ILC-N での核子構造研究

山形大学
Yamagata University

- 核子構造の研究目的・手法
- ILCでの核子構造研究
  - 電子・陽電子衝突実験
  - 固定標的実験
    - Electron Ion Collider (EIC) 計画

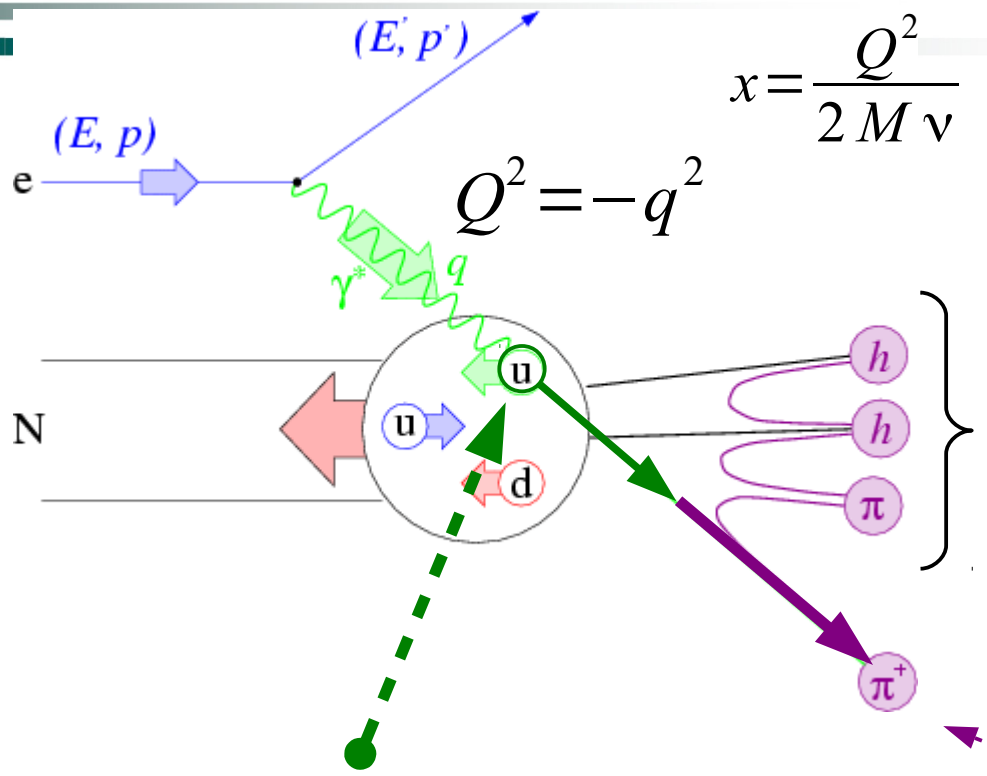
宮地　義之@山形大学

核子構造研究と深非弾性散乱

$$\nu = E - E'$$

$$x = \frac{Q^2}{2M\nu}$$

$$e\,N \rightarrow e'\,h\,X$$



$$z = \frac{E_h}{\nu}$$

$$\sigma^{eN \rightarrow e'hX} = \sum_q f^{N \rightarrow q} \otimes \hat{\sigma}^{eq \rightarrow e'q} \otimes D^{q \rightarrow h}$$

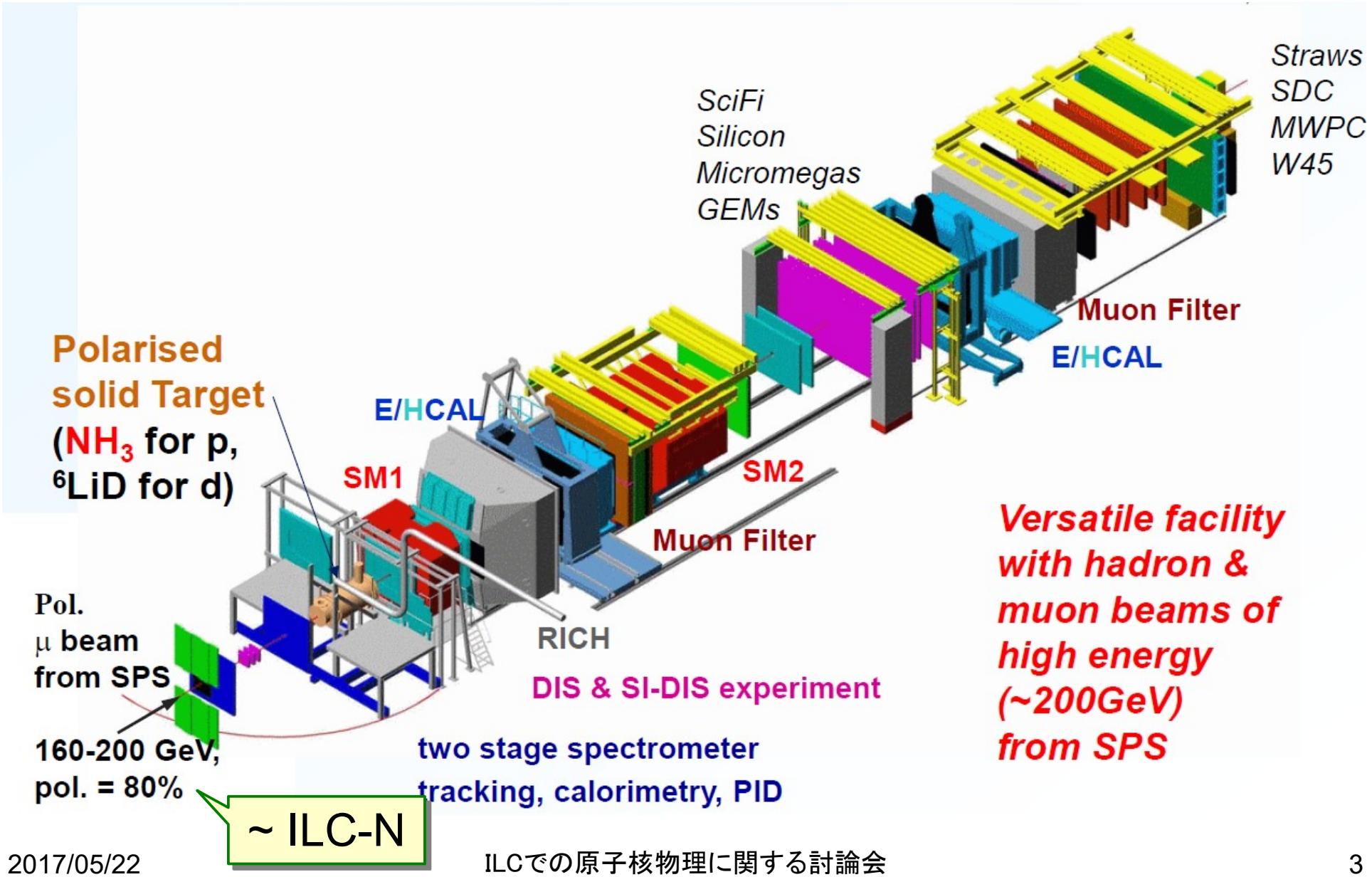
Parton **D**istribution **F**unction

$$f\left(x, Q^2\right)$$

Fragmentation **F**unction

$$D\left(z, Q^2\right)$$

CERN-COMPASS



“レプトン-パートン散乱” と ”ハドロン構造”

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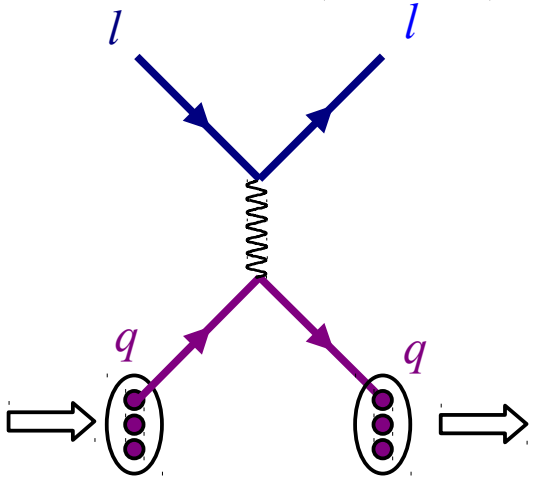
深非弾性散乱

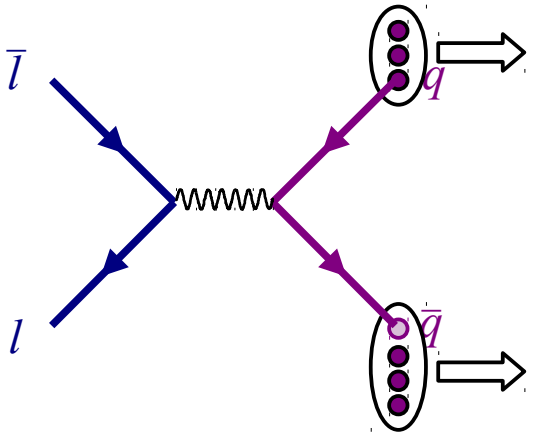
$$l + h \rightarrow l'\left(+h'\right) + X$$



電子・陽電子衝突

$$l + \bar{l} \rightarrow h + X$$

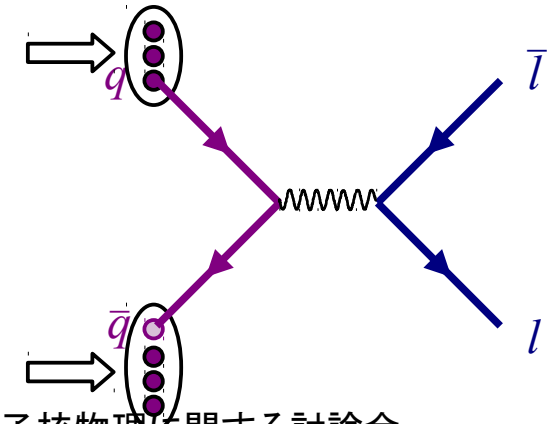
(Belle/BaBar)



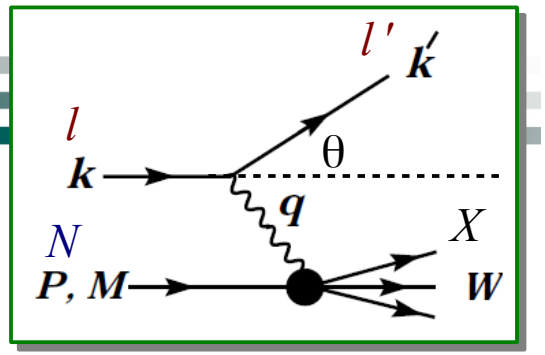
ドレル・ヤン反応

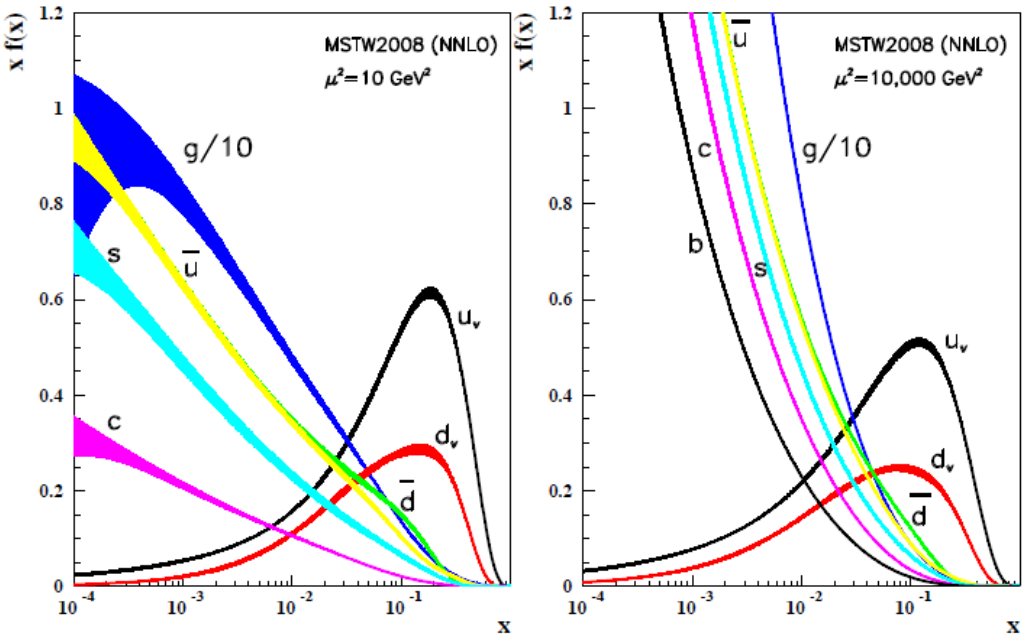
$$h_1 + h_2 \rightarrow l + \bar{l} + X$$

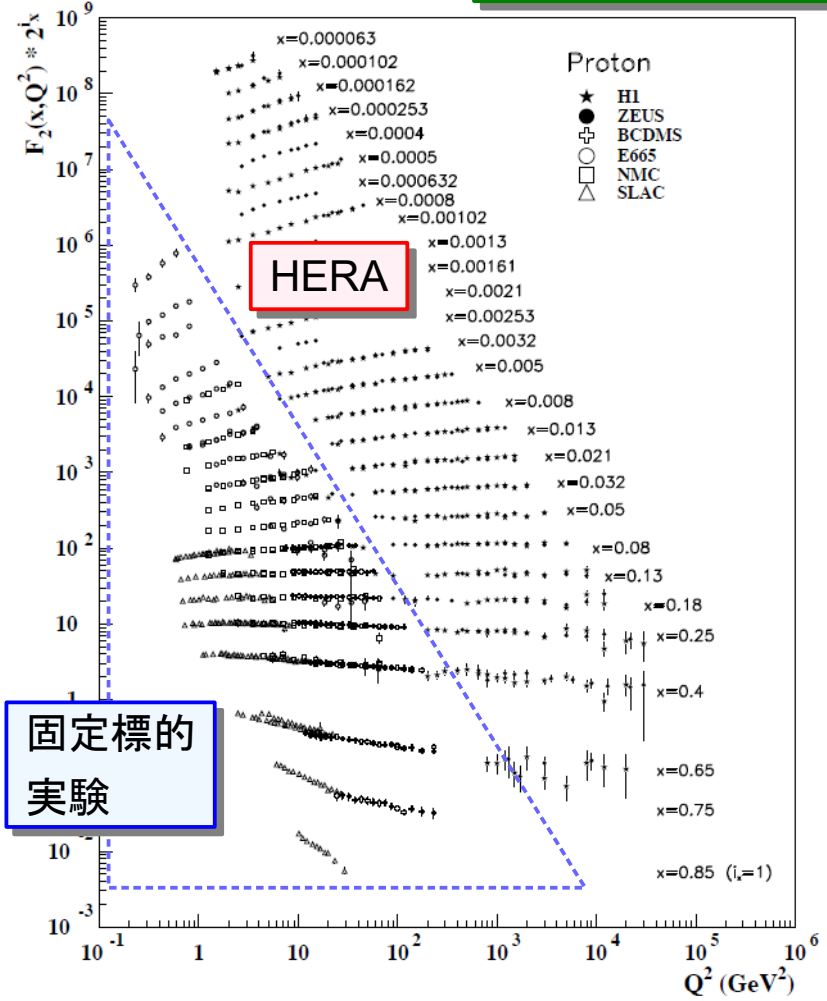
(SeaQuest)

