

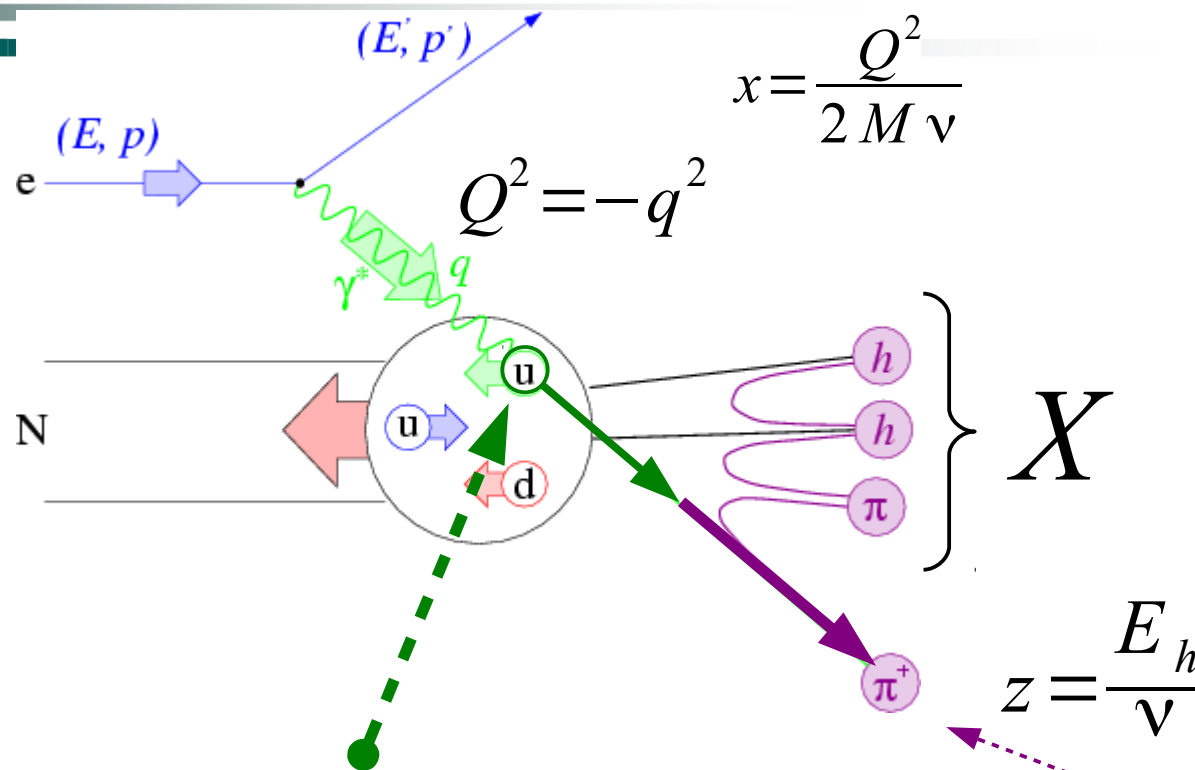
- 核子構造の研究目的・手法
- ILCでの核子構造研究
  - 電子・陽電子衝突実験
  - 固定標的実験
    - Electron Ion Collider (EIC) 計画

宮地 義之@山形大学

# 核子構造研究と深非弾性散乱

$$\nu = E - E'$$

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



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

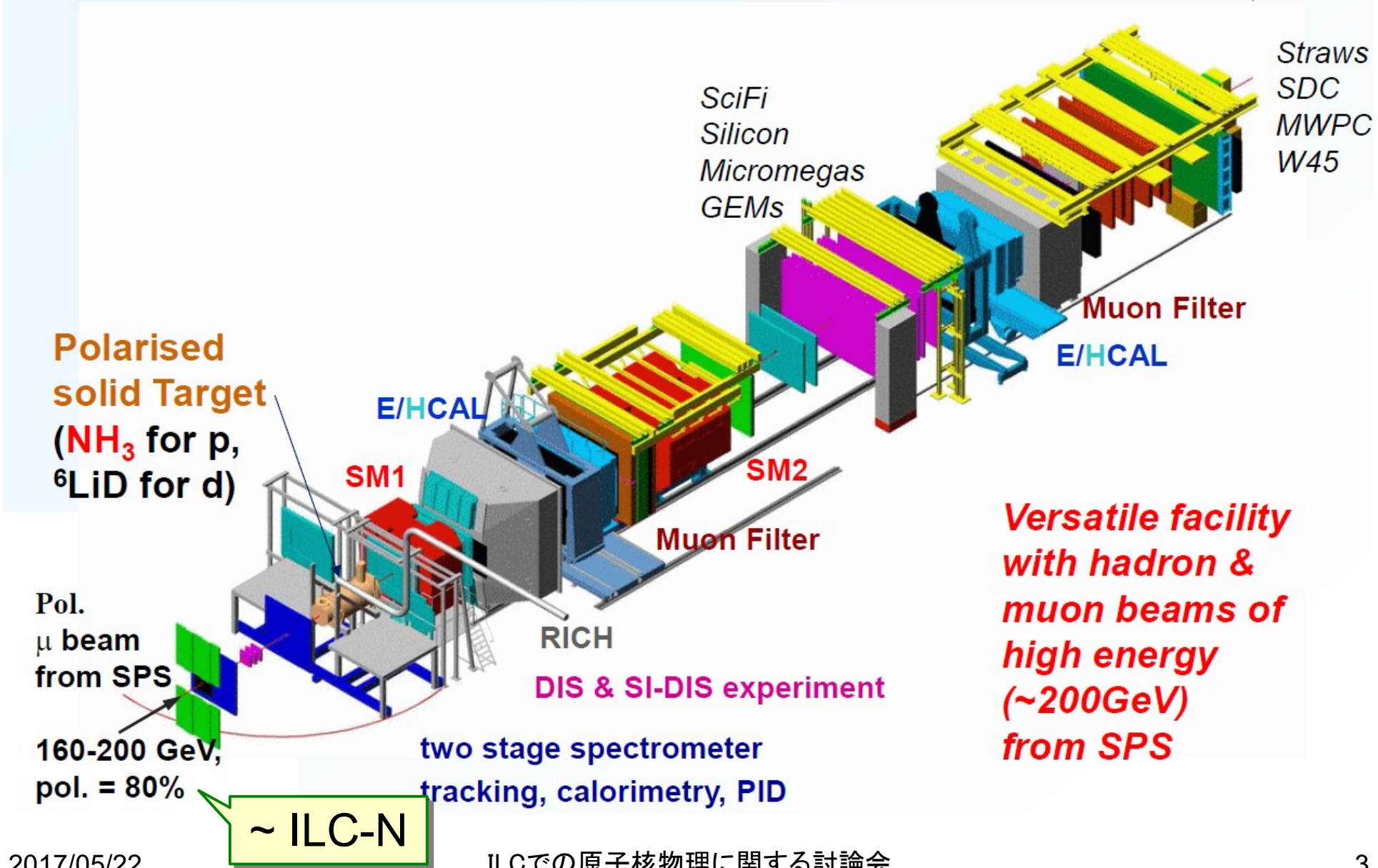
Parton Distribution Function

$$f(x, Q^2)$$

Fragmentation Function

$$D(z, Q^2)$$

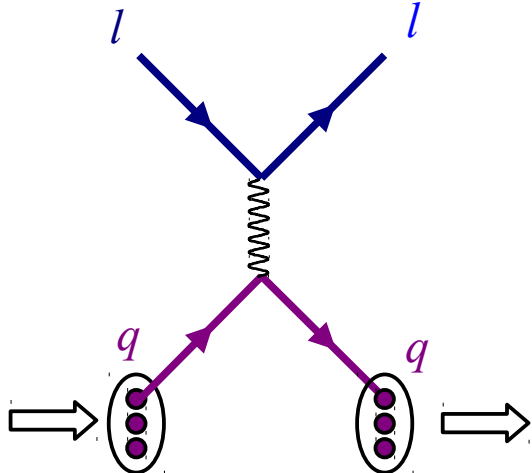
# CERN-COMPASS



# “レプトン-パートン散乱” と “ハドロン構造”

## 深非弾性散乱

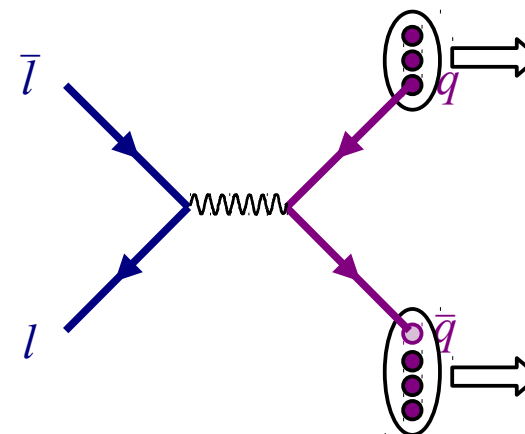
$$l + h \rightarrow l' (+ h') + X$$



## 電子・陽電子衝突

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

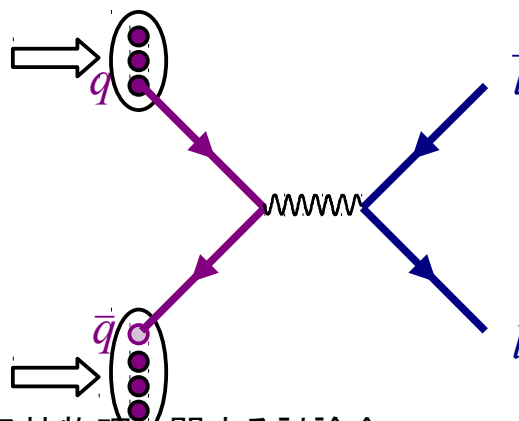
(Belle/BaBar)



## ドレール・ヤン反応

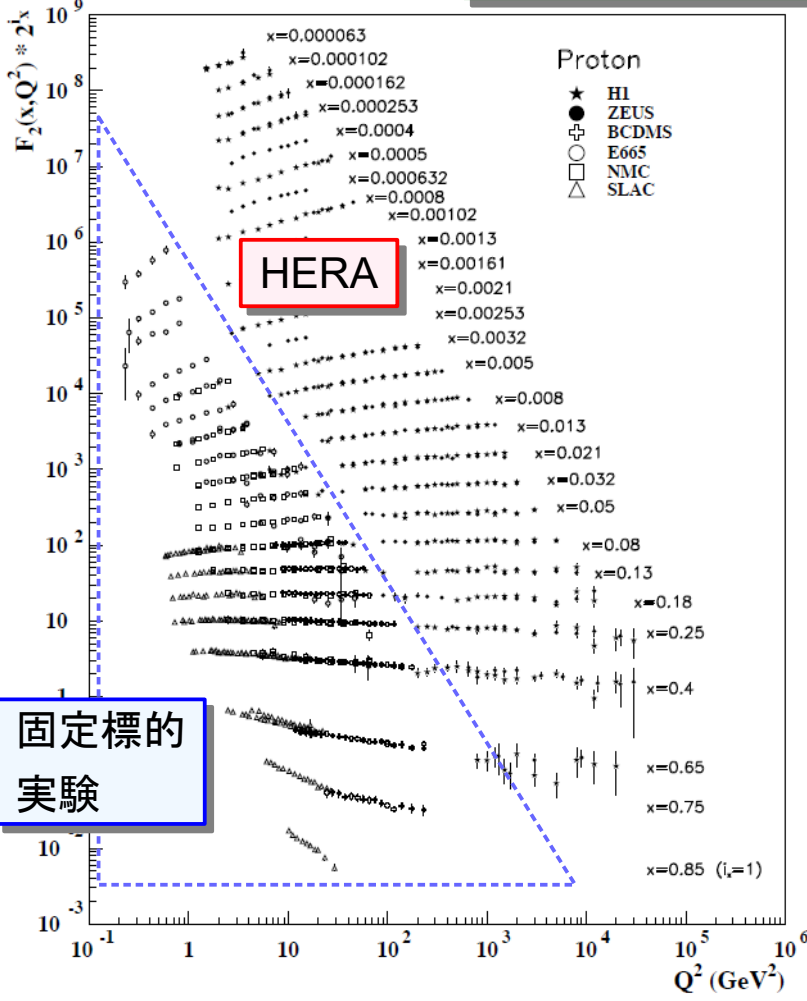
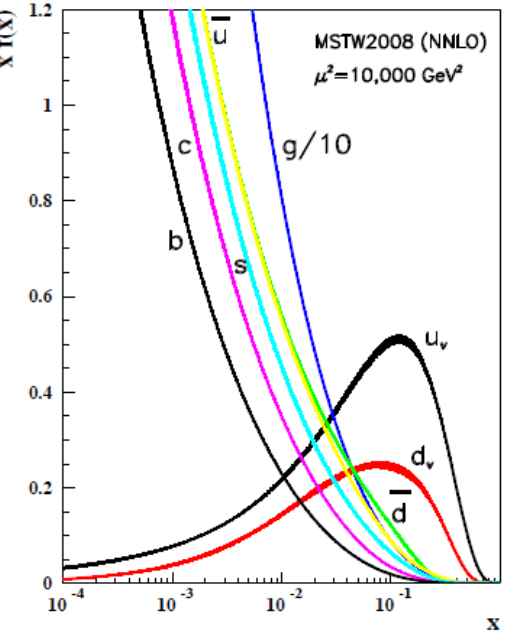
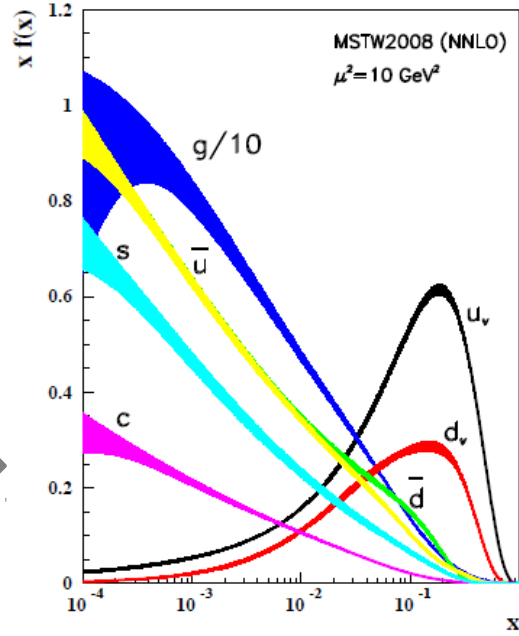
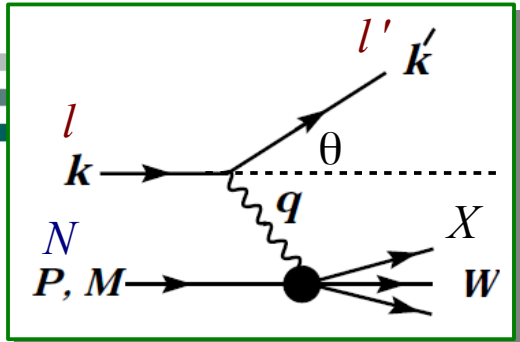
$$h_1 + h_2 \rightarrow l + \bar{l} + X$$

(SeaQuest)

