HEP Seminar, Chung-Yuan Christian University
April 12th, 2016

Drell-Yan Experiments for determining quark structure of the nucleon

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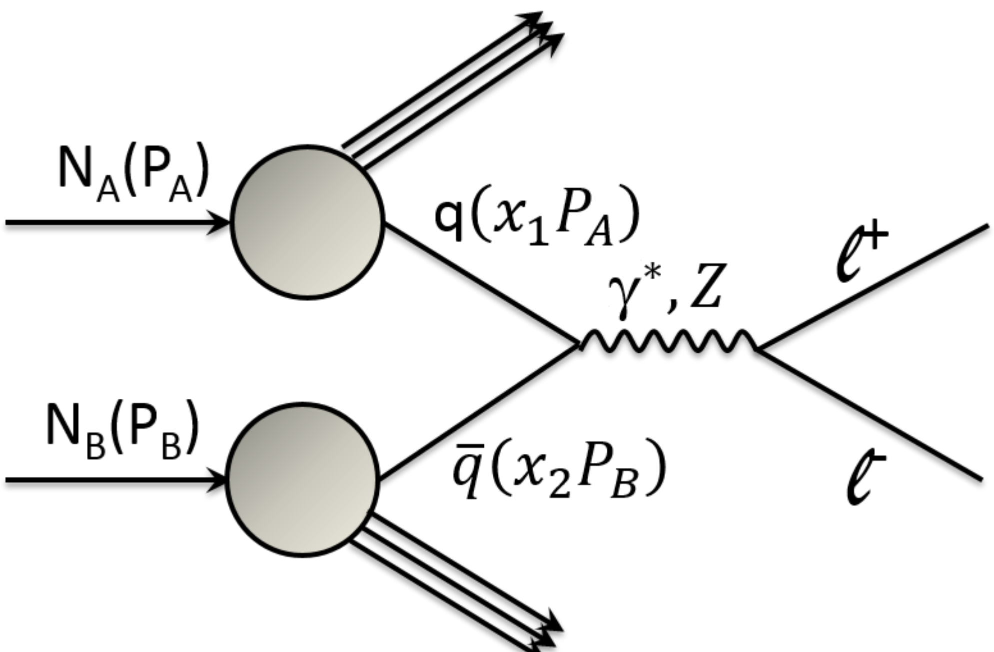
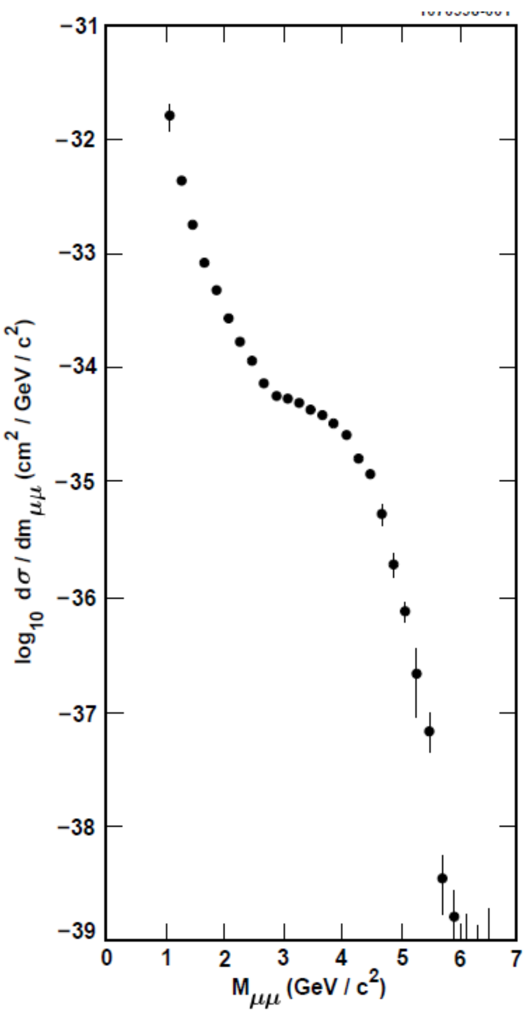


Outline

- Introduction of Drell-Yan Process:
  - History & Formalism
  - Success and Failure
  - QCD effect
- Flavor structure of nucleon sea & E906/SeaQuest experiment at FNAL
- k_T structure of nucleon quarks & COMPASS experiment at CERN
- Transverse space of nucleon quarks & exclusive Drell-Yan proposal at J-PARC
- Summary

Massive Dimuon Pairs in Hadron Collisions

J.H. Christenson et al., PRL 25 (1970) 1523



- Target: p+U→V+X
- Found: p+U→μμ +X
- Observation:
  - Shoulder-like structure around 3 GeV. Evidence of J/ψ was absent due to bad momentum resolution.
  - Rapid fall-off of cross section with the dimuon mass (~1/M^5).

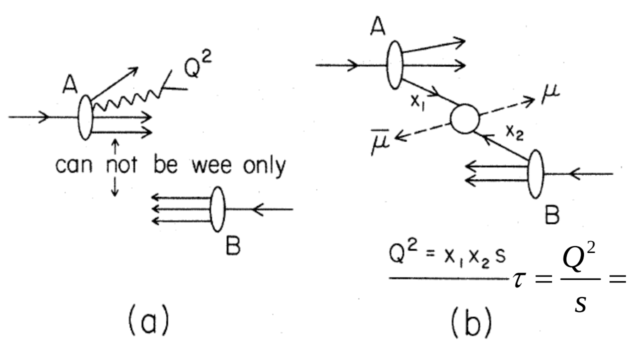
The Drell-Yan Process

S.D. Drell and T.M. Yan, PRL 25 (1970) 316

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \to \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.



$$\tau = \frac{Q^2}{s} = x_1 x_2$$

FIG. 1. (a) Production of a massive pair Q^2 from one of the hadrons in a high-energy collision. In this case it is kinematically impossible to exchange "wee" partons only. (b) Production of a massive pair by parton-antiparton annihilation.

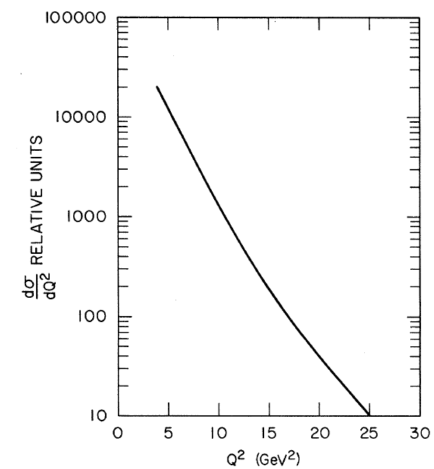


FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributions and with relative normalization.

$$\frac{d\sigma}{dQ^2} = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\mathfrak{F}(\tau) = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\int_0^1 dx_1 \int_0^1 dx_2\, \delta(x_1x_2-\tau)\sum_a \lambda_a^{-2} F_{2a}(x_1) F_{2\bar{a}}{}'(x_2),$$

Tung-Mow Yan 顏東茂

Professor of Physics

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BS, 1960, National Taiwan University. Ph.D., 1968, Harvard University. Research Associate, Stanford Linear Accelerator Center, 1968-70. Assistant Professor, Physics, Cornell University, 1970-76. Associate Professor, Physics, Cornell University, 1976-81. Professor, Physics, Cornell University, 1981-present. Visiting appointments at: Stanford Linear Accelerator Center, 1973-74. Theory Division, CERN, 1977-78. Physics Department, National Taiwan University, 1986. Institue of Physics, Academia Sinica, Taipei, Taiwan, 1991-92. National Center of Theoretical Sciences, Hsinchu, Taiwan, 1997. Alfred Sloan Fellow, 1974-78. Fellow, American Physics Society.

Drell-Yan "naïve" Parton Model

T.M. Yan, hep-ph/9810268

- Sid and I got interested in the process for two reasons:
  (1) we were looking for application of the parton model outside deep inelastic lepton scatterings, and
  (2) we wanted to understand if the rapid decrease of the cross section with the muon pair mass could be reconciled with the point-like cross sections observed in the deep inelastic electron scattering.

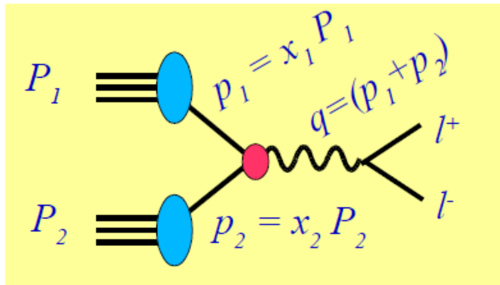
Drell-Yan "naïve" Parton Model

T.M.Yan, hep-ph/9810268

- The key idea in our approach was the impulse approximation.
- In infinite momentum frame, $\tau_{probe} \ll \tau_{initial\ state}$. The constituents could be treated as free.
- The cross section in the impulse approximation is a product of the probability to find the particular parton configuration and the cross section for the free parton(s).

Formalism

Kinematics in the Hadronic Frame



$$P_1 = \frac{\sqrt{s}}{2}(1,0,0,+1) \qquad P_1^2 = 0$$

$$P_2 = \frac{\sqrt{s}}{2}(1,0,0,-1) \qquad P_2^2 = 0$$

$$s = (P_1+P_2)^2 = \frac{\hat{s}}{x_1 x_2} = \frac{\hat{s}}{\tau}$$

Therefore

$$\tau = x_1 x_2 = \frac{\hat{s}}{s} \equiv \frac{Q^2}{s}$$

Fractional energy² between partonic and hadronic system

$$\frac{d\sigma}{dQ^2} = \sum_{q,\bar{q}} \int dx_1 \int dx_2 \left\{ q(x_1)\bar{q}(x_2) + \bar{q}(x_1) q(x_2) \right\} \hat{\sigma}_0 \, \delta(Q^2 - \hat{s})$$

Hadronic cross section

Parton distribution functions

Partonic cross section

$$\frac{4\pi\alpha^2}{9\hat{s}} Q_i^2 \equiv \hat{\sigma}_0$$

F. Olness, CTEQ 2004 Summer School

Drell-Yan Experiments

http://hepdata.cedar.ac.uk/review/dy/

Home Page
Other Data Reviews
Reaction Database

CONTENTS

HEPDATA ON-LINE DATA REVIEW

Compilation of Data on Drell Yan Production Cross Sections .

publication:
W J Stirling and M R Whalley 1993 *J.Phys.G.Nucl.Part.Phys:* 19 D1-D102

HEPDATA ON-LINE DATA REVIEW

Experiments

- CERN-NA3
- CERN-NA10
- CERN-WA11
- CERN-WA39
- CERN-R108
- CERN-R209
- CERN-R808
- CERN-UA2
- Fermilab-E288
- Fermilab-E325
- Fermilab-E326
- Fermilab-E439
- Fermilab-E444
- Fermilab-E537
- Fermilab-E605
- Fermilab-E615
- Fermilab-E740(D0)
- Fermilab-E741(CDF)
- Fermilab-E772
- Fermilab-E866(NUSEA)

Measurements of:-

- p p --> mu+ mu- X
- p p --> e+ e- X
- pbar p --> mu+ mu- X
- pbar p --> e+ e- X
- p Nucleus --> mu+ mu- X
- pbar Nucleus --> mu+ mu- X
- pi+ Nucleus --> mu+ mu- X
- pi- Nucleus --> mu+ mu- X

This is an archive of experimental data on Drell Yan production cross sections. Data are given in both tabular and graphical form for invariant cross seciotns and transverse momentum distributions from experiments at CERN and Fermilab.

Select data from a specific experimental collaboration:

CERN	Fermilab
NA3 NA10 WA11 WA39 R108 R209 R808 UA2	E288 E325 E326 E439 E444 E537 E605 E615 E740(D0) E741(CDF) E772 E866(NUSEA)

or select data for a specific measurement:

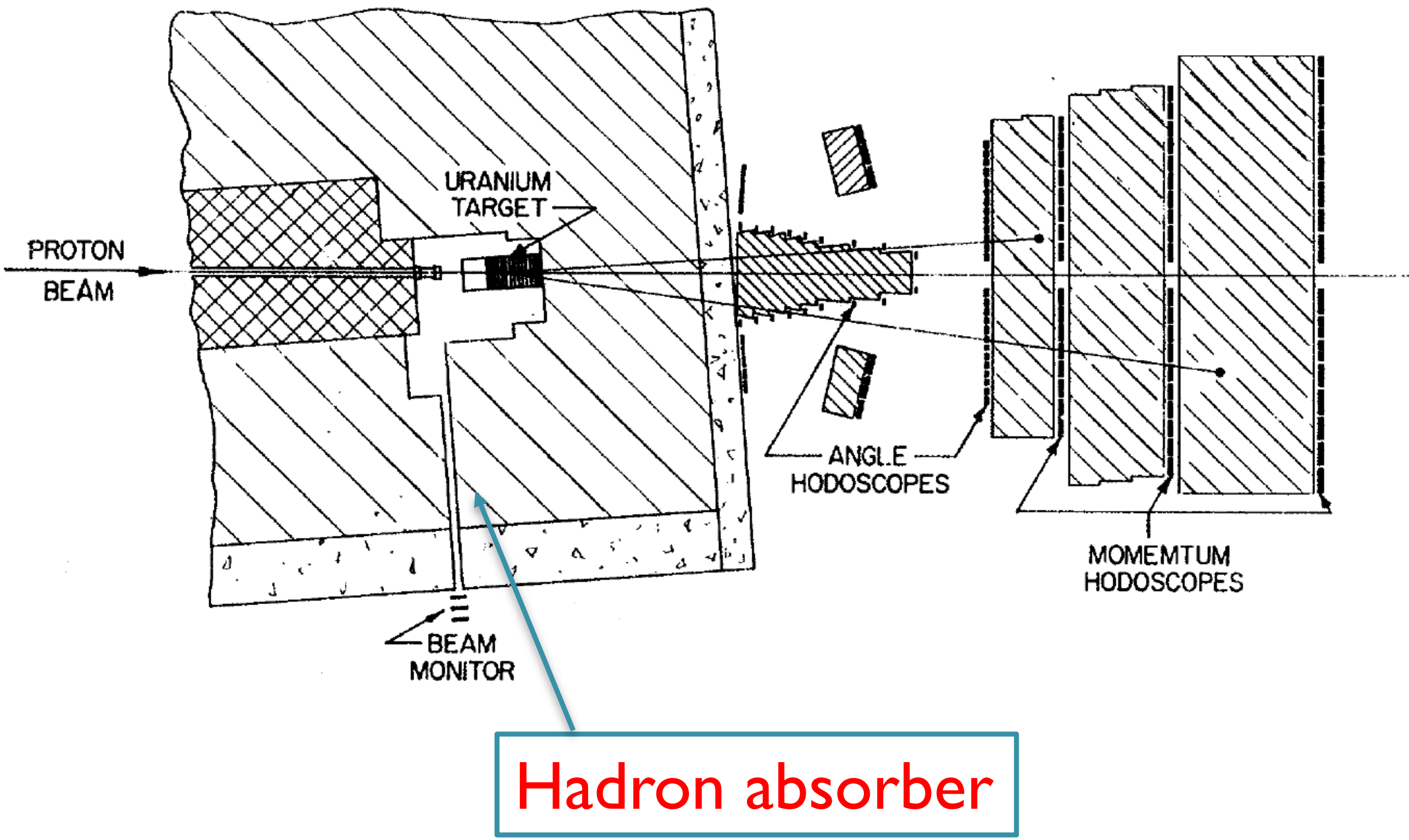
Measurement	Measurement
p p --> mu+ mu- X p p --> e+ e- X pbar p --> mu+ mu- X pbar p --> e+ e- X	p Nucleus --> mu+ mu- X pbar Nucleus --> mu+ mu- X pi+ Nucleus --> mu+ mu- X pi- Nucleus --> mu+ mu- X

Please send any comments on this service to hepdata@projects.hepforge.org

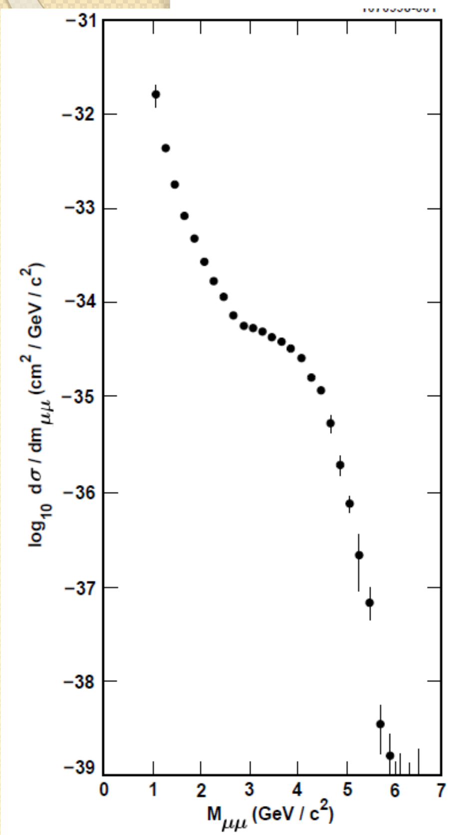
Massive Dimuon Pairs in Hadron Collisions

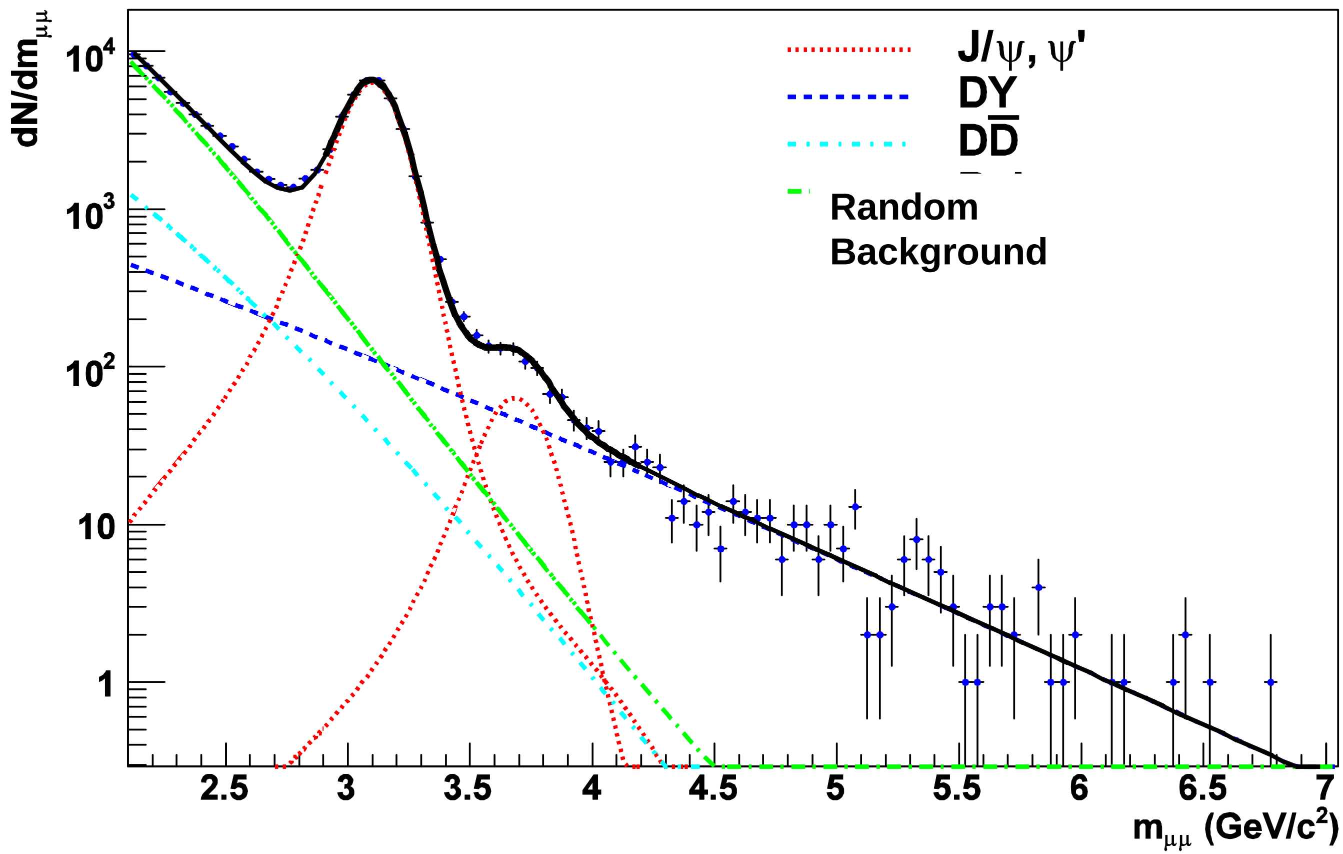
J.H. Christenson et al., PRL 25 (1970) 1523

$$(\vec{P}^{\mu+}, \vec{P}^{\mu-})\,|_{lab}, s \Rightarrow (M^{\gamma^*}, x_F{}^{\gamma^*}, x_1{}^{q}, x_2{}^{\bar{q}})\,|_{CMS}$$



Dimuon Invariant Mass Spectrum



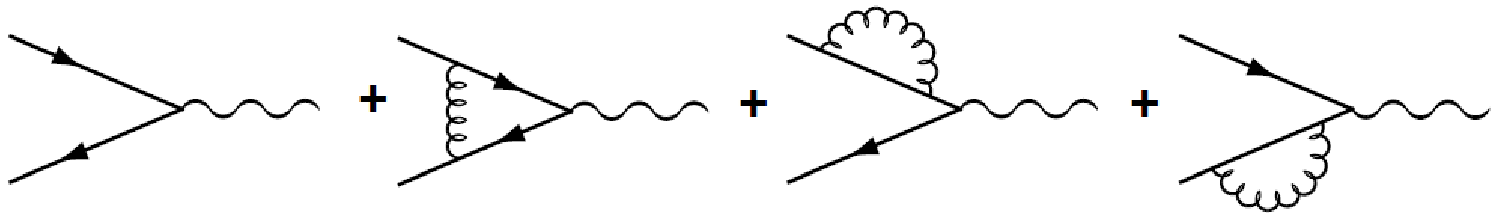


Indium-Indium collisions at 158 GeV/nucleon
NA60, PRL 99 (2007) 132302

Success and Failure of the "naïve" Drell-Yan parton model

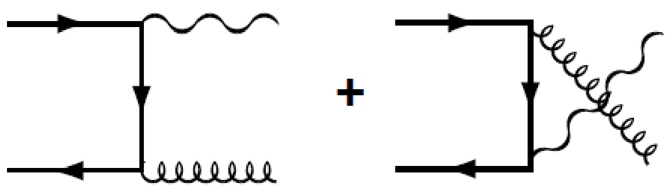
- Success:
  - Scaling of the cross sections (depends on x_1 and x_2 only)
  - Nuclear dependence (cross section depends linearly on the mass A)
  - Angular distributions ($1+\cos^2\theta$)
- Failure:
  - Absolute cross sections (a factor of 2-3 larger than expected)
  - Transverse momentum distributions (much larger $\langle p_T \rangle$ than 200-300 MeV)

Drell-Yan Process with QCD Effect



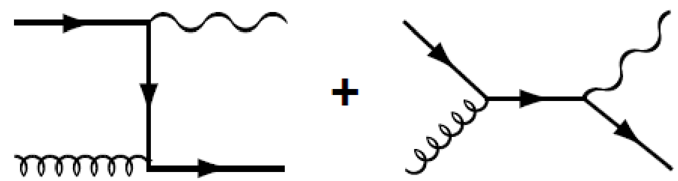
(a)

Quark-antiquark annihilation



(b)

Quark-antiquark annihilation



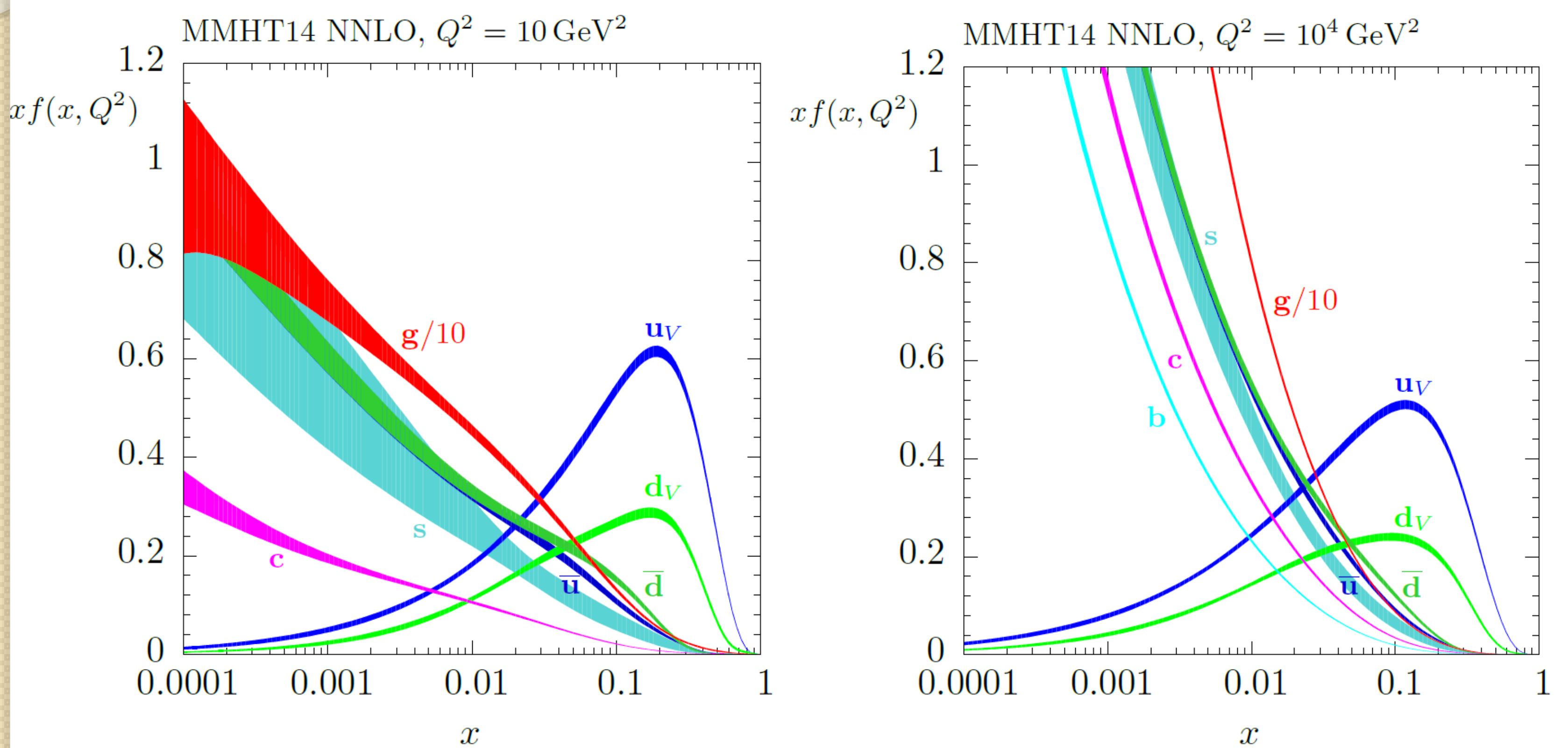
(c)

Quark-gluon Compton scattering

Drell-Yan Process with QCD Effect

- Scaling: The logarithmic corrections in Q^2 can be absorbed by Q^2-dependent quark and antiquark distribution functions of the hadrons. Scaling is violated but only logarithmically
- Absolute cross section: LO, NLO.
- Angular distribution: Lam-Tung relation.
- Transverse momentum distribution: A large transverse momentum of the lepton pair can be produced by recoil of quarks or gluons.

