Probing the Proton's Quark Dynamics in Semi-Inclusive Pion and Kaon electroproduction with CLAS12 at JLab

Giovanni Angelini

LNF - July 11, 2018

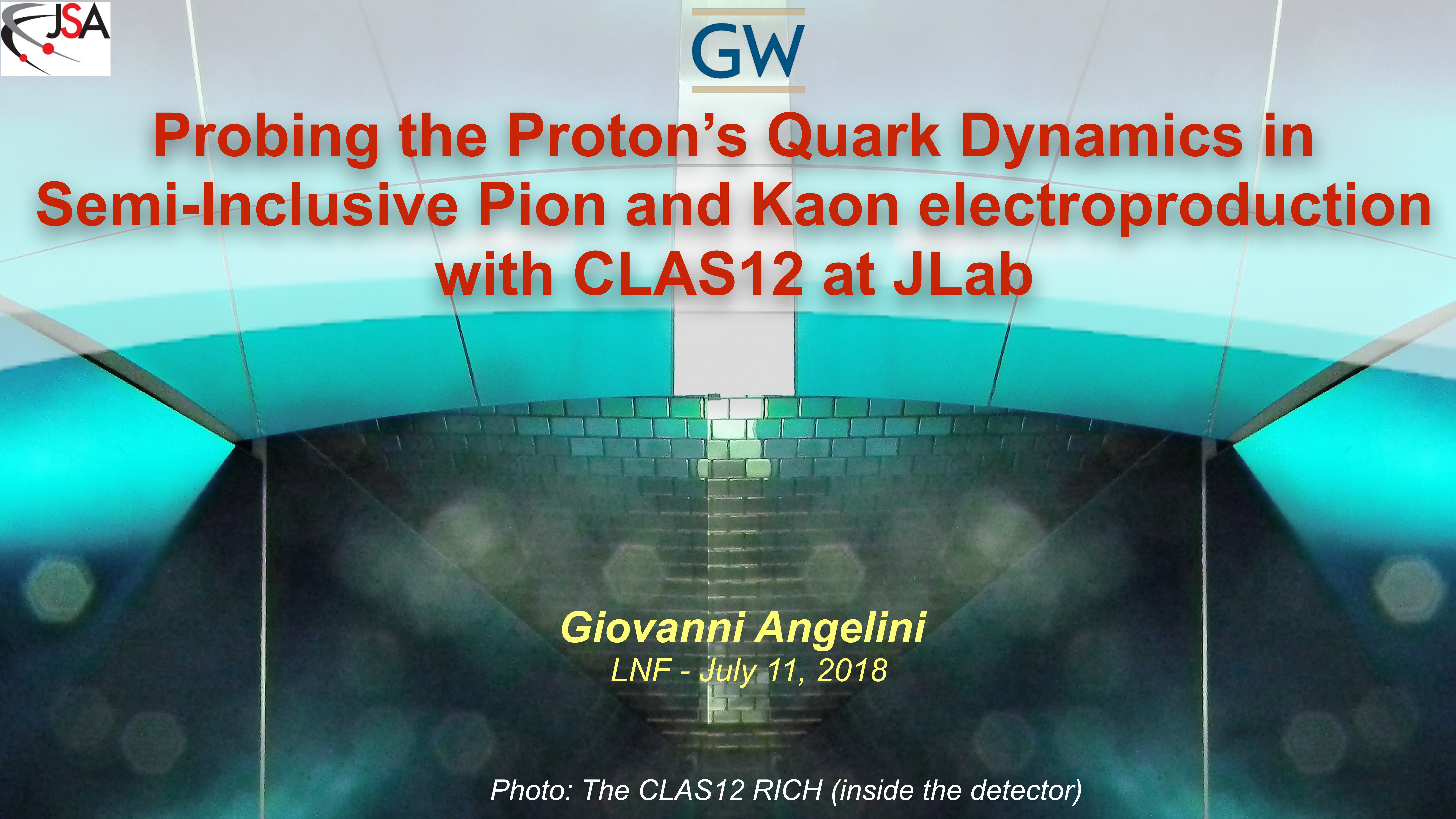


Photo: The CLAS12 RICH (inside the detector)

Outline

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Deep-Inelastic Scattering & SIDIS: A theoretical Overview

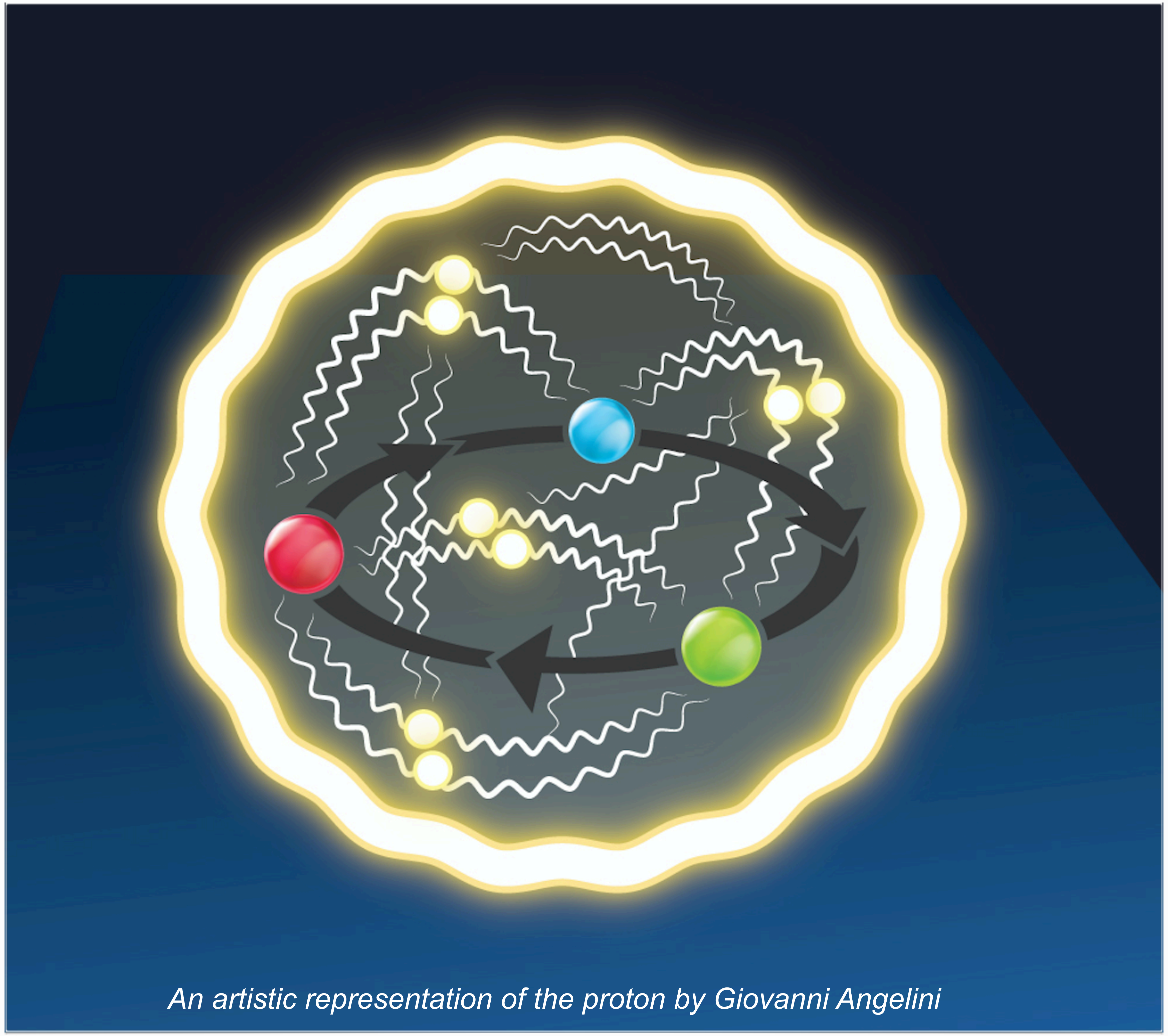
Connect the Structure Functions to the proton inner dynamics

CLAS12: The detector and its capability

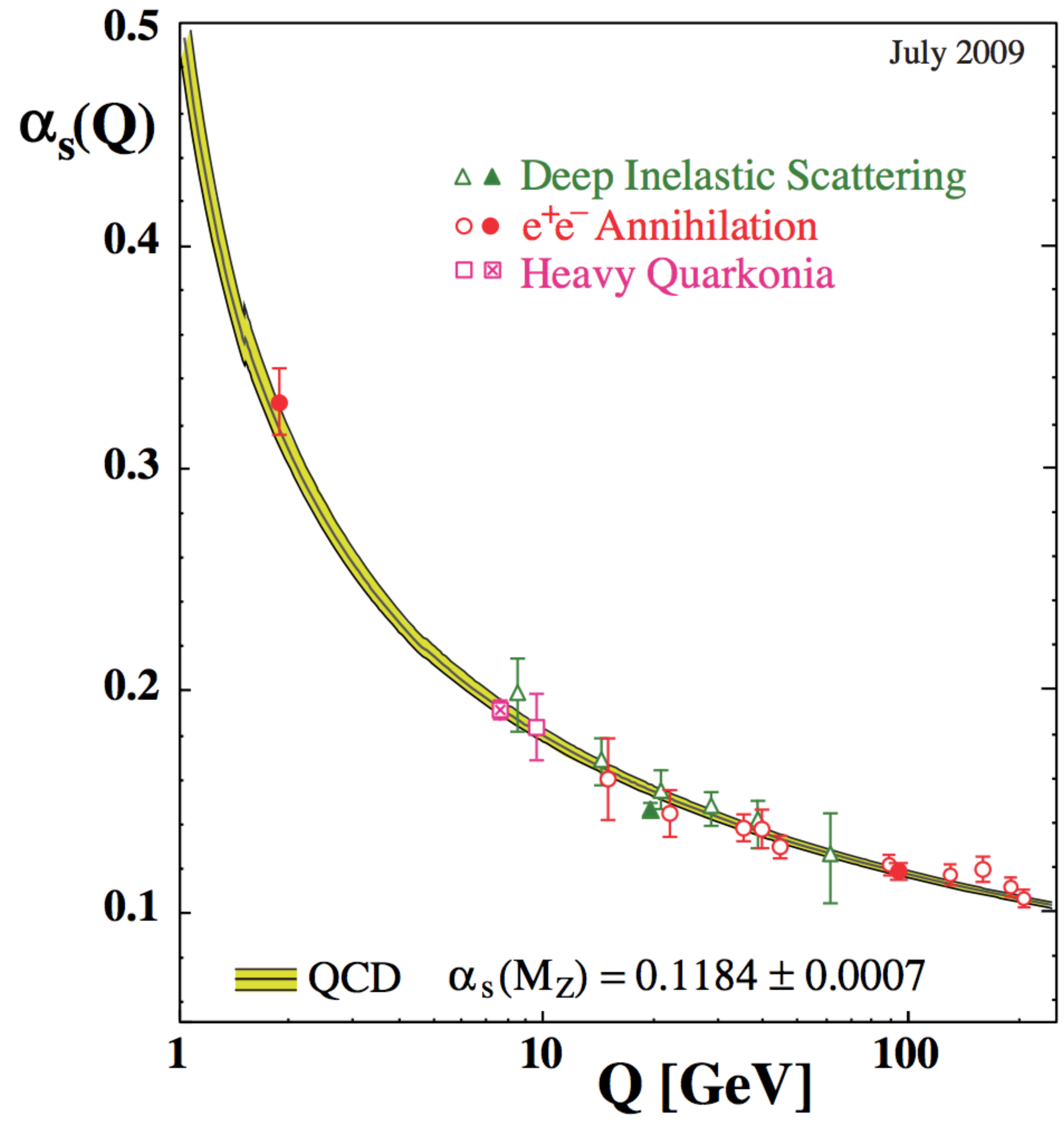
The PID and the CLAS12 RICH: an INFN project

Expected results: pion and kaon electroproduction from unpolarized hydrogen target.

The structure of the Proton



An artistic representation of the proton by Giovanni Angelini

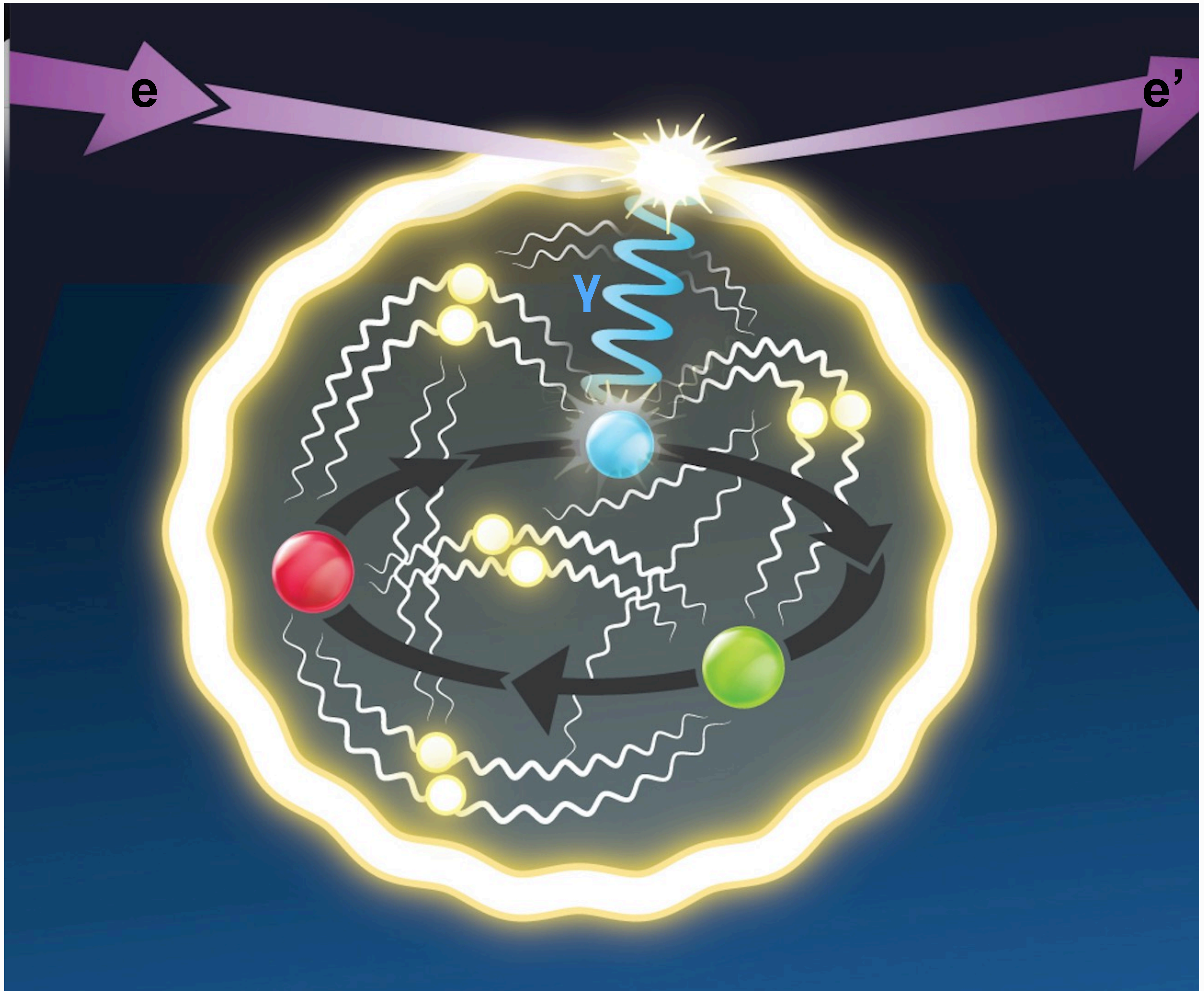


PDG

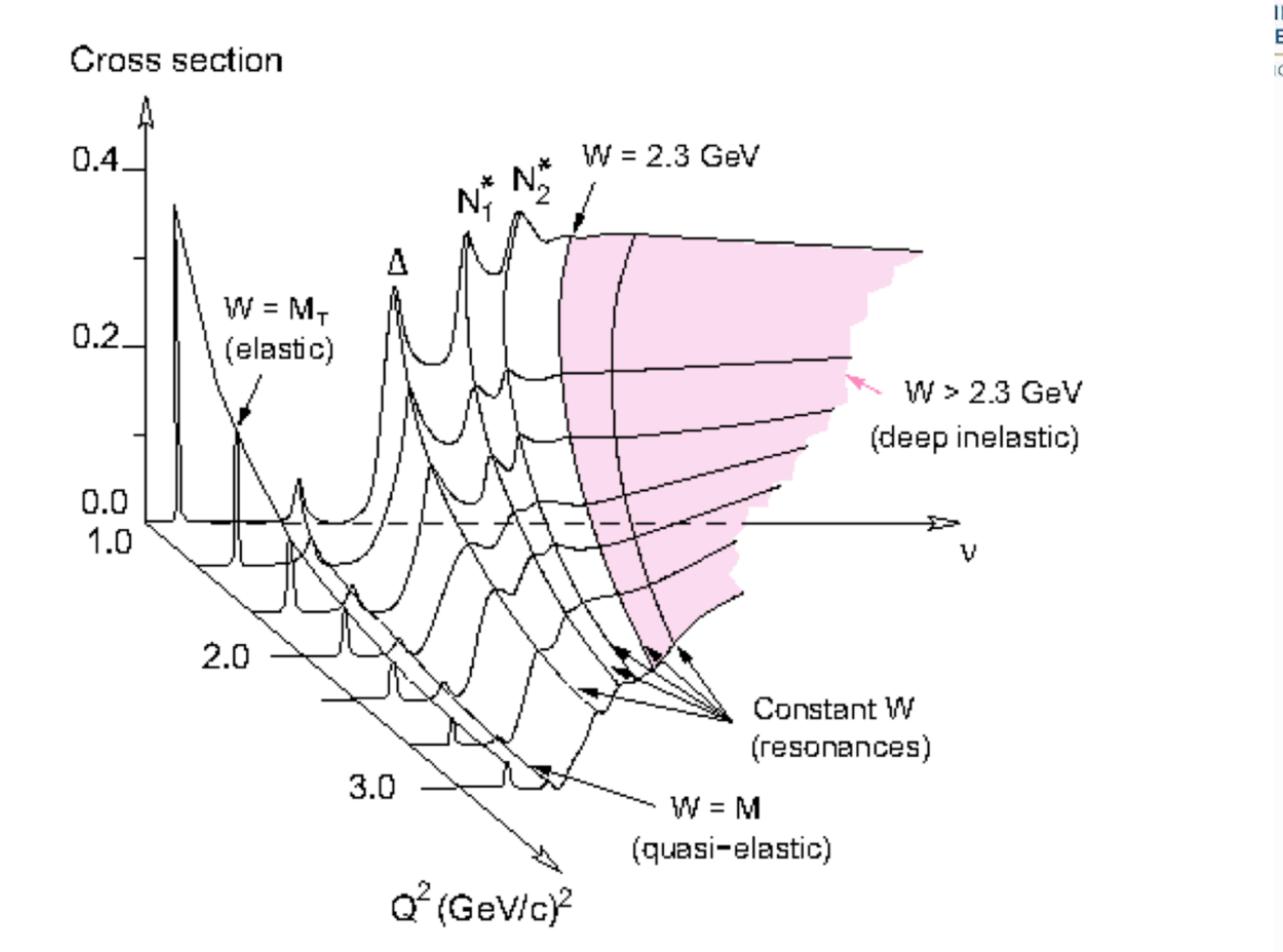
Challenges:

- **Radius**
- **Mass**
- **Spin**

Proton structure & Deep Inelastic Scattering



An artistic representation of the ep scattering by Giovanni Angelini



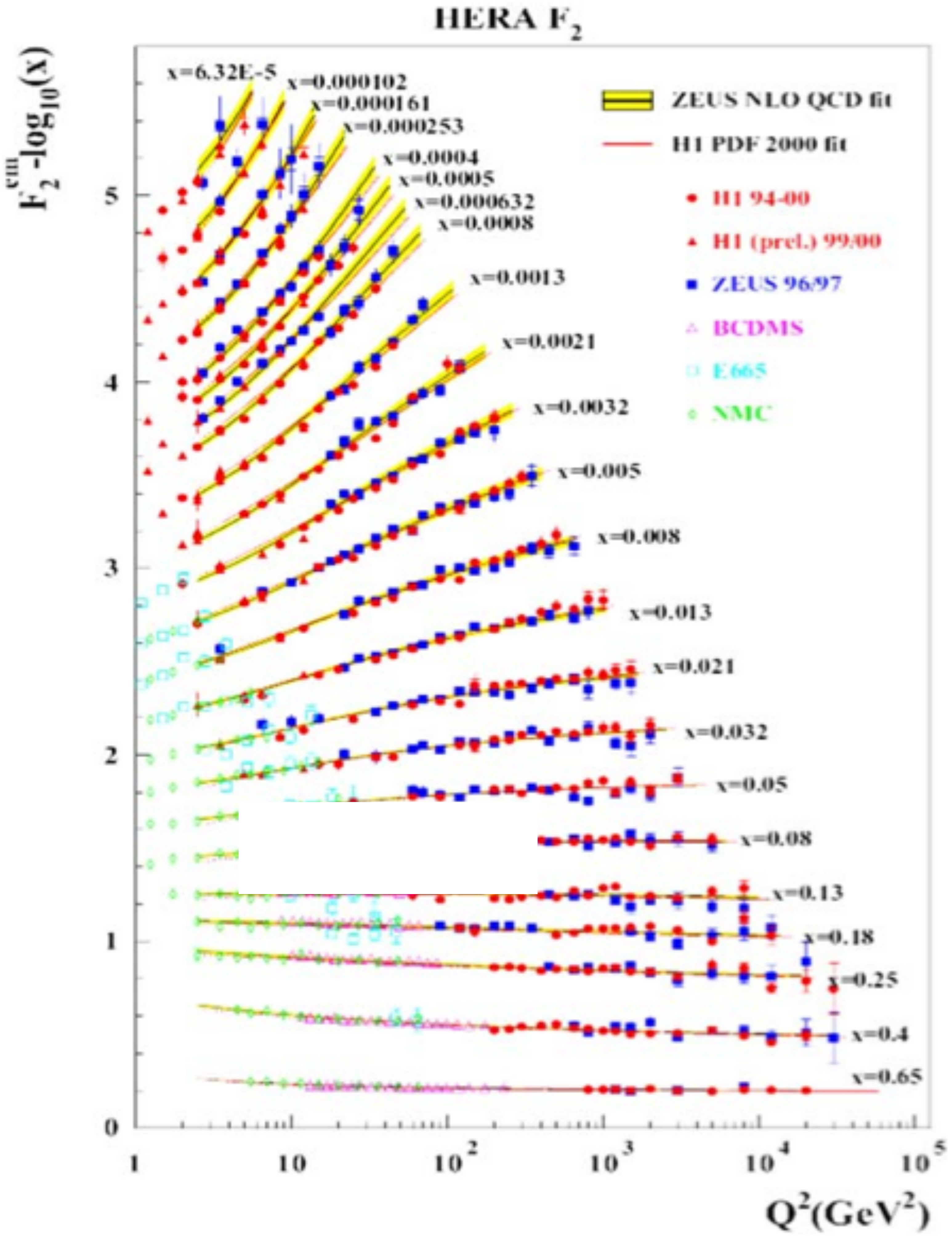
DIS

Lepton scattering (one vertex is purely QED)

High momentum (short wavelength)

We want to scatter on a single "parton" incoherently (high momentum means short time for interaction)

DIS summary



$$d\sigma \propto L_{\mu\nu} W^{\mu\nu}$$

Calculable in QED

Parametrized by Structure Functions (process dependent)

