HUGS2023

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Studying strange quark suppression with global QCD analysis

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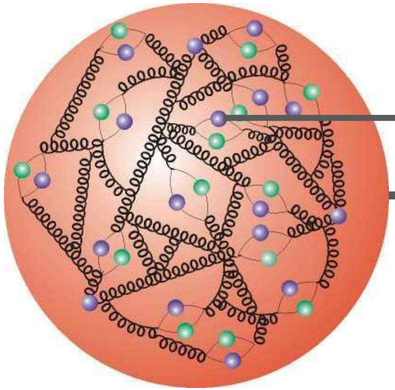
CHARTERED 1693

How quarks and gluons are distributed within the proton?



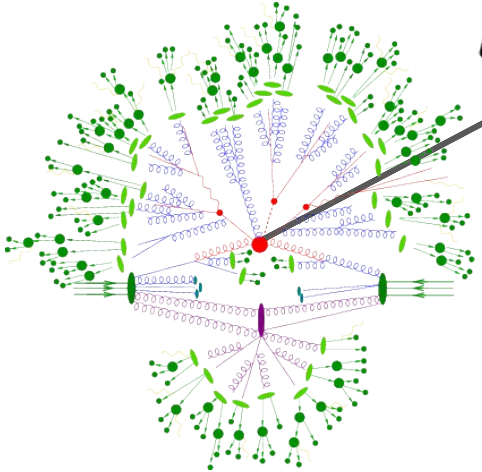
k $\quad \xi = \frac{k^+}{P^+}$

P

$f_i(\xi)$

parton distribution functions (PDFs)

Hadron structure



k $\quad \zeta = \frac{p_h^+}{k^+}$

h

$d_{h/j}(\zeta)$

fragmentation functions (FFs)

Hadron formation

Factorization in Reactions

Measurable

Calculable

?!?!??!

DIS

$$\ell + N \rightarrow \ell' + X \quad \Rightarrow \quad \frac{d^2\sigma^{\mathrm{DIS}}}{dx\,dQ^2} = \sum_i \frac{d^2\hat{\sigma}_i^{\mathrm{DIS}}}{dx\,dQ^2} \otimes f_i$$

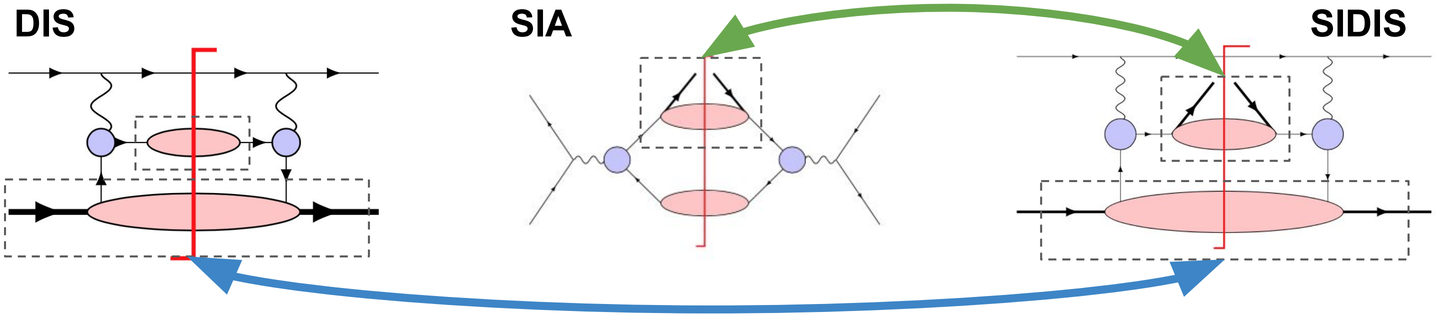
SIA

$$\ell^+ + \ell^- \rightarrow h^\pm + X \quad \Rightarrow \quad \frac{d^2\sigma^{\mathrm{SIA}}}{dQ^2\,dz} = \sum_i \frac{d^2\hat{\sigma}_i^{\mathrm{SIA}}}{dQ^2\,dz} \otimes d_i$$

SIDIS

$$\ell^+ + N \rightarrow \ell' + h^\pm + X \quad \Rightarrow \quad \frac{d^3\sigma^{\mathrm{SIDIS}}}{dx\,dQ^2\,dz} = \sum_{i,j} \frac{d^3\hat{\sigma}_{ij}^{\mathrm{SIDIS}}}{dx\,dQ^2\,dz} \otimes f_i \otimes d_j$$

Universality



cross sections described by **universal non-perturbative** functions, e.g. PDFs, FFs

PDFs and FFs Parameterization

Regge theory

Counting rules

$$T(x, \mu_o, \mathbf{a}) = \mathrm{N}\frac{x^{\alpha}(1-x)^{\beta}(1+\gamma\sqrt{x}+\delta x)}{\int_0^1 dy\, y^{\alpha+1}(1-y)^{\beta}(1+\gamma\sqrt{y}+\delta y)}$$

Constrained using symmetry and sum rules

Isospin

$$f_{u/n} = f_{d/p}$$

$$f_{d/n} = f_{u/p}$$

$$f_{\bar{u}/n} = f_{\bar{d}/p}$$

$$f_{\bar{d}/n} = f_{\bar{u}/p}$$

Sum rules

$$\int_0^1 dx\,[f_{u/p}(x) - f_{\bar{u}/p}(x)] = 2$$

$$\int_0^1 dx\,[f_{d/p}(x) - f_{\bar{d}/p}(x)] = 1$$

$$\int_0^1 dx\,[f_{s/p}(x) - f_{\bar{s}/p}(x)] = 0$$

$$\int_0^1 dx\, x\,[f_g + f_{u^+} + f_{d^+} + f_{s^+} + f_{c^+} + f_{b^+}] = 1$$

Bayesian Inference

Posterior Distribution **Likelihood Function** **Prior Distribution**

$$\rho(\mathbf{a}|\text{data}) \sim \mathcal{L}(\text{data}|\mathbf{a})\pi(\mathbf{a})$$

$$E[\mathcal{O}] = \int d^n a\, \rho(\mathbf{a}|\text{data})\mathcal{O}(\mathbf{a})$$

$$V[\mathcal{O}] = \int d^n a\, \rho(\mathbf{a}|\text{data})[\mathcal{O}(\mathbf{a}) - E(\mathcal{O})]^2$$

This is a choice

Min, max, penalties, regulators, etc.

$$\mathcal{L}(\text{data}|\mathbf{a}) = \exp\left[-\frac{1}{2}\chi^2(\mathbf{a},\text{data})\right]$$

Gaussian likelihood

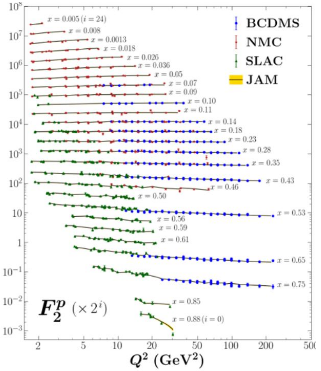
Monte Carlo Framework

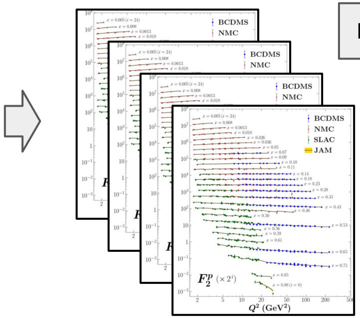
$$E[\mathcal{O}] \simeq \frac{1}{N}\sum_k \mathcal{O}(a_k) \qquad V[\mathcal{O}] \simeq \frac{1}{N}\sum_k \Big(\mathcal{O}(a_k) - E[\mathcal{O}]\Big)^2$$

