Nucleon Partonic Structure study with Exclusive Drell-Yan experiment at J-PARC

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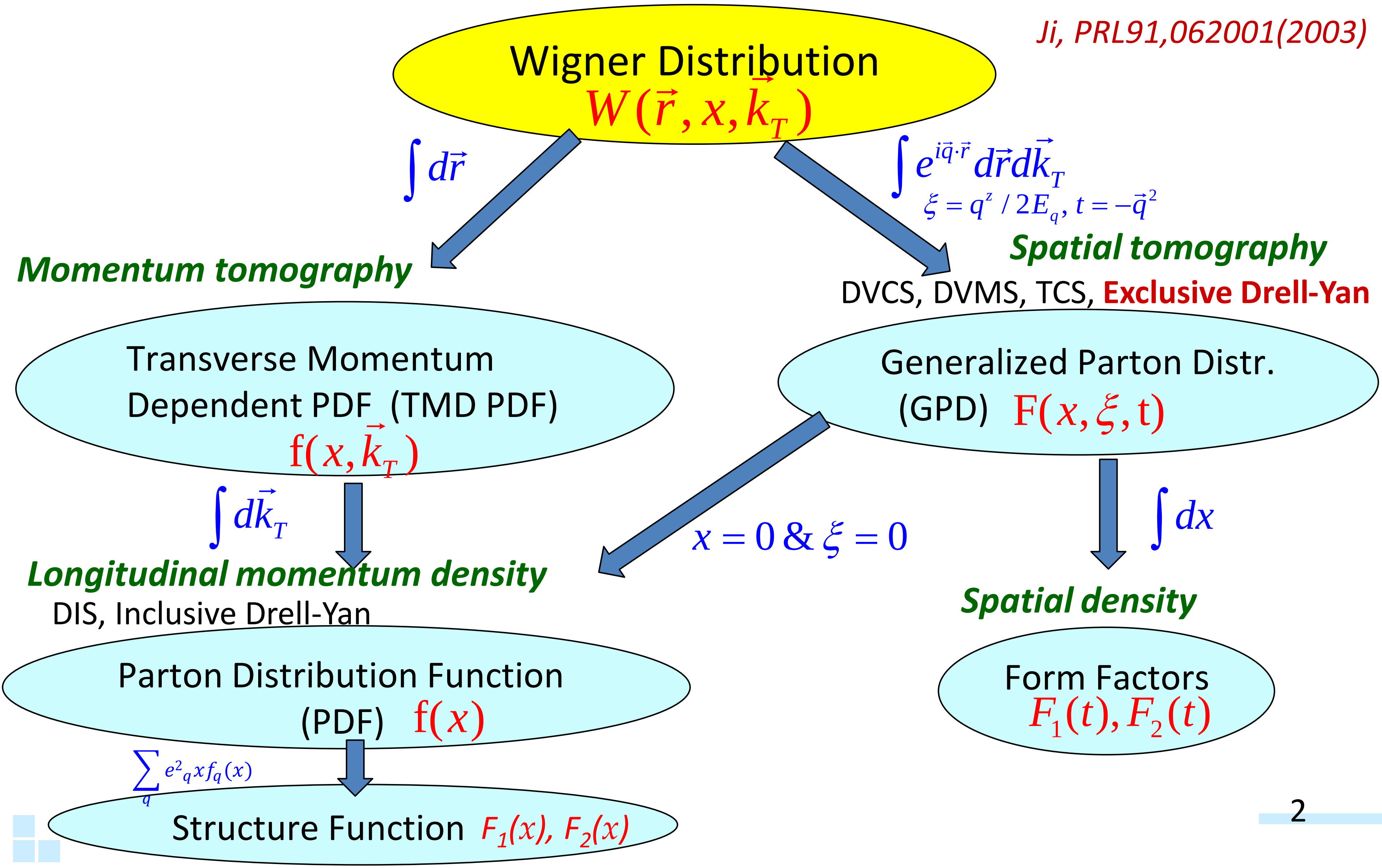
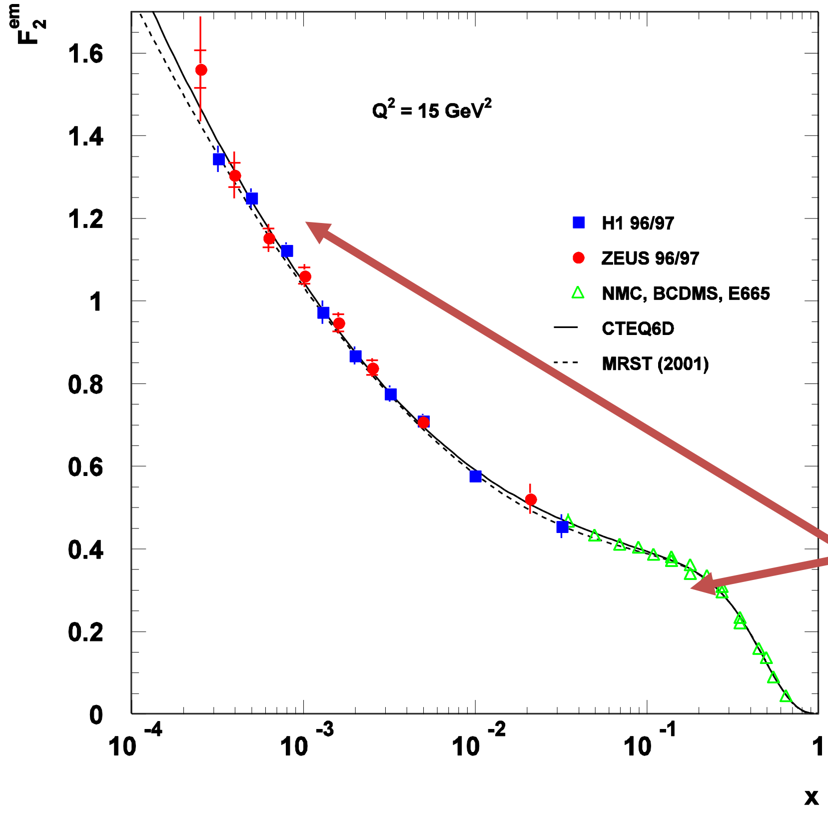
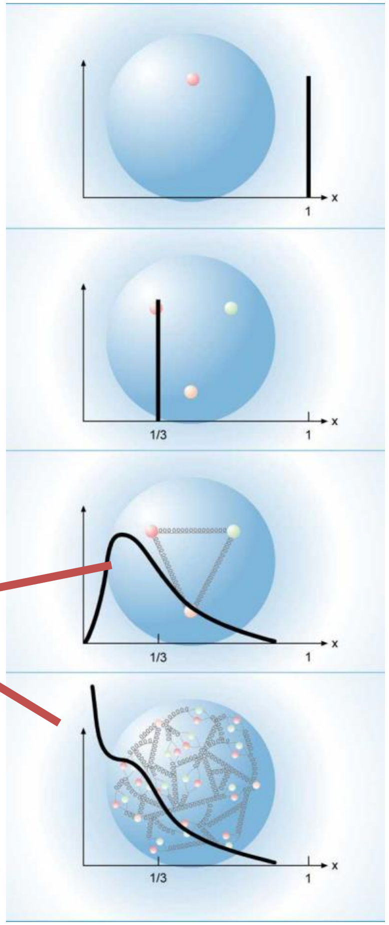
Spinfest workshop, 22th-24th Jul. 2015

Parton Distributions in Protons



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



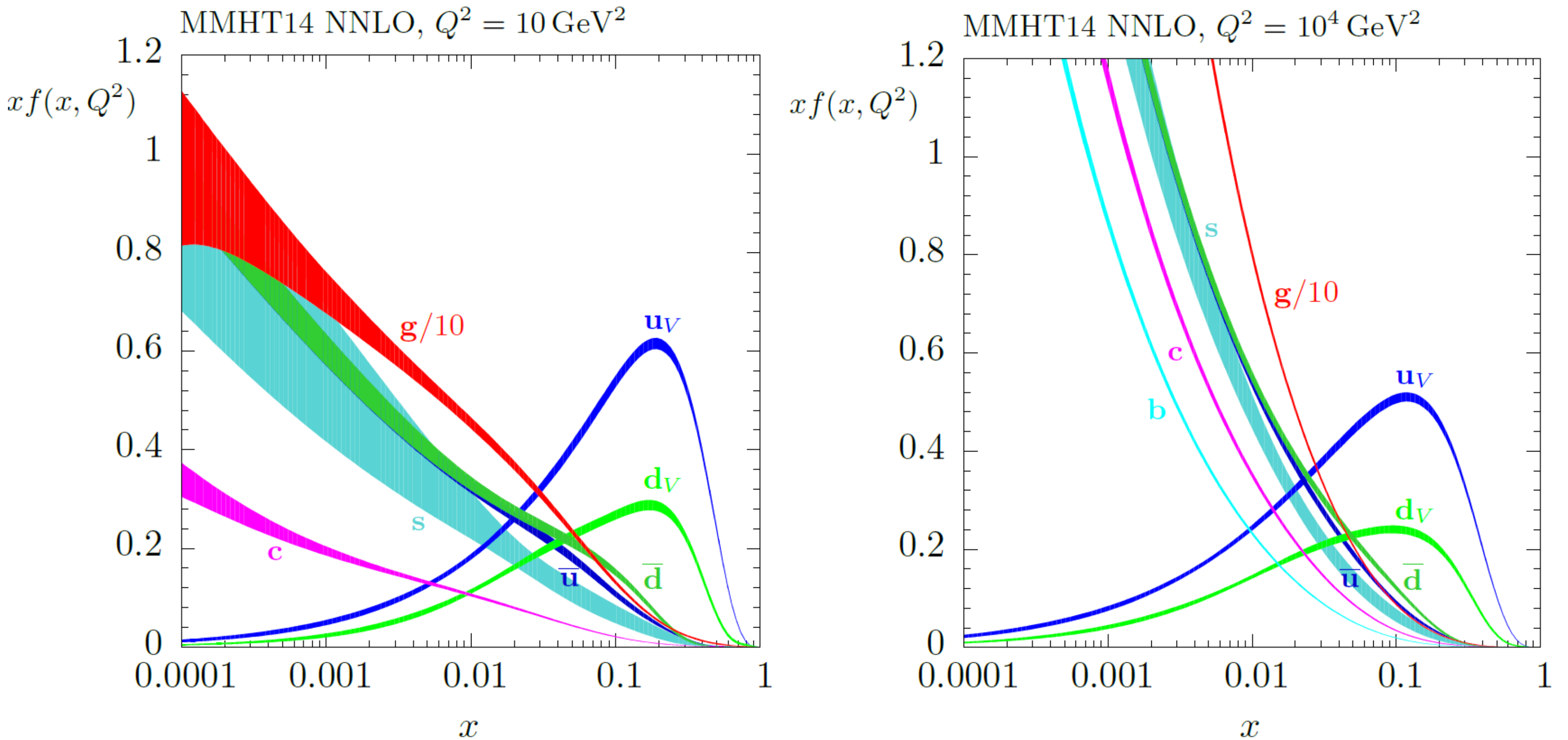


Bjorken x: longitudinal momentum fraction

Parton Distribution Function (PDF) of Proton

MMHT 2014 PDFs

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



Main Processes in Global PDF Analysis

Eur. Phys. J. C (2009) 63: 189–285

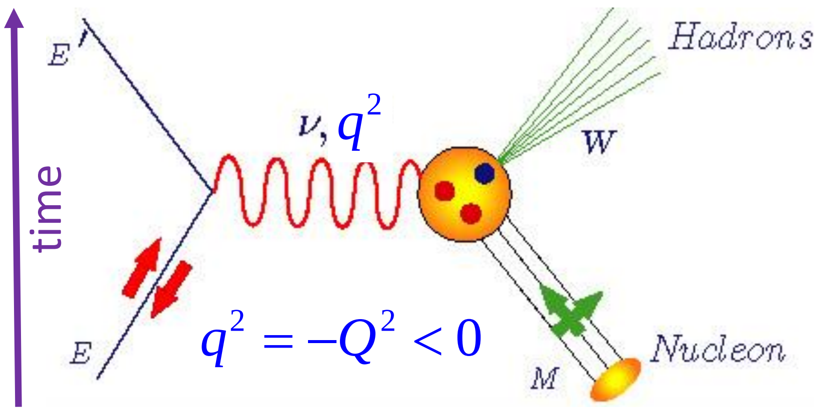
Process	Subprocess	Partons	x range
$\ell^\pm\{p,n\} \to \ell^\pm X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
$\ell^\pm n/p \to \ell^\pm X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
$pp \to \mu^+\mu^- X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \to \mu^+\mu^- X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu})N \to \mu^-(\mu^+)X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
$\nu N \to \mu^-\mu^+ X$	$W^* s \to c$	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	$x \gtrsim 0.05$

