JAM19: A combined global analysis of collinear PDFs and FFs

Carlota Andrés

Jefferson Lab

QCD evolution

Argonne National Lab, USA

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In Collaboration with: N. Sato, J. Ethier and W. Melnitchouk

arXiv:1905.03788 [hep-ph]

JAM19

What is JAM19?

First simultaneous analysis of unpolarized PDFs and FFs

Why JAM19?

To study the strange quark distribution

Motivation II

- The strange PDF is less known than the non strange light flavors

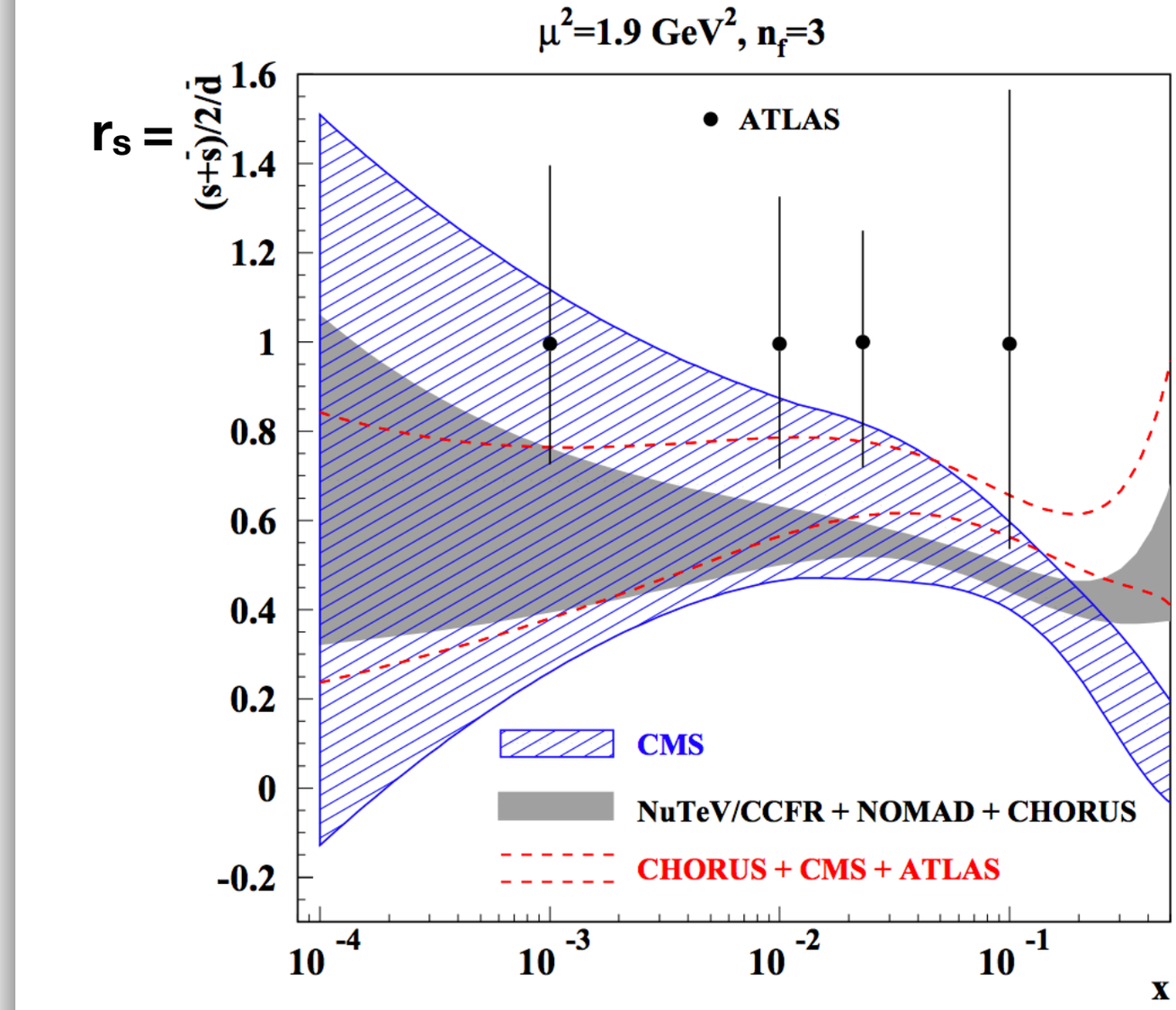
- Traditionally: neutrino-(heavy) nucleus DIS data used to extract the strange PDF.
    - Drawbacks: nuclear effects

- W and Z inclusive production in p-p collisions also sensitive to flavor separation
    - Drawbacks: tension between CMS and ATLAS results?

Motivation II

Motivation II

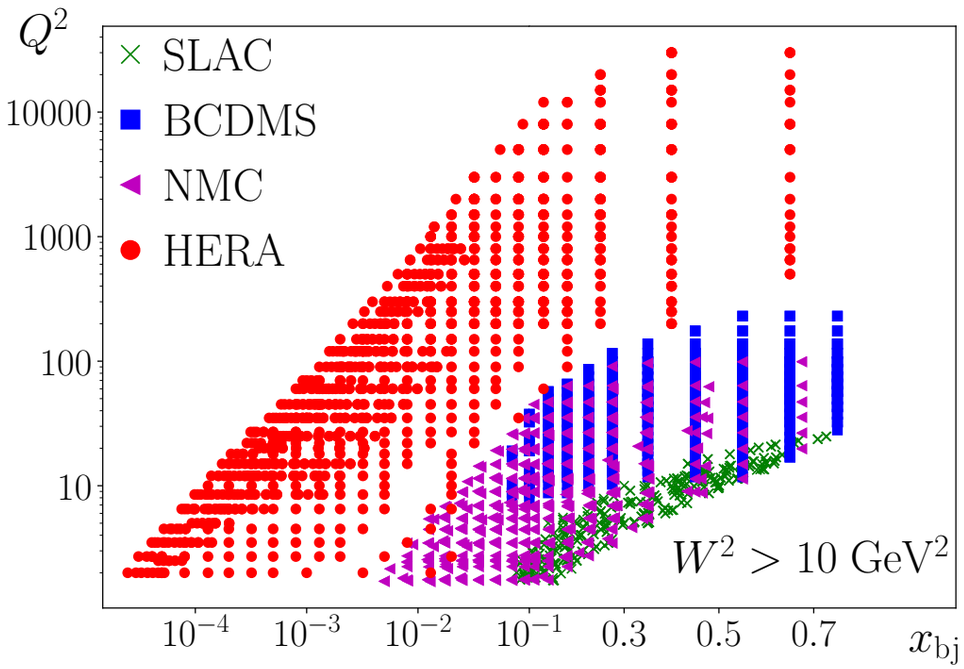
Alhekin et al. arXiv:1404.6469 [hep-ph]



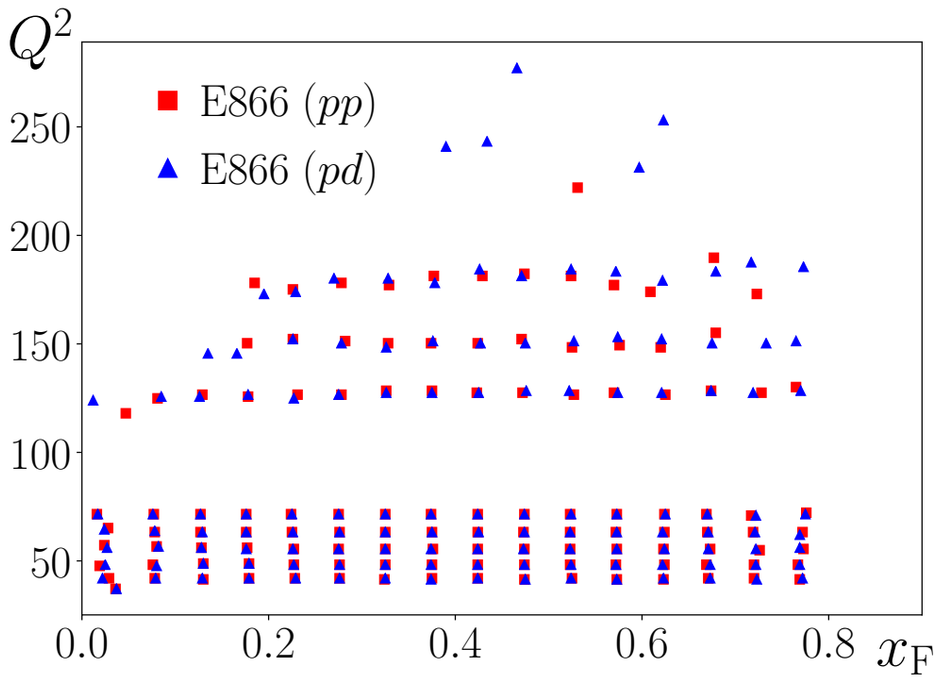
Why don't we use SIDIS?

Setup: JAM19 data

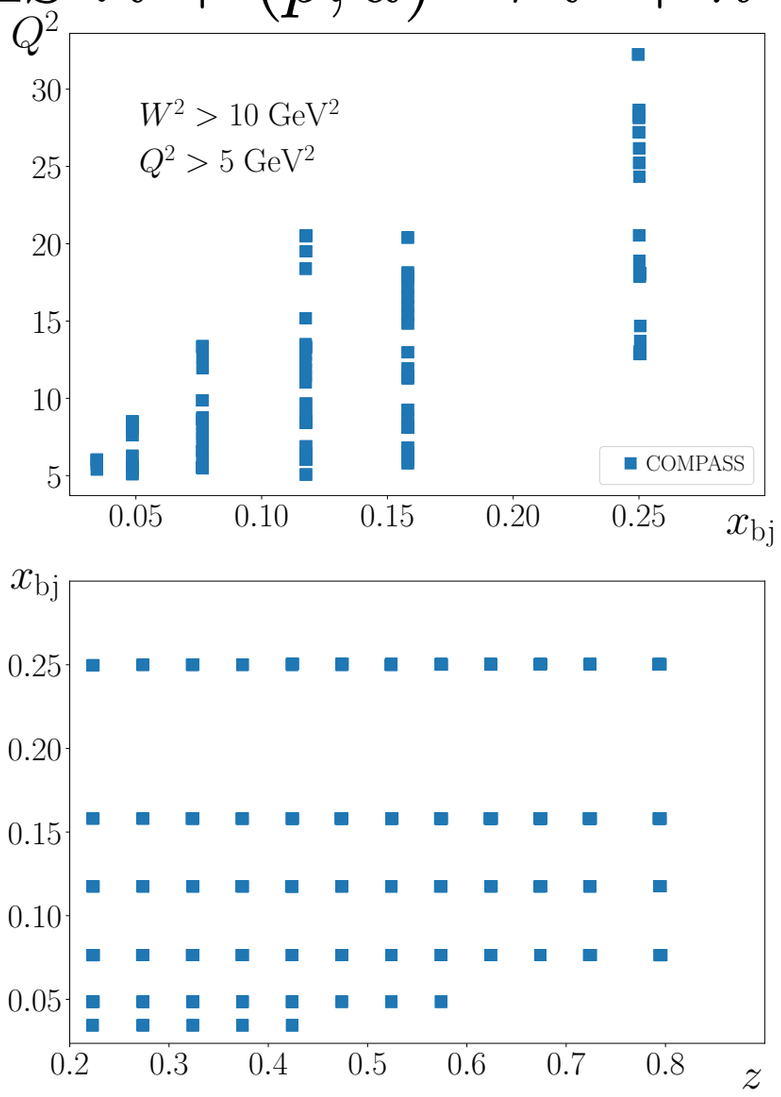
$$\text{DIS} : l + (p, d) \to l' + X$$



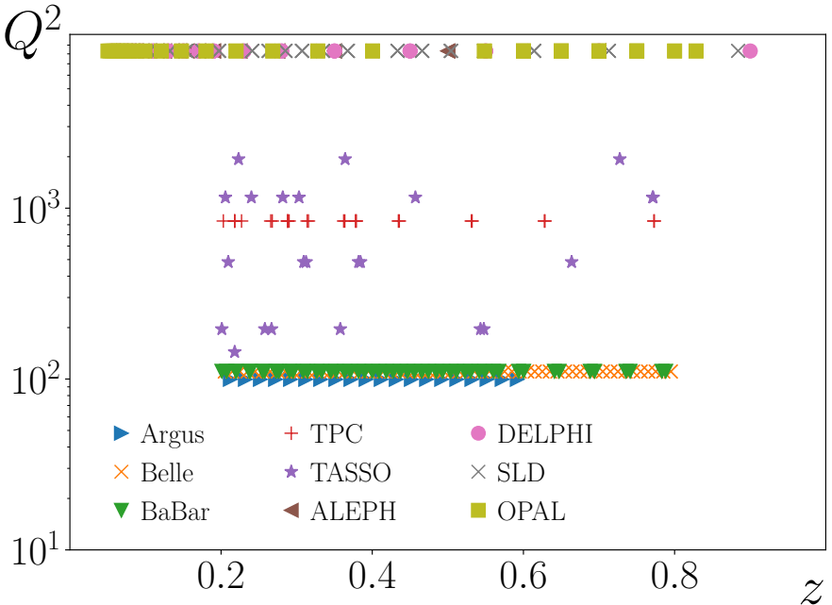
$$\text{DY} : p + (p, d) \to l\bar{l} + X$$



$$\text{SIDIS} : l + (p, d) \to l' + h + X$$



$$\text{SIA} : e^+ + e^- \to h + X$$



Setup: theory

- All observables computed at NLO in pQCD
- DGLAP truncated evolution at order α_s in Mellin space
- DIS cross sections computed at leading twist
- Nuclear smearing for deuterium DIS
- Heavy quark treatment : ZM-VFN
- Fitting methodology:
    - MC (multi-steps), k-means clustering, extended reduced χ^2

Why MC?

$$\chi^2 = \sum_e^{N_{exp}} \sum_i^{N_{data}} \frac{(D_i^e - T_i)^2}{(\sigma_i^e)^2}$$

- Typical PDF parametrization:

$$x\Delta f(x) = Nx^a(1-x)^b(1+c\sqrt{x}+dx)$$

- Perform single χ^2-fit: → Multiple local minima!

Parameters difficult to constrain

Hessian method for uncertainties → Introduces tolerance criteria

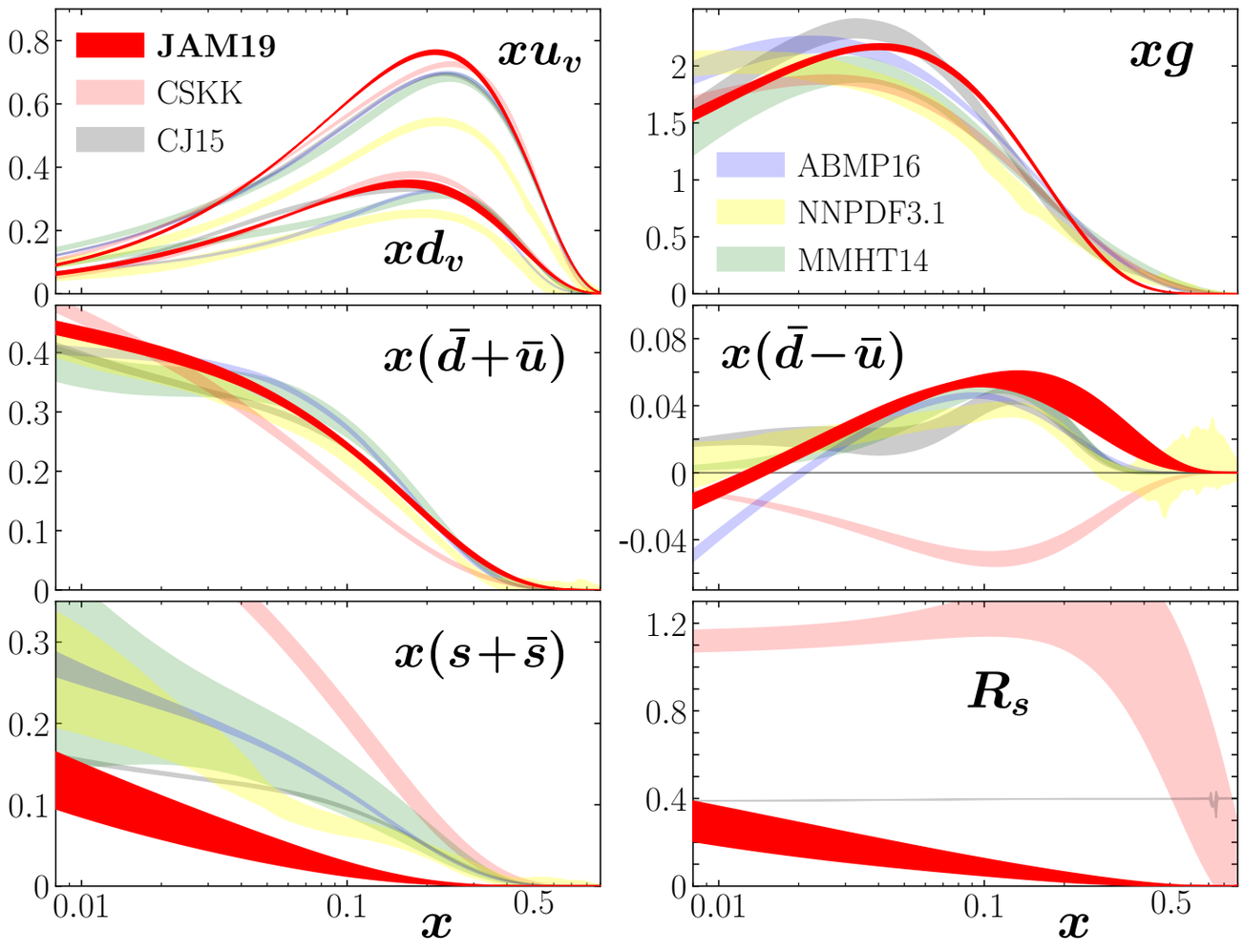
Unsuitable for simultaneous analysis of collinear distributions

- Monte Carlo methods:
  - Allows efficient exploration of the parameter space
  - Uncertainties directly obtained from MC replicas

PDF results

JAM19 PDFs

arXiv:1905.03788 [hep-ph]



$Q^2 \approx m_c^2$

DIS(p, d)
DY(pp, dd)
SIA$(\pi^{\pm}, K^{\pm})$
SIDIS$(\pi^{\pm}, K^{\pm})$

JAM19 PDFs

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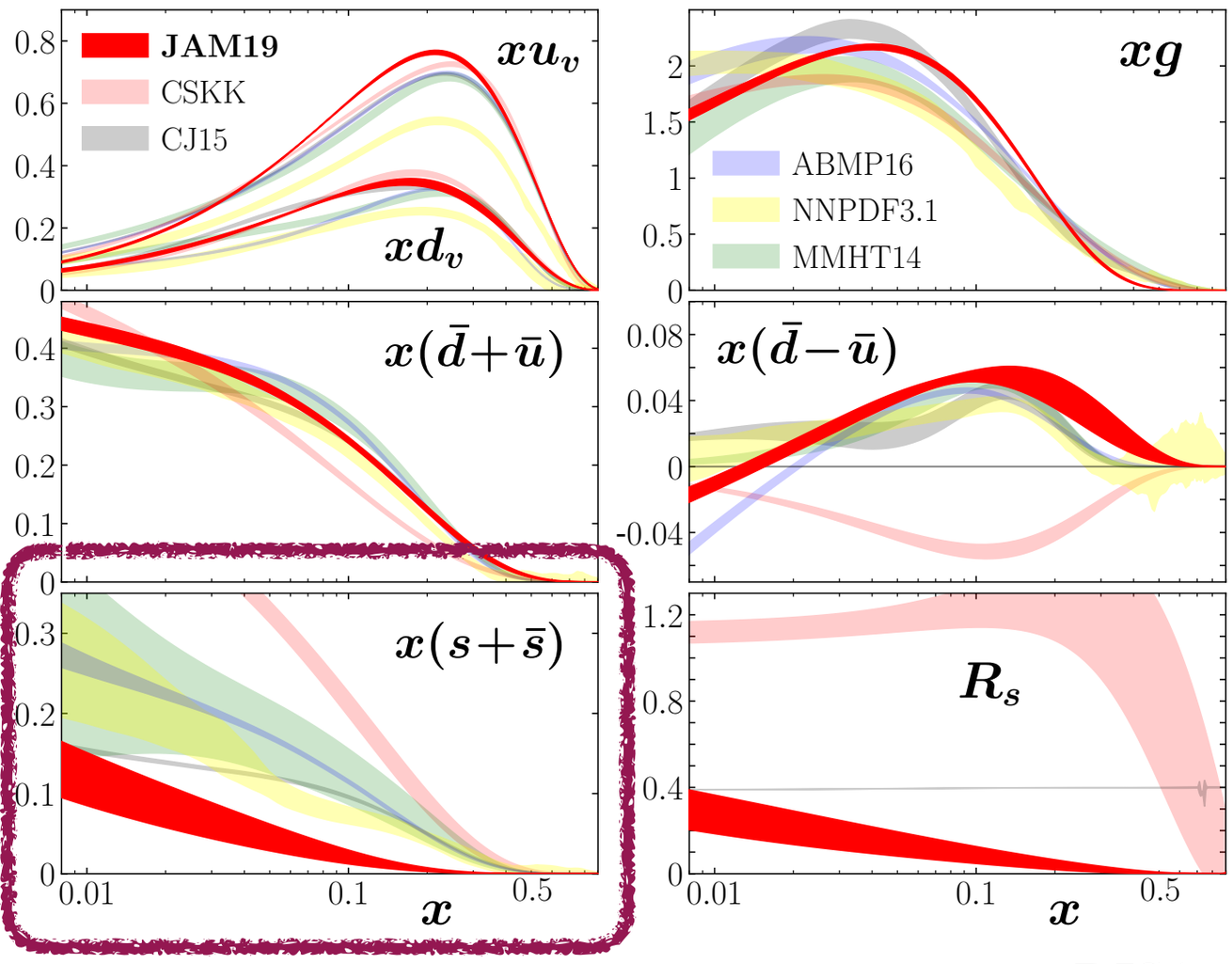

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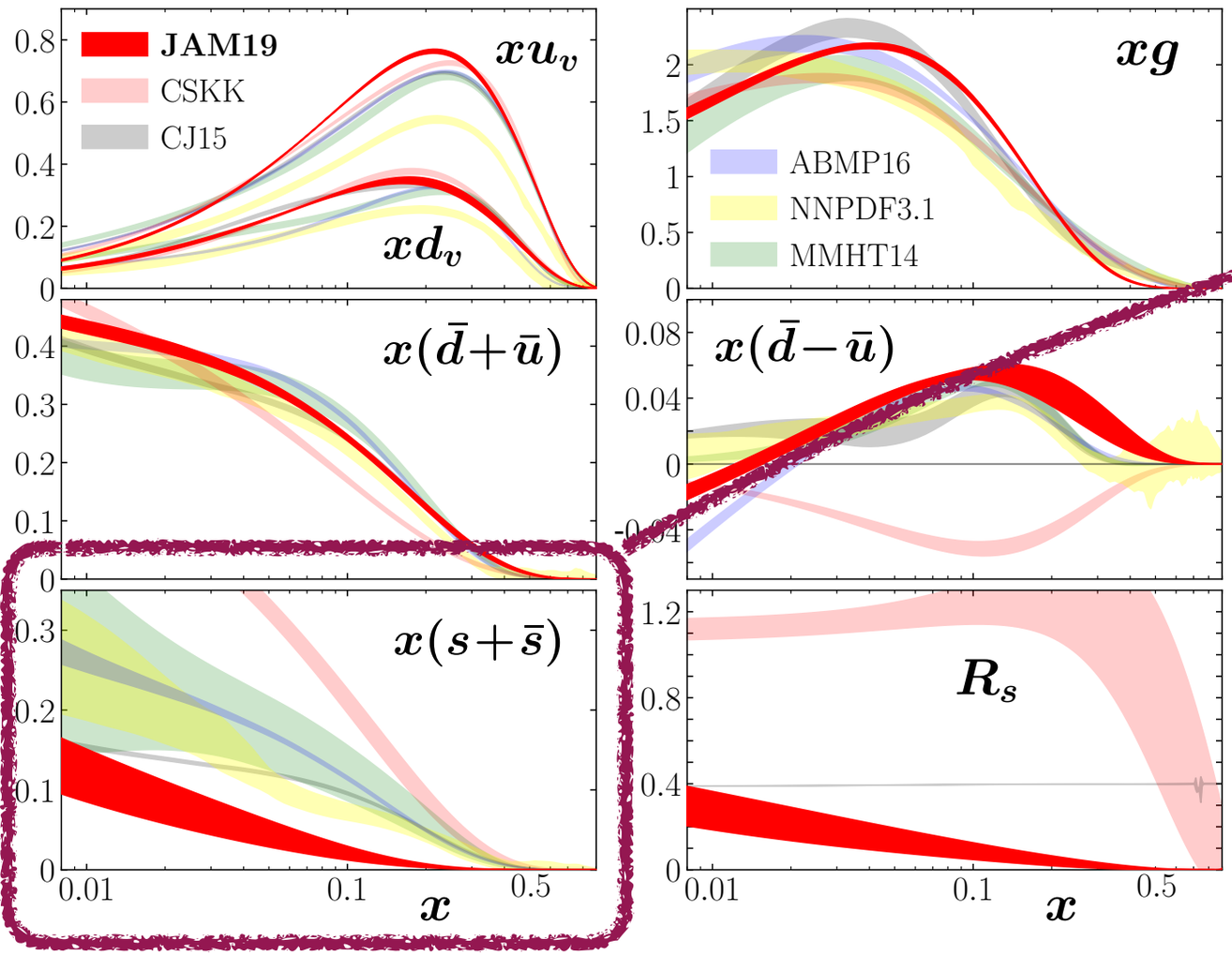

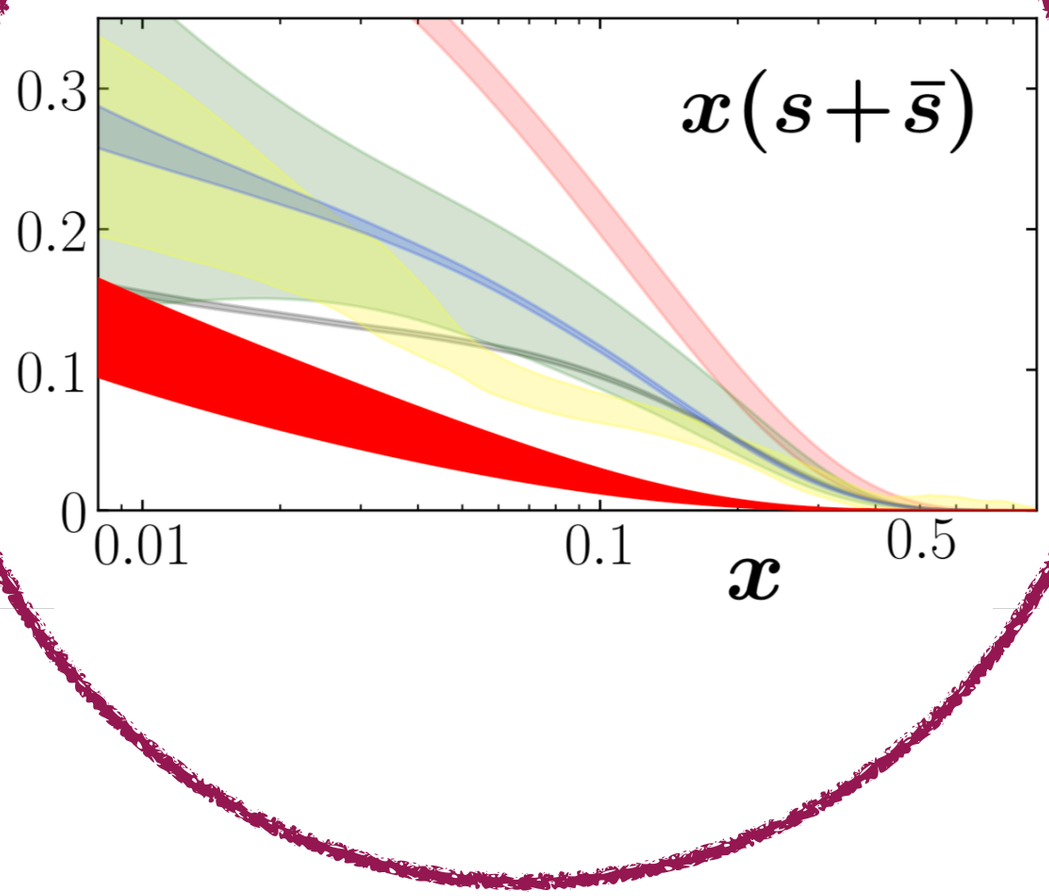

Strong strange suppression

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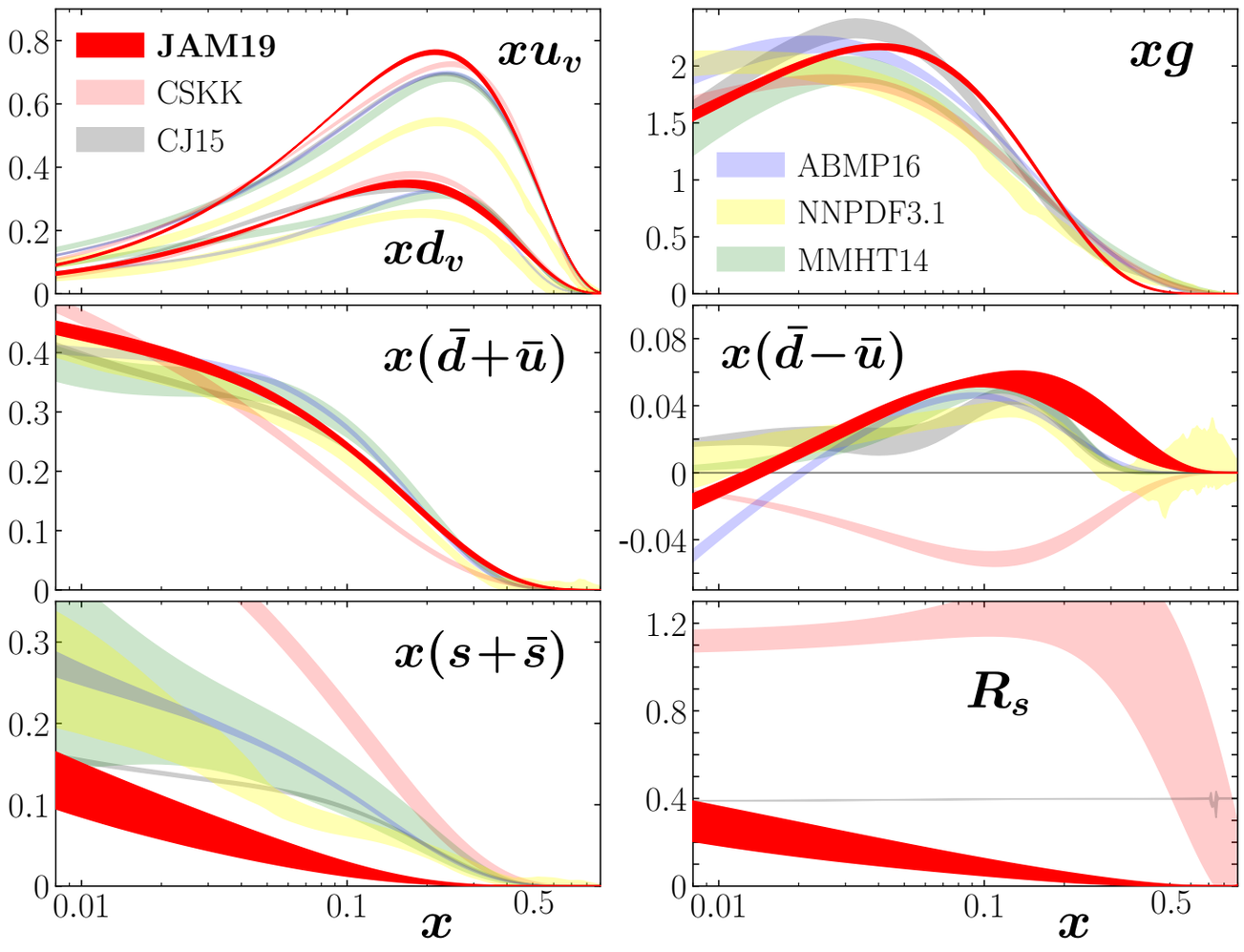

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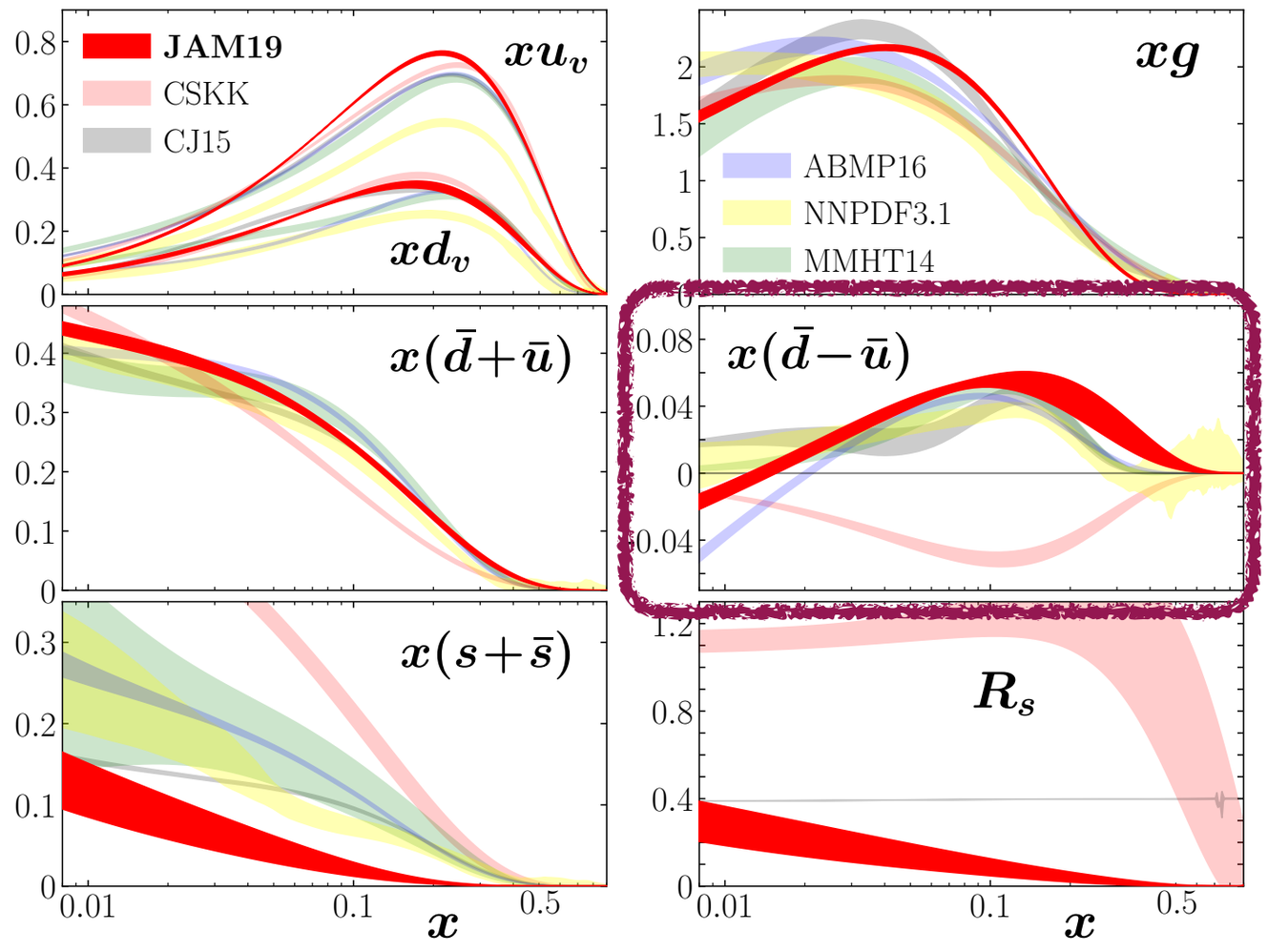

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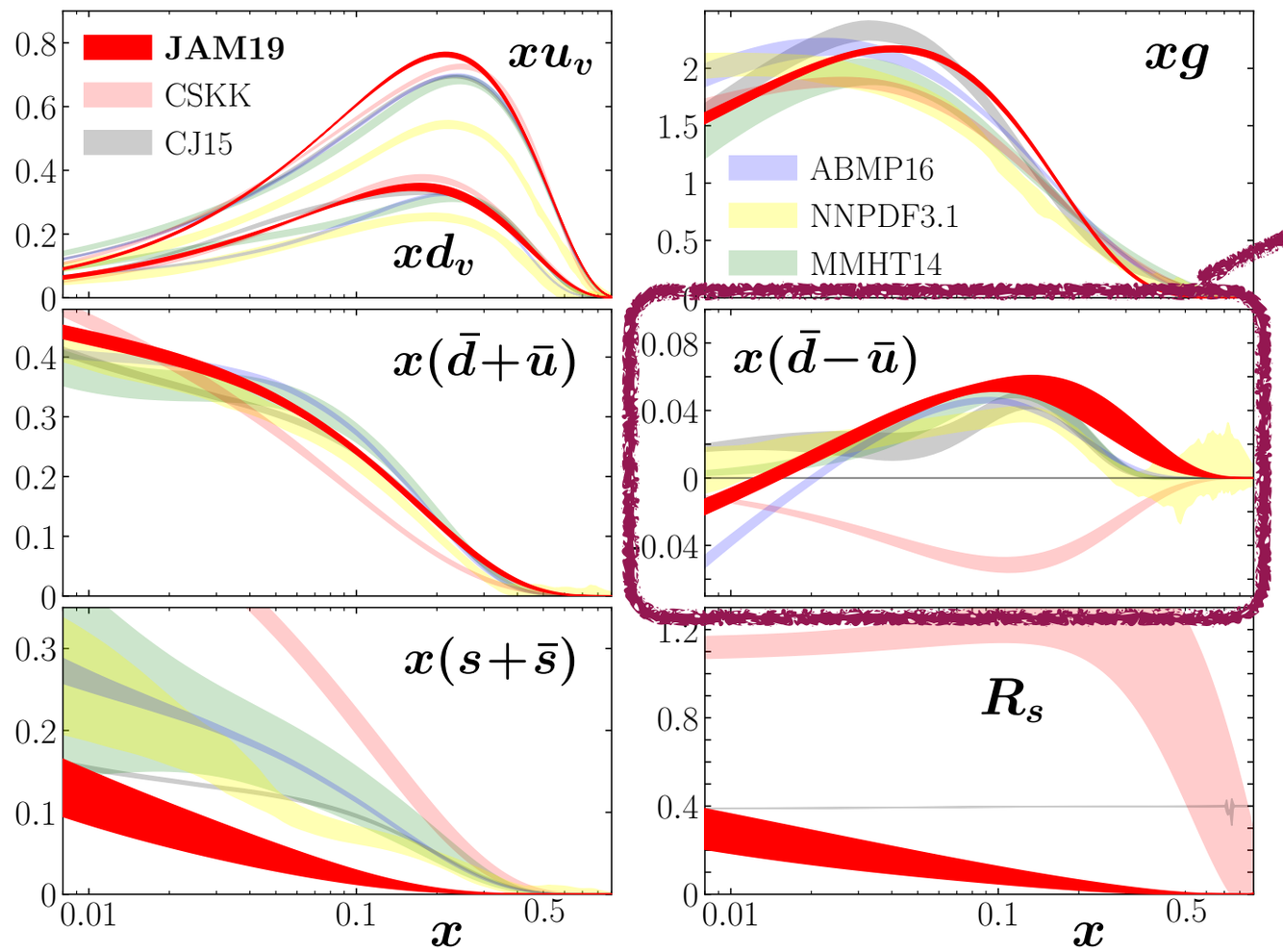

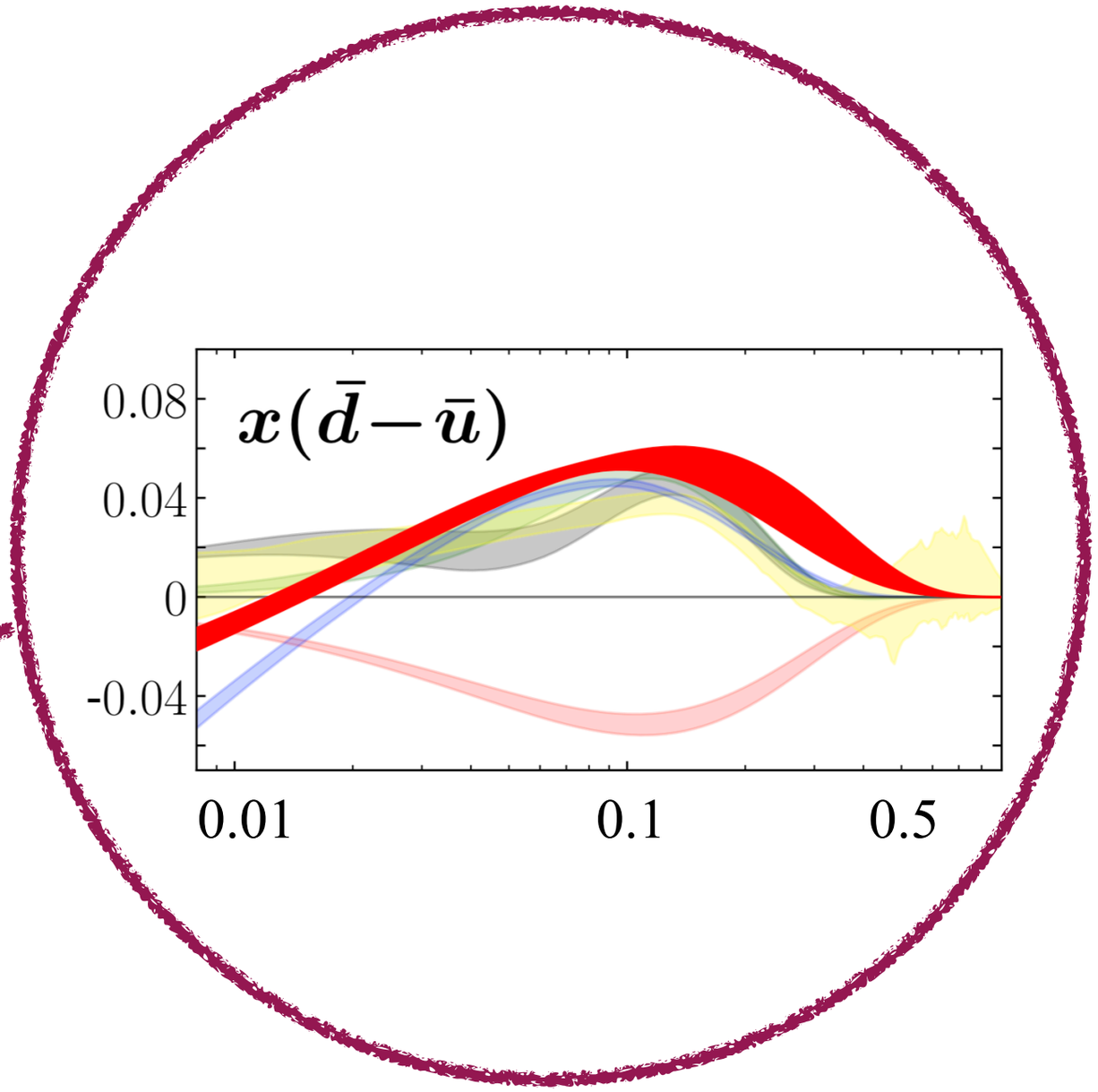

$\bar{d} - \bar{u} > 0$ at x ~ 0.1 – 0.2

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FF results

JAM19: FF

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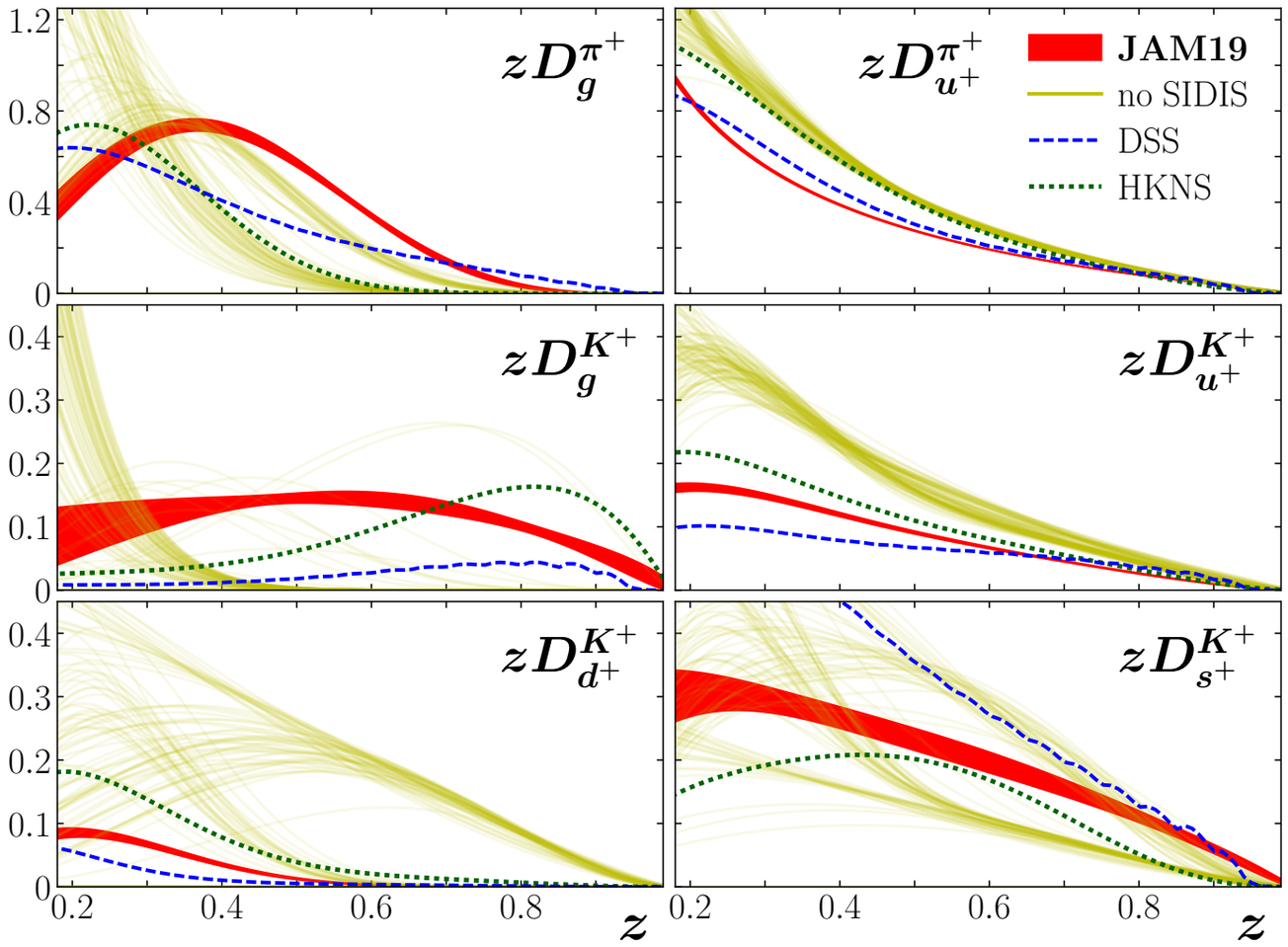