4 structure functions: $F_1(x,Q^2)$; $F_2(x,Q^2)$; $g_1(x,Q^2)$; $g_2(x,Q^2)$

Bjorken limit

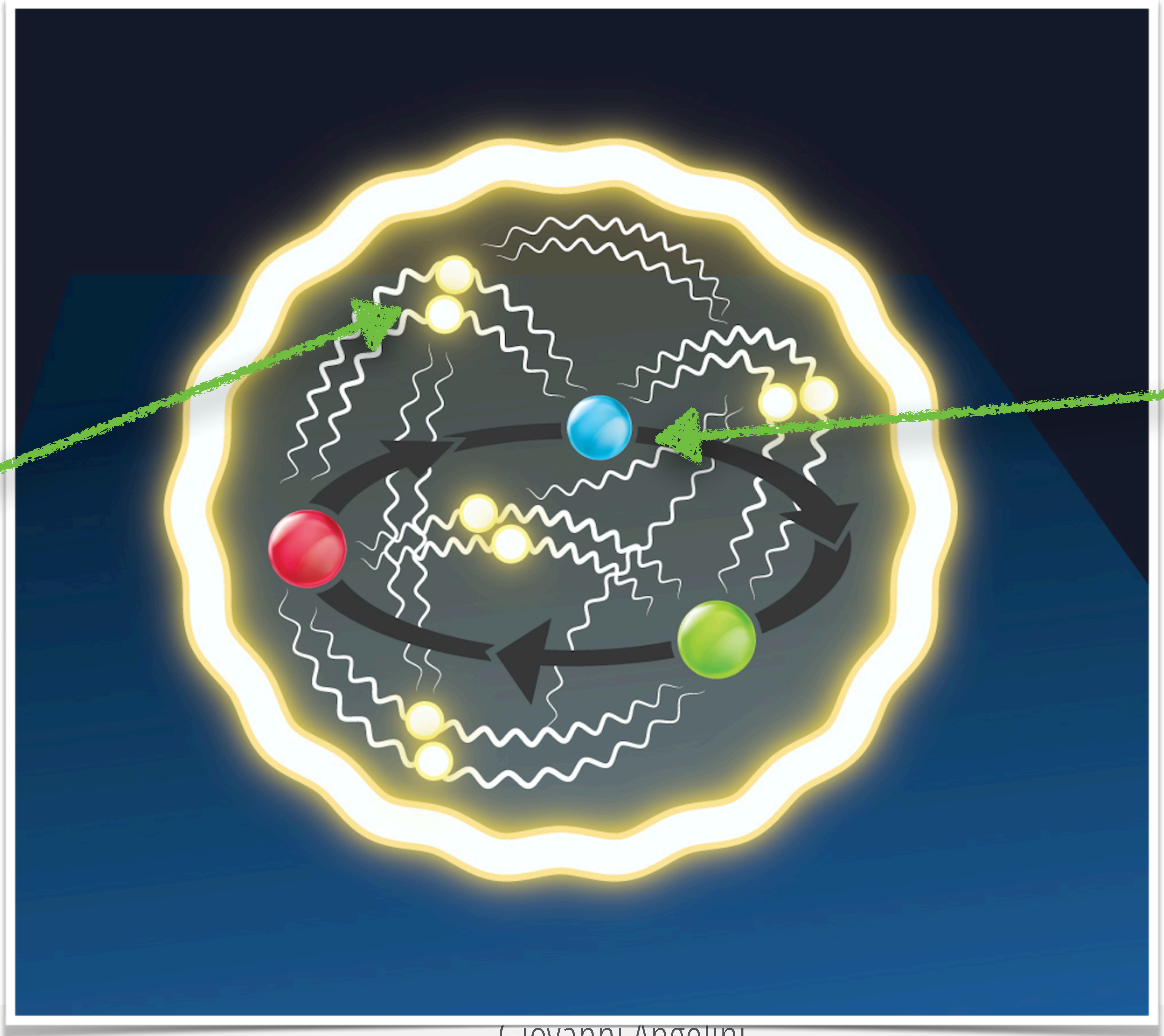
$F_2(x) = 2xF_1(x)$ **Unpolarized DF** ⟶ $f_1(x)$

$g_1(x)$ **Helicity DF** $g_2(x) \sim 0$

PDFs give the probability to find a quark with a fraction x of the proton momentum, and with a spin in a given direction with respect to the proton momentum

Factorization

If I hit one quark from a pair,
I want an interaction much faster than recombination time .



If I hit one valence quark, the time scale of interaction should be much shorter than the interaction between the other quarks.

FACTORIZATION:

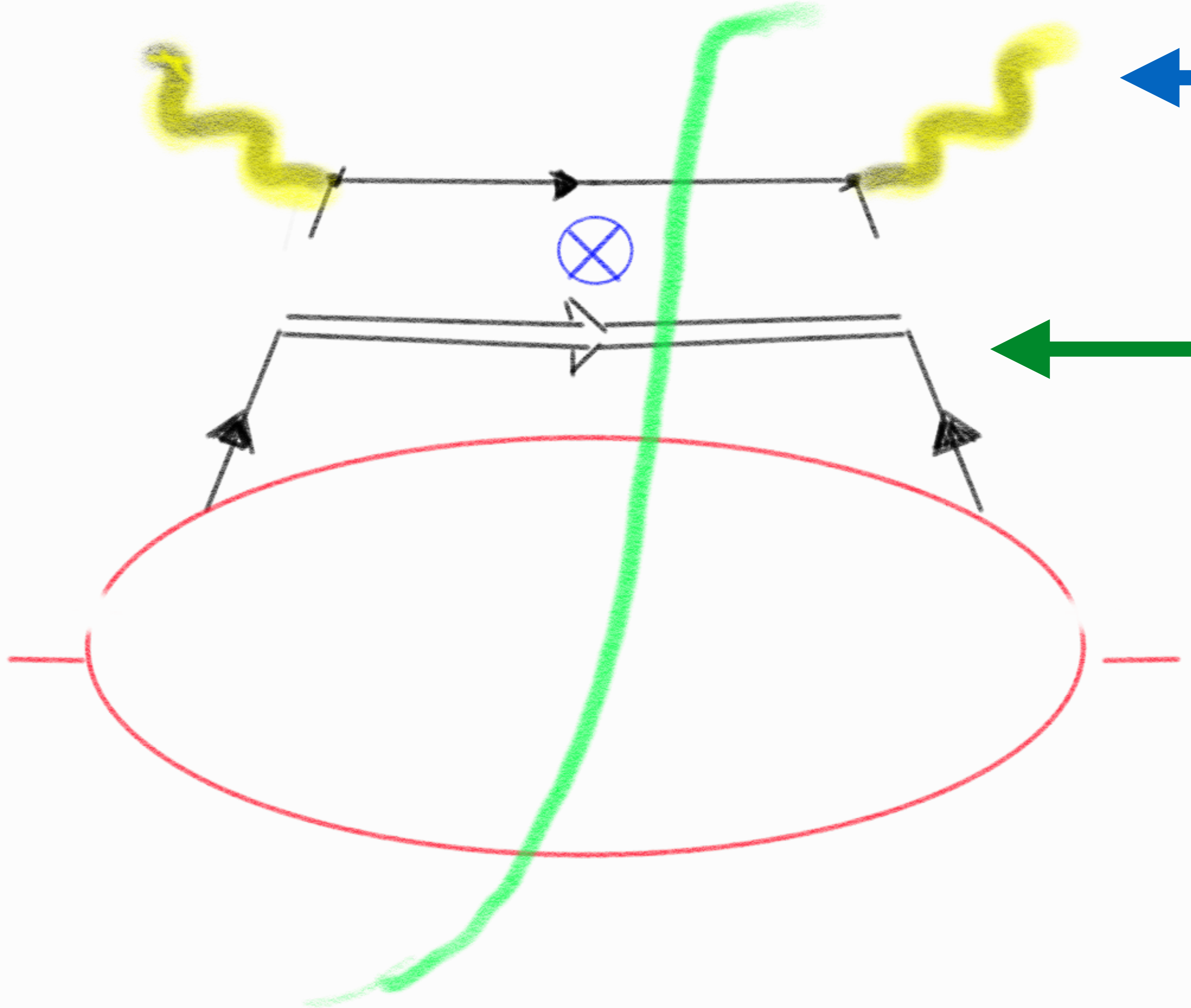
Fast interaction:
the scattering on 1 parton
(Hard part)

Slow interaction:
The interaction via gluons
(Soft part)

Factorization

Hard Part:

Soft part:



This part of the process is scattering of an electron on a fermion: Leptonic Tensor

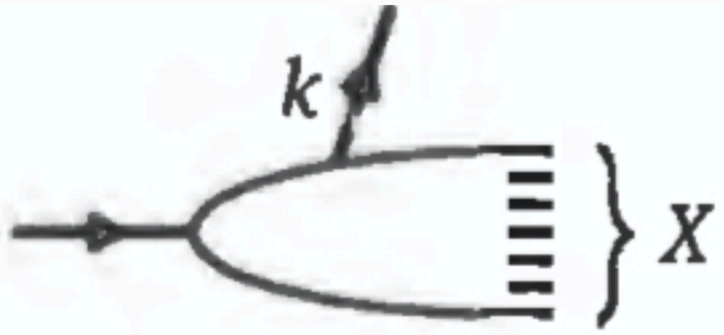
Wilson's line introduced ad hoc for the Gauge invariance (next slides)

This object cannot be calculated but can be parametrized in functions: Partonic Distribution Functions

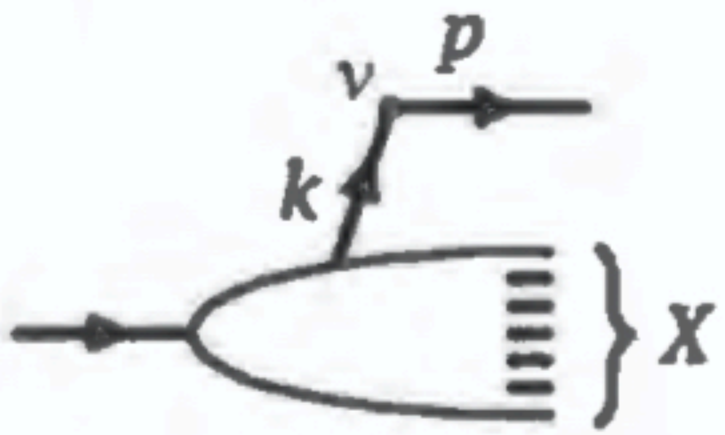
Hadronic tensor can be parametrized in terms of Structure functions.

Structure functions are process dependent quantities, the idea of the factorization is to be able to write it in terms of universal function: Partonic Distribution Functions (PDF)

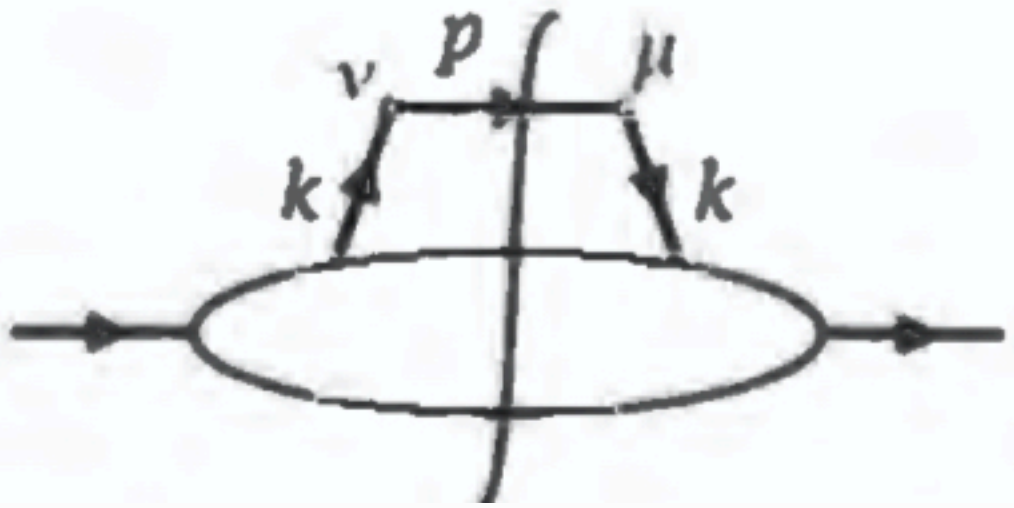
Step by step



$$= \langle X|\,\psi_\alpha(0)\,|P\rangle$$



$$= \bar{u}^\lambda_\beta(p)\,(\gamma^\nu)^{\beta\alpha}\,\langle X|\,\psi_\alpha(0)\,|P\rangle$$



$$\sim [\gamma^\mu\,(\not{p} + m)\,\gamma^\nu]^{\beta\alpha}\,\langle P|\,\overline{\psi}_\beta(0)\,|X\rangle\,\langle X|\,\psi_\alpha(0)\,|P\rangle\,;$$

Wilson's Line in QCD

Using the completeness relation on the X states, on-mass shell condition:

$$W^{\mu\nu}=\frac{1}{4\pi}\sum_q e_q^2\sum_X\int\frac{d^3p_X}{(2\pi)^3 2E_X}\int d^4z\, e^{i(P+q-p_x-p)\cdot z}[\gamma^\mu(\not{p}+m)\gamma^\nu]^{\beta\alpha}<P|\,\overline{\psi_\beta}\,(0)|X><X|\psi_\alpha(0)]|P>$$

Step by step

Translation Operator:

$$\langle P| J^{\dagger\mu}(0) |X\rangle e^{i(P\, p_x)x} = \langle P| J^{\dagger\mu}(Z) |X\rangle$$

On-shell condition to get rid of the 3-D integral:

$$\int \frac{d^3 p_X}{(2\pi)^3 2p^0} = \int \frac{d^4p}{(2\pi)^4}\delta(p^2 - m^2)\theta(p^0),$$

$$W^{\mu\nu} = \frac{1}{2}\sum_q e_q^2 \int d^4k\delta((k+q)^2)\theta(k^0 - q^0)Tr(\phi_q\gamma^\mu(\not{k} + \not{q})\gamma^\nu)$$

$$k = p - q,$$

Correlator

$$\phi^q_{\alpha\beta} = \int \frac{d^4z}{(2\pi)^4} e^{-ik\cdot z} \langle P| \overline{\psi}_\beta(z)\psi_\alpha(0) |P\rangle$$

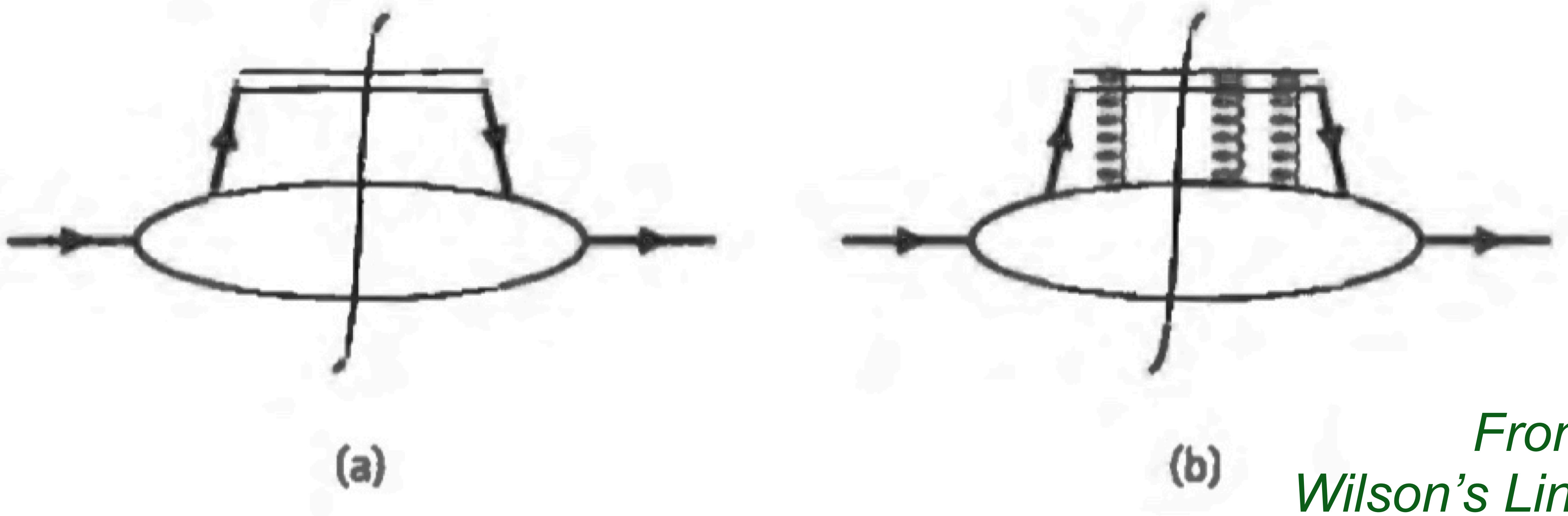
The quark-quark correlator : Gauge Invariance

$$\phi_{\alpha\beta} = \int \frac{d^4z}{(2\pi)^4} e^{-ikz} \langle P| \overline{\psi}_{\beta}(z)\psi_{\alpha}(0)|P\rangle$$

Here the fields are at point z and 0. I need to be sure that this object is Gauge Invariant.

I introduce a Wilson's Line that connects z to 0 in order to keep the Gauge Invariant

$$\phi_{\alpha\beta} = \int \frac{d^4z}{(2\pi)^4} e^{-ikz} \langle P| \overline{\psi}_{\beta}(z)\, U_{[z;0]}\psi_{\alpha}(0)|P\rangle$$



From: Wilson's Line in QCD

Fig. 5.14: (a) The gauge-invariant quark correlator function, with a cut Wilson line. (b) The Wilson lines inside the definition of the correlator account for the resummation of soft gluons.

Eikonial approximation:

An highly energetic fermion doesn't change path if emits soft gluons.

The W. line is a color rotation on the bare quark;

$$|\psi_{eik}\rangle = U_{[0;-\infty]}\, |\psi_{bare}\rangle$$

Under this approximation it can be proven that a Wilson's line is a summation of all the soft and linear gluons (even non soft if they are collinear) emitted along that Fermion's path .

The quark-quark correlator : Gauge Invariance

$$\phi_{\alpha\beta} = \int \frac{d^4z}{(2\pi)^4} e^{-ikz} \langle P| \overline{\psi}_{\beta}(z)\psi_{\alpha}(0)|P\rangle$$

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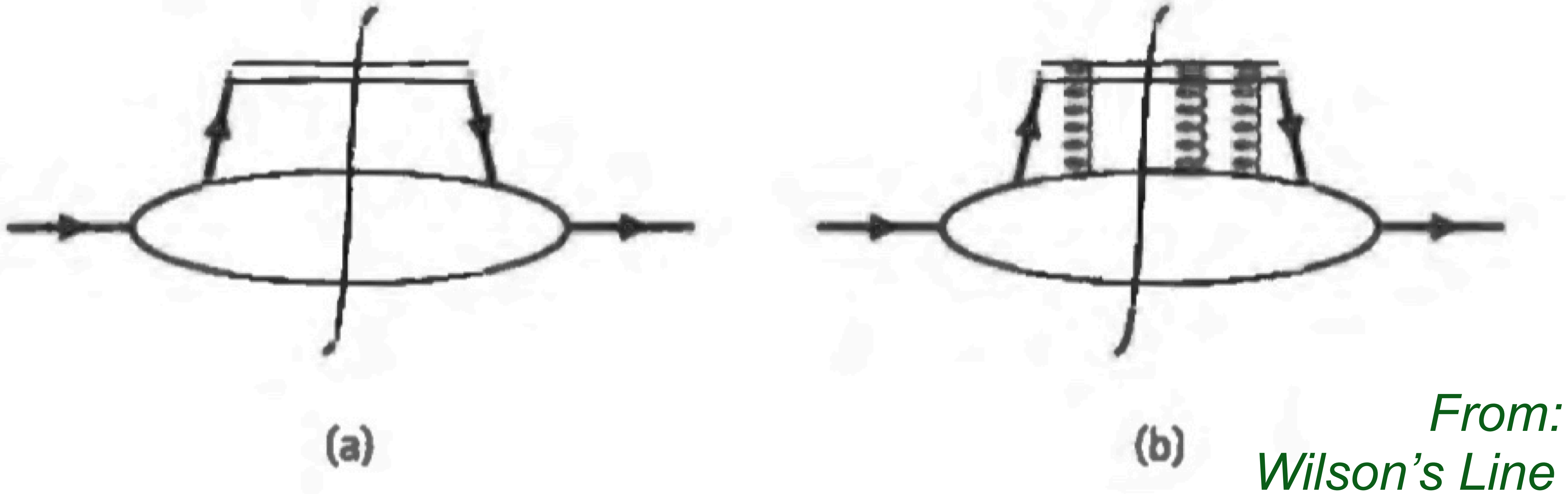


Fig. 5.14: (a) The gauge-invariant quark correlator function, with a cut Wilson line. (b) The Wilson lines inside the definition of the correlator account for the resummation of soft gluons.

From:
Wilson's Line in QCD

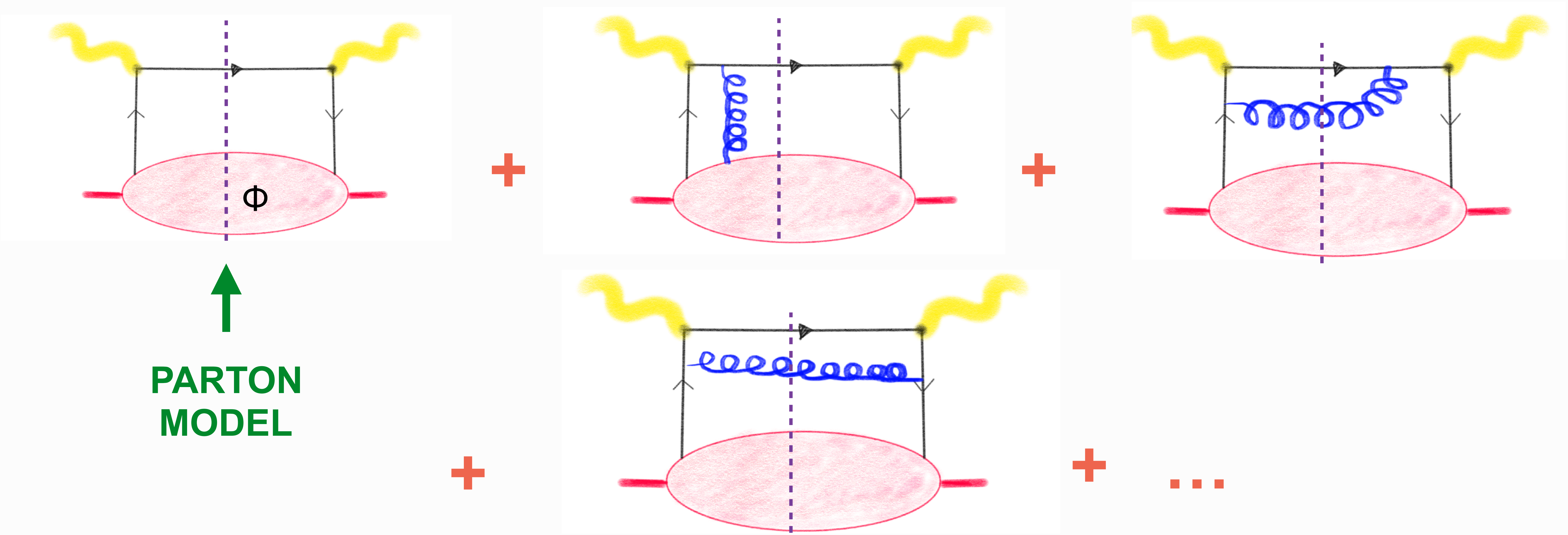
In light-cone frame, using the Gauge

$$A^{+}=0$$

it can be shown that U = 1

The correlator is independent of the choice of the Wilson's line path

Higher orders



The partonic distribution functions that appears in higher orders diagrams are referred as higher twist.

