Leading Neutron Production in DIS :Target Fragmentation and One-Pion-Exchange

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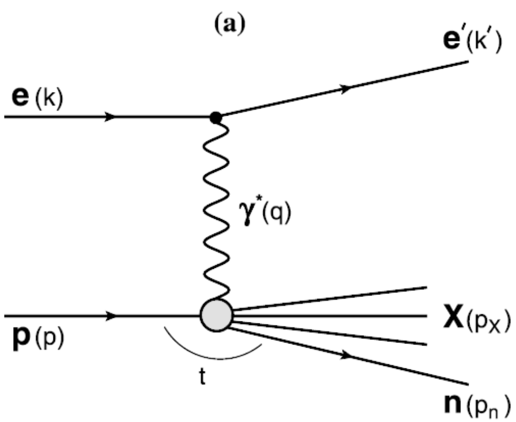
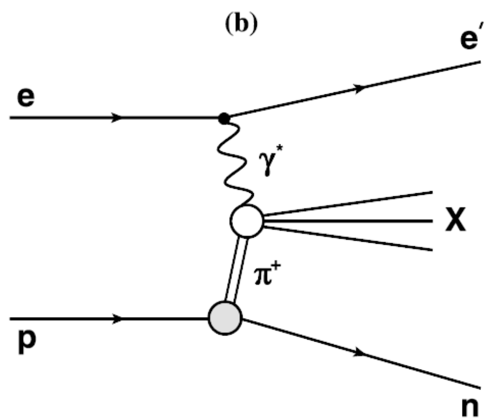
Group research works done with
Satyajit Puhan and Chia-Yu Hsieh

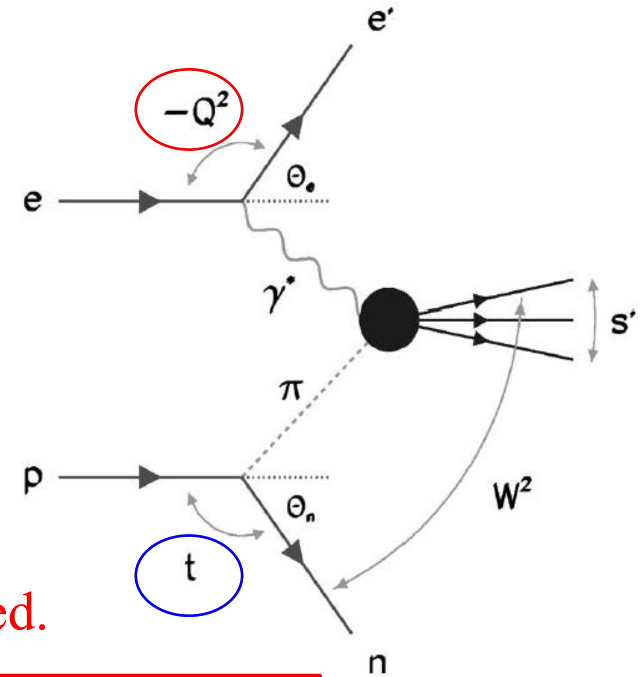
Outline

- Measurements of Leading-neutron production in DIS: DESY (H1 & ZEUS)
- Mechanisms:
  - Sullivan process: pion flux and pion structure functions
  - DIS target fragmentation: PYTHIA
- Comparison of H1 and ZEUS data with contributions of Sullivan process and DIS target fragmentation
- Summary

Reaction Diagrams and Kinematic Variables Q^2, x, x_L, t







t and p_T of n are correlated.

$$Q^2 = -q^2, \qquad x = \frac{Q^2}{2p \cdot q}, \qquad y = \frac{p \cdot q}{p \cdot k},$$

$$\boxed{y = q \cdot P/(k \cdot P) \simeq Q^2/(sx)}$$

$$W^2 = (P + k - k')^2 = m_p^2 + Q^2(1-x)/x$$

$$\boxed{\begin{aligned} x_L &= 1 - \frac{q \cdot (p - p_n)}{q \cdot p} \simeq E_n/E_p, \\ t &= (p - p_n)^2 \simeq -\frac{p_T^2}{x_L} - (1 - x_L)\left(\frac{m_n^2}{x_L} - m_p^2\right), \end{aligned}}$$

$$\boxed{p_T \simeq x_L E_p \theta_n}$$

$$x_\pi = \frac{x}{1 - x_L}$$

Reaction Diagrams and Kinematic Variables Q^2, x, x_L, t

Leading-neutron cross section

$$\frac{d^4\sigma(ep \to enX)}{dx\, dQ^2\, dx_L\, dt} = \frac{4\pi\alpha^2}{x\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LN(4)}(Q^2, x, x_L, t).$$

Structure function

$$F_2^{\mathrm{LN(3)}}(x, Q^2, x_\mathrm{L}) \equiv \int_0^{p_\mathrm{T}^{\max}} F_2^{\mathrm{LN(4)}}(x, Q^2, x_\mathrm{L}, p_\mathrm{T})\, dp_\mathrm{T}$$

$$\frac{d^3\sigma(ep \to enX)}{dx\, dQ^2\, dx_L} = \boxed{\int_{t_0}^{t_{\min}} \frac{d^4\sigma(ep \to enX)}{dx\, dQ^2\, dx_L\, dt}\, dt} = \frac{4\pi\alpha^2}{x\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LN(3)}(Q^2, x, x_L),$$

where the integration limits are

$$t_{\min} = -(1 - x_L)\left(\frac{m_n^2}{x_L} - m_p^2\right) \quad \text{and}$$

$$t_0 = -\frac{(p_T^{\max})^2}{x_L} + t_{\min}.$$

H1: Forward Neutron Calorimeter (FNC)

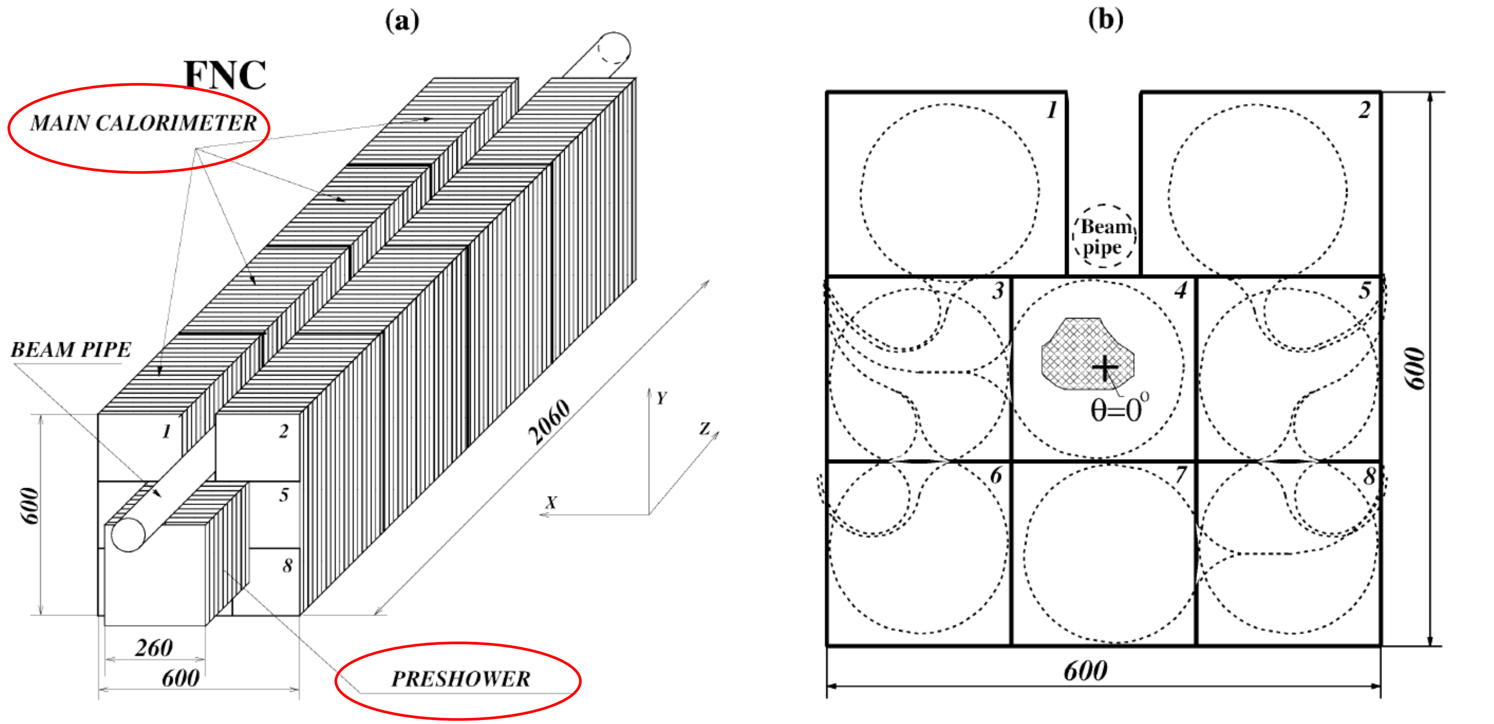
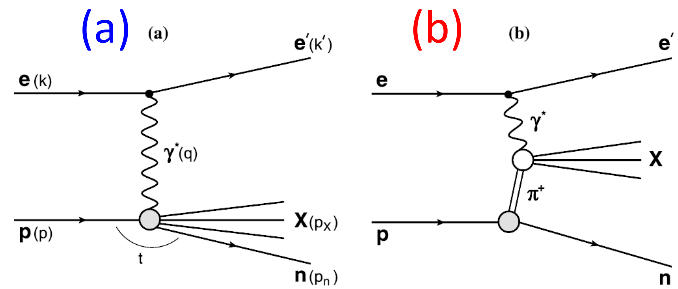


Fig. 2 (**a**) Schematic view of the FNC. (**b**) Layout of tiles on an active board of the Main Calorimeter; the position of readout fibres is indicated by *dotted lines*; the *hatched* area shows the geometrical acceptance window defined by the beam line elements. The position corresponding to $\theta = 0°$ is also indicated. All dimensions are given in mm

DESY: H1 and ZEUS Experiments

Quantity	H1	ZEUS
E_e (GeV)	27.5	27.5
E_p (GeV)	920	820
Q^2 (GeV^2)	$6 < Q^2 < 100$	$4 < Q^2 < 10^4$
x_B	$1.5 \times 10^{-4} < x_B < 3.0 \times 10^{-2}$	$8.0 \times 10^{-5} < x_B < 1.0 \times 10^{-1}$
y	$0.02 < y < 0.60$	–
W^2 (GeV^2)	> 4	–
E'_e (GeV)	> 11	> 10
θ_e	$156° < \theta_e < 175°$	–
θ_n (mrad)	< 0.75	< 0.80
p_T (GeV)	< 0.20	$< 0.656\, x_L$
x_L	0.32–0.95	0.20–1.00
x_L bins	7	12

