GPD study at J-PARC

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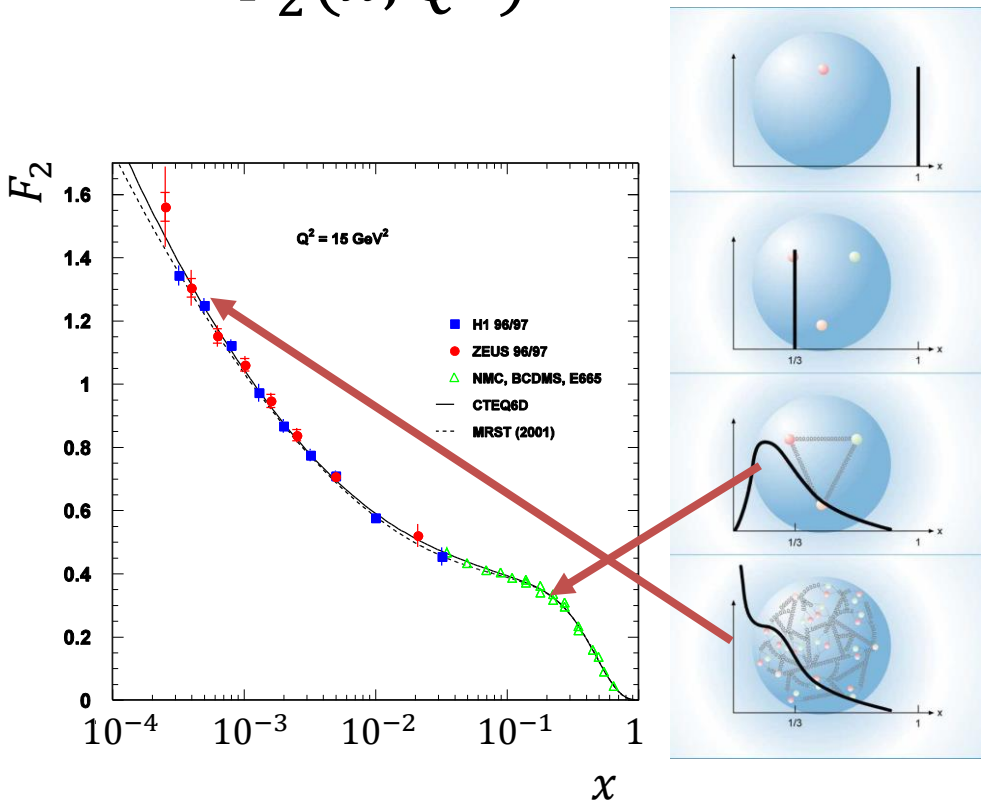
The 10th Circum-Pan-Pacific Spin Symposium on High Energy Spin Physics (Pacific Spin 2015)
6th Oct. 2015, Academia Sinica, Taiwan

Outline

- **PDF** from Space-like(DIS) and Time-like(Drell-Yan) processes
- **GPD** from Space-like(DVCS, DVMP) and Time-like(Exclusive meson-induced Drell-Yan) processes
- Feasibility study of exclusive pion-induced Drell-Yan ($\pi^- p \rightarrow \mu^+ \mu^- n$) experiment at J-PARC
- Summary

Structure Function and PDF

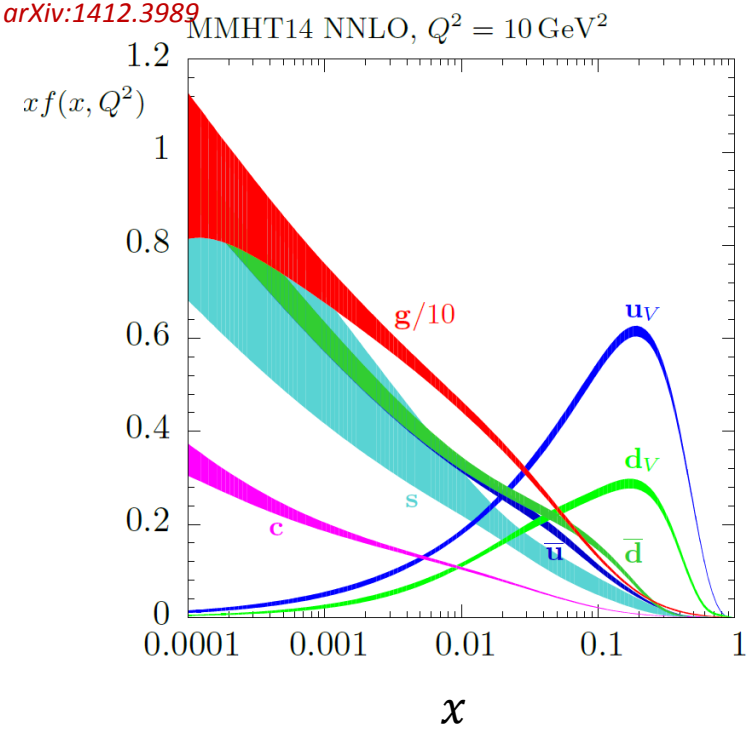
Structure Function $F_2(x, Q^2)$



Parton Distribution Function (PDF)

MMHT 2014 PDFs

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

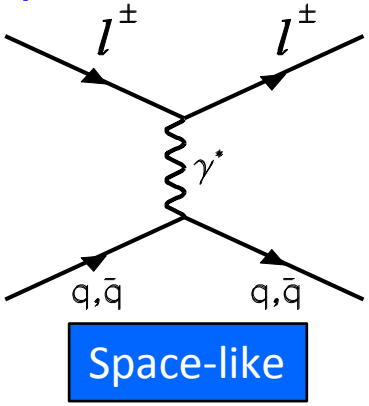


Bjorken x : longitudinal momentum fraction

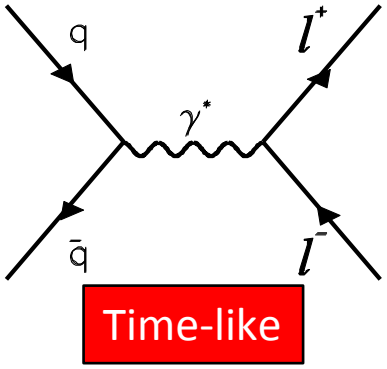
Extraction of **PDF**

Complementarity between **Space-like** and **Time-like** processes

Deep Inelastic Scattering (DIS)



Drell-Yan process



Main Processes in Global PDF Analysis

Process	Subprocess	Partons	x range	
$\ell^{\pm}\{p,n\} \to \ell^{\pm}X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$	DIS
$\ell^{\pm} n/p \to \ell^{\pm}X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$	
$pp \to \mu^+\mu^- X$	$u\bar{u}, dd \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$	Drell-Yan
$pn/pp \to \mu^+\mu^- X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$	
$\nu(\bar{\nu})N \to \mu^-(\mu^+)X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$	DIS
$\nu N \to \mu^-\mu^+ X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$	
$\bar{\nu} N \to \mu^+\mu^- X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$	
$e^{\pm} p \to e^{\pm} X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$	
$e^+ p \to \bar{\nu} X$	$W^+\{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$	
$e^{\pm} p \to e^{\pm} c\bar{c} X$	$\gamma^* c \to c, \gamma^* g \to c\bar{c}$	c, g	$0.0001 \lesssim x \lesssim 0.01$	
$e^{\pm} p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$	
$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$	
$p\bar{p} \to (W^{\pm} \to \ell^{\pm}\nu)X$	$ud \to W, \bar{u}\bar{d} \to W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$	
$p\bar{p} \to (Z \to \ell^+\ell^-)X$	$uu, dd \to Z$	d	$x \gtrsim 0.05$	

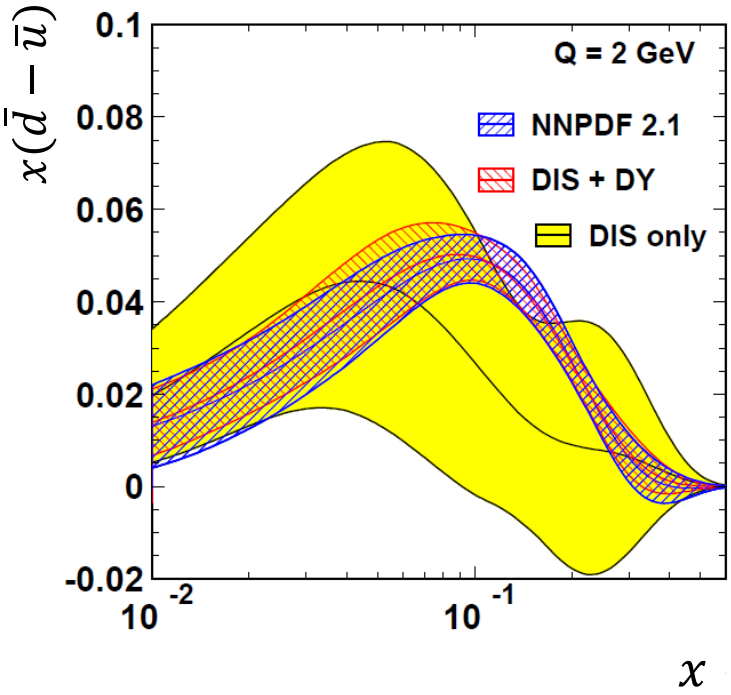
Eur. Phys. J. C (2009) 63: 189–285

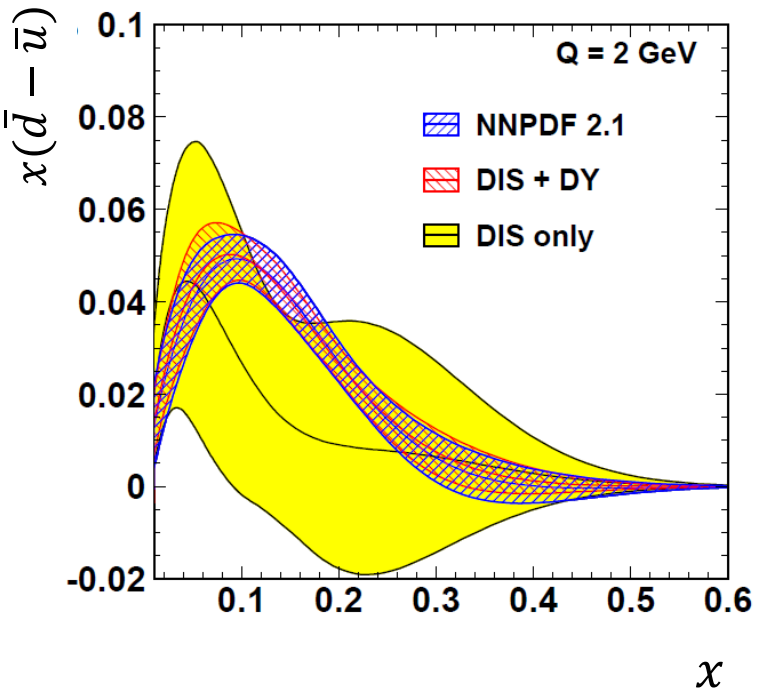
Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)