In higher twist contributions I have a quark-gluon-quark correlator.

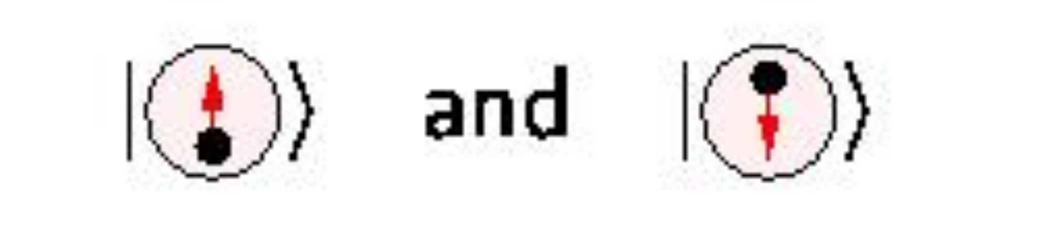
Distribution functions and eigenstates

Chiral eigenstates: $\psi_{R/L} = \frac{1}{2}(1 \pm \gamma_5)\psi$

in pictures:

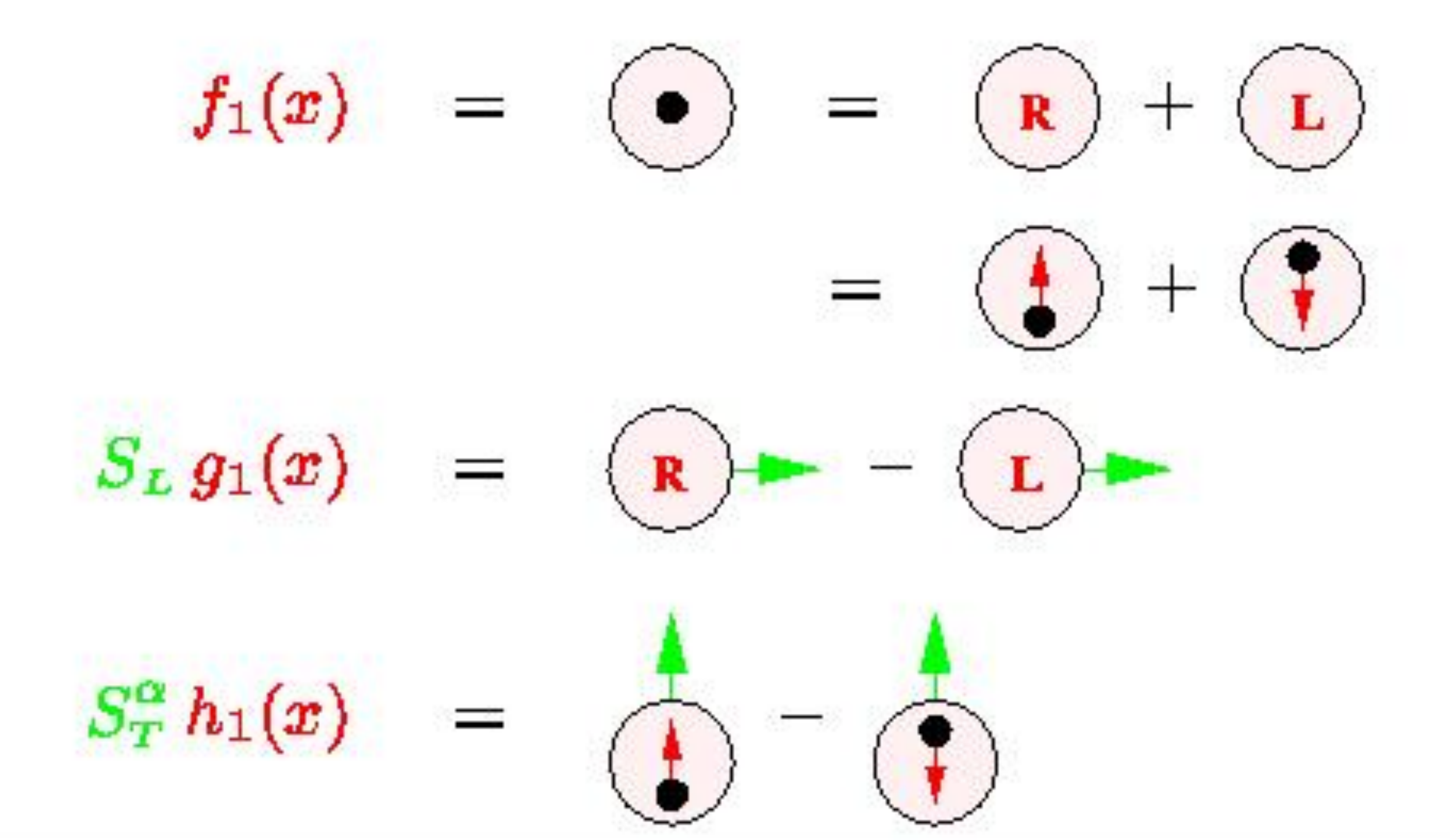
Transverse spin eigenstates: $\psi_{\uparrow/\downarrow} = \frac{1}{2}(1 \pm \gamma^{\alpha}\gamma_5)\psi$

in pictures:



Distribution functions : $$Tr[\Gamma\phi] = \int d^4z e^{ik\cdot z} < PS|\psi(0)\,\Gamma\,\overline{\psi(z)}\,|PS>$$

Dirac matrices base: $\Gamma = \{1, \gamma^{\mu}, \gamma^{\mu}\gamma_5, i\gamma^5, i\sigma^{\mu\nu}\gamma_5\}$



In light-cone frame:

$$f_1(x) = \frac{1}{2}Tr[\phi\gamma^{+}] = \int \frac{dz^{-}}{2\pi} e^{ip\cdot z} < P,S|\,\overline{\psi}\,(0)\gamma^{+}\psi(z)\,|P,S>$$

$$S_L g_1(x) = \frac{1}{2}Tr[\phi\gamma^{+}\gamma_5] = \int \frac{dz^{-}}{2\pi} e^{ip\cdot z} < P,S|\,\overline{\psi}\,(0)\gamma^{+}\gamma_5\,\psi(z)\,|P,S>$$

Matrix Representation

Bacchetta, Boglione, Henneman & Mulders - PRL 85 (2000) 712

MATRIX REPRESENTATION FOR SPIN 1/2

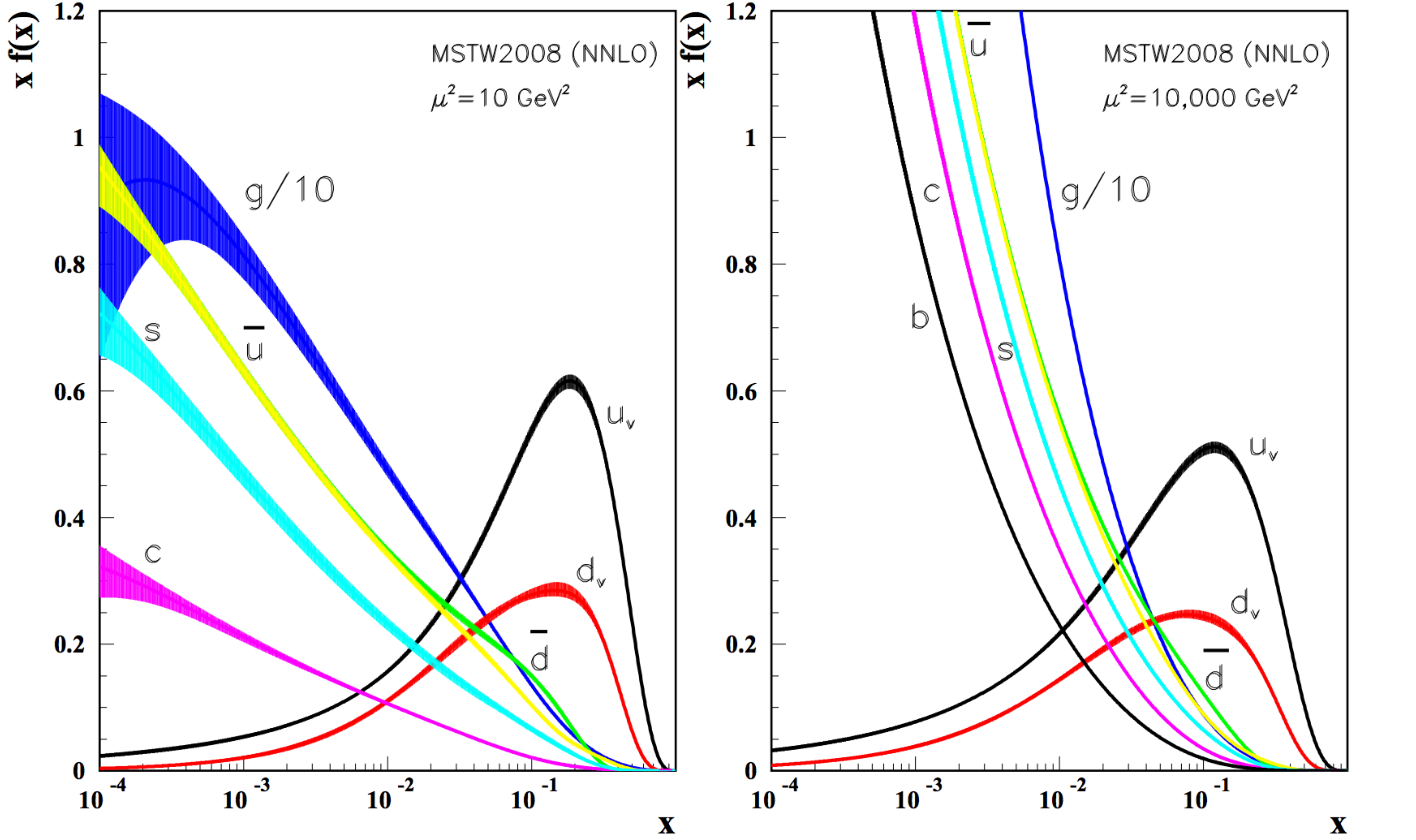
p_T-integrated distribution functions:

For a spin 1/2 hadron (e.g. nucleon) the quark production matrix in quark⊗nucleon spin space is given by (HELICITY BASE)

$$M^{(\mathrm{prod})} = \begin{pmatrix} f_1 + g_1 & 0 & 0 & 2\,h_1 \\ 0 & f_1 - g_1 & 0 & 0 \\ 0 & 0 & f_1 - g_1 & 0 \\ 2\,h_1 & 0 & 0 & f_1 + g_1 \end{pmatrix}$$

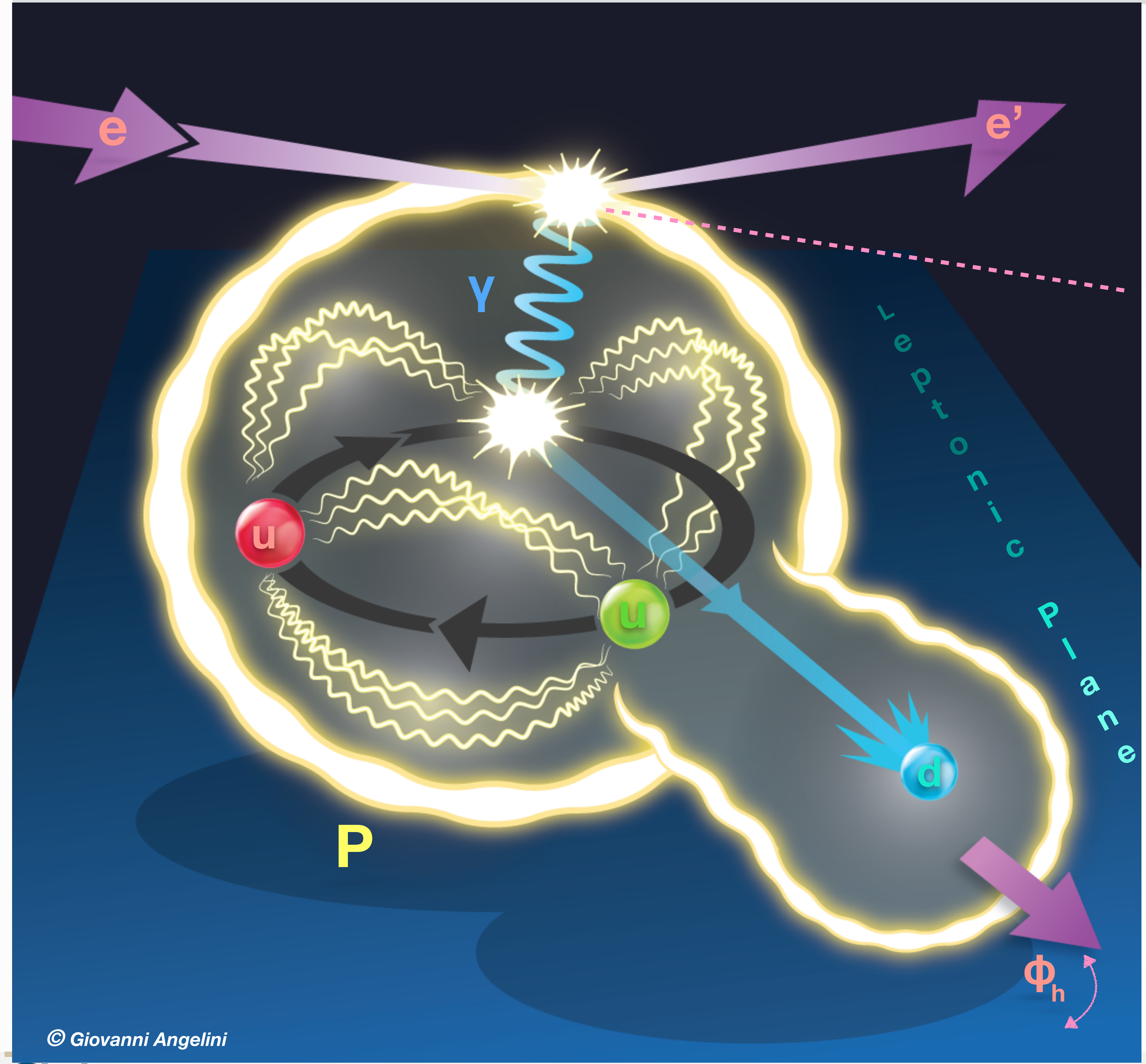
OFF DIAGONALS ELEMENTS ARE CHIRAL ODD: NOT OBSERVABLE IN DIS

PDF Global Results (DIS)

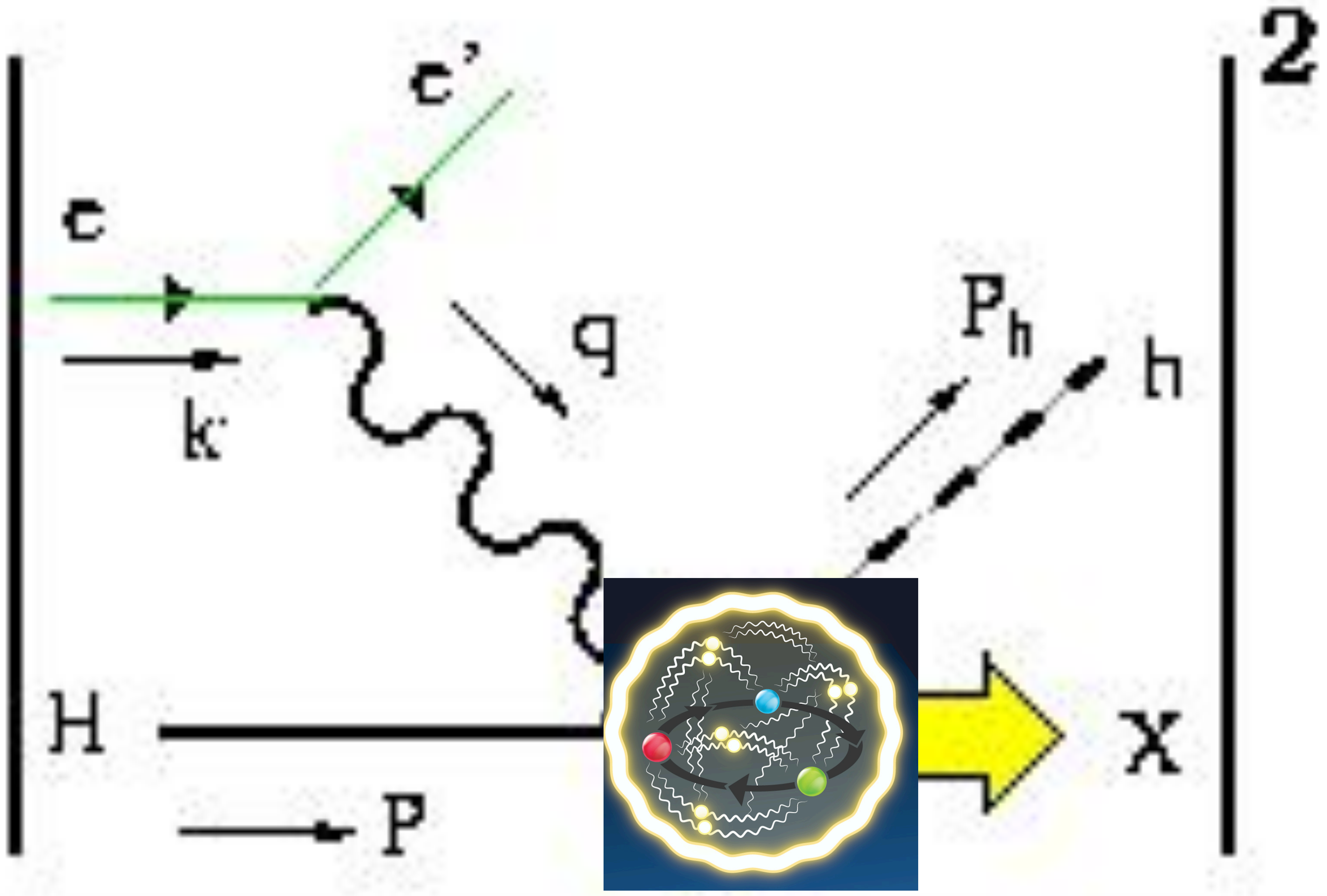


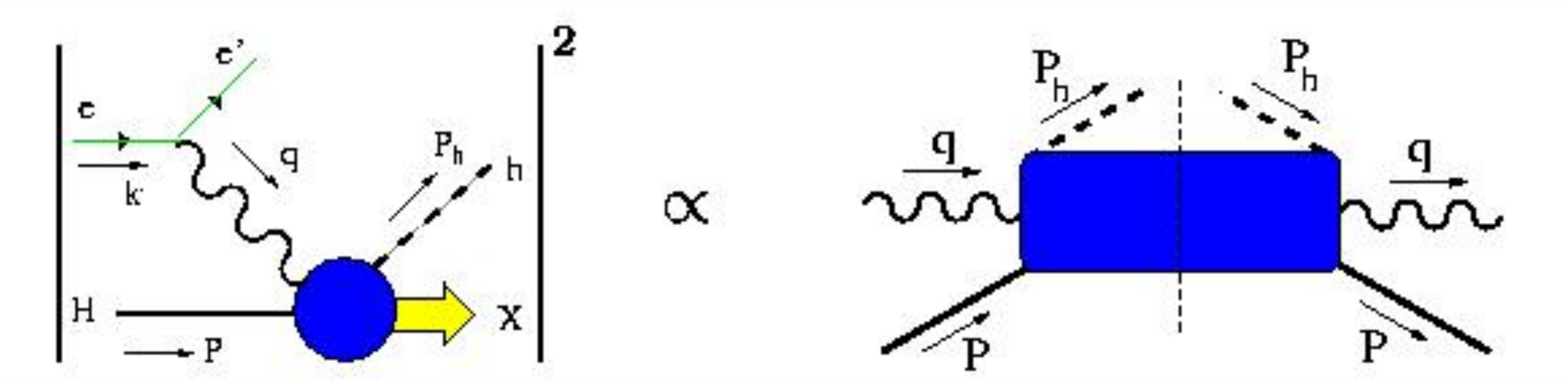
PDG 2011

Semi Inclusive Deep Inelastic Scattering

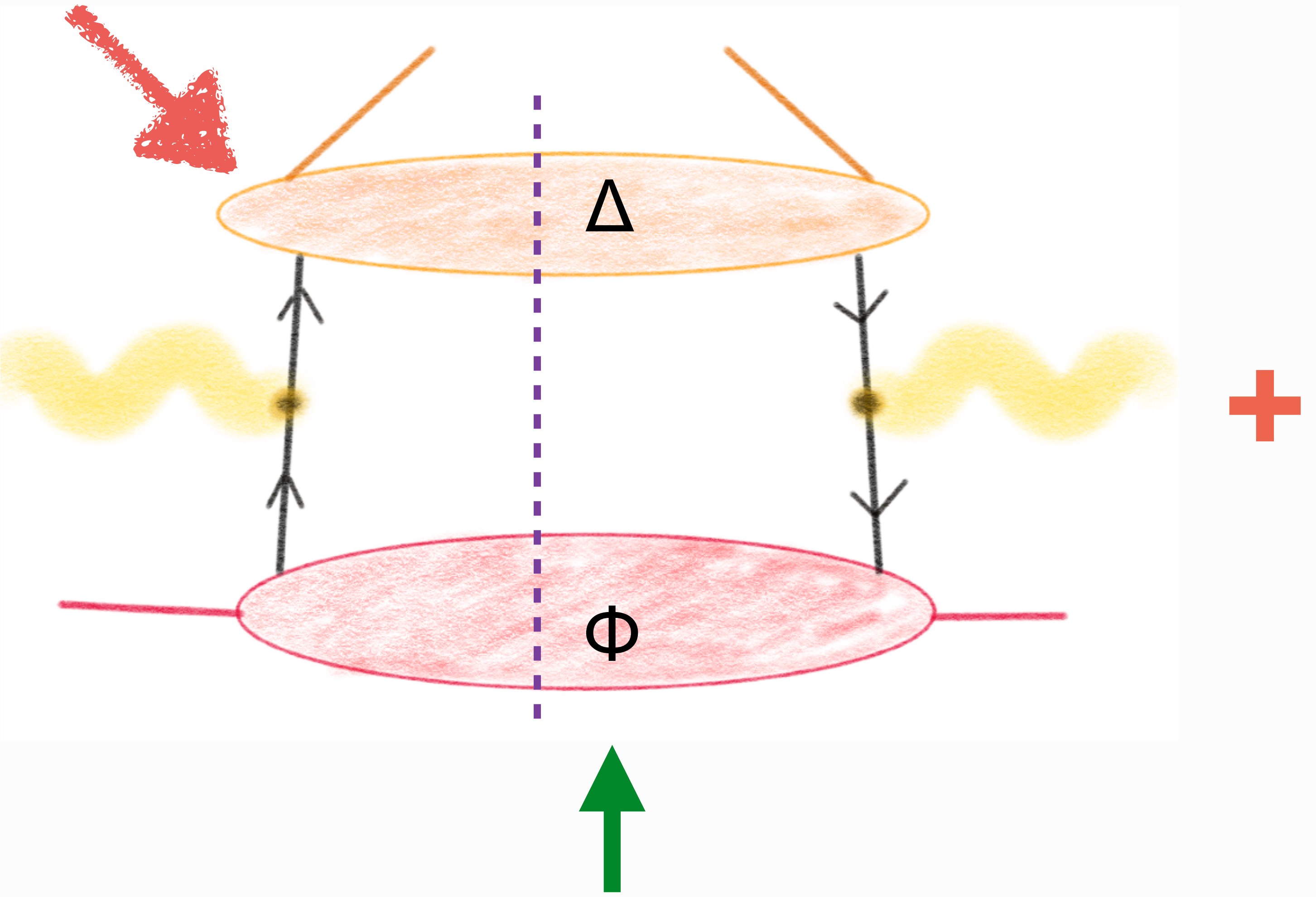


SIDIS: By tagging a final hadron, ejected from the proton, I can get information on the momentum distribution of quarks and gluons in the proton.

