Strangeness in the Proton from W+charm Production and SIDIS Data

Nobuo Sato

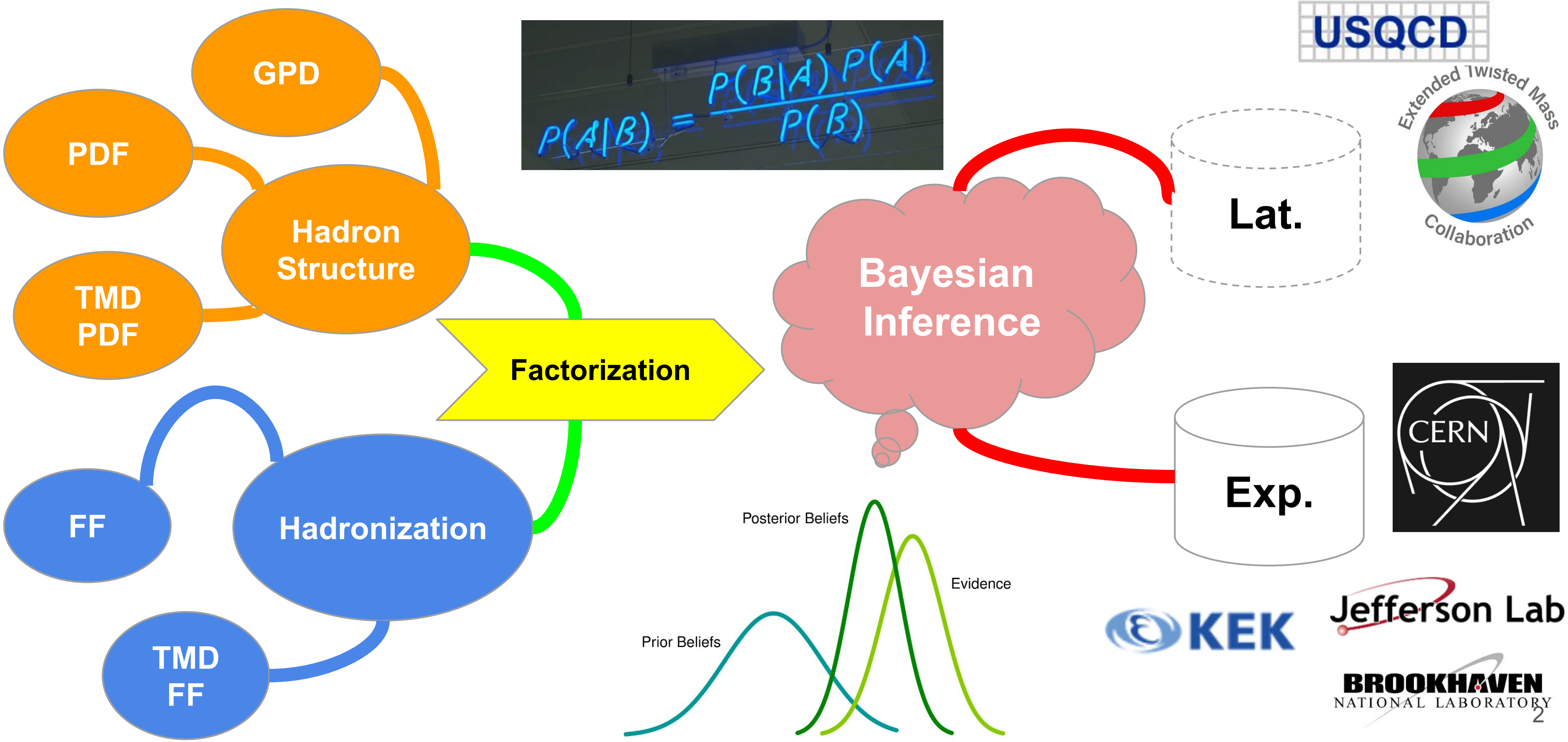
WILLIAM & MARY
CHARTERED 1693

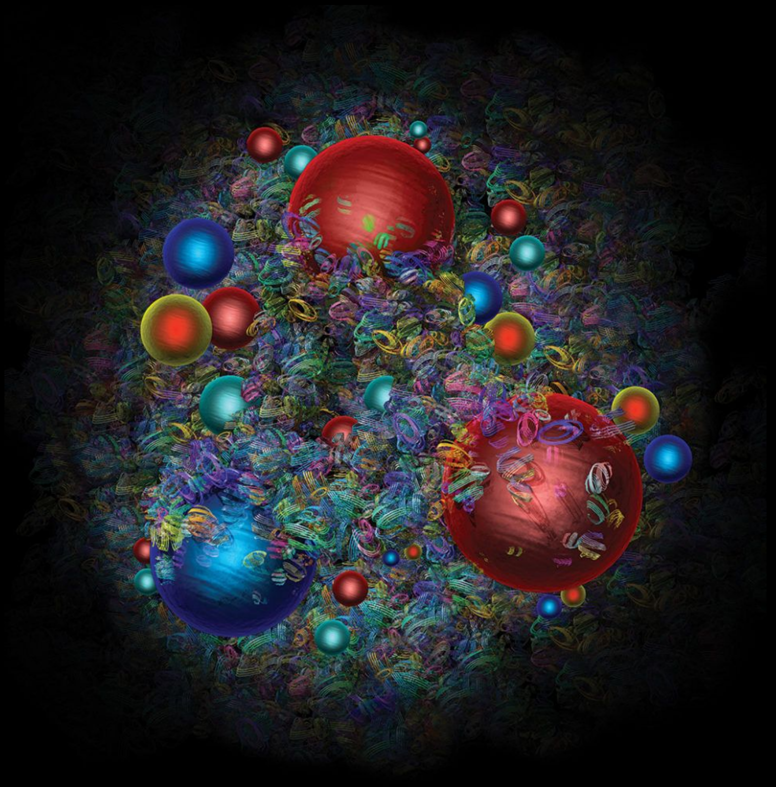
Anderson, Melnitchouk NS, '24
https://inspirehep.net/literature/2864324

JLab theory center, Jan 15 2024

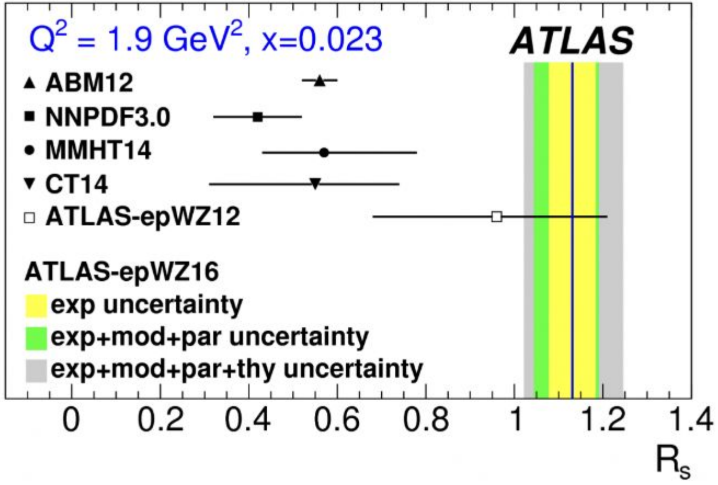
Jefferson Lab

Holistic approach to QCD global analysis



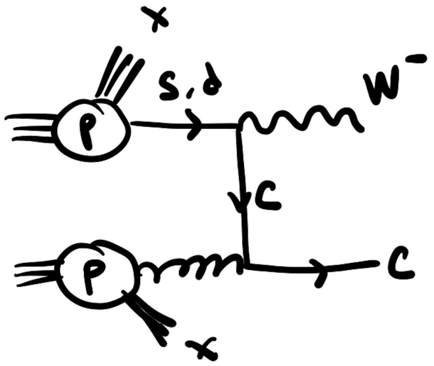


What is the strange quark content in the proton?



