KEK theory center workshop on
J-PARC hadron physics in 2014

2F Conference room, Ibaraki Quantum Beam Research Center
February 10 - 12, 2014, Tokai, Ibaraki, Japan

High-energy hadron experiments at J-PARC

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in collaboration with
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K. Tanaka *(Juntendo),* ***J.C. Peng*** *(UIUC)*

Outline

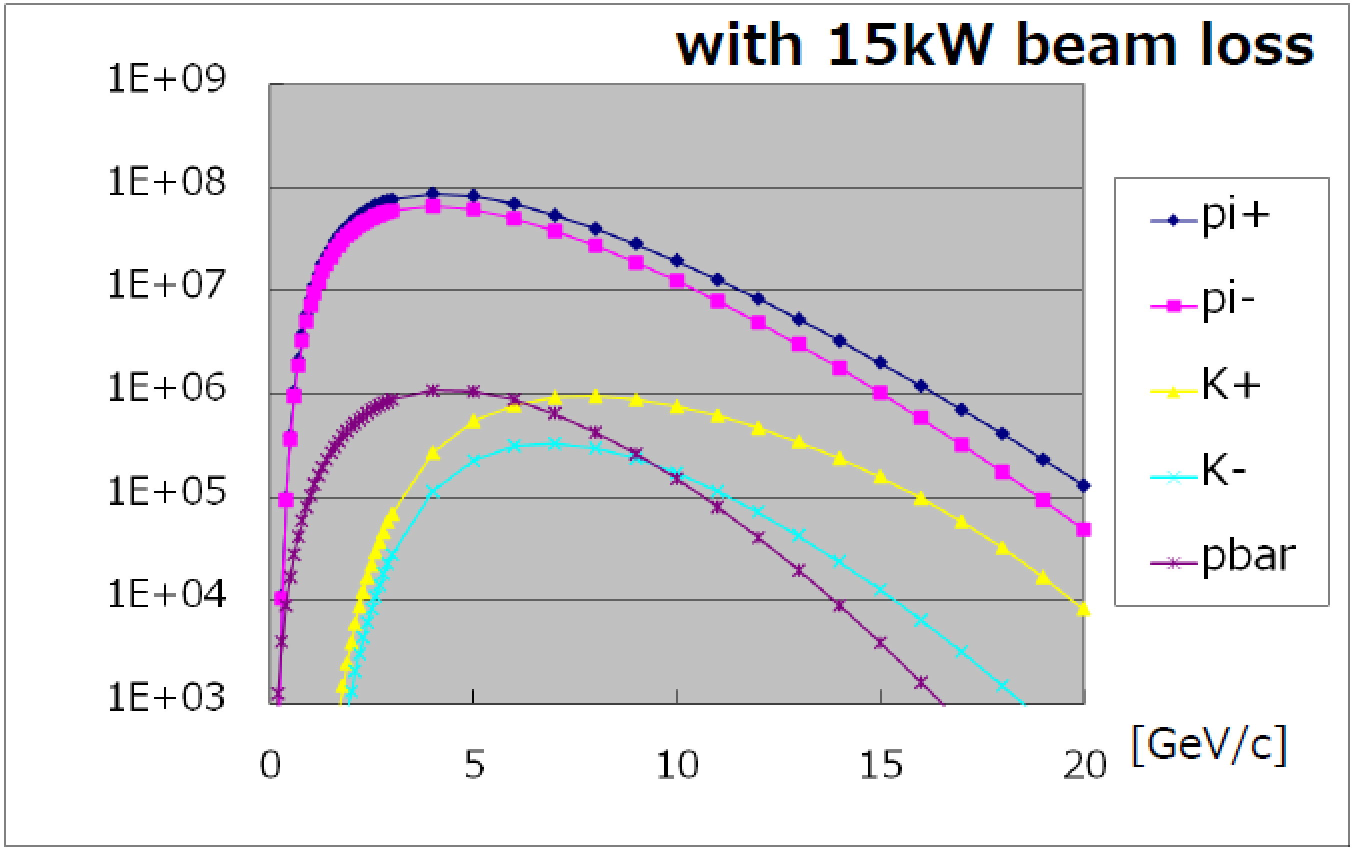
- Uniqueness of hadron physics studied at HiPBL of J-PARC
- Selected Physics Processes:
  - Drell-Yan process
  - Hard exclusive process
  - Charmed production process
- Feasibility study of Drell-Yan processes in the conceptual detector system
- Summary

R. Muto, KEK

secondary beam intensity

beam loss limit @ SM1:15kW

(limited by the thickness of the tunnel wall)

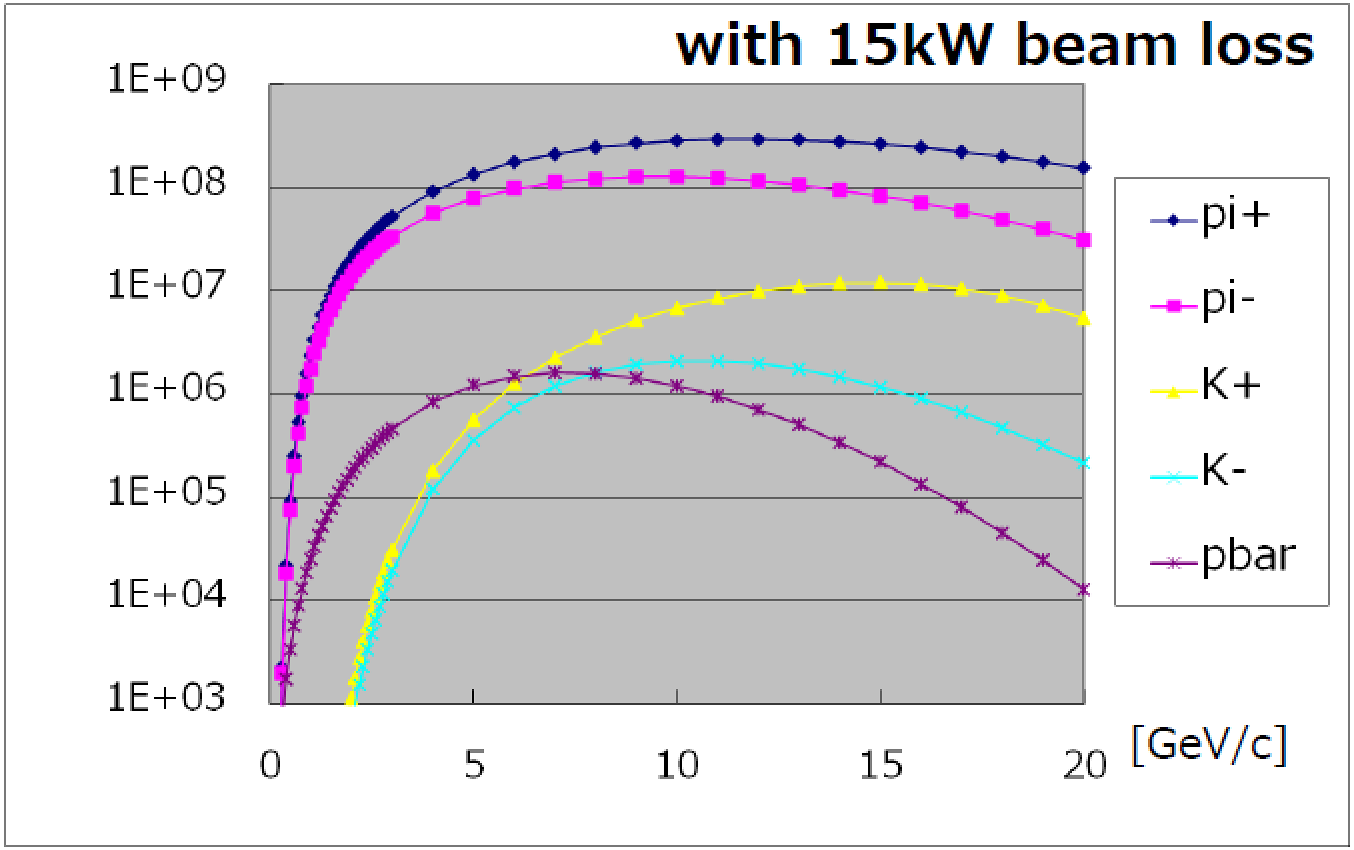


extraction angle : 5°

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

MENU

- 1st circular
- 2nd circular
- Program (slides)
- Participants
- Location: KEK
- Kenkyu-Honkan (M01)
- Kobayashi Hall
- Lounge for banquet
- Seminar Hall
- Visitor information (English)
- Visitor information (Japanese)
- How to reach KEK (General guide)
- Bus/taxi to KEK (Our original guide)
- to Urban hotel (Our original guide)
- KEK restaurant hours
- Nearby restaurants

[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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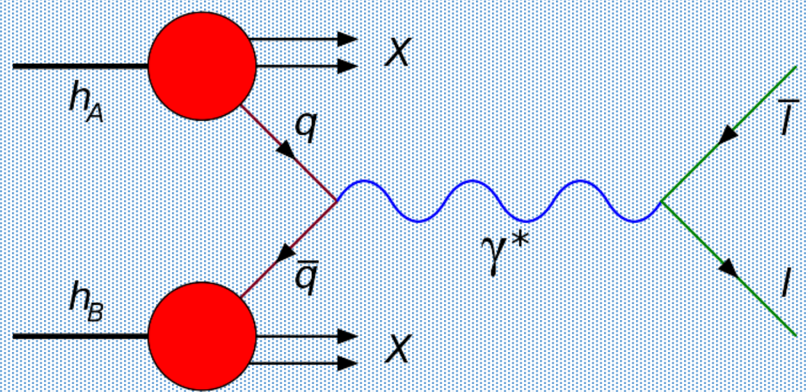
--------------------------- Program ---------------------------

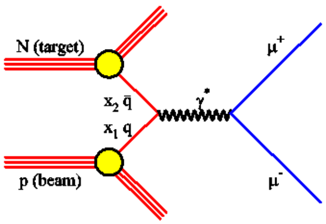
Selected Physics Processes

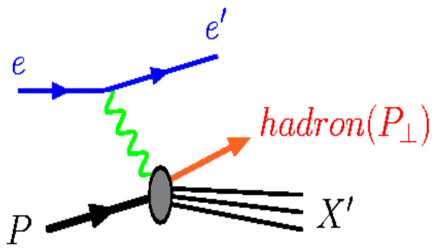
- Drell-Yan process
  - Inclusive pion-induced Drell-Yan
  - Exclusive pion-induced Drell-Yan
- Hard exclusive production process
  - Exclusive pion-N Lambda(1405) production
- Charmed production process
  - Inclusive pion-induced J/psi production
  - Exclusive pion-N J/psi production
  - Exotic charm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



Drell-Yan process

Wigner Distribution





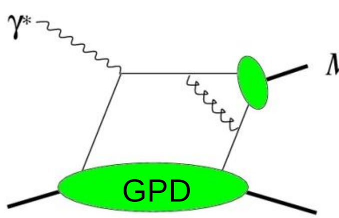
Wigner Distribution
$W(\vec{r}, x, \vec{k}_T)$

Ji, PRL91,062001(2003)

d^3r

$d^2k_t dz$

F.T.



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

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

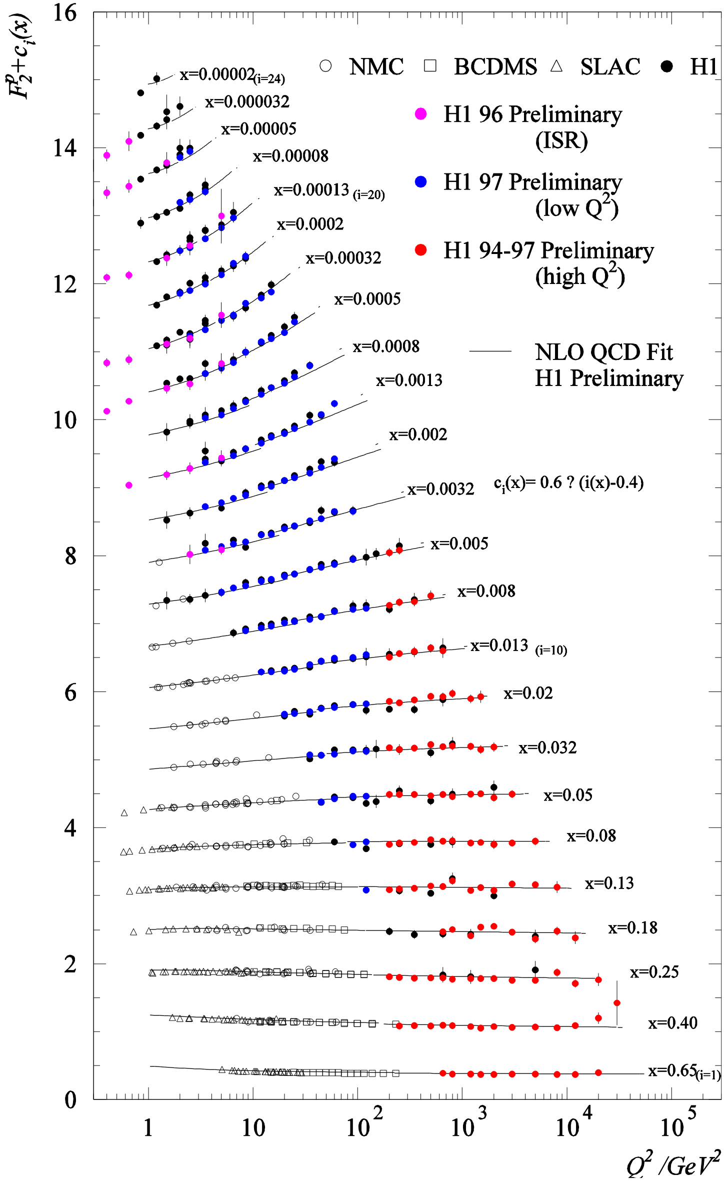
d^2k_t

dx

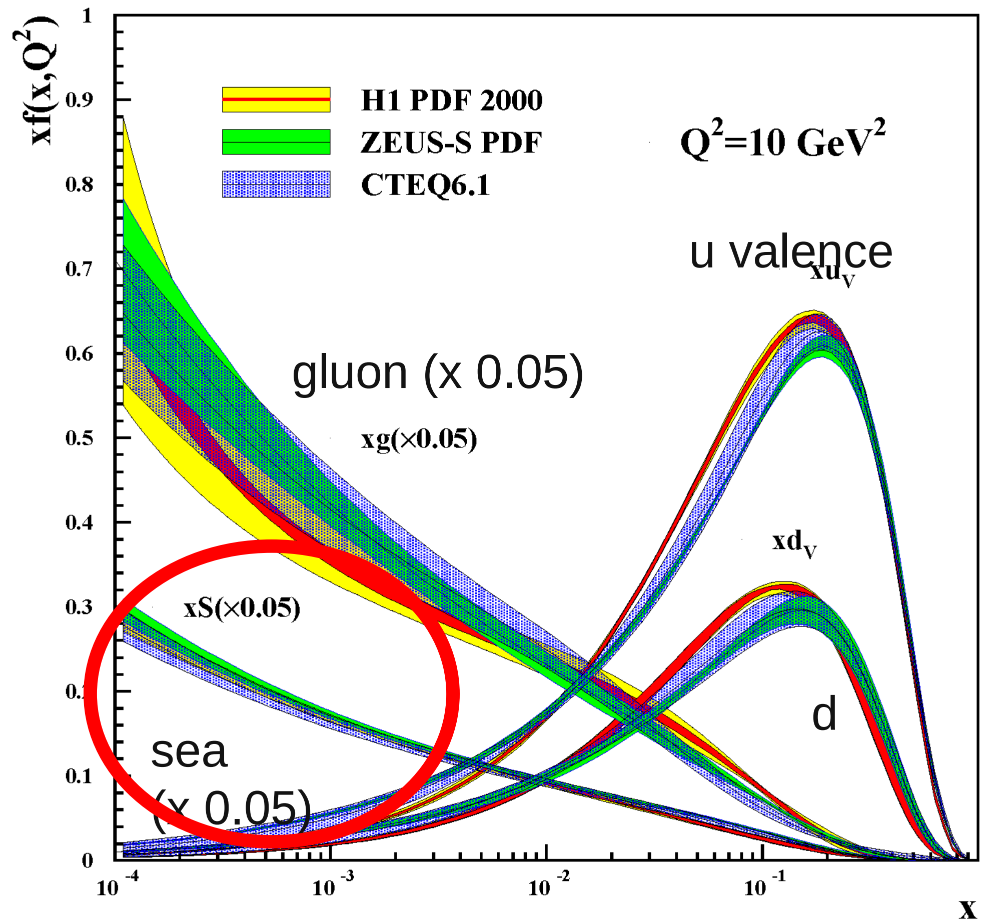
PDF $f(x)$

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

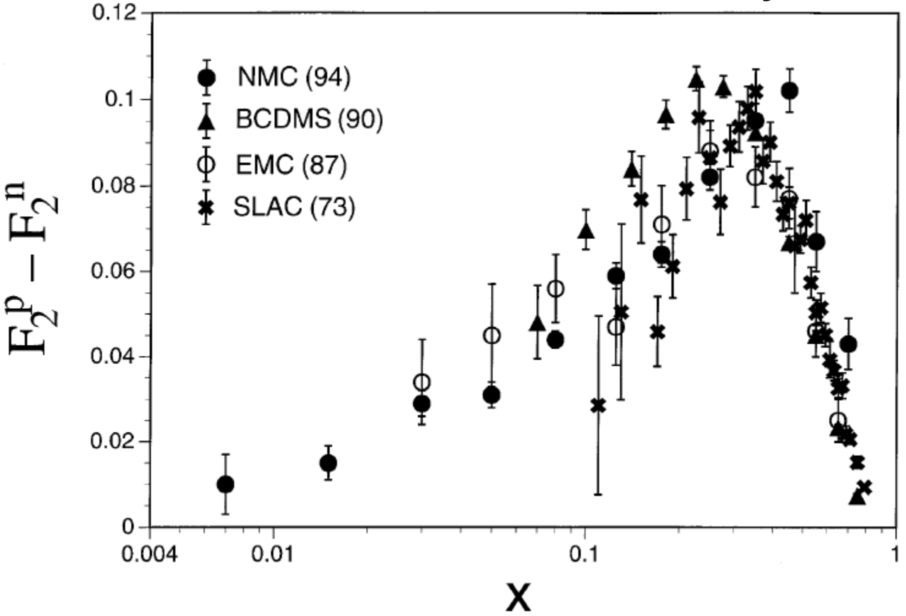
$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x)) / x] dx$$

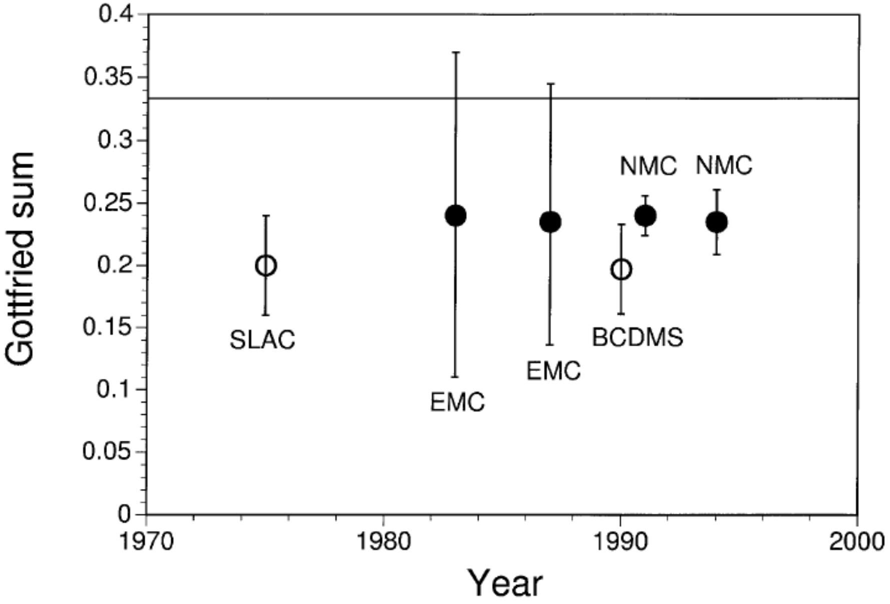
$$= \frac{1}{3}\int_0^1 (u_v(x) - d_v(x))\, dx + \frac{2}{3}\int_0^1 (\bar{u}(x) - \bar{d}(x))\, dx$$

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

Experimental Measurement of Gottfried Sum

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





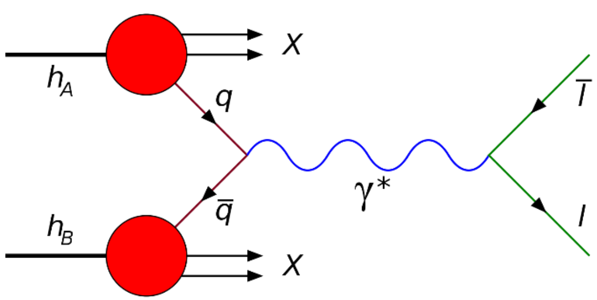
New Muon Collaboration (NMC), Phys. Rev. D50 (1994) R1

