Exclusive Drell-Yan for studying GPDs at J-PARC

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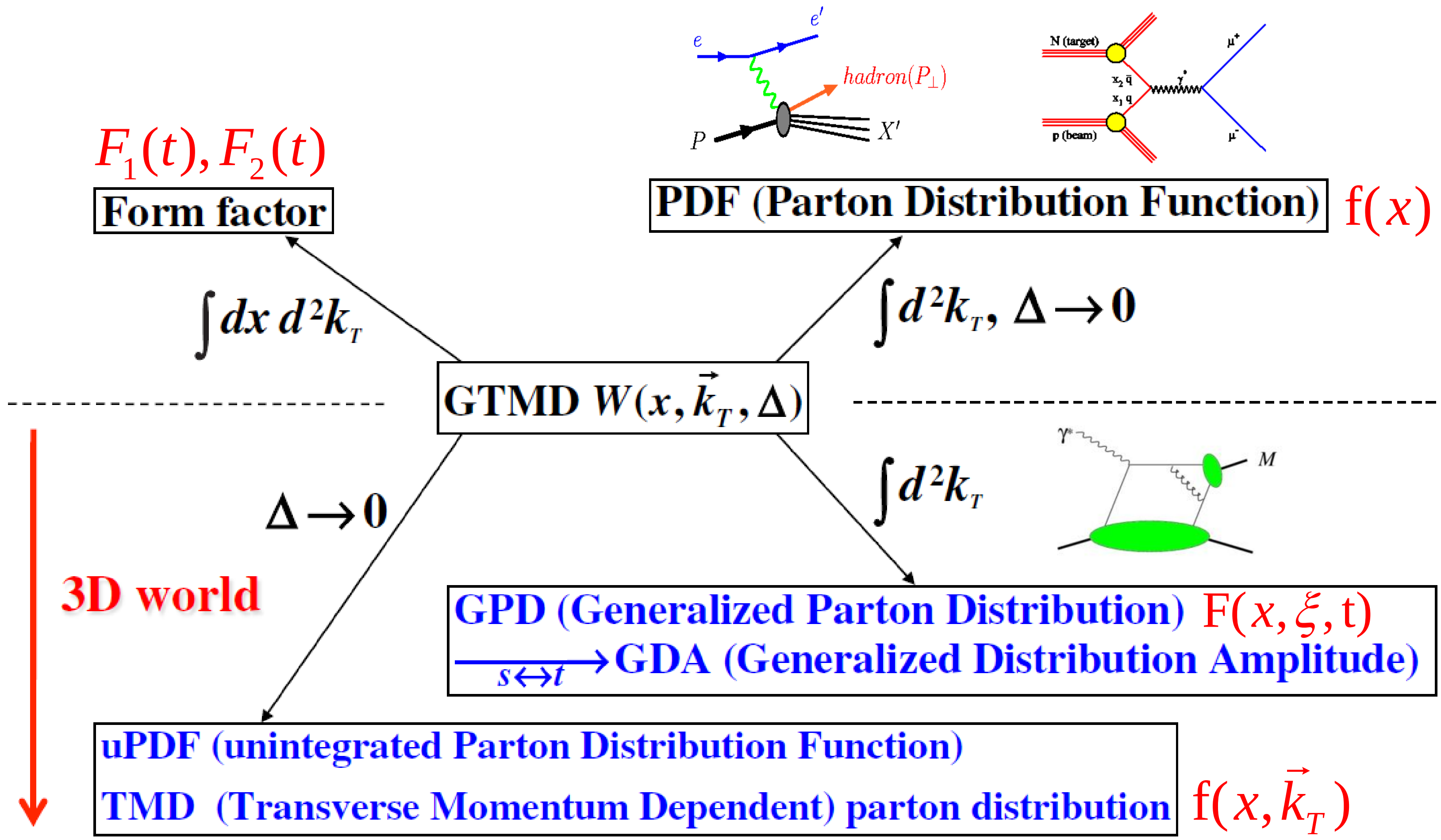
Based on the paper of Takahiro Sawada, Wen-Chen Chang, Shunzo Kumano, Jen-Chieh Peng, Shinya Sawada, Kazuhiro Tanaka, Phys. Rev. D93 (2016) 114034 [arXiv:1605.00364]

Outline

- Measuring GPDs in a timelike approach – Exclusive Drell-Yan Process
- Drell-Yan Process: inclusive, semi-exclusive and exclusive ones
- Measurement at J-PARC:
  - **High-momentum beamline at J-PARC**
  - **Feasibility study**
  - **Impacts and prospects**
- Summary

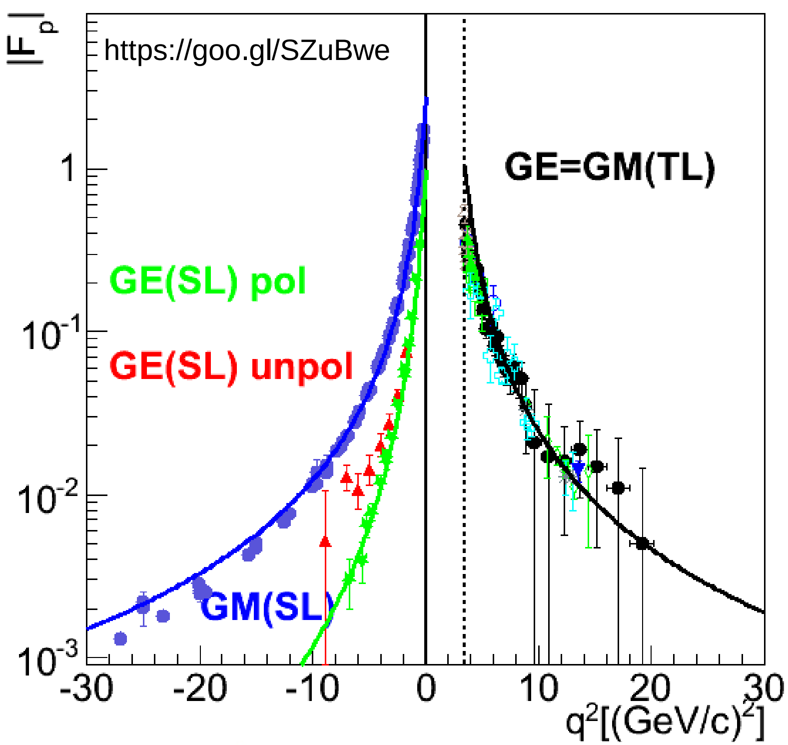
Generalized Transverse-Momentum-Dependent Parton Distribution Functions (GTMDs)



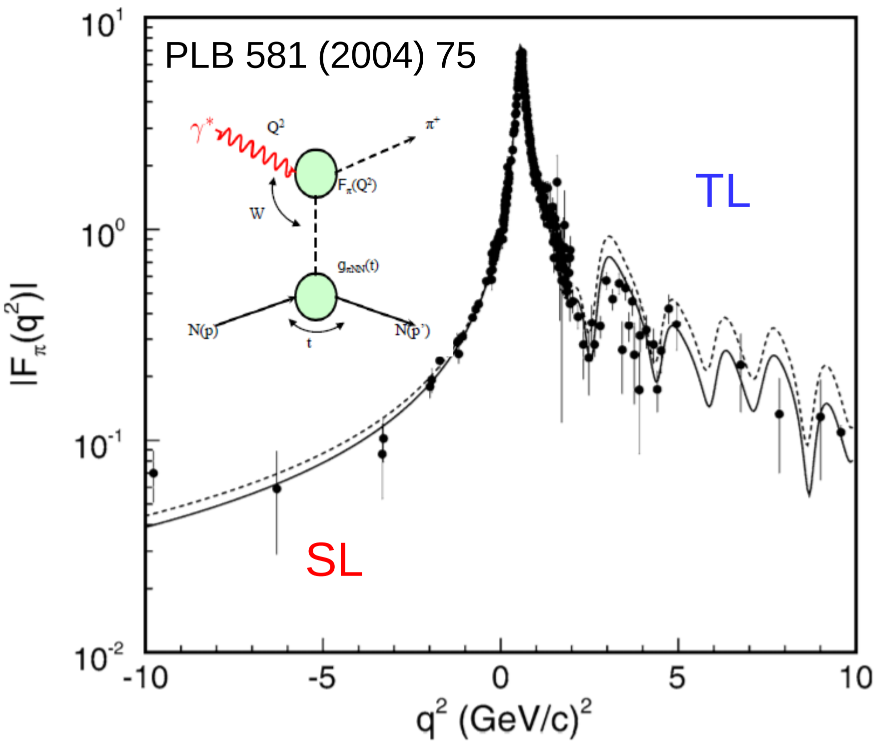
JHEP 08 (2008) 038; 08 (2009) 056

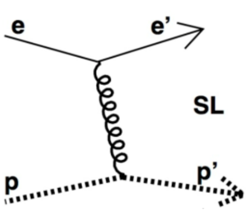
Electromagnetic Form Factors

proton

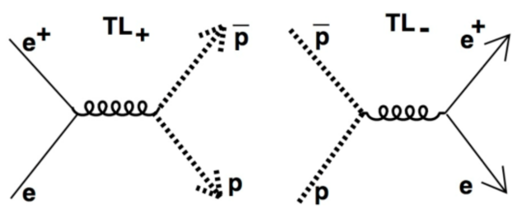


pion



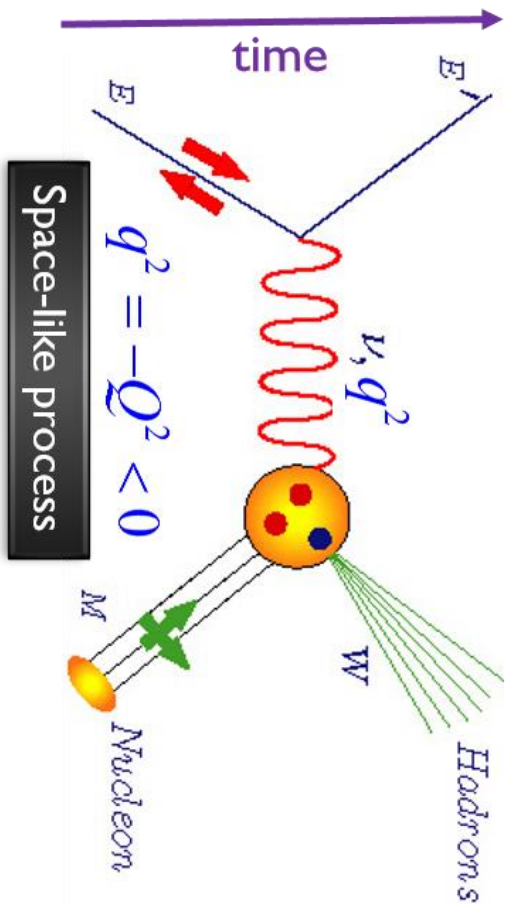


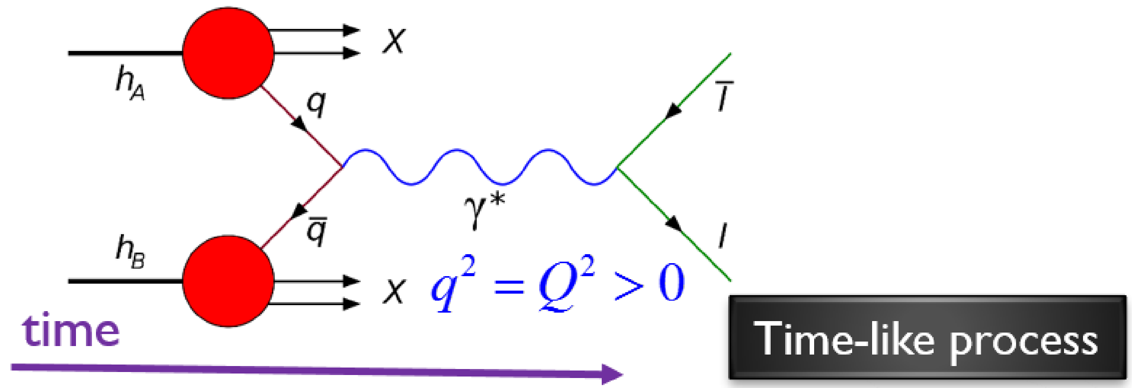
Space-like ($q^2 < 0$):
elastic scattering

