Experimentally Probing The Emergence of Hadron Mass

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Physics Division
Argonne National Laboratory
18 November 2020

U.S. DEPARTMENT OF ENERGY
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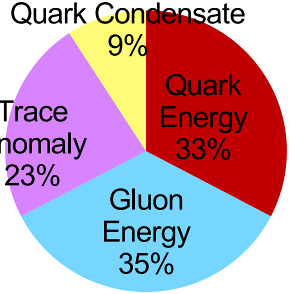
Proton's Mass

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update

- Only a small part of the Proton's mass may be attributed to the Higgs mechanism.
- From where does the remainder emerge?
- Caveat:
  Consider a frame invariant definition of mass
  $\vec{P}^2 \neq \sum \vec{P_i}^{\,2}$
- Rest frame decomposition



Y-B Yang, et al, Phys. Rev. Lett. 121, 212001 (2018)

Rest Frame decomp. of proton mass

- Chiral limit trace anomaly
  $\langle P(p)|\Theta_0|P(p)\rangle = -p_\mu p_\mu = m_N^2$
  – Mass entirely from gluons

QUARKS

u

$m_u = 2.16^{+0.49}_{-0.26}$ MeV
$m_u/m_d = 0.47^{+0.06}_{-0.07}$

d

$m_d = 4.67^{+0.48}_{-0.17}$ MeV
$m_s/m_d = 17–22$
$\overline{m} = (m_u+m_d)/2 = 3.45^{+0.55}_{-0.15}$ MeV

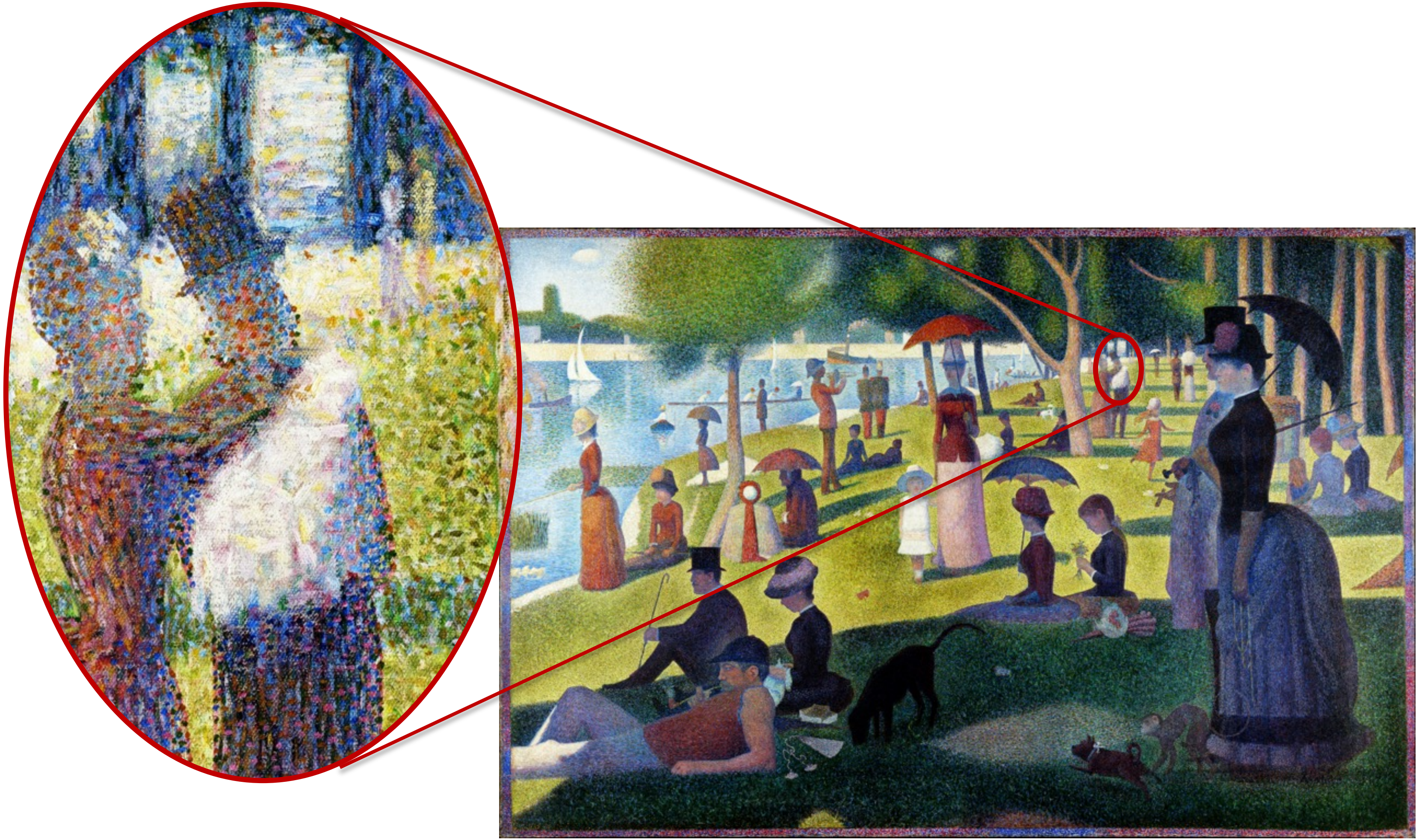
s

$m_s = 93^{+11}_{-5}$ MeV
$m_s\,/\,((m_u + m_d)/2) = 27.3^{+0.7}_{-1.3}$

$$\sum q_{\text{Valence}} = 9 \text{ GeV} \ll M_{\text{Proton}} = 938\ GeV$$
$$\sum q_{\text{Valence}} \approx 0.1 \times M_{\text{Proton}}$$

THE PROTON

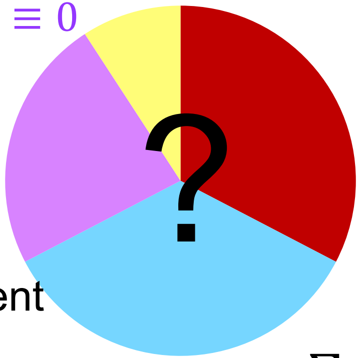
The Proton, Higgs Mass Only



Meson Mass

- Pion,
  - $M_\pi \approx {}^2/_3\, M_{\text{Proton}}$ Constituent Quarks
  - $M_\pi \approx 0$ Chiral limit Goldstone Boson
  - Chiral limit trace anomaly
    $$\langle P(p)|\Theta_0|P(p)\rangle = -p_\mu p_\mu = m_\pi^2 \equiv 0$$
    - No Gluons in Chiral limit
  - Higgs mechanism & DCSB*
- Kaon
  - $M_K \approx {}^1/_3\, M_{\text{Proton}} + X M_\Lambda$ Constituent Quarks
  - s-quark addition causes Higgs mechanism & DCSB to rebalance

*DCSB $\Longrightarrow$ Dynamical Chiral Symmetry Breaking



Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update

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$m_s = 93^{+11}_{-5}$ MeV
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$$\sum q^{\pi}_{\text{Valence}} = 7\ \text{GeV} \ll M_\pi = 140\ GeV$$
$$\sum q^{\pi}_{\text{Valence}} \approx 0.05 \times M_\pi$$

$$\sum q^{K}_{\text{Valence}} = 95\ \text{GeV} \ll M_K = 494\ GeV$$
$$\sum q^{K}_{\text{Valence}} \approx 0.2 \times M_K$$

KEY QUESTIONS

- Do we understand the trace anomaly?
  - Is there any glue in the pion?
  - Is there any glue in the Kaon?
- Do we understand the energy-mass distribution
  - of the pion?
  - of the Kaon?
- What is the difference between the pion and Kaon energy-mass distributions?
- How do we relate this to the proton?
  - We need consistent QCD explanation

Experimentally need to know π, π/K and K PDF's
(also nice to know PDF's from lattice QCD)

Consider How PDF's Are Determined

Global fits

- No single experiment determines a particular distribution $q(x)$, $\bar{q}(x)$, $g(x)$, etc.
  - ***Need to consider all data with physics-based constraints***
  - Some have more sensitivity though—see PDFSense *Phys.Rev.D* 98 (2018) 9, 094030
- Make assumptions (e.g. for the pion, based on sum rules)

$$\int_0^1 (u(x) - \bar{u}(x))dx = 1 \qquad \int_0^1 x[q(x) + \bar{q}(x) + g(x)]dx = 1$$

- Make more assumptions about the analytic form
  - e.g. $Ax^{\alpha}(1-x)^{\beta} f(x)$
  - Notable exception NNPDF

What Can Be Measured?

