The EIC

Charlotte Van Hulse
University of Alcalá

AdT
Comunidad de Madrid

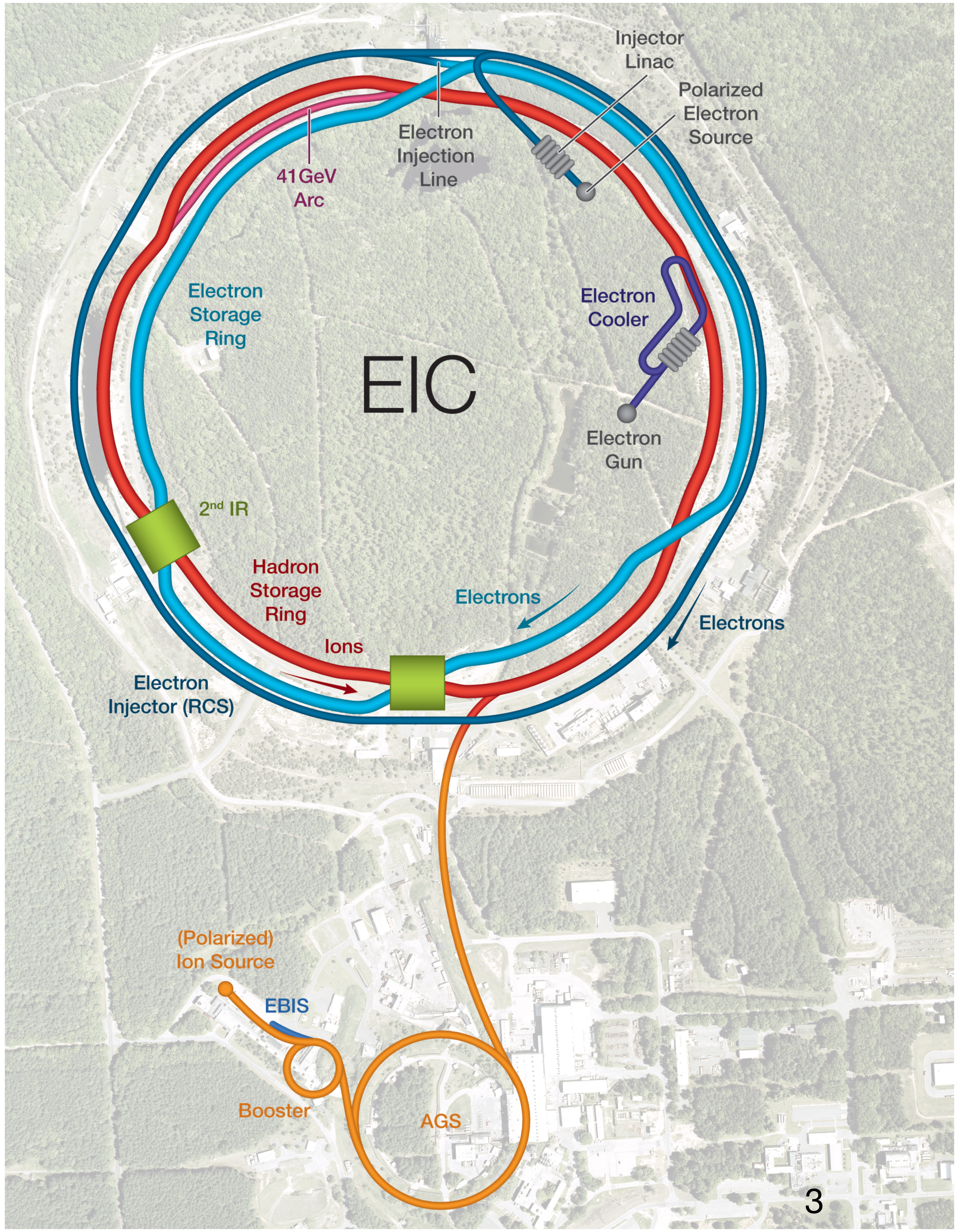
22nd STFC Nuclear Physics Summer School
University of Durham
11–24 August 2024

On the menu

- EIC machine: overview
- ePIC: the first EIC detector
- Why an EIC?
  - Nucleon spin
  - Multi-dimensional nucleon structure
  - Saturation
  - Hadronisation

The electron-ion collider (EIC)

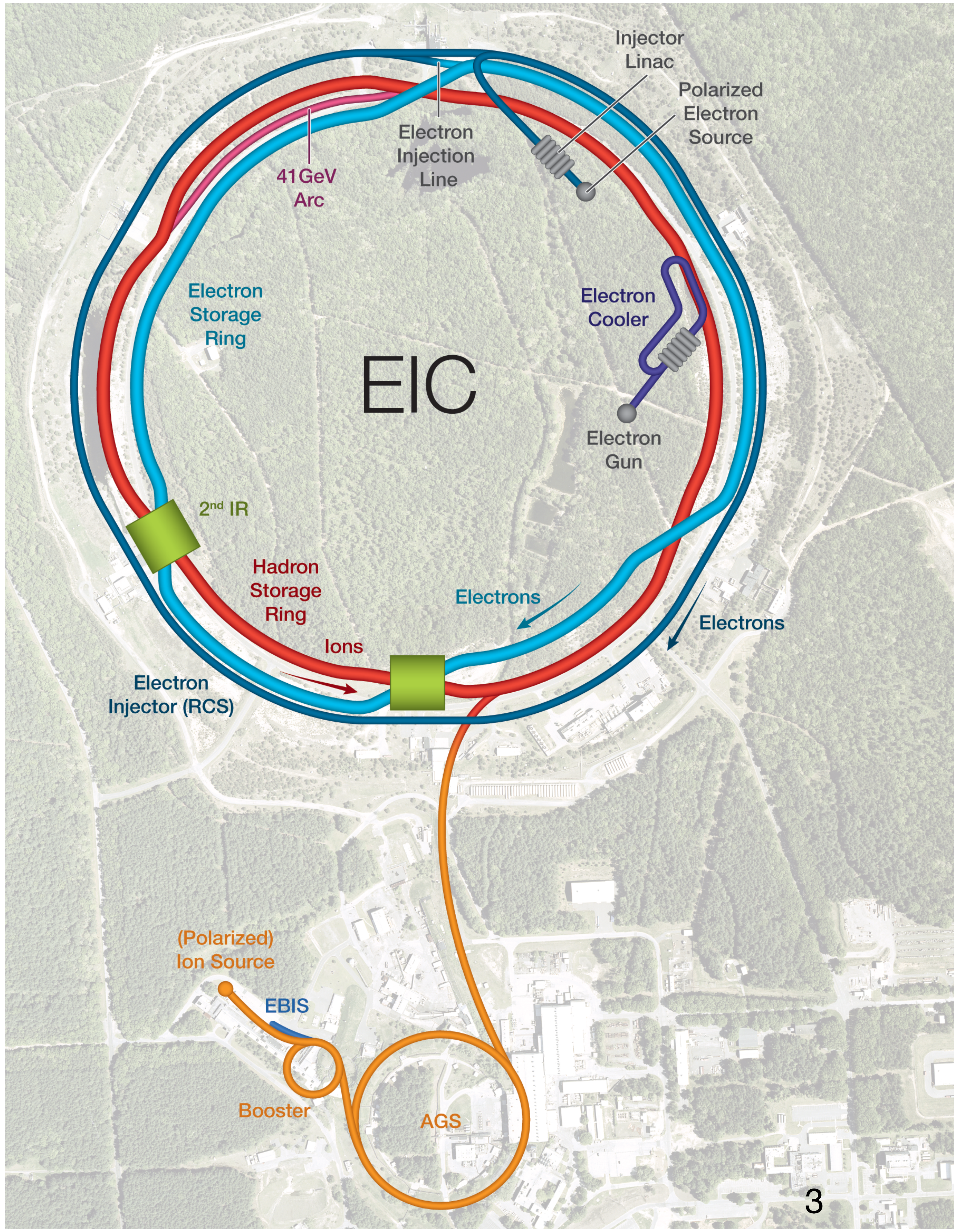
The electron-ion collider (EIC)



- Based on RHIC:
  - use existing hadron storage ring energy: 41–275 GeV
  - add electron storage ring in RHIC tunnel energy: 5–18 GeV

$\rightarrow \sqrt{s} = 29 - 141$ GeV

The electron-ion collider (EIC)



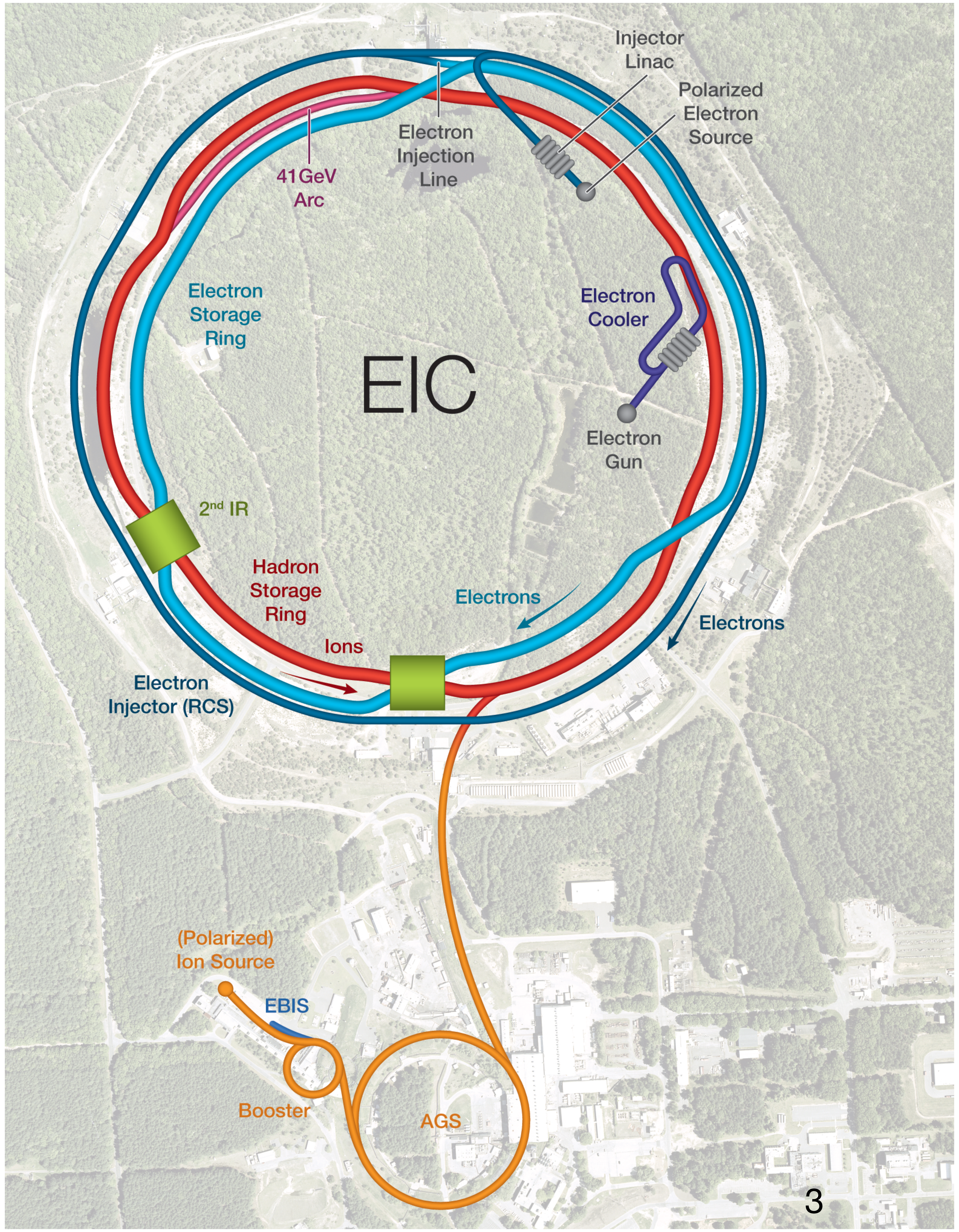
- Based on RHIC:
  - use existing hadron storage ring energy: 41–275 GeV
  - add electron storage ring in RHIC tunnel energy: 5–18 GeV

$\rightarrow \sqrt{s} = 29 - 141$ GeV

- $\vec{e} + \vec{p}^{\uparrow}, \vec{d}^{\uparrow}, \overrightarrow{He}^{\uparrow}$, unpolarised ions up to U

~ 70% polarisation

The electron-ion collider (EIC)



- Based on RHIC:
  - use existing hadron storage ring energy: 41–275 GeV
  - add electron storage ring in RHIC tunnel energy: 5–18 GeV

  $\rightarrow \sqrt{s} = 29 - 141$ GeV

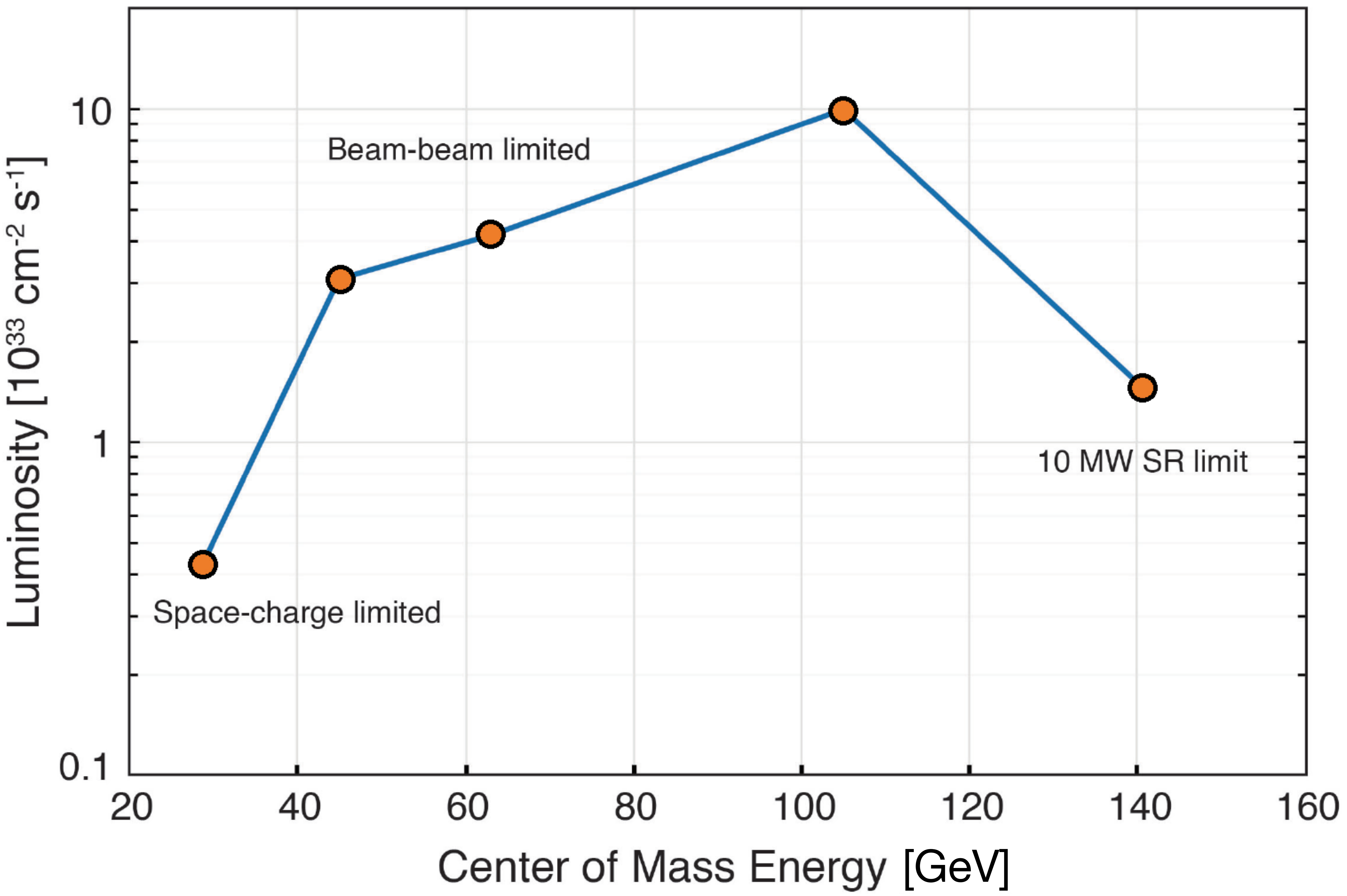
- $\vec{e} + \vec{p}^{\uparrow}, \vec{d}^{\uparrow}, \overrightarrow{He}^{\uparrow}$, unpolarised ions up to U