H1



Eur. Phys. J. C (2010) 68: 381–399 387

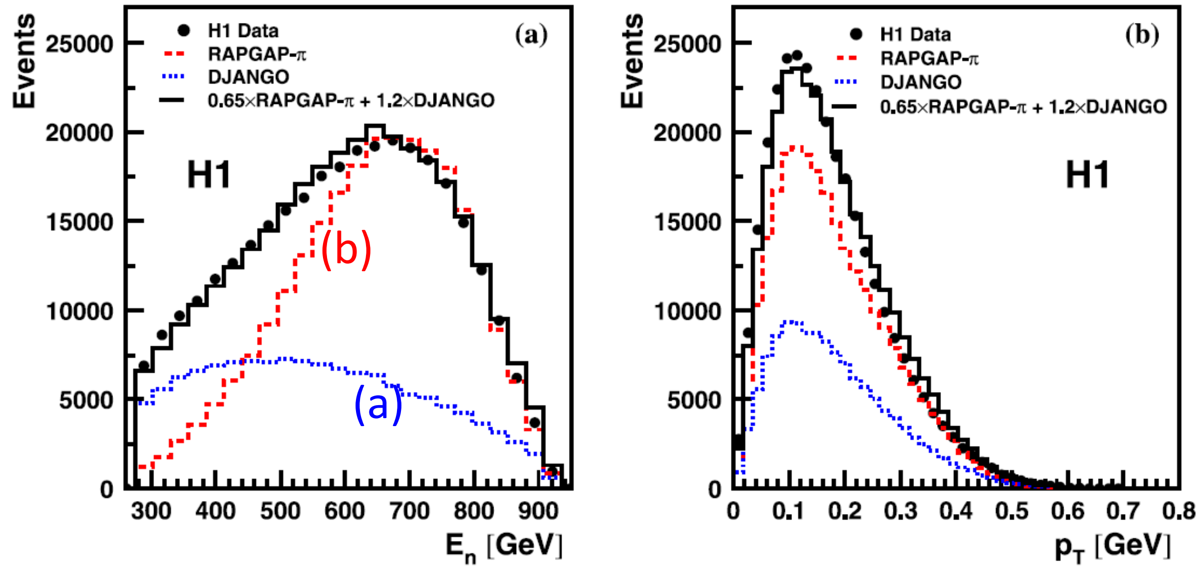
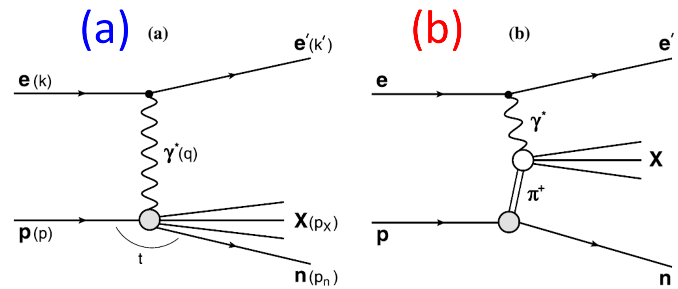
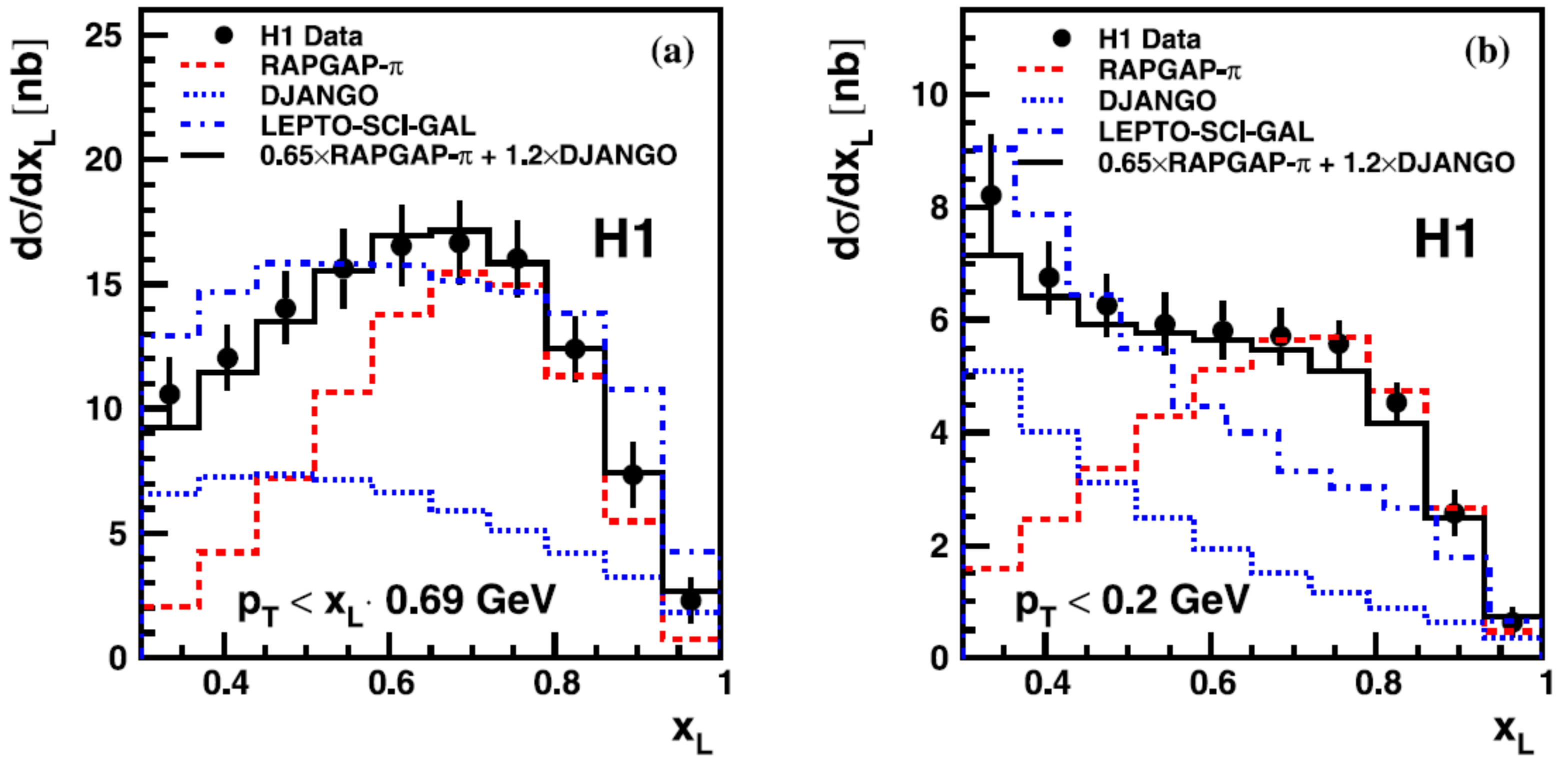


Fig. 3 The observed neutron energy (**a**) and transverse momentum (**b**) distributions in the kinematic range $6 < Q^2 < 100\ \mathrm{GeV}^2$ and $1.5 \cdot 10^{-4} < x < 3 \cdot 10^{-2}$. The data are compared to the predictions of RAPGAP-π (*dashed line*) and DJANGO (*dotted line*) Monte Carlo simulations. Also shown is a weighted combination of those two simulations (*full line*), as described in Sect. 3.4

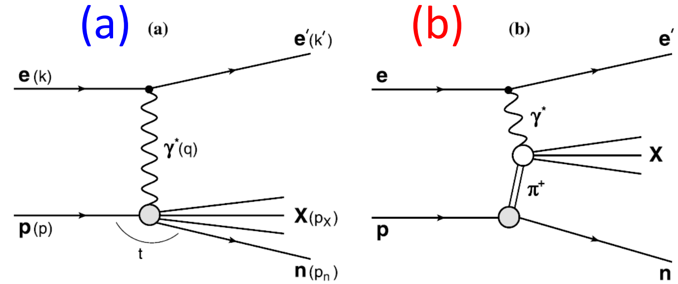
tion in this region. The best description of the data is achieved if the predictions of the RAPGAP-π and DJANGO Monte Carlo programs are added, using weighting factors of 0.65 and 1.2 for RAPGAP-π and DJANGO, respectively. This Monte Carlo combination is labelled as "0.65× RAPGAP-π + 1.2×DJANGO" in the figures and is used to correct the data.

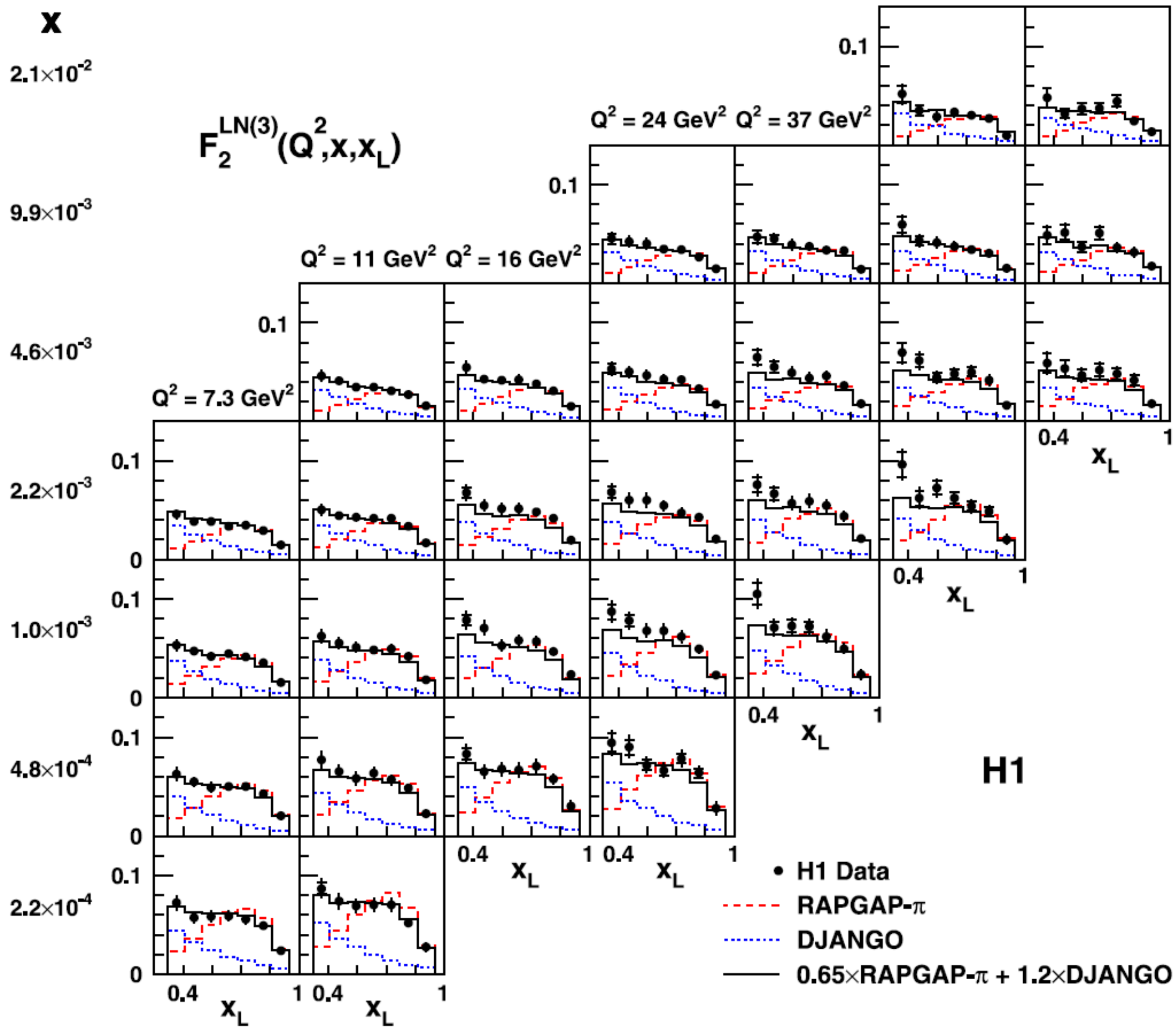
H1


(a)
(a)
e (k)
e′(k′)
γ*(q)
p (p)
X(pX)
t
n (pn)
(b)
(b)
e
e′
γ*
X
π+
p
n


dσ/dxL [nb]
H1 Data
RAPGAP-π
DJANGO
LEPTO-SCI-GAL
0.65×RAPGAP-π + 1.2×DJANGO
(a)
H1
pT < xL · 0.69 GeV
xL
(b)
H1
pT < 0.2 GeV
xL

H1


(a)
(a)
e (k)
e′(k′)
γ*(q)
p (p)
X (p_X)
t
n (p_n)
(b)
(b)
e
e′
γ*
X
π+
p
n


x
2.1×10^-2
9.9×10^-3
4.6×10^-3
2.2×10^-3
1.0×10^-3
4.8×10^-4
2.2×10^-4
F2^LN(3)(Q^2,x,x_L)
Q^2 = 7.3 GeV^2
Q^2 = 11 GeV^2
Q^2 = 16 GeV^2
Q^2 = 24 GeV^2
Q^2 = 37 GeV^2
0.1
0
0.4
x_L
1
H1
H1 Data
RAPGAP-π
DJANGO
0.65×RAPGAP-π + 1.2×DJANGO

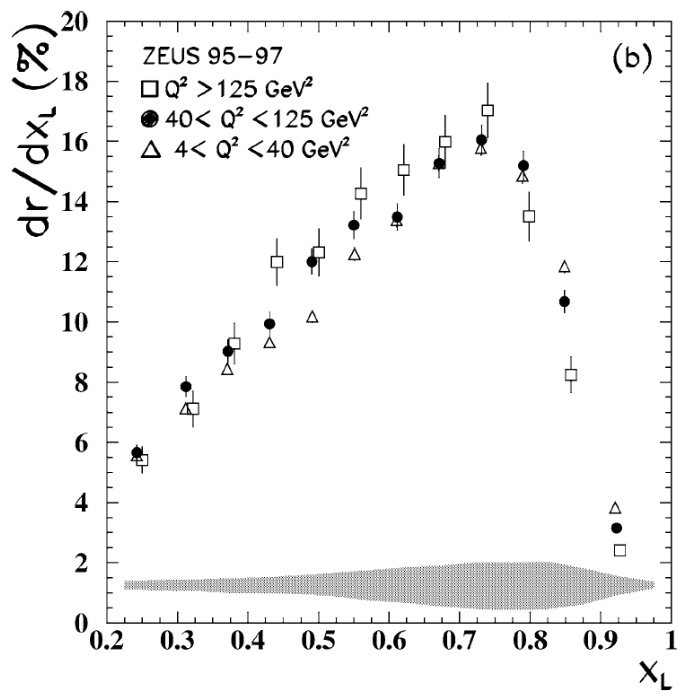
ZEUS

$$\boxed{r(x, Q^2, x_L) = \frac{d^3\sigma^{ep\to e'Xn}/dx\,dQ^2\,dx_L}{d^2\sigma^{ep\to e'X}/dx\,dQ^2}\Delta x_L = \frac{n_{obs}(x, Q^2, x_L)}{A(x_L)N_{obs}(x, Q^2)},}$$

$$F_2^{LN(3)}(x, Q^2, x_L) = \frac{r(x, Q^2, x_L)}{\Delta x_L}\boxed{F_2(x, Q^2)}$$

$$\boxed{F_2^{LN(3)}(x, Q^2, x_L) = 2f_{\pi N}(\bar{x}_L)F_2^{\pi}(x_\pi, Q^2).}$$

