# $\Delta M_W \leq 10\ \mathrm{MeV}/c^2$ at the LHC:
## a forlorn hope?

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Hamburg, the 7th June, 2009

# Electroweak Standard Model

$$\alpha,\ M_Z,\ G_F$$

Higgs ?, supersymmetry ?, …

$$M_{W,}\ \sin^2(\theta_W),\ \Gamma_W,\ M_{W+}\text{-}\ M_{W-}\ ,\Gamma_{W+}\text{-}\ \Gamma_{W+}\ \ldots$$

# The question:

Can we really improve the measurement precision of the EW parameters at the LHC?

# Reported work

- **Goal:** Evaluate the achievable precision of the EW SM parameter measurement at the LHC. Propose a coherent, LHC-dedicated strategy to measure: $M_{W,}$, $\sin^2(\theta_W)$, $\Gamma_W$, $M_{W+}$- $M_{W-}$ ,$\Gamma_{W+}$- $\Gamma_{W+}$

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- Luminosity: 10 fb $^{-1}$
- Trigger and Acceptance cuts: $p_{T,l} > 20$ GeV/c, $|\eta_l| <2.5$
- Event generators: WINHAC/ZINHAC (spin amplitudes)
- Simulation: parameterized response of the ATLAS detector
- Study based on $O(10^{10})$ simulated events
- The team: F. Fayette, W. Placzek, K. Rejzner, A. Siodmok, M.W. Krasny, in collaboration with F. Dydak (IN2P3-COPIN cooperation program 05-116)

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- **This presentation:** M_W measurement (CERN-PH-EP/2010-007, arXiv:1004.2597 [hep-ex], submitted to EPJC)

# Current precision of the W mass
## (for an integrated LHC luminosity of 10 $fb^{-1}$)

LEP: $\Delta M_W = 33\ MeV/c^2$

Tevatron: $\Delta M_W = 31\ MeV/c^2$

ATLAS TDR: $\Delta M_W \approx 25\ MeV/c^2$

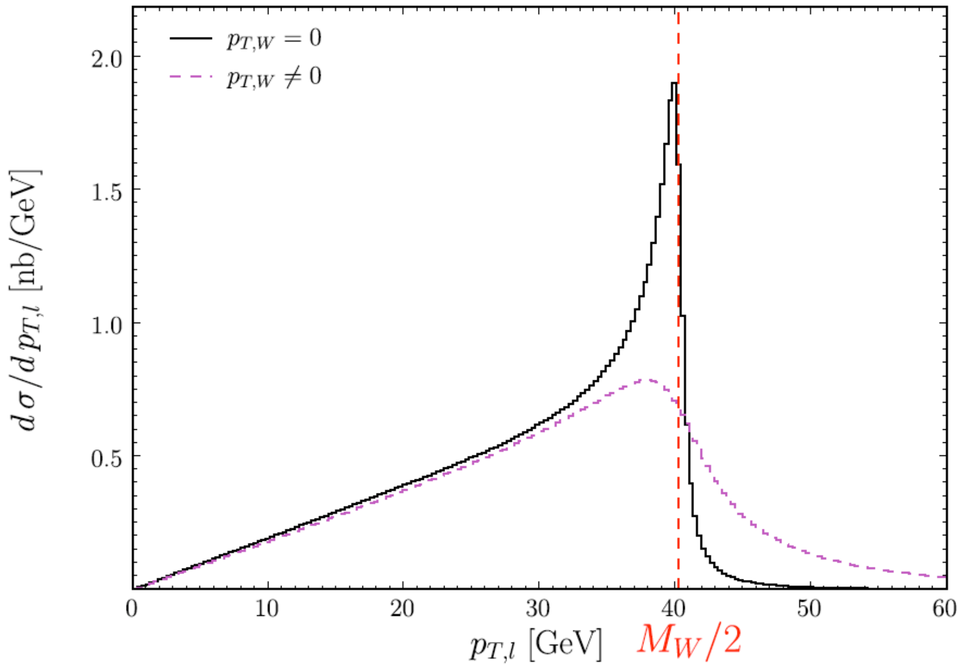
N. Besson et al., Eur. Phys. J. C57 (2008) 627: $\Delta M_W \approx 7\ MeV/c^2$

CMS TDR: $\Delta M_W \approx 30\ MeV/c^2$

(pdf contribution < 10 $MeV/c^2$)