Better Sensitivity to Quark Distributions

- Pionic Drell-Yan
  - CERN NA3 & NA10, Fermilab E615
  - CERN COMPASS/AMBER
- π-DIS w/Leading Hadron
  - HERA, JLab,
  - EIC

Better Sensitivity to Gluon Distributions

- Direct Photon
  - CERN WA70
  - CERN AMBER
- J/Ψ production
  - CERN AMBER

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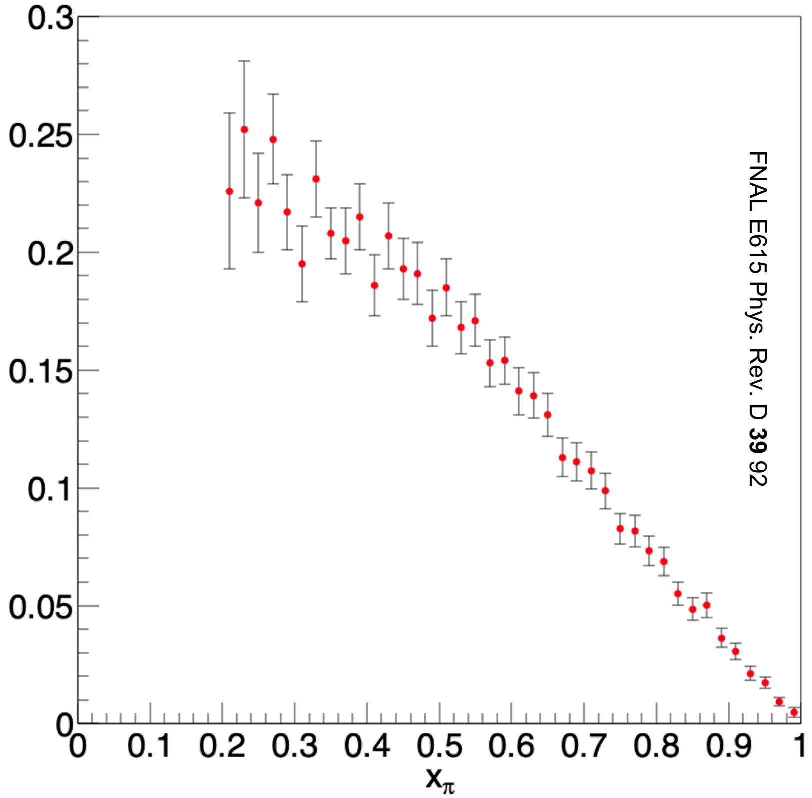
Pion Valence Distribution at Large-x

- Issue: What is the shape at large-x?

$$A^{\pi} x^{\alpha} (1 - x)^{\beta}$$

- Can we validate that β > 2?



FNAL E615 Phys. Rev. D **39** 92

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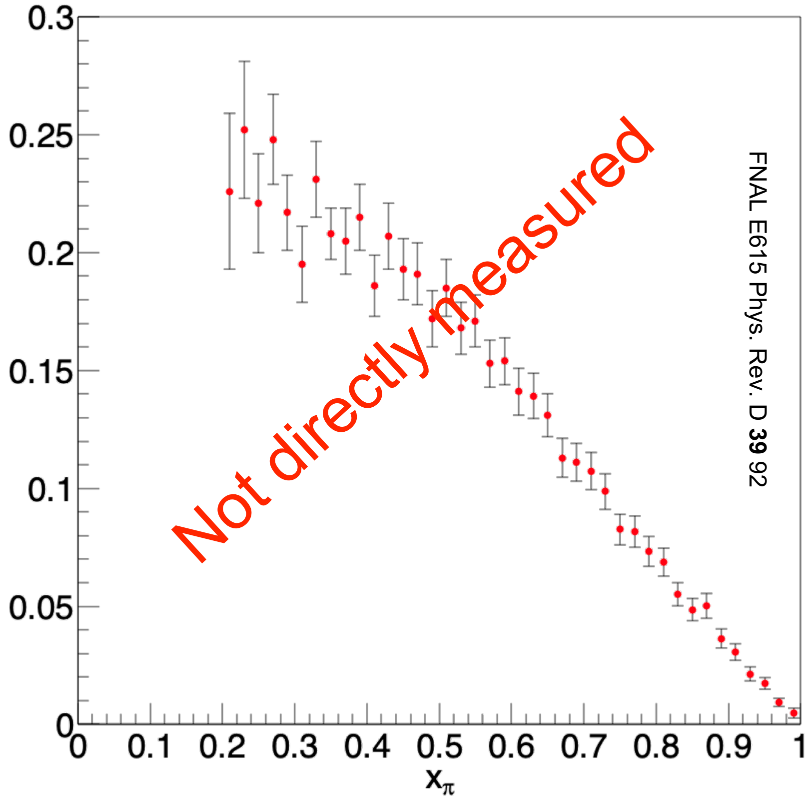


J/ψ

Pion Valence Distribution at Large-x

- Issue: What is the shape at large-x?

$$A^{\pi} x^{\alpha} (1-x)^{\beta}$$

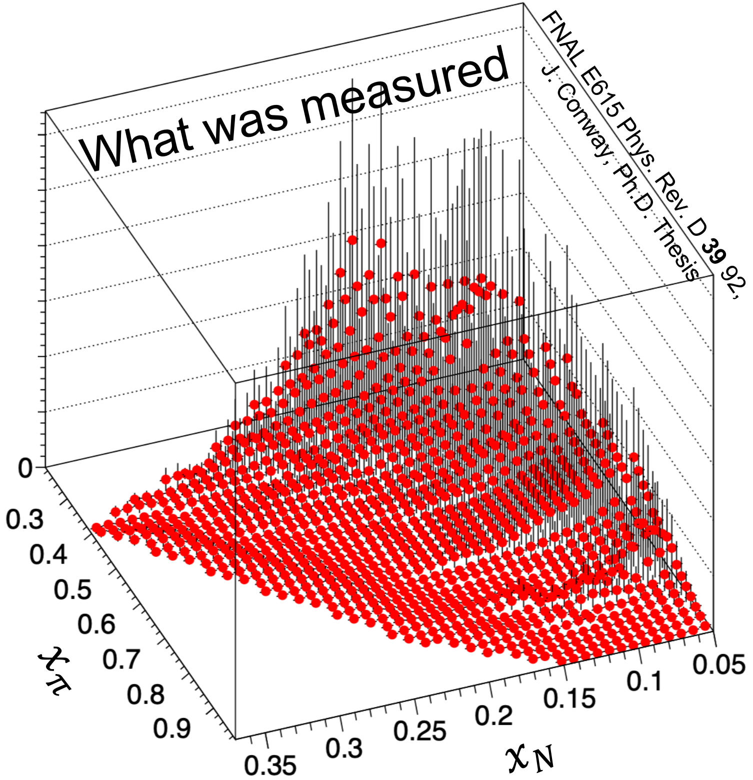
- Can we validate that $\beta > 2$?

- What is a sufficiently "free" form

$$A^{\pi} x^{\alpha} (1-x)^{\beta} \boldsymbol{f(x)}$$

  – NNPDF

- What is a sufficient calculation of the cross section?
  – Soft gluon re-summation necessary



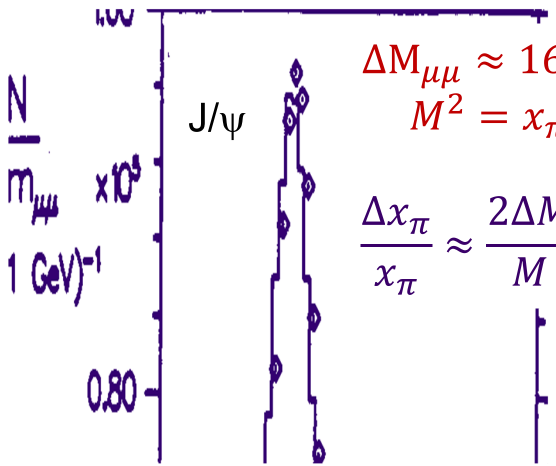
- How do the sea and gluon distributions affect this?

