Interplay of target mass and threshold corrections in large-x PDF determination

and much more...

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Hampton U. and Jefferson Lab

Intersections of BSM Phenomenology and QCD for New Physics Searches

INT, Seattle, October 22nd, 2015

Plan

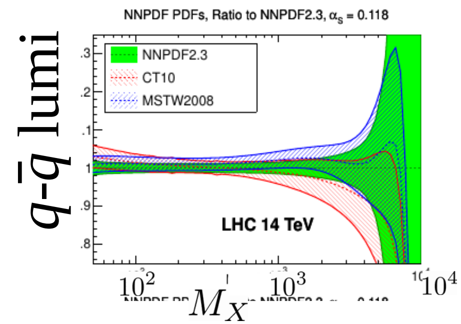
- **Intersections**
  - Hadronic, nuclear, particle physics
  - A global approach across subfields
- **Proton PDFs**
  - Proton vs. nuclear targets
- **The CJ15 PDFs** – almost finalized !!
  - Deuteron corrections and the *d*/*u* ratio
  - How to use proton targets to study the deuteron
  - Connection to lattice QCD
- **Threshold resummation: the new PDF frontier**
  - Interplay of Target Mass and Threshold corrections
- **Conclusions**

Intersections

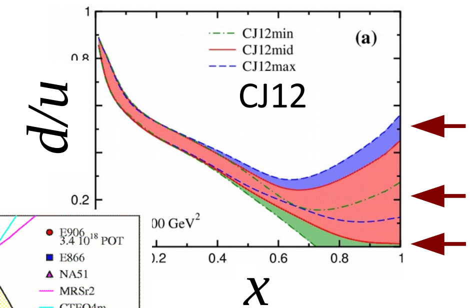
Why (n)PDFs ?

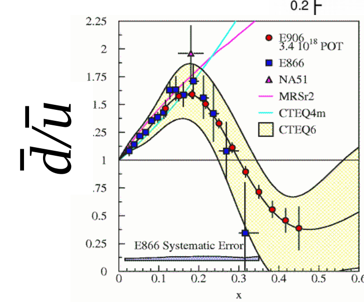
Accardi – Mod.Phys.Lett. A28 (2013) 35
Forte and Watt – Ann.Rev.Nucl.Part.Sci. 63 (2013) 291

- **High-energy** *(large to small x)*
  - Beyond the Standard Model searches
  - Precision (Higgs) physics
  - NuTeV weak mixing angle
  - Small-*x* and gluonic "matter"

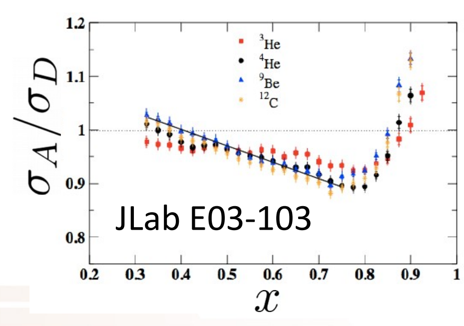


- **Hadron structure** *(large to medium x)*
  - Effects of confinement on valence quarks
  - q – qbar asymmetries; isospin asymmetry
  - Strangeness, intrinsic charm

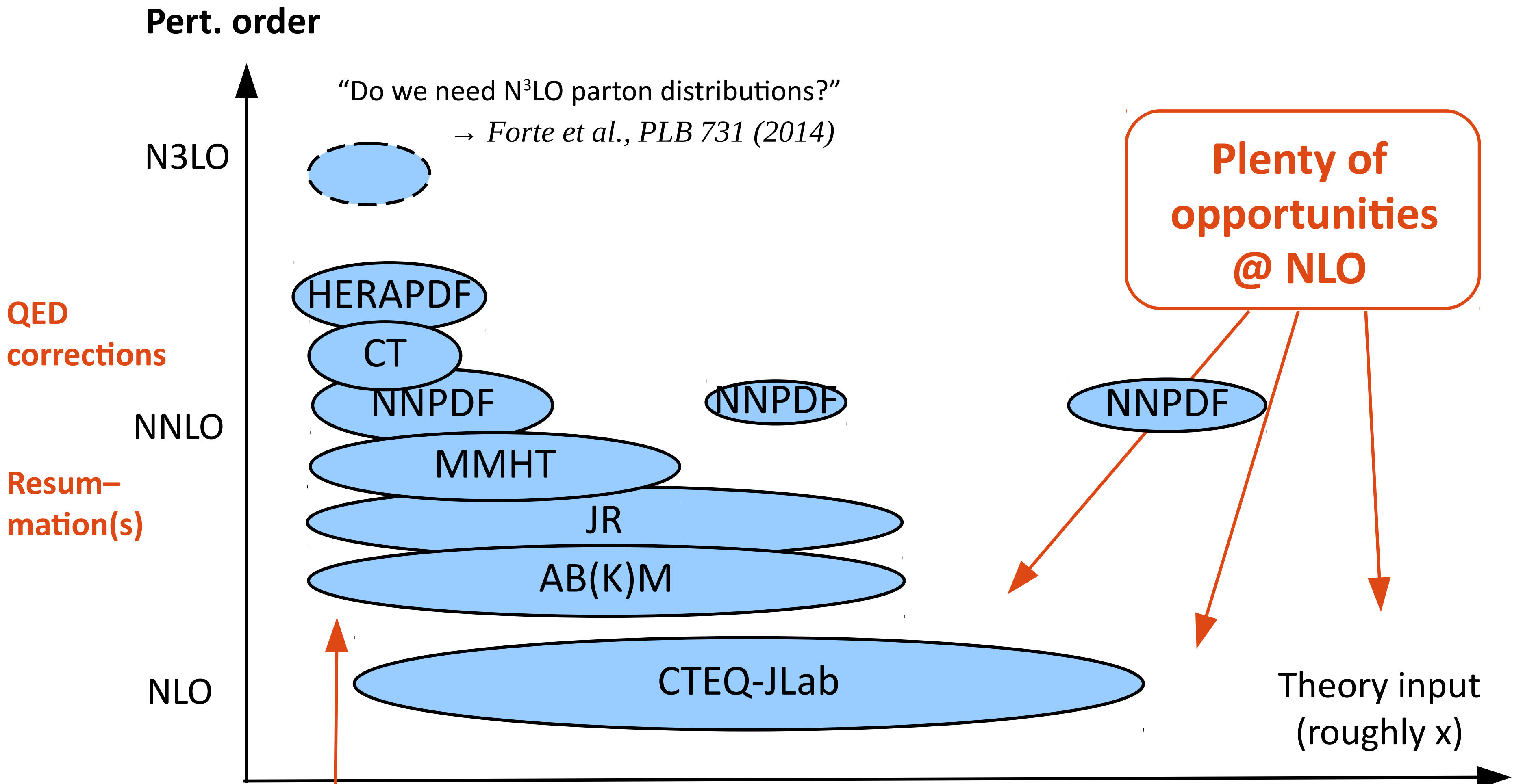




- **Nuclear Physics**
  - Bound nucleons, EMC effect, SRC
  - p+A and A+A collisions at RHIC / LHC
  - Color propagation in nuclear matter

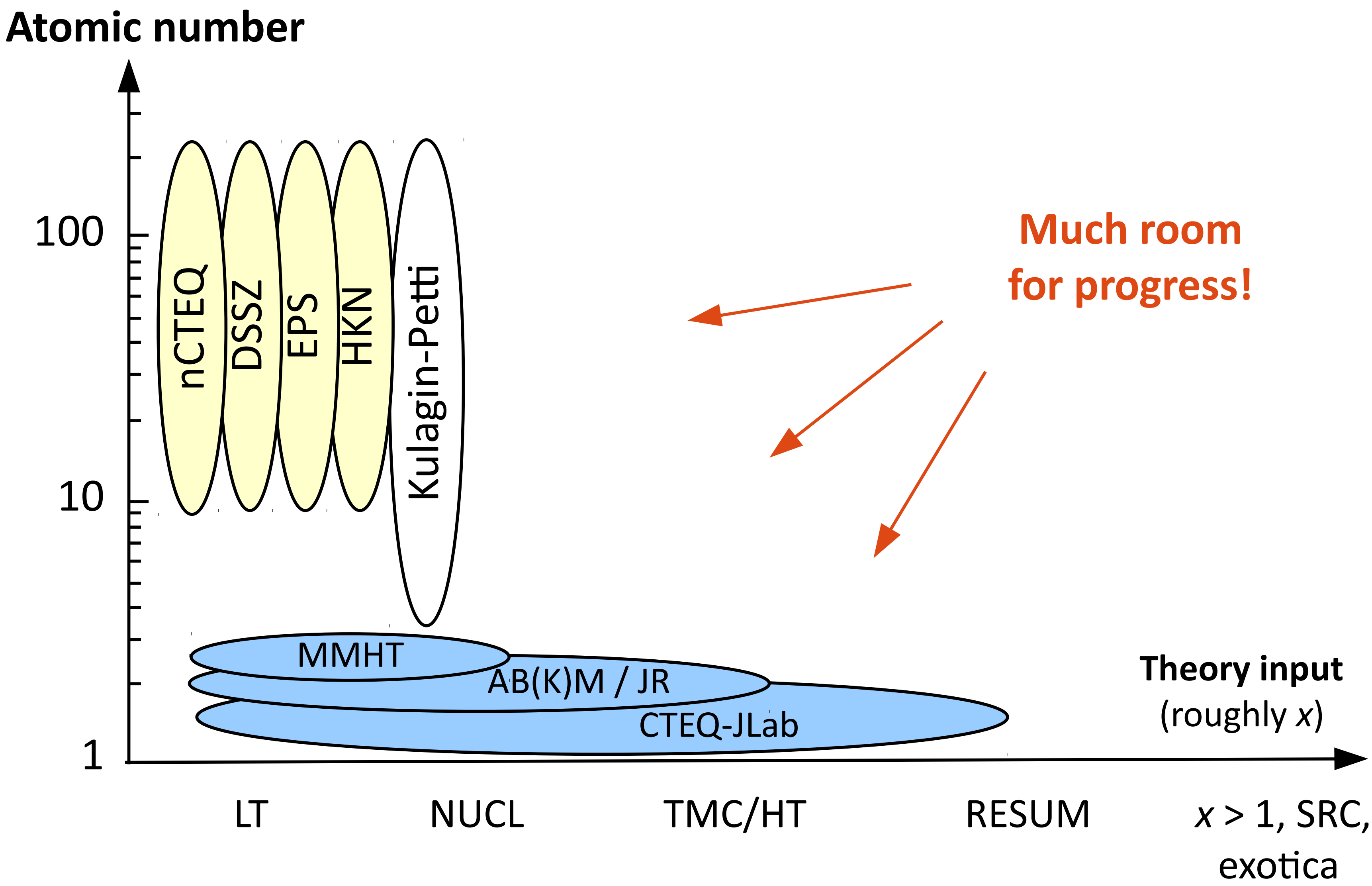


A PDF landscape



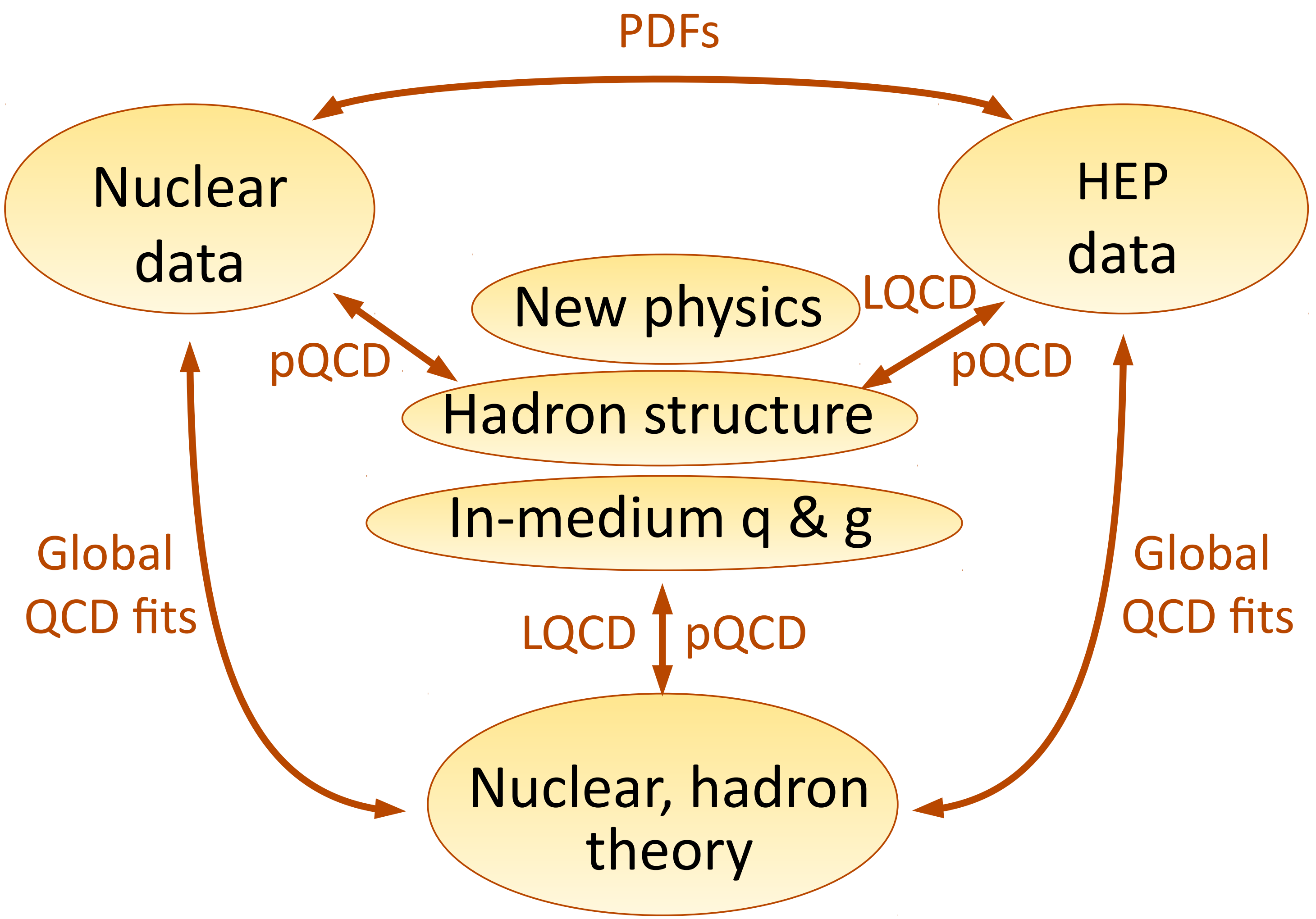
On the way to "1% precision" ←→ **theory uncertainties (scale, as, HQ scheme, masses...)**

A nPDF landscape



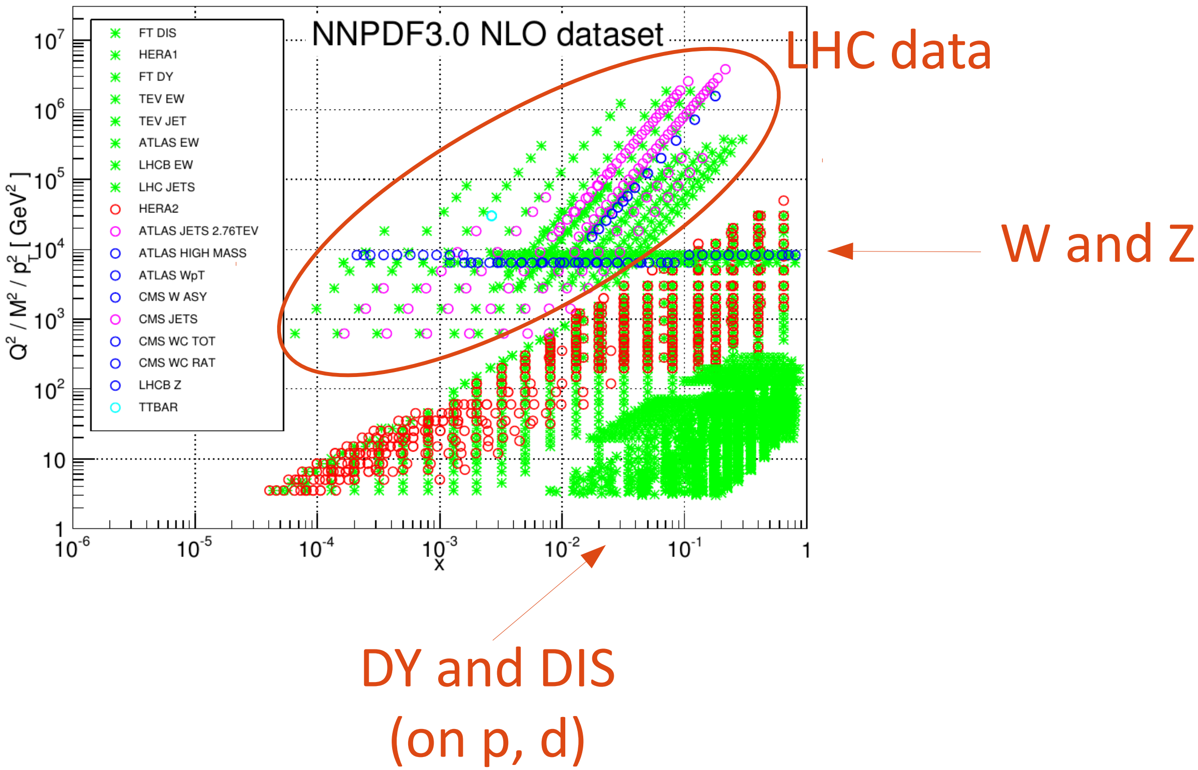
Needs the betrothal of HEP and NUCL

- A global approach across subfields

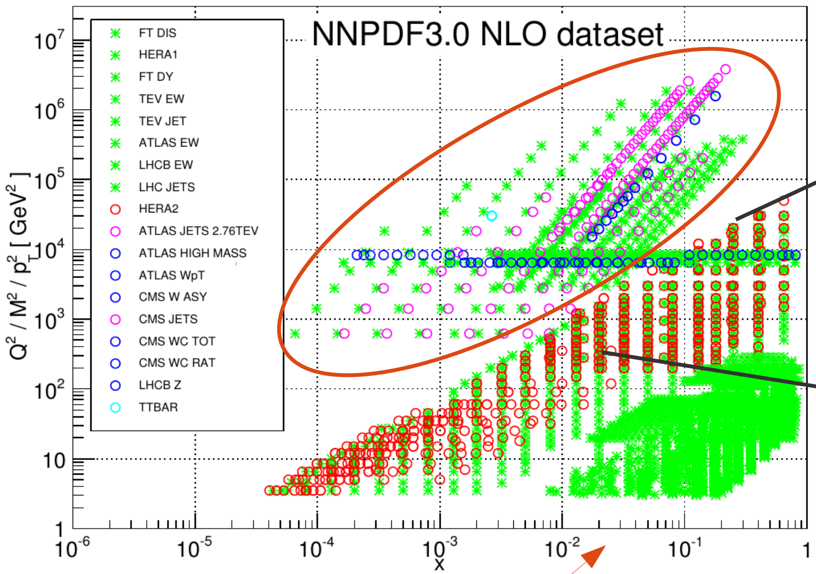


Proton PDFs

Data coverage



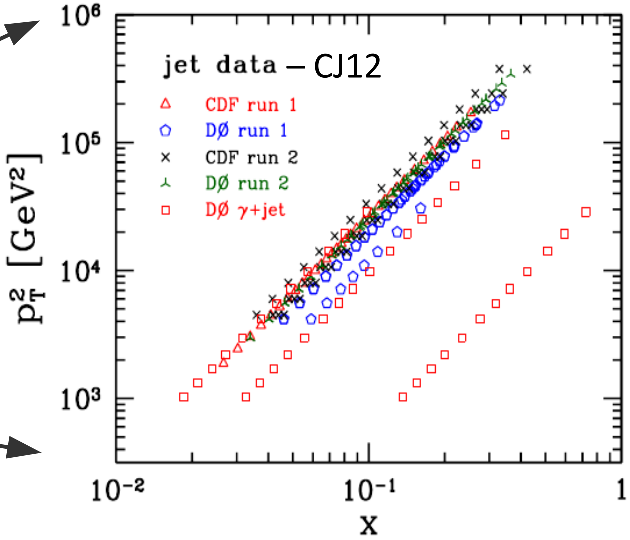
Data coverage



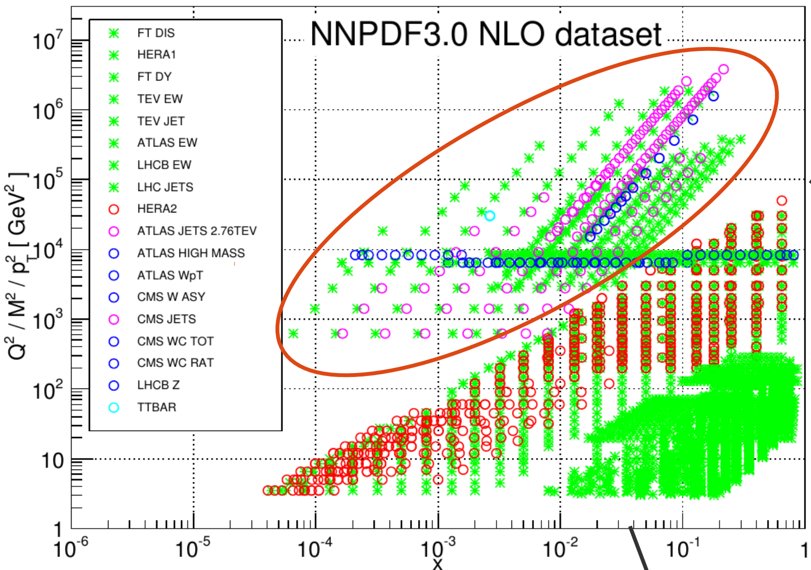
LHC data

DY and DIS
(on p, d)