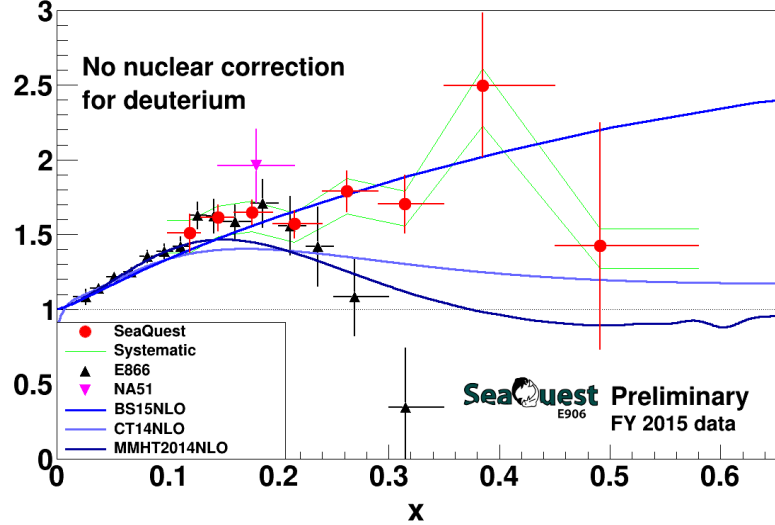
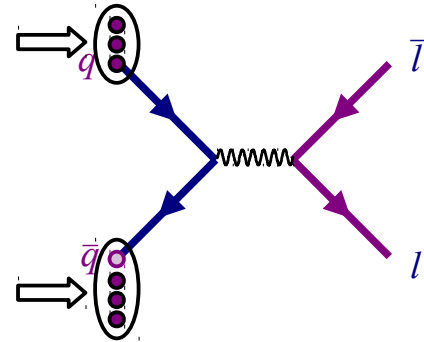
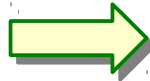




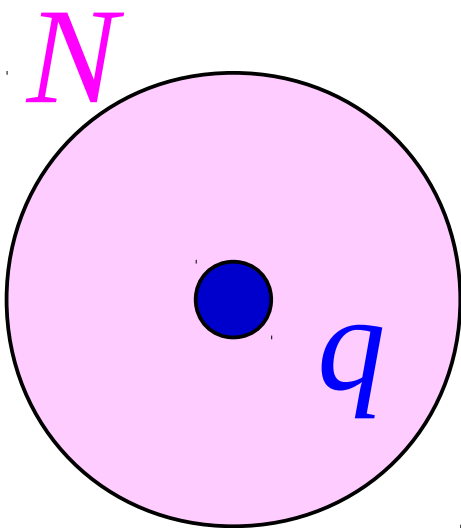
# 非偏極パートン分布関数



固定標的  
実験

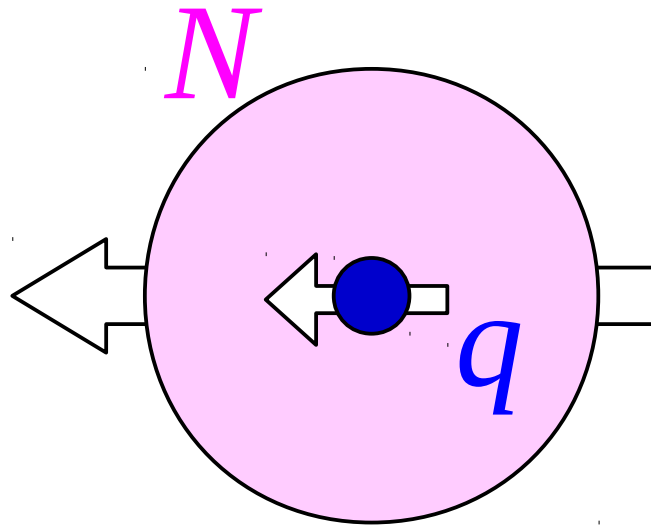


# スピン依存パートン分布



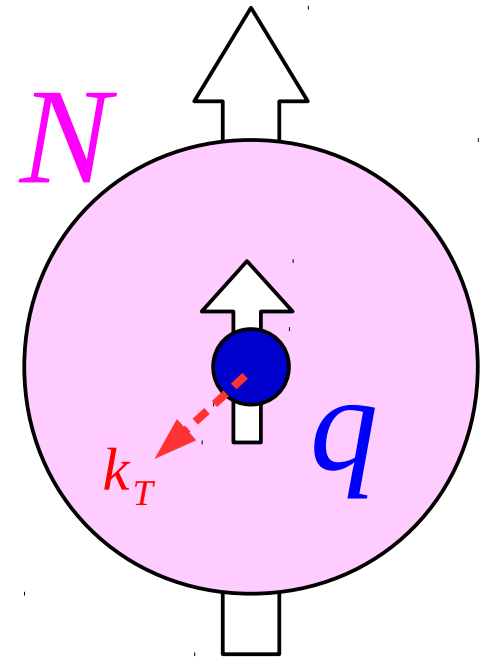
$$q(x)$$

momentum



$$\Delta q(x)$$

spin



$$h_1(x)$$

transverse spin

~ angular momentum

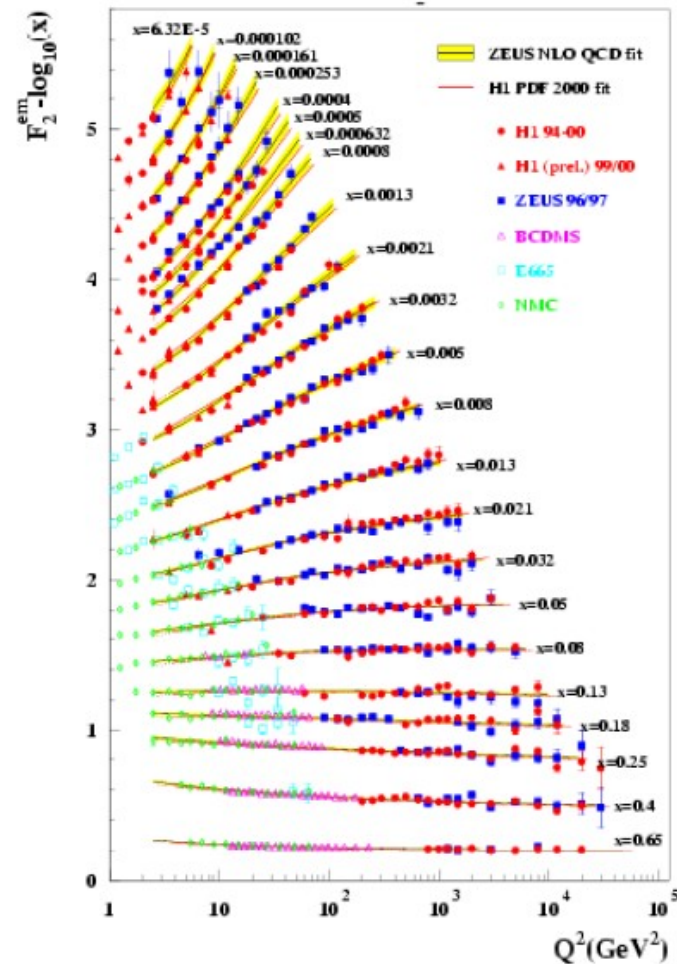


# World Data on $F_2^p$

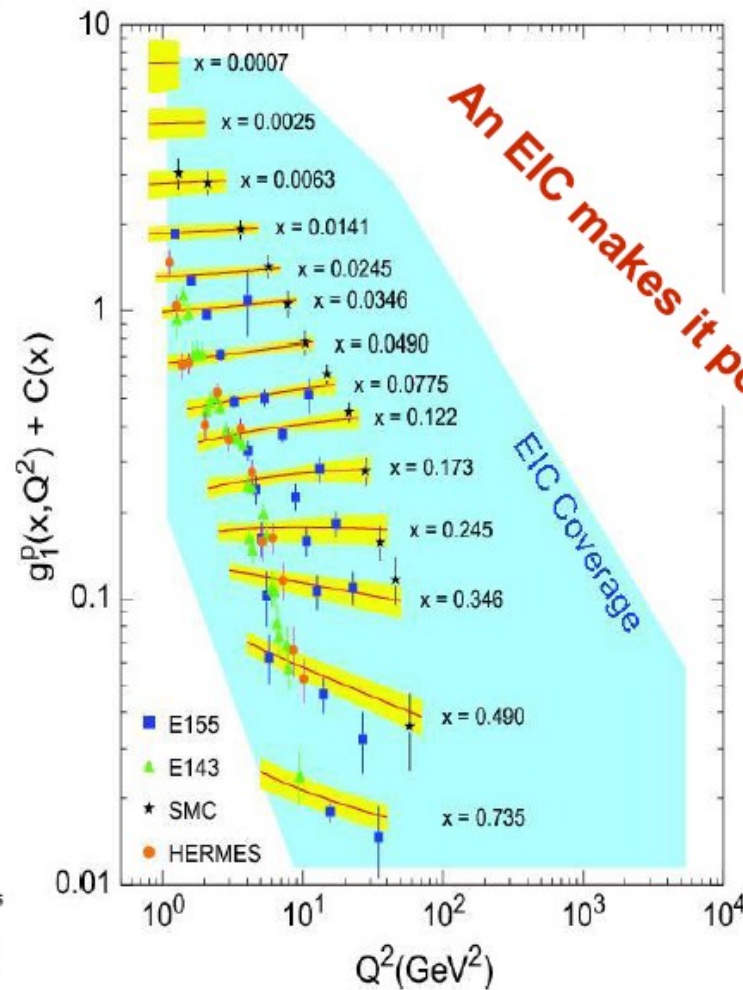
# World Data on $g_1^p$

# World Data on $h_1^p$

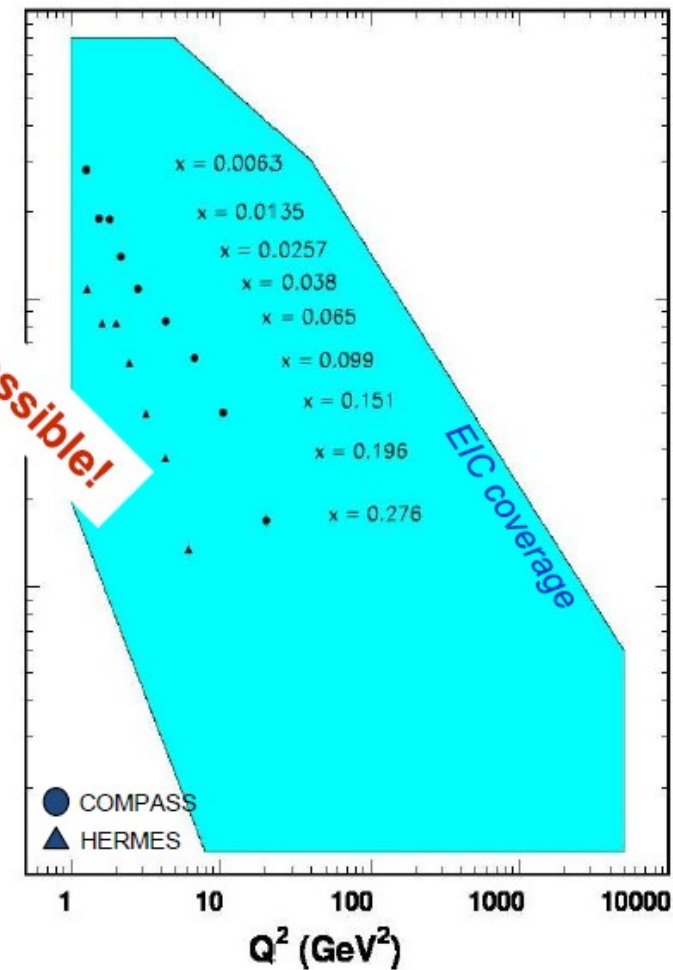
$$F_{UT}^{\sin(\phi_h+\phi_s)}(x, Q^2) + C(x) \propto h_1$$



momentum



spin

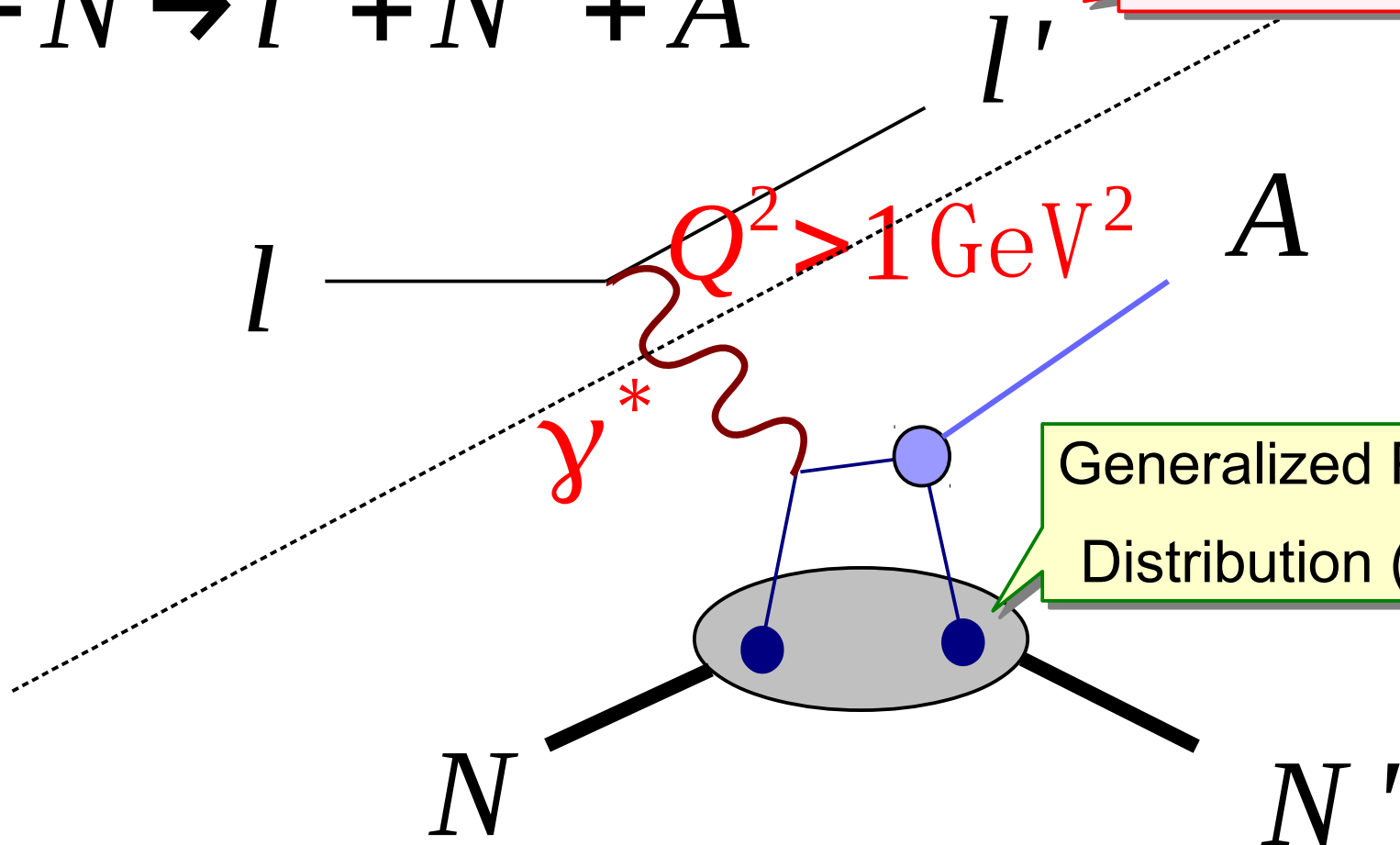


transverse spin ~  
angular momentum

# 包括的測定から排他的生成測定へ

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

パートン構造



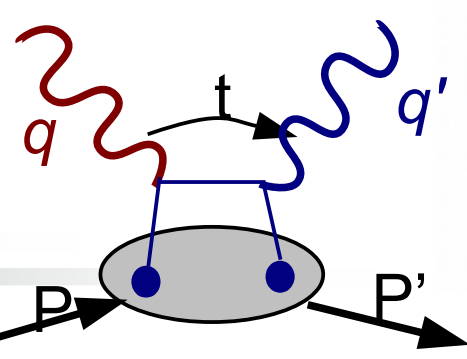
Generalized Parton Distribution (GPD)