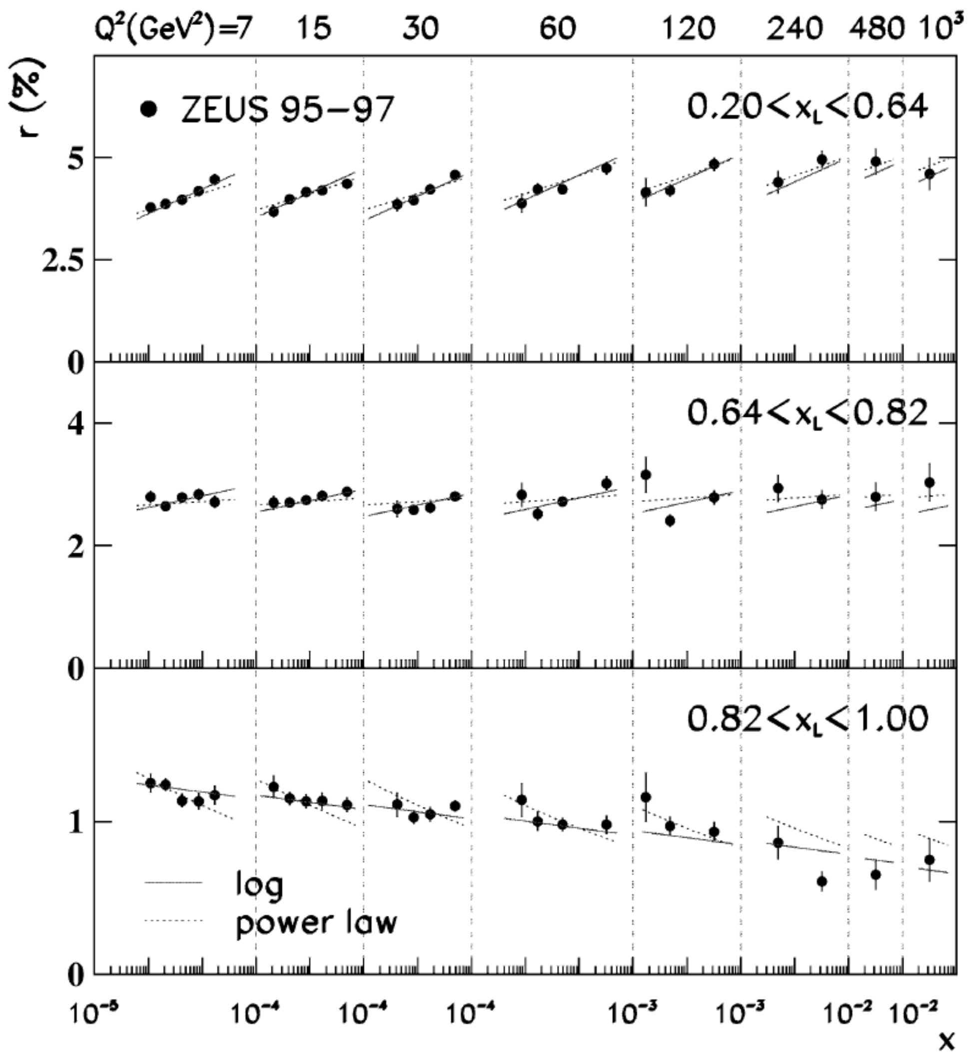
$$F_2^{\pi}(x_\pi) = \frac{r(x, x_L)}{\Delta x_L}F_2^P(x)\frac{1}{2f_{\pi N}(\bar{x}_L)}$$

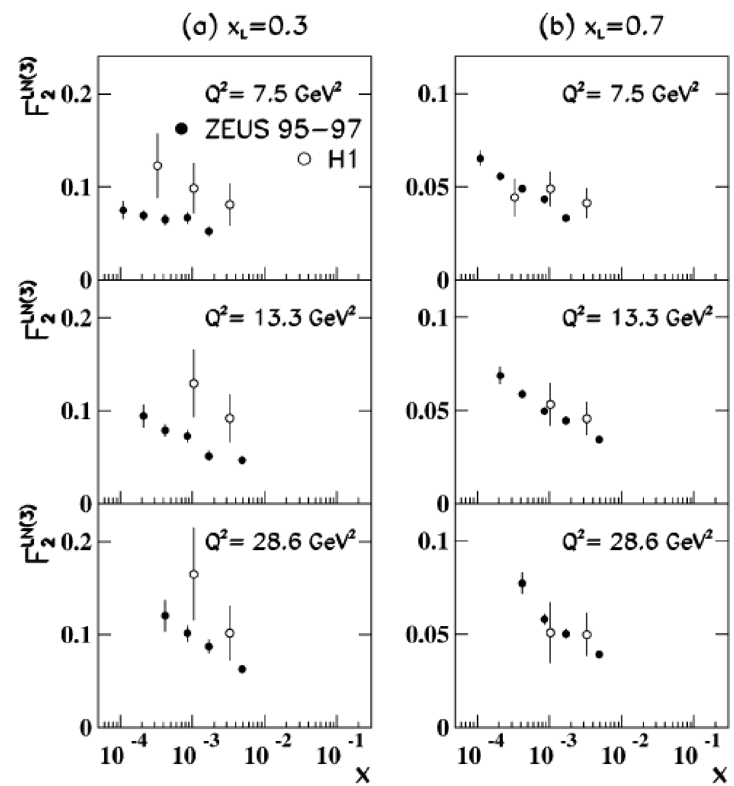


ZEUS

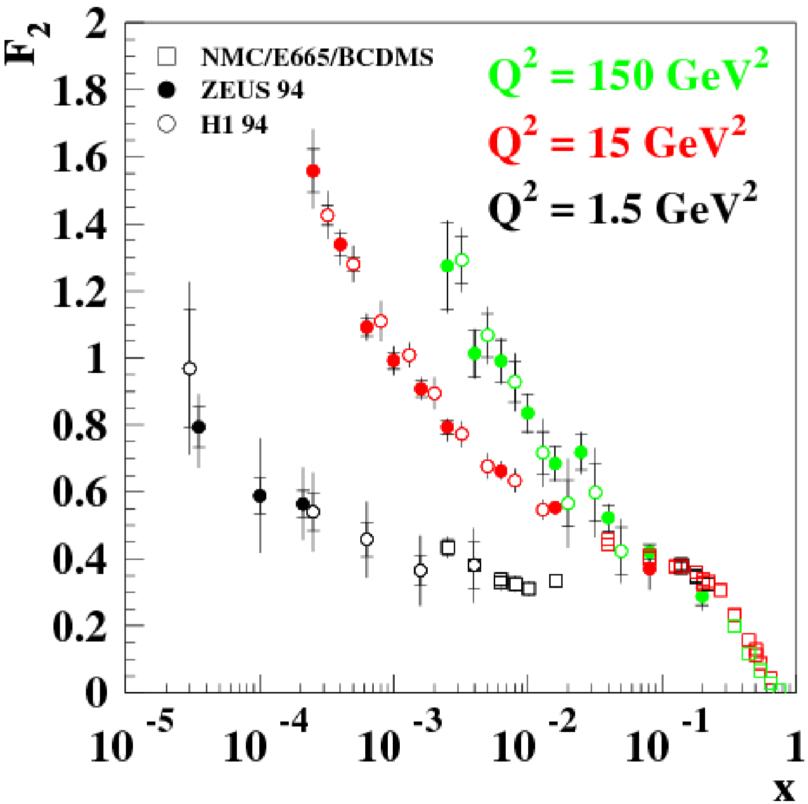
$$F_2^p(x_B, Q^2)$$

$$F_2^{\mathrm{LN}(3)}(x, Q^2, x_{\mathrm{L}}) = \frac{r(x, Q^2, x_{\mathrm{L}})}{\Delta x_{\mathrm{L}}} \boxed{F_2(x, Q^2)}$$





F2 Structure Function & PDFs



$$F_2^\pi(x_\pi,Q^2) = x_\pi \sum_q e_q^2 \Big[q^\pi(x_\pi,Q^2) + \bar{q}^\pi(x_\pi,Q^2) + \frac{\alpha_s(Q^2)}{2\pi} \left(C_q^{\overline{\mathrm{MS}}} \otimes (q^\pi + \bar{q}^\pi) + C_g^{\overline{\mathrm{MS}}} \otimes g^\pi \right) \Big]$$

$$(C \otimes f)(x_\pi) = \int_{x_\pi}^1 \frac{d\xi}{\xi}\, C\left(\frac{x_\pi}{\xi}\right) f(\xi,Q^2).$$

The NLO Wilson coefficient functions in the $\overline{\mathrm{MS}}$ scheme are given by

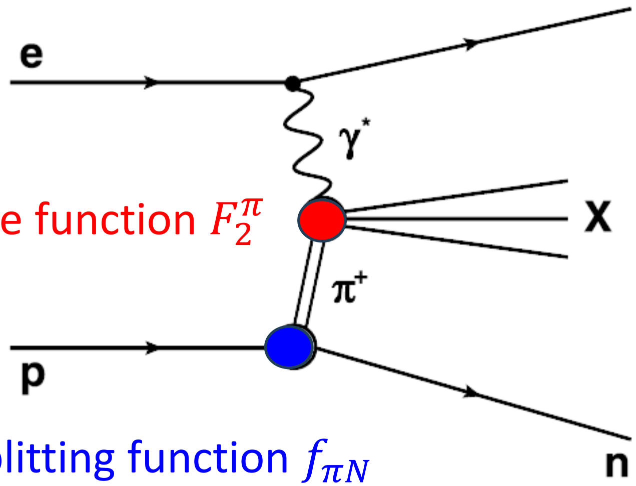
$$C_q^{\overline{\mathrm{MS}}}(z) = C_F \Big[2\left(\frac{\ln(1-z)}{1-z}\right)_+ - \frac{3}{2}\left(\frac{1}{1-z}\right)_+ - (1+z)\ln(1-z) - \frac{1+z^2}{1-z}\ln z + 3 + 2z - \left(\frac{\pi^2}{3} + \frac{9}{2}\right)\delta(1-z) \Big],$$

and

$$C_g^{\overline{\mathrm{MS}}}(z) = T_R \left[\left((1-z)^2 + z^2\right) \ln\left(\frac{1-z}{z}\right) - 8z^2 + 8z - 1 \right]$$

One-pion-exchange model

$$F_2^{\mathrm{LN(3)}}(x, Q^2, x_L) = 2 f_{\pi N}(\bar{x}_L) F_2^{\pi}(x_\pi, Q^2).$$



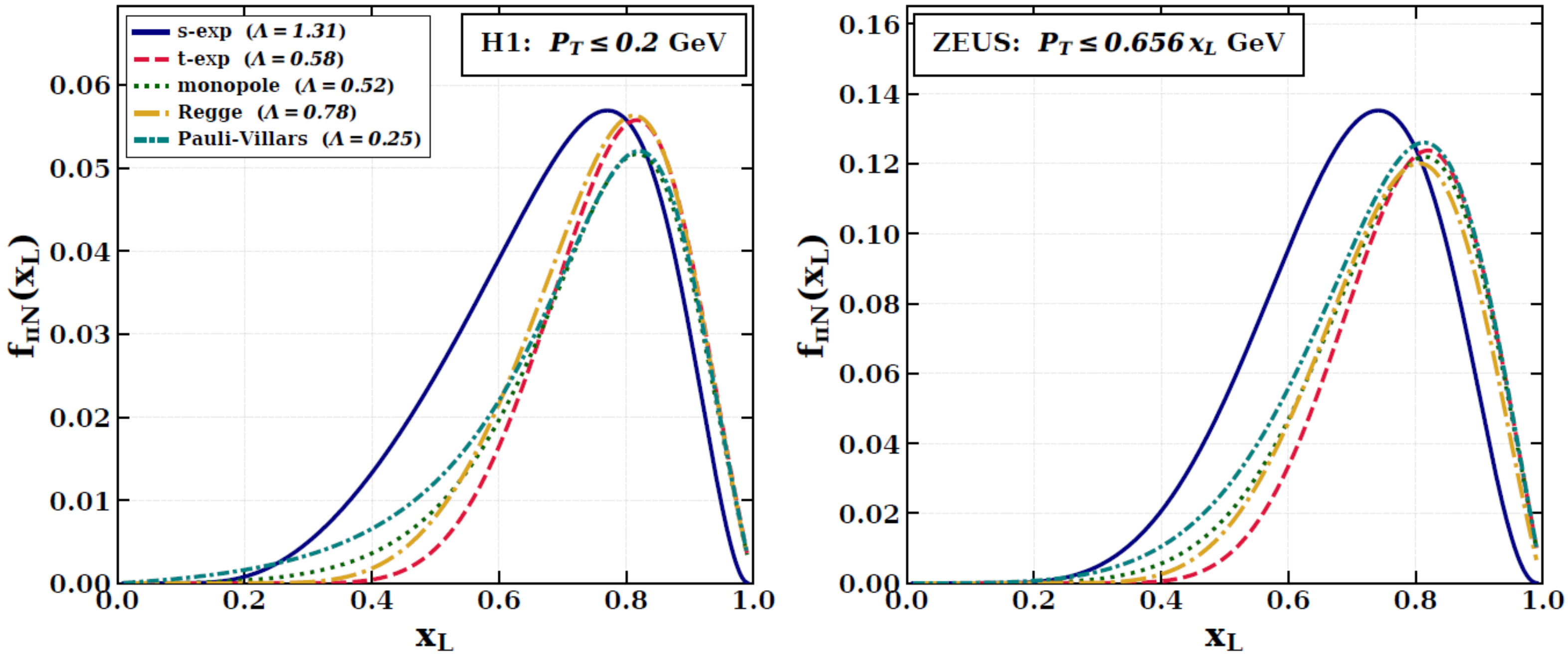
Pion structure function F_2^π

Splitting function $f_{\pi N}$

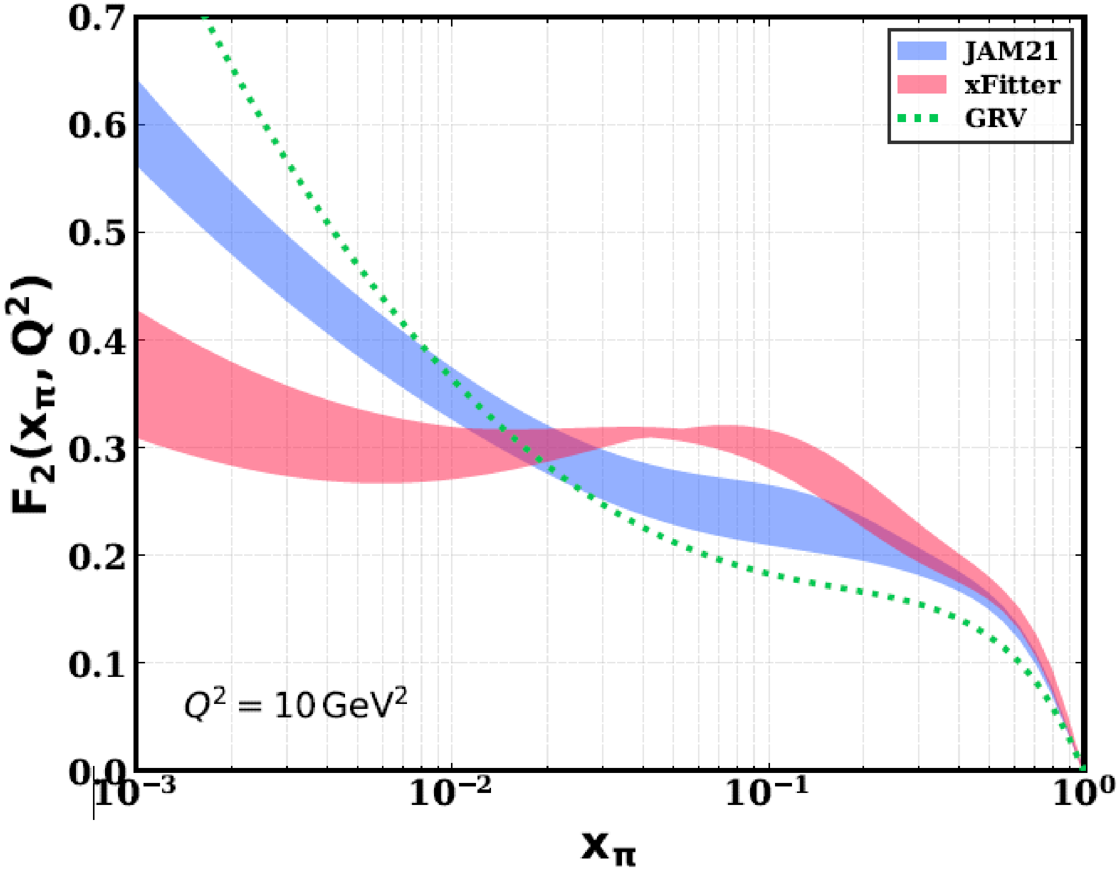
$$f_{\pi N}(\bar{x}_L) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \int dk_\perp^2 \, \frac{\bar{x}_L [k_\perp^2 + \bar{x}_L^2 M^2]}{x_L^2 D_{\pi N}^2} |\mathcal{F}|^2,$$