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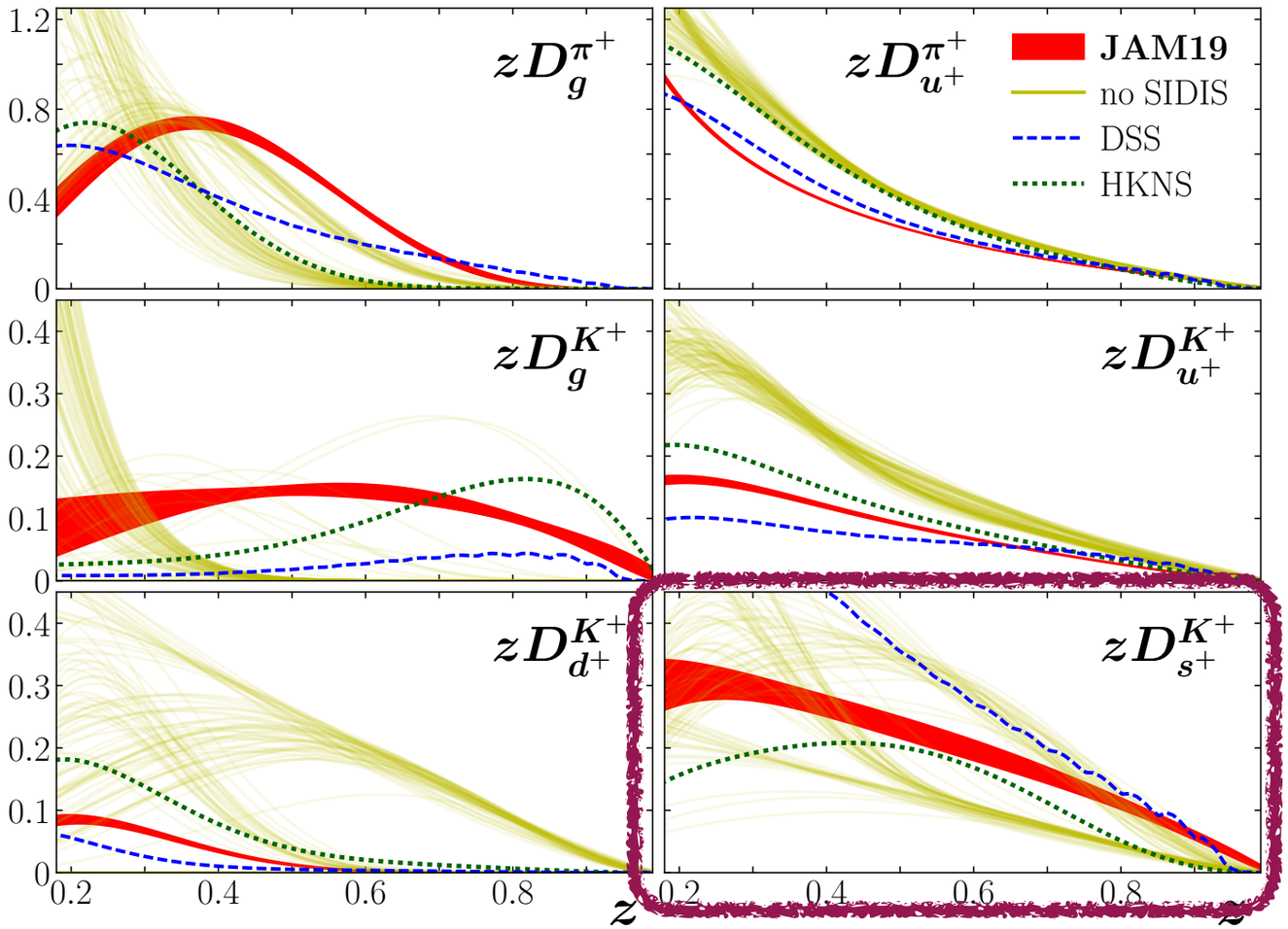

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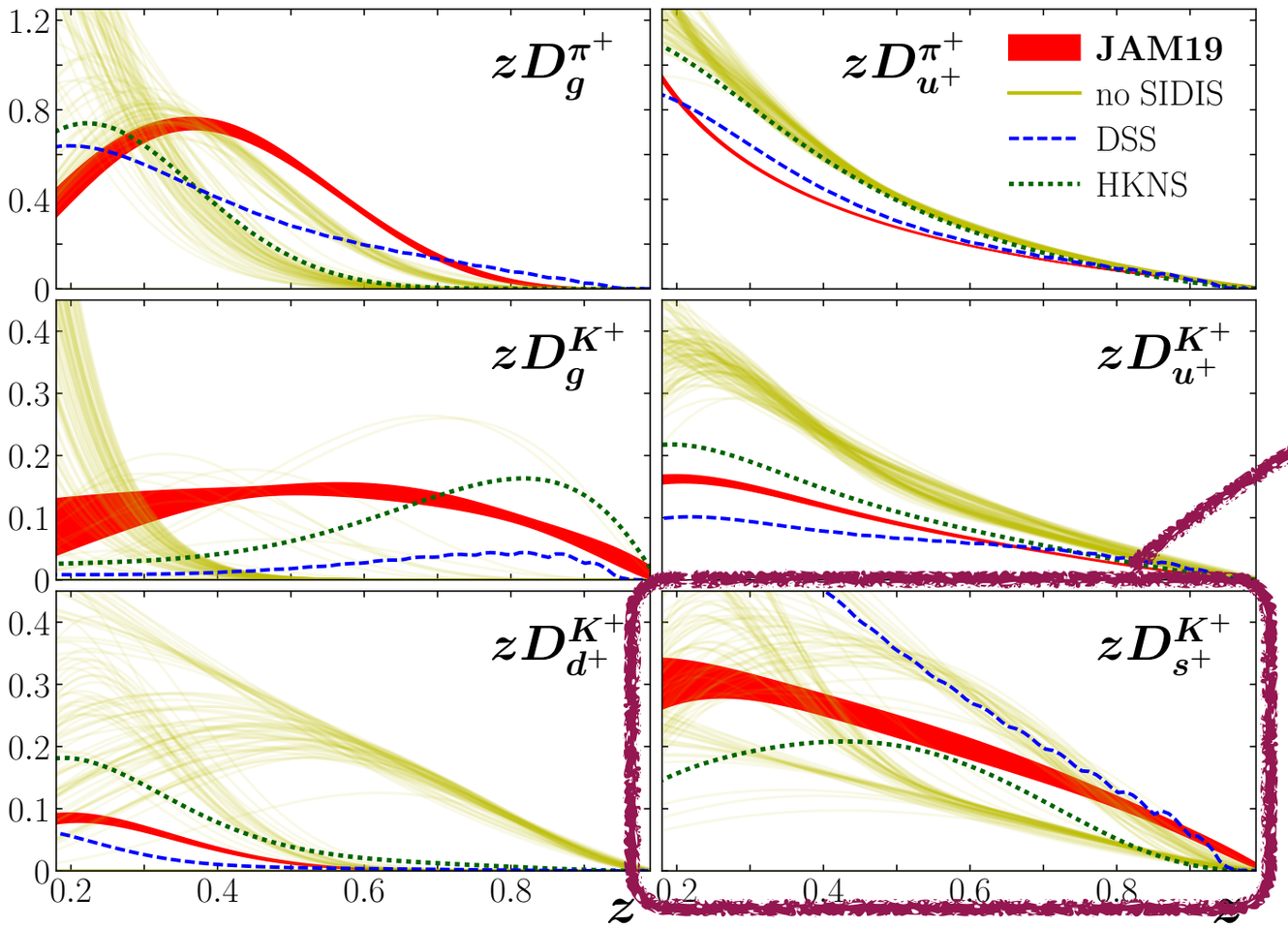
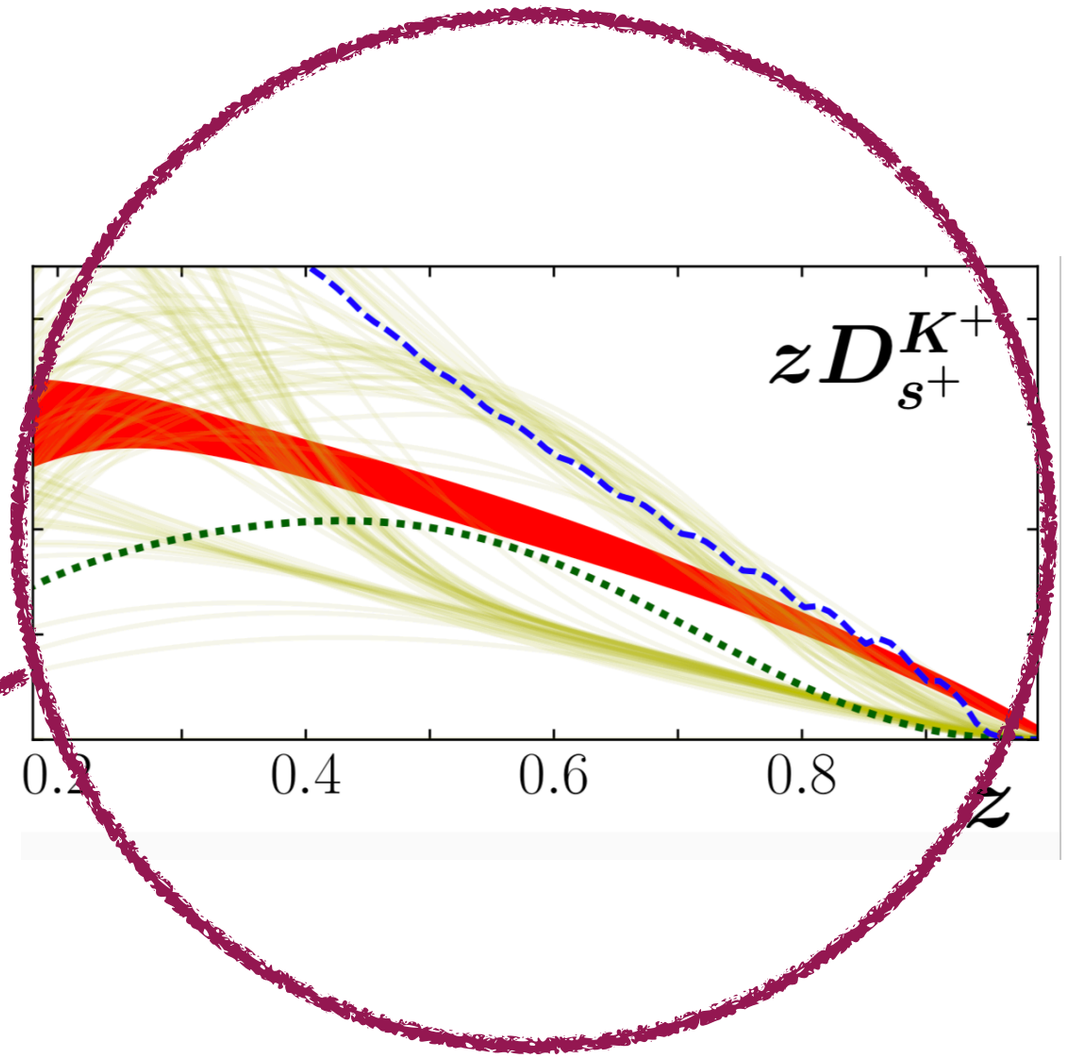


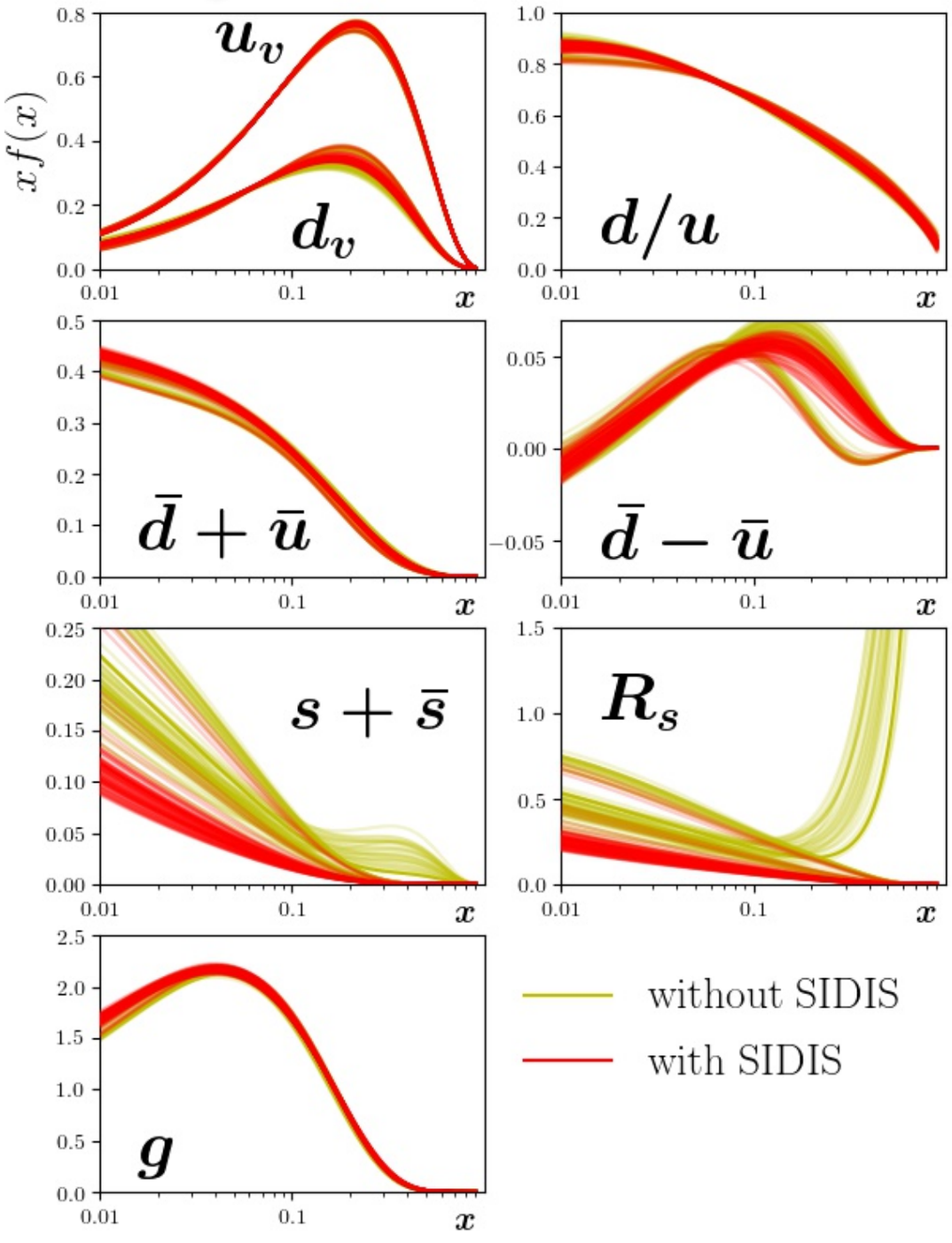


Large $\tilde{s} \to K^+$

$Q^2 \approx m_c^2$

Impact of SIDIS data

Impact of SIDIS data on PDFs



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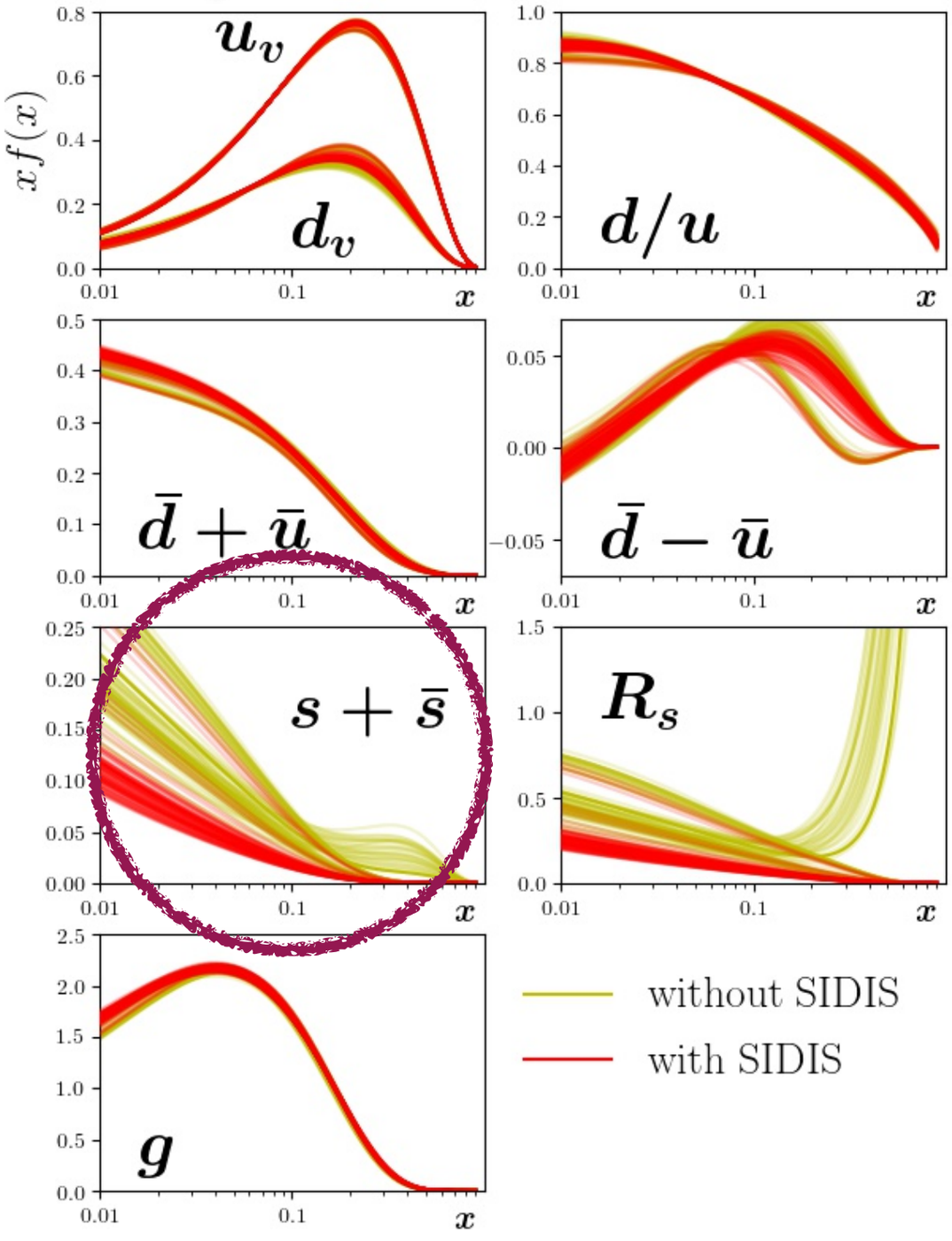

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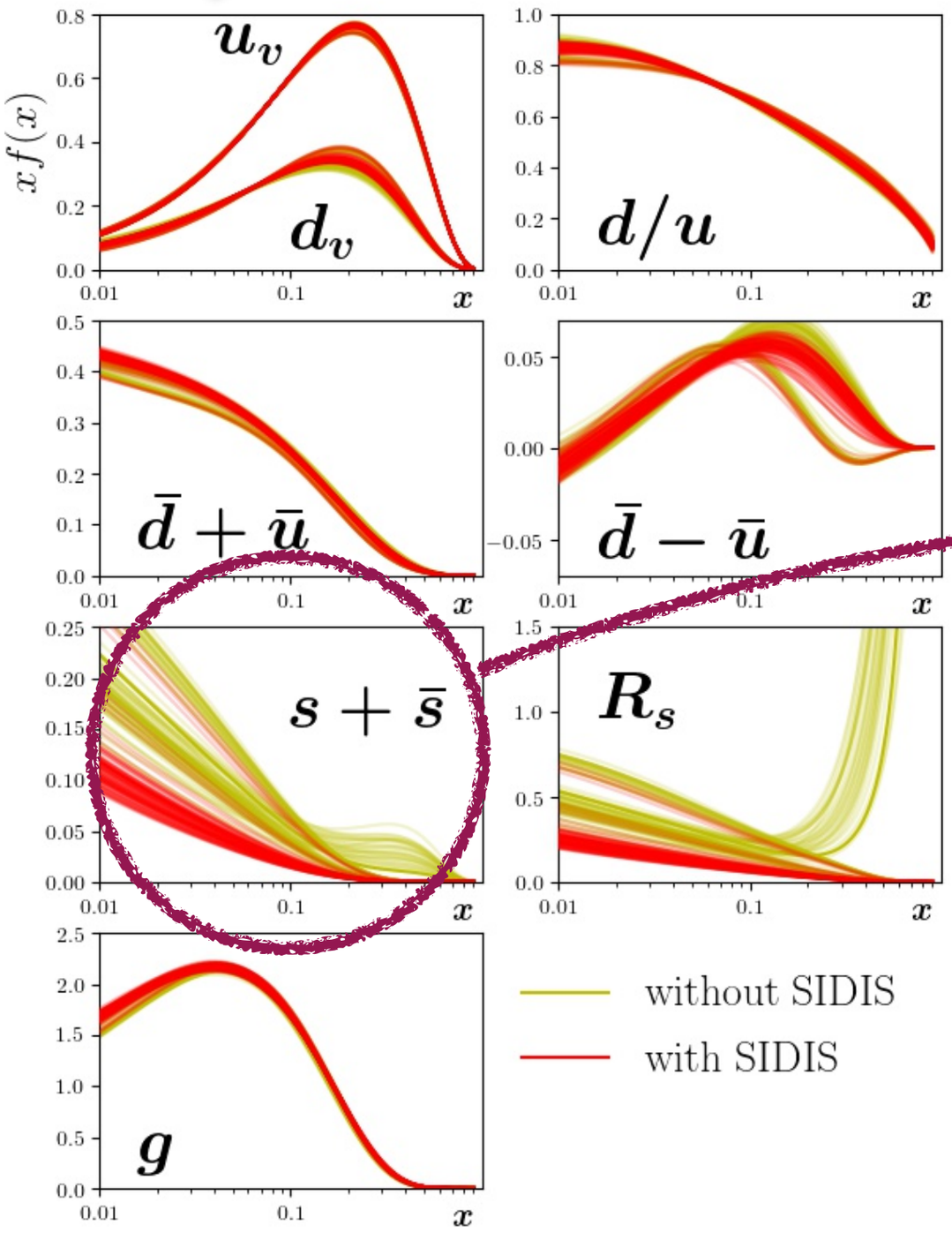

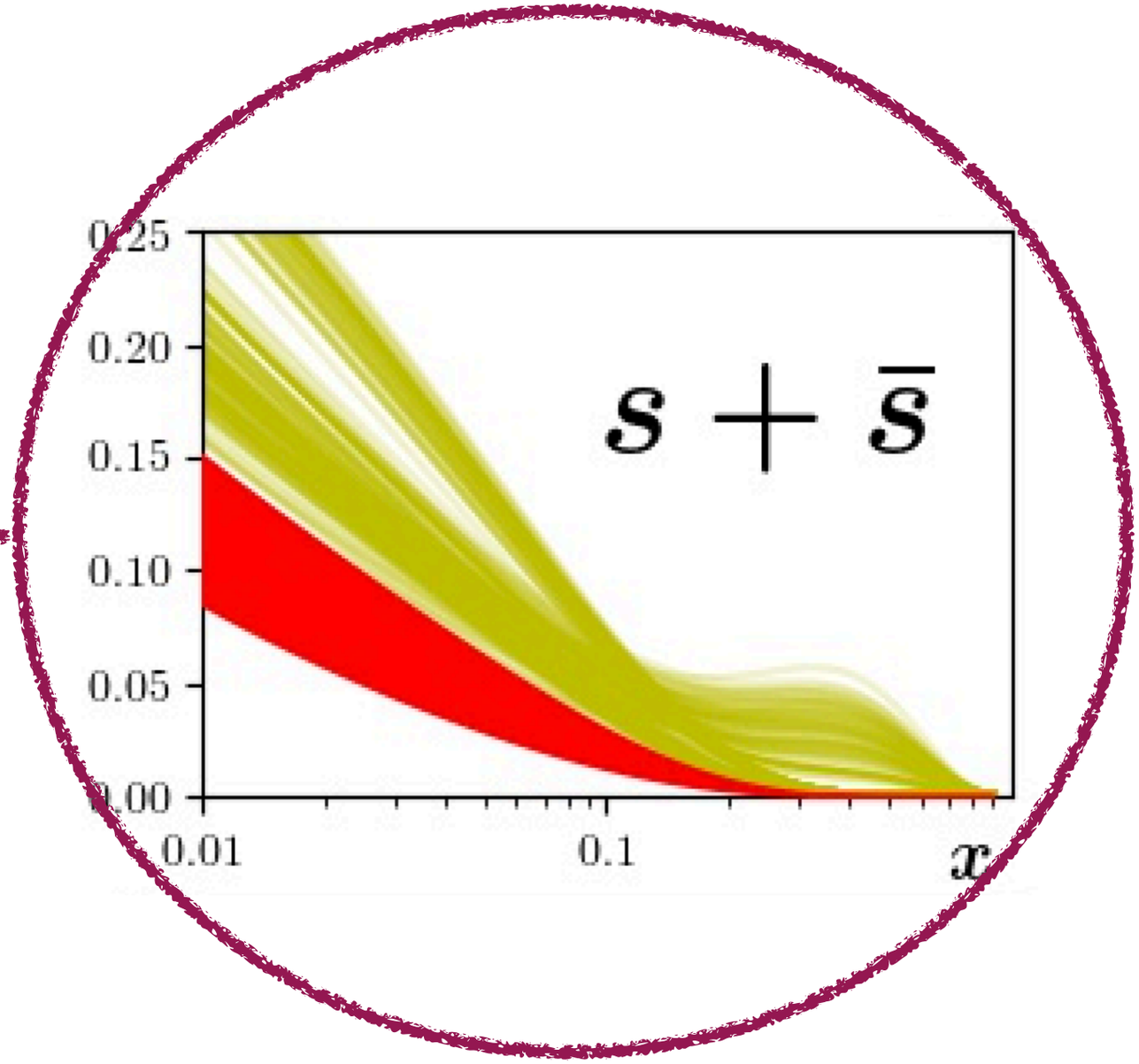

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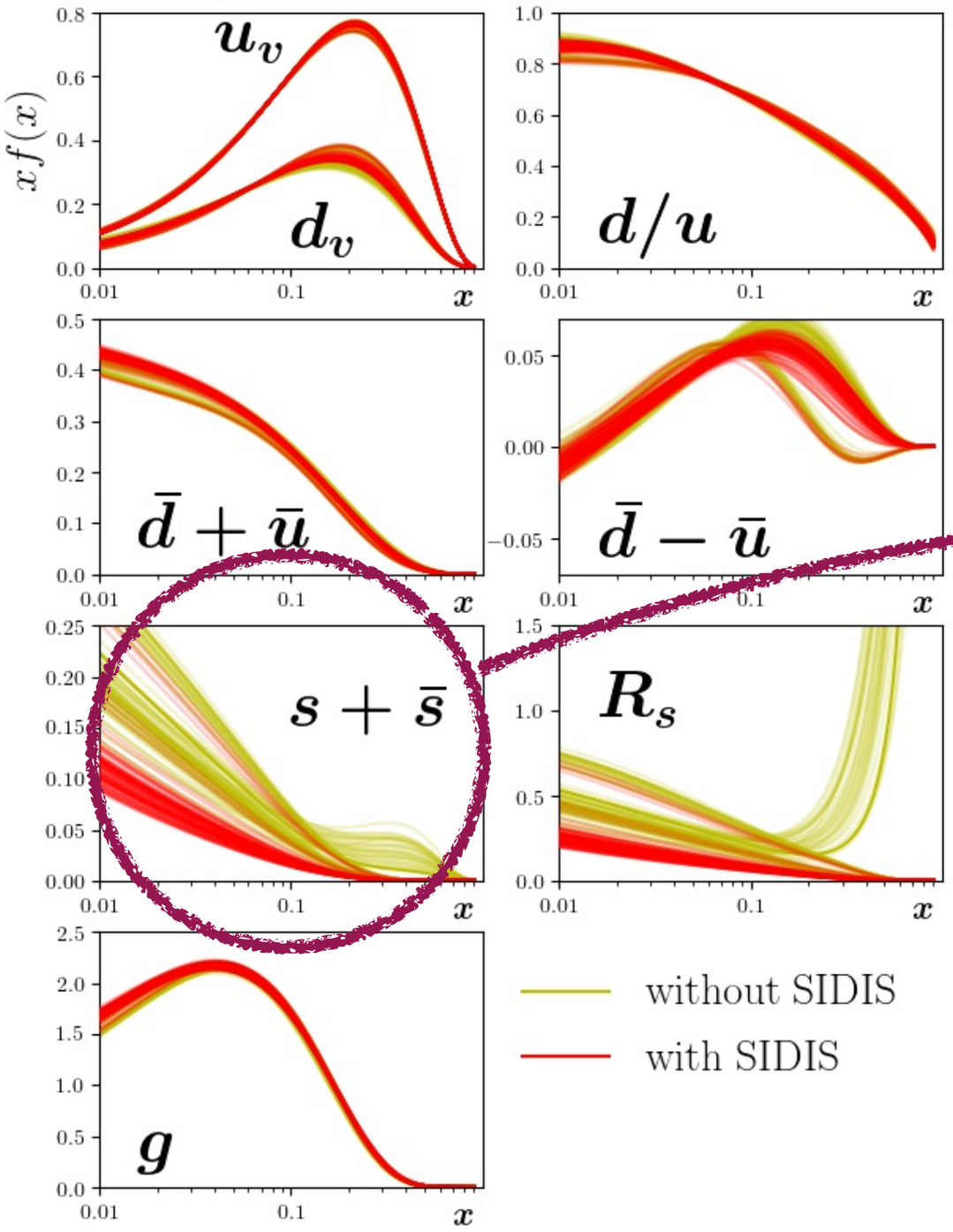

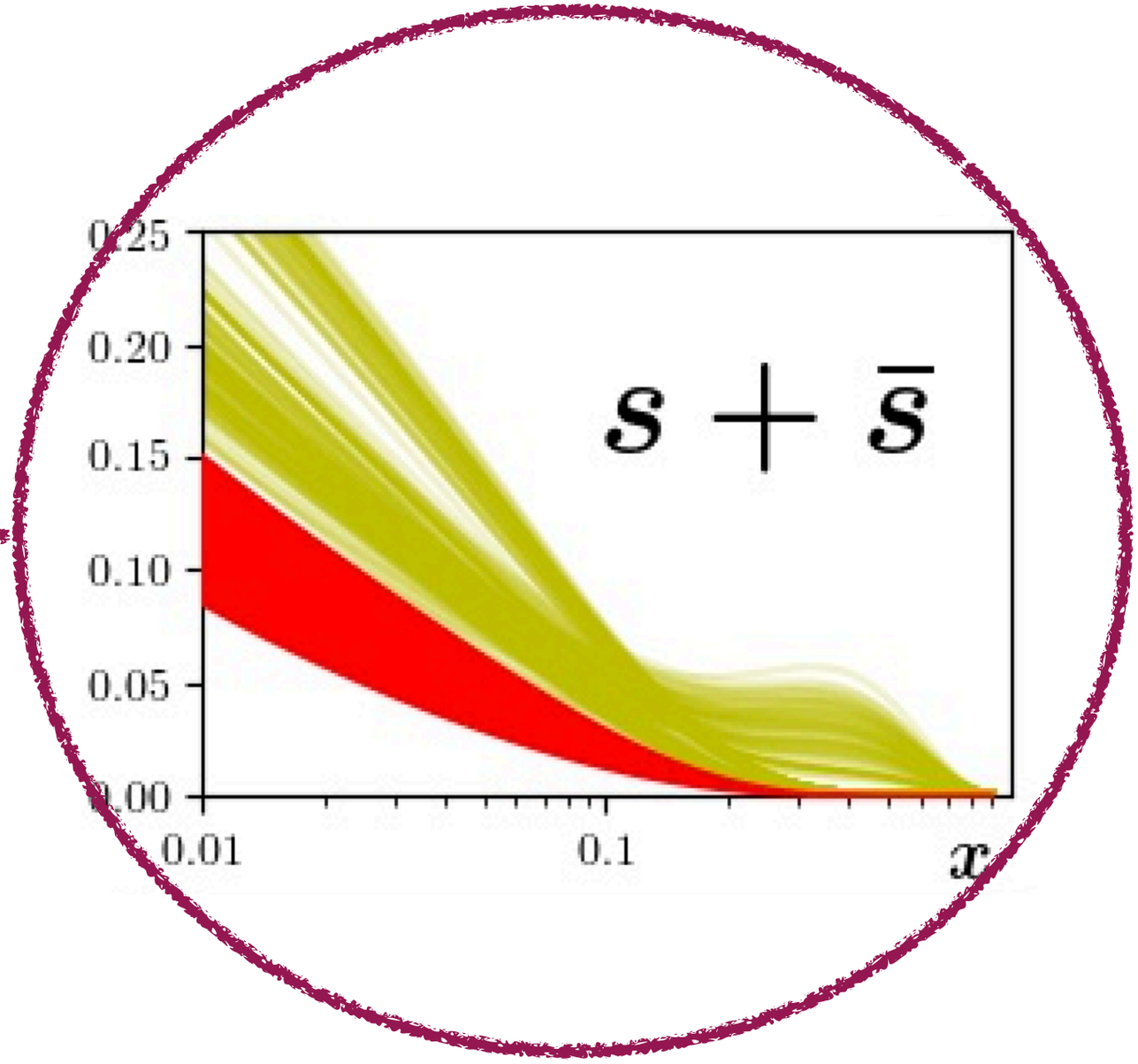

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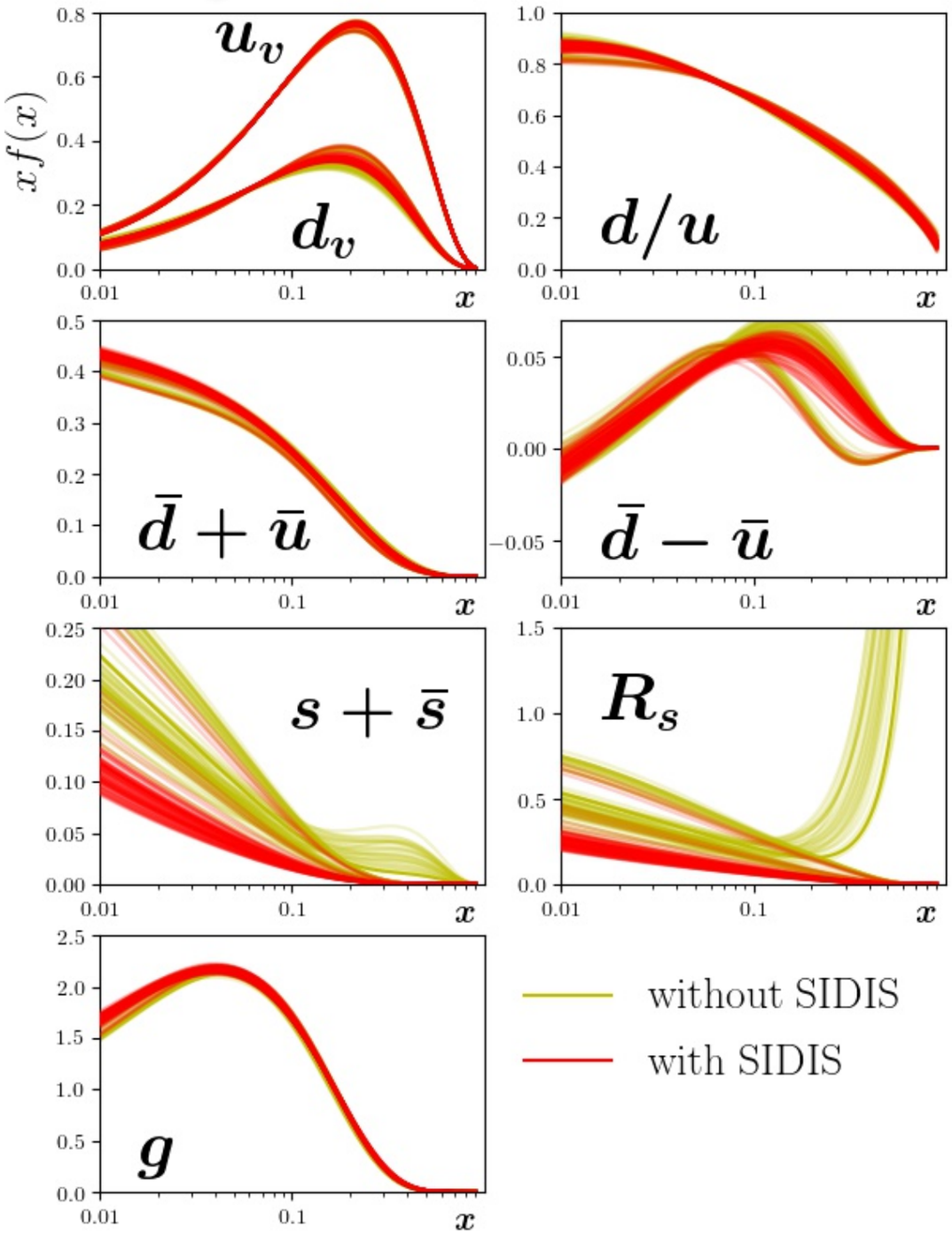

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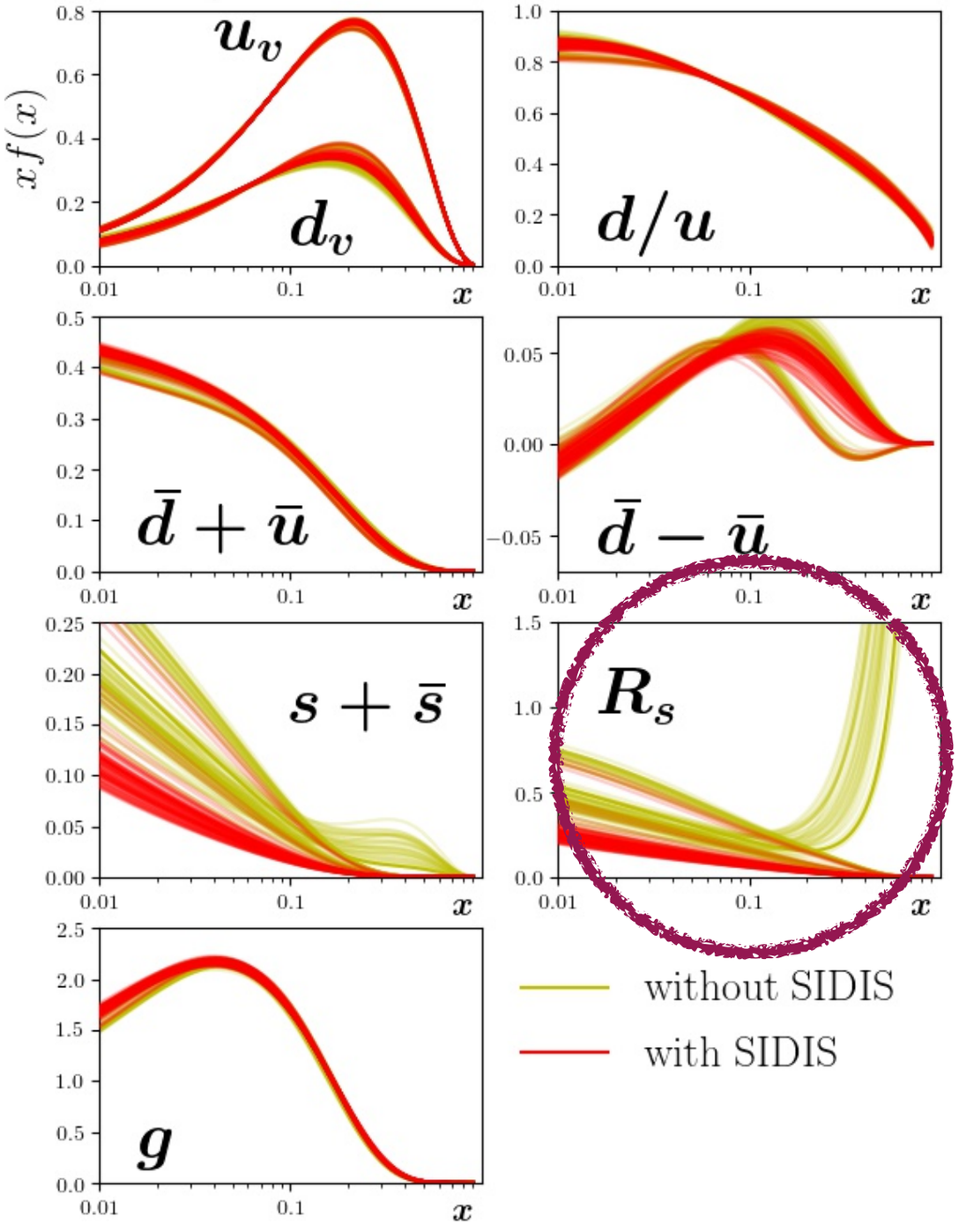

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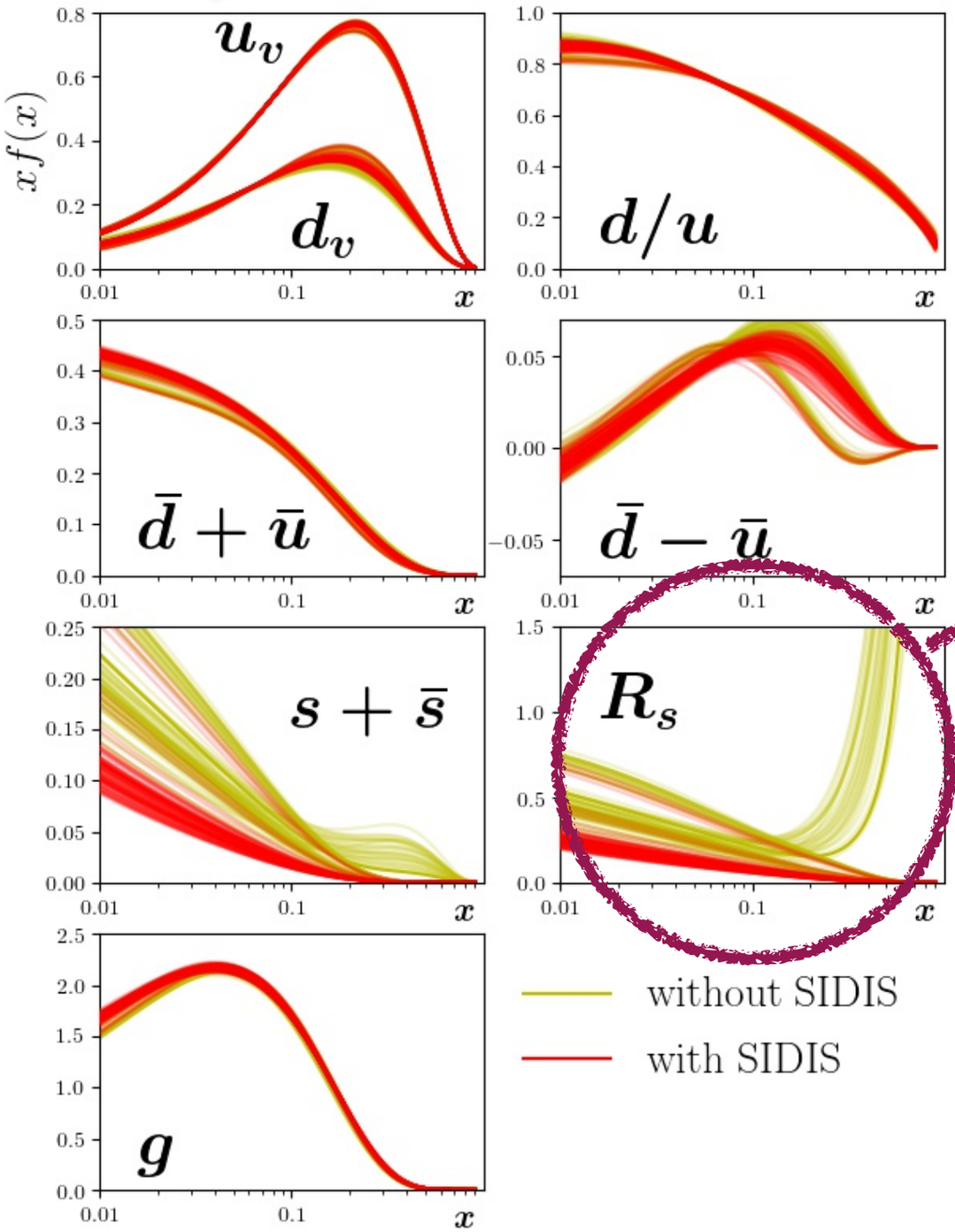

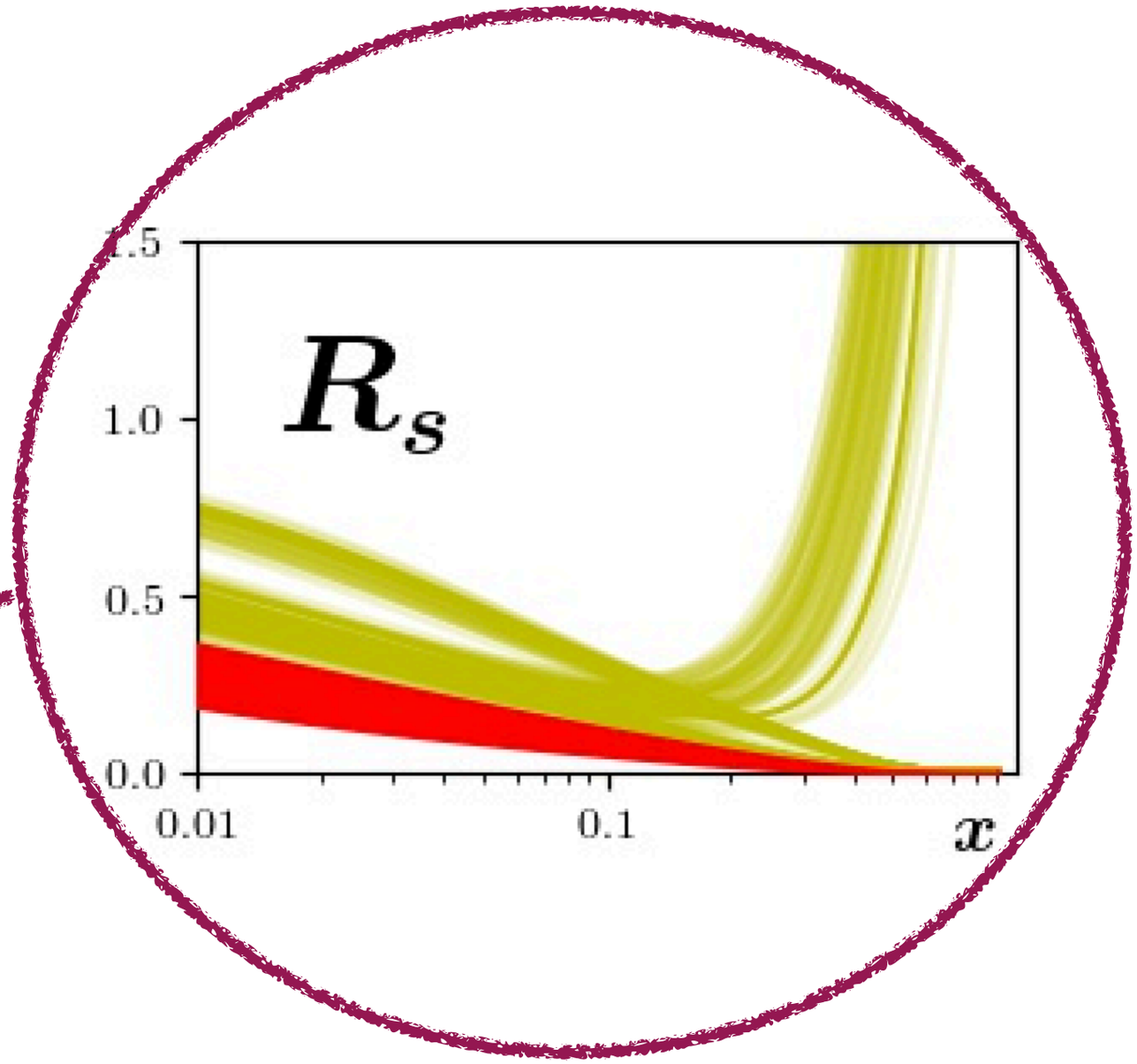

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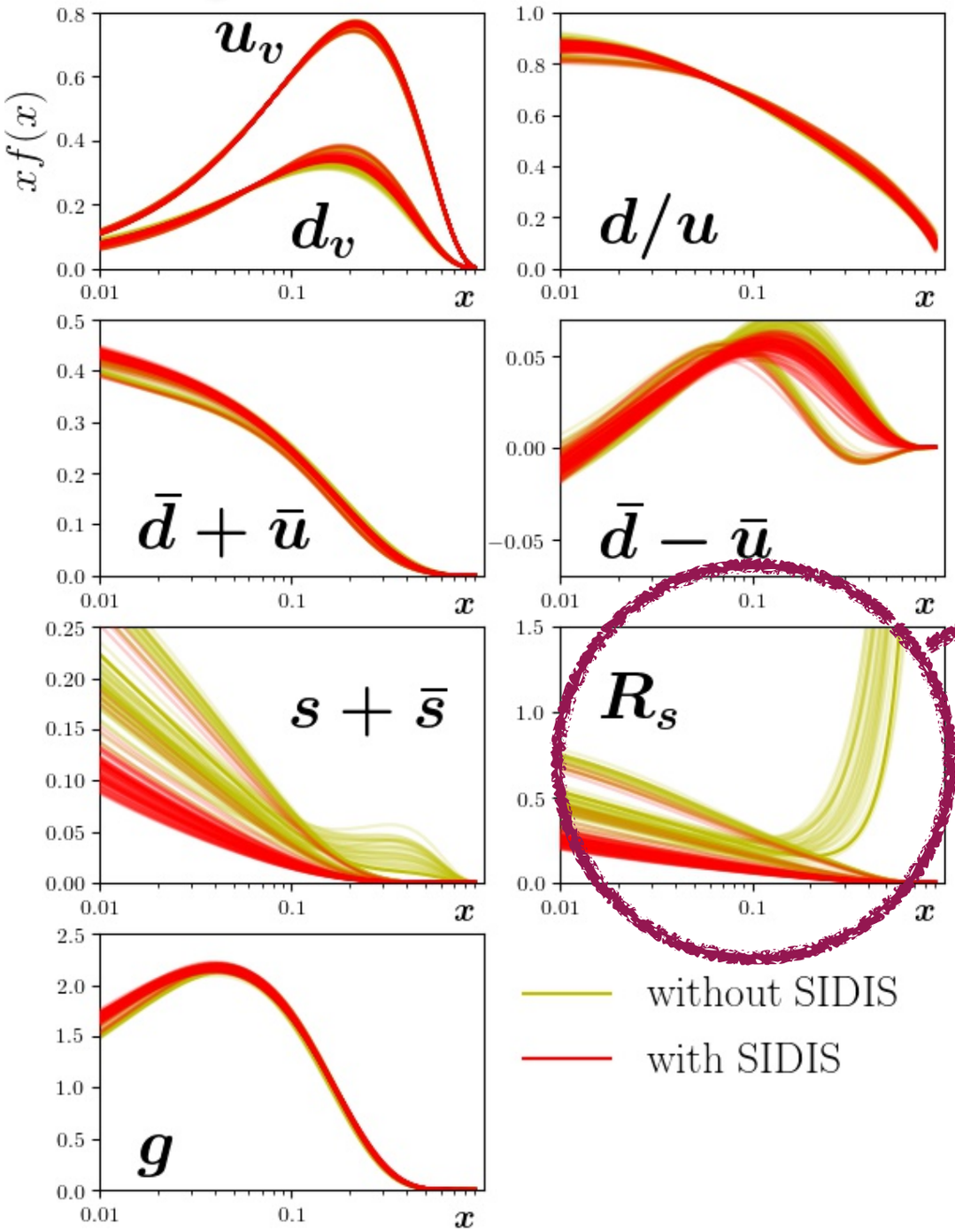

