ILCのハドロン物理
(Hadron Physics at ILC)

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第11回高エネルギーQCD・構造関数勉強会
山形大学、2017年3月24日（金）
https://indico2.riken.jp/indico/conferenceDisplay.py?confId=2463

March 24, 2017

Hadron physics
with fixed targets at ILC

ILC-N: Electron-hadron deep inelastic scattering with fixed targets

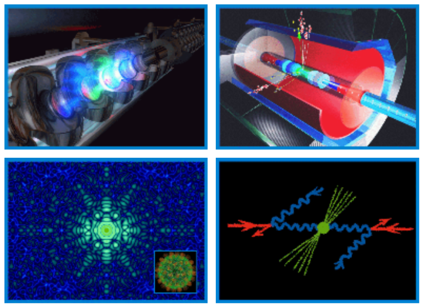
There is a possible physics report for the TESLA project (2001) at http://tesla.desy.de/new_pages/TDR_CD/start.html.

TESLA

The Superconducting Electron-Positron Linear Collider

with an Integrated X-Ray Laser Laboratory

Technical Design Report



TESLA Brochure (PDF document, 53.7 MB)

TDR Request

TESLA

Technical Design Report

PART VI

Appendices

Editors:

R. Klanner
Chapter 1: V. Telnov
Chapter 2: U. Katz, M. Klein, A. Levy
Chapter 3: R. Kaiser, W.-D. Nowak
Chapter 4: E. DeSanctis, J.-M. Laget, K. Rith

Contents:

TESLA-N: Physics at the stage of 2001

3 TESLA-N: Electron Scattering with Polarised Targets

The TESLA-N Study Group

M. Anselmino[12], E.C. Aschenauer[4], S. Belostotski[10], W. Bialowons[4], J. Blümlein[4],
V. Braun[11], R. Brinkmanı
A. Gute[5], J. Harmsen[3], R.
P. Kroll[14], E. Leader[7], B.
W. Meyer[3], N. Meyners[4],
L. Niedermeier[11], K. Ogar
K. Rith[5], D. Ryckbosch[6],
der Steenhoven[9], D. von F

Electron-ion collider projects and ILC

The EIC Science case: a report on the joint BNL/INT/JLab program

Gluons and the quark sea at high energies:
distributions, polarization, tomography

arXiv:1108.1713 (551 pages)

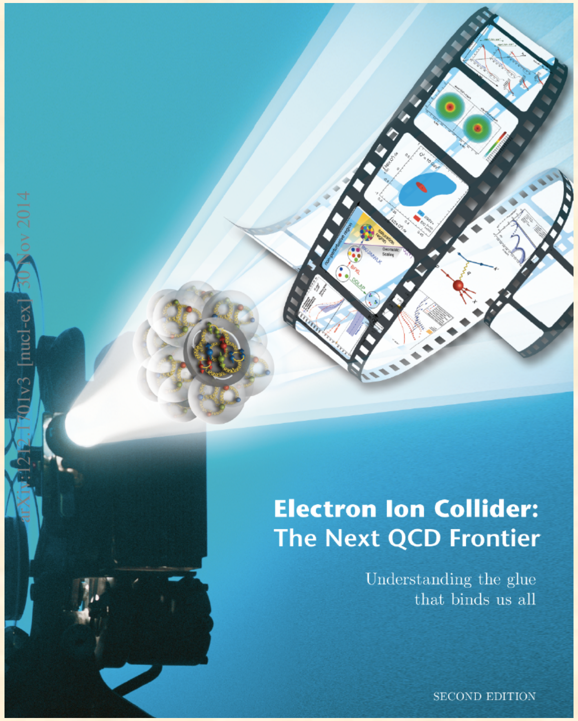
CERN

BNL

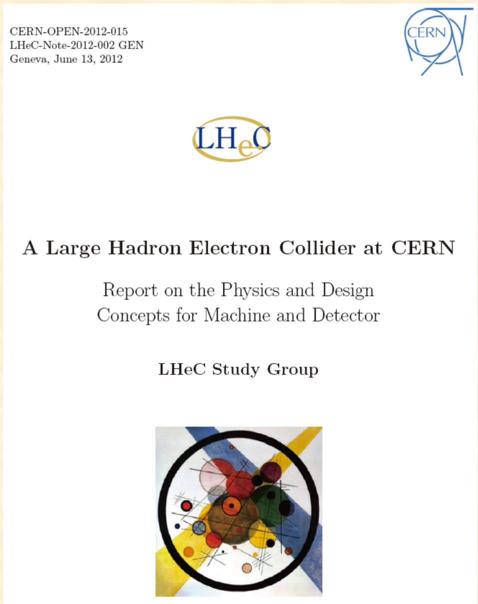
JLab

High Intensity Heavy Ion Accelerator Facility (HIAF)

arXiv:1212.1701 (180 pages)



J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001(632 pages)



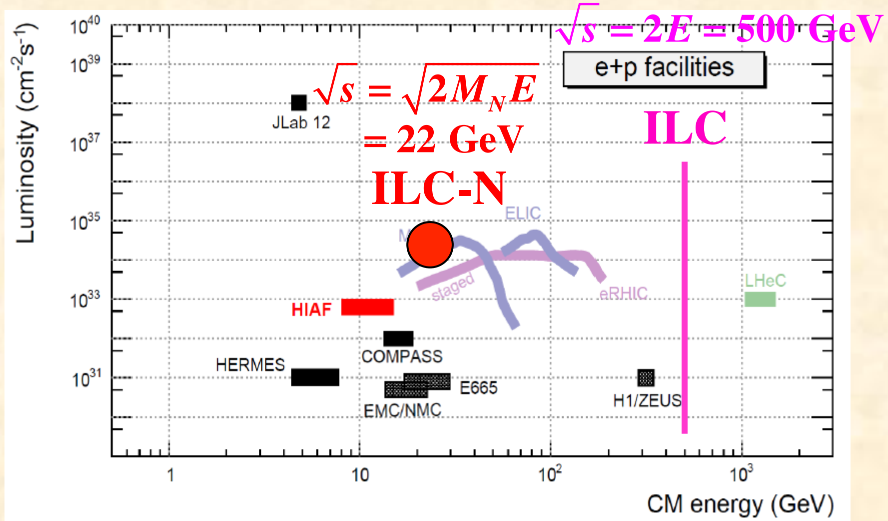
CERN-OPEN-2012-015
LHeC-Note-2012-002 GEN
Geneva, June 13, 2012

LHeC

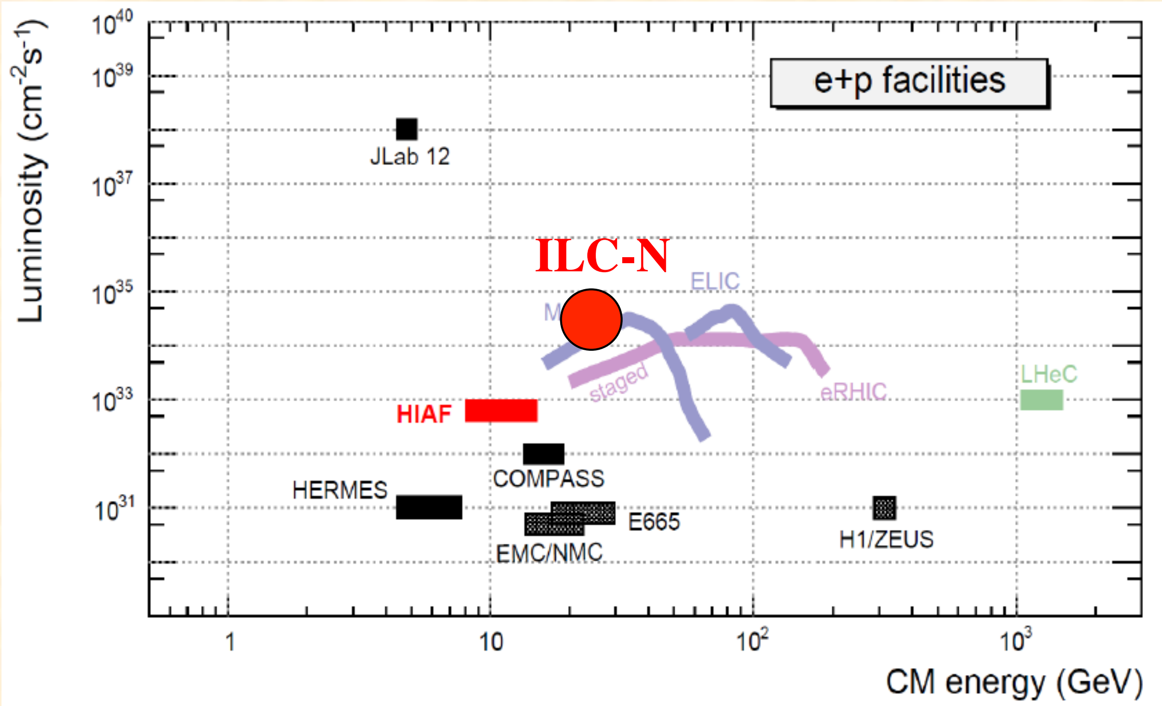
A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