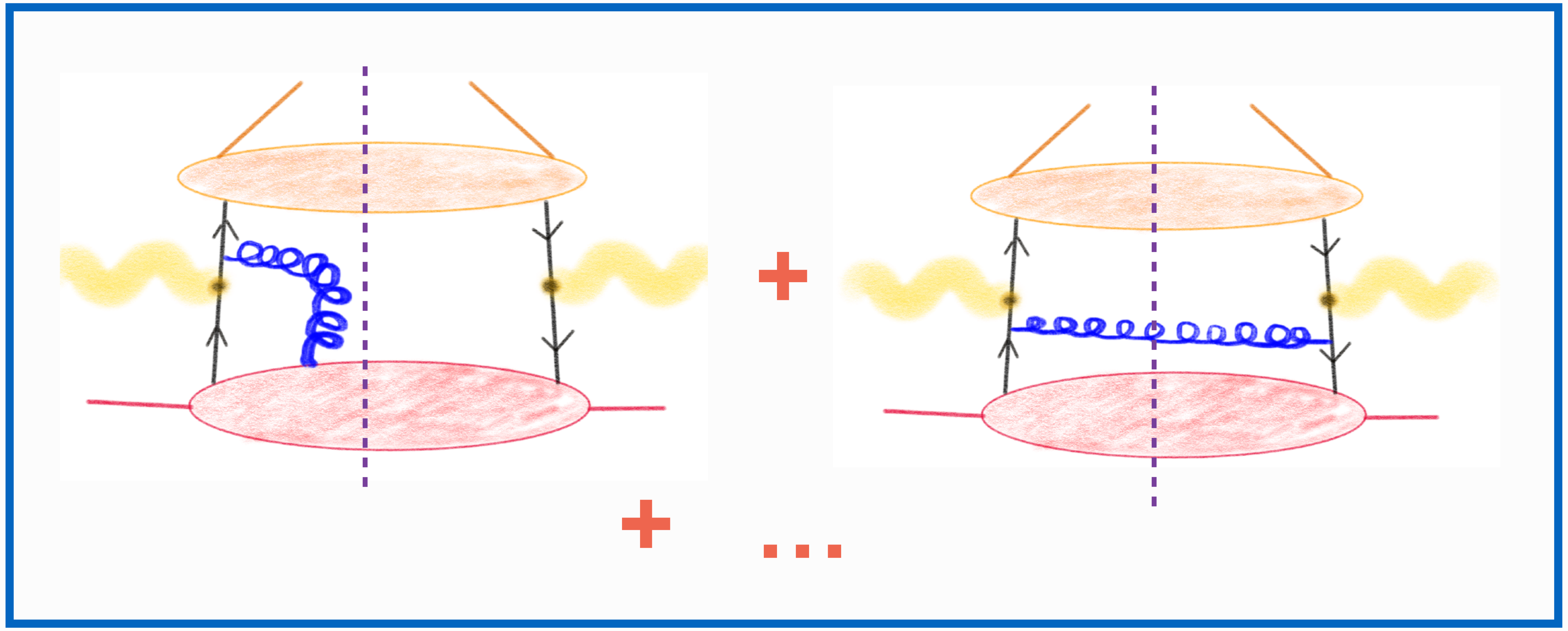




This is an extra correlation
that takes into account
the hadronization

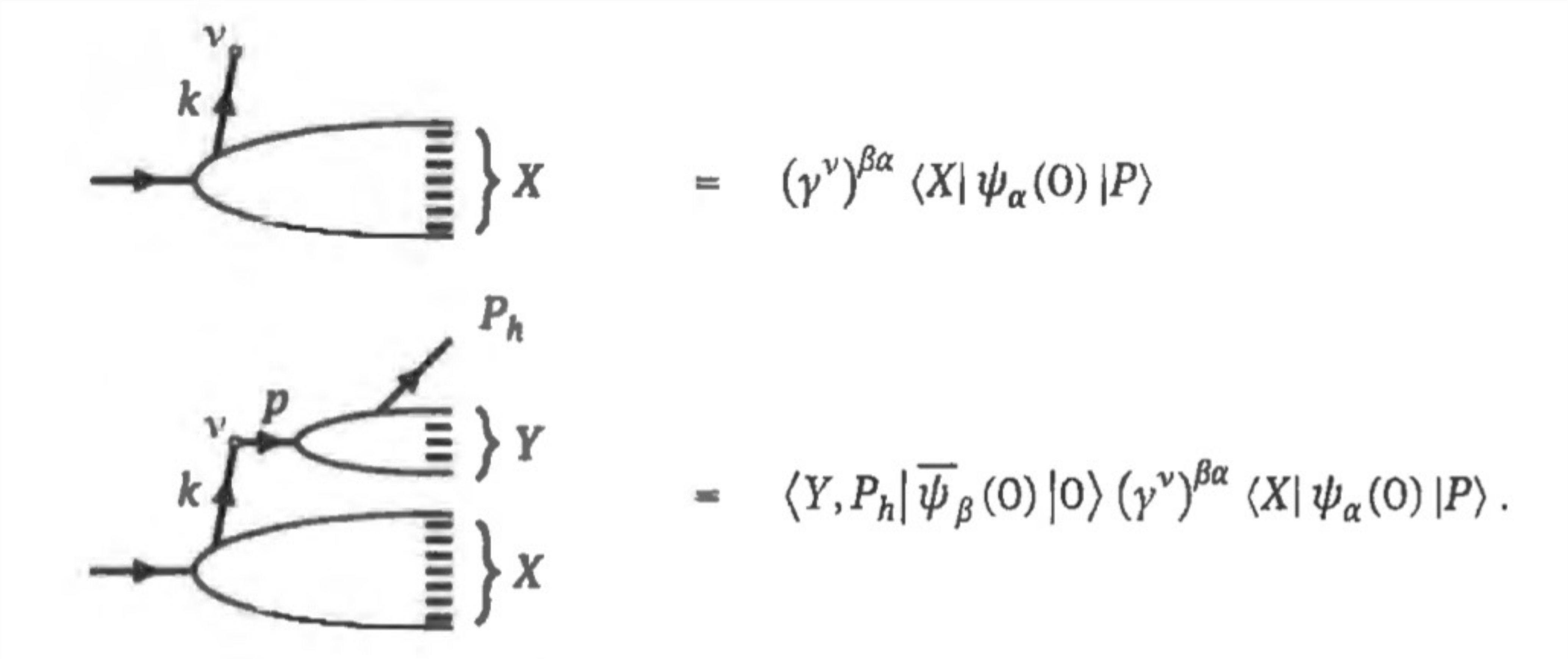


PARTON
MODEL

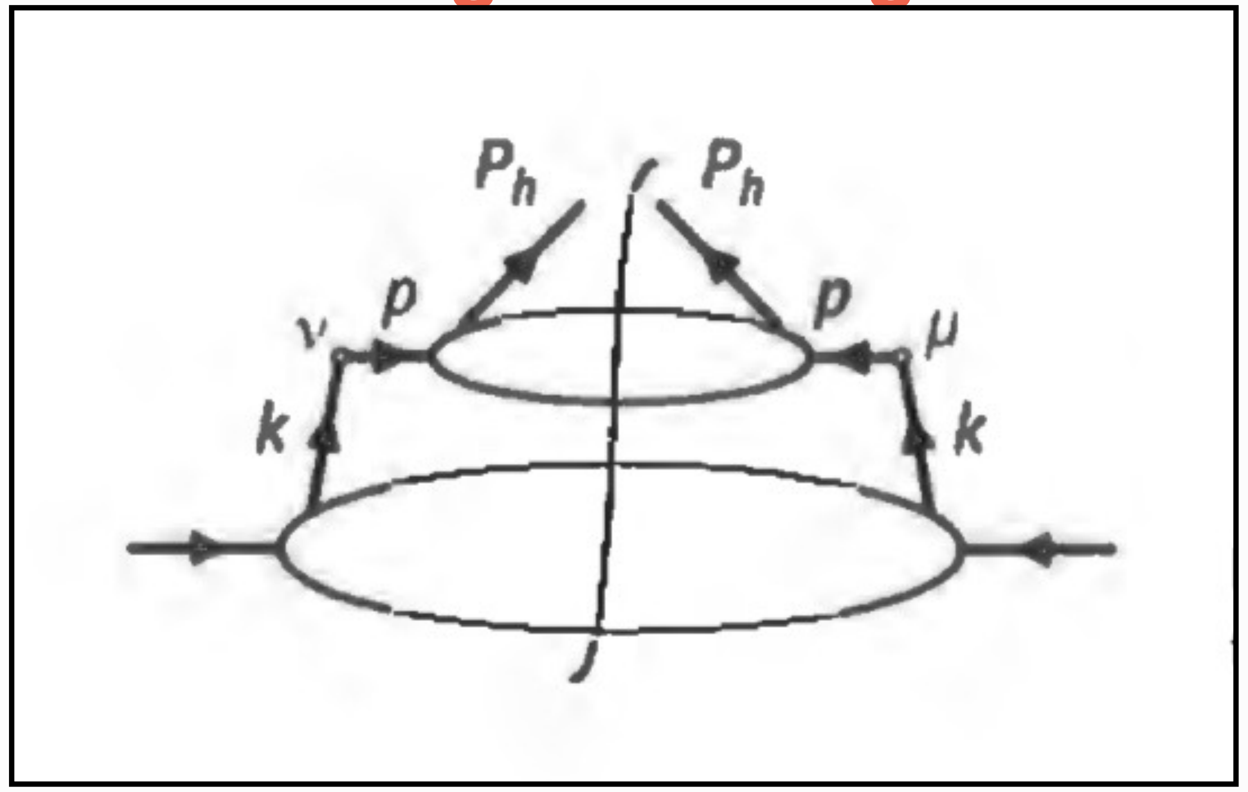


Higher Twists

SIDIS correlators



Leading twist diagram



Similar steps to what done in the DIS case lead to:

$$W^{\mu\nu}=\frac{1}{2}\sum_q e_q^2\int d^4k\,d^4p\,\delta^4(k+q-p)\,Tr[\phi(k,P)\gamma^\mu\Delta(p,P_h)\gamma^\nu]$$

$$\phi_{\alpha\beta}=\int\frac{d^4z}{16\pi^4}e^{-ik\cdot z}<P|\overline{\psi_\beta}(z)\psi_\alpha(0)|P>$$

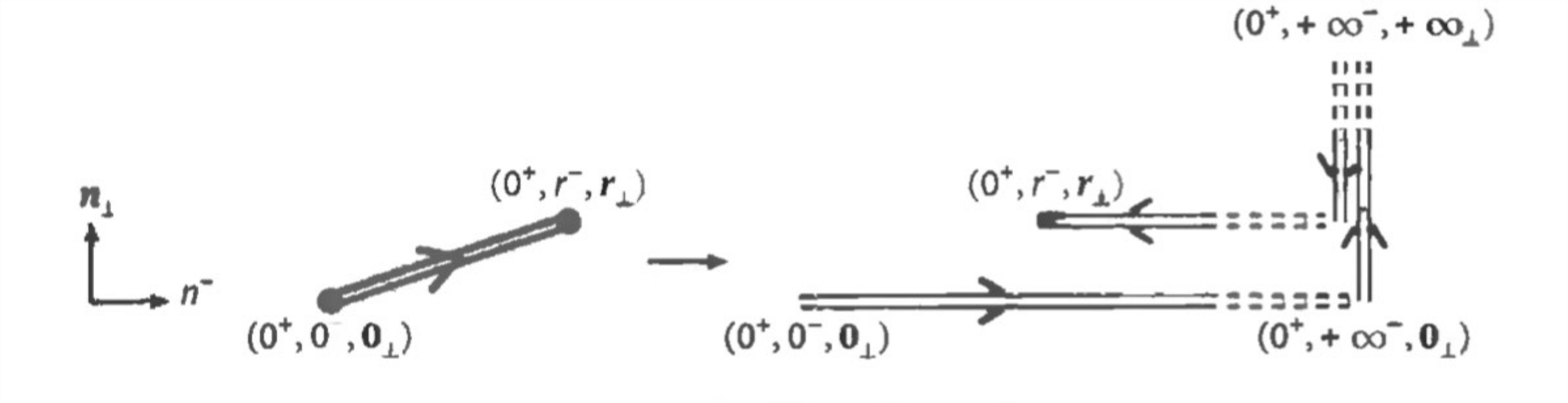
$$\Delta_{\alpha\beta}=\int\frac{d^4z}{16\pi^4}e^{-ik\cdot z}<0|\psi_\alpha(0)|P_h><P_h|\overline{\psi_\beta(z)}|0>$$

**The two correlatiors can be rewritten in terms of transverse momentum and the functions that parametrize their structure are:
TMDs and FFs**

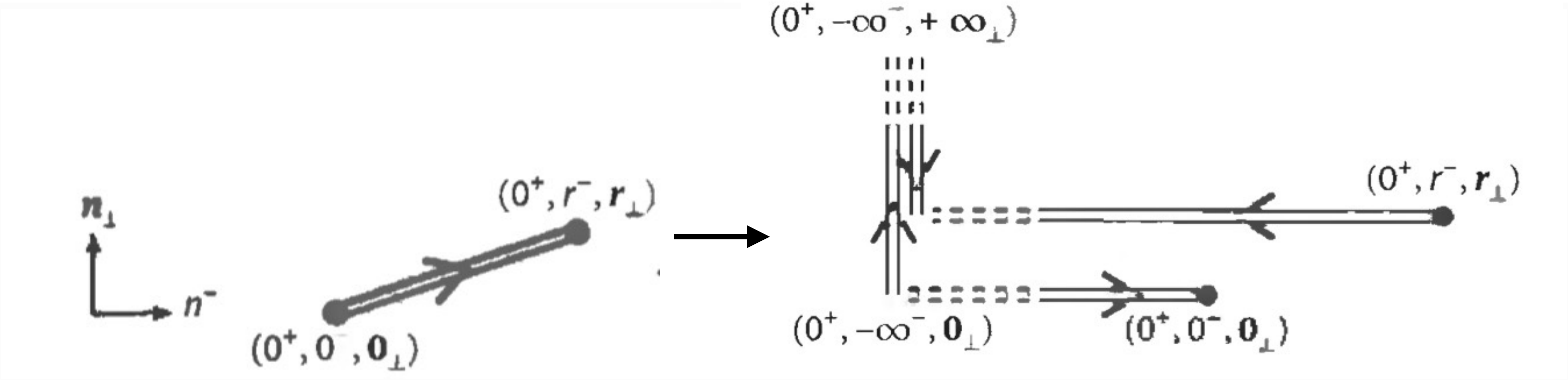
Wilson's line in SIDIS

For Gauge invariance I need to insert a Wilson's line that connects two space time coordinates in the longitudinal direction and **in the transverse direction .**

SIDIS:



Drell-Yan:

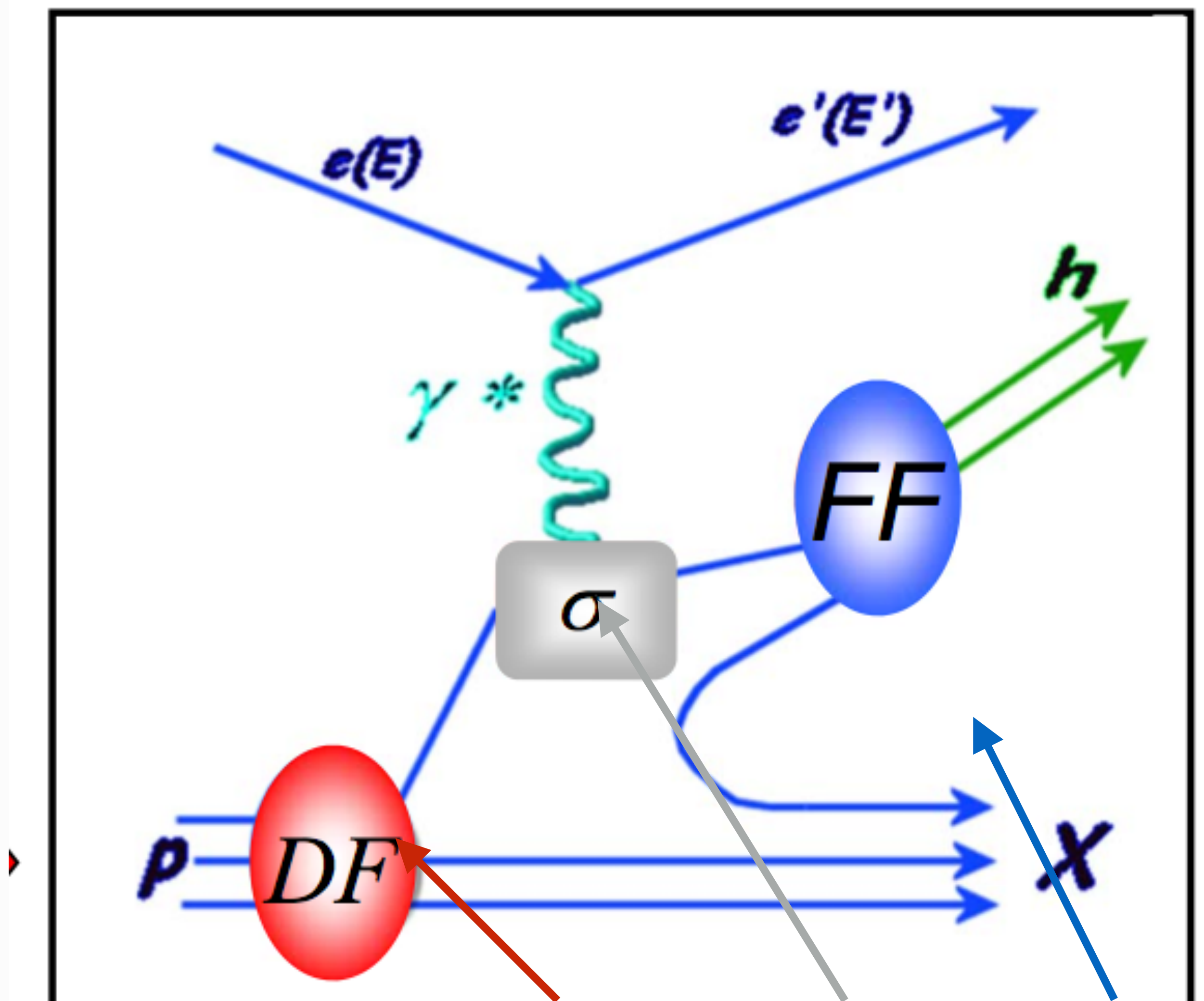


As consequence odd TMDs will have a different in sign in Drell-Yan: Prediction

SIDIS in a nutshell

- **DIS: eP→eX** Only **collinear** information. **Factorization proven.**
- **Structure Functions (process dependent) rewritten in terms of universal functions.**

Semi Inclusive Deep Inelastic Scattering



$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

Nucleon / Quark	Unpol.	Long.	Trans.
Unpol.	f_1		$f_{1T}^{\perp}$ -
Long.		g_{1L} -	g_{1T} -
Trans.	$h_1^{\perp}$ -	$h_{1L}^{\perp}$ -	h_{1T} - $h_{1T}^{\perp}$ -

Fragmentation Functions (FF)				
		quark		
		U	L	T
had.	U	D_1 Unpol. FF		$H_1^{\perp}$ - Collins FF

$h_1^{\perp}$ *Boer-Mulders: distribution of transversely pol. quark in unpol. nucleon*

Factorization of the cross section

$$F \sim \sum_q PDF^q \otimes FF^q$$

In the Bjorken Limit:

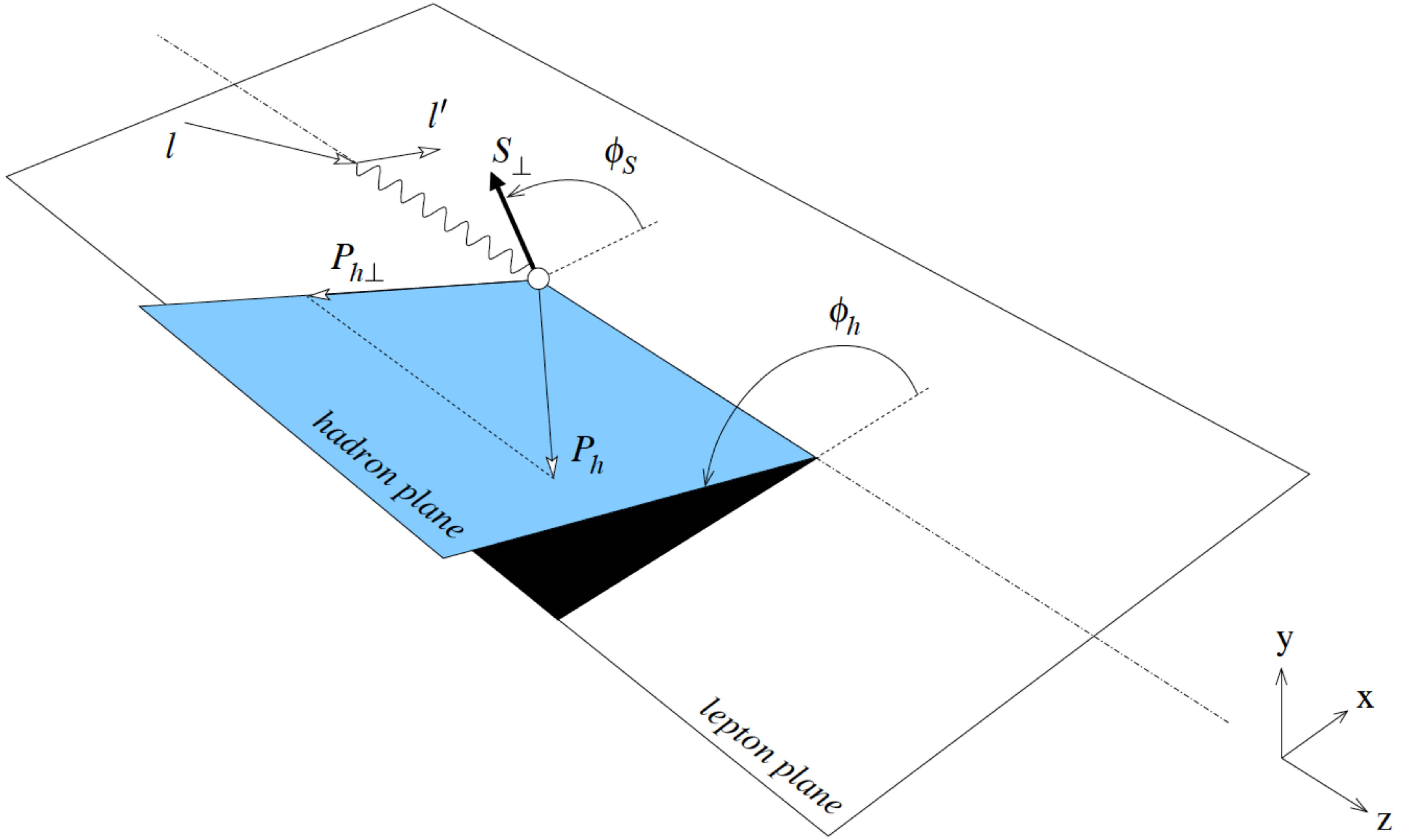
$$Q^2 \to \infty$$
$$2P\cdot q \to \infty$$
$$P\cdot P_h \to \infty$$

fixed $\begin{cases} x = Q^2/2P\cdot q \\ z = P\cdot P_h/P\cdot q \end{cases}$

SIDIS Cross Section

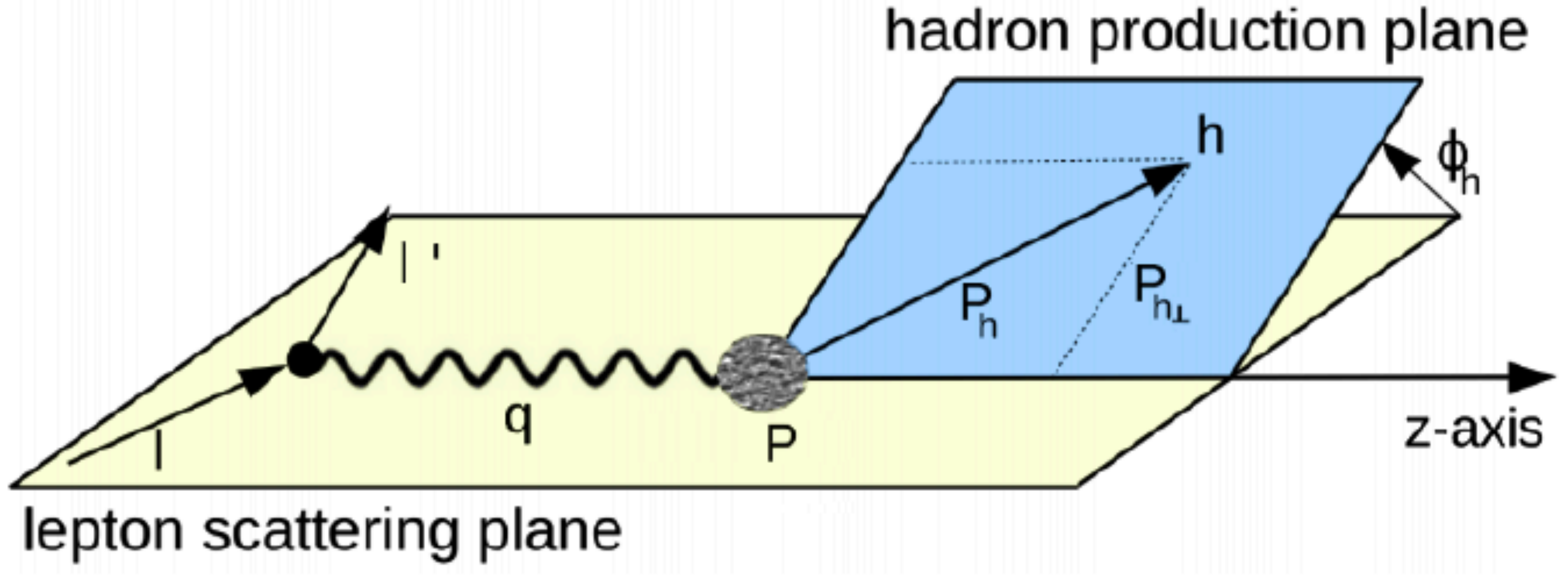
18 Model-Independent Structure Functions (one photon exchange approx) $F(x,z,Q^2,P_{h\perp})$