DIS

Drell-Yan

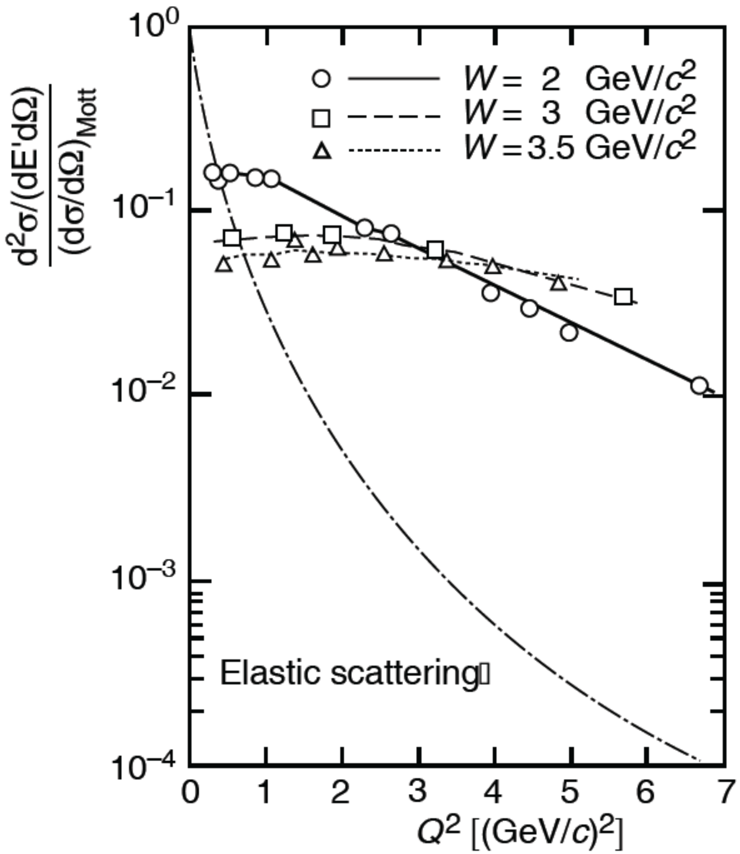
DIS

Deep Inelastic Scattering (DIS)



Space-like process

q^2 :Four-momentum transfer
x : Bjorken variable (=$Q^2/2M\nu$)
ν : Energy transfer
M : Nucleon mass
W : Final state hadronic mass

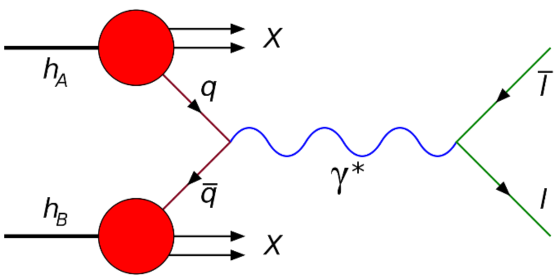


$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}[W_2(\nu,Q^2) + 2W_1(\nu,Q^2) * \tan^2(\theta/2)]$$

$$= \sigma_{Mott}[F_2(x,Q^2)/\nu + 2F_1(x,Q^2)/M * \tan^2(\theta/2)]$$

Drell-Yan process

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



Time-like process

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.

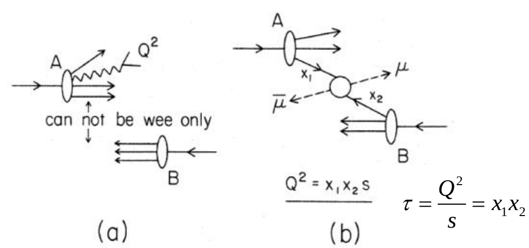


FIG. 1. (a) Production of a massive pair Q^2 from one of the hadrons in a high-energy collision. In this case it is kinematically impossible to exchange "wee" partons only. (b) Production of a massive pair by parton-antiparton annihilation.

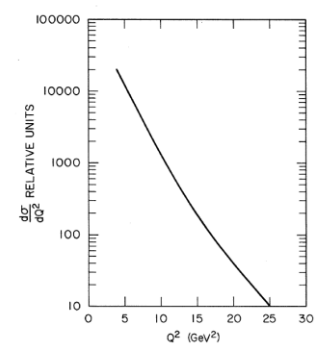


FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributions and with relative normalization.

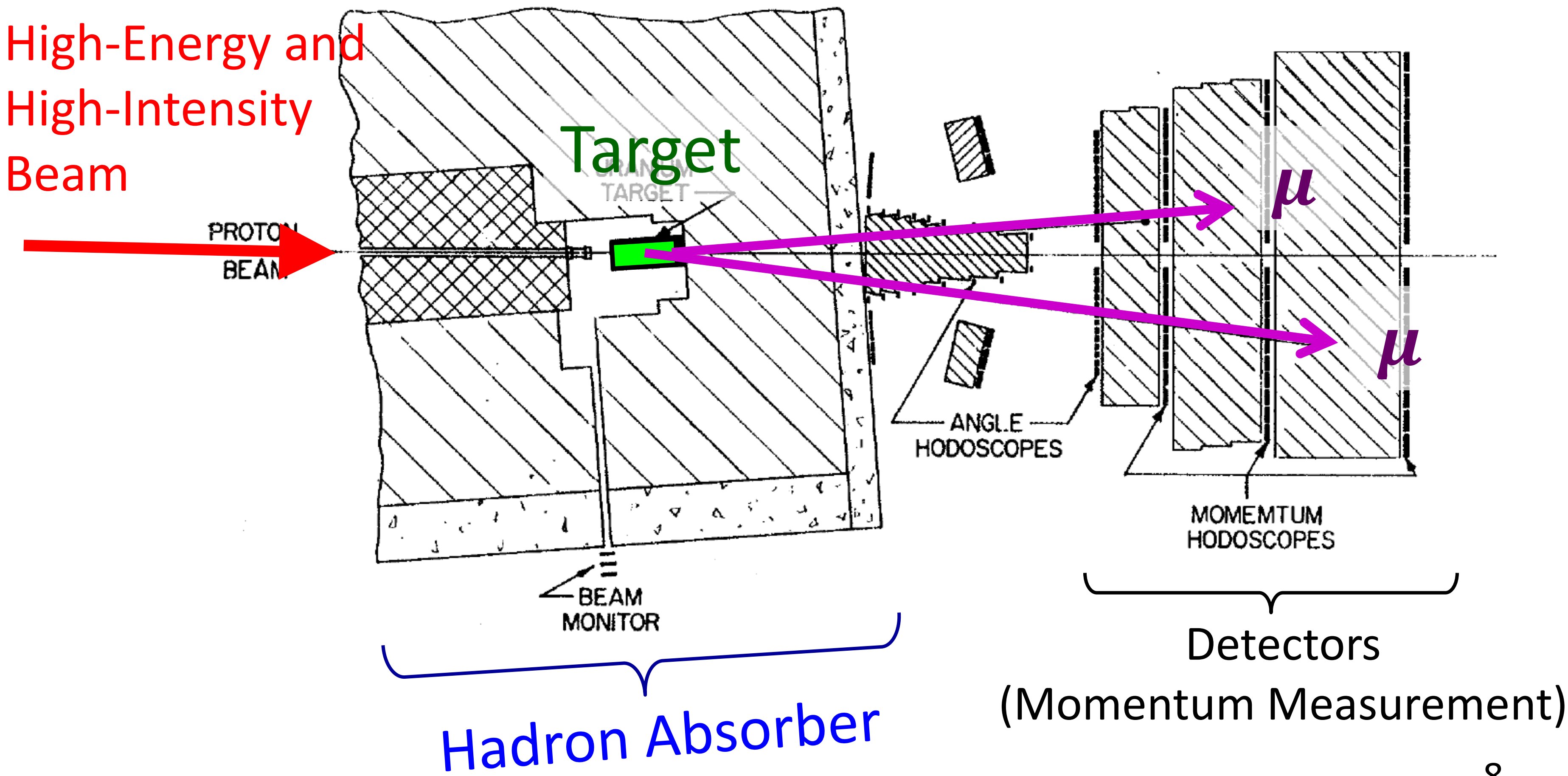
$$\frac{d\sigma}{dQ^2} = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\mathfrak{F}(\tau) = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\int_0^1 dx_1 \int_0^1 dx_2 \delta(x_1x_2-\tau)\sum_a \lambda_a^{-2} F_{2a}(x_1) F_{2\bar{a}}'(x_2),$$

Layout of Drell-Yan experiment

at AGS

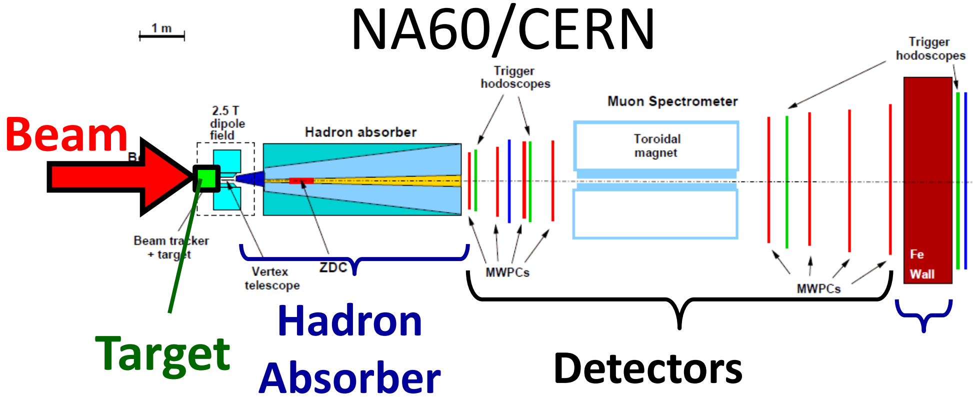
J.H. Christenson et al., PRL 25 (1970) 1523