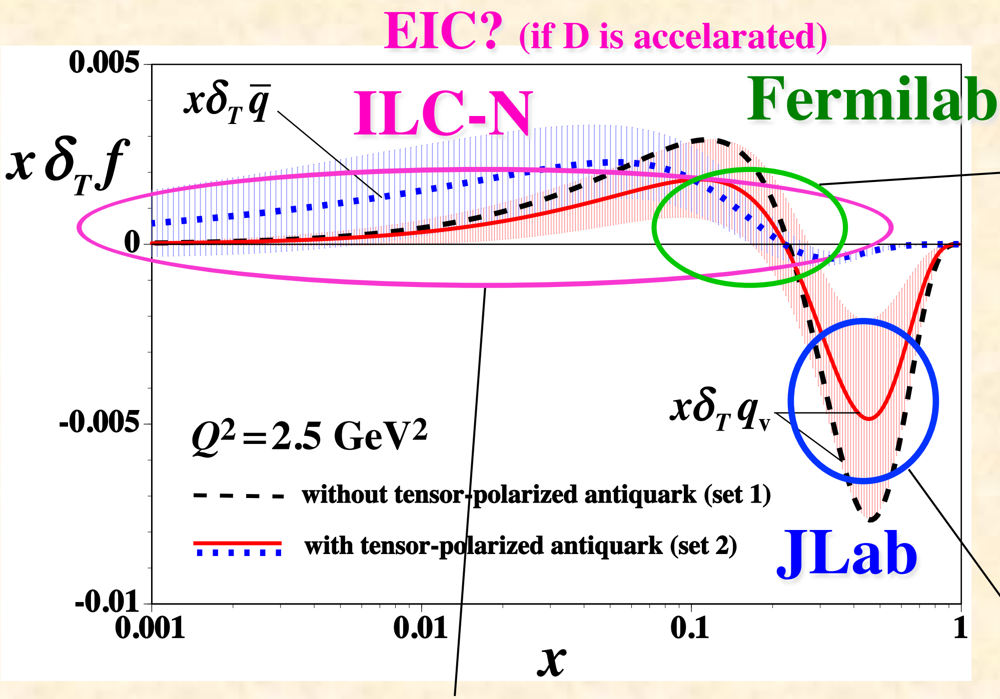
LHeC Study Group

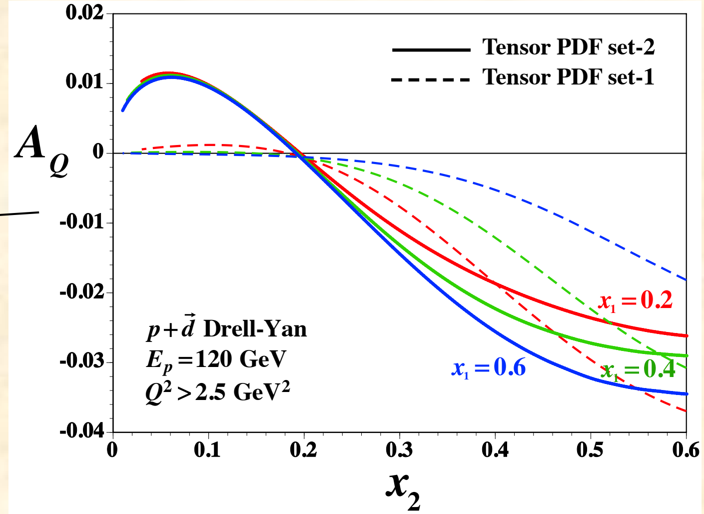


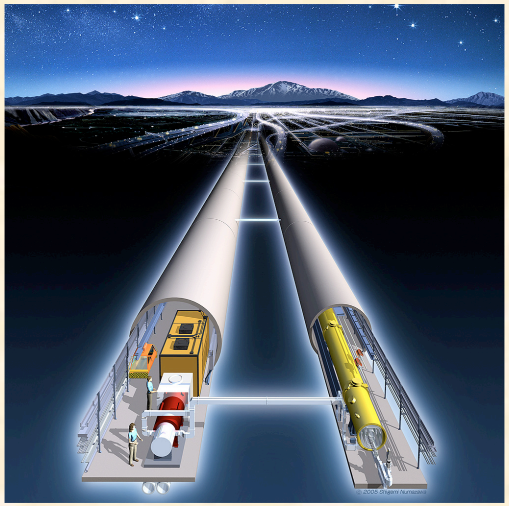
Possible ILC-N projects should be investigated beyond the line of TESLA-N and also beyond the COMPASS project.

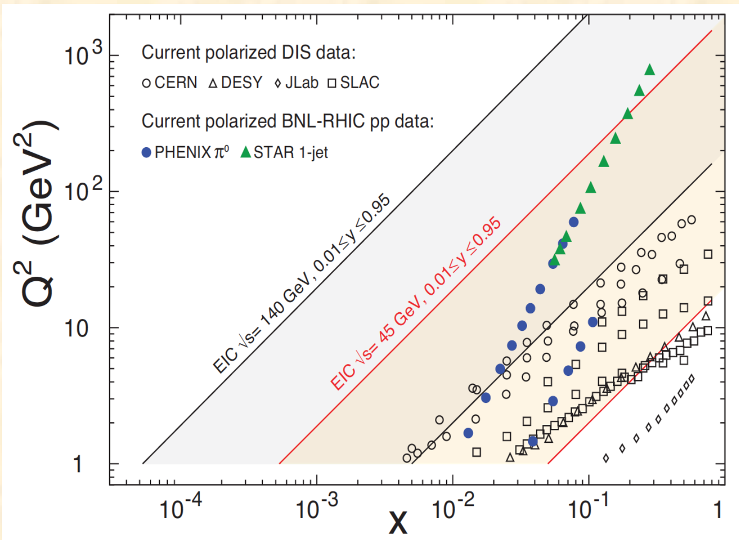


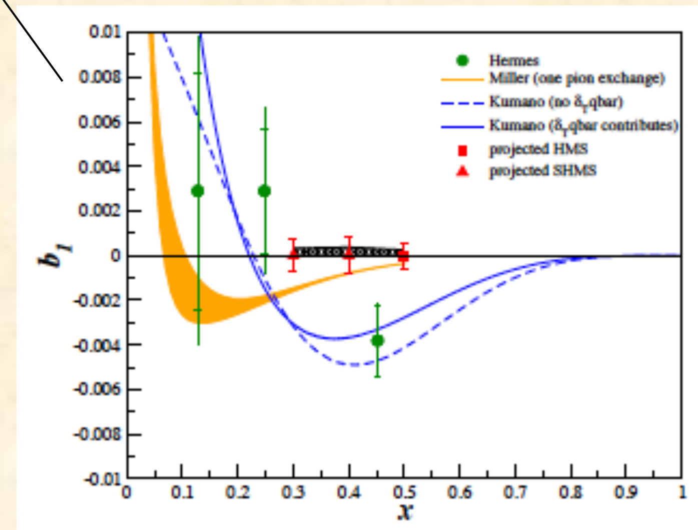
Small-x physics of b_1 at EIC











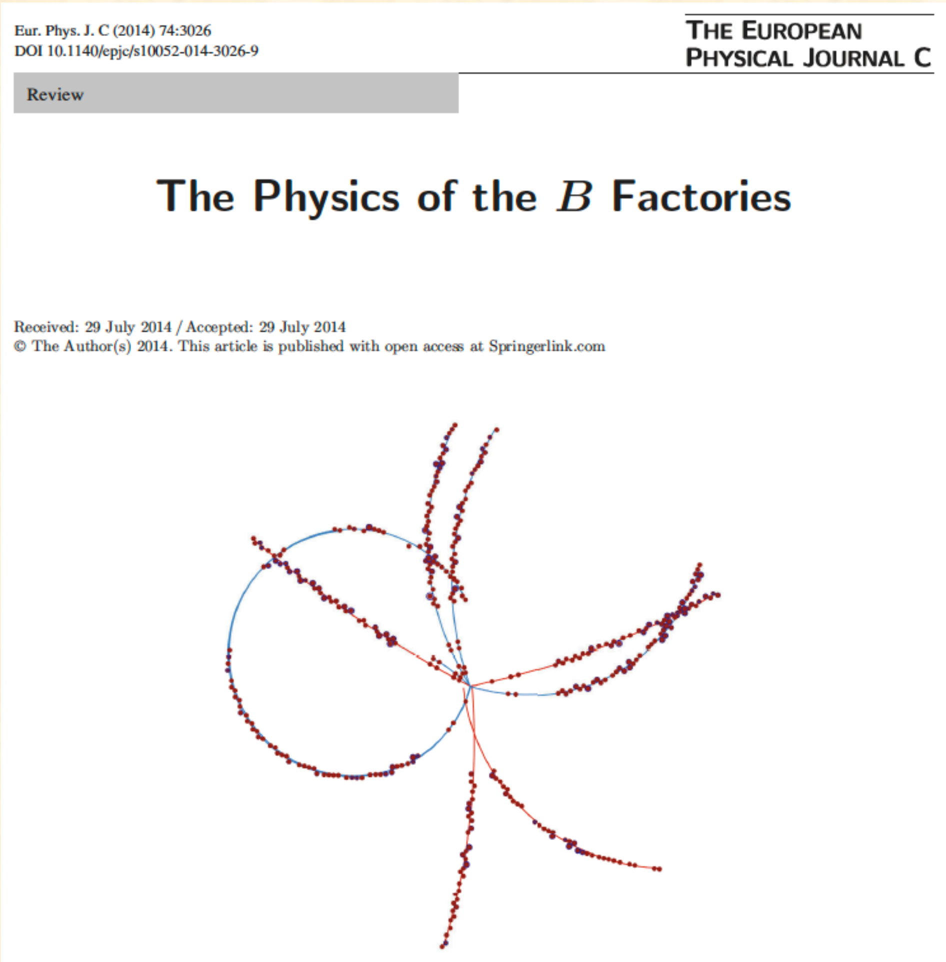
Possible ILC-N projects should be investigated
beyond the line of TESLA-N and also beyond
the COMPASS project.
→ under investigations •••