  ~ 70% polarisation

- $\mathscr{L} = 10^{33-34}$ cm^{-2} s^{-1}

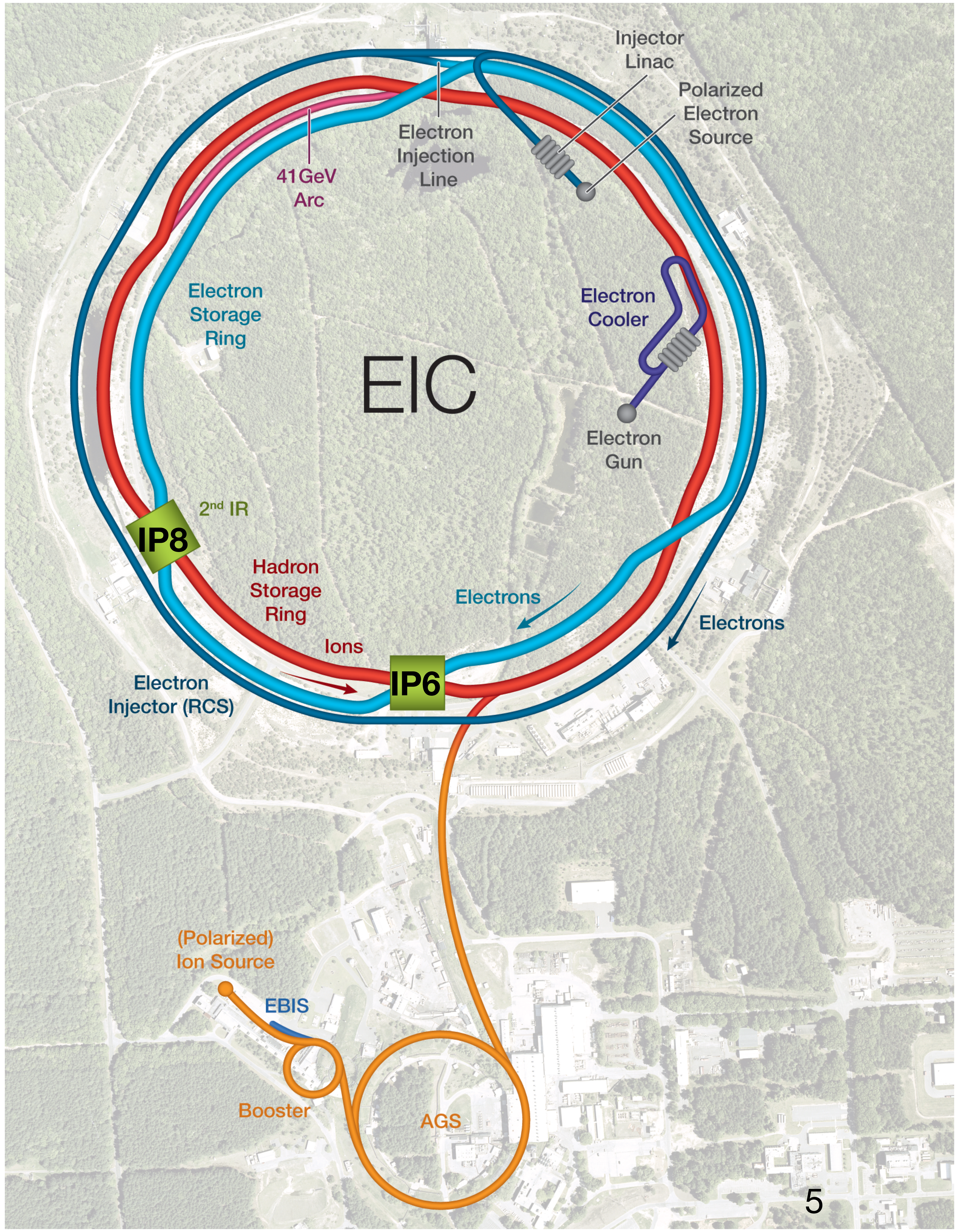
  $\leftrightarrow \mathscr{L}_{\text{int}} = 10 - 100$ fb^{-1}/year

Luminosity and centre-of-mass energy: ep collisions



Luminosity for eA similar within factor 2–3

The electron-ion collider (EIC)



- Based on RHIC:
  - use exiting hadron storage ring
    energy: 41–275 GeV
  - add electron storage ring in RHIC tunnel
    energy: 5–18 GeV

  $\rightarrow \sqrt{s} = 29 - 141$ GeV (per nucleon)

- ion beam: proton to Uranium

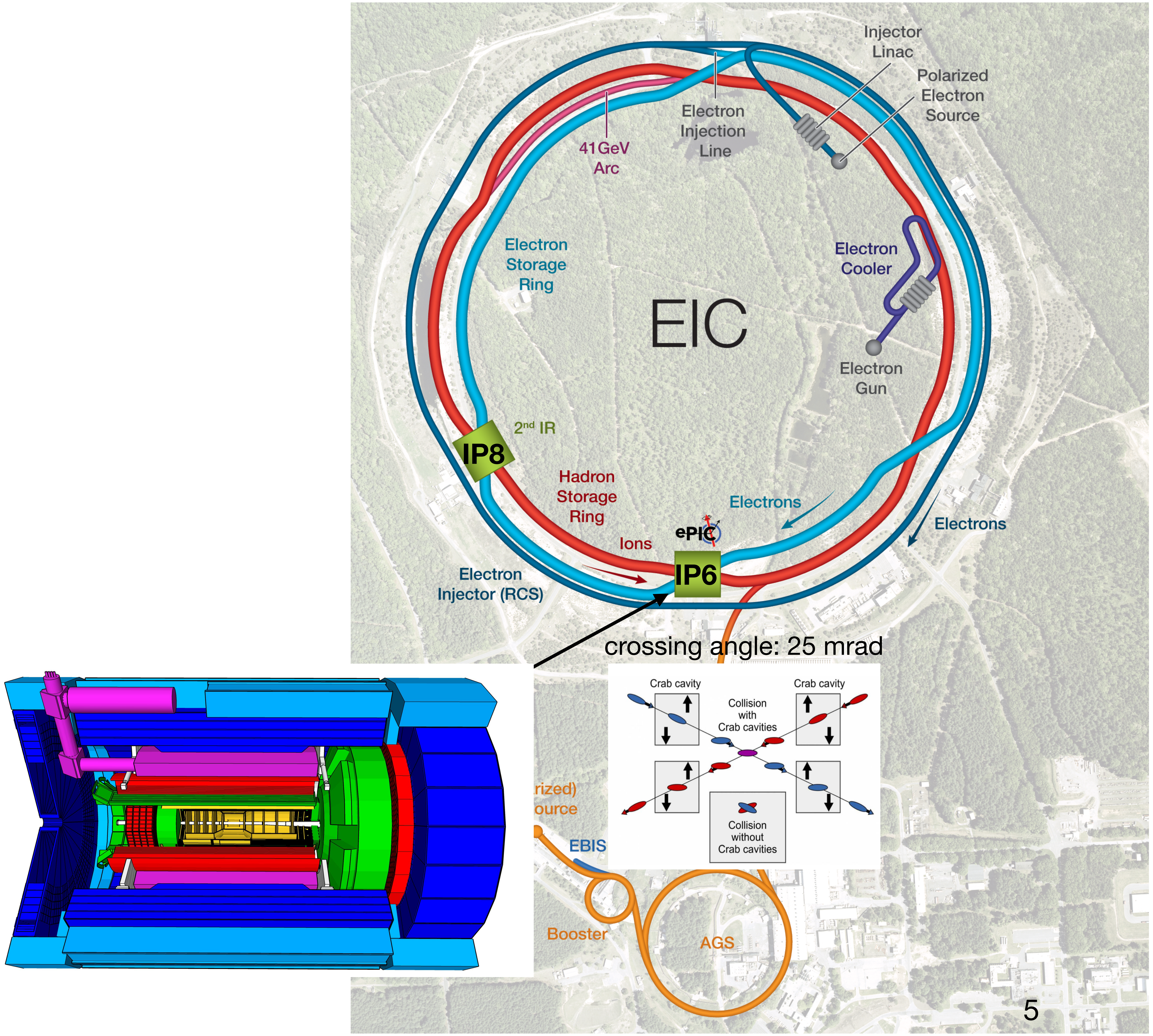
- $\vec{e} + \vec{p}^{\uparrow}, \vec{d}^{\uparrow}, \overrightarrow{He}^{\uparrow}$

  ~ 70% polarisation

- $\mathscr{L} = 10^{33-34}$ cm^{-2} s^{-1}

  $\leftrightarrow \mathscr{L}_{\text{int}} = 10 - 100$ fb^{-1}/year

The electron-ion collider (EIC)



- Based on RHIC:
  - use exiting hadron storage ring energy: 41–275 GeV
  - add electron storage ring in RHIC tunnel energy: 5–18 GeV

  $\rightarrow \sqrt{s} = 29 - 141$ GeV (per nucleon)

- ion beam: proton to Uranium

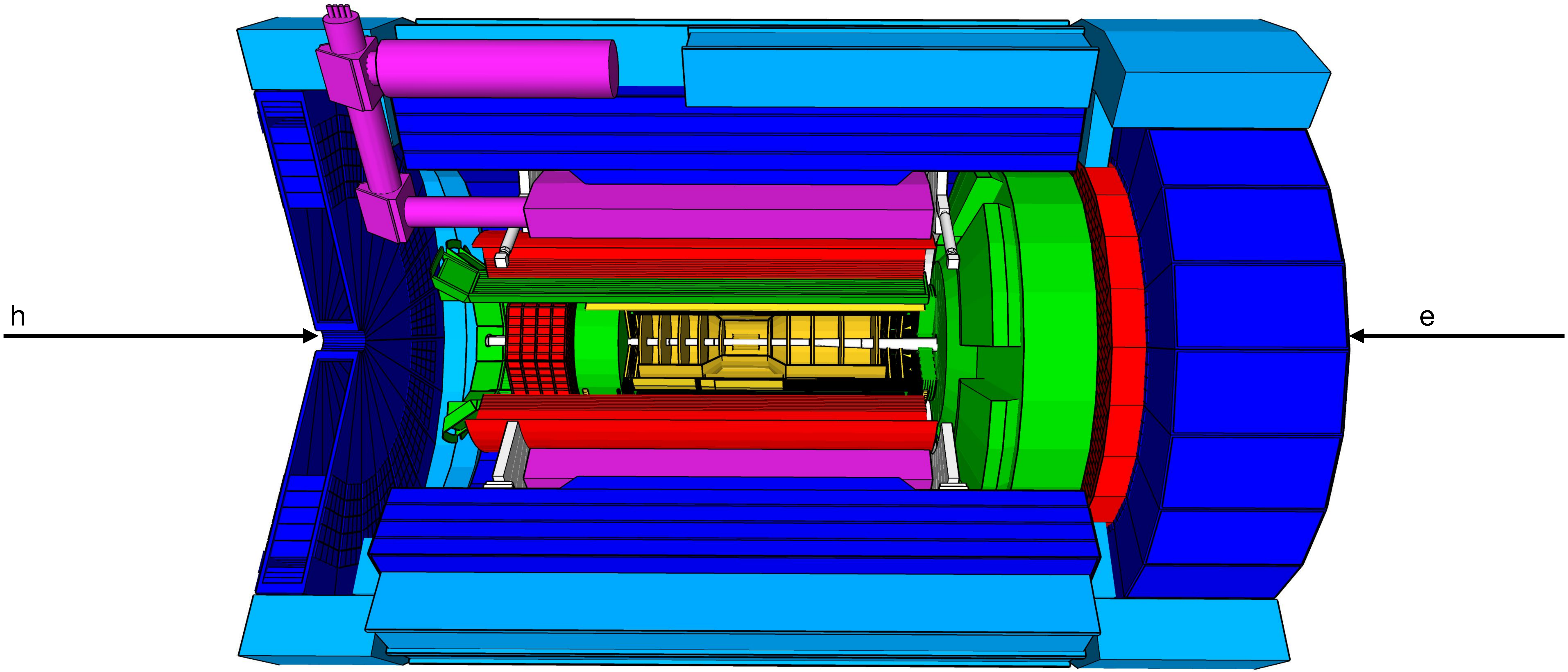
- $\vec{e} + \vec{p}^{\uparrow}, \vec{d}^{\uparrow}, \overrightarrow{He}^{\uparrow}$