Extraction of **PDF**

Complementarity between **Space-like** and **Time-like** processes

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



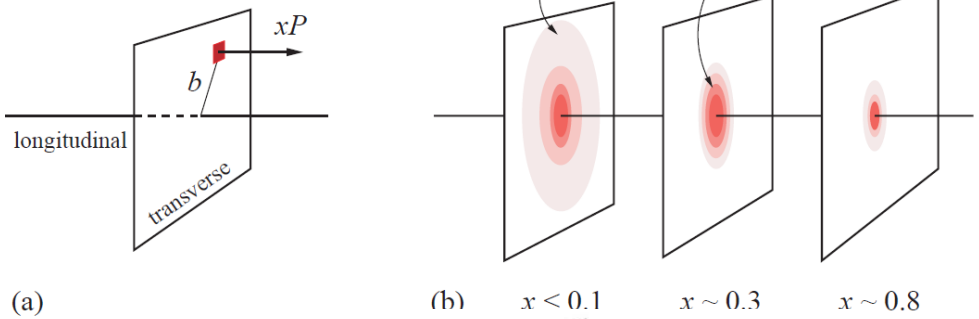


E. Pereza and E. Rizvib, arXiv:1208.1178

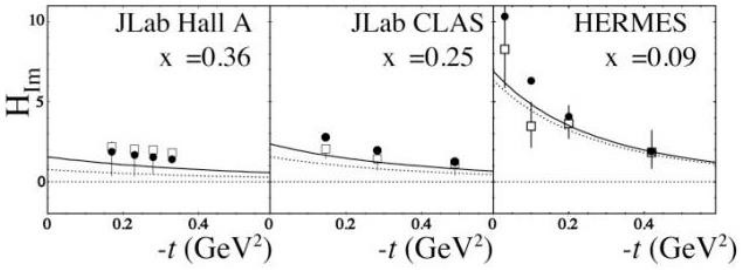
Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)

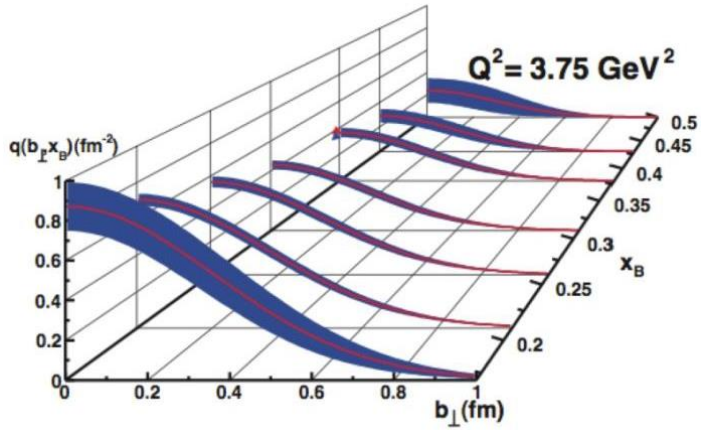
Generalized Parton Distribution (GPD)

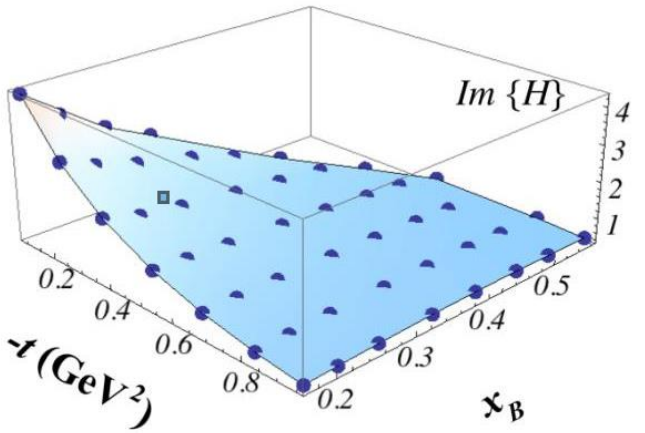
Spatial tomography



JLAB12 CDR. arXiv:1208.1244

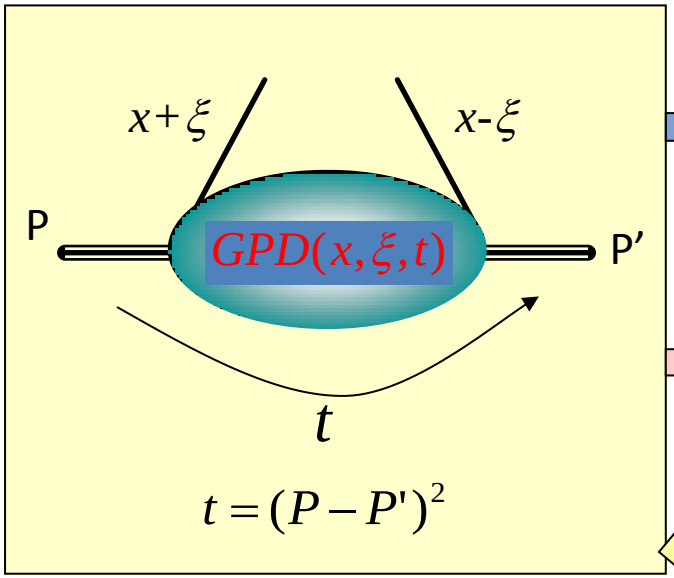






- 1+2D description of the nucleon structure
- Correlations among longitudinal momenta and transverse positions
- Connection to quark orbital angular momentum

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

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

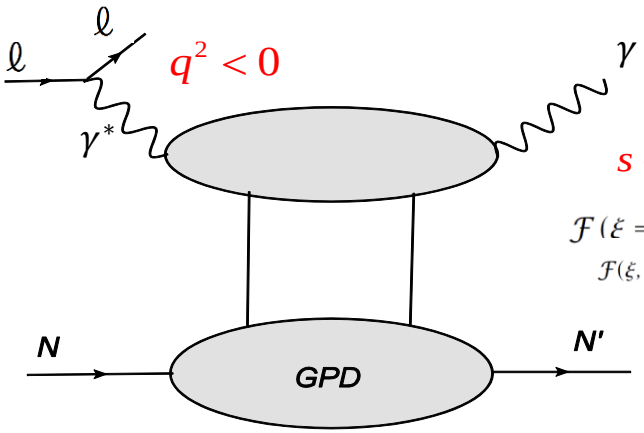
The orbital angular momentum of quarks can be known.

Extraction of **GPD**

Space-like vs. **Time-like** Processes

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

Deeply Virtual Compton Scattering (DVCS)

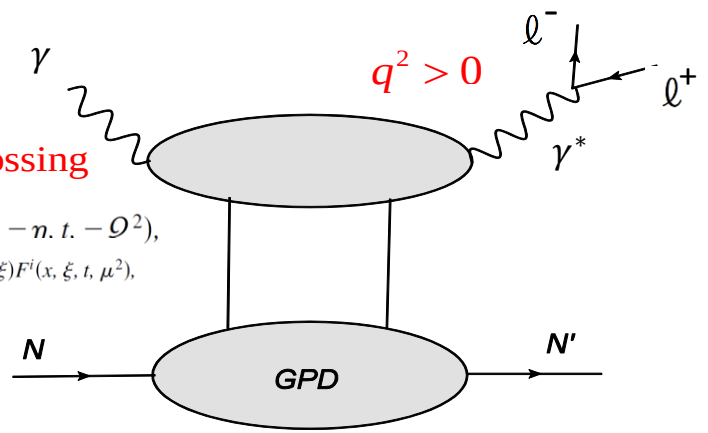


$s \leftrightarrow u$ channel crossing

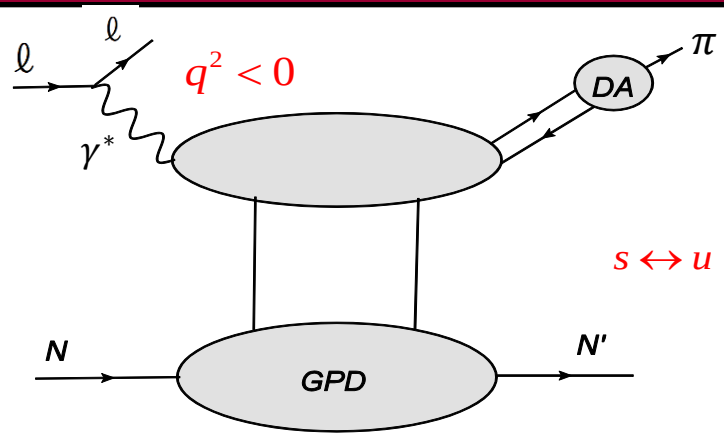
$$\mathcal{F}(\xi = n.t.\ \mathcal{Q}^2) \overset{\text{SL}\to\text{TL}}{\Rightarrow} \mathcal{F}(\xi = -n.t.\ -\mathcal{Q}^2),$$

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

Time-like Compton Scattering (TCS)

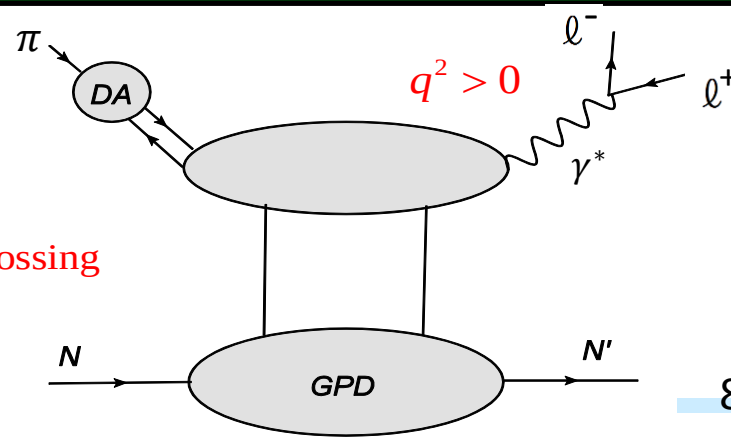


Deeply Virtual Meson Production (DVMP)



$s \leftrightarrow u$ channel crossing

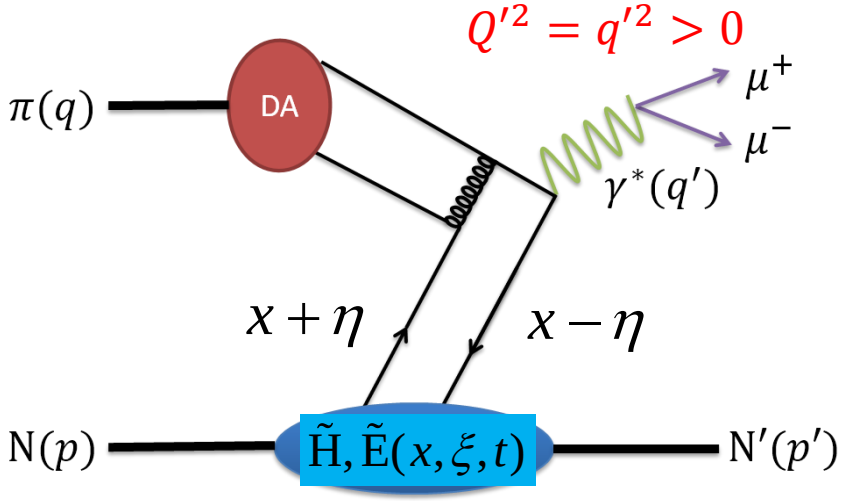
Exclusive meson-induced DY



Exclusive pion-induced DY

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

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



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

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

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

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

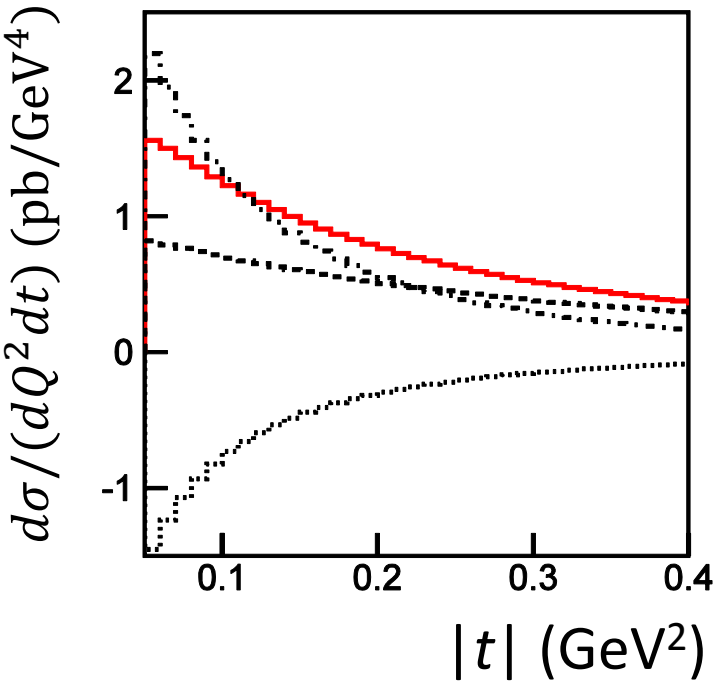
$$\frac{d\sigma}{dQ'^2\, dt}(\pi^- p \to \gamma^* n) = \frac{4\pi\alpha_{\mathrm{em}}^2}{27}\frac{\tau^2}{Q'^8} f_\pi^2 \times \left[(1-\eta^2)\left|\widetilde{\mathcal{H}}^{du}\right|^2 - 2\eta^2 \mathrm{Re}\left(\widetilde{\mathcal{H}}^{du*}\widetilde{\mathcal{E}}^{du}\right) - \eta^2 \frac{t}{4M^2}\left|\widetilde{\mathcal{E}}^{du}\right|^2\right],$$