運動量比  $x$  毎に形状因子を測る

弾性散乱  $\Rightarrow$  形状因子



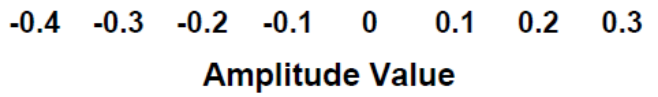
# 実光子排他的生成: Deeply Virtual Compton Scattering



GPD

HERMES DVCS	Legend	Asymmetries	References	Category
$A_C^{\cos(0\phi)}$ $A_C^{\cos\phi}$ $A_C^{\cos(2\phi)}$ $A_C^{\cos(3\phi)}$	<ul style="list-style-type: none"> <li>● Hydrogen</li> <li>▲ Deuterium</li> <li>■ Hydrogen Pure</li> </ul>	Beam Charge Asymmetries	<div style="border: 1px solid green; padding: 5px;">                     PRL 87 (2001) 182001                      PRD 75 (2007) 011103                      JHEP 11 (2009) 083                      JHEP 07 (2012) 032                      JHEP 10 (2012) 042                      NPB 829 (2010) 1                 </div>	H
$A_{LU}^{\sin\phi}$ $A_{LU}^{\sin(2\phi)}$ $A_{LU,I}^{\sin\phi}$ $A_{LU,DVCS}^{\sin\phi}$ $A_{LU,I}^{\sin(2\phi)}$	Beam Spin Asymmetries			
$A_{UT,I}^{\sin(\phi-\phi_2)}$ $A_{UT,DVCS}^{\sin(\phi-\phi_2)}$	$\propto \text{Re}H$  $\propto \text{Im}H$	Target Spin Asymmetries	<div style="border: 1px solid green; padding: 5px;">                     JHEP 06 (2008) 066                      PLB 704 (2011) 15                 </div>	E
$A_{UT,I}^{\sin(\phi-\phi_2)\cos\phi}$ $A_{UT,I}^{\cos(\phi-\phi_2)\sin\phi}$		Double Spin Asymmetries		
$A_{LT,I}^{\cos(\phi-\phi_2)}$ $A_{LT,BH+DVCS}^{\cos(\phi-\phi_2)}$ $A_{LT,I}^{\sin(\phi-\phi_2)\sin\phi}$ $A_{LT,I}^{\cos(\phi-\phi_2)\cos\phi}$		$p \uparrow \downarrow$ Double Spin Asymmetries		
$A_{UL}^{\sin\phi}$ $A_{UL}^{\sin(2\phi)}$	$p \leftrightarrow \rightarrow$	Target Spin Asymmetries	<div style="border: 1px solid green; padding: 5px;">                     JHEP 06 (2010) 019                      NPB 842 (2011) 265                 </div>	$\tilde{H}$
$A_{LL}^{\cos(0\phi)}$ $A_{LL}^{\cos\phi}$ $A_{LL}^{\cos(2\phi)}$		Double Spin Asymmetries		

クォーク全角運動量  $\leftrightarrow$



using 27.6 GeV Pol. e- (e+) beam  
 の原子核物理に関する討論会

# 電子・陽電子衝突実験：B-factory での成果

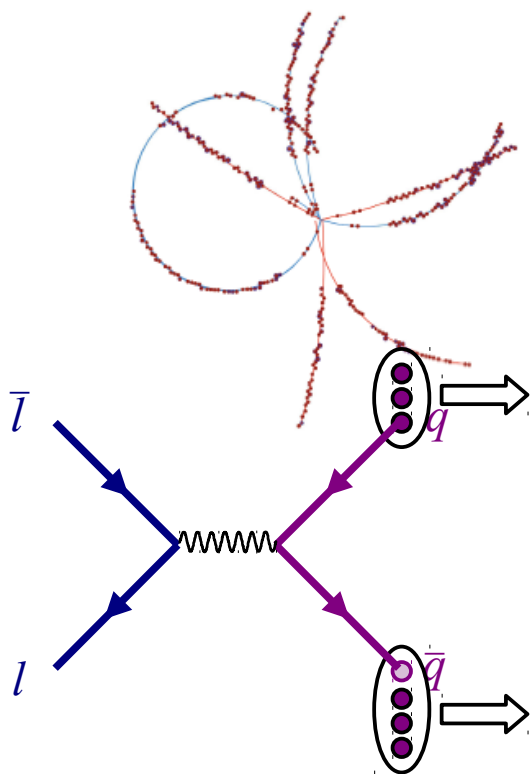
Eur. Phys. J. C (2014) 74:3026  
DOI 10.1140/epjc/s10052-014-3026-9

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  
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Springer

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# 電子・陽電子衝突実験：B-factory での成果

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

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Review

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# ILCでの核子構造研究の可能性

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

QCD

@ B-Factory

# Fragmentation function measurements

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

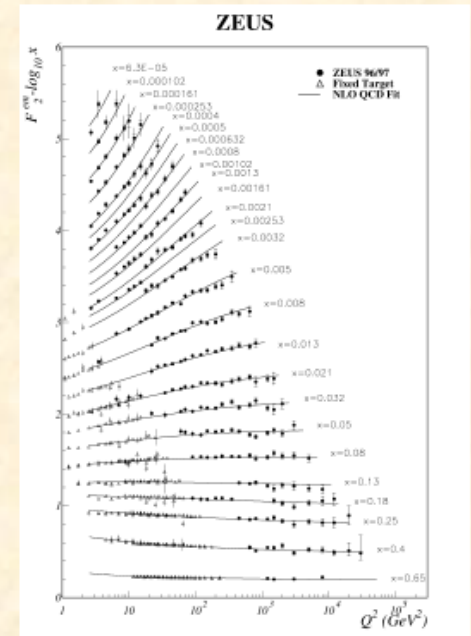
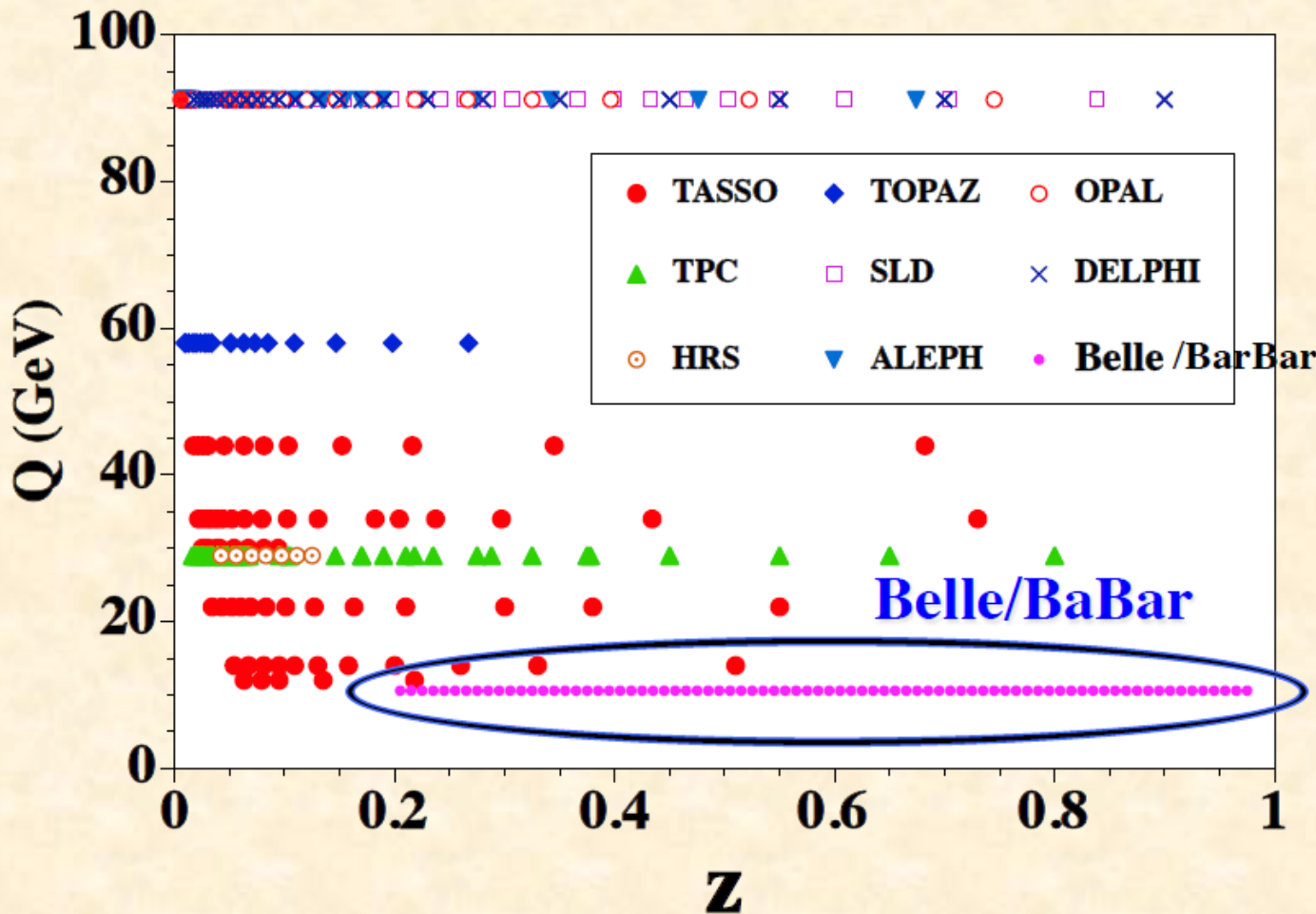
$Q = 1000 \text{ GeV}$

$Q = 500 \text{ GeV}$

$Q = 250 \text{ GeV}$

ILC

Scale evolution of  $D_i^h$   
→ gluon fragmentation function

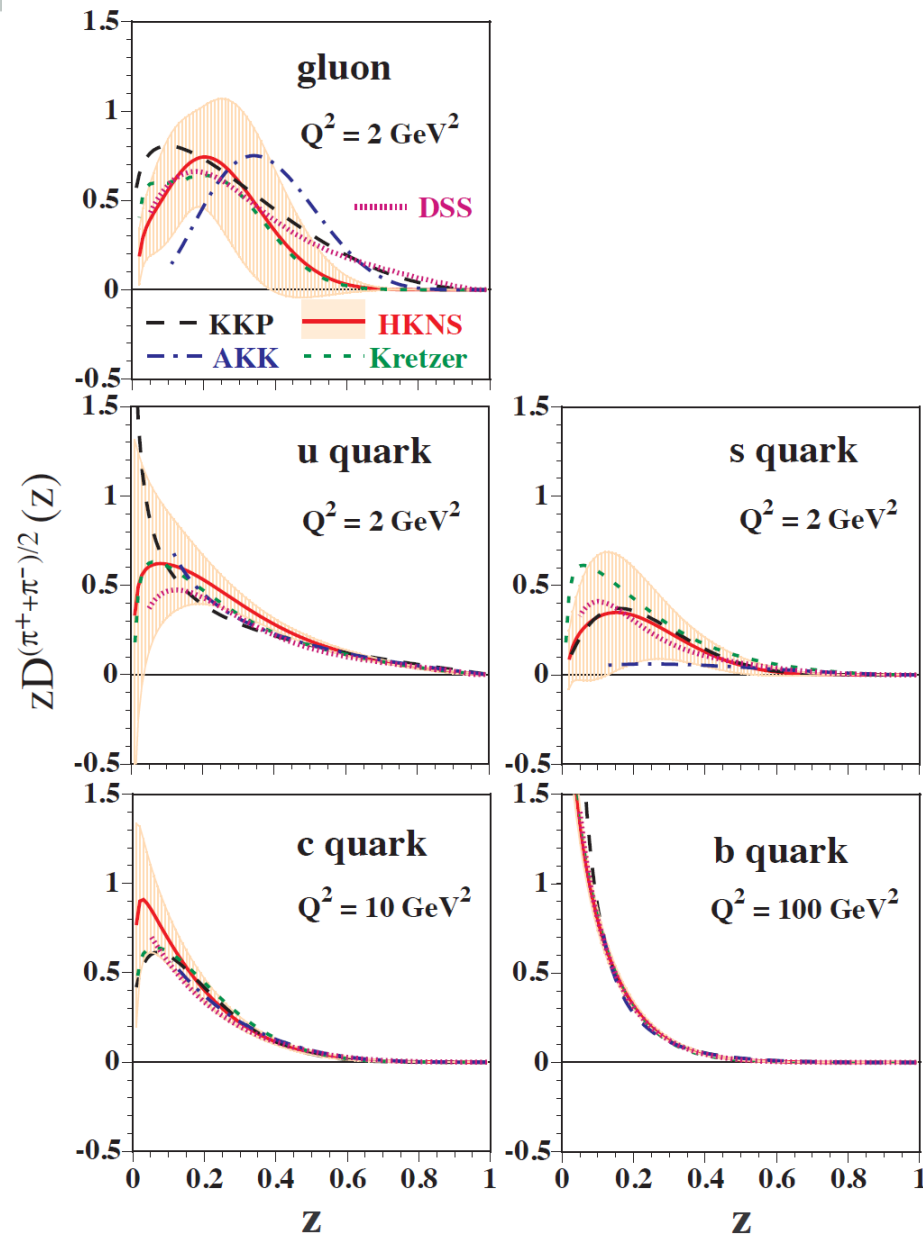
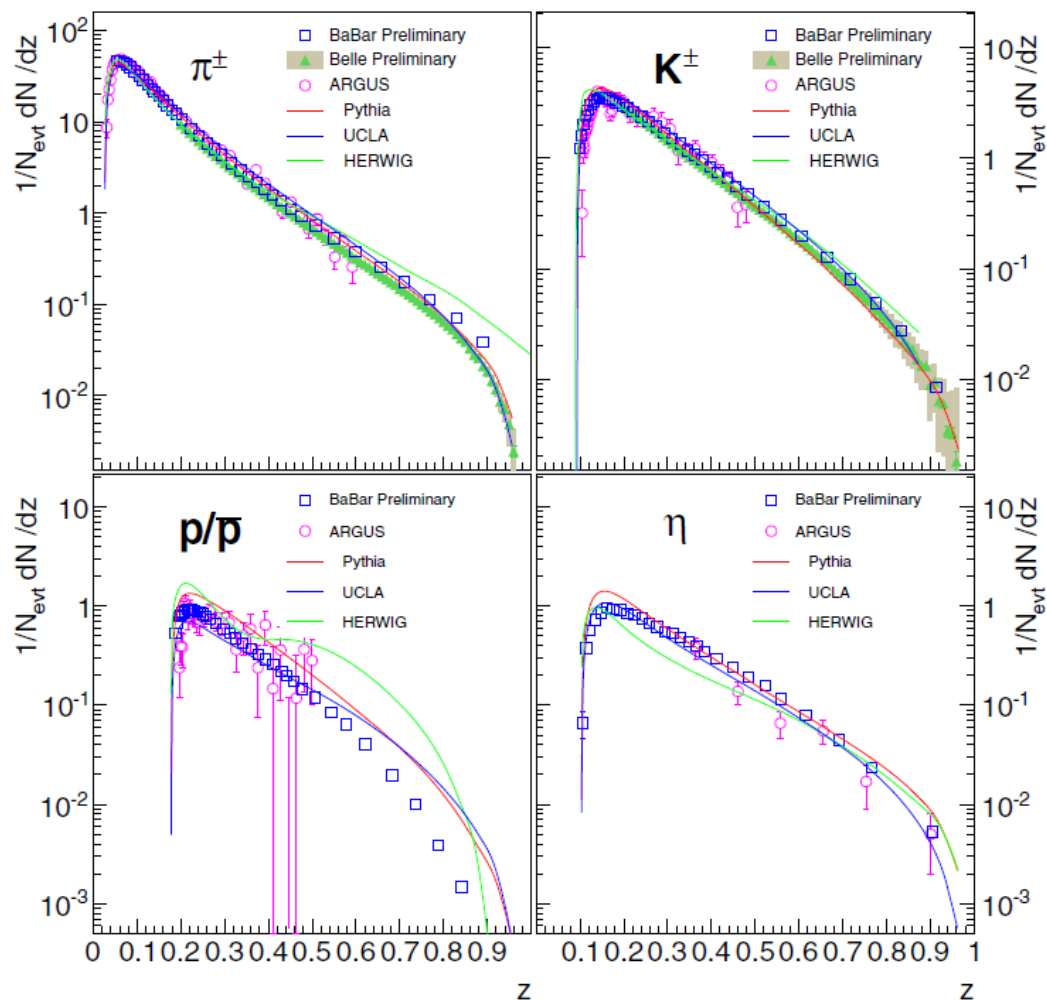