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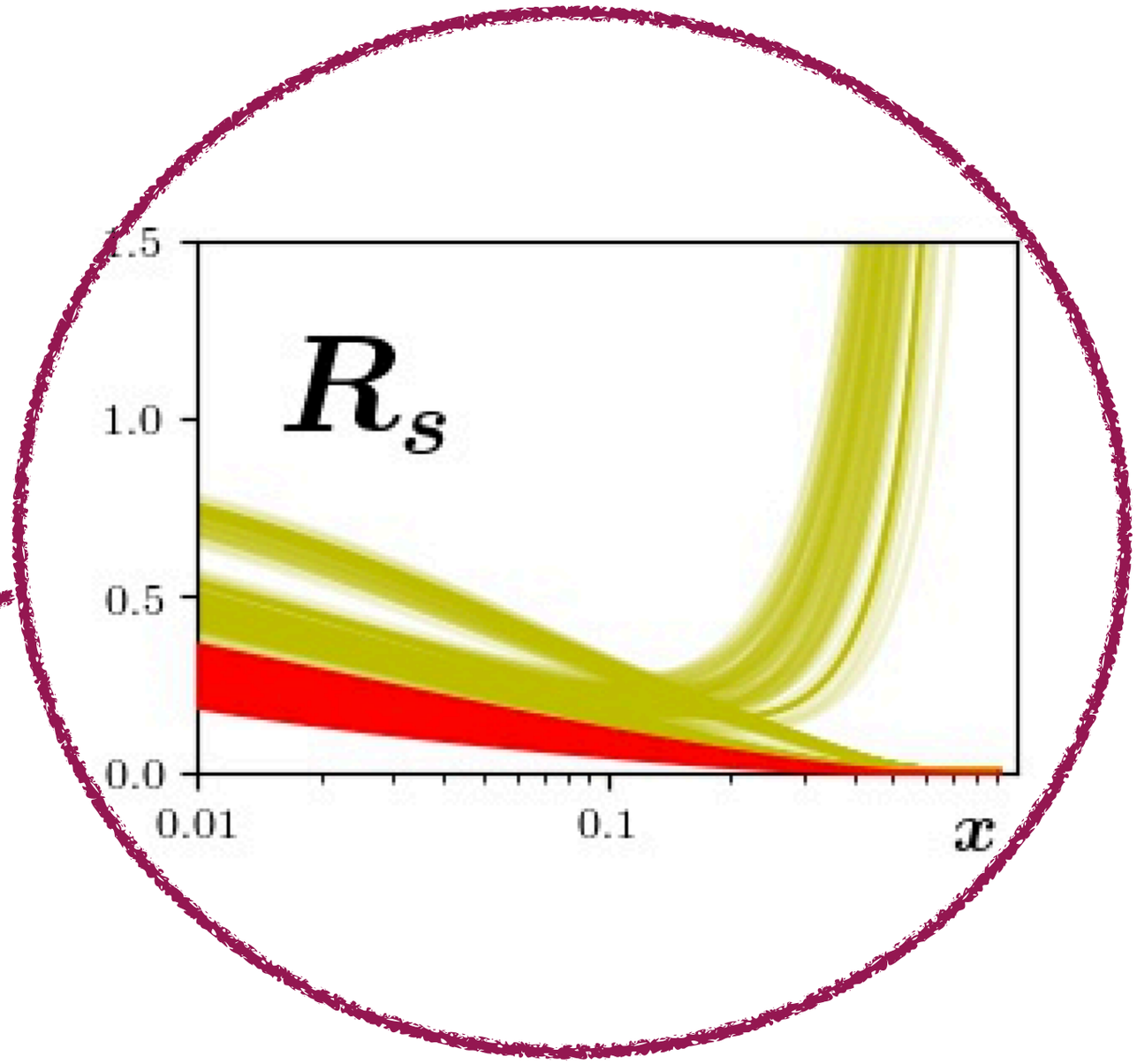
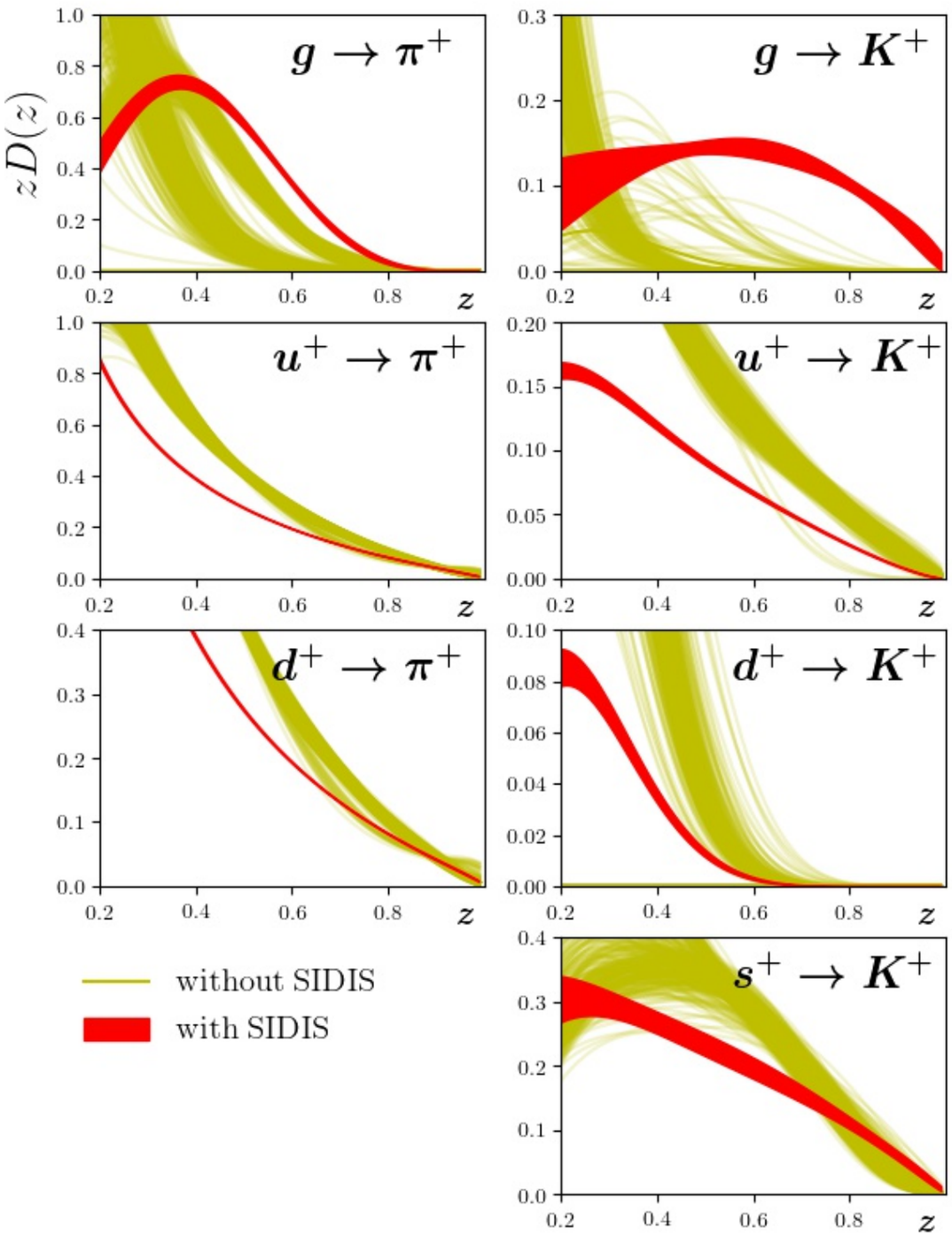


Strong strange suppression

Impact of SIDIS data on FF

$$q^+ = q + \bar{q}$$



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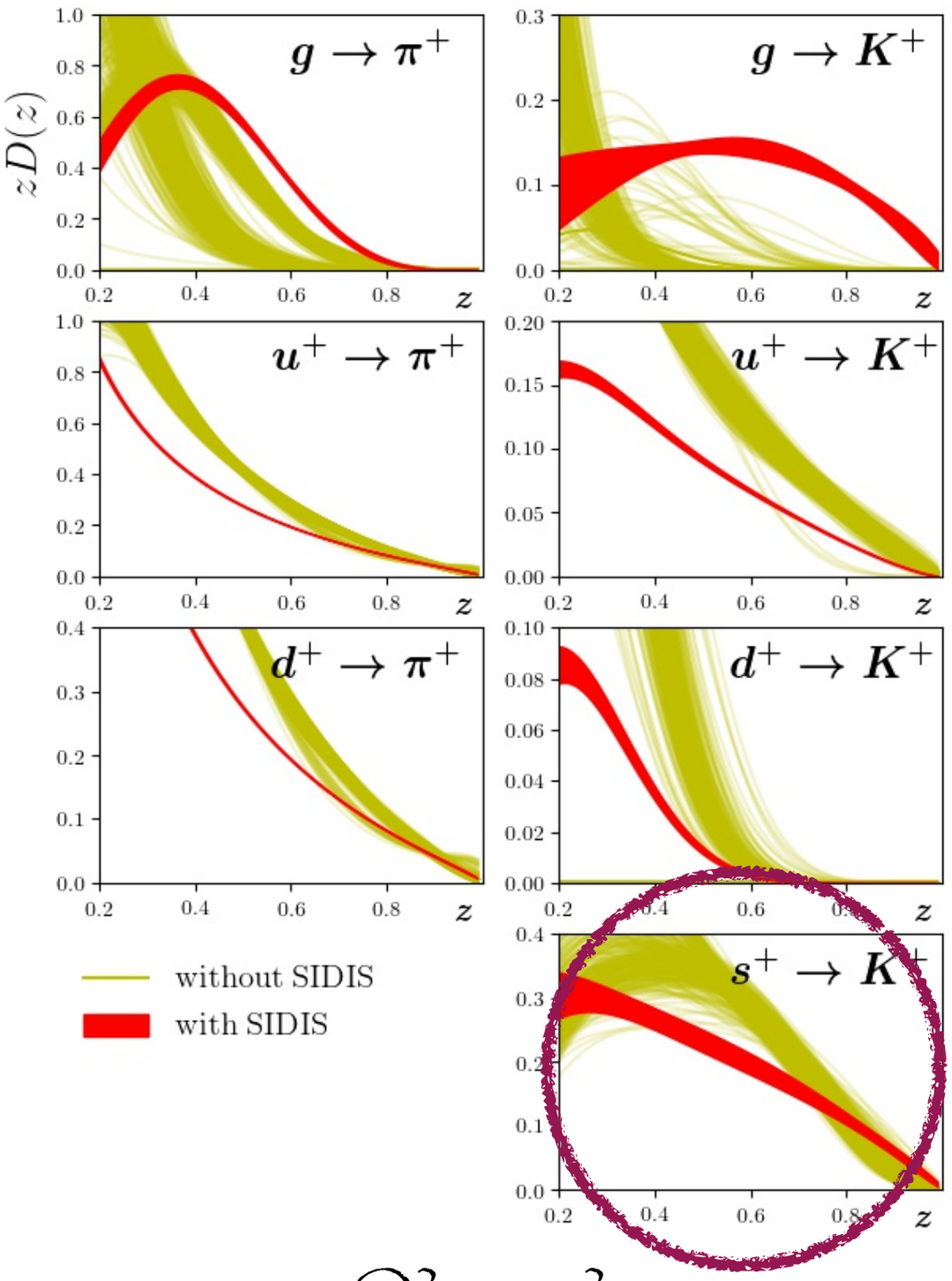

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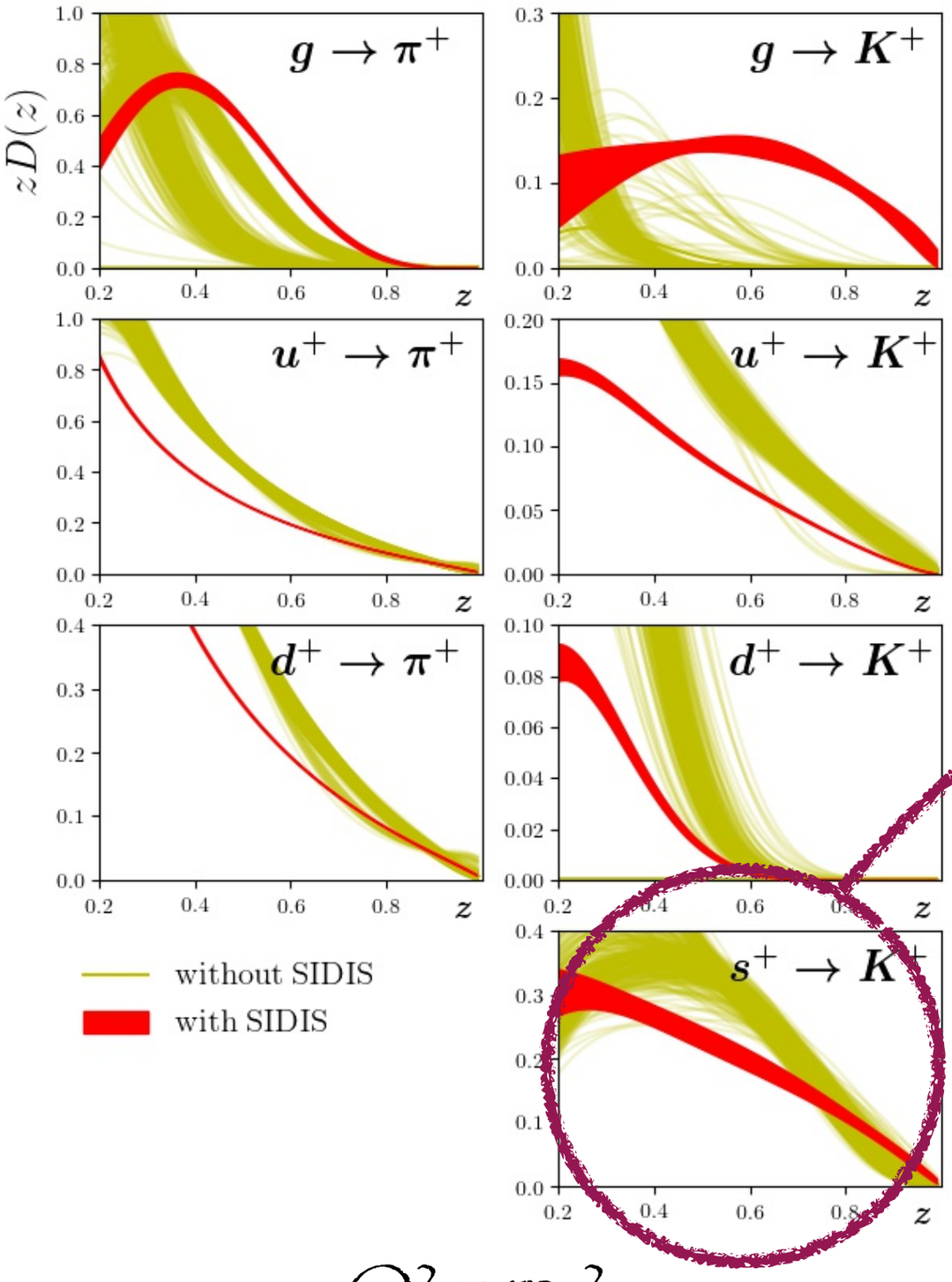

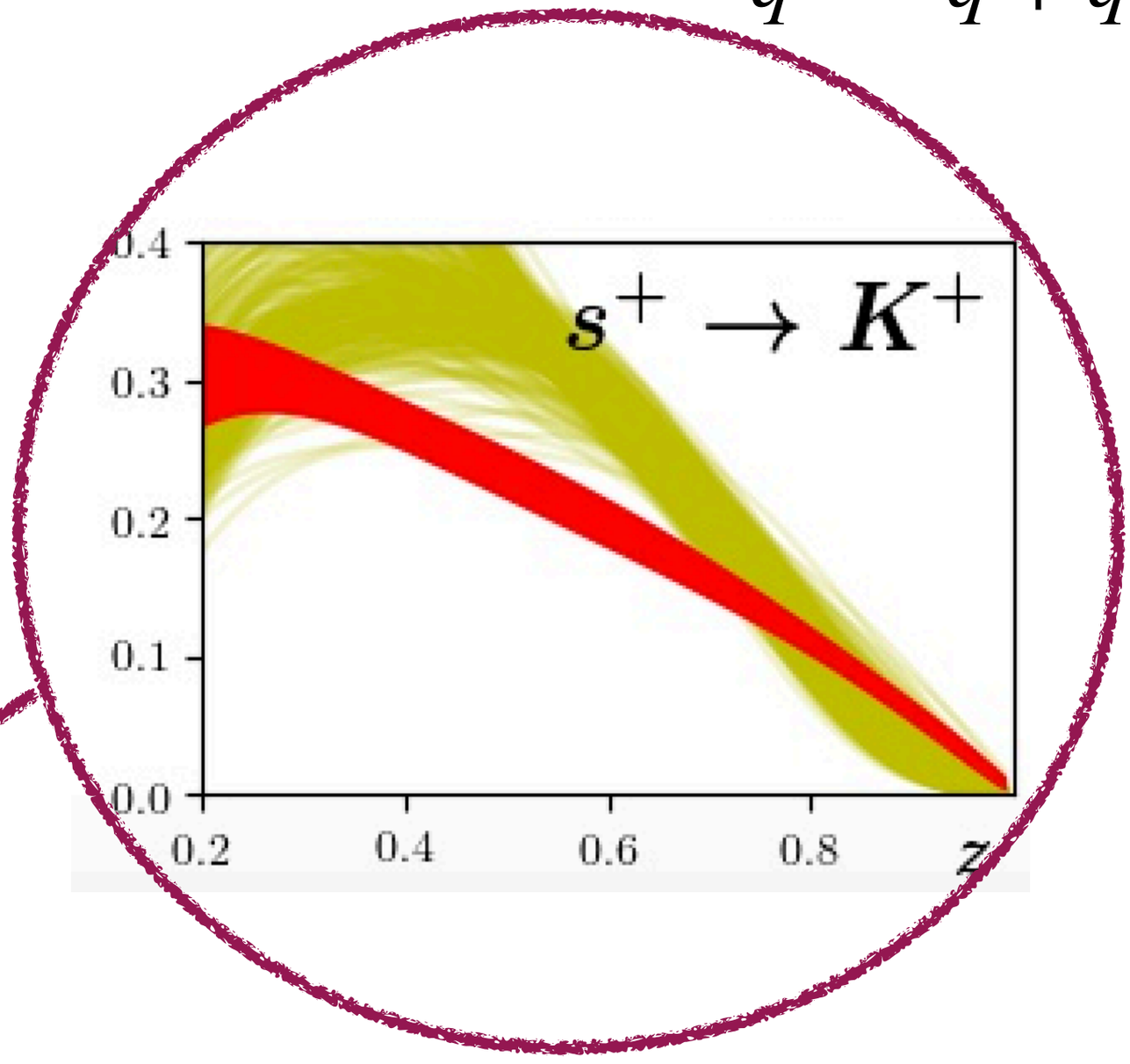

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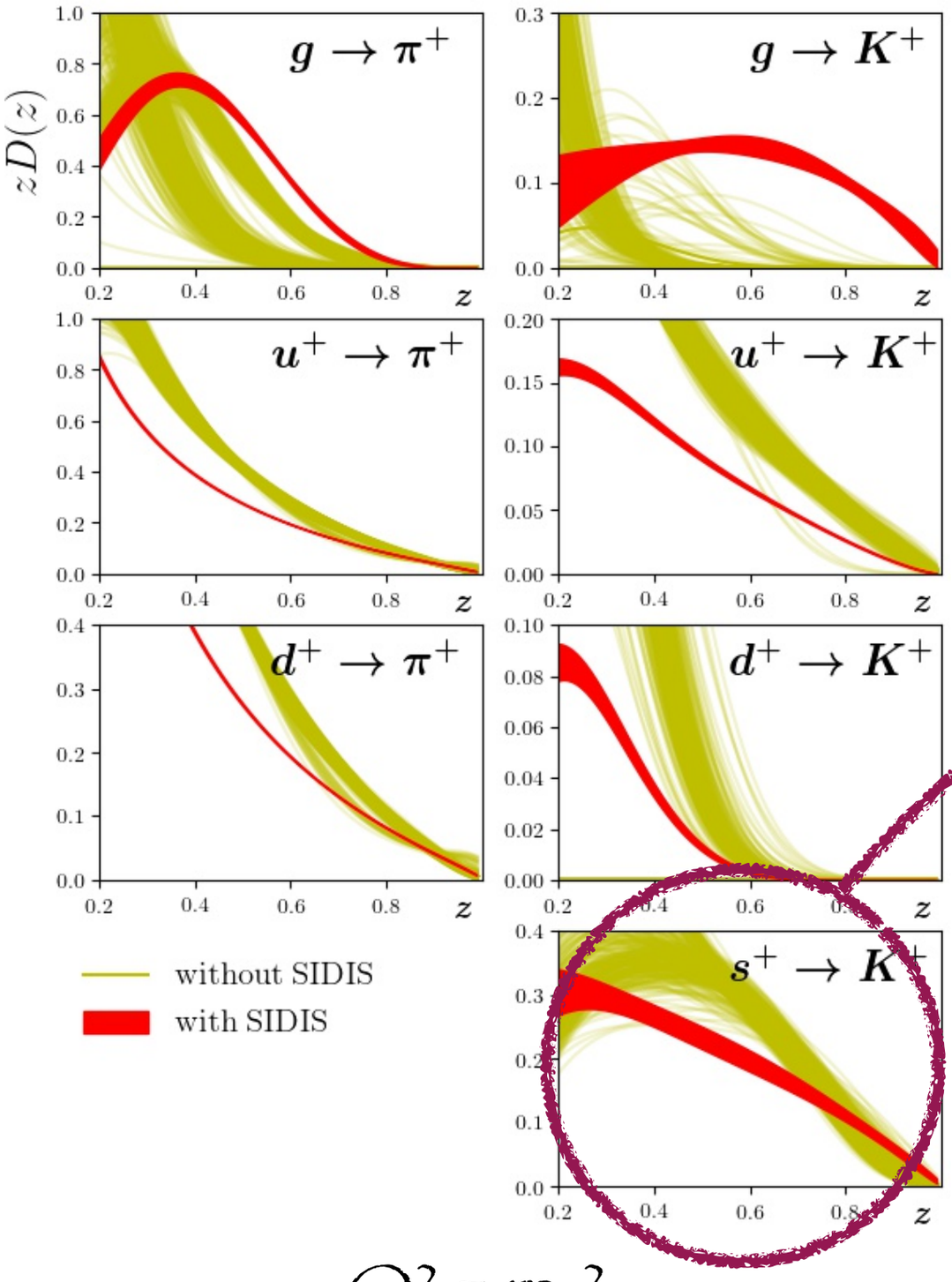

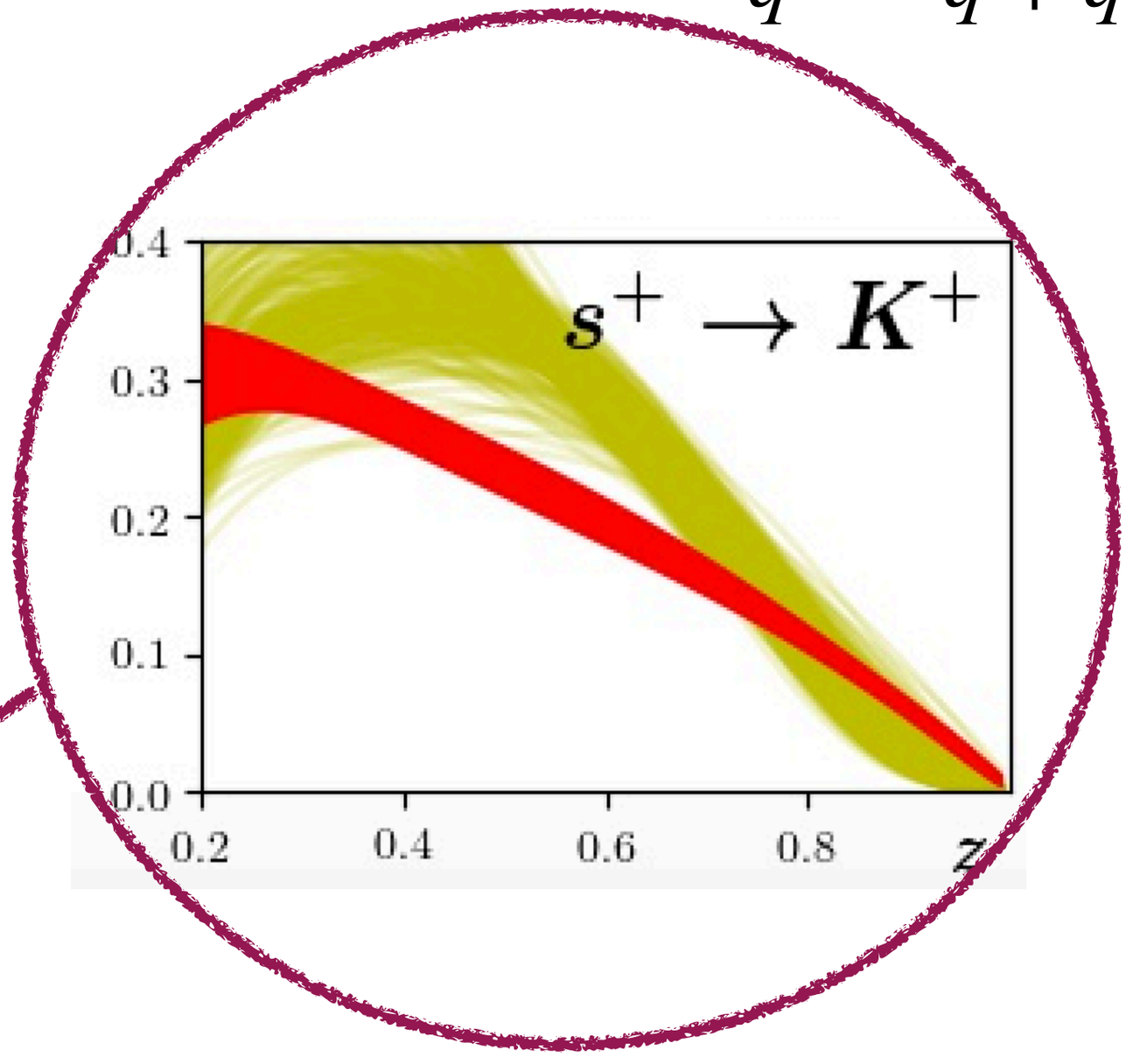

Constraints on

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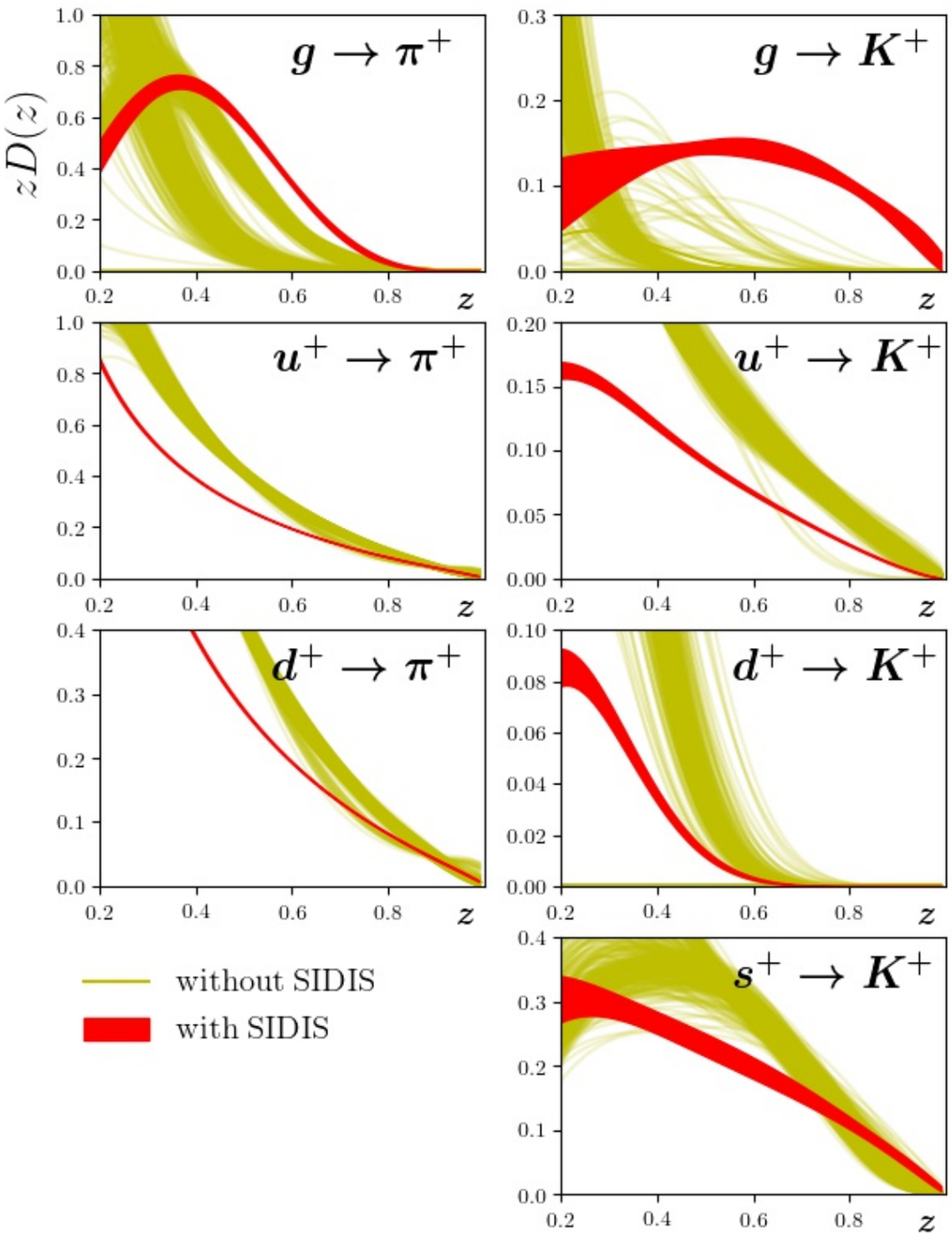

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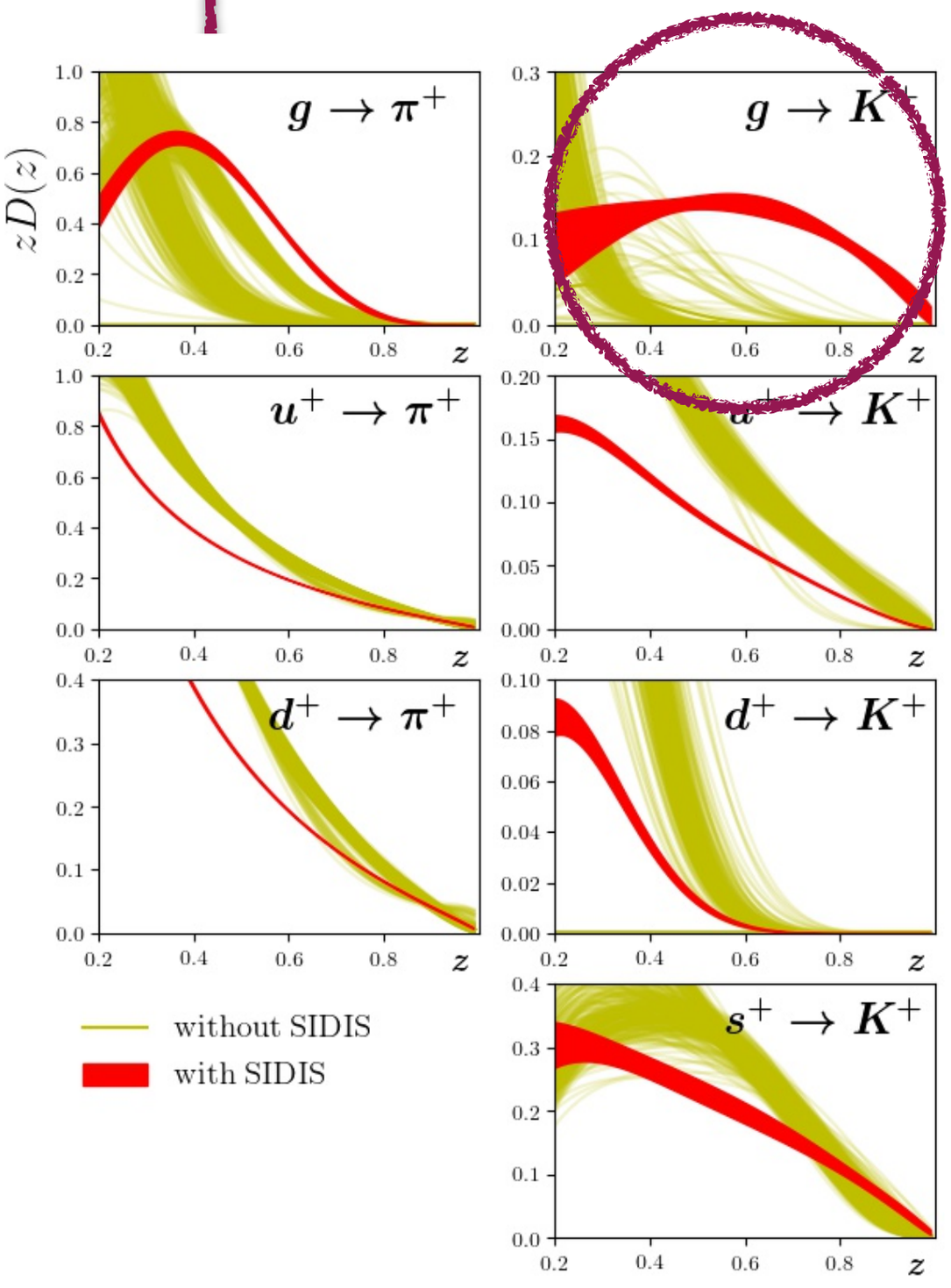

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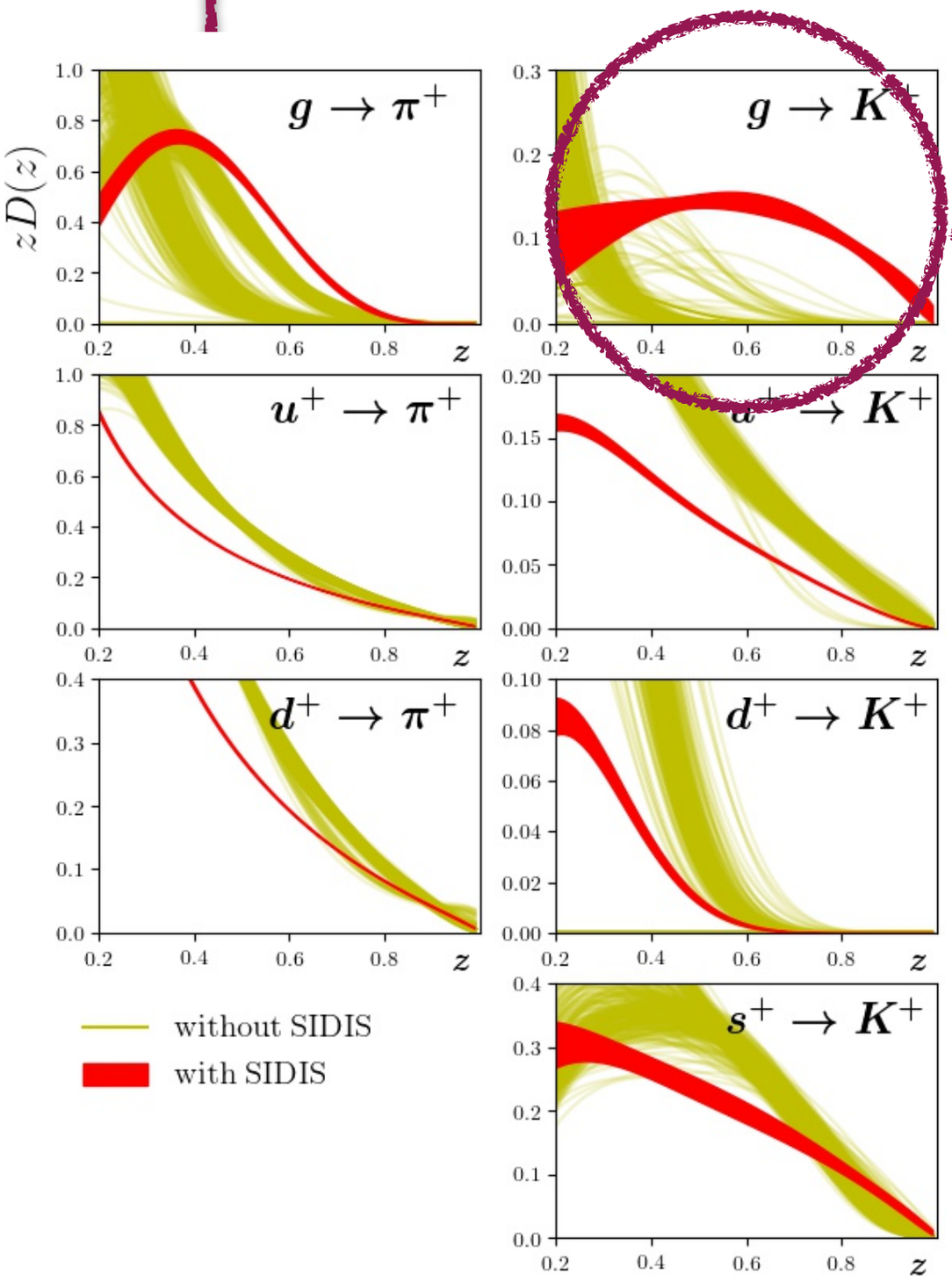

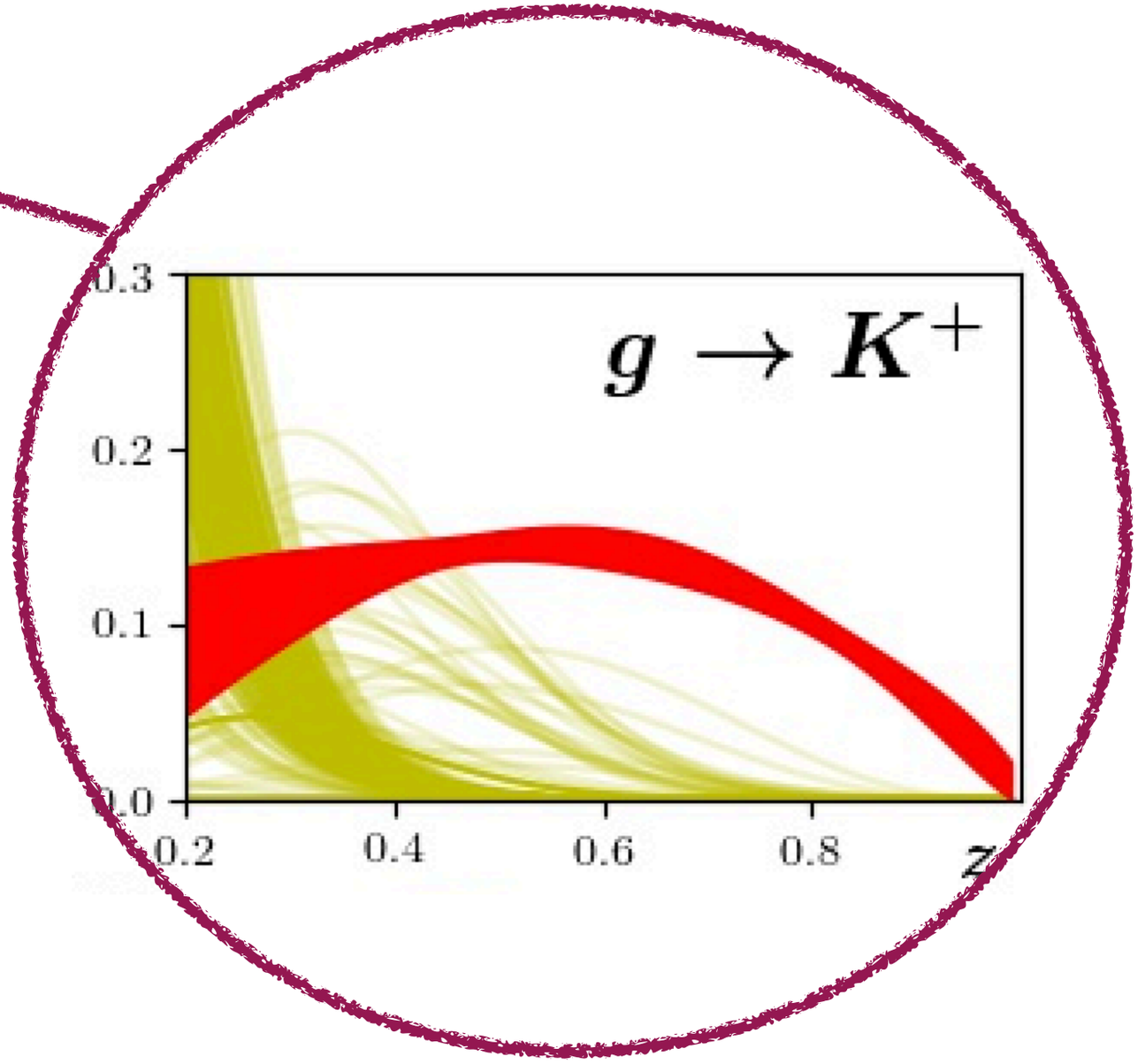

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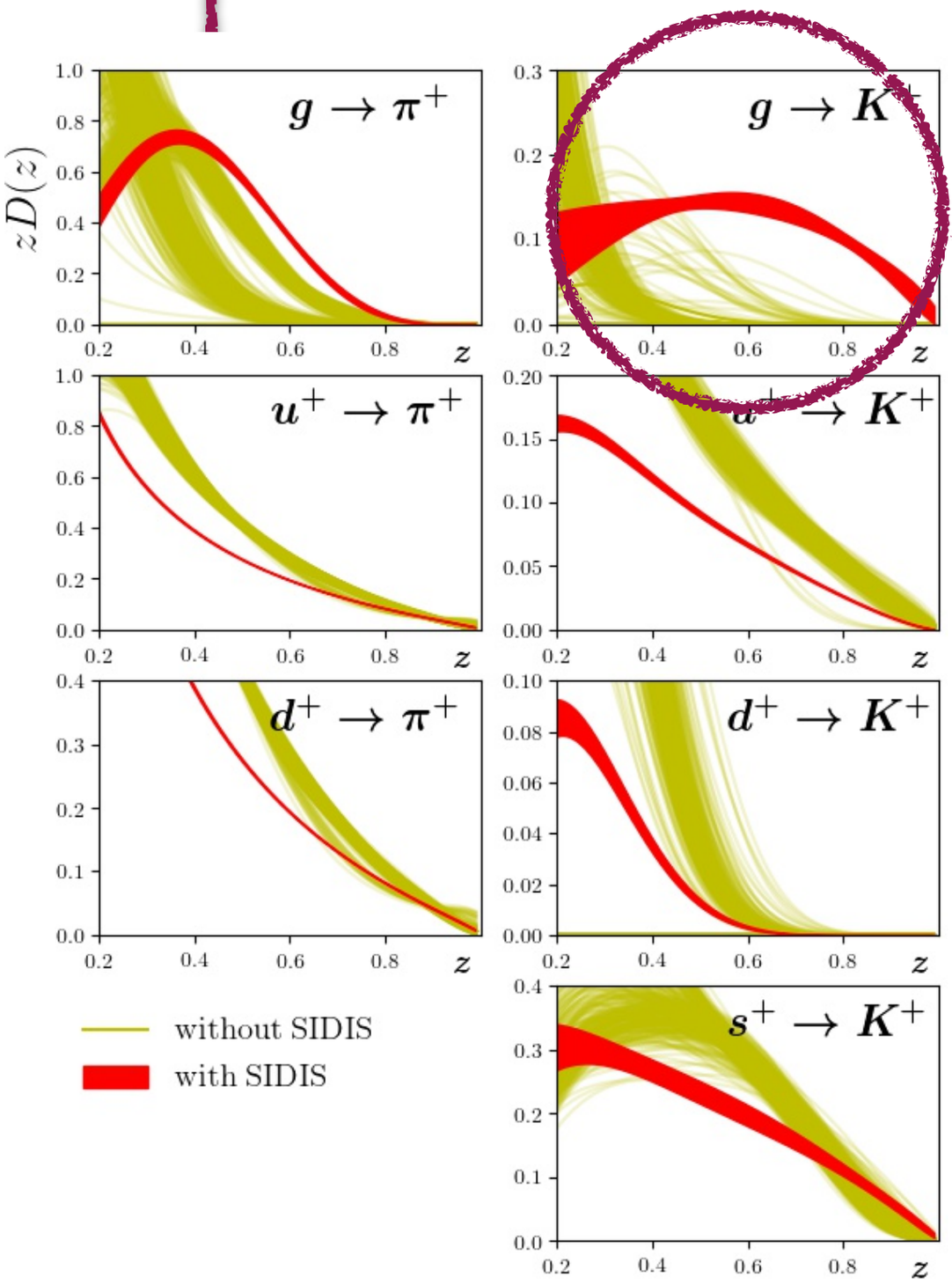

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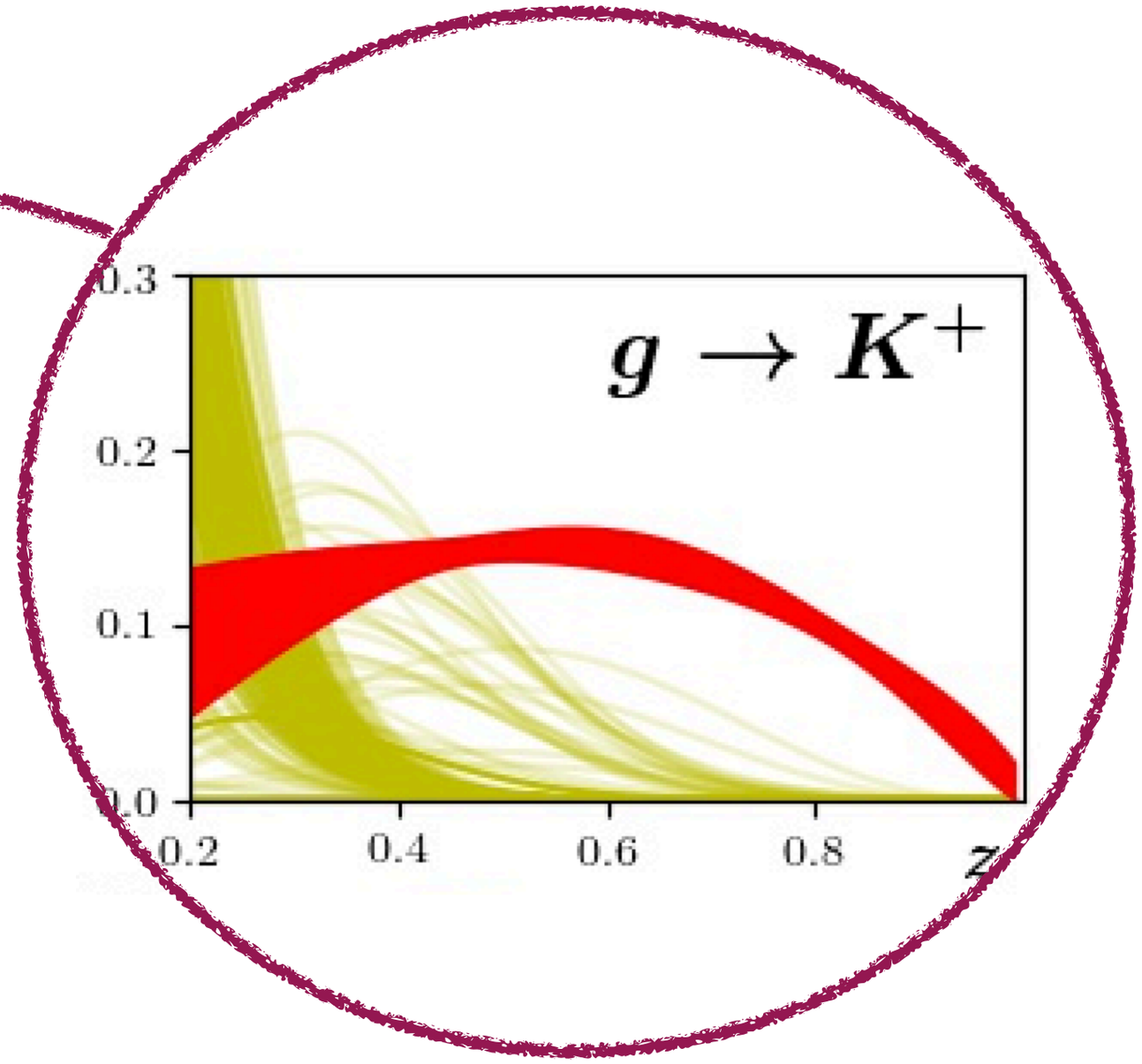

