TDIS Collaboration Meeting
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JAM analysis of pion PDFs

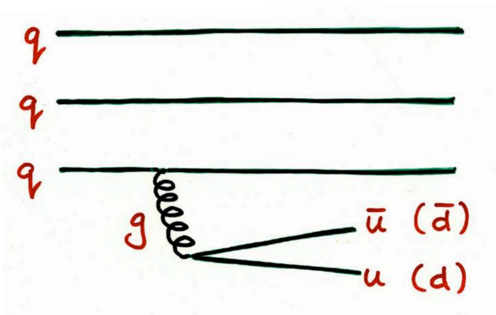
Wally Melnitchouk

Jefferson Lab

collaborators: Patrick Barry (North Carolina State U ⟶ JLab PDF)
Nina Cao (Harvard U / REU)
Chueng Ji (North Carolina State U)
Nobuo Sato (JLab "Isgur Fellow")

Sea of the proton

- From text-books: perturbative QCD expected to generate symmetric $q\bar{q}$ sea via gluon radiation into $q\bar{q}$ pairs

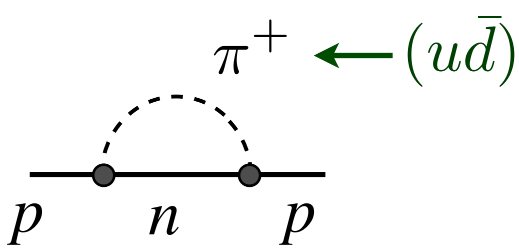


$\longrightarrow$ since u and d quarks nearly degenerate, expect flavor-symmetric light-quark sea

$$\bar{d} \approx \bar{u}$$

Ross, Sachrajda (1979)

- (Almost) from text-books: Thomas suggested that chiral symmetry of QCD ("low energy") should have consequences for antiquark PDFs in the nucleon ("high energy")

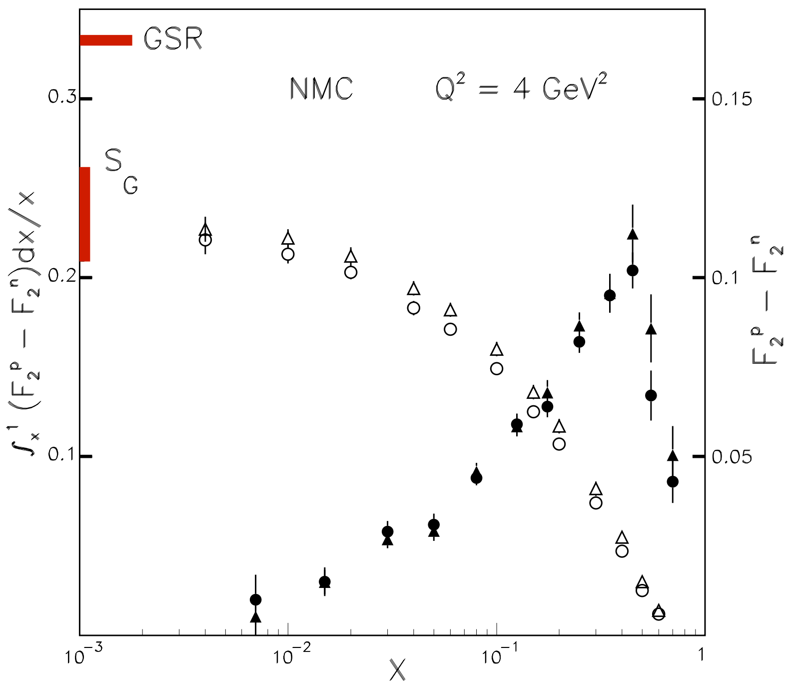


$\longrightarrow$ $\bar{d} > \bar{u}$

Thomas (1984)

Sea of the proton

- First clear experimental support for $\bar{d} \neq \bar{u}$ came from measurement of Gottfried sum observed by NMC

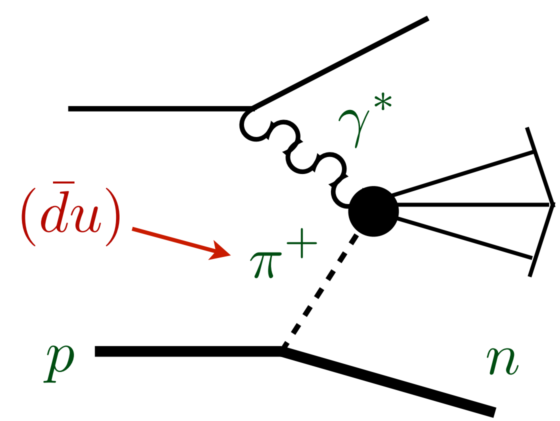


NMC (1991, 1994)

$$\int_0^1 \frac{dx}{x}(F_2^p - F_2^n) = \frac{1}{3} - \frac{2}{3}\int_0^1 dx\,(\bar{d} - \bar{u})$$
$$= 0.235(26)$$

→ violation of "Gottfried sum rule"!

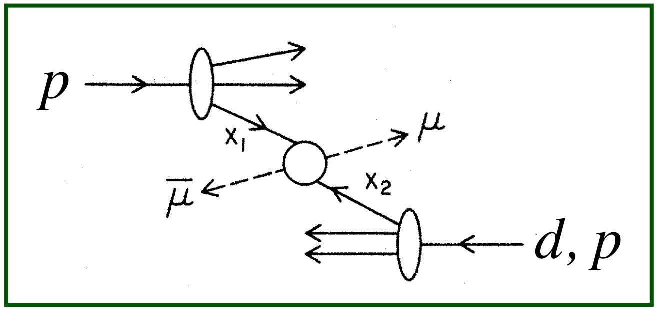
→ Sullivan process — DIS from pion cloud of the nucleon



Sullivan (1972)

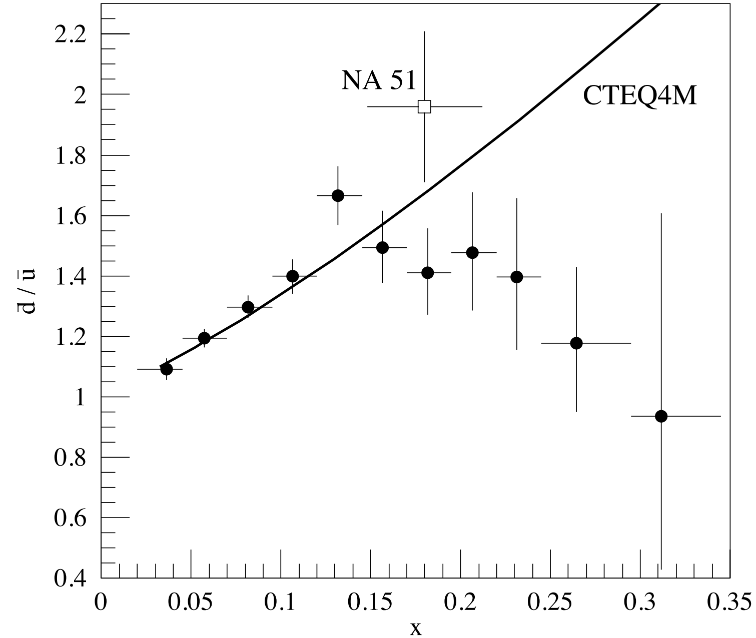
Sea of the proton

- x dependence of $\bar{d} - \bar{u}$ asymmetry established in Fermilab E866 pp/pd Drell-Yan experiment



$$\frac{d\sigma}{dx_1 dx_2} \sim \sum_q e_q^2\, q(x_1)\, \bar{q}(x_2) \; + \; (x_1 \leftrightarrow x_2)$$

$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \quad \text{for } x_1 \gg x_2$$



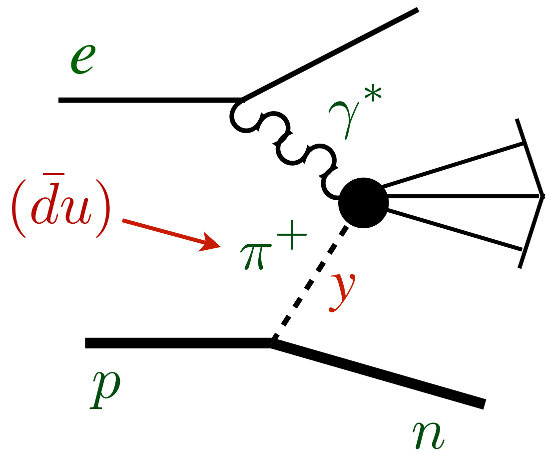
E866 (2001)

→ strong enhancement of $\bar{d}$ at $x \sim 0.1 - 0.2$

→ intriguing behavior at large x hinting at possible sign change of $\bar{d} - \bar{u}$