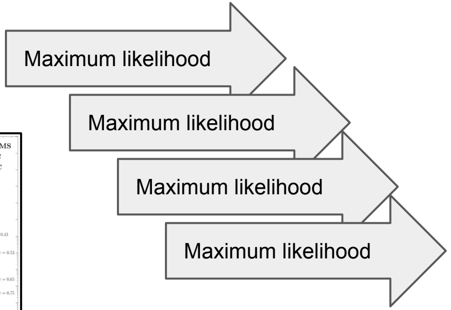
$$d_{k,i}^{(\mathrm{pseudo})} = d_i^{(\mathrm{original})} + \alpha_i R_{k,i}$$

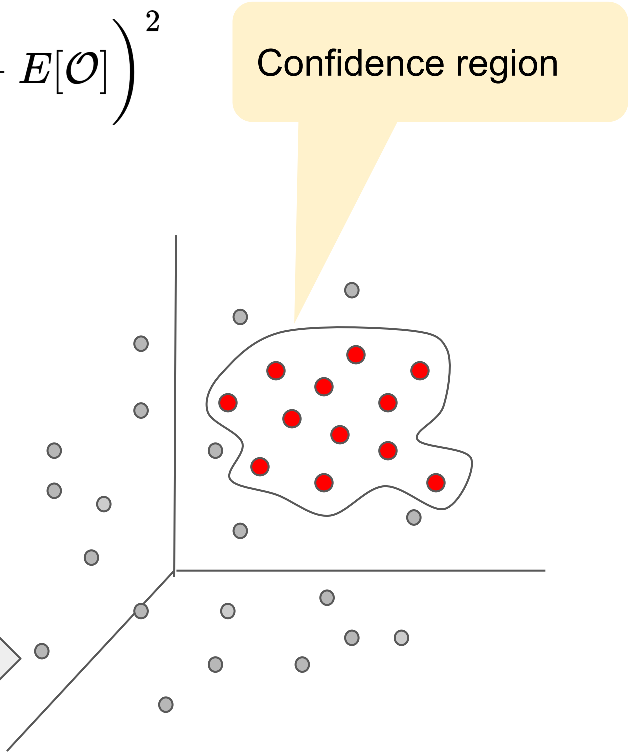
Original data

Replica data



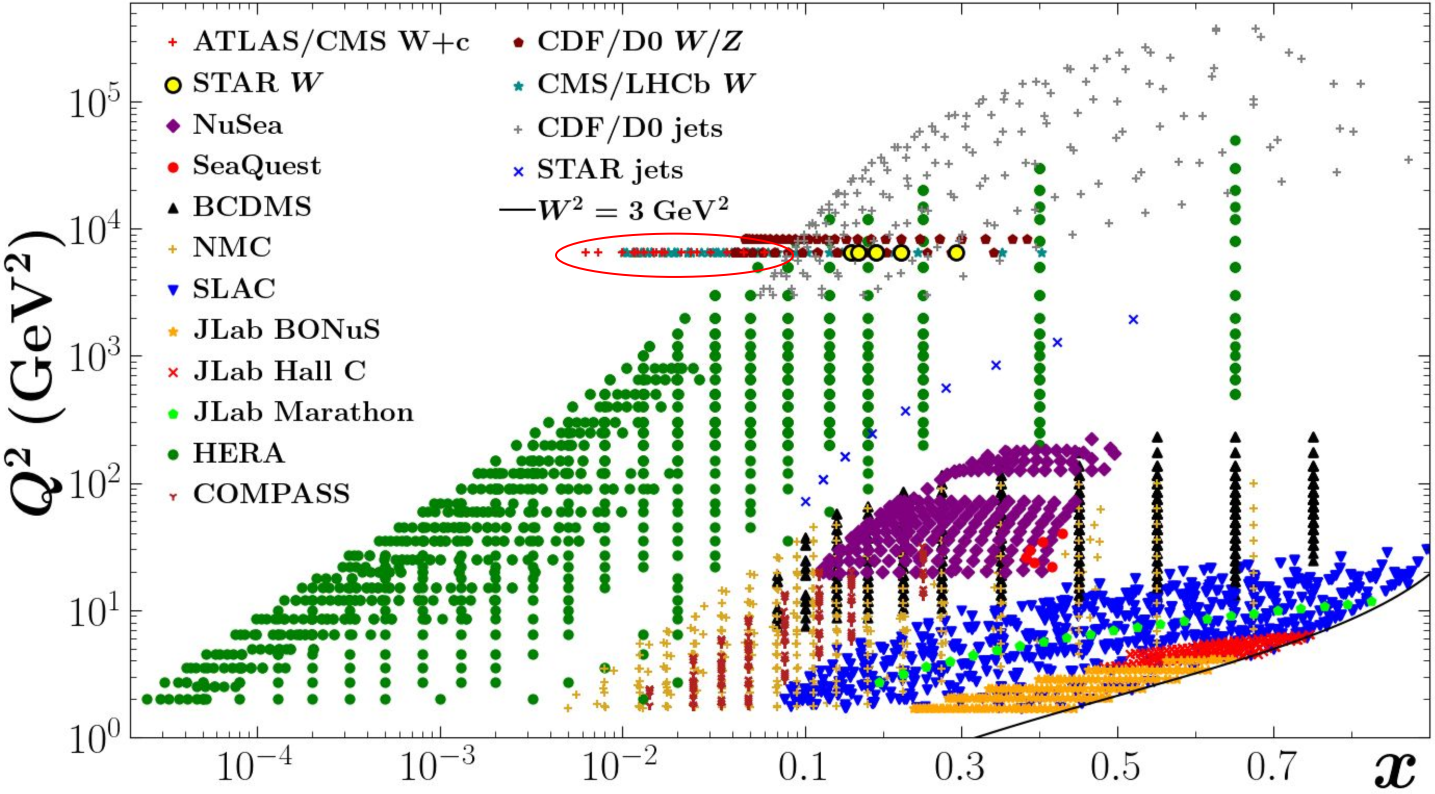






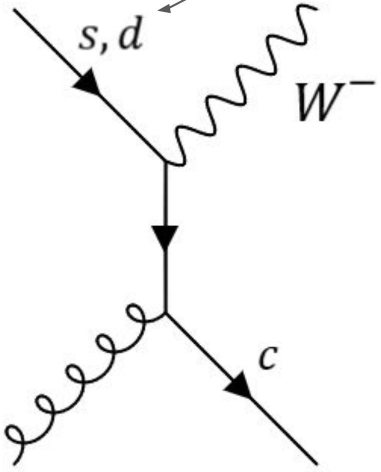
Parameter space

JAM23 Global Analysis

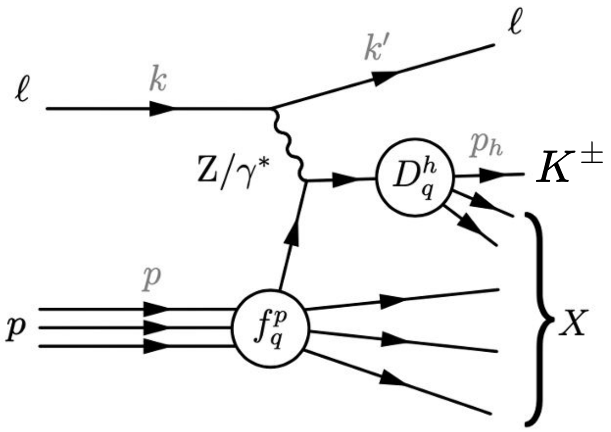


Kinematic coverage of datasets used in analysis. X is Bjorken-x for DIS and Feynman-x for vector boson and jet production. Q^2 is four-momentum transfer squared for DIS, mass squared of intermediate boson for vector boson production, and transverse momentum squared for jet production.

