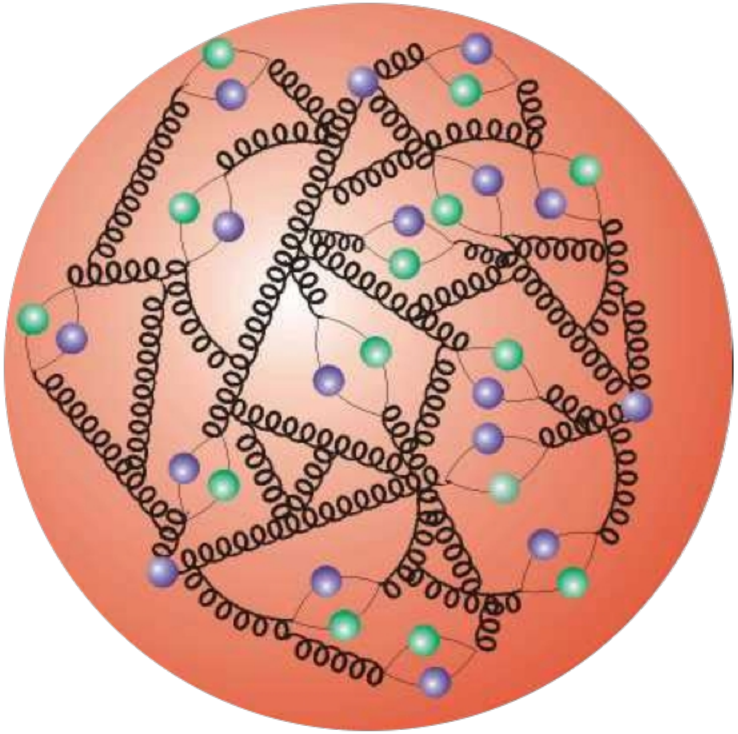
Structure functions
& parton densities WG

personalised HIGHLIGHTS



every week

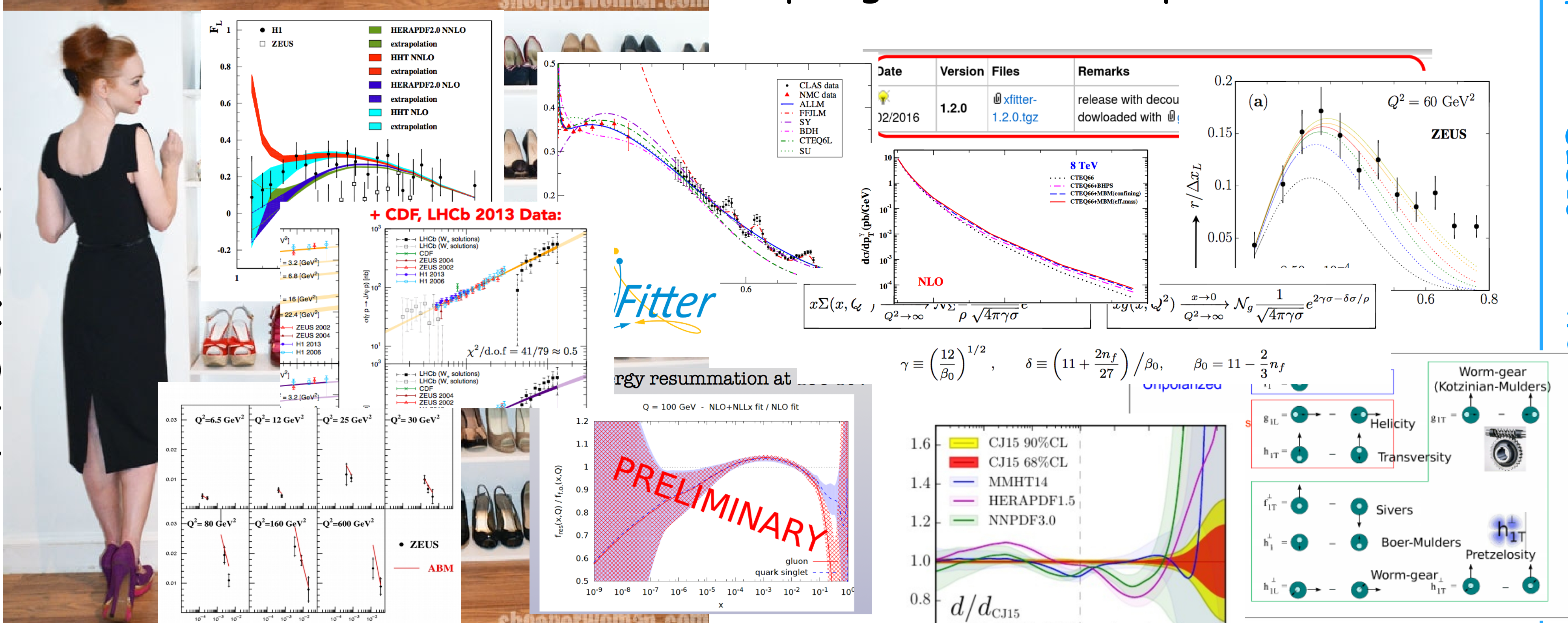
- Very full session, 10 slots, joined with
  - Future Experiments
  - QCD & Hadronic Final States
  - Electroweak Physics & BSM

  → included in this summary

43 talks!

By necessity highlights, not full summary.
Apologies to talks/topics not included!

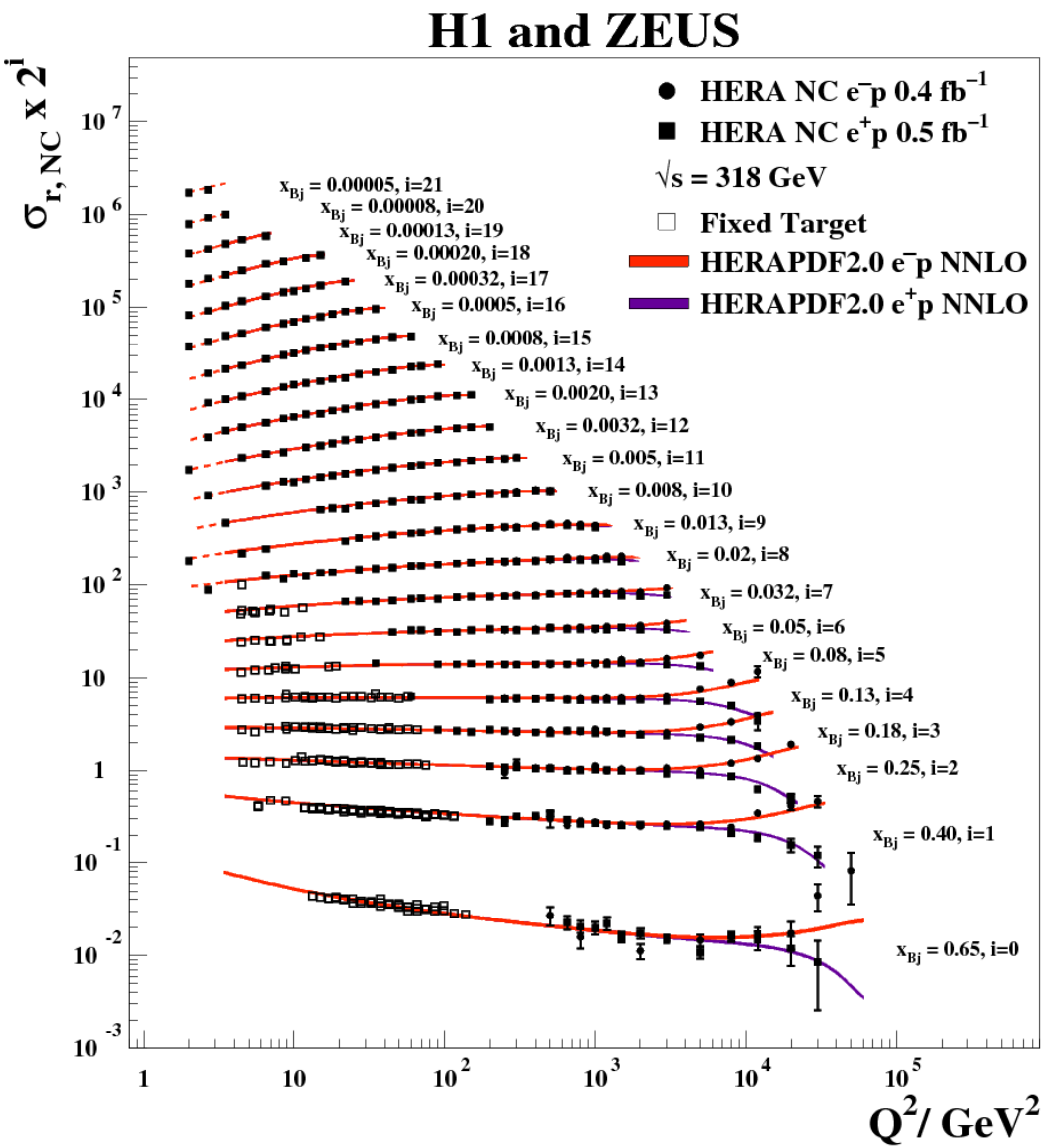
this week

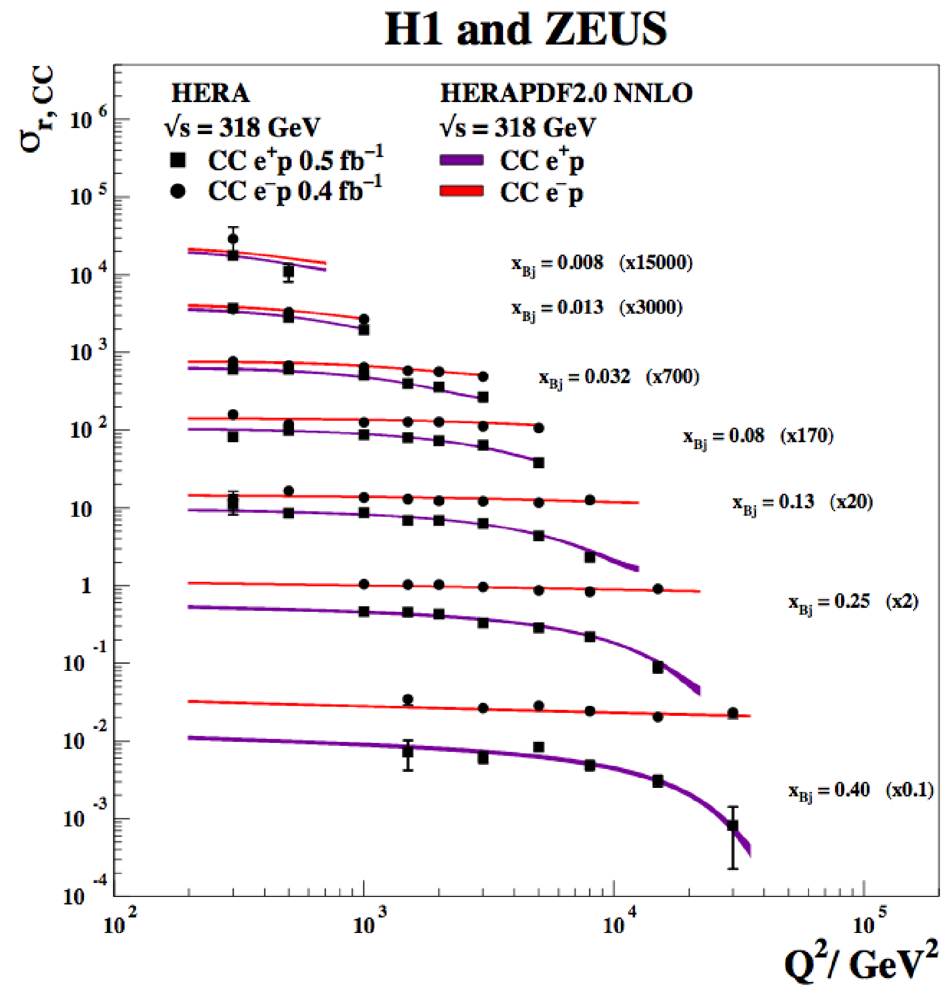


R. McNulty, R. Thorne, K. Wichmann

DIS16

HERA inclusive data core of every PDF extraction



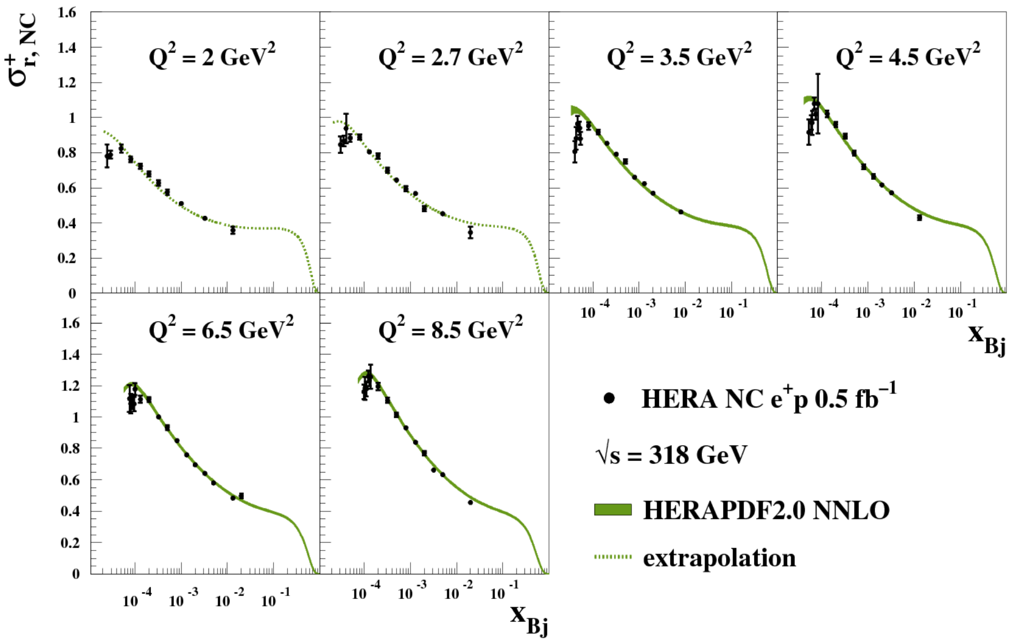


In NC: QCD scaling @ moderate x
Scaling violation @ low and high x

Helicity effects in CC

Low Q^2 & low x NC data poorly described

A. Cooper-Sarkar



→ Consider higher twist corrections acting at <u>low x</u> (I. Abt et al. arXive:1604.02299)

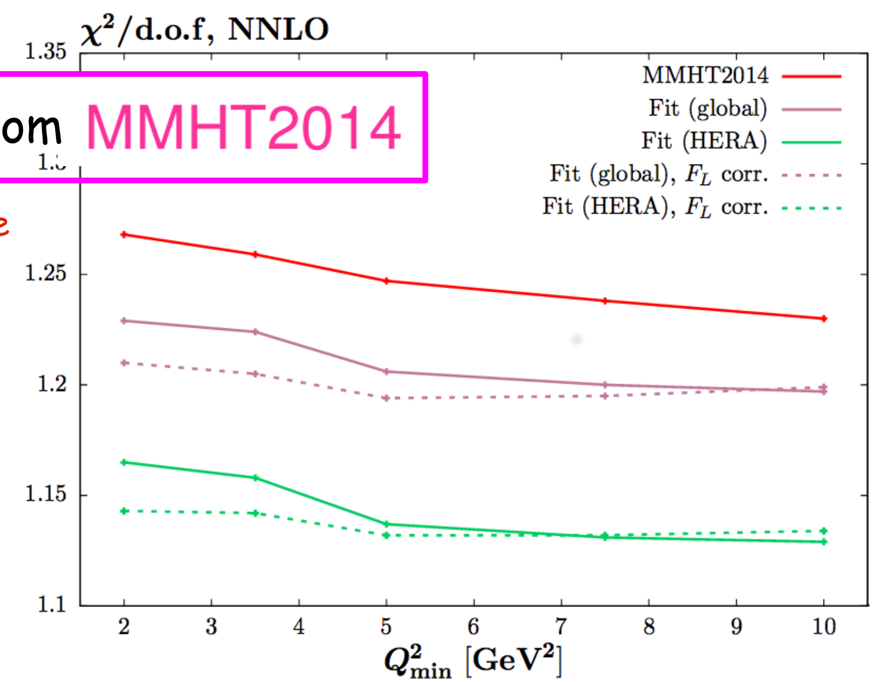
$$F_{2,L} = F_{2,L}\,(1 + A_{2,L}{}^{HT}/Q^2)$$

χ^2 improved, modification of F_L favored

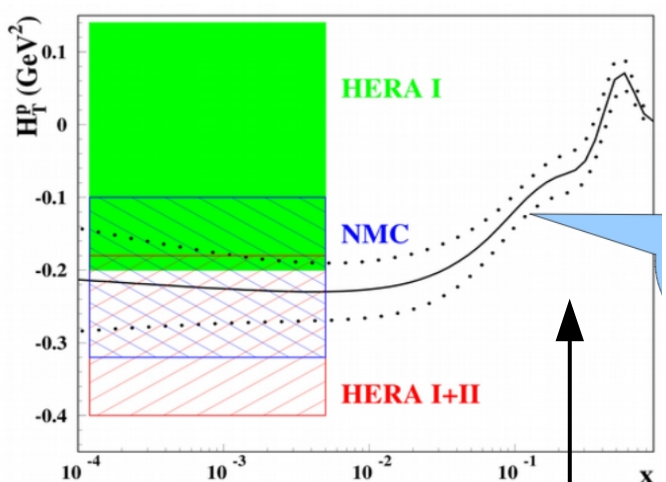
$$A_2{}^{HT} = 0.12 \pm 0.07\ \text{GeV}^2$$
$$A_L{}^{HT} = 5.5 \pm 0.6\ \text{GeV}^2$$

similar study coming from MMHT2014

R. Thorne



S. Alekhin

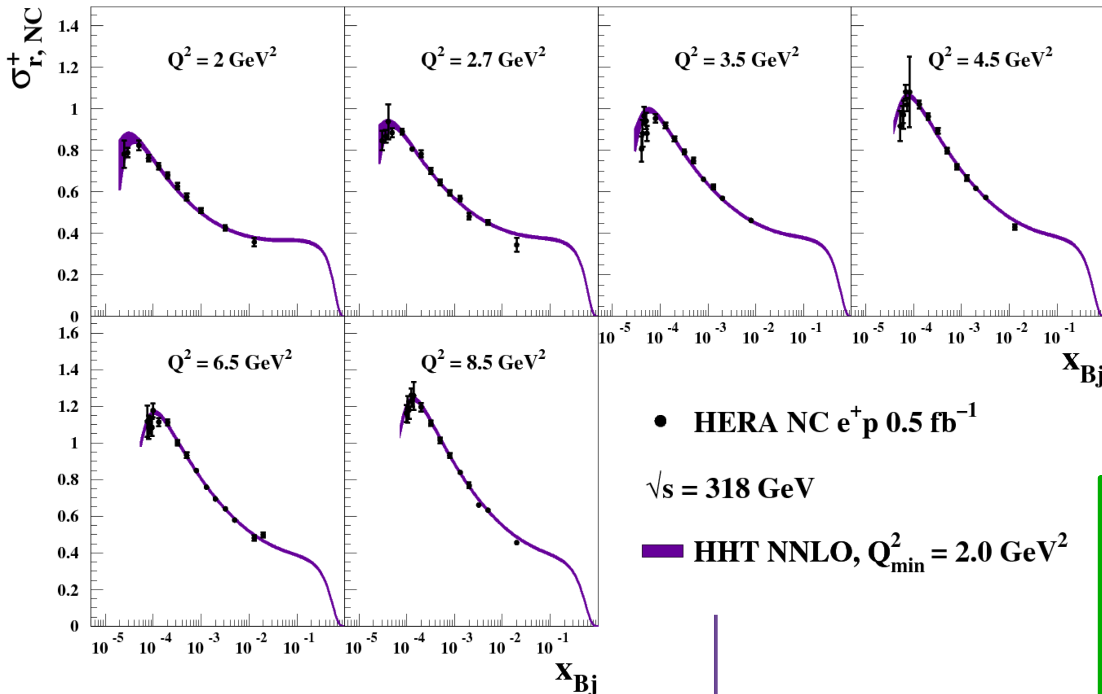


... and ABM

$$F_{2,L} = F_{2,L}(\text{leading twist}) + H_{2,L}(x)/Q^2 \qquad H(x) = x^h P(x)$$

