Meeting on High-energy hadron physics at J-PARC
February 13 (Thursday), 2014

Study of (Exclusive) Hard Processes with Hadron Beams at J-PARC

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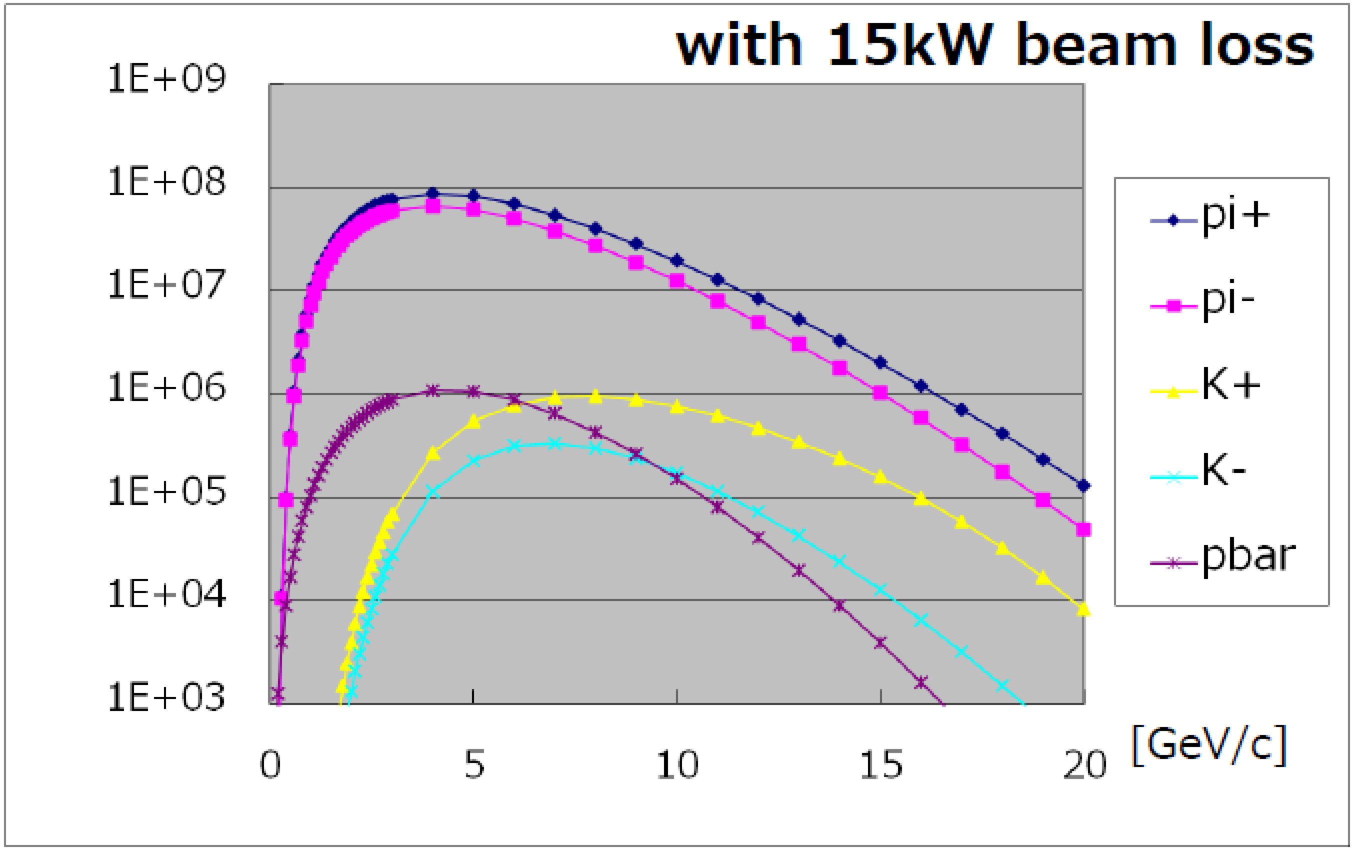
Outline

- Uniqueness of hadron physics studied at HiPBL of J-PARC
- Selected Physics Processes:
  - Drell-Yan process
  - Hard exclusive process
  - Charmed production process
- Feasibility study
- Summary

R. Muto, KEK

secondary beam intensity

beam loss limit @ SM1:15kW
(limited by the thickness of the tunnel wall)



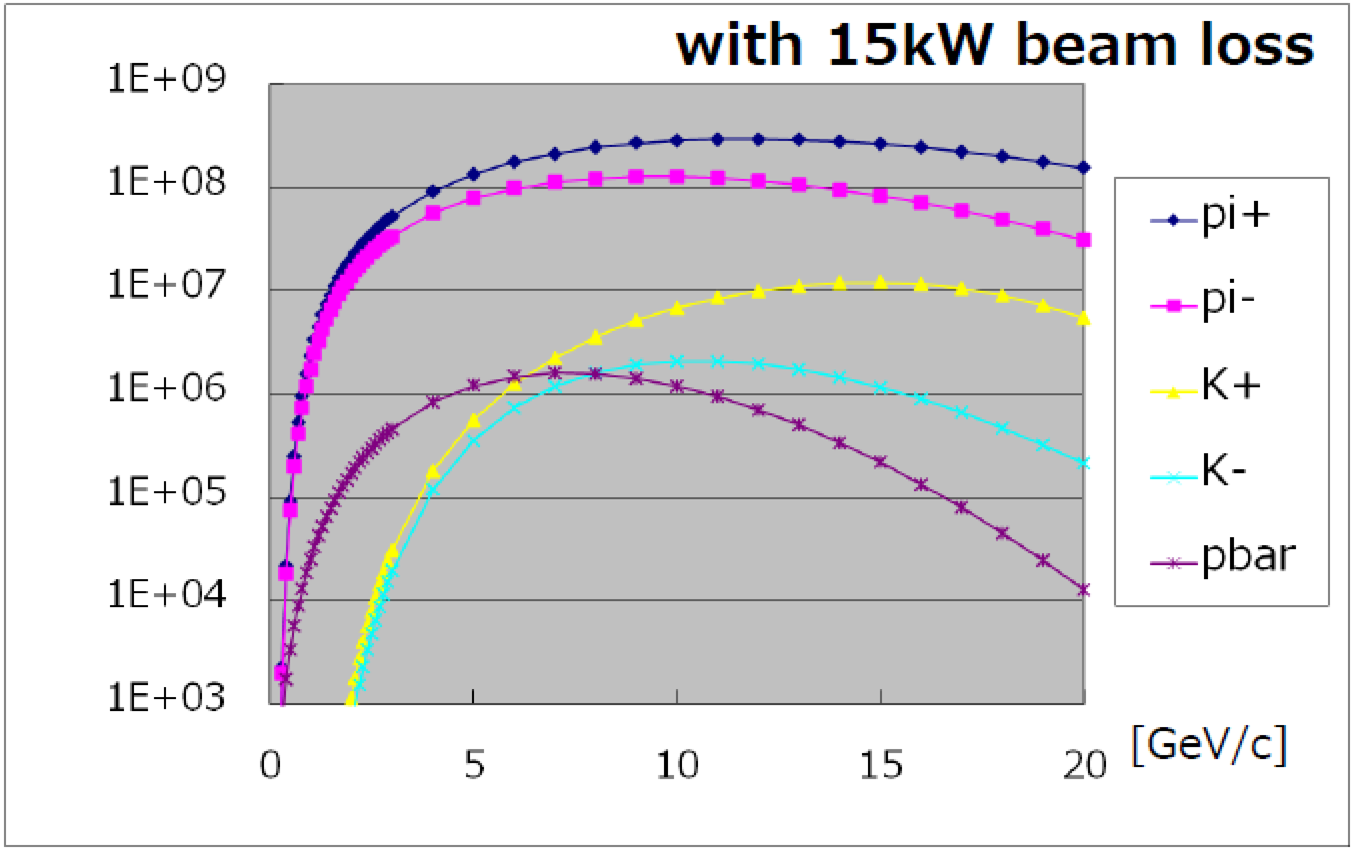
extraction angle : 5°

R. Muto, KEK

secondary beam intensity

beam loss limit @ SM1:15kW

(limited by the thickness of the tunnel wall)



extraction angle : 0°

R. Muto, KEK

expected secondary beam intensity

	p (GeV/c)	Yield 5°	Yield 0°
π+	5	**8.2E7**	**1.3E8**
π+	10	**1.9E7**	**2.8E8**
π-	5	**6.0E7**	**7.8E7**
π-	10	**1.2E7**	**1.3E8**
K+	5	**5.4E5**	**5.6E5**
K+	10	**7.6E5**	**6.8E6**
K-	5	**2.3E5**	**3.6E5**
K-	10	**1.7E5**	**2.1E6**
p bar	5	**1.1E6**	**1.2E6**
p bar	10	**1.5E5**	**1.2E6**

30 GeV proton

15 kW loss target

$(\Delta p/p)\Delta\Omega$:
0.16 msr%

beam line length :
120 m

Sanford-Wang
formula

Beam Configuration

- Primary 30-GeV proton beam at 10^{10}-10^{12}/s.
- Secondary beam:
  - Pion: 10-20 GeV at 10^{7}-10^{8}/s .
  - Kaon: 10-15 GeV at 10^{6}-10^{7}/s.
  - Anti-proton: 5-10 GeV at 10^{6}/s.

Uniqueness of hadron physics studied at HiPBL of J-PARC

- The beam energy at J-PARC at 10-20 GeV might be most ideal for discerning the quark-hadron transition in the strong interaction and studying the hard exclusive processes.
  - Valance-like partonic degrees of freedom of hadrons could be discerned, compared to the collisions at low-energy regime.
  - Reasonably large cross sections, compared to the collisions at higher energy.

http://www-conf.kek.jp/hadron1/j-parc-hm-2013/

KEK theory center workshop on
Hadron physics with high-momentum hadron beams at J-PARC in 2013
Kobayashi Hall, 1st Floor, Kenkyu-Honkan (15th, 18th)
Seminar Hall, 1st Floor, 3rd buildling (16th, 17th)
January 15 - 18, 2013, KEK, Tsukuba, Japan

[Update]
2012.08.09
Home page,
1st circular

2012.11.30

→ → A large size picture (4MB.jpg)

The talk files are available in "[MEN

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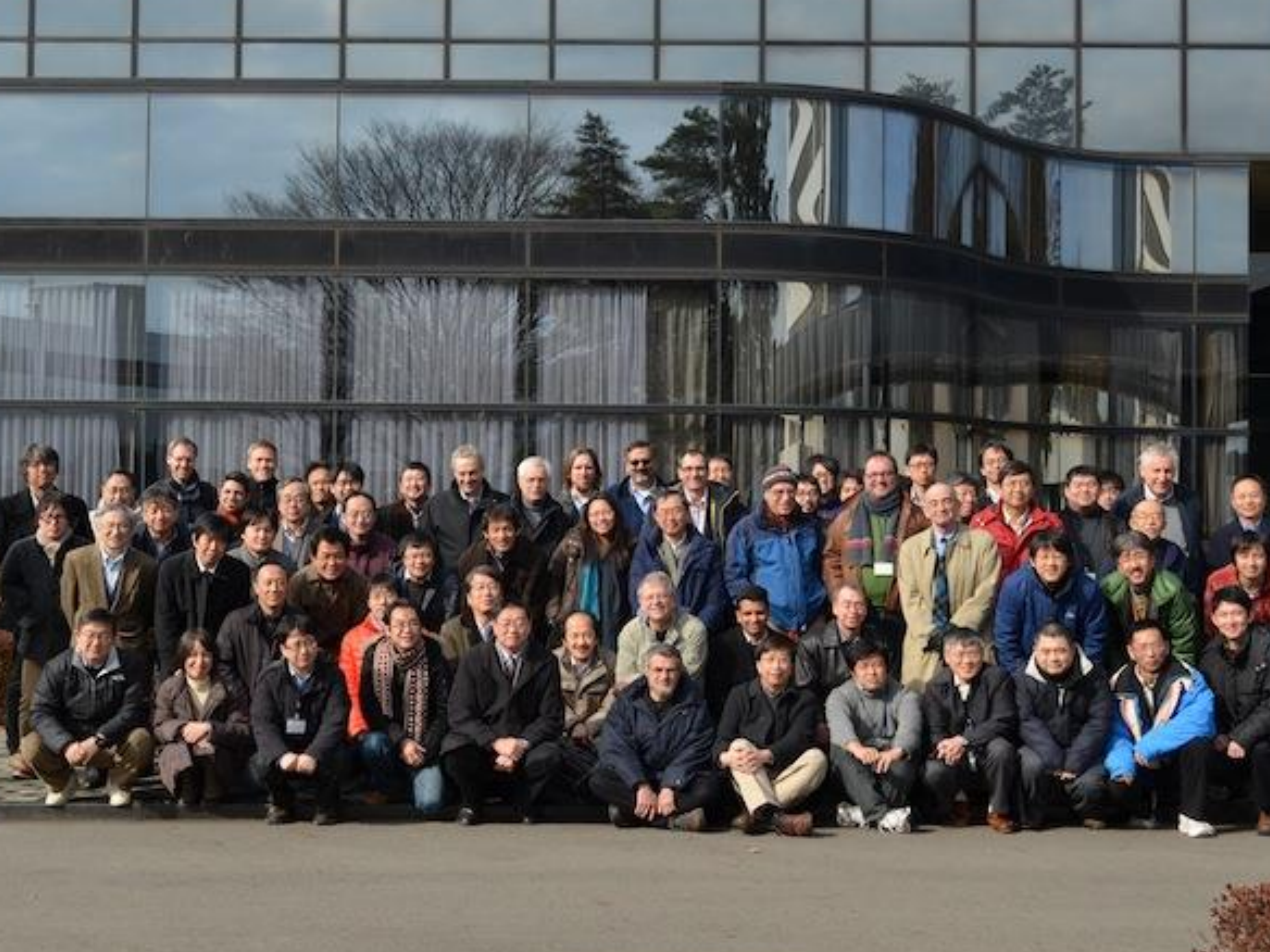
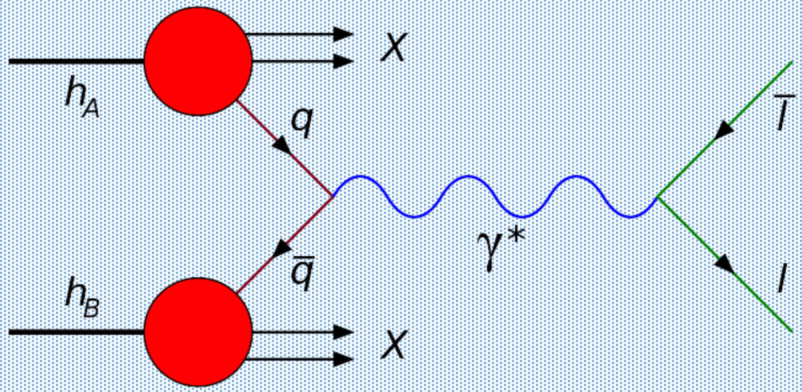


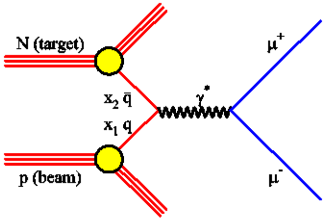
Selected Physics Processes

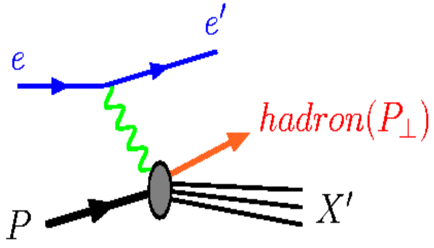
- Drell-Yan process
  - Inclusive pion-induced Drell-Yan
  - Exclusive pion-induced Drell-Yan
- Hard exclusive production process
  - Exclusive pion-N Lambda(1405) production
- Charmed production process
  - Inclusive pion-induced J/psi production
  - Exclusive pion-N J/psi production
  - Exotic charm baryons



Drell-Yan process

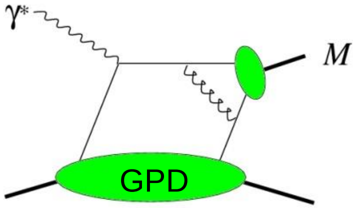
Wigner Distribution





Wigner Distribution
$W(\vec{r}, x, \vec{k}_T)$

Ji, PRL91,062001(2003)



d^3r

$d^2k_t dz$
F.T.

Transverse Momentum Dependent PDF $f(x, \vec{k}_T)$

Generalized Parton Distr.
$H(x, \xi, t)$

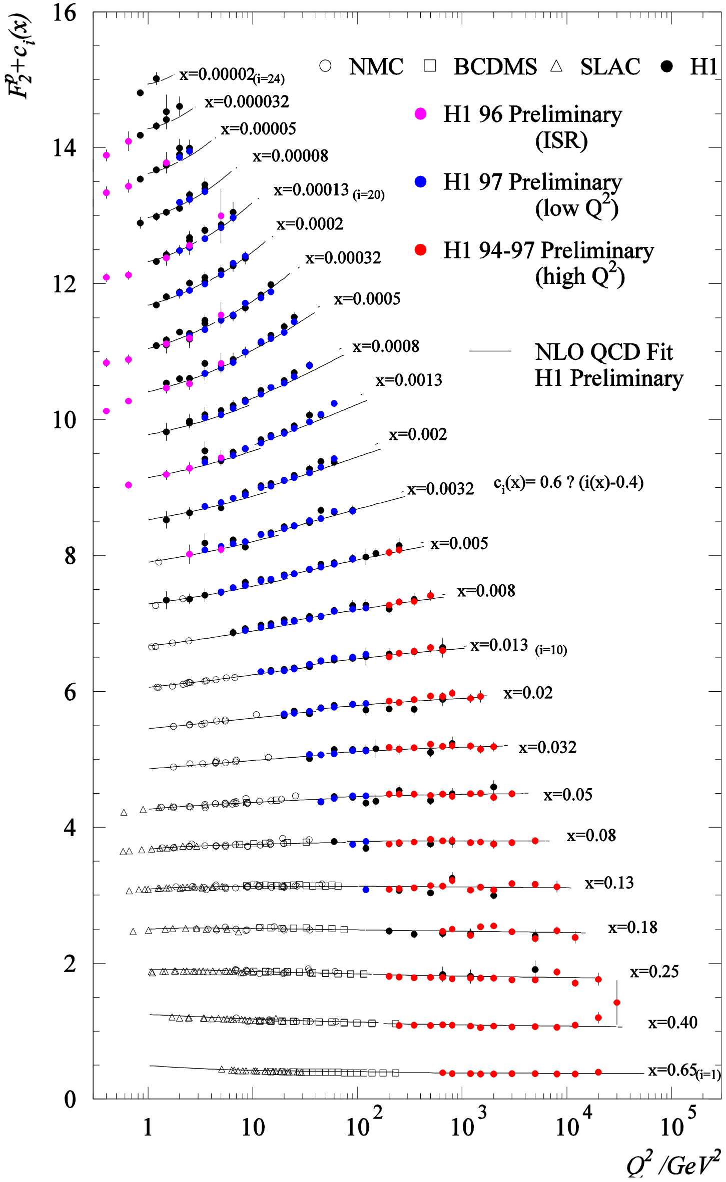
d^2k_t

dx

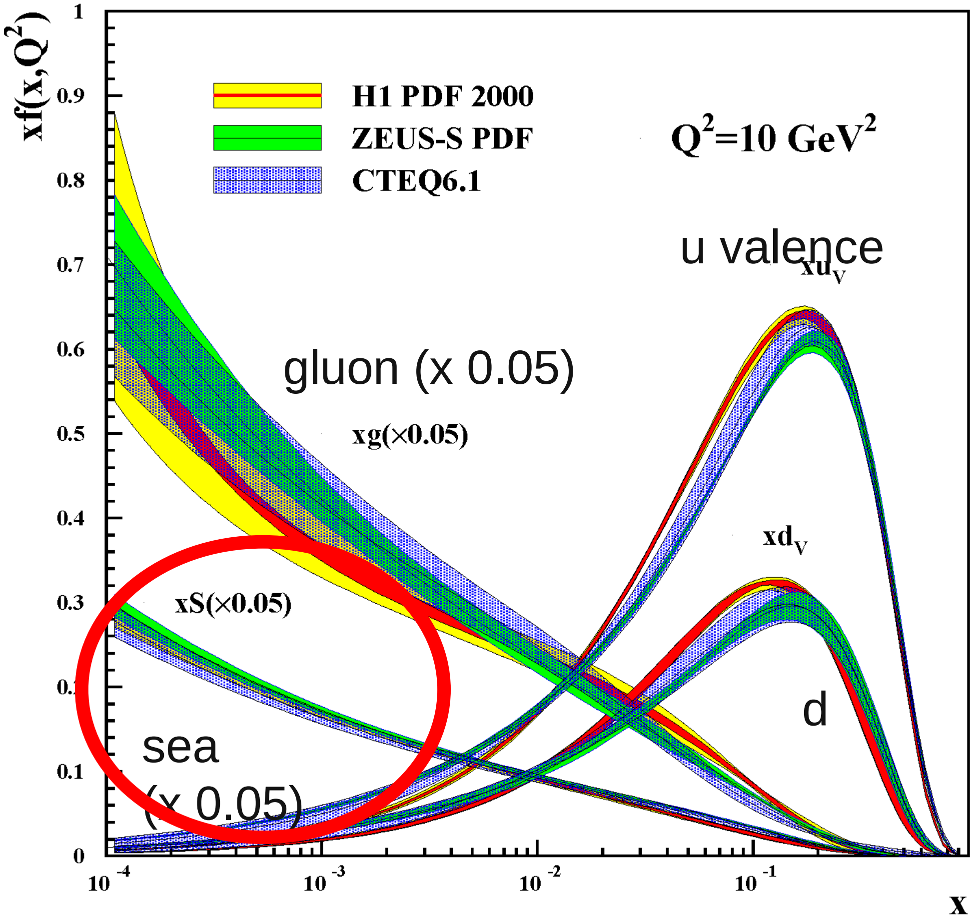
PDF
$f(x)$

Form Factors
$F_1(t), F_2(t)$

Unpolarized Parton Distributions (CTEQ6)



$$F_2(x,Q^2) = \sum_i e_i^2 x[q_i(x,Q^2) + \bar{q}_i(x,Q^2)]$$



Is $\bar{u} = \bar{d}$ in the proton?

Gottfried Sum Rule

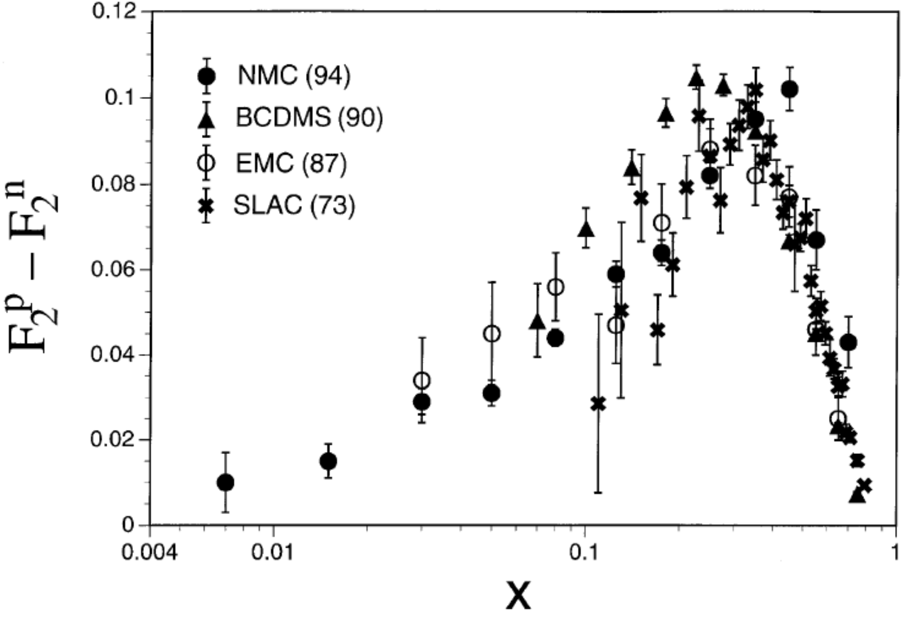
$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x))/x]dx$$

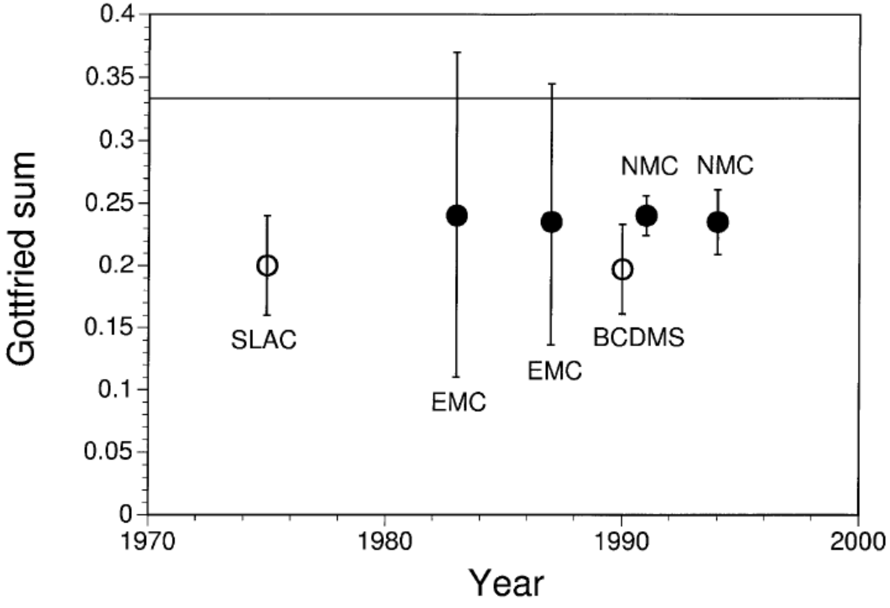
$$= \frac{1}{3}\int_0^1 (u_v(x) - d_v(x))\ dx + \frac{2}{3}\int_0^1 (\bar{u}(x) - \bar{d}(x))\ dx$$

$$= \frac{1}{3} \quad (\text{if } \bar{u}(x) = \bar{d}(x))$$

Experimental Measurement of Gottfried Sum

S. Kumano, Physics Reports, 303 (1998) 183





New Muon Collaboration (NMC), Phys. Rev. D50 (1994) R1

$$S_G = 0.235 \pm 0.026$$

(Significantly lower than 1/3 !)