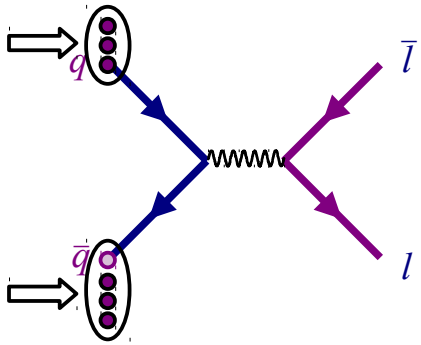


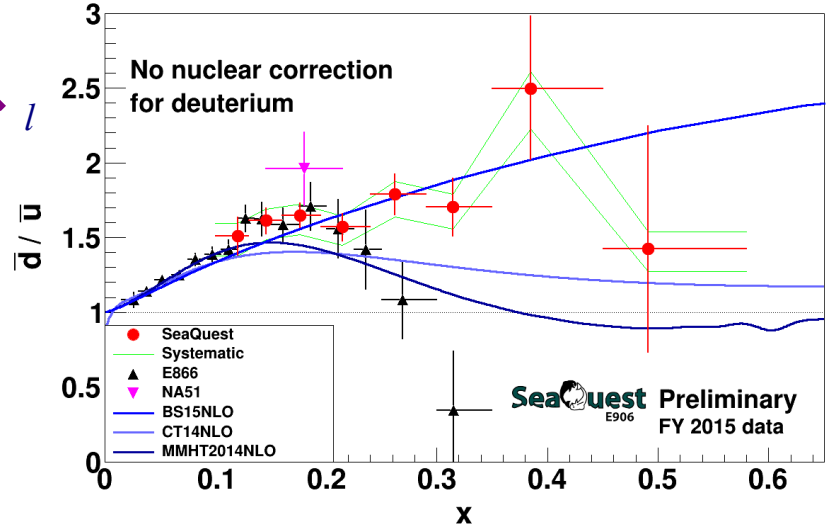
非偏極パートン分布関数



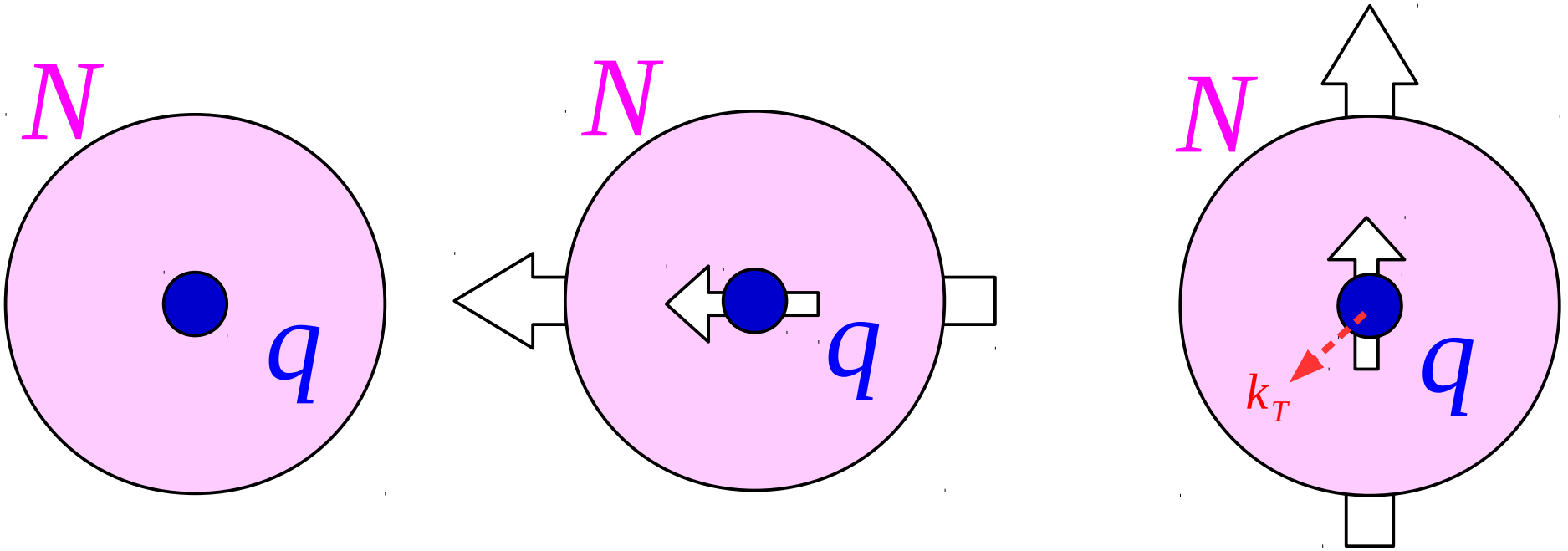








スピン依存パートン分布



$q(x)$

momentum

$\Delta q(x)$

spin

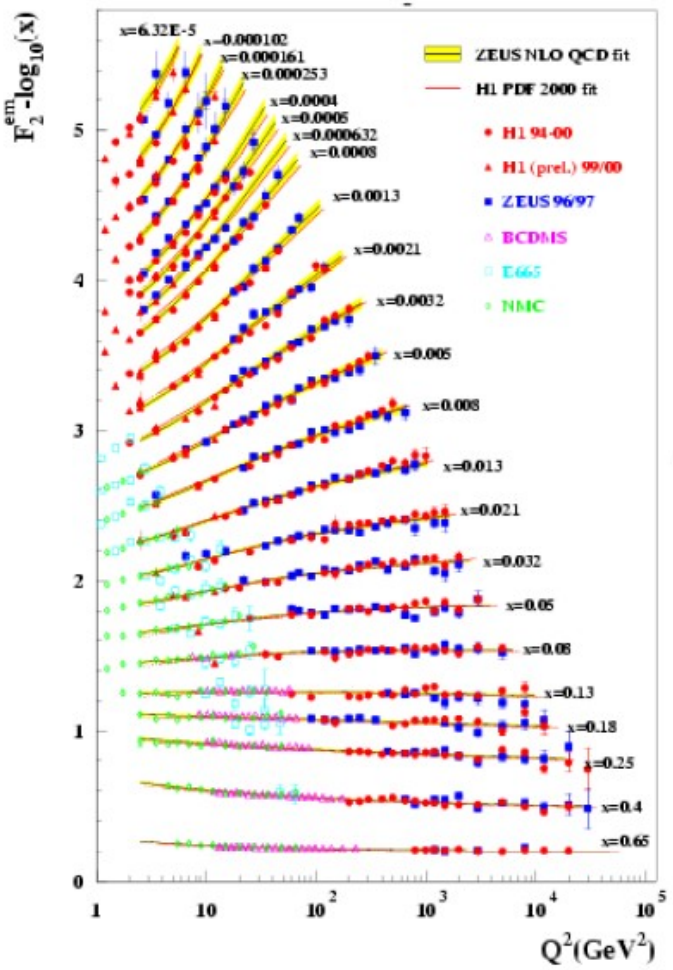
$h_1(x)$

transverse spin

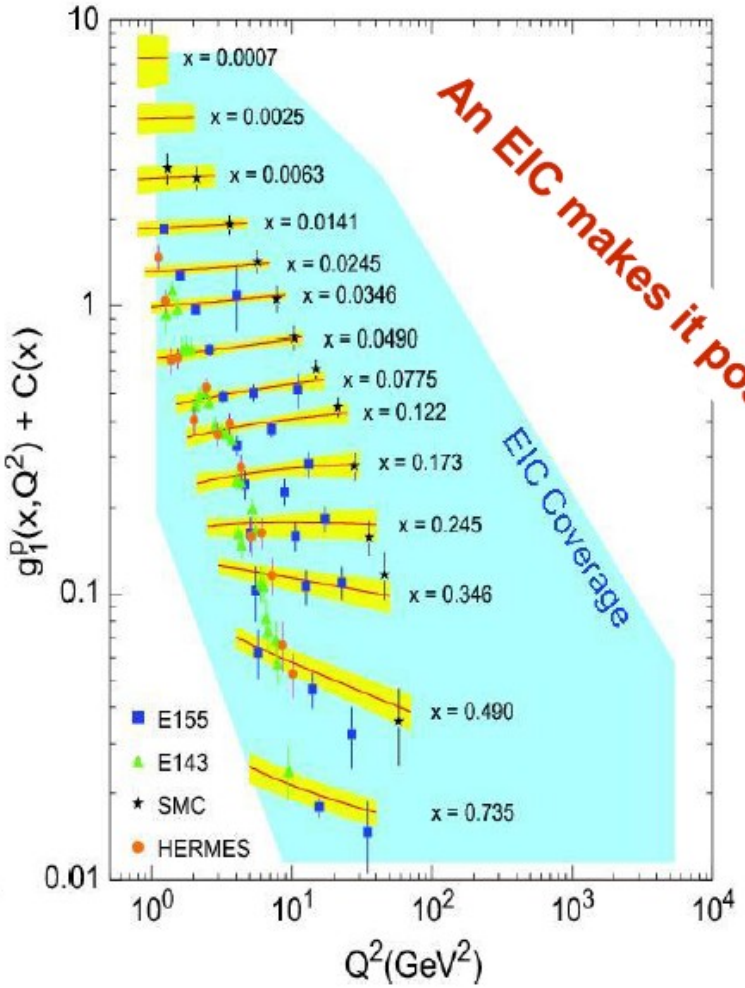
~ angular momentum

World Data on F_2^p World Data on g_1^p World Data on h_1^p

$$F_{UT}^{\sin(\phi_h+\phi_s)}(x,Q^2) + C(x) \propto h_1$$

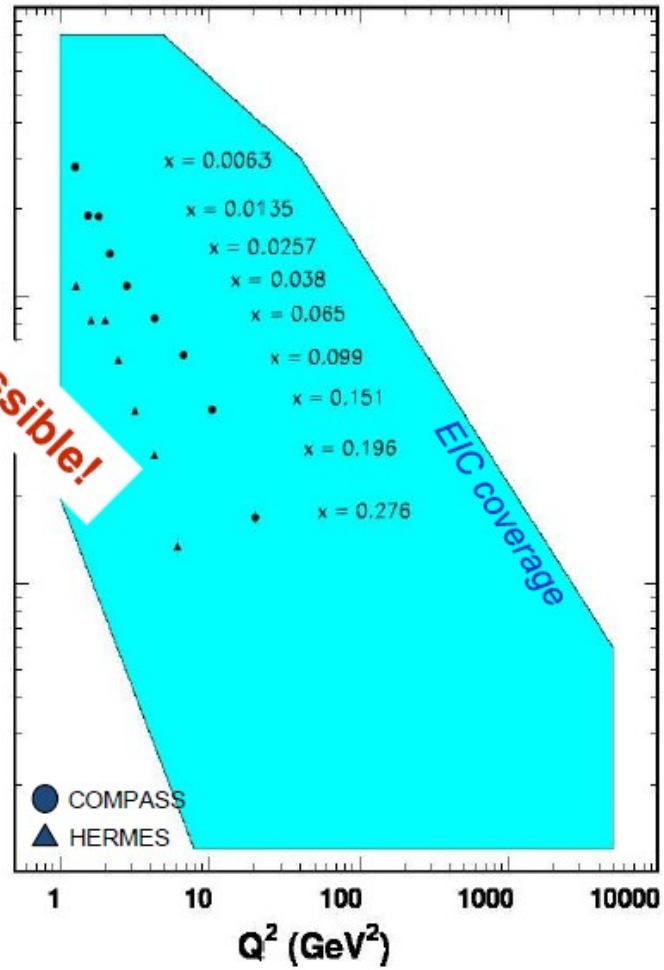


momentum



spin

An EIC makes it possible!



transverse spin ~ angular momentum

包括的測定から排他的生成測定へ

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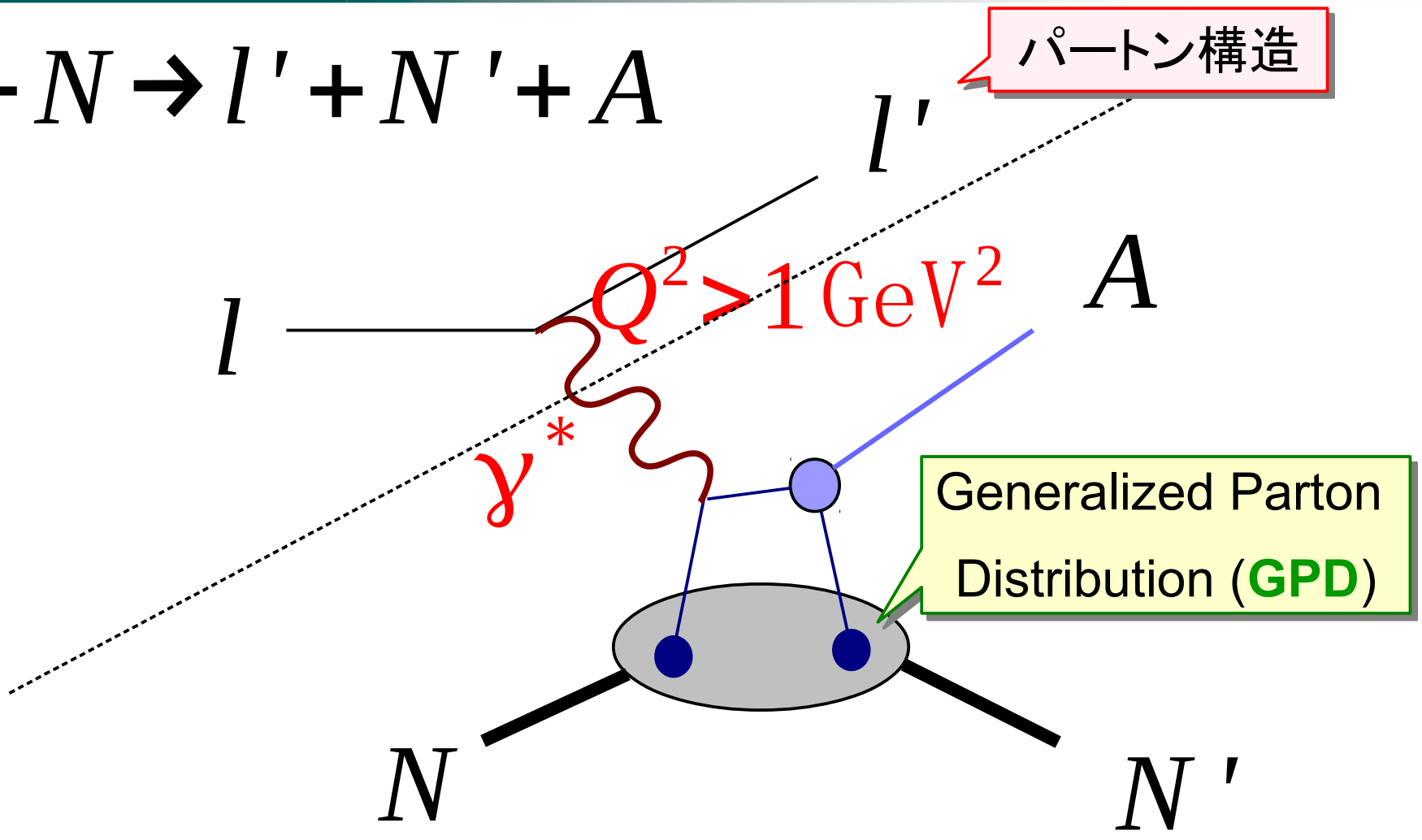
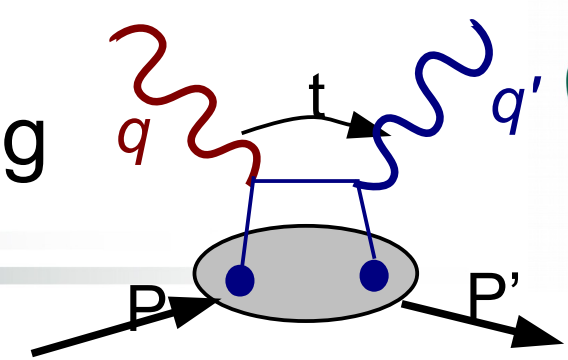
$l + N \rightarrow l' + N' + A$



運動量比 x 毎に形状因子を測る

弾性散乱　⇒　形状因子

実光子排他的生成:
Deeply Virtual Compton Scattering



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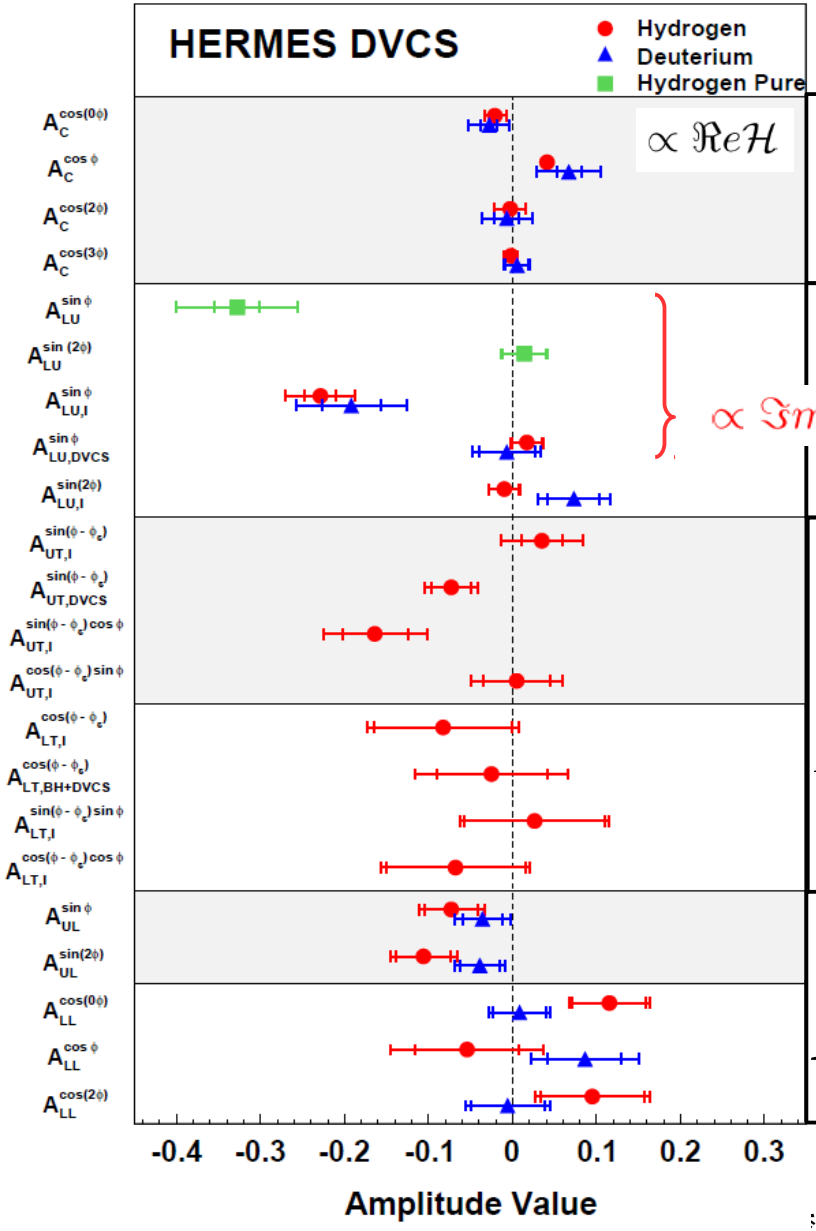
GPD