Constraints on

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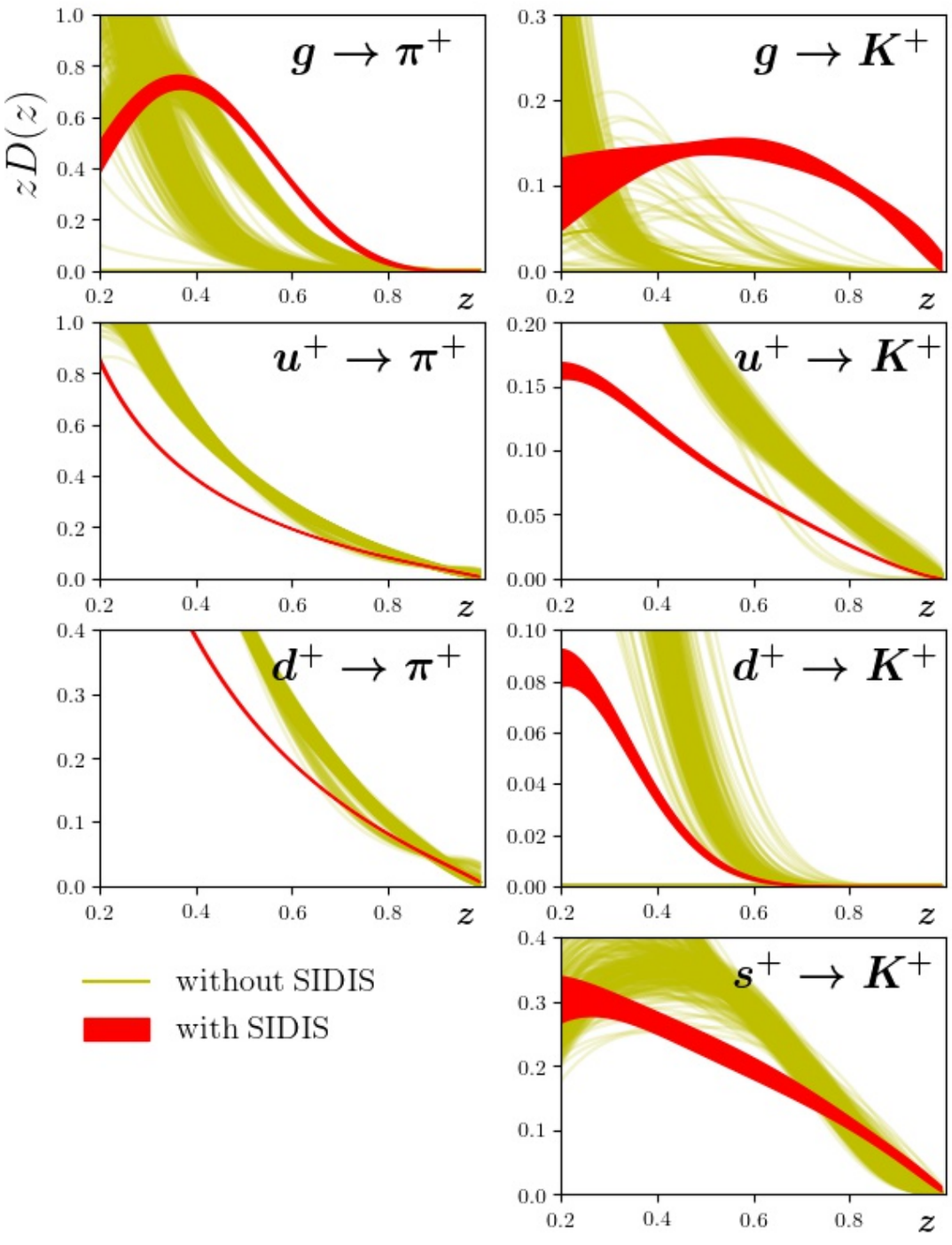

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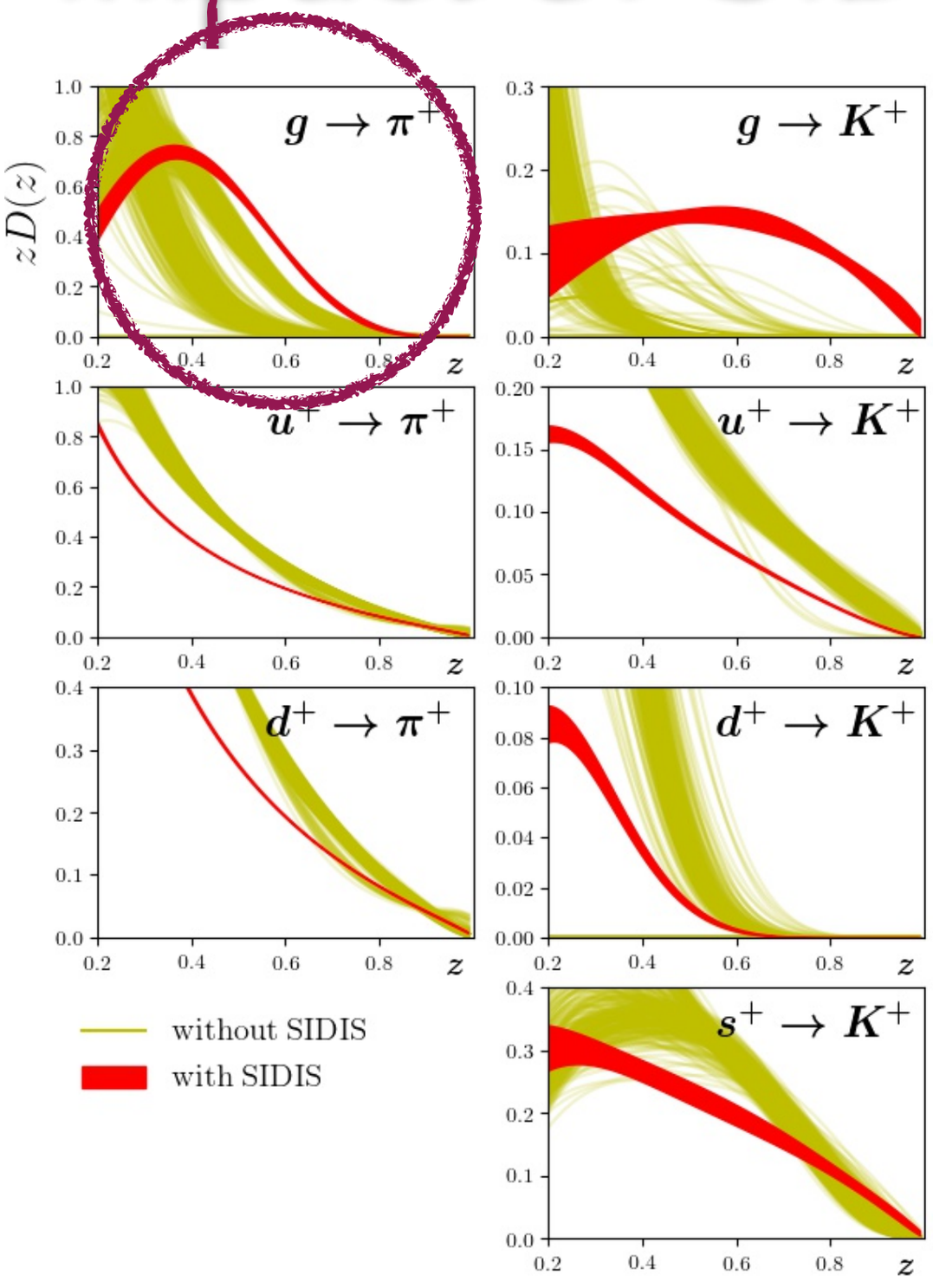

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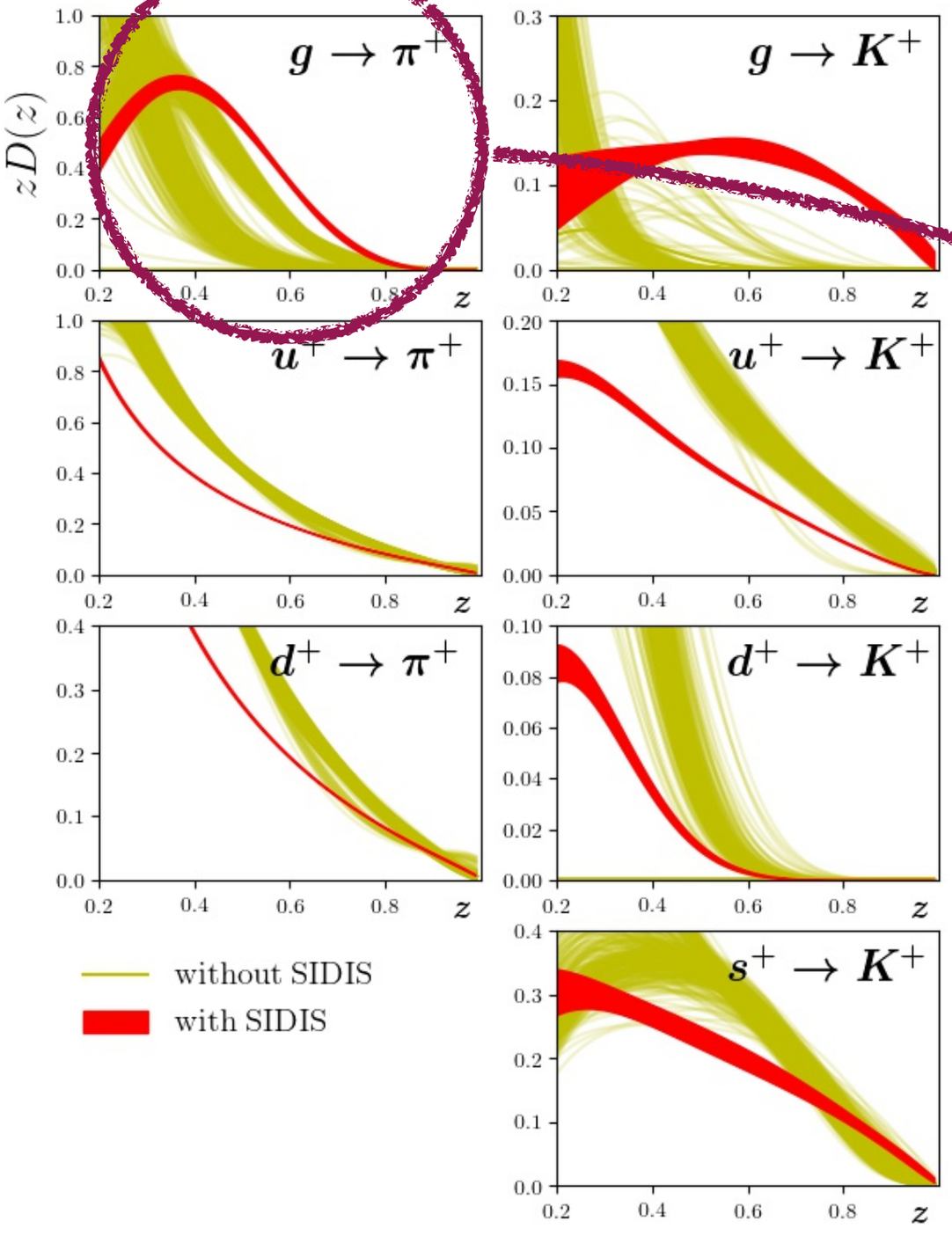
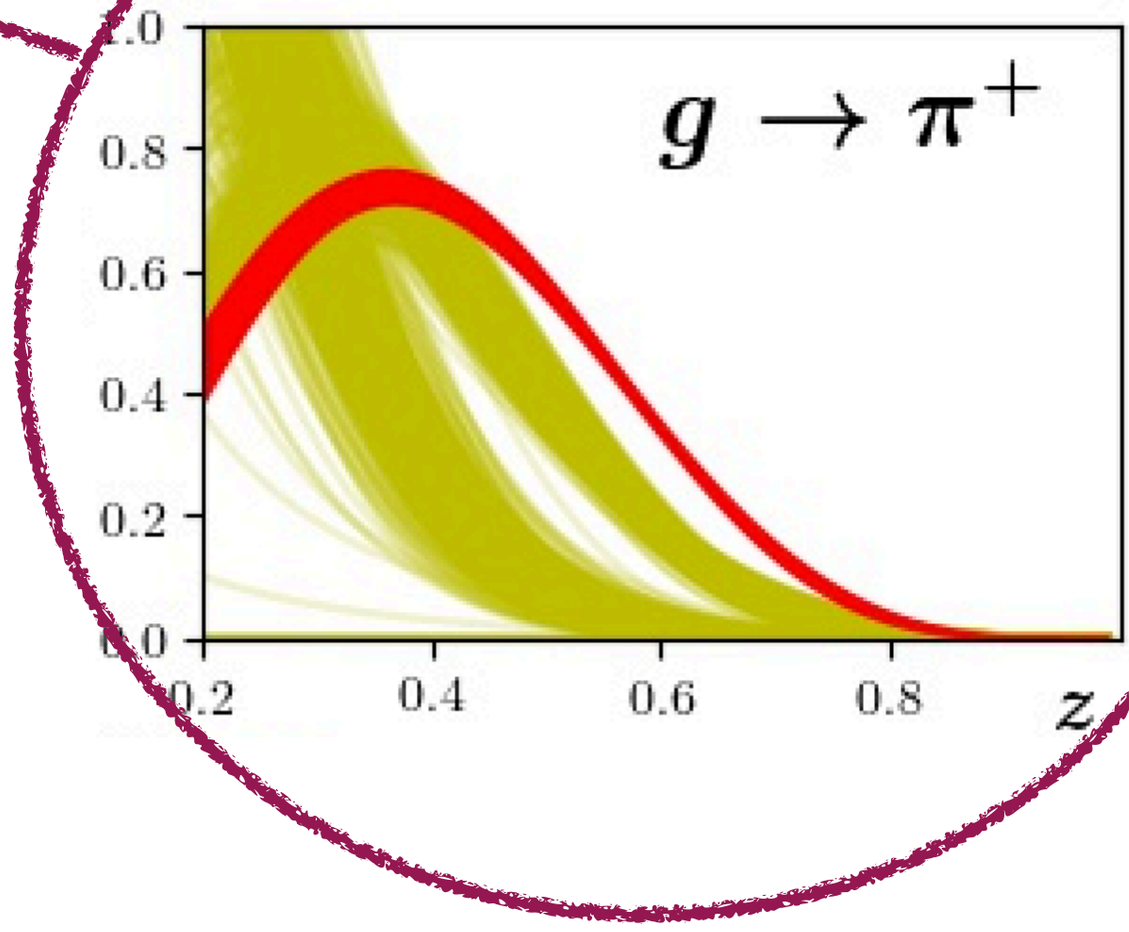
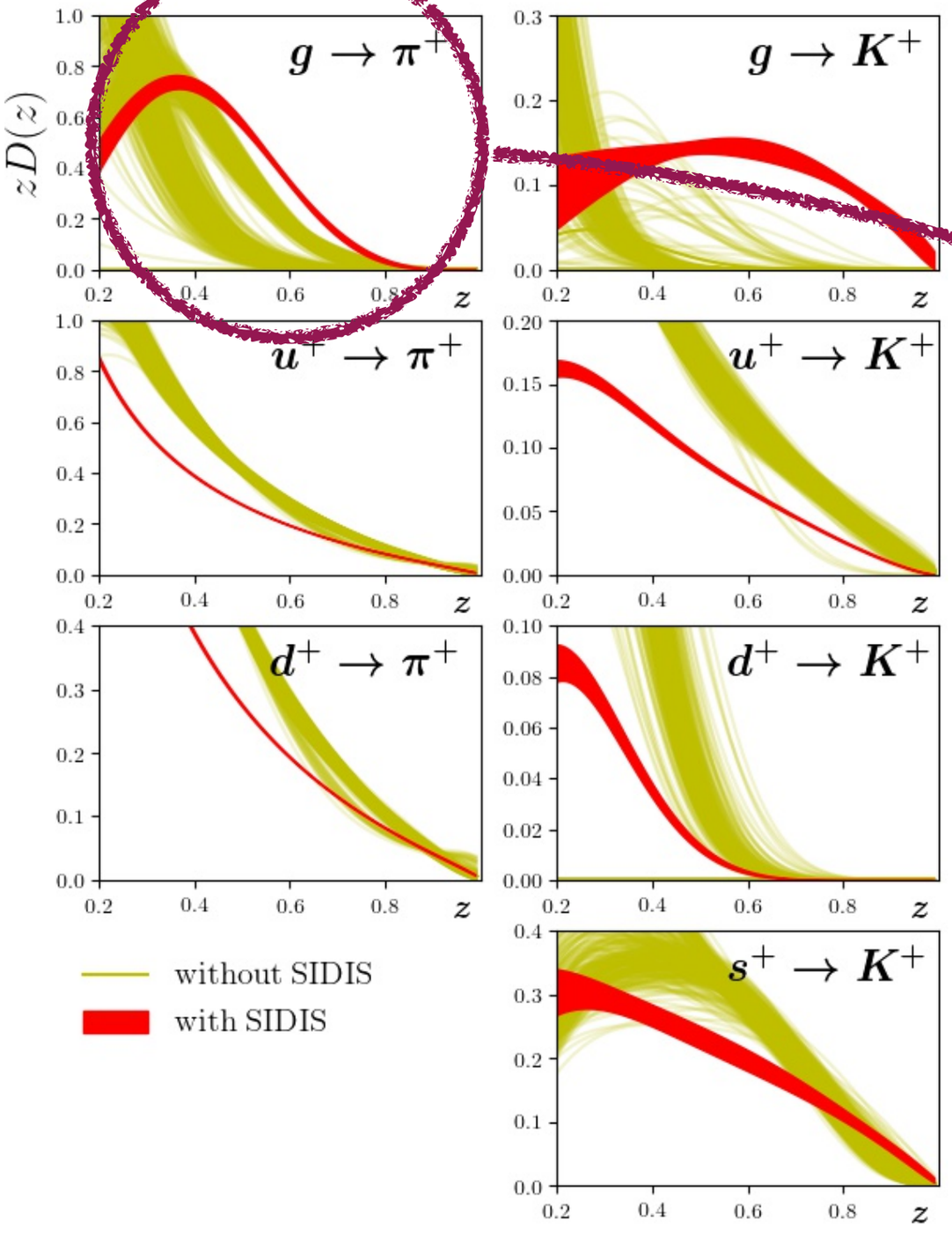