Parton distributions: MMHT 2014 PDFs



L. A. Harland-Lang, A. D. Martin, P. Motylinski, R.S. Thorne, arXiv:1412.3989

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

Gottfried Sum Rule

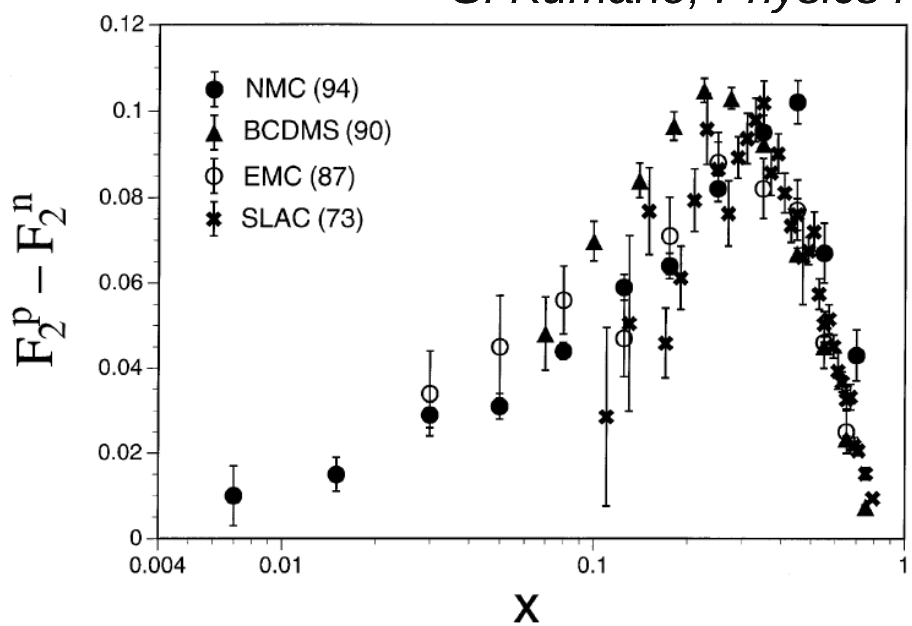
$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x)) / x] dx$$

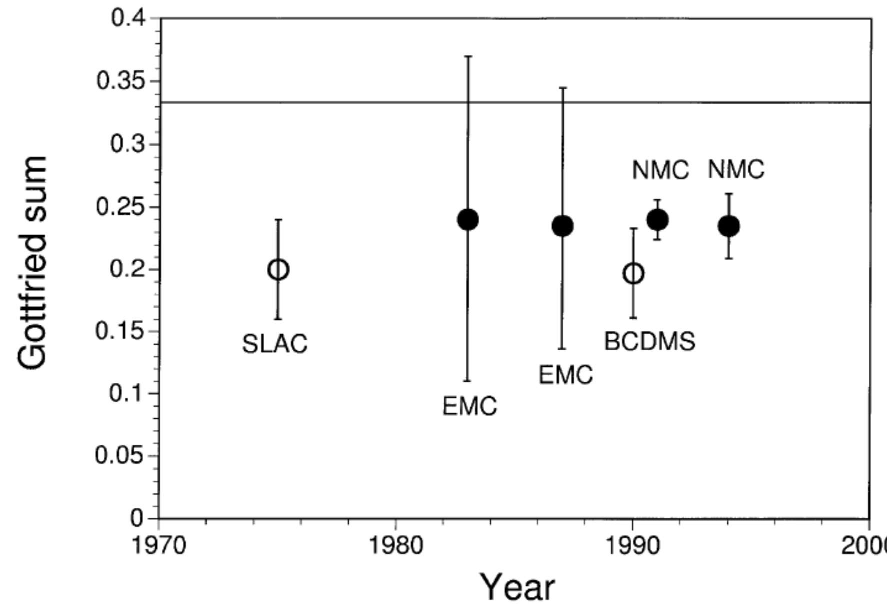
$$= \frac{1}{3}\int_0^1 (u_v(x) - d_v(x))\ dx + \frac{2}{3}\int_0^1 (\bar{u}(x) - \bar{d}(x))\ dx$$

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

Experimental Measurement of Gottfried Sum

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





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

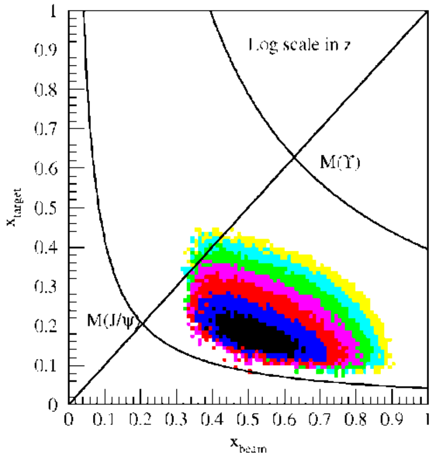
$$S_G = 0.235 \pm 0.026$$

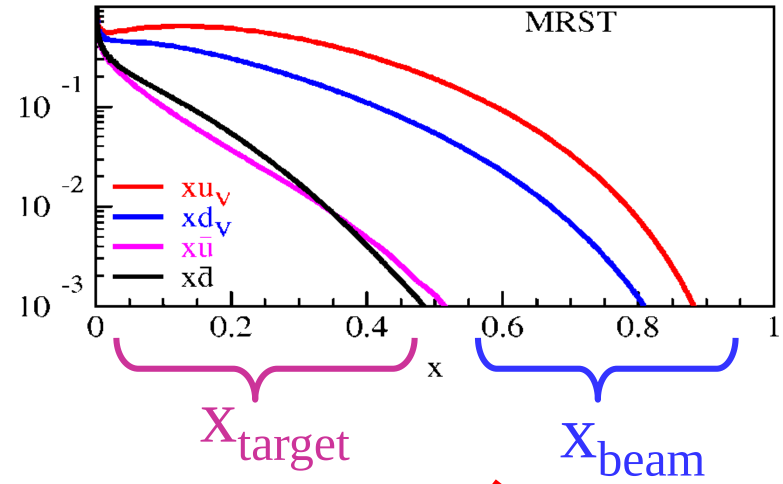
(Significantly lower than 1/3 !)

x-dependence of Sea Quarks

Acceptance for fixed-target experiment:

$x_{beam} >> x_{target}$



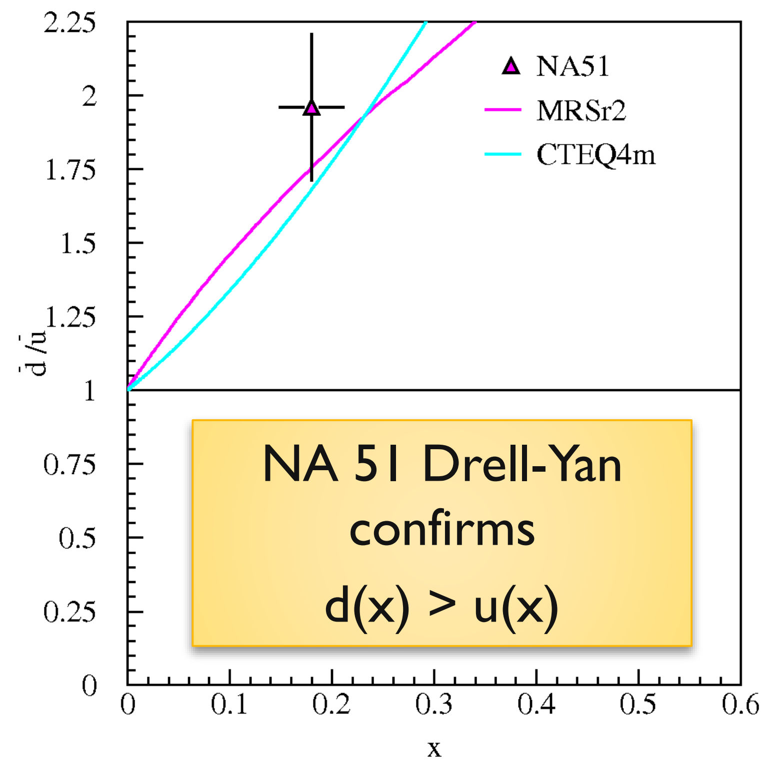


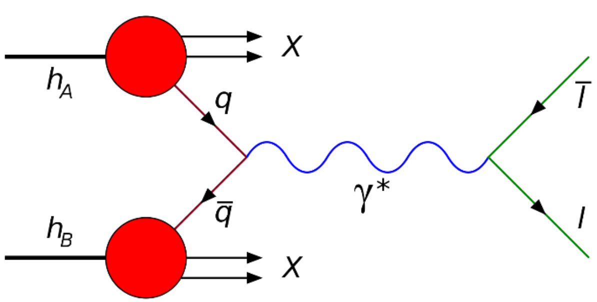
$$\frac{d^2\sigma}{dx_{beam}dx_{target}} = \frac{4\pi\alpha^2}{9x_{beam}x_{target}}\frac{1}{s}\sum_i e_i^2[q_i(x_{beam})\bar{q}_i(x_{target}) + \bar{q}_i(x_{beam})q_i(x_{target})]$$

$$\frac{\sigma^{pd}}{2\sigma^{pp}}\Big|_{x_{beam} >> x_{target}} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_{target})}{\bar{u}(x_{target})}\right]$$

Light Antiquark Flavor Asymmetry: Drell-Yan Experiments

- 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 $x = 0.18$





Light Antiquark Flavor Asymmetry: Drell-Yan Experiments

- Naïve Assumption: $\bar{d}(x) = \bar{u}(x)$
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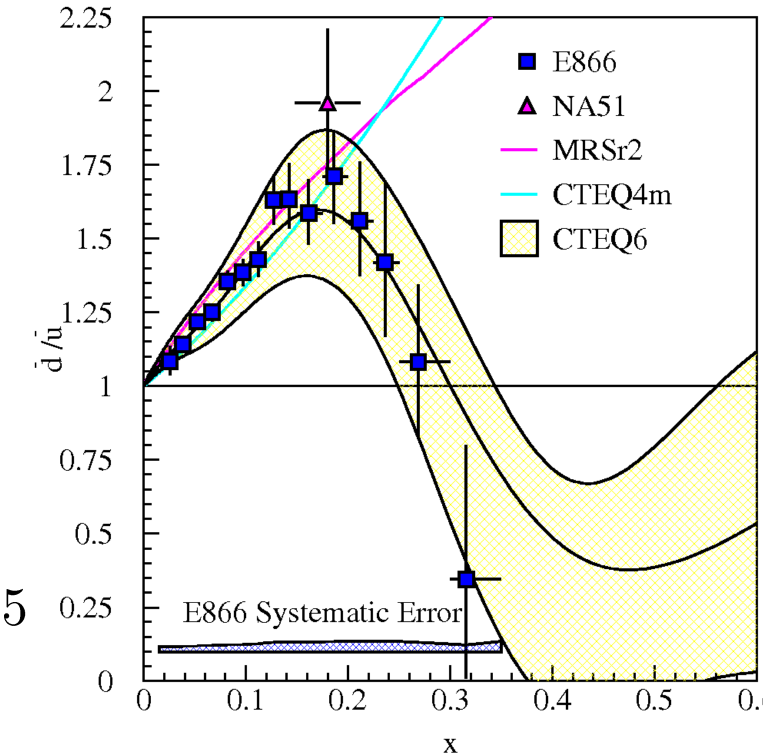
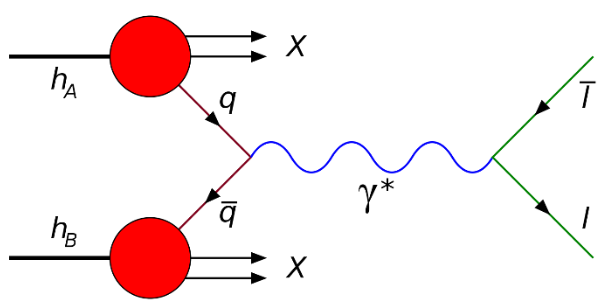
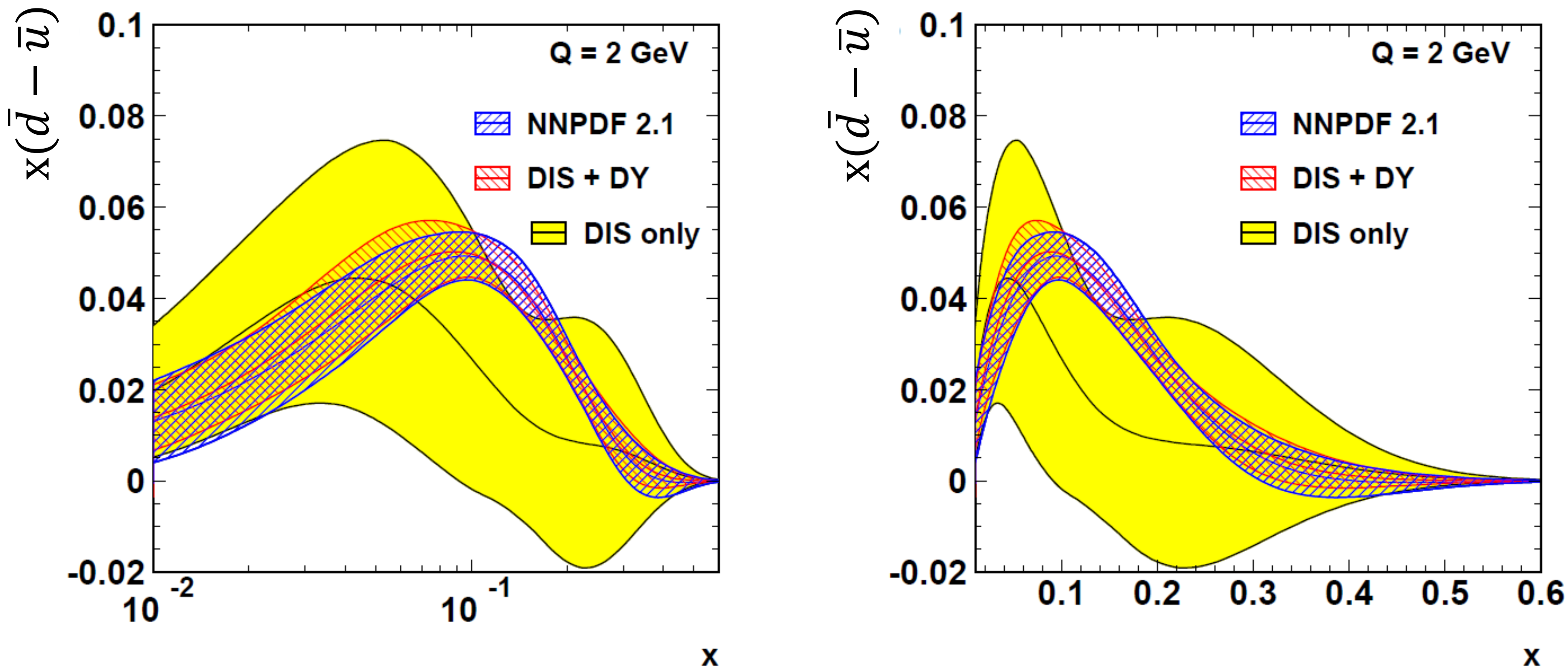
- NA51 (Drell-Yan, 1994):
  $\bar{d} > \bar{u}$ at $x = 0.18$
- E866/NuSea (Drell-Yan, 1998):
  $\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$



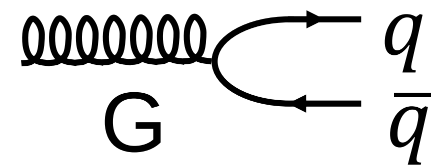


Constraint of $x(\bar{d} - \bar{u})$ in Global Analysis



E. Pereza and E. Rizvib, arXiv:1208.1178

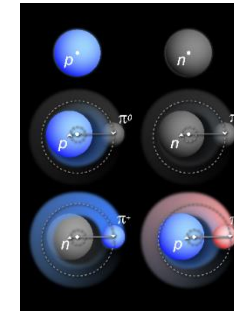
Origin of $\bar{u}(x) \neq \bar{d}(x)$: Perturbative QCD effect?



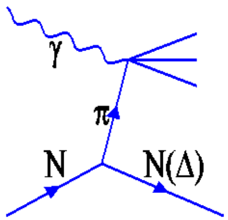
- Pauli blocking
  - $g \rightarrow u\bar{u}$ is more suppressed than $g \rightarrow d\bar{d}$ in the proton since |p>=|uud> (Field and Feynman 1977)
  - pQCD calculation (Ross, Sachrajda 1979)
  - Bag model calculation (Signal, Thomas, Schreiber 1991)
- Chiral quark-soliton model (Pobylitsa et al. 1999)
- Instanton model (Dorokhov, Kochelev 1993)
- Statistical model (Bourrely et al. 1995; Bhalerao 1996)
- Balance model (Zhang, Ma 2001)

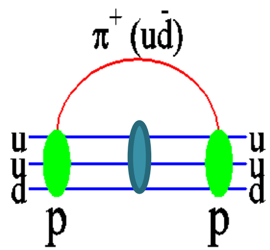
The valance-quark configuration affects the gluon splitting.

Origin of $\bar{u}(x) \neq \bar{d}(x)$: Non-perturbative QCD effect?



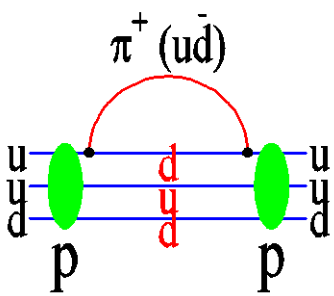
- Meson cloud in the nucleons (Thomas 1983, Kumano 1991): Sullivan process in DIS.





$$p \rightarrow N\pi;\ \pi^{+} : \pi^{0} : \pi^{-} = 2:1:0$$

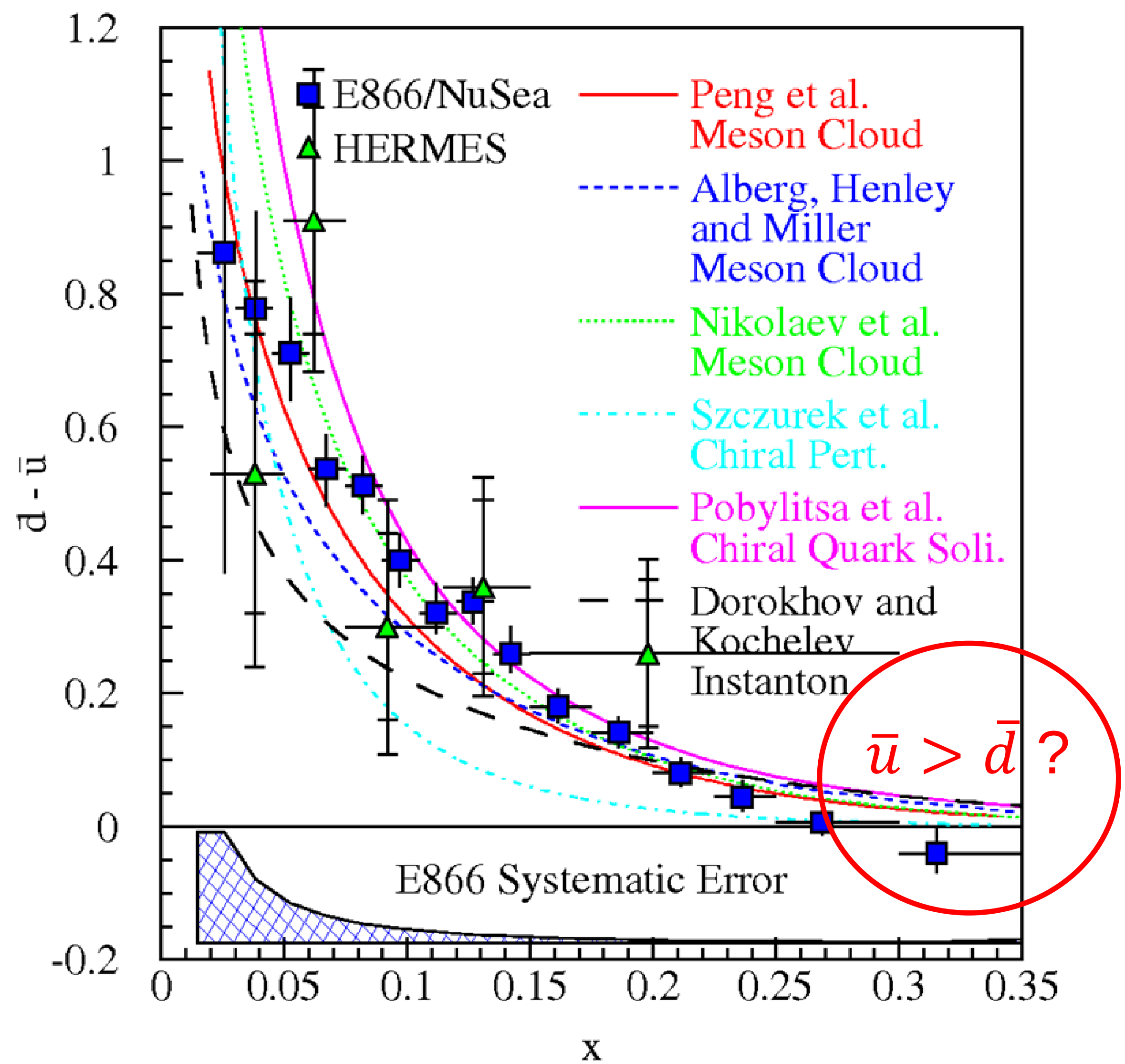
- Chiral quark model (Eichten et al. 1992; Wakamatsu 1992): Goldstone bosons couple to valence quarks.



$$q \rightarrow q\pi;\ \pi^{+} : \pi^{0} : \pi^{-} = 4:3:2$$

Pion cloud is a source of antiquarks in the protons and it lead to $\bar{d} > \bar{u}$.

$\bar{d}(x) - \bar{u}(x)$ vs. Theoretical Models

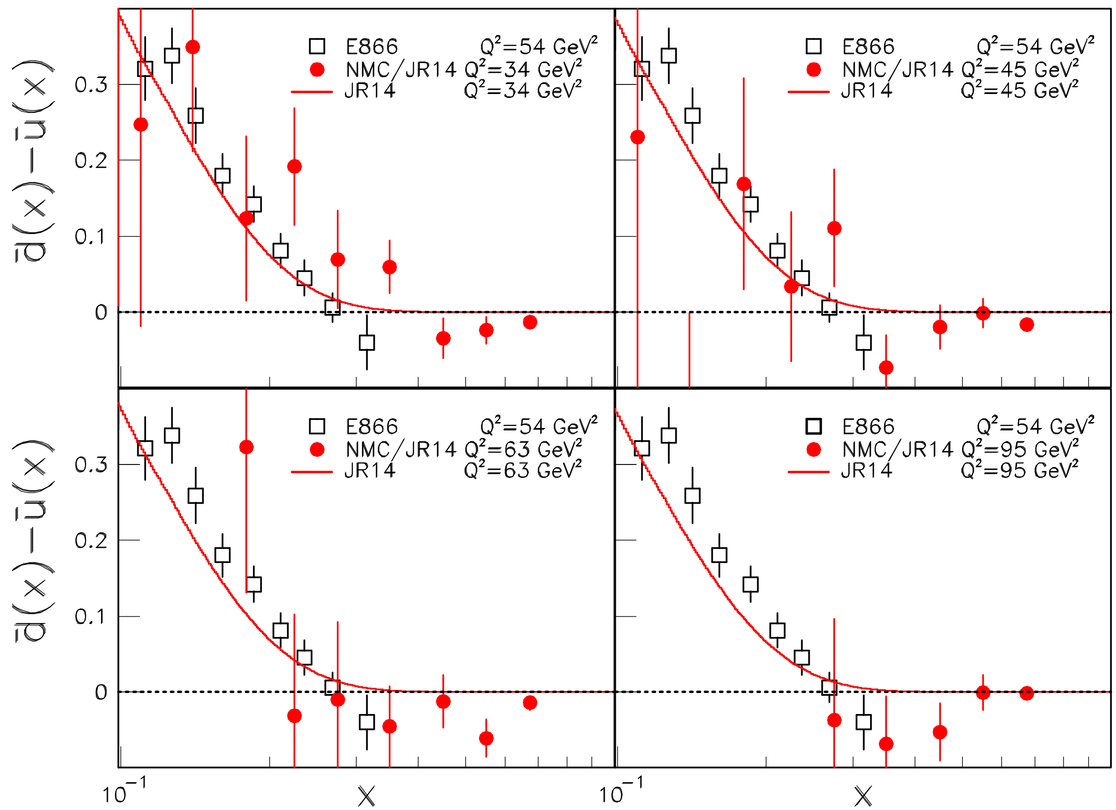


Momentum Dependence of the Flavor Structure of the Nucleon Sea: NMC vs E866

J.C. Peng, W.C. Chang, H.Y. Cheng, T.J. Hou and K.F. Liu, PLB 736 (2014) 411

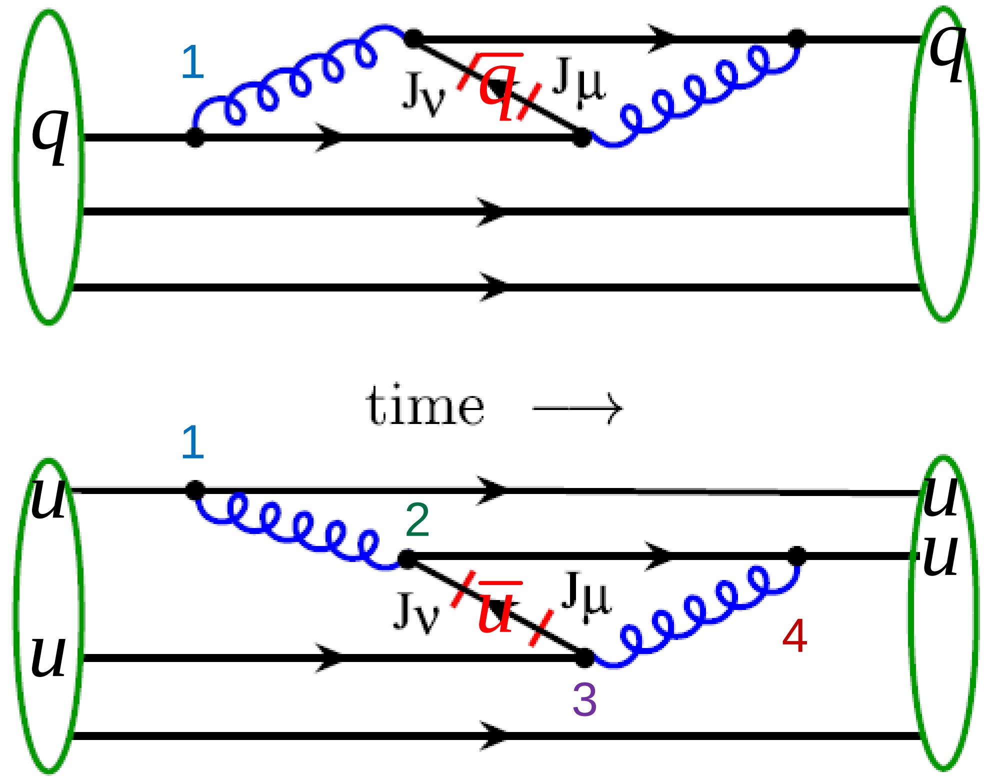
$$\bar{d}(x) - \bar{u}(x) = \frac{1}{2}[u_v(x) - d_v(x)] - \frac{3}{2x}[F_2^p(x) - F_2^n(x)].$$

NMC/JR14 JR14 NMC



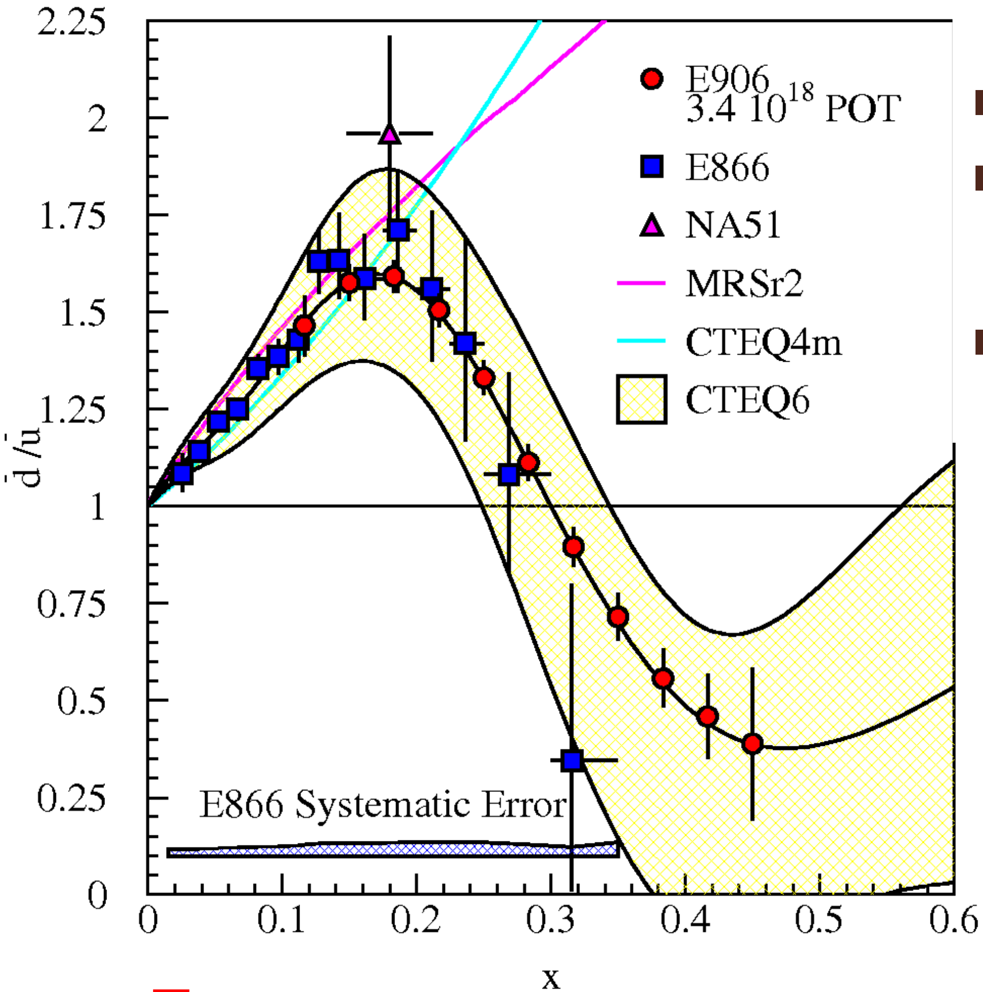
Diagrams of QCD quantum fluctuation $\bar{u} > \bar{d}$

J.C. Peng, W.C. Chang, H.Y. Cheng, T.J. Hou and K.F. Liu, PLB 736 (2014) 411



1. Gluon radiation
2. Gluon spliiting
3. $q\bar{q}$ recombination
4. Gluon absorption

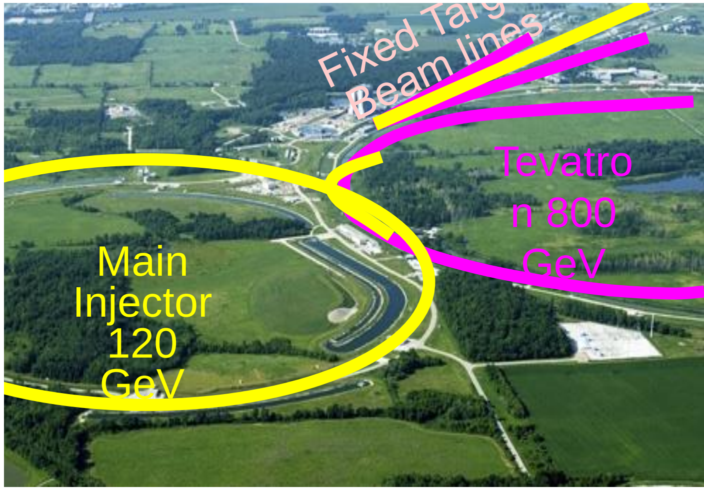
$\bar{d}(x)/\bar{u}(x)$ Measured by FNAL E906/SeaQuest Experiment



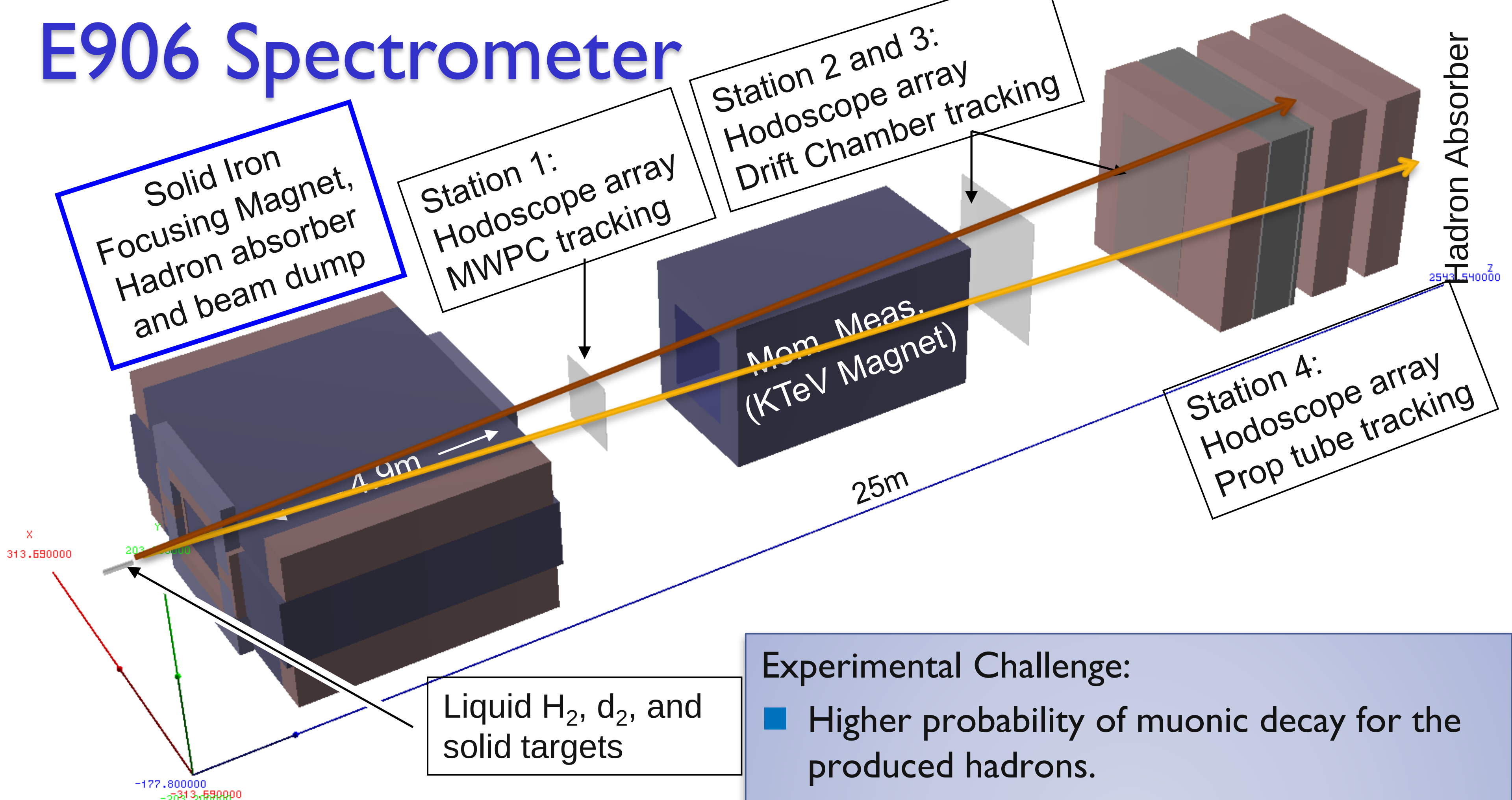
$(\bar{d}(x)/\bar{u}(x))$ up to $x_T \sim 0.45$

Fermilab E906

- $x_B x_T = \frac{M}{s}$; smaller s, larger x_T
- Unpolarized Drell-Yan using 120 GeV proton beam from Main Injector
- ^{1}H, ^{2}H, and nuclear targets



E906 Spectrometer



Experimental Challenge:

- Higher probability of muonic decay for the produced hadrons.
- Larger multiple scattering for the muon traveling through hadron absorber and solid magnet.
- Worse duty factor for beam structure.
- Higher singles rates.