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} &= \\
&\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad+S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\quad+\varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\quad+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\quad+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$



A.Baccheta et al., "Semi-inclusive deep inelastic scattering at small transverse momentum", JHEP 0702, 093 (2007)

Unpolarized Cross Section



$$e(l)P(P) \rightarrow e(l')h(P_h)X$$

ε is the ratio between the longitudinal and transverse photon flux
λ beam helicity

$$\frac{d^6\sigma}{dxdydzd\phi_h dP_{h\perp}^2} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}(1+\frac{\gamma^2}{2x})[F_{UU,T} + \epsilon F_{UU,L} + \epsilon \cos 2\phi_h F_{UU}^{\cos 2\phi_h} + \sqrt{2\epsilon(1+\epsilon)}\, cos\phi_h F_{UU}^{cos\phi_h} + \lambda_e \sqrt{2\epsilon(1-\epsilon)}\, sin\phi_h F_{LU}^{\sin\phi_h}],$$

Transfer momentum

$Q^2 = -(l-l')^2$

Squared Invariant mass of the final state

$W^2 = (P+q)^2$

Quark longitudinal momentum fraction

$x = \frac{Q^2}{2P\cdot q}$

Fractional energy of the virtual photon

$y = \frac{P\cdot q}{P\cdot l}$

Final state hadron momentum fraction

$z = \frac{P\cdot P_h}{P\cdot q}$

$$d\sigma = d\sigma_0(1 + A_{UU}^{cos\phi} cos\phi + A_{UU}^{cos2\phi} cos2\phi + \lambda_e A_{LU}^{sin\phi} sin\phi).$$

$$A_{LU}^{sin\phi} = \frac{\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{sin\phi}}{F_{UU,T} + \epsilon F_{UU,L}}, \quad A_{UU}^{cos\phi} = \frac{\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{cos\phi}}{F_{UU,T} + \epsilon F_{UU,L}}, \quad A_{UU}^{cos2\phi} = \frac{\epsilon F_{UU}^{cos2\phi}}{F_{UU,T} + \epsilon F_{UU,L}}.$$

Multiplicities

DIS

$$\frac{d\sigma}{dx\,dQ^2\,d\psi} = \frac{2\alpha^2}{xQ^4}\frac{y^2}{2(1-\varepsilon)}\left\{F_{UU,T}(x,Q^2) + \varepsilon F_{UU,L}(x,Q^2)\right\}.$$

Same kinematic Factor

$$F_{UU,T}(x,Q^2) = F_T(x,Q^2) = 2xF_1(x,Q^2) = \sum_h \int z\,dz F_{UU,T}(x,z,Q^2)$$

SIDIS

$$\frac{d\sigma}{dx\,dQ^2\,d\psi\,dz\,d\phi_h\,d|\boldsymbol{P}_{h\perp}|^2} = \frac{\alpha^2}{xQ^4}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left\{F_{UU,T} + \varepsilon F_{UU,L}\right\}.$$

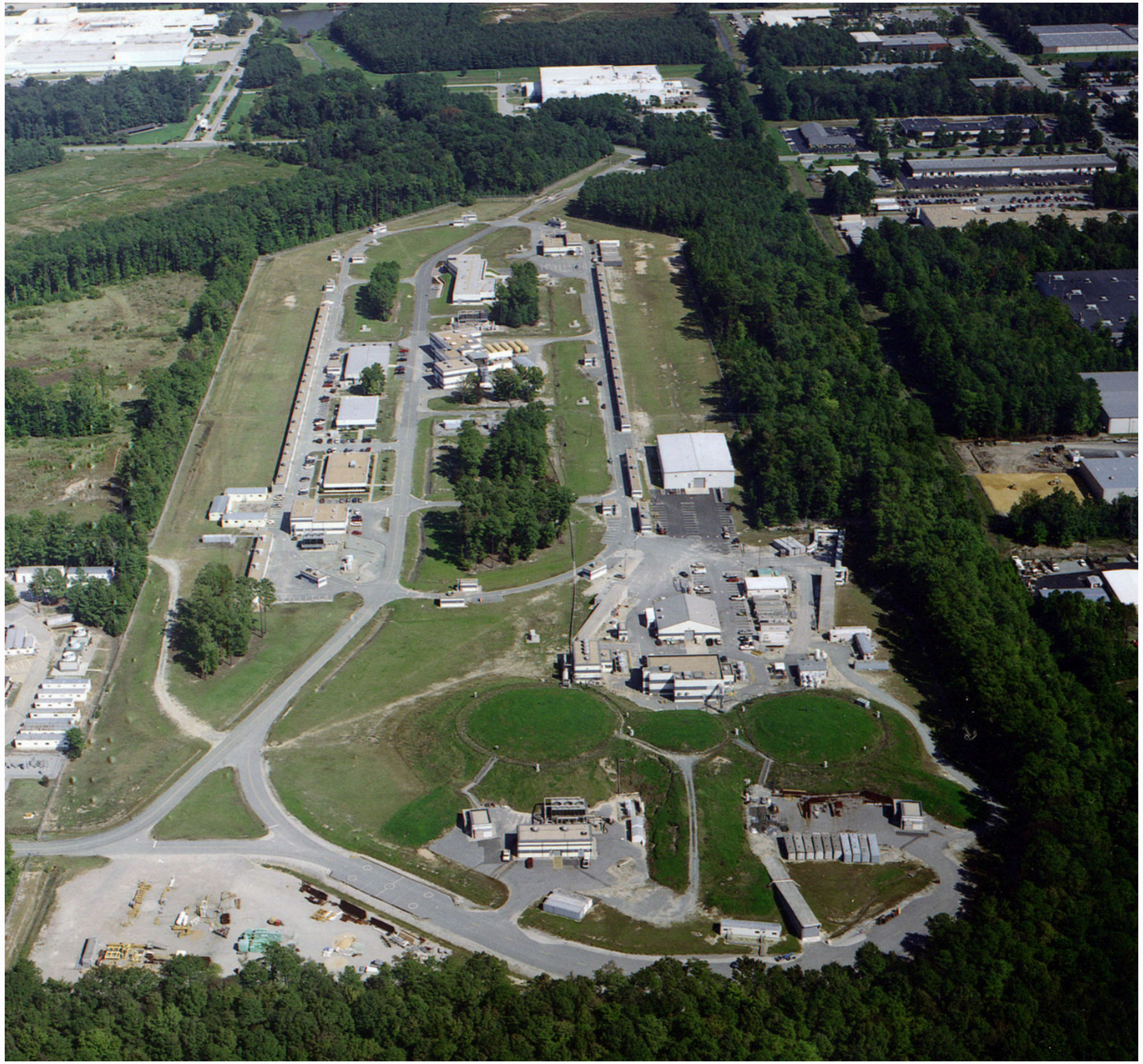
$$F_{UU,T}(x,z,Q^2) = \int d^2\vec{P}_{h,\perp} F_{UU,T}(x,z,P^2_{h,\perp},Q^2)$$

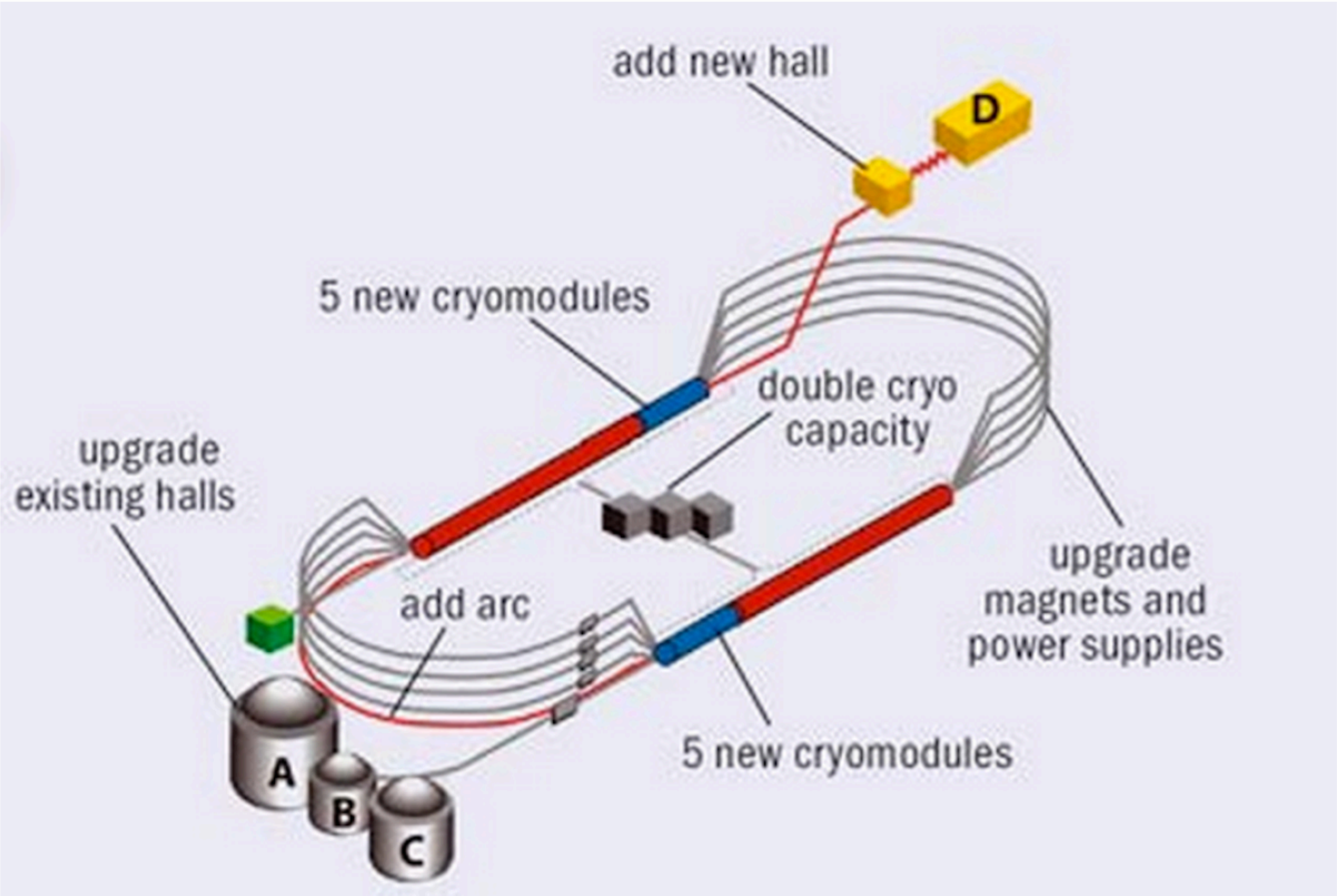
Multiplicity definition:

$$m_N^h(x,z,P^2_{hT},Q^2) = \frac{d\sigma_N^h/dx\,dz\,dP^2_{hT}dQ^2}{d\sigma_{\mathrm{DIS}}/dx\,dQ^2}$$

$$m_N^h(x,z,P^2_{hT},Q^2) = \frac{\pi F_{UU,T}(x,z,P^2_{hT},Q^2) + \pi\,\varepsilon F_{UU,L}(x,z,P^2_{hT},Q^2)}{F_T(x,Q^2) + \varepsilon F_L(x,Q^2)}$$

CEBAF Accelerator (JLab)





E = 12GeV   I = 200μA   Pol. 85%

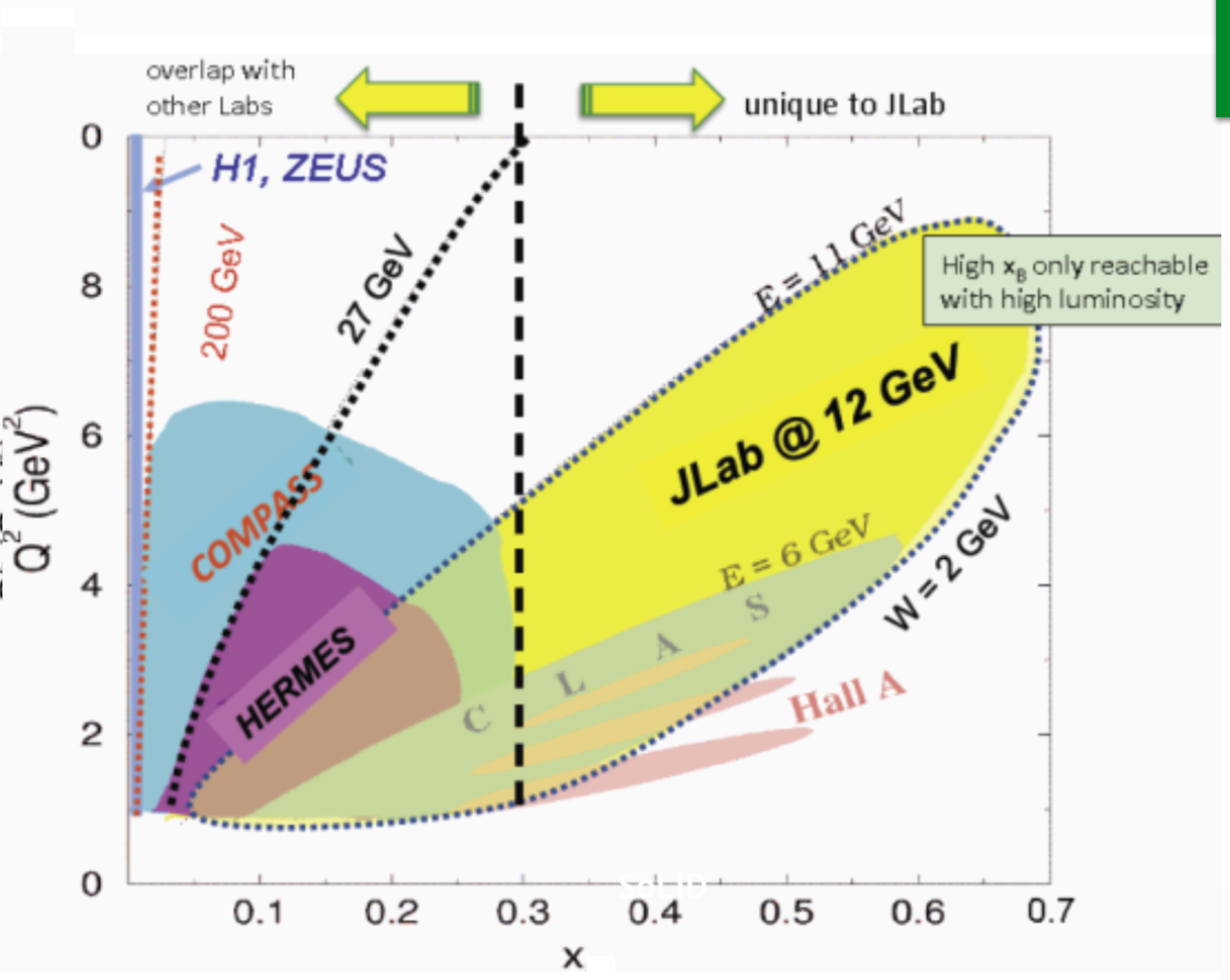
HALL B:

E = 10.6 GeV

I = 90 μA

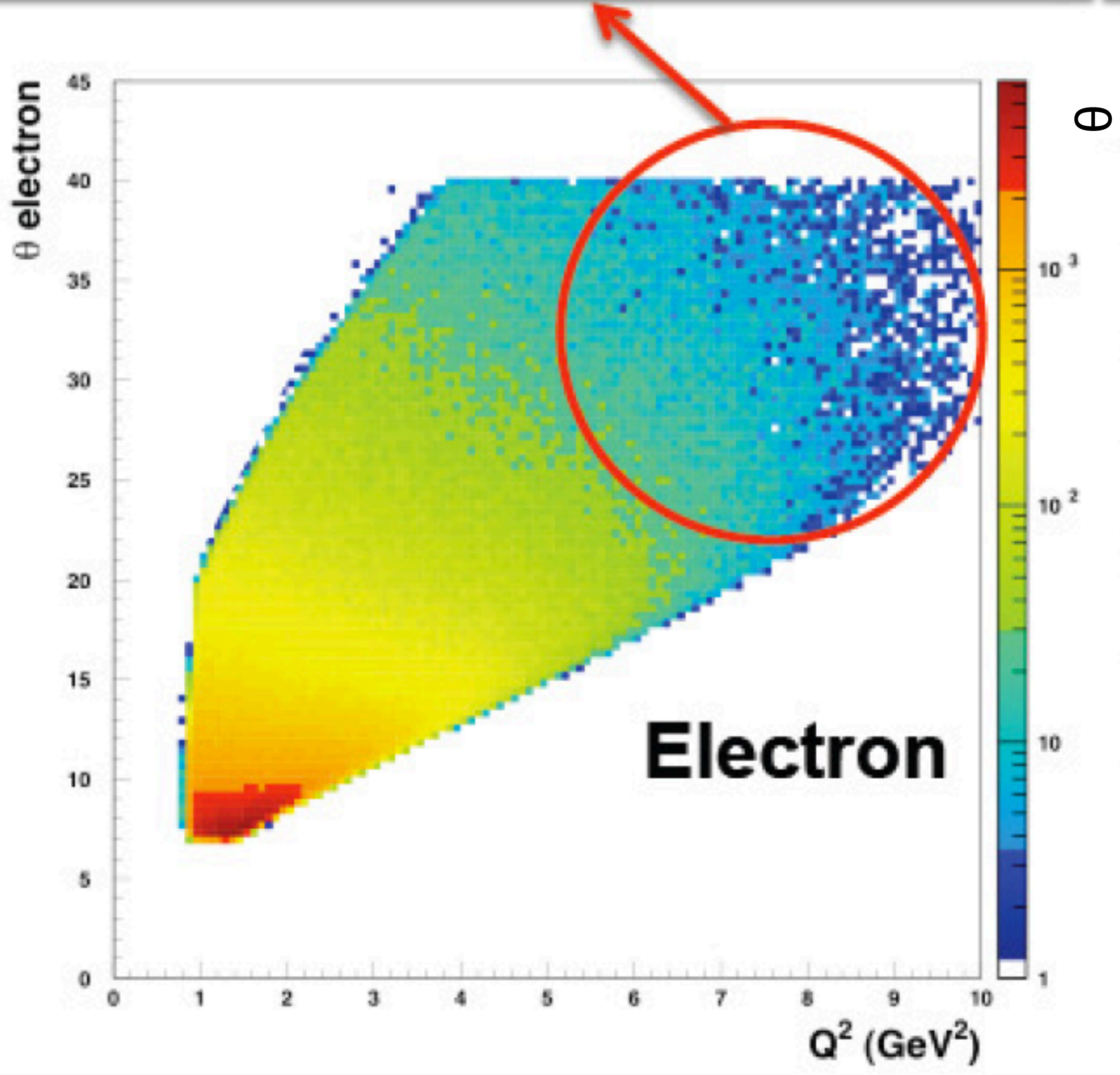
Luminosity up to $10^{35} cm^{-2} s^{-1}$