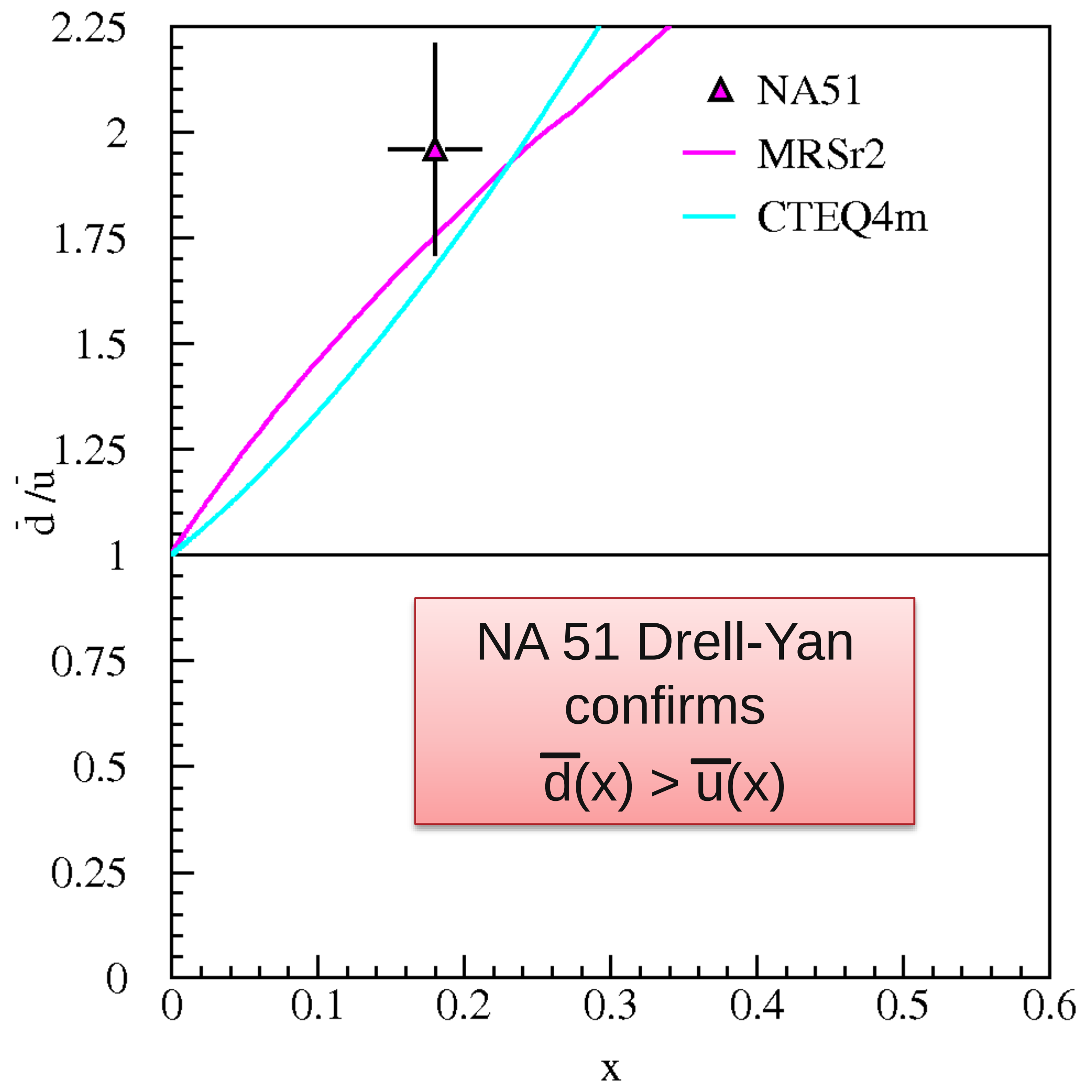
$$S_G = 0.235 \pm 0.026$$

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





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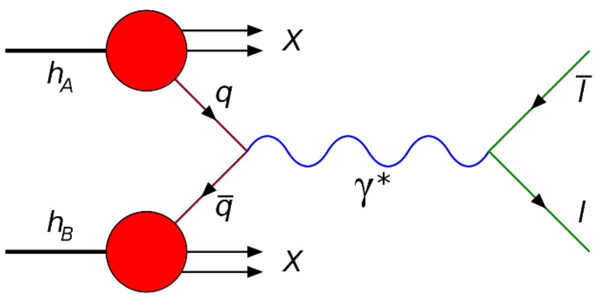
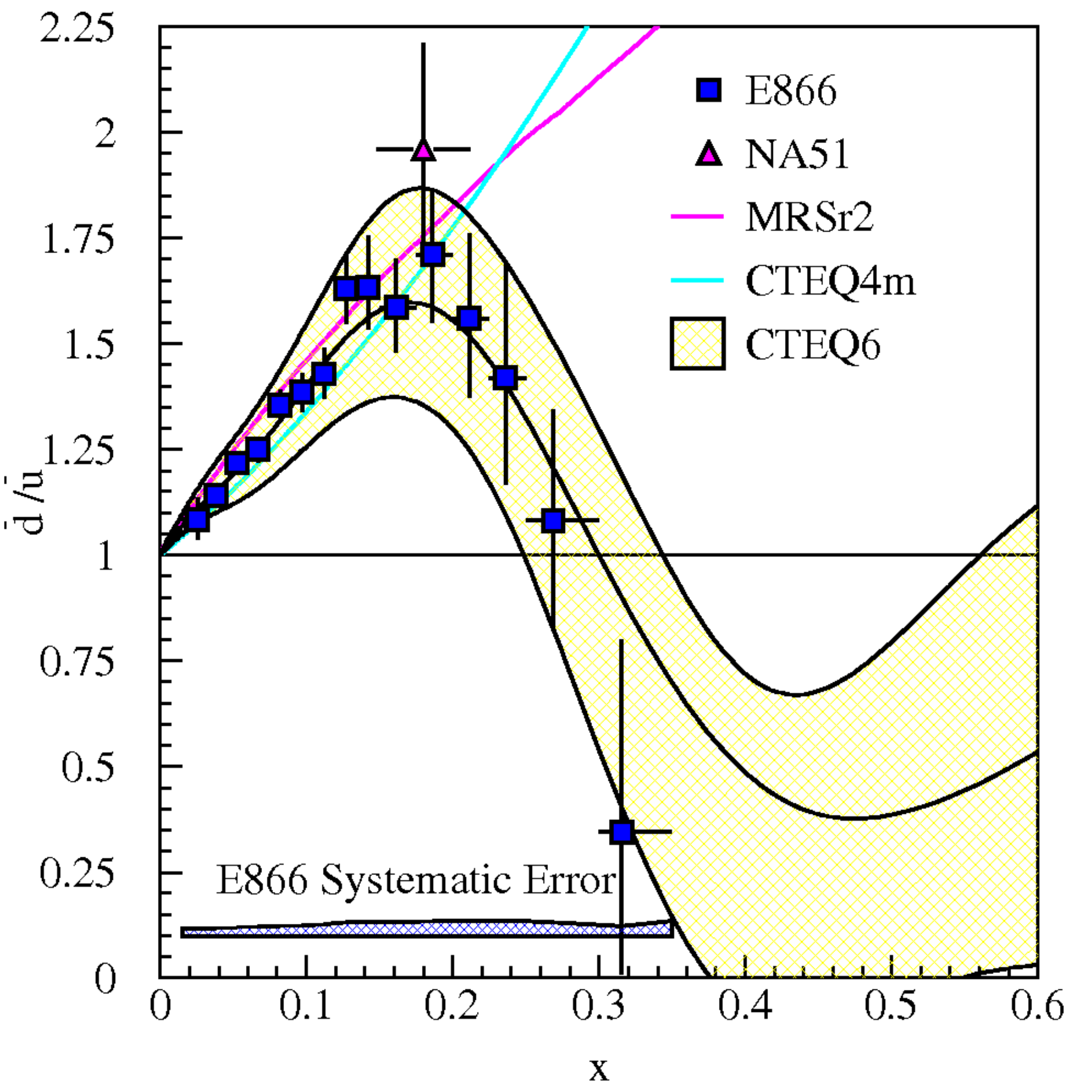
- NA51 (Drell-Yan, 1994)

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

- E866/NuSea (Drell-Yan, 1998)

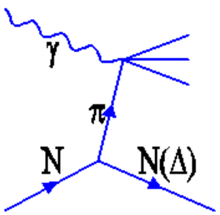
$$\bar{d}(x)/\bar{u}(x) \text{ for } 0.015 \leq x \leq 0.35$$

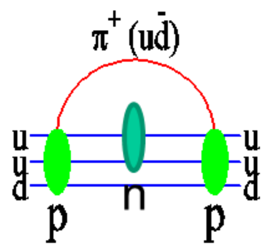




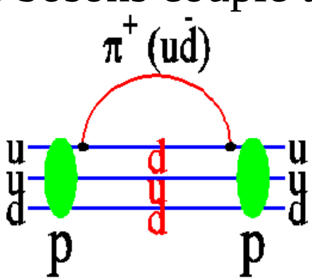
Origin of $\bar{u}(x) \neq \bar{d}(x)$?

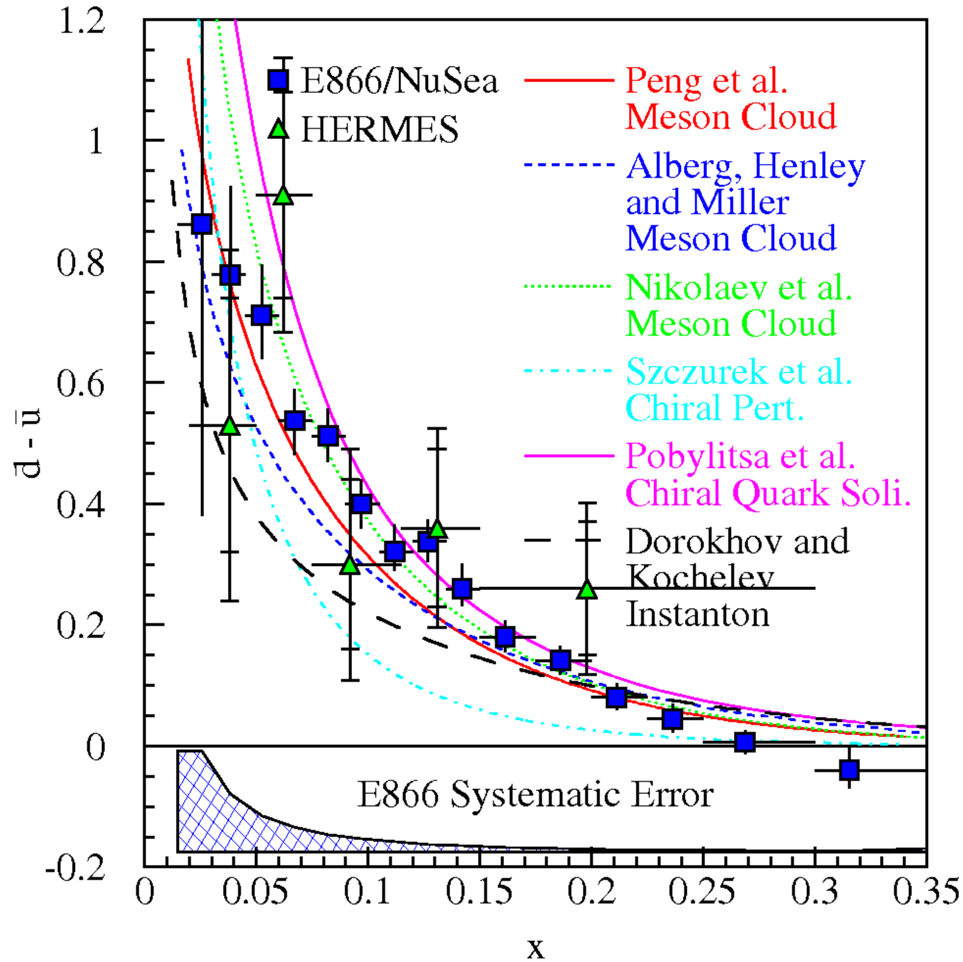
- **Pauli blocking of valance quarks**
- **Meson cloud in the nucleons** (Thomas 1983, Kumano 1991): Sullivan process in DIS.



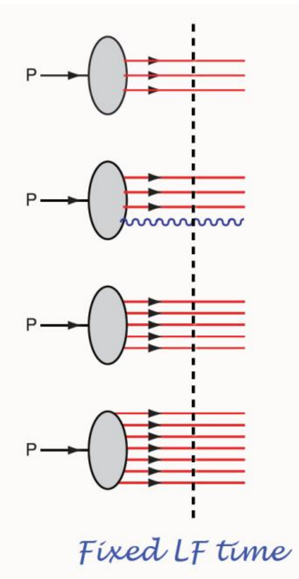


- **Chiral quark model** (Eichten et al. 1992; Wakamatsu 1992): Goldstone bosons couple to valence quarks.





Intrinsic Charm Quarks in Light-Front 5q Fock States



In the 1980's Brodsky, Hoyer, Peterson, Sakai (BHPS) suggested the existence of "intrinsic" charm (PLB 93,451; PRD 23, 2745).

$$| p >= P_{3q} | uud > + P_{5q} | uudQ\bar{Q} > + P_{3q+g} | uudg > .....$$

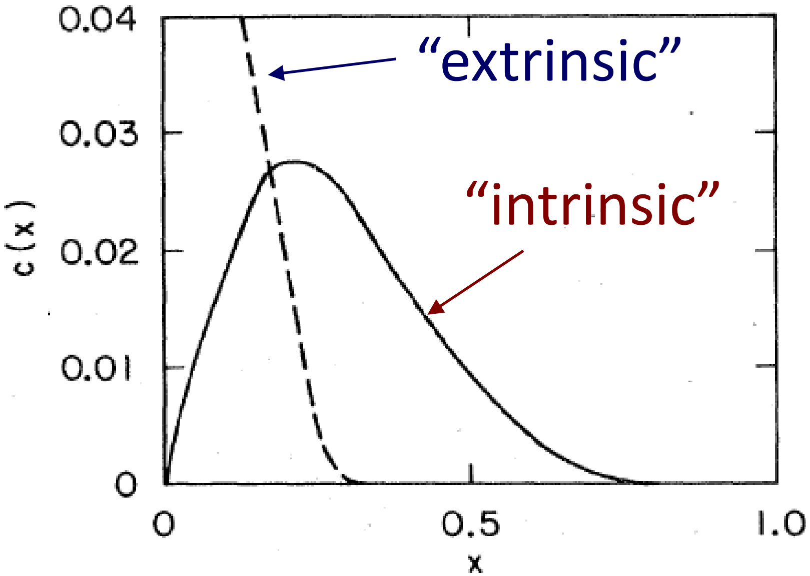
$$P(x_1, ..., x_5) = N_5 \delta(1 - \sum_{i=1}^{5} x_i) / [m_p^2 - \sum_{i=1}^{5} \frac{m_i^2}{x_i}]^2$$

- Dominant Fock state configurations have the minimal invariant mass, i.e. the ones with equal-rapidity constituents.
- The large charm mass gives the c quark a larger x than the other comoving light partons, more valence-like.

Intrinsic Charm Quarks in Light-Front 5q Fock States

Brodsky, Hoyer, Peterson, Sakai (BHPS)
PLB 93,451 (1980); PRD 23, 2745 (1981)

The "intrinsic"-charm from $|uudc\bar{c}\rangle$ is "valence"-like and peak at large x unlike the "extrinsic" sea ($g \to c\bar{c}$)



The $|uudc\bar{c}\rangle$ intrinsic-charm can lead to large contribution to charm production at large x_F

Search for the lighter "intrinsic" sea quark

$$| p\rangle = P_{3q} \,| uud\rangle + P_{5q} \,| uudQ\bar{Q}\rangle + \cdots\cdots$$

No conclusive experimental evidence for intrinsic-charm so far

Are there experimental evidences for the intrinsic

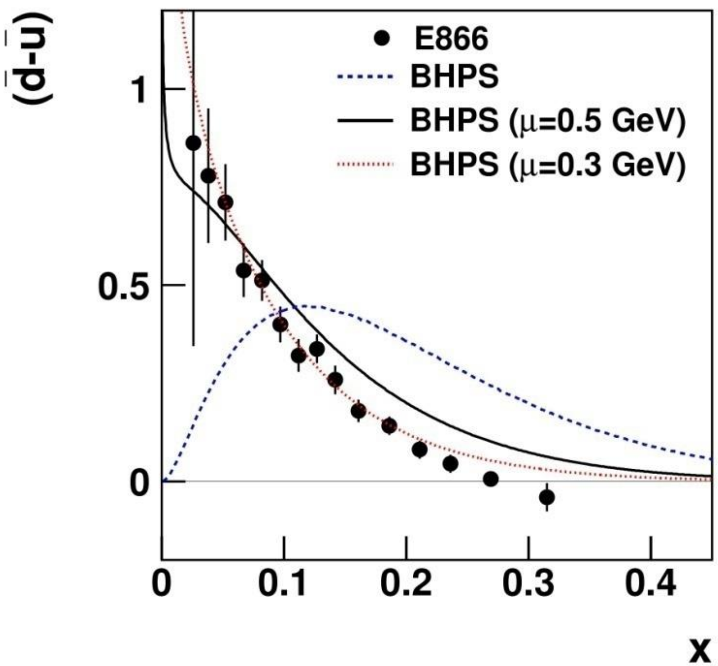
$| uudu\bar{u}\rangle, | uudd\bar{d}\rangle, | uuds\bar{s}\rangle$ 5-quark states ?

$$P_{5q} \sim 1/m_Q^2$$

The 5-quark states for lighter quarks have larger probabilities!

Data of $\bar{d}(x)-\bar{u}(x)$ vs. Light-Front 5q Fock States

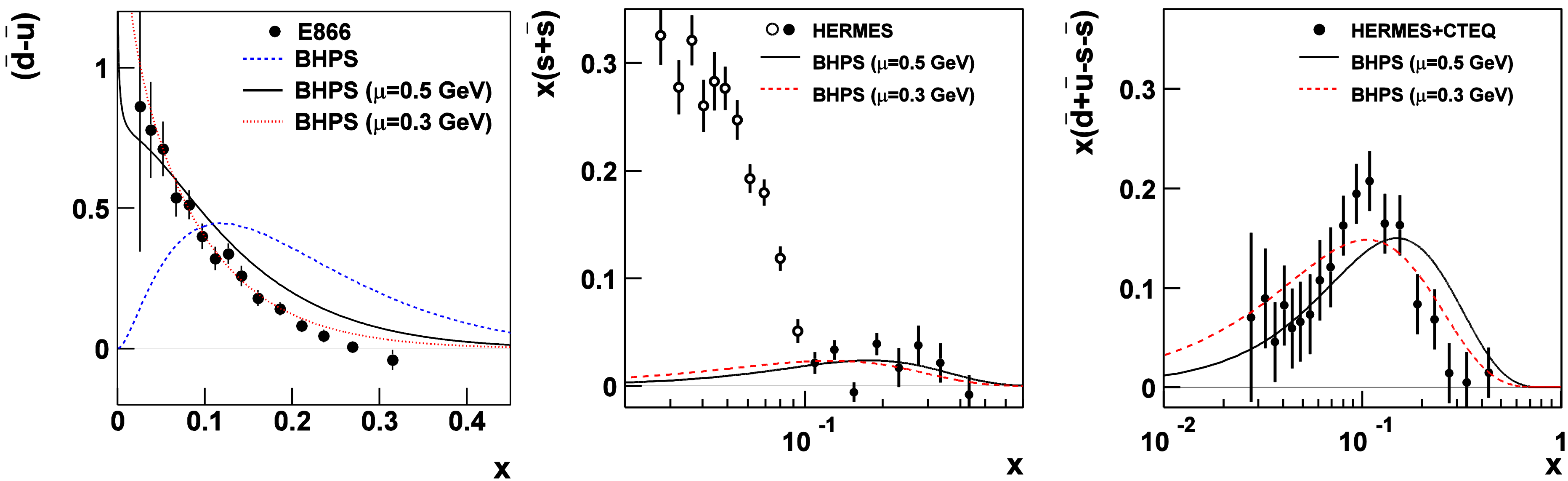
$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$



- The data are in good agreement with the 5q model after evolution from the initial scale μ to Q^2=54 GeV^2
- The difference of these two 5-quark components could be determined.

Chang and Peng, PRL 106, 252002 (2011)

Extraction of various 5q-components for light quarks



$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$

$P_5^{uuds\bar{s}} = 0.024$

$P_5^{uudu\bar{u}} + P_5^{uudd\bar{d}} - 2P_5^{uuds\bar{s}} = 0.314$

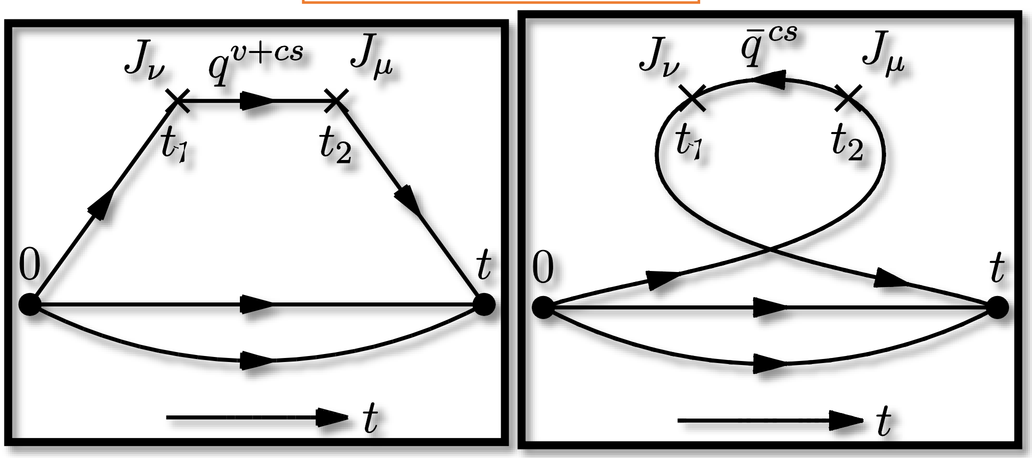
$$P_5^{uudd\bar{d}} = 0.240; \quad P_5^{uudu\bar{u}} = 0.122; \quad P_5^{uuds\bar{s}} = 0.024$$

Chang and Peng, PLB 704, 197 (2011)

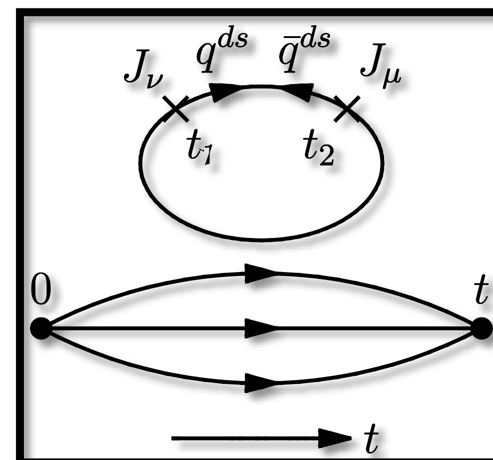
Diagrams of Nucleon Hadronic Tensor in Path-Integral Formalism

$$W_{\mu\nu} = \frac{1}{2M_N V} \langle N | \int \frac{d^3x}{2\pi} e^{-iq\cdot x} J_\nu(x,t_1) J_\mu(0,t_2) | N \rangle$$

Connected Diagram



Disconnected Diagram



Valence and Connected Sea			
$u^{v+cs}(x)$	$\bar{u}^{cs}(x)$	$d^{v+cs}(x)$	$\bar{d}^{cs}(x)$
Disconnected Sea			
$u^{ds}(x) + \bar{u}^{ds}(x)$	$d^{ds}(x) + \bar{d}^{ds}(x)$	$s(x) + \bar{s}(x)$	$c(x) + \bar{c}(x)$

Connected and Disconnected Sea

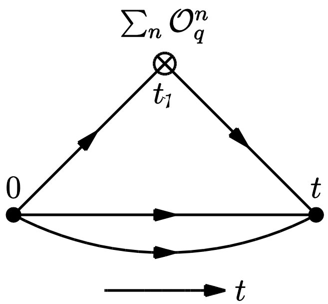
Liu and Dong, PRL 72, 1790 (1994)

- $q^{ds}(x)=\bar{q}^{ds}(x)$, where q=u, d, s; $s(x)=\bar{s}(x)$
- $\bar{u}^{ds}(x)=\bar{d}^{ds}(x)$
- $q^{cs}(x)=\bar{q}^{cs}(x)$, where q=u, d
- Origin of $\bar{u}(x)\neq\bar{d}(x)$: $\bar{u}^{cs}(x)\neq\bar{d}^{cs}(x)$
- Small-x behaviors:
  - $q^{valence}(x)$, $q^{cs}(x) \sim x^{-1/2}$
  - $q^{ds}(x) \sim x^{-1}$

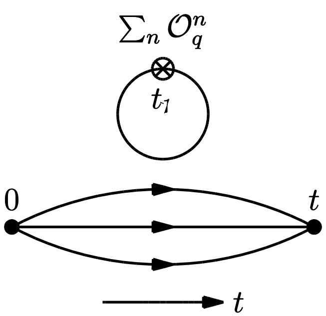
How to separate these two components?