  ~ 70% polarisation

- $\mathscr{L} = 10^{33-34}$ cm^{-2} s^{-1}

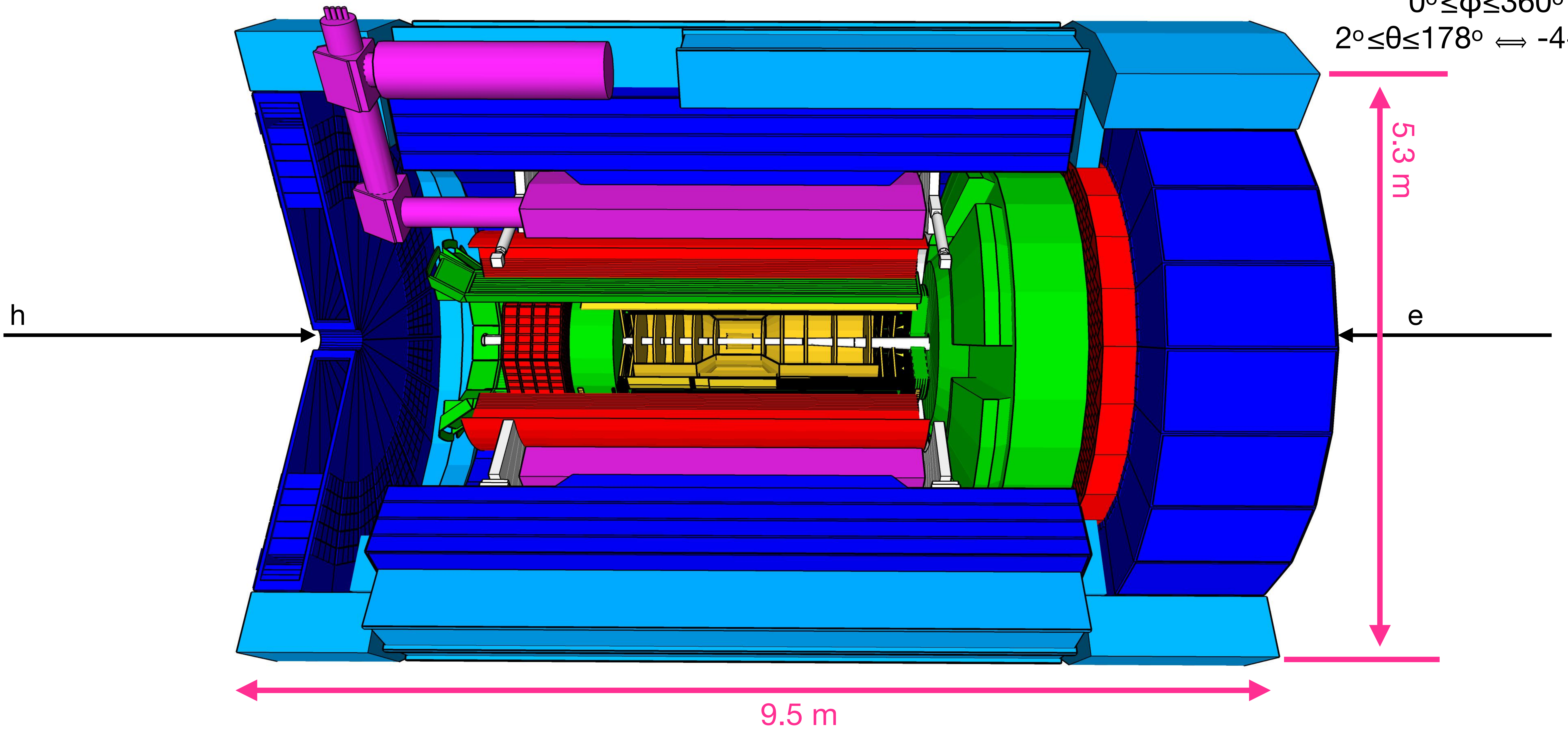
  $\leftrightarrow \mathscr{L}_{\text{int}} = 10 - 100$ fb^{-1}/year

The electron-proton/ion collider (ePIC) detector



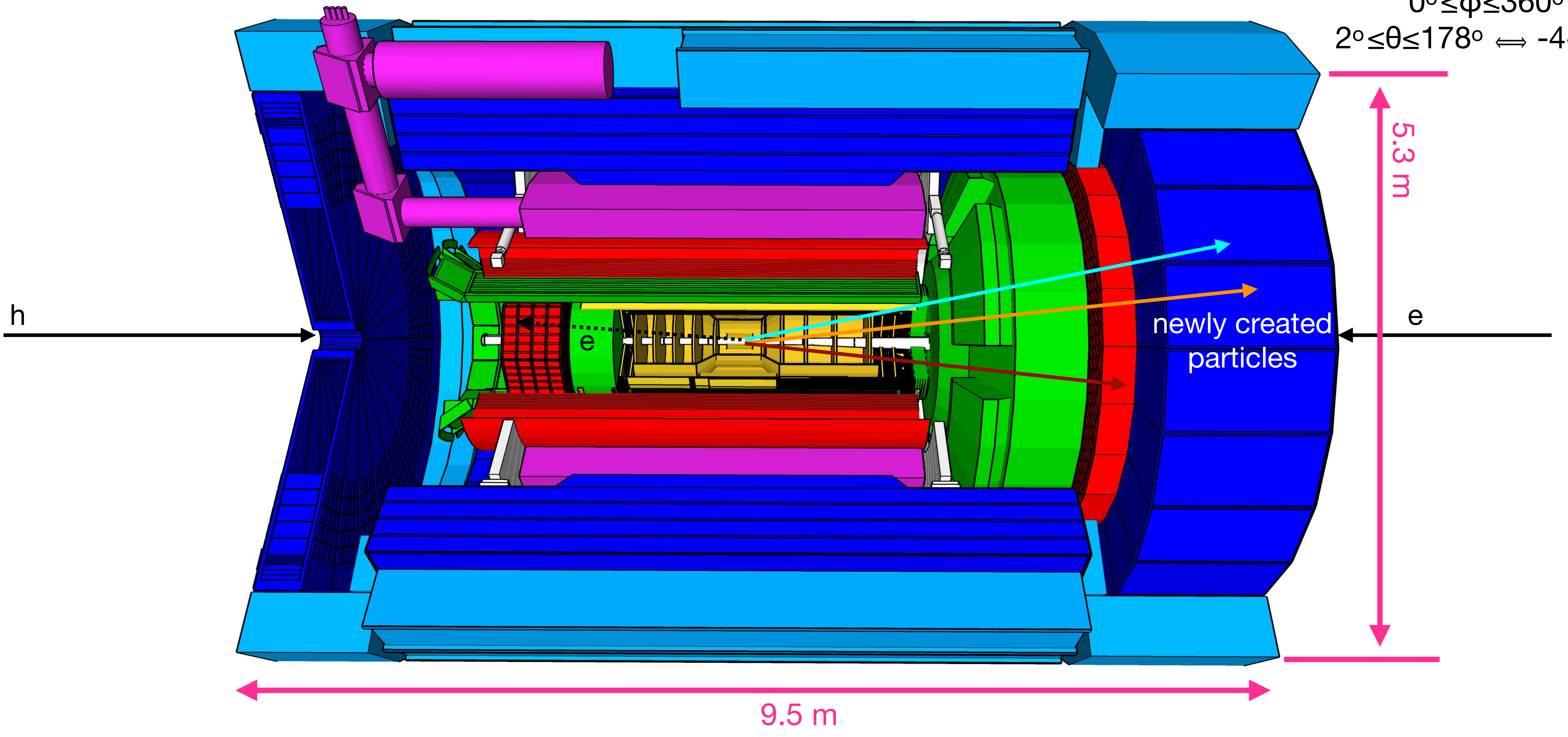
The electron-proton/ion collider (ePIC) detector

hermetic coverage:
$0^o \leq \phi \leq 360^o$
$2^o \leq \theta \leq 178^o \Longleftrightarrow -4 < \eta < 4$



The electron-proton/ion collider (ePIC) detector

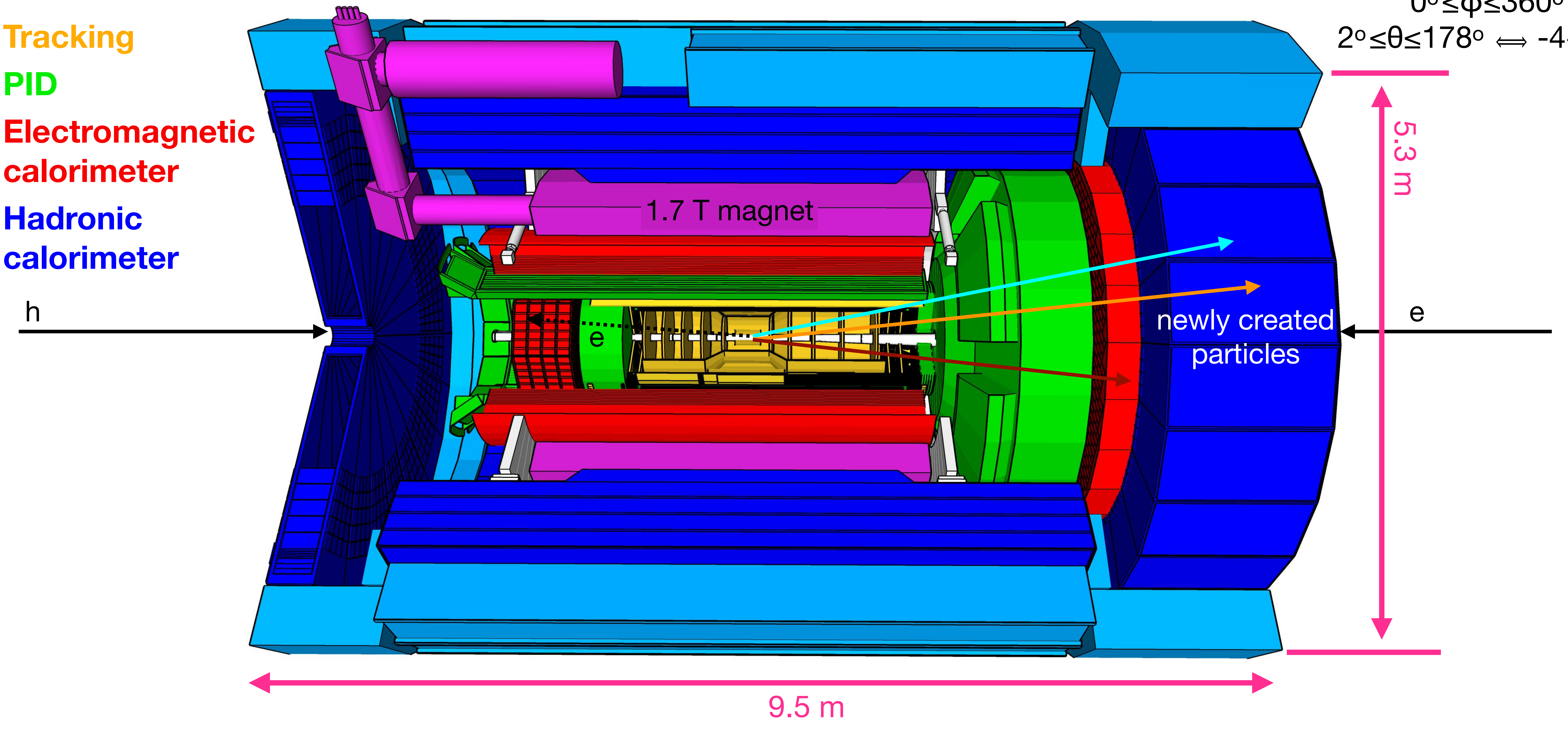
hermetic coverage:
0°≤ϕ≤360°
2°≤θ≤178° ⟺ -4<η<4



The electron-proton/ion collider (ePIC) detector

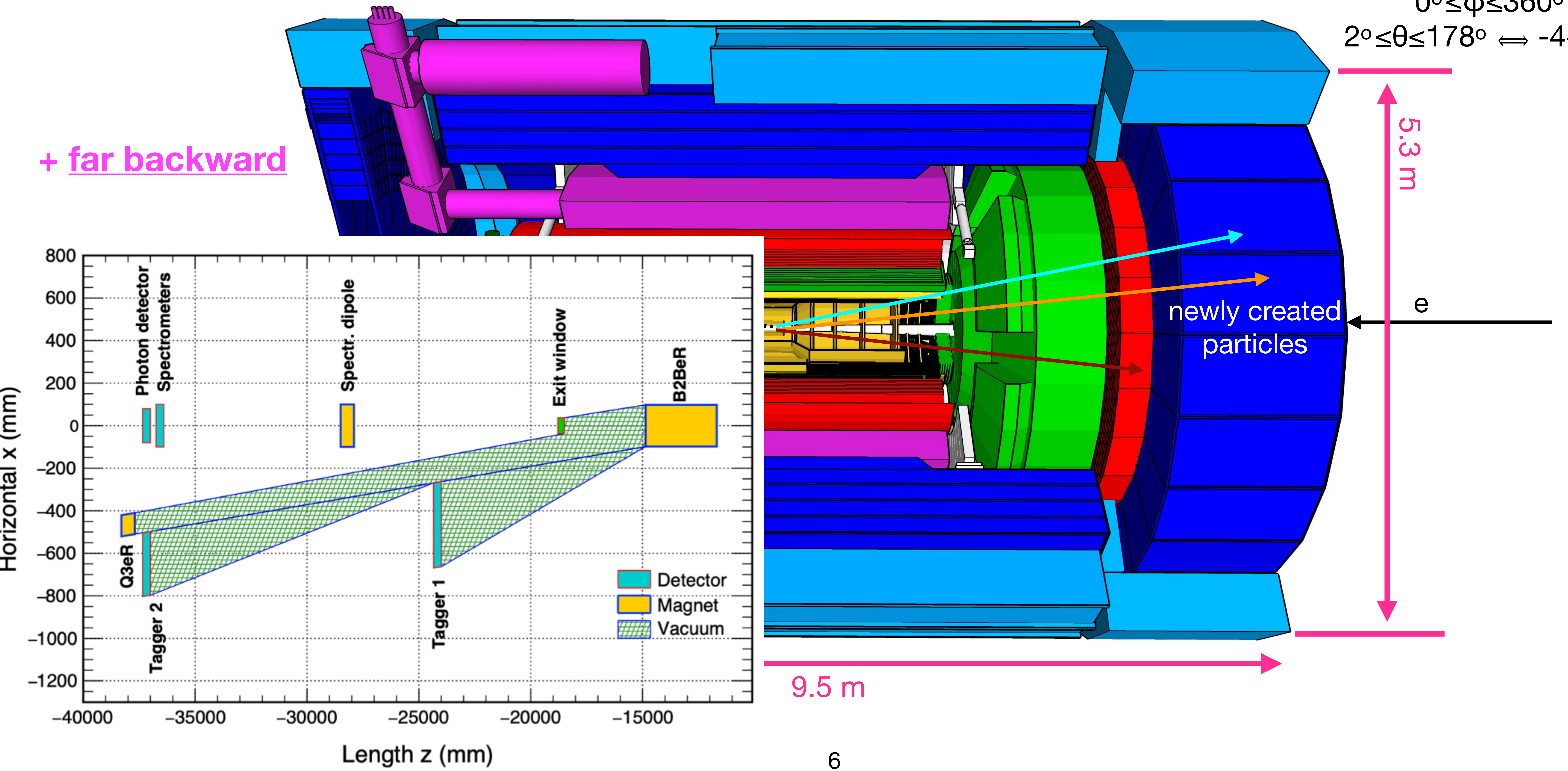
- Tracking
- PID
- Electromagnetic calorimeter
- Hadronic calorimeter