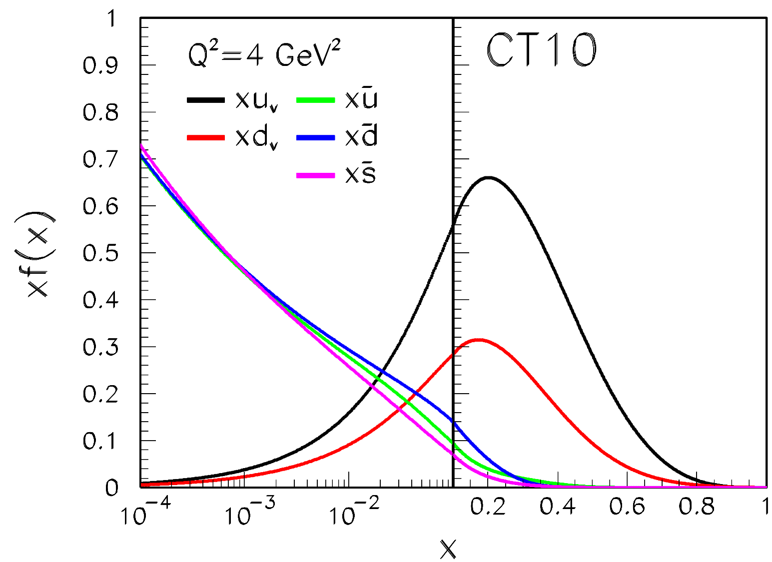


Time-like ($q^2 > 0$):
e+e- or hadron pair
annilhlation

Parton Density Functions of Protons



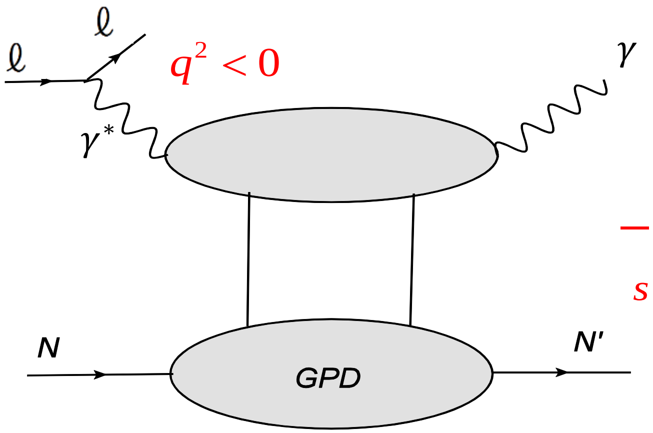




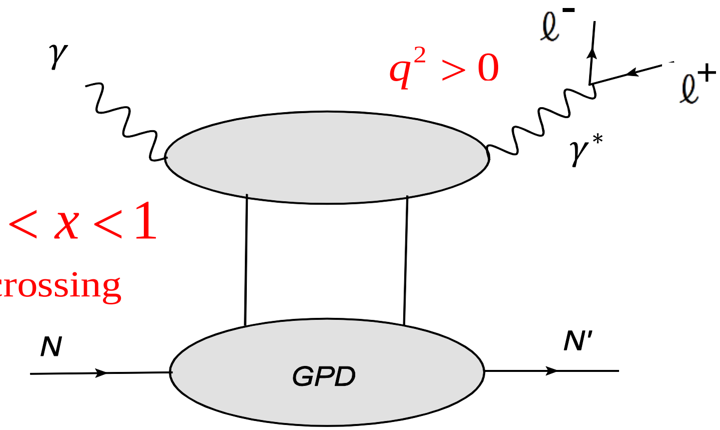
Generalized Parton Distributions

Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Compton Scattering



Time-like Compton Scattering

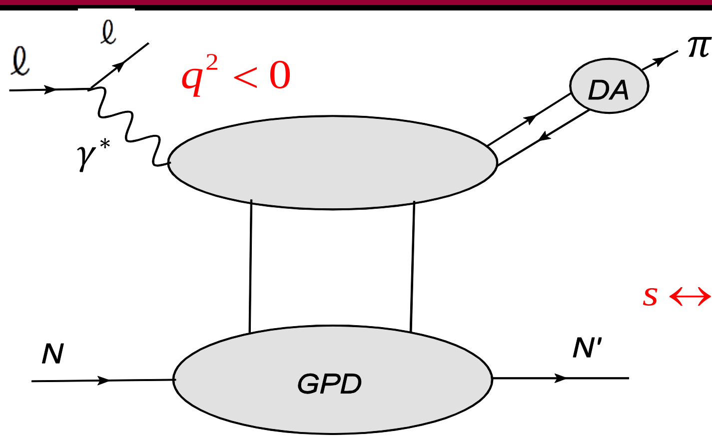


$t < 0$

$-1 < x < \xi, \xi < x < 1$

$s \leftrightarrow u$ channel crossing

Deeply Virtual Meson Production

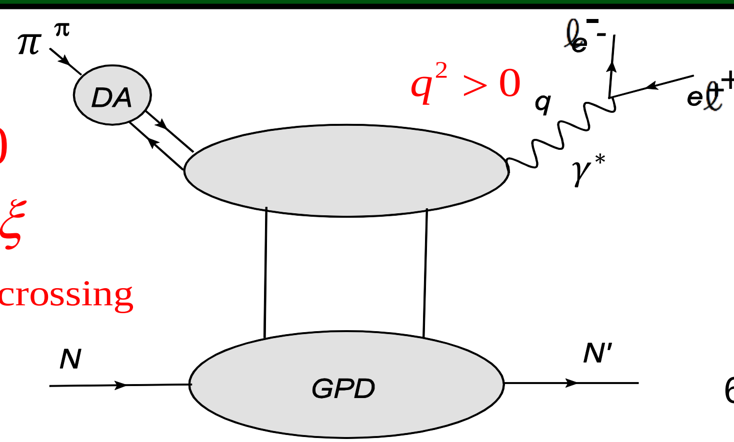


$t < 0$

$|x| < \xi$

$s \leftrightarrow u$ channel crossing

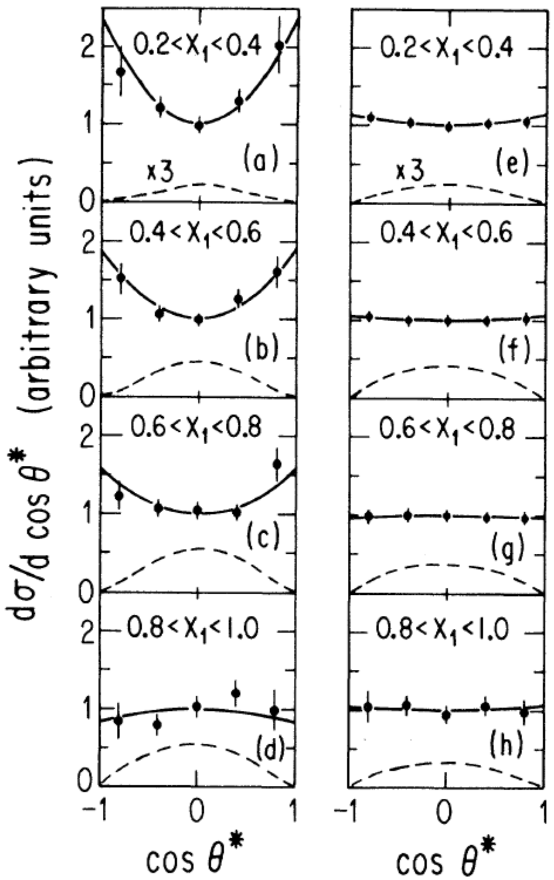
Exclusive meson-induced DY



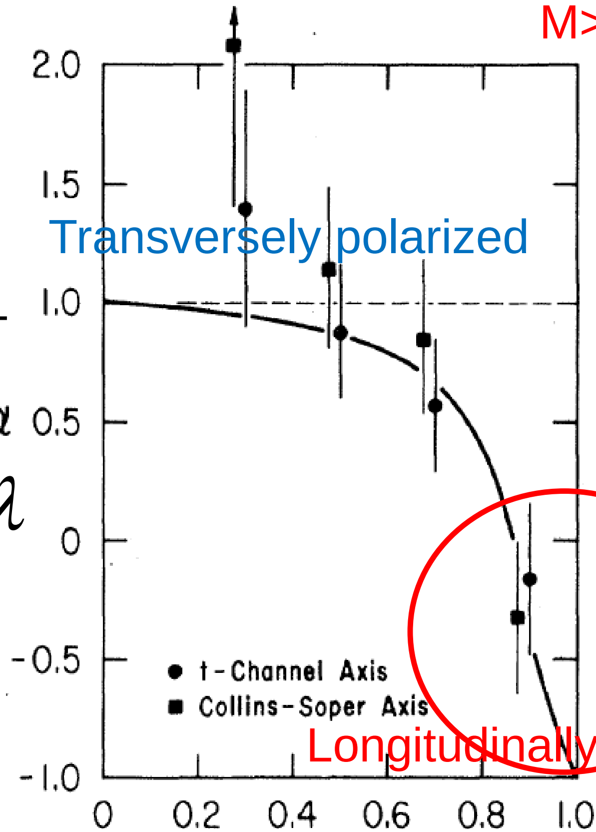
CIP (PRL 43, 1219 (1979))

225 GeV pion-

M> 4 GeV



$\cos\theta$ GJ frame



Transversely polarized

+1

$= \lambda$

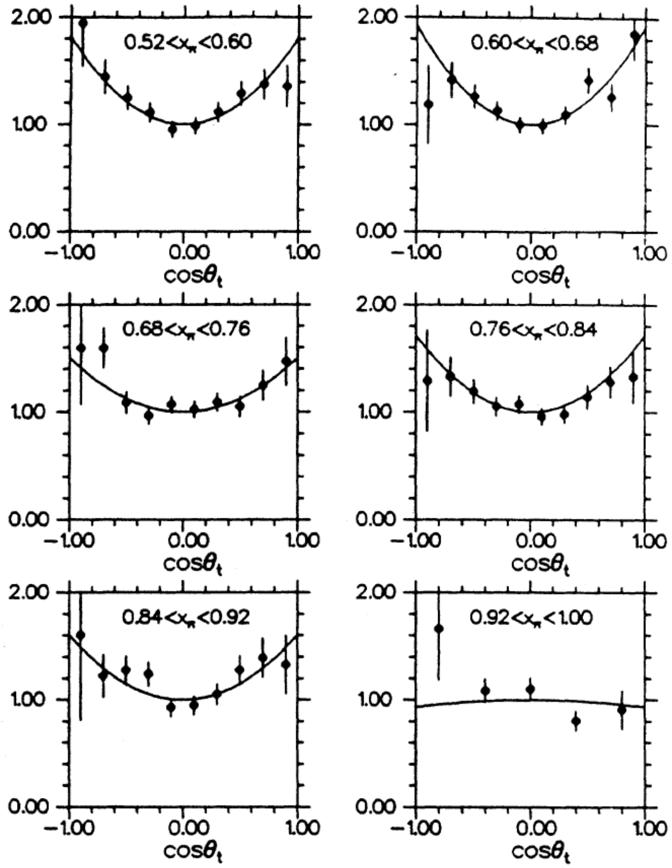
-1

Longitudinally polarized

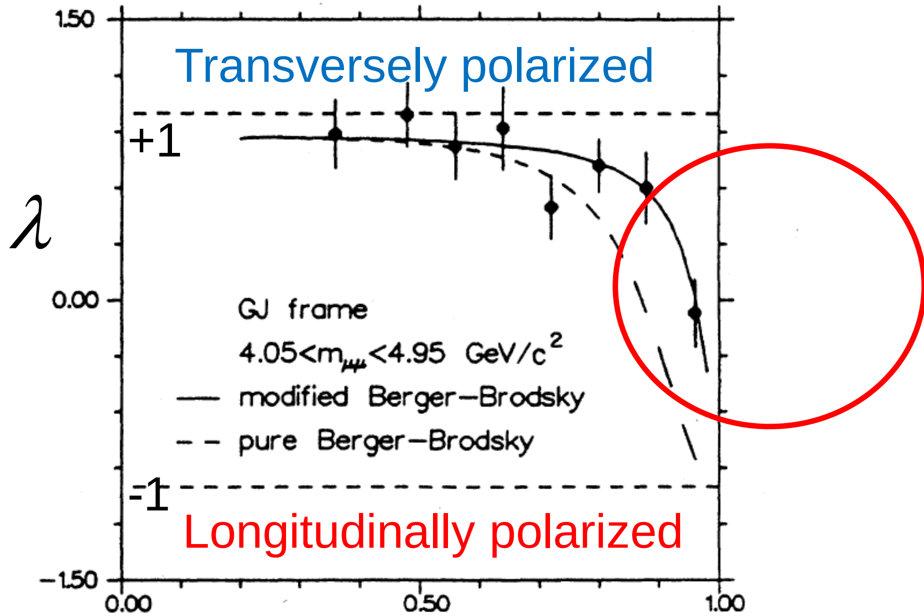
x_π

Higher Twist Effect at large x_π

E615 (PRD 39, 92 (1989))