$$R_S = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

Enhanced strange sensitive observables



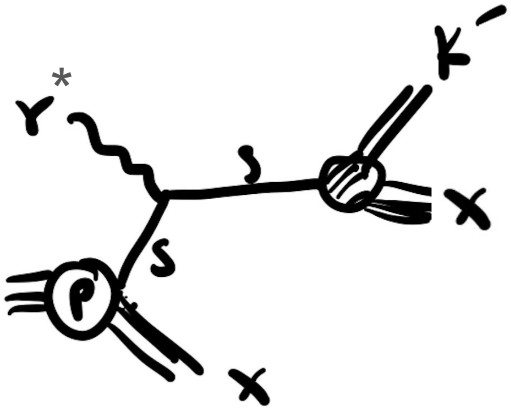
$$p + p \rightarrow W^- + c + X$$

$$p + p \rightarrow W^+ + \bar{c} + X$$

ATLAS

CMS

Compact Muon Solenoid



$$e + p \rightarrow e' + K^- + X$$

$$e + p \rightarrow e' + K^+ + X$$

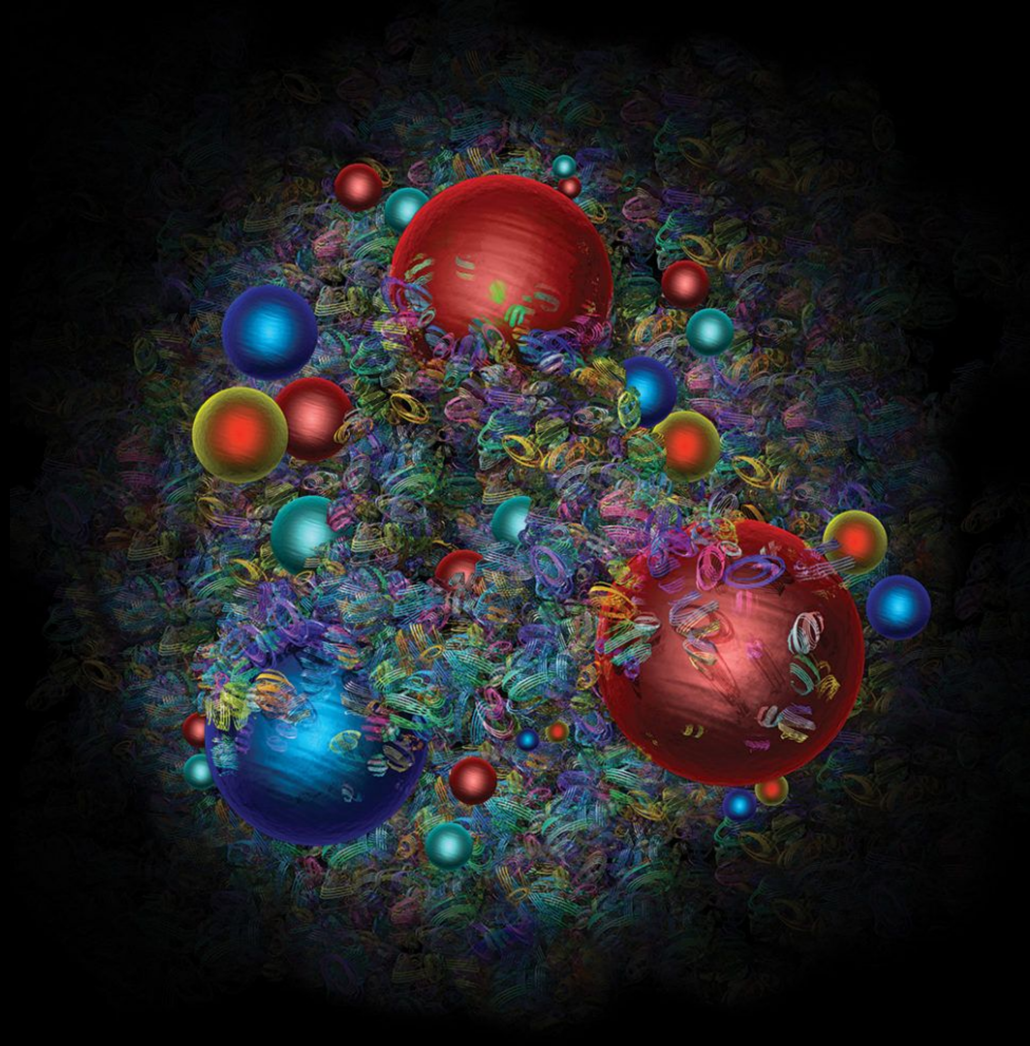
COMPASS

25 years

1997 - 2022

Outline

1. Theory & modeling
2. Data selection
3. Results
4. Summary



Theory framework

$$p + p \rightarrow W + c + X$$

$$\frac{d\sigma^{W+c}}{d|\eta|} = \sum_{a,b} \int_{x_a}\int_{x_b} d\hat{x}_a \, d\hat{x}_b \, f_a(\hat{x}_a, \mu_F) \, f_b(\hat{x}_b, \mu_F) \, \widehat{\sigma}^{W+c}_{a,b}\left(\frac{\hat{x}_a}{x_a}, \frac{\hat{x}_b}{x_b}, \mu_F, \mu_R\right)$$

$$\mathcal{H}_{ij} \otimes f_i \otimes f_j = \int_{x_1^{\min}}^{1} dx_1 \int_{x_2^{\min}}^{1} dx_2 \, \mathcal{H}_{ij}(x_1, x_2) \, f_i(x_1) \, f_j(x_2)$$

$$= \frac{1}{(2\pi i)^2} \int dN_1 \int dN_2 \, F_i(N_1) \, F_j(N_2) \left[\int_{x_1^{\min}}^{1} dx_1 \int_{x_2^{\min}}^{1} dx_2 \, \mathcal{H}_{ij}(x_1, x_2) \, x_1^{-N_1} \, x_2^{-N_2} \right]$$

Mellin tables

- Hard kernels computed using MCFM software @ NLO
- Construct Mellins space tables using the MC parton level data provided by MCMC
- We don't use K-factor approach as conventional practice

Theory framework

$$\ell + N \to \ell + h^{\pm} + X$$

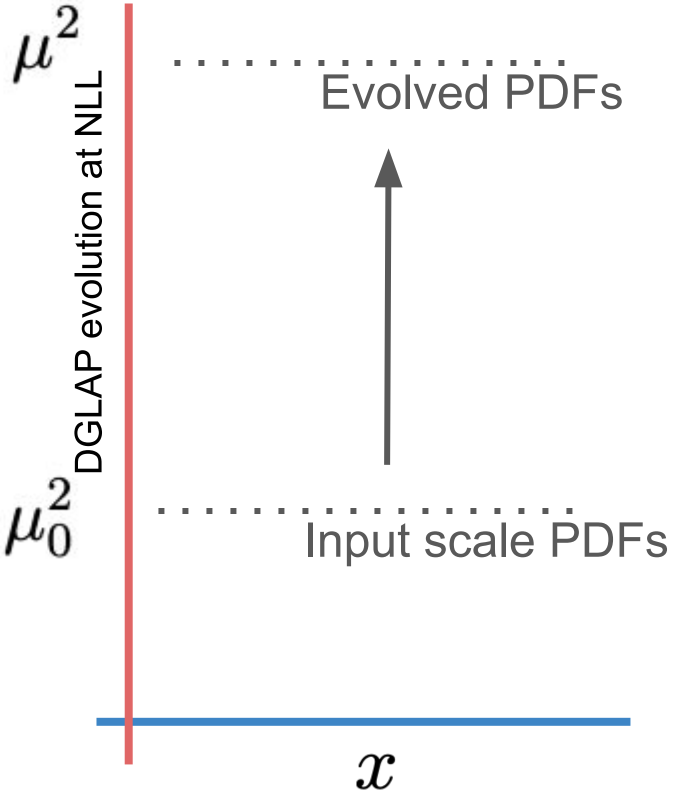
$$\frac{d\sigma^h}{dx_B\, dz_h\, dQ^2} = \sum_{a,b} \int_{z_h}\int_{x_B} d\hat{x}\, d\hat{z}\, f_a(\hat{x}, \mu_F)\, D_b^h(\hat{z}, \mu_F)\, \widehat{\sigma}_{a,b}^h\left(\frac{\hat{x}}{x_B}, \frac{\hat{z}}{z_h}, \mu_F, \mu_R, Q\right)$$

01' Stratmann, Vogelsang

$$\frac{d\sigma_{\text{SIDIS}}}{dQ^2 dx_{\text{Bj}} dz_h} = \sum_{ijkl} \frac{1}{(2\pi i)^2} \int dN\, x_{\text{Bj}}^{-N} \int dM\, z_h^{-M}\, \widetilde{\mathcal{H}}_{ik}^{\text{SIDIS}}(N, M, \mu) \times U_{ij}^{\text{S}}(N, \mu, \mu_0)\, \widetilde{f}_j(\mu_0)\, U_{kl}^{\text{T}}(M, \mu, \mu_0)\, \widetilde{D}_j^h(M, \mu_0).$$

- Mellin space hard kernels @ NLO from analytic approach.
- No K-factor approach

PDF modeling



Shape functions

$$f(x, \mu; \boldsymbol{a}) = \frac{N}{\mathcal{M}} x^{\alpha}(1-x)^{\beta}(1+\gamma\sqrt{x}+\delta x),$$

$$\mathcal{M} = B[\alpha+2, \beta+1] + \gamma B[\alpha+\tfrac{5}{2}, \beta+1] + \delta B[\alpha+3, \beta+1],$$

Valence and Sea

$$u_v \equiv u - \bar{u}, \qquad d_v \equiv d - \bar{d},$$

$$\bar{u} = S_1 + \delta\bar{u}, \qquad \bar{d} = S_1 + \delta\bar{d},$$

$$s = S_2 + \delta s, \qquad \bar{s} = S_2 + \delta\bar{s},$$

99 shape parameters for PDFS and FFs

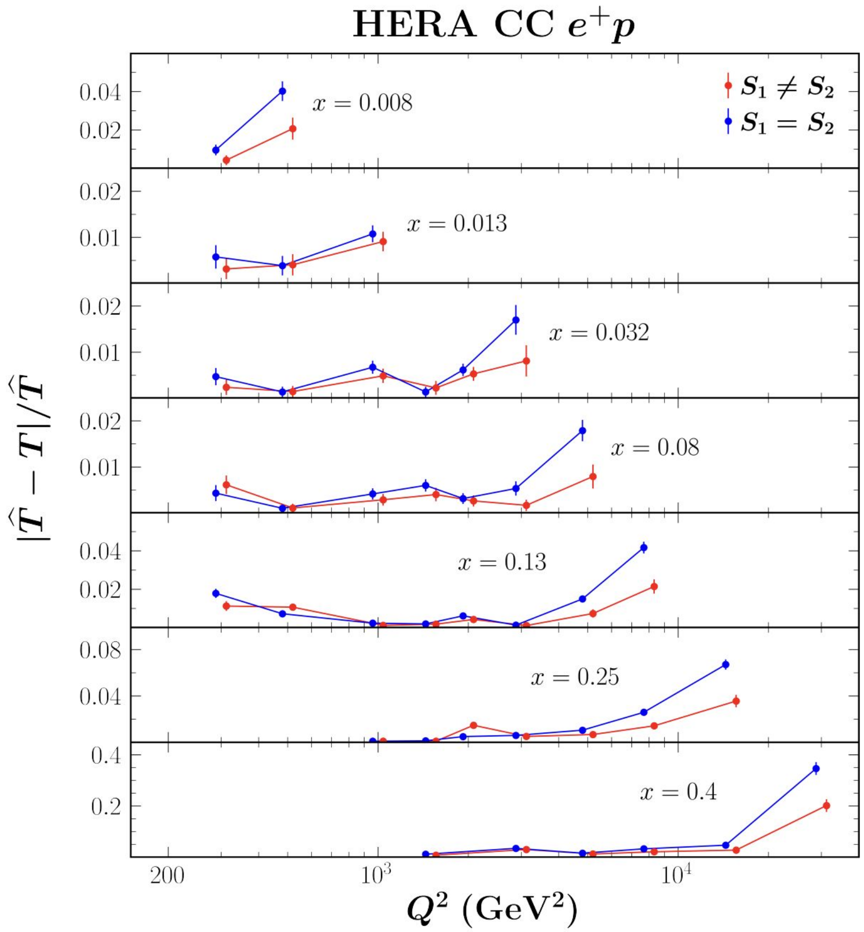
Sum Rules

$$\int_0^1 \mathrm{d}x\, u_v = 2, \qquad \int_0^1 \mathrm{d}x\, d_v = 1, \qquad \int_0^1 \mathrm{d}x\, (s - \bar{s}) = 0,$$

$$\int_0^1 \mathrm{d}x\, x\left(\sum_q (q+\bar{q}) + g\right) = 1$$

Symmetric or asymmetric sea at small x

$$\bar{u} = S_1 + \delta\bar{u}, \qquad \bar{d} = S_1 + \delta\bar{d},$$
$$s = S_2 + \delta s, \qquad \bar{s} = S_2 + \delta\bar{s},$$



$$\widehat{T}_{i,e} \equiv \sum_k r_e^k \widetilde{\beta}_{i,e}^k + \frac{T_{i,e}}{N_e}$$

