Exploring the Valence Quark Structure of the Pion

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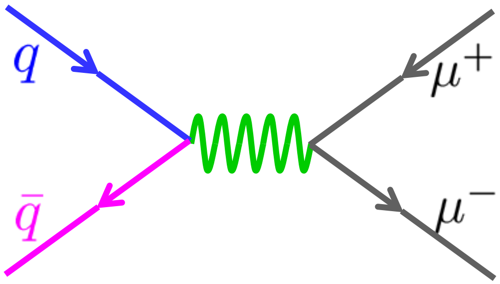
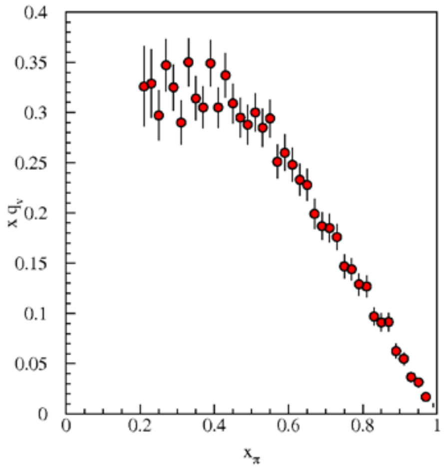
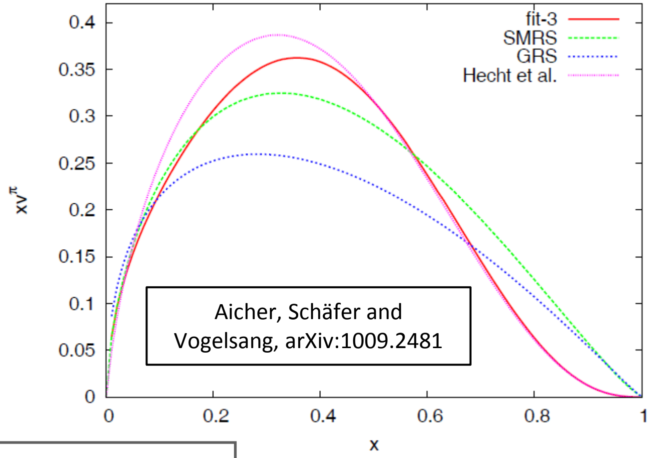
14 October 2010



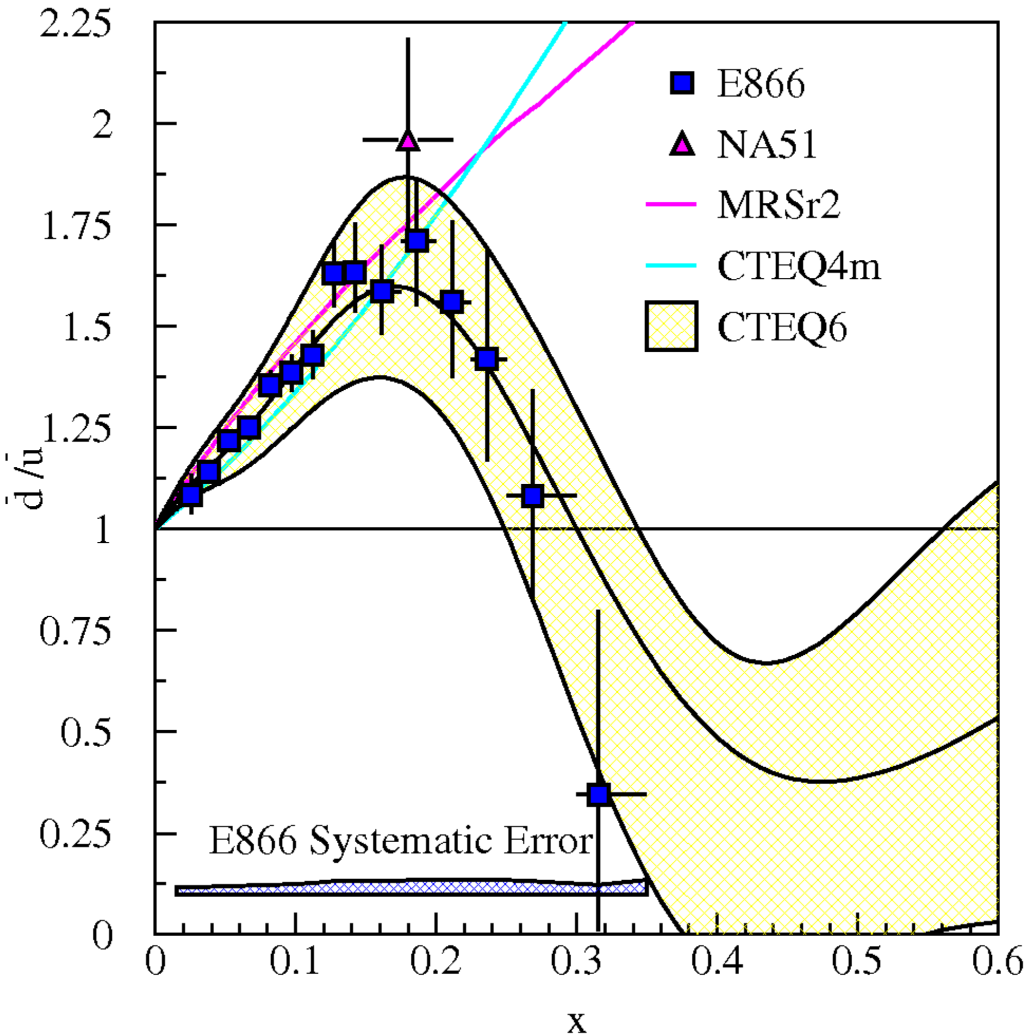


1. Why are we interested in the pion?
2. What do we know about the pion?
3. What does the data tell us about the pion valence structure?



This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

Why are should you be interested in the pion?



Ratio of anti-down to anti-up quarks in the proton as extracted from pp and pd Drell-Yan

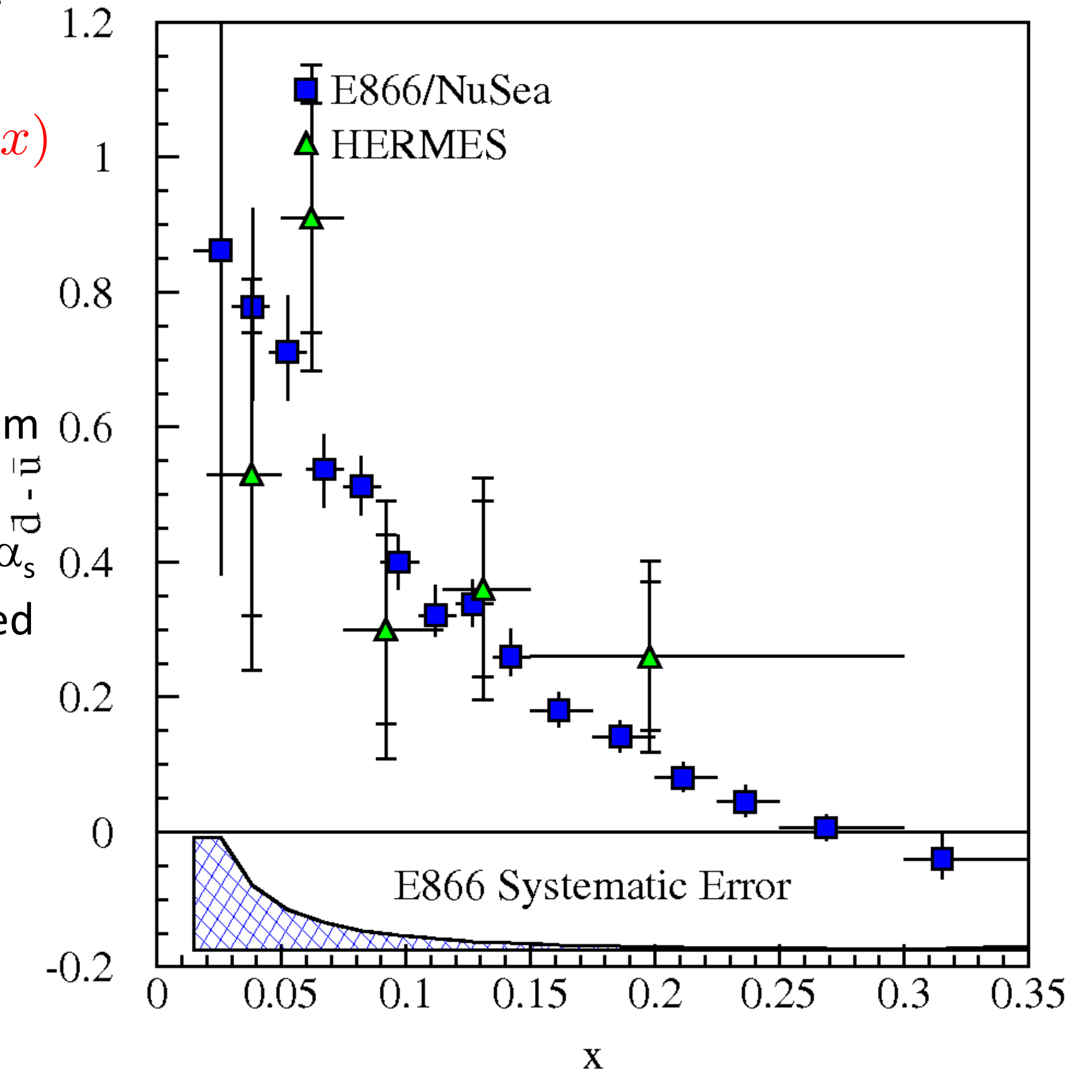
- Because I can't explain this graph without them.
  - Simple pQCD does not provide the factor of 1.5 asymmetry
  - Could a pion cloud solve the problem? (See almost everyone's talk including Tim Londergan's talk earlier today)

Why are should you be interested in the pion?

- There is a gluon splitting component which is symmetric

$$\bar{d}_{\mathrm{pQCD}}(x) \equiv \bar{u}_{\mathrm{pQCD}}(x) \equiv \bar{q}_{\mathrm{pQCD}}(x)$$

- $\bar{d}(x) - \bar{u}(x)$
  - Symmetric sea via pair production from gluons subtracts away
  - No Gluon contribution at 1st order in α_s
  - Nonperturbative models are motivated by the observed difference



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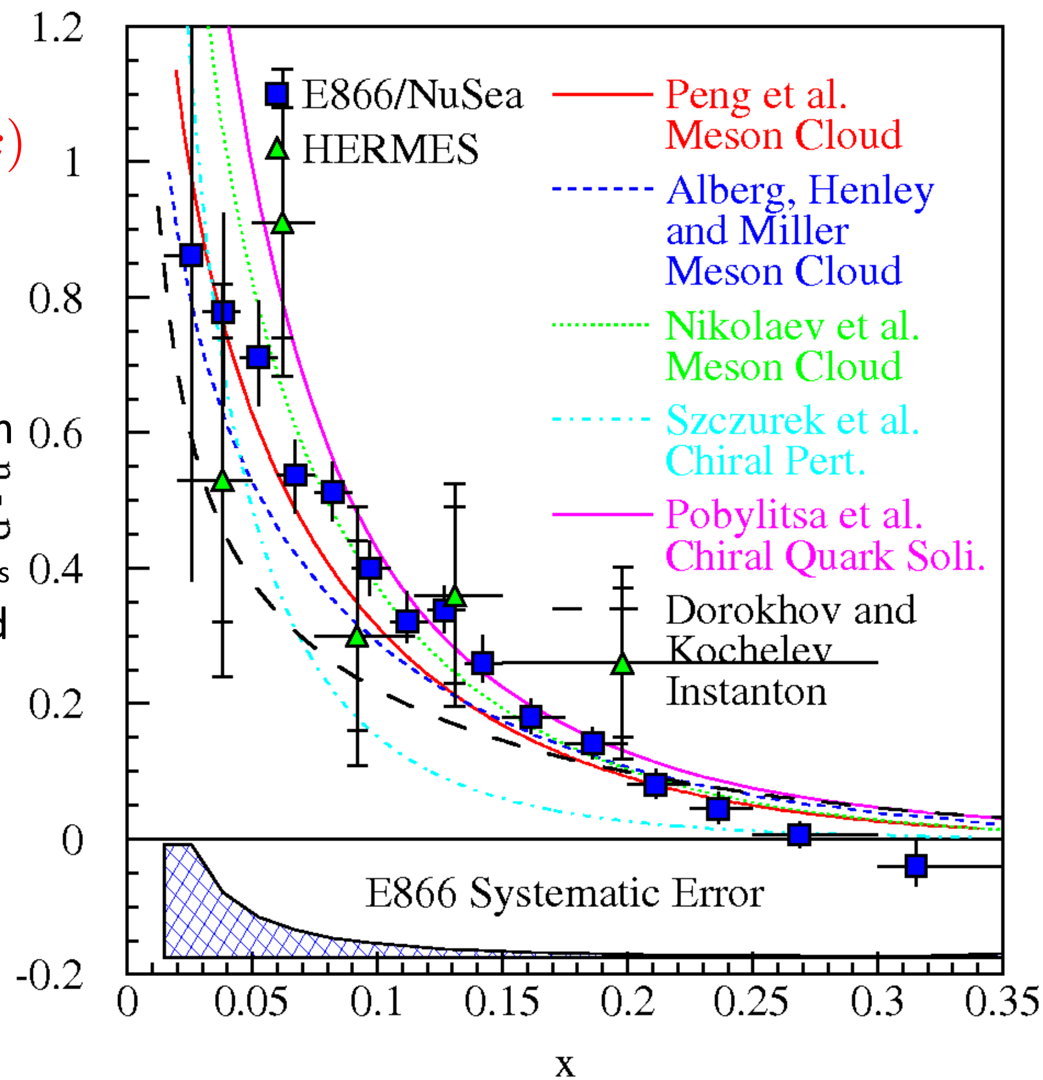


Why are should you be interested in the pion?