Light Antiquark Flavor Asymmetry: Drell-Yan Exps

- Naïve Assumption:

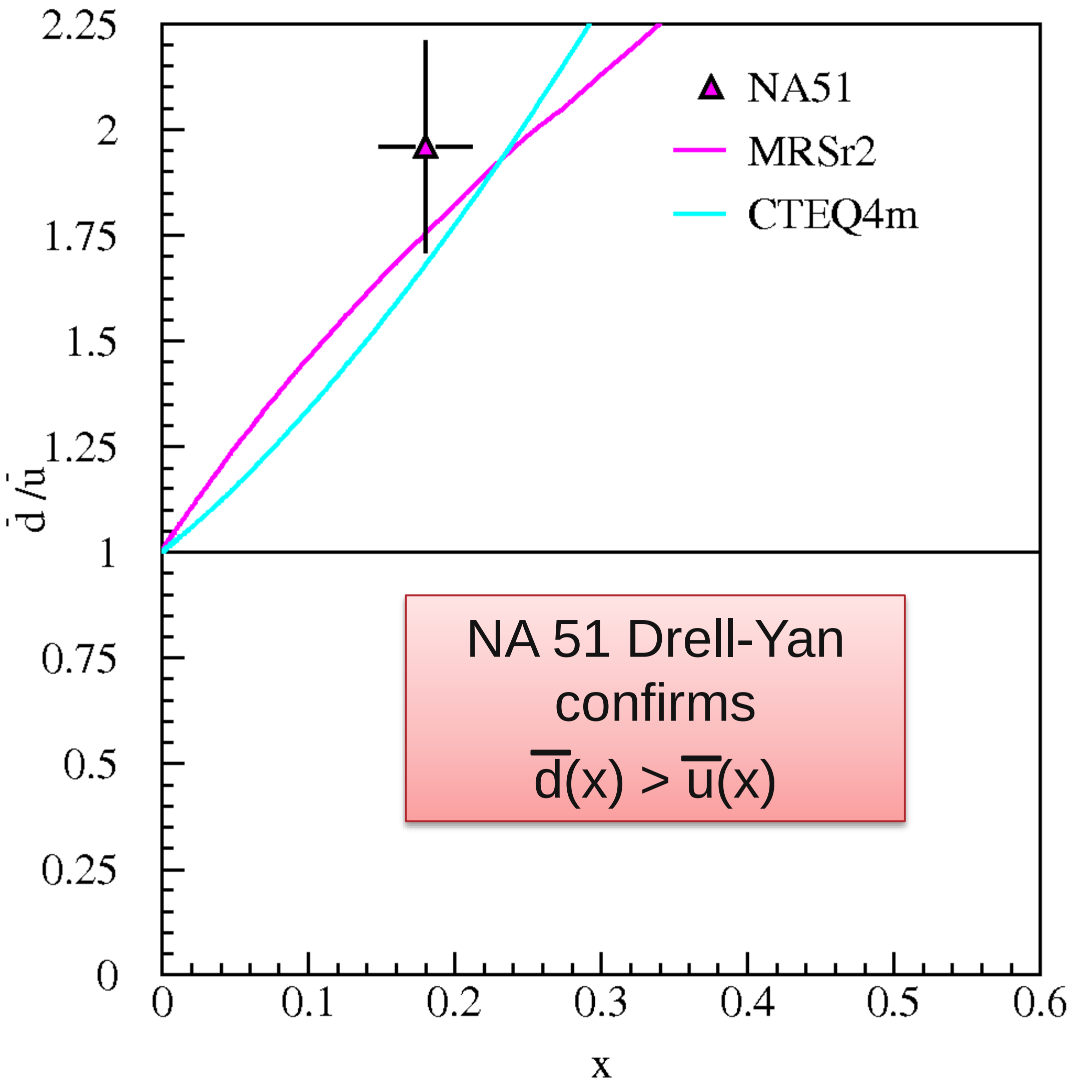
$$\bar{d}(x) = \bar{u}(x)$$

- NMC (Gottfried Sum Rule)

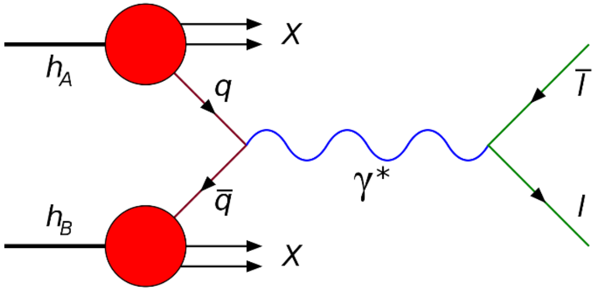
$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$

- NA51 (Drell-Yan, 1994)

$$\bar{d} > \bar{u} \text{ at } x = 0.18$$



NA 51 Drell-Yan confirms $\bar{d}(x) > \bar{u}(x)$



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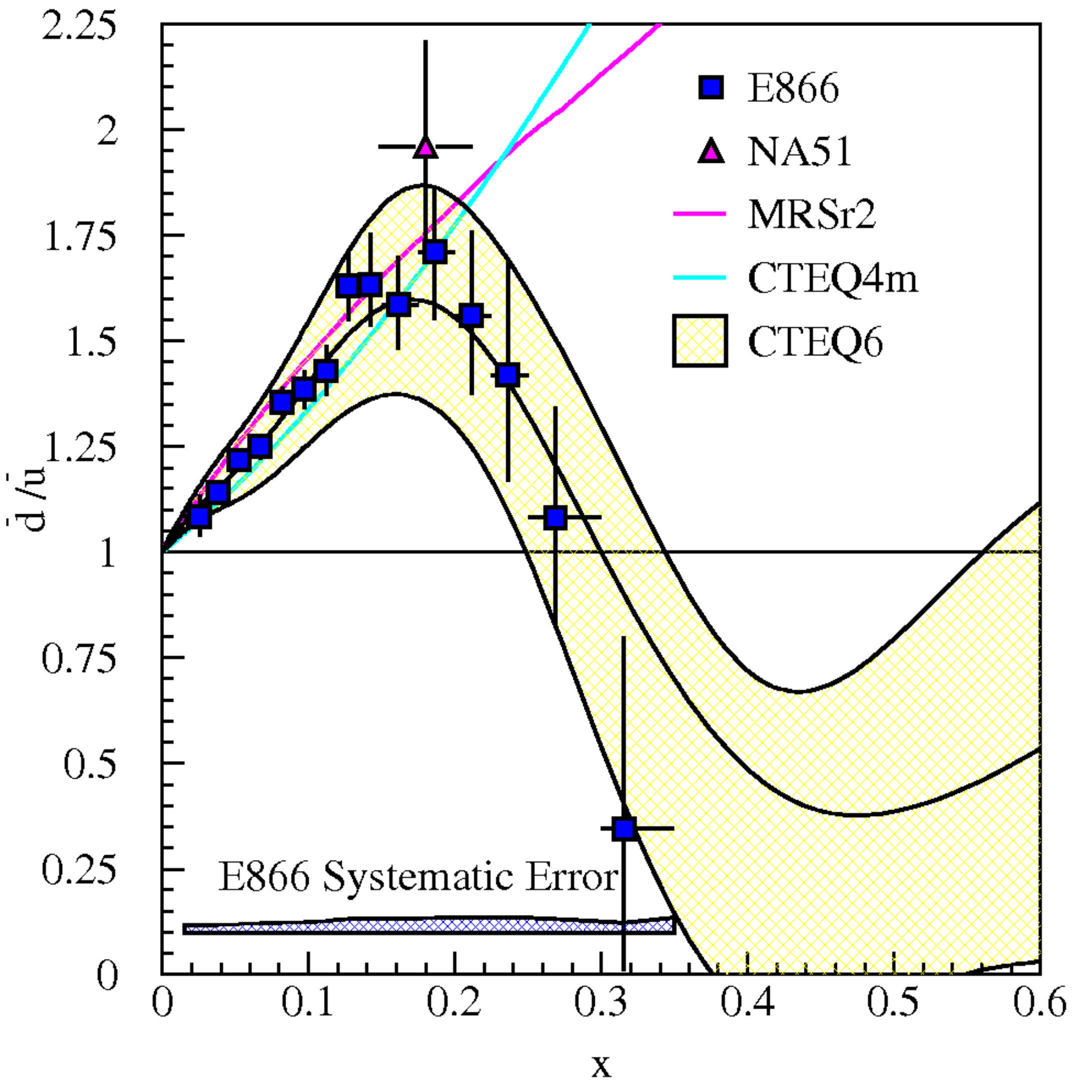
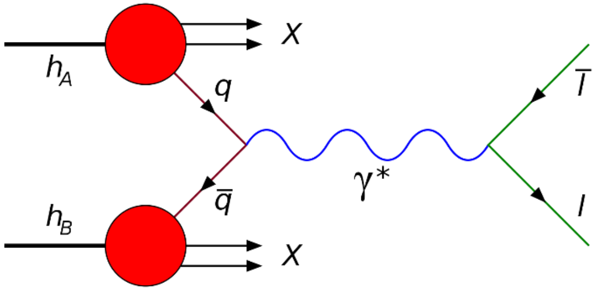
- E866/NuSea (Drell-Yan, 1998)

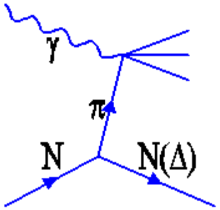
$$\bar{d}(x)/\bar{u}(x) \text{ for } 0.015 \leq x \leq 0.35$$

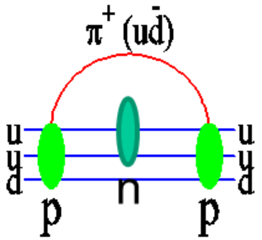




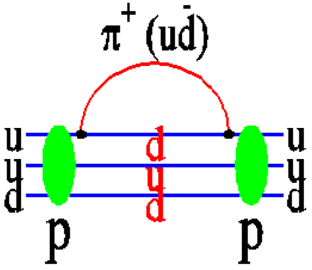
Origin of $\bar{u}(x)\neq\bar{d}(x)$?

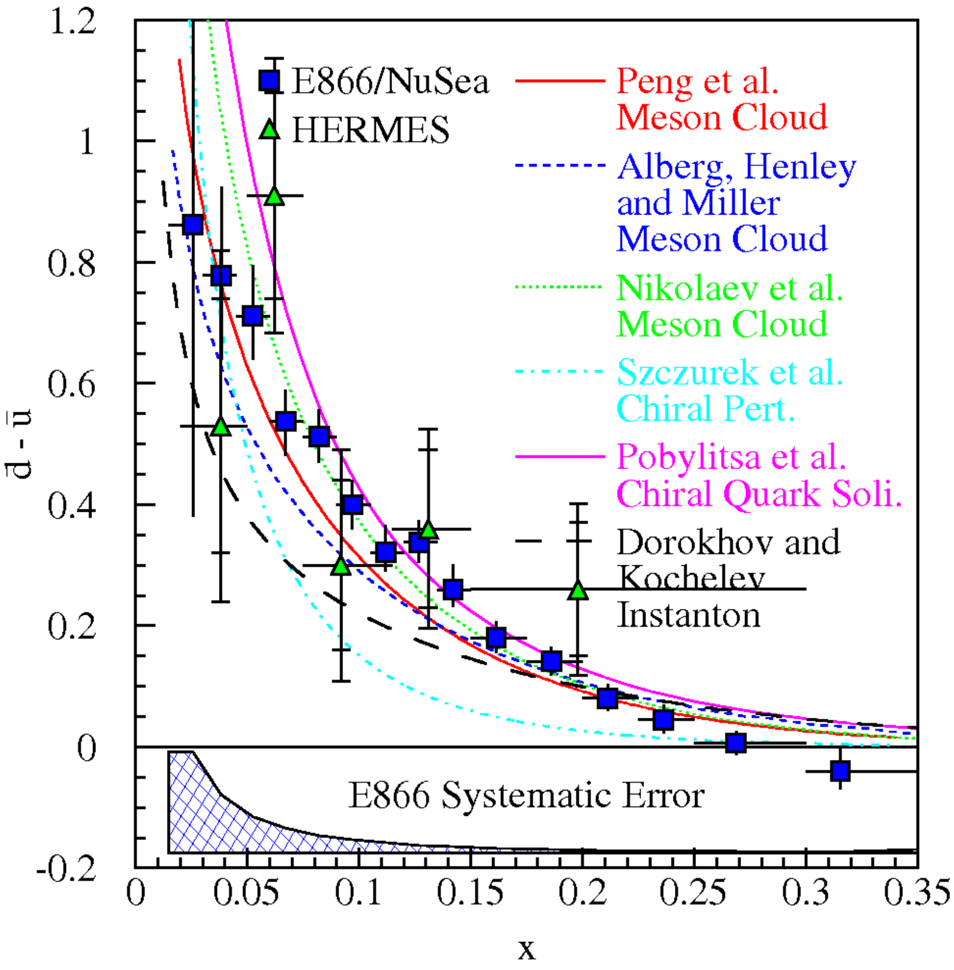
- **Pauli blocking of valance quarks**
- **Meson cloud in the nucleons** (Thomas 1983, Kumano 1991): Sullivan process in DIS.





- **Chiral quark model** (Eichten et al. 1992; Wakamatsu 1992): Goldstone bosons couple to valence quarks.

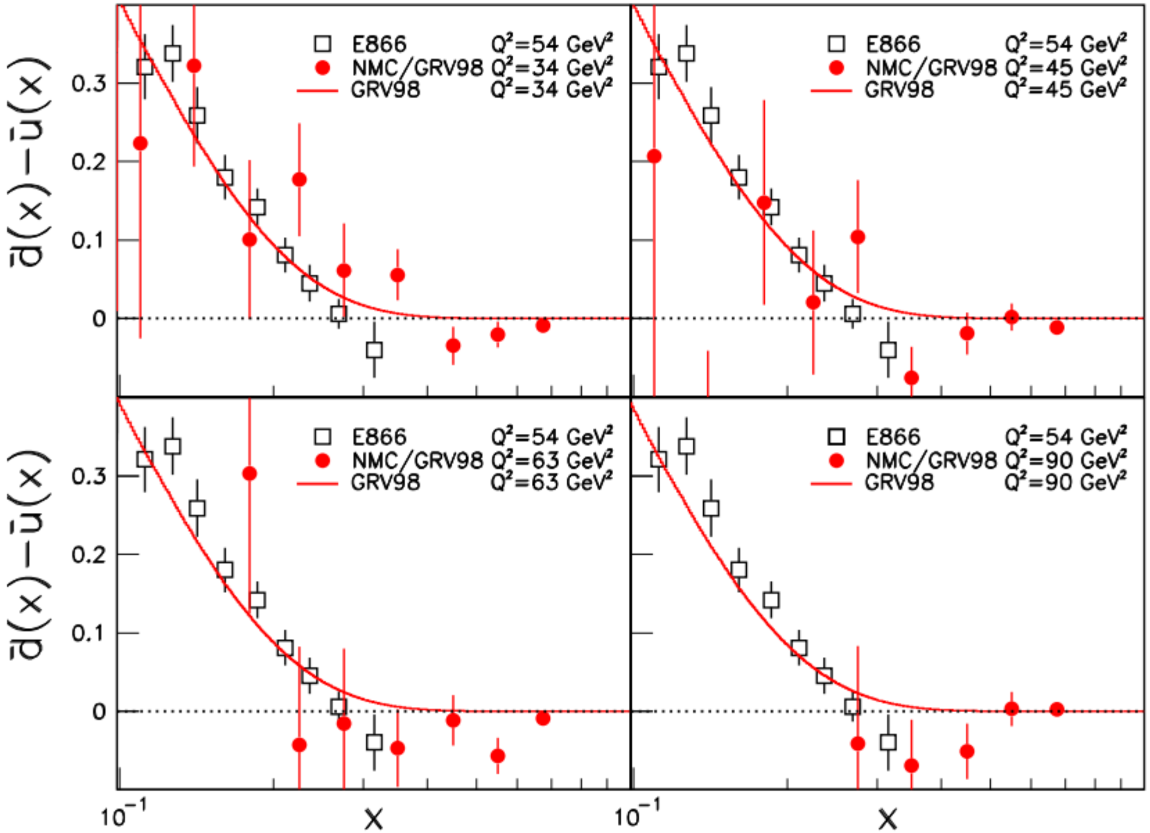




Momentum Dependence of the Flavor Structure of the Nucleon Sea

GRV98 NMC

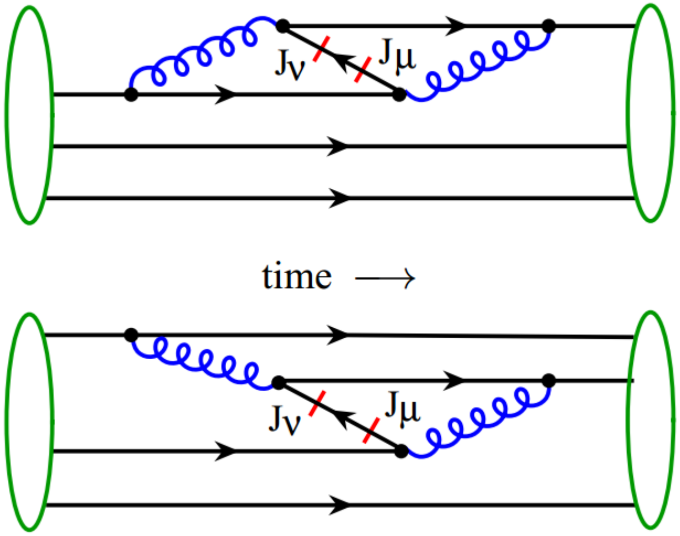
$$\bar{d}(x) - \bar{u}(x) = \frac{1}{2}[u_v(x) - d_v(x)] - \frac{3}{2x}[F_2^p(x) - F_2^n(x)].$$



Peng et al., arXiv:1401.1705

Momentum Dependence of the Flavor Structure of the Nucleon Sea

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



Peng et al., arXiv:1401.1705

1. Fluctuation of a valence quark into a quark and a highly virtual gluon,
2. A quick splitting of the gluon into a quark and antiquark pair
3. Annihilation or recombination of the quark and the newly produced antiquark into a highly virtual gluon, which is then
4. Absorbed by the quark.

Extracting d-bar/-ubar From Drell-Yan Scattering

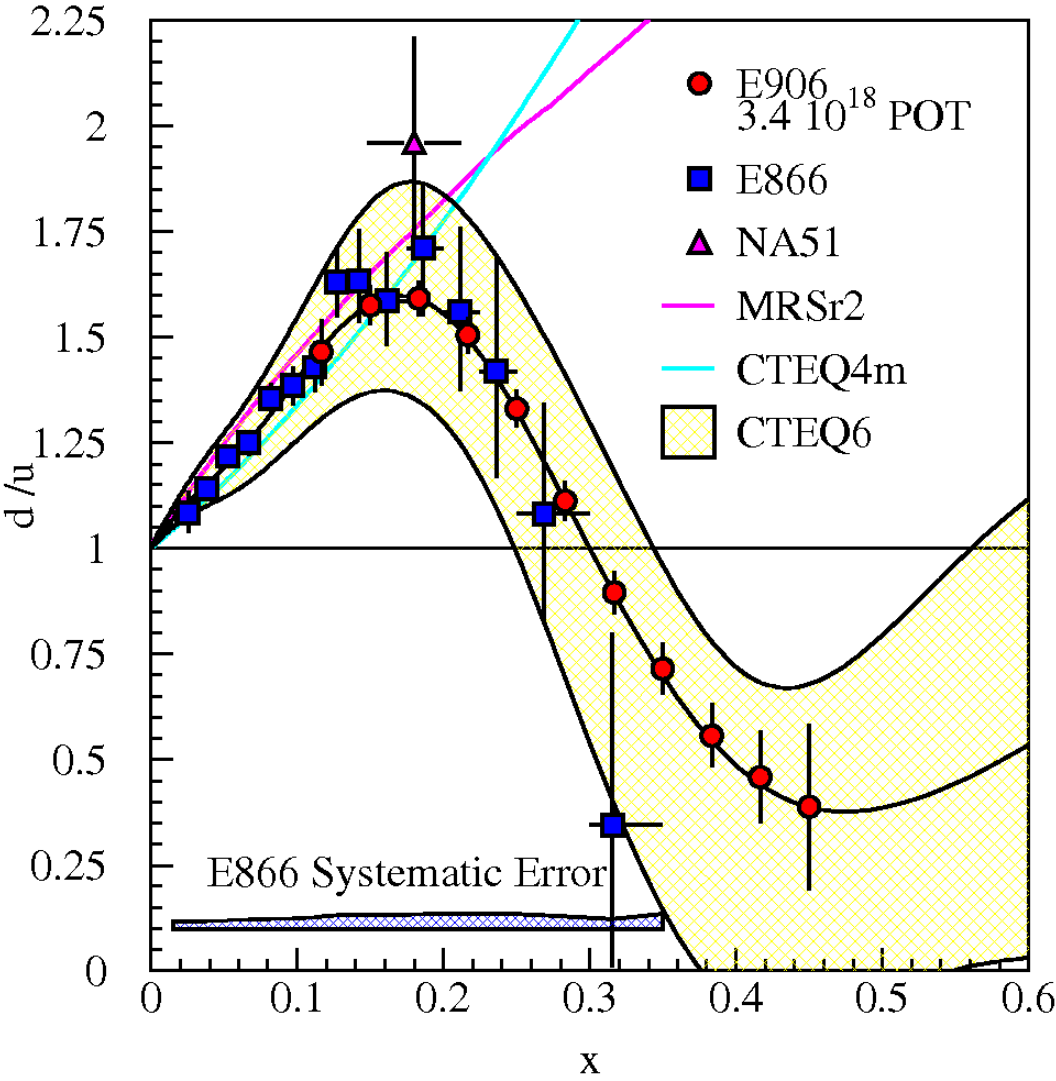
Ratio of Drell-Yan cross sections

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

(in leading order—E866 data analysis confirmed in NLO)

- Global NLO PDF fits which include E866 cross section ratios agree with E866 results
- Fermilab E906/Drell-Yan will extend these measurements and reduce statistical uncertainty.
- E906 expects systematic uncertainty to remain at approx. 1% in cross section ratio.

K. Nakano’s talk

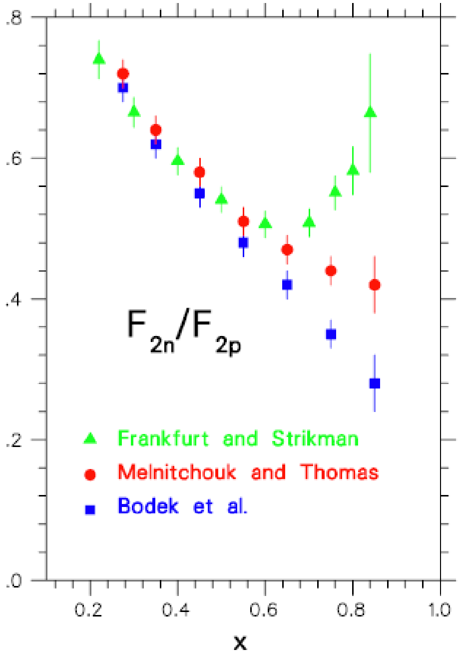


J.C. Peng

$d(x)/u(x)$ at large x

$$\frac{F_2^n}{F_2^p} \approx \left(1+4\frac{d(x)}{u(x)}\right) / \left(4+\frac{d(x)}{u(x)}\right)$$ for large *x*

Model dependence of extracting F_2^n from F_2^d



Need to measure d/u without using deuteron

3

1

Model predictions at large *x*

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

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

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

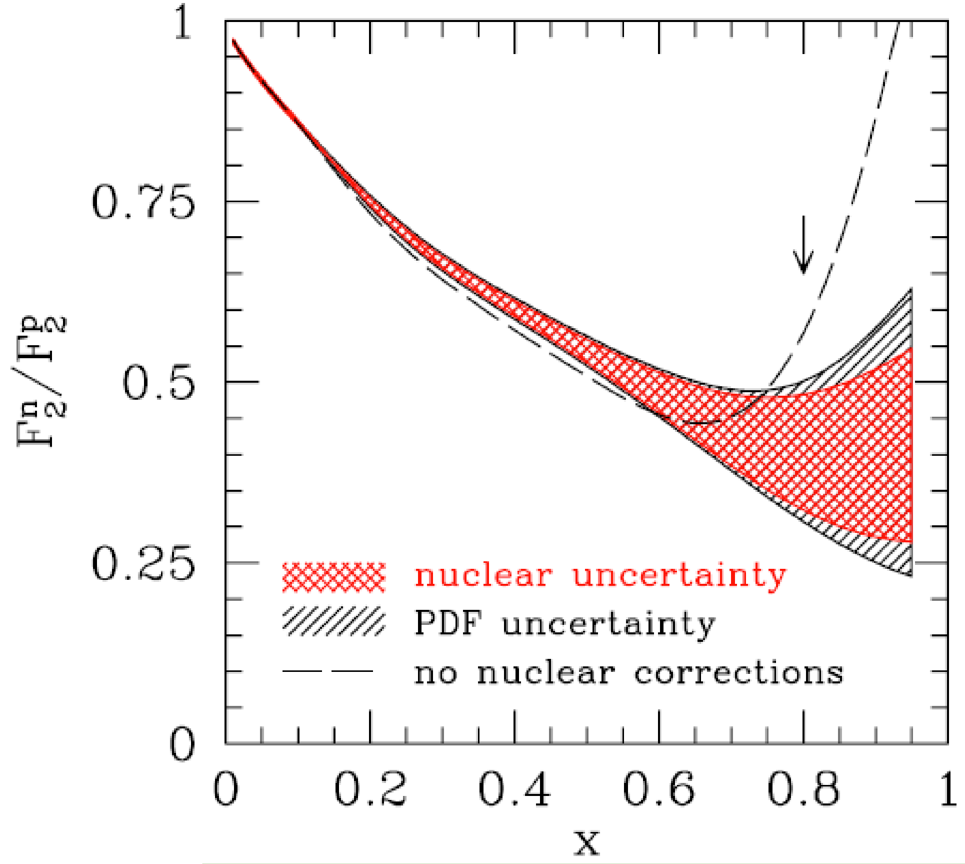
$$\frac{d}{u} = 0 \qquad \frac{F_2^n}{F_2^p} = \frac{1}{4}$$

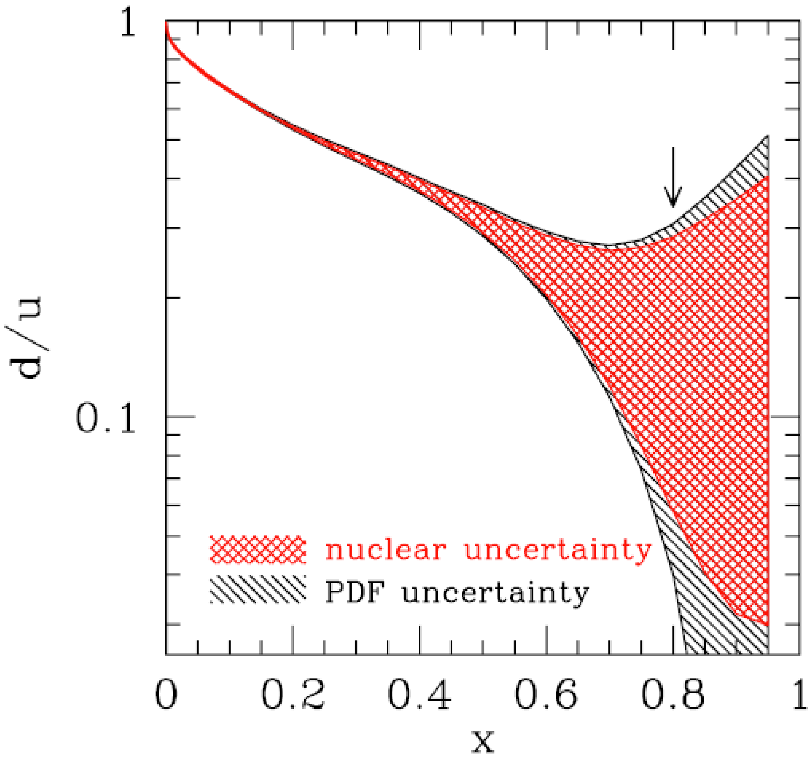
3) Dominance of $S_Z=0$ diquark configurations (Farrar, Jackson)

Ignoring terms with $S_Z=1$ diquarks, then

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

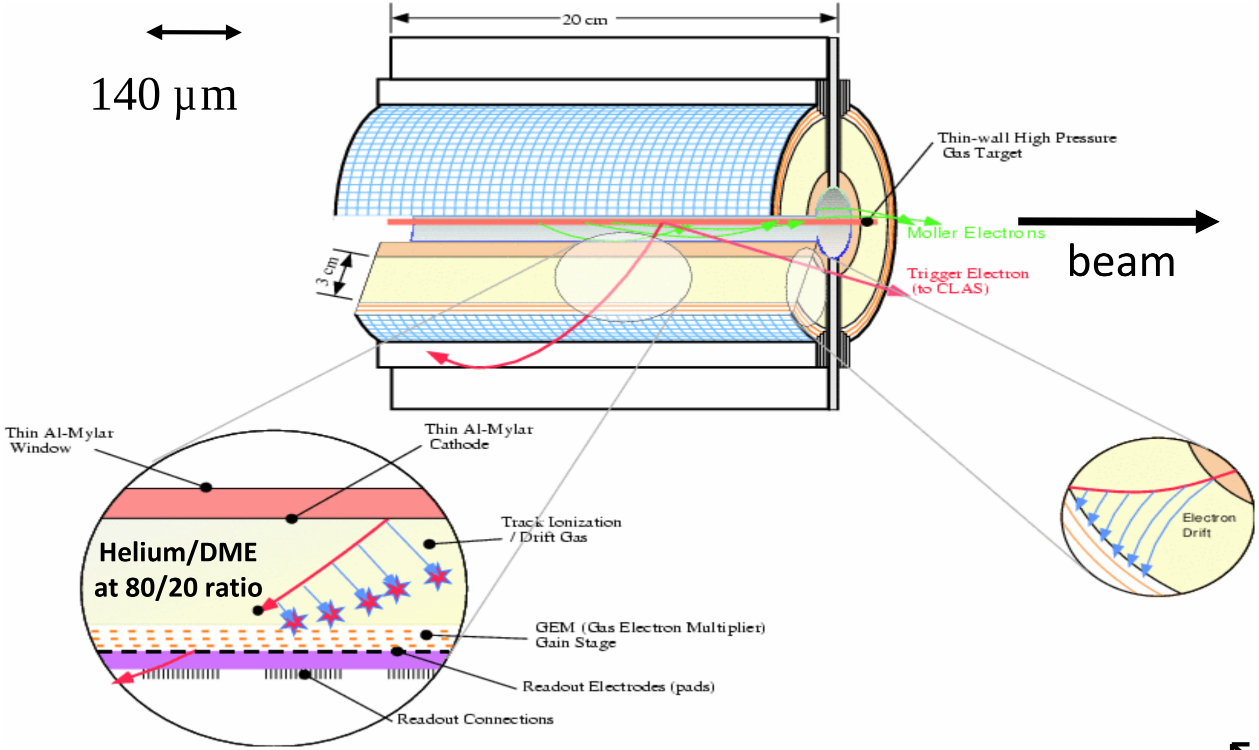
A. Accardi et al.
Phys. Rev. D 84, 014008 (2011)





- Deuteron wave function at short distances (Fermi motion)
- Nucleon off-shell effect
- Nuclear correction

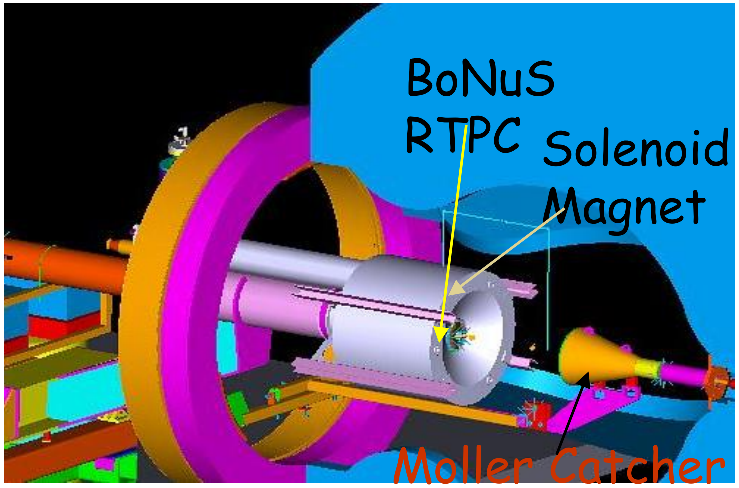
Experimental Setup II: BoNuS RTPC

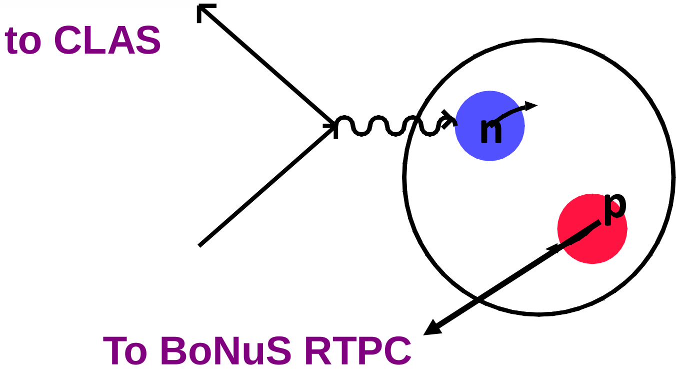


Fit RTPC points to determine helix of proton trajectory.

Momentum determined from track curvature in solenoid field.

dE/dx along track in RTPC also provides momentum information.