Differential Cross Sections (Q^2, t, τ)

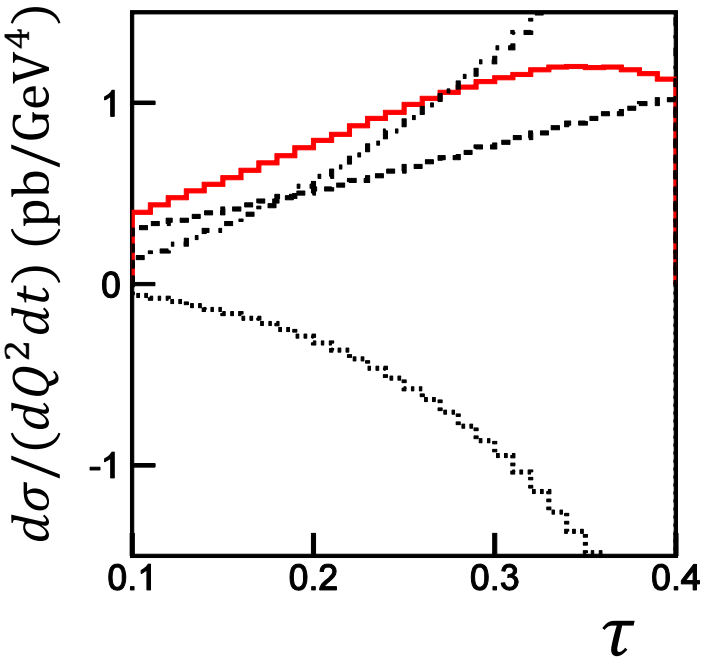
E.R. Berger, M. Diehl, B. Pire, PLB 523 (2001) 265

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

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



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

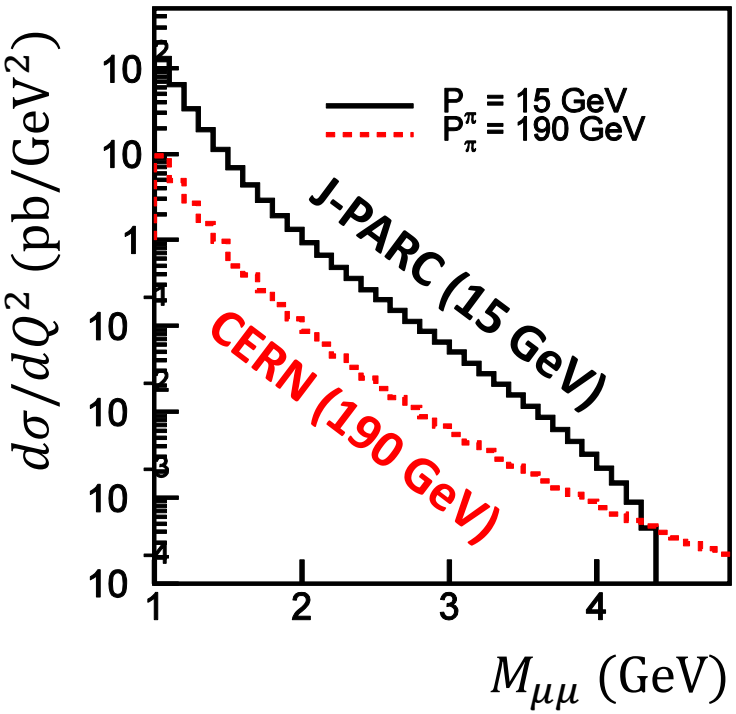


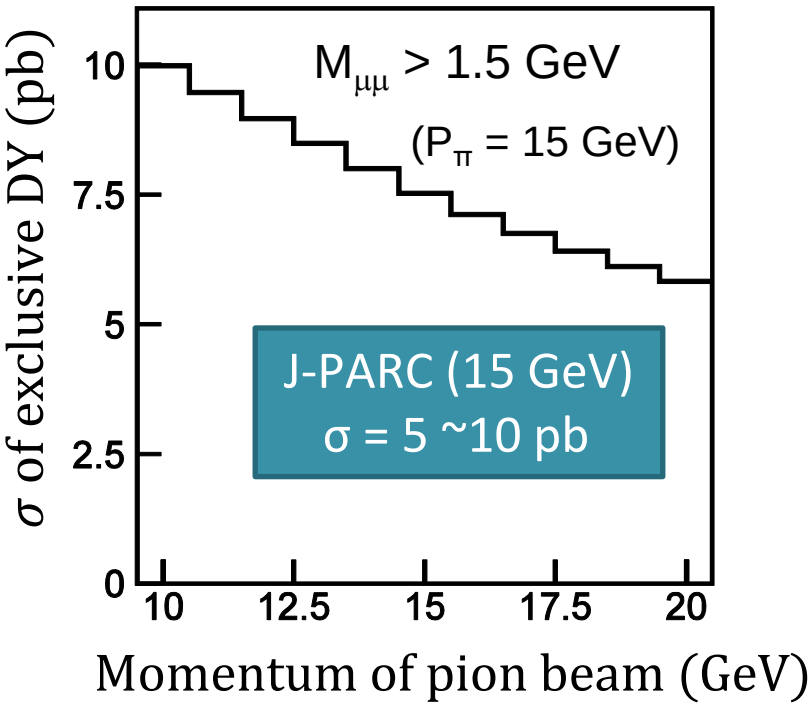
Production is dominant at forward angles

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

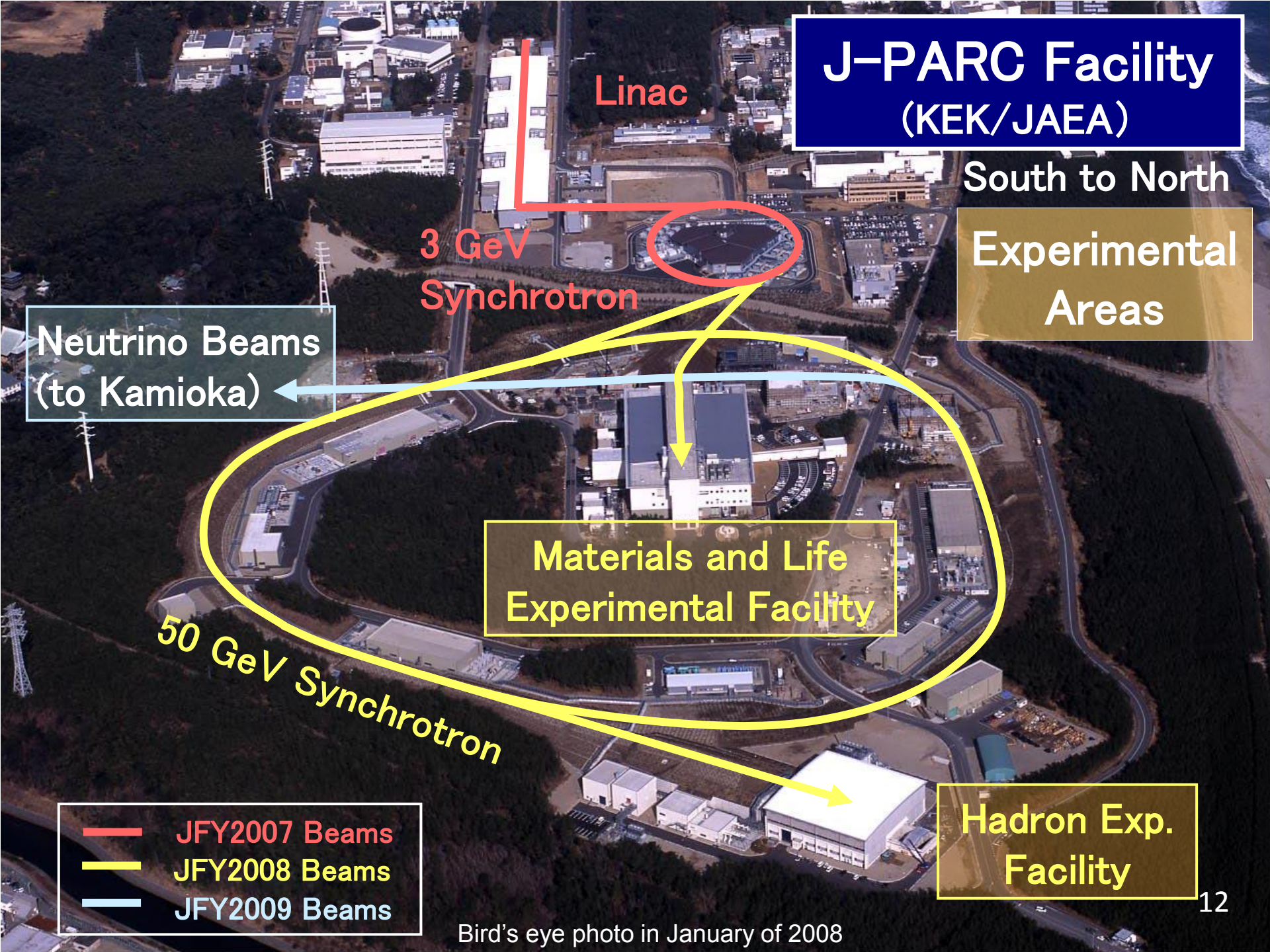
CERN (190 GeV) vs. J-PARC (15 GeV)