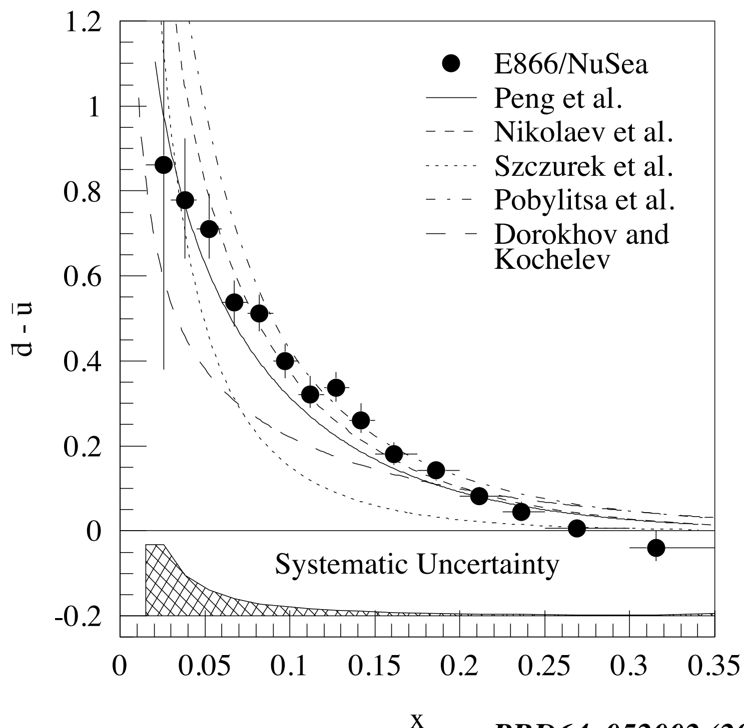
Sea of the proton — pion contributions

- General agreement with pion cloud models



$$(\bar{d} - \bar{u})(x) = \int_x^1 \frac{dy}{y} f_{\pi^+ n}(y)\, \bar{q}_v^{\pi}(x/y)$$

$p \to \pi^+ n$ splitting function ("flux factor")



PRD64, 052002 (2001)

→ shape qualitatively reproduced by most models (except at high x),
— but *is there a direct connection with QCD?*

Chiral effective field theory

- Rigorous connection with QCD established via chiral EFT

$$\mathcal{L}_{\rm eff} = \frac{g_A}{2f_\pi}\,\bar\psi_N \gamma^\mu \gamma_5\, \vec\tau\cdot\partial_\mu\vec\pi\,\psi_N - \frac{1}{(2f_\pi)^2}\,\bar\psi_N\gamma^\mu\,\vec\tau\cdot(\vec\pi\times\partial_\mu\vec\pi)\,\psi_N + \ \ldots$$

Weinberg (1967)

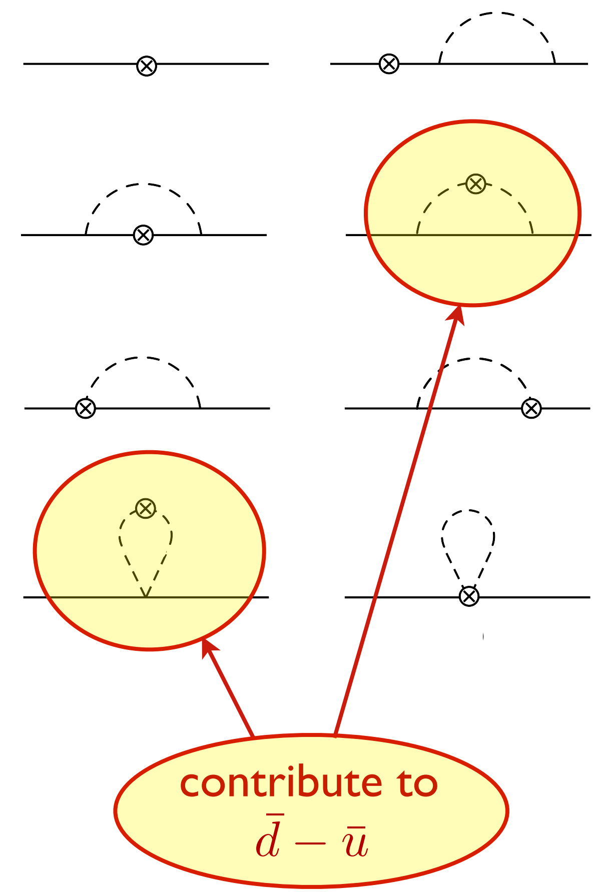
→ lowest order πN interaction includes pion rainbow and tadpole contributions

→ matching quark- and hadron-level operators

$$\mathcal{O}_q^{\mu_1\cdots\mu_n} = \sum_h c_{q/h}^{(n)}\ \mathcal{O}_h^{\mu_1\cdots\mu_n}$$

yields convolution representation

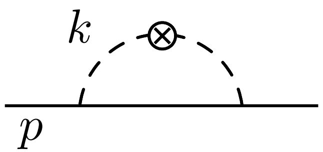
$$q(x) = \sum_h \int_x^1 \frac{dy}{y} f_h(y)\, q_v^h(x/y)$$



Ji, WM, Thomas (2013)

Chiral effective field theory

- Splitting functions for various diagrams computed in chiral theory
  e.g. pion rainbow diagram



$$f_\pi(y) = f^{(\mathrm{on})}(y) + f^{(\delta)}(y)$$

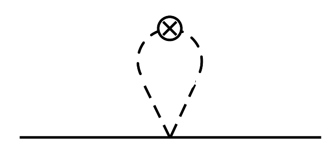
has on-shell $(y = k^+/p^+ > 0)$ and $\delta(y)$ contributions!

$$f^{(\mathrm{on})}(y) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \int dk_\perp^2 \, \frac{y(k_\perp^2 + y^2 M^2)}{[k_\perp^2 + y^2 M^2 + (1-y) m_\pi^2]^2} \, \mathcal{F}^2$$

$$f^{(\delta)}(y) = \frac{g_A^2}{4(4\pi f_\pi)^2} \int dk_\perp^2 \, \log\left(\frac{k_\perp^2 + m_\pi^2}{\mu^2}\right) \delta(y) \; \mathcal{F}^2$$

- Bubble diagram contributes only at $y = 0$ (hence $x = 0$)

$$f^{(\mathrm{bub})}(y) = \frac{8}{g_A^2} \; f^{(\delta)}(y)$$



$\longrightarrow$ contributes to lowest moment, but not at $x > 0$

Salamu, Ji, WM, Wang
PRL 114, 122001 (2015)

Chiral effective field theory

- For point-like nucleons and pions, integrals divergent

  $\longrightarrow$ finite size of nucleon provides natural regularization scale (but does not prescribe form of regularization)

$\mathcal{F} = \Theta(\Lambda^2 - k_\perp^2)$ $k_\perp$ cutoff

$\mathcal{F} = \exp\left[(M^2 - s)/\Lambda^2\right]$ s-dep. exponential

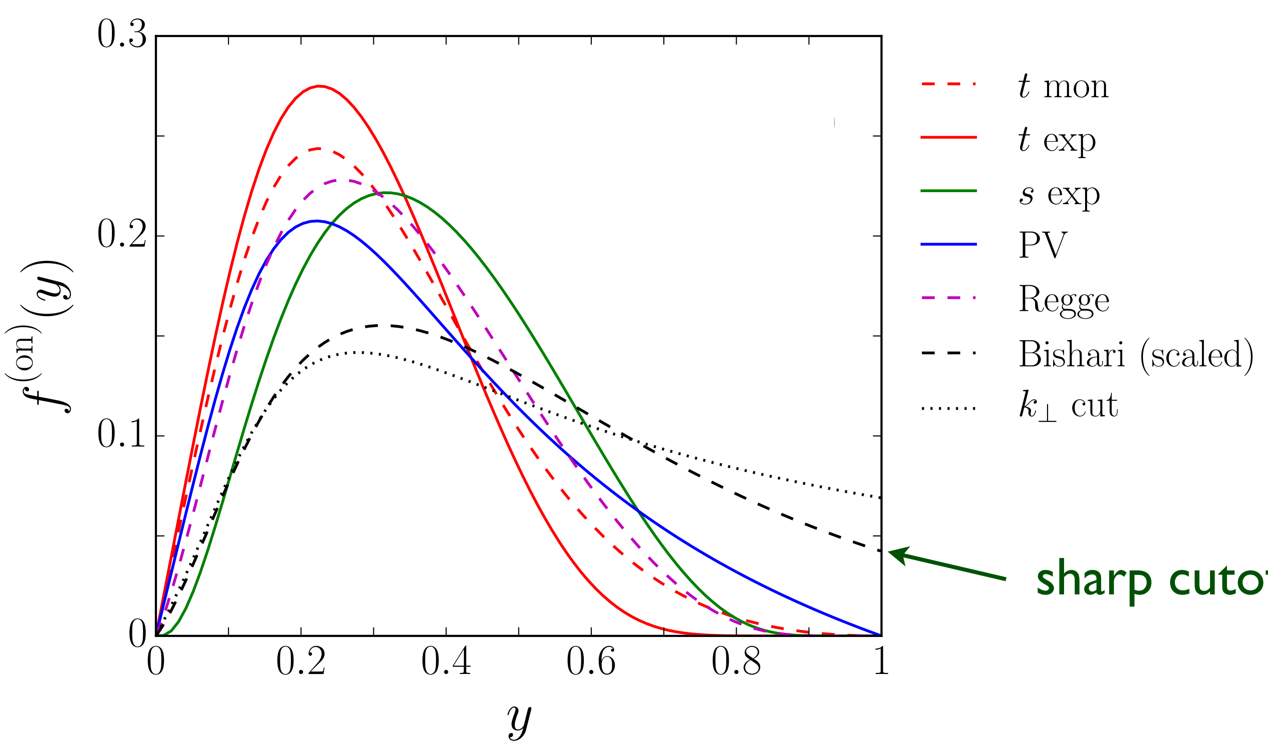
$\mathcal{F} = \left(\frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - t}\right)$ t monopole

