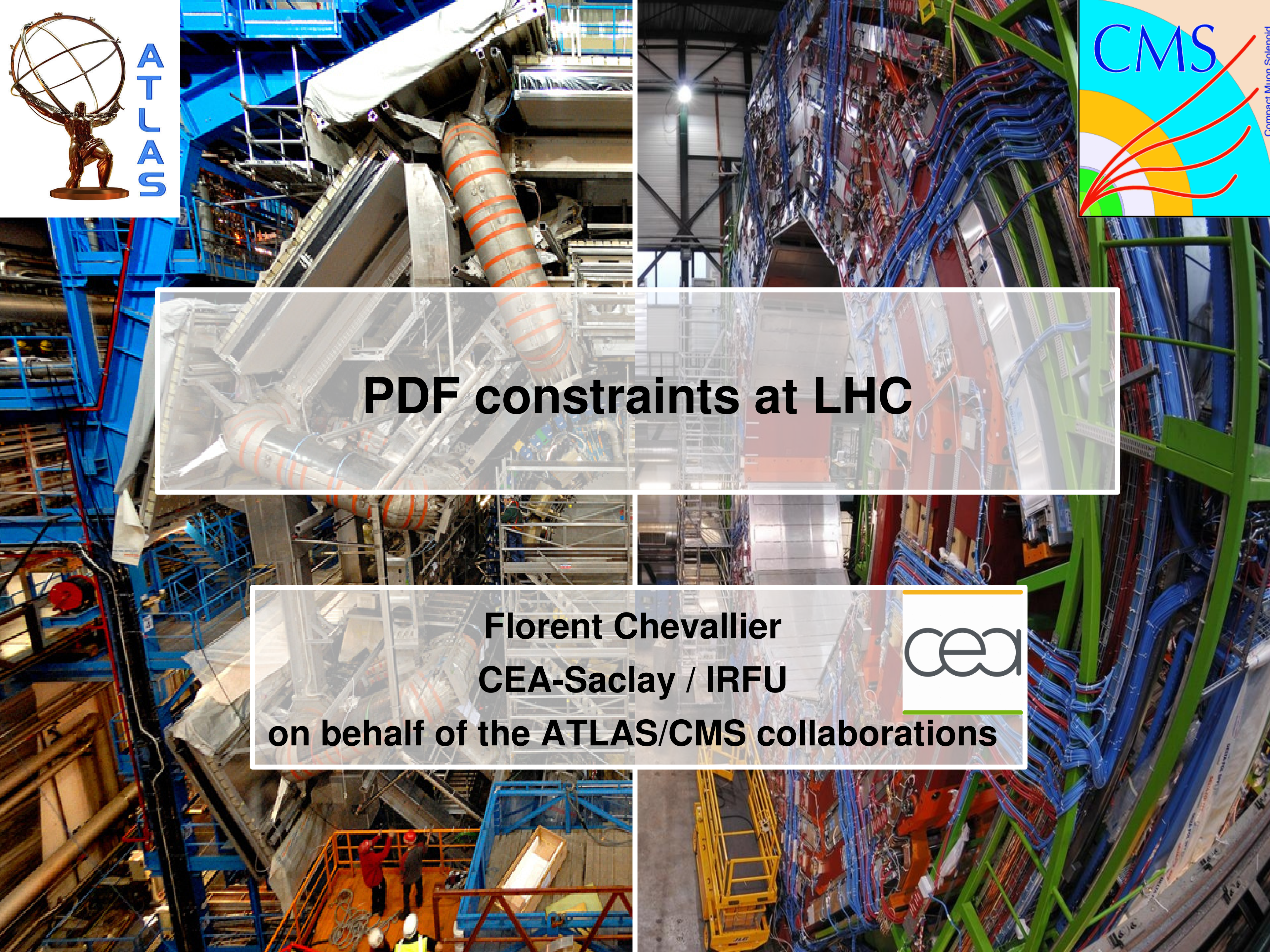

PDF constraints at LHC

Florent Chevallier

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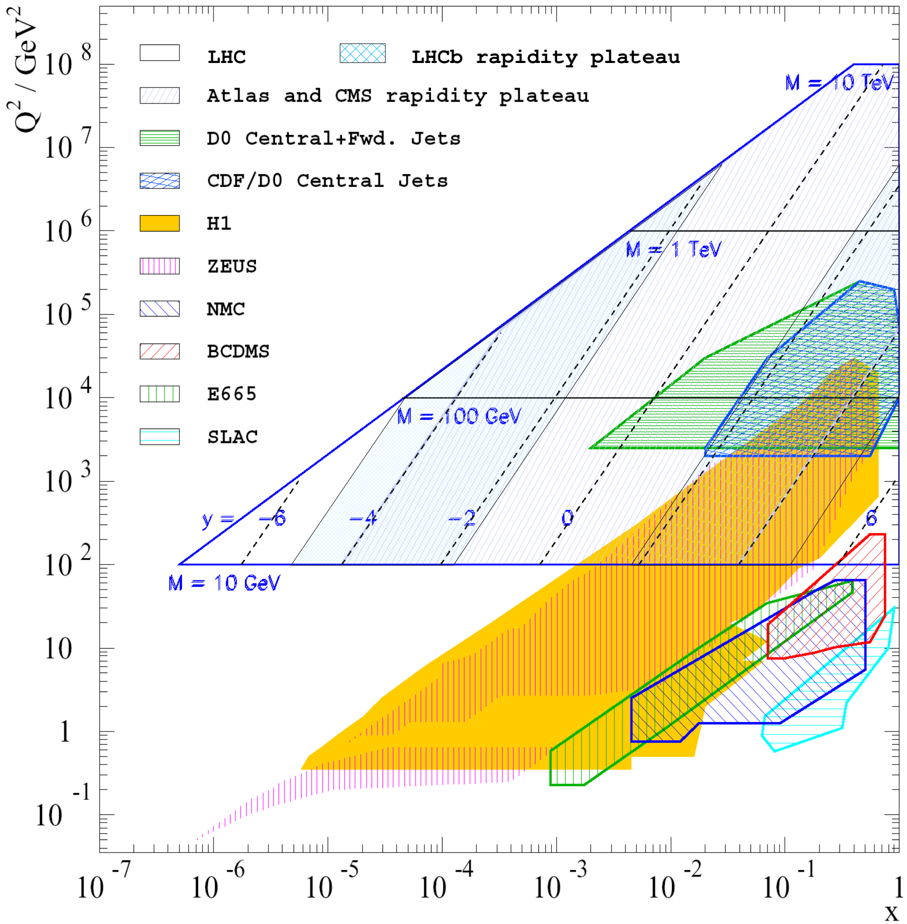
on behalf of the ATLAS/CMS collaborations

LHC will probe a new x & Q^2 domain

- *Low x & High Q^2*
  $x < 10^{-3}$ $Q^2 > 10^6$ GeV²
- *Connection with other (x, Q^2) regions*
  Use of LO/NLO DGLAP equations
  NNLO/CCFM/BFKL ? non-linear effects ?

Requirements for PDF constraints

- *Observable precisely measured*
  Low statistical errors
  Low experimental systematic errors
  → New techniques at LHC
- *Observable free of new physics*
  Absorb new physics effects in PDFs

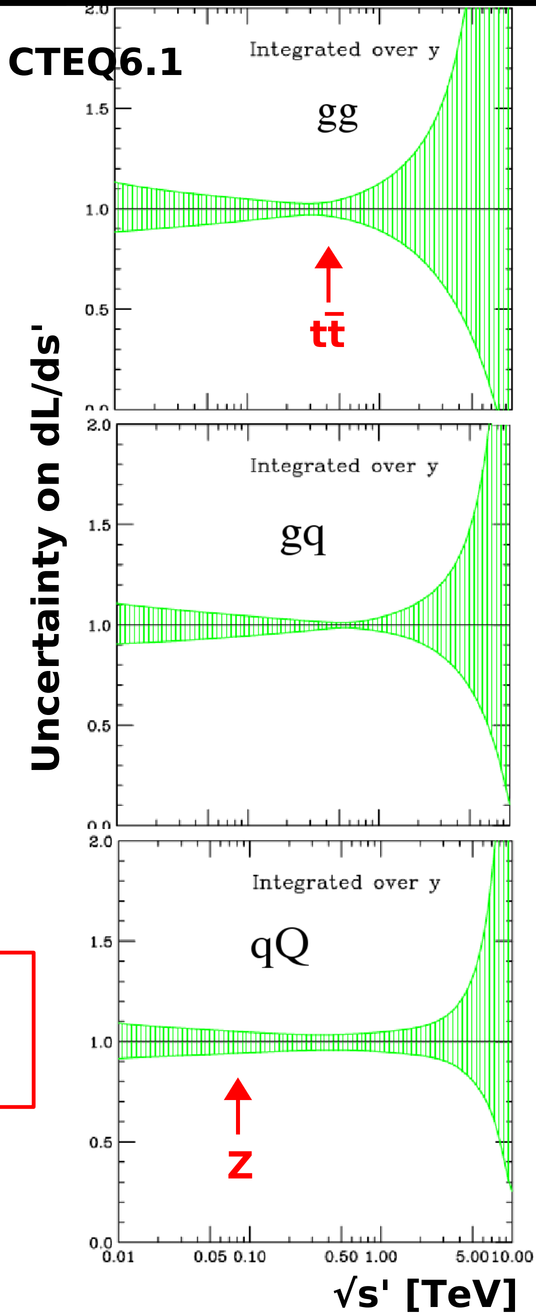


PDF can be constrained by LHC measurements using :
→ Cross-sections and shape of EW or QCD processes
→ Ratios of cross-sections or direct fits of PDF

PDF uncertainties at the LHC

- *Large PDF uncertainties at low & high Q^2*
  $d\sigma/\sigma > 10\ \%$
- *Error is small for SM processes*
  $d\sigma/\sigma \sim 5\%$ for W, Z, $t\bar{t}$

⇒ **A high level of precision is needed for theoretical partonic cross-sections and for LHC measurements before starting constraining the PDF**



PDF constraints at LHC

Outline

1. **The LHC and the experiments**
2. **PDF constraints with jets**
3. **PDF constraints with W**
4. **PDF constraints with Z**
5. **Improvements of PDF contraints with W & Z**
6. **Conclusion**

Outline

1. **The LHC and the experiments**
   - The LHC
   - ATLAS & CMS
2. PDF constraints with jets
3. PDF constraints with W
4. PDF constraints with Z
5. Improvements of PDF contraints with W & Z
6. Conclusion