Beam Charge Asymmetries

Beam Spin Asymmetries

PRL 87 (2001) 182001
PRD 75 (2007) 011103
JHEP 11 (2009) 083
JHEP 07 (2012)032
JHEP 10 (2012) 042
NPB 829 (2010) 1

H

$p^{\uparrow\downarrow}$

Target Spin Asymmetries

Double Spin Asymmetries

JHEP 06 (2008) 066
PLB 704 (2011) 15

E

クォーク全角運動量⇔

$p^{\leftrightarrow}$

Target Spin Asymmetries

Double Spin Asymmetries

JHEP 06 (2010) 019
NPB 842 (2011) 265

$\tilde{H}$

using 27.6 GeV Pol. e- (e+) beam

電子･陽電子衝突実験：B-factory での成果

山形大学
Yamagata University

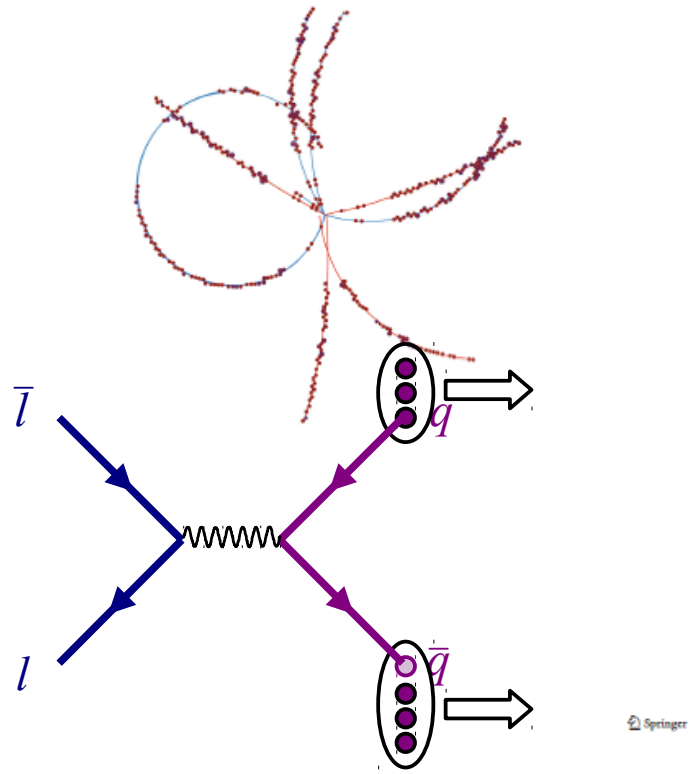
Eur. Phys. J. C (2014) 74:3026
DOI 10.1140/epjc/s10052-014-3026-9

THE EUROPEAN PHYSICAL JOURNAL C

Review

The Physics of the B Factories

Received: 29 July 2014 / Accepted: 29 July 2014 / Published online: 19 November 2014



電子・陽電子衝突実験：B-factory での成果

山形大学
Yamagata University

Eur. Phys. J. C (2014) 74:3026
DOI 10.1140/epjc/s10052-014-3026-9

THE EUROPEAN PHYSICAL JOURNAL C

Review

The Physics of the B Factories

ILCでの核子構造研究の可能性

山形大学
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- 電子・陽電子衝突実験
  - 破砕関数測定: 非偏極・偏極破砕関数
  - 二光子過程
    - Transition Form Factor
    - Generalized Distribution Amplitude
    - Photon Structure Function

QCD
@ B-Factory

- “偏極”固定標的による実験
  - Electron Ion Collider 計画との関係

Fragmentation function measurements

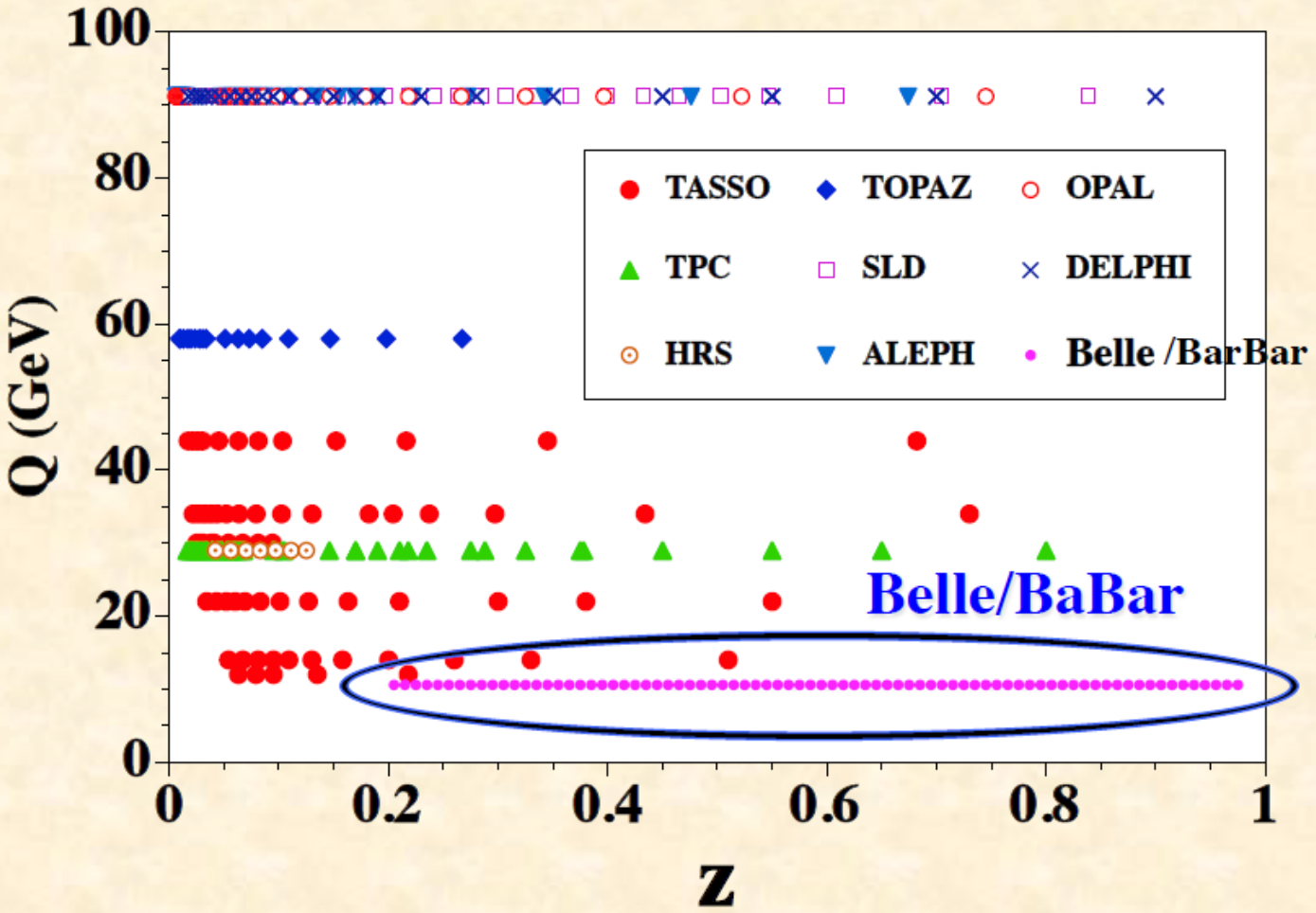
$D_i^h(z,Q^2)$

$Q = 1000\,\mathrm{GeV}$

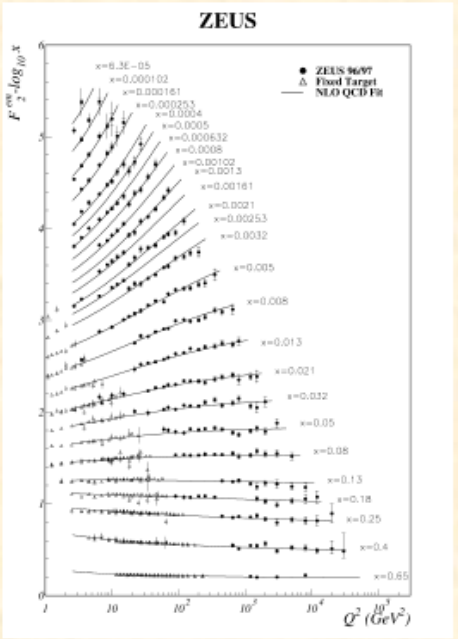
$Q = 500\ \mathrm{GeV}$

$Q = 250\,\mathrm{GeV}$

ILC



Scale evolution of D_i^h
→ gluon fragmentation function



Scale evolution of F_2
→ gluon distribution

“非偏極”破砕関数

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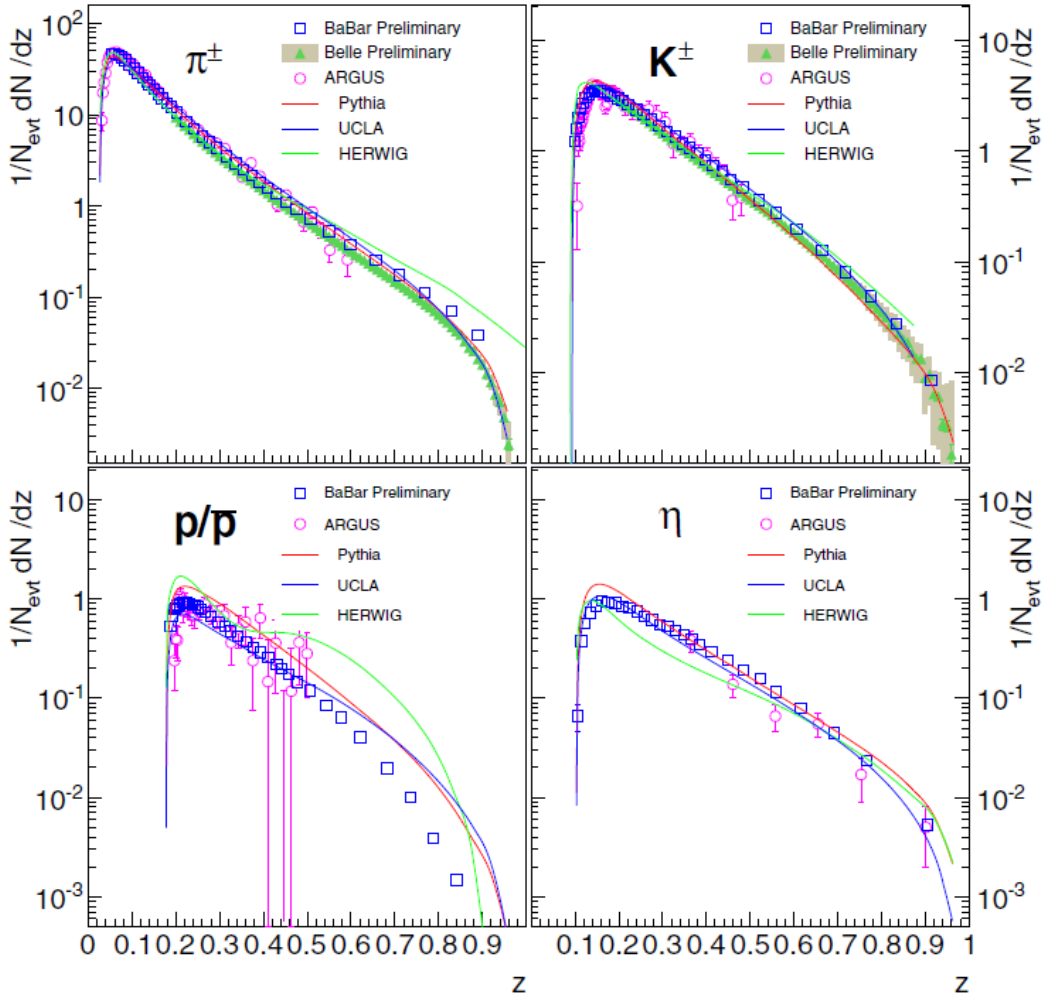
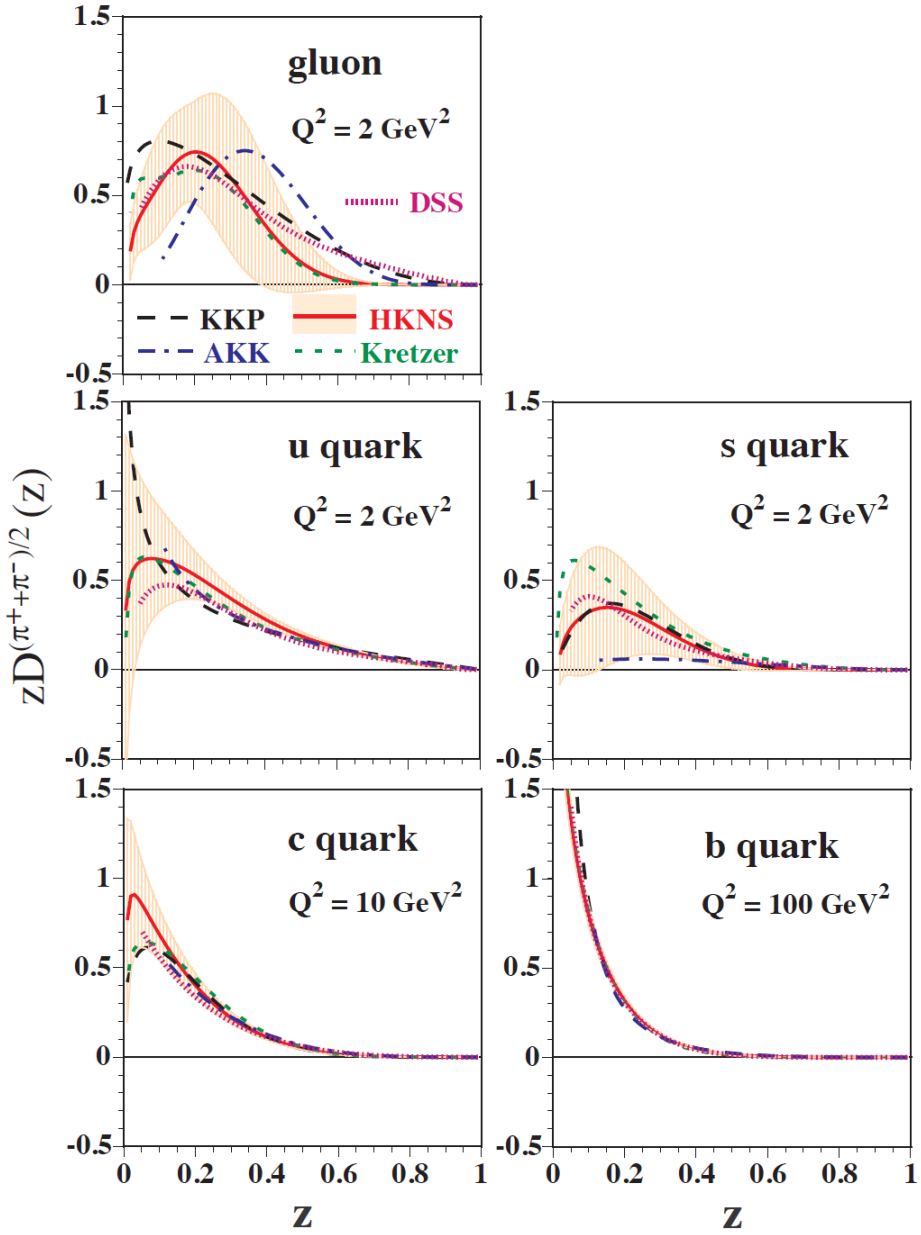
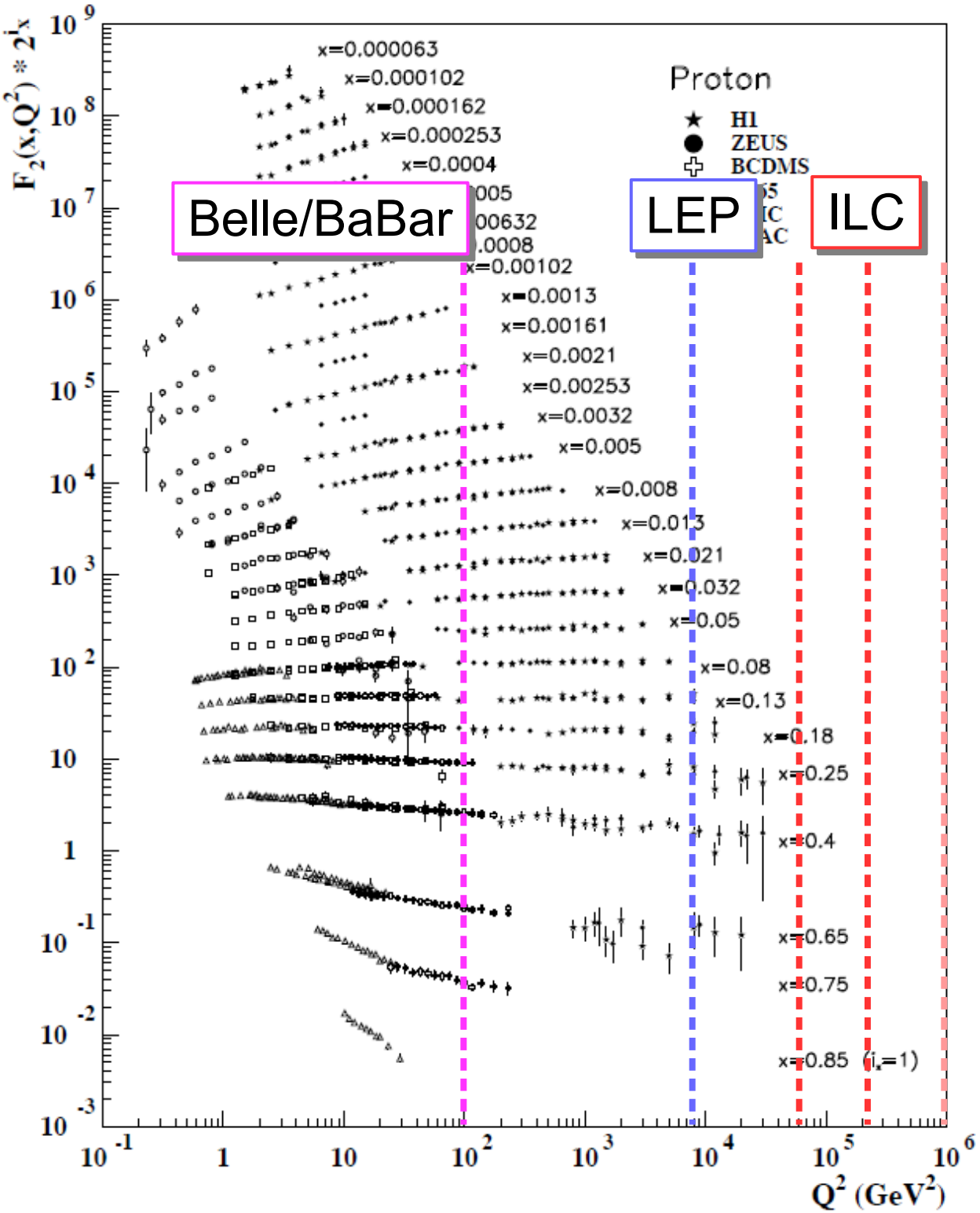
Eur. Phys. J. C (2014) 74:3026