Note: The field of 3D structure functions of hadrons has been developed
after the TESLA-N project.
Please look at Miyachi's talk files (previous talk in this workshop)
for the details.

e^+e^- hadron physics at ILC

Hadron structure functions, Fragmentations functions at KEKB

The Physics of the B Factories,
A. V. Bevan *et al*. (S. Kumano 47th author)
Eur. Phys. J. C 74 (2014) 3026 (928 pages).


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

KEKB → ILC

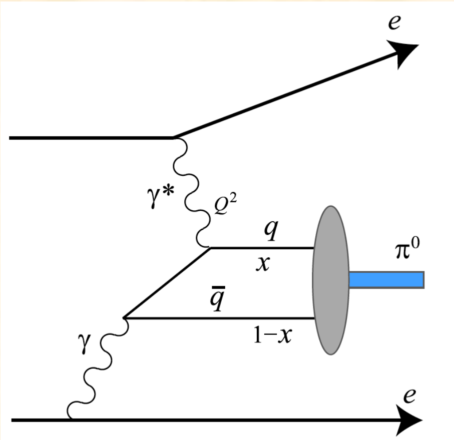
- Form factors in the asymptotic region
- Fragmentation functions at large Q^2
- Two-photon physics for hadron tomography
- Photon structure functions
- …

Form factors in the asymptotic region

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

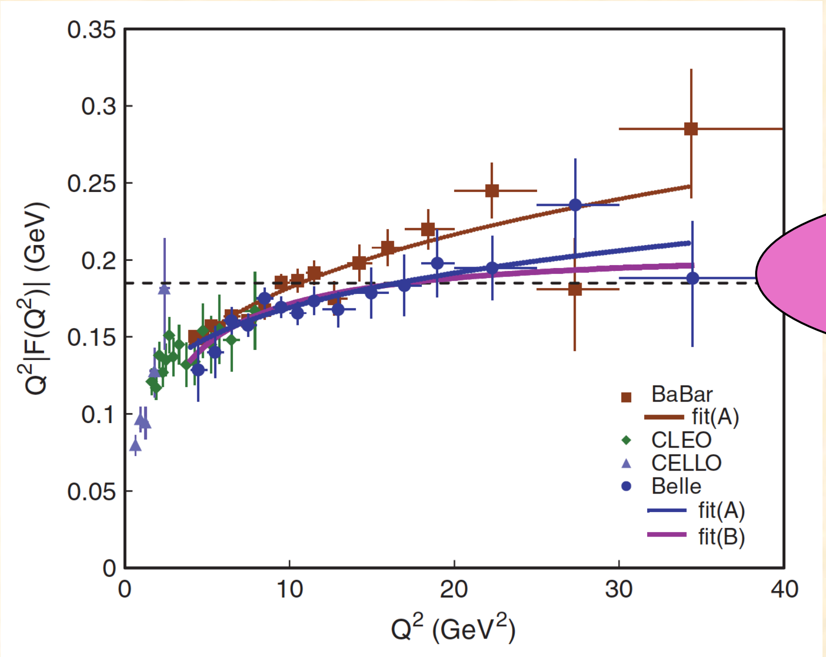
$\gamma + \gamma^* \to \pi^0$

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

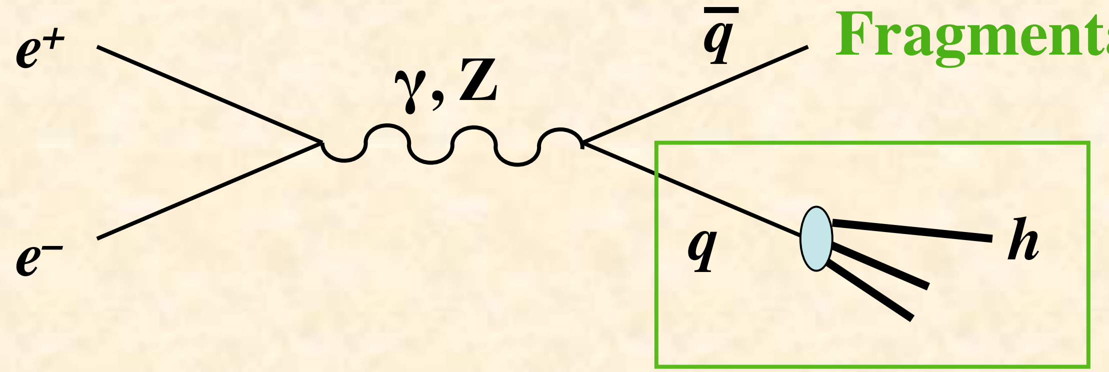


ILC

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



Fragmentation functions at large Q^2 @ILC



Fragmentation: hadron production from a quark, antiquark, or gluon

Fragmentation function is defined by

$$F^h(z,Q^2) = \frac{1}{\sigma_{tot}} \frac{d\sigma(e^+e^- \to hX)}{dz}$$

$$z \equiv \frac{E_h}{\sqrt{s}/2} = \frac{2E_h}{Q}$$ (Energy fraction = hadron energy scaled to the beam energy)

σ_{tot} = total hadronic cross section

$$= \sum_q \sigma_0^q(s) \left[1 + \frac{\alpha_s(s)}{\pi} \right]$$

$$\sigma_0^q(s) = \frac{4\pi\alpha^2}{s} \left[e_q^2 + (\gamma\text{-}Z \text{ interference}) + (Z \text{ term}) \right]$$

Theoretically $F^h(z,Q^2) = \sum_i \int_z^1 \frac{dy}{y} C_i\left(\frac{z}{y},Q^2\right) D_i^h(y,Q^2)$

Recent progress

N. Sato et al., PRD 94 (2016) 114004

First Monte Carlo analysis of fragmentation functions from single-inclusive e^+e^- annihilation

N. Sato,[1] J. J. Ethier,[2] W. Melnitchouk,[1] M. Hirai,[3] S. Kumano,[4,5] and A. Accardi[1,6]

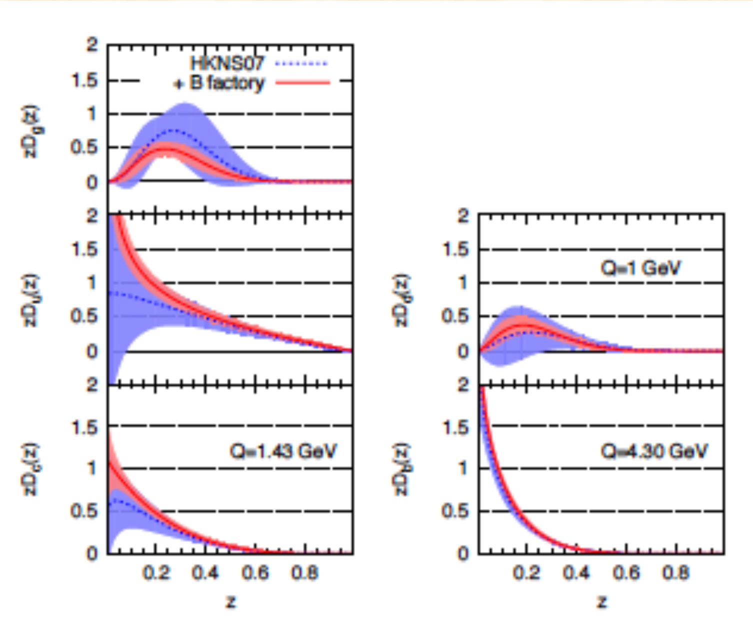
M. Hirai et al., PTEP 2016 (2016) 113B04