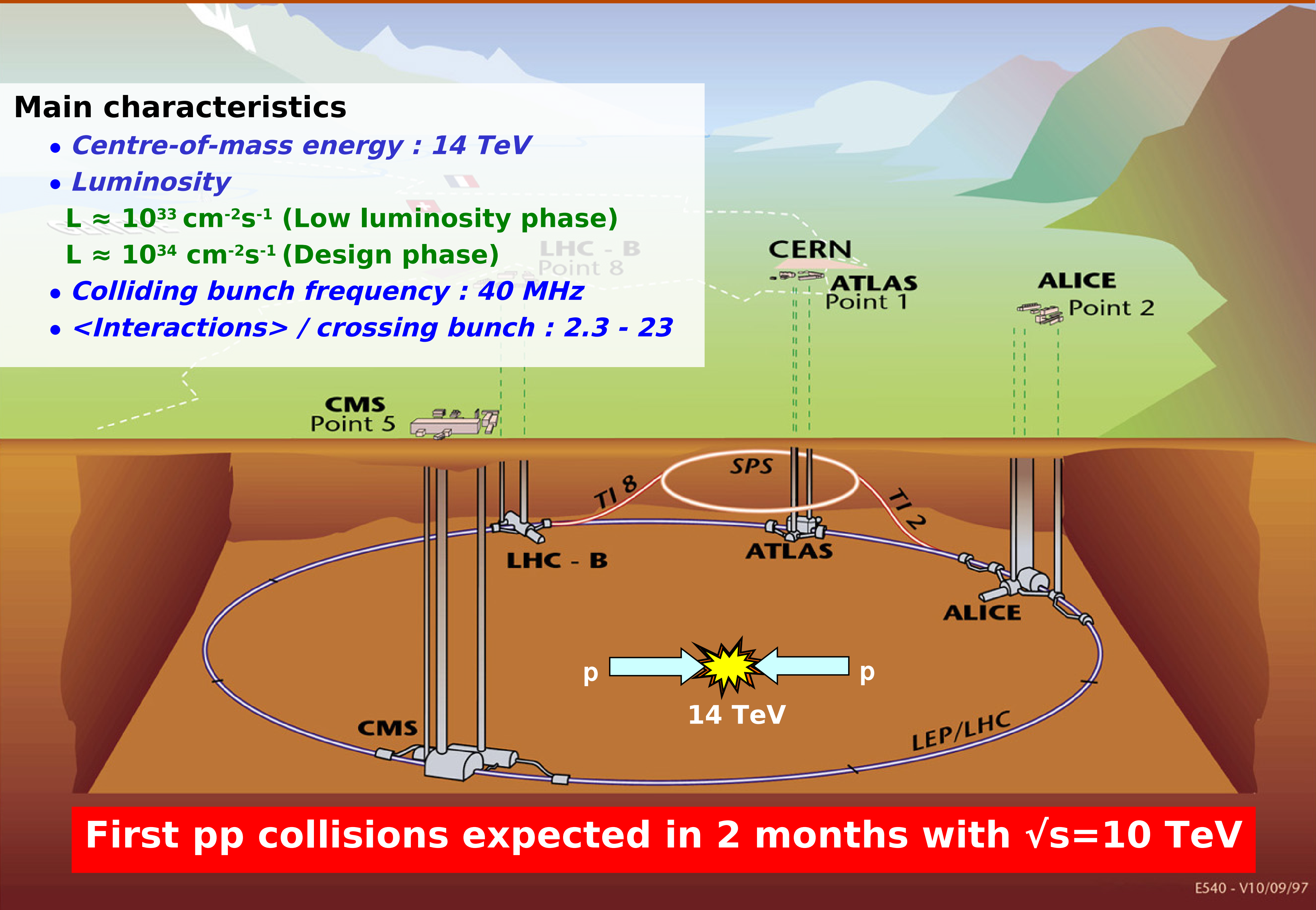
The LHC ring

Main characteristics

- ***Centre-of-mass energy : 14 TeV***
- ***Luminosity***

  $L \approx 10^{33}$ cm^{-2}s^{-1} (Low luminosity phase)

  $L \approx 10^{34}$ cm^{-2}s^{-1} (Design phase)
- ***Colliding bunch frequency : 40 MHz***
- ***<Interactions> / crossing bunch : 2.3 - 23***



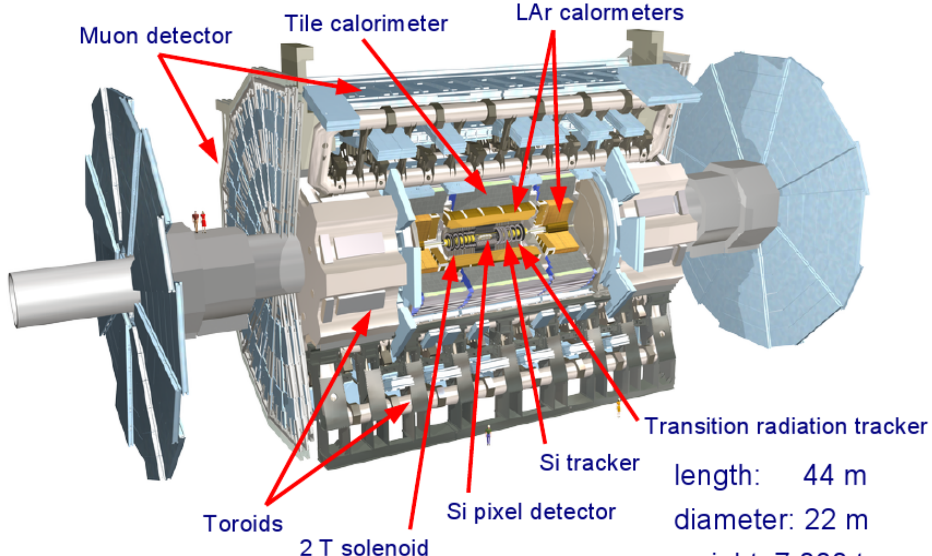
First pp collisions expected in 2 months with $\sqrt{s}$=10 TeV

The detectors ATLAS & CMS

Detectors for high-p_T and forward physics

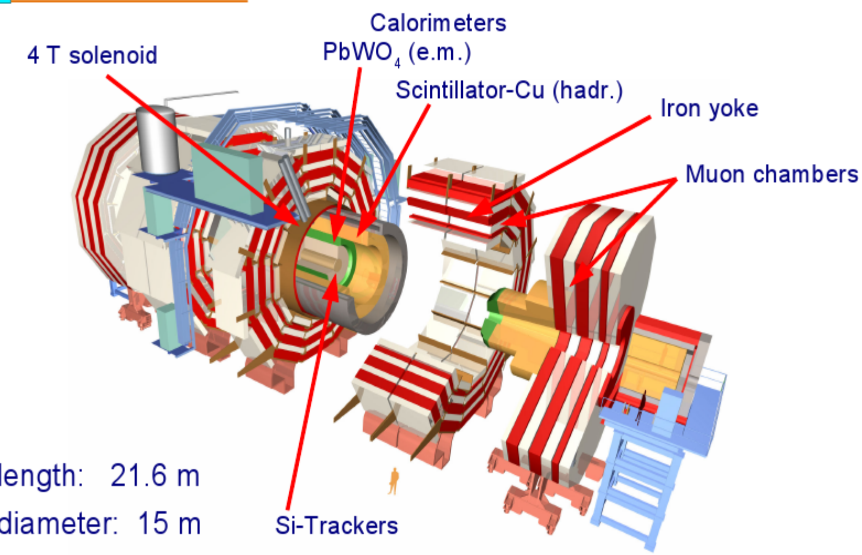
- ***Tracking system***
- ***Calorimeter***
- ***Muon spectrometer***

A Toroidal Lhc ApparatuS (ATLAS)



length: 44 m
diameter: 22 m
weight: 7 000 t

Compact Muon Solenoid (CMS)



length: 21.6 m
diameter: 15 m
weight: 12 500 t

Identification & precise measurements of EW & QCD observables at high energy, p_T and rapidity

→ gives informations on PDF at low/high x & high Q^2

PDF constraints at LHC

Outline

1. The LHC and the experiments
2. **PDF constraints with jets**
   - Di-jets cross-sections
   - γ+jets cross-sections
   - Heavy flavour jets
3. *PDF constraints with W*
4. *PDF constraints with Z*
5. *Improvements of PDF contraints with W & Z*
6. *Conclusion*

PDF constraints with di-jet cross-section

Motivations

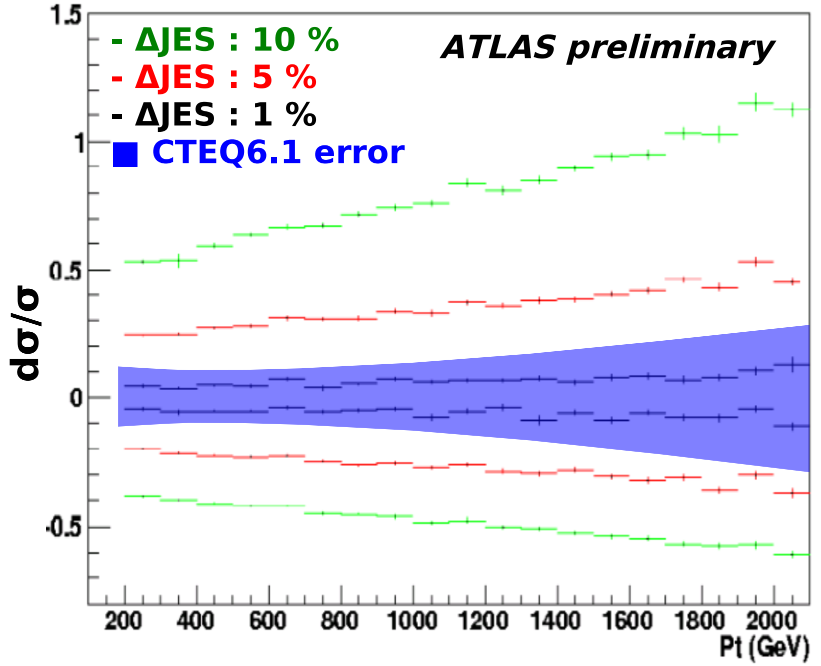
- ***High cross-section***
  $d\sigma/\sigma$ = 1% (stat) @ p_T = 2 TeV with 100 fb^{-1}
- ***LHC will probe unexplored (x, Q^2) domains***
- ***Non-DGLAP evolution sensitivity***
  Forward di-jets

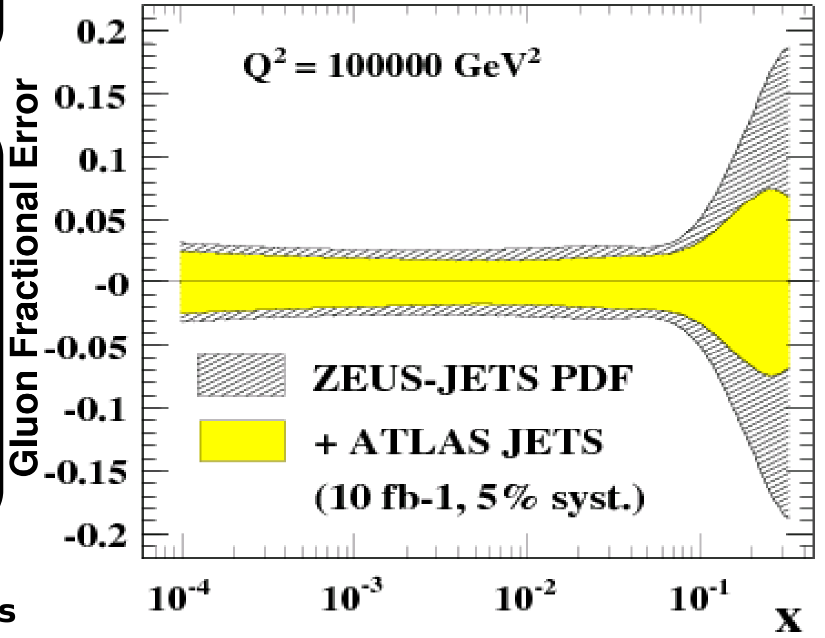
Main issues

- ***Minimum-bias & underlying events***
  Dominated by soft processes
- ***Precise jet calibration***
  Δ JES ~ 1% @ 1 TeV

PDF fitting using pseudo-data

- ***Assess the potential of LHC data***
  Generate 10 fb^{-1} of di-jet events
  → 1 year at low luminosity
- ***Preliminary results***
  LHC data can constrain the high x-gluon
  Small improvement if increasing statistics

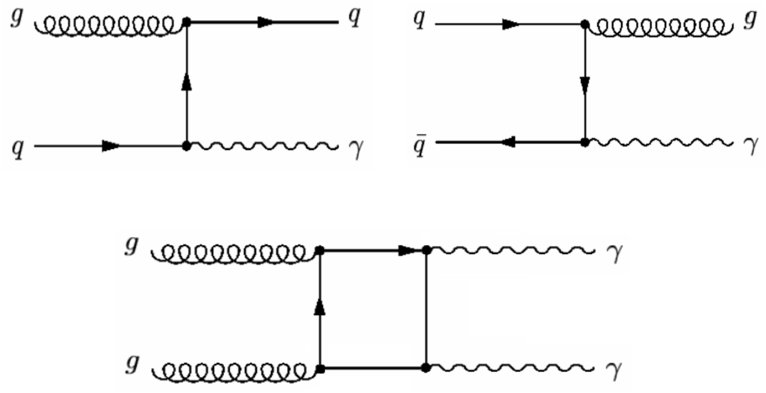




PDF constraints with γ+jet production

Different LO production mechanisms

- ***$q\bar{q}/qg \rightarrow \gamma + jets$***
- ***$gg \rightarrow \gamma + \gamma + X$***



