J-PARCハドロン実験施設
と
そこでの核子構造研究の可能性

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Contents

- Overview of J-PARC
- Hadron Facility
- Nucleon Structure Research with Drell-Yan
  - A series of Fermilab experiments
- New Drell-Yan Experiments
  - E906/SeaQuest and J-PARC P04
- Toward New Step of Structure Study
  - 2D to 3D, importance of the orbital angular momentum
  - Possibility of spin-related experiments at J-PARC
- R&D
  - High momentum beam line
  - Polarized target
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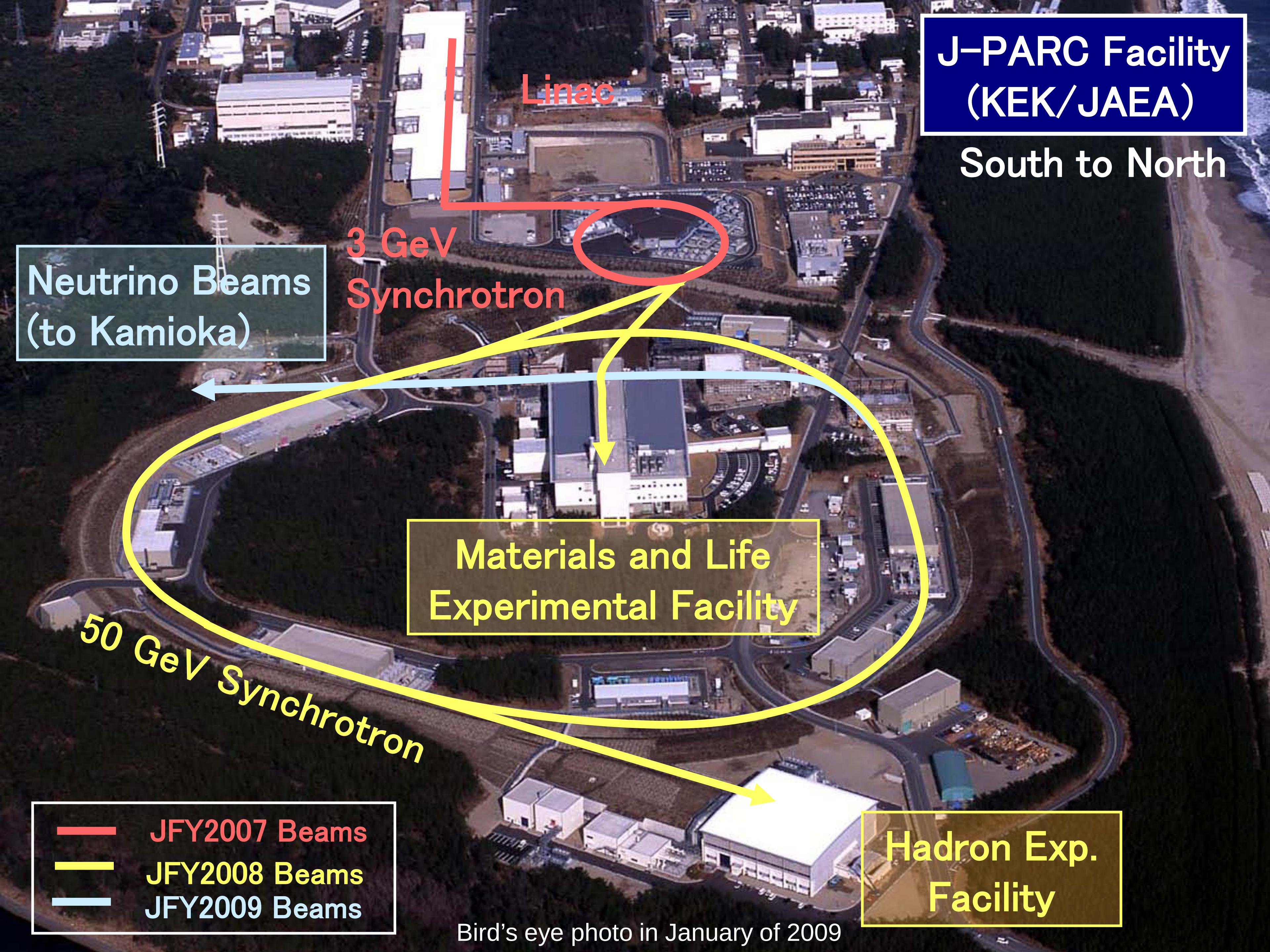
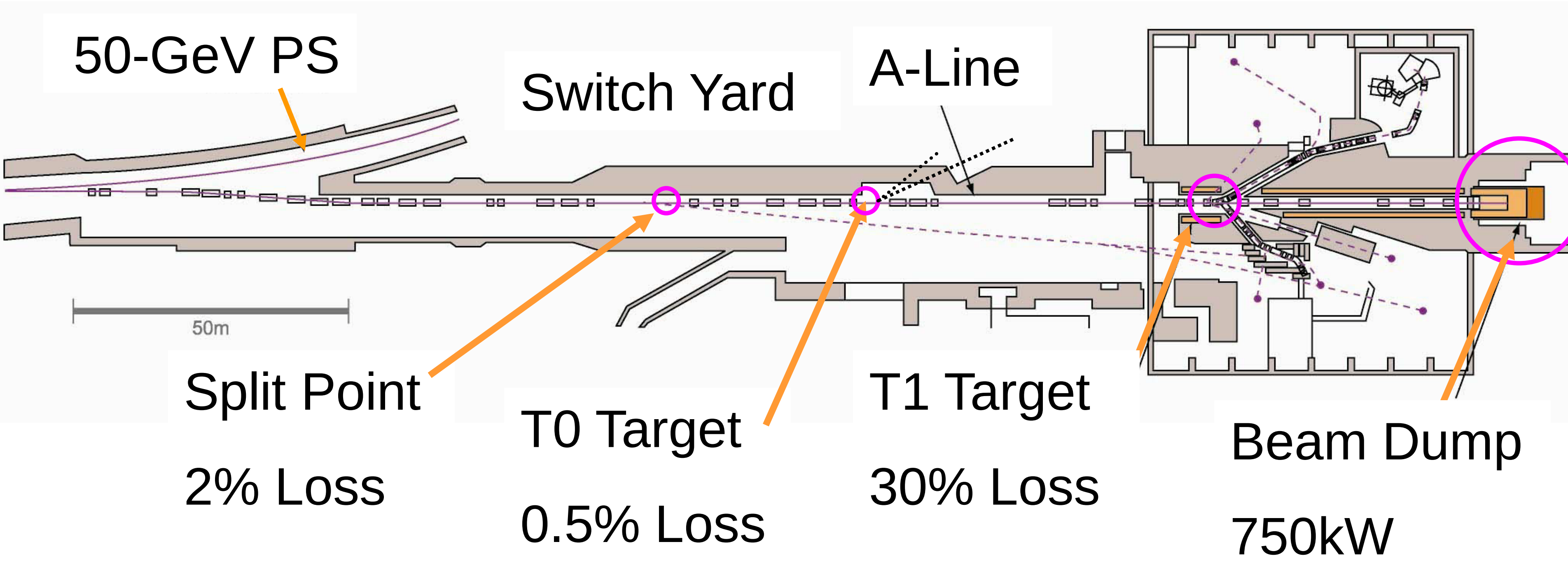
  - 40GeV? Pol. beam? Pi beams?
- Sumnmary


J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental Facility
50 GeV Synchrotron
Hadron Exp.
Facility
JFY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2009

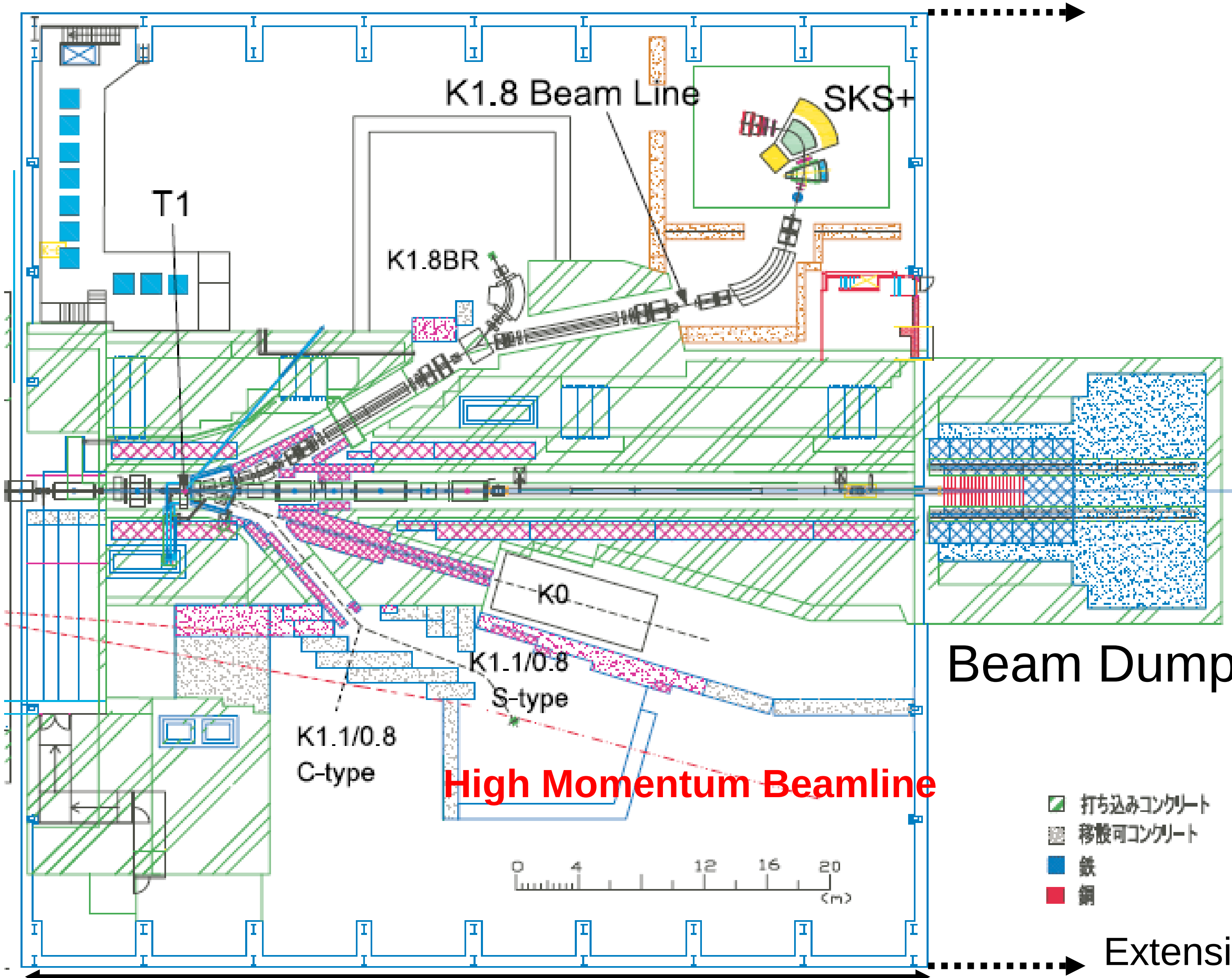
Hadron Hall (Phase 1)

NP-HALL
56m(L) × 60m(W)



Hadron Experimental Hall (Phase I)

