Determination of strangeness using data from neutrino experiments and hadron collider

Investigations into the Strange Sea Quark Distribution

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Based on:
Determination of Strange Sea Quark Distributions from Fixed-target and Collider Data
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DESY

The strange sea quark puzzle

- Strange sea quarks only weakly constrained by HERA data

- LHC data seems to suggest enhancement of strange sea quarks compared to expectations from fixed target experiments:
  ATLAS fit to W/Z data [Phys. Rev. D85 (2012) 072004, Phys.Rev.Lett. 109 (2012) 012001]

  … but not confirmed by CMS data [Phys. Rew. D 90 (2014) 032004]

- Currently among largest sources of uncertainties on
  W mass measurements at the LHC [ATL-PHYS-PUB-2014-015]

- Investigate these discrepancies and the consistency of the measurements in a joint QCD analysis with data from Fixed-target and Collider Data

The fixed-target data: Neutrino scattering off Fe-target

- **NuTeV and CCFR [Phys.Rev. D64, 112006 (2001)]**
  Measurement of absolute differential di-muon cross-section $\sigma_{\mu\mu}/dxdy$
  Minimal muon energy threshold of 5 GeV

- **NOMAD [Nucl.Phys. B876, 339 (2013)]**
  Measurement of ratio $R_{\mu\mu} = \sigma_{\mu\mu}/CC$ (inc. charged current cross-section)
  as function of E, x and partonic center-of-mass, $\sqrt{s}$
  → *cancellation of uncertainties including nuclear corrections*

  Minimal muon energy threshold 3 GeV
  → *larger phase space reduces extrapolation (previous data)*
  reducing sensitivity to charm quark fragmentation
  but inclusive branching ratio B_μ requires still extra effort
  (backup slides)

  Increased data set
  → *3 x the statistics of NuTeV and CCFR data sets*

The fixed-target data: Charm production in emulsions

- **CHORUS [New J.Phys. 13,093002 (2011)]**

Measurement of ratio $R_C = \sigma_C/CC$ (inc. charged current cross-section)
with the total charm cross section σ_C
as function of the neutrino energy E_ν
→ *Ratio cancels uncertainties including nuclear corrections*

direct detection of charmed hadrons and their decays
→ *measurement of visible neutrino energy and charm decay length*
→ *no dependence on branching ratio* B_μ

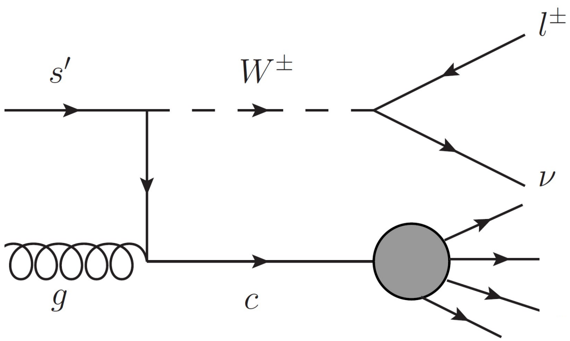
no definite energy threshold, but lower energy resolution
→ *reducing even further sensitivity to charm quark fragmentation*

Total of 2013 events
→ *low statistics*

restriction on the kinematic region used for analysis of $Q^2 > 1$ GeV

The collider data: LHC measurements of W+charm

- Detection of associated charm quark
  by semi-leptonic decay into muon or
  charmed hadron in various decay channels



ATLAS [JHEP 05, 068 (2014)]
Measurement of $|\eta_\ell|$ cross section up to 2.5 **at hadron level**
compared to prediction using aMC@NLO (NLO in W+c)