Ratio of Momentum Fraction between s and u in DI by Lattice QCD

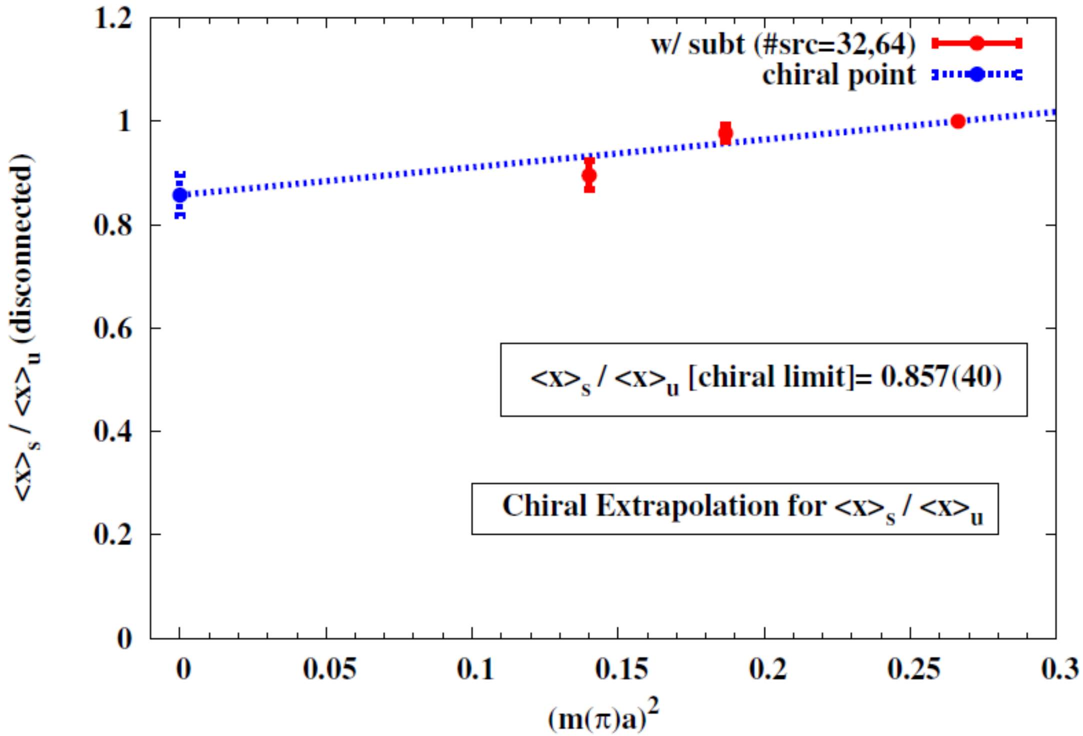
Connected Insertion (CI)



Disconnected Insertion (DI)



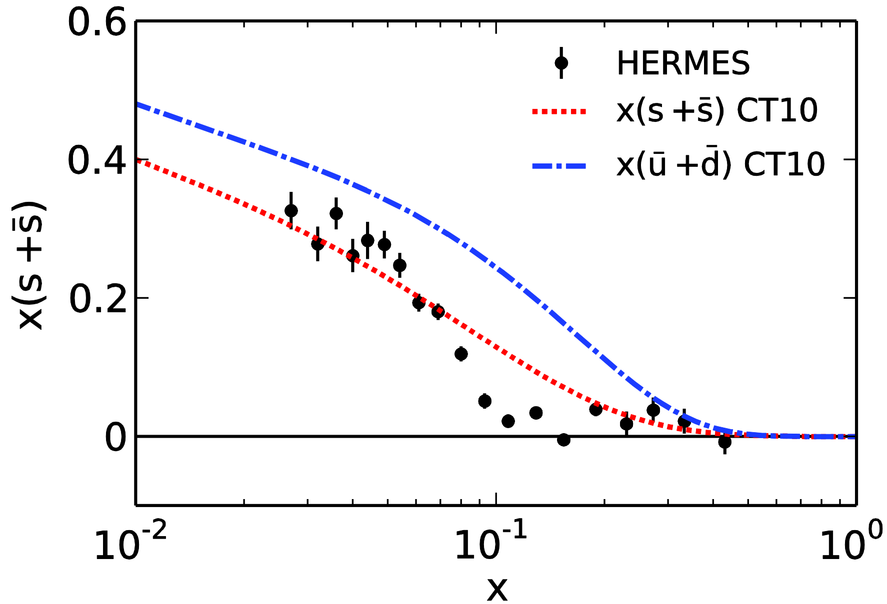
Doi, et al. PoS LATTICE2008:163, 2008

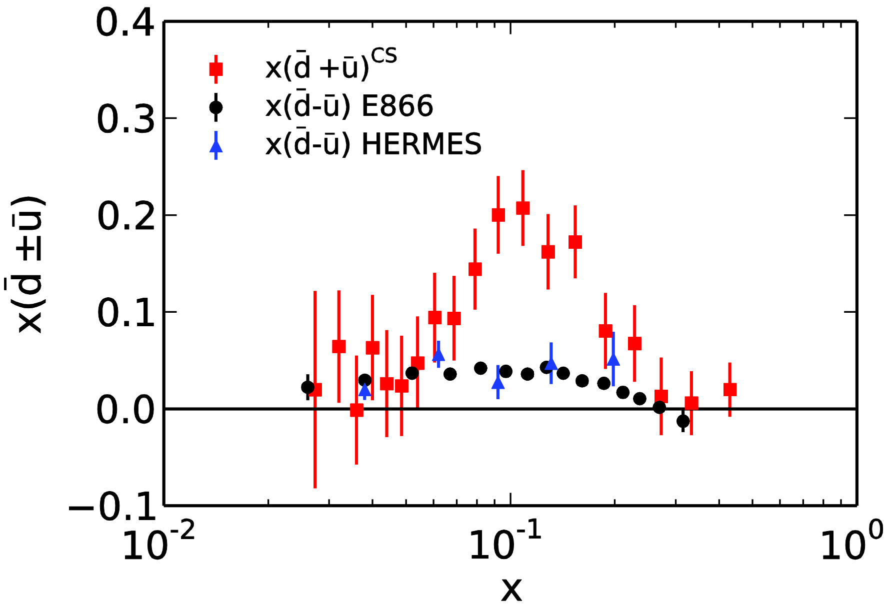


$$R = \frac{\langle x\rangle_{s+\bar{s}}}{\langle x\rangle_{u+\bar{u}}(\mathrm{DI})} = \frac{\langle x\rangle_{s+\bar{s}}}{\langle x\rangle_{\bar{u}^{\mathrm{ds}}+\bar{d}^{\mathrm{ds}}}} = 0.857(40).$$

Connected Sea $\bar{u}^{CS}(x)+\bar{d}^{CS}(x)$

$$\begin{aligned}&\bar{u}^{CS}(x)+\bar{d}^{CS}(x)\\&=(\bar{u}(x)+\bar{d}(x))-(\bar{u}^{DS}(x)+\bar{d}^{DS}(x))\\&=(\bar{u}(x)+\bar{d}(x))\Big|_{\text{CT10}}-\frac{1}{R}(s(x)+\bar{s}(x))\Big|_{\text{HERMES}}\end{aligned}$$

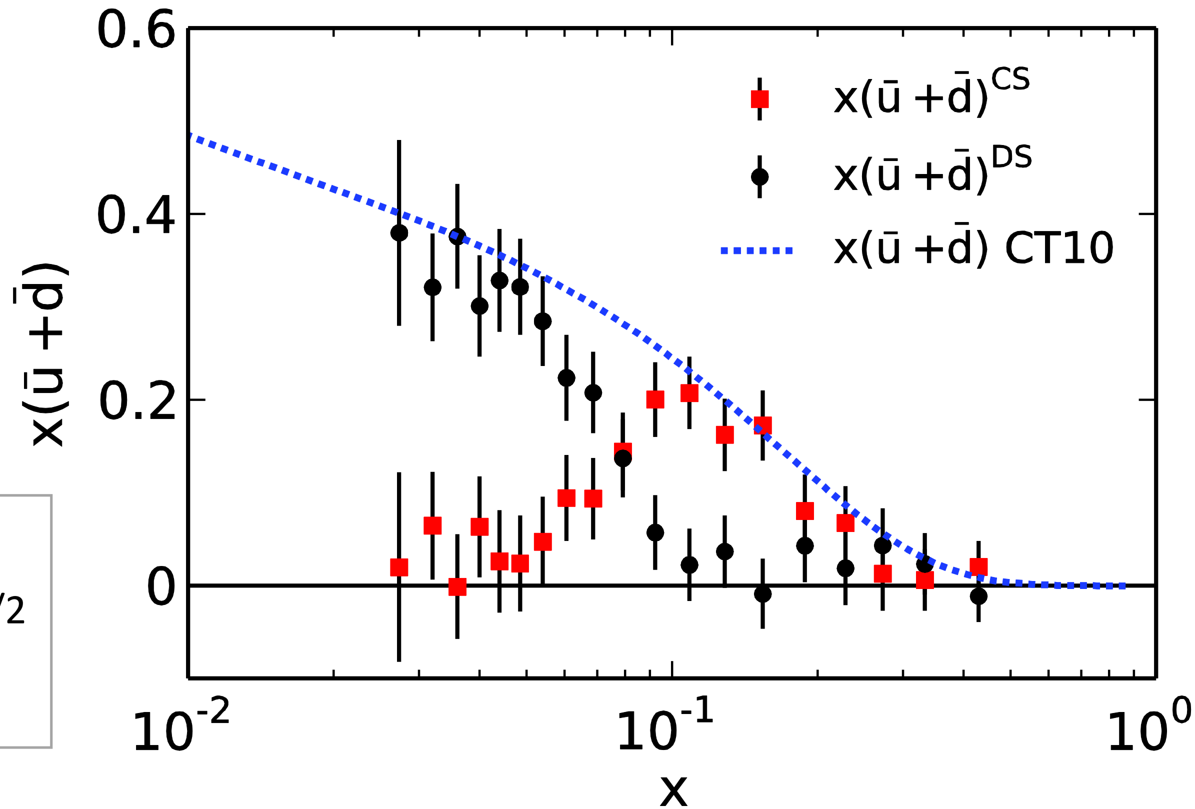




$$\begin{aligned}&\bar{d}(x)-\bar{u}(x)\\&=(\bar{d}^{CS}(x)-\bar{u}^{CS}(x))+(\bar{d}^{DS}(x)-\bar{u}^{DS}(x))\\&=(\bar{d}^{CS}(x)-\bar{u}^{CS}(x))\end{aligned}$$

Liu, Chang, Cheng and Peng, PRL 109, 252002 (2012)

Small-x Behaviors of CS and DS



Small-x behavior:

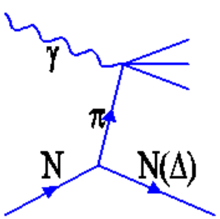
•Valence and CS $\sim x^{-1/2}$

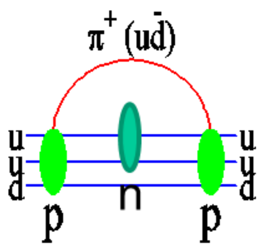
•DS$\sim x^{-1}$

Liu, Chang, Cheng and Peng, PRL 109, 252002 (2012)

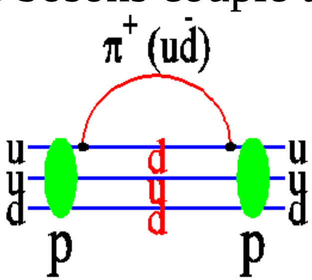
Origin of $\bar{u}(x) \neq \bar{d}(x)$?

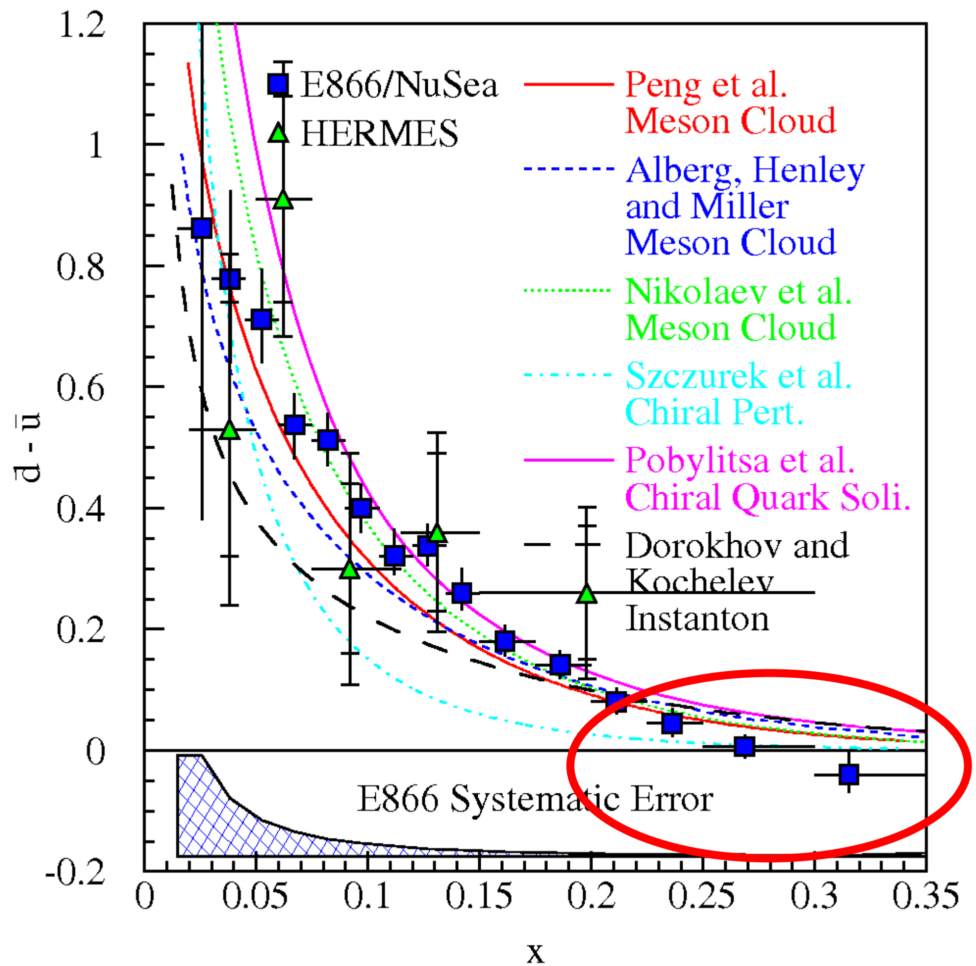
- **Pauli blocking of valance quarks**
- **Meson cloud in the nucleons** (Thomas 1983, Kumano 1991): Sullivan process in DIS.





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

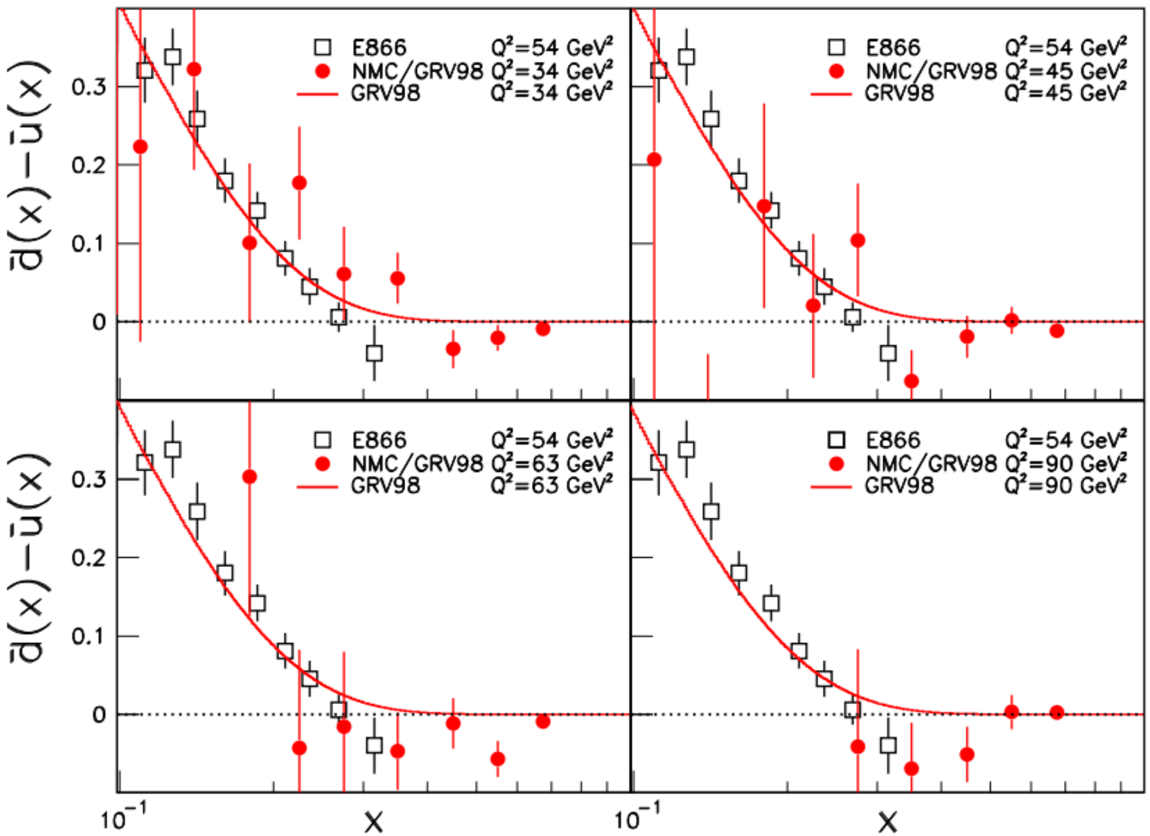




Momentum Dependence of the Flavor Structure of the Nucleon Sea

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

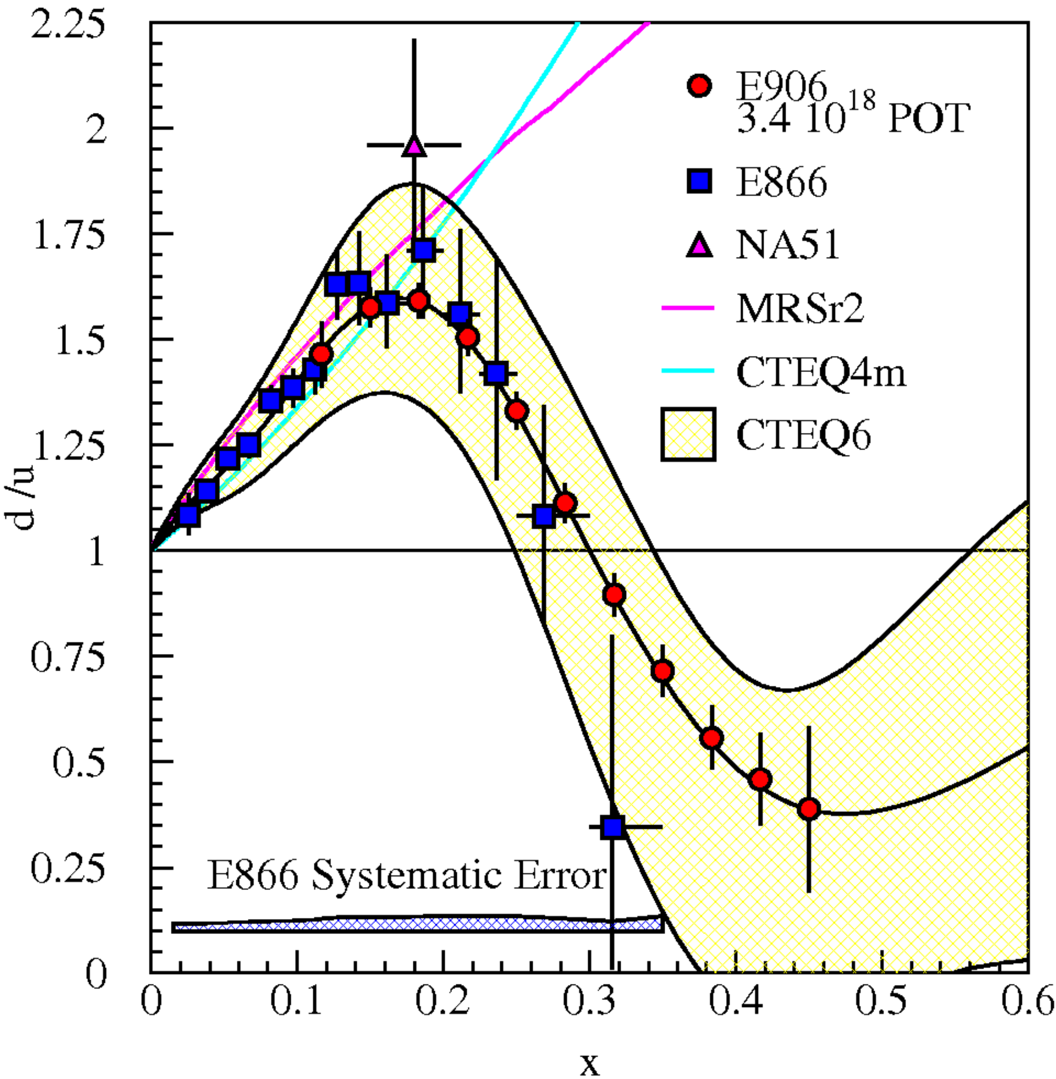
Extracting d-bar/-ubar From Drell-Yan Scattering

Ratio of Drell-Yan cross sections

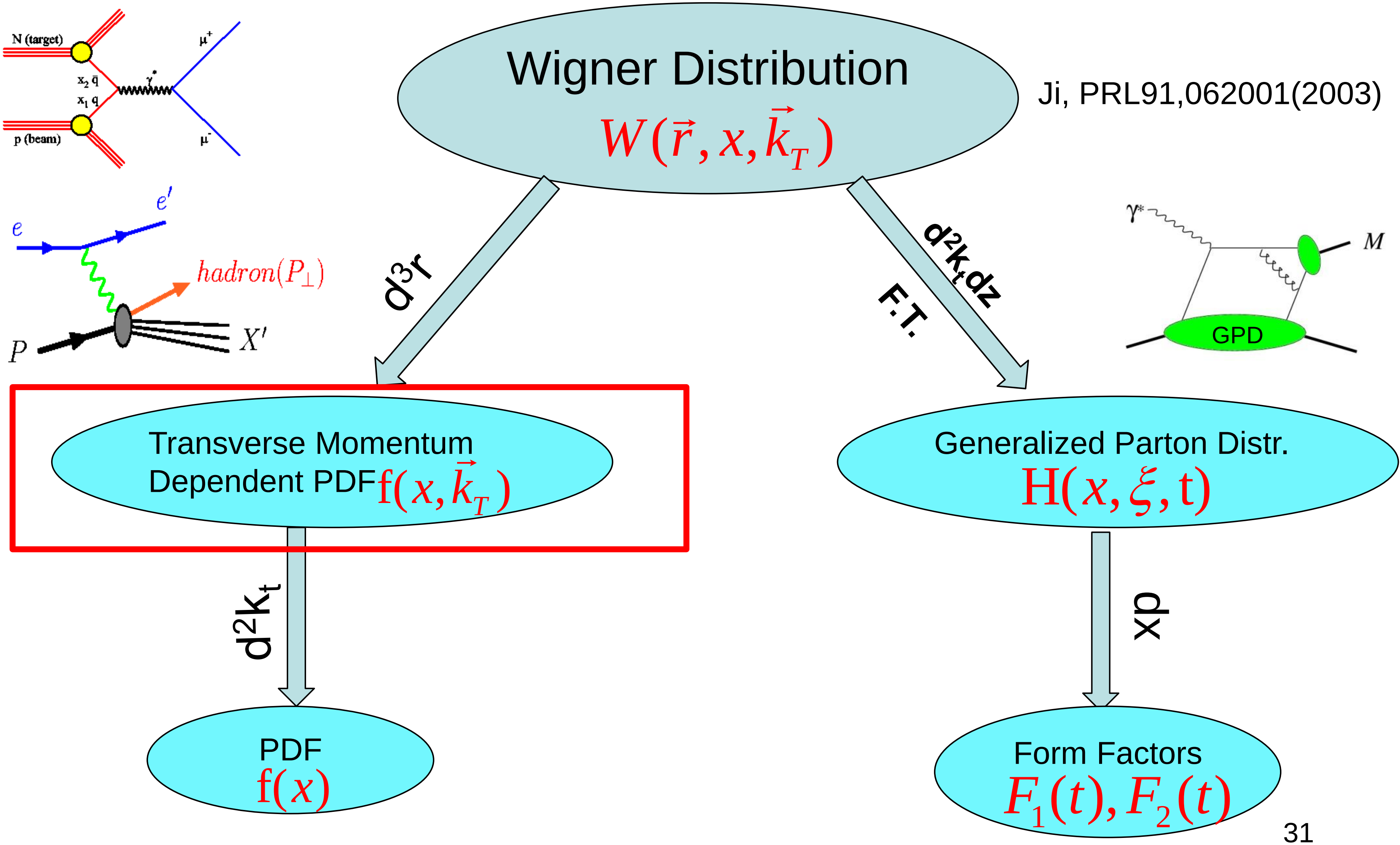
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

(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.