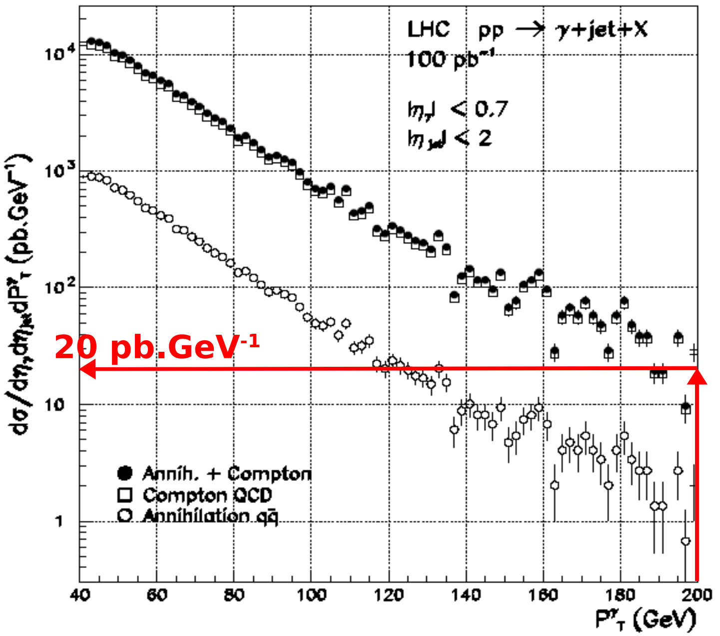
Motivations

- ***High cross-section***
- ***Low level of QCD background at high p_T***
- ***Lower systematic errors***

  Calibration of photons seems easier than jets

  But : EM calorimeter calibrated with $Z \rightarrow ee$

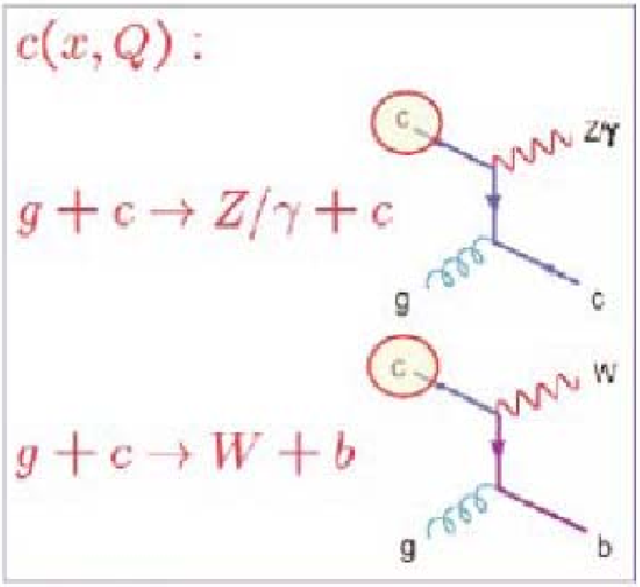
  Non linearity effects ?
- ***Helps to calibrate the energy of jets***

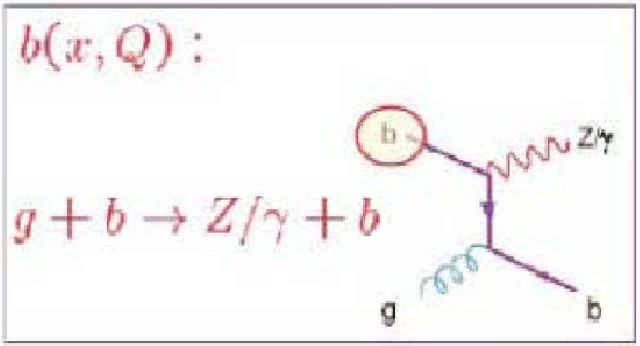


PDF constraints on heavy flavours

Different LO production mechanisms

- *g c/b → jet + c/b*
- *g c/b → Z/γ* c/b*
- *g c/b → $W^{\pm}$ b/t*





Motivations

- *Cross-checks with heavy flavour PDF*
  Evolution functions g → $Q\bar{Q}$
- *"intrinsic" charm component in proton*
  Models of Brodsky *et al.*
  |p> = |uud> + |uudu$\bar{u}$> + |uudc$\bar{c}$> + …

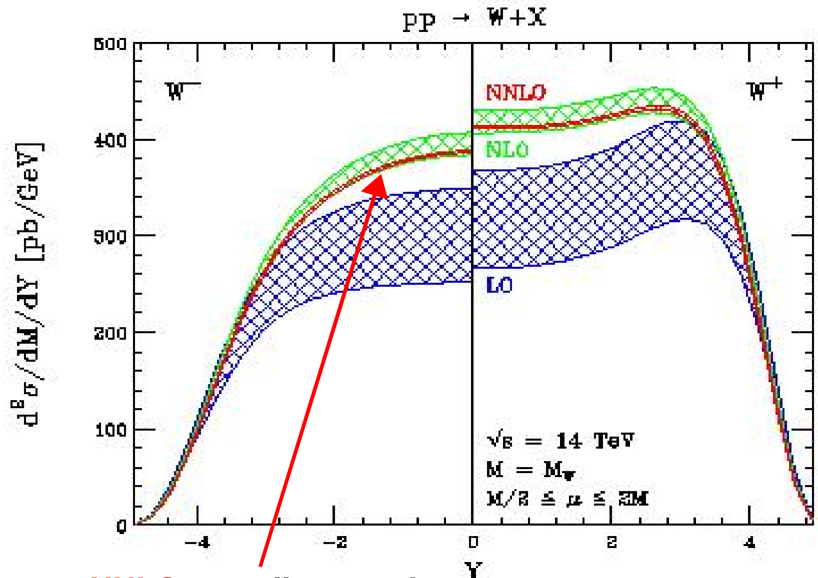
Main issues

- *Uncertainties on partonic cross-section*
  Mixed EW-QCD processes
- *NLO cross-section is often higher than LO*
- *Selection of a pure HF subsample*
  Contamination with light flavours
  → high level of background

PDF constraints at LHC

Outline

1. The LHC and the experiments
2. PDF constraints with jets
3. ***PDF constraints with W***
    - *W cross-section*
    - *Example of PDF constraints with LHC data*
4. *PDF constraints with Z*
5. *Improvements of PDF contraints with W & Z*
6. *Conclusion*

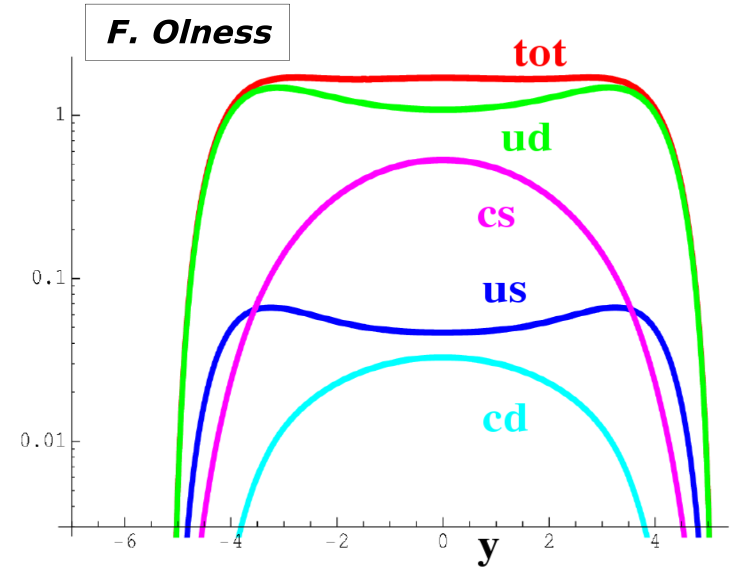


Motivations

- *Small theoretical uncertainties*
- *Low statistical errors*
  σ(W±→lν) ~ 20 nb → 10^6 events with 50 pb^{-1}
  dσ/σ < 0.1%
- *Small experimental systematics*
  Low level of background
  Selection efficiency measured from data
  dσ/σ < a few %
- *Sensitivity to heavy quark PDFs*
  Main processes : ud, cs → W±

NNLO : small corrections ~%
residual scale dependence < 1%

dσ/dy(W⁺) at LHC



PDF constraints with W cross-sections

Observables sensitive to PDFs

- ***$\sigma(pp \rightarrow W)$***
  - $d\sigma/\sigma$ > 4-8 % (PDF)
  - Quark region : $5.10^{-4} < x < 5.10^{-2}$
  - → not where quark PDFs are best known
- ***$d\sigma/dp_T(l)$***
  - $d\sigma/dp_T(W)$ not directly accessible
  - → need a precise measurement of $\not{E}_T$
- ***$d\sigma/d\eta(l)$***
  - Main sensitivity in the high-y region
  - → constrain low-x gluon PDFs
- ***Charge asymmetry***

$$A_W = \frac{W^+ - W^-}{W^+ + W^-} \approx \frac{u_v - d_v}{u_v + d_v + 2q_{sea}} \quad \text{at LO}$$

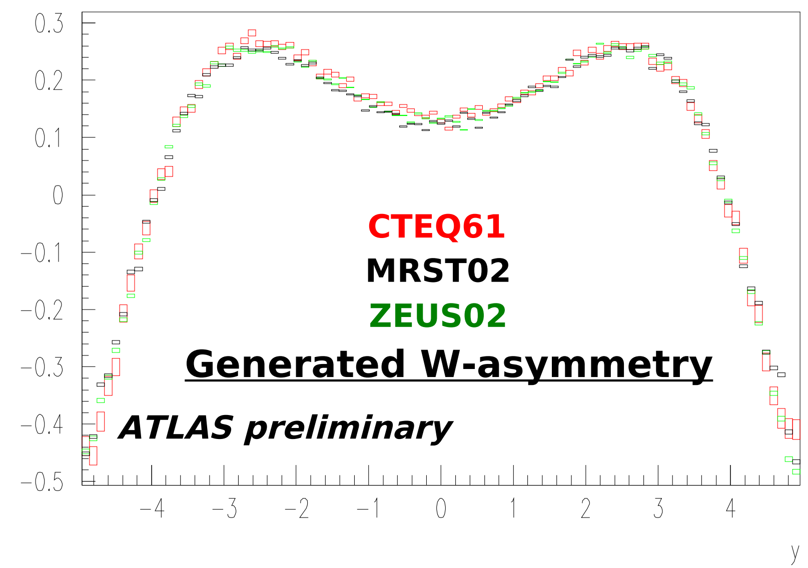
Less sensitive to systematics

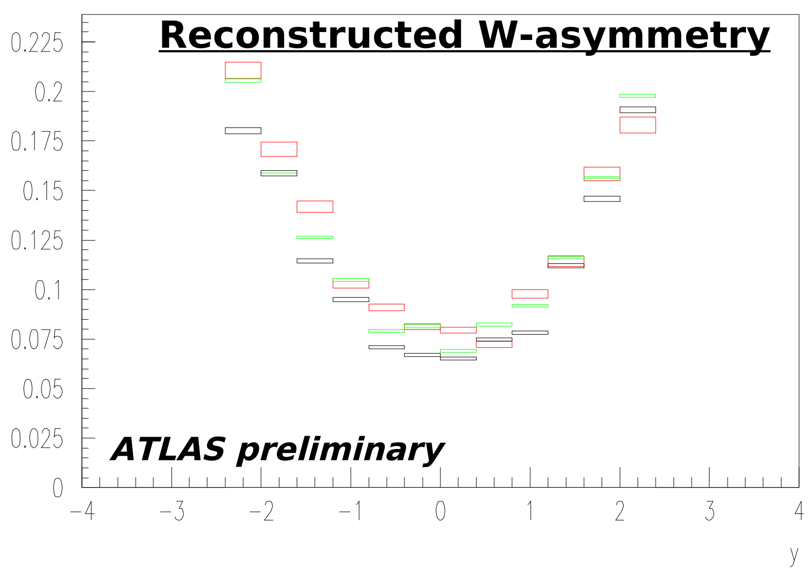
In practice : lepton charge asymmetry

Differences between the MRST and CTEQ

→ Differences in the valence distributions

→ constrain low-x valence quarks PDFs





PDF constraints with W pseudo-data

Goal

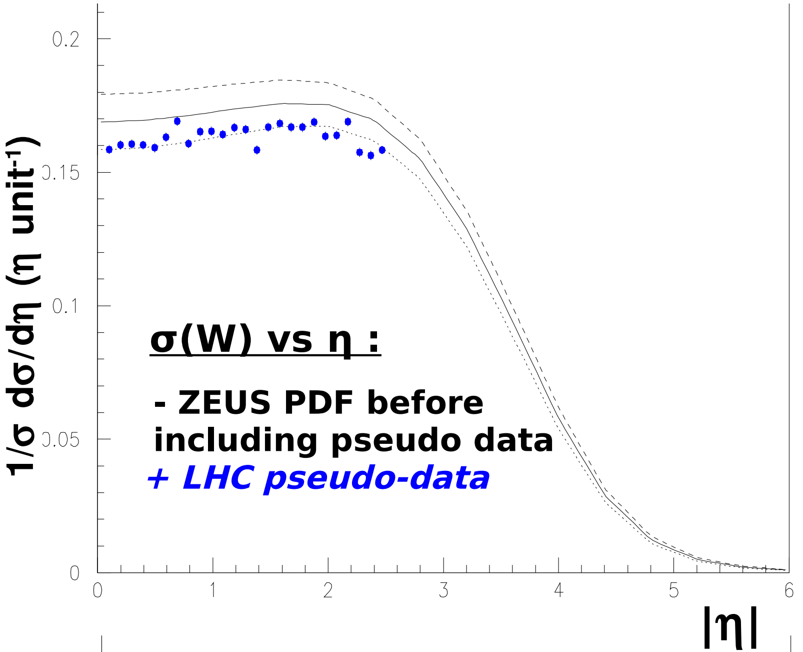
- ***Assess the gain in precision of PDF***
  - **Constrain low-x gluon PDF with LHC data**
  - **Use normalized dσ/dη(l)**
  - **→ lower systematics**