hermetic coverage:
0º≤ϕ≤360º
2º≤θ≤178º ⟺ -4<η<4



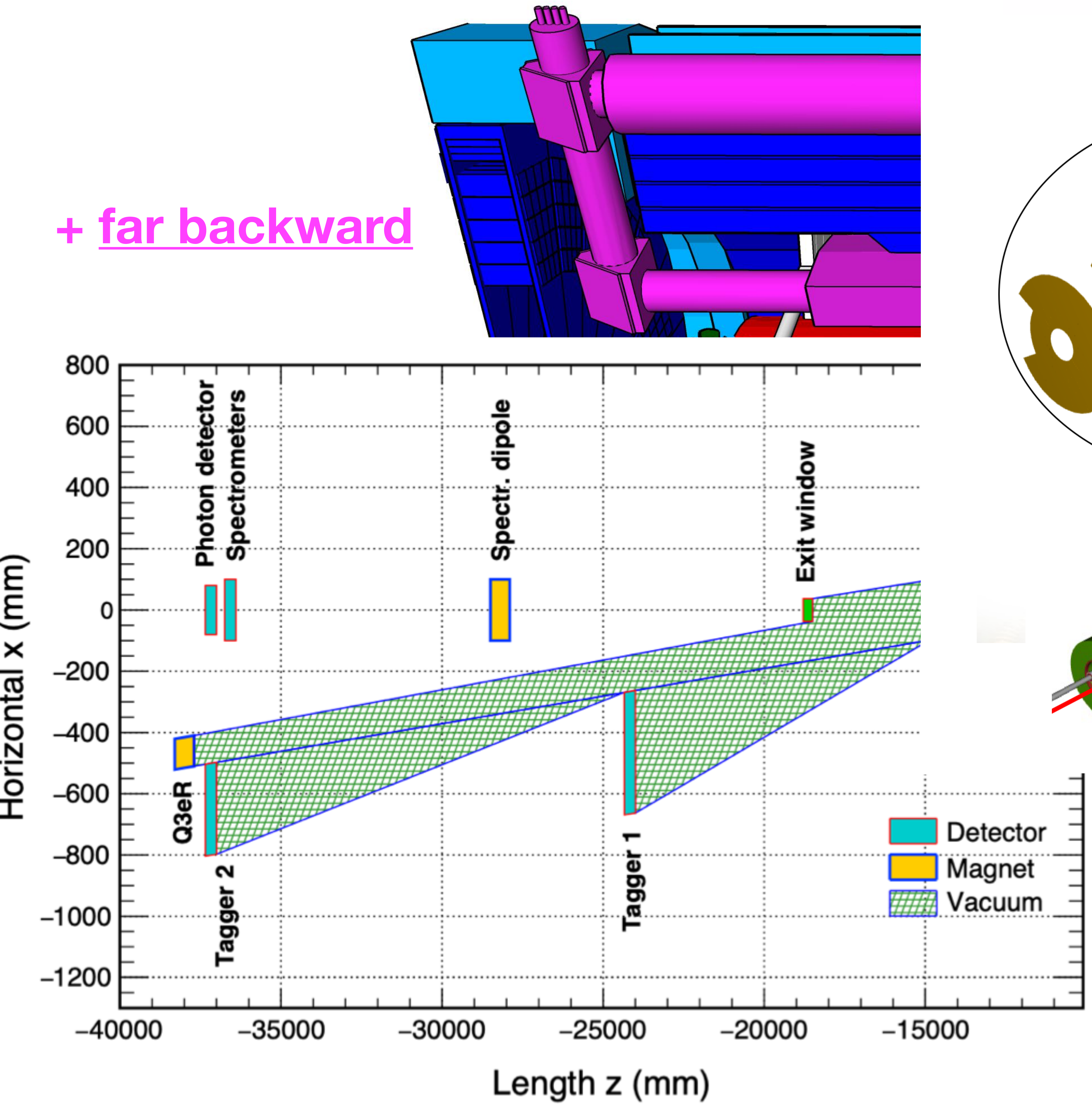
The electron-proton/ion collider (ePIC) detector

hermetic coverage:
$0^o \leq \phi \leq 360^o$
$2^o \leq \theta \leq 178^o \iff -4<\eta<4$