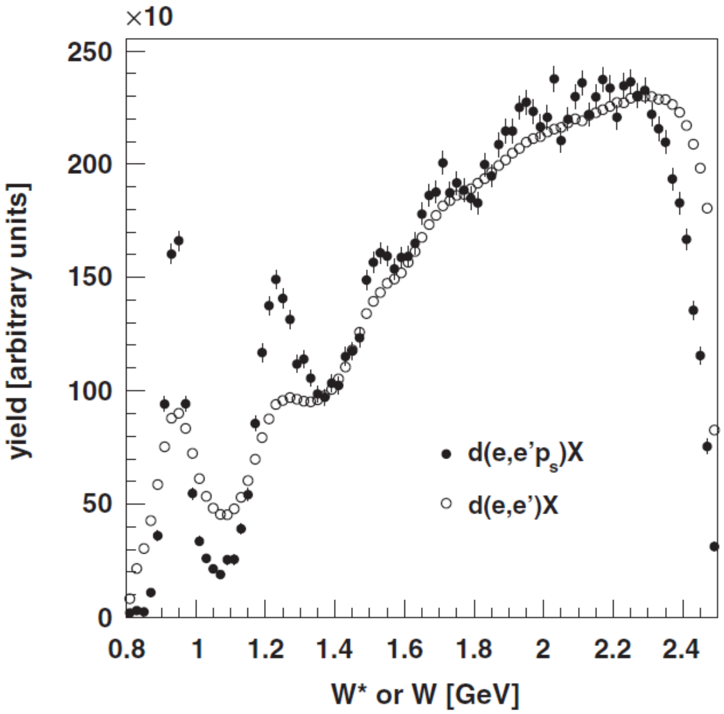


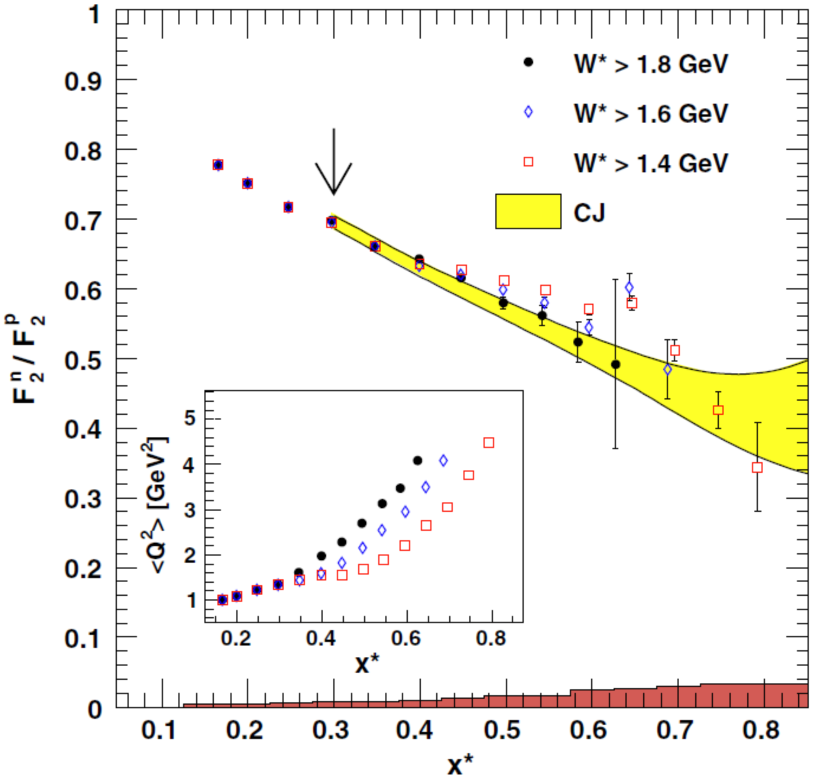


M. Eric Christy

Neutron F_2 Structure Function via Spectator Tagging

PRL 108, 142001 (2012)





$$0.65 < Q^2 < 4.52 \text{ GeV}$$

$$0.2 < x < 0.8$$

Pion-Induced DY
Without OR With Spectator Tagging

$$\frac{\pi^- p}{\pi^- d}(x_f) \approx \frac{\bar{u}^{\pi}(x_1)u^p(x_2)}{\bar{u}^{\pi}(x_1)u^n(x_2)+\bar{u}^{\pi}(x_1)u^p(x_2)} \approx \frac{u^p(x_2)}{d^p(x_2)+u^p(x_2)}$$

$$\frac{\pi^- p}{\pi^- n}(x_f) \approx \frac{\bar{u}^{\pi}(x_1)u^p(x_2)+d^{\pi}(x_1)\bar{d}^p(x_2)}{\bar{u}^{\pi}(x_1)u^n(x_2)+d^{\pi}(x_1)\bar{d}^n(x_2)} \approx \frac{\bar{u}^{\pi}(x_1)u^p(x_2)}{\bar{u}^{\pi}(x_1)d^p(x_2)}$$

$$\frac{\pi^+ p}{\pi^+ d}(x_f) \approx \frac{\bar{d}^{\pi}(x_1)d^p(x_2)}{\bar{d}^{\pi}(x_1)d^n(x_2)+\bar{d}^{\pi}(x_1)d^p(x_2)} \approx \frac{d^p(x_2)}{u^p(x_2)+d^p(x_2)}$$

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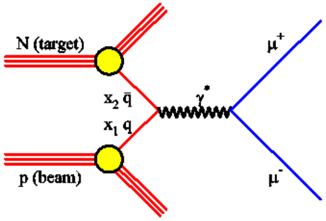
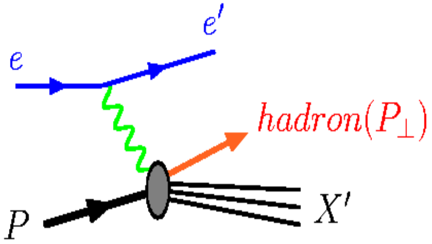
$$\frac{\pi^- p}{\pi^+ p}(x_f) \approx \frac{\bar{u}^{\pi}(x_1)u^p(x_2)}{\bar{d}^{\pi}(x_1)d^p(x_2)} \approx \frac{u^p(x_2)}{d^p(x_2)}$$

Wigner Distribution





Wigner Distribution

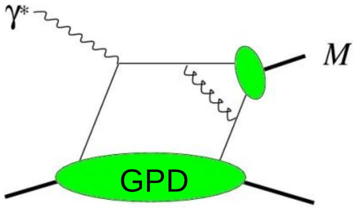
$W(\vec{r}, x, \vec{k}_T)$

Ji, PRL91,062001(2003)

d^3r

d^2k_tdz

F.T.



Transverse Momentum Dependent PDF $f(x, \vec{k}_T)$

Generalized Parton Distr. $H(x, \xi, t)$

d^2k_t

dx

PDF $f(x)$

Form Factors $F_1(t), F_2(t)$

Transverse momentum dependent (TMD) PDF

three distribution functions are necessary to describe the quark structure of the nucleon at LO in the collinear case

taking into account the quark intrinsic transverse momentum k_T,

At leading order 8 PDFs are needed.

T-odd

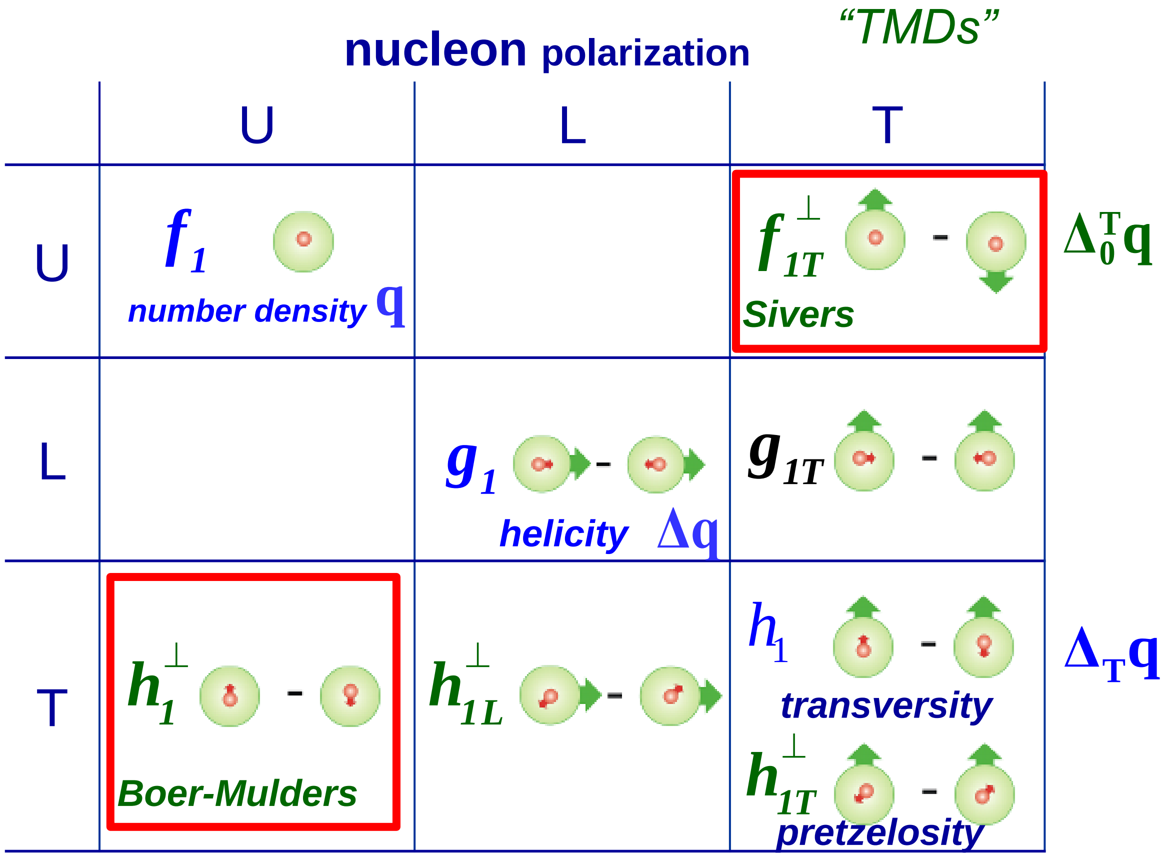
Sivers function $f_{1T}^{\perp}(x, k_T)$

correlation between the transverse spin of the nucleon and the transverse momentum of the quark

sensitive to orbital angular momentum

Boer-Mulders function $h_1^{\perp}(x, k_T)$

correlation between the transverse spin and the transverse momentum of the quark in unpol nucleons



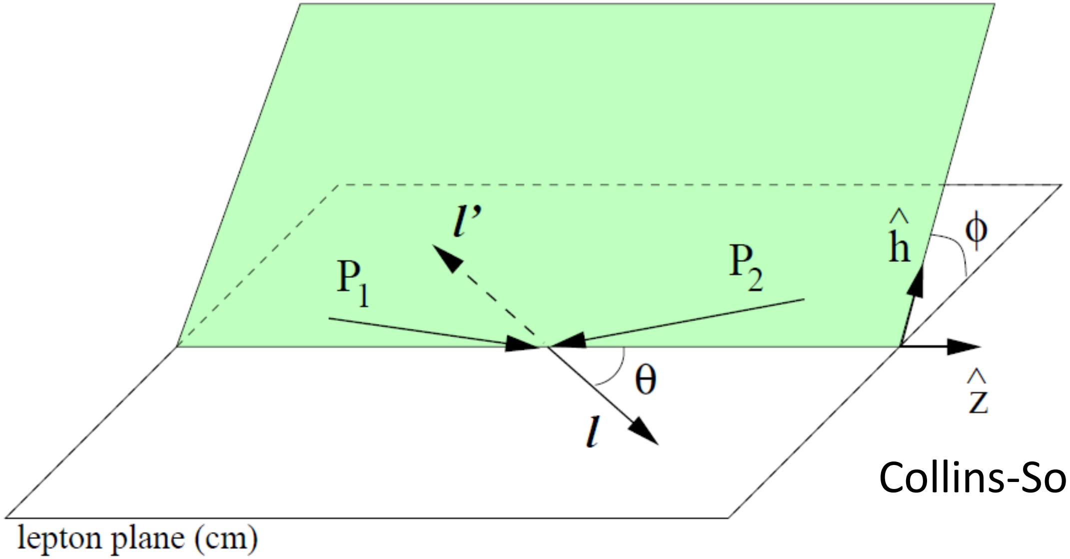
“TMDs”

nucleon **polarization**

quark polarization

	U	L	T	
U	f_1 *number density* q		$f_{1T}^{\perp}$ - *Sivers*	$\Delta_0^T q$
L		g_1 - *helicity* Δq	g_{1T} -	
T	$h_1^{\perp}$ - *Boer-Mulders*	$h_{1L}^{\perp}$ -	h_1 - *transversity* $h_{1T}^{\perp}$ - *pretzelosity*	$\Delta_T q$

Angular Distribution of Lepton Pair



Collins-Soper Frame

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

$$\propto (W_T(1+\cos^2\theta)+W_L(1-\cos^2\theta)+W_\Delta\sin 2\theta\cos\phi+W_{\Delta\Delta}\sin^2\theta\cos 2\phi)$$

$q\bar{q}$ annilation parton model:

$O(\alpha_s^0)$ λ=1, μ=ν=0; $W_T=1, W_L=0$

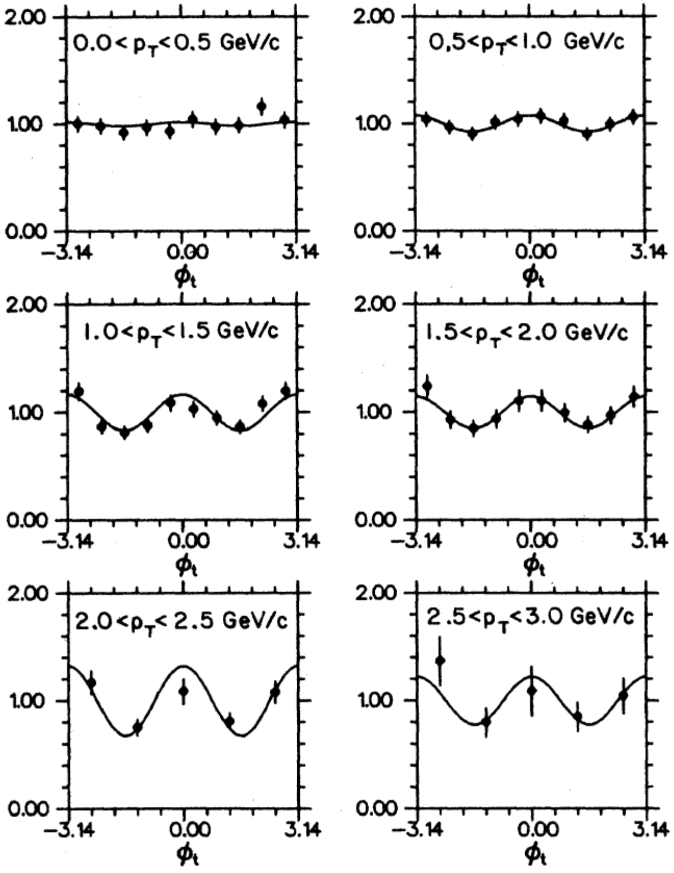
Lam and Tung (PRD 18, 2447, (1978))
Lam-Tung Relation

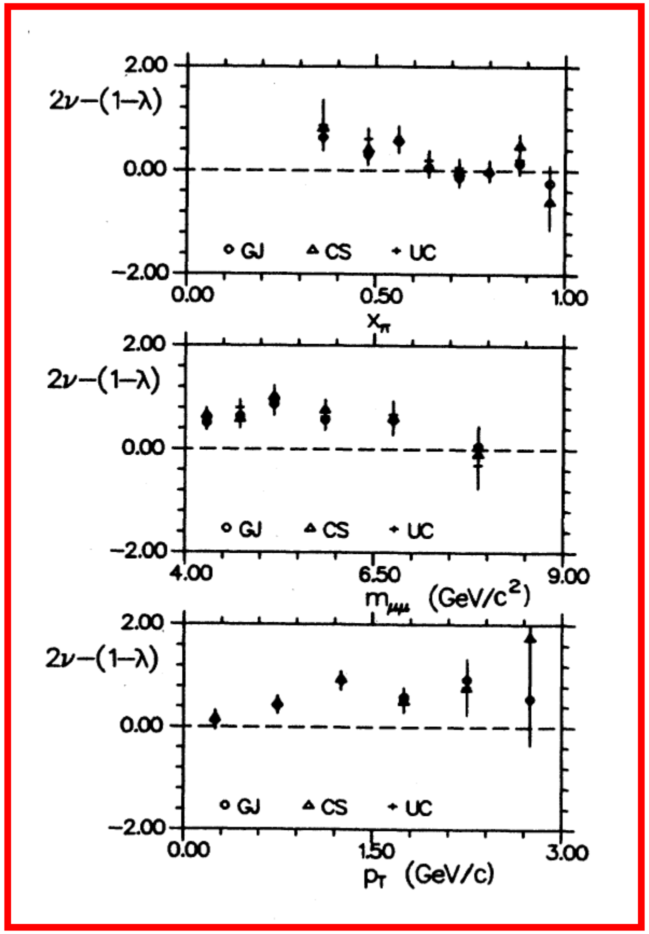
$$\frac{d\sigma}{d\Omega} \propto [W_T(1+\cos^2\theta)+W_L(1-\cos^2\theta)+W_\Delta \sin 2\theta \cos\phi + W_{\Delta\Delta}\sin^2\theta\cos 2\phi]$$

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

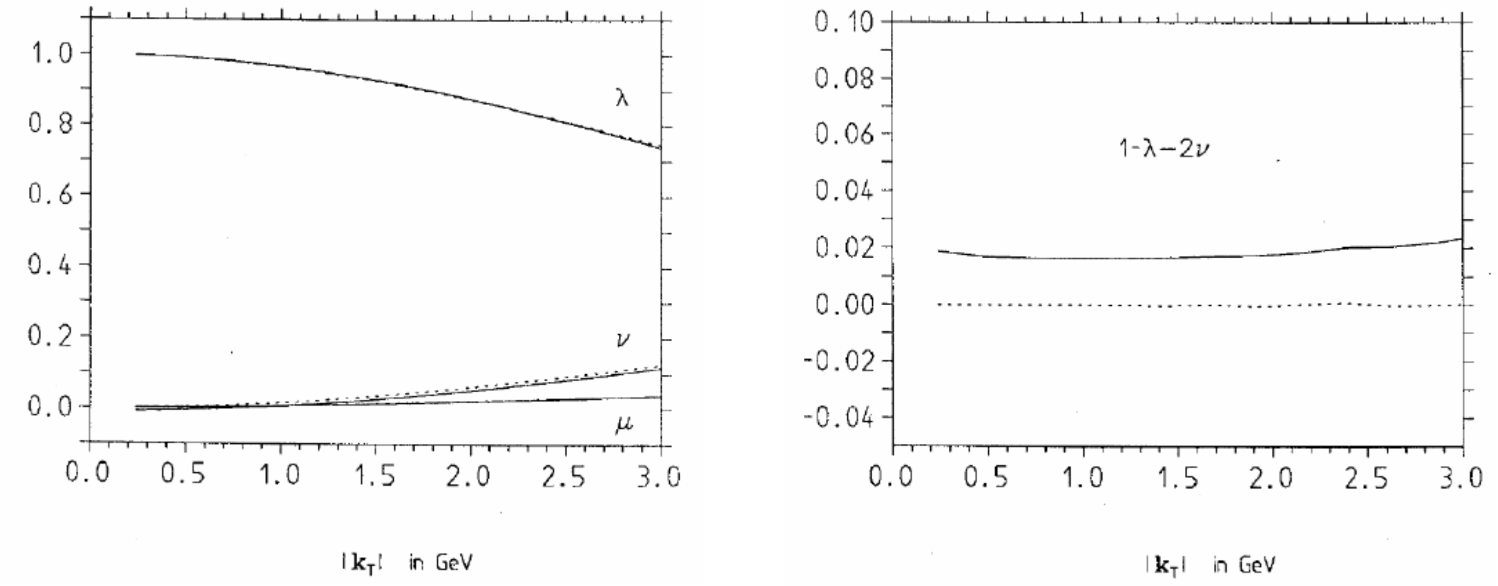
pQCD: $\mathrm{O}(\alpha_s^1)$, $W_L = 2W_{\Delta\Delta}$; $1-\lambda-2\nu=0$

E615 (PRD 39, 92 (1989))
Violation of LT Relation





Angular asymmetries in Drell-Yan in theory



Dashed lines: $\mathcal{O}(\alpha_s)$; Solid lines: $\mathcal{O}(\alpha_s^2)$; $Q = 8$ GeV

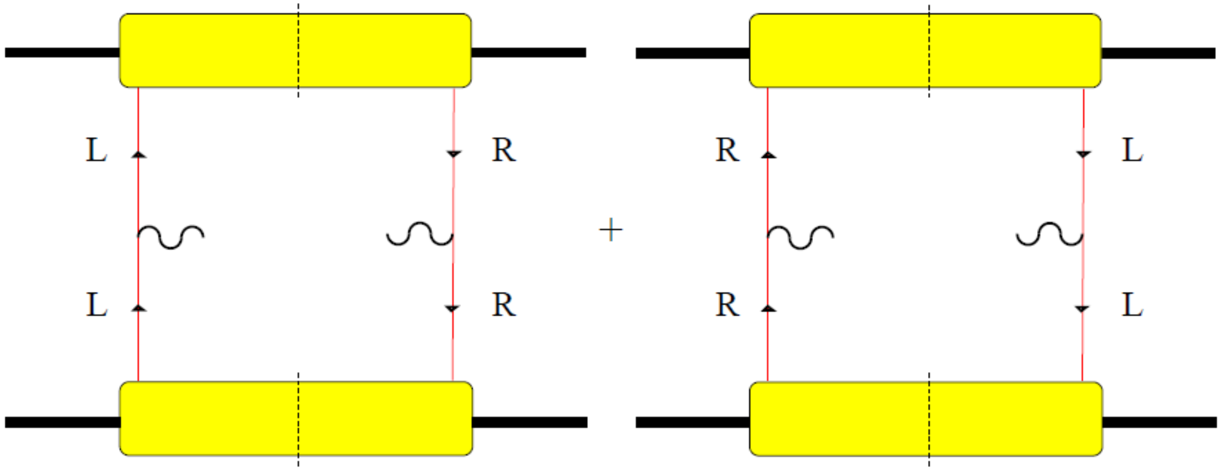
Brandenburg, Nachtmann & Mirkes, ZPC 60 (1993) 697

D. Boer

Angular asymmetry requires helicity flip

The $\cos 2\phi$ asymmetry arises from an interference between $+1$ and -1 photon helicities

$\nu \neq 0$

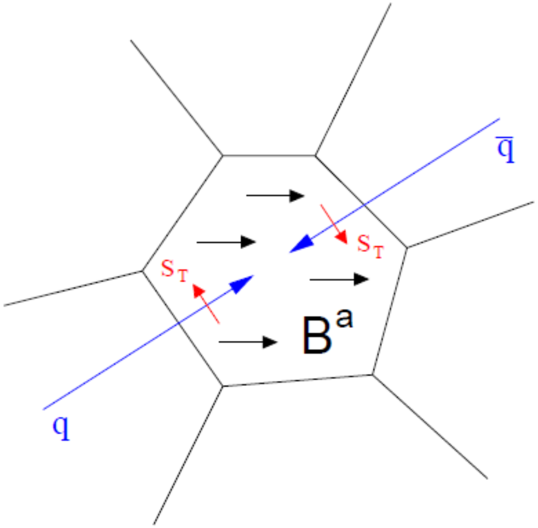


This requires transversely polarized quark-antiquark annihilation

D. Boer

Explanation as a QCD vacuum effect

The QCD vacuum can induce a spin correlation between an annihilating $q\,\bar{q}$



Chromo-magnetic Sokolov-Ternov effect:
spin-flip gluon synchrotron emission leading to a correlated polarization of q and qbar.

The spin density matrix becomes:

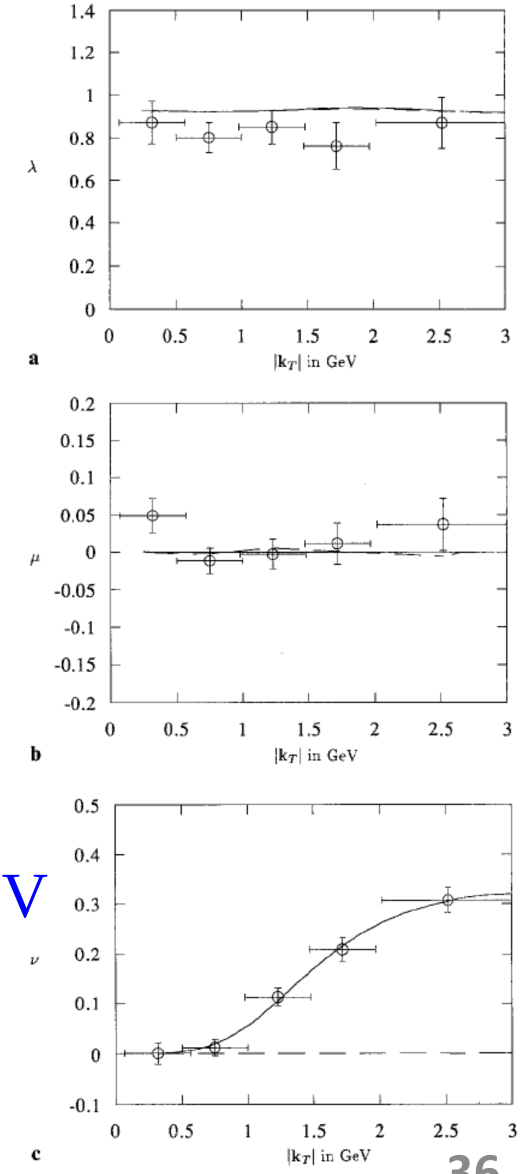
$$\rho^{(q,\bar{q})} = \frac{1}{4}\{\mathbf{1}\otimes\mathbf{1} + F_j\,\boldsymbol{\sigma}_j\otimes\mathbf{1} + G_j\,\mathbf{1}\otimes\boldsymbol{\sigma}_j + H_{ij}\,\boldsymbol{\sigma}_i\otimes\boldsymbol{\sigma}_j\}$$

If $H_{ij} = F_i G_j$, then the spin density matrix factorizes

$$\rho^{(q,\bar{q})} = \frac{1}{2}\{\mathbf{1} + F_j\,\boldsymbol{\sigma}_j\}\otimes\frac{1}{2}\{\mathbf{1} + G_j\,\boldsymbol{\sigma}_j\}$$

Brandenburg, et. al (Z. Phy. C60,697 (1993))
QCD Vacuum Effect

On average no quark polarization, but a spin correlation between an annihilating quark and antiquark is caused by nontrivial QCD vacuum.



$q\bar{q}$ spin density matrix contains terms:

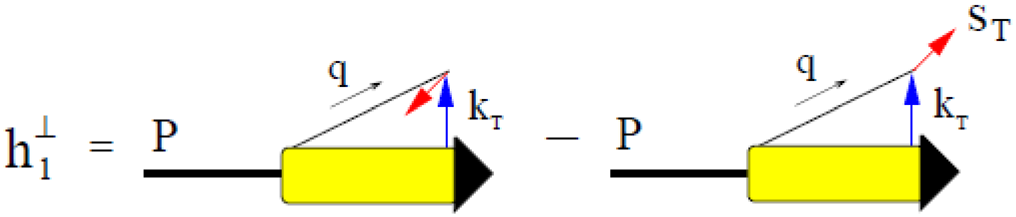
$$H_{ij}(\vec{\sigma}\cdot\vec{e}_i)(\vec{\sigma}\cdot\vec{e}_j)$$

$$1-\lambda-2\nu \simeq -4\kappa \simeq -4\frac{H_{22}-H_{11}}{1+H_{33}}$$

$$\kappa=\kappa_0\frac{|k_T|^4}{|k_T|^4+m_T^4},\ \kappa_0=0.17,\ m_T=1.5\text{ GeV}$$

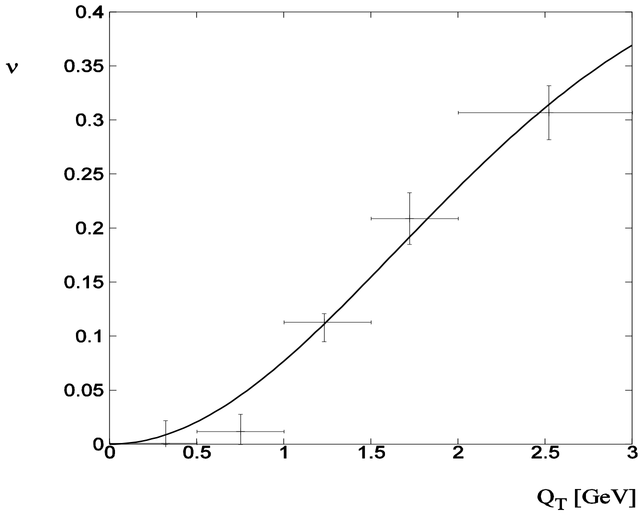
For large $|k_T|$, $\kappa\to\kappa_0$, a constant value.