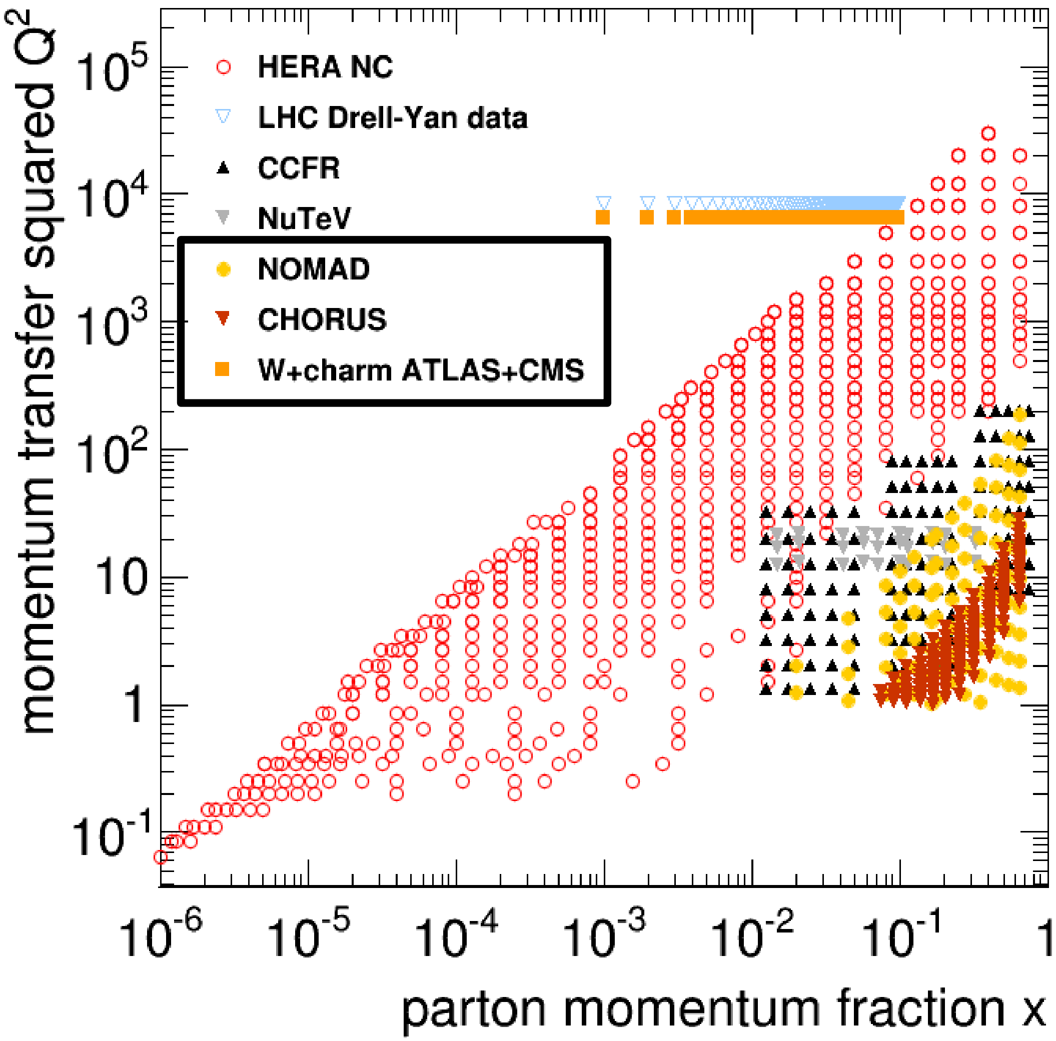
minimum lepton p_T of 20 GeV

CMS [JHEP 02, 013 (2014)]
Measurement of $|\eta_\ell|$ cross section up to 2.1 **at parton level**
compared to prediction using MCFM interfaced to APPLGRID

minimum lepton p_T of 35 GeV

Further input data sets

- Deep inelastic scattering (DIS) neutral current (NC) inclusive production
- DIS charm production
- Fermilab fixed-target Drell-Yan (DY) FNAL-E-605 and FNAL-E-866
- LHC DY



- **Study the effect of the new data with strange sensitivity**

Investigation into the impact of new data

Impact of single data sets

NuTeV/CCFR +

1) **NOMAD**
2) **CHORUS**
3) **CMS**

Combined Impact of new data sets

NuTeV/CCFR +

4) **CHORUS + NOMAD**
$\rightarrow$ *impact of (anti)-neutrino induced charm data*

5) **ATLAS + CMS**
$\rightarrow$ *consistency check in view of different strange distributions obtained by experiments*

6) **CHORUS + ATLAS + CMS**
$\rightarrow$ *impact data sets independent of semi-leptonic branching ratio* B_μ

Fit ingredients and data treatment

- **QCD to good approximation at NNLO accuracy**
  - → NNLO evolution
  - → NNLO massless DIS and DY coefficient functions
  - → NLO+massive DIS coefficient functions **(fixed flavor number scheme)**
    - NLO + NNLO threshold corrections for neutral current (NC)
    - NNLO description of charge current (CC) above $Q \gg m_{charm}$
    - running masses ($\overline{MS}$ scheme of heavy-quark masses)
  - → NNLO exclusive DY (DYNNLO 1.3 / FEWZ 3.1)