1. Explains quark asymmetry in nucleon sea. $\bar{d}(x)/\bar{u}(x)$

Meson Cloud in the nucleon

Sullivan process in DIS

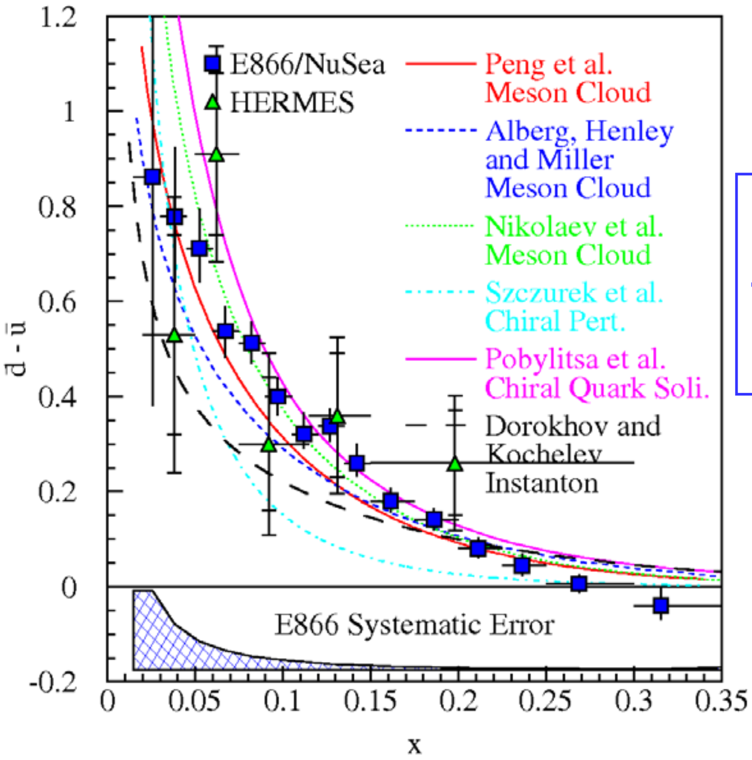
$|p\rangle = |p_0\rangle + \alpha\,|N\pi\rangle + \beta\,|\Delta\pi\rangle + \ldots$

(See Tim Londergan's talk earlier today)

Chiral Quark

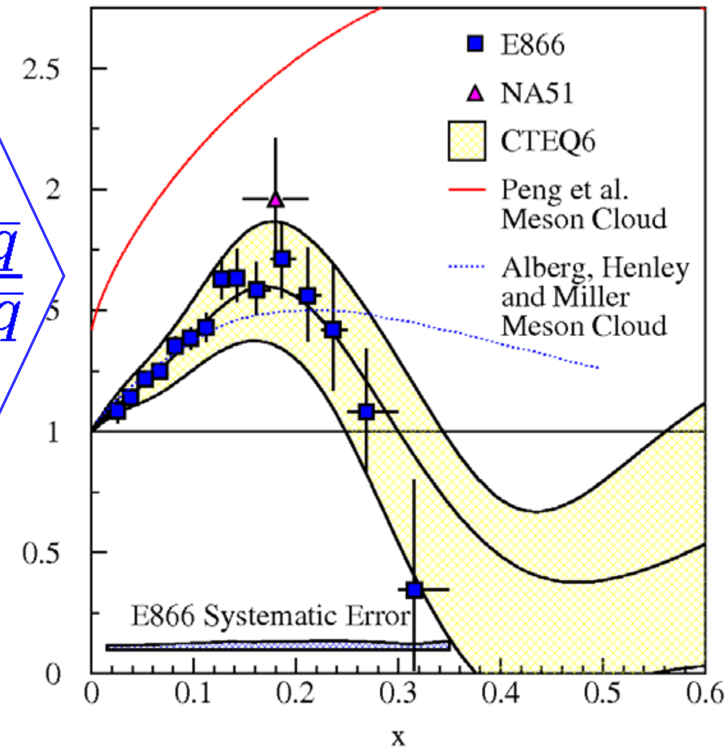
Interaction between Goldstone Bosons and valence quarks

$\bar{u} \to \bar{d}\pi^+ \qquad \bar{d} \to \bar{u}\pi^-$



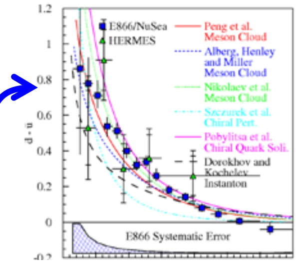
$$\frac{\bar{d}}{\bar{u}} = \frac{\bar{d}^{\pi} + \bar{q}}{\bar{u}^{\pi} + \bar{q}}$$

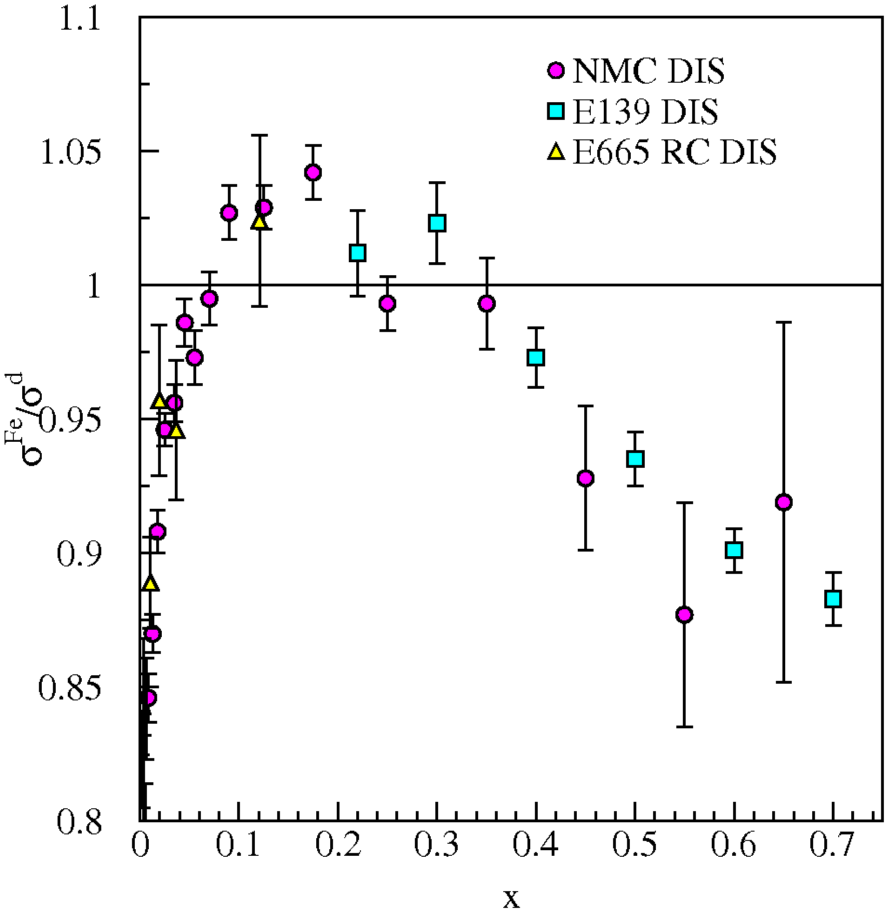
Perturbative sea apparently dilutes meson cloud effects at large-x

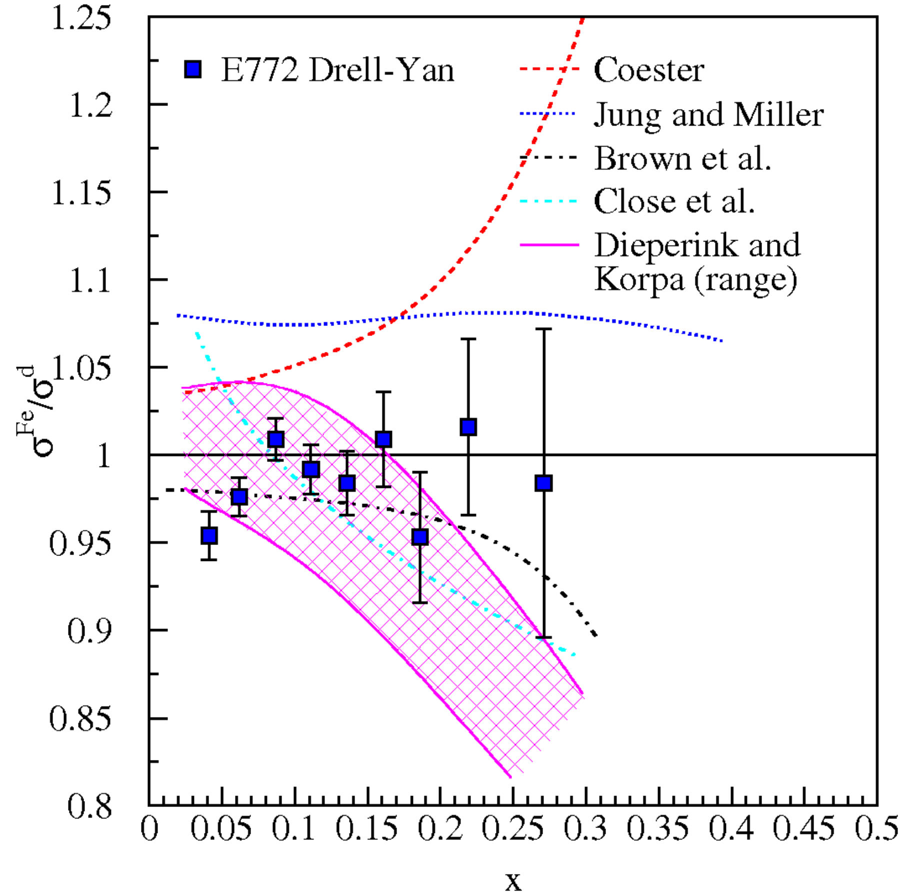


Why are should you be interested in the pion?

1. Explains quark asymmetry in nucleon sea. $\bar{d}(x)/\bar{u}(x)$
2. Key role in nuclear binding and structure (maybe?).







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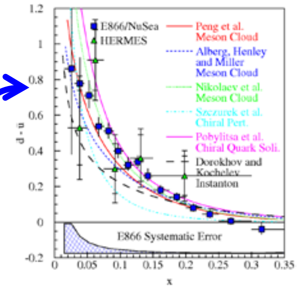

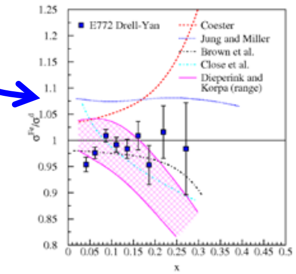

Pion parton distributions play a role in nucleon and nuclear parton distributions

QCD tells us how the parton distributions evolve, once we know them, but not what they are.

However, in both cases, these are **not on-shell pions**

3. Simple quark-antiquark system (valence).
   a. Should have an easy theoretical interpretation.
   b. What about mass—constituent quark mass ≈300 MeV each?
4. QCD's Goldstone Boson

Many models make specific predictions about the **large–x valence structure** of the pion

Models of the Pion

- Nambu and Jona-Lasinio Model:
  - R. Davidson, E. Arriola, PLB (1995)
  - J.T. Londergan *et al.* PLB (1994).
  - T. Shigetani *et al.* PLB (1993).
- Dyson Schwinger Equation:
  - M. Hecht *et al.* PRD (2001).
- Chiral Quark Model:
  - K. Suzuki, W. Weise, NPA (1998).
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- Light-front constituent quark models:
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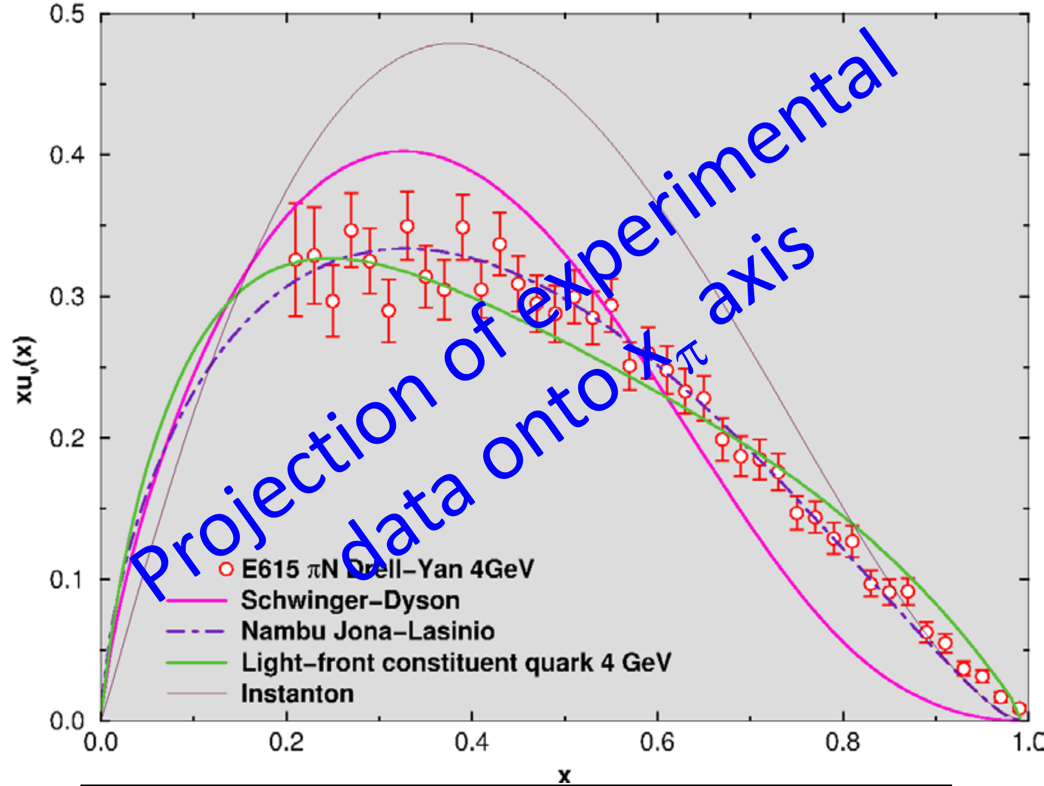
and more



At some base q_0
NJL: $xq(x)/\ (1-x)^{\beta}\ \beta = 1$
pQCD: $xq(x)/\ (1-x)^{\beta}\ \beta = 2$
DSE: $xq(x)/\ (1-x)^{\beta}\ \beta \approx 1.9$
Evolution to experimental Q increases β.