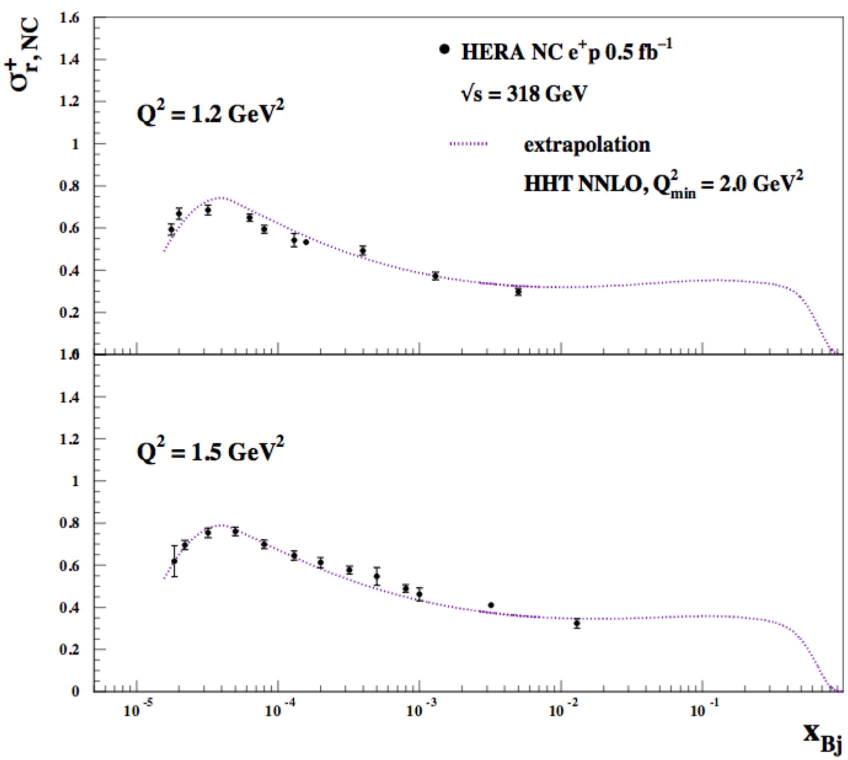
R. McNulty, R. Thorne, K. Wich

ary



A. Cooper-Sarkar

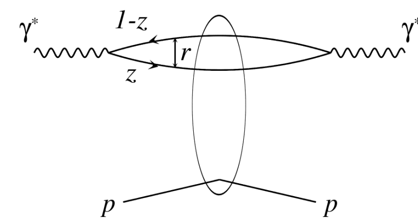
→ description of data much improved even for fits starting at 2 GeV^2

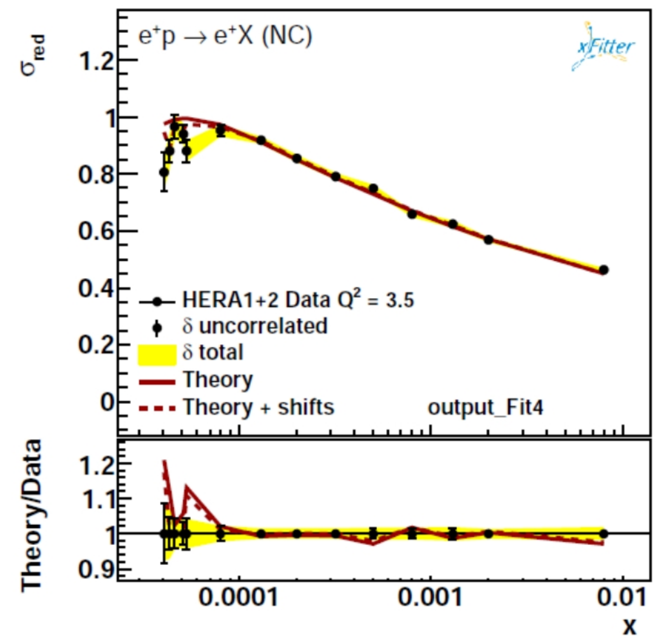


A. Luszczak

→ Consider BGK dipole model with saturation for x < 0.01

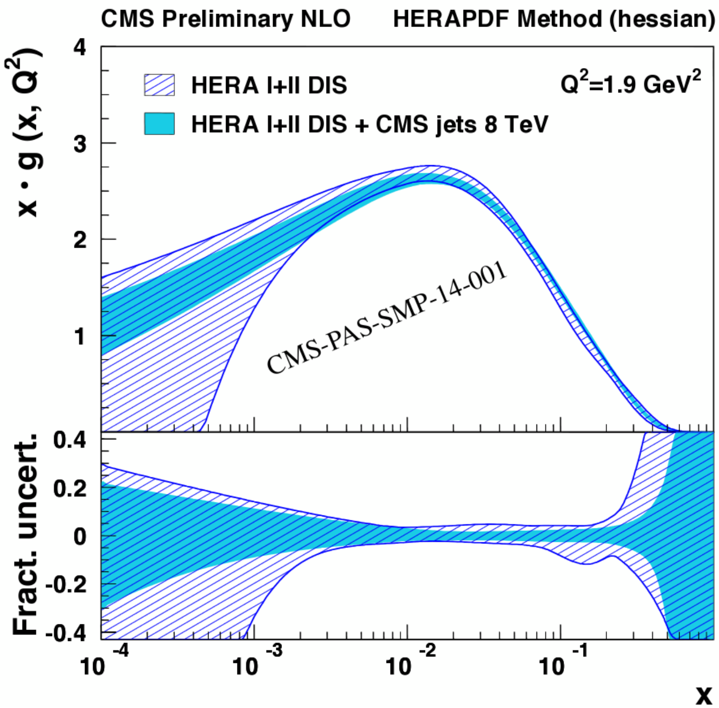
- $\chi^2/Np \to 1$





Use additional data to constrain PDFs

JETS



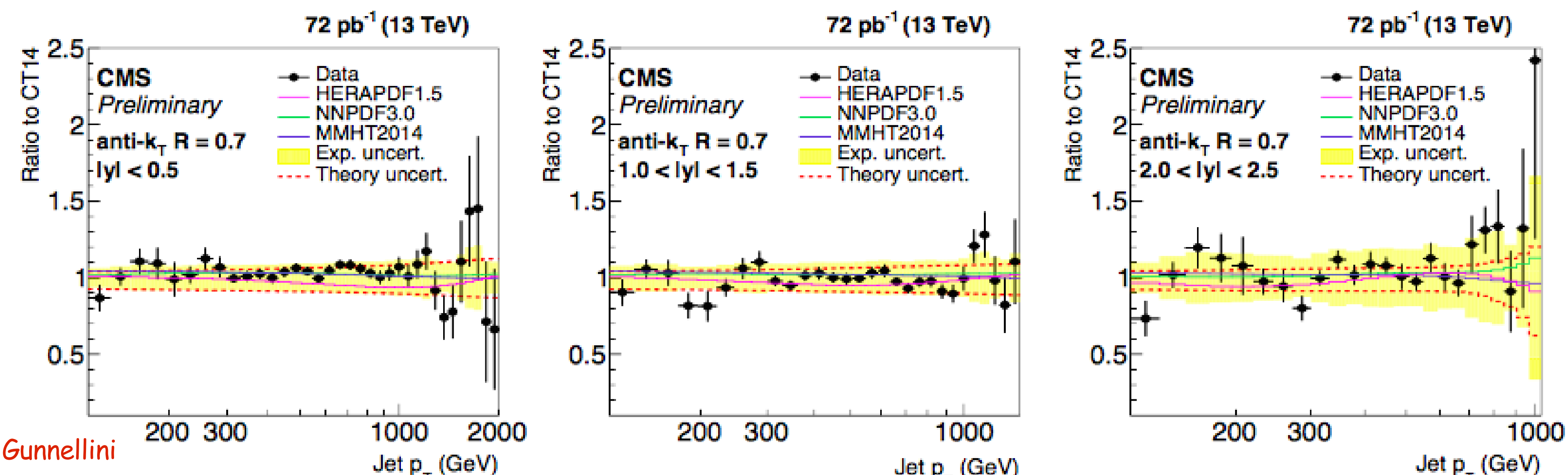
E. Eren

- Reduction of uncertainties for gluon @ 8 TeV
- Similar impact expected from 13 TeV data

R. McNulty, R. Thorne, K. Wichma

Inclusive jet cross section at 13 TeV: ratios

NEW



P. Gunnellini

Jets at low Q^2 @ HERA

NEW

Double-differential Dijet cross sections

$$\langle P_T \rangle = \frac{P_{T,1} + P_{T,2}}{2}$$

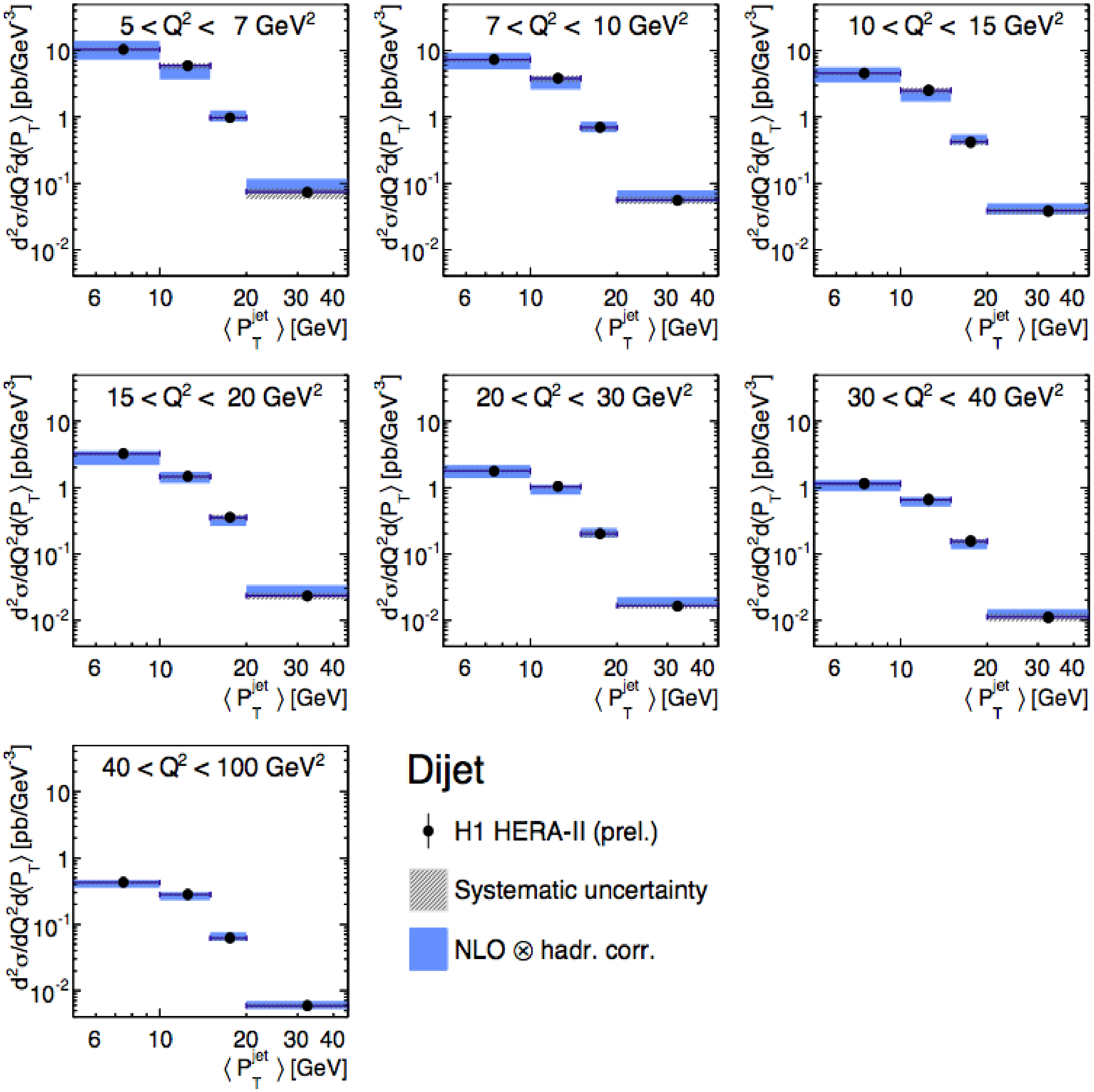
High precision

- Exp. uncertainty dominated by jet energy scale and model uncertainty

Compared with NLO

- NLO gives reasonable description over full kinematic range
- Large k-factors may indicate relevant contributions beyond NLO
- Large uncertainties from scale variation