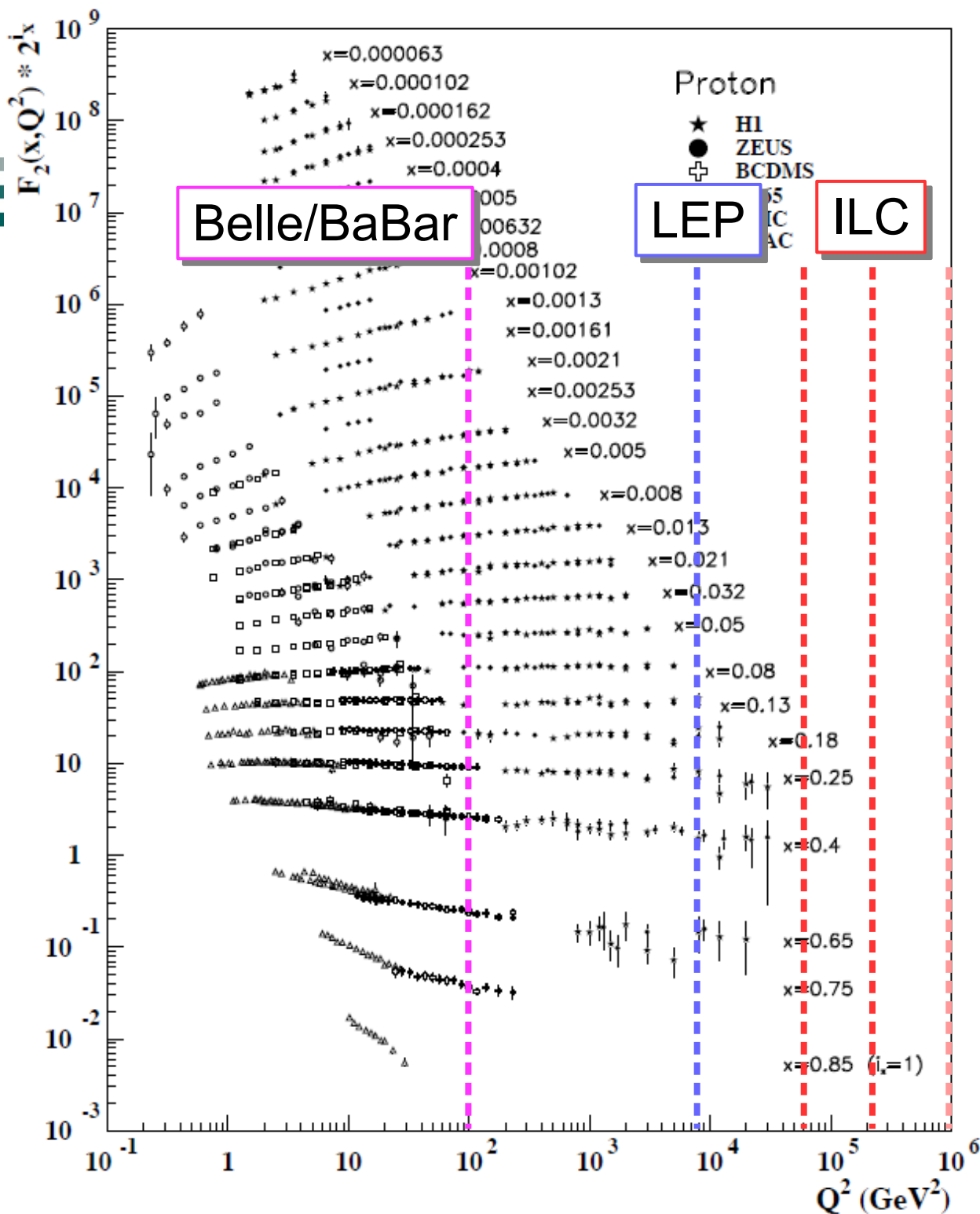
Scale evolution of  $F_2$   
→ gluon distribution



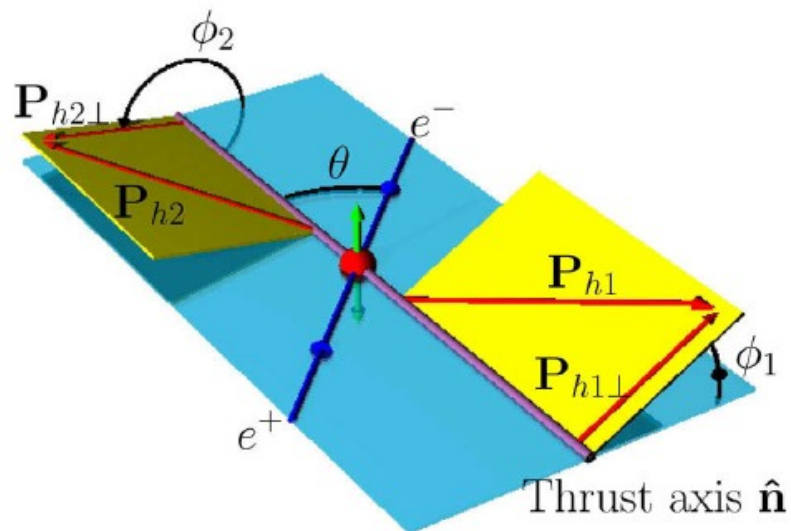
# “非偏極”破碎関数

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

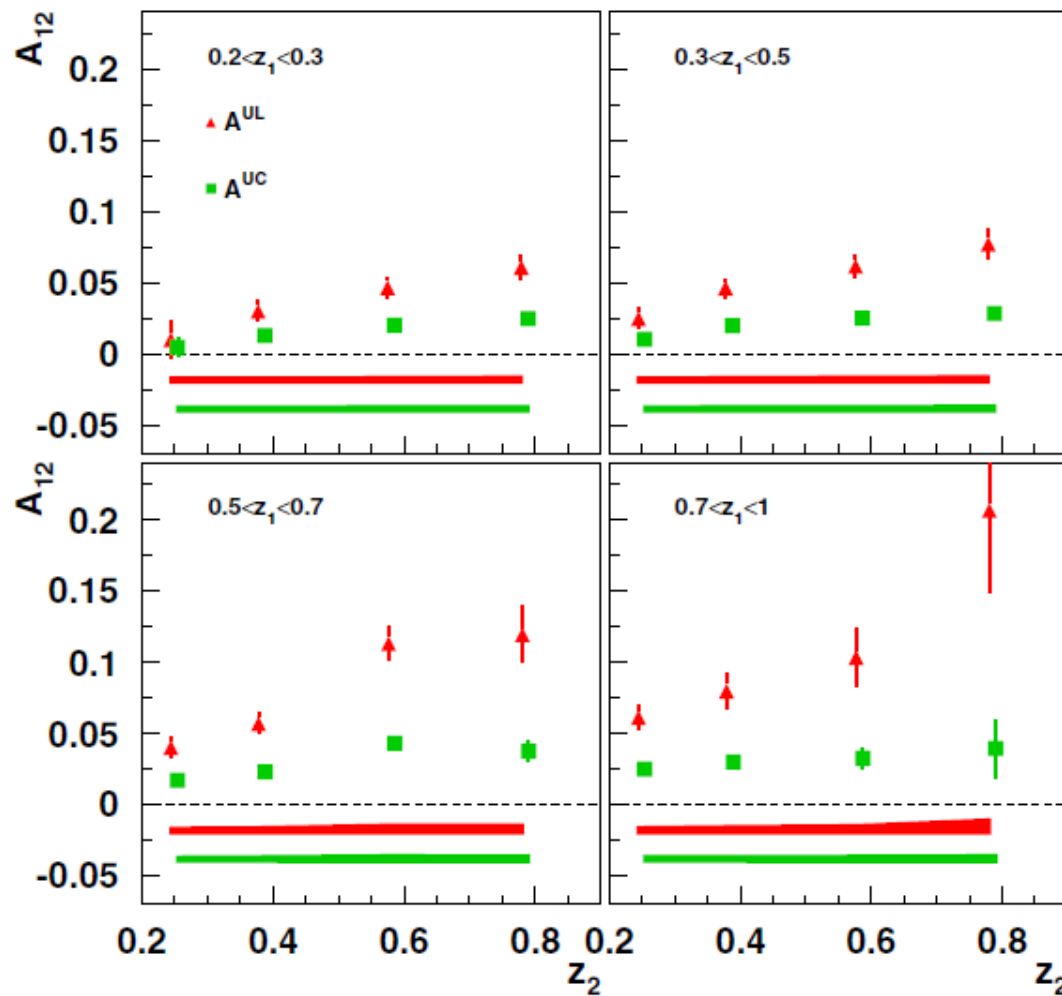




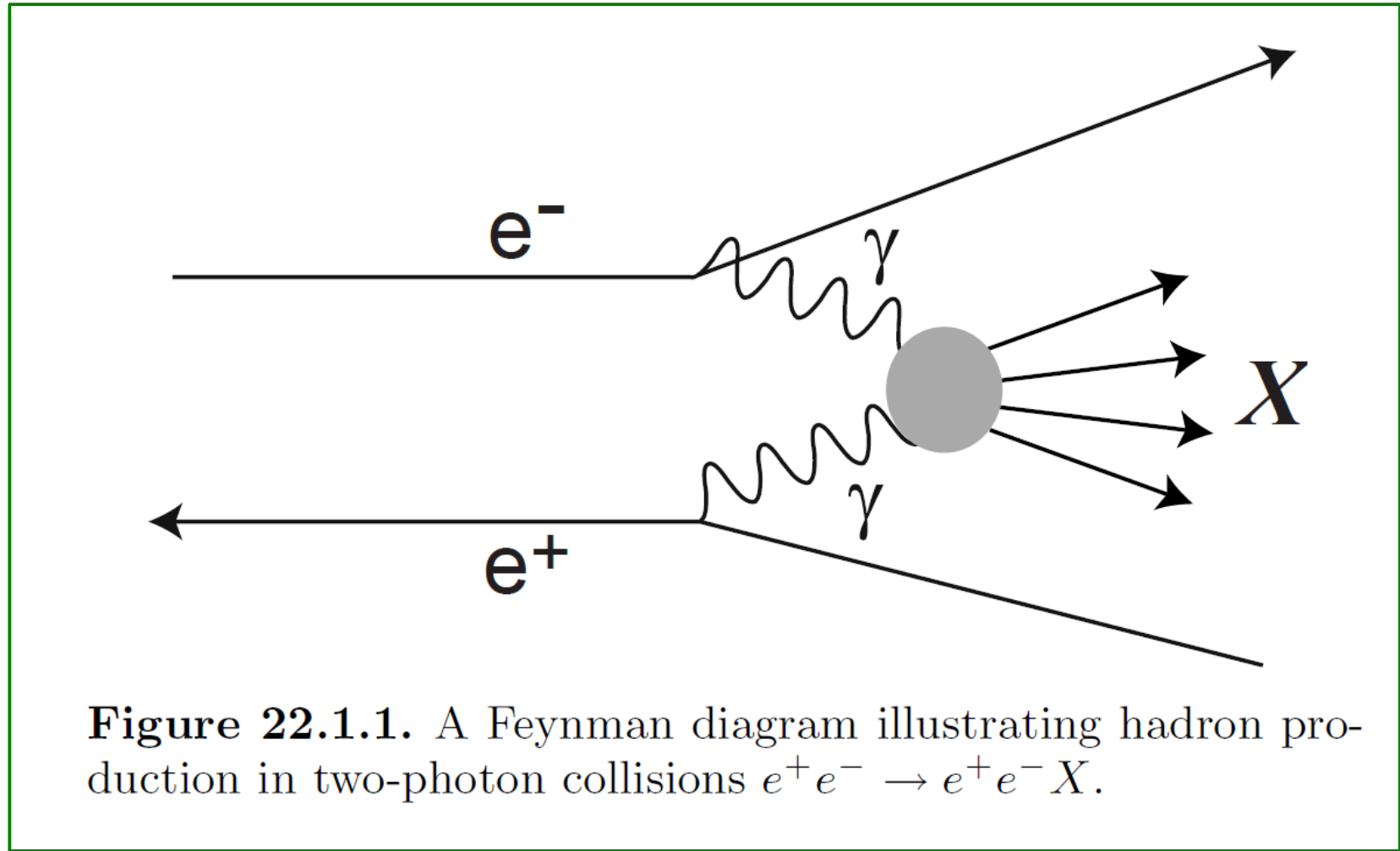
# 偏極破碎関数



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



# Two photon processes

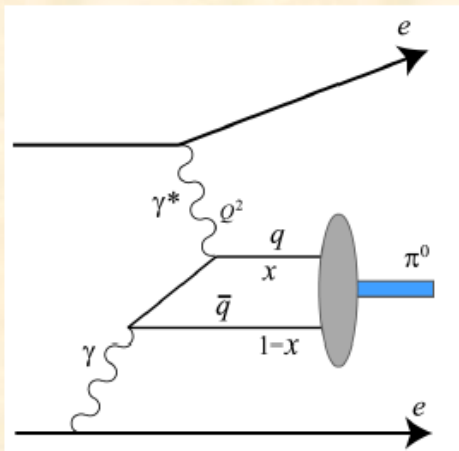


**Figure 22.1.1.** A Feynman diagram illustrating hadron production in two-photon collisions  $e^+e^- \rightarrow e^+e^-X$ .

