Constraints on PDFs from ATLAS measurements

Kristin Lohwasser

DESY

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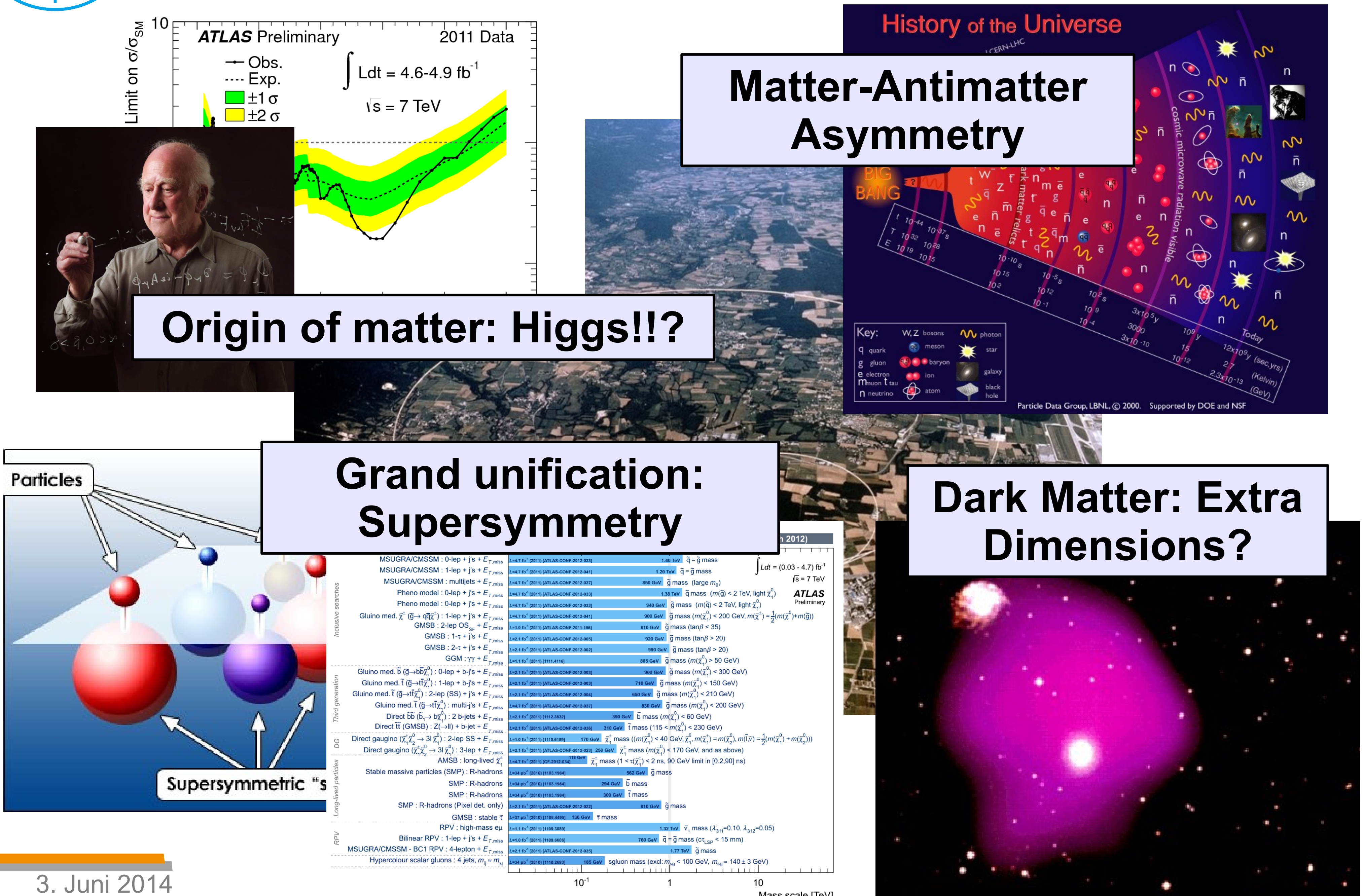
HELMHOLTZ ASSOCIATION

Outline of the talk

- Interactions at hadron colliders
- Parton Distribution Function (PDFs) and their Extraction
- Measurements at the LHC to constrain the PDFs
- Inclusive W and Z measurements
- W+charm: Direct sensitivity to strange content
- Outlook: Is this really needed?

Open questions in particle physics



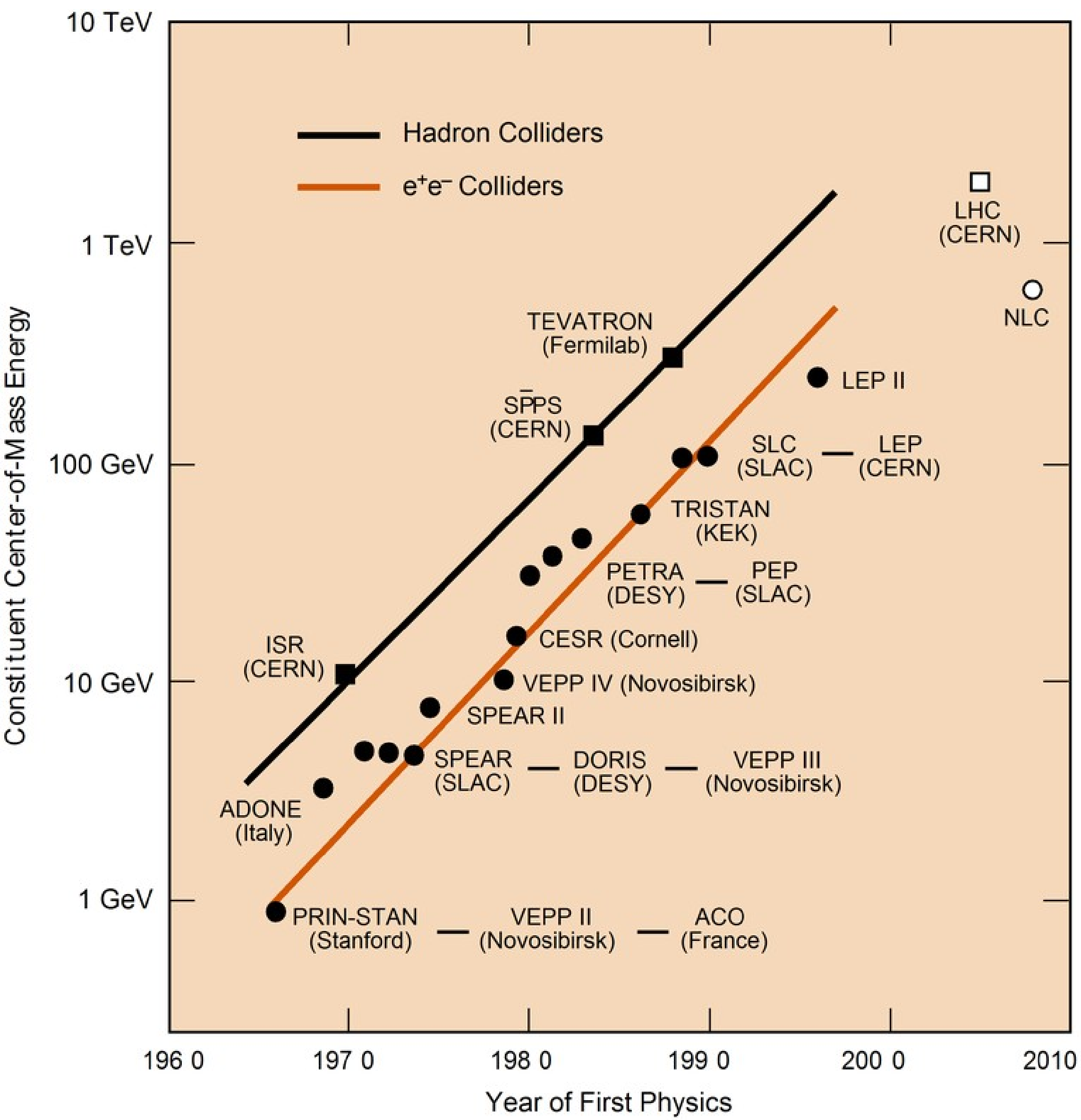
Matter-Antimatter Asymmetry

Origin of matter: Higgs!!?

Grand unification: Supersymmetry

Dark Matter: Extra Dimensions?

Road to discovery



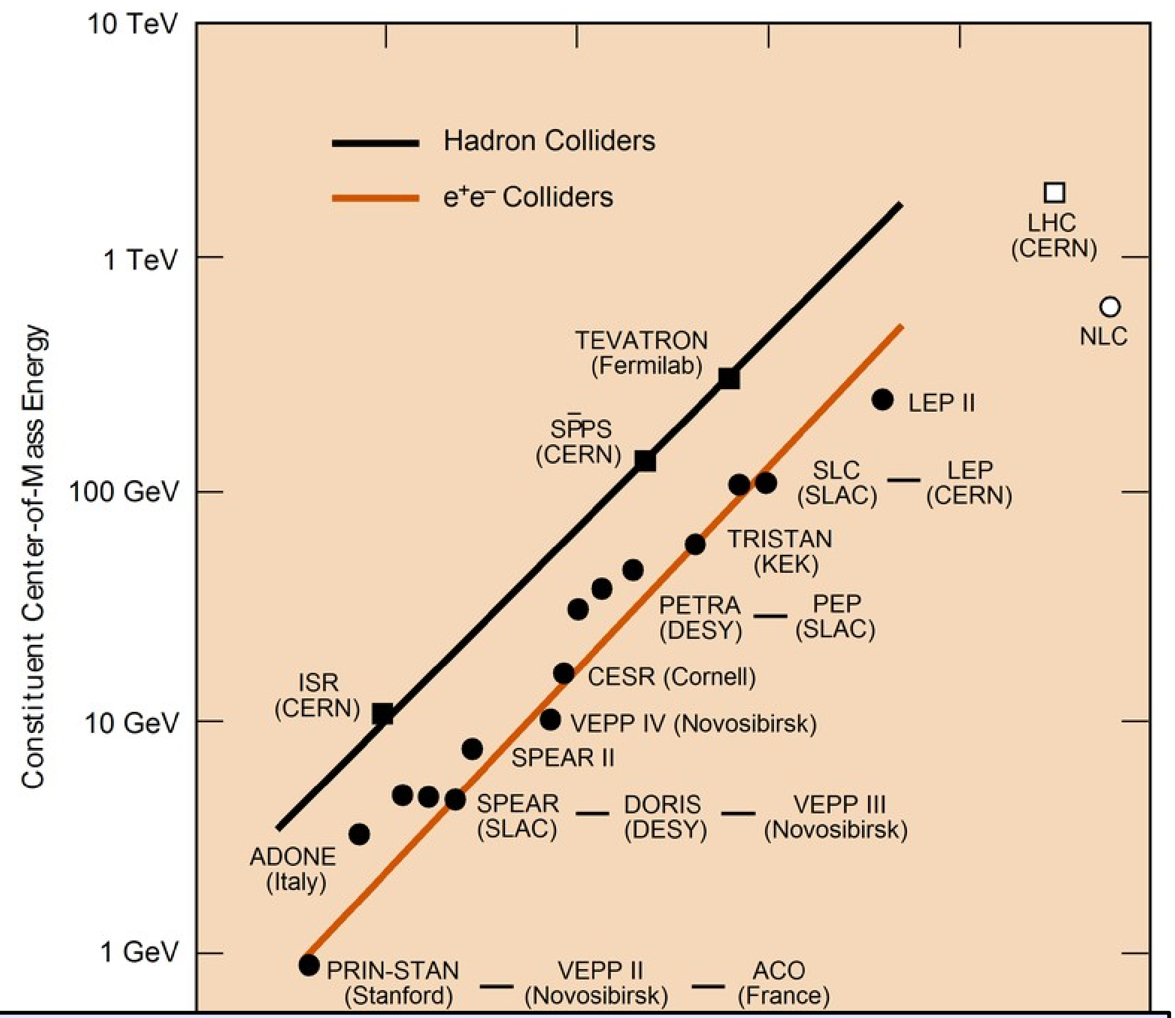
Lepton Colliders

- Very clean environment
- Well suited for precision measurements
- Huge losses due to synchrotron radiation in ring colliders → Limit centre-of-mass energy
- Huge design cost for linear collider

Road to discovery

Hadron Collider

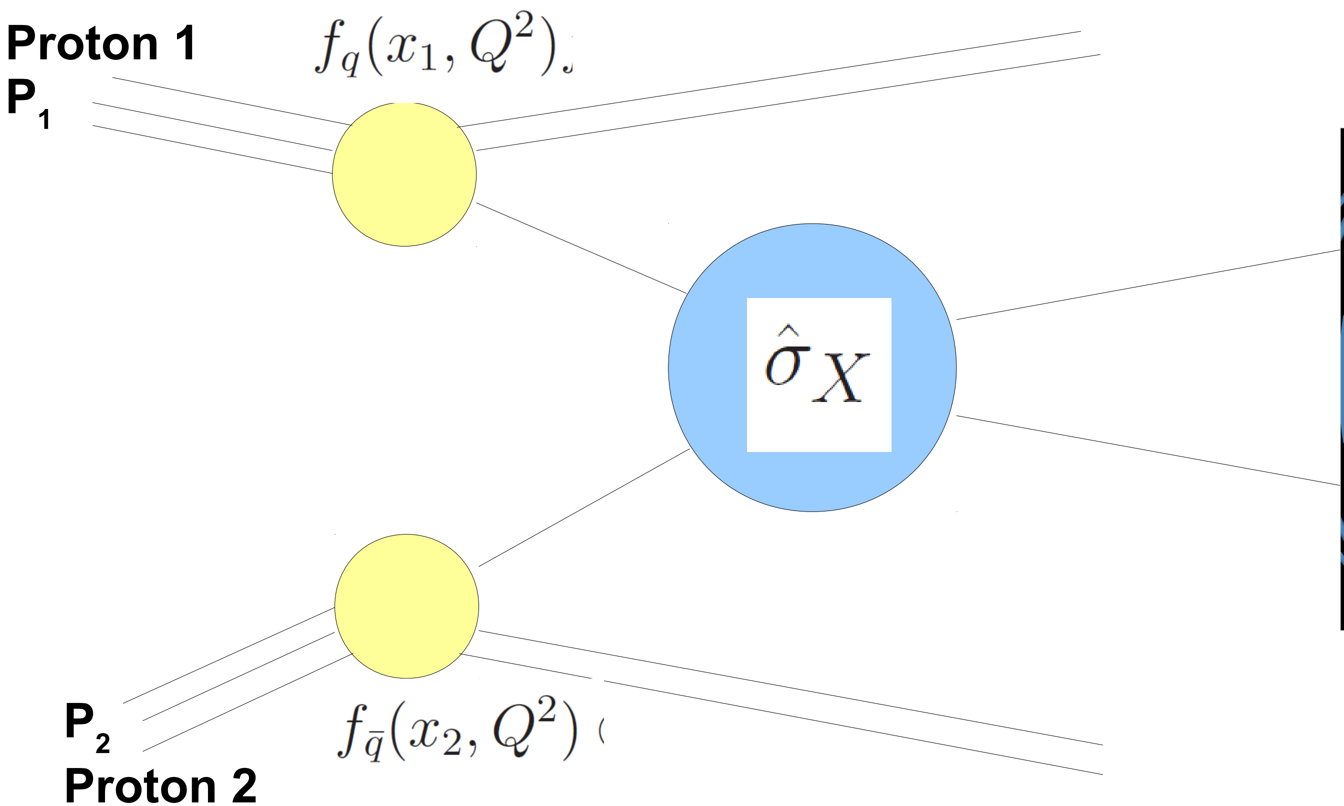
- Higher centre-of-mass energy
- Less losses due to synchrotron radiation – more efficient use of ressources
- Less clean environment
- Need to understand our initial states very well

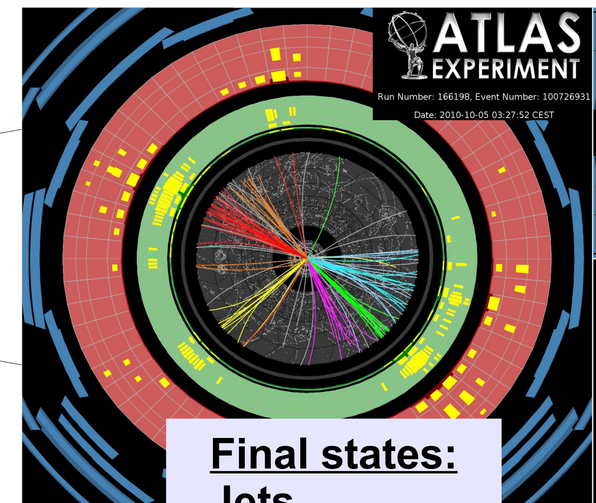


Challenge for Lepton Colliders:	**technical design**
Hadron Colliders:	**theoretical understanding**

Interactions at hadron colliders

$f_q(x_1, Q^2)$ **Probability to find parton with momentum fraction x in proton**





<u>Final states:</u>
Jets,
Leptons,
missing ET

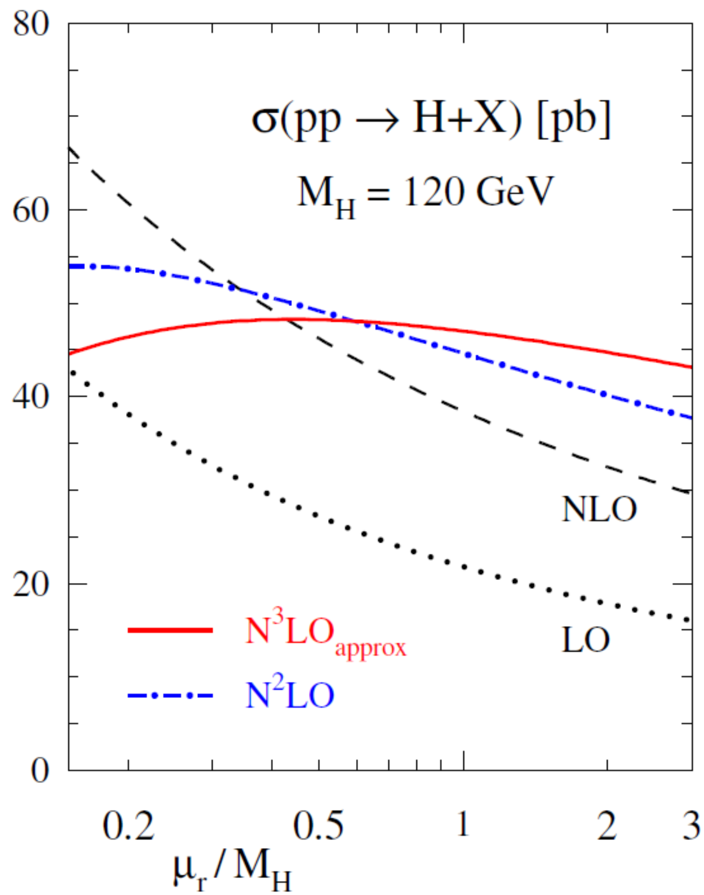
phenomenological part

Analytical part

$$\sigma_{PP\rightarrow X} = PDF \otimes \sigma_{\mathrm{hardscatter}} = \sum_q \int dx_1 dx_2 f_q(x_1, Q^2) f_{\bar{q}}(x_2, Q^2) \otimes \hat{\sigma}_{q\bar{q}\rightarrow X}(\alpha, Q^2)$$

Analytical Part: Problem of the theorists...