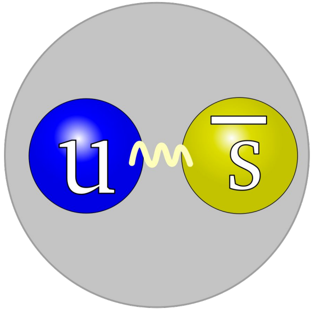
Strange quark through W+charm and SIDIS



Direct sensitivity to strange quark!



$$d\sigma^{\mathrm{SIDIS}_{K^+}} \sim 2(u+d)D_u^{K^+} + \bar{s}D_{\bar{s}}^{K^+}$$

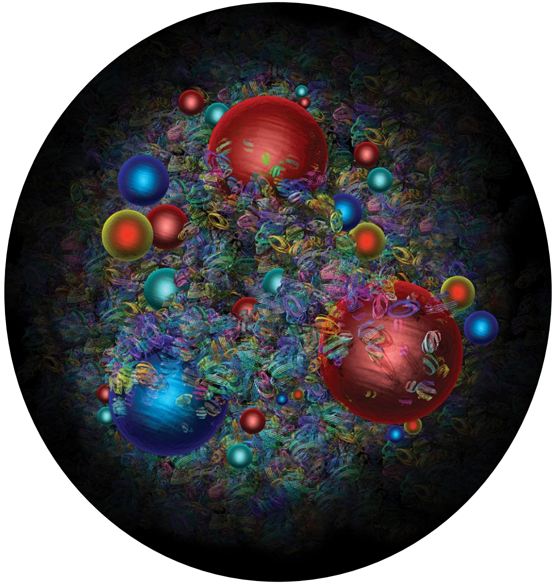


K⁺

g + s → W + c contributes to about 90% of LO production

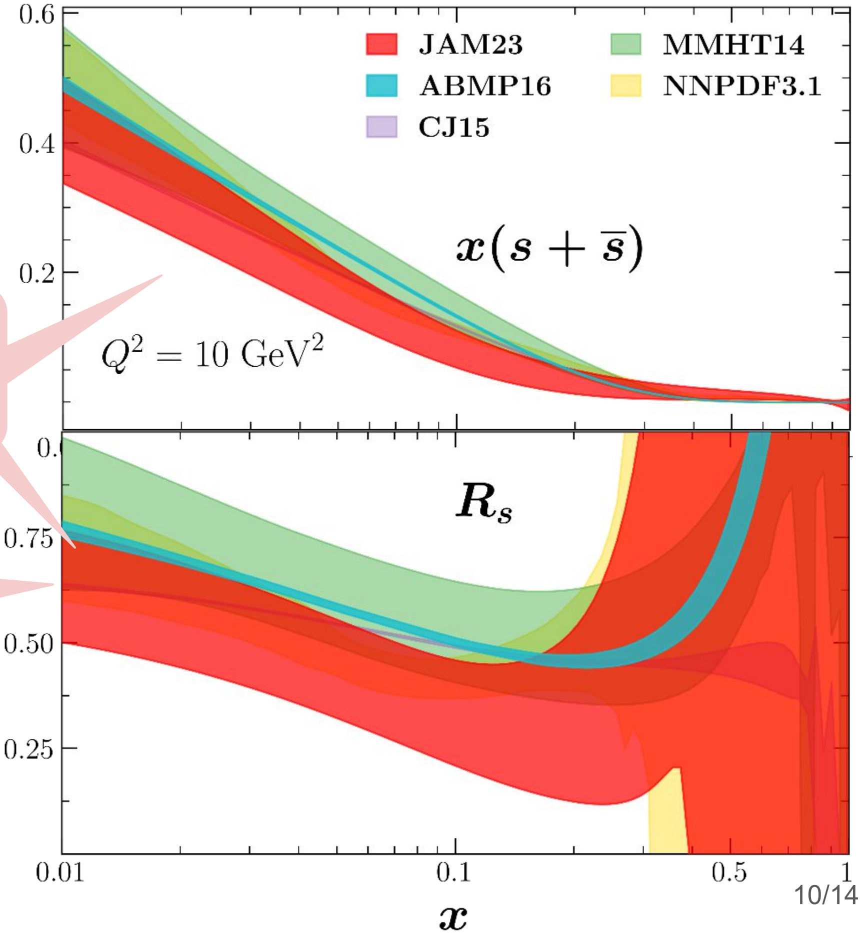
g + d → W + c is the remaining 10%

Strange quark suppression

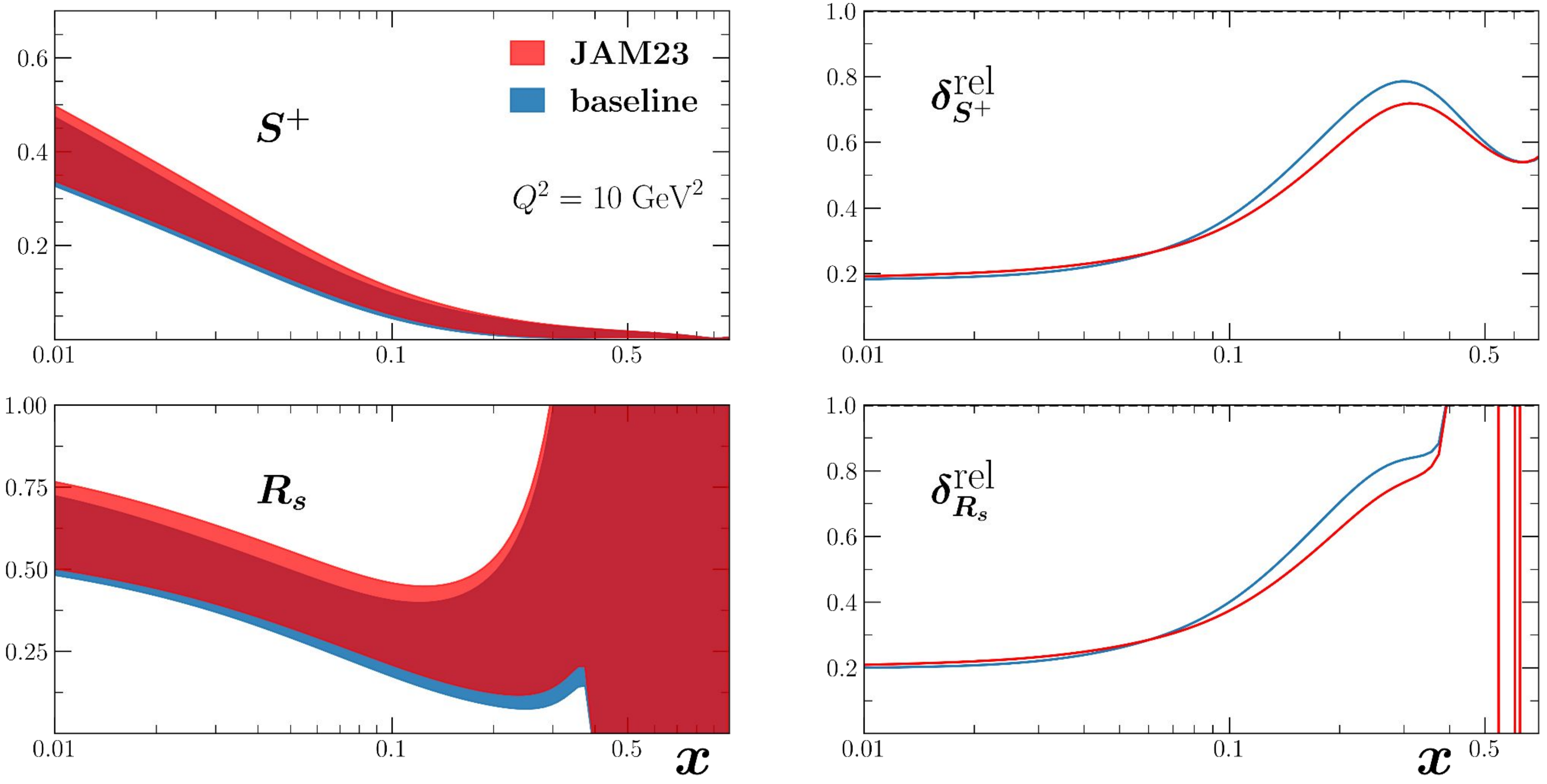


Strange quark suppression

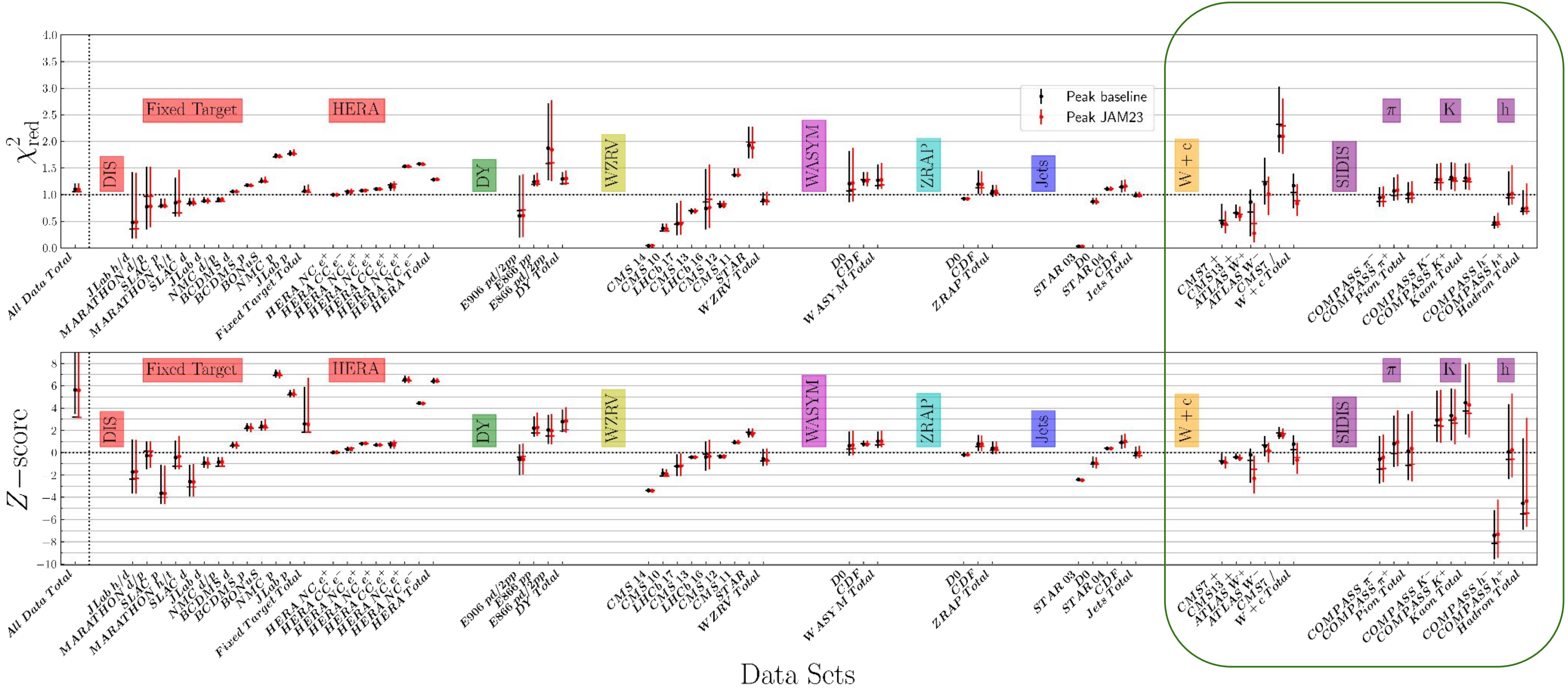
$$R_s = \frac{s+\bar{s}}{\bar{d}+\bar{u}}$$



W+charm Impact



χ^2 and Z-score



Summary

- **Global analysis performed using DIS, Drell-Yan, W/Z production, jet production, SIDIS, SIA, and W+charm data**
- **W+charm data had little impact on the suppression and constraint of the strange PDF**
- **Strange PDF still heavily suppressed due to SIDIS datasets (primarily $K^{\pm}$)**
- **Overall agreement in χ^2 between W+charm and SIDIS data, along with remaining datasets in global fit**

Outlook

- **Findings will be published soon, after completing further study**
- **Include remaining ATLAS W/Z production data into global analysis**
- **Implement neutrino-DIS from CERN and FermiLab to further constrain strange PDF**

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Thank you!

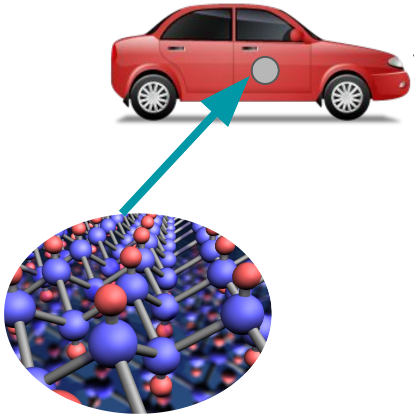
Extra Slides

So how do we get hadron structure from experimental data?

What part of this is the
"internal structure"?