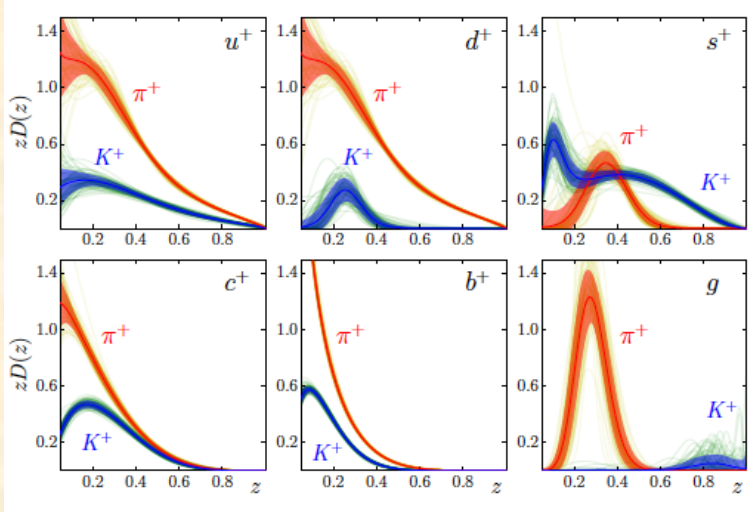
PTEP

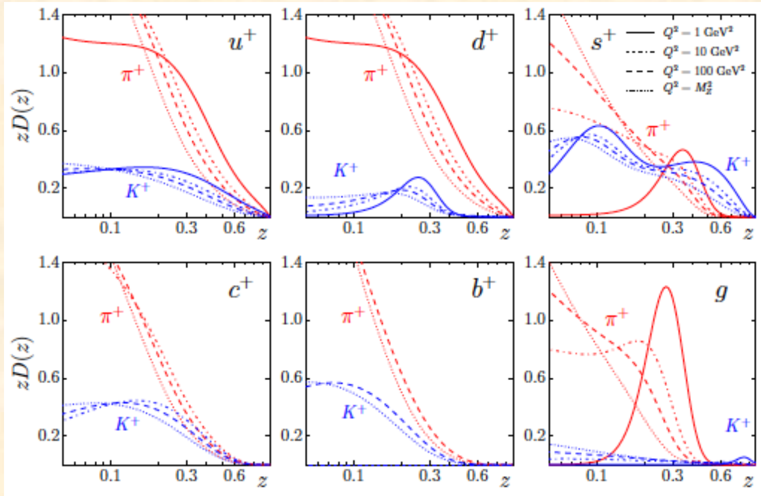
Prog. Theor. Exp. Phys. **2016**, 00000 (19 pages)
DOI: 10.1093/ptep/0000000000

Impacts of B-factory measurements on determination of fragmentation functions from electron-positron annihilation data

M. Hirai[1,2], H. Kawamura[3,4], S. Kumano[4,5], and K. Saito[2]

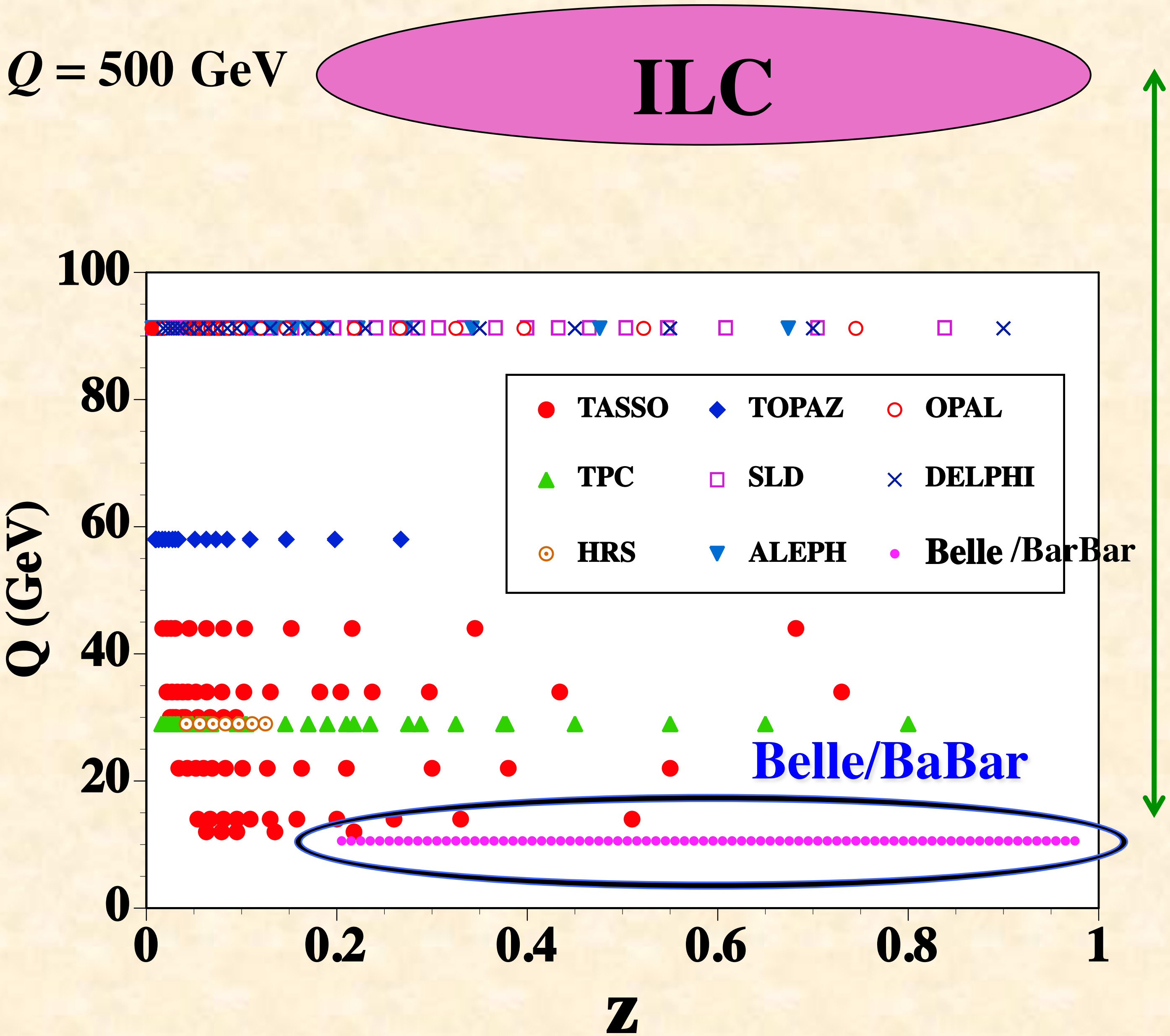




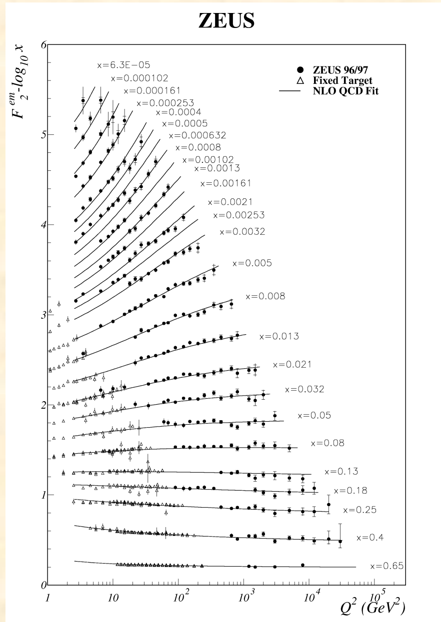


Fragmentation function measurements

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

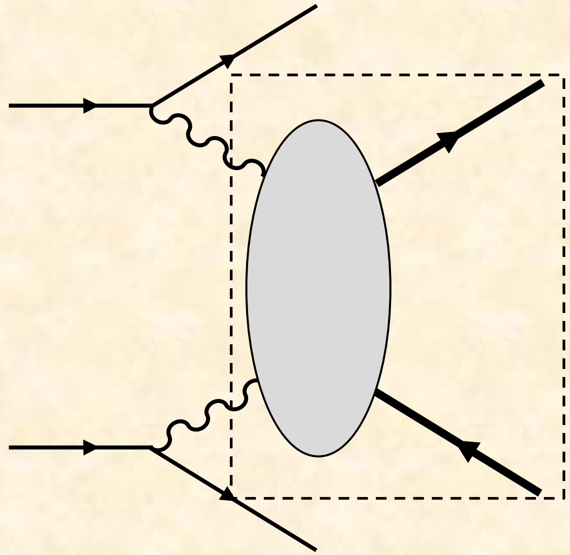


Scale evolution of D_i^h
→ gluon fragmentation function



Scale evolution of F_2
→ gluon distribution

Two-photon physics for hadron tomography



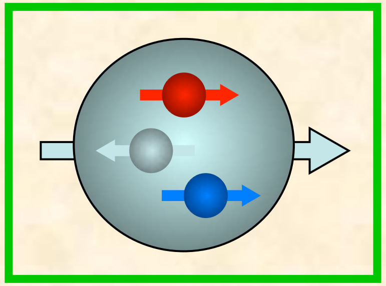
$$\gamma\gamma \to h\bar{h}$$

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

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

Recent progress on origin of nucleon spin

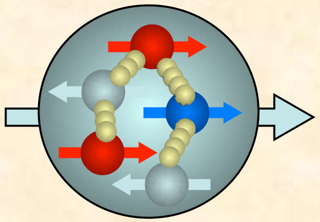
"old" standard model



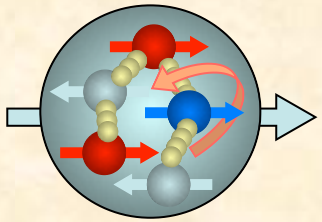
$$p_{\uparrow} = \frac{1}{3\sqrt{2}}\left(uud\left[2\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow\right] + \text{permutations}\right)$$

$$\Delta q(x) \equiv q_{\uparrow}(x) - q_{\downarrow}(x)$$

$$\Delta\Sigma = \sum_i \int dx\left[\Delta q_i(x) + \Delta\bar{q}_i(x)\right] \to 1\ (100\%)$$