Wigner Distribution



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

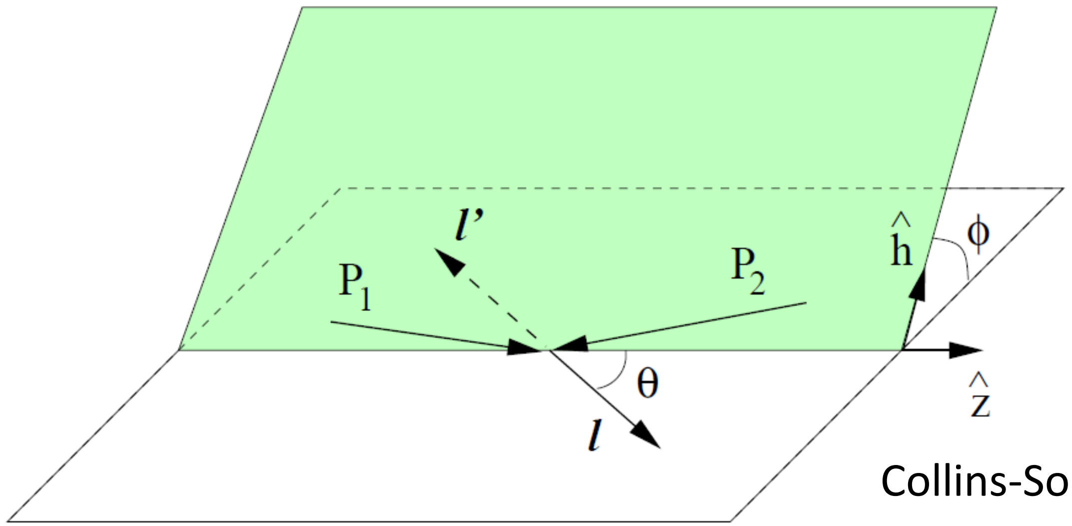
Sivers function $f_{1T}^{\perp}(x, k_T)$
correlation between the transverse spin of the nucleon and the transverse momentum of the quark
sensitive to orbital angular momentum

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"

quark polarization \ nucleon 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; $W_T = 1, W_L = 0$

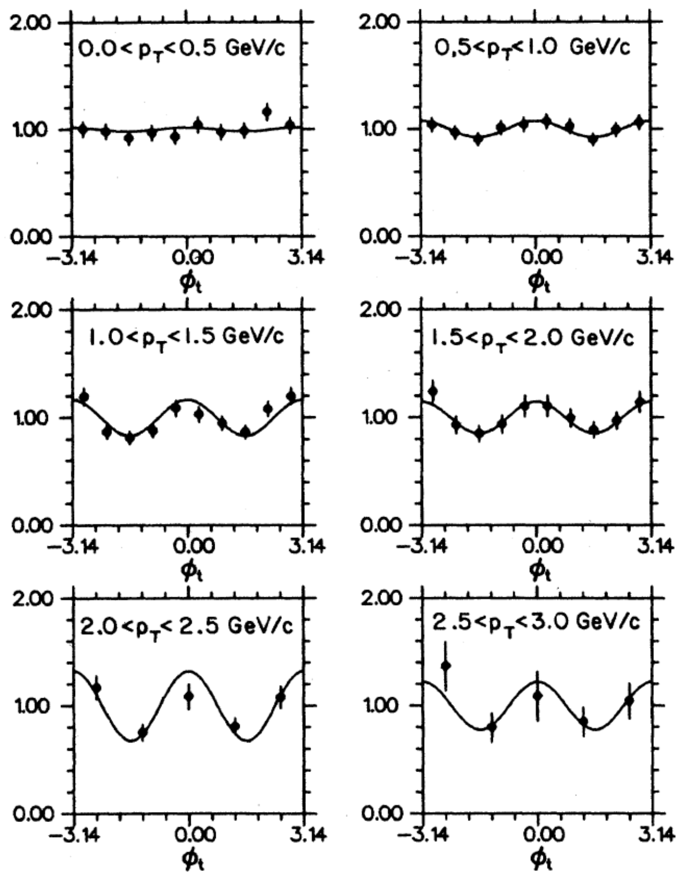
Lam and Tung (PRD 18, 2447, (1978)) Lam-Tung Relation

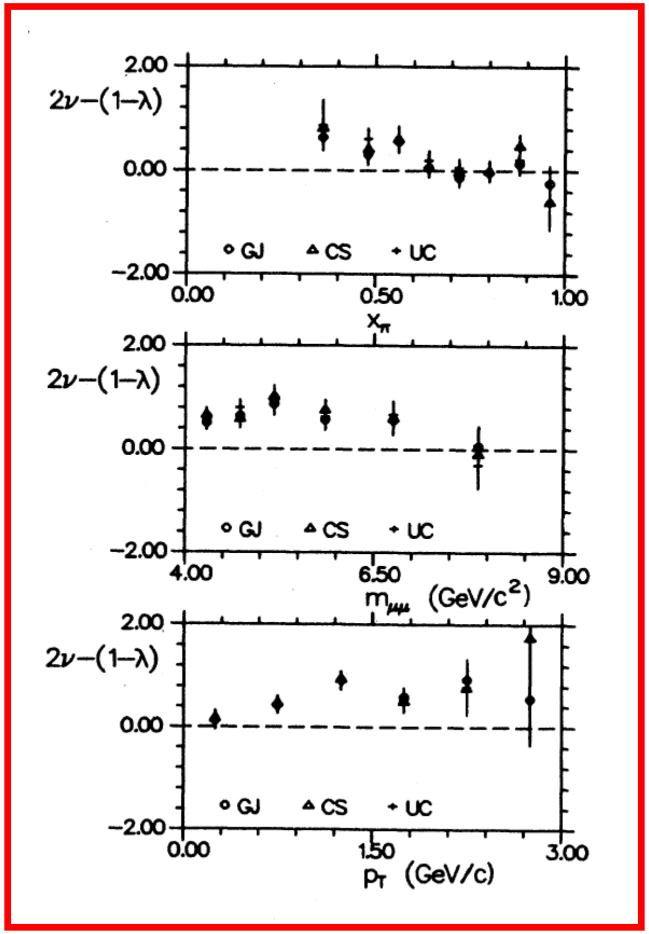
$$\frac{d\sigma}{d\Omega} \propto [W_T(1+\cos^2\theta) + W_L(1-\cos^2\theta) + W_\Delta \sin 2\theta \cos\phi + W_{\Delta\Delta}\sin^2\theta\cos 2\phi]$$

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

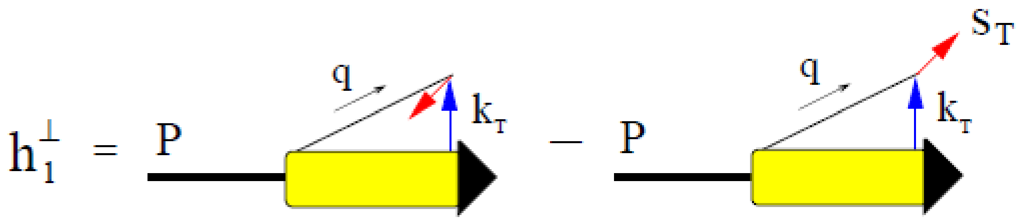
pQCD: $O(\alpha_s^1)$, $W_L = 2W_{\Delta\Delta}$; $1-\lambda-2\nu=0$

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

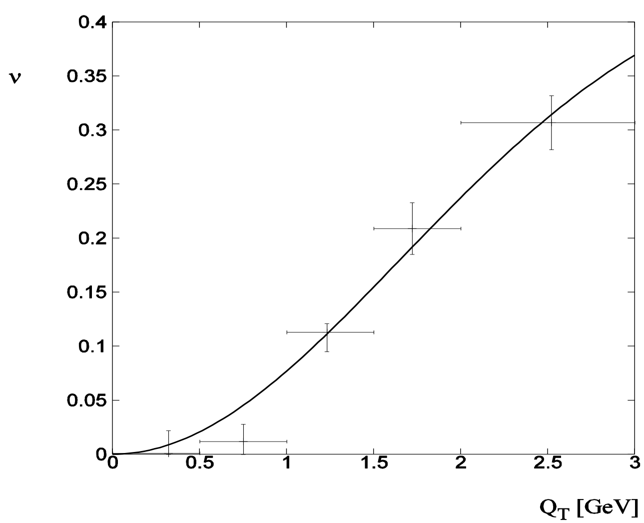




Boer (PRD 60, 014012 (1999))
Hadronic Effect, Boer-Mulders Functions



- 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 $\frac{\nu}{2} \propto h_1^{\perp}(N)\overline{h}_1^{\perp}(\pi)$



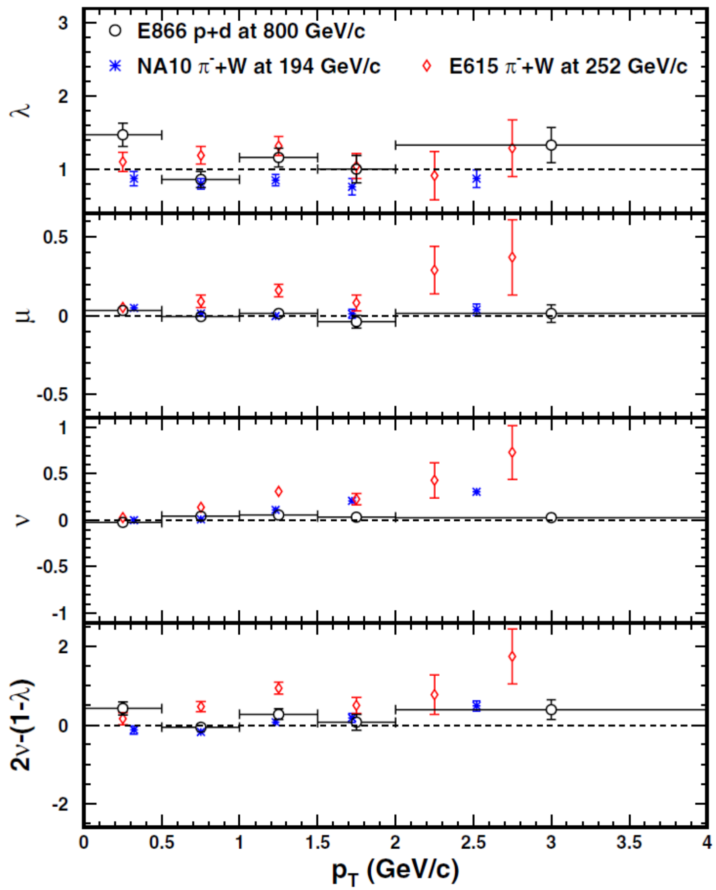
$$h_1^{\perp}(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x),$$

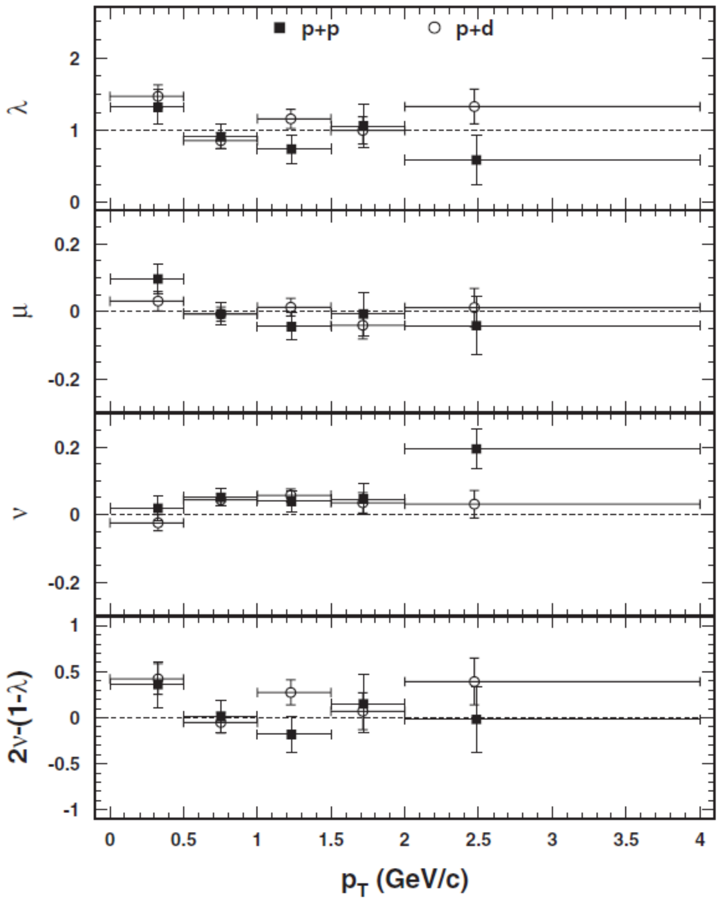
$$\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2}, \quad \kappa_1 = C_{H_1} C_{H_2}/2$$

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

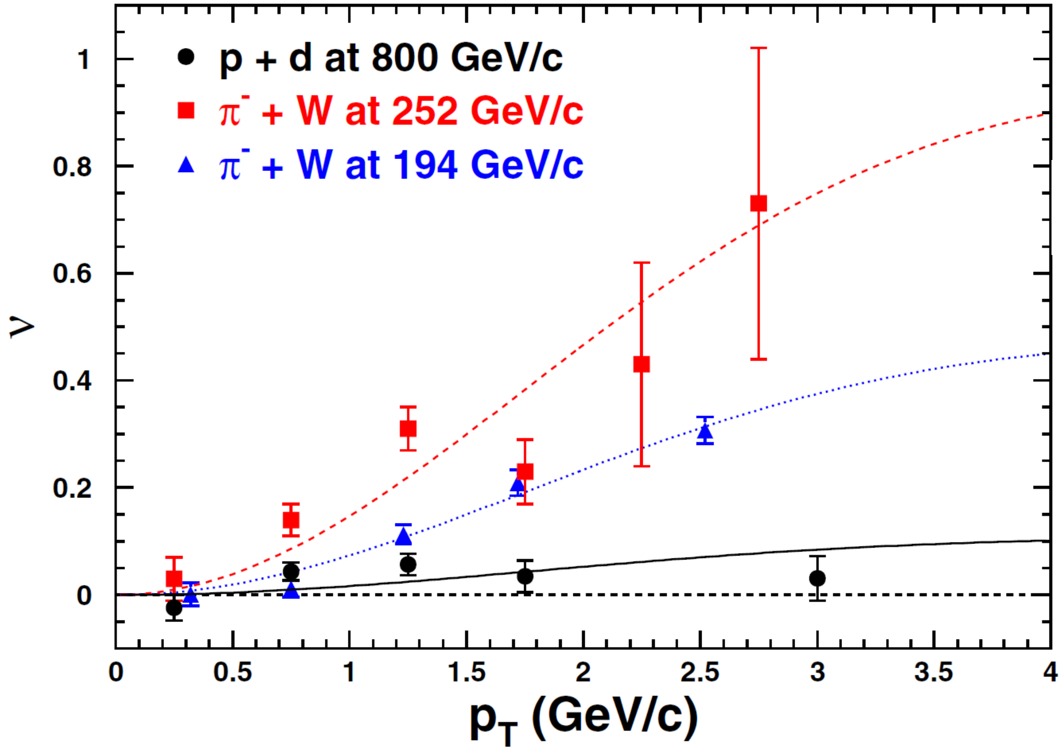
Consistency of factorization in term of TMDs

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



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

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

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

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

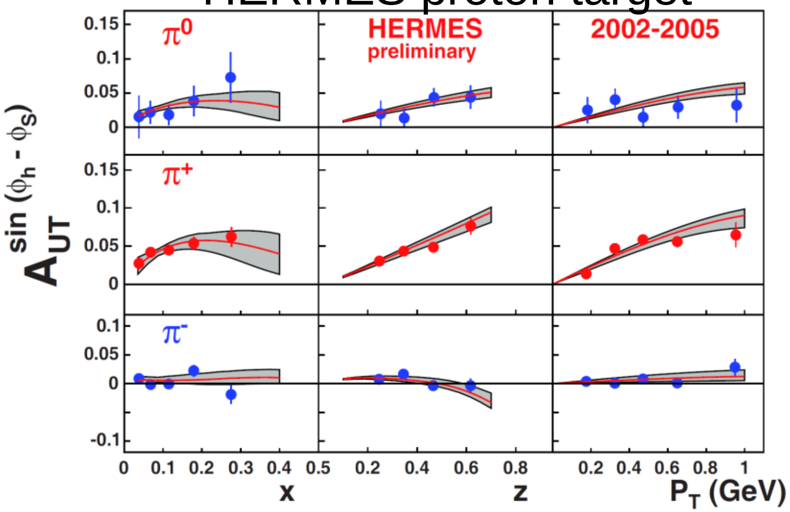
$\nu(pd \rightarrow \mu+\mu- X) \sim$ [valence $h_1^{\perp}(p)$] * [sea $h_1^{\perp}(p)$]

Sea-quark BM functions are much smaller than valence quarks

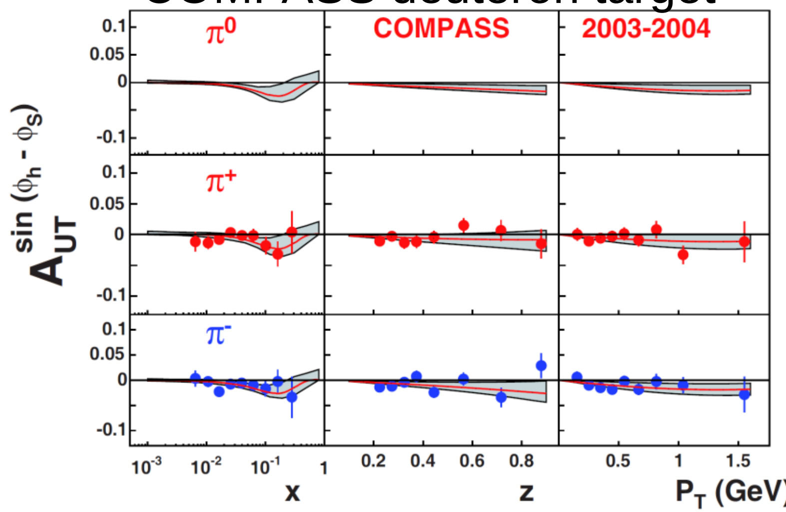
Global Analysis of SIDIS from HERMES and COMPASS

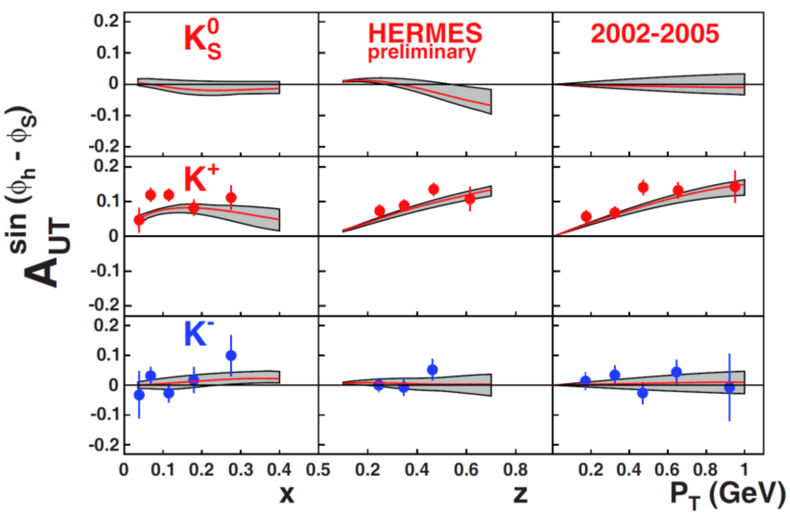
M. Anselmino et al., Eur.Phys.J.A39:89-100,2009