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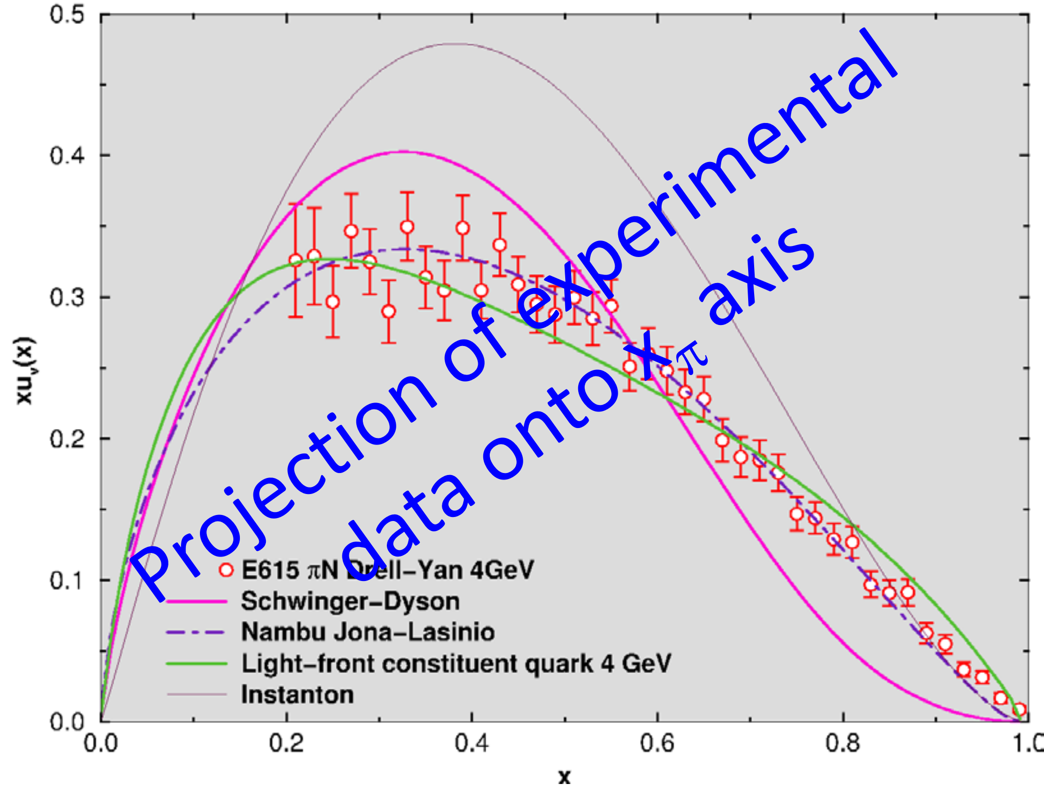

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Evolution to experimental Q increases β.

As an experimentalist, I can say, "data agrees with the model" and "data rules out the model"

Consider the Available Data

Consider the Available Data

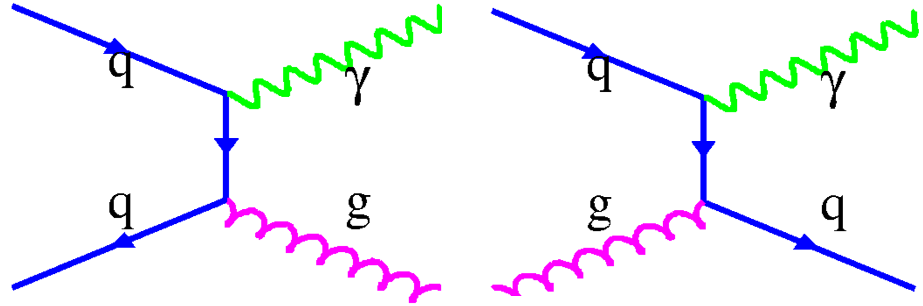
No on-mass pion targets—only pion-hadron data

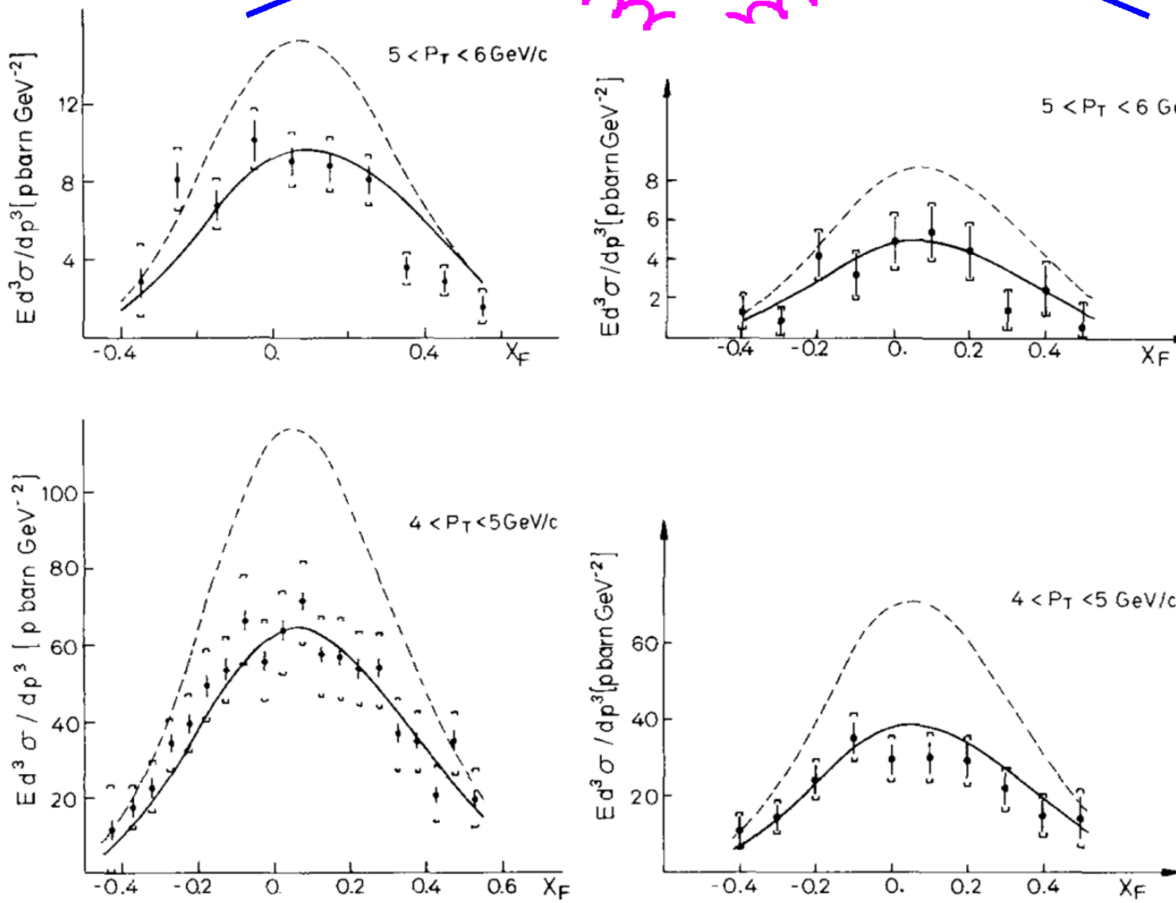
- Direct photos in πp interactions
- Drell-Yan πA interaction
    - π^+/π^- ratios
    - Absolute πA cross sections

Experimental Tools for π structure

- Direct photos in πp interactions
  - Sensitive to gluon distributions.

    [CERN WA 70, Z. Phys. **C37** 535 (1988)]





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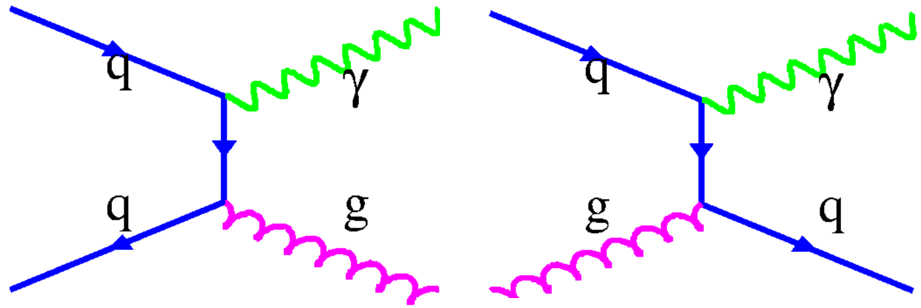


Assume parameterization

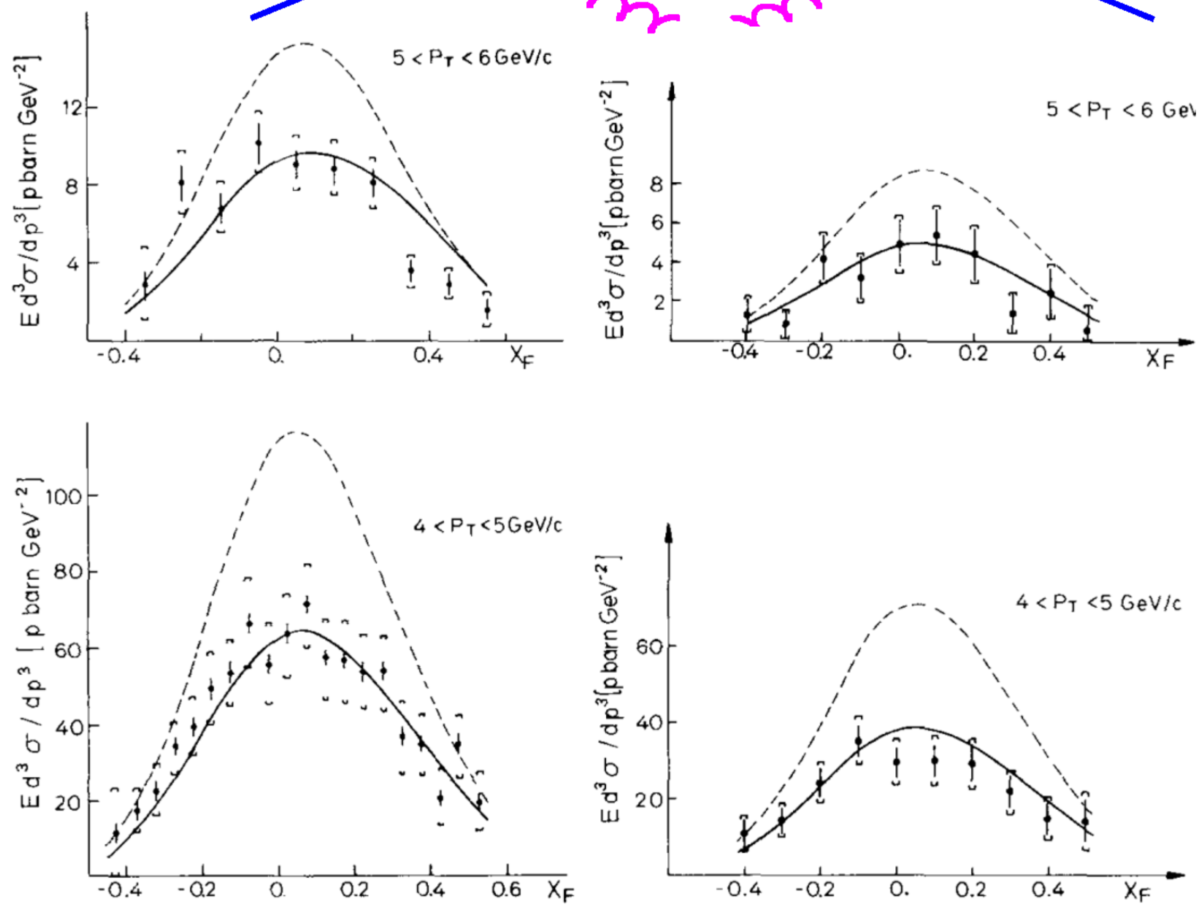
SMRS, PR**D45** 2349 (1992)