Boer (PRD 60, 014012 (1999))
Hadronic Effect, Boer-Mulders Functions



- Boer-Mulders Function $h_1^\perp$: a correlation between quark's k_T and transverse spin in an unpolarized hadron

- $h_1^\perp$ can lead to an azimuthal dependence with $\frac{\nu}{2} \propto h_1^\perp(N)\bar{h}_1^\perp(\pi)$



$$h_1^\perp(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x),$$

$$\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2}, \qquad \kappa_1 = C_{H_1} C_{H_2}/2$$

$$\kappa = \frac{\nu}{2} \rightarrow 0 \text{ for large } |k_T|$$

Consistency of factorization in term of TMDs

D. Boer

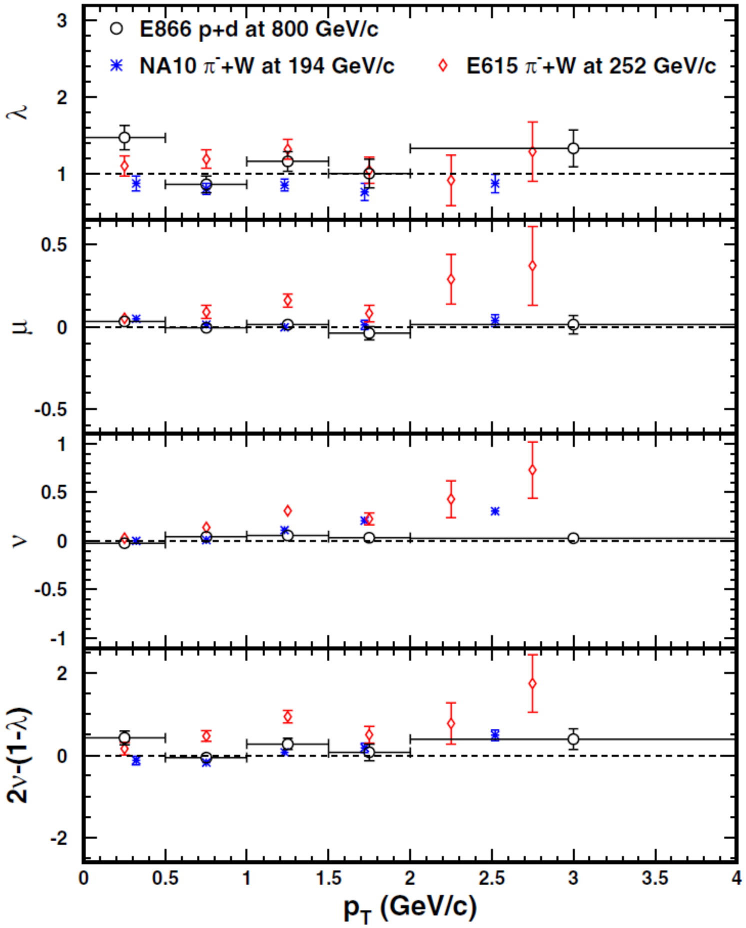
Hadronic effect versus vacuum effect

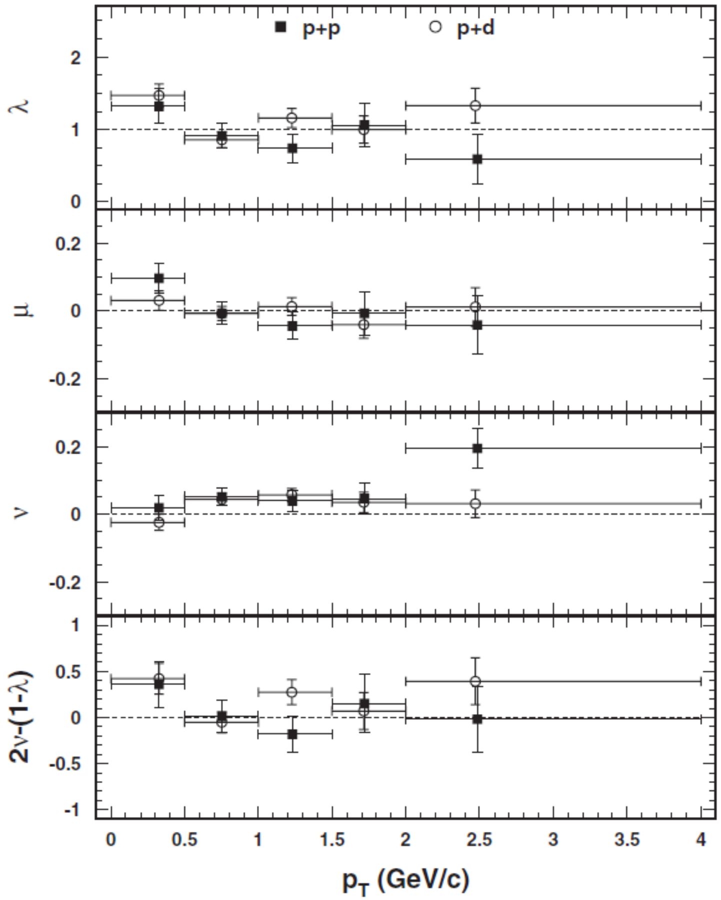
	$h_1^\perp \neq 0$	QCD vacuum effect
$\rho^{(q,\bar{q})}$	$\rho^{(q)} \otimes \rho^{(\bar{q})}$	possibly entangled
Q dependence	$\kappa \sim 1/Q$	?
large Q_T limit	$\kappa \to 0$	need not disappear ($\kappa \to \kappa_0$)
flavor dependence	yes	flavor blind
x dependence	yes	if yes, then not hadron blind

D.B., Brandenburg, Nachtmann & Utermann, EPJC 40 (2005) 55

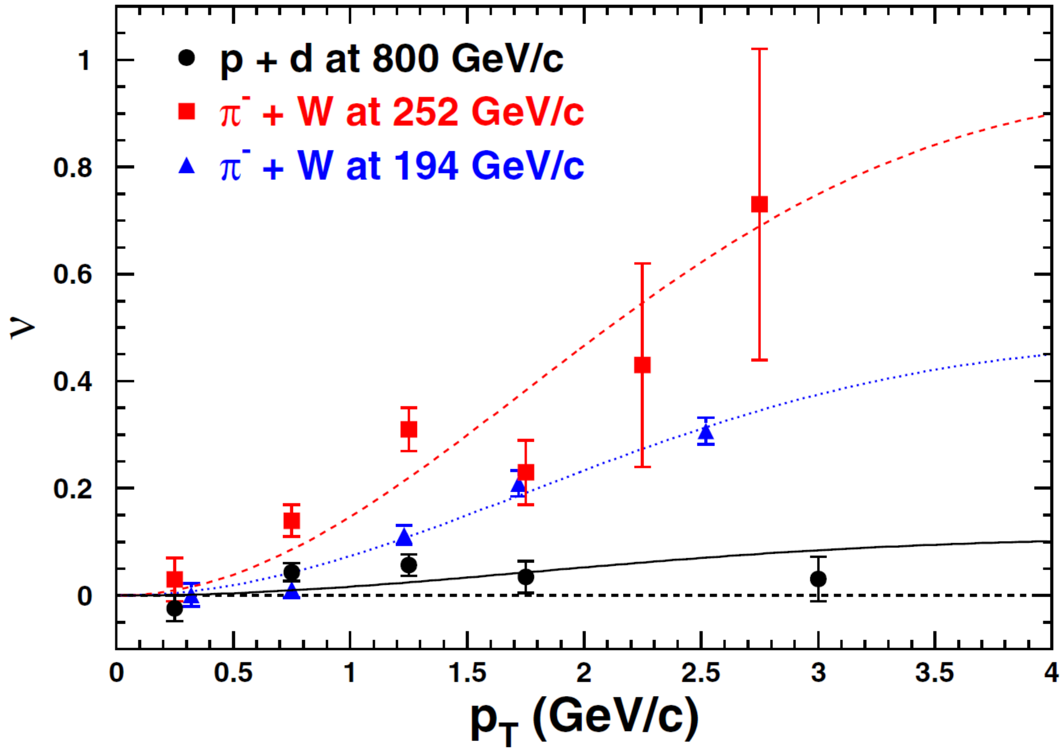
Different experiments ($\pi^{\pm}, p, \bar{p}, \ldots$ beams) are needed in different kinematical regimes

E866 (PRL 99 (2007) 082301; PRL 102 (2009) 182001) Consistency of LT relation for DY events in pd, pp





E866 (PRL 99 (2007) 082301)
Azimuthal cos2Φ Distribution of DY events in pd



$$h_1^{\perp}(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x),$$

$$\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2},$$

$$\kappa_1 = C_{H_1} C_{H_2}/2$$

$v(\pi^- W \rightarrow \mu^+ \mu^- X) \sim$ [valence $h_1^{\perp}(\pi)$] * [valence $h_1^{\perp}(p)$]

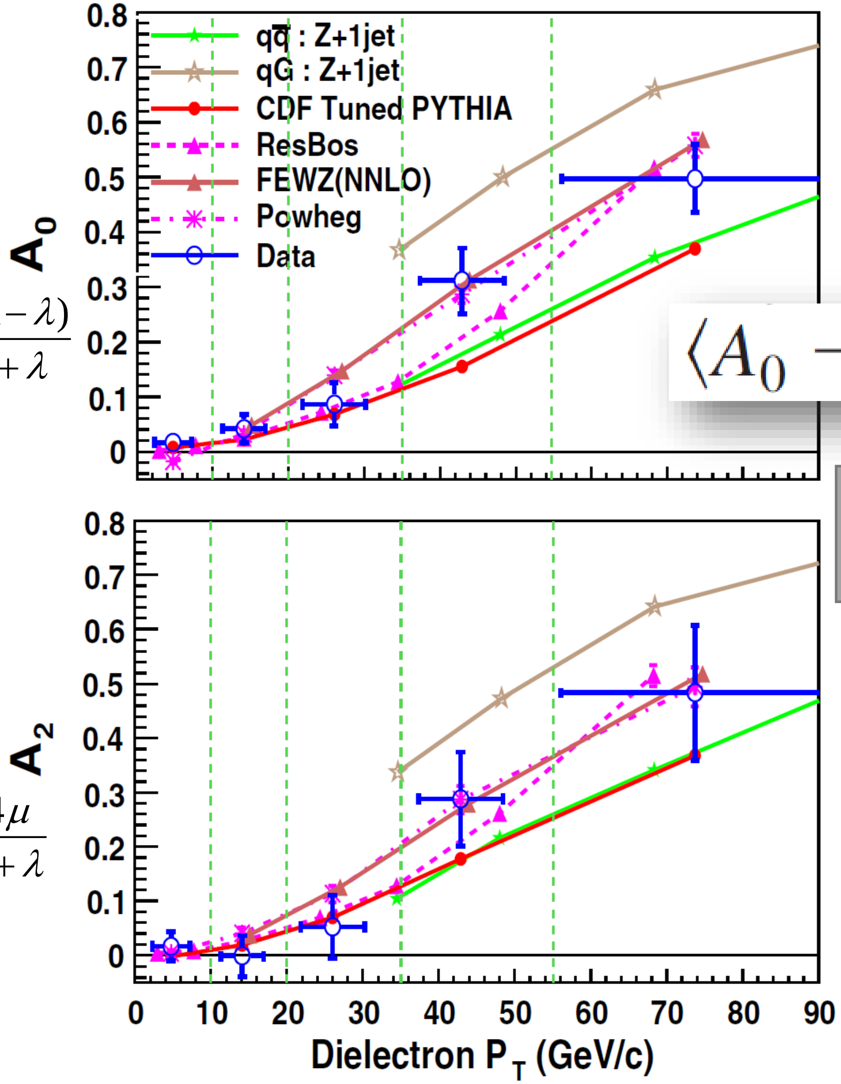
$v(pd \rightarrow \mu + \mu - X) \sim$ [valence $h_1^{\perp}(p)$] * [sea $h_1^{\perp}(p)$]

Sea-quark BM functions are much smaller than valence quarks

CDF (PRL 106, 241801 (2011))
Angular Distribution of p-pbar DY at Z pole

$$A_0 = \frac{2(1-\lambda)}{3+\lambda}$$

$$A_2 = \frac{4\mu}{3+\lambda}$$



$$\langle A_0 - A_2 \rangle = 0.02 \pm 0.02$$

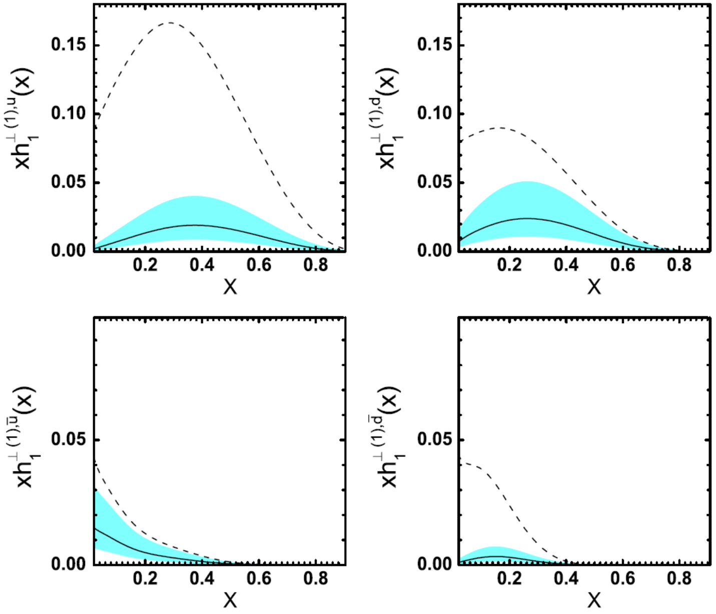
A good agreement with the Lam-Tung relation A_0-A_2=0

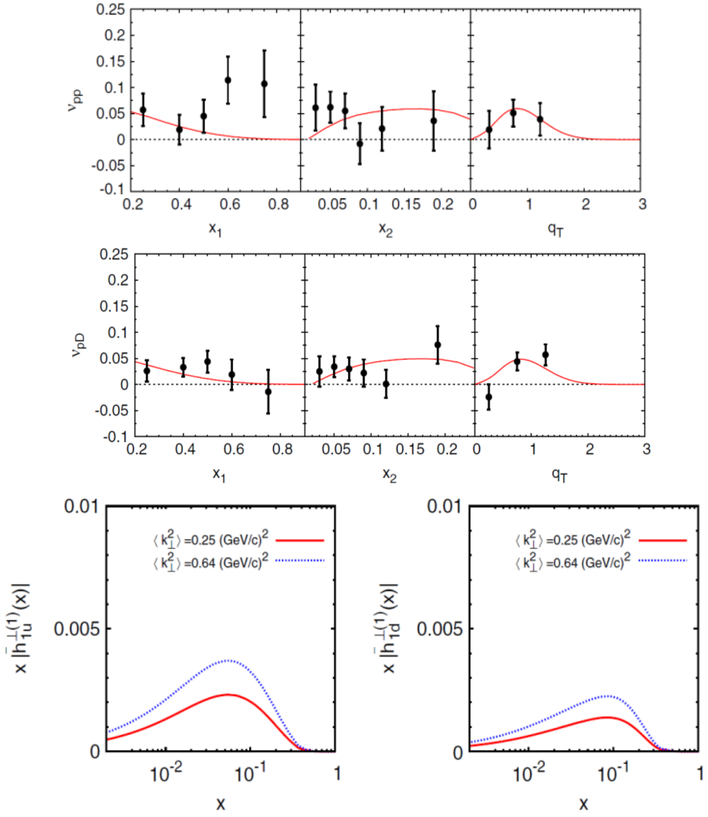
Boer-Mulders functions from unpolarized pD and pp Drell-Yan

Z. Lu and I. Schmidt,
PRD 81, 034023 (2010)

V. Barone et al.,
PRD 82, 114025 (2010)

$$h_1^{\perp q}(x, \boldsymbol{p}_T^2) = h_1^{\perp q}(x) \frac{1}{\pi p_{bm}^2} \exp\left(-\frac{\boldsymbol{p}_T^2}{p_{bm}^2}\right).$$

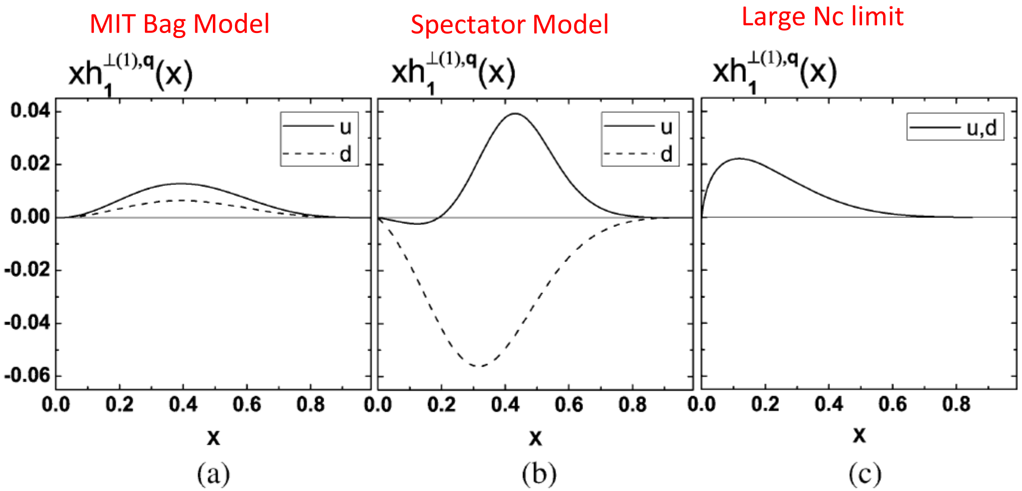




Sign of BM functions and their flavor dependence?

Flavor separation of the Boer–Mulders function

Z. Lu et al. (PLB 639 (2006) 494)

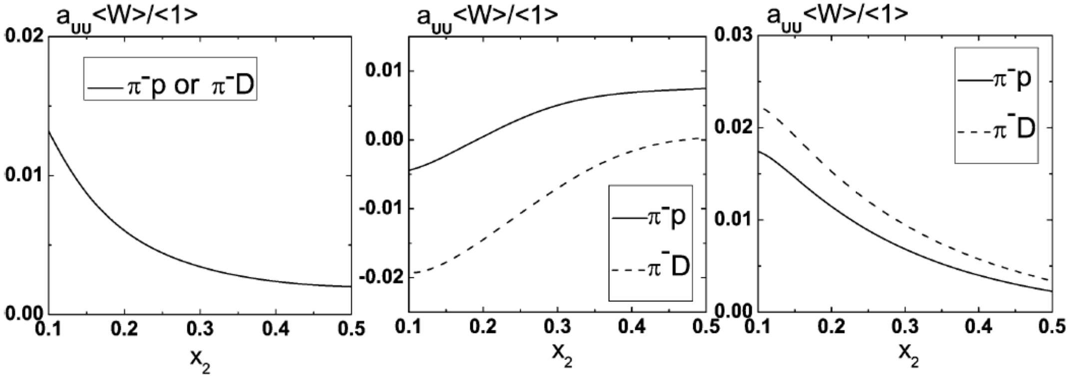

MIT Bag Model

Spectator Model

Large Nc limit

(a) (b) (c)

$$\langle W\rangle = \left\langle \frac{q_T^2\cos 2\phi}{4M_AM_B}\right\rangle = \int d\phi d^2q_T\,\frac{d\sigma(h_Ah_B\to l\bar{l}X)}{d\Omega dx_Adx_Bd^2q_T}\,\frac{q_T^2\cos 2\phi}{4M_AM_B}$$



(a) (b) (c)

Deuterium target

Glauber gluons in pion-induced Drell-Yan processes

C.P. Chang and H-n. Li, PLB 726 (2013) 262; arXiv:1305.4694

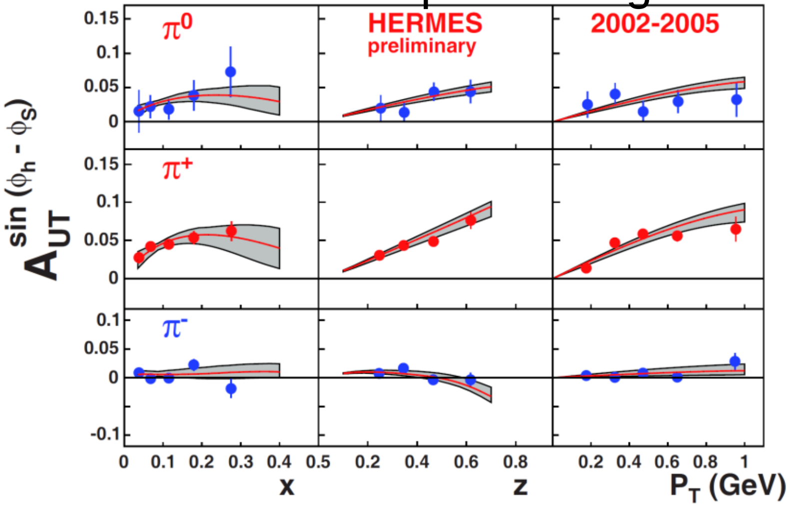
- The Glauber Gluon in the pion, the Nambu-Goldstone boson, is responsible for the violation of L-T relations in pion-induced DY.
- The proposal could be discriminated from the effects of BM functions by pbar+p DY.

The proposal could also be tested by kaon-induced DY.

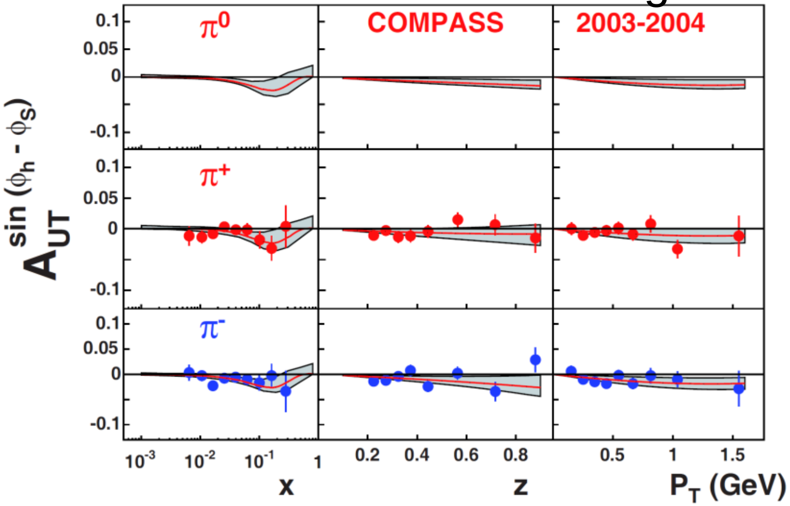
Global Analysis of SIDIS from HERMES and COMPASS

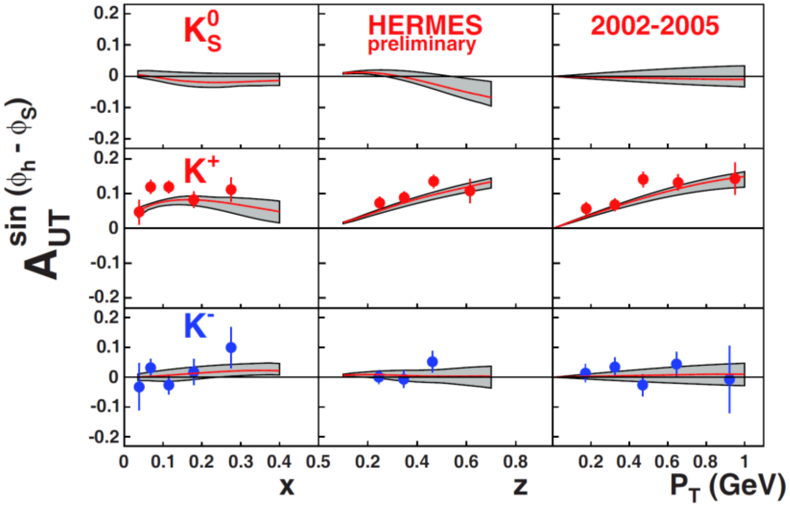
M. Anselmino et al., Eur.Phys.J.A39:89-100,2009

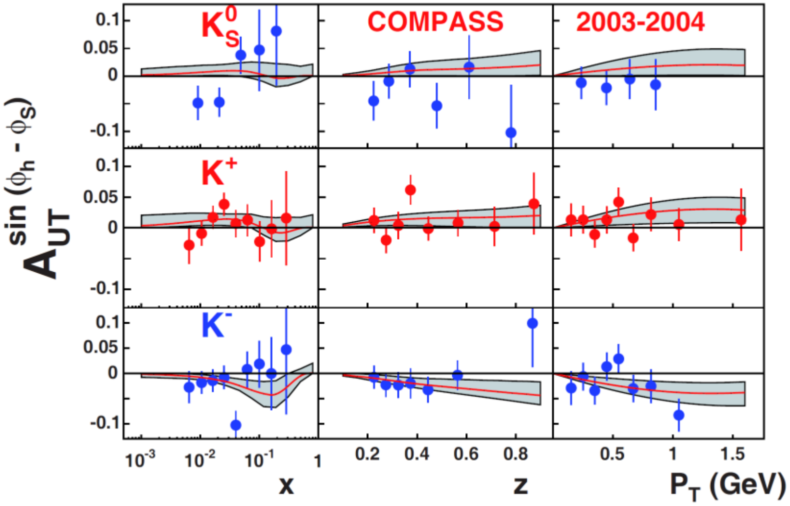
HERMES proton target



COMPASS deuteron target

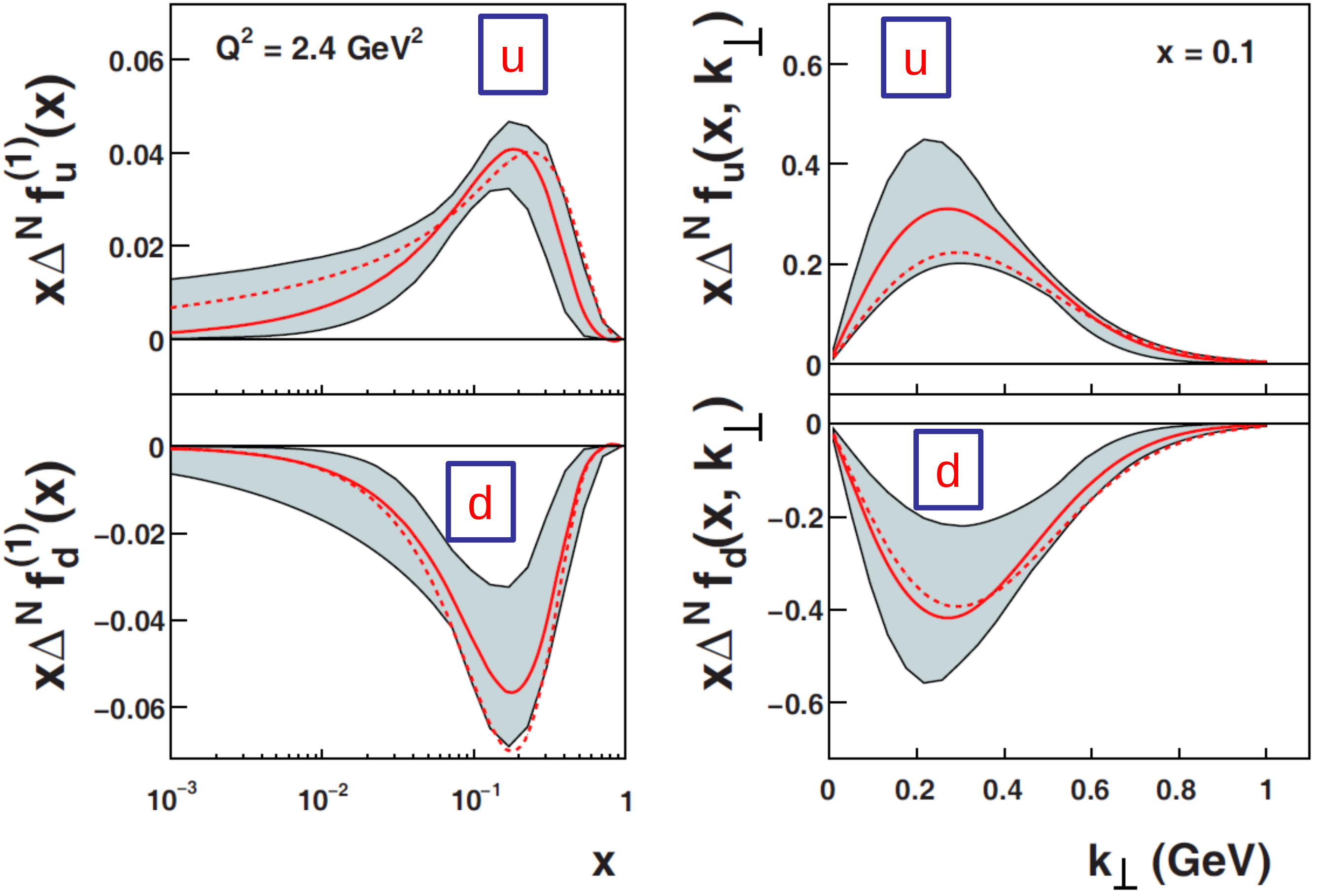






Sivers Functions from SIDIS

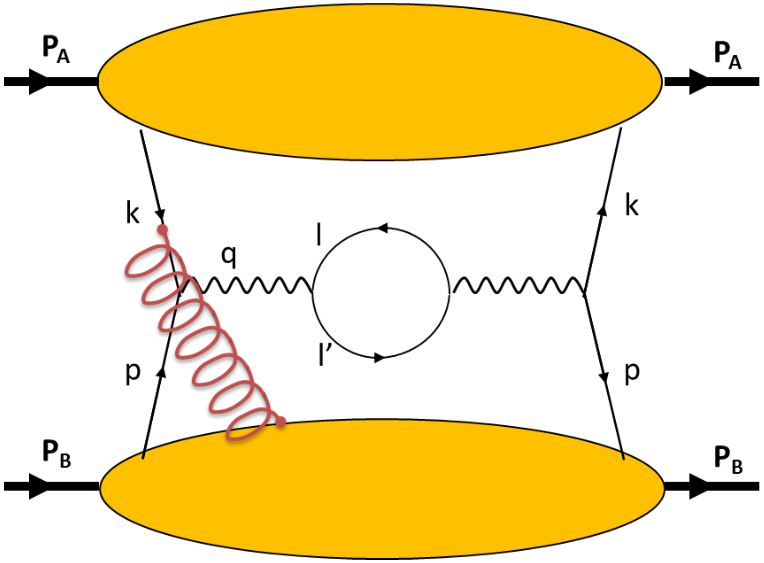
M. Anselmino et al., Eur.Phys.J.A39:89-100, 2009



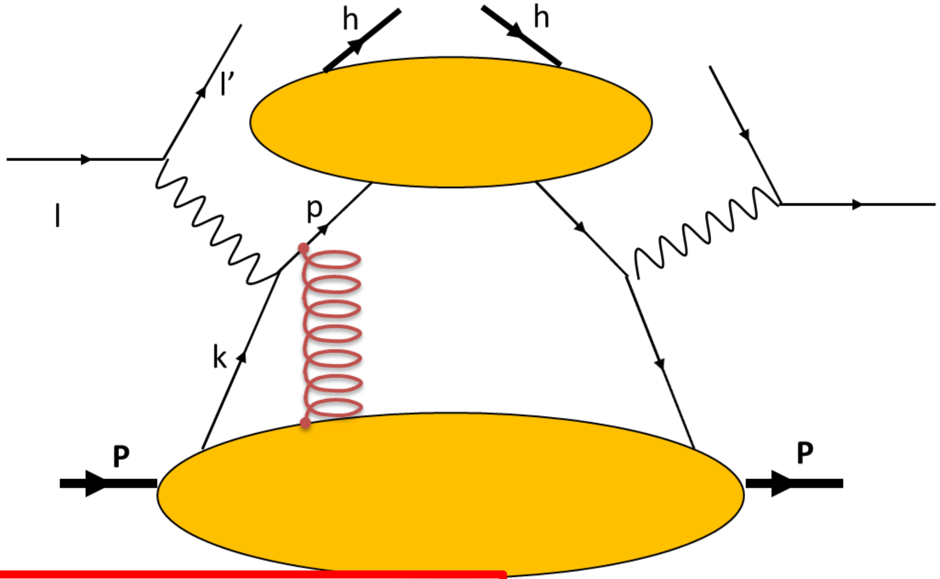
Sign Change of Sivers & Boer-Mulders Functions

J.C. Collins, Phys. Lett. B 536 (2002) 43
A.V. Belitsky, X. Ji, F. Yuan, Nucl. Phys. B 656 (2003) 165
D. Boer, P.J. Mulders, F. Pijlman, Nucl. Phys. B 667 (2003) 201
Z.B. Kang, J.W. Qiu, Phys. Rev. Lett. 103 (2009) 172001

Drell-Yan



SIDIS



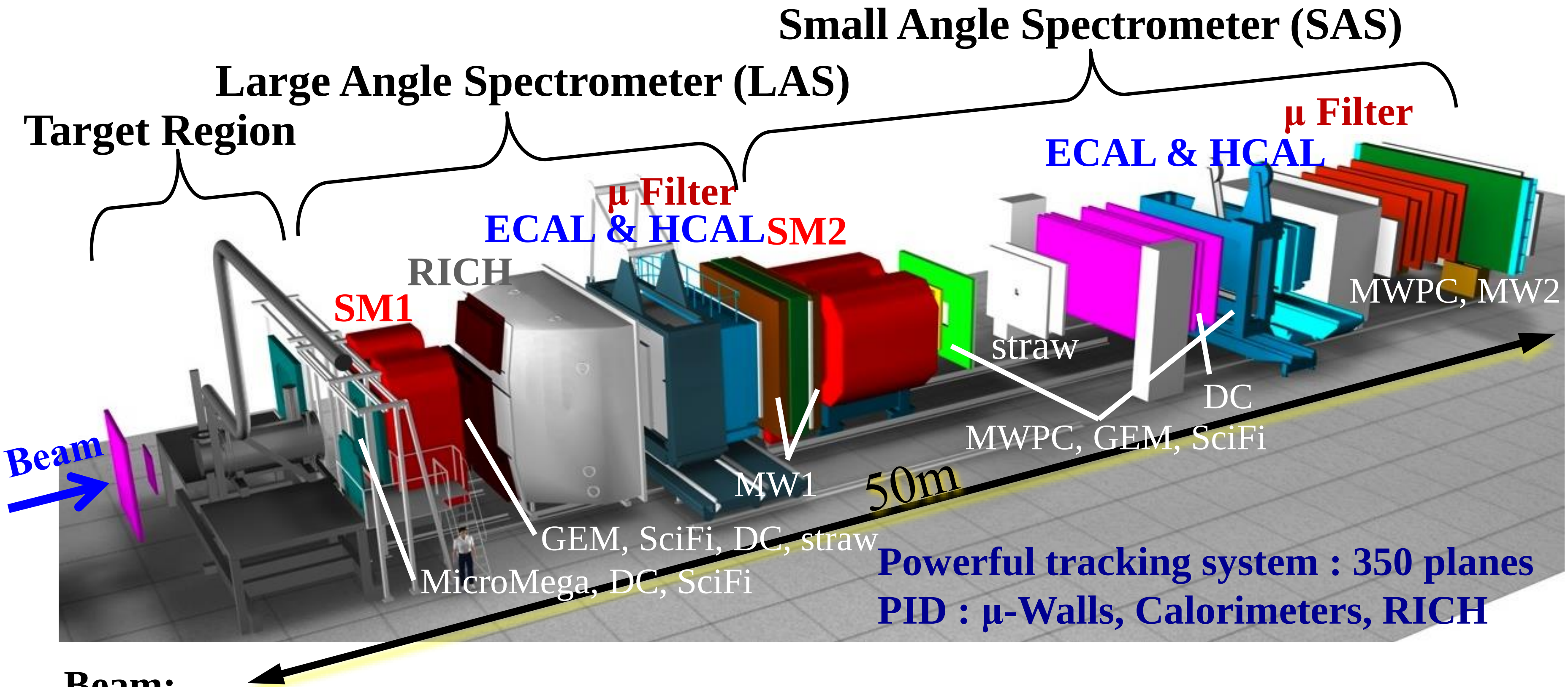
$$\text{Sivers, BM}\,|_{DY} = -1 * \text{Sivers, BM}\,|_{SIDIS}$$