# Form factors in the asymptotic region

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

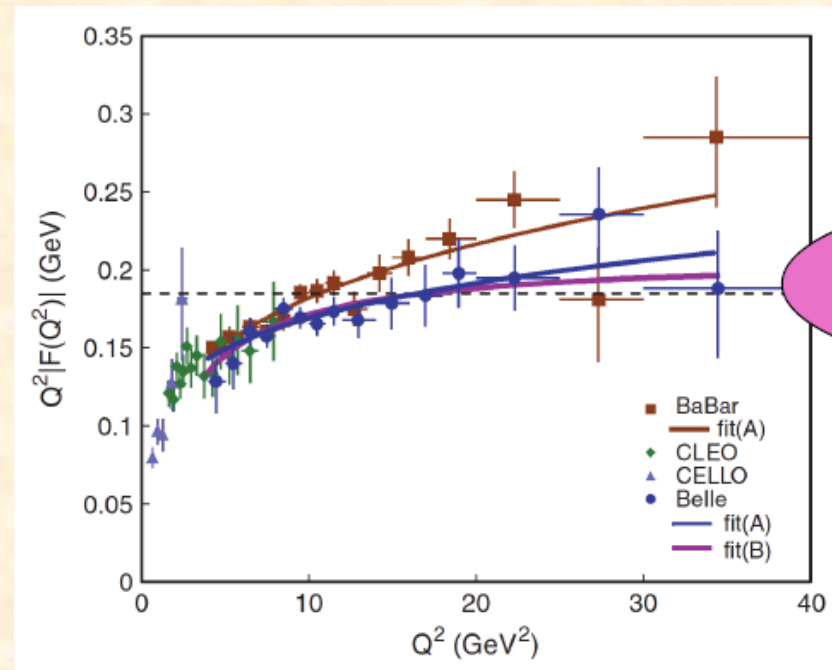
$$\gamma + \gamma^* \rightarrow \pi^0$$



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

## ILC

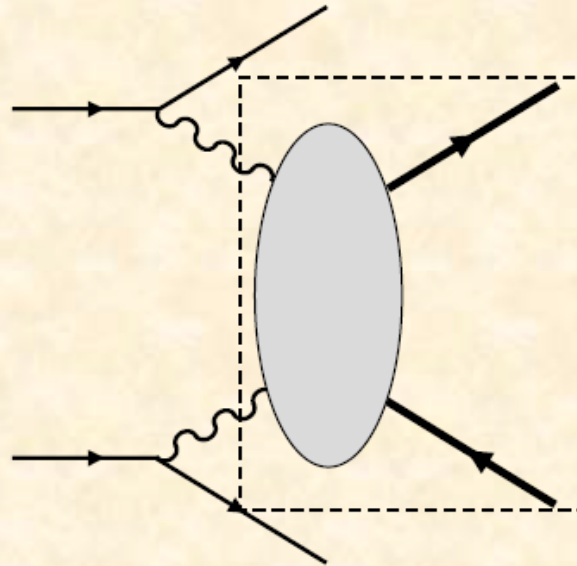
- Investigate the form factor in the asymptotic region
- Discrepancies between Belle and BaBar



ILC



# Two-photon physics for hadron tomography



$$\gamma\gamma \rightarrow h\bar{h}$$

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

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

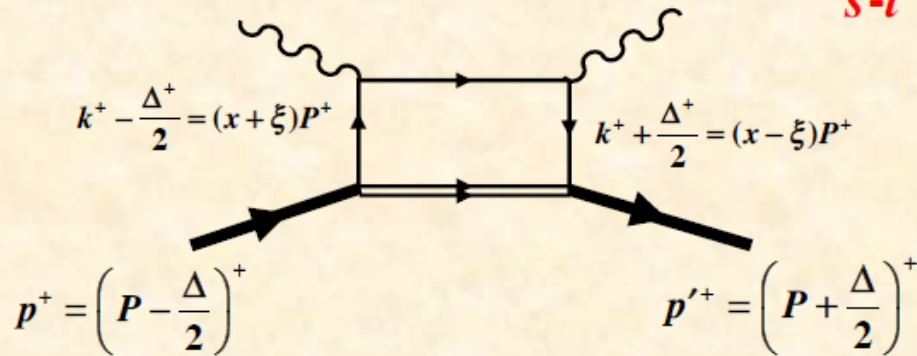
# GPD $H_q^h(x, \xi, t)$ and GDA $\Phi_q^{h\bar{h}}(z, \zeta, W^2)$

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

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

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

$H_q^h(x, \xi, t)$



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

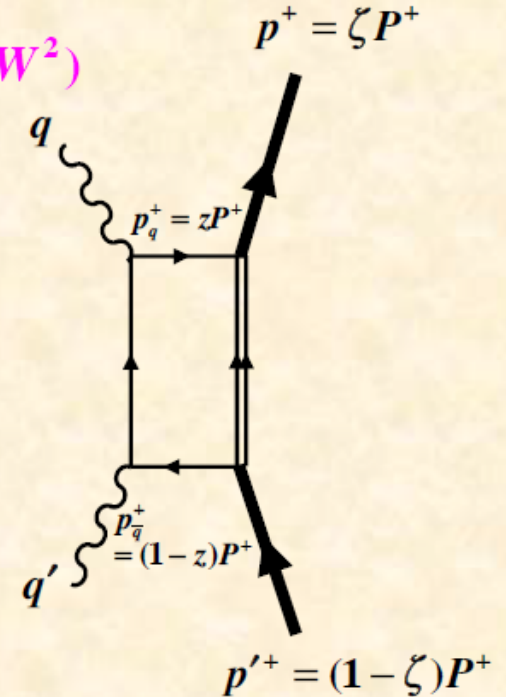
Bjorken variable:  $x = \frac{Q^2}{2p \cdot q}$

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

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

$\longleftrightarrow$   
**s-t crossing**

$\Phi_q^{h\bar{h}}(z, \zeta, W^2)$



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

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

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

# Cross section: form factor dependence

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

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

Constituent-counting rule

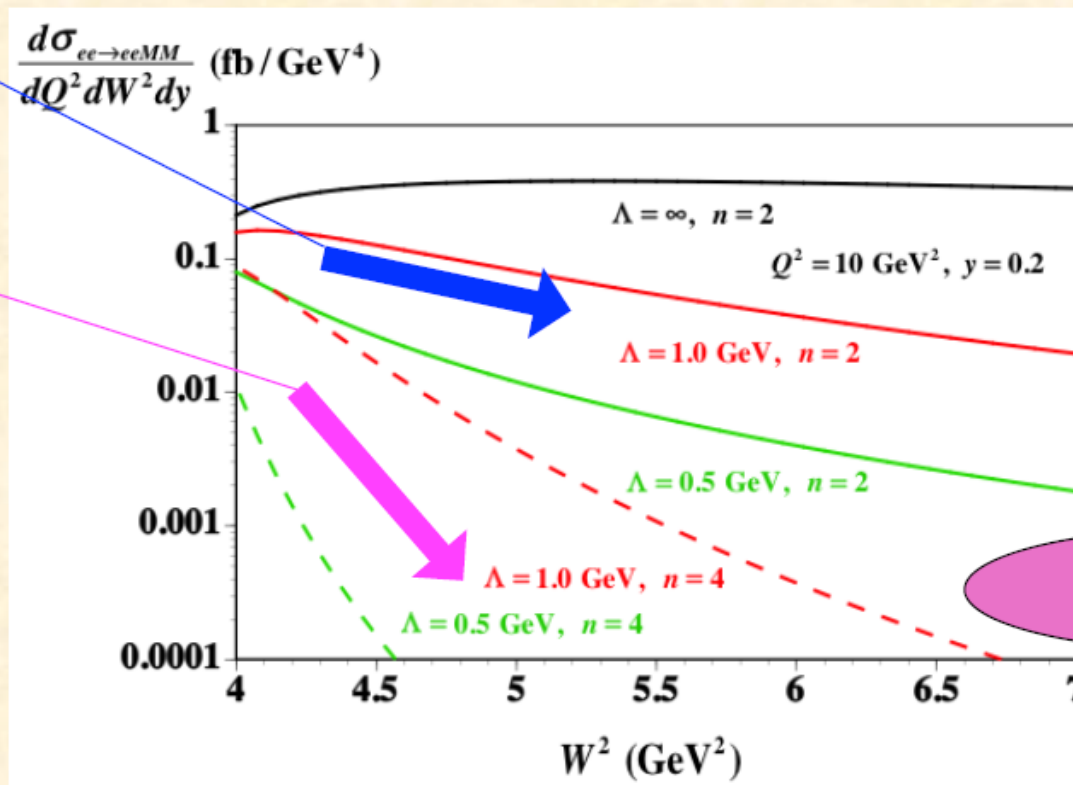
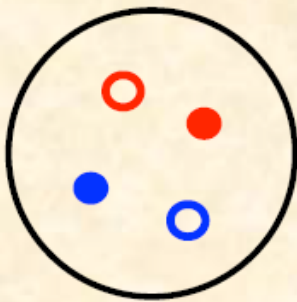
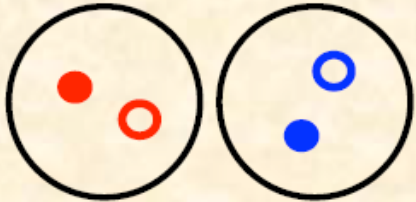
$n = 2$ : ordinary meson

$n = 4$ : molecule or tetra-quark

Ordinary  $q\bar{q}$



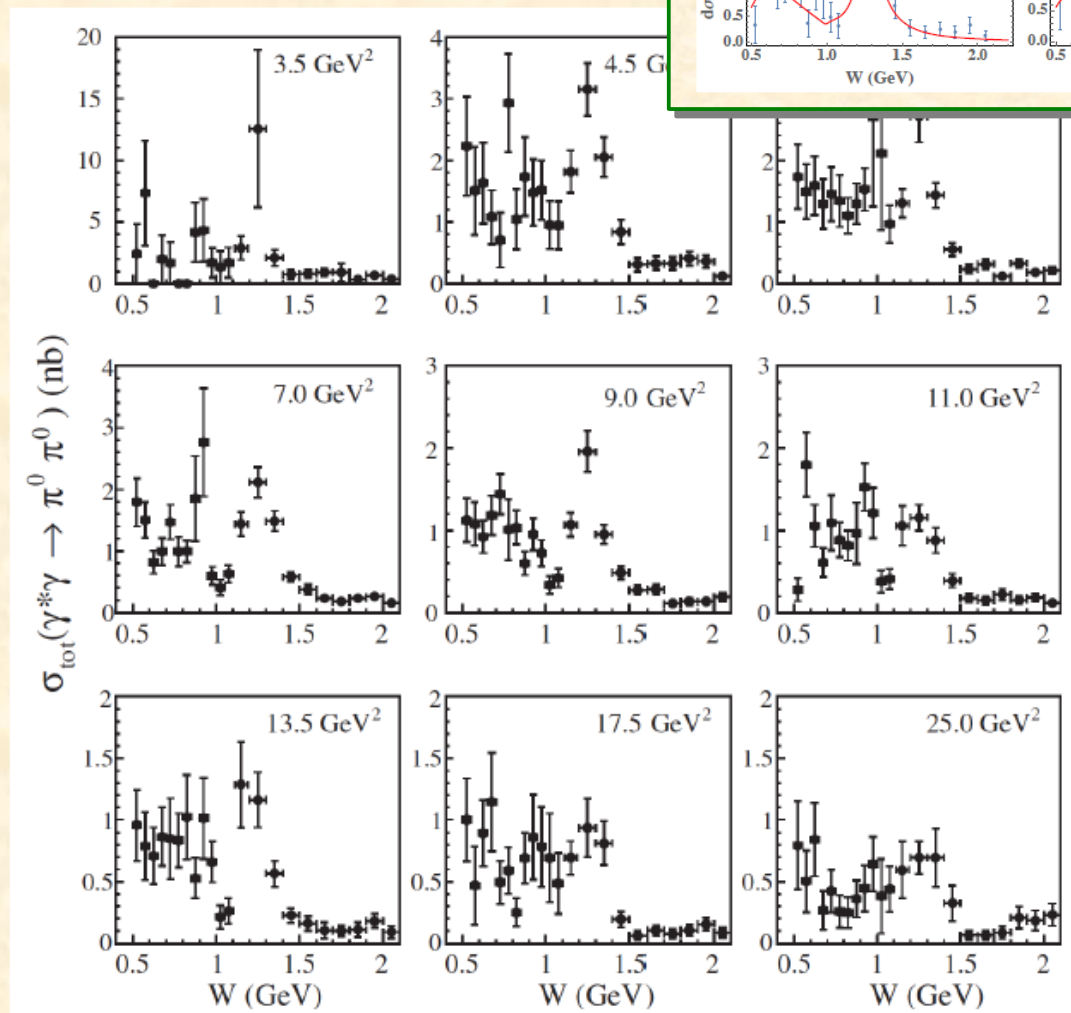
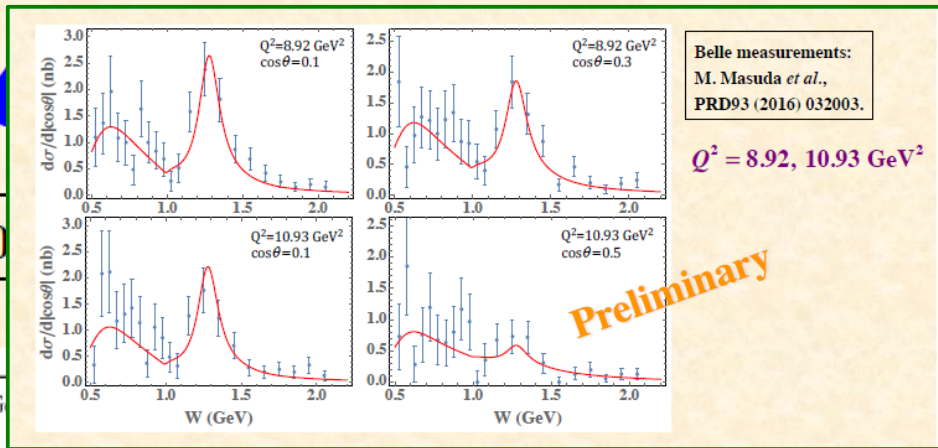
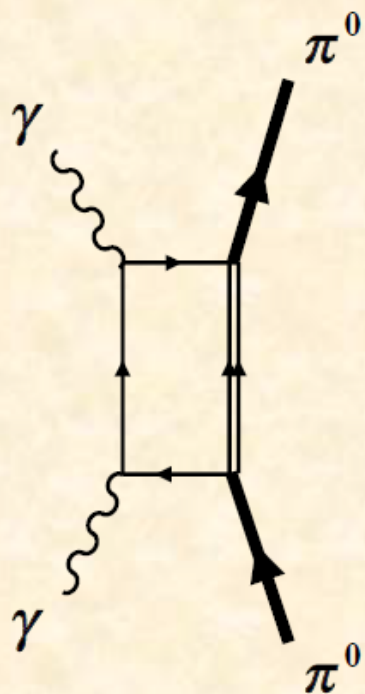
Molecule  $K\bar{K}$   
or tetra-quark  $qq\bar{q}\bar{q}$





