CJ15 global PDF analysis with new electroweak data

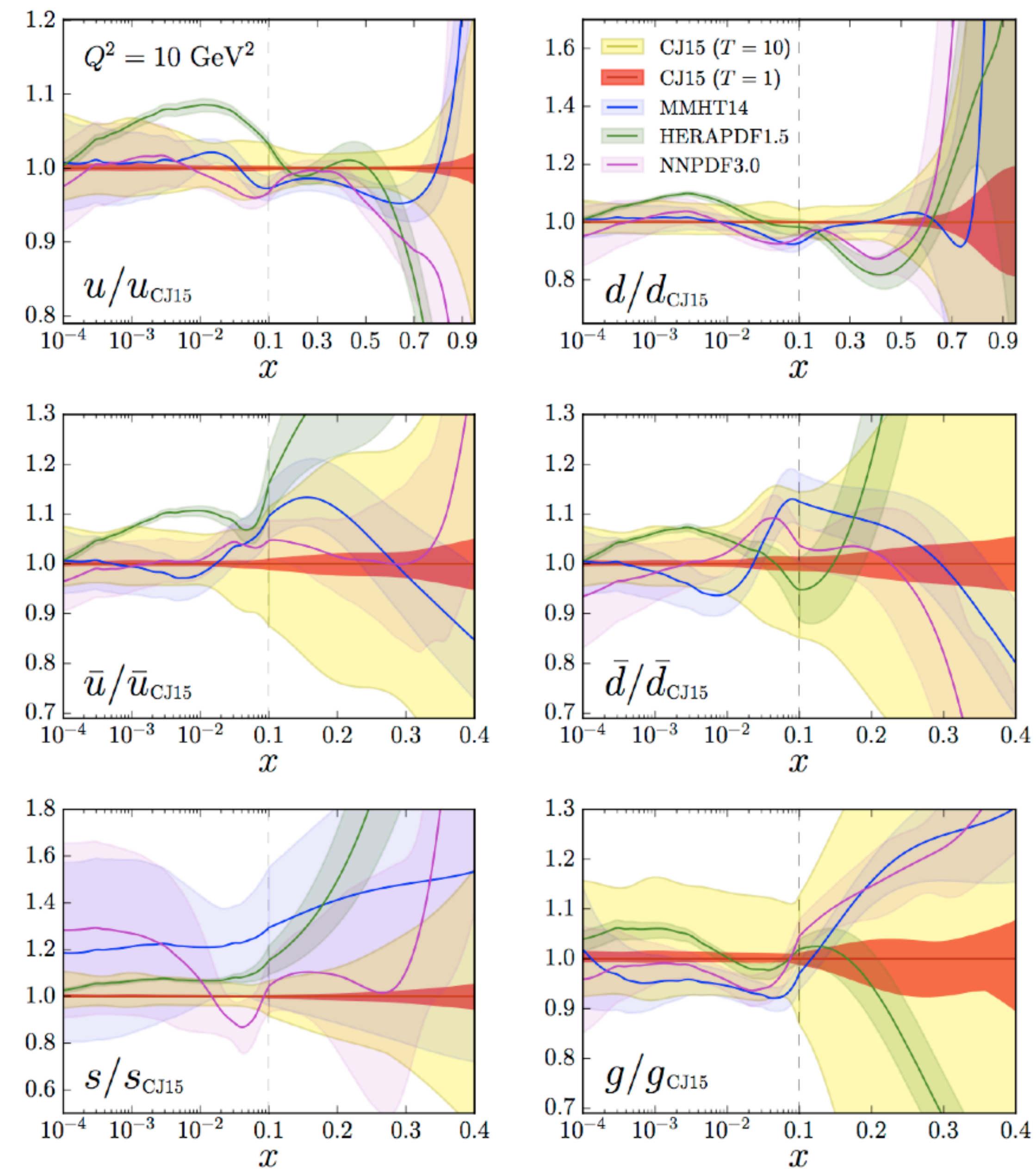
+ new Drell-Yan

Sanghwa Park for the CJ Collaboration

Stony Brook University

CTEQ-JLab Collaboration

- CTEQ-based NLO QCD analysis with focus on large-x region (https://www.jlab.org/theory/cj)
- Relaxing kinematic cuts, maximizing use of large-x DIS data
- Large-x treatment, nuclear corrections
- Latest public release: CJ15 (A. Accardi et. al, Phys. Rev. D 93 114017 (2016))
- Recent developments/Ongoing efforts:
  - Including full JLab 6GeV, LHC, RHIC, DY data
  - Nuclear corrections for deuteron target
  - F2 neutron extraction
  - EIC impact studies
  - APPLgrid implementation (J. Xiaoxian) into the CJ fit package



CJ15 datasets

Observable	Experiment	# points	χ^2				
			LO	NLO	NLO (OCS)	NLO (no nucl)	NLO (no nucl/D0)
DIS F_2	BCDMS (p) [81]	351	426	**438**	436	440	427
	BCDMS (d) [81]	254	292	**292**	289	301	301
	SLAC (p) [82]	564	480	**434**	435	441	440
	SLAC (d) [82]	582	415	**376**	380	507	466
	NMC (p) [83]	275	416	**405**	404	405	403
	NMC (d/p) [84]	189	181	**172**	173	174	173
	HERMES (p) [86]	37	57	**42**	43	44	44
	HERMES (d) [86]	37	52	**37**	38	36	37
	Jefferson Lab (p) [87]	136	172	**166**	167	177	166
	Jefferson Lab (d) [87]	136	131	**123**	124	126	130
DIS F_2 tagged	Jefferson Lab (n/d) [21]	191	216	**214**	213	219	219
DIS σ	HERA (NC e^-p) [85]	159	315	**241**	240	247	244
	HERA (NC e^+p 1) [85]	402	952	**580**	579	588	585
	HERA (NC e^+p 2) [85]	75	177	**94**	94	94	93
	HERA (NC e^+p 3) [85]	259	311	**249**	249	248	248
	HERA (NC e^+p 4) [85]	209	352	**228**	228	228	228
	HERA (CC e^-p) [85]	42	42	**48**	48	45	49
	HERA (CC e^+p) [85]	39	53	**50**	50	51	51
Drell-Yan	E866 (pp) [29]	121	148	**139**	139	145	143
	E866 (pd) [29]	129	202	**145**	143	158	157
W/charge asymmetry	CDF (e) [88]	11	11	**12**	12	13	14
	DØ (μ) [17]	10	18	**20**	19	29	28
	DØ (e) [18]	13	49	**29**	29	14	14
	CDF (W) [89]	13	16	**16**	16	14	14
	DØ (W) [19]	14	35	**14**	15	82	—
Z rapidity	CDF (Z) [90]	28	108	**27**	27	26	26
	DØ (Z) [91]	28	26	**16**	16	16	16
jet	CDF (run 2) [92]	72	29	**15**	15	23	25
	DØ (run 2) [93]	110	90	**21**	21	14	14
γ+jet	DØ 1 [94]	16	16	**7**	7	7	7
	DØ 2 [94]	16	34	**16**	16	17	17
	DØ 3 [94]	12	35	**25**	25	24	25
	DØ 4 [94]	12	79	**13**	13	13	13
total		4542	5935	**4700**	4702	4964	4817
total + norm			6058	**4708**	4710	4972	4826
χ^2/datum			1.33	**1.04**	1.04	1.09	1.07

Fixed target DIS (p, d target), Tagged DIS

DIS (e-p collider)

Drell-Yan

W asymmetry, Z (Tevatron)

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(p, d target),
Tagged DIS

DIS (e-p collider)

Drell-Yan

W asymmetry, Z
(Tevatron)

+ New datasets

Full JLab 6GeV data
JLab 12 GeV
(Hall C F2, Marathon,..)

LHC W/Z
(ATLAS, CMS, LHCb)

RHIC W/Z

Drell-Yan (SeaQuest)

Sensitive to sea quarks at intermediate to large-x region

CJ15 parameterization

A. Accardi et. al, Phys. Rev. D 93 114017 (2016)

- Standard 5 parameter functional form:

$$xf(x, Q_0^2) = a_0 x^{a_1}(1-x)^{a_2}(1 + a_3\sqrt{x} + a_4 x)$$

applies to valence *u, d*, $\bar{u} + \bar{d}$ and g. (+ sum rules)