Moch, Vogt '05



- Partonic cross section calculation
- Higher order corrections
  NLO → NNLO → …..
- Renormalization Scale dependence
- Factorization Scale dependence
- Electroweak input-parameter scheme
- ….

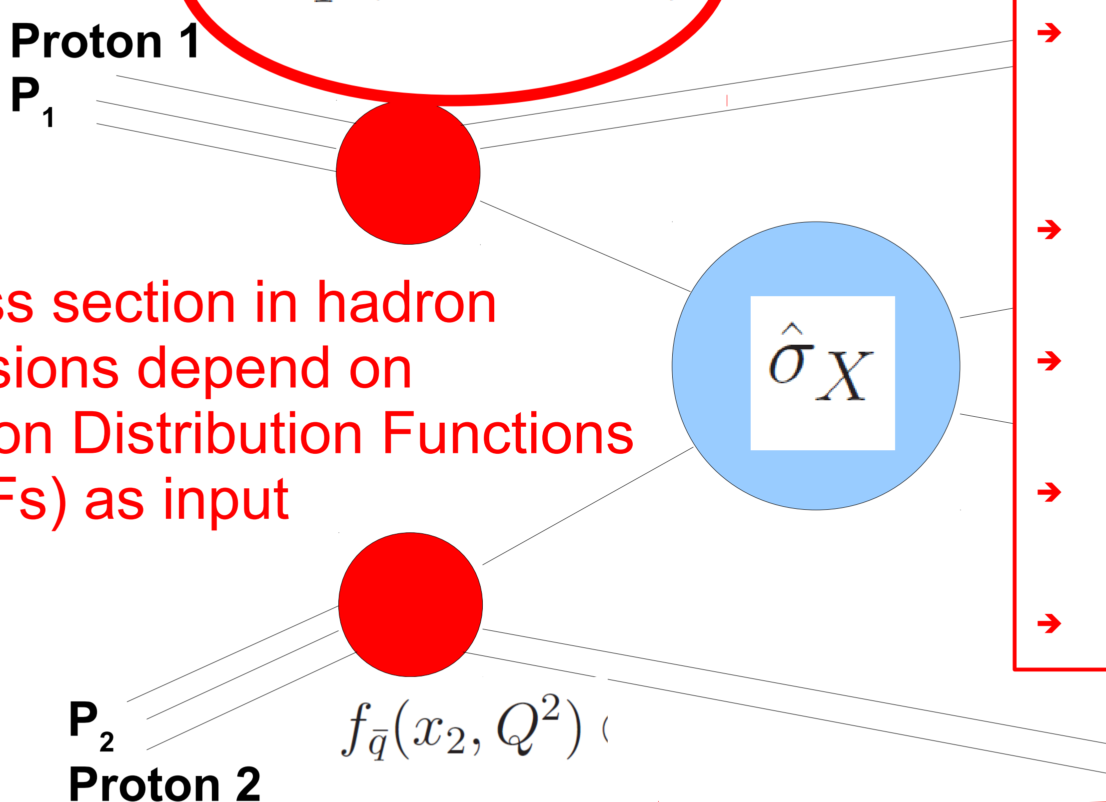
phenomenological part

Analytical part

$$\sigma_{PP\to X} = PDF \otimes \sigma_{\text{hardscatter}} = \sum_q \int dx_1 dx_2 f_q(x_1, Q^2) f_{\bar{q}}(x_2, Q^2) \otimes \hat{\sigma}_{q\bar{q}\to X}(\alpha, Q^2)$$

Phenomenological Part: The proton

$$f_q(x_1, Q^2)$$



Cross section in hadron collisions depend on Parton Distribution Functions (PDFs) as input

- Not calculable from first principles!!!
- Dependence on input data
- Fitting scheme
- PDF parametrization
- ....

phenomenological part

Analytical part

$$\sigma_{PP\to X} = PDF \otimes \sigma_{\text{hardscatter}} = \sum_q \int dx_1 dx_2 f_q(x_1, Q^2) f_{\bar{q}}(x_2, Q^2) \otimes \hat{\sigma}_{q\bar{q}\to X}(\alpha, Q^2)$$

Parton Distribution Functions (PDF)

- Probability to find a parton q carrying momentum fraction x of the proton momentum to enter a collision at a momentum transfer squared Q^2

$$f_q(x_1, Q^2)$$

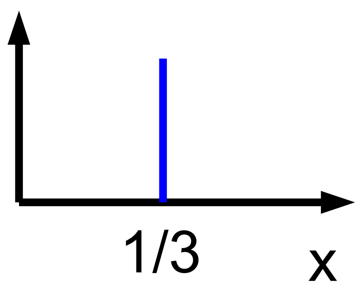
Momentum fraction x

- Probability to find a parton q carrying momentum fraction x of the proton momentum to enter a collision at a momentum transfer squared Q^2

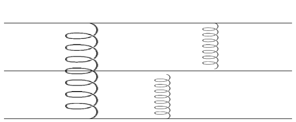
$$f_q(\boxed{x_1}, Q^2)$$

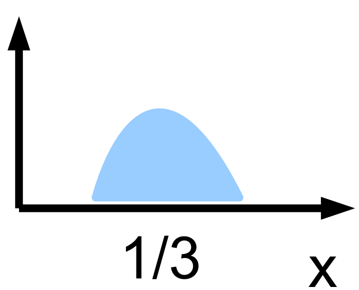
The full picture

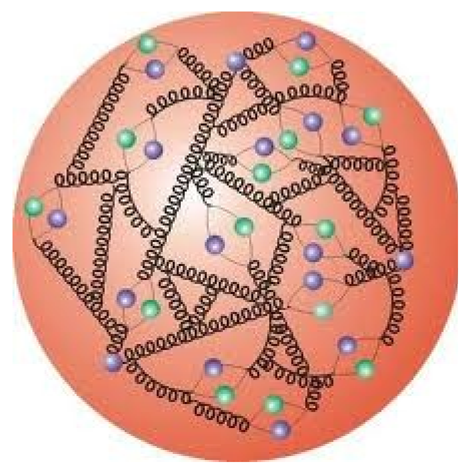
3 valence quarks without interaction

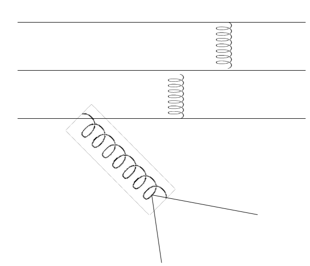


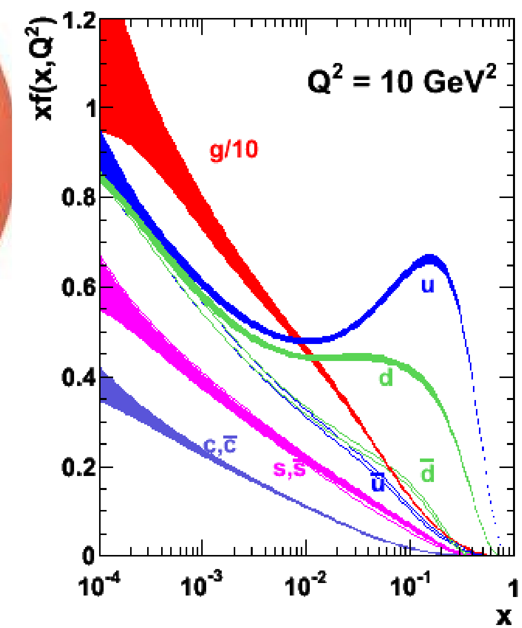
3 valence quarks with interactions









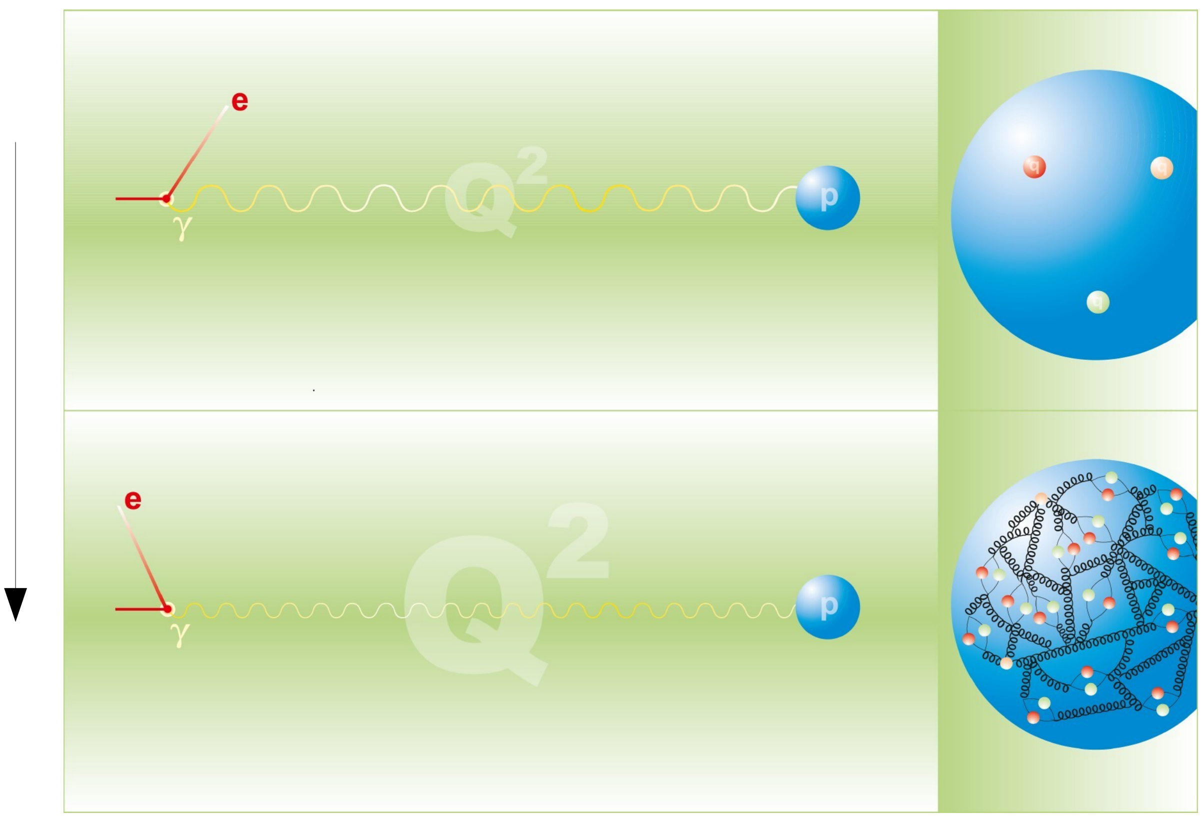


Momentum transfer squared Q^2

- Probability to find a parton q carrying momentum fraction x of the proton momentum to enter a collision at a momentum transfer squared Q^2

$$f_q(x_1, Q^2)$$

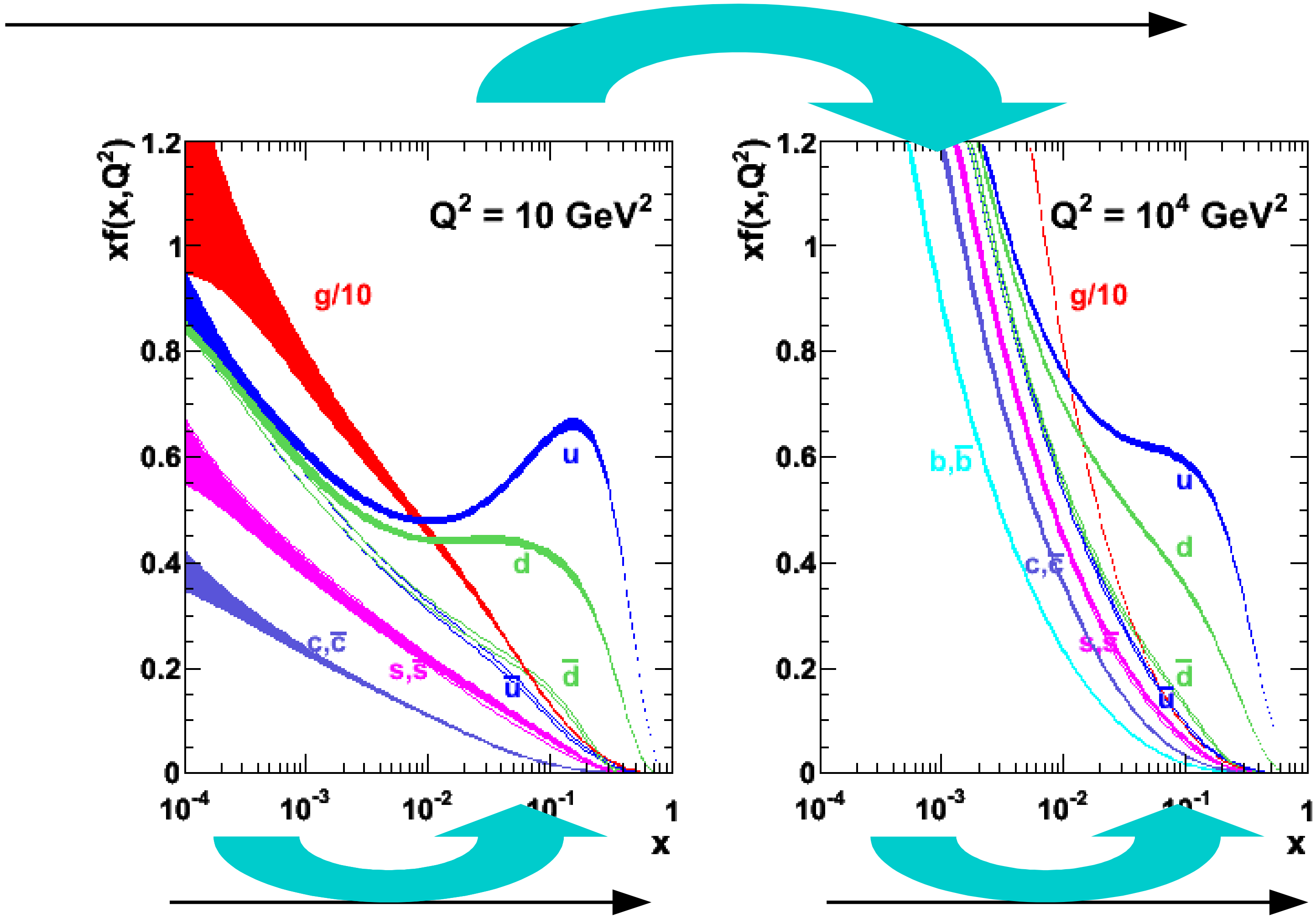
- Higher Q^2
- Smaller wavelength
- More resolution power



$$\frac{\Delta E}{\Delta t} \leq \hbar/2$$

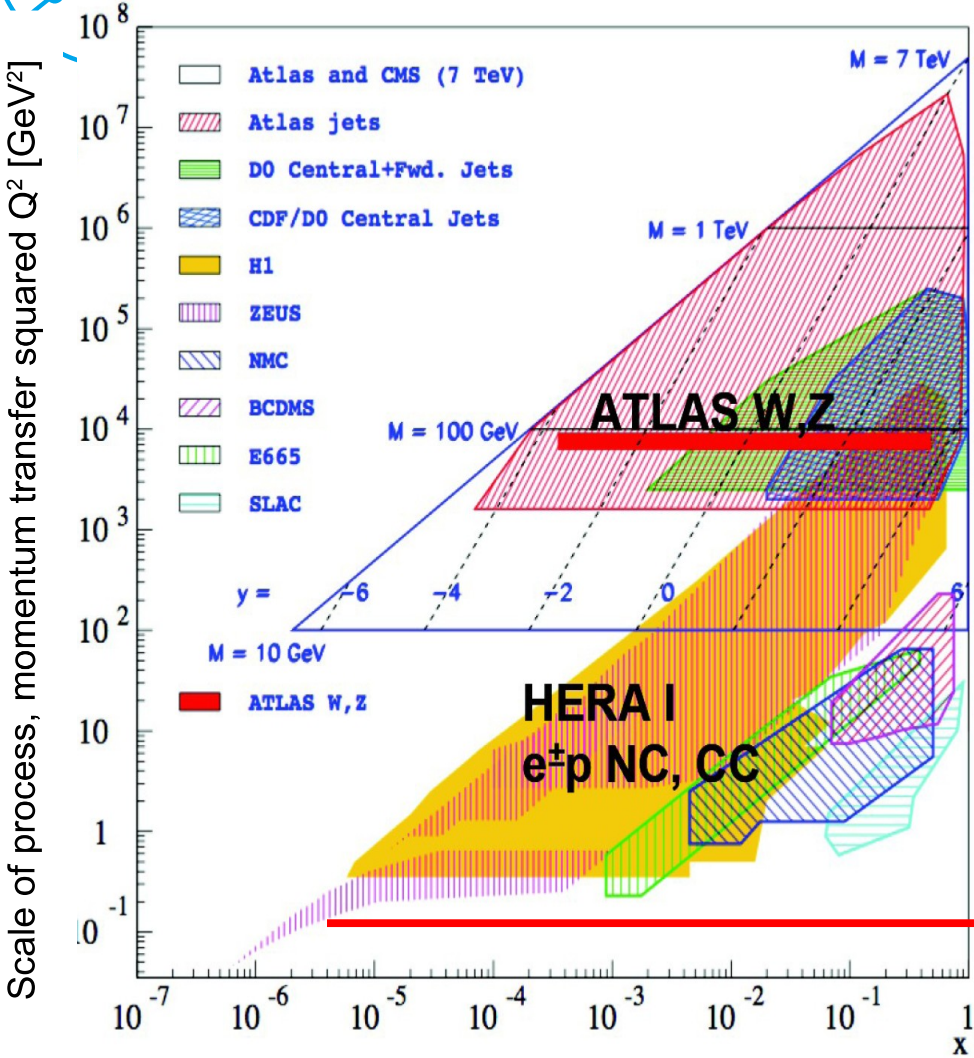
Dependence on x and Q^2

Q^2 dependence: higher resolution, more gluon and sea quark contributions



x dependence: valence quarks carry higher momentum

Procedure of PDF fits I



- Evolve input PDFs with DGLAP equations
- Calculate observables using (N)(N)LO and compare to experiments
- Minimize global Chi2 between data and theory

starting scale $Q^2 \sim 1.5$ - 2 GeV

- Groups:

MSTW/MRST	(global fit, up to NNLO)
CTEQ / CT	(global fit, up to NLO, now NNLO)
NNPDF	(global fit, neural network PDFs)
HERA PDFs	(Hera collider data only so far)

Procedure of PDF fits II

- Parametrize x distributions for all parton flavours

$$q(x, Q^2) = x^{\alpha}(1-x)^{\beta} P(x; \lambda_1, ..., \lambda_n).$$

  - $x \rightarrow 0$ $\bar{u} = \bar{d}$, q µ x^{a1}
  - $x \rightarrow 1$ q $(1 - x)^{a2}$ (quark counting rules)
  - P(x, …) medium-x range, just convenient form

Example (NNPDF): 29 input parameters

$$xu_v(x, Q^2) = A_u x^{\eta_1}(1-x)^{\eta_2}(1+\epsilon_u\sqrt{x}+\gamma_u x)$$
$$xd_v(x, Q^2) = A_d x^{\eta_3}(1-x)^{\eta_4}(1+\epsilon_d\sqrt{x}+\gamma_d x)$$
$$xS(x, Q^2) = A_S x^{\delta_S}(1-x)^{\eta_S}(1+\epsilon_S\sqrt{x}+\gamma_S x)$$
$$x\Delta(x, Q^2) = A_\Delta x^{\eta_\Delta}(1-x)^{\eta_S+2}(1+\gamma_\Delta+\delta_\Delta x^2)$$

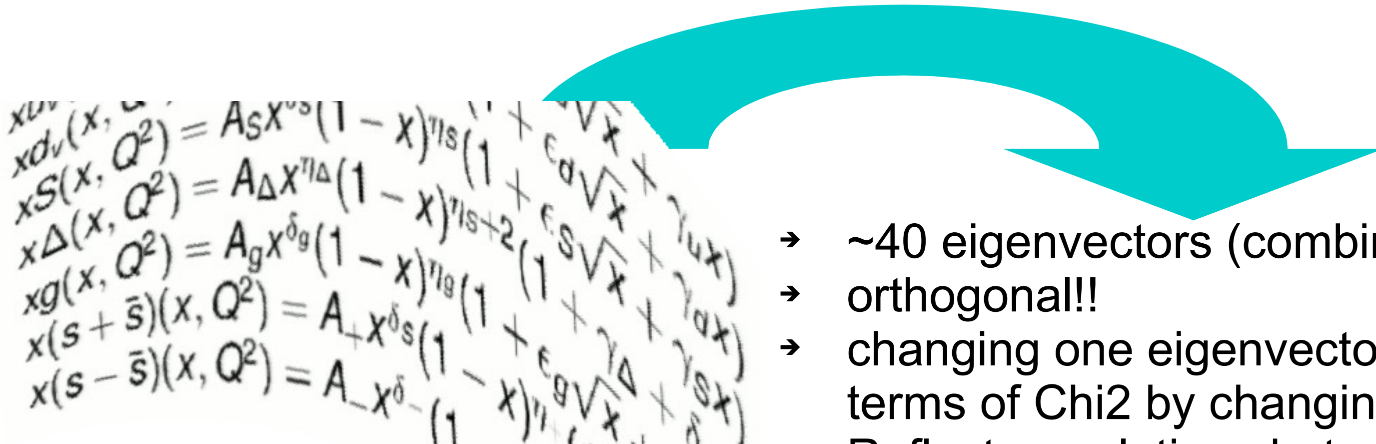
Δ = Sea asymmetry $\bar{u}$ - $\bar{d}$

$$xg(x, Q^2) = A_g x^{\delta_g}(1-x)^{\eta_g}(1+\epsilon_g\sqrt{x}+\gamma_g x) + A_{g'} x^{\delta_{g'}}(1-x)^{\eta_{g'}}$$
$$x(s+\bar{s})(x, Q^2) = A_+ x^{\delta_S}(1-x)^{\eta_+}(1+\epsilon_S\sqrt{x}+\gamma_S x)$$
$$x(s-\bar{s})(x, Q^2) = A_- x^{\delta_-}(1-x)^{\eta_-}(1+x/x_0)$$

- Create PDFs with default starting values at given scale Q^2

Error estimation

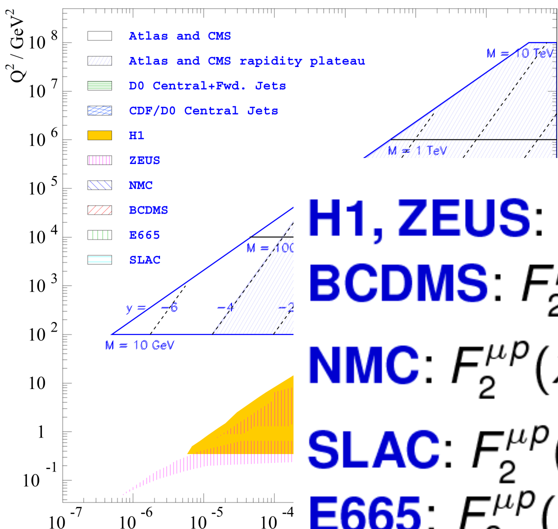
- Use **Hessian Approach** (most PDF groups):
  Transform original PDF parametrizations into eigenvector basis



- ~40 eigenvectors (combinations of PDF parameters)
- orthogonal!!
- changing one eigenvector cannot be compensated in terms of Chi2 by changing another one as well
- Reflect correlations between input observables

- Use **MC replica approach** (mostly NNPDF):
  Prepare pseudo data replicas of the input data samples, which are randomly varied within their errors,
  Fit them and extract PDF and errors from mean + RMS of replica PDFs

Kinematic phase space covered by inputs



➔ Not all experiments provide insight to all parton distributions at all x values!!

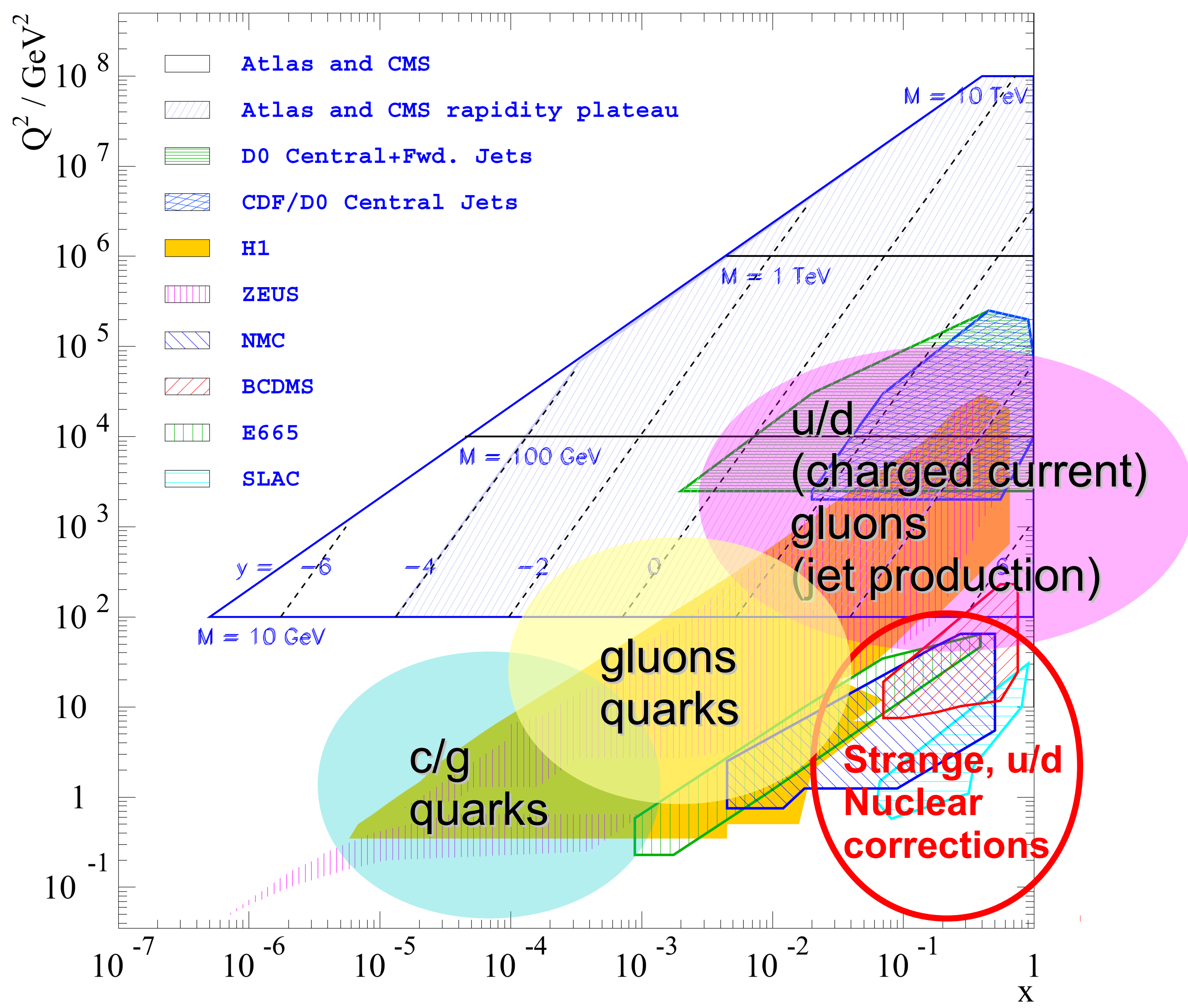
H1, ZEUS: $F_2^{e^{\pm}p}(x, Q^2)$
BCDMS: $F_2^{\mu p}(x, Q^2)$, $F_2^{\mu d}(x, Q^2)$
NMC: $F_2^{\mu p}(x, Q^2)$, $F_2^{\mu d}(x, Q^2)$, $\frac{F_2^{\mu n}(x,Q^2)}{F_2^{\mu p}(x,Q^2)}$
SLAC: $F_2^{\mu p}(x, Q^2)$, $F_2^{\mu d}(x, Q^2)$
E665: $F_2^{\mu p}(x, Q^2)$, $F_2^{\mu d}(x, Q^2)$
CCFR, NuTeV, CHORUS: $F_{2,3}^{\nu(\bar{\nu})p}(x, Q^2)$

$\Rightarrow$ q, $\bar{q}$ at all x; g at moderate and small x

E605, E702, E866: $pN \rightarrow \mu\bar{\mu} + X$ $\Rightarrow$ $\bar{q}$, (g)
E605: Drell-Yan p, n asymmetry $\Rightarrow$ $\bar{u}$, $\bar{d}$
CDF: W rapidity asymmetry $\Rightarrow$ u/d ratio at high-x
CDF, D0: Inclusive jet data $\Rightarrow$ g at high-x
CCFR, NuTeV: Dimuon data $\Rightarrow$ s, $\bar{s}$ sea

There is kinematic phase space not covered!

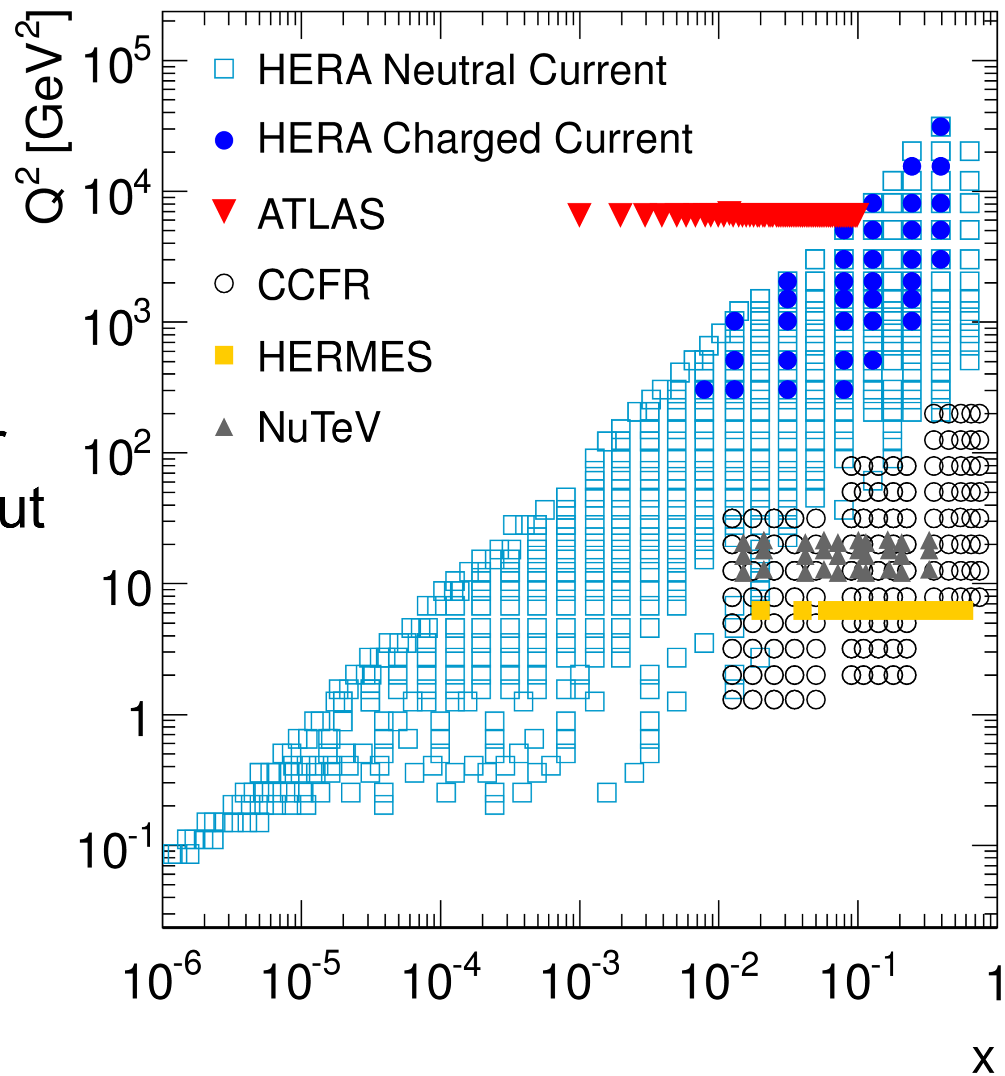
Kinematic phase space covered by inputs



Constraints on the strange quark PDF

- **HERA Neutral Current:**
  general quark, charm partons and gluon
- **HERA Charged Current:**
  down and strange partons
- **CCFR, NuTeV, HERMES:**
  strange quark PDF, large nuclear corrections or only LO theory input
- **ATLAS W/Z data:**
  new possibility to disentangle flavours, sensitivity to strange

- **Only weak constraints on the strange sea of the proton**



- PDFs are necessary input for precise predictions at hadron colliders
- Determined in global fits on data using certain assumptions
- Data does not necessarily constrain all interesting phase space
- PDF uncertainties do play a role in important measurements
  (W Mass, Higgs measurements, various searches)
- Need to improve PDFs through measurements at the LHC itself

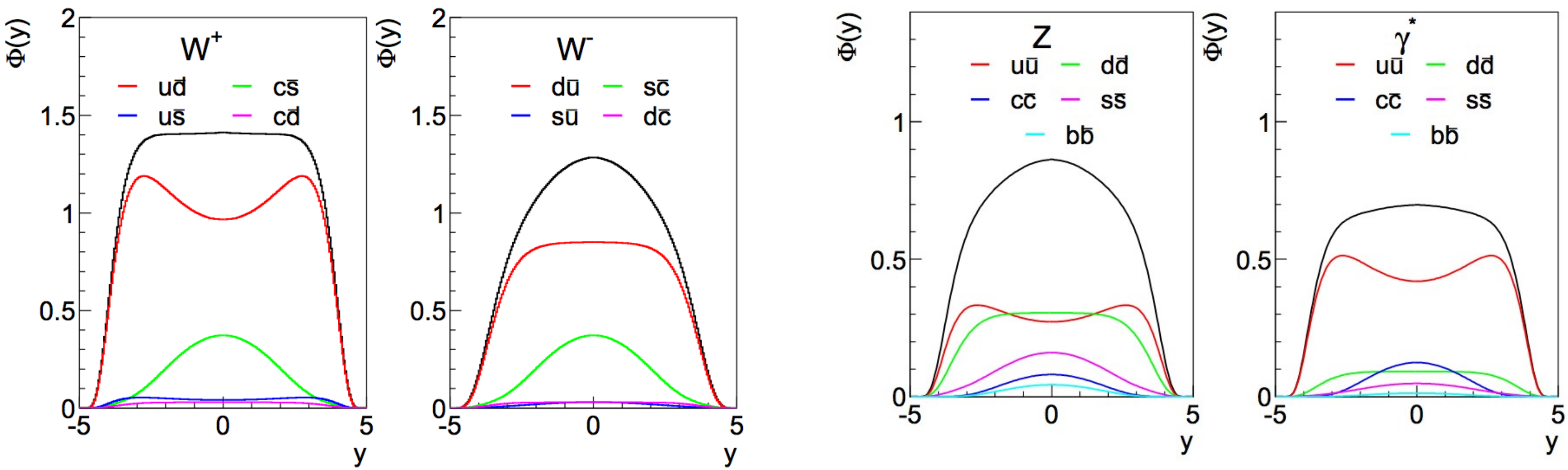
Differential cross section measurement of W and Z Bosons production

Cross section measurement of W + charm production

Determination of strange quark density

Measurement of W and Z Bosons

➔ Composition of incoming parton flavours different for W and Z production



Important for PDF fits: Precisely calculable in QCD to NNLO

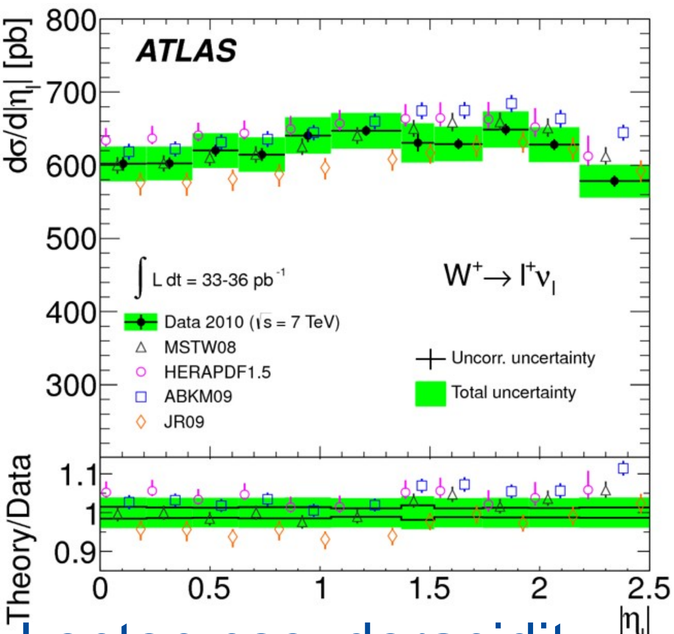
- Sensitive to u/d differences
- Boost towards high y due to u valence contribution
- Strange and charm important for production at central rapidity

Strange-induced processes contribute up to 20% !