$\cos\theta$

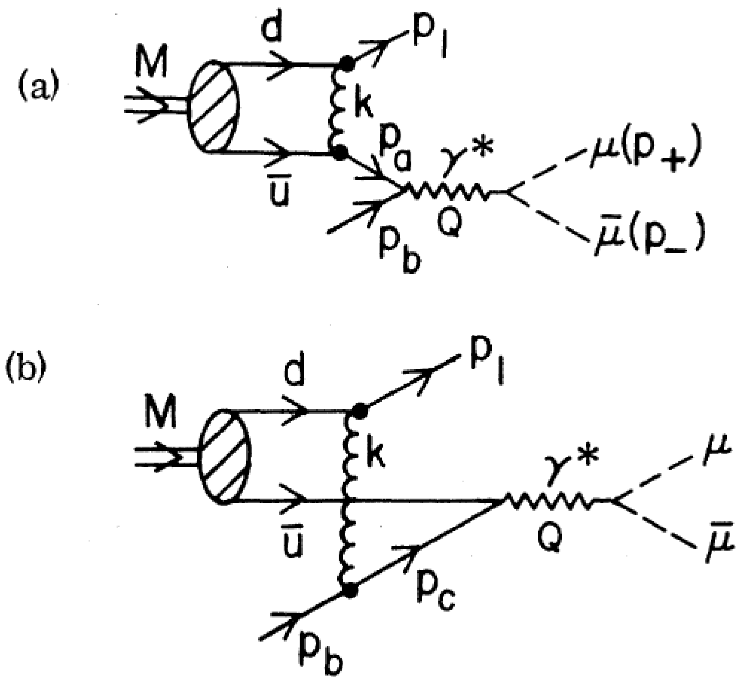


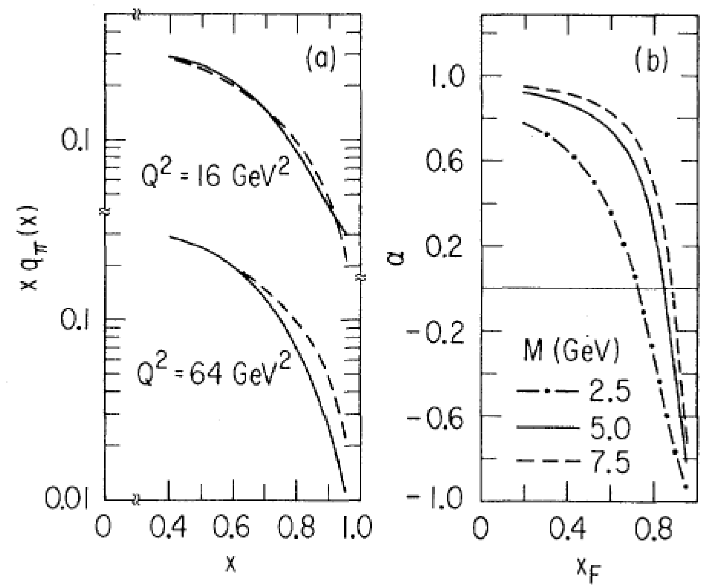
x_π

Higher Twist Effect at large x_π

Berger and Brodsky (PRL 42, 940, (1979))

$$d\sigma \propto (1+\alpha\cos^2\theta)$$

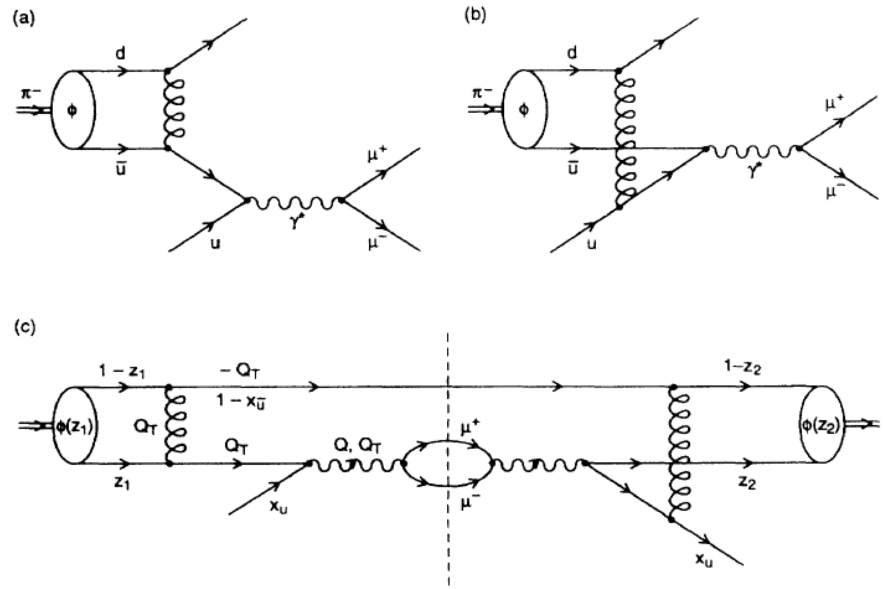




$$d\sigma \propto (1-x_\pi)^2(1+\cos^2\theta)+\frac{4x_\pi^2\left\langle k_T^2\right\rangle}{9m_{\mu\mu}^2}\sin^2\theta$$

Pion Distribution Amplitude

Brandenburg et al. (PRL 73, 939 (1994))

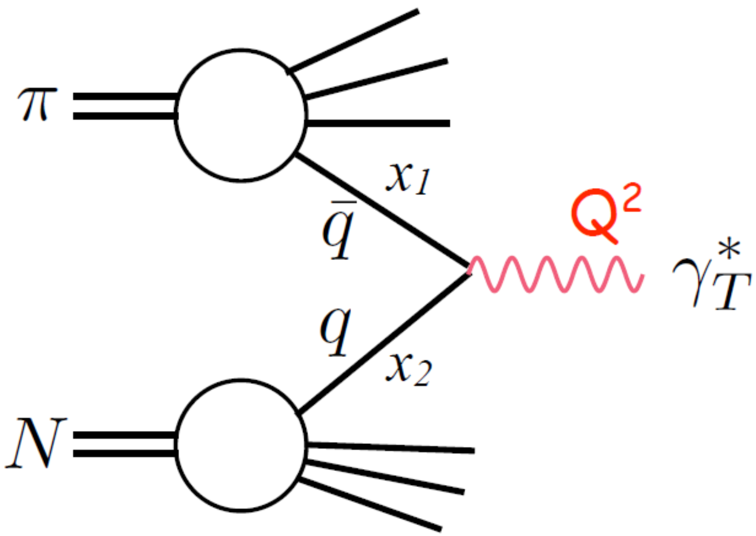


$$\frac{Q^2\, d\sigma(\pi^- N \to \mu^+\mu^- X)}{dQ^2\, dQ_T^2\, dx_L\, d\Omega} = \frac{1}{(2\pi)^4}\frac{1}{64}\int_0^1 dx_u\, G_{u/N}(x_u)\int_0^1 dx_{\bar u}\, \frac{x_{\bar u}}{1 - x_{\bar u} + Q_T^2/Q^2}\,|M|^2$$
$$\times\, \delta(x_L - x_{\bar u} + x_u - Q_T^2 s^{-1}(1 - x_{\bar u})^{-1})$$
$$\times\, \delta(Q^2 - s x_u x_{\bar u} + Q_T^2(1 - x_{\bar u})^{-1}) + \{u \to \bar d, \bar u \to d\}.$$

$$M = \int_0^1 dz\, \phi(z, \tilde Q^2) T\,,$$

Pion distribution amplitude: distribution of LC momentum fractions in the lowest-particle number valence Fock state.

Drell-Yan in the Bj limit: $Q^2 \to \infty$ at fixed x



$$Q^2 = x_1 x_2 s \to \infty$$

$x_1, x_2 ; x_F = x_1 - x_2$ fixed

Transversely polarized photon, since quarks are ~ on-shell

Leading twist: One active parton in beam and target hadrons

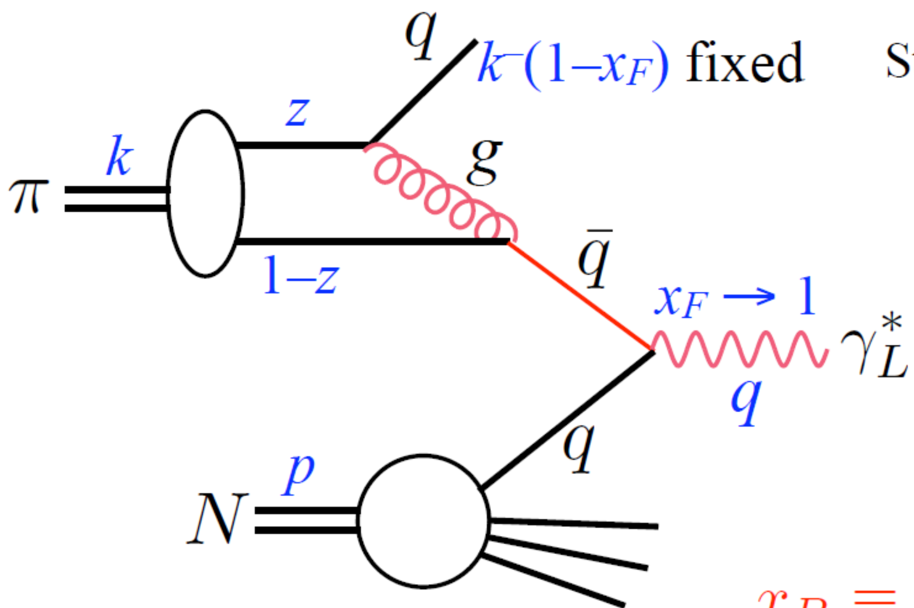
Spectators are incoherent with the hard subprocess

Factorization: $\sigma = f_{\bar{q}/\pi}(x_1) f_{q/N}(x_2) \hat{\sigma}(\bar{q}q \to \gamma^*)$

Higher twist corrections are of order $\dfrac{1}{Q^2}\dfrac{1}{1-x}$

P. Hoyer, M. Jrvinen and S. Kurki, JHEP 0810 (2008) 086, arXiv: 0808.0626

Drell-Yan in the BB limit: $Q^2 \to \infty$ at fixed $Q^2(1-x_F)$



Stopped parton coherent with γ^*

$\bar{q}, g$ virtualities of order Q^2

$\Rightarrow$ *higher twist process*

: Longitudinal polarization

$$x_B \equiv \frac{q^+}{p^+} = \frac{Q^2}{2q\cdot p} = \frac{Q^2}{s} \quad \text{fixed}$$

The hadronic mass

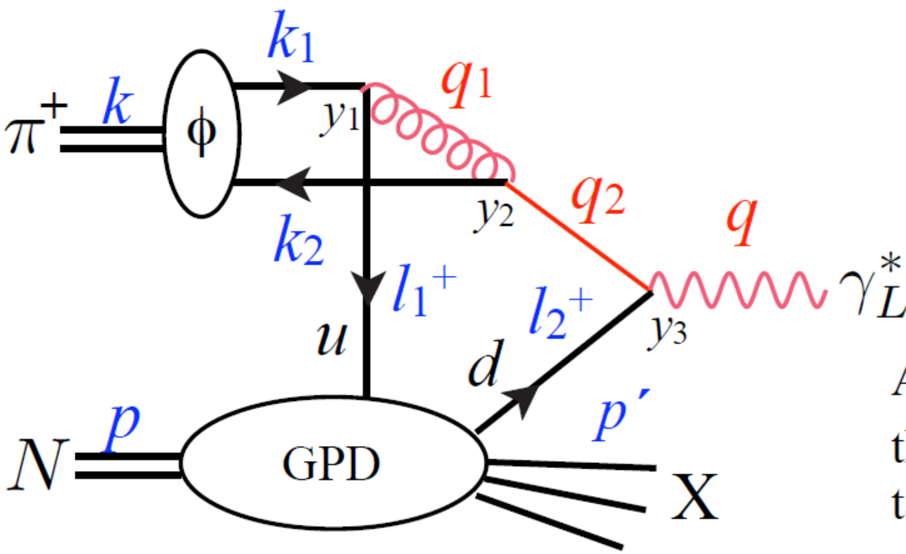
$$M_X^2 \equiv (k+p-q)^2 \simeq (1-x_B)[s(1-x_F)+m_N^2] \quad \text{fixed}$$

Stopped quark is comoving with the target.
Its interactions in the target affect the hard subprocess.

P. Hoyer, M. Jrvinen and S. Kurki, JHEP 0810 (2008) 086, arXiv: 0808.0626

Hence the stopped quark should be connected to the target:

$k_1 = (0^+, zk^-, \boldsymbol{k}_\perp)$
$k_2 = (0^+, (1-z)k^-, -\boldsymbol{k}_\perp)$



Since $q_1^2 \approx -zk^- l_1^+ \to \infty$

the pion wave function contributes through its *distribution amplitude* ϕ

Also q_2^2, q_1^-, $q_2^- \to \infty$, hence the space-time separation of the target interaction points y_1, y_3 is

$$\begin{aligned} |\boldsymbol{y}_{1\perp} - \boldsymbol{y}_{3\perp}| &= \mathcal{O}(1/Q) \to 0 \\ |y_1^+ - y_3^+| &= \mathcal{O}(1/Q^2) \to 0 \\ |y_1^- - y_3^-| &= \mathcal{O}(1/\ell_1^+) \text{ finite} \end{aligned}$$

For each final state X the target matrix element is given by a GPD with skewness

$$l_2^+ - l_1^+ = q^+ = x_B\, p^+$$

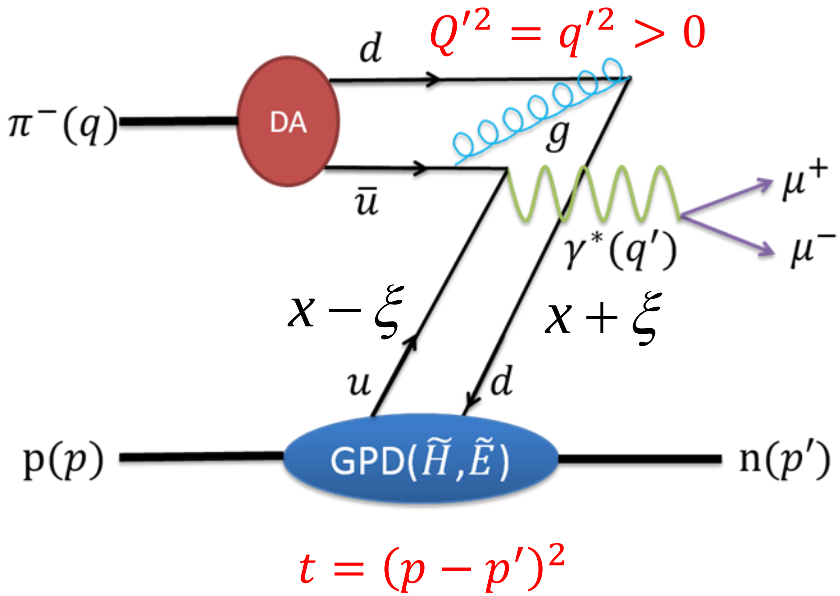
Using perturbative propagators for the gluon q_1 and d-quark q_2 and adding three more diagrams we get