Optimized theory to match with data

- We use nuisance parameters to distort the theory within the quoted experimental systematic uncertainties.
- Rigidity or flexibility of PDF modeling correlates with the sizes of systematic shifts.
- Strategy: add flexibility to minimize the size of theory distortions
- HERA's CC is best described with S1 and S2 to be different

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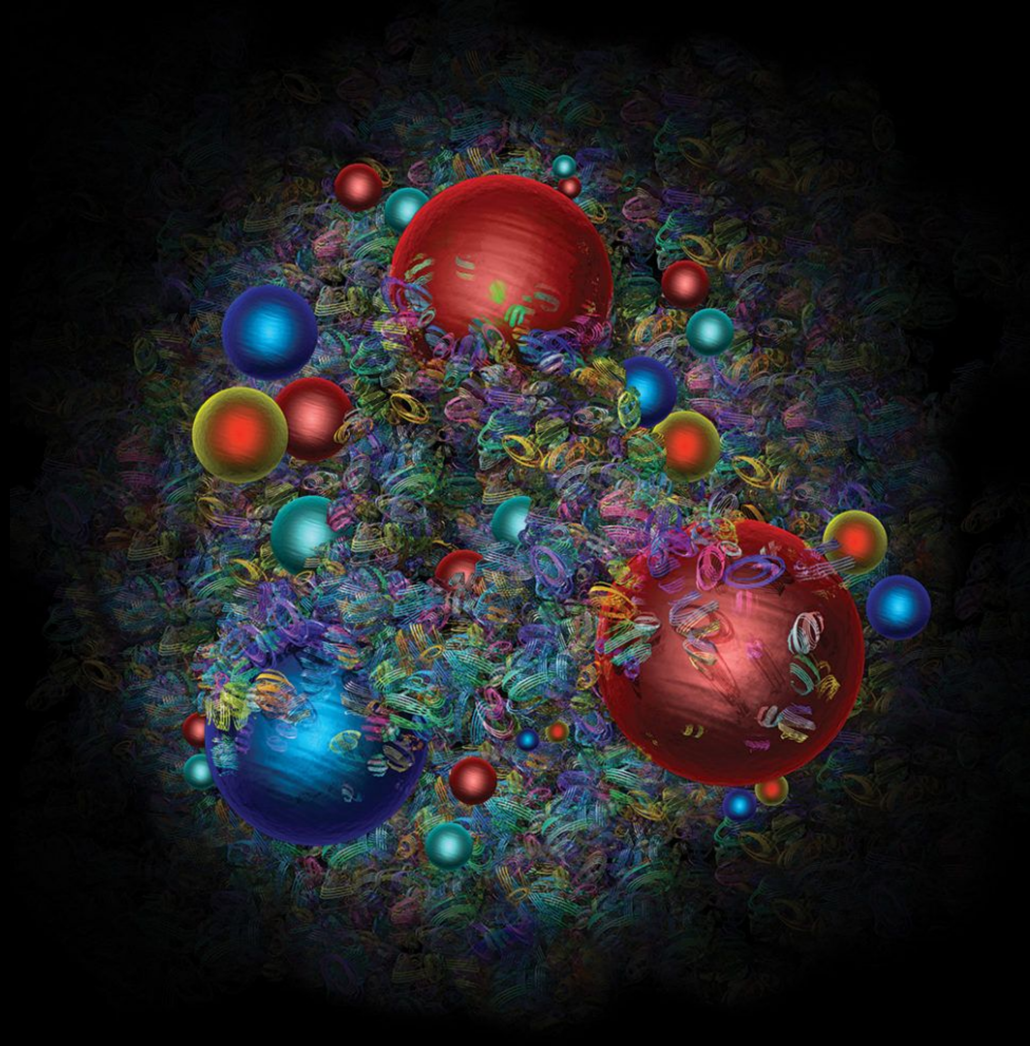
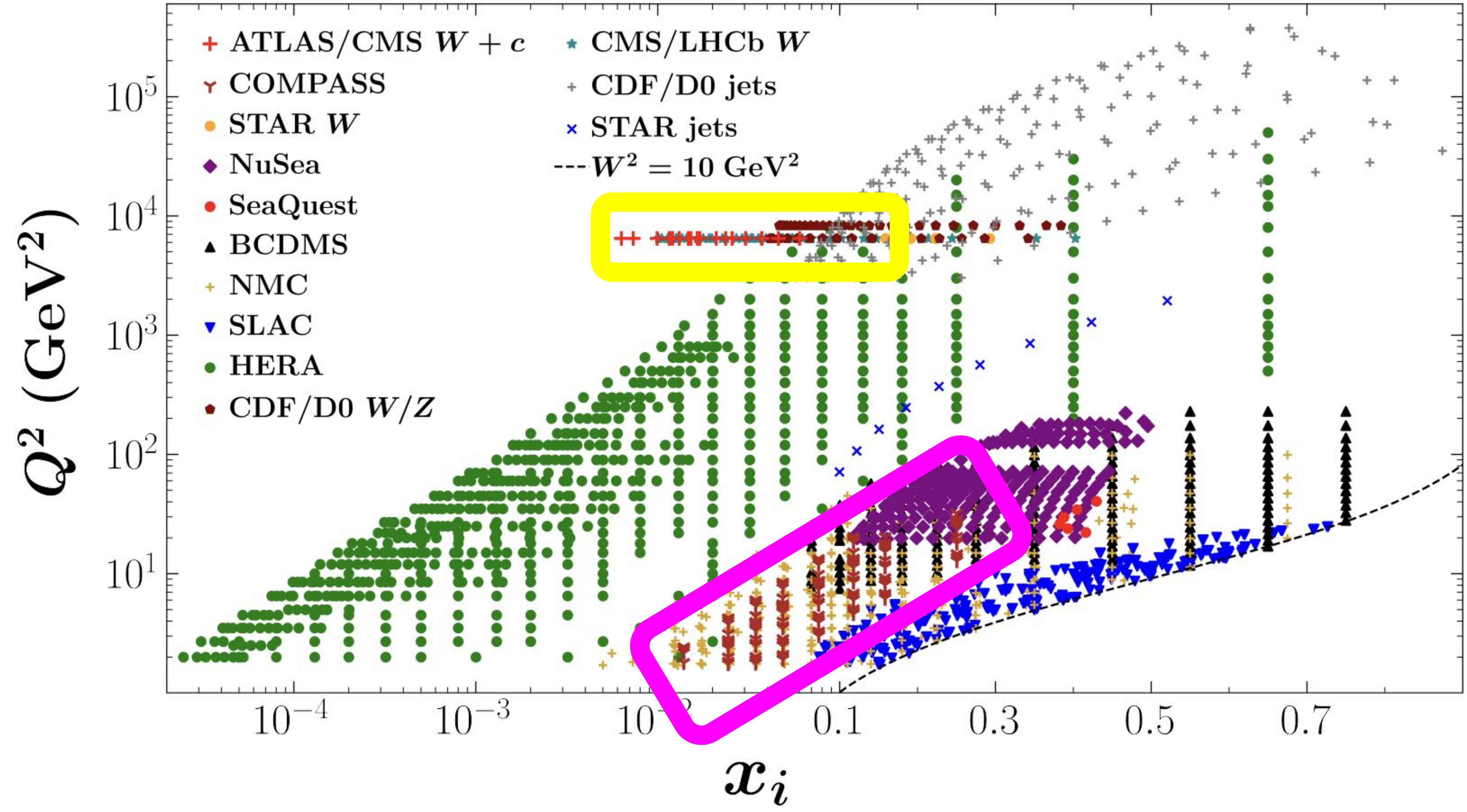