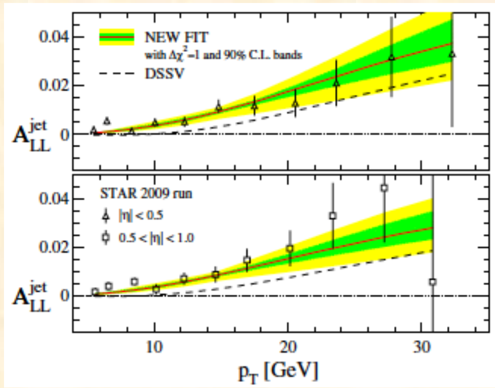


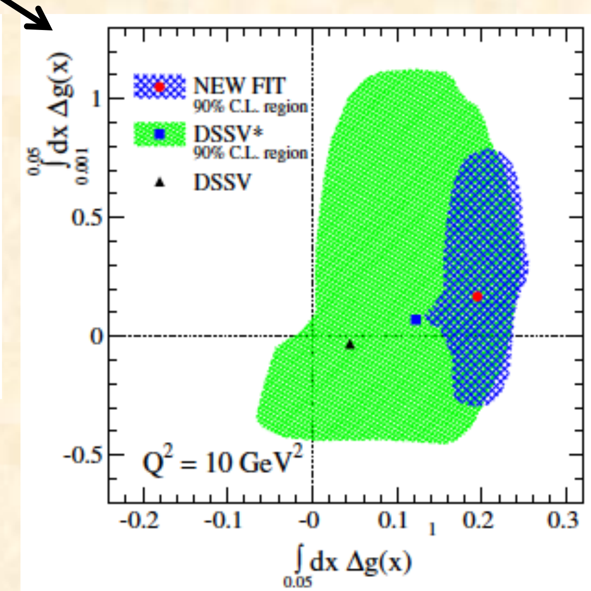
gluon spin



angular momentum

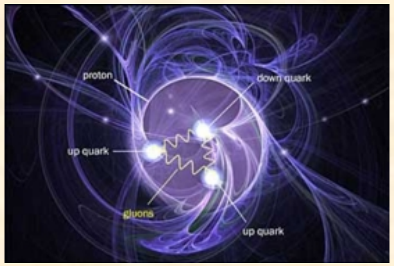
→ **next pages**





$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_{q,g}$$

CNN (2014)

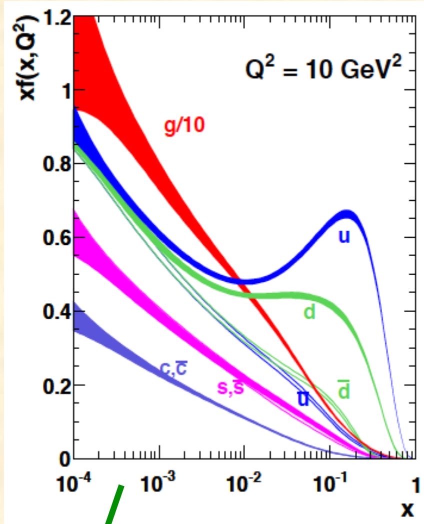


Scientific American (2014)

Wigner distribution and various structure functions

Wigner operator: $\hat{w}(k_+,\vec{k}_\perp,\vec{r}) \equiv \int d\xi\_ d^2\xi_\perp e^{i\left(\xi\_ k_+ - \vec{\xi}_\perp \cdot \vec{k}_\perp\right)} \bar{\psi}\left(\vec{r}-\vec{\xi}/2\right)\psi\left(\vec{r}+\vec{\xi}/2\right)$

Wigner distribution: $W(x,\vec{k}_\perp,\vec{r}) \equiv \int \frac{d^3q}{(2\pi)^3} \langle \vec{q}/2 | \hat{w}(\vec{r},k_+,\vec{k}_\perp) | -\vec{q}/2 \rangle, \quad x = k_+ / p_+$



Form factor

$\int dx\, d^2k_\perp$

PDF (Parton Distribution Function)

$\int d^2k_\perp d^3r$

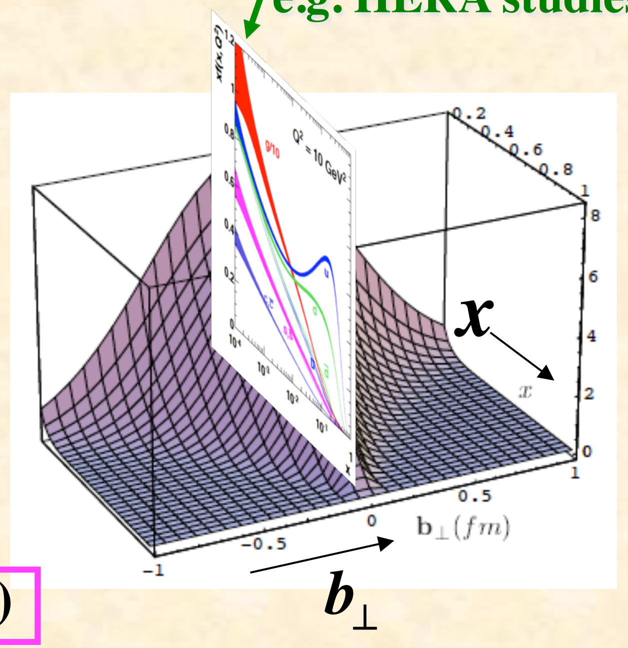
Wigner distribution $W(x,\vec{k}_\perp,\vec{r})$

e.g. HERA studies

3D world

$\int d^3r$

$\int d^2k_\perp dz$



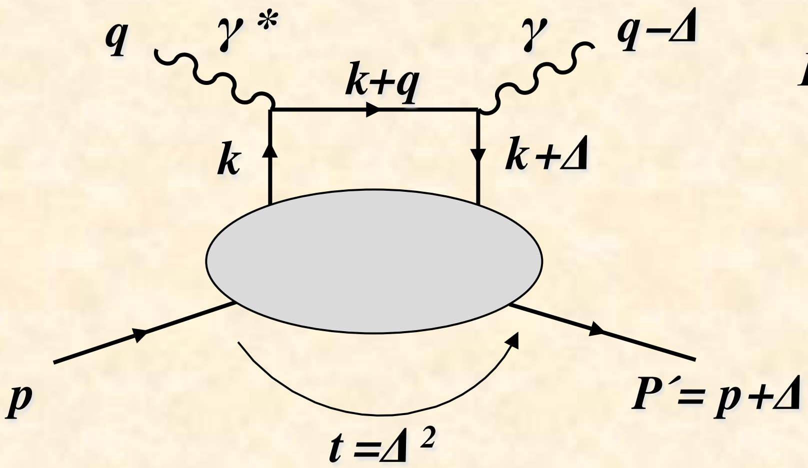
TMD (Transverse Momentum Dependent) parton distribution

GPD (Generalized Parton Distribution)

s-*t* crossing →

$\gamma\gamma \to h\bar{h}$ GDA (Generalized Distribution Amplitude)

Generalized Parton Distributions (GPDs)



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

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

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

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

GPDs are defined as correlation of off-forward matrix:

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p' | \bar{\psi}(-z/2)\gamma^+\psi(z/2) | p \rangle \Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[H(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E(x,\xi,t)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u(p)\right]$$

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p' | \bar{\psi}(-z/2)\gamma^+\gamma_5\psi(z/2) | p \rangle \Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[\tilde{H}(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}(x,\xi,t)\bar{u}(p')\frac{\gamma_5\Delta^+}{2M}u(p)\right]$$