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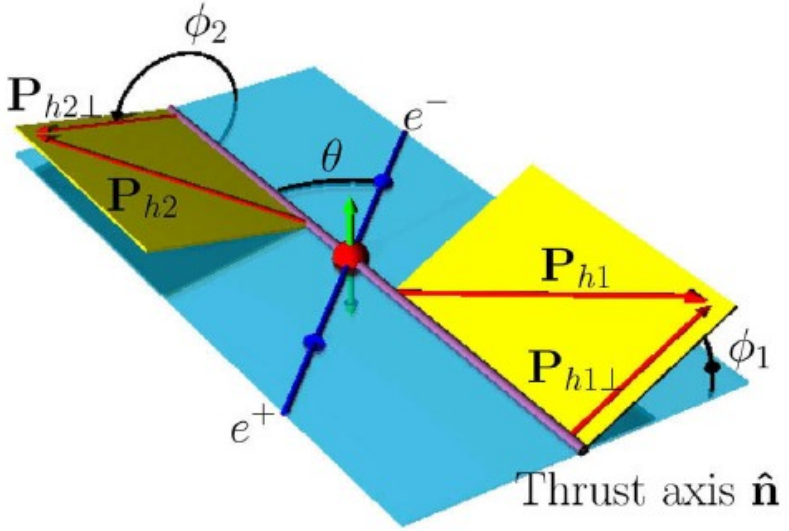
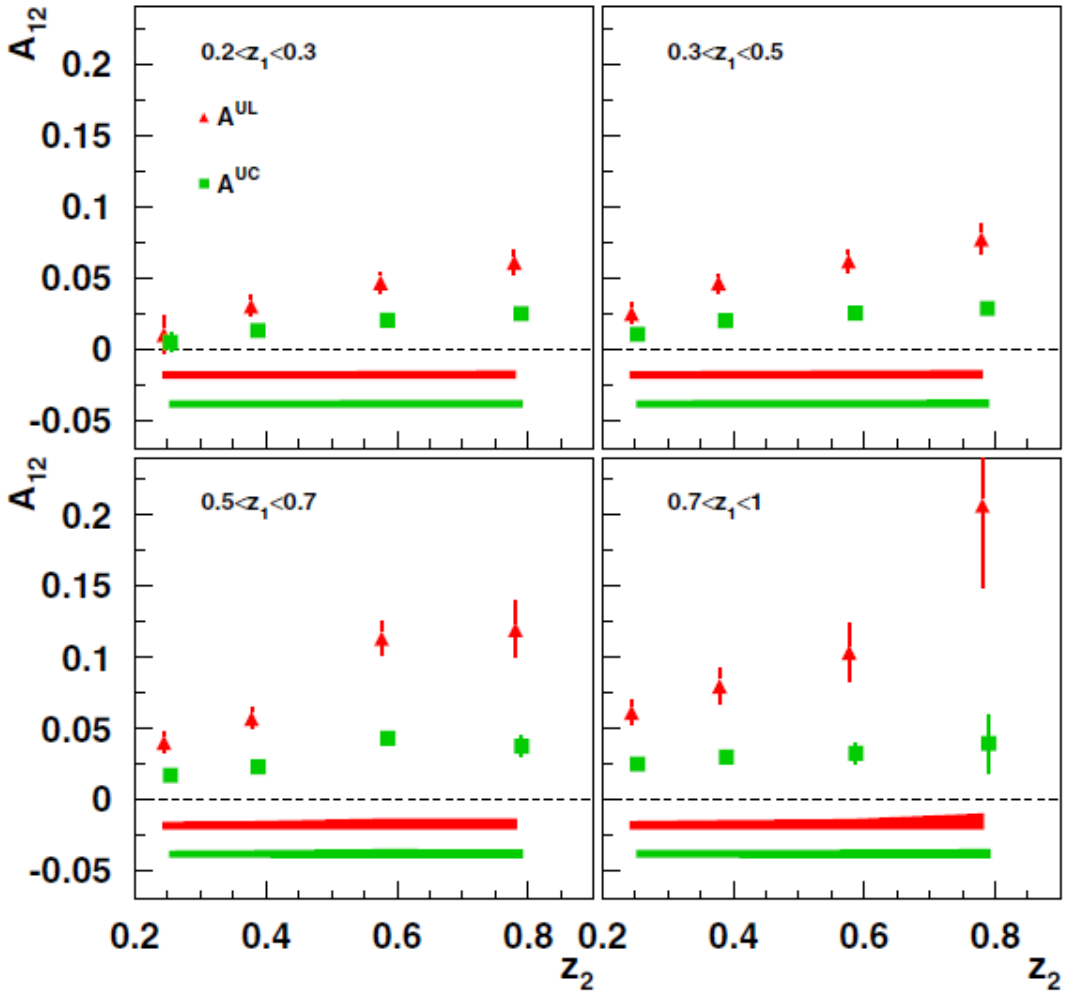
偏極破砕関数



$$A_{12} \sim \langle \cos(\phi_1 + \phi_2) \rangle$$



Two photon processes

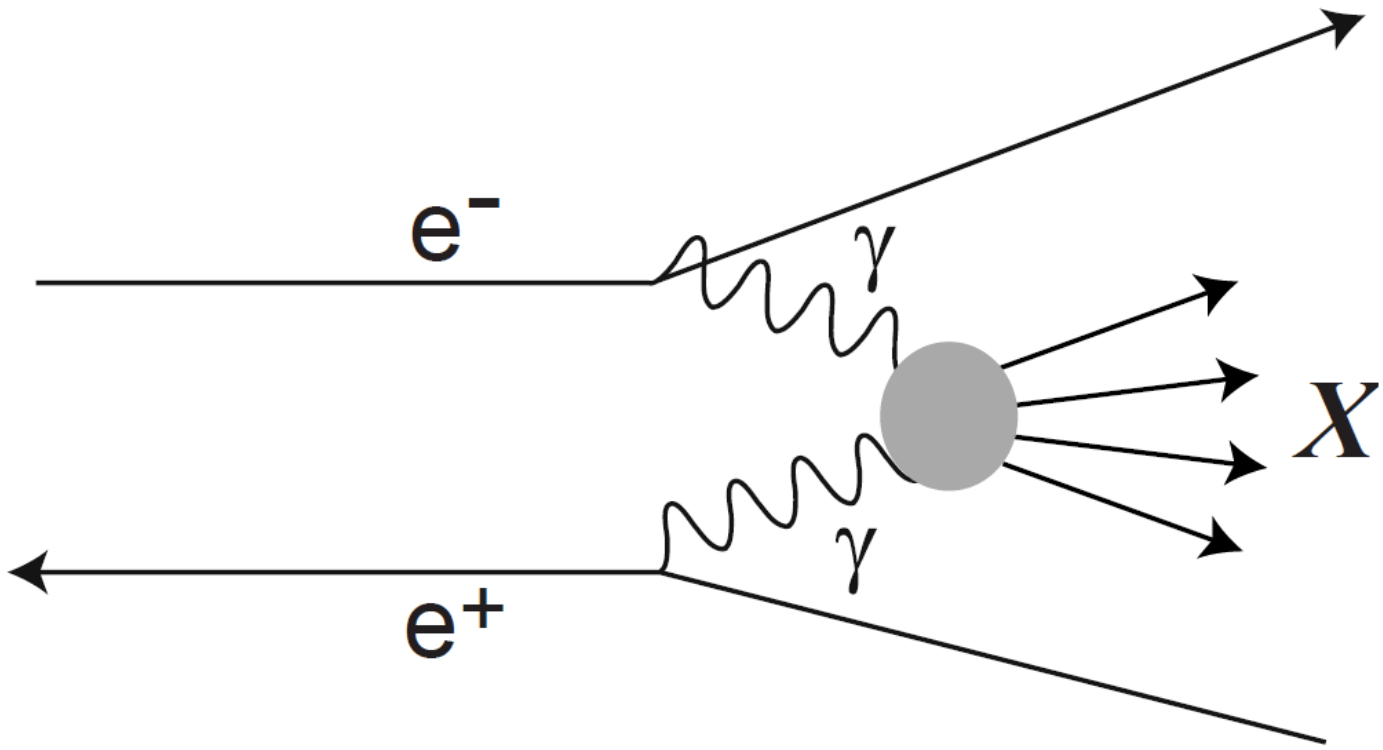


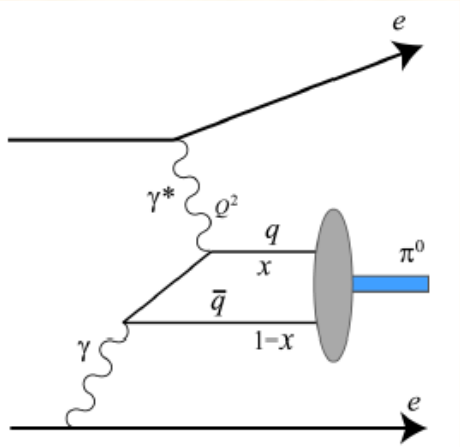
Figure 22.1.1. A Feynman diagram illustrating hadron production in two-photon collisions $e^+e^- \to e^+e^- X$.

Form factors in the asymptotic region

Belle collaboration (S. Uehara *et al.*), PRD 86 (2012) 092007.

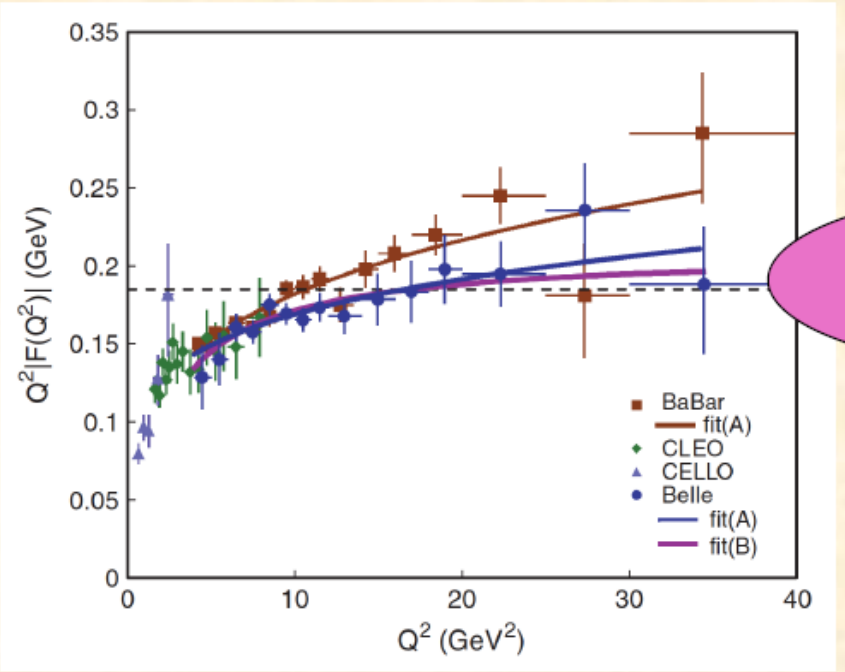
$$\gamma + \gamma^* \to \pi^0$$

$$F(Q^2) = \frac{\sqrt{2} f_\pi}{3} \int_0^1 dx \frac{\phi_\pi(x)}{xQ^2} + \mathcal{O}(1/Q^4).$$



ILC

- **Investigate the form factor in the asymptotic region**
- **Discrepancies between Belle and BaBar**



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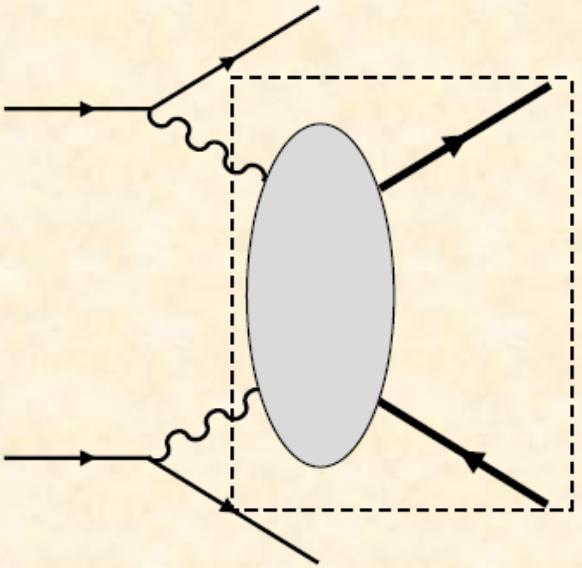
Two-photon physics for hadron tomography



$$\gamma\gamma \to h\bar{h}$$

H. Kawamura and S. Kumano,
Phys. Rev. D 89 (2014) 054007.

S. Kumano and Q.-T. Song,
Research in progress.

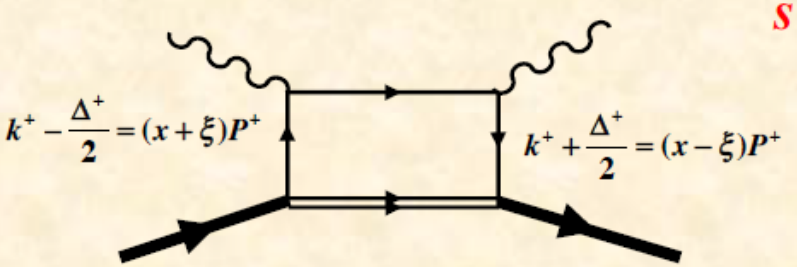
GPD $H_q^h(x,\xi,t)$ and GDA $\Phi_q^{h\bar{h}}(z,\zeta,W^2)$