$$\mathcal{F} = \begin{cases} \text{(i) } \exp\left((M^2 - s)/\Lambda^2\right) & s\text{-dep exponential} \\ \text{(ii) } \exp\left(D_{\pi N}/\Lambda^2\right) & t\text{-dep exponential} \\ \text{(iii) } (\Lambda^2 - m_\pi^2)/(\Lambda^2 - t) & t\text{-dep monopole} \\ \text{(iv) } \bar{x}_L^{-\alpha_\pi(t)} \exp\left(D_{\pi N}/\Lambda^2\right) & \text{Regge} \\ \text{(v) } [1 - D_{\pi N}^2/(\Lambda^2 - t)^2]^{1/2} & \text{Pauli-Villars} \end{cases}$$

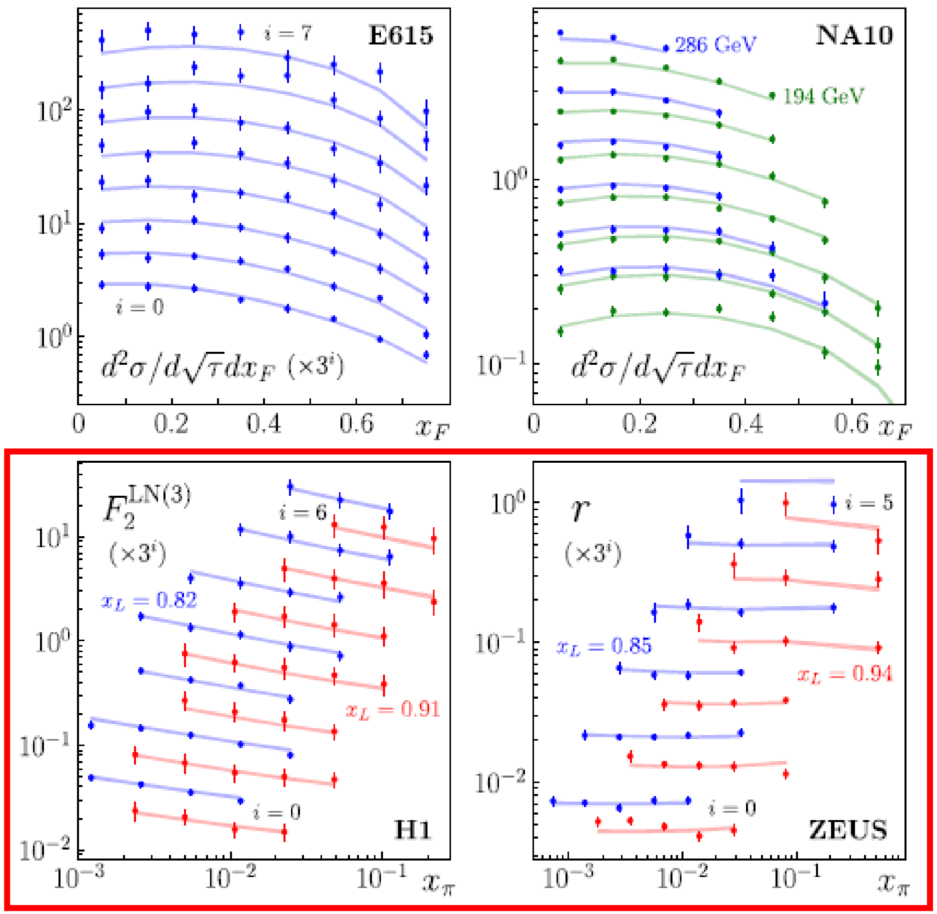
Pion Flux $f_{\pi \mathrm{N}}(x_L)$

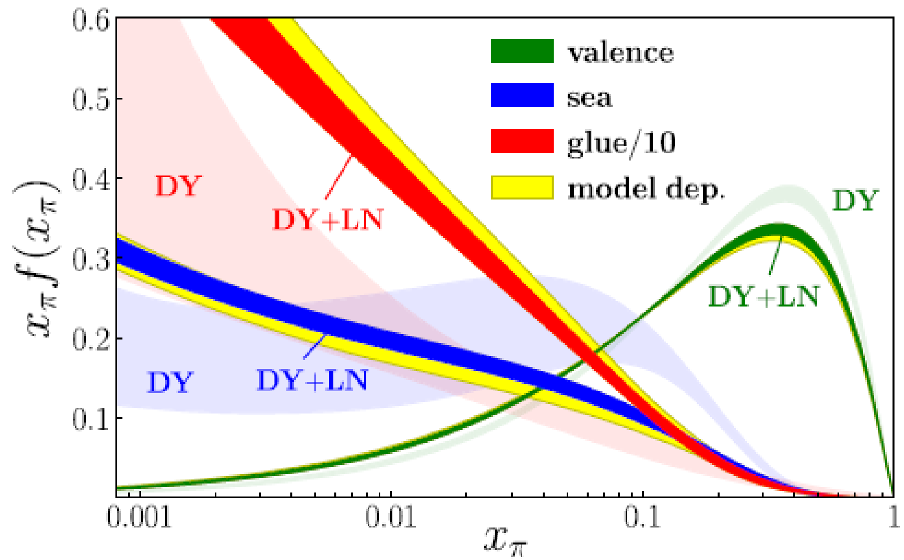


Pion Structure Function
$F_2(x_\pi, Q^2 = 10\ GeV^2)$



Pion PDFs: JAM18
[Barry et al., PRL 121, 152001 (2018)]

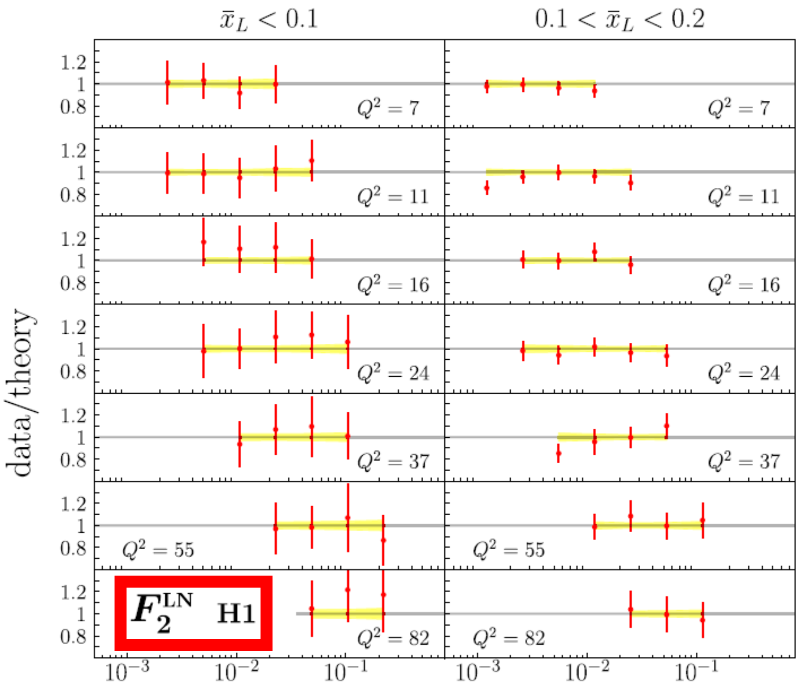




- Uncertainties are much reduced using DY+LN, as compared to DY alone.

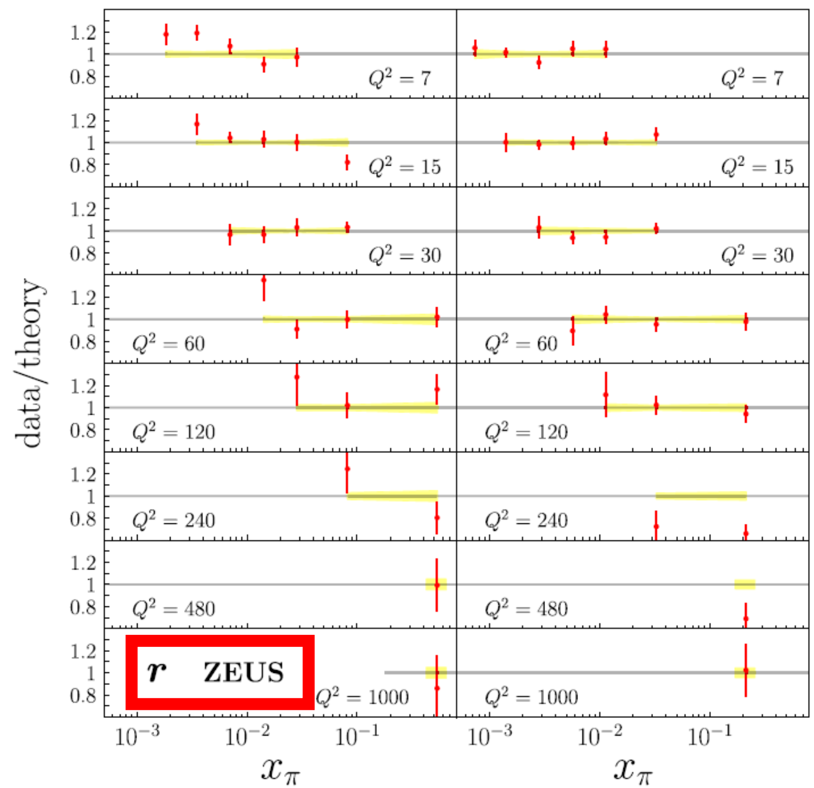
Pion PDFs: JAM21
[Cao et al., PRD 103, 114014 (2021)]