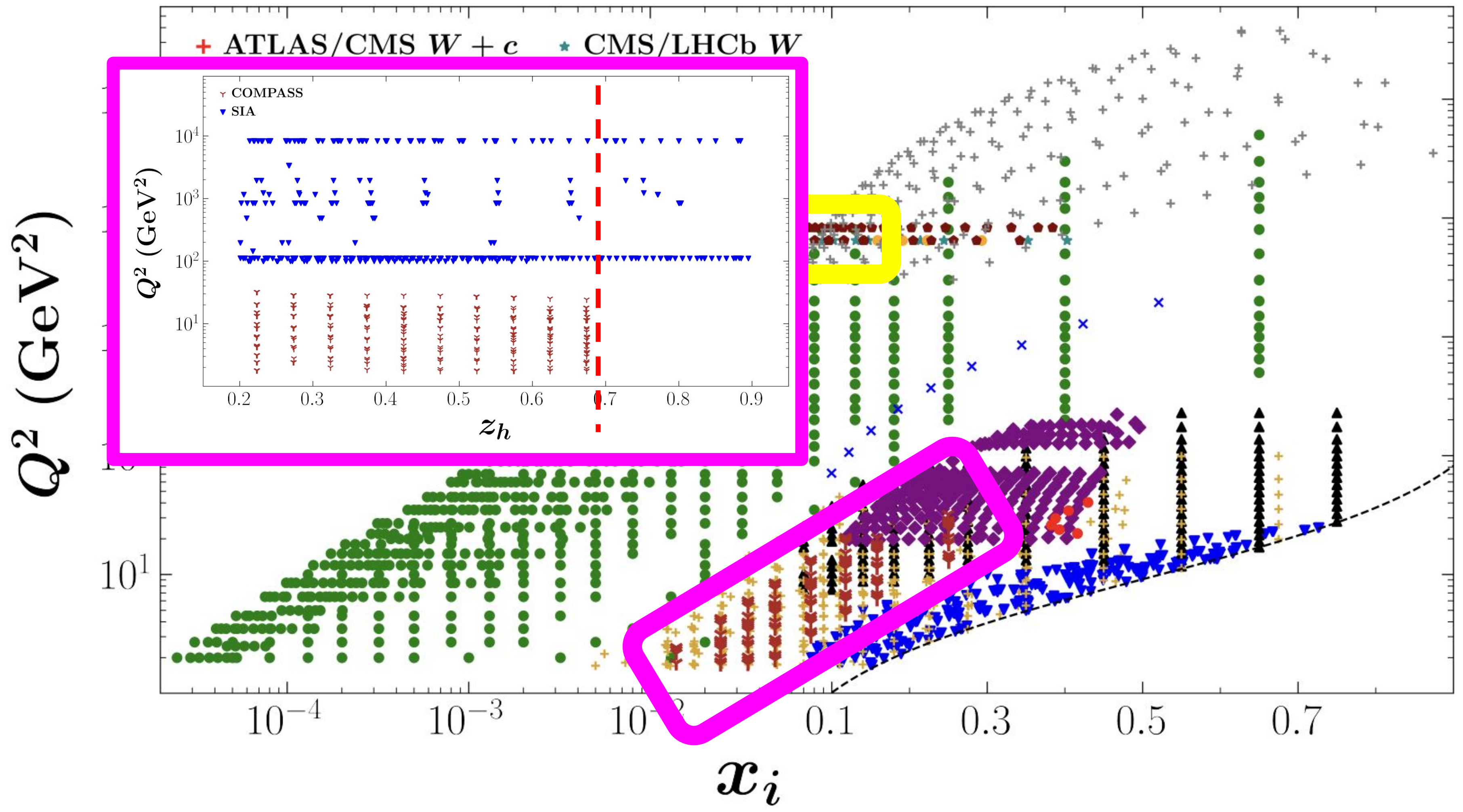
TABLE I. Summary of processes, observables and their connection to PDFs and FFs.

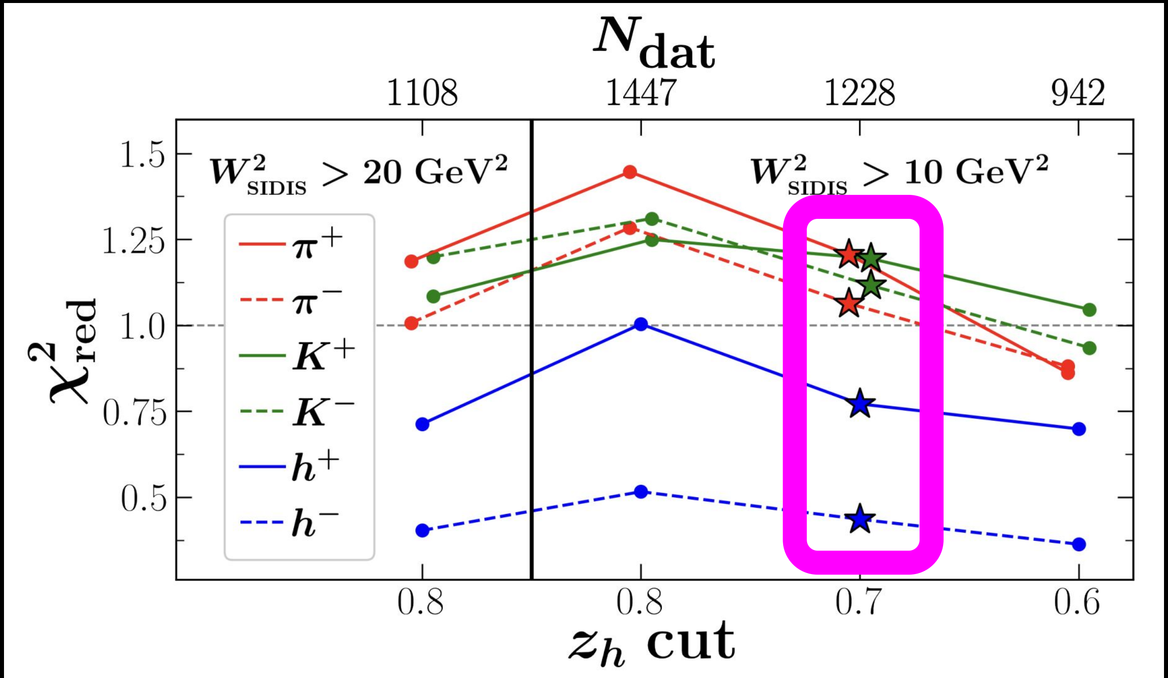
Process	Observables	Cuts	PDFs/FFs
$\ell + (p, d) \to \ell' + X$	$F_2, \sigma_{\rm red}$ [36–40]	$Q^2 > m_c^2$ $W^2 > 10$ GeV^2	$f_{i/p}$
$\ell + d \to \ell' + (\pi^\pm, K^\pm, h^\pm) + X$	dM^h/dz_h [41, 42]	$Q^2 > m_c^2$, $W^2_{\rm SIDIS} > 10$ GeV^2 $0.2 < z_h < 0.7$	$f_{i/p}$ $D_i^{(\pi^+, K^+, h^+)}$
$p + (p, d) \to \ell\bar{\ell} + X$	$d\sigma^{p/d}/dx_F\, dQ^2$ [2, 3]		$f_{i/p}$
$p + (p, \bar{p}) \to W + X$	$A_W,\ A_\ell,\ \sigma^{W^+}/\sigma^{W^-}$ [19–21, 23, 43–47]		$f_{i/p}$
$p + \bar{p} \to Z/\gamma^* + X$	$d\sigma/dy$ [48, 49]		$f_{i/p}$
$p + (p, \bar{p}) \to \text{jet} + X$	$d\sigma/d\eta\, dp_T$ [50–52]	$p_T > 8$ GeV	$f_{i/p}$
$p + p \to W + c + X$	$d\sigma/d\eta$ [25–27]		$f_{i/p}$
$\ell + \bar{\ell} \to (\pi^\pm, K^\pm, h^\pm) + X$	$d\sigma/dz_h$ [53–68]	$0.2 < z_h < 0.9$	$D_i^{(\pi^+, K^+, h^+)}$

- **Multiple reactions to optimize PDF modeling and test universality**
- **Simultaneous inference on PDFS and FFs**



ATLAS/CMS $W + c$
COMPASS
STAR W
NuSea
SeaQuest
BCDMS
NMC
SLAC
HERA
CDF/D0 W/Z
CMS/LHCb W
CDF/D0 jets
STAR jets
$W^2 = 10$ GeV^2
Q^2 (GeV^2)
x_i
10^1
10^2
10^3
10^4
10^5
10^{-4}
10^{-3}
10^{-2}
0.1
0.3
0.5
0.7


ATLAS/CMS $W+c$
CMS/LHCb W
COMPASS
SIA
Q^2 (GeV^2)
z_h
Q^2 (GeV^2)
x_i



$$W^2_{\mathrm{SIDIS}} = (p + q - p_h)^2$$

- Not all the available SIDIS data can be described consistently.
- Needs to perform additional cuts to isolate the phase space region that can be described by the model.
- There are multiple effects: HMC, TMCs, Current vs. Target hadronization, power corrections.
- We use z and Wsidis values to isolate the region of compatibility