Forward limit: PDFs

$$H(x,\xi,t)\big|_{\xi=t=0} = f(x), \quad \tilde{H}(x,\xi,t)\big|_{\xi=t=0} = \Delta f(x),$$

First moments: Form factors

Dirac and Pauli form factors F_1, F_2 $\quad \int_{-1}^{1} dx\, H(x,\xi,t) = F_1(t), \quad \int_{-1}^{1} dx\, E(x,\xi,t) = F_2(t)$

Axial and Pseudoscalar form factors G_A, G_P $\quad \int_{-1}^{1} dx\, \tilde{H}(x,\xi,t) = g_A(t), \quad \int_{-1}^{1} dx\, \tilde{E}(x,\xi,t) = g_P(t)$

Second moments: Angular momenta

Sum rule: $J_q = \dfrac{1}{2}\int_{-1}^{1} dx\, x\left[H_q(x,\xi,t=0) + E_q(x,\xi,t=0)\right], \quad J_q = \dfrac{1}{2}\Delta q + L_q$

Progress in exotic hadrons

$q\bar{q}$ Meson
q^3 Baryon

$q^2\bar{q}^2$ Tetraquark
$q^4\bar{q}$ Pentaquark
q^6 Dibaryon
…
$q^{10}\bar{q}$ e.g. Strange tribaryon
…
gg Glueball
…

- Θ^+(1540)???: LEPS
  Pentaquark?
  $uudd\bar{s}$?
- Kaonic nuclei?: KEK-PS, …
  Strange tribaryons, …
  $K^- pnn$, $K^- ppn$?
  $K^- pp$?
- X (3872), Y(3940): Belle
  Tetraquark, $D\bar{D}$ molecule
  $c\bar{c}$
  $D^0(c\bar{u})\bar{D}^0(\bar{c}u)$
  $D^+(c\bar{d})D^-(\bar{c}d)$?
- D_{sJ}(2317), D_{sJ}(2460): BaBar, CLEO, Belle
  Tetraquark, DK molecule
  $c\bar{s}$
  $D^0(c\bar{u})K^+(u\bar{s})$
  $D^+(c\bar{d})K^0(d\bar{s})$?
- Z (4430): Belle
  Tetraquark, …
  $c\bar{c}u\bar{d}$, D molecule?
- P_c (4380), P_c (4450): LHCb
  $u\bar{c}udc$, $\bar{D}(u\bar{c})\Sigma_c^*(udc)$, $\bar{D}^*(u\bar{c})\Sigma_c(udc)$ molecule?
- …

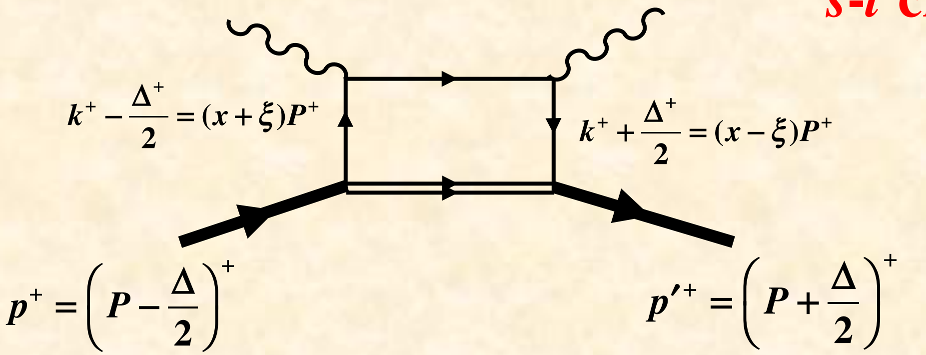
GPD $H_q^h(x,\xi,t)$ and GDA $\Phi_q^{h\bar{h}}(z,\zeta,W^2)$

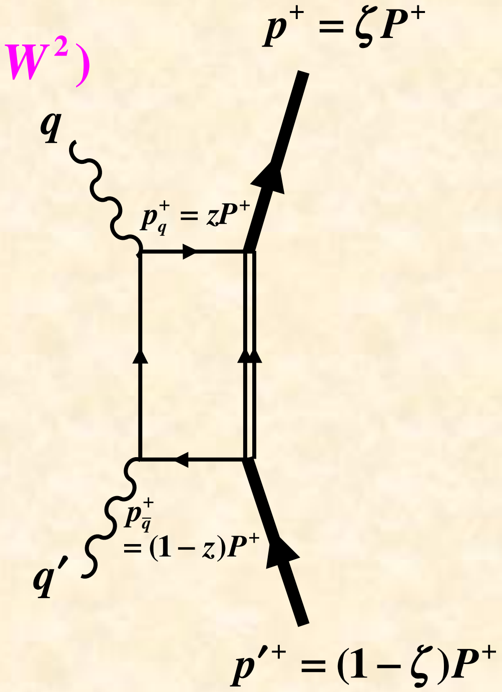
GPD: $H_q(x,\xi,t) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle h(p')|\bar{\psi}(-y/2)\gamma^+\psi(y/2)|h(p)\rangle\Big|_{y^+=0,\vec{y}_\perp=0}$, $P^+ = \frac{(p+p')^+}{2}$

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

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

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





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

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

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

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

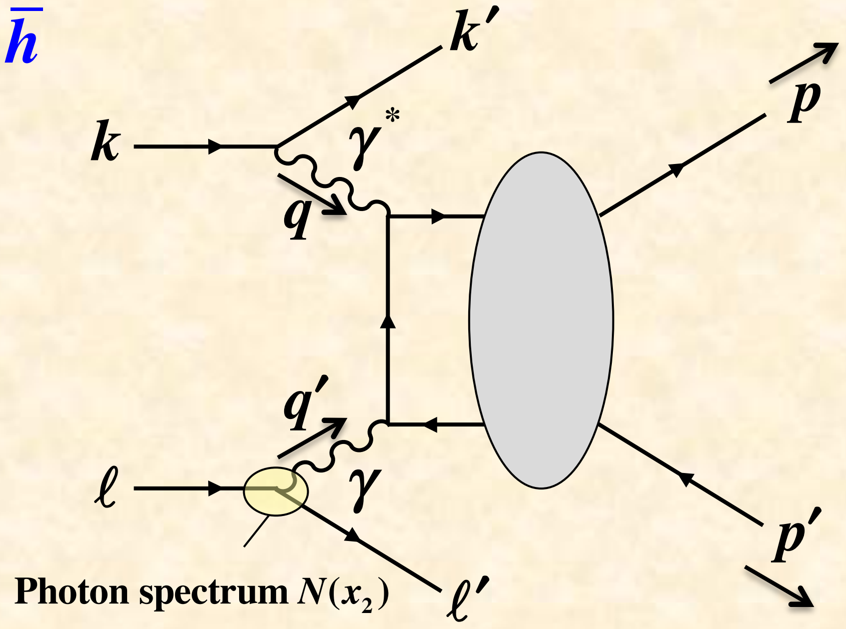
Bjorken variable for $\gamma\gamma^*$: $z = \frac{Q^2}{2q\cdot q'}$

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 for $e^+ + e^- \to e^+ + e^- + h + \bar{h}$

$$\frac{d\sigma_{ee\to ee\pi\pi}}{dQ^2 dW^2 d(\cos\theta) d\phi dx_2} = N(x_2) \frac{d\sigma_{e\gamma\to e\pi\pi}}{dQ^2 dW^2 d(\cos\theta) d\phi}, \quad x_2 = \frac{s_{e\gamma}}{s_{ee}}$$



Cross section for $e + \gamma \to e' + h + \bar{h}$

$$d\sigma = \frac{1}{4\sqrt{(k\cdot q')^2 - k^2 q'^2}} \overline{\sum_{\lambda_\gamma, \lambda_e, \lambda'_e}} \left| M(e\gamma \to e' h\bar{h}) \right|^2 d\Phi_3$$

$$M(e\gamma \to e' h\bar{h}) = \bar{u}(k')(ie\gamma^\mu) u(k) \frac{ig^{\mu\nu}}{q^2} T_{\nu\rho} \varepsilon^\rho(q')$$

$$T_{\mu\nu} = i\int d^4\xi \, e^{-i\xi\cdot q} \left\langle h(p)\bar{h}(p') \right| T J^{em}_\mu(\xi) J^{em}_\nu(0) \left| 0 \right\rangle = -g_{T\,\mu\nu} e^2 \sum_q \frac{e_q^2}{2} \int_0^1 dz \frac{2z-1}{z(1-z)} \Phi_q^{\pi\pi}(z,\zeta,W^2)$$