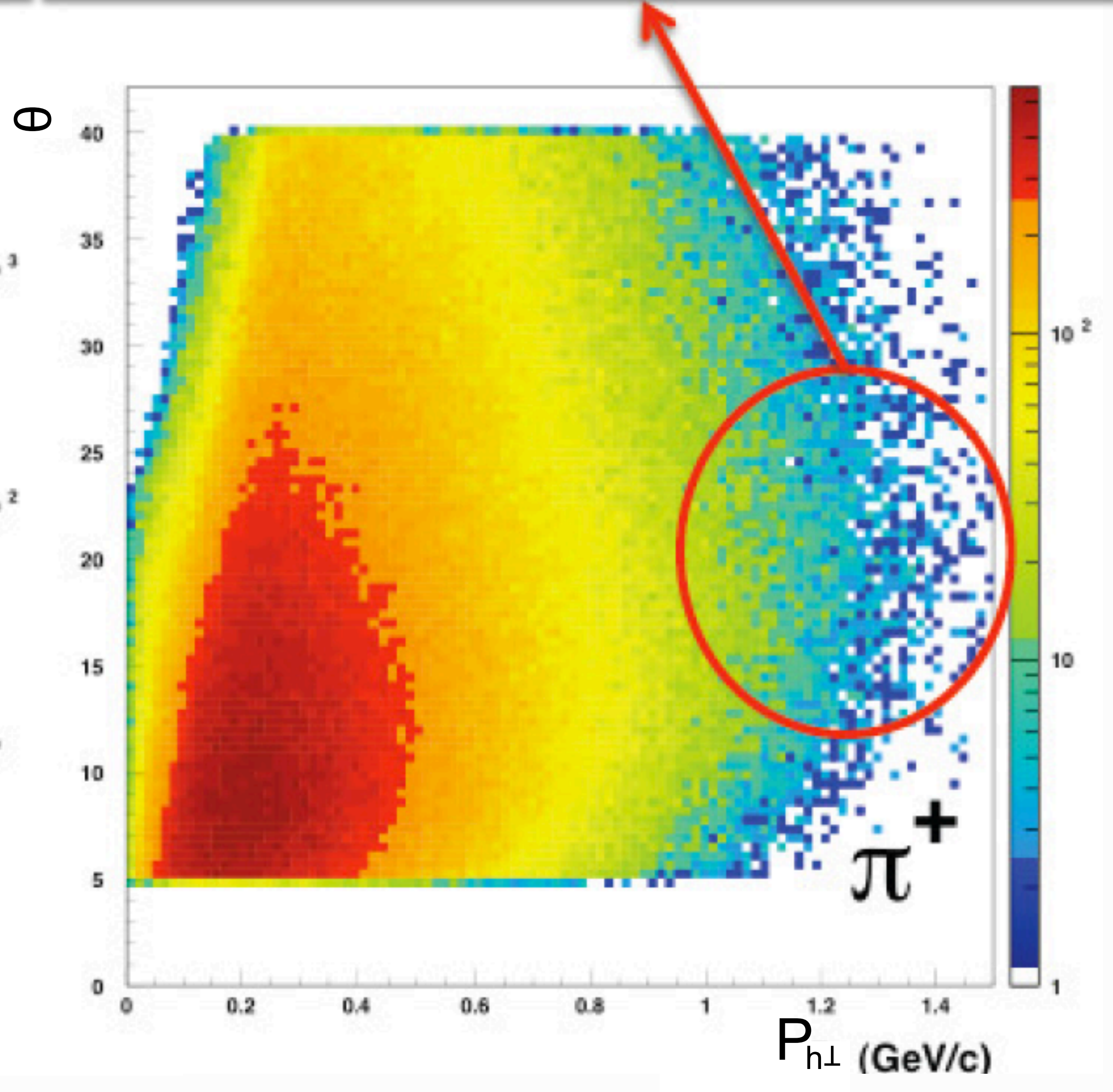
CLAS12 Kinematic Coverage



Large electron scattering angles (>20°) mandatory to reach high Q^2 values

Intermediate angular range (15-25°) mandatory to reach high $P_{h\perp}$ values





MC Simulation

The CLAS12 forward detector is perfectly suitable for high-Q^2 and high-$P_{h\perp}$ measurements since it is designed to cover up to 40° angles

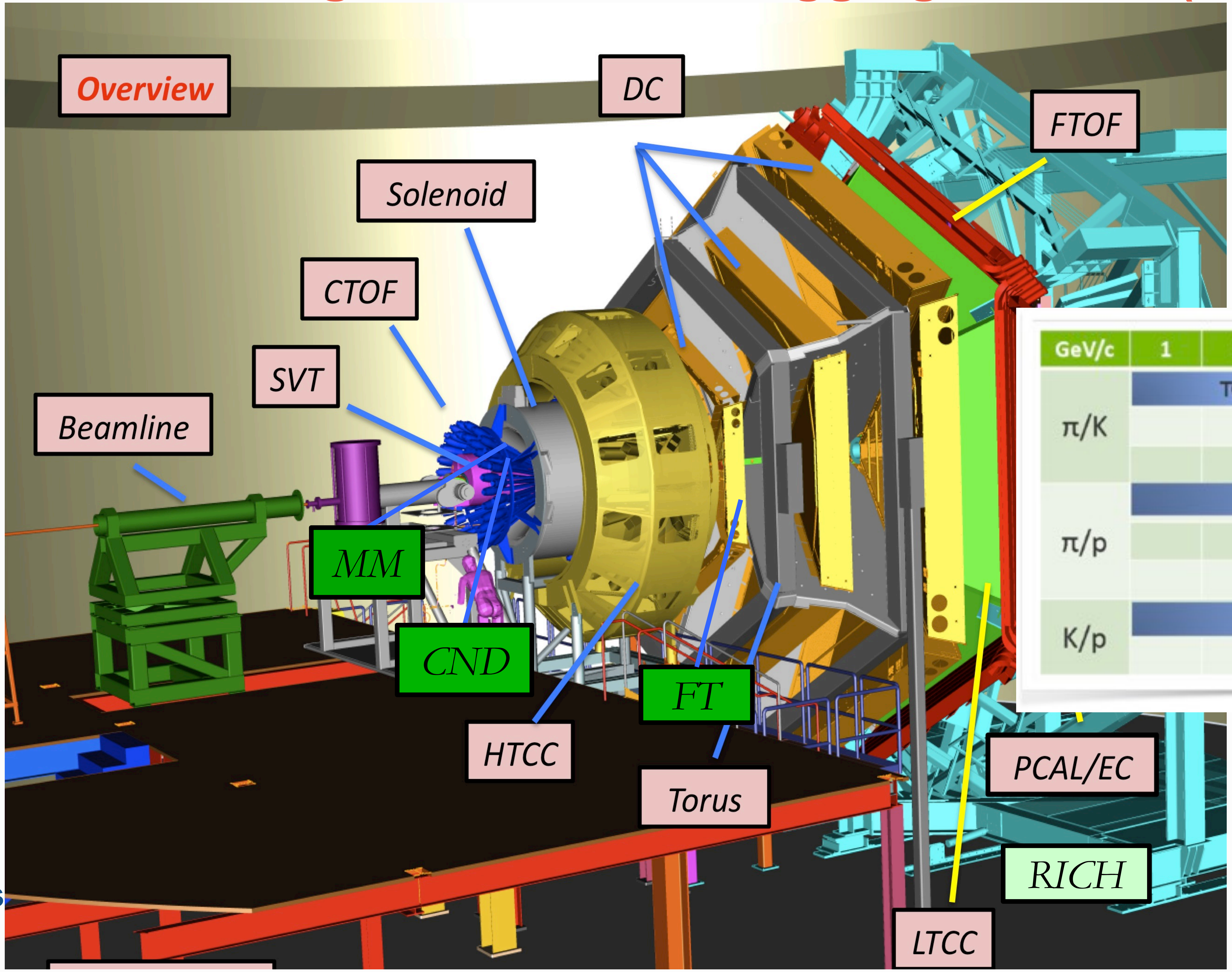
CLAS12 : The detector

Data taking started at the begging of 2018 (Hydrogen target)

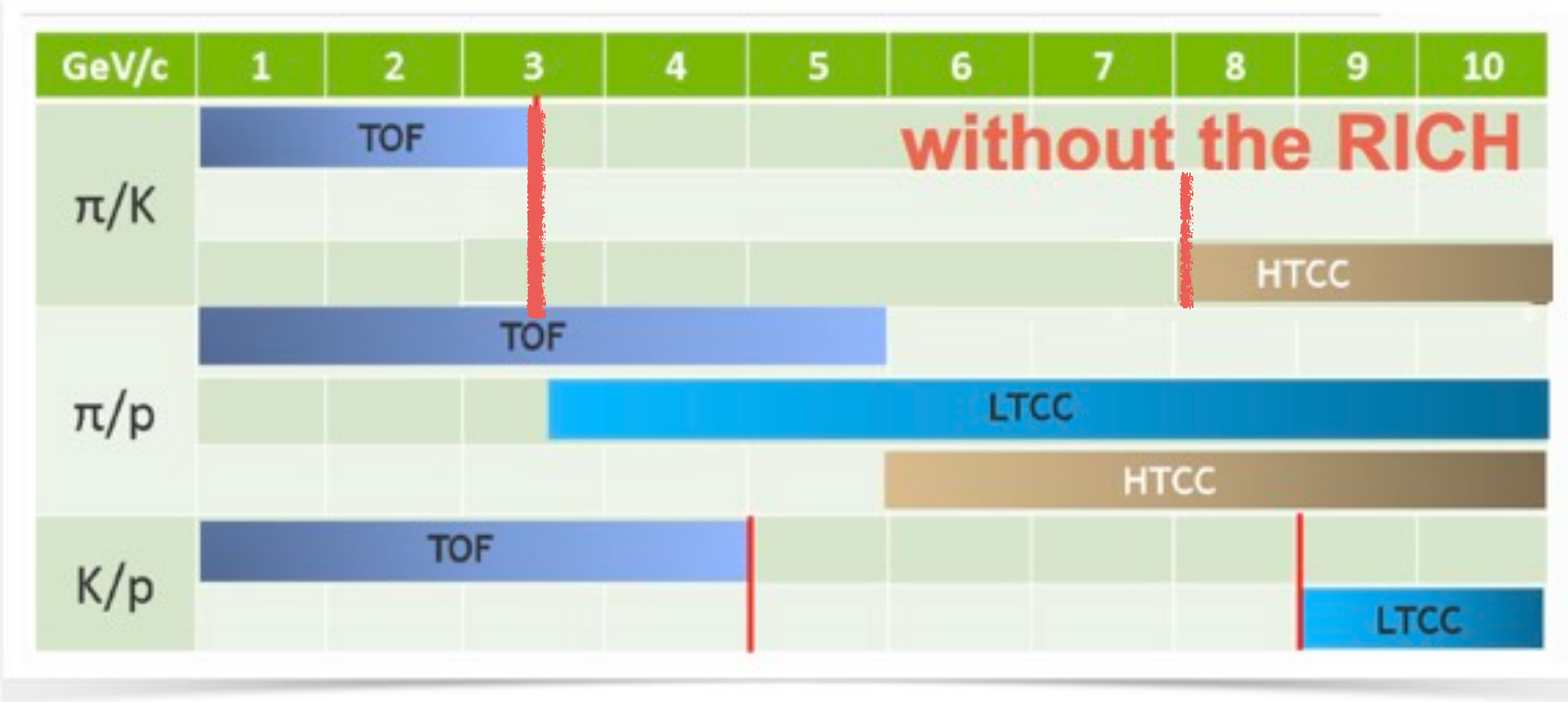
Forward Detector (FD)
- TORUS magnet
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter
- Forward Tagger
- RICH detector

Central Detector (CD)
- Solenoid magnet
- Silicon Vertex Tracker
- Central Time-of-Flight
- Central Neutron Det.
- MicroMegas

Beamline
- Photon Tagger
- Shielding
- Polarized - Unpol Targets



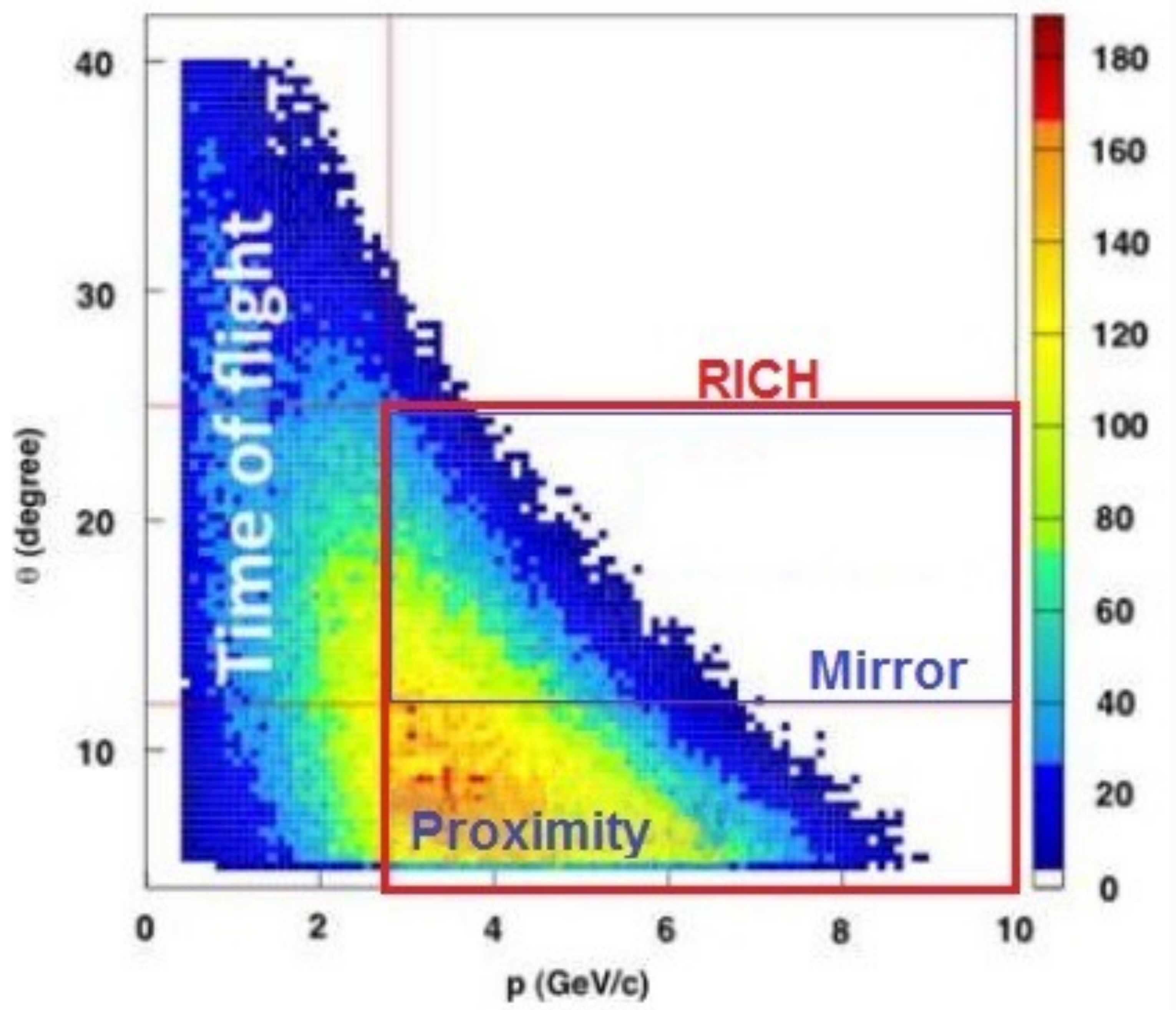
Particle Identification

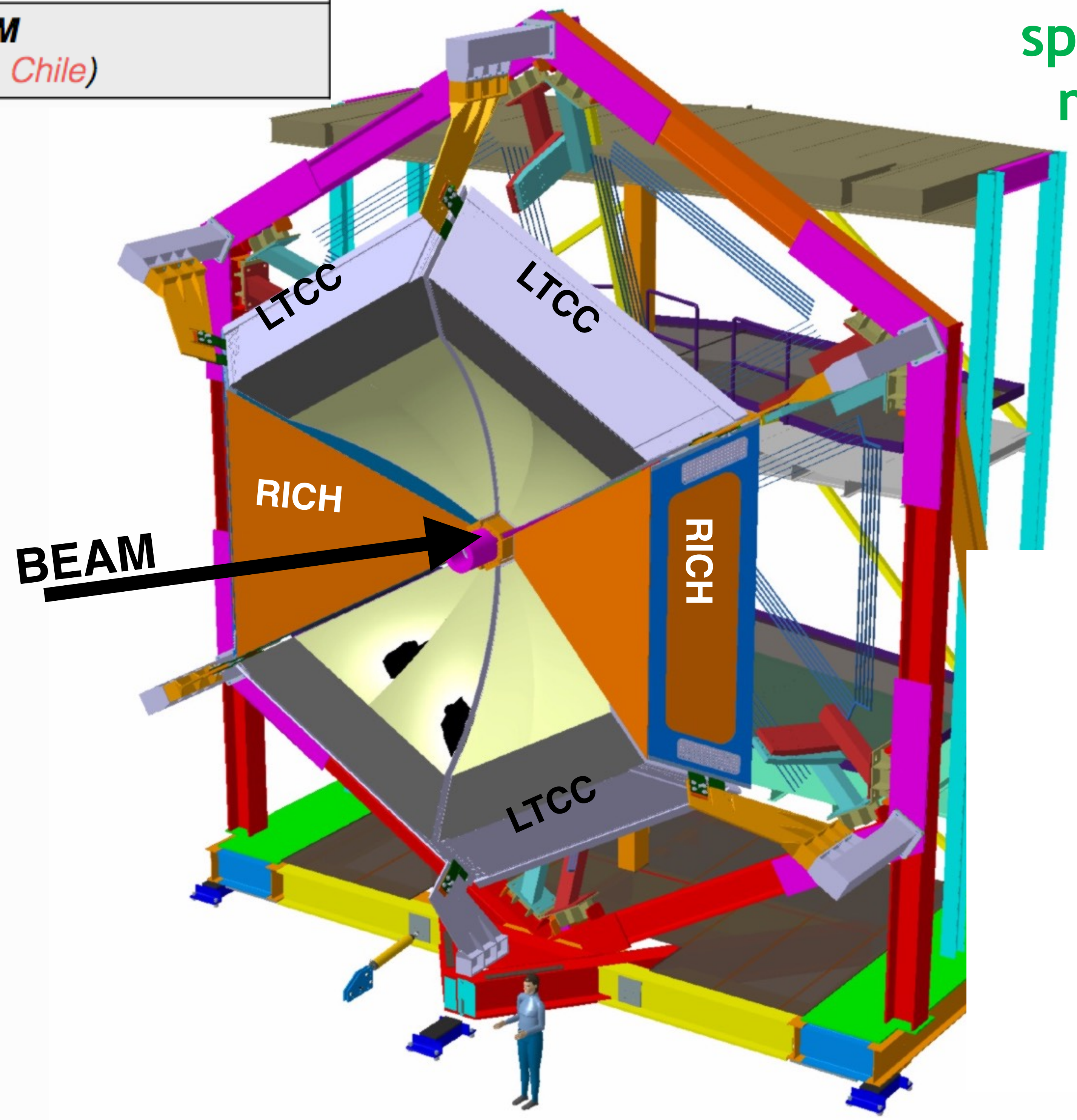


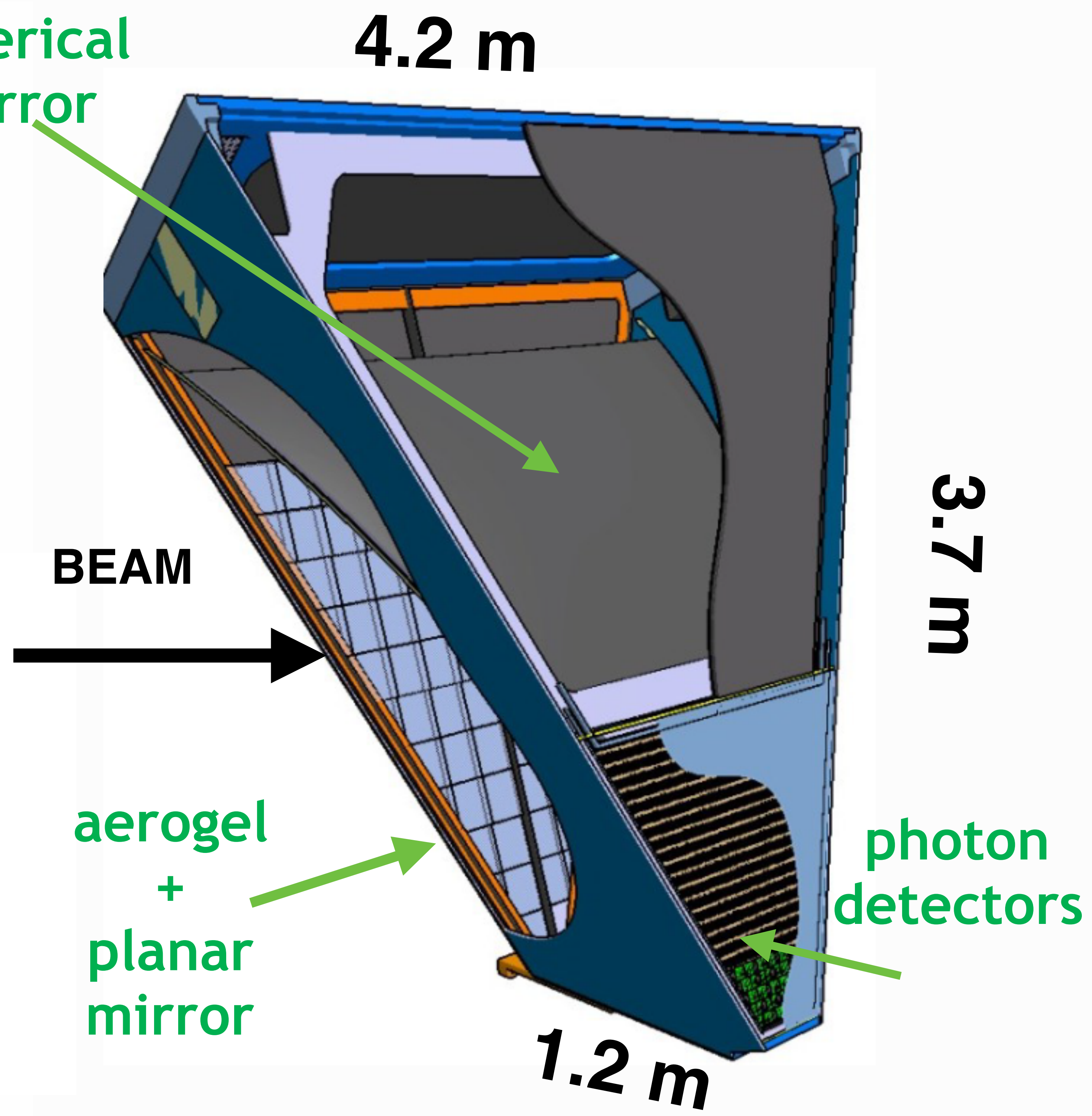
The CLAS12 RICH

***INFN** (Italy)* *Bari,Ferrara,Genova,LNF Frascati,Roma/ISS*	***Jefferson Lab*** *(Newport News,USA)*
Argonne National Lab *(Argonne, USA)*	***Duquesne University*** *(Pittsburgh, USA)*
The George Washington University *(Washington DC, USA)*	***Glasgow University*** *(Glasgow, UK)*
J. Gutenberg Universitat Mainz *(Mainz, Germany)*	***Kyungpook National University*** *(Daegu, Korea)*
University of Connecticut *(Storrs, USA)*	***UTFSM*** *(Valparaiso, Chile)*