GPD: $$H_q(x,\xi,t)=\int\frac{dy^-}{4\pi}e^{ixP^+y^-}\left\langle h(p')\left|\bar{\psi}(-y/2)\gamma^+\psi(y/2)\right|h(p)\right\rangle\Big|_{y^+=0,\vec{y}_\perp=0},\qquad P^+=\frac{(p+p')^+}{2}$$

GDA: $$\Phi_q(z,\zeta,s)=\int\frac{dy^-}{2\pi}e^{izP^+y^-}\left\langle h(p)\bar{h}(p')\left|\bar{\psi}(-y/2)\gamma^+\psi(y/2)\right|0\right\rangle\Big|_{y^+=0,\vec{y}_\perp=0}$$

DA: $$\Phi_q^h(z,\zeta,s)=\int\frac{dy^-}{2\pi}e^{izP^+y^-}\left\langle h(p)\left|\bar{\psi}(-y/2)\gamma^+\gamma_5\psi(y/2)\right|0\right\rangle\Big|_{y^+=0,\vec{y}_\perp=0}$$

$H_q^h(x,\xi,t)$ $\longleftrightarrow$ $\Phi_q^{hh}(z,\zeta,W^2)$: *s-t* crossing



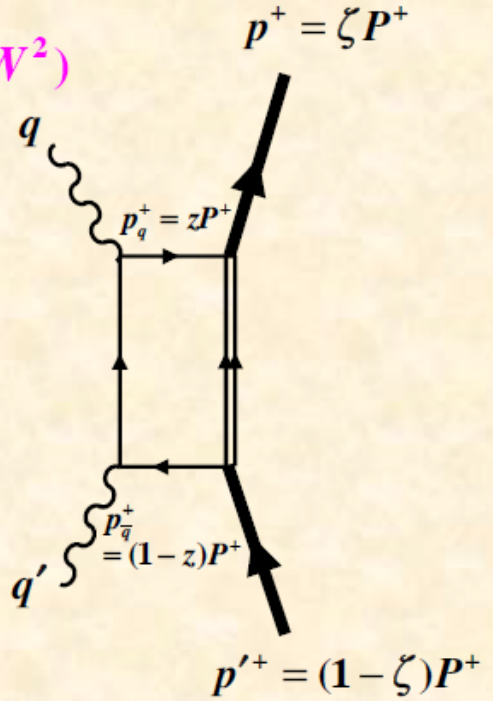
$$p^+=\left(P-\frac{\Delta}{2}\right)^+,\qquad p'^+=\left(P+\frac{\Delta}{2}\right)^+$$

$$P=\frac{p+p'}{2},\quad \Delta=p'-p$$

Bjorken variable: $x=\dfrac{Q^2}{2p\cdot q}$

Momentum transfer squared: $t=\Delta^2$

Skewness parameter: $\xi=\dfrac{p^+-p'^+}{p^++p'^+}=-\dfrac{\Delta^+}{2P^+}$



Bjorken variable for $\gamma\gamma^*$: $z=\dfrac{Q^2}{2q\cdot q'}$

Light-cone momentum ratio for h in $h\bar{h}$: $\zeta=\dfrac{p^+}{P^+}=\dfrac{1+\beta\cos\theta}{2}$