Large x_F limit

- **Bj limit ($Q^2 \to \infty$, at fixed x_1)**, cross sections = **pion PDF** * **nucleon PDF** * hard kernel
- **BB limit ($Q^2 \to \infty$, at fixed $Q^2(1-x_F)$)**, cross sections = |**pion DA**|^2 * **nucleon multi-parton distribution** * hard kernel
- **Exclusive DY ($Q^2 \to \infty$, at fixed t and τ)**, cross sections = |**pion DA** * **nucleon GPD** * hard kernel |^2

$\pi N \to l^+ l^- N$ (Leading-twist)

E.R. Berger, M. Diehl, B. Pire, PLB 523 (2001) 265



$$\tau = \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s - M_N^2} \qquad \xi = \frac{(p-p')^+}{(p+p')^+} = \frac{\tau}{2-\tau}$$

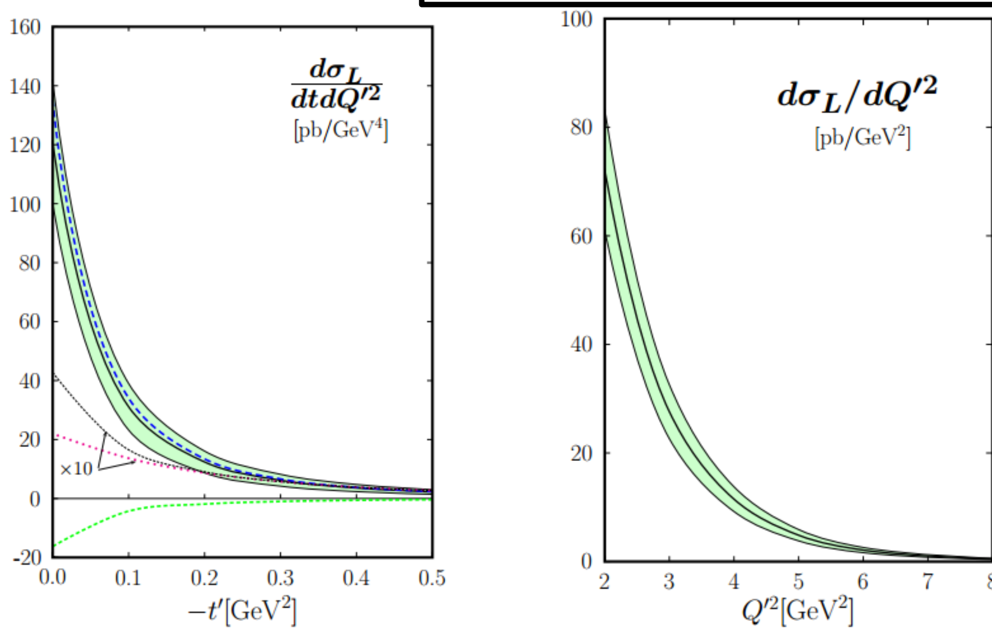
$$\tilde{x} = -\frac{(q+q')^2}{2(p+p')\cdot(q+q')} \approx -\frac{Q'^2}{2s - Q'^2} = -\xi$$

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

$$\boxed{\begin{aligned}\left.\frac{d\sigma_L}{dt dQ'^2}\right|_\tau = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \Big[&(1-\xi^2)|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)|^2 \\ &- 2\xi^2 \mathrm{Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^* \tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right) - \xi^2 \frac{t}{4m_N^2}|\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)|^2\Big],\end{aligned}}$$

Differential cross sections with an updated time-like pion FF

S.V. Goloskokov, P. Kroll, PLB 748 (2015) 323



$Q'^2 = 4\,\mathrm{GeV}^2$ and $s = 20\,\mathrm{GeV}^2$ solid lines with error bands: full result

pion pole, $|\langle \widetilde{H}^{(3)} \rangle|^2$, interference, short dashed: leading-twist contribution

time-like pion FF: $Q'^2|F_\pi(Q'^2)| = 0.88 \pm 0.04\,\mathrm{GeV}^2$ (CLEO, BaBar, $J/\Psi \to \pi^+\pi^-$)

phase $(\exp[i\delta(Q'^2)])$ from disp. rel. Belicka et al(11) for $Q'^2 < 8.9\,\mathrm{GeV}^2$

$\delta = 1.014\pi + 0.195(Q'^2/\mathrm{GeV}^2 - 2) - 0.029(Q'^2/\mathrm{GeV}^2 - 2)^2$

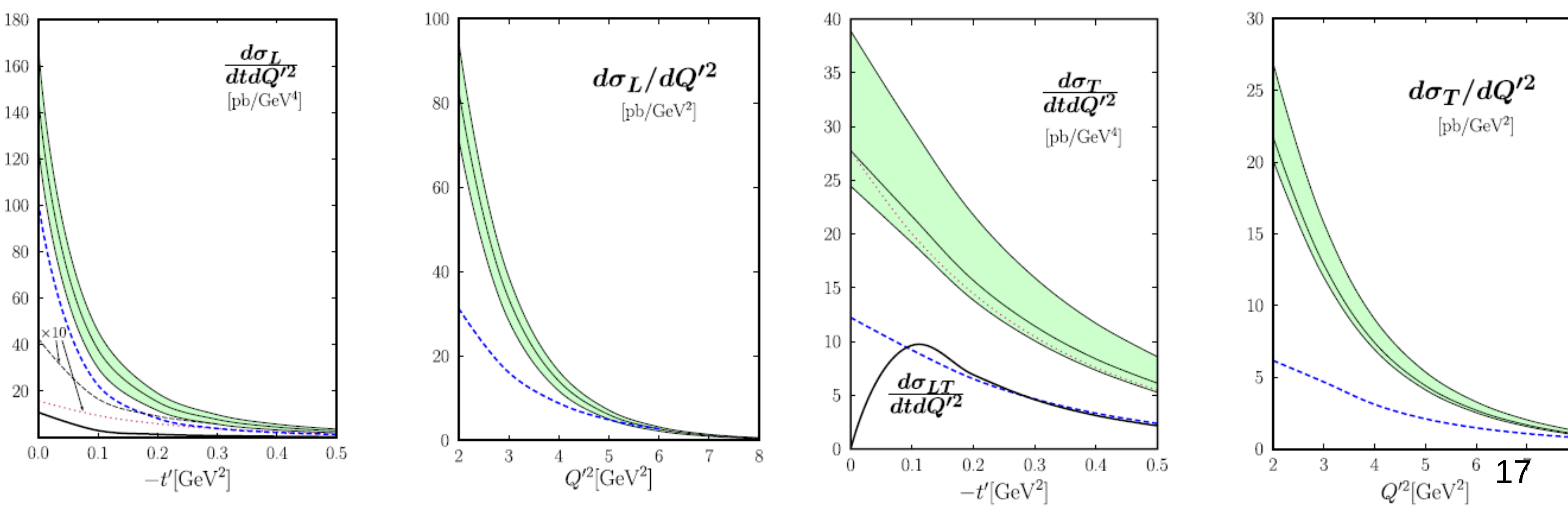
for $Q'^2 \geq 8.9\,\mathrm{GeV}^2$: $\delta = \pi$, the LO pQCD result

Beyond the Leading Twist

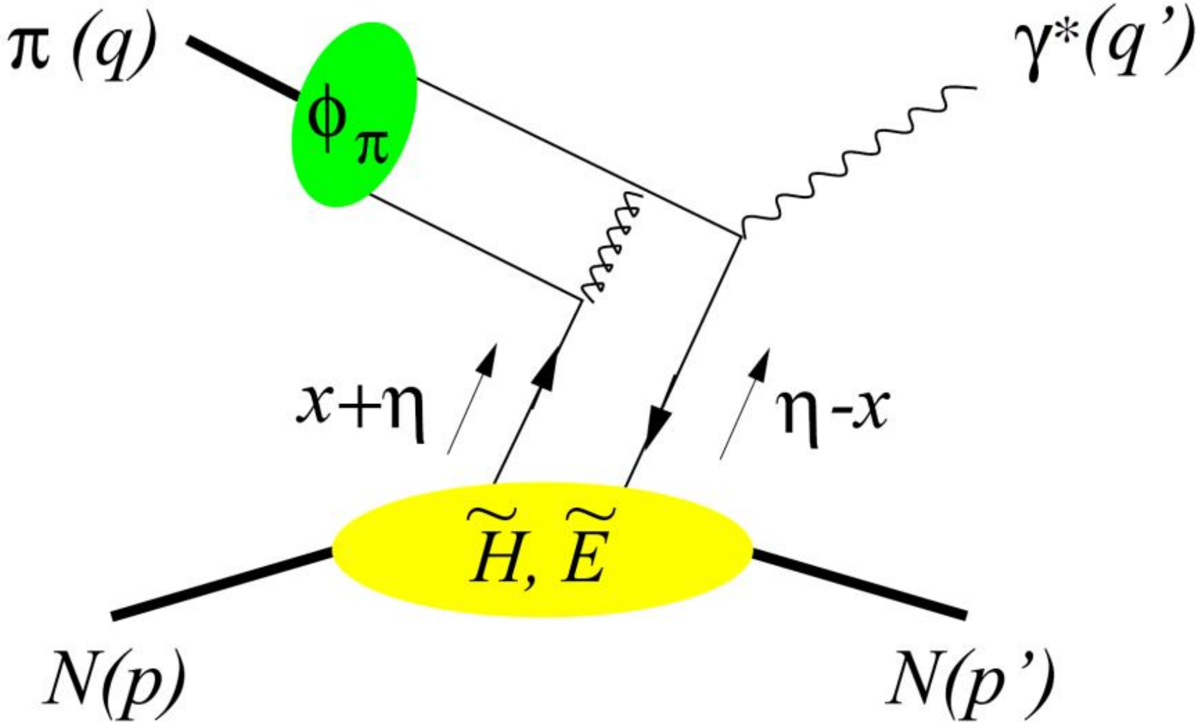
S.V. Goloskokov, P. Kroll, PLB 748 (2015) 323

$$\frac{d\sigma}{dt\,dQ'^2\,d\cos\theta\,d\varphi} = \frac{3}{8\pi}\left(\sin^2\theta\,\frac{d\sigma_L}{dt\,dQ'^2} + \frac{1+\cos^2\theta}{2}\,\frac{d\sigma_T}{dt\,dQ'^2} + \frac{\sin 2\theta\cos\varphi}{\sqrt{2}}\,\frac{d\sigma_{LT}}{dt\,dQ'^2} + \sin^2\theta\cos 2\varphi\,\frac{d\sigma_{TT}}{dt\,dQ'^2}\right)$$