xL=0.91 xL=0.82



H1

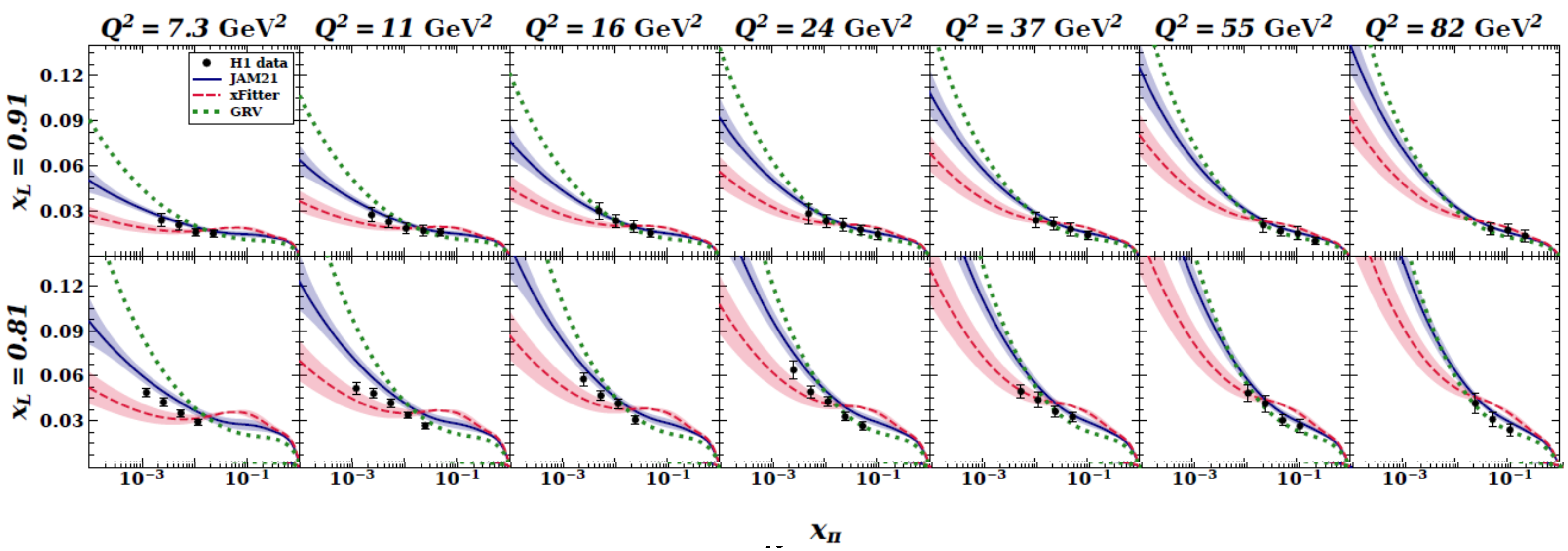
xL=0.94 xL=0.85



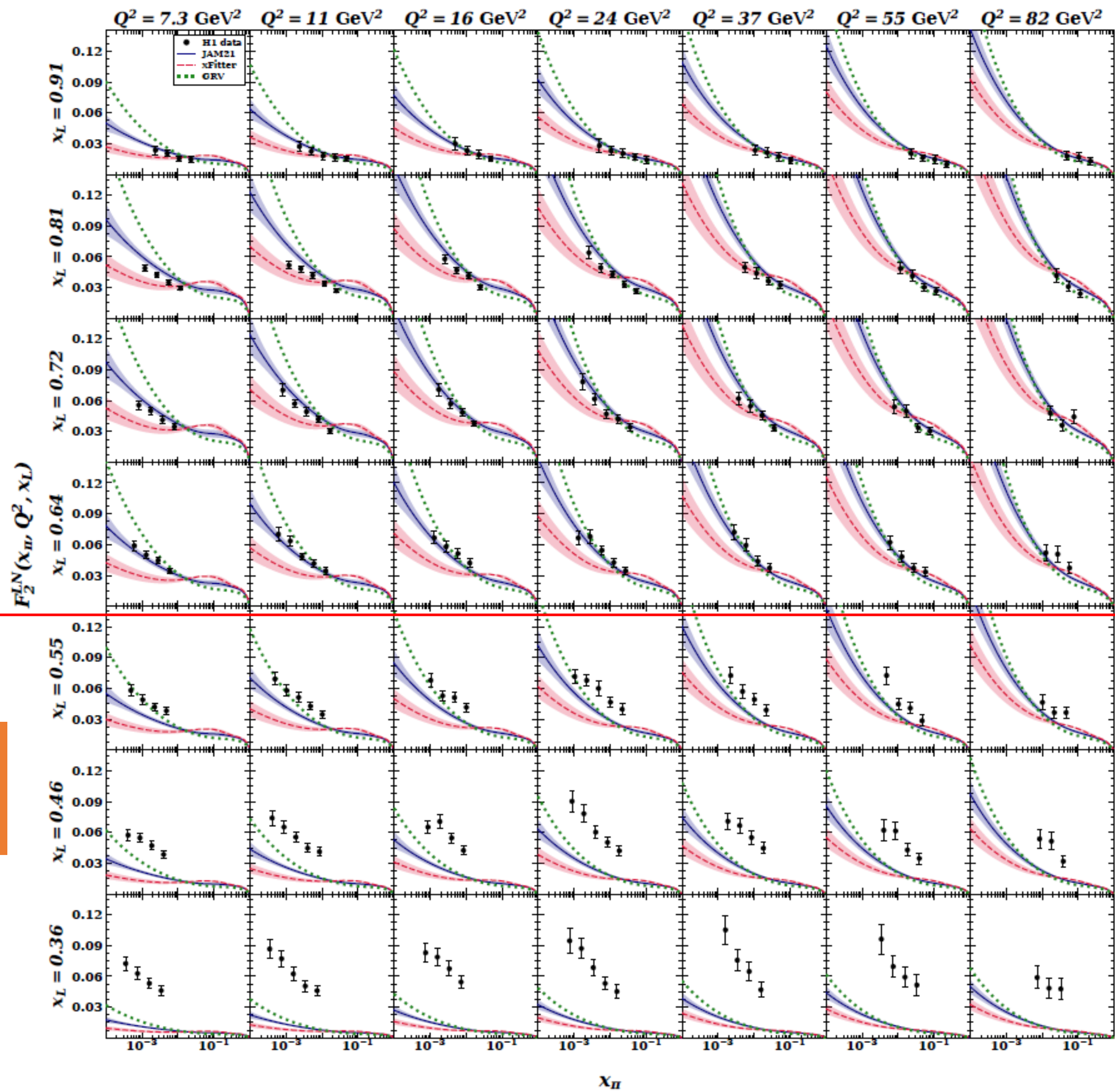
ZEUS

H1 vs. One-Pion-Exchange

Good agreement with calculations with JAM21 PDFs



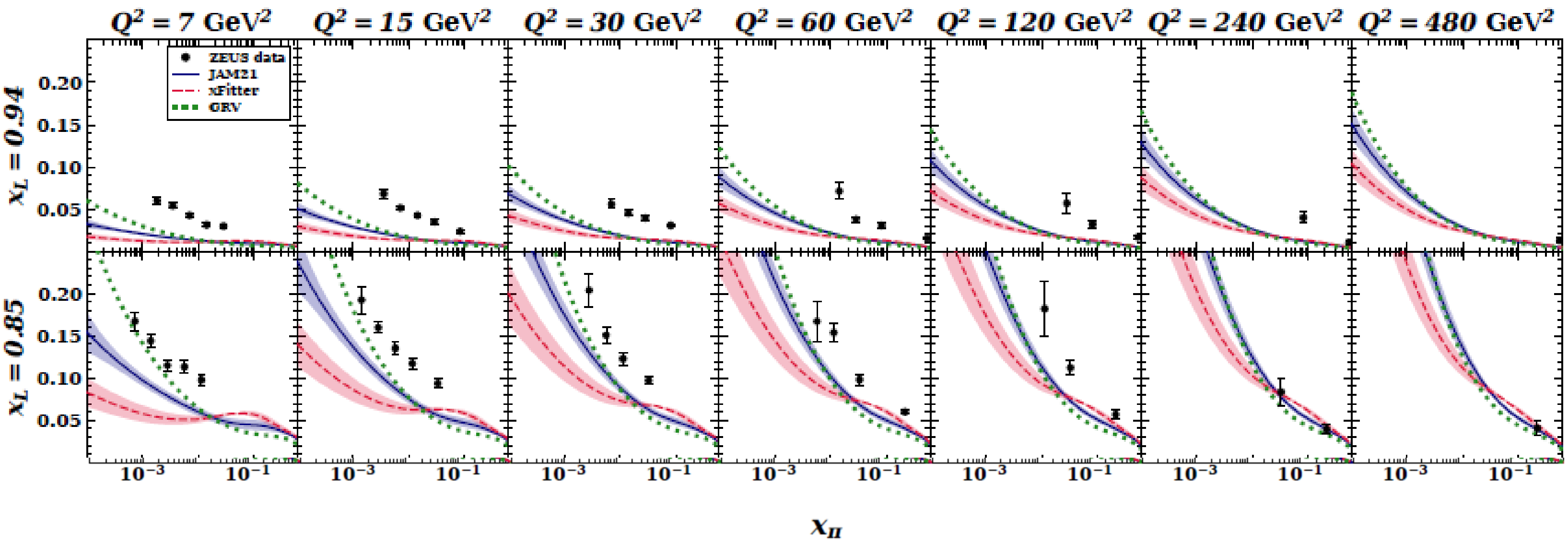
H1 vs. One-Pion-Exchange



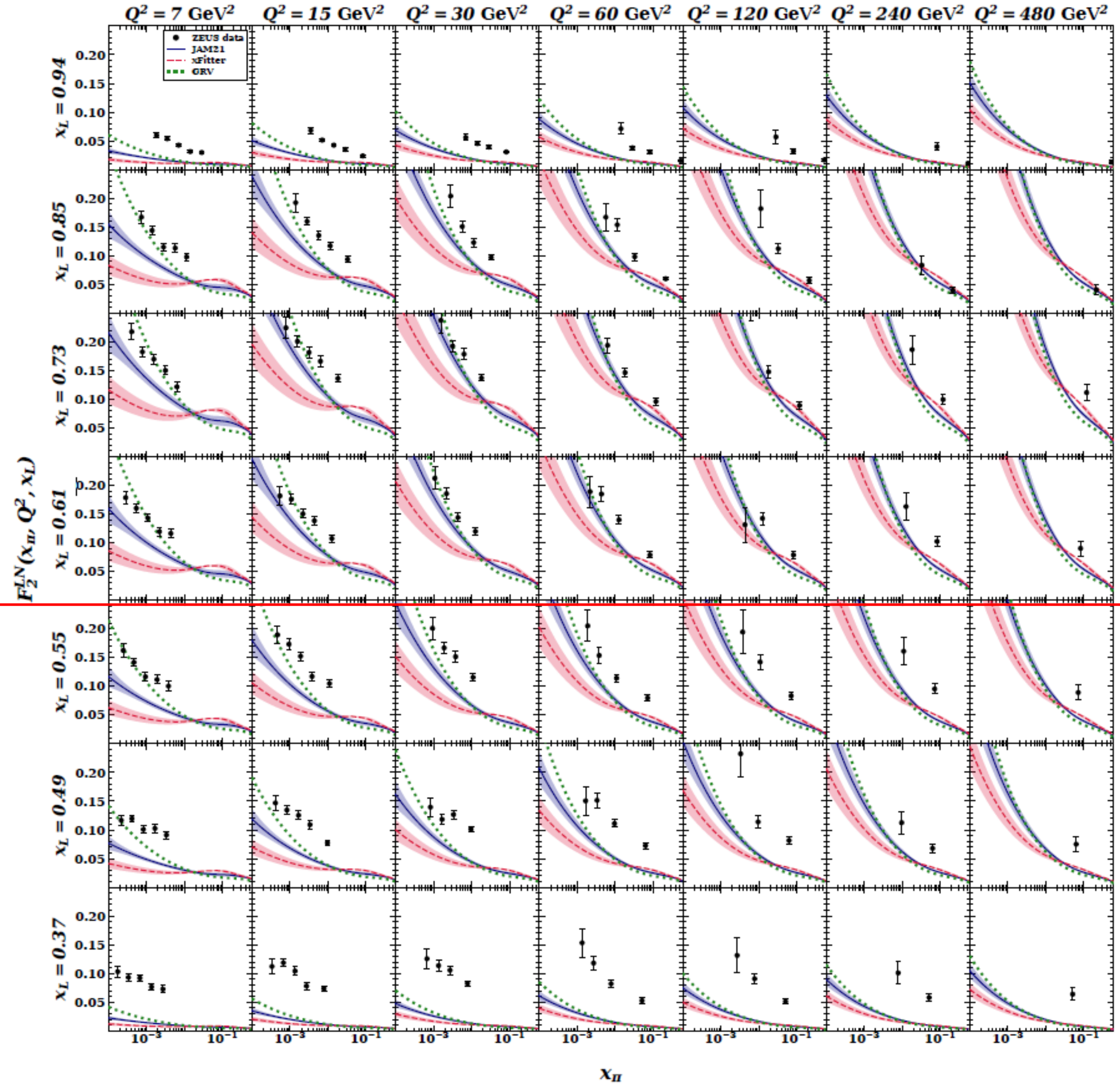
Deviation seen at smaller xL

ZEUS vs. One-Pion-Exchange

Significant disagreement with calculations with JAM21 PDFs!



