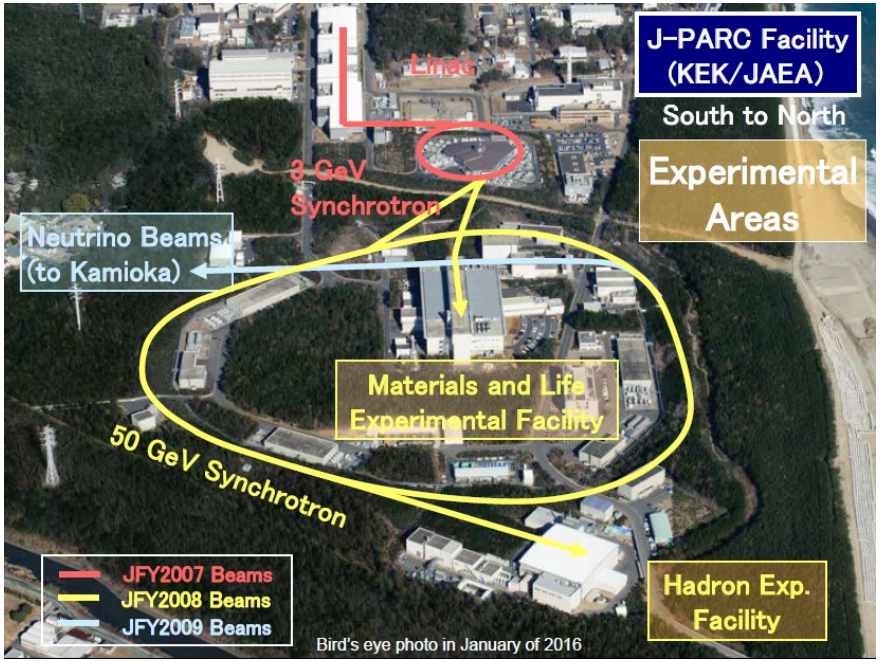
Dilepton Production with High Momentum Meson Beams at J-PARC

Jen-Chieh Peng

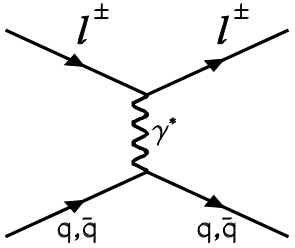
University of Illinois at Urbana-Champaign

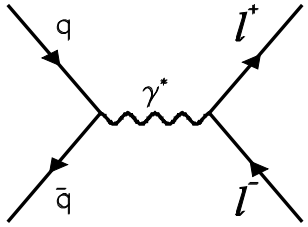
Reimei Symposium on "Synergies in Hadron Physics between J-PARC and JLab"
Jefferson Lab, November 5, 2019



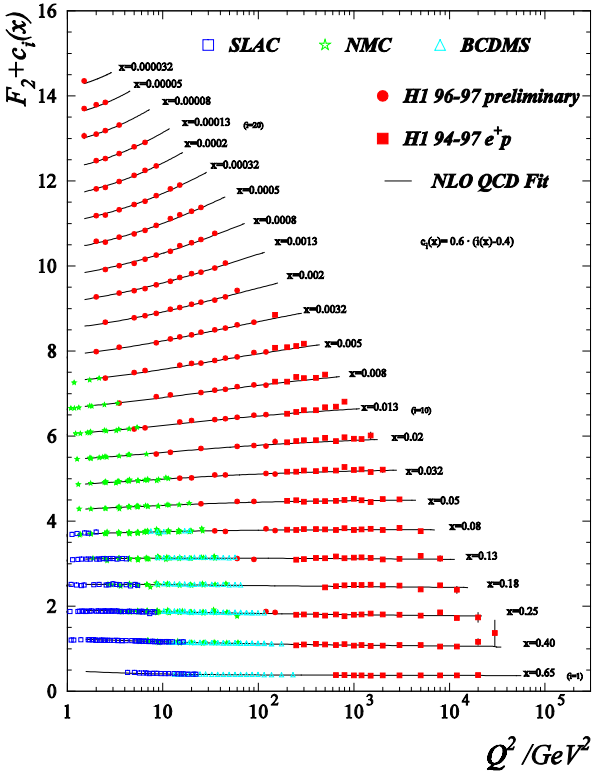
Complementality between DIS and Drell-Yan

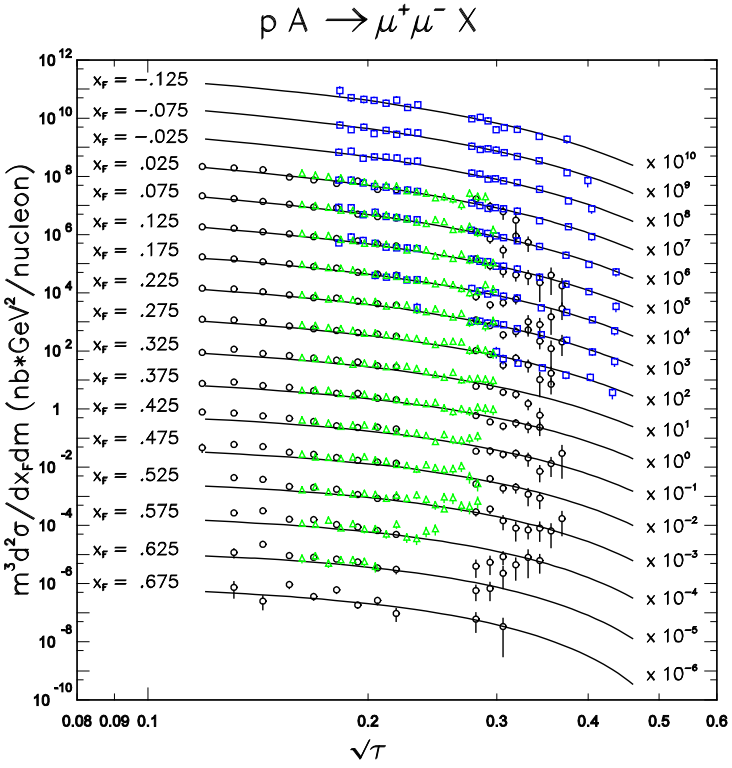
DIS





Drell-Yan





Ann.Rev.Nucl. Part. Sci. 49 (1999) 217;

Peng and Qiu, Prog. Part. Nucl. Phys. 76 (2014)43

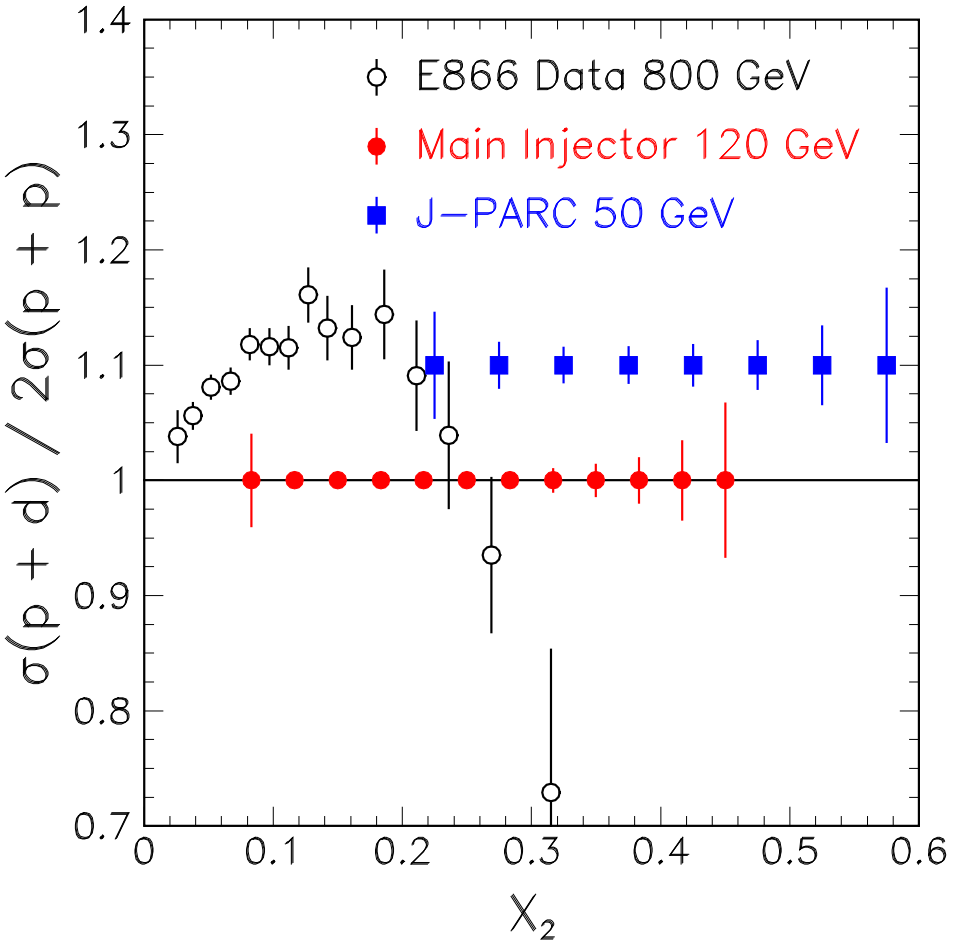
Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)

Challenges and opportunities of dilepton experiments at J-PARC

- Challenges
  - Beam energies are relatively low (30-50 GeV proton, and secondary pion, kaon, antiproton at lower energies)
- Opportunities
  - Very few existing data at this energy region
  - Some novel hadron physics topics could be well studied at relatively low energies
  - Polarized beam/target offers new possibilities

$\bar{d}/\bar{u}$ at large x?