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





CERN (190 GeV)
σ = 0.65 pb



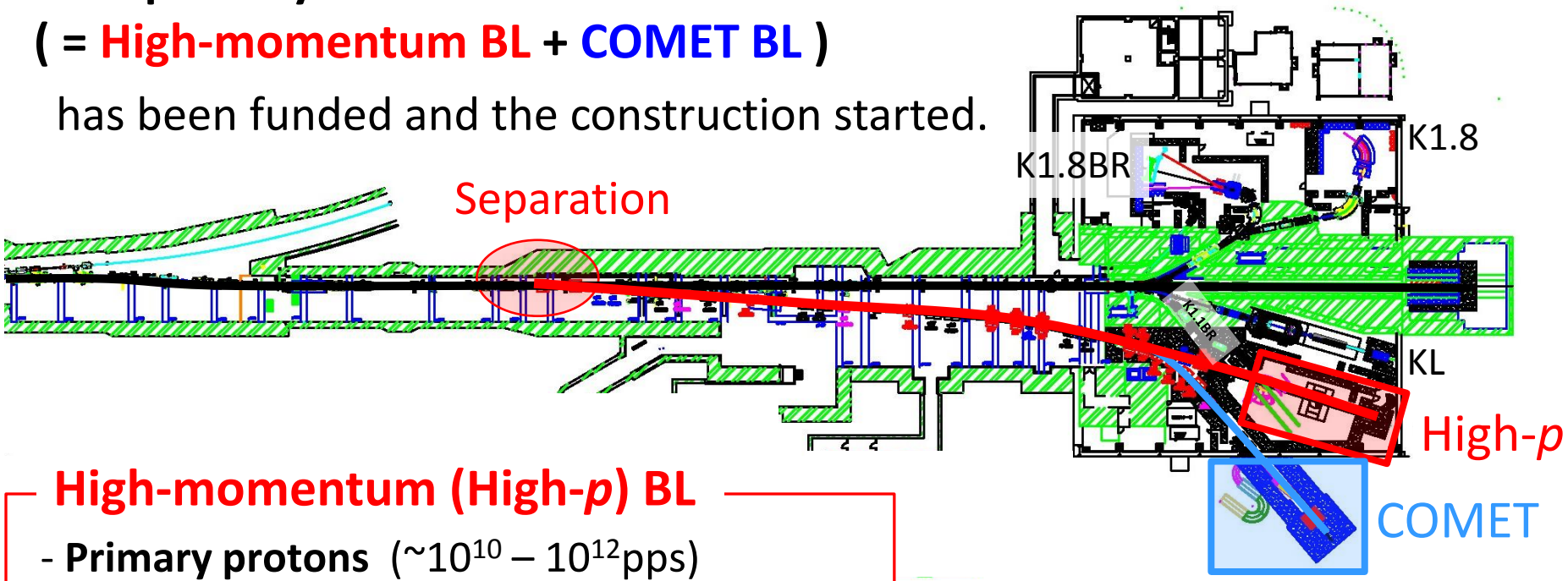
Bird's eye photo in January of 2008

New Primary Proton Beam Line

New primary Proton BL

(= High-momentum BL + COMET BL)

has been funded and the construction started.



High-momentum (High-*p*) BL

- **Primary protons** (~10^{10} – 10^{12}pps)

  E16 (ϕ meson) is considered to be the first experiment.

- **Unseparated secondary particles** (π, K, $\bar{p}$)

  High-resolution secondary beam by adding several quadrupole and sextupole magnets.

COMET BL

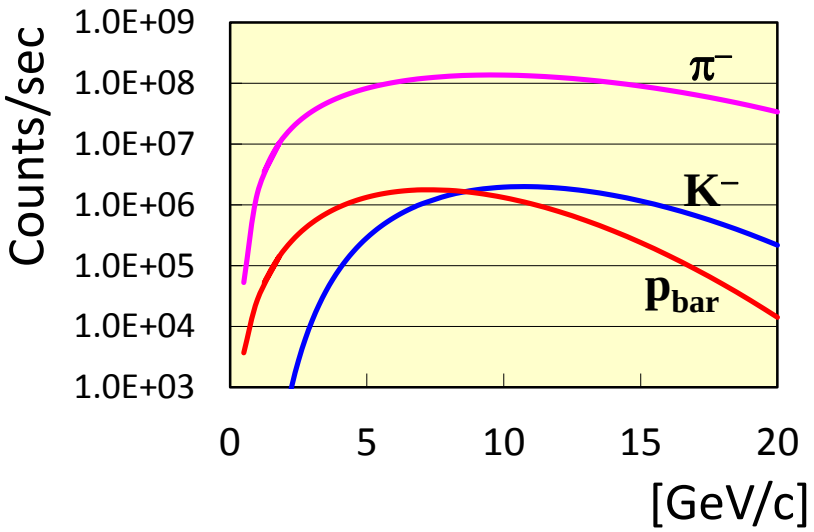
- Search for m to e conversion
- 8 GeV, 50 kW protons
- Branch from the high-momentum BL
- Annex building is being built at the south side.

J-PARC High-momentum BL

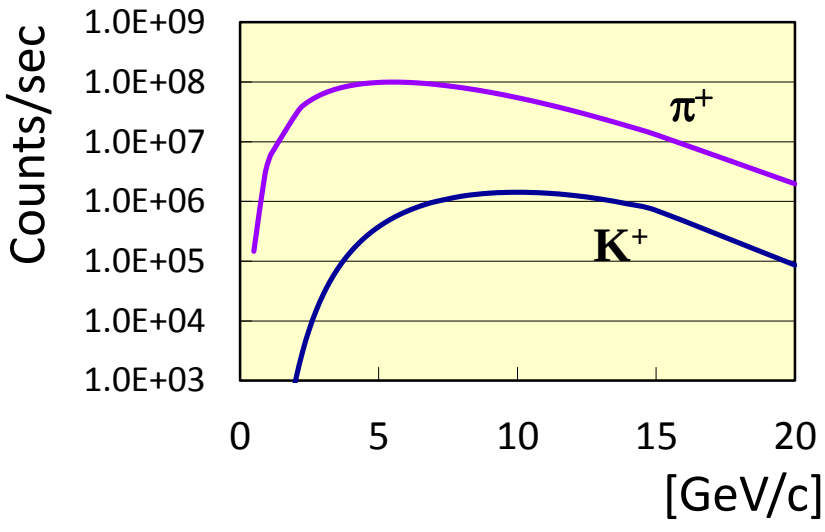
Unseparated secondary beams

- High-intensity secondary Pion beam
- High-resolution beam: $\Delta p/p$ ~ 0.1%

Negative Hadron Beams
(Prod. Angle = 0 deg.)



Positive Hadron Beams
(Prod. Angle = 3.1 deg.)



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

Basic Layout of Drell-Yan Experiment

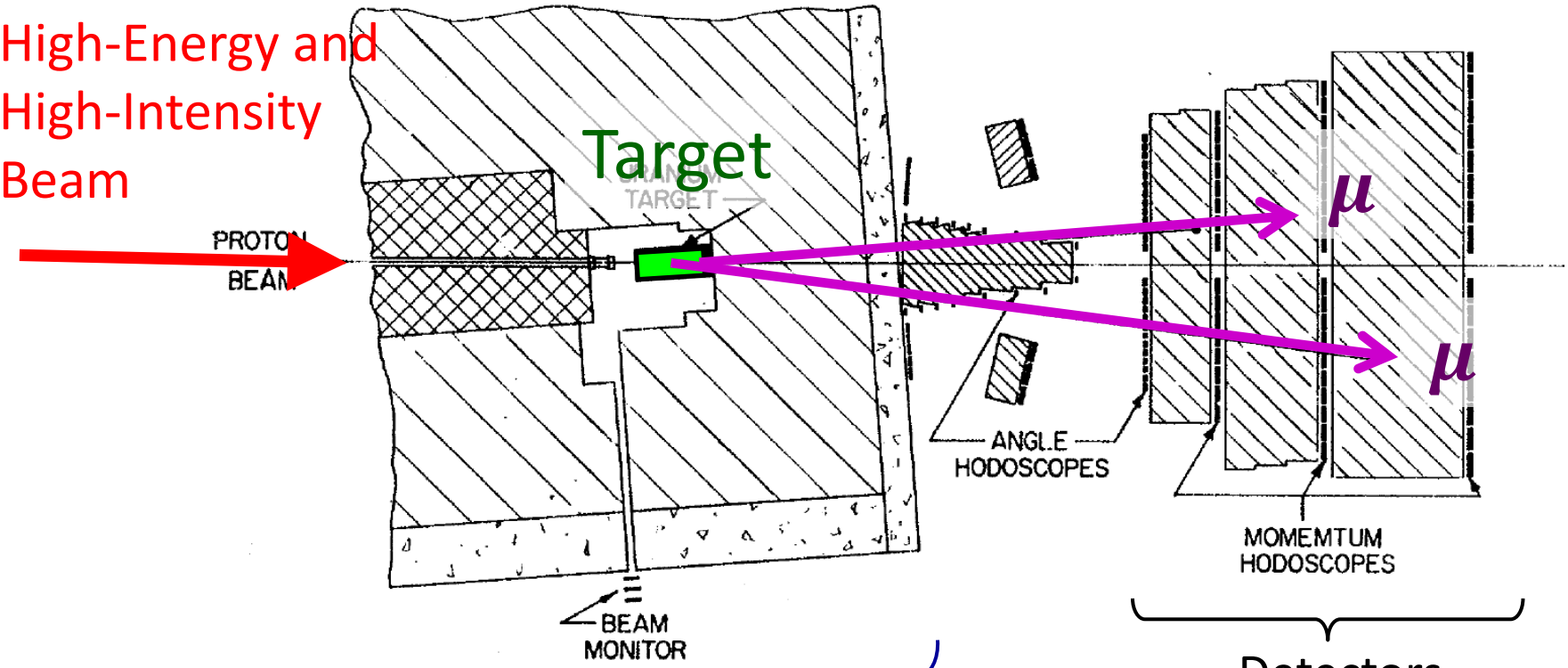
~ Earliest Date ~

at AGS

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

$$p\,\mathrm{U} \rightarrow \mu^+\mu^- X$$

High-Energy and High-Intensity Beam



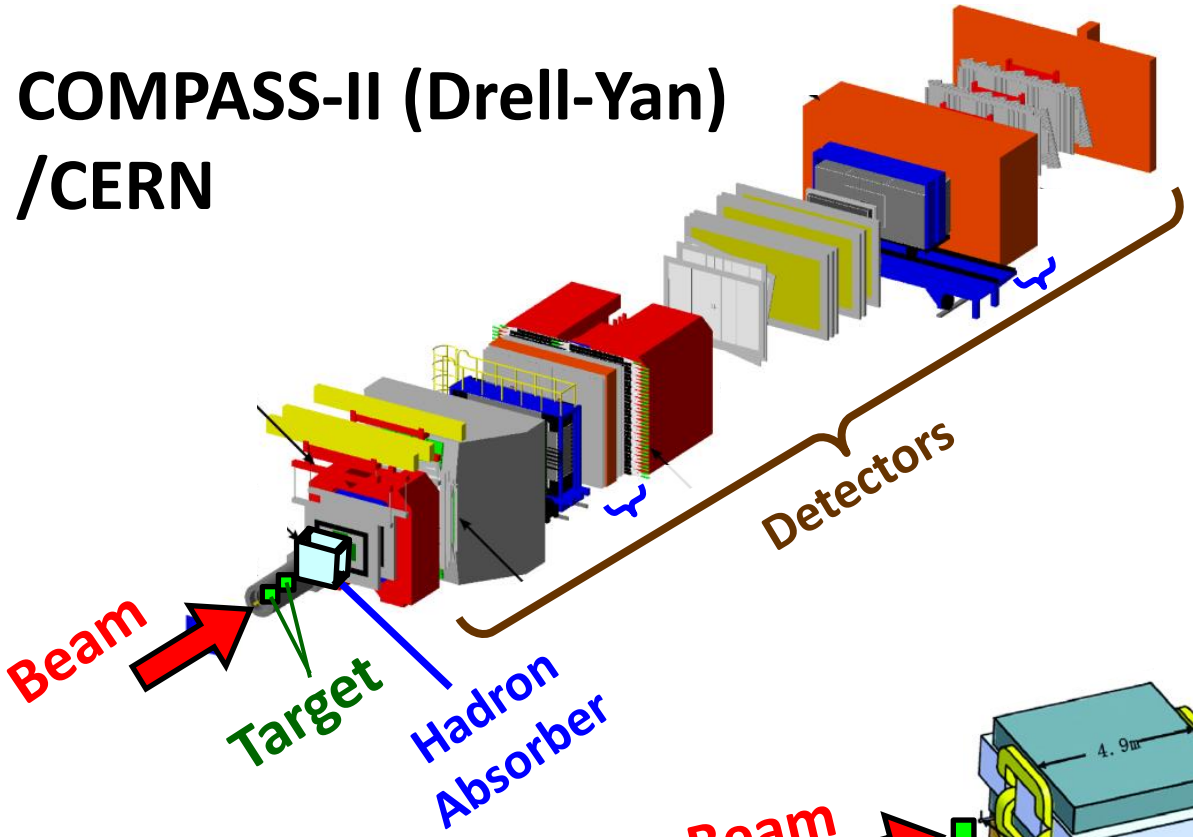
Hadron Absorber (Material Wall)