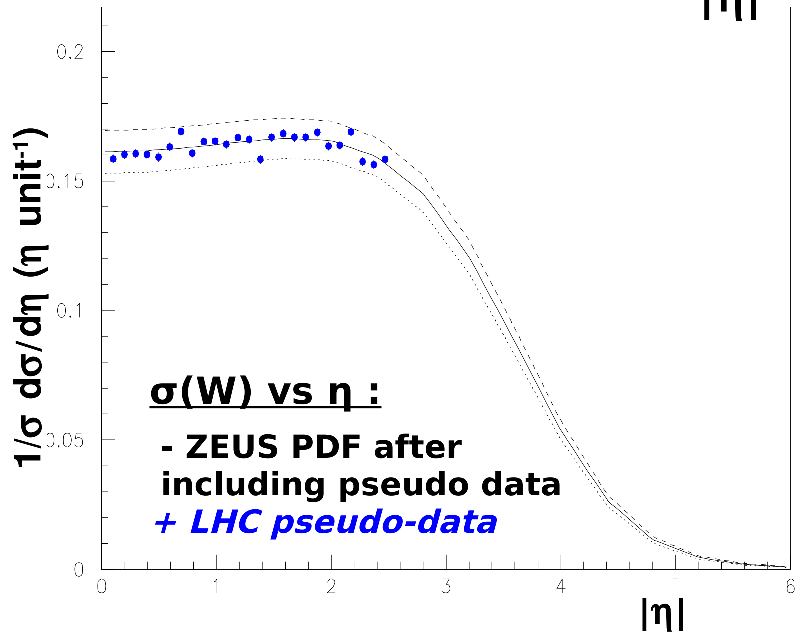
Simulate real experimental conditions

- ***Generate W events***
  - **10^6 events → 50 pb^{-1}**
  - **Simulate detector & reconstruction effects**
- ***Measure dσ/dη(l)***
  - **Systematic uncertainty assessed to 4%**
- ***include this data in the global ZEUS PDF fit***

Results on $xg(x) = x^{-\lambda}$

- ***Low-x gluon shape parameter λ***
  - **$\lambda = -0.200\ (46) \rightarrow \lambda = -0.181\ (30)$**
  - **Mean value is shifted**
  - **Uncertainty is reduced by -41%**
- ***New PDF uncertainties on dσ/dη(l)***
  - **Still much larger than experimental errors**





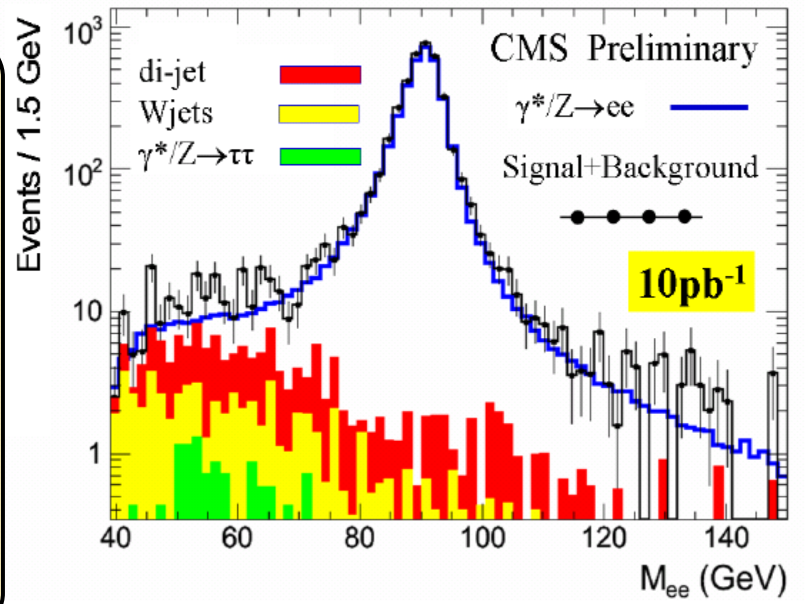
Outline

1. The LHC and the experiments
2. PDF constraints with jets
3. *PDF constraints with W*
4. ***PDF constraints with Z***
    - ***Z cross-section***
    - ***High-rapidity Z***
5. *Improvements of PDF contraints with W & Z*
6. *Conclusion*

Z cross-section measurement at LHC

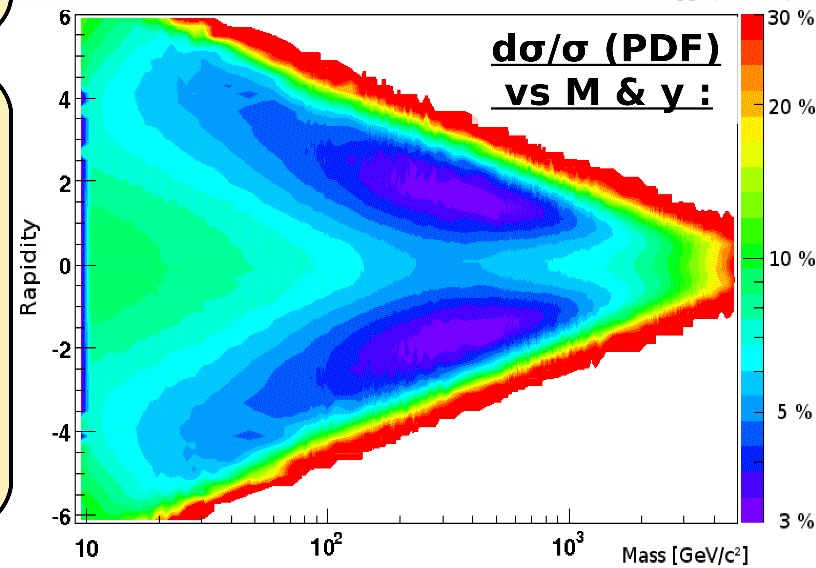
Motivations

- *Small theoretical uncertainties*
  Partonic process known at NNLO
  $d\sigma/\sigma < 1\%$ (PRD 094008)
- *Small statistical uncertainties*
  $\sigma(Z \to ll) \sim 2$ nb $\to 10^6$ events with 500 pb^{-1}
  $\to d\sigma/\sigma < 0.1\%$
- *Small experimental systematics*
  Low level of background
  Selection efficiency measured from data
  $\to d\sigma/\sigma < 2 - 5\%$



Effect of PDF uncertainties on $\sigma_{Z/\gamma}$

- *Uncertainty on normalization*
  High Z/γ^* mass & rapidity : $d\sigma/\sigma$=10-20%
  Around Z peak : $d\sigma/\sigma$= 5 - 7%
- *Uncertainty on acceptance*
  $d\sigma/\sigma$ (PDF) ~1%
- *Uncertainty on selection efficiency*
  $d\sigma/\sigma$ (PDF) ~ 3%



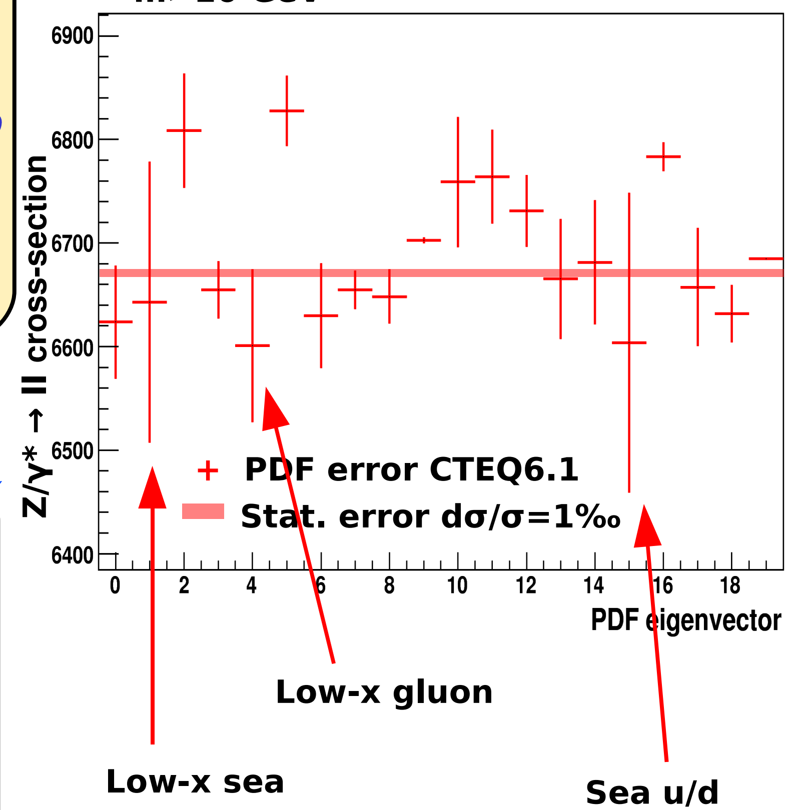
⇒ **The uncertainties on $\sigma_{Z/\gamma}$ mainly come from PDFs**

PDF constraints with Z cross-section

LHC will explore low-x partons

- *(x, Q^2) parameters covered with 1 fb^{-1}*
  - $100 \lesssim Q^2 \lesssim 10^5$ GeV^2
  - $3.10^{-4} < x < 0.1$
- *Main contributions of PDF uncertainties at LO*
  - Low-x sea quarks
  - Low-x gluon
  - Ratio between sea u & d quarks

PDF error on $\sigma_{Z/\gamma}$ vs PDF eigenvector
m>10 GeV



PDF constraints with Z data

- *Constraints within models*
  - Sea & gluon free parameters in PDFs
- *Constraints between different PDF modelling*
  - Low-Q^2 functional form
  - Evolution of PDF with scale

⇨ **A very precise measurement is required.**
→ Need to reduce the effect of PDFs uncertainties on the acceptance & selection efficiency before the measurement of σ(Z).