Pion Valence Distribution at Large-x

- Issue: What is the shape at large-x?

$$A^{\pi}x^{\alpha}(1-x)^{\beta}$$

- Can we validate that β > 2?
  - Perhaps not with the data at hand

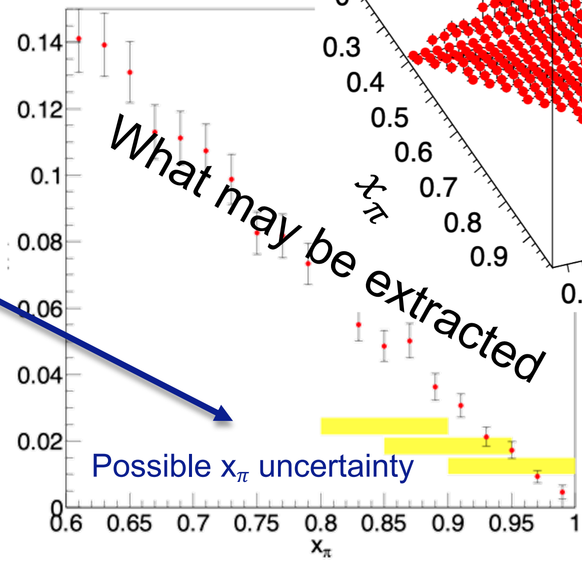


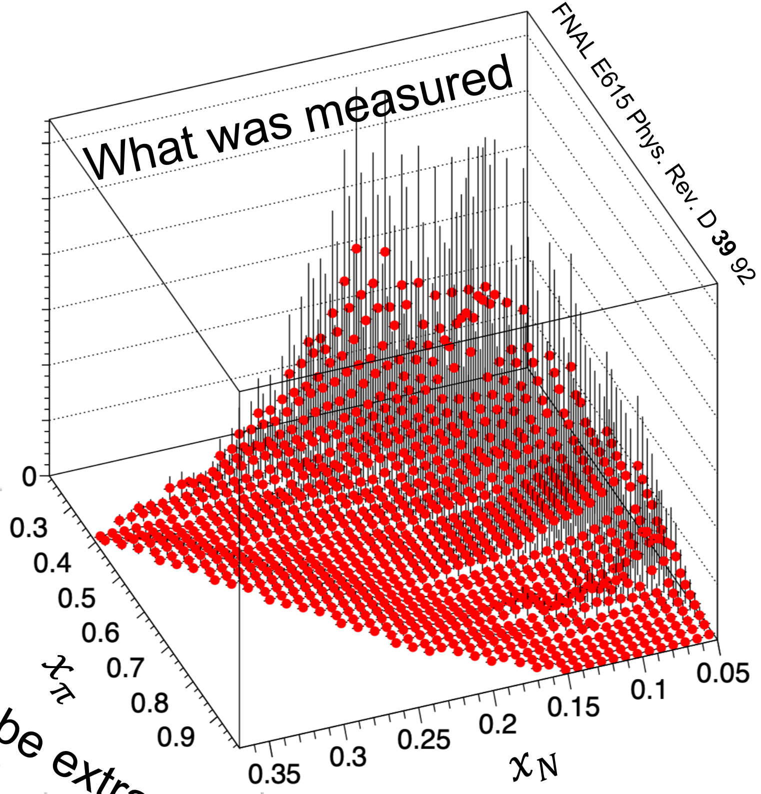
$\Delta M_{\mu\mu} \approx 165\ MeV$

$M^2 = x_\pi x_N s$

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

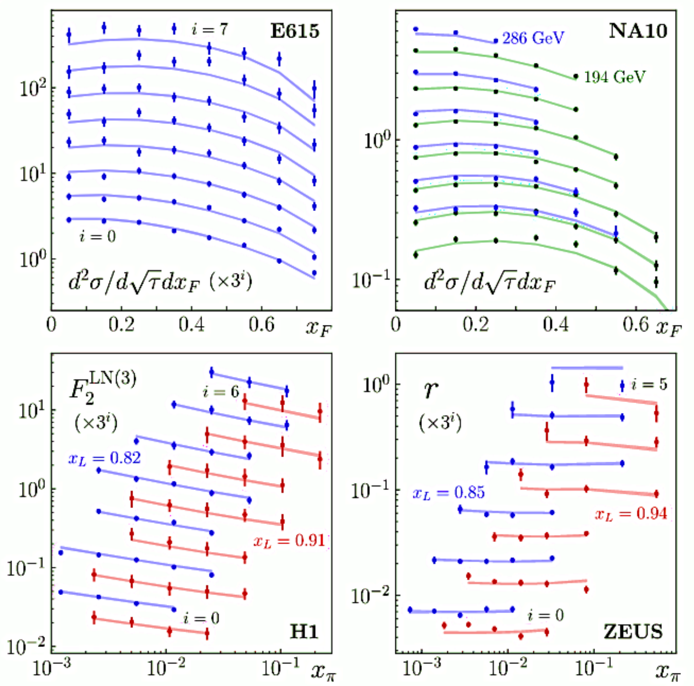
x_π resolution not quoted in paper or thesis





Pion Valence Distribution at Large-x

JAM Phys. Rev. Lett. 121,152001 (2018)

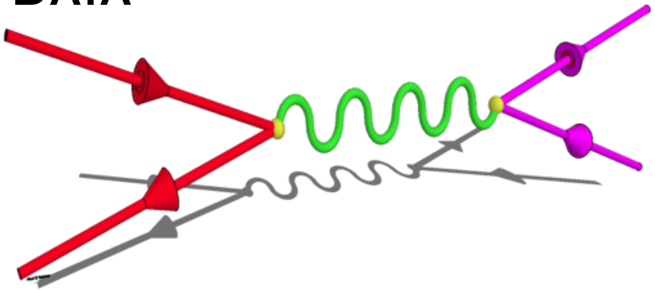


- Issue: What is the shape at large-x?

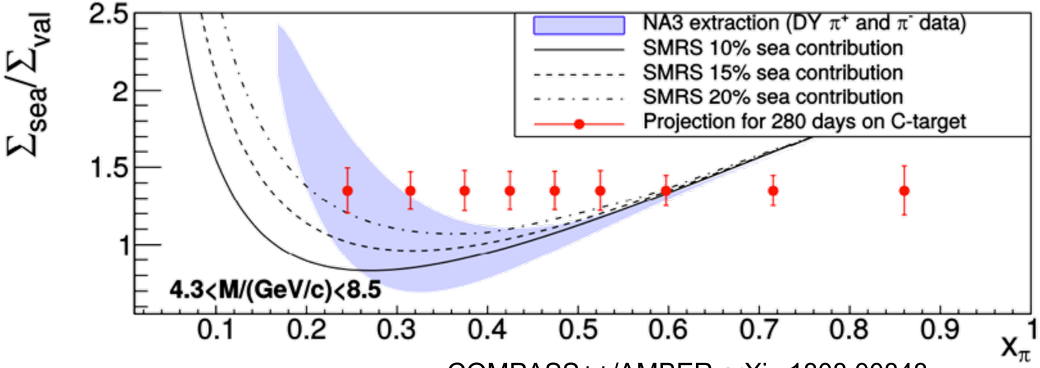
$$A^{\pi} x^{\alpha} (1-x)^{\beta}$$

- Can we validate that β > 2?
  - Perhaps not with the data at hand
- Remember data from both NA10 and NA3
  - NA3 data has both $\pi^{-}(\bar{u}d)$ and $\pi^{+}(\bar{d}u)$ data
    Sensitivity to pion sea quarks
    - Is there a pion sea?
    - Does it arise (solely) from gluons?
- JAM collaboration has considered these data

