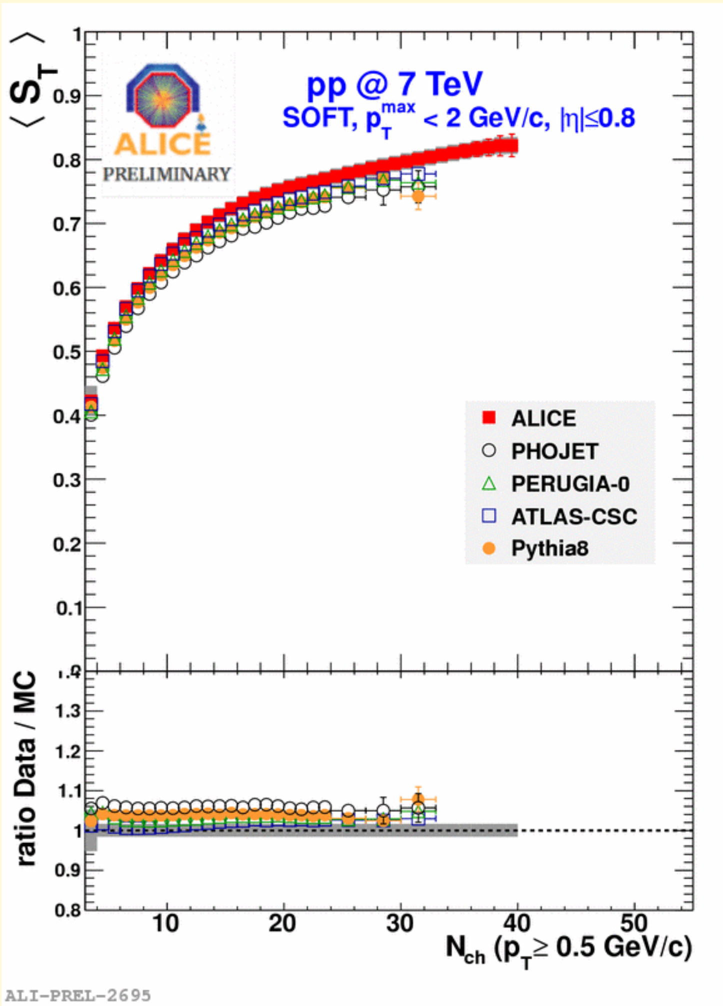
.... see also the CMS ridge effect

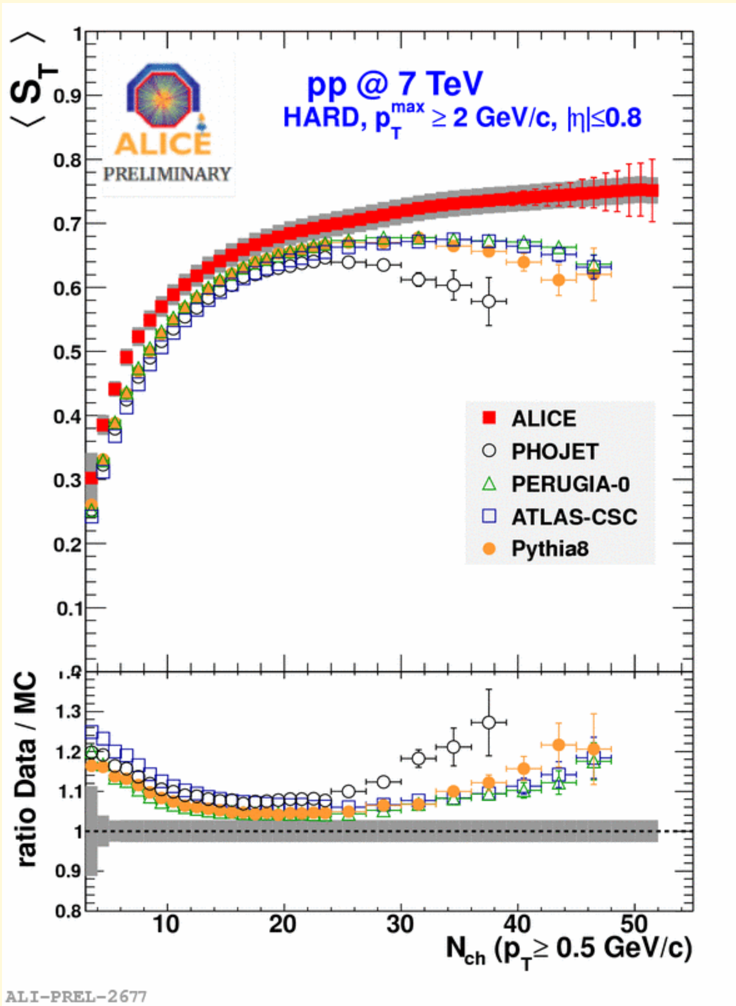
Further insight and puzzles on large-N_{ch} events