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

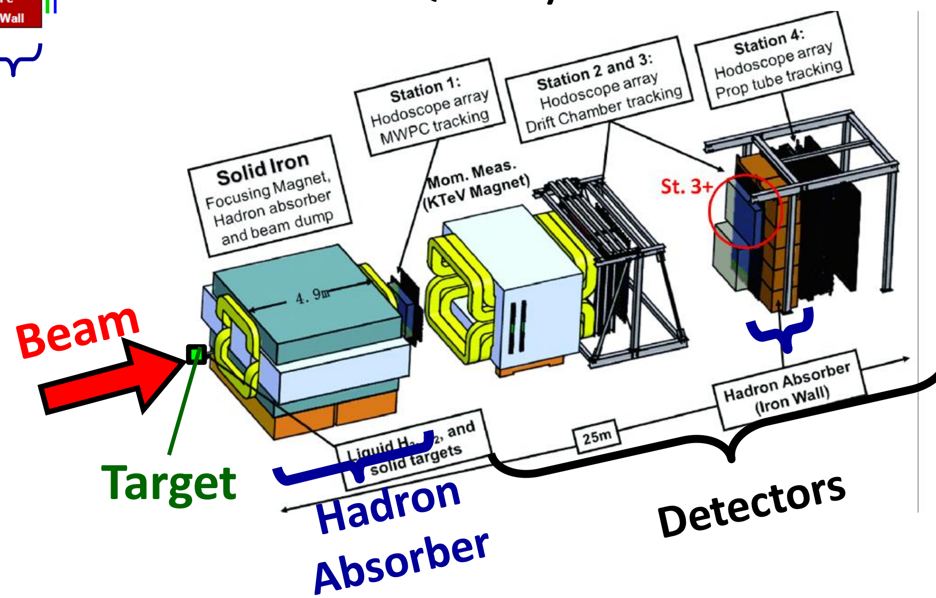


Layout of Drell-Yan experiment

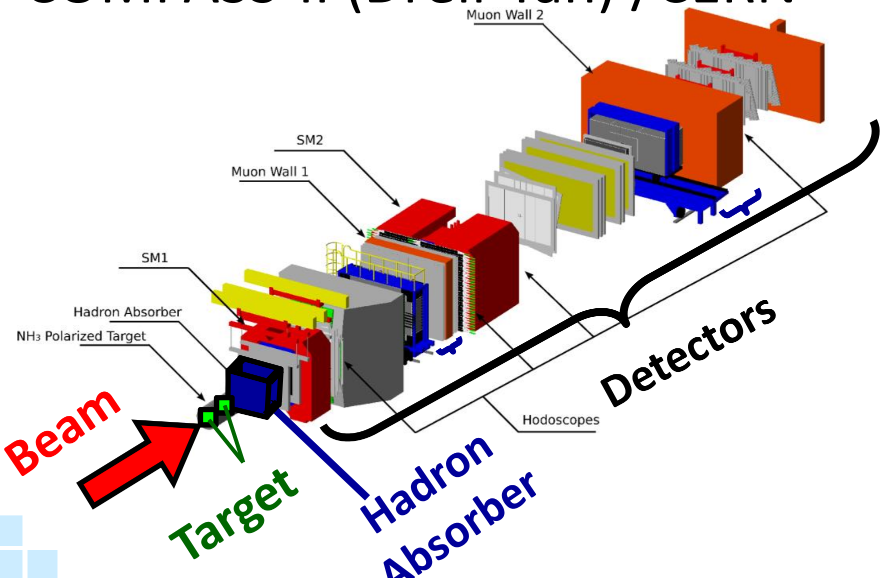
NA60/CERN



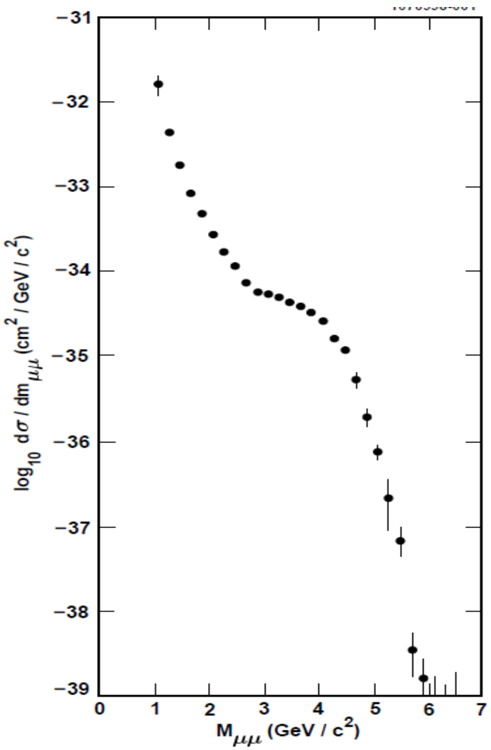
SeaQuest/Fermilab



COMPASS-II (Drell-Yan) /CERN

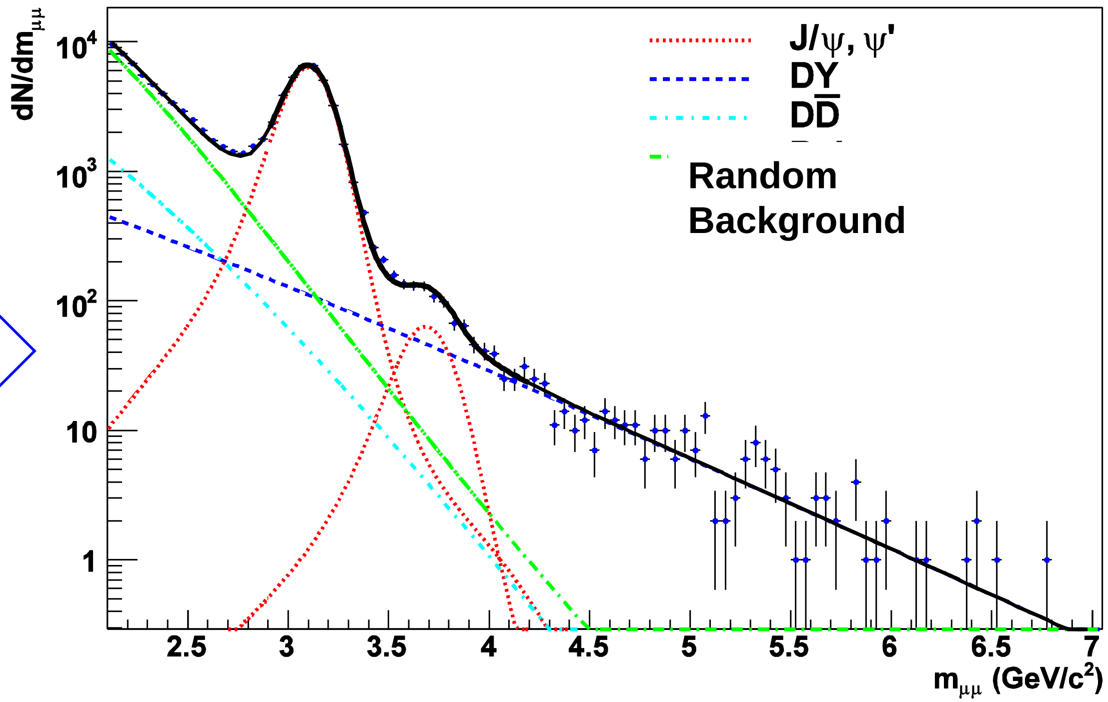


Dimuon Invariant Mass Spectrum



proton-Uranium collisions at AGS.

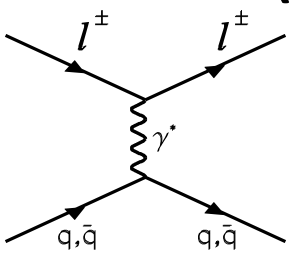
J.H. Christenson et al., PRL 25 (**1970**) 1523

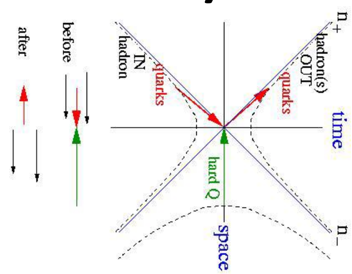


Indium-Indium collisions at 158 GeV/nucleon
NA60, PRL 99 (**2007**) 132302

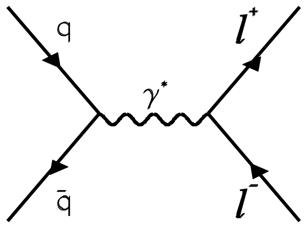
Complementarity between DIS and Drell-Yan

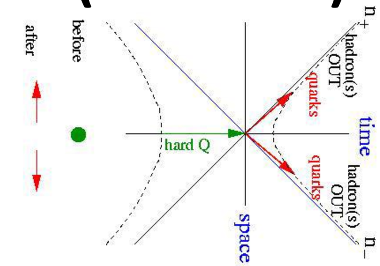
DIS (space-like)

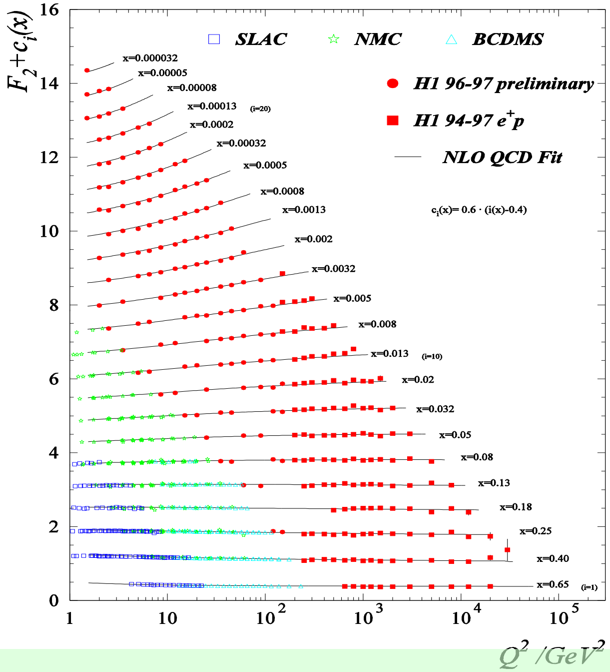


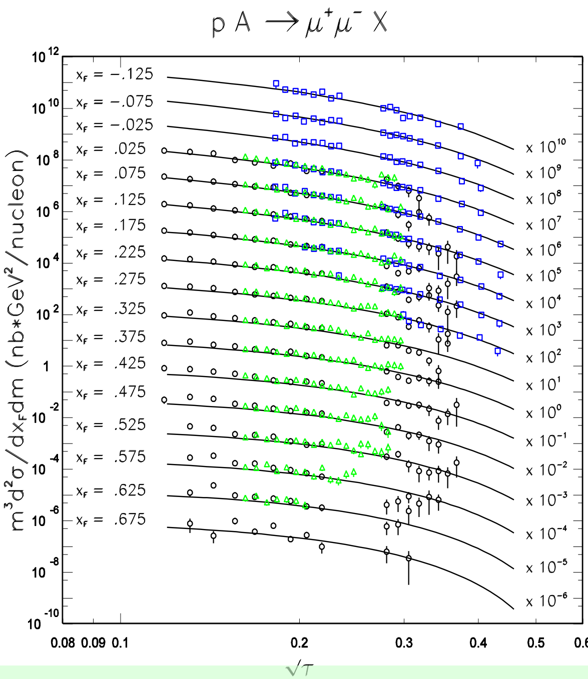


Drell-Yan (time-like)





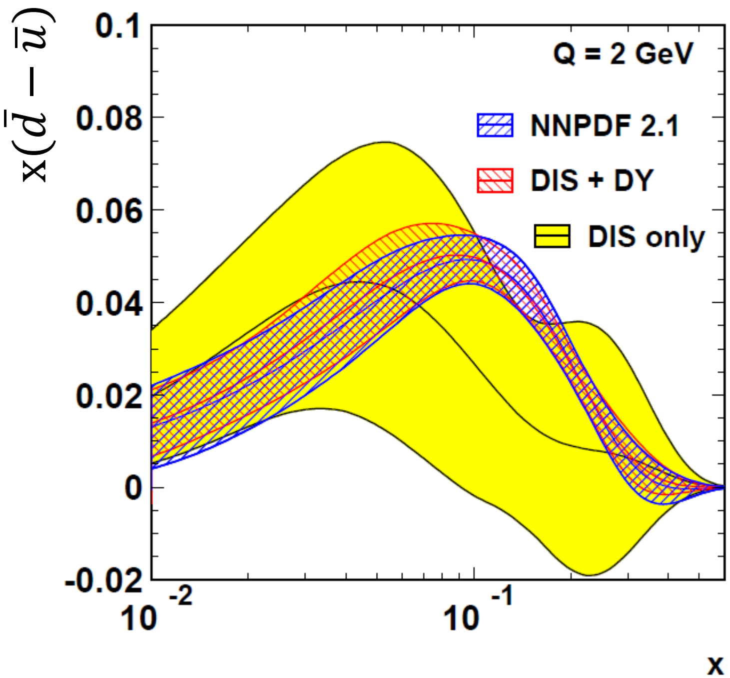


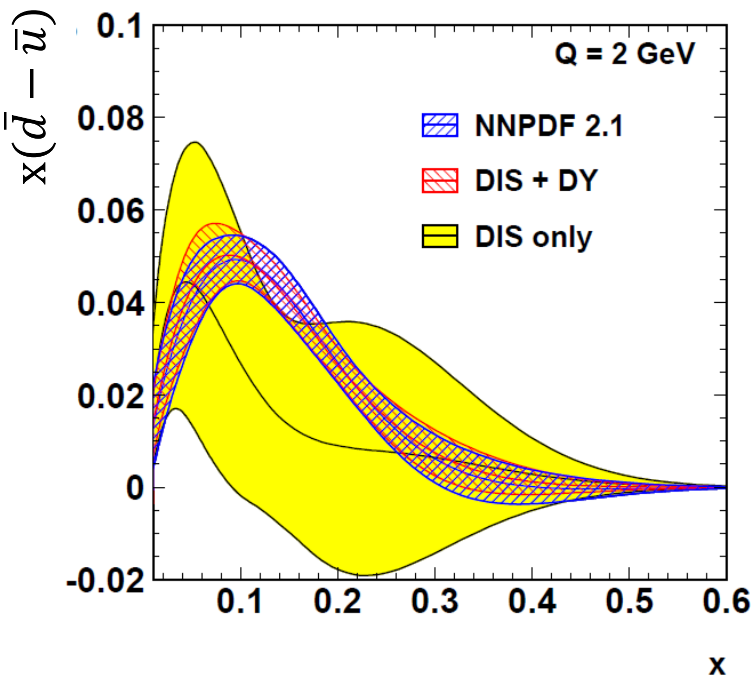


Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)

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

E. Pereza and E. Rizvib, arXiv:1208.1178



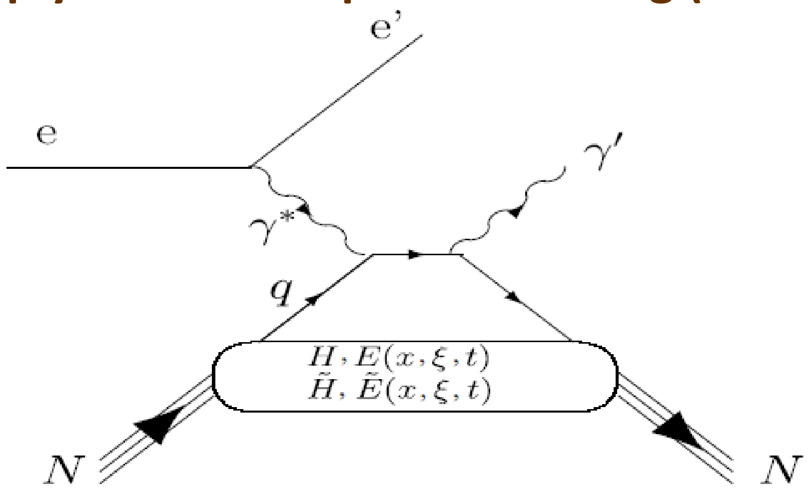


Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)

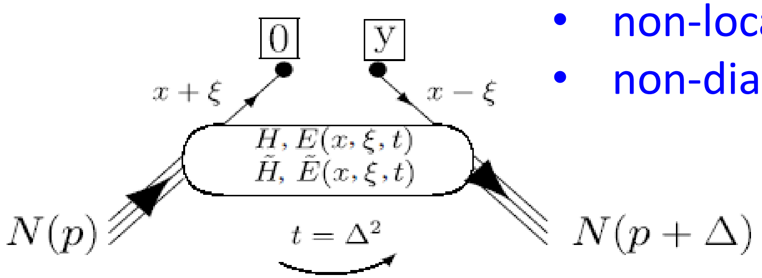
Generalized Parton Distribution (GPD)