PDF constraints with Z cross-section

LHC will explore low-x partons

- *(x, Q^2) parameters covered with 1 fb^{-1}*
  - $100 \lesssim Q^2 \lesssim 10^5$ GeV^2
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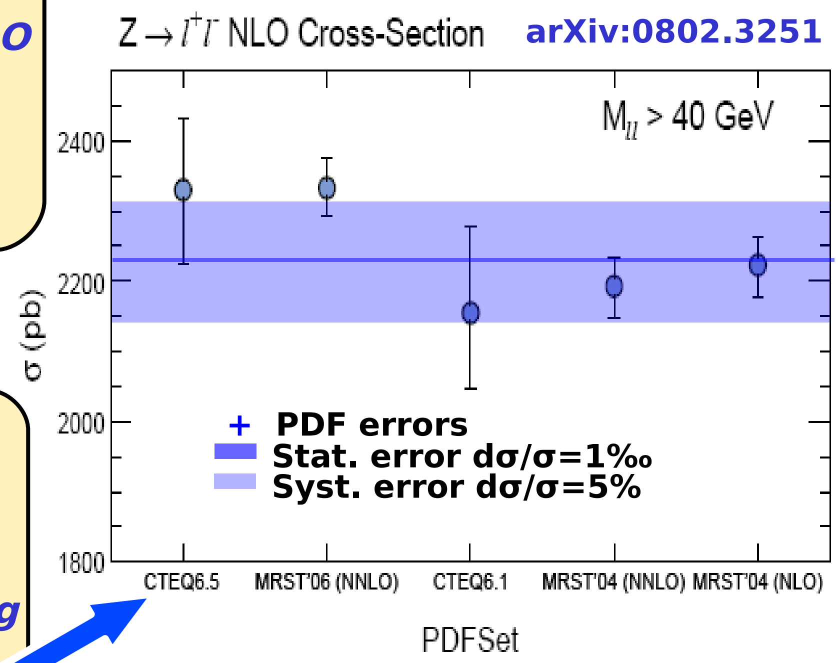
arXiv:0802.3251

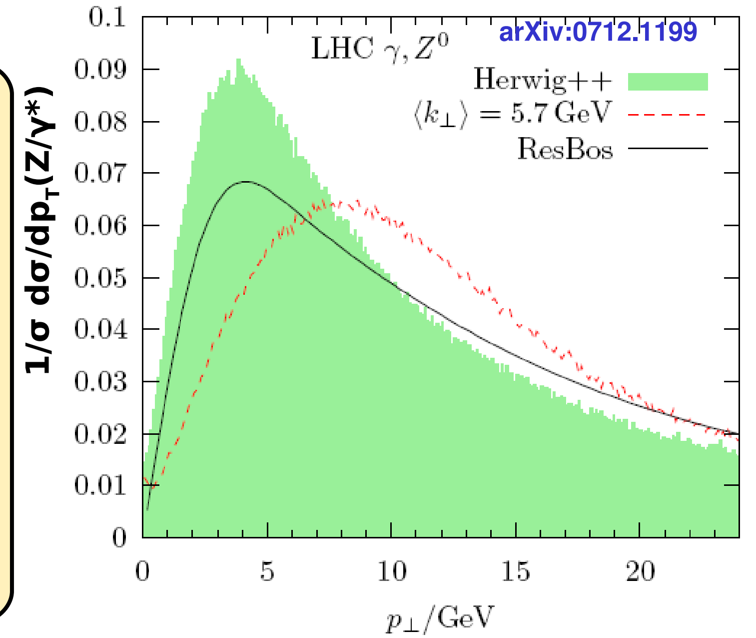


A very precise measurement is required.
→ Need to reduce the effect of PDFs uncertainties on the acceptance & selection efficiency before the measurement of σ(Z).

Reduction of acceptance uncertainties on Z cross-section with prior PDF constraints

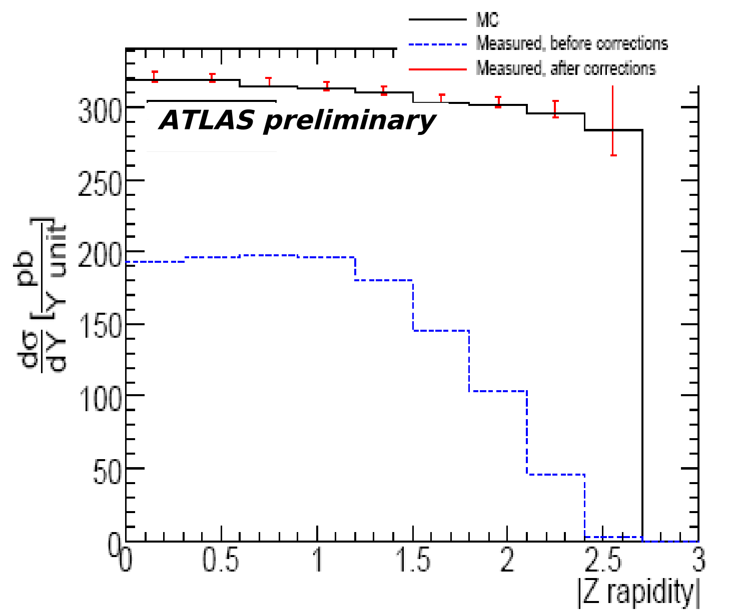
Reduction of uncertainties

- ***$p_T(l)$ measurements***
  Sensitivity to PDFs diluted
- ***$p_T(Z/\gamma^*)$ measurements***
  Helps to constrain universal model of non-perturbative soft gluon radiation
- ***$y(Z/\gamma^*)$ measurements***
  Sensitivity in the high-y region (high & low x)
  Limitations by detector acceptance



Other measurements that constrain PDF

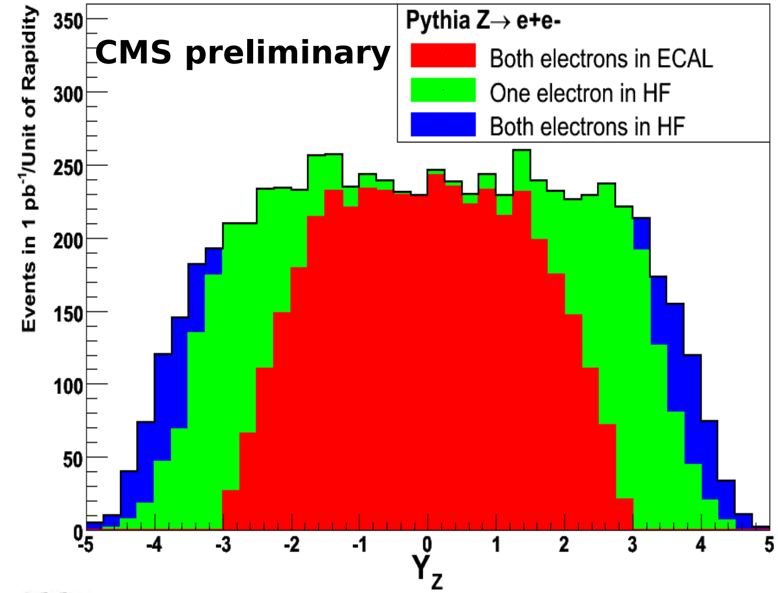
- ***$d\sigma/dM(Z/\gamma^*)$***
  Sensitivity to low-x & $Q^2<200^2\text{GeV}^2$ regions
  $Q^2<200^2\ \text{GeV}^2 \rightarrow x<0.1$
- ***Asymmetry A_{FB}***
  Experimental systematic errors are reduced
  Main issues : Need to estimate the quark & antiquark directions & reconstruction of foward leptons



PDF constraints with high-rapidity Z

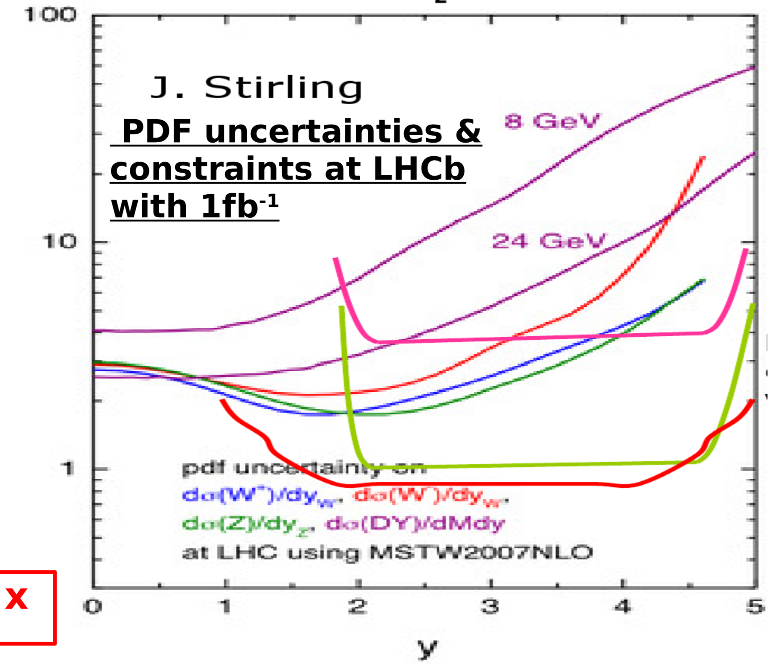
Motivations

- *Important for Z cross-section measurements*
  - σ^{tot} , $d\sigma/dy$
- *Sensitivity to PDFs*
  - Probes a mixture of high/low x at high Q^2
  - Large uncertainties of PDFs in this region
- *Complementarity with LHCb*
  - LHCb coverage : $1.8 < |\eta| < 5$
  - Selects γ^* down to $x \sim 10^{-6}$ and $Q^2 \sim 25$ GeV^2
- *Overlaps with TeVatron and HERA*



Main difficulties

- *Reconstruction of forward leptons*
  - High rapidity Z → high |η| leptons
  - Possible with the high segmentation forward calorimeters of ATLAS/CMS
- *High level of fake leptons*
  - QCD & γ backgrounds
  - Difficult to simulate & estimate
  - → real data needed



Nice opportunity to cross-check PDFs at low x

PDF constraints at LHC

Outline

1. The LHC and the experiments
2. PDF constraints with jets
3. *PDF constraints with W*
4. *PDF constraints with Z*
5. ***Improvements of PDF constraints with W & Z***
   - ***Ratio of cross-section***
   - ***Shape of distributions***
   - ***Direct fits of PDFs on data***
6. *Conclusion*

Cross-normalizing experiments

Problematics

- ***Reduction of experimental systematic uncertainties***

$$\sigma^{\text{exp}} = \frac{N}{L\,.\,\varepsilon} \qquad \frac{d\sigma}{\sigma} = \frac{dN}{N} \oplus \frac{dL}{L} \oplus \frac{d\varepsilon}{\varepsilon}$$

Statistical errors

Luminosity measurement

Acceptance & selection efficiencies

Measurement of ratios

- ***Correlated uncertainties cancel***

$$R = \frac{\sigma}{\sigma^{\text{ref}}} = \frac{N}{L\,.\,\varepsilon} / \frac{N^{\text{ref}}}{L\,.\,\varepsilon^{\text{ref}}} \qquad \frac{dR}{R} = \frac{dN}{N} \oplus \frac{dN^{\text{ref}}}{N^{\text{ref}}} \oplus 0 \oplus \frac{d(\varepsilon/\varepsilon^{\text{ref}})}{\varepsilon/\varepsilon^{\text{ref}}}$$

No luminosity uncertainty

Additionnal terms from the reference measurement

→ larger uncertainty if uncorrelated systematics

Global variables

- ***Shape of distributions (mean values, RMS, ...)***
- ***Fits of distributions***

PDF constraints with σ_W/σ_Z

Motivations

- ***Similar selection procedure***

  Isolated leptons

  ~ Same p_T range

  Can be selected using same trigger
- ***Similar LO partonic process***

  Quark initial state; singlet final state
  Similar QCD corrections
- ***Behave similarly under PDF variations***

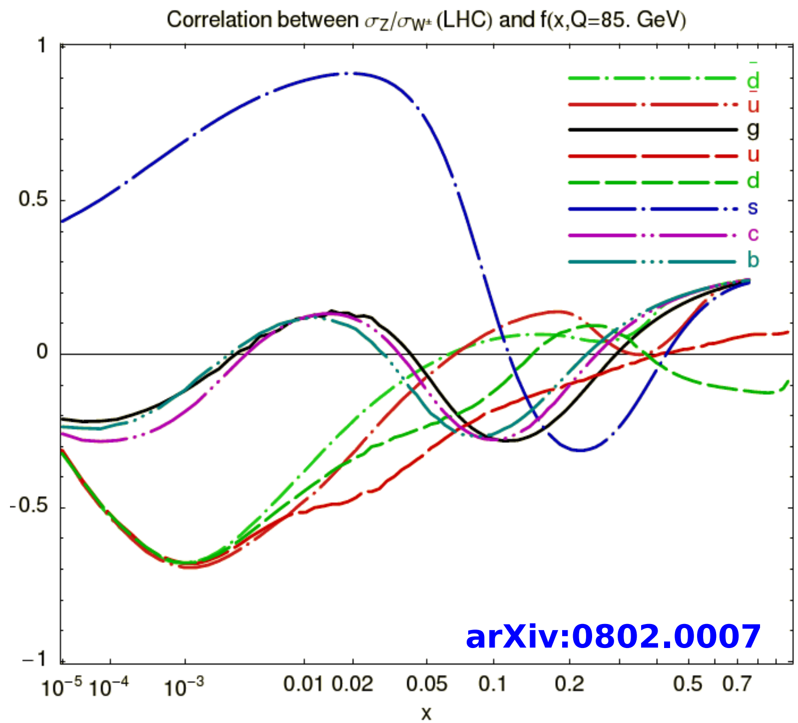
  ~ Same x, Q^2

  Initial partons mainly from sea

Remaining PDF uncertainties

- ***Mostly due to strange PDF***

  increases x3 compared to CTEQ6.1 as a result of free strangeness in CTEQ6.6



⇨ **Measurements of σ_W/σ_Z impose strong constraints on the strange quark parametrisation**