J-PARC Proposal P-04 (Peng and Sawada)



10^{12} protons per spill (3 s)

50-cm long LH_2 / LD_2 targets

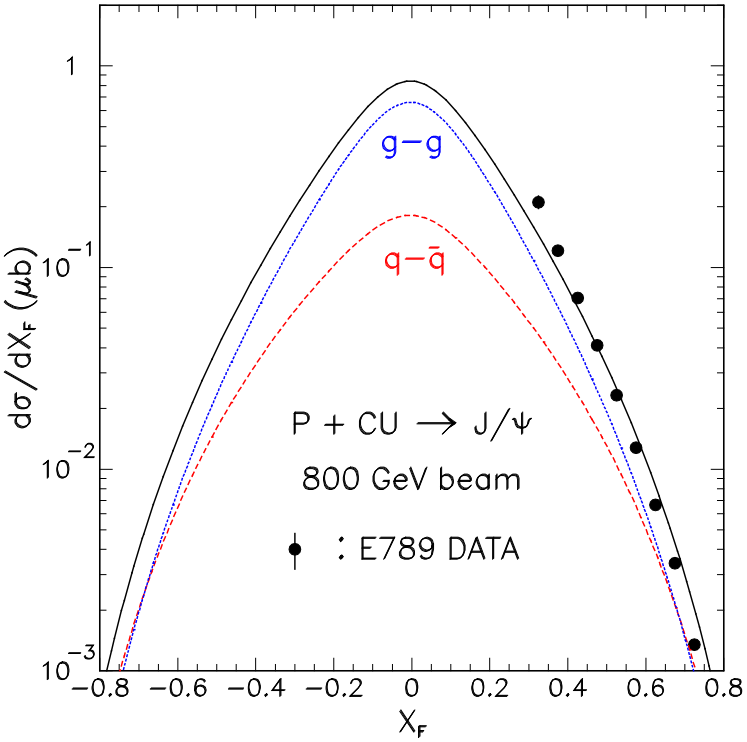
60-day runs for each targets

assuming 50% efficiency

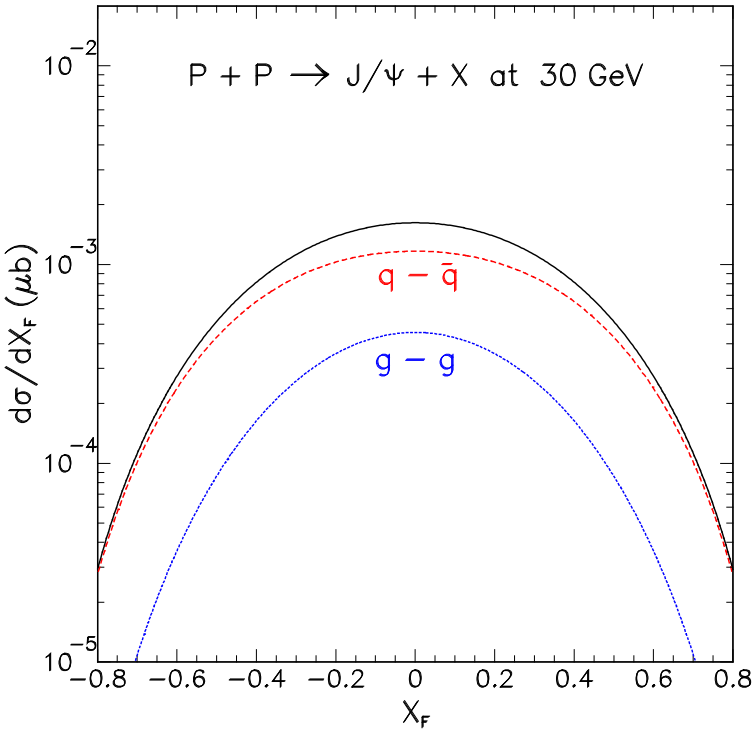
$p + p$ D-Y at 50 GeV also directly measure $\bar{u}$ at large x

J/Ψ Production at 30 GeV

At 800 GeV, J/Ψ production is dominated by gluon-gluon fusion



At 30 GeV J/Ψ production is dominated by quark-antiquark annihilation



J/Ψ production at 30 GeV is sensitive to quark and antiquark distributions

May be possible using the J-PARC high-momentum proton beam and the E16 spectrometer (designed for detecting e+ e- decay of Φ mesons)

Possible dilepton physics with pion beam

- $d(x)/u(x)$ at large x for proton
- Valence quark distribution of pion at large x
- Exclusive dilepton production to study nucleon GPD, pions distribution amplitude (DA) and pion-nucleon Transition Distribution Amplitude (TDA)
- Meson beams at J-PARC complement many hadron physics programs at JLab 12 GeV upgrade

Ratios of $d(x)/u(x)$ at large x?

$$|p\rangle \uparrow = \frac{1}{\sqrt{2}} u\uparrow (ud)_{S=0,S_Z=0} + \frac{1}{\sqrt{18}} u\uparrow (ud)_{S=1,S_Z=0} - \frac{1}{3} u\downarrow (ud)_{S=1,S_Z=1}$$

$$- \frac{1}{3} d\uparrow (uu)_{S=1,S_Z=0} + \frac{\sqrt{2}}{3} d\downarrow (uu)_{S=1,S_Z=1}$$

1) SU(6) symmetry

$$\frac{d}{u} = \frac{1}{2} \qquad \frac{F_2^n}{F_2^p} = \frac{2}{3}$$

2) Dominance of $S = 0$ diquark configurations (Close, Carlitz)

Ignoring terms with $S = 1$ diquarks, then

$$\frac{d}{u} = 0 \qquad \frac{F_2^n}{F_2^p} = \frac{1}{4}$$

2) Dominance of $S_Z = 0$ diquark configurations (Farrar, Jackson)

Ignoring terms with $S_Z = 1$ diquarks, then

$$\frac{d}{u} = \frac{1}{5} \qquad \frac{F_2^n}{F_2^p} = \frac{3}{7}$$

Measuring $d(x)/u(x)$ at large x with pion-induced Drell-Yan?

$\sigma_{DY}(\pi^- + p) \sim 4\bar{u}^{\pi^-}(x_1)u^p(x_2)$ for large x_1 and x_2

$\sigma_{DY}(\pi^+ + p) \sim \bar{d}^{\pi^+}(x_1)d^p(x_2)$ for large x_1 and x_2

hence

$$\frac{\sigma_{DY}(\pi^+ + p)}{\sigma_{DY}(\pi^- + p)} \sim \frac{\bar{d}^{\pi^+}(x_1)d^p(x_2)}{4\bar{u}^{\pi^-}(x_1)u^p(x_2)} \sim \frac{1}{4}\frac{d^p(x_2)}{u^p(x_2)}$$

No nuclear correction for deuteron is needed

However, there are no $\pi^+ + p$ Drell-Yan data yet !

Can one extract meson PDFs from J/Ψ production?

Difference between $(\pi^- + p)$ and $(\pi^+ + p)$ J/Ψ cross sections

$$\sigma_{J/\Psi}(\pi^- + p) \propto V_\pi(x_1)[u(x_2) + \bar{d}(x_2)] + S_\pi(x_1)[u(x_2) + d(x_2) + \bar{u}(x_2) + \bar{d}(x_2)]$$

$$\sigma_{J/\Psi}(\pi^+ + p) \propto V_\pi(x_1)[d(x_2) + \bar{u}(x_2)] + S_\pi(x_1)[u(x_2) + d(x_2) + \bar{u}(x_2) + \bar{d}(x_2)]$$

$$\sigma_{J/\Psi}(\pi^- + p) - \sigma_{J/\Psi}(\pi^+ + p) \propto V_\pi(x_1)[u_V(x_2) - d_V(x_2)]$$

Only the valence-quark term remains!

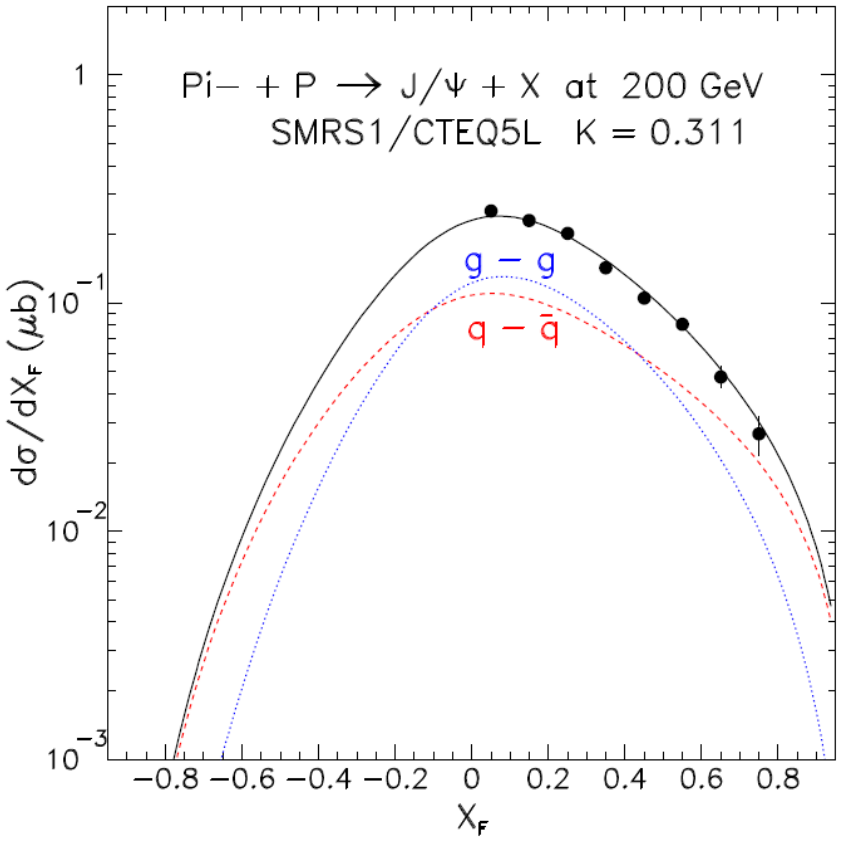
$\sigma_{J/\Psi}(\pi^- + p) - \sigma_{J/\Psi}(\pi^+ + p)$ is positive

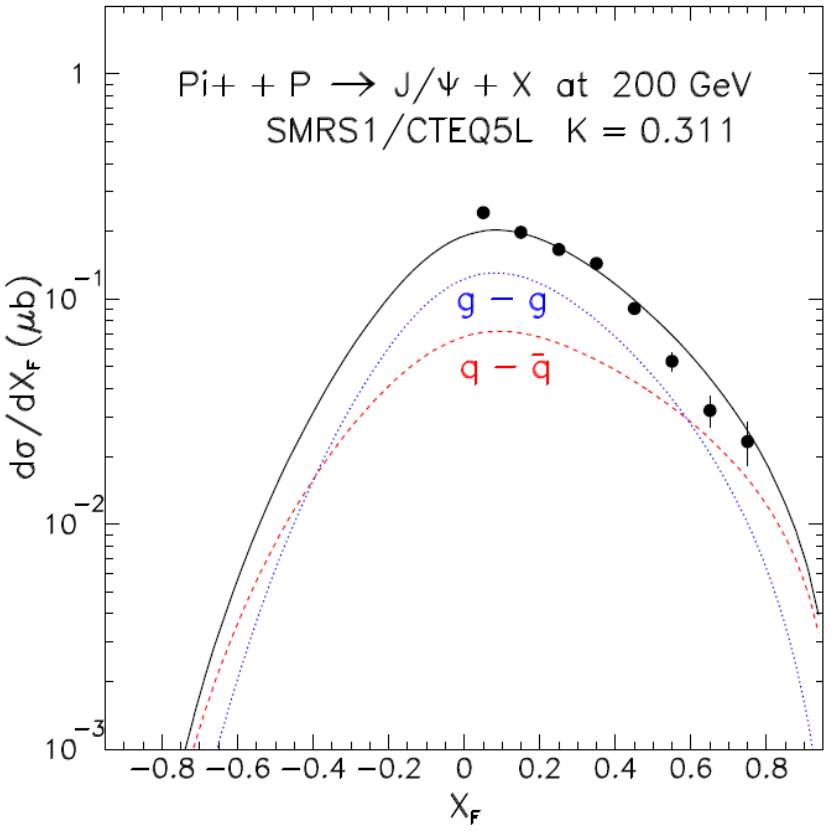
Directly proportional to $u_V(x_2) - d_V(x_2)$

Directly proportional to $V_\pi(x_1)$

Are there relevant data already?