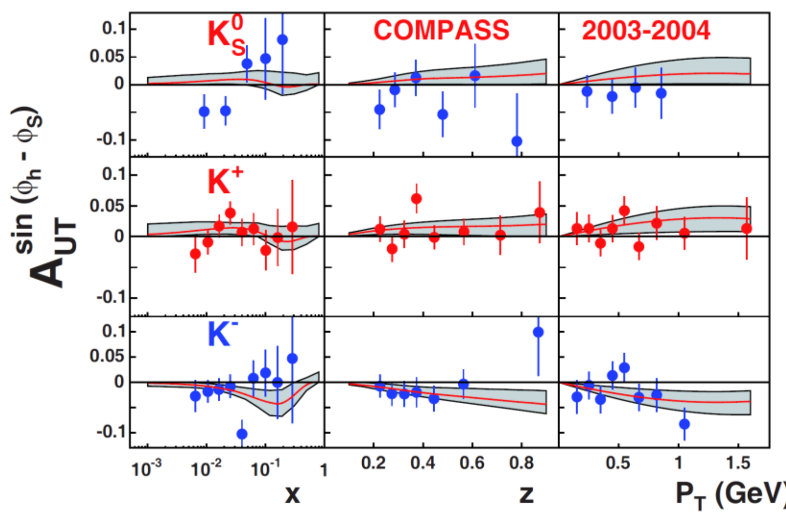
HERMES proton target



COMPASS deuteron target

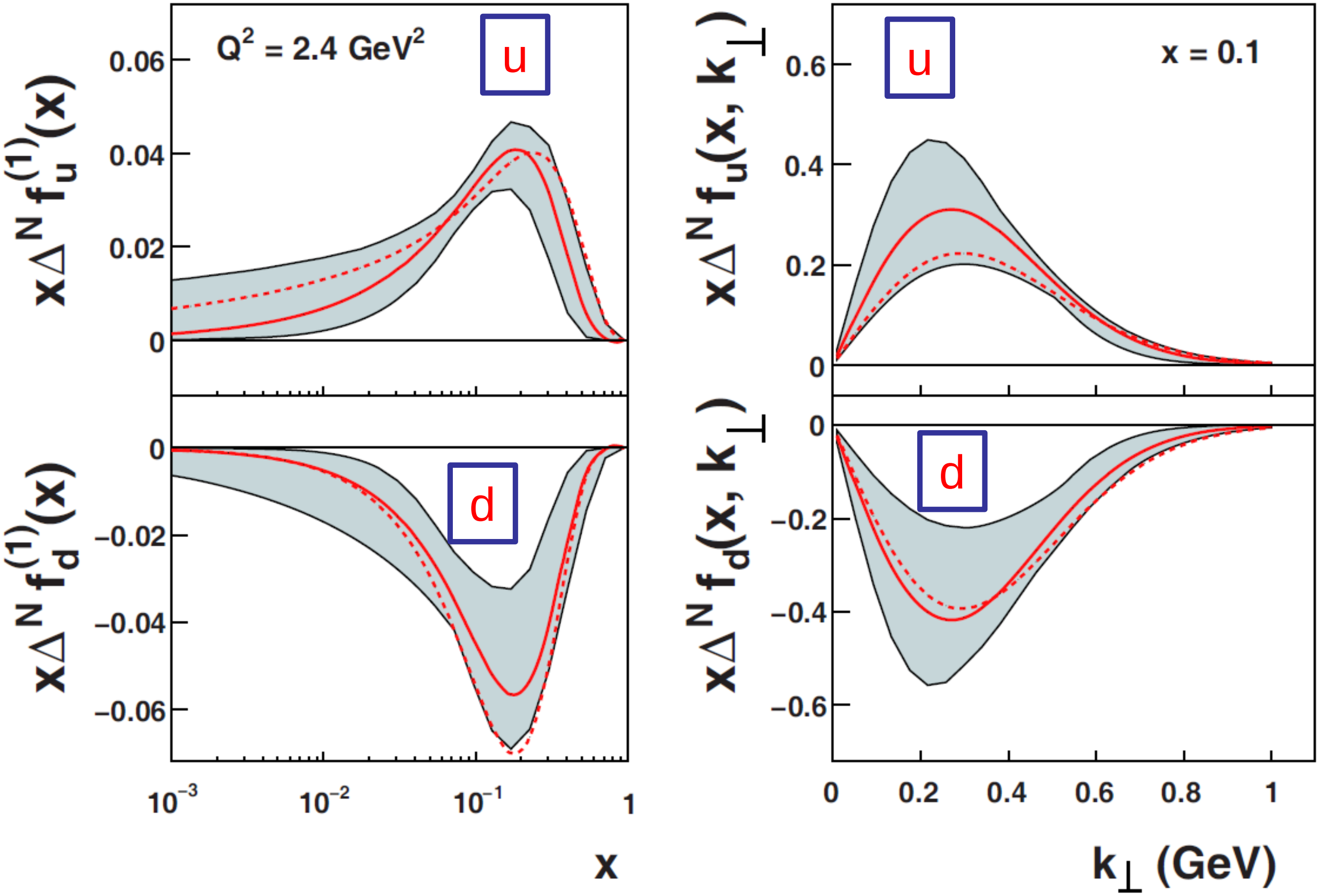






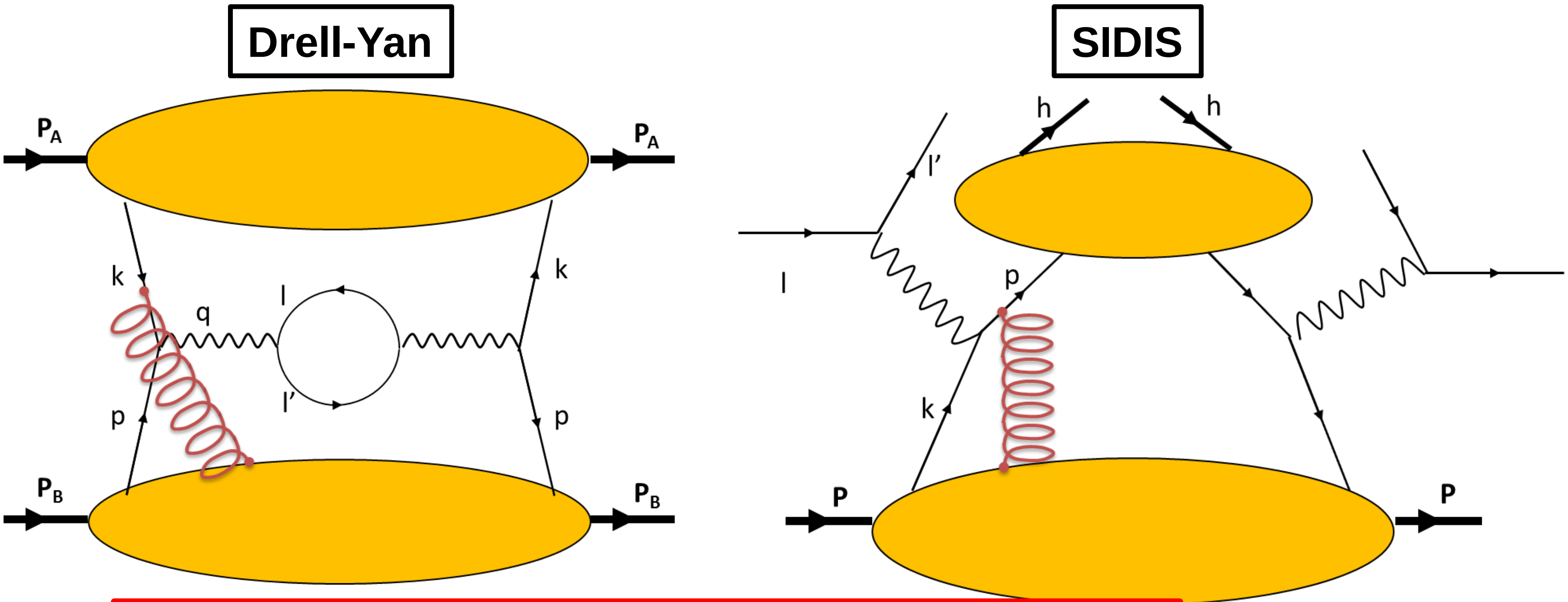
Sivers Functions from SIDIS

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



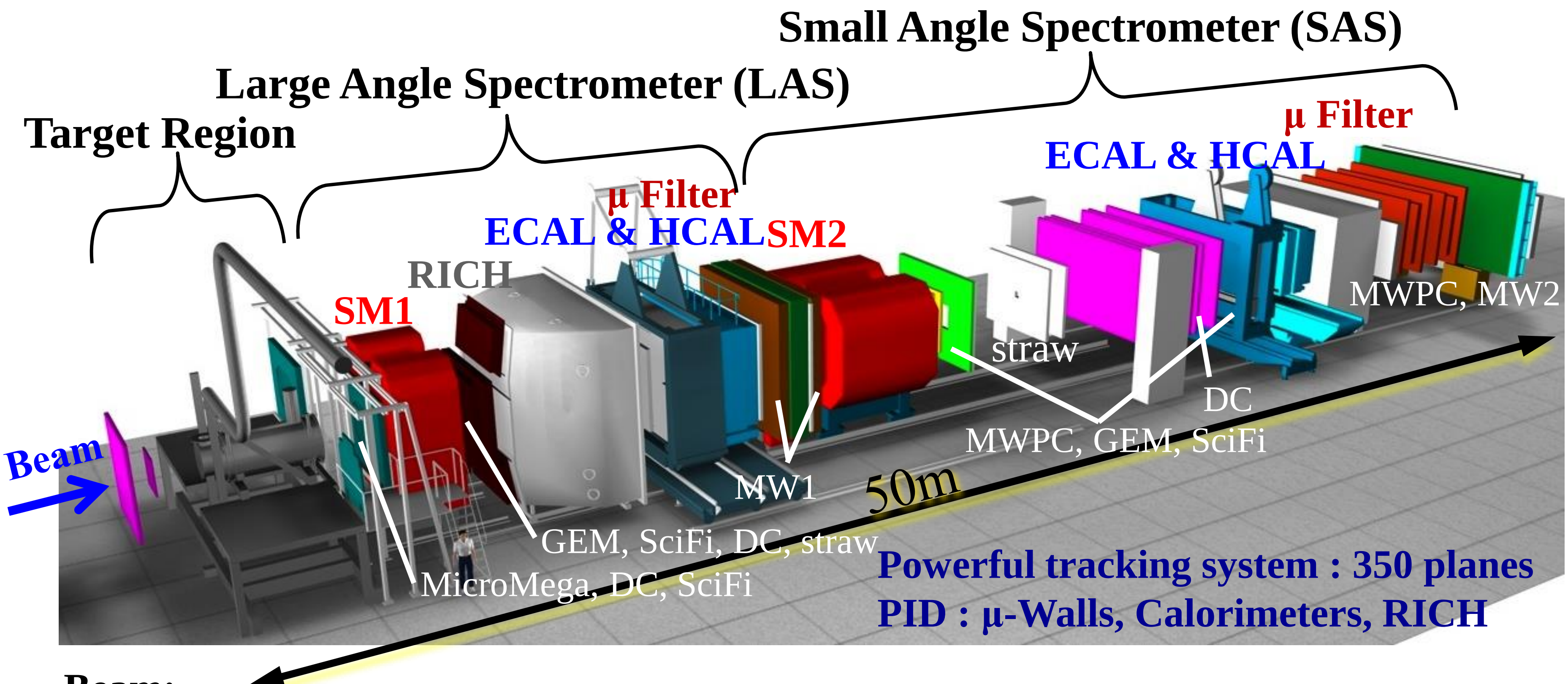
$$\text{Sivers, BM}\,|_{DY} = -1 * \text{Sivers, BM}\,|_{SIDIS}$$

- 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)	2×10^{33} cm^{-2} s^{-1}	2014
PAX (GSI)	$p^\uparrow + \bar{p}$	collider $\sqrt{s}$ = 14 GeV	$x_1 = 0.1 - 0.9$	2×10^{30} cm^{-2} s^{-1}	>2017
PANDA (GSI)	$\bar{p} + p^\uparrow$	15 GeV $\sqrt{s}$ = 5.5 GeV	$x_2 = 0.2 - 0.4$	2×10^{32} cm^{-2} s^{-1}	>2016
J-PARC	$p^\uparrow + p$	50 GeV $\sqrt{s}$ = 10 GeV	$x_1 = 0.5 - 0.9$	1×10^{35} cm^{-2} s^{-1}	>2015 ??
NICA (JINR)	$p^\uparrow + p$	collider $\sqrt{s}$ = 20 GeV	$x_1 = 0.1 - 0.8$	1×10^{30} cm^{-2} s^{-1}	>2014
PHENIX (RHIC)	$p^\uparrow + p$	collider $\sqrt{s}$ = 500 GeV	$x_1 = 0.05 - 0.1$	2×10^{32} cm^{-2} s^{-1}	>2018
RHIC internal target phase-1	$p^\uparrow + p$	250 GeV $\sqrt{s}$ = 22 GeV	$x_1 = 0.25 - 0.4$	2×10^{33} cm^{-2} s^{-1}	>2018
RHIC internal target phase-2	$p^\uparrow + p$	250 GeV $\sqrt{s}$ = 22 GeV	$x_1 = 0.25 - 0.4$	6×10^{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	$x_1 = 0.3 - 0.9$	1×10^{36} cm^{-2} s^{-1}	>2014

COMPASS Setup



Beam:

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

Hadron beam : π^+, π^+, K^+, K^-, p

Target:

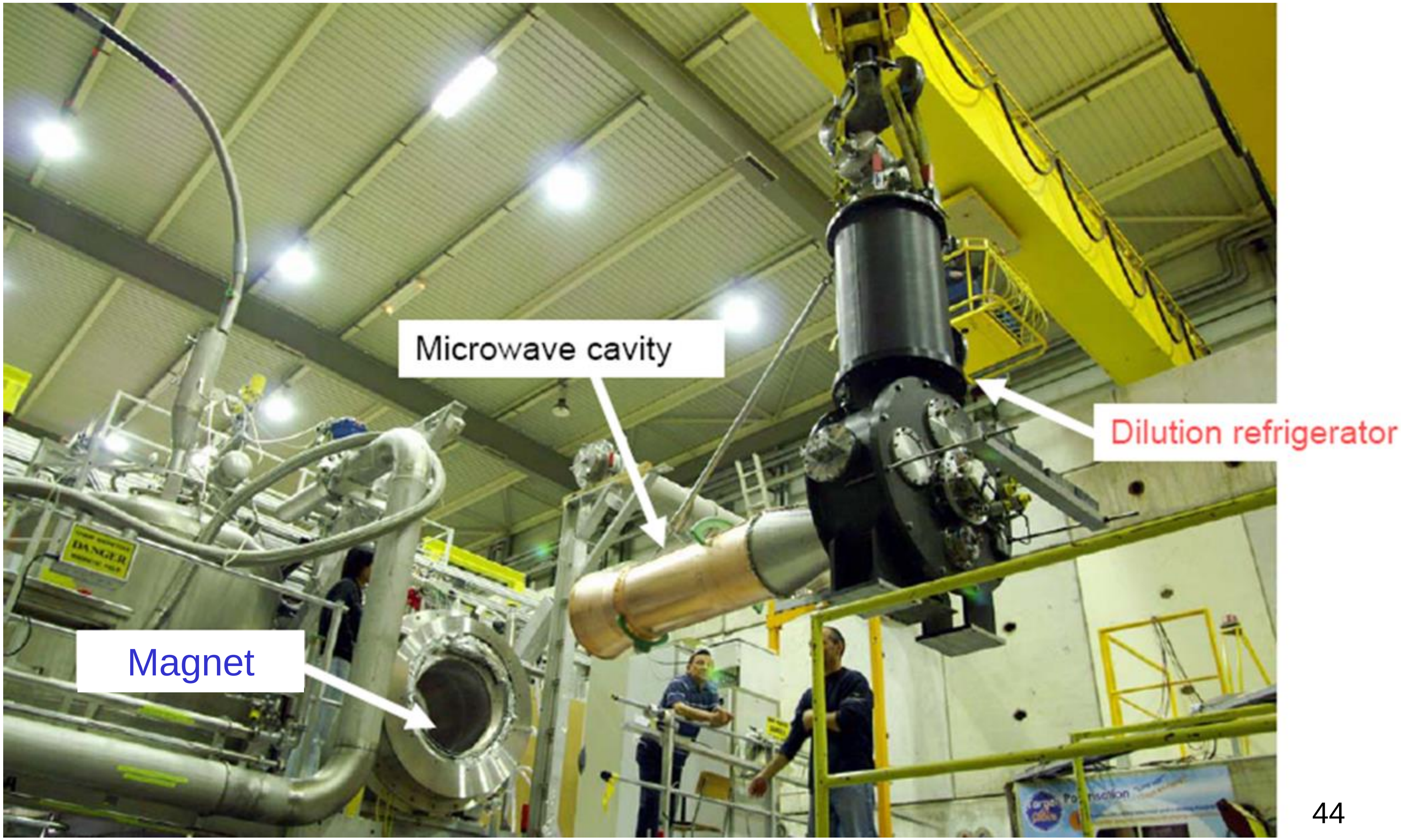
Polarized NH_3 and ^6LiD target

Liquid hydrogen target

Nuclear target

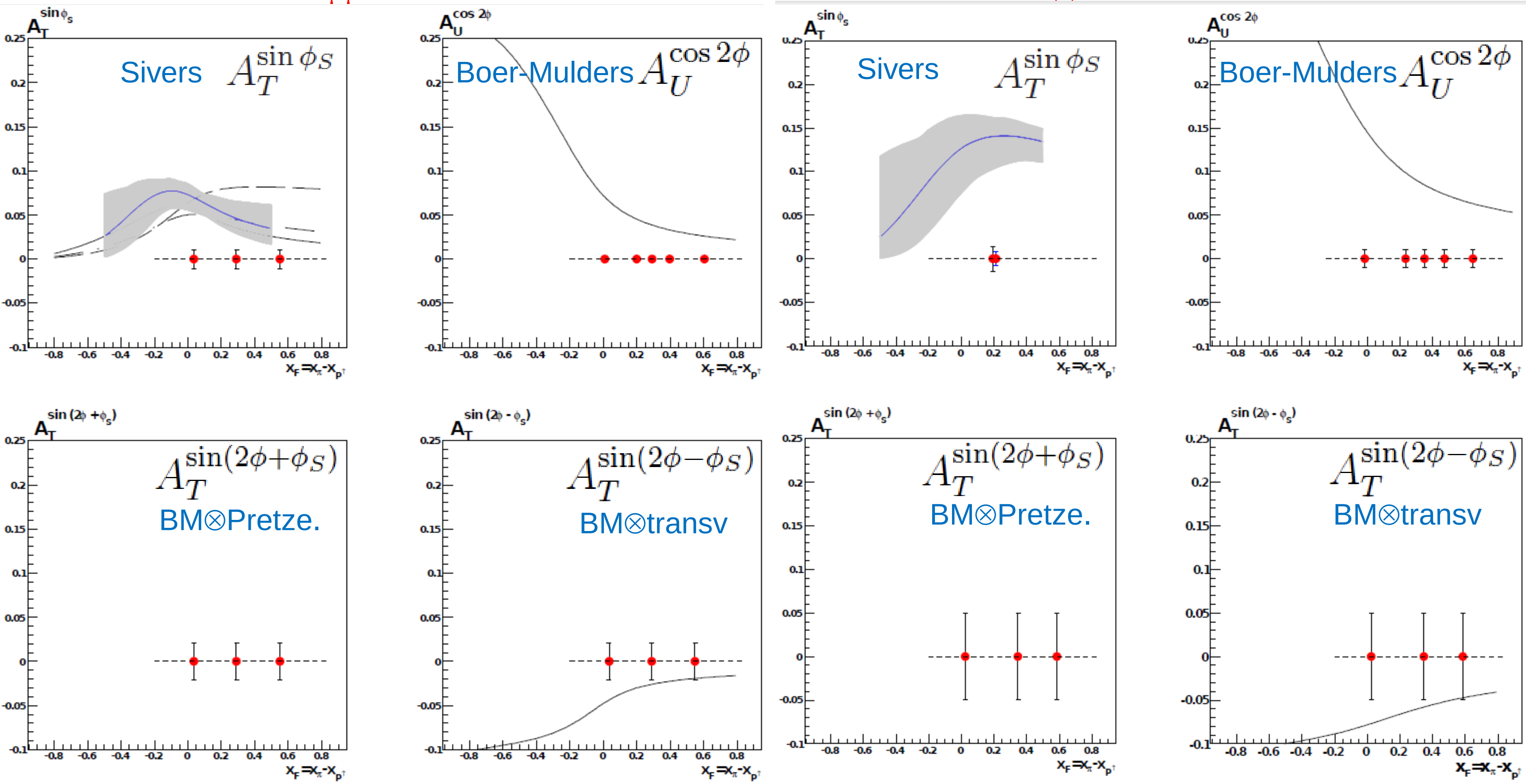
Various Combinations of Beam & Target

Key Elements of Polarized DY Exp.: Polarized NH_3 Target

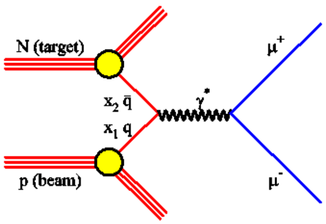


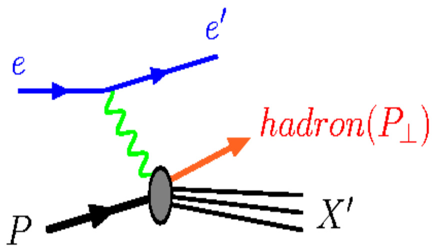
Theoretical Predictions vs. COMPASS Expected Precision

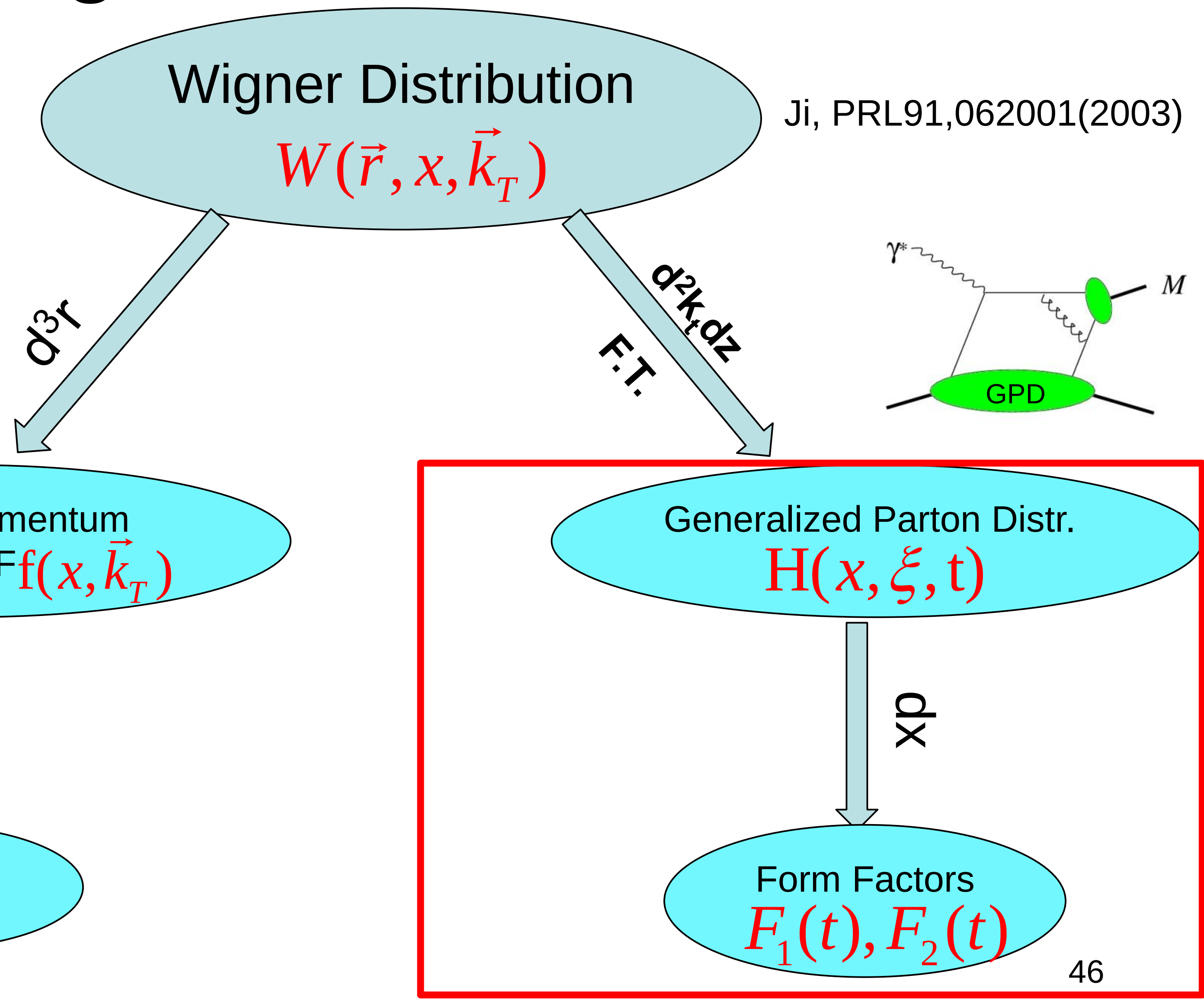
$2 \leq M_{\mu\mu} \leq 2.5\,\mathrm{GeV/c^2}$ $4 \leq M_{\mu\mu} \leq 9\,\mathrm{GeV/c^2}$



Wigner Distribution





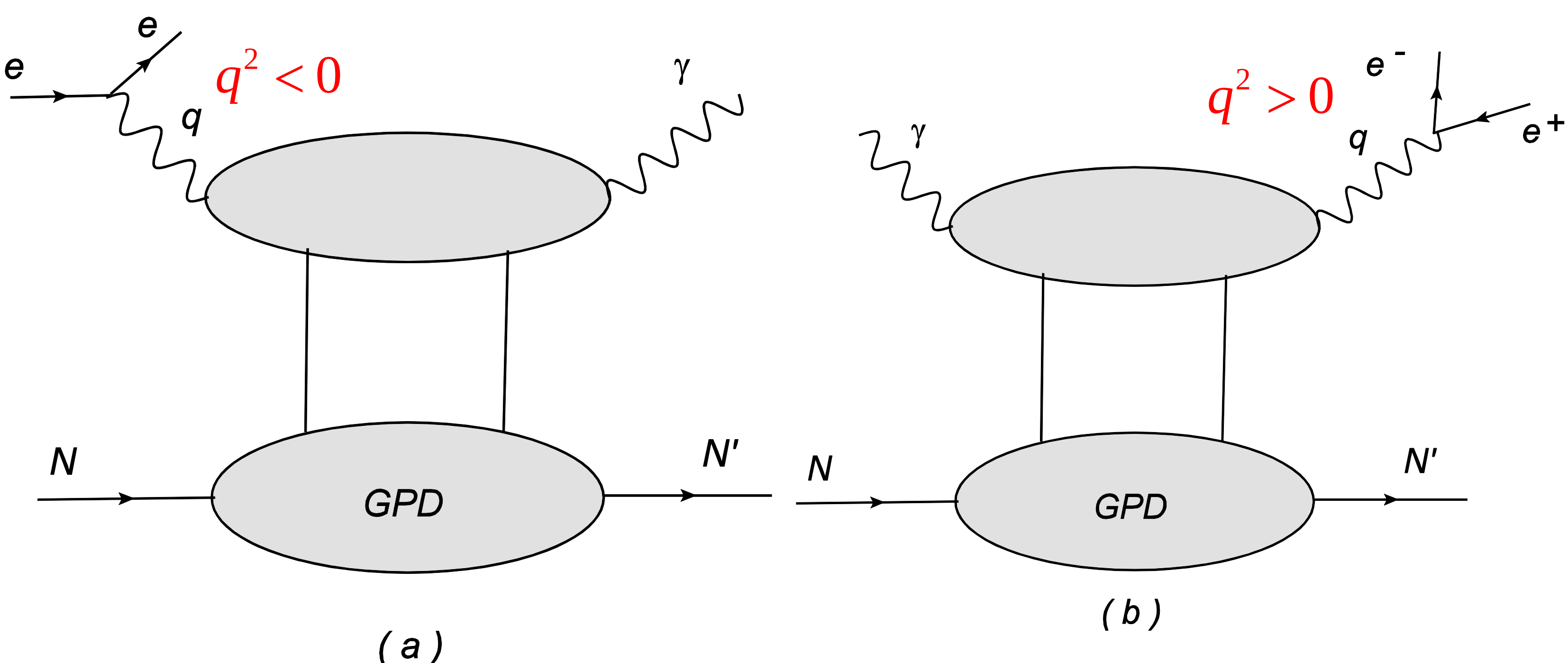


Ji, PRL91,062001(2003)