V. Buge et al., CERN-CMS-NOTE-2006-061: $\Delta M_W \approx 20\ MeV/c^2$

# What influences the Jacobian peak position?




$M_W$ is determined from $p_{t,l}$ distribution:

For $\Delta(M_W)$ =10 MeV, need to control the peak position with 0.01% (~4 MeV) precision - use the Z-boson spectra as the standard candle

The peak position is driven by the $M_W$ value… but also biased by:

## Tevatron and LHC

- < $p_{T,W}$> ($x_1$, $x_2$, $m_s$, $m_c$) - ~5000 MeV
- momentum scale calibration - ~400 MeV/%
- …

## LHC-specific effects

- W-polarization - ~2000 MeV for " ↑ - ↓ "
- W-charge asymmetry - ~300 MeV for "(+) - (-) "
- relative $l^+/l^-$ momentum calibration ~60 MeV/%
- …

The LHC-specific effects - largely ignored in all the previous studies - need to be understood to a very high precision at the LHC

# Roots of the LHC specific problems

…at the LHC we collide pp not p$\bar{p}$ like at the Tevatron, in addition much higher $E_{CM}$

→ Symmetry relations not at work:

at the LHC, contrary to the Tevatron: " $W^+ \neq W^-$ ", $\uparrow_W \neq \uparrow_Z$ (polarization)

- need of separate analyses of $W^+$ and $W^-$, and similarly $Z^+$ and $Z^-$, no charge-blind analysis possible (like in p$\bar{p}$ collisions at the Tevatron)
- need to control the relative calibration of the $l^+$/ $l^-$ momentum scales, Z-peak of little use

→ Collisions at much higher energy!

at the LHC ~30% of W and Z bosons are produced by s,c and b quarks

- need to understand heavy flavours with much better precision

For the LHC precision EW programme we need to know the proton valence/sea and flavour structure with much higher precision than that required at the Tevatron…

Can we constrain the PDFs with a required precision using W and Z boson data collected at the LHC?

…No, we cannot. External constraints are needed.

# Unconstrained PDF degrees of freedom at the LHC

Assume: $s(x)=\bar{s}(x)$, $c(x)=\bar{c}(x)$, $b(x)=\bar{b}(x)$ then:

- 5 sea-quark flavours (u,d,s,c,b) + 2 valence quark flavours ($u^{(v)}$, $d^{(v)}$) 7 unknown PDFs:
- 4 constraints coming from the ($p_{T,l}$, $\eta_l$) spectra for $W^+$, $W^-$, "$Z^+$" and "$Z^-$" decays
- 7-4=3 degrees of freedom in the flavour-dependent pdf's remain unconstrained at the LHC

Important note:

At the Tevatron only the first quark family is relevant. In addition p collides with $\bar{p}$.

This leaves only 2 (out of 7) flavour dependent pdf's. They are over-constrained by the the $\eta_l$ dependence of the Z and W cross-sections

# The 3 least-constrained degrees of freedom:

1. $u^{(v)} - d^{(v)}$ - a missing constraint for the 1st family
2. s - c - a missing constraint for the 2nd family
3. b - a missing constraint for the 3rd family

Note:

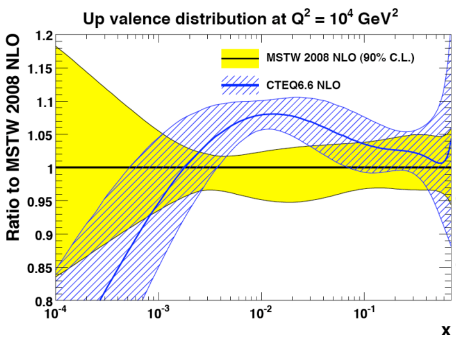
- $u^{(v)}$ can move up and $d^{(v)}$ move down such that the rapidity distribution of Z-boson remain unchanged, the same for s and c
- The non-singlet partonic distributions have only small scale dependence (they are robust with respect to the choice: (1) of QCD evolution scheme and (2) of order of perturbative expansion, their uncertainty reflects directly the uncertainties of the experimental data used in the QCD fits