- **Deuteron corrections in DIS**
  - → Fermi motion, off-shell effects

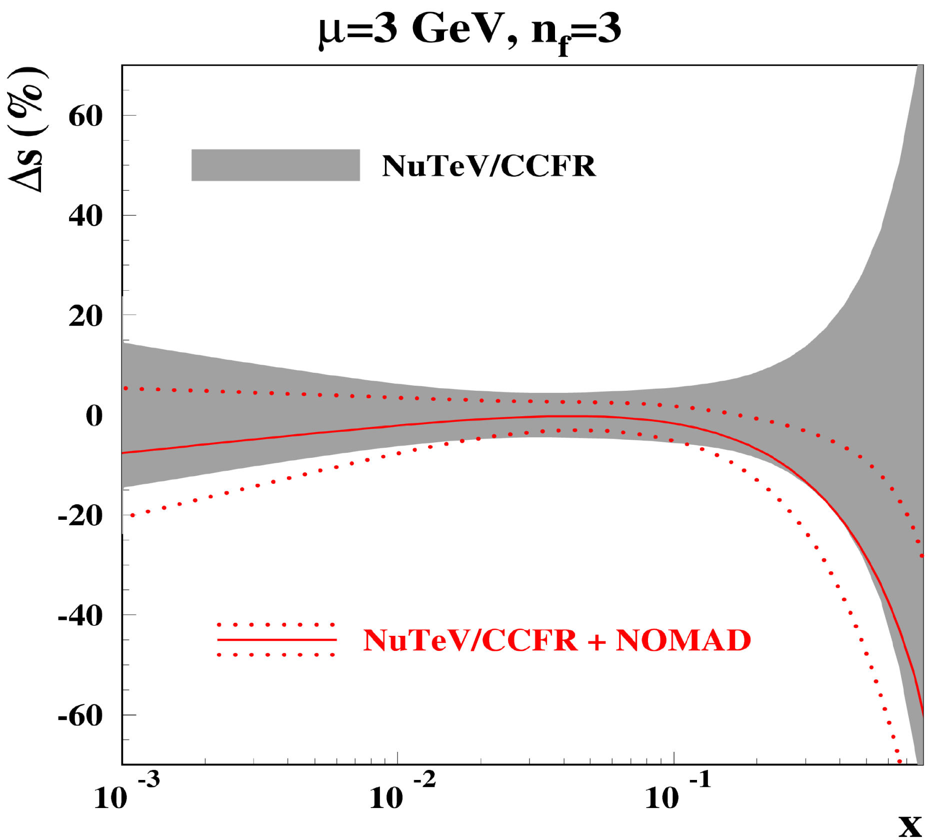
- **Power corrections in DIS**
  - → target mass effects
  - → dynamical twist-4 terms

For ATLAS and CMS data,
a **fast interpolation grid** is used
Phys.Rev. D89, 054028 (2014)

- **Starting scale Q_0 = 3 GeV**

- **Strange parametrization** $s(x,\mu_0) = A_s x^{a_s}(1-x)^{b_s}$

1) NuTeV/CCFR + NOMAD



> **Reduces strange density above x>0.1**

> **Reduction of uncertainty**

→ largest effect at high-x due to better coverage of NOMAD

→ χ^2/NDP = 49 / 48 (number of data points)

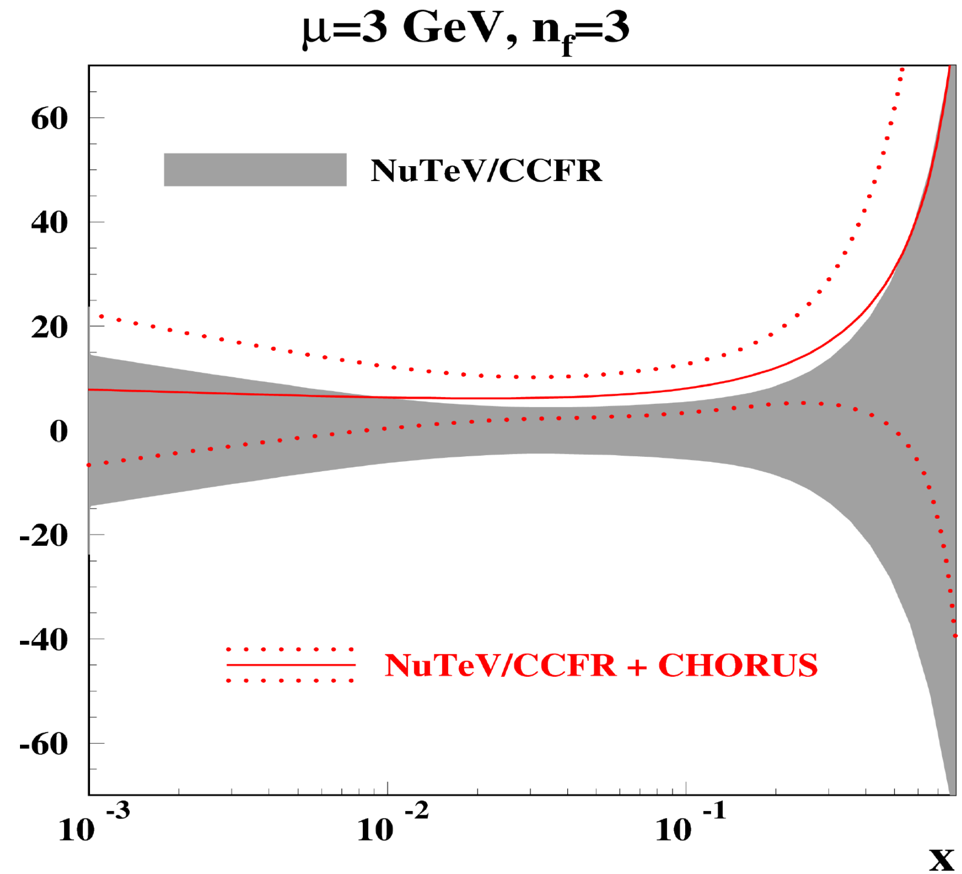
→ Some deviations of partial fits from total fit – but all within uncertainty