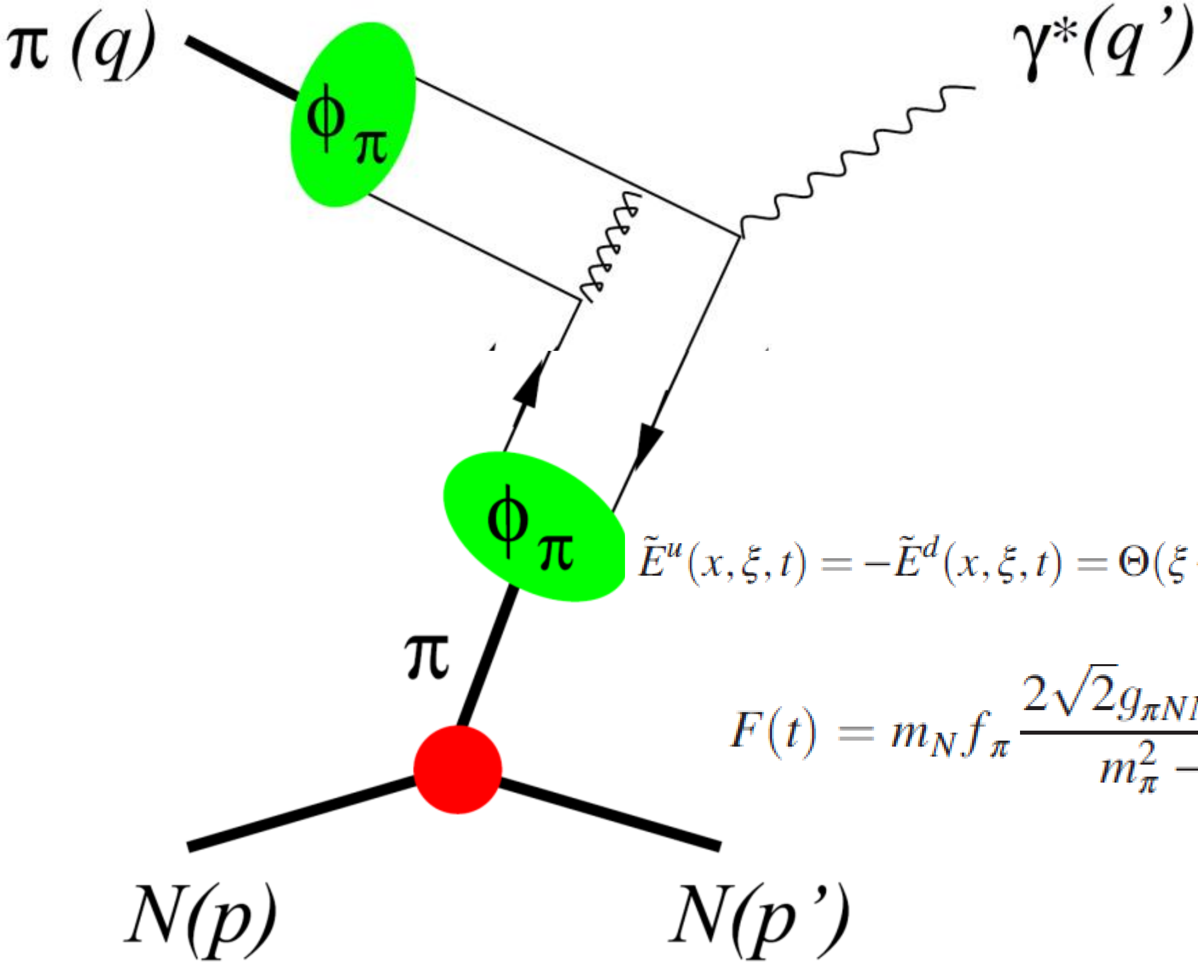
Transversity GPDs: H_T, $\bar{E}_T$



Leading-Twist Diagram



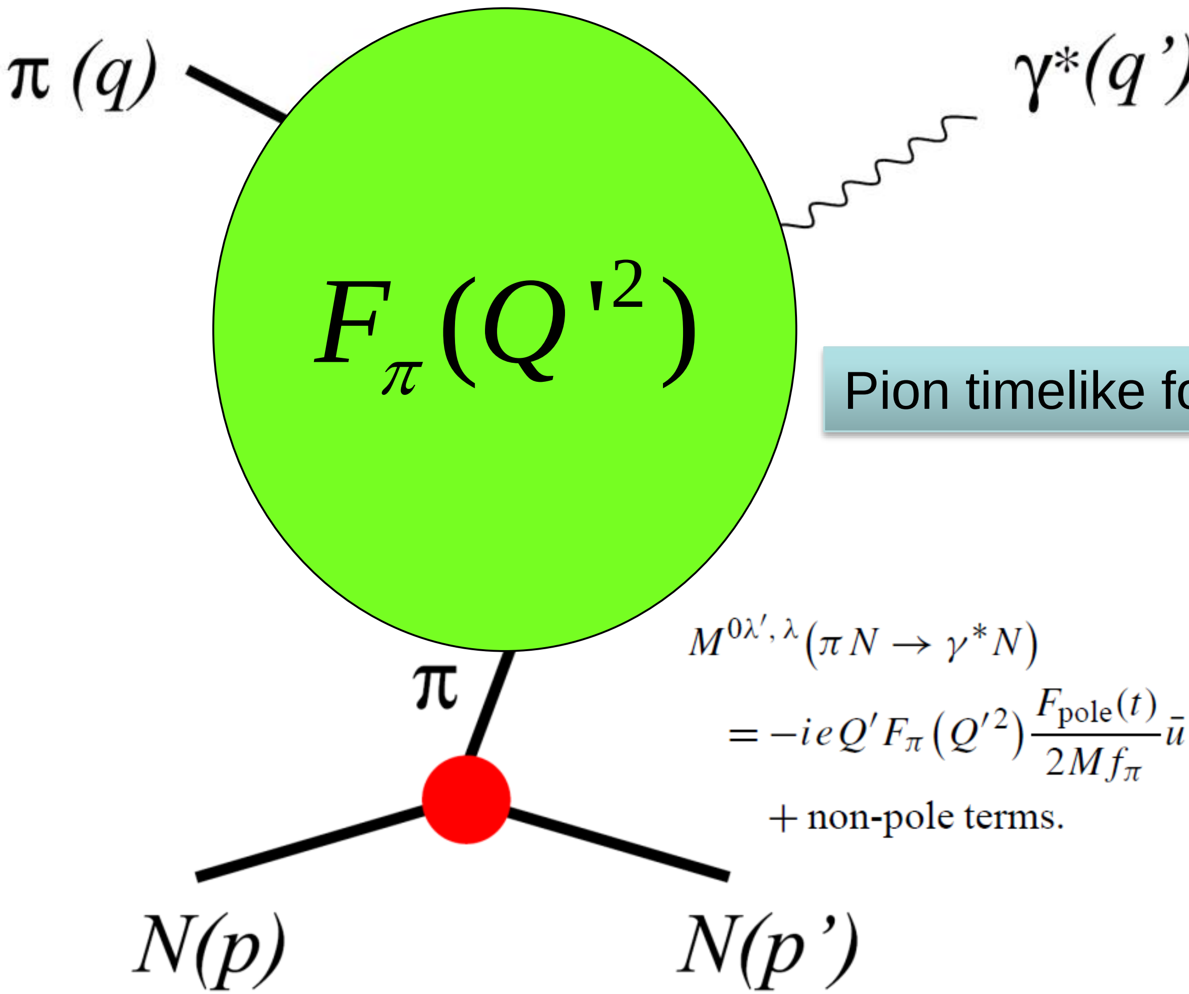
Pion-pole Dominance for $\tilde{E}$



$$\tilde{E}^u(x,\xi,t) = -\tilde{E}^d(x,\xi,t) = \Theta(\xi - |x|)\frac{F(t)}{2\xi}\phi_\pi(x/\xi),$$

$$F(t) = m_N f_\pi \frac{2\sqrt{2} g_{\pi NN} \tilde{F}(t)}{m_\pi^2 - t}.$$

Pion Timelike FFs

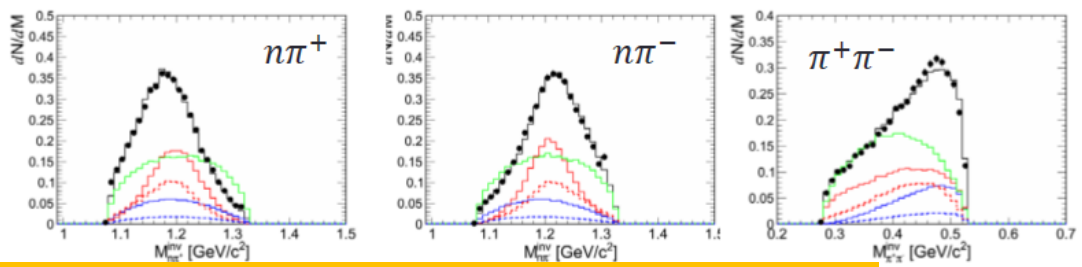


Pion timelike form factors

$$M^{0\lambda',\lambda}(\pi N \to \gamma^* N)$$
$$= -ie\,Q' F_\pi(Q'^2)\frac{F_{\text{pole}}(t)}{2M f_\pi}\bar{u}(p',\lambda')\gamma_5 u(p,\lambda)$$
$$+ \text{non-pole terms.}$$

HADES: $\pi^- p \rightarrow n e^+ e^-$ with P_{π^-}<1 GeV

Electromagnetic TFF for baryons (N*)



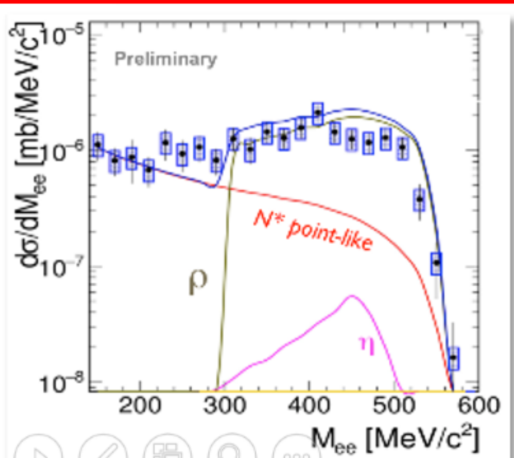
Hadronic final states used in PWA (A. Sarantsev; BONN/GATCHINA)

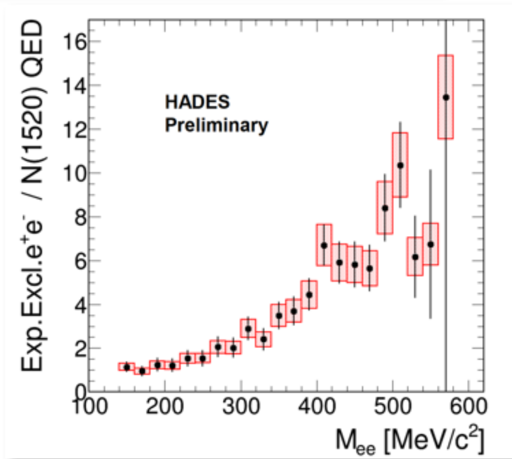
$\pi^- + p \rightarrow \pi^- + \pi^+ + n$

p_π = [656, 690, 748, 800] MeV

$$\pi^- p \rightarrow N^* \rightarrow n(\gamma^*, \rho, \eta ...) \rightarrow n e^+ e^-$$

--- ρN





$\pi^- + p \rightarrow e^- + e^+ + n$

- Prediction for dilepton invariant mass assuming strict VMD.
- Evidence for intermediate ρ propagation in both s- (baryon resonance) and t-channel.
- em TFF shows VDM-like rise
- Also seen in space-like at CLAS

I.G. Aznauryan & V. D. Burkert, NSTAR-2017

Optimization of Exclusive Drell-Yan Measurement

- Factorization requirements: $Q^2 \gg 1\, GeV^2$
- Large cross sections:
  - Cross sections decrease rapidly with an increase of Q^2. $Q^2 < 9\, GeV^2$
  - $\sqrt{s}$ should be small enough to keep $\sqrt{\tau} = \frac{Q}{\sqrt{s}} = \sqrt{x_\pi x_N}$ large enough. Take $Q = 2\, GeV$, $\sqrt{\tau} = \sqrt{0.5 * 0.3} = 0.39$, $\sqrt{s} = 5\, GeV$, pion beam momentum should be less than 15 GeV.

Optimization of Exclusive Drell-Yan Measurement

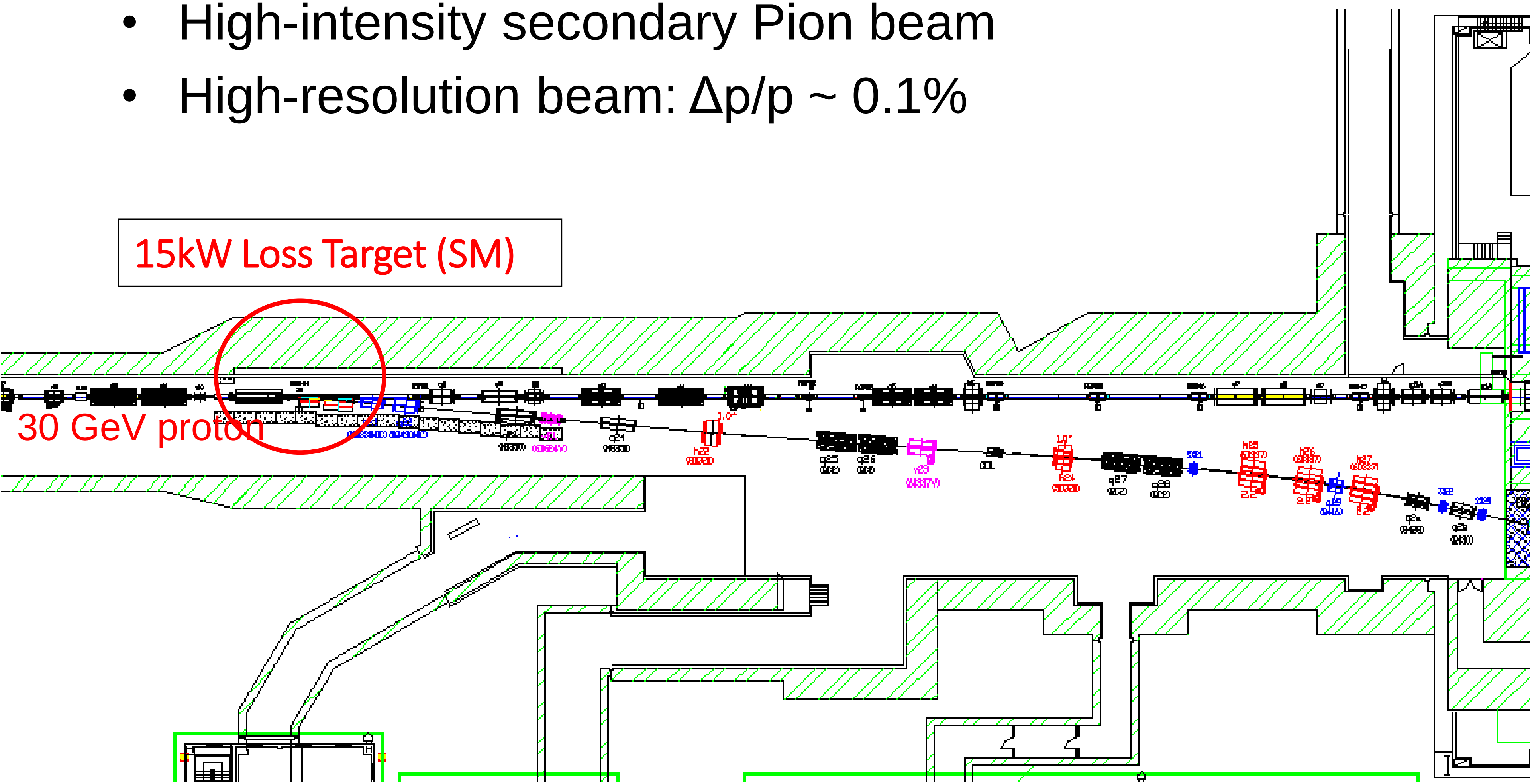
- Ensuring exclusivity: missing-mass technique
  - Good resolution for missing mass
  - Open aperture without the hadron absorber before measuring the momentum of lepton tracks
  - Reasonably low track multiplicity

The high-momentum beam line at J-PARC with 10-20 GeV π^- beam ($\sqrt{s} = \mathbf{4-6}$ GeV) is appropriate for measuring the exclusive Drell-Yan process.