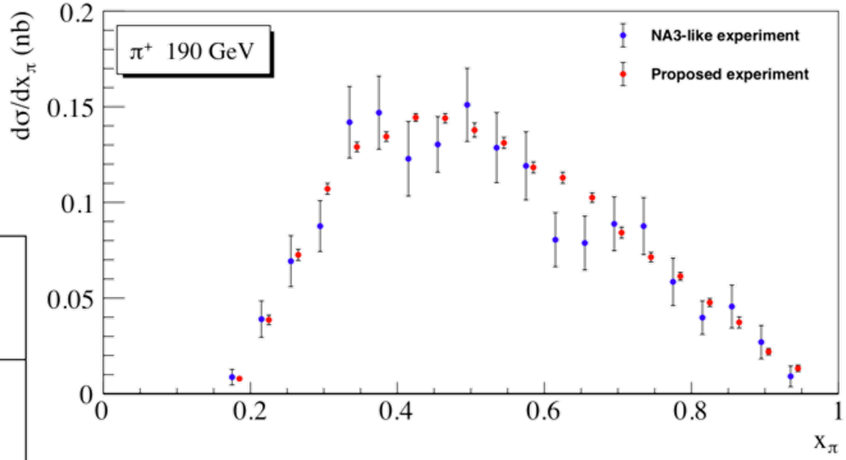
KEY MEASUREMENT: PION INDUCED DRELL-YAN DATA



- π^- induced Drell-Yan data
  - Valence quark determination
- Ratio of π^-/π^+ Drell-Yan
  - Sea quark determination
- Data with sufficient resolution



COMPASS++/AMBER arXiv:1808.00848



COMPASS++/AMBER

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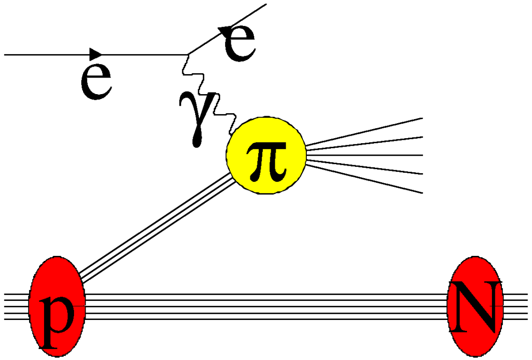
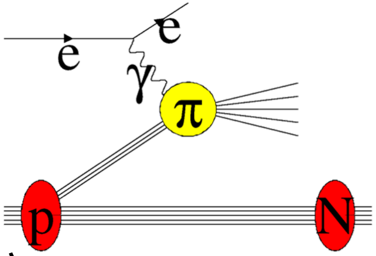


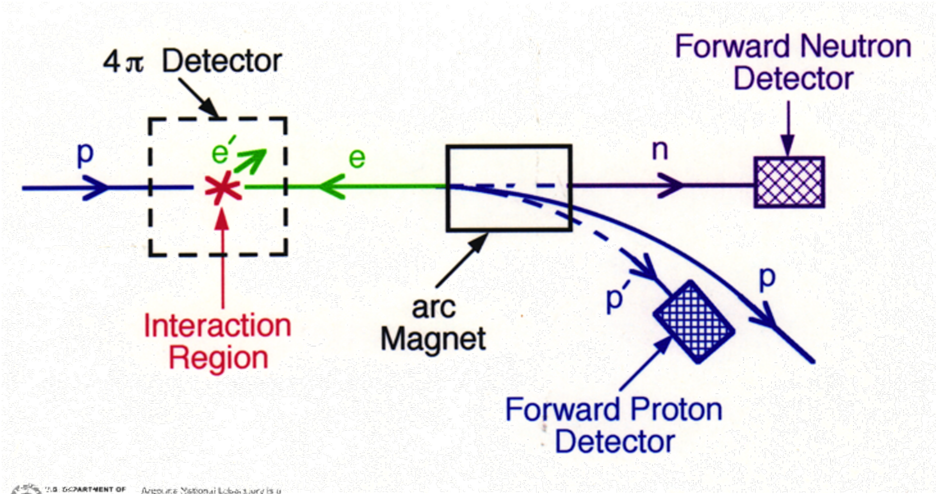
LEADING HADRON VIRTUAL PION DIS

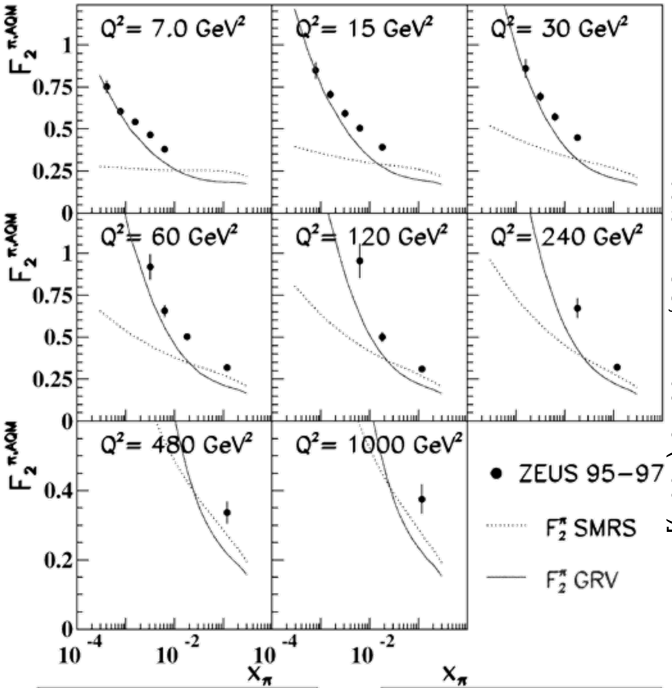
Sullivan Process



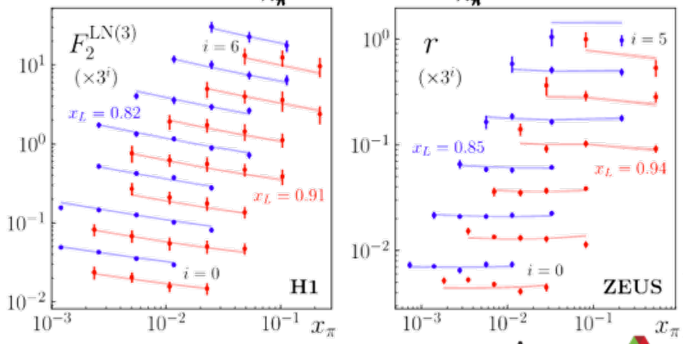
$$|p\rangle = |p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle + \cdots$$

- Use pions floating around proton as a target
- Tag with beam-like neutron





HERA data ZEUS, NPB637 3 (2002)]



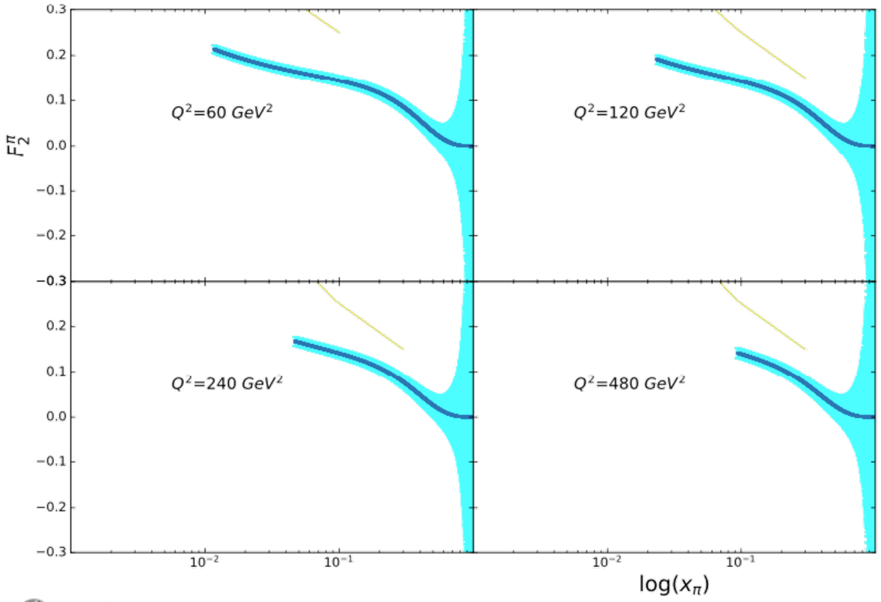
JAM,PRL 121,152001 (2018)