Data from the NA3 paper and Ph.D thesis

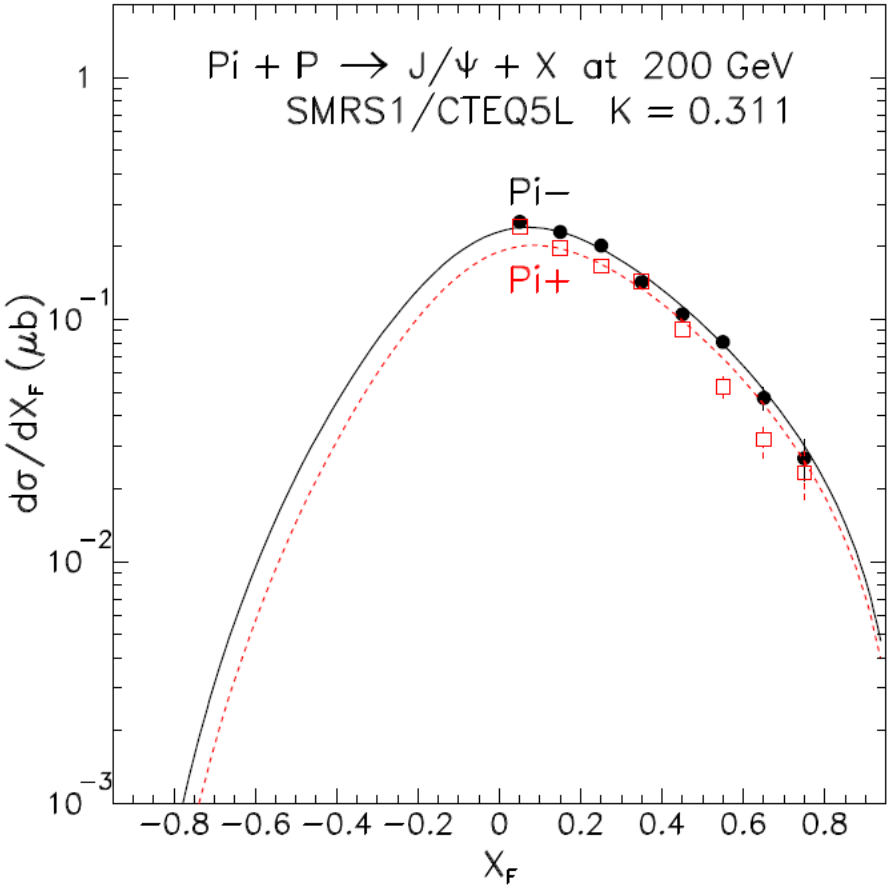




Calculations using Color Evaporation Model

$g-g$ fusion is the same for both, but $q-\bar{q}$ annihilation is larger for $\pi^- + p$ than for $\pi^- + p$

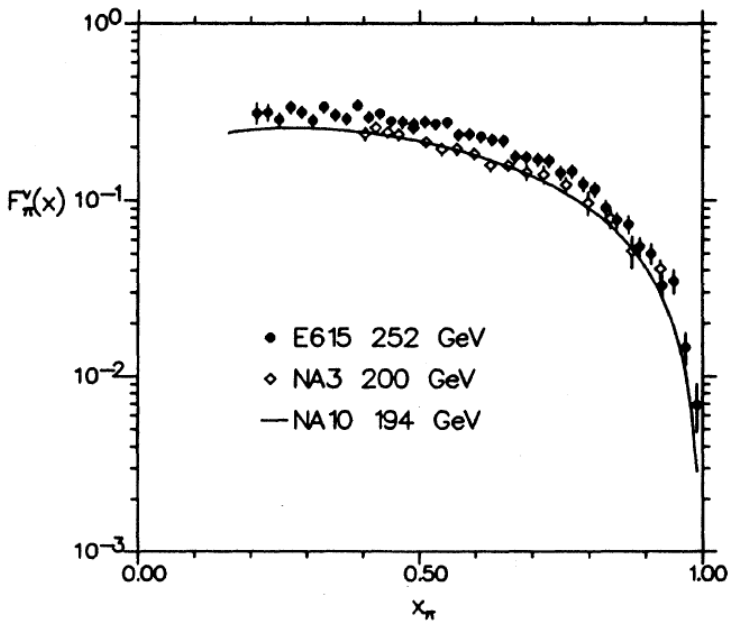
Comparison between the NA3 data and CEM calculations based on current pion and nucleon PDFs

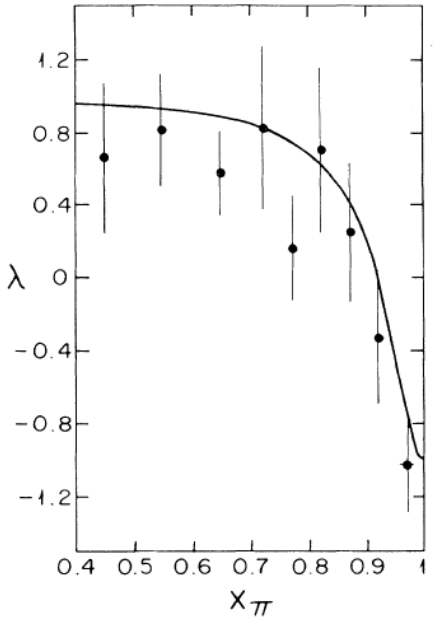


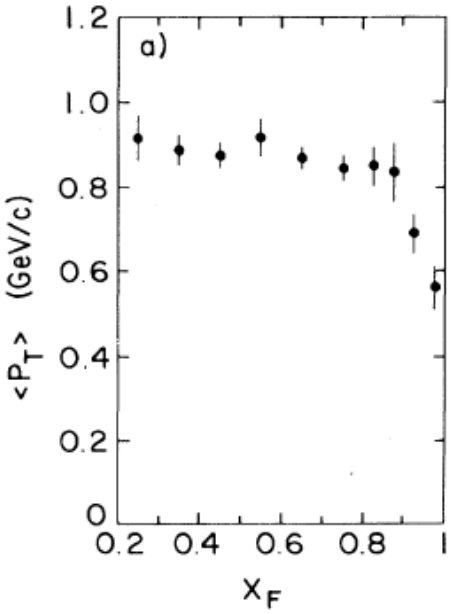
$$\sigma_{J/\Psi}(\pi^- + p) - \sigma_{J/\Psi}(\pi^+ + p) \propto V_\pi(x_1)[u_V(x_2) - d_V(x_2)]$$

Sensitive to $V_\pi(x_1)$ and $u_V(x_2) - d_V(x_2)$

Measure Meson PDF with Drell-Yan Process







- Valence distribution at large *x* (comparison with Dyson-Schwinger Equation calculation)
- Polarization of virtual photon at large *x* (transition from transverse to longitudinal polarization?)
- Modification of p_T distribution at large *x*?

Being pursued at COMPASS

Exclusive Drell-Yan measurements at J-PARC?

- Exclusive Drell-Yan with meson and antiproton beams are the time-like processes complementary to the deeply virtual meson production at Jlab, HERMES and COMPASS
- Exclusive Drell-Yan with meson beam at J-PARC will also complement the program at FAIR using antiproton beam

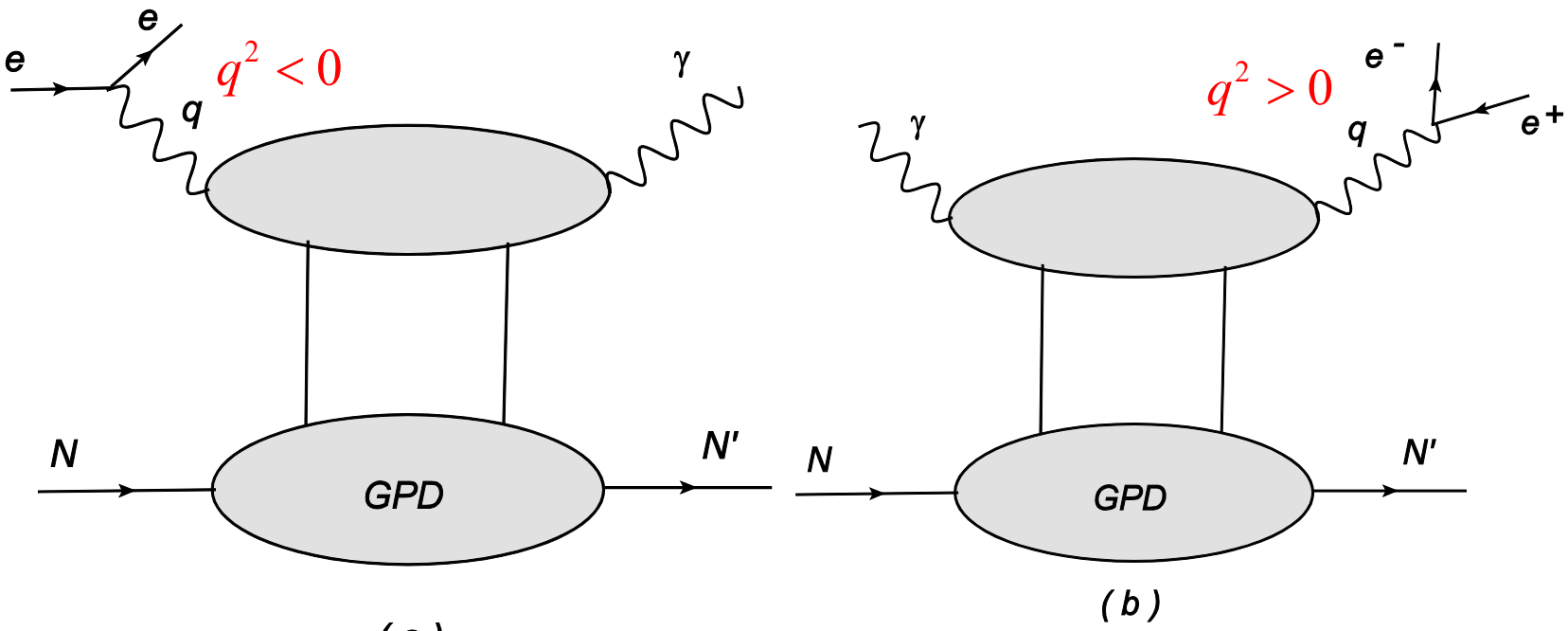
DVCS versus time-like Compton scattering