Detectors (Momentum Measurement)

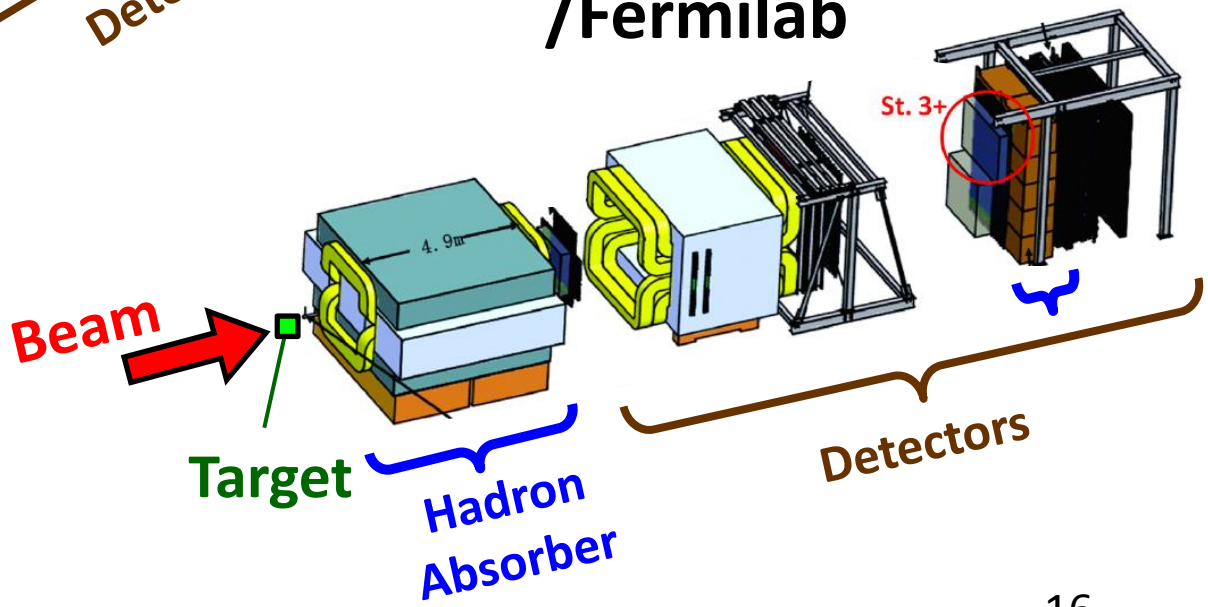
Basic Layout of Drell-Yan Experiment

~ Recent Date ~

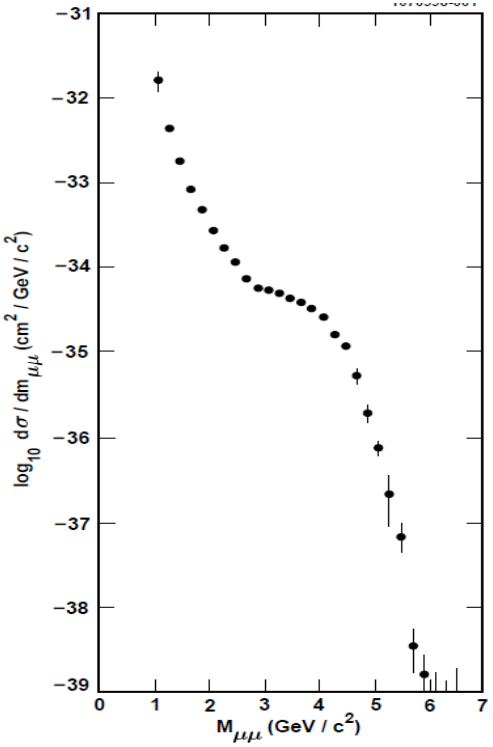
COMPASS-II (Drell-Yan) /CERN



SeaQuest /Fermilab

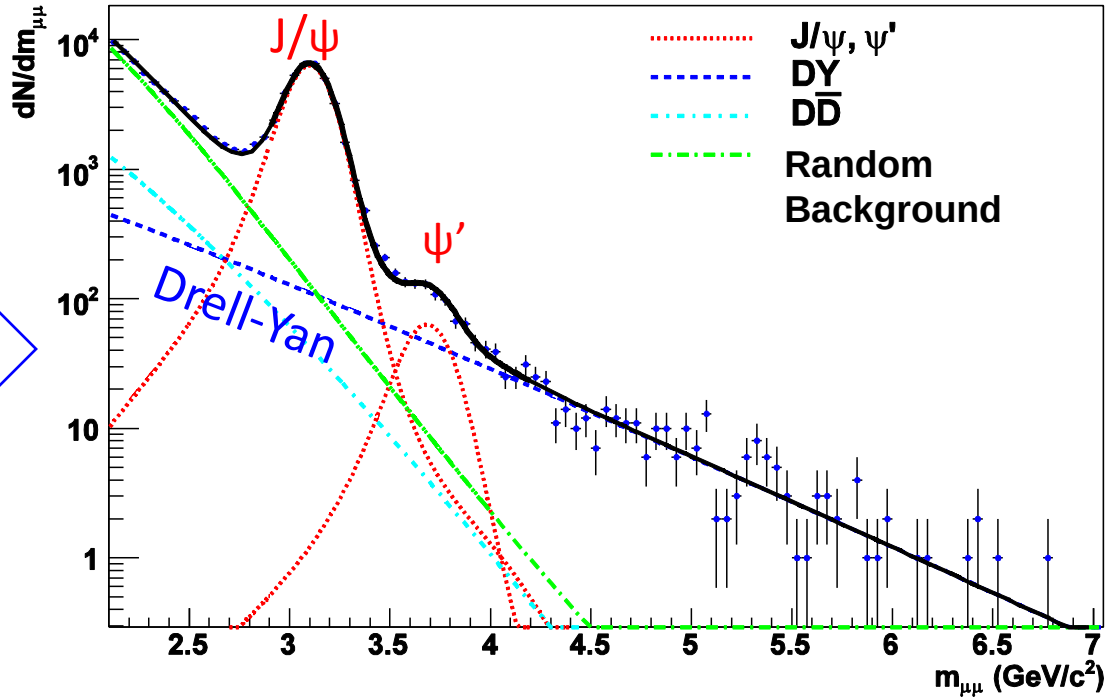


Dimuon Invariant Mass Spectrum



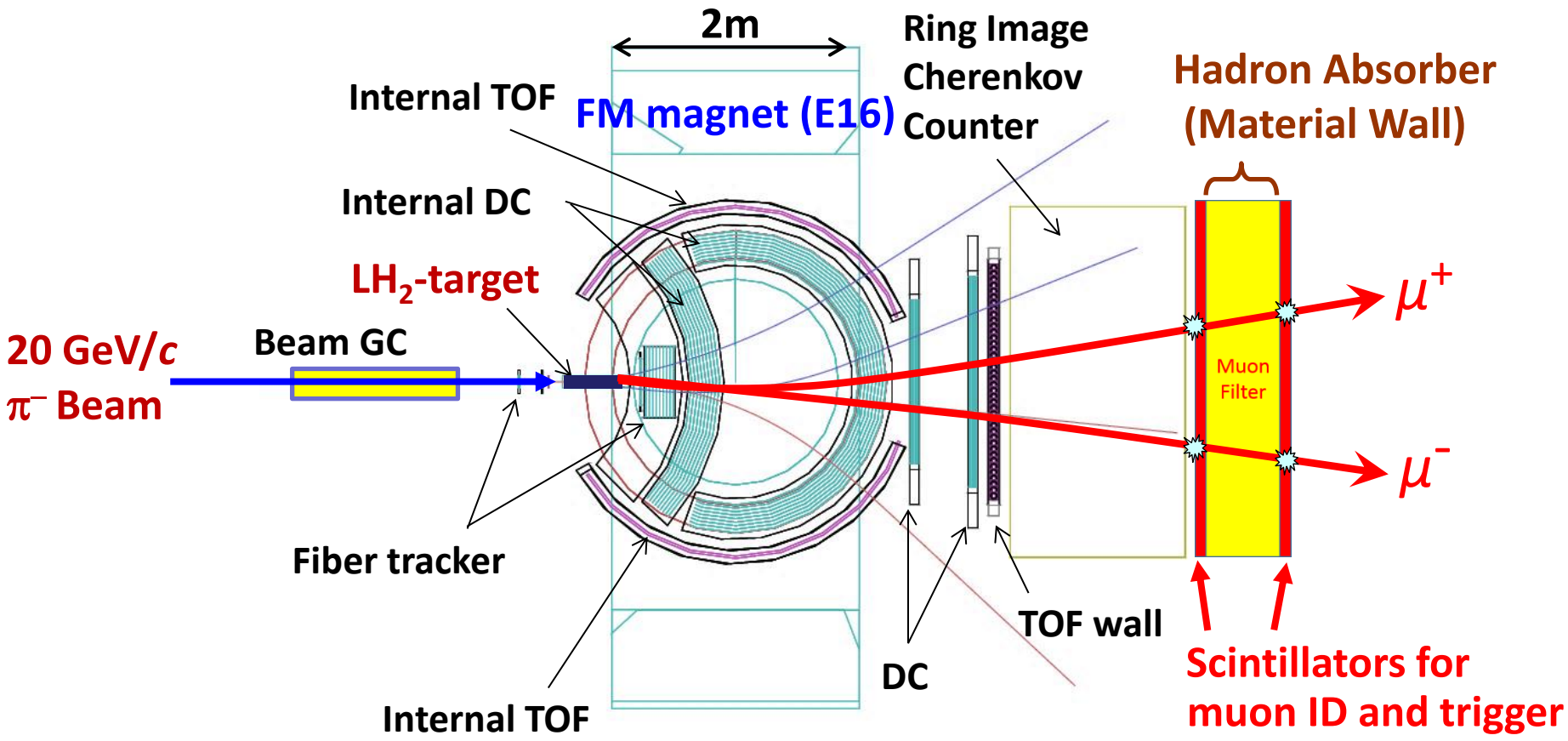
proton-Uranium collisions at AGS.

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



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

Extension of J-PARC E50 Experiment for Drell-Yan ($\pi^- p \rightarrow \mu^+ \mu^- X$) measurement



Original Configuration for Charmed Baryon Spectroscopy

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

Extension part

Proposal is currently being prepared.