# KEKB-Belle measurement

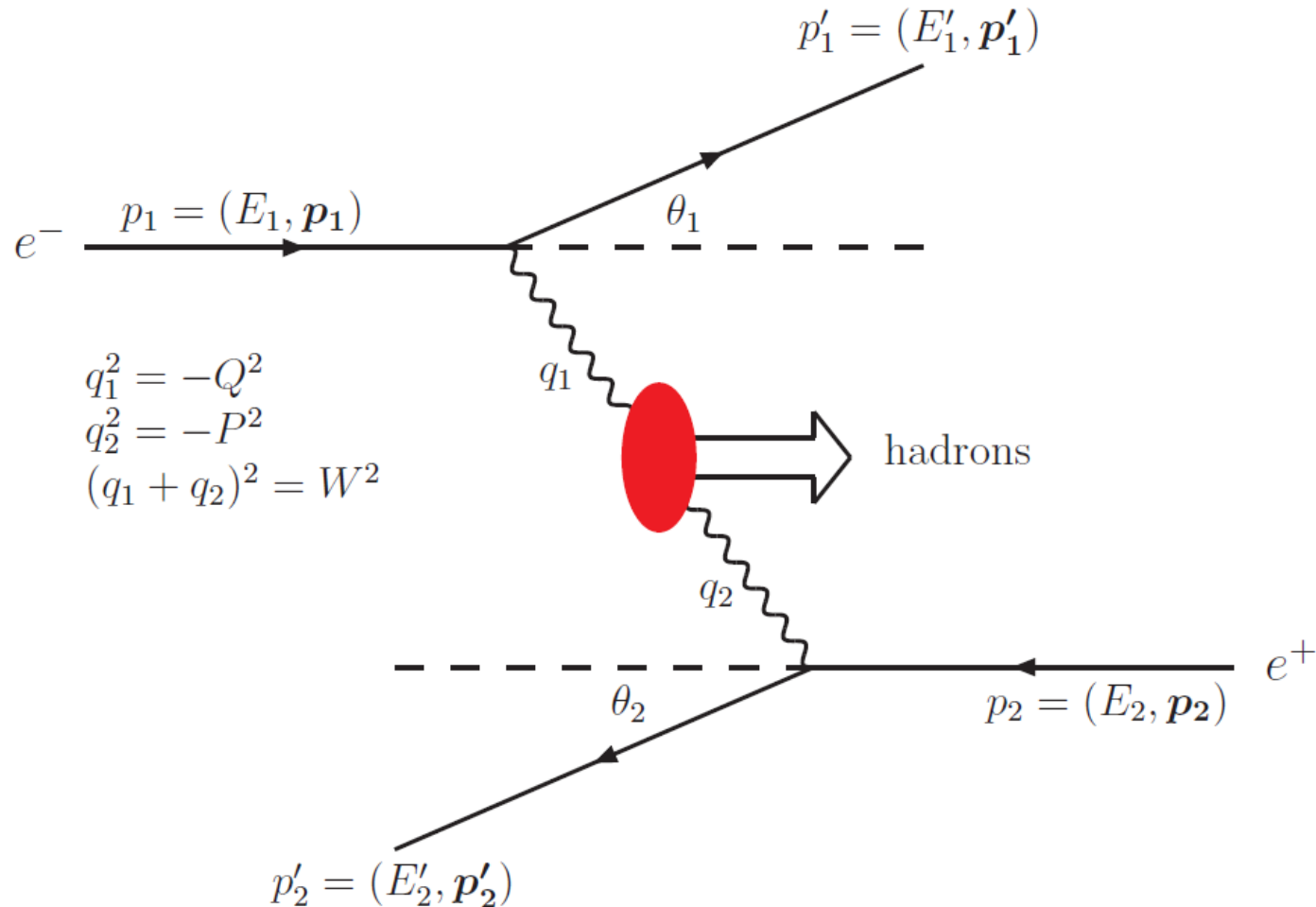
M. Masuda *et al.*, Phys. Rev. D 93 (2016) 0



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

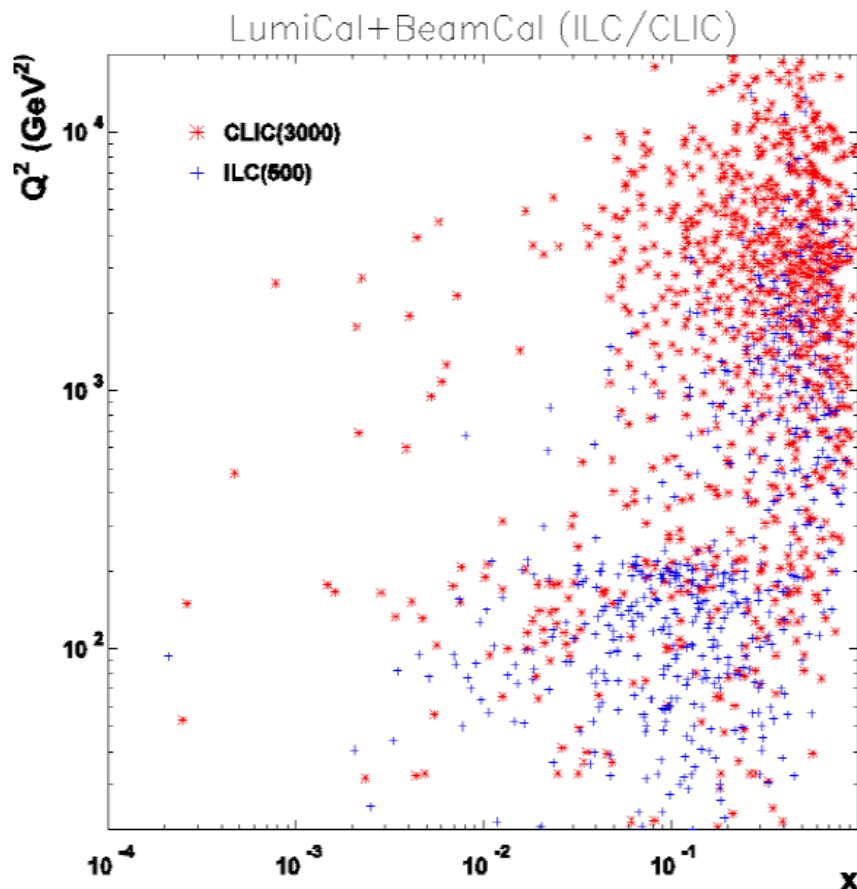


Fig. 2. Kinematical plane ( $x$ ,  $Q^2$ ) with simulated single-tagged events for the case of detecting scattered electrons at the LumiCal and BeamCal detectors.

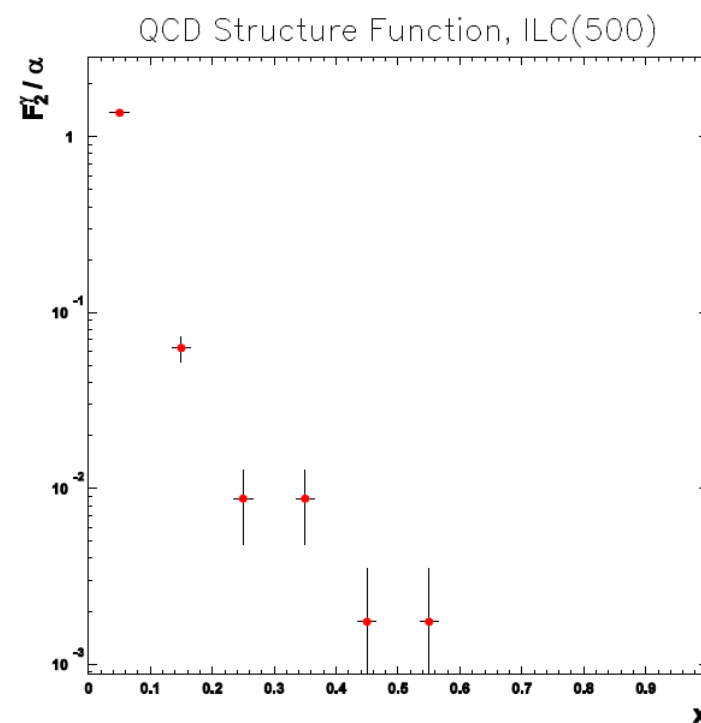
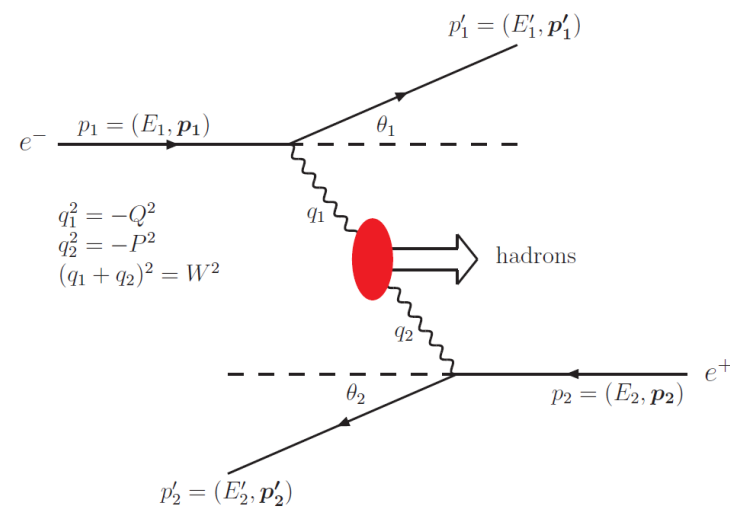
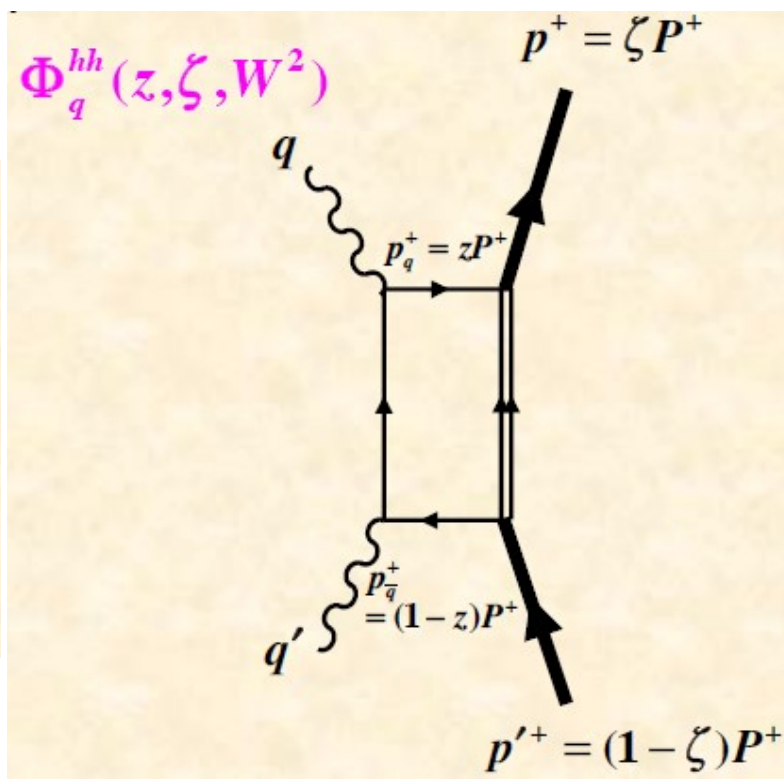
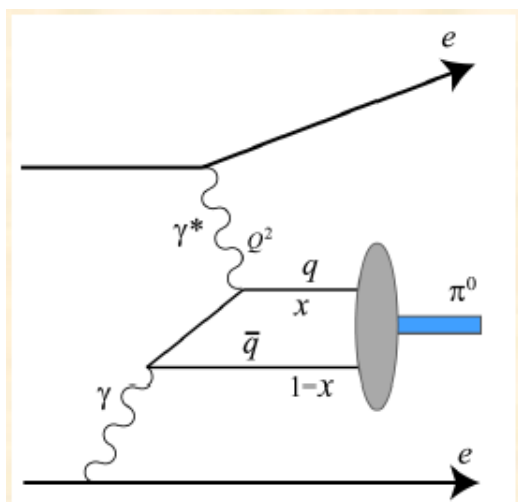
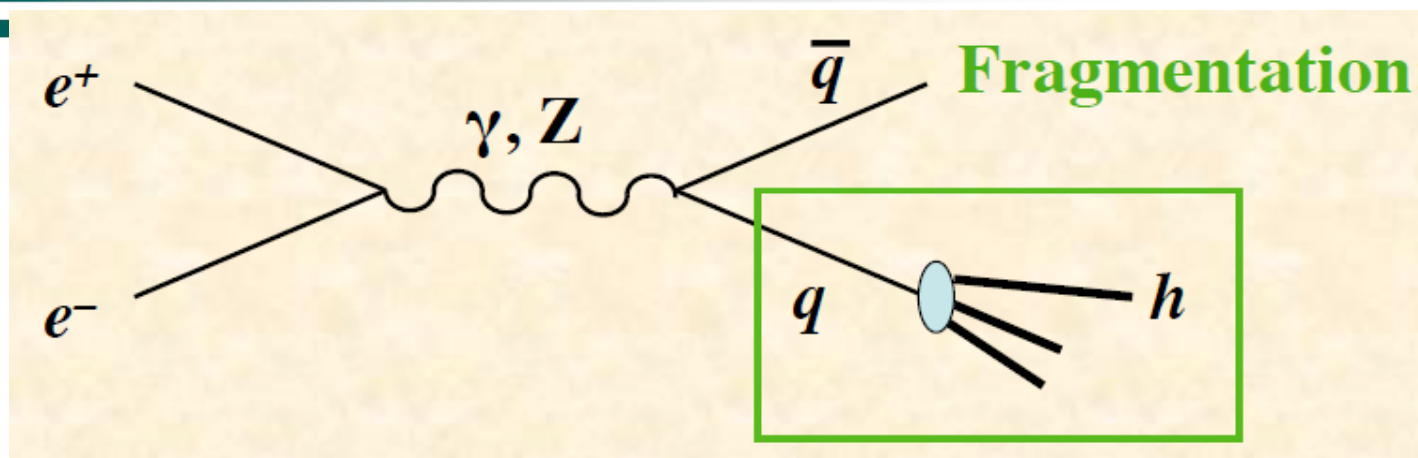
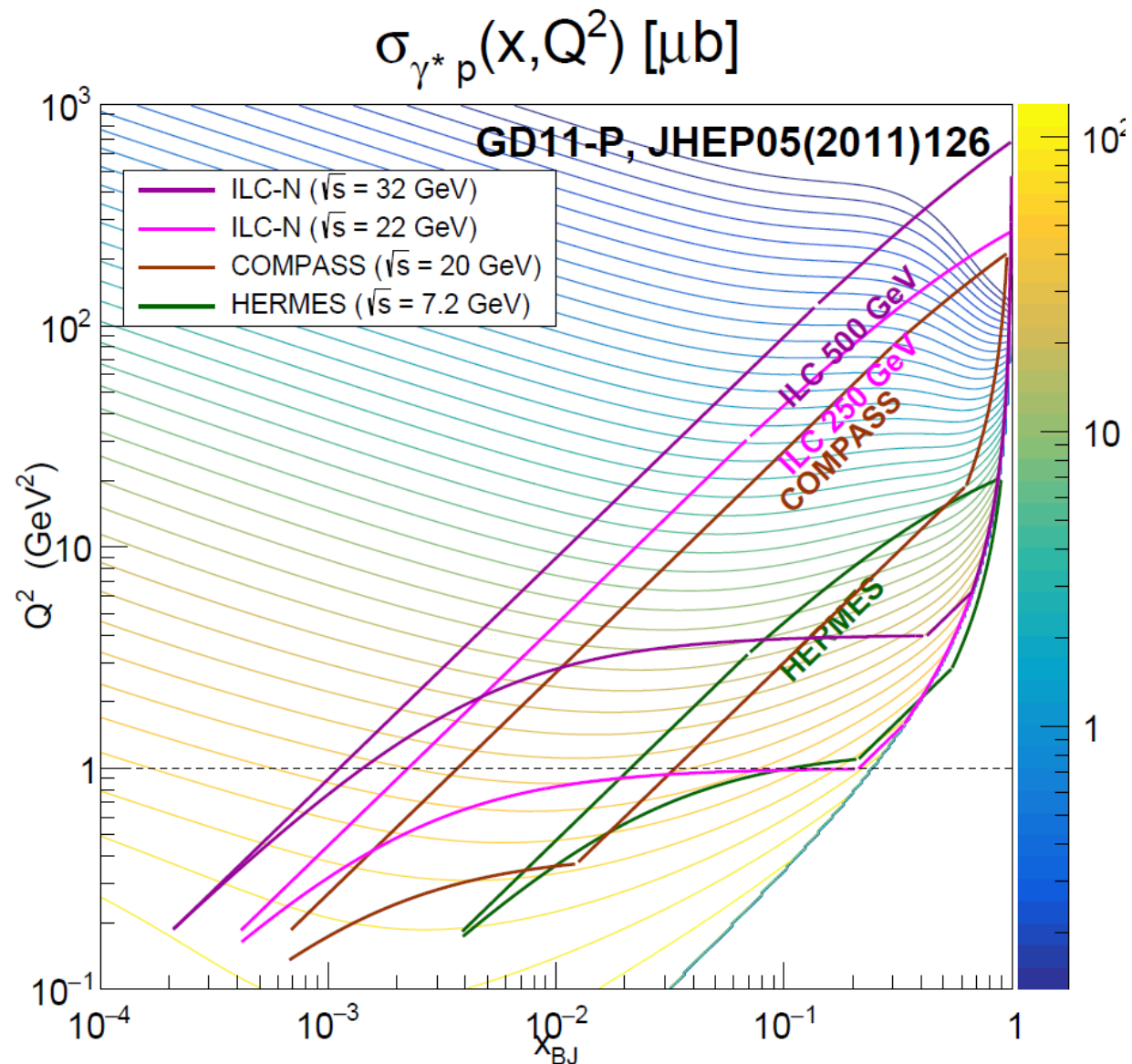


Fig. 6. The hadronic photon structure function divided by the fine structure constant as a function of  $x$  variable for the mean value of  $Q^2$  equal to 119 GeV<sup>2</sup>. The errors are statistical only.