Factorization

Want to see
internal structure



But we only see debris

Mellin Transform

Need to evolve PDFs and FFs to experimental energy scales

$$f(x)\otimes g(x) = \int_x^1 \frac{d\xi}{\xi} f\left(\frac{x}{\xi}\right) g(\xi)$$

Convolution

Mellin transform

$$F(N) = \int_0^1 dx\, x^{N-1} f(x)$$

Inverse Mellin transform

$$f(x) = \frac{1}{2\pi i}\int_c dN\, x^{-N} F(N)$$

$$\mathcal{M}[f(x)\otimes g(x)] = F(N)G(N)$$

DGLAP Evolution Equations

Need to evolve PDFs and FFs to experimental energy scales

$$\frac{\partial}{\partial \ln \mu^2} f_{j/H}(x,\mu^2) = \sum_{j'} \int_x^1 \frac{d\xi}{\xi} P_{jj'}(\xi,\mu^2) f_{j'/H}(x/\xi,\mu^2)$$

$$\frac{\partial}{\partial \ln \mu^2} F_{j/H}(N,\mu^2) = \sum_{j'} P_{jj'}(N,\mu^2) F_{j'/H}(N,\mu^2)$$

$$\frac{\partial F_{\pm j}}{\partial \ln \mu^2} = P_{\mathrm{NS}}^{\pm} F_{\pm j} \qquad \frac{\partial F_{-}}{\partial \ln \mu^2} = P_{\mathrm{NS}}^{-} F_{-}$$

→ Non-singlet evolution

$$\frac{\partial}{\partial \ln \mu^2} \begin{pmatrix} F_+ \\ F_g \end{pmatrix} = \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \begin{pmatrix} F_+ \\ F_g \end{pmatrix}$$

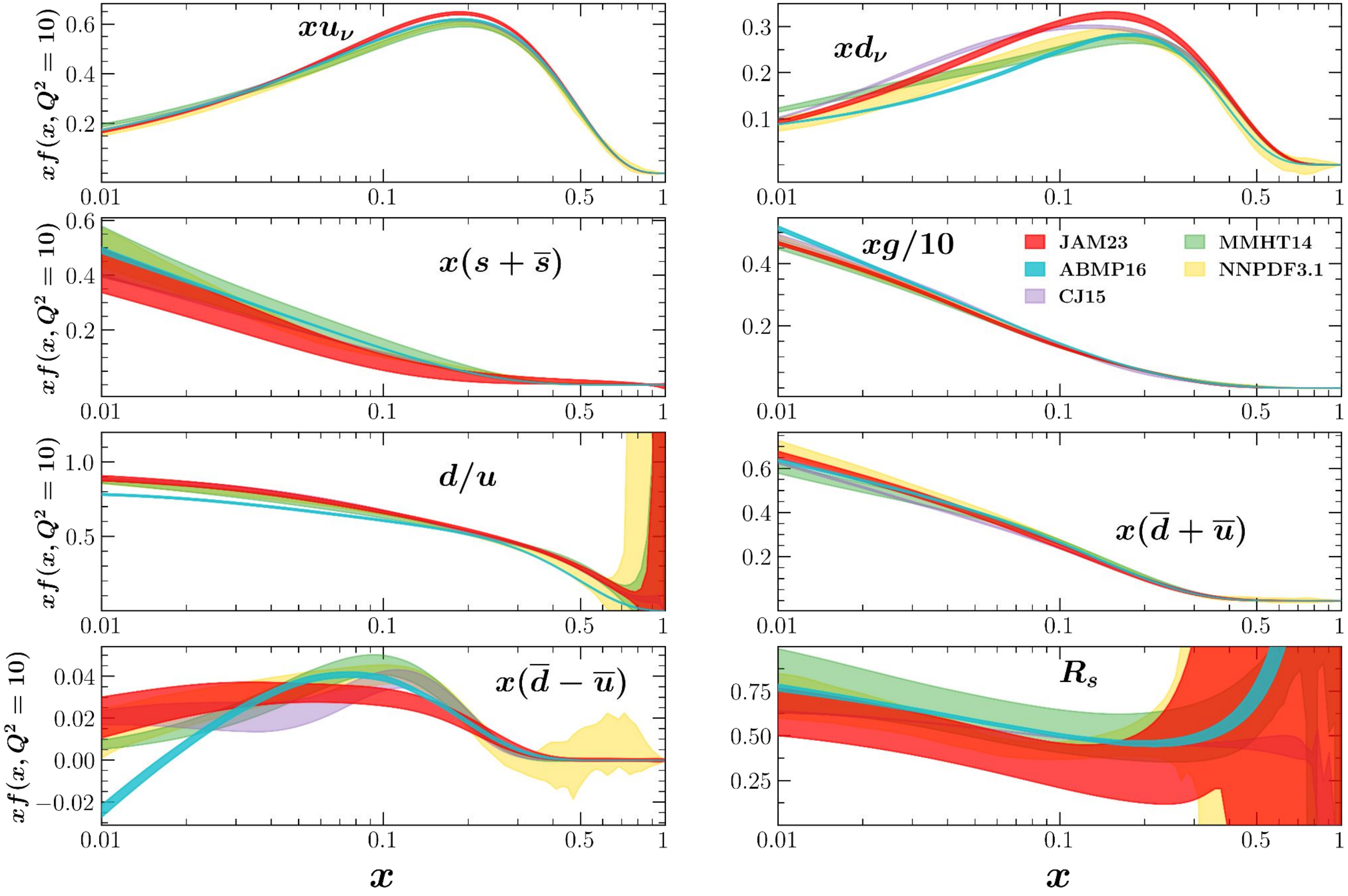
→ Singlet evolution

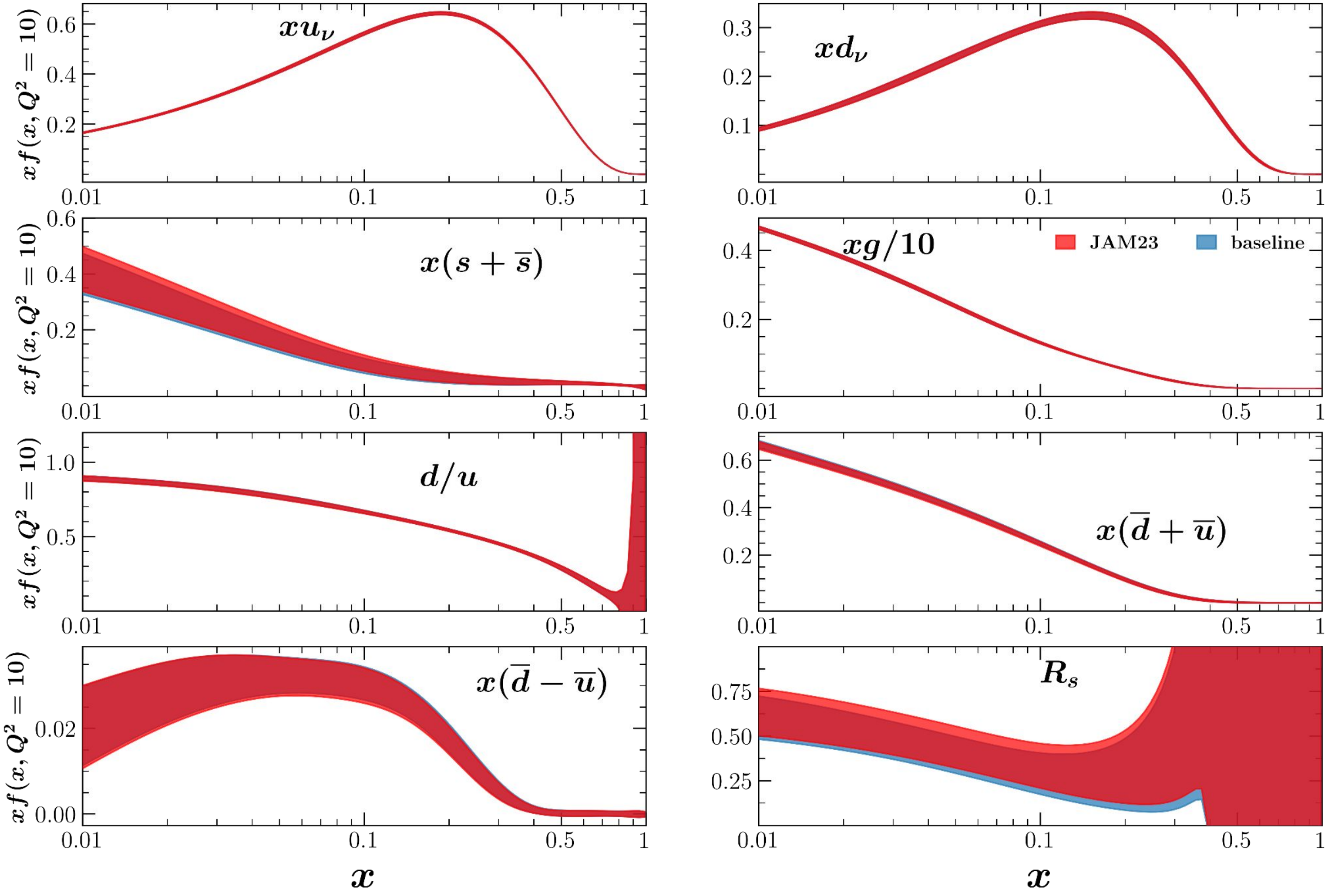
$$\frac{\partial \chi^2}{\partial r_e^k} = 0$$