$\mathcal{F} = \left[1 - \frac{(t - m_\pi^2)^2}{(t - \Lambda^2)^2}\right]^{1/2}$ Pauli-Villars

$\mathcal{F} = \exp\left[(t - m_\pi^2)/\Lambda^2\right]$ t exponential

$\mathcal{F} = y^{-\alpha_\pi(t)} \exp\left[(t - m_\pi^2)/\Lambda^2\right]$ Regge

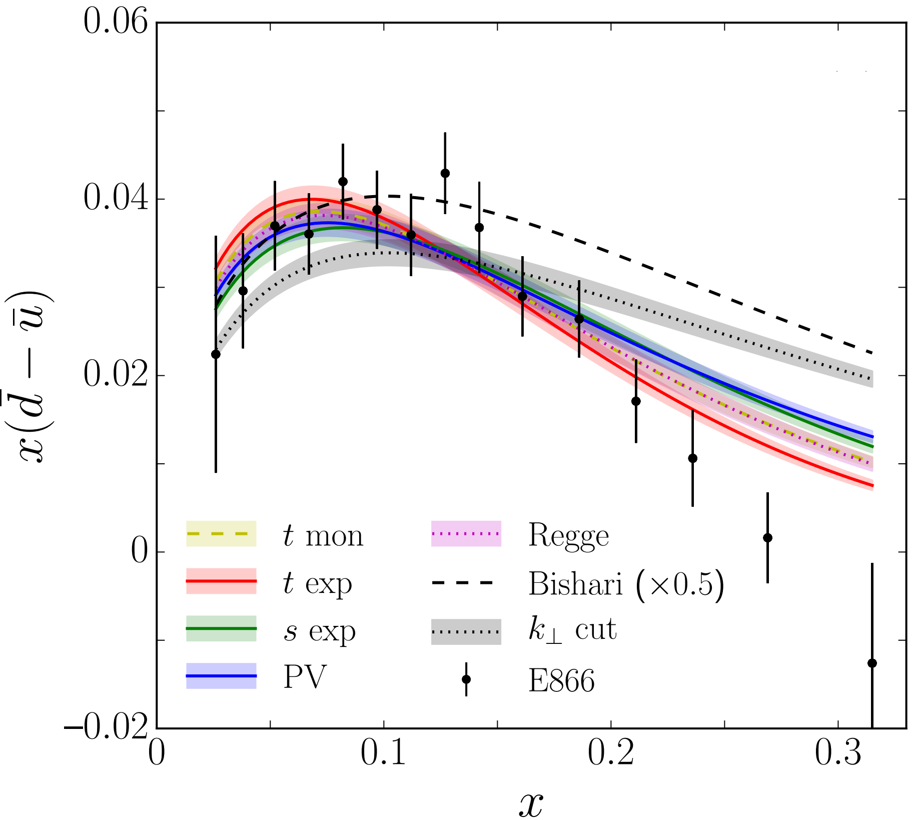
e.g. on-shell function



sharp cutoffs

Chiral effective field theory

- E866 $\bar{d} - \bar{u}$ data can be fitted with range of regulators



average pion "multiplicity"

$$\langle n \rangle_{\pi N} = 3 \int_0^1 dy\, f_N^{(\mathrm{on})}(y)$$
$$\sim\ 0.25 - 0.3$$

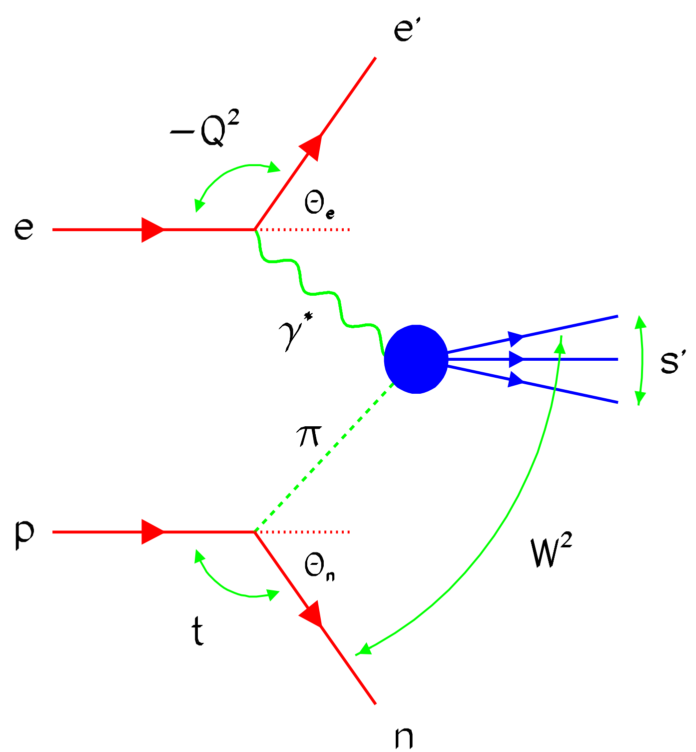
→ with exception of $k_\perp$ cutoff and Bishari models, all others give reasonable fits, $\chi^2 \lesssim 1.5$

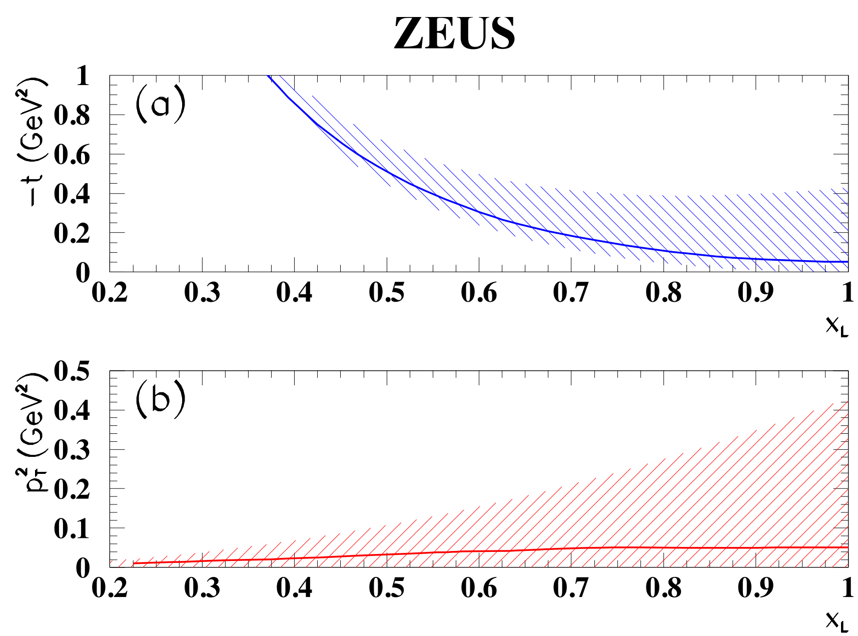
→ are there other data that can be more discriminating?

Leading neutron production

Leading neutron production at HERA

- ZEUS & H1 collaborations measured spectra of neutrons produced at very forward angles, $\theta_n < 0.8$ mrad





$x_L \approx 1 - y$

→ can data be described within same framework as E866 asymmetry?

→ simultaneous fit never previously been performed!

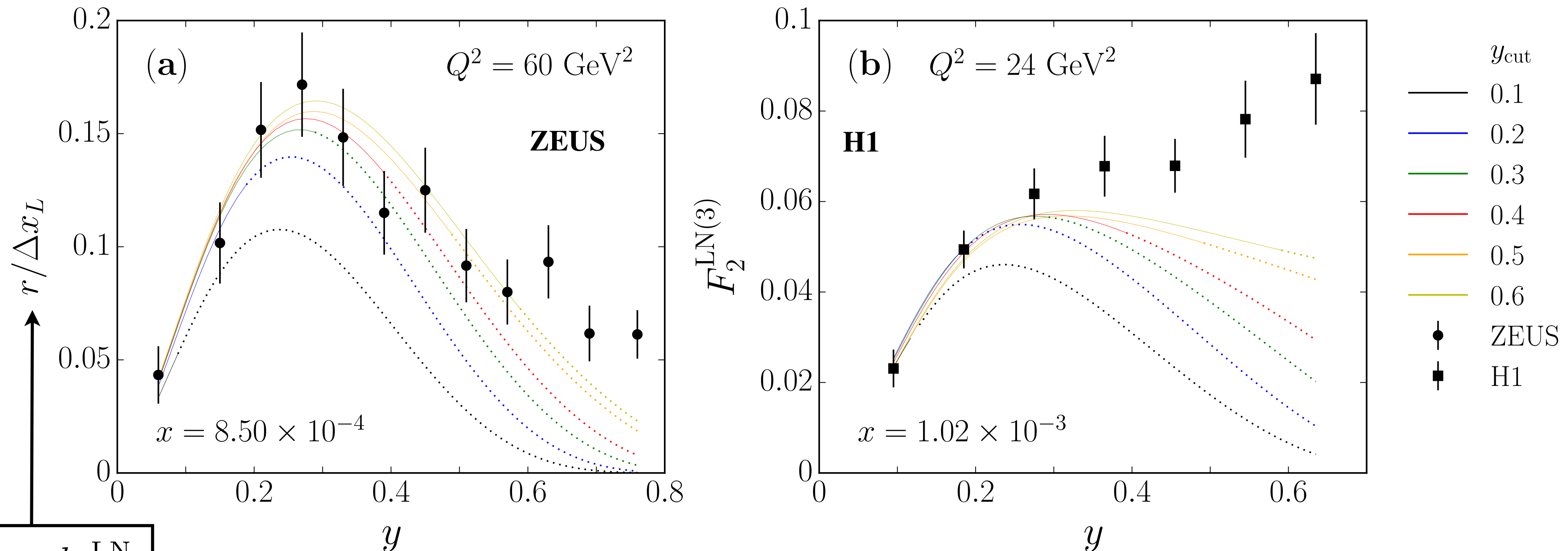
Leading neutron production at HERA

- Measured LN differential cross section (integrated over $p_\perp$)

$$\frac{d^3\sigma^{\mathrm{LN}}}{dx\, dQ^2\, dy} \sim F_2^{\mathrm{LN}(3)}(x, Q^2, y)$$

$\boxed{2 f_N^{(\mathrm{on})}(y)\, F_2^\pi(x/y, Q^2)}$ for π exchange

e.g.