Measurement: W/Z cross sections

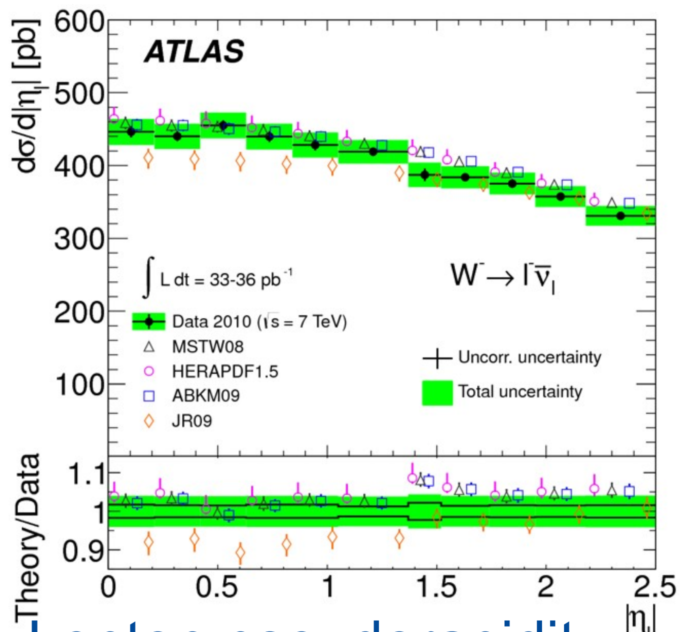
- Differential measurement with 33-36 pb^{-1} at $\sqrt{s}$ = 7 TeV
- Comparison with NNLO predictions: Good overall agreement
- Some deviations, in particular high rapidity range
- Distributions measured with bin-to-bin correlated errors, ~2% uncertainty

W^{+} Boson



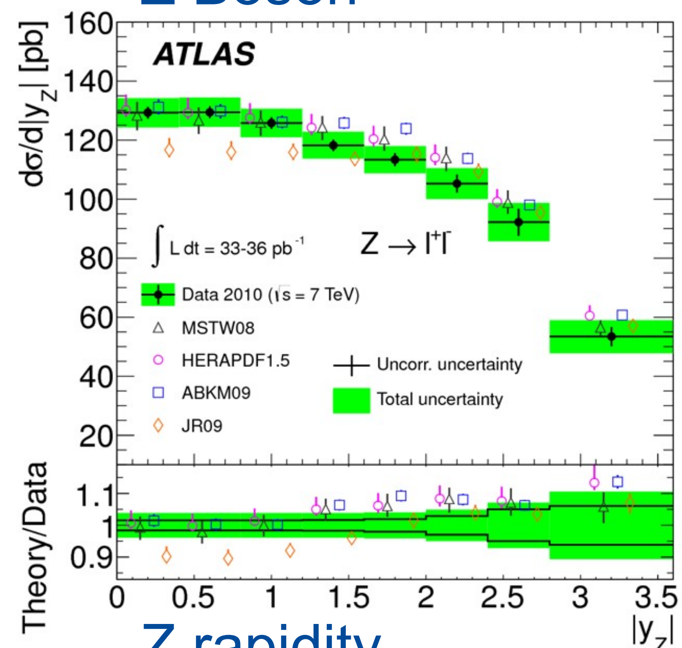
Lepton pseudorapidity

W^{-} Boson



Lepton pseudorapidity

Z Boson



Z rapidity

PDF Analysis of ATLAS W and Z data

- Fits are performed using the HERAFitter framework
  (NNLO QCD fits with variable flavour number scheme, EWK parameters in G_μ-scheme)

- Input data are
  HERA I combined data (NC + CC) **[JHEP 1001:109(2010)]**
  ATLAS W/Z data **[Phys. Rev. D85 (2012) 072004]**

Fixed strange fit

- 13 free parameters
- Fixed:
  - Fraction of strange sea to strange down quarks

$$r_s = 0.5 \frac{s + \bar{s}}{\bar{d}} = 0.5$$

global fits (CCFR, NuTev)

- $x\bar{s}(x) = xs(x)$: *no* strange asymmetry

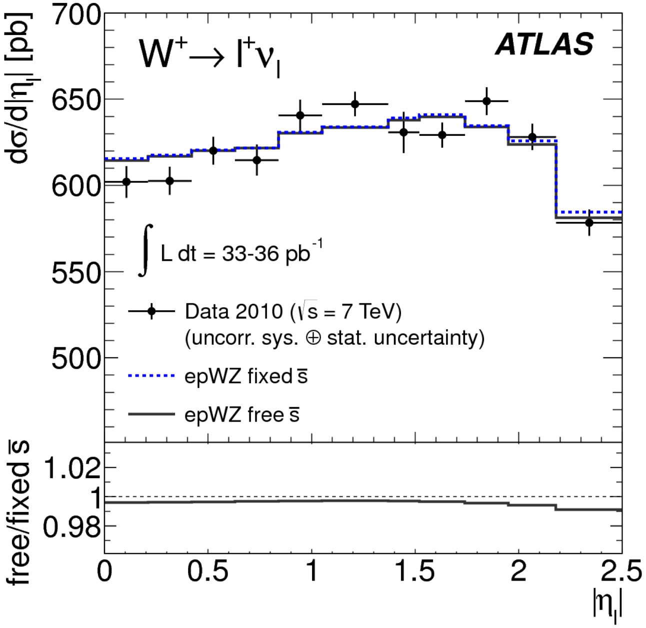
Free strange fit

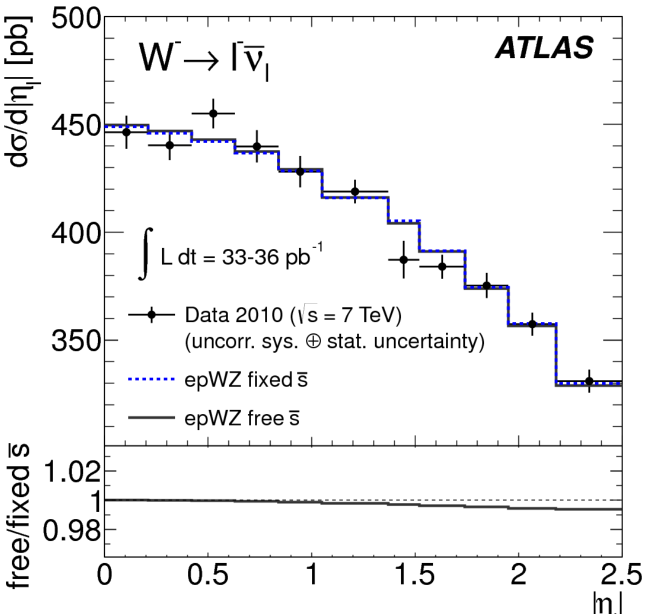
- 15 free parameters
- Strange parametrisation:

$$xq_i(x) = A_i x^{B_i} (1-x)^{C_i}$$

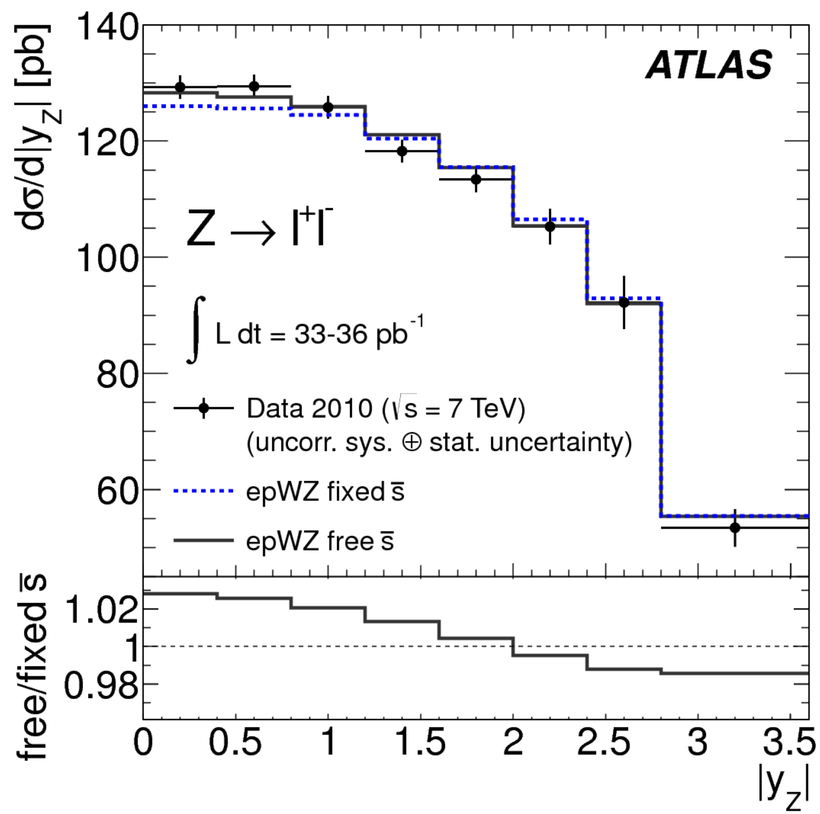
- B (slope) fixed to anti-down value
- A (normalization): free
- C (x → 1, counting rules): free
- $x\bar{s}(x) = xs(x)$: *no* strange asymmetry

Comparison of fits with ATLAS data



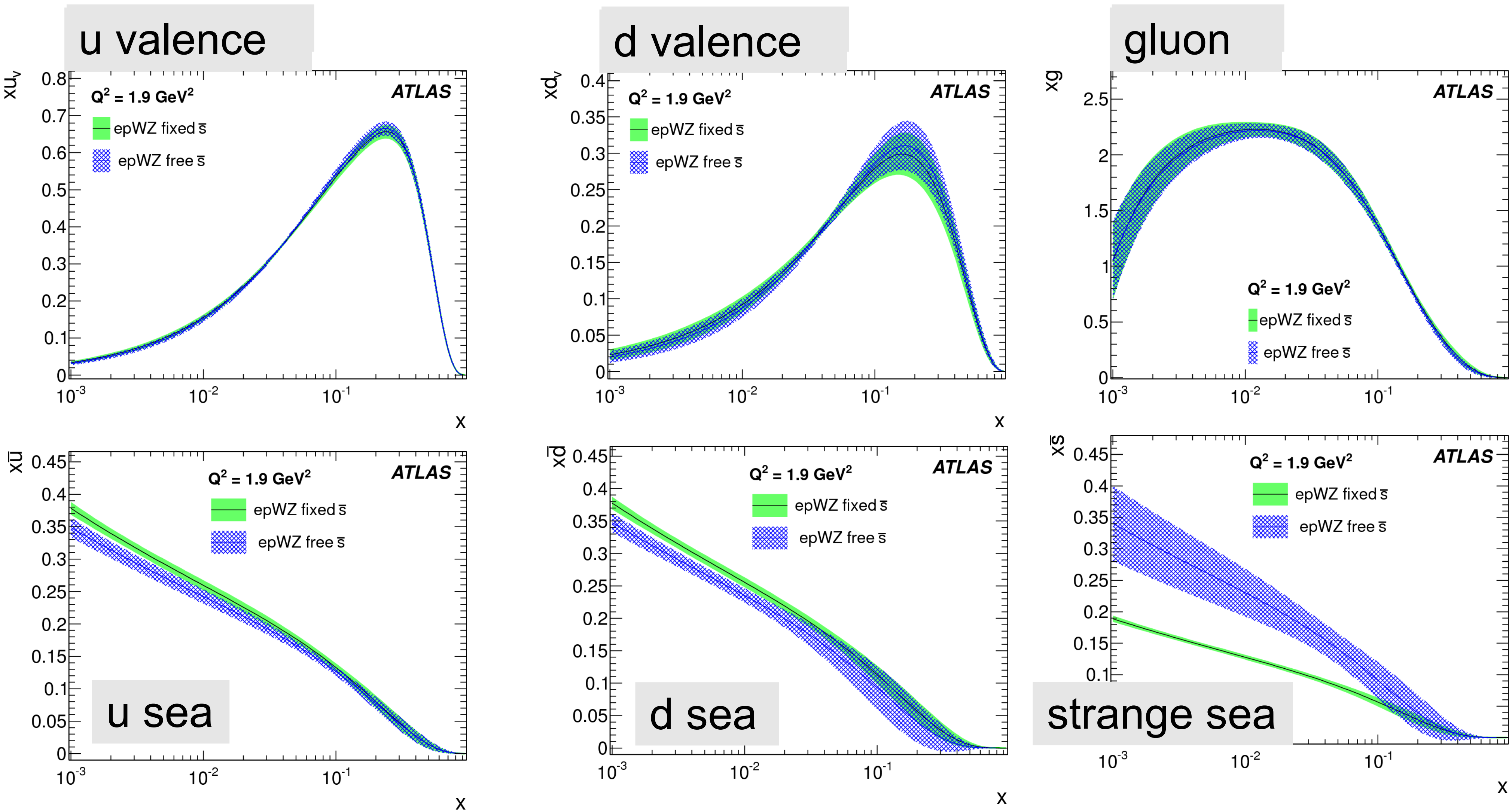


	Fixed strange	Free strange
Total χ^2/ndf	546.1 / 567	538.4 / 565
Partial χ^2**/ndf** (ATLAS only)	44.5 / 30	33.9 / 30



Results in terms of PDF distributions

- Large increase in strange sea content, while u/d sea quark slightly lower
- Other distributions remain unchanged



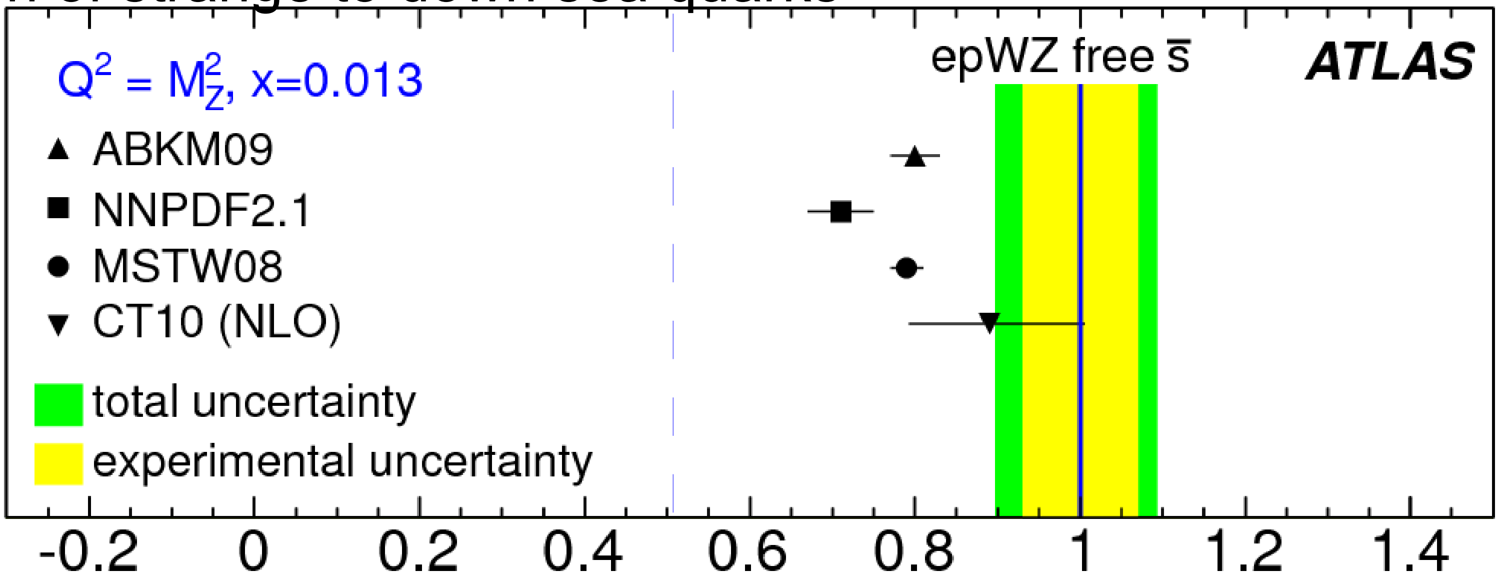
Enhanced strange contribution – at $Q^2 = M_Z$

Final results:

$$r_s = 1.00 \pm 0.20_{\mathrm{exp}} \pm 0.07_{\mathrm{mod}} {}^{+0.10}_{-0.15}{}_{\mathrm{par}} {}^{+0.06}_{-0.07}{}_{\alpha_S} \pm 0.08_{\mathrm{th}}$$

Experimental errors from data
Model uncertainty (variation of charm mass, Q^2 cut and starting scale values)
Parametrization uncertainty (additional polynomial and free slope parameter)
Variation of α_s, theoretical uncertainties on differential predictions on W/Z production