$$xg_\pi(x) = A_\pi^g (1-x)^\eta$$

$$\eta \approx 2.1$$

$$G_\pi \equiv \int_0^1 xg_\pi(x)dx = 0.47$$

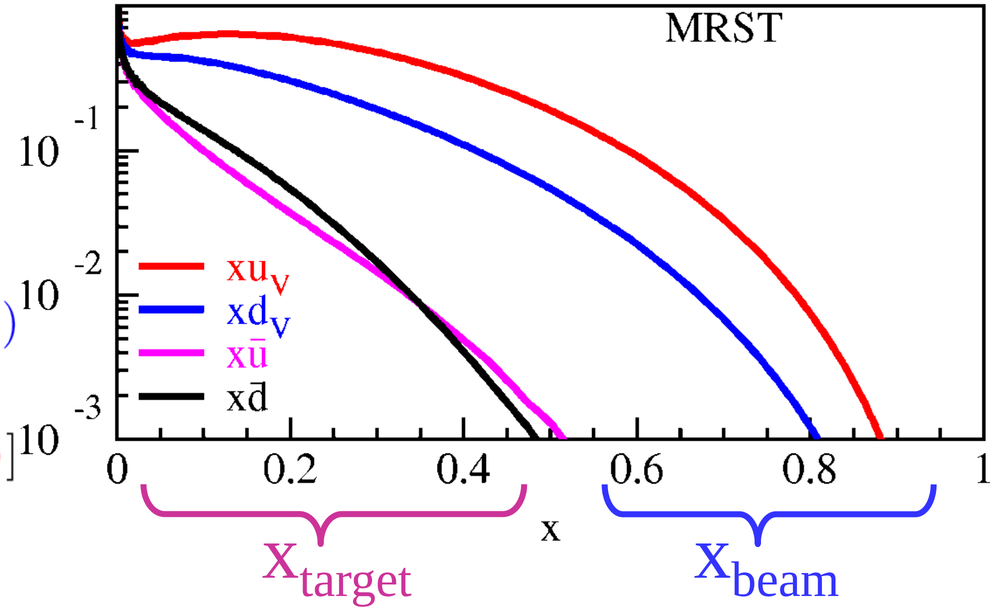
Half of pion's momentum is carried by glue



Drell-Yan Cross Section

- Measured cross section is a convolution of beam and target parton distributions

$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,\dots\}} e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + \bar{q}_b(x_b) q_t(x_t)\right]$$



- **π^- beam**

$$\left.\frac{d^2\sigma}{dx_\pi dx_N}\right|_{\pi^- N} = \frac{4\pi\alpha^2}{x_\pi x_N s}\left[\frac{4}{9}\bar{u}_\pi(x_\pi)u_N(x_N) + \frac{1}{9}d_\pi(x_\pi)\bar{d}_N(x_N) + \frac{4}{9}u_\pi(x_\pi)\bar{u}_N(x_N) + \frac{1}{9}\bar{d}_\pi(x_\pi)d_N(x_N)\right]$$

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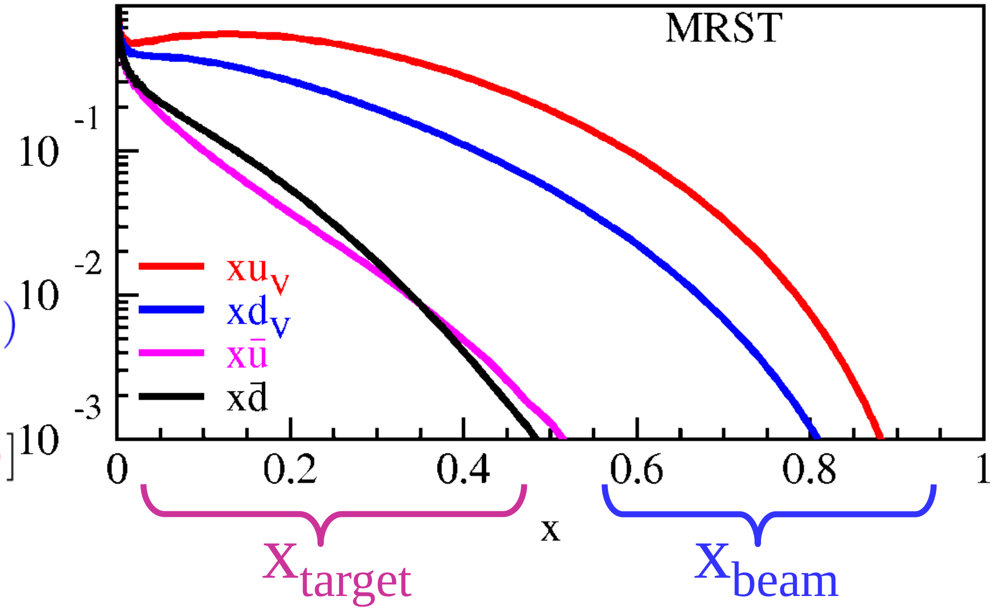
- u-quark dominance
  $(2/3)^2$ vs. $(1/3)^2$



- **π^- beam**
  - Valence beam anti-u quark and u target quark

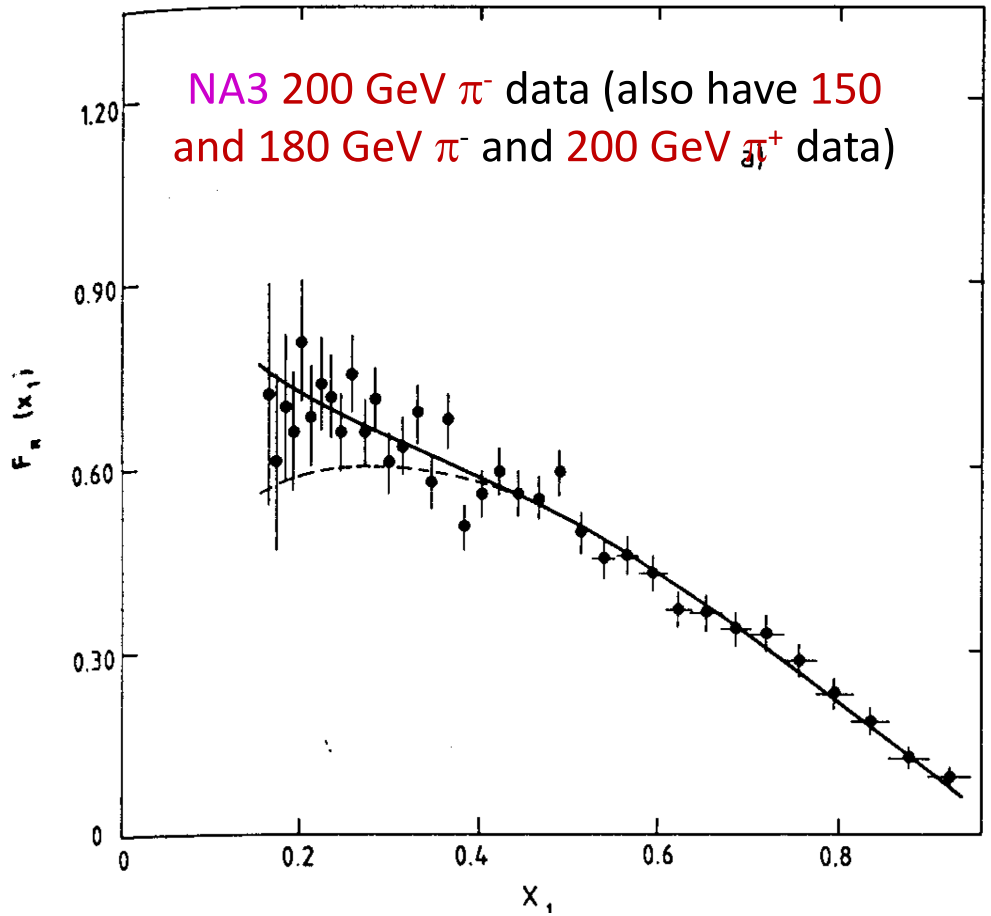
$$\left.\frac{d^2\sigma}{dx_\pi dx_N}\right|_{\pi^- N} = \frac{4\pi\alpha^2}{x_\pi x_N s}\left[\frac{4}{9}\bar{u}_\pi(x_\pi) u_N(x_N) + \frac{1}{9} d_\pi(x_\pi) \bar{d}_N(x_N) + \frac{4}{9} u_\pi(x_\pi) \bar{u}_N(x_N) + \frac{1}{9} \bar{d}_\pi(x_\pi) d_N(x_N)\right]$$

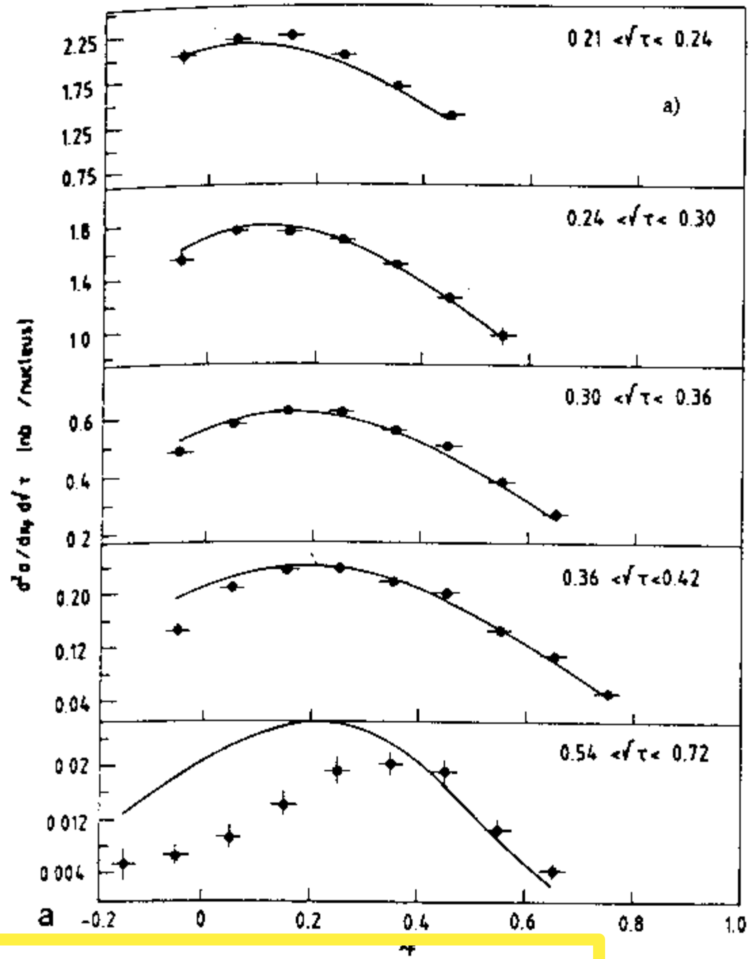
Valence × Valence

Valence-sea × ¼

Sea-sea × ¼

Pion Drell-Yan Data: CERN NA3 ($\pi^{\pm}$) NA10 (π^{-})





NA10 194 GeV π^- data

$$Q_\pi^{\mathrm{sea}} \equiv \int_0^1 x q_\pi^{\mathrm{sea}}(x)\,dx = 0.01$$

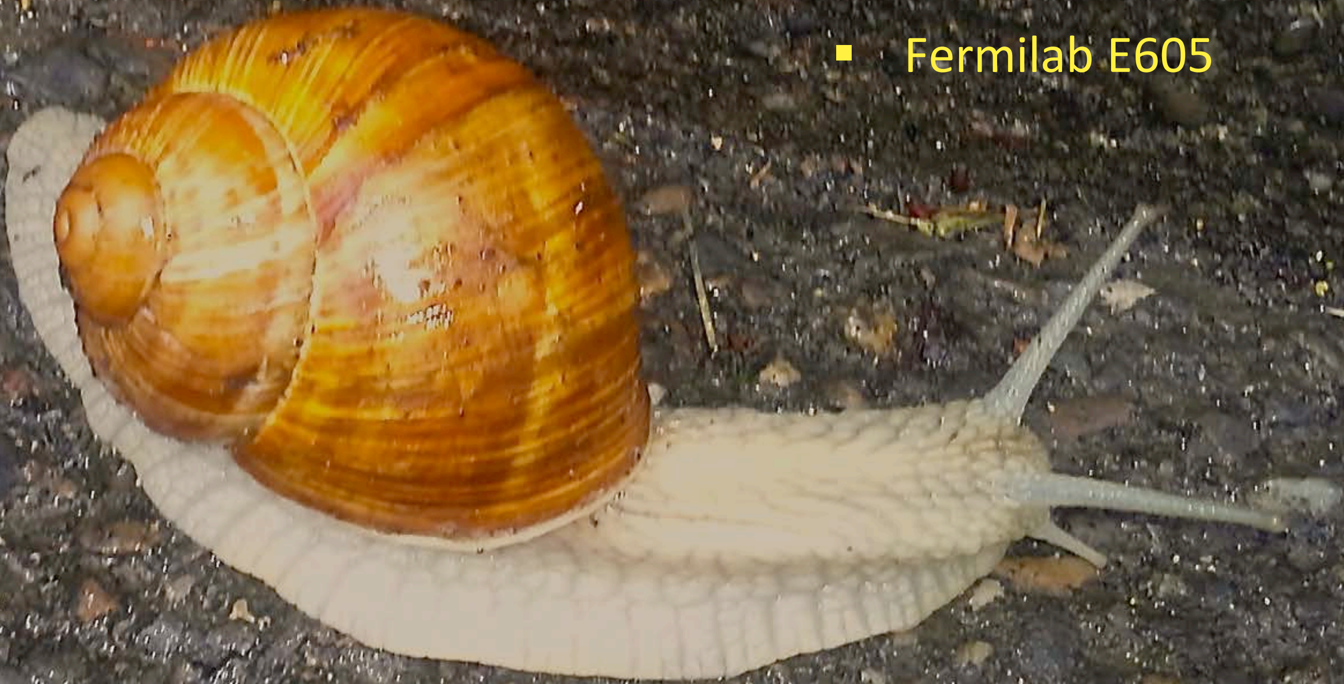
Very small quark sea in the pion

Valence structure

I've been slow in getting here, but. . .