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

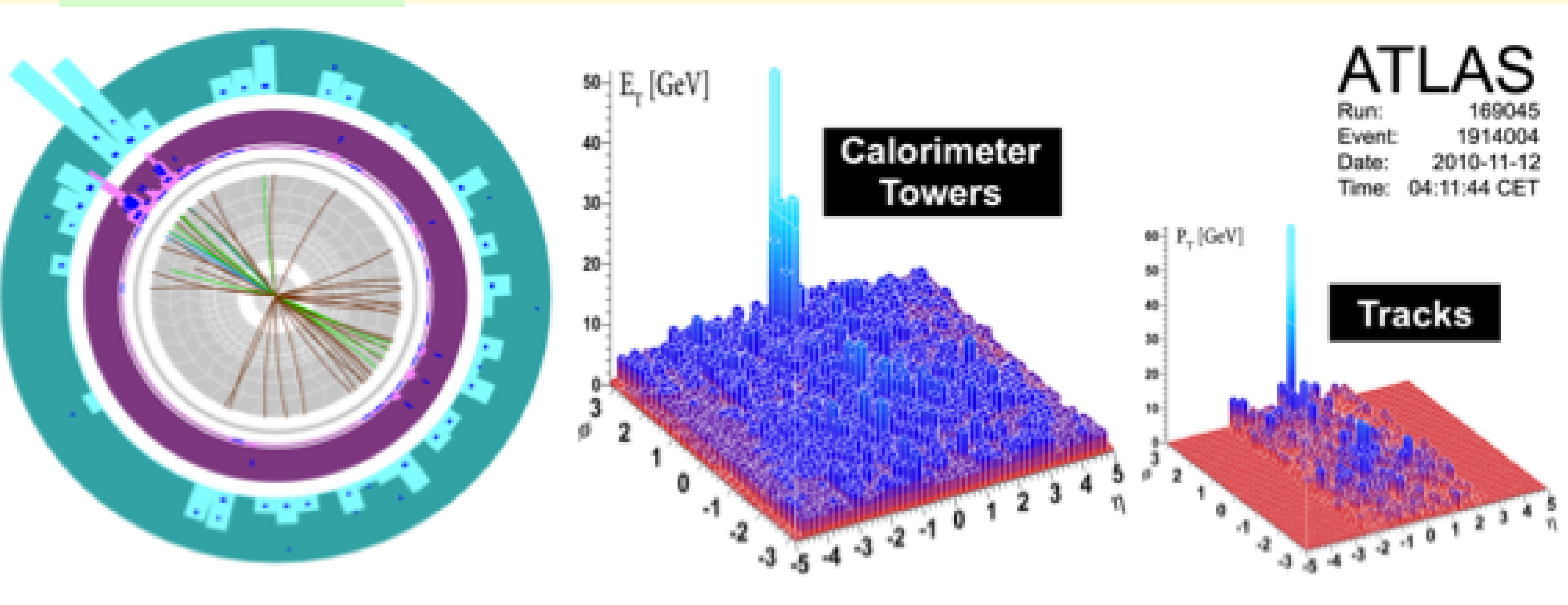
Open challenge:

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

Hard probes in Pb-Pb collisions ....

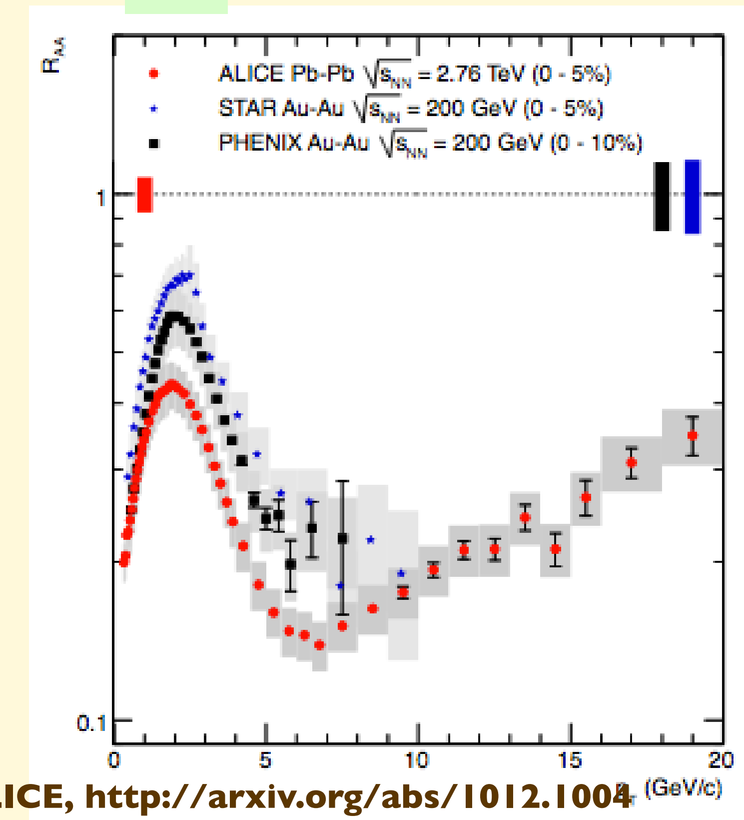
- $\sqrt{S_{NN}}$ = 2.76 TeV => 14 times larger than any previous heavy ion experiment (RHIC)