M. Guidal, H. Moutarde and M. Vanderhaeghen, Rep. Prog. Phys. 76 (2013) 066202

Deeply virtual Compton scattering (DVCS)



GPD



- non-local
- non-diagonal

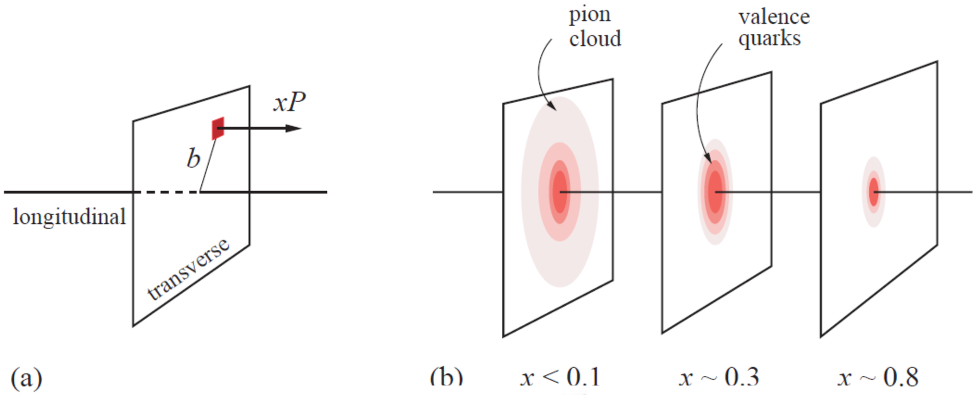
$$\frac{P^+}{2\pi}\int \mathrm{d}y^- e^{\mathrm{i}xP^+y^-}\langle p'|\bar{\psi}_q(0)\gamma^+\psi_q(y)|p\rangle\Big|_{y^+=\vec{y}_\perp=0}$$
$$= H^q(x,\xi,t)\,\bar{N}(p')\gamma^+N(p) + E^q(x,\xi,t)\,\bar{N}(p')\mathrm{i}\sigma^{+\nu}\frac{\Delta_\nu}{2m_N}N(p),$$

$$\frac{P^+}{2\pi}\int \mathrm{d}y^- e^{\mathrm{i}xP^+y^-}\langle p'|\bar{\psi}_q(0)\gamma^+\gamma^5\psi_q(y)|p\rangle\Big|_{y^+=\vec{y}_\perp=0}$$
$$= \tilde{H}^q(x,\xi,t)\,\bar{N}(p')\gamma^+\gamma_5N(p) + \tilde{E}^q(x,\xi,t)\,\bar{N}(p')\gamma_5\frac{\Delta^+}{2m_N}N(p),$$

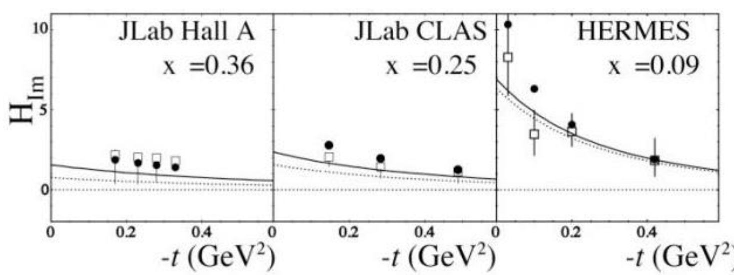
$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

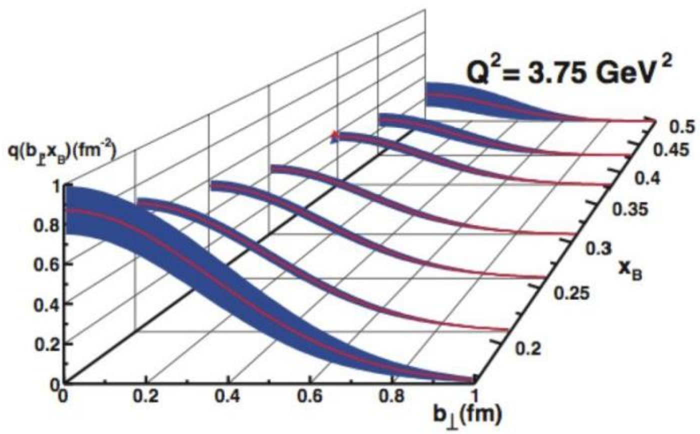
Generalized Parton Distribution (GPD)

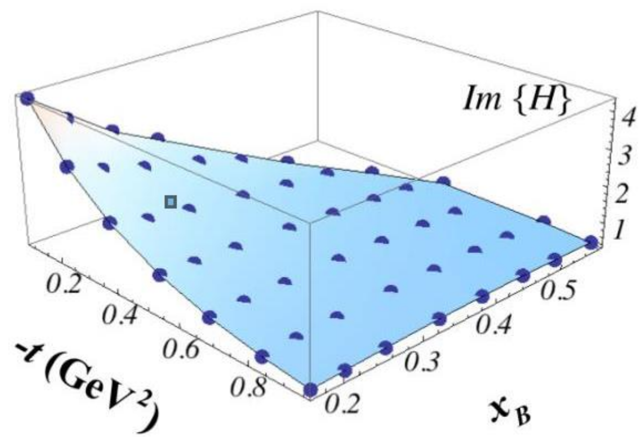
Spatial tomography



JLAB12 CDR, arXiv:1208.1244

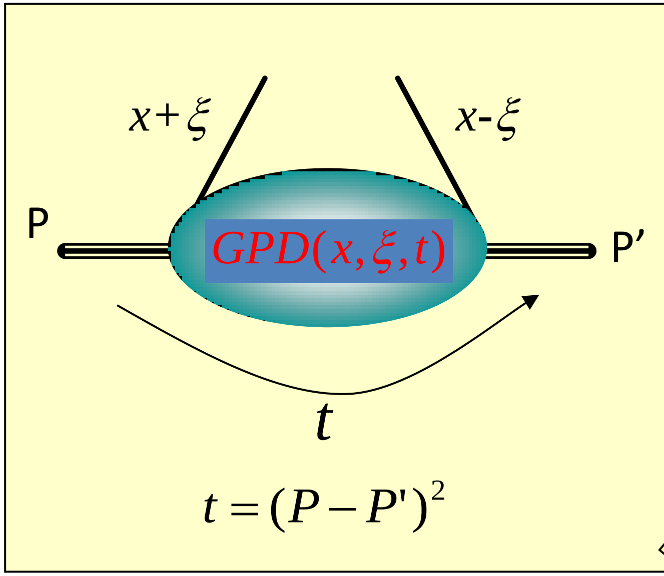






- 1+2D description of the nucleon structure
- Correlations among longitudinal momenta and transverse positions
- Connection to quark orbital angular momentum

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

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

The orbital angular momentum of quarks can be known.

Space-like vs. Time-like Processes

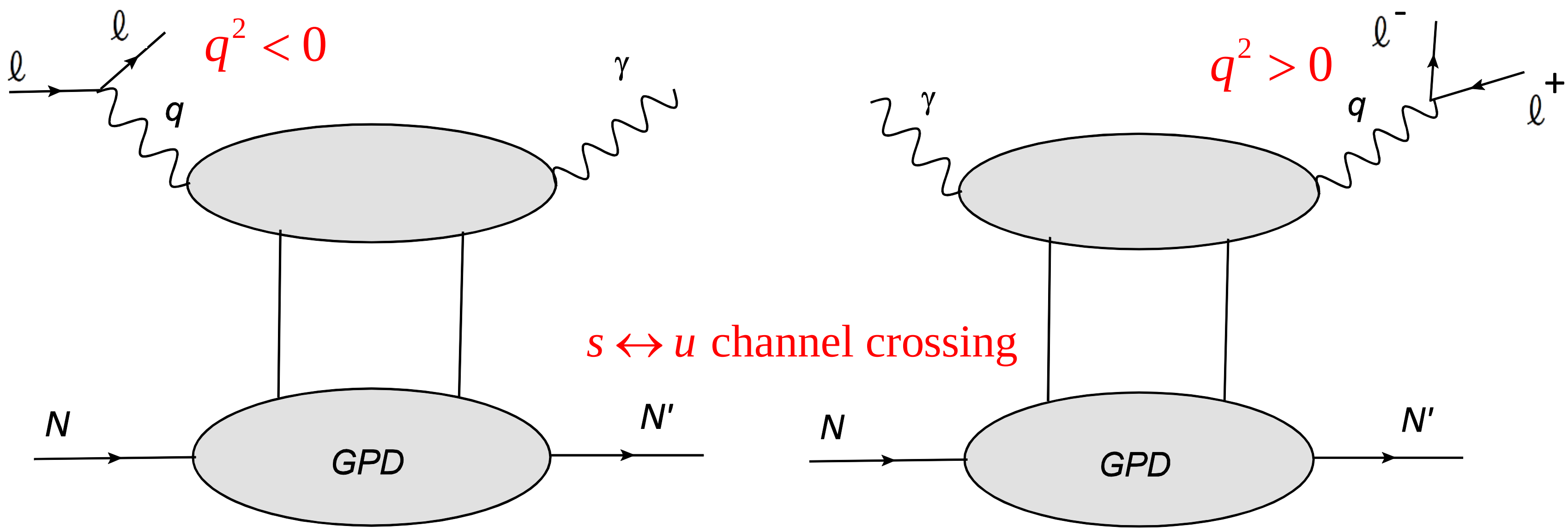
Muller et al., PRD 86 031502(R) (2012)

$\gamma^* + N \rightarrow \gamma + N'$

DVCS
(Deeply Virtual Compton Scattering)

$\gamma + N \rightarrow \gamma^* + N'$

TCS
(Timelike Compton Scattering)



$s \leftrightarrow u$ channel crossing

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

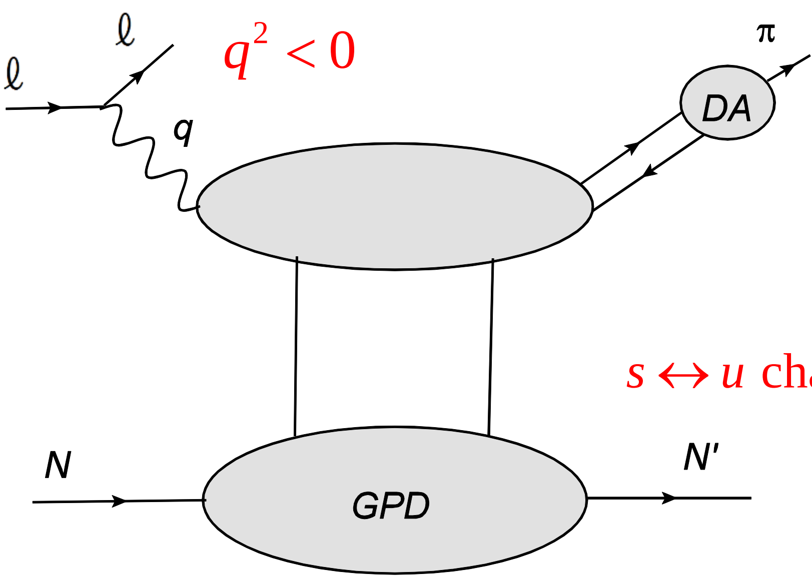
$$\mathcal{F}(\xi, t, \mathcal{Q}^2) = \int_{-1}^{1} dx \sum_{i=u,d,\cdots,g} {}^{S}T^i(x, \xi) F^i(x, \xi, t, \mu^2),$$

Space-like vs. Time-like Processes

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

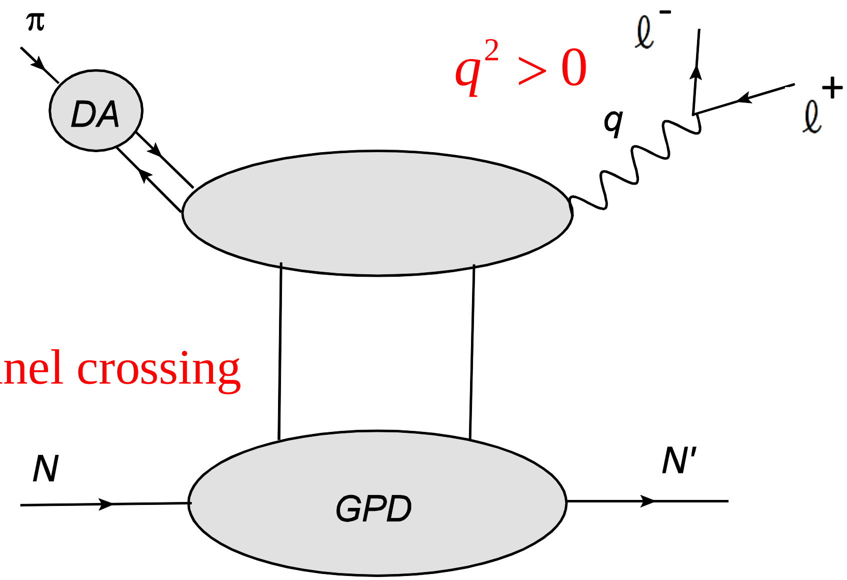
$\gamma^* + N \rightarrow \pi + N'$

DVMP
(Deeply Virtual Meson Production)