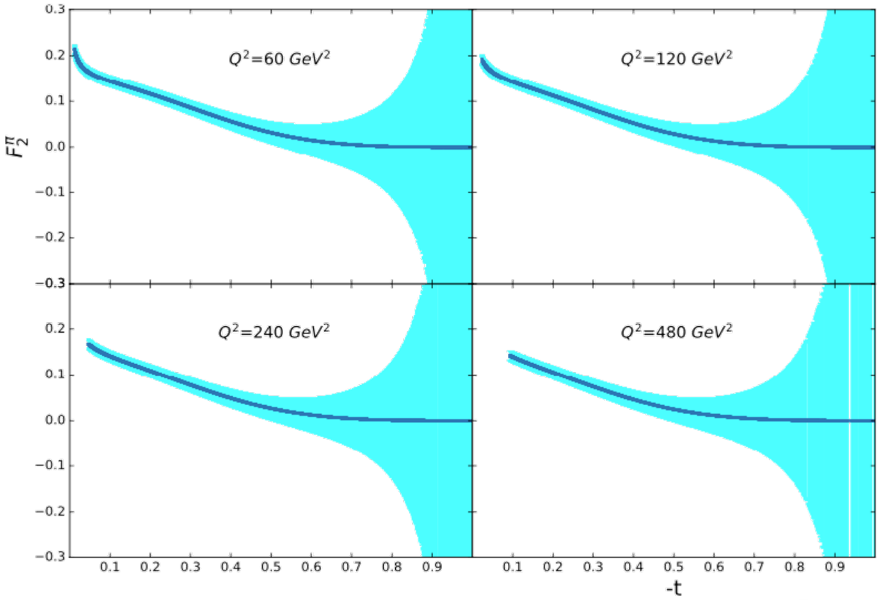
Leading Hadron Virtual Pion DIS

Sullivan Process

$$|p\rangle = |p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle + \cdots$$

Possible kinematic reach and precision at the EIC





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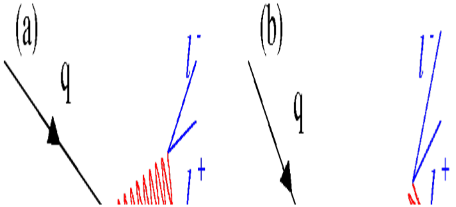
- J/Ψ production
  - CERN AMBER

$$\int_0^1 x[q(x) + \bar{q}(x) + \boldsymbol{g(x)}]dx = 1$$

- ***g(x)*** determined by "what's left over"
- NLO sensitivity in Drell-Yan



Direct Photons

- WA 70

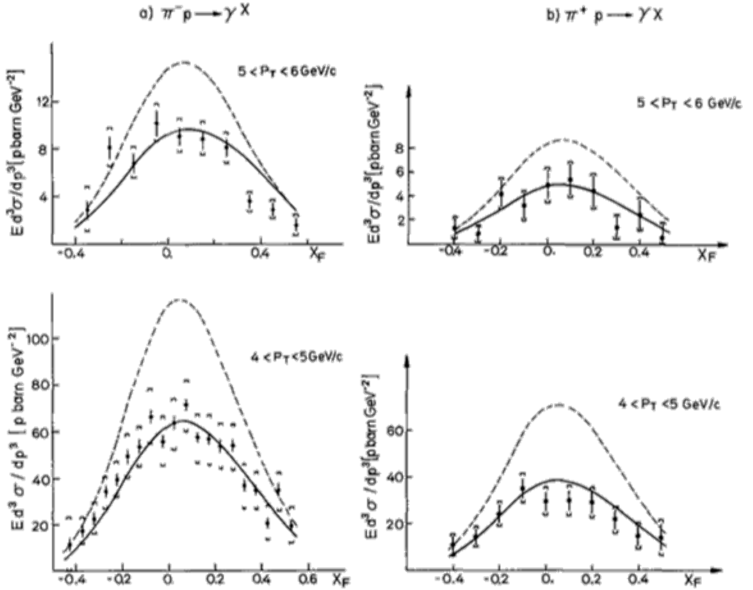
$$G_\pi = \int_0^1 xg(x)dx = 0.33 - 0.43$$

SMRS Phys. Rev. D **45**, 2349 (1992)

$$xg^\pi(x) = A_g^\pi(1-x)^\eta \;\; \eta \approx 2.1$$

1/3 to 1/2 glue in momentum space?

WA70, Z. Phys. C **37**, 535 (1988)



- Chiral limit trace anomaly

$$\langle P(p)|\Theta_0|P(p)\rangle = -p_\mu p_\mu = m_\pi^2 \equiv 0$$

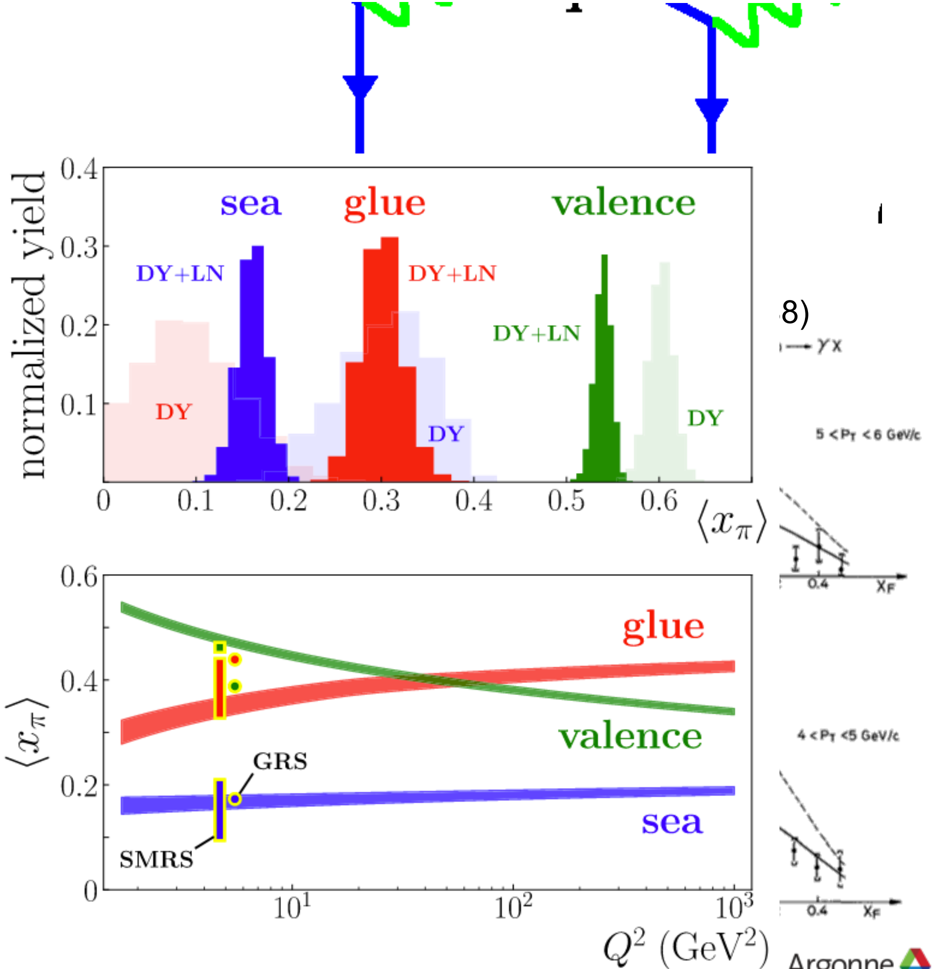
– No Gluons in Chiral limit

Direct Photons

- JAM analysis

$$G_\pi = \int_0^1 xg(x)dx \approx {}^1/_3$$

JAM, Phys. Rev. Lett. 121,152001 (2018)