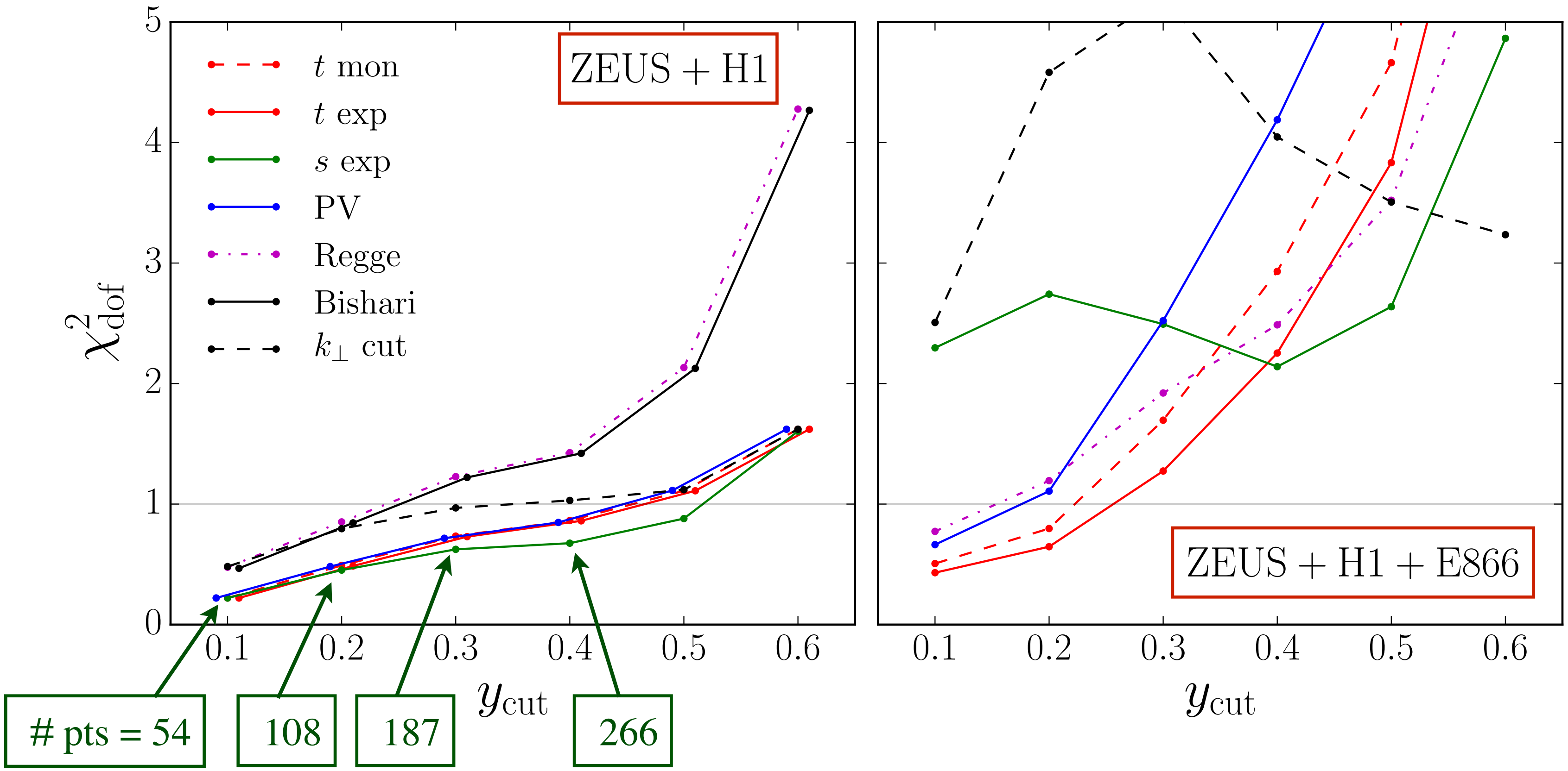


$$\boxed{r = \frac{d\sigma^{\mathrm{LN}}}{d\sigma^{\mathrm{inc}}}}$$

$\longrightarrow$ quality of fit depends on range of y fitted

Leading neutron production at HERA

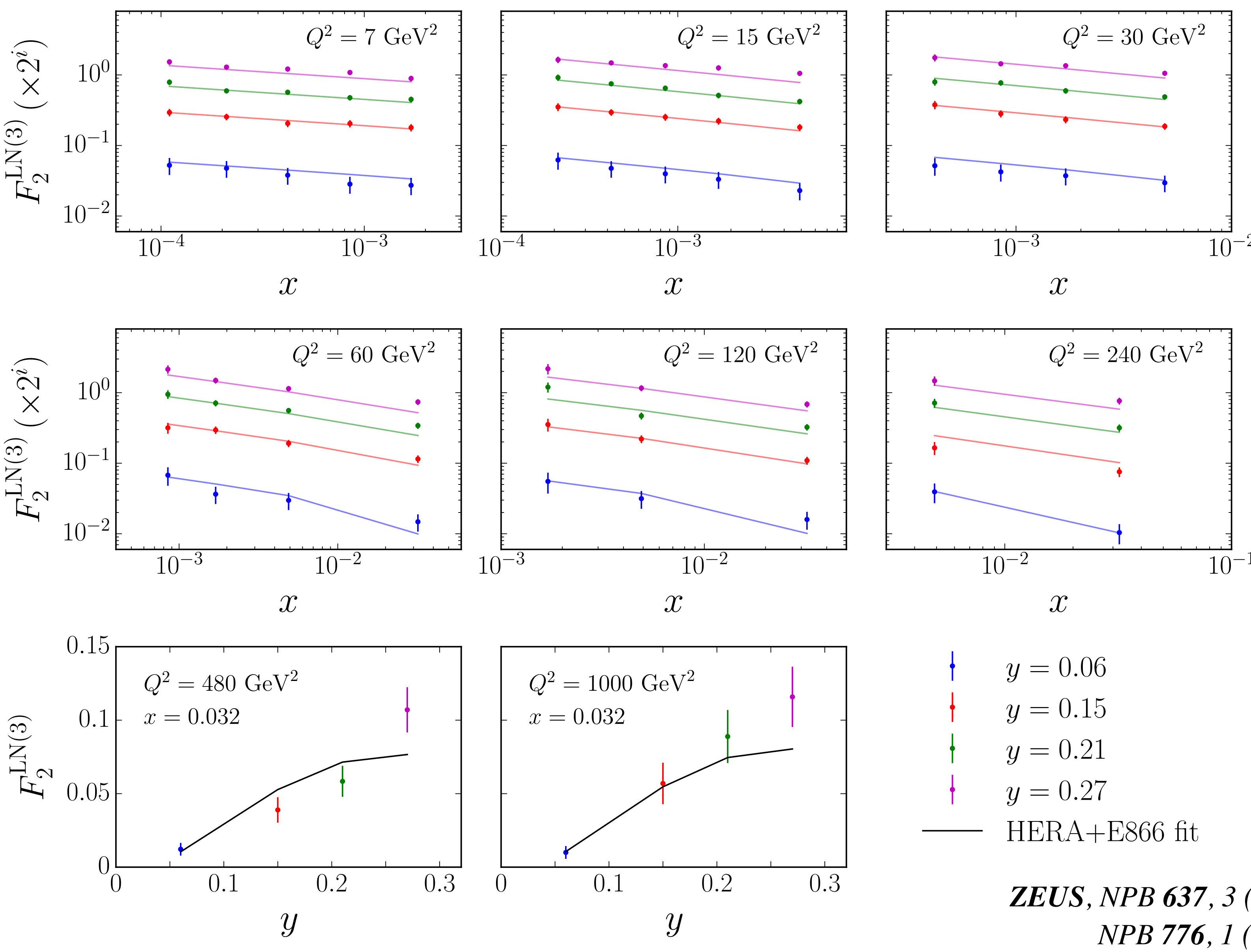
- Combined fit to HERA LN and E866 Drell-Yan data



→ best fits for largest number of points afforded by t-dependent exponential (and t monopole) regulators