$$\gamma^* + N \to \gamma + N$$

Deeply Virtual Compton Scattering

$$\gamma + N \to \gamma^* + N$$

Timelike Compton Scattering

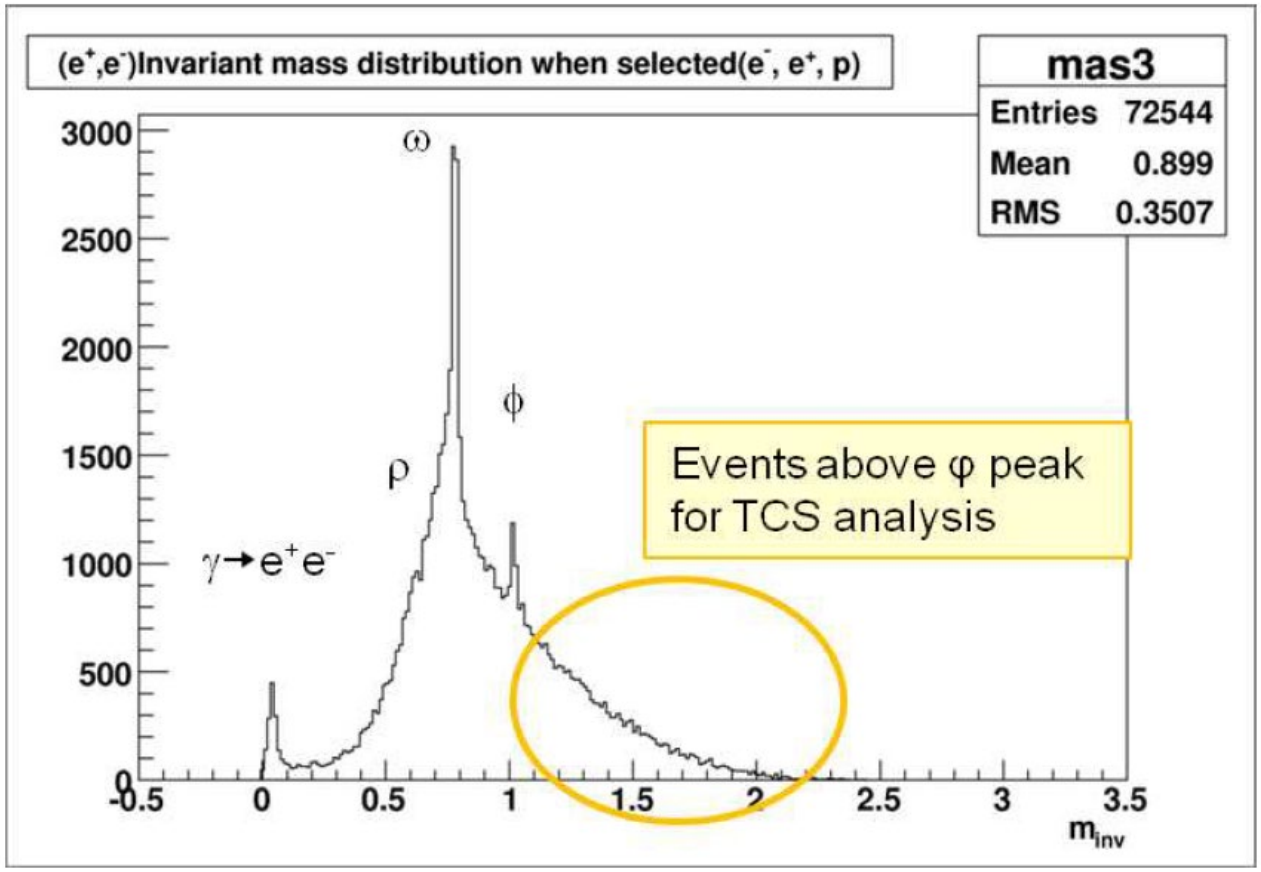


$$\mathcal{F}(\xi = \eta, t, \mathcal{Q}^2) \overset{\text{SL}\to\text{TL}}{\Rightarrow} \mathcal{F}(\xi = -\eta, t, -\mathcal{Q}^2),$$

$$\mathcal{F}(\xi, t, \mathcal{Q}^2) = \int_{-1}^{1} dx \sum_{i=u,d,\cdots,g} {}^{S}T^i(x, \xi) F^i(x, \xi, t, \mu^2),$$