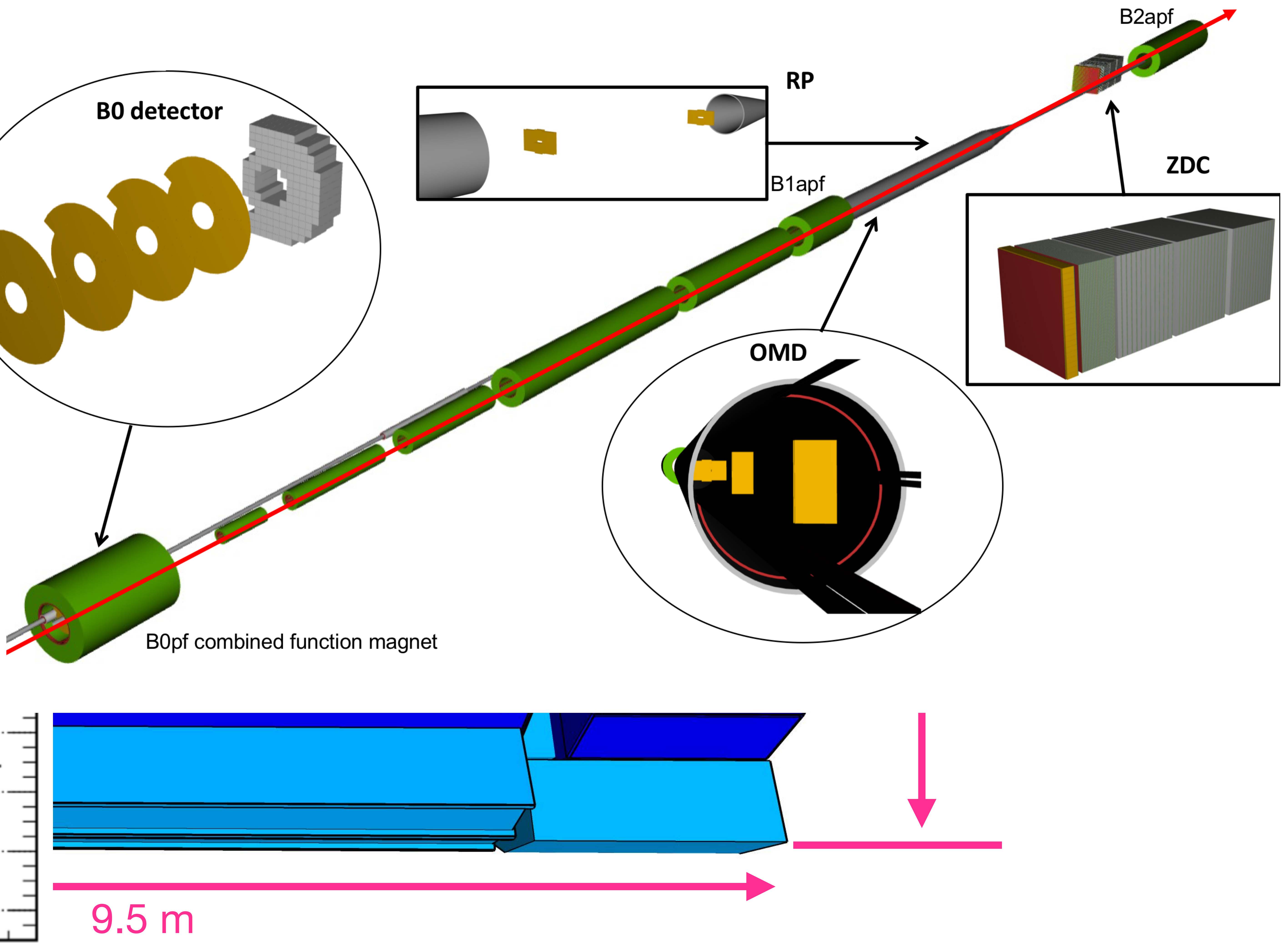


The electron-proton/ion collider (ePIC) detector

+ far backward

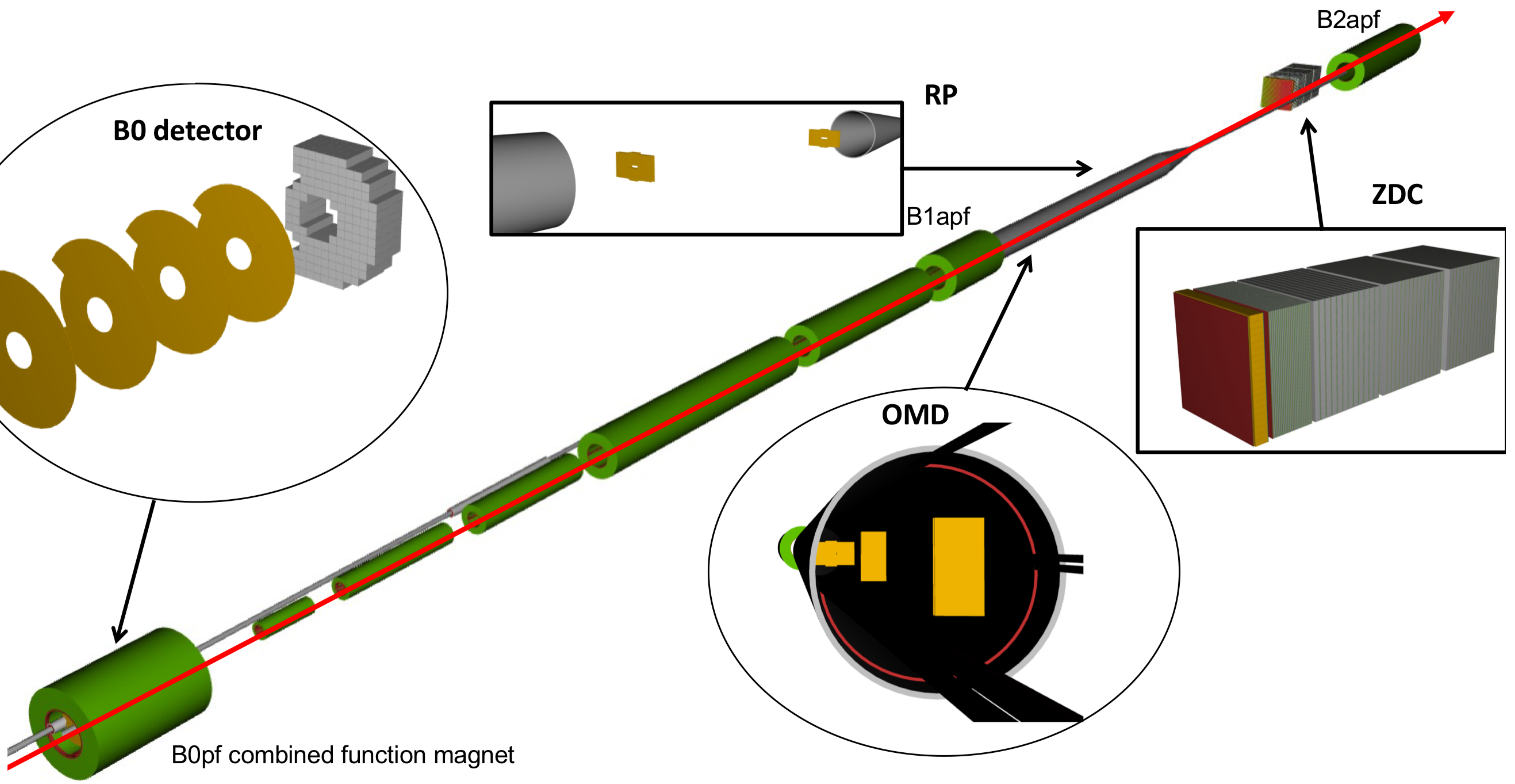


+ far forward

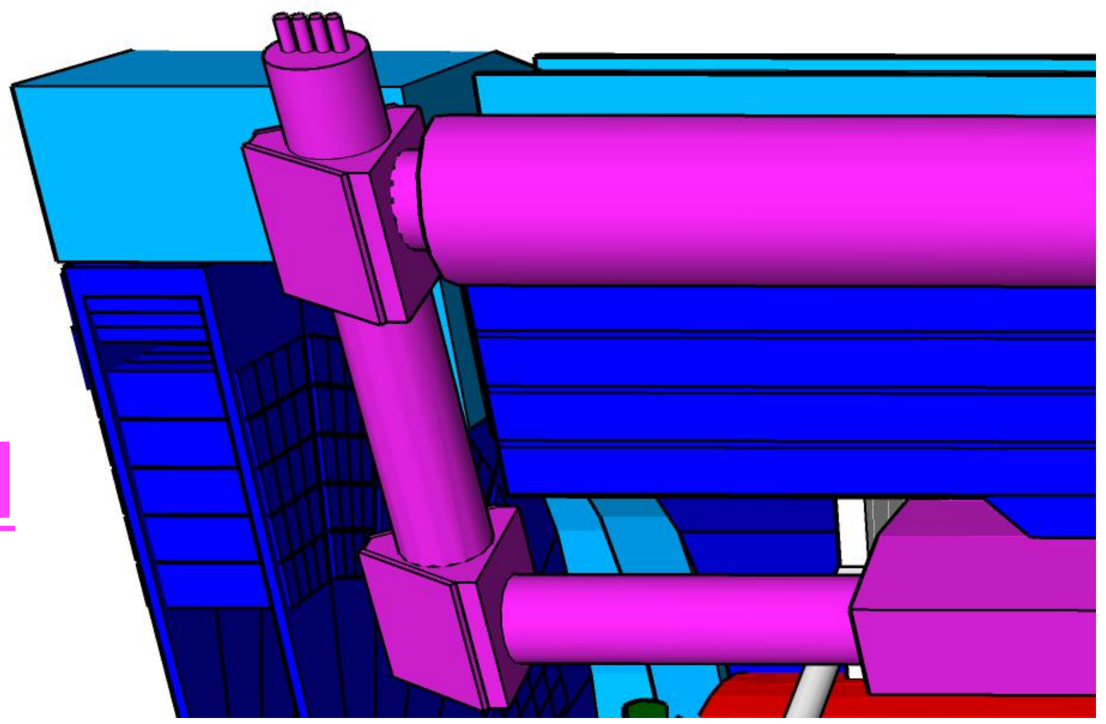


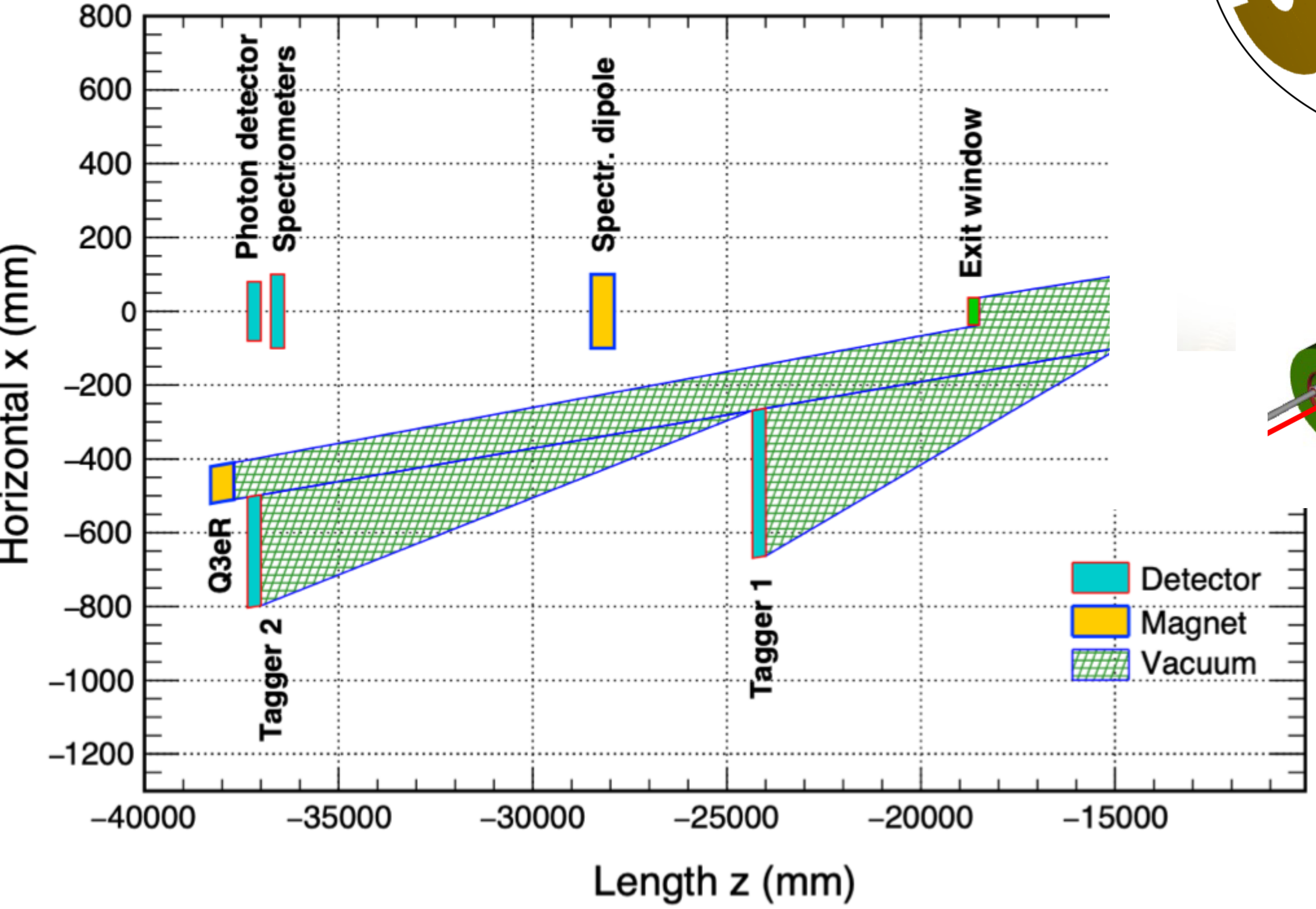
The electron-proton/ion collider (ePIC) detector

+ far forward



+ far backward





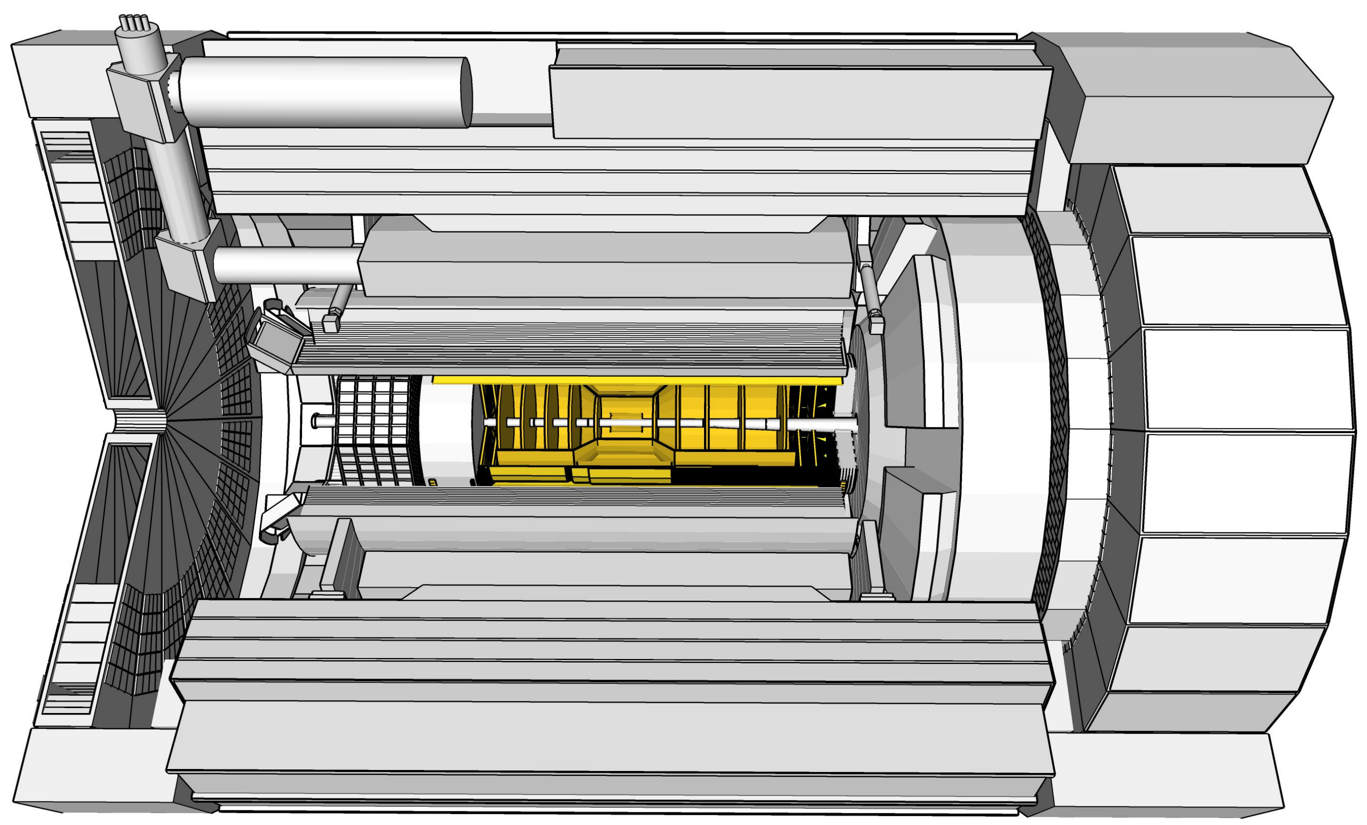
Data acquisition:
- no trigger
- all collision data is digitised
- with strong zero-suppression at front-end electronics

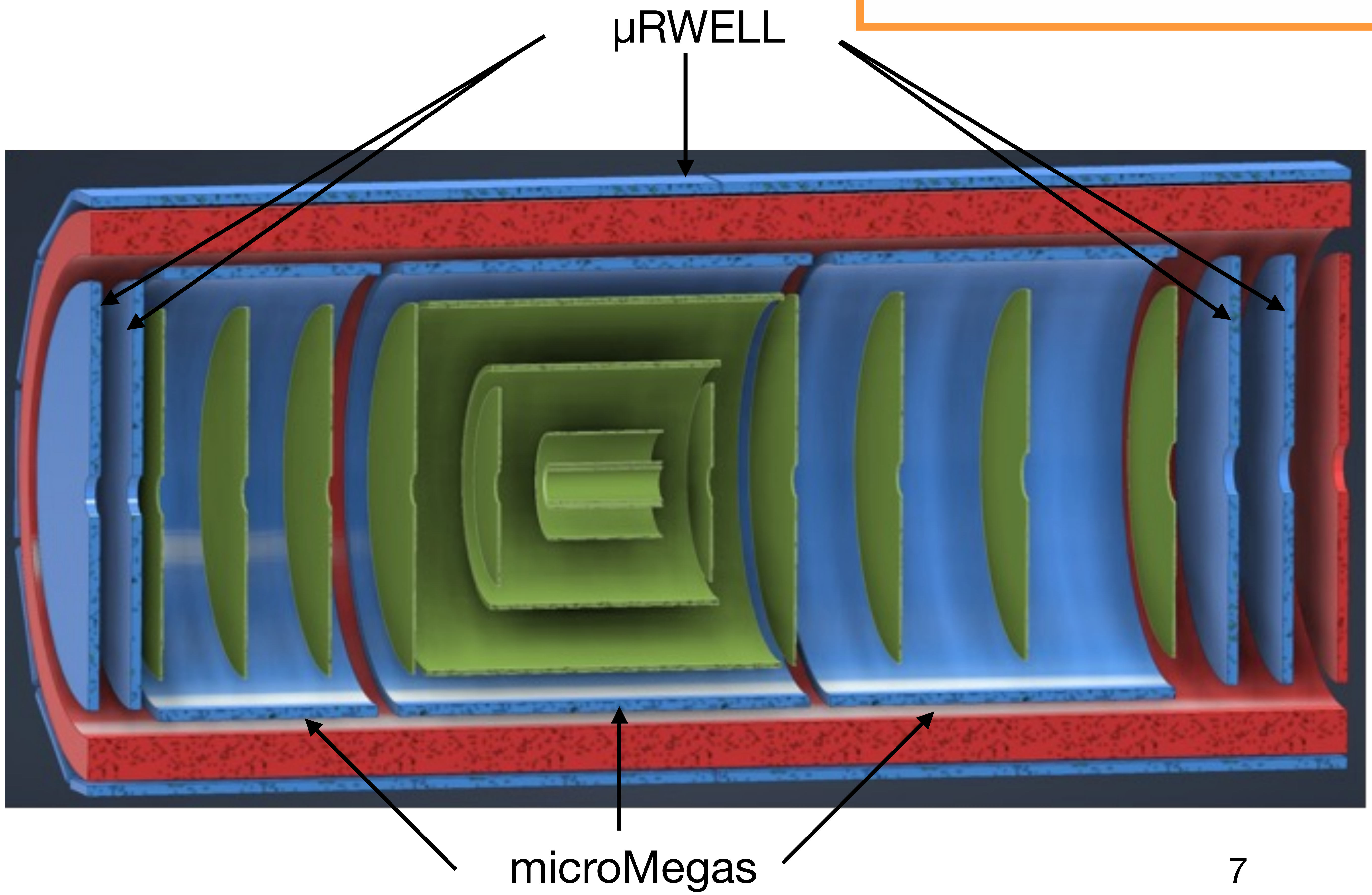
Tracking system

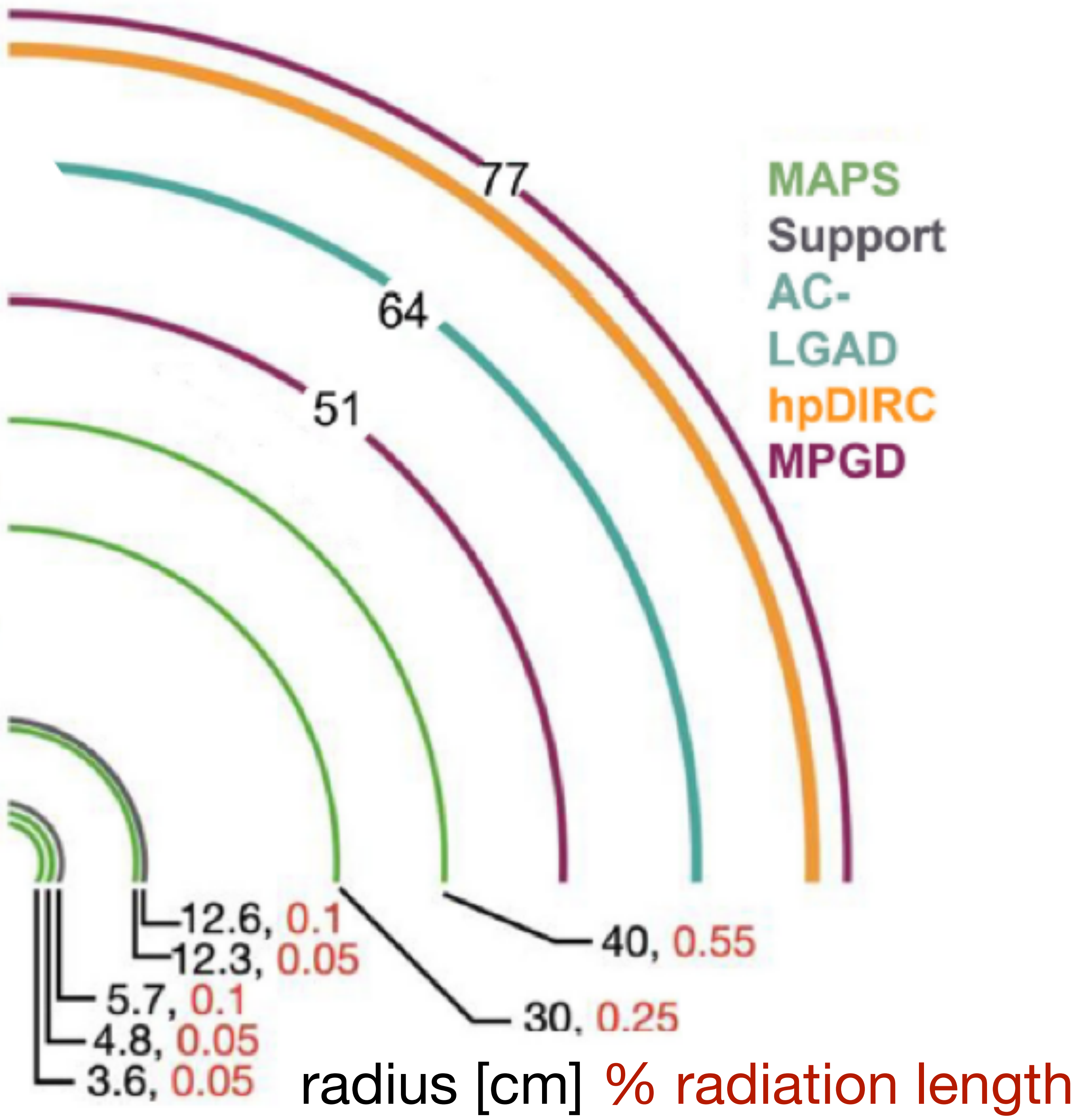
1.7 T magnet

- Monolithic Active Pixel Sensor (MAPS) Silicon vertexing/inner tracker
- Micro-pattern gaseous detectors