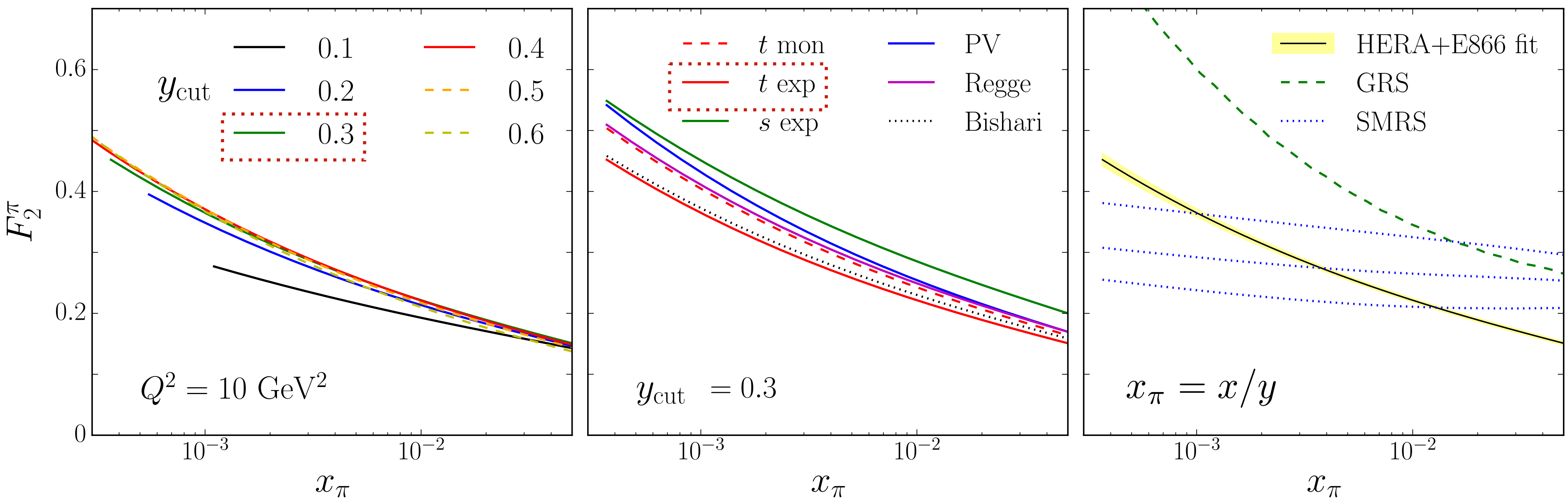
Leading neutron production at HERA

- Fit to ZEUS LN spectra for $y_{\rm cut} = 0.3$ (t-dependent exponential)



ZEUS, *NPB* ***637***, *3 (2002)*
NPB ***776***, *1 (2007)*

Extracted pion structure function

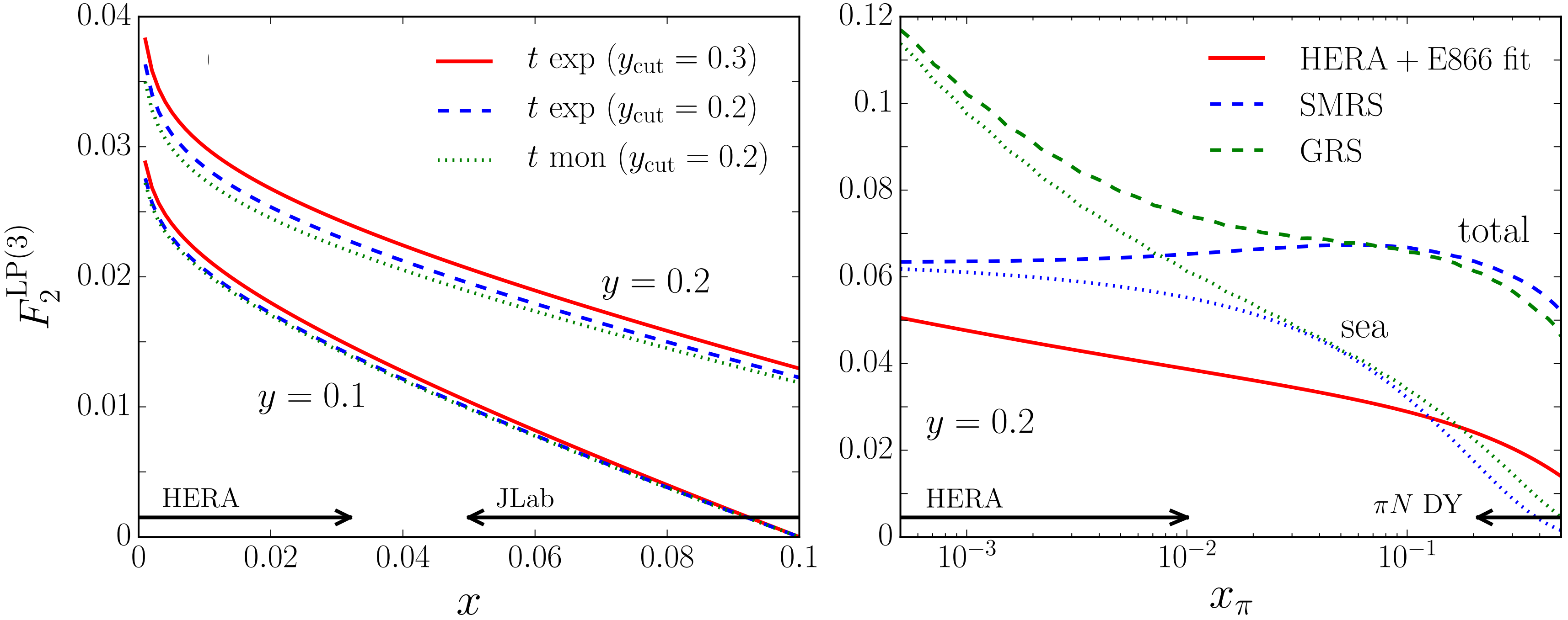


$$F_2^\pi = N\, x_\pi^a\, (1 - x_\pi)^b, \quad a = a_0 + a_1 \eta$$
$$\eta \sim \log(\log Q^2)$$

→ stable values of F_2^π at $4\times 10^{-4} \lesssim x_\pi \lesssim 0.03$ from combined fit

→ shape similar to GRS fit to πN Drell-Yan data (for $x_\pi \gtrsim 0.2$), but smaller magnitude

Predictions at TDIS kinematics



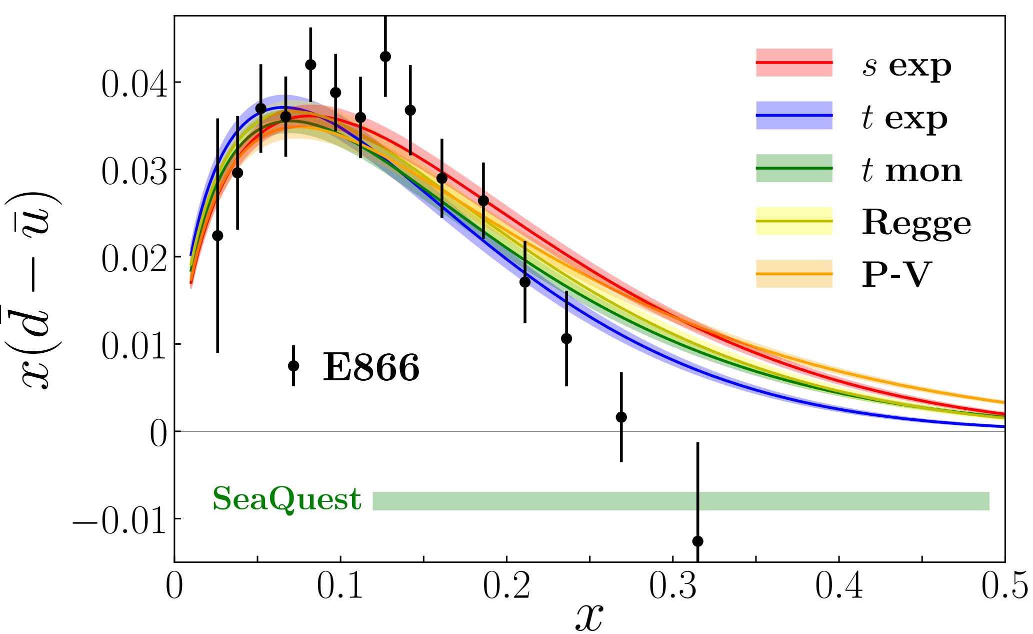
→ JLab TDIS experiment can fill gap in x_π coverage between HERA and πN Drell-Yan kinematics

JAM-pion QCD analysis

PDFs in the pion

- E866 $\bar{d} - \bar{u}$ data can be well described within chiral EFT framework

$$\bar{d} - \bar{u} = \left[f_\pi^{(\mathrm{rbw})} + f_\pi^{(\mathrm{bub})} \right] \otimes \bar{q}_v^\pi$$



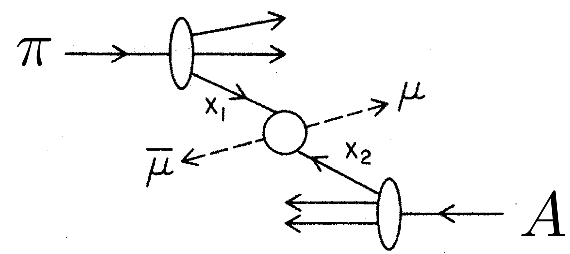
Barry, Sato, WM, C.-R. Ji
PRL 121, 152001 (2018)

$\longrightarrow$ depends also on pion PDF … which can be fit simultaneously!