Time-like Compton Scattering at JLab

$$\gamma + p \rightarrow e^+ + e^- + p$$

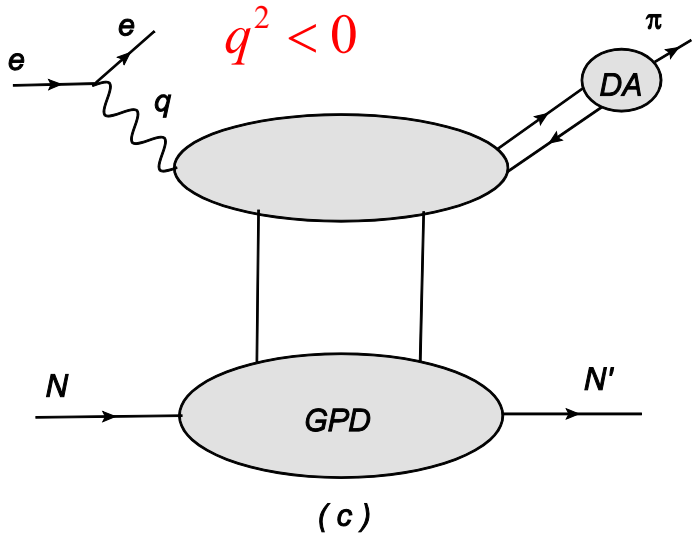


T. Horn et al, AIP Conf. Proc. 1374 (2011) 542

DEMP versus exclusive dilepton production

$$\gamma^* + N \rightarrow \pi + N'$$

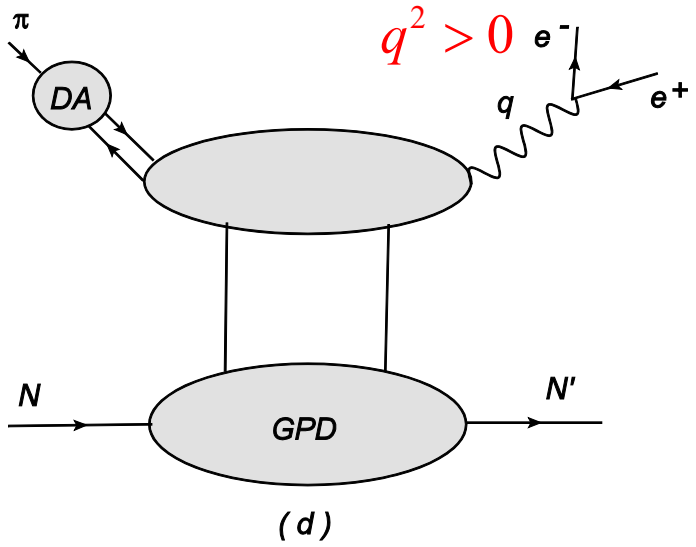
Deep Exclusive Meson Production



space-like photon

$$\pi + N \rightarrow \gamma^* + N'$$

Exclusive Dilepton Production

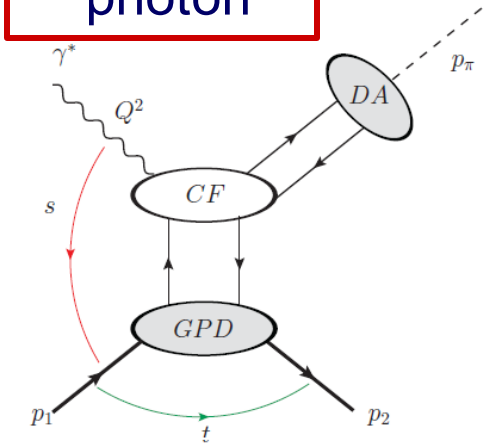


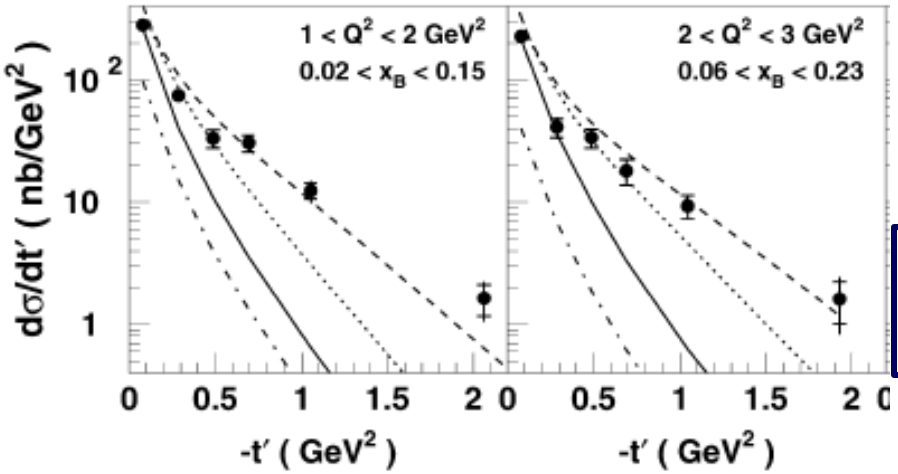
time-like photon

DEMP from JLab and HERMES

Space-like photon

Forward-angle $\gamma^* p \to \pi^+ n$ with 27.6 GeV $e^{\pm}$

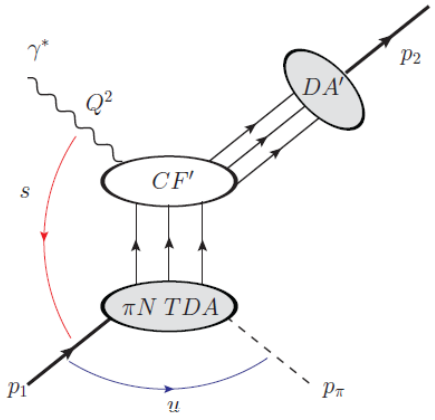


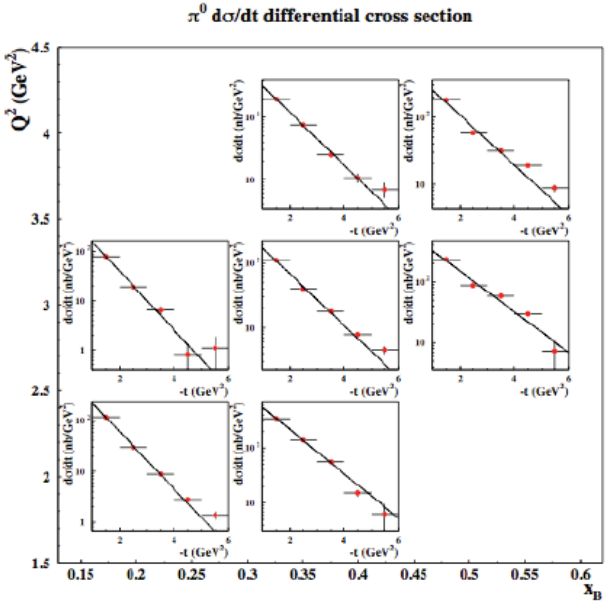


Hermes, Phys. Lett. B659 (2008) 486

Sensitive to pion's DA and nucleon's GPD

Backward-angle $\gamma^* p \to \pi^0 \mathrm{p}$ with 5.75 GeV e^-





CLAS, AIP 1560 (2013) 576

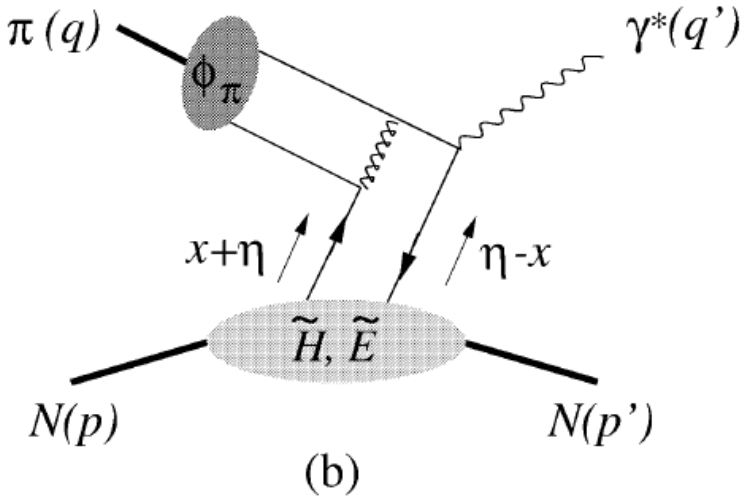
Sensitive to nucleon's DA and πN TDA

Exclusive dilepton production in πN interaction

$$\pi^- p \to \gamma^* n \to \mu^+ \mu^- n$$

E. Berger, M. Diehl, B. Pire, Phys. Lett. B523 (2001) 265

Probe pion distribution amplitude (ϕ_π) and nucleon GPD ($\tilde{H}, \tilde{E}$)



(b)

Bjorken variable $\tau = \frac{Q'^2}{s - M^2}$

skewness $\eta = \frac{(p-p')^+}{(p+p')^+} = \frac{\tau}{2-\tau}$

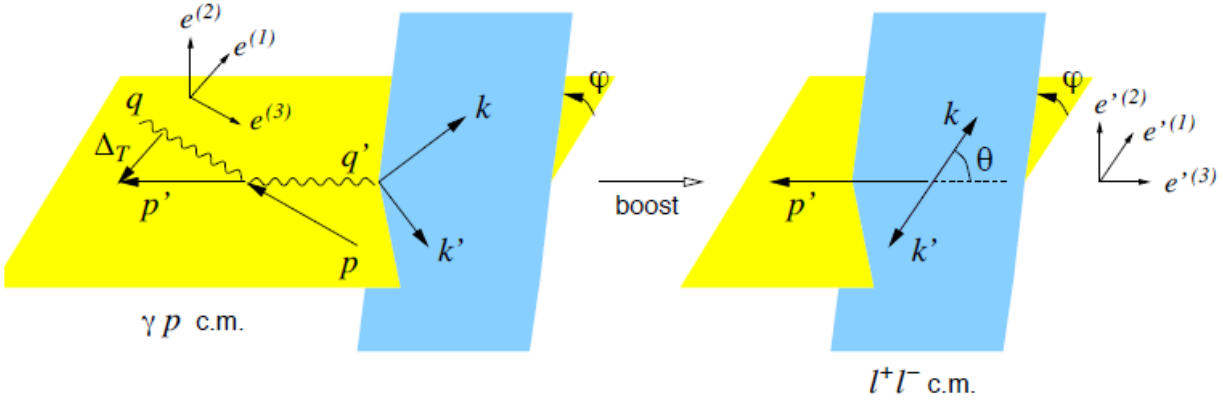
$$\frac{d\sigma}{dQ'^2\, dt\, d(\cos\theta)\, d\varphi} = \frac{\alpha_{em}}{256\,\pi^3}\frac{\tau^2}{Q'^6}\sum_{\lambda',\lambda}|M^{0\lambda',\lambda}|^2 \sin^2\theta$$

$$M^{0\lambda',\lambda}(\pi^- p \to \gamma^* n) = -ie\frac{4\pi}{3}\frac{f_\pi}{Q'}\frac{1}{(p+p')^+}\bar{u}(p',\lambda')\left[\gamma^+\gamma_5\,\tilde{\mathcal{H}}^{du}(\eta,t) + \gamma_5\frac{(p'-p)^+}{2M}\,\tilde{\mathcal{E}}^{du}(\eta,t)\right]u(p,\lambda)$$

$$\tilde{\mathcal{H}}^{du}(\eta,t) = \frac{8\alpha_S}{3}\int_{-1}^{1} dz\,\frac{\phi_\pi(z)}{1-z^2}\int_{-1}^{1} dx\left[\frac{e_d}{-\eta-x-i\epsilon} - \frac{e_u}{-\eta+x-i\epsilon}\right]\left[\tilde{H}^d(x,\eta,t) - \tilde{H}^u(x,\eta,t)\right]$$

Longitudinally polarized dilepton is expected

$$\pi^- p \to \gamma^* n \to \mu^+ \mu^- n$$

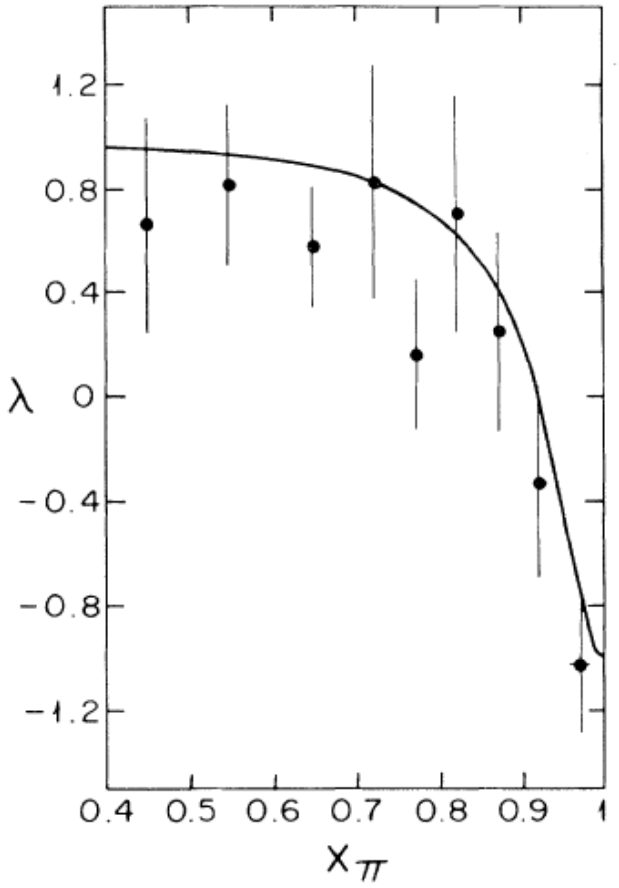


$$\frac{d\sigma}{dQ'^2\, dt\, d(\cos\theta)\, d\varphi} = \frac{\alpha_{\rm em}}{256\,\pi^3}\,\frac{\tau^2}{Q'^6}\,\Sigma_{\lambda',\lambda}\,|M^{0\lambda',\lambda}|^2 \sin^2\theta$$

Crucial Test of the validity of the twist expansion

Transversely polarized dilepton for inclusive Drell-Yan

Evidence for longitudinally polarized dilepton in meson-induced Drell-Yan at large x?



$$\frac{d\sigma}{d\Omega} \propto (1+\lambda\cos^2\theta)$$

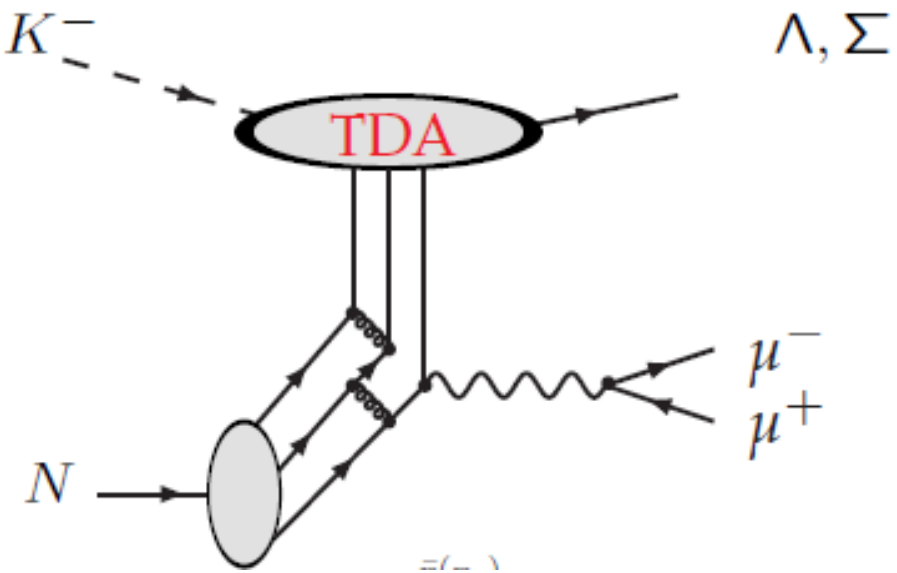
$\lambda = 1$: transversely polarized

$\lambda = -1$: longitudinally polarized

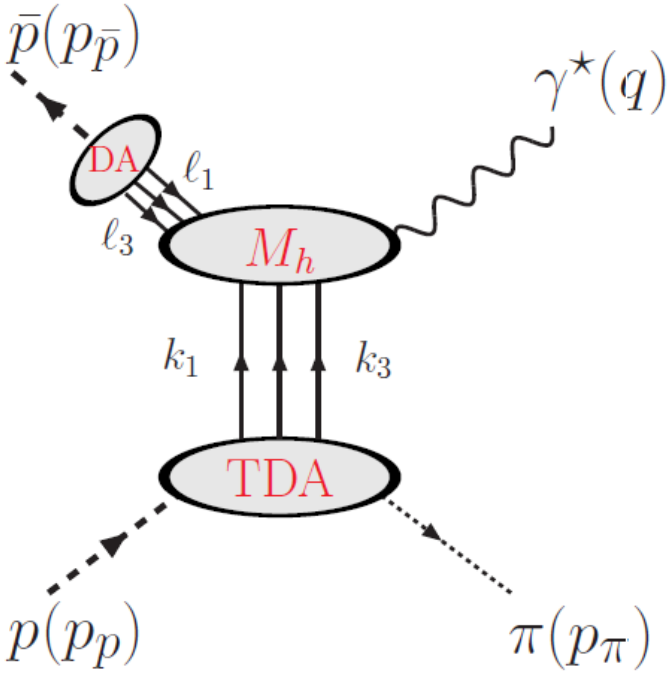
As $x_\pi \to 1$, inclusive Drell-Yan becomes exclusive dilepton!