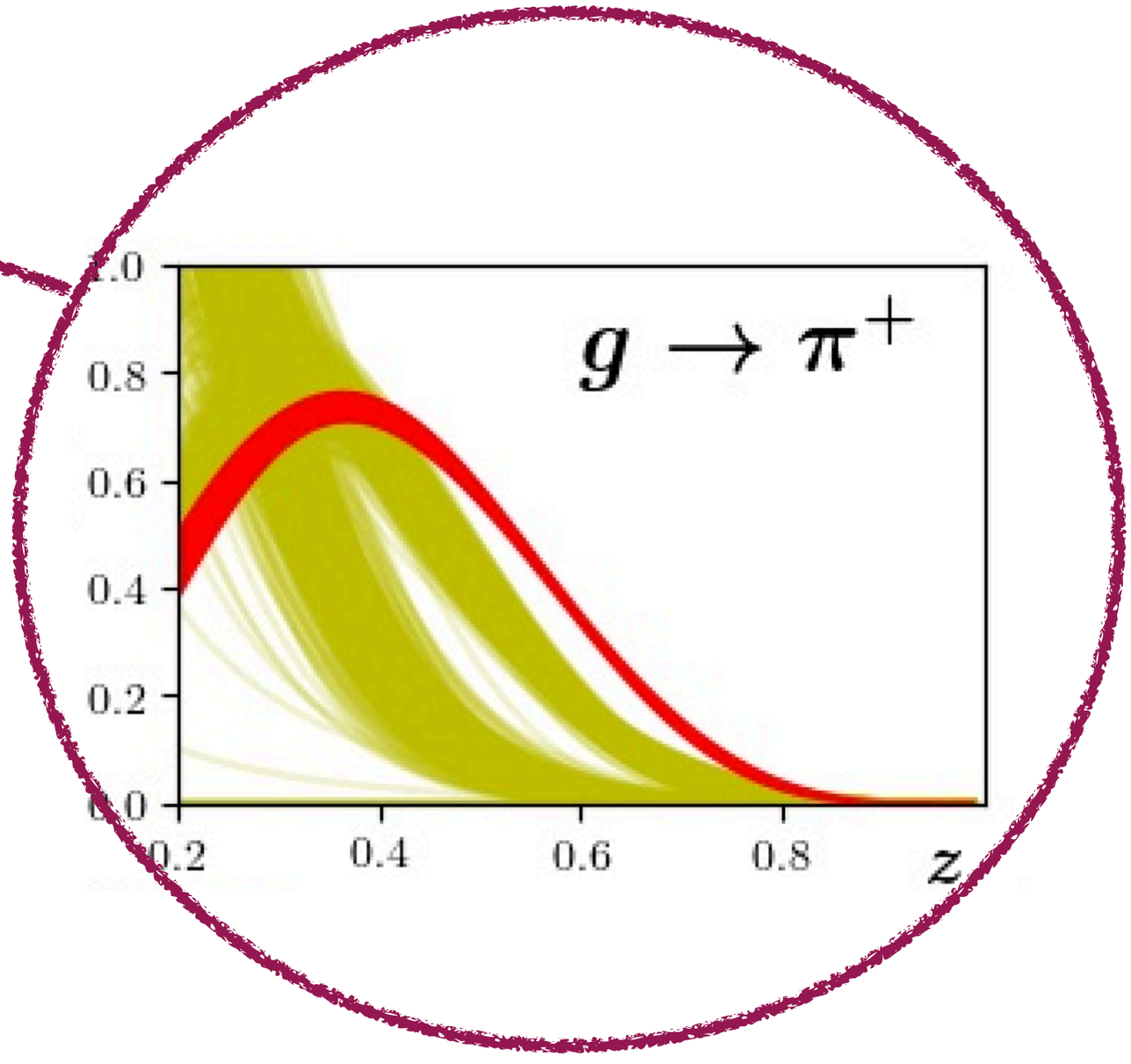


$Q^2 \approx m_c^2$

Impact of SIDIS data on FF



$Q^2 \approx m_c^2$



Constraints on

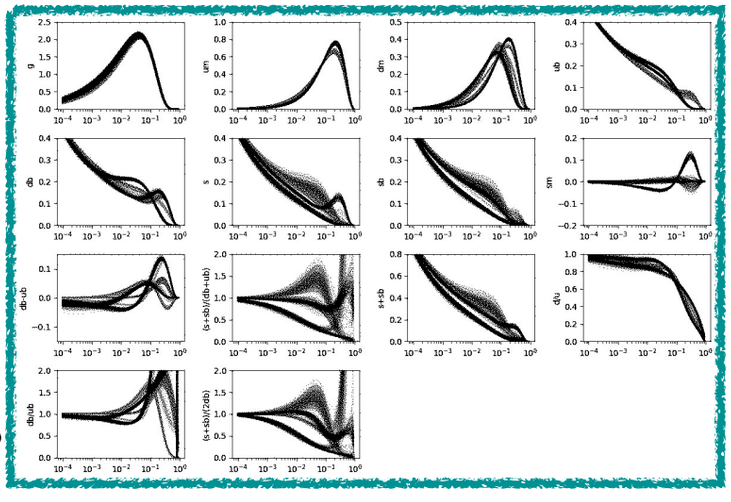
$g \to \pi^+$

JAM19

methodology

JAM 19: multi-step fitting

PDFs



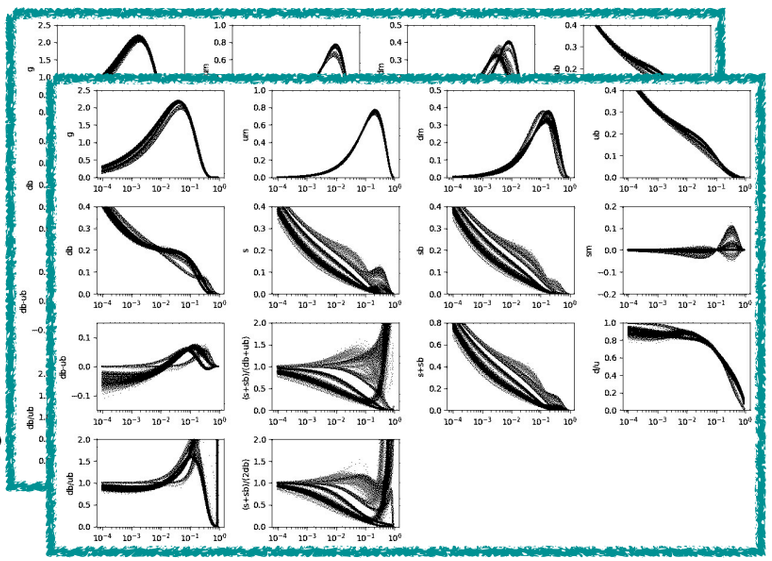
$xf(x)$

x

+ DIS data

JAM 19: multi-step fitting

PDFs



$xf(x)$

x

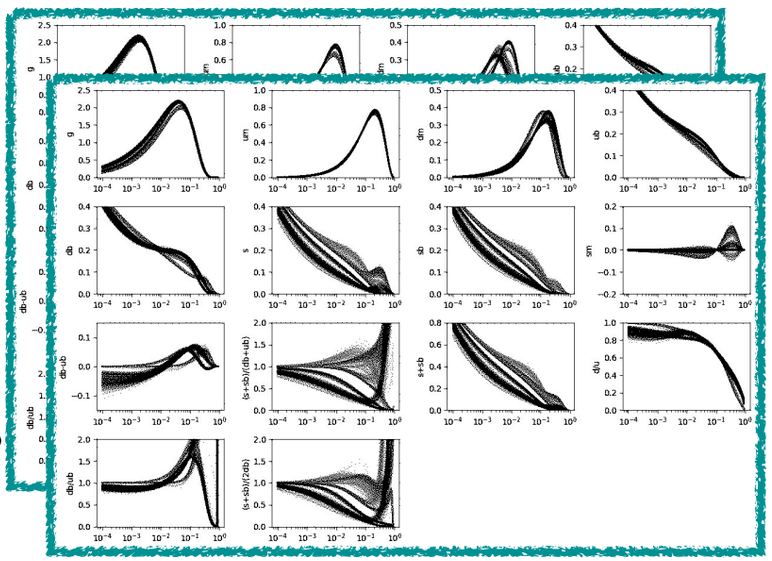
+ DIS data

+ DIS + DY data

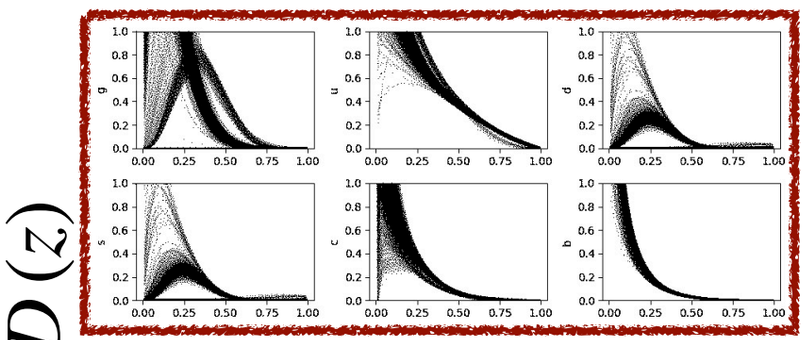
JAM 19: multi-step fitting

PDFs

PION FF



$x f(x)$



$z D(z)$

z

x

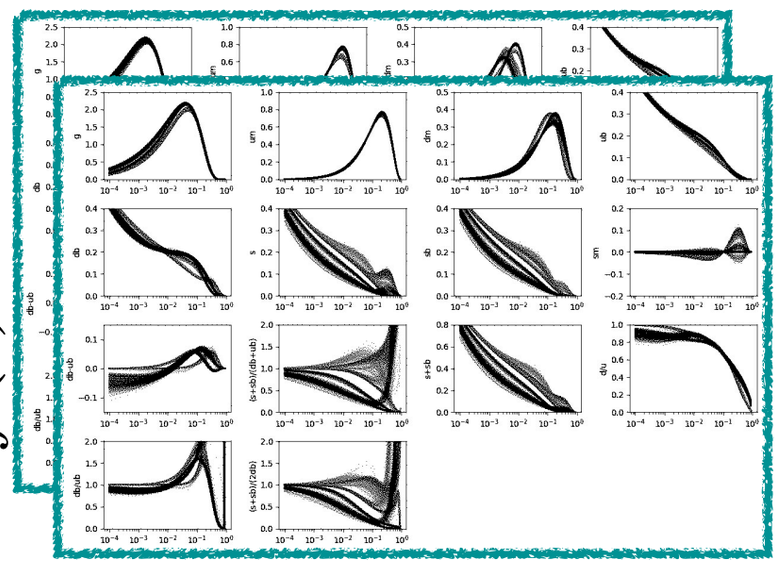
+ DIS data

+ SIA pion data

+ DIS + DY data

JAM 19: multi-step fitting

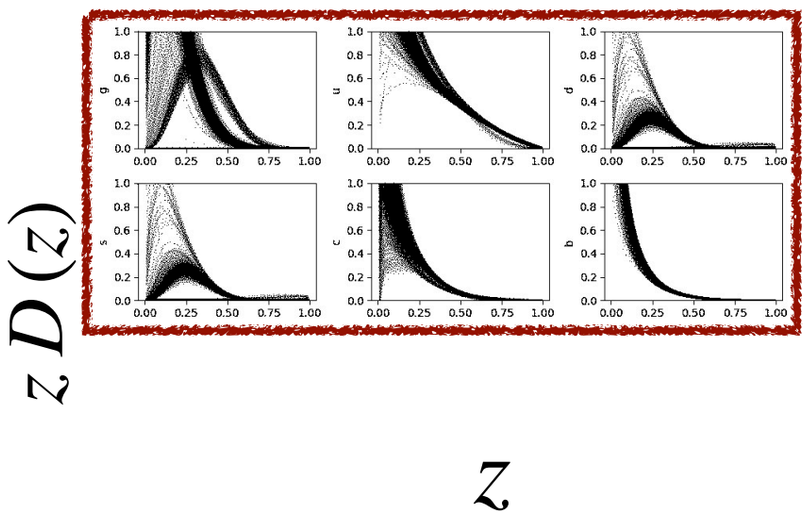
PDFs



+ DIS data

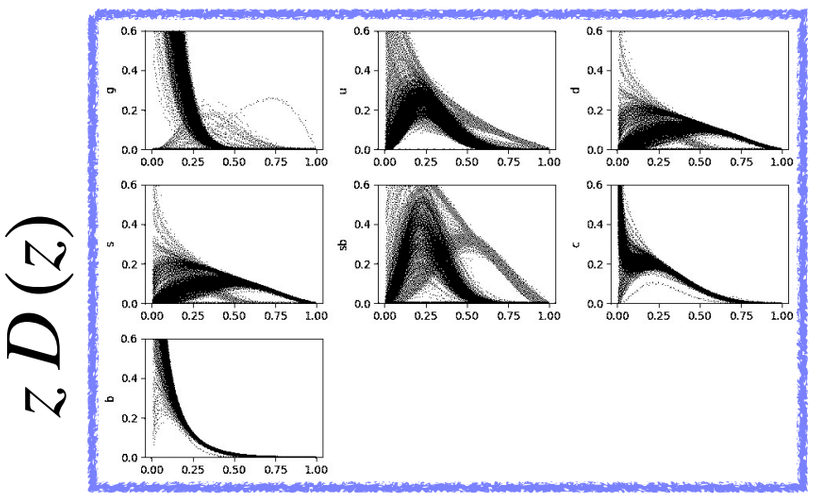
+ DIS + DY data

PION FF



+ SIA pion data

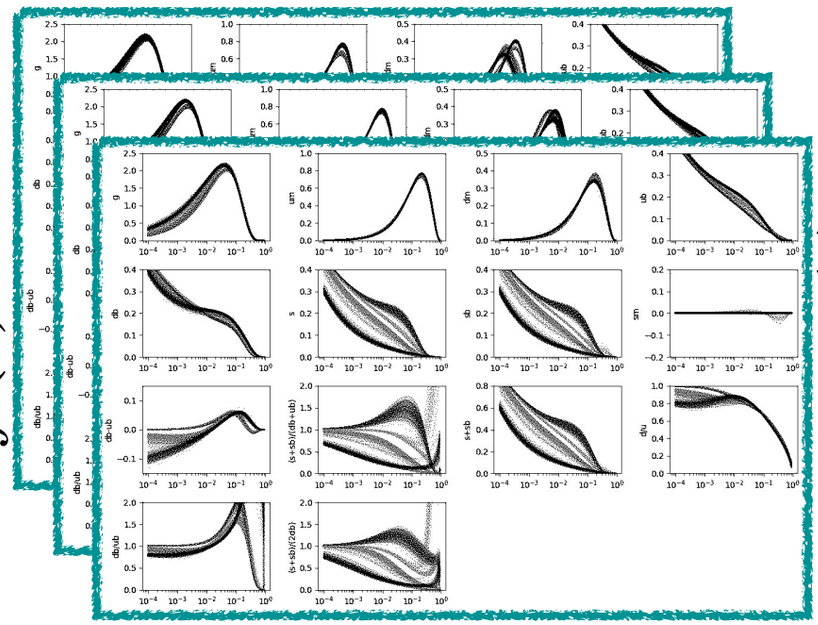
KAON FF



+ SIA kaon data

JAM 19: multi-step fitting

PDFs

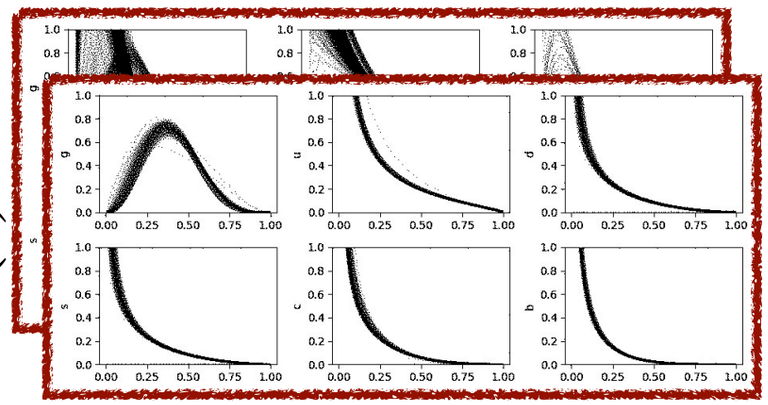


$x f(x)$

x

+ DIS data
+ DIS + DY data
+ SIDIS data

PION FF

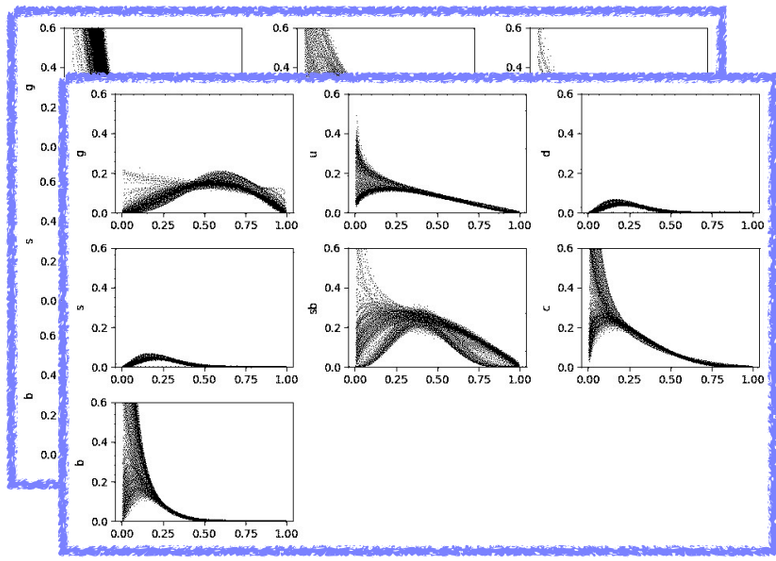


$z D(z)$

z

+ SIA pion data
+ SIDIS pion data

KAON FF

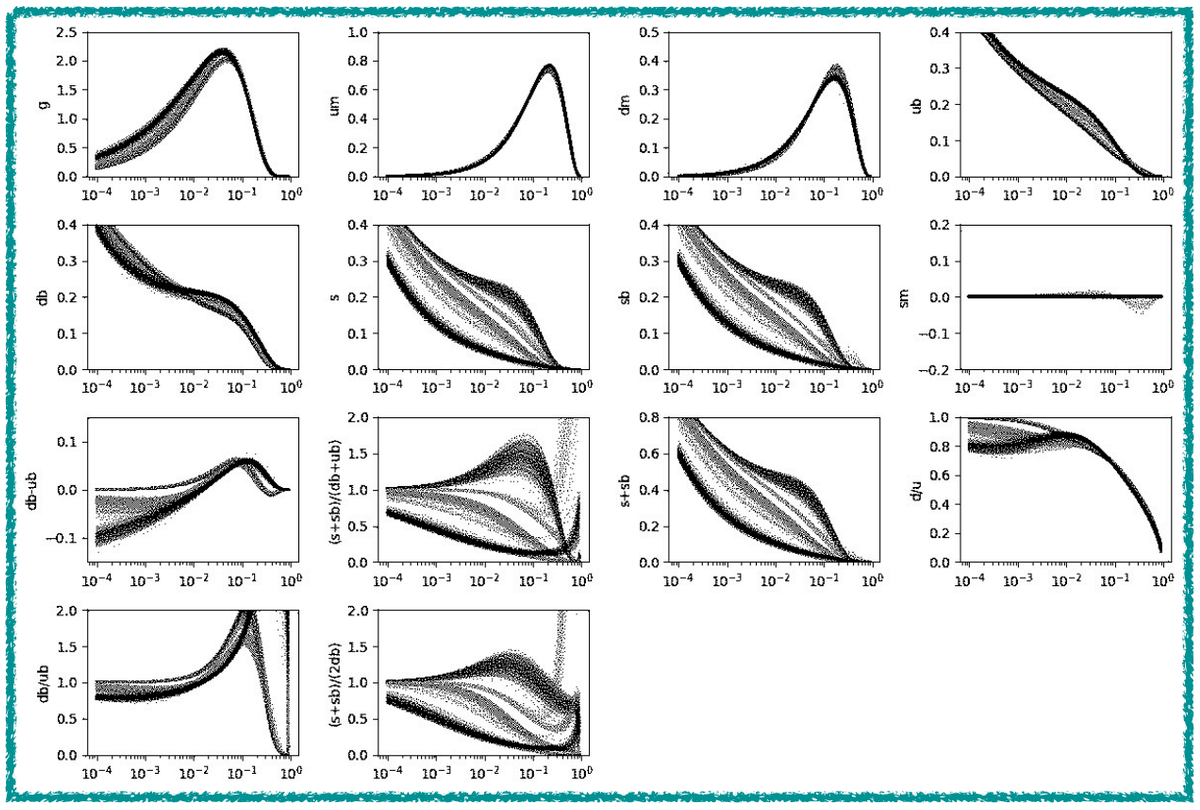


$z D(z)$

z

+ SIA kaon data
+ SIDIS kaon data

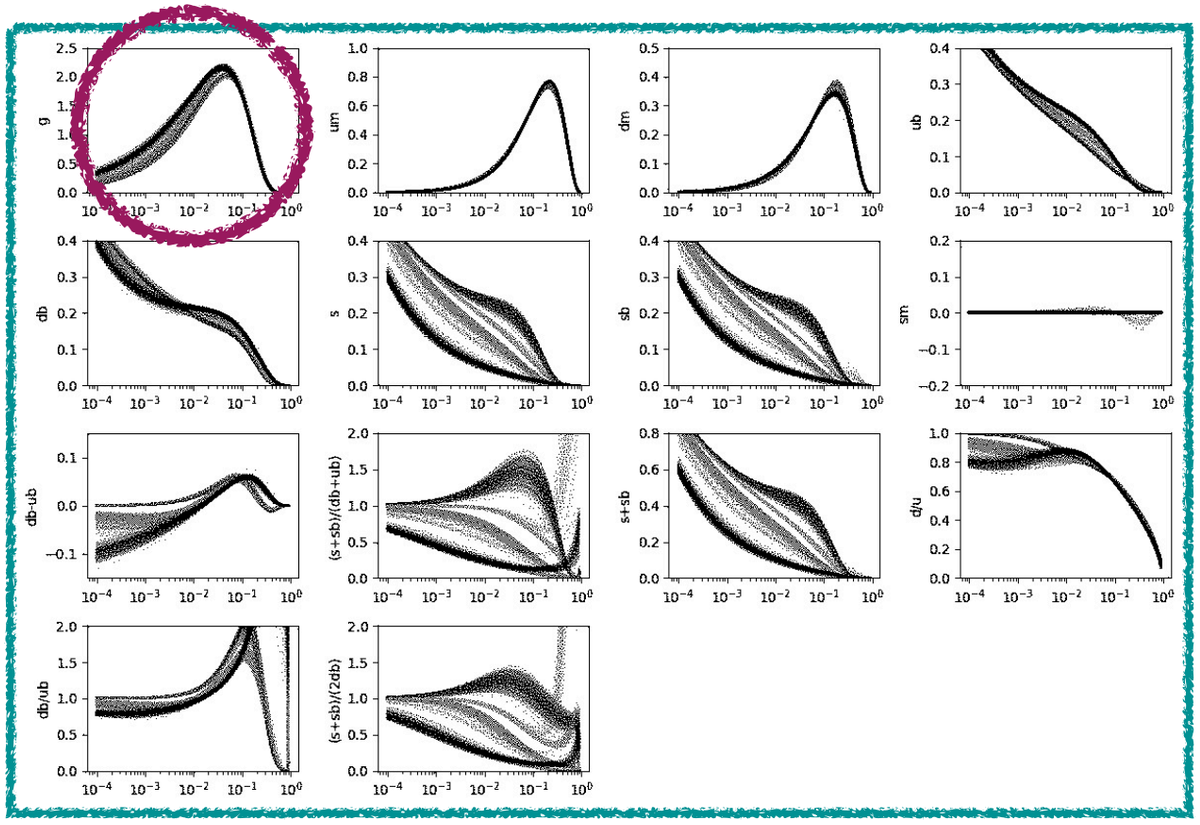
Discrminating multiple solutions



$x f(x)$

x

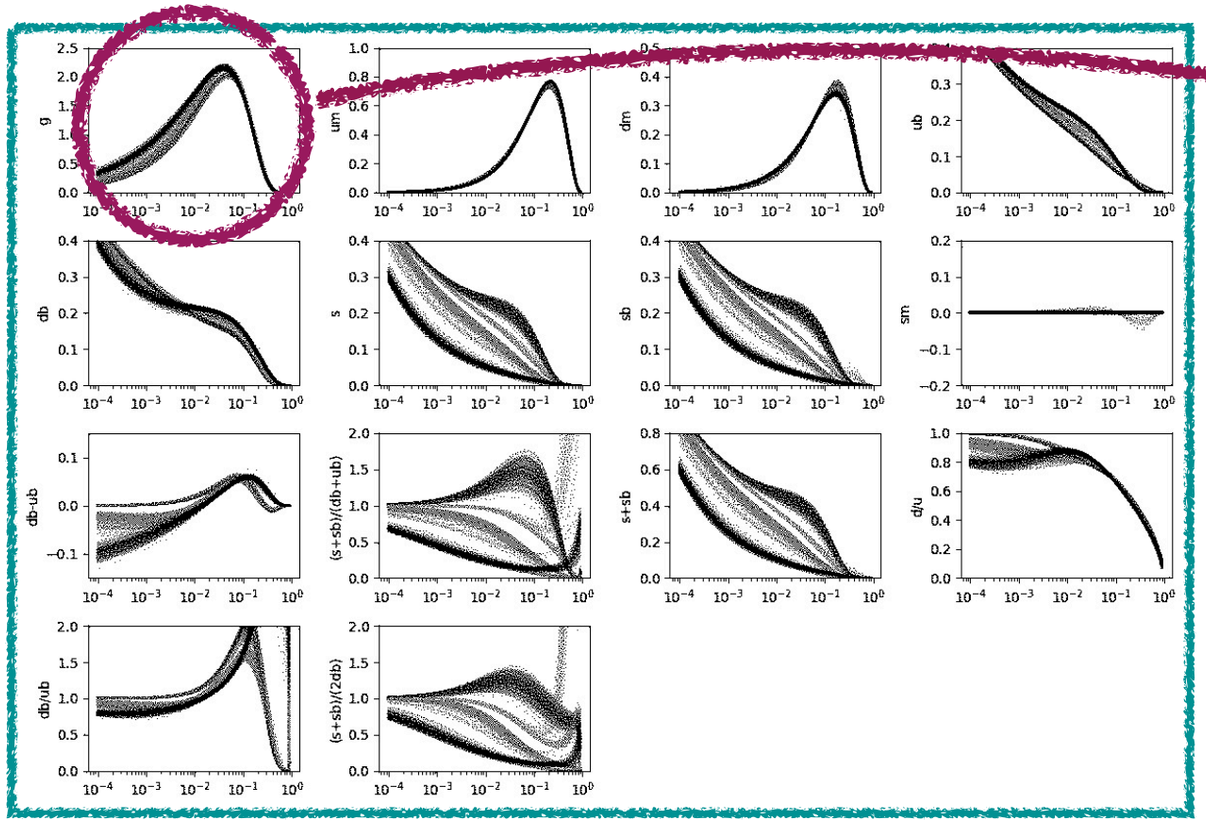
Discrminating multiple solutions



$x f(x)$

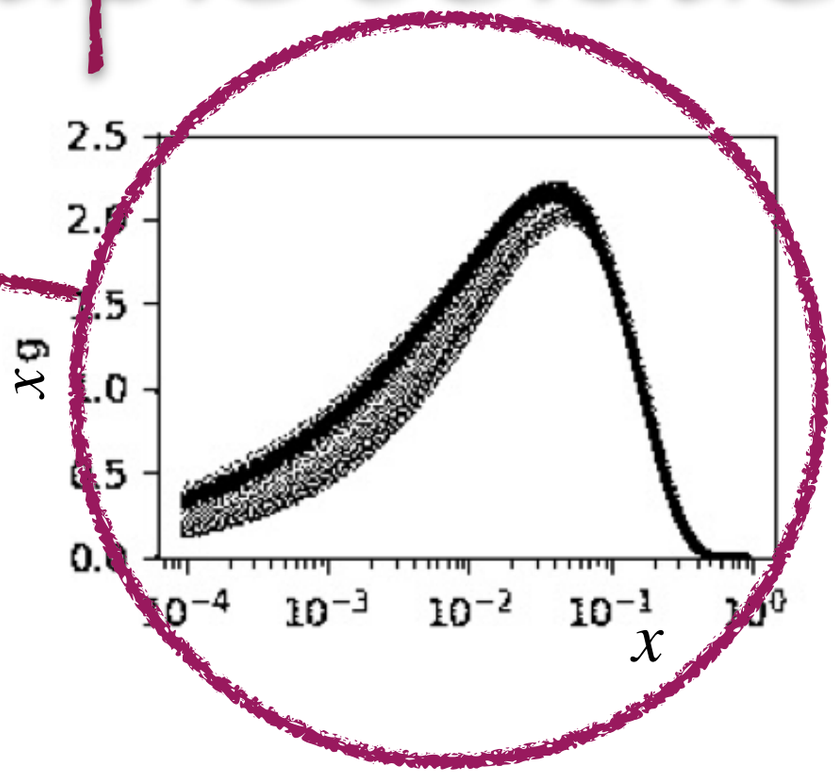
x

Discrminating multiple solutions

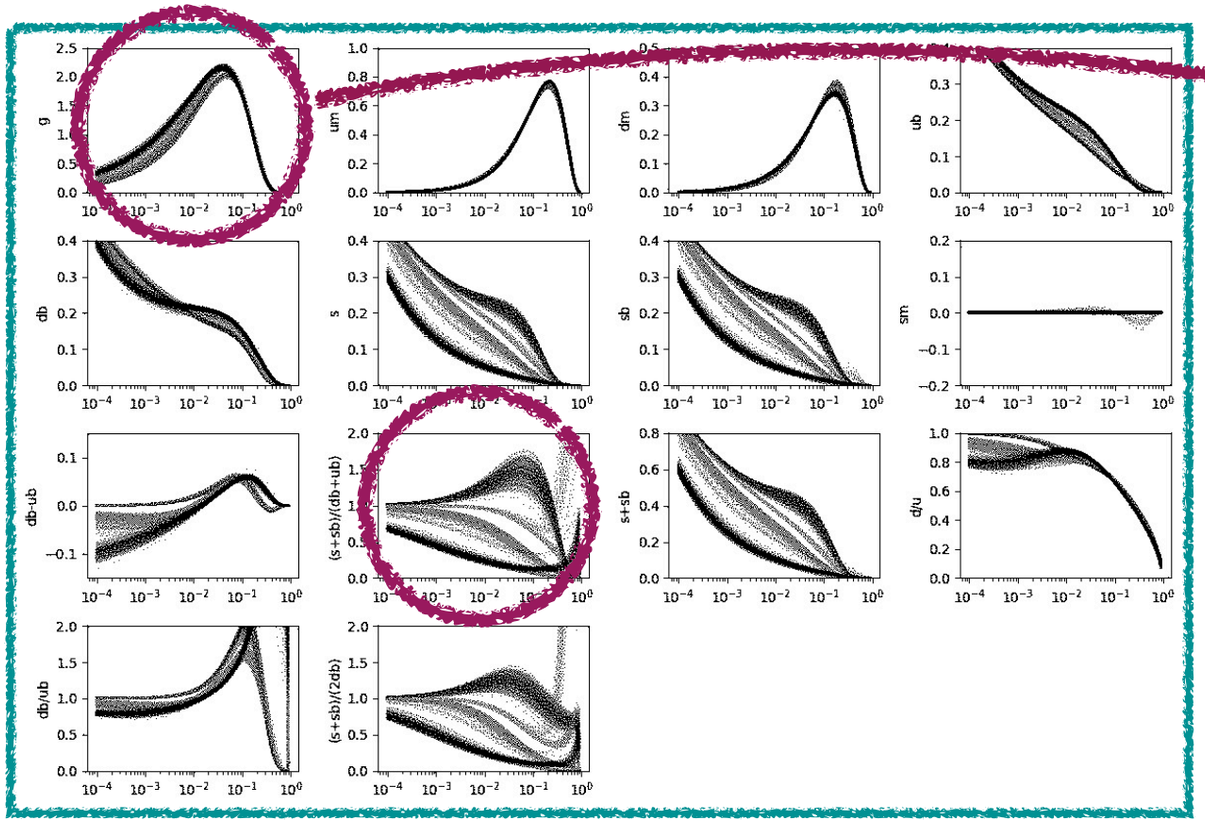


$x f(x)$

x

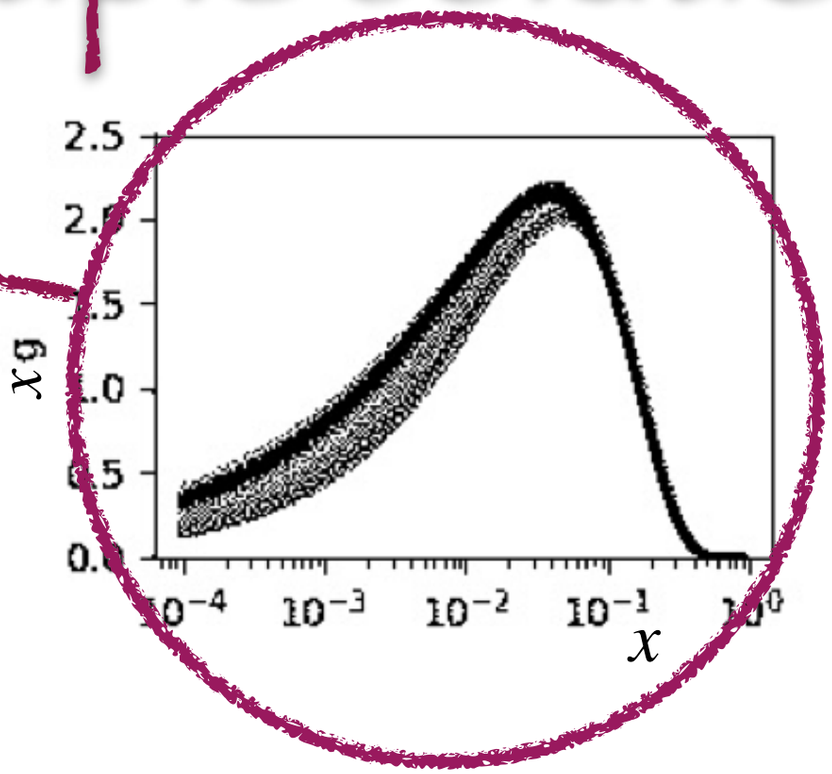


Discrminating multiple solutions

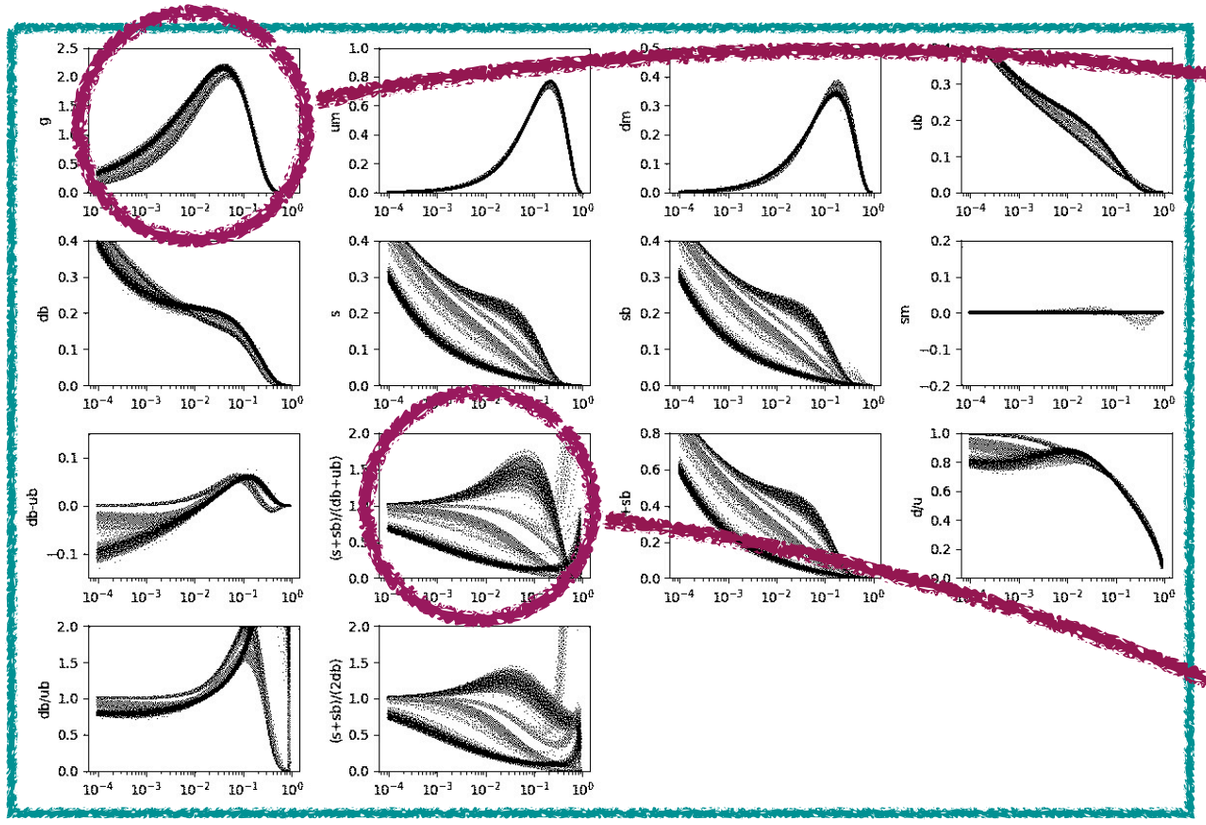


$x f(x)$

x

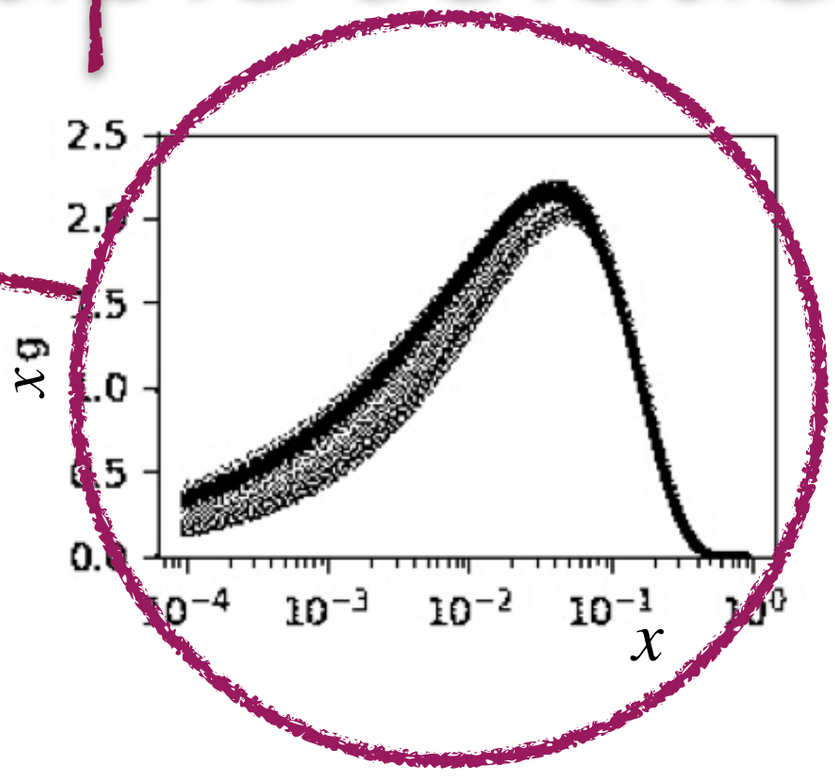


Discriminating multiple solutions

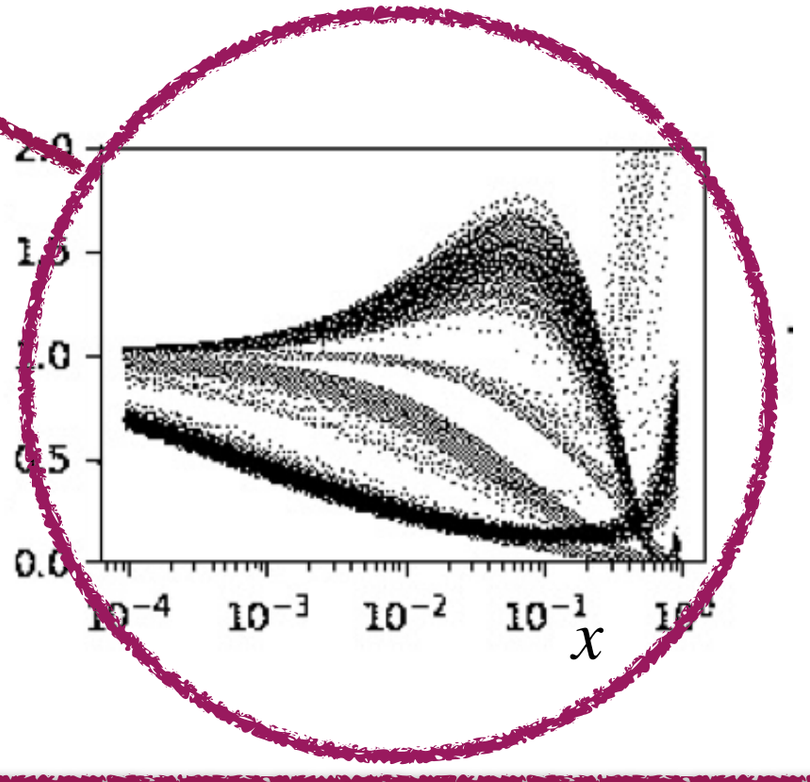


$x f(x)$

x



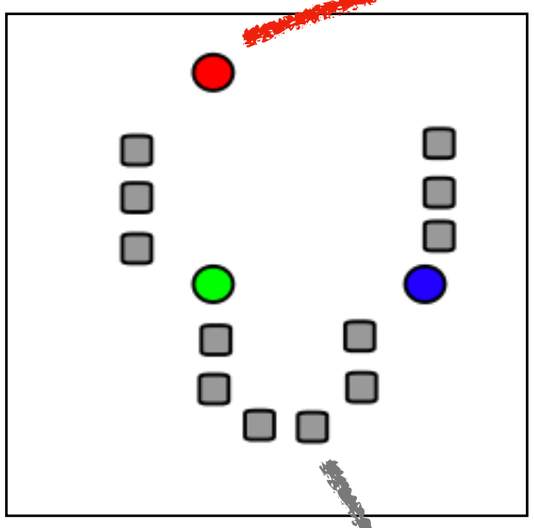
$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$