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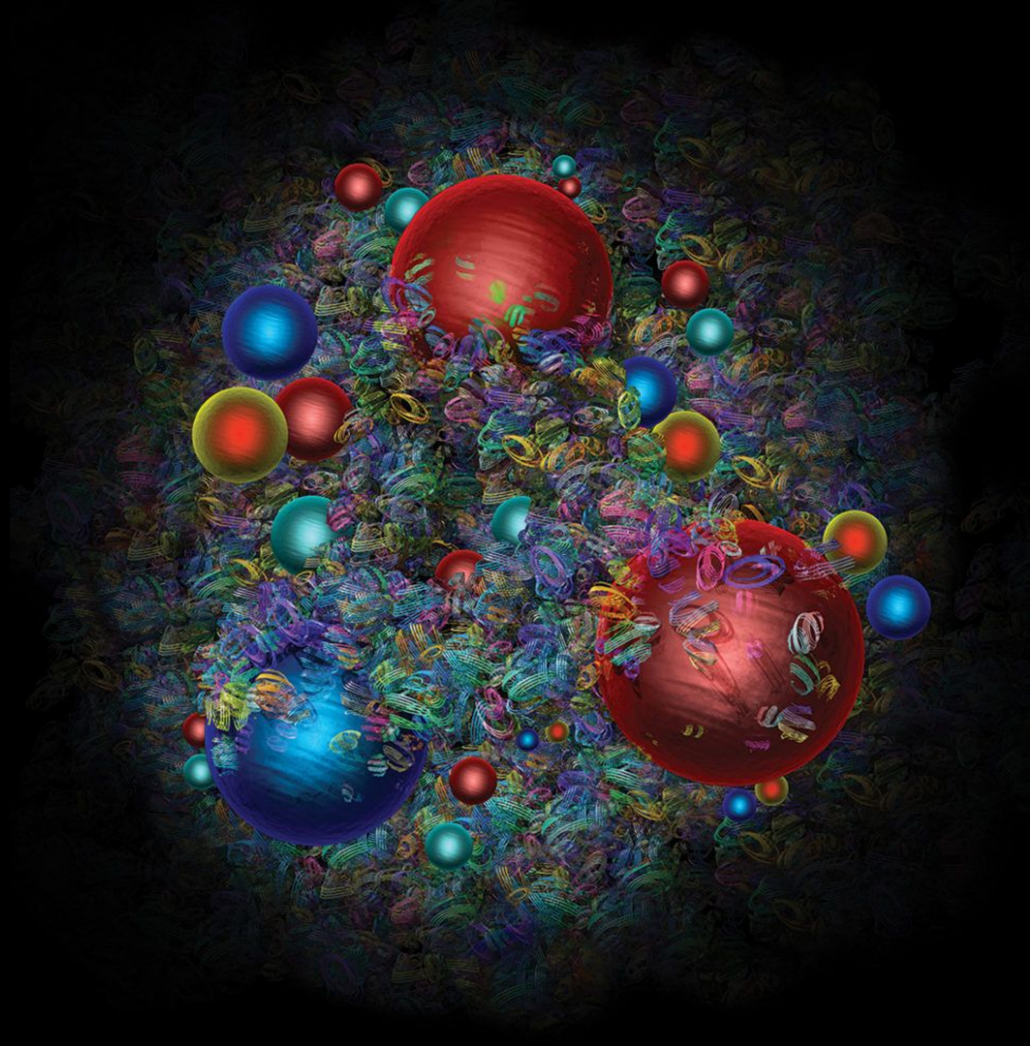
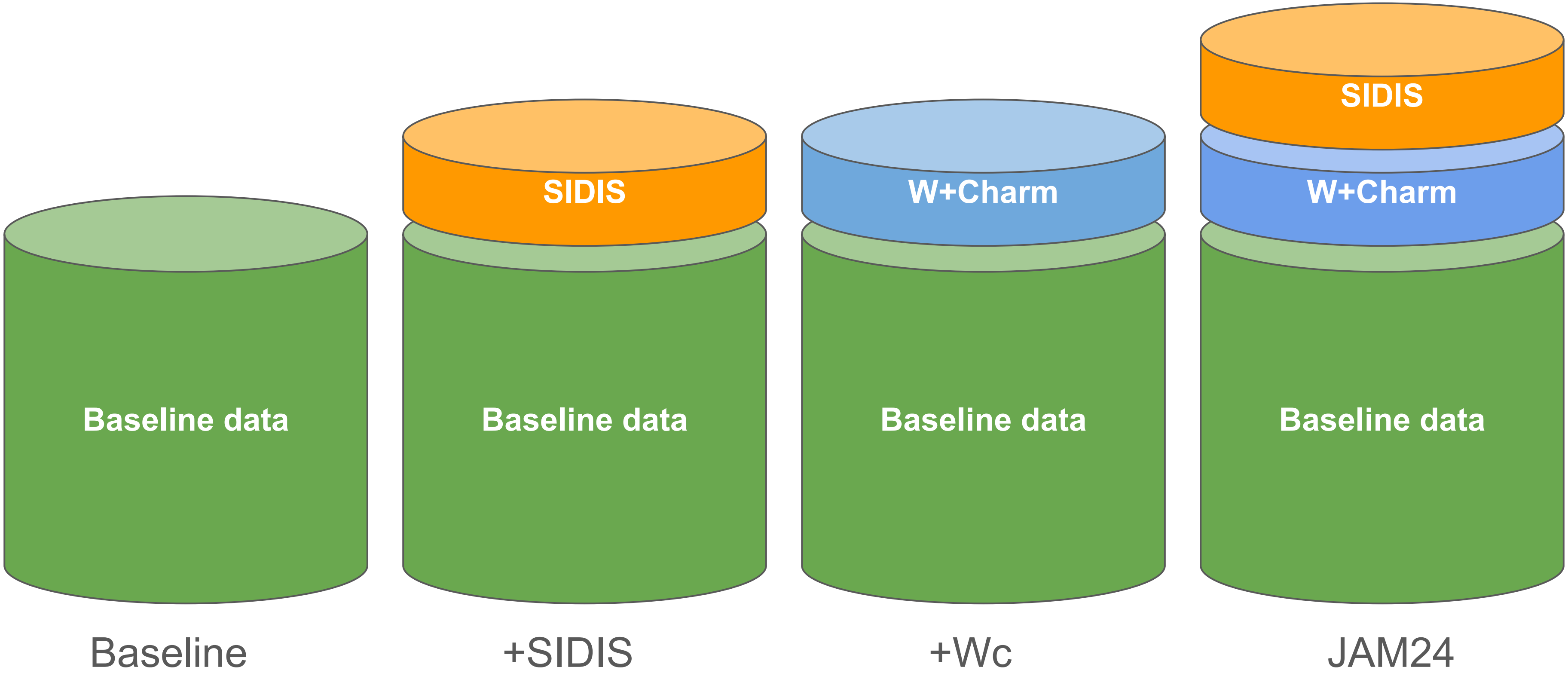
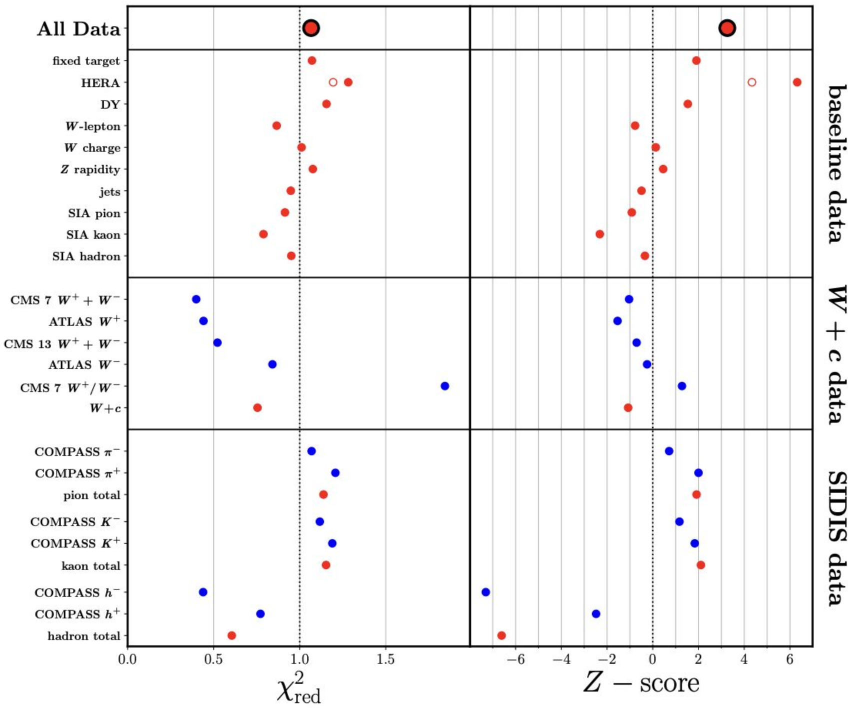


Analysis scenarios



Process	$N_{\rm dat}$	baseline	+SIDIS	+W-charm	**JAM24**
		$\chi^2_{\rm red}$ (Z-score)			
DIS					
fixed target [36–39]	1495	1.06 (1.66)	1.07 (1.95)	1.06 (1.52)	**1.07 (1.91)**
HERA [40]	1185	1.27 (6.02)	1.29 (6.40)	1.26 (5.97)	**1.28 (6.32)**
Drell-Yan [2, 3]	205	1.14 (1.36)	1.16 (1.61)	1.14 (1.41)	**1.16 (1.53)**
W-lepton asymmetry [19–21, 23, 43, 44, 47]	70	0.83 (−1.02)	0.92 (−0.44)	0.81 (−1.11)	**0.87 (−0.77)**
W charge asymmetry [45, 46]	27	1.00 (0.08)	1.15 (0.62)	1.01 (0.12)	**1.01 (0.13)**
Z rapidity [48, 49]	56	1.05 (0.33)	1.05 (0.33)	1.10 (0.57)	**1.08 (0.46)**
Inclusive jets [50–52]	198	0.97 (−0.32)	0.96 (−0.35)	0.97 (−0.24)	**0.95 (−0.49)**
W + charm [25–27]	37	— (—)	— (—)	0.64 (−1.73)	**0.75 (−1.08)**
SIDIS					
$\pi^\pm$ [41]	410	— (—)	1.12 (1.64)	— (—)	**1.14 (1.92)**
$K^\pm$ [42]	408	— (—)	1.17 (2.29)	— (—)	**1.15 (2.11)**
$h^\pm$ [41]	410	— (—)	0.61 (−6.48)	— (—)	**0.61 (−6.61)**
SIA					
$\pi^\pm$ [53–68]	231	0.91 (−0.32)	0.90 (−1.07)	0.91 (−0.32)	**0.91 (−0.92)**
$K^\pm$ [53–55, 57–68]	213	0.51 (−6.26)	0.80 (−2.20)	0.51 (−6.26)	**0.79 (−2.32)**
$h^\pm$ [53–55, 58, 61–65]	120	0.73 (−2.31)	0.93 (−0.52)	0.73 (−2.31)	**0.95 (−0.34)**
Total	**5065**	1.07 (2.82)	1.07 (3.49)	1.08 (3.35)	**1.07 (3.26)**



Figures of Merit

$$\chi^2_{\rm red} \equiv \frac{1}{N_{\rm dat}} \sum_{i,e} \left(\frac{d_{i,e} - \mathrm{E}\,[\widehat{T}_{i,e}]}{\alpha_{i,e}} \right)^2 , \quad \widehat{T}_{i,e} \equiv \sum_k r_e^k \widetilde{\beta}_{i,e}^k + \frac{T_{i,e}}{N_e}$$