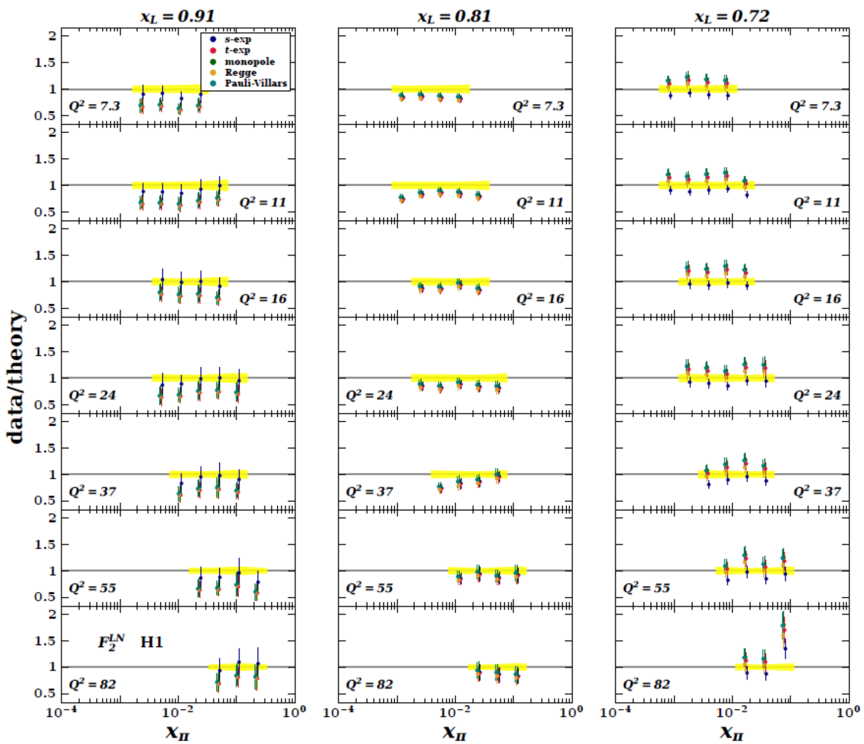
ZEUS vs. One-Pion-Exchange



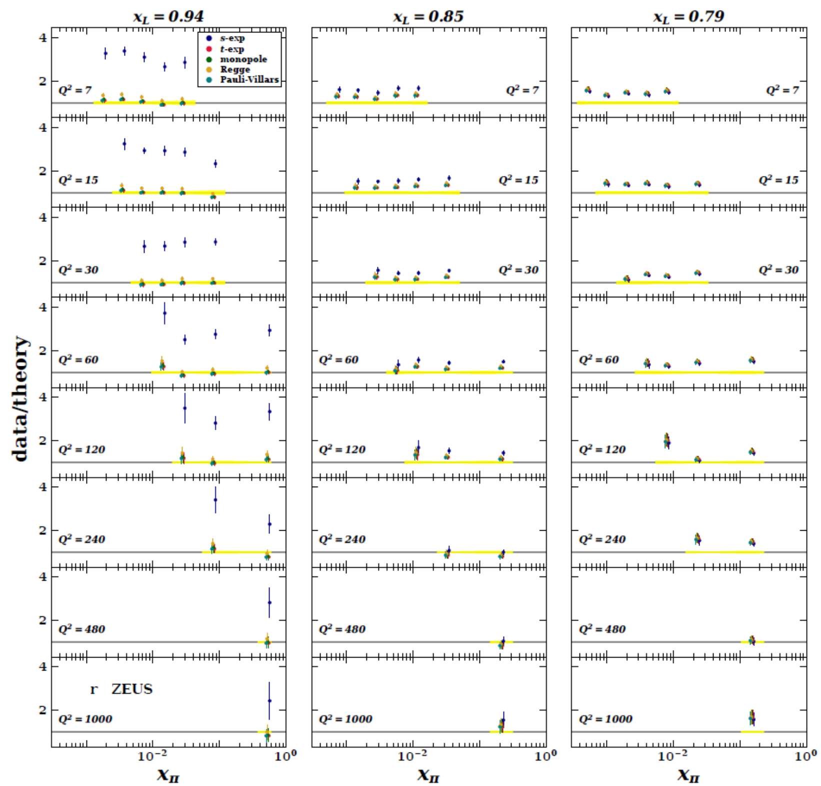
Deviation seen at smaller xL

Data/Theory: H1 & ZEUS

H1



ZEUS



PYTHIA 8: Beam Remnants

https://pythia8.web.cern.ch/manuals/pythia8317/BeamRemnants.html

- **Primordial kT**: the primordial kT of partons of hard-scattering subsystems
- **Colour flow**: the assignment of colour flow in the beam remnants
  - mode BeamRemnants:remnantMode
    (default = 0; minimum = 0; maximum = 1) Switch to choose between the two different colour models for the beam remnant.
  - option 0 : The old beam remnant model.
  - option 1 : The new beam remnant model.

PYTHIA 8: Colour Reconnection

https://pythia8.web.cern.ch/manuals/pythia8317/ColourReconnection.html

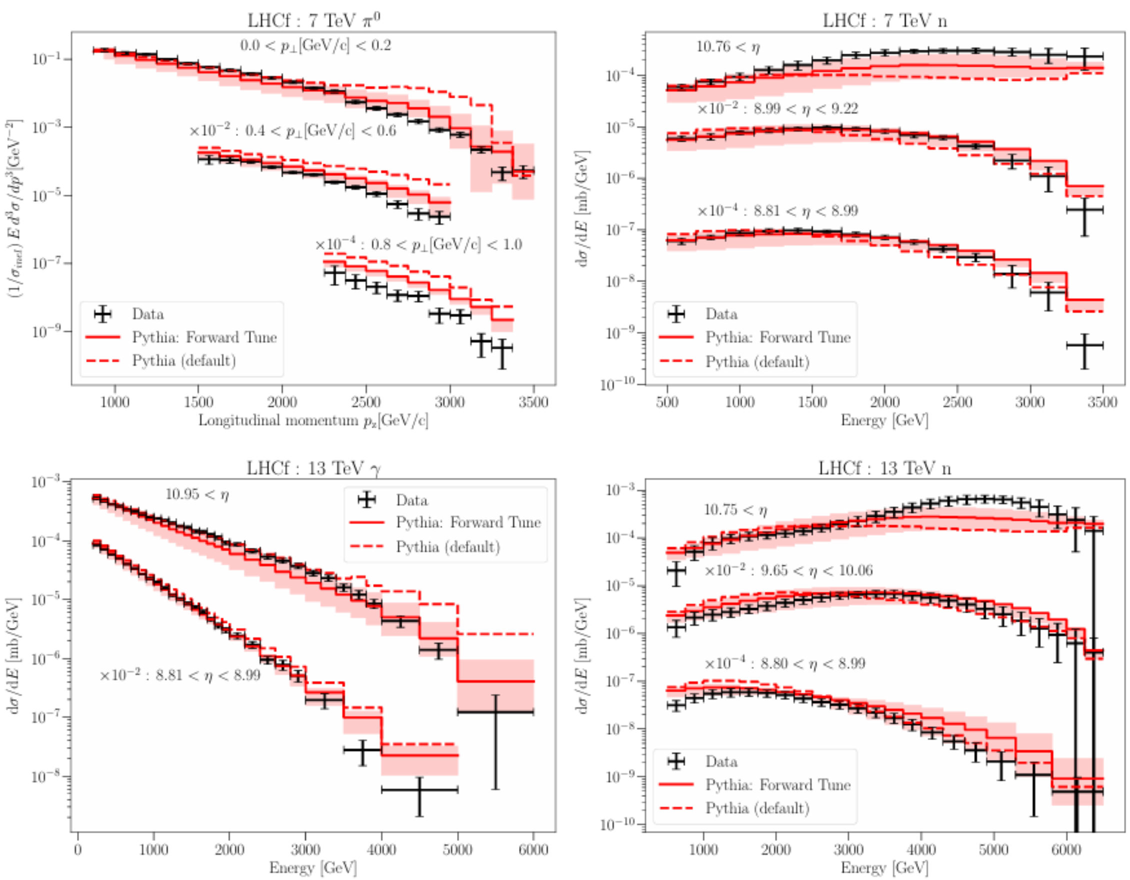
`flag` **ColourReconnection:reconnect** (`default = on`)
Allow or not a system to be merged with another one.

`mode` **ColourReconnection:mode** (`default = 0`; `minimum = 0`; `maximum = 4`)
Determine which model is used for colour reconnection. Beware that some settings may need to be changed to

`option` **0** : The MPI-based original Pythia 8 scheme.
`option` **1** : The new more QCD based scheme. Should be combined ewith `BeamRemnants:remnantMode = 1.`
`option` **2** : The new gluon-move model.
`option` **3** : The SK I *e^+ e^-* CR model. Requires `ColourReconnection:forceResonance = on` (and default `P`
`option` **4** : The SK II *e^+ e^-* CR model. Requires `ColourReconnection:forceResonance = on` (and default `I`

Tuning pythia for forward physics experiments

PRD 109, 016010 (2024), arXiv:2309.08604



Full name	Shorthand	Baseline (QCDCR)	Forward Tune	Uncertainty
`BeamRemnants:dampPopcorn`	d_{pop}	1	0	
`BeamRemnants:hardRemnantBaryon`	f_{remn}	off	on	
`BeamRemnants:aRemnantBaryon`	a_{remn}	-	0.36	
`BeamRemnants:bRemnantBaryon`	b_{remn}	-	1.69	
`BeamRemnants:primordialKTsoft`	σ_{soft}	0.9	0.58	$0.26 \ldots 1.27$
`BeamRemnants:primordialKThard`	σ_{hard}	1.8	1.8	
`BeamRemnants:halfScaleForKT`	Q_{half}	1.5	10	
`BeamRemnants:halfMassForKT`	m_{half}	1	1	
`BeamRemnants:primordialKTremnant`	σ_{remn}	0.4	0.58	$0.26 \ldots 1.27$

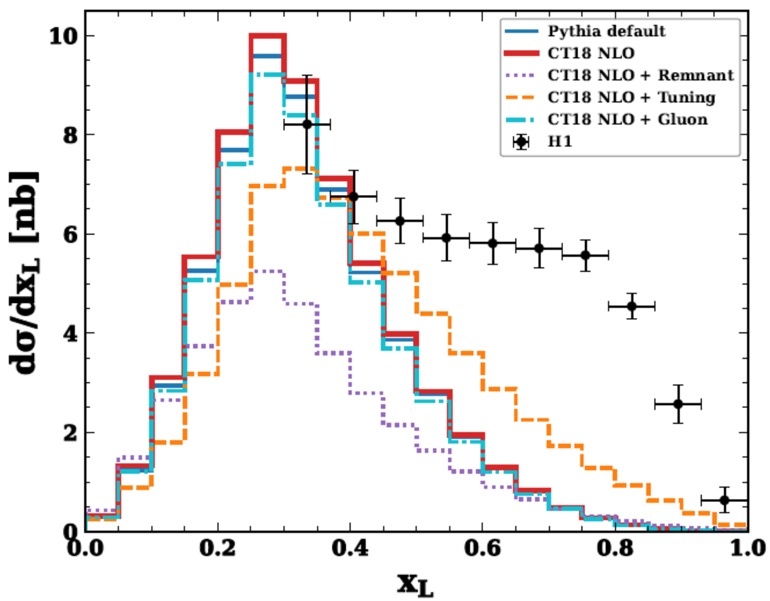
PYTHIA:
LN from DIS Target Fragmentation

Configuration	**Modified PYTHIA8 settings**
PYTHIA default	None
CT18 NLO	Proton PDF $\to$ CT18NLO
CT18 NLO + Remnant	CT18NLO Proton PDF BeamRemnants:remnantMode = 1 ColourReconnection:mode = 1
CT18 NLO + Tuning	CT18NLO Proton PDF ColourReconnection:allowJunctions = on BeamRemnants:dampPopcorn = 0 BeamRemnants:hardRemnantBaryon = on BeamRemnants:aRemnantBaryon = 0.36 BeamRemnants:bRemnantBaryon = 1.69 BeamRemnants:primordialKTsoft = 0.58 BeamRemnants:primordialKTremnant = 0.58
CT18 NLO + Gluon	CT18NLO Proton PDF BeamRemnants:remnantMode = 0 ColourReconnection:mode = 2

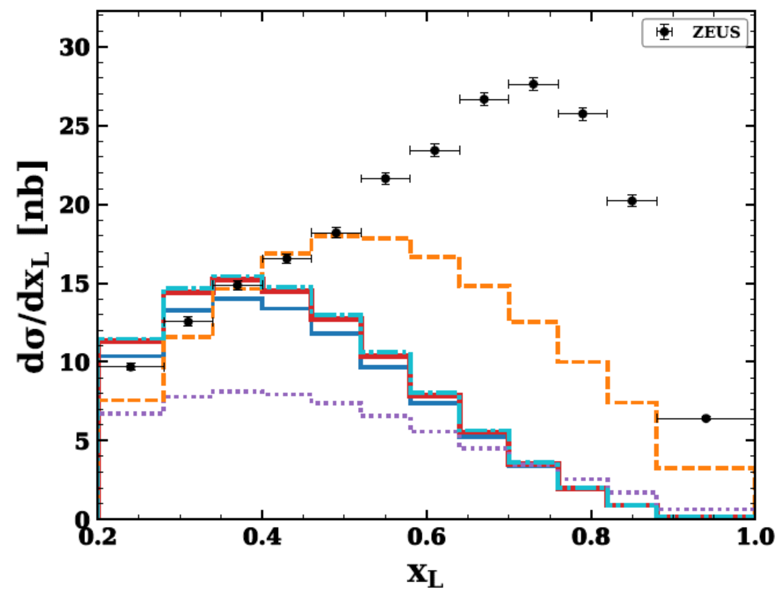
“Tuning pythia for forward physics experiments”
PRD 109, 016010 (2024)