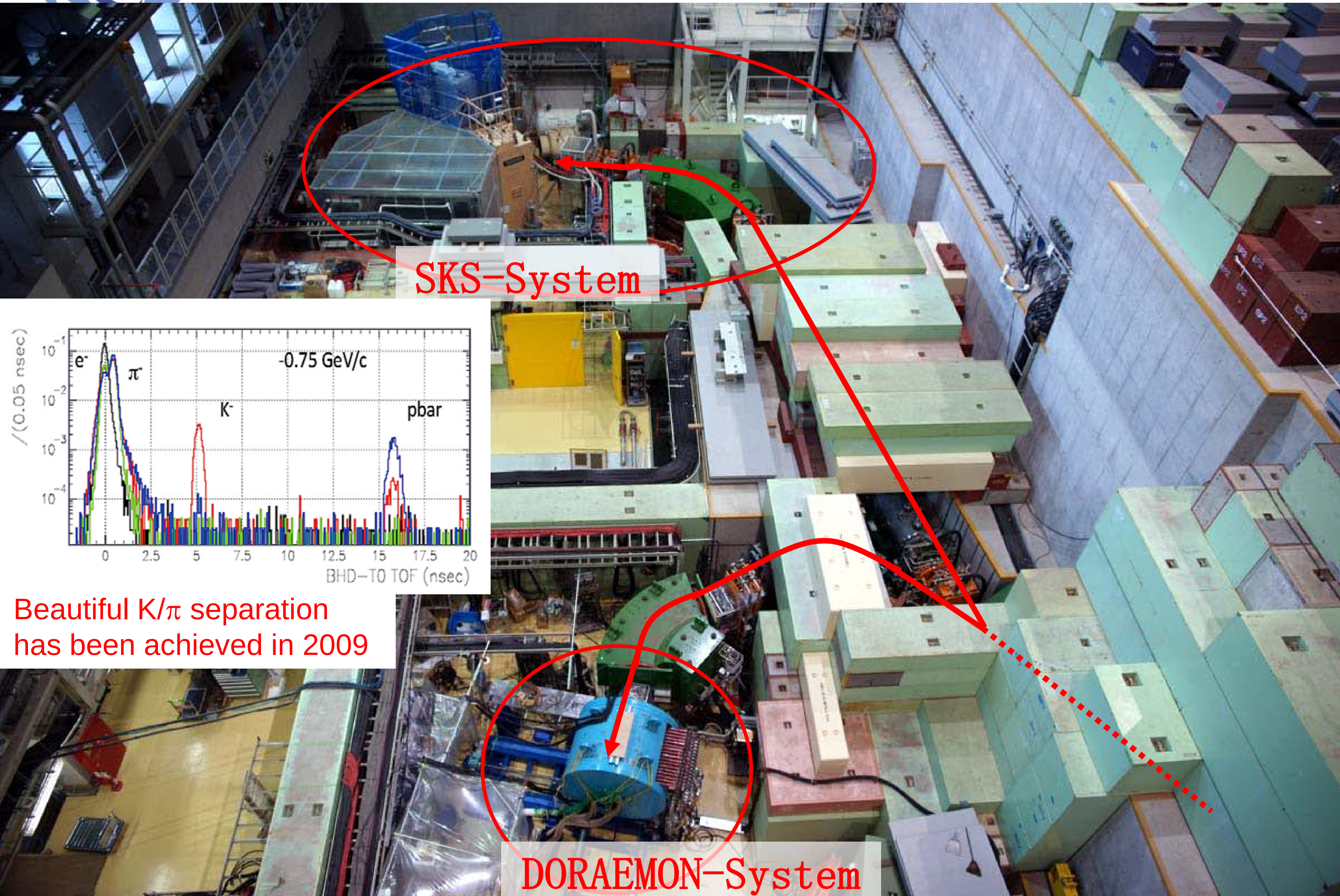
A-Line



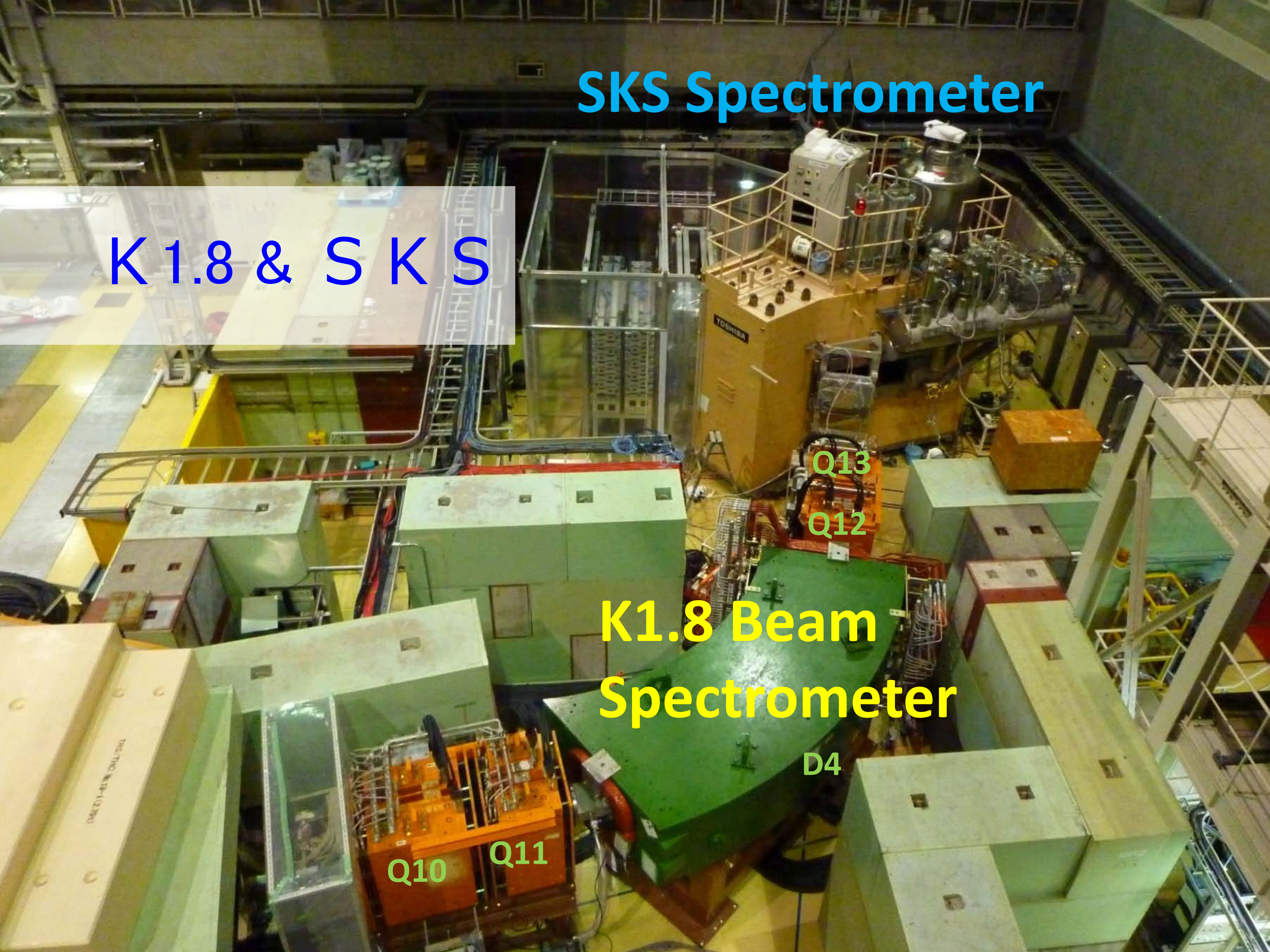
56 m

Extension
in Phase II

North Side: K1.8, K1.8BR

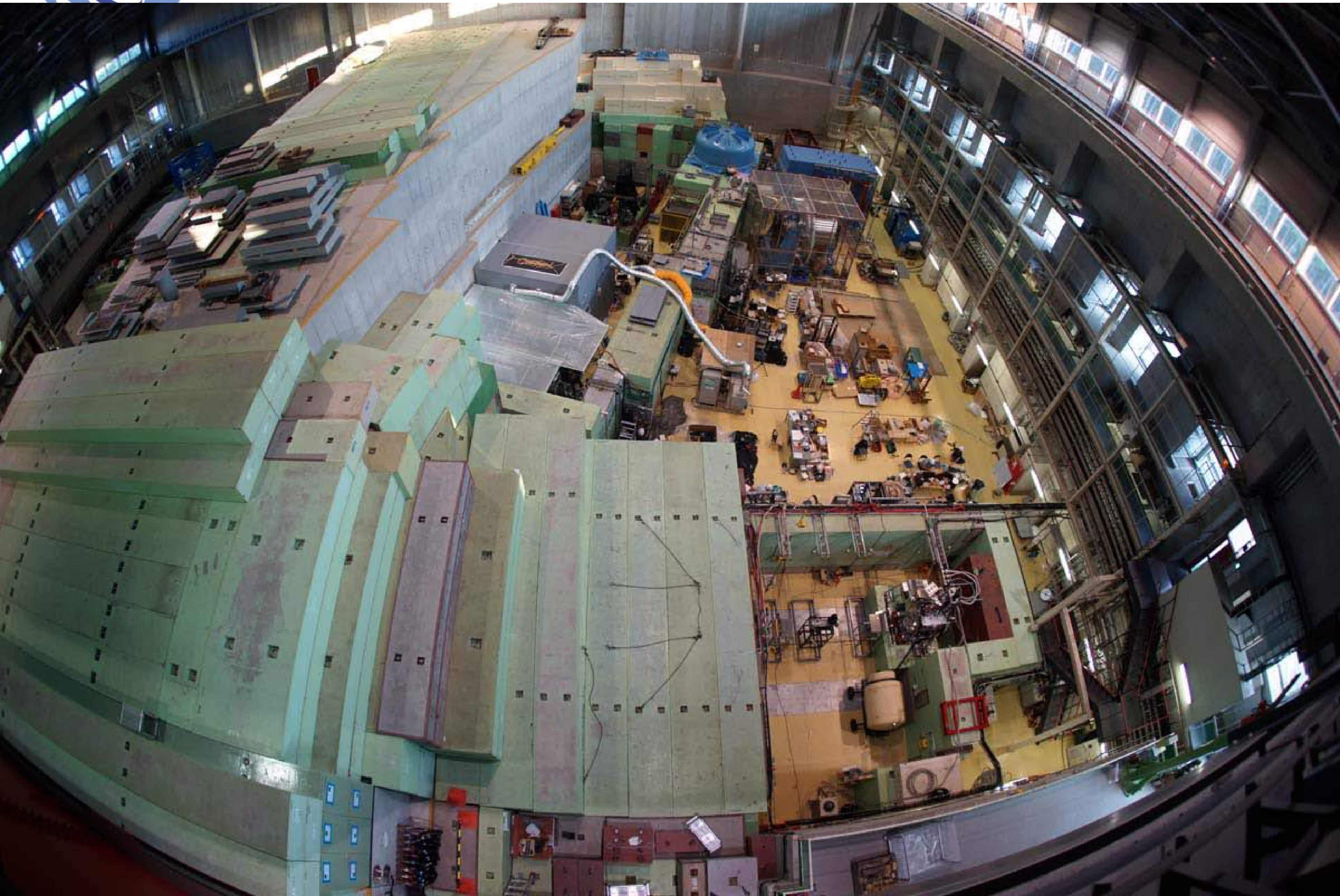


Beautiful K/π separation has been achieved in 2009


SKS Spectrometer
K 1.8 & S K S
TOSHIBA
Q13
Q12
K1.8 Beam
Spectrometer
D4
Q11
Q10

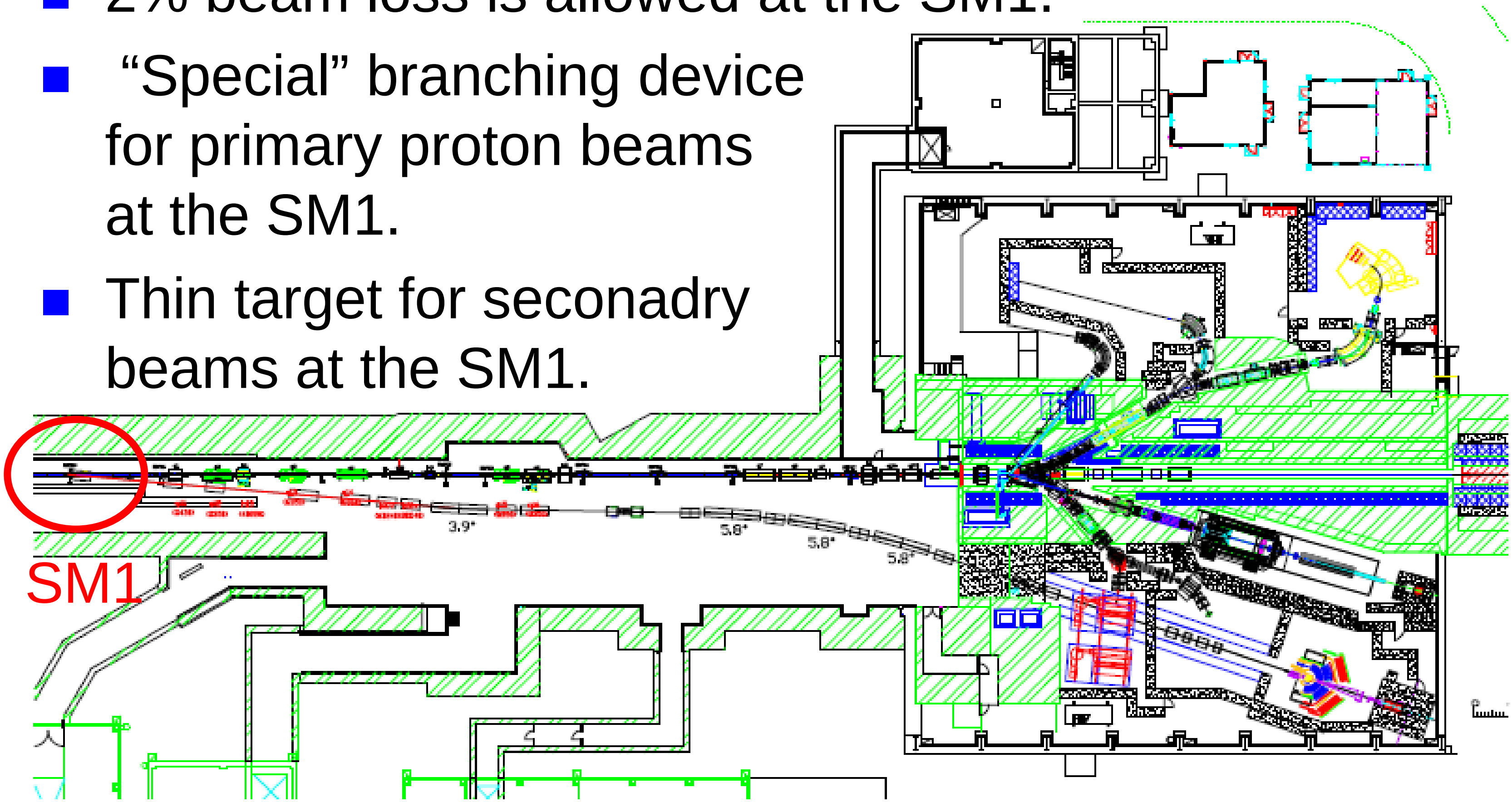
2010年9月28日ハドロンホール南側

Oct. 15, 2010



High-Momentum Beam Line

- Separated at the SM1 in the switchyard.
- 2% beam loss is allowed at the SM1.
- "Special" branching device for primary proton beams at the SM1.
- Thin target for seconadry beams at the SM1.