$\pi + N \rightarrow \gamma^* + N'$

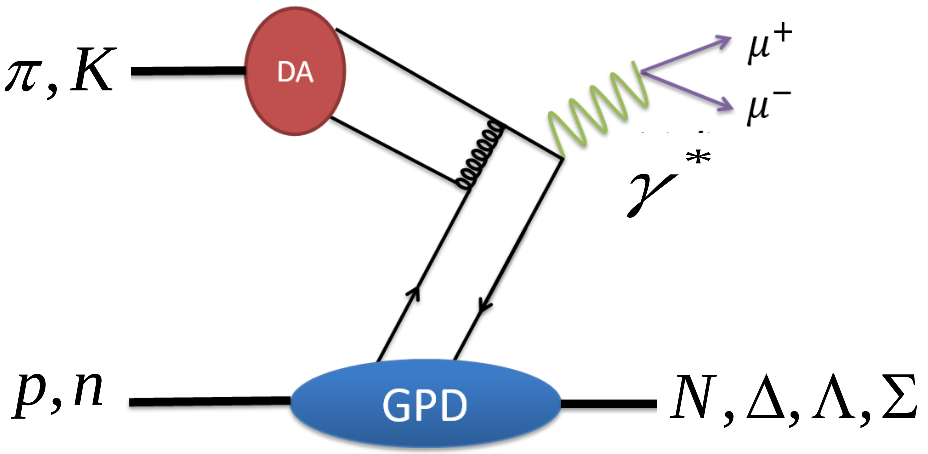
Exclusive Meson-induced DY



$s \leftrightarrow u$ channel crossing

“GPD” and “Transition GPD”

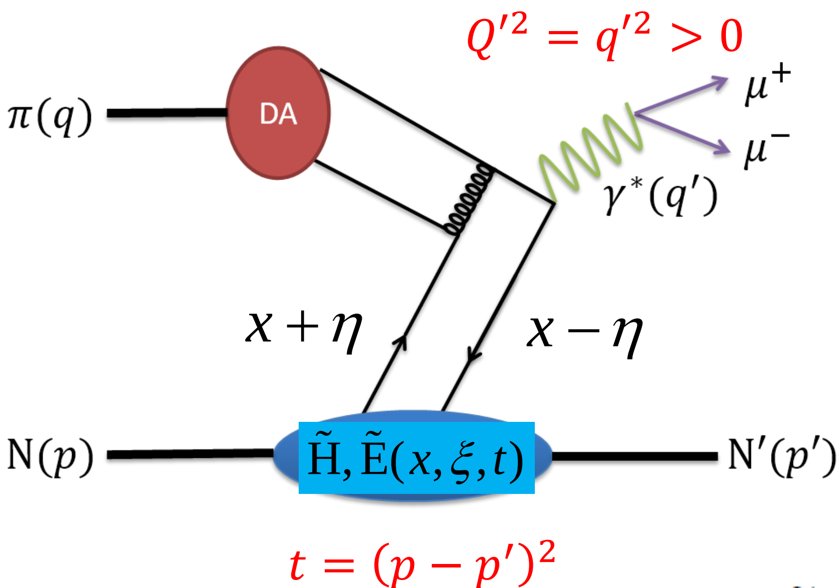
- $\pi^- \mathrm{p} \to \gamma^* n$
- $\pi^- \mathrm{p} \to \gamma^* \Delta^0$
- $\pi^- \mathrm{n} \to \gamma^* \Delta^-$
- $\pi^+ \mathrm{n} \to \gamma^* \mathrm{p}$
- $\pi^+ \mathrm{p} \to \gamma^* \Delta^{++}$
- $\pi^+ \mathrm{n} \to \gamma^* \Delta^+$
- $K^- \mathrm{p} \to \gamma^* \Lambda$
- $K^- \mathrm{p} \to \gamma^* \Lambda(1405)$
- $K^- \mathrm{p} \to \gamma^* \Lambda(1520)$
- $K^- \mathrm{n} \to \gamma^* \Sigma^-$
- $K^+ \mathrm{n} \to \gamma^* \Theta^+$



Exclusive pion-induced DY

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

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



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

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

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

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

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

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

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

$$t = (p-p')^2 \qquad \tau = \frac{Q'^2}{2pq} \approx \frac{Q'^2}{s-M_N^2} = x_B$$

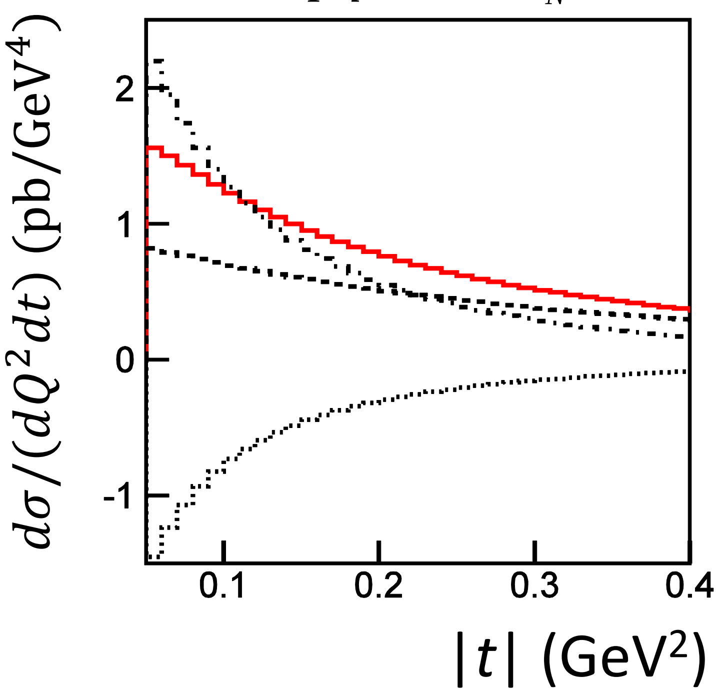
$$Q'^2 = q'^2 > 0 \qquad \eta = \frac{(p-p')^+}{(p+p')^+} = \frac{\tau}{2-\tau}$$

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

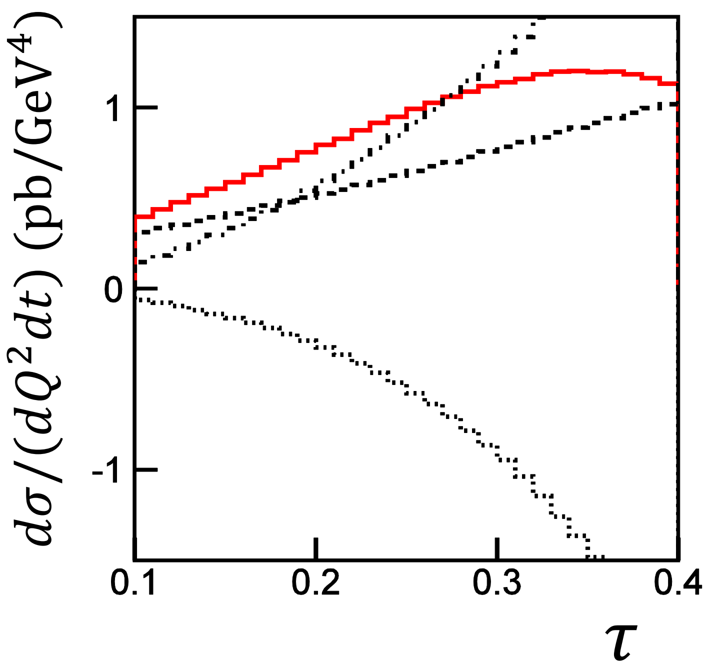
E.R. Berger, M. Diehl, B. Pire, PLB 523 (2001) 265

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

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



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

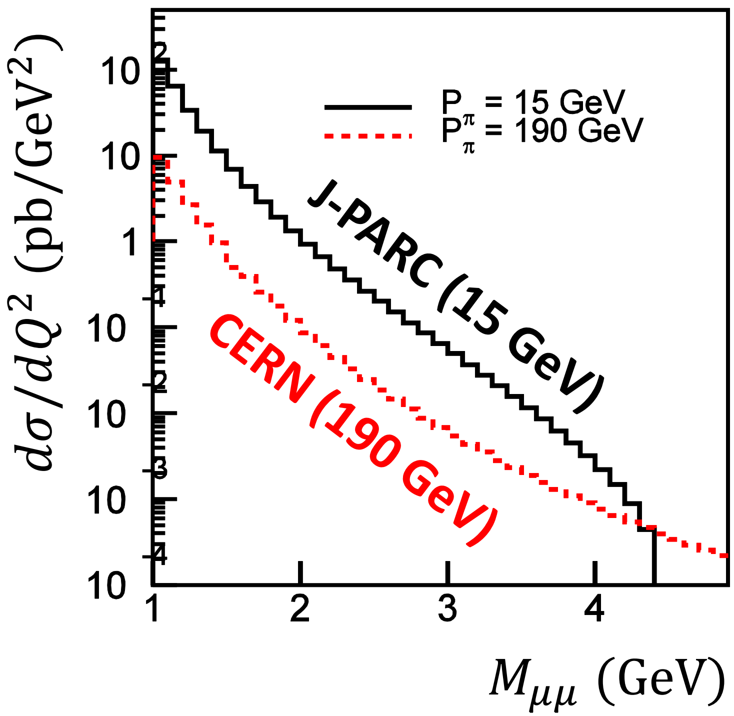


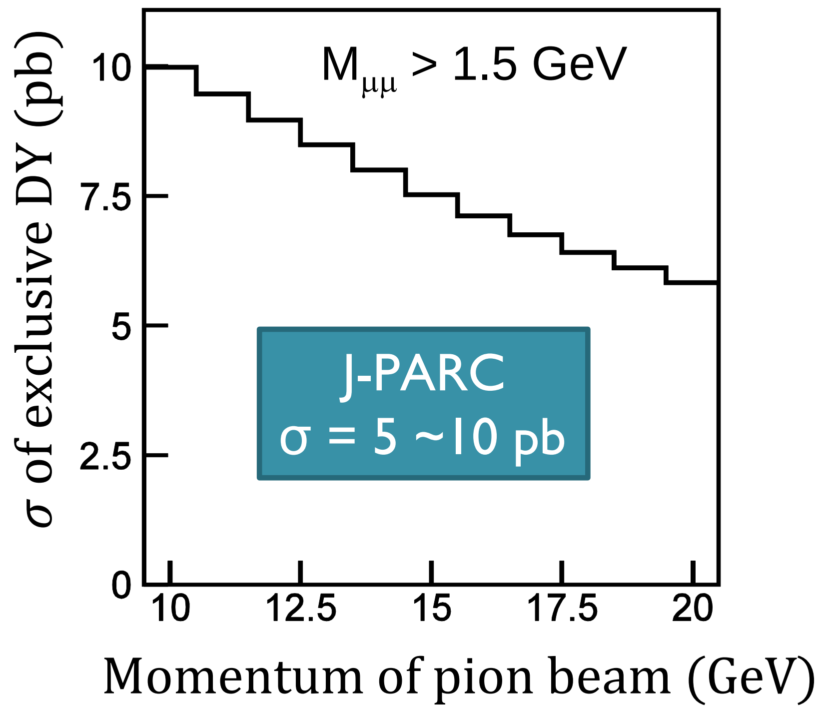
Production is dominant at forward angles

Cross sections increase toward small s ($\rightarrow$ low beam energy)