Data precision overshoots significantly theory precision



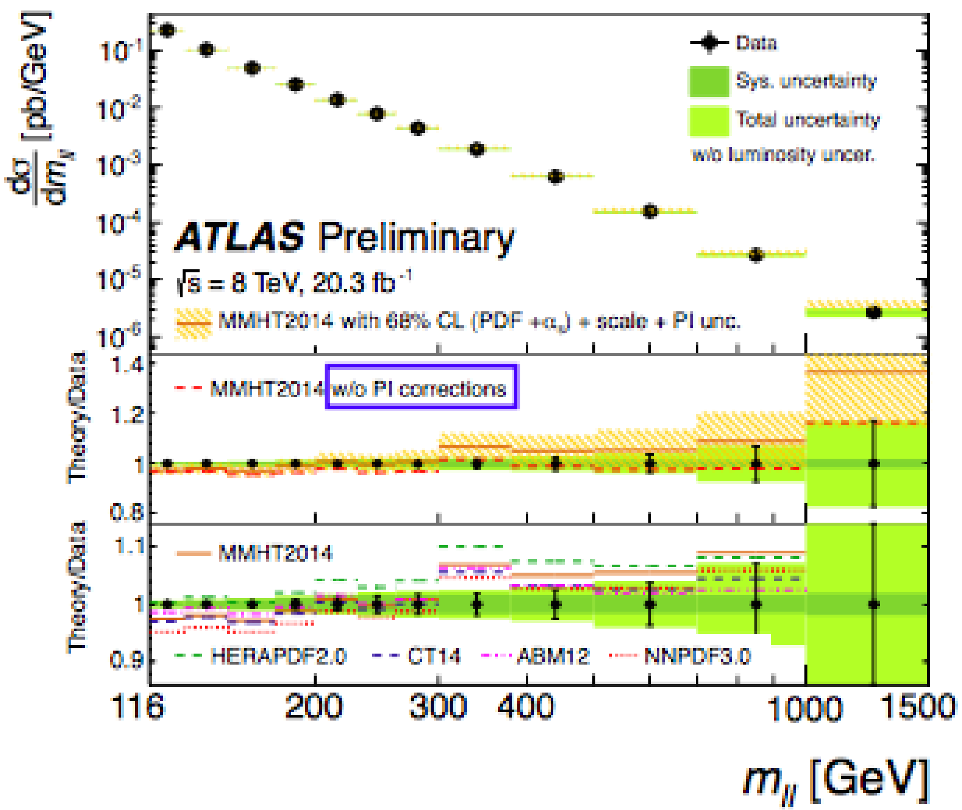
D. Britzger

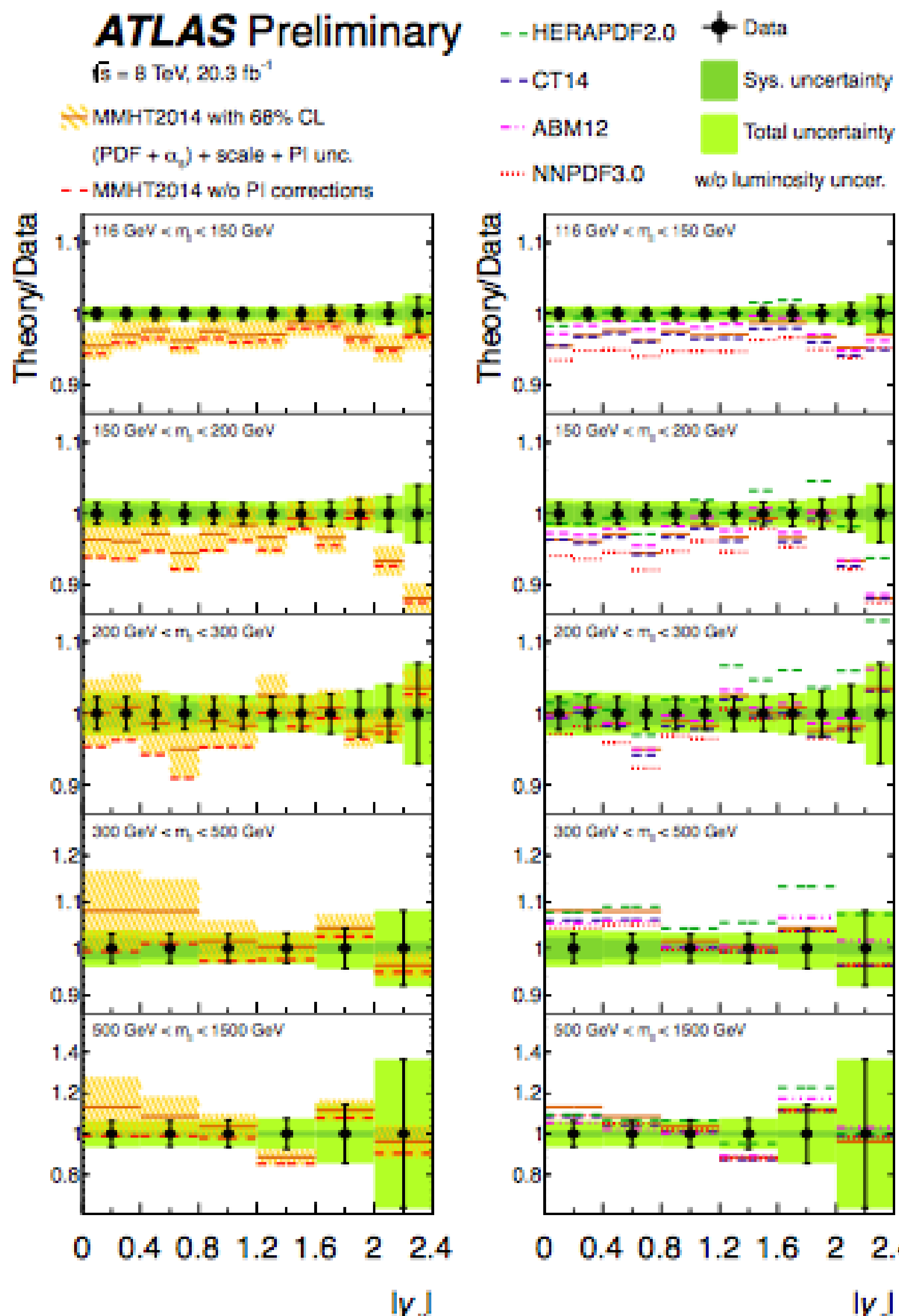
Use additional data to constrain PDFs

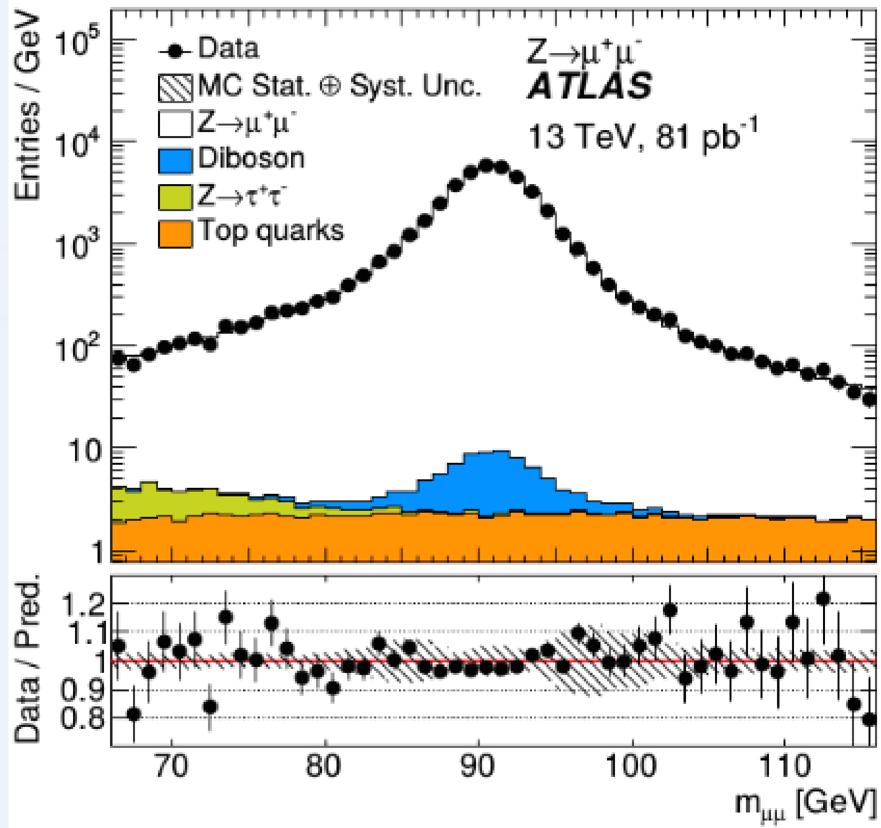
EW observables

High mass Drell-Yan: results and comparison to theory II/II

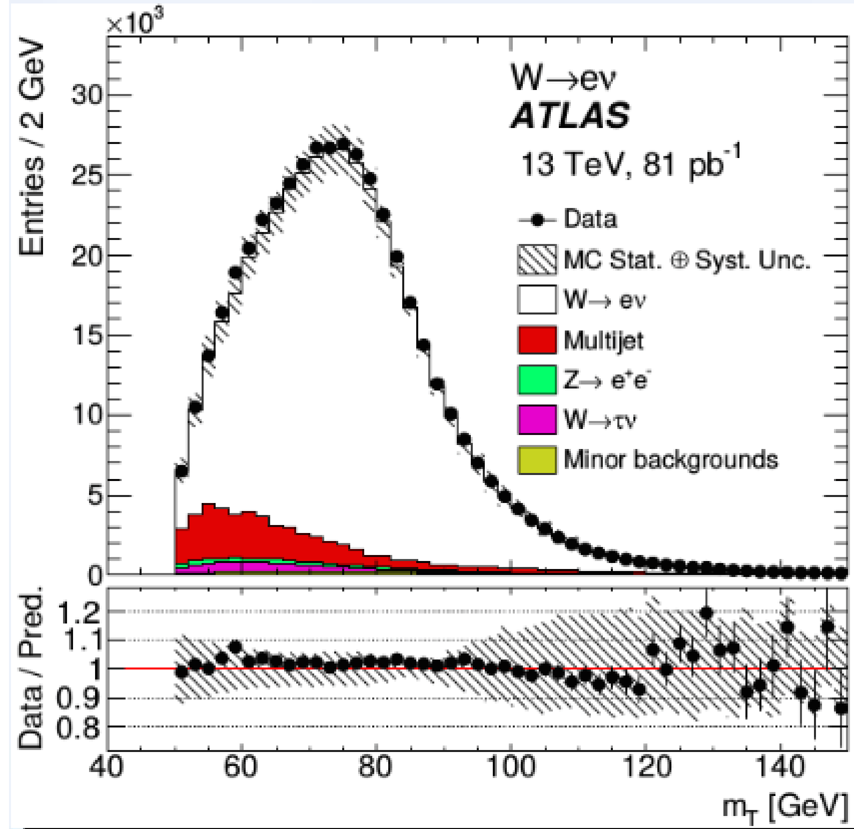
- The measured cross-sections are compared to theoretical predictions using a selection of recent PDFs.
- Theory uncertainties are larger than measurement uncertainties => potential for PDF constraints.
- Photon induced contribution reaches 15%.





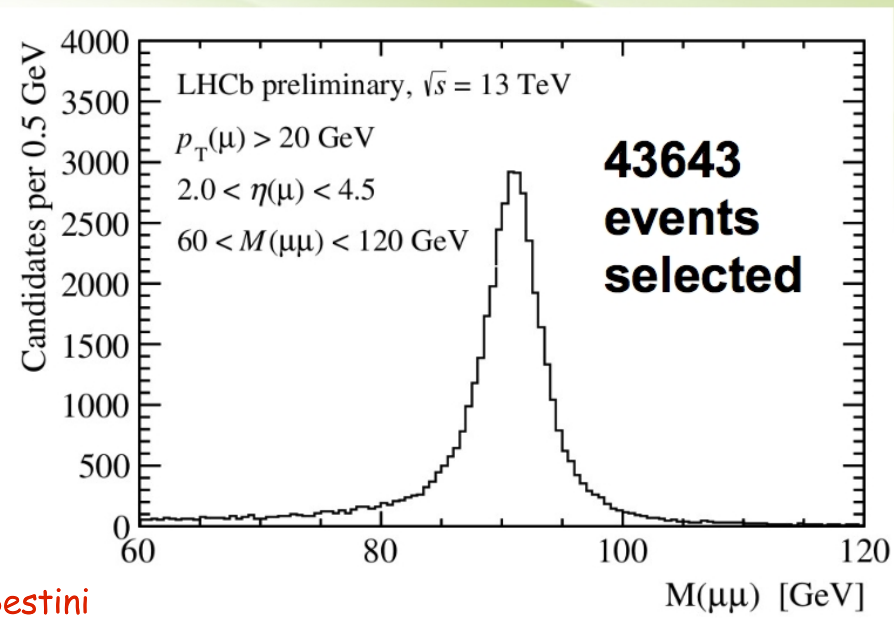


H. Pirumov



NEW

LHCb-CONF-2016-002



L. Sestini

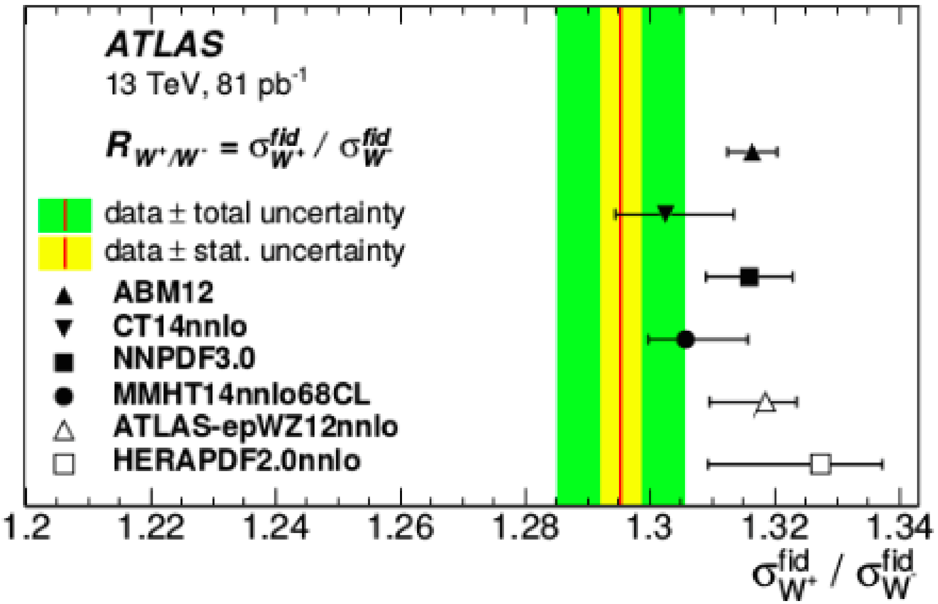
Z and W bosons @ 13 TeV

R. McNulty, R. Thorne, K. Wichmann

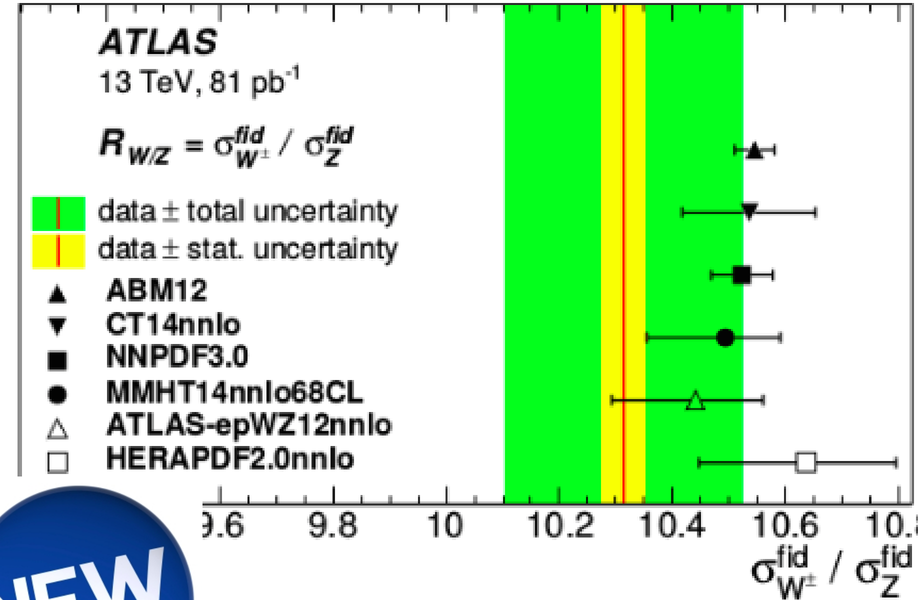
DIS16

WG1 Summary

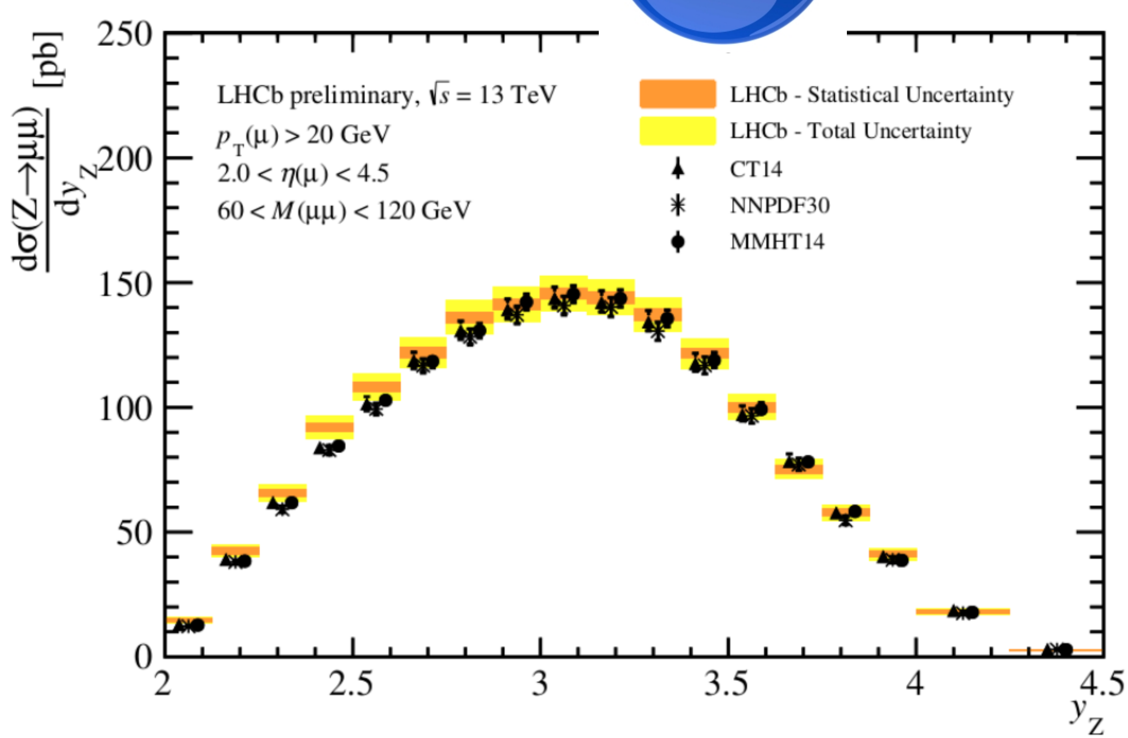
- Sensitive to (u_v - d_v) at low x



- Constrains strange quarks



NEW

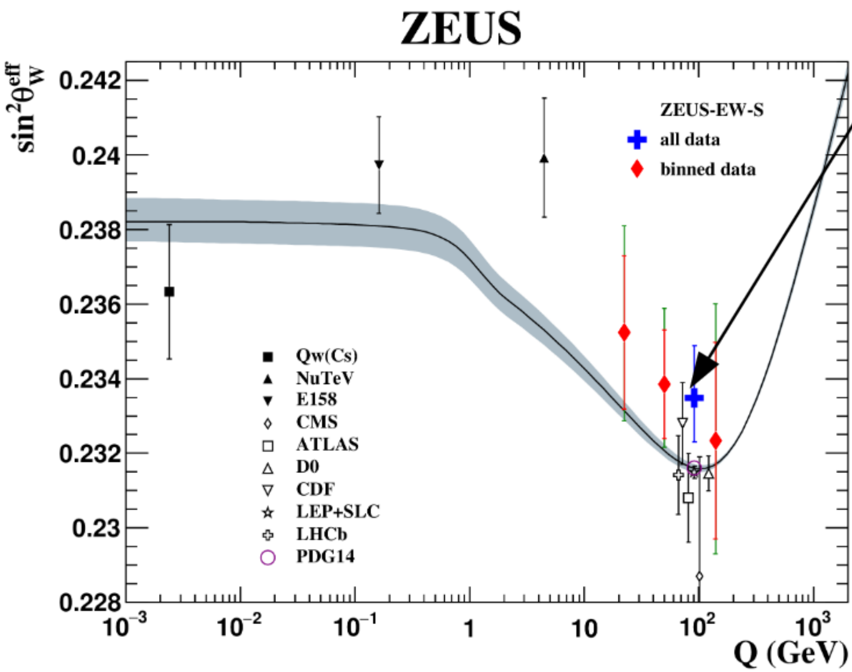


Extractions of $\sin^2\theta_W$

R. McNulty, R. Thorne, K. Wichmann

V. Myronenko

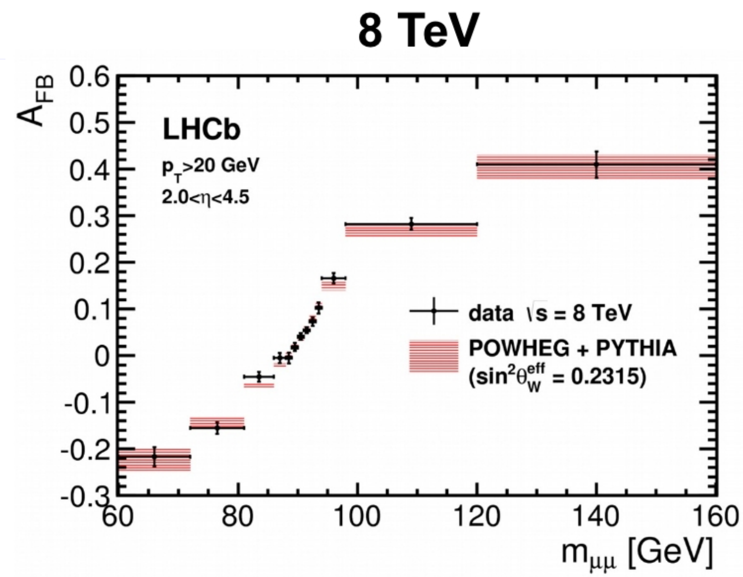
$$\sin^2\theta_W = 0.2252 \pm 0.0011_{(exp/fit)}\,{}^{+0.0003}_{-0.0001}(mod)\,{}^{0.0007}_{-0.0001}(par) = \mathbf{0.2252}^{+0.0013}_{-0.0011}(tot)$$

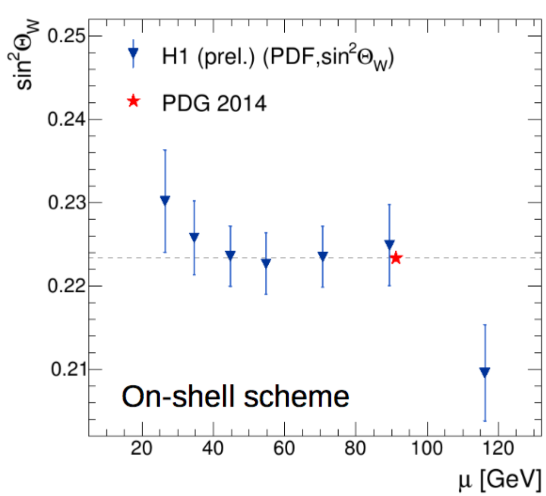


First time running from single machine!

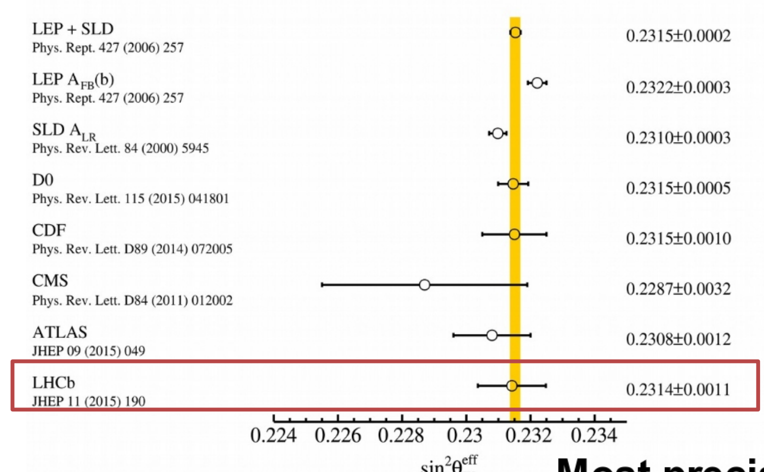
The forward backward asymmetry is defined as: $A_{FB} = \dfrac{N_F - N_B}{N_F + N_B}$

N_F : number of forward decay ($\cos\theta^* > 0$)
N_B : number of backward decay ($\cos\theta^* < 0$)





D. Britzger

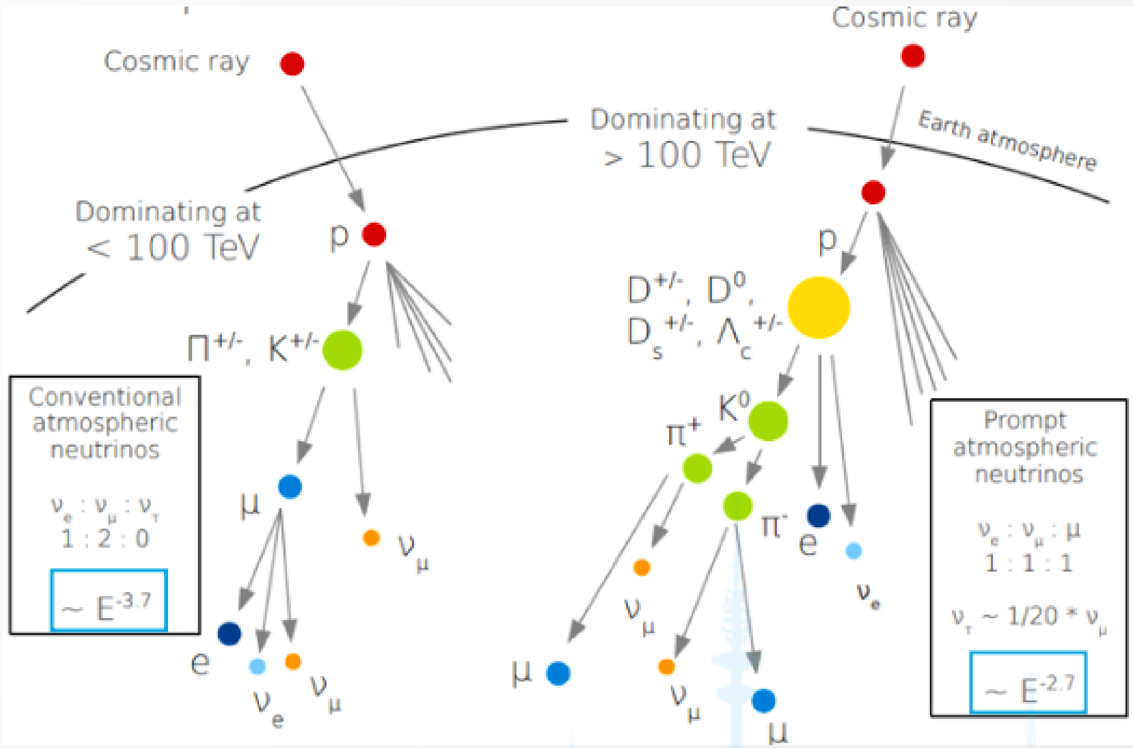


L. Sestini

Most precise $\sin^2\theta^{eff}_W$ measurement at LHC!