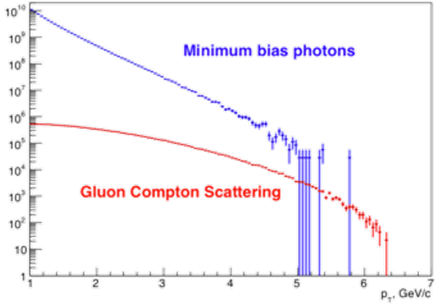
- Chiral limit trace anomaly

$$\langle P(p)|\Theta_0|P(p)\rangle = -p_\mu p_\mu = m_\pi^2 \equiv 0$$

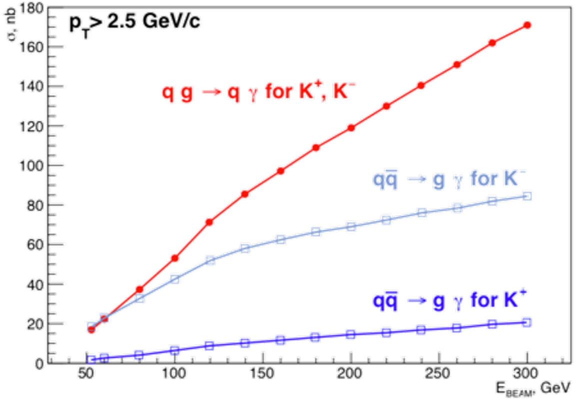
– No Gluons in Chiral limit

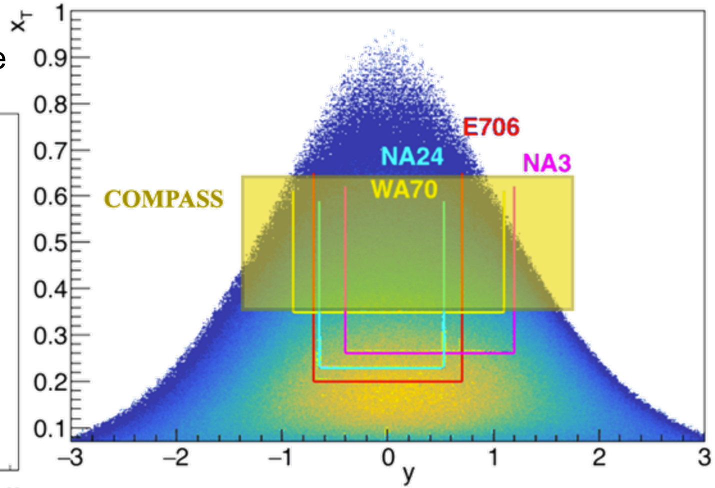
Gluon Sensitivity

- COMPASS/AMBER
  - –Direct photons
    - Large background

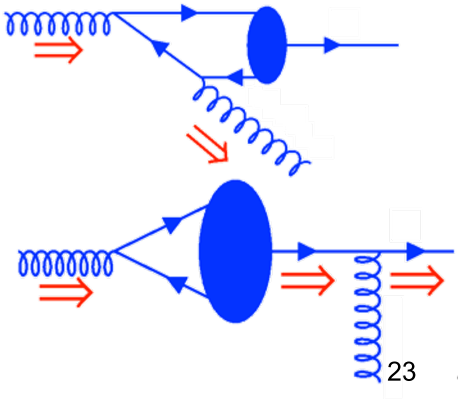


COMPASS/AMBER
Direct Photon Kinematic Coverage





  - –J/Ψ production
    - $\bar{q}q \to J/\psi$
    - $qg \to J/\psi$
    - $\bar{q}g \to J/\psi$
    - $gg \to J/\psi$
    - Need to ~~get rid of~~ understand excess color in production model (Color evaporation vs NRQCD)



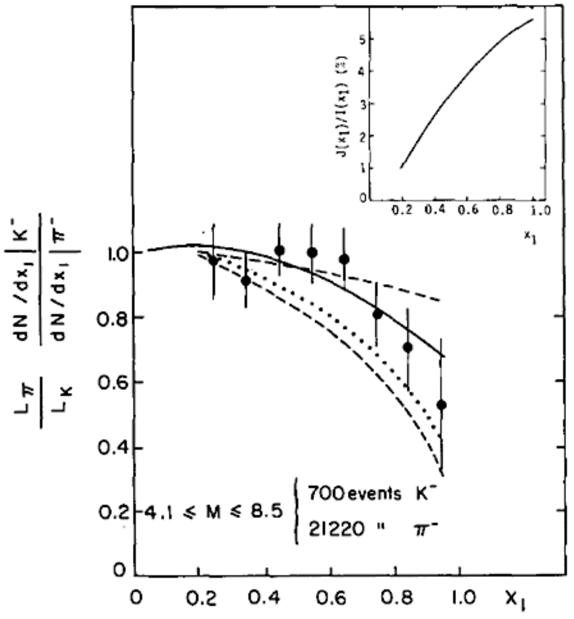
QCD

- To “see” QCD in full color these measurements must be repeated for the kaon

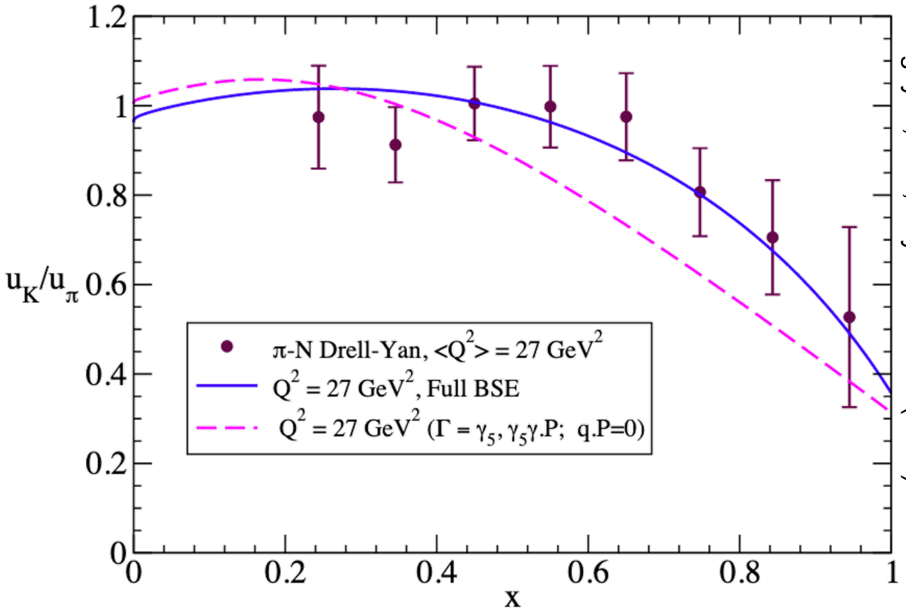
- ***<u>Cannot over emphasize this</u>***

PION TO KAON RATIOS

- Regime in which Higgs mechanism begins to show importance



Badier, et al, Phys. Lett. B 93, 354 (1980)



T. Nguyen, et al, Phys. Rev. **C 83** (2011) 062201

Predictions of the K/π Drell-Yan ratio based on Bethe-Salpeter Equations (BSE)

Pion to Kaon ratios

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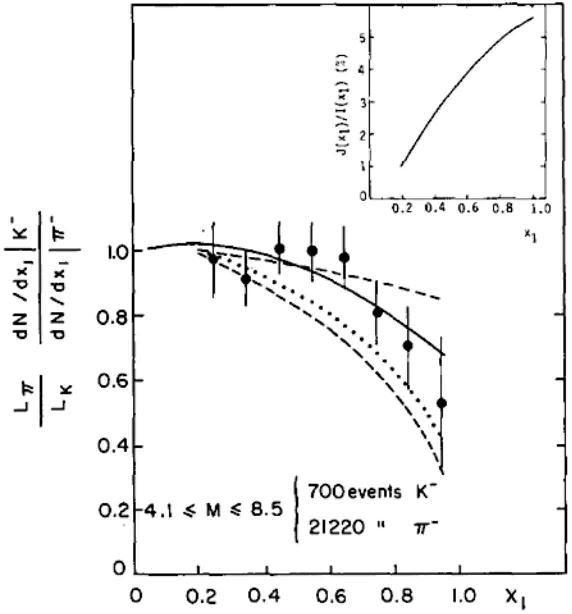