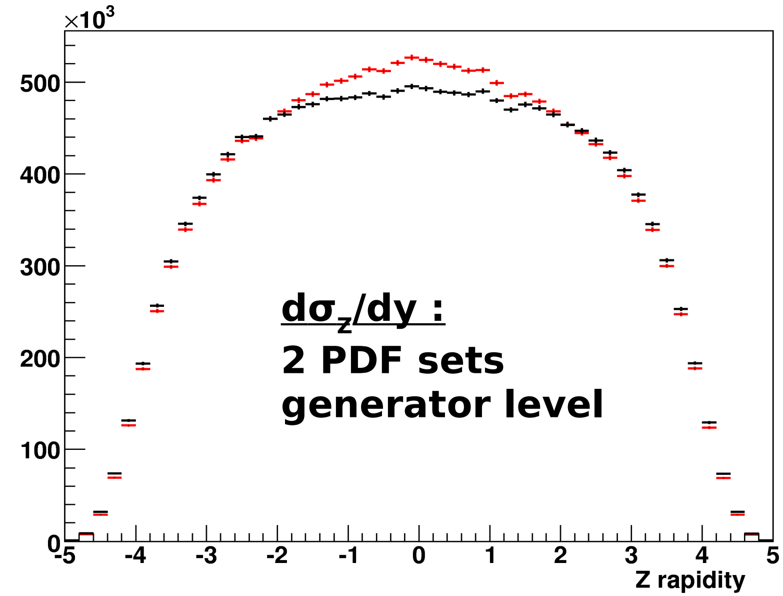
PDF constraints with RMS of $d\sigma_{Z,W}/dy$

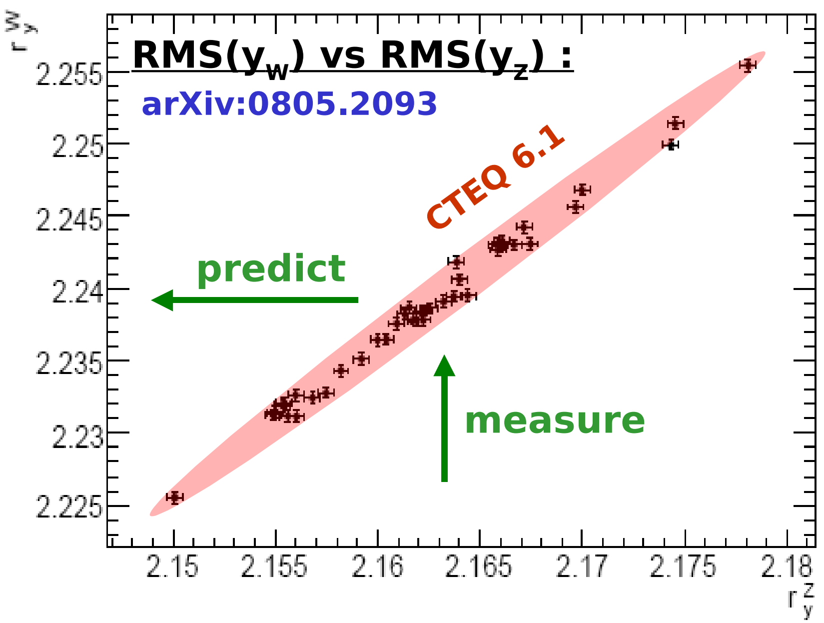
W & Z rapidity distributions

- ***Estimate the width with RMS ($y_{W,Z}$)***
- ***Strong correlation***

  Compare RMS (y_W) and RMS (y_Z)

  → Make ratios RMS(y_W)/RMS (y_Z)





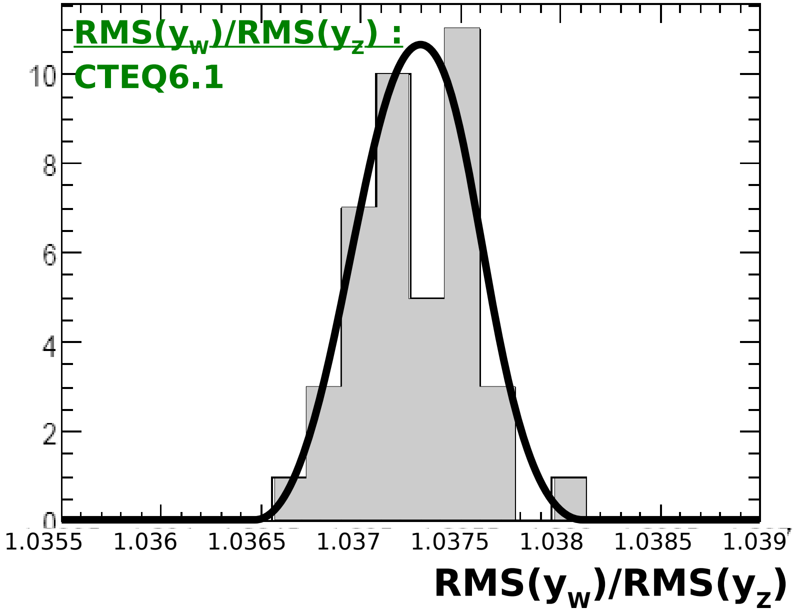
PDF constraints with RMS of $d\sigma_{Z,W}/dy$

RMS ratios

- ***Precise prediction***

  Spread of RMS : 7.10^{-3}

  Spread of RMS ratio : 7.10^{-4}



Comparisons between different PDF sets

- ***Different theoretical frameworks***

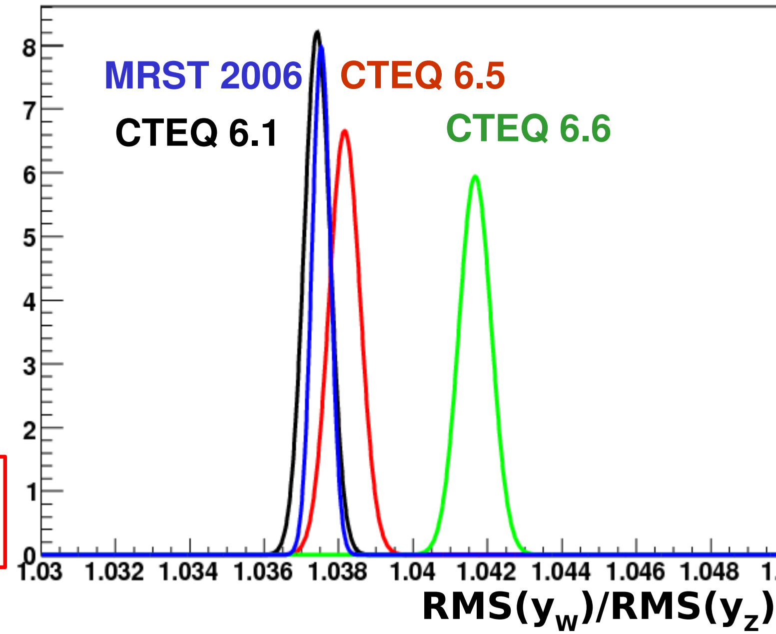
  LO, NLO or heavy quarks treatment

  → compatible predictions

- ***Different starting assumptions***

  Parametrization on s(x)

  → uncompatible predictions



⇨ **What is the validity of the underlying hypotheses on PDF parametrizations ?**

PDF parametrizations from Z cross-sections

Effective description of PDFs

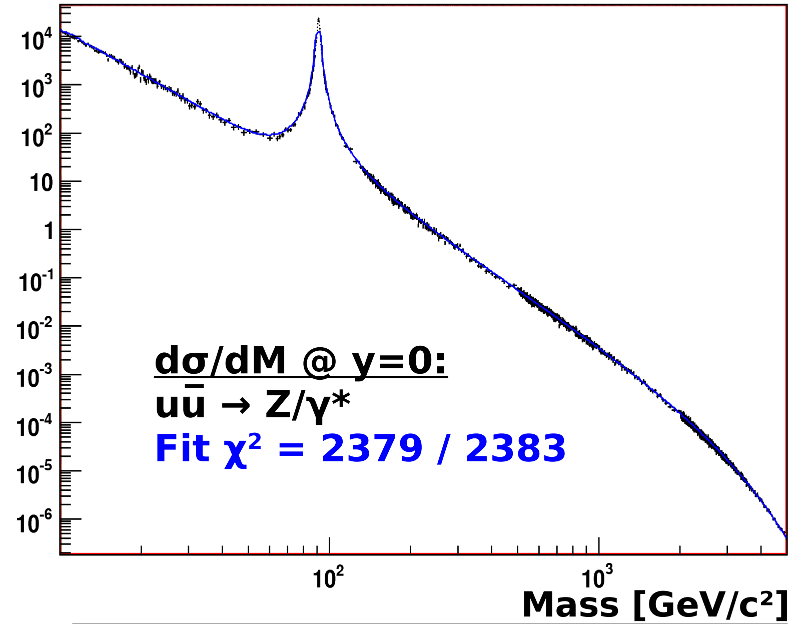
- *Use low-$Q^2 \approx m_p{}^2$ CTEQ parametrization*

  $f(x, Q^2) = x^{\alpha} \ (1-x)^{\beta} \ (1+\gamma x)^{\delta}$

  low-x high-x valence
- *Add an effective Q^2 dependence*

  $\alpha = a + b \ln Q^2$

  $\beta = c + d \ln Q^2$



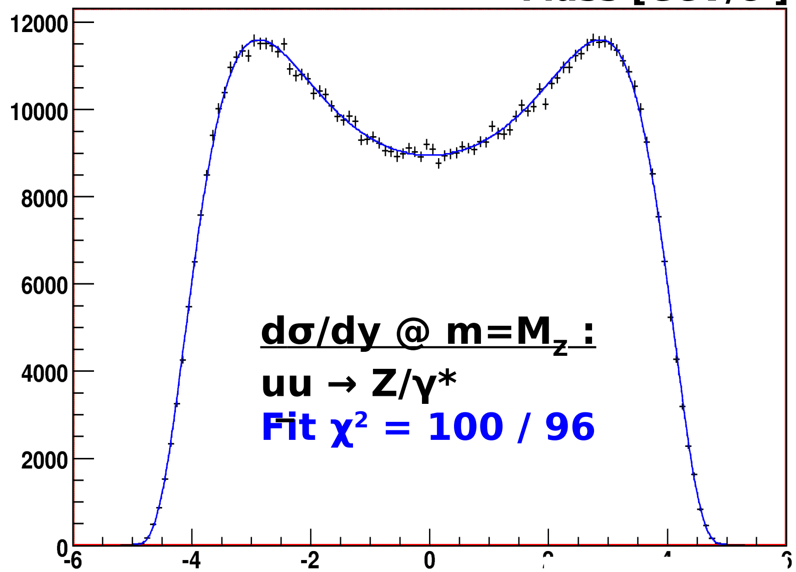
Results

- *Good description of dσ/dM & dσ/dy*

  Same parameters describe dσ/dM & dσ/dy
- *Universal description of sea quarks*

  Comparison between quark flavours

  Same values for a, b



Example of contraints on PDF

- *Error on "b"*

  $\Delta b / b = 5\ \%$ (CTEQ6.1 PDF)

  $\Delta b / b = 0.5\ \%$ (using 1 fb^{-1} LHC data)

⇨ Fits of PDFs directly on data could provide strong constraints

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Summary & conclusion

Importance of PDF for physics

- One of the main sources of systematic errors on physics processes
- PDF uncertainties can compromise precision SM physics and BSM discoveries

LHC is a low-x machine

- Many experimental data allow to constrain low-x PDF : Z/γ*, W, jets, ...
- Low-x nuclear studies in p-A & A-A collisions

Expected constraints on PDFs with LHC

- Accurate precision on non-perturbative PDF parameters
- Validity of the functional forms of non-perturbative PDFs (s, u_v-d_v, u/d, ...)
- Evolution functions : NLO/NNLO DGLAP ? Add BFKL ? CCFM ?