Space-like vs. Time-like Processes

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

Deeply Virtual Compton Scattering | Timelike Compton Scattering

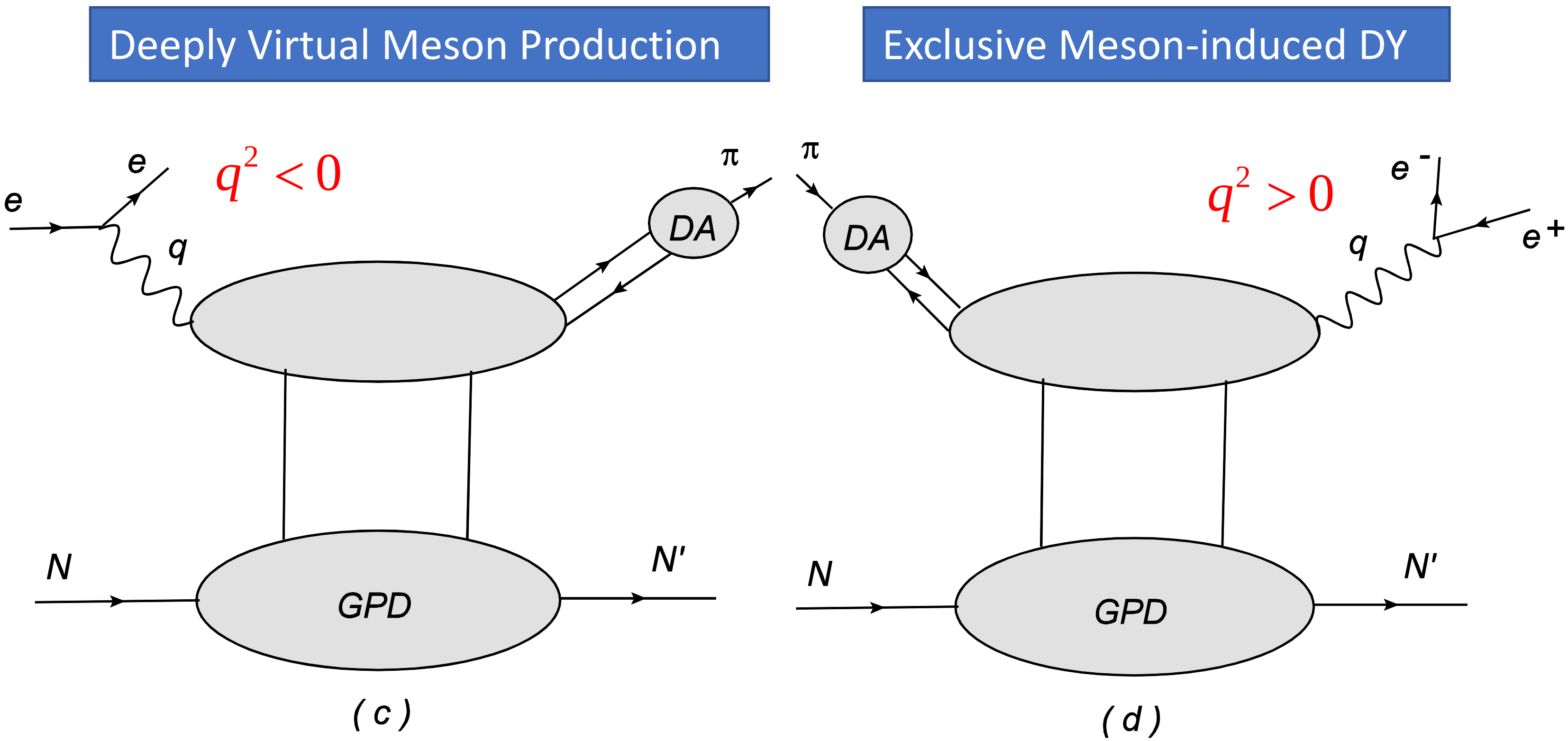


$$\mathcal{F}(\xi = \eta, t, \mathcal{Q}^2) \overset{\mathrm{SL}\to\mathrm{TL}}{\Rightarrow} \mathcal{F}(\xi = -\eta, t, -\mathcal{Q}^2),$$

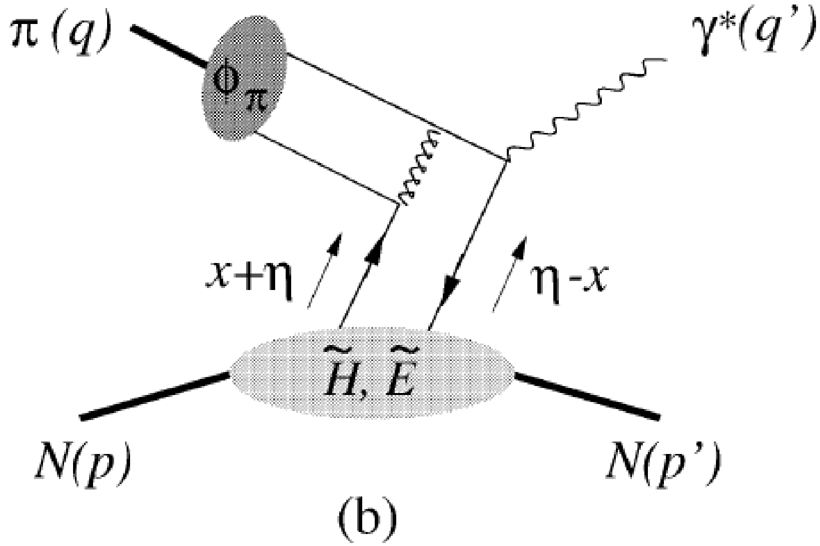
$$\mathcal{F}(\xi, t, \mathcal{Q}^2) = \int_{-1}^{1} dx \sum_{i=u,d,\cdots,g} {}^{S}T^{i}(x, \xi) F^{i}(x, \xi, t, \mu^2),$$

Space-like vs. Time-like Processes

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



$\pi N \rightarrow \mu^+\mu^- N$
(PLB 523 (2001) 265)



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

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

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

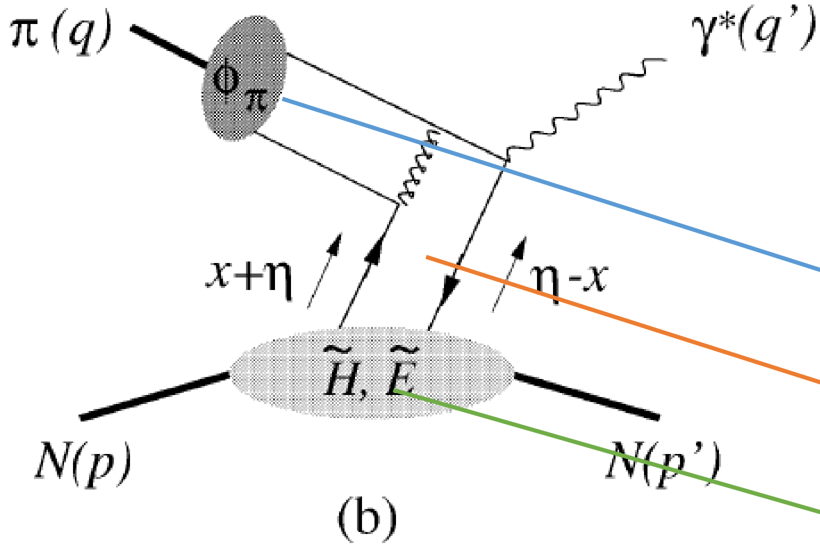
$$t = (p-p')^2$$
$$Q'^2 = q'^2 > 0$$

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

$\pi N \rightarrow \mu^+ \mu^- N$

(PLB 523 (2001) 265)

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



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

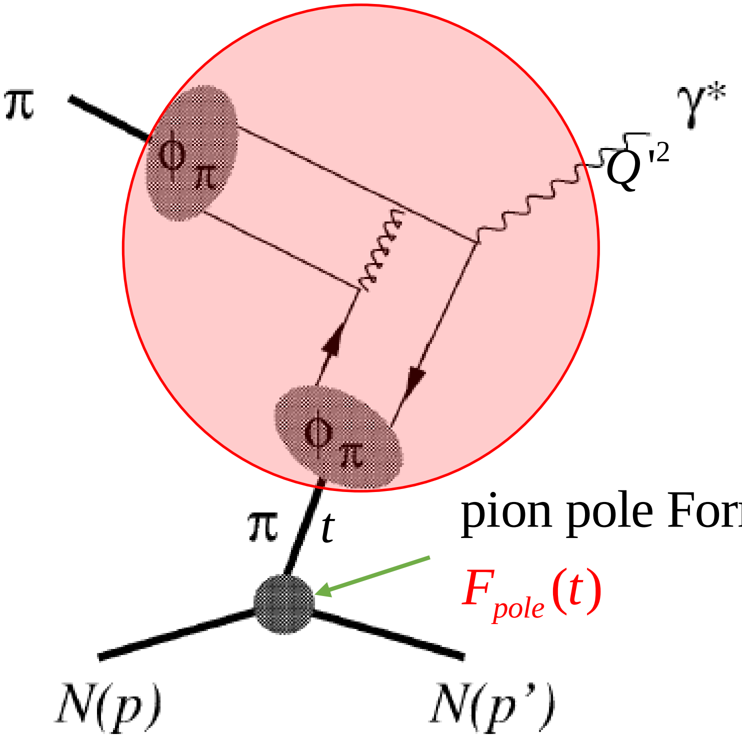
$$\frac{d\sigma}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = \frac{\alpha_{\rm em}}{256\pi^3}\frac{\tau^2}{Q'^6}\sum_{\lambda',\lambda}\left|M^{0\lambda',\lambda}\right|^2\sin^2\theta,$$

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

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

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

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

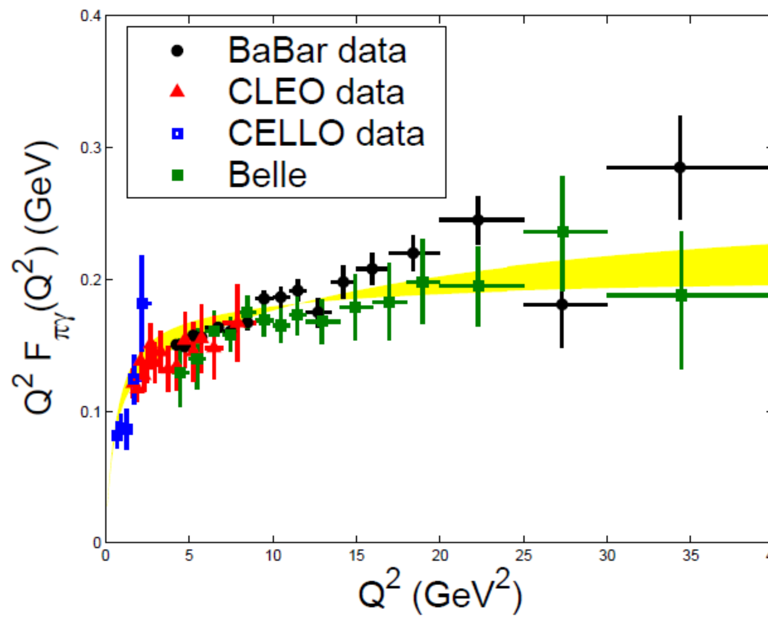


pion pole Form Factor

$F_{pole}(t)$

Pion-Photon Transition Form Factor

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



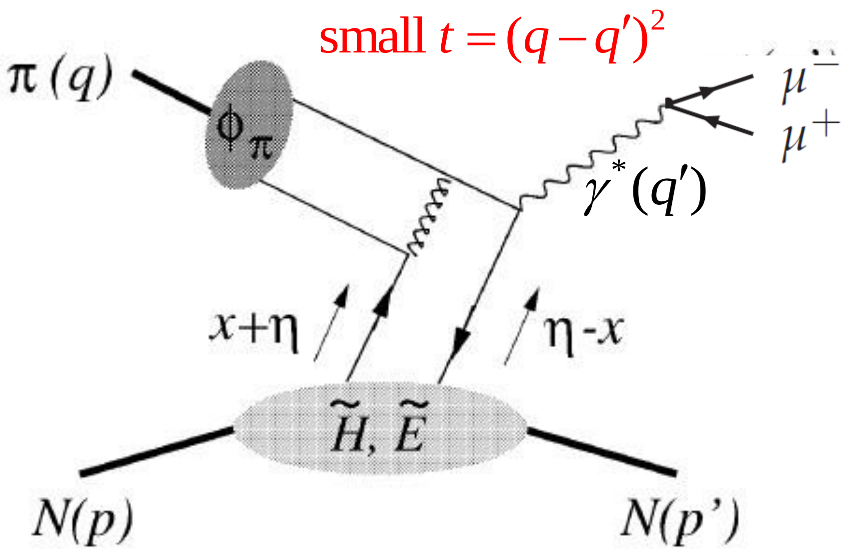
$$M^{0\lambda',\lambda}(\pi N \to \gamma^* N)$$

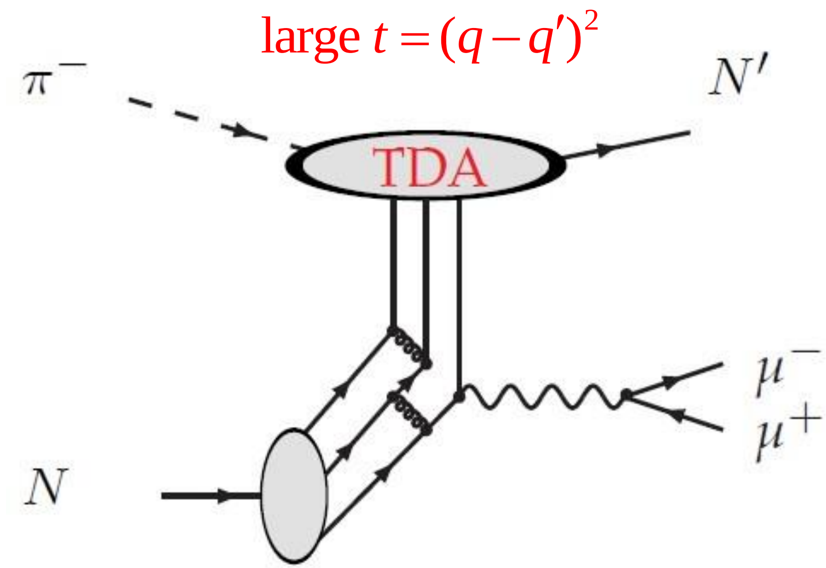
$$= -ieQ' F_\pi(Q'^2) \frac{F_{\text{pole}}(t)}{2Mf_\pi} \bar{u}(p',\lambda')\gamma_5 u(p,\lambda)$$

$$+ \text{non-pole terms.} \qquad (11)$$

Exclusive Pion-Induced Drell-Yan Process

Bernard Pire , IWHS2011





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.

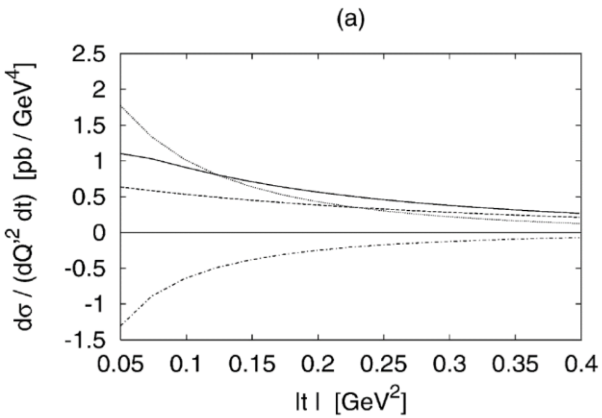
TDA : π-N transistion distritribution amplitude

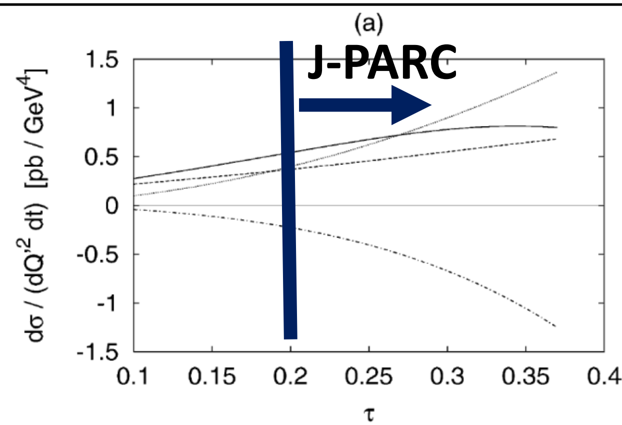
- TDA characterizes the next-to-minimal valence Fock state of hadrons.
- TDA of pion-nucleon is related to the pion cloud of nucleons.

πN→μ+μ-N (PLB 523 (2001) 265)

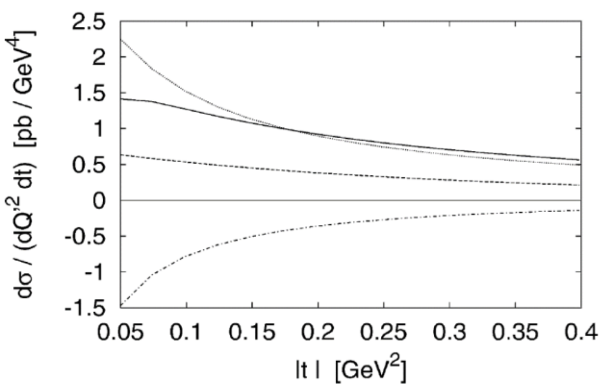
$Q'^2 = q'^2 = 5\ GeV^2$

Cross section increases toward small s!

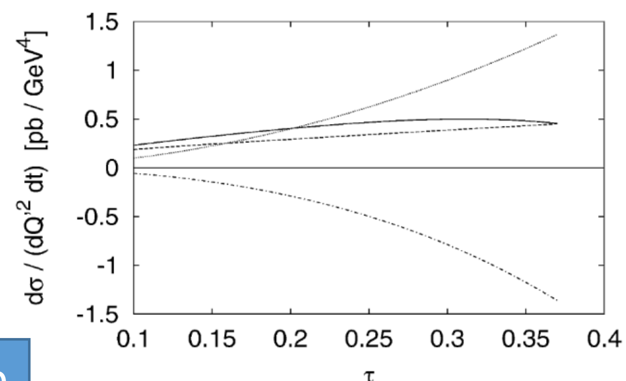




Pion-pole Dominance



Pion-pole Dominance

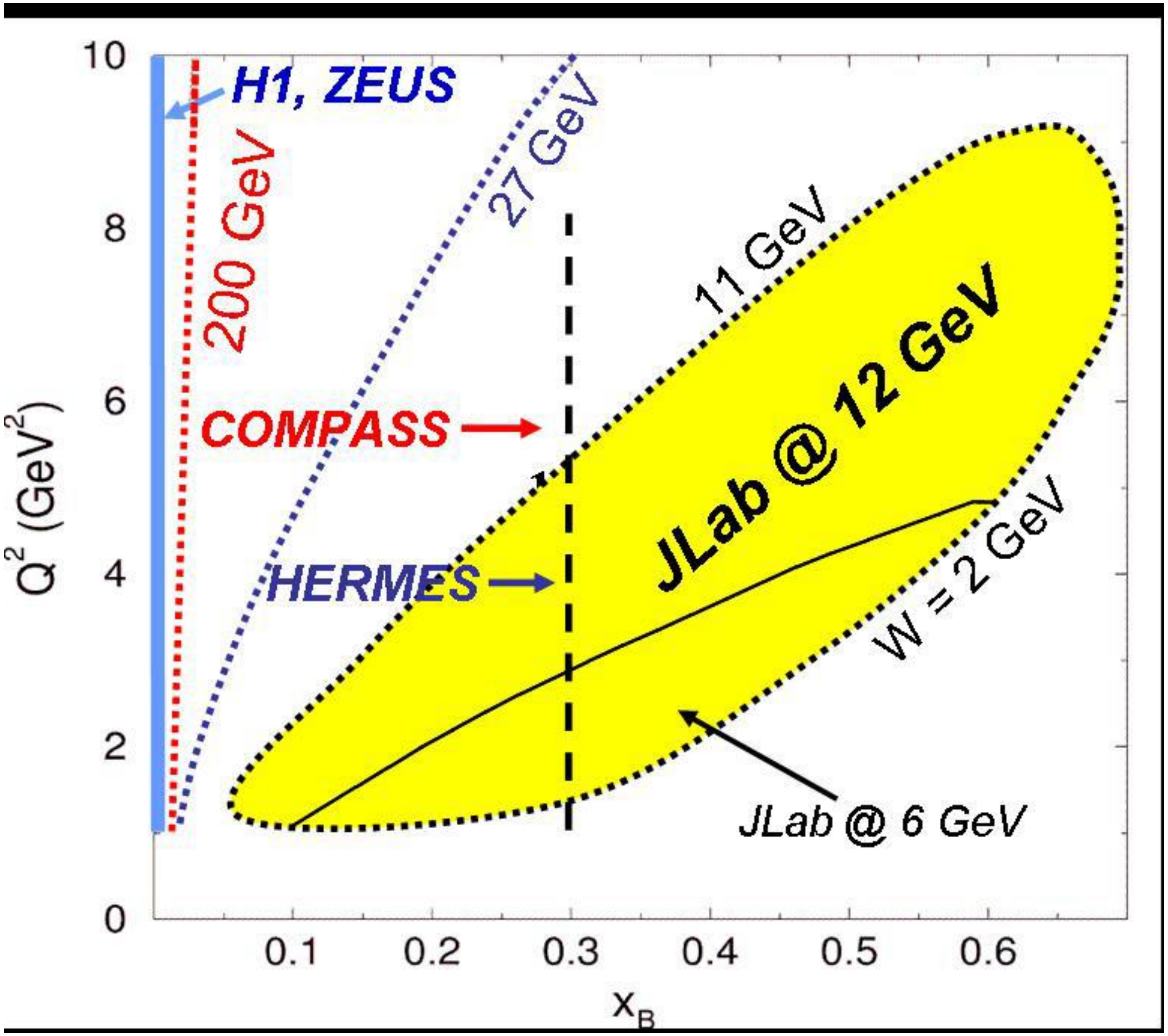


1-10 pb

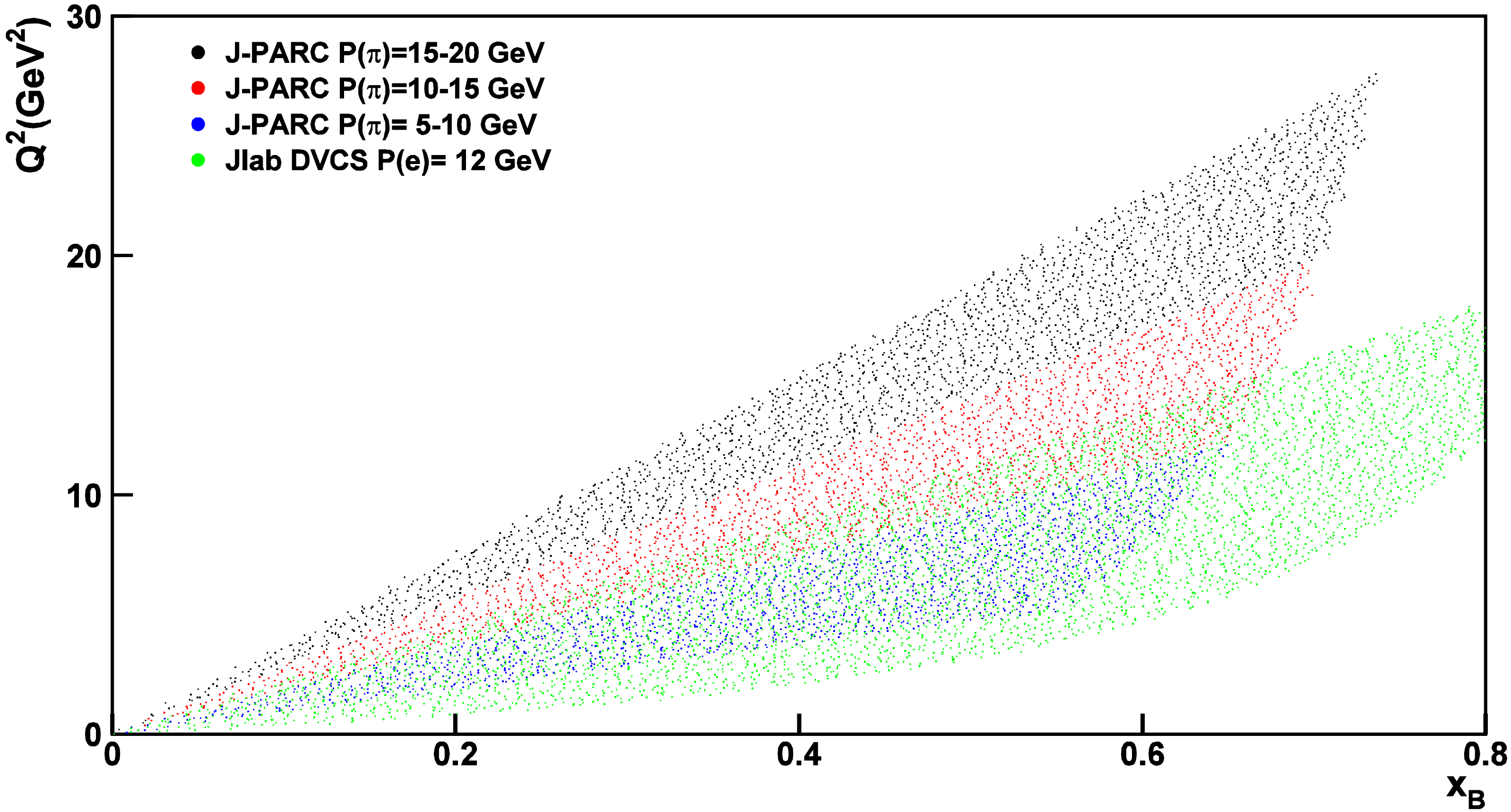
$t = (p - p')^2$=-0.2 GeV²

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

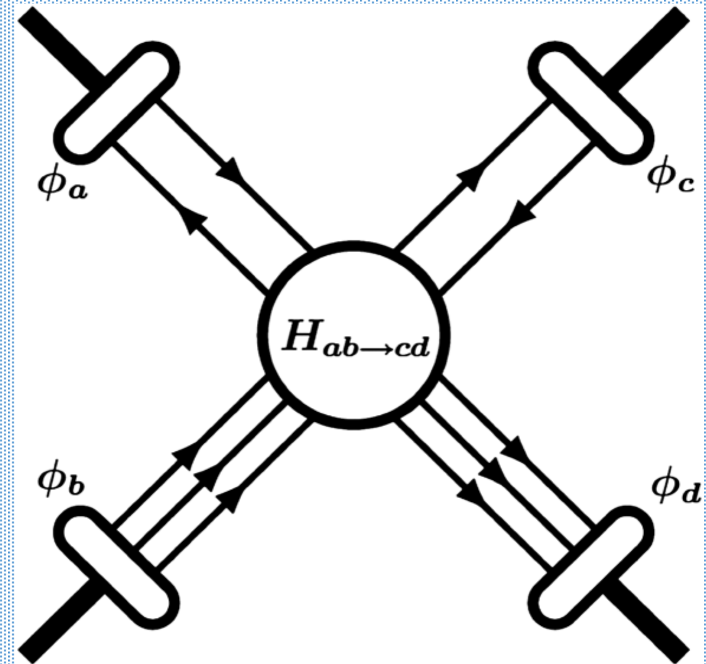
GPD(x_B,Q^2) in space-like regime



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.