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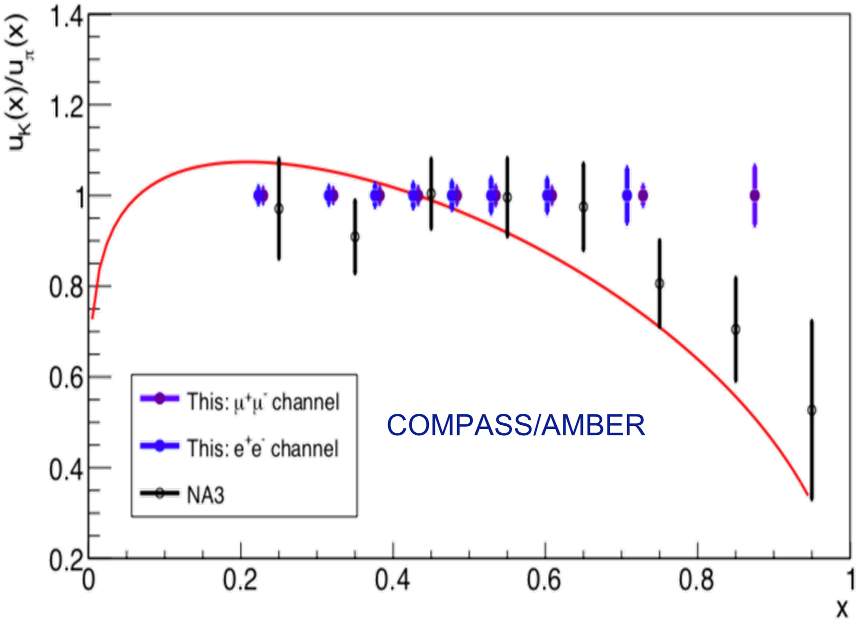
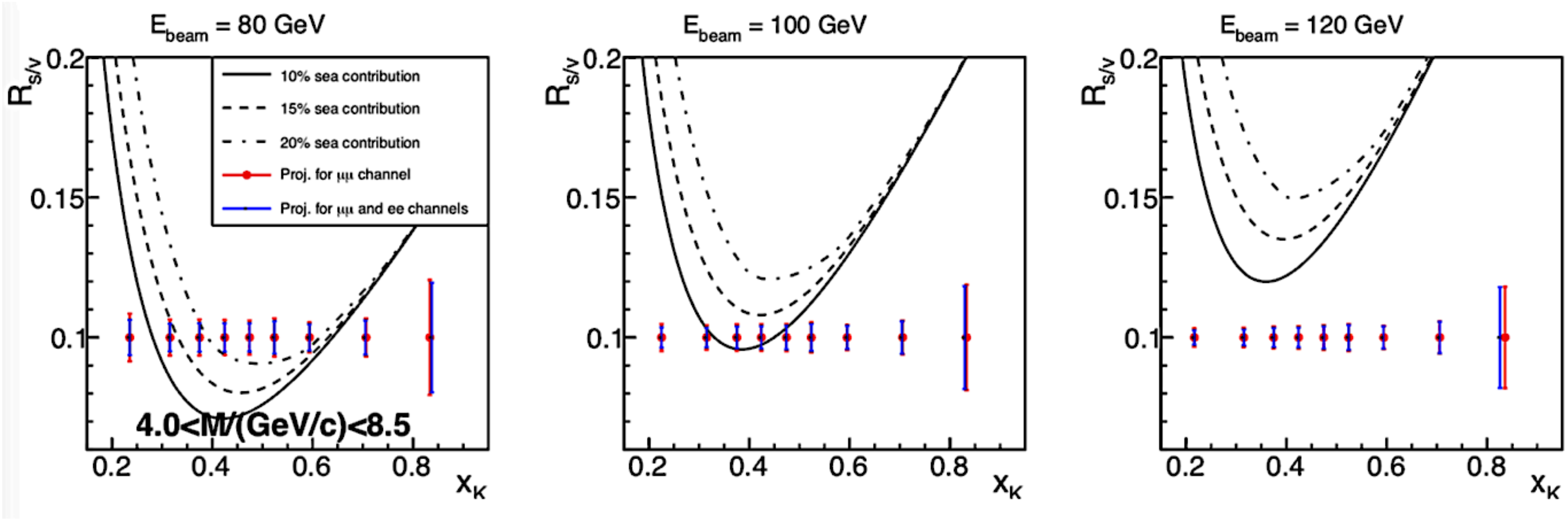


Predictions of the K/π Drell-Yan ratio based on Bethe-Salpeter Equations (BSE)

KAON DRELL-YAN
COMPASS++/AMBER

- Ratio of Valence to sea quarks in the Kaon



Argonne NATIONAL LABORATORY

THE EMERGENCE OF THE BIG PICTURE FROM TINY DOTS OF COLOR?

PAUL E REIMER
Physics Division
Argonne National Laboratory
18 November 2020

U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

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

Measurement Requests

Pion measurements are not enough!

Pion:

- π^- and π^+ Drell-Yan with attention to kinematic resolution (quark-antiquark)
- direct photons (gluon)
- J/ψ production (gluon)

Kaon:

- K$^-$ and K$^+$ Drell-Yan with attention to kinematic resolution (quark-antiquark)
- direct photons (gluon)
- J/ψ production (gluon)

$$|p\rangle = |p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle + c|\Lambda K\rangle \cdots$$

EIC Sulivan Process

- Leading neutron

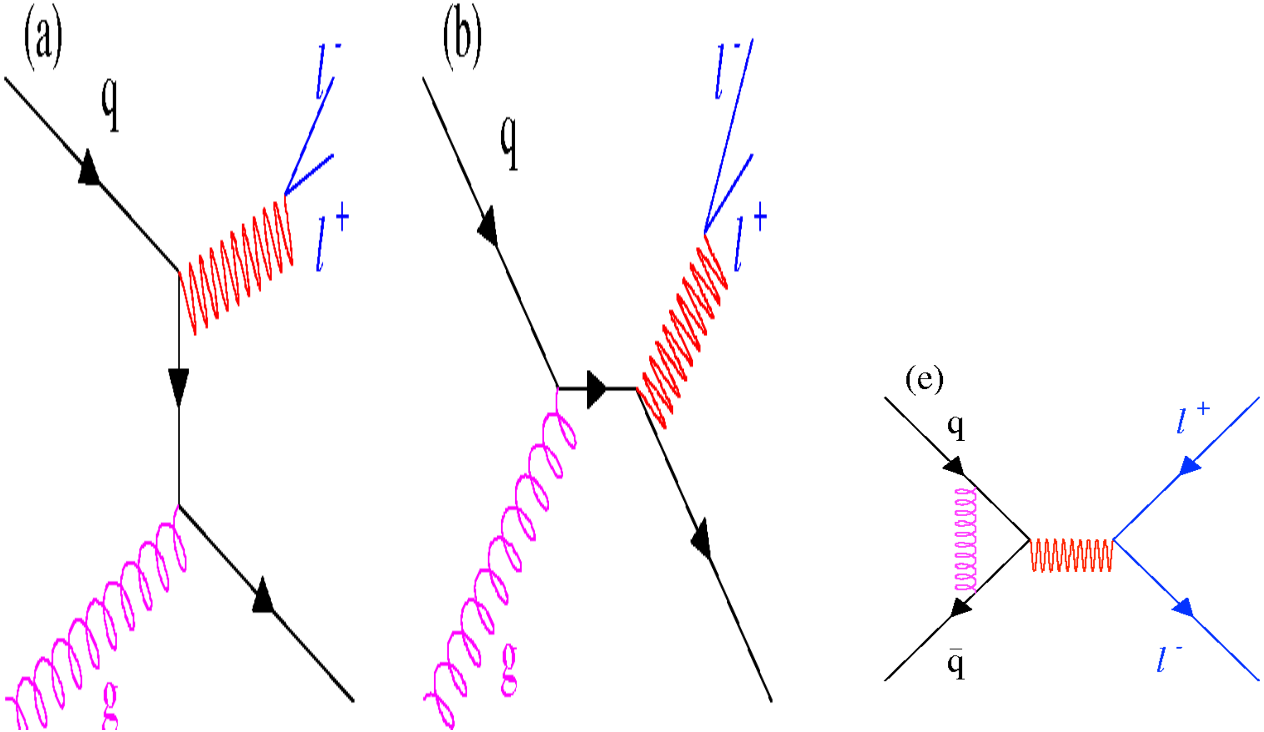
EIC Sulivan Process

- Leading Lambda

Ratios of K/π may be sufficient

Global analysis with demonstrated consistency

Extra stuff


(a)
q
l -
l +
g
(b)
q
l -
l +
g
(e)
q
q̄
l +
l -

BASIC CONTENT SLIDE

ONE OR TWO LINES FOR HEADLINE

$\pi^{\pm}$ $I^G(J^P) = 1^-(0^-)$

$\pi^{\pm}$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
139.57039±0.00018 OUR FIT	Error includes scale factor of 1.8.			