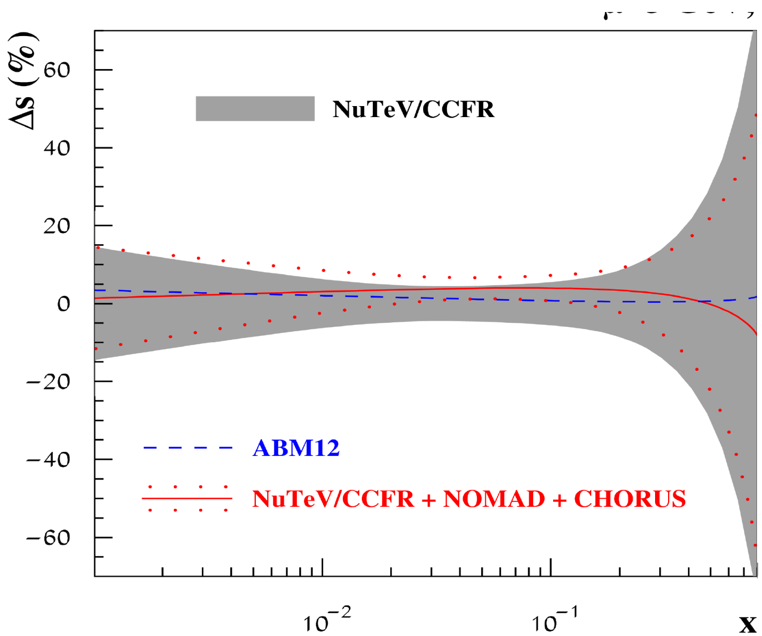
2+4) NuTeV/CCFR + CHORUS (+NOMAD)