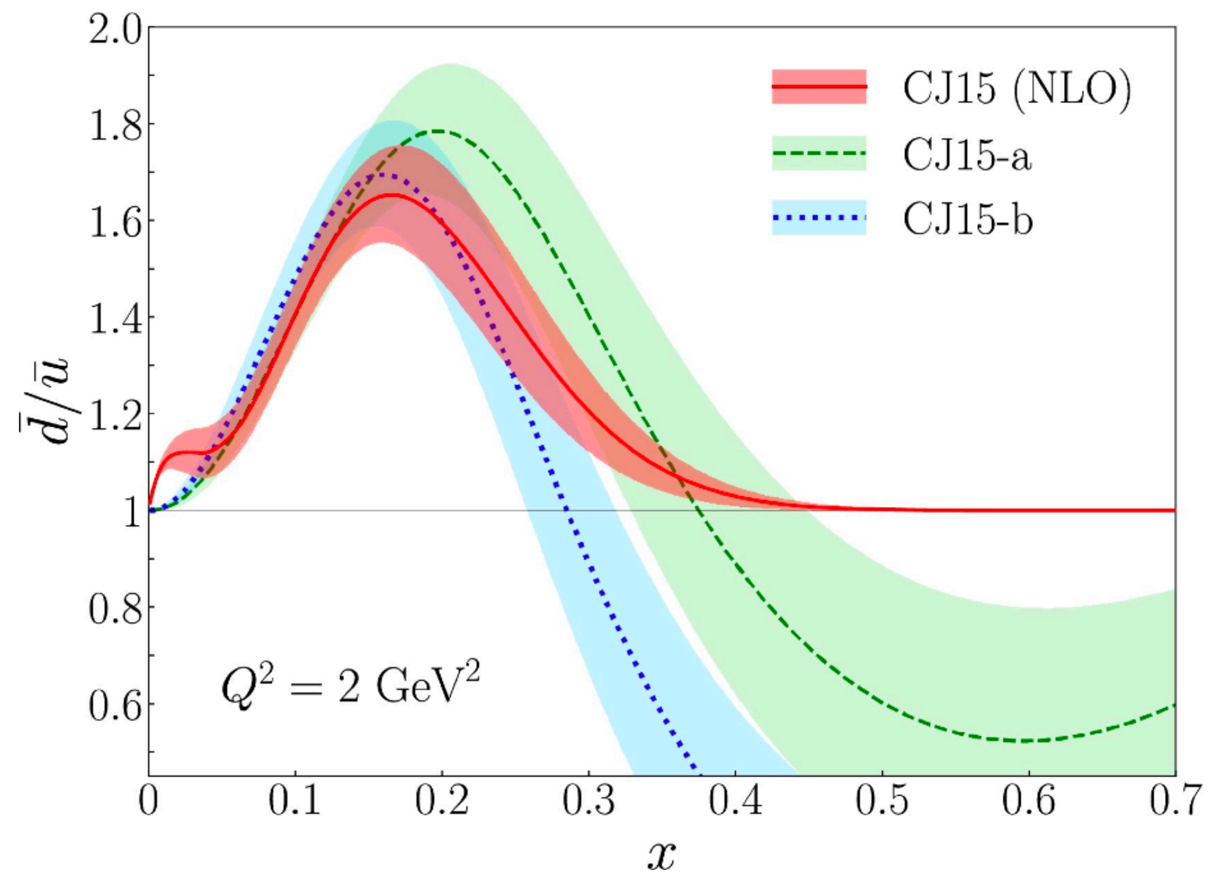
- Direct parameterization of $\bar{d}/\bar{u}$ ratio:

$$\frac{\bar{d}}{\bar{u}} = a_0 x^{a_1}(1-x)^{a_2} + 1 + a_3 x(1-x)^{a_4}$$

and ensure $\bar{d}/\bar{u} \rightarrow 1$ at x → 1

CJ15 variations

- Studied shape of $\bar{d} - \bar{u}$ using extracted neutron structure functions with different sea parameterizations and datasets
  A. Accardi, C. E. Keppel, S. Li, W. Melnitchouk, and J. F. Owens, PLB 801 135143 (2020)



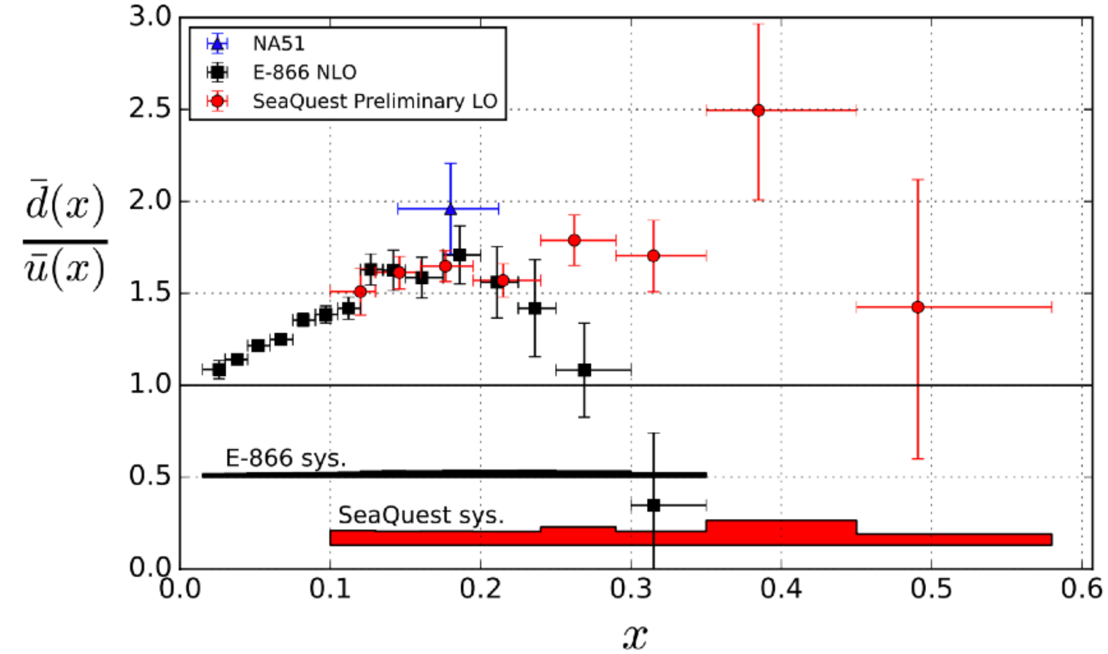
- CJ15-a:

  Using same data sets as CJ15 with more conventional parameterization for sea
  → **allows $\bar{d}/\bar{u}$ < 1 in some x region**

$$\bar{d} - \bar{u} = a_0 x^{a_1} (1-x)^{a_3} (1 + a_3\sqrt{x} + a_4 x)$$

Flavor asymmetry of nucleon sea

K. Nagai (DIS2018)



- First hint of flavor asymmetry by NMC (1991) PRL 66 (1991) 2712
- Significant flavor asymmetry confirmed as well as x-dependence by Drell-Yan data
- $\bar{d} - \bar{u}$ sign change at x ~ 0.3? - No complete model description of the data (E866)
- E866 currently provides the strongest constraint on $\bar{d}/\bar{u}$ - need more data!
  - Motivated SeaQuest experiment - extending x coverage up to x ~ 0.5. Preliminary result show $\bar{d} - \bar{u}$ stays positive ($\bar{d}/\bar{u} > 1$)
  - STAR W data