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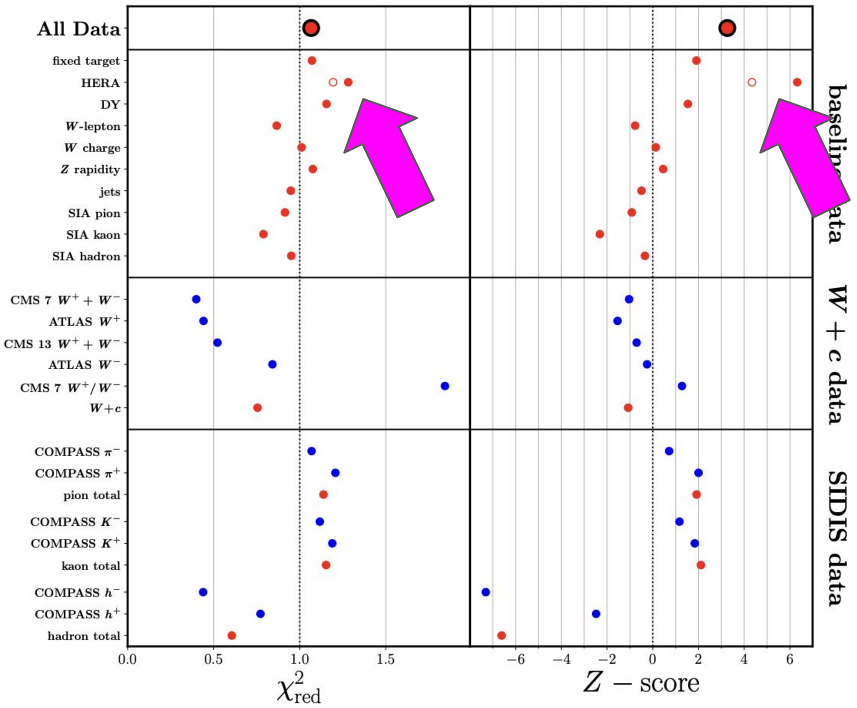

Figures of Merit

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[19–21, 2					
W charge a					
[45, 46]					
Z rapidity					
Inclusive je					
W + charm					
SIDIS					
$\pi^\pm$ [41]					
$K^\pm$ [42]					
$h^\pm$ [41]					
SIA					
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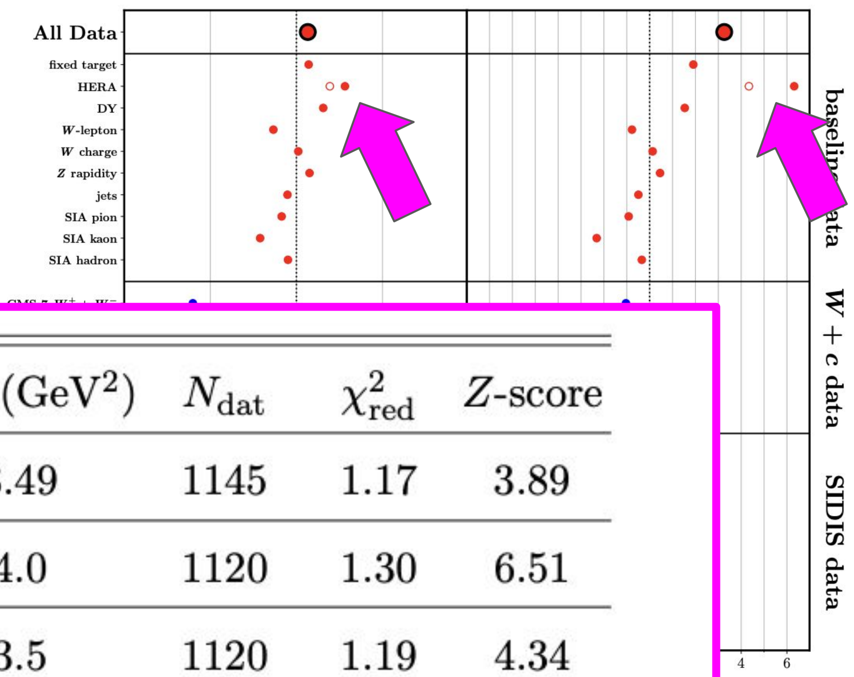

Analysis	pQCD accuracy	$Q^2_{\rm cut}$ (GeV^2)	$N_{\rm dat}$	$\chi^2_{\rm red}$	Z-score
NNPDF4.0 [73]	NNLO	3.49	1145	1.17	3.89
CT18 [74]	NNLO	4.0	1120	1.30	6.51
JAM24	NLO	3.5	1120	1.19	4.34
	NLO	m_c^2	1185	1.28	6.32

$$\chi^2_{\rm red} \equiv \frac{1}{N_{\rm dat}} \sum_{i,e} \left(\frac{\cdots}{\alpha_{i,e}} \right) \quad \cdots \, T_{i,e} = \sum_k r^k_e \, \widetilde{\beta}^k_{i,e} + \frac{T_{i,e}}{N_e}$$

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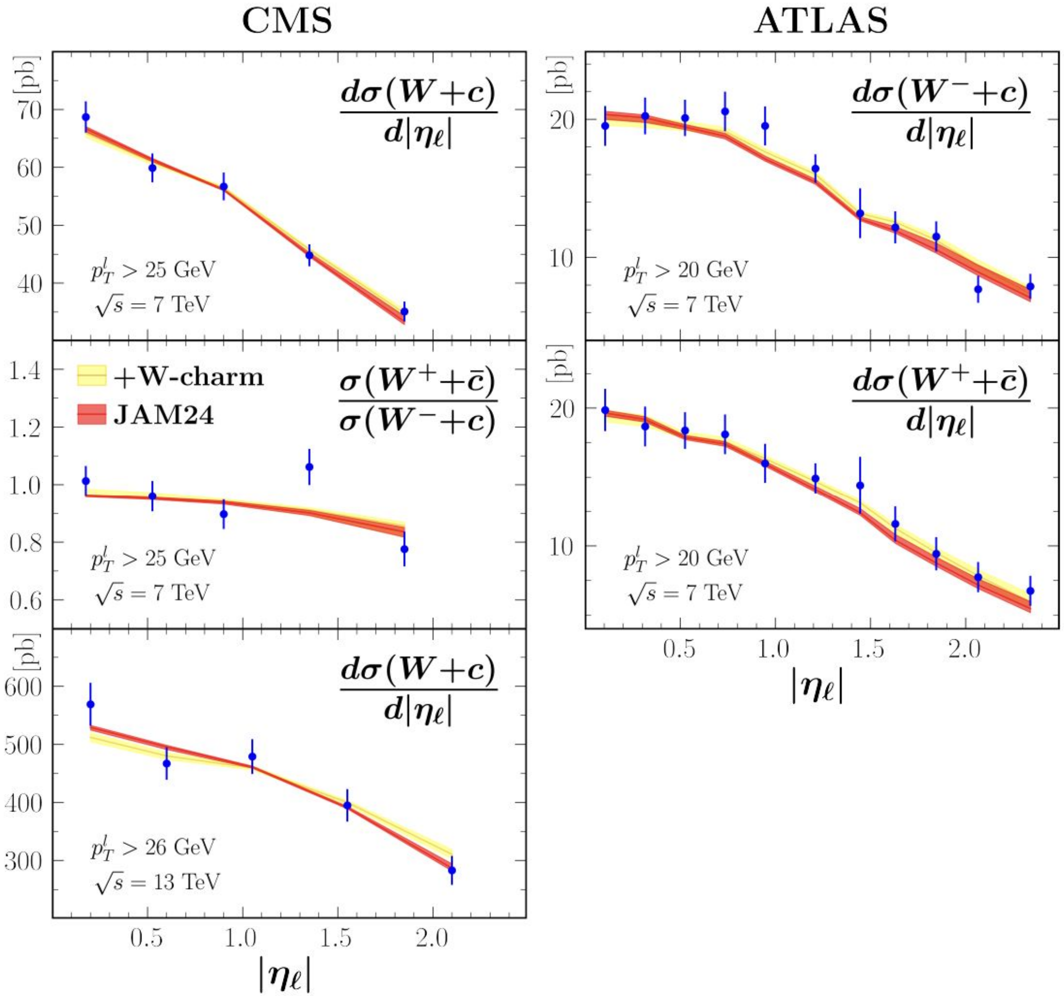
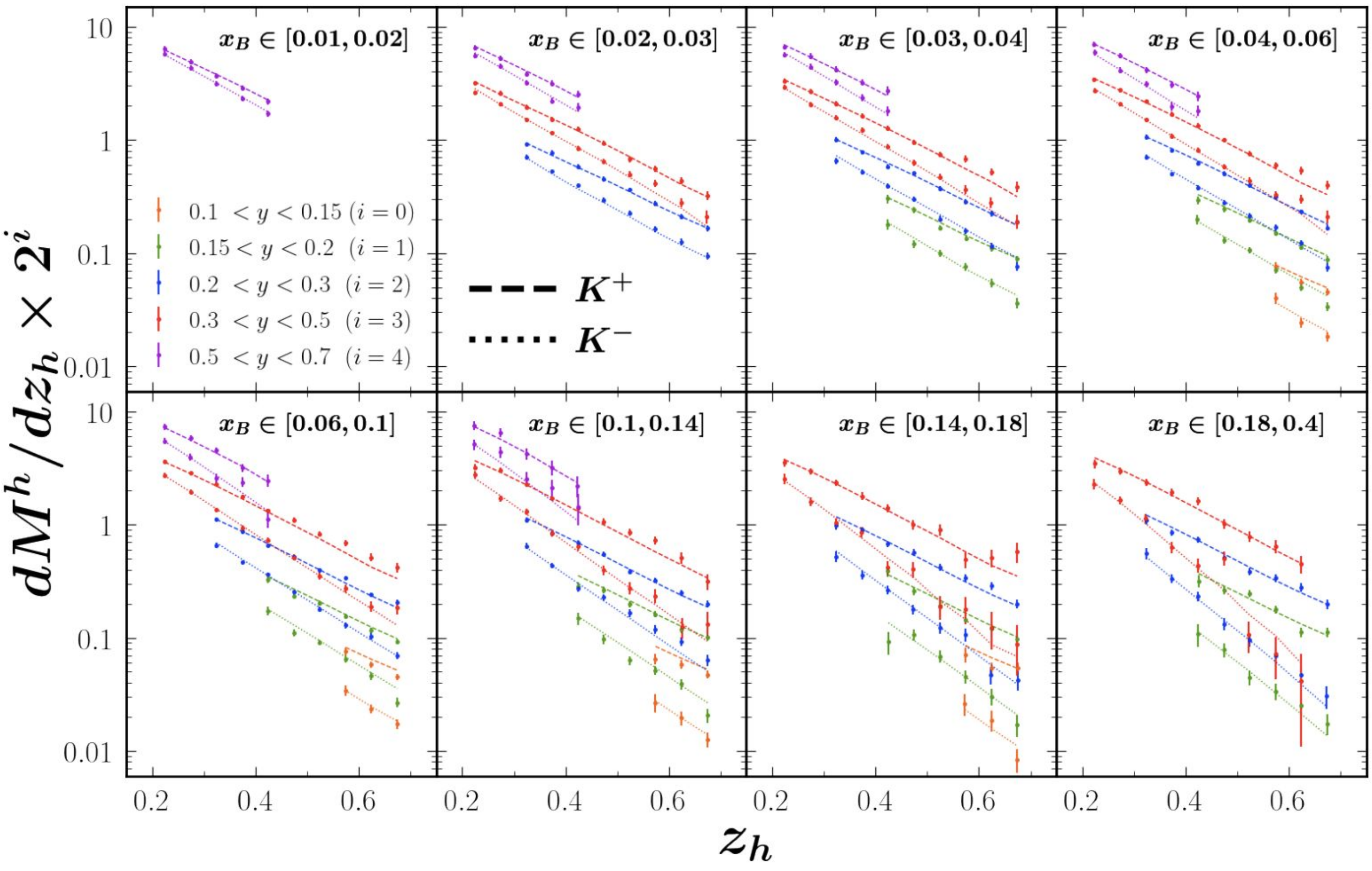