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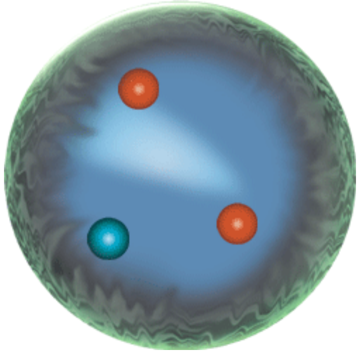
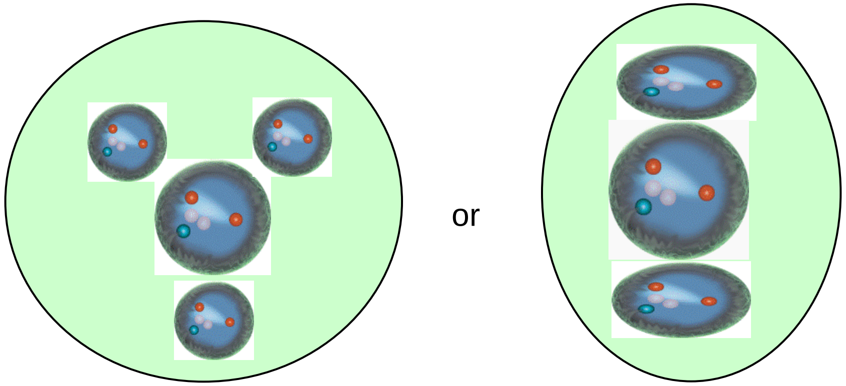
核子の形？（ビジュアル系な素朴な疑問）

- 核子＝３つのバレンスクォーク(?)
  - 形は？球形？？"均一"？？？
  - 核の中の核子の形は？



average spacing at ρ_{nm} ~ 1.8 fm
Radius of a nucleon ~ 0.8 fm
average spacing at $3\rho_{nm}$ ~ 1.3 fm

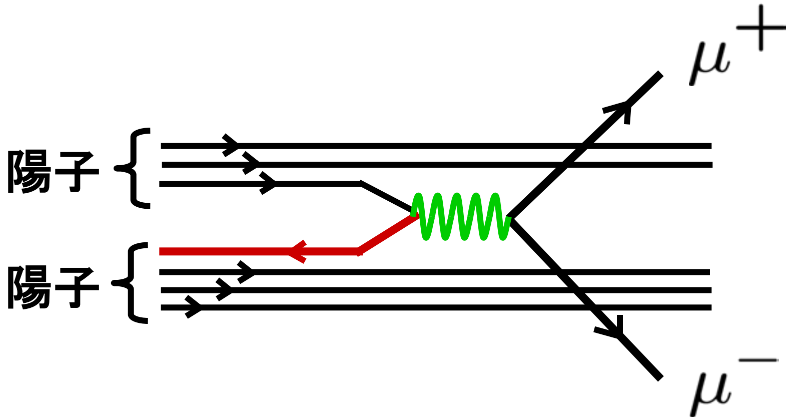
"nucleons" held apart by short range repulsion
but even in ^{208}Pb, half the nucleons are in the surface

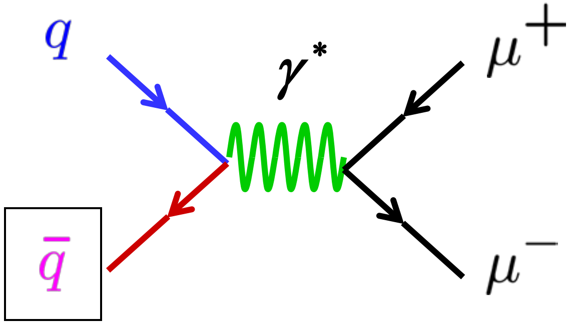


  - **海クォーク(sea quark)の分布はどうなってるの？**

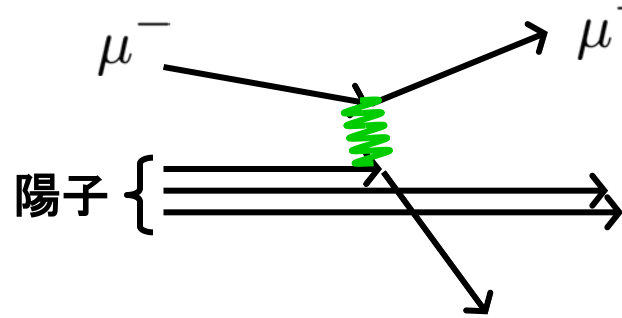
Drell-Yan過程

陽子ー陽子衝突によるドレル・ヤン過程

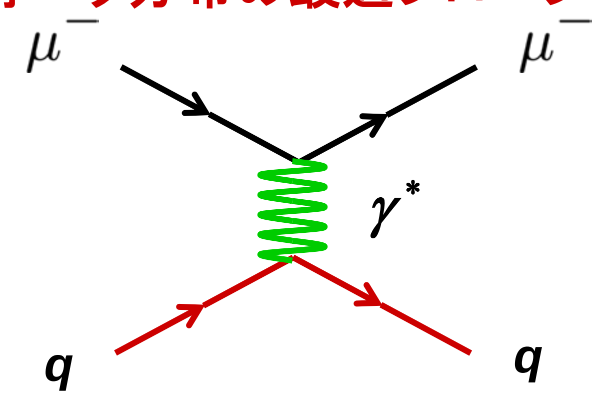




ミューオンー陽子深非弾性散乱



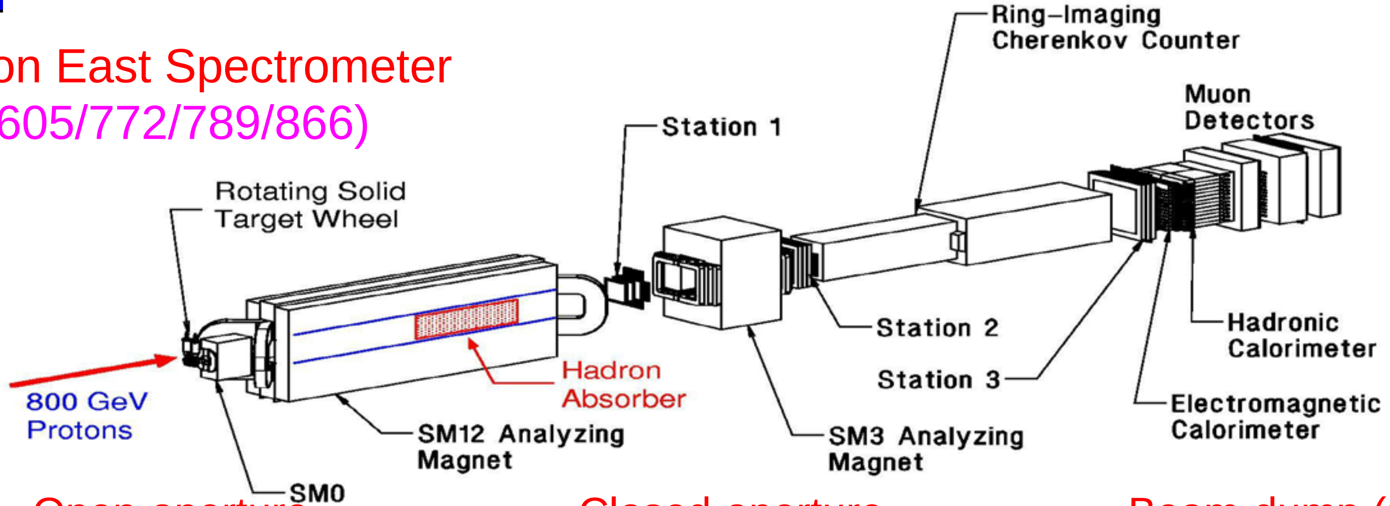
レプトン散乱は **物質(例:陽子)中のクォーク分布の最適プローブ**



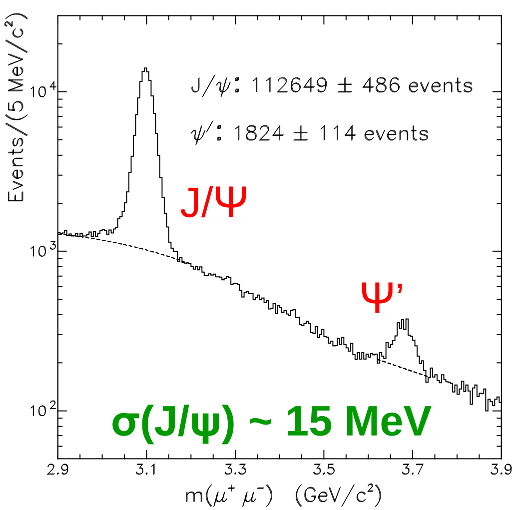
Drell-Yan過程は 反クォーク工場:反クォーク(海クォーク)分布の最適プローブ

Drell-Yan測定の例：Fermilab Experiments

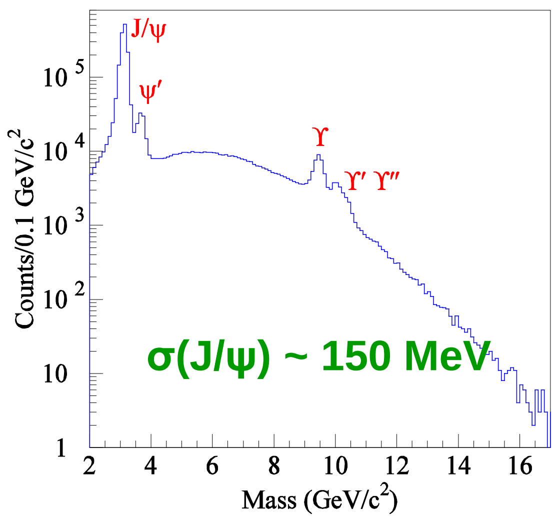
Meson East Spectrometer
(E605/772/789/866)



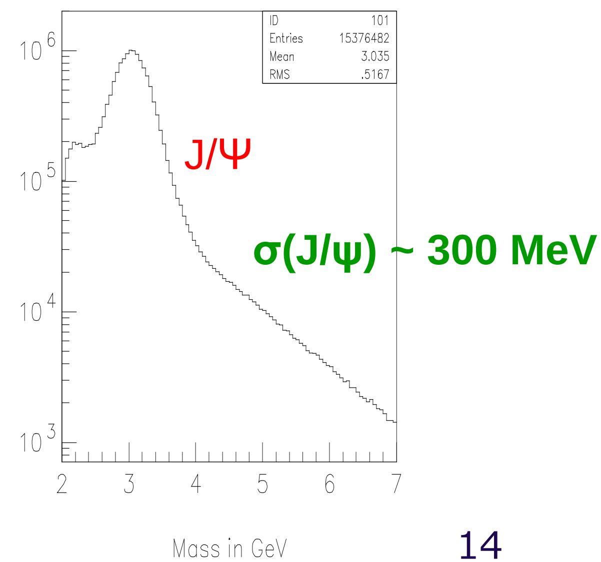
Open-aperture



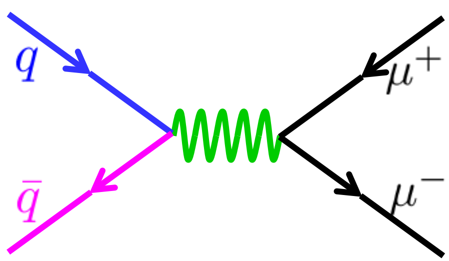
Closed-aperture

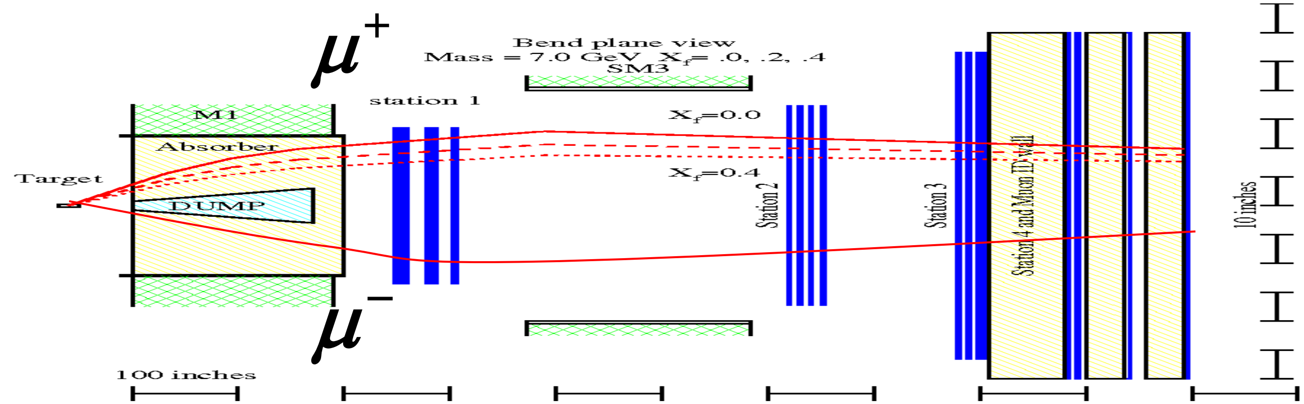


Beam-dump (Cu)



Drell-Yan過程の運動学





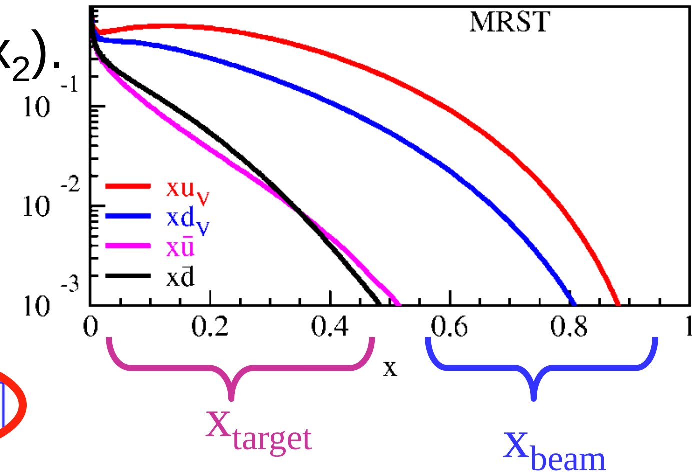
- For each event measure 3-momentum of each μ
- Assume that it is a muon to get 4-momentum

- Reconstruct M^2_γ, p_T^γ, $p_{||}^\gamma$
- $M^2_\gamma = x_1 x_2 s$,
- $x_F = 2p_{||}^\gamma / s^{1/2} = x_1 - x_2$

Drell-Yan過程の運動学

Detector acceptance chooses x_{target} (x_1) and x_{beam} (x_2).