Data:

- CERN NA3
- CERN NA10
- Fermilab E605



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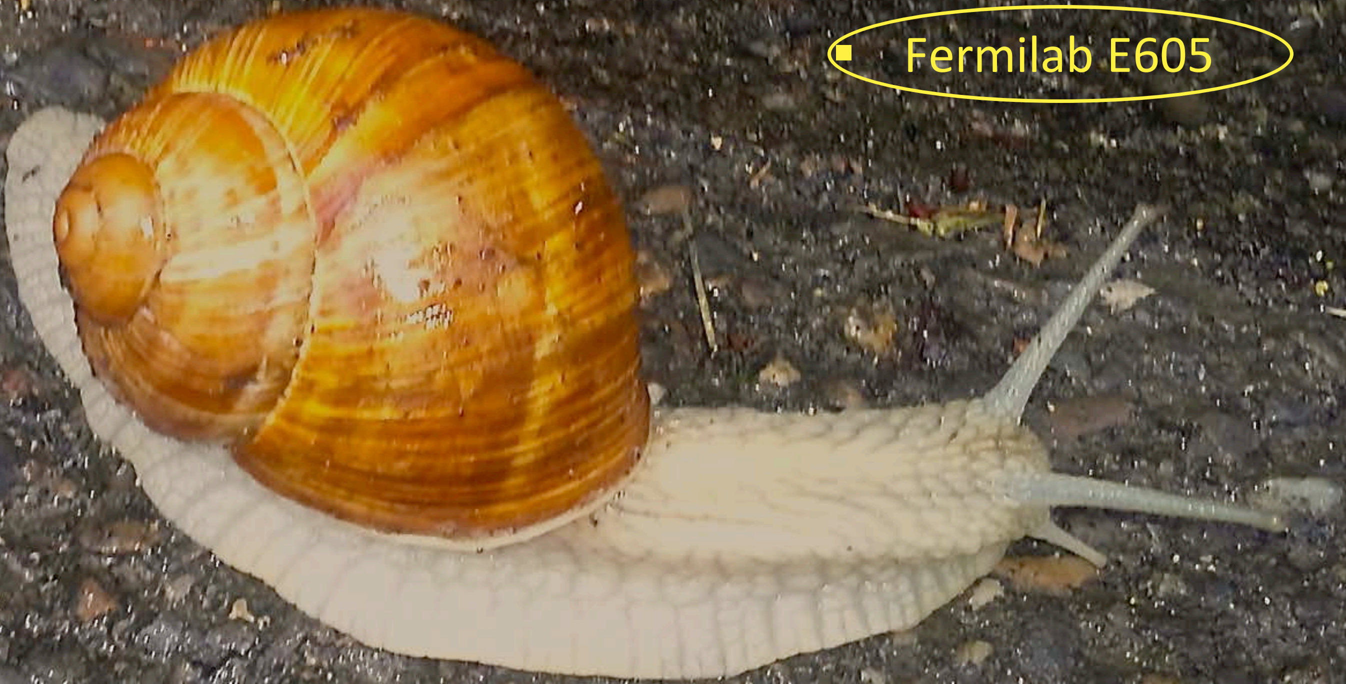

Pion Drell-Yan Data: Fermilab E615

PHYSICAL REVIEW D VOLUME 39, NUMBER 1 1 JANUARY 1989

Experimental study of muon pairs produced by 252-GeV pions on tungsten

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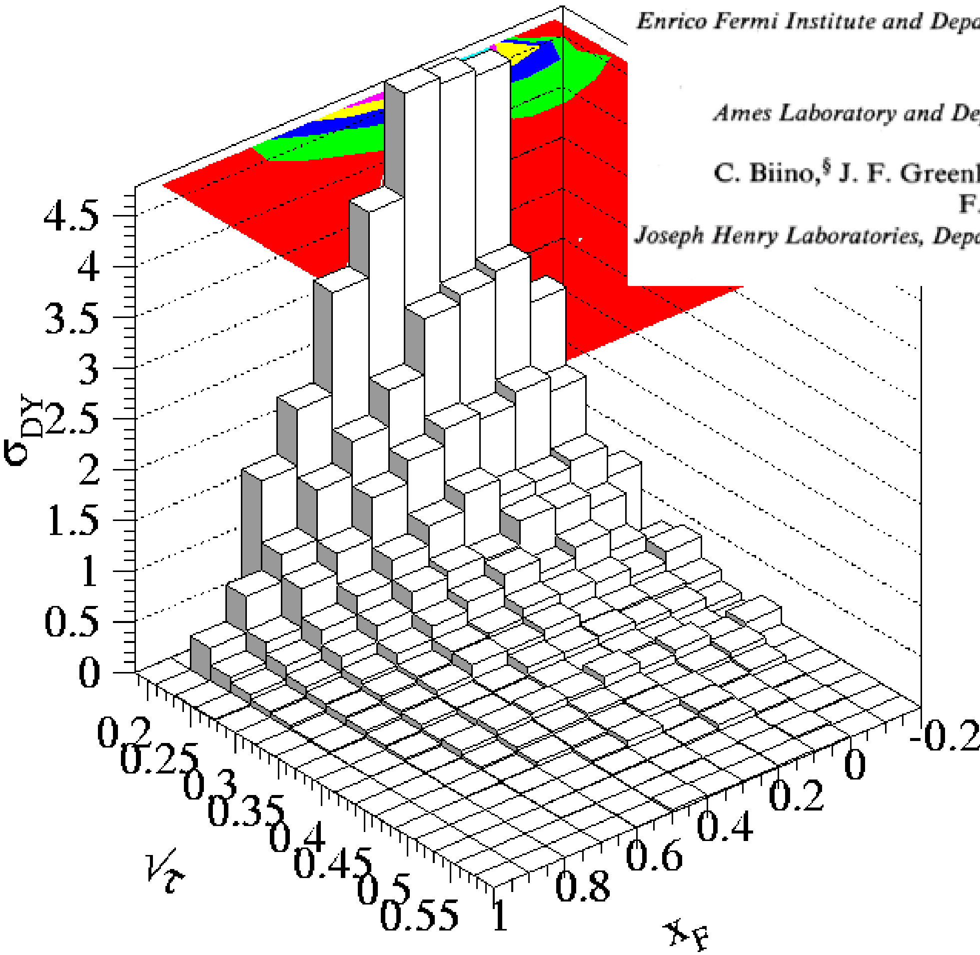

Fermilab E615

- 252 GeV π^-W Drell-Yan
- Projected each data point onto x_π axis (diagonal)
- Valence quark distributions extracted assuming
  $xq(x) = A\, x^{\alpha}(1-x)^{\beta}$

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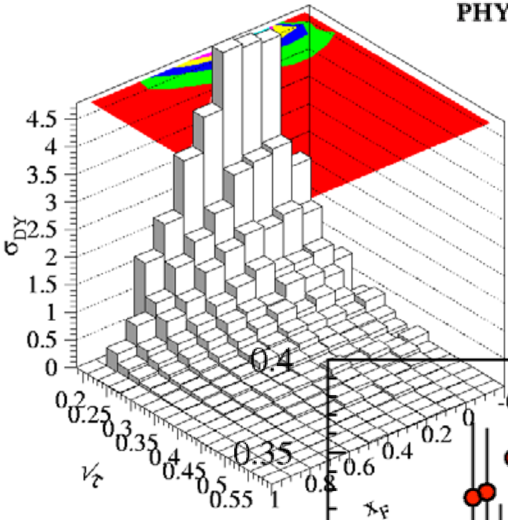

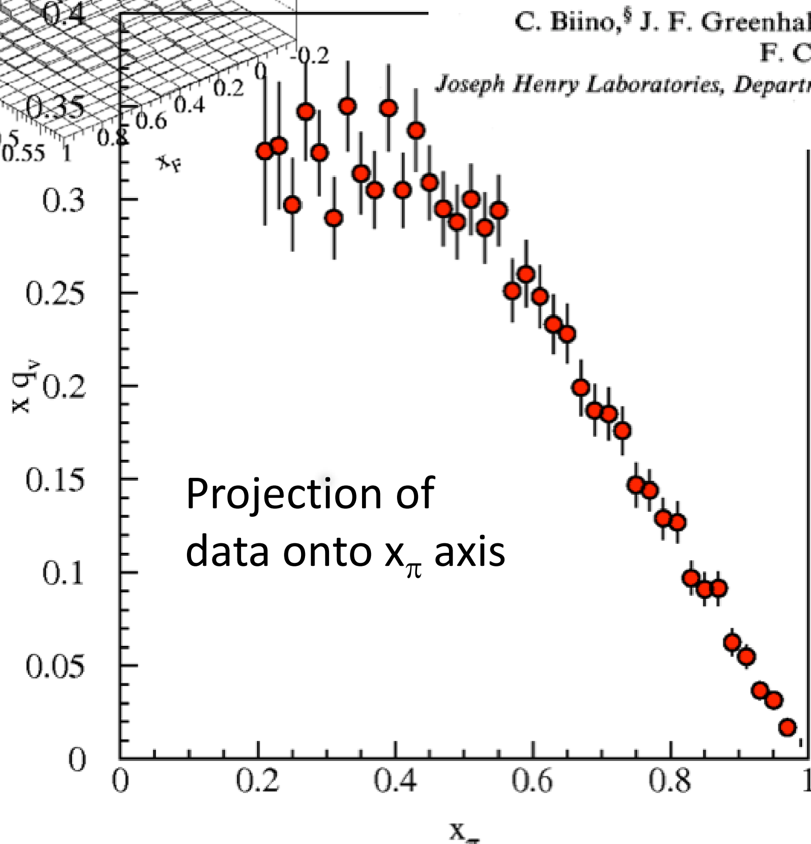

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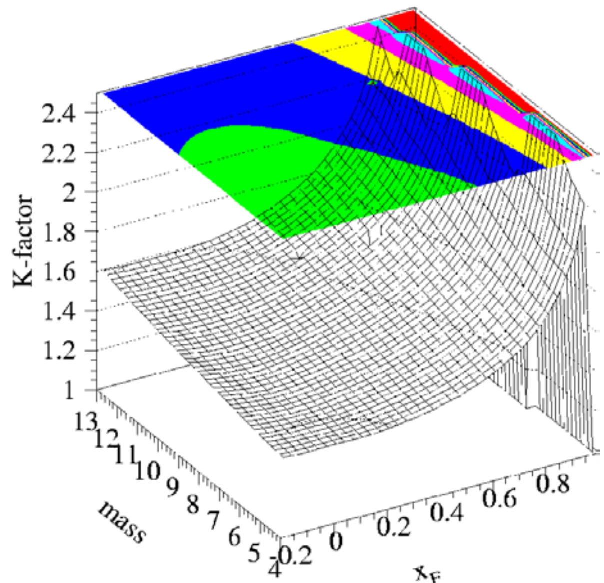
Could it be a problem with the treatment of the raw data?

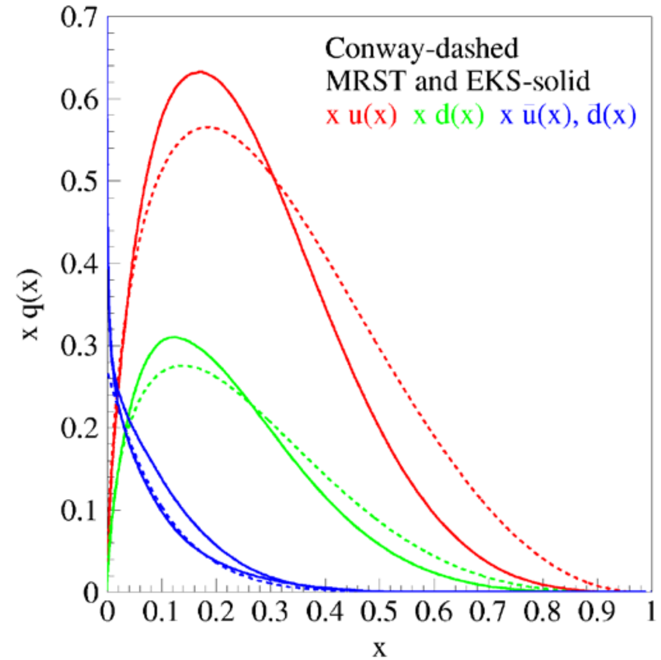
- More flexible parameterization (Hecht *et al.)*
- Modern **Proton** PDF w/nuclear corrections
- Inclusion of NLO terms rather than K-Factor
  - Look at 800 GeV *proton-proton* Drell-Yan:

$$xu_v(x) = A_0 x^{\alpha}(1-x)^{\beta}$$

$$xu_v(x) = A_0 x^{\alpha}(1-x)^{\beta} \times \left(1 - \epsilon\sqrt{x} + \gamma x\right)$$

Proton-proton K-factor is not constant at high x_F (high x_π)!