Tevatron Jets

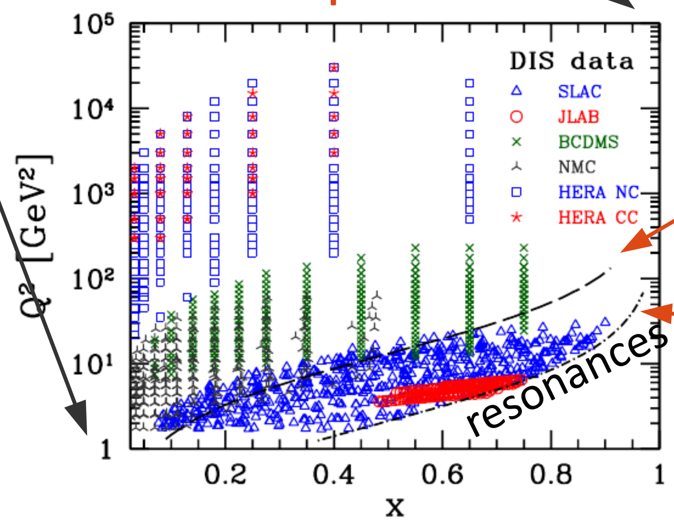


Data coverage



LHC data

DIS – prot. & deut.



standard cut

$W^2 \gtrsim 14\ \mathrm{GeV}^2$

CJ12 / 15

$W^2 \gtrsim 3\ \mathrm{GeV}^2$

– CJ12

Large-x, small-Q^2 corrections

- **$1/Q^{2n}$ suppressed:**
  - Higher-twists (non-pert. parton correlations)
    → in practice, fitted to low-Q^2 DIS data
  - Target mass corrections

  Under control
  (extracted "HT" include residual power corrections)

  Accardi et al. 2010
  Alekhin et al. 2004-

  - Heavy quark masses → hot debates
  - Current jet invariant mass, ...
- **Non-suppressed**
  - Nuclear corrections or deuteron targets → *Melnitchouk [WG1]; Thorne [WG1]*
  - Threshold resummation → calculations available
- **Flexible *d*-quark parametrization**
  - Need to allow d/u → finite, as x → 1
    (as required in theoretical models)
  - *e.g.* $d'(x) = d(x) + \alpha x^\beta u(x)$ [used in CJ12, analogous one in CT14]

alternative approach → Liuti [WG1]

Global fits overview

See parallel talks in WG1

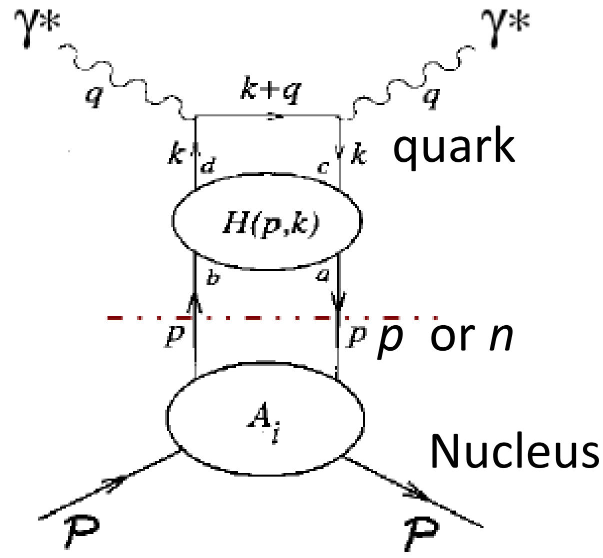
NEW! Also from RHIC (Tevatron new W,Z)

	JLab	HERA I+II (NEW!)	Tevatron new W,Z	LHC	di-μ	Nucl.	HT TMC	Flex *d*	Resum
NEW! HERAPDF2.0		✓	¤						
NEW! CT14			✓ ¤¤	✓	✓			✓	
NEW! MMHT14			✓ ¤¤	✓	✓	✓			
NEW! NNPDF3.0				✓	✓		(✓)		✓
[GJR14]	✓			✓	✓	✓	✓		
CJ12 * (→ CJ15)	✓	(✓)	(✓)		✗	✓	✓	✓	
ABM12 **					✓	✓	✓		

* NLO only ** No jet data ¤ but see 1503.05221 → *Placakyte* ¤¤ no reconstructed W

Deuteron corrections

- No free neutron → use deuteron
- **CJ: Nuclear modeling**
  - ✔ Connects to underlying nuclear theory
  - ✔ Can reject models → verify assumptions
  - ✔ Cross check with other processes
    - DY(p+d), ^{3}He, polarized DIS, ...
  - ✘ Continuous vs. discrete parameters



Low-energy factorization issues

Renorm. of nucl. operators, gauge inv., FSI, ...

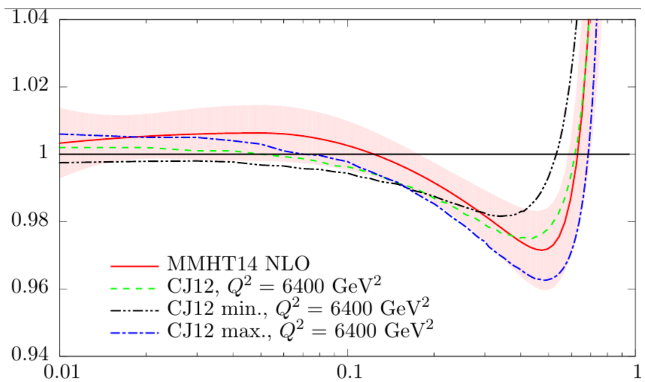
- **MMHT: parametrize D/(p+n) ratio**
  - ✔ Nuclear uncertainty straightforward
  - ✔ No "model bias" (beside parametrization)
  - ✘ Limited nuclear physics output
  - ✘ May be missing non-negligible Q^2 dependence
  - ✘ Needs one parametrization per process

$$\mathcal{N}[1 + a_1 \ln^2(x_p/x)] \quad x < x_p$$
$$\mathcal{N}[1 + a_2 \ln^2(x_p/x) + a_3 \ln^{20}(x_p/x)] \quad x > x_p$$

Deuteron corrections

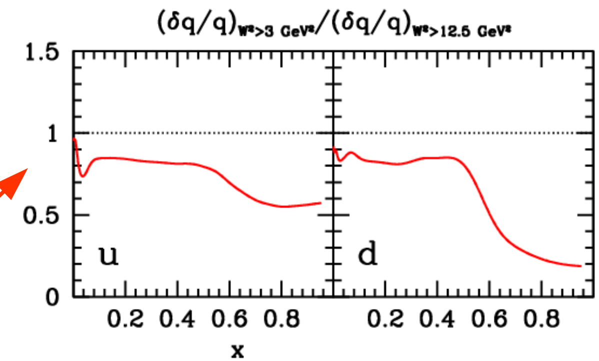
- The 2 complementray strategies agree
  - Can use reliably, extend to lower W^2

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



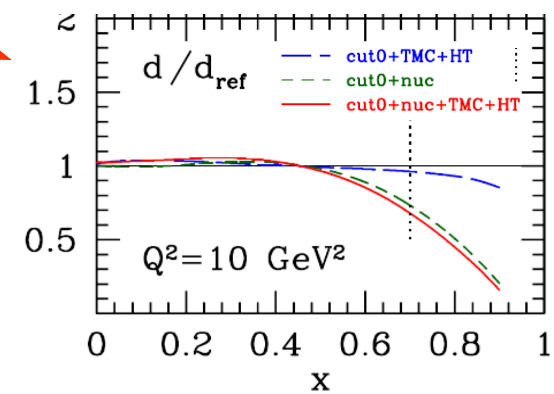
MMHT14, arXiv:1410.3989

Reduced PDF uncertainty
with SLAC/JLab data



CJ12 – MPLA 28 (2013)

d-quark suppression



CJ10 – PRD81 (2010)

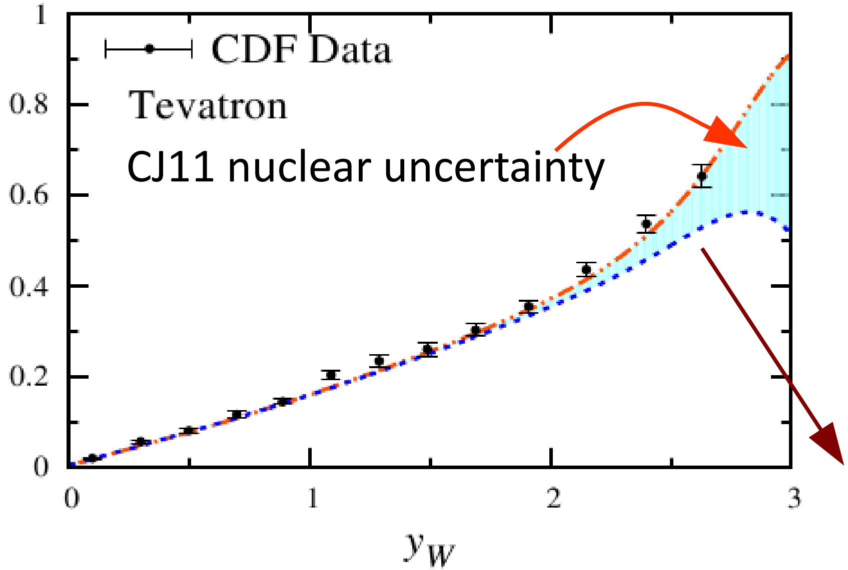
- **Nucl / HEP symbiosis:**
  - *W* and *Z* → constrain d-quark → constrain deuteron corrections
  - Abundant DIS deuteron data → precise *u*/*d* flavor separation

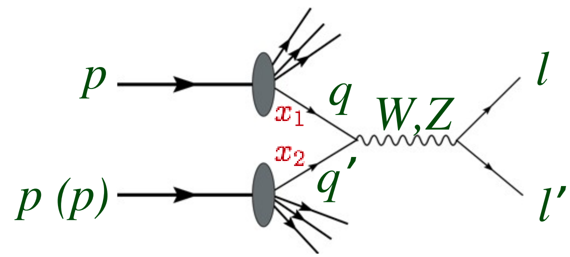
Use protons to study nuclei (!)

Accardi, Mod.Phys.Lett. A28(2013)35

Brady, A.A., Melnitchouk, Owens, JHEP 1206 (2012) 019

- **Directly reconstructed W:**
  - highest sensitivity to large *x*

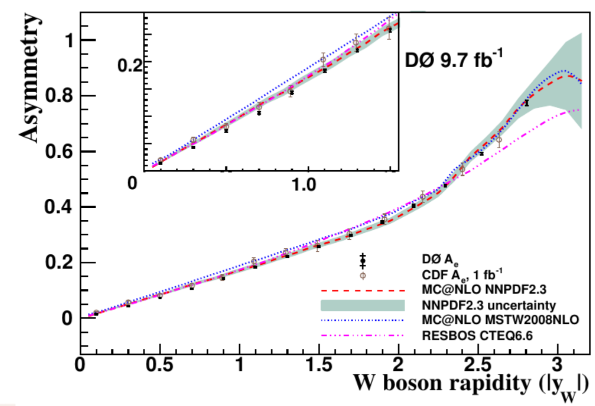




$$A_W(y) \approx \frac{d/u(x_2) - d/u(x_1)}{d/u(x_2) + d/u(x_1)}$$

sensitive to *d* at high *x* → Can constrain Deuteron models!

- **New precise DØ data (+BONUS) determine d-quark**
  - *W;* also $W \rightarrow l+\nu$ and *Z* (but less sensitive)
- **Use DIS on Deuteron to:**
  - Constrain nuclear model / parameters
  - Reduce d-quark uncertainty



The CJ15 parton distributions

CJ15 – data set

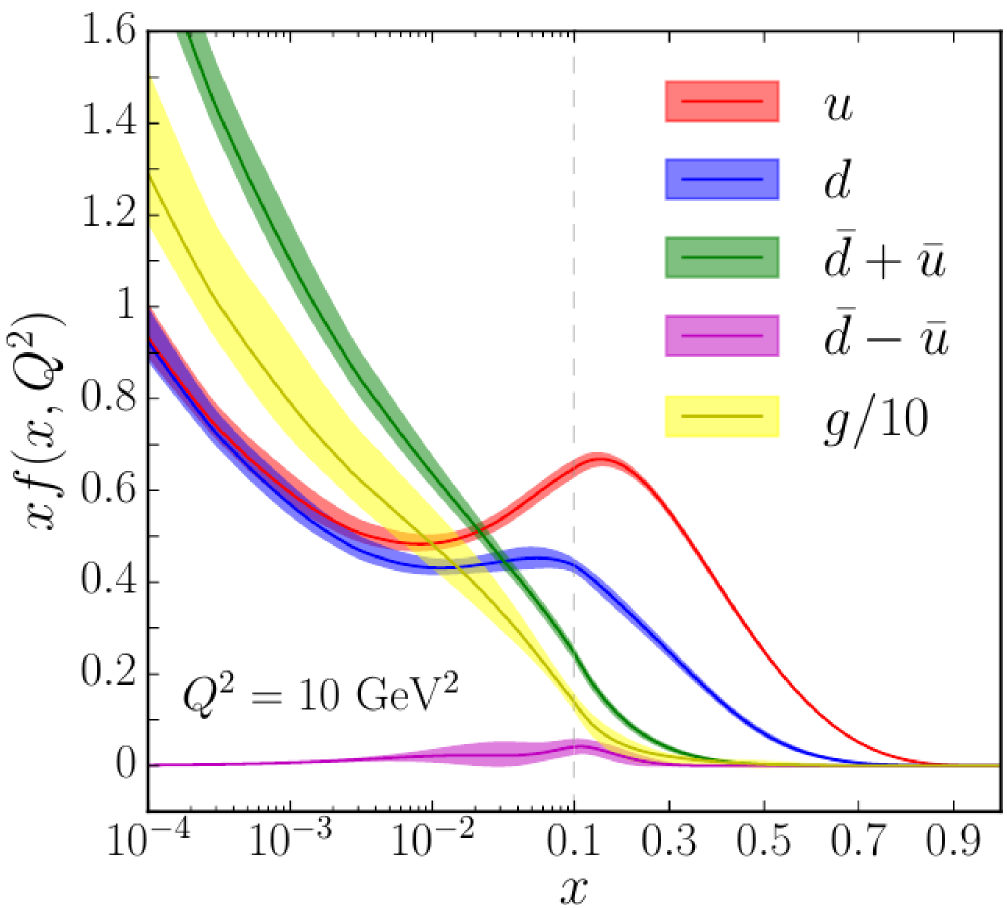
	experiment	# points	χ^2 NLO	χ^2 LO
DIS F_2	BCDMS (p) [23]	351	437	432
	BCDMS (d) [23]	254	294	299
	NMC (p) [24]	275	407	414
	NMC (d/p) [25]	189	172	180
	SLAC (p) [26]	564	435	496
	SLAC (d) [26]	582	372	417
	JLab (p) [27]	136	166	164
	JLab (d) [27]	136	124	127
	JLab (n/d) [85]	191	217	224
DIS σ	HERA (NC e^-p) [28]	145	112	161
	HERA (NC e^+p) [28]	408	541	872
	HERA (CC e^-p) [28]	34	19	19
	HERA (CC e^+p) [28]	34	31	33
Drell-Yan	E605 (pCu) [45]	119	93	104
	E866 (pp) [29]	121	139	155
	E866 (pd) [29]	129	144	191
	E866 (pd/pp) [30]	12	9	9
W/charge asymmetry	CDF (e) [31]	11	12	11
	DØ (μ) [32]	10	20	21
	DØ (e) [33]	13	27	56
	CDF (W) [34]	13	15	12
	DØ (W) [35]	14	16	47
Z rapidity	CDF (Z) [36]	28	27	79
	DØ (Z) [37]	28	16	23
jet	CDF (run 2) [39]	72	15	22
	DØ (run 2) [41]	110	21	46
γ+jet	DØ 1 [42]	16	6	20
	DØ 2 [42]	16	15	40
	DØ 3 [42]	12	25	35
	DØ 4 [42]	12	13	77
total		4035	**3941**	4786
total + norm			**3950**	4918
χ^2/dof			**0.98**	1.22

← BONuS F_2^n/F_2^d

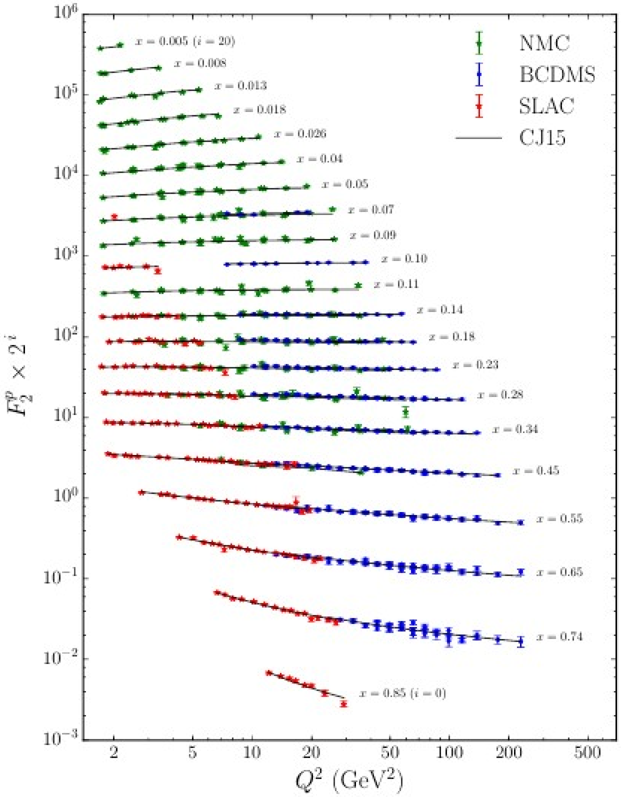
← D0 A_l

← D0 A_W

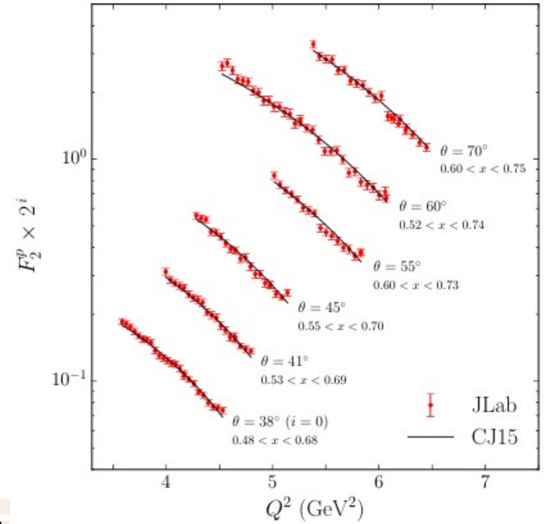
CJ15 – PDFs



u
d
$\bar{d} + \bar{u}$
$\bar{d} - \bar{u}$
$g/10$
$Q^2 = 10$ GeV^2
$x\,f(x, Q^2)$
x



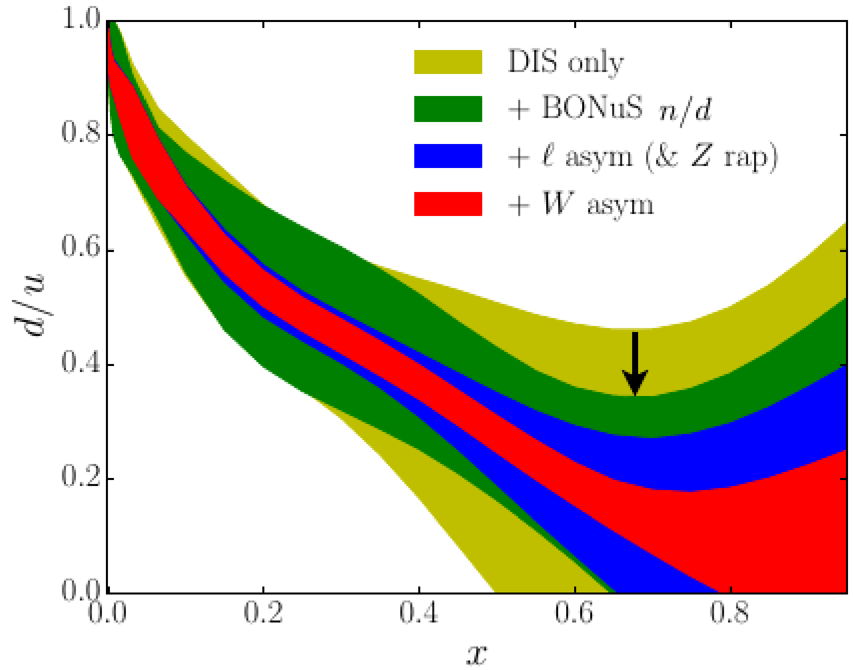
NMC
BCDMS
SLAC
CJ15
$x = 0.005$ ($i = 20$)
$x = 0.85$ ($i = 0$)
$F_2^p \times 2^i$
Q^2 (GeV^2)



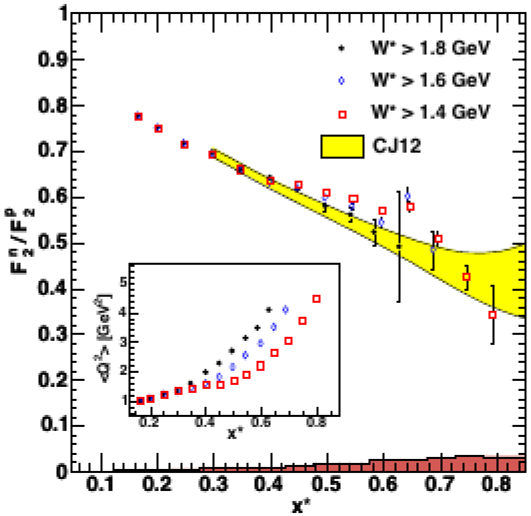
$\theta = 70°$ $0.60 < x < 0.75$
$\theta = 60°$ $0.52 < x < 0.74$
$\theta = 55°$ $0.60 < x < 0.73$
$\theta = 45°$ $0.55 < x < 0.70$
$\theta = 41°$ $0.53 < x < 0.69$
$\theta = 38°$ ($i = 0$) $0.48 < x < 0.68$
JLab
CJ15
$F_2^p \times 2^i$
Q^2 (GeV^2)