Nuisance fitting parameters

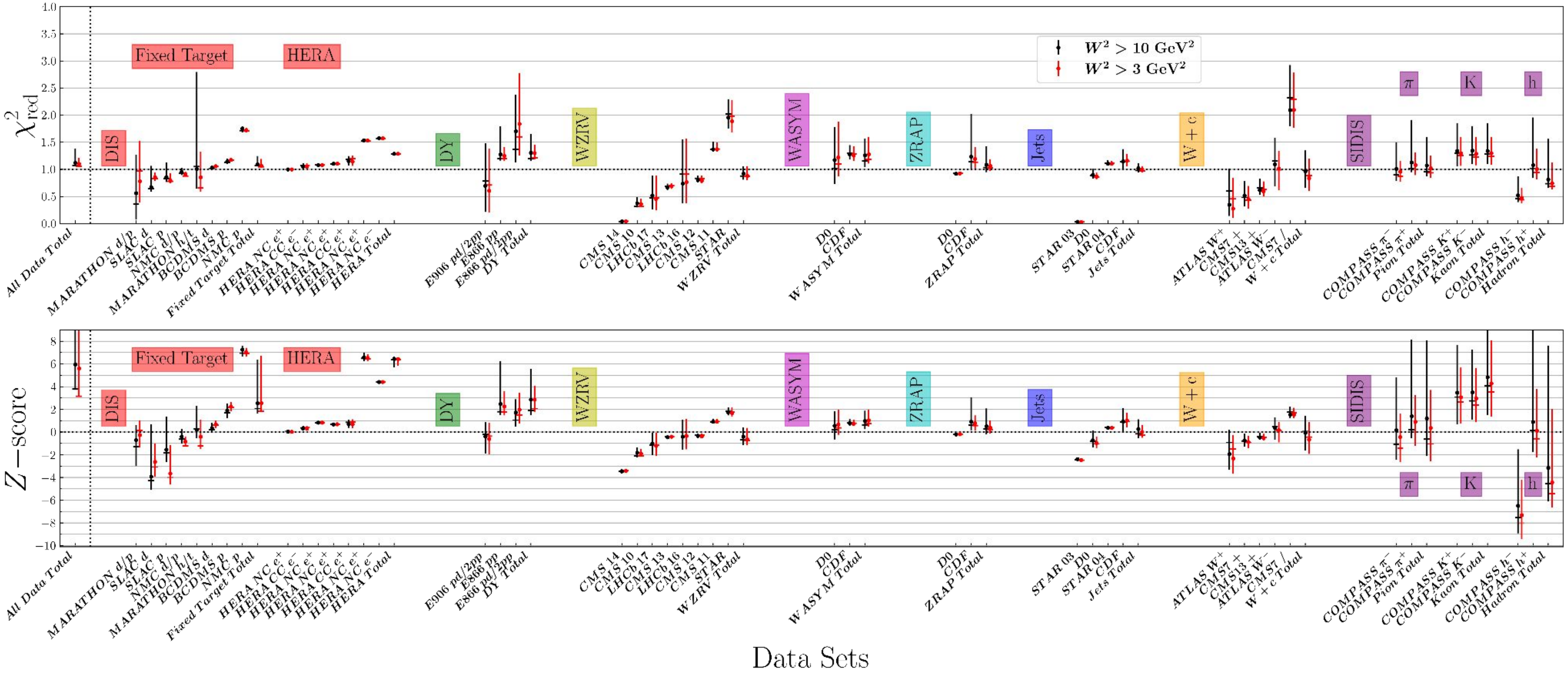
Penalties for the Nuisance parameters

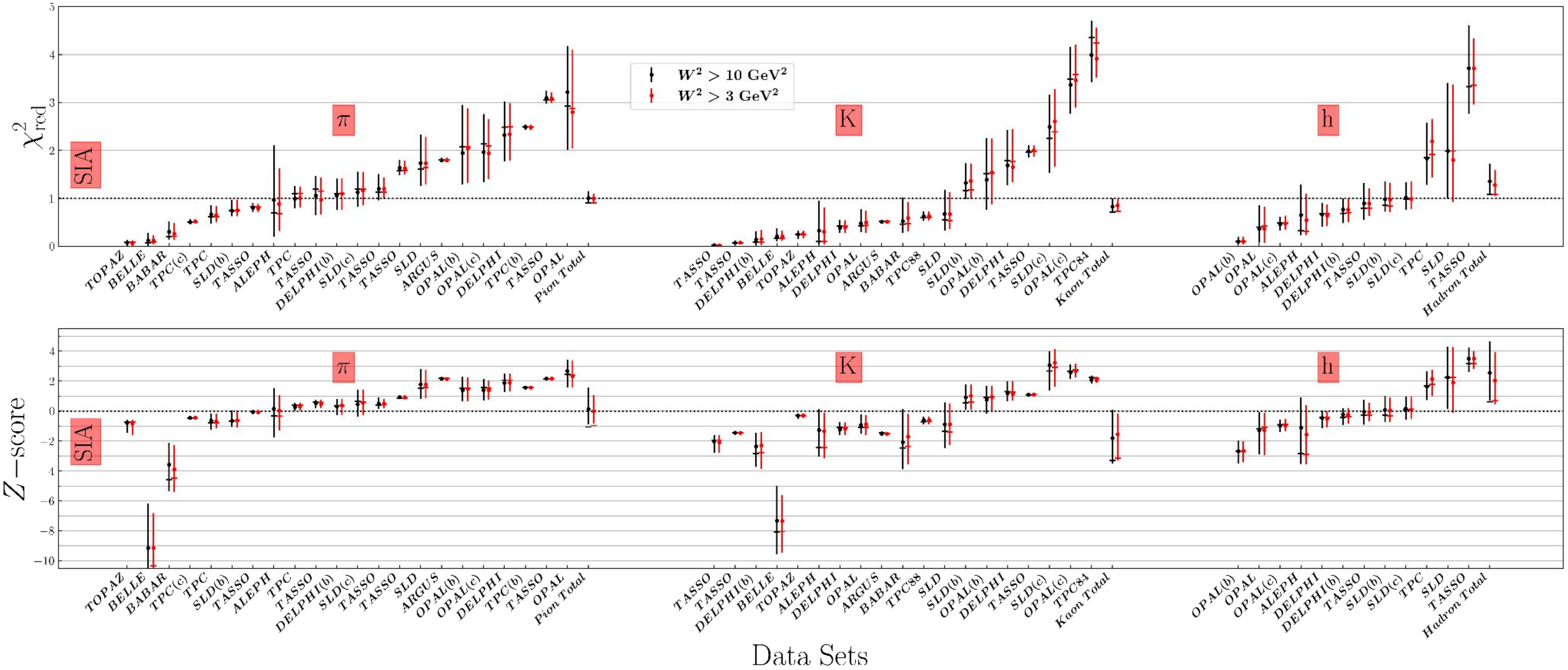
$$\chi^2(\mathbf{a}) = \sum_{i,e} \left(\frac{d_{i,e} - \sum_k r_e^k \beta_{i,e}^k - T_{i,e}(\mathbf{a})/N_e}{\alpha_{i,e}} \right)^2 + \sum_k (r_e^k)^2 + \sum_e \left(\frac{1 - N_e}{\delta N_e} \right)^2$$