- **Strange distribution pulled upwards for all x**

- **Opposite to NOMAD:**
  Combined NOMAD/CHORUS fit compensates: *no change*

- **Reduced uncertainties**

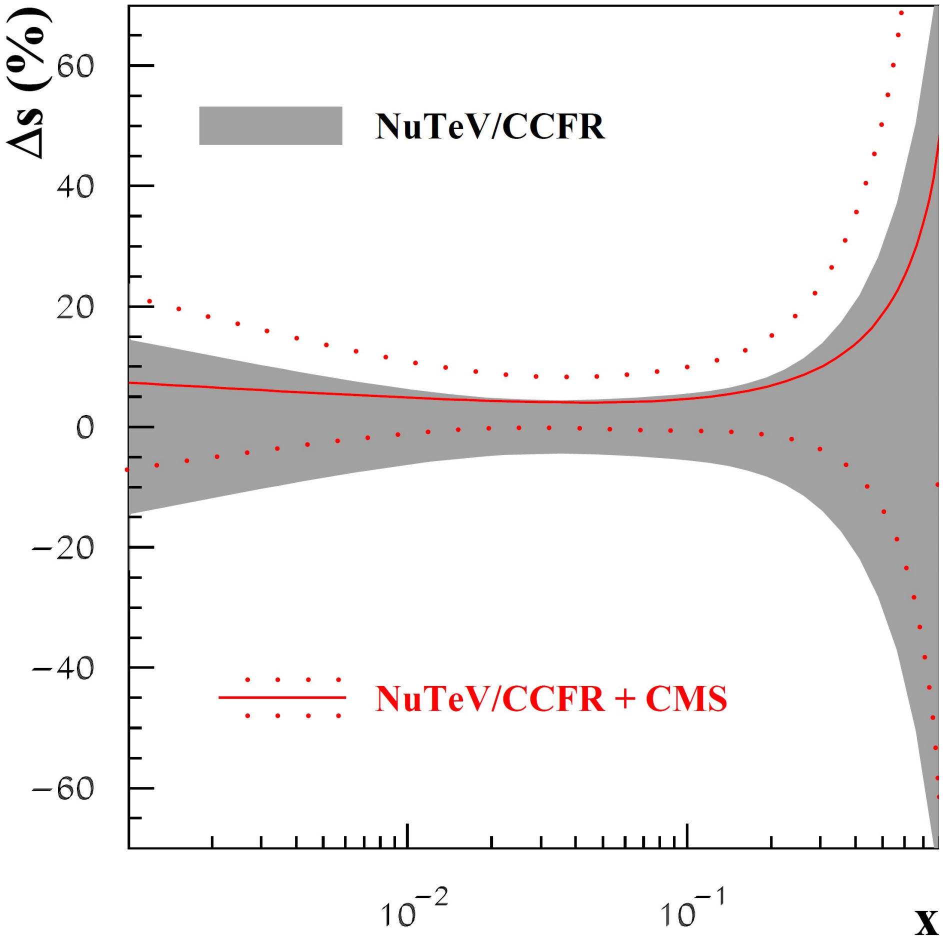




→ χ^2/NDP = 5-9 / 6 (number of data points)

→ CHORUS data somewhat higher than fits

3) NuTeV/CCFR + CMS



- **Strange slightly enhanced for CMS data**
- **Enhancement increases if only CMS or CMS+CHORUS are used**
  poorly constrained strange
  → fix low-x strange exponent
  $a_s = -0.234 \pm 0.036$ from all neutrino data for fit stability

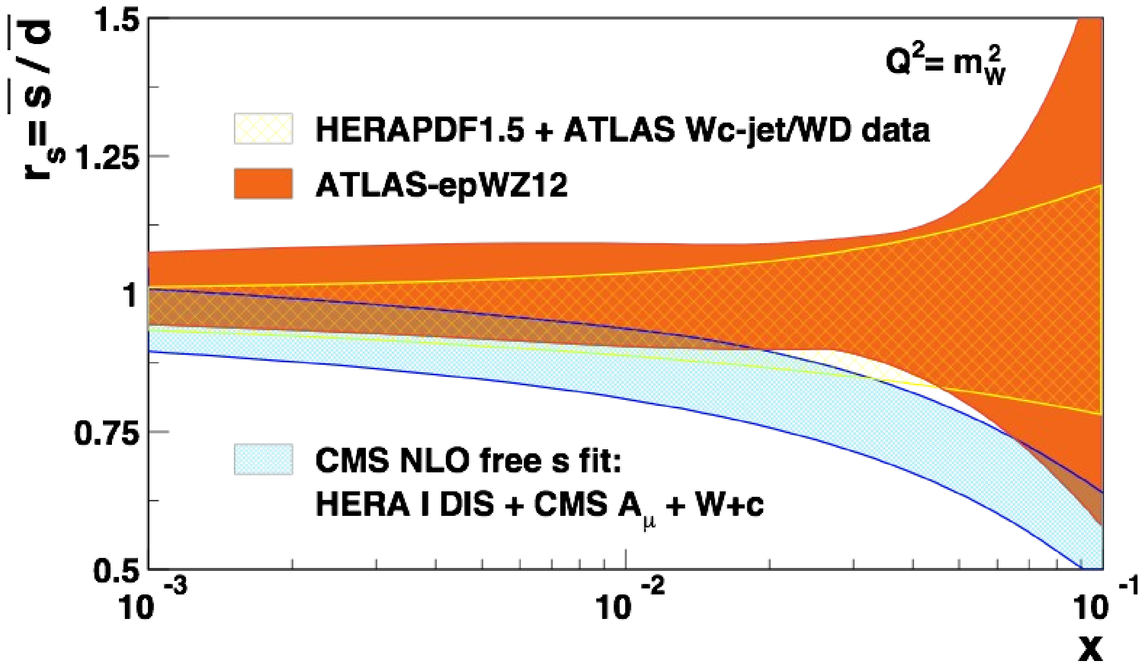
→ Extracted strange suppression consistent with previous CMS result

5) ATLAS + CMS

> **Strange suppression**
> → Quantifies strange quark distribution compared to $\bar{d}$-valence