  μRWELL/microMegas: timing & pattern recognition
- AC-LGAD based TOF: PID & additional tracking point





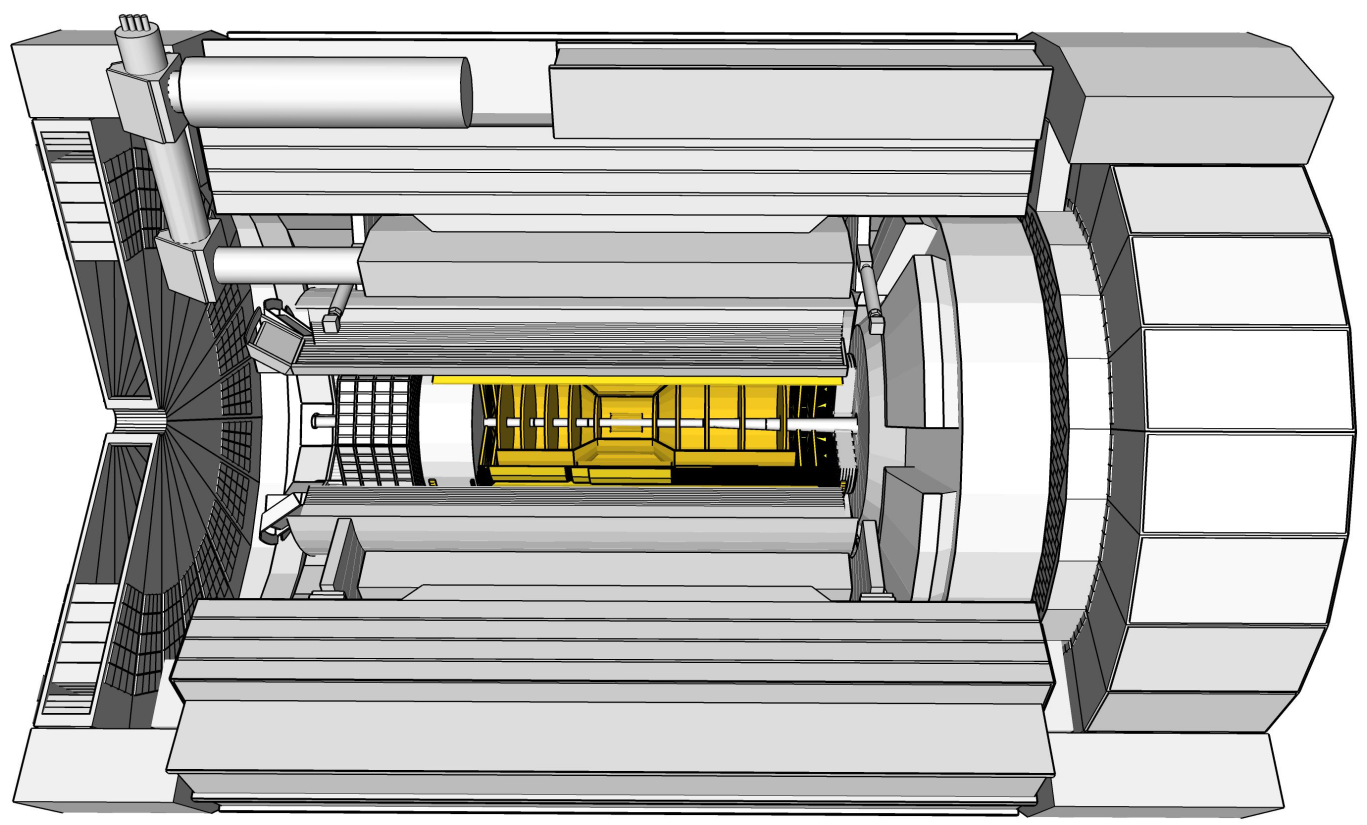


Tracking system

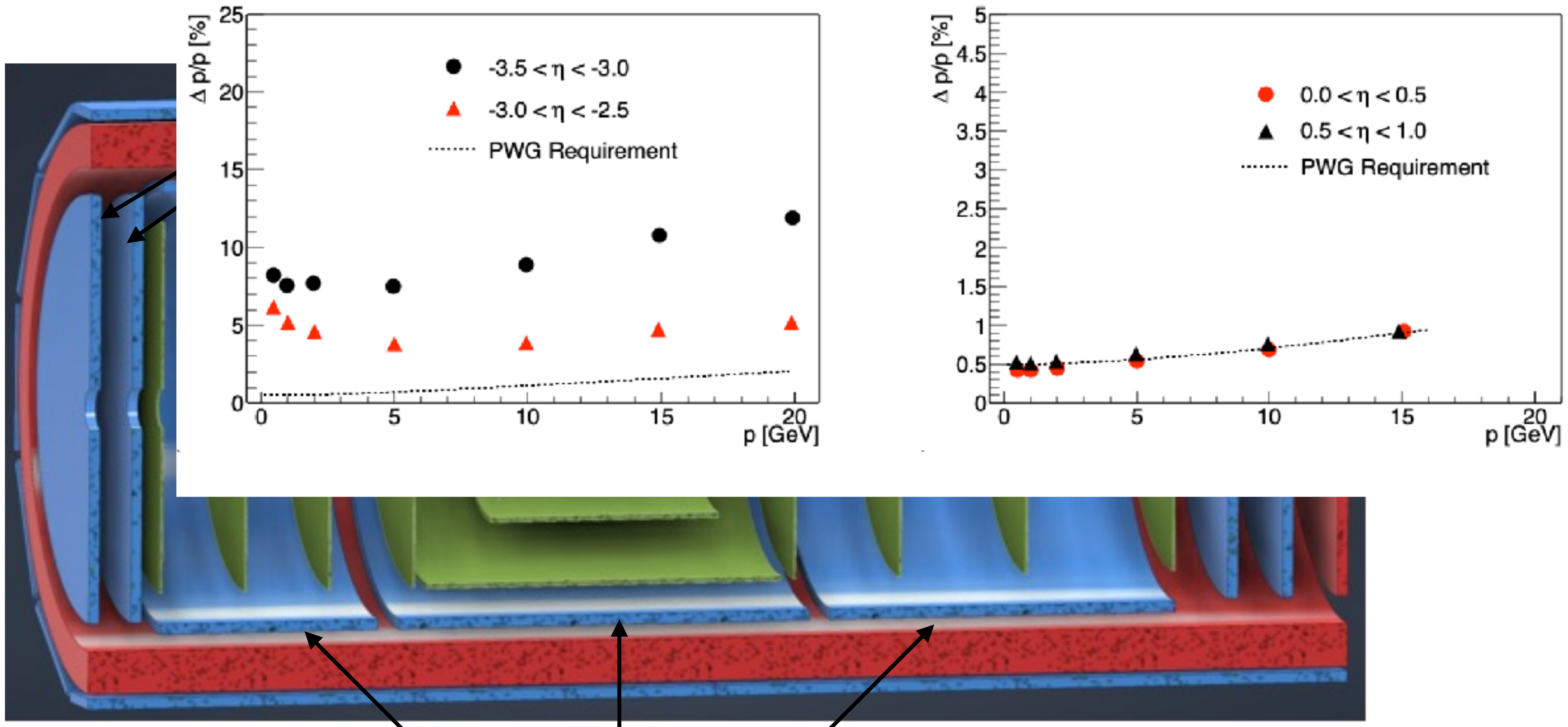
1.7 T magnet

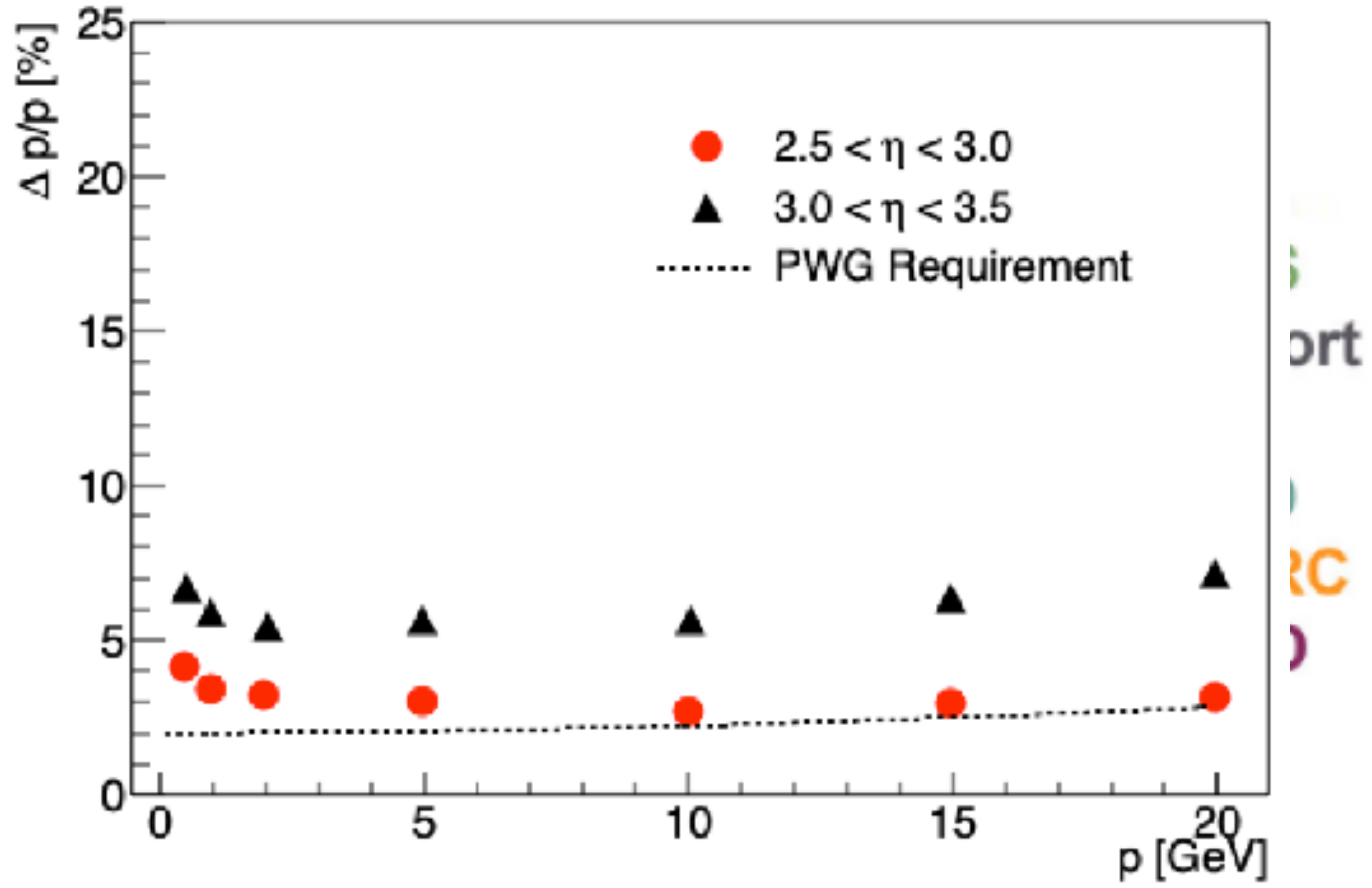
- Monolithic Active Pixel Sensor (MAPS) Silicon vertexing/inner tracker
- Micro-pattern gaseous detectors

  μRWELL/microMegas:
  timing & pattern recognition
- AC-LGAD based TOF:
  PID & additional tracking point