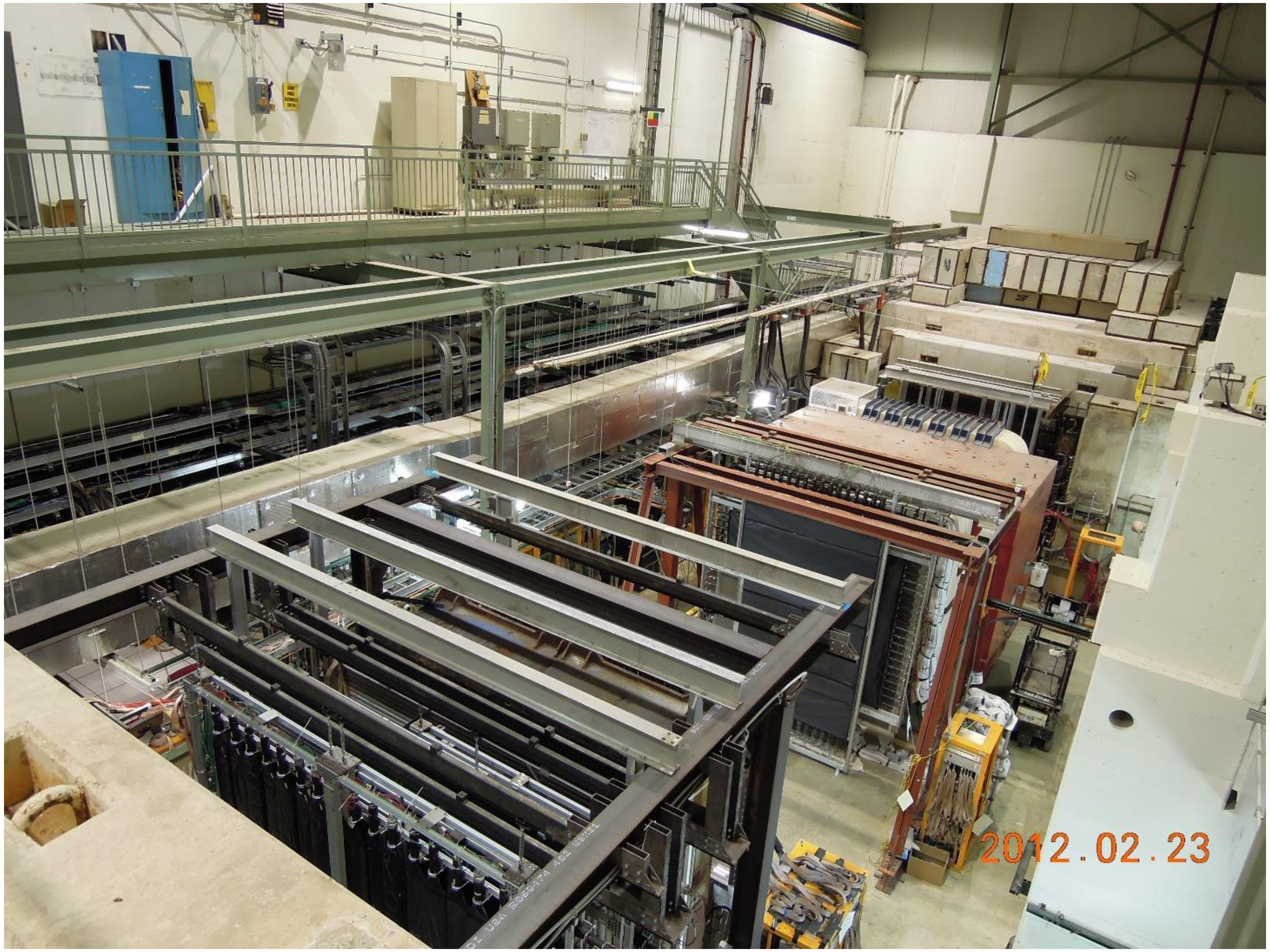
Solid iron magnet

- Reuse SM3 magnet coils
- Sufficient Field with reasonable coils
- Beam dumped within magnet

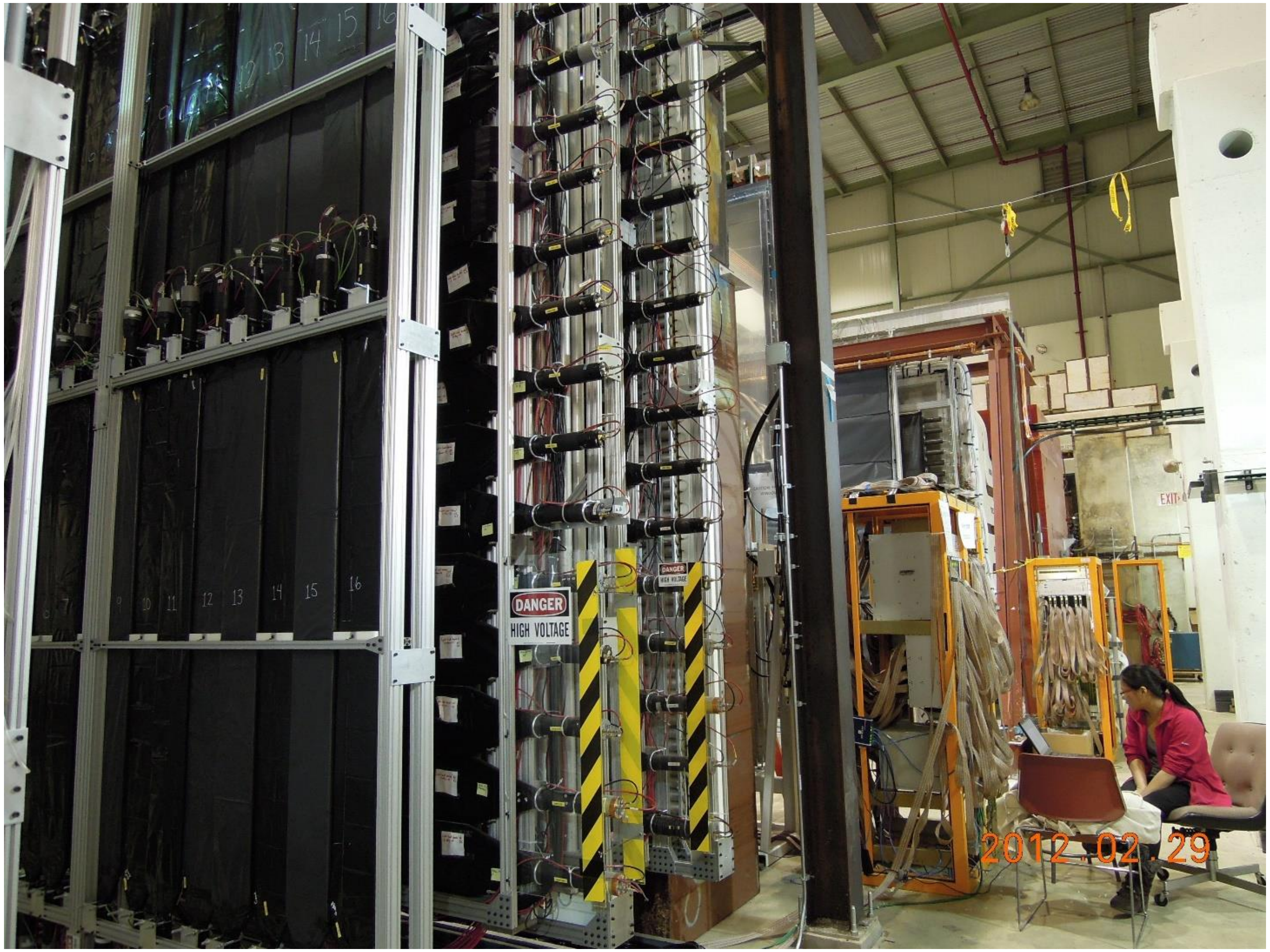
E906/SeaQuest (since 2007)

- Contributions from Taiwan team:
  - Readout electronics: 蘇大順、**王素音**、張定華、姚錫泓
  - FPGA dimuon trigger system: **許軒豪**、張定華、**王素音**
  - DAQ：陳彥竹、**王素音**
  - Hodoscope:陳彥竹
- Schedules:
  - Run 1 (March – April, 2012): commissioning run.
  - Run 2 (Nov, 2013 – August, 2014) : 1st physics run.
  - Run 3 (Oct, 2014 – August, 2015): 2nd physics run.
  - Run 4 (Oct, 2015 – August, 2016): 3rd physics run.

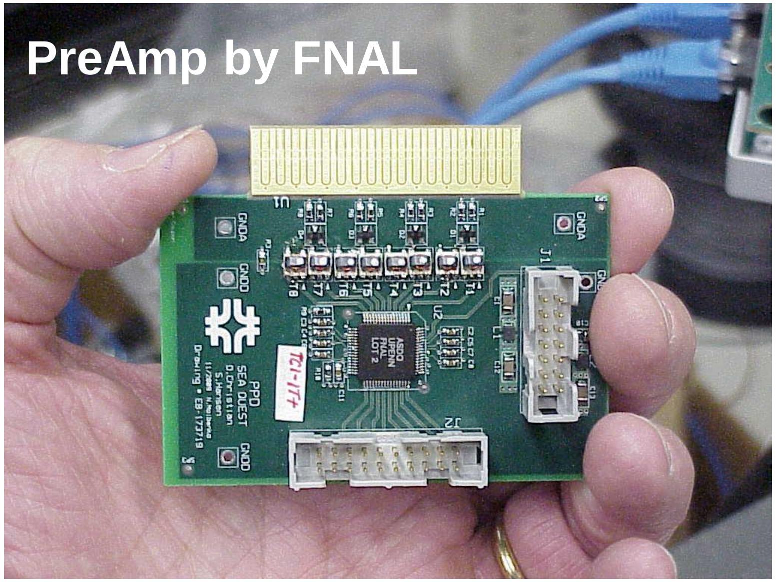
Fermilab NM4/KTeV Hall

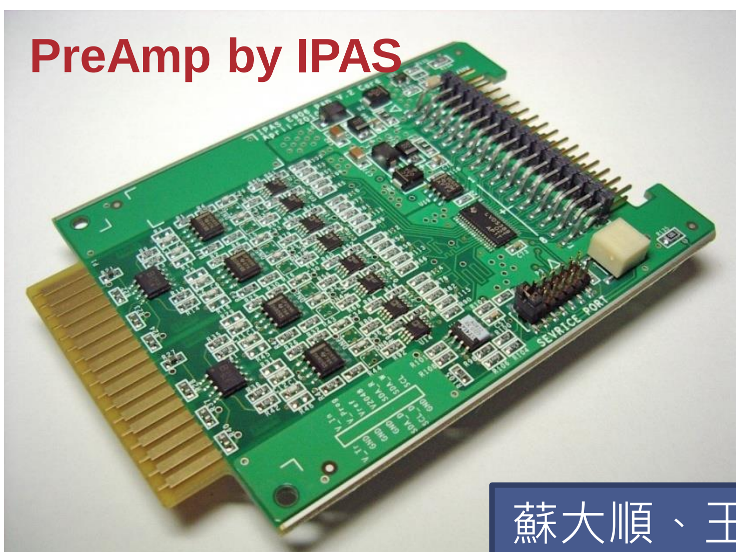


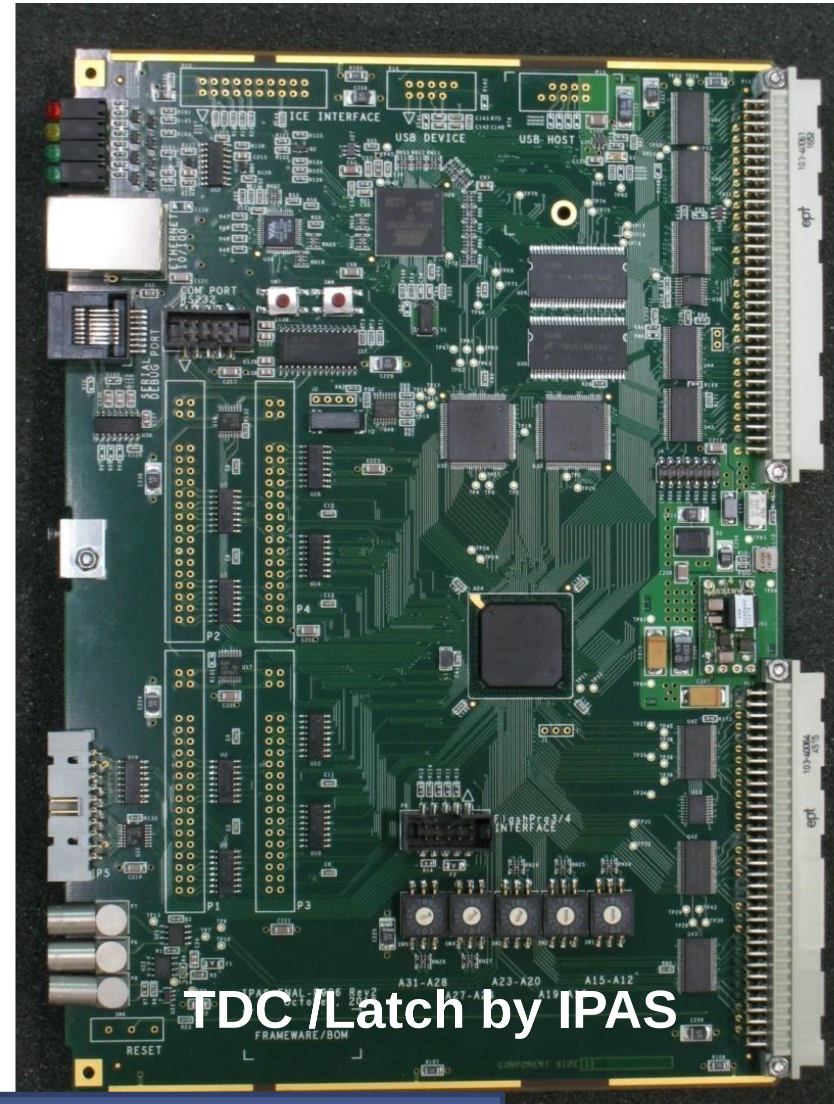
Fermilab NM4/KTeV Hall



Readout Electronics

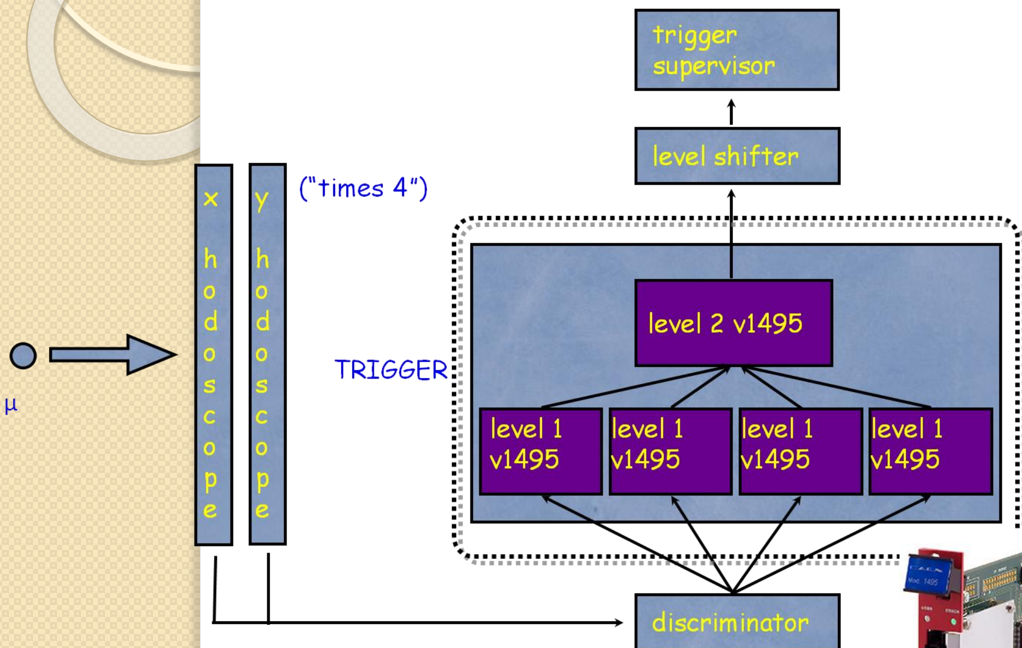

PreAmp by FNAL


PreAmp by IPAS


TDC /Latch by IPAS

蘇大順、王素音、張定華、姚錫泓

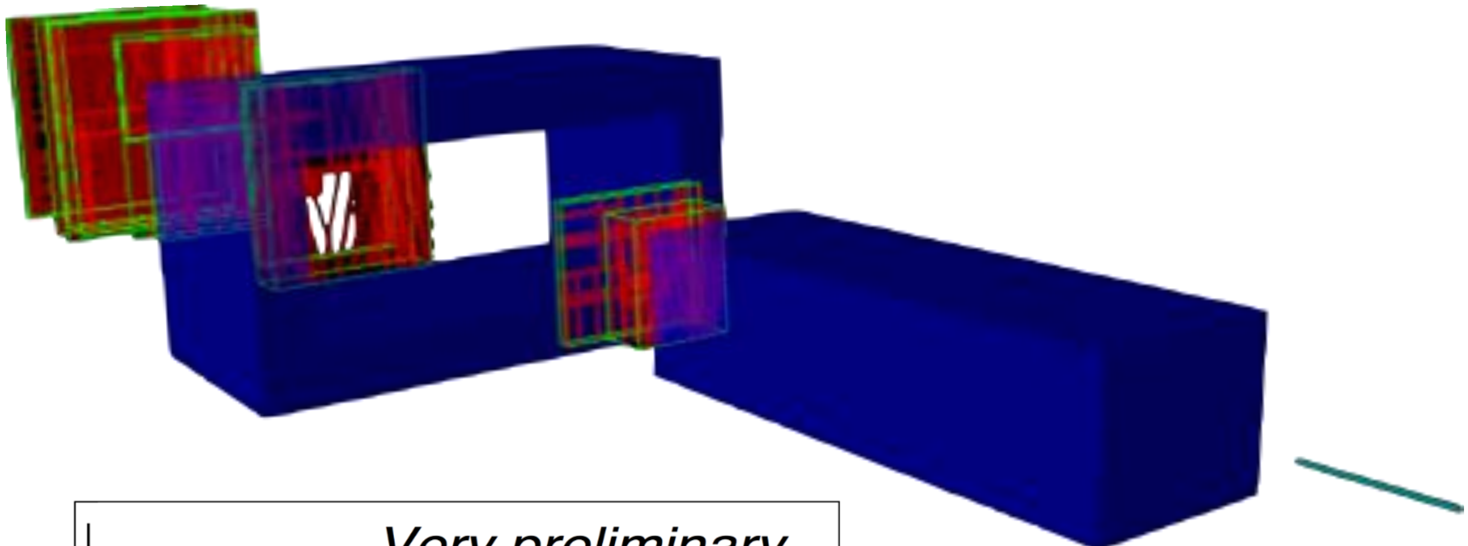
Dimuon Online Trigger

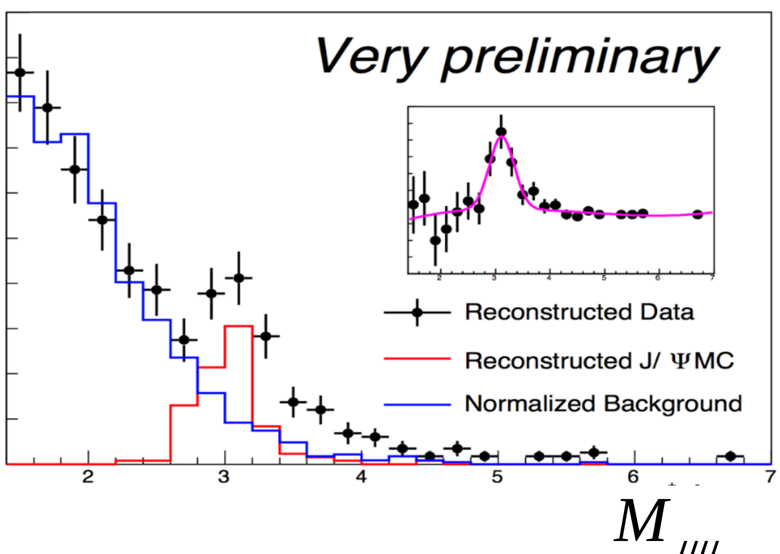


- Online trigger system is composed of 5 CAEN V1495 FPGA modules.
- Without deadtime, the decision of a di-muon trigger or a single-muon trigger can be made within 200 ns, based on the input of 400 channels of the four hodoscopes.

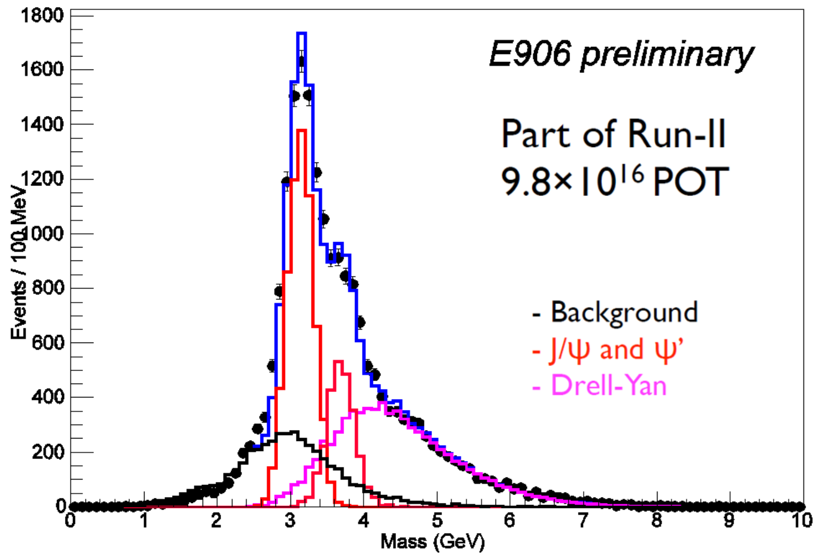
許軒豪、張定華、王素音

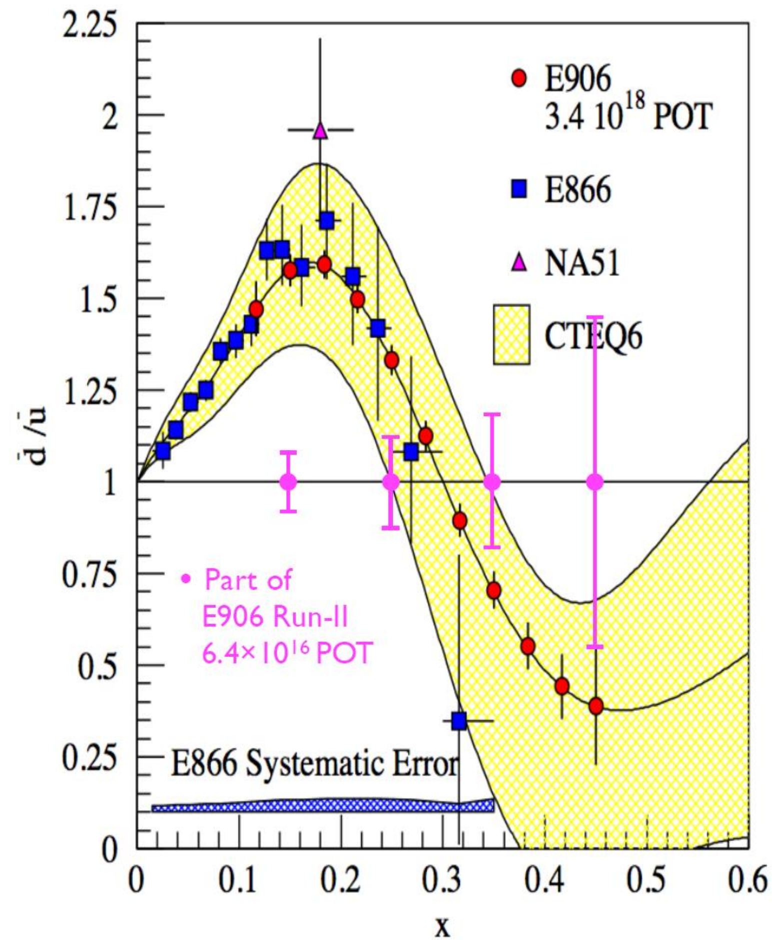
E906 Run 1
(March – April, 2012)