- QCD gluon gauge link (Wilson line) in the initial state (DY) vs. final state interactions (SIDIS).
- ***Experimental confirmation of the sign change will be a crucial test of perturbative QCD and TMD physics.***

Planned Polarized Drell-Yan Experiments

experiment	particles	energy	x_1 or x_2	luminosity	timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	190 GeV $\sqrt{s}$ = 17.4 GeV	x_2 = 0.2 – 0.3 $x_2 \sim$ 0.05 (low mass)	2 x 10^{33} cm^{-2} s^{-1}	2014
PAX (GSI)	$p^{\uparrow} + \bar{p}$	collider $\sqrt{s}$ = 14 GeV	x_1 = 0.1 – 0.9	2 x 10^{30} cm^{-2} s^{-1}	>2017
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15 GeV $\sqrt{s}$ = 5.5 GeV	x_2 = 0.2 – 0.4	2 x 10^{32} cm^{-2} s^{-1}	>2016
J-PARC	$p^{\uparrow} + p$	50 GeV $\sqrt{s}$ = 10 GeV	x_1 = 0.5 – 0.9	1 x 10^{35} cm^{-2} s^{-1}	>2015 ??
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 20 GeV	x_1 = 0.1 – 0.8	1 x 10^{30} cm^{-2} s^{-1}	>2014
PHENIX (RHIC)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 500 GeV	x_1 = 0.05 – 0.1	2 x 10^{32} cm^{-2} s^{-1}	>2018
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	x_1 = 0.25 – 0.4	2 x 10^{33} cm^{-2} s^{-1}	>2018
RHIC internal target phase-2	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	x_1 = 0.25 – 0.4	6 x 10^{34} cm^{-2} s^{-1}	>2018
A_nDY RHIC (IP-2)	$p^{\uparrow} + p$	500 GeV $\sqrt{s}$ = 32 GeV	x_1 = ??	?? cm^{-2} s^{-1}	?
pol. SeaQuest (FNAL)	$p^{\uparrow} + p$ / $p + p^{\uparrow}$	120 GeV $\sqrt{s}$ = 15 GeV	x_1 = 0.3 – 0.9	1 x 10^{36} cm^{-2} s^{-1}	>2014

COMPASS Setup



Powerful tracking system : 350 planes

PID : μ-Walls, Calorimeters, RICH

Beam:

Polarized lepton beam : μ^+, μ^- 50-280 GeV/c

Hadron beam : π^+, π^+, K^+, K^-, p

Target:

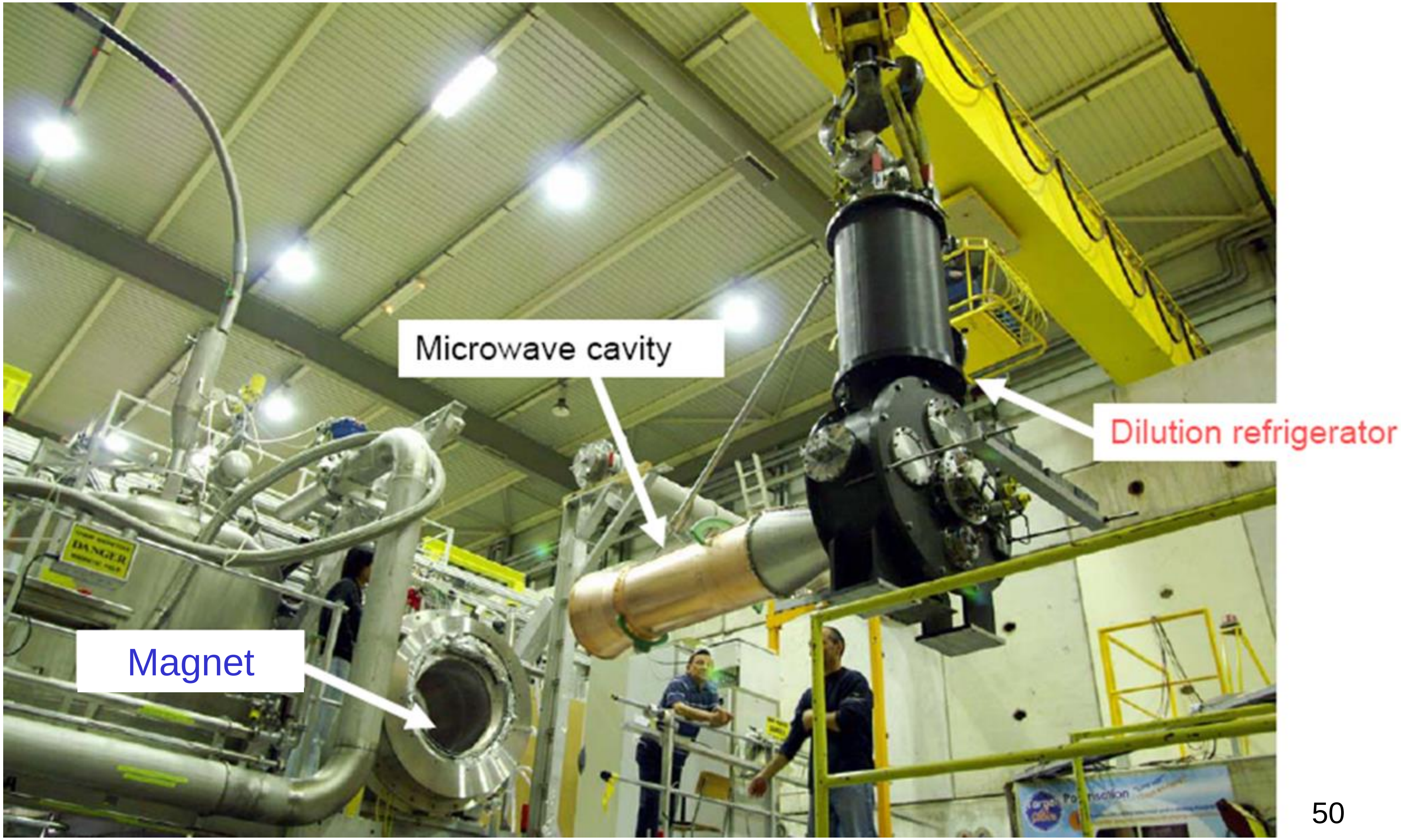
Polarized NH_3 and ^6LiD target

Liquid hydrogen target

Nuclear target

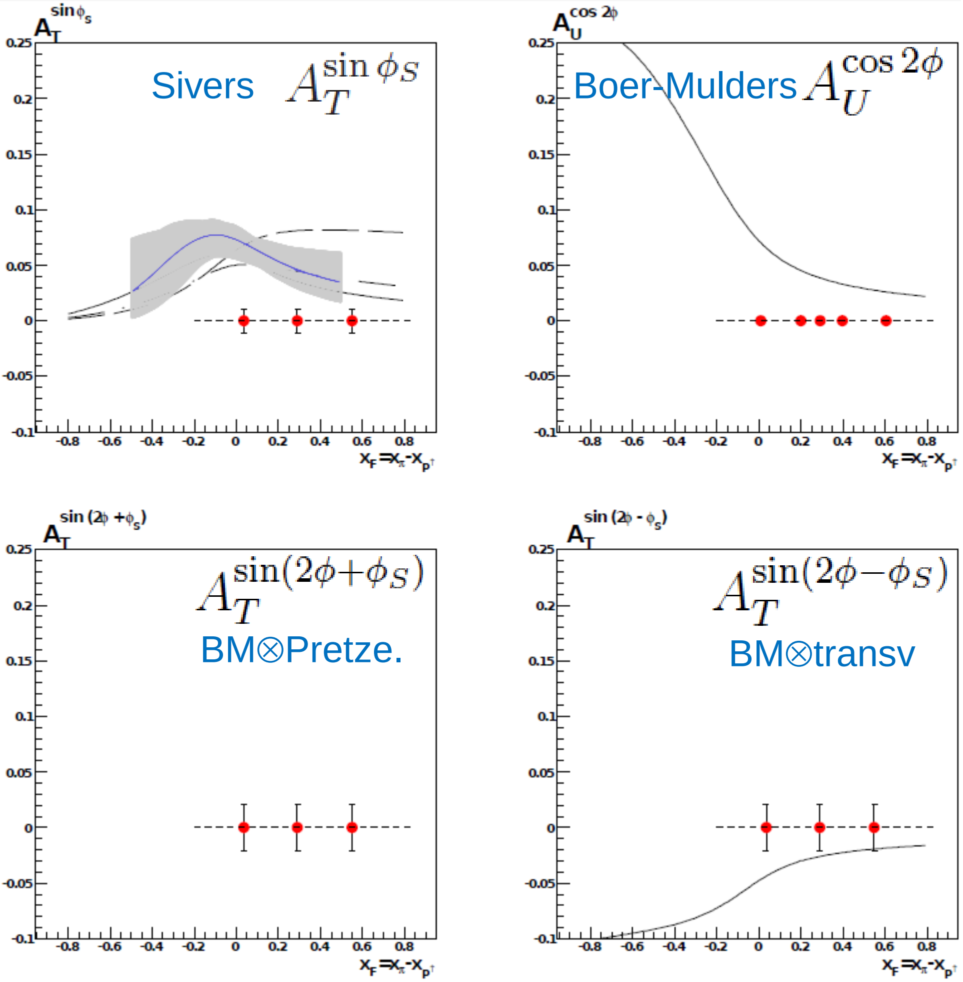
Various Combinations of Beam & Target

Key Elements of Polarized DY Exp.: Polarized NH_3 Target

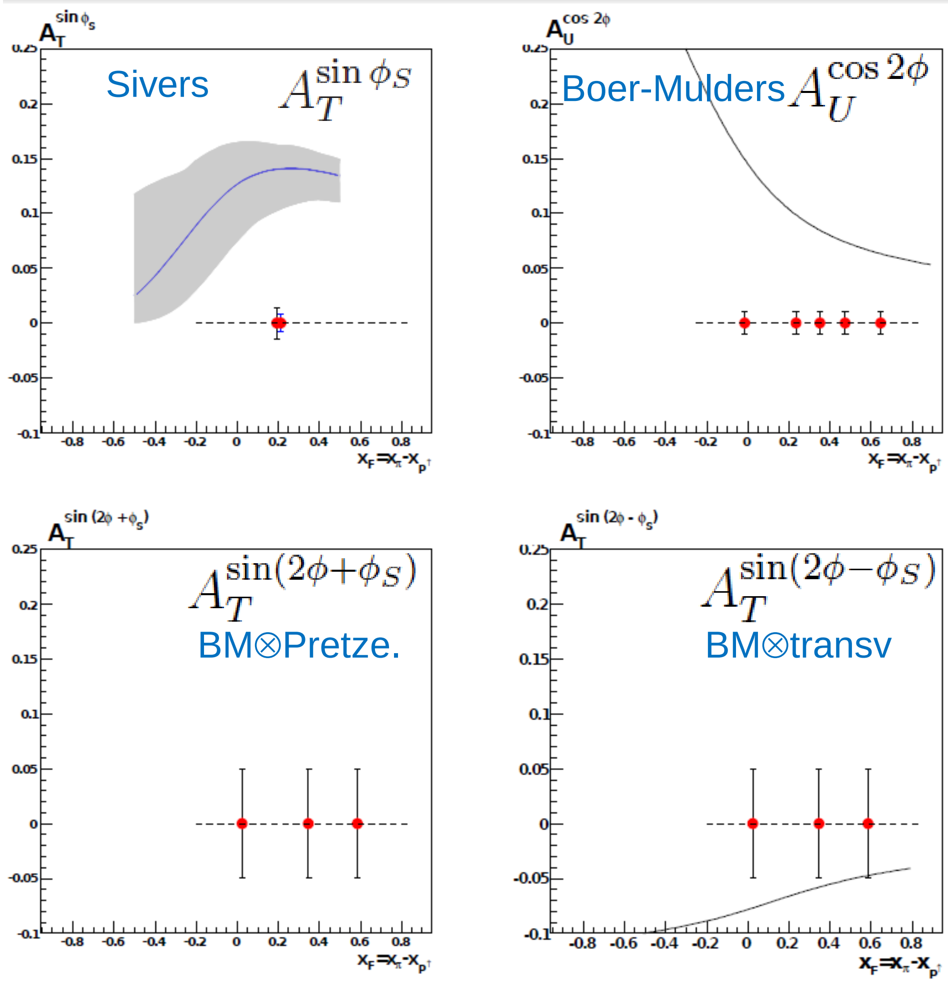


Theoretical Predictions vs. COMPASS Expected Precision

$2 \leq M_{\mu\mu} \leq 2.5\,\mathrm{GeV/c^2}$

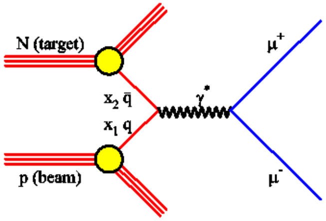


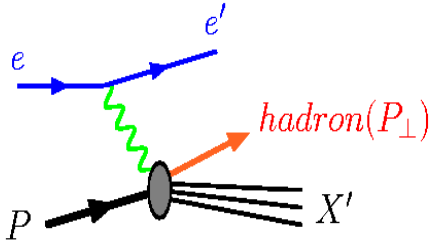
$4 \leq M_{\mu\mu} \leq 9\,\mathrm{GeV/c^2}$



T. Sawada’s talk

Wigner Distribution

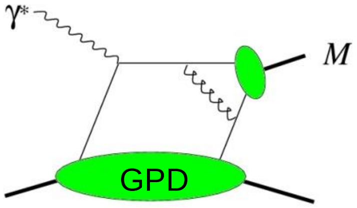




Wigner Distribution

$W(\vec{r}, x, \vec{k}_T)$

Ji, PRL91,062001(2003)



d^3r

$d^2k_t dz$

F.T.

Transverse Momentum Dependent PDF $f(x, \vec{k}_T)$

d^2k_t

PDF

$f(x)$

Generalized Parton Distr.

$H(x, \xi, t)$

dx

Form Factors

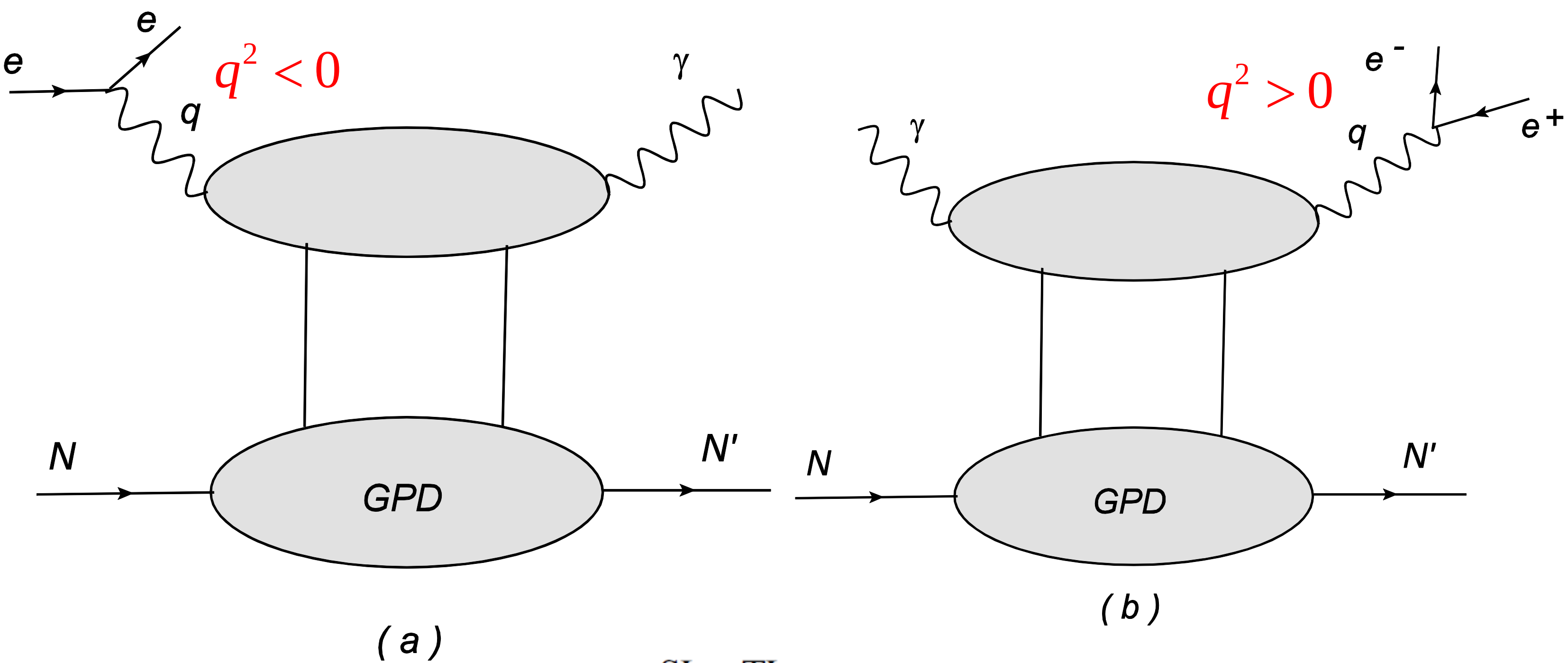
$F_1(t), F_2(t)$

Space-like vs. Time-like Processes

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

Deeply Virtual Compton Scattering

Timelike Compton Scattering



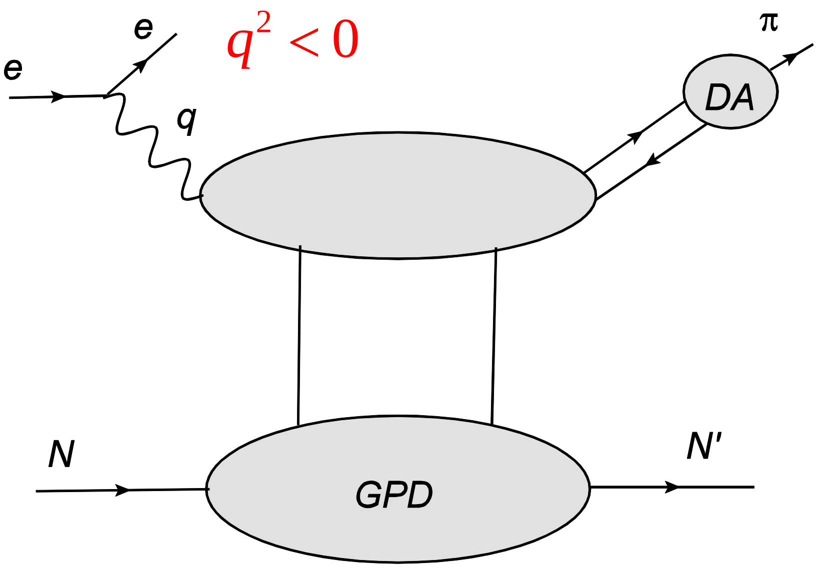
$$\mathcal{F}(\xi = \eta, t, \mathcal{Q}^2) \overset{\mathrm{SL}\to\mathrm{TL}}{\Rightarrow} \mathcal{F}(\xi = -\eta, t, -\mathcal{Q}^2),$$

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

Space-like vs. Time-like Processes

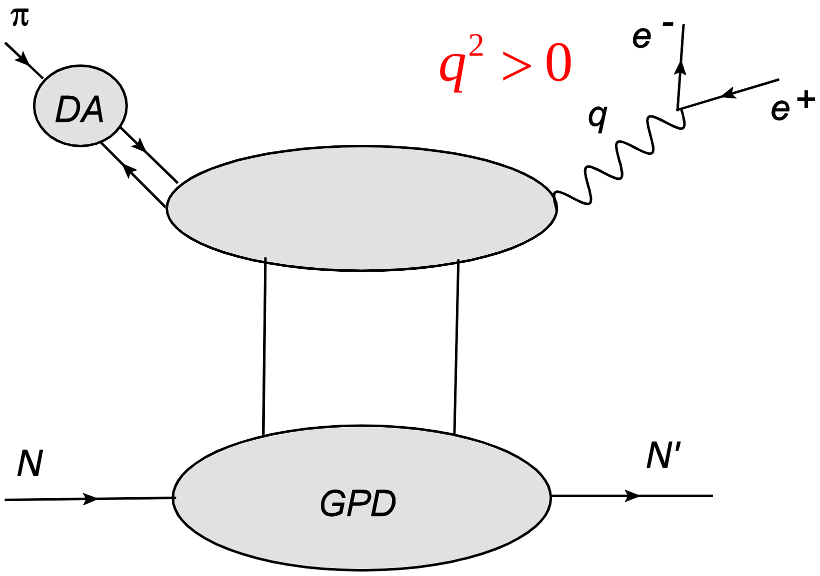
Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Meson Production



(c)

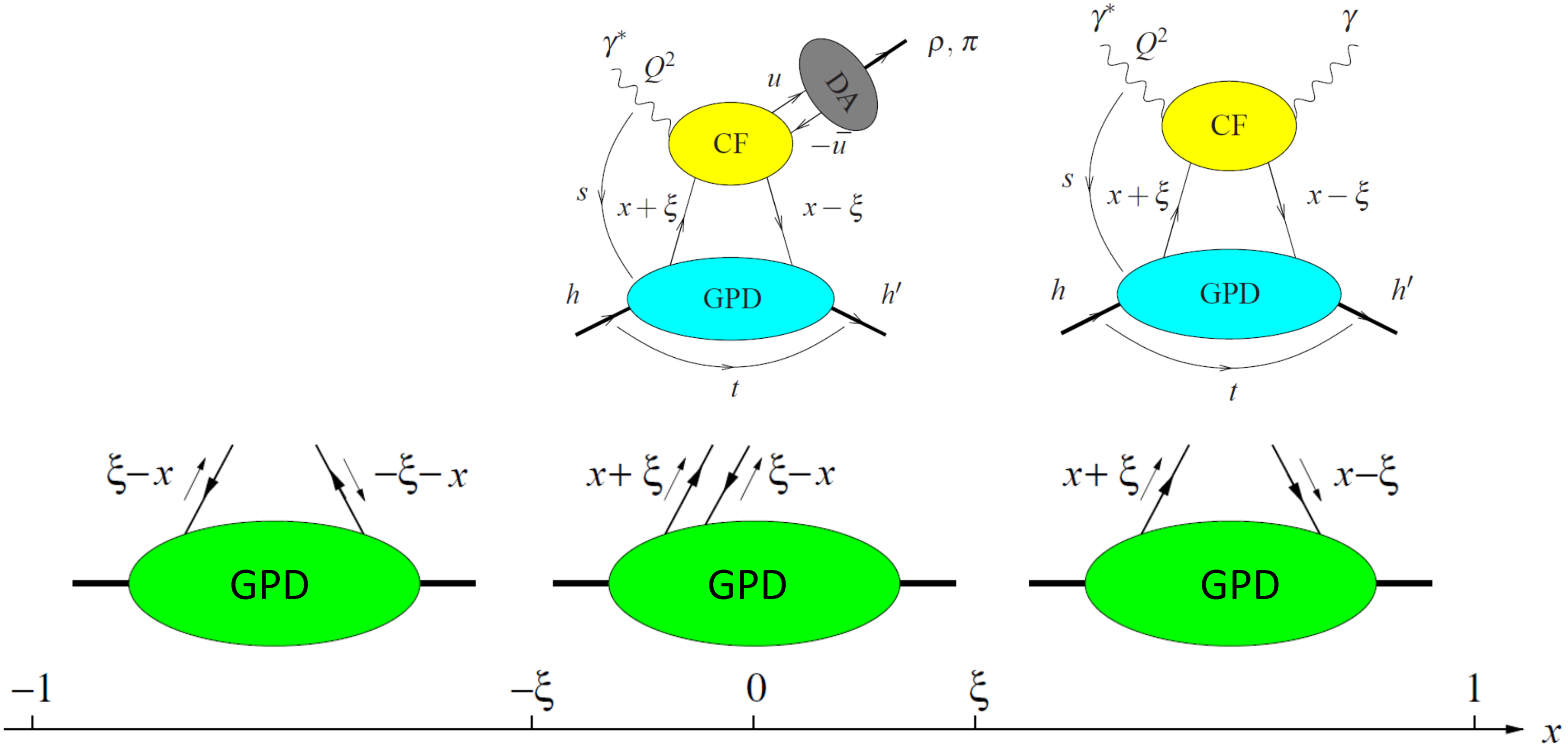
Exclusive Meson-induced DY



(d)

Parton Interpretation of GPDs

(Phys. Rept, 388, 41 (2003); arXiv:1302.2888)



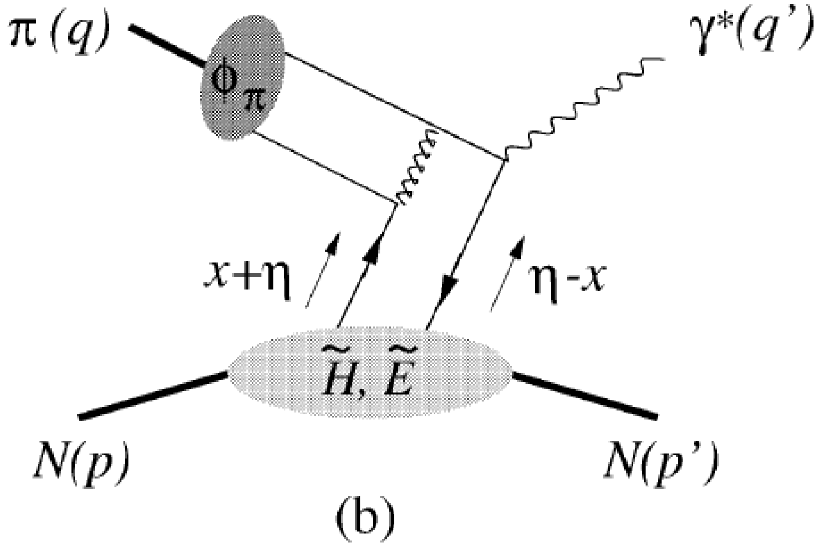
DGLAP-II:
-1<x<-ξ
PDFs of antiquarks

ERBL:
|x|<ξ
DAs of mesons

DGLAP-I:
ξ<x<1
PDFs of quarks

πN→μ+μ-N

(PLB 523 (2001) 265)



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

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

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

$$t = (p-p')^2$$

$$Q'^2 = q'^2 > 0$$

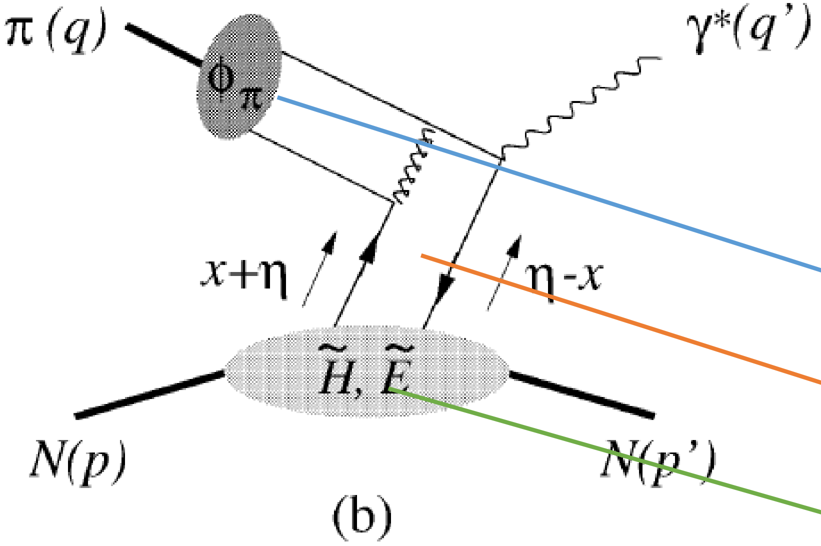
$$\tau = \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s-M_N^2}$$

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

πN→μ+μ-N

(PLB 523 (2001) 265)

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



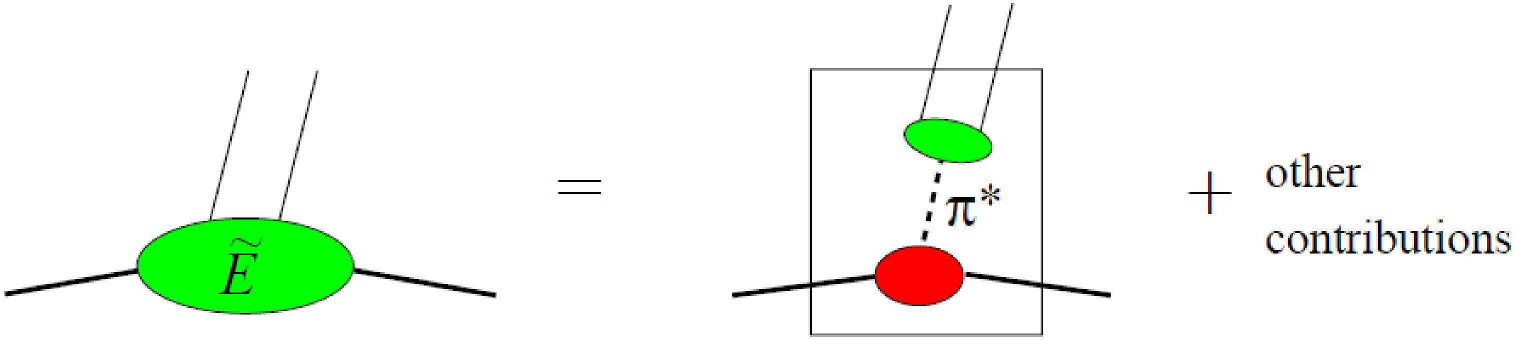
$$\widetilde{\mathcal{H}}^{du}(\xi,\eta,t)$$
$$= \frac{8}{3}\alpha_S \int_{-1}^{1} dz\, \frac{\phi_\pi(z)}{1-z^2}$$
$$\times \int_{-1}^{1} dx \left[\frac{e_d}{\xi - x - i\epsilon} - \frac{e_u}{\xi + x - i\epsilon}\right]$$
$$\times \left[\widetilde{H}^d(x,\eta,t) - \widetilde{H}^u(x,\eta,t)\right],$$