Most of measurements will be dominated by systematics at LHC

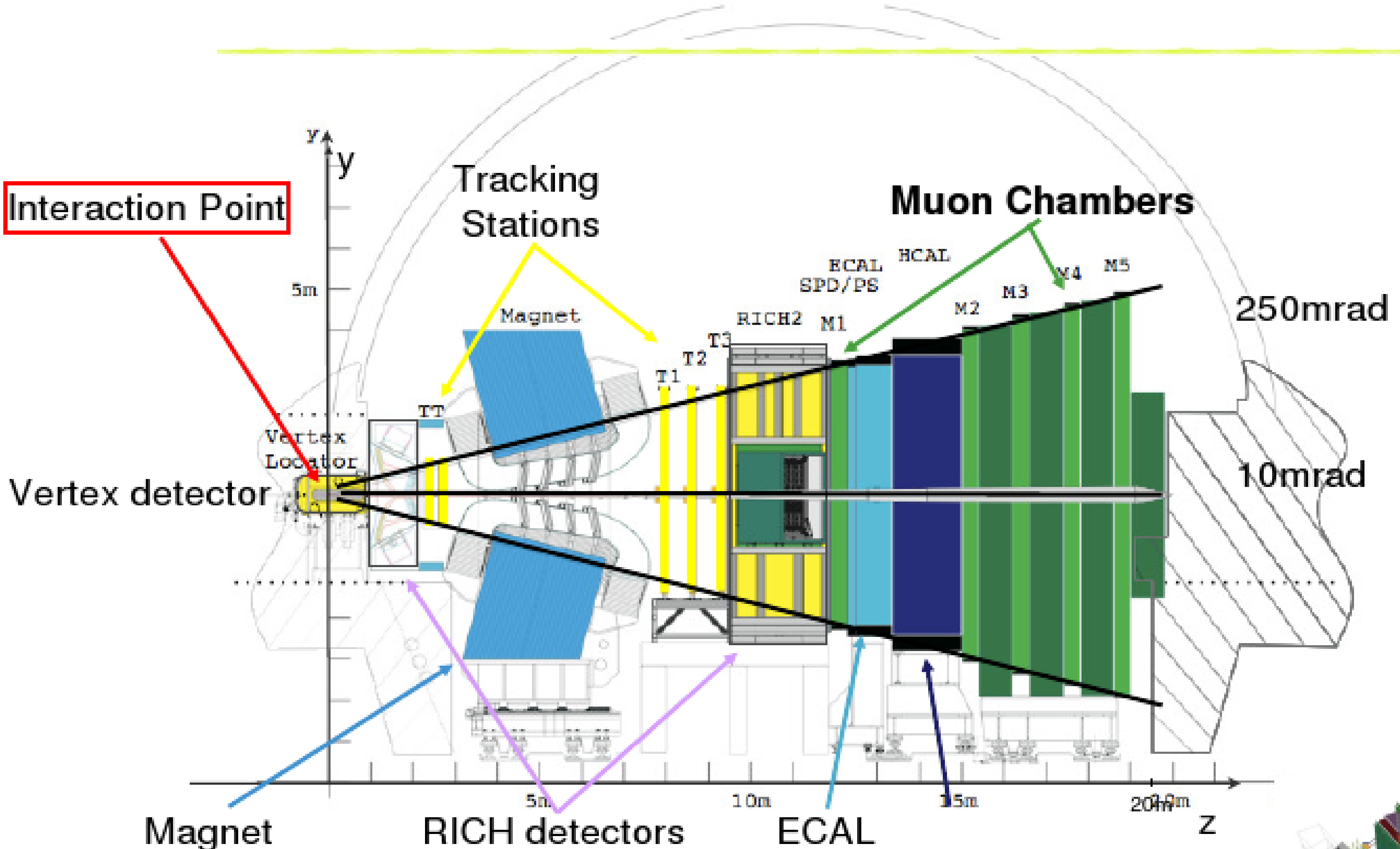
- Use of ratios to cancel correlated systematics
- Use of correlations between PDF among different physics processes

Precise theoretical predictions are strongly required

- Implementation of higher order QCD & EW corrections in partonic processes

LHC physics and PDFs are intrinsically connected, with major improvements expected.

LHCb: a *forward* spectrometer



Ratios:LHC to Tevatron pdf luminosities

- Processes that depend on qQ initial states (e.g. chargino pair production) have small enchancements
- Most backgrounds have gg or gq initial states and thus large enhancement factors (500 for W + 4 jets for example, which is primarily gq) at the LHC
- W+4 jets is a background to tT production both at the Tevatron and at the LHC
- tT production at the Tevatron is largely through a qQ initial states and so qQ->tT has an enhancement factor at the LHC of ~10
- Luckily tT has a gg initial state as well as qQ so total enhancement at the LHC is a factor of 100
  - but increased W + jets background means that a higher jet cut is necessary at the LHC
  - known known: jet cuts have to be higher at LHC than at Tevatron

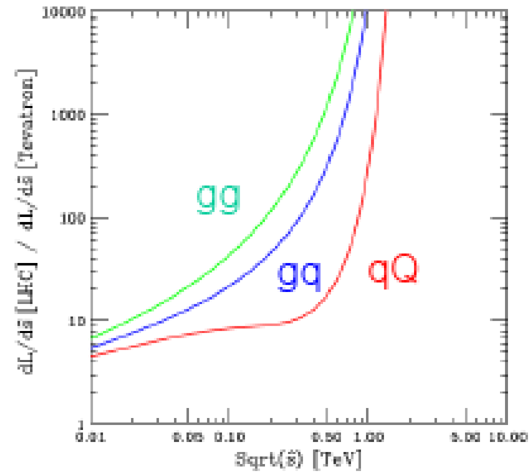


Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{s}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$ (bottom).

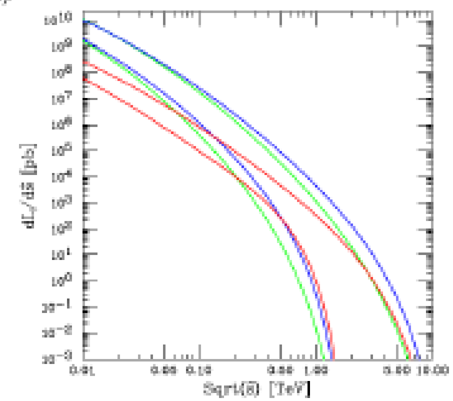


Figure 10. The parton-parton luminosity $\left[\frac{1}{s}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. The top family of curves are for the LHC and the bottom for the Tevatron.

Differences between PDF sets

Different data sets in the global PDF fit

- *Different sub-selection of data*
- *different treatment of experiemental systematic errors*

Different assumptions

- *Tolerance to define 1 σ error*

  CTEQ: $\Delta\chi 2=100$

  MRST: $\Delta\chi 2=50$

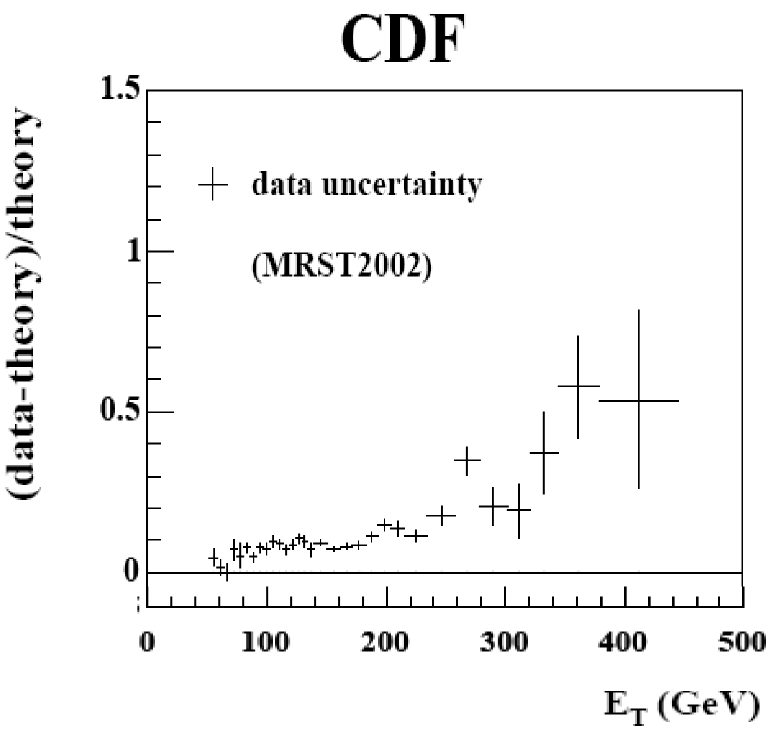
  Alekhin: $\Delta\chi 2=1$
- *Parametric forms*

  $F(x, Q_0^2) = Ax^a(1-x)^b\ P(x)$
- *Theoretical assumptions*

  sea flavour symmetry

  u/d→1 when x→0
- *Factorisation & renormalisation scheme & scale*
- Q^2_0
- α_s
- *Treatment of heavy flavours*

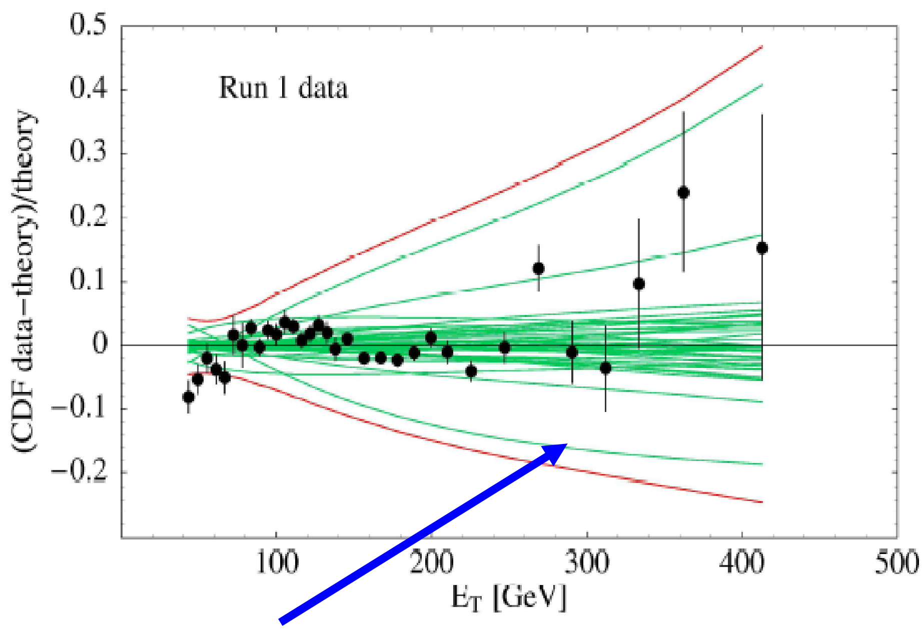
New physics & PDF uncertainties : an example



Recall the excess of high Et jets reported by CDF in 1995...

"any claim about the presence or absence of new physics is not defensible"

PDFs was a possible explanation. It was realized that a higher gluon density at high x could accommodate these data, while remaining in agreement with other data.



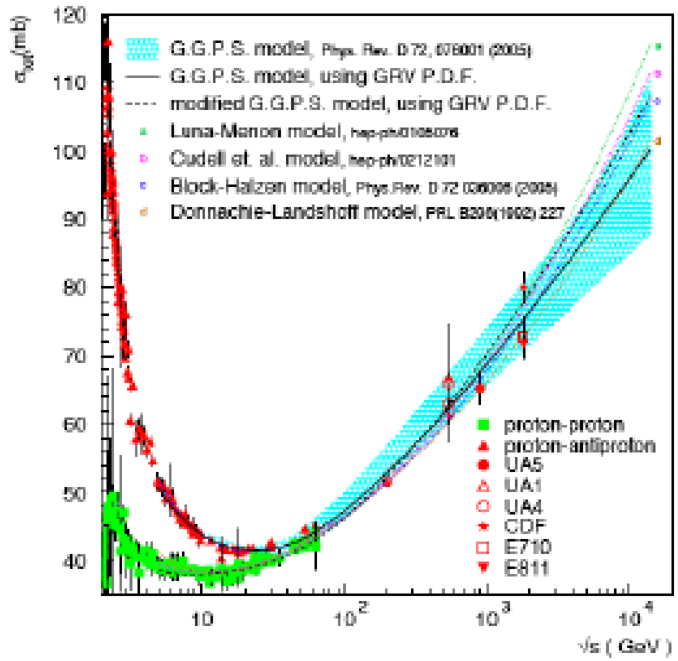
The Tevatron jet data are in agreement with global fits today, taking into account the large uncertainty due to the uncertainties on the high-x gluon.