Prompt vs. conventional flux

The energy spectrum from semi-leptonic decay products depends on a hadronic **critical energy**, *below* which the **decay probability** is > **interaction probability**



Courtesy: Anne Schukraft

For **pions & kaons**, this critical energy is low (decay length is long) hence the leptonic energy spectrum is soft. For **charmed mesons**, the critical energy is high: they **decay** *promptly* to highly energetic leptons

The atmospheric neutrino flux from the decay of pions & kaons is the **conventional flux**, whereas that from charm decay is called the **prompt flux**

Prompt flux not seen so far

limit of 0.54×ERS @ 90% C.L. from combined IC59 + IC79 + IC86 data

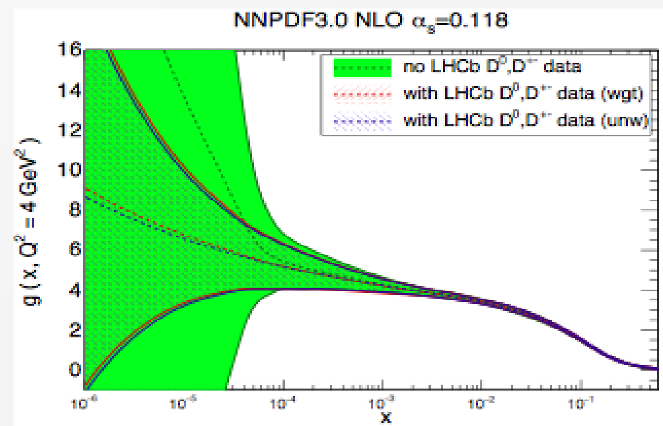
Complementarity with LHC physics: gluon PDFs at low x

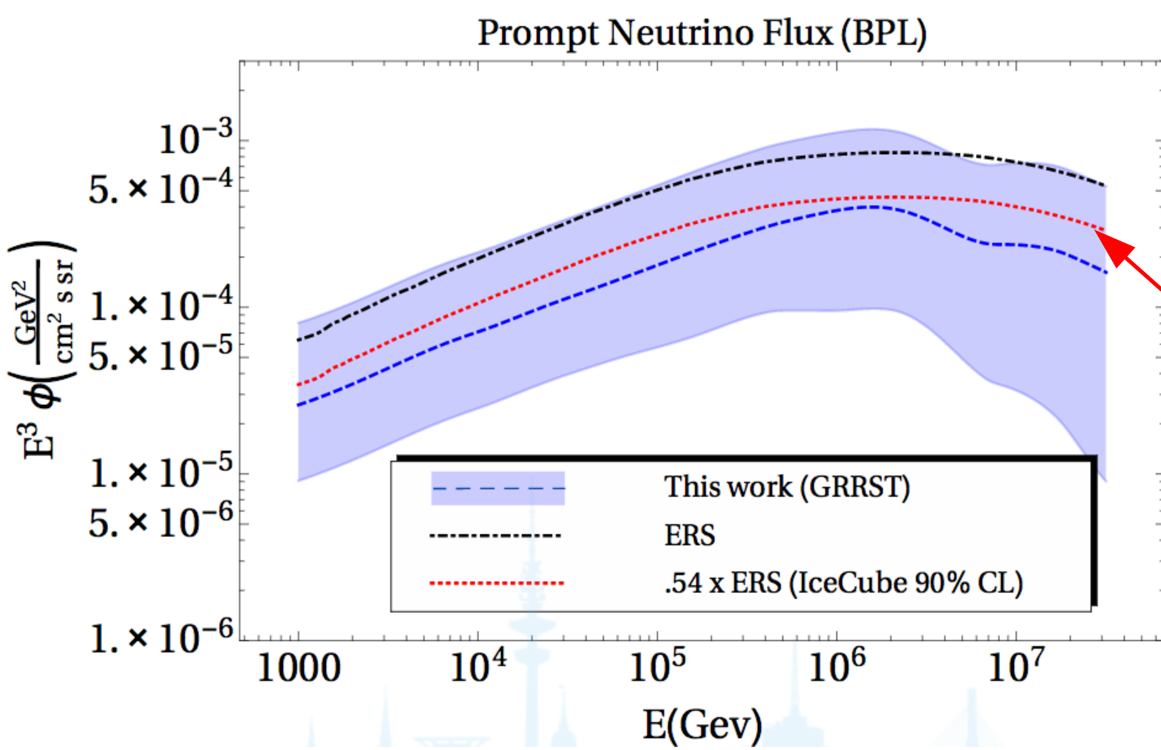
arXiv: 1506.08025

9

Small-x Gluon NNPDF: LHCb constraints

- We utilize charm production data from LHCb to **reduce the uncertainties in the small-x gluon PDF**
- Similar strategy as the one used by the **PROSA** collaboration in the HERAfitter framework arXiv: 1503.04581
- By using a **Bayesian re-weighting technique**, the impact of the new data is estimated. 75 data points added to NNPDF3.0 analysis

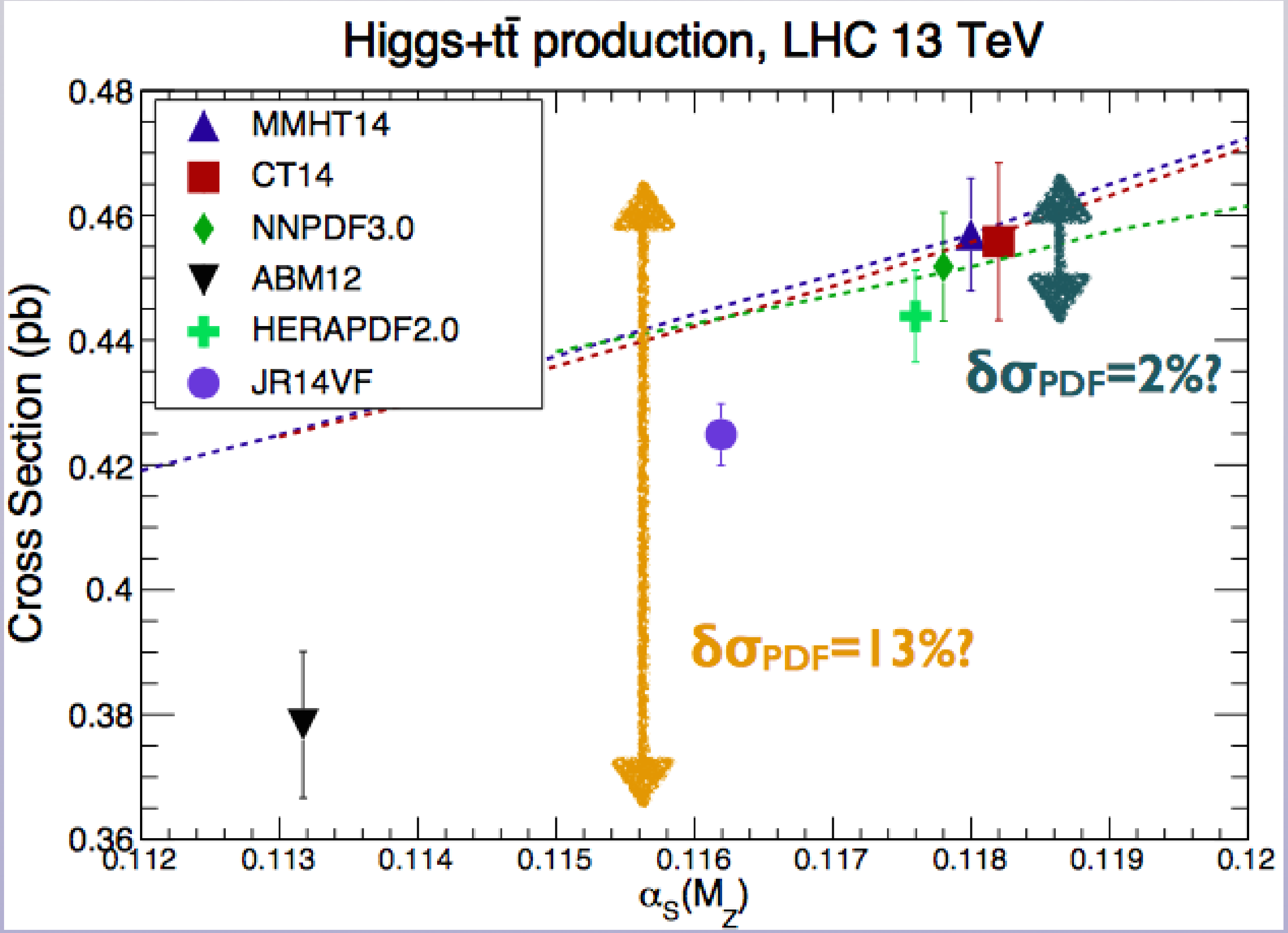




Consistency with IceCube bounds

Why do we need a recommendation?

Depending on how the **total PDF uncertainty on a given cross-section** is defined, results can differ by large amount, dramatically **degrading the BSM discovery potential of the LHC**



Usage of the PDF4LHC15 sets

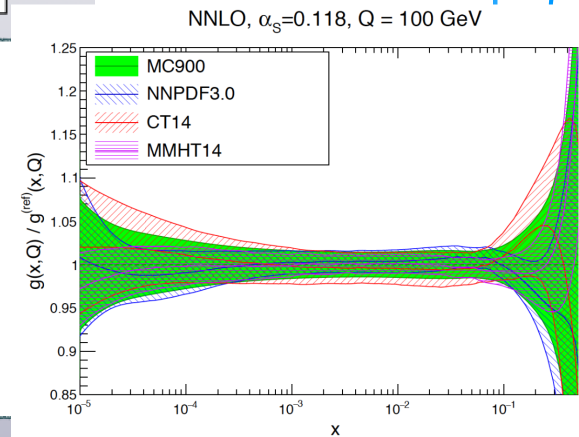
1. **Comparisons between data and theory for Standard Model measurements**

   Recommendations: Use *individual PDF sets*, and, in particular, as many of the modern PDF sets [5–11] as possible.

2. **Searches for Beyond the Standard Model phenomena**

   Recommendations: Use the `PDF4LHC15_mc` sets.

   Rationale: BSM searches, in particular for *new massive particles in the TeV scale*, often require the knowledge of PDFs in regions where available experimental constraints are limited, notably close to the hadronic threshold where $x \to 1$ [127]. In these extreme kinematical regions the PDF uncertainties are large, the *Monte Carlo combination of PDF sets is likely to be non-Gaussian. c.f.* Figs. 10 and 11.



3. **Calculation of PDF uncertainties in situations when computational speed is needed, or a more limited number of error PDFs may be desirable**

   Recommendations: Use the `PDF4LHC15_30` sets.

4. **Calculation of PDF uncertainties in precision observables**

   Recommendation: Use the `PDF4LHC15_100` sets.

   Rationale: For several LHC phenomenological applications, the highest accuracy is sought for, with, in some cases, the need to *control PDF uncertainties to the percent level*, as currently allowed by the development of high-order computational techniques in the QCD and electroweak sectors of the Standard Model.

Recommendations for PDF usage

Two distinct cases are considered:

I. Precision theory predictions, a class of predictions, either within or beyond SM

Recommendation: Use the individual PDF sets ABM12, CJ15, CT14, JR14, HERA-PDF2.0, MMHT14 and NNPDF3.0 (or as many as possible), together with the respective uncertainties for the chosen PDF set, the strong coupling $\alpha_s(M_Z)$ and the heavy quark masses m_c, m_b and m_t.

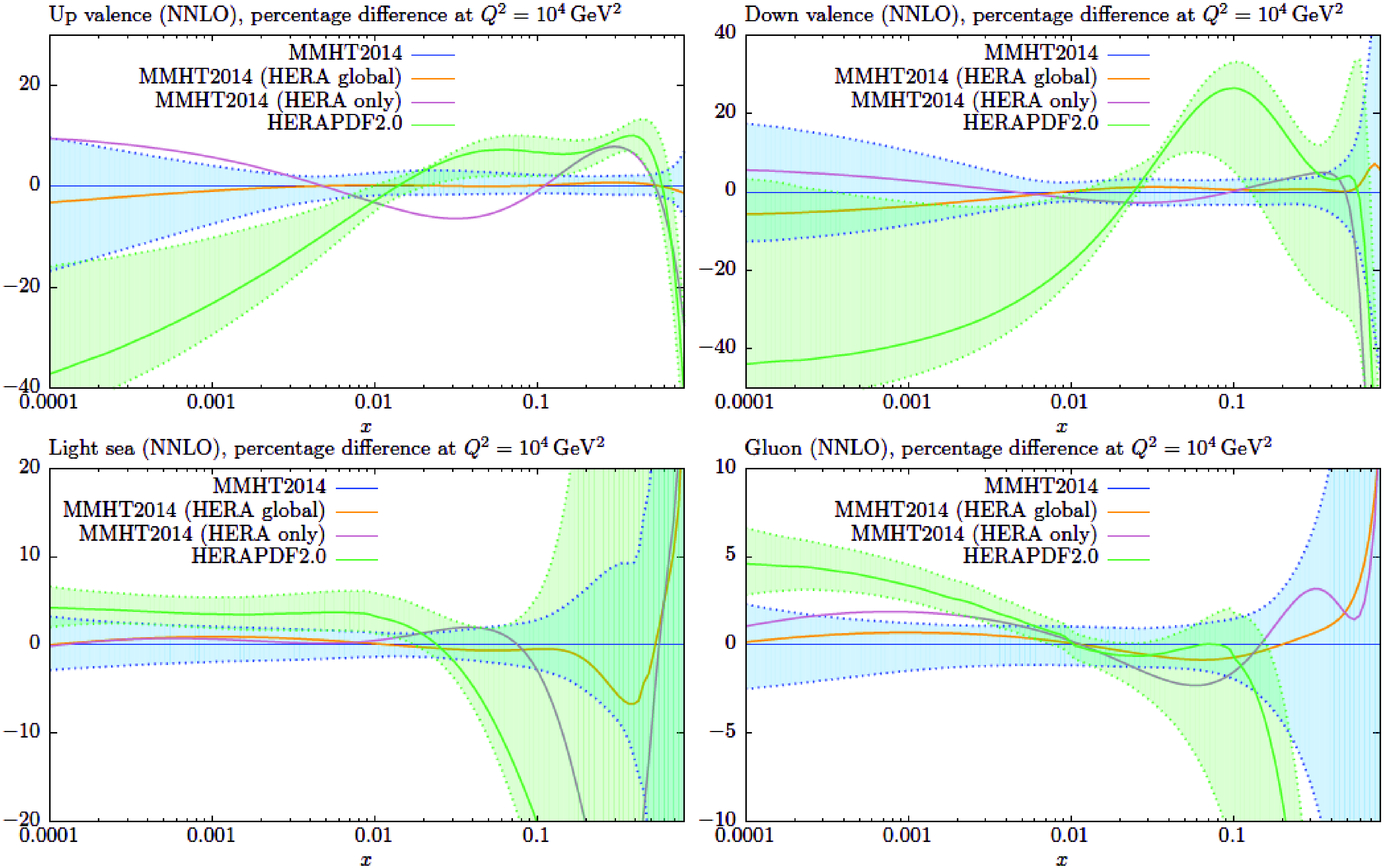
II. Other theory predictions

Recommendation: Use any one of the PDF sets listed in `LHAPDF(v6)`.

Note: the recent developments in modern tools often allow to include different PDFs in the theory calculations via *reweighting* methodology (i.e. weights from different PDFs stored on event basis)

→ allows to evaluate effects from different PDFs in efficient way

Fits to global data sets and HERAI+II data.



HERA II modified PDFs very well within MMHT2014 uncertainties.
PDFs from HERA II data only fit in some ways similar to HERAPDF2.0.

Uncertainties reduce a little.

	MMHT14	MMHT14 (HERA global)
W Tevatron (1.96 TeV)	$2.782^{+0.056}_{-0.056}$ $\binom{+2.0\%}{-2.0\%}$	$2.789^{+0.050}_{-0.050}$ $\binom{+1.8\%}{-1.8\%}$
Z Tevatron (1.96 TeV)	$0.2559^{+0.0052}_{-0.0046}$ $\binom{+2.0\%}{-1.8\%}$	$0.2563^{+0.0047}_{-0.0047}$ $\binom{+1.8\%}{-1.8\%}$
W^+ LHC (7 TeV)	$6.197^{+0.103}_{-0.092}$ $\binom{+1.7\%}{-1.5\%}$	$6.221^{+0.100}_{-0.096}$ $\binom{+1.6\%}{-1.5\%}$
W^- LHC (7 TeV)	$4.306^{+0.067}_{-0.076}$ $\binom{+1.6\%}{-1.8\%}$	$4.320^{+0.064}_{-0.070}$ $\binom{+1.5\%}{-1.6\%}$
Z LHC (7 TeV)	$0.964^{+0.014}_{-0.013}$ $\binom{+1.5\%}{-1.3\%}$	$0.966^{+0.015}_{-0.013}$ $\binom{+1.6\%}{-1.3\%}$
W^+ LHC (14 TeV)	$12.48^{+0.22}_{-0.18}$ $\binom{+1.8\%}{-1.4\%}$	$12.52^{+0.22}_{-0.18}$ $\binom{+1.8\%}{-1.4\%}$
W^- LHC (14 TeV)	$9.32^{+0.15}_{-0.14}$ $\binom{+1.6\%}{-1.5\%}$	$9.36^{+0.14}_{-0.13}$ $\binom{+1.5\%}{-1.4\%}$
Z LHC (14 TeV)	$2.065^{+0.035}_{-0.030}$ $\binom{+1.7\%}{-1.5\%}$	$2.073^{+0.036}_{-0.026}$ $\binom{+1.7\%}{-1.3\%}$
Higgs Tevatron	$0.874^{+0.024}_{-0.030}$ $\binom{+2.7\%}{-3.4\%}$	$0.866^{+0.019}_{-0.023}$ $\binom{+2.2\%}{-2.7\%}$
Higgs LHC (7 TeV)	$14.56^{+0.21}_{-0.29}$ $\binom{+1.4\%}{-2.0\%}$	$14.52^{+0.19}_{-0.24}$ $\binom{+1.3\%}{-1.7\%}$
Higgs LHC (14 TeV)	$47.69^{+0.63}_{-0.88}$ $\binom{+1.3\%}{-1.8\%}$	$47.75^{+0.59}_{-0.72}$ $\binom{+1.2\%}{-1.5\%}$
$t\bar{t}$ Tevatron	$7.51^{+0.21}_{-0.20}$ $\binom{+2.8\%}{-2.7\%}$	$7.57^{+0.18}_{-0.18}$ $\binom{+2.4\%}{-2.4\%}$
$t\bar{t}$ LHC (7 TeV)	$175.9^{+3.9}_{-5.5}$ $\binom{+2.2\%}{-3.1\%}$	$174.8^{+3.3}_{-5.3}$ $\binom{+1.9\%}{-3.0\%}$
$t\bar{t}$ LHC (14 TeV)	970^{+16}_{-20} $\binom{+1.6\%}{-2.1\%}$	964^{+13}_{-19} $\binom{+1.3\%}{-2.0\%}$