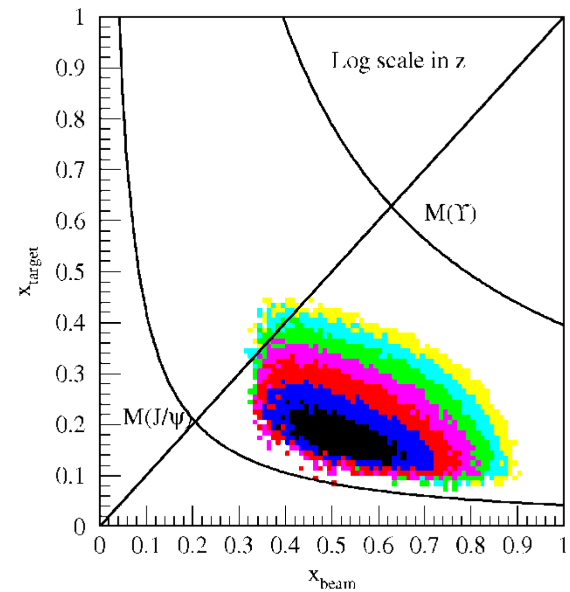
- Fixed target: high $x_F = x_{beam} - x_{target}$
- Valence Beam quarks at high-x.
- Sea Target quarks at low/intermediate-x



$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum e^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

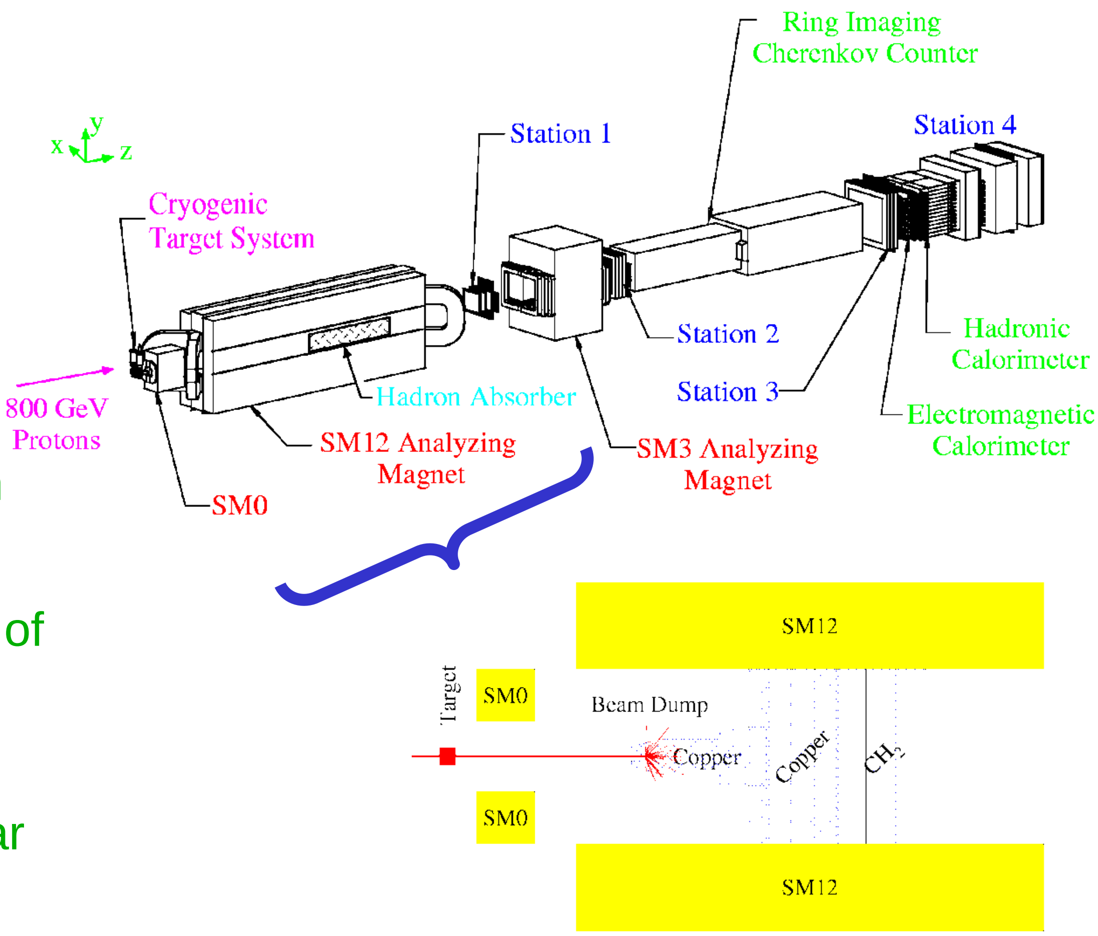
- While previous experiments were done at 800 GeV, E906 uses 120-GeV Main Injector beams.
  - Cross section scales as 1/s
    - *7 x that of 800 GeV beam*
  - Backgrounds, primarily from J/ψ decays scale as s
    - *7 x Luminosity for same detector rate as 800 GeV beam*

50 x statistics!!



Fermilab E866 Spectrometer: Long History

- E605: 1978-1985 US-Japan
  - Study of single and pair production of leptons and hadrons at very high transverse momenta
- E772: 1986-1988
  - Nuclear dependence of DY and quarkonium production
- E789: 1989-1991
  - Search for two body decay of heavy quark mesons
- E866/Nusea: 1993-1996
  - Determination of d-bar/u-bar ratio of the proton via DY



海クォークの構造：これまでの実験データ

- pQCD – Gluon splitting? i.e. $\bar{d}(x) = \bar{u}(x)$
- NMC (Gottfried Sum Rule)

$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x))/x]dx$$
$$= \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u}_p(x) - \bar{d}_p(x))\, dx$$
$$= \frac{1}{3} \quad (if\ \bar{u}_p = \bar{d}_p)$$

$S_G = 0.235 \pm 0.026$

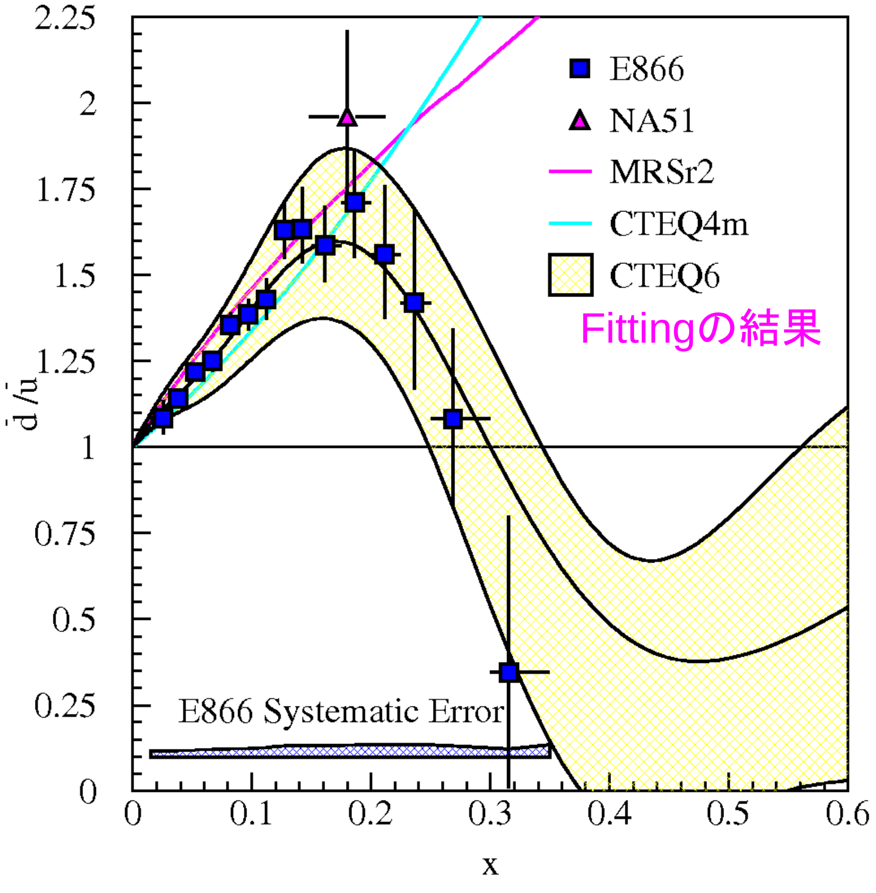
$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$

- NA51 (Drell-Yan)

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

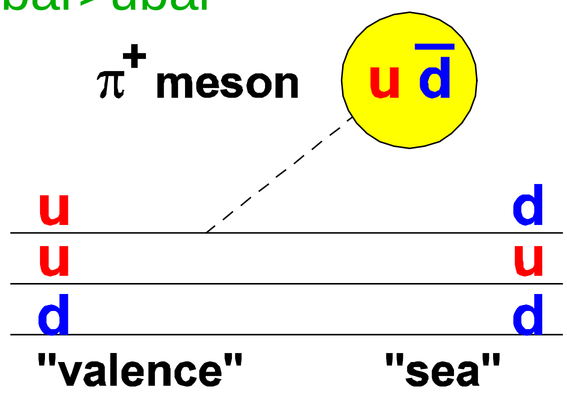
- E866 (Drell-Yan)

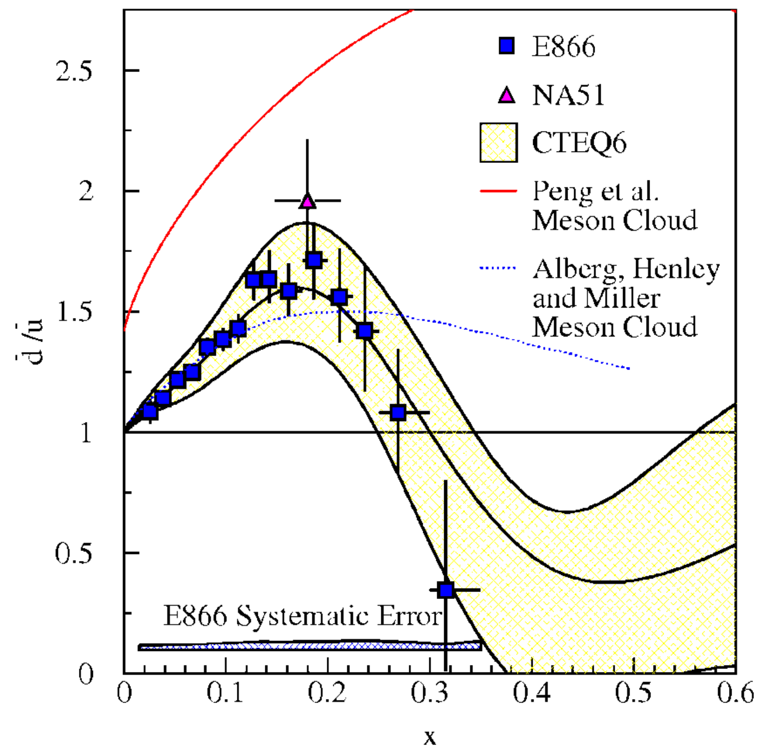
$\bar{d}(x)/\bar{u}(x)$ for $0.015 \le x \le 0.35$