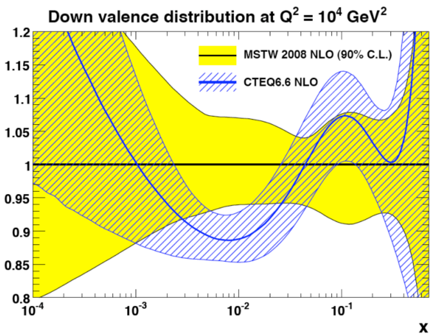
# Present precision of: "missing" PDF and its impact on the $M_W$ measurement error

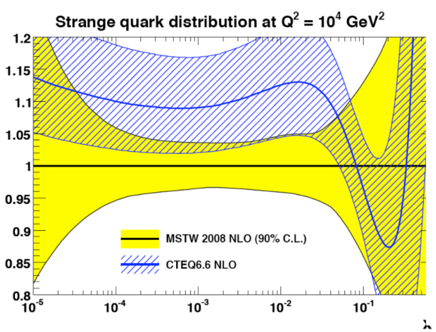
| | $\Delta M_{\mathrm{W}}$ |
|---|---|
| $u_{\mathrm{v}}^{\mathrm{bias}} = 1.05\, u_{\mathrm{v}}$<br>$d_{\mathrm{v}}^{\mathrm{bias}} = d_{\mathrm{v}} - 0.05\, u_{\mathrm{v}}$ | $+79\ \mathrm{MeV}/c^2$ |
| $u_{\mathrm{v}}^{\mathrm{bias}} = 0.95\, u_{\mathrm{v}}$<br>$d_{\mathrm{v}}^{\mathrm{bias}} = d_{\mathrm{v}} + 0.05\, u_{\mathrm{v}}$ | $-64\ \mathrm{MeV}/c^2$ |

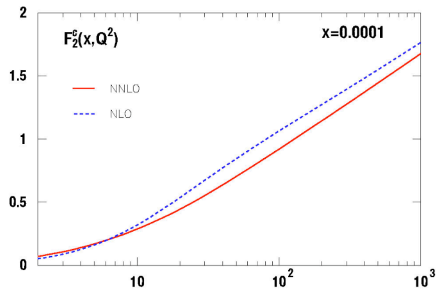
| | $\Delta M_{\mathrm{W}}$ |
|---|---|
| $c^{\mathrm{bias}} = 0.9\, c$<br>$s^{\mathrm{bias}} = s + 0.1\, c$ | $+148\ \mathrm{MeV}/c^2$ |
| $c^{\mathrm{bias}} = 1.1\, c$<br>$s^{\mathrm{bias}} = s - 0.1\, c$ | $-111\ \mathrm{MeV}/c^2$ |

| | $\Delta M_{\mathrm{W}}$ |
|---|---|
| $b^{\mathrm{bias}} = 1.2\, b$ | $+42\ \mathrm{MeV}/c^2$ |
| $b^{\mathrm{bias}} = 0.8\, b$ | $-39\ \mathrm{MeV}/c^2$ |




The uncertainty in the non-singlet distributions are driven by the precision of the experimental data and their phenomenological interpretation rather than by the precision of the QCD fits!!!

Example: $u_v$-$d_v$ driven by the NMC "p/d" data (2%), E866 "D-Y" data (4%), nucl. corr (2%)

…The precision of $M_W$ cannot be improved at the LHC…

(…the same conclusion for $\sin^2(\theta_W)$, $\Gamma_W$, $M_{W+}$- $M_{W-}$ ,$\Gamma_{W+}$- $\Gamma_{W+}$,

…e.g. $\Delta\sin^2(\theta_W) \sim 0.001$, $\Delta\Gamma_W \sim$ 50 MeV, !… note feedback on $M_W$ )

…neither now nor at the completion phase of the canonical LHC programme

# The way forward

- LHC-specific measurement and analysis strategy

and

- An extension of the canonical LHC proton collision programme:

deuteron-deuteron collisions at the LHC

or

DIS experiment with deuterium and hydrogen target

LOI for such an experiment submitted to SPSC and LHCC

# LHC specific strategy (elements)

1.Precision observables:

| | | |
|---|---|---|
| **LHC + Tevatron** | $$\mathcal{A}_{\rm W}(p_{\rm T,l},\eta_{\rm l}) = \frac{\Sigma_{\rm W^+}(p_{\rm T,l},\eta_{\rm l}) - \Sigma_{\rm W^-}(p_{\rm T,l},\eta_{\rm l})}{\Sigma_{\rm W^+}(p_{\rm T,l},\eta_{\rm l}) + \Sigma_{\rm W^-}(p_{\rm T,l},\eta_{\rm l})},$$ | sensitive to $M_{W+}$ - $M_{W-}$ and $\Gamma_{W+}$ - $\Gamma_{W-}$ |
| | $$\mathcal{A}_{\rm Z}(y_{\rm ll},p_{\rm T,ll},p_{\rm T,l},\eta_{\rm l}) = \frac{\Sigma_{\rm Z^+}(y_{\rm ll},p_{\rm T,ll},p_{\rm T,l},\eta_{\rm l}) - \Sigma_{\rm Z^-}(y_{\rm ll},p_{\rm T,ll},p_{\rm T,l},\eta_{\rm l})}{\Sigma_{\rm Z^+}(y_{\rm ll},p_{\rm T,ll},p_{\rm T,l},\eta_{\rm l}) + \Sigma_{\rm Z^-}(y_{\rm ll},p_{\rm T,ll},p_{\rm T,l},\eta_{\rm l})},$$ | sensitive to $\sin^2(\theta_W)$ |
| | $$\mathcal{R}_{\rm WZ}(p_{\rm T,l},\eta_{\rm l}) = \frac{\Sigma_{\rm W^+}(p_{\rm T,l},\eta_{\rm l}) + \Sigma_{\rm W^-}(p_{\rm T,l},\eta_{\rm l})}{\Sigma_{\rm Z^+}(p_{\rm T,l},\eta_{\rm l}) + \Sigma_{\rm Z^-}(p_{\rm T,l},\eta_{\rm l})},\ \text{and}$$ | sensitive to $\alpha_{s,}$ $M_{W+}$+ $M_{W-,}$ and $\Gamma_{W+}$ + $\Gamma_{W-}$ |
| | $$\mathcal{R}_{\rm Z}^{\rm norm}(p_{\rm T,ll},y_{\rm ll}) = \frac{\Sigma_{\rm Z}(p_{\rm T,ll},y_{\rm ll})}{\Sigma_{\rm l^+l^-}^{\rm norm}},$$ | dedicated method of absolute normalization |
| **DIS** | $$\mathrm{Asym}_{\rm DIS}^{(p,n)}(x,Q^2) = \frac{\frac{d^2\sigma^p}{dxdQ^2}(x,Q^2) - \frac{d^2\sigma^n}{dxdQ^2}(x,Q^2)}{\frac{d^2\sigma^p}{dxdQ^2}(x,Q^2) + \frac{d^2\sigma^n}{dxdQ^2}(x,Q^2)}$$ | missing constraint for $d_v$, $\bar{d}$, $u_v$, $\bar{u}$ |

2. Two dimensional PDFs ($k_T$,x)

3. Experimental procedures to control of all the relative QCD effects for W and Z bosons (Z as a candle for EW effects)

# Conclusions and outlook

- The measurement of the EW SM parameters at the LHC require a dedicated measurement and analysis programme in order to improve the LEP and the Tevatron ones. A programme of such a type has been developed and evaluated.

- For the ultimate measurement precision of the EW SM parameters the Tevatron and the LHC data will eventually have to be combined using the same, “measurement-bias-robust” observables. Their interpretation in terms of the future EW field-theory will have to be based upon a full experimental control of all the parasitic QCD effects. In the proposed scheme, they are absorbed into two-dimensional $(x,k_T)$ flavour-dependent PDFs - fully constrained by LHC and Tevatron W and Z observables **plus the proton/neutron DIS cross section**