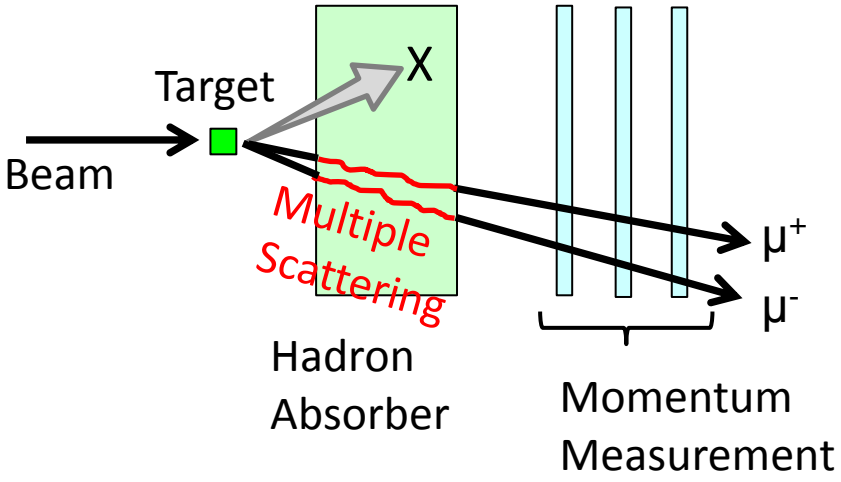
Identifying the Exclusive Drell-Yan Process with Missing Mass Technique

$$\underbrace{\pi^- p}_{\text{in}} \rightarrow \underbrace{\mu^+\mu^-}_{\text{out (measured)}} X$$

$$M_X^2 = \left(\sum E_{in} - \sum E_{out}\right)^2 - \left(\sum \boldsymbol{p}_{in} - \sum \boldsymbol{p}_{out}\right)^2$$

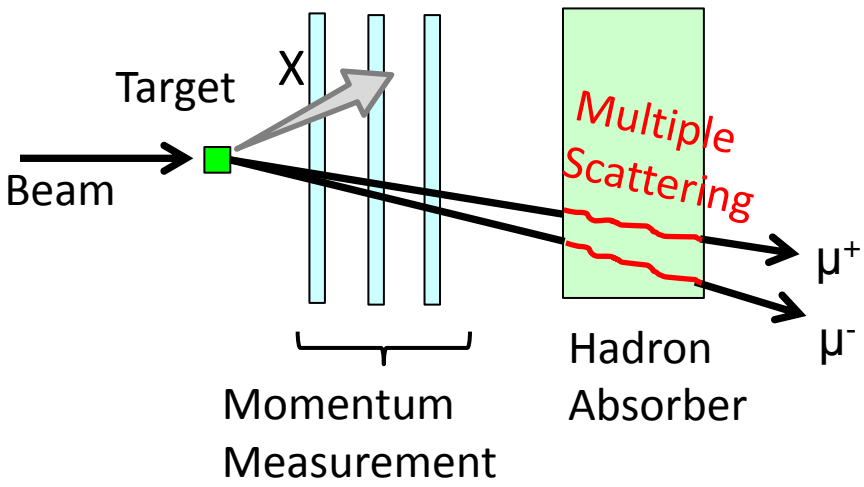
- Exclusive Drell-Yan process
  $M_X = M_n$ (0.9396 GeV/c^2)
- Inclusive Drell-Yan process, other Backgrounds
  $M_X > M_n$

Typical Drell-Yan experiment



Worse Resolution for M_x

Proposed Drell-Yan experiment



Best resolution for M_x

J-PARC E50 + Muon ID

Special Features

- **(Relatively) lower beam energy**
  → Higher total cross section of exclusive Drell-Yan process
- **Open aperture** without hadron absorber before momentum measurement
  → Minimizing the multiple-scattering effect.
  → Identifying the exclusive Drell-Yan process with missing mass technique
- **Muon ID** and momentum measurement at the forward angles

J-PARC High-*p* BL + E50 + Muon ID will provide the best opportunity to measure the **exclusive Drell-Yan process ($\pi^- p \to \mu^+ \mu^- n$)**

Yield Estimation

Event Generator

- Inclusive Drell-Yan

  Pythia 6.4.26 + LHAPDF 5.8.9

- Exclusive Drell-Yan

  GPD:

  Pire 2001: EPJC 23, 675 (2002)

  Kroll 2013: EPJC 73, 2278 (2013)

  Kroll 2015: arXiv: 1506.04619

- Background

  JAM 1.132

Particle Transportation + Detector Response

Geant 4.9.3

(E50 spectrometer + Muon ID)

Total Cross Section

Inclusive Drell-Yan ($M_{\mu\mu}$>1.5 GeV)

	π^-	π^+
10 GeV	2.11 nb	0.323 nb
15 GeV	2.71 nb	0.493 nb
20 GeV	3.08 nb	0.616 nb

Exclusive Drell-Yan ($M_{\mu\mu}$>1.5 GeV, $|t-t_0|$<0.5 GeV^2)

	π^- (Pire 2001)	π^- (Kroll 2013)	π^- (Kroll 2015)
10 GeV	6.28 pb	17.53 pb	140 pb
15 GeV	4.66 pb	10.64 pb	20 pb
20 GeV	3.69 pb	7.24 pb	

Hadronic Background

	π^-	π^+
10 GeV	26.9 mb	24.8 mb
15 GeV	25.8 mb	24.1 mb
20 GeV	25.1 mb	23.5 mb

Experimental Conditions

- **Target** : 57cm LH_2 (n_{TGT} = 4 g/cm^2)
- **ε(DAQ*Tracking*PID)** = 0.9*0.7*0.9
- **Beam momentum resolution**: $\Delta p/p$ = 0.1 %
- **Detector resolution**: $\Delta M/M$ = 1 %
- **Exclusive DY**: ~ 1.2 events/day/pb for $I_{beam}=10^7$ π^-/sec
- **π^- beam momentum**: 10/15/20 GeV/c
- **Data Taking Period**: 50 days