海クォークの構造

- グルーオンsplittingだけではdbar=ubarしか説明できない。
- 「中間子雲」モデル
  - dbar>ubar

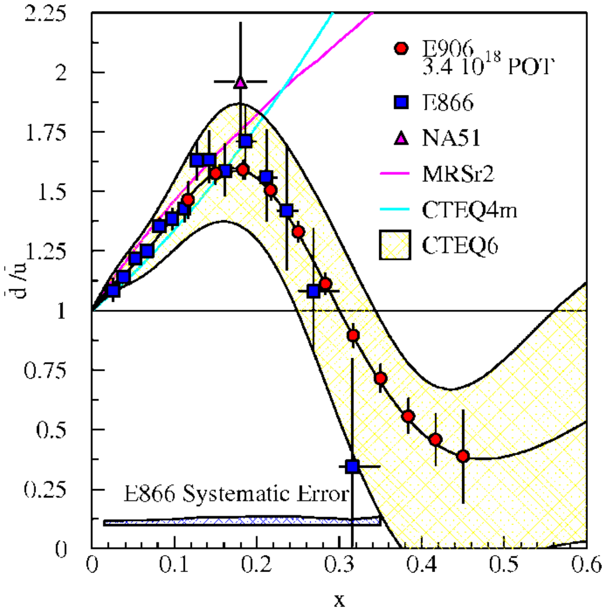




- どのような描像もdbar<ubarは説明できない！

Fermilab E906/SeqQuest実験

- 目的:0.25 < x < 0.45 でdbar/ubarを測定し、より広い範囲でのdbar/ubarとそのx依存性を明らかにする。
- 陽子ビーム:FNAL Main Injector からの120GeVビーム
  - 2×10^{12}/sec on target
- スペクトロメータ:既存の資産を最大限生かしながら建設する。
  - 日本グループはStation 3を主として担当する。



Advantages of 120 GeV Main Injector

The (very successful) past:

Fermilab E866/NuSea

- Data in 1996-1997
- ^{1}H, ^{2}H, and nuclear targets
- 800 GeV proton beam

The future:

Fermilab E906

- Data in 2010-12
- ^{1}H, ^{2}H, and nuclear targets
- 120 GeV proton Beam

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$

- Cross section scales as 1/s
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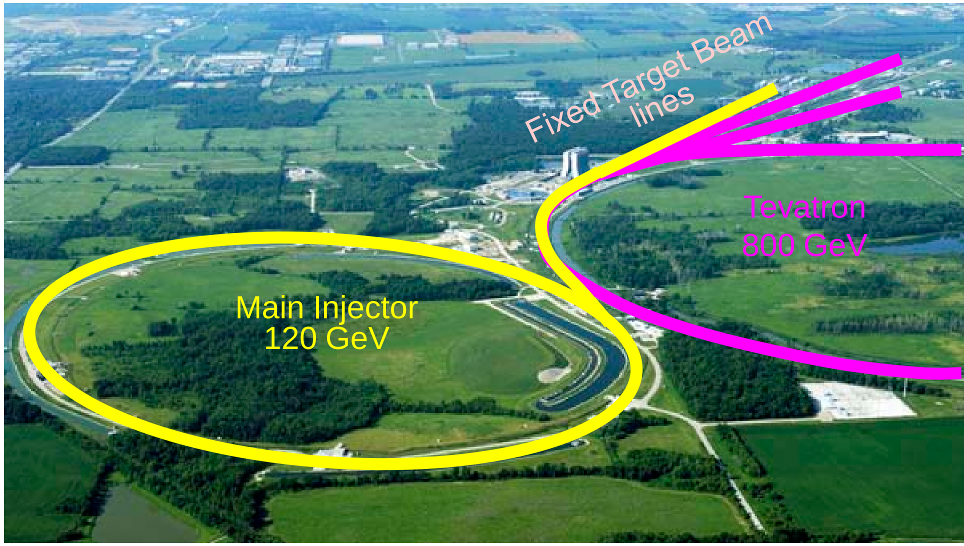
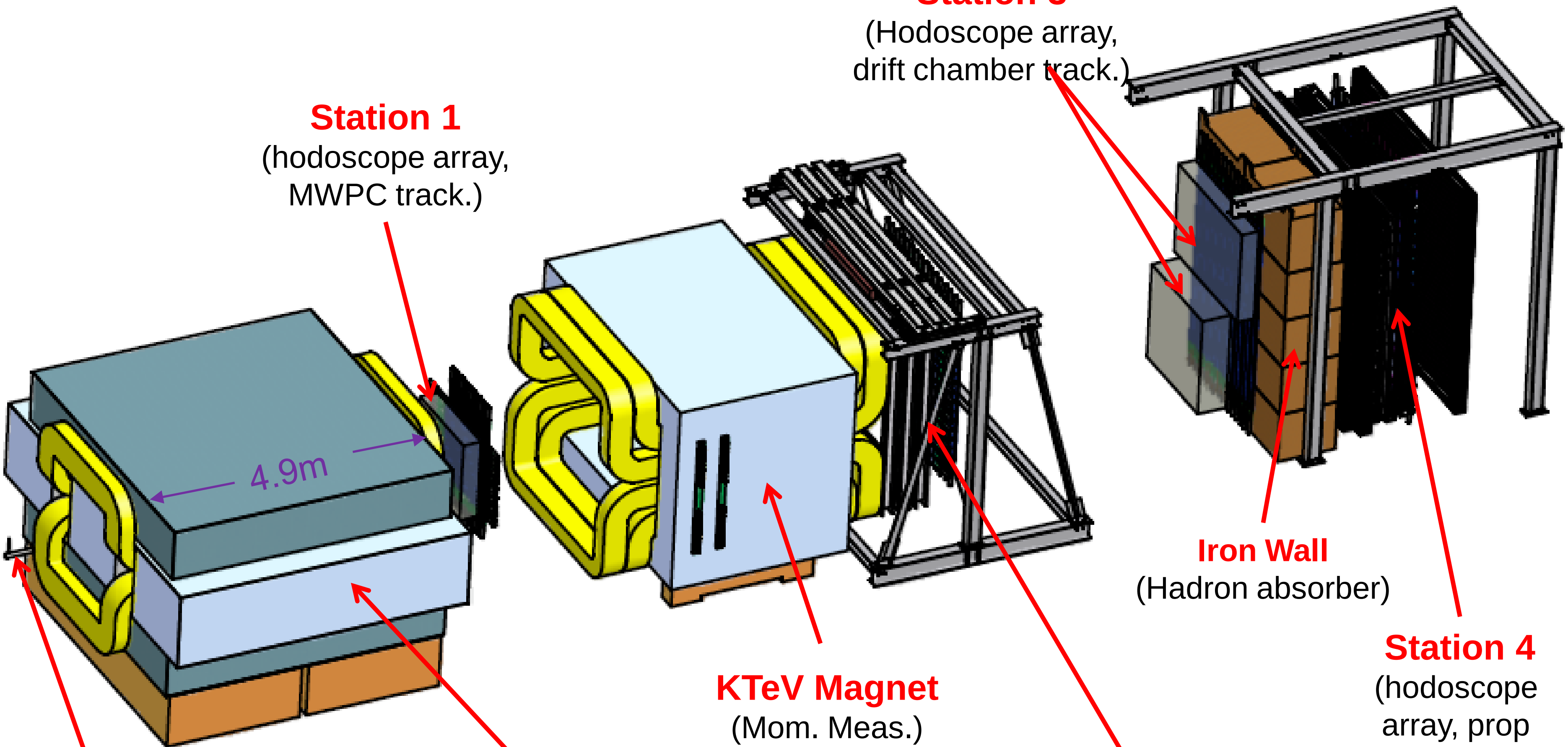
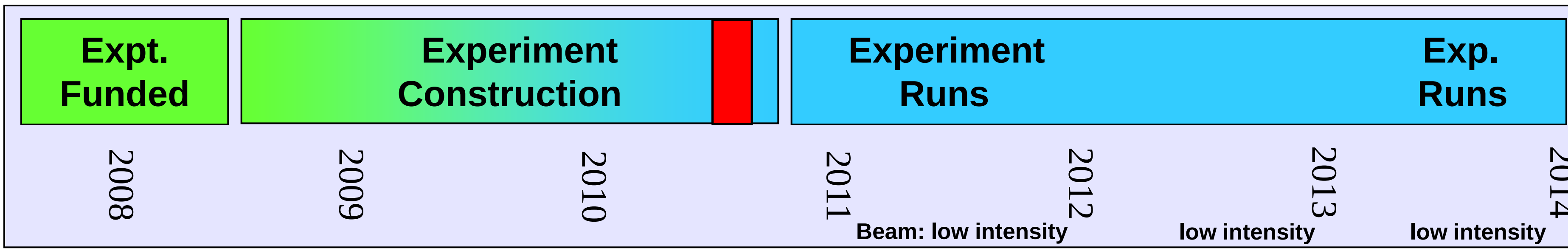


Drell-Yan Spectrometer for E-906/SeaQuest (25m long)



Fermilab Seaquest Timelines

- Fermilab PAC approved the experiment in 2001, but experiment was not scheduled due to concerns about “proton economics”
- Stage II approval in December 2008
- Expect to start running around Thanksgiving for 2 years of data collection



w/ Tevatron extension

Apparatus available for future programs at, *e.g.* Fermilab, J-PARC or RHIC

➡ significant interest from collaboration for continued program

実験プロポーザルとストラテジー

- Fermilab E906/SeaQuest: Main Injector with 120-GeV protons
  - 2010-2013
  - Mid x region, really d-bar/u-bar < 1??
- J-PARC P04: Experiment with 30 and 50-GeV protons
  - 2014-
  - Experimental apparatus mainly from E906
  - Ep = 30 GeV at the beginning
    - J/Psi physics
  - Ep = 50 GeV at the next stage with unpol beams for higher x
  - Polarized target and / or polarized beams
    - New proposal is under preparation.

Antiquarks in nucleons

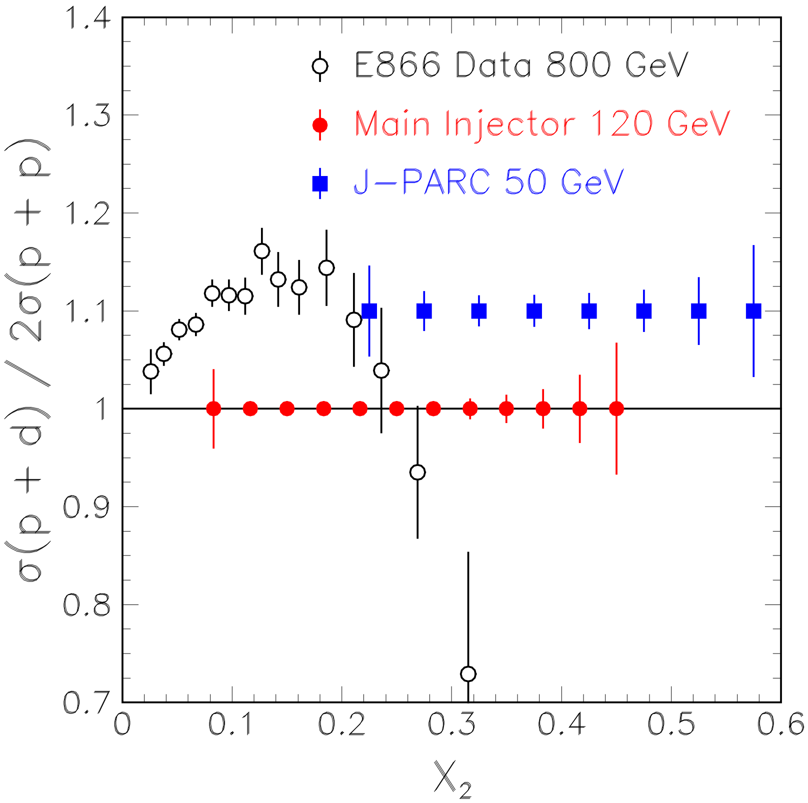
- dbar/ubar at Large x using 50 GeV Protons.
- J-PARC can measure d-bar/u-bar at larger x.