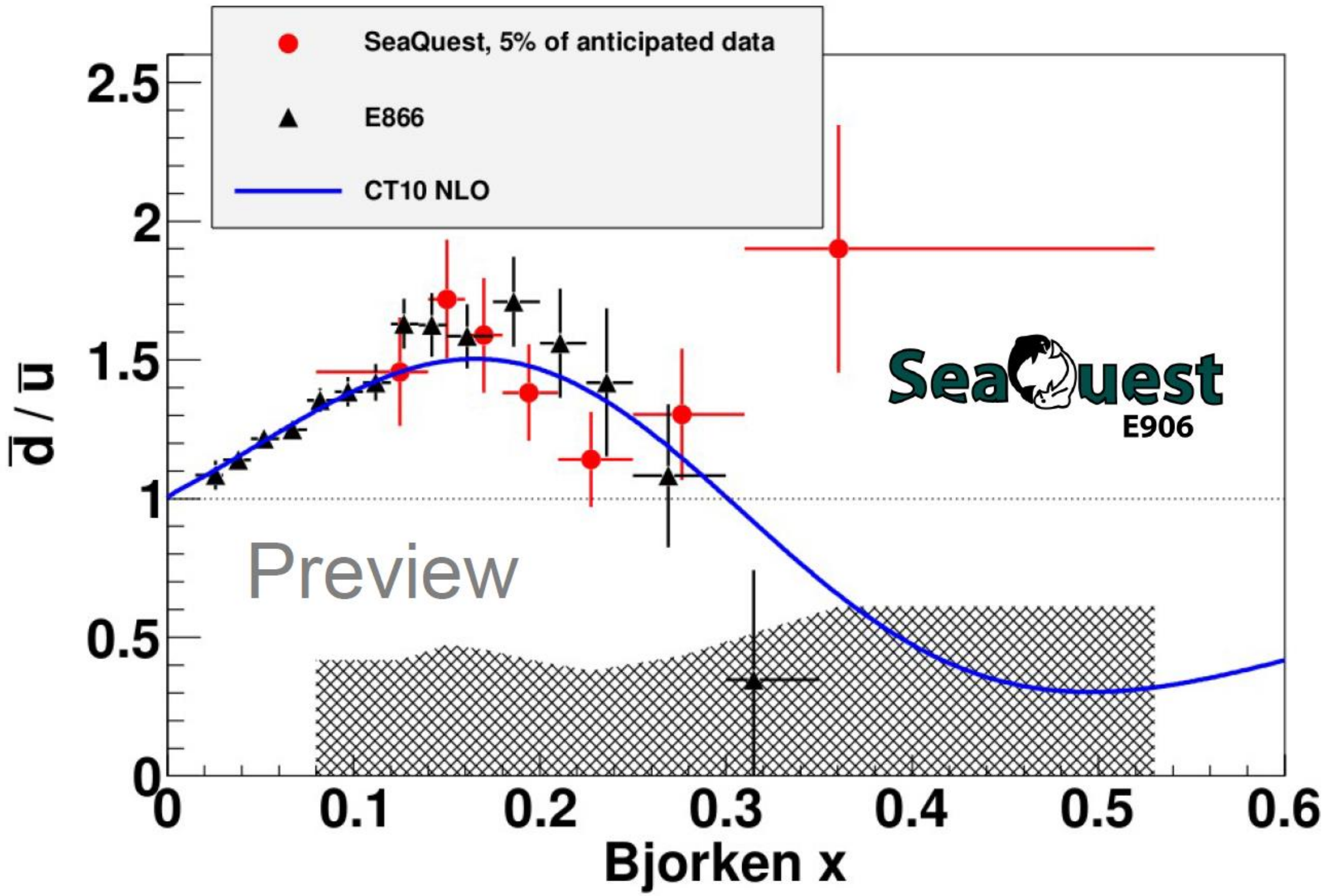


E906 Run 2
(Nov, 2013 – August, 2014)

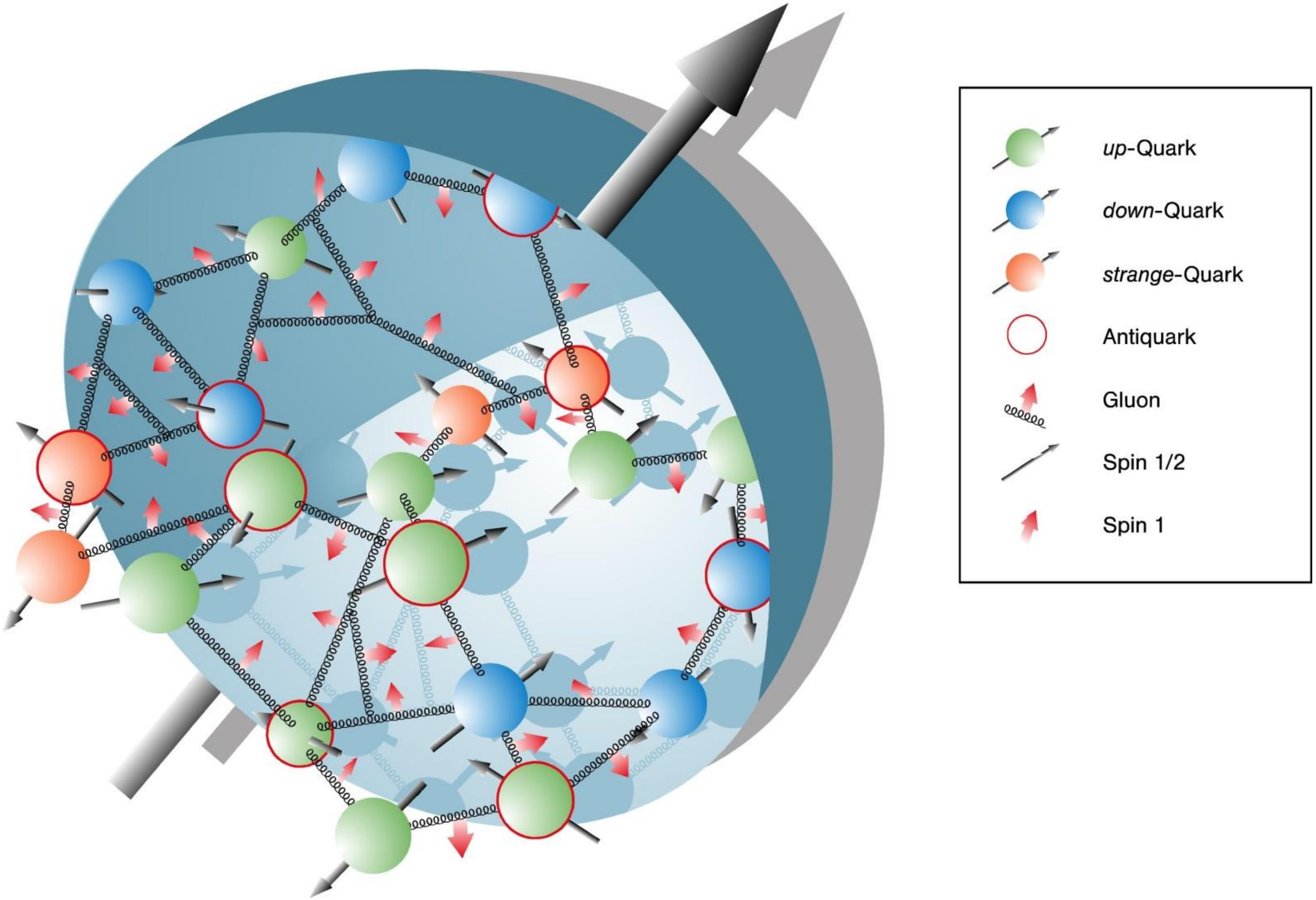




Preliminary Results of $\bar{d}/\bar{u}(x)$



Origin of Proton Spin



High energy spin experiments

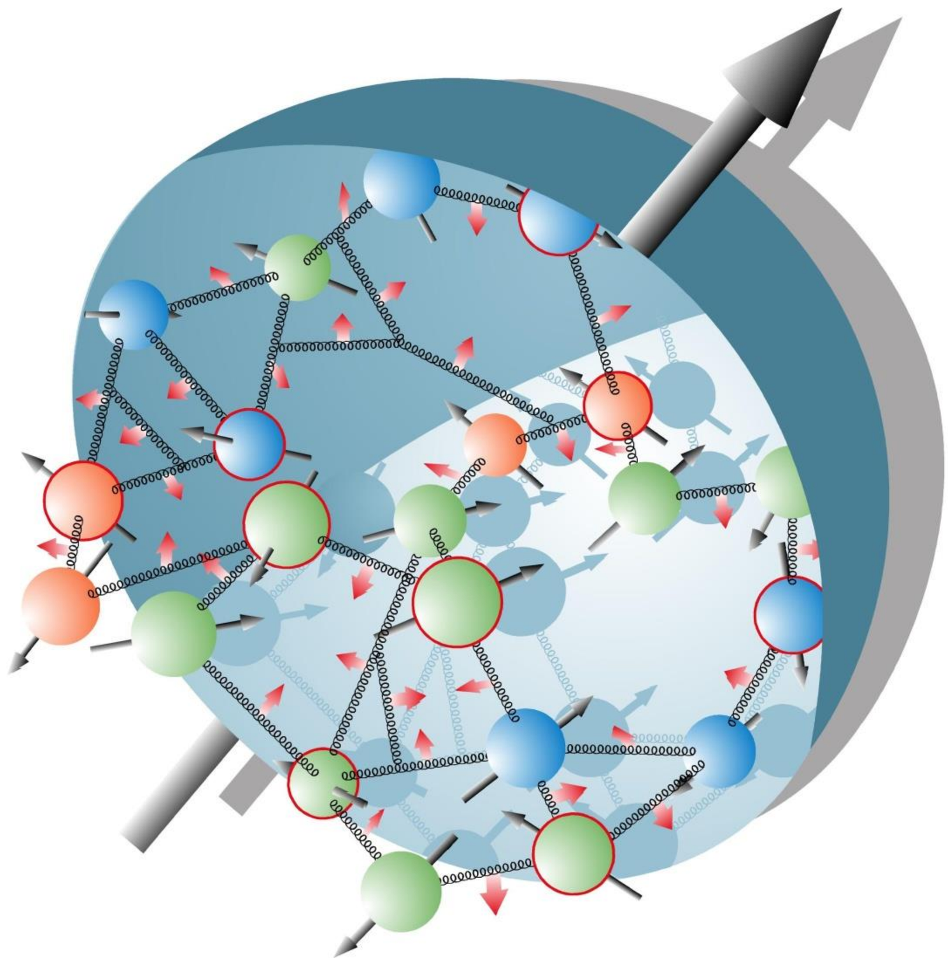
C.A. Aidala, S.D. Bass, D. Hasch, G.K. Mallot, Rev. Mod. Phys. 85, 655–691 (2013)

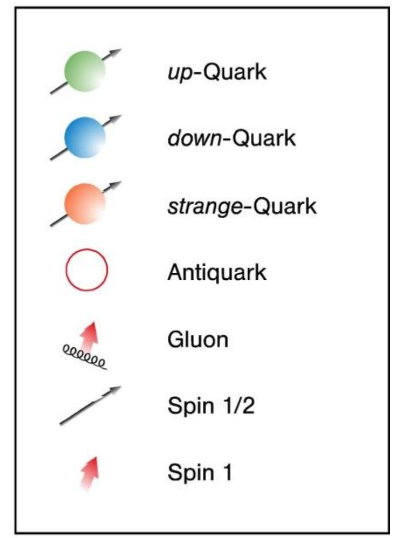
Experiment	Year	Beam	Target	Energy (GeV)	Q^2 (GeV^2)	x
Completed experiments						
SLAC – E80, E130	1976–1983	e^-	H-butanol	$\lesssim$23	1–10	0.1–0.6
SLAC – E142/3	1992–1993	e^-	NH_3, ND_3	$\lesssim$ 30	1–10	0.03–0.8
SLAC – E154/5	1995–1999	e^-	NH_3, ^{6}LiD, ^{3}He	$\lesssim$ 50	1–35	0.01–0.8
CERN – EMC	1985	μ^+	NH_3	100, 190	1–30	0.01–0.5
CERN – SMC	1992–1996	μ^+	H/D-butanol, NH_3	100, 190	1–60	0.004–0.5
FNAL E581/E704	1988–1997	p	p	200	$\sim$ 1	$0.1 < x_F < 0.8$
Analyzing and/or Running						
DESY – HERMES	1995–2007	e^+, e^-	H, D, ^{3}He	$\sim$ 30	1–15	0.02–0.7
CERN – COMPASS	2002–2012	μ^+	NH_3, ^{6}LiD	160, 200	1–70	0.003–0.6
JLab6 – Hall A	1999–2012	e^-	^{3}He	$\lesssim$ 6	1–2.5	0.1–0.6
JLab6 – Hall B	1999–2012	e^-	NH_3, ND_3	$\lesssim$ 6	1.-5	0.05–0.6
RHIC – BRAHMS	2002–2006	p	p (beam)	2× (31–100)	$\sim$ 1–6	$-0.6 < x_F < 0.6$
RHIC – PHENIX, STAR	2002+	p	p (beam)	2× (31–250)	$\sim$ 1–400	$\sim$ 0.02–0.4
Approved future experiments (in preparation)						
CERN – COMPASS–II	2014+	μ^+, μ^-	unpolarized H_2	160	$\sim$ 1–15	$\sim$ 0.005–0.2
		π^-	NH_3	190		$-0.2 < x_F < 0.8$
JLab12 – HallA/B/C	2014+	e^-	HD, NH_3, ND_3, ^{3}He	$\lesssim$12	$\sim$ 1–10	$\sim$ 0.05–0.8

Pacific Spin 2015

http://www.phys.sinica.edu.tw/PacSPIN2015

Origin of Proton Spin





Quark spin(~30%)

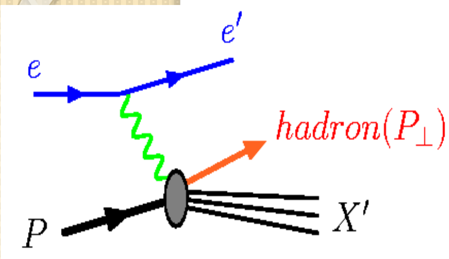
Gluon spin(~0)

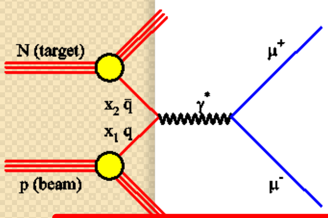
$$\frac{1}{2}\Big|^{proton} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q$$

Quark orbital angular momentum(?)

$$\overrightarrow{L_Z} = \overrightarrow{r_T} \times \overrightarrow{P_T}$$

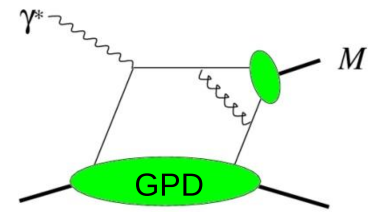
Parton Distributions of Protons





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

Ji, PRL91,062001(2003)



$\int d\vec{r}$

$\int e^{i\vec{q}\cdot\vec{r}} d\vec{r} d\vec{k}_T$

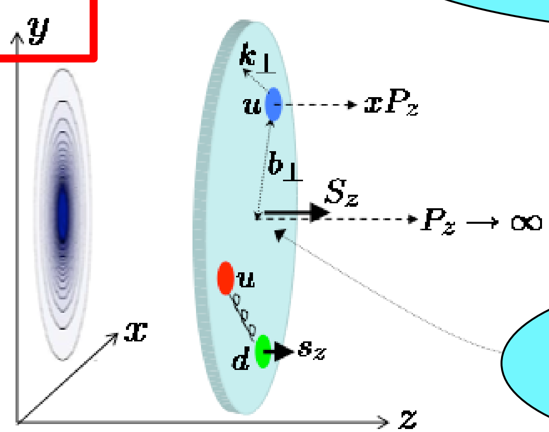
$\xi = q^z / 2E_q, \; t = -\vec{q}^2$

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

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

$\int d\vec{k}_T$

$\int dx$

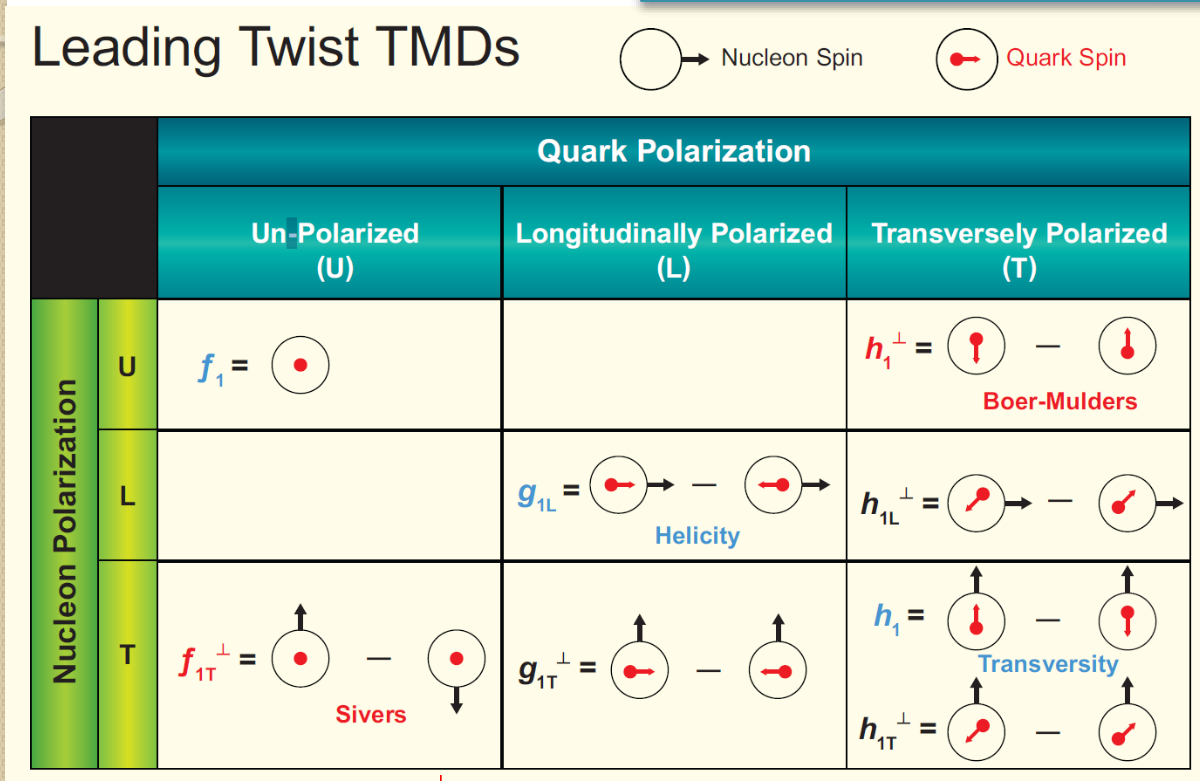


PDF
$f(x)$

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

Transverse momentum dependent (TMD) PDF

Transverse momentum $\overrightarrow{P_T}$



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

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

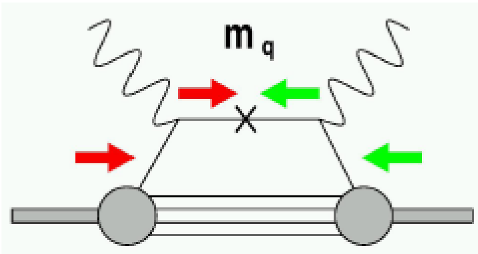
Sivers function $f_{1T}^\perp(x, k_T)$

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

sensitive to orbital angular momentum

arXiv:1212.1701

How to measure SSAs?



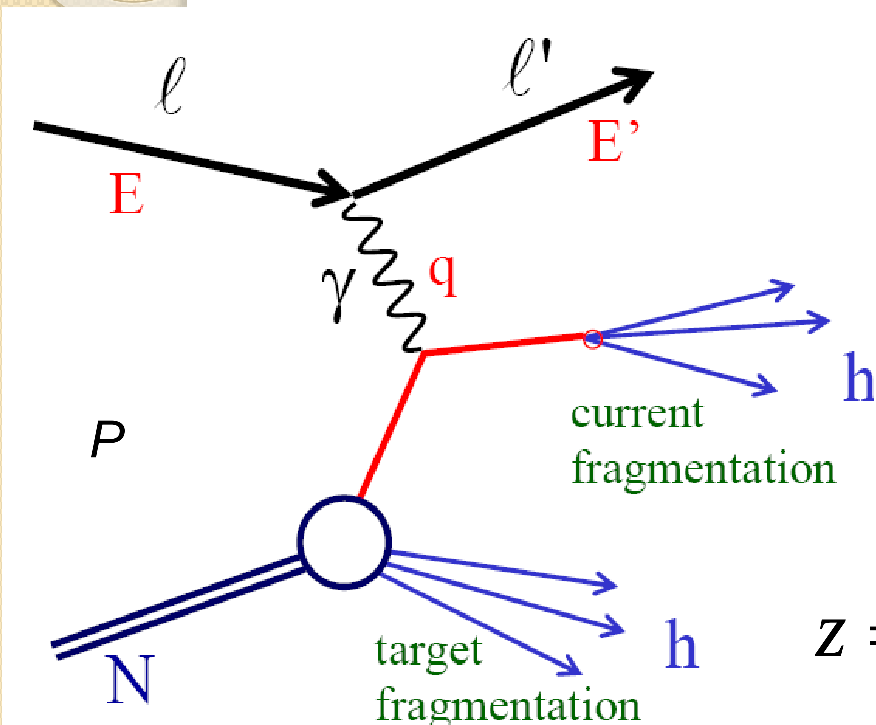
Chiral-odd → not accessible in DIS

Require another chiral-odd object

- **Semi-Inclusive DIS**: ambiguity associated with fragmentation process
  - Single-hadron (Collins fragmentation function, Sivers function)
  - Two hadrons (Interference fragmentation function)
  - Vector meson polarization
  - Λ – polarization
- **Drell-Yan**: small cross sections but free from fragmentation
- **Proton-proton collision**: inclusive single-hadron, prompt jet, prompt photon production

Semi-Inclusive DIS (SIDIS)

$$q^2 = (l - l')^2 = -Q^2$$



$$W^2 = (P + q)^2$$

Bjorken scaling variable

$$x = Q^2 / (2P \cdot q)$$

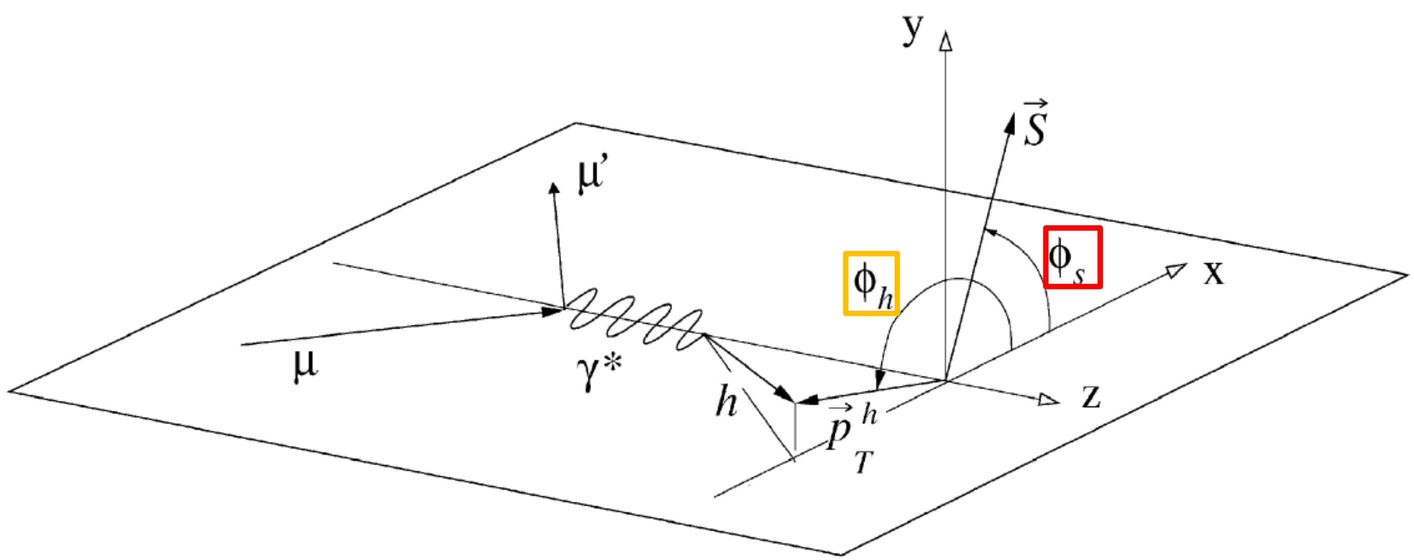
Energy fraction carried by γ

$$y = (P \cdot q) / (P \cdot l) = (E - E') / E$$

Energy fraction carried by h

$$z = (P \cdot P_h) / (P \cdot q) = E_h / (E - E')$$

Collins and Sivers Asymmetries in SIDIS



$$A_T^h \equiv \frac{d\sigma(\vec{S}_\perp) - d\sigma(-\vec{S}_\perp)}{d\sigma(\vec{S}_\perp) + d\sigma(-\vec{S}_\perp)} = \left|\vec{S}_\perp\right| \cdot \left[D_{NN} \cdot A_{Coll} \cdot \sin(\phi_h + \phi_S - \pi) + A_{Siv} \cdot \sin(\phi_h - \phi_S) \right]$$

Collins asymmetry

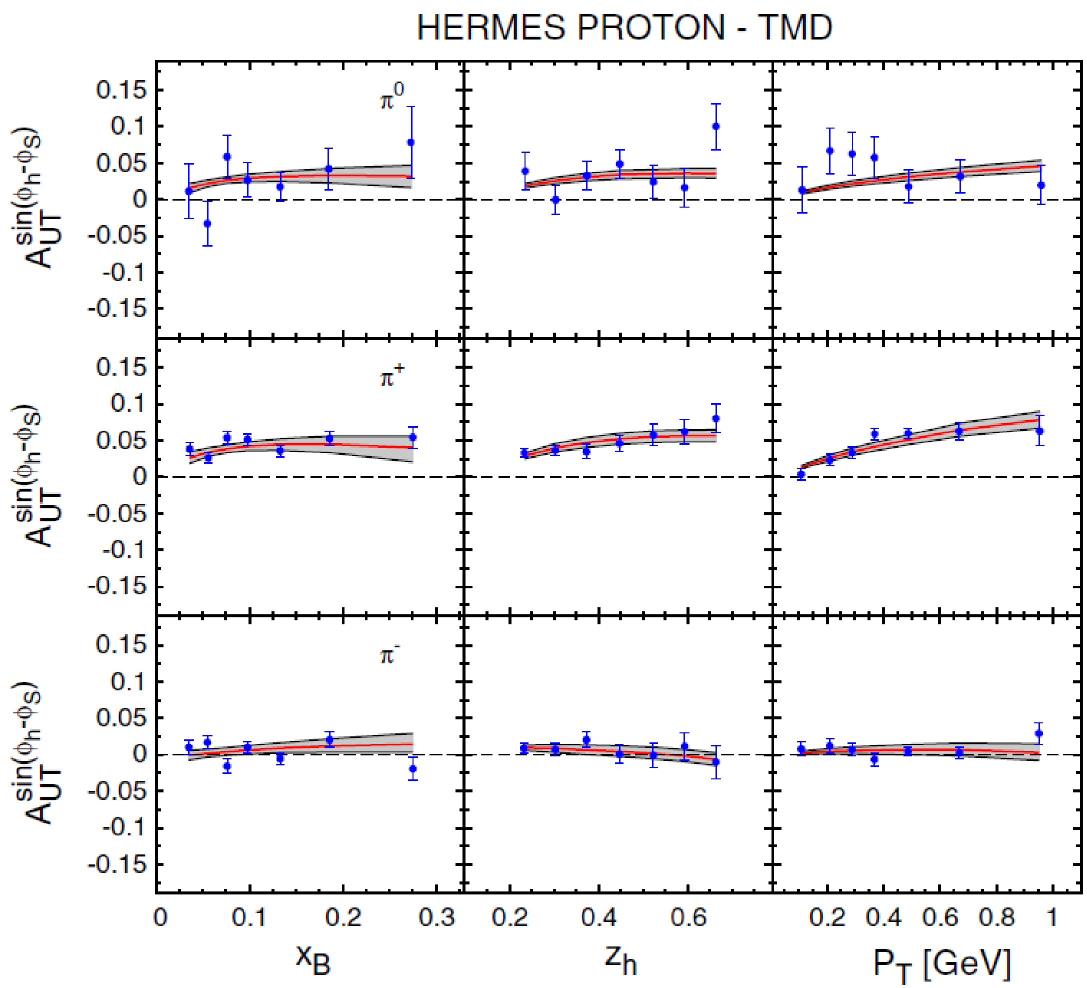
$$A_{Coll} = \frac{\Sigma_q \left[e_q^2 \cdot \Delta_{Tq}(x) \cdot \Delta_T^0 D_q^h(z, p_T^h) \right]}{\Sigma_q \left[e_q^2 \cdot q(x) \cdot D_q^h(z, p_T^h) \right]}$$

Sivers asymmetry

$$A_{Siv} = \frac{\Sigma_q \left[e_q^2 \cdot \Delta_{Tq}^0(x, p_T^h / z) \cdot D_q^h(z, p_T^h) \right]}{\Sigma_q \left[e_q^2 \cdot q(x, p_T^h / z) \cdot D_q^h(z) \right]}$$