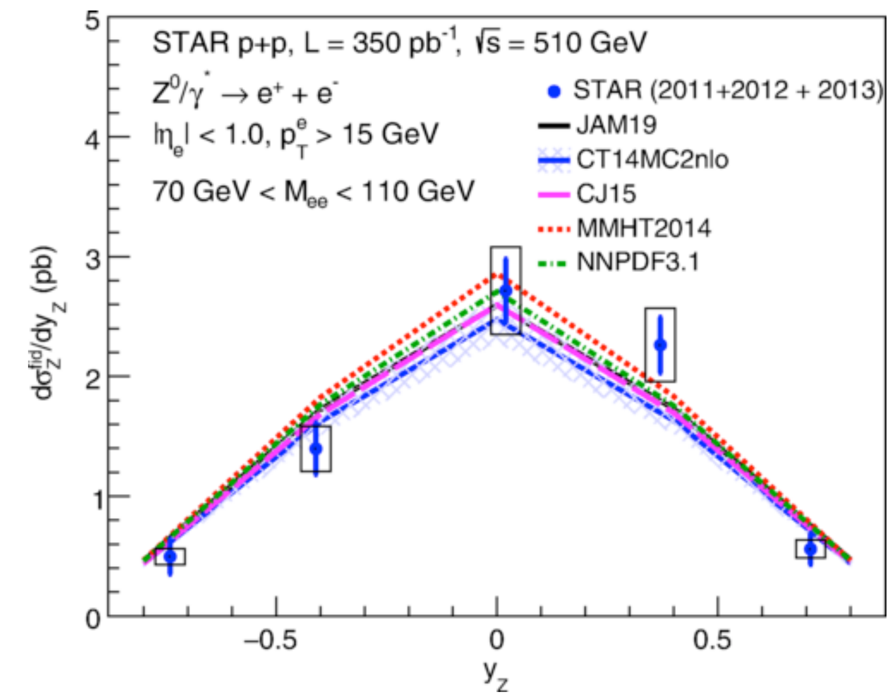
RHIC-W/Z impact in CJ15-a NLO

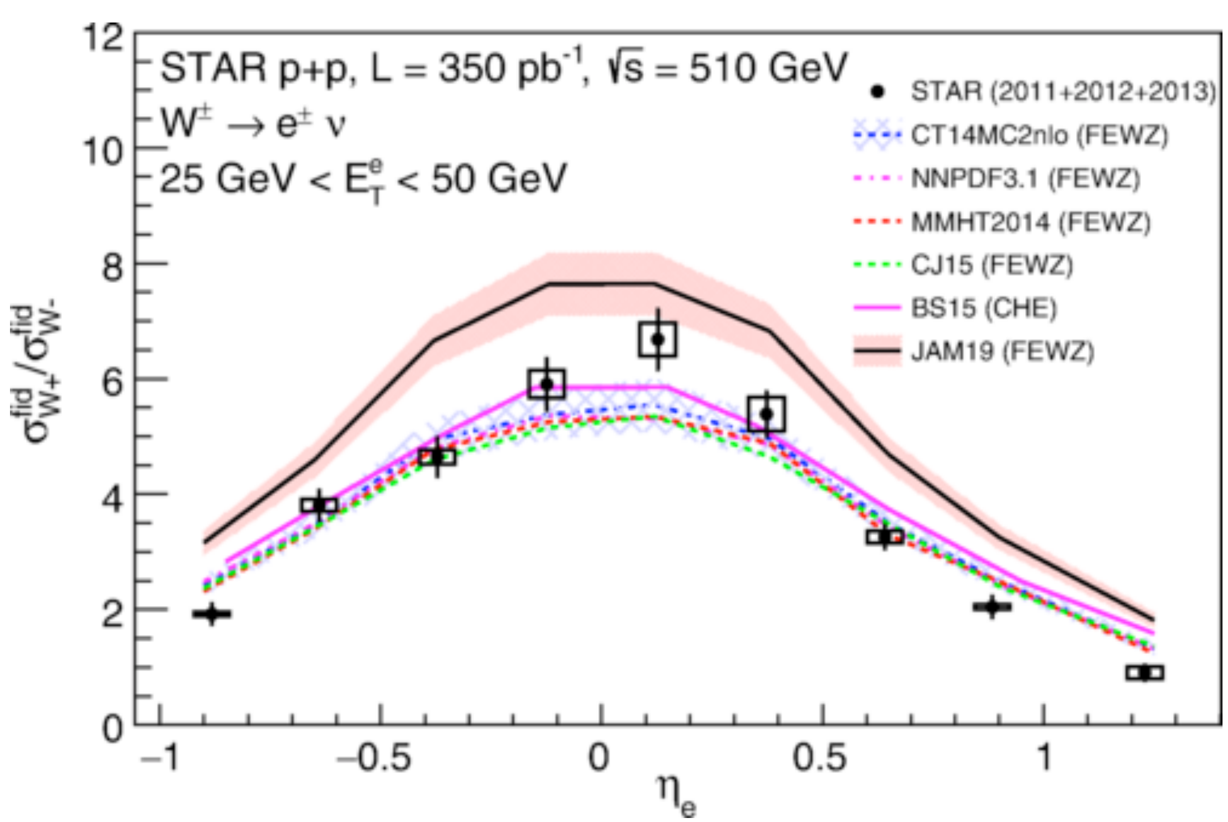
Phys. Rev. D 103 012001

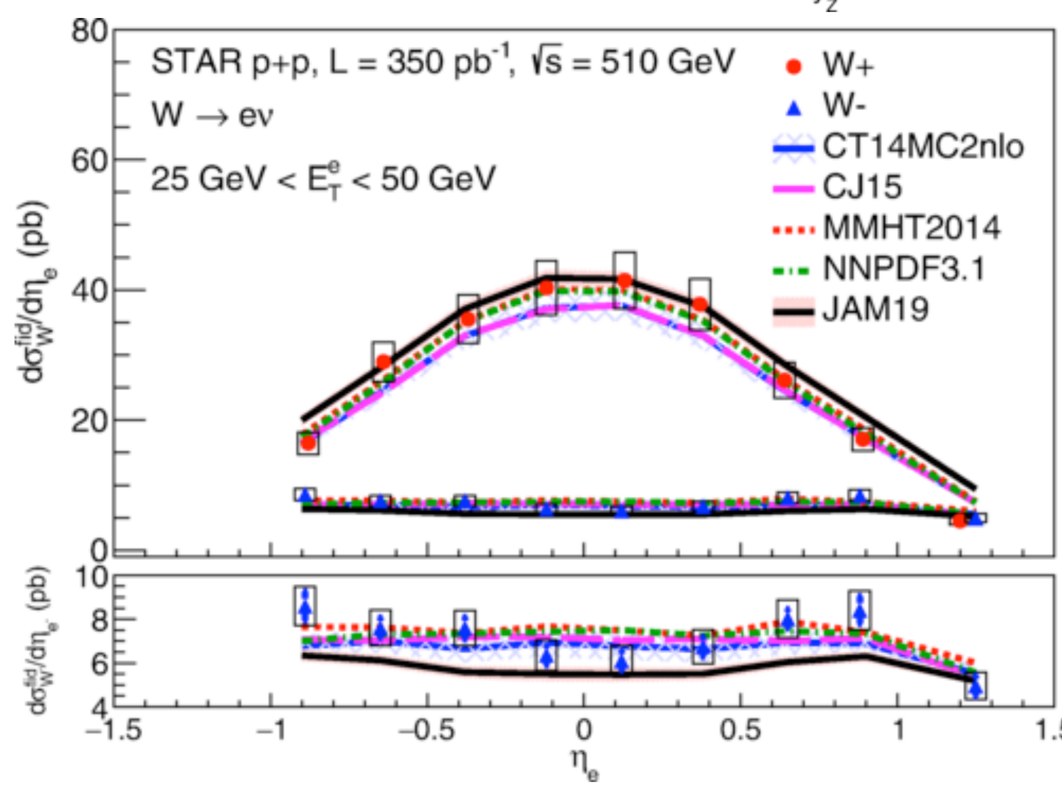
Talk by J. Nam on Thursday

Recently published RHIC-STAR data

- **W decay lepton ratio vs lepton psedorapidity**
- **W decay lepton differential cross sections**
- **Z cross sections**
- W and Z total cross sections and W/Z ratio