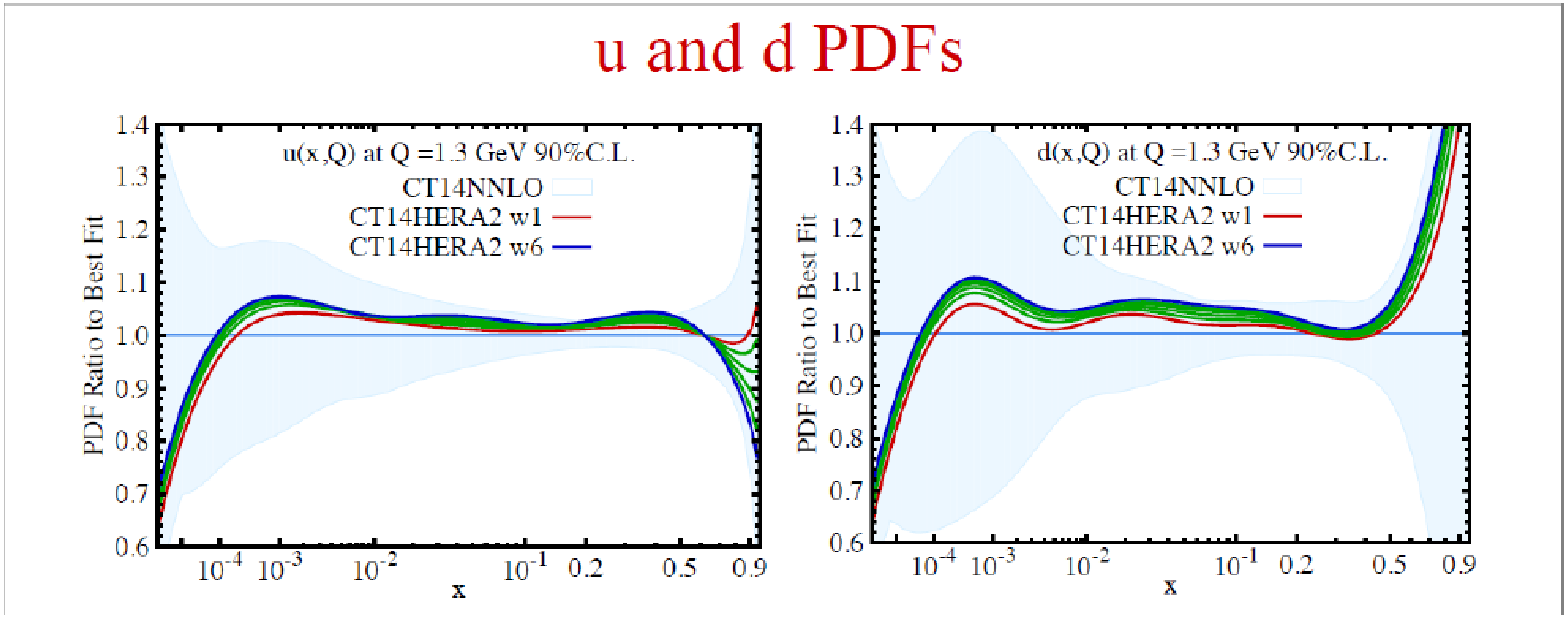
At most a $10 - 20\%$ reduction in uncertainties. Very small changes in central values.

Tension between HERAI+II e^- charged current data and other data.

Breakdown of fit quality in subsets of data

	no. points	NLO χ^2_{HERA}	NLO χ^2_{global}	NNLO χ^2_{HERA}	NNLO χ^2_{global}
correlated penalty		79.9	113.6	73.0	92.1
CC e^+p	39	43.4	47.6	42.2	48.4
CC e^-p	42	52.6	70.3	47.0	59.3

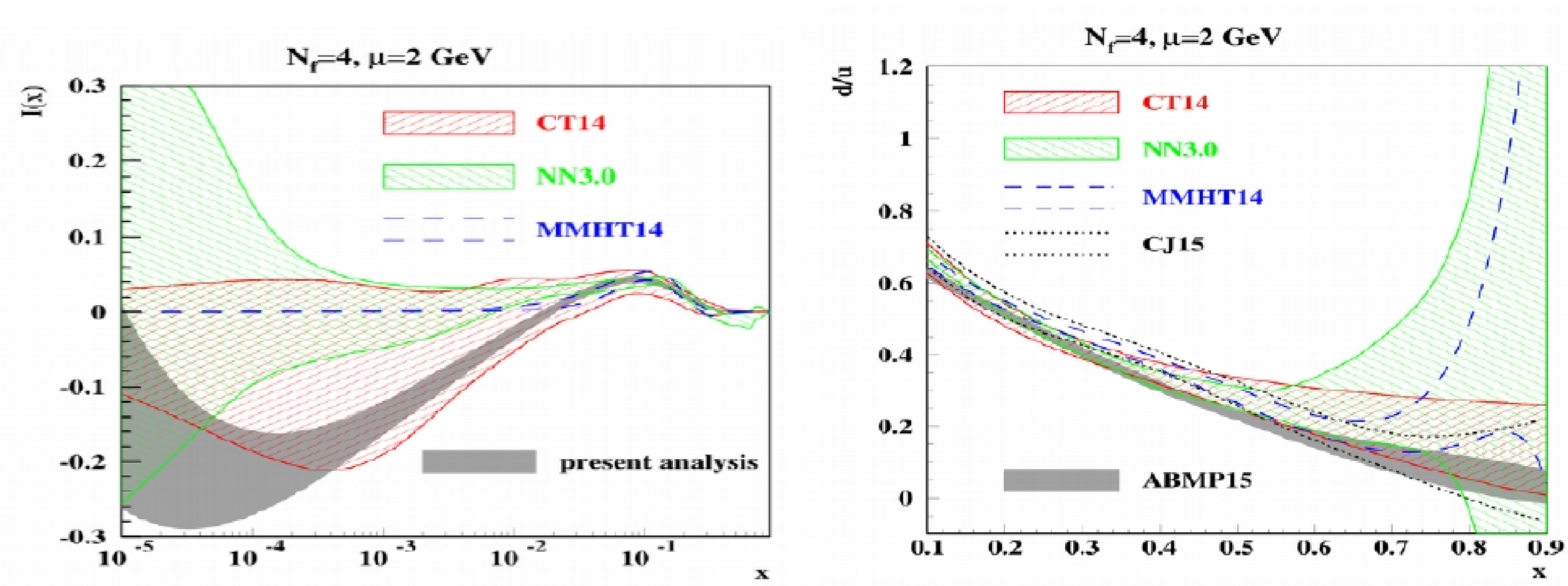
Also seen in shift in CT14 up quark near $x = 0.3$ if high weight given to data - Schmidt.



Look out for effect in e.g. high rapidity W^+ production.

Open questions on $\bar{d} - \bar{u}$ at small x and d/u as $x \to 1$.

Impact of the forward Drell-Yan data

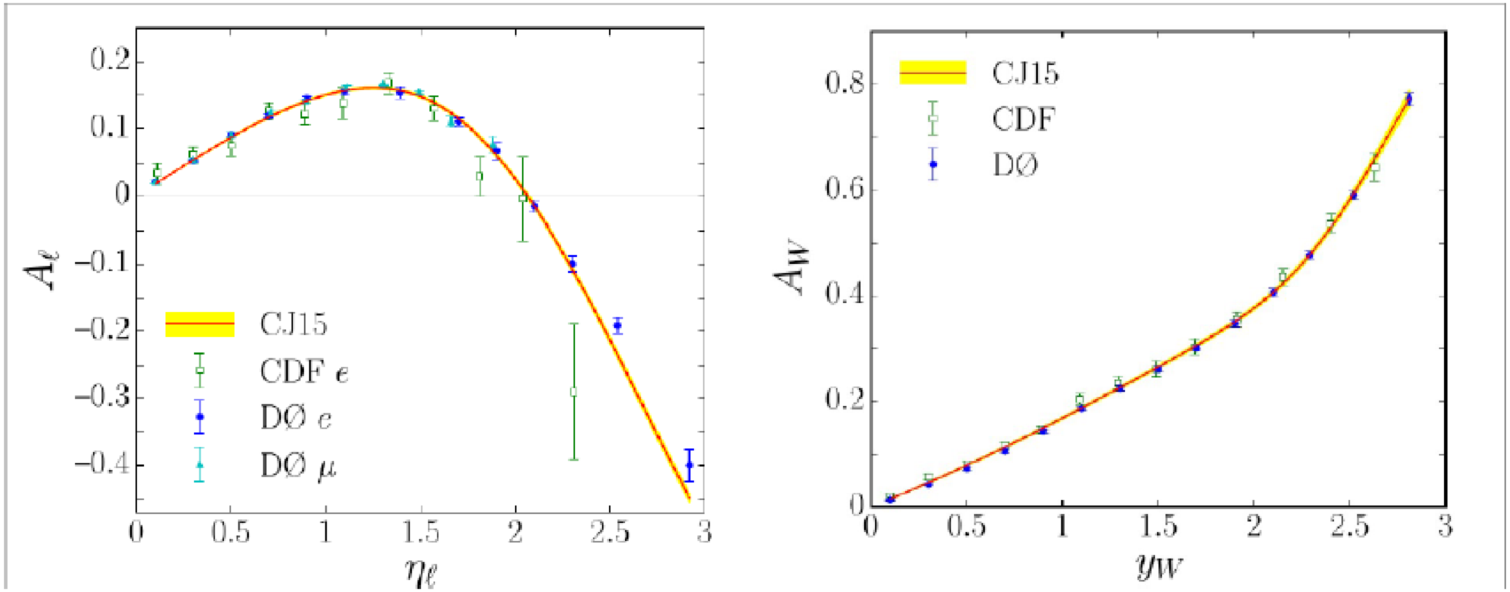


sa, Blümlein, Moch, Plačakytė, hep-ph/1508.07923

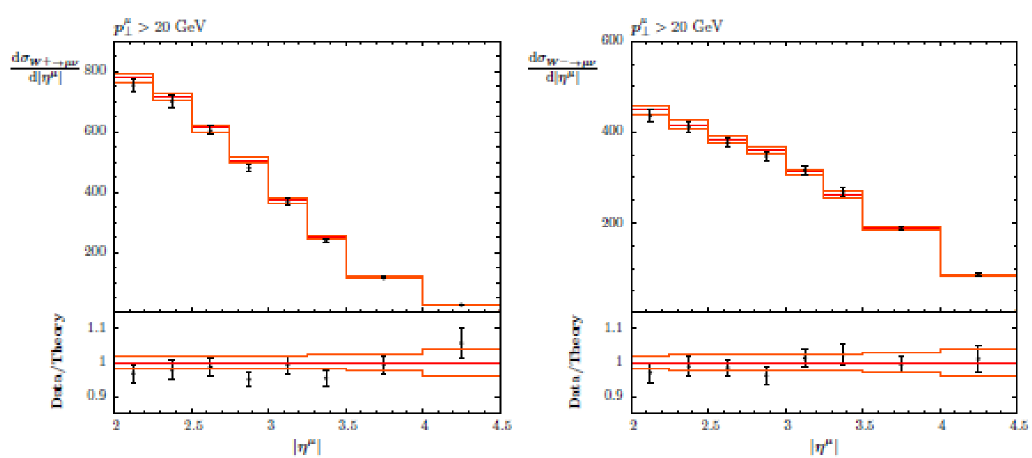
Accardi, et al. hep-ph/1603.08906

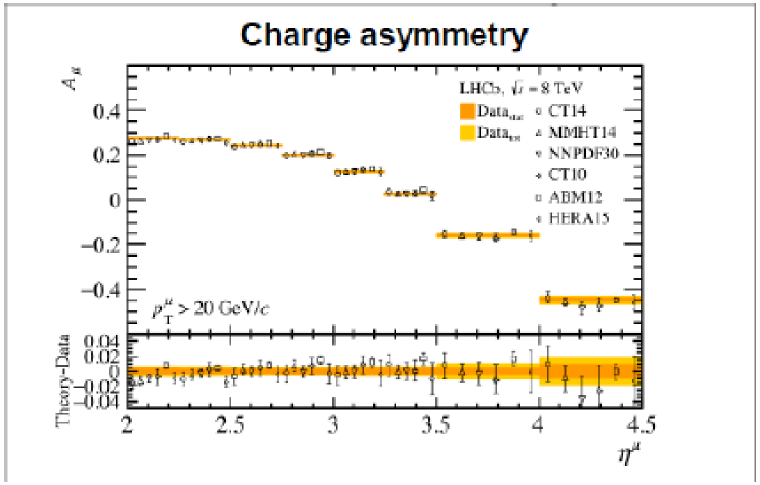
Strong claims made based on W^+, W^- from $D0$ and LHCb - Alekhin.

However, CJ15 fit $D0$ data (as do CT14 - not as well), and see no requirement for small-x $\bar{d} - \bar{u}$ difference.



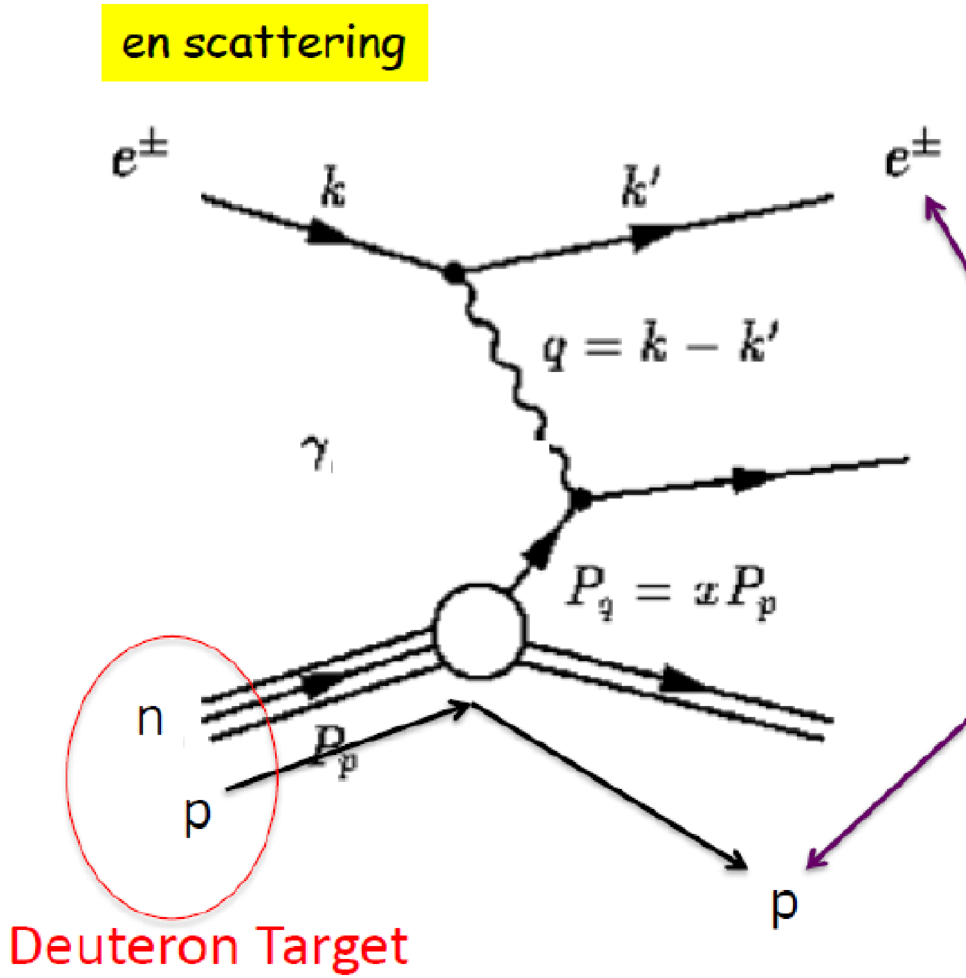
Similarly, e.g. MMHT14 compared very well to data on high rapidity W production at LHCb at 7 TeV and many sets compare well to W production at LHCb at 8 TeV. Obvious area to focus further study.

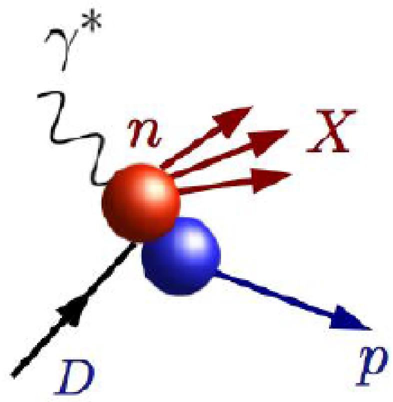




Gottfried Sum Rule Keppel

BONUS (Barely Off-Shell Neutron Structure) Experiment at JLab





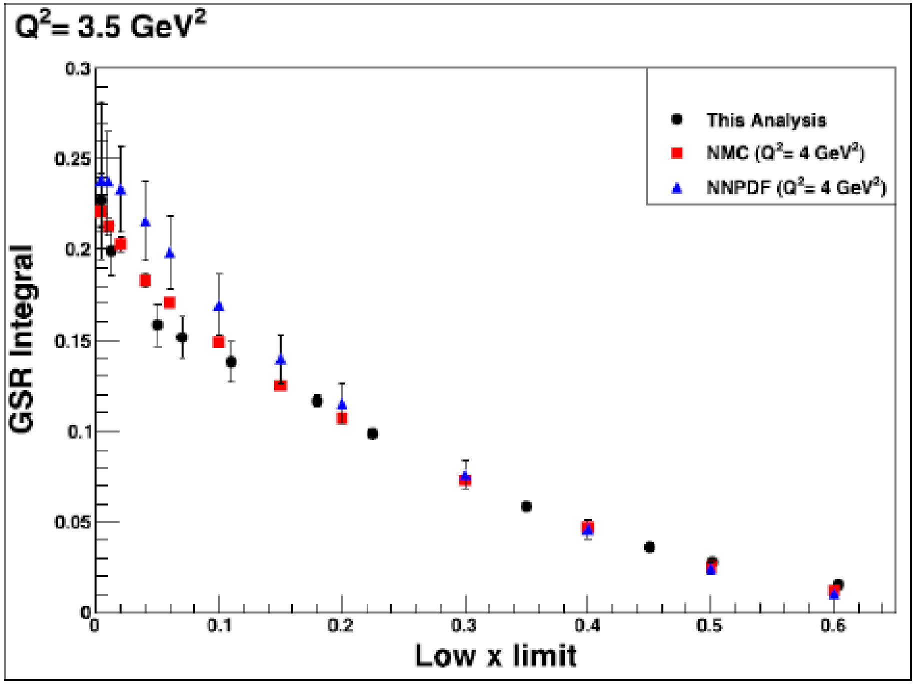
Measure DIS electron *in coincidence* with proton tag

- Protons at ***low*** momentum
  - Optimize bound/free nucleon structure
  - *~70 MeV, challenging!*
- Protons at backward angle
  - Minimize final state interactions

Effectively measure free neutron PDFs.