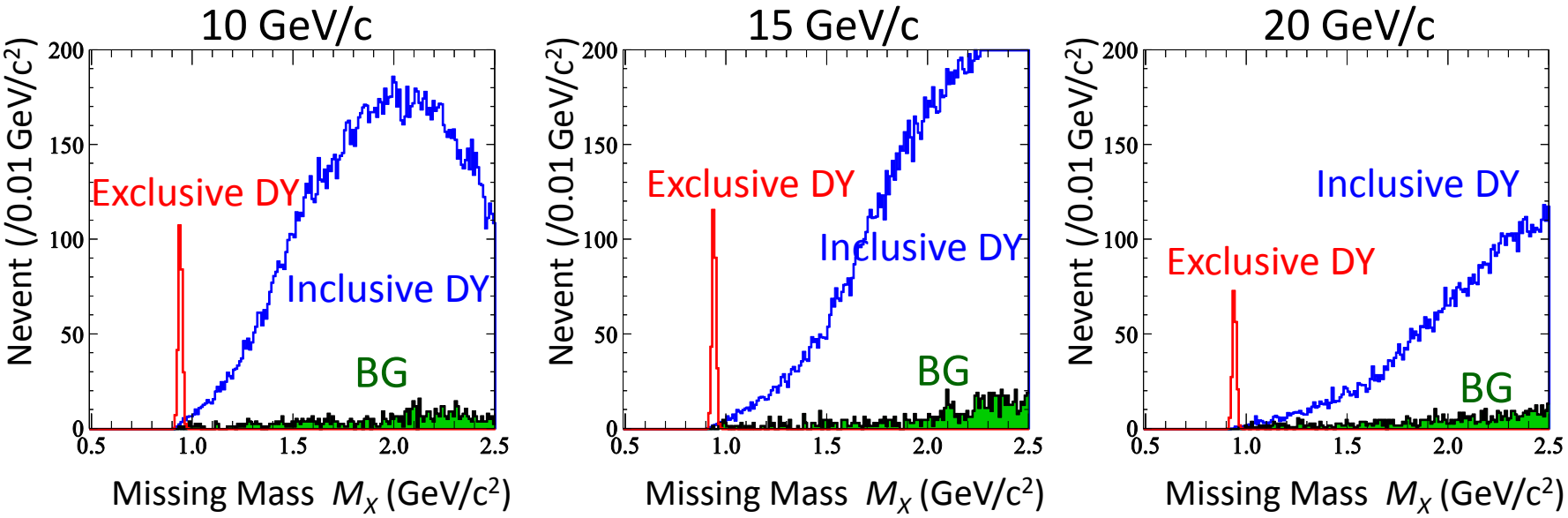
Expected Missing Mass M_X distribution

Data Taking Period: 50 days

$1.5 < M_{\mu^+\mu^-} < 2.9$ GeV/c^2

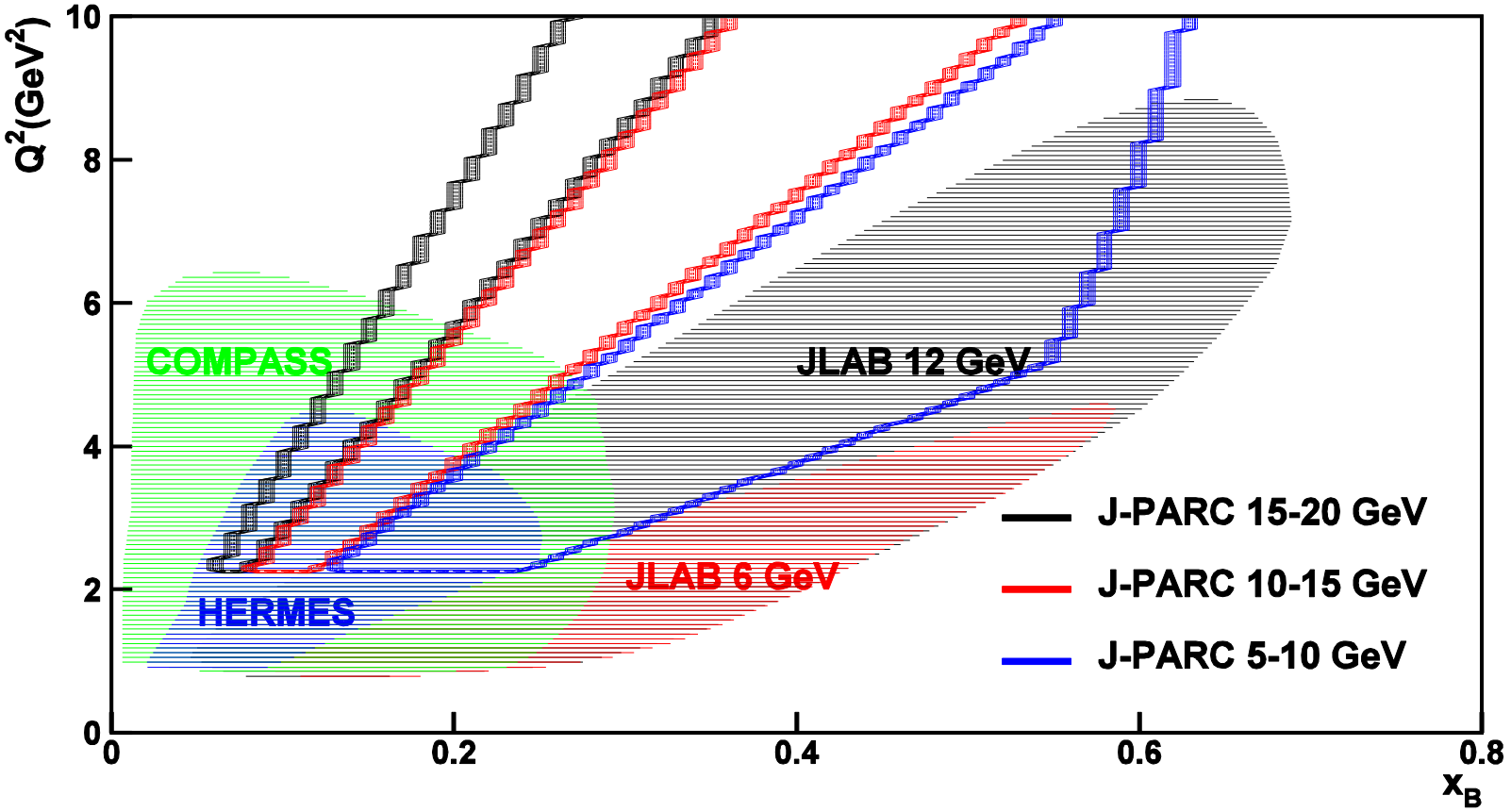
Preliminary

π^- Beam Momentum



- 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



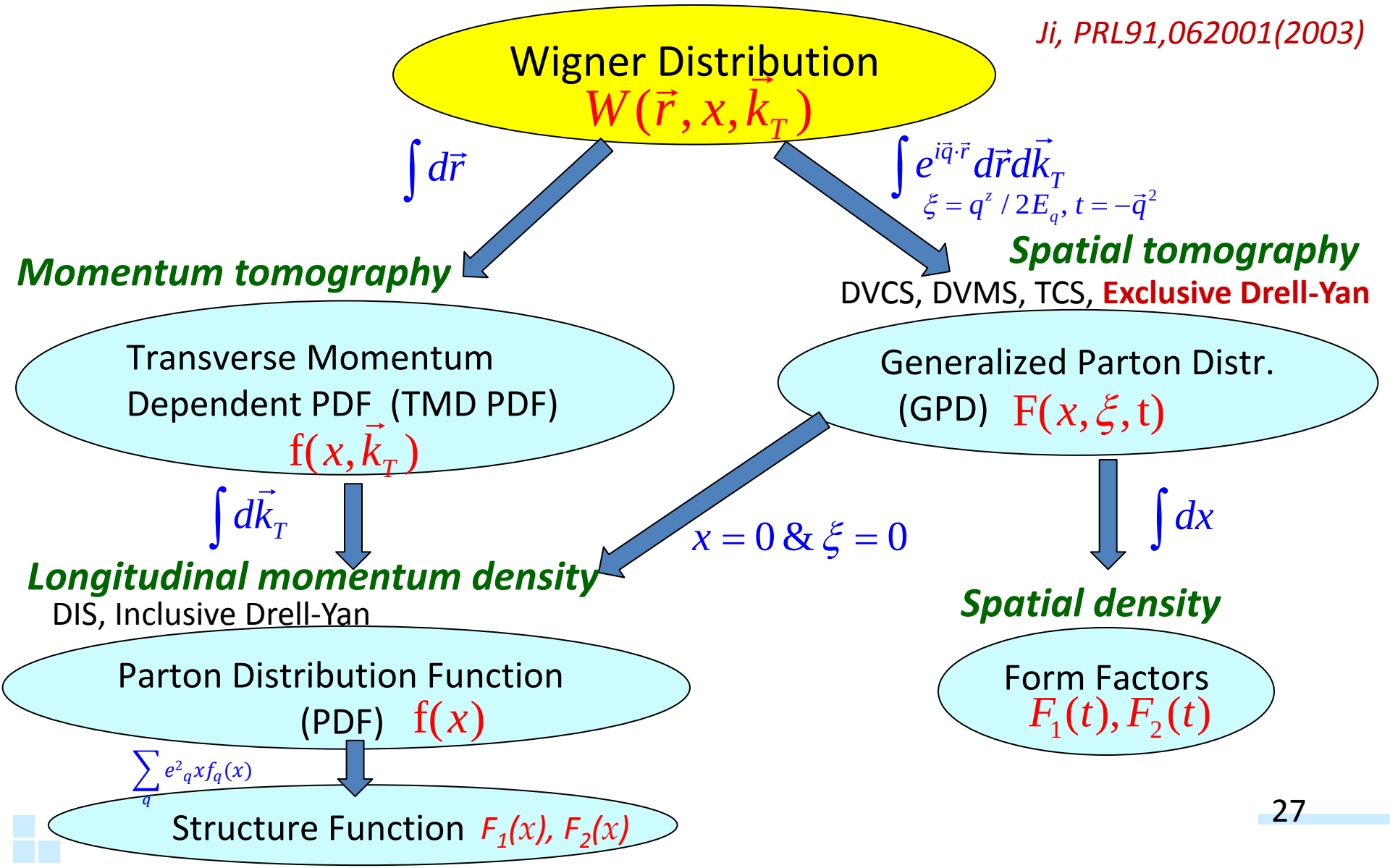
- J-PARC: **Time-like** approach and **large-Q^2** region.

Summary

- High-energy hadron beam at J-PARC is unique for studying hard exclusive processes.
- **Measurement of GPD through the exclusive π-induced Drell-Yan process at J-PARC** will offer
  - Information of **GPD at large-Q^2 region.**
  - Test of **universality of GPD in space-like and time-like processes.**
  - Test of **QCD-evolution properties of GPD.**
  - Test of **factorization of exclusive Drell-Yan process.**
- The preliminary study of the measurement with J-PARC E-50 spectrometers is **feasible**.

Spares

Nucleon Partonic Structure



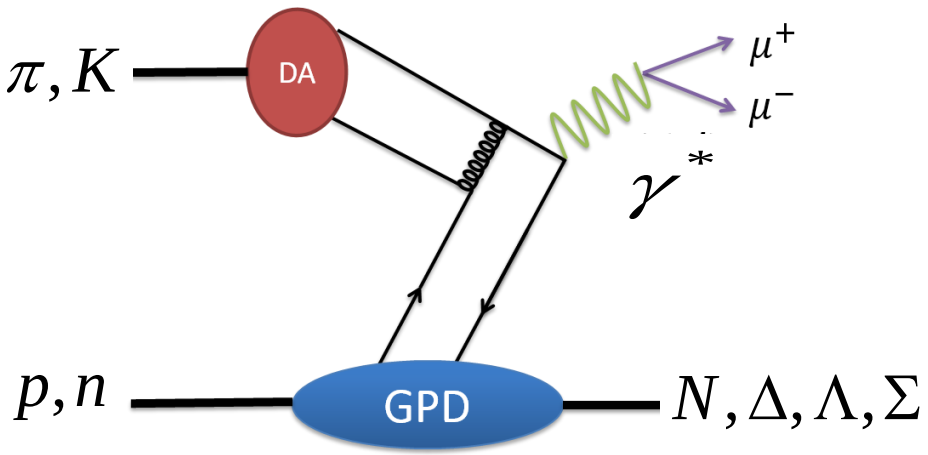
Physics Programs at J-PARC E50 + Muon ID

- **Charm and Strange production**
  - Charmed Baryon Spectroscopy *(E50)*
    - Di-quark Correlation in Heavy-quark system
  - Ξ baryon (S= -2) spectroscopy *(LOI by M. Naruki and K. Shirotori)*
- **Hard exclusive process**
  - Exclusive $\Lambda(1405)$ production at large angles
    - Valence quark structure of $\Lambda(1405)$
  - Transition GPD
- **Drell-Yan process**
  - Exclusive pion-induced Drell-Yan
    - GPD of proton
    - Pion DA
  - Inclusive pion-induced Drell-Yan:
    - $d(x)/u(x)$ at large x
    - Violation of Lam-Tung relation, BM functions
    - Pion PDF
- Many interesting physics ideas are left out, e.g. the studies using nuclear targets and polarized beam/target.

“GPD” and “Transition GPD”

- $\pi^- \mathrm{p} \to \gamma^* n$
- $\pi^- \mathrm{p} \to \gamma^* \Delta^0$
- $\pi^- \mathrm{n} \to \gamma^* \Delta^-$
- $\pi^+ \mathrm{n} \to \gamma^* \mathrm{p}$
- $\pi^+ \mathrm{p} \to \gamma^* \Delta^{++}$
- $\pi^+ \mathrm{n} \to \gamma^* \Delta^+$

- $K^- \mathrm{p} \to \gamma^* \Lambda$
- $K^- \mathrm{p} \to \gamma^* \Lambda(1405)$
- $K^- \mathrm{p} \to \gamma^* \Lambda(1520)$
- $K^- \mathrm{n} \to \gamma^* \Sigma^-$
- $K^+ \mathrm{n} \to \gamma^* \Theta^+$



Inclusive DY

$(\pi^+/\pi^-)\ p \rightarrow \mu^+\mu^- X$

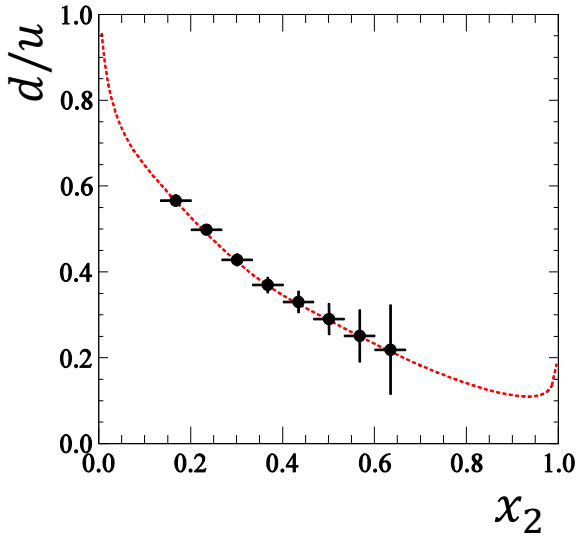
d/u measurement with E-50 Spectrometer + MuID

π^+ beam 150 days
π^- beam 50 days

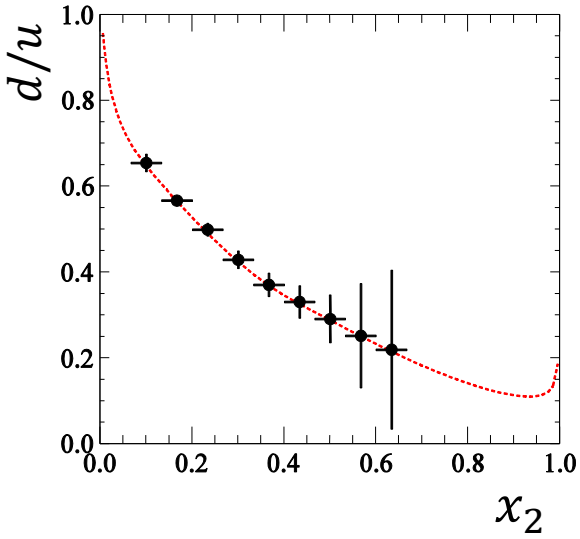
$1.5 < M_{\mu^+\mu^-} < 2.9\ \mathrm{GeV/c^2}$