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

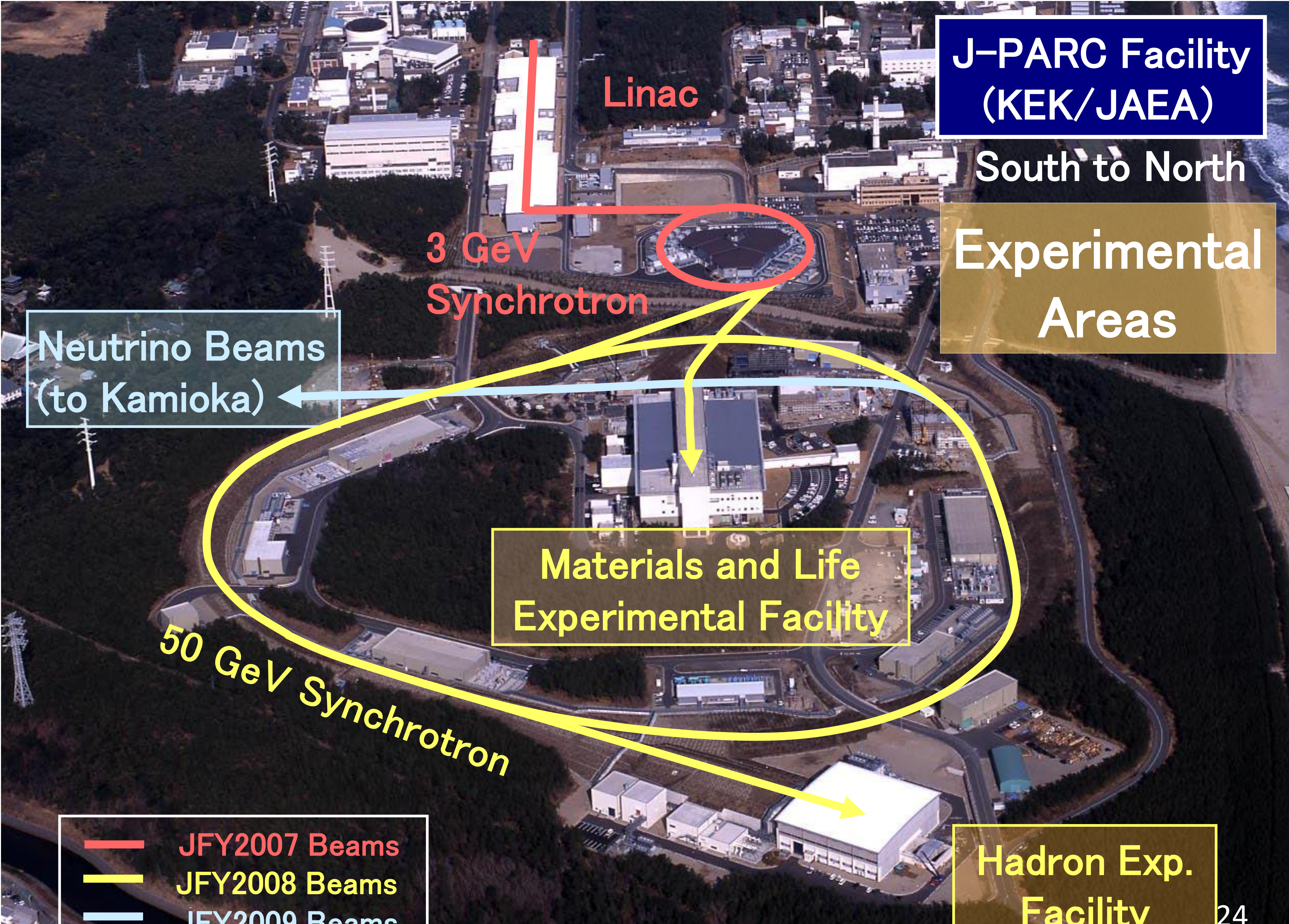
E.R. Berger, M. Diehl, B. Pire, PLB 523 (2001) 265





CERN (Pπ=190 GeV)
σ = 0.65 pb

Feasibility study of Drell-Yan experiment at J-PARC High momentum beam line



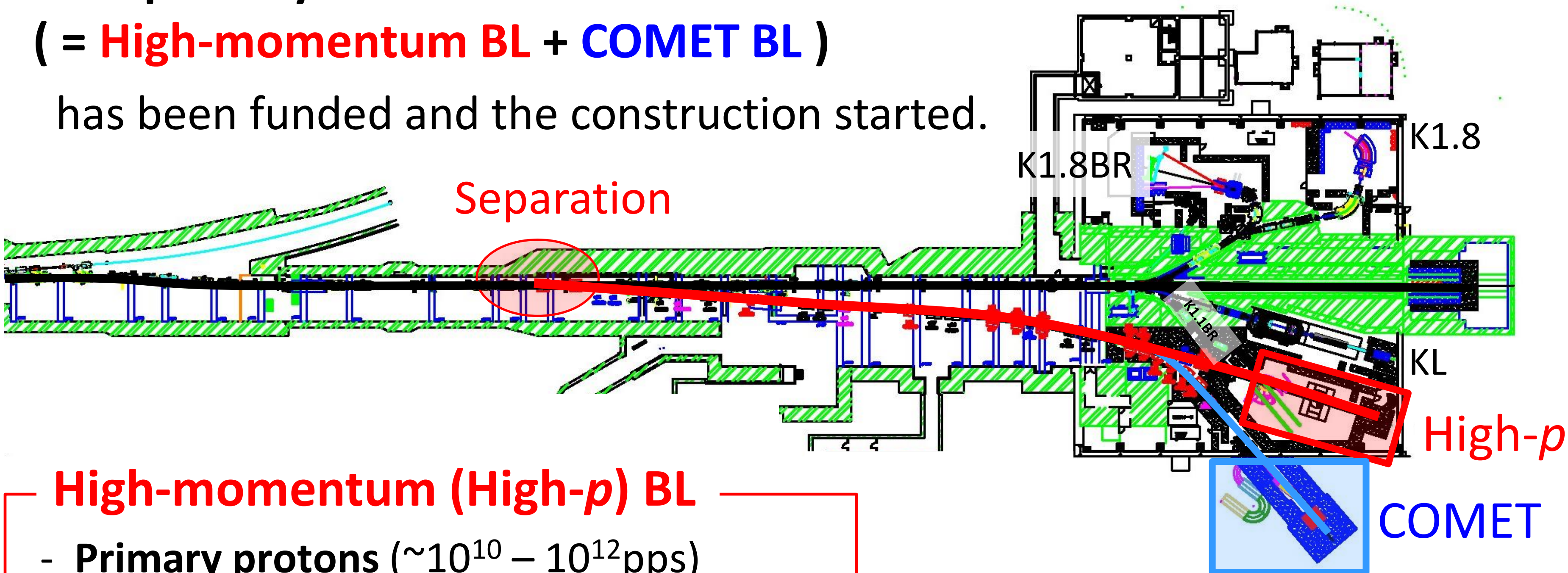
Bird's eye photo in January of 2008

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

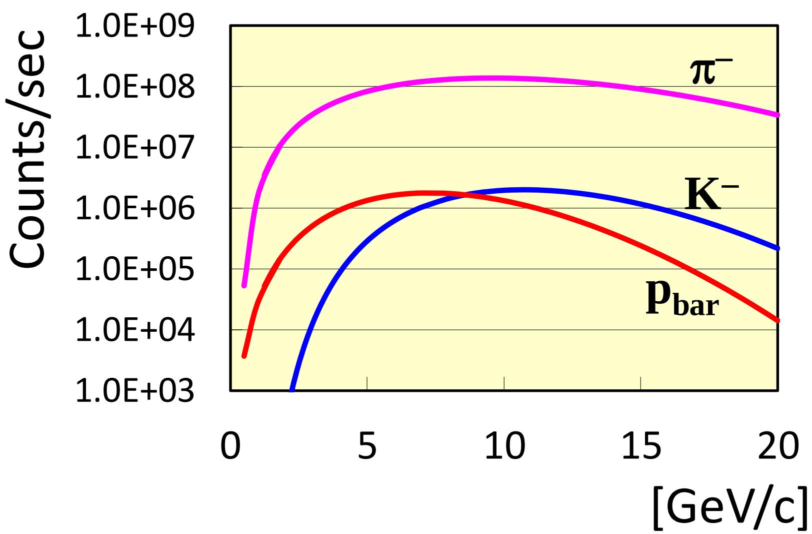
- Search for m to e conversion
- 8 GeV, 50 kW protons
- Branch from the high-momentum BL
- Annex building is being built at the south side.