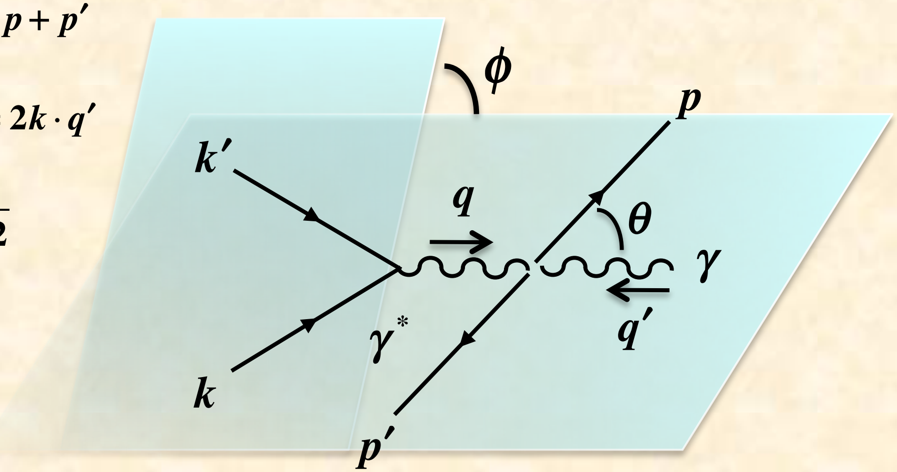
$$\Phi_q^{h\bar{h}}(z,\zeta,W^2) = \int \frac{dx^-}{2\pi} e^{-izP^+x^-} \left\langle h(p)\bar{h}(p') \right| \bar{q}(x^-)\gamma^+ q(0) \left| 0 \right\rangle_{x^+=0, \vec{x}_\perp=0}, \quad P = p + p'$$

$$\frac{d\sigma_{e\gamma\to e\pi\pi}}{dQ^2 dW^2 d(\cos\theta) d\phi} = \frac{\alpha^3}{16\pi} \frac{\beta}{s_{e\gamma}^2} \frac{1}{Q^2(1-\ \varepsilon)} \left| A_{(+,+)}(\zeta, W^2) \right|^2, \quad s_{e\gamma} = (k+q')^2 = 2k\cdot q'$$

longitudinal-transverse polarization ratio of γ^*: $\varepsilon = \dfrac{1-y}{1-y+y^2/2}$

$$A_{(+,+)} = \varepsilon_\mu^{(+)}(q) \varepsilon_\nu^{(+)}(q') T^{\mu\nu} / e^2 = \sum_q \frac{e_q^2}{2} \int_0^1 dz \frac{2z-1}{z(1-z)} \Phi_q^{hh}(z,\zeta,W^2)$$

A simple form: $\Phi_q^{h\bar{h}}(z,\zeta,W^2) = N_h z^\alpha (1-z)^\beta (2z-1)\zeta(1-\zeta) F_{h(q)}(s)$



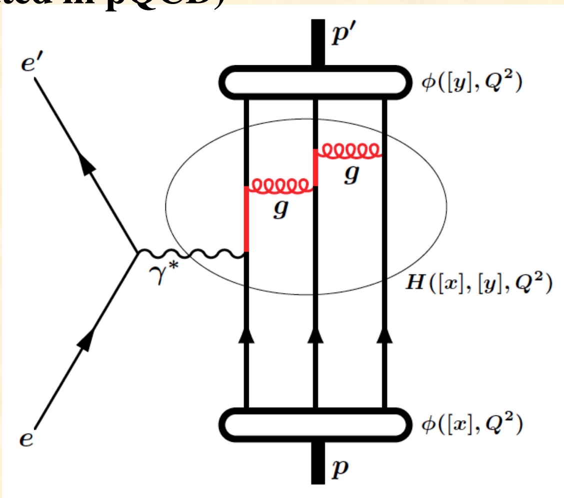
Constituent-counting rule in perturbative QCD: Form factor

Consider the magnetic form factor of the proton

$$\langle p' | J^\mu | p \rangle \simeq \bar{u}(p')\gamma^\mu G_M(Q^2) u(p) \text{ at } Q^2 = -q^2 \gg m_N^2$$

$$G_M(Q^2) = \int d[x]d[y]\phi_p([y]) H_M([x],[y],Q^2)\phi_p([x])$$

ϕ_p = proton distribution amplitude, H_M = hard amplitude (calculated in pQCD)



In the Breit frame with $q = (0, \vec{q})$, $|\vec{p}| = |\vec{p}'| \equiv P \sim O(Q)$.

$u^\dagger u = 2E \Rightarrow$ External quark line: $u \sim \sqrt{P} \sim \sqrt{Q}$

$$\langle p' | J^\mu | p \rangle \simeq \bar{u}(p')\gamma^\mu G_M(Q^2) u(p) \sim (\sqrt{Q})^2 G_M(Q^2)$$

- Two quark propagators: $\dfrac{1}{Q^2}$
- Two gluon propagators: $\dfrac{1}{(Q^2)^2}$
- Six external quark lines: $(\sqrt{Q})^6$

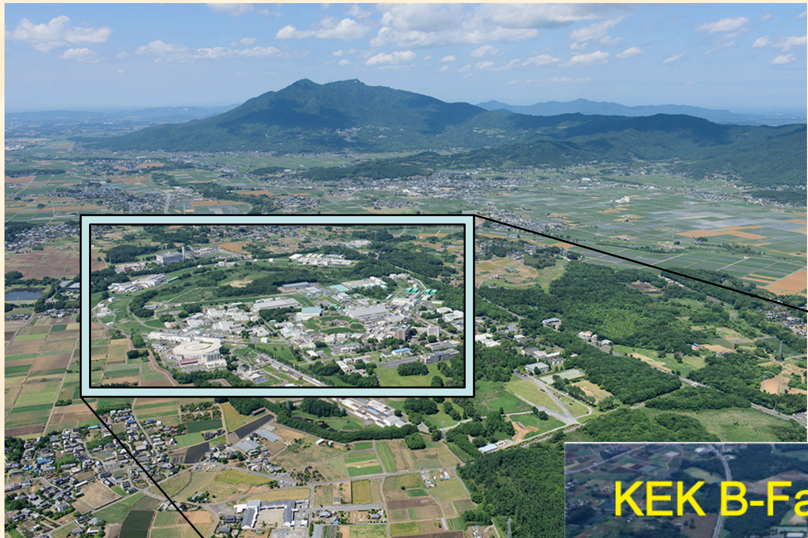
$$\langle p' | J^\mu | p \rangle \sim \frac{1}{Q^2}\frac{\alpha_s(Q^2)}{(Q^2)^2}(\sqrt{Q})^6 = \frac{\alpha_s(Q^2)}{(Q^2)^{3/2}}$$

$$\Rightarrow G_M(Q^2) \sim \frac{1}{(\sqrt{Q})^2}\langle p' | J^\mu | p \rangle \sim \frac{1}{(Q^2)^{1/2}}\frac{\alpha_s(Q^2)}{(Q^2)^{3/2}} = \frac{\alpha_s(Q^2)}{(Q^2)^2} \sim \frac{1}{t^{n_N-1}}, \quad n_N = 3, \quad -t = Q^2$$

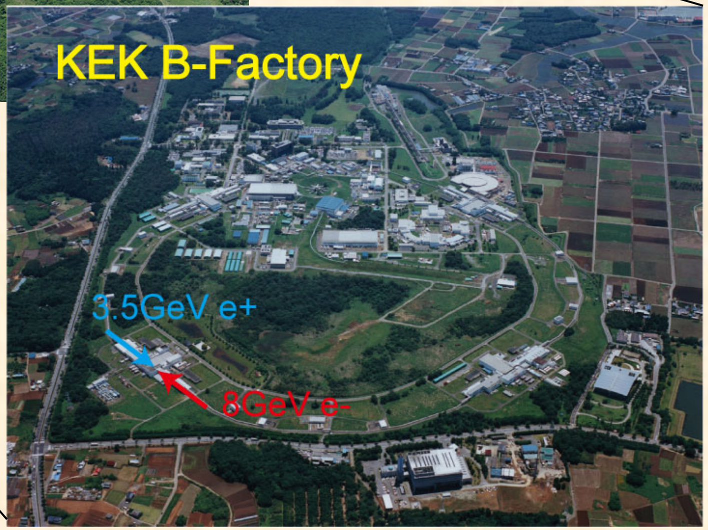
Counting rule for the form factor: $G_M(Q^2) \sim \dfrac{1}{t^{n_N-1}}$, $n_N = 3$

Experimental studies of GDAs in future

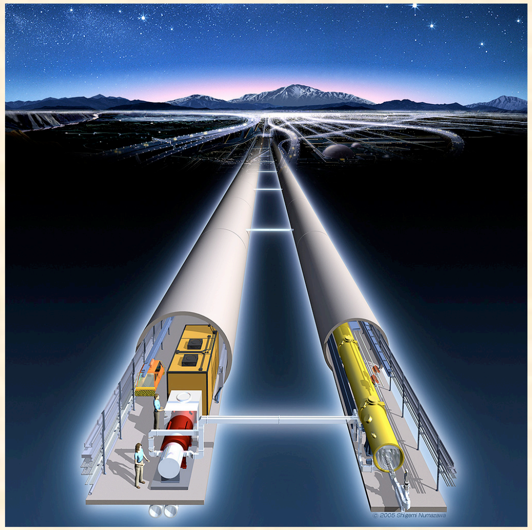
$\gamma\gamma \to h\bar{h}$ for internal structure of exotic hadron candidate h



KEK B-factory



Linear Collider ?