PYTHIA:
LN from DIS Target Fragmentation

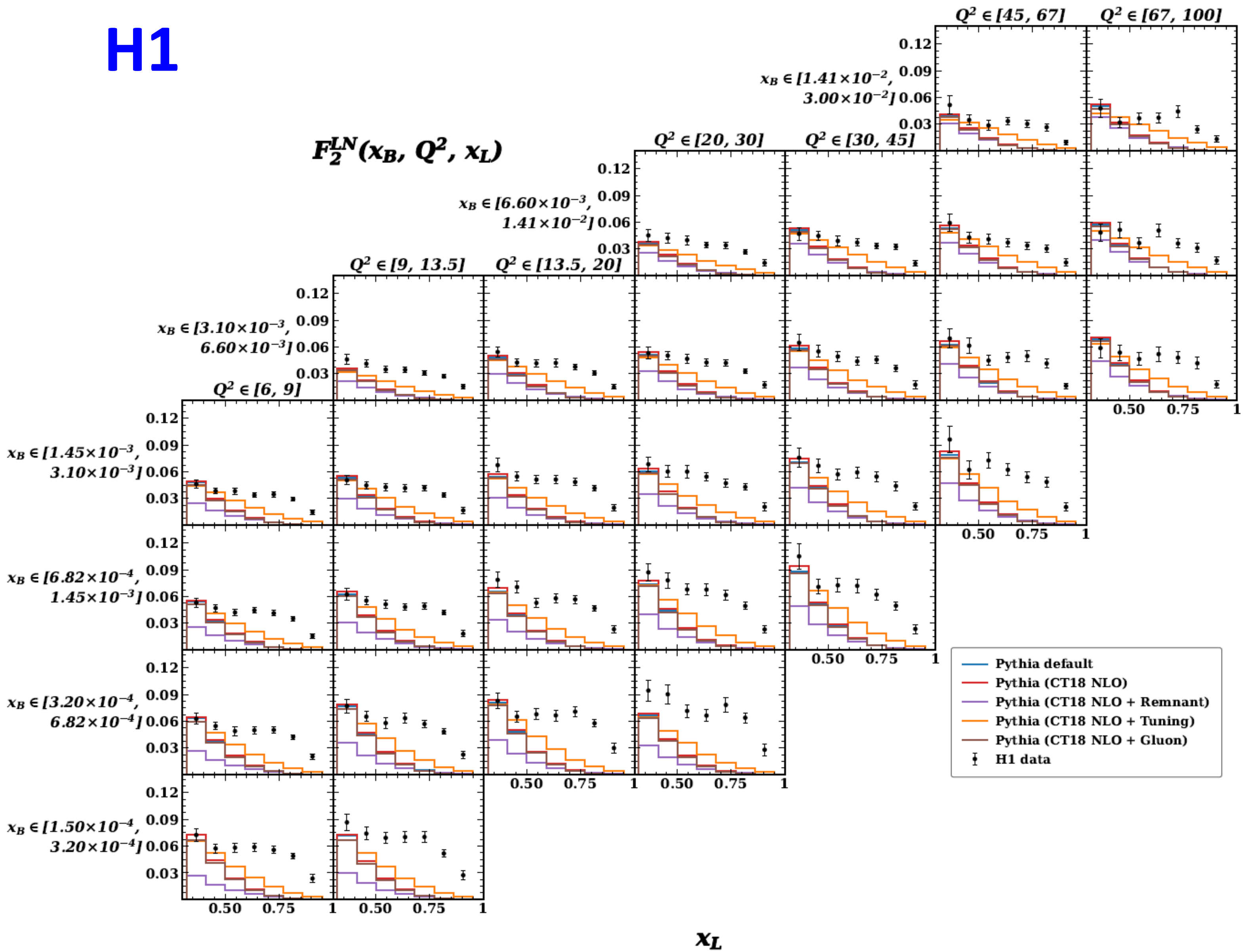
H1



ZEUS

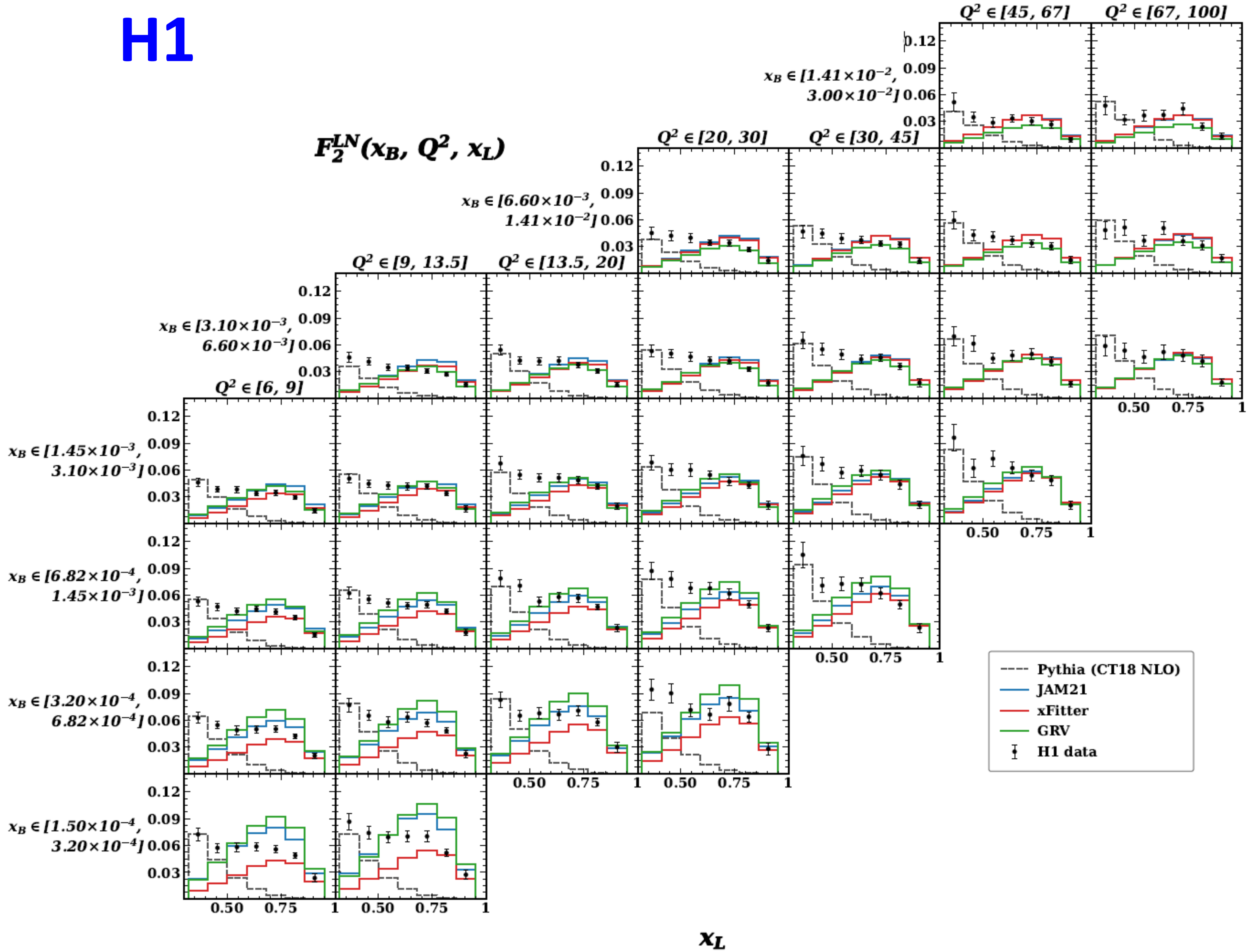


H1



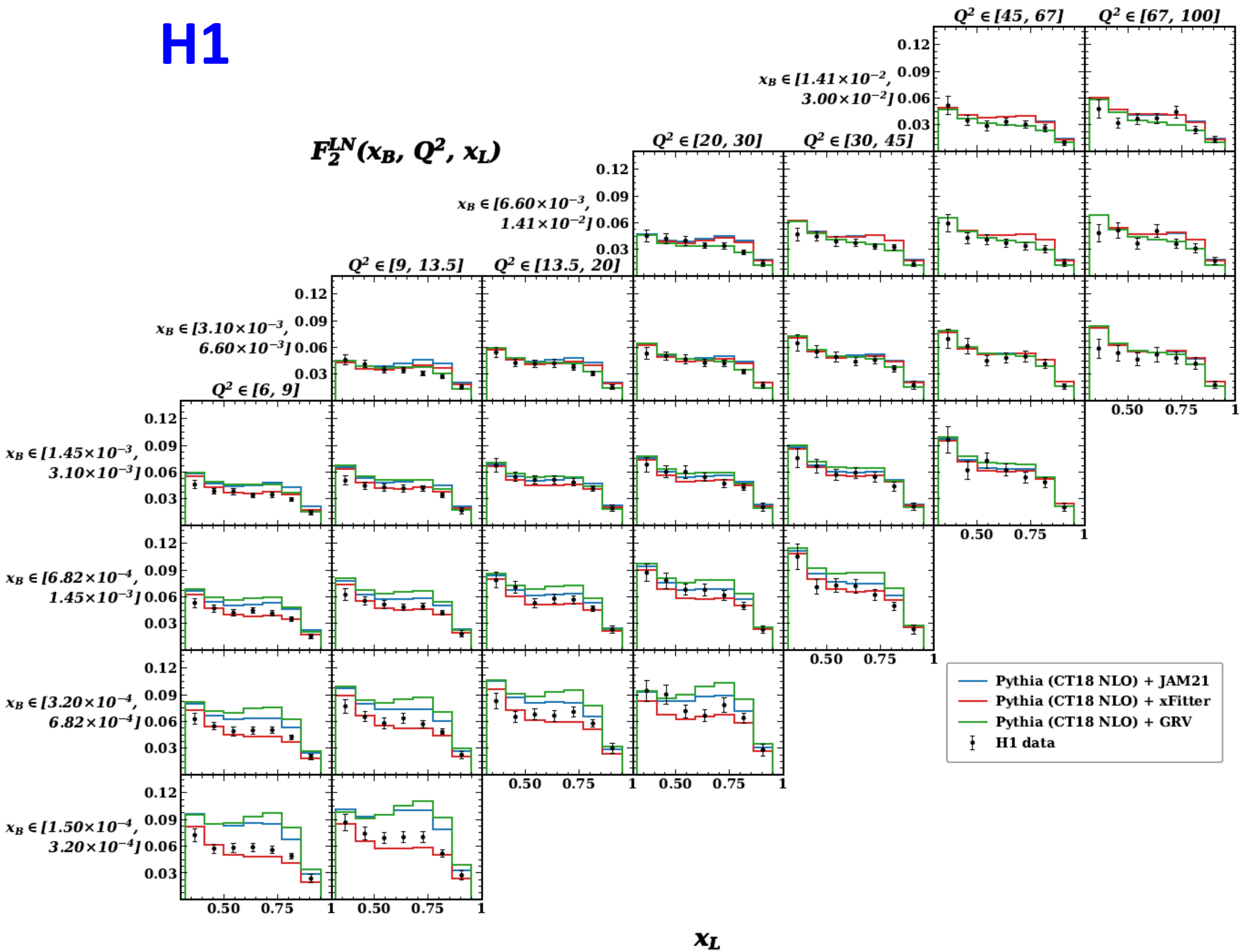
$F_2^{LN}(x_B, Q^2, x_L)$
$Q^2 \in [6, 9]$
$Q^2 \in [9, 13.5]$
$Q^2 \in [13.5, 20]$
$Q^2 \in [20, 30]$
$Q^2 \in [30, 45]$
$Q^2 \in [45, 67]$
$Q^2 \in [67, 100]$
$x_B \in [1.41\times10^{-2}, 3.00\times10^{-2}]$
$x_B \in [6.60\times10^{-3}, 1.41\times10^{-2}]$
$x_B \in [3.10\times10^{-3}, 6.60\times10^{-3}]$
$x_B \in [1.45\times10^{-3}, 3.10\times10^{-3}]$
$x_B \in [6.82\times10^{-4}, 1.45\times10^{-3}]$
$x_B \in [3.20\times10^{-4}, 6.82\times10^{-4}]$
$x_B \in [1.50\times10^{-4}, 3.20\times10^{-4}]$
0.12
0.09
0.06
0.03
0.50
0.75
1
x_L
Pythia default
Pythia (CT18 NLO)
Pythia (CT18 NLO + Remnant)
Pythia (CT18 NLO + Tuning)
Pythia (CT18 NLO + Gluon)
H1 data

H1



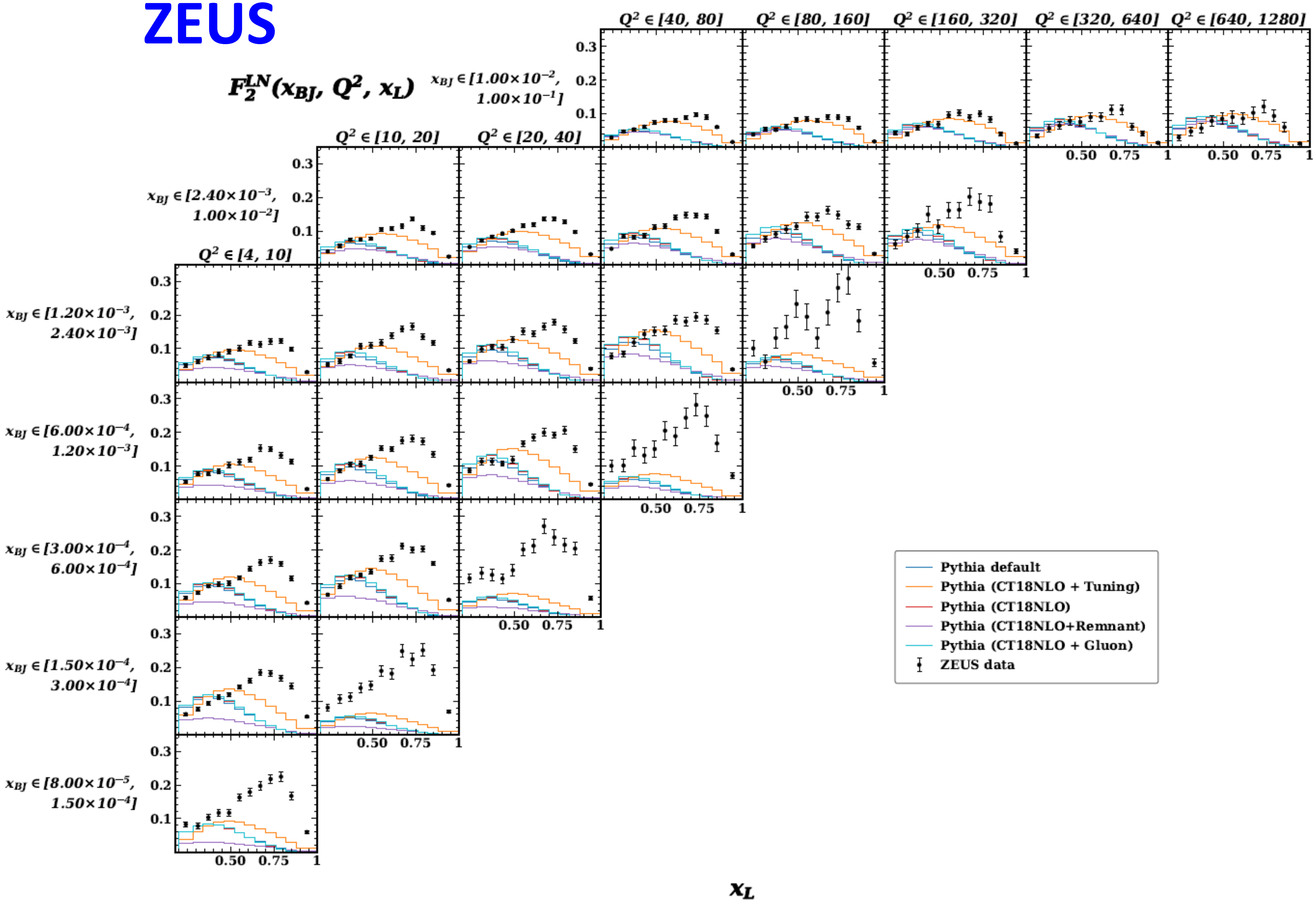
$F_2^{LN}(x_B, Q^2, x_L)$
$Q^2 \in [6, 9]$
$Q^2 \in [9, 13.5]$
$Q^2 \in [13.5, 20]$
$Q^2 \in [20, 30]$
$Q^2 \in [30, 45]$
$Q^2 \in [45, 67]$
$Q^2 \in [67, 100]$
$x_B \in [1.41\times10^{-2}, 3.00\times10^{-2}]$
$x_B \in [6.60\times10^{-3}, 1.41\times10^{-2}]$
$x_B \in [3.10\times10^{-3}, 6.60\times10^{-3}]$
$x_B \in [1.45\times10^{-3}, 3.10\times10^{-3}]$
$x_B \in [6.82\times10^{-4}, 1.45\times10^{-3}]$
$x_B \in [3.20\times10^{-4}, 6.82\times10^{-4}]$
$x_B \in [1.50\times10^{-4}, 3.20\times10^{-4}]$
0.12
0.09
0.06
0.03
0.50
0.75
1
Pythia (CT18 NLO)
JAM21
xFitter
GRV
H1 data
x_L