Beam Momentum

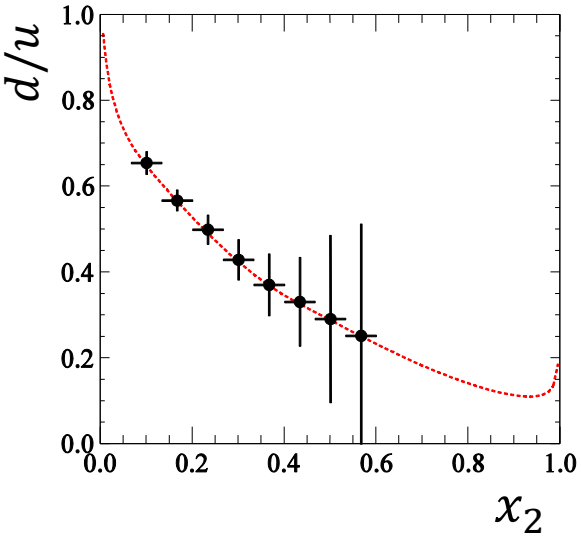
10 GeV



15 GeV



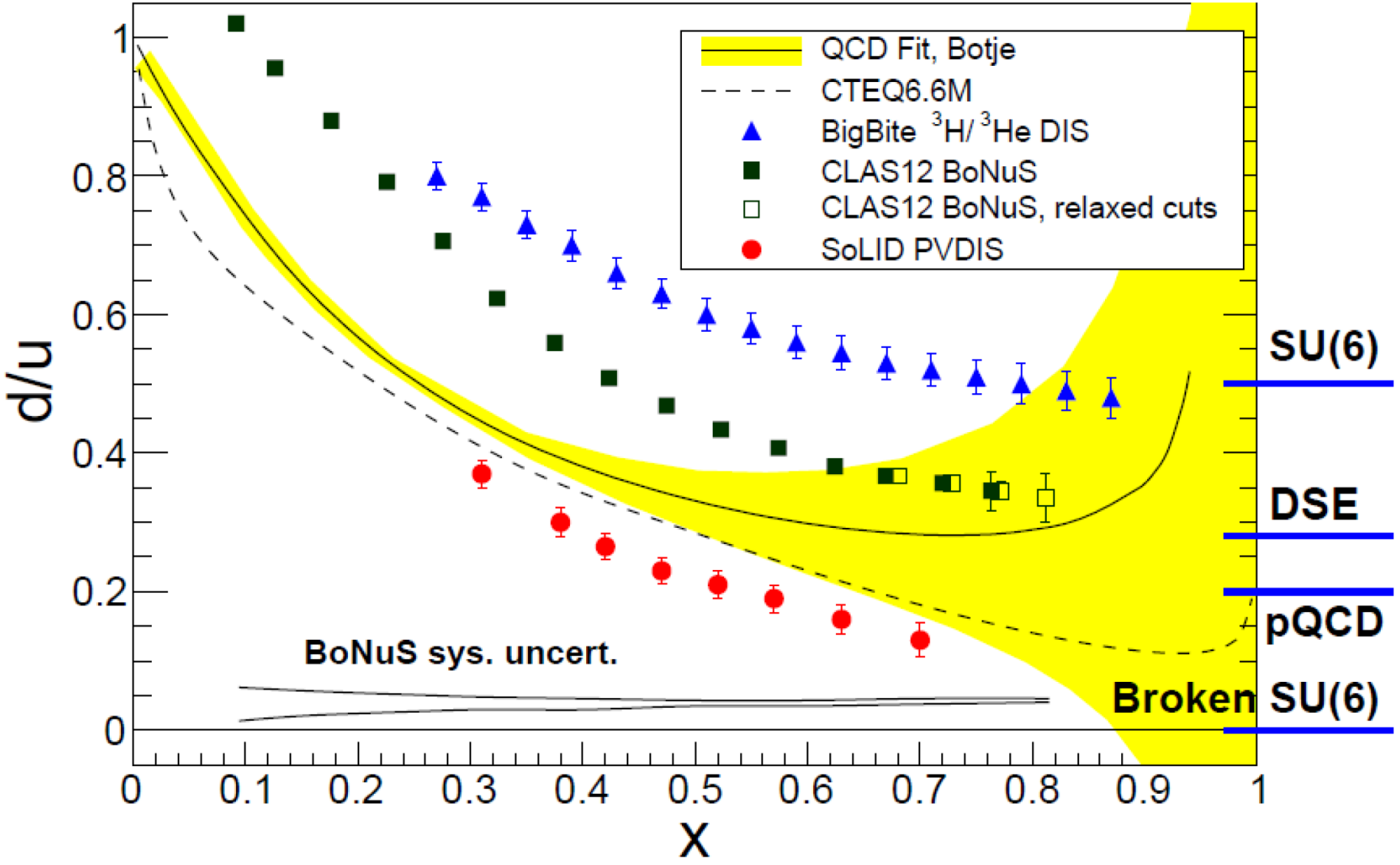
20 GeV



Statistics strongly depends on the prod. angle for secondary beam

Red lines : CTEQ6.6M

Projected 12 GeV d/u Extractions



DNP, Oct. 2014, Jen-Chieh Peng

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

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

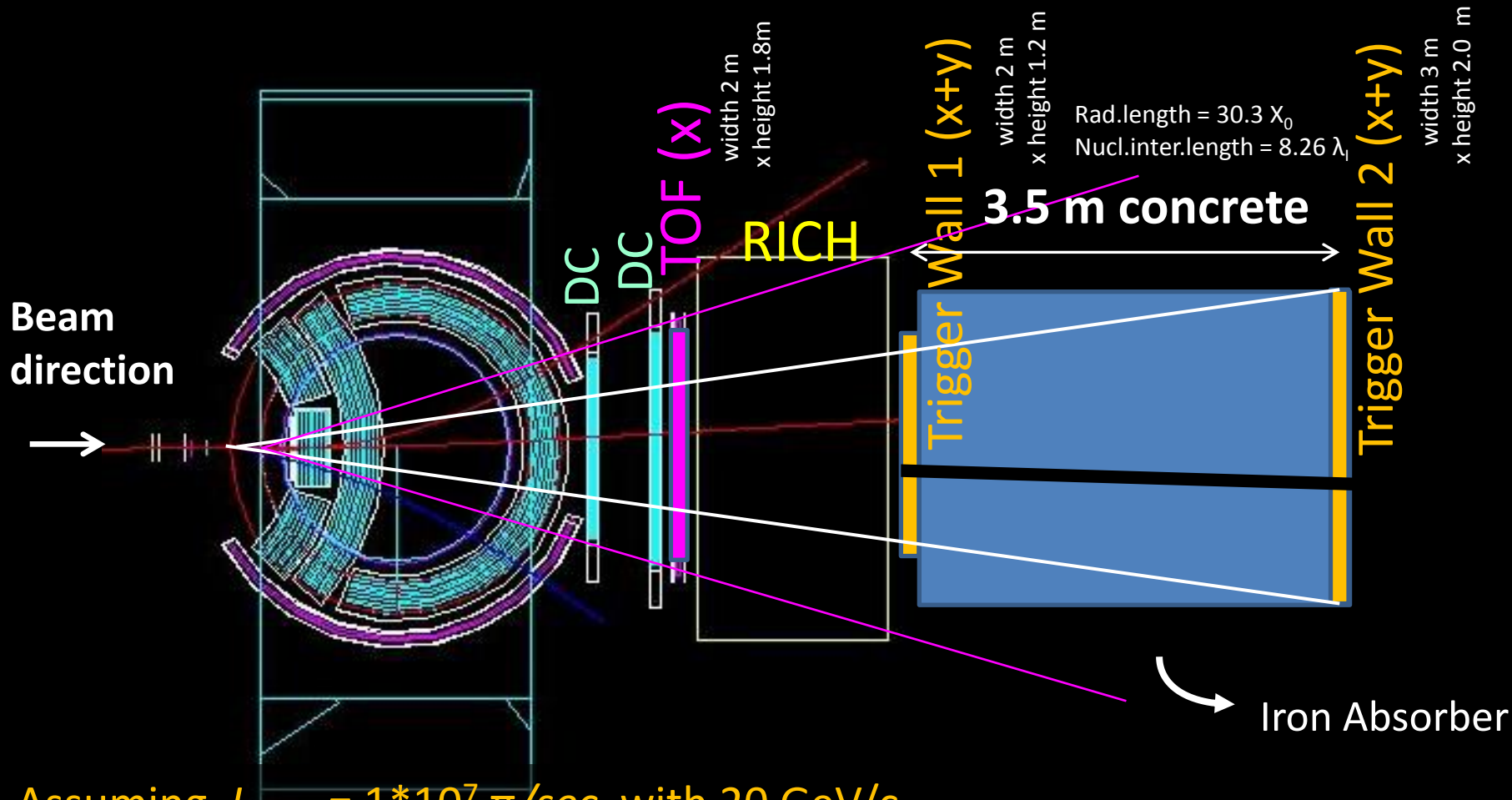
$\sigma_{DY}(\pi^+ + p) \sim \bar{d}^{\pi^+}(x_1)d^p(x_2)$ for large x_1 and x_2

hence

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

No nuclear correction for deuteron is needed

Dedicated Designs of Hadron Absorber and Trigger



Assuming I_{beam} = 1*10^7 π/*sec* with 20 GeV/c

Level-1 trig (nTOF >= 2 && nTrig1 >= 2 && nTrig2 >= 2) ~ 0.85 kHz

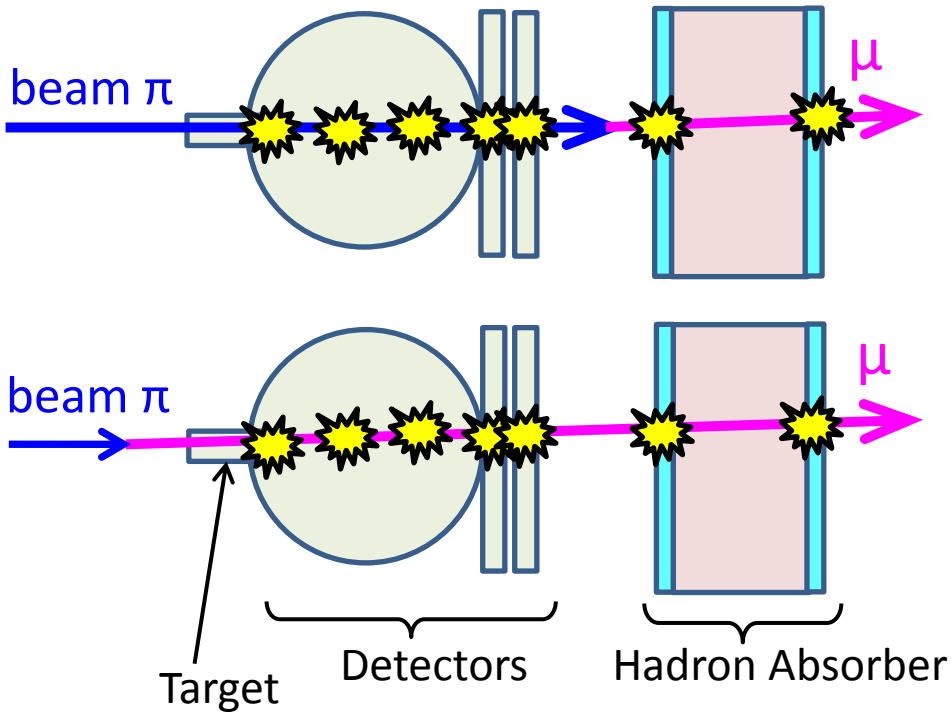
Level-2 trig (Level-1 trig && single muon trigger x2) ~ 0.26 kHz

Level-3 trig (Level-2 trig && dimuon trigger matrix) not yet

Main backgrounds and their rejections

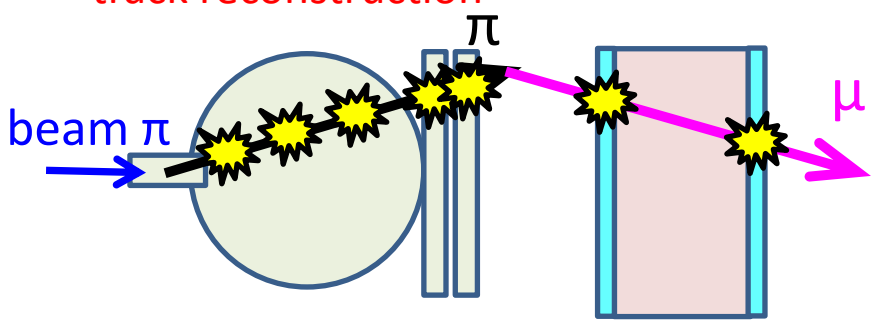
Beam decay

Removing by $|p|$ and *polar angle*.

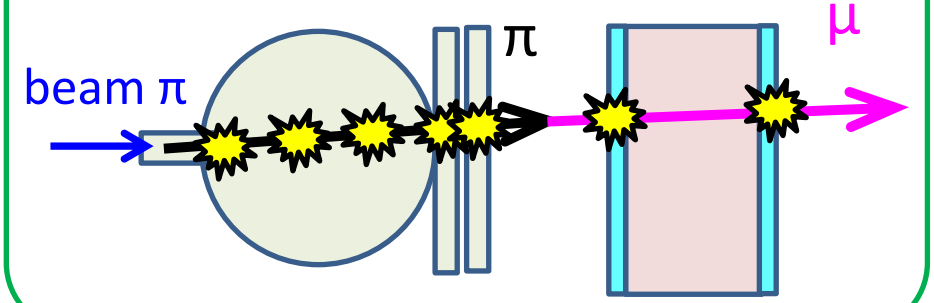


Produced Meson decay

Removing by the consistency of track and trigger hit and χ^2 probability of track reconstruction



Main background



+ pile-up (multiple beam in one event)