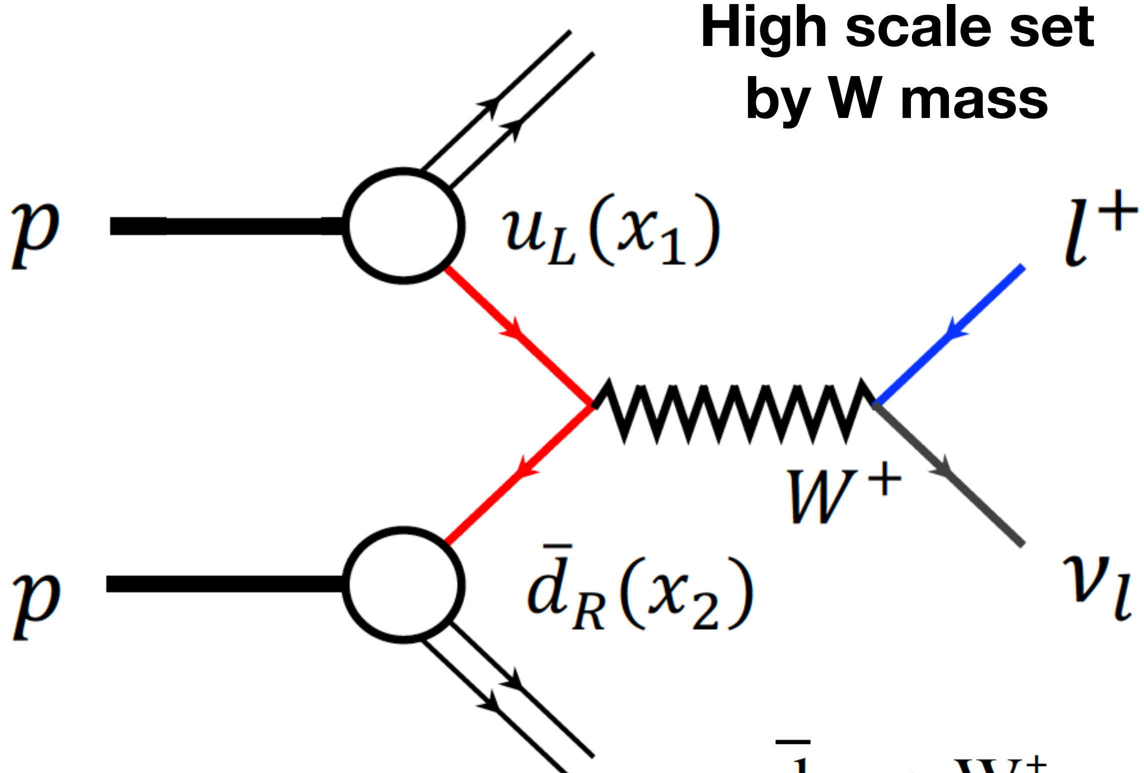






W boson production in p+p collisions

High scale set by W mass



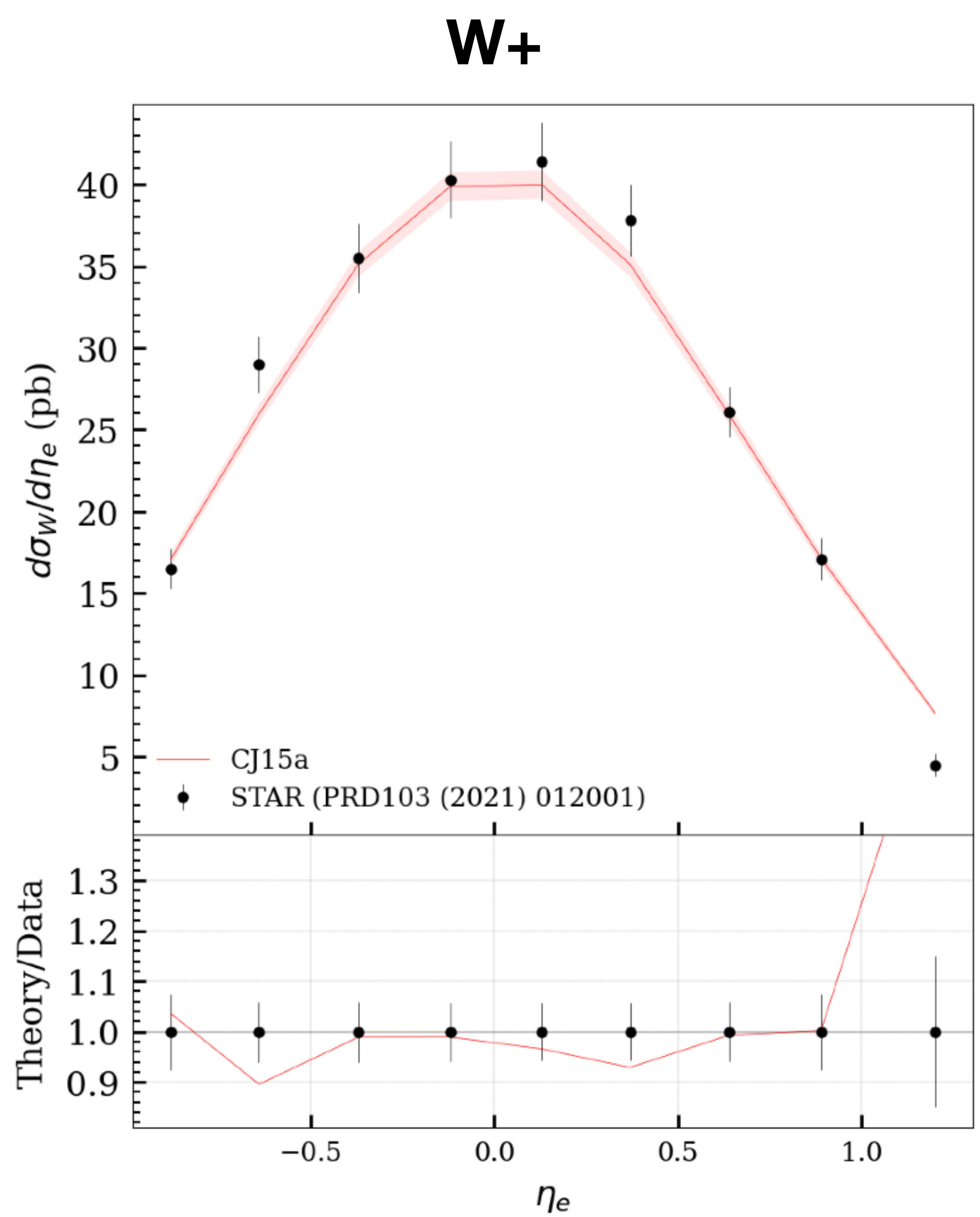
$$u_L \bar{d}_R \rightarrow W^+$$

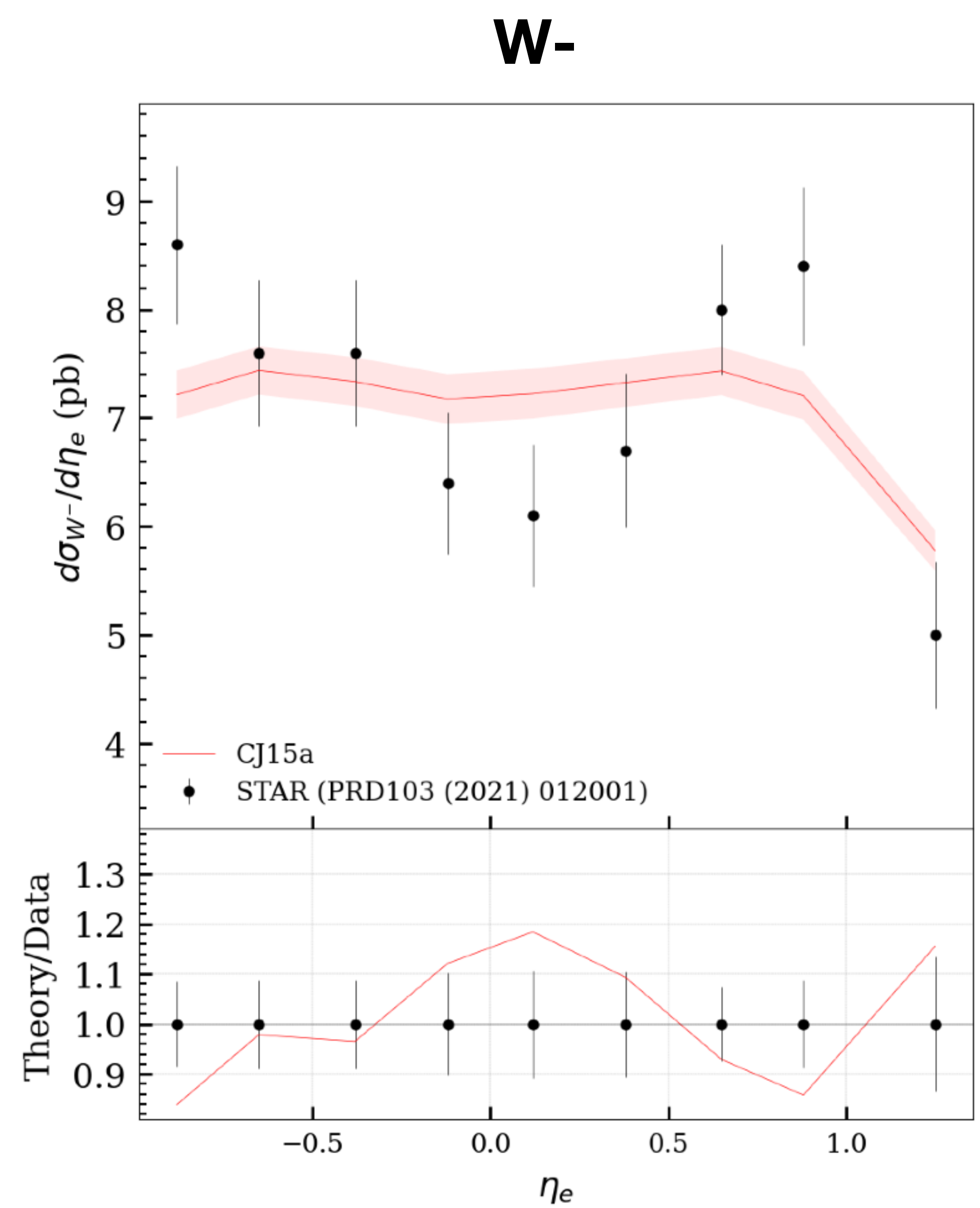
$$d_L \bar{u}_R \rightarrow W^-$$

$$\frac{\sigma^{W+}}{\sigma^{W-}} \approx \frac{u(x_1)\bar{d}(x_2) + u(x_2)\bar{d}(x_1)}{d(x_1)\bar{u}(x_2) + d(x_2)\bar{u}(x_1)}$$

- Unique access to sea quarks, complimentary to other observables (DIS, Drell-Yan)
- W couples only to left-handed quark and right-handed antiquark
- W^+/W^- distinguishes between quarks and antiquarks
- No fragmentation functions needed