J-PARC High-*p* BL

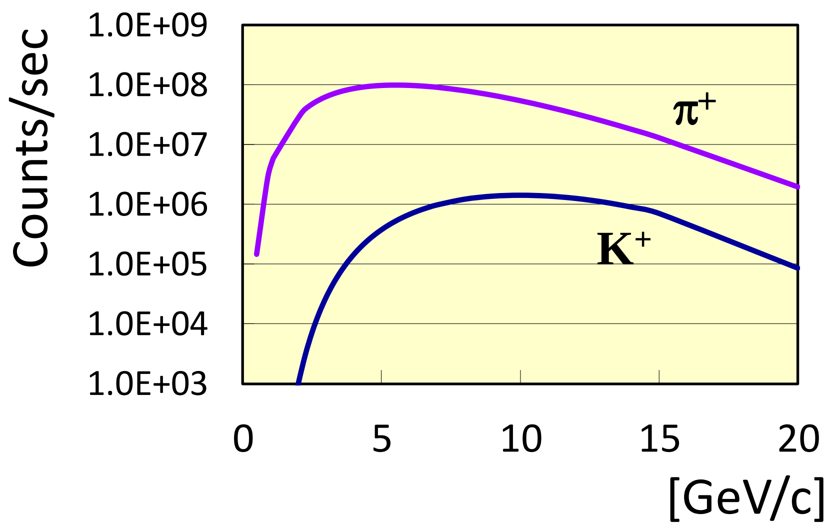
Unseparated secondary beams

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

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



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

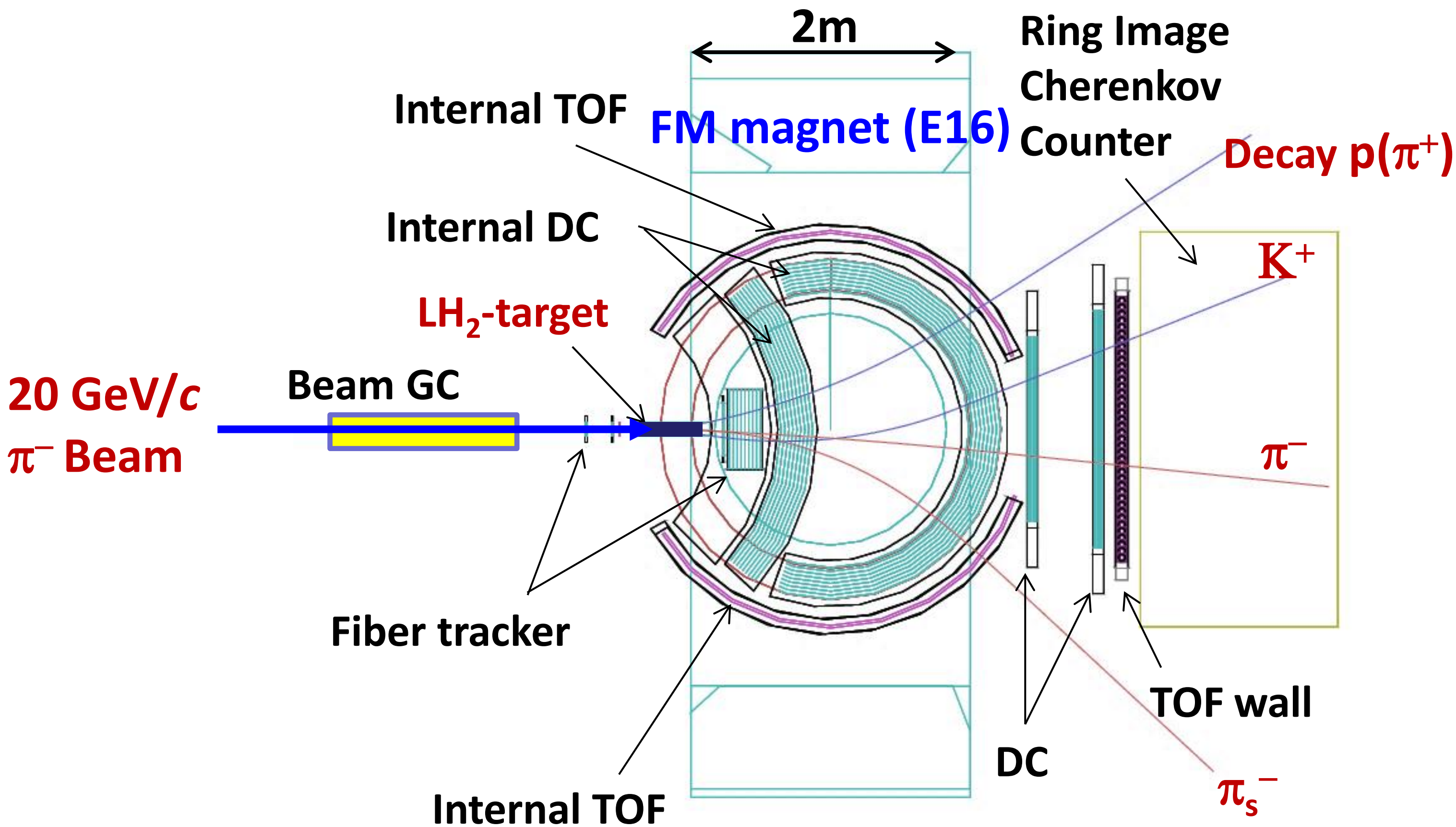


* Sanford-Wang: 15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m

J-PARC E50

for Charmed Baryon Spectroscopy

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

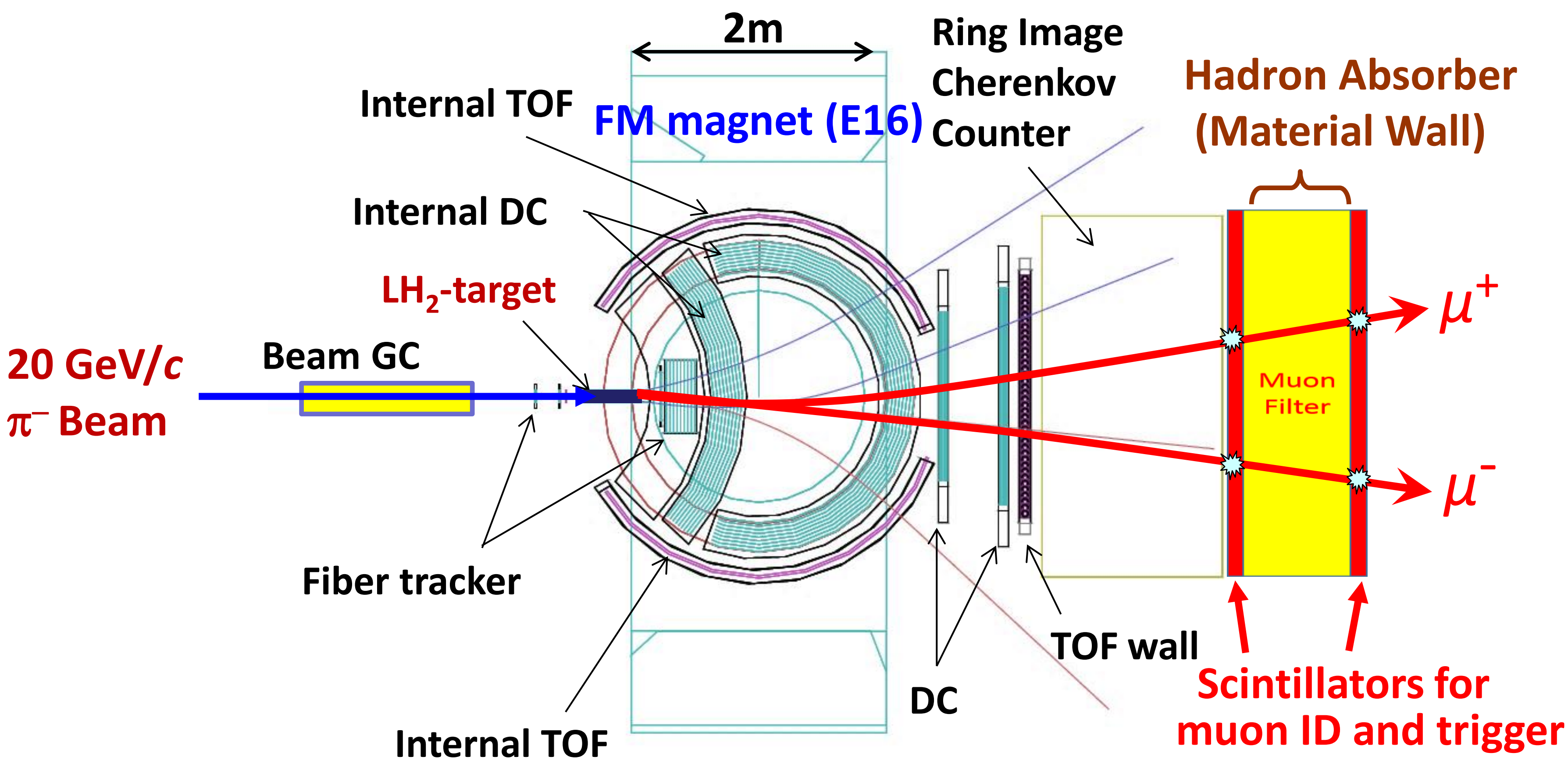


Acceptance: ~ 60% for D^*, ~80% for decay p^+

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

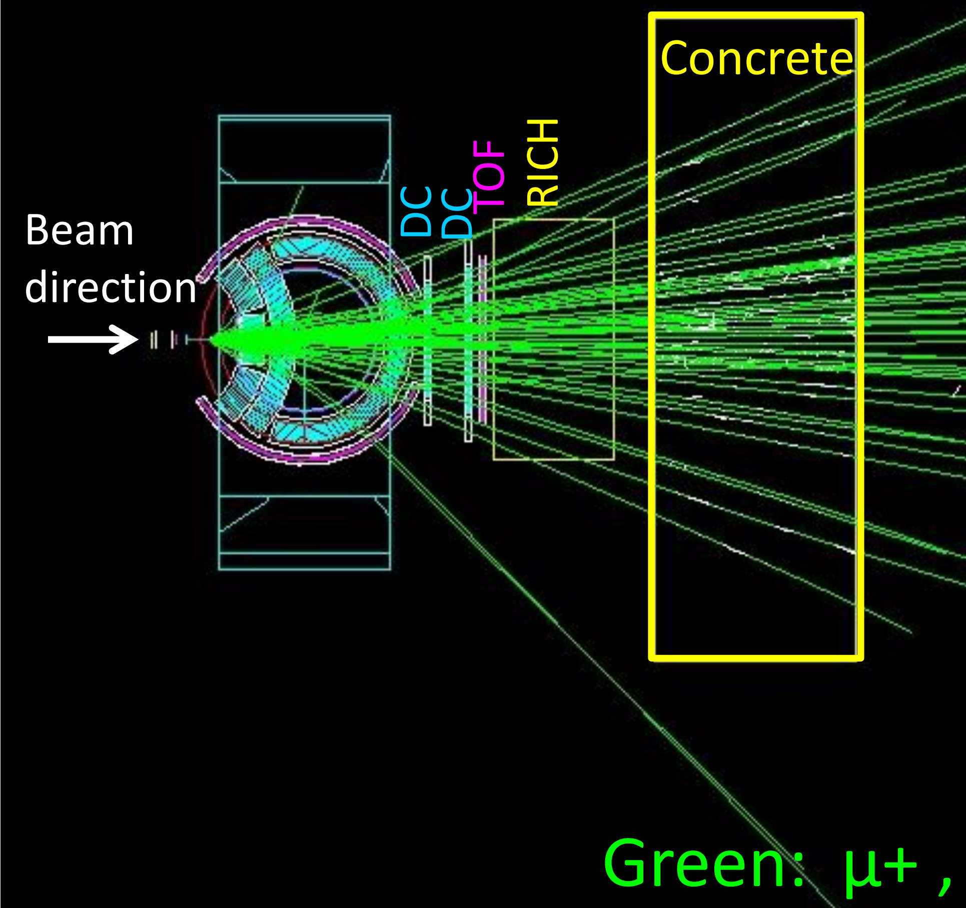
J-PARC E50 Spectrometer + Muon ID

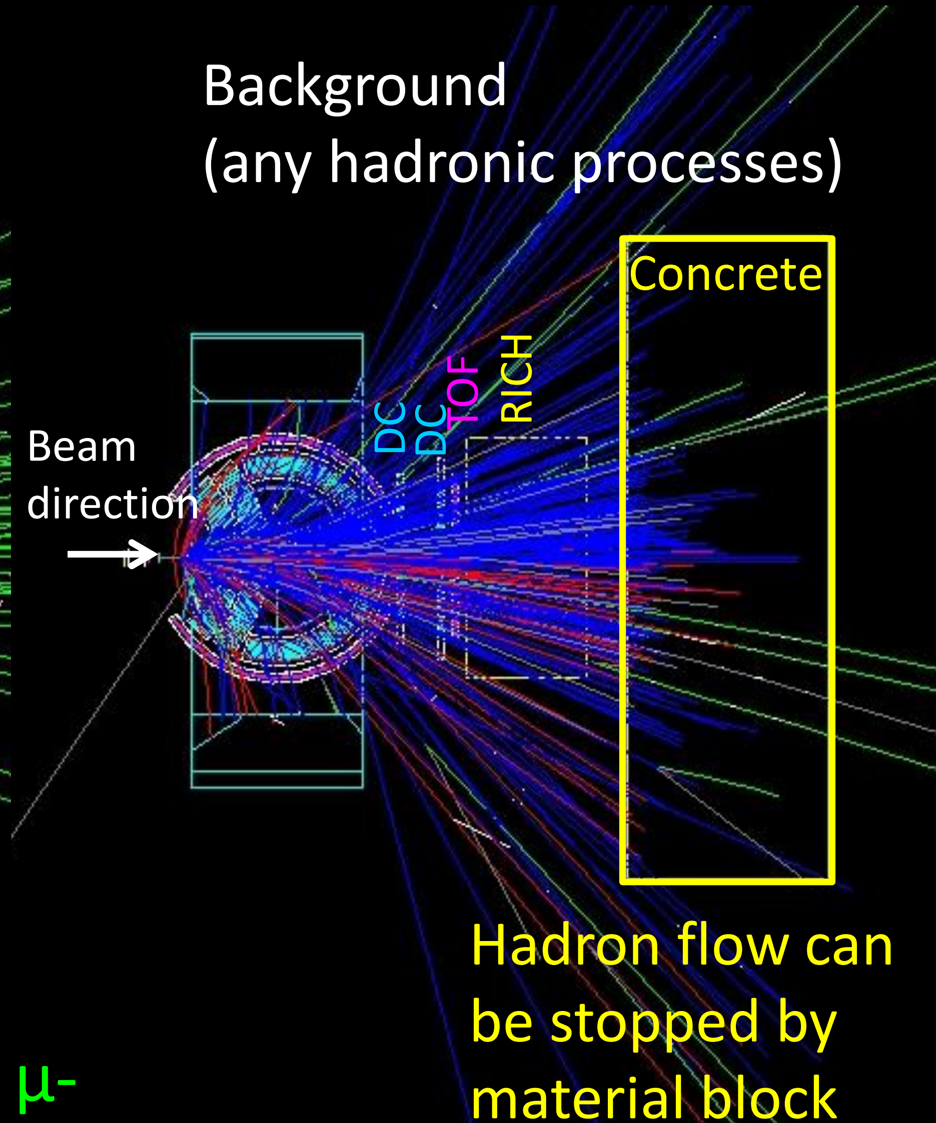
→ Drell-Yan ($\pi^- p \rightarrow \mu^+\mu^- X$) measurement



In parallel with the "*normal*" E50 exp.

Hadron Absorber





Hadron flow can be stopped by material block

Green: μ+ , μ-

Red,Blue: Chaged hadrons

J-PARC E50 Spectrometer + 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 provides 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

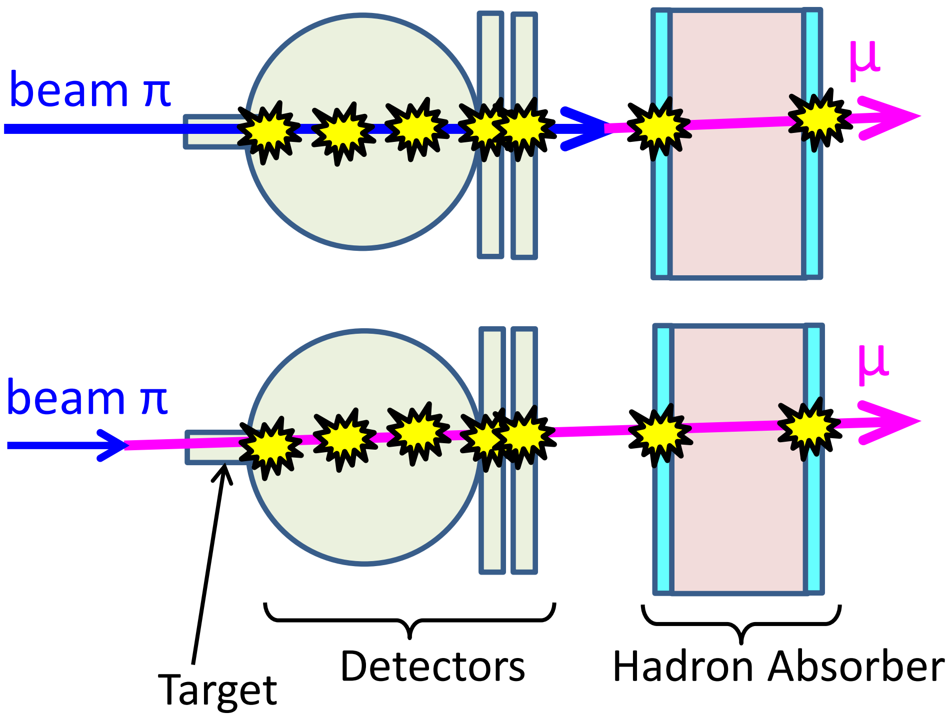
Experimental Conditions

- **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/s
- **π^- beam momentum**: 10/15/20 GeV/c
- **Beam time**: 50 days

Main backgrounds and their rejections

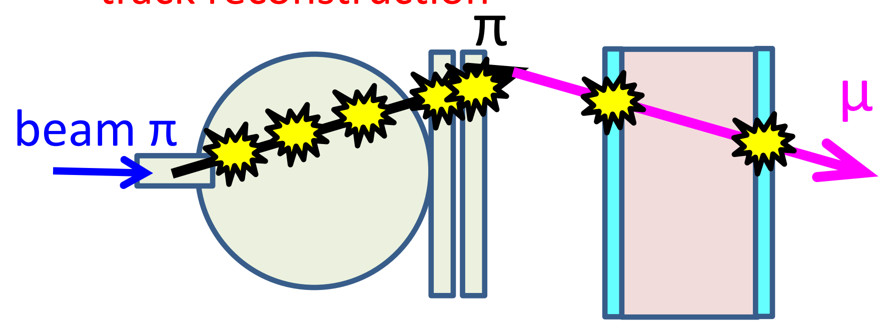
Beam decay

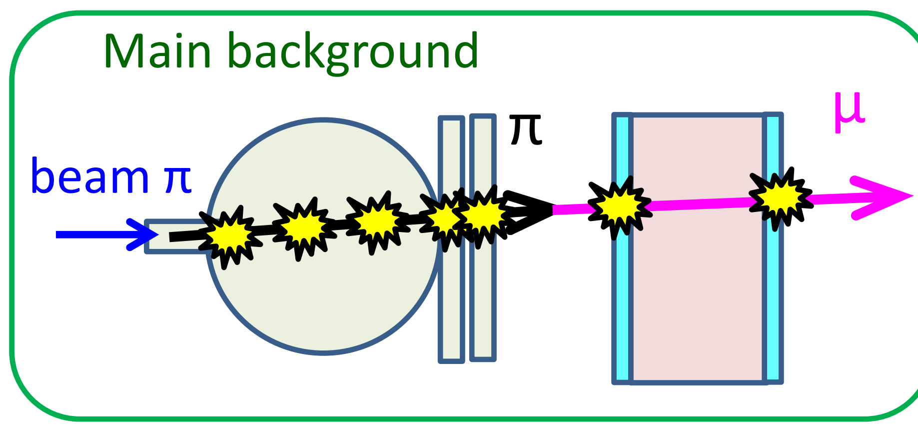
Removing by $|p|$ and *polar angle*.