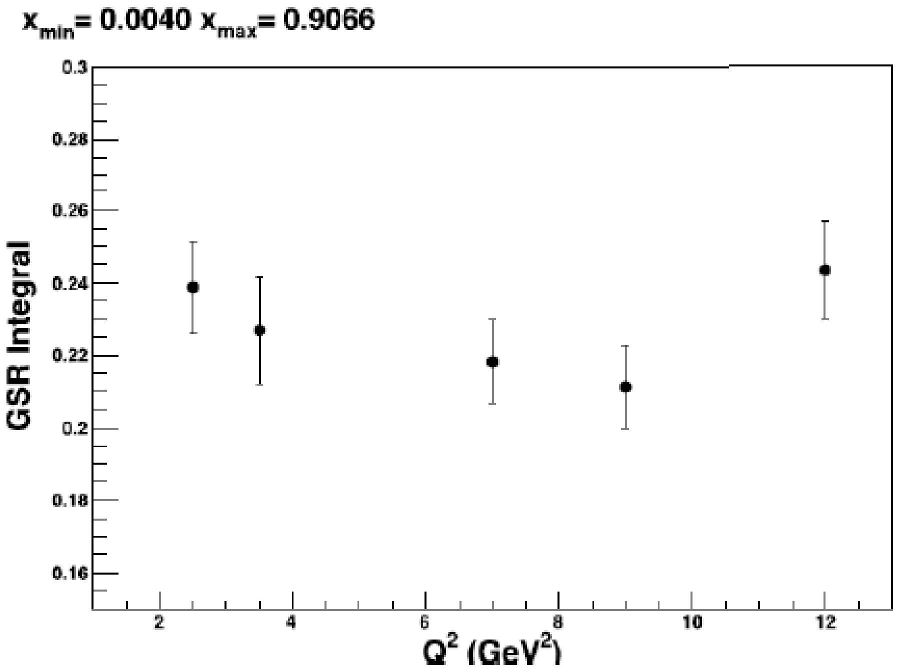
Allows a re-examination of the Gottfried sum rule down to $x = 0.004$ (extraploation at higher Q^2).

Again implications for low-x $\bar{d} - \bar{u}$.



Gottfried Sum Rule

Q^2	GSR Full	GSR - TM+HT	GSR LO
2.5	0.239	0.245	0.244
3.5	0.227	0.229	0.229
7.0	0.218	0.219	0.224
9.0	0.211	0.211	0.218
12.0	0.243	0.244	0.256



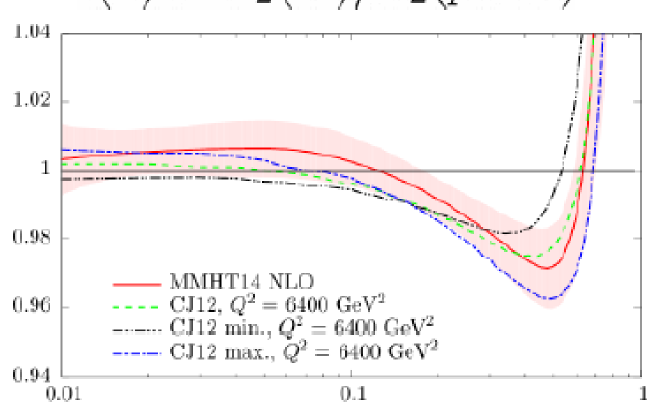
Simulanteous study of precision proton and deuteron data fit/verify deuteron corrections - Accardi.

NUCL / HEP symbiosis

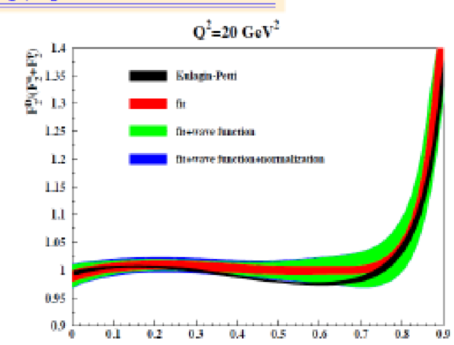
Observable	Experiment	# points	χ^2 LO	NLO	NLO (OCS)	NLO (no nucl)
DIS F_2	BCDMS (p) [81]	351	430	**438**	436	440
	BCDMS (d) [81]	254	297	**292**	289	301
	SLAC (p) [82]	564	488	**434**	435	441
	SLAC (d) [82]	582	396	**376**	380	507
DIS F_2 tagged	Jefferson Lab (n/d) [21]	191	218	**214**	213	219
W/charge asymmetry	CDF (e) [88]	11	11	**12**	12	13
	DØ (μ) [17]	10	37	**20**	19	29
	DØ (e) [18]	13	20	**29**	29	14
	CDF (W) [89]	13	16	**16**	16	14
	DØ (W) [19]	14	39	**14**	15	82
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26

- Ignoring nuclear dynamics, SLAC(d) and D0(W) pull d quark in opposite directions
  - **D0 (W) data determine nuclear corrections !!**
  - other asymmetries inconclusive by themselves
  - **BONUS data validate DO(W) analysis**

$$c(x) = F_2(D)/F_2(p+n)$$



RATIO F_2^D/F_2^N FROM GLOBAL FITS

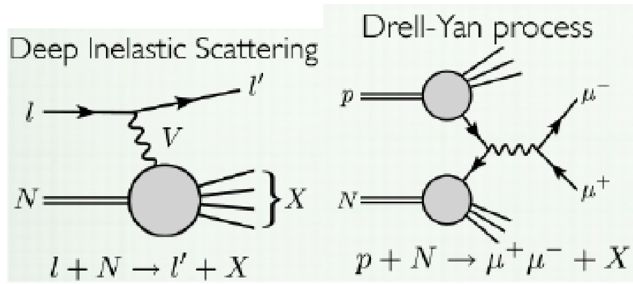


- *Experimental uncertainty from error matrix in global PDF fit;*
- *Systematic uncertainty related to the choice of the deuteron wave function;*
- *Systematic uncertainty related to the overall normalization of BCDMS D data.*

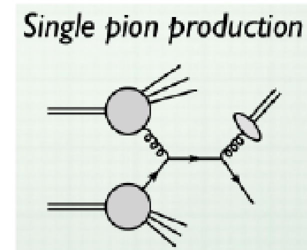
Nuclear PDFs - nCTEQ15 - Kusina

- NC DIS & DY

CERN BCDMS & EMC & NMC
N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)
FNAL E-665
N = (D, C, Ca, Pb, Xe)
DESY Hermes
N = (D, He, N, Kr)
SLAC E-139 & E-049
N = (D, Ag, Al, Au, Be,C, Ca, Fe, He)
FNAL E-772 & E-886
N = (D, C, Ca, Fe,W)



- Single pion production (new)



RHIC - PHENIX & STAR
N = Au

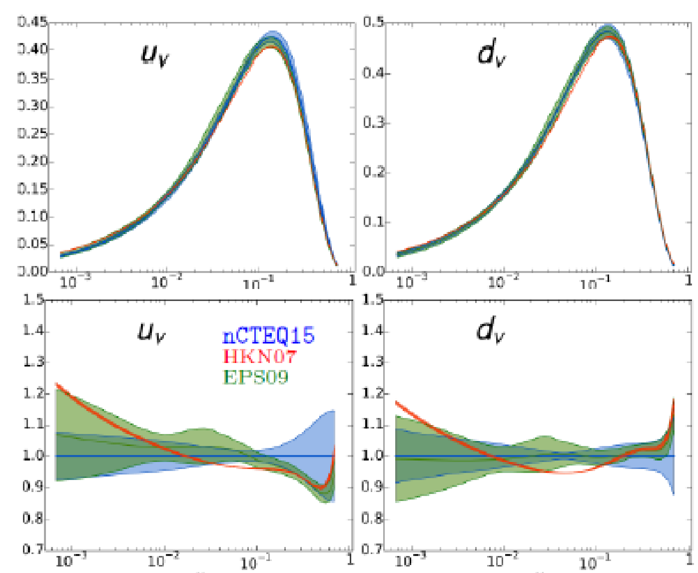
Also include some new LHC data on $p - Pb$ scattering via reweighting, but little impact yet.

No neutrino data included.

Valence nuclear distributions

Full lead nucleus distribution:

$$f^{Pb} = \frac{82}{208} f^{p/Pb} + \frac{208-82}{208} f^{n/Pb}$$



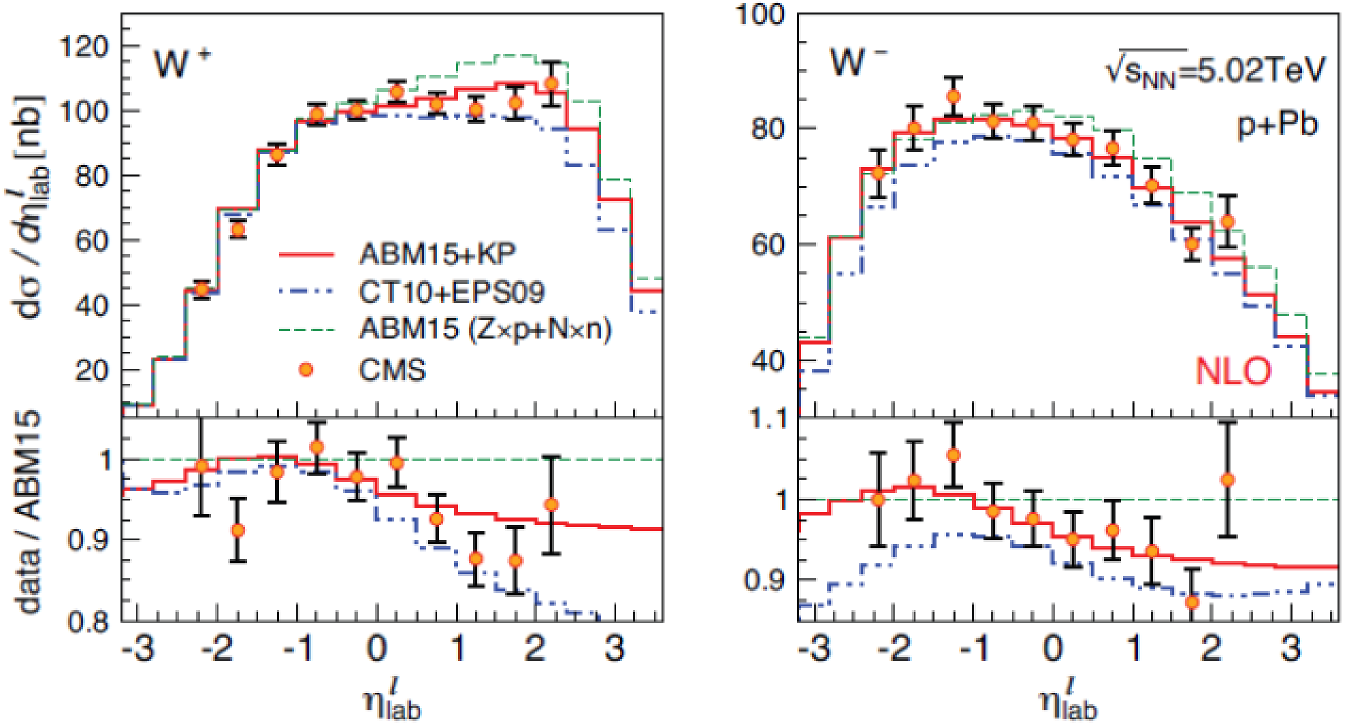
Kulagin-Petti nuclear PDFs.

✦ DIFFERENT EFFECTS on parton distributions (PDF) are taken into account:

$$q_{a/A} = q_a^{p/A} + q_a^{n/A} + \delta q_a^{\mathrm{MEC}} + \delta q_a^{\mathrm{coh}} \qquad a = u, d, s.....$$

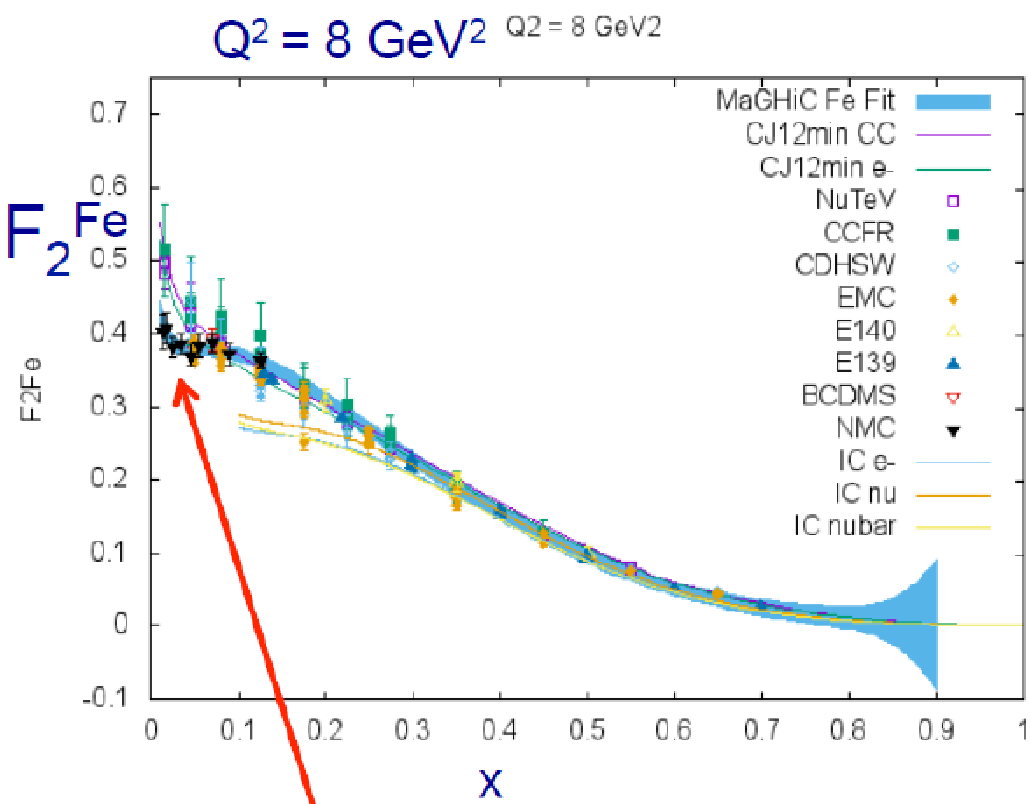
- $q_a^{p(n)/A}$ PDF in bound p(n) with Fermi Motion, Binding (FMB) and Off-Shell effect (OS)
- $\delta q_a^{\mathrm{MEC}}$ nuclear Meson Exchange Current (MEC) correction
- $\delta q_a^{\mathrm{coh}}$ contribution from coherent nuclear interactions: Nuclear Shadowing (NS)

PREDICTIONS FOR $W^{\pm}$ DIFFERENTIAL CROSS-SECTIONS



Difference between neutral and charged current nuclear data
Keppel

Results: F_2^{Fe} Data – NOT a ratio to deuterium!



LARGE discrepancy at small x between neutrino and charged lepton data

$2 < Q^2 < 20$ GeV^2, bin-centered to 8 GeV^2

MaGHiC fit is to charged lepton data (Malace, Gaskell, Higinboham, Cloet, Int. J. Mod. Phys. E 23 (2014) 1430013)

Cloet fit is valence only
- good agreement!

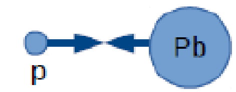
Charged lepton data agree with charged lepton and neutrino with neutrino

Remarkable agreement of all data at x > 0.1, 18/5 works within ~5%

Good agreement at high x, but less supression in the neutrino nuclear structure functions at low x.

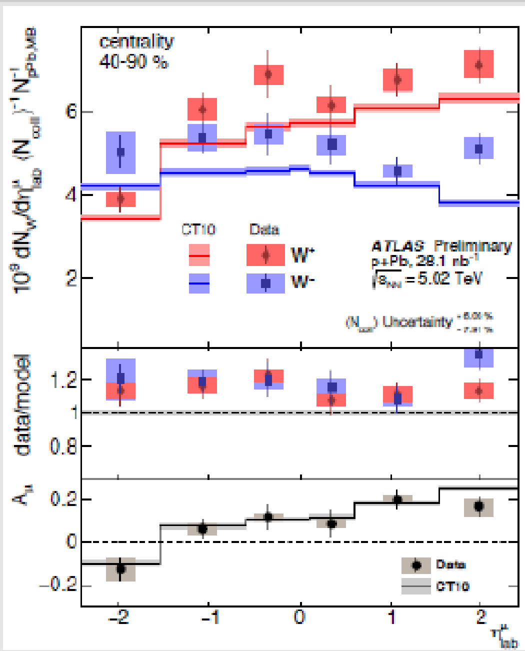
Detailed studies in nuclear collisions.

W bosons in p+Pb collisions

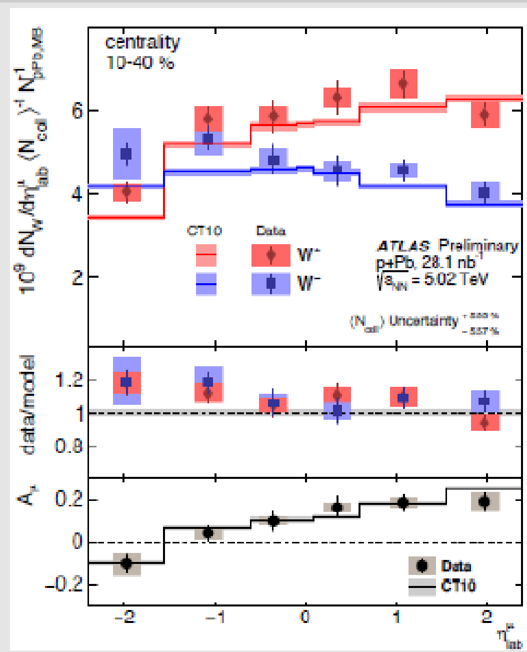


ATLAS-CONF-2015-056

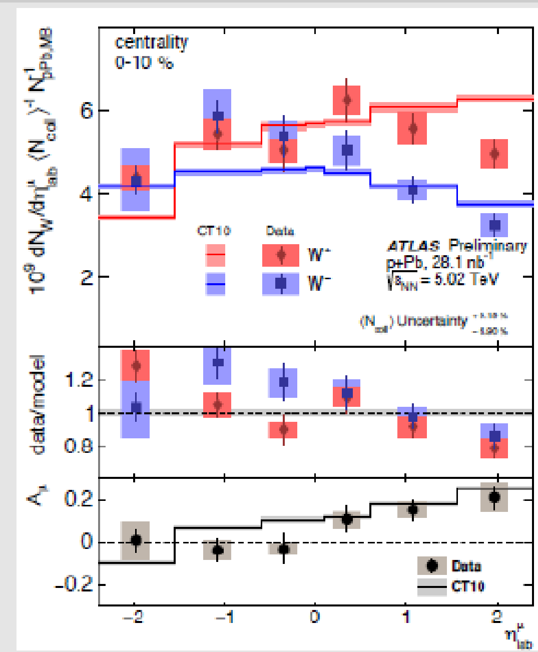
peripheral



mid-central



central



- W production vs η^{μ}_{lab} for three centrality bins normalized to number binary collisions and minimum-bias events
- Centrality dependence of nuclear modifications ?

Neutron distribution expected to be broader than proton in nucleaus Helenius.

So called neutron skin effect.