- W+c has a preference for a slightly larger strange quark PDF
- SIDIS data lowers the strange quark PDF. Hint of tension?

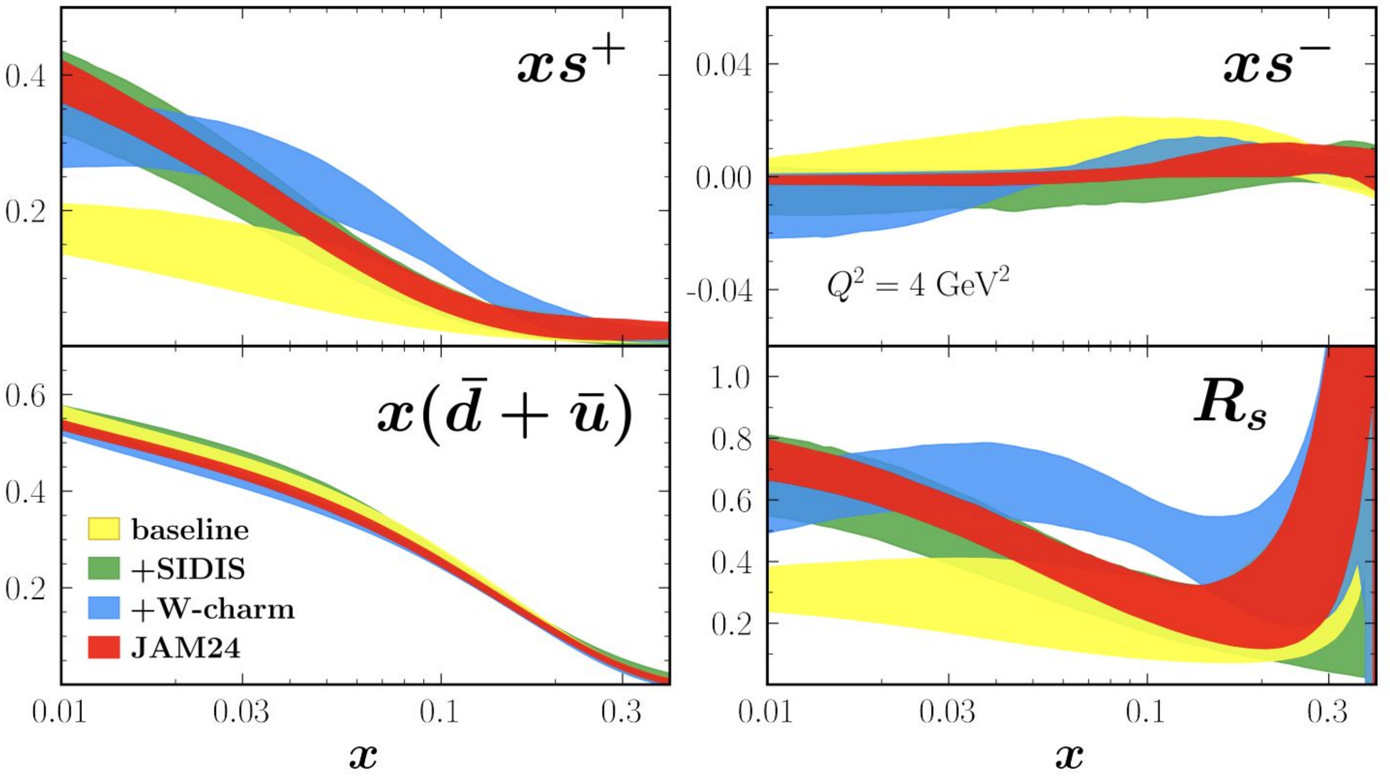


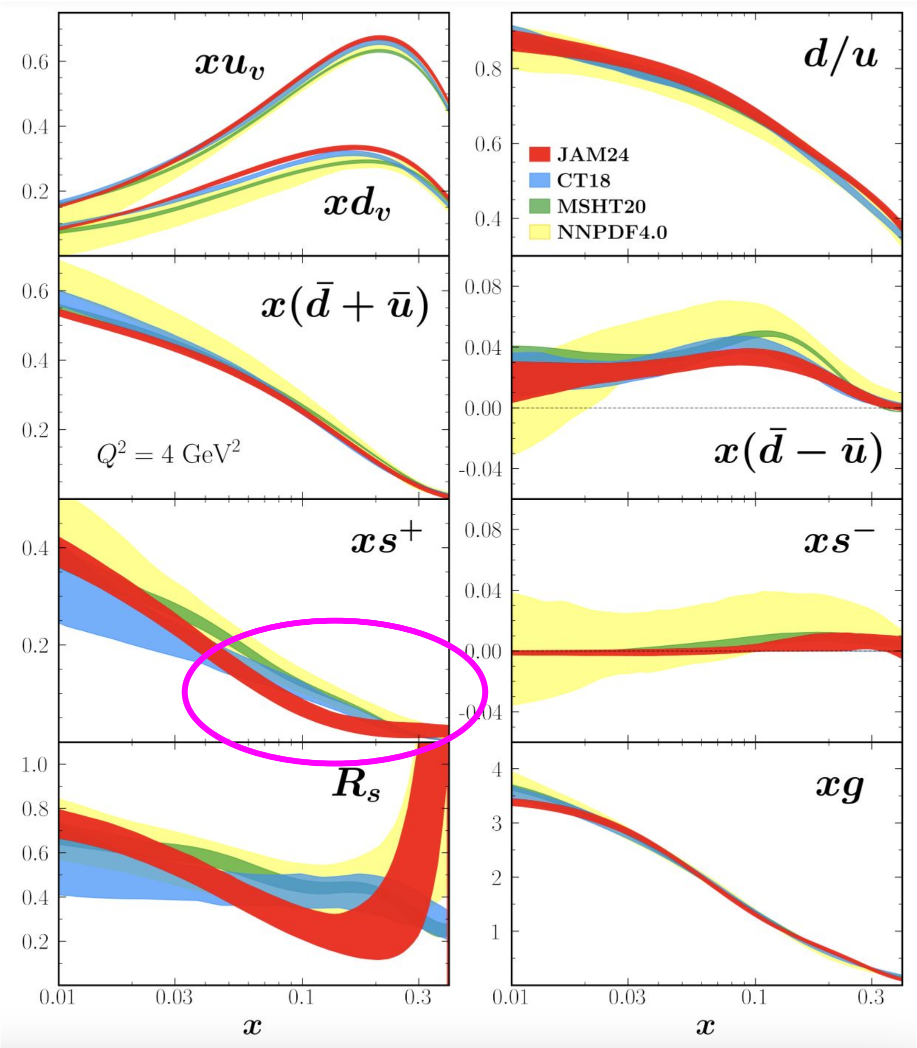
$x_B \in [0.01, 0.02]$
$x_B \in [0.02, 0.03]$
$x_B \in [0.03, 0.04]$
$x_B \in [0.04, 0.06]$
$x_B \in [0.06, 0.1]$
$x_B \in [0.1, 0.14]$
$x_B \in [0.14, 0.18]$
$x_B \in [0.18, 0.4]$
$0.1 < y < 0.15$ $(i = 0)$
$0.15 < y < 0.2$ $(i = 1)$
$0.2 < y < 0.3$ $(i = 2)$
$0.3 < y < 0.5$ $(i = 3)$
$0.5 < y < 0.7$ $(i = 4)$
K^+
K^-
$dM^h/dz_h \times 2^i$
z_h
10
1
0.1
0.01
0.2
0.4
0.6