Produced Meson decay

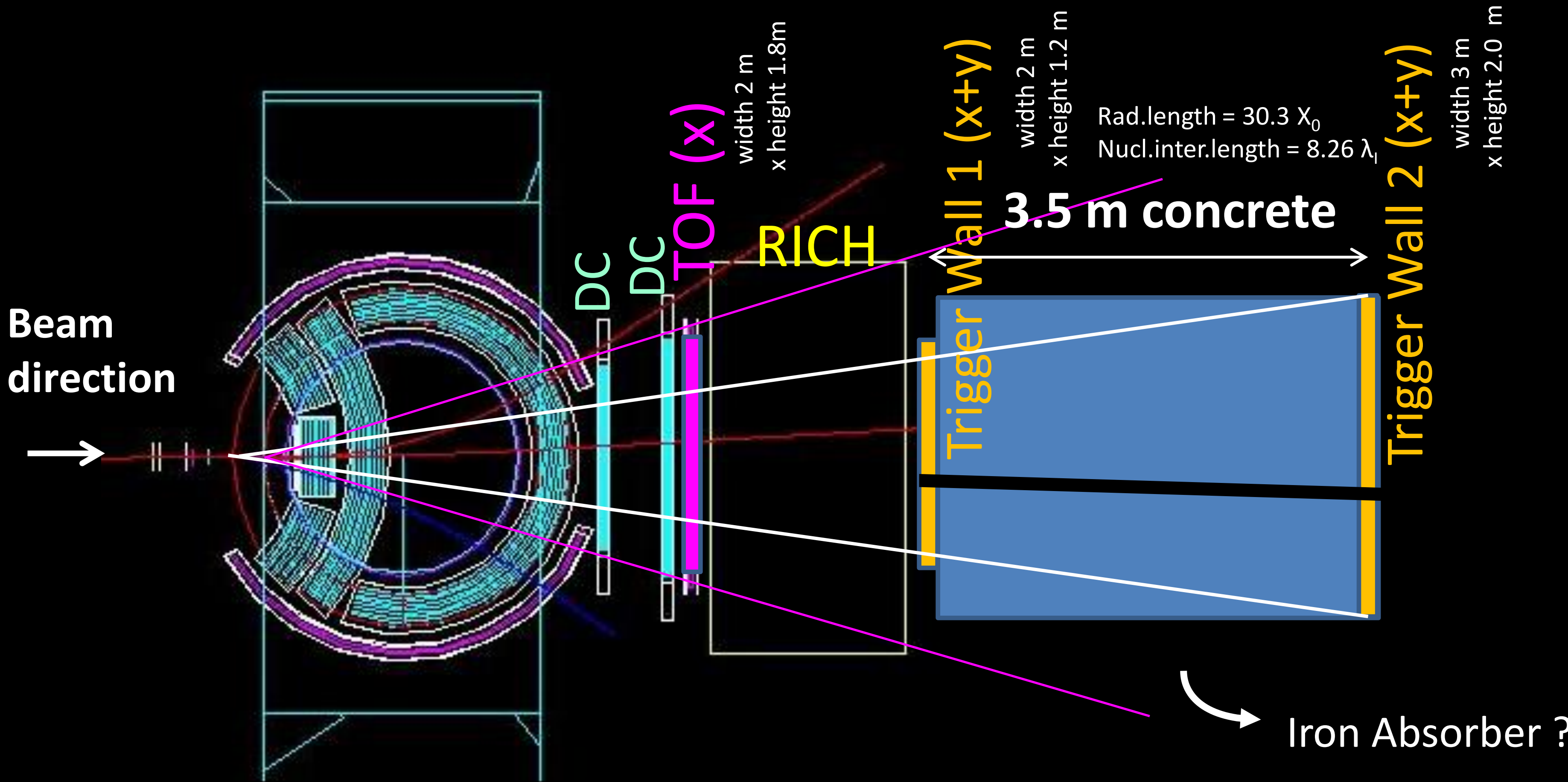
Removing by the consistency of track and trigger hit and χ^2 probability of track reconstruction





+ pile-up (multiple beam in one event)

Dedicated Designs of Hadron Absorber and Trigger



Assuming $I_{beam} = 1*10^7\ \pi/sec$ 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

Yield Estimation

Beam Energy	10 GeV/c	15 GeV/c	20 GeV/c
Beam Intensity	High	←	Low
Total Cross Section			
of Exclusive DY	High	←	Low
of Inclusive DY	Low	→	High
Acceptance	Low	→	High

	π^- beam (prod. angle 0 deg)		π^+ beam (prod. angle 3.1 deg)
Beam Intensity	High	←	Low
Total Cross Section of DY	High	←	Low

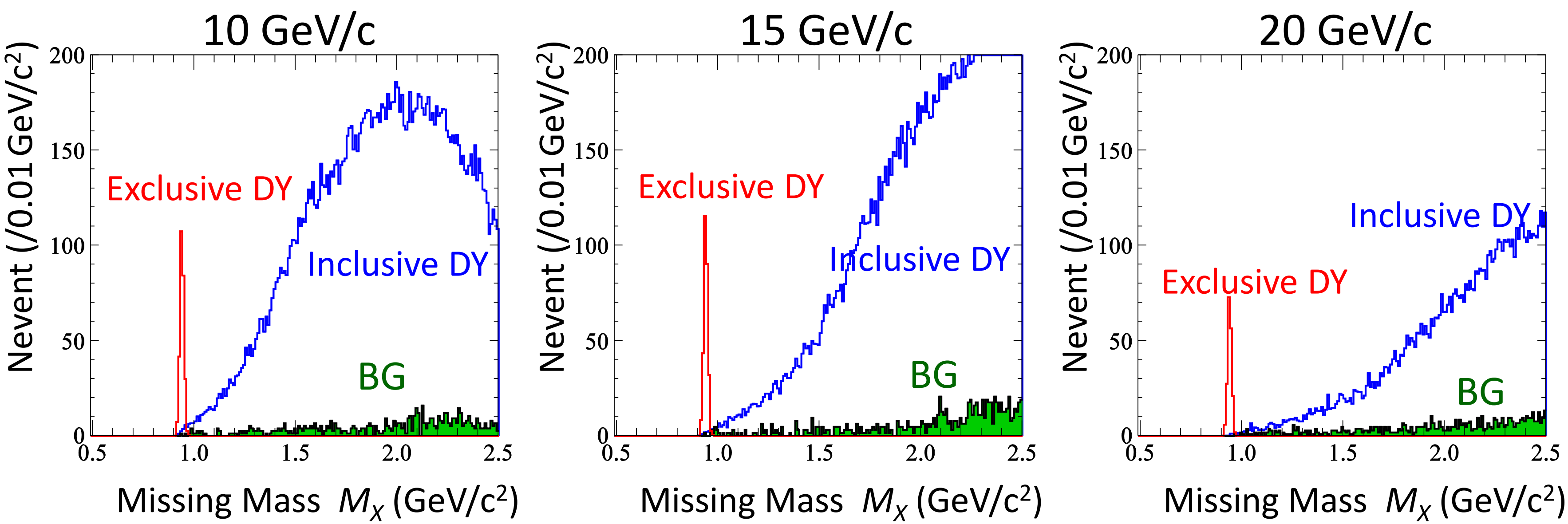
Missing Mass M_X in E-50 Spectrometer + MuID

π^- beam 50 days

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

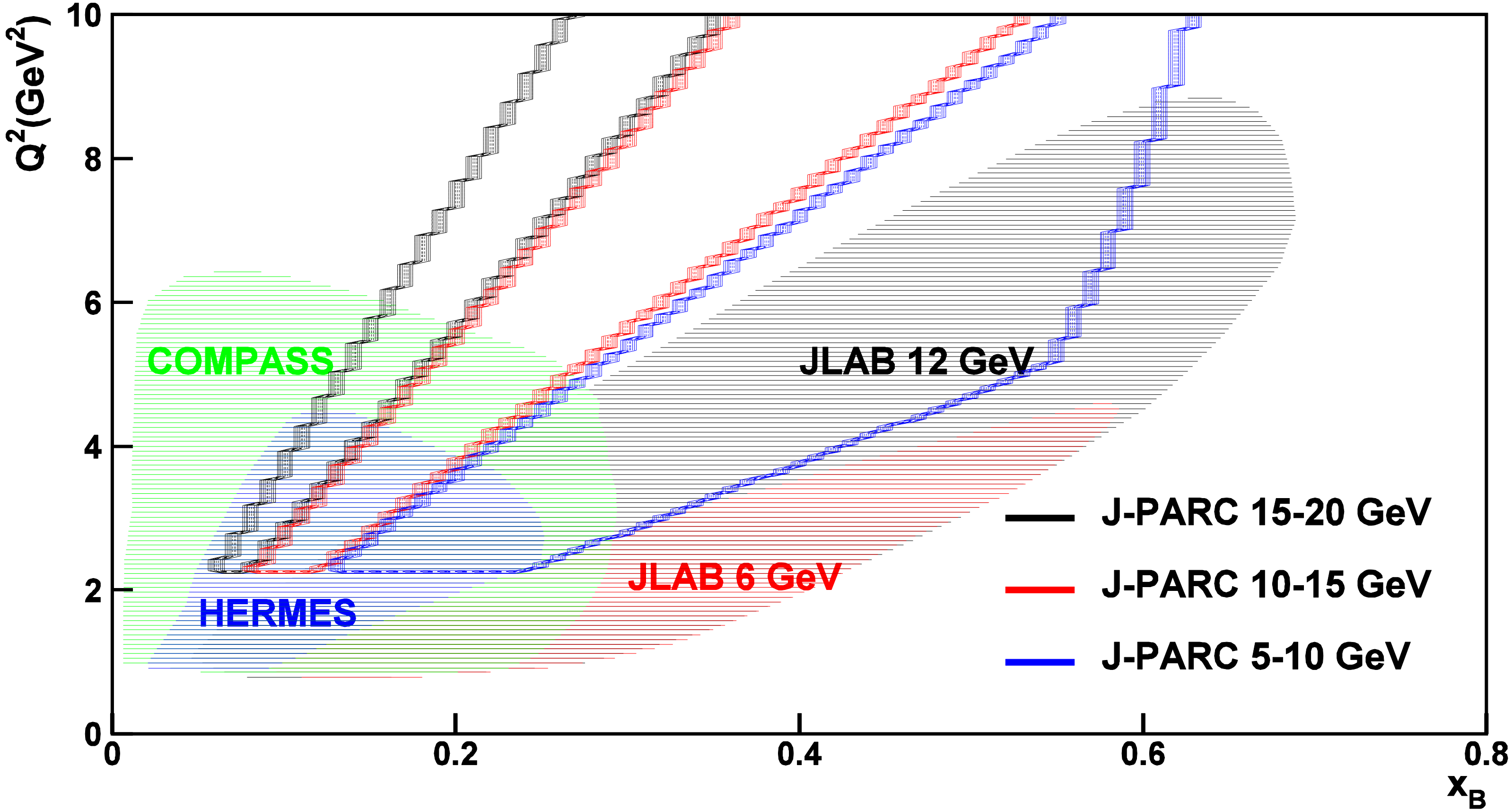
Preliminary
(w/o pile-up)

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.

Impacts of GPD measurements at J-PARC

- 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.

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

Talked by S. Kumano

- **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

This talk

- Many interesting physics ideas are left out, e.g. the studies using nuclear targets and polarized beam/target.

Summary

- High-energy hadron beam at J-PARC is unique for studying hard exclusive processes.
- Rich information of longitudinal momentum and transverse size are encoded in GPD.
- Measurement of GPD in the exclusive π-induced DY process at J-PARC will offer important understanding on
  - **GPD at large Q^2 region**
  - **Universality of GPD in the space-like and time-like processes.**
- The preliminary study of the measurement with E-50 spectrometers is feasible.
- We very much welcome the collaboration in carrying out the proposal/experiment.

Collaboration

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