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

- High-intensity secondary Pion beam
- High-resolution beam: Δp/p ~ 0.1%

15kW Loss Target (SM)



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

- High-intensity secondary Pion beam
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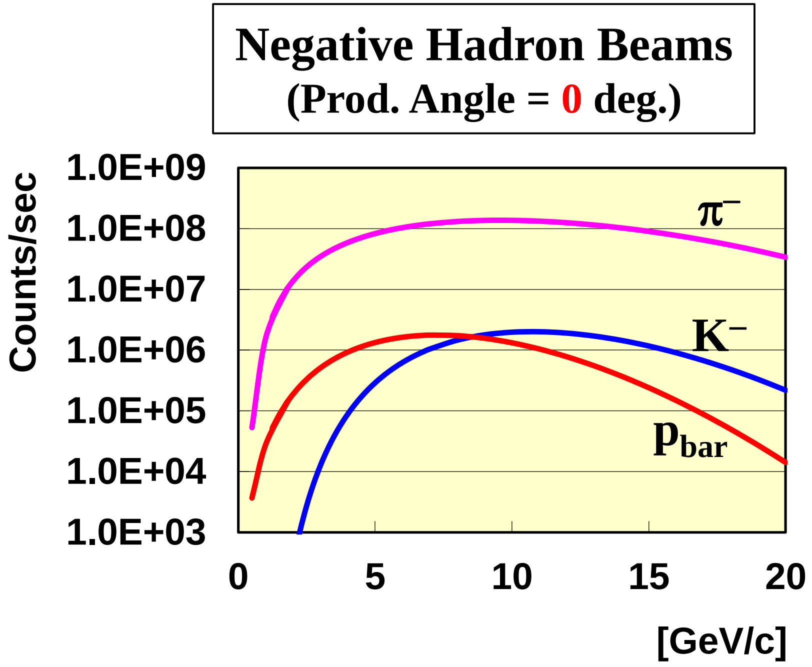
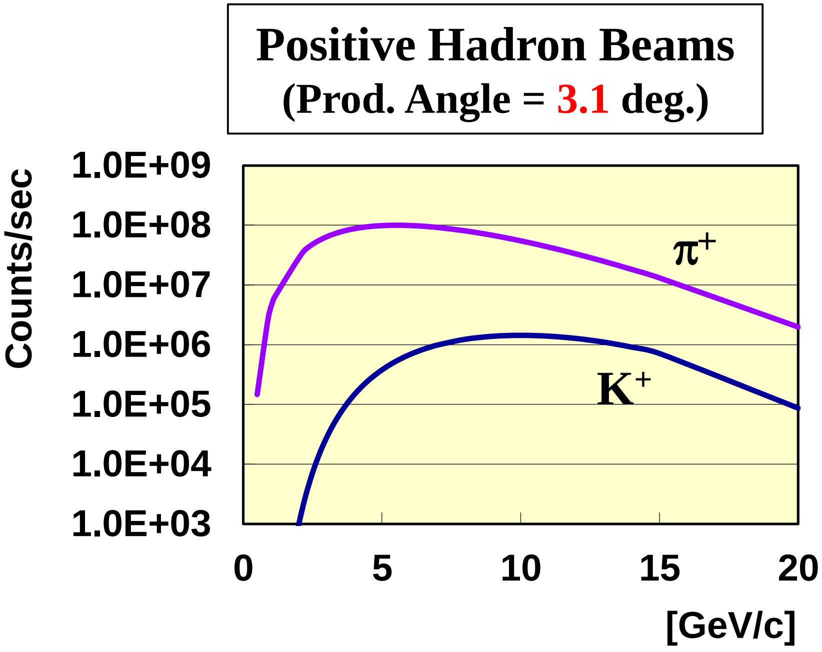




*** Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m**

GPD Models

BMP2001

E. R. Berger, M. Diehl and B. Pire, Eur. Phys. J. C 23 (2002) 675
E. R. Berger, M. Diehl and B. Pire, Phys. Lett. B 523 (2001) 265

$$\tilde{H}^{d,u}(x,\xi,t) = \tilde{H}^{d,u}(x,\xi,0)\,[g_A(t)/g_A(0)]$$

Here, $\tilde{H}^q(x,\xi,0)$ is constructed from an ansatz based on double distributions as an integral $\tilde{H}^q(x,0,0) = \Delta q(x)$ combined with a certain profile function generating the skewness ξ dependence

$\phi_\pi(z) \to (3/4)(1-z^2)$ asymptotic form

GK2013

P. Kroll, H. Moutarde and F. Sabatie, Eur. Phys. J. C 73 (2013) 1, 2278

The parameters are determined from the HERMES data on the cross sections and target asymmetries for pi+ electroproduction

$$\phi_\pi(z) = (3/4)(1-z^2)[1 + a_2 C_2^{(3/2)}(z)]$$

$$\text{with } a_2\ (\mu = 2\ \text{GeV}) = 0.22$$

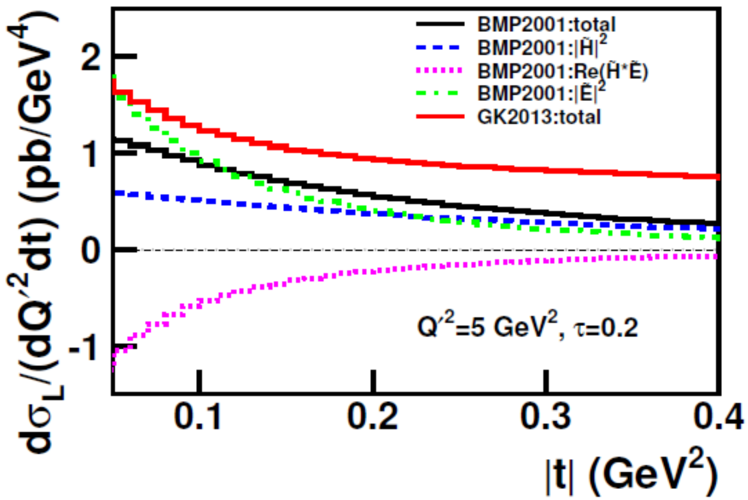
Differential cross sections

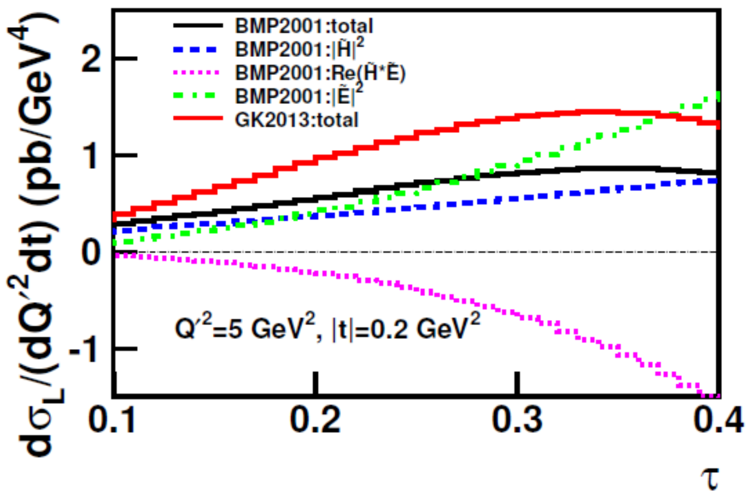
$$\left.\frac{d\sigma_L}{dt\,dQ'^2}\right|_\tau = \frac{4\pi\alpha_{\rm em}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \Big[(1-\xi^2)|\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)|^2 - 2\xi^2 {\rm Re}\left(\tilde{\mathcal{H}}^{du}(\tilde{x},\xi,t)^* \tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)\right) - \xi^2\frac{t}{4m_N^2}|\tilde{\mathcal{E}}^{du}(\tilde{x},\xi,t)|^2\Big],$$

$$Q'^2 = q'^2 = 5\ GeV^2$$

at $\tau = \dfrac{Q'^2}{2pq} \approx \dfrac{Q'^2}{s - M_N^2} = 0.2$

at $t = (p-p')^2 = -0.2\ GeV^2$

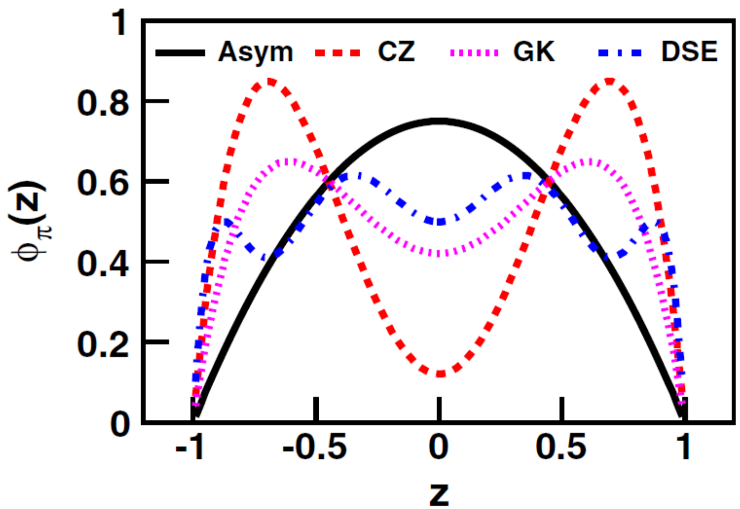




Production is dominant at forward angles

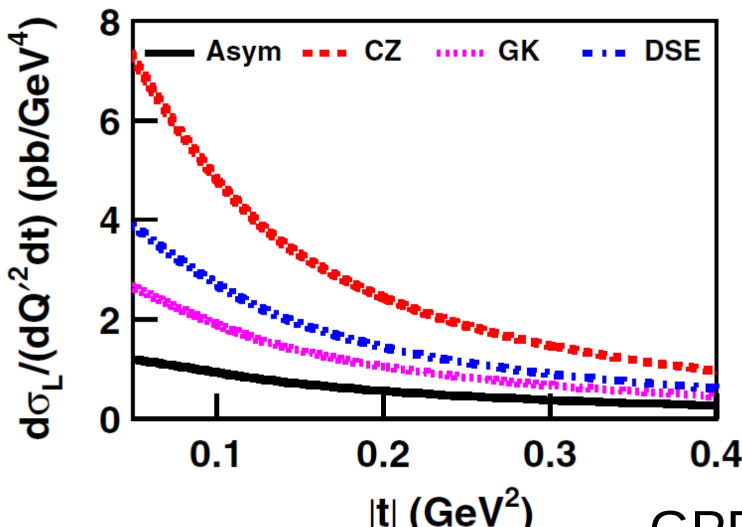
Cross sections increase toward small *s* (→ low beam energy)

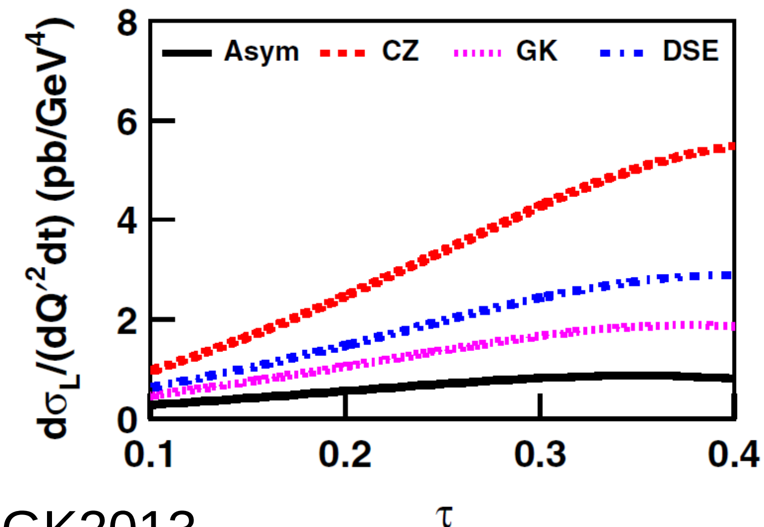
Sensitivity to Pion DAs



$$\Phi_\pi(x,\mu) = 6x(1-x)\sum_{n=0,2,4,\ldots}^{\infty} a_n(\mu)C_n^{3/2}(2x-1).$$