10^{12} protons per spill (3 s)

50-cm long LH_2 / LD_2 targets

60-day runs for each targets

assuming 50% efficiency



Motivation of an experiment at J-PARC

- Muon pair measurement from p+p, p+d, and p+A reactions

- Drell-Yan
  - Sea quark flavor asymmetry at larger x_{target}
  - Spin-labeled structure at large x_{target}
  - Paton energy loss in cold nuclear matter
- J/Psi
  - production mechanism
  - nuclear dependence
- Open charm and others

- If polarized target → more spin structure (P24)
- And if polarized beam → much more spin structure (P24)

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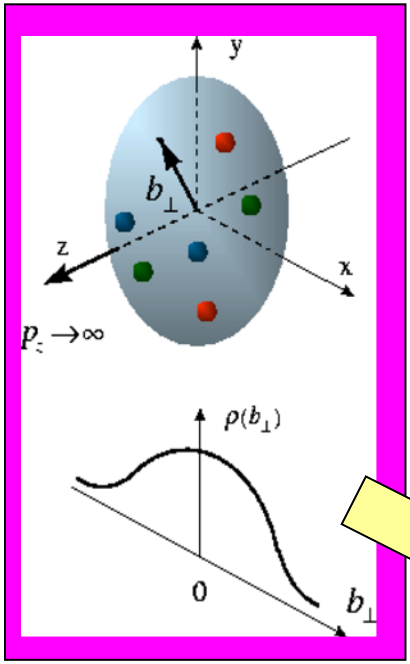
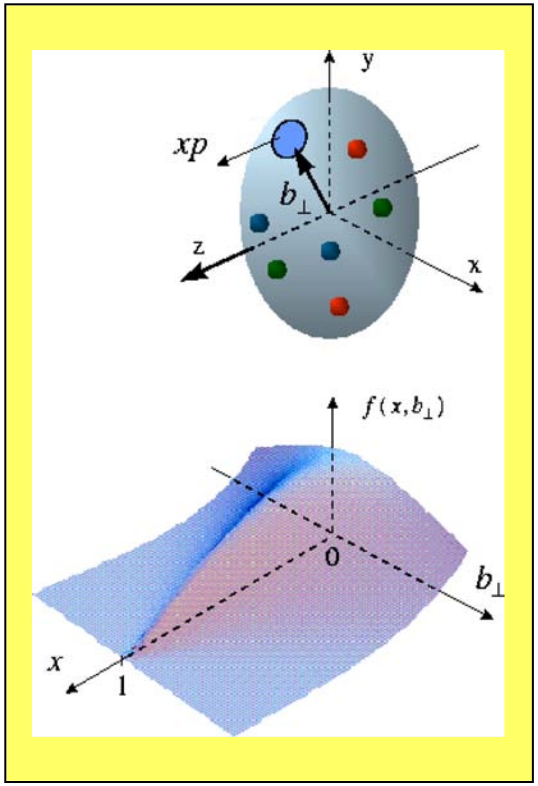
  - 40GeV? Pol. beam? Pi beams?
- Summary

“2D to 3D” and “static” to “dynamic”

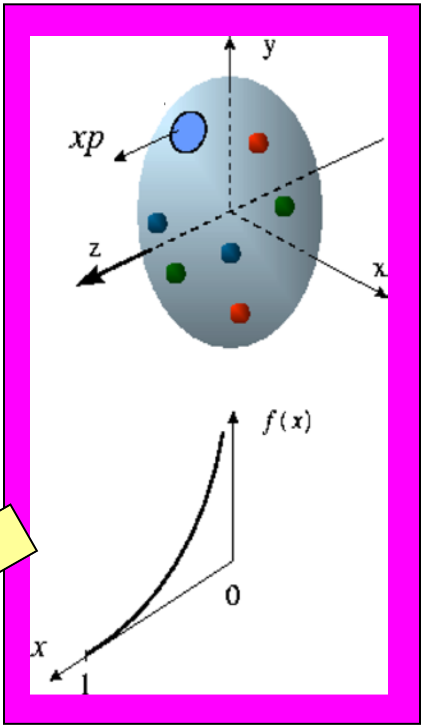
X. Ji, D. Mueller, A. Radyushkin, …
M. Burkardt, … Interpretation in impact parameter space



Proton form factors, transverse charge & current densities



Correlated quark momentum and helicity distributions in transverse space - GPDs



Structure functions, quark longitudinal momentum & helicity distributions

Angular mom: essential info for 3D and dynamic understanding

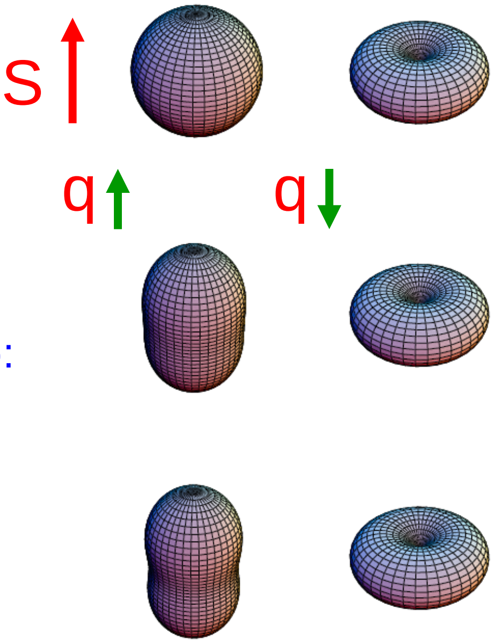
$$\frac{1}{2} = \frac{1}{2}\underline{\Delta\Sigma} + \underline{\Delta g} + L$$

~25% small?

- So, understanding of the orbital angular momentum is the key issue.
- Understanding of the orbital angular momentum needs not only longitudinal momentum and helicity distribution but also transverse distribution.
- Now the slogan should be “2D to 3D”.
- Transverse distribution can be expressed by
  - Generalized Parton Distirubions (GPDs)
    - Form factor (transverse) + Structure Function (longitudinal) = 3D nucleon structure,
  - Transverse Momentum-dependent Distributions (TMDs)
    - Bohr-Mulders fn, Sivers fn. etc.
- Extensive theoretical investigation on this field is being done.

Nucleon Shape? (a naïve question)

– How about the shape labeled with “spin”s?
  - G. A. Miller, Phys. Rev. C68, 022201(R) (2003)
    - Spin dependent density operator
    - Shapes of the proton. Proton spin is vertical direction. Left column: quark spin parallel to proton spin. Right column: quark spin anti-parallel to proton spin. K (quark momentum): 1 to 4 GeV/c (from upper to lower).
  - G. A. Miller, Phys. Rev. C76, 065209 (2007)
    - Transverse momentum dependent parton density and spin dependent density operator



$$\rho_{RT}\left(\mathbf{K}_T,\mathbf{n}_T,\mathbf{S}_T\right)/M=\tilde{f}_1\left(K_T^2\right)+\tilde{h}_1\left(K_T^2\right)\mathbf{n}\cdot\mathbf{S}_T+\frac{\left(\hat{\mathbf{n}}_T\cdot\mathbf{K}_T\hat{\mathbf{S}}_T\cdot\mathbf{K}_T-\frac{1}{2}K_T^2\hat{\mathbf{n}}\cdot\hat{\mathbf{S}}_T\right)}{M^2}\tilde{h}_{1T}^{\perp}\left(K_T^2\right)$$

Boer-Mulders Fn.(integrated over x) :

can be measured with the Drell-Yan process

- non-zero Boer-Mulders fn. → non-spherical spin dependent density

Drell-Yan angular distributions

- Boer-Mulders function $h_1^{\perp}(x, k_T^2)$
  - angular distribution of unpolarized Drell-Yan

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

  - correlation between transverse quark spin and quark transverse momentum in an unpolarized proton

$$N(\phi)\propto h_1^{\perp q}(x_1,k_\perp^2)\cdot\frac{(\hat{P}\times\vec{k}_\perp)\cdot\vec{S}_q}{M}\cdot h_1^{\perp\bar{q}}(x_2,\bar{k}_\perp^2)\cdot\frac{(\hat{P}\times\vec{\bar{k}}_\perp)\cdot\vec{S}_{\bar{q}}}{M}$$

$$\nu\propto\left(\frac{h_1^\perp}{f_1}\right)\left(\frac{\overline{h}_1^\perp}{\overline{f}_1}\right)$$

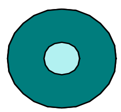
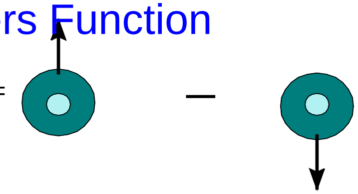
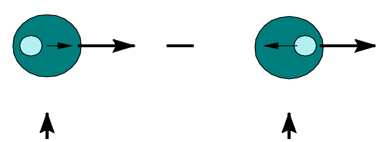
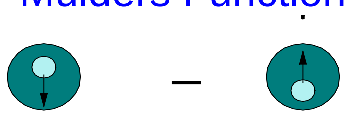
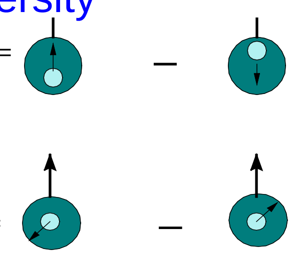
Spin-labeled structure can be measured even with unpolarized experiments.

偏極ビーム・標的が利用可能になったら…

- J-PARC dimuon 実験のスピン物理メニュー
  - 縦偏極 A_{LL} of Drell-Yan
    - sea-quark 偏極のフレーバー非対称性
  - 横偏極 A_N of Drell-Yan
    - Sivers関数（$\sin(\phi-\phi_S)$ term）
    - transversity分布関数 & Boer-Mulders関数（$\sin(\phi+\phi_S)$ term）
  - 横偏極 A_{TT} of Drell-Yan
    - transversity分布関数
  - その他（30-GeV）
    - J/Ψ: Drell-Yan と同様のメニュー?
    - A_N of open charm: Sivers関数
    - (neutron-tagged Drell-Yan)

"Leading-Twist" TMD Quark Distributions

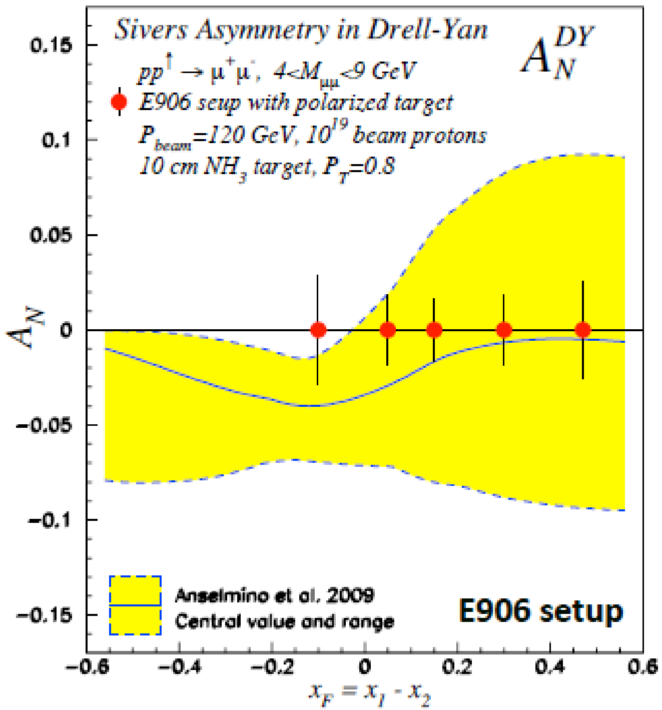
TMD: Transverse Momentum-dependent Distribution

Nucleon \ Quark	Unpol.	Long.	Trans.
Unpol.	$f_1 =$ 		Sivers Function $f_{1T}^{\perp} =$ 
Long.		$g_{1L} =$ 	$g_{1T} =$ 
Trans.	Bohr-Mulders Function $h_1^{\perp} =$ 	$h_{1L}^{\perp} =$ 	Transversity $h_{1T} =$, $h_{1T}^{\perp} =$ 

$$\delta q = \int_0^1 dx \left[h_1^q(x) - h_1^{\bar{q}}(x)\right]$$

An Example of Sivers at 120 GeV

Constrain f_{1T}/f_1 to ±2% for u-bar.



Xiaodong Jian, Drell-Yan Workshop at Santa Fe, Oct 31- Nov 1, 2010.

Needs polarized NH3 solid target.

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- Toward New Step of Structure Study
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- R&D
  - High momentum beam line
  - Polarized target
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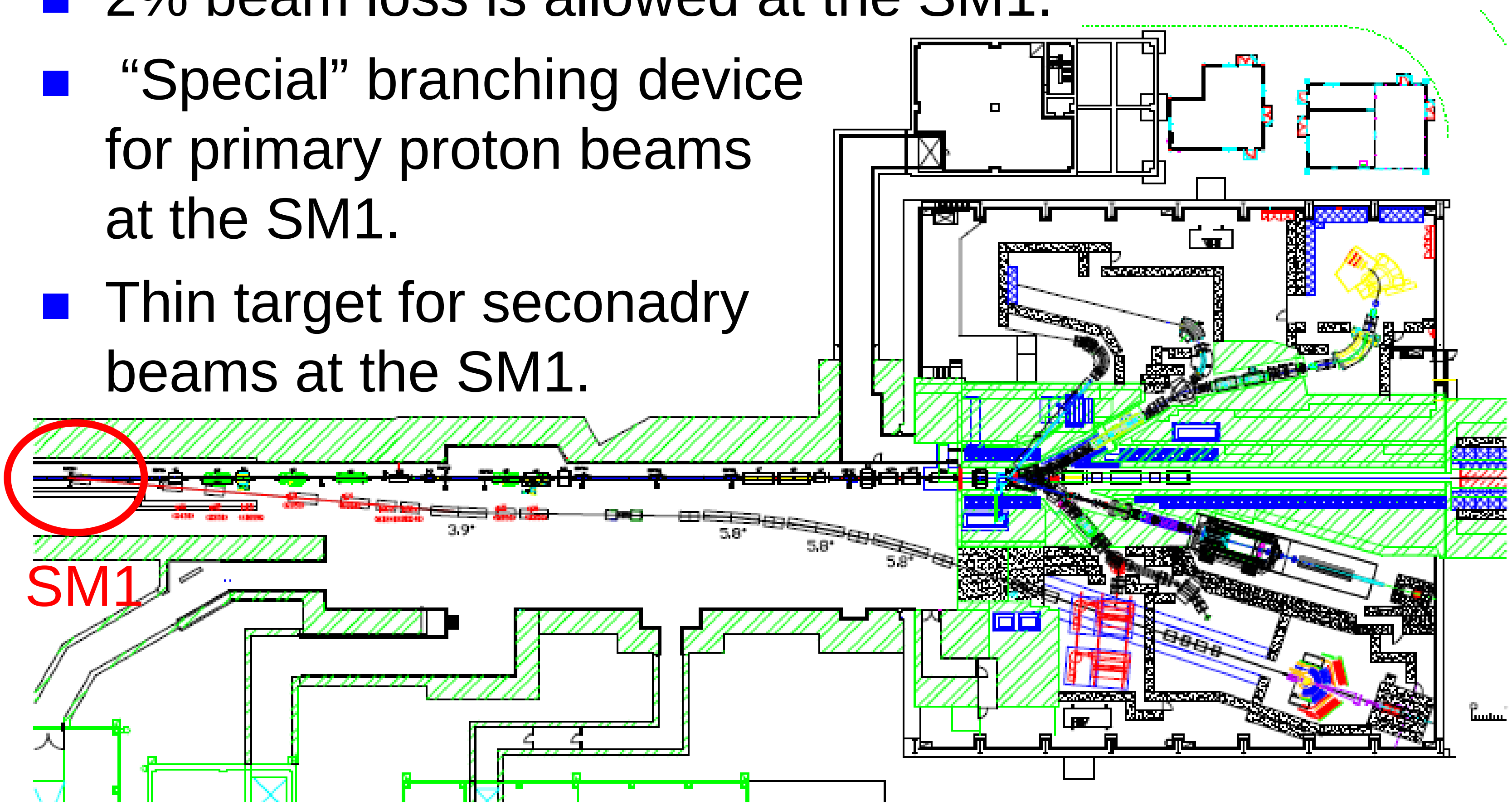
  - 40GeV? Pol. beam? Pi beams?
- Summary