PDFs in the pion

- PDFs in the pion (in principle) simpler to compute than baryons, but are more difficult to study experimentally

$\longrightarrow$ most information has come from pion-nucleus (tungsten) Drell-Yan data (CERN, Fermilab)



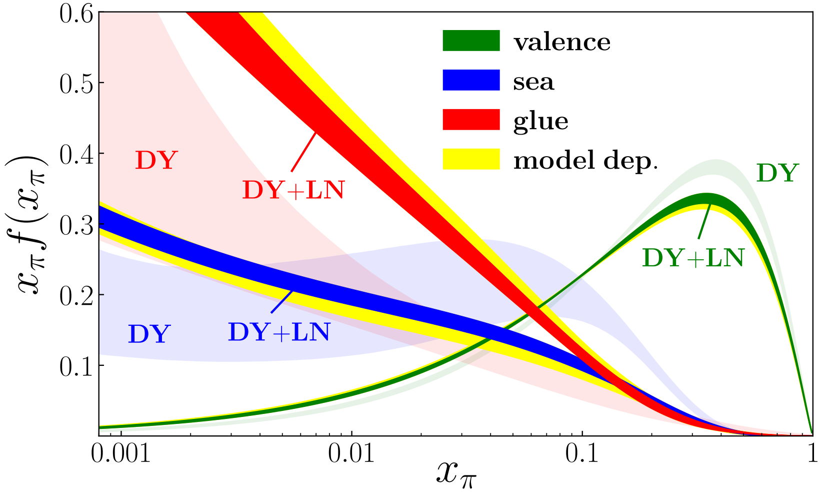
$\longrightarrow$ constrains valence PDFs at $x \gg 0$ (uncertainty from gluon resummation)

$\longrightarrow$ pion sea quark & gluon PDFs at small x mostly unconstrained by Drell-Yan data alone

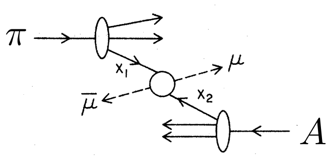
$\longrightarrow$ include pion-nucleus Drell-Yan data + LN HERA data in global QCD analysis of pion PDFs

PDFs in the pion

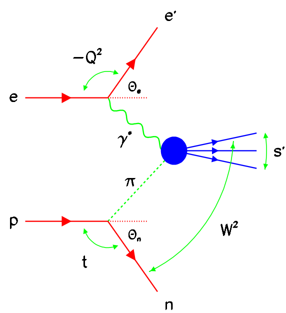
- MC analysis combining pQCD with chiral EFT to fit πN Drell-Yan + leading neutron electroproduction data from HERA



DY = πN Drell-Yan data (medium/high x)



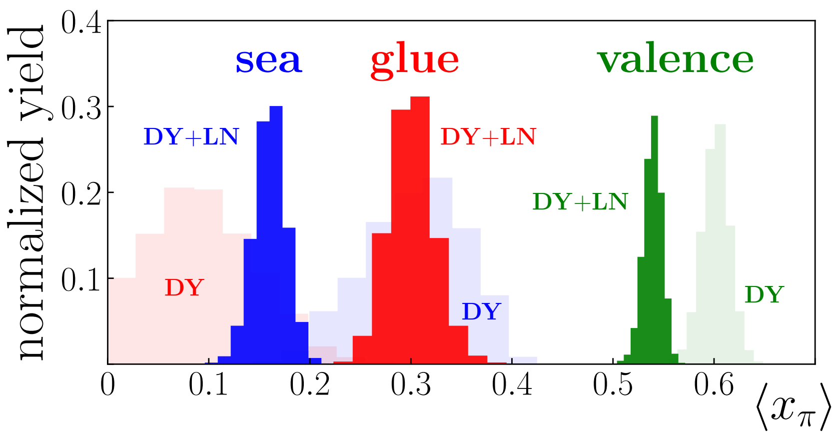
LN = leading neutron electroproduction (low x)

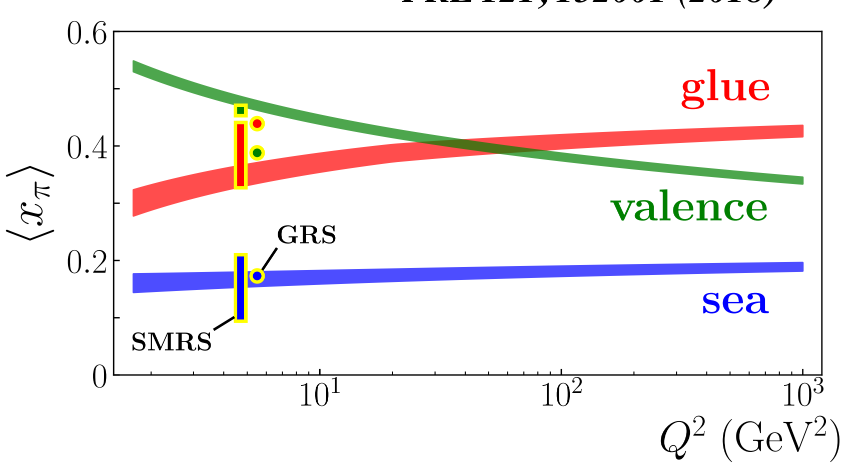


$\longrightarrow$ TDIS!

- Larger gluon fraction in the pion than without LN constraint

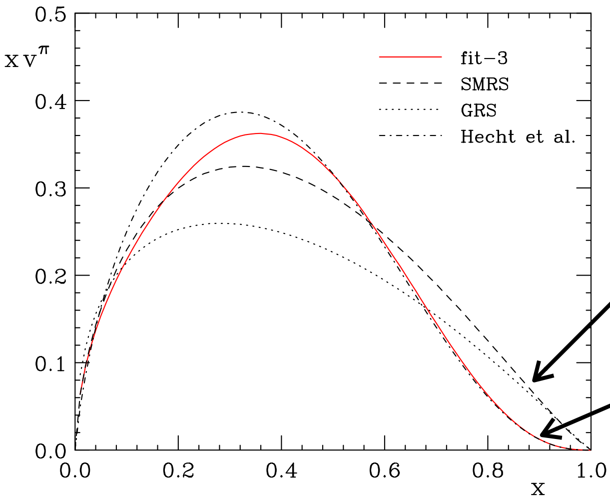
Barry, Sato, WM, C.-R. Ji
PRL 121, 152001 (2018)





PDFs in the pion

- $x \to 1$ behavior of pion PDF is controversial: $\sim (1-x)$ or $(1-x)^2$?

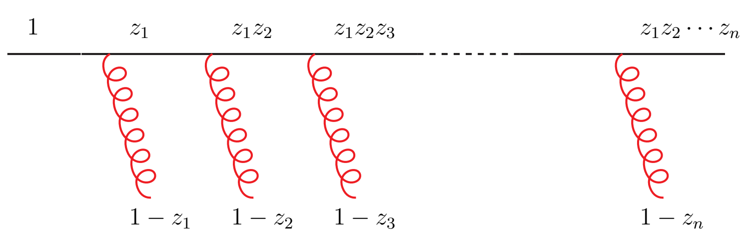


Aicher, Schafer, Vogelsang (2010)

no resummation: more consistent with $\sim (1-x)$

with resummation: more consistent with $\sim (1-x)^2$

- Hard scattering coefficient function kinematically enhanced when $z \to 1$ because of gluon emissions



Barry, Sato, Ji, WM (2020)

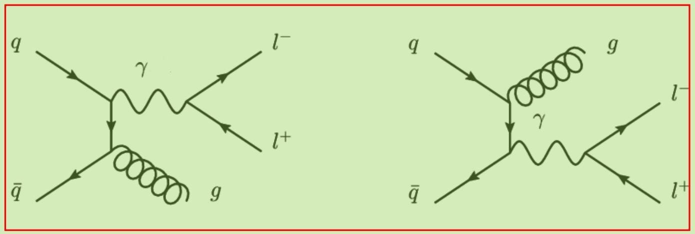
$\longrightarrow$ effect of resummation on phenomenology?

Resummation in a nutshell

- Next to leading order, real gluon emissions

Real emissions

$$C_{q\bar{q}}^{\mathrm{real}} = \frac{C_F \alpha_S}{\pi}\left[\frac{\delta(y)+\delta(1-y)}{2}\left[(1+z^2)\left(\frac{1}{1-z}\ln\frac{Q^2(1-z)^2}{\mu^2 z}\right)_+ + 1 - z\right]\right.$$
$$\left. + \frac{1}{2}\left[\frac{(1-z)^2}{z}y(1-y)\right]\left[\frac{1+z^2}{1-z}\left(\left[\frac{1}{y}\right]_+ + \left[\frac{1}{1-y}\right]_+\right) - 2(1-z)\right]\right]$$



- Plus distributions come from subtraction procedure of collinear singularities
- When $z \to 1$, $\log(1-z)$ can be large and potentially spoil perturbation
  - Appear in all orders in a predictable manner
- Significant contributions to cross section occur in soft gluon emissions and follow the pattern

$$d\hat{\sigma}_{N^k LO}^{q\bar{q}} \propto \alpha_S^k \frac{\ln^{2k-1}(1-z)}{1-z} + \ldots$$

Resummation in a nutshell

- Phase space needs to be broken up and factorized
- A convenient way to do this is by Mellin transforms

$$\log(1-z) \to \log N$$

- Kernels will exponentiate in Mellin space

Subtract the matching to make sure these terms are only counted once!