Fraction of strange to down sea quarks

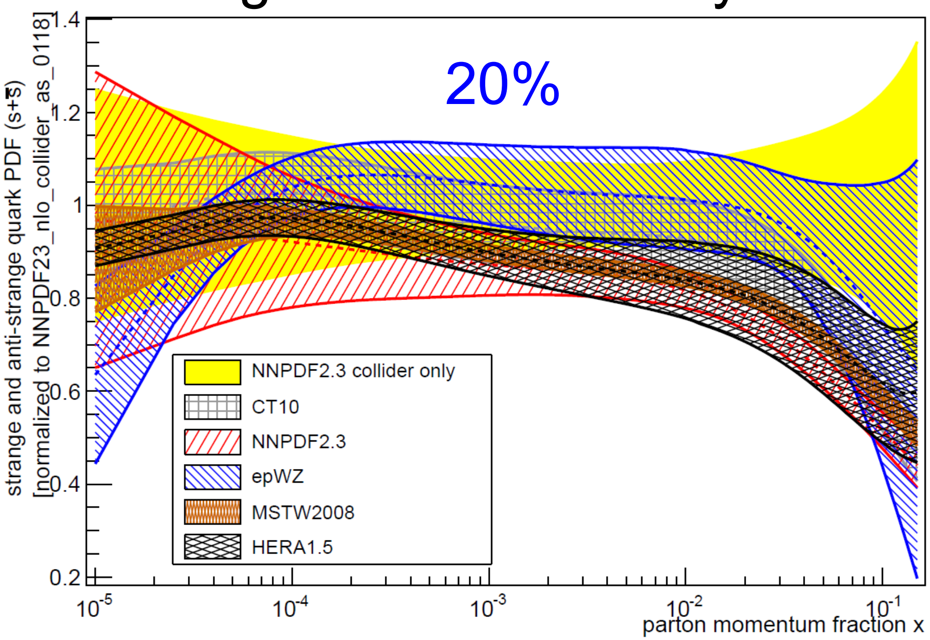


r=0.5 (fixed at Q_0)   r=1.00 (free)

$$r_s = 0.5 \frac{s + \bar{s}}{\bar{d}}$$

A quick review of the strange PDF

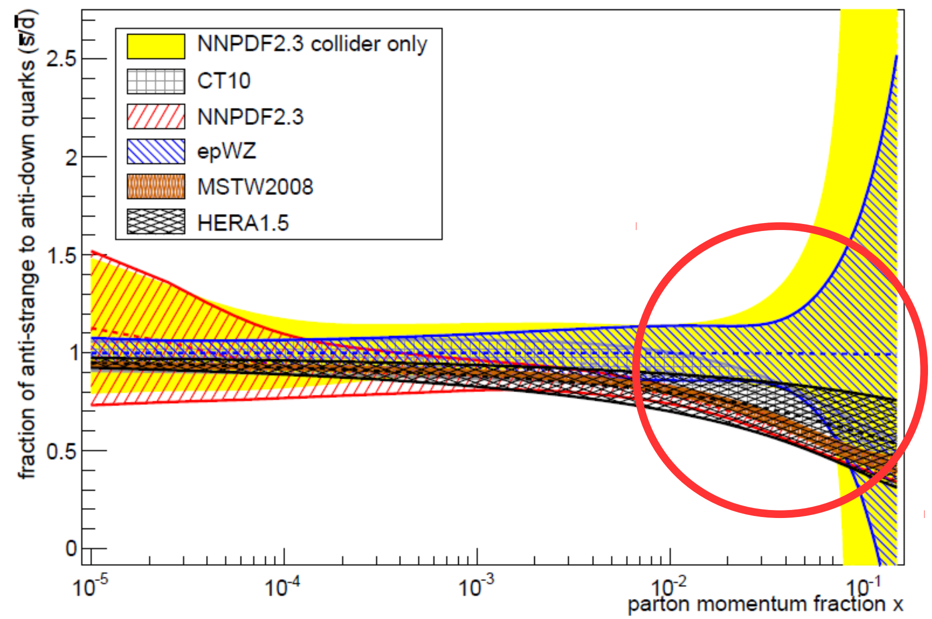
Strange PDF uncertainty



ATLAS data

Fixed target data

Anti-Strange to anti-down fraction



ATLAS data

Fixed target data

- Weak constraints in currently used data sets
  Large spread of predictions

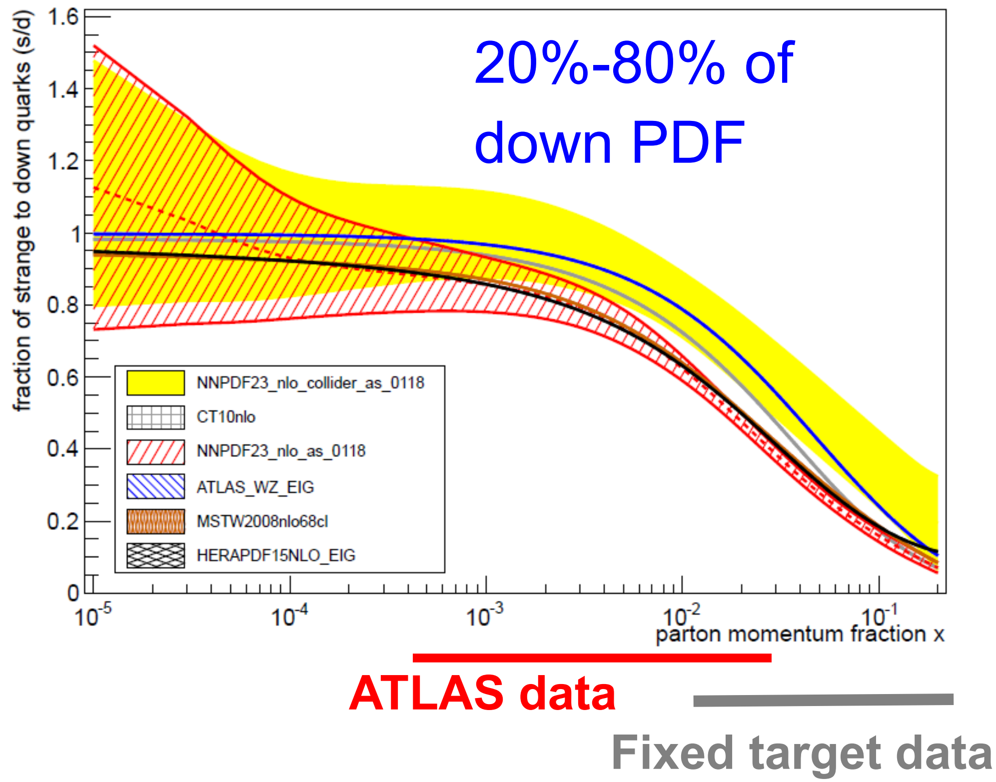
- Big difference between NNPDF sets
  (with and without low energy data)

- Frequent model assumption:
  Strange suppressed with regard to down

- epWZ (HERA+ATLAS): non suppression
- Likewise: NNPDF collider only
  (without neutrino charm low energy data)

A quick review of the strange PDF II

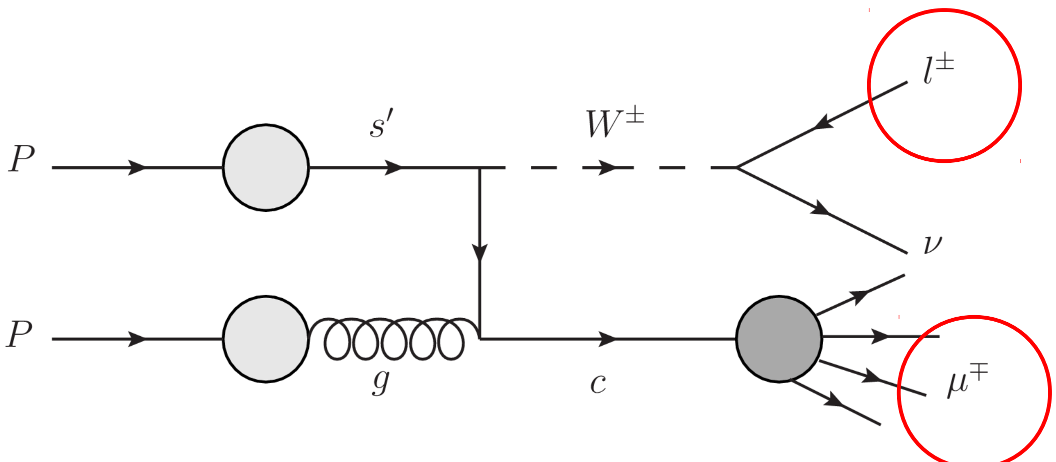
Strange to down fraction



- Even for strange in comparison to (valence) down quark large differences
- Especially visible in the LHC kinematic range

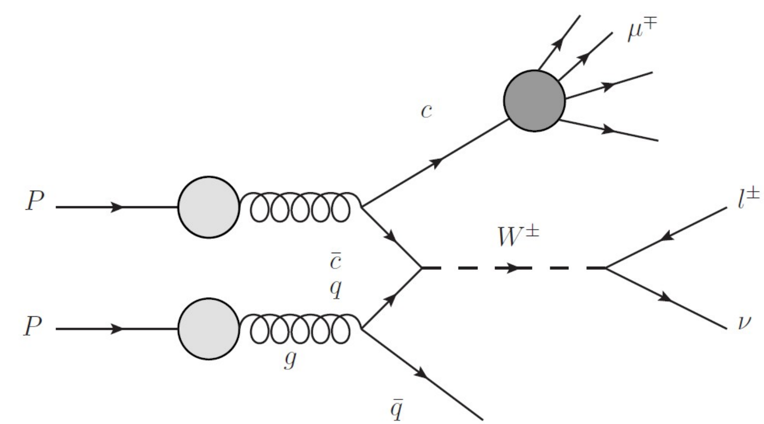
Measurement of W+charm production

- „Tagging“ the charm parton with a soft muon / D(*) Meson



Fragmentation with
semi-leptonic decay into muon /
reconstruction of D(*) meson

- Opposite sign of muon / D(*) meson and W decay lepton → signal extraction! cancels symmetric backgrounds (e.g. gluon splitting, g → $c\bar{c}$)

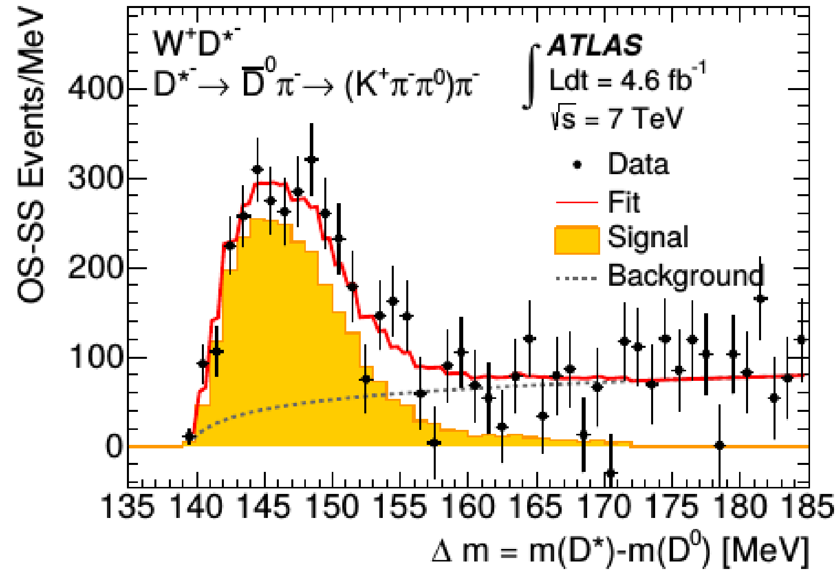


- LO order production of W+c via gluon-quark fusion: g+s or g+d

- NLO processes: higher number of jets additional to charm jet
  other incoming parton combinations possible

W+charm selections

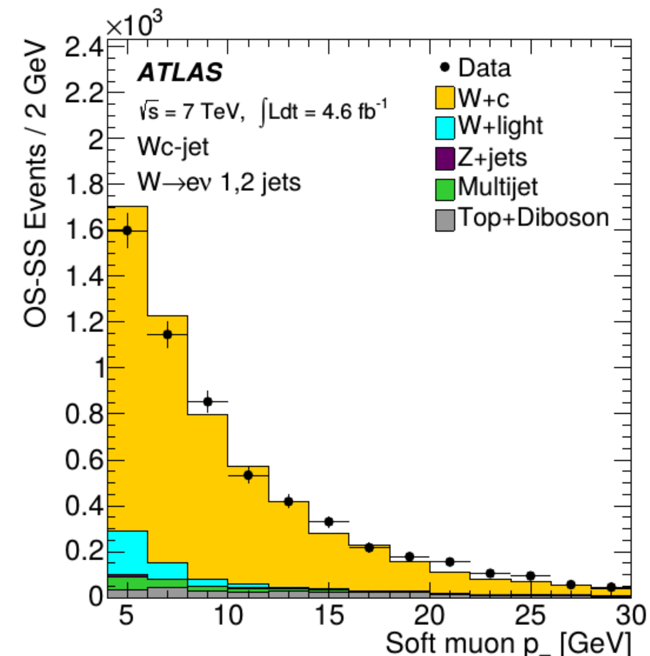
- **Usual W selection (slightly larger than CMS)**
  - **p_T > 20 GeV**
  - **E_T^{Miss} > 25 GeV**
  - **m_T > 40 GeV**



- **Charm selection**
  - **W+c:** μ>4 GeV inside jet (p_T > 25 GeV, |η|<
  - **W+D$^{(*)}$:** D(*) p_T> 8 GeV, |η|<2.2

- **Inclusive and differential**
  - **W+c:** same binning as for W/Z analysis
  - **W+D$^{(*)}$:** coarser, merged binning (4 bins)

Luminosity of 4.46fb^{-1} (1.8% uncertainty)



- **c-Jets:** Extrapolated from <3 jet events (to reject $t\bar{t}$) corrected for semileptonic branching ratio. Any c-hadron with p_T > 5 GeV inside jet

- **D-mesons:** Using following decay modes:

$D^{*+} \to D^0 \to K^-\pi^+$

$\to K^-\pi^+\pi^0$

$\to K^-\pi^+\pi^+\pi^-$

Comparison to predictions

Predictions with aMC@NLO

Showered with Herwig++ v 2.6.3

Generated with CT10 NLO PDF

Predictions for other PDFs obtained by PDF reweighting (68% uncert. level)

Charm fragmentation fractions

rescaled to LEP/HERA measurements according to Ref.arXiv:1112.3757

Charm fragmentation function validated by generating e^+e^- events and comparing to LEP/BELLE data

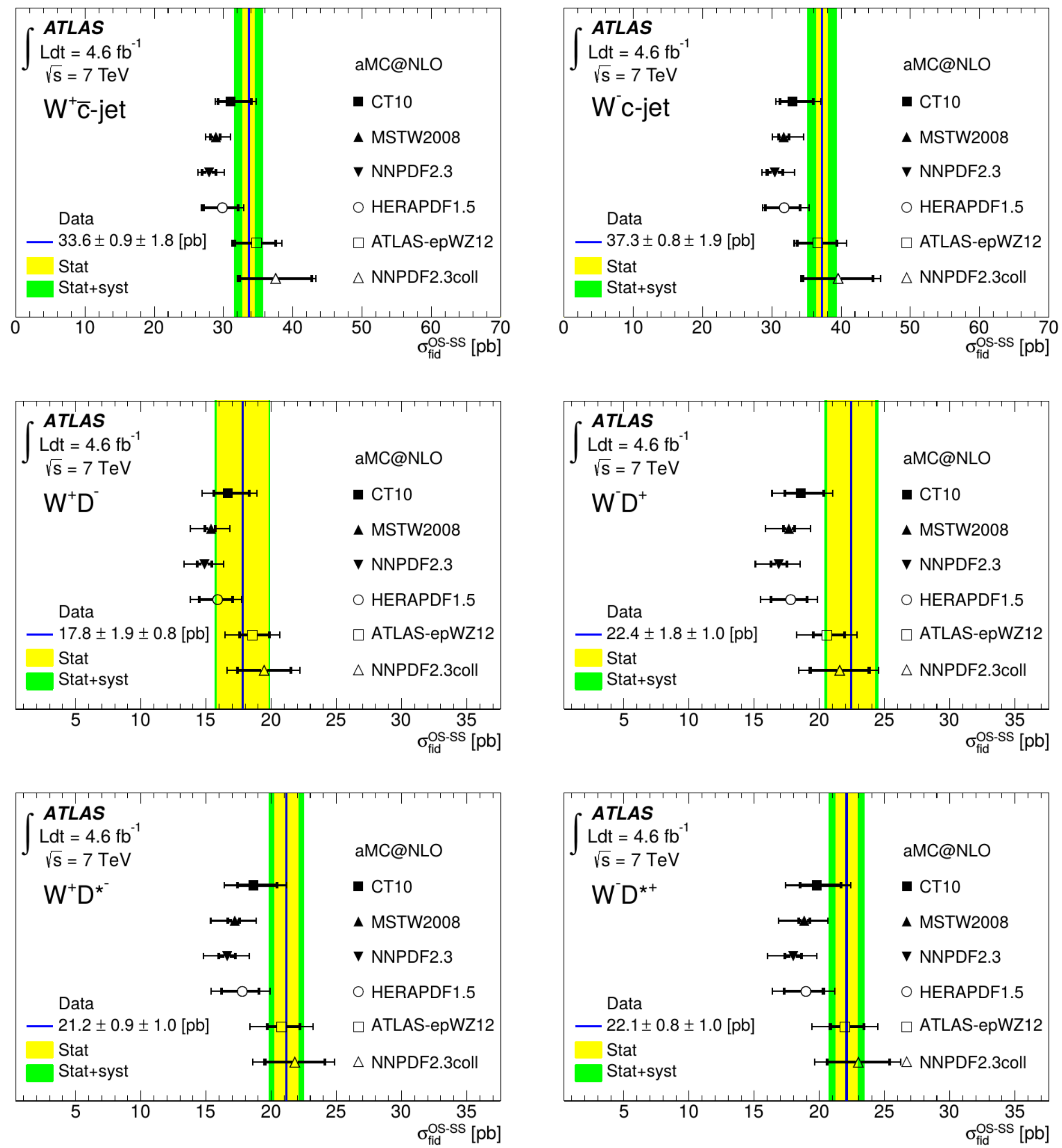
Scale

Variation of μ_R and μ_F: from ½μ to 2μ

Investigated on total+fiducial cross sectior aMC@NLO and MCFM

Parton shower

Compare Pythia to Herwig++



Crucial difference to CMS measurement:
No Particle → Parton corrections

Evaluation of PDFs

Quantitative comparison with of measurements with predictions

using extended χ^2 formalism, taking into account theory predictions

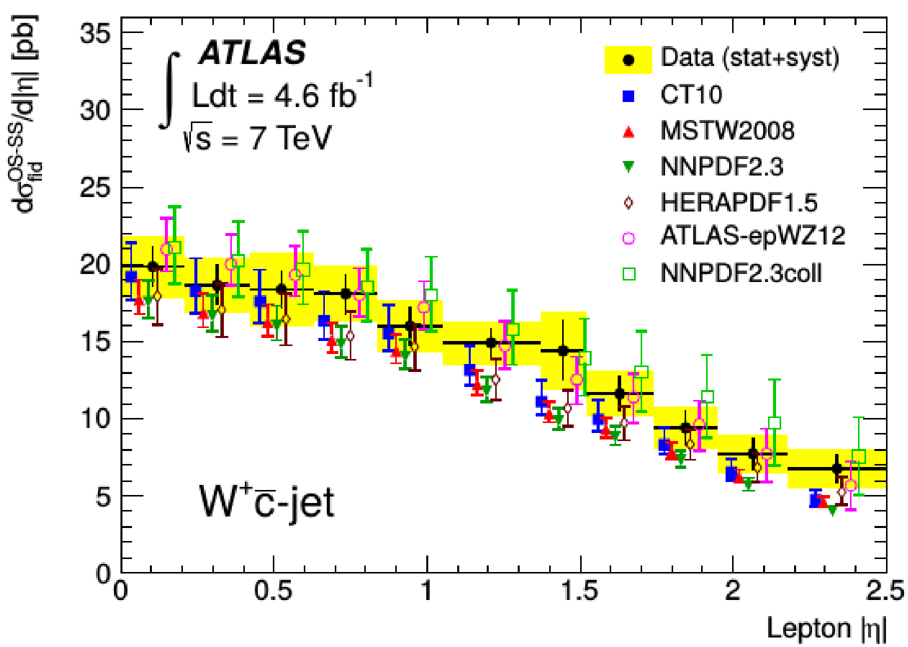
$$\chi^2 = \sum_{k,i} w_k^i \frac{\left[\mu_k^i - m^i\left(1 + \sum_j \gamma_{j,k}^i b_j + \sum_j (\gamma^{\rm theo})_{j,k}^i b_j^{\rm theo}\right)\right]^2}{(\delta_{{\rm sta},k}^i)^2 \Delta_i^k + (\delta_{{\rm unc},k}^i m^i)^2} + \sum_j b_j^2 + \sum_j (b_j^{\rm theo})^2,$$