$\phi_\pi(z,\mu)$	Asymptotic [41]	CZ [42]	GK [51]	DSE [52]
a_2	0	2/3	0.22	0.20
a_4	0	0	0	0.093
a_6	0	0	0	0.055
μ^2 (GeV^2)	1	0.25	4	4

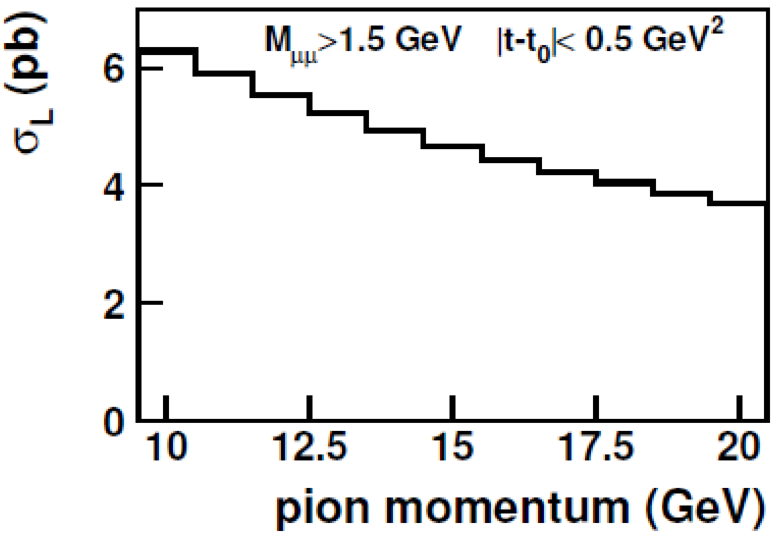




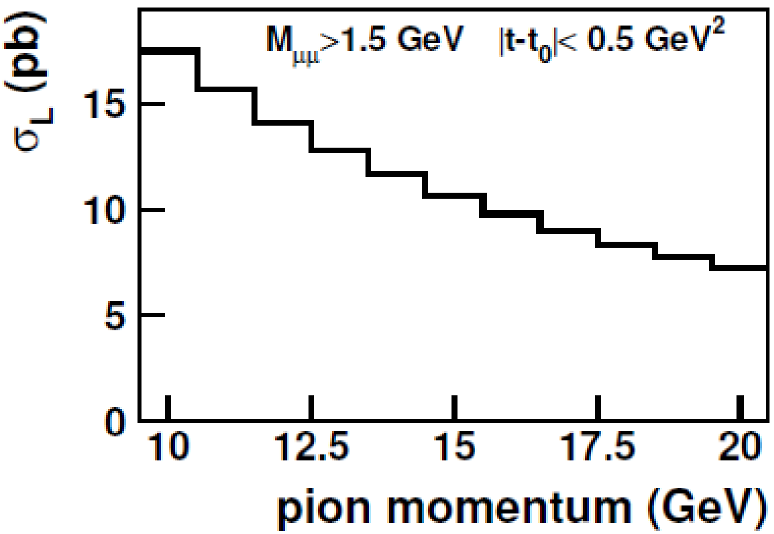
GPDs: GK2013

Total LO cross sections

BMP2001



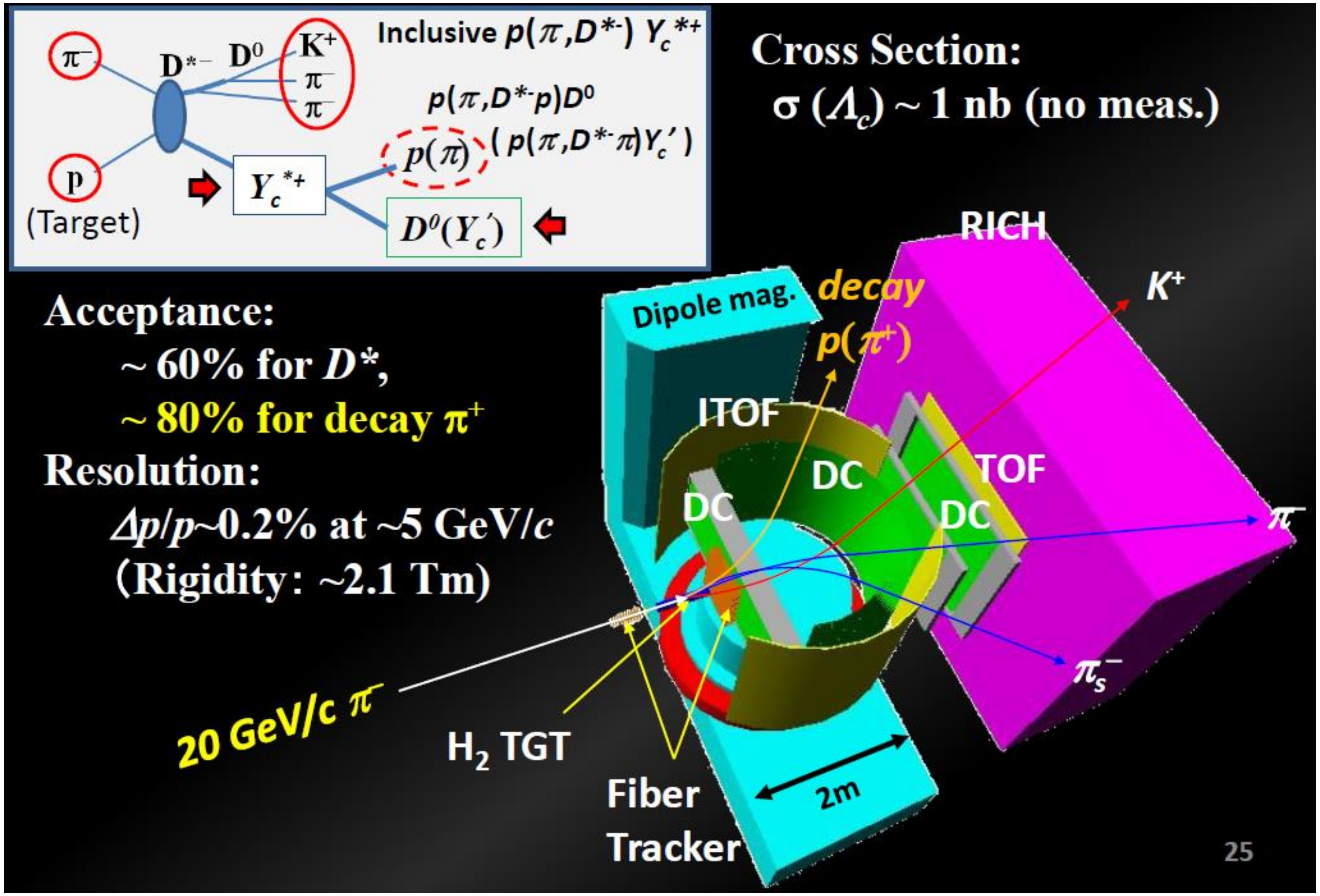
GK2013



J-PARC (Pπ=10-20 GeV) σ = 5 ~15 pb
CERN COMPASS (Pπ= 190 GeV) σ = 0.65 pb

J-PARC E50 Experiment
(Charmed Baryon Spectroscopy)

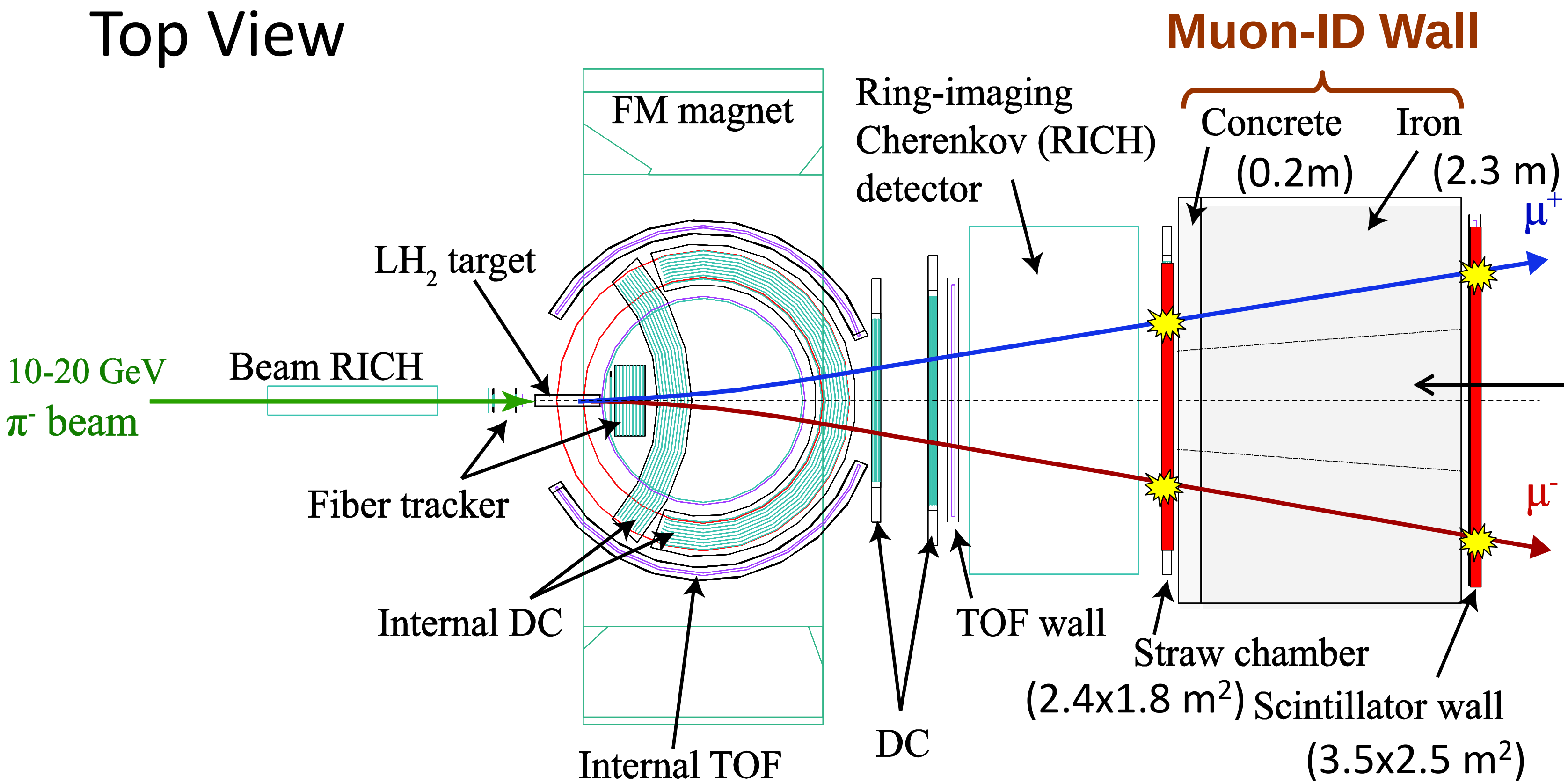
Stage-1 approved by J-PARC PAC-18, August 12, 2014.



H. Noumi, KEK workshop 2015

Extension of J-PARC E50 Experiment for Drell-Yan measurement

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.