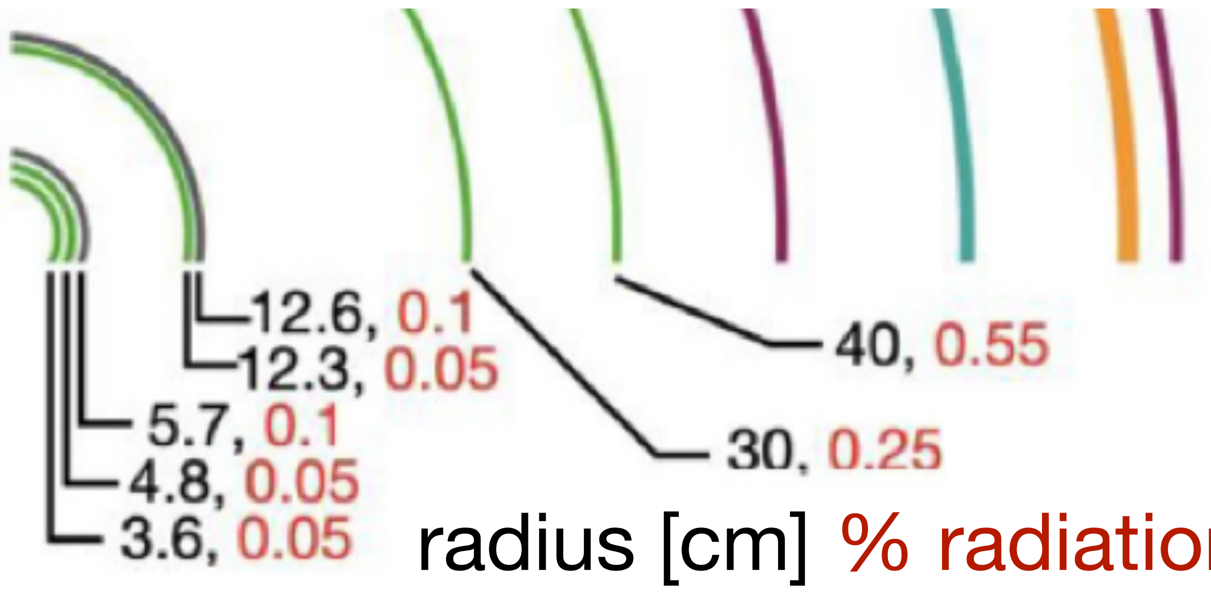


momentum resolution





microMegas



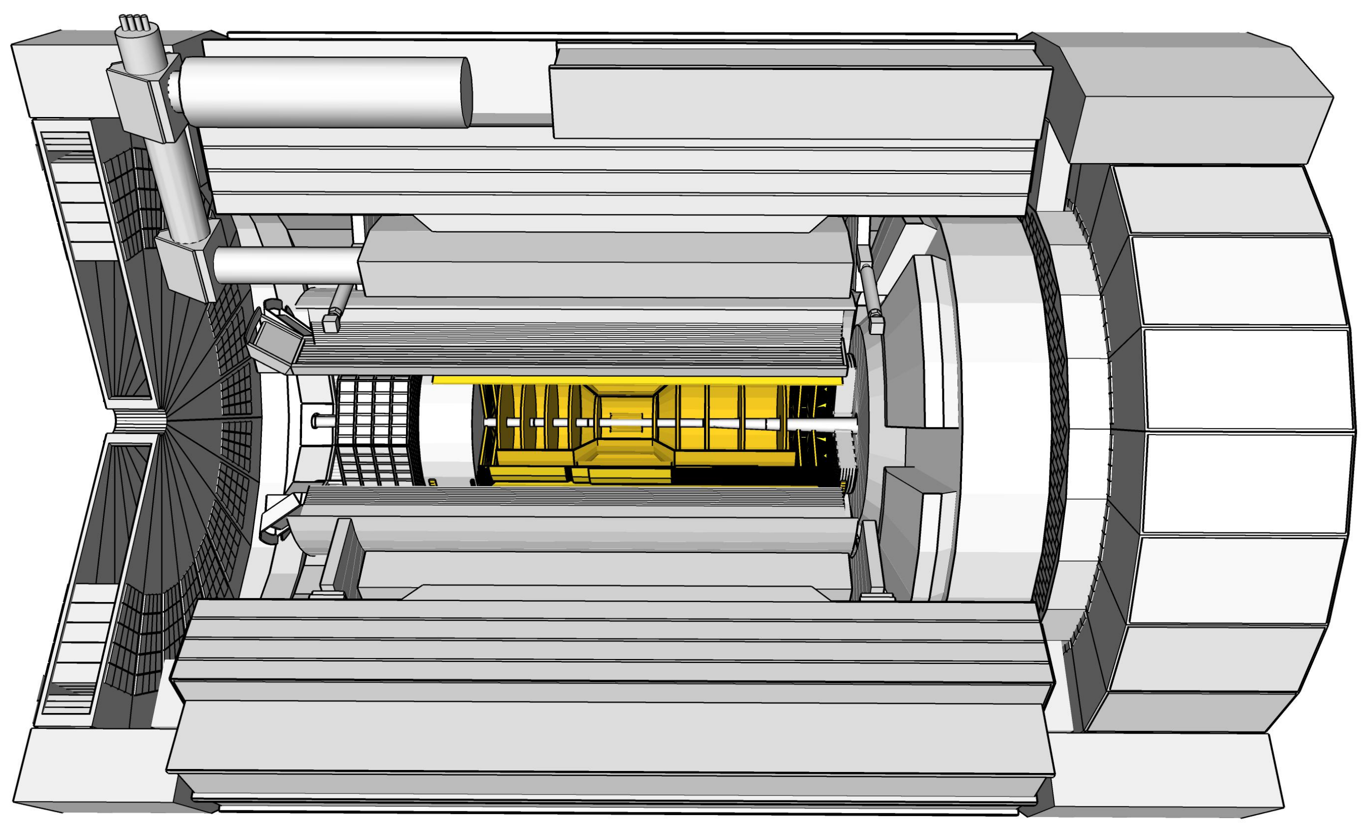
radius [cm] % radiation length

Tracking system

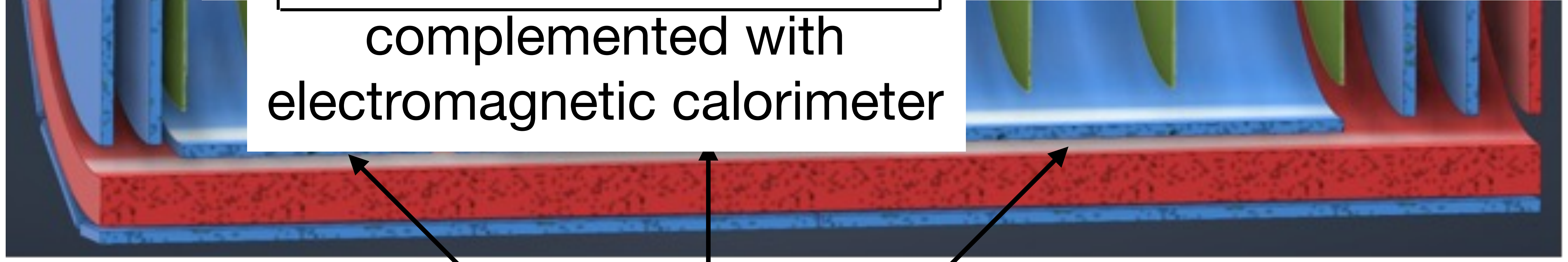
1.7 T magnet

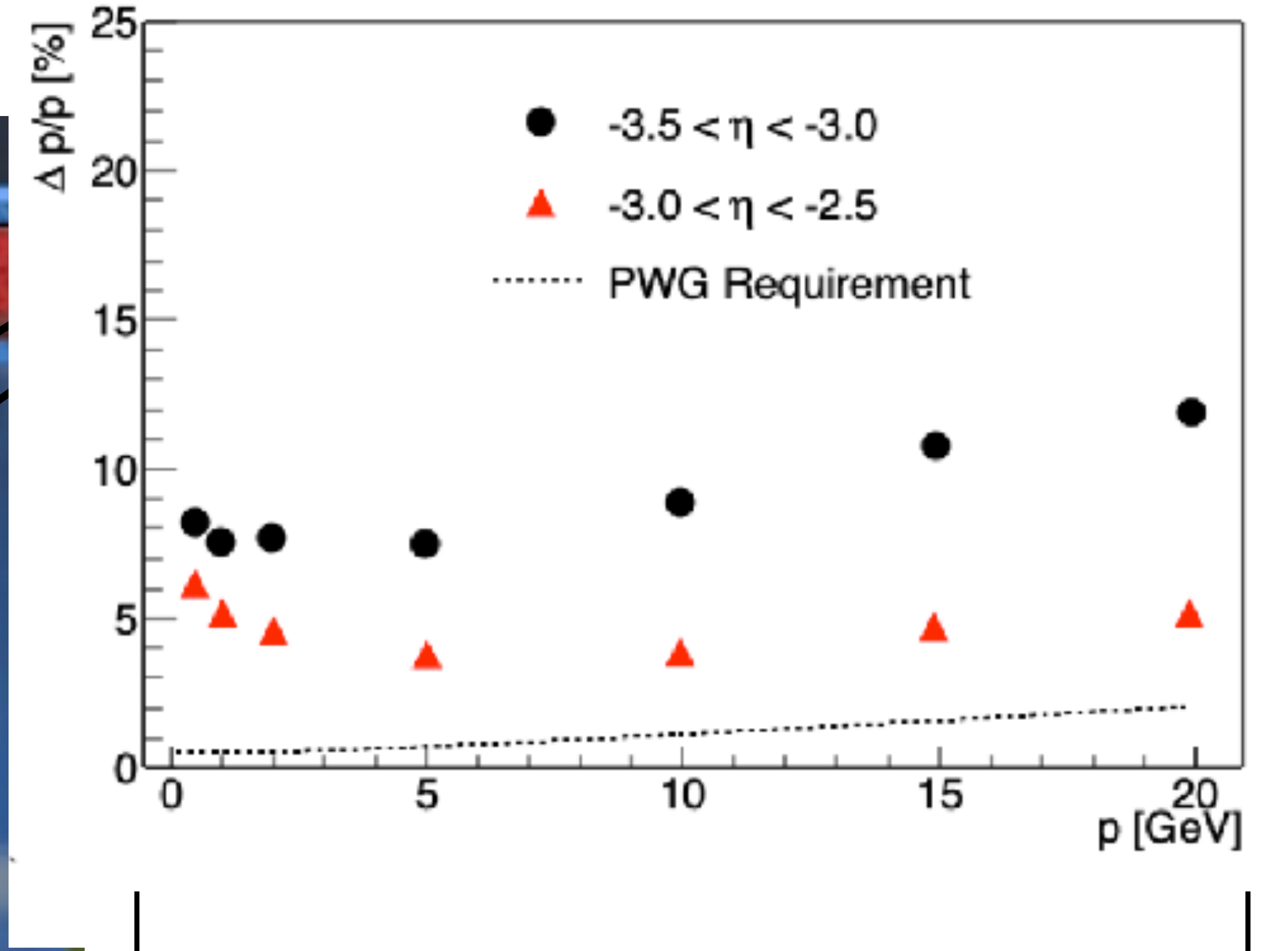
- Monolithic Active Pixel Sensor (MAPS) Silicon vertexing/inner tracker
- Micro-pattern gaseous detectors

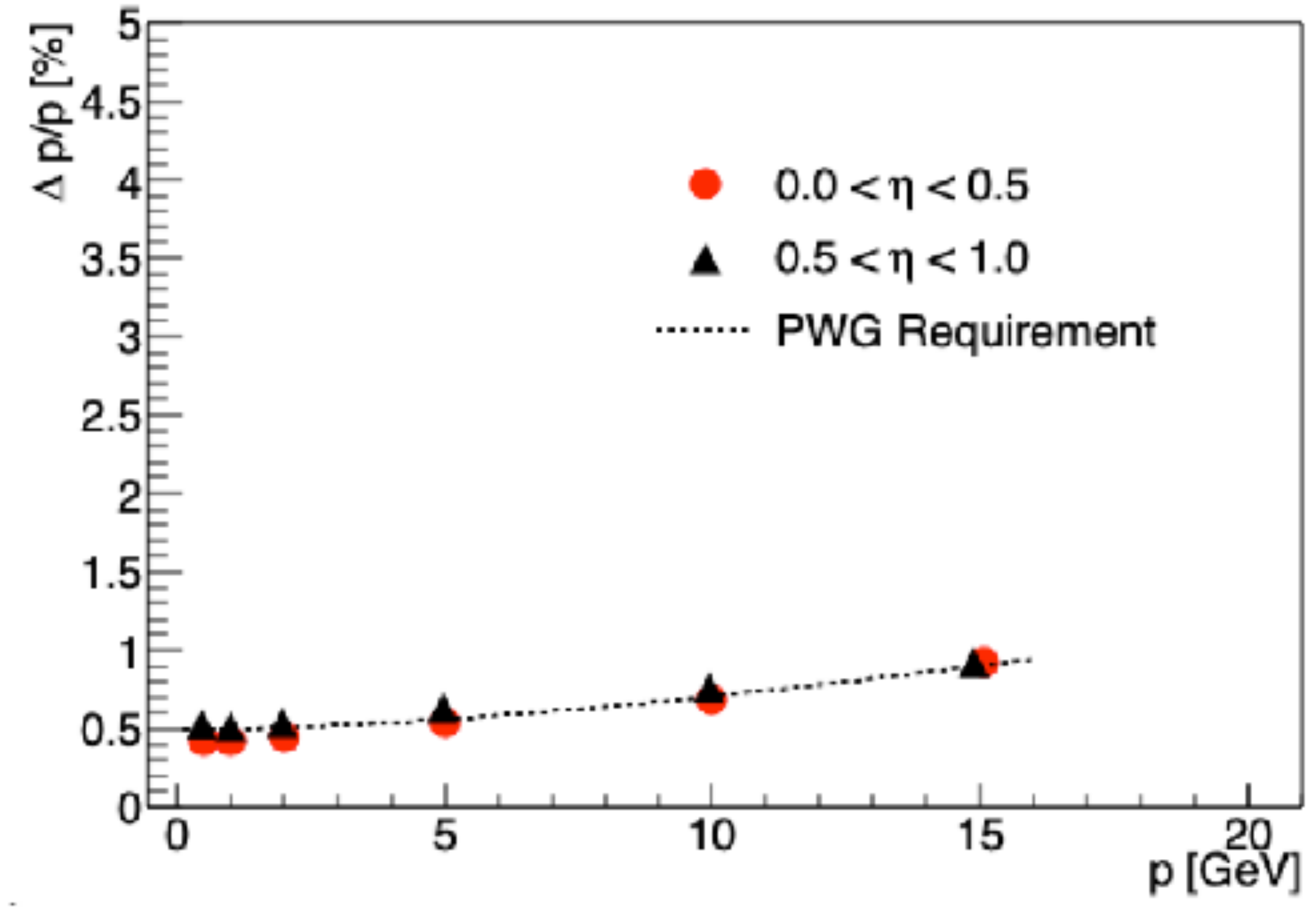
  μRWELL/microMegas:
  timing & pattern recognition
- AC-LGAD based TOF:
  PID & additional tracking point