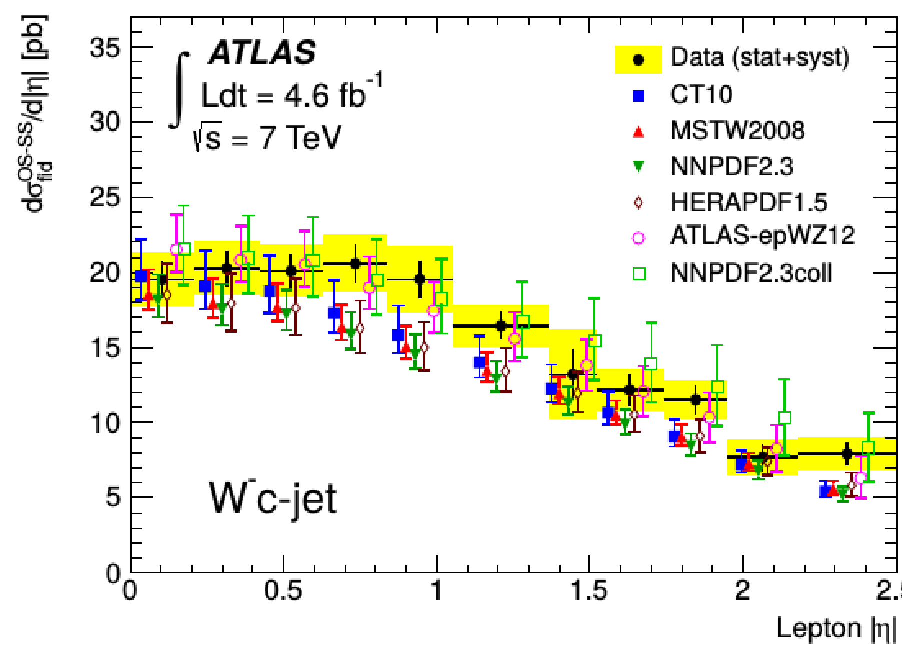
With $\Delta_i^k = \mu_k^i m^i \left(1 - \sum_j \gamma_{j,k}^i b_j - \sum_j (\gamma^{\rm theo})_{j,k}^i b_j^{\rm theo}\right)$

matrix $(\gamma^{(\rm theo)})^i_{j,k}$ represents relative correlated systematic uncertainty j on theory predictions

(→ single PDF eigenvectors, fragmentation, scale uncertainty) in bin i for dataset k

Fit minimizes b_j and $b_j^{\rm theo}$ – measured cross sections are fixed





Comparison to predictions

	CT10	MSTW2008	HERAPDF1.5	ATLAS-epWZ12	NNPDF2.3	NNPDF2.3coll
$W^+\bar{c}$-jet (χ^2/ndof)	3.8/11	6.1/11	3.5/11	3.1/11	8.5/11	2.9/11
W^-c-jet (χ^2/ndof)	9.0/11	10.3/11	8.3/11	6.3/11	10.5/11	6.1/11
W^+D^- (χ^2/ndof)	3.6/4	3.7/4	3.7/4	3.4/4	3.8/4	3.4/4
W^-D^+ (χ^2/ndof)	3.7/4	4.6/4	3.3/4	2.0/4	4.7/4	1.6/4
W^+D^{*-} (χ^2/ndof)	2.9/4	6.0/4	2.2/4	1.7/4	8.1/4	1.6/4
W^-D^{*+} (χ^2/ndof)	3.0/4	4.4/4	2.4/4	1.6/4	4.2/4	1.4/4
N_{exp}	114	114	114	114	114	114
N_{theo}	28	22	16	20	40	40
Correlated χ^2 (exp)	0.8	1.8	0.9	1.1	2.2	1.0
Correlated χ^2 (theo)	6.2	1.9	2.6	0.1	7.4	0.2
Correlated χ^2 (scale)	0.6	2.5	1.1	0.0	2.7	0.0
Total χ^2/ndof	33.6/38	41.3/38	28.0/38	19.2/38	52.1/38	18.2/38

Nexp = number of nuisance parameters for experimental systematic uncertainties
Ntheo = number of nuisance parameters for theoretical systematic uncertainties
correlated χ^2 for the sources

PDF generally in agreement with measurement, NNPDF2.3 is disfavoured

Scale uncertainty dominant for MSTW and NNPDF

→ theoretical improvements needed

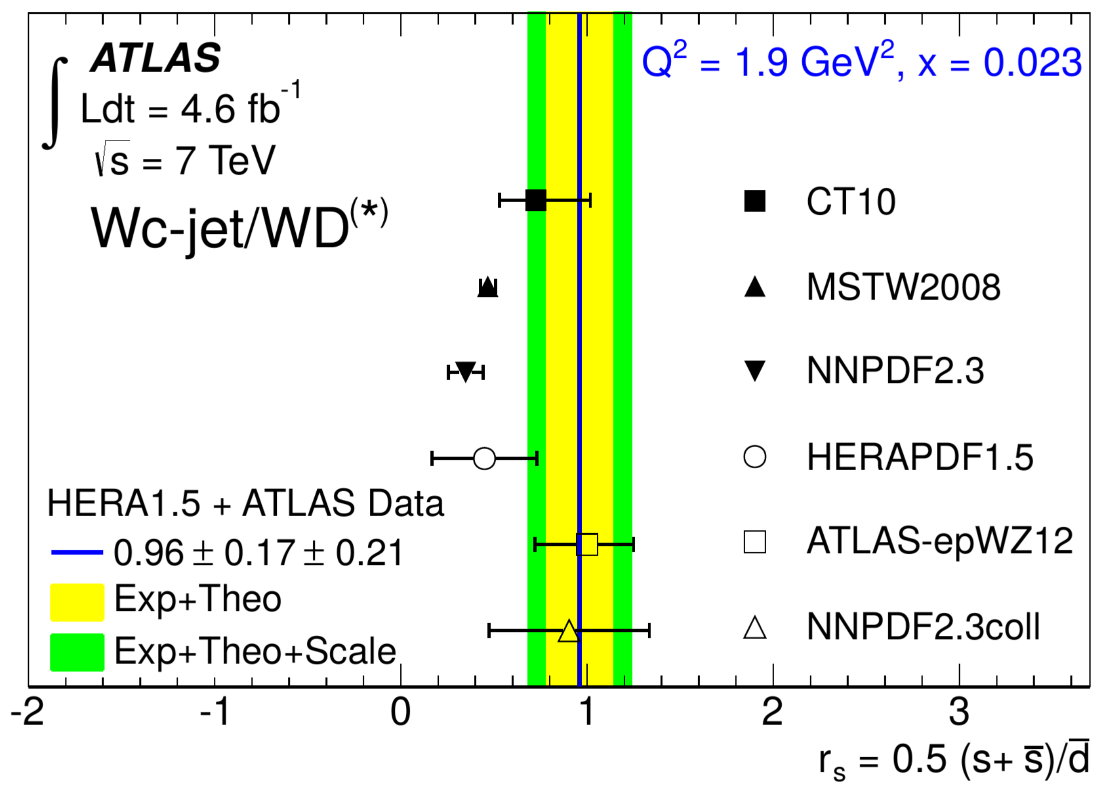
Analysis of parameter r_s

- Ratio of strange to down sea quarks is regulated in HERA PDF by one single parameter (PDF eigenvector: f_s)

- Analyze shift in f_s eigenvector in fit when comparing with data
  → Free fit of strange to down sea content of proton

$$r_s \equiv 0.5(s+\bar{s})/\bar{d} = f_s/(1-f_s) = 0.96\,^{+0.16}_{-0.18}\,^{+0.21}_{-0.24}$$

Confirms previous ATLAS findings from 2010 (W/Z fit)



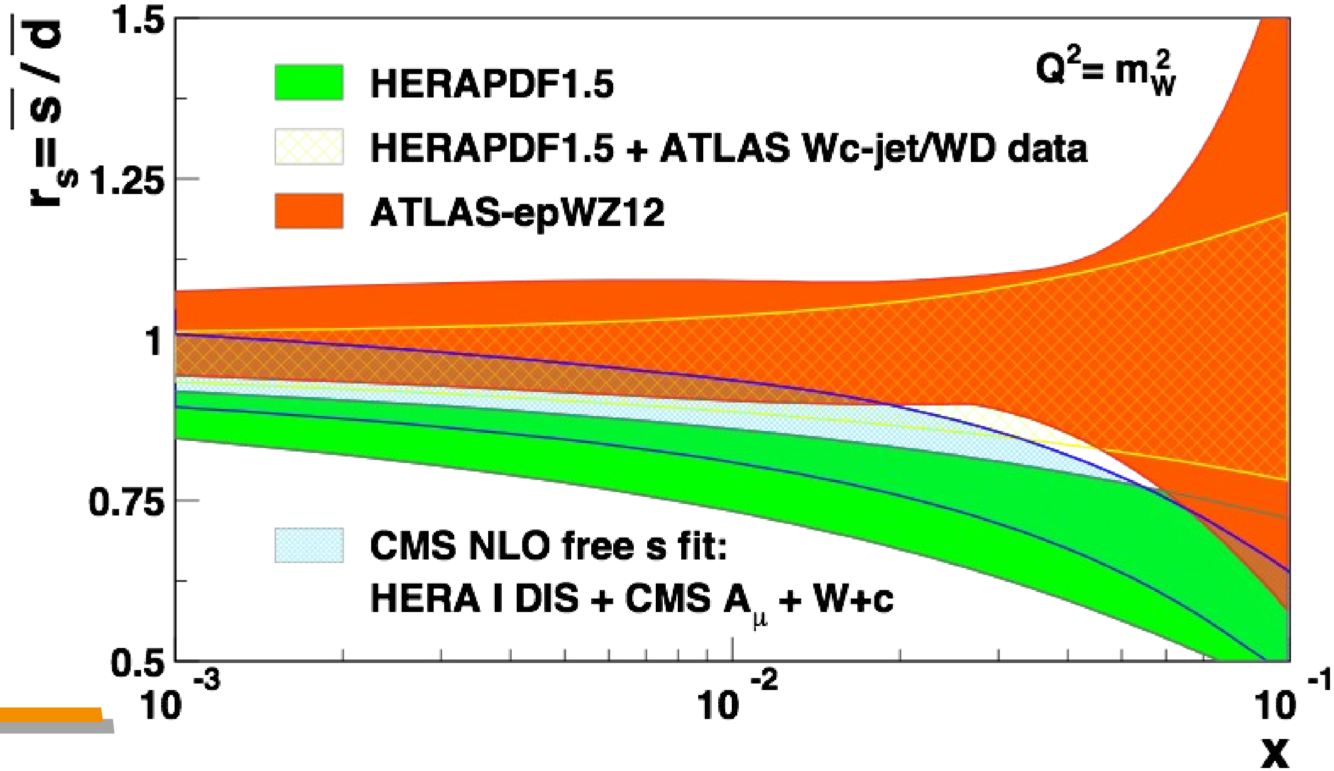
Data publish on HEPData:
http://hepdata.cedar.ac.uk/view/ins1282447

Comparison with CMS findings

- CMS published a similar measurement with subsequent PDF analysis:
  combining W→μν charge asymmetry (no E_T^{Miss} cuts, p_T>25 GeV, |η|<2.4)

  and W+c/D(*) analysis (no E_T^{Miss} cuts, p_T>35 GeV, |η|<2.1, m_T>40/55 GeV)
  → *some kinematic phase space differences (also for c-decays)*

  Anti-kT **parton** level jets with ΔR=1.0 (vs Anti-kT, ΔR=0.4 **particle** jets)



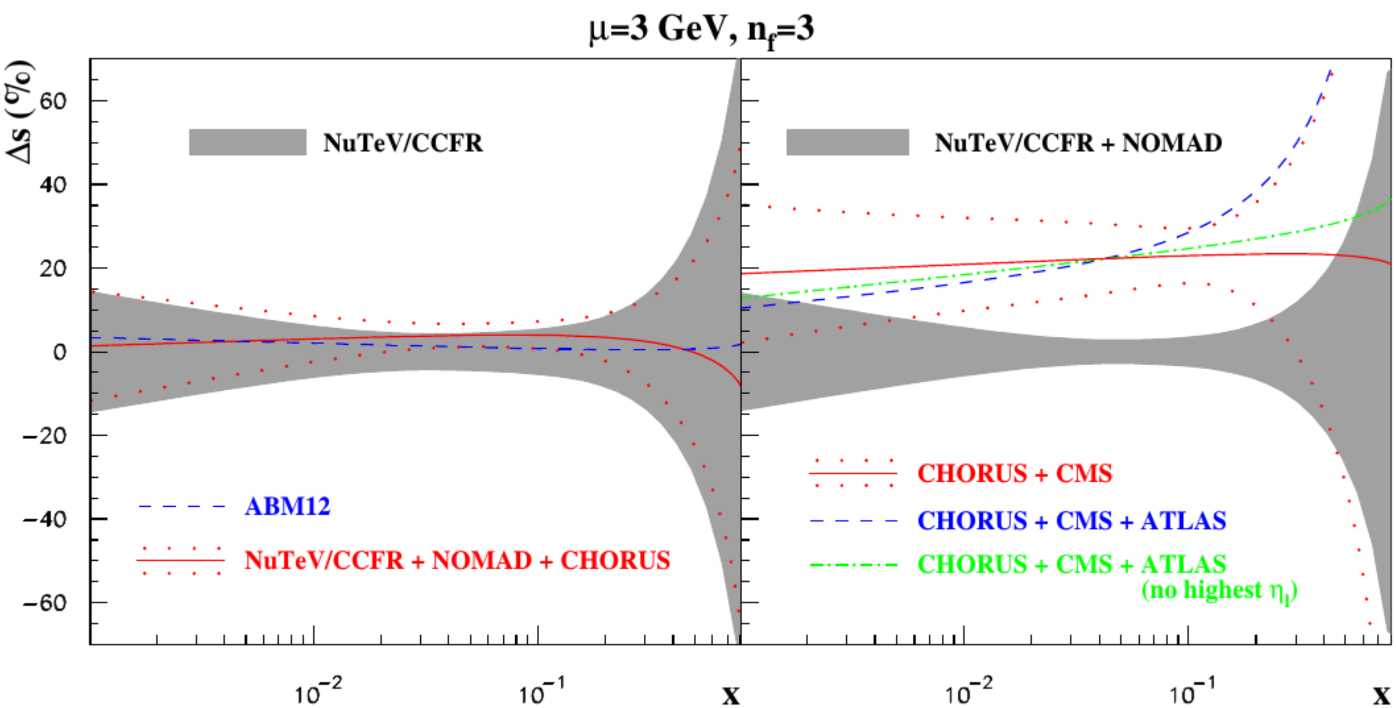
Strange supression still evident for CMS fit

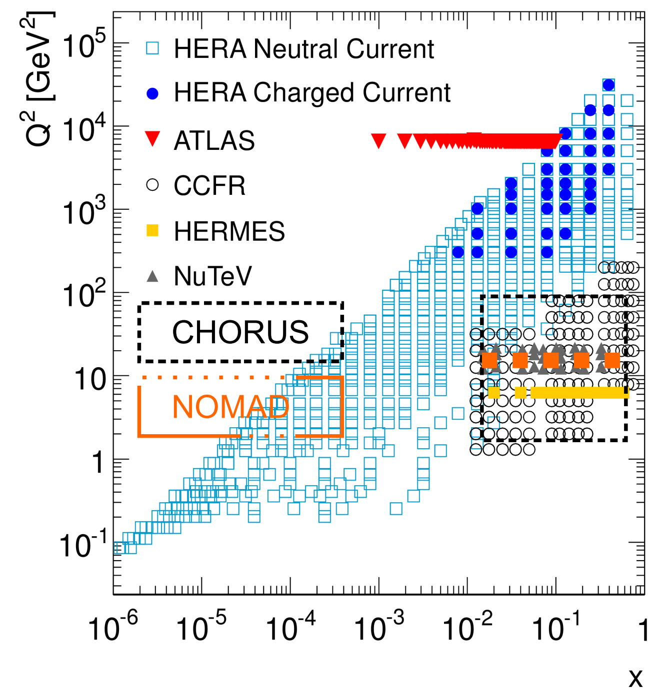
(~same settings as for ATLAS fit)

Common χ^2 fit of ATLAS and CMS data

- ABM fitting group: Study of strangeness using fits to new low energy data (CHORUS and NOMAD)

- Comparison to ATLAS and CMS W+c results using χ^2 formalism [arXiv:1310.3059]





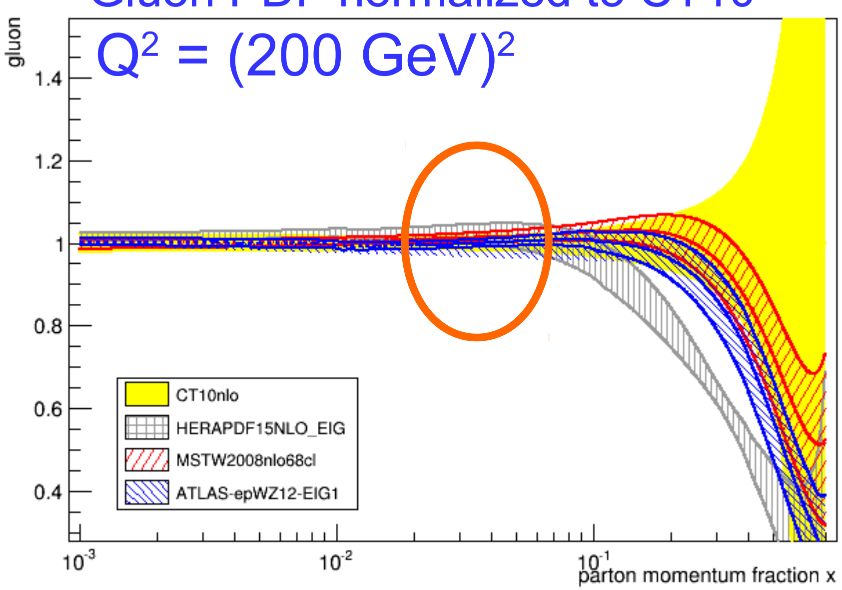
- Fits incorporating ATLAS and CMS data are compatible
  Highest |η| bin (2.18-2.50) ~outside CMS range

- **Tensions with low energy data sets**

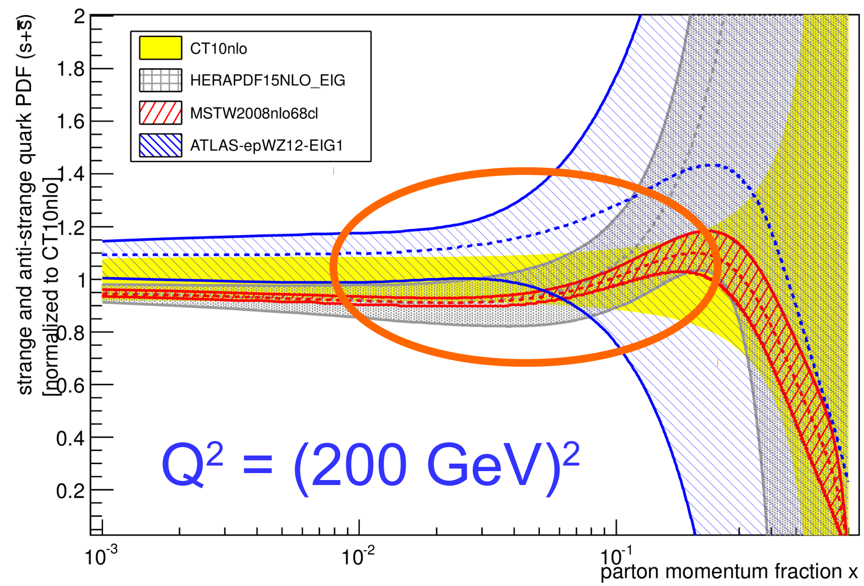
Is this relevant at all?