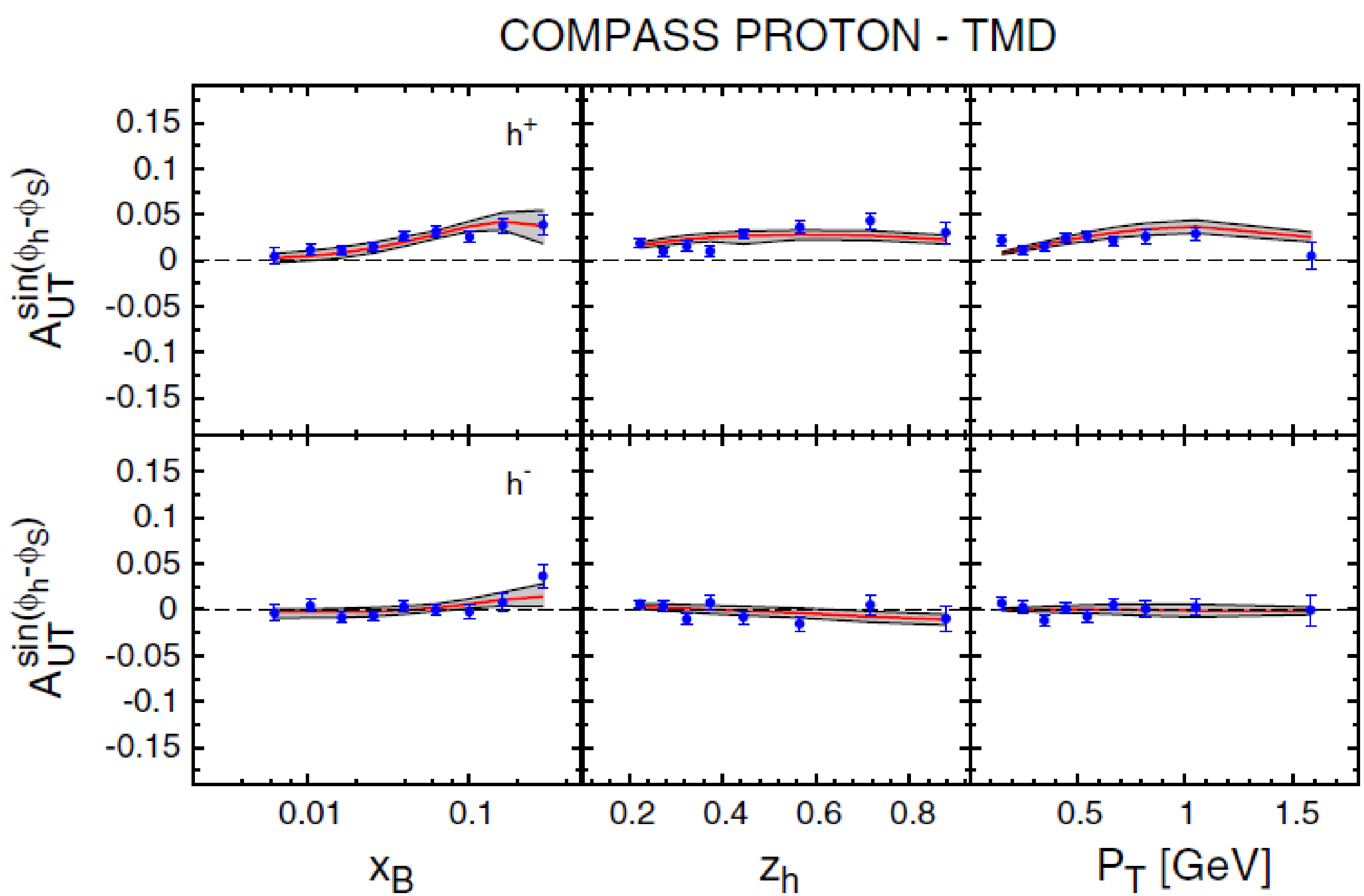
Global Analysis of Sivers Functions from SIDIS

M. Anselmino et al., PRD 86 (2012) 014028



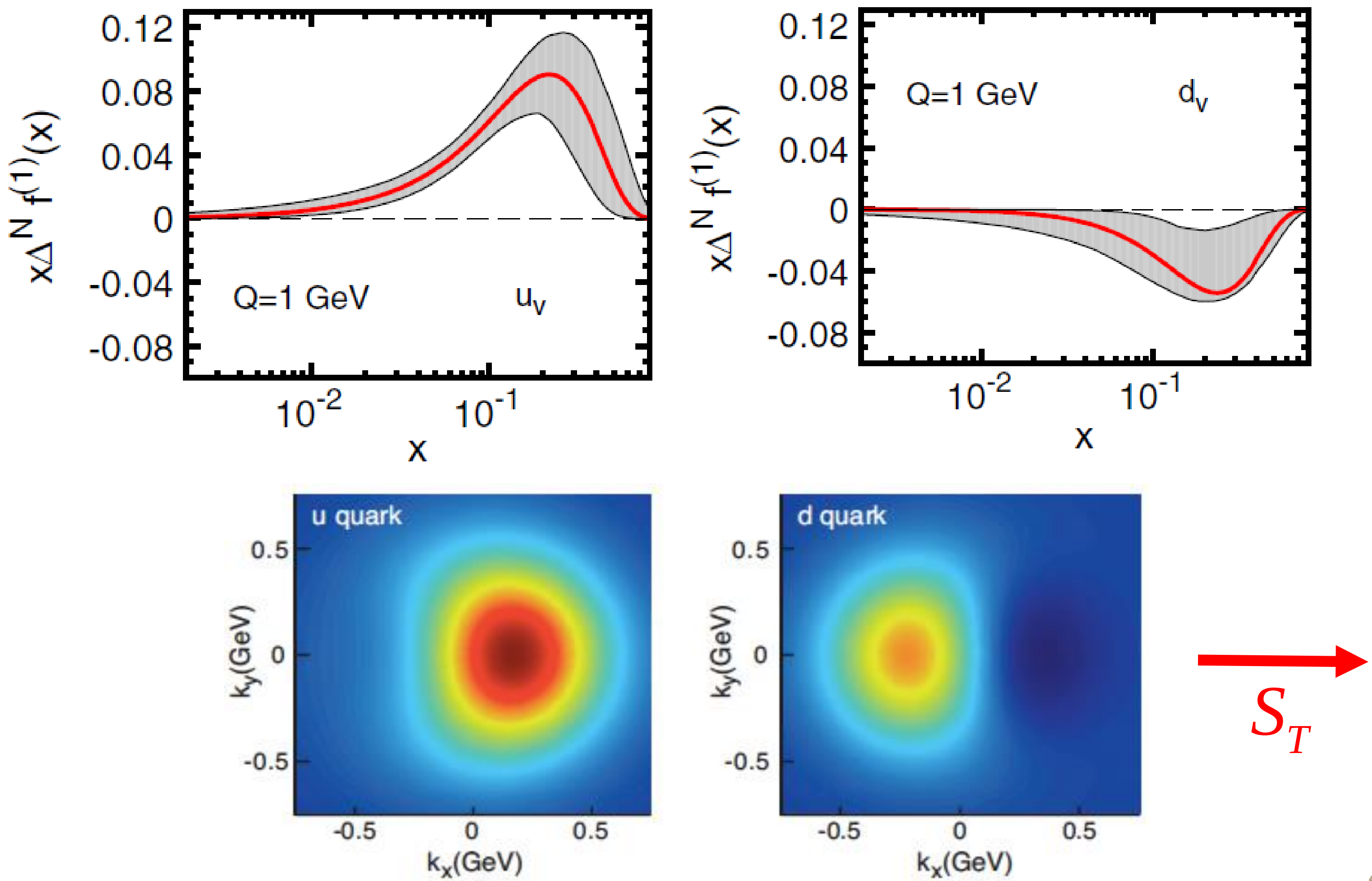
Global Analysis of Sivers Functions from SIDIS

M. Anselmino et al., PRD 86 (2012) 014028



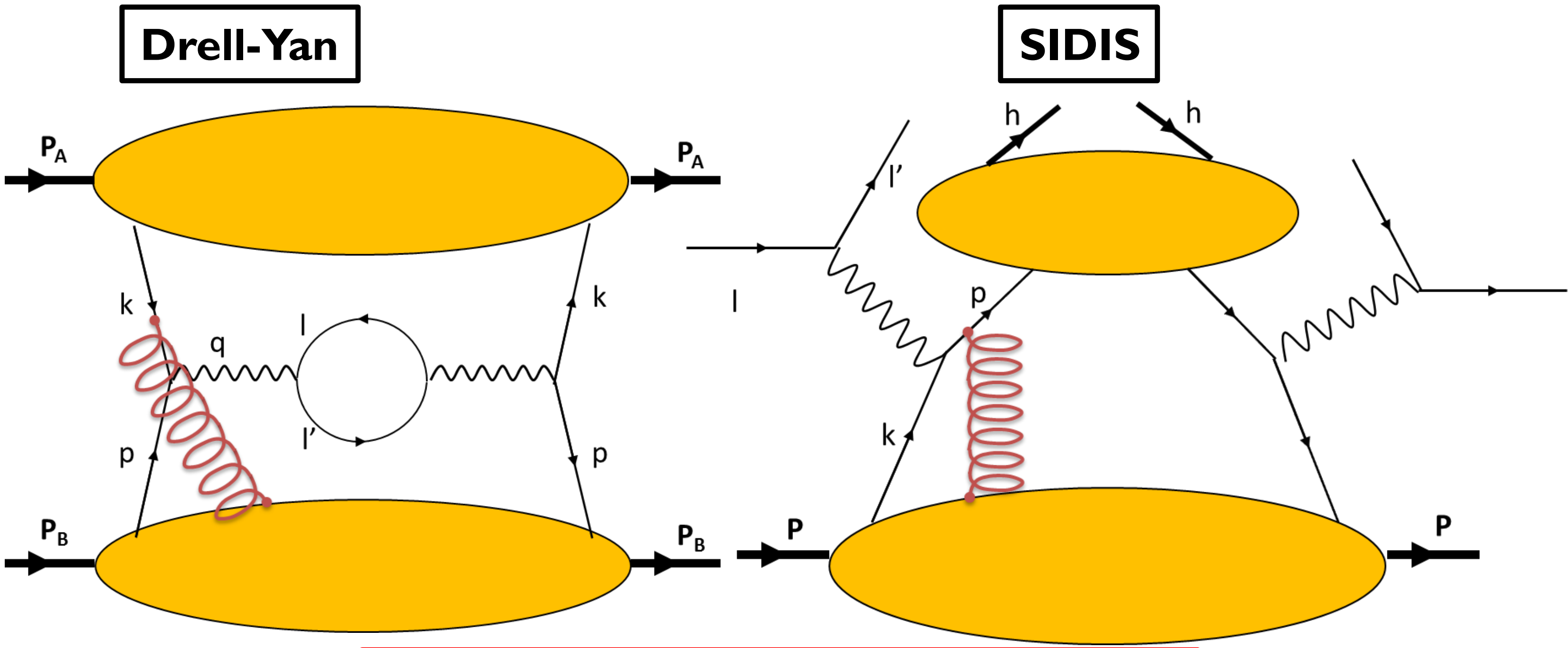
Global Analysis of Sivers Functions from SIDIS

M. Anselmino et al., PRD 86 (2012) 014028



Non-Universality of Sivers Functions

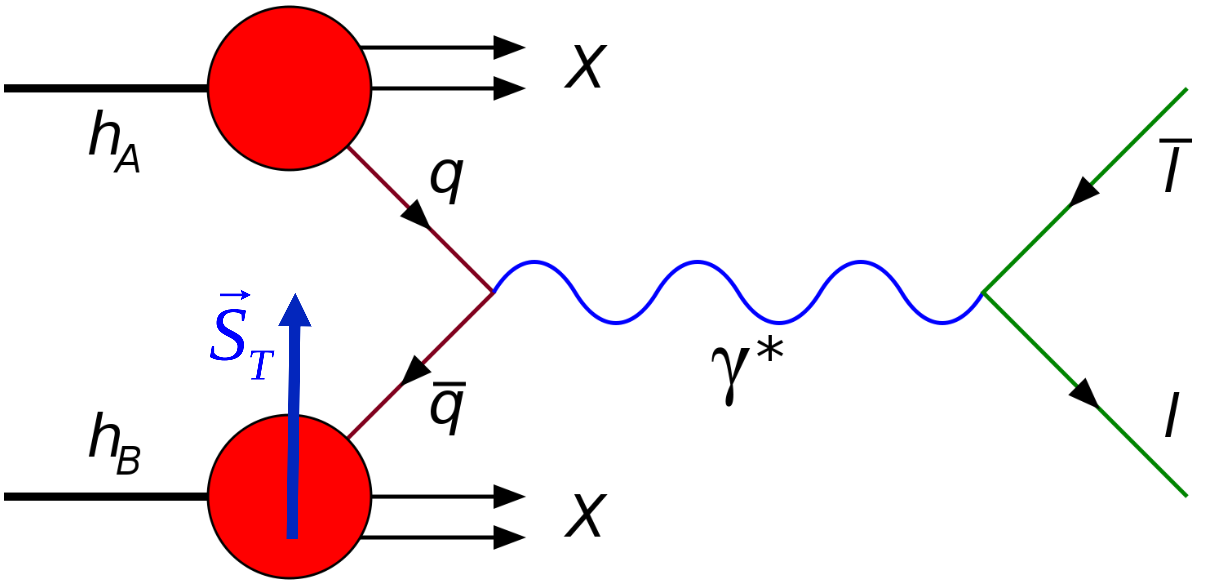
J.C. Collins, Phys. Lett. B 536 (2002) 43; A.V. Belitsky, X. Ji, F. Yuan, Nucl. Phys. B 656 (2003) 165; D. Boer, P.J. Mulders, F. Pijlman, Nucl. Phys. B 667 (2003) 201; Z.B. Kang, J.W. Qiu, Phys. Rev. Lett. 103 (2009) 172001



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

- 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.***

Transversely-polarized Drell-Yan experiments !!!



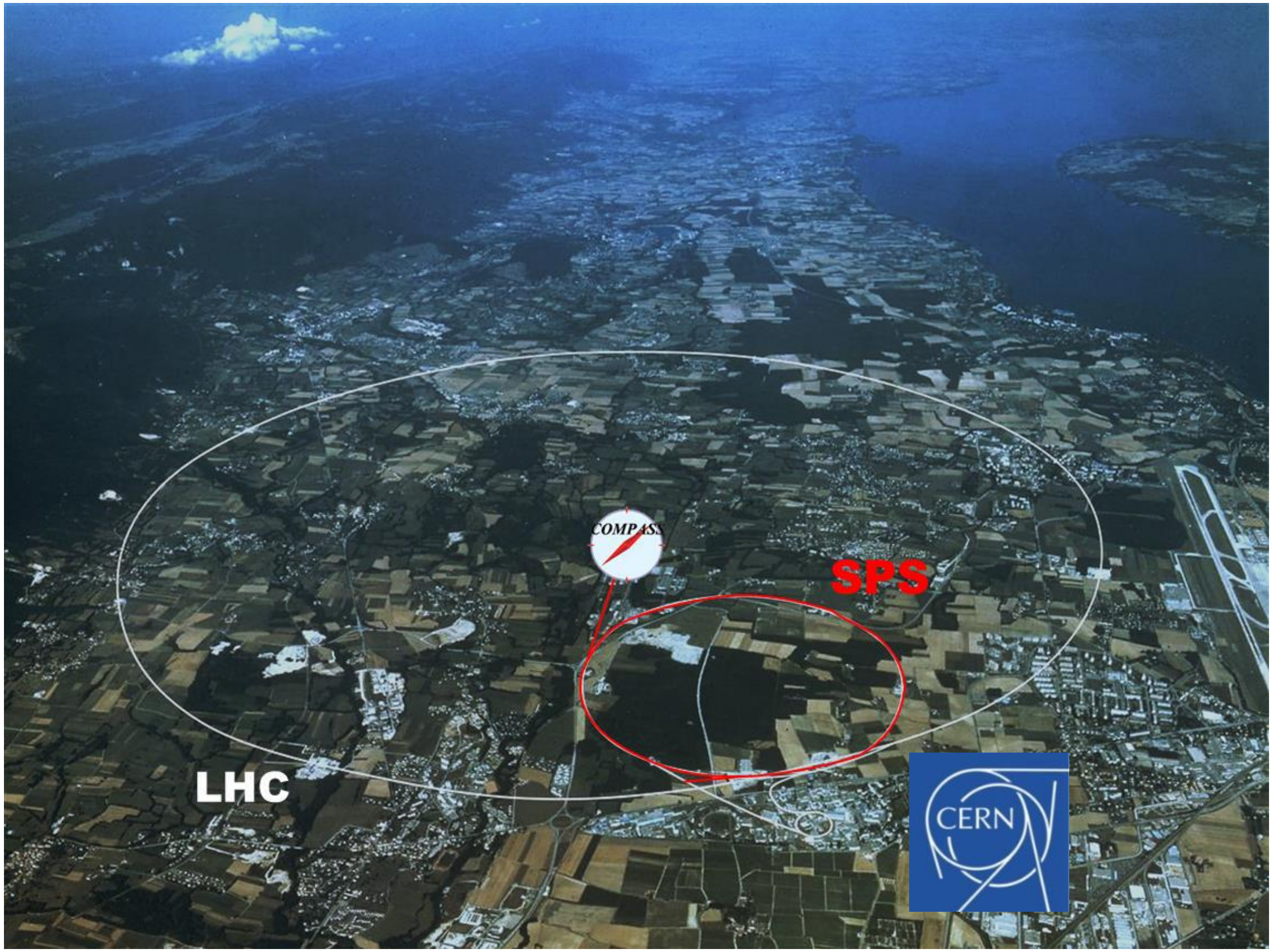
Planned Polarized Drell-Yan Experiments

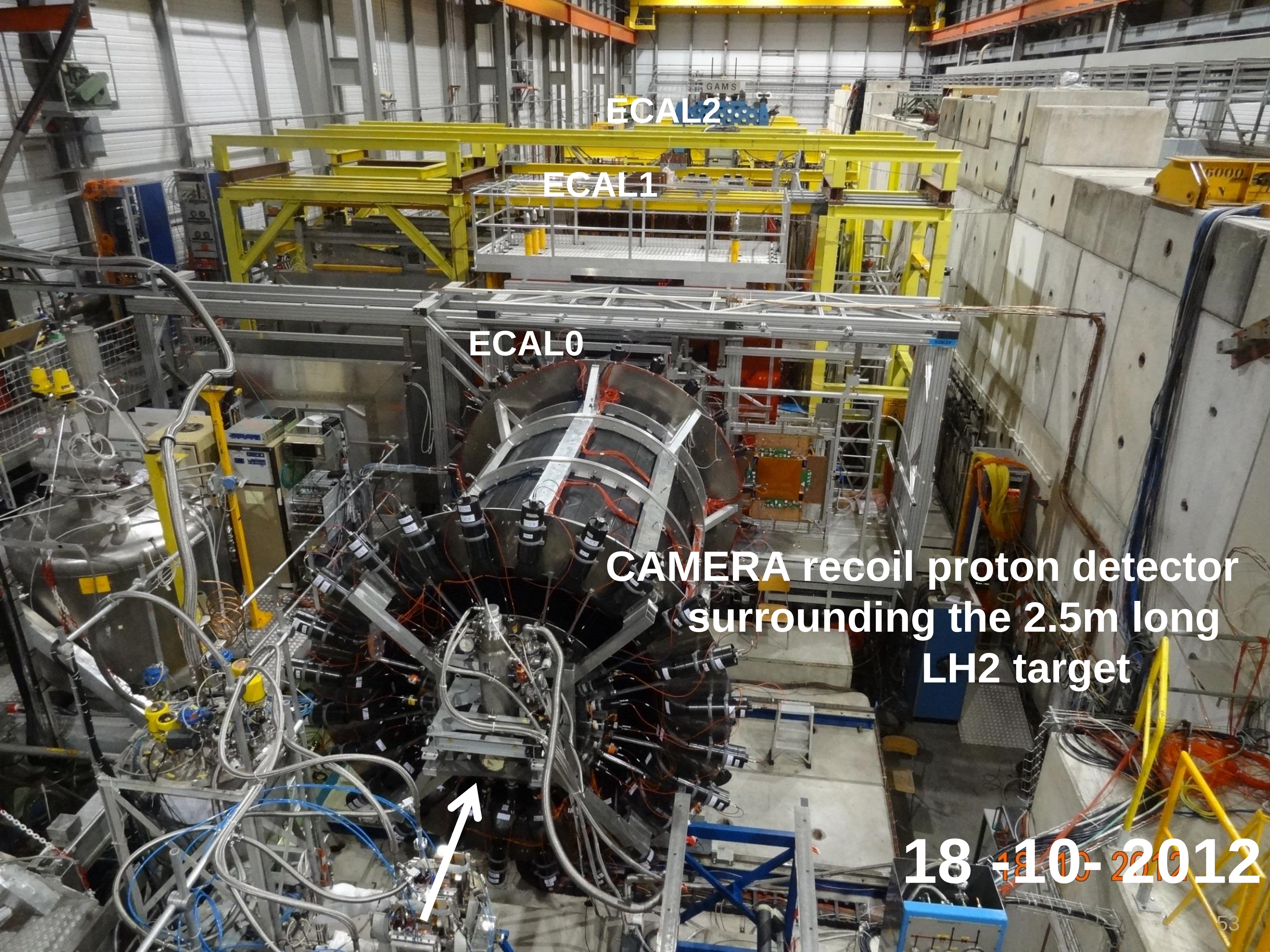
experiment	particles	energy	x_1 or x_2	luminosity	timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s}$ = 17.4 GeV	$x_t = 0.2 - 0.3$	2×10^{33} cm^{-2} s^{-1}	2014, 2018
PAX (GSI)	$p^{\uparrow} + p_{bar}$	collider $\sqrt{s}$ = 14 GeV	$x_b = 0.1 - 0.9$	2×10^{30} cm^{-2} s^{-1}	>2017
PANDA (GSI)	$p_{bar} + p^{\uparrow}$	15 GeV $\sqrt{s}$ = 5.5 GeV	$x_t = 0.2 - 0.4$	2×10^{32} cm^{-2} s^{-1}	>2016
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 20 GeV	$x_b = 0.1 - 0.8$	1×10^{30} cm^{-2} s^{-1}	>2018
PHENIX (RHIC)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 500 GeV	$x_b = 0.05 - 0.1$	2×10^{32} cm^{-2} s^{-1}	>2018
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	$x_b = 0.25 - 0.4$	2×10^{33} cm^{-2} s^{-1}	>2018
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	$x_b = 0.25 - 0.4$	6×10^{34} cm^{-2} s^{-1}	>2018
FNAL Pol tgt (E1039)	$p + p^{\uparrow}$	120 GeV $\sqrt{s}$ = 15 GeV	$x_t = 0.1 - 0.45$	3.4×10^{35} cm^{-2} s^{-1}	2016
FNAL Pol beam (E1027)	$p^{\uparrow} + p$	120 GeV $\sqrt{s}$ = 15 GeV	$x_b = 0.35 - 0.85$	2×10^{35} cm^{-2} s^{-1}	2018

COMPASS Collaboration

(Common Muon and Proton Apparatus for Structure and Spectroscopy)

- 24 institutions from 13 countries – nearly 250 physicists
- Fixed-target experiment at SPS north area
- Physics programs:
  - Nucleon spin and partonic structures
  - Hadron spectroscopy




GAMS
ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
18 -10- 2012

COMPASS Setup (Drell-Yan Runs)

Beam:

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

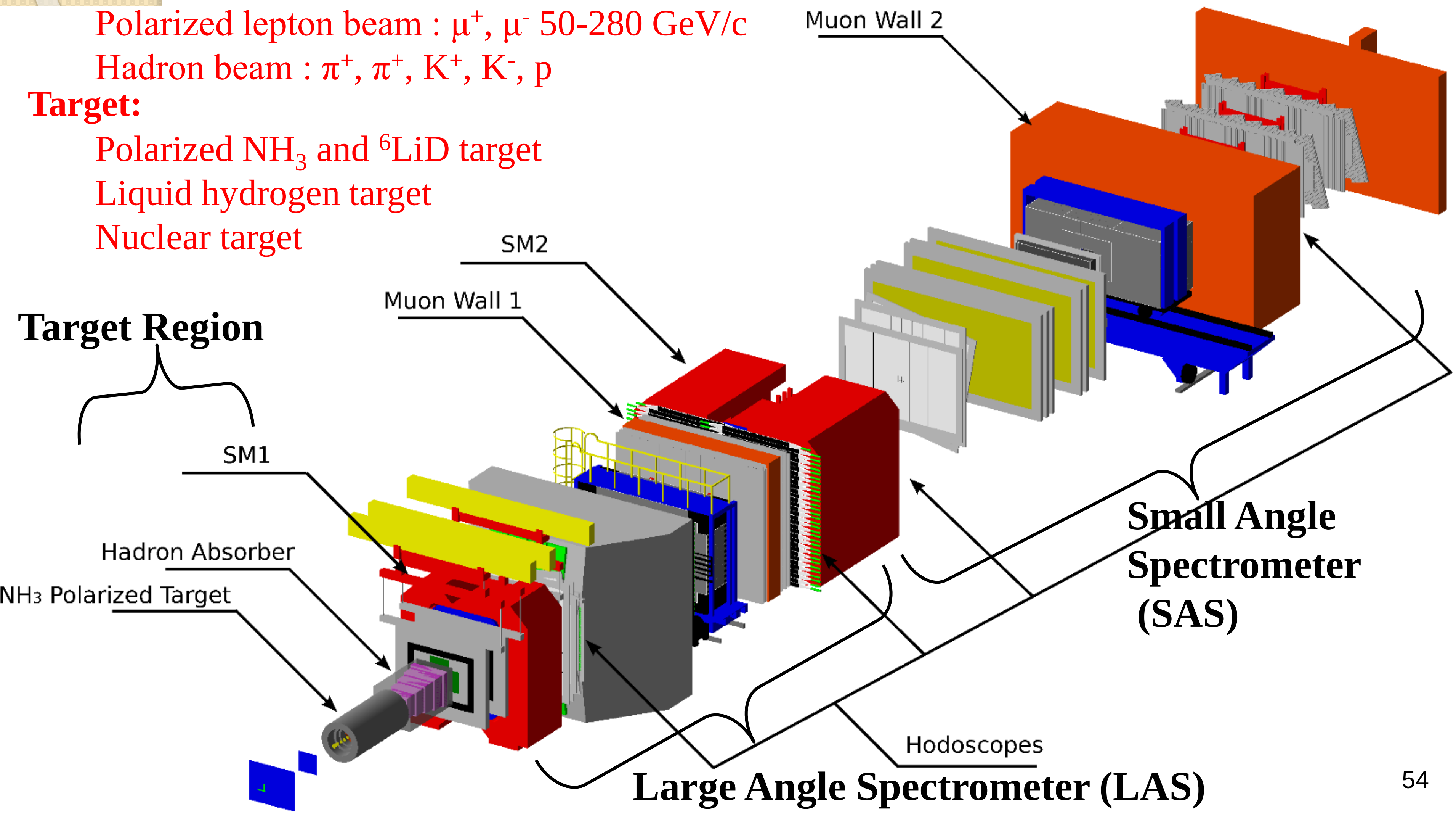
Hadron beam : π^+, π^+, K^+, K^-, p

Target:

Polarized NH_3 and ^6LiD target

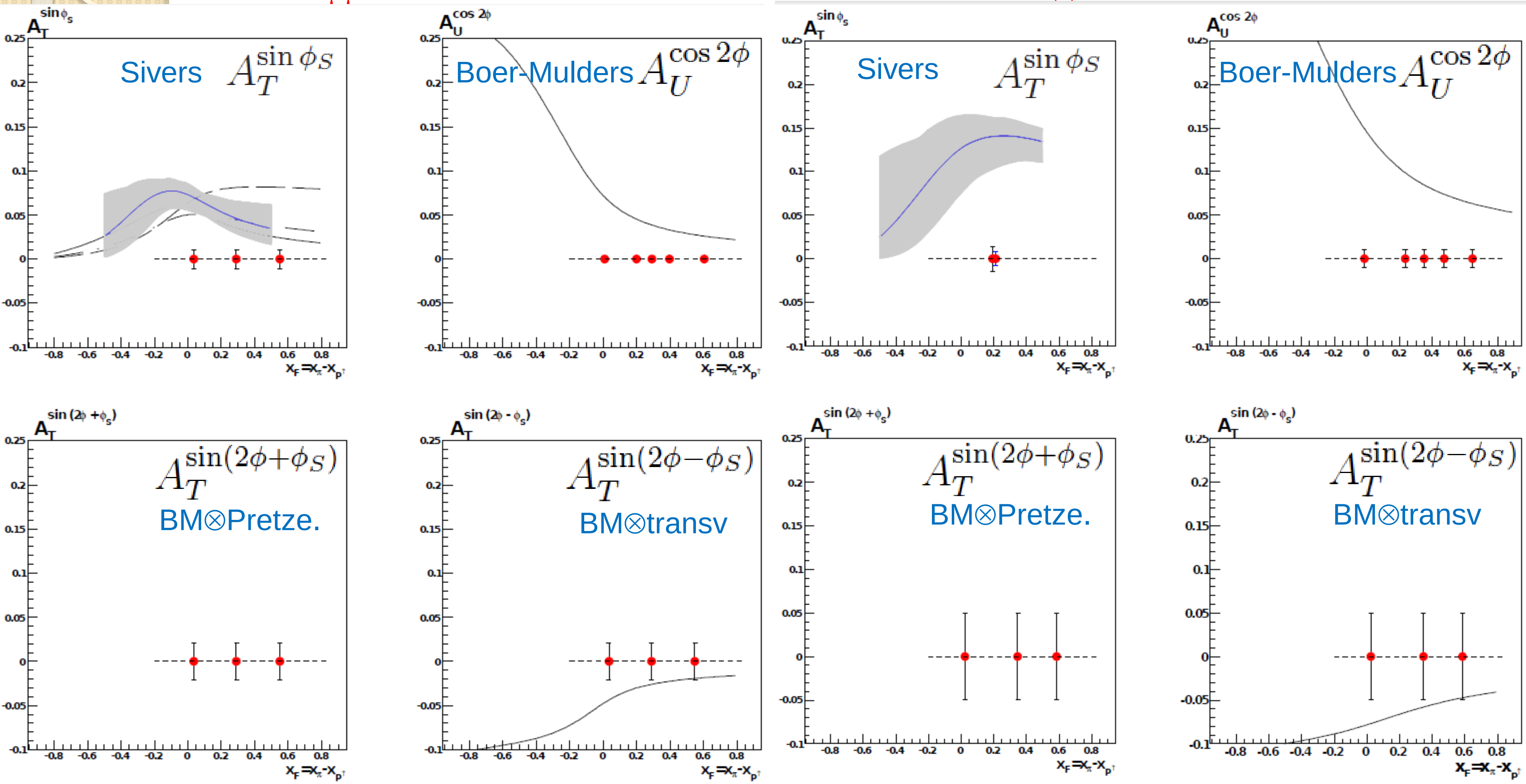
Liquid hydrogen target

Nuclear target



Theoretical Predictions vs. Expected Precision

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

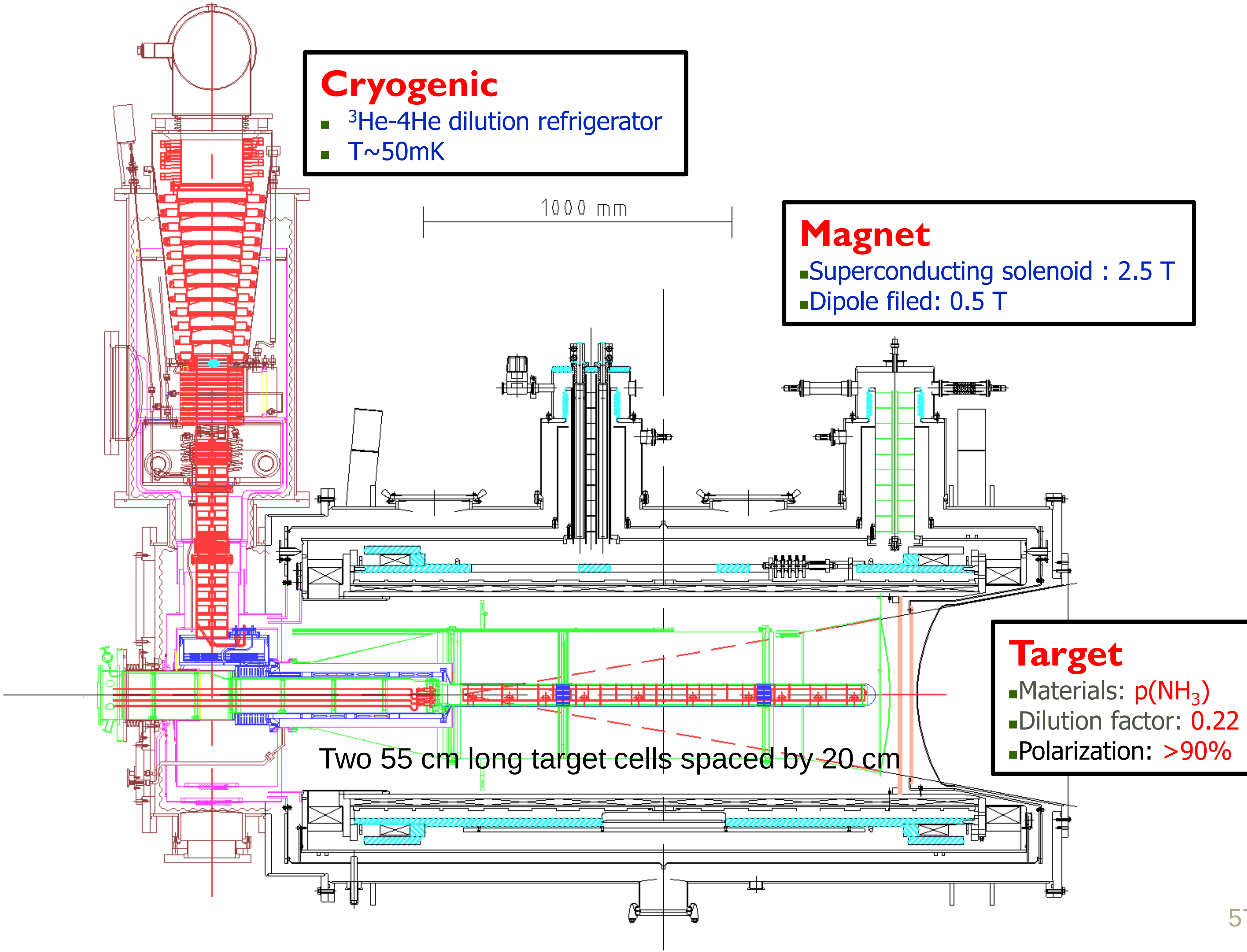


M. Anselmino et. Al, Eur.Phys.J.A39:89-100,2009.
V. Barone et al., Phys. Rept. 359 (2002) 1.
B. Zhang et al., Phys. Rev. D77 (2008) 054011,

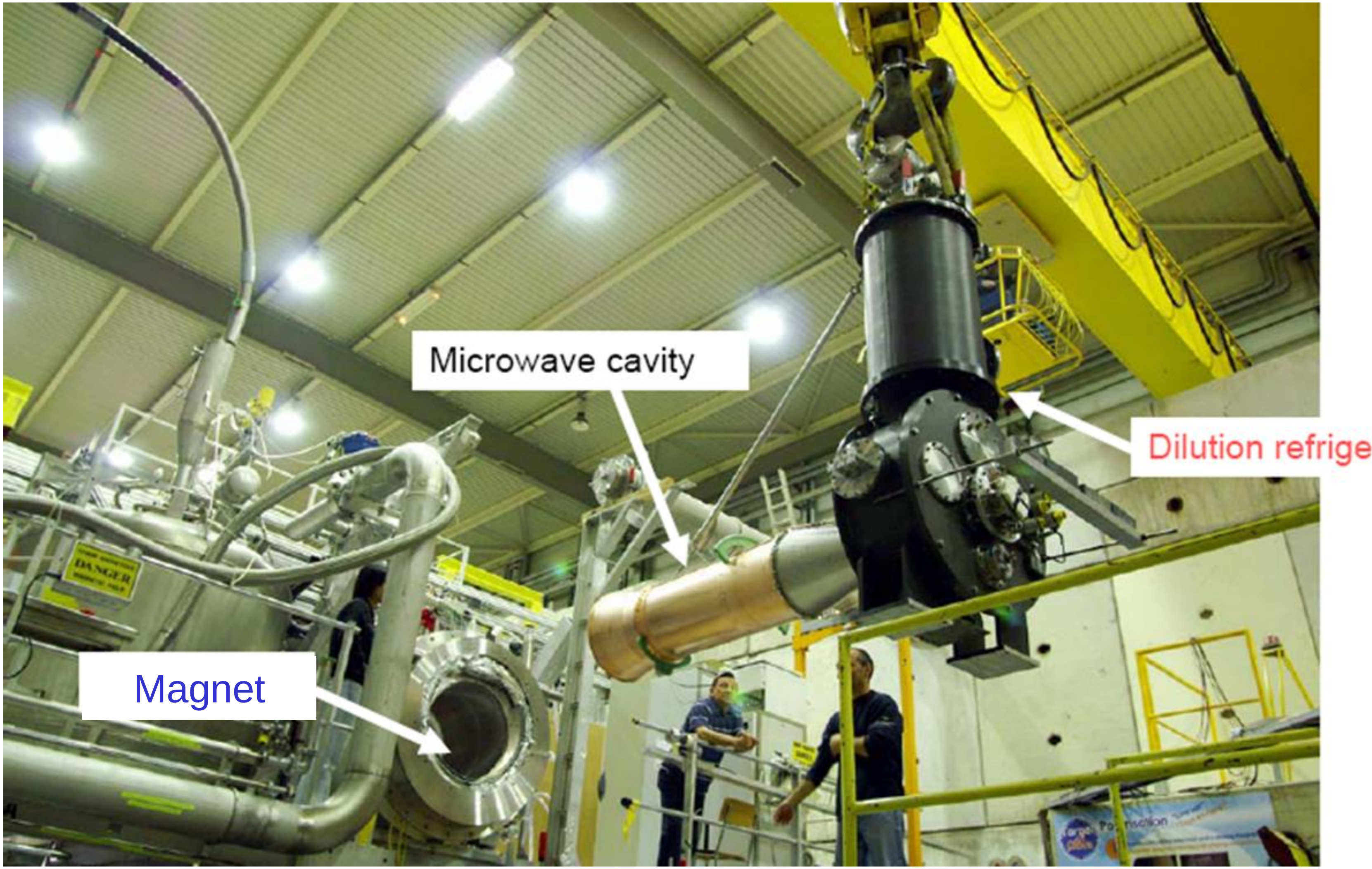
COMPASS Drell-Yan (since 2011)

- Contributions from Taiwan team:
  - Readout electronics of new DC5 chamber:
    朱明禮、林志勳、鄧宇勝、**謝佳諭**
  - Monte-Carlo and feasibility study:
    澤田崇広、**謝佳諭、連昱翔**、姚錫泓
- Schedules:
  - Oct – Dec 2014: commission run.
  - May – Nov 2015: polarized Drell-Yan measurement.

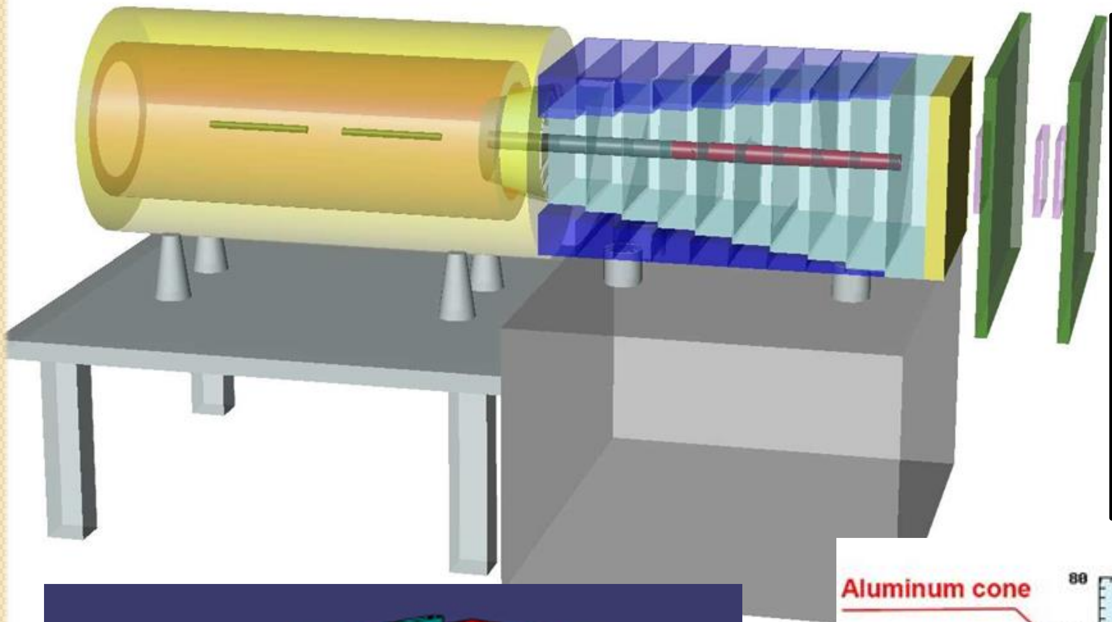
Polarized NH_3 Target



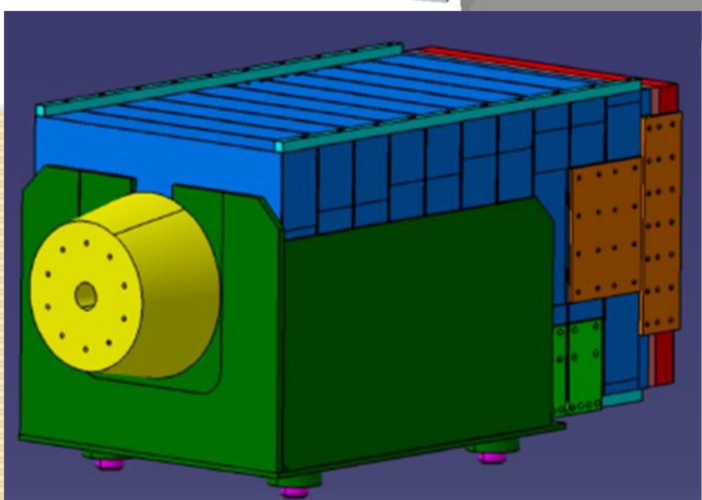
Polarized NH_3 Target

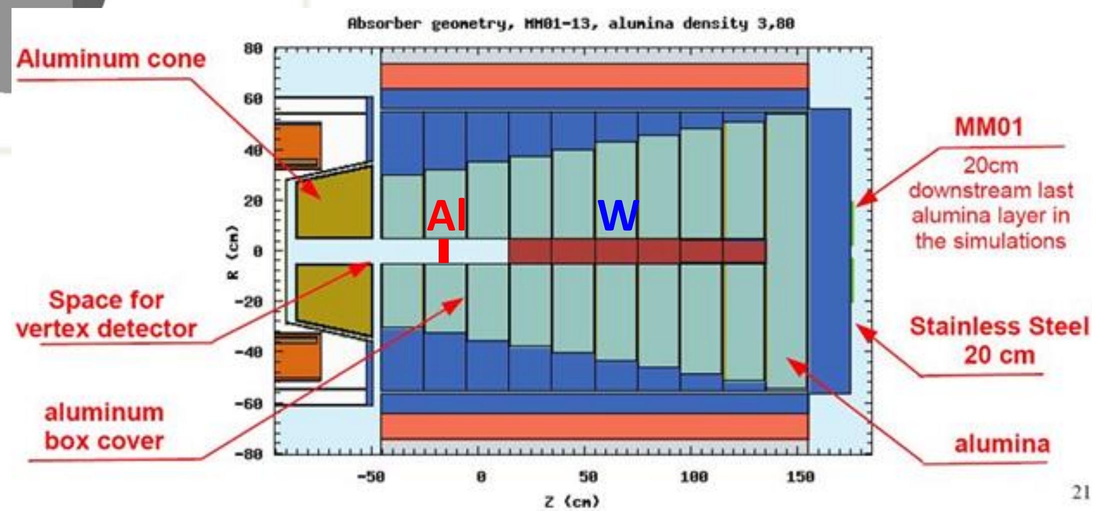


Hadron Absorber & Nuclear Targets

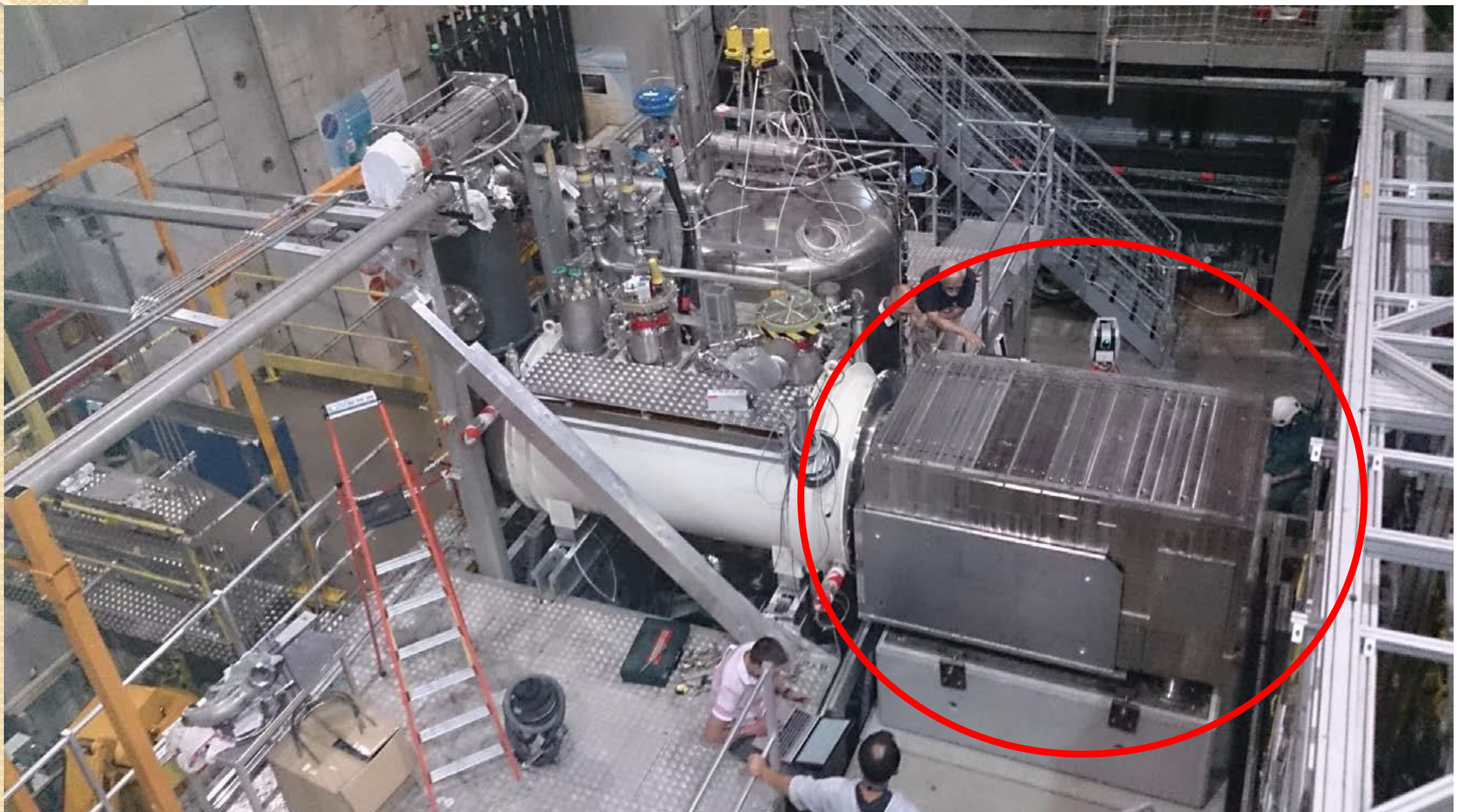


- Absorber: 236 cm long, made of Al_2O_3.
- Beam plug: 120 cm long, made of tungsten.
- Radiation lengths (multiple scattering for μ): $x/X_0 = 33.53$
- Hadronic interaction lengths (stopping power for π): $x/\lambda_{int} = 7.25$
- 7cm Al target

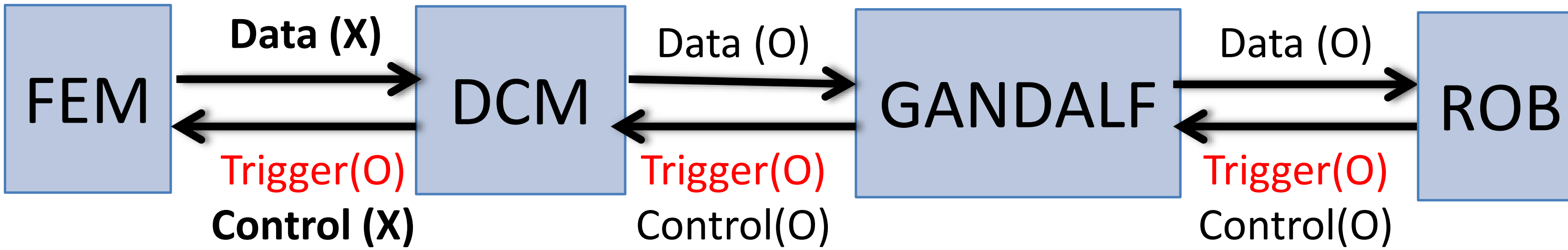


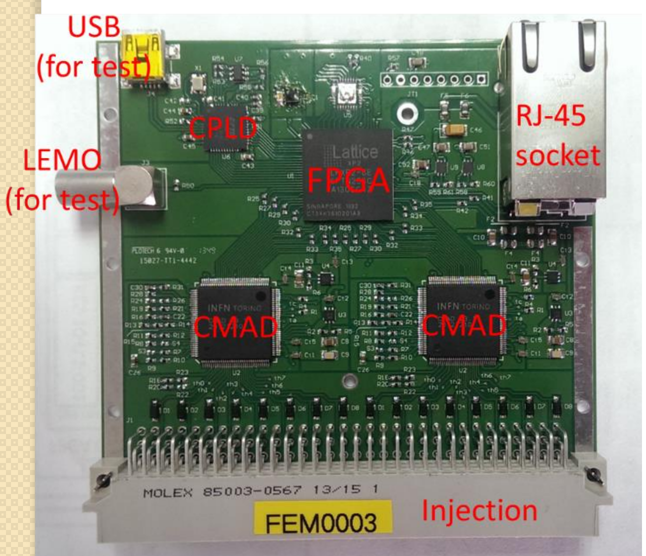


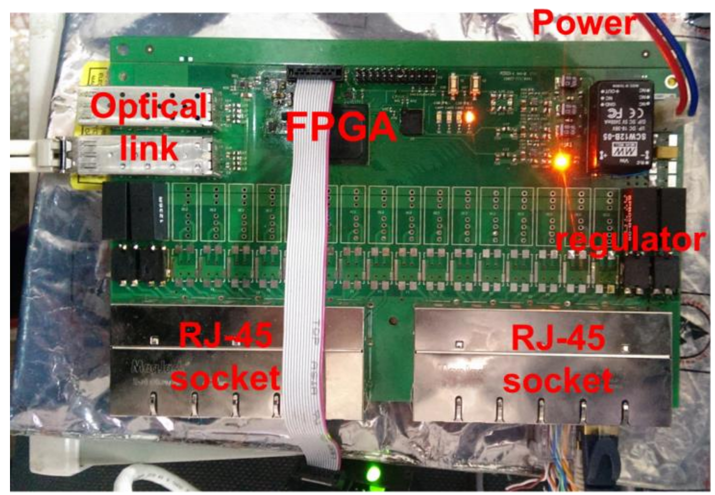
Hadron Absorber & Nuclear Targets



Readout Electronics for COMPASS DC5



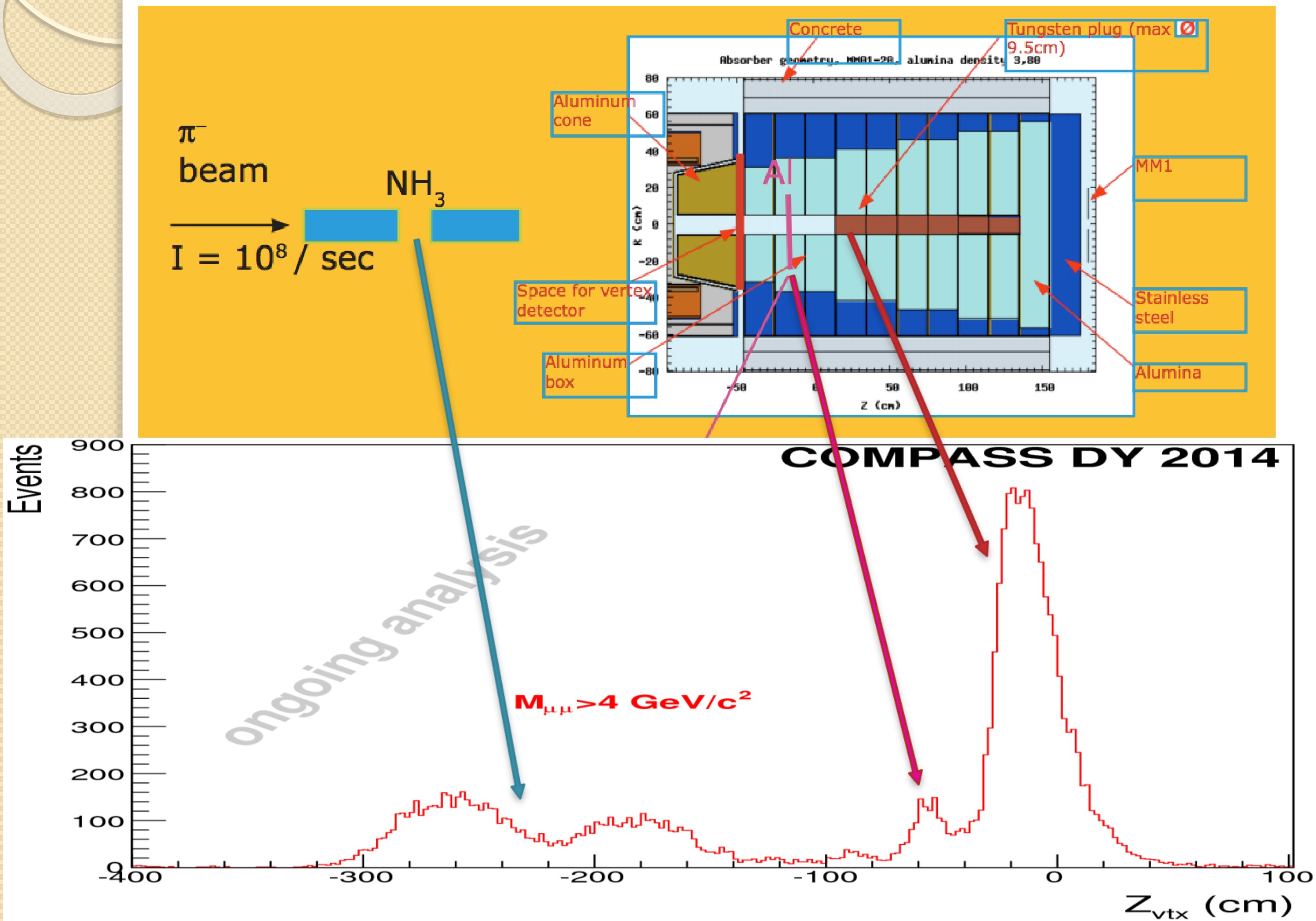




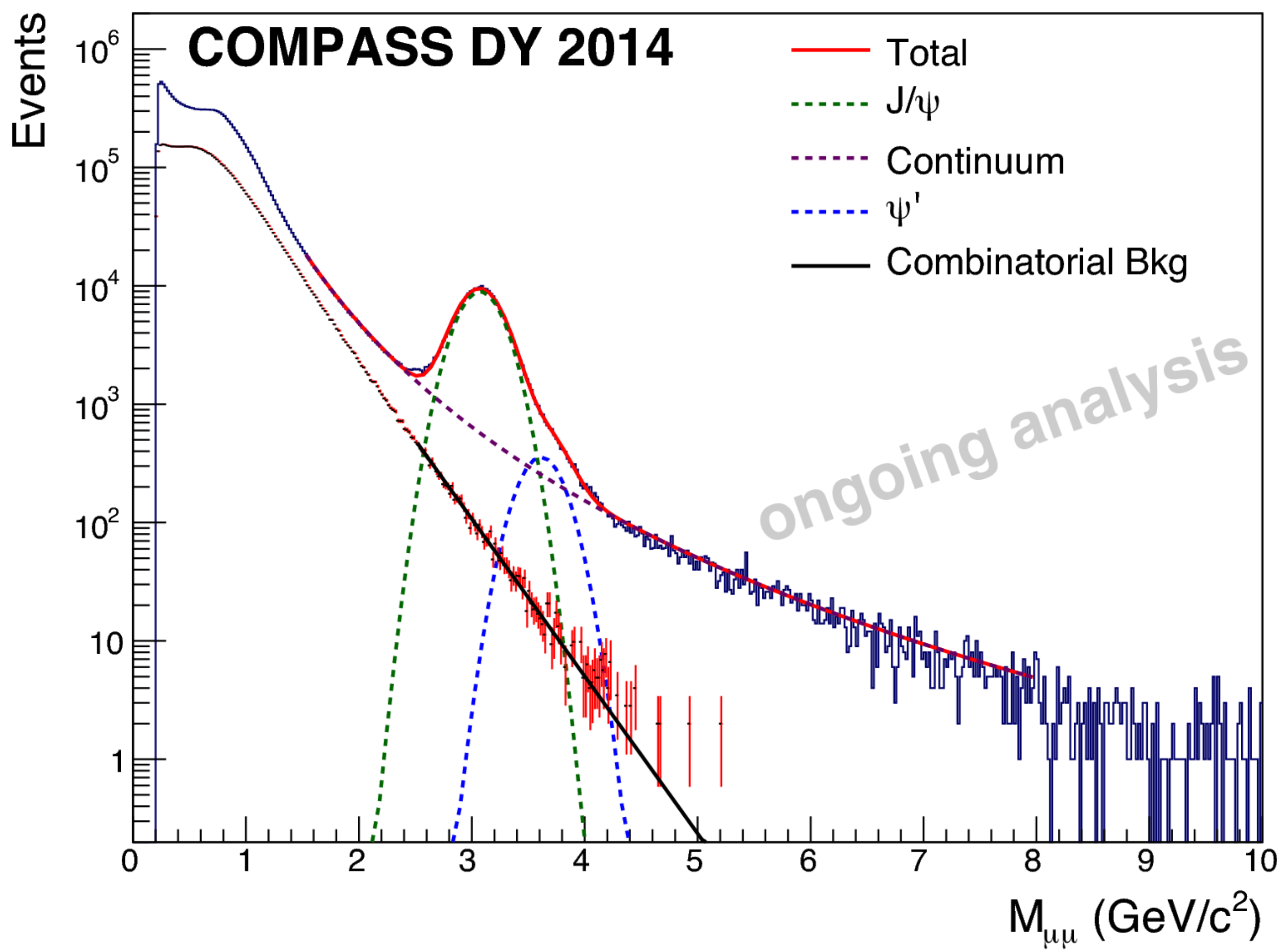
朱明禮、林志勳、鄧宇勝、謝佳諭

COMPASS DC5

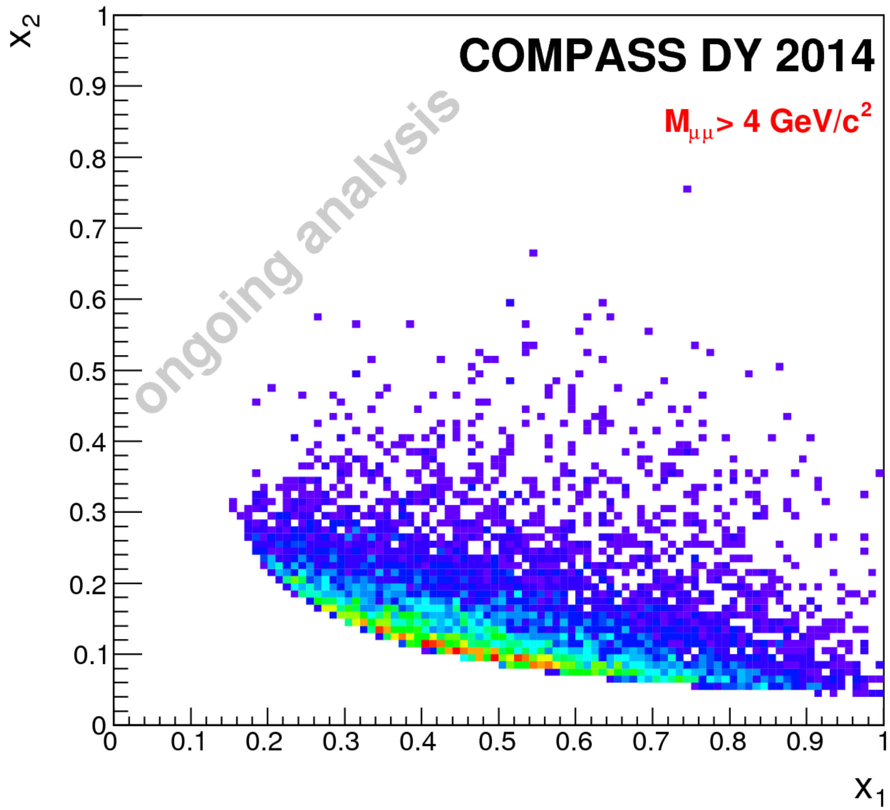
Dimuon Vertex Distributions (2014 DY)