Hard exclusive production process

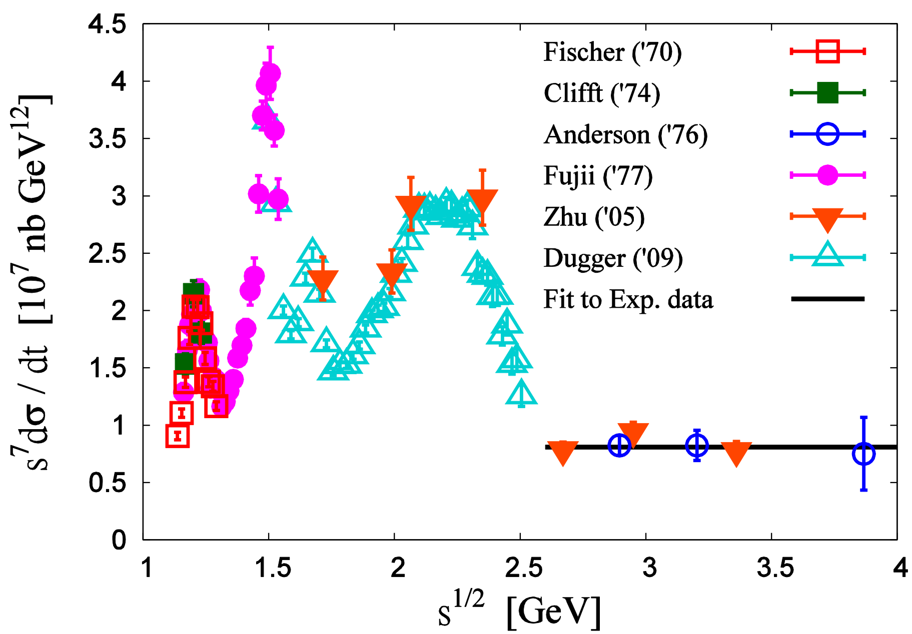
Constituent-Counting Rule in Hard Exclusive Process

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

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

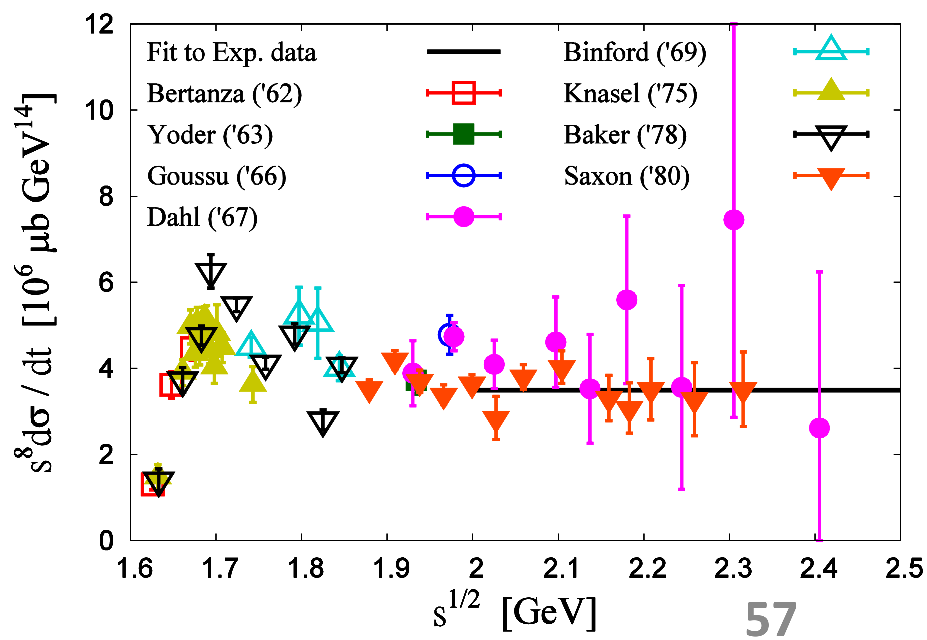
$$n=1+3+2+3=7$$

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



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

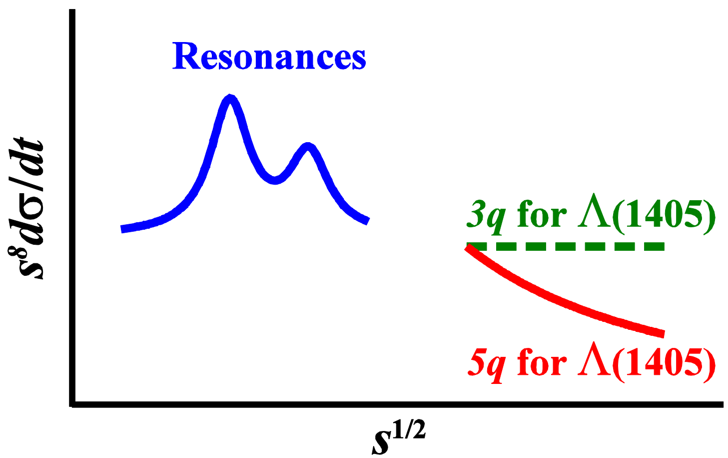
$$\pi^{-}+p\to K^{0}+\Lambda$$

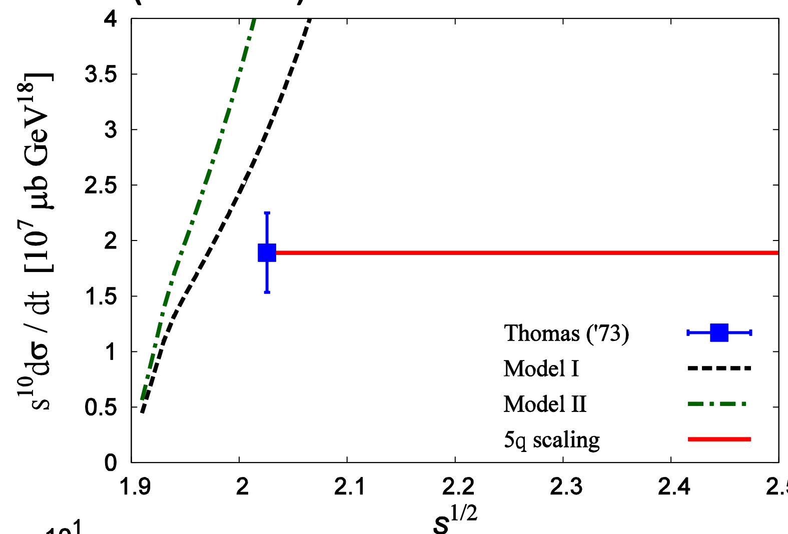


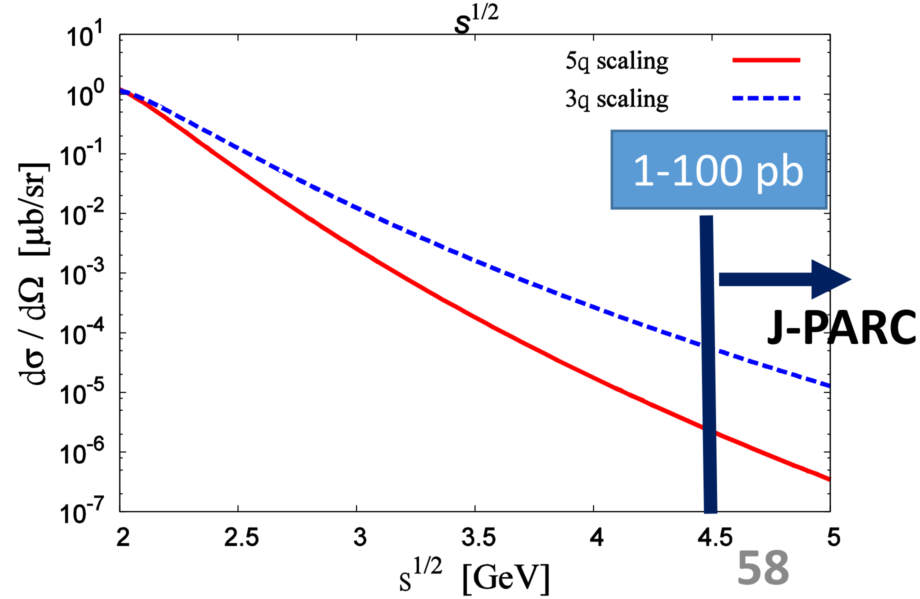
Quark Degrees of $\Lambda(1405)$

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

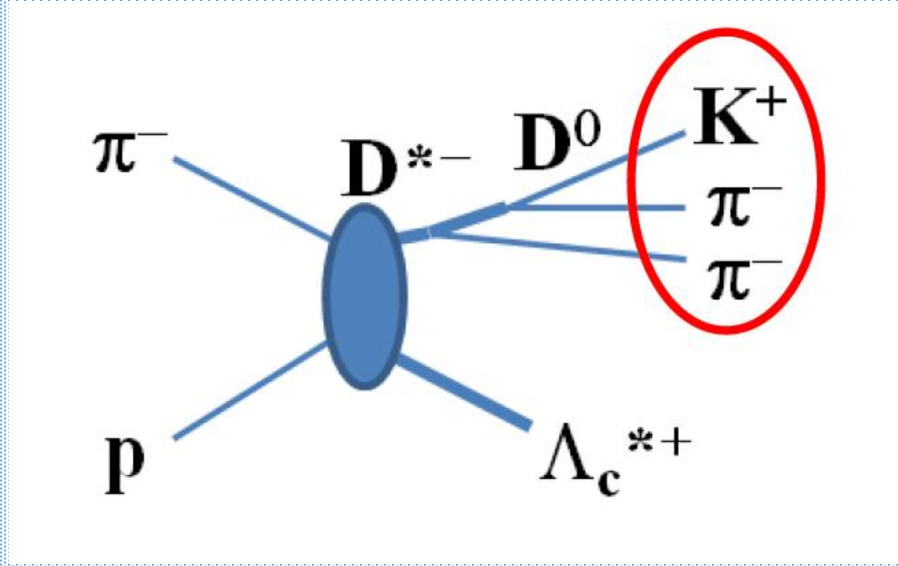
$$\pi^- + p \to K^0 + \Lambda(1405)$$







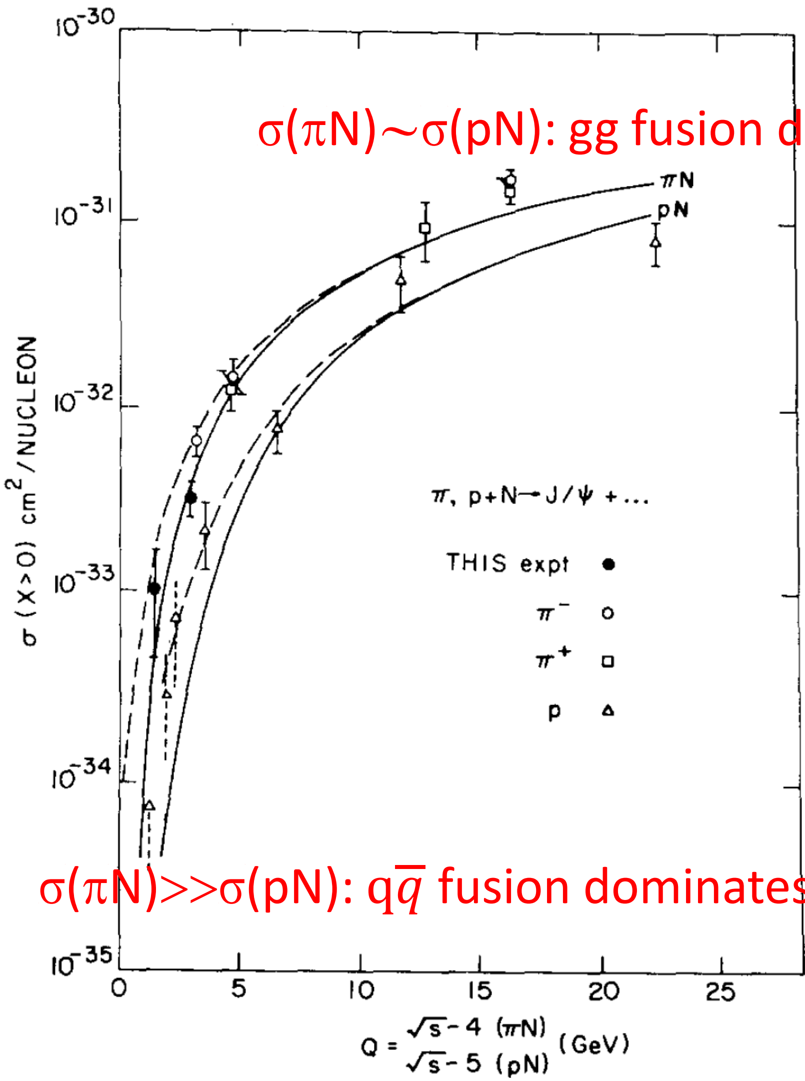
T. Sekihara's talk

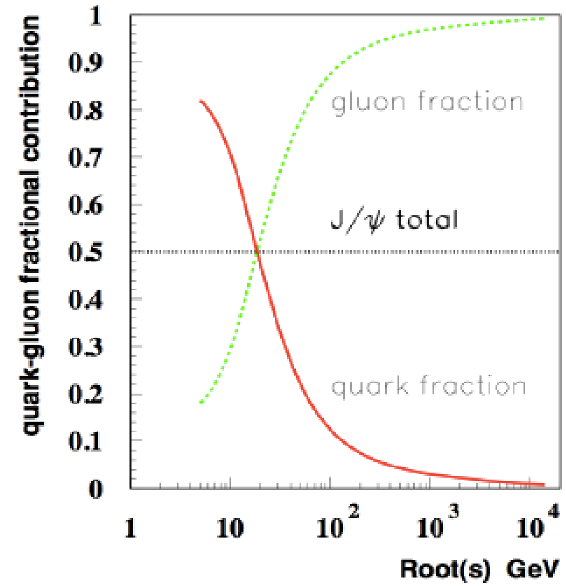


Charmed production process

J/ψ production in 22 GeV πCu collisions

Nucl. Phys. B179 (1981) 189

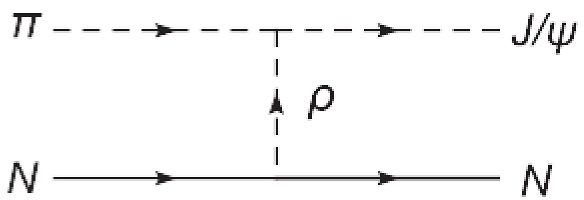




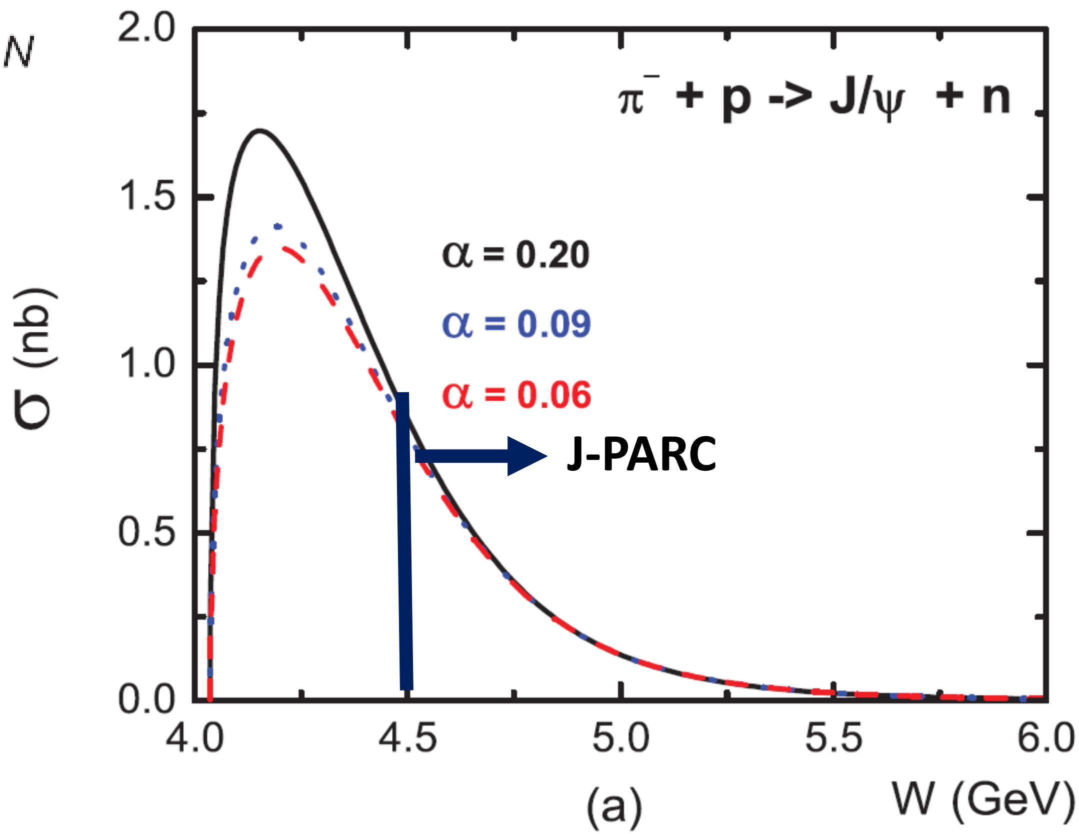
In fig. 3 we show the energy dependence of the J/ψ production cross sections for $x > 0$ for both incident pions and protons [10]. Again, the dashed curves refer to the original quark fusion model [6] while the solid curves include the threshold condition. We have also examined the J/ψ decay angular 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)

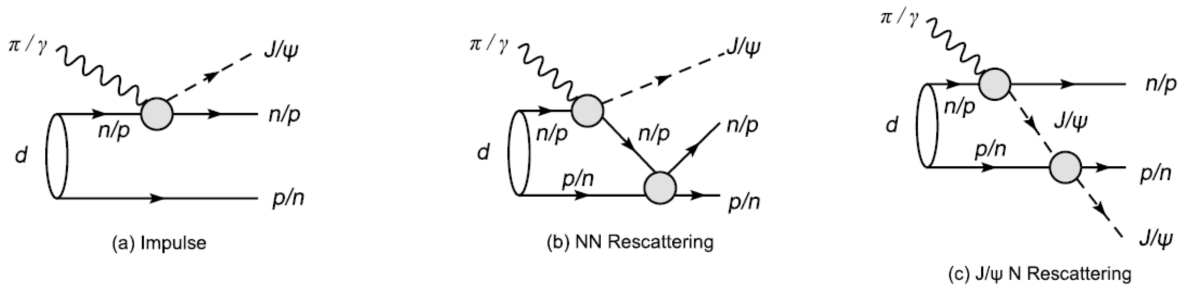


$$v_{J/\Psi N, J/\Psi N}(r) = -\alpha \frac{e^{-\mu_0 r}}{r}$$



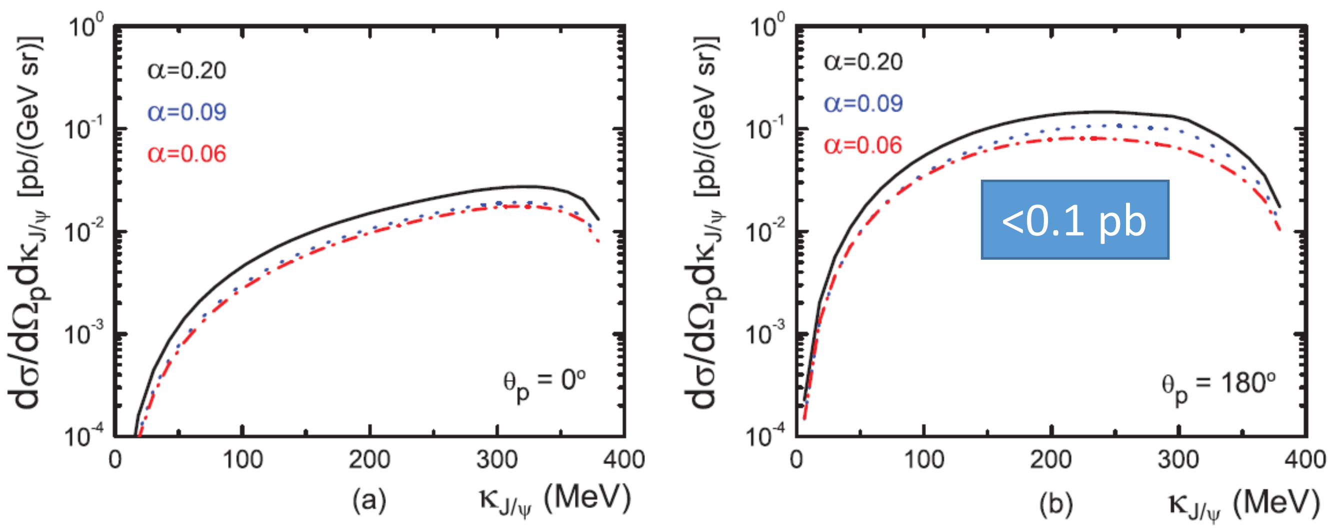
J/ψ-N Interaction Strength

Wu and Lee, PRC 88, 015205 (2013)