xu_ν
xd_ν
$x(s+\bar{s})$
$xg/10$
JAM23
ABMP16
CJ15
MMHT14
NNPDF3.1
d/u
$x(\bar{d}+\bar{u})$
$x(\bar{d}-\bar{u})$
R_s
$xf(x,Q^2=10)$
x



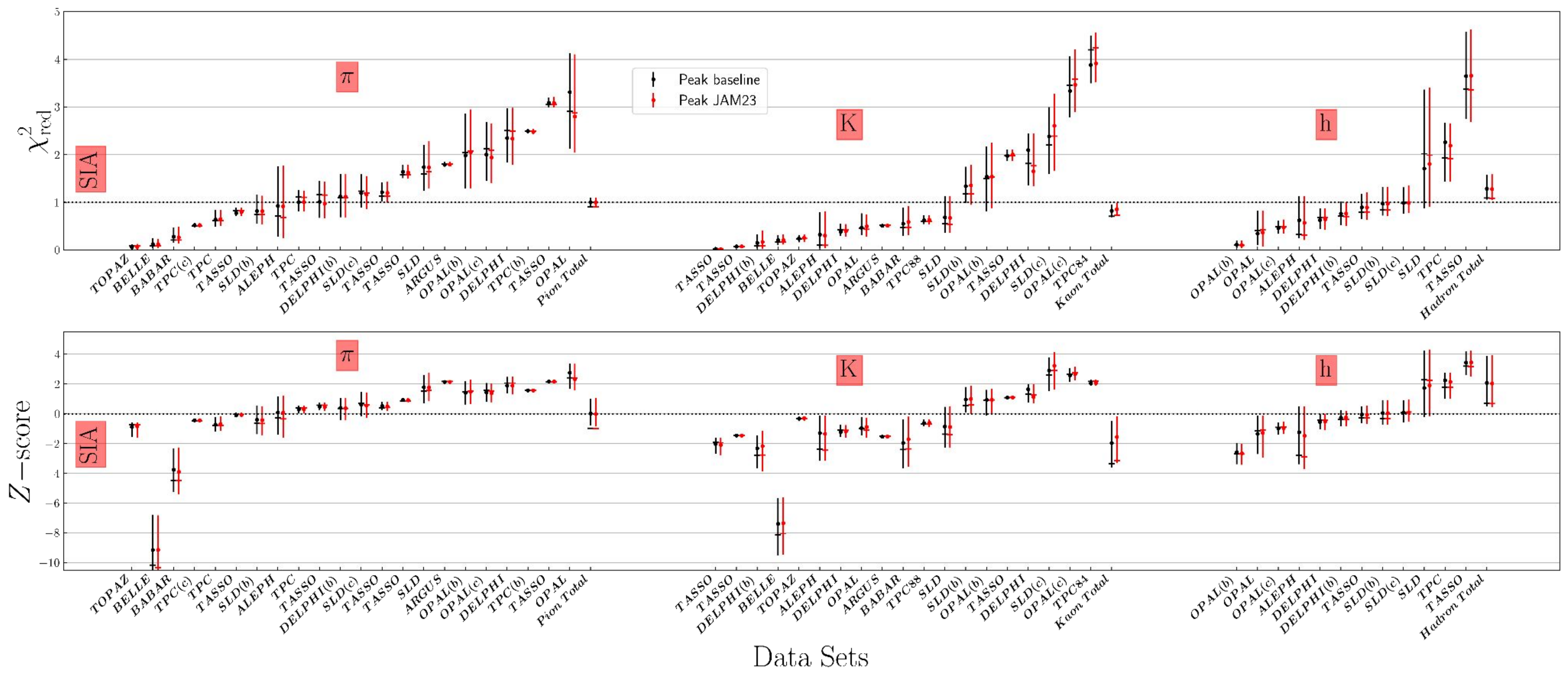
xu_ν
xd_ν
$x(s+\bar{s})$
$xg/10$
JAM23
baseline
d/u
$x(\bar{d}+\bar{u})$
$x(\bar{d}-\bar{u})$
R_s
$xf(x, Q^2 = 10)$
0.01
0.1
0.5
1
x


$\chi^2_{\rm red}$
$Z-$score
Data Sets
$W^2 > 10$ GeV^2
$W^2 > 3$ GeV^2
DIS
Fixed Target
HERA
DY
WZRV
WASYM
ZRAP
Jets
W + c
SIDIS
π
K
h
All Data Total
MARATHON d/p
SLAC d
SLAC p
NMC d/p
MARATHON h/t
BCDMS d
BCDMS p
NMC p
Fixed Target Total
HERA NC e+
HERA CC e−
HERA NC e+
HERA NC e+
HERA CC e+
HERA NC e+
HERA NC e−
HERA Total
E906 pd/2pp
E866 pp
E866 pd/2pp
DY Total
CMS 14
CMS 10
LHCb 17
CMS 13
LHCb 16
CMS 12
CMS 11
STAR
WZRV Total
D0
CDF
WASYM Total
D0
CDF
ZRAP Total
STAR 03
D0
STAR 04
CDF
Jets Total
ATLAS W+
CMS7 +
CMS13 +
ATLAS W−
CMS7 /
W + c Total
COMPASS π−
COMPASS π+
Pion Total
COMPASS K+
COMPASS K−
Kaon Total
COMPASS h−
COMPASS h+
Hadron Total