Jet quenching



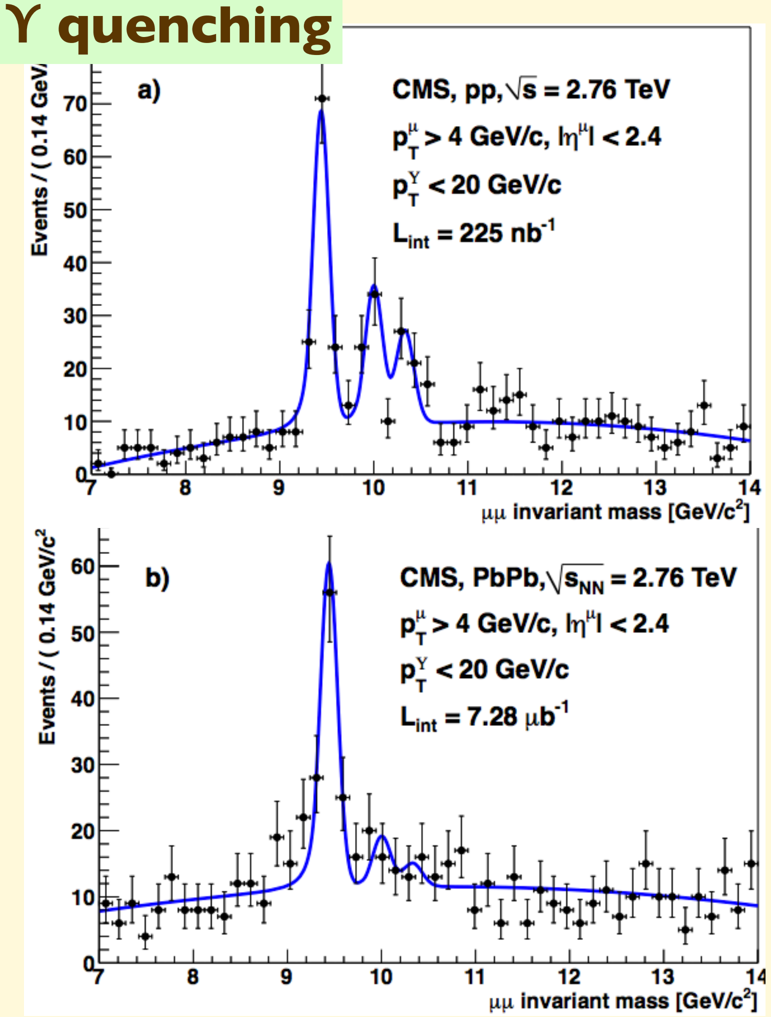
ATLAS, http://arxiv.org/abs/1011.6182

R_{AA}

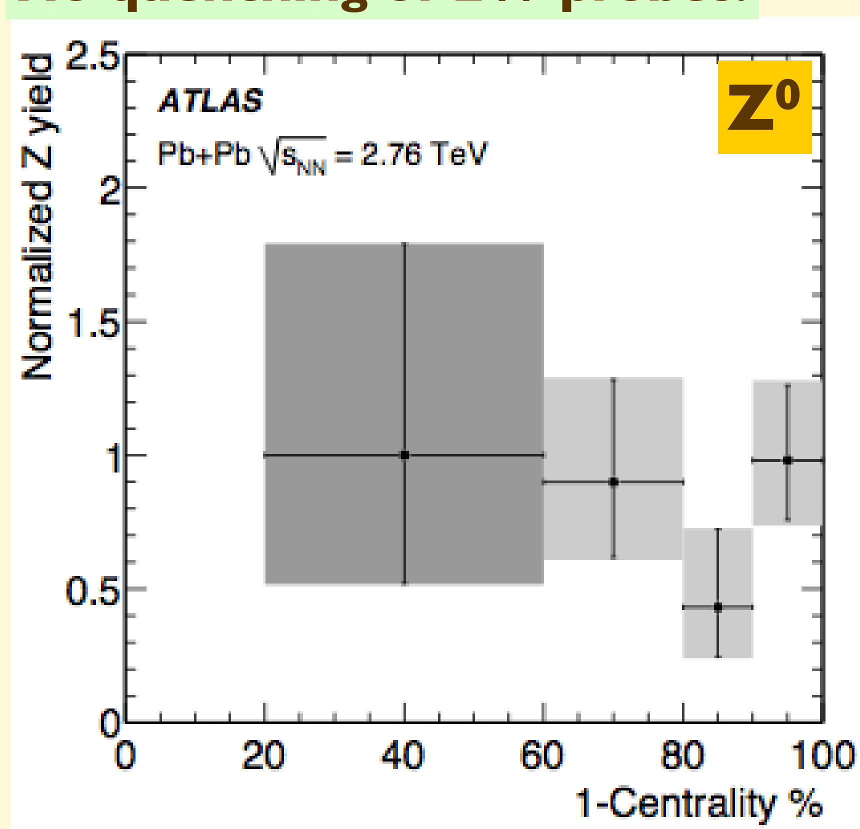


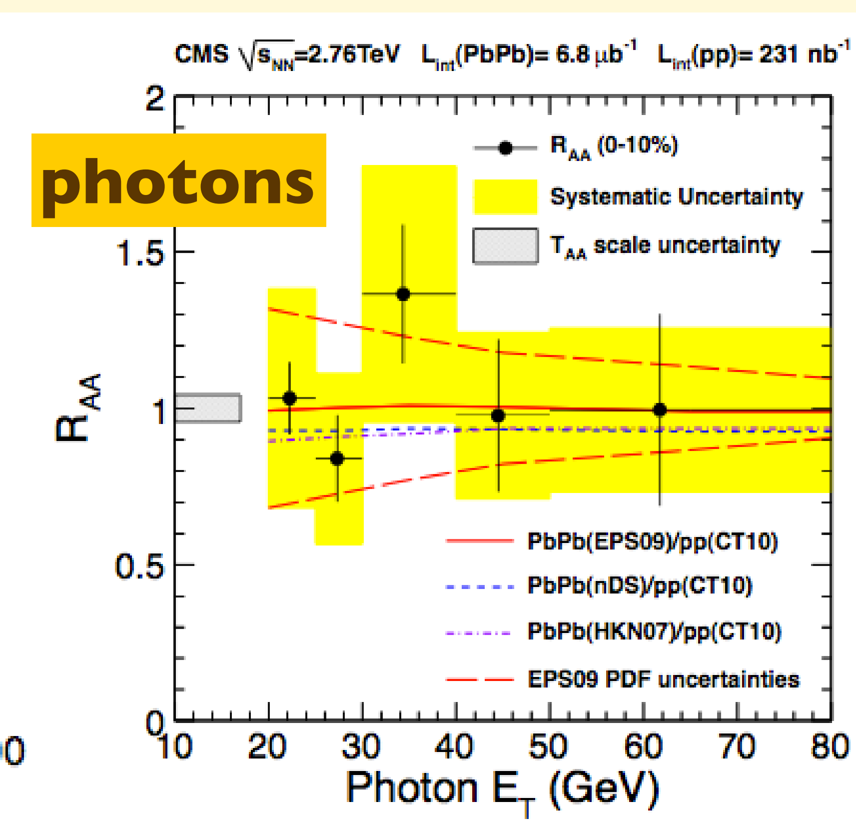
ALICE, http://arxiv.org/abs/1012.1004

Υ quenching



No quenching of EW probes:





ATLAS, http://arxiv.org/abs/1012.5419

CMS, http://arxiv.org/abs/1201.3093

Conclusions

Conclusions

- **Higgs or new physics are *not* jumping at us**
  - wherever it is, it's hiding well, and we'll suffer to dig it out!
  - better be ready with finely honed theory tools!

Conclusions

- **Higgs or new physics are *not* jumping at us**
  - wherever it is, it's hiding well, and we'll suffer to dig it out!
  - better be ready with finely honed theory tools!
- **LHC measurements moved to a new, and perhaps unexpected, phase of quantitative and precision level**
  - proton structure (cross sections, PDFs)
  - final state dynamics
  - extreme kinematical configurations
  - EW and flavour sector parameters

Conclusions

- **Higgs or new physics are *not* jumping at us**
  - wherever it is, it's hiding well, and we'll suffer to dig it out!
  - better be ready with finely honed theory tools!

- **LHC measurements moved to a new, and perhaps unexpected, phase of quantitative and precision level**
  - proton structure (cross sections, PDFs)
  - final state dynamics
  - extreme kinematical configurations
  - EW and flavour sector parameters

- **In view of this, there is a scope for a fresh reassessment of the LHC potential to perform precision measurements and to explore new frontiers in the understanding of fundamental interactions**
  - SM dynamics
  - study of the properties of the soon-to-be-discovered Higgs
  - exploration of BSM phenomena