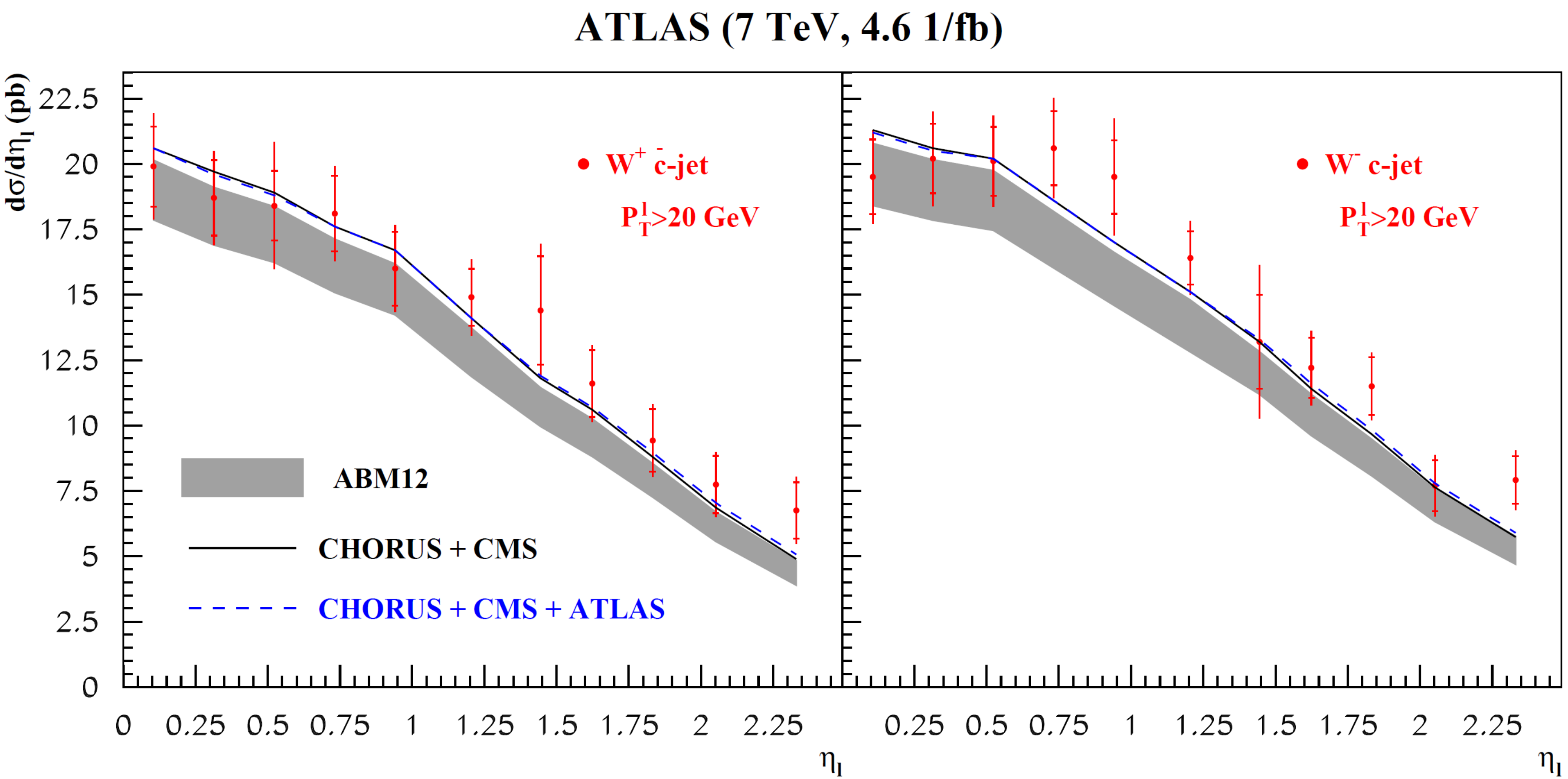
$$r_s(x,\mu^2) = \frac{s(x,\mu^2)+\bar{s}(x,\mu^2)}{2\bar{d}(x,\mu^2)}$$

> **Difference in r_s determined from fits of either experiement**
> → Depends on parametrisation, high-x region not covered by data