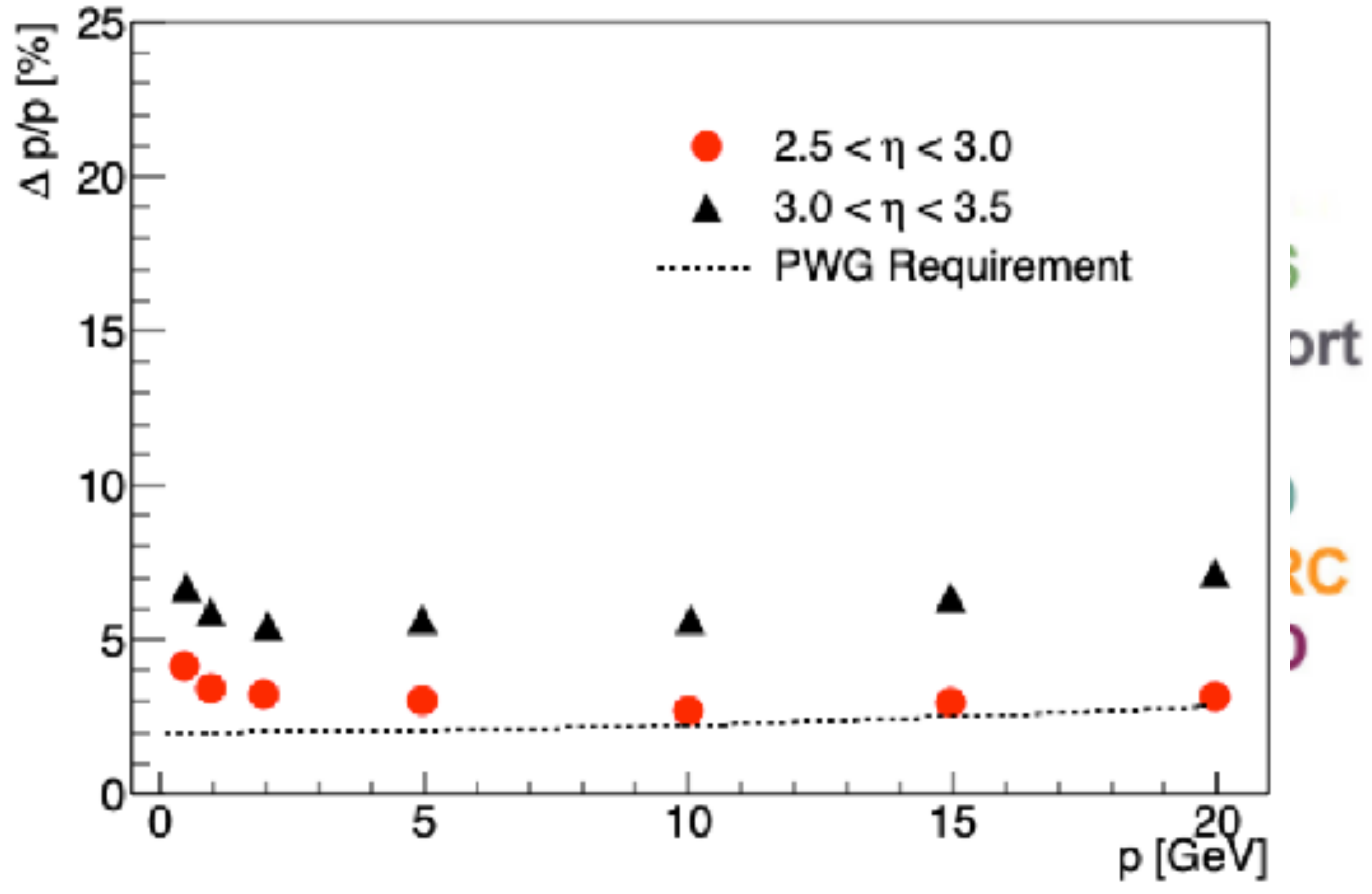


momentum resolution

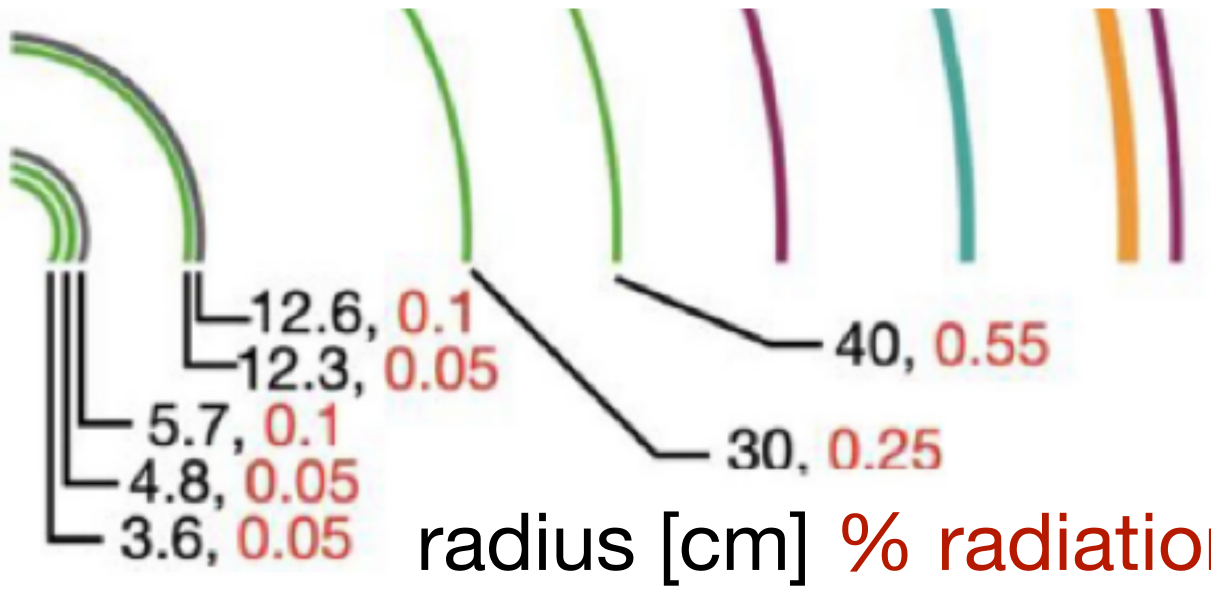








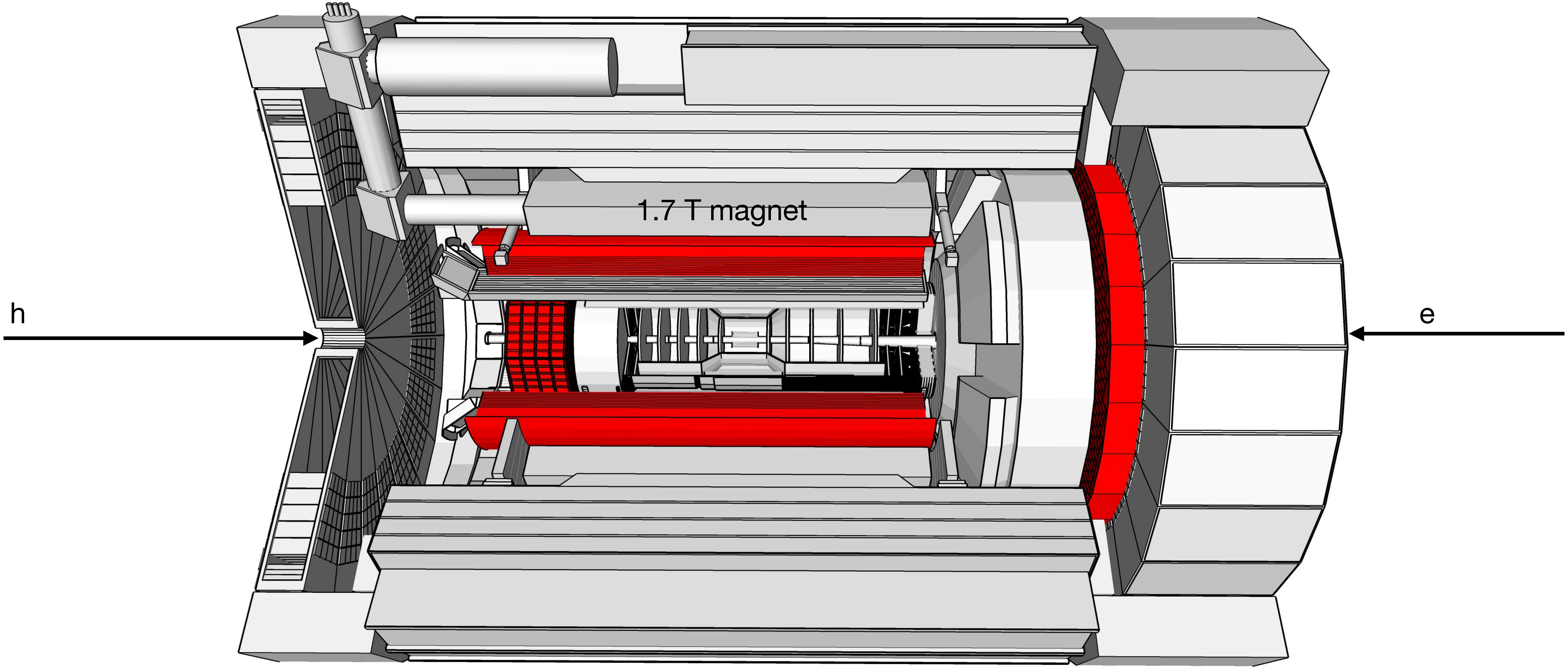
complemented with electromagnetic calorimeter



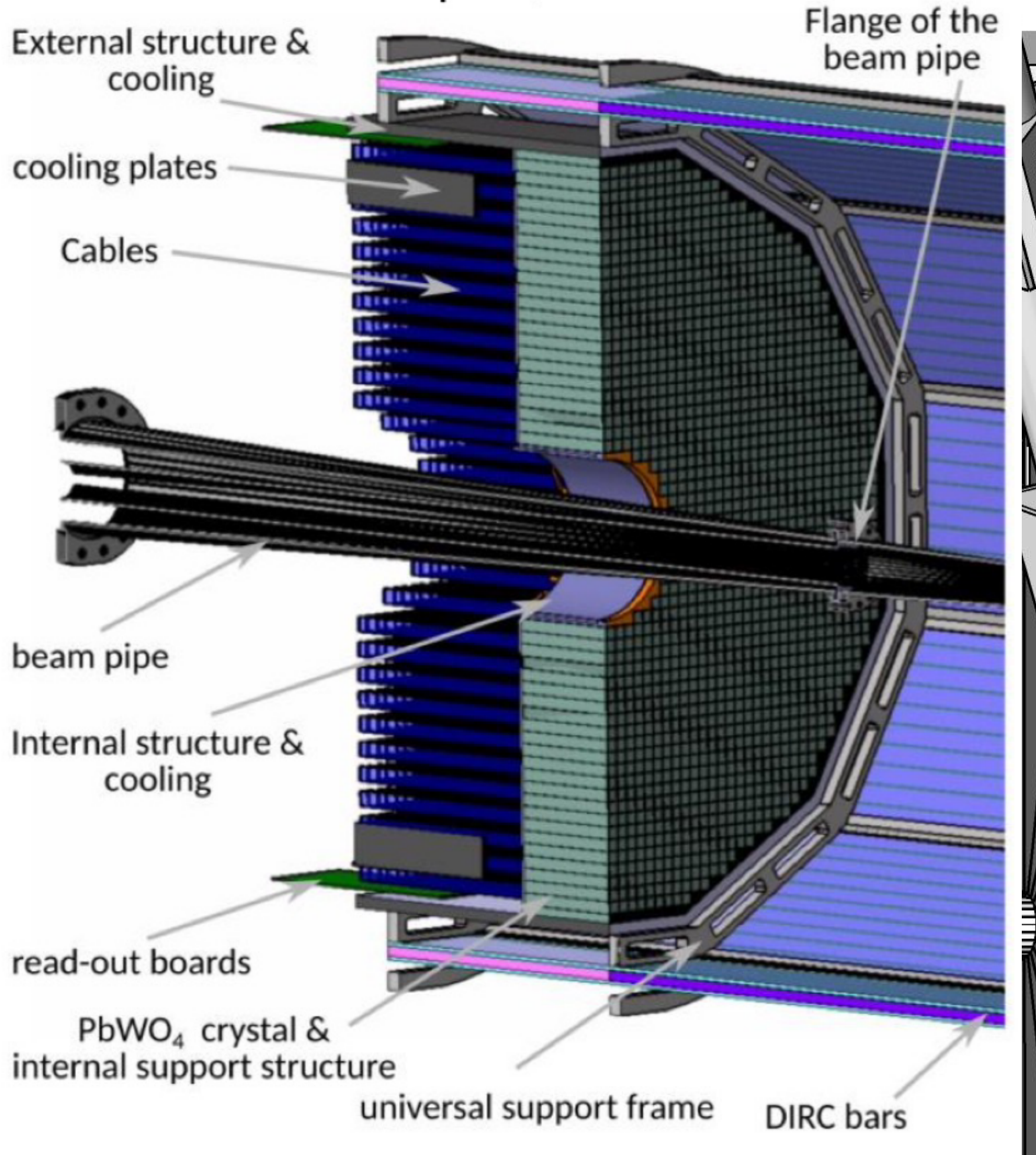
microMegas

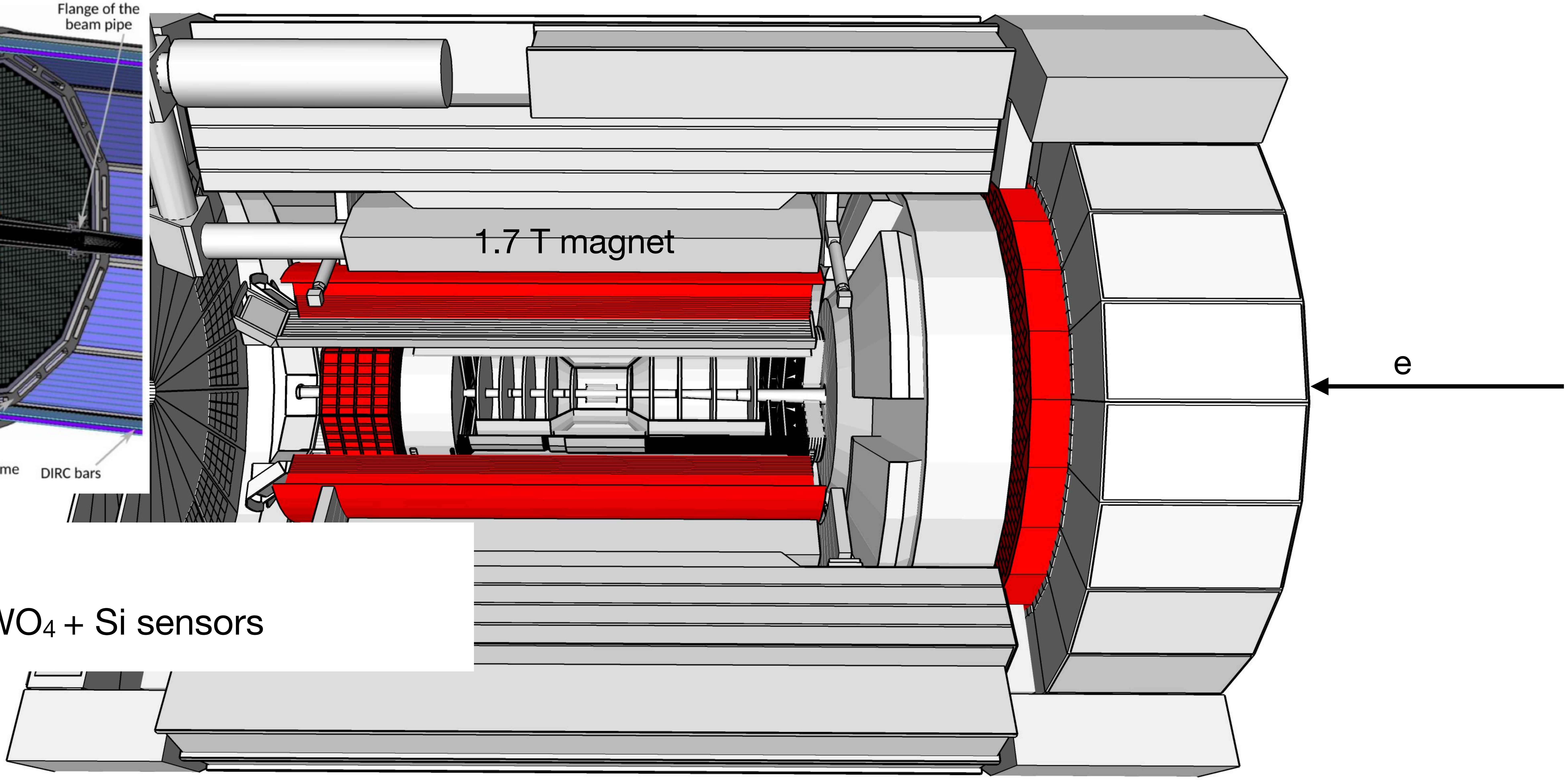
radius [cm] % radiation length

Electromagnetic calorimeter