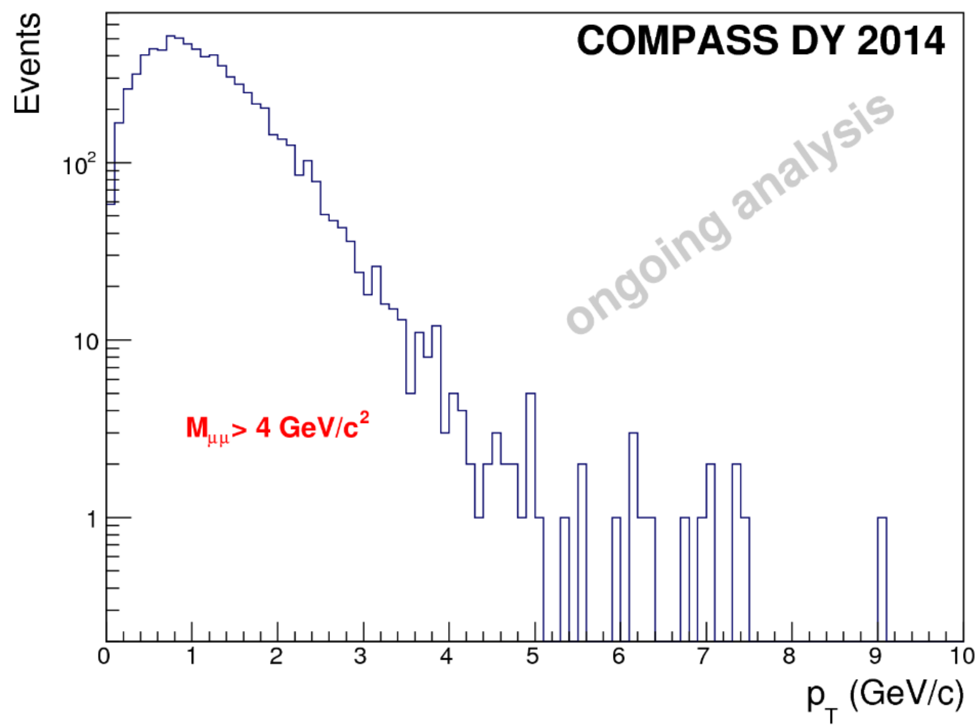


Dimuon Invariant-mass Distributions (2014 COMPASS DY)



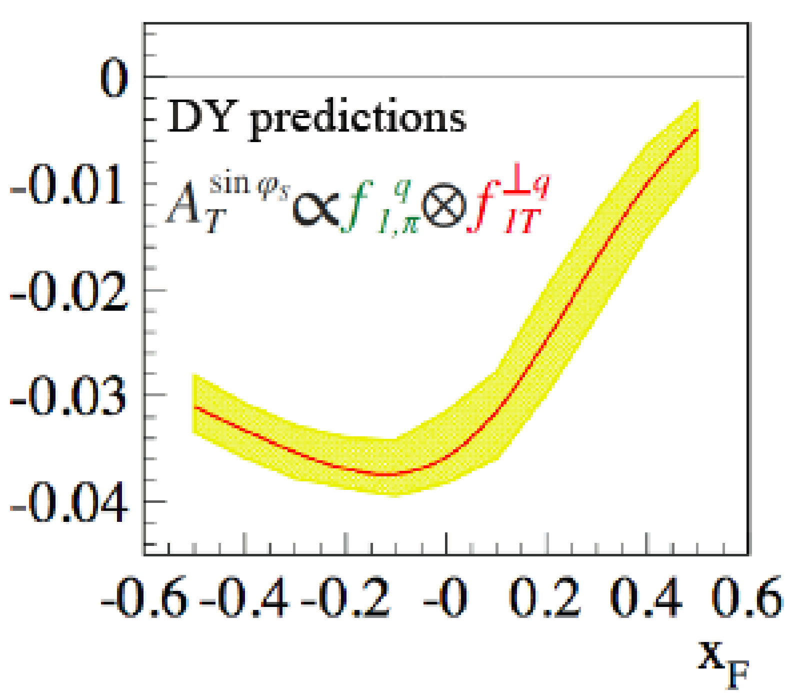
Dimuon x_1,x_2 and p_T Distributions (2014 COMPASS DY)



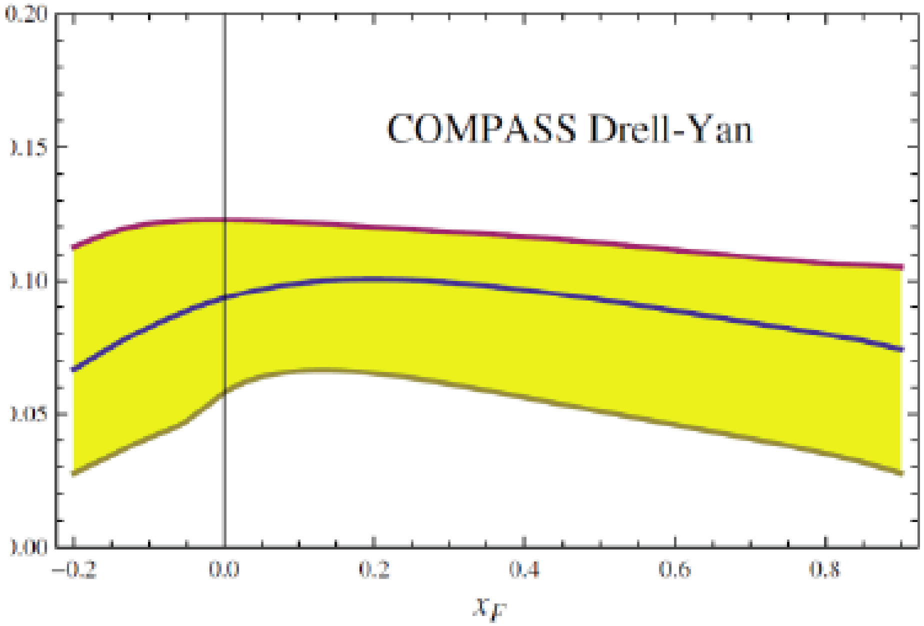


2015 - Sivers sign change (dis)claim

After the first year of data taking (~100 days in 2015 compare to 280 in Proposal) we most probable will be able to (dis)claim the sign change at 3 σ level only if the asymmetry is large ~0.1



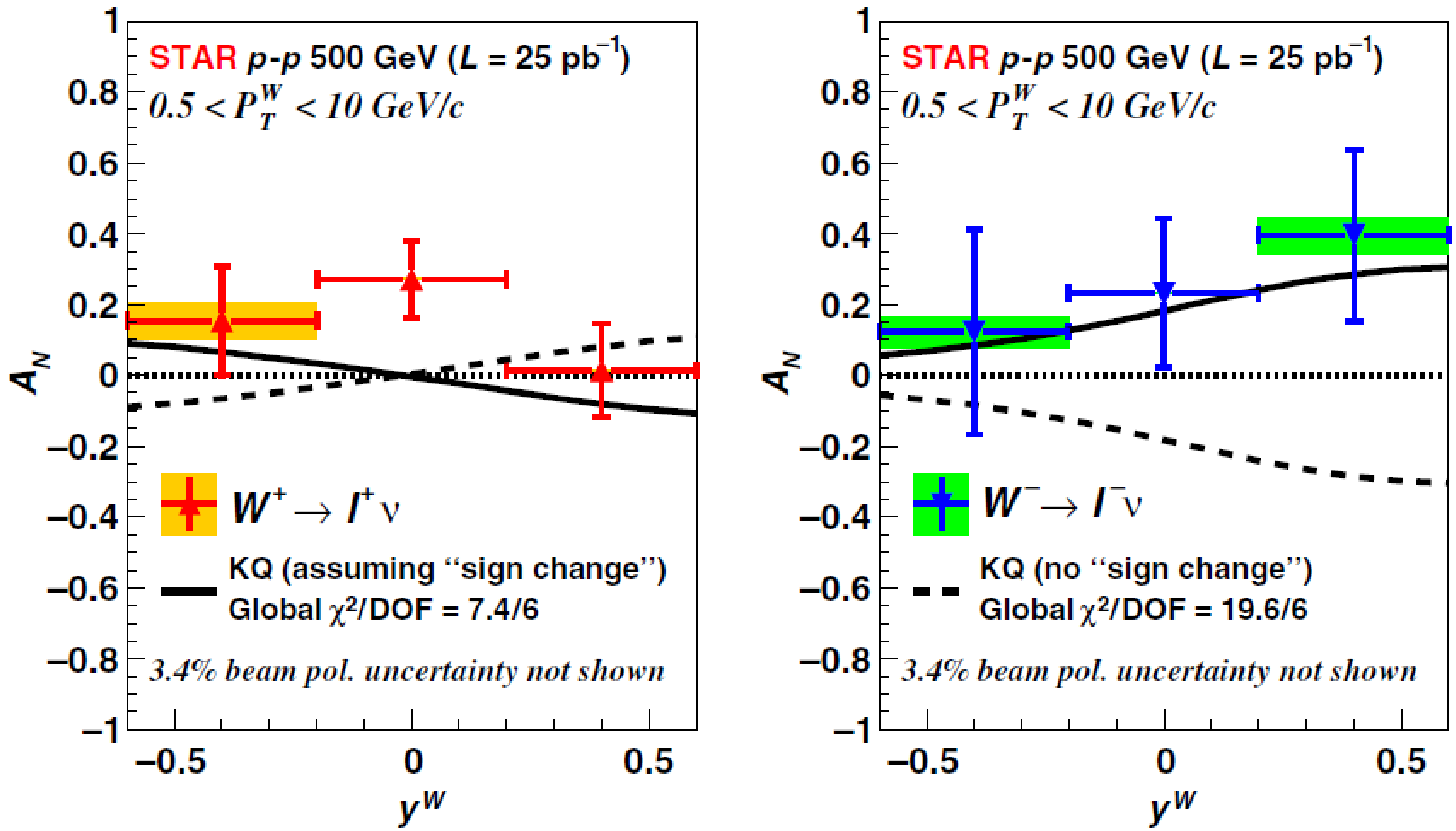
M.G. Echevarria et al., "*QCD Evolution of the Sivers Asymmetry*", PRD 89 074013 (2014)



P. Sun and F. Yuan, "*Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production*". PRD 88 11, 114012 (2013)

Transverse SSA of W in polarized pp collisions at RHIC

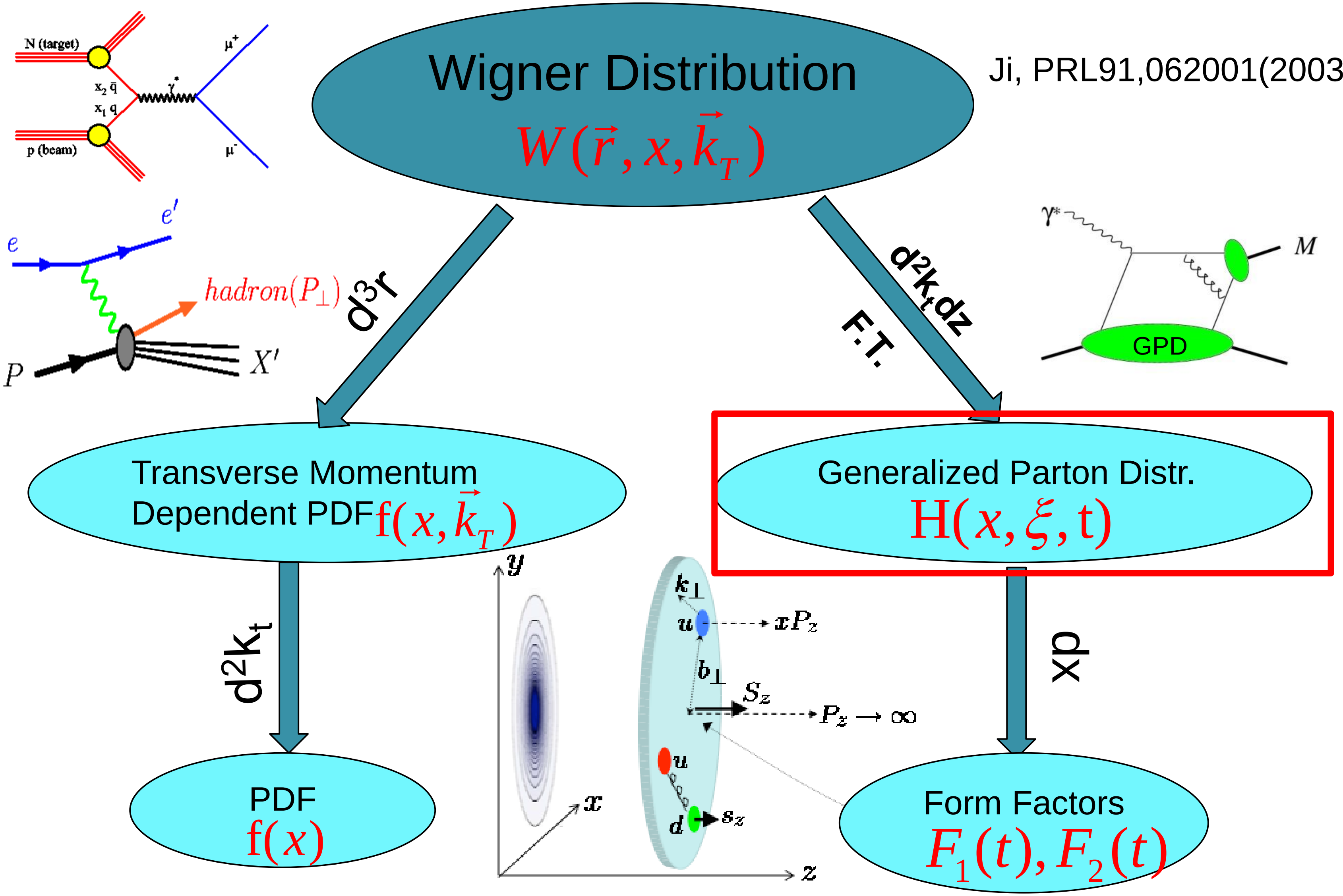
(PRL 116, 132301 (2016); arXiv:1511.06003)



$$A_N = \frac{1}{\langle P \rangle} \frac{\sqrt{N_\uparrow(\phi)N_\downarrow(\phi+\pi)} - \sqrt{N_\uparrow(\phi+\pi)N_\downarrow(\phi)}}{\sqrt{N_\uparrow(\phi)N_\downarrow(\phi+\pi)} + \sqrt{N_\uparrow(\phi+\pi)N_\downarrow(\phi)}},$$

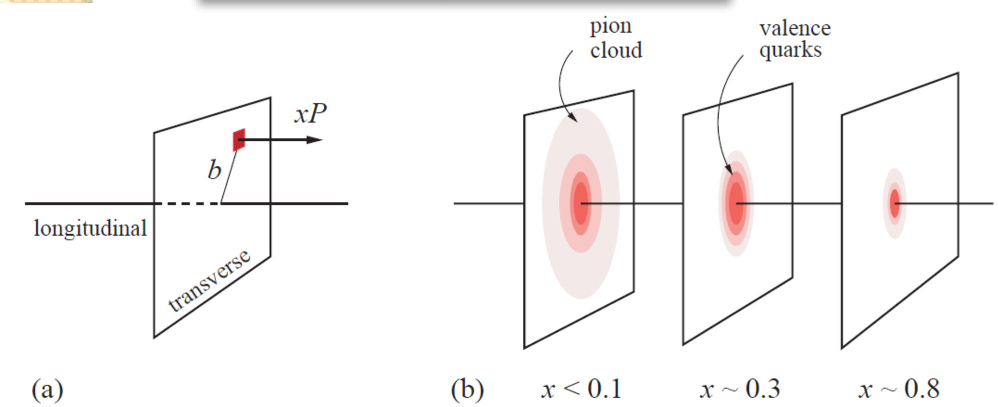
Nucleon Partonic Structure

Ji, PRL91,062001(2003

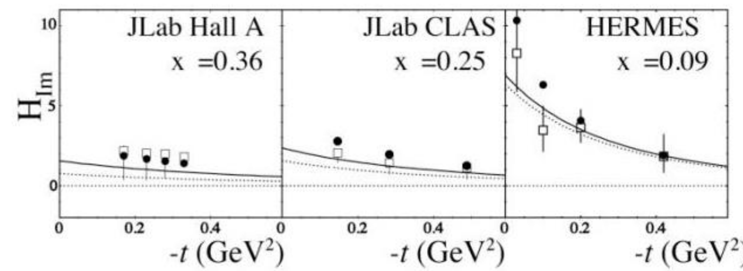


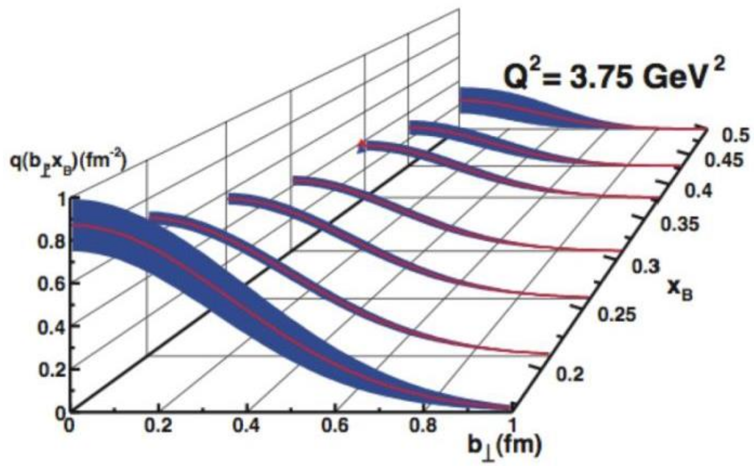
Generalized Parton Distribution

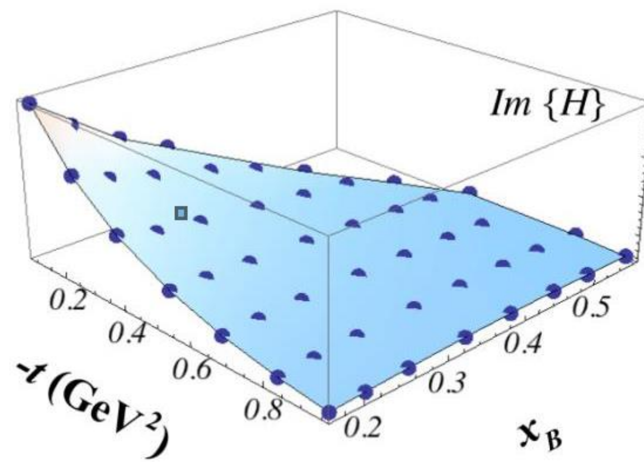
Transverse position $\vec{r_T}$



JLAB12 CDR, arXiv:1208.1244

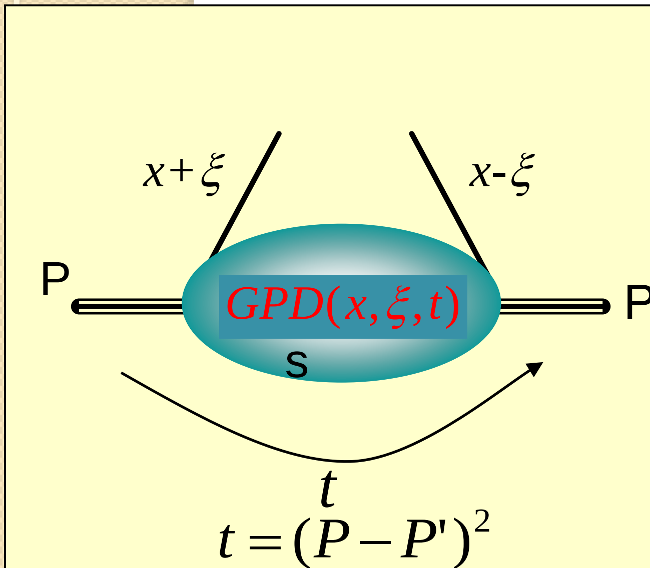






- 1+2D description of the nucleon structure
- Correlations among longitudinal momenta and transverse positions
- Connection to quark orbital angular momentum

Generalized Parton Distribution (GPD)



$t = \xi = 0$

$$H_f(x,0,0) = q_f(x) = -\bar{q}_f(-x)$$

$$\tilde{H}_f(x,0,0) = \Delta q_f(x) = -\Delta\bar{q}_f(-x)$$

The first moments

$$\int_{-1}^{1} dx \sum_f H_f(x,\xi,t) = F_1(-t)$$

$$\int_{-1}^{1} dx \sum_f E_f(x,\xi,t) = F_2(-t)$$

$$\int_{-1}^{1} dx \sum_f \tilde{H}_f(x,\xi,t) = G_A(-t)$$

$$\int_{-1}^{1} dx \sum_f \tilde{E}_f(x,\xi,t) = G_p(-t)$$

The second moments

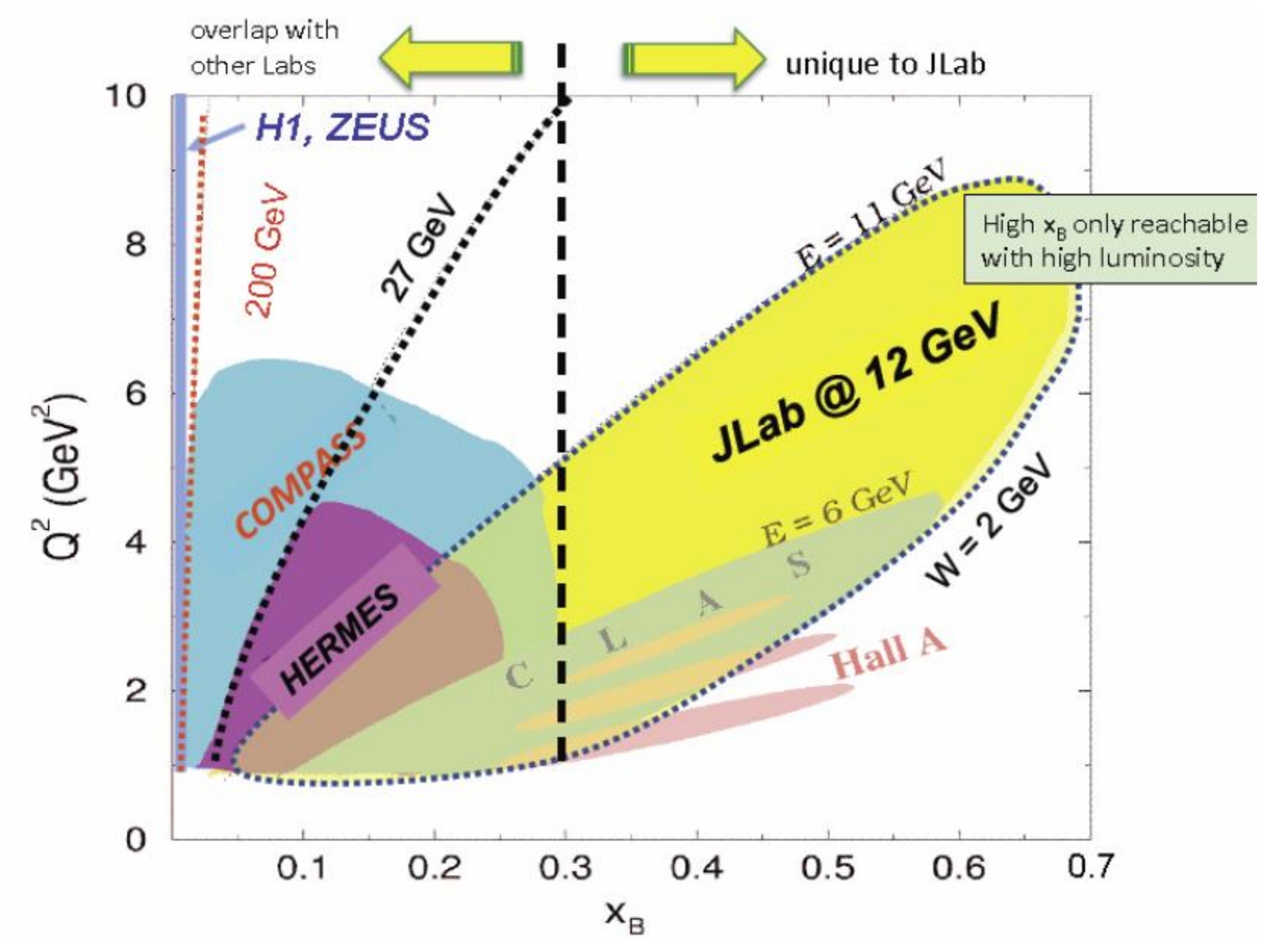
	γ^μ	$\gamma^\mu\gamma^5$
no spin flip	$H_f(x,\xi,t)$	$\tilde{H}_f(x,\xi,t)$
spin flip	$E_f(x,\xi,t)$	$\tilde{E}_f(x,\xi,t)$

Ji's sum rule

$$J_f = \frac{1}{2}\Delta\Sigma^f + L^f = \frac{1}{2}\int_{-1}^{1} xdx\, [H_f(x,\xi,0) + E_f(x,\xi,0)]$$

The orbital angular momentum of quarks can be known.