Effect of new data sets on d/u ratio

→ new JLab (BONuS) data reduces error at $x \sim 0.6$



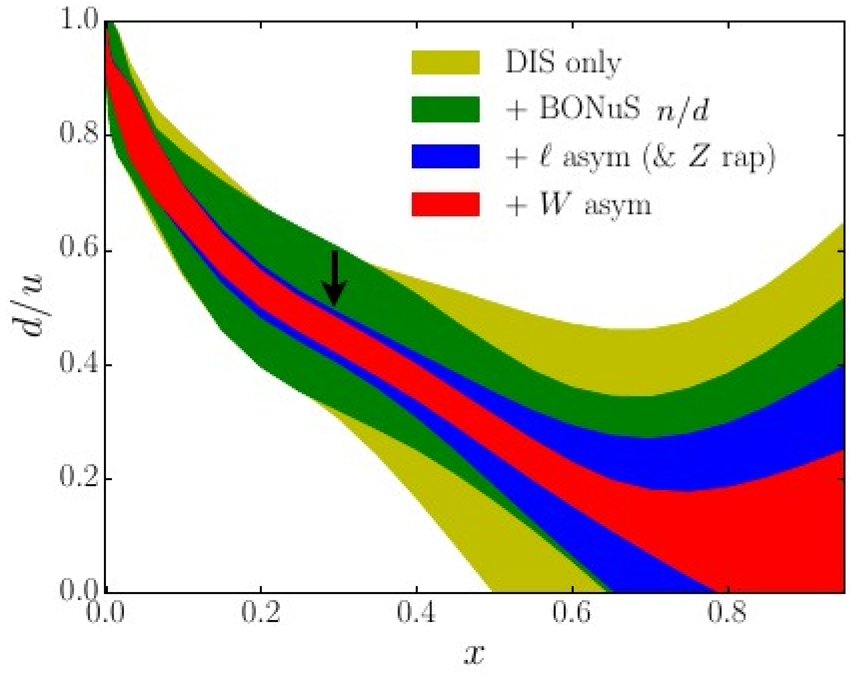
BONuS: spectator proton tagging in semi-inclusive *ed* DIS

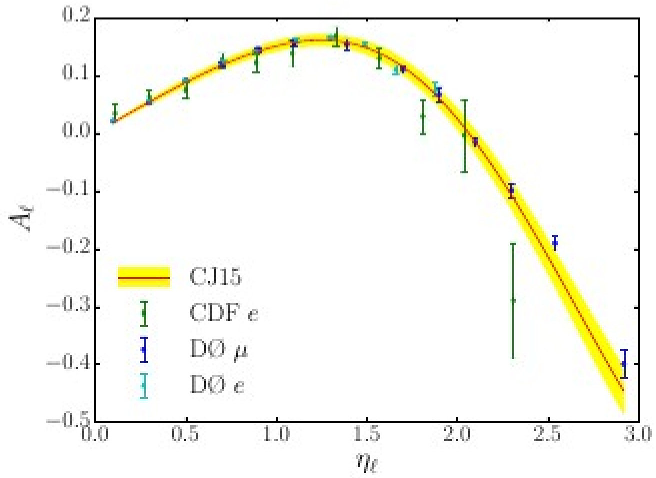


Baillie et al. *PRL* ***108***, *142001 (2012)*

Effect of new data sets on d/u ratio

- → new JLab (BONuS) data reduces error at $x \sim 0.6$
- → significant reduction from new lepton asymmetry data (little effect from Z rap. data)





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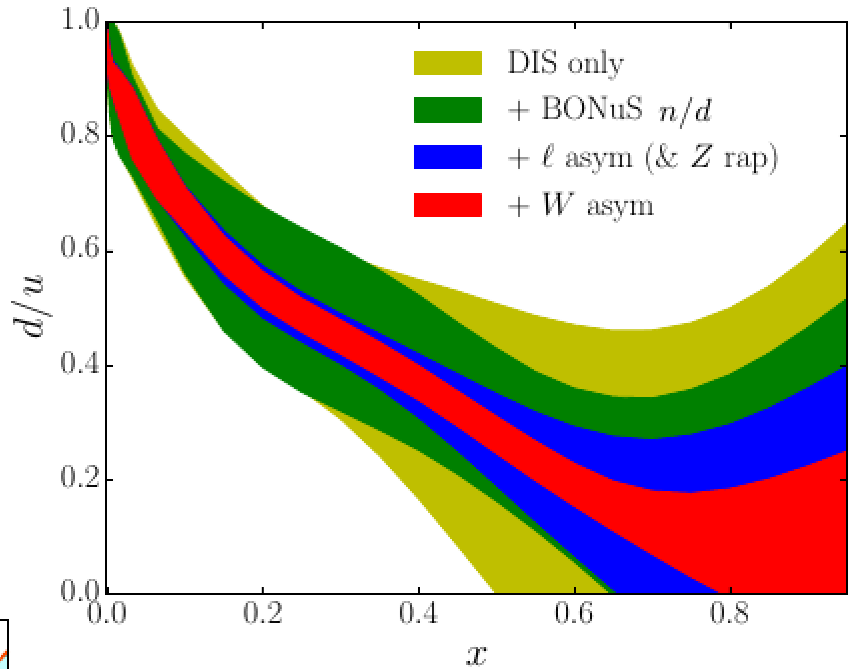

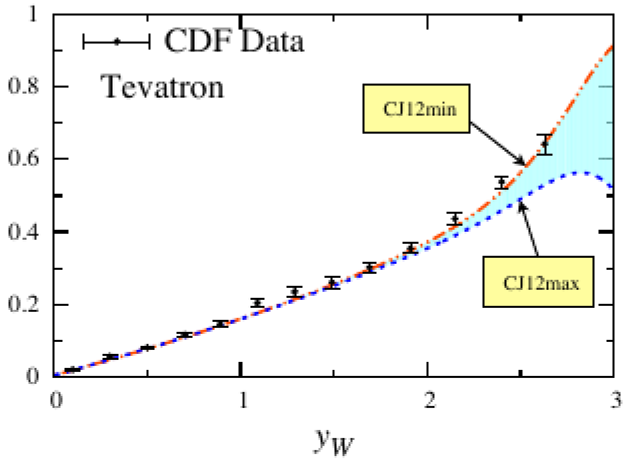

→ W asymmetry at large W rapidity more sensitive to d/u at high x

→ earlier CDF data preferred smaller ("CJ12min") nuclear corrections

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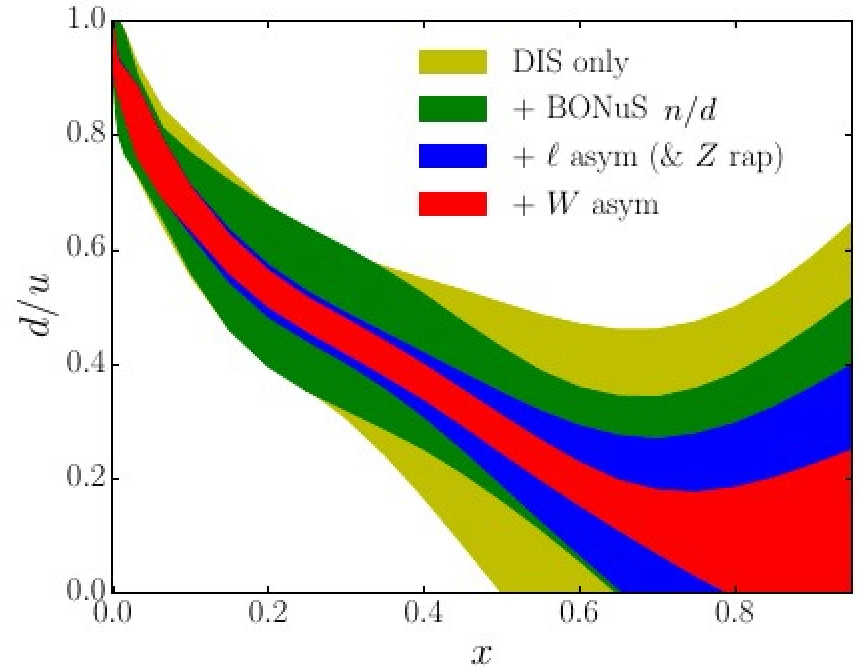

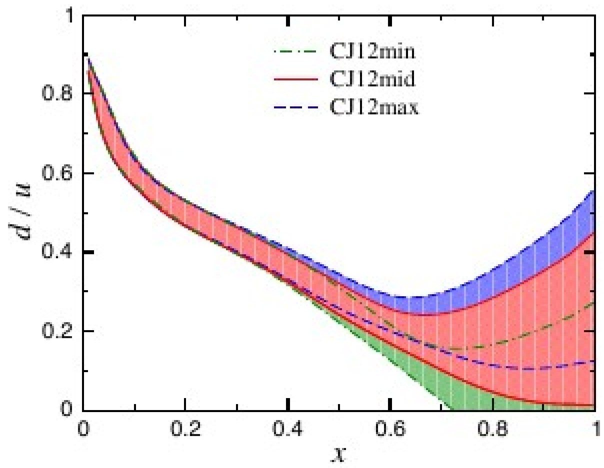

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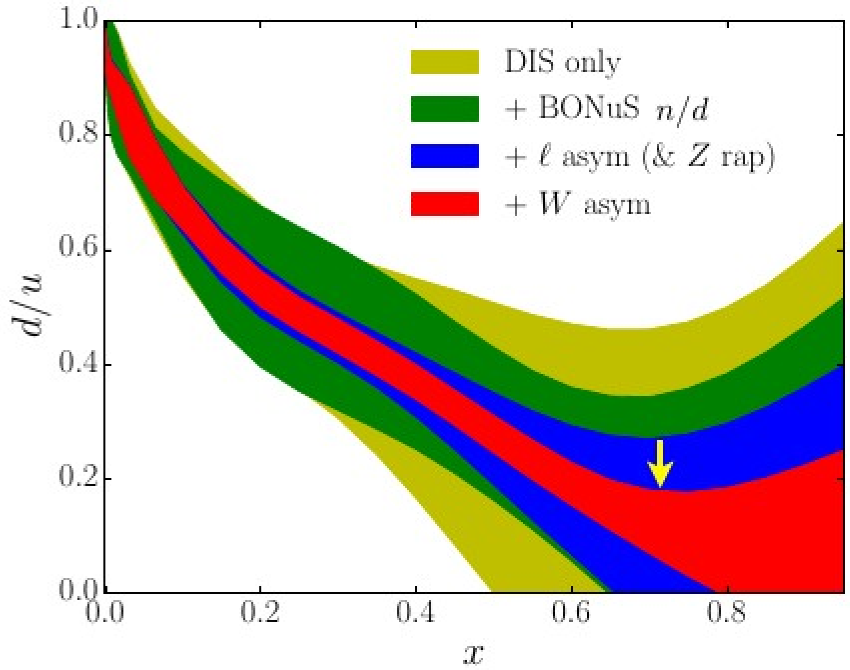
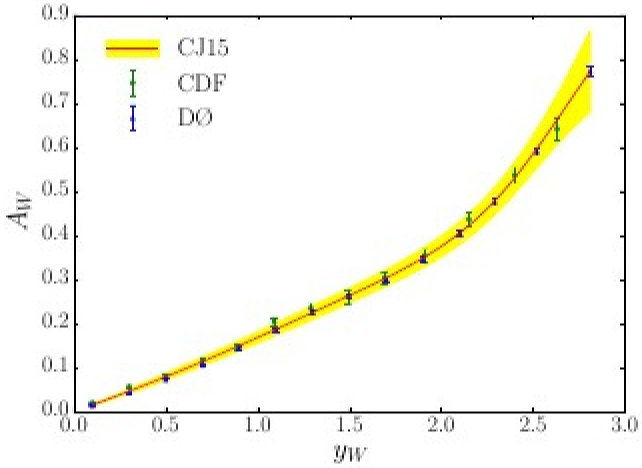




→ W asymmetry at large W rapidity more sensitive to d/u at high x

→ new D0 data reduce uncertainties at $x \sim 0.6 - 0.7$, strongly favor models with small (but nonzero) nuclear corrections

Hadronic phsyics output

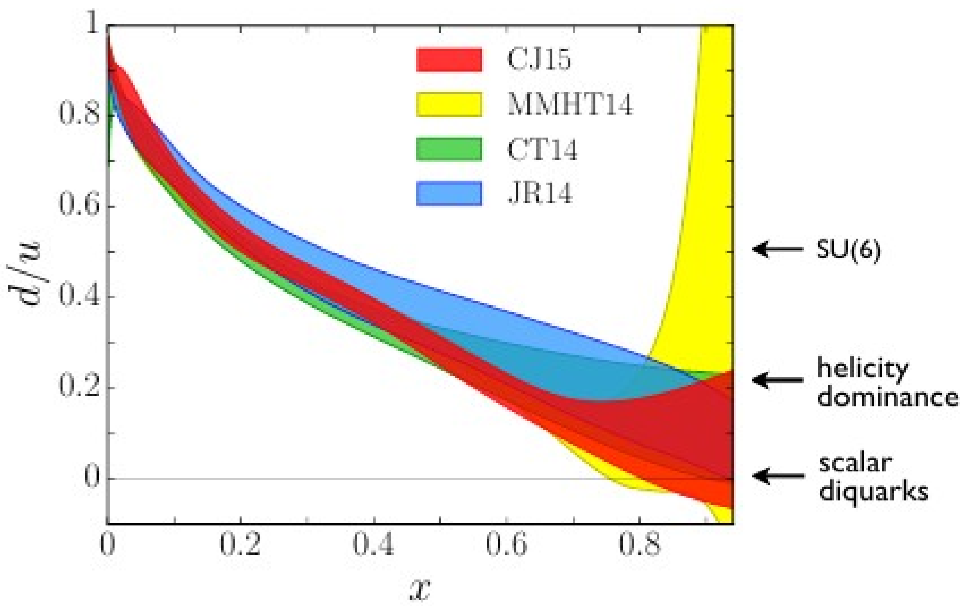
→ d/u ratio at high x of interest for nonperturbative models of nucleon

→ more flexible parametrization

$$d \;\to\; d + b\,x^c\,u$$

allows finite, nonzero $x = 1$ limit

(standard PDF form gives 0 or ∞ unless $a_2^d = a_2^u$)



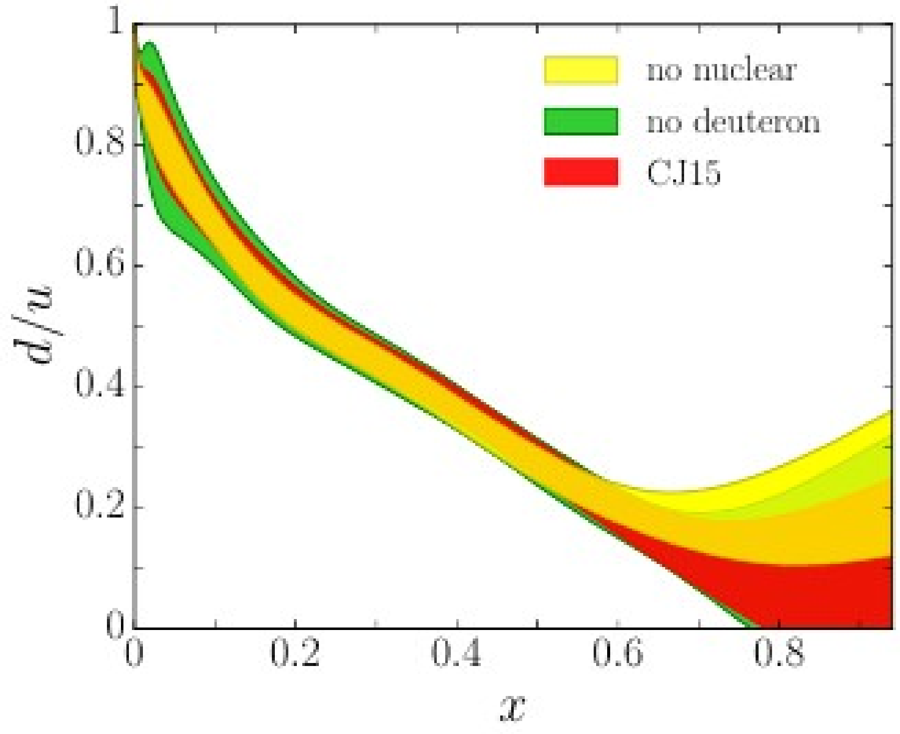
MMHT14: fitted deuteron correction, “standard” d parametrization

CT14: flexible d parametrization, no nuclear corrections

JR14: similar deuteron correction, no lepton/W asymmetry data

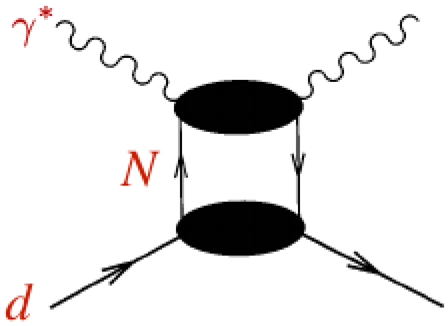
Effect of new data sets on d/u ratio

→ deuterium data, and proper treatment of nuclear corrections, are important for *accuracy* and *precision* of d/u determination at $x > 0.6$



Nuclear corrections

- At large x, DIS dominated by incoherent sscattering from individual nucleons



$$q^d(x,Q^2) = \int \frac{dz}{z} dp^2\, f_{N/d}(z,p^2)\, \tilde{q}^N(x/z,p^2,Q^2)$$

nucleon momentum distribution in d ("smearing function")

PDF in bound (off-shell) nucleon

$$\rightarrow \quad z = \frac{p\cdot q}{p_d\cdot q} \approx 1 + \frac{p_0+\gamma p_z}{M} \quad \left[p_0 = M+\varepsilon, \quad \varepsilon = \varepsilon_d - \frac{\vec{p}^{\,2}}{2M}\right]$$

momentum fraction of d carried by N

$\rightarrow$ at finite Q^2, smearing function depends on $\gamma = \sqrt{1+4M^2x^2/Q^2}$

- Offshell expansion; parametrize first order coefficient; fix x1 with valence sum rule

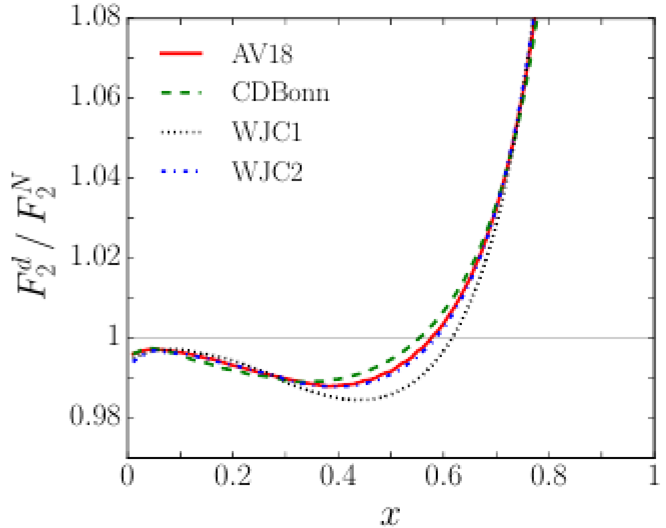
$$\tilde{q}^N(x,p^2) = q^N(x)\left[1+\frac{(p^2-M^2)}{M^2}\,\delta q^N(x)\right]$$

$$\delta q^N = C_N(x-x_0)(x-x_1)(1+x-x_0) \qquad \int_0^1 dx\, \delta q^N(x)\left(q^N(x)-\bar{q}^N(x)\right) = 0$$

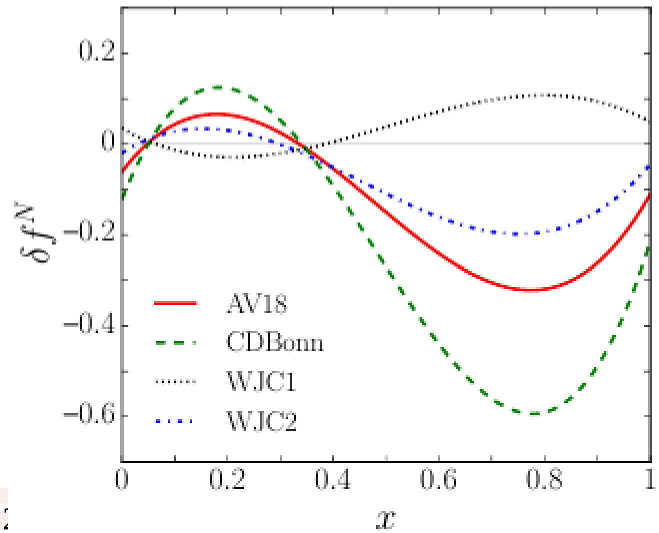
Constrained by D0 data (!)