- YES!!! The LHC has discovered a new boson – the Higgs particle
- ATLAS and CMS are searching for further new resonances and aim to measure diboson production precisely
- Higgs production at $Q^2 \sim (200\text{ GeV})^2 \rightarrow$ for central production x~0.25

Gluon PDF normalized to CT10



strange PDF normalized to CT10



Summary

- PDF uncertainties do play a role in important measurements
- Need better constraints for measurements at the LHC
- Need to measure PDFs at the LHC itself
- Not a trivial task!
  High precision needed!
  Account for correlations between measurements (biases in the global fits)
- These are improtant measurements!
  Improvements in PDFs have direct impact on all other measurements

More controversy

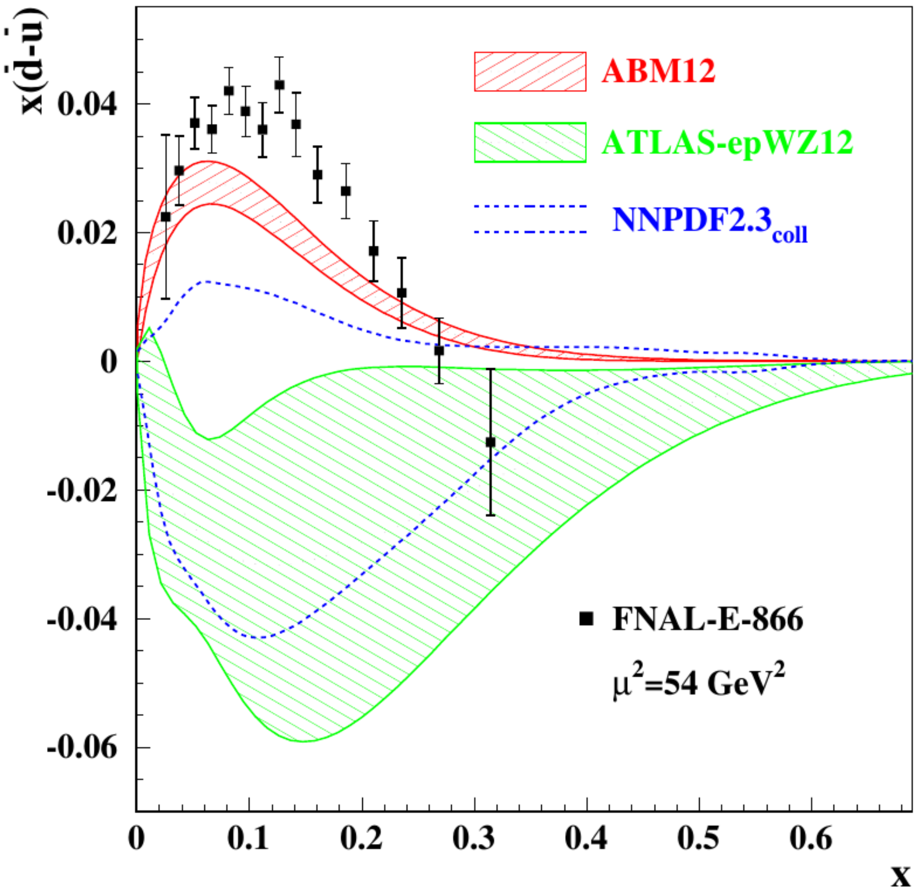
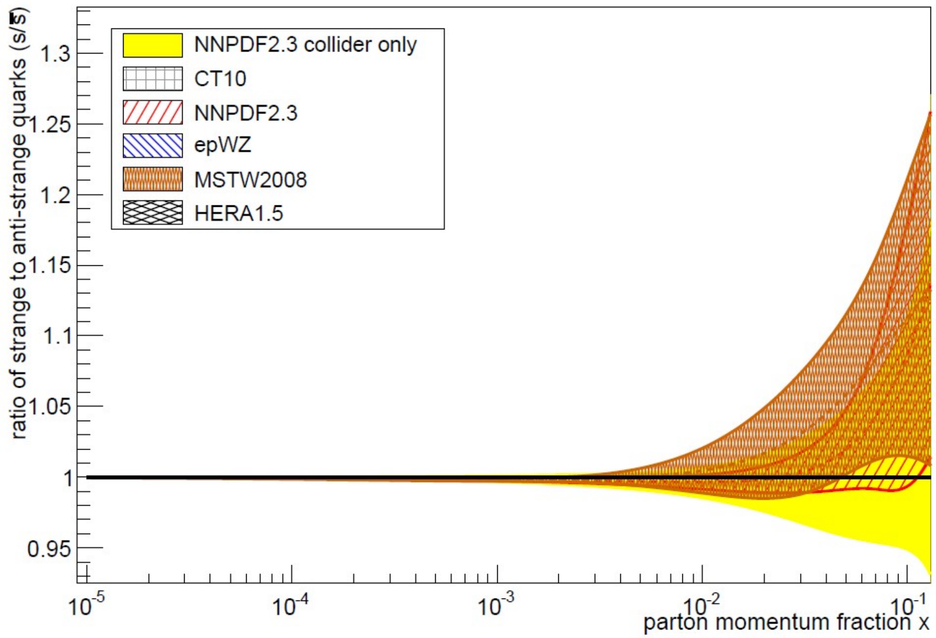


FIG. V.2: The 1σ band for sea iso-spin asymmetry $x(\bar{d}-\bar{u})$ at the scale of $\mu^2 = 54$ GeV^2 versus x obtained in the ABM12 t (right-tilted hatch) in comparison to ones obtained by ATLAS [9] (left-tilted hatch) and NNPDF [15] (dashes) using the LHC and HERA collider data only as well as to the values of $x(\bar{d}-\bar{u})$ extracted from the FNAL-E-866 data [48] within the Born approximation (points).

Strange asymmetry

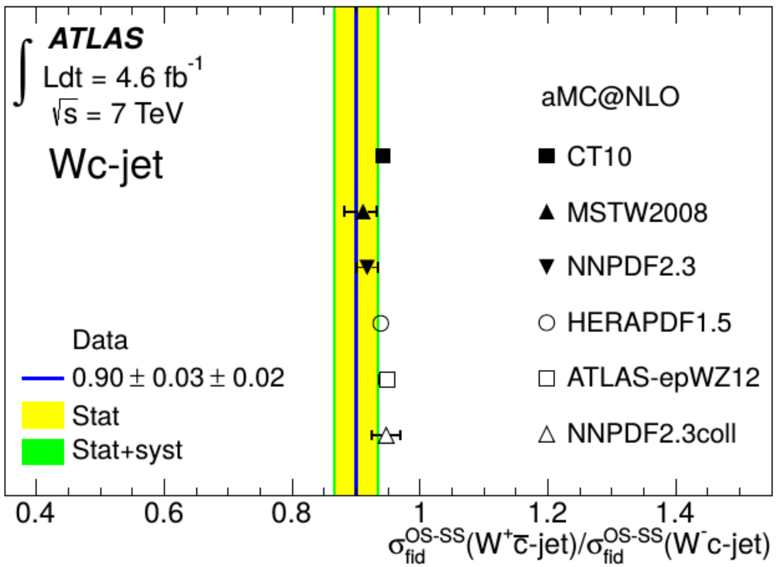


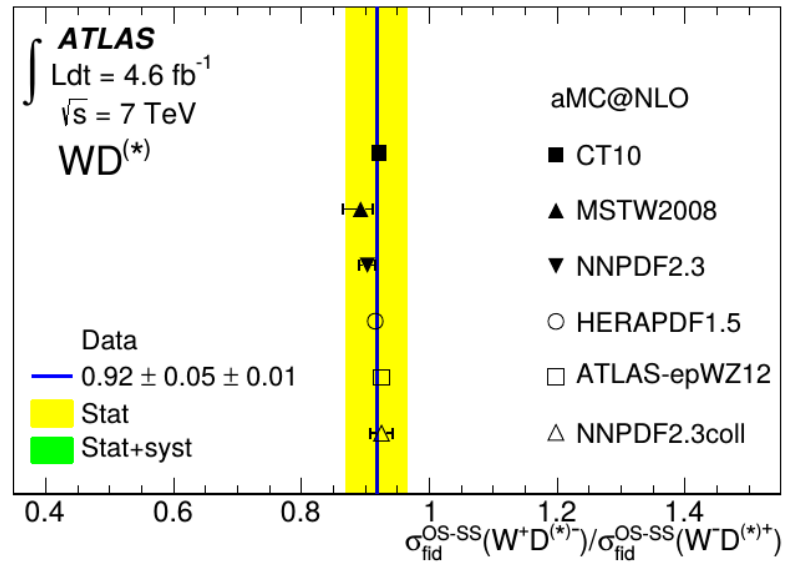
- CT10, Hera and epWZ have symmetric strange PDF
- Asymmetry allowed for NNPDF and MSTW
  coming from CCFR and NuTeV data (68% C.L.)

- Combined W+c/D(*) results will be sensitive for more statistics (2012)

Ratio measurement

- PDFs are limiting factor to many measurements
  Previous studies, W mass determination





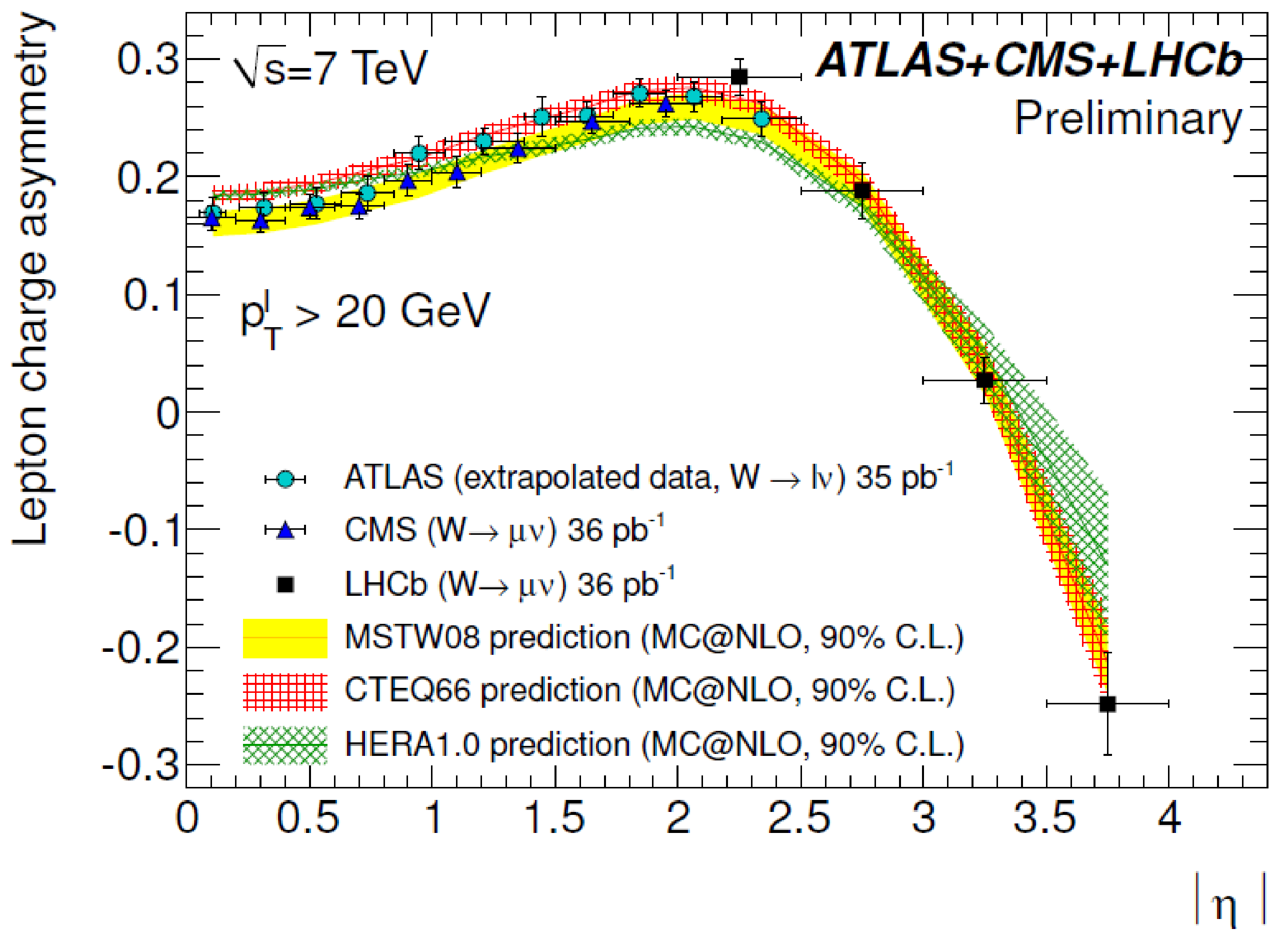
Ratio W+/W- is smaller than 1
due to valence down contribution
Deviation of predicted value might be
due to strange sea asymmetry
Take CT10 prediction (no asymmetry)
→ get estimate of sensitivity

$$A_{s\bar{s}} = (2 \pm 3)\%$$

	$\sigma_{\rm fid}^{\rm OS-SS}(WD^{(*)})/\sigma_{\rm fid}(W)$ [%]
W^+D^-	0.55 ± 0.06 (stat) ± 0.02 (syst)
W^+D^{*-}	0.66 ± 0.03 (stat) ± 0.03 (syst)
W^-D^+	1.06 ± 0.08 (stat) ± 0.04 (syst)
W^-D^{*+}	1.05 ± 0.04 (stat) ± 0.05 (syst)

TABLE X. Measured fiducial cross-section ratios $\sigma_{\rm fid}^{\rm OS-SS}(WD^{(*)})/\sigma_{\rm fid}(W)$ together with the statistical and systematical uncertainty.

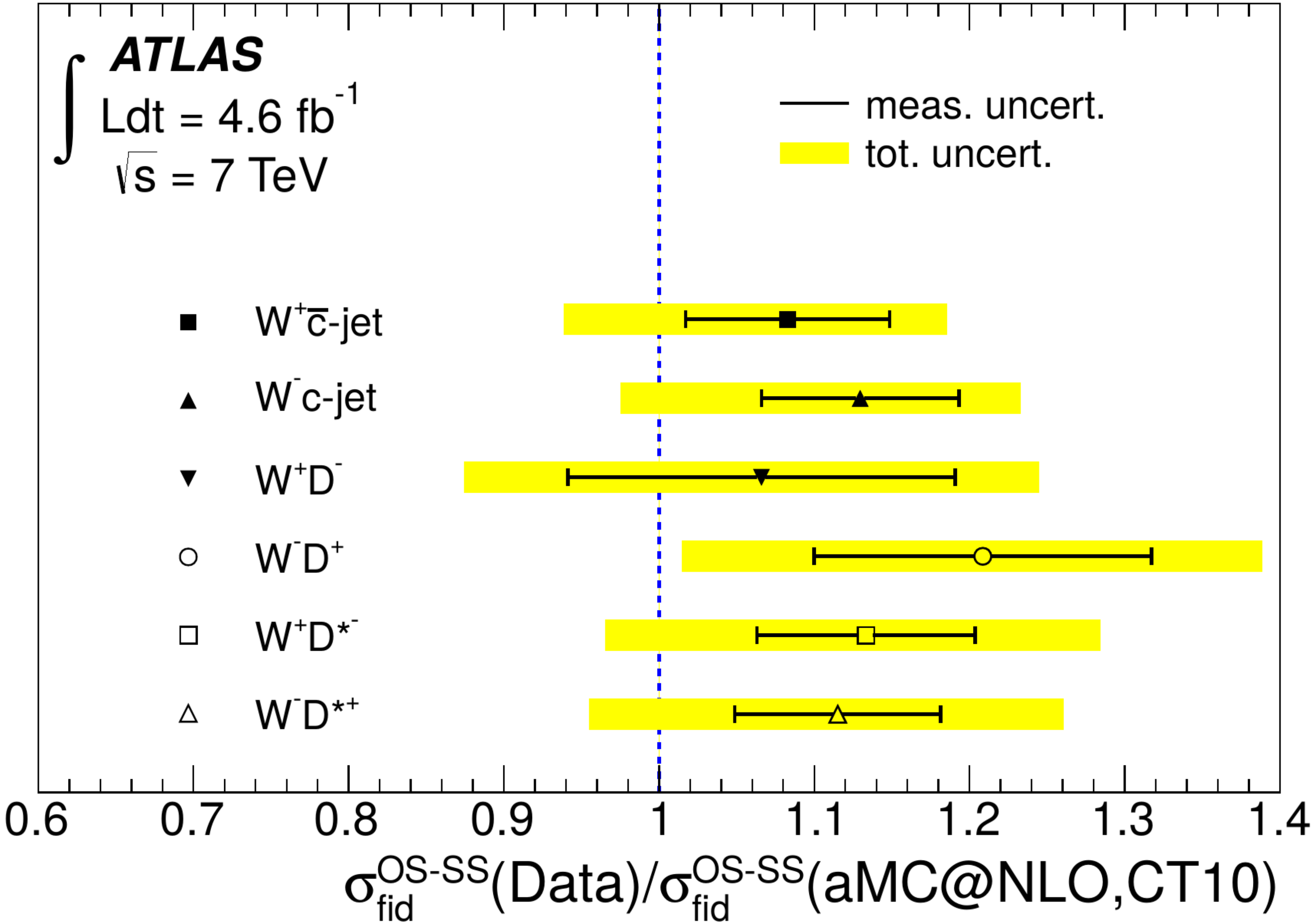
A measurement over the full LHC range



[ATLAS-CONF-2011-129]