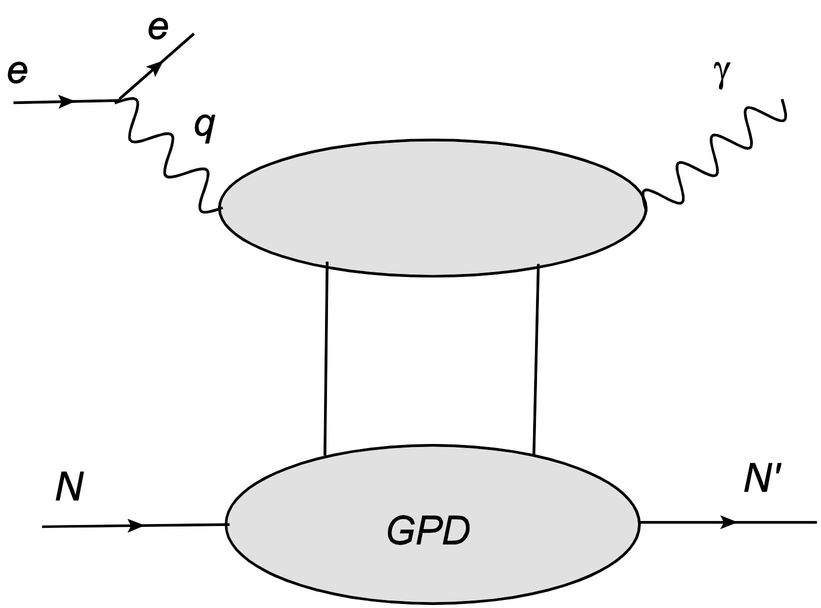
Worldwide Activities for Measuring GPD



arXiv:1208.1244

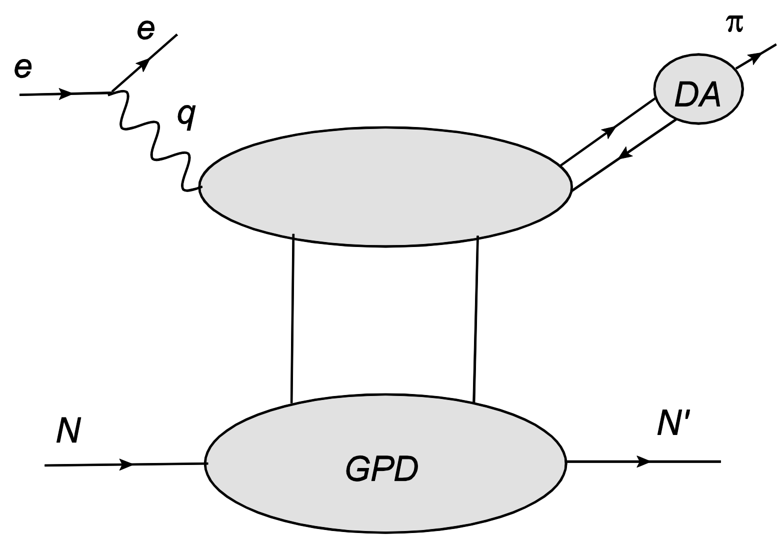
Explore GPD by Electron Beams

Deeply Virtual Compton Scattering



(a)

Deeply Virtual Meson Production



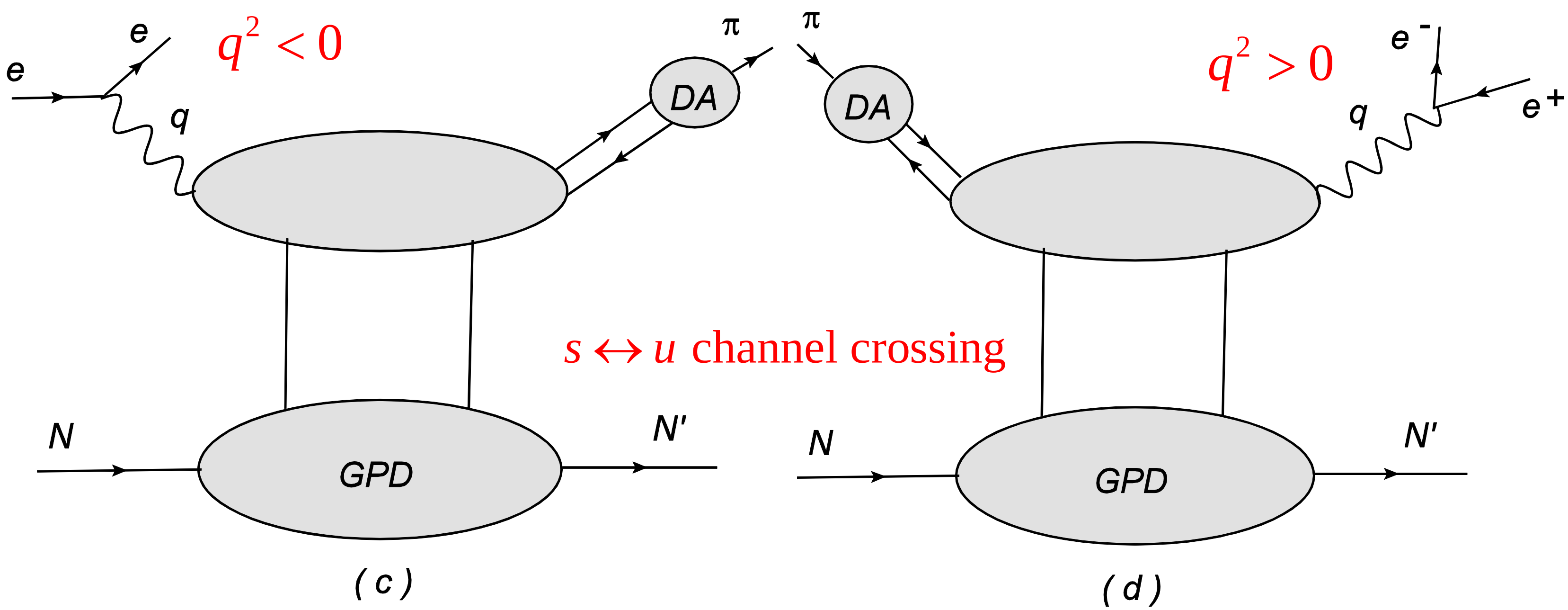
(c)

HERMES, JLAB, COMPASS

Spacelike vs. Timelike Processes

Deeply Virtual Meson Production

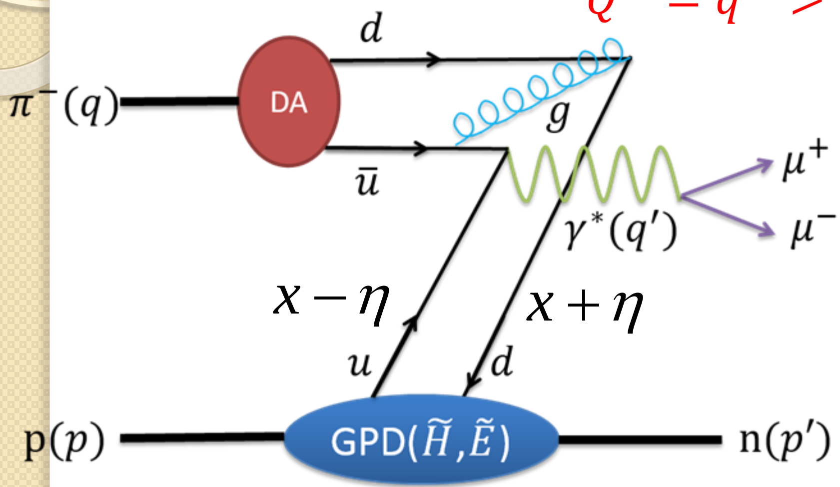
Exclusive Meson-induced DY



$\pi N \to \gamma^* N$ (Exclusive Drell-Yan)

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

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



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

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

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

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

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

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

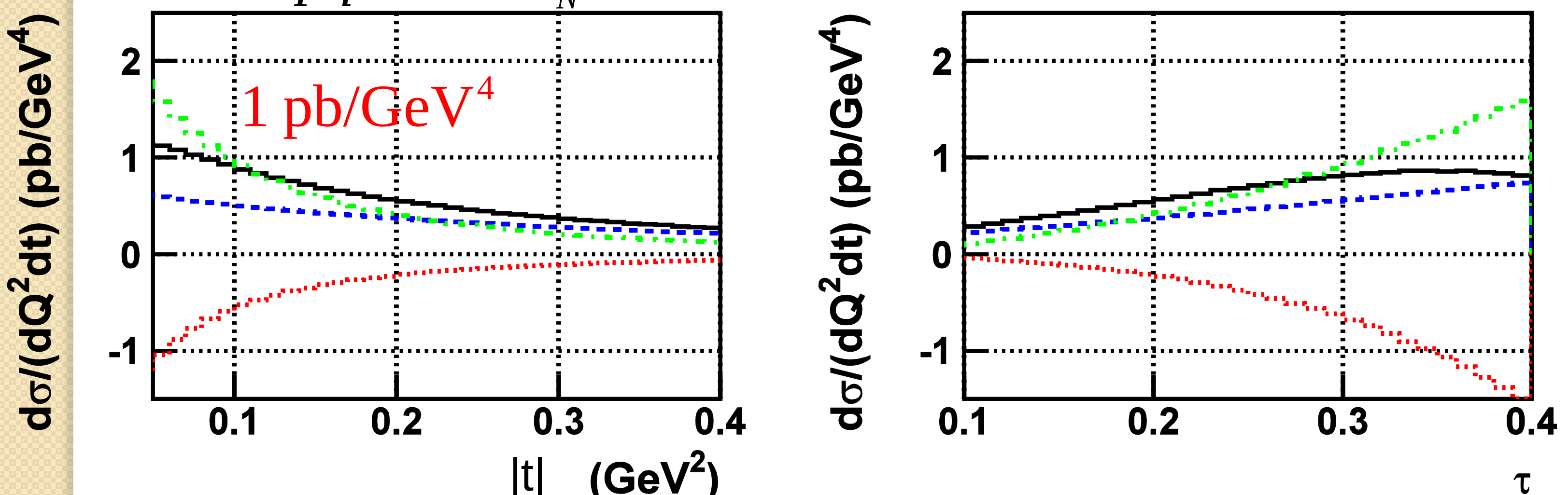
E.R. Berger, M. Diehl, B. Pire, PLB 523 (2001) 265

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

Cross sections increase toward small s!

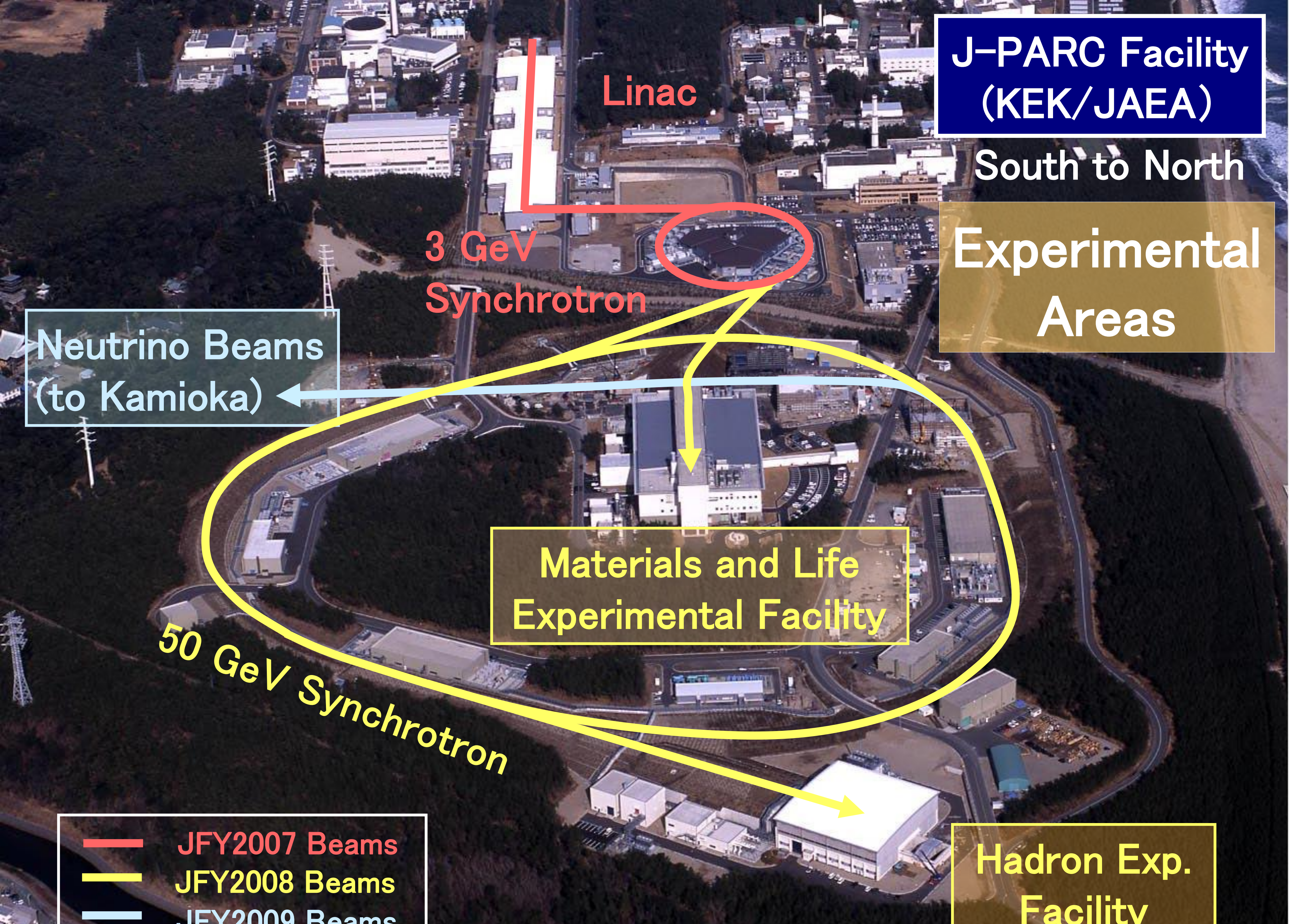
$$\tau = \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s - M_N^2} = 0.2$$

$t = (p - p')^2$=-0.2 GeV²



$$(1-\eta^2)\left|\widetilde{\mathcal{H}}^{du}\right|^2 \quad - 2\eta^2\, \mathrm{Re}\left(\widetilde{\mathcal{H}}^{du*}\widetilde{\mathcal{E}}^{du}\right) \quad - \eta^2 \frac{t}{4M^2}\left|\widetilde{\mathcal{E}}^{du}\right|^2$$

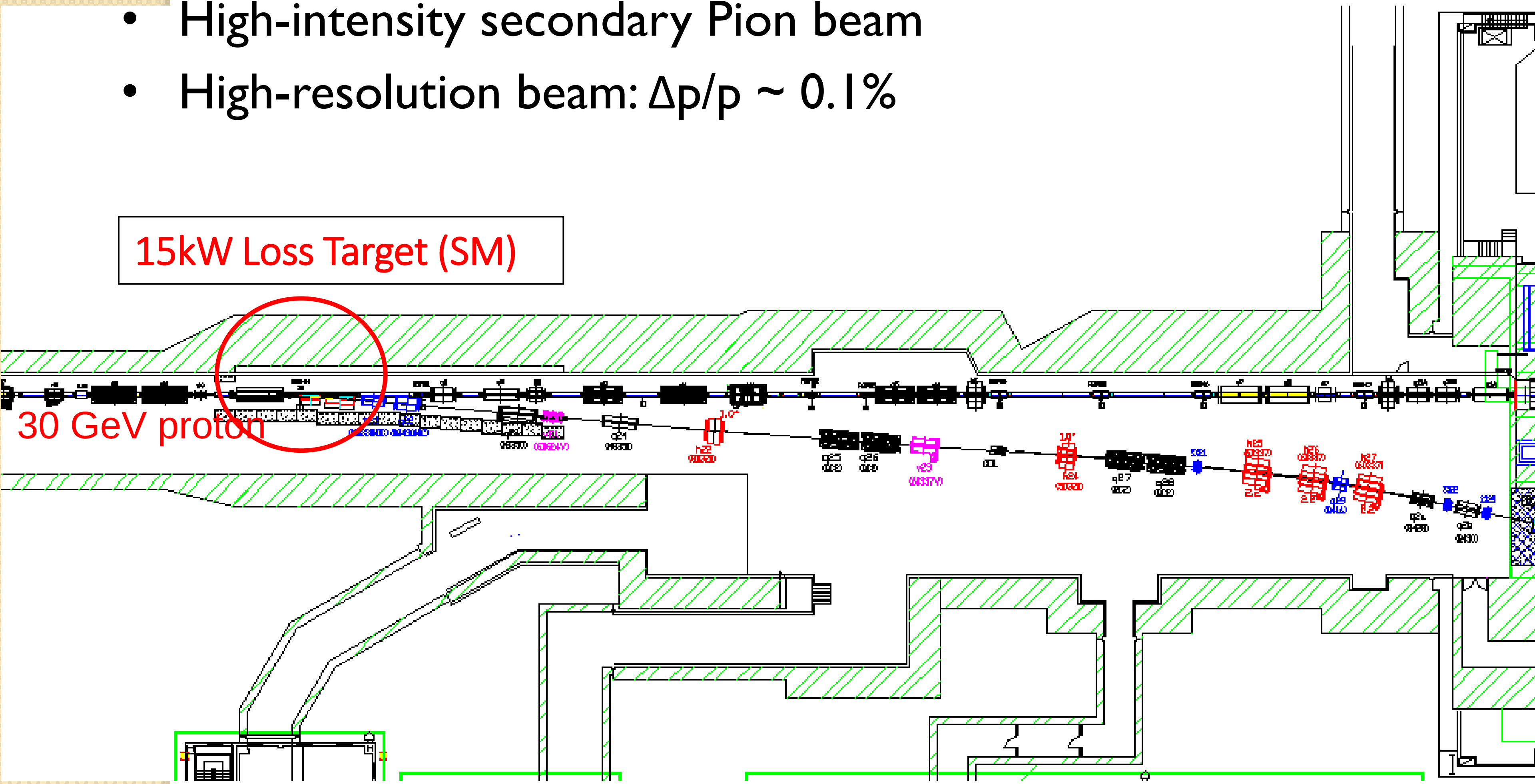
blue red green



Bird's eye photo in January of 2008

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

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



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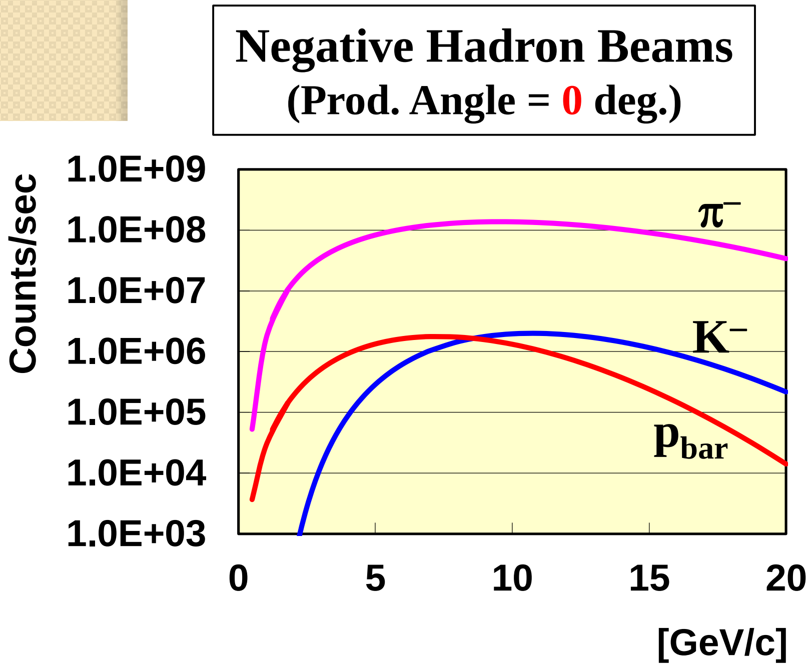
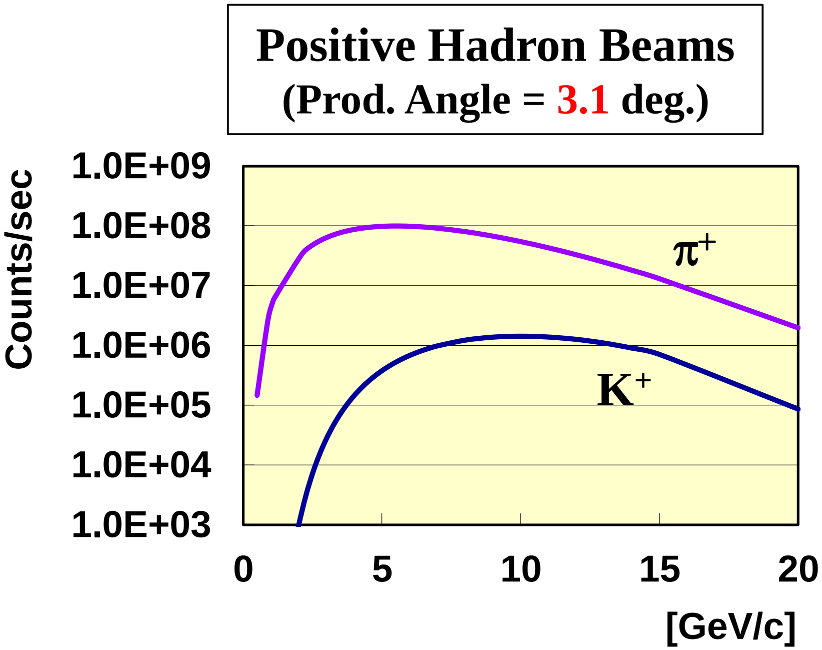
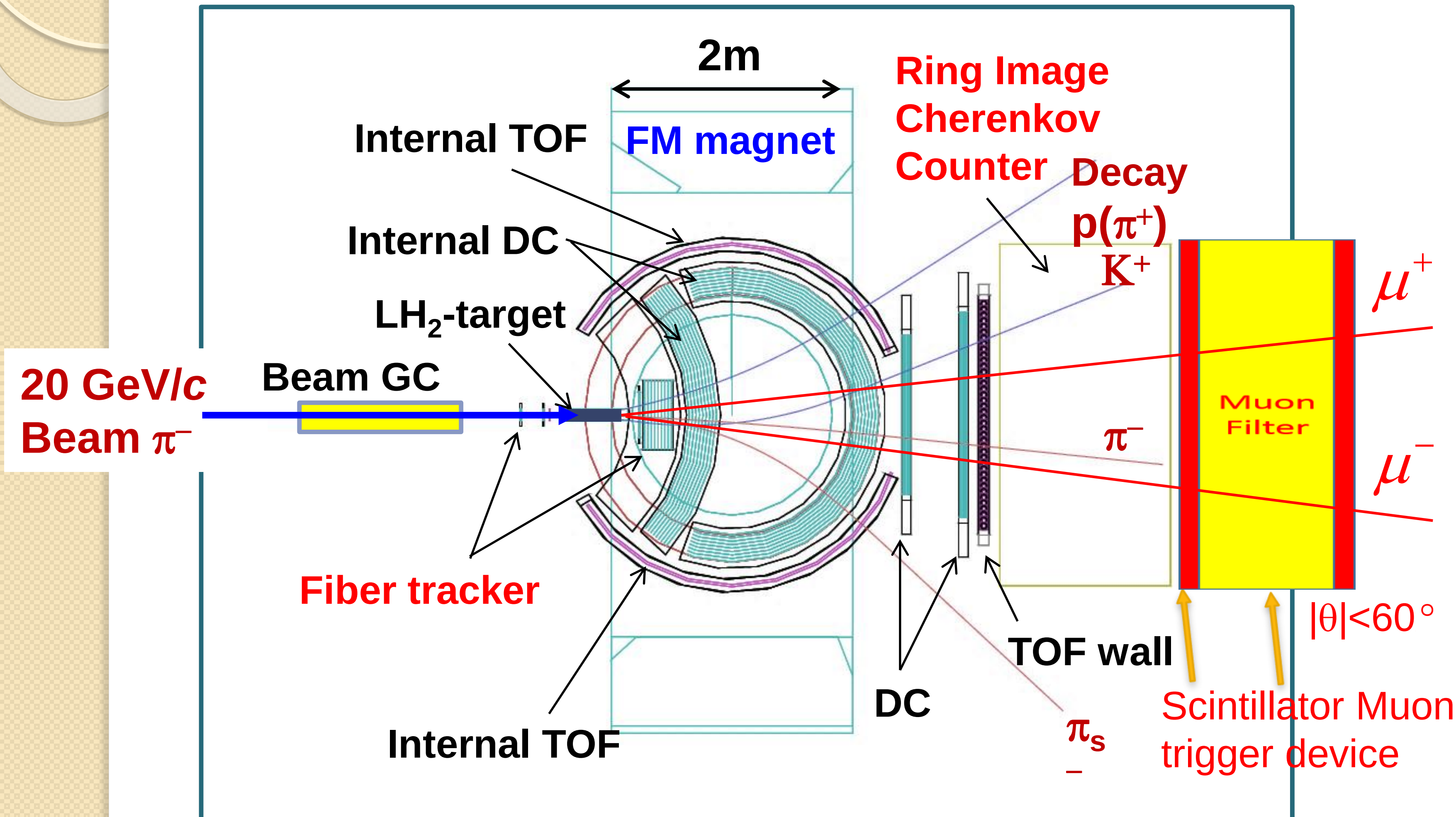




* Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m

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

Missing-Mass Technique in E-50 Spectrometer + MuID



Acceptance: ~ 60% for D^*, ~80% for decay π^+

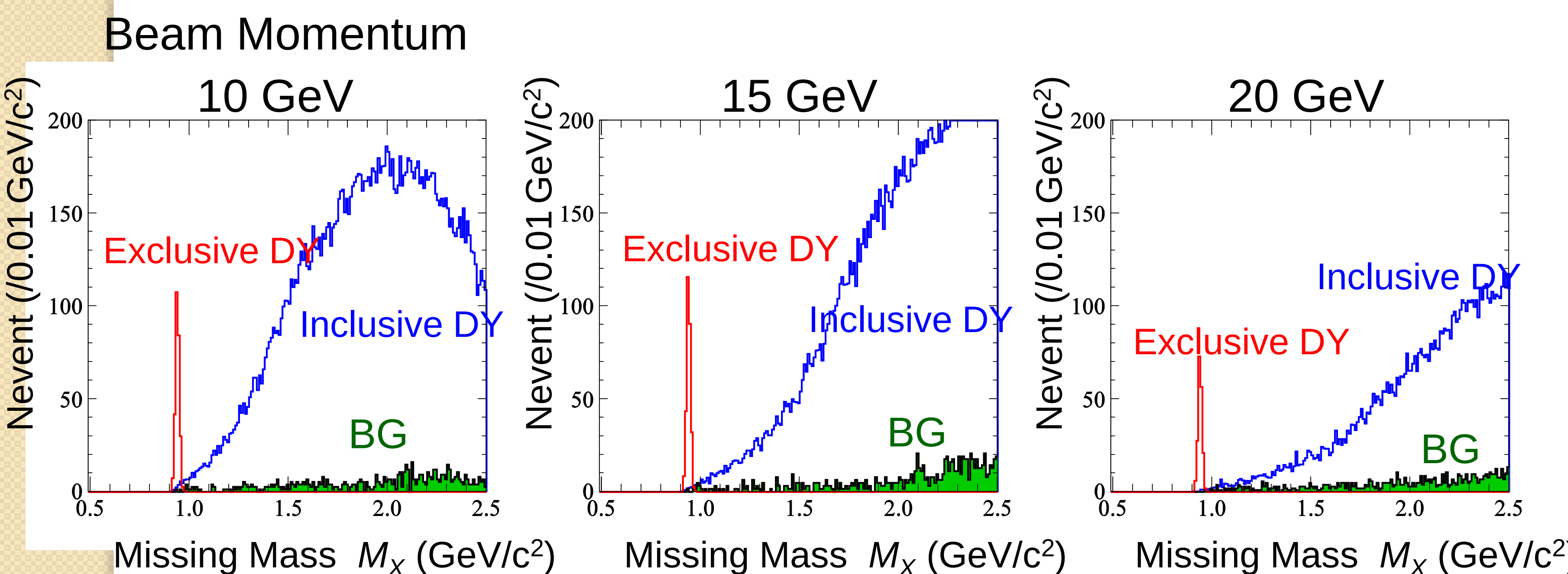
Resolution: $\Delta p/p$~0.2% at ~5 GeV/c （Rigidity：~2.1 Tm)

$\pi^- p \rightarrow \mu^+\mu^- X$

M_X In E-50 Spectrometer + MuID

π⁻ beam 50 days

$1.5 < M_{\mu^+\mu^-} < 2.9$ GeV/c²



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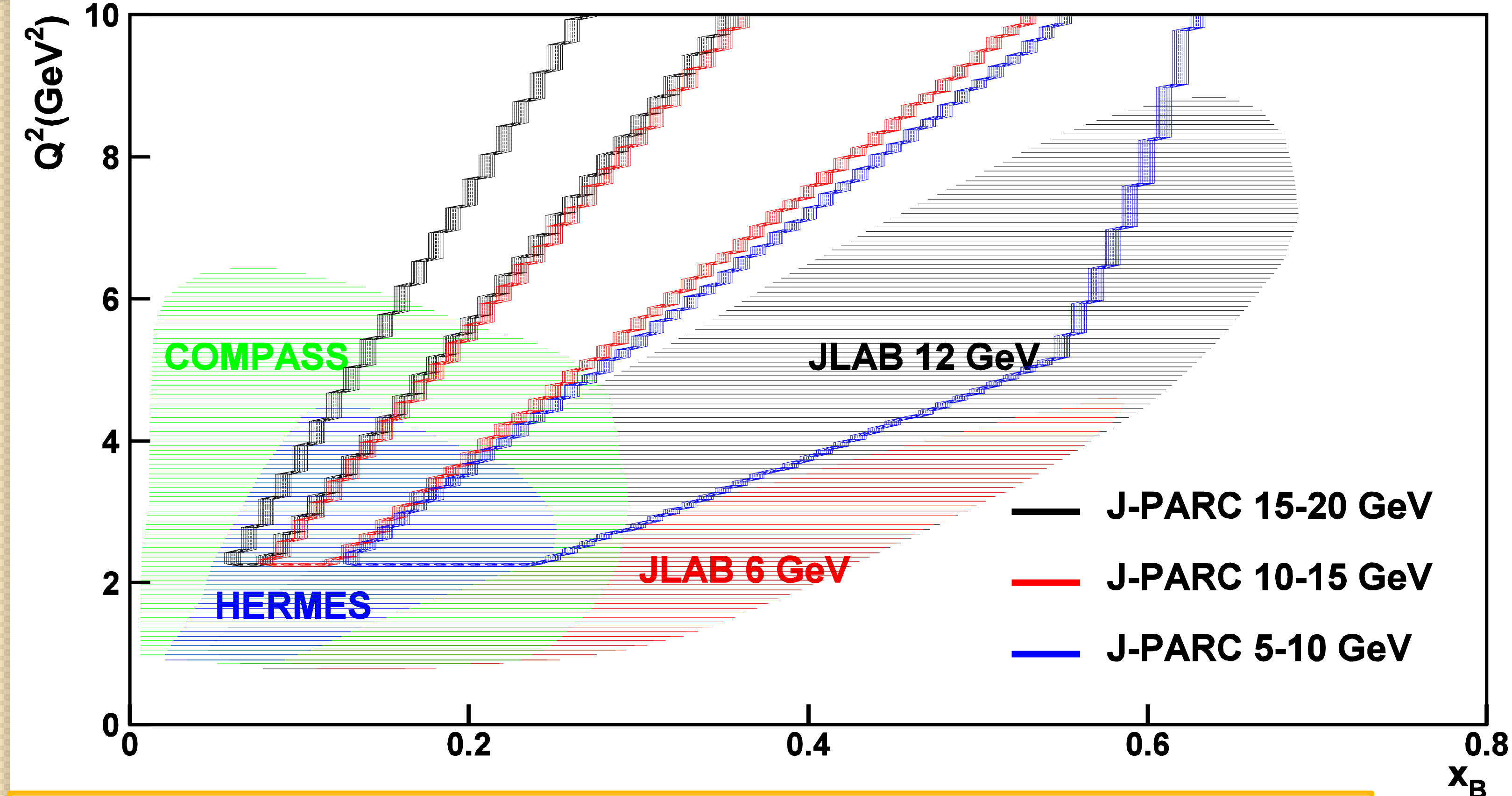
S. Kumano (KEK)
J.C. Peng (UIUC)
T. Sawada (AS)
W.C. Chang (AS)

- The signal of exclusive Drell-Yan processes can be clearly identified in the missing mass spectrum of dimuon pairs.
- Because of the low event rate, this program could be accommodated into the E50 experiment.

GPD(x_B,t;Q^2) from space-like and time-like processes

Large-Q^2 region



- J-PARC: **time-like** approach and **large-Q^2** region.

Summary

- Drell-Yan process is a powerful tool to explore the partonic structures of nucleons. We are moving ahead from 1d- to 3d-imaging of nucleons.
- Unique information of flavor structure of sea quarks has been obtained with Drell-Yan experiments.
- A successful measurement of Sivers functions in Drell-Yan process will mark a milestone of perturbative QCD and TMD physics.
- The measurement of exclusive meson-induced Drell-Yan process at J-PRAC will explore GPD in time-like process and large-Q^2 region.