# Conclusions and outlook

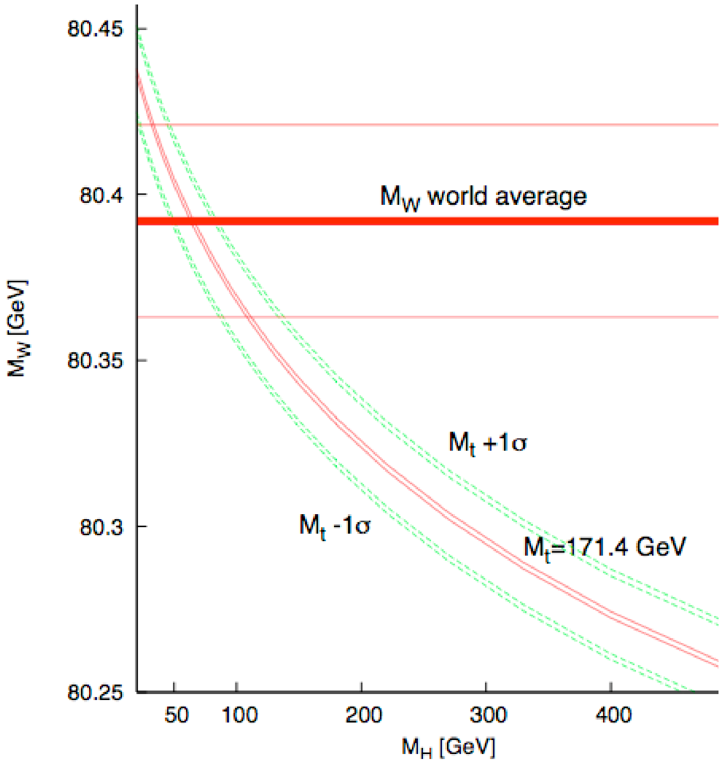
- Measurement of the proton/neutron DIS cross section appears to be the simplest and minimal way of complementing the LHC and Tevatron measurements (an alternative program involves running light isoscalar ions in the LHC machine) - its precision will determine the ultimate understanding of polarization of the W and Z bosons produced by the LHC.

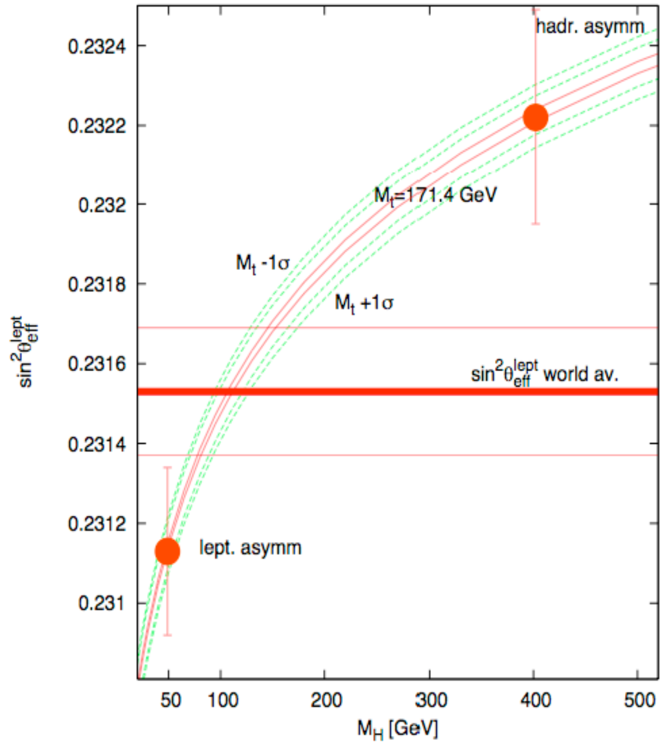
- The DIS experiment and the LHC-programme-oriented measurements at the Tevatron will not be made unless there is a recognition - within the LHC community - that an auxiliary, LHC-support programme is indispensable for a success of a competitive EW-precision programme at the LHC