- The "wrong" nuclear corrections creates tension between DIS(D) and W asym
  - The fits then choses the "right" one

- **Deuteron to nucleon "EMC" ratio** D/(p+n)
  - Stable w.r.t. choice of nucleon wave function
  - WJC1 disfavored χ^2-wise
  - No evidence for antishadowing

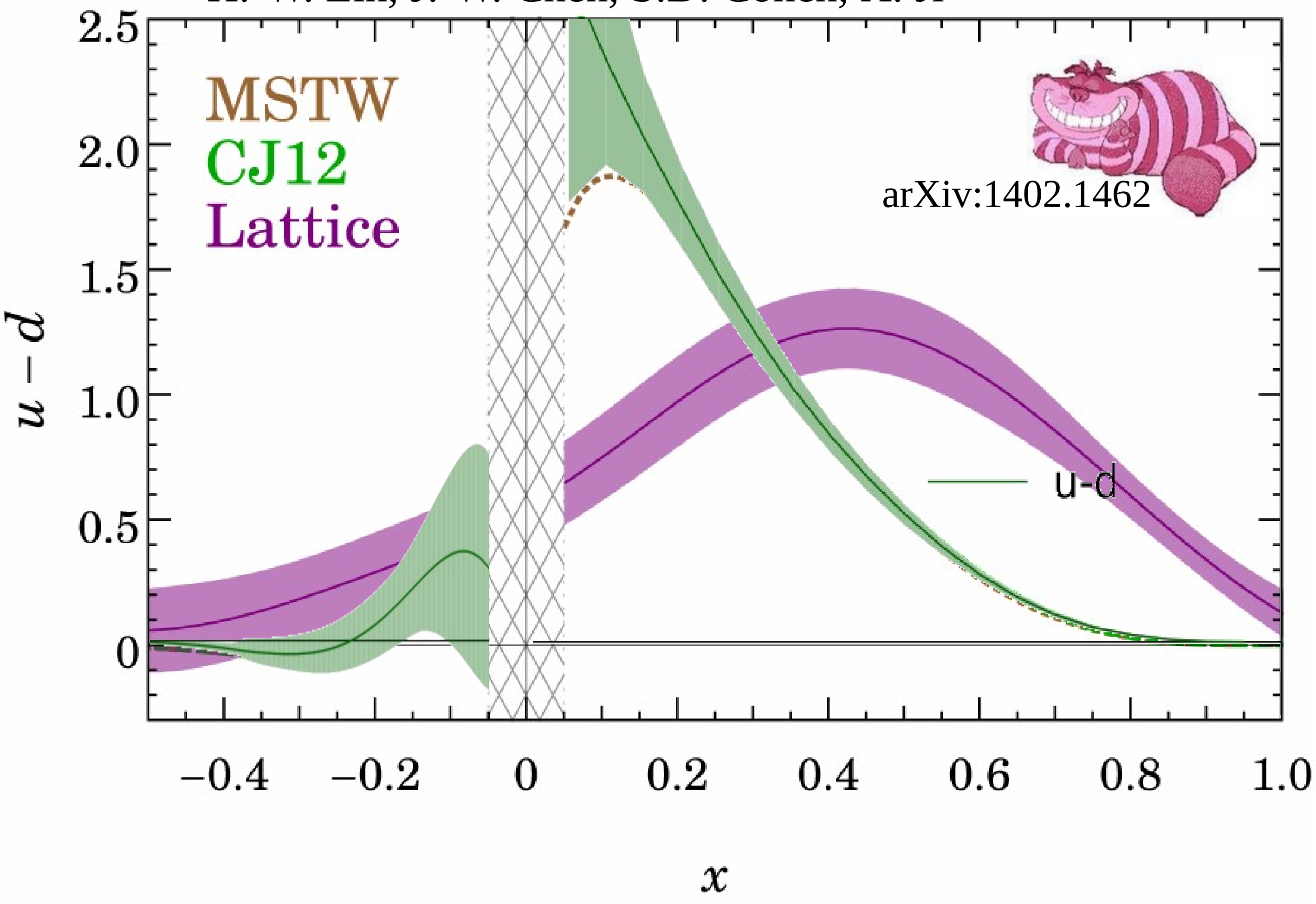


- **Off shell correction – first time in Deuteron!**
  - Stable shape
  - Magnitude compensates for wave function's missing / excessive strength
  - Physical result or fitting away other physics?
  - **Can we get guidance from lattice QCD?**



New lattice QCD technique: PDFs in x-space

H.-W. Lin, J.-W. Chen, S.D. Cohen, X. Ji



CJ12 bands courtesy of J. Guerrero

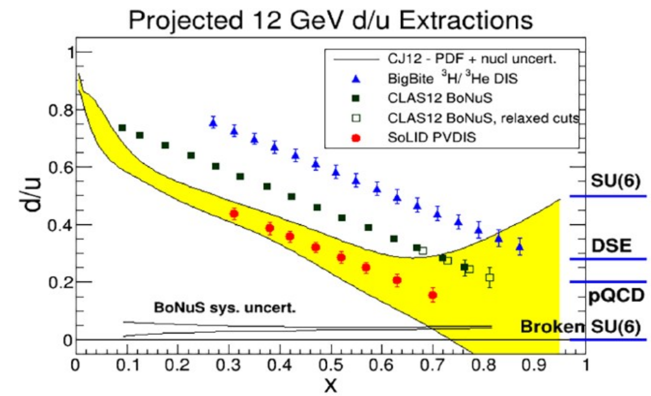
Can we adapt these to study off-shell PDF modifications?

Threshold resummation: the new PDF frontier

Why yet another large-x correction??

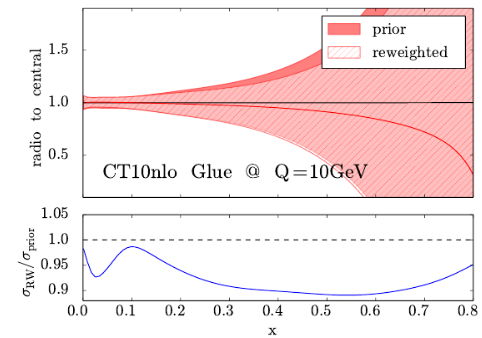
- **New precision data in the (very) near future:**
  - Jlab 12 tagged DIS, PVDIS
  - RHIC W, Z
  - W+c at LHCb, ...

2016 Long Range Plan:



- **Direct photons:**
  removes tensions in old, but unused, data
  - Resummation allows use in global fits
  - 10% reduction in large-*x* gluon errors

N. Sato, Ph.D. thesis 2014

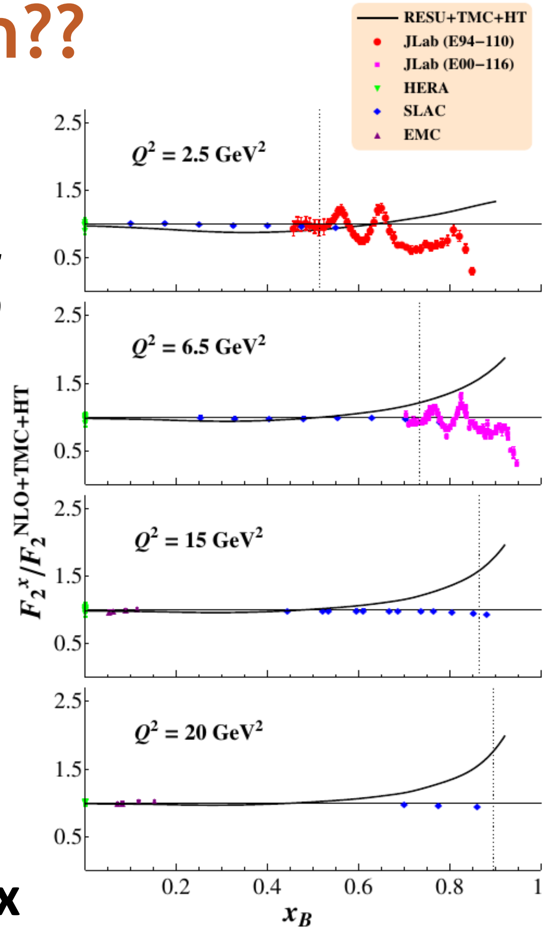


- **Drell-Yan:** *Alekhin et al., PRD74 (2006)*
  accidental cancellation at NLO of large effects?
  - At NNLO, tension with DIS, vector bosons
  - Resummation effects are large
    - Need to be revisited

Why yet another large-x correction??

- **Effects extend down to not so large x**
  - For example in DIS

Accardi, Anderle, Ringer
PRD 91 (2015)



- **Need "resummed" PDFs for precision physics at LHC**
  - To use with resummed partonic cross sections:
    - t-tbar
    - squark and sgluino production
    - ....

- **Resummed u- and d-quarks suppressed at high x**
  - Implications for nPDF extraction ?
  - Does it also suppress or enhance the d/u ratio ?
  - Gluon anti-correlated to d, u → enhanced at large x
    → are we underpredicting radiative charm at large x ?

Brief history of PDFs with large-x resummation

- **2005: first evaluation of threshold corrections effects on u-quark**
  - *Corcella, Magnea, Phys.Rev. D72 (2005) 074017*
- **2015: combining resummation with Target Mass Corrections**
  - *Accardi, Anderle, Ringer, Phys.Rev. D91 (2015) 3, 034008*
- **2015: first fit of PDFs with threshold corrections**
  - *NNPDF (Bonvini et al.), JHEP 1509 (2015) 191*
  - Data on DIS only
- **More work to do!**

But need consistent inclusion of resummation on top of other large x corrections

Target mass corretions - an overview

Schienbein et al., JPG 35 (2008); Brady, A.A., Hobbs, Melnitchouk, PRD 84 (2011)

- **Kinematics:**

$$p^\mu p_\mu = M^2 \; ; \; q^\mu q_\mu = -Q^2 \; ; \; p^\mu q_\mu = Q^2/(2x_B)$$

$$\Longrightarrow \boxed{q^\mu = -\xi \, n_+^\mu + \frac{Q^2}{2\xi} \, n_-^\mu}$$

$n_\pm^\mu =$ Light-cone unit vectors

Nachtmann variable $\xi = \dfrac{2x_B}{1+\rho}$

$$\rho^2 = 1 + 4x_B^2 M^2/Q^2$$

- **Naively**:

$$x_B \xrightarrow{TMC} \xi \qquad F_{T,L}(x_B) \xrightarrow{TMC} F_{T,L}(\xi)$$

Target mass corretions - an overview

Schienbein et al., JPG 35 (2008); Brady, A.A., Hobbs, Melnitchouk, PRD 84 (2011)

- Identify ***power suppressed*** *(in $M^2/Q^2 = \rho^2 - 1$)* ***but leading twist terms***
  - **OPE:** resummed to all orders *Georgi, Politzer, De Rujula 1979*

$$F_T^{OPE}(x_B, Q^2) = \frac{1+\rho}{\rho} F_T^{(0)}(\xi, Q^2) + \frac{\rho^2 - 1}{\rho^2} \int_\xi^1 dy\, \mathcal{F}_\mathcal{T}[y, F_T^{(0)}(y)]$$

  - **Collinear Factorization**: up to $O(M^4/Q^4)$ *Ellis, Furmanski, Petronzio 1979*

$$F_T^{EFP}(x_B, Q^2) = F_T^{OPE}(x_B, Q^2) + O(M^4/Q^4)$$

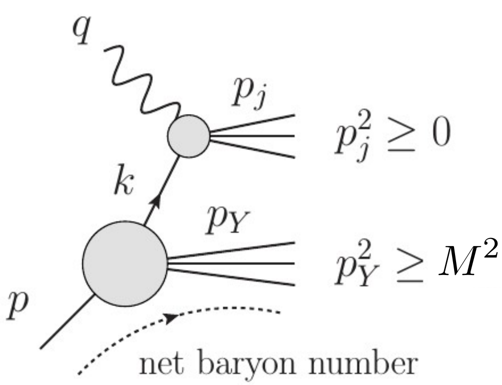
- **THRESHOLD PROBLEM – predicts scattering at $x_B > 1$!**
  (1) Neglect of partonic kinematic (m_N=0 implicitly used here)
  (2) Non uniform convergence of power series

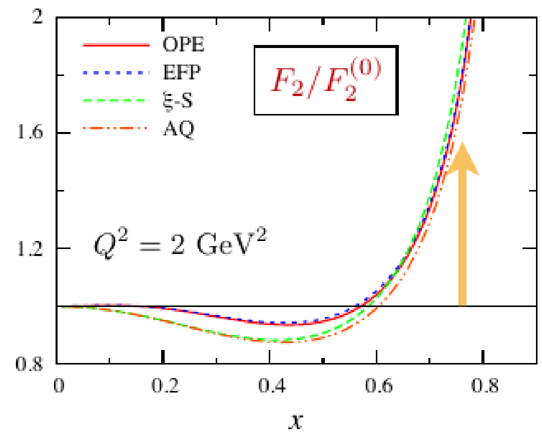
Correct partonic kinematics

Accardi, Qiu, JHEP (2008)

- Impose $M^2 \neq 0$ in the handbag diagram → phase space close at x_B=1

$$F_T^{AQ}(x_B, Q^2) = \sum_f \int_\xi^{\xi/x_B} \frac{dy}{y} f(y, Q^2)\, \mathcal{C}_T^f(y/\xi)$$





Brady et al., PRD ***84****, 074008 (2011)*

- Questions:
  - How to extend this fix to the power suppressed LT terms?
  - Phase space in parton's momentum fraction x is reduced:
    How to perform threshold resummation?

Threshold resummation

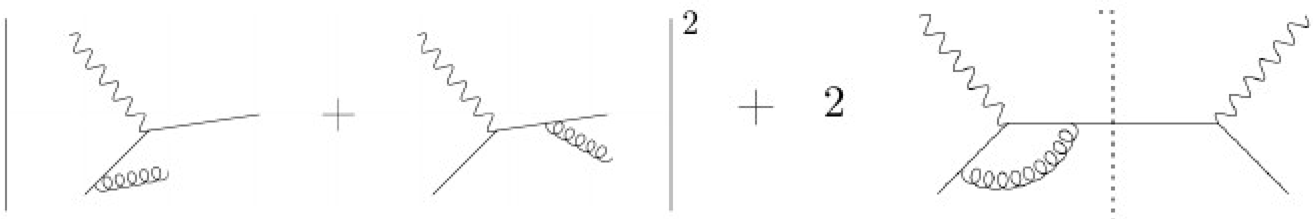
Accardi, Anderle, Ringer
PRD 91 (2015)

- Perturbative expansion

$$F_T^{AQ}(x_B, Q^2) = \sum_f \int_{x_B}^1 \frac{dx}{x} f(x/\xi, Q^2)\, \mathcal{C}_T^f(x)$$

$$\mathcal{C}_T^f = \mathcal{C}_T^{f(0)} + \frac{\alpha_s(\mu^2)}{2\pi}\mathcal{C}_T^{f(1)} + \mathcal{O}(\alpha_s^2)$$

- At large x_B, scattered quark carries large $y = x/\xi$:
  - Only soft gluons ($x \to 0$) can be emitted



$$C_{q,\mathrm{th}}^{1,(1)}(x) = C_F\left[(1+x^2)\left(\frac{\ln(1-x)}{1-x}\right)_+ - \frac{3}{2}\frac{1}{(1-x)_+} - \left(\frac{9}{2}+\frac{\pi^2}{3}\right)\delta(1-x)\right]$$

Spoils perturbative convergence also if $\alpha_s \ll 1$

Threshold resummation

Accardi, Anderle, Ringer
PRD 91 (2015)

- These "threshold" divergences need to be resummed:
  - Mellin transform $$\int \frac{dy}{y} f(y)\mathcal{C}_T(y/\xi) \longrightarrow f^N \mathcal{C}_T^N$$
  - Exponentiate the divergent pieces in the hard scattering C_T^N, keep finite pieces, Mellin transform back

$$\mathcal{C}_T^N = H_q \times \Delta_q^N \times J_q^N$$

$$\log \Delta_q^N \equiv \int_0^1 dx \frac{x^N - 1}{1-x} \int_{Q^2}^{(1-x)^2 Q^2} \frac{dk_\perp^2}{k_\perp^2} A_q(\alpha_s(k_\perp^2)),$$

$$\log J_q^N \equiv \int_0^1 dx \frac{x^N - 1}{1-x} \left\{ \int_{(1-x)^2 Q^2}^{(1-x)Q^2} \frac{dk_\perp^2}{k_\perp^2} A_q(\alpha_s(k_\perp^2)) + \frac{1}{2} B_q(\alpha_s((1-x)Q^2)) \right\}$$

calculable perturbatively

Threshold resummation with TMC

Accardi, Anderle, Ringer
PRD 91 (2015)

- With TMCs, partonic phase space does not extend any longer to y=1

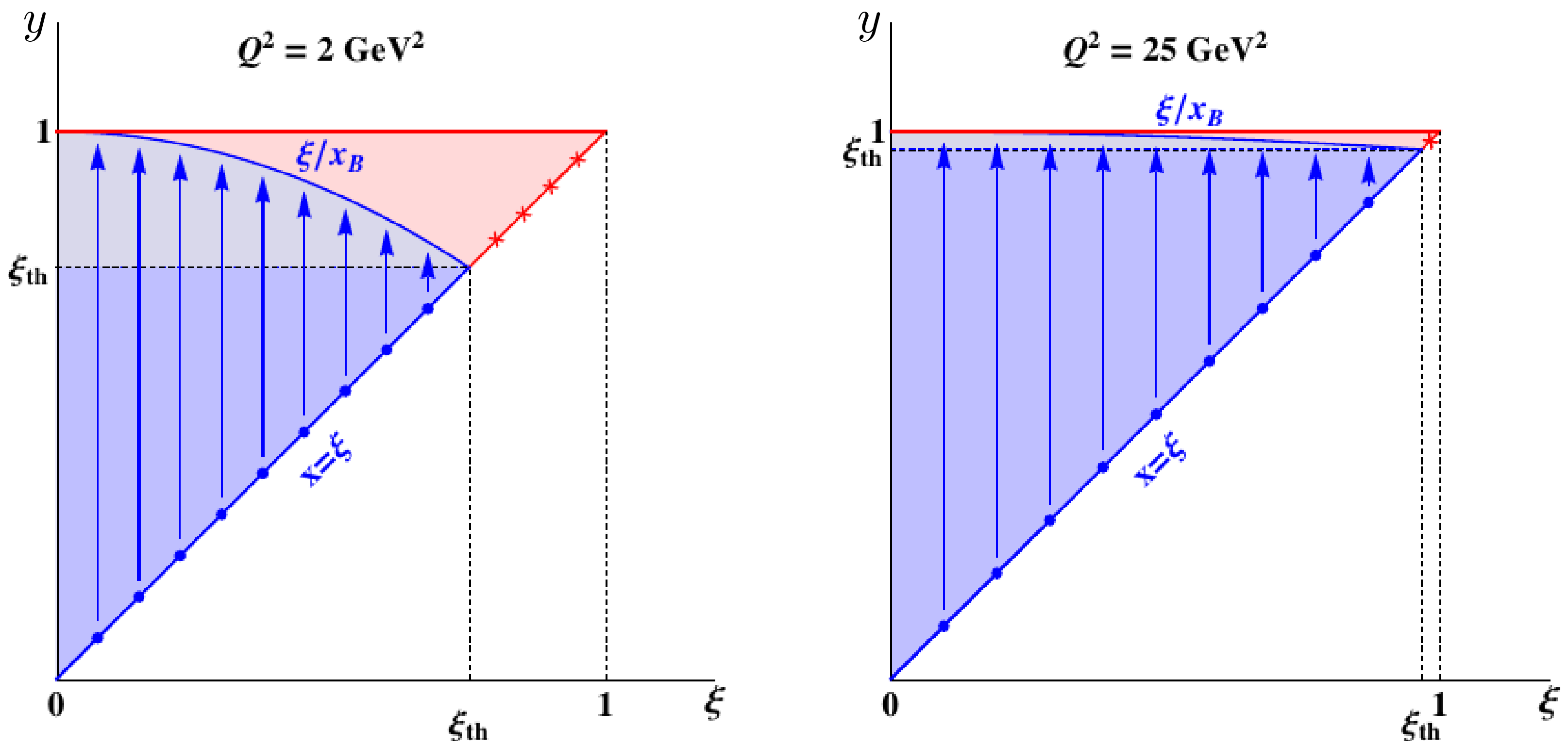


FIG. 3. On the left (right) hand side the integration regions for $Q^2 = 2$ GeV^2 ($Q^2 = 25$ GeV^2) concerning Eq. (37) are shown. The blue dots denote the boundary where the threshold singularities arise and the arrows indicate the direction of integration.

$$\xi_{th} = \frac{1}{1 + \sqrt{1 + 4M^2/Q^2}}$$

Threshold resummation with TMC

Accardi, Anderle, Ringer
PRD 91 (2015)

- Trick: separate integration in 2 pieces

$$F_{T,f} = \int_{\xi}^{\xi_{th}} \frac{dy}{y} \mathcal{C}_T^f\left(\frac{\xi}{y}\right) f(y) + \int_{\xi_{th}}^{\xi/x_B} \frac{dy}{y} \mathcal{C}_T^f\left(\frac{\xi}{y}\right) f(y)$$

- First one is finite, divergences in second; Mellin transform

$$F_{T,f}^N = \left(\int_0^1 dy y^{N-1} \mathcal{C}_T^f(y)\right)\left(\int_0^{\xi_{th}} dy y^{N-1} f(y)\right) = C_T^{f,N} f_{\xi_{th}}^N$$

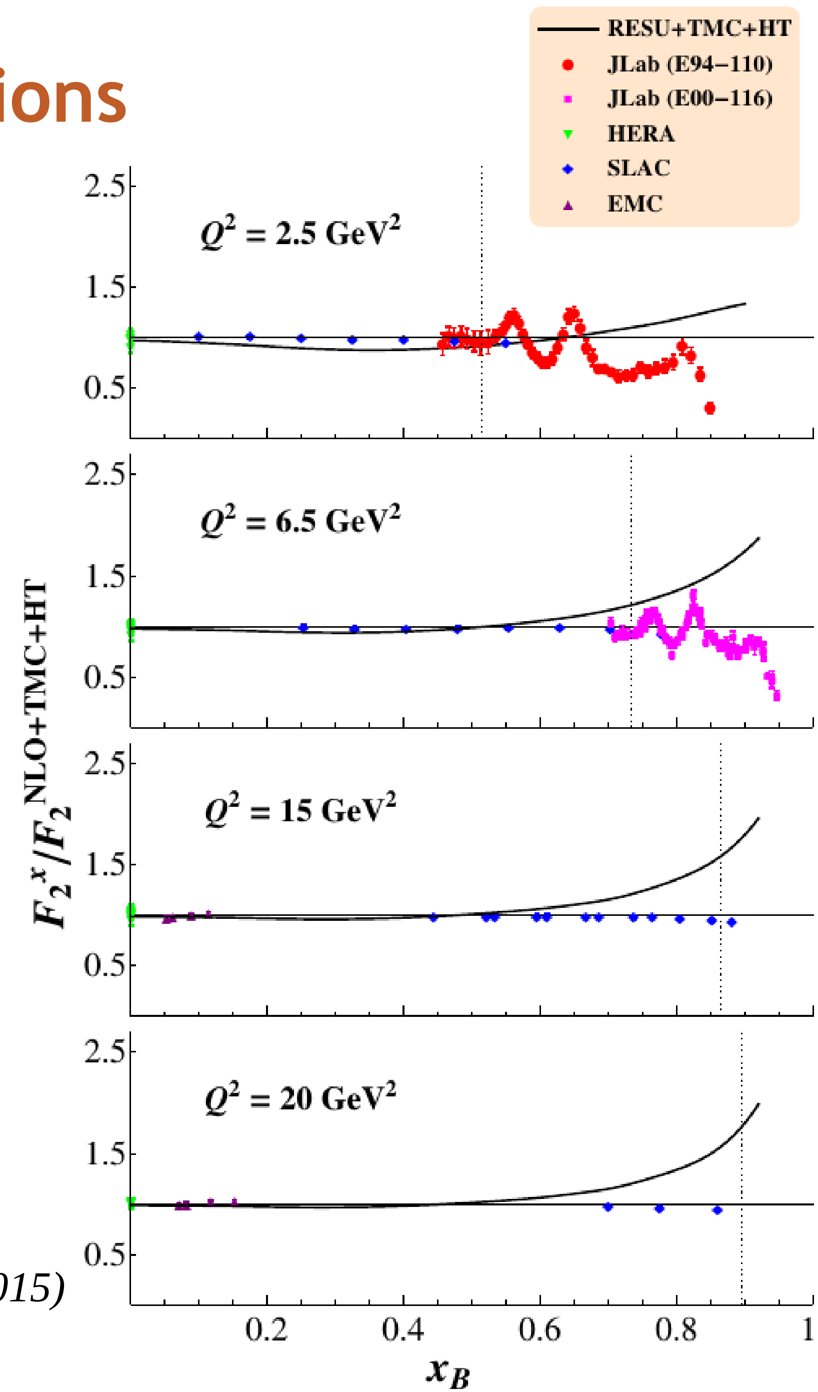
Truncated PDF moments

- Exponentiate $C_T^{1,N}$ as before, Mellin tramsform back

$$\mathcal{F}_{1,\mathrm{res}}(x_B, Q^2) = \int_{\mathcal{C}_N} \frac{dN}{2\pi i} x_B^{-N} \; \mathcal{C}_{q,\mathrm{res}}^{1,N}(Q^2/\mu^2, \alpha_s(\mu^2)) f_{\xi_{th}}^N(\mu^2)$$

Resummed structure functions

- F2: resummed vs. NLO
  - **Points**:
    bin-centered data / NLO theory
  - **Lines**:
    NLO+resummation / NLO theory
- **Resummation effects decrease with decreasing Q^2**
  - TMCs harden F2 at small Q^2
- Large effect in DIS region x > 0.5-0.6



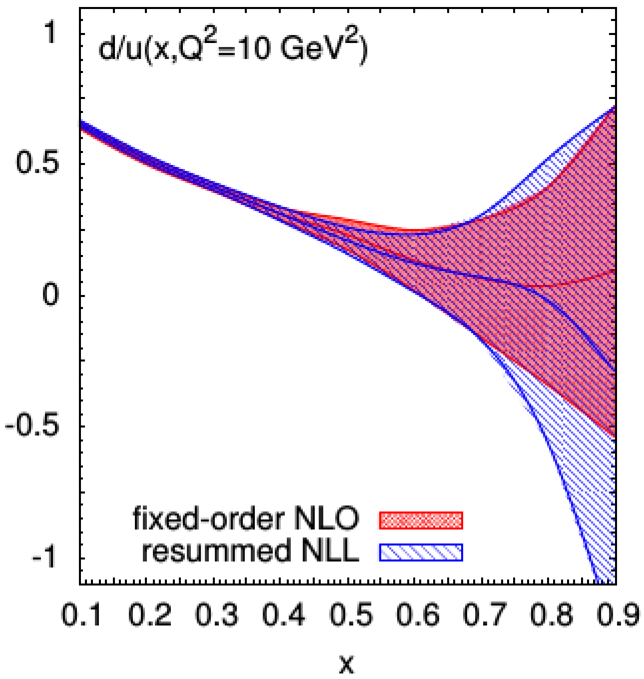
Accardi, Anderle, Ringer, PRD 91 (2015)

Resummed PDFs

- Let's do global fits with resummed theory
  - What's the effect on the (“resummed”) PDFs ?