Invariant mass of $h\bar{h}$: $W^2=(p+p')^2$

Cross section: form factor dependence

$$\Phi_q^{h\bar{h}(I=0)}(z,\zeta,W^2) \propto F_h(W^2)$$

$$F_h(W^2) = \frac{1}{\left[1+(W^2-4m_h^2)/\Lambda^2\right]^{n-1}}$$

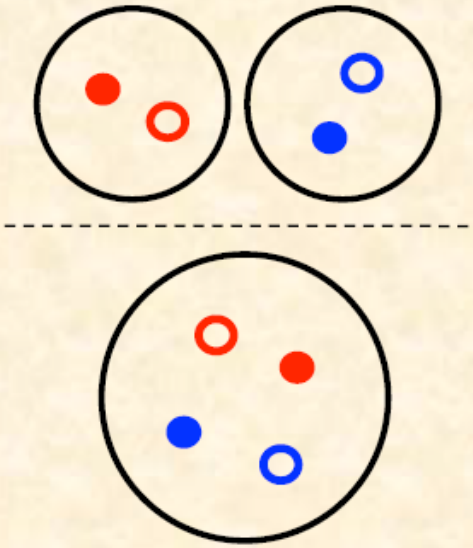
Constituent-counting rule

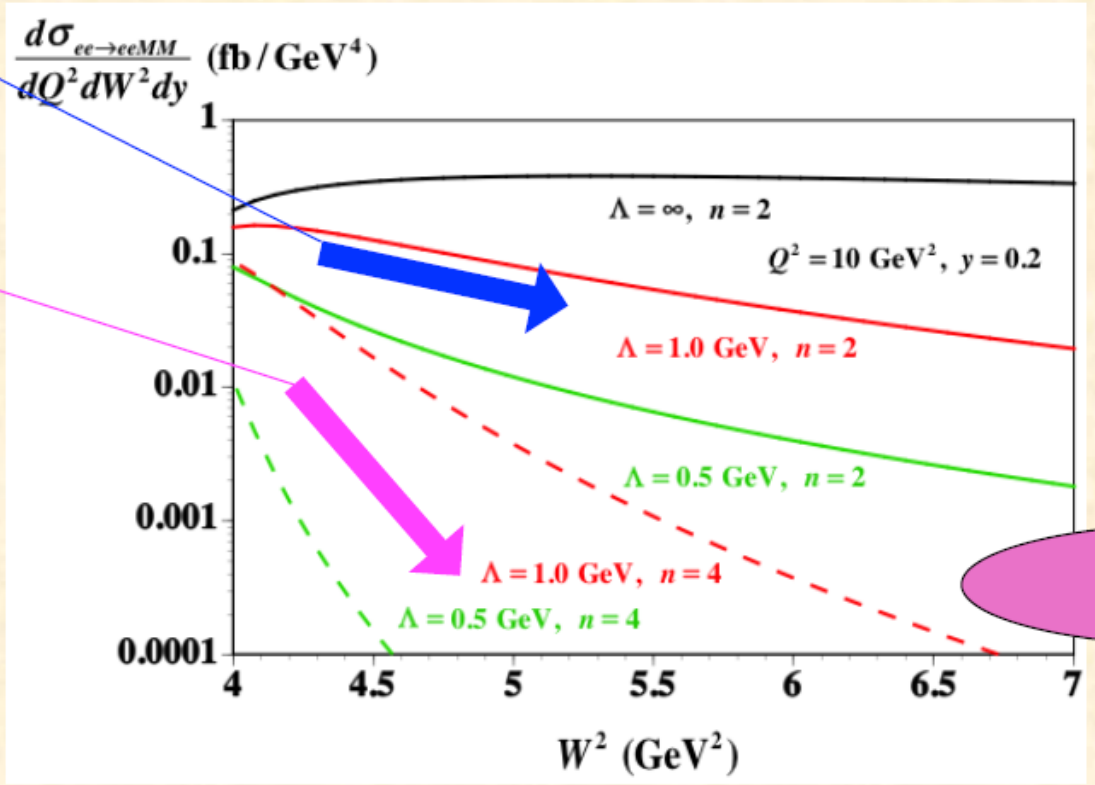
$n=2$: ordinary meson

$n=4$: molecule or tetra-quark

Ordinary $q\bar{q}$

Molecule $K\bar{K}$
or tetra-quark $qq\bar{q}\bar{q}$

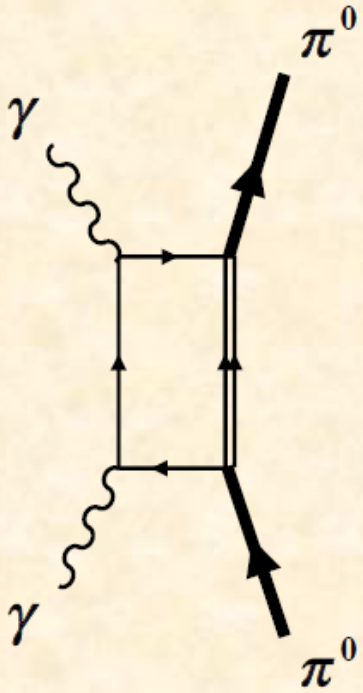


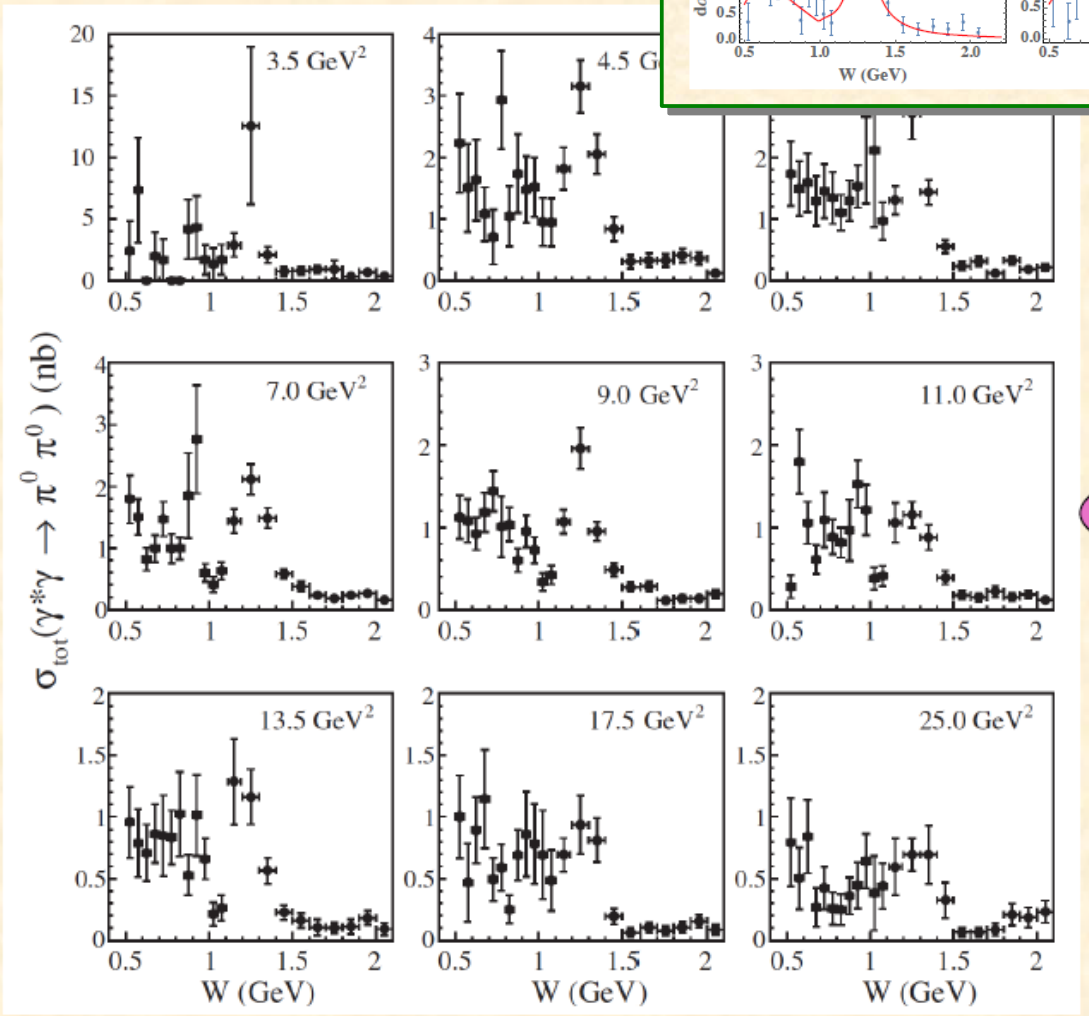


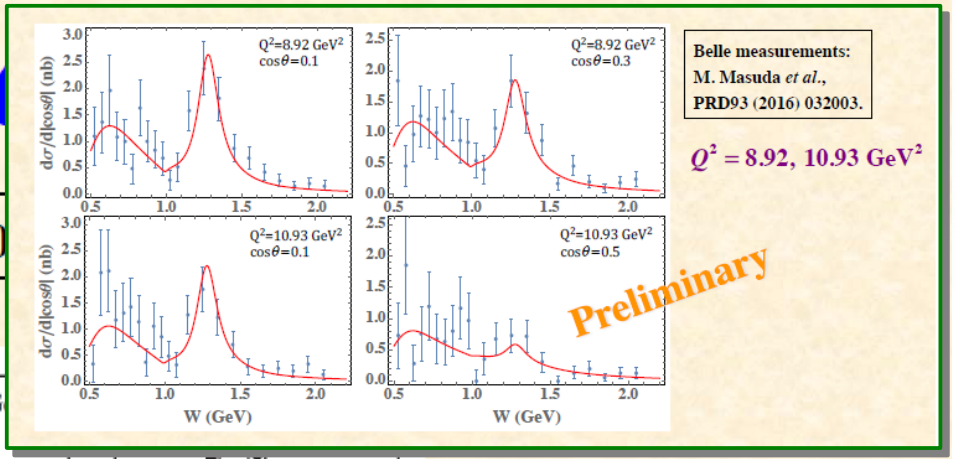
ILC

KEKB-Belle measurement

M. Masuda *et al.*, Phys. Rev. D 93 (2016) 0







ILC

- Very Large Q^2
- Large W^2

for extracting GDAs

Photon structure function

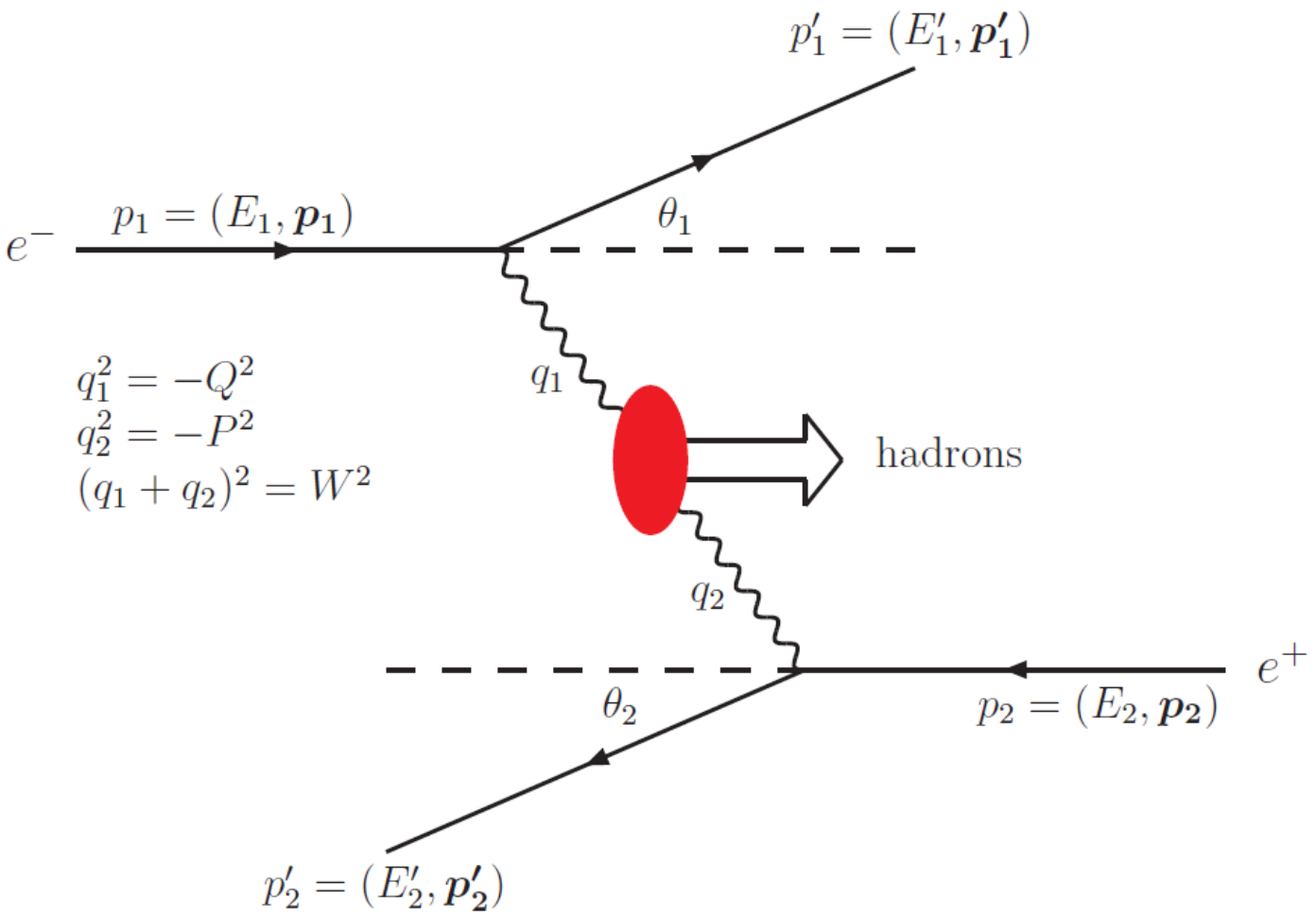


Figure 7: Kinematics of the two photon process

Berger, Ch. J.Mod.Phys. 6 1023-1043

Photon structure at ILC

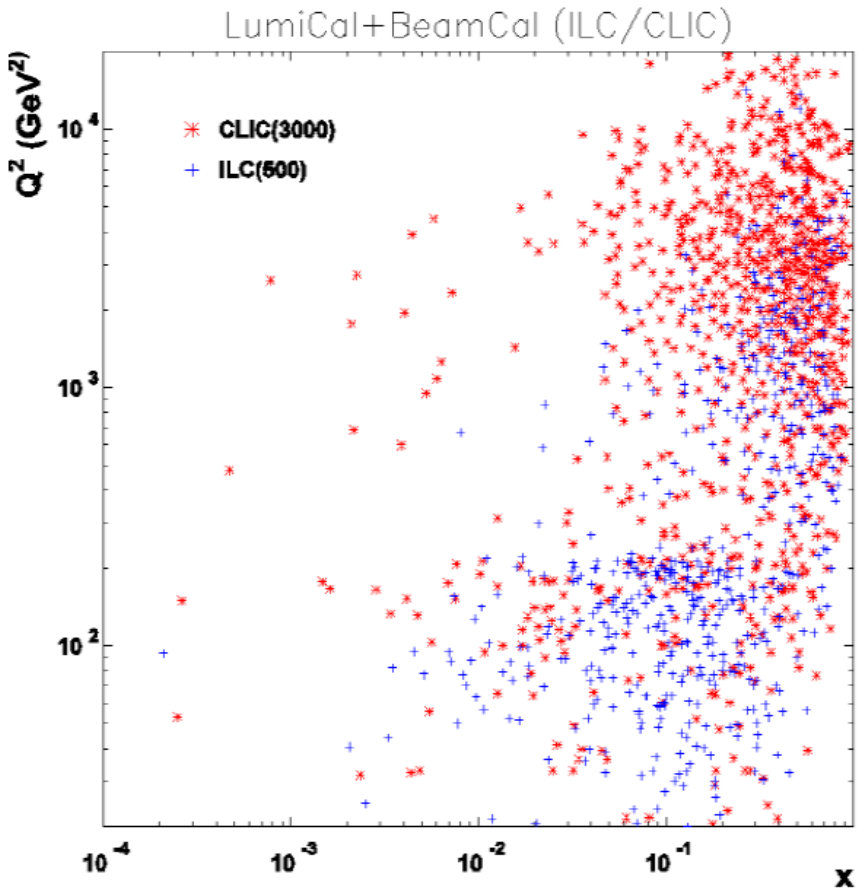


Fig. 2. Kinematical plane (x, Q^2) with simulated single-tagged events for the case of detecting scattered electrons at the LumiCal and BeamCal detectors.

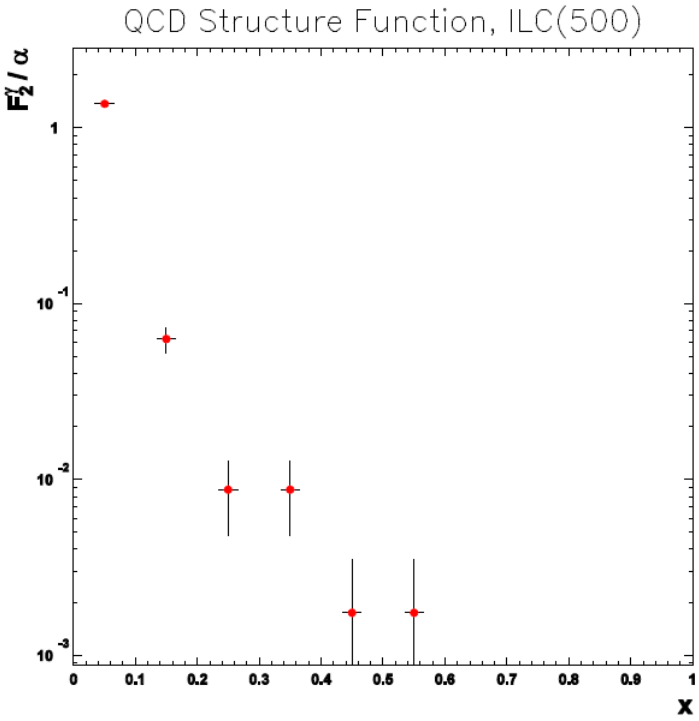
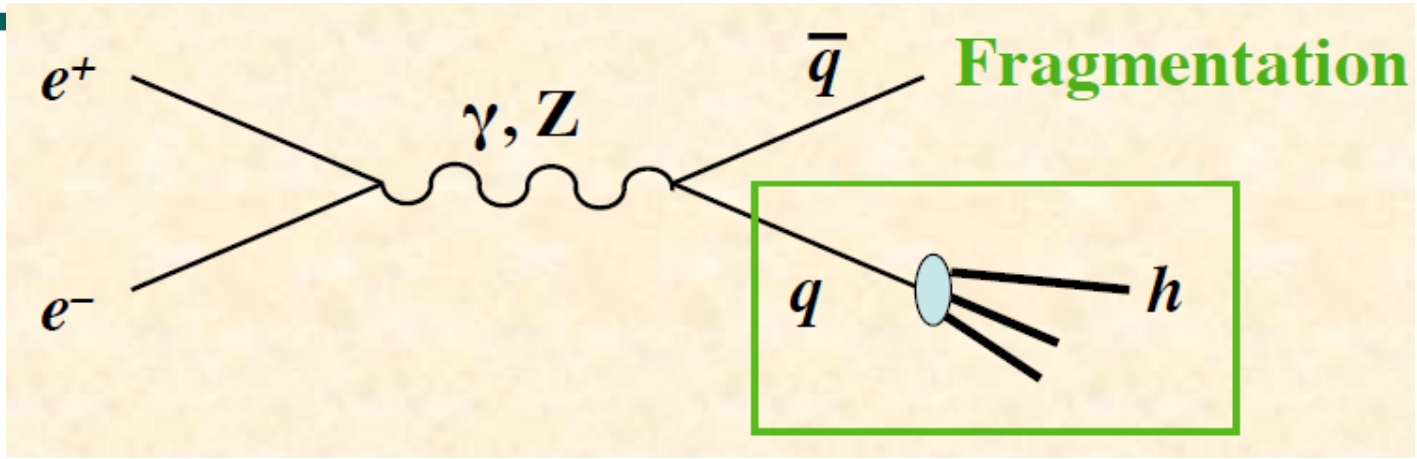
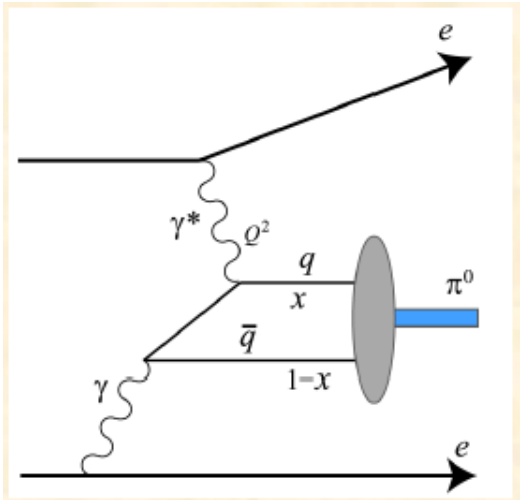
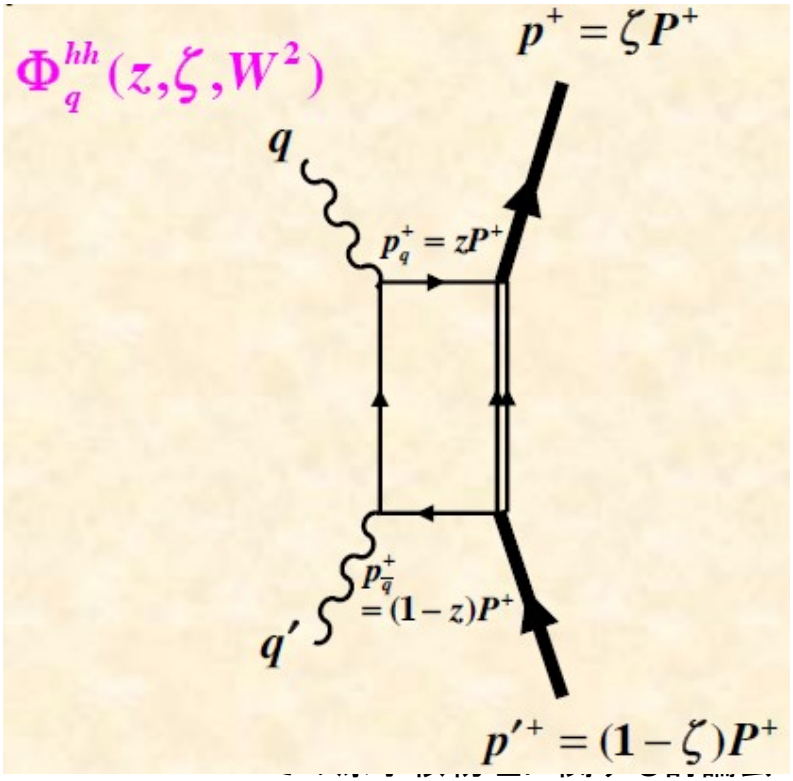


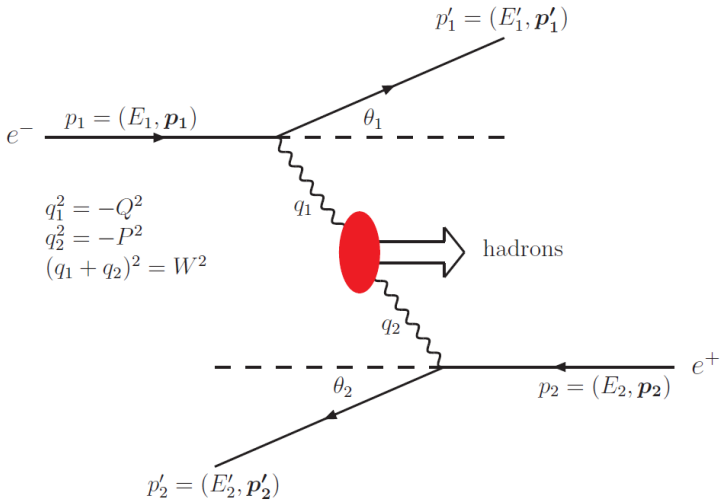
Fig. 6. The hadronic photon structure function divided by the fine structure constant as a function of x variable for the mean value of Q^2 equal to 119 GeV^2. The errors are statistical only.

P. Kruna, T. Wojtoń, L. Zawiejski, arXiv:1503.07373


Fragmentation
e^+
e^-
γ, Z
$\bar{q}$
q
h


e
γ*
Q^2
q
x
$\bar{q}$
1−x
γ
π^0
e


$\Phi_q^{hh}(z,\zeta,W^2)$
$p^+ = \zeta P^+$
q
$p_q^+ = zP^+$
$p_{\bar{q}}^+ = (1-z)P^+$
q′
$p'^+ = (1-\zeta)P^+$


$p_1' = (E_1', \boldsymbol{p}_1')$
e^-
$p_1 = (E_1, \boldsymbol{p}_1)$
θ_1
$q_1^2 = -Q^2$
$q_2^2 = -P^2$
$(q_1+q_2)^2 = W^2$
q_1
hadrons
q_2
e^+
θ_2
$p_2 = (E_2, \boldsymbol{p}_2)$
$p_2' = (E_2', \boldsymbol{p}_2')$

ILCでの固定標的実験

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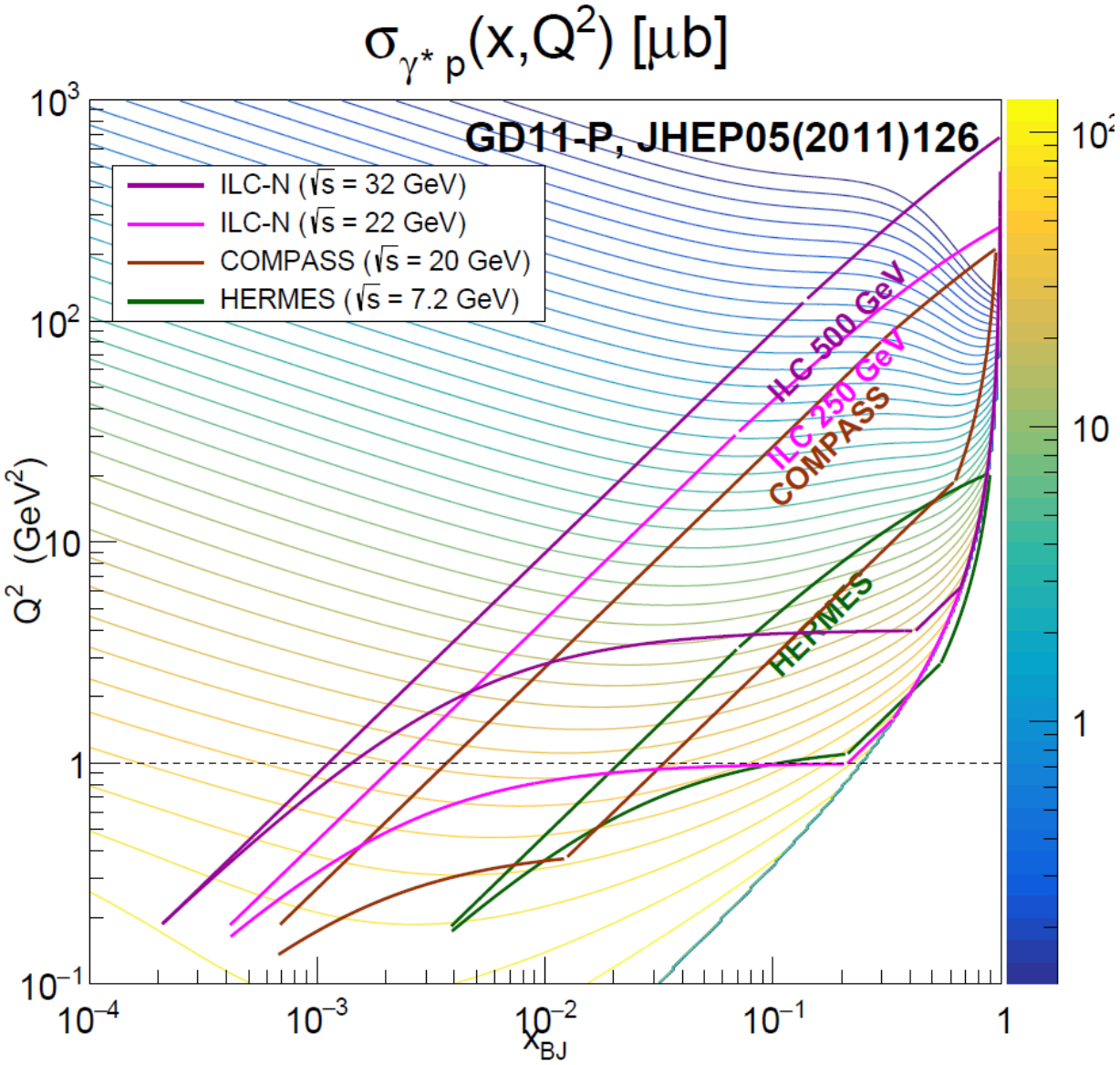
Yamagata University