# supplementary slides

# The LHC precision challenges

F. Zwirner talk at the Paris Workshop on “High Energy Physics in the LHC Era

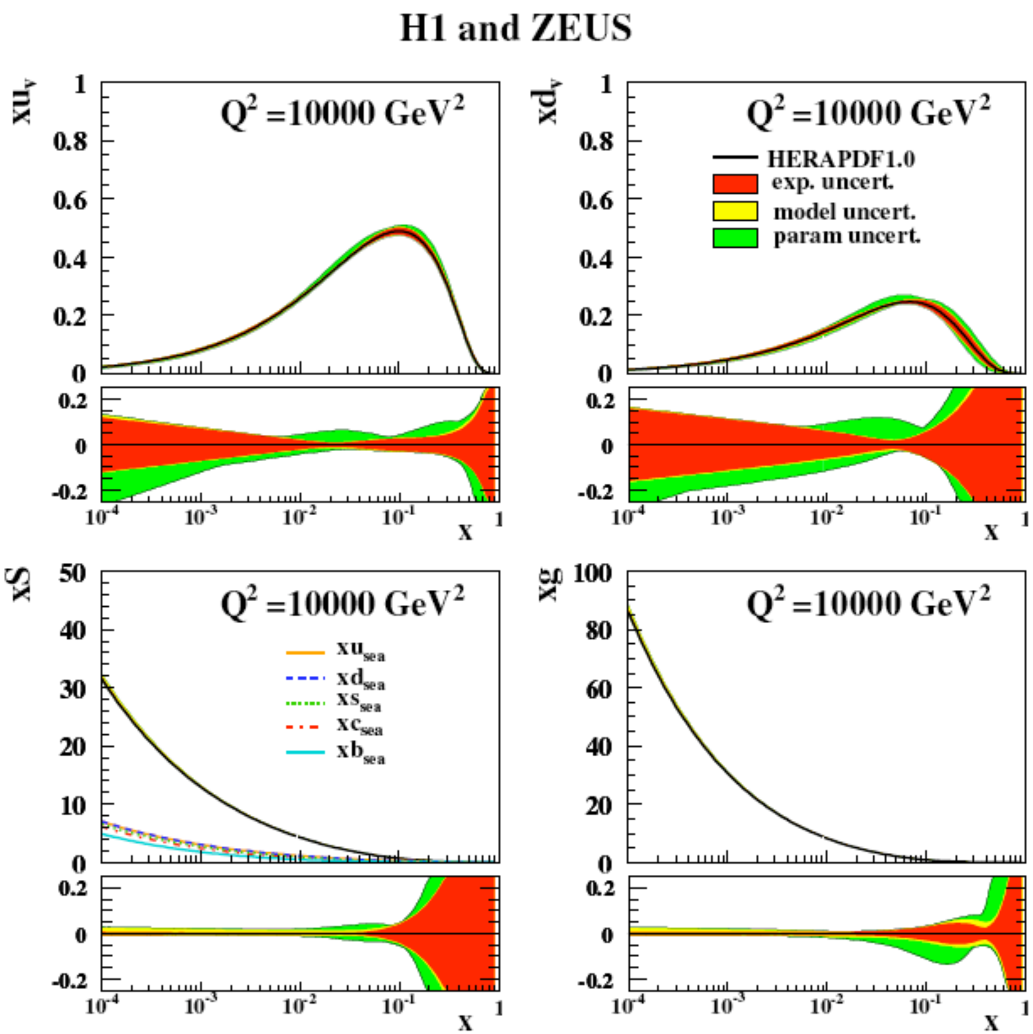


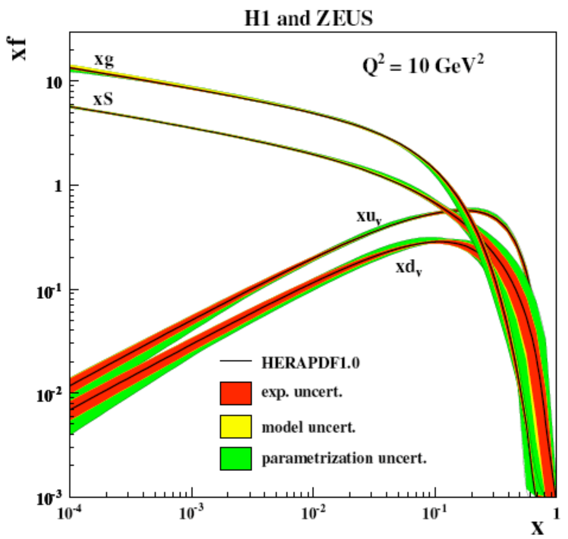



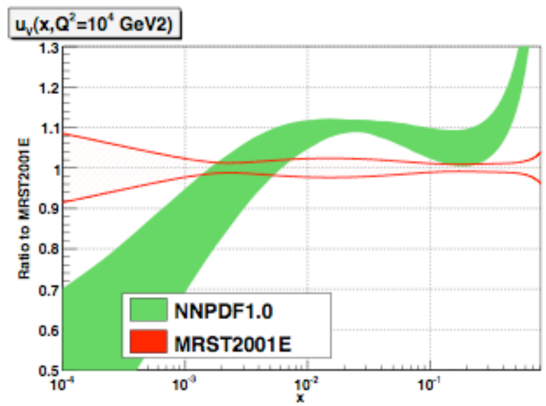

LHC absolute precision limit:
2 MeV/$c^2$ (LEP $M_Z$ precision)