High-Momentum Beam Line

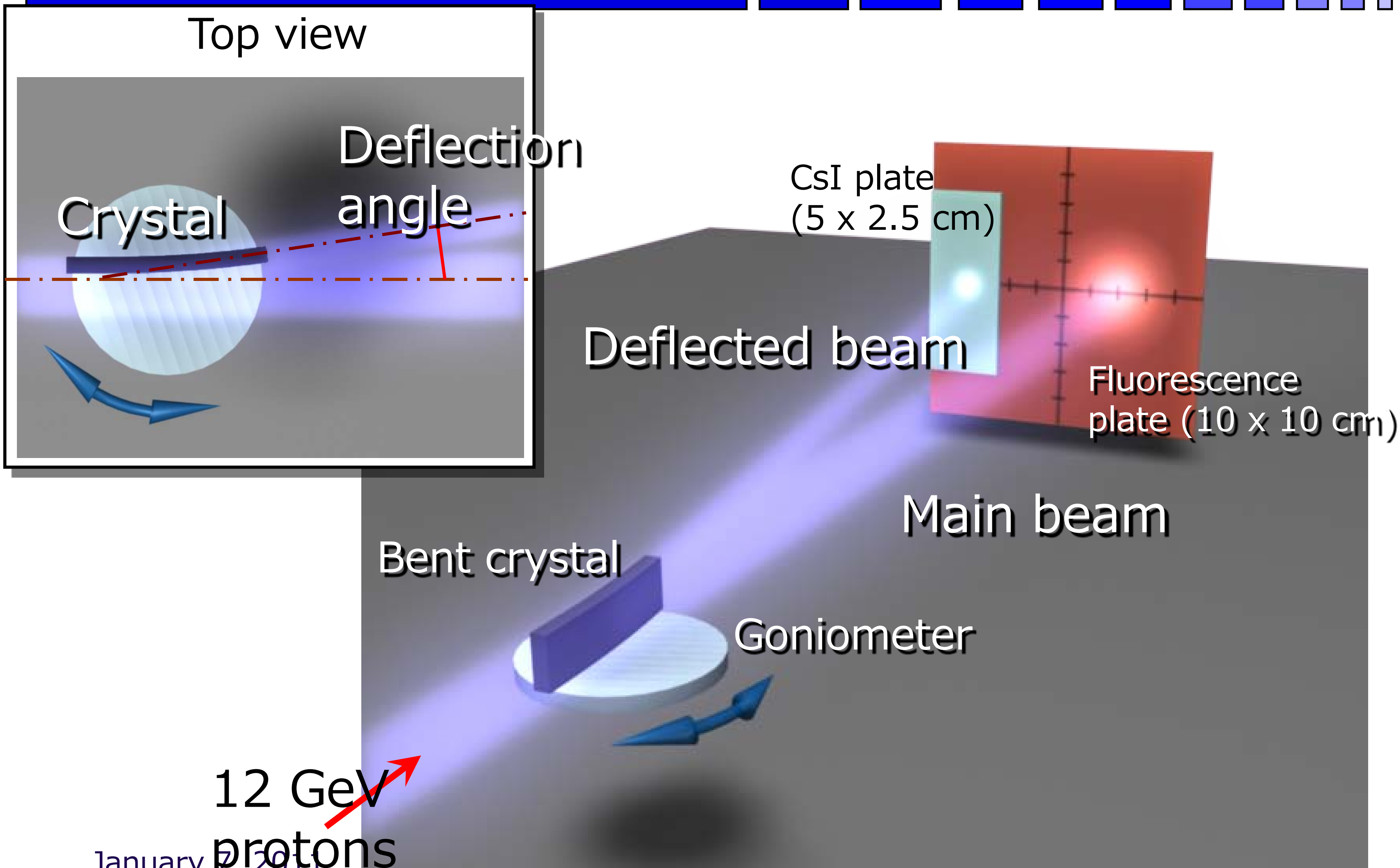
- Separated at the SM1 in the switchyard.
- 2% beam loss is allowed at the SM1.
- “Special” branching device for primary proton beams at the SM1.
- Thin target for seconadry beams at the SM1.



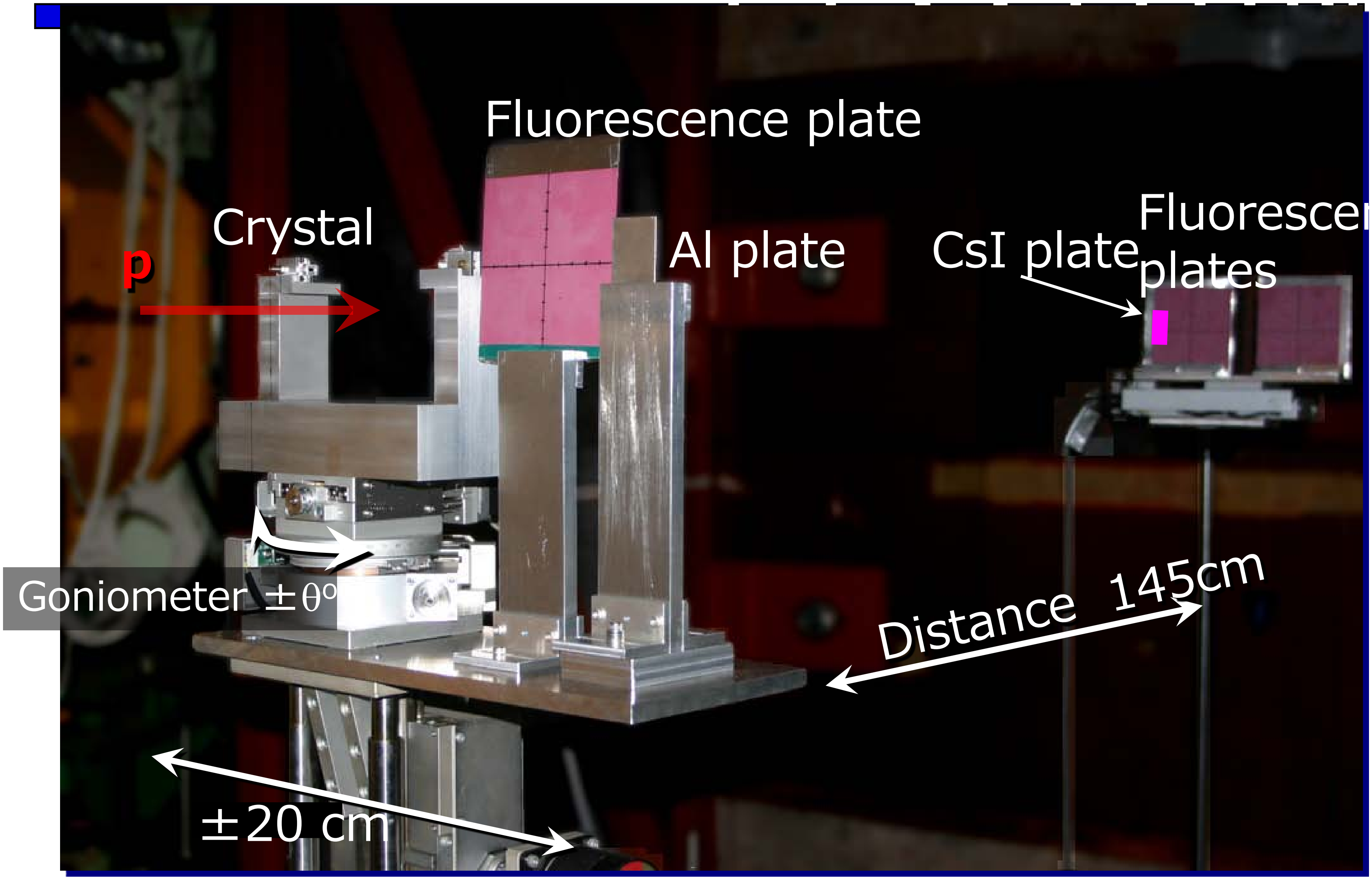
Device R&D for proton beam branching

- Main beam: 10^{13} – 10^{14} protons/spill
  → Branched beam: 10^{9} – 10^{10} or 10^{12} protons/spill
- Conventional method: Electrostatic septum and/or Lambertson magnet
  - Septum: similar to the one used at the slow extraction from the 50-GeV Main Ring.
  - Limited bending power
  - Magnet has an issue on radiation and heat.
- Advanced method: Bent Crystal
  - Principle was proved at a test experiment at KEK-PS.
  - Need realistic test and design
    - application for Grant-in-aid for scientific research (Kakenhi)
    - Already a part of R&D is being started.

Schematic drawing of the experiment

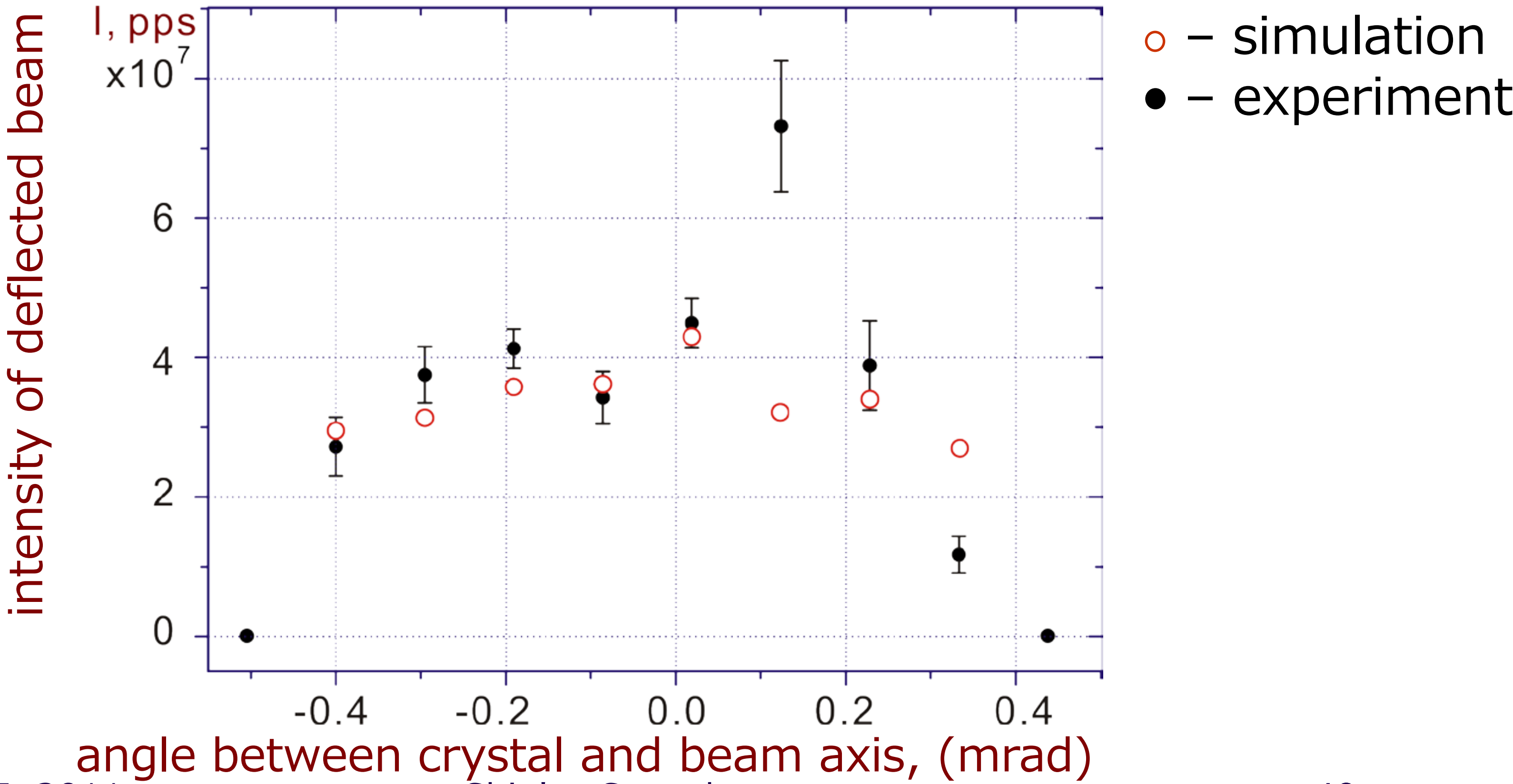


Experimental setup



Simulation vs. Experimental data

Experimental intensity of the deflected beam compared with the best fitted simulation (CATCH) for the beam divergence of **0.6 mrad** and normalization factor for the d. b. intensity of **1/0.93**.