- ILC-偏極電子ビーム
  - E = 125 GeV
    - COMPASS 以下
  - E = 250 GeV
  - E = 500 GeV



The Electron Ion Collider

For e-N collisions at the EIC:

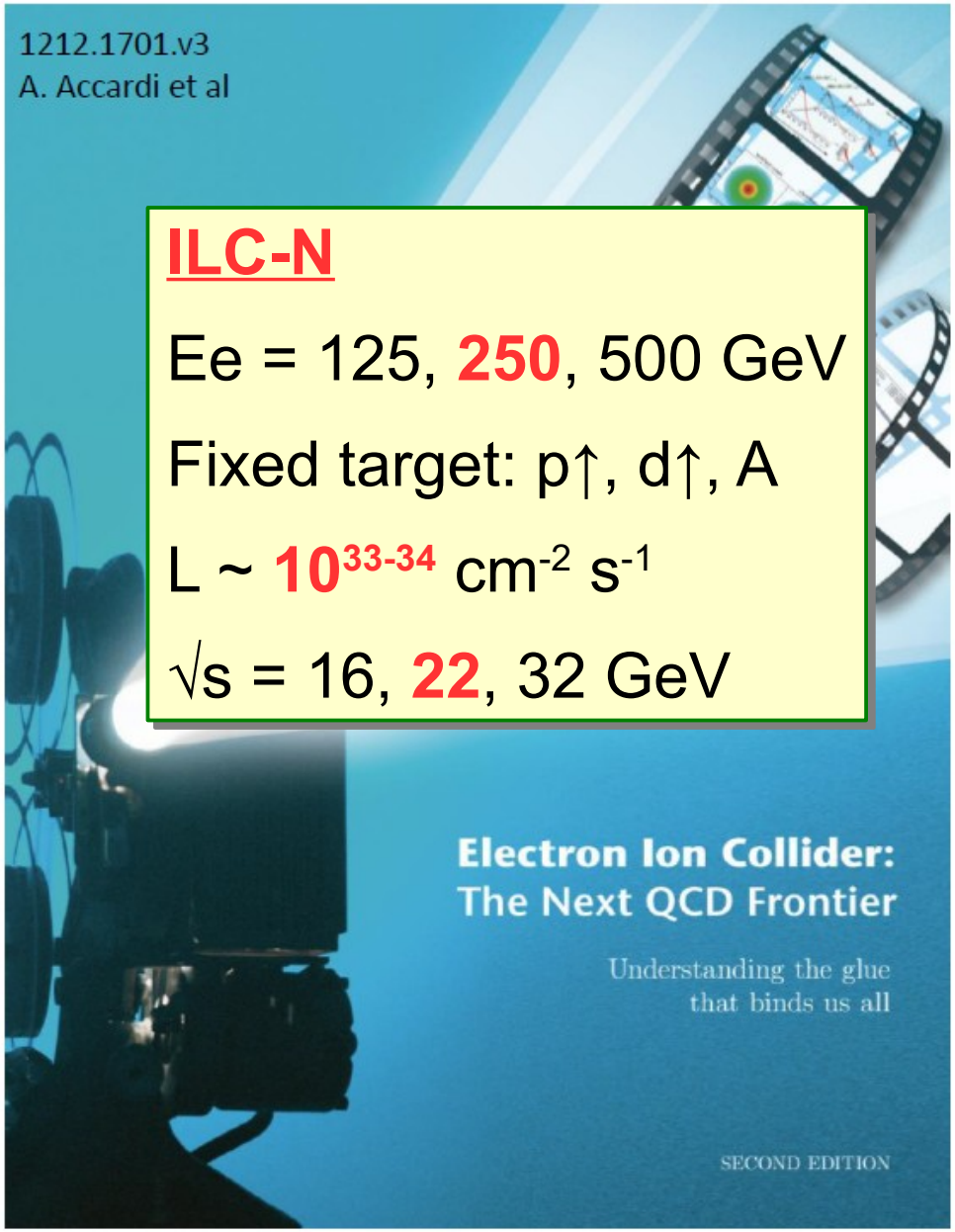
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 3-10(20) GeV
- ✓ Luminosity L_{ep} ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$
  100-1000 times HERA
- ✓ 20-~100 (140) GeV Variable CoM

For e-A collisions at the EIC:

- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Two proposals for realization of the science case -
both designs use DOE's significant investments in infrastructure



Electron Ion Collider

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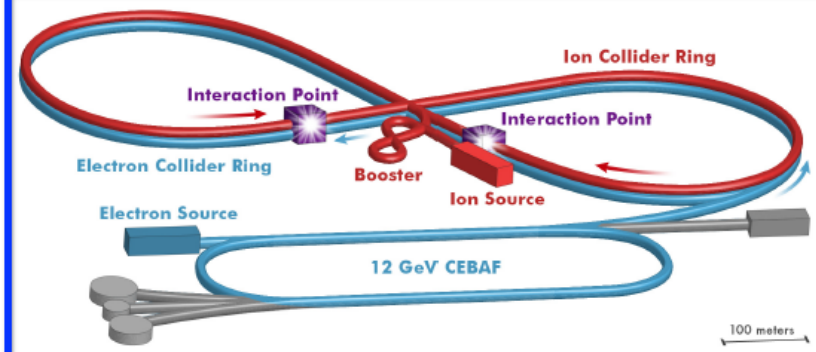
Accelerator designs….



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Ring-Ring Design

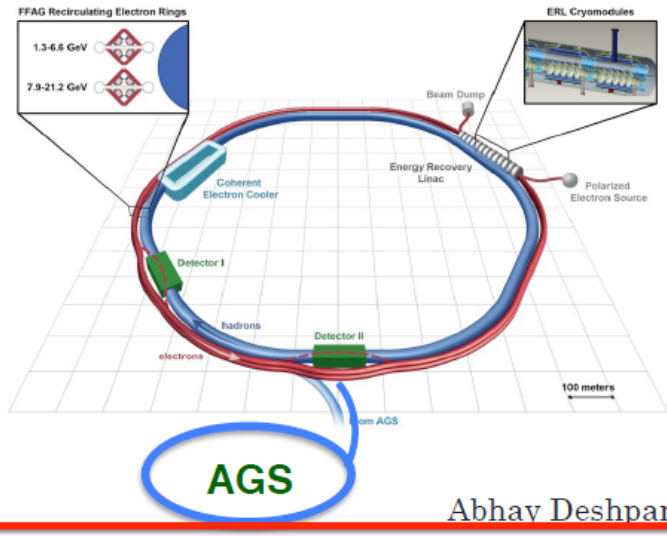
Bow-Tie shaped ring to address the polarization preservation without Siberian snakes

V. Ptitsyn, eRHIC

Linac-Ring design
(also developing a Ring-Ring design)

Uses existing Blue Ring from RHIC
And a multi-pass 1.3 GeV ERL

@BNL



Stony Brook University

Abhay Deshpande

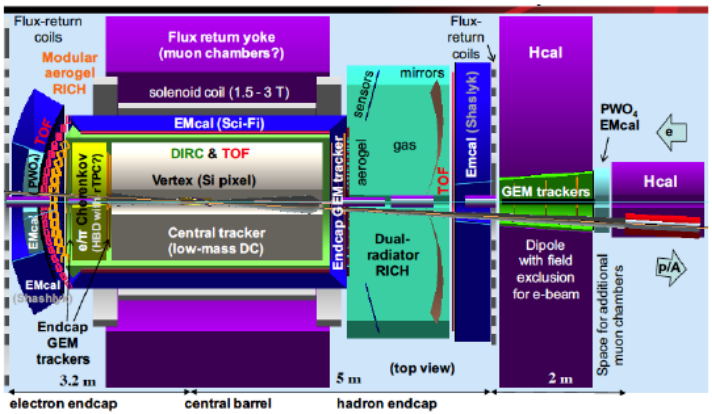
Electron Ion Collider

山形大学
Yamagata University

Wednesday, July 7, 16 | State of EIC @ EICUG ANL | 17

The Detector Ideas... (not to scale!)

R. Yoshida, JLEIC WG

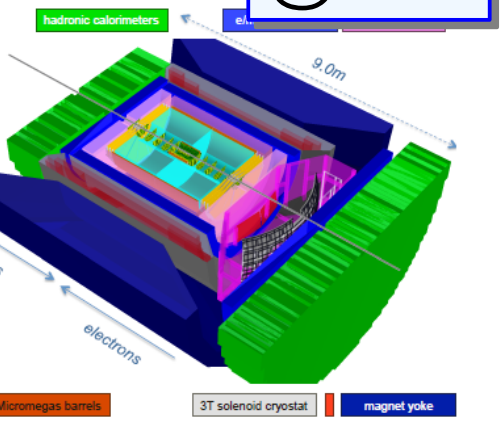


A. Kise

@JLab

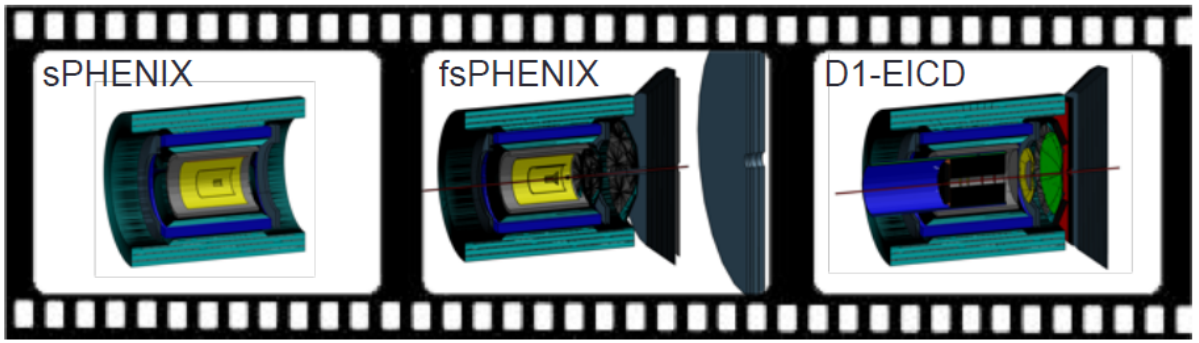
A detailed microscopic simulation of "e/p+HCal" electron identification is in progress

If needed, the setup can be appended at $\eta < -1$ by other electron ID detectors like preshower and/or TRD



K. Barish

@BNL



Stony Brook University

Abhay Deshpande

段階的にアップグレード

EIC: $\sqrt{s}$ = 45 GeV, 0.01 < y < 0.95

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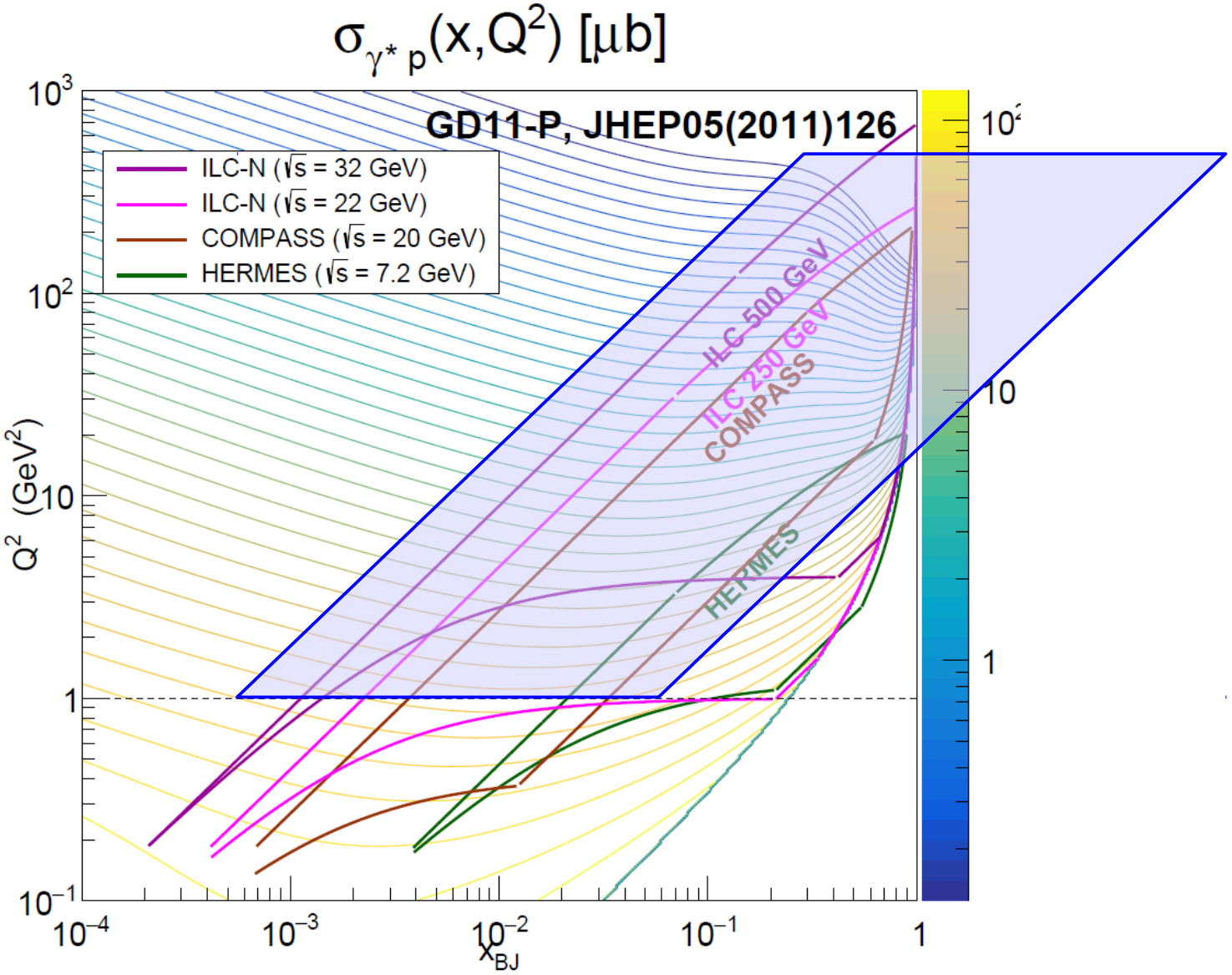

EIC: $\sqrt{s}$ = 140 GeV, 0.01 < y < 0.95

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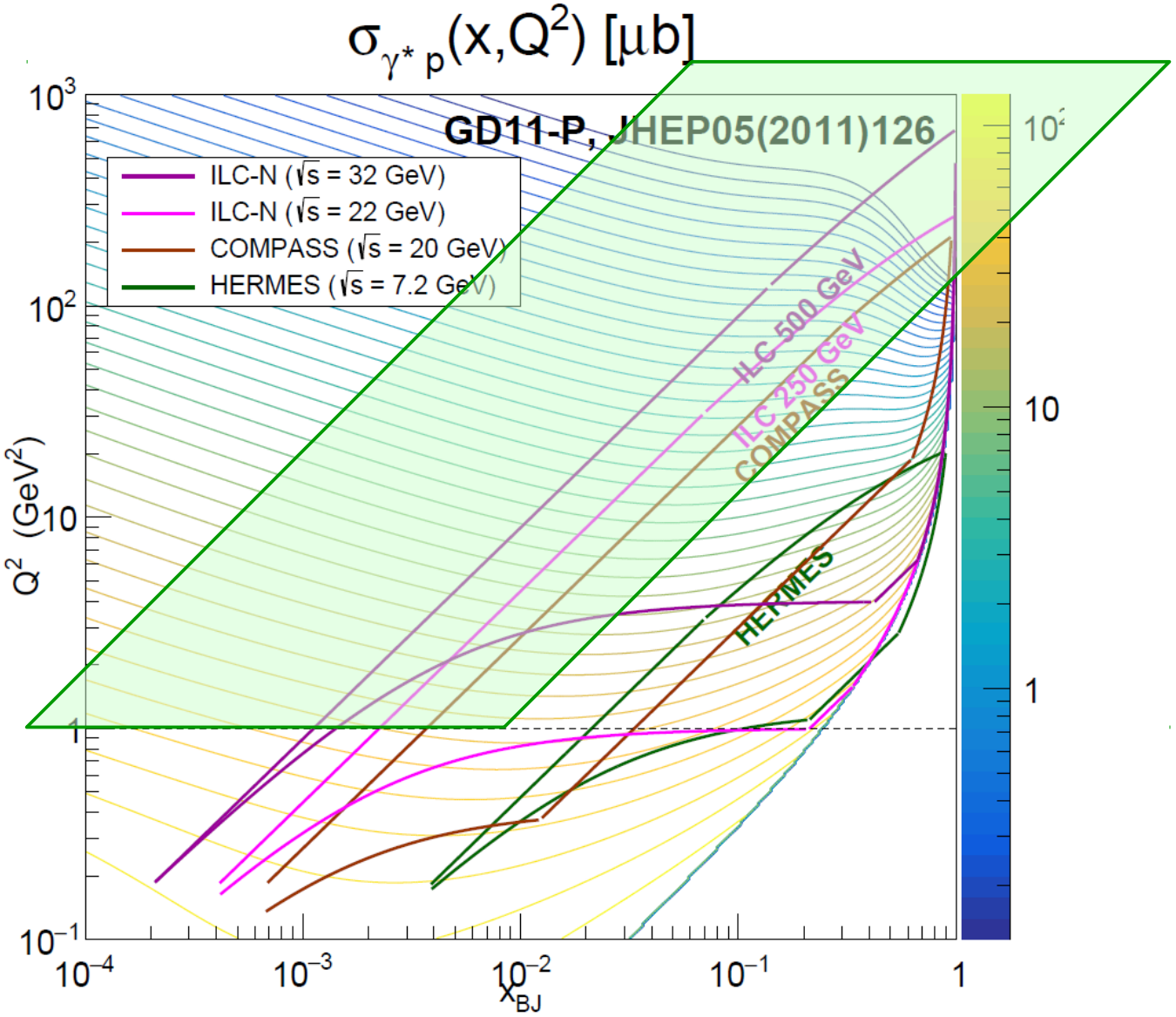