# ILCでの固定標的実験

- 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/<sup>3</sup>He
- ✓ e beam 3-10(20) GeV
- ✓ Luminosity  $L_{ep} \sim 10^{33-34} \text{ cm}^{-2}\text{sec}^{-1}$   
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

1212.1701.v3

A. Accardi et al

## ILC-N

$E_e = 125, 250, 500 \text{ GeV}$

Fixed target: p $\uparrow$ , d $\uparrow$ , A

$L \sim 10^{33-34} \text{ cm}^{-2} \text{ s}^{-1}$

$\sqrt{s} = 16, 22, 32 \text{ GeV}$

**Electron Ion Collider:**  
The Next QCD Frontier

Understanding the glue  
that binds us all

SECOND EDITION

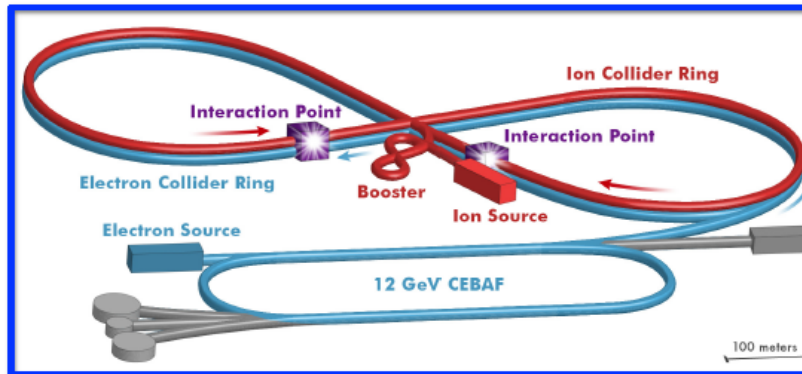
# Electron Ion Collider

Wednesday, July 7, 16

State of EIC @ EICUG ANL

15

## Accelerator designs....



@JLab

Ring-Ring Design

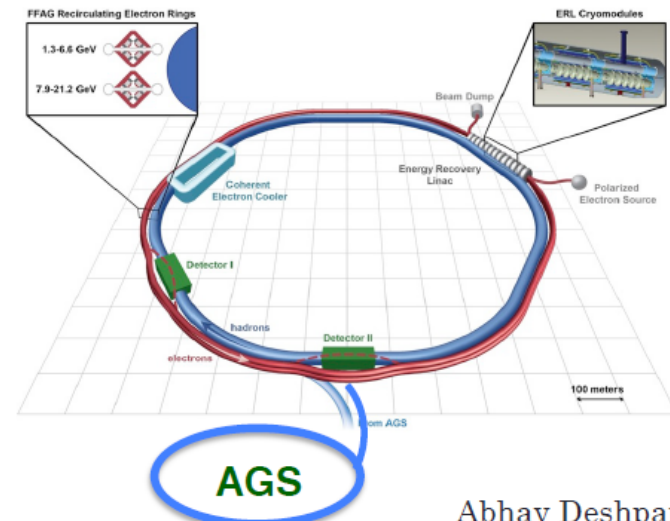
Bow-Tie shaped ring to address the polarization preservation without Siberian snakes

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





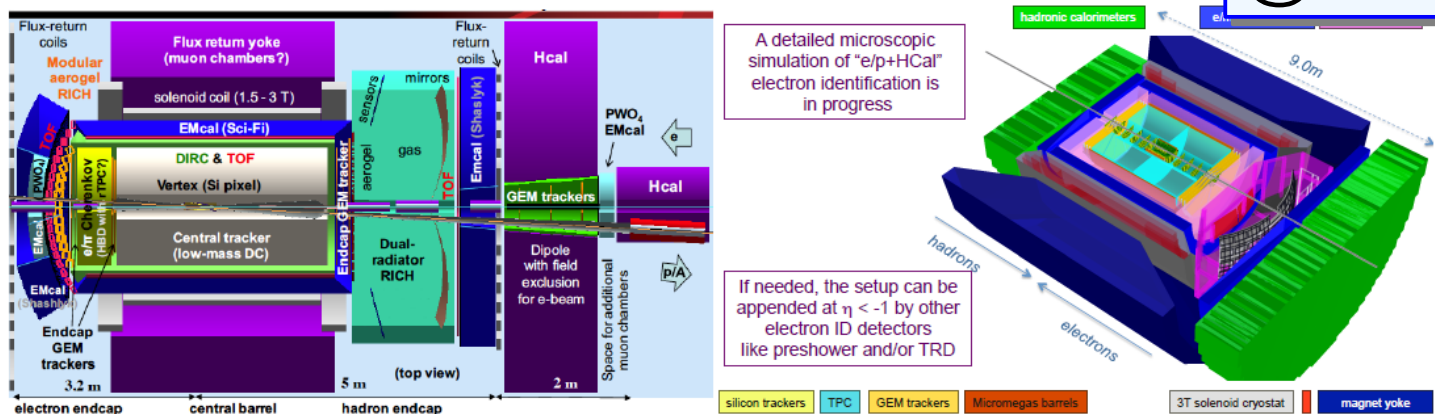
# Electron Ion Collider

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

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

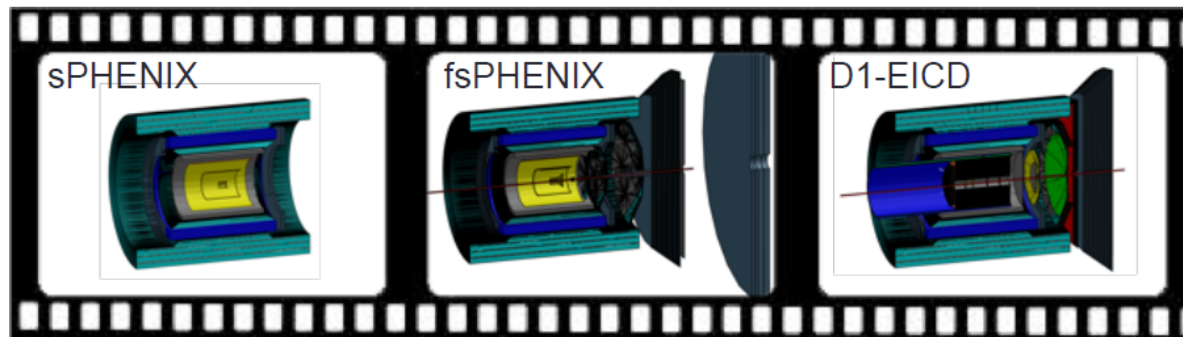
R. Yoshida, JLEIC WG

A. Kise @JLab



@BNL

K. Barish

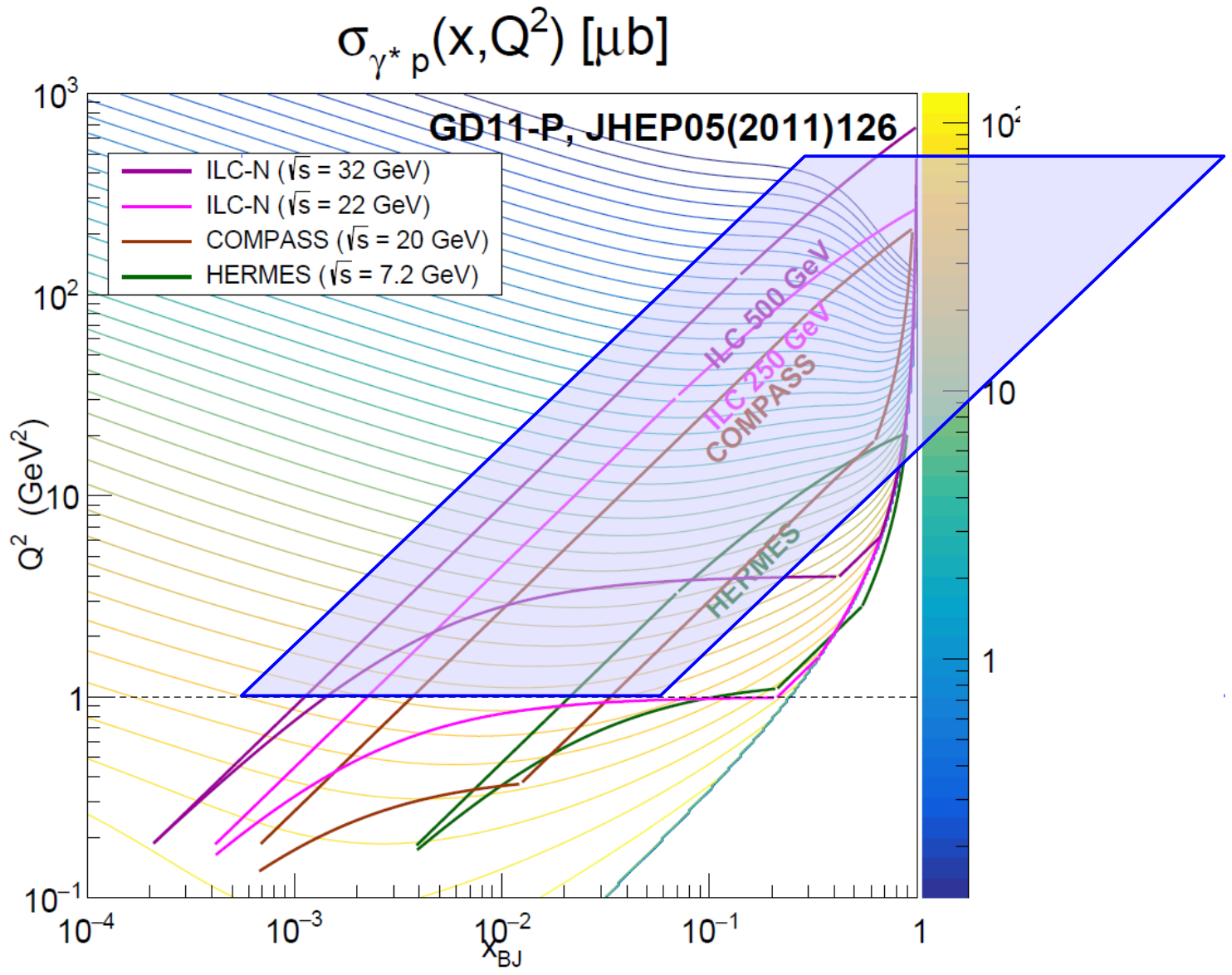


 Stony Brook University

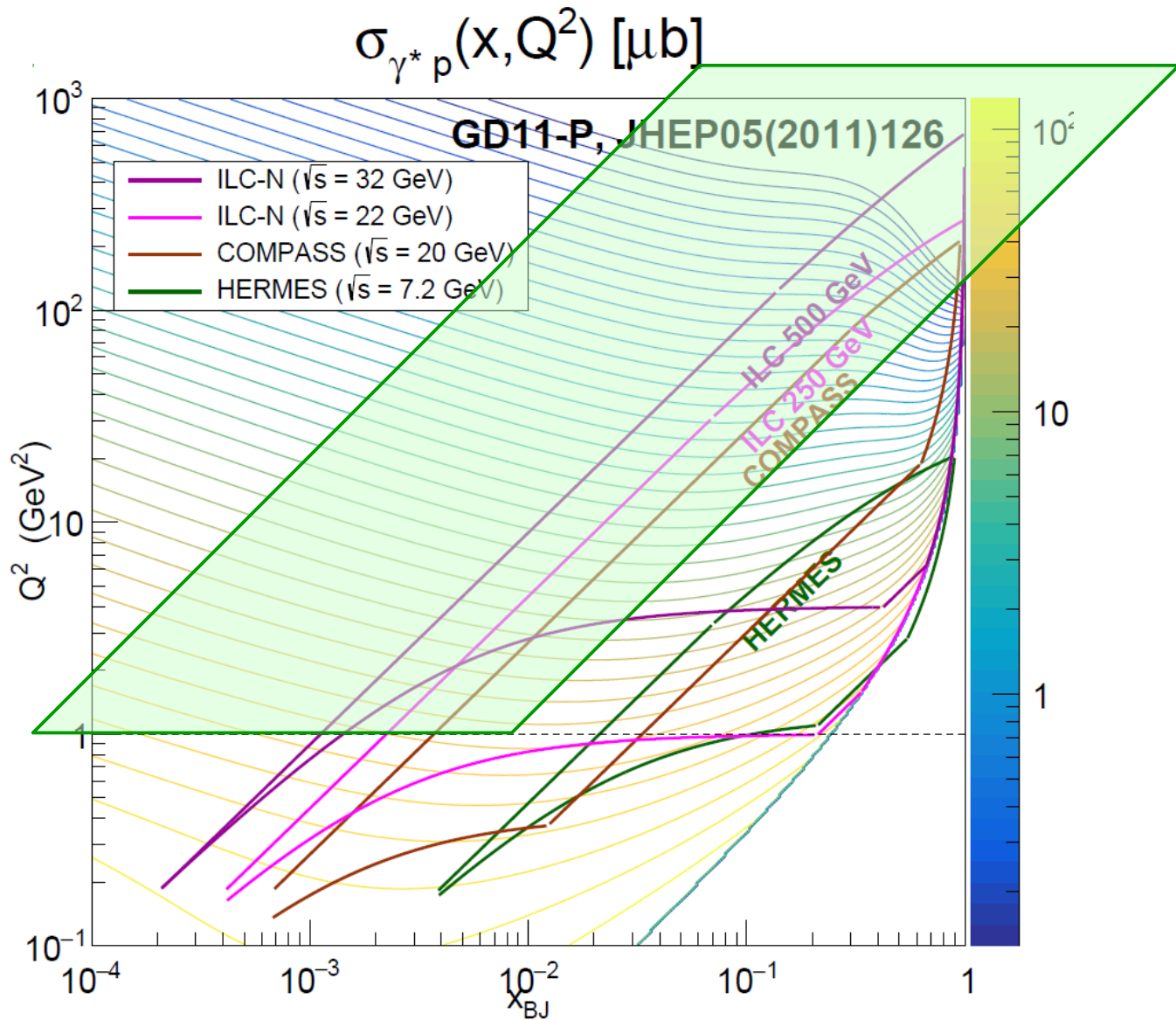
Abhay Deshpande

段階的にアップグレード

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



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



# HERMES, COMPASS 実験

	HERMES@DESY	COMPASS@CERN
Beam	Pol. e <sup>+</sup> /e <sup>-</sup> in HERA e-ring E = 27.6 GeV $e^{-/←}, e^{-/→}, e^{+/←}, e^{+/→}$	Pol. μ <sup>+</sup> /μ <sup>-</sup> E = 160~200 GeV $\mu^{+/←}, \mu^{-/→}$ @ 160 GeV
Target	L-pol. H/D <div style="float: right; border: 1px solid blue; padding: 2px;">Δq, ΔG</div>	L-pol. H/D
	T-pol. H <div style="float: left; border: 1px solid green; padding: 2px;">GPD-E</div> <div style="float: right; border: 1px solid red; padding: 2px;">TMD</div>	T-pol. H/D
	U-pol. H/D <div style="float: left; border: 1px solid green; padding: 2px;">GPD-H</div>	
	U-pol. H/D + recoil <div style="float: right; border: 1px solid green; padding: 2px;">GPD-H</div>	U-pol. H + recoil