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

$$t = (p-p')^2$$
$$Q'^2 = q'^2 > 0$$

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

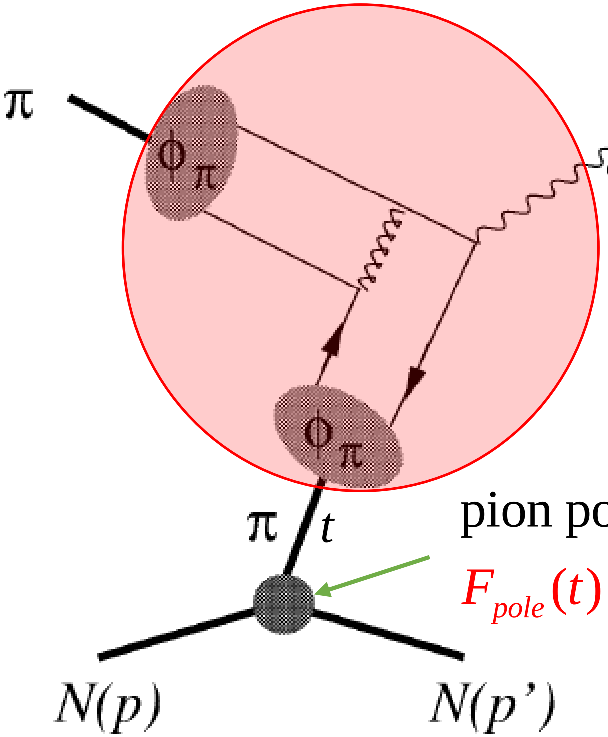
Pion-pole Dominance



$$\tilde{E}^{u-d}(x,\xi,t)\overset{t\to m_\pi^2}{\longrightarrow}\theta(|x|<|\xi|)\frac{1}{2|\xi|}\,\phi_\pi\left(\frac{x+\xi}{2\xi}\right)\frac{4m^2g_A(0)}{m_\pi^2-t}$$

Pion-pole Dominance (PLB 523 (2001) 265)

pion Timelike Form Factor $F_\pi(Q'^2)$

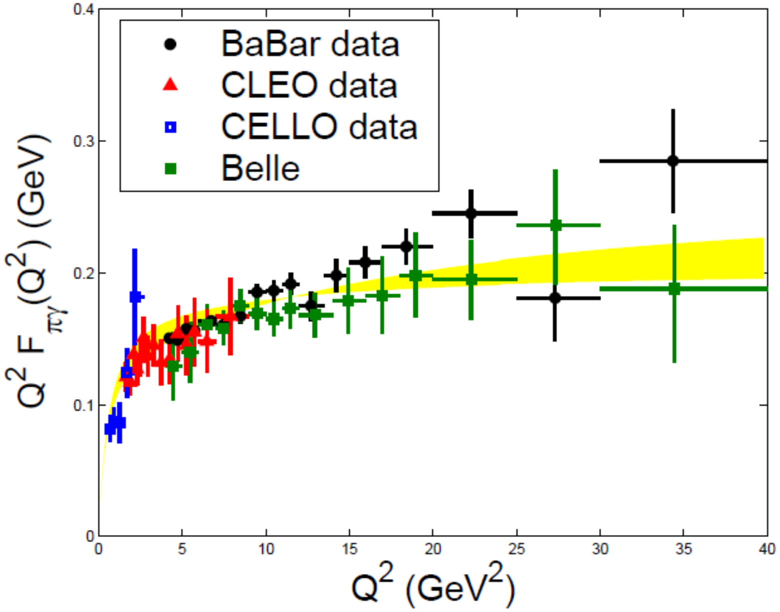


pion pole Form Factor

$F_{pole}(t)$

Pion-Photon Transition Form Factor

$F_{\pi\gamma}(Q'^2)$ in e^+e^- process

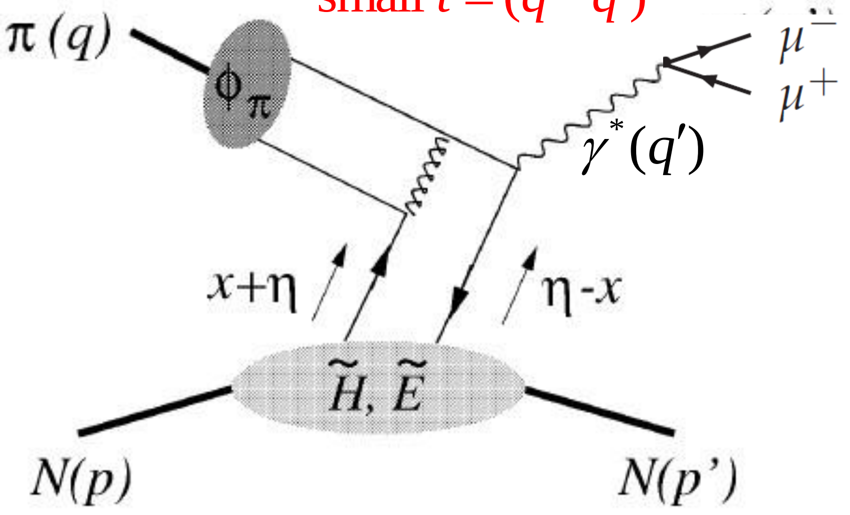


$$
\begin{aligned}
&M^{0\lambda',\lambda}(\pi N \to \gamma^* N) \\
&\quad = -ieQ'F_\pi(Q'^2)\frac{F_{\text{pole}}(t)}{2Mf_\pi}\bar{u}(p',\lambda')\gamma_5 u(p,\lambda) \\
&\qquad + \text{non-pole terms.} \qquad\qquad (11)
\end{aligned}
$$

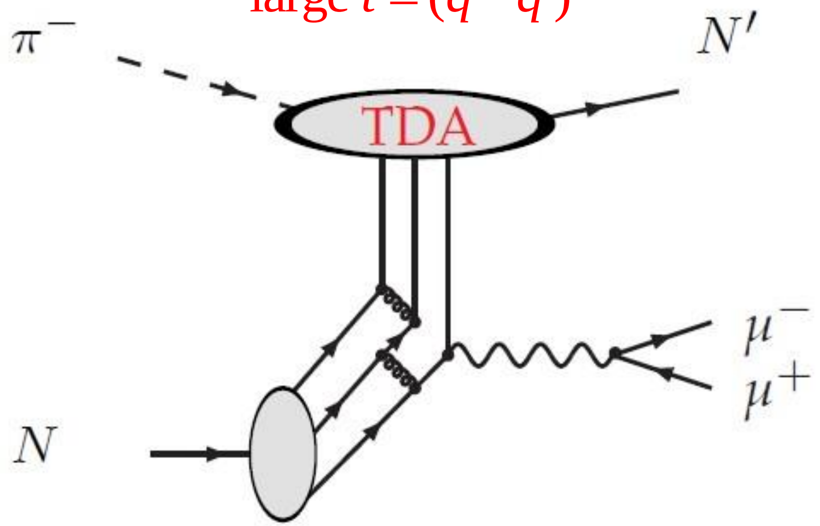
Exclusive Pion-Induced Drell-Yan Process

Bernard Pire , IWHS2011

small $t = (q - q')^2$



large $t = (q - q')^2$



ϕ_π : pion distritribution amplitude (DA)

- DA characterizes the minimal valence Fock state of hadrons.
- DA of pion are also explored by pion-photon transition form factor in Belle and Barbar Exps.

TDA : π-N transistion distritribution amplitude

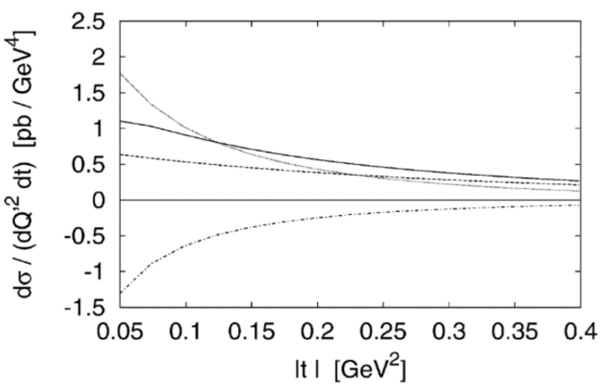
- TDA characterizes the next-to-minimal valence Fock state of hadrons.
- TDA of pion-nucleon is related to the pion cloud of nucleons.

πN→μ+μ-N (PLB 523 (2001) 265)

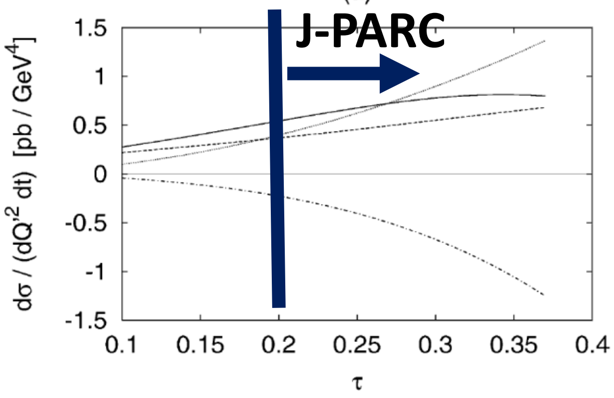
$\boldsymbol{Q'^2 = q'^2 = 5\ GeV^2}$

Cross section increases toward small s!

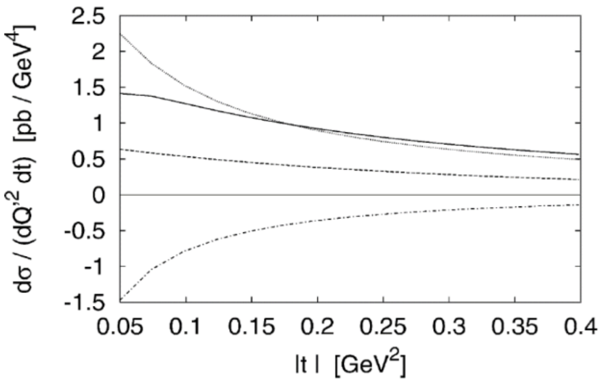
(a)



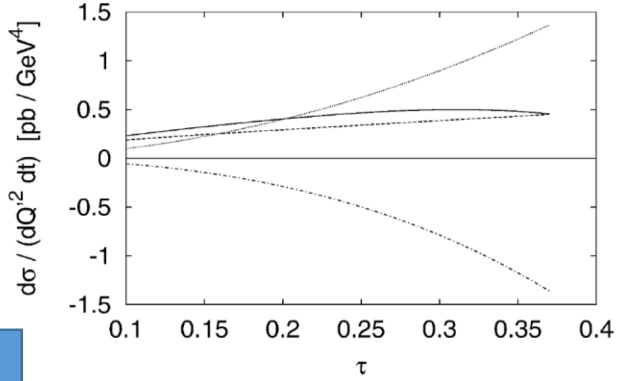
(a)



(b) Pion-pole Dominance



(b) Pion-pole Dominance

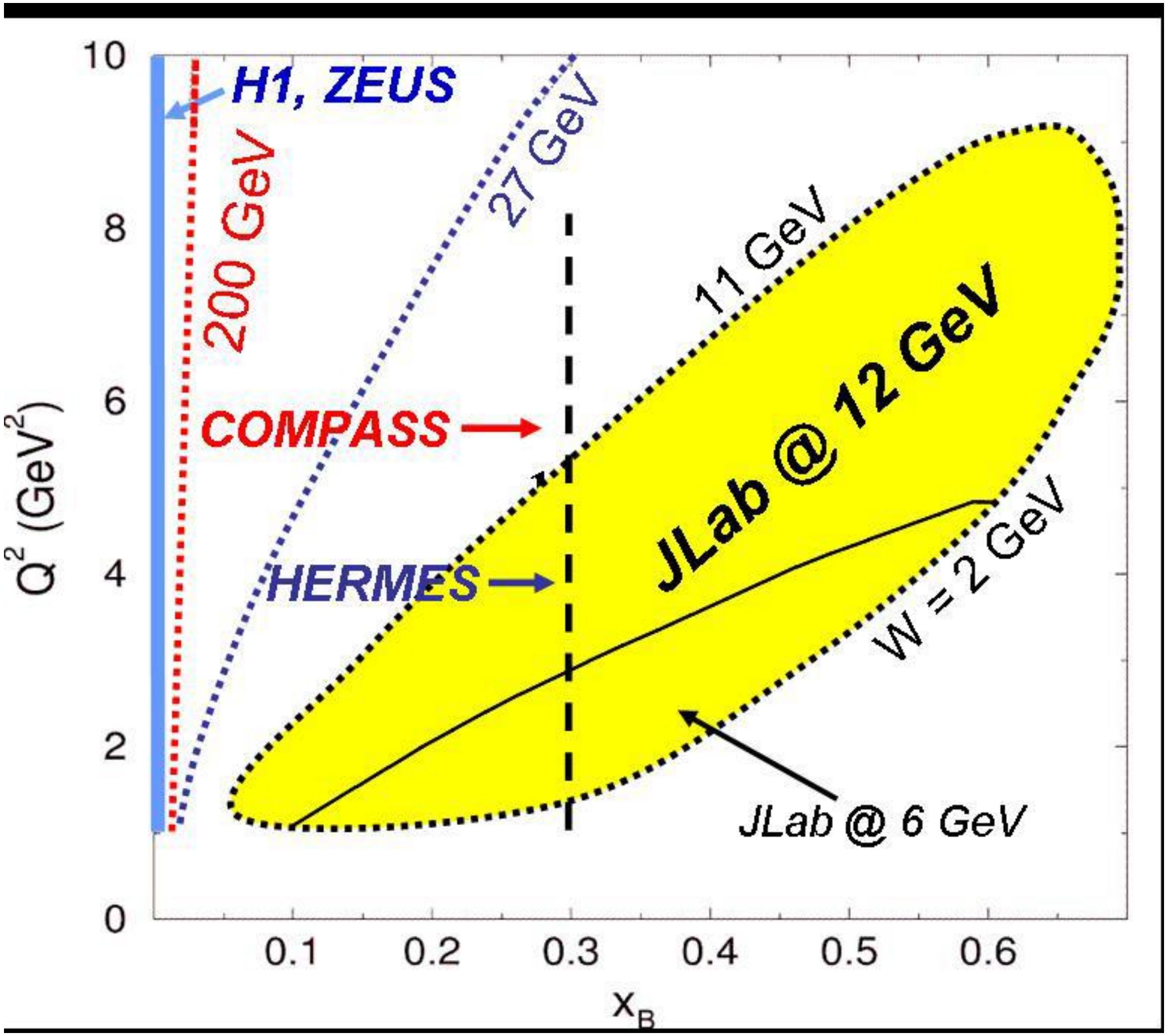


1-10 pb

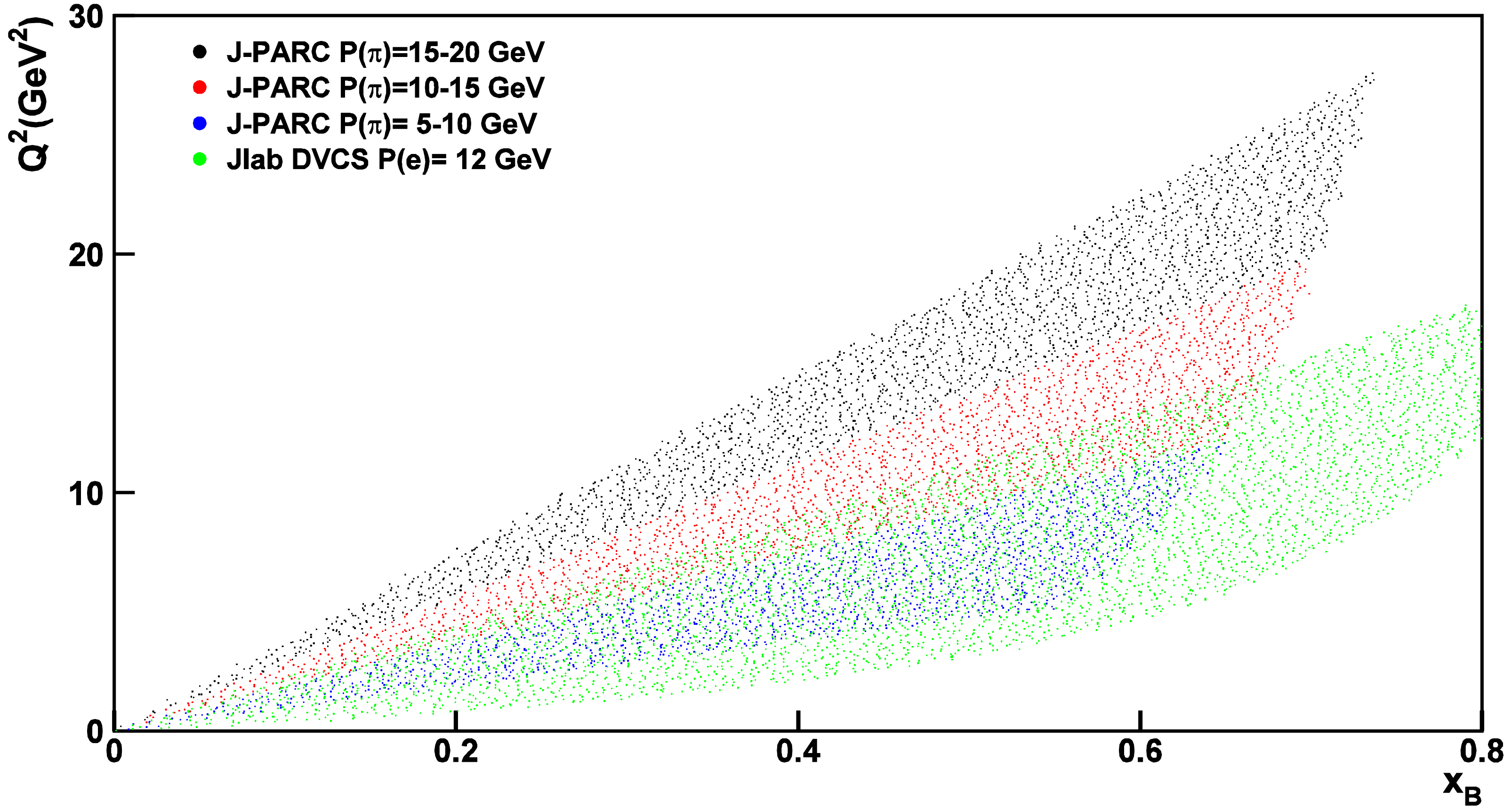
$t = (p - p')^2$=-0.2 GeV²

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

GPD(x_B,Q^2) in space-like regime



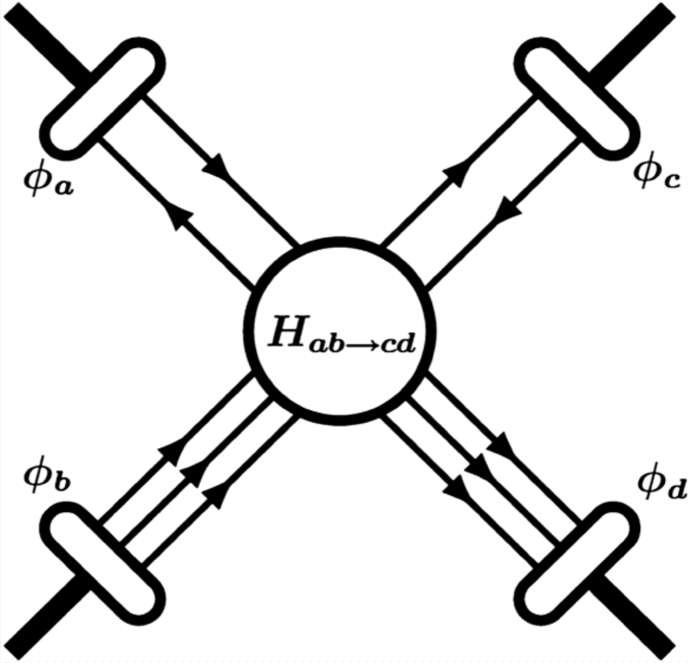
GPD(x_B,Q^2) in both space-like and time-like regime



J-PARC program has the uniqueness at large-Q^2 region in the valence region and the results with low-momentum pion beam (5-10 GeV, blue region) could be cross-checked with JLab's.

GPD & TDA

- The extraction of GPD and TDA (next-generation PDF functions besides TMD) from data will rely on an approach of global analysis and therefore require the measurement of several observables for different channels and reactions, over a wide phase space.
- J-PARC's results in the time-like region will be complementary to what to be obtained in space-like region from the deeply virtual Compton scattering (DVCS) deeply virtual meson scattering (DVMS) process to be measured in JLab.



Hard exclusive production process

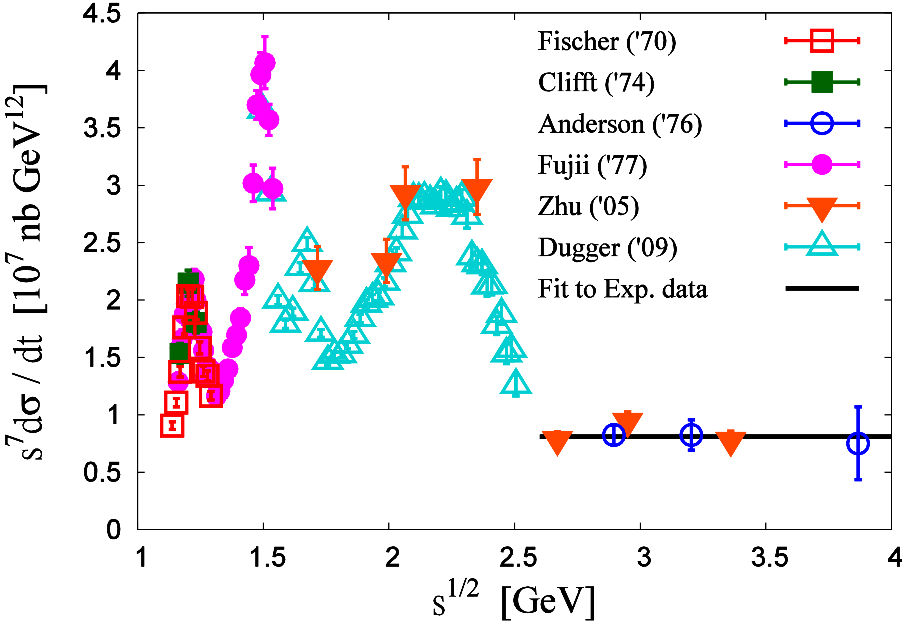
Constituent-Counting Rule in Hard Exclusive Process

Kawamura et al., PRD 88, 034010 (2013)

$$\frac{d\sigma}{dt}(a+b\rightarrow c+d)=\frac{1}{s^{n-2}}f(\theta_{CM}) \quad n=n_a+n_b+n_c+n_d$$

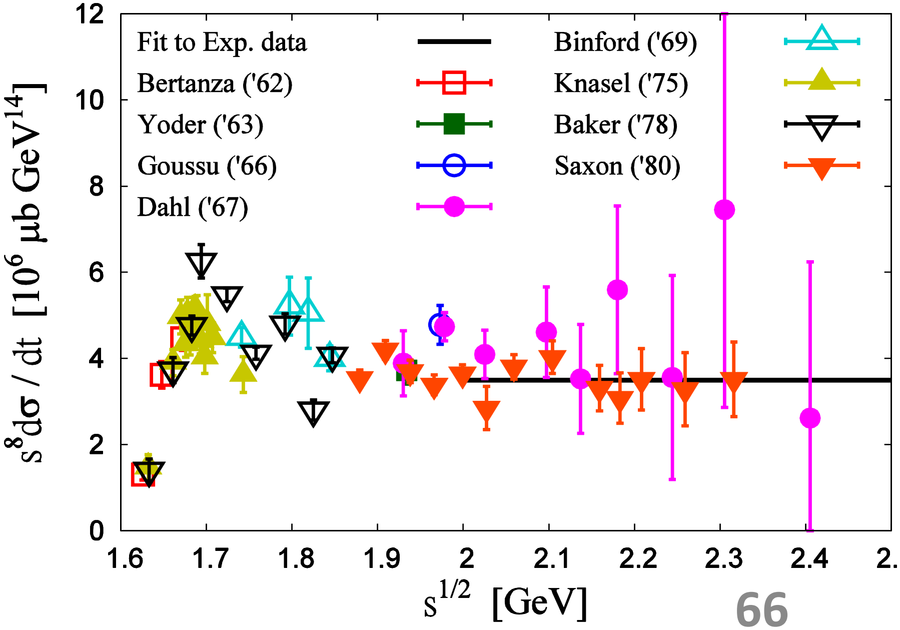
$$n=1+3+2+3=7$$

$$\gamma+p\rightarrow\pi^{+}+n$$



$$n=2+3+2+3=8$$

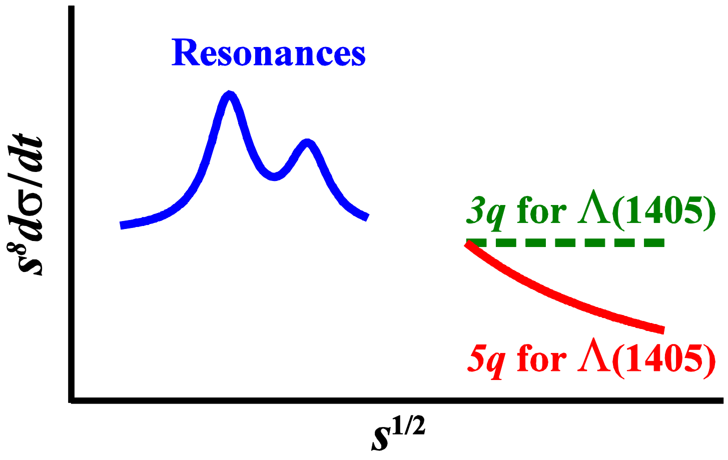
$$\pi^{-}+p\rightarrow\mathrm{K}^{0}+\Lambda$$

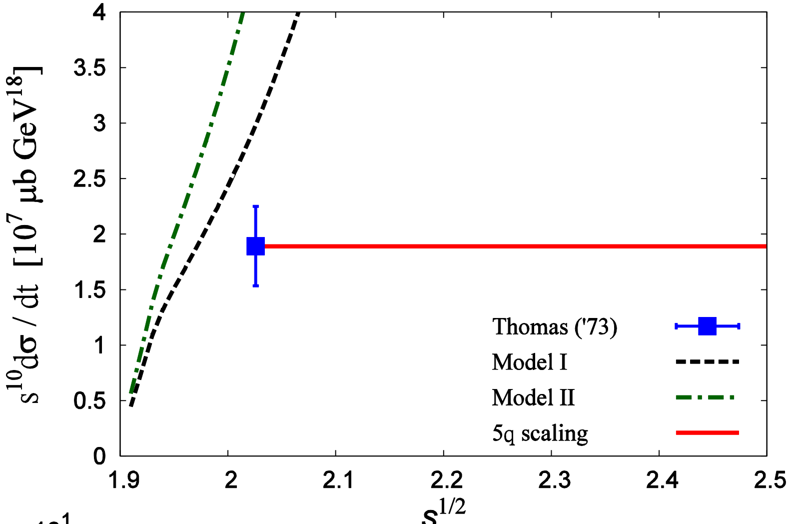


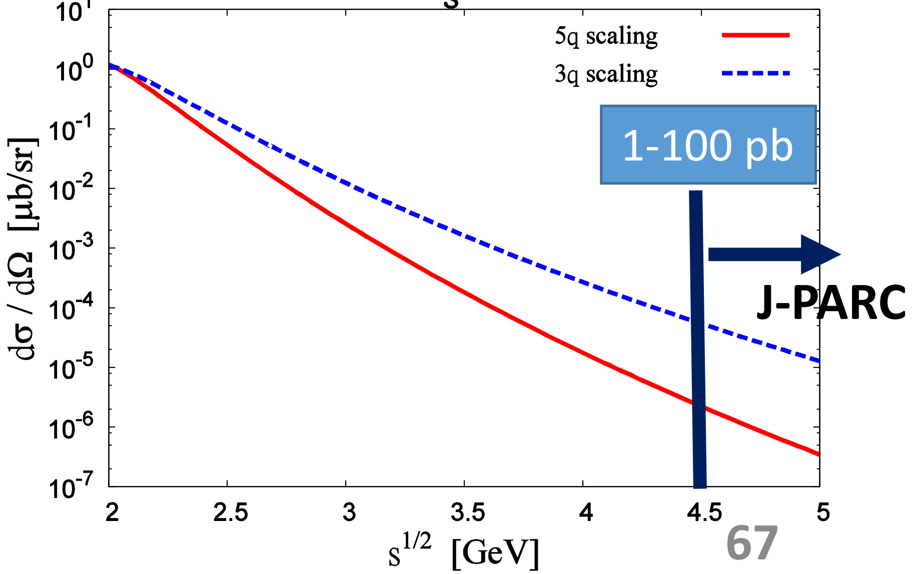
Quark Degrees of Λ(1405)