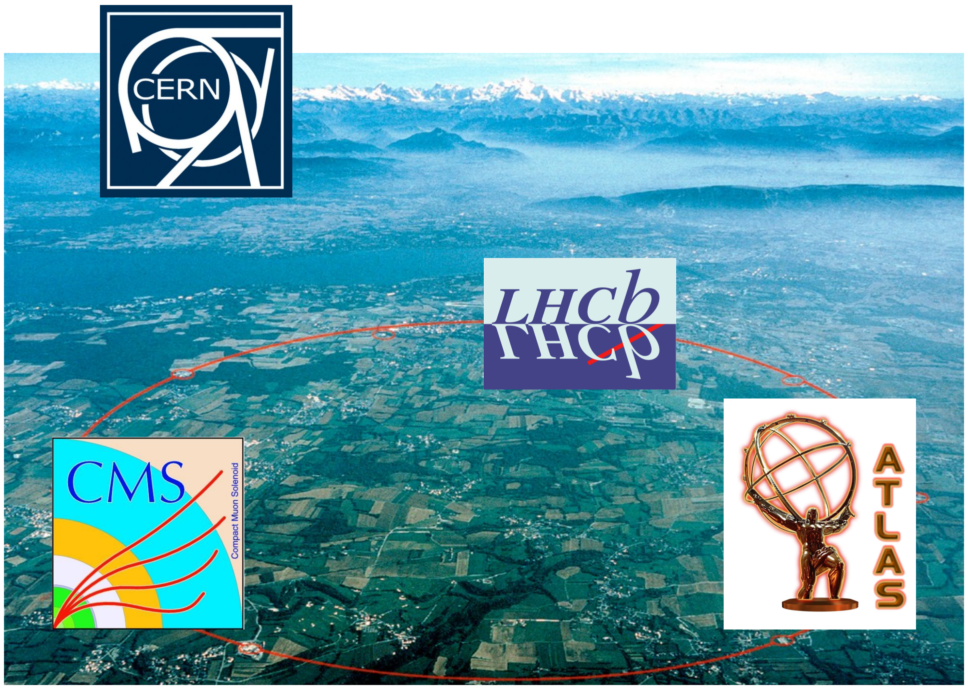
- LHCb Collaboration measures W and Z production at high rapidity
- Sensitive to the extreme x-range
- LHC electro weak working (LHC-EWWG) coordinates 2011 measurements
  (consistent treatment of correlations, uncertainties, etc.
  successfull example: **Combined HERA data**)

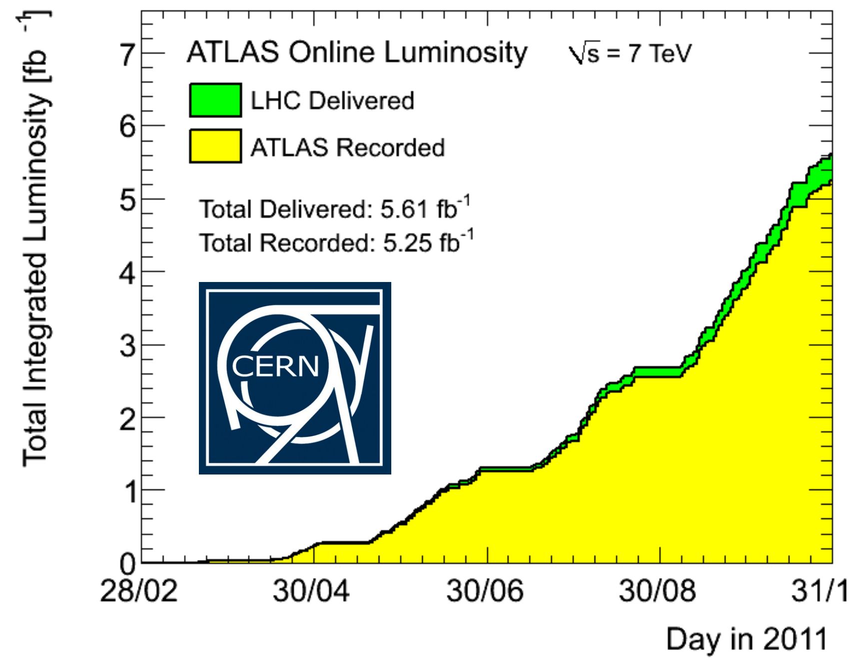
Backup slides



Preliminary results for W+c

New data from the LHC





p-p collider

Data taking since march 2010 at

$\sqrt{s}$ = 7 TeV

(8 TeV since this year)

<u>LHC</u>

2010: Integrated luminosity ~45 pb^{-1}

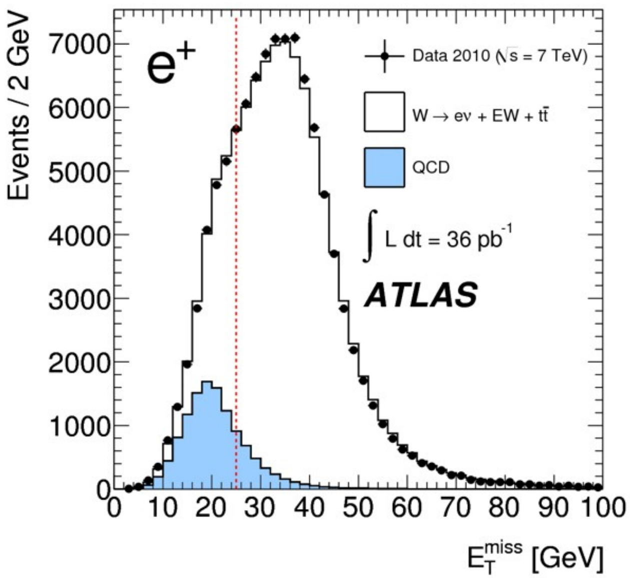
2011: Integrated Luminosity ~5 fb^{-1}

LHCb: ~ 1 fb^{-1}

2012: Integrated Luminosity ~20 fb^{-1}

LHCb: ~ 2 fb^{-1}

Selection criteria for W bosons

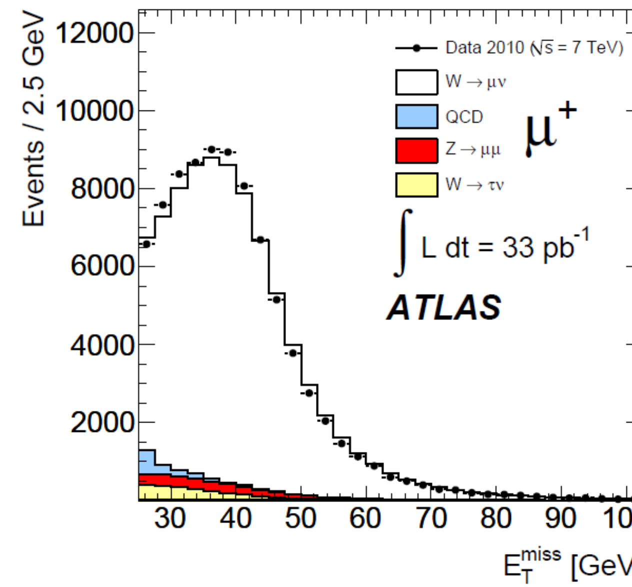


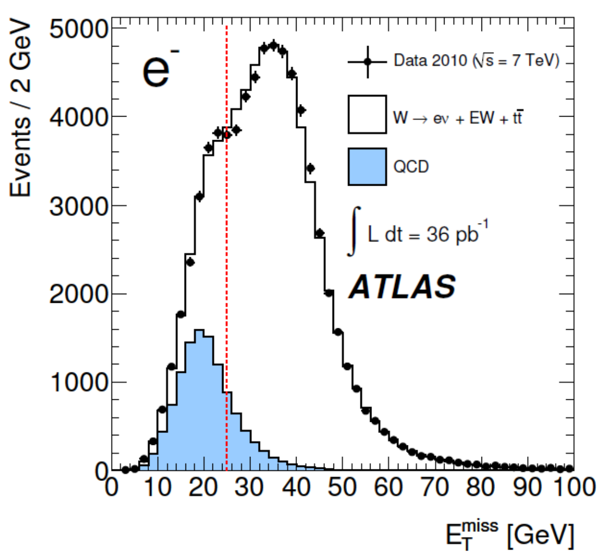
- $p_{T,l}$ > 20 GeV
- e: $|\eta_e|$ <2.47
- μ: $|\eta_\mu|$ <2.4

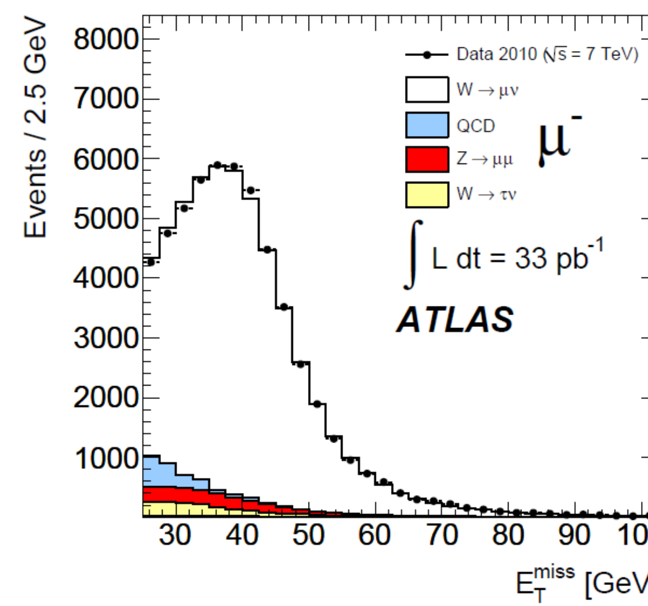
- Single lepton trigger
- Calorimeter Isolation

- E_T^{Miss} > 25 GeV
- $m_T(W)$ > 40 GeV

- ~140000 candidates
- ~8% background



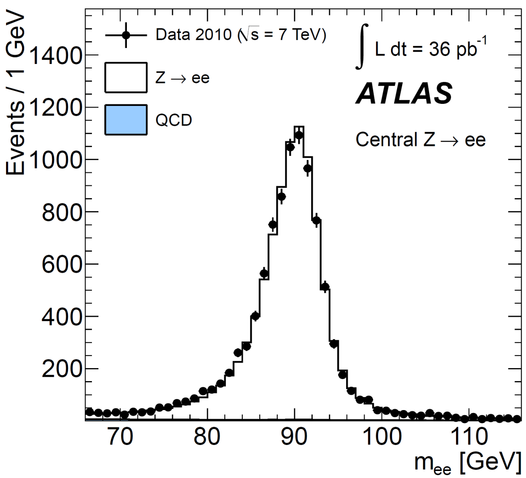


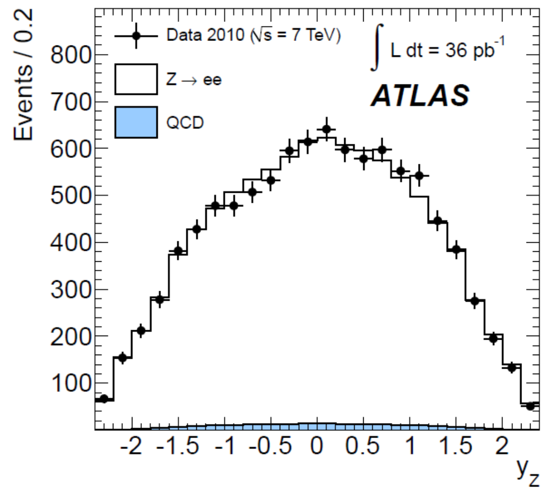


Selection criteria for Z bosons

All Z bosons: $p_{T,l}$ > 20 GeV
66 < M_Z < 116 GeV

Central-Central Z

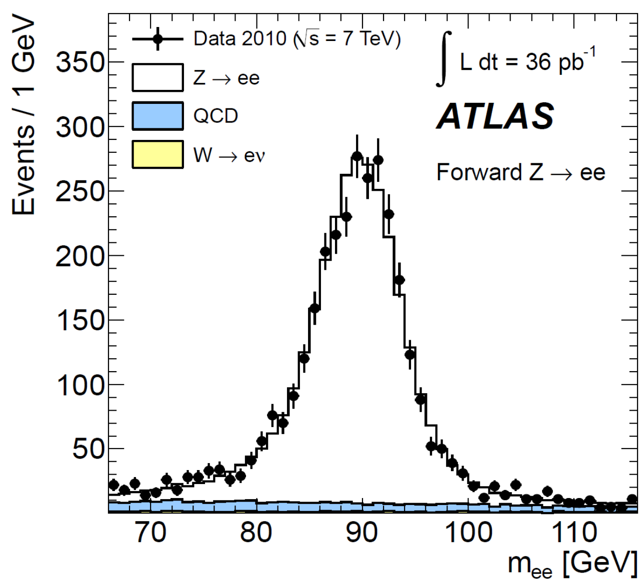


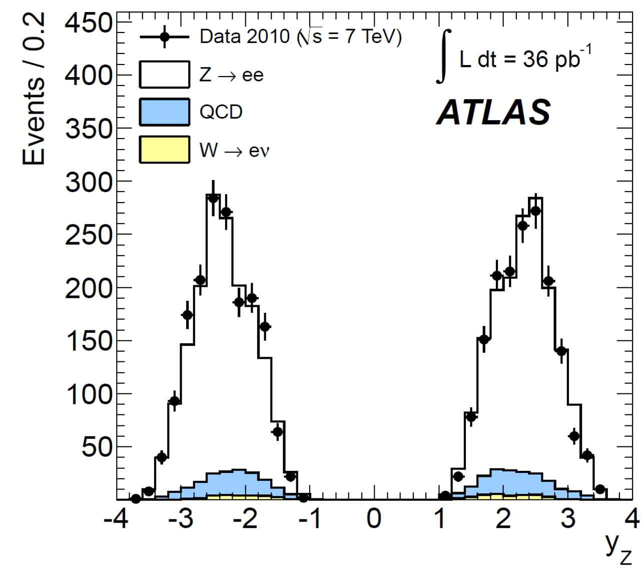


- e: $|\eta_e|$ <2.47; μ: $|\eta_\mu|$ <2.4
- Opposite charge
- ~12000 candidates
- 1-2 % background
- Single lepton trigger

Central-Forward Z

- Only electrons:
  $|\eta^1|$ < 2.47,
  2.5 < $|\eta^2|$ < 4.9
- 33000 candidates
- 11% background
- Single lepton trigger





Methodology and systematic

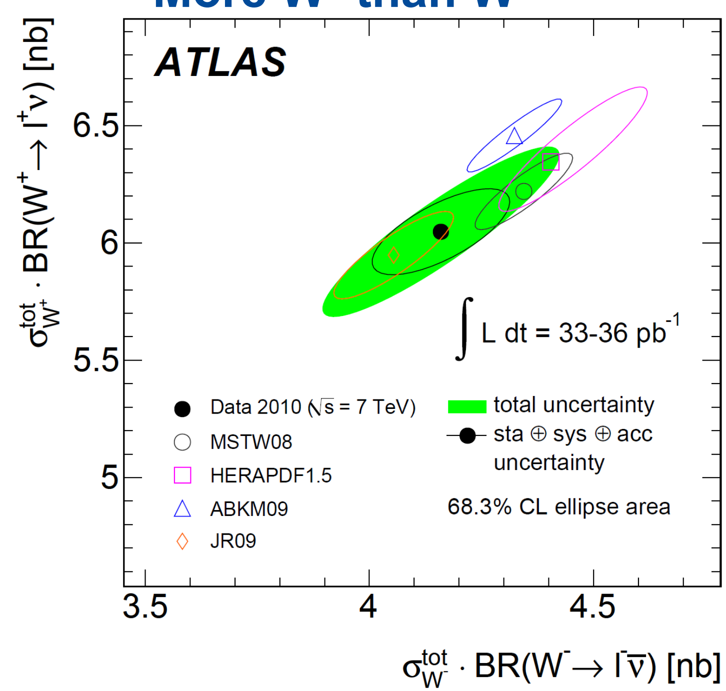
- Measure primarily within fiducial region to minimize dependence on theoretical acceptance extrapolation to full phase space (~1.5-2.1% extra syst.)

$$\sigma = \frac{N^{\mathrm{obs}} - N^{\mathrm{bkg}}}{\mathcal{L} \times C_{W/Z} (\times A_{W/Z})}$$

$$C_{W/Z} = \frac{N^{W/Z}_{\mathrm{MC,rec}}}{N^{W/Z}_{\mathrm{MC,gen,fid}}}$$

$$A_{W/Z} = \frac{N^{W/Z}_{\mathrm{MC,gen,fid}}}{N^{W/Z}_{\mathrm{MC,gen,all}}}$$

More u than d
More W^+ than W^-



- Define common fiducial region (extrapolations for e.g. transition regions)
- Combine electron and muon data with full treatment of correlations
- Fiducial integrated cross section:
  1-2% total experimental error
  3.4% luminosity
- Dominant are object reconstruction, identification and QCD background

Evaluation of PDFs

The notation follows the one introduced in equation (9.1). The matrix $(\gamma^{\text{theo}})^i_{j,k}$ represents the relative correlated systematic uncertainties on the theory predictions and quantifies the influence of the uncertainty source j on the prediction in bin i and data set k. The parameters b_j^{theo} are defined analogously to the parameters b_j and represent the shifts introduced by a correlated uncertainty source j of the predictions. The χ^2 function is minimised with respect to b_j and b_j^{theo} with the cross-section measurements, μ, fixed to the values determined in section 9.1.

Equation (9.3) is further extended to account for asymmetric uncertainties on the predictions. The asymmetric uncertainties are described by parabolic functions

$$f_i(b_j^{\text{theo}}) = \omega_{i,j}(b_j^{\text{theo}})^2 + \gamma_{i,j} b_j^{\text{theo}}, \tag{9.5}$$

which replace the terms $(\gamma^{\text{theo}})^i_{j,k} b_j^{\text{theo}}$ of equation (9.3). The coefficients of $f_i(b_j^{\text{theo}})$ are determined from the values of the cross sections calculated when the parameter corresponding to source j is set to its nominal value $+S^+_{i,j}$ and $-S^-_{i,j}$ where the $S^\pm_{i,j}$ are the up and down uncertainties of the respective PDF sets.[6] The coefficients are given by

$$\gamma_{i,j} = \frac{1}{2}\left(S^+_{i,j} - S^-_{i,j}\right) \tag{9.6}$$

$$\omega_{i,j} = \frac{1}{2}\left(S^+_{i,j} + S^-_{i,j}\right). \tag{9.7}$$