- **NNPDF3.0 with threshold resummation** → E.Nocera' talk
  - Reduced data set cf. fixed order NNPDF3.0
  - Large $W^2 > 12.3$ GeV^2 cut
    - keeps only $x_B < 0.7$ data
    - Not much data in “resummation” region at x > 0.5-0.6

Plot courtesy of E.Nocera

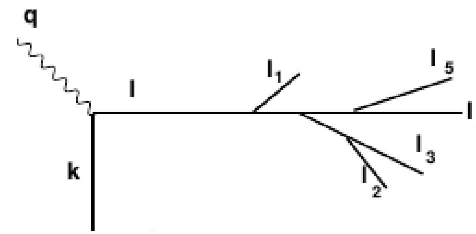


- Small effect on d, u singularly
  - even less on d/u

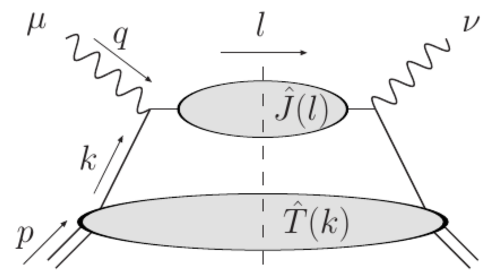
- **Need to lower the W cut !!**

Let's go non-perturbative

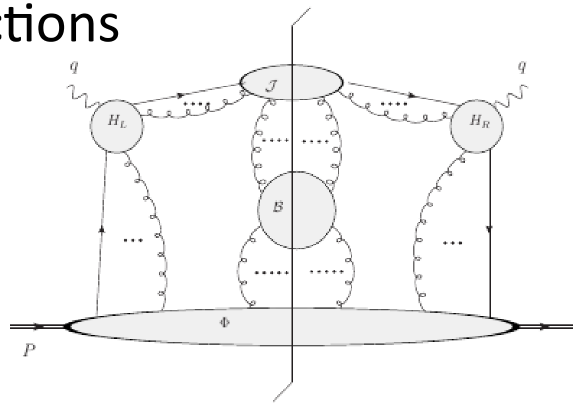
- **Soft-gluon resummation** *Catani et al., '90s*
  - pQCD treatment of large *log(1-x)*
  - *Pushes perturbative calculations*



- **Collinear Jet functions** *Accardi and Qiu, 2008*
  - *Can be seen as non-perturbative extension of soft-gluon emission*



- **Bridging the rapidity gap**
  - Eventually, need to account for soft interactions
  - Soft factors? *Collins, Rogers, Stasto, 2008*
    (TMD / fully unintegrated factorization)

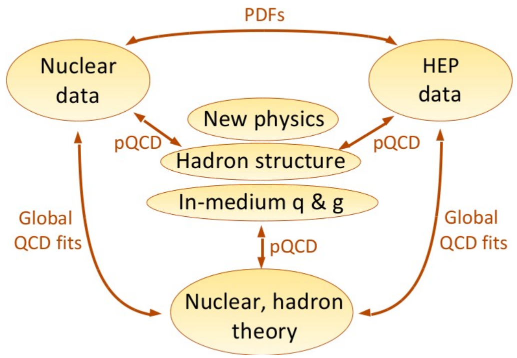


Conclusions

Conclusions

- **Entering a new precision era in large-x PDFs**
  - New data (now and in the future), new fitting approaches
  - Conquering nuclear corrections
  - Time for threshold resummation

- **High-energy and nuclear physics need to work together!**
  - Progress in hadron / nuclear structure
  - Precision PDFs for BSM searches



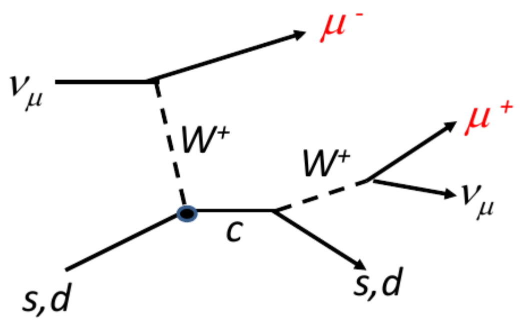
- **Next steps:**
  - the betrothal of PDFs and nPDFs!
  - Use lattice QCD fro nuclear PDF modifications

Appendix: strangeness fits

Strangeness and strangeness asymmetry

$$s^{\pm}(x) = s(x) \pm \bar{s}(x) \qquad [s^{\pm}] = \int_0^1 dx\, x\, s^{\pm}(x)$$

- In pre-LHC fits, mostly constrained by ν+A data
  - CCFR inclusive DIS
  - NuTeV muon pair production
  - NOMAD and CHORUS



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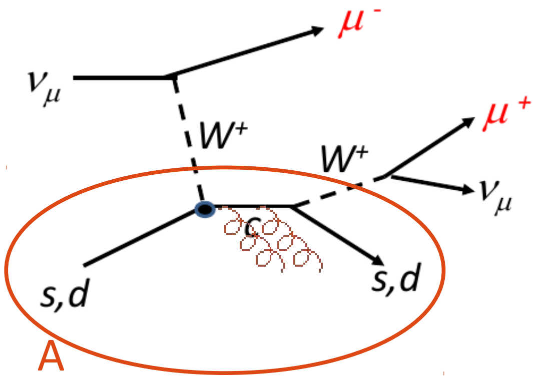

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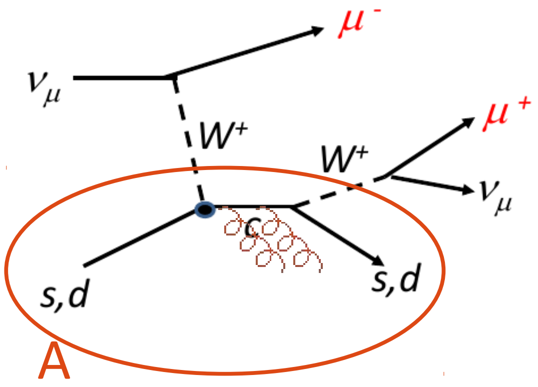
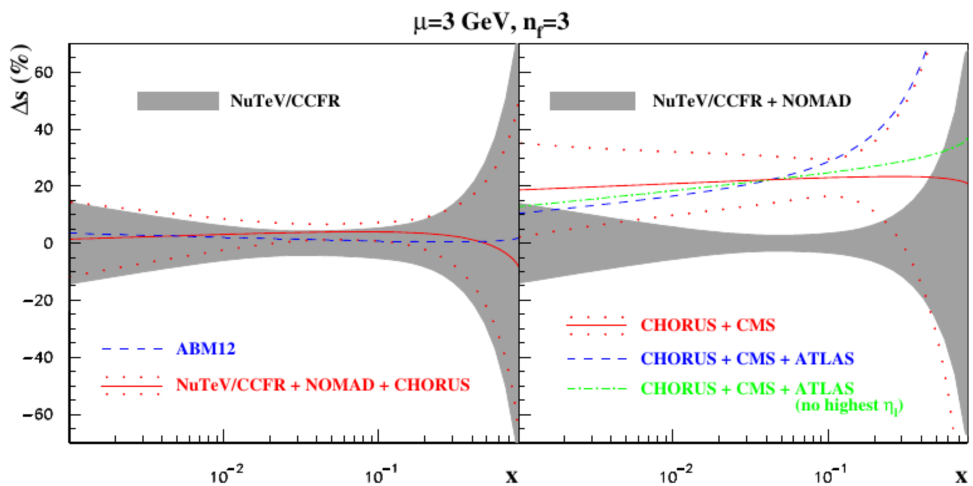


- **Nuclear corrections again...**
  - **Initial state nuclear wave-function mods**
    - Partly under control using **nPDFs**
    - But: double counting!! → either use in nPDF or in PDF fits !
  - **Final state propagation of the charm quark / D meson**
    - Not under theoretical / phenomenological control (*cf.* heavy quark "puzzle" in A+A at RHIC, LHC)

Strange tensions

- ν+*A* → dimuons *vs.* ***p*+*p* → *W*+*c*** at LHC *Alekhin et al., arXiv:1404.6469*



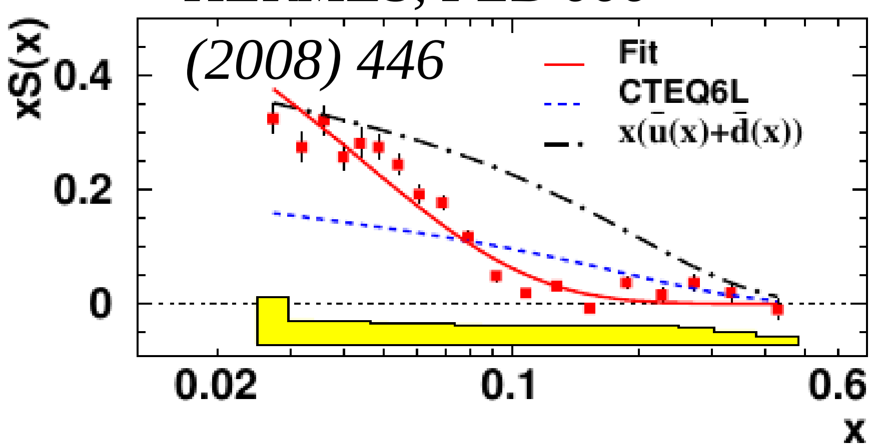
$$g\, s_p \rightarrow W\, c$$

FSI ?

$$\nu\, s_A \rightarrow \mu^-\, \mu^+\, \nu_\mu\, s$$

- **Kaons in *e*+*p* at HERMES**
  - But.. fragmentation functions uncertainty

HERMES, PLB 666 (2008) 446



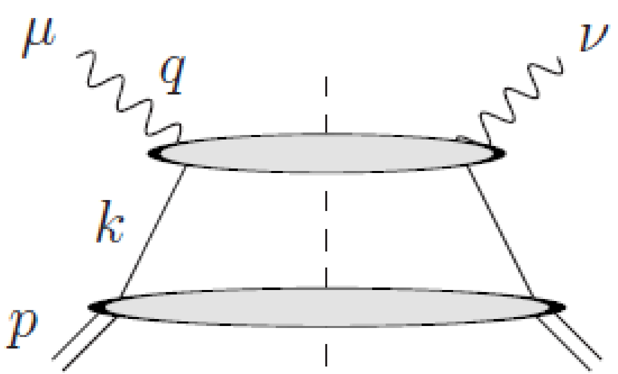
Strangeness and strangeness asymmetry

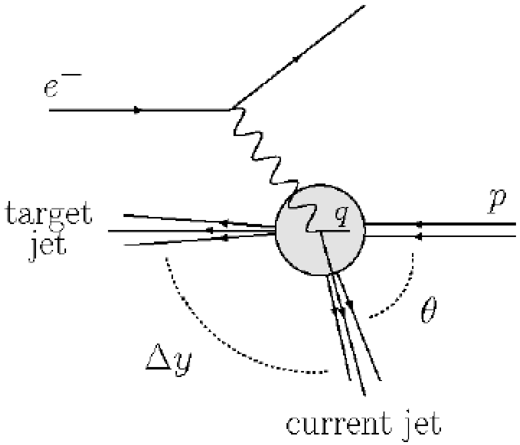
- In my opinion: **Don't use ν+A data in proton PDF analysis!!**
  - **Use neutrino data only for nPDFs**
    - combine with *W/Z* in p+A → nuclear strange
    - fit proton's strange PDF with, say, LHC/RHIC *W(+c), Z*
  - **Anchor nPDFs to proton PDFs, use nuclear data:**
    - Detect deviations from free proton strangeness
    - *W* and *Z* from RHIC, LHC → fit IS nuclear strangeness
    - Dimuons in ν+A → fit charm's FS "energy loss"
      (rather than subsuming in proton's s-quark)

Appendix: Resonance region

Confronting the resonance region*

- But: **where can we expect the handbag diagram to be valid ?**





- Current and jet separation in rapidity $y = \frac{1}{2} \ln p_h^+ / p_h^-$ with LO kinematics,

$$\Delta y \approx y_q - y_p = \log \frac{2\sqrt{2}\nu}{Q} \frac{1}{\sqrt{1 - Q^2/(2MxE)}}$$

- Berger criterion: $\Delta y > 2 \ (4)$ [Berger, ANL-HEP-CP-87-045, 1987; Mulders, hep-ph/0010199]

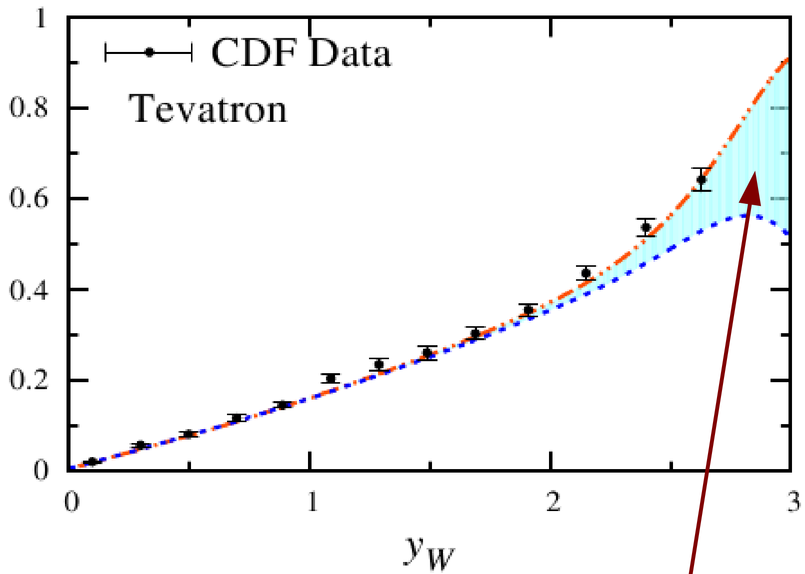
* *in collaboration with Simona Malace – see arXiv:1101.5148*

Appendix:
Very large x
at Tevatron and LHC

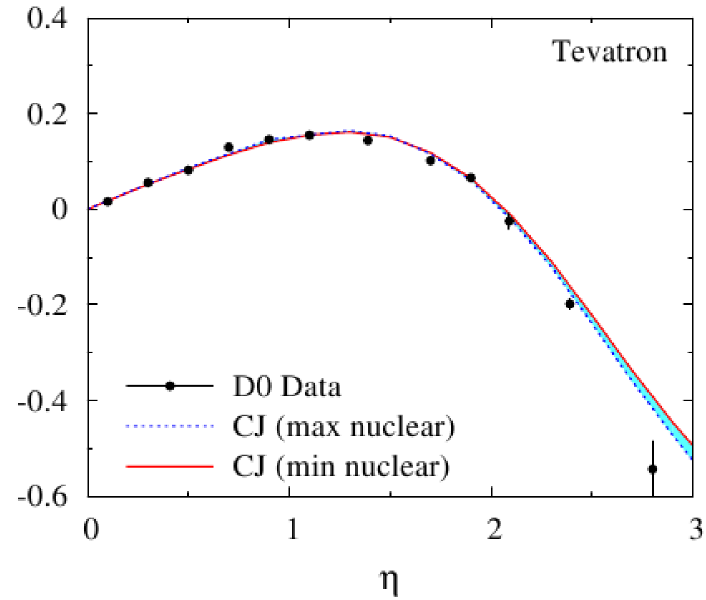
W charge asymmetry at Tevatron

Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

Directly reconstructed W:
- highest sensitivity to large *x*



From decay lepton W → l+ν:
- smearing in *x*



sensitive to *d* at high *x* → Can constrain Nuclear models!

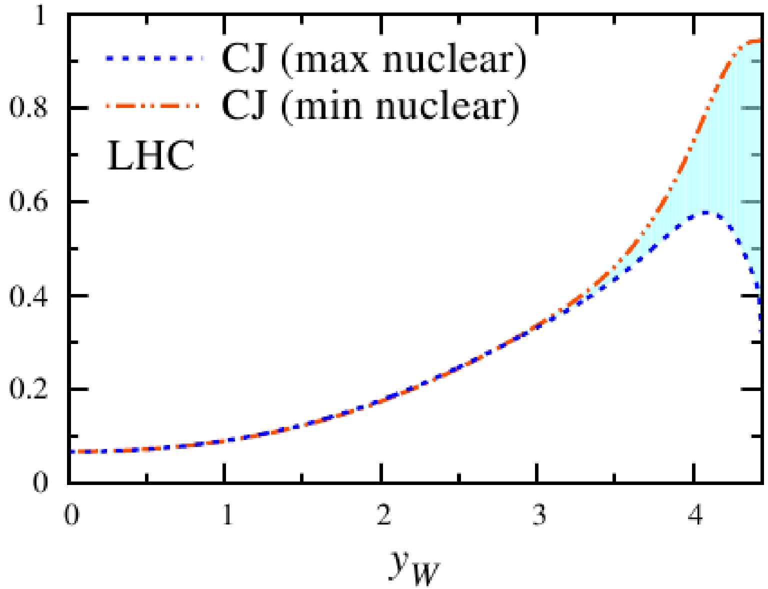
- Too little large-*x* sensitivity in lepton asymmetry:
  - **need reconstructed *W***

W charge asymmetry at LHC

Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

Directly reconstructed W:

- highest sensitivity to large *x*



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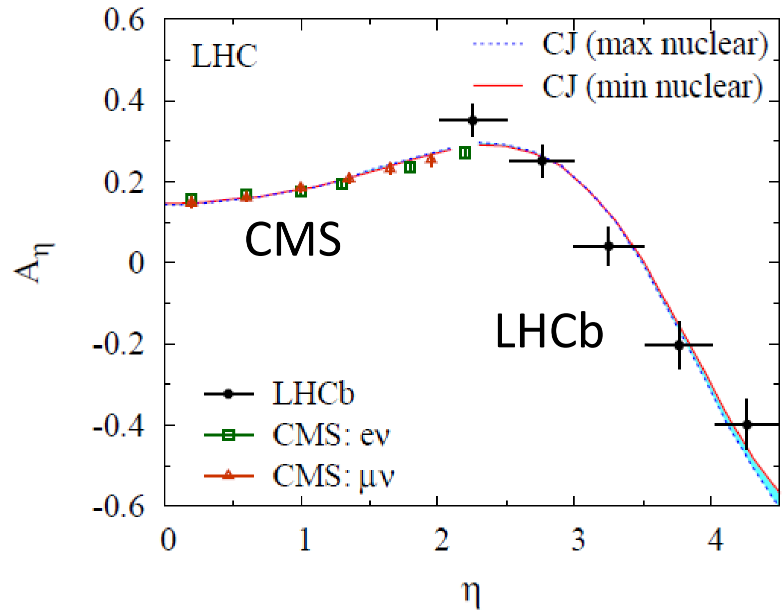
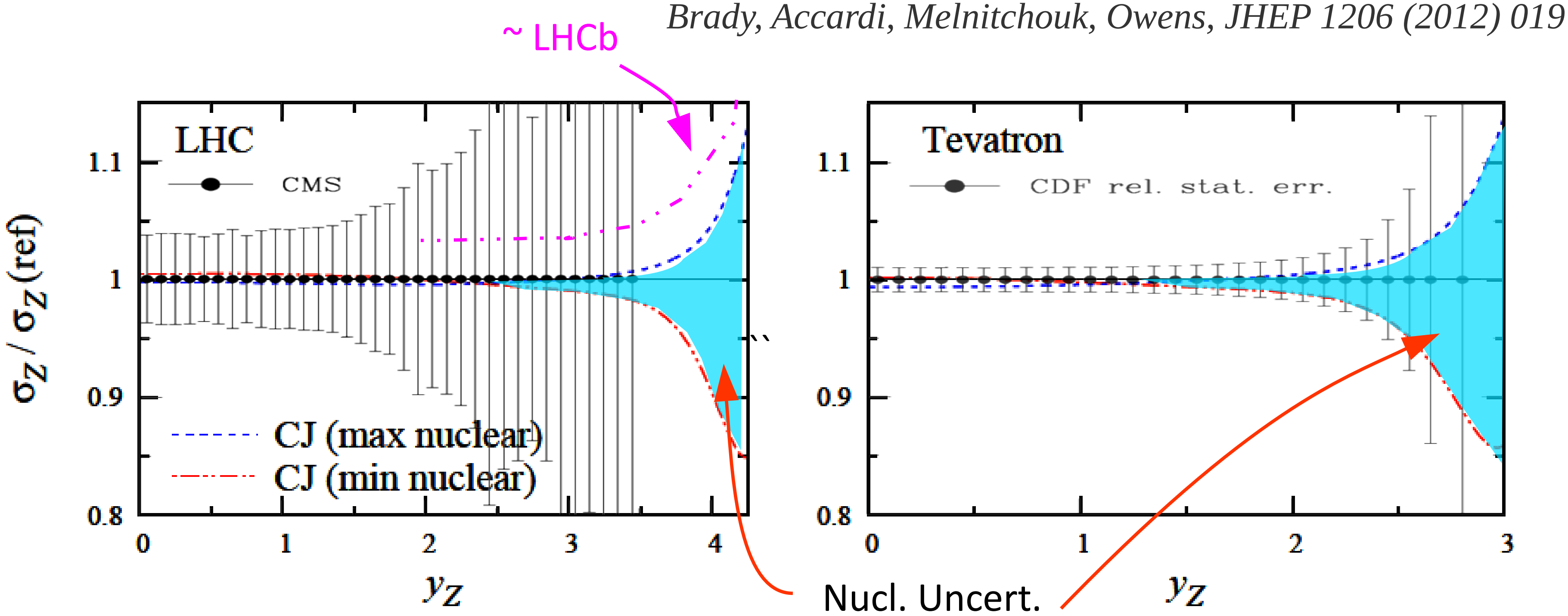