H1



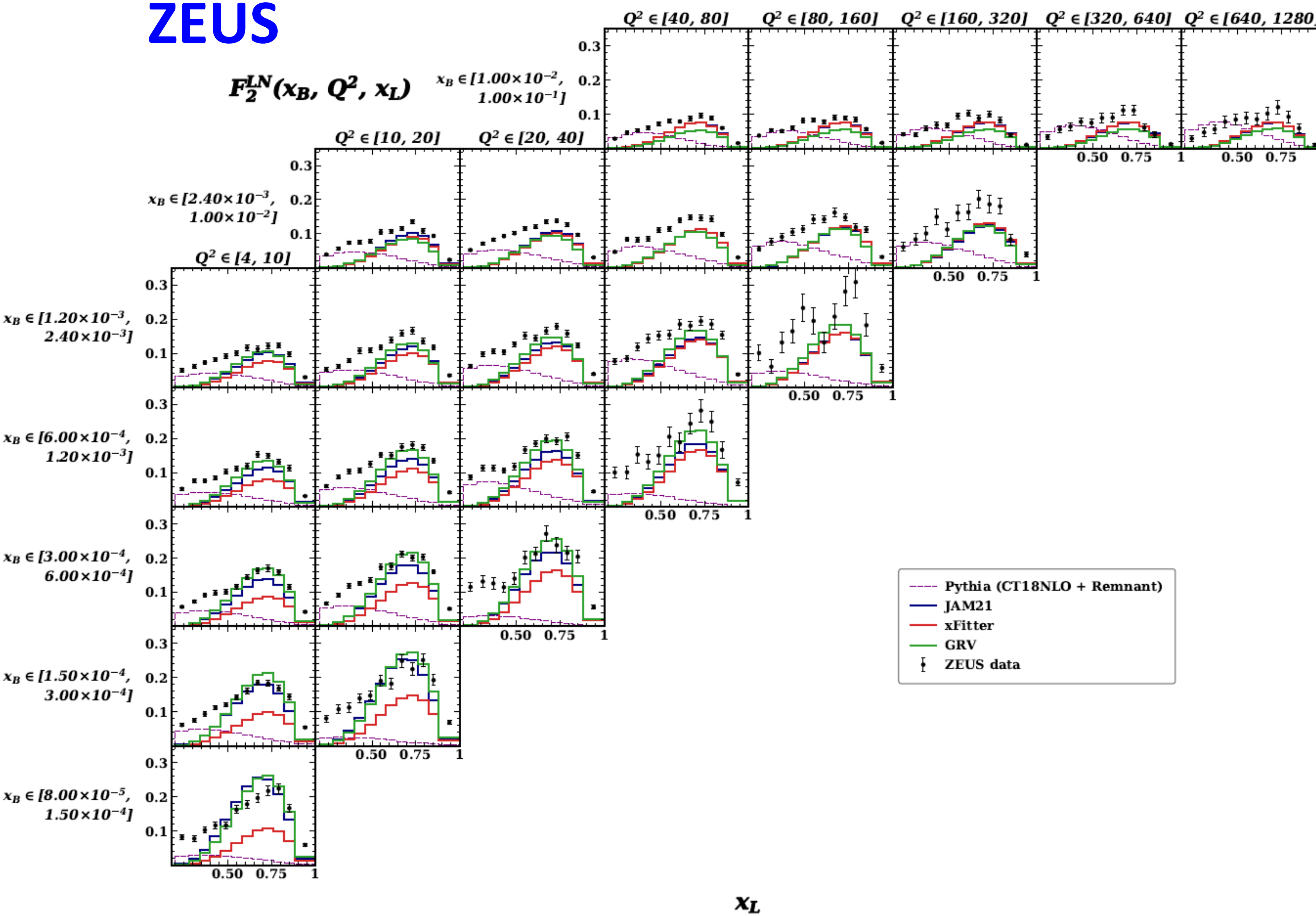
$F_2^{LN}(x_B, Q^2, x_L)$
$Q^2 \in [6, 9]$
$Q^2 \in [9, 13.5]$
$Q^2 \in [13.5, 20]$
$Q^2 \in [20, 30]$
$Q^2 \in [30, 45]$
$Q^2 \in [45, 67]$
$Q^2 \in [67, 100]$
$x_B \in [1.41\times10^{-2}, 3.00\times10^{-2}]$
$x_B \in [6.60\times10^{-3}, 1.41\times10^{-2}]$
$x_B \in [3.10\times10^{-3}, 6.60\times10^{-3}]$
$x_B \in [1.45\times10^{-3}, 3.10\times10^{-3}]$
$x_B \in [6.82\times10^{-4}, 1.45\times10^{-3}]$
$x_B \in [3.20\times10^{-4}, 6.82\times10^{-4}]$
$x_B \in [1.50\times10^{-4}, 3.20\times10^{-4}]$
0.12
0.09
0.06
0.03
0.50
0.75
1
Pythia (CT18 NLO) + JAM21
Pythia (CT18 NLO) + xFitter
Pythia (CT18 NLO) + GRV
H1 data
x_L

ZEUS



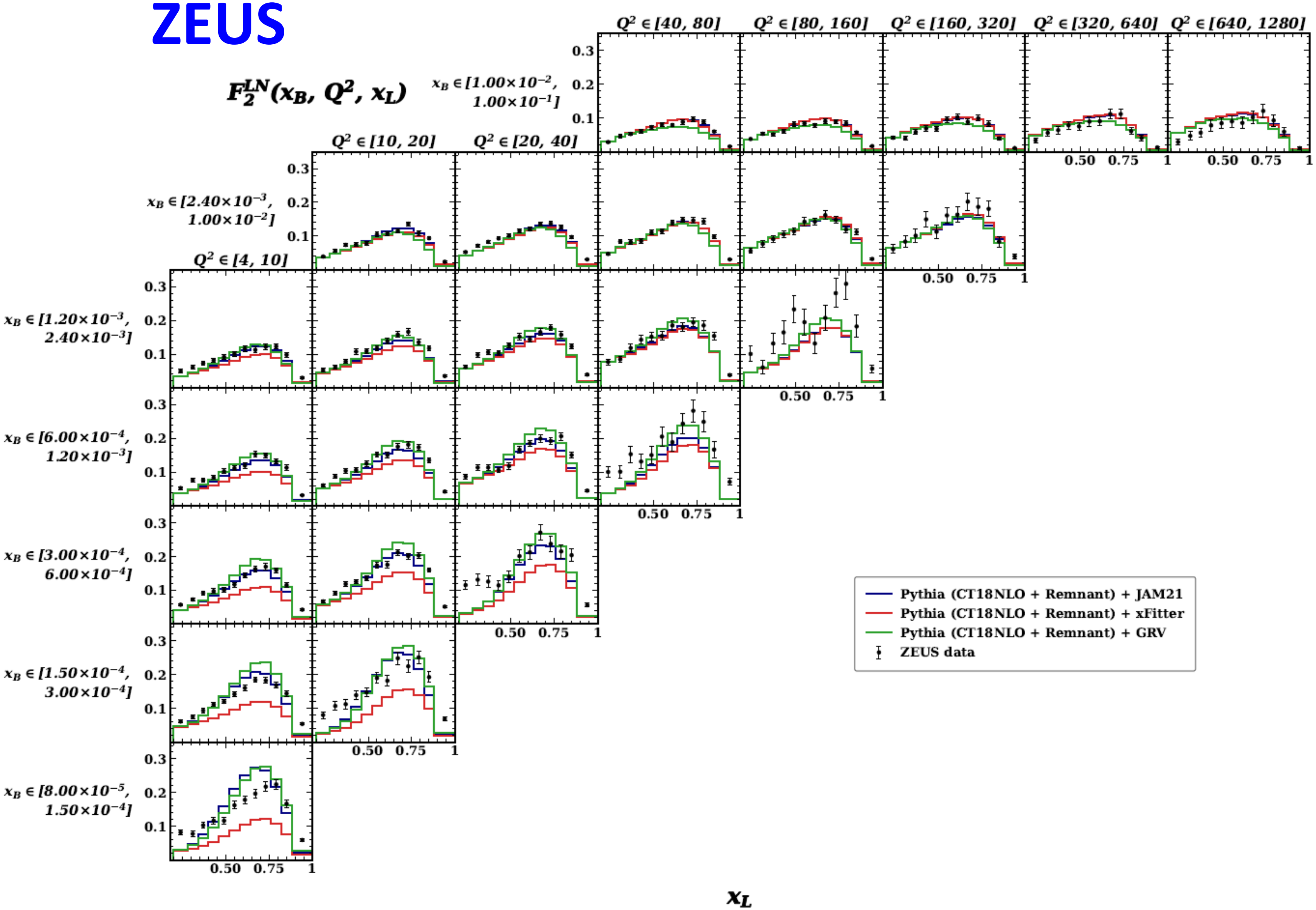
$F_2^{LN}(x_{BJ}, Q^2, x_L)$
$Q^2 \in [4, 10]$
$Q^2 \in [10, 20]$
$Q^2 \in [20, 40]$
$Q^2 \in [40, 80]$
$Q^2 \in [80, 160]$
$Q^2 \in [160, 320]$
$Q^2 \in [320, 640]$
$Q^2 \in [640, 1280]$
$x_{BJ} \in [1.00\times10^{-2}, 1.00\times10^{-1}]$
$x_{BJ} \in [2.40\times10^{-3}, 1.00\times10^{-2}]$
$x_{BJ} \in [1.20\times10^{-3}, 2.40\times10^{-3}]$
$x_{BJ} \in [6.00\times10^{-4}, 1.20\times10^{-3}]$
$x_{BJ} \in [3.00\times10^{-4}, 6.00\times10^{-4}]$
$x_{BJ} \in [1.50\times10^{-4}, 3.00\times10^{-4}]$
$x_{BJ} \in [8.00\times10^{-5}, 1.50\times10^{-4}]$
0.1
0.2
0.3
0.50
0.75
1
x_L
Pythia default
Pythia (CT18NLO + Tuning)
Pythia (CT18NLO)
Pythia (CT18NLO+Remnant)
Pythia (CT18NLO + Gluon)
ZEUS data

ZEUS



$F_2^{LN}(x_B, Q^2, x_L)$
$Q^2 \in [4, 10]$
$Q^2 \in [10, 20]$
$Q^2 \in [20, 40]$
$Q^2 \in [40, 80]$
$Q^2 \in [80, 160]$
$Q^2 \in [160, 320]$
$Q^2 \in [320, 640]$
$Q^2 \in [640, 1280]$
$x_B \in [1.00\times10^{-2}, 1.00\times10^{-1}]$
$x_B \in [2.40\times10^{-3}, 1.00\times10^{-2}]$
$x_B \in [1.20\times10^{-3}, 2.40\times10^{-3}]$
$x_B \in [6.00\times10^{-4}, 1.20\times10^{-3}]$
$x_B \in [3.00\times10^{-4}, 6.00\times10^{-4}]$
$x_B \in [1.50\times10^{-4}, 3.00\times10^{-4}]$
$x_B \in [8.00\times10^{-5}, 1.50\times10^{-4}]$
0.1
0.2
0.3
0.50
0.75
1
Pythia (CT18NLO + Remnant)
JAM21
xFitter
GRV
ZEUS data
x_L

ZEUS



F_2^LN(x_B, Q^2, x_L)
Q^2 ∈ [4, 10]
Q^2 ∈ [10, 20]
Q^2 ∈ [20, 40]
Q^2 ∈ [40, 80]
Q^2 ∈ [80, 160]
Q^2 ∈ [160, 320]
Q^2 ∈ [320, 640]
Q^2 ∈ [640, 1280]
x_B ∈ [1.00×10^-2, 1.00×10^-1]
x_B ∈ [2.40×10^-3, 1.00×10^-2]
x_B ∈ [1.20×10^-3, 2.40×10^-3]
x_B ∈ [6.00×10^-4, 1.20×10^-3]
x_B ∈ [3.00×10^-4, 6.00×10^-4]
x_B ∈ [1.50×10^-4, 3.00×10^-4]
x_B ∈ [8.00×10^-5, 1.50×10^-4]
0.1
0.2
0.3
0.50
0.75
1
x_L
Pythia (CT18NLO + Remnant) + JAM21
Pythia (CT18NLO + Remnant) + xFitter
Pythia (CT18NLO + Remnant) + GRV
ZEUS data

Summary

- The DIS LN production at large xL is relevant to the pion PDFs within the framework of one-pion-change Sullivan process.
- We adopt the pion flux parameterization as done in the extraction of JAM pion PDFs and perform the calculations of Sullivan process contribution. We could repeat a nice description of the H1 data at two largest xL bins by this contribution. However, the data/theory is about 3 for the ZEUS data at two largest xL bins.
- The differential F2LN(xB, Q2, xL) measured by H1 and ZEUS could be reasonably well described by sum of DIS target fragmentation simulated by PYTHIA and Sullivan process without ad-hoc scaling parameters. Including all data points across all measured xL range in the global analysis of pion PDFs seems promising.