Other exclusive dilepton reactions sensitive to meson-baryon TDA

$K^- N \to \Lambda \gamma^*$



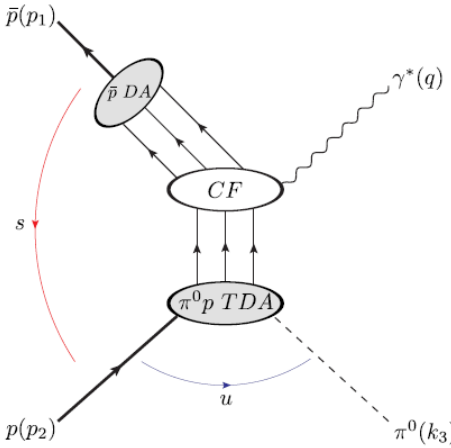
$\bar{p}N \to \gamma^* \pi$

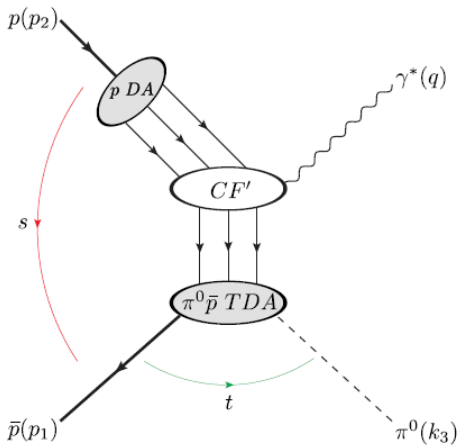


Experimental access to Transition Distribution Amplitudes with the $\bar{\text{P}}$ANDA experiment at FAIR

EPJ A51 (2015) 107

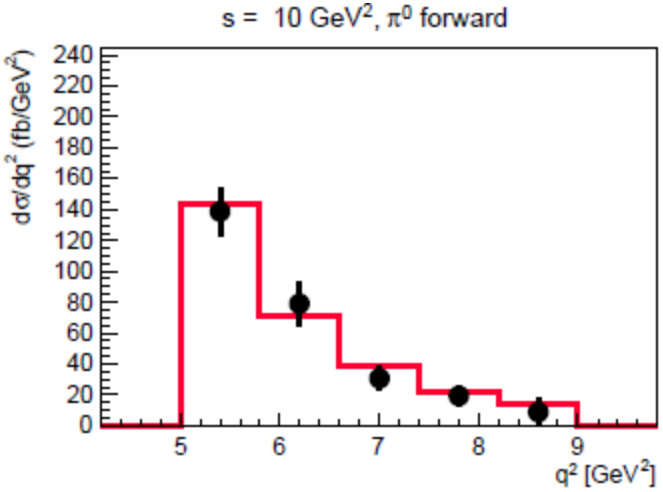
The $\bar{\text{P}}$ANDA Collaboration

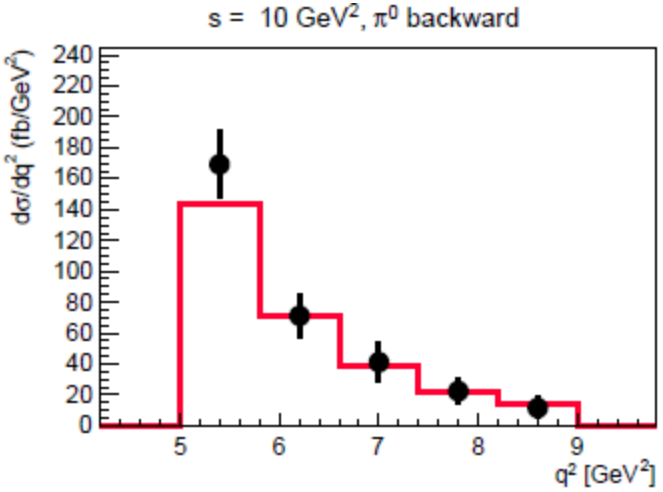




$$\bar{p}p \to \pi^0 e^+ e^-$$

at PANDA



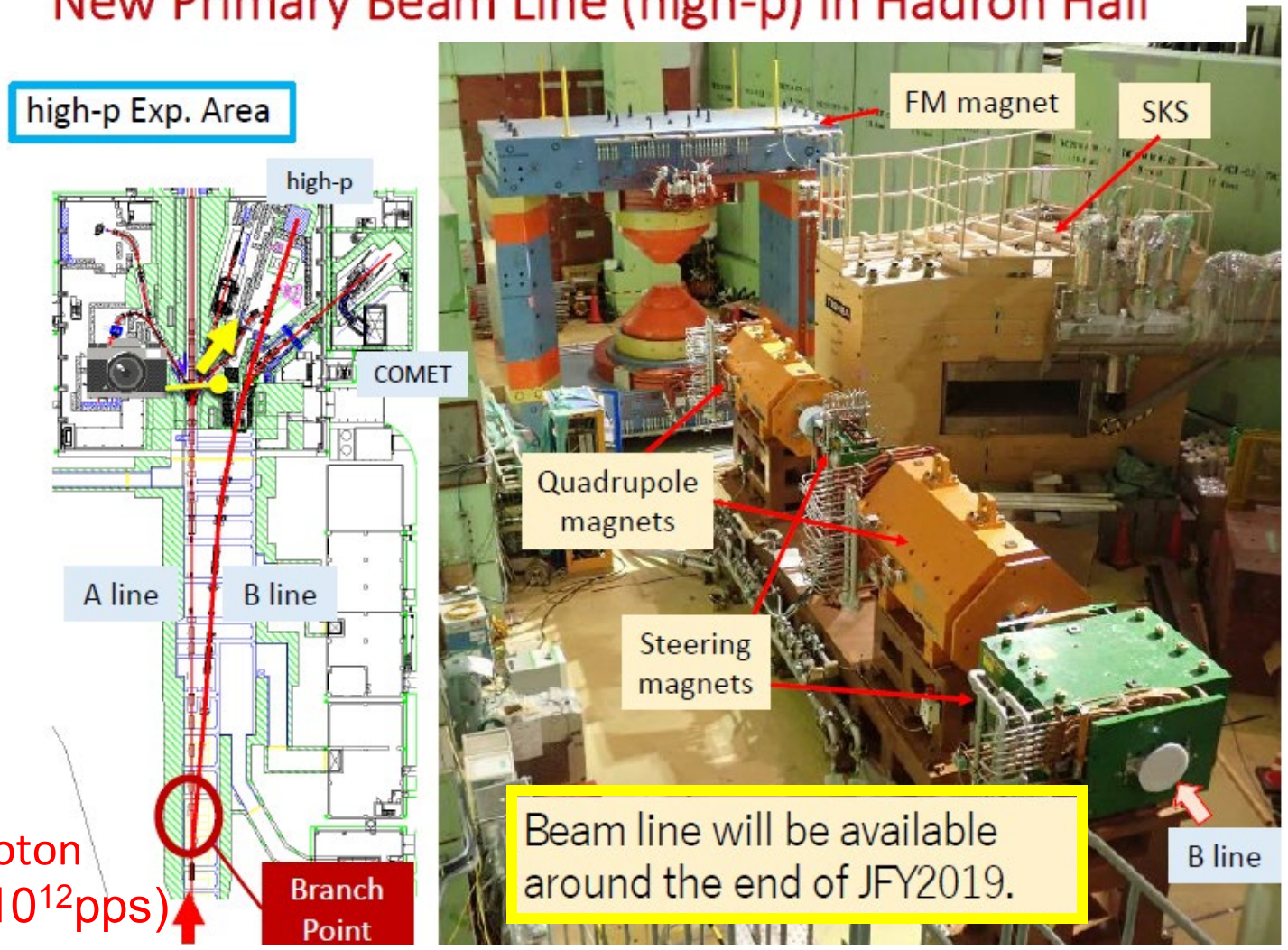


Can also be measured at J-PARC

J-PARC High-momentum Beam Line (Hi-P BL)

[S. Sawada, Pacific Spin 2019]

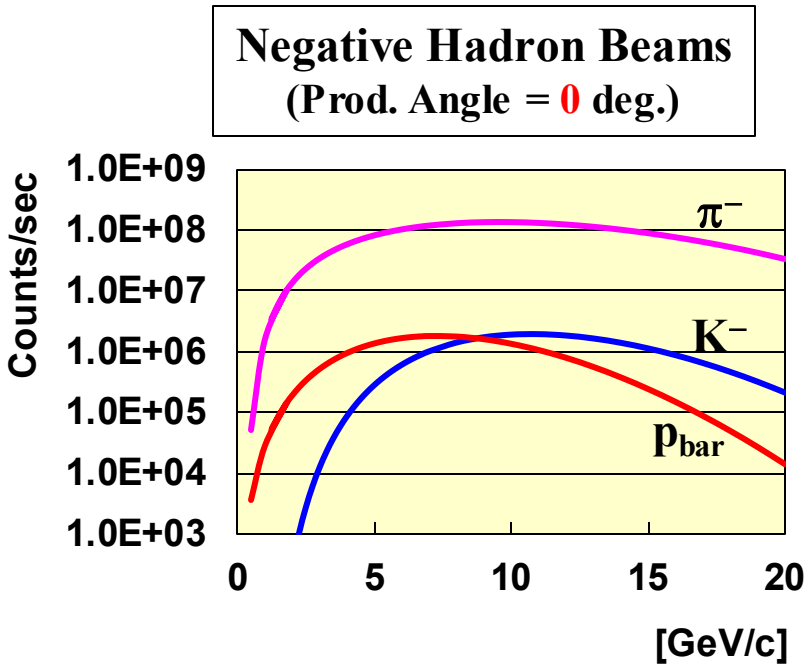
New Primary Beam Line (high-p) in Hadron Hall

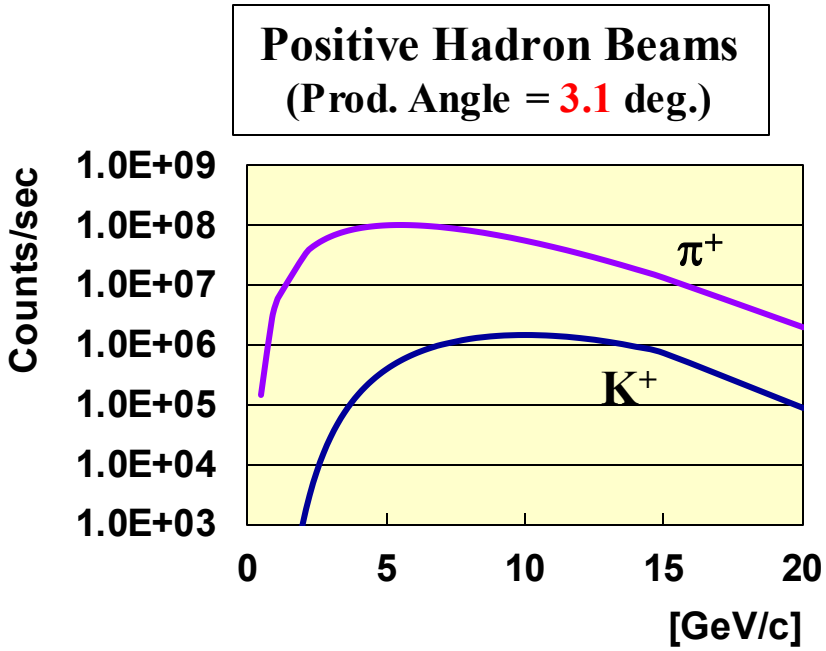


30 GeV proton
(~10^{10} – 10^{12}pps)

Unseparated Secondary Beam In High-momentum Beam Line

- High-intensity secondary Pion beam of [5,15] GeV
- High-resolution beam: Δp/p ~ 0.1%