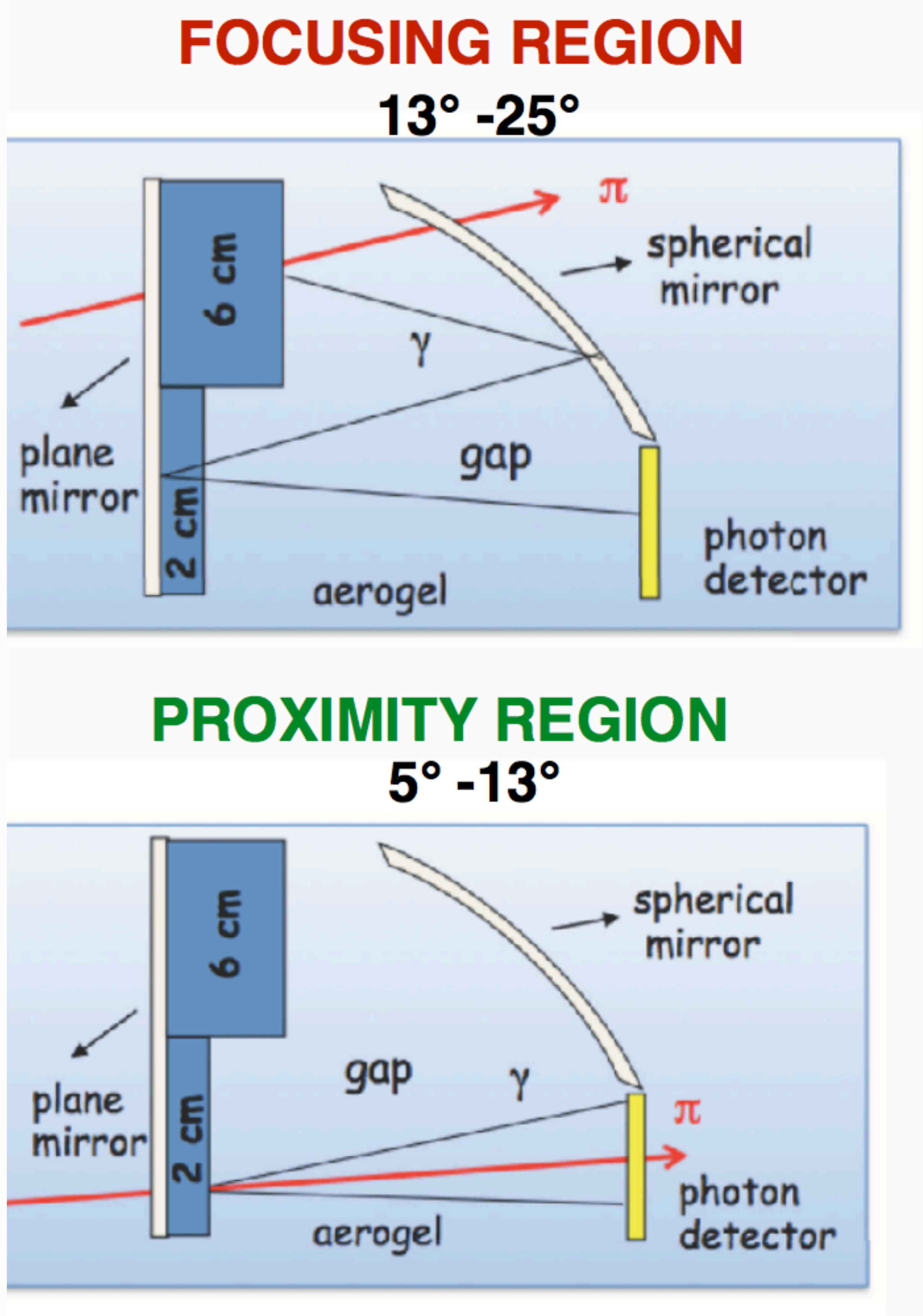
The CLAS12 RICH will provide the PID in the 3-8 GeV/c momentum range





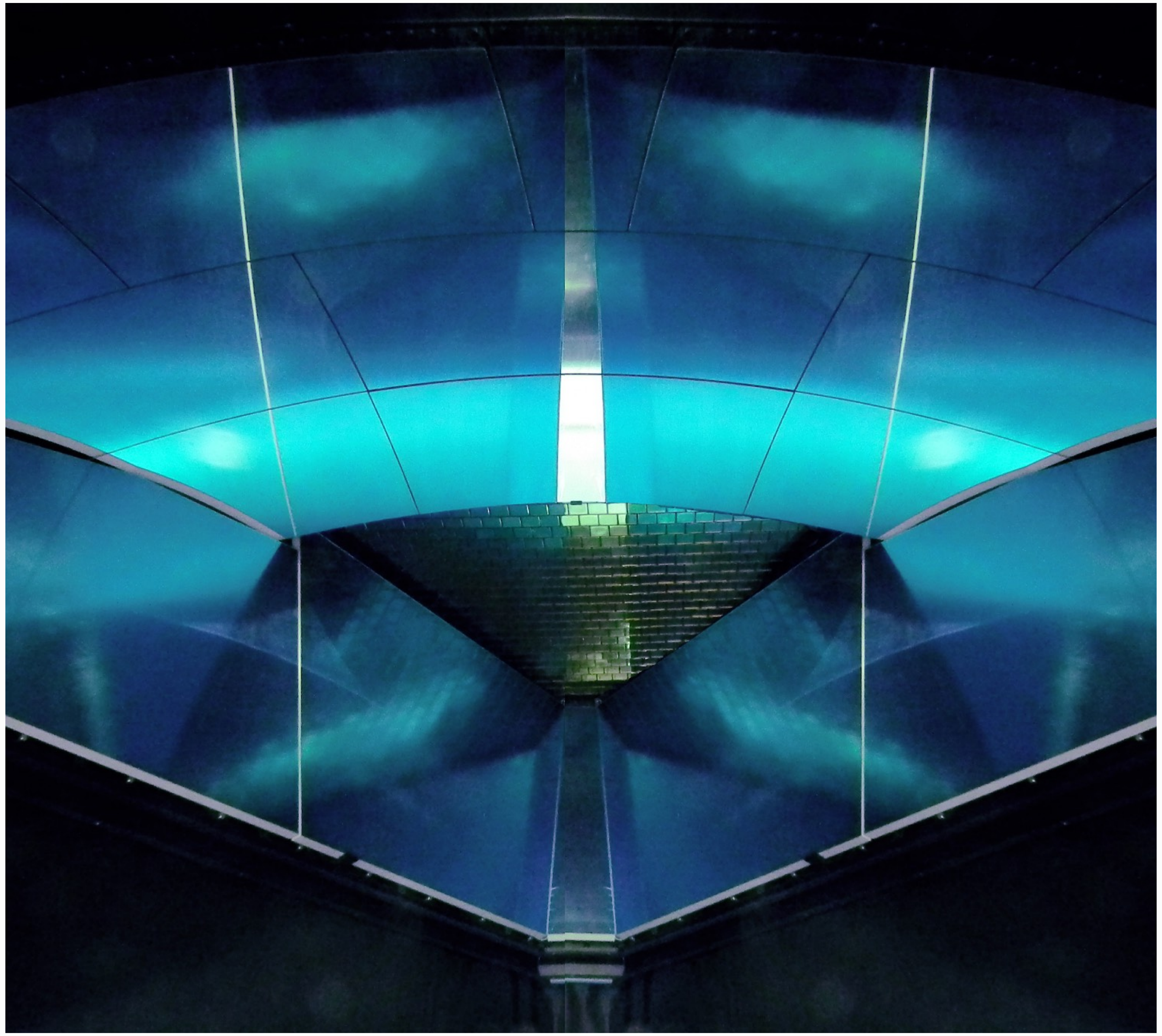


The RICH innovative geometry



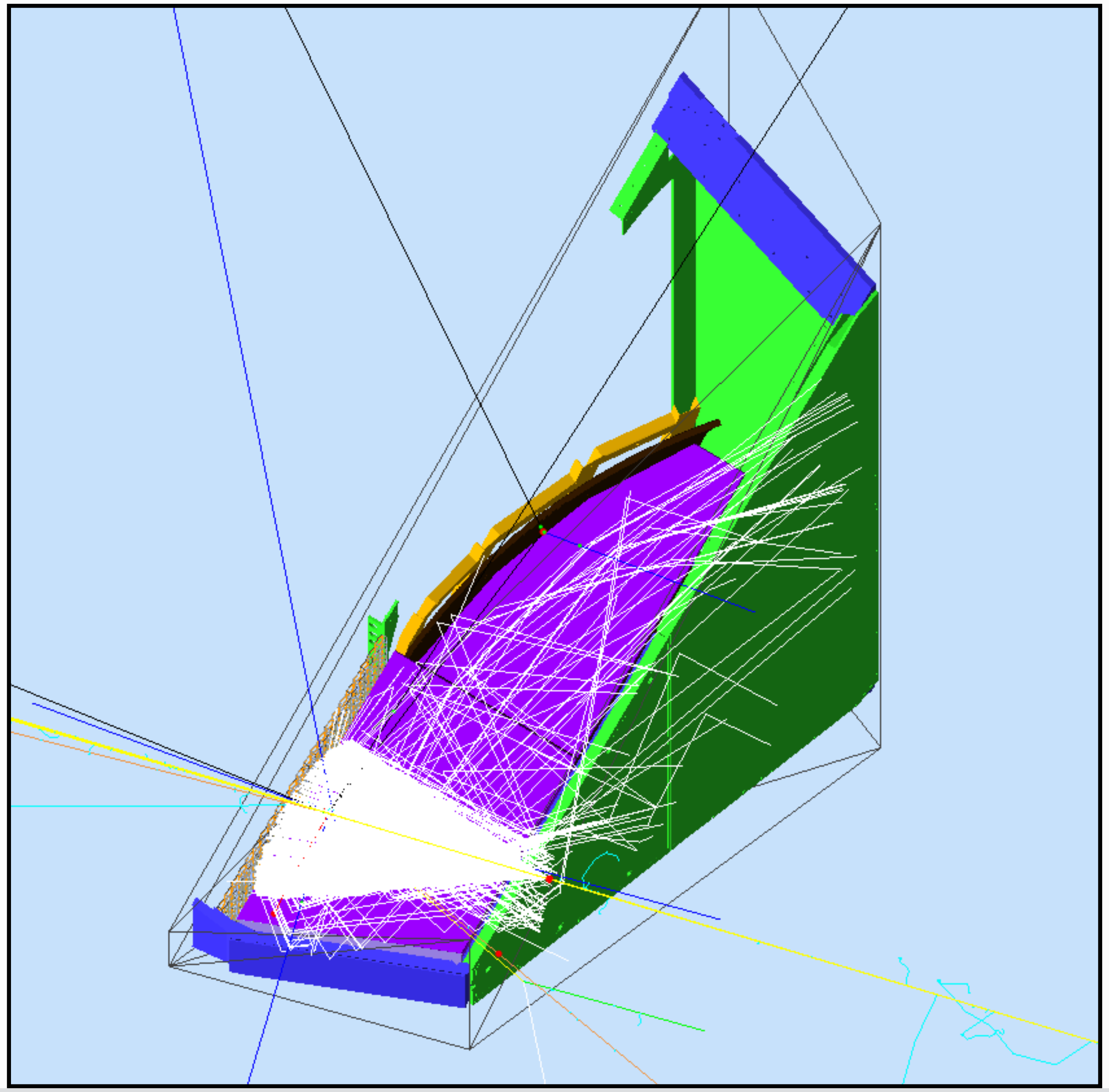
- Multiple passage of Cherenkov photons in aerogel
- 3 m path length
- Thick aerogel (3cm+3cm) to compensate photon loss
- Spherical mirrors to focus the light onto the photodetector arrays

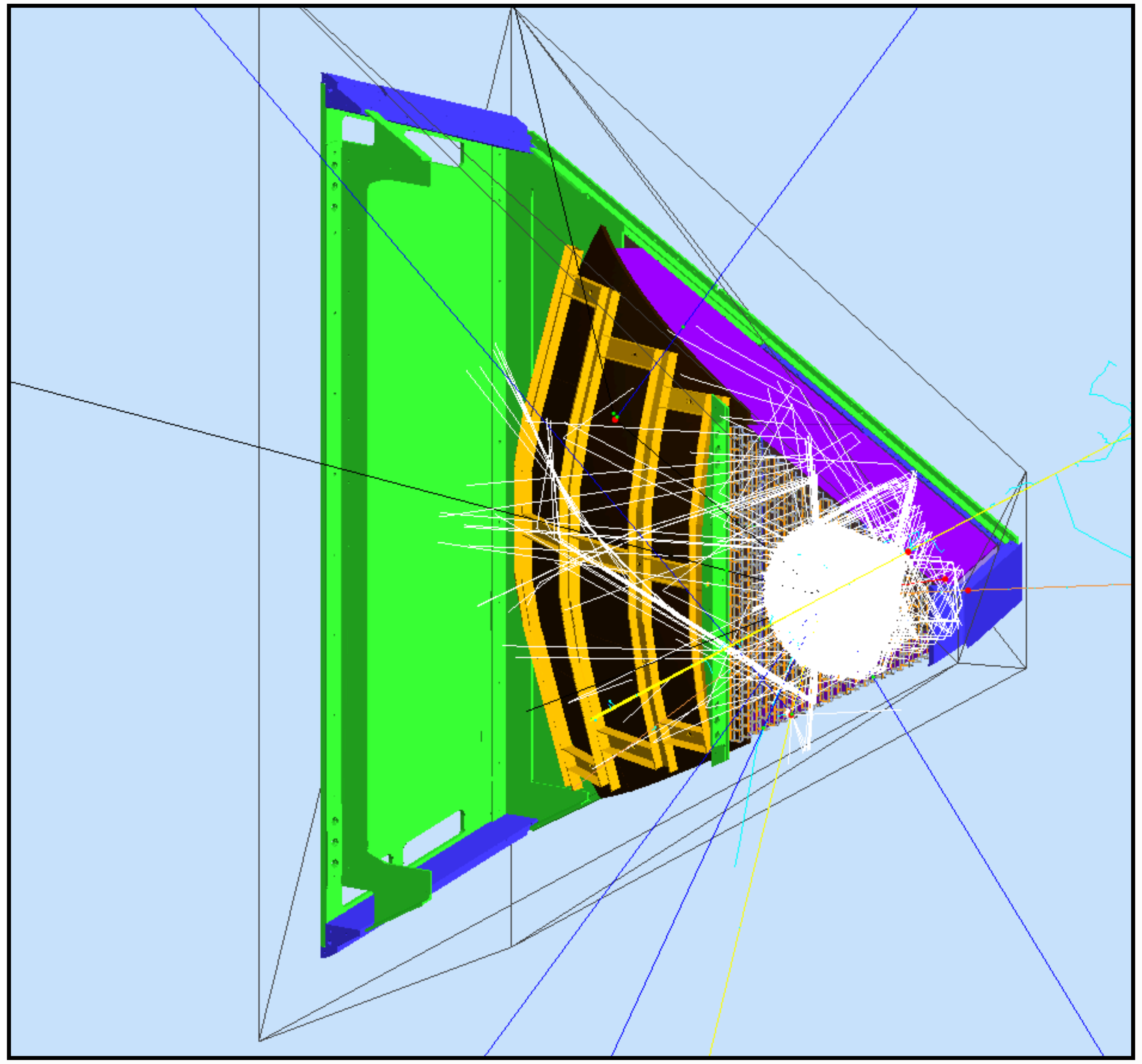
- Direct imaging of the Cherenkov photons
- 1m gap
- Thin aerogel (2cm)



The CLAS12 RICH Simulation

Geant4 Simulation:



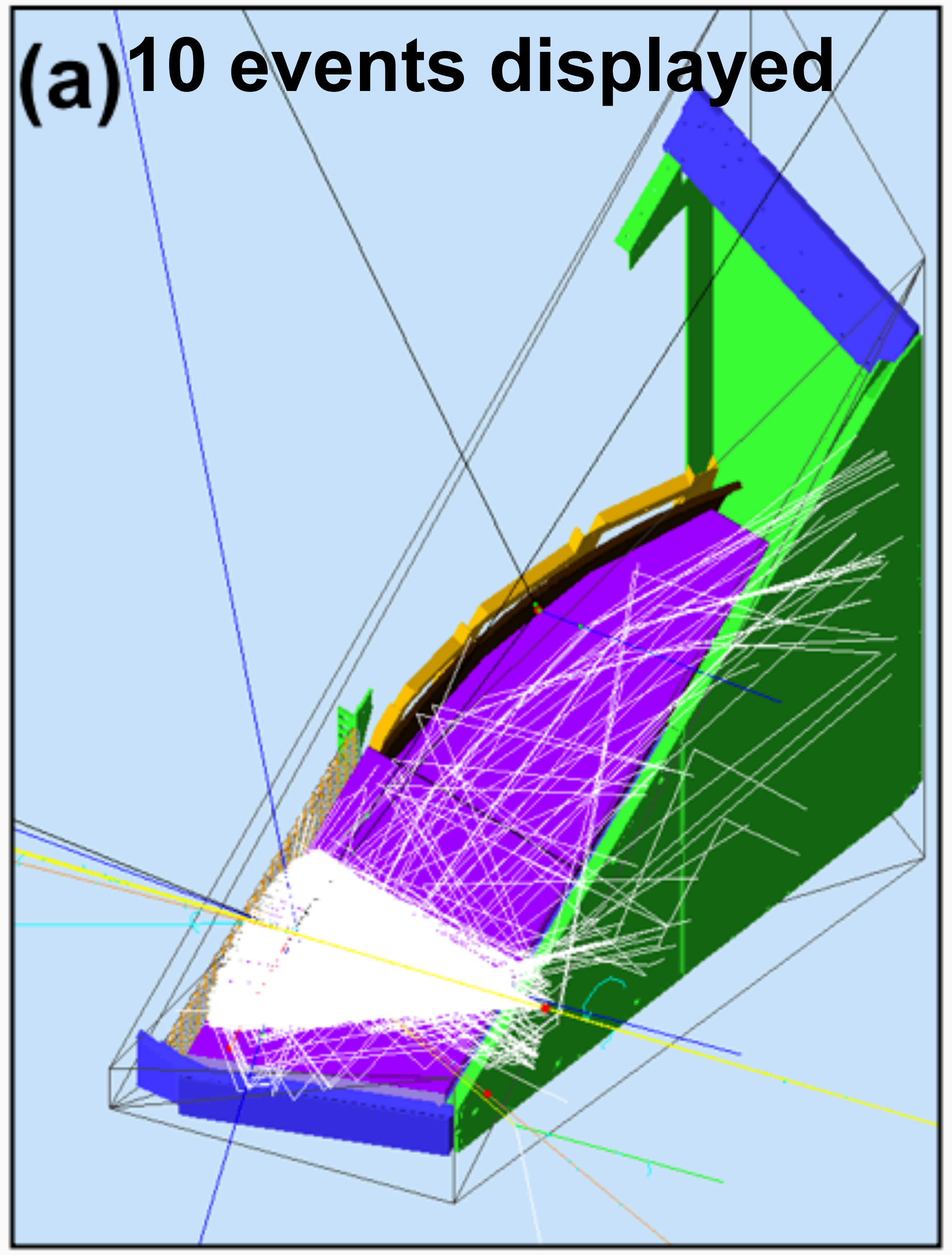


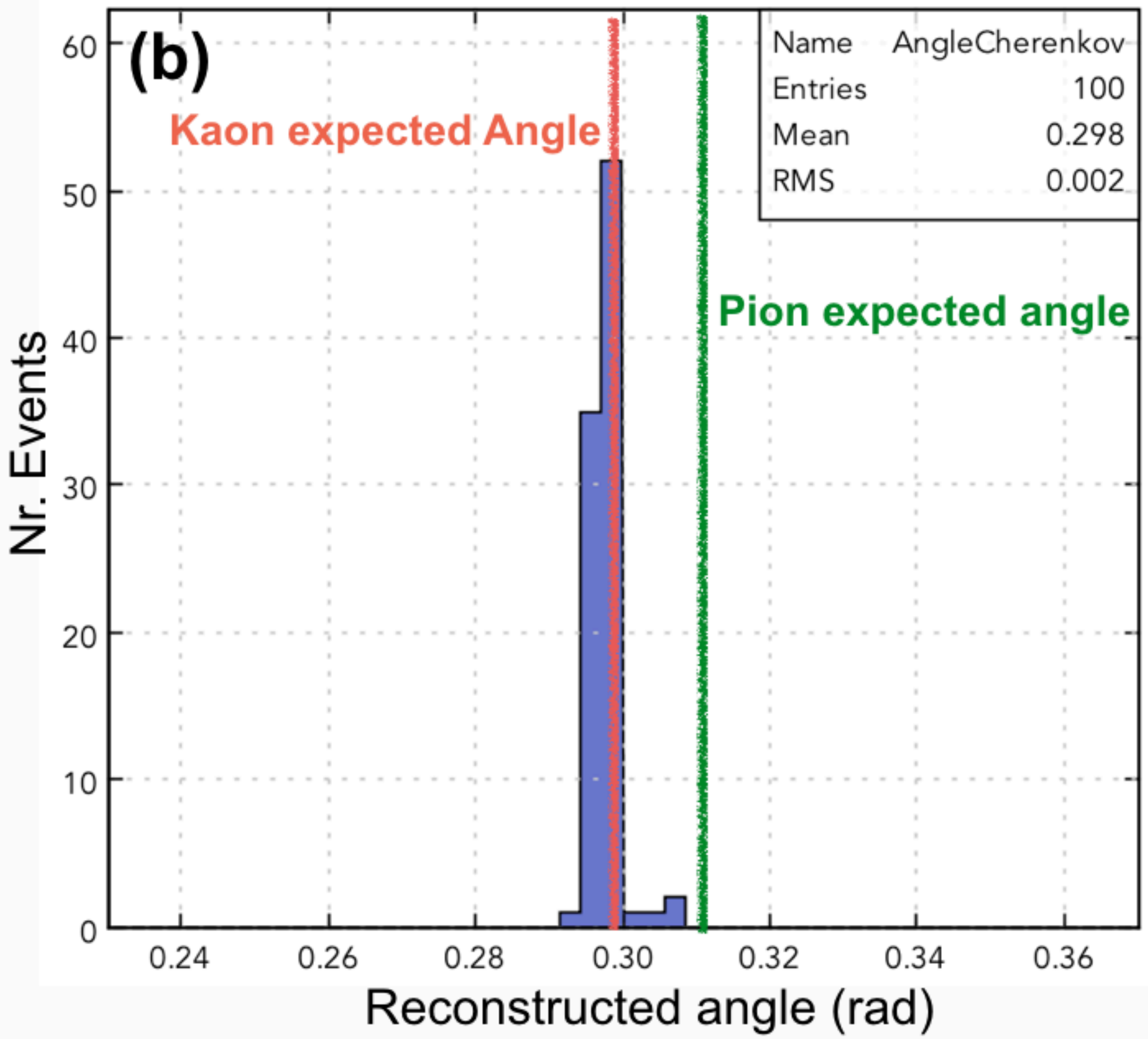
We used CAD projects and imported in the simulation.

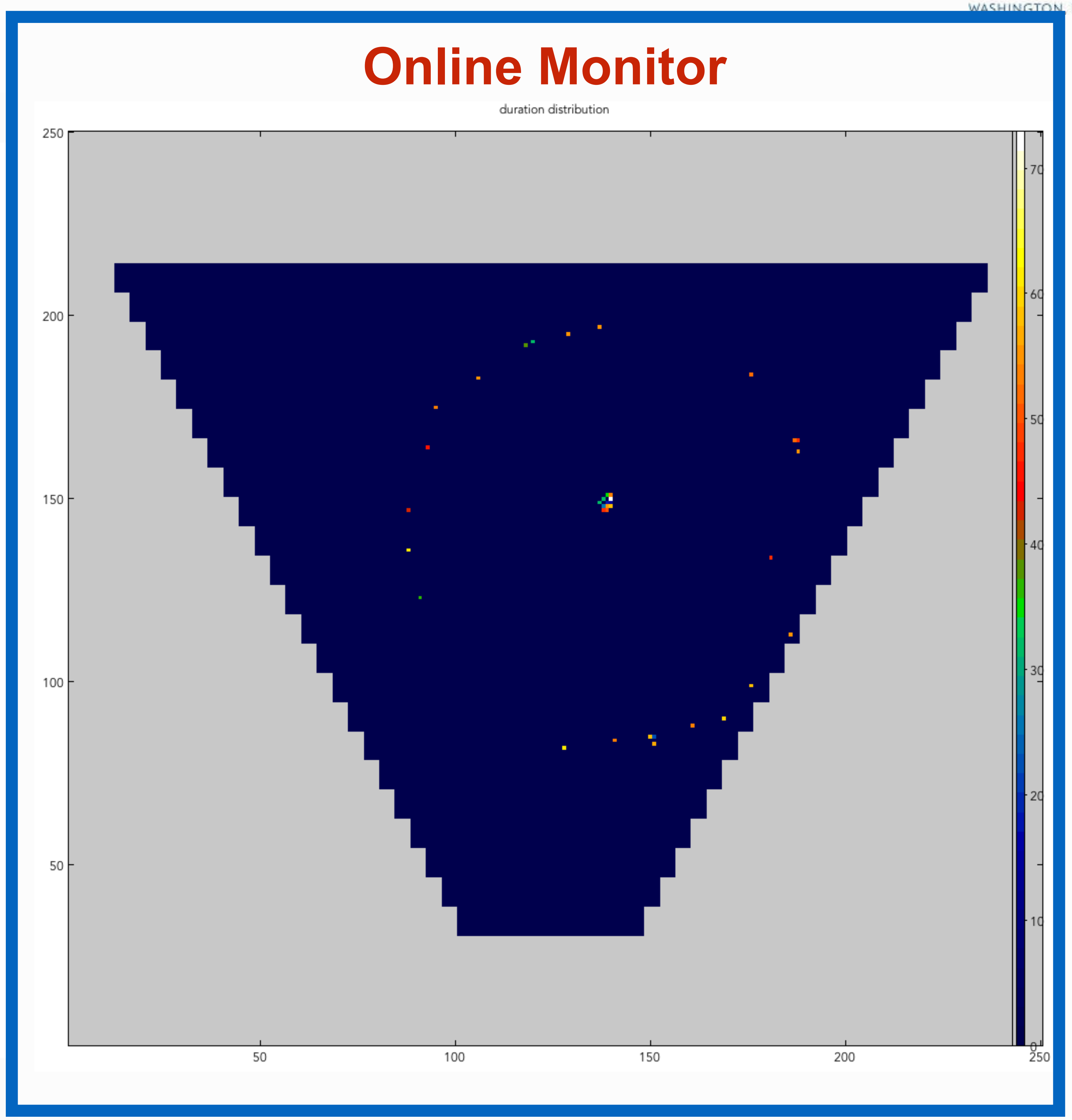
Today most of the CLAS12 detectors have adopted the same strategy with an overall increase of performance.