k-means clustering

E.g. $f(x) = x^{\alpha}(1-x)^{\beta}$

(α^*, β^*) : centroid



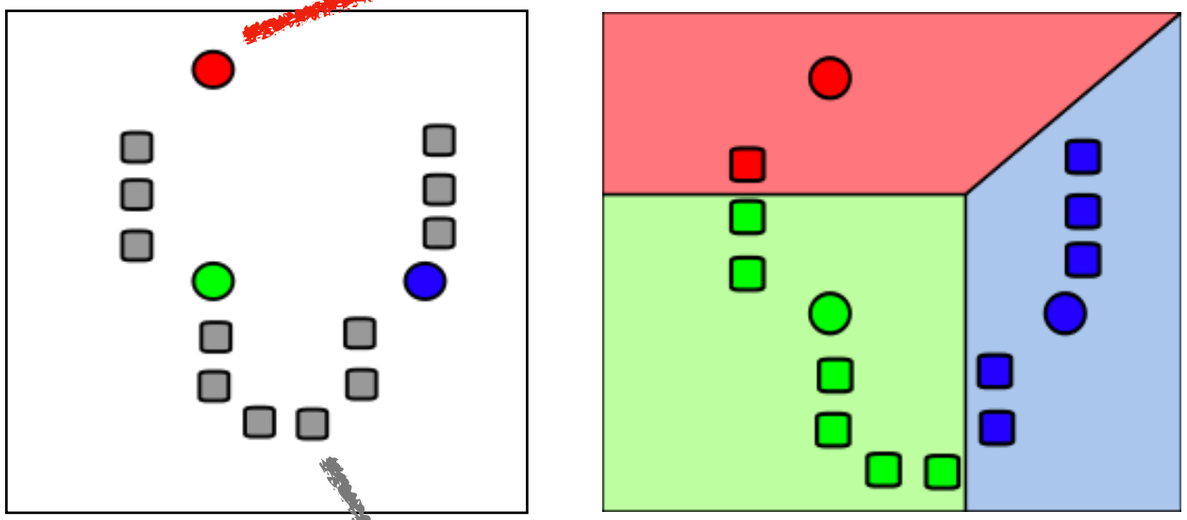
Initialization

(α_i, β_i) : replica

k-means clustering

E.g. $f(x) = x^{\alpha}(1-x)^{\beta}$

(α^*, β^*) : centroid



Initialization

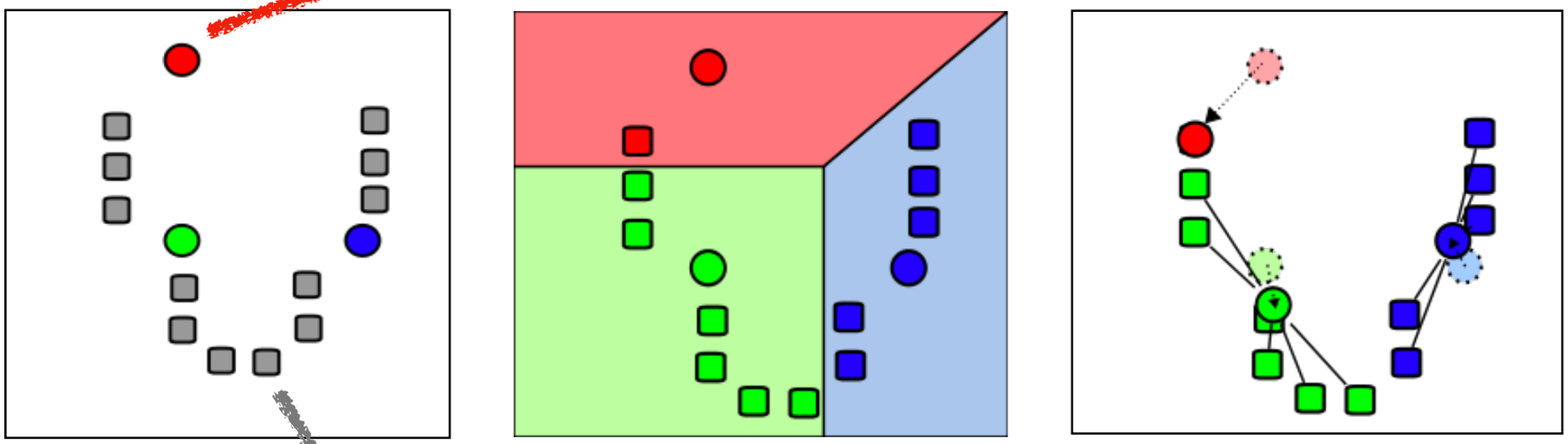
Assignment

(α_i, β_i) : replica

k-means clustering

E.g. $f(x) = x^{\alpha}(1-x)^{\beta}$

(α^*, β^*) : centroid



Initialization

Assignment

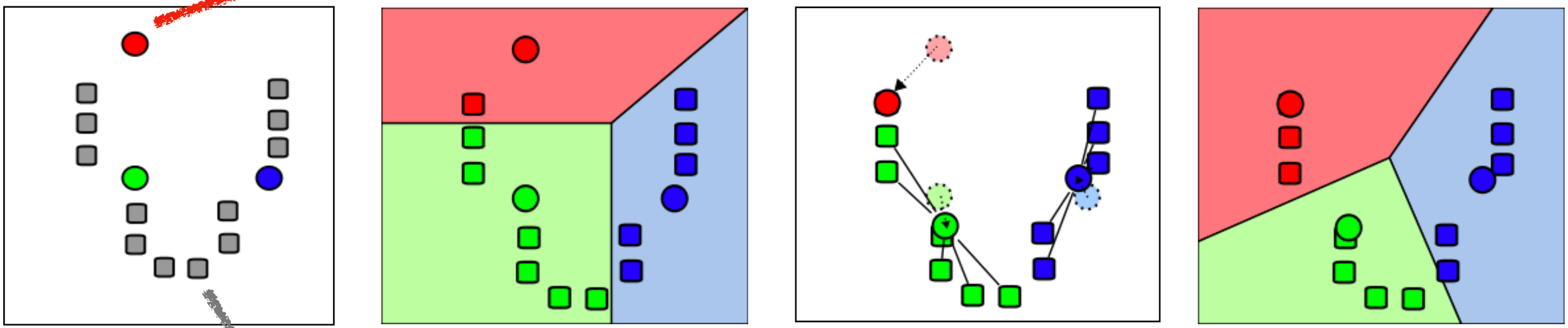
Update

(α_i, β_i) : replica

k-means clustering

E.g. $f(x) = x^{\alpha}(1-x)^{\beta}$

(α^*, β^*) : centroid



Initialization

Assignment

Update

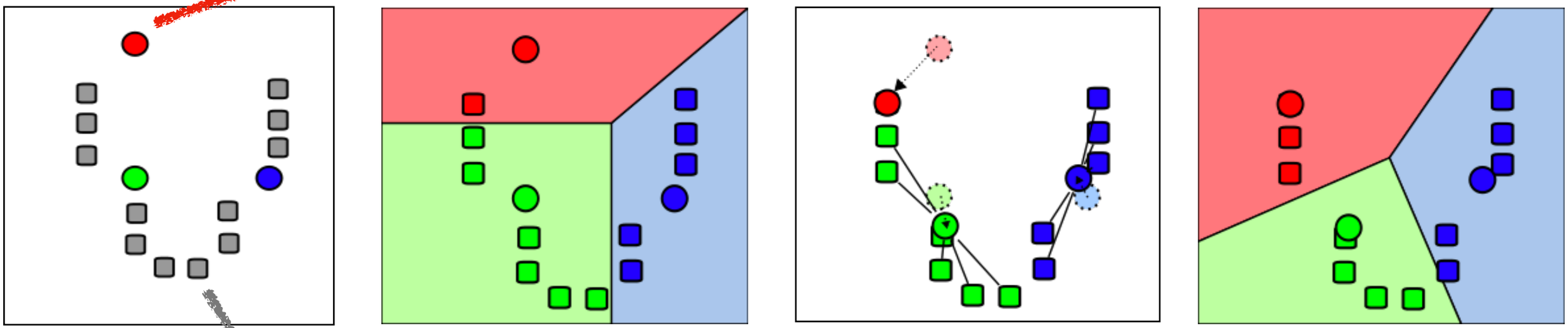
Assignment

(α_i, β_i) : replica

k-means clustering

E.g. $f(x) = x^{\alpha}(1-x)^{\beta}$

(α^*, β^*) : centroid



Initialization

Assignment

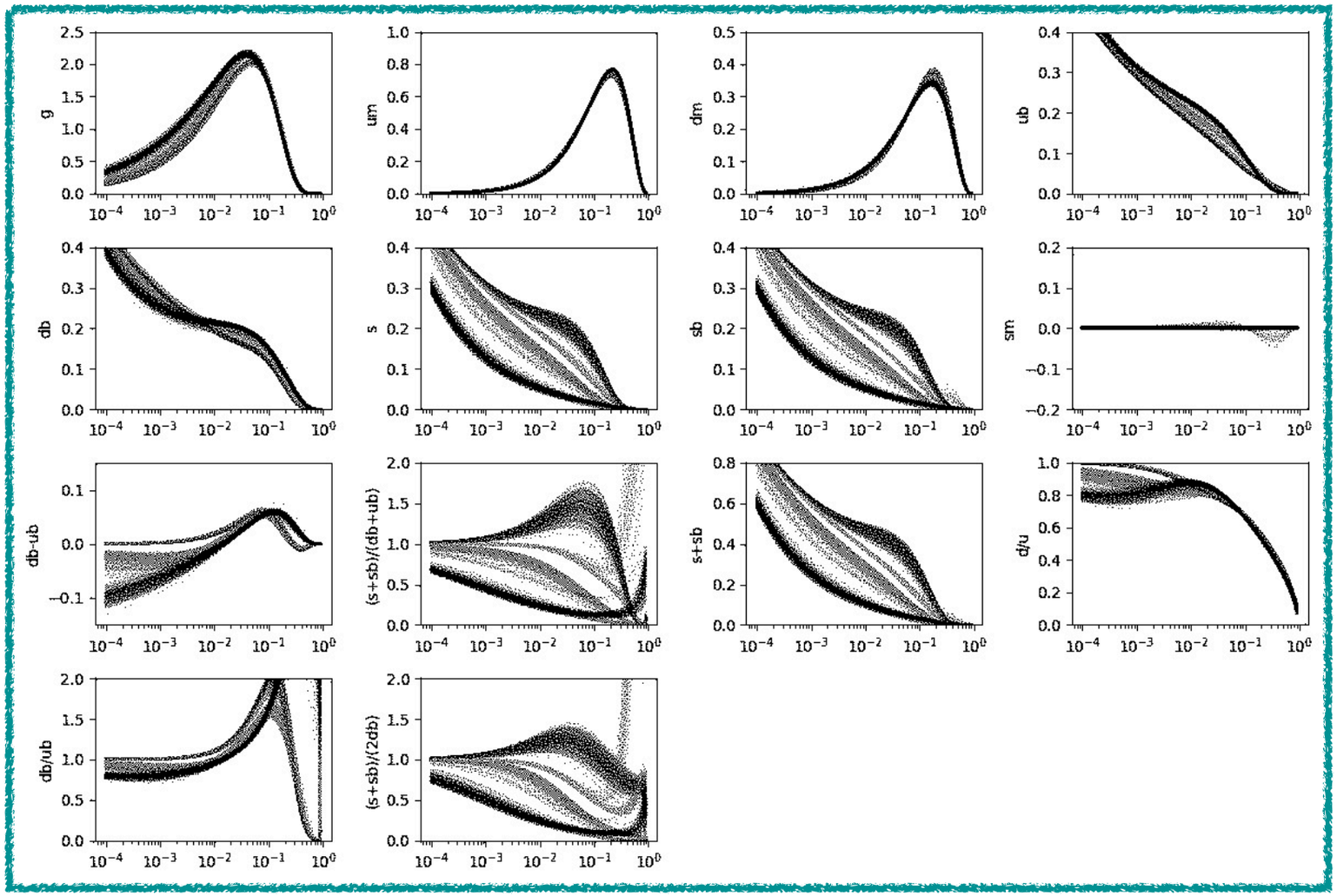
Update

Assignment

Repeat until convergence

(α_i, β_i) : replica

Discrminating multiple solutions

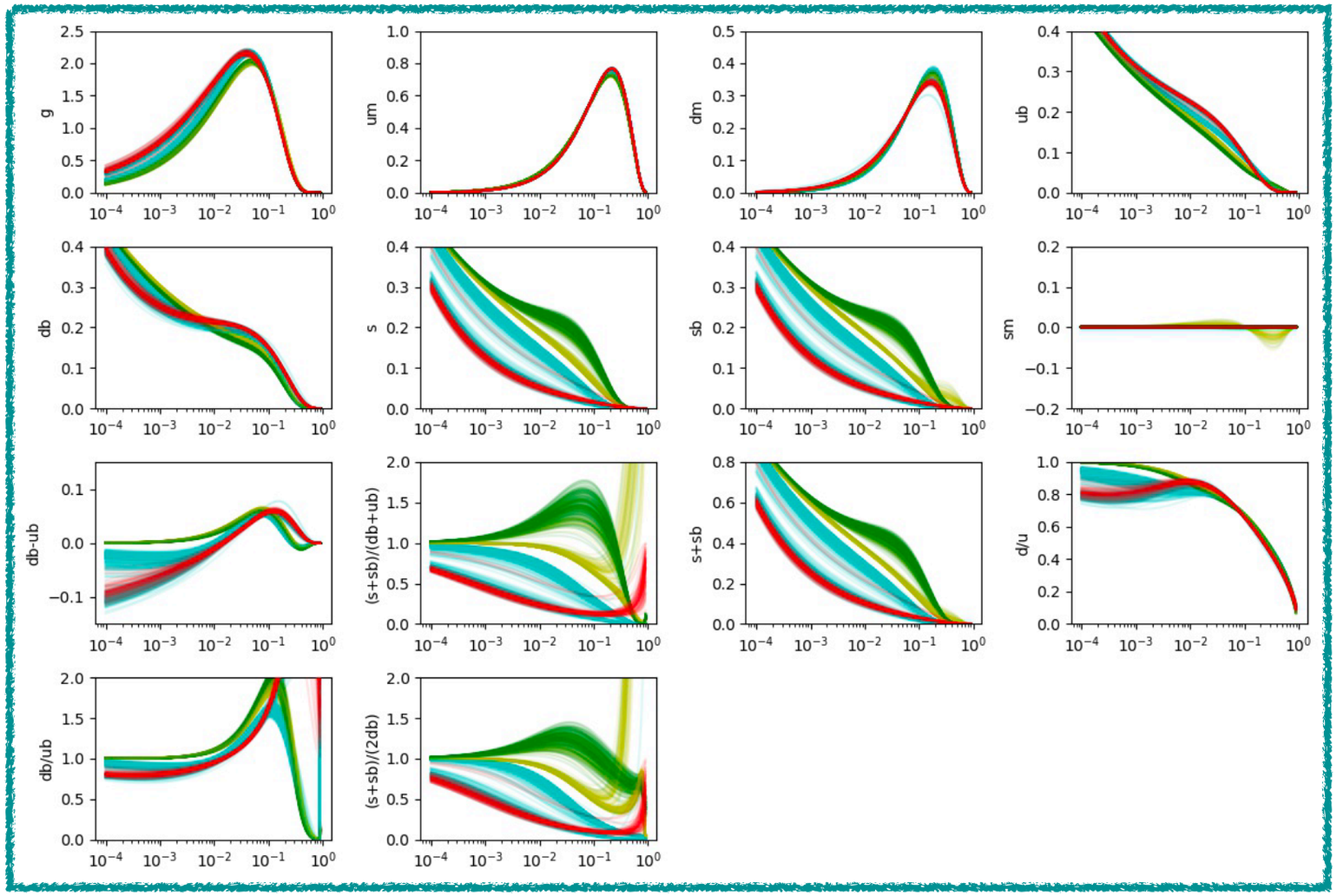


+ DIS data

+ DIS + DY data

+ SIDIS data

Discrminating multiple solutions



+ DIS data

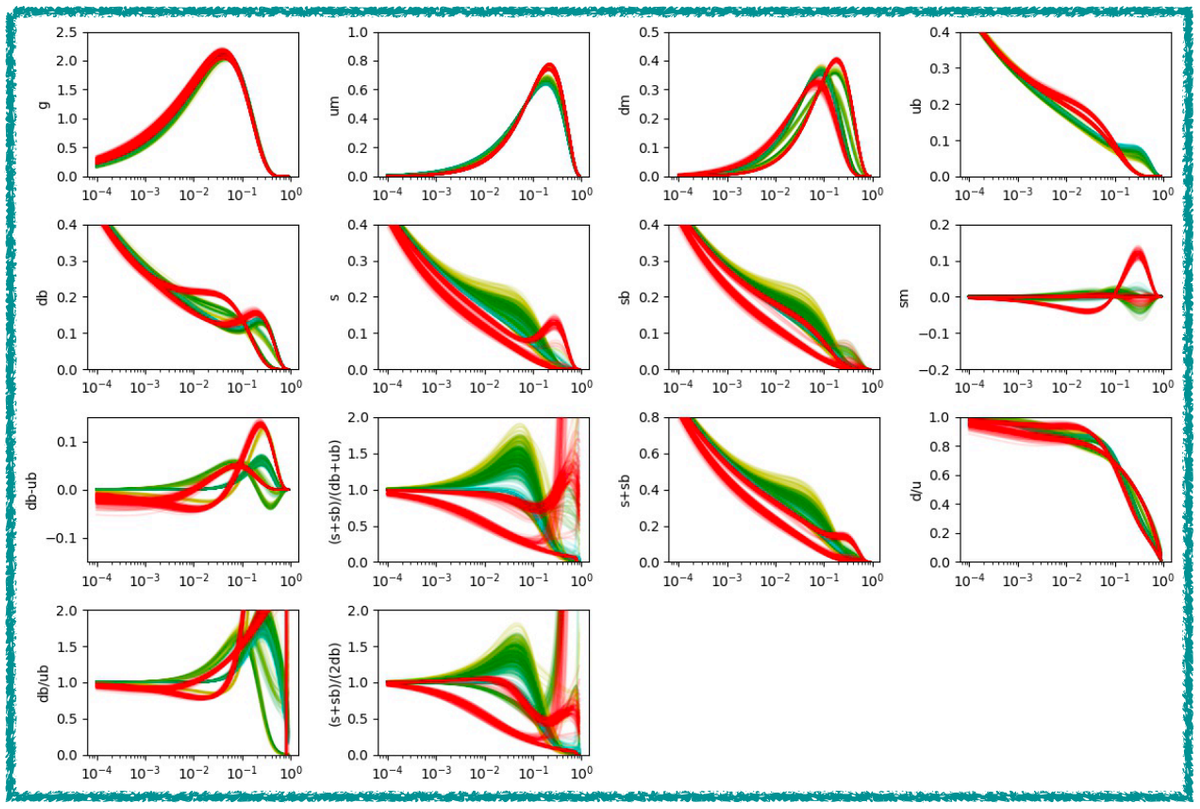
+ DIS + DY data

+ SIDIS data

Constraints on R_s

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

PDFs



$x f(x)$

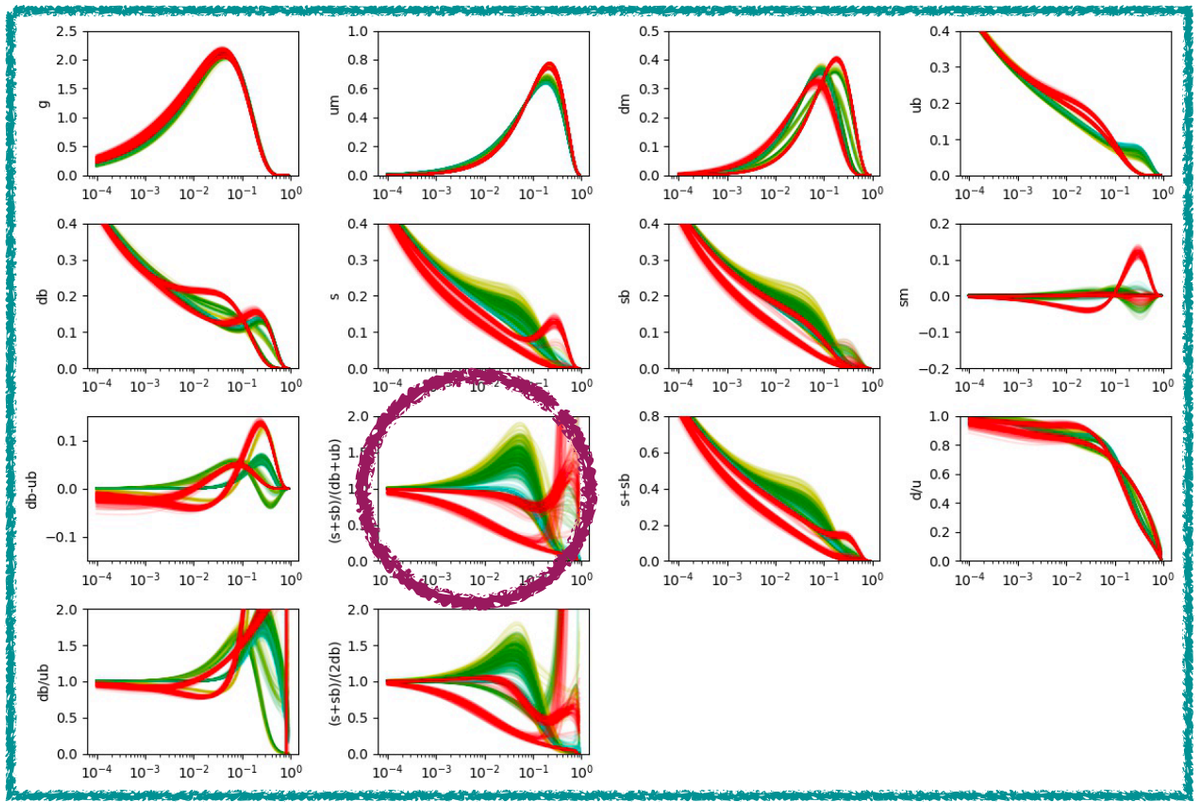
x

+ DIS data

Constraints on R_s

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

PDFs



$x f(x)$

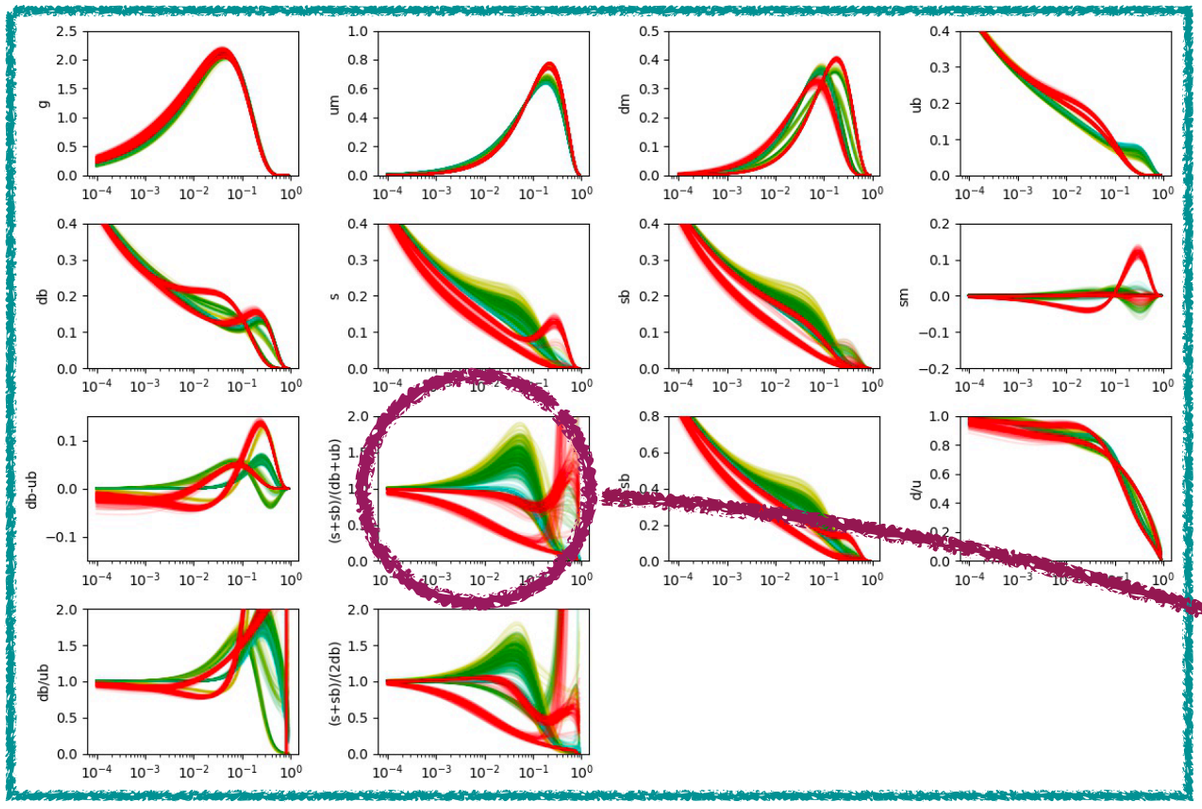
x

+ DIS data

Constraints on R_s

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

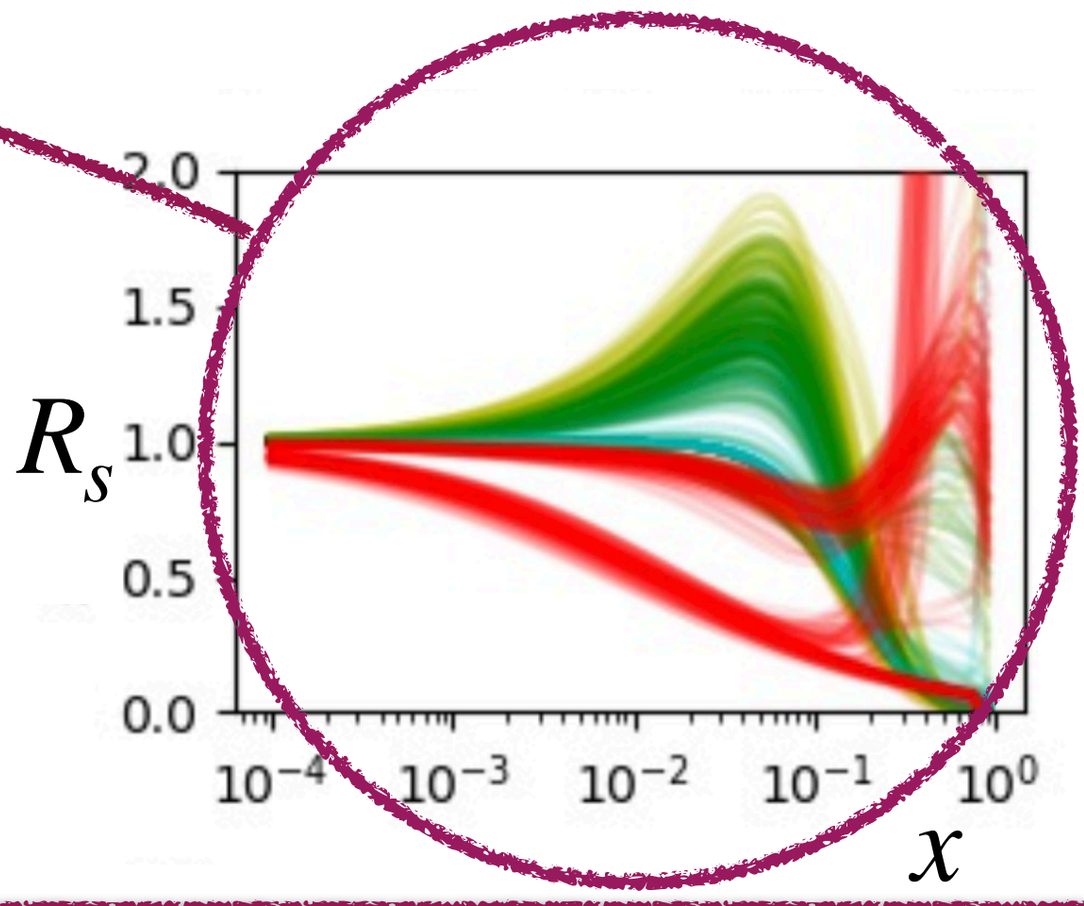
PDFs



$x f(x)$

x

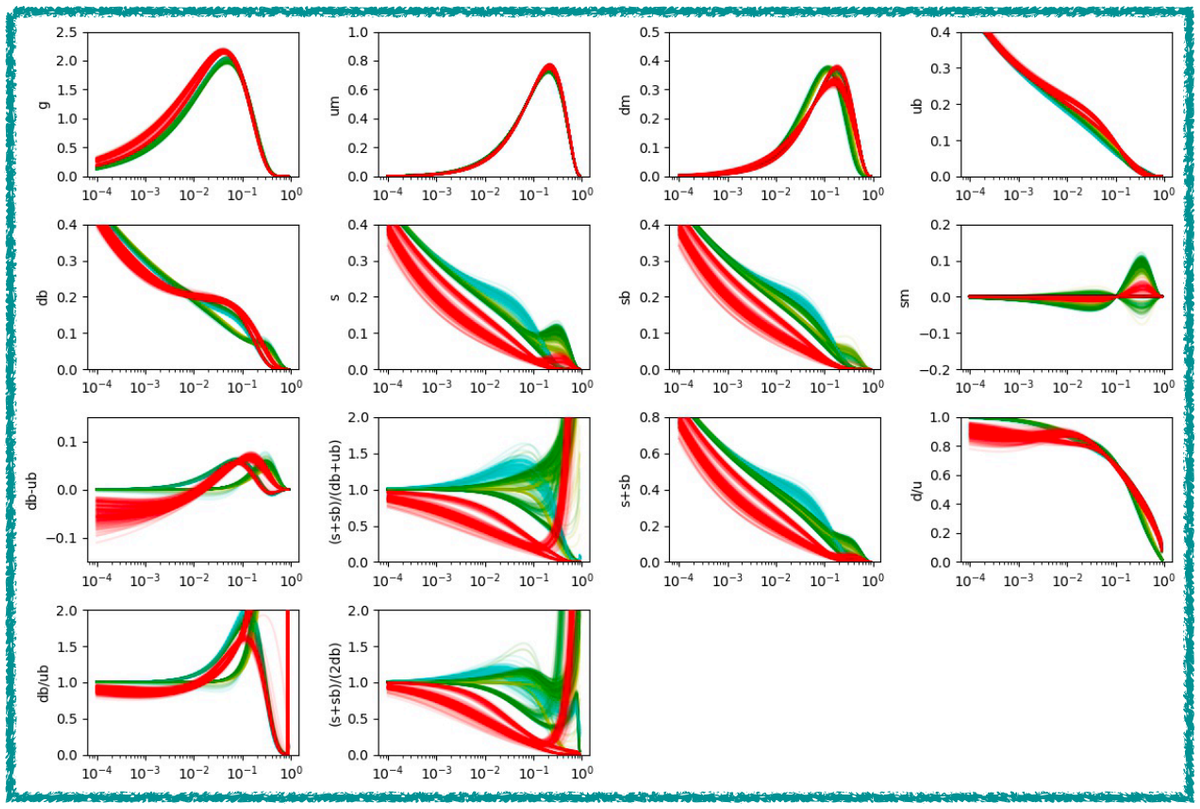
+ DIS data



Constraints on R_s

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

PDFs



$x f(x)$

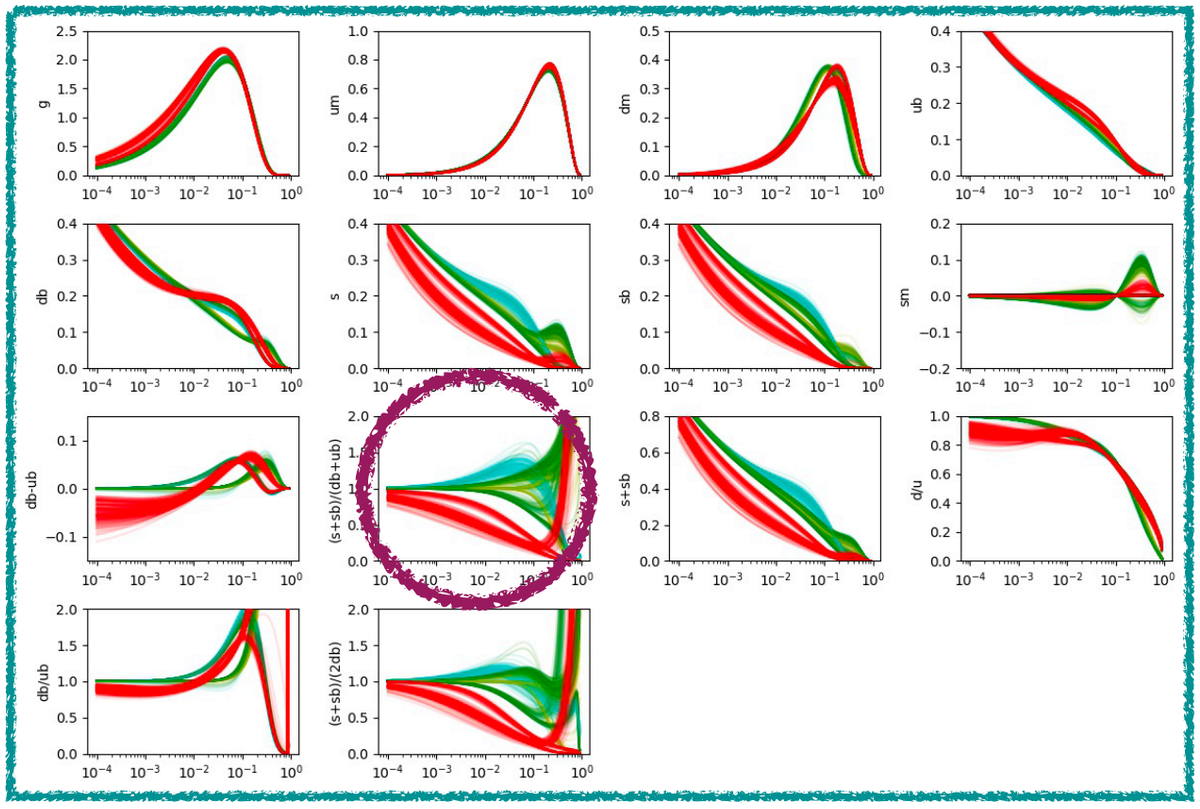
x

+ DIS data
+ DY data

Constraints on R_s

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

PDFs



$x f(x)$

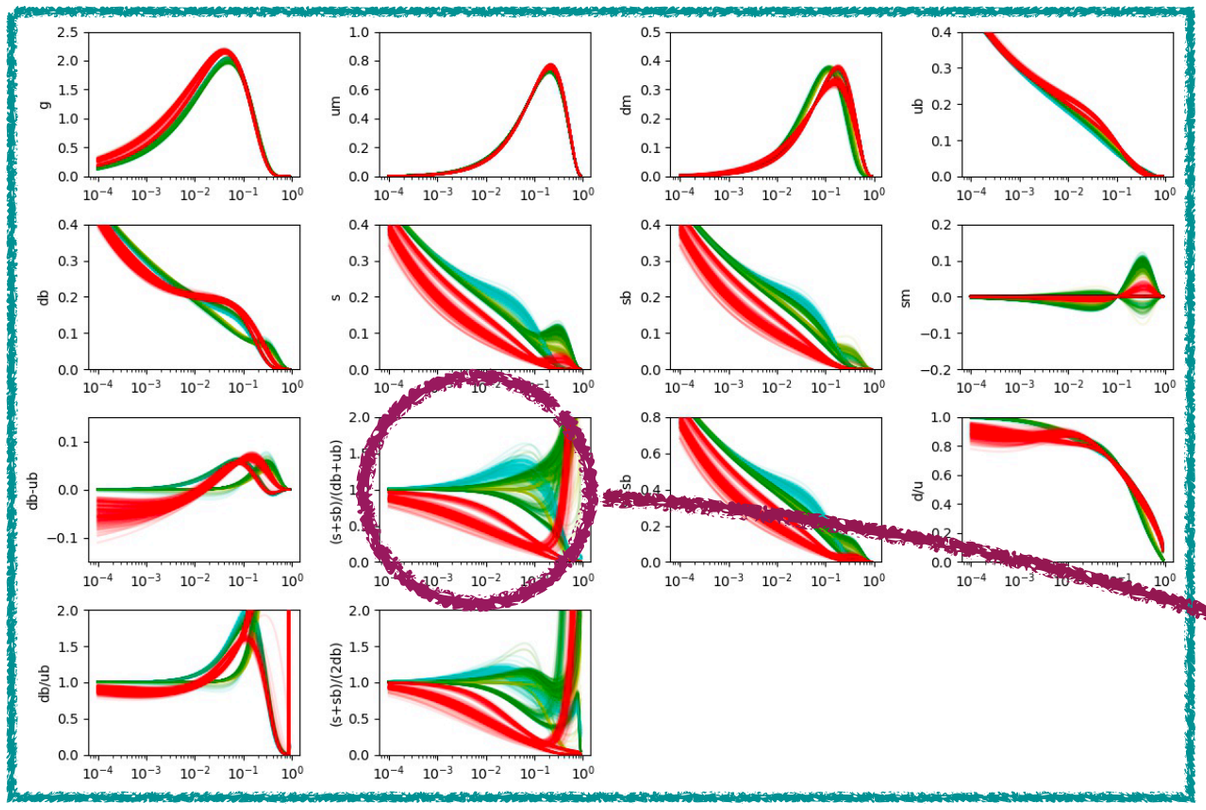
x

+ DIS data
+ DY data

Constraints on R_s

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

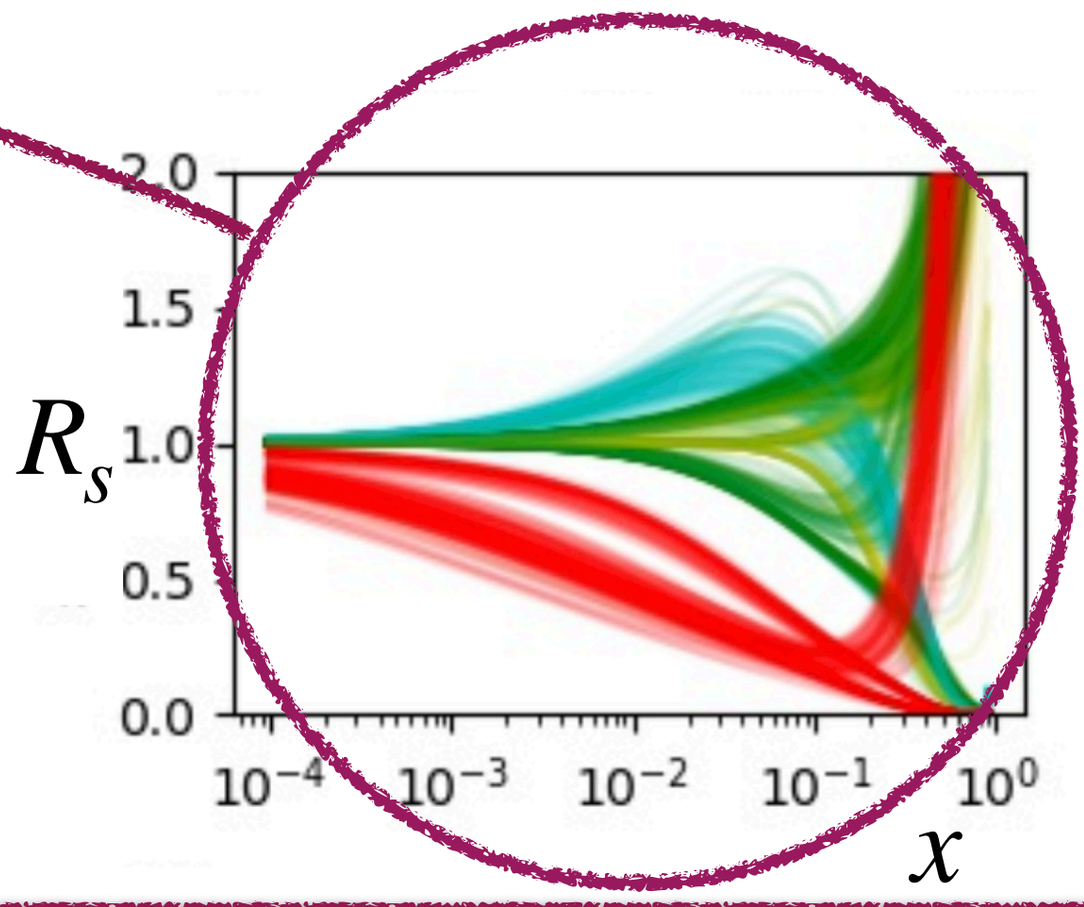
PDFs



$x f(x)$

x

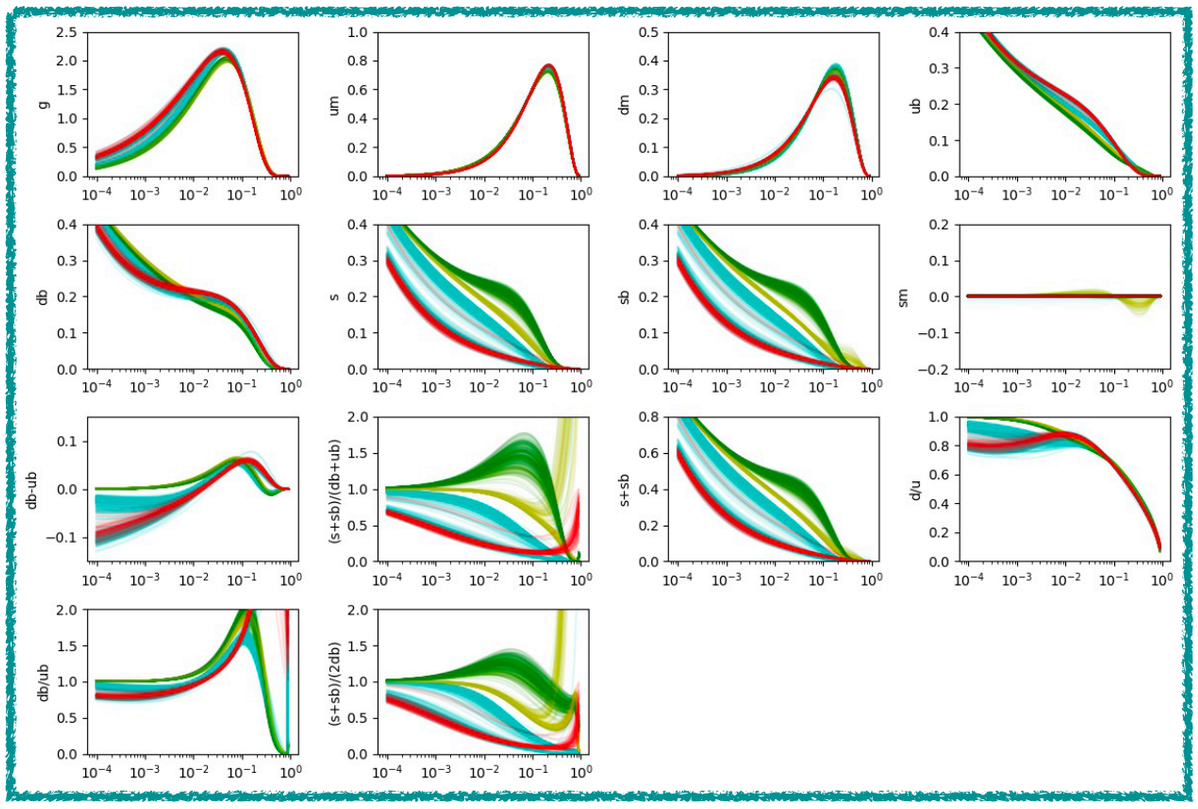
+ DIS data
+ DY data



Constraints on R_s

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

PDFs



$x f(x)$

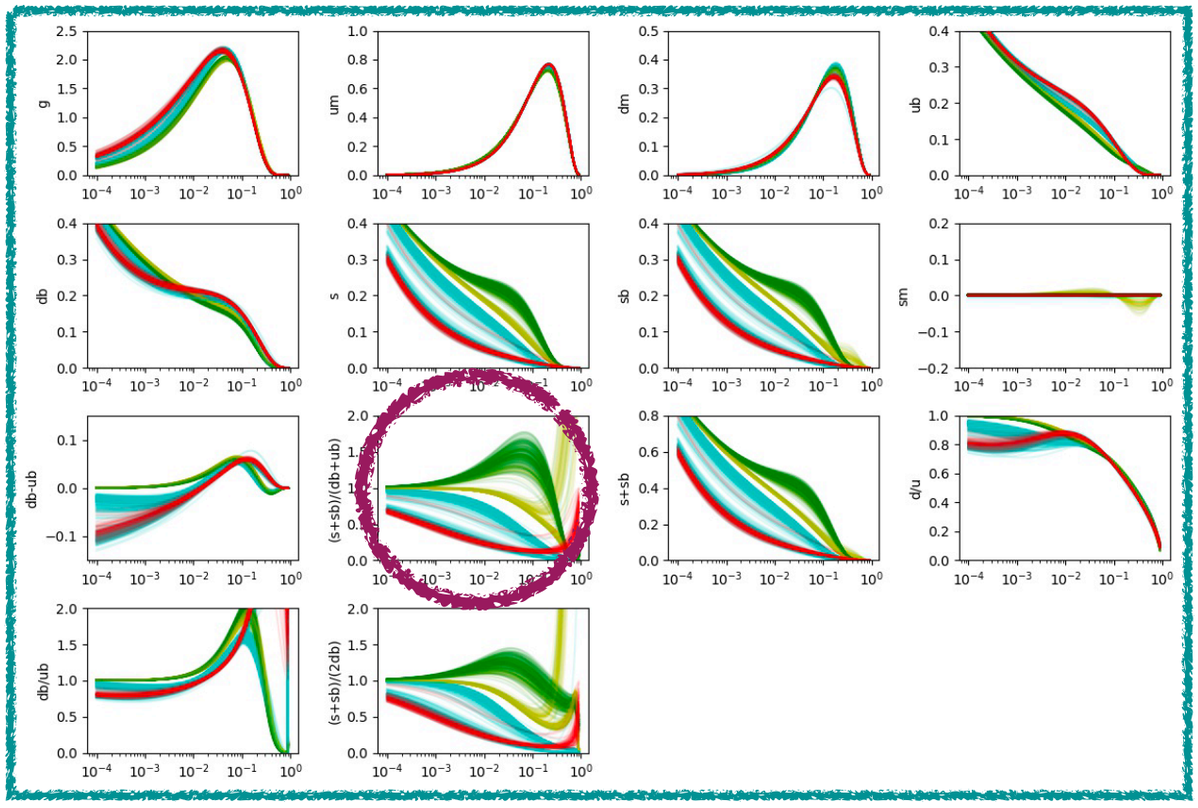
x

+ DIS data
+ DY data
+ SIA + SIDIS data

Constraints on R_s

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

PDFs



$x f(x)$

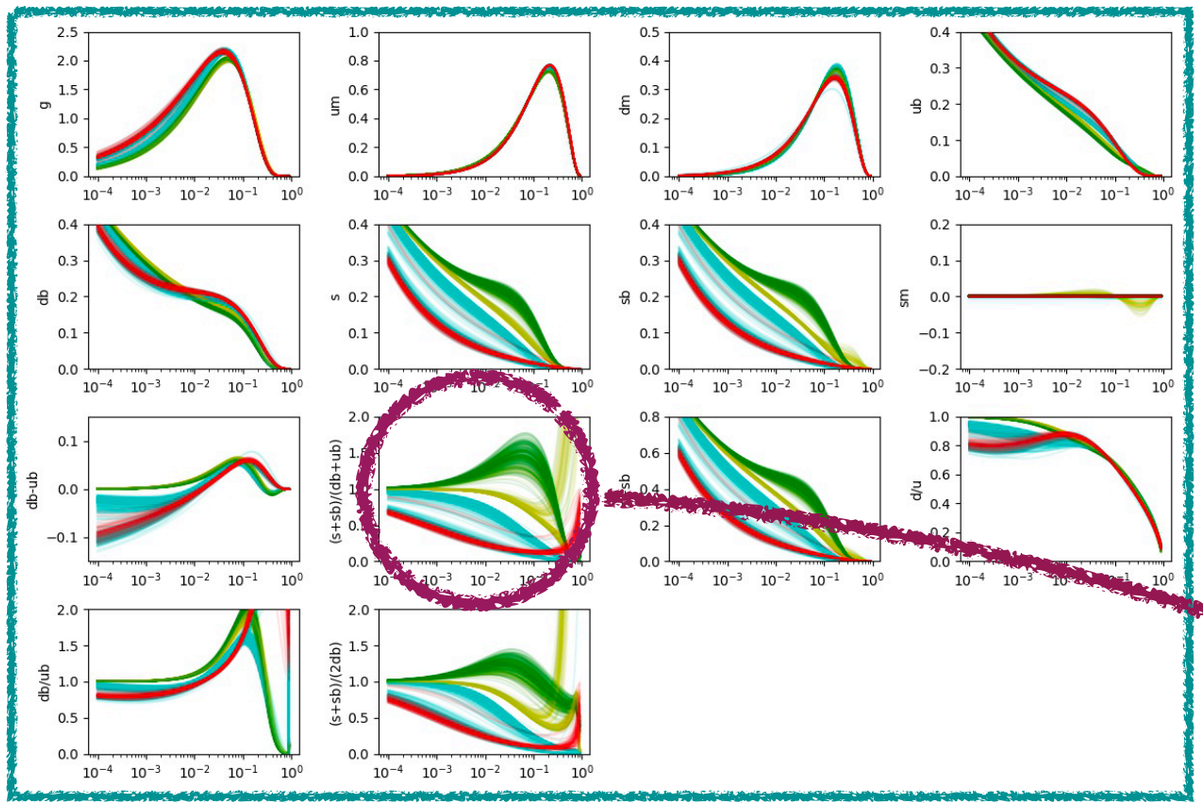
x

+ DIS data
+ DY data
+ SIA + SIDIS data

Constraints on R_s

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

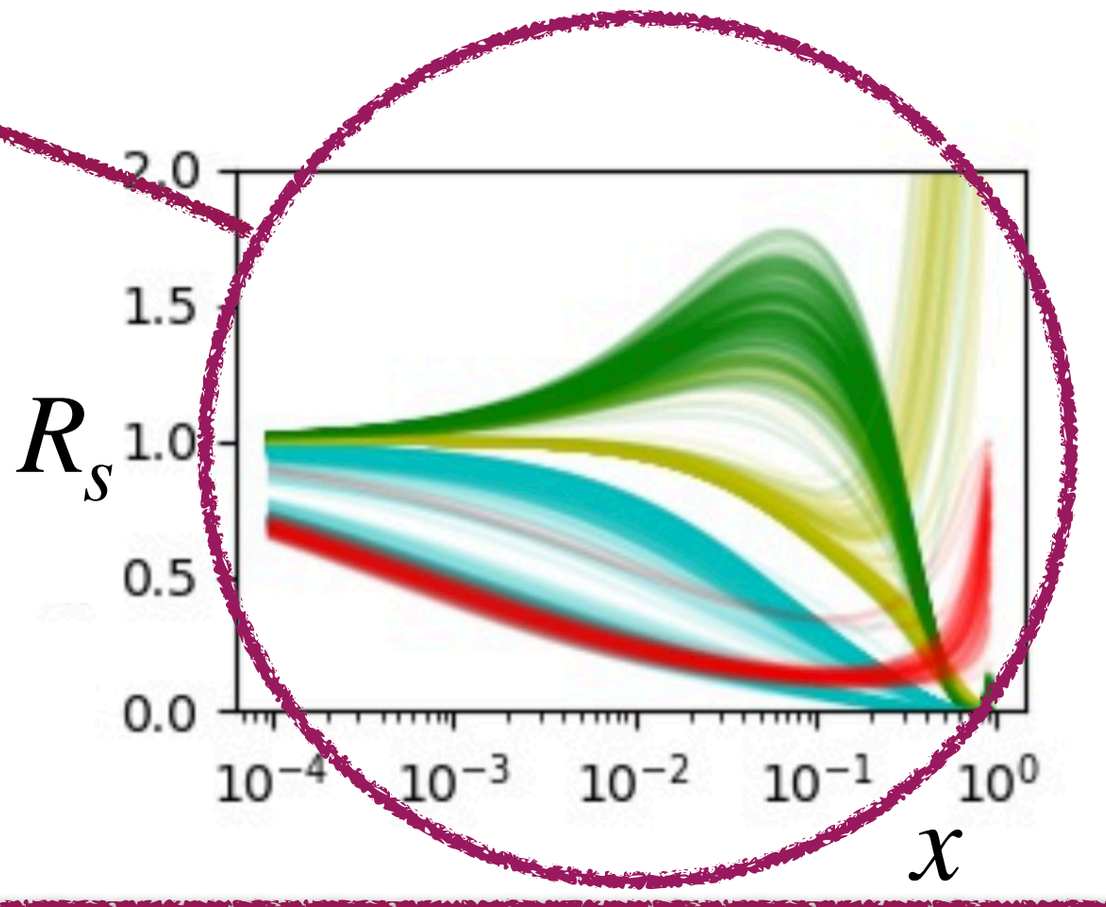
PDFs



$x f(x)$

x

+ DIS data
+ DY data
+ SIA + SIDIS data



SIDIS K-

Unfavored solutions

Large $s(x)$

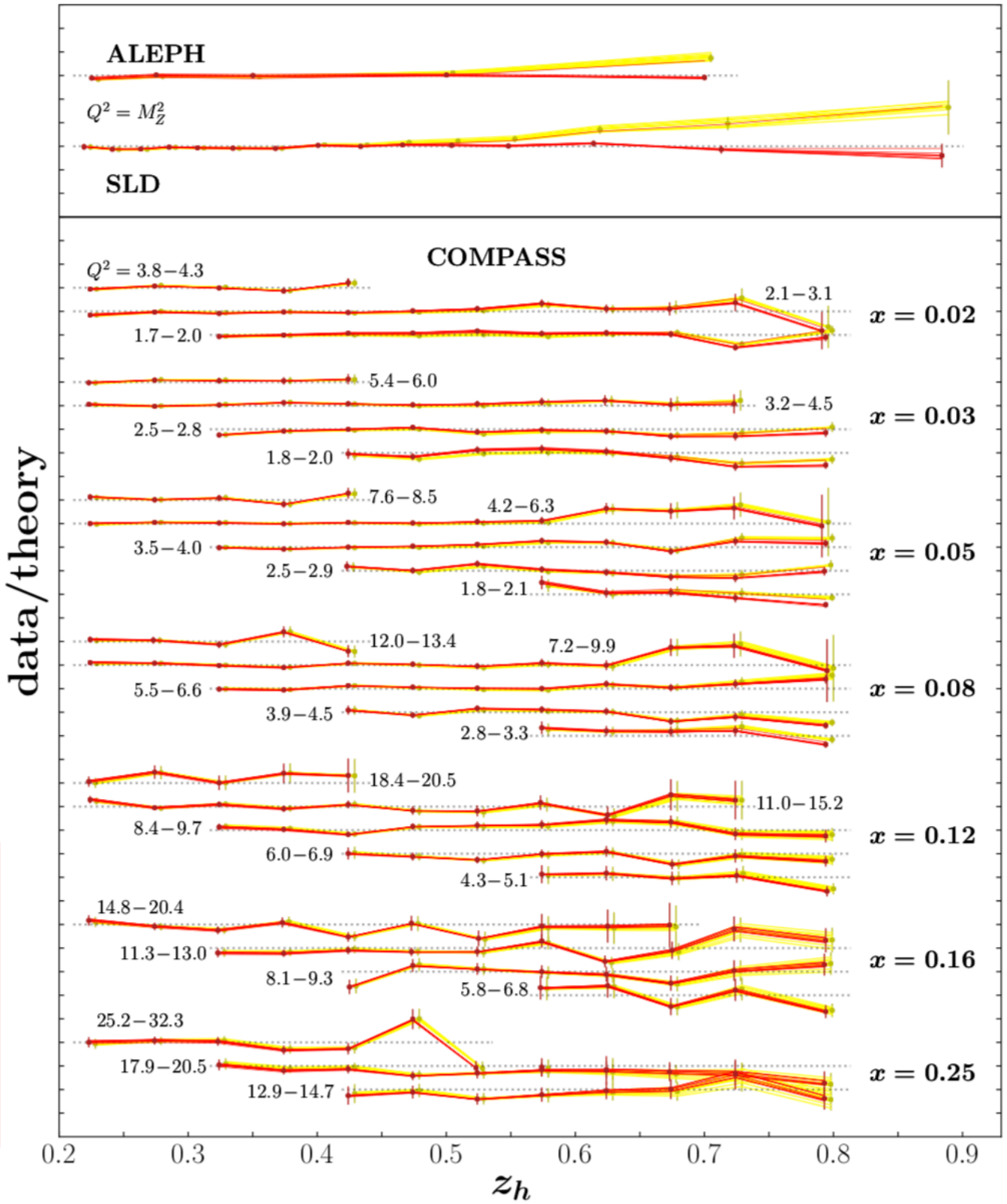
Small $D_{s^\pm}^{K^\pm}(z)$

Favored solutions

Large $D_{s^\pm}^{K^\pm}(z)$

Small $s(x)$

$\chi^2_{\text{SLD}} = 4.10$	$\chi^2_{\text{SLD}} = 1.38$
$\chi^2_{\text{ALEPH}} = 4.62$	$\chi^2_{\text{ALEPH}} = 0.34$

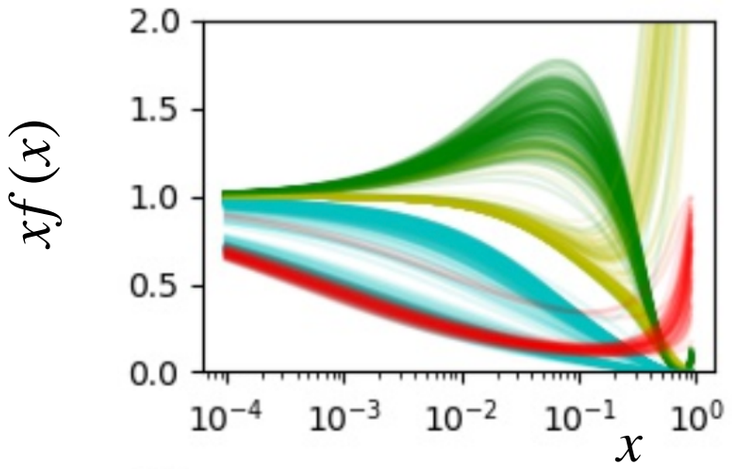


SIA

SIDIS

JAM19: Selection criteria

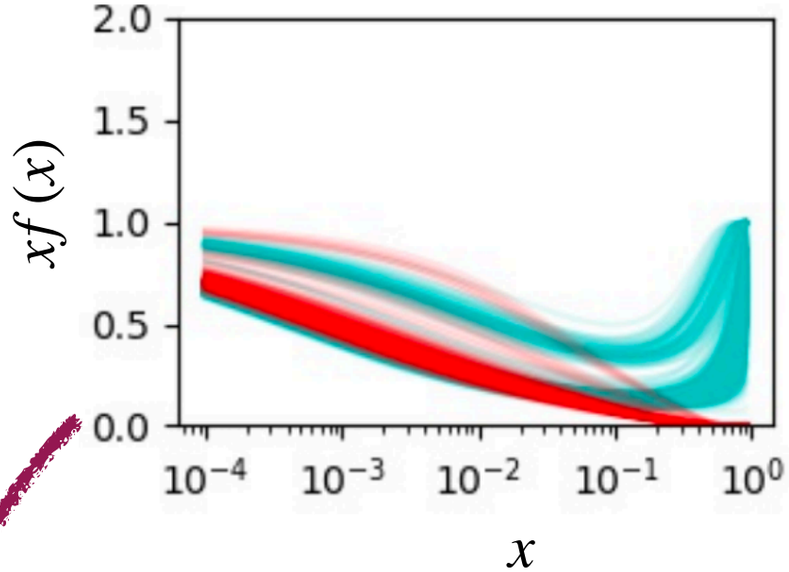
- Apply K-mean clustering

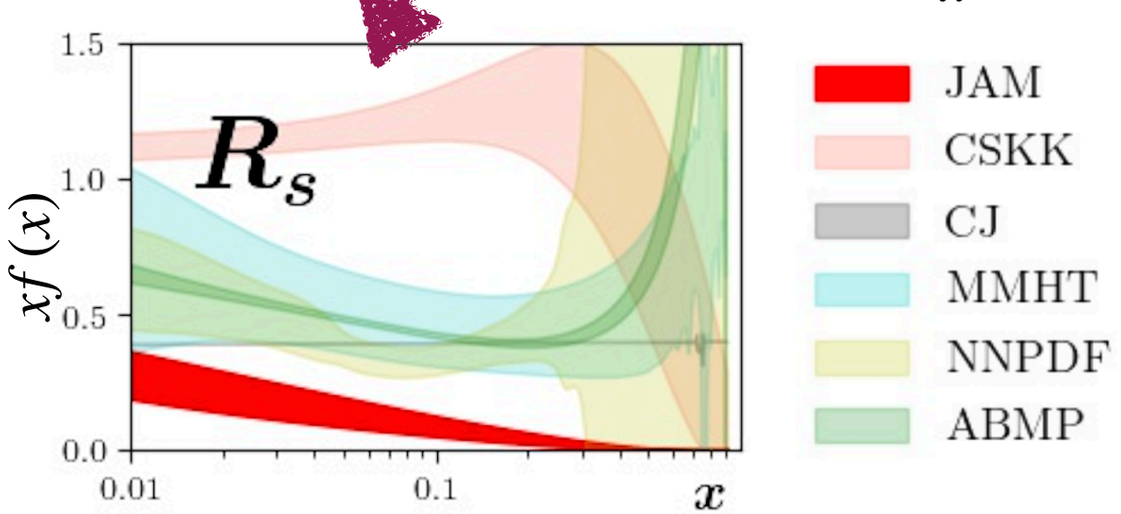


- Classify clusters by increasing order in extended reduced χ^2

$$\frac{\chi^2}{N_{\rm tot}} + \sum_{\rm exp} \frac{\chi^2_{\rm exp}}{N_{\rm exp}}$$

- Perform a new sampling with flat priors around the best cluster





Summary

- MC statistical methods are important for a robust extraction of non-perturbative collinear distributions

→ Crucial for future Global TMDs, GPDs analysis

- First MC fit of PDFs and FFs using DIS, DY, SIDIS and SIA data

- JAM19 Methodology: MC (multi-steps), k-means clustering, extended reduced χ^2

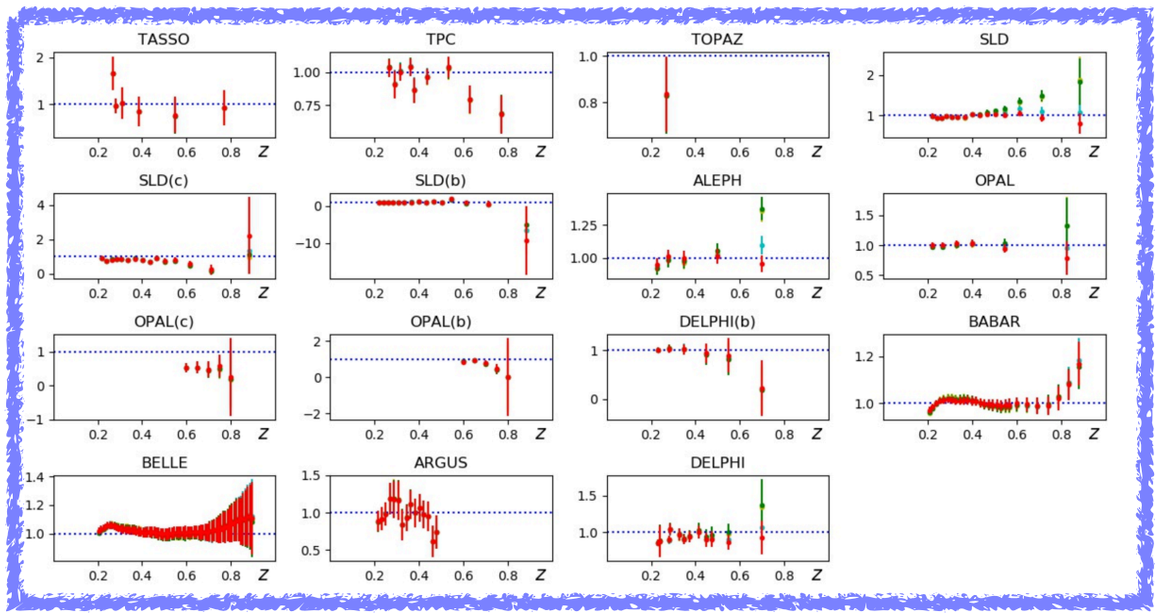
- Strange PDF strongly suppressed

Thanks

Backup

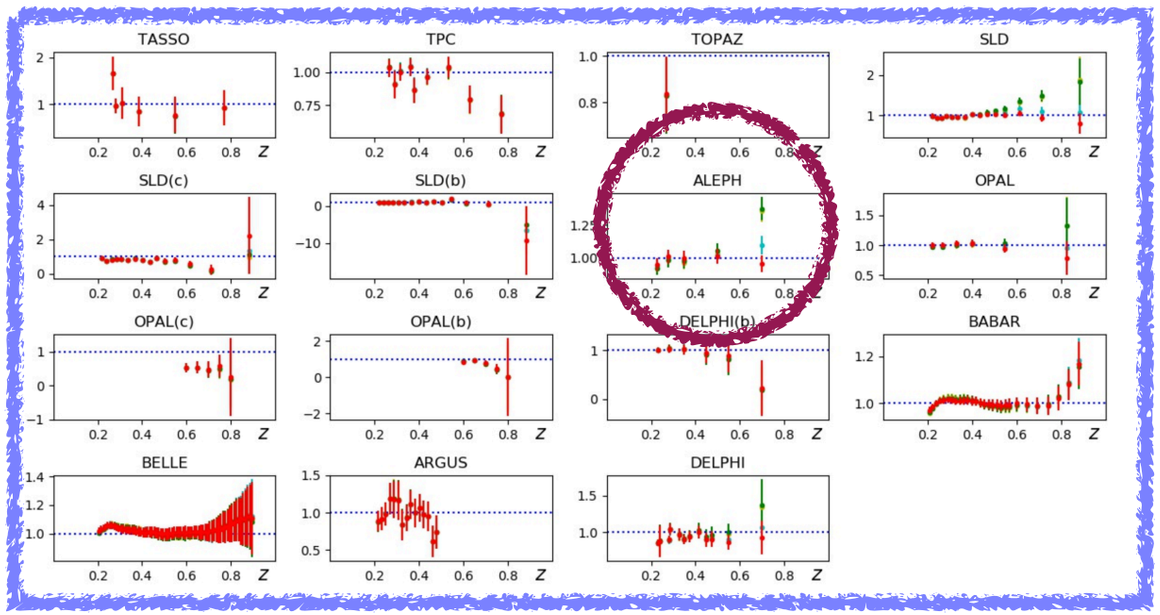
SIA K+/K- data

Data/Theory

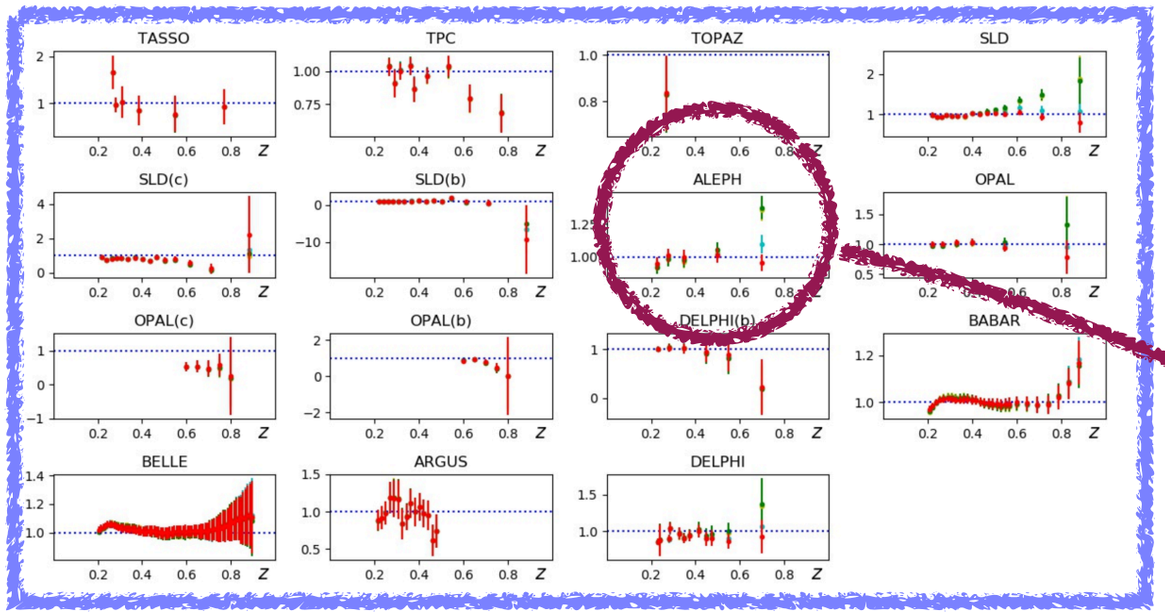


SIA K+/K- data

Data/Theory



SIA K+/K- data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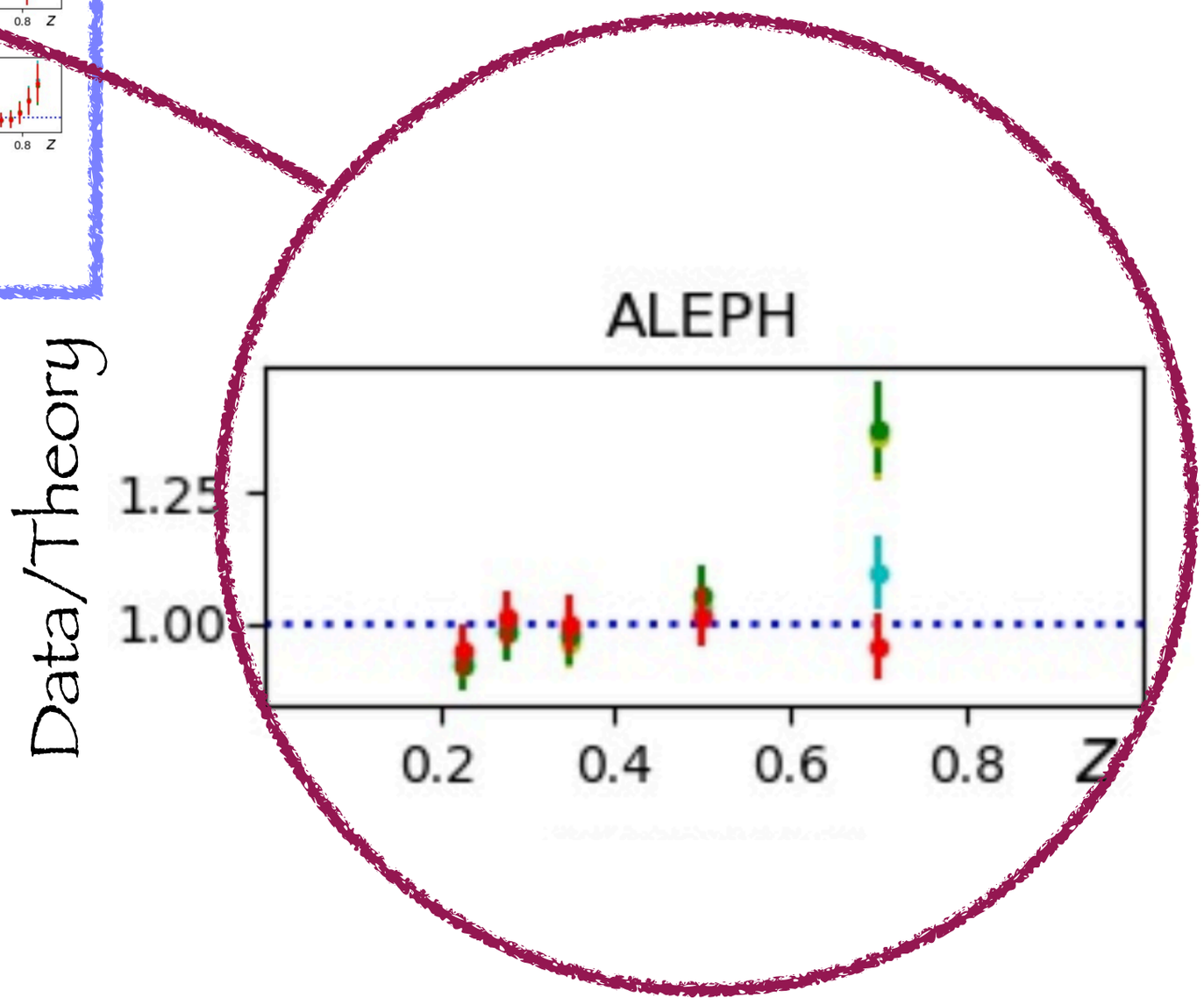
TPC
TOPAZ
SLD
SLD(c)
SLD(b)
ALEPH
OPAL
OPAL(c)
OPAL(b)
DELPHI(b)
BABAR
BELLE
ARGUS
DELPHI
Data/Theory
Z


ALEPH
Data/Theory
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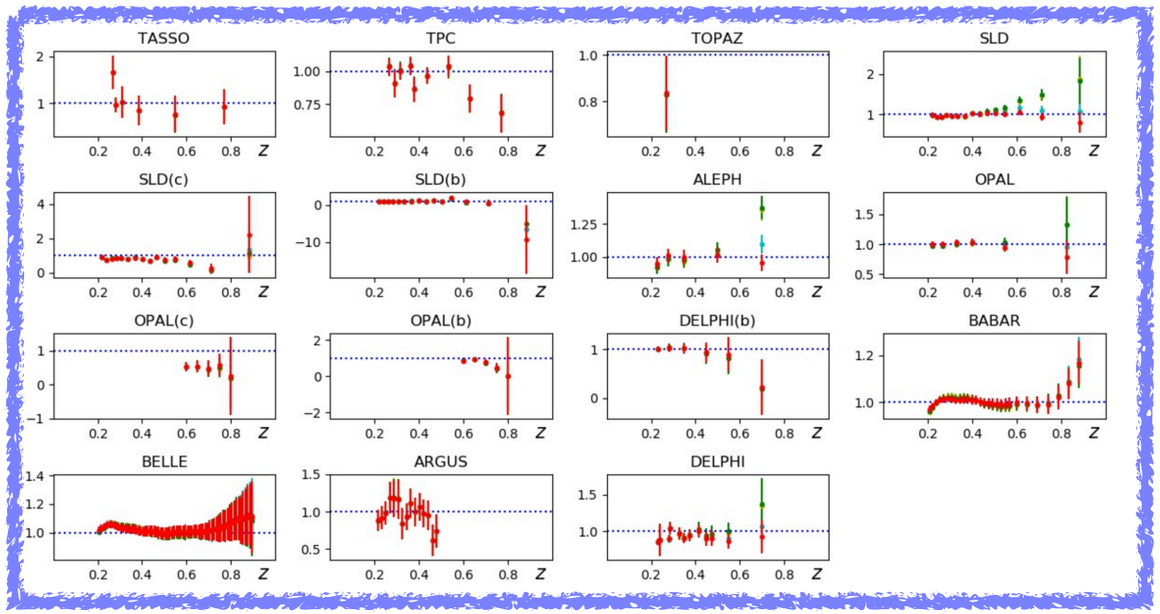
0.6
0.8
Z

SIA K+/K- data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TPC
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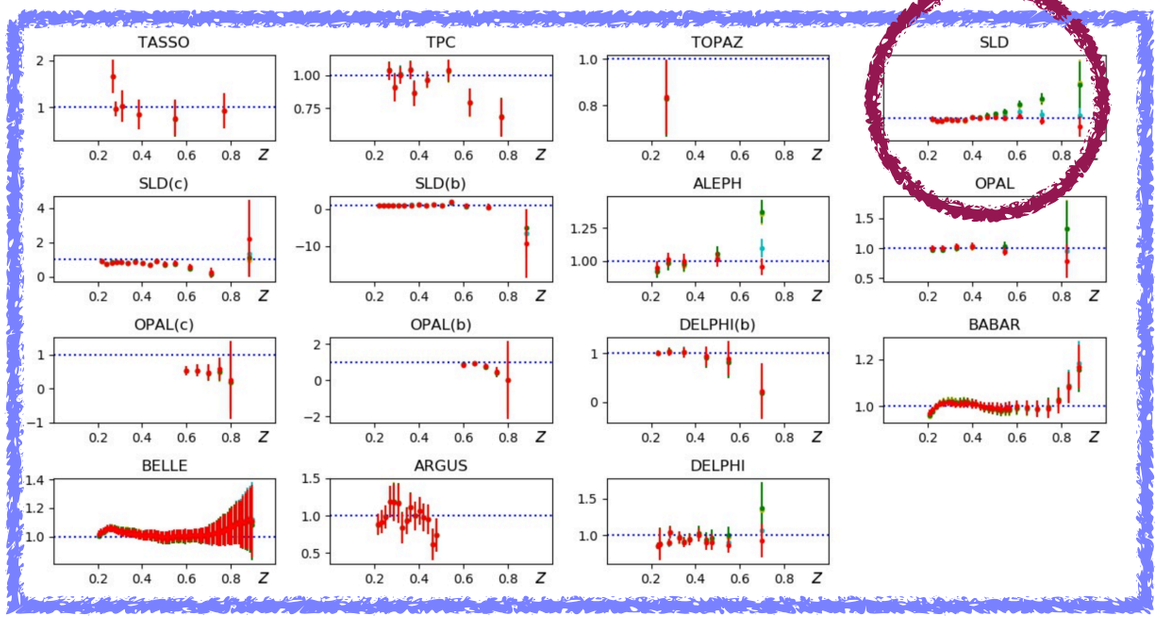
SLD
SLD(c)
SLD(b)
ALEPH
OPAL
OPAL(c)
OPAL(b)
DELPHI(b)
BABAR
BELLE
ARGUS
DELPHI
Data/Theory
z

SIA K+/K- data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TPC
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SLD(c)
SLD(b)
ALEPH
OPAL
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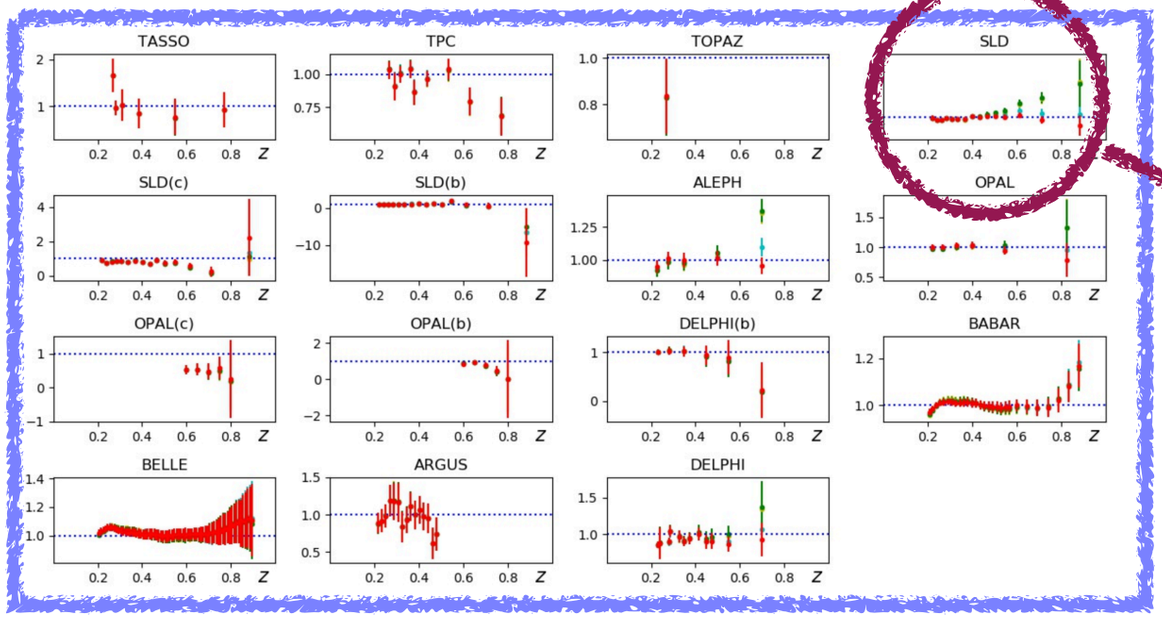
OPAL(b)
DELPHI(b)
BABAR
BELLE
ARGUS
DELPHI
Data/Theory
z

SIA K+/K- data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TPC
TOPAZ
SLD
SLD(c)
SLD(b)
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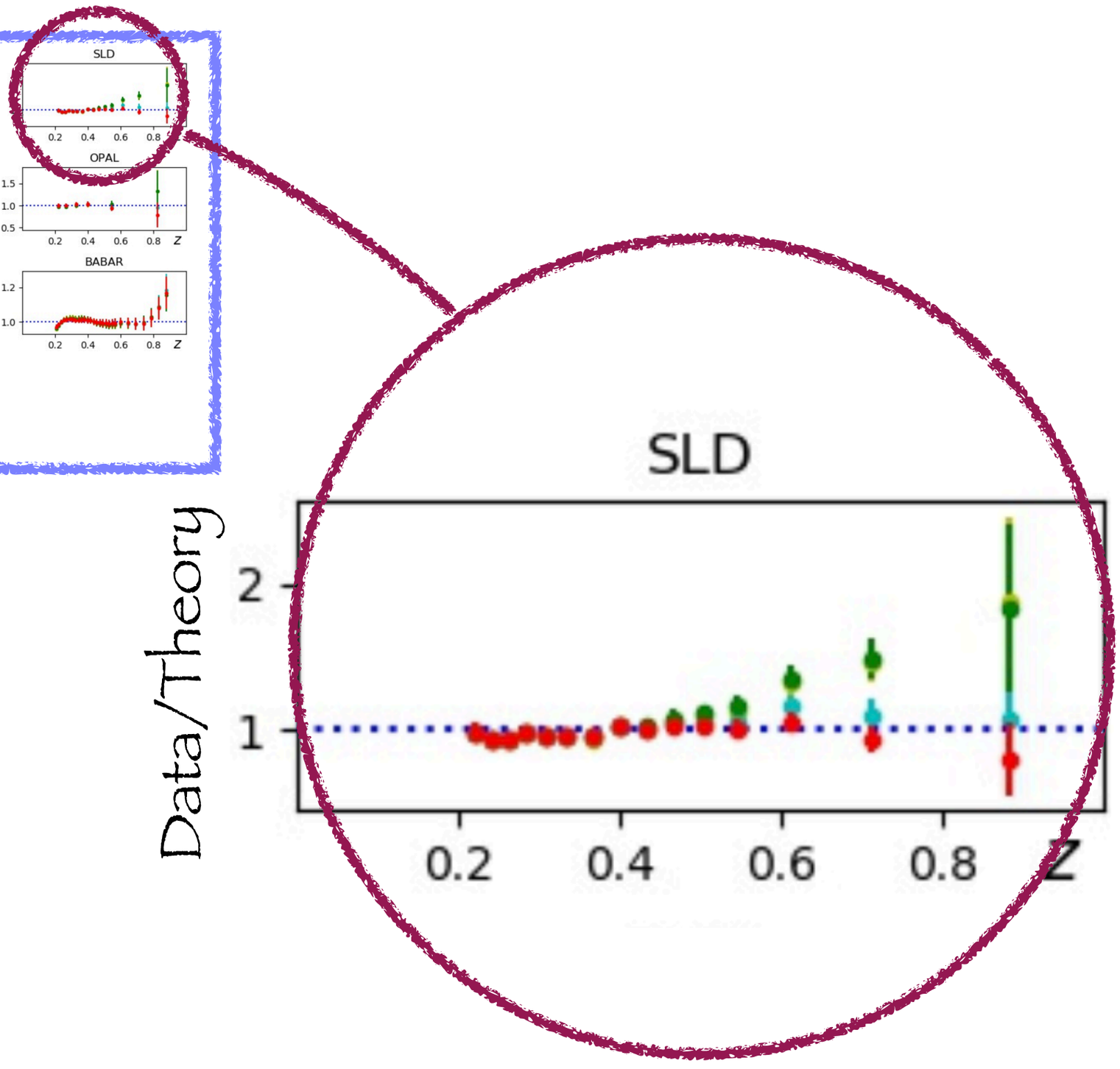
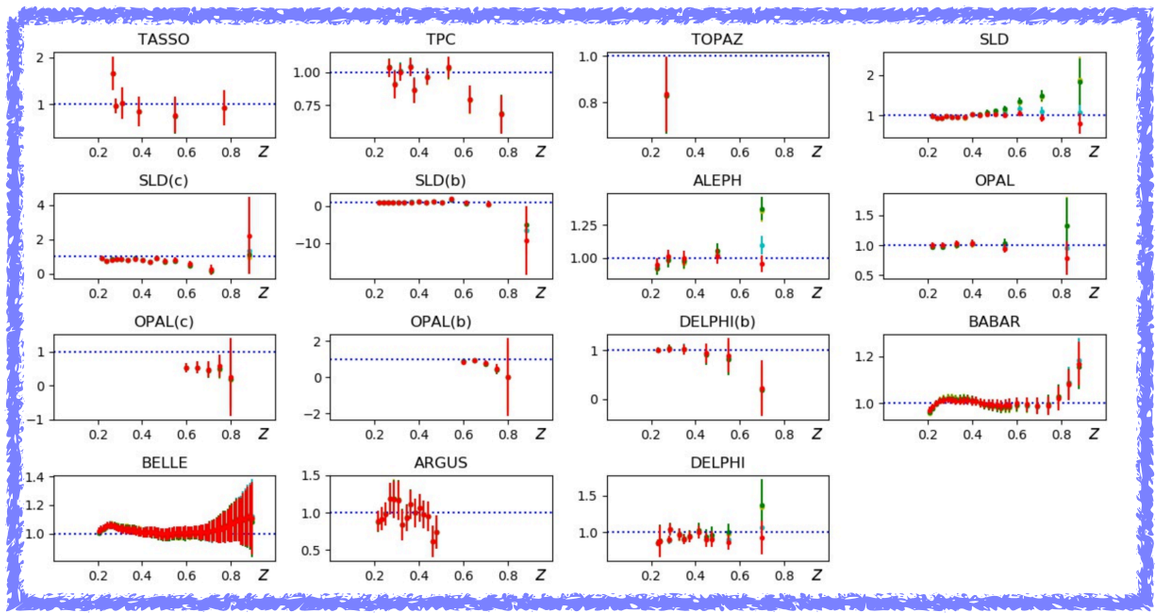
OPAL
OPAL(c)
OPAL(b)
DELPHI(b)
BABAR
BELLE
ARGUS
DELPHI
Data/Theory
Z