- **Would be nice to reconstruct *W* at LHCb**
  - Definitely needs more statistics
  - Is it at all possible?? (too many holes in detector?)
  - Systematics in *W* reconstruction?
  - **What about RHIC, AFTER@LHC?**

Z rapidity distribution

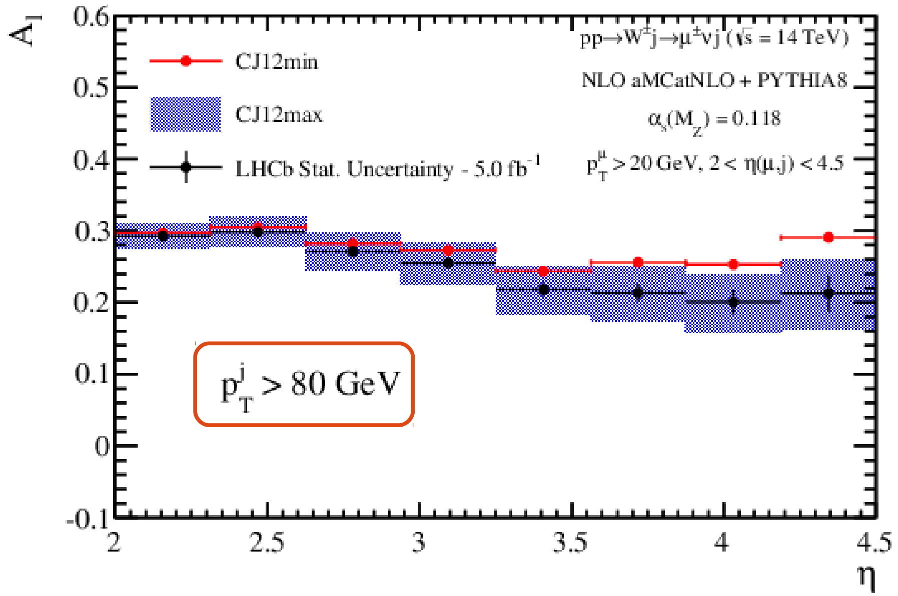
Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

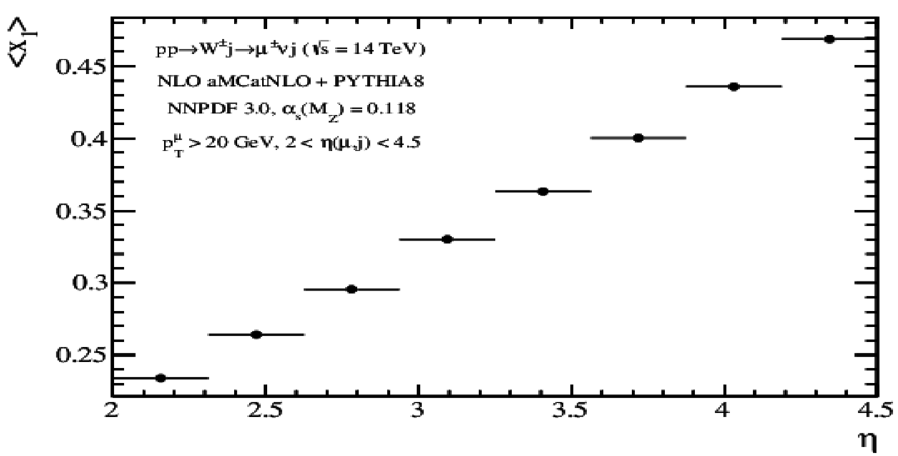


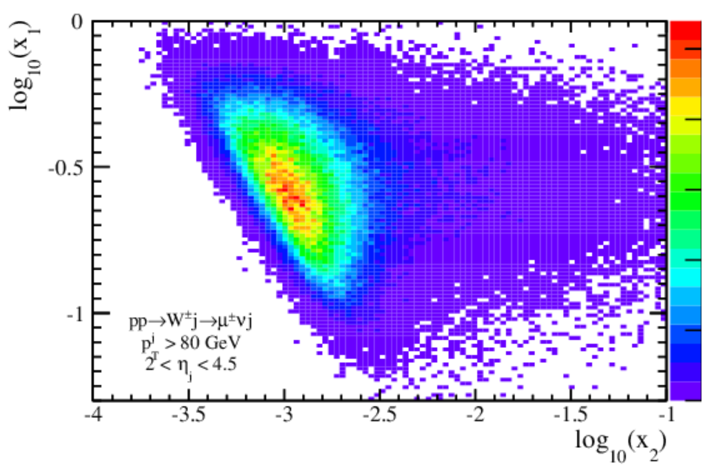
- Direct Z reconstruction is unambiguous in principle, but:
  - **Needs better than 5-10% precision at large rapidity**
  - Experimentally achievable?
    - At LHCb? RHIC? AFTER@LHC?
    - Was full data set used at Tevatron?

W+c at LHCb

S.Farry and R.Gauld, Benasque workshop, Feb 2015







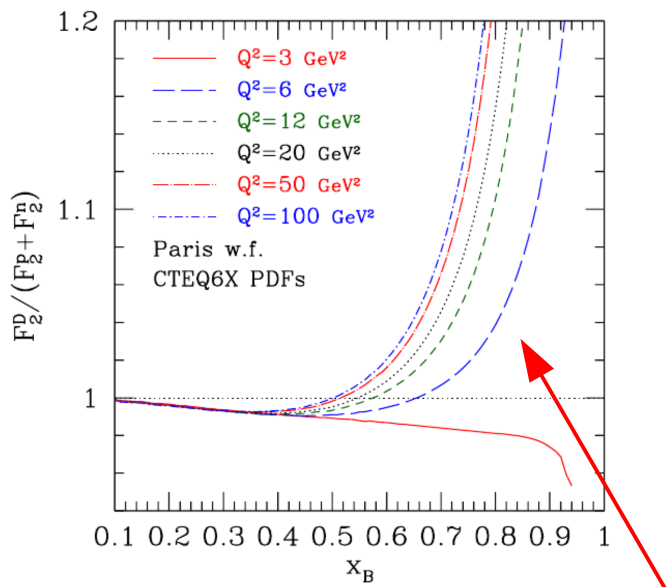
Appendix:
Nuclear corrections

CJ12 Deuteron corrections

- No free neutron! Best proxy: Deuteron
  - Parton distributions (to be fitted)
  - nuclear wave function (AV18, CD-Bonn, WJC1, …)
  - Off-shell nucleon modification (model dependent)

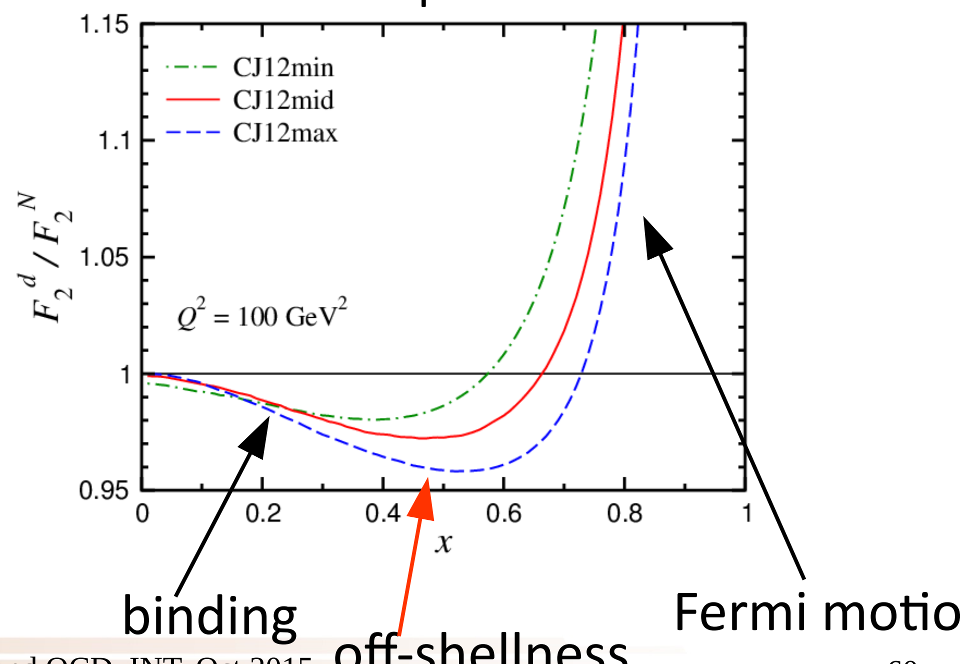
} Theoretical uncertainty

$$F_{2d}(x_B,Q^2) = \int_{x_B}^{A} dy\, \mathcal{S}_A(y,\gamma) F_2^{TMC+HT}(x_B/y,Q^2) \left(1 + \frac{\delta^{off} F_2(x)}{F_2(x)}\right)$$



Strong Q^2 dependence at large x !

Bound vs. free proton+neutron



Nuclear corrections for p+d DY

Ehlers, AA, Brady, Melnitchouk, PRD90 (2014)

- Same nuclear model for DY cross sections

$$\sigma^{pd}(x_p, x_d) = \sum_N \int_{x_d}^{1} \frac{dz}{z} \left[f(z) + f^{(\mathrm{off})}(z)\, \delta\sigma^{pN}\left(x_p, \frac{x_d}{z}\right) \right] \sigma^{pN}\left(x_p, \frac{x_d}{z}\right)$$

Same as in DIS
(in Bj. limit)

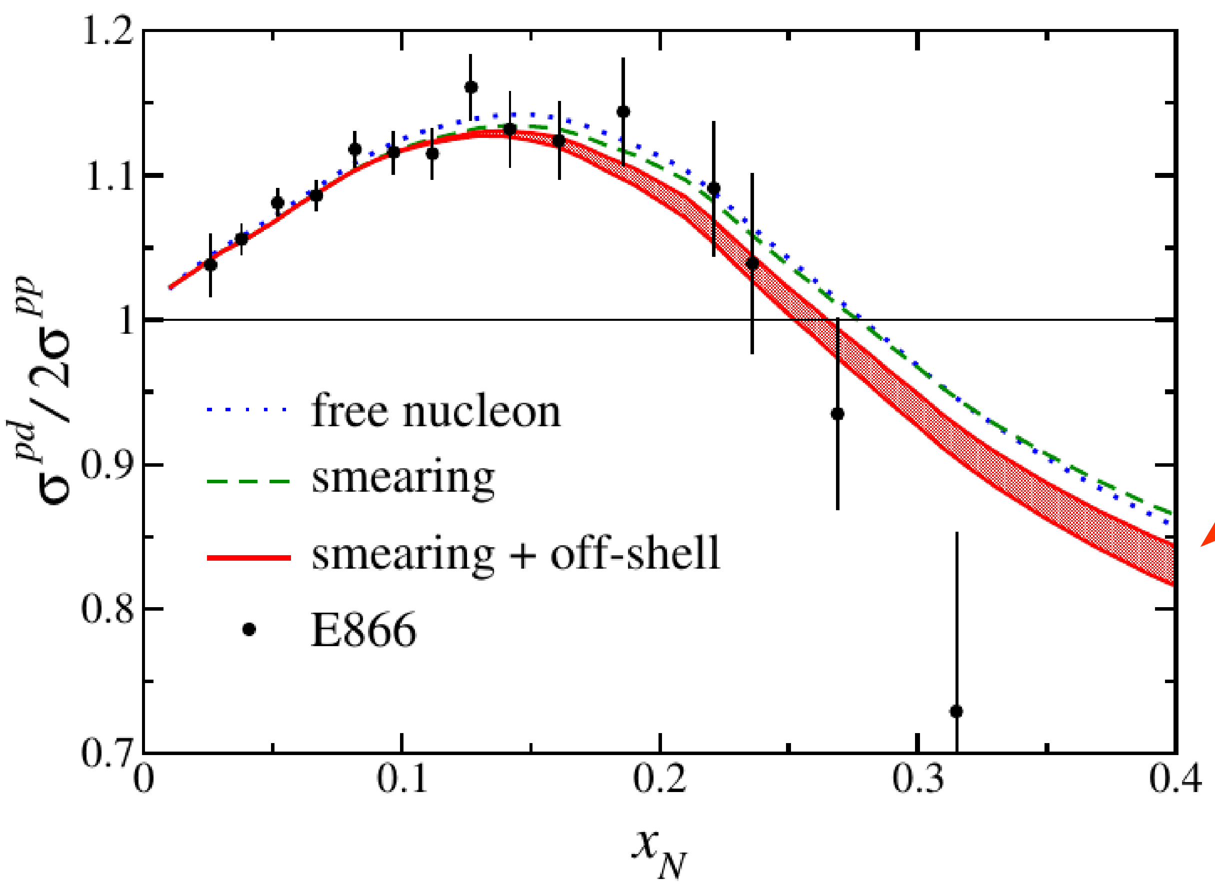
- Off-shell model extended to sea quarks and gluons
  - Spectral function in suitable spectator model

$$\widetilde{q}(x, p^2) = \int dw^2 \int_{-\infty}^{\hat{p}^2_{\max}} d\hat{p}^2\, D_q(w^2, \hat{p}^2, x, p^2)$$

- Pion-cloud effects also studied *Kamano, Lee, PRD86 (2012)*

Nuclear corrections…

Ehlers, AA, Brady, Melnitchouk, PRD90 (2014)

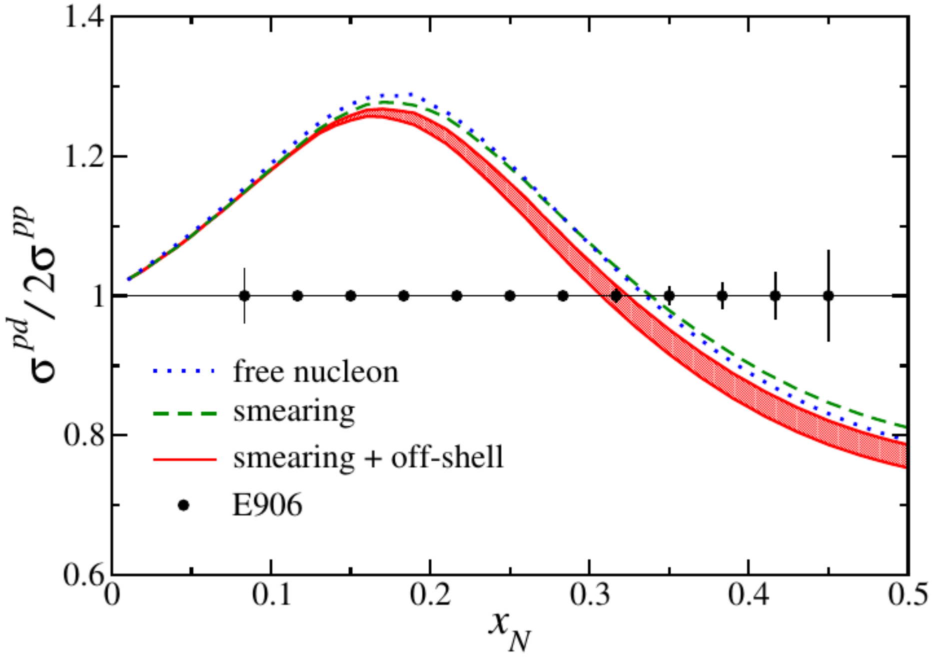


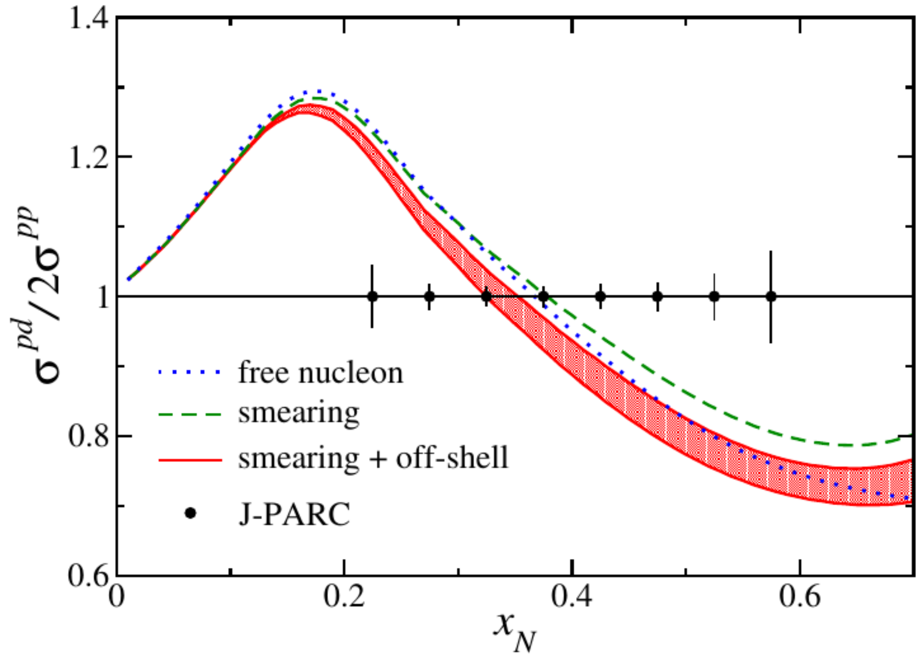
Red band: combined wave fn. & off-shell model uncertainty

- Off-shell corrections help makes dbar-ubar stay positive

Future DY reaches into large-x

Ehlers, AA, Brady, Melnitchouk, PRD90 (2014)





- **E906/Sea Quest:** off-shell effects even more important
- **J-PARC:** can cross-check nuclear smearing vs. DIS

Sea quarks

Charge symmetry breaking

- **E866 lepton pairs:**

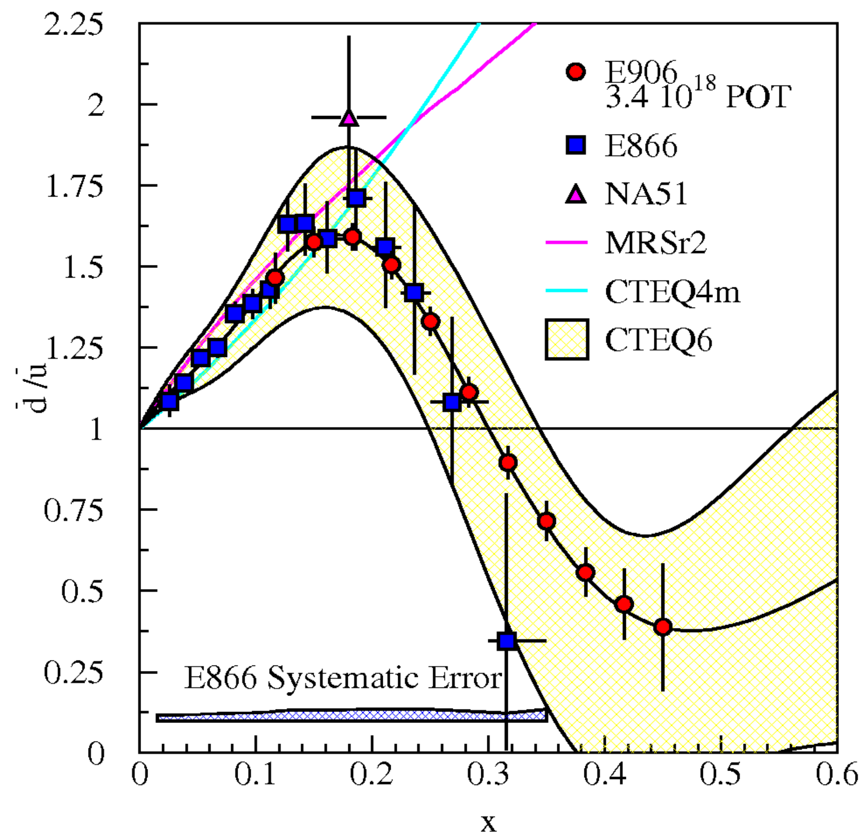
$$\bar{d}(x) - \bar{u}(x) \neq 0 \text{ at } \; x > 0.1$$

  - Maybe even negative (a theory challenge...)