$K^{\pm}$ $I(J^P) = \frac{1}{2}(0^-)$

$K^{\pm}$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
493.677±0.016 OUR FIT	Error includes scale factor of 2.8.			

p $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

p MASS (MeV)

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
938.2720813±0.0000058	MOHR	16	RVUE	2014 CODATA value

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update

QUARKS

The *u*-, *d*-, and *s*-quark masses are estimates of so-called "current-quark masses," in a mass-independent subtraction scheme such as $\overline{\text{MS}}$ at a scale $\mu \approx 2$ GeV. The *c*- and *b*-quark masses are the "running" masses in the $\overline{\text{MS}}$ scheme. This can be different from the heavy quark masses obtained in potential models.

u $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$m_u = 2.16^{+0.49}_{-0.26}$ MeV Charge $= \frac{2}{3}\ e$ $I_z = +\frac{1}{2}$

$m_u/m_d = 0.47^{+0.06}_{-0.07}$

d $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$m_d = 4.67^{+0.48}_{-0.17}$ MeV Charge $= -\frac{1}{3}\ e$ $I_z = -\frac{1}{2}$

$m_s/m_d = 17\text{–}22$

$\overline{m} = (m_u+m_d)/2 = 3.45^{+0.55}_{-0.15}$ MeV

s $I(J^P) = 0(\frac{1}{2}^+)$

$m_s = 93^{+11}_{-5}$ MeV Charge $= -\frac{1}{3}\ e$ Strangeness $= -1$

$m_s\ /\ ((m_u + m_d)/2) = 27.3^{+0.7}_{-1.3}$

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u $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$m_u = 2.16^{+0.49}_{-0.26}$ MeV Charge $= \frac{2}{3}$ e $I_z = +\frac{1}{2}$

$m_u/m_d = 0.47^{+0.06}_{-0.07}$

d $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$m_d = 4.67^{+0.48}_{-0.17}$ MeV Charge $= -\frac{1}{3}$ e $I_z = -\frac{1}{2}$

$m_s/m_d = 17\text{–}22$

$\overline{m} = (m_u+m_d)/2 = 3.45^{+0.55}_{-0.15}$ MeV

s $I(J^P) = 0(\frac{1}{2}^+)$

$m_s = 93^{+11}_{-5}$ MeV Charge $= -\frac{1}{3}$ e Strangeness $= -1$

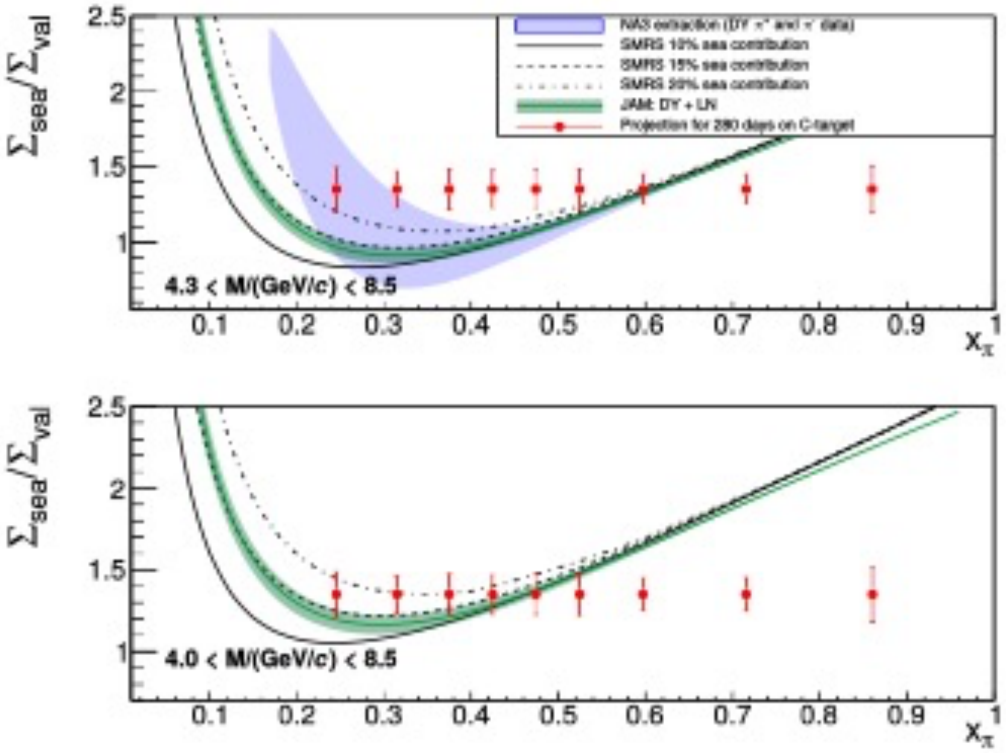
$m_s \;/\; ((m_u + m_d)/2) = 27.3^{+0.7}_{-1.3}$

LIGHT PIONS AND HEAVY KAONS AND PROTONS

Lattice challenges from AMBER 2024

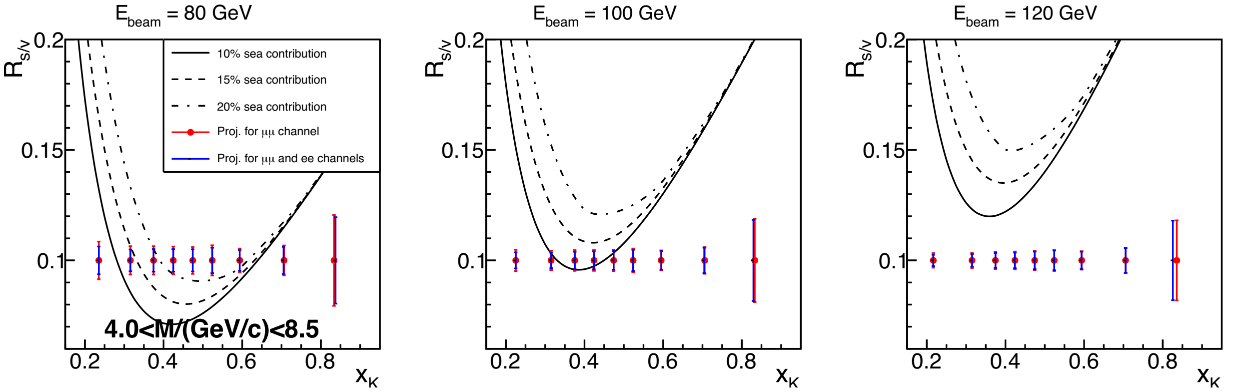
- What can the pion PDF's tell us about QCD mass emergence?

- What does a lattice-based calculation of a π-PDF mean with a M_π >= 300 MeV?



LIGHT PIONS AND HEAVY KAONS AND PROTONS

Lattice challenge
AMBER 2027



- What can the ratio of π
  us about mass, QCD a
- Or is a Kaon just a 500 MeV pion in a lattice?

Expected statistical uncertainty for Kaon sea to valence quark ratio.

Not Drell-Yan, but

- Gluon PDFs for pions and Kaons via prompt photon detection.