	LL	NLL	...	N^{p}LL
LO	1	--	...	--
NLO	$\alpha_s \log(N)^2$	$\alpha_s \log(N)$	...	--
NNLO	$\alpha_s^2 \log(N)^3$	$\alpha_s^2 \log(N)^2$	...	--
...	...	...	...	...
N^{k}LO	$\alpha_s^k \log(N)^{k+1}$	$\alpha_s^k \log(N)^k$	...	$\alpha_s^k \log(N)^{k-(p-1)}$

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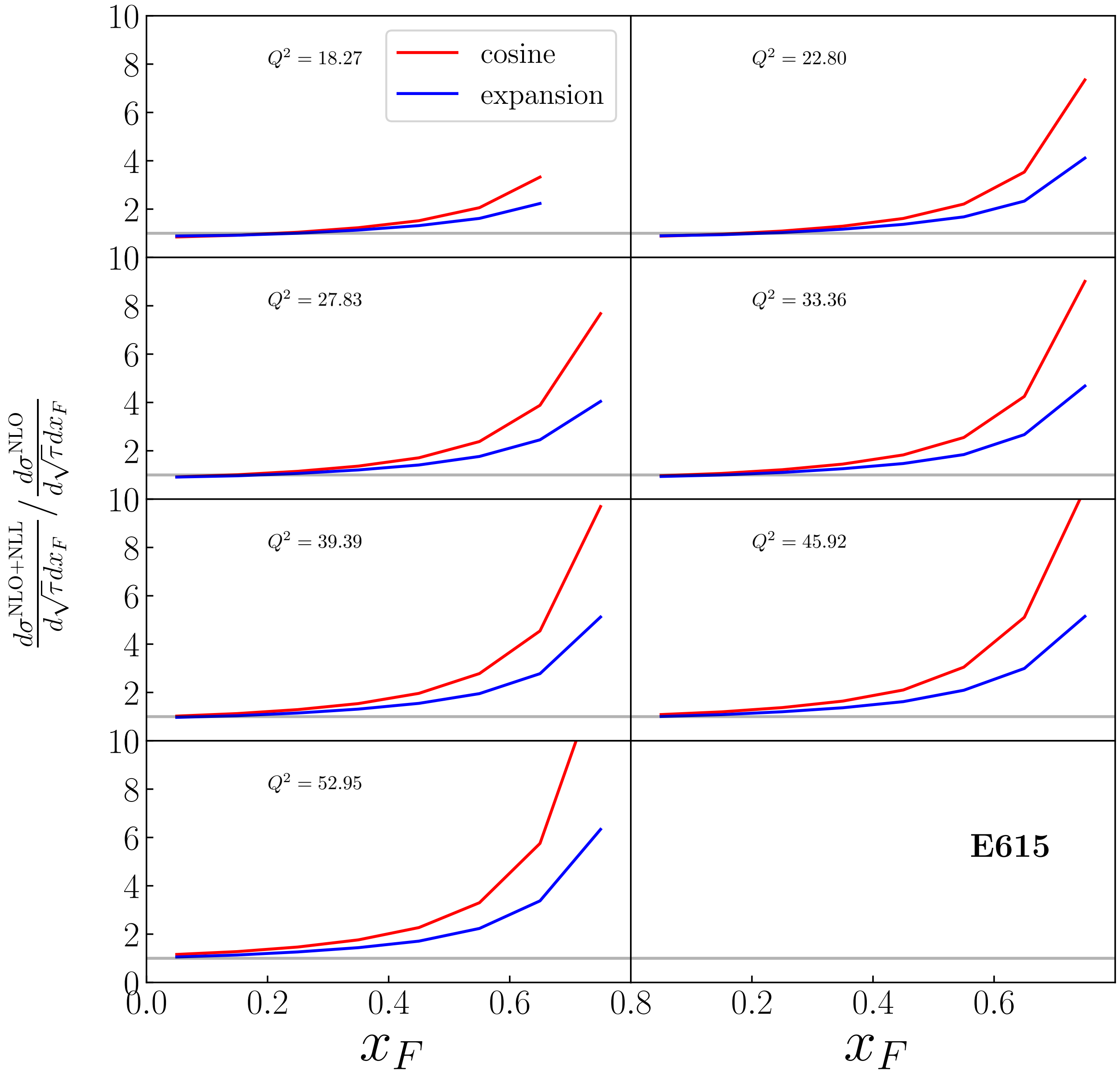
NLL corrections



Barry et al. (2020)

→ "K-factor" = ratio of (NLO+NLL) to NLO

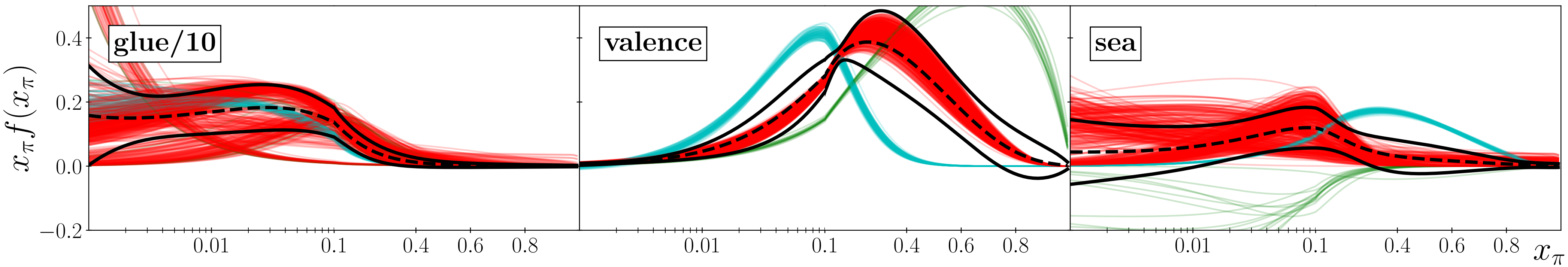
→ large enhancement at high x_F

→ strong (factor ~2) dependence on resummation prescription

→ Aicher *et al*. used "expansion" method

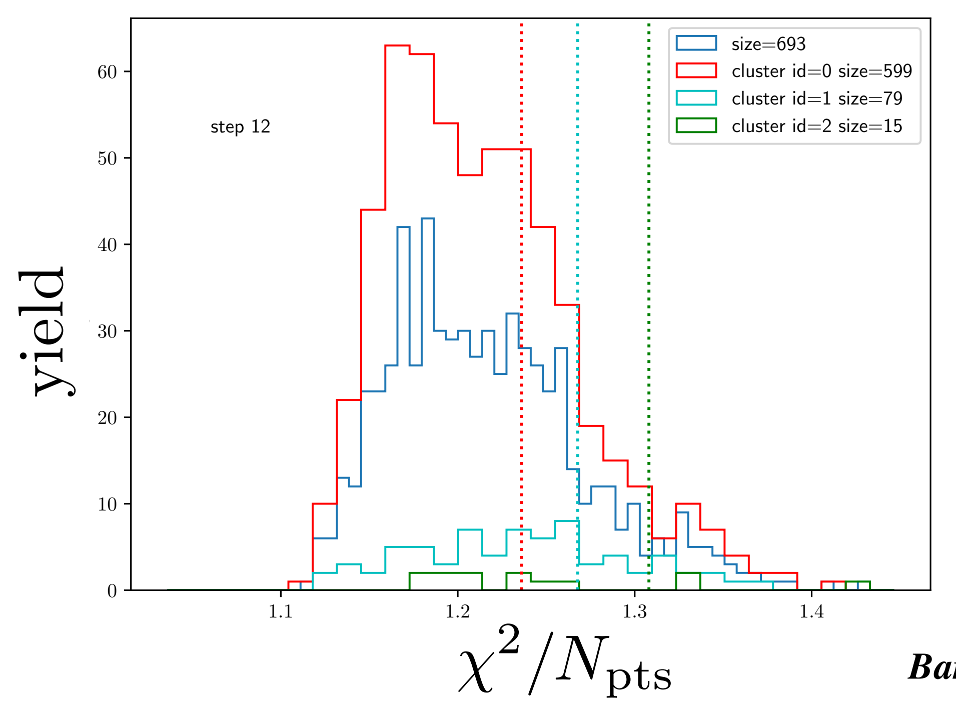
→ third prescription (more exact) currently in progress