- **E906 / SeaQuest**
  - Will focus on large *x*

- **LHC W/Z production:**
  - Access to $x \sim 0.01$ range

- **But** $\frac{\bar{d}}{\bar{u}} \neq \frac{\sigma_{pp}}{\sigma_{pd}} - 1$



Theory corrections needed for few % level accuracy

Appendix:
Large-x data

New Large-x data: a partial list

- **DIS data minimally sensitive to nuclear corrections**
  - DIS with slow spectator proton (BONUS)
    - Quasi-free neutrons
  - $^3He/^3H$ ratios (Marathon)

Jlab

- **Data on free (anti)protons, sensitive to *d***
  - *e+p*: parity-violating DIS **HERA** *(e^+ vs. e^-)*, ***EIC, LHeC***
  - $\nu+p$, $\bar{\nu}+p$: **ShiP, ELBNF Near Detector, MINERvA**
  - *p+p, $\bar{p}$+p* at large positive rapidity
    - *W* charge asymmetry, *Z* rapidity distribution

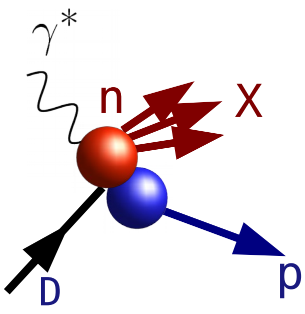
Tevatron: CDF, D0
LHCb(?) RHIC !!
AFTER@LHC

- **"Drell-Yan" data**
  - *Dimuons:* **E906, J-PARC (?)**
  - *p+d* at large negative rapidity – dileptons; *W, Z*
    - Sensitive to nuclear corrections, cross-checks *e+d*

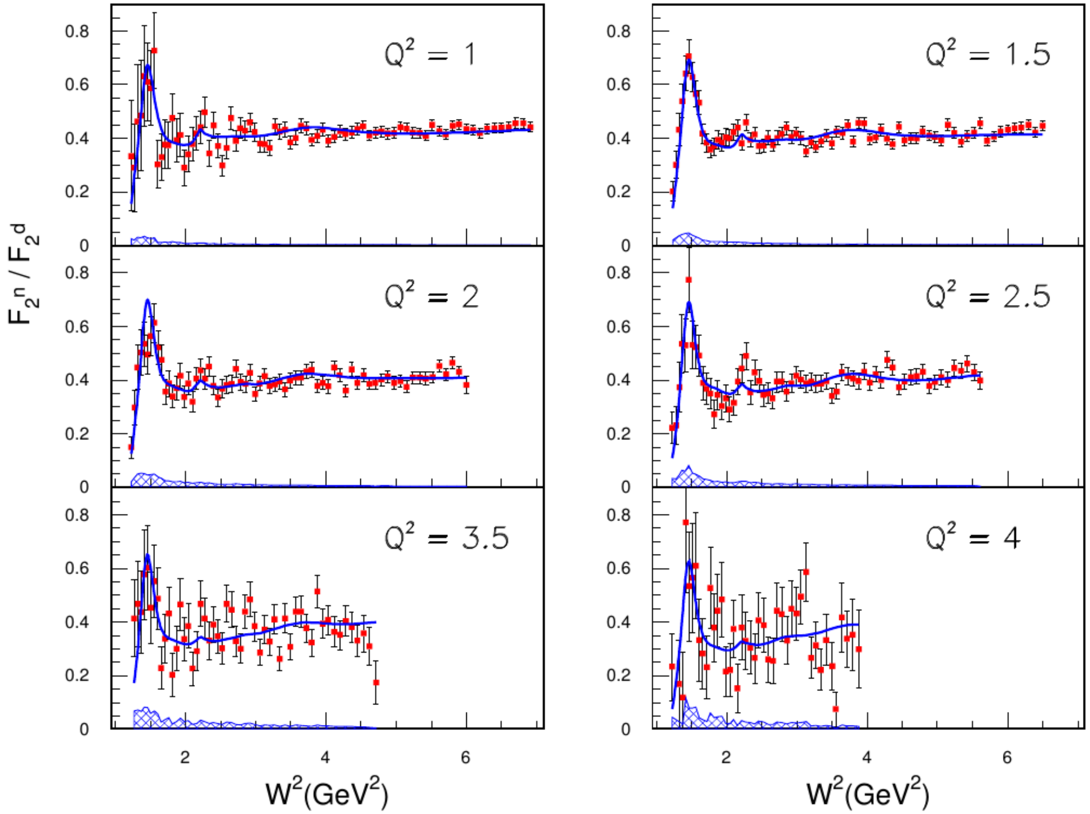
RHIC ??
AFTER@LHC
…

JLab 6 GeV: Quasi-free neutrons for today

- **Spectator proton tagging**
  - Nuclear corrections minimized experimentally



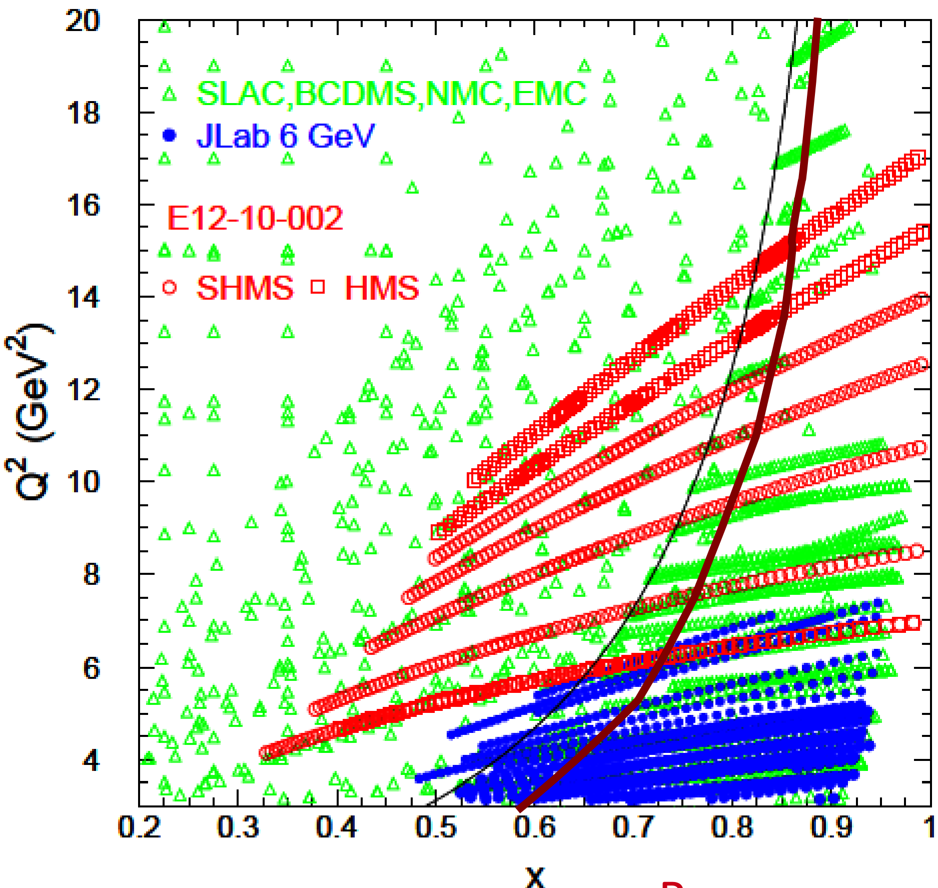
***BONUS coll.**,,. Tkachenko et al. arXiv:1402.2477*



JLab 12 - proton, deuteron structure functions

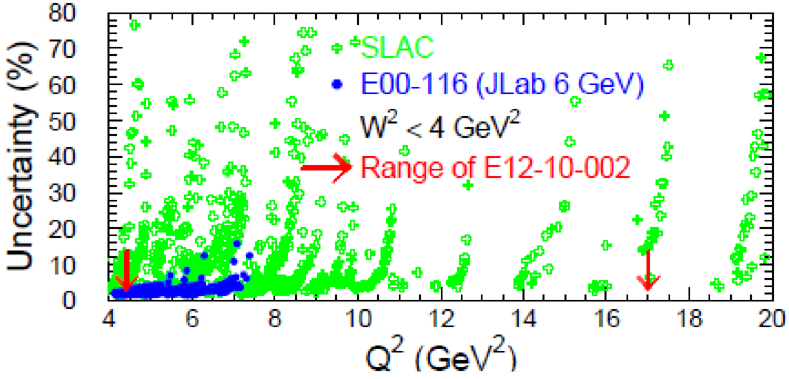
Jlab12 experiment E12-10-002

CJ cut: $W^2 > 3\ \mathrm{GeV}^2$



DIS region

Resonance region

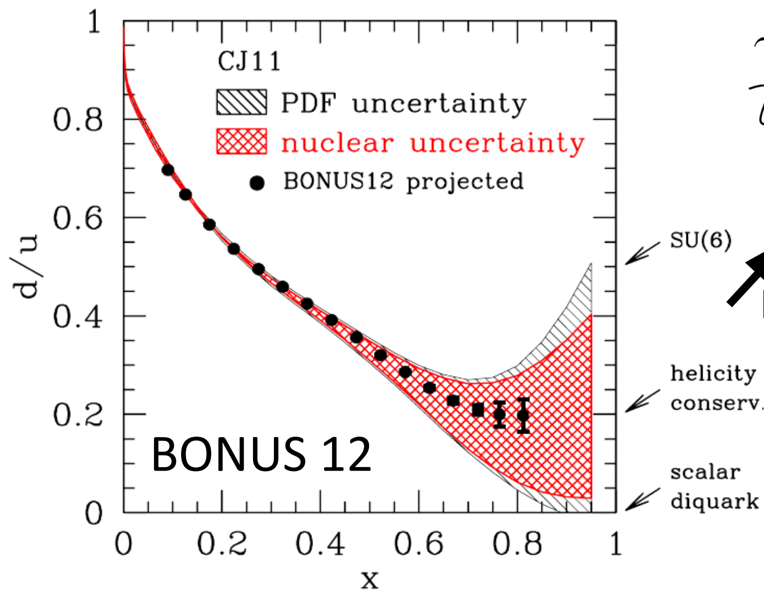


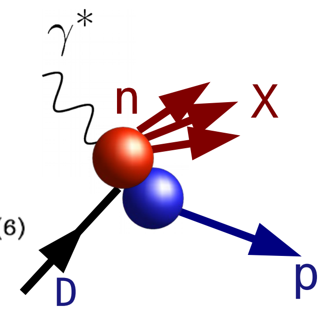
- **JLab 12 GeV**
  - More than double Q^2 range
  - Similar precision as JLab **6 GeV** (largely improve cf. **SLAC**)

JLab 12: Quasi-free neutrons for tomorrow

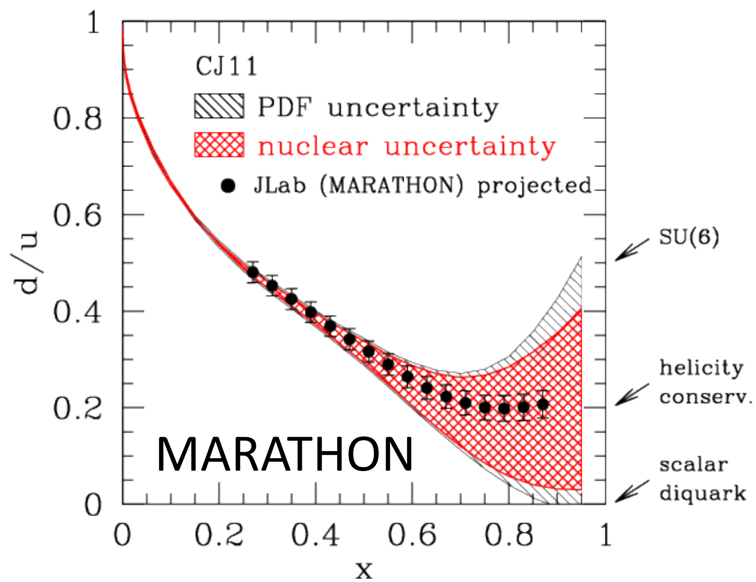
- Nuclear corrections largely cancel:
  - **Spectator tagging**
  - **$^3He/^3H$ cross sec. ratio**

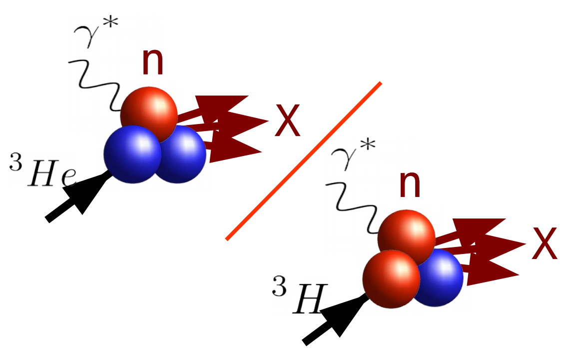
JLab E12-06-113





JLab E12-10-103



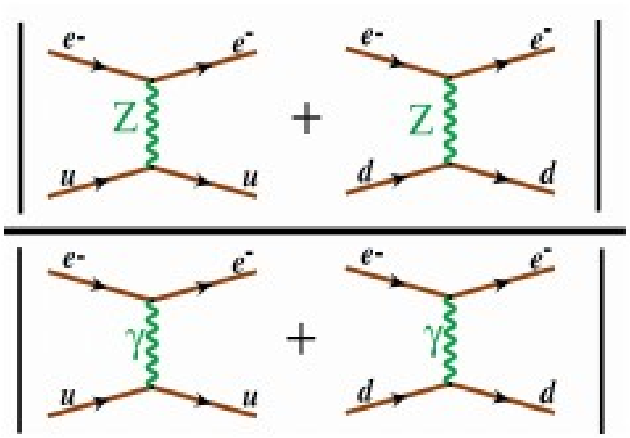


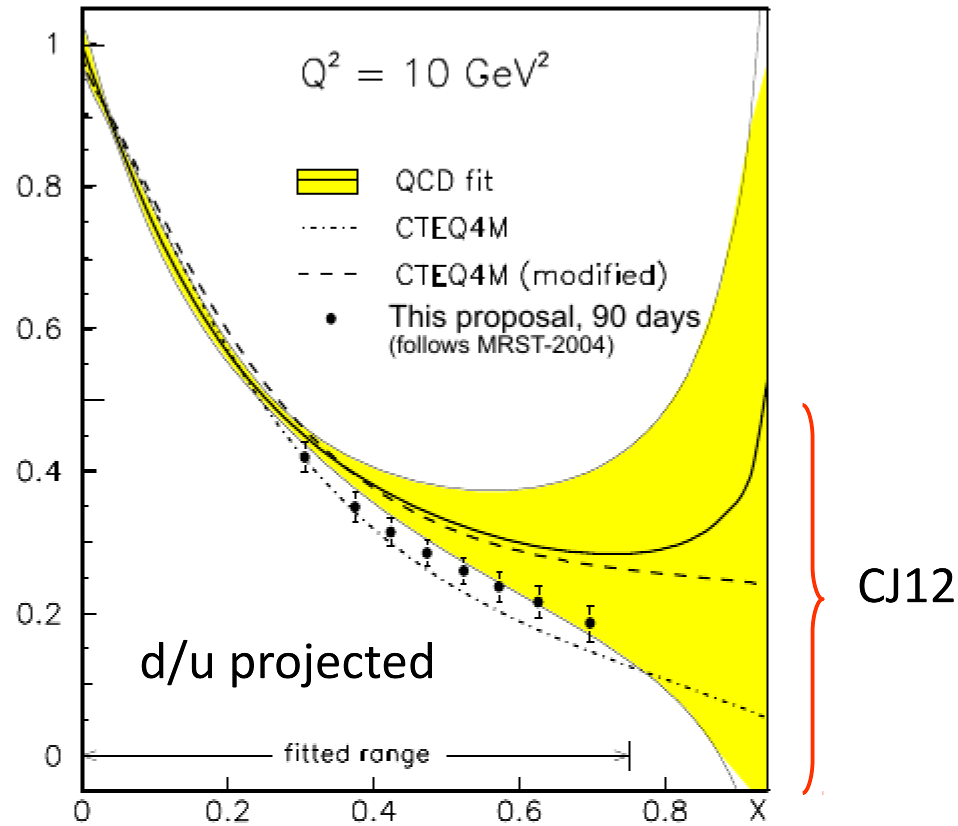
JLab 12: Parity-Violating DIS

Jlab12 experiment E12-10-007

- Longitudinally polarized electrons → PV asymmetry

$$A_{LR} = A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{\tilde{A}_Z}{A_\gamma}$$





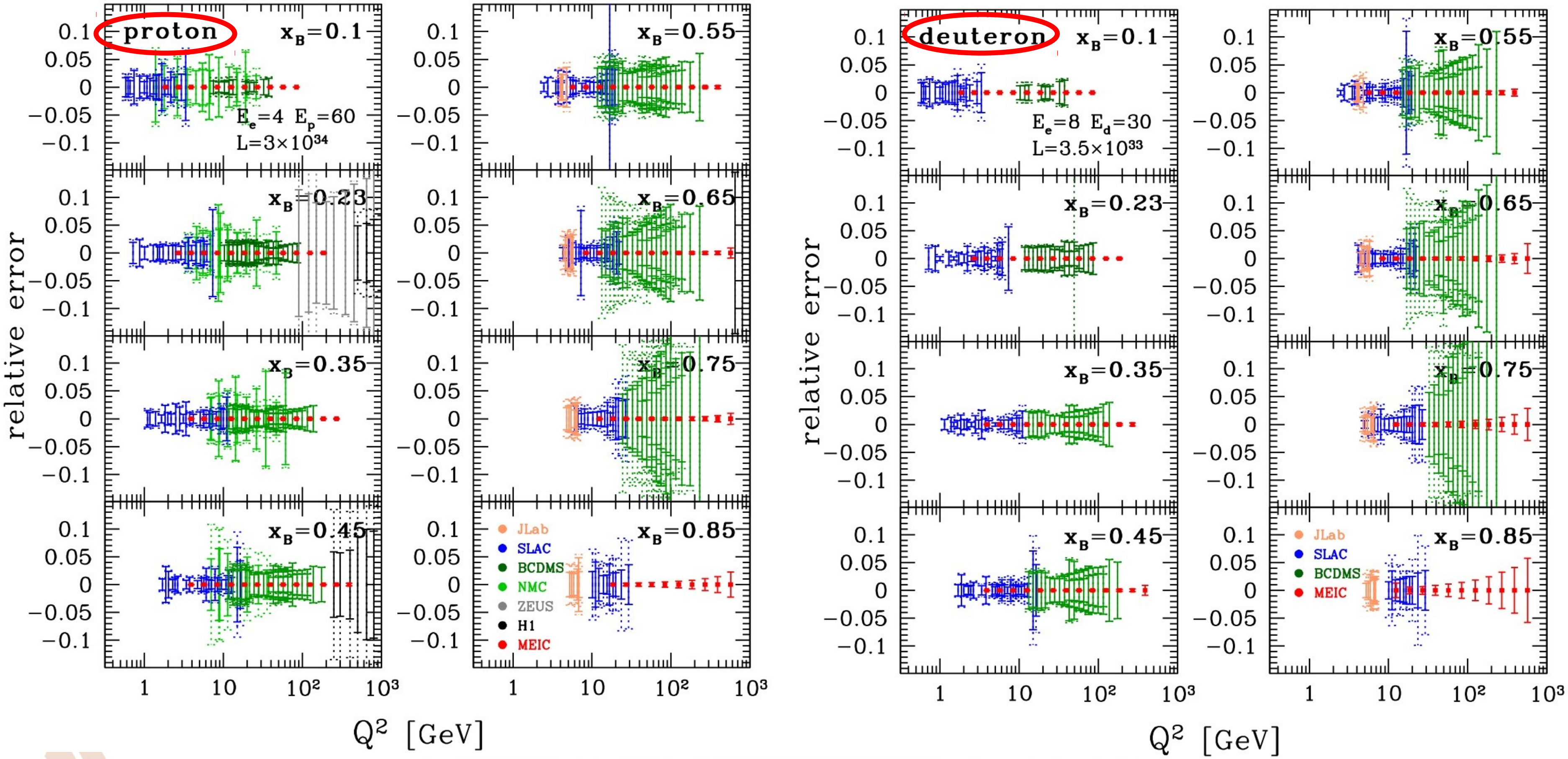
Appendix:
old and new experiments

- examples -

At the EIC

- **Neutral current DIS**
  - MEIC √s = 31 GeV (ca. 2010)
  - Pseudo data using "CTEQ6X" fits, L=230 (35) fb^{-1}

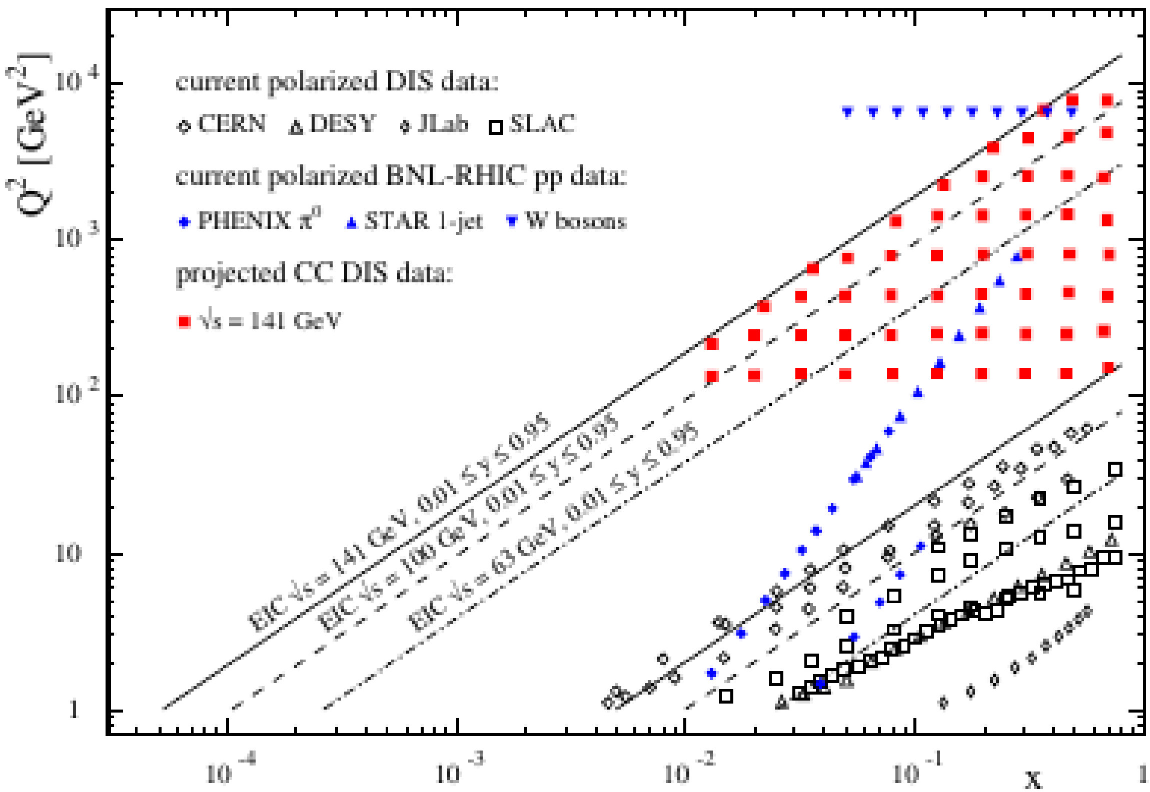
[Accardi, Ent, Keppel, 2010]