This eigenvector is dominated by the high-x gluon parameter.

Cross section determinations at the LHC

$$\sigma = \frac{\#\,\text{events} * \text{acceptance}}{L}$$

- L depends on a knowledge of the total inelastic cross section and of the fraction of the cross section accessed by the trigger
- Fair amount of uncertainty on extrapolation to LHC
    - ln(s) or $\ln^2(s)$ behavior
    - rely on Roman pot measurements
        - not right away
    - extrapolating measured cross section to full inelastic cross section will still have uncertainties (and may take time/analysis)



don't expect better than a 15-20% uncertainty on any cross section during first year of running; (ultimately maybe 5%)

>>pdf uncertainties

we need precision cross sections to normalize to, at first and maybe always

Ratios : cross-normalizing theory

Data-driven predictions :

$$\sigma_{pred} = \left(\frac{\sigma}{\sigma^{REF}} \right)_{pred} \left(\sigma^{REF} \right)_{meas}$$

- Poor prediction
- Precise prediction
- Measurement

σ^{pred} can then be :

- ***compared against σ^{meas}***

  search for, or interpretation of new physics
- ***Used as input for precision measurements***

Motivations

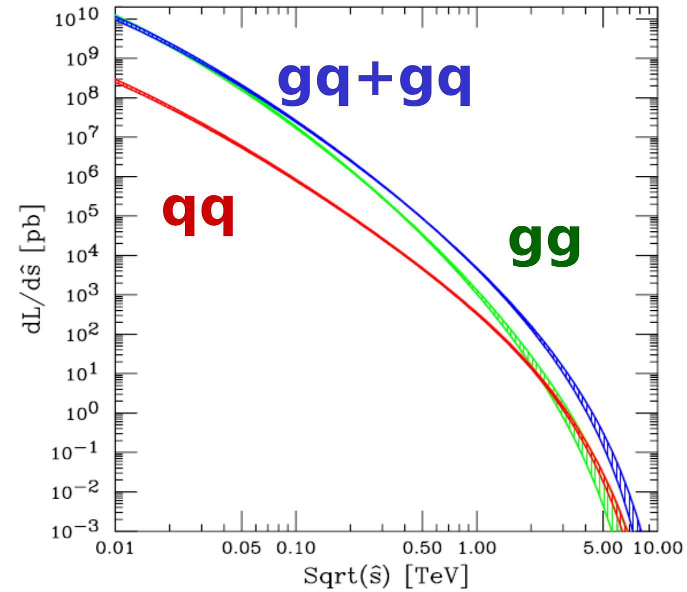
- *High cross-section*
  $d\sigma/\sigma$ = 1% (stat) @ p_T = 2 TeV with 100 fb^{-1}
- *LHC will probe unexplored (x, Q^2) domains*
- *Non-DGLAP evolution sensitivity*
  Forward di-jets

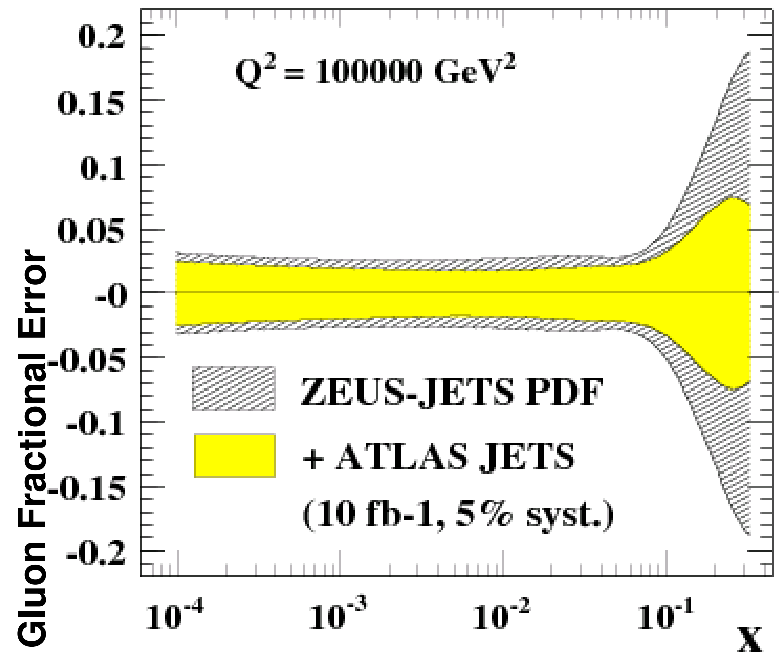
Main issues

- *Minimum-bias and the underlying event*
  Dominated by soft processes
- *Precise jet calibration*
  Δ JES ~ 1% @ 1 TeV

PDF fitting using pseudo-data

- *Assess the potential of LHC data*
  Generate 10 fb^{-1} of di-jet events
  → 1 year at low luminosity
- *Preliminary results*
  LHC data can constrain the high x-gluon
  Small improvement if increasing statistics

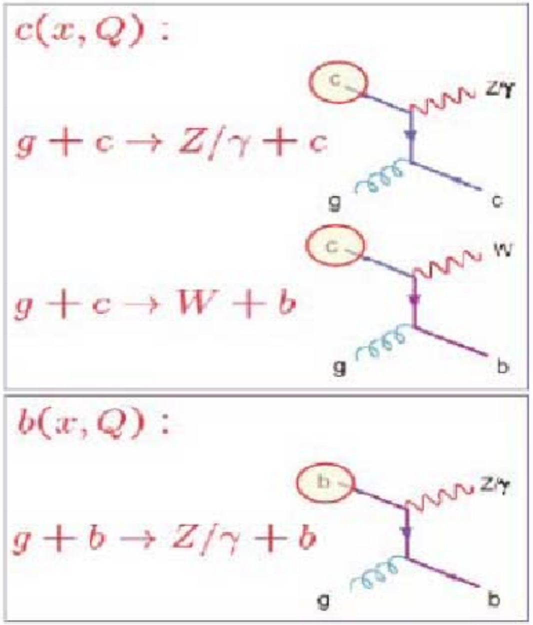




PDF constraints on heavy flavours

Different LO production mechanisms

- *g c/b → jet + c/b*
- *g c/b → Z/γ* c/b*
- *g c/b → W± b/t*

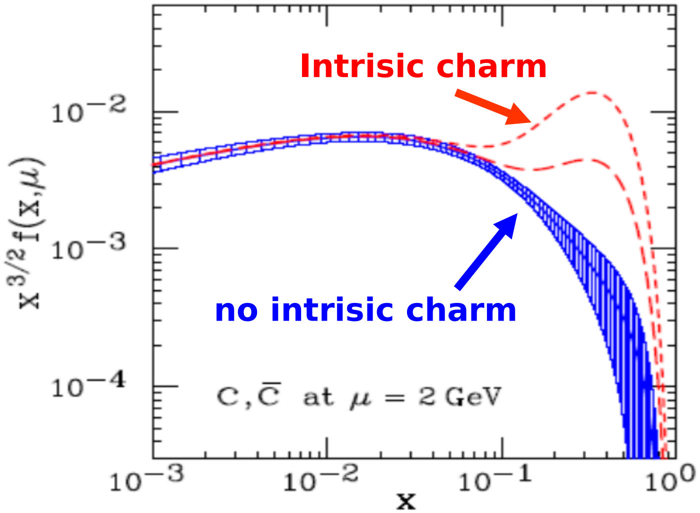


Motivations

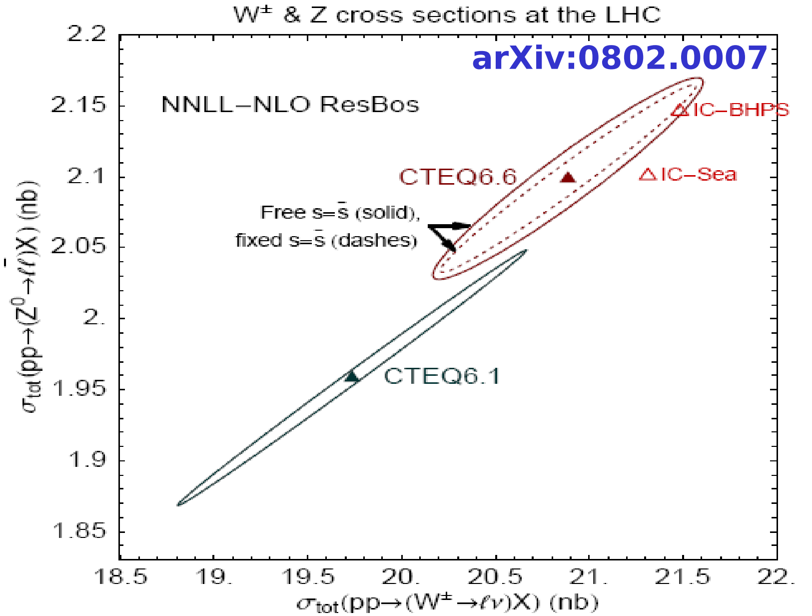
- *Cross-checks with heavy flavour PDF*
  Evolution functions g → $Q\bar{Q}$
- *"intrinsic" charm component in proton*
  Models of Brodsky *et al.*
  $|p\rangle = |uud\rangle + |uudu\bar{u}\rangle + |uudc\bar{c}\rangle + \dots$

Main issues

- *Uncertainties on partonic cross-section*
  Mixed EW-QCD processus
  NLO cross-section is often higher than LO
- *Selection of a pure HF subsample*
  Contamination with light flavours
  → high level of background

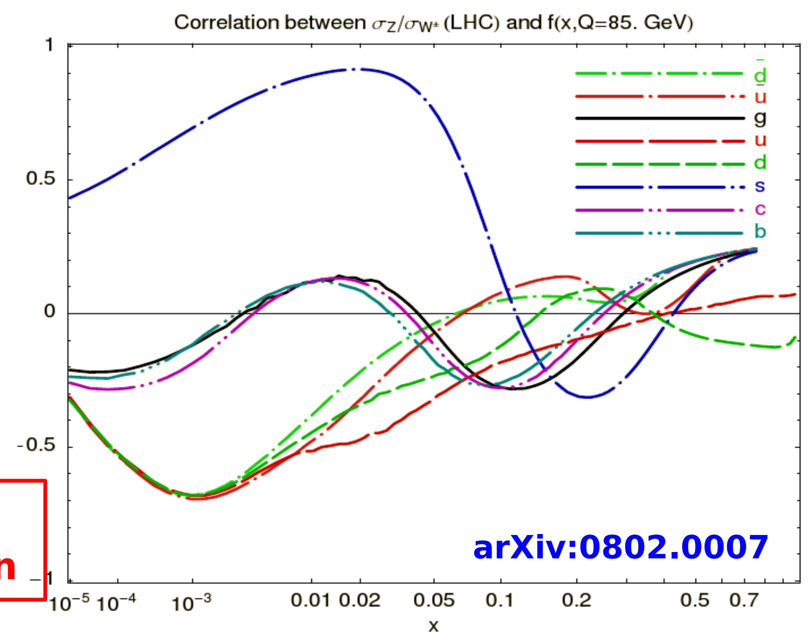


PDF constraints with σ_W/σ_Z



Motivations

- ***Similar selection procedure***
  - **Isolated leptons**
  - **~ Same p_T range**
  - **Can be selected using same trigger**
- ***LO partonic process***
  - **Quark initial state; singlet final state**
  - **Similar QCD corrections**
- ***Behave similarly under PDF variations***
  - **~ Same x, Q^2**
  - **Initial partons mainly from sea**



Remaining PDF uncertainties

- ***Mostly due to strange PDF***
  - **increases x3 compared to CTEQ6.1 as a result of free strangeness in CTEQ6.6**

⇨ **Measurements of σ_W/σ_Z imposes strong constraints on strange quark parametrisation**