SLD
Data/Theory
Z

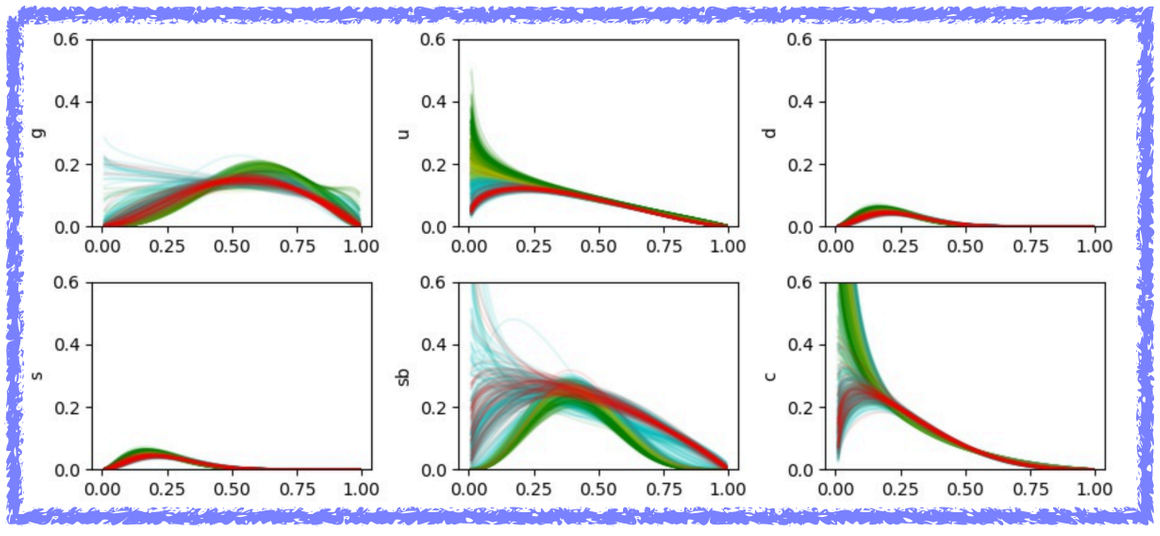
SIA K+/K- data

Data/Theory



z

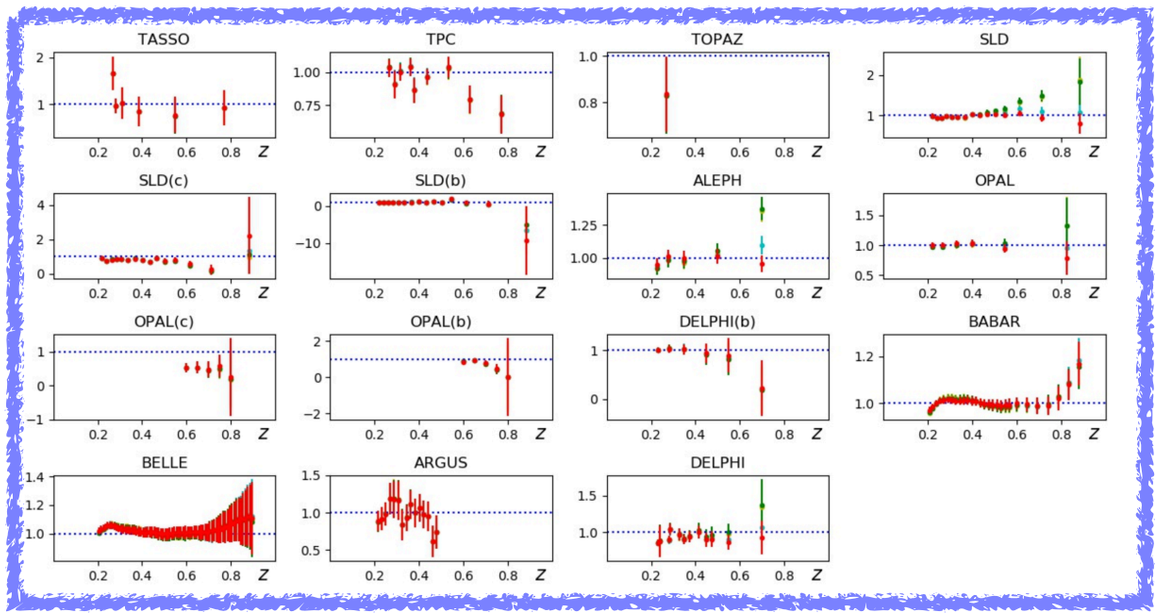
$zD_q^{K^+}$



z

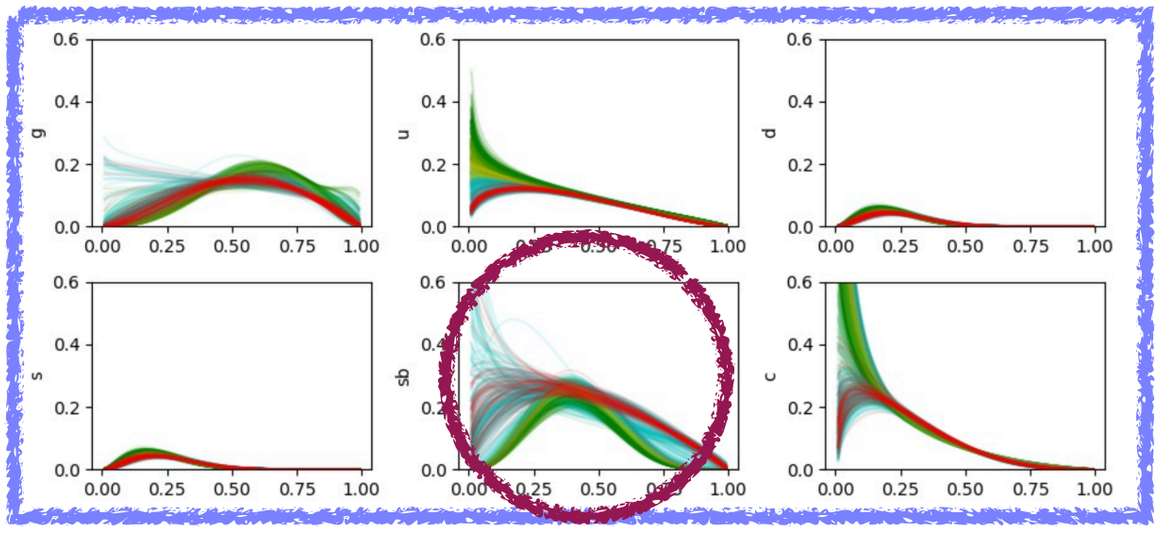
SIA K+/K- data

Data/Theory



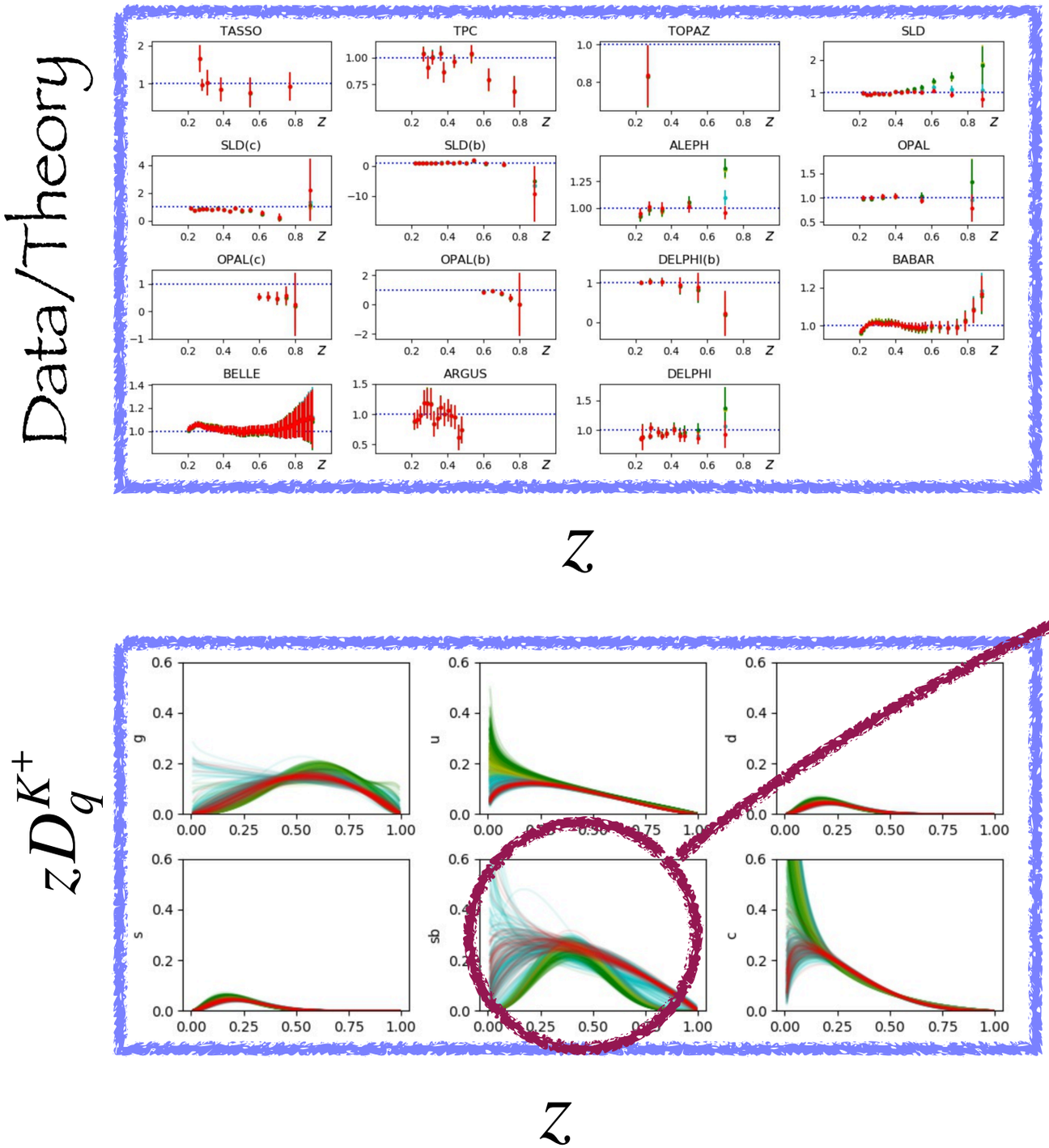
z

$zD_q^{K^+}$

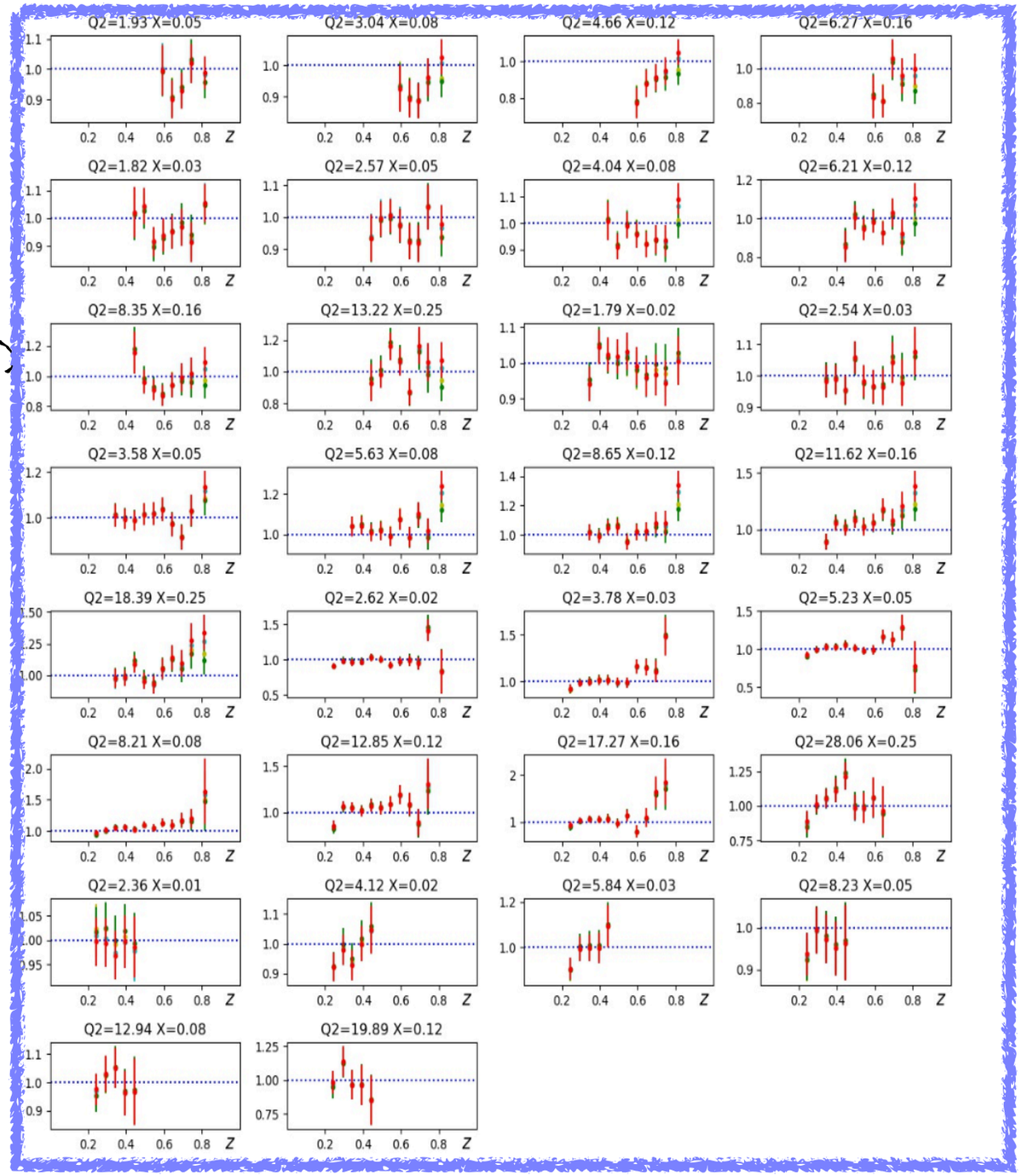


z

SIA K+/K- data


Data/Theory
TASSO
TPC
TOPAZ
SLD
SLD(c)
SLD(b)
ALEPH
OPAL
OPAL(c)
OPAL(b)
DELPHI(b)
BABAR
BELLE
ARGUS
DELPHI
z
$zD_q^{K^+}$
g
u
d
s
sb
c
$\bar{s} \to K^+$

SIDIS K+ data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Q2=2.57 X=0.05
Q2=4.04 X=0.08
Q2=6.21 X=0.12
Q2=8.35 X=0.16
Q2=13.22 X=0.25
Q2=1.79 X=0.02
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Q2=17.27 X=0.16
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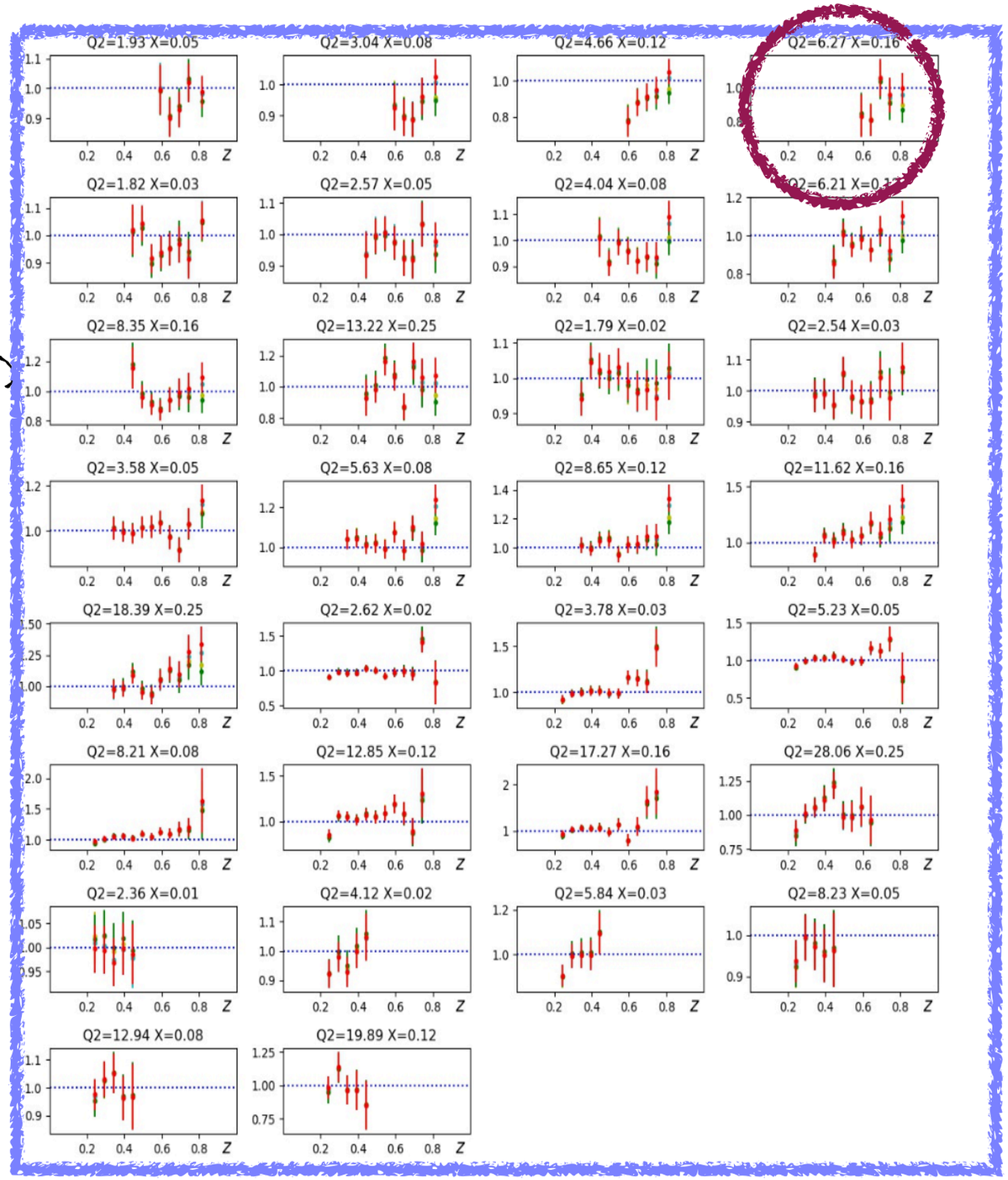
Q2=2.36 X=0.01
Q2=4.12 X=0.02
Q2=5.84 X=0.03
Q2=8.23 X=0.05
Q2=12.94 X=0.08
Q2=19.89 X=0.12
Data/Theory
z

SIDIS K+ data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Q2=4.12 X=0.02
Q2=5.84 X=0.03
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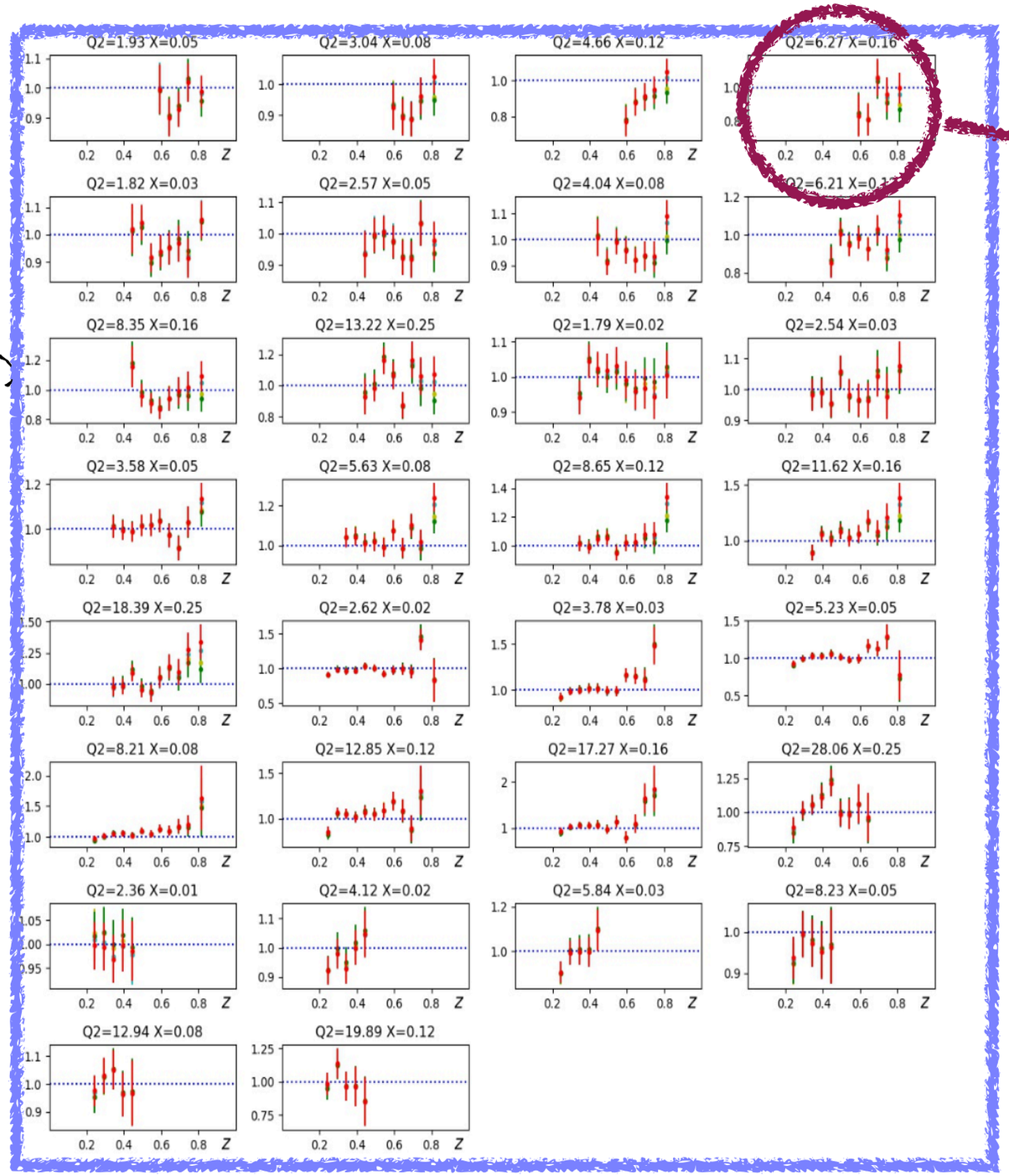
Q2=19.89 X=0.12
Data/Theory
z

SIDIS K^+ data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Q2=4.12 X=0.02
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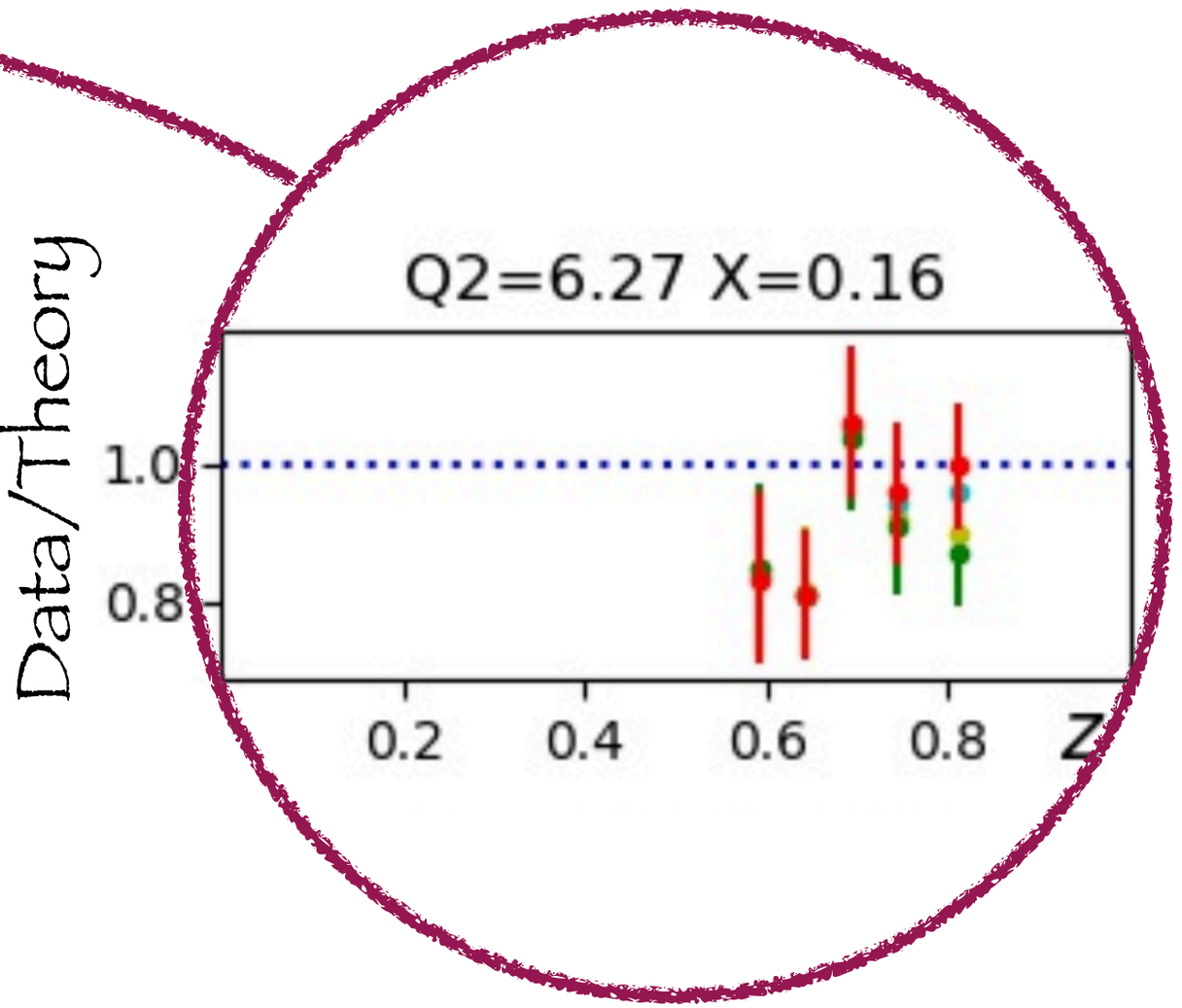
Q2=12.94 X=0.08
Q2=19.89 X=0.12
Data/Theory
z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Data/Theory
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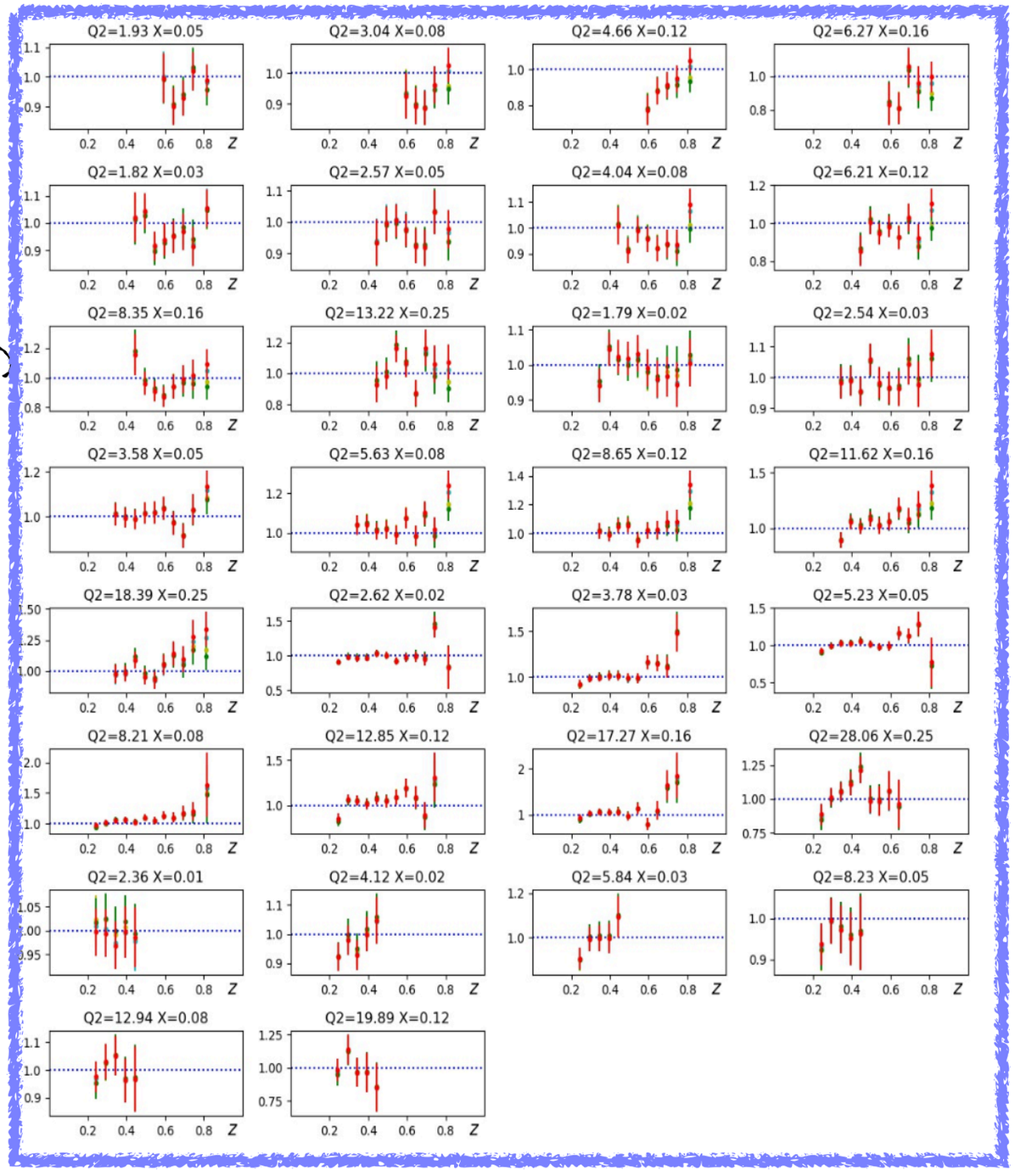
0.8
0.2
0.4
0.6
0.8
Z

SIDIS K- data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Q2=13.22 X=0.25
Q2=1.79 X=0.02
Q2=2.54 X=0.03
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Q2=8.65 X=0.12
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Q2=18.39 X=0.25
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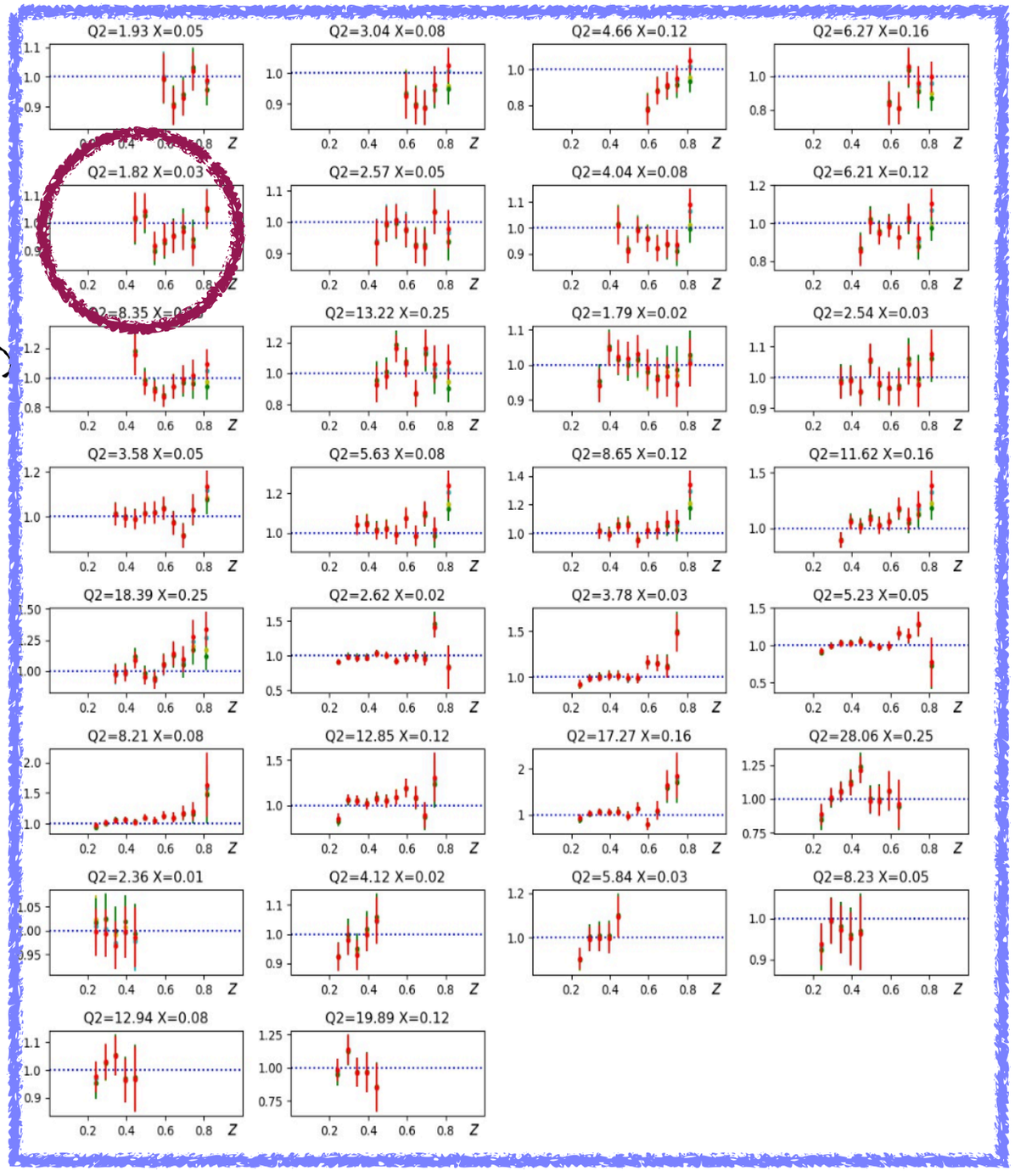
Q2=12.85 X=0.12
Q2=17.27 X=0.16
Q2=28.06 X=0.25
Q2=2.36 X=0.01
Q2=4.12 X=0.02
Q2=5.84 X=0.03
Q2=8.23 X=0.05
Q2=12.94 X=0.08
Q2=19.89 X=0.12
Data/Theory
z

SIDIS K- data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Q2=2.54 X=0.03
Q2=3.58 X=0.05
Q2=5.63 X=0.08
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Q2=11.62 X=0.16
Q2=18.39 X=0.25
Q2=2.62 X=0.02
Q2=3.78 X=0.03
Q2=5.23 X=0.05
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Q2=12.85 X=0.12
Q2=17.27 X=0.16
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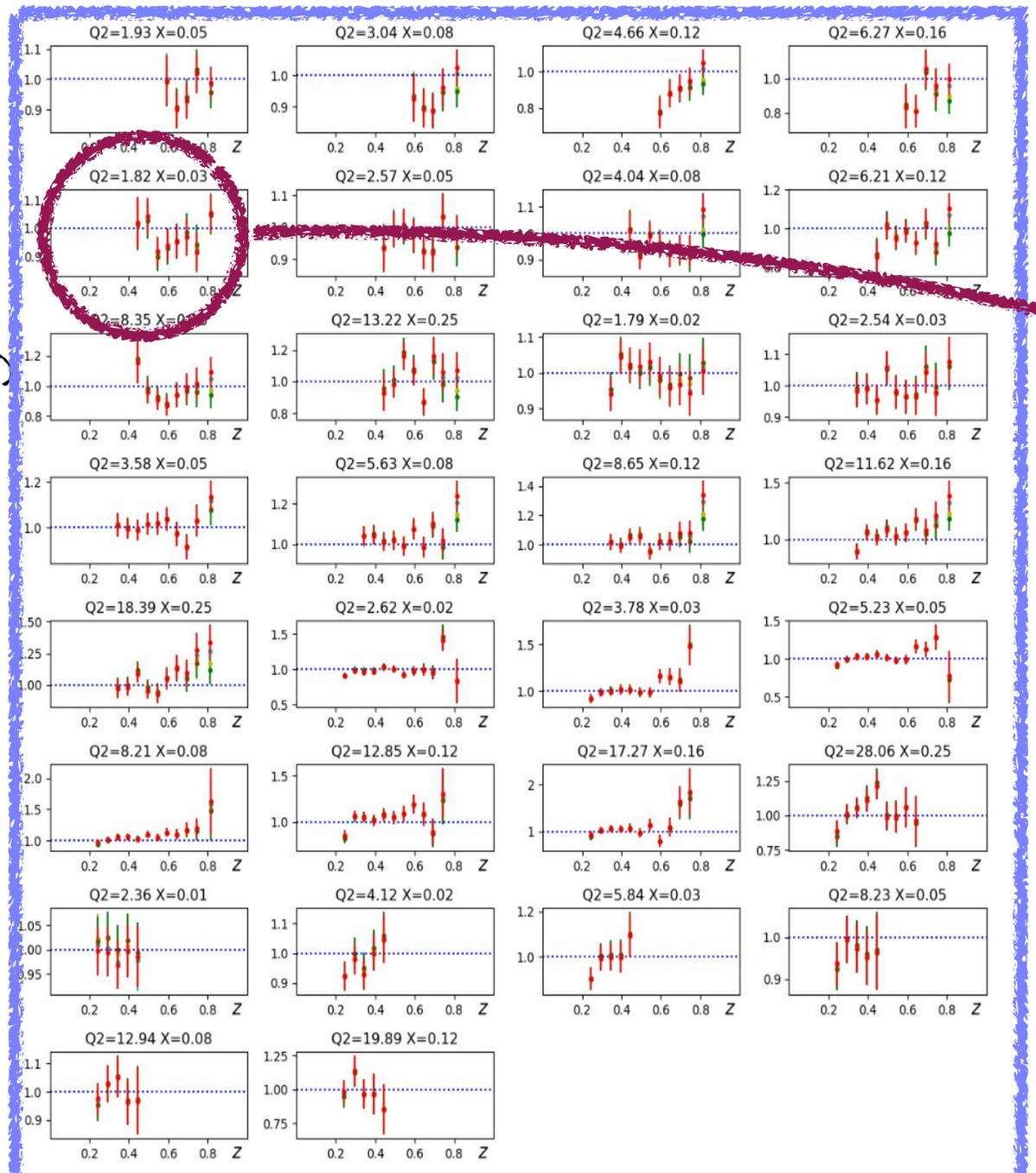
Q2=2.36 X=0.01
Q2=4.12 X=0.02
Q2=5.84 X=0.03
Q2=8.23 X=0.05
Q2=12.94 X=0.08
Q2=19.89 X=0.12
Data/Theory
z

SIDIS K- data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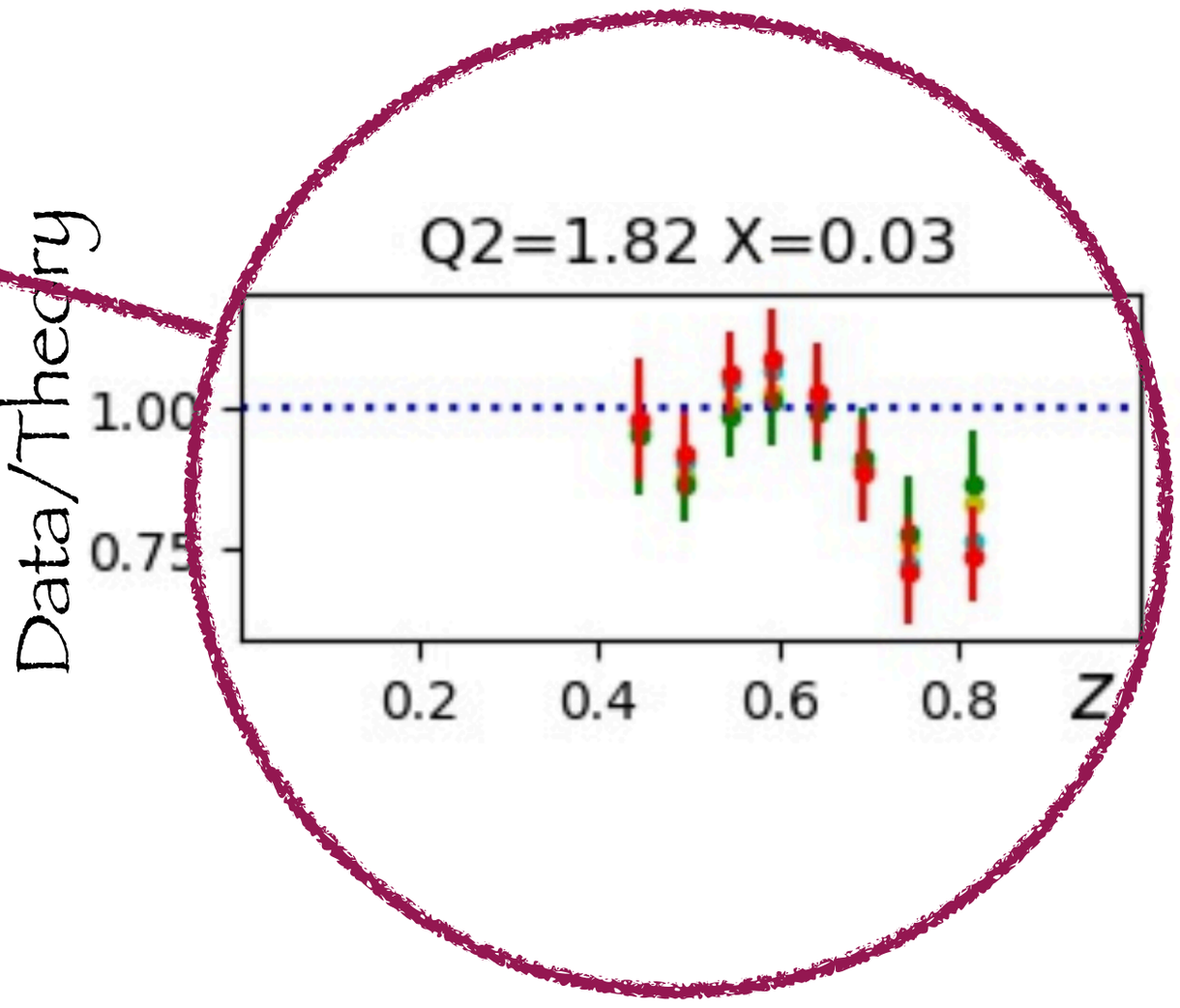
Data/Theory
z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Data/Theory
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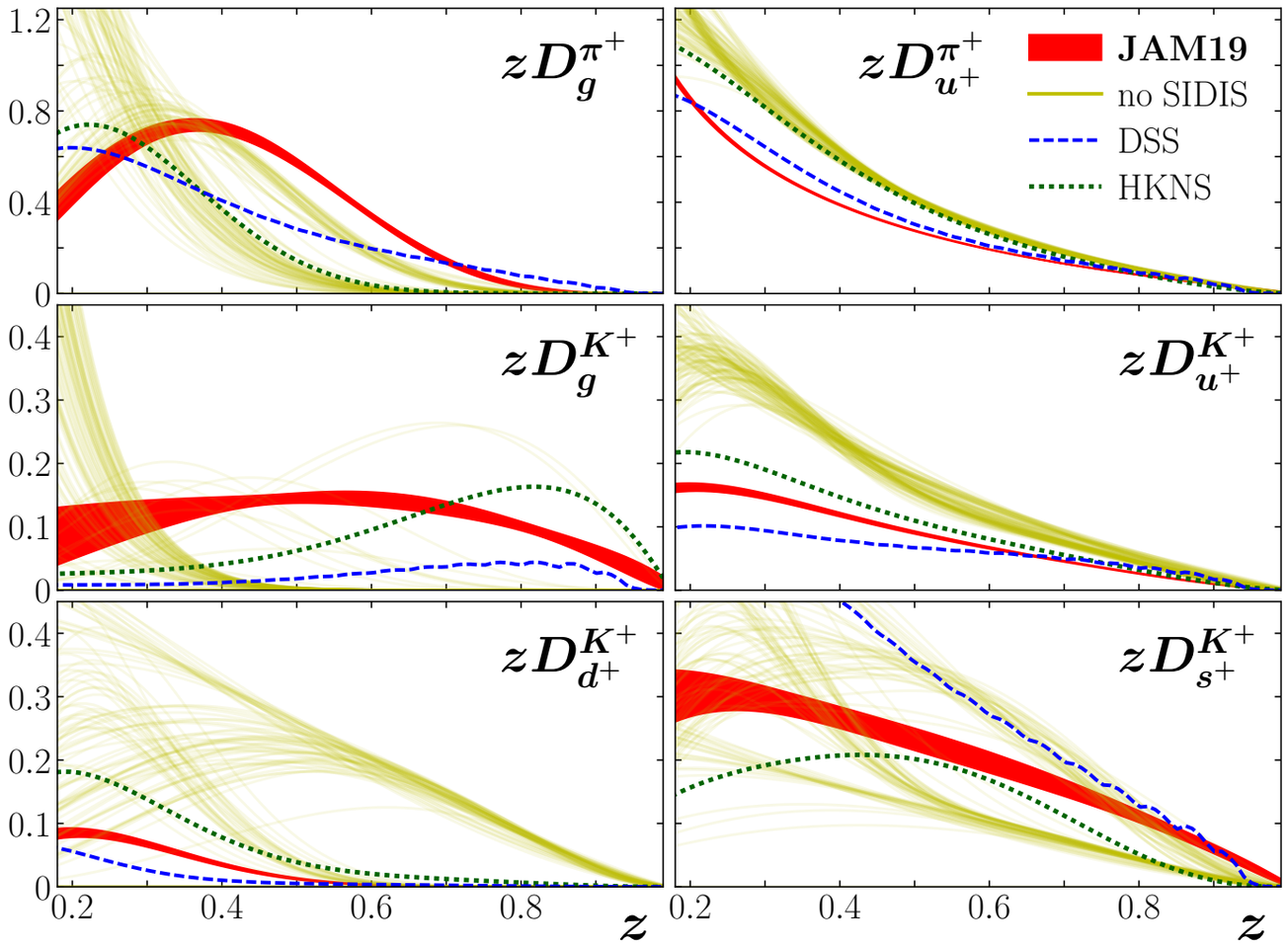
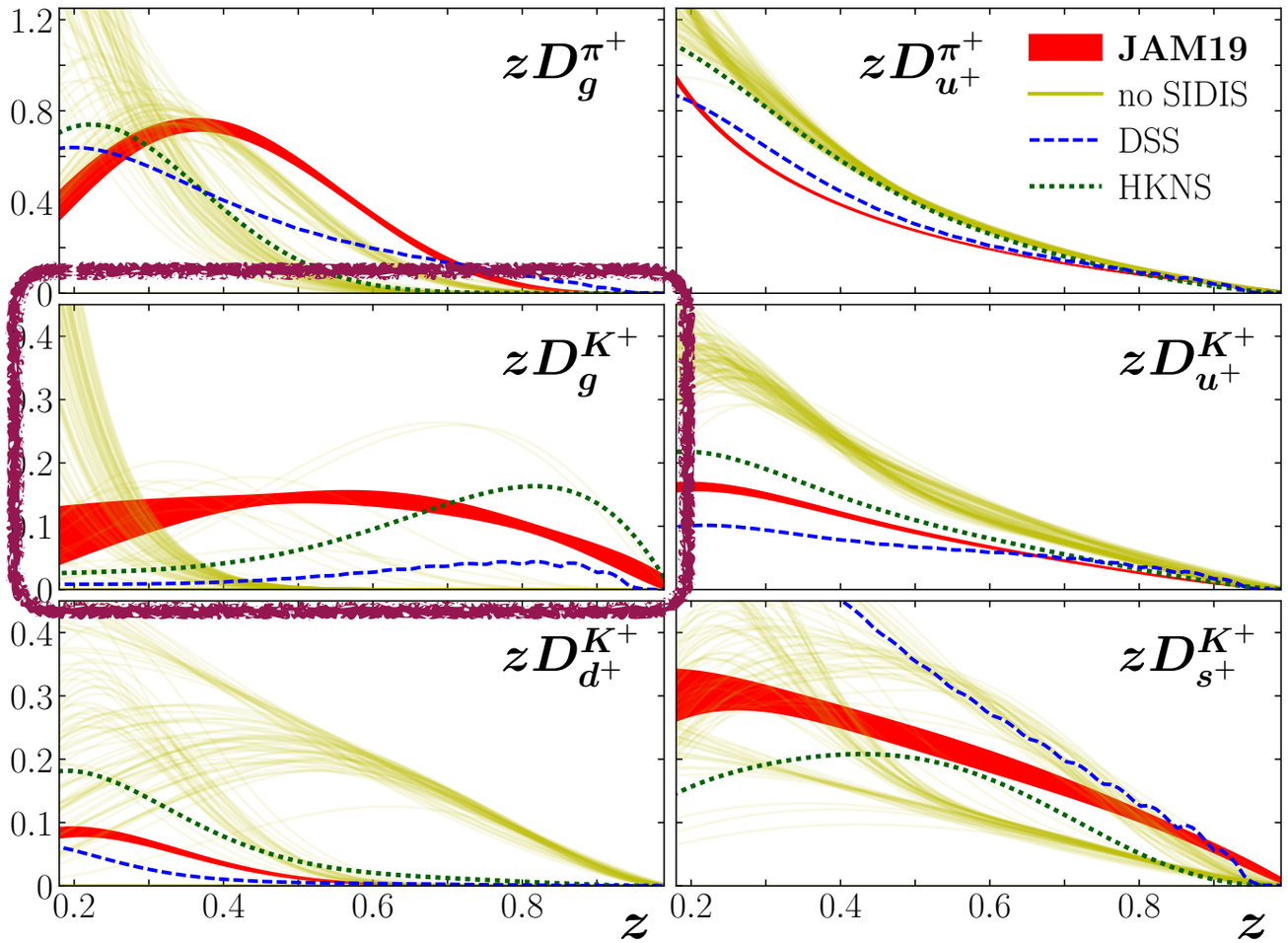
Z