Data vs CJ comparisons

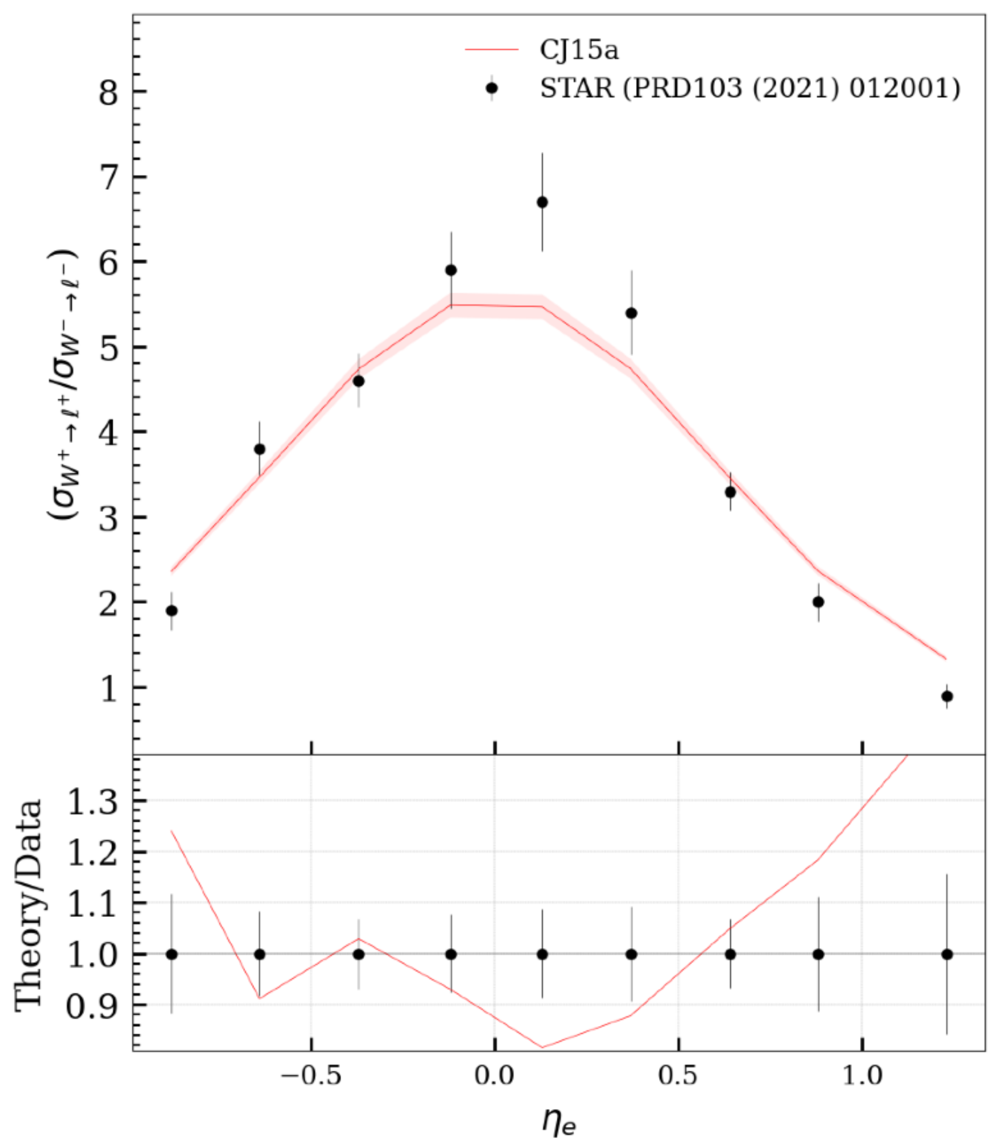




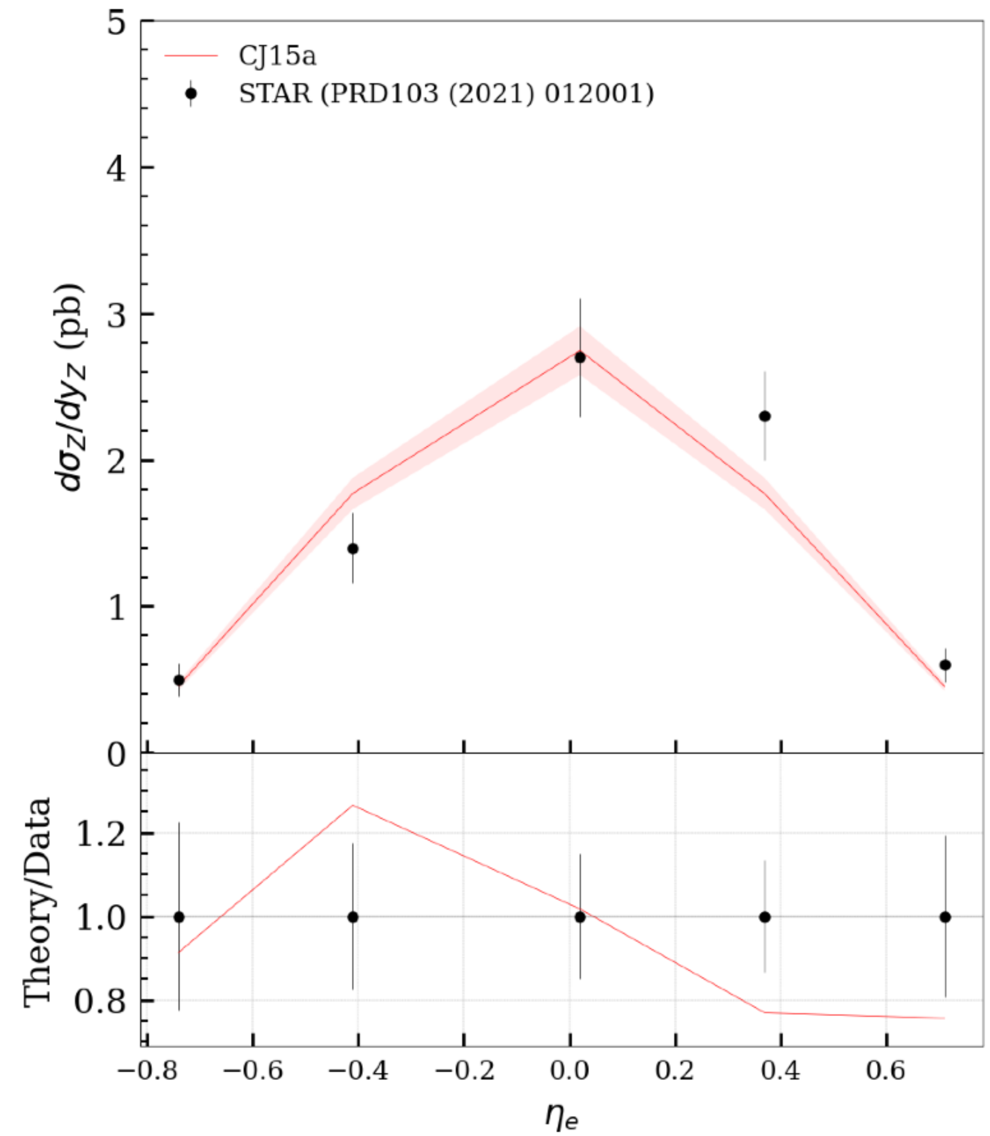
Reasonable agreement with W^+ cross section, but not well describe W^- data

Data vs CJ comparisons

Decay lepton charge ratio

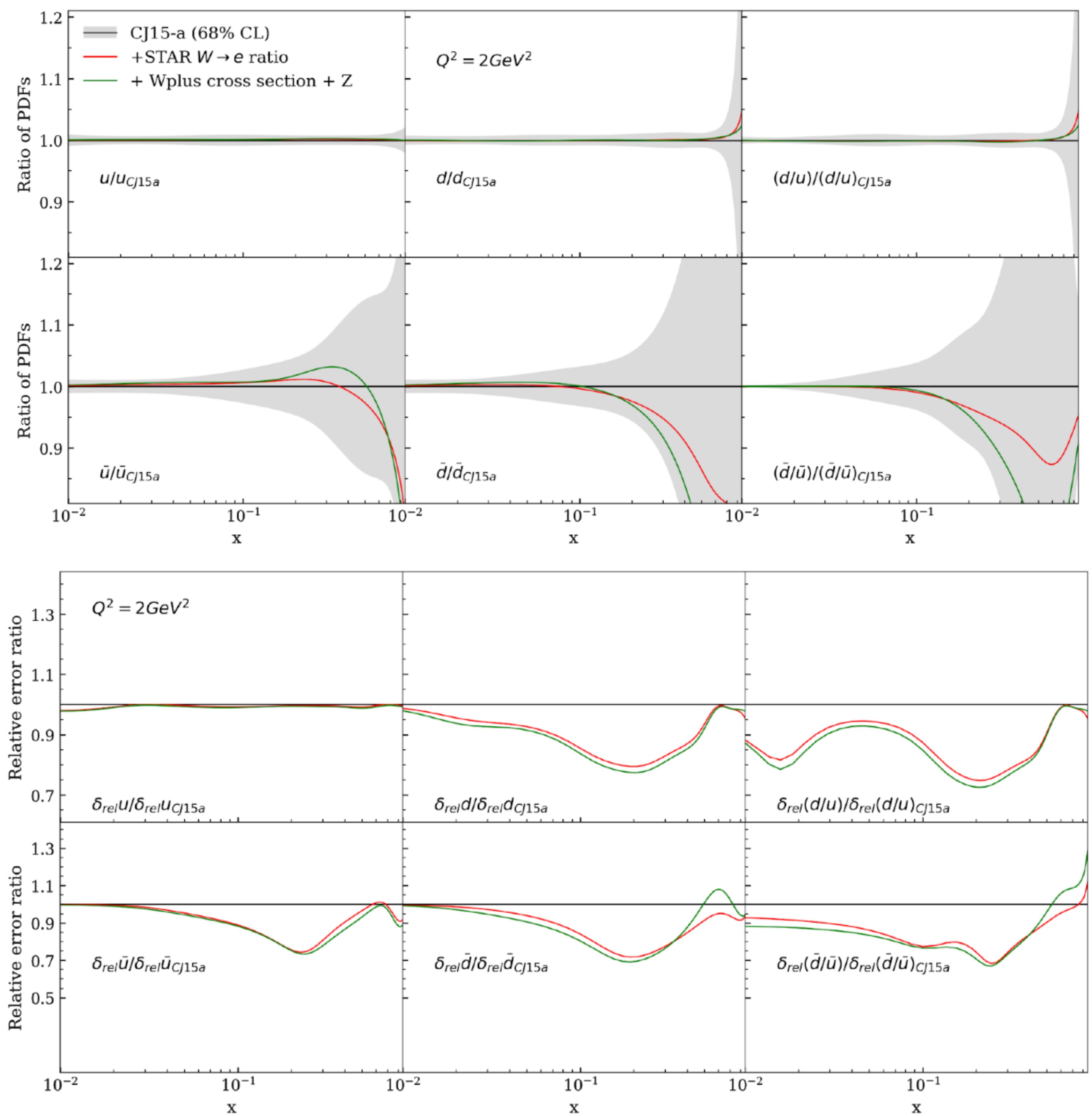


Z



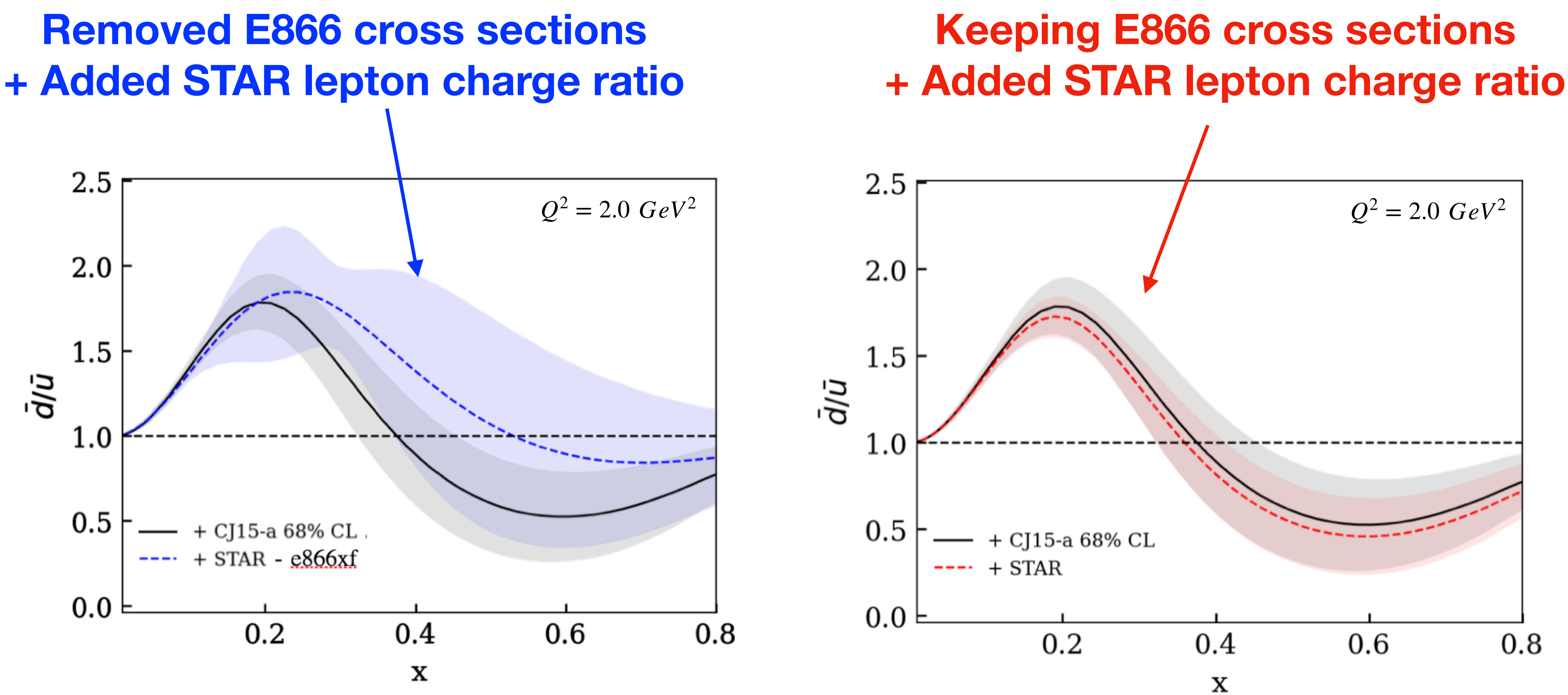
Charge ratio and Z cross sections can be reasonably described by CJ15