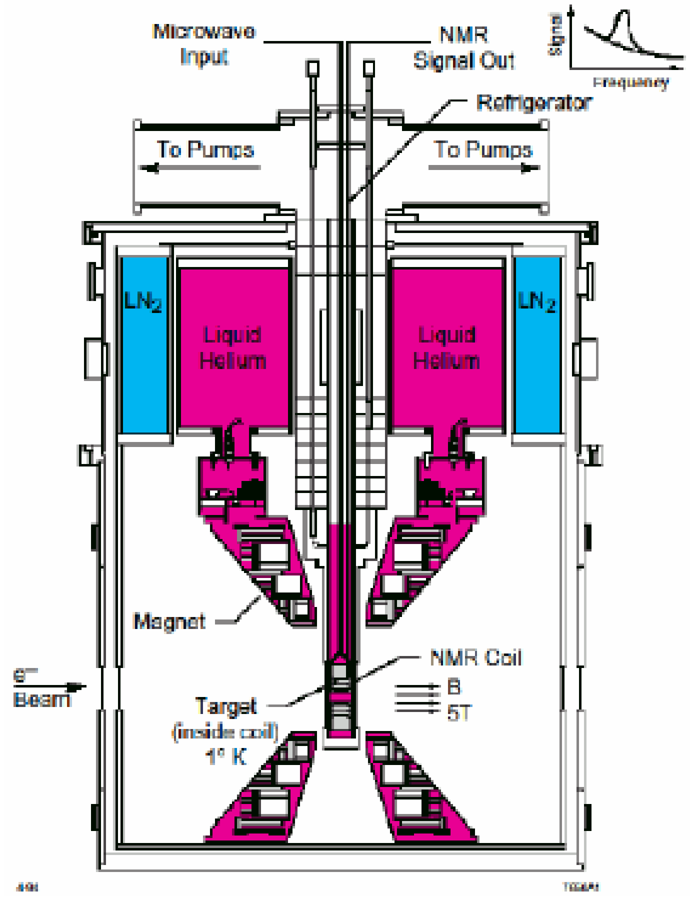
Branching of 10^7 protons from 10^{12} ppp was achieved.

R&D Issues at J-PARC

- Crystal fabrication
  - Crystals were made by Italian and Russian collaborators so far.
  - A test to fabricate a thick (~1mm) bent silicon crystal has been started at a company in Japan.
- Radiation and heat resistant goniometer system inside the vacuum at the separation point
  - Vacuum chamber and goniometer system are being fabricated.
- Radiation hardness is to be tested.

R&D of Polarized Target

- R&D for polarized solid target is underway with Kakenhi by Yuji Goto (RIKEN) and co. (@ Yamagata and KEK)
  - Don Crabb



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40 or 50 GeV?

- The design of the main ring (synchrotron) of J-PARC is 50 GeV.
- In the course of the construction, some parts of the accelerator components were redesigned and fabricated with 30 or 40 GeV, mainly due to shortage of money and R&D period.
- Upgrade to 40 and 50 GeV needs money.
- 40 GeV is relatively easier.
  - Possibility of Drell-Yan measurement at 40 GeV should be investigated seriously.
- Appealing with physics cases should be important.

Unseparated Beams (30GeV)

- 30GeV protons + 2% loss copper target. Production angle of 4 degree and $(\Delta p/p)\Delta\Omega$ = 0.2msr%.

	Momentum (GeV/c)	$d\sigma/dpd\Omega$ (mb/sr/GeV/c)	Yield at SM1 (per 10^{14} protons)	Yield at 120m (per 10^{14} protons)
π^+	5	1400	3.7E7	2.4E7
π^+	10	210	1.1E7	8.9E6
π^-	5	1000	2.6E7	1.7E7
π^-	10	130	6.7E6	5.4E6
K^+	5	130	3.3E6	1.3E5
K^+	10	28	1.4E6	2.8E5
K^-	5	61	1.6E6	6.4E4
K^-	10	7.0	3.6E5	7.2E4
pbar	5	11	2.8E5	2.8E5
pbar	10	1.1	5.7E4	5.7E4

- Even with 30 GeV protons, enough intensity can be obtained especially for pions!

Unseparted Beams (50GeV)

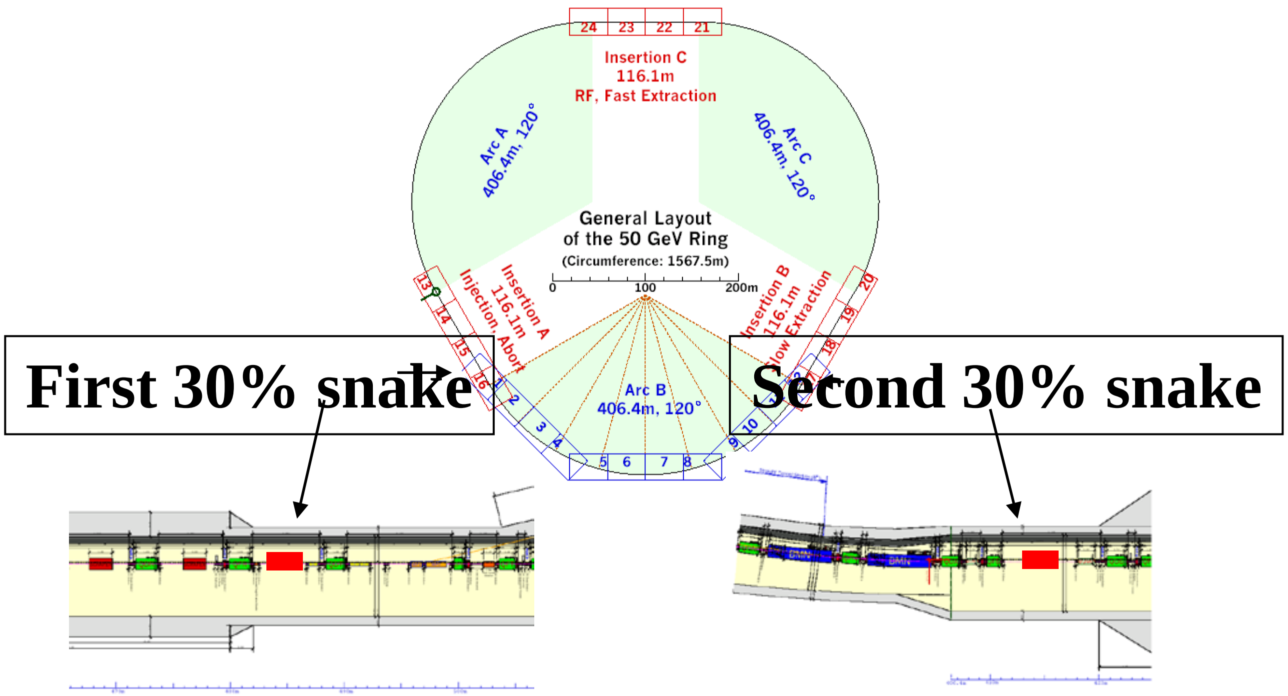
- 50GeV protons + 2% loss copper target. Production angle of 4 degree and $(\Delta p/p)\Delta\Omega$ = 0.2msr%.

	Momentum (GeV/c)	$d\sigma/dpd\Omega$ (mb/sr/GeV/c)	Yield at SM1 (per 10^{14} protons)	Yield at 120m (per 10^{14} protons)
π^+	5	3700	9.5E7	6.2E7
π^+	10	930	4.7E7	3.8E7
π^-	5	3700	9.5E7	6.2E7
π^-	10	700	3.6E7	2.9E7
K^+	5	440	1.1E7	4.4E5
K^+	10	120	6.2E6	1.2E6
K^-	5	220	5.7E6	2.3E5
K^-	10	56	2.9E6	5.8E5
pbar	5	53	1.4E6	1.4E6
pbar	10	16	8.4E5	8.4E5

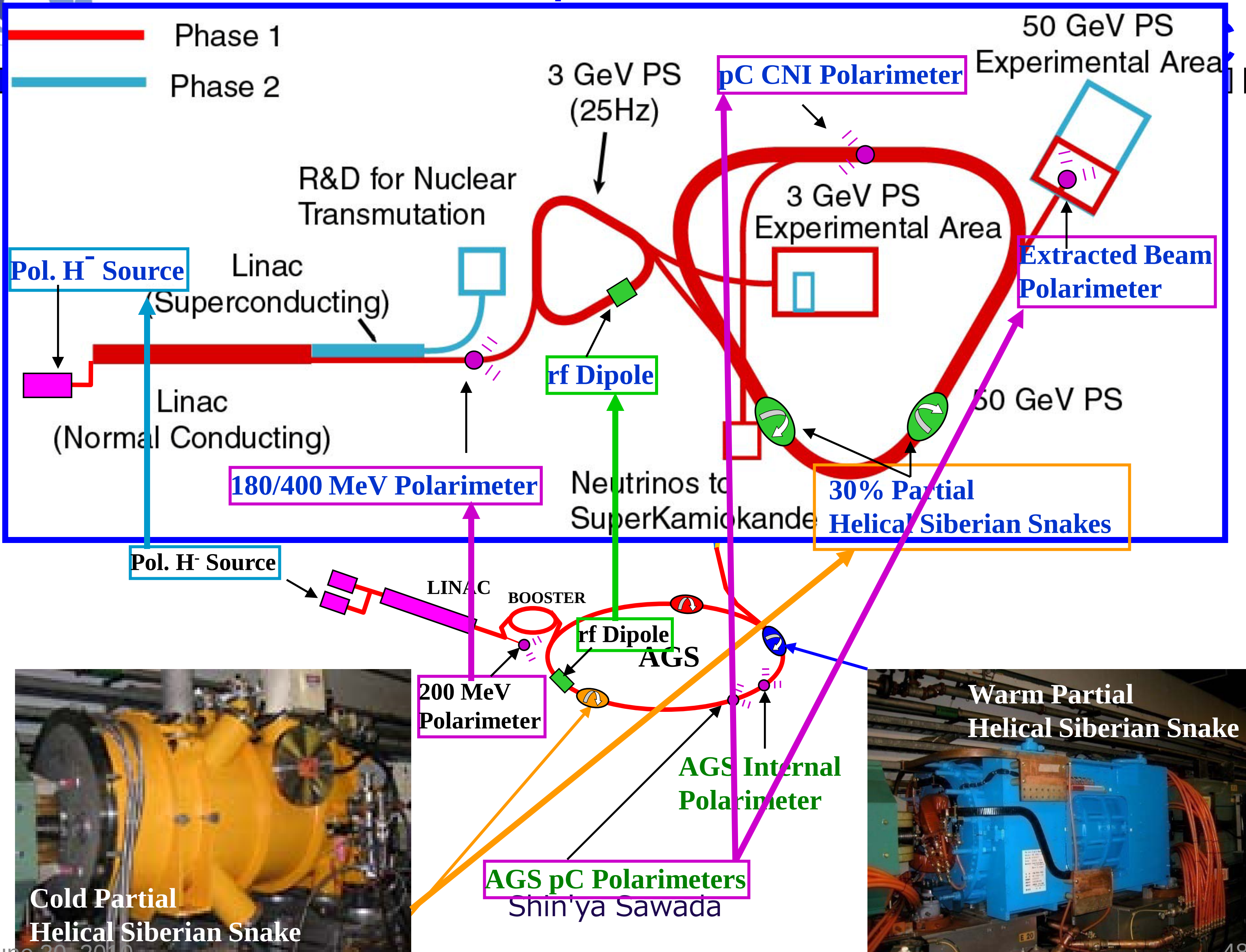
- To get more intensity for higher momentum beams, extraction at more forward angles can be considered.

偏極ビーム？

- P24として提案→「実験と装置・施設を分けよ」→新しいプロポーザルへ。
- unpolarized → polarized target → polarized beam
  - polarized beam study by BNL & KEK groups
  - possible locations of partial snakes in MR



Polarized proton acceleration at J-



Summary

- Hadron experiments have started at J-PARC.
- Drell-Yan experiment with lower energy is being done at Fermilab with 120 GeV protons.
- Similar experiment (and nearly identical setup) with 50 GeV (i.e. larger x) has been proposed to J-PARC.
- Next generation experiments should be on orbital angular momentum or 3-dimensional measurements.
- R&D for polarized targets and high momentum beam line are underway.
- Physics cases are important for higher beam energy and polarized beam acceleration.