- Higher twist terms?

Fit of Drell-Yan Data in NLO

- Number of valence quarks [defines normalization on $q_\pi^v(x)$]:

$$\int_0^1 q_\pi^{\mathrm{Val}}(x)\,dx = 1$$

- Total momentum conservation:

$$2\int_0^1 x q_\pi^{\mathrm{v}}(x)dx + 6\int_0^1 x q_\pi^{\mathrm{sea}}(x)dx + G_\pi = 1$$

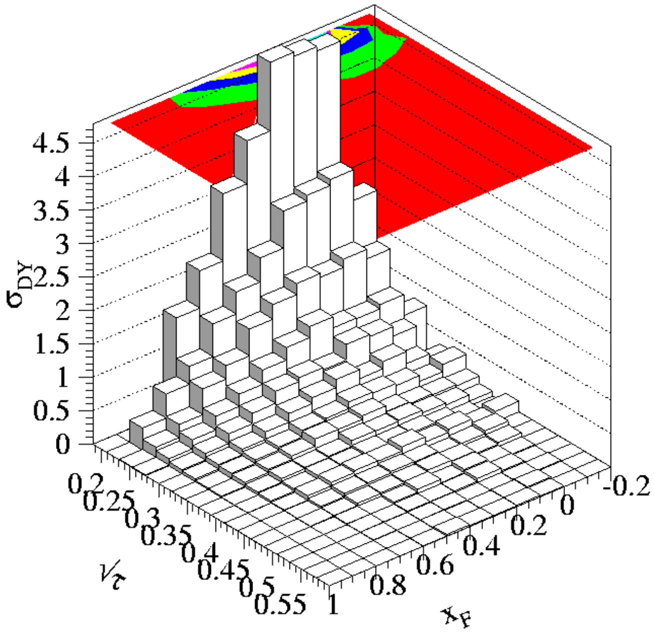
- Gluon content determined from other data (NA3/10 and WA80 direct photon)

$$G_\pi \equiv \int_0^1 x g_\pi(x)dx = 0.47$$

- Sea quark parameterization from fits to π^+/π^- Drell-Yan data

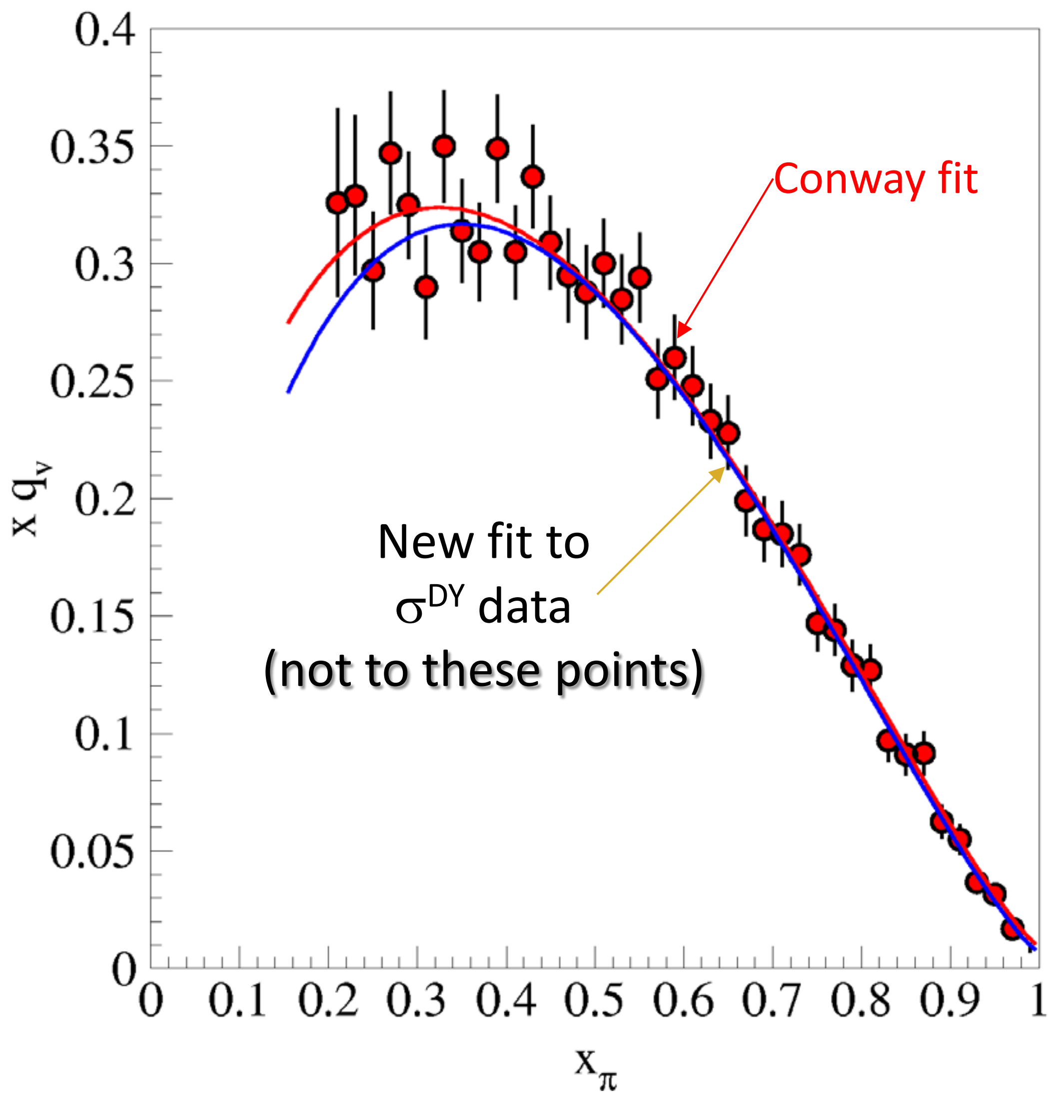
$$x q_\pi^{\mathrm{sea}}(x) = A_\pi^{\mathrm{sea}}(1-x)^\delta$$

$$\delta = 8.4$$

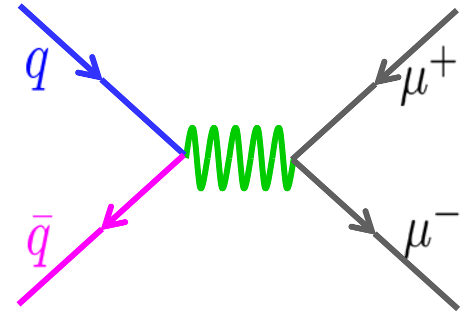


What did we learn?

- Even with new freedom from parameterization, curve does not change.
- Weak higher twist effects.
- Data do NOT prefer convex-up shape at high-x_π as required by DSE analysis!
- But this is not the end of the story!



Soft Gluon Resummation



$$\frac{d\sigma}{dQ^2 d\eta} = \sigma_0 \sum_{a,b} \int_{x_1^0}^{1} \frac{dx_1}{x_1} \int_{x_2^0}^{1} \frac{dx_2}{x_2} \left[q_a^{\pi}(x_1) q_b^{p}(x_2) \right.$$
$$\left. \times\, \omega_{ab}\left(x_1, x_1^0, x_2, x_2^0, Q/\mu\right)\right]$$

- ω_{ab} is hard scattering function
- Resum large logarithmic “soft” gluon contributions which arise as

$$z = \frac{Q^2}{\hat{s}} = \frac{\tau}{x_1 x_2} \to 1$$

- Accomplished with combined Mellin and Fourier transform of the cross section

  Aicher, Schäfer and Vogelsang, Phys. Rev. Lett. **105**, 252003 (2010)
- Refit of pion Drell-Yan data

Fit of Drell-Yan Data by ASV

- Number of valence quarks [defines normalization on $q_\pi^v(x)$]:

$$\int_0^1 q_\pi^{\mathrm{Val}}(x)\,dx = 1$$

- Total momentum conservation:

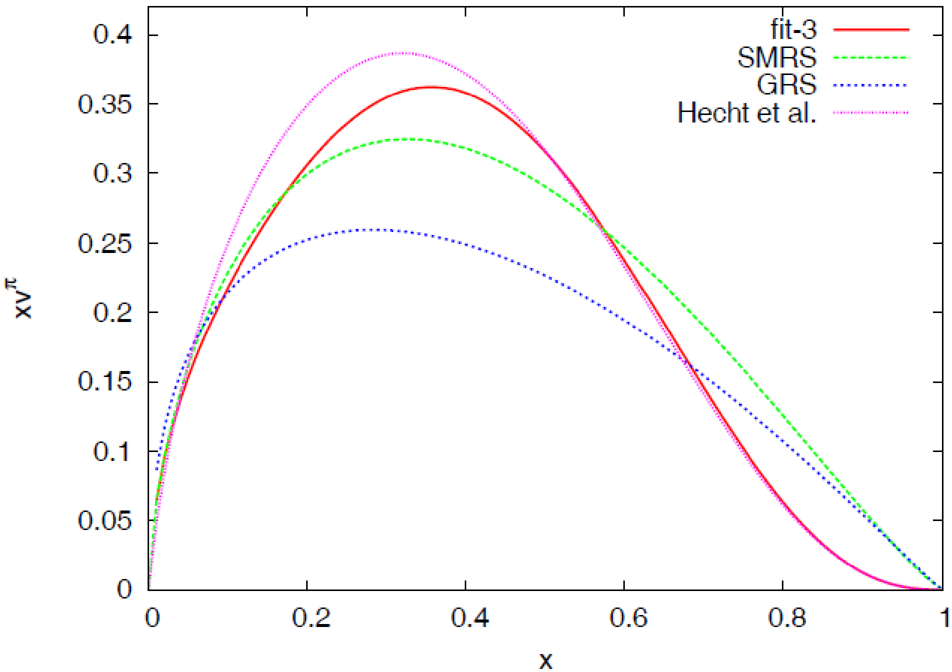
$$2\int_0^1 x q_\pi^{\mathrm{v}}(x)dx + 6\int_0^1 x q_\pi^{\mathrm{sea}}(x)dx + G_\pi = 1$$

ASV replaced constraint with assumed values of $2\langle xq_\pi\rangle$. Effectively ignores Gluon and Sea Quark data

TABLE I. Results for our NLL threshold-resummed fits to the Fermilab E615 Drell-Yan data [1].

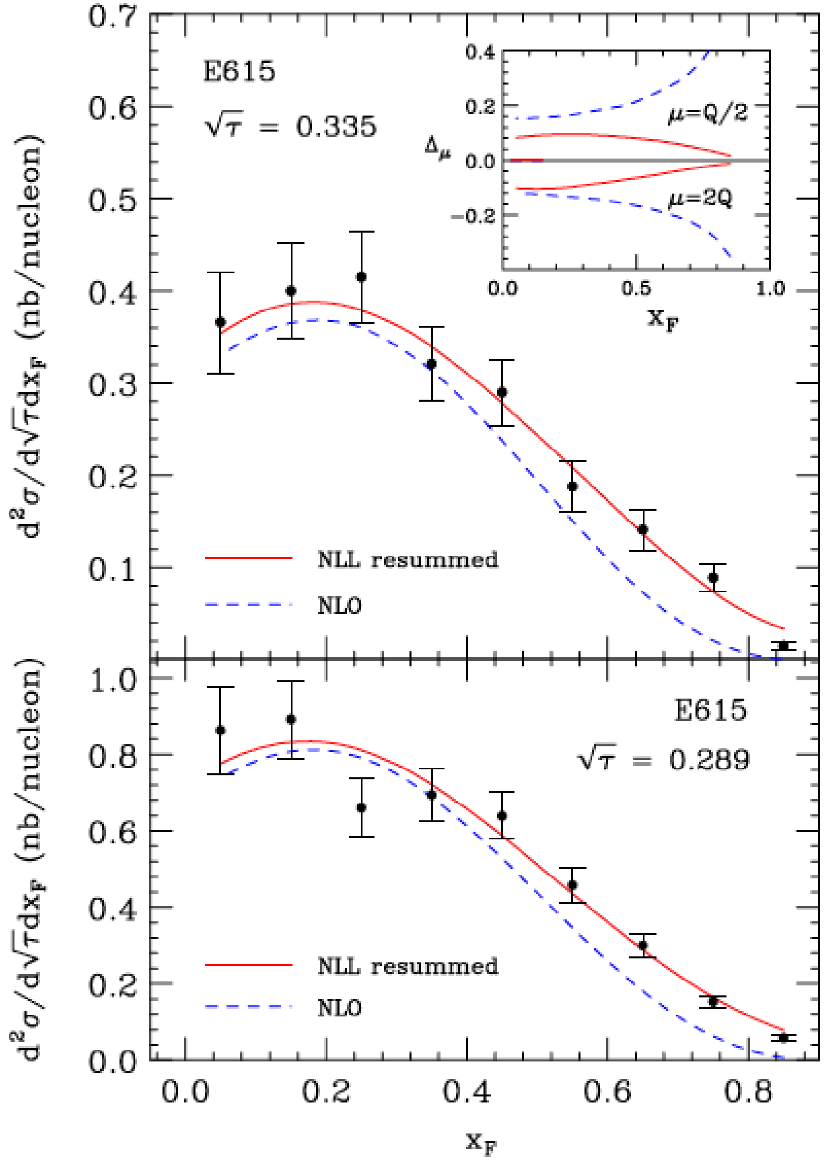
Fit	$2\langle xv^\pi\rangle$	α	β	γ	K	χ^2 (no. of points)
1	0.55	0.15 ± 0.04	1.75 ± 0.04	89.4	0.999 ± 0.011	82.8 (70)
2	0.60	0.44 ± 0.07	1.93 ± 0.03	25.5	0.968 ± 0.011	80.9 (70)
3	0.65	0.70 ± 0.07	2.03 ± 0.06	13.8	0.919 ± 0.009	80.1 (70)
4	0.7	1.06 ± 0.05	2.12 ± 0.06	6.7	0.868 ± 0.009	81.0 (70)