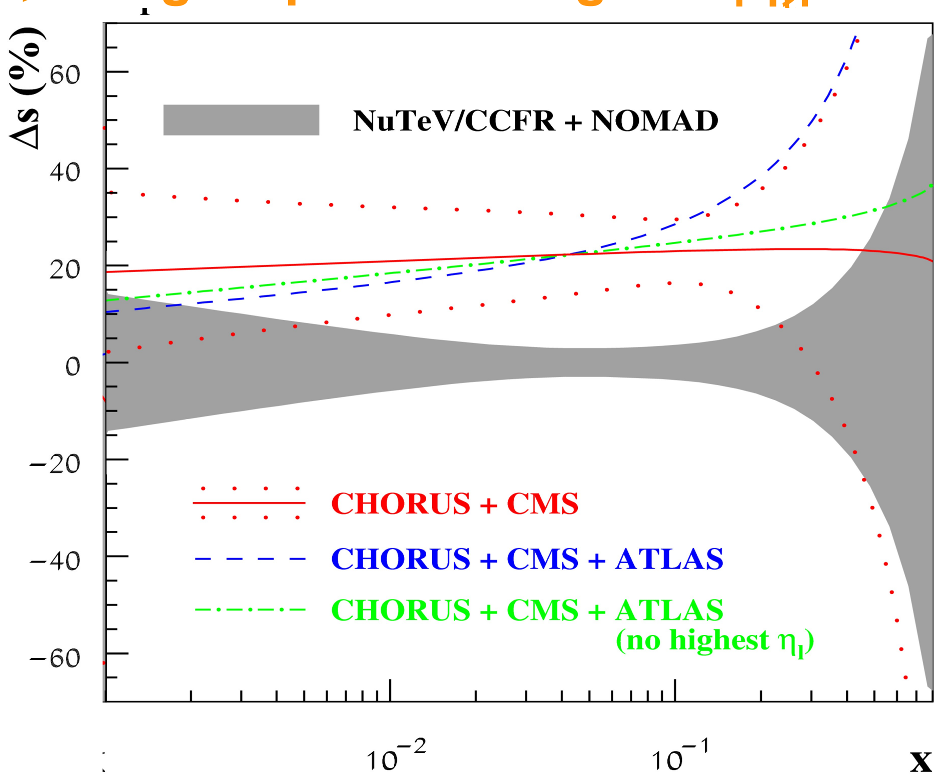
5) ATLAS + CMS

- **ATLAS data well described by fits using CHORUS+CMS data**
  - → χ^2/NDP = 34.5 / 30
  - → Data are consistent!



6) CHORUS + ATLAS + CMS versus NuTeV/CCFR+NOMAD

- **Data without reliance on ratio B_μ generally increases strangeness**
- **Largest pull from highest $|\eta_\ell|$-bin of ATLAS experiment**



- **Strange suppression:**

This analysis

$$r_s = 0.56 \pm 0.04$$

ATLAS profiling of HERAPDF

$$r_s = 0.96 \,{}^{+0.16}_{-0.18}\,{}^{+0.21}_{-0.24}$$

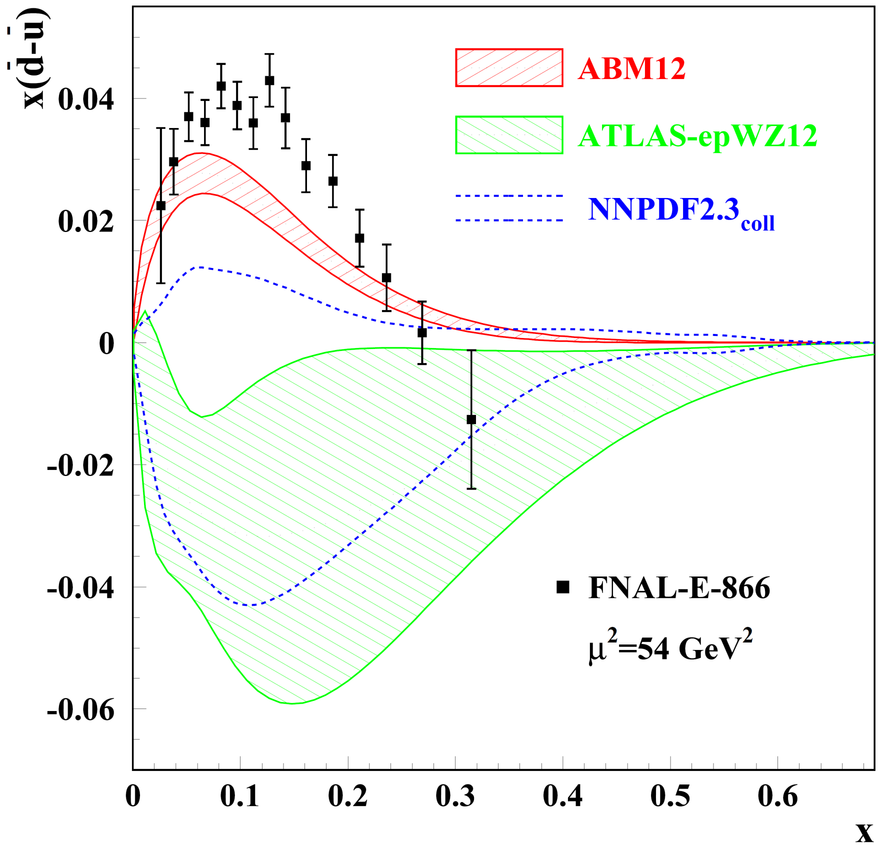
- **Correlation of strange with $\bar{d}$-valence:**