Multiple solutions



→ minimal prescription for threshold resummation with cosine method

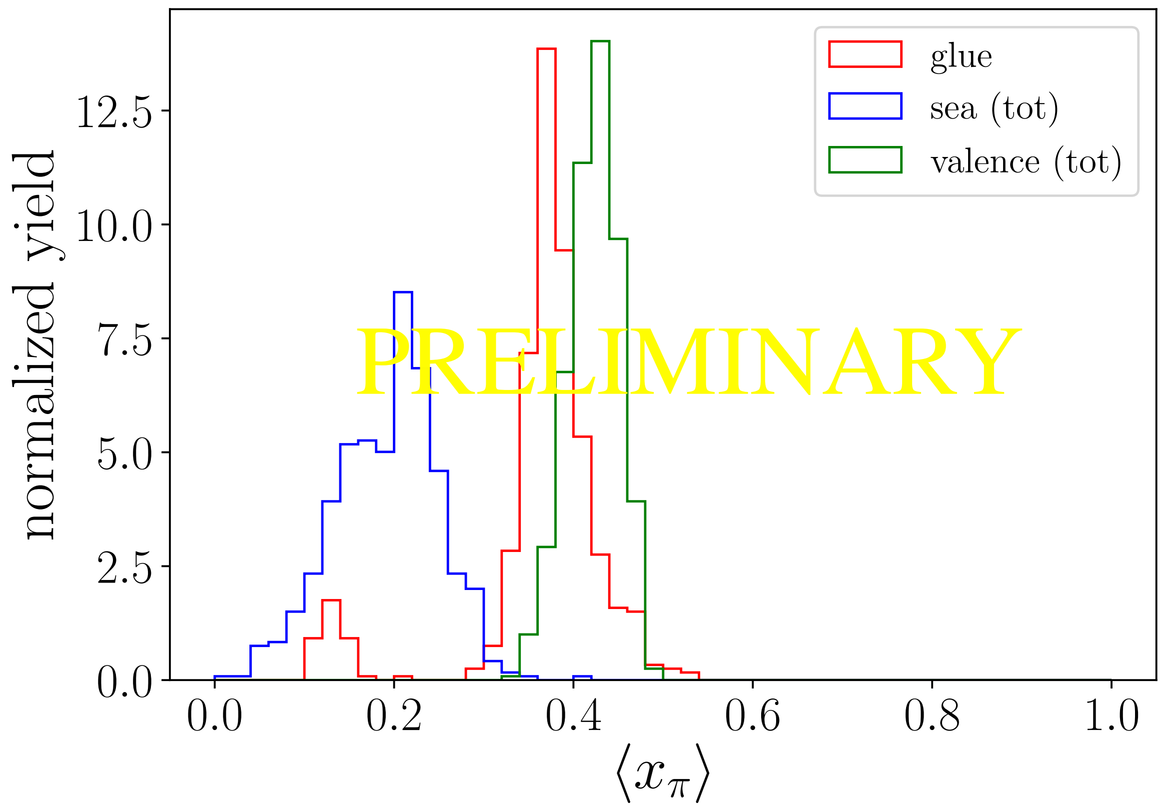
→ multiple solutions appear in full fit to DY & LN data (trade-offs between valence and sea strength)

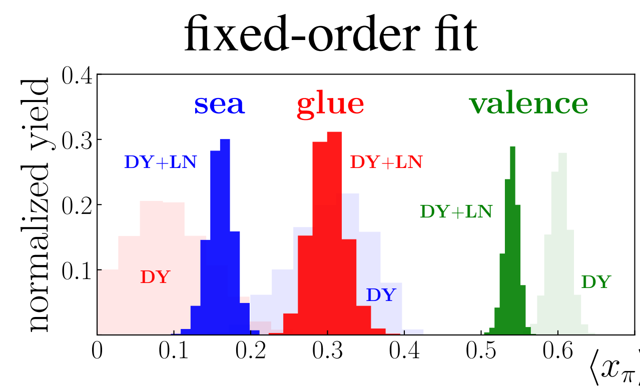


→ red solutions give the better χ^2 but the other solutions are not much worse

Barry et al. (2020)

Momentum fractions

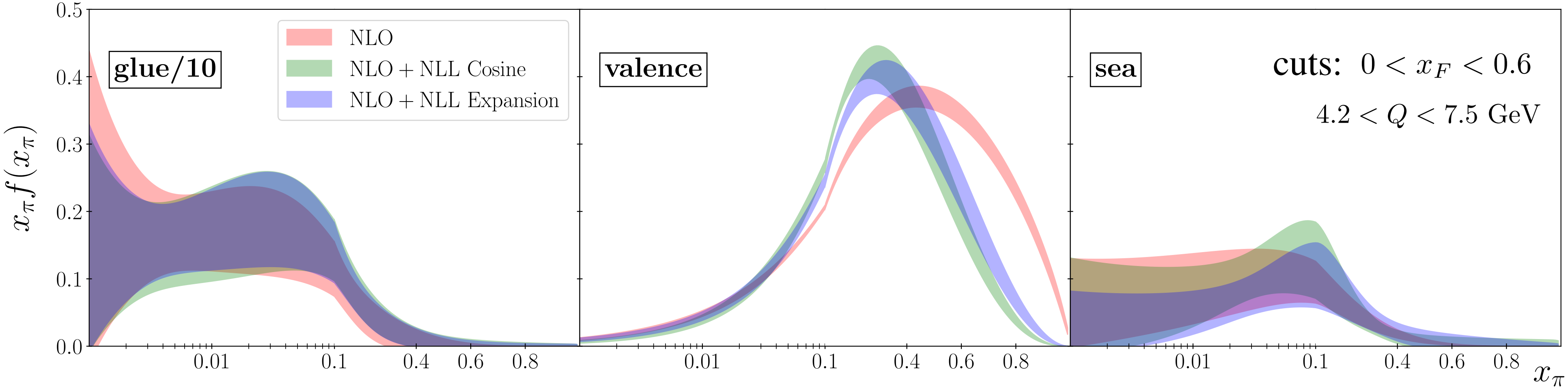




$\longrightarrow$ gluon has higher momentum fraction $(\sim 40\%)$ compared with fixed-order case $(\sim 30\%)$ (with small second cluster at ~ 0.12)

$\longrightarrow$ valence quark has lower momentum fraction $(\sim 40\%)$ than fixed-order $(\sim 55\%)$

Pion PDFs with resummation



Barry et al. (2020)

→ comparison of fixed-order (NLO) and resummed (NLO + NLL cosine & NLO + NLL expansion prescriptions) fit results

→ both NLL prescriptions give softer valence PDF at high x

Cosine Method

exp.	chi2	npts	chi2/npts
H1 (LN)	22.07	58	0.38
ZEUS (LN)	72.75	50	1.46
E615 (DY)	72.19	55	1.31
NA10 (DY)	48.97	36	1.36
NA10 (DY)	27.85	20	1.39
total	**243.82**	**219**	**1.11**

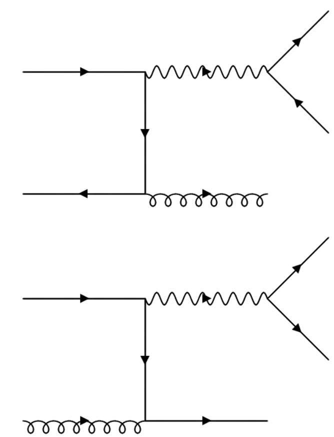
Expansion Method

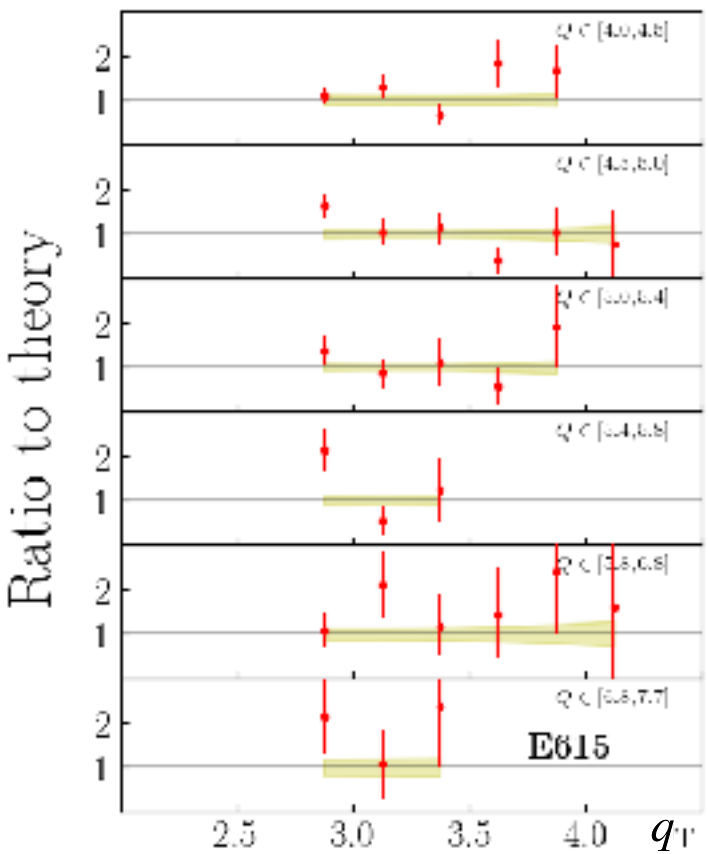
exp.	chi2	npts	chi2/npts
H1 (LN)	21.93	58	0.38
ZEUS (LN)	74.39	50	1.49
E615 (DY)	57.77	55	1.05
NA10 (DY)	26.58	36	0.74
NA10 (DY)	15.29	20	0.76
total	**195.96**	**219**	**0.89**

Transverse momentum dependence

- New analysis examines whether large-q_T DY data can be simultaneously described with q_T-integrated DY + HERA LN data

  $\longrightarrow$ large-q_T photon requires hard gluon to recoil against — sensitivity to gluon PDF in pion at high x





Nina Cao et al. (2020)

$\longrightarrow$ first time that one has been able to describe q_T spectra $(q_T > 2.9\ \mathrm{GeV})$ spectra in terms of collinear PDFs!

$\longrightarrow$ open path to pion TMD studies

Outlook

- We have a systematic way of describing flavor asymmetries in the proton in terms of chiral symmetry properties of QCD!

- Consistent description requires simultaneously fitting pion PDFs to Drell-Yan and leading neutron ($\rightarrow$ leading proton) data

  $\longrightarrow$ map out pion structure from low x to high x

- Full analysis with threshold resummation almost complete

  $\longrightarrow$ insights into high-x pion PDFs

- Extend analysis to incorporate transverse momentum

  $\longrightarrow$ pion PDFs ("3-d structure")

- Framework easily extended to kaon structure, when data available