# ILC-Nで目指すべきもの

- 運動学的領域
    - CERN-COMPASSより low-x, high- $Q^2$ 
      - $E = 250 \text{ GeV}$  ではあまりかわらない。(500 GeVならば・・・)
    - EIC ( $\sqrt{s} = 20 \sim 100 (140) \text{ GeV}$ )
  - 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 ( $\sqrt{s} = 7 \text{ GeV}$ ) の測定
    - Jlab ( $\sqrt{s} = 5 \text{ GeV}$ )での計画
- COMPASSで未測定



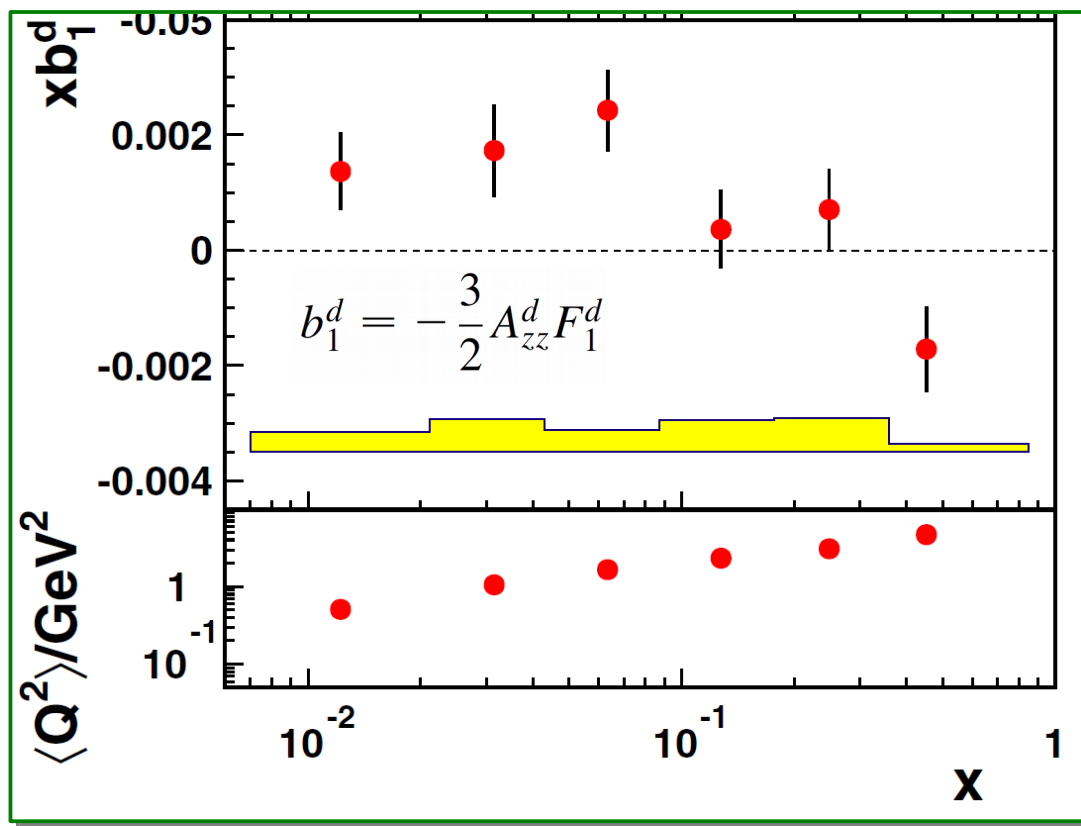
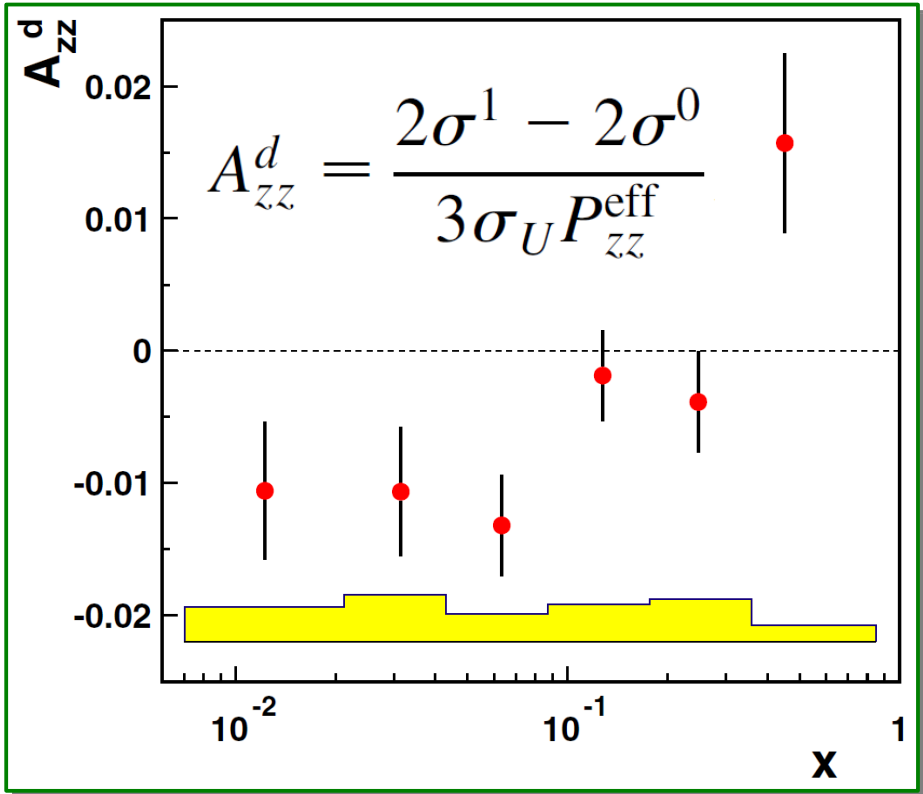
# HERMESでの構造関数 $b_1$ 測定

$$P_{zz} = P_T$$

$$P_z = P_V$$

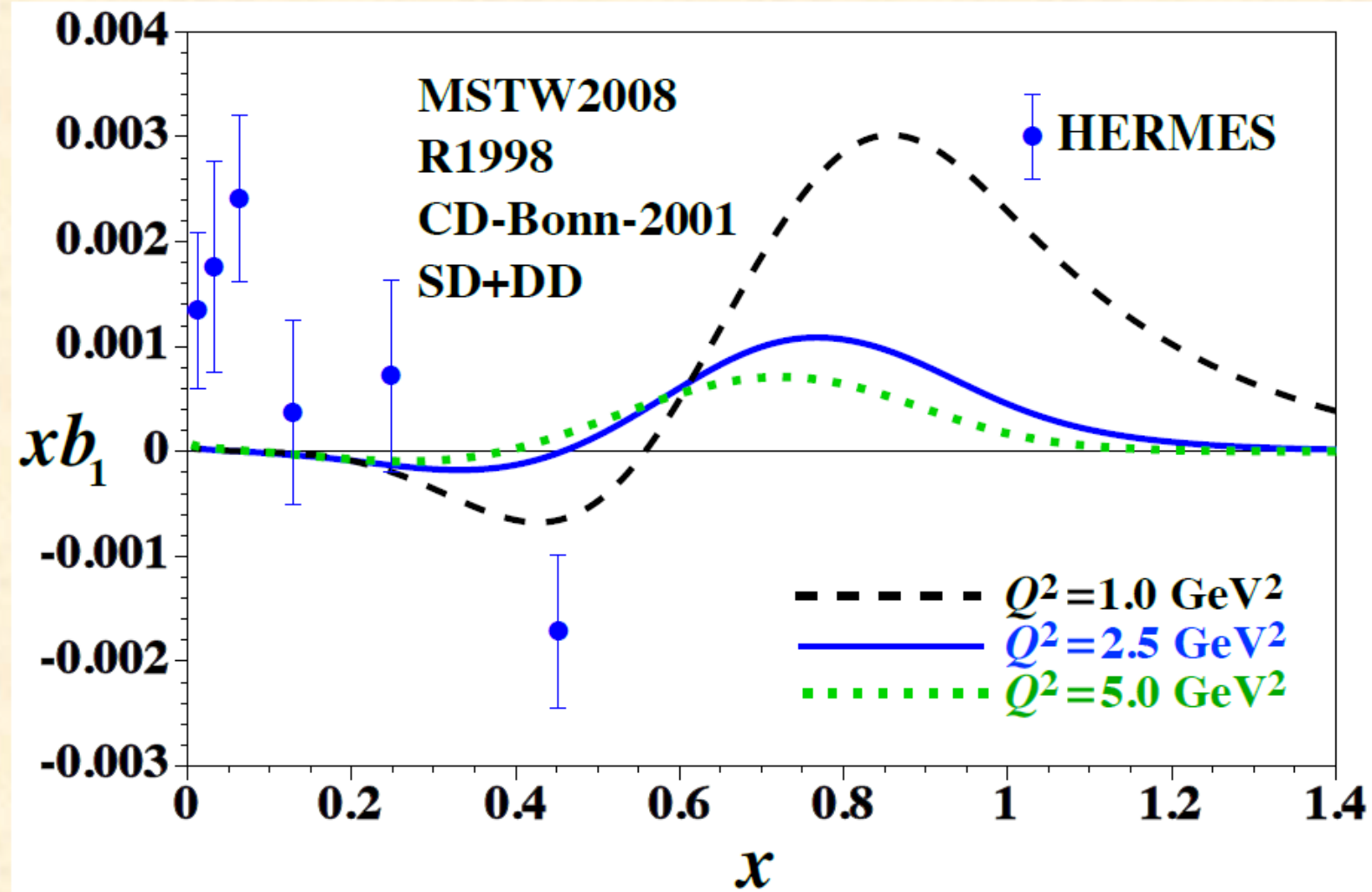


- 27.6 GeV 偏極電子
- テンソル偏極重陽子標的



$\langle Q^2 \rangle / \text{GeV}^2$

# 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.  $\text{ND}_3$  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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M. Jones, C. Keith, S. Wood, J. Zhang  
*Thomas Jefferson National Accelerator Facility, Newport News, VA 23606*

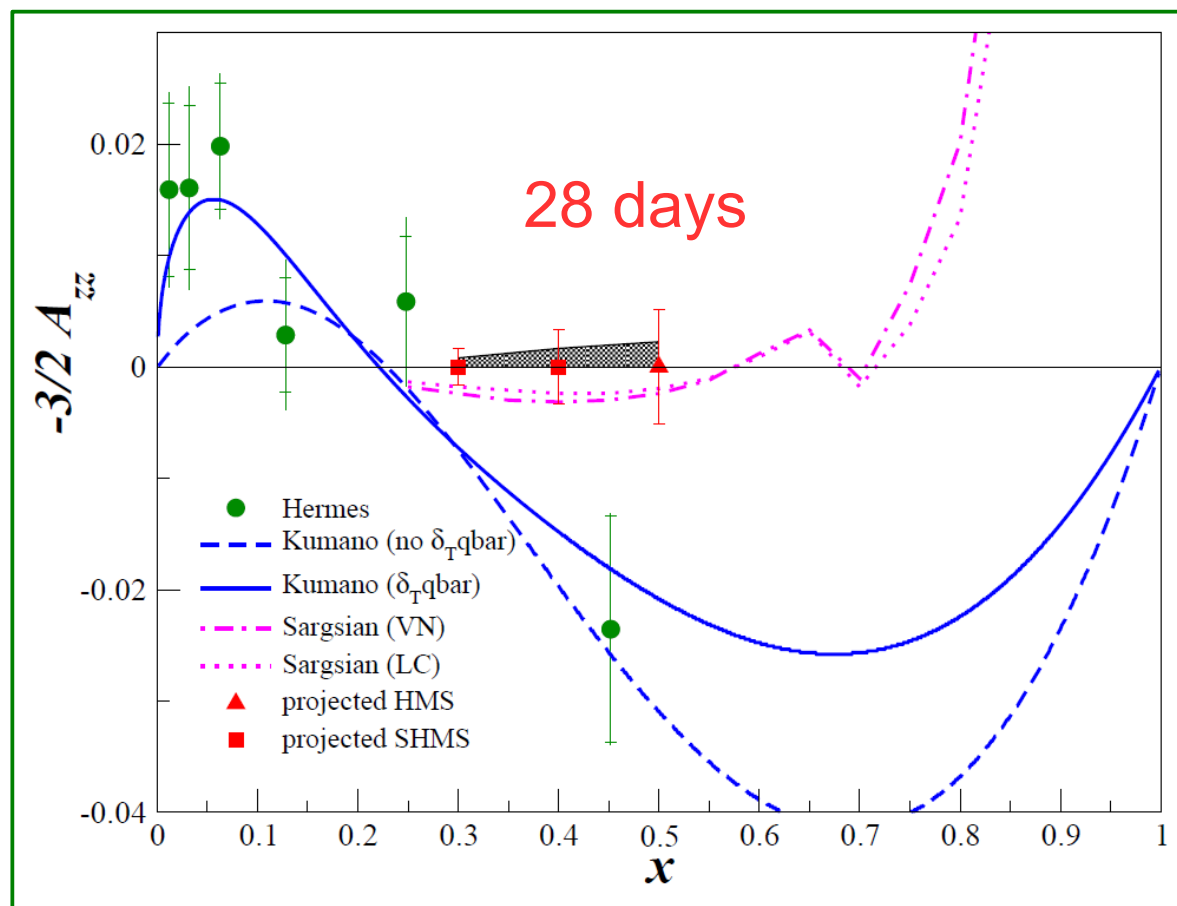
N. Kalantarians (co-spokesperson), O. Rondon (co-spokesperson)  
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# まとめ

- 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？