HERMES, COMPASS 実験

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	HERMES@DESY	COMPASS@CERN
Beam	Pol. e+/e- in HERA e-ring E = 27.6 GeV $e^{-/\leftarrow}, e^{-/\rightarrow}, e^{+/\leftarrow}, e^{+/\rightarrow}$	Pol. μ+/μ- E = 160~200 GeV $\mu^{+/\leftarrow}, \mu^{-/\rightarrow}$ @ 160 GeV
Target	L-pol. H/D	L-pol. H/D
	T-pol. H	T-pol. H/D
	U-pol. H/D	
	U-pol. H/D + recoil	U-pol. H + recoil

Δq, ΔG
GPD-E
TMD
GPD-H
GPD-H

ILC-Nで目指すべきもの

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- 運動学的領域
  - CERN-COMPASSより low-x, high-Q^2
    - E = 250 GeV ではあまりかわらない。(500 GeVならば・・・)
  - EIC ($\sqrt{s}$ = 20 ~ 100 (140) GeV)
- 高精度COMPASS実験?
- 横偏極標的＋反跳陽子検出 : DVCS
  - HERMES: 非偏極標的＋反跳陽子検出
  - **COMPASS将来計画(2019年以降)**
- 重陽子テンソル構造
  - HERMES($\sqrt{s}$ = 7 GeV)の測定
  - Jlab ($\sqrt{s}$ = 5 GeV)での計画

COMPASSで未測定

HERMESでの構造関数 b_1 測定

$$P_{zz} = P_T$$
$$P_z = P_V$$

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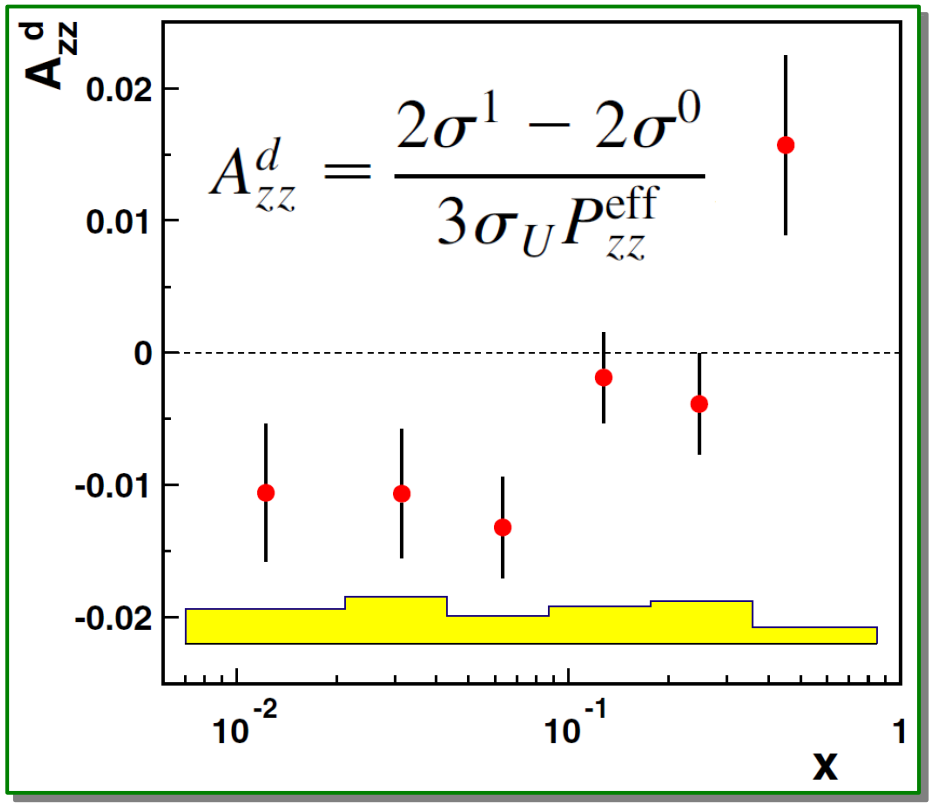
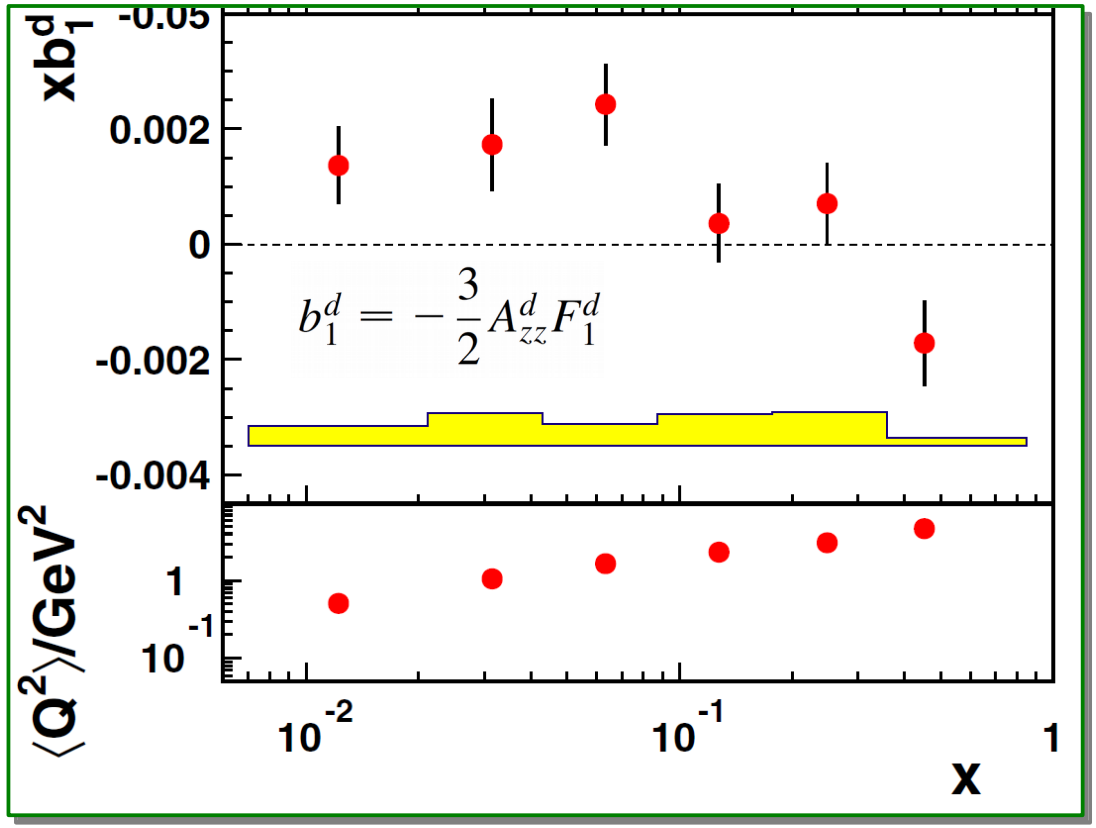
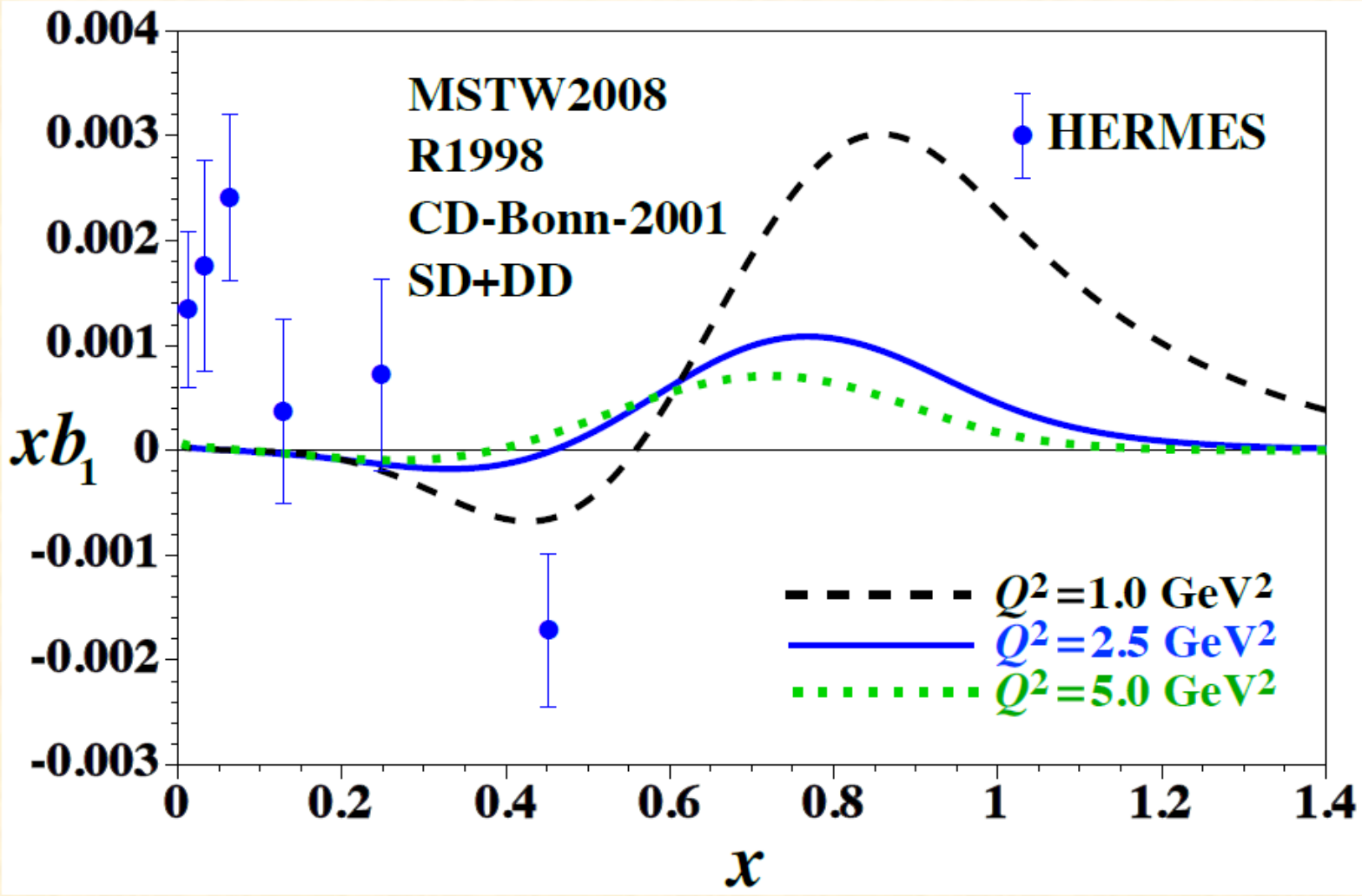
- 27.6 GeV 偏極電子
- テンソル偏極重陽子標的





Comparison with HERMES measurements



$|b_1(\text{theory})| \ll |b_1(\text{HERMES})|$ at $x < 0.5$

Standard convolution model does not work for the deuteron tensor structure!?

固体標的による b_1 測定

※ ILC-N: e-, 250 GeV, ~ 20 nA

偏極DISでの可能性

Beam: e-, 11 GeV (@Hall C), ~100 nA

Target: **Pol. ND_3 solid target**

LOI-11-003@JLab

The Deuteron Tensor Structure Function b_1

A Proposal to Jefferson Lab PAC-38
(Update to LOI-11-003)

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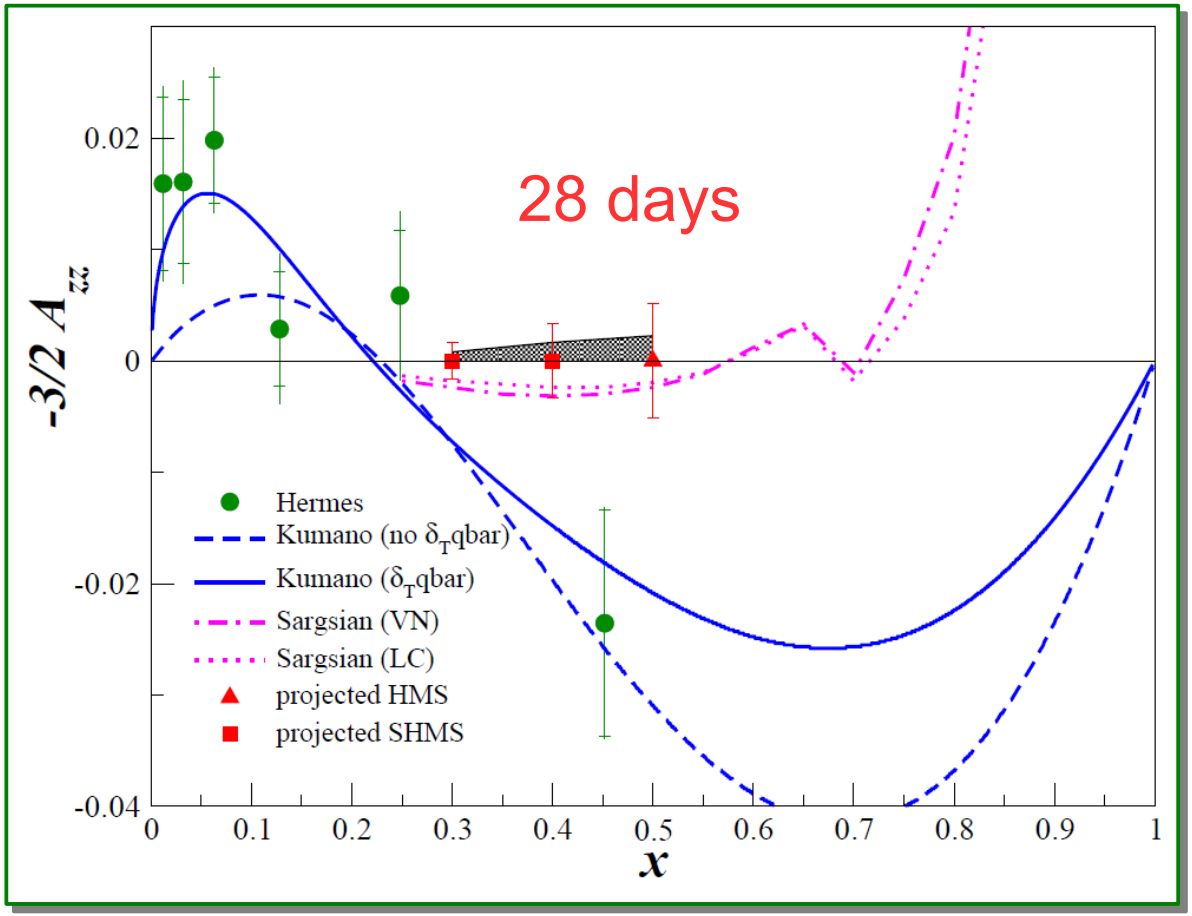

まとめ

山形大学
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- 核子構造研究
  - “パートン”によるハドロン内部構造の理解
  - 様々なパートン散乱過程による多角的研究
    - 深非弾性散乱
    - 陽子陽子衝突
    - 電子･陽電子消滅
- ILCでの核子ハドロン内部構造研究
  - 二光子過程
    - Transition Form Factor, Generalized Distribution Amplitude, Photon Structure
  - 固定標的
    - EICとの競合： 重陽子テンソル構造？