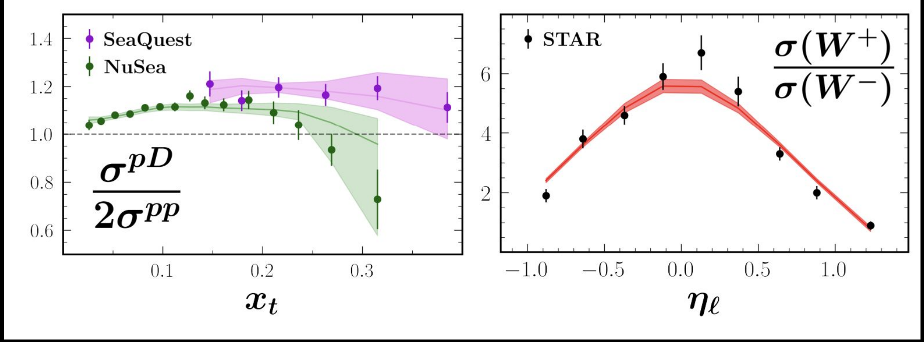
- SIDIS and Wc changes indicates different trends of strange for x<0.05

  W enhance sidis spresses
- s-sbar asymmetry consistent within errors

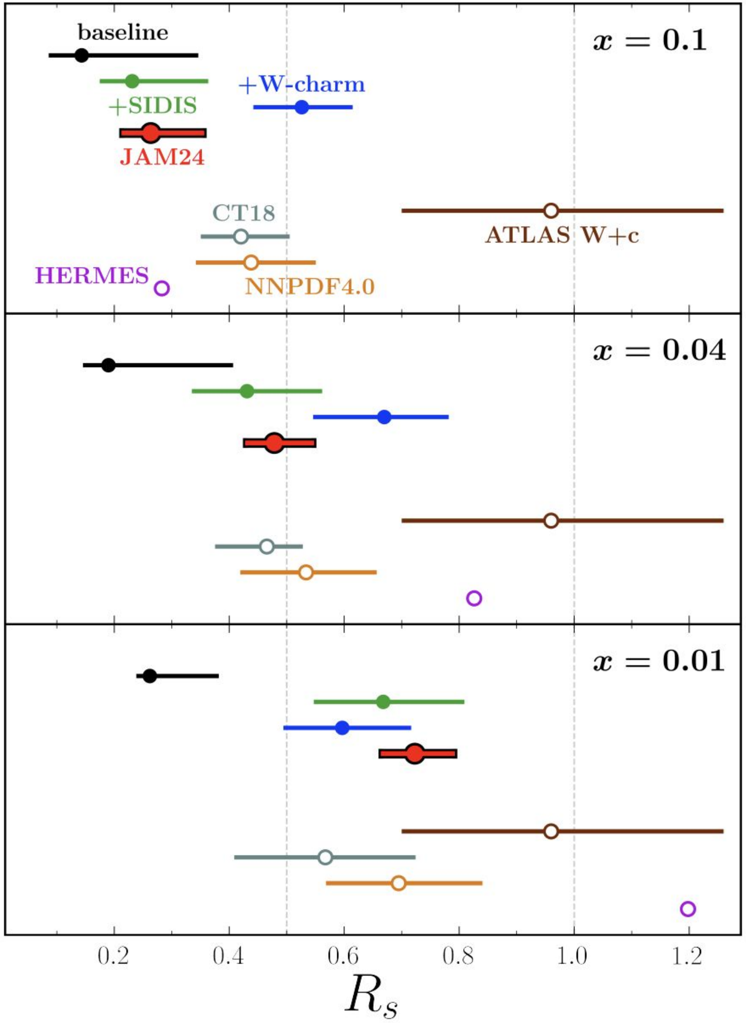
- No changes in db+ub

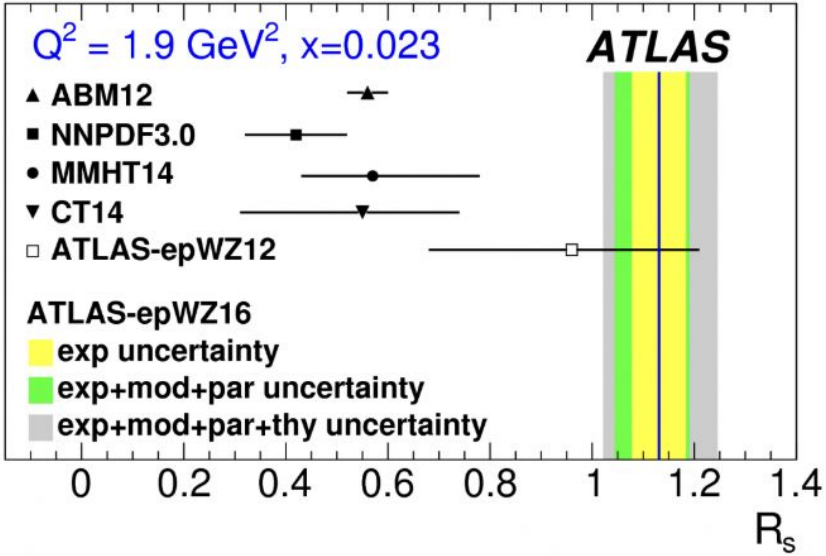




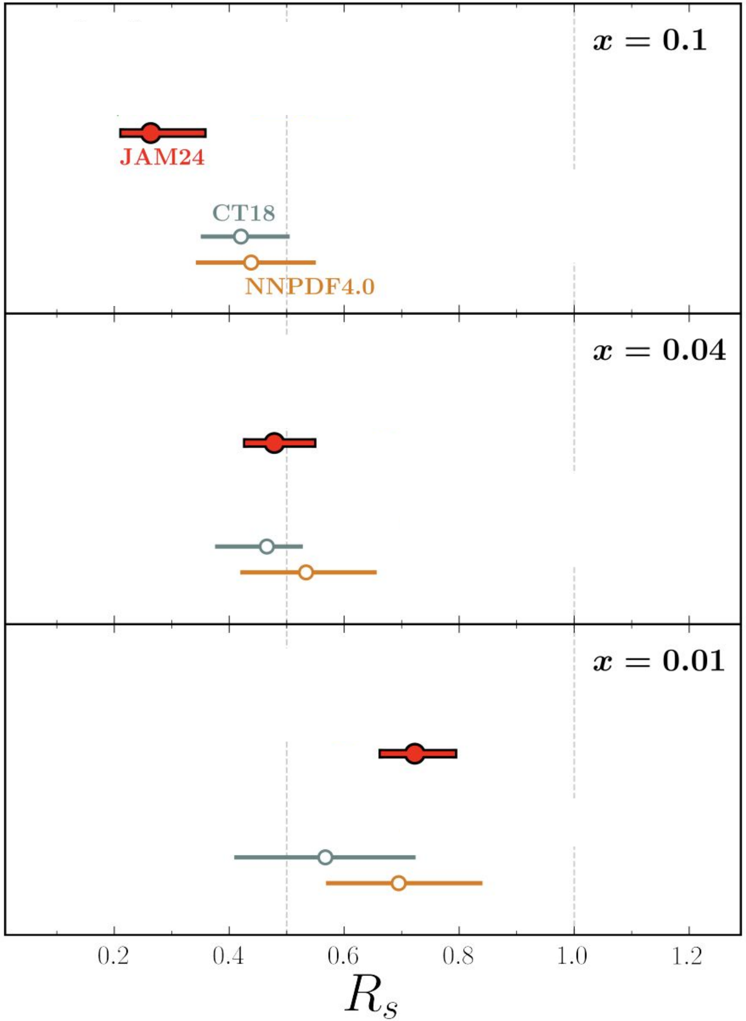


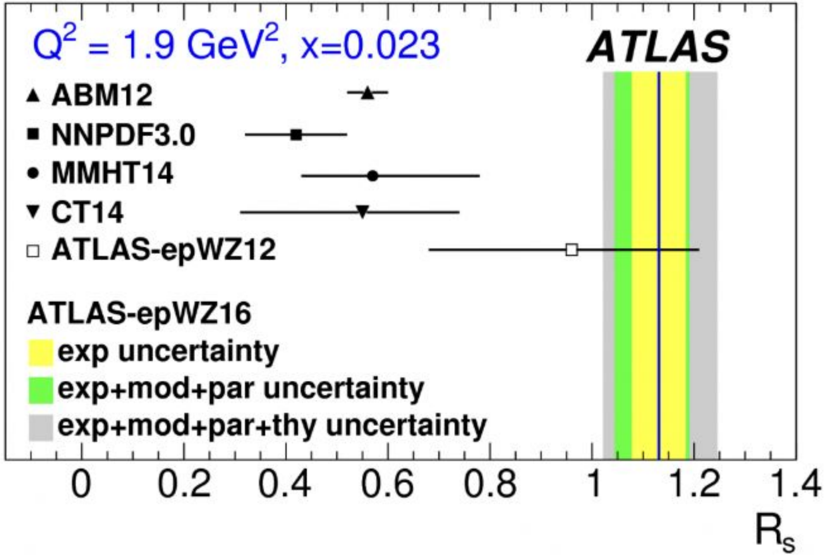
- JAM24 valence pdfs are larger than other groups sitting at the upper end
- The db-ub asymmetry is slightly more suppressed than previous analysis
- The combined effect of W+c and SIDIS gives stronger constraints on strange quark PDFs
- The symmetric sea (Rs=1) is disfavored both by SIDIS and collider data





- Strange suppression in Rs is both confirmed by SIDIS and W+charm data
- SIDIS and W+charm agree on Rs at smaller x but becomes more in tension as x->1





- JAM24 analysis on strange is largely compatible with other analysis for x<0.1
- Around x~0.1, some differences are visible.
- Additional information is needed to map out the strange content inside protons above x>0.1

Summary & outlook

- W+charm data and SIDIS can be described simultaneously within a QCD global analysis

- SIDIS data has at present the larger impact on the determination of strange quark PDF

- The analysis indicates a large suppression of the the strange quark PDFs relative to the light quark sector -> the proton is less strange!

- Additional data sensitive to strange quark PDFs are needed.
    - Parity violating DIS (JLab 12,+22, EIC)
    - Neutrino DIS (need to explore nuclear effects)
    - Synergies with LQCD