Kawamura et al., PRD 88, 034010 (2013)

$$\pi^- + p \rightarrow \mathrm{K}^0 + \Lambda(1405)$$







T. Sekihara's talk

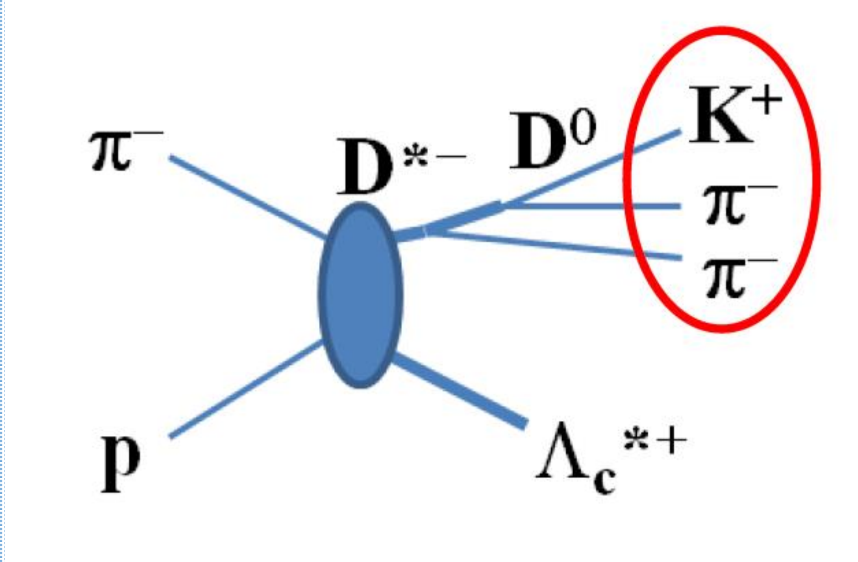
H. Kawamura's talk

Experimental Difficulties

$$\pi^- + p \rightarrow \mathrm{K}^0 + \Lambda(1405)$$

$$\mathrm{K}^0 \rightarrow \pi^+ + \pi^-$$

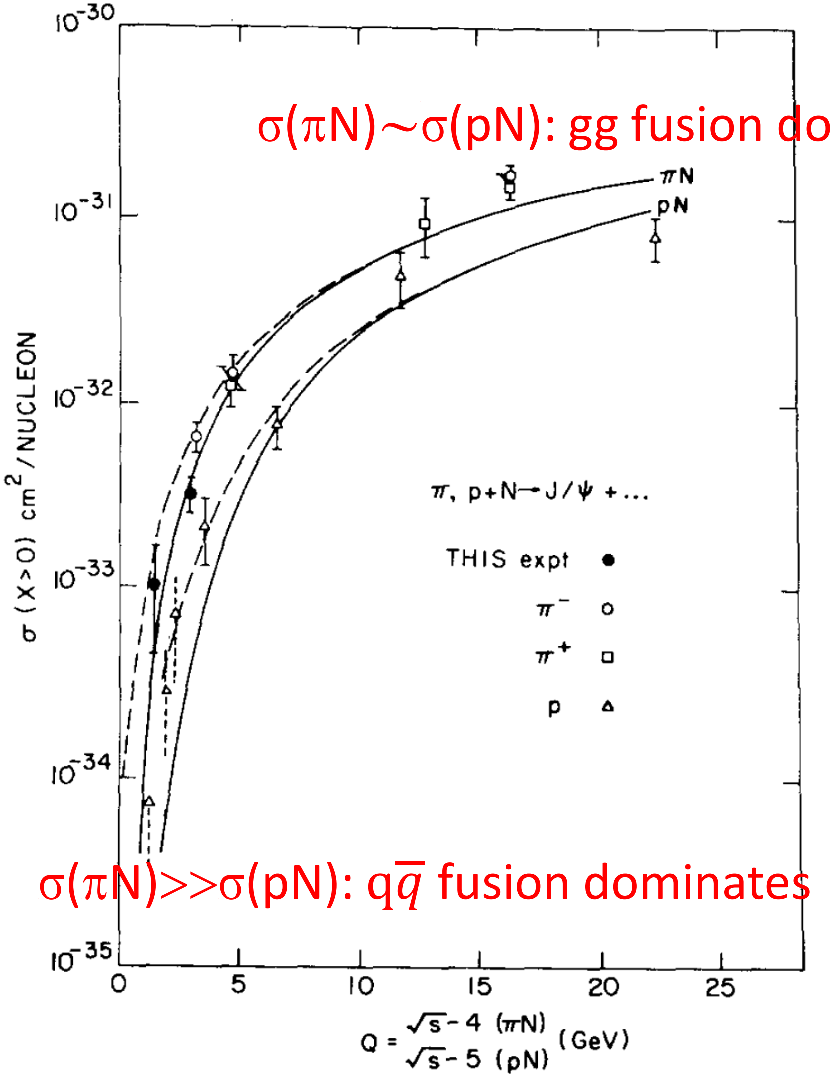
$$\Lambda(1405) \rightarrow \pi + \Sigma$$



Charmed production process

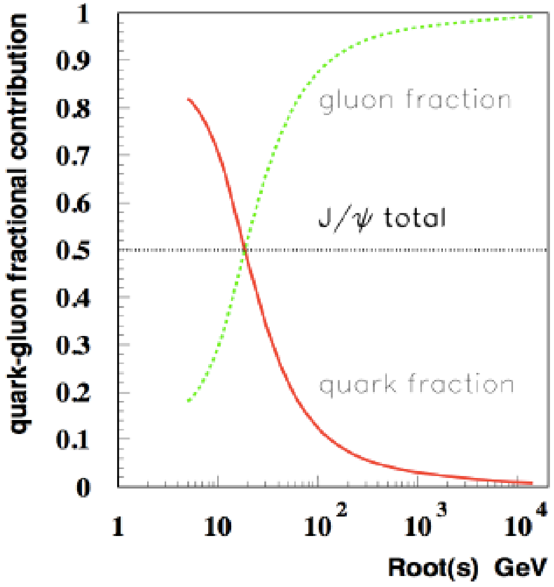
J/ψ production in 22 GeV πCu collisions

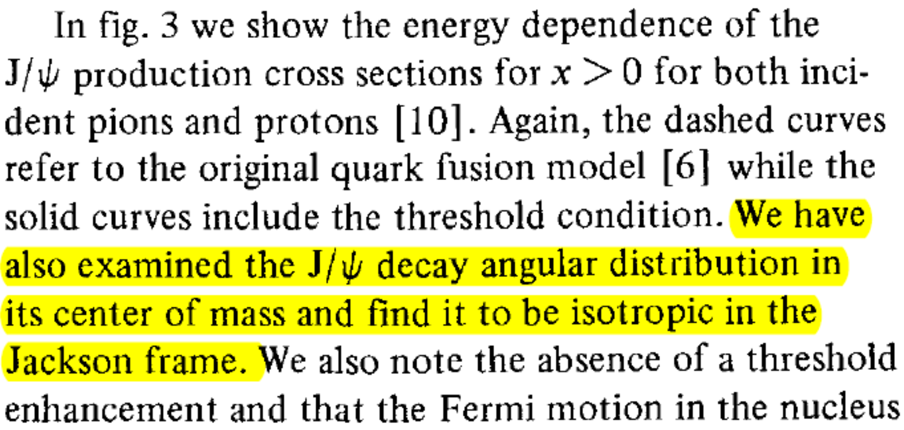
Nucl. Phys. B179 (1981) 189



σ(πN)~σ(pN): gg fusion dominates

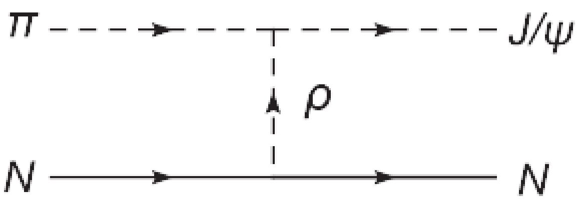
σ(πN)>>σ(pN): q$\bar{q}$ fusion dominates



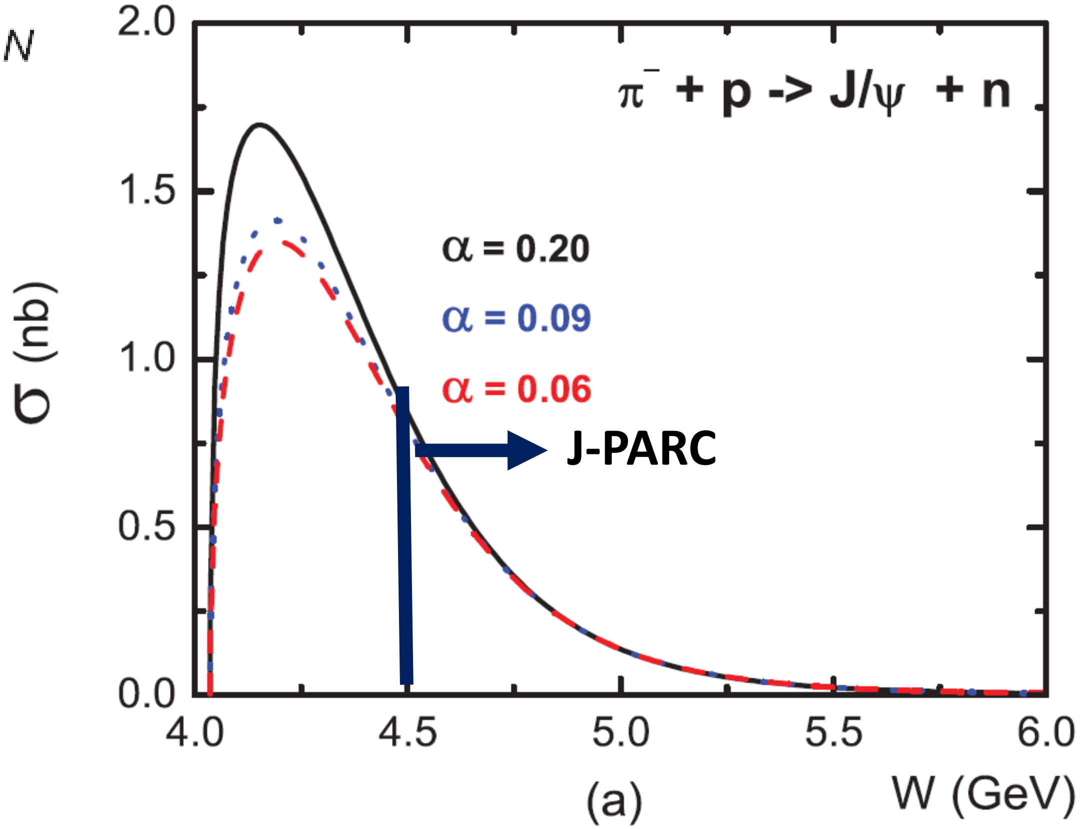

In fig. 3 we show the energy dependence of the J/ψ production cross sections for $x > 0$ for both incident pions and protons [10]. Again, the dashed curves refer to the original quark fusion model [6] while the solid curves include the threshold condition. We have also examined the J/ψ decay angular distribution in its center of mass and find it to be isotropic in the Jackson frame. We also note the absence of a threshold enhancement and that the Fermi motion in the nucleus

J/ψ-N Interaction Strength

Wu and Lee, PRC 88, 015205 (2013)

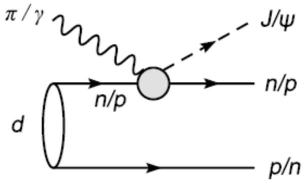


$$v_{J/\Psi N,J/\Psi N}(r) = -\alpha\frac{e^{-\mu_0 r}}{r}$$

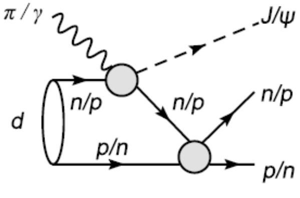


J/ψ-N Interaction Strength

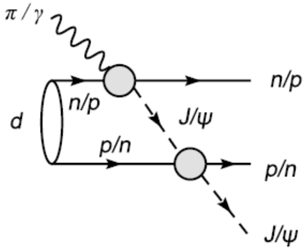
Wu and Lee, PRC 88, 015205 (2013)



(a) Impulse



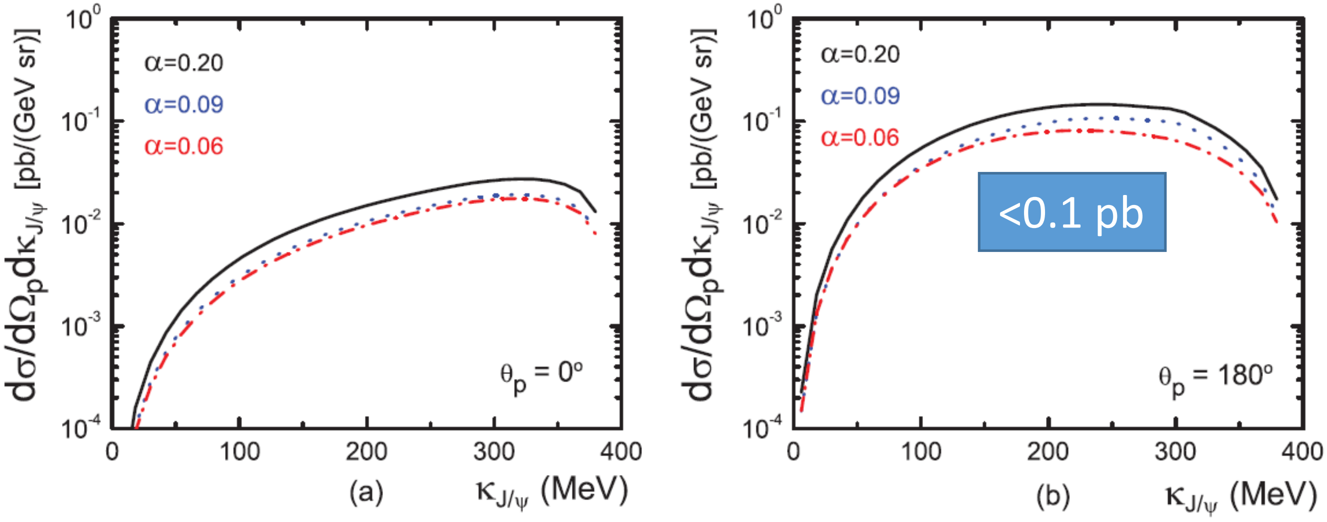
(b) NN Rescattering



(c) J/ψ N Rescattering

$$v_{J/\Psi N, J/\Psi N}(r) = -\alpha \frac{e^{-\mu_0 r}}{r}$$

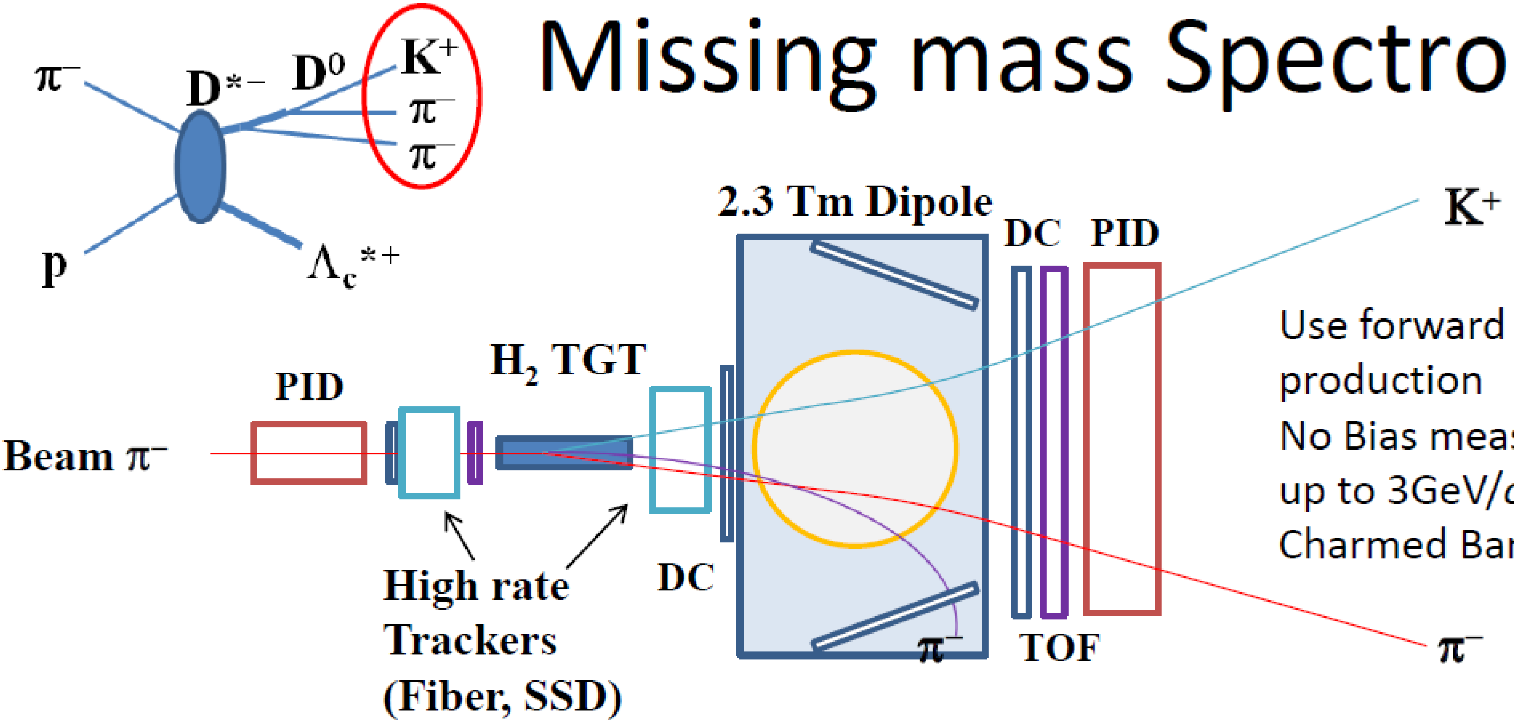
$$\pi^{+} + d \rightarrow J/\psi + p + p$$



<0.1 pb

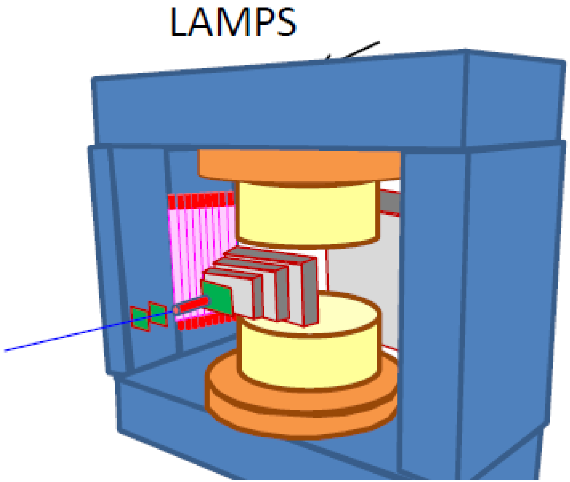
Look for production of hidden charm bound state. arXiv:1212.2440

Missing mass Spectroscopy



Use forward D mesons production

No Bias measurements up to 3GeV/c^2 of Charmed Baryon mass

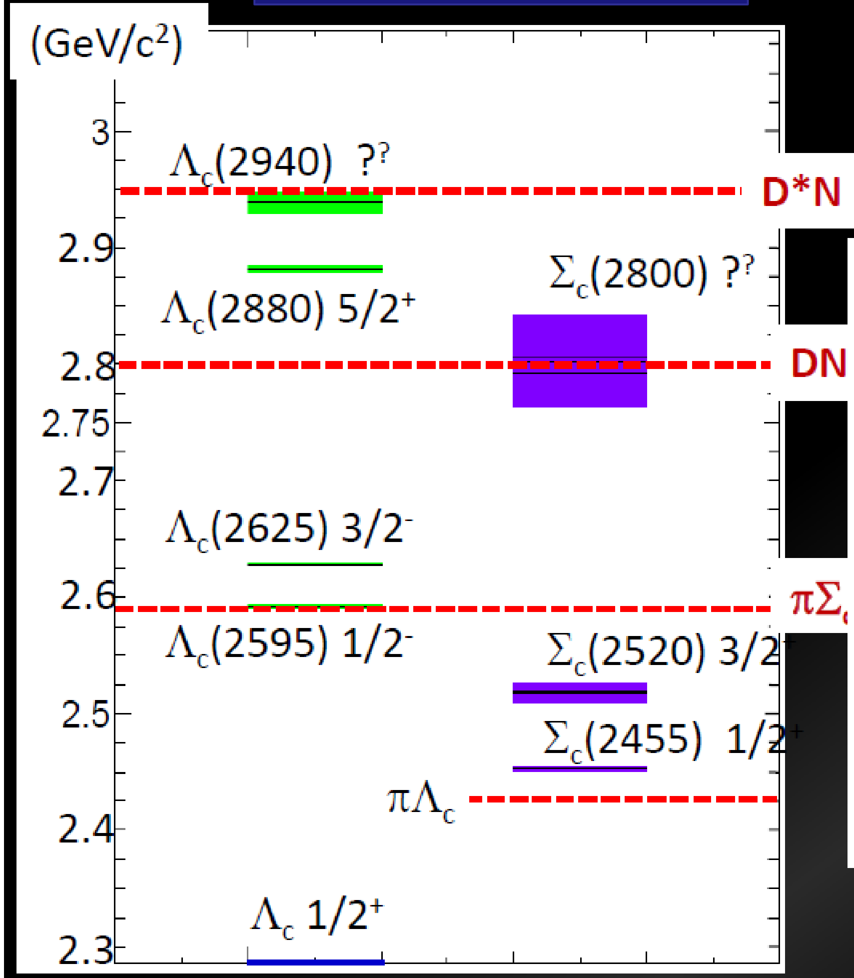


- Large Acceptance, Multi-Particle
  - K, π from D^0 decays
  - Soft π from D^{*-} decays
  - (Decay products from Y_c*)
- High Resolution
- High Rate
  - SFT/SSD op. >10M/spill at K1.8

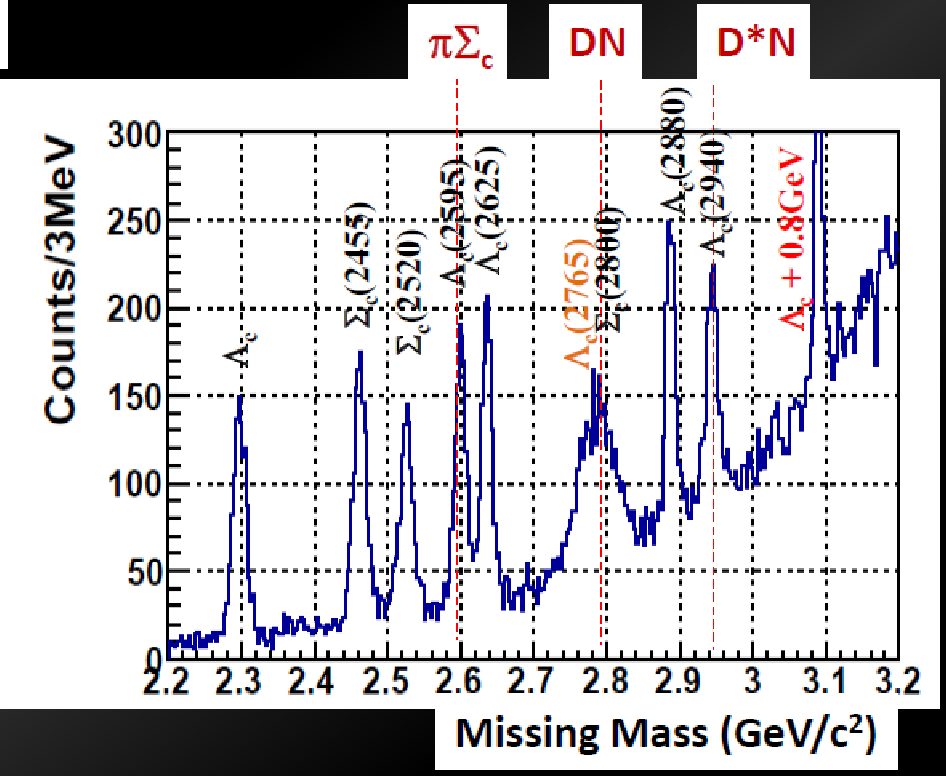
- Good mass resolution is required
  - D^0 meson: 4.5 MeV, D* meson: 0.7 MeV

Expected Spectrum in the (π,D^{*-}) reaction

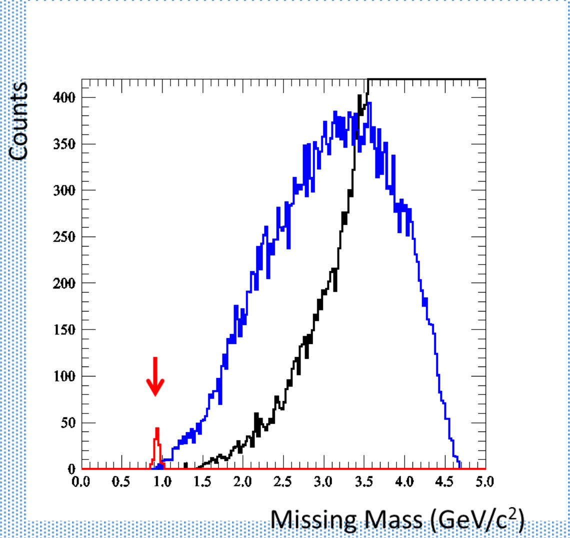
H. Noumi's talk



Signal: 1 nb/Yc* :~1000 events
BG: 1.8 mb (JAM)



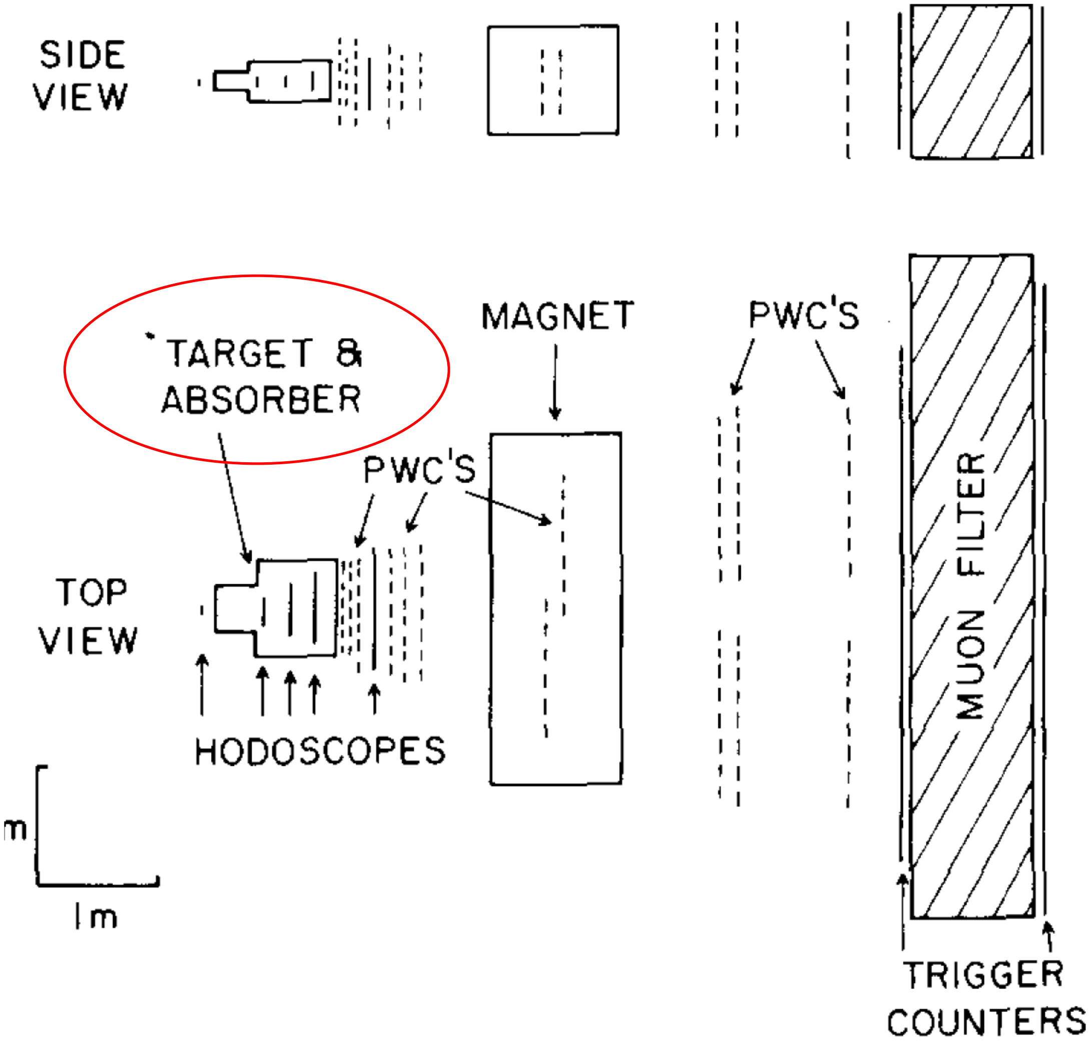
Feasibility study of Drell-Yan processes in the conceptual detector system



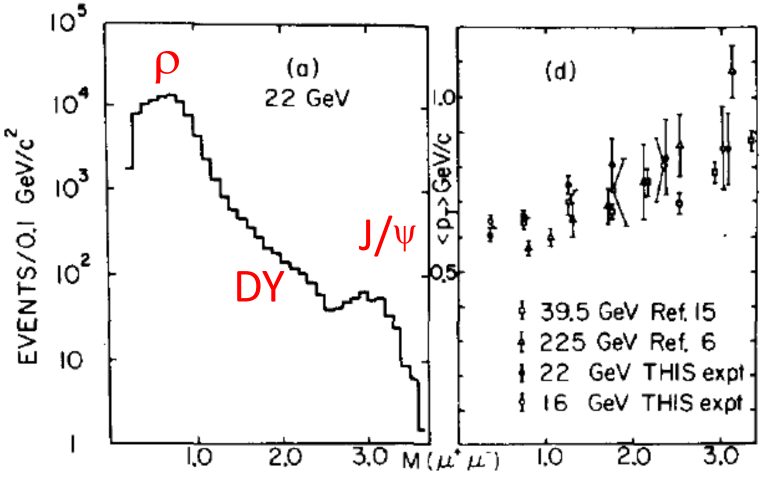
πN di-lepton experiments at low energies

- BNL (πN at 16 and 22 GeV):
  - Phys. Lett. B81 (1979) 397: di-lepton spectra
  - Phys. Lett. B81 (1979) 401: J/psi
  - Phys. Lett. B85 (1979) 427: Drell-Yan model
  - Phys. Lett. B85 (1979) 432: pion structure function
- IHEP, USSR (πN at 27 and 40 GeV):
  - Nucl. Phys. B179 (1981) 189

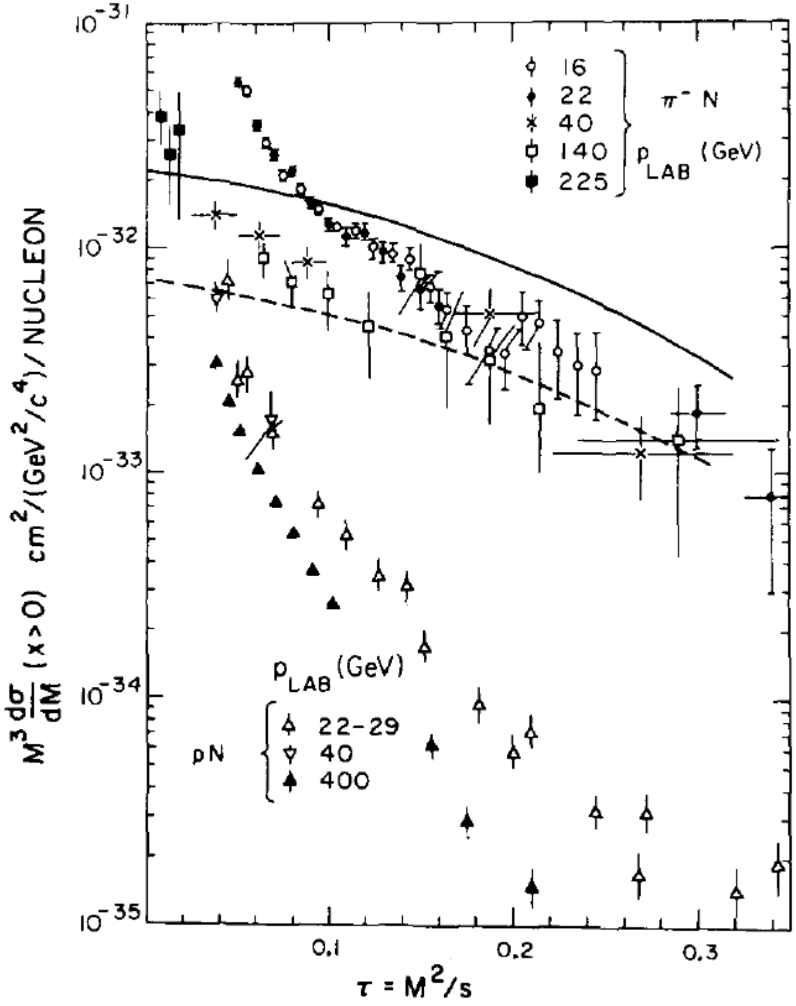
Hadron Absorber (24 inches of Brass)



Muon pair production in 22 GeV πCu collisions



$< p_T >$ increases with $M_{\mu\mu}$



No results of angular distributions.