Soft Gluon Resummation



$$xq_V^\pi(x) = A_V^\pi x^\alpha (1-x)^\beta \left(1+\gamma x^\delta\right)$$

β = 2.03 ±0.06



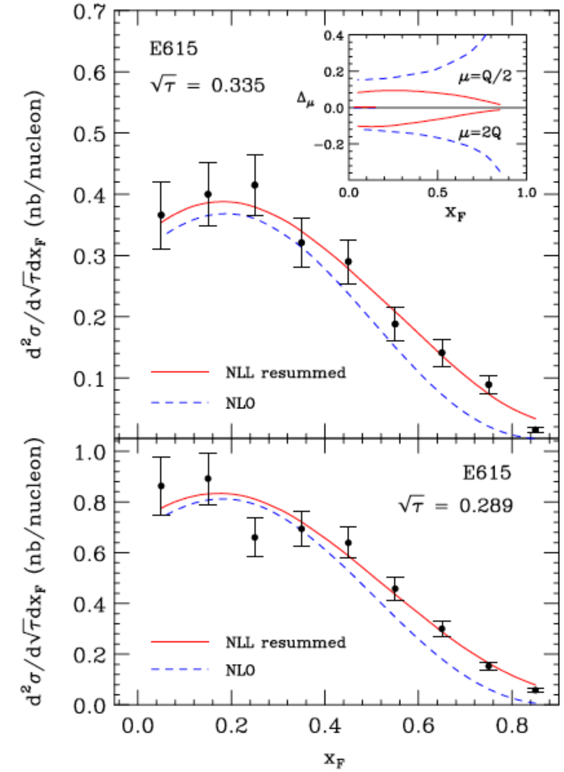
QCD and Dyson-Schwinger survive!

pQCD: $xq(x)/ (1-x)^\beta$ β = 2

DSE: $xq(x)/ (1-x)^\beta$ β≈ 1.9

Conclusions

- Large x_{Bj} structure of the pion is interesting
  - Pion cloud & antiquark flavor asymmetry
  - Nuclear Binding
  - Simple QCD state & Goldstone Boson
- Even with NLO fit and modern parton distributions, pion did not agree with pQCD and Dyson-Schwinger
- **Soft Gluon Resummation saves the day!**
  - What does this mean for other large-x_{Bj} Drell-Yan data?



Aicher, Schäfer and Vogelsang, Phys. Rev. Lett. **105**, 252003 (2010)

Future

- Additional high statistical data to come from CERN-COMPASS
- Include Direct Photon and CERN $\pi^{\pm}$ in fit

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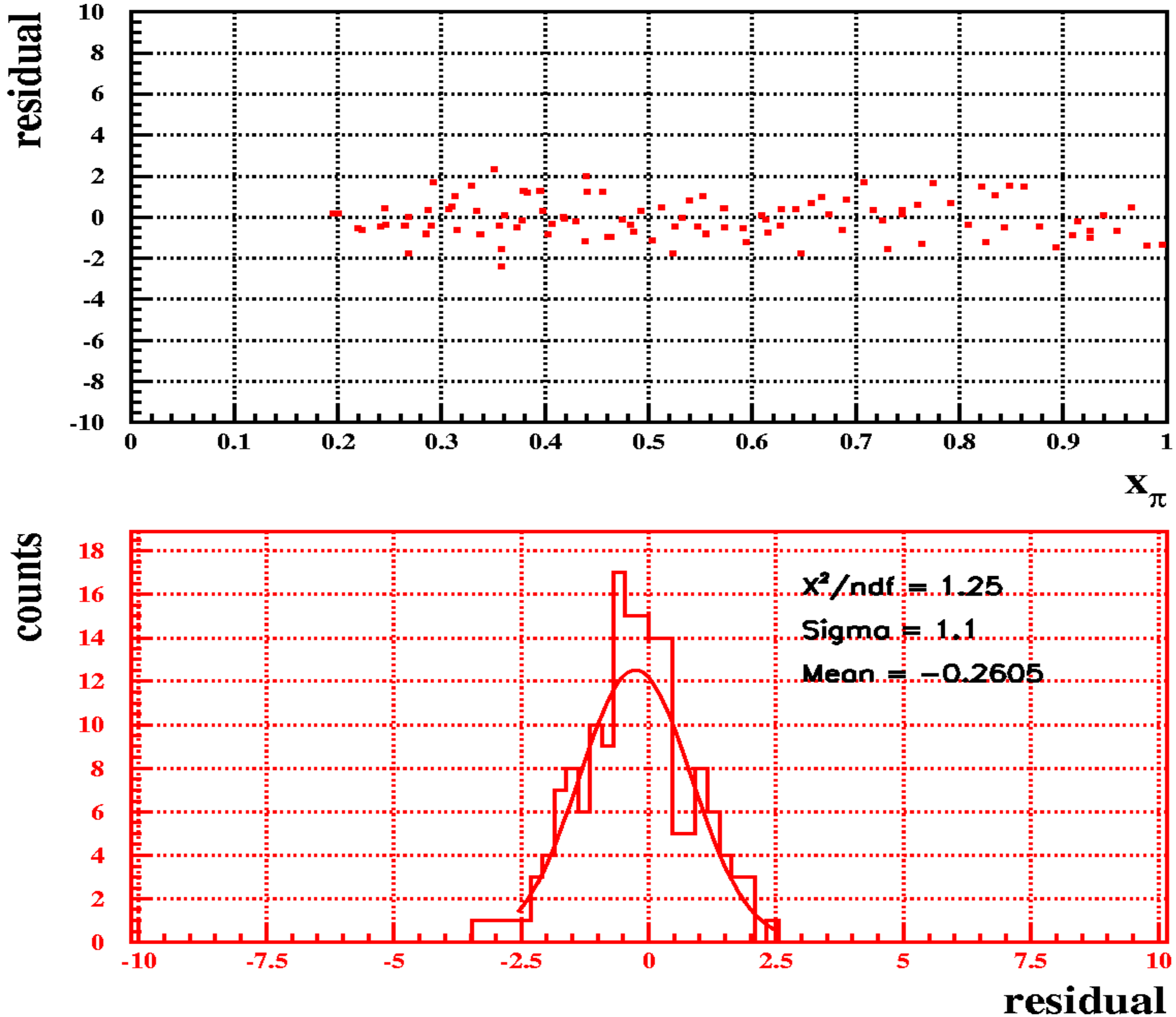
Backup

Good Fit? Residuals

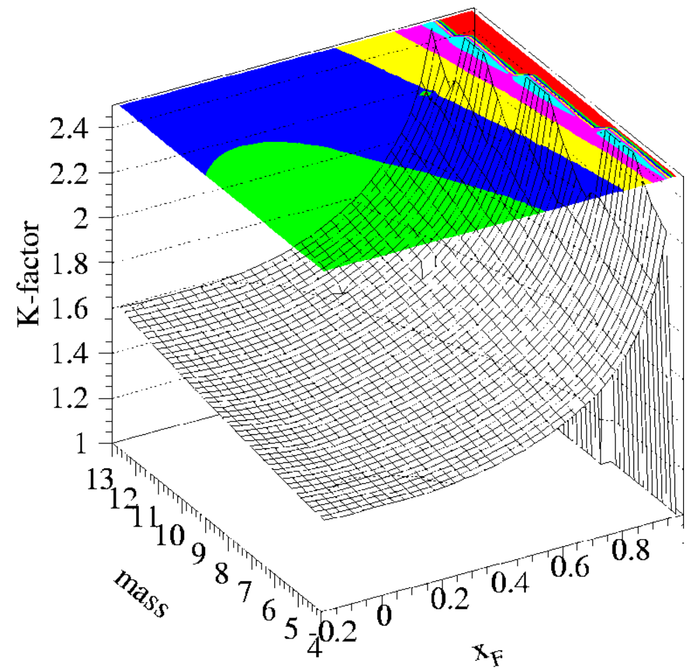


Caveat: The K factor

- K factor relates Leading Order to Next-to-Leading order cross section calculations:

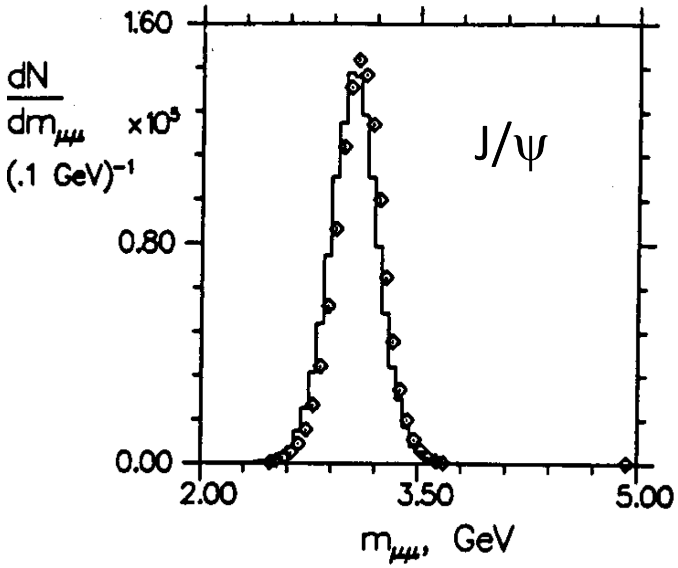
  $\sigma^{exp} \approx \sigma^{NLO} \cong K\,\sigma^{LO}$ where $K \approx 2$
- Taken to be a constant *independent* of kinematics— Is it?
- Possibly NLO analysis will show DSE behavior.
- NLO fit can be done— remember this is "work in progress"—but at the cost of computer time.

Look at 800 GeV *proton-proton* Drell-Yan:



Proton-proton K-factor is not constant at high x_F (high x_π)!

Caveat: x_π Resolution

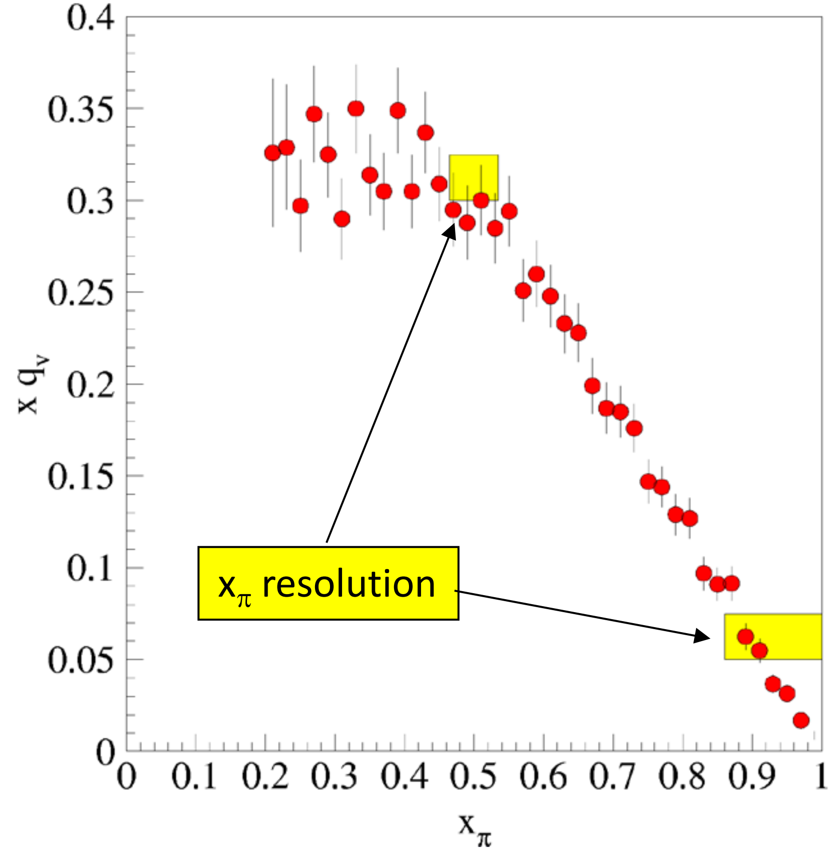


$$\Delta M_{\mu\mu} \approx 165 \text{ MeV}$$

$$M^2 = x_\pi x_N s$$

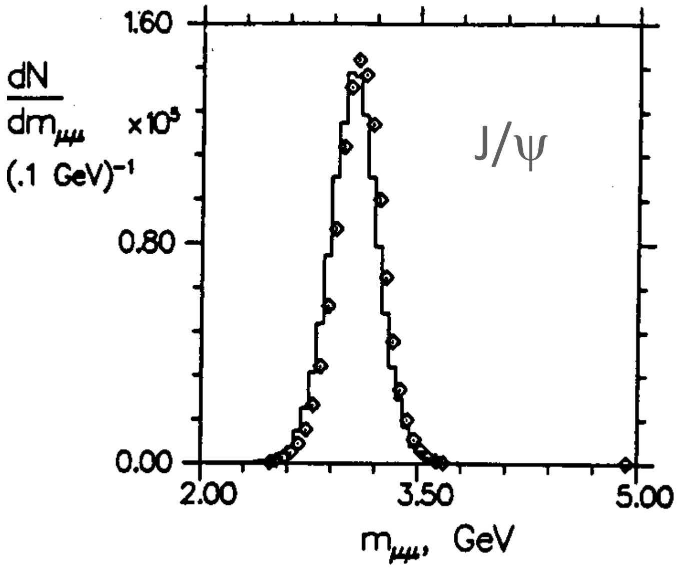
$$\frac{\Delta x_\pi}{x_\pi} \approx \frac{2\Delta M}{M} \approx 0.1$$