Impact of STAR data in CJ15-a



- Ratio to the baseline CJ15-a
- Lepton charge ratio has most constraining power over $\bar{d}/\bar{u}$
- The data covers the range of ~ 0.1< x < 0.3 (partially overlap with E866 data at different Q^2)

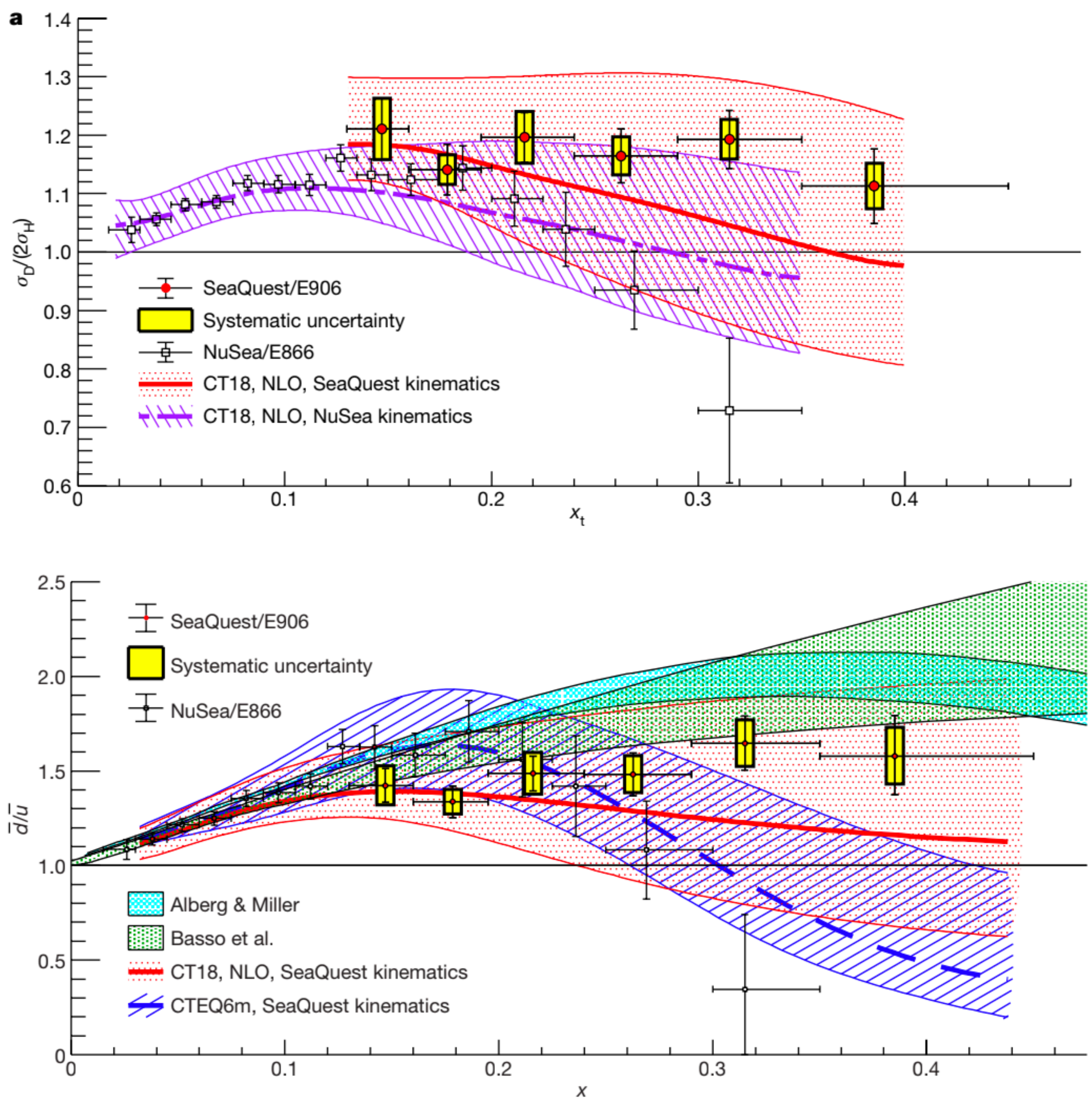
$\bar{d}/\bar{u}$ ratio with STAR data



E866 data determine the shape of the ratio
STAR data is compatible with CJ15-a, in agreement with E866 but no x coverage x > ~0.3

More on the flavor asymmetry

Dove et. al. Nature 590, 561 – 565 (2021)



Talk by K. Nagai on Thursday

E866 (NuSea) results show show significant flavor asymmetry as well as x-dependence

Also suggested a potential sign change of $\bar{d} - \bar{u}$ at x~0.3 with large uncertainty

Needed more data with extended x coverage — SeaQuest

New SeaQuest Drell-Yan result shows the ratio stays above 1 at large-x!

SeaQuest impact in CJ15-a

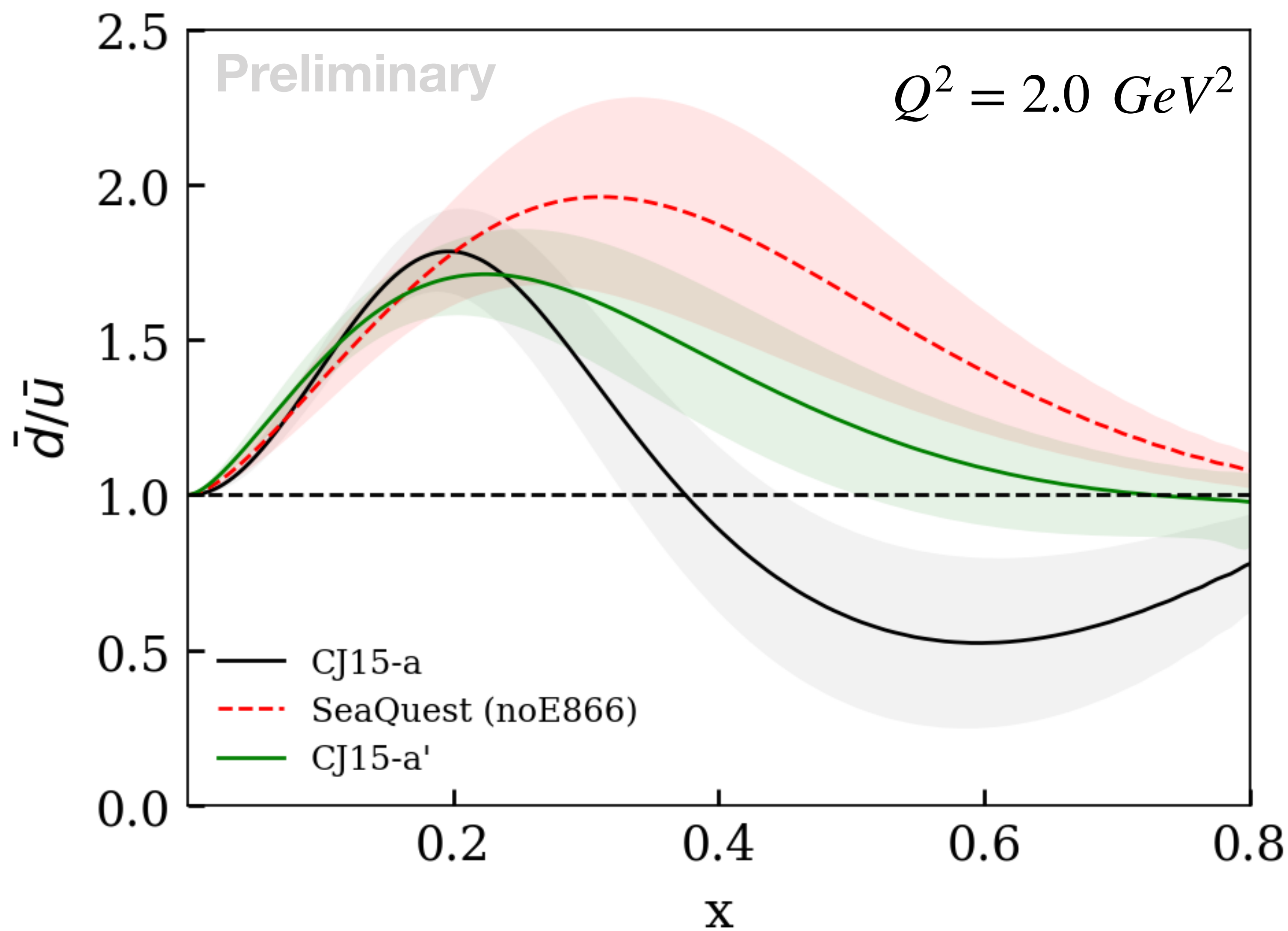
Preliminary SeaQuest fits

Datasets/ Fits	E866 cross sections	E866 Ratio	SeaQuest
—	✓		
·······			✓
—		✓	✓

Incorporating the spectrometer acceptance corrections

$$\left(\frac{\sigma_D}{2\sigma_H}\right)_i = \frac{\sum A_{ij}\sigma_D^{calc}(x_t, x_b, M)}{2\sum A_{ij}\sigma_H^{calc}(x_t, x_b, M)},$$