- σ(DY) scales with τ
- σ(πN)>>σ(pN)

Muon pair production in 22 GeV πCu collisions

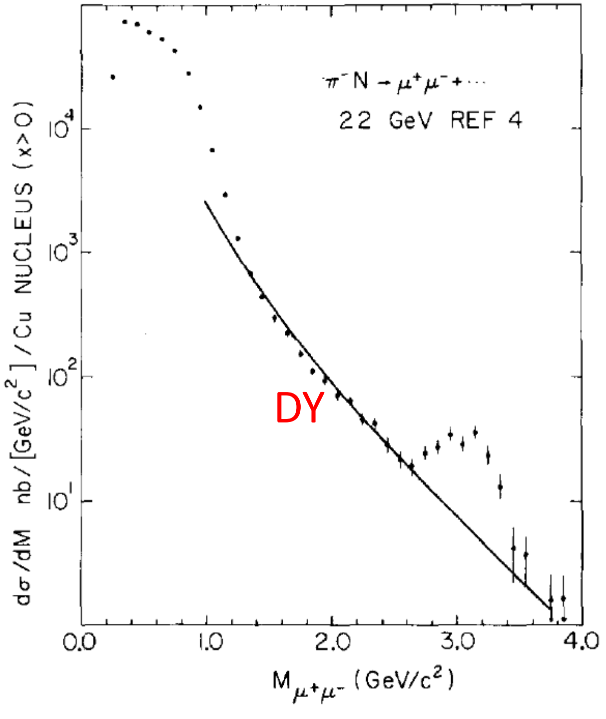
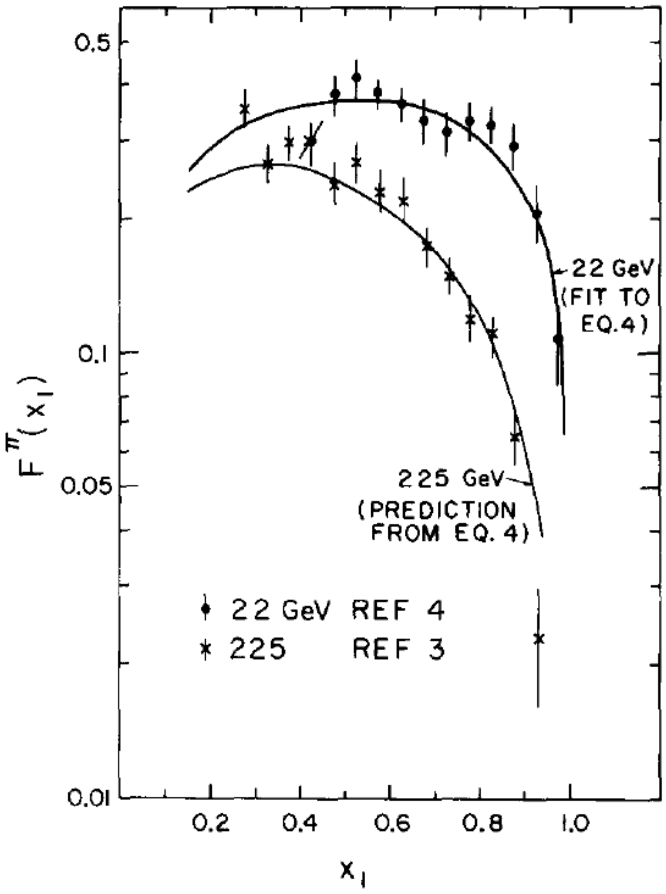
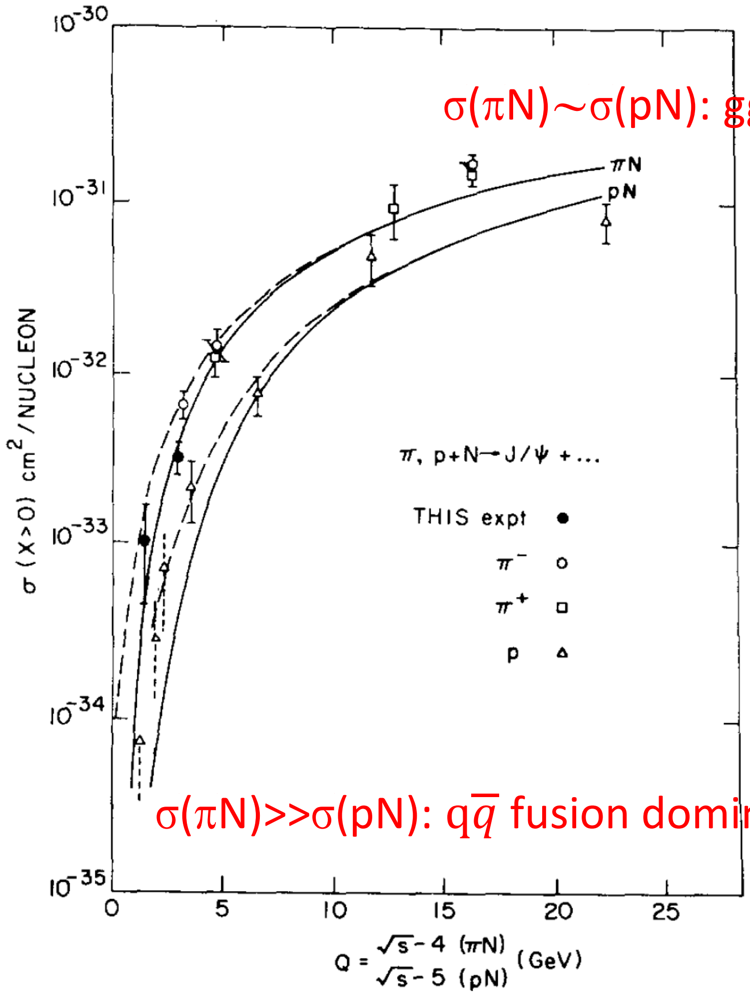


Fig. 3. The differential cross section $d\sigma/dM$ for dimuon production by 22 GeV π^- on a Cu target. The curve is the prediction of the Drell–Yan model using the observed pion structure function and the formalism of ref. [1].

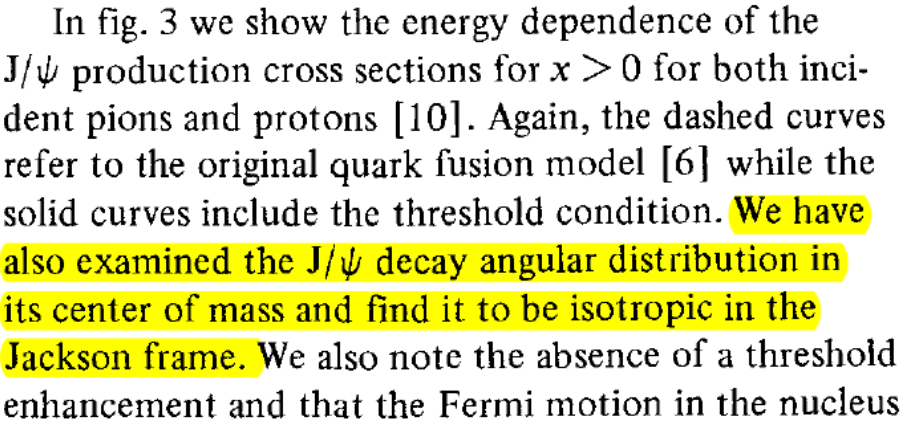


J/ψ production in 22 GeV πCu collisions



σ(πN)~σ(pN): gg fusion dominates

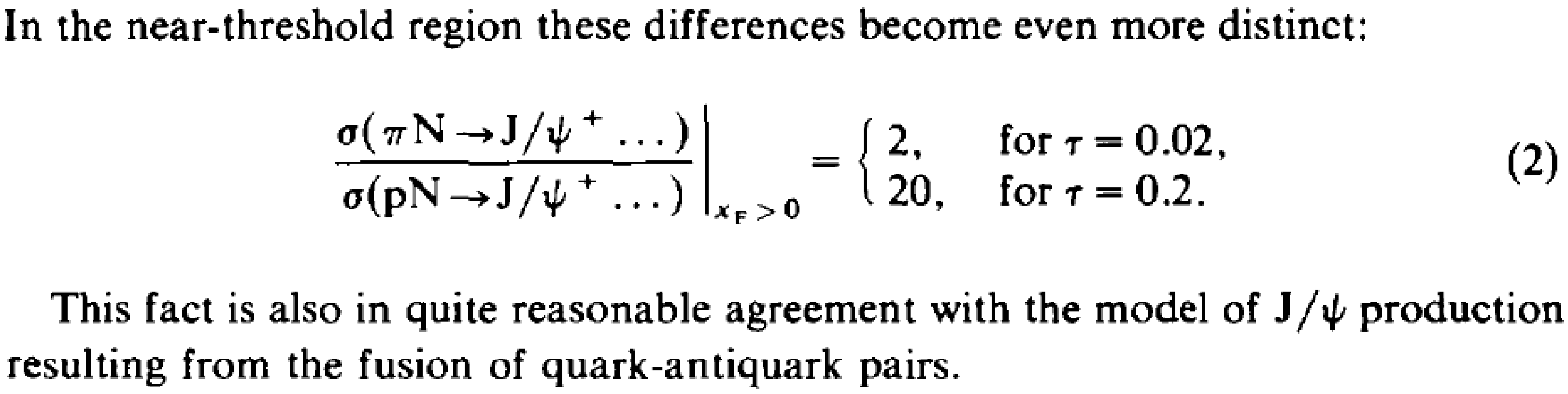
σ(πN)>>σ(pN): q$\bar{q}$ fusion dominates



In fig. 3 we show the energy dependence of the J/ψ production cross sections for $x > 0$ for both incident pions and protons [10]. Again, the dashed curves refer to the original quark fusion model [6] while the solid curves include the threshold condition. We have also examined the J/ψ decay angular distribution in its center of mass and find it to be isotropic in the Jackson frame. We also note the absence of a threshold enhancement and that the Fermi motion in the nucleus

Violation of Lam-Tung relation remains at low energies?

Muon pair production in 27 and 40 GeV πN collisions



In the near-threshold region these differences become even more distinct:

$$\left.\frac{\sigma(\pi N \to J/\psi^{+} \ldots)}{\sigma(pN \to J/\psi^{+} \ldots)}\right|_{x_F > 0} = \begin{cases} 2, & \text{for } \tau = 0.02, \\ 20, & \text{for } \tau = 0.2. \end{cases} \qquad (2)$$

This fact is also in quite reasonable agreement with the model of J/ψ production resulting from the fusion of quark-antiquark pairs.

Precise information of the angular distributions of Drell-Yan and J/ψ will be essential in understanding their production mechanisms at low energies.

πN Di-lepton Production: Drell-Yan & J/ψ

- Drell-Yan:
  - Pion partonic structure
  - BM function (Violation of L-T relation)
  - Pion DA
  - Valance-quark distributions at large-x
  - Parton energy loss
  - Nuclear PDF
  - Low-mass di-lepton spectrum
- J/ψ:
  - Production mechanism at low energies
  - Intrinsic charm of pion at large xF

- **Beam**: pion
- **Target**: proton, deuteron and nuclei
- **Detector**: hadron absorber, muon identification, di-muon trigger
- **Pros**: well-established approach, complementary to COMPASS.
- **Cons**: bad momentum resolutions due to relatively large multiple-scattering effect in hardon absorber.

pN Di-lepton Production: Drell-Yan & J/ψ

- Drell-Yan:
    - p+d/p+p ratio measurement for u,d sea quark of nucleon at large-x.
    - BM function (Violation of L-T relation)
    - Parton energy loss
    - Nuclear PDF
    - Low-mass di-lepton spectrum
    - Forward-backward asymmetry in decay angular distribution of Drell-Yan for probing Weinberg angle at low Q^2
- J/ψ:
    - Production mechanism at low energies; J/Psi production as an alternative Drell-Yan to probe the sea-quark in nucleon.
    - Intrinsic charm of proton at large xF

- **Beam**: proton (30 GeV)
- **Target**: proton, deuteron and nuclei
- **Detector**: hadron absorber, muon identification, di-muon trigger
- **Pros**: well-established approach, complementary to E906/SeaQuest.
- **Cons**: small cross section; bad momentum resolution of muons due to relatively large multiple-scattering effect.

KN Dilepton Production: Drell-Yan & J/ψ

- Drell-Yan:
  - K+d/K+p ratio measurement for strange sea quark of nucleon at large-x.
  - Kaon partonic structure
  - BM function or Glauber gluon responsible for L-T relation violation
- J/ψ:
  - Production mechanism at low energies.
  - Intrinsic charm of kaon at large xF

- **Beam**: kaon
- **Target**: proton, deuteron and nuclei
- **Detector**: beam PID, hadron absorber, muon identification, di-muon trigger
- **Pros**: novel measurement other than NA3.
- **Cons**: bad momentum resolution of muons due to relatively large multiple-scattering effect.

πN Exclusive Di-lepton Production

- Nucleon GPD
- Pion DA
- Pion-Nucleon TDA

- **Beam**: pion
- **Target**: proton, deuteron and nuclei
- **Detector**: hadron absorber, muon identification, di-muon trigger
- **Pros**: novel measurement for determining GPD; complementary to Jlab, GSI and COMPASS.
- **Cons**: bad momentum resolution of muons becomes crucial in ensuring the exclusive production; relatively small production cross section (1 pb).

πN Hard Exclusive Hadron Production

- Hadron tomography
- Color transparency
- Charmed baryons
- Heavy exotics

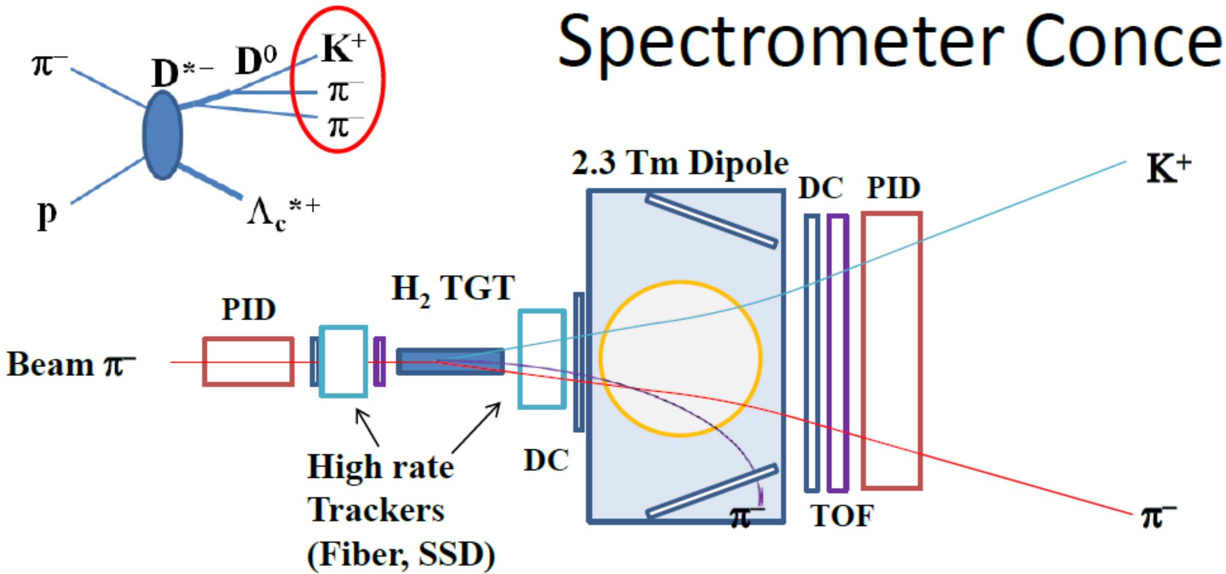
- **Beam**: pion-
- **Target**: proton, deuteron and nuclei
- **Detector**: good spectrometer
- **Pros**: novel measurement, large cross section
- **Cons**: Large background, online trigger might be needed.

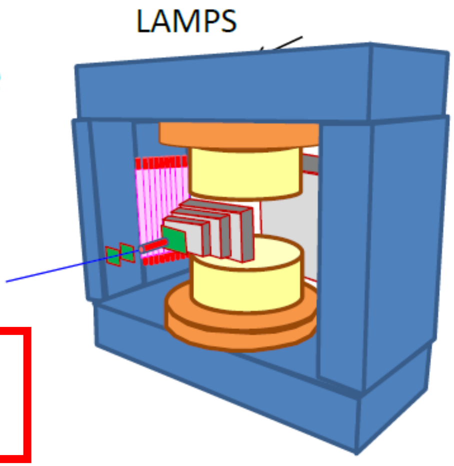
Conceptual Detector System

- Beam PID: possibility of utilizing kaon and anti-p beams
- Open aperture without hadron absorber before momentum determination: minimize multiple-scattering of muons
- Spectrometer with good momentum resolution and particle ID
- Muon ID in the forward direction at the very downstream

J-PARC P50 Spectrometer

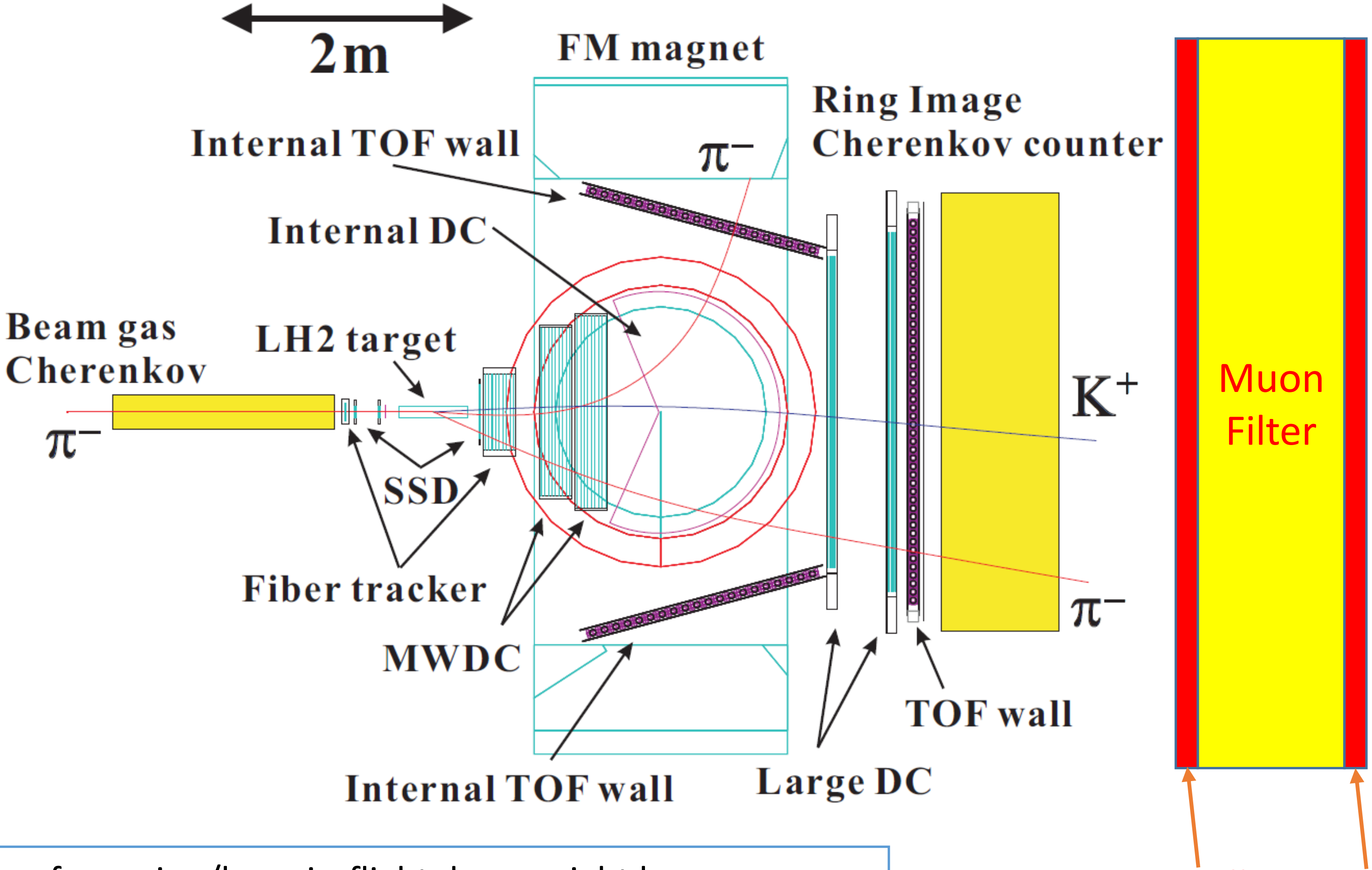
Spectrometer Concept





- Large Acceptance, Multi-Particle
  - *K*, *π* from D^0 decays
  - Soft π from D^{*-} decays
  - (Decay products from Y_c^*)
- High Resolution
- High Rate
  - SFT/SSD op. >10M/spill at K1.8

J-PARC P50 Spectrometer + MuID

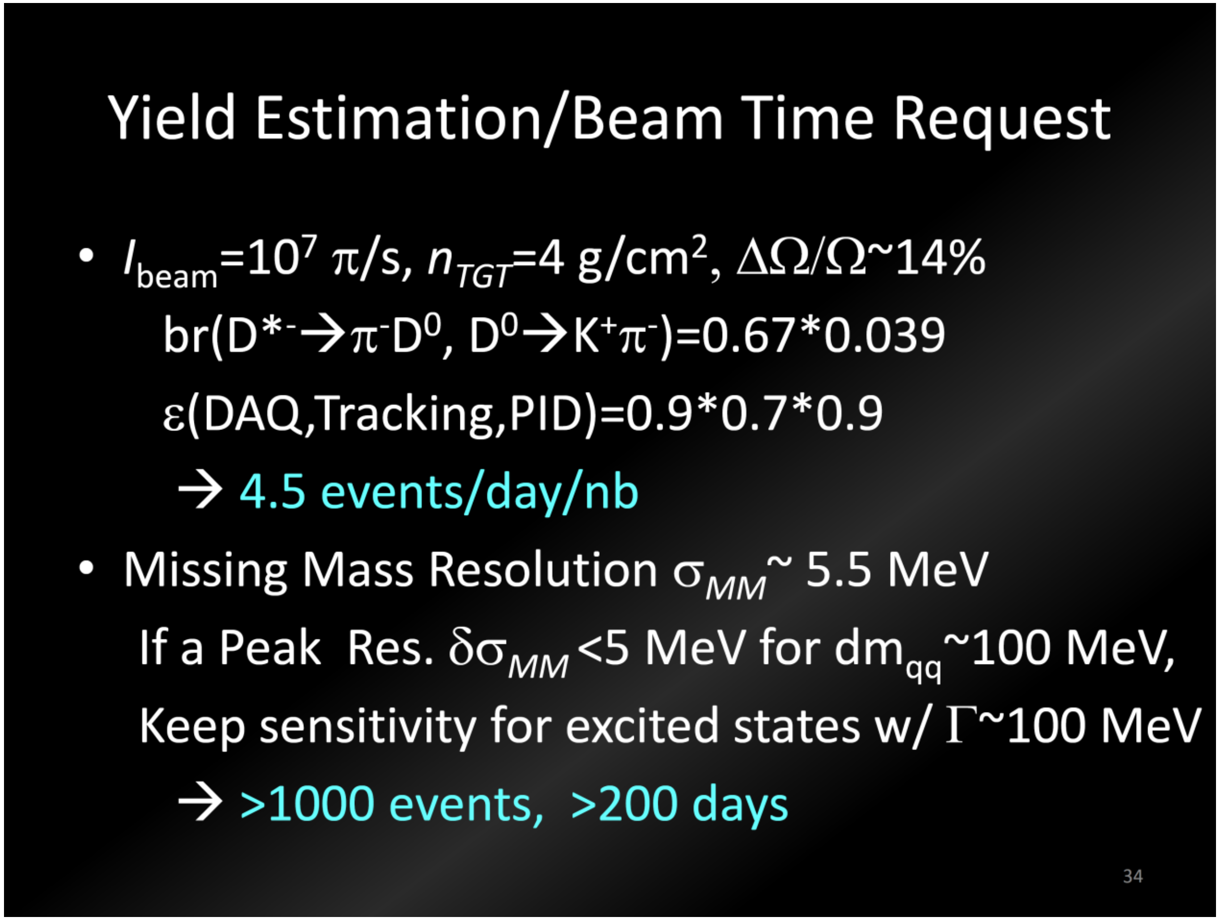


Muons from pion/kaon in-flight decay might be a concern.

|θ|<60°

Scintillator Muon trigger device

Yield Estimation from J-PARC P50



Yield Estimation/Beam Time Request

- $I_{beam}=10^7\ \pi/s$, $n_{TGT}=4\ g/cm^2$, $\Delta\Omega/\Omega$~14%
  $br(D^{*-} \rightarrow \pi^- D^0,\ D^0 \rightarrow K^+\pi^-)=0.67*0.039$
  ε(DAQ,Tracking,PID)=0.9*0.7*0.9
  → 4.5 events/day/nb
- Missing Mass Resolution σ_{MM}~ 5.5 MeV
  If a Peak Res. $\delta\sigma_{MM}$<5 MeV for dm_{qq}~100 MeV,
  Keep sensitivity for excited states w/ Γ~100 MeV
  → >1000 events, >200 days

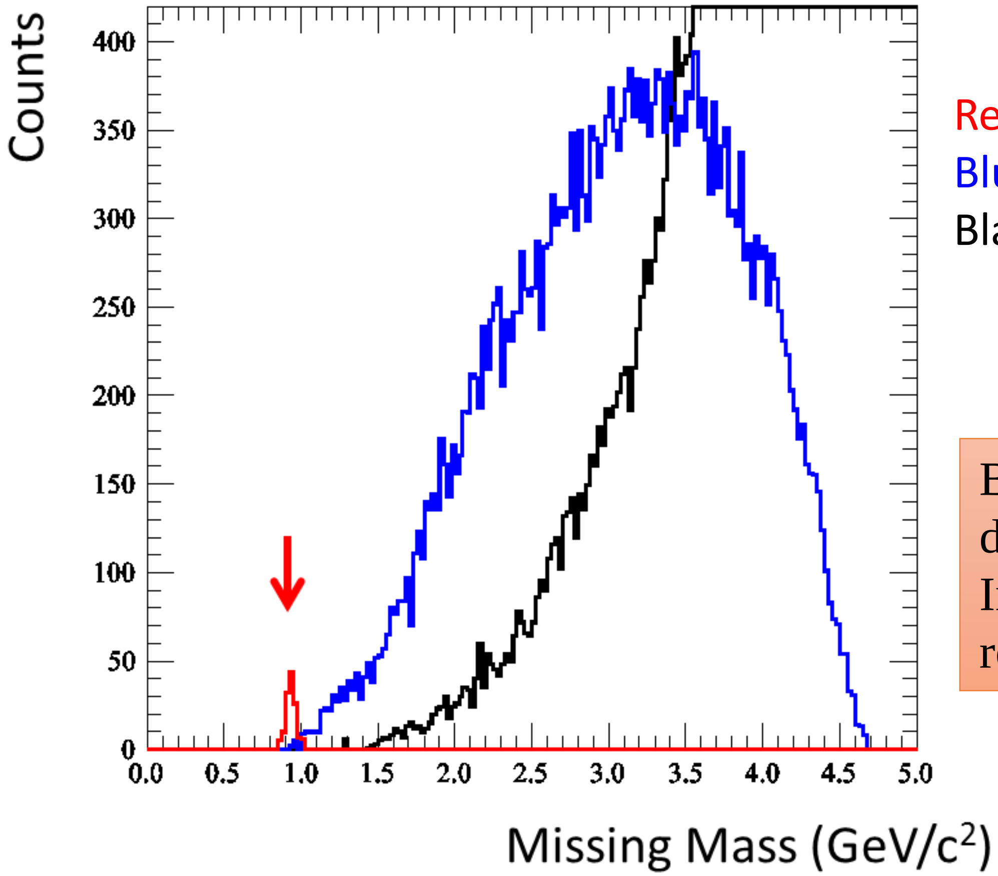
Yield Estimation based on J-PARC P50 Parameters

- $I_{\mathrm{beam}}=10^7$ π/s, $n_{TGT}=4$ g/cm^2 (57cm LH2), ΔΩ/Ω~100% , ε(DAQ, Tracking, PID)=0.9*0.7*0.9

→1 events/day/pb

- Beam time of 200 days
  - Inclusive pion-induced Drell-Yan: OK
  - Exclusive pion-induced Drell-Yan: Marginally OK
  - Exclusive pion-N Lambda(1405) production: OK (multi-particle acceptance?)
  - Inclusive pion-induced J/psi production: OK
  - Exclusive pion-N J/psi production: NO

20-GeV π- + proton→μ+μ-X Seen In P-50 Spectrometer



After 200 days data-taking

Red: Exclusive DY (1 pb)

Blue: Inclusive DY (500 pb)

Black: vector meson decay (25 mb)

Assumption: Δp/p = 0.2 %

Background from the pion/kaon in-flight decay is not included and will be studied. In principle this background could be removed using like-sign subtraction.

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Summary (I)

- The high-energy hadron beam at J-PARC might be most ideal tool for the hard exclusive processes where valance-like partonic structure of hadrons could be studied .
- The study of π-induced DY/charm production and hard exclusive processes will offer important understanding on many aspects of QCD via
  - **Nucleon structure**: sea quarks PDF; TMD, GPD, TDA
  - **pion structure**: DA and Timelike FF
  - **Structure of exotic hadrons**
  - **J/ψ production mechanism, exotic charmed baryons**

Summary (II)

- Spectrometer with large acceptance and good mass resolution is required. The measurement using P-50 conceptual spectrometer is feasible. Longer target cell is preferred.
- Deuterium target together with the possibility of measuring recoiled protons will enable the measurement of flavor separation of BM functions and valance-quark distributions at large-x.