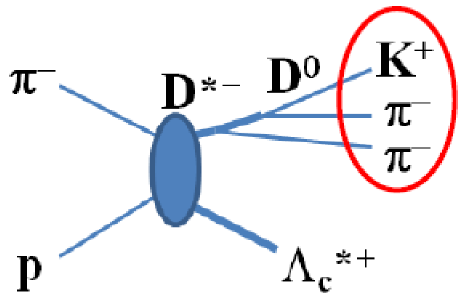
$$v_{J/\Psi N, J/\Psi N}(r) = -\alpha \frac{e^{-\mu_0 r}}{r}$$

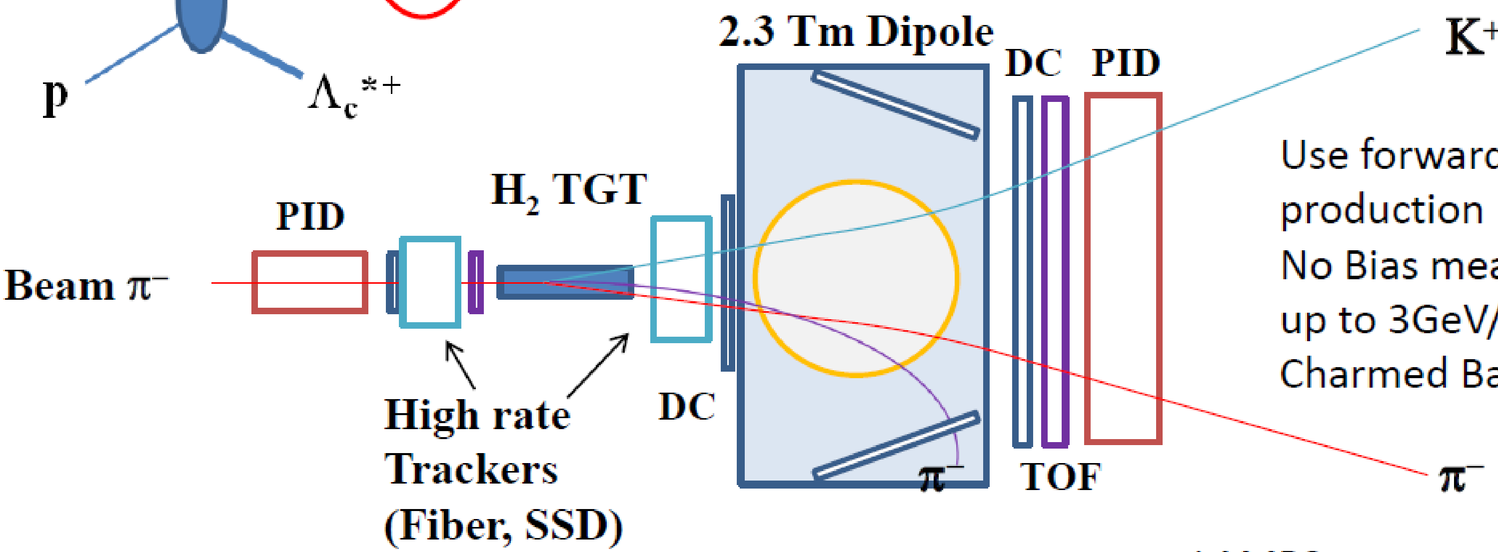
$$\pi^+ + d \rightarrow J/\psi + p + p$$



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

Missing mass Spectroscopy

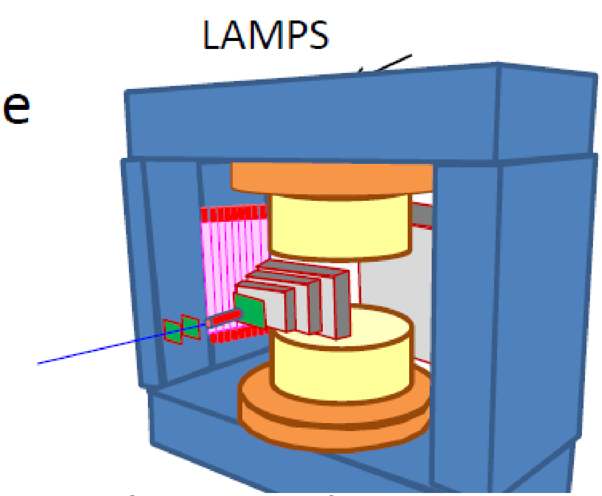




Use forward D mesons production

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

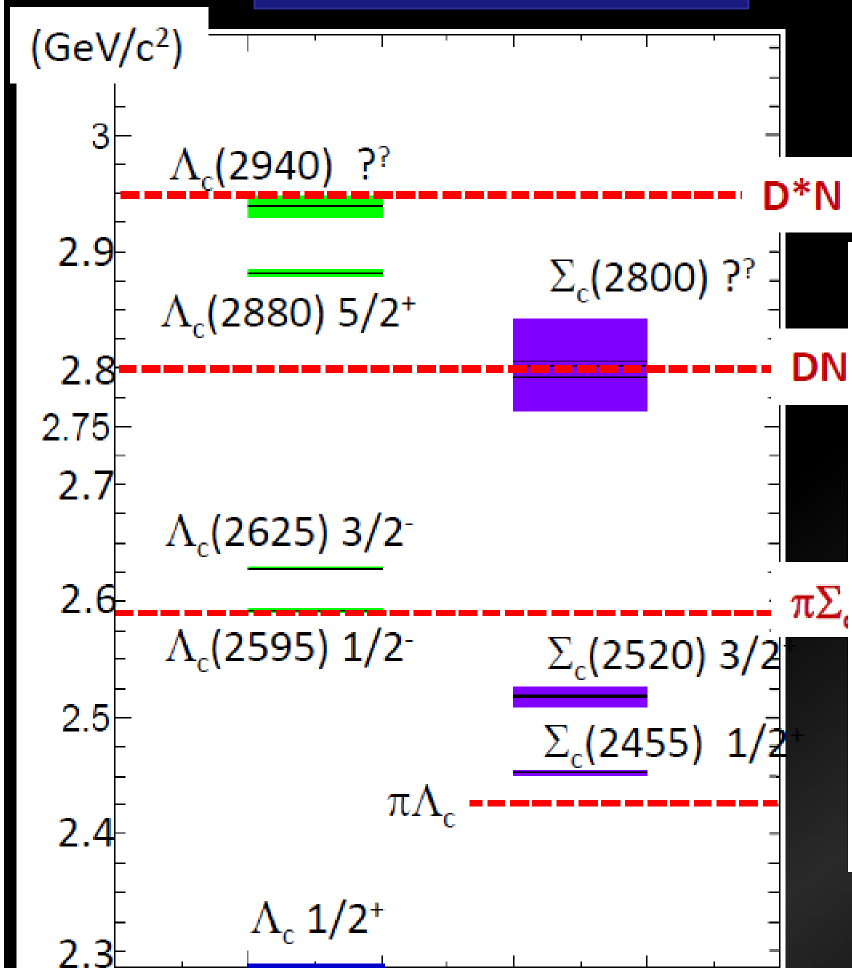
- Large Acceptance, Multi-Particle
  - K, π from D^0 decays
  - Soft π from D^{*-} decays
  - (Decay products from Y_c*)
- High Resolution
- High Rate
  - SFT/SSD op. >10M/spill at K1.8



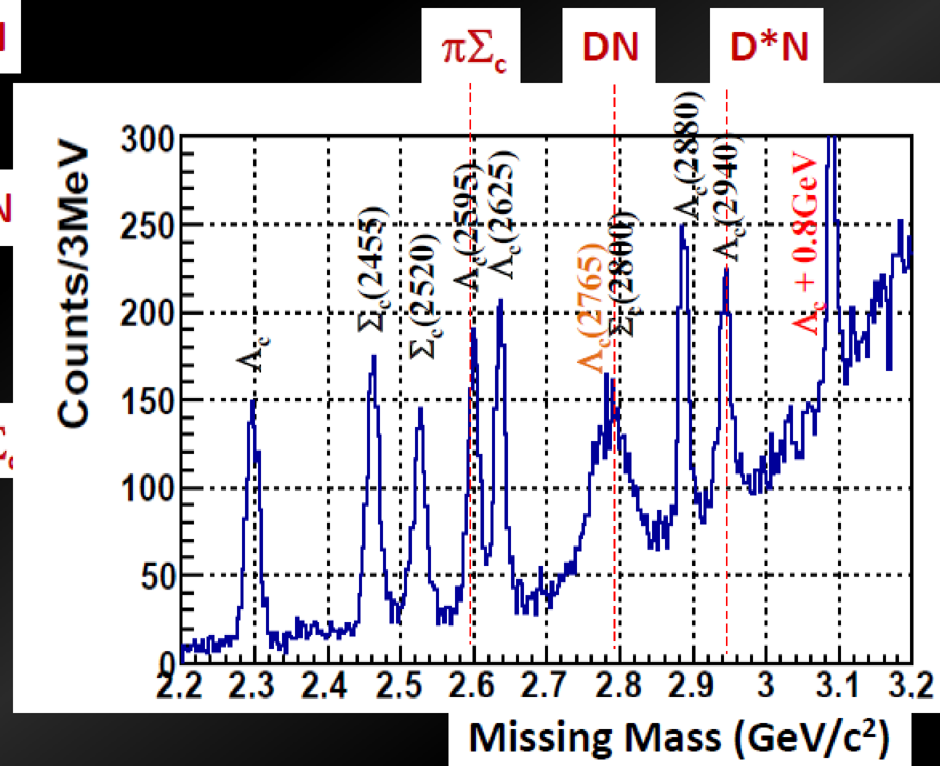
- Good mass resolution is required
  - D^0 meson: 4.5 MeV, D* meson: 0.7 MeV

Expected Spectrum in the (π,D*⁻) reaction

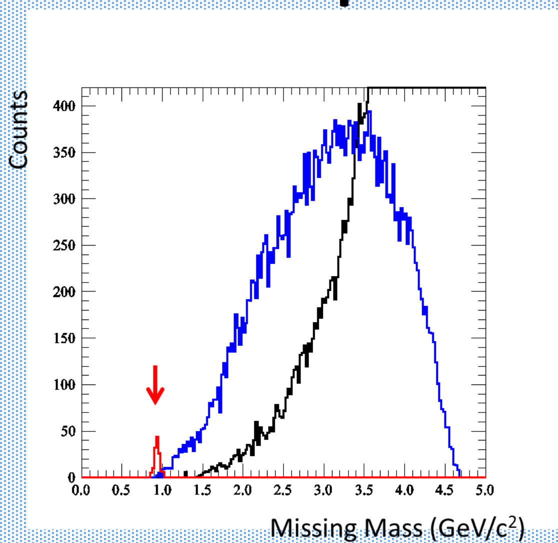
H. Noumi's talk



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



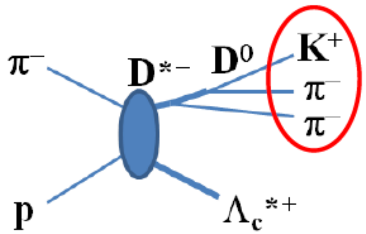
Feasibility study of Drell-Yan processes in the conceptual detector system



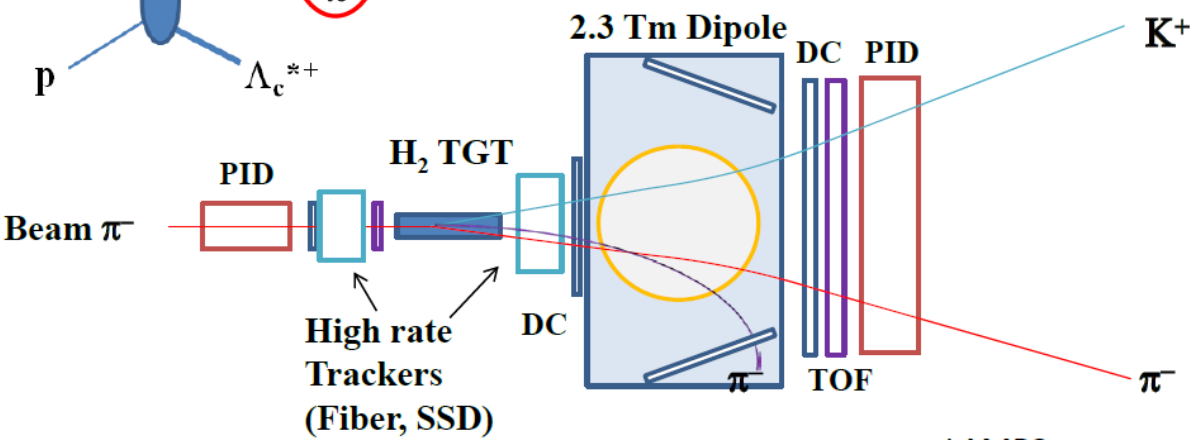
Conceptual Detector System

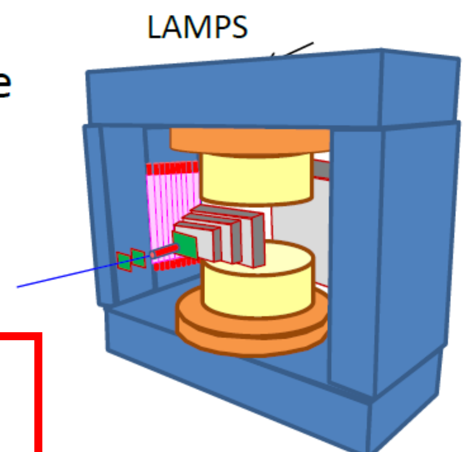
- Beam PID: possibility of utilizing kaon and anti-p beams
- Open aperture without hadron absorber before momentum determination: minimize multiple-scattering of muons
- Spectrometer with good momentum resolution and particle ID
- Muon ID in the forward direction at the very downstream

J-PARC P50 Spectrometer



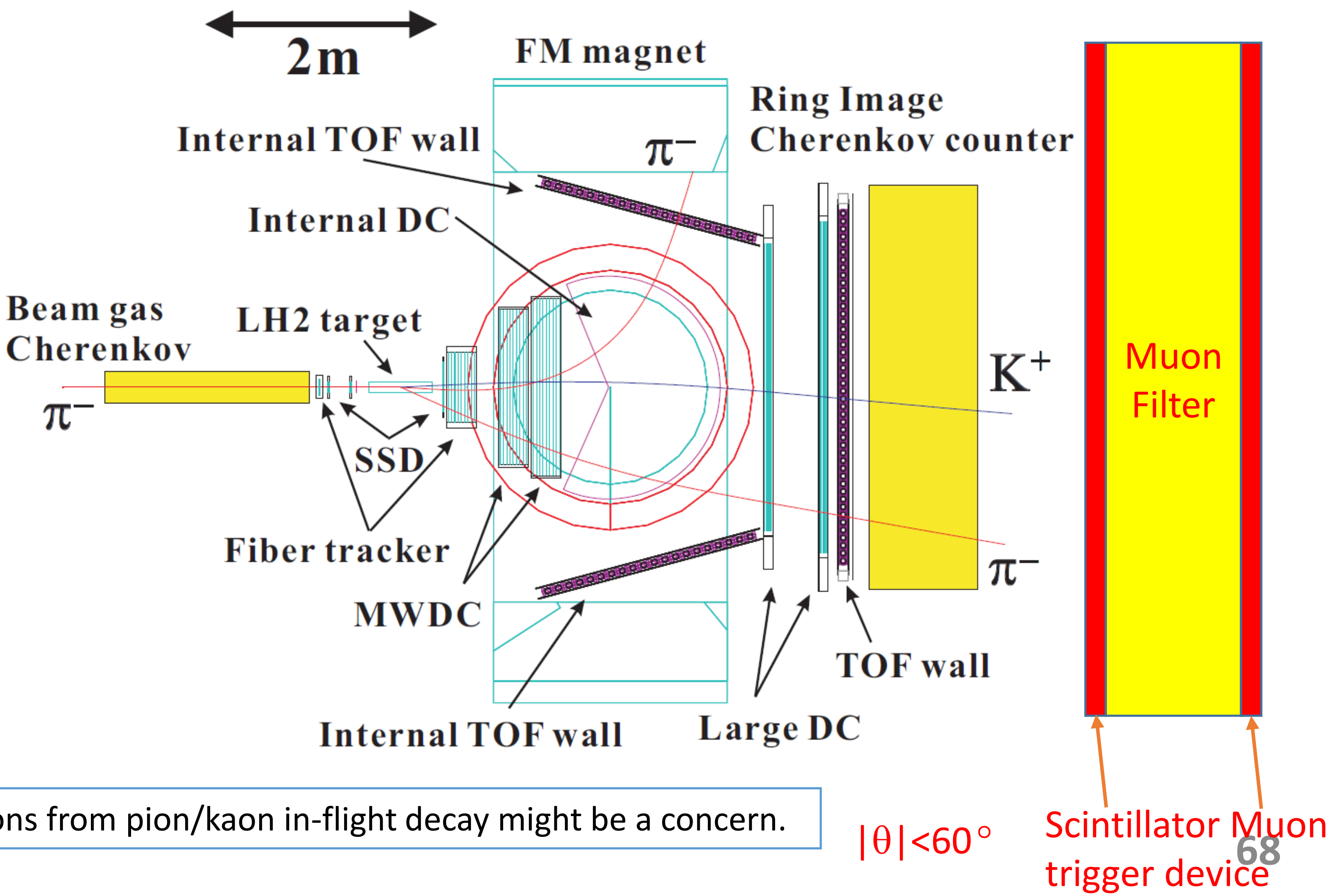
Spectrometer Concept





- 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

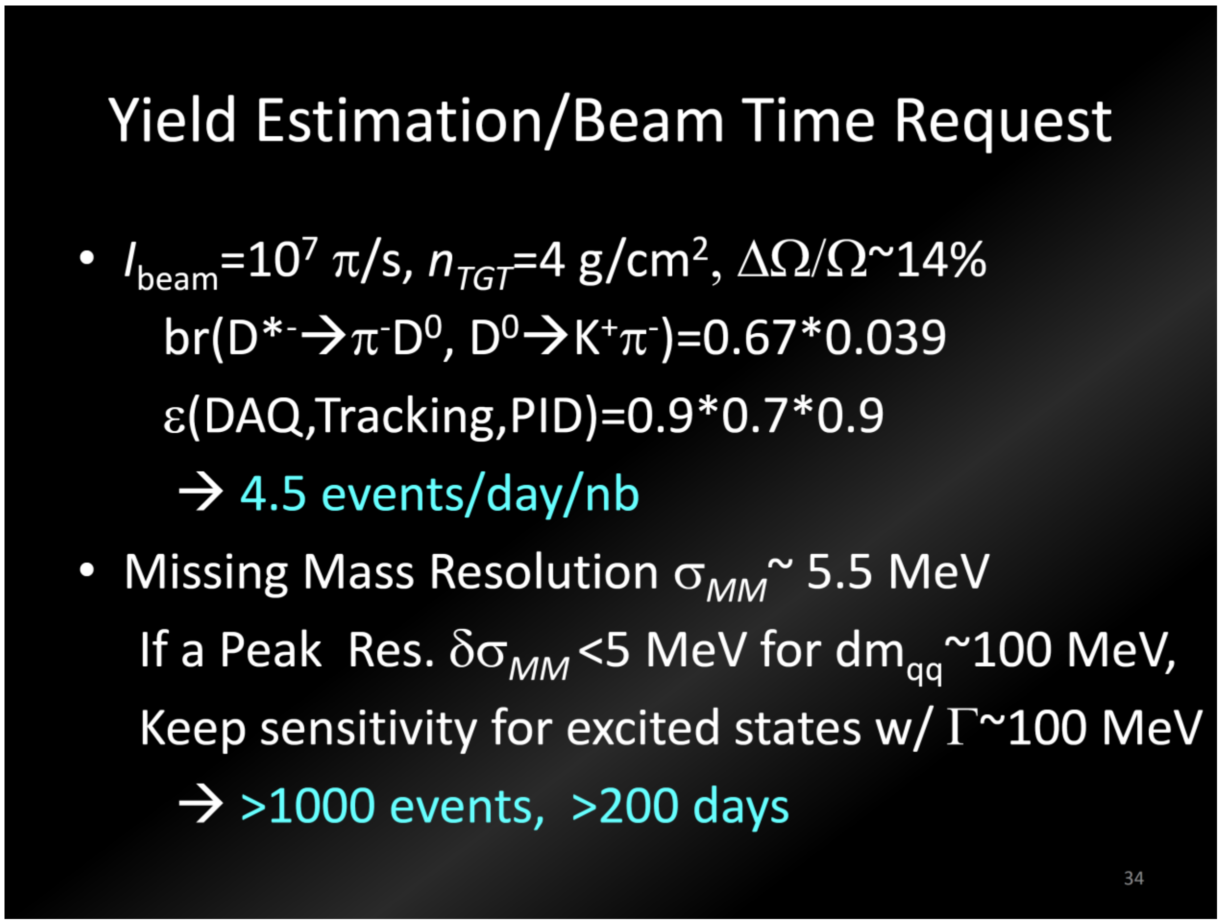
J-PARC P50 Spectrometer + MuID



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

$|\theta|<60°$

Yield Estimation from J-PARC P50



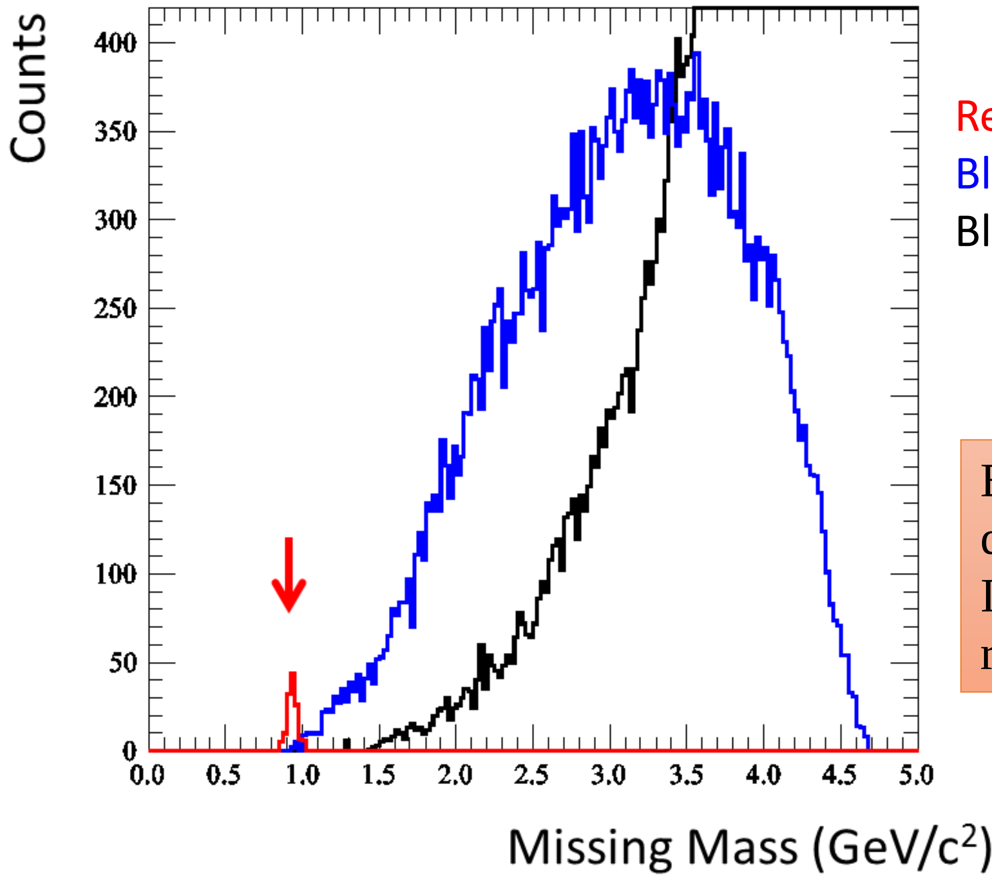
Yield Estimation based on J-PARC P50 Parameters

- $I_{beam}=10^7$ 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→$\mu^+\mu^-$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: $\Delta p/p = 0.2$ %

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.

Takahiro Sawada

Summary

- 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**
- Spectrometer with large acceptance and good mass resolution is required. The measurement using P-50 conceptual spectrometer is feasible.