Neutron-skin effect

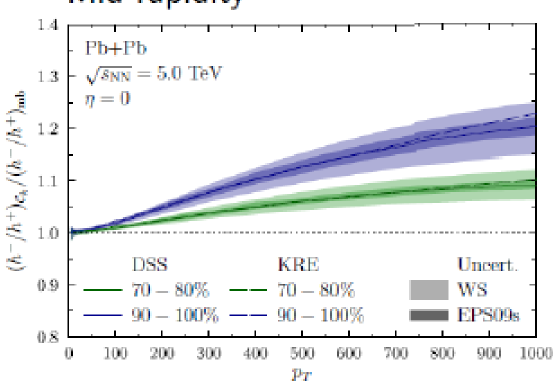
- Tail of neutrons extends farther
- We use parameters [C.M. Tarbert *et al.*, PRL 112 (2014) 24, 242502]
  - $R_p = 6.680$ fm, $R_n = 6.70 \pm 0.03$ fm
  - $d_p = 0.447$ fm, $d_n = 0.55 \pm 0.03$ fm

$\Rightarrow$ Modification for EM-sensitive observables in peripheral collisions

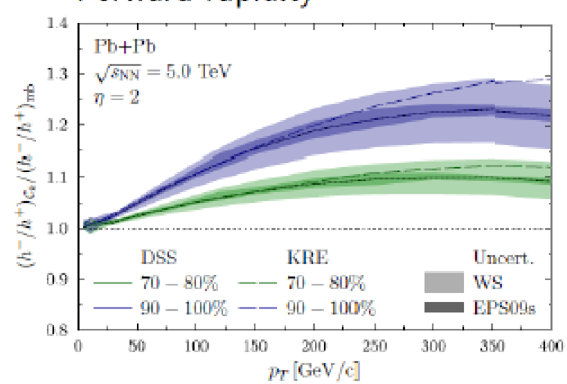
Charged hadrons

- Normalize with minimum bias h^-/h^+ (Ratio unity without NS-effect)

Mid-rapidity



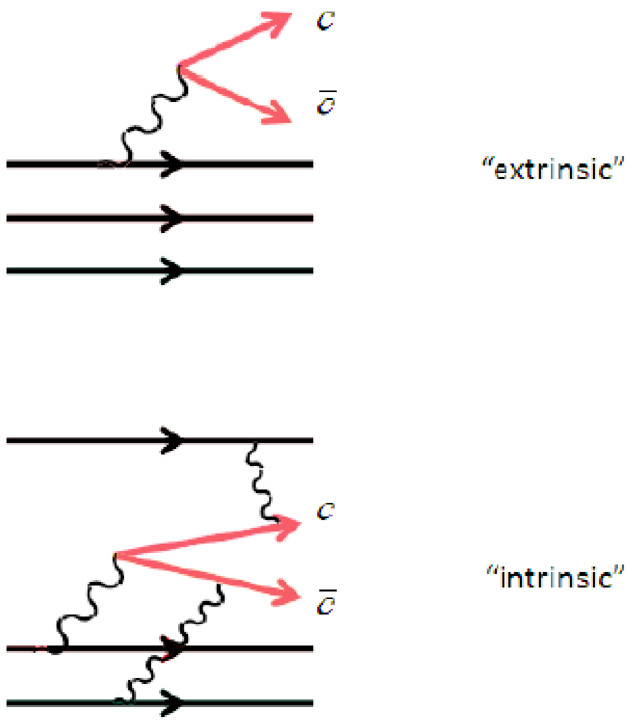
Forward rapidity

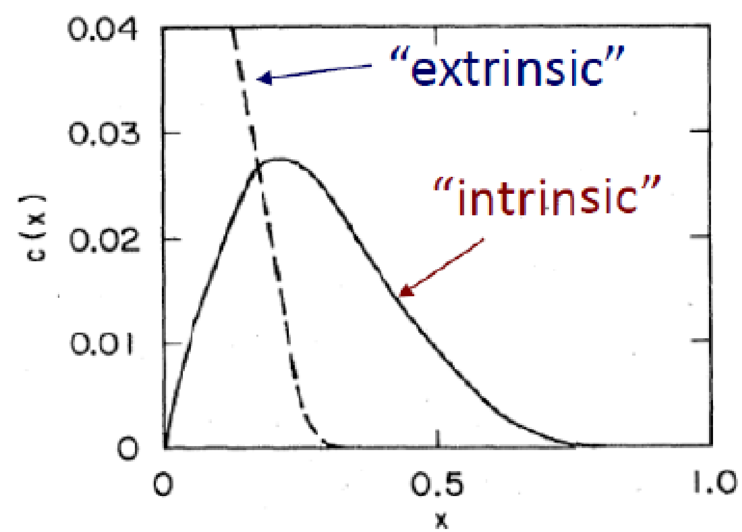


- FF-dependence cancels almost completely
  $\Rightarrow$ Observable robust against uncertainties in fragmentation
- nPDF-uncertainties remain small
- With $\eta = 2$ NS-effect enhanced at lower p_T

Intrinsic (Fitted) charm

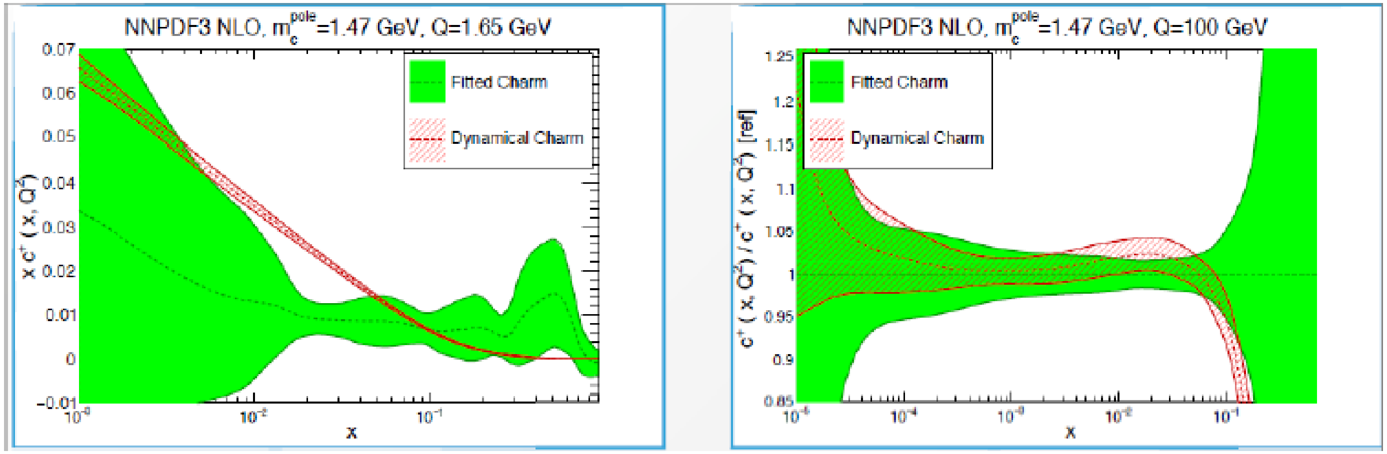
Intrinsic vs extrinsic



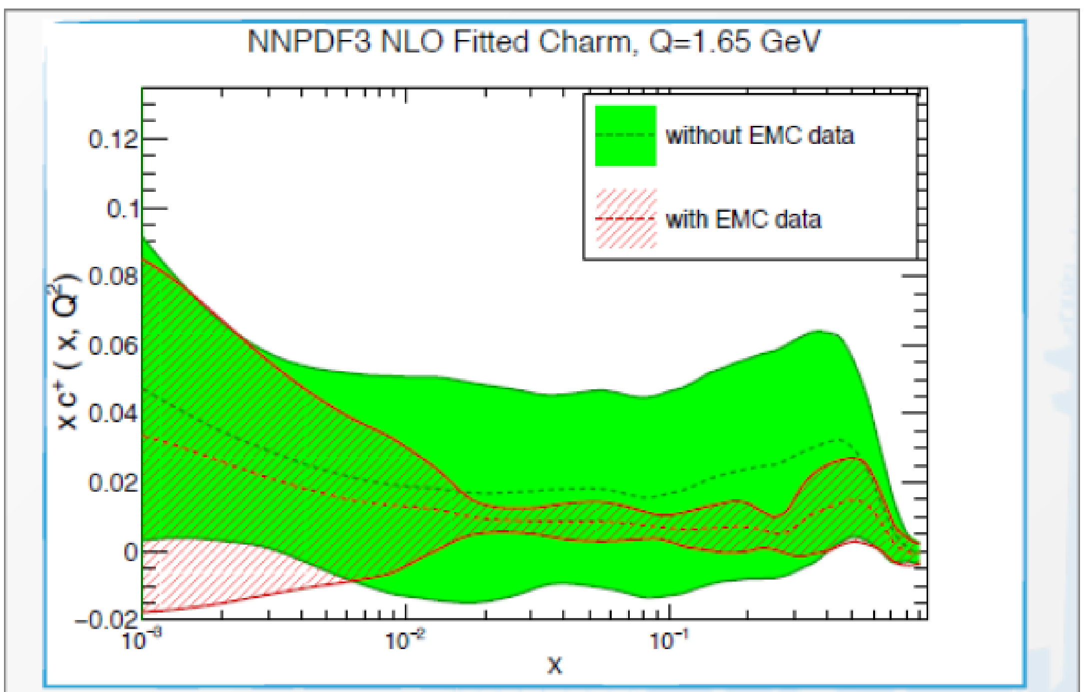


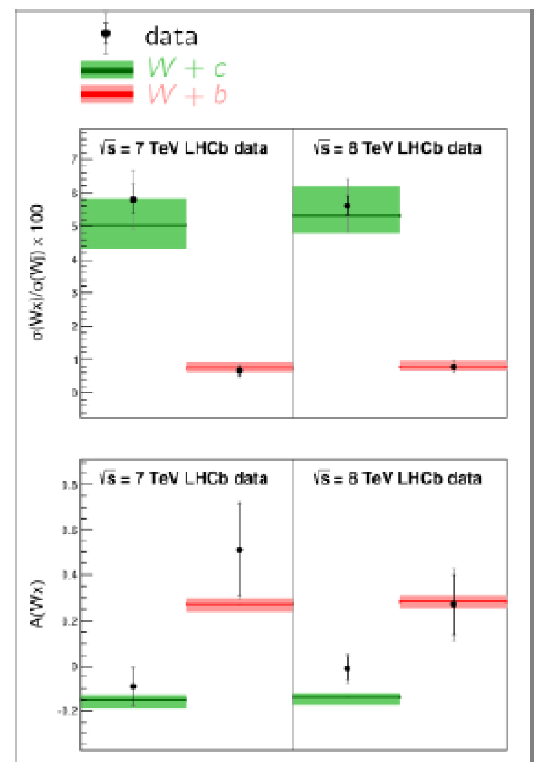
The intrinsic charm originating from the five-quark Fock state is to be separated from the extrinsic charm produced in the splitting of gluons into $c\bar{c}$.

NNPDF study Rottoli. Fitted charm lower than dynamical charm in some places, particularly if EMC data is fit. Larger uncertainty if not.

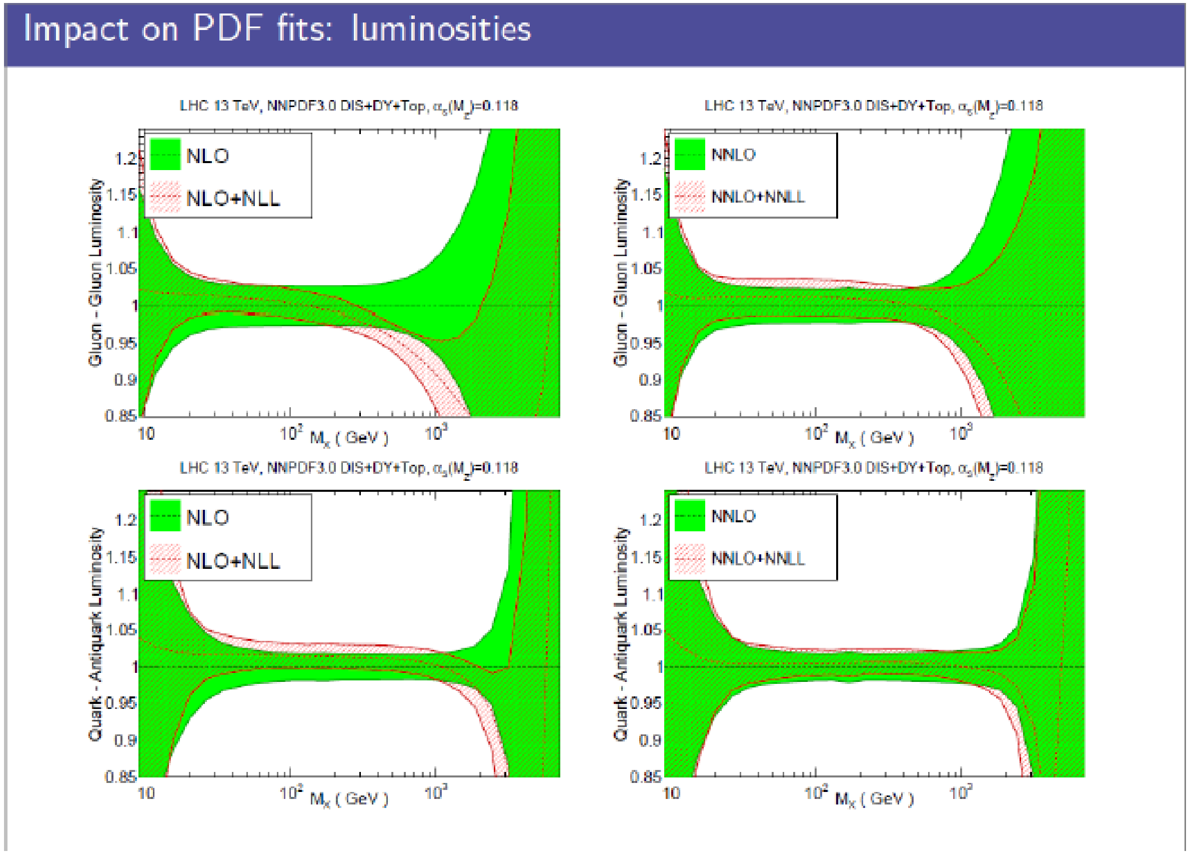


Implications for predictions for $W, Z + c$ data.

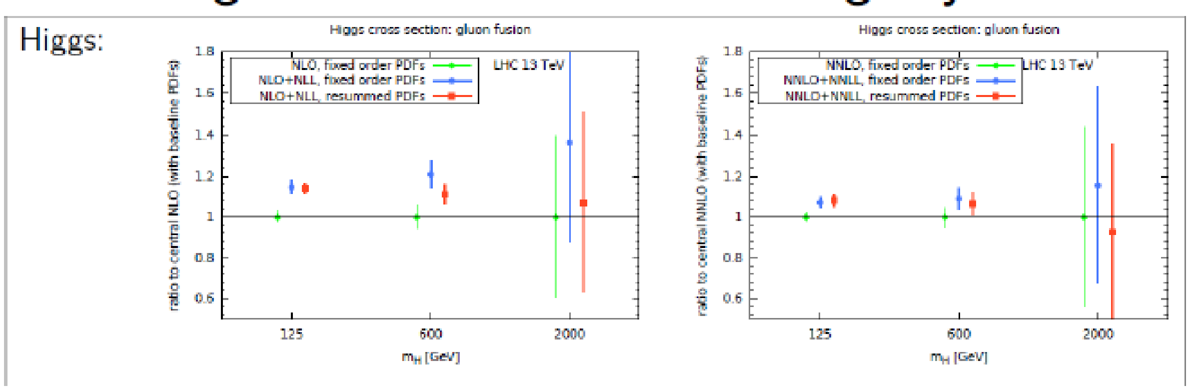




Threshold resummations Bonvini.



Larger at NLO than NNLO. Also some effect from data missed out in the fit. Correct PDFs bring cross section back slightly towards fixed order.



Also very preliminary results on small-x resummation.

Asymptotic behaviour Nocera.

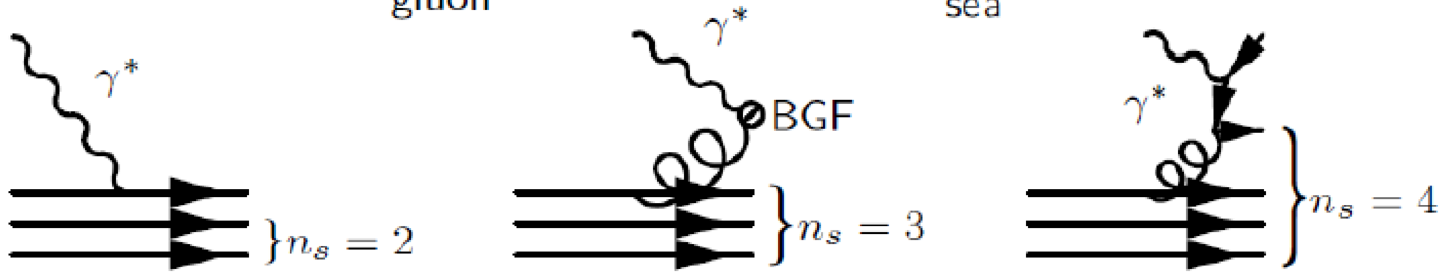
Comparison with quark counting rules expectations

f_i	Q^2 [GeV^2]	$\beta_{f_i}(x_b = 0.9, Q^2)$ NNPDF3.0	CT14	MMHT14	ABM12	CJ15	b_{f_i}
u_V	2.0	$+2.94 \pm 0.52$	$+3.11 \pm 0.28$	$+3.37 \pm 0.07$	$+3.38 \pm 0.06$	$+3.50 \pm 0.01$	~ 3
	10.0	$+3.30 \pm 0.69$	$+3.38 \pm 0.29$	$+3.62 \pm 0.07$	$+3.61 \pm 0.05$	$+3.78 \pm 0.01$	
d_V	2.0	$+3.03 \pm 1.96$	$+3.27 \pm 0.37$	$+2.05 \pm 0.59$	$+4.72 \pm 0.43$	$+3.42 \pm 0.06$	~ 3
	10.0	$+3.23 \pm 1.88$	$+3.52 \pm 0.36$	$+2.29 \pm 0.59$	$+4.92 \pm 0.42$	$+3.68 \pm 0.05$	
S	2.0	$+6.86 \pm 7.25$	$+6.41 \pm 1.22$	$+8.19 \pm 0.68$	$+8.16 \pm 0.38$	$+7.73 \pm 0.18$	~ 7
	10.0	$+6.76 \pm 6.71$	$+6.91 \pm 1.14$	$+6.83 \pm 0.88$	$+8.51 \pm 0.38$	$+8.15 \pm 0.18$	
g	2.0	$+2.95 \pm 1.25$	$+5.08 \pm 2.18$	$+1.65 \pm 0.23$	$+4.18 \pm 0.06$	$+6.11 \pm 0.33$	~ 5
	10.0	$+3.25 \pm 0.98$	$+5.13 \pm 0.51$	$+2.24 \pm 0.23$	$+4.44 \pm 0.06$	$+4.91 \pm 0.33$	

At large x, quark counting rules predict that $\boxed{x f_i \sim (1-x)^{2n_s - 1}}$

(n_s is the minimum number of spectator partons, not struck in a hard scattering process)

valence gluon sea

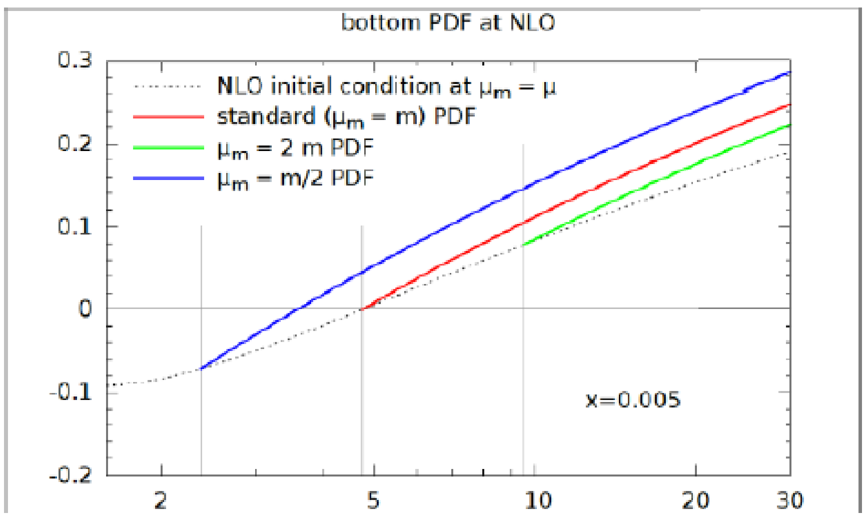


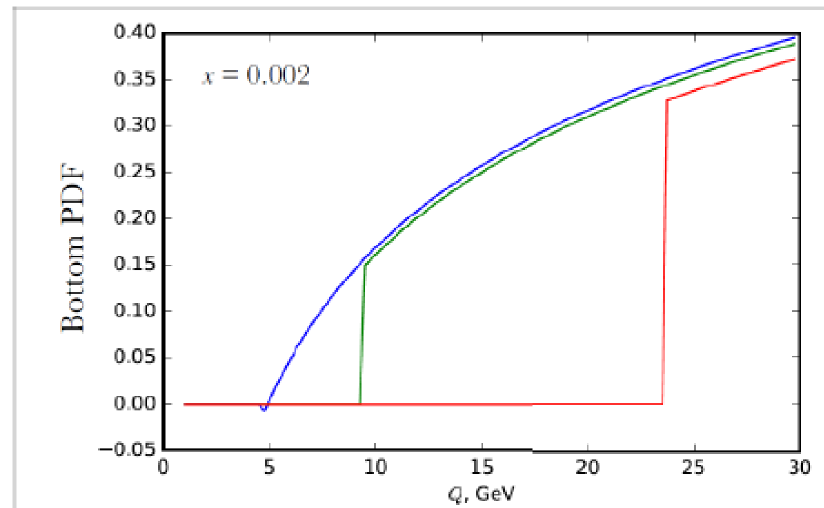
It is unclear from the quark model argument at which scale quark counting rules hold (fortunately the scale dependence of $\beta_{f_i}(x, Q^2)$ is reasonably moderate)

APFEL update Bertone

Displaced Heavy-Quark Thresholds

Diminished sensitivity at higher orders.