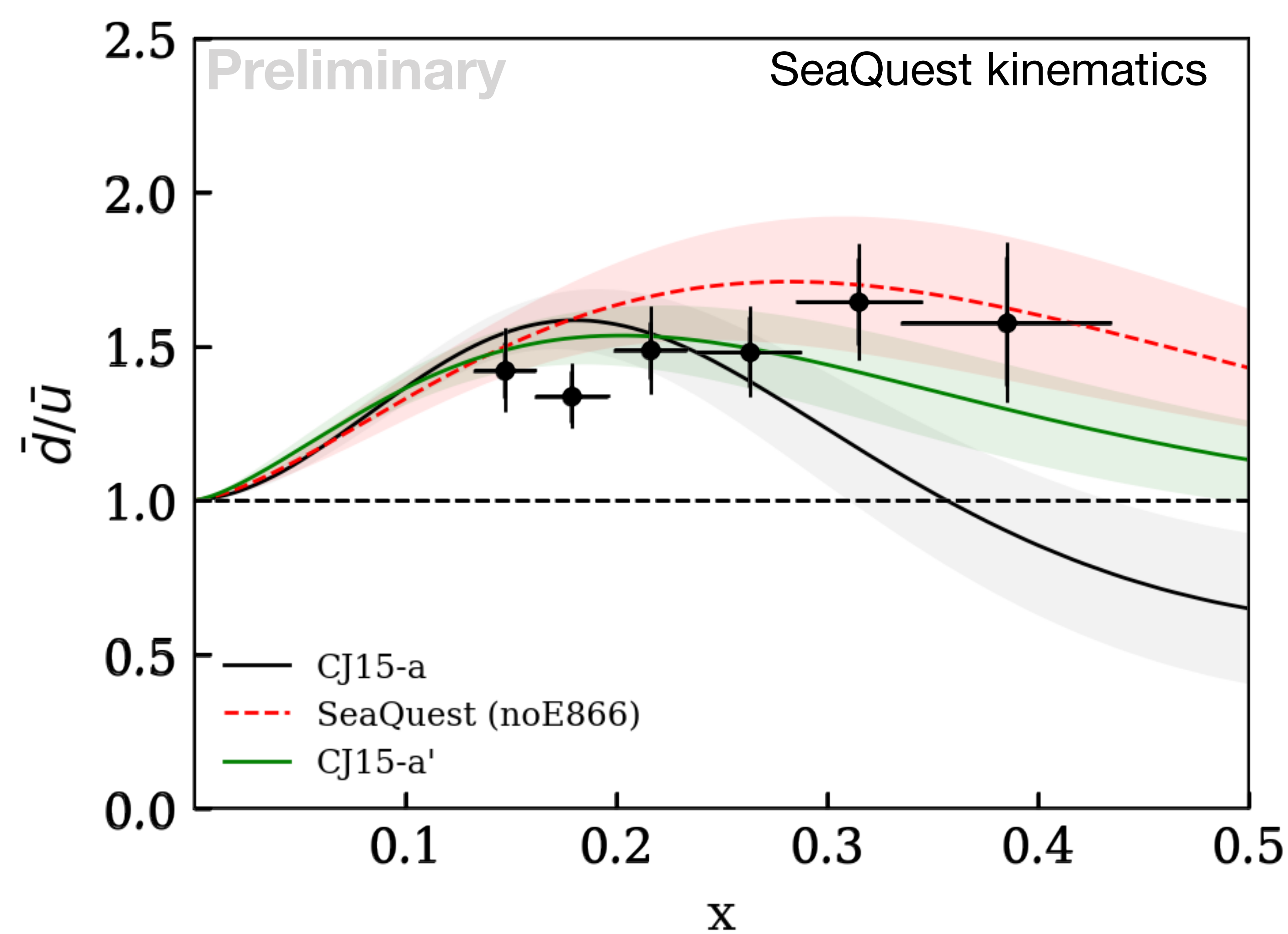
x_t \ x_b	0.30–0.35	0.35–0.40	0.40–0.45	0.45–0.50	0.50–0.55	0.55–0.60	0.60–0.65	0.65–0.70	0.70–0.75	0.75–0.80
0.130–0.160						0.0007 0.589 0.158 4.54	0.0064 0.628 0.153 4.60	0.0175 0.675 0.148 4.68	0.0304 0.723 0.144 4.77	0.0370 0.772 0.144 4.92
0.160–0.195				0.0007 0.489 0.191 4.56	0.0071 0.528 0.184 4.63	0.0188 0.576 0.178 4.74	0.0299 0.624 0.176 4.91	0.0366 0.673 0.176 5.09	0.0432 0.722 0.176 5.27	0.0471 0.772 0.175 5.45
0.195–0.240		0.0001 0.394 0.235 4.55	0.0023 0.433 0.225 4.65	0.0105 0.477 0.217 4.78	0.0205 0.524 0.216 4.99	0.0298 0.574 0.215 5.21	0.0384 0.623 0.215 5.43	0.0456 0.672 0.214 5.63	0.0510 0.722 0.215 5.84	0.0557 0.772 0.214 6.04
0.240–0.290		0.0015 0.383 0.267 4.76	0.0078 0.427 0.264 4.99	0.0176 0.475 0.263 5.24	0.0270 0.524 0.262 5.50	0.0364 0.574 0.262 5.75	0.0436 0.623 0.262 6.00	0.0499 0.672 0.262 6.24	0.0550 0.722 0.261 6.46	0.0591 0.771 0.262 6.69
0.290–0.350	0.0002 0.341 0.324 4.95	0.0035 0.379 0.319 5.18	0.0120 0.426 0.316 5.46	0.0207 0.475 0.316 5.76	0.0298 0.524 0.316 6.05	0.0379 0.574 0.315 6.33	0.0455 0.623 0.315 6.60	0.0518 0.673 0.315 6.85	0.0544 0.722 0.314 7.10	0.0568 0.771 0.314 7.34
0.350–0.450	0.0006 0.339 0.384 5.38	0.0052 0.377 0.390 5.72	0.0125 0.425 0.386 6.04	0.0203 0.474 0.386 6.38	0.0268 0.524 0.385 6.69	0.0336 0.573 0.384 7.00	0.0374 0.623 0.384 7.29	0.0405 0.672 0.384 7.58	0.0415 0.722 0.383 7.85	0.0413 0.771 0.382 8.11



SeaQuest impact in CJ15-a

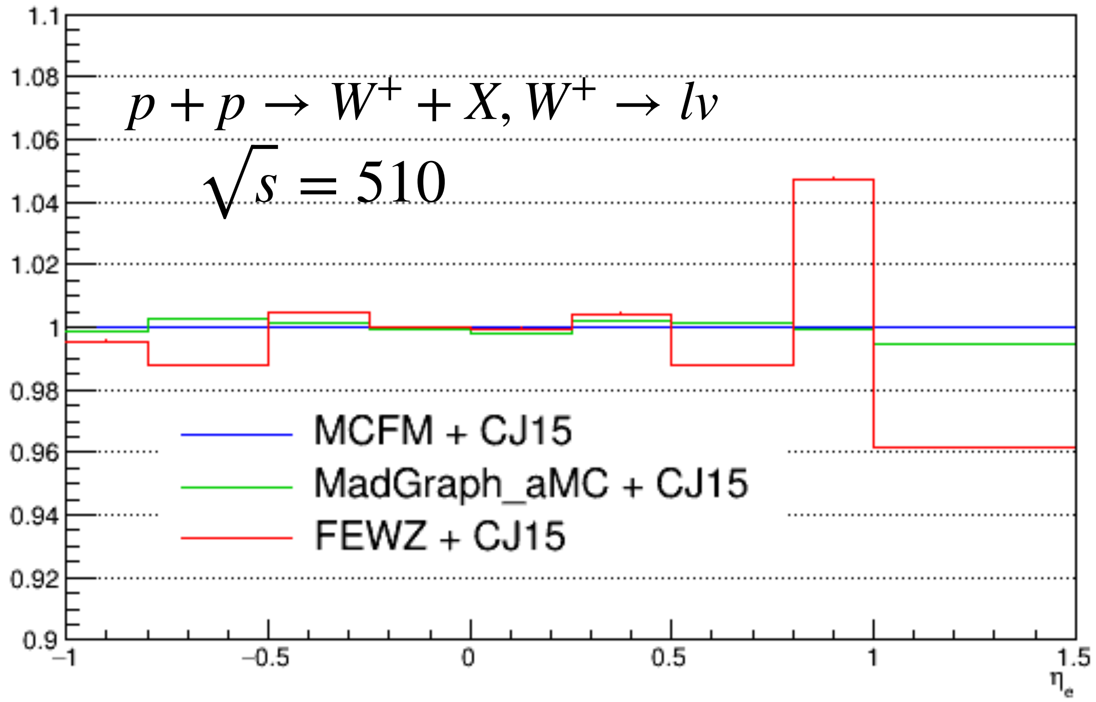
SeaQuest data pulls the data up at large-x region even with the parameterization that allows the ratio goes to below 1 at x->1