$W^2 > 10$ GeV^2
$W^2 > 3$ GeV^2
$\chi^2_{\rm red}$
SIA
π
K
h
TOPAZ
BELLE
BABAR
TPC(c)
TPC
SLD(b)
TASSO
ALEPH
TPC
TASSO
DELPHI(b)
SLD(c)
TASSO
TASSO
SLD
ARGUS
OPAL(b)
OPAL(c)
DELPHI
TPC(b)
TASSO
OPAL
Pion Total
TASSO
TASSO
DELPHI(b)
BELLE
TOPAZ
ALEPH
DELPHI
OPAL
ARGUS
BABAR
TPC88
SLD
SLD(b)
OPAL(b)
DELPHI
TASSO
SLD(c)
OPAL(c)
TPC84
Kaon Total
OPAL(b)
OPAL
OPAL(c)
ALEPH
DELPHI
DELPHI(b)
TASSO
SLD(b)
SLD(c)
TPC
SLD
TASSO
Hadron Total
Z−score
Data Sets

JAM23 Global Analysis



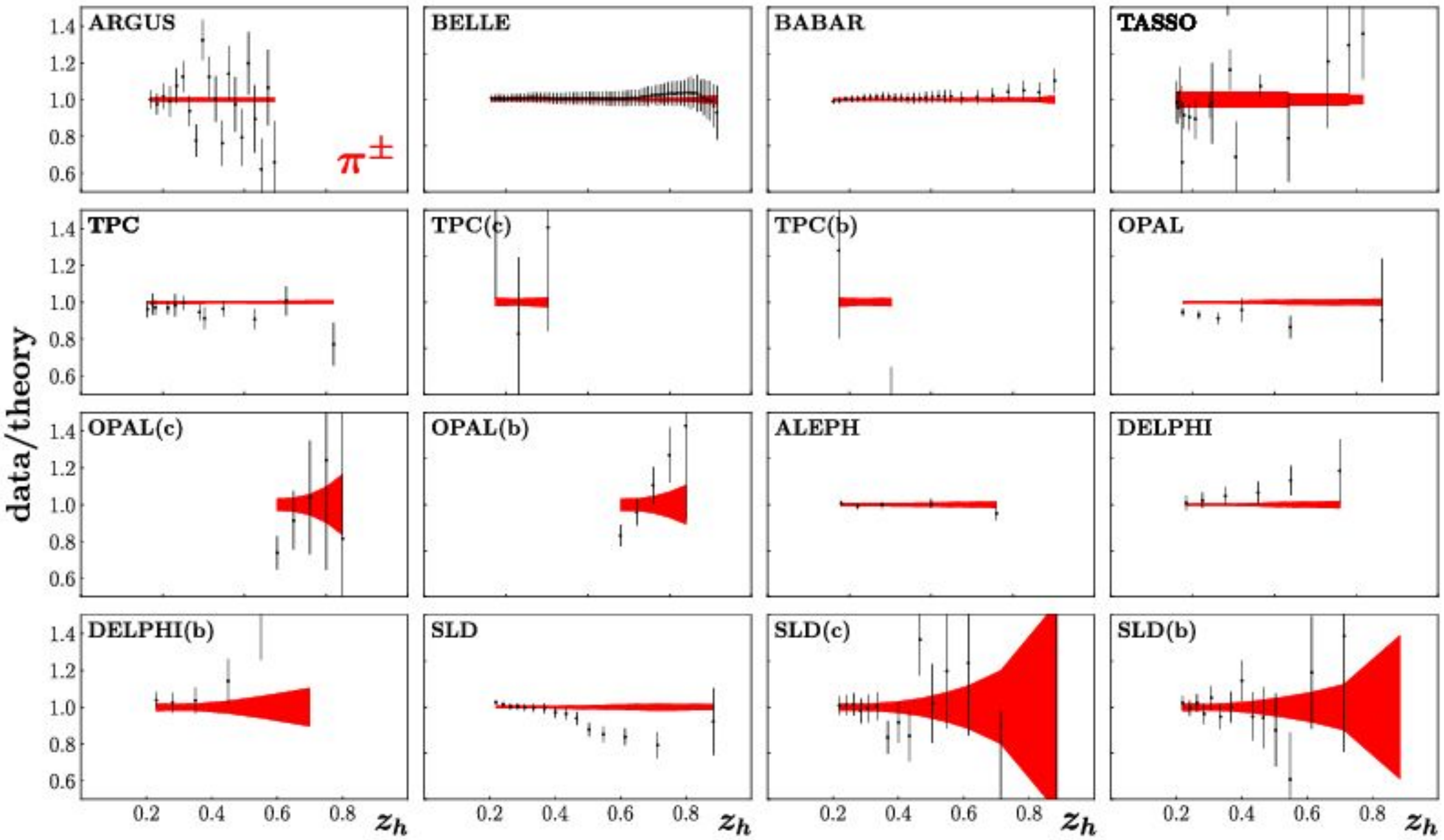


FIG. 7. Data to theory ratios for SIA $\pi^{\pm}$ production cross sections versus z_h, with the bands indicating the uncertainty on the fitted result.

N. Sato, et al., Phys. Rev. D 101, 074020 – Published 17 April 2020

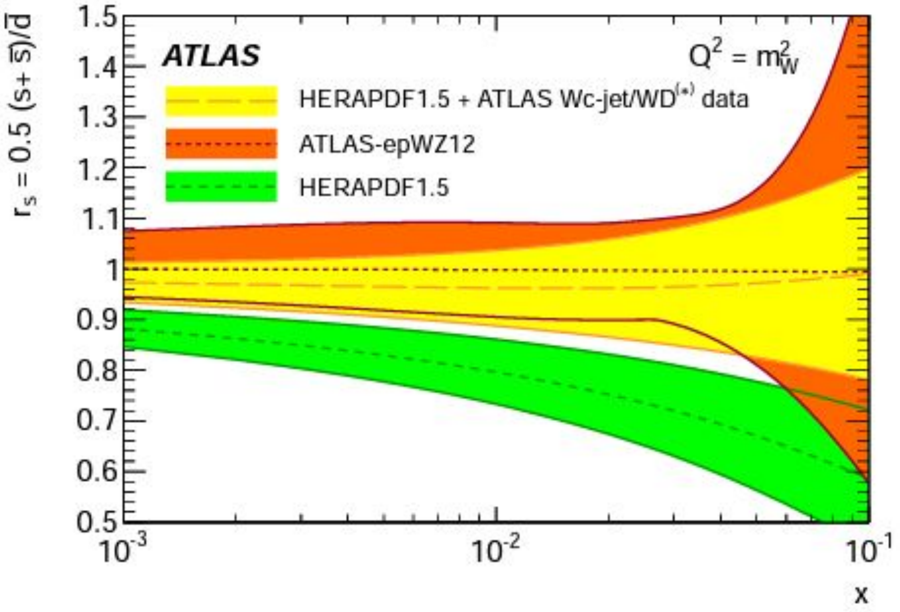


Figure 14. Ratio of strange-to-down sea-quark distributions $r_s = 0.5(s+\bar{s})/\bar{d}$ as a function of x as assumed in HERAPDF1.5 PDF compared to the ratio obtained from the fit including the ATLAS Wc-jet/$WD^{(*)}$ data and the ratio obtained from ATLAS-epWZ12. The error band on the ATLAS Wc-jet/$WD^{(*)}$ measurements represents the total uncertainty. The ratio r_s is shown at $Q^2 = m_W^2$.

The ATLAS collaboration., Aad, G., Abajyan, T. *et al. J. High Energ. Phys.* 2014, 68 (2014).