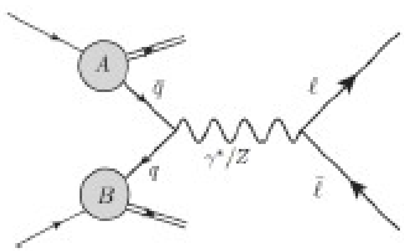
At the EIC

- **Charged current DIS**
  - plot for polarized scattering, similar for unpolarized
  - Not optimized at large-x: likely to add a bin around x = 0.85

[Aschenauer et al, 2013]

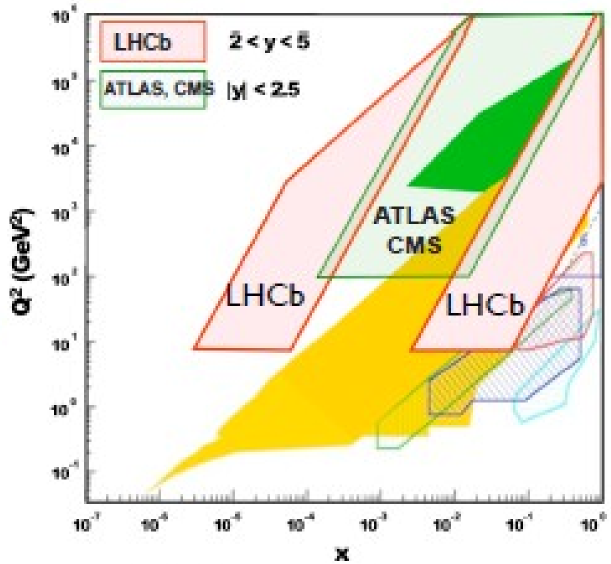


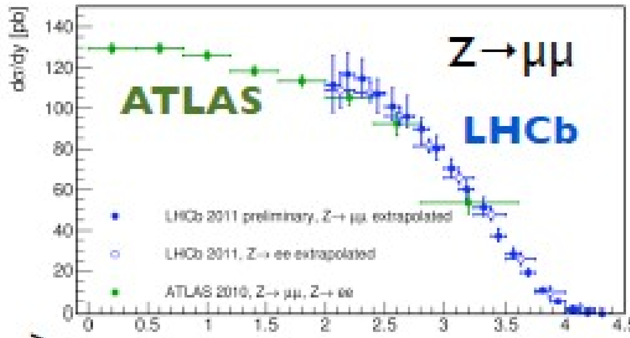
Constraints from the LHC: Electroweak Boson Production

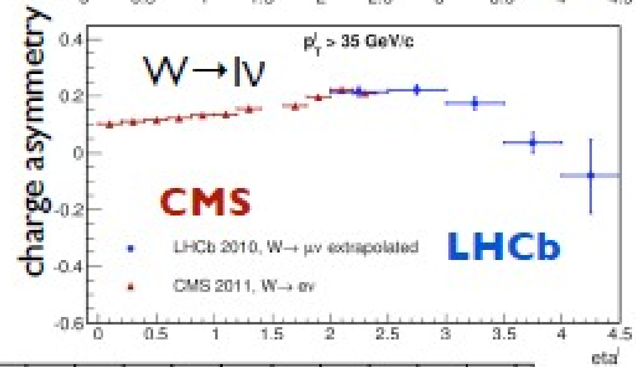


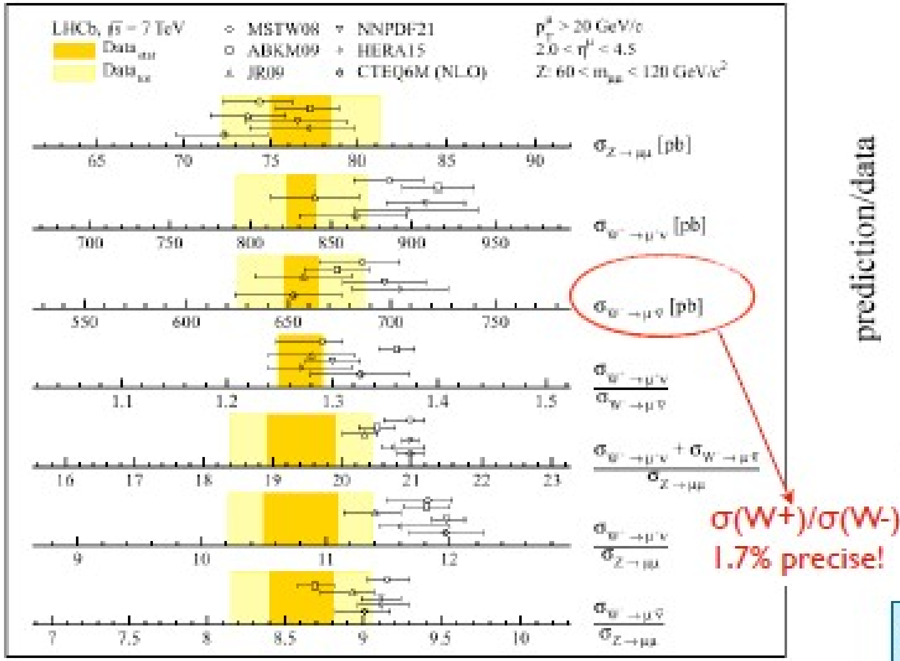
probe light quarks at low and high x

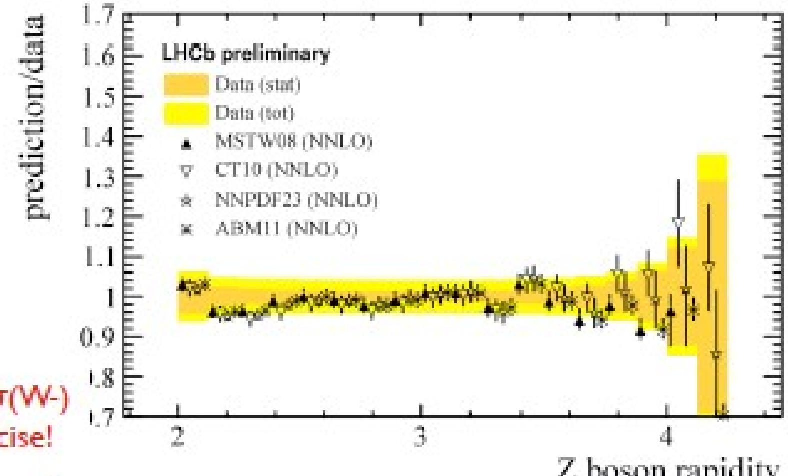
LHCb (S.Tourneur)







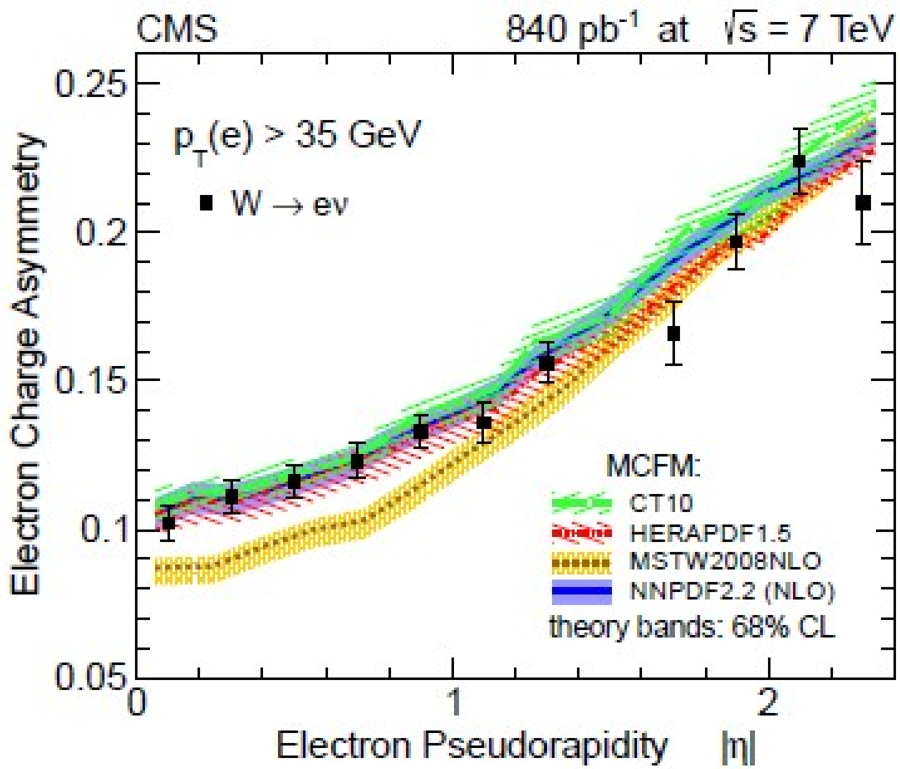




Systematic error comparable with PDF error
Benchmarking different PDF sets

K. Lipka, DIS'13 WG1 summary

W lepton asymmetry at LHC



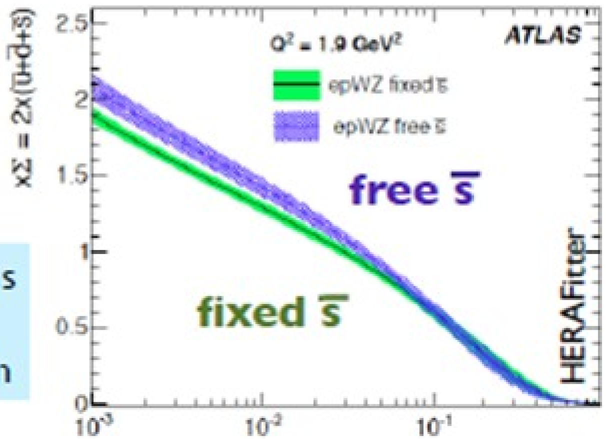
Sensitive both to d/u at $x > 0.1$ and $\bar{u}/\bar{d}$ at $x \sim 0.01$ (not constrained well by other experiments)

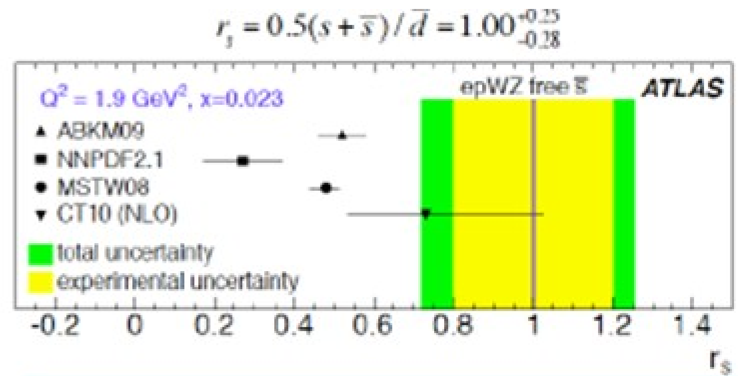
Constraints on strangeness: *W,Z, W+c*

ATLAS *(K. Nikolics)*

$\sqrt{s}$=7 TeV, L=35 pb^{-1}

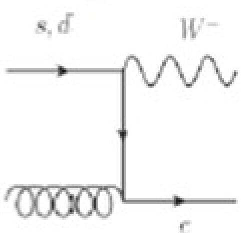
Z,W rapidity distributions sensitive to strangeness in the proton





data disfavors strangeness suppression

W+c probe strangeness



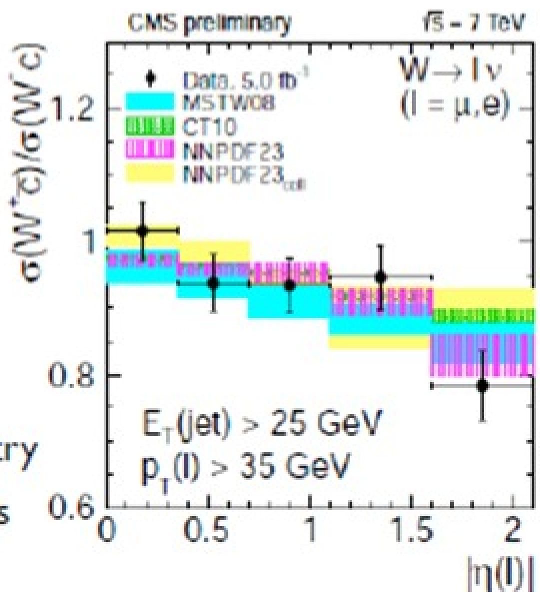
+ c.c.

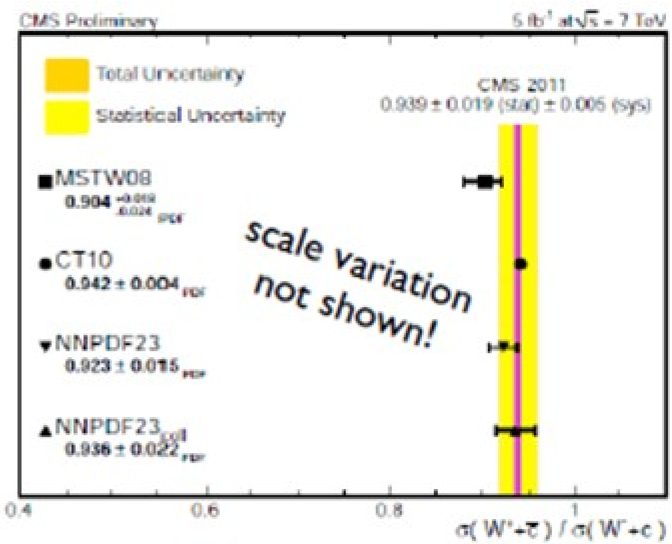
(E.Vryonidou)

Ratios: $\frac{W^+ + \bar{c}}{W^- + c}, \frac{W+c}{W+jets}$

Strangeness and strange asymmetry

Precise data could constrain PDFs





K. Lipka, DIS’13 WG1 summary

Constraints on strangeness: $K^{\pm}$ at the EIC

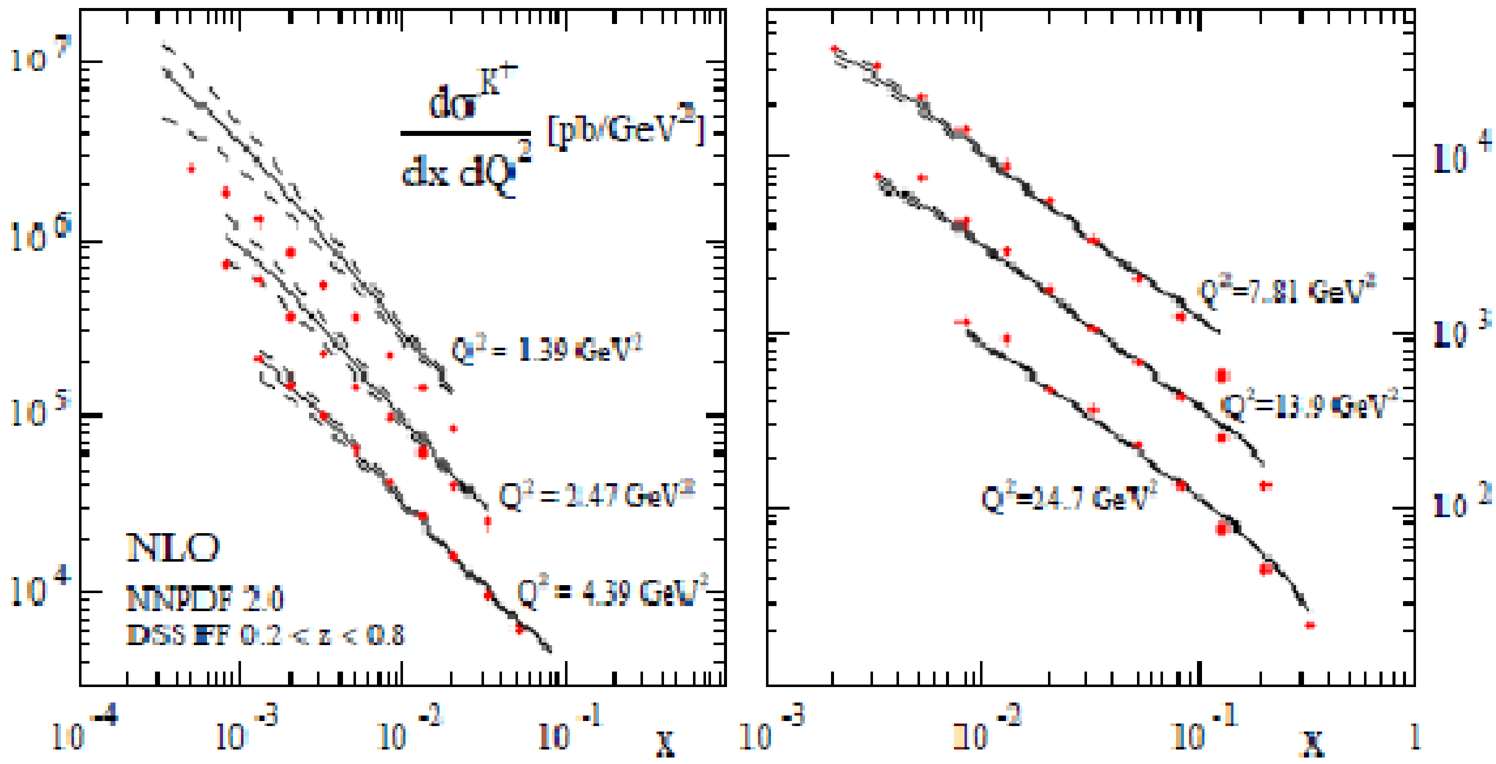


Figure 1.10. SIDIS cross section for K^+ production at NLO accuracy using NNPDF2.0 PDFs [47]. The dashed lines denote the PDF uncertainties. Also shown (points) are the results from a PYTHIA simulation (see text).

Aschenauer, Stratmann, in 1108.1713

Intrinsic charm at the EIC

The ultimate test of the intrinsic charm mechanism is possible in charm SIDIS at the EIC with modest luminosities

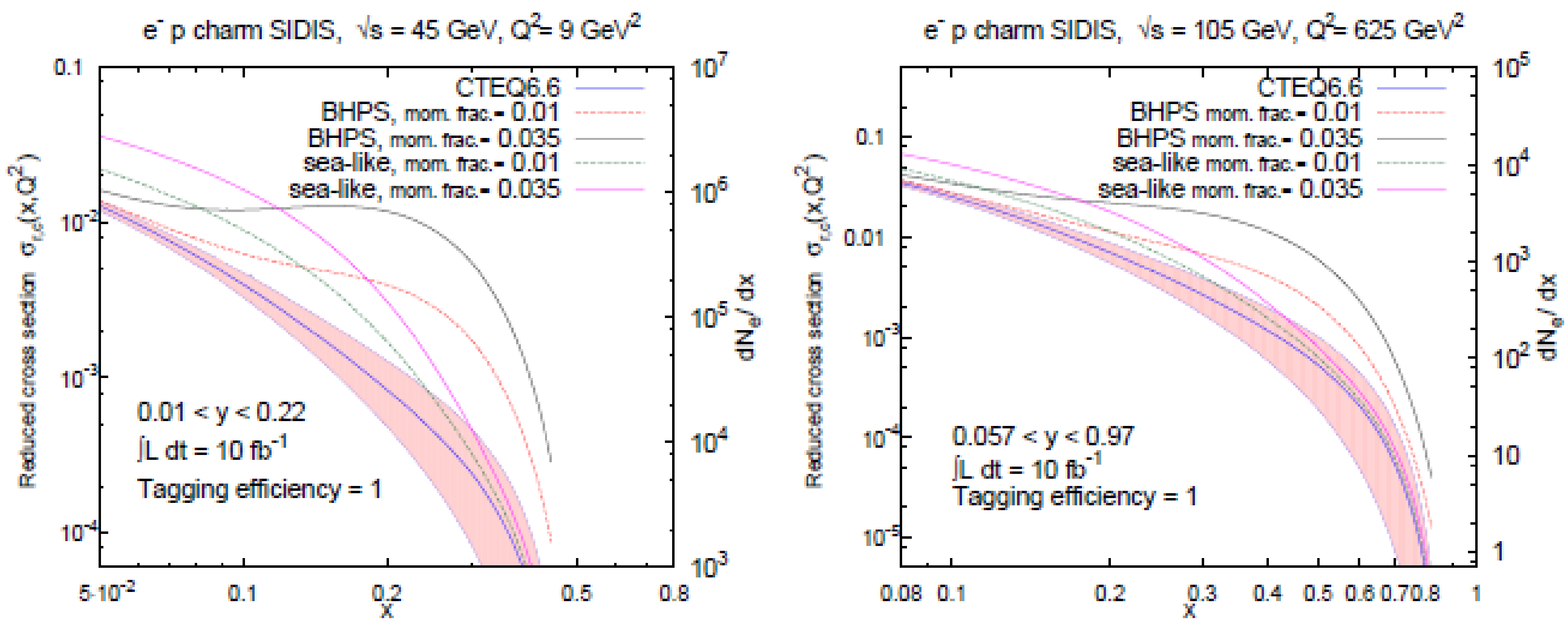


Figure 1.20. Charm contribution to the reduced NC e^-p DIS cross section at $\sqrt{s} = 45$ and 105 GeV. For each IC model, curves for charm momentum fractions of 1% and 3.5% are shown. For comparison we display the number of events dN_e/dx for 10 fb^{-1}, assuming perfect charm tagging efficiency.

Guzzi, Nadolsky, Olness, Sec. 1.9 in 1108.171