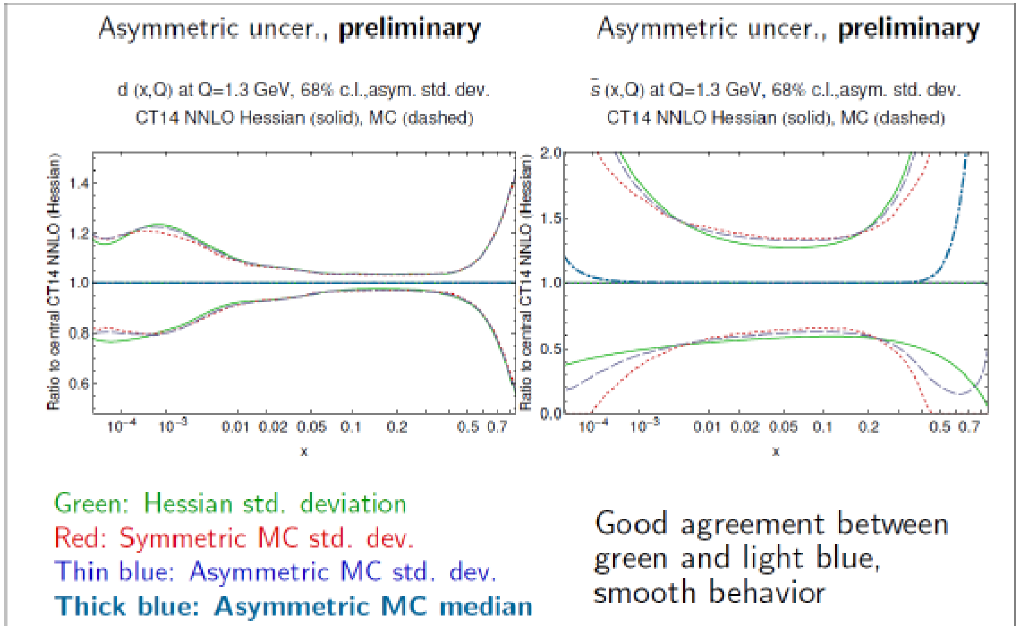
xFitter update and report - Zenaiev.

xFitter (former HERAFitter): an open source QCD fit framework

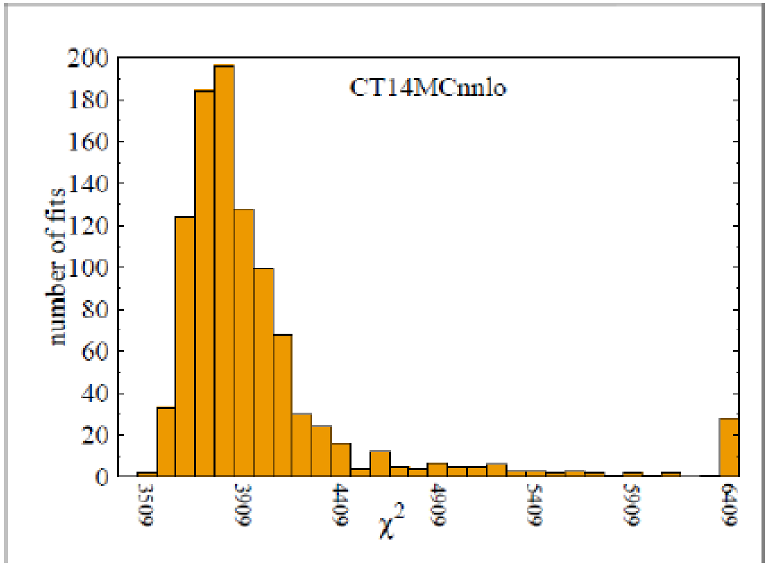
[EPJ C75 (2015) 304]

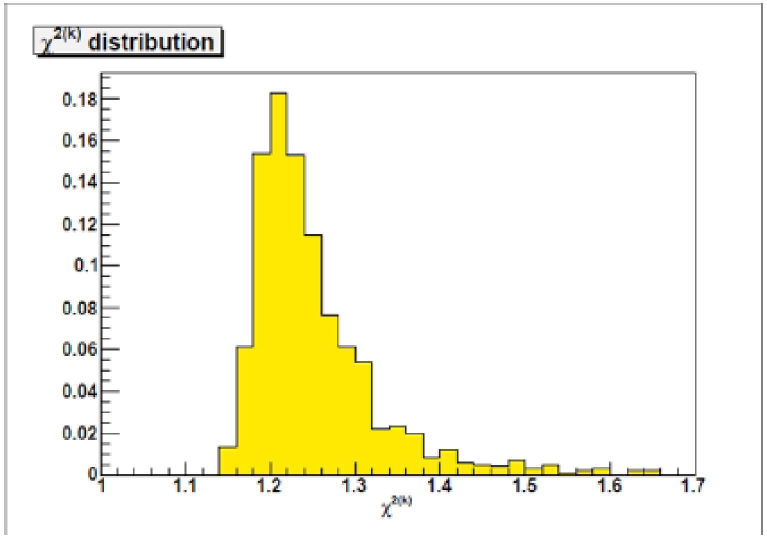
- on theory side: a unique QCD framework to address theoretical differences
- on experimental side: assess consistency and/or impact of new data
- additional dedicated studies by xFitter developers

CT14 replicas Hou. Study of asymmetric uncertaities.



Also plot of χ^2 distribution for 1000 replicas with 28 eigenvectors and tolerance $\sim$ 40 for one sigma. Extremely similar to NNPDF from completely different approach.





Session on transverse momentum dependent PDFs.

Why Transverse Momentum Dependent PDFs?

Goal: full TMD PDFs

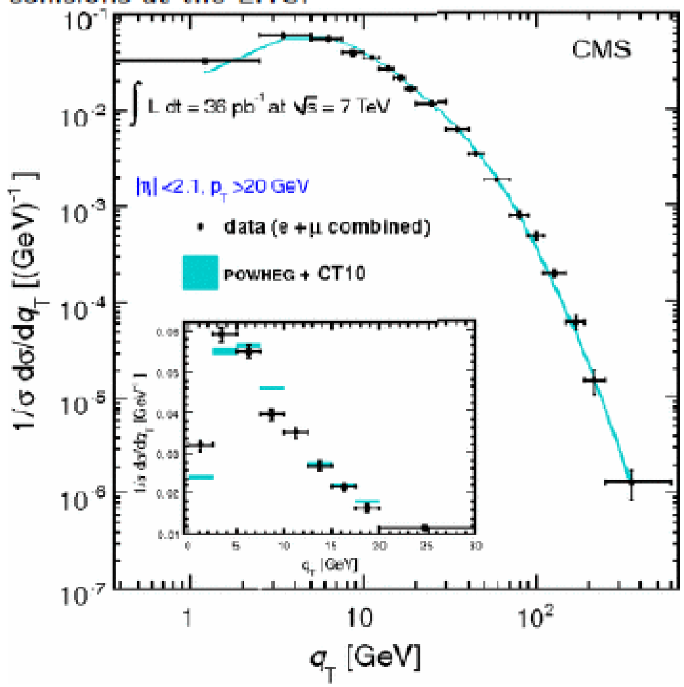
TDMs are important in studies on:

- resummation at all orders in the QCD coupling to many observables in high-energy hadronic collisions,
- nonperturbative information on hadron structure,
- perturbative region at very low k_T where QCD evolution equations (DGLAP, BFKL, CCFM) describe processes
- a proper and consistent simulation of parton showers,
- multi-scale problems in hadronic collisions,
- ...

Acta Physica Polonica B, Vol. 46 (2015), Transverse Momentum Dependent (TMD) Parton Distribution Functions: Status and Prospects

Important processes: Drell-Yan hadroproduction of electroweak gauge bosons, Higgs production...

Example:
The Z-boson transverse momentum q_T spectrum in p
collisions at the LHC:



S. Chatrchyan et al., Phys. Rev. D 85, 032002 (2012)

4

New large scale project including full coupled evolution. Lots now to do Lelek.

Evolution using MC method:

In this presentation: MC results obtained with updated and improved ▸ uPDFevolv code:

old version:

- ccfm evolution,
- only gluon and valence quark evolution (separately)
- all loop $P(z)$,
- 1- or 2-loop-α_s.
- $f(x, t)$,

Evolution applicable only for small x, not very high Q^2 and all kinematically allowed k_T.

new version:

- full coupled quark and gluon DGLAP evolution (gluon, sea and valence evolution)
- fixed flavour number scheme (only u,d,s)
- LO in $P(z)$ (we plan to have NLO in $P(z)$),
- 1-loop-α_s (but also 2-loop-α_s implemented).
- $xf(x, t)$,

Evolution over the whole range in x, Q^2 and all kinematically allowed k_T.

https://updfevolv.hepforge.org/

Also saturation effects Taheri Monafred.

TMDlib - `https://tmdlib.hepforge.org` and
TMDplotter - `https://tmdplotter.desy.de` - Connor.

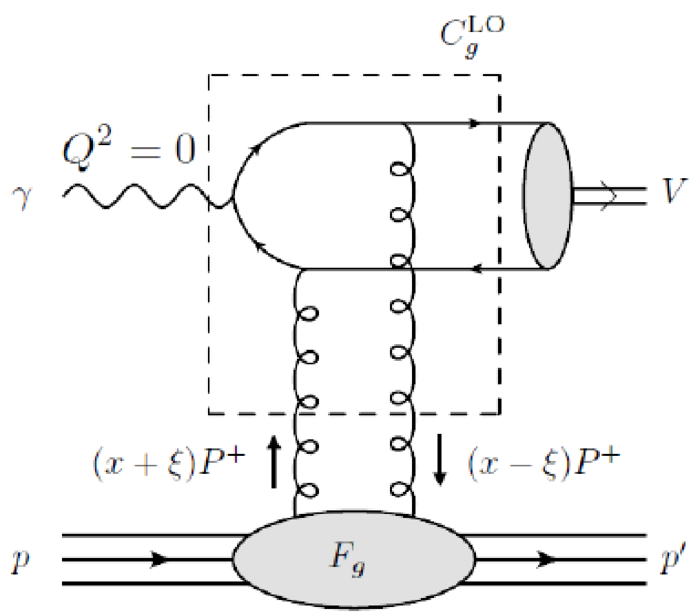
Also TMD talk by Lykasov.

Exclusive $J/\Psi, \Upsilon$ production Jones

- Sensitive to Generalised Parton Distributions (GPDs)
  - Conjectured to be related to PDFs Shuvaev 99
- Must describe formation of HVM
  - Relativistic corrections unknown - could be large or small

Frankfurt, Koepf, Strikman 96, 98; Hoodbhoy 97

General Setup & Assumptions



- Assume process factorises:
  $$C_{g/q} \otimes F_{g/q} \otimes \phi_{c\bar{c}}^{J/\psi}$$
- HVM formation described in NRQCD, we take only the leading term: $\langle O_1 \rangle \propto \Gamma\left[V \to e^+e^-\right]$
- Compute at (Mandelstam) $t = 0$, restore assuming $\sigma \sim \exp(-Bt)$
- Unpolarised, helicity non-flip
  $$F_g(x,\xi,0) = \sqrt{1-\xi^2}\mathcal{H}_g(x,\xi,0)$$

Amplitude:

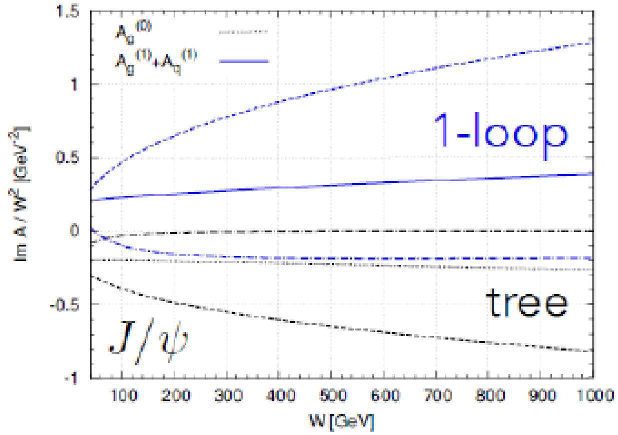
Contributes at NLO (on C_q)

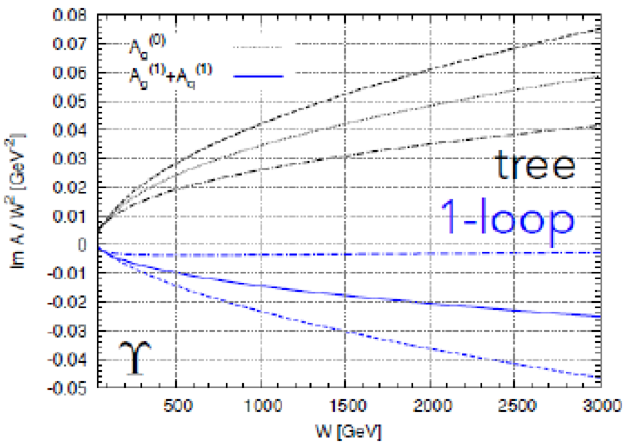
$$T \propto \int_{-1}^{1} \mathrm{d}x \left[C_g(x,\xi)\, F_g(x,\xi) + \sum_{q=u,d,s} C_q(x,\xi)\, F_q(x,\xi) \right]$$

Setup follows: Ivanov, Schäfer, Szymanowski, Krasnikov, 2004

Photoproduction Amplitudes

GPDs obtained using full Shuvaev Transform from CTEQ66 Martin et al. 09





- J/ψ receives huge (opposite sign) loop corrections
- Loop corrections can dominate tree level contribution
- Very large variation with change of scale $\mu_R^2 = \mu_F^2 = (m^2/2, m^2, 2m^2)$

- ϒ still has sizeable (negative) loop corrections: NLO CS very suppressed compared to LO CS
- Tree level dominates loop corrections
- Variation with scale less dramatic

13

In principle stable framework for calculation, but uncertainty to soem degree in relating gluon to skewed parton distribution, and known loop corrections lead to large corrections, particularly for J/Ψ.

PDFs on the Lattice Steffens

The light cone distributions:

$x = \frac{k^+}{P^+}$

$0 \le x \le 1$

Distributions can be defined in an Infinite Momentum Frame: P_3, P^+ goes to infinite

Quasi distributions:

P_3 large but finite

Some constituents can be moving backward or even with momentum greater than P_3

$x < 0$ or $x > 1$ is possible

Usual partonic interpretation is lost

- Relating finite to infinite momentum
- Axial gauge $A_3 = 0$
- UV divergence regulate with $|k_T| \le \Lambda \sim \frac{1}{a}$
- Renormalization scale μ

$$\begin{aligned} q(x,\mu) &= \tilde{q}(x,\Lambda,P_3) - \frac{\alpha_s}{2\pi}\tilde{q}(x,\Lambda,P_3)\,\delta Z_F^{(1)}\left(\frac{\mu}{P_3},\frac{\Lambda}{P_3}\right) \\ &\quad - \frac{\alpha_s}{2\pi}\int_{-1}^{1} Z^{(1)}\left(\frac{x}{y},\frac{\mu}{P_3},\frac{\Lambda}{P_3}\right)\tilde{q}(y,\Lambda,P_3)\frac{dy}{|y|} + \mathcal{O}(\alpha_s^2) \end{aligned}$$

Desired quantity

From the lattice

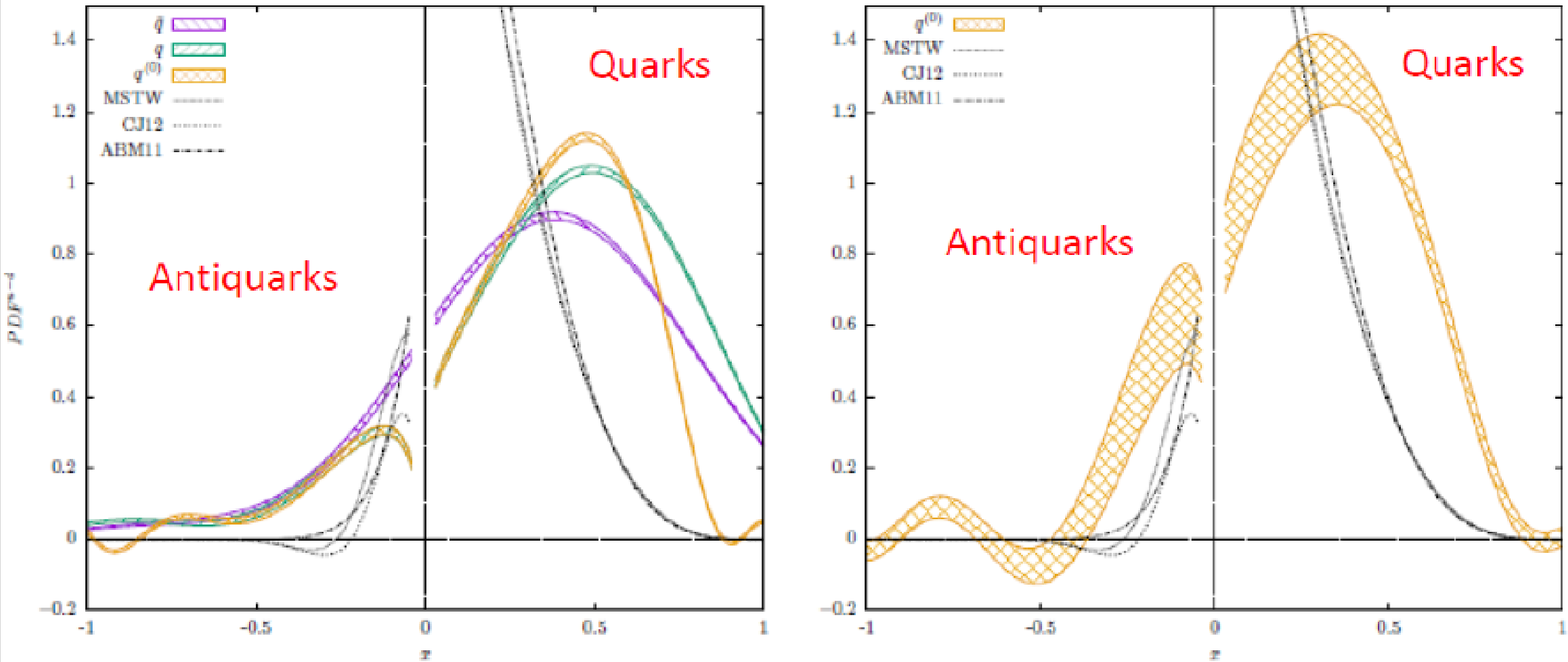
From pQCD. How to calculate them?

Calculate Quasi distributions at finite longitudinal momentum rather than in infinite momentum frame.

Try to transform to correct limit.

$u(x) - d(x)$

Crossing relation: $\overline{q}(x) = -q(-x)$



$P_3 = \frac{4\pi}{L}$ $P_3 = \frac{6\pi}{L}$

$P_3 = 2\pi/L$ on available lattices corresponds to about $0.4 \mathrm{GeV}$.

Limited to about 1.6 GeV at best, but can see improvements as better lattices are used.

Look forward to future developments.

Thank you for your patience ;)