Cross section: form factor dependence

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

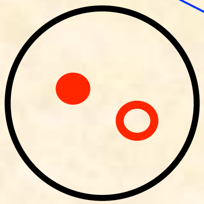
$$F_h(W^2) = \frac{1}{\left[1+(W^2-4m_h^2)/\Lambda^2\right]^{n-1}}$$

Constituent-counting rule

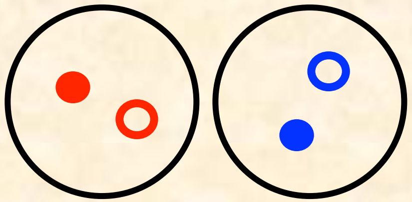
$n = 2$: ordinary meson

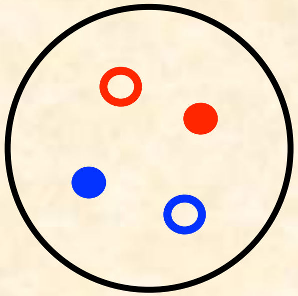
$n = 4$: molecule or tetra-quark

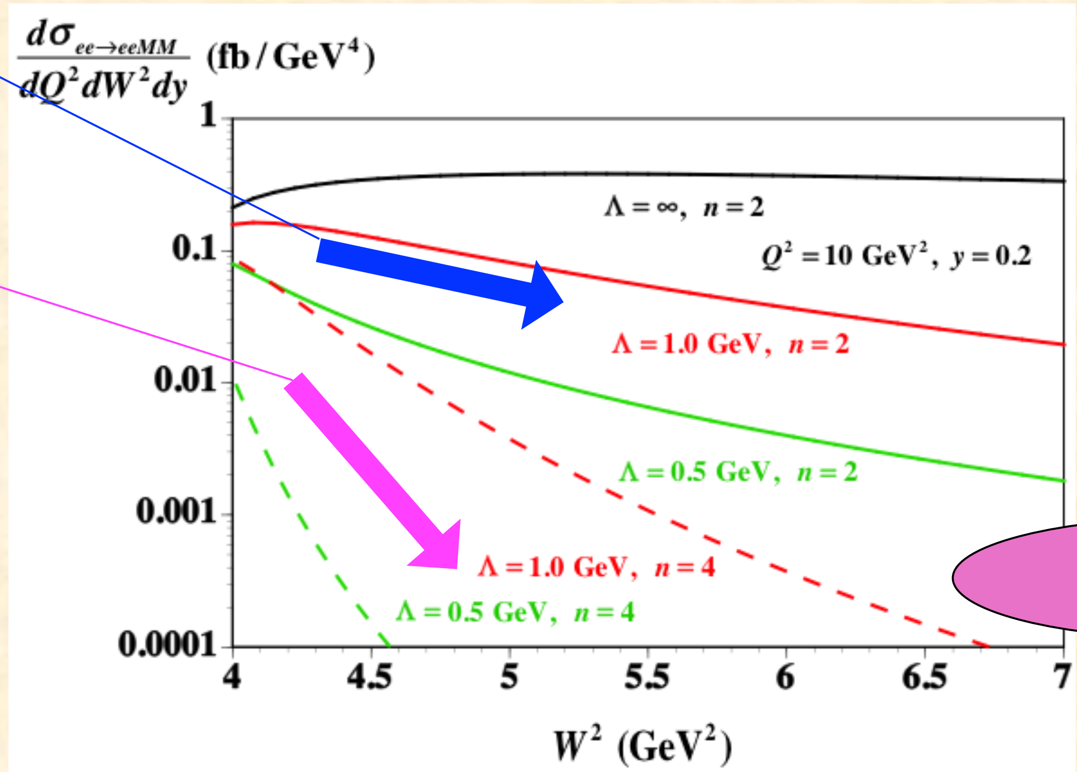
Ordinary $q\bar{q}$



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



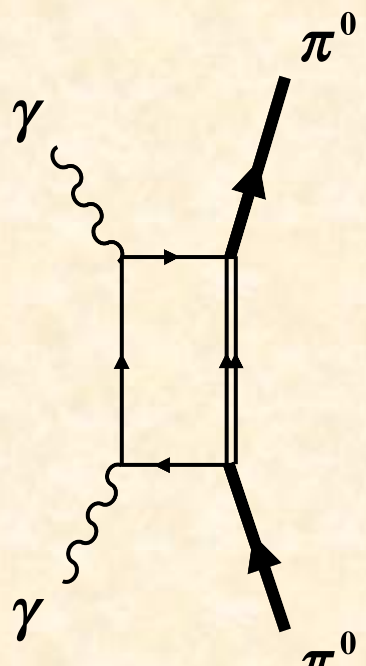


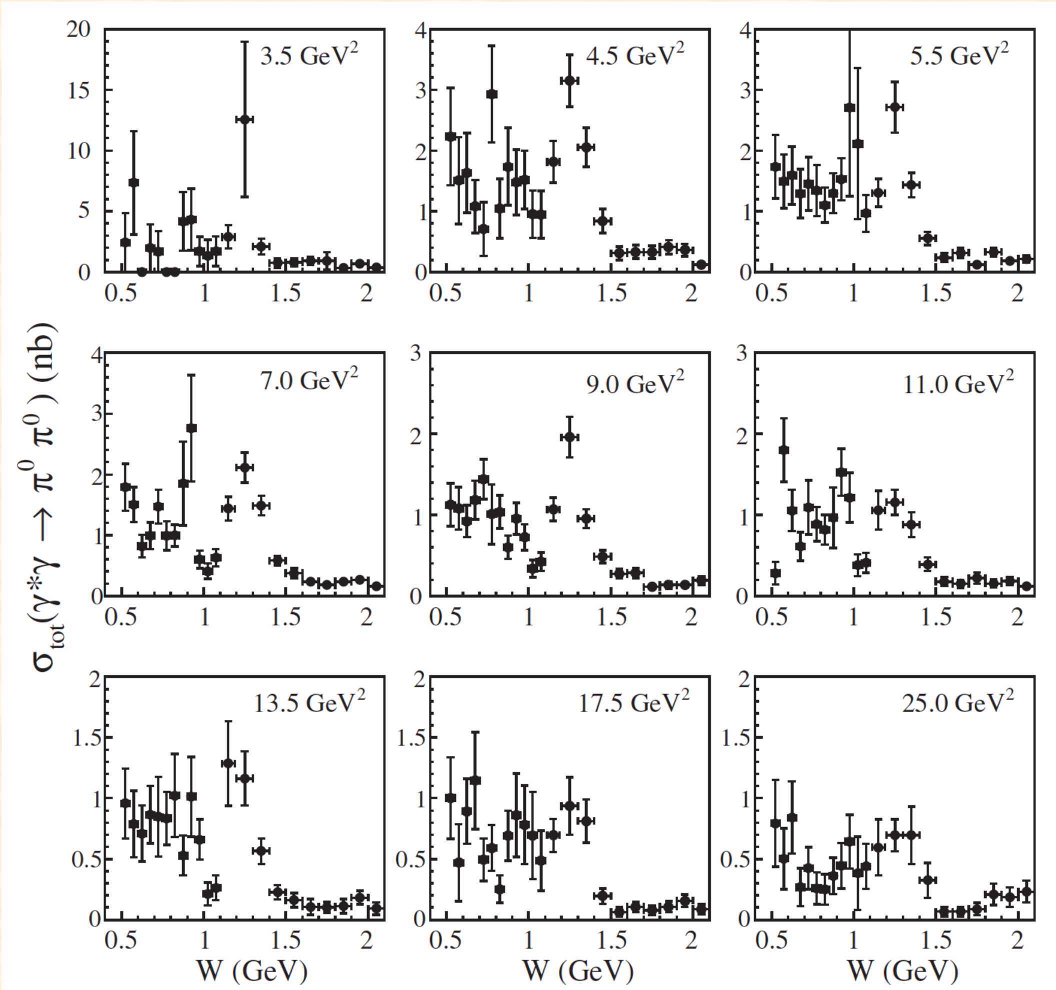


ILC

KEKB-Belle measurement (2016)

M. Masuda *et al.*, Phys. Rev. D 93 (2016) 032003 (arXiv:1508.06757).





ILC

- **Very Large Q^2**
- **Large W^2**

for extracting GDAs

Photon structure functions

Summary

- e^+e^+ hadron physics $\rightarrow$ unique opportunities to hadron-structure physics
  in the perturbative region, hadron tomography,
  exotic hadron structure, fragmentation functions, $\cdots$

- ILC-N hadron physics $\rightarrow$ still investigate uniqueness beyond the TESLA-N
  and COMPASS projects, although more precisions
  are expected than COMPASS measurements.

The End

The End