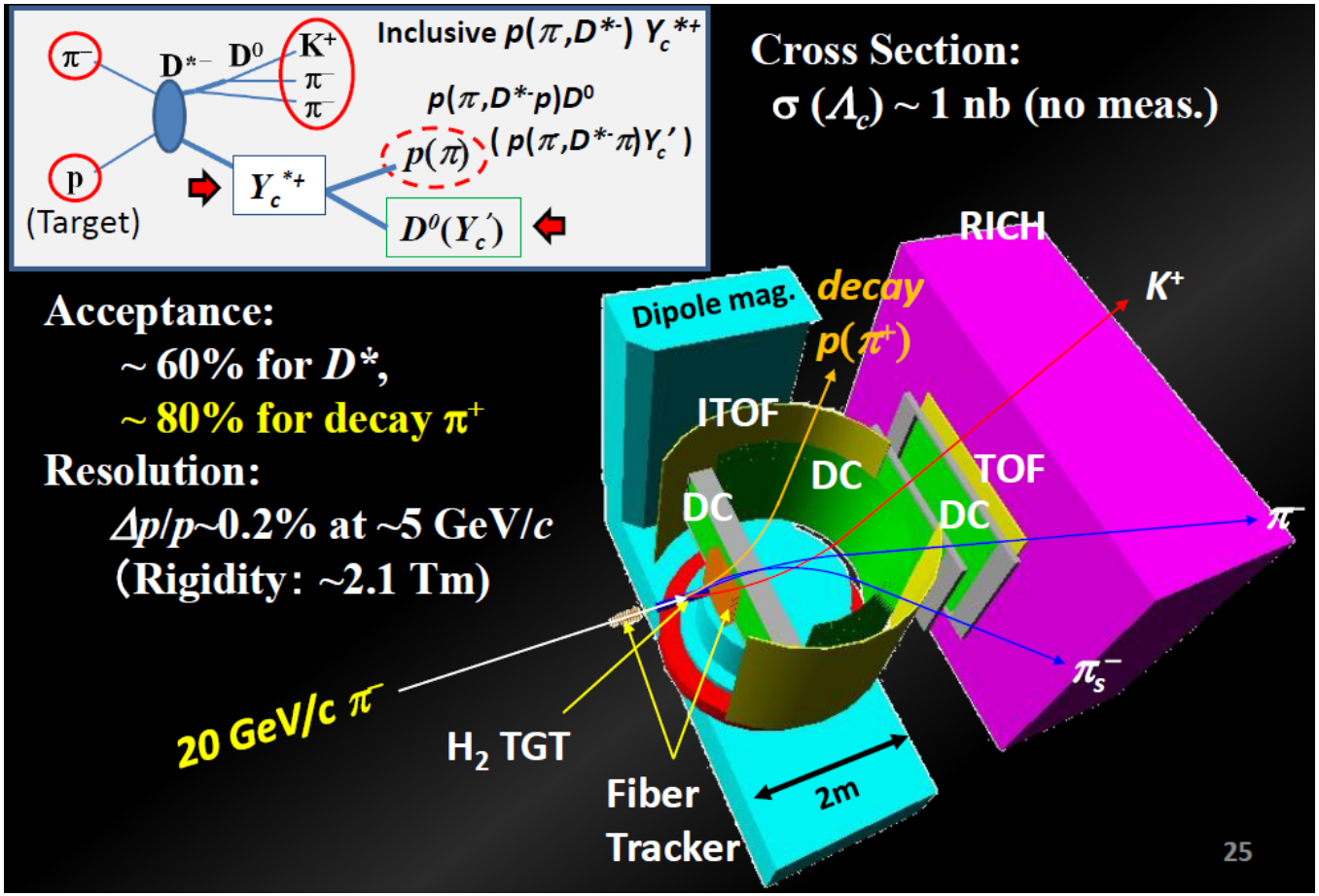




*** Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m**

J-PARC E50 Experiment
(Charmed Baryon Spectroscopy)

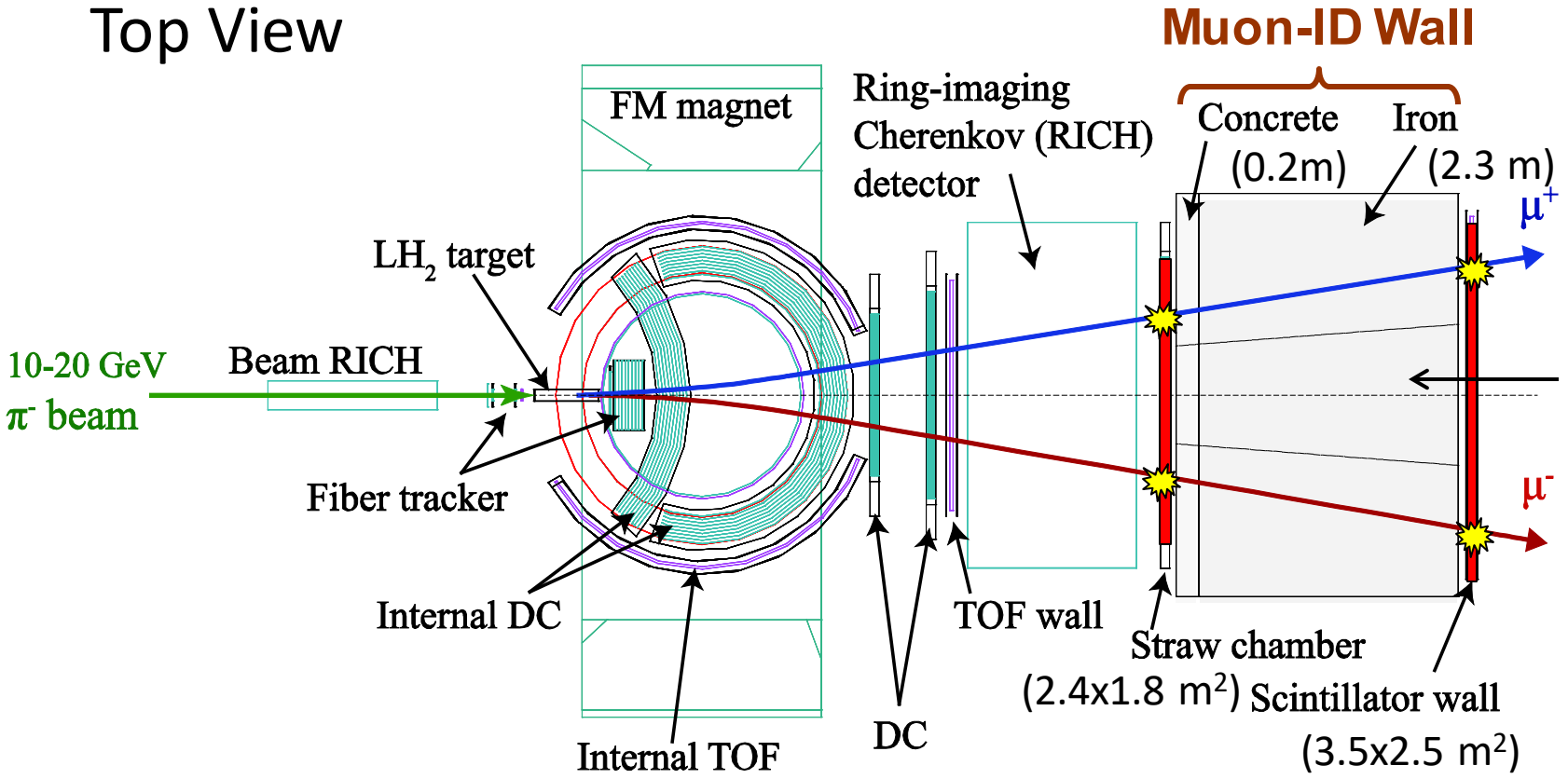
Stage-1 approved by J-PARC PAC-18, August 12, 2014.



From H. Noumi

Exclusive Drell-Yan measurement in J-PARC E50 Spectrometer

Top View



Original Configuration
for Charmed Baryon Spectroscopy

Stage-1 approved by J-PARC PAC-18, August 12, 2014.

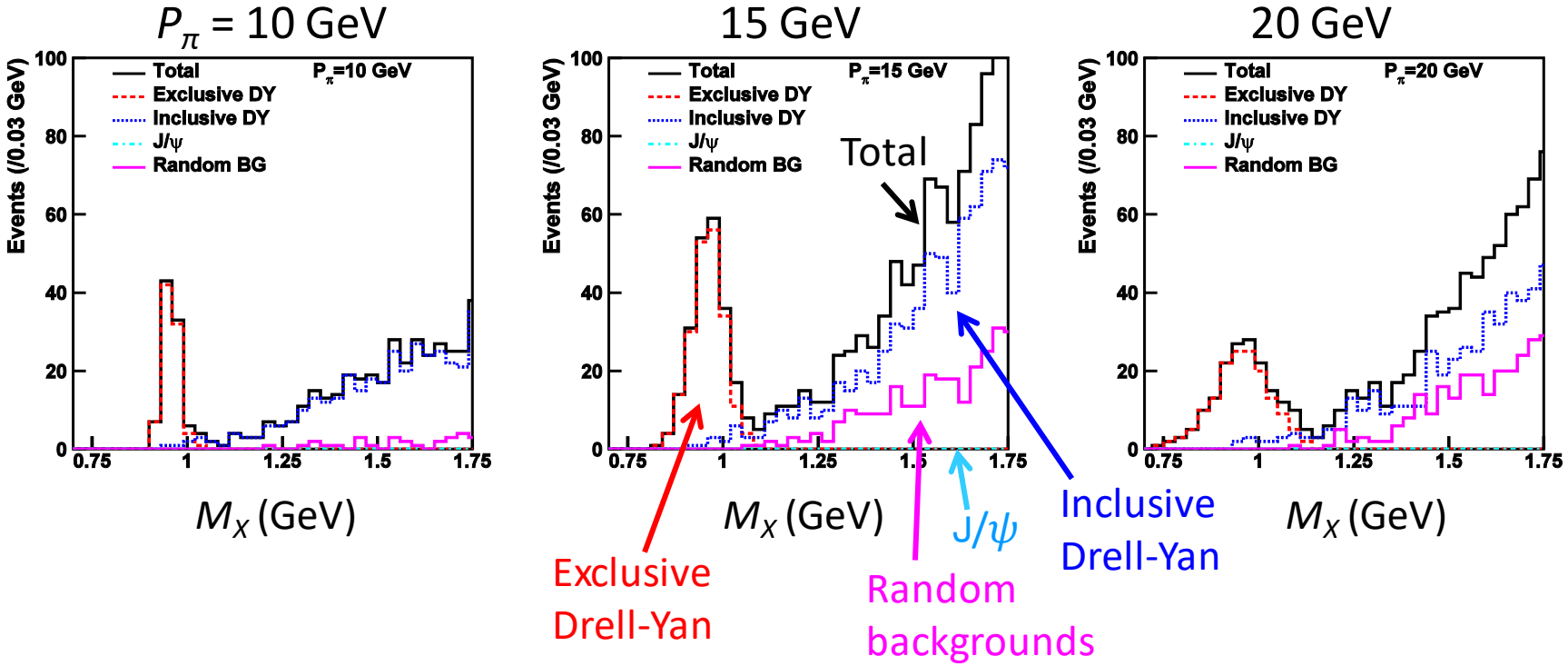
Extension part

Proposal is currently being prepared.