LHC absolute precision limit:
~0.0001 (statistical -200 $fb^{-1}$)

# Discussion of the present PDF uncertainties
## valence/sea

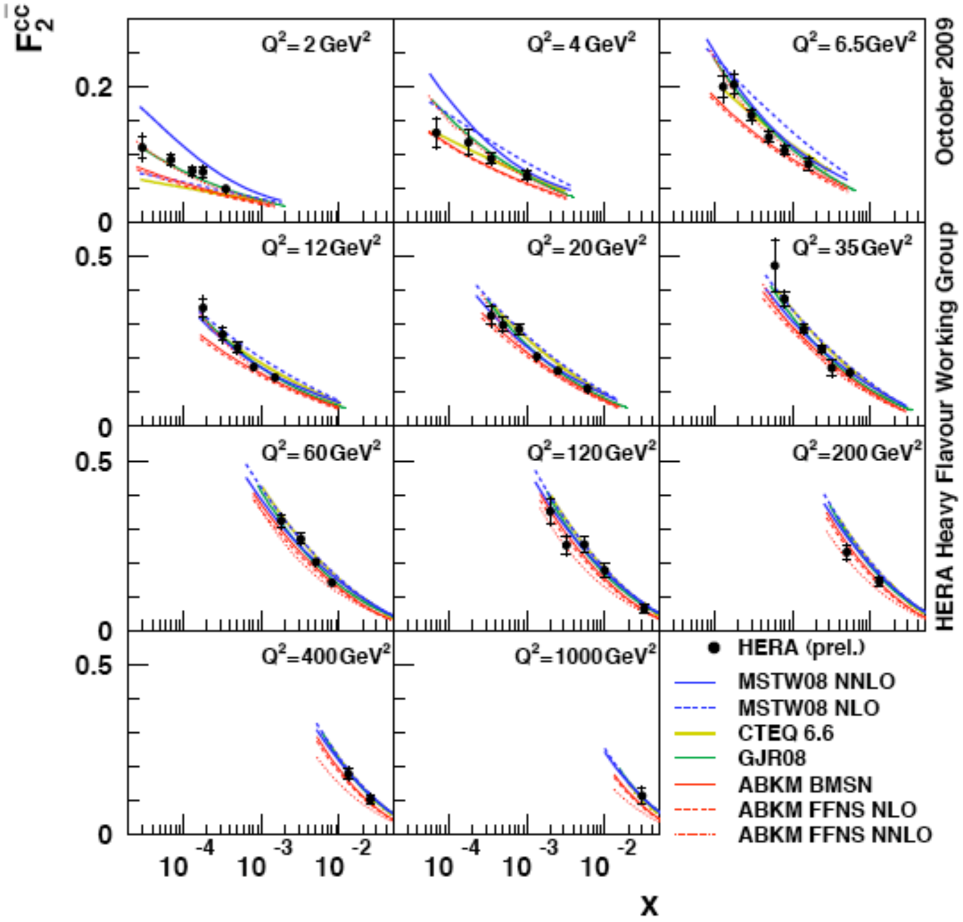


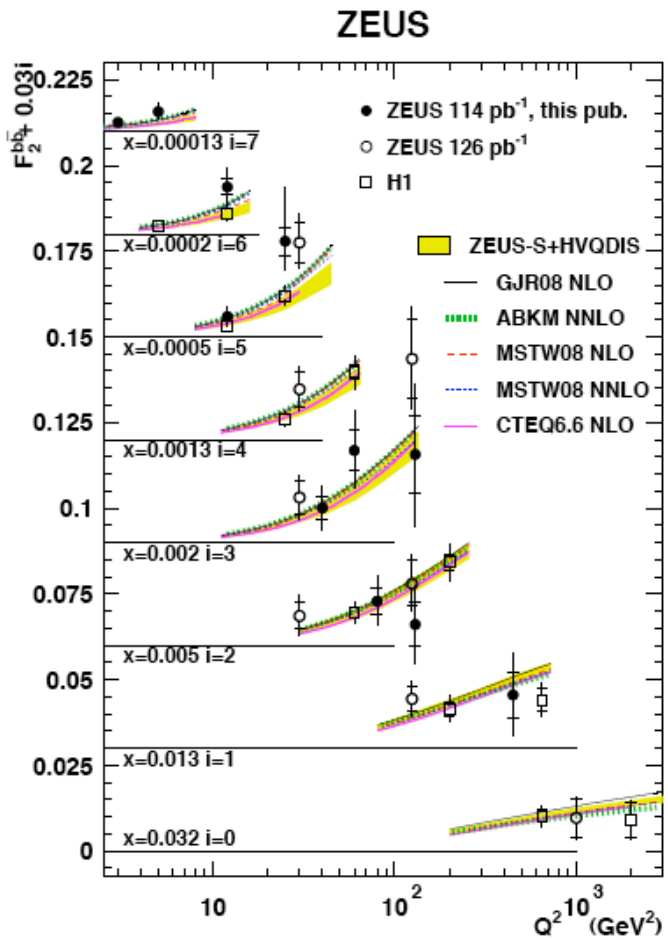



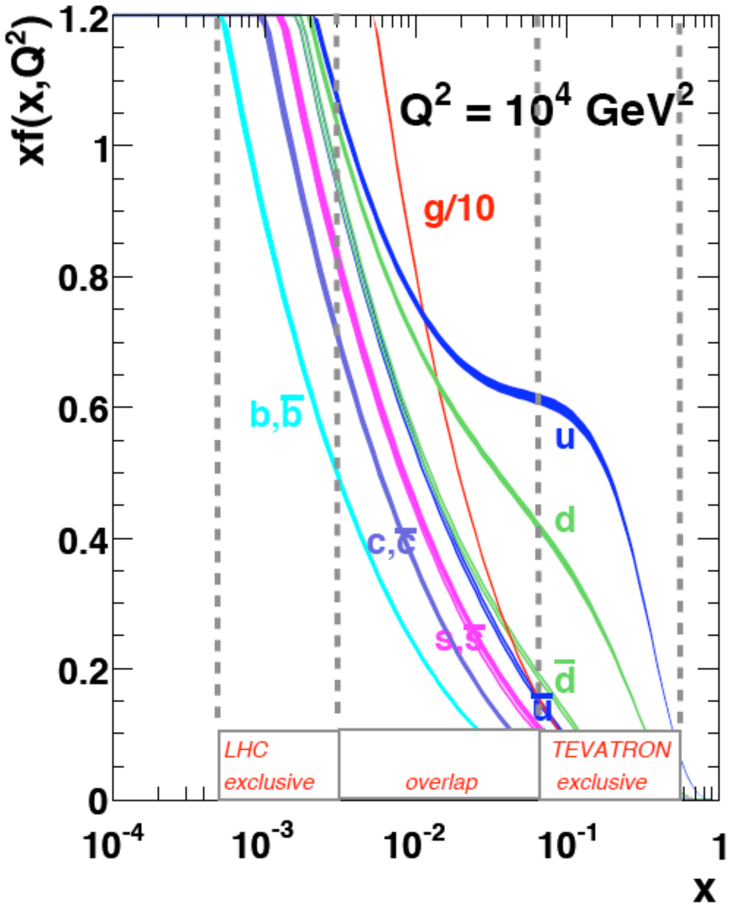
# Discussion of the present PDF uncertainties

## heavy flavours



The need for the new proton/neutron DIS cross-section asymmetry measurement - unmatched precision of the present DIS data and the future LHC data)




$\mathcal{O}_{D\text{-}Y} \sim \bar{q}(x_{low})q(x_{high}) + q(x_{low})\bar{q}(x_{high})$

## Tevatron:

need only u/d, use $W^-/W^+$ data

…ambiguity $u/d(x_{low})$ vs $u/d(x_{high})$

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## LHC:

need u/d, but also $u_v/d_v$, and $(u_v+d_v)/(u+d)$

…both at $x_{low}$ and $x_{high}$

In the overlap region use $W^-/W^+$ (Tevatron and LHC) + F-B asymmetry in Z-decays (LHC)

Adequate external constraint needed either in the Tevatron exclusive region (SPS) or in the LHC exclusive region (eRHIC, ”resurrected” HERA)

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The form of the constraint:

$A(p,n) \sim u_v - d_v + 2(u+d-u_v-d_v)$