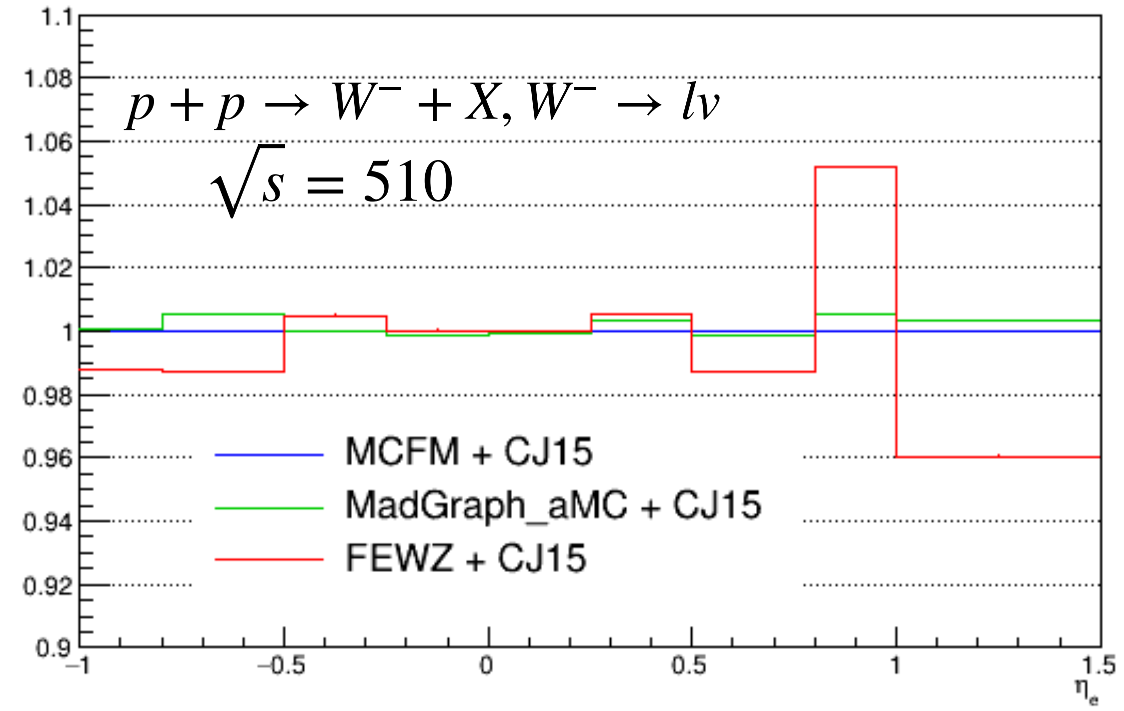
Datasets/ Fits	E866 cross sections	E866 Ratio	SeaQuest
	✓		
			✓
		✓	✓



Summary and outlook

- New data sensitive to sea quarks are studied with CJ framework
  - RHIC W data provide constraints on light quark PDFs at a moderate x region
    - In agreement with E866 within the kinematic range where the data covers
  - SeaQuest data pulls the light sea quark ratio up and the data shows that the ratio stays above 1
    - Further studies with the SeaQuest result ongoing
- Working towards to a new release with LHC, RHIC, SeaQuest data


$p + p \to W^+ + X, W^+ \to l\nu$
$\sqrt{s} = 510$
MCFM + CJ15
MadGraph_aMC + CJ15
FEWZ + CJ15
η_e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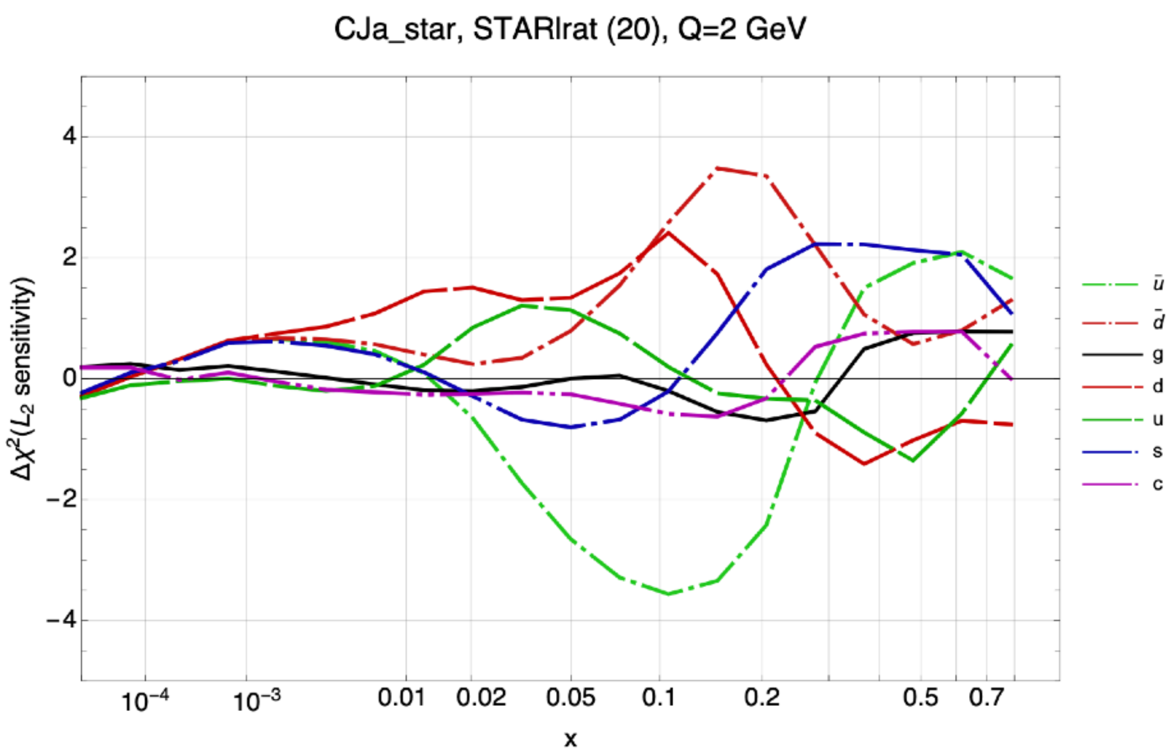
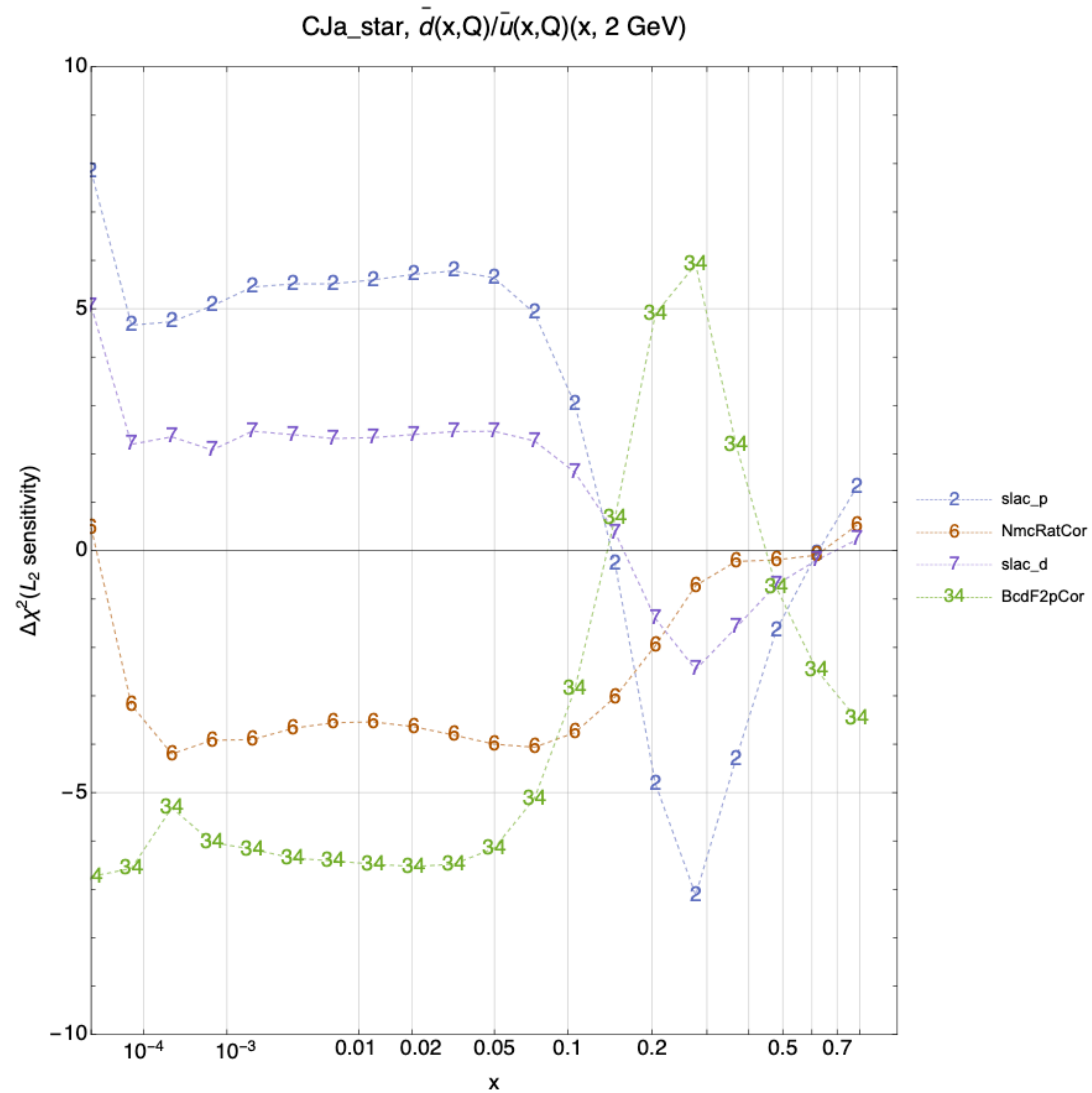

CJa_star, STARlrat (20), Q=2 GeV
$\Delta\chi^2(L_2$ sensitivity)
x
$\bar{u}$
$\bar{d}$
g
d
u
s
c


CJa_star, $\bar{d}(x,Q)/\bar{u}(x,Q)(x, 2$ GeV)
$\Delta\chi^2(L_2$ sensitivity)
x
slac_p
NmcRatCor
slac_d
BcdF2pCor