Missing-mass M_X spectra

Takahiro Sawada, Wen-Chen Chang, Shunzo Kumano, Jen-Chieh Peng, Shinya Sawada, Kazuhiro Tanaka, Phys. Rev. D93 (2016) 114034

π^- Beam Momentum



- Data Taking: 50 days
- $1.5 < M_{\mu^+\mu^-} < 2.9$ GeV
- $|t - t_0| < 0.5$ GeV^2
- "GK2013" GPDs

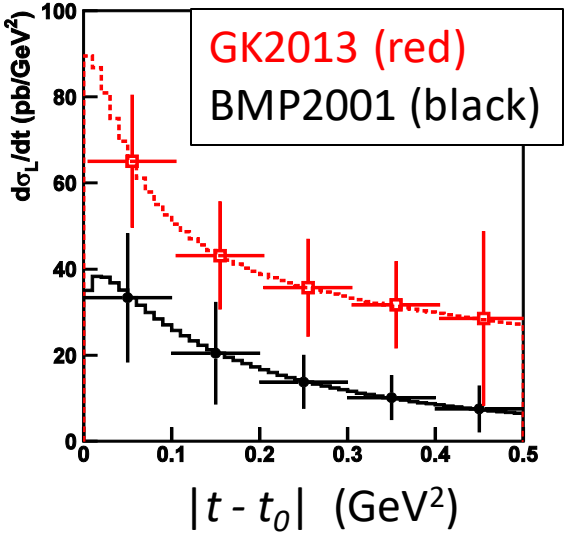
The exclusive Drell-Yan events could be identified by the signature peak at the nucleon mass in the missing-mass spectrum for all three pion beam momenta.

Expected Statistical Sensitivity

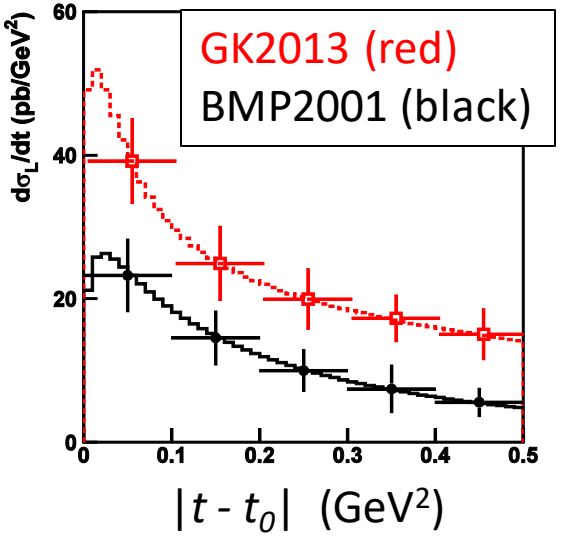
Takahiro Sawada, Wen-Chen Chang, Shunzo Kumano, Jen-Chieh Peng, Shinya Sawada, Kazuhiro Tanaka, Phys. Rev. D93 (2016) 114034

π^- Beam Momentum

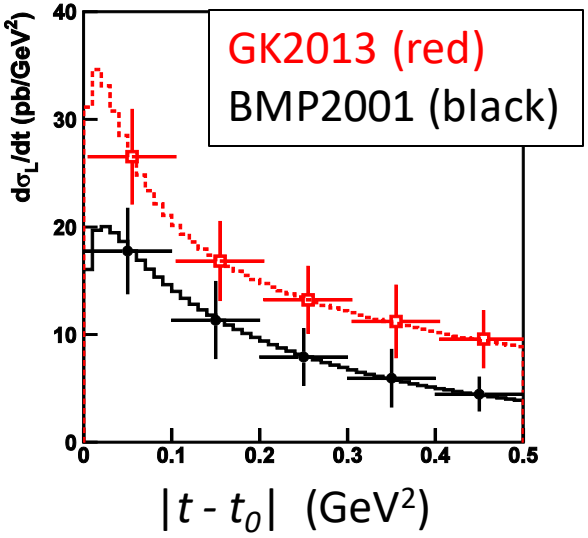
P_π = 10 GeV



15 GeV



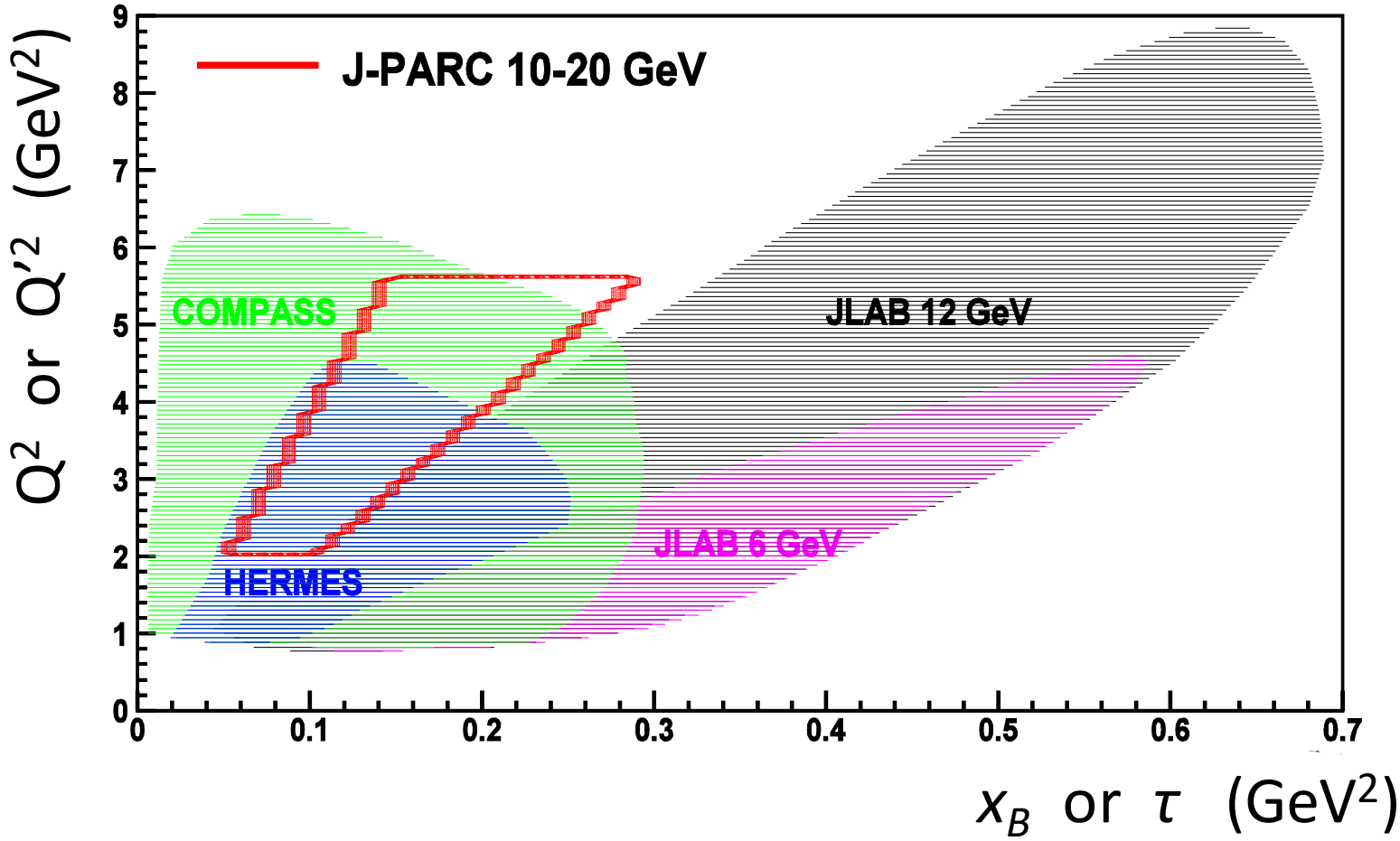
20 GeV



- Data Taking: 50 days
- $1.5 < M_{\mu^+\mu^-} < 2.9$ GeV
- $|t - t_0| < 0.5$ GeV^2

The statistics sensitivity is good enough for discriminating the predictions from two current GPD models.

Kinematic regions of GPDs explored by space-like and time-like processes



- JLAB, HERMES, COMPASS → Space-like approach
- J-PARC → **Time-like** approach

LETTER OF INTENT

Studying Generalized Parton Distributions with Exclusive Drell-Yan process at J- PARC

JungKeun Ahn,[1] Sakiko Ashikag,[2] Wen-Chen Chang,[3,*] Seonho Choi,[4] Stefan Diehl,[5] Yuji Goto,[6] Kenneth Hicks,[7] Youichi Igarashi,[8] Kyungseon Joo,[5] Shunzo Kumano,[9,10] Yue Ma,[6] Kei Nagai,[3] Kenichi Nakano,[11] Masayuki Niiyama,[12] Hiroyuki Noumi,[13,8,†] Hiroaki Ohnishi,[14] Jen-Chieh Peng,[15] Hiroyuki Sako,[16] Shin'ya Sawada,[8,‡] Takahiro Sawada,[17] Kotaro Shirotori,[13] Kazuhiro Tanaka,[18,10] and Natsuki Tomida[13]

A total of 23 collaborators from Japan, Korea, U.S. and Taiwan

Submitted to the 27th J-PARC PAC, Jan. 16th - 18th 2019

Summary

- High momentum beam line at J-PARC offer interesting opportunities to explore meson and nucleon structures (PDF, GPD, DA, TDA) through inclusive and exclusive dilepton production.
- Exclusive reactions using meson beams at J-PARC complement JLab 12 GeV and FAIR hadron physics program.
- First measurements appear feasible using the proposed E50 spectrometer. Further studies are required.