JAM19: FF



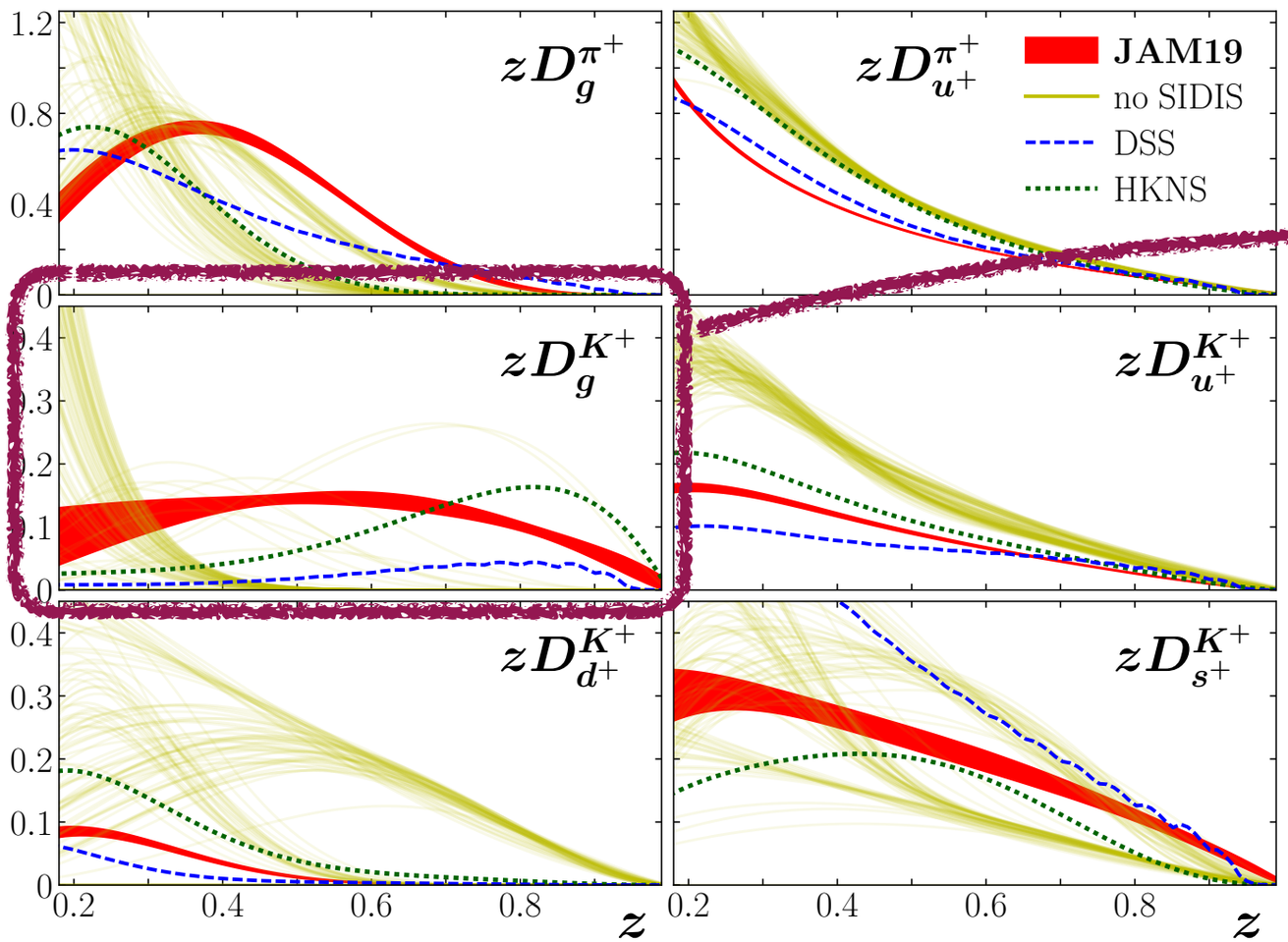
$Q^2 \approx m_c^2$

JAM19: FF

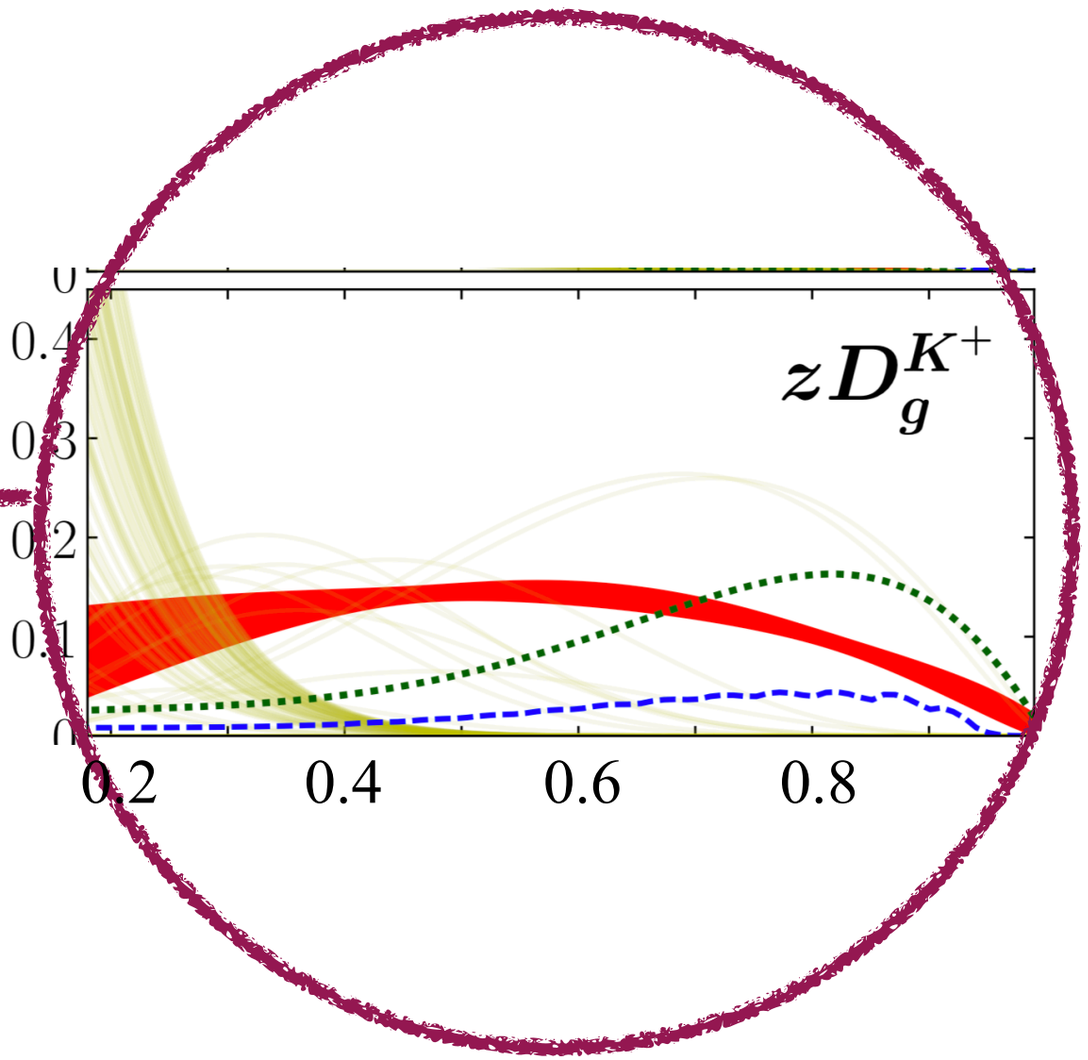


$Q^2 = m_c^2$

JAM19: FF



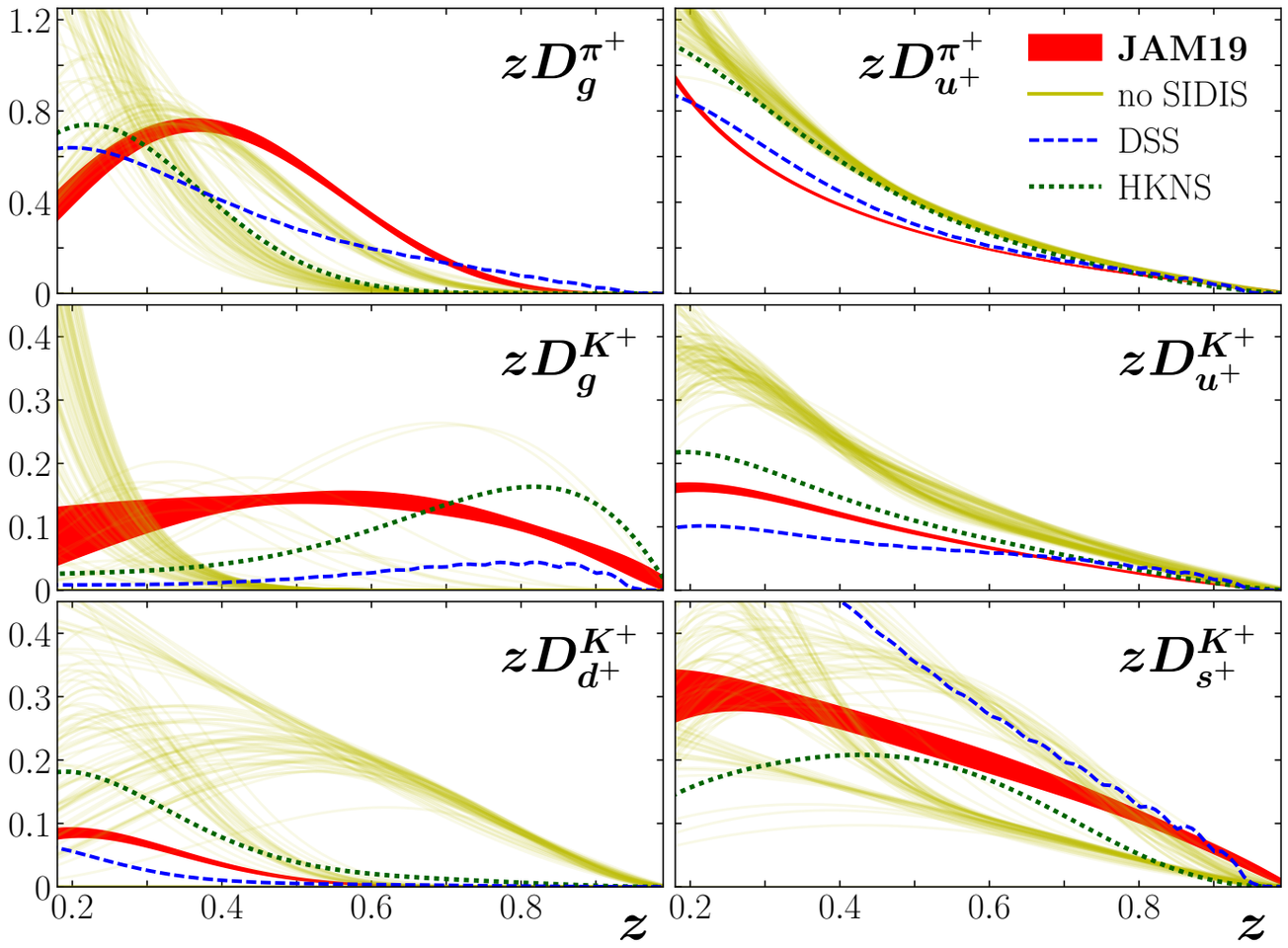
$Q^2 \approx m_c^2$



Constraints on

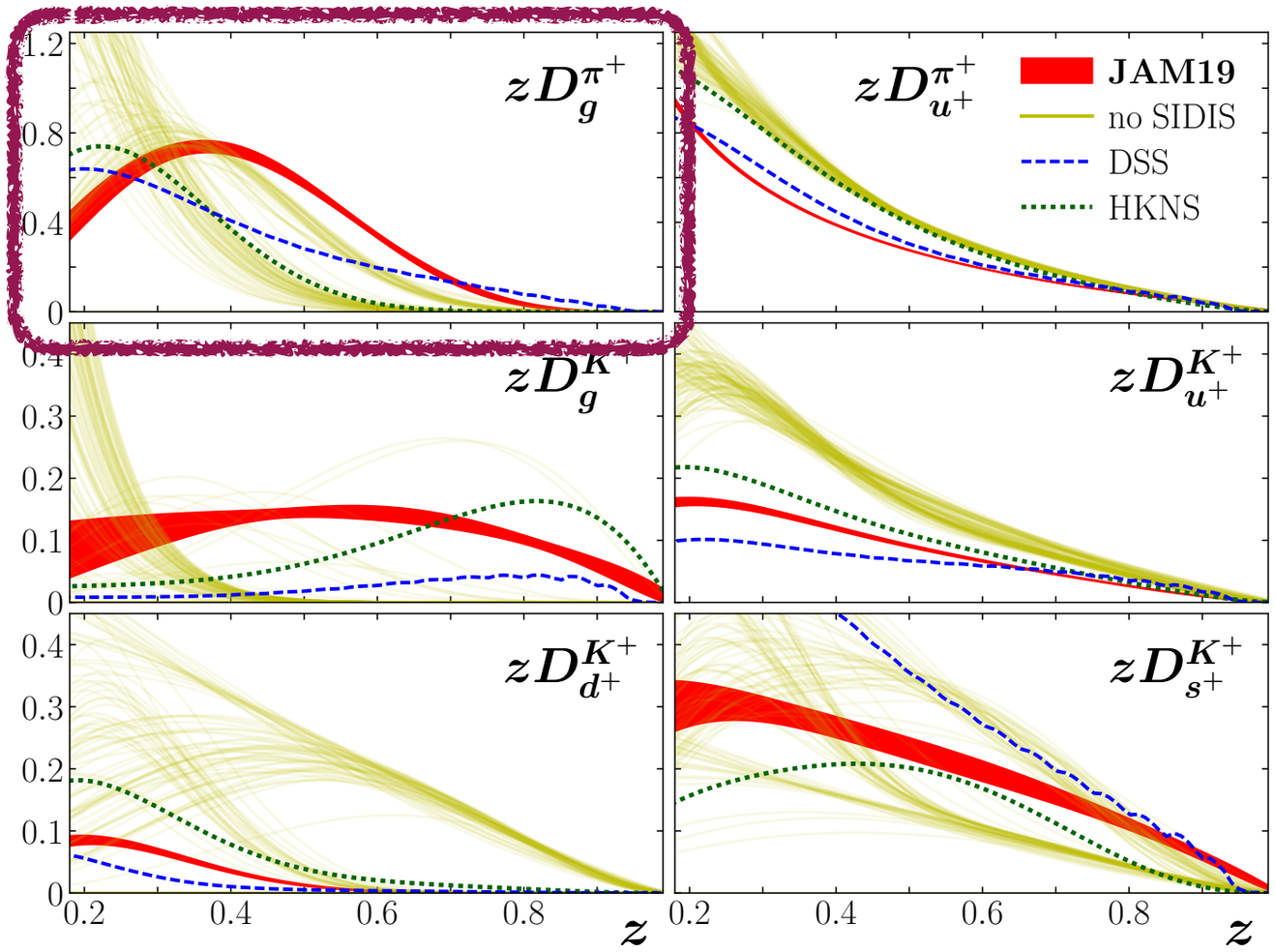
$g \to K^+$

JAM19: FF



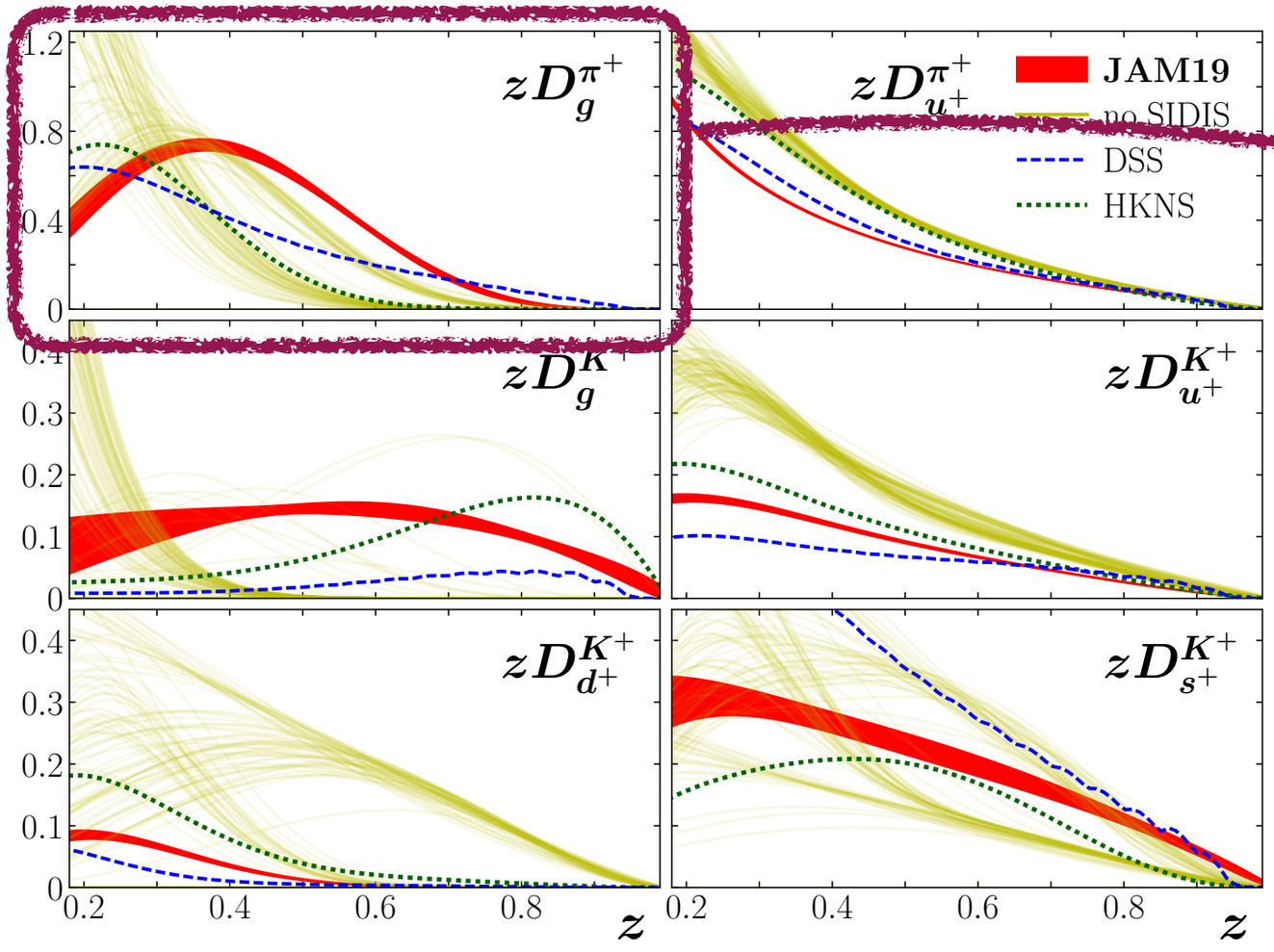
$Q^2 \approx m_c^2$

JAM19: FF

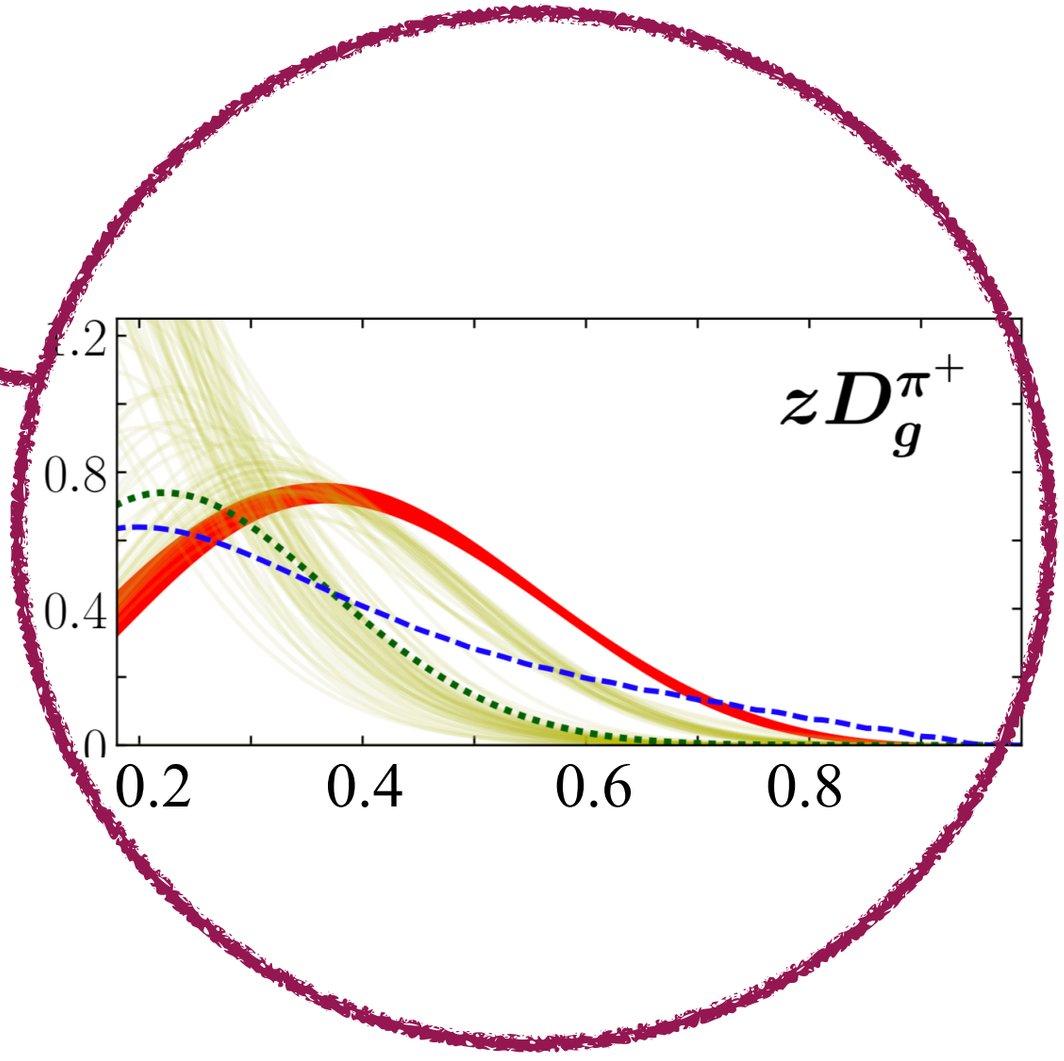


$Q^2 \approx m_c^2$

JAM19: FF



$Q^2 \approx m_c^2$



Constraints on

$g \to \pi^+$

Evolution of JAM

Iterative MC fitting technique

		JAM15	JAM16	JAM17	JAM18
Process	DIS	☑	☒	☑	☑
	SIA	☒	☑	☑	☑
	SIDIS	☒	☒	☑	☑
	DY	☒	☒	☒	☑
Function	f	☒	☒	☒	☑
	Δf	☑	☒	☑	☑
	D_f^h	☒	☑	☑	☑

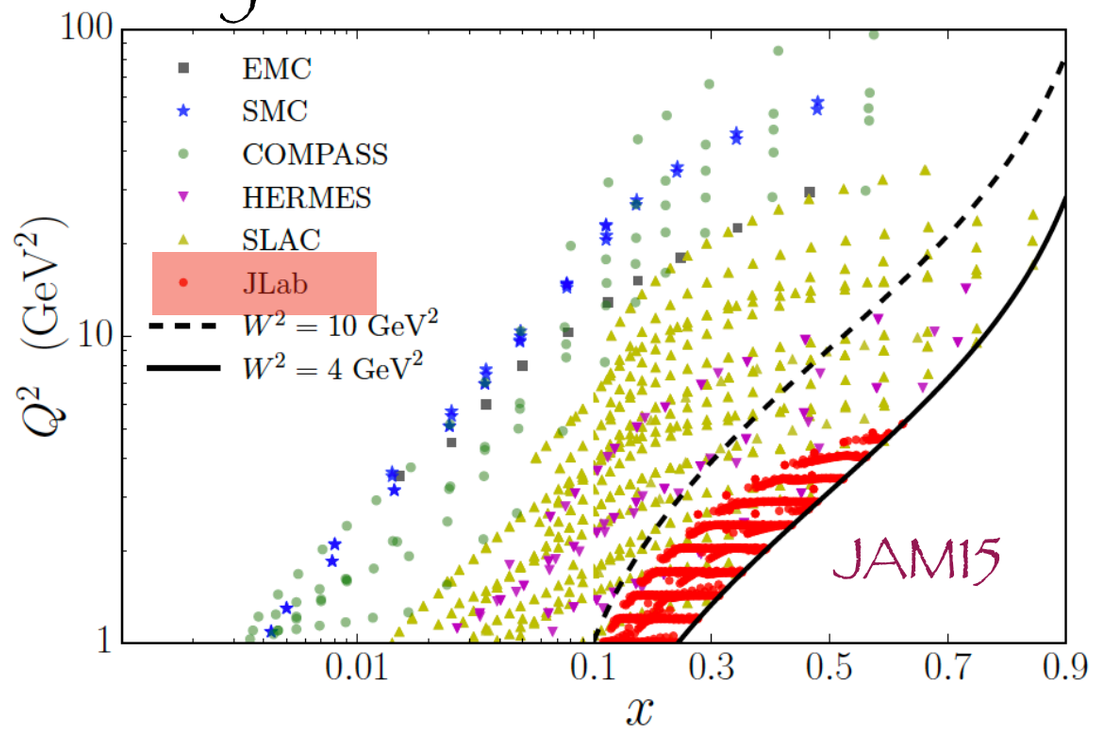
Uses CJ12 NLO unpolarized PDFs

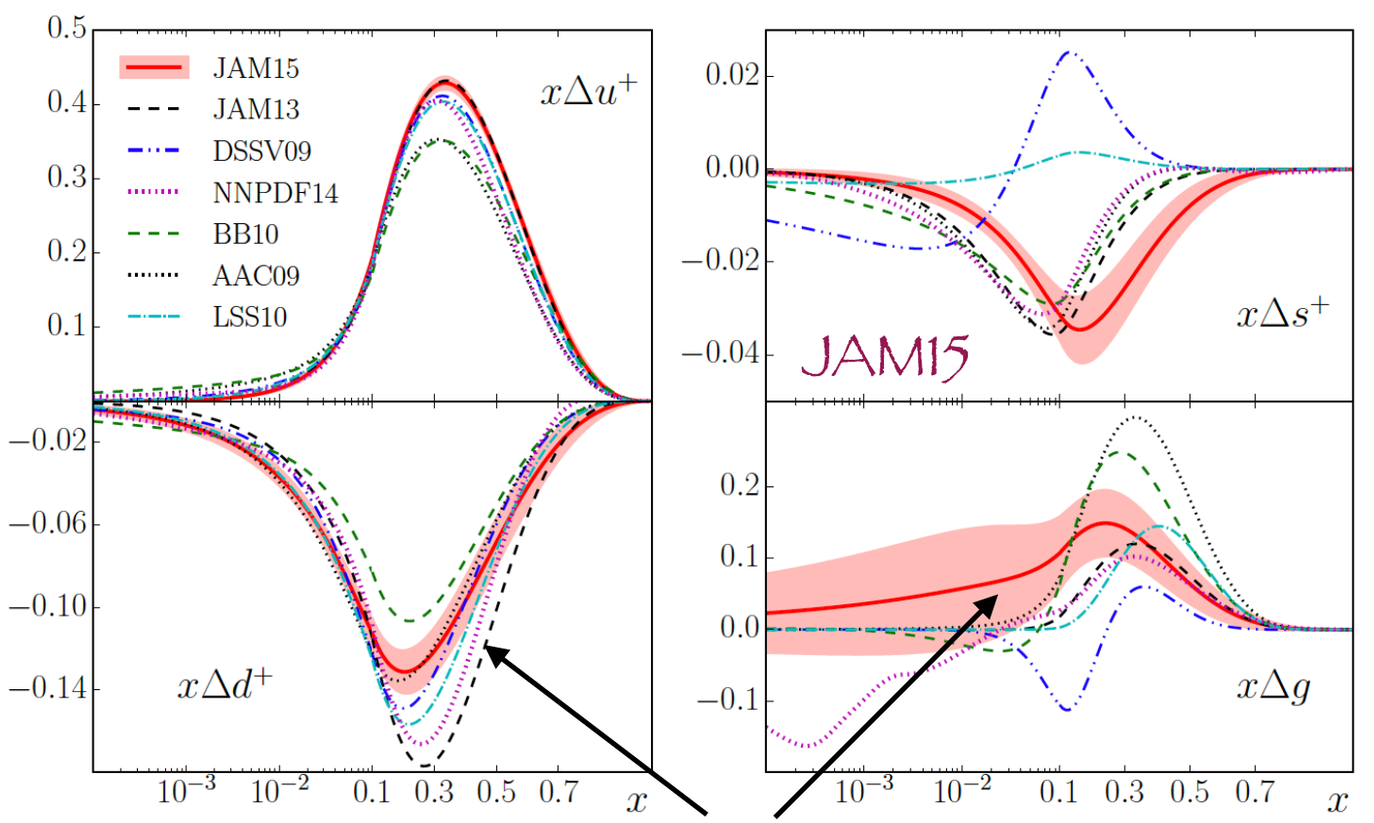
- Δu^+ and Δd^+ consistent with previous analysis
- Δs^+ slightly harder

Sato, Melnitchouk, Kuhn, Ethier, Accardi
Phys. Rev. D 93, 074005 (2016)

JAM15

IMC analysis + all available JLab data

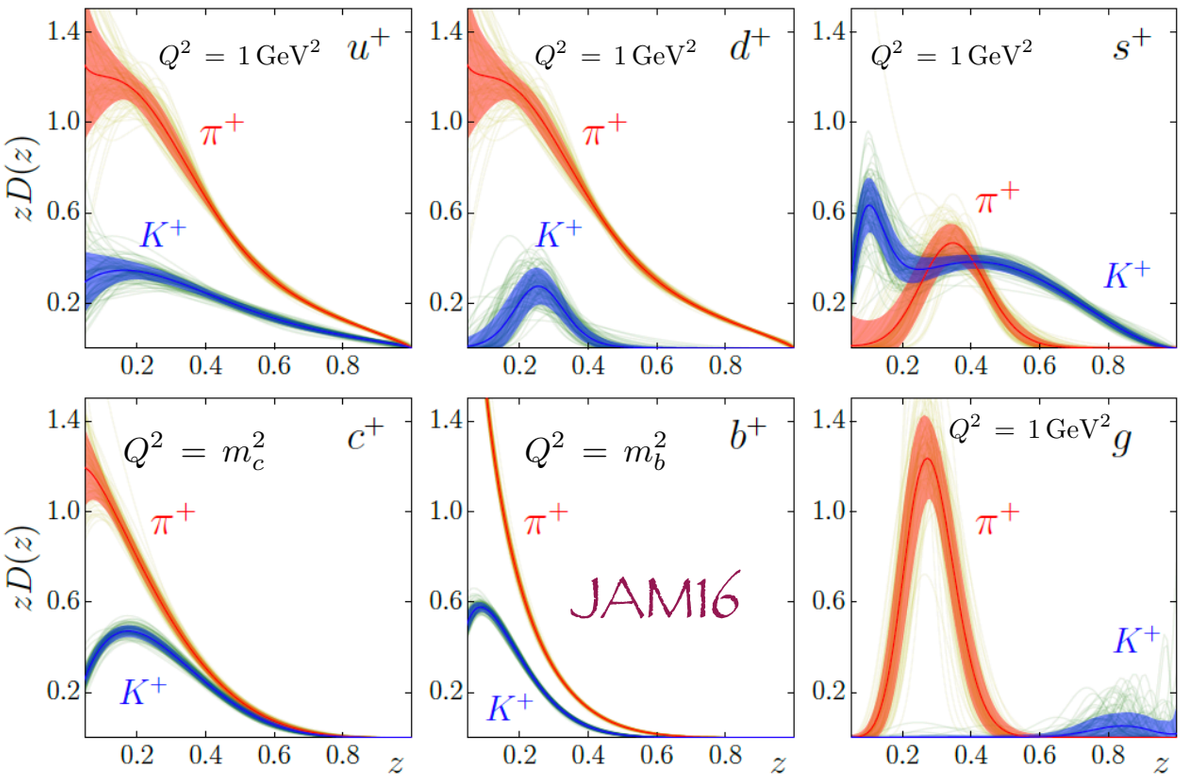




Impact of JLab data

JAM16

- First IMC analysis of FFs
- Only SIA included



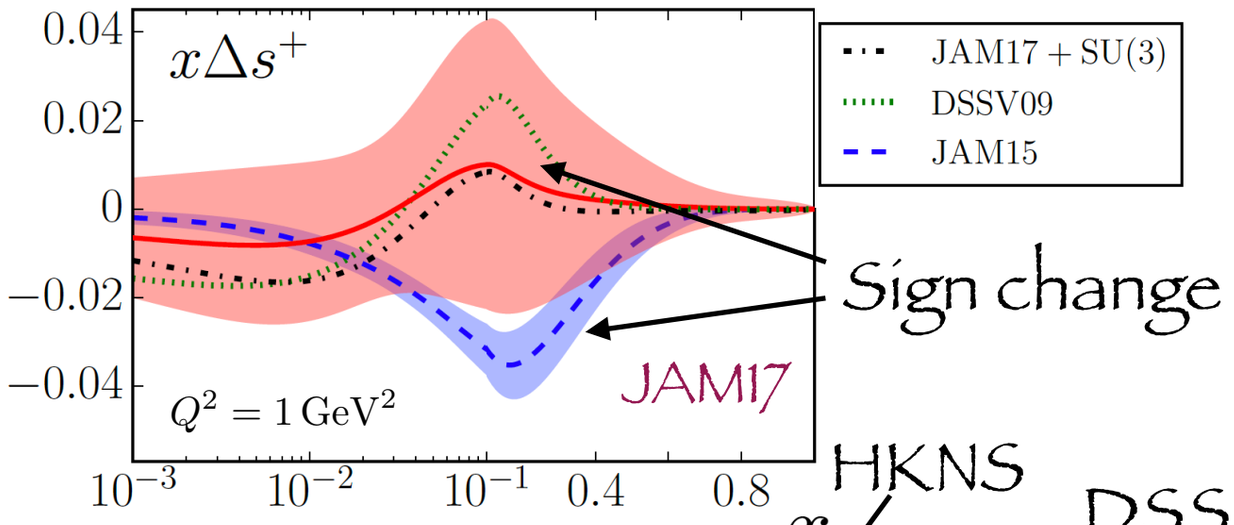
Sato, Ethier, Melnitchouk, Hirai, Kumano and Accardi

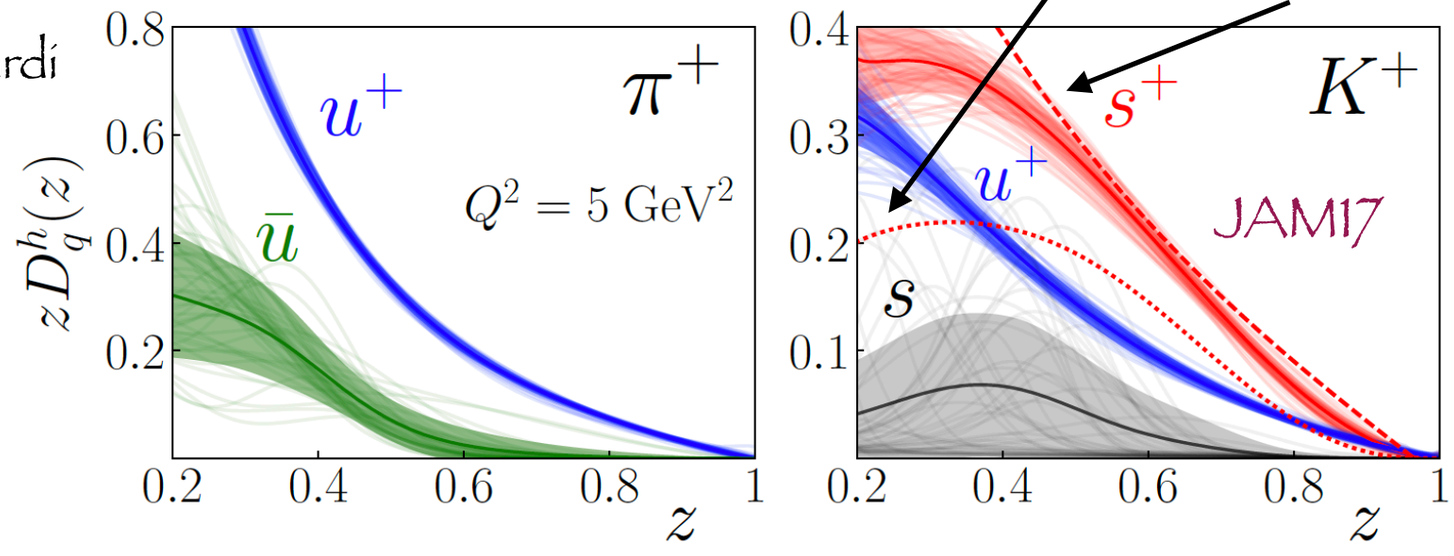
Phys. Rev. D 94, 114004 (2016)

JAM17 FFs better agreement with other analysis

JAM17

- First (simultaneous) MC analysis of polarized PDFs and FFs
- Polarized SIDIS, polarized DIS and SIA included





41 Ethier, Sato, Melnitchouk: Phys. Rev. Lett. 119, 132001 (2017)

chi2

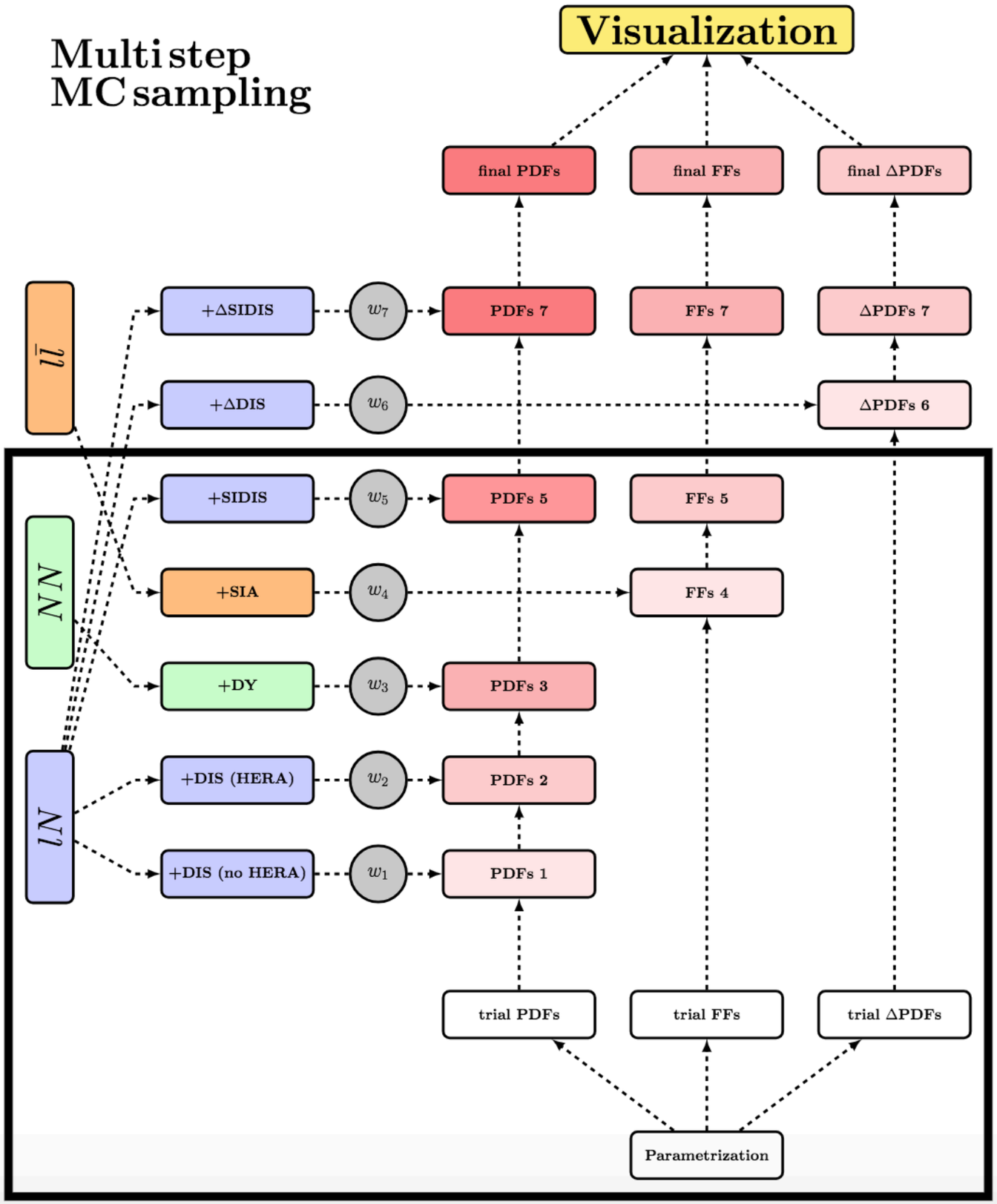
Reaction	$N_{\rm dat}$	χ^2	$\chi^2/N_{\rm dat}$
SIDIS	992	1243.12	1.25
SIA	444	562.80	1.27
DIS	2680	3437.96	1.28
DY	250	416.29	1.67

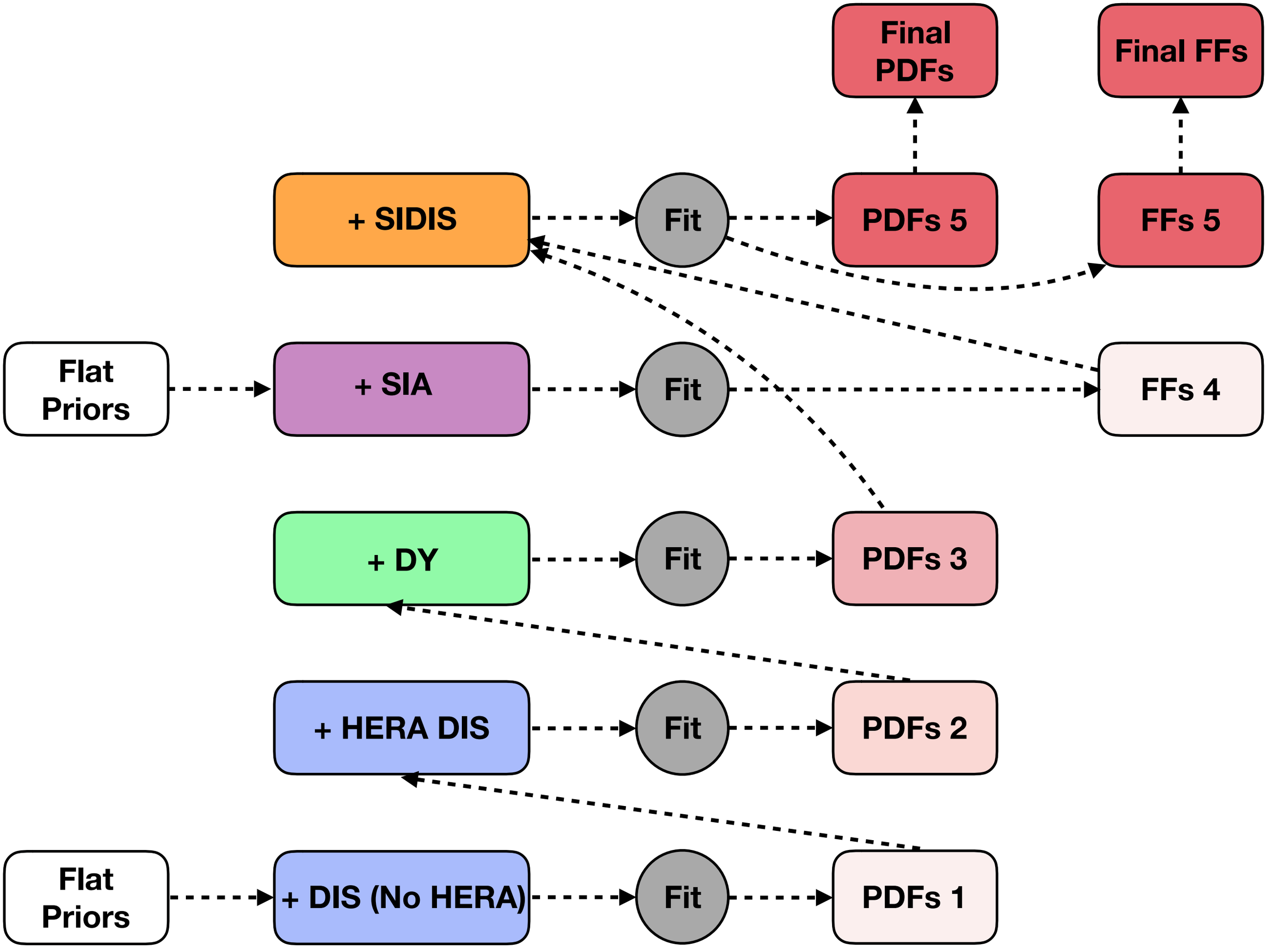
Reaction	$N_{\rm dat}$	χ^2	$\chi^2/N_{\rm dat}$
SIDIS ($\pi^\pm$)	498	585.48	1.18
SIDIS($K^\pm$)	494	657.64	1.33
SIA($\pi^\pm$)	231	247.27	1.07
SIA ($K^\pm$)	213	315.53	1.48

Experiment	target	hadron	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
COMPASS	d	π^+	249	1.26
COMPASS	d	π^-	249	1.09
COMPASS	d	K^+	247	1.24
COMPASS	d	K^-	247	1.43

JAM19

Multistep MC sampling




Final PDFs
Final FFs
+ SIDIS
Fit
PDFs 5
FFs 5
Flat Priors
+ SIA
Fit
FFs 4
+ DY
Fit
PDFs 3
+ HERA DIS
Fit
PDFs 2
Flat Priors
+ DIS (No HERA)
Fit
PDFs 1