The CLAS12 RICH Reconstruction

Simulation : 100 Kaons
Momentum: 6 GeV/c







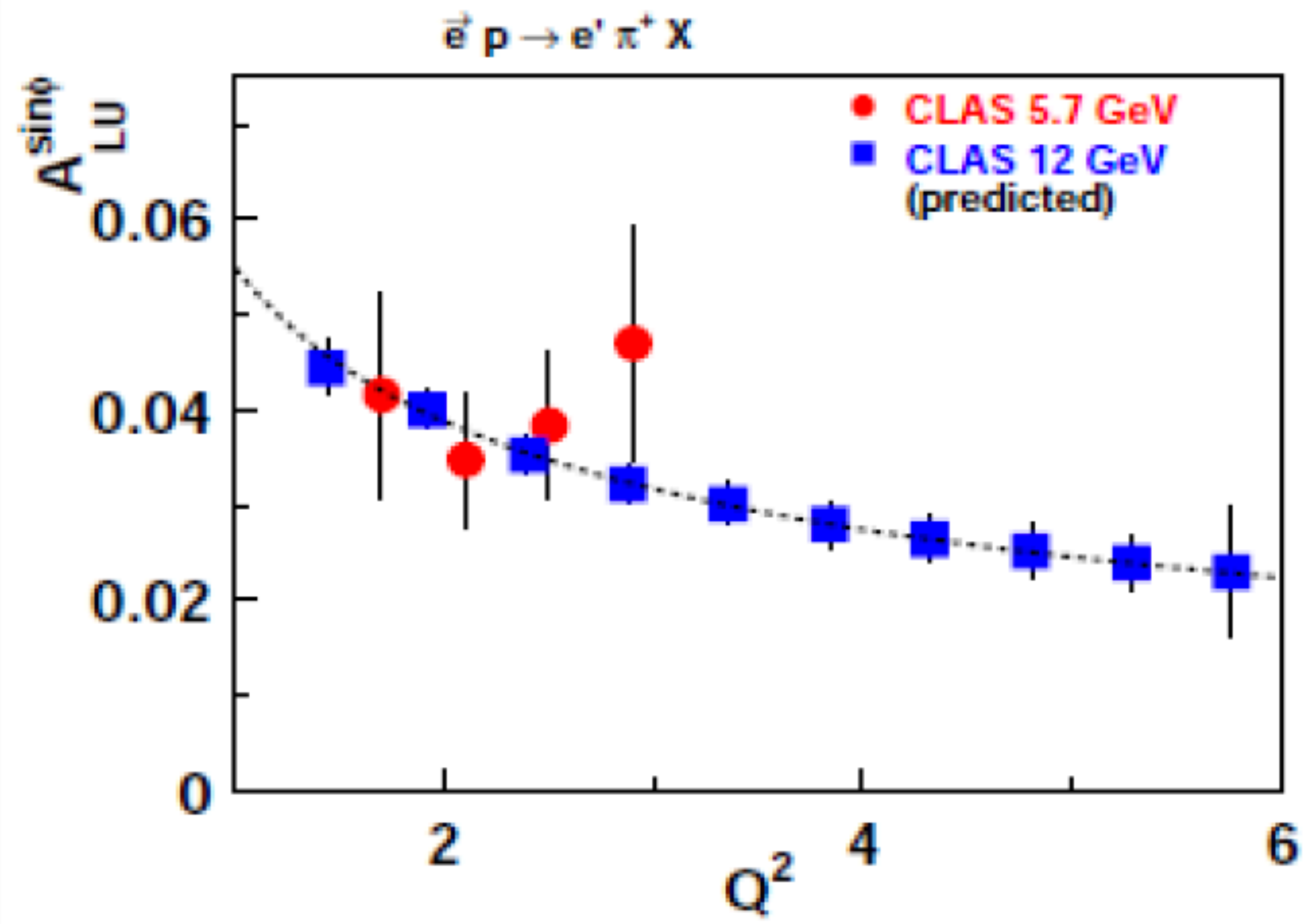
The algorithm has been applied successfully on data. Optimization for the reflections is under development by the collaboration.

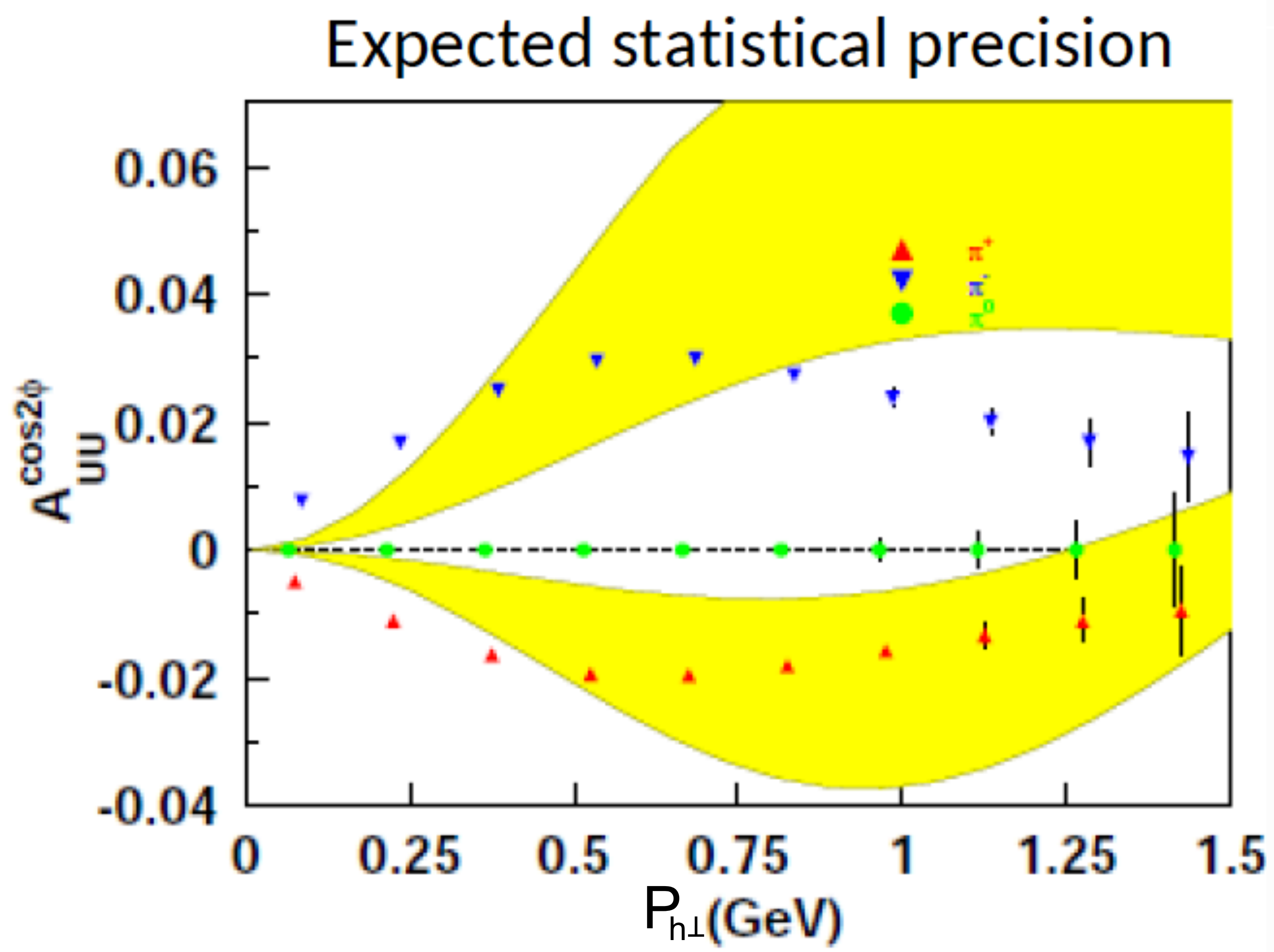
Expected Results with CLAS12

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

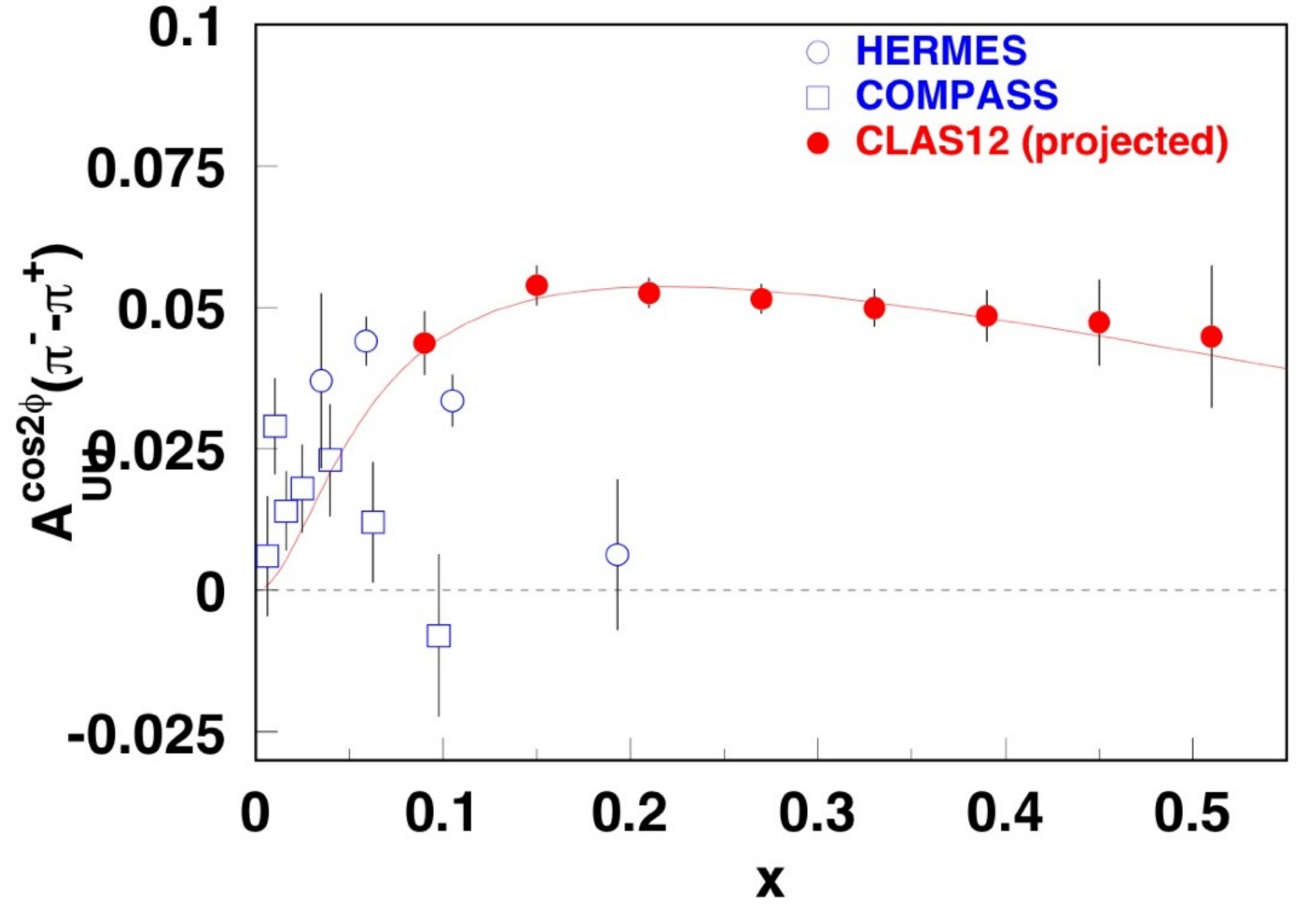
CLAS12 Preliminary Simulations

	$A_{LU}^{sin\phi}$	$A_{UU}^{cos\phi}$	$A_{UU}^{cos2\phi}$
Identified particle	π	π	π
Beam polarization	3%	-	-
Acceptance correction	1%	3%	1%
Radiative correction	3%	3%	3%
Fitting procedure	3%	4%	4%





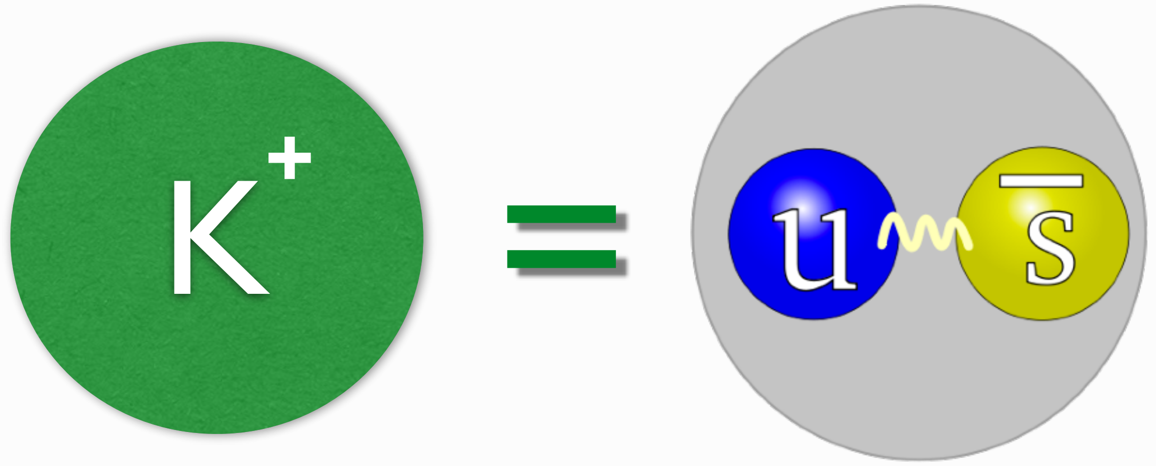
Perturbative and radiative correction are considered flavor blind



Simulation performed with CLASDIS package (an Implementation of PEPSI Lund MC) tested with CLAS6 data

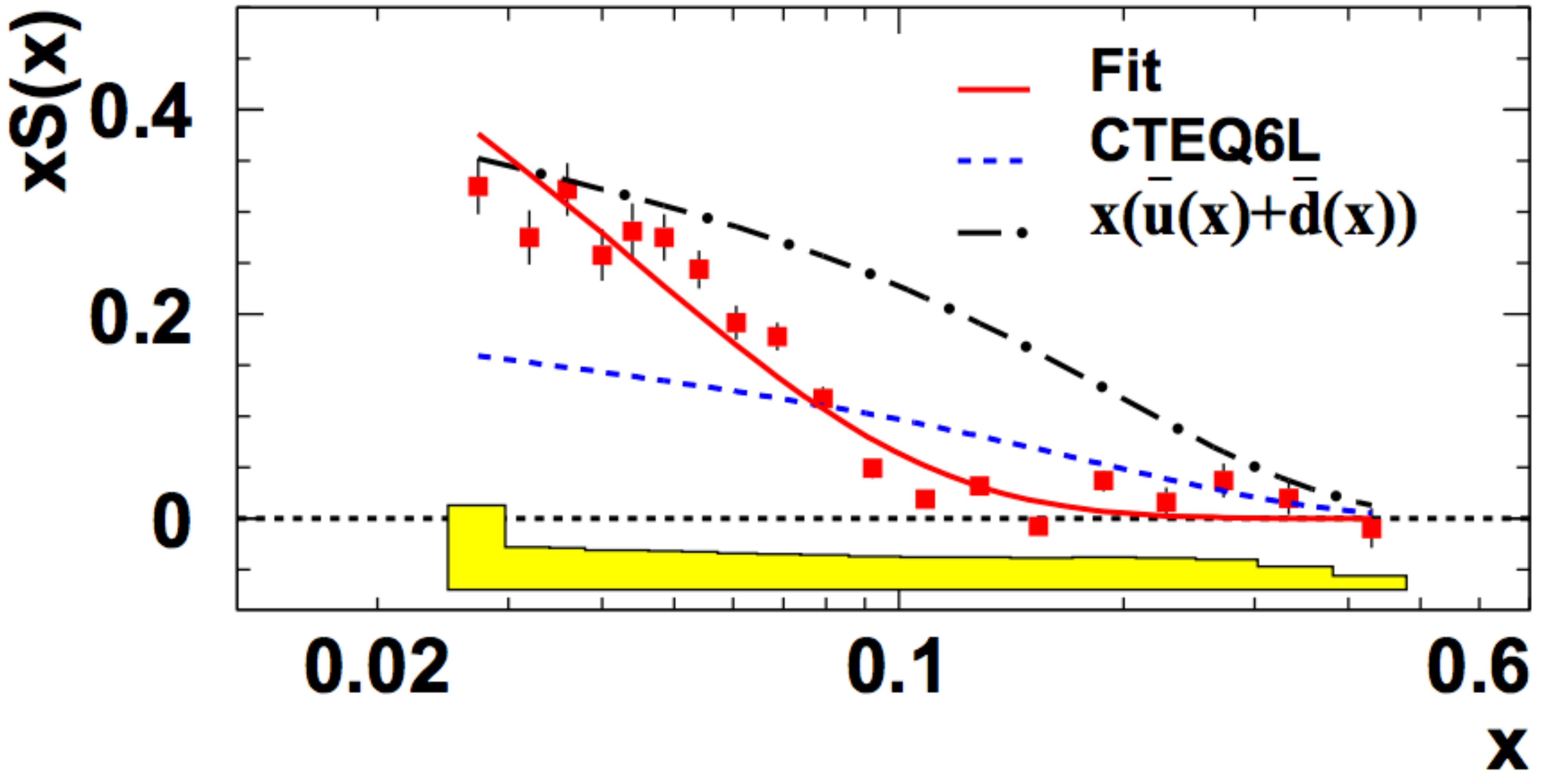
Probing Strangeness

Thanks to the PID provided by the RICH detector it will be possibile to study Kaon electroproduction with high precision at CLAS12.

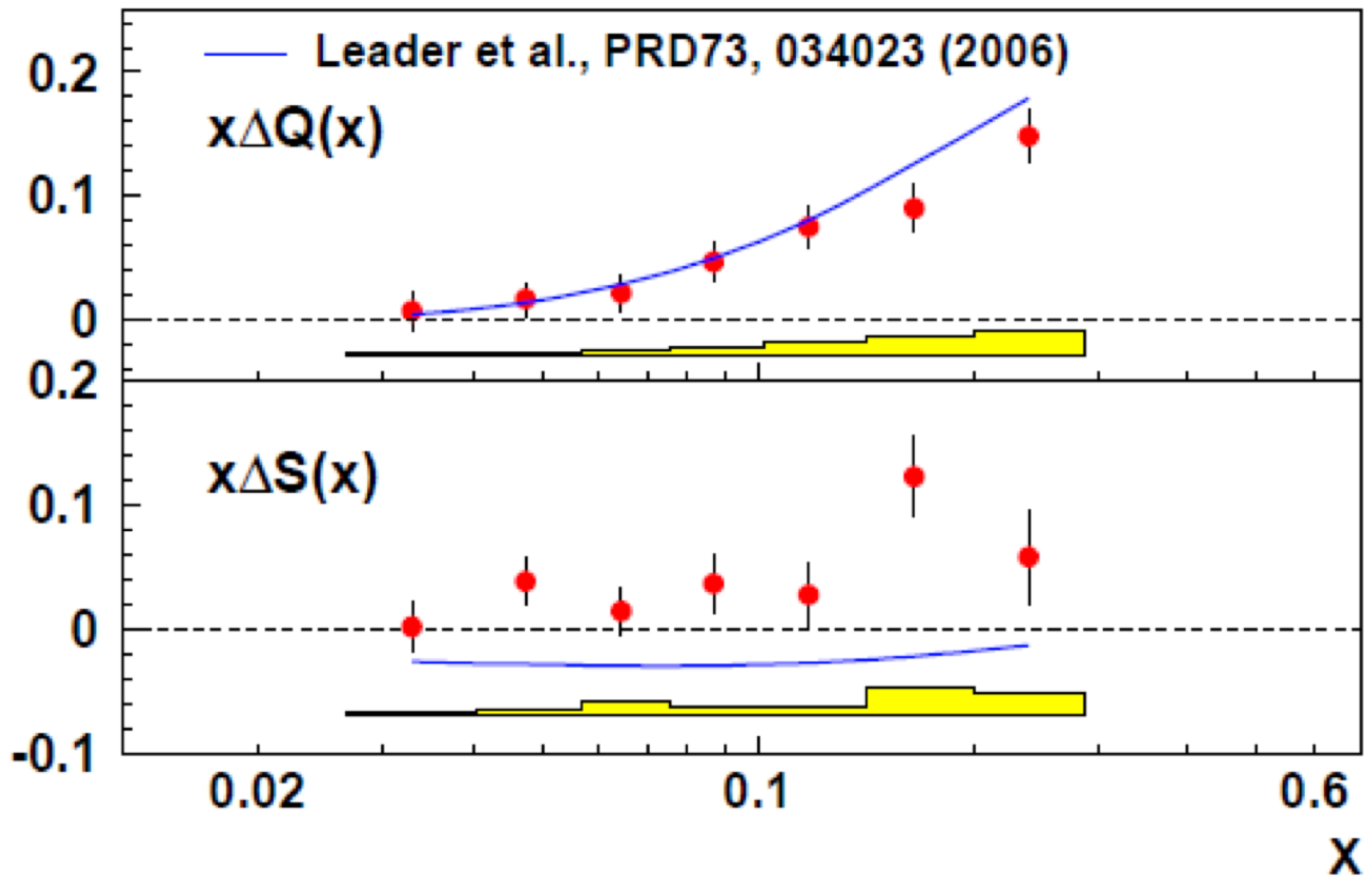


Hermes found an opposite sign in cos2φ for K^- respect π^-

Strangeness Unpolarized Distribution



Strangeness Helicity Distribution



Status of the Analysis

We are doing new simulations with all the information gathered on the status of the detectors.

We are cooking about 20% of the data taken so far :
Preliminary BSA and Neutral Pion multiplicities will be presented at the DNP conference in October 2018

Thank you !