x_π resolution not quoted in paper or thesis



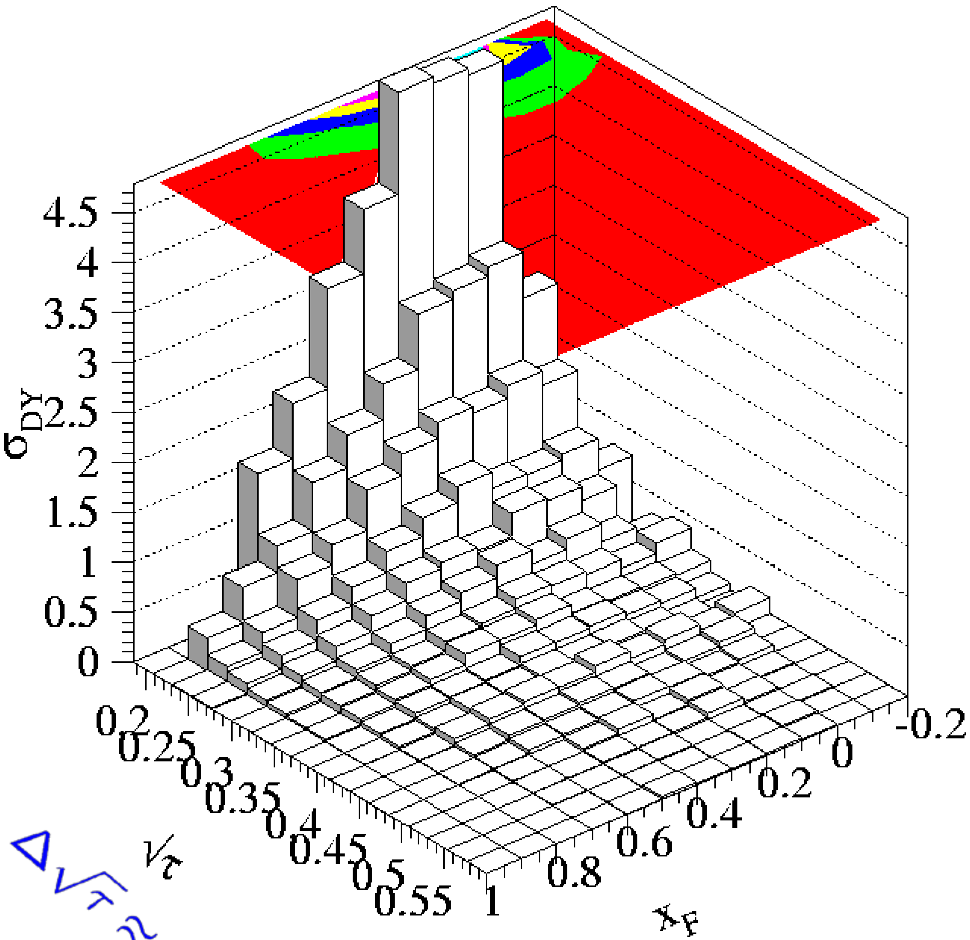
Best case, x_π and x_N contribute equally (E866 experience $\Delta x_\pi = 5\ \Delta x_N$) $\Delta\ x_\pi/x_\pi$¼ 0.14)

Caveat: x_π Resolution (cont.)



$$\Delta M_{\mu\mu} \approx 225 \text{ MeV}$$

$$\sqrt{\tau} = M\sqrt{s}$$



$\Delta_{\sqrt{\tau}} \approx 0.01$

Resolution misrepresentation arises from projecting into x_π-x_N space.

Drell-Yan Polarization & Higher Twist

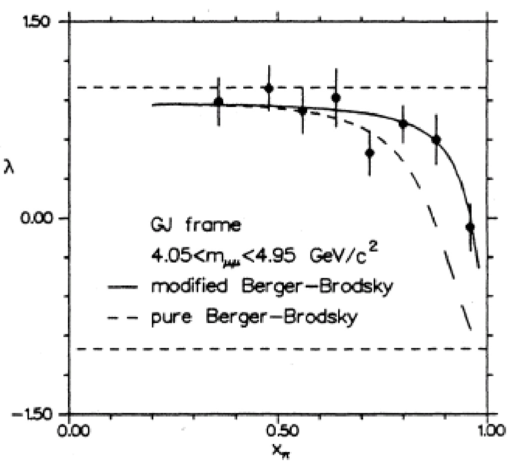
- Drell-Yan is transversly polarized:

  $d\sigma$ / $1+\lambda \cos^2(\theta)$

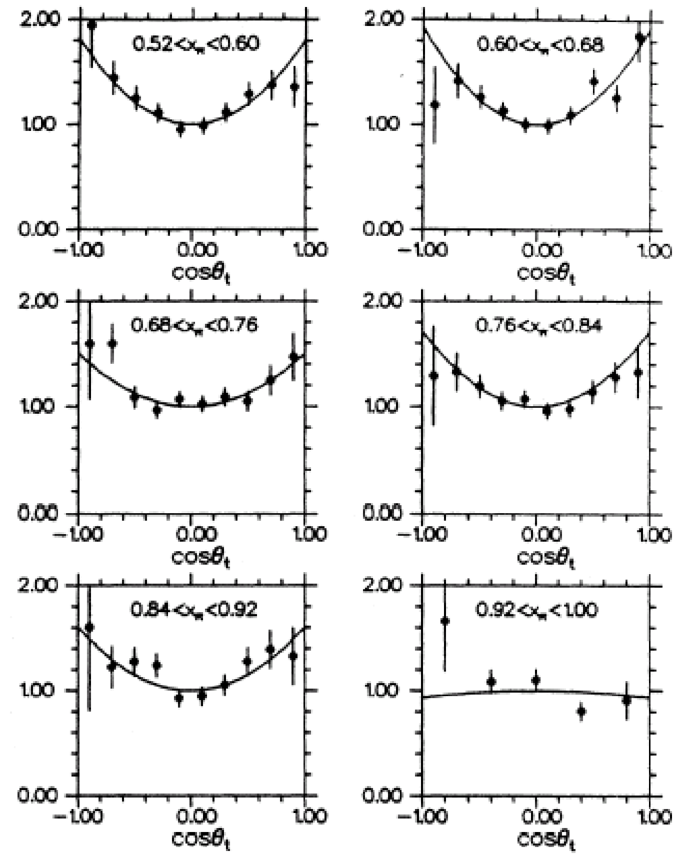
- High x_π show higher twist—Berger and Brodsky:

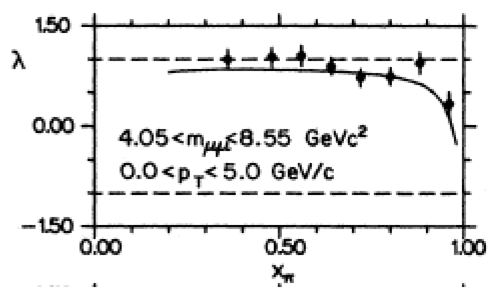
  $d\sigma$ / $(1-x_\pi)^2[1+\cos^2(\theta)]$

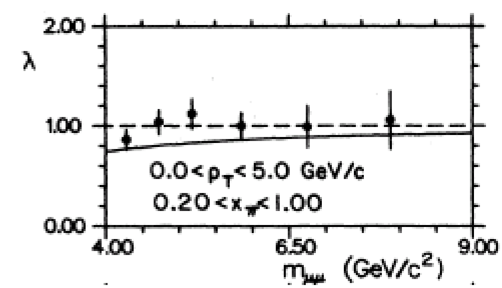
  $+ 4/9\ x_\pi h k_T^2 i \sin^2(\theta)$ / m^2



Include higher twist term in parameterization!



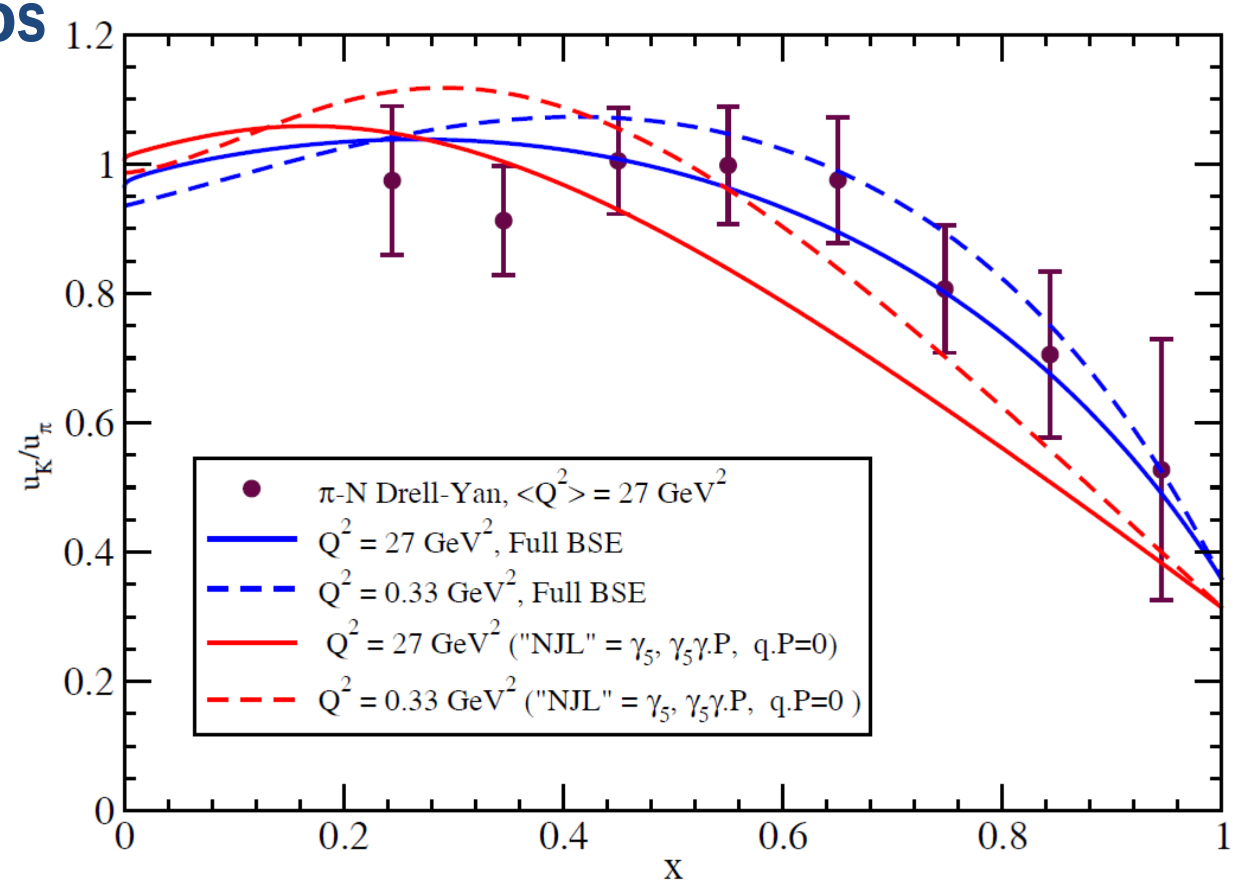




K/π Drell-Yan Ratios

More recent developments:

- Predictions of the K/p Drell-Yan ratio based on Bethe-Salpeter Equations (BSE)
- Can we get a Kaon beam to test this high-x_{Bj} structure of the Kaon?



A. Bashir, T. Nguyen, C.D. Roberts and P.C. Tandy Phys.Rev. C83 (2011) 062201

Data: Badier *et al.* Phys. Lett. **B93** 354 (1980)

Experimental Tools for π structure

- Deeply Inelastic Scattering:

  "pion targets are not abundant" Hecht

  - DIS on virtual pions:

    ep→eNx HERA data [ZEUS, NPB637 3 (2002)]

    Possible JLab and EIC.