Simulation

Assumptions:

- Target : 57cm LH_2 (n_{TGT} = 4 g/cm^2)
- Beam momentum resolution($\Delta p/p$) = 0.1 %
- 1.83/1.58/1.00 $*10^7$ π^- /spill for 10/15/20 GeV beam
- Data Taking: 50 days (*Proposal of E50: 100 days)
- E50 spectrometers + μ ID system

Expected cross sections for the exclusive/inclusive Drell-Yan processes

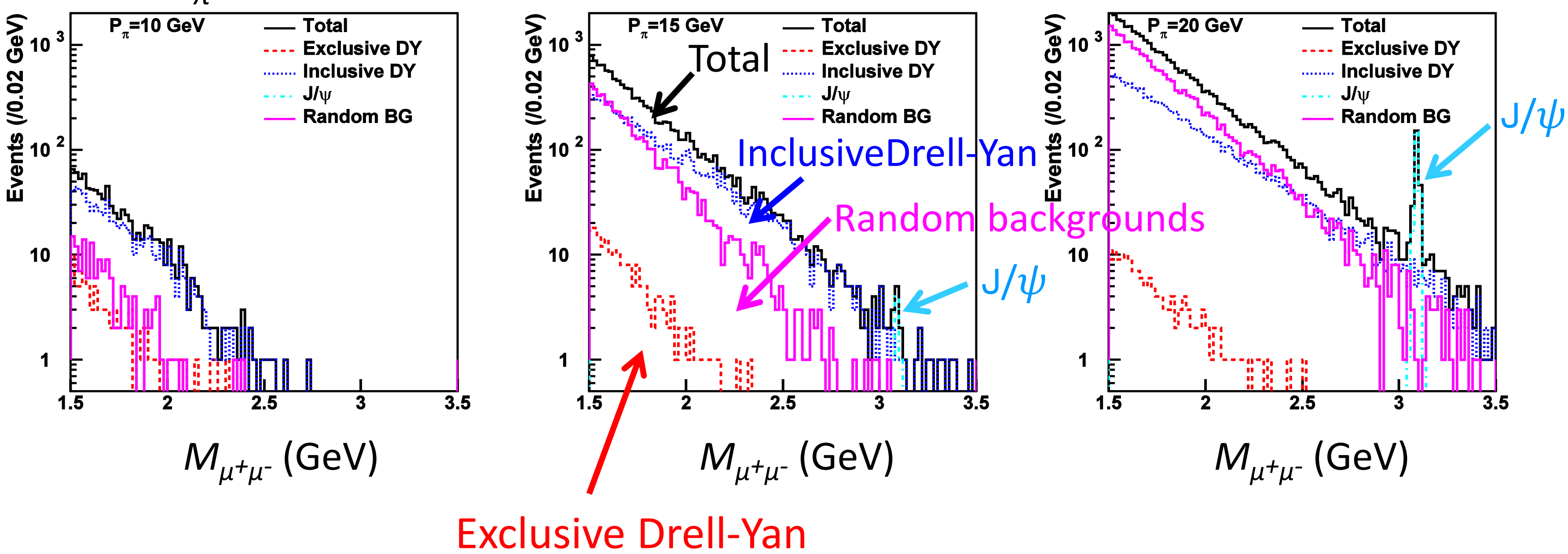
	Exclusive Drell-Yan $\left(\begin{array}{l} M_{\mu^+\mu^-} > 1.5 \text{ GeV}, \\ \lvert t - t_0 \rvert < 0.5 \text{ GeV}^2 \end{array} \right)$		Inclusive Drell-Yan $(M_{\mu^+\mu^-} > 1.5 \text{ GeV})$
	"BMP2001"	"GK2013"	
P_π= 10 GeV	6.29 pb	17.53 pb	2.11 nb
P_π= 15 GeV	4.67 pb	10.65 pb	2.71 nb
P_π= 20 GeV	3.70 pb	7.25 pb	3.08 nb

・Total hadronic interaction cross sections of $\pi^- p$ is about 20-30 mb while the production of J/ψ is about 1-3 nb

Invariant mass $M_{\mu^+\mu^-}$ spectra

π^- Beam Momentum

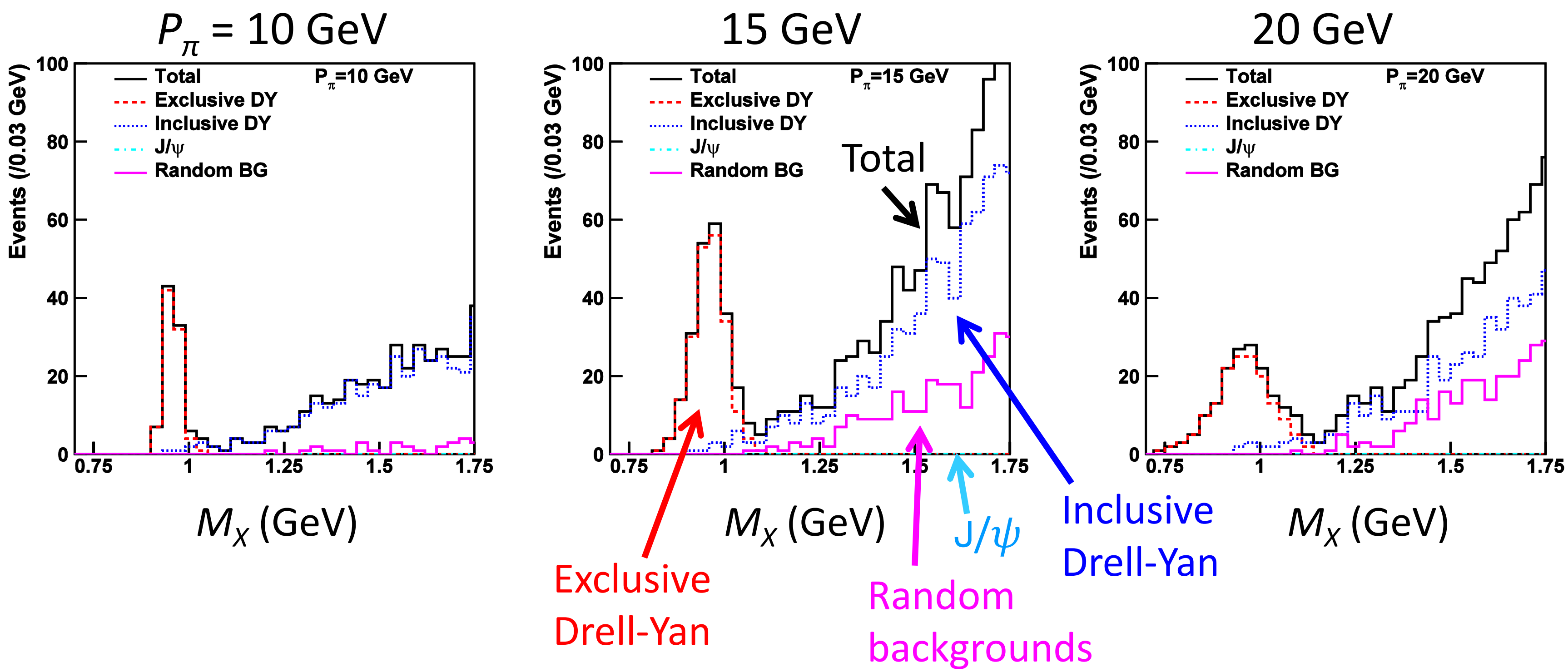
P_π = 10 GeV 15 GeV 20 GeV



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

Missing-mass M_X spectra

π^- Beam Momentum



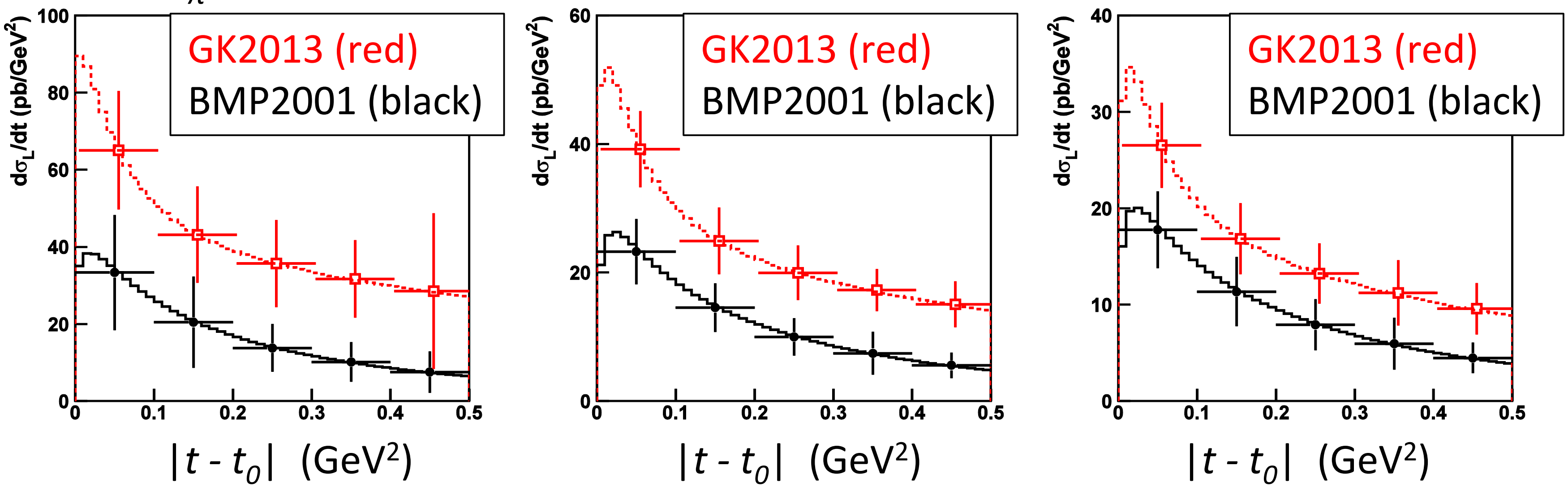
- Data Taking: 50 days
- $1.5 < M_{\mu^+\mu^-} < 2.9$ GeV
- $|t - t_0| < 0.5$ GeV^2
- "GK2013" GPDs

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

π^- Beam Momentum

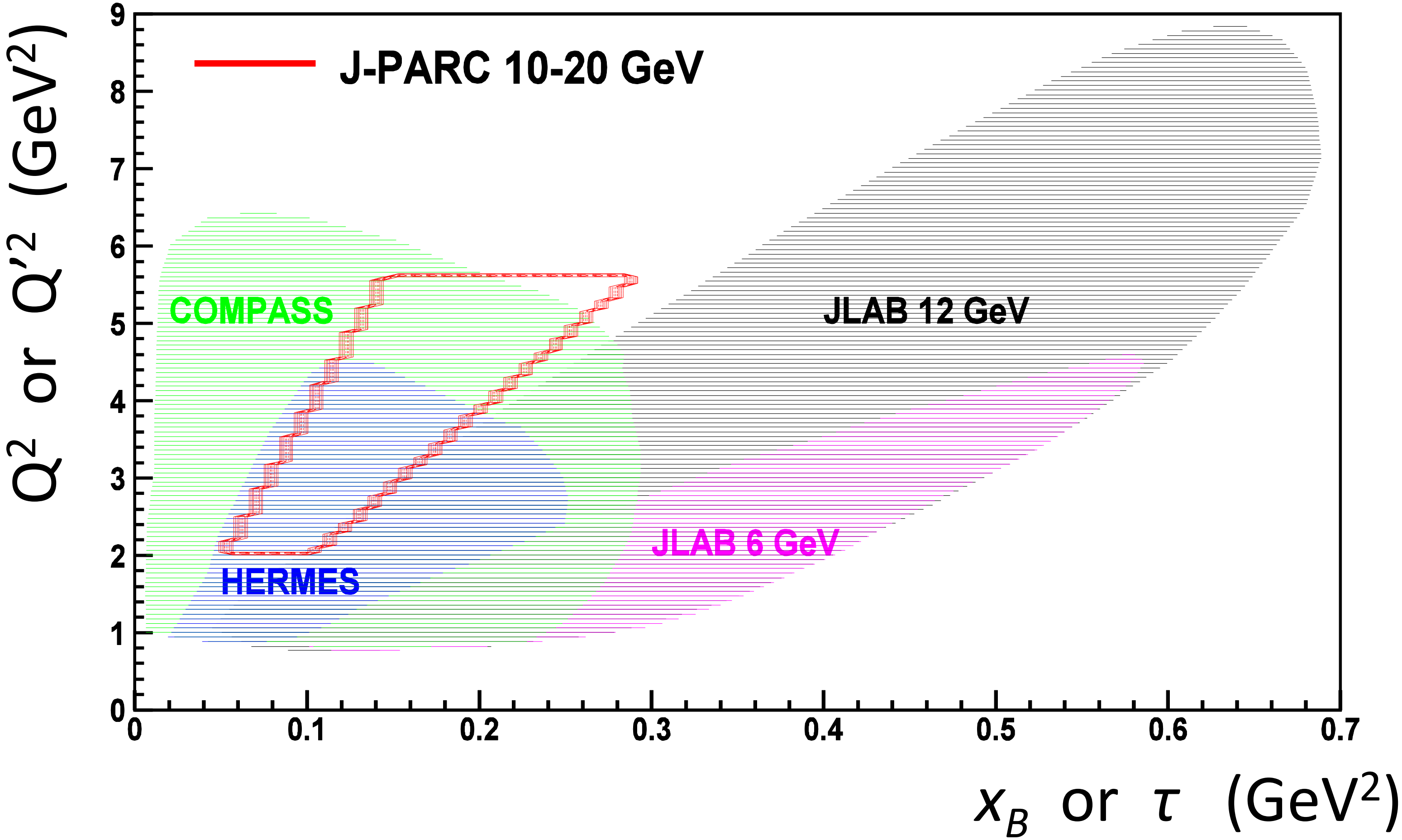
P_π = 10 GeV 15 GeV 20 GeV



- 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

Impacts and Prospects

- Impacts:
  - Factorization of exclusive Drell-Yan process.
  - Universality of GPDs in space-like and time-like processes.
  - Pion DAs and FFs.
  - Separation of contributions from GPDs and transversity-GPDs through the dilepton angular distributions.
- Prospects: with an increase of beam time (50→100 days) and beam luminosity and optimization of setup
  - GPD at large-Q^2 region
  - QCD-evolution properties of GPDs

Expected Timeline

- Beamline:
  - – High-P beamline: by April, 2020
  - – Target for secondary beams: by April, 2023
- Experiment:
  - – LoI: by December, 2018
  - – Proposal within E50 experiment: by 2019

Summary

- Measurements of the exclusive π-induced DY process will bring important understandings on
  - Factorization of exclusive Drell-Yan process
  - Universality of GPDs in the space-like and time-like processes
  - Pion DAs, FFs,…
- Preliminary study shows that such measurement is feasible with E-50 spectrometers in the coming high-momentum beamline at J-PARC.
- Submission of full proposal to J-PARC is expected by 2019. Interested collaborators are more than welcome.