Larger strangeness compensated in ATLAS analysis by $x(\bar{d}-\bar{u})$
For this analysis constrained by FNAL-E-866 data

Some discrepancies in $x(\bar{d}-\bar{u})$

- Correlation of strange with $\bar{d}$-valence
  leads to discrepancies with FNAL-E-866 experiment

$x(\bar{d}-\bar{u})$ ~ 0 for other fits / data



- Based on

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

Conclusions

- **Investigation into strange quark content of the proton**
  $\longrightarrow$ Addition of new neutrino and collider data sets

- **Little impact on central value**
  due to higher statistics neutrino-Fe data (NOMAD)

- **Strangeness enhanced by 20% for data**
  not relying on semi-leptonic branching ratio B_μ
  $\longrightarrow$ for both emulsion-neutrino and LHC collider data

- **Inclusion of ATLAS and CMS data in one fit without problems**
  $\longrightarrow$ data fully compatible
  $\longrightarrow$ highest ATLAS of $|\eta_\ell|$-bin with most effect

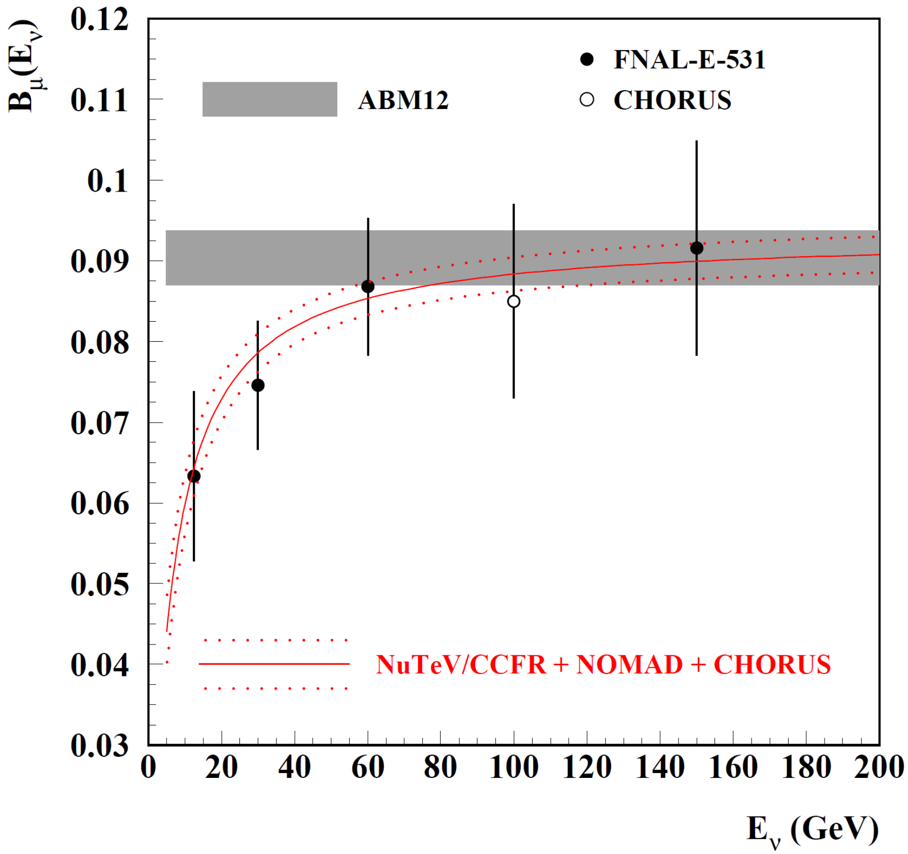
- **3% uncertainty on LHC measurements needed to improve strange fit**

Backup

First picture to appear when you google "vienna strange"

Backup: Energy-dependent branching ratio

- Branching ratio depends on semi-leptonic branching fractions and production fractions, which are dependent on neutrino energy



$$B_\mu = \sum_h B_\mu^h f_h(E_\nu)$$

- Fitted simultaneously with PDFs with constraints from emulsion data

$$B_\mu(E_\nu) = \sum_h r^h(E_\nu) B_\mu^h = a/(1+b/E_\nu)$$

$$B_\mu(E_\nu) = \frac{B_\mu^{(0)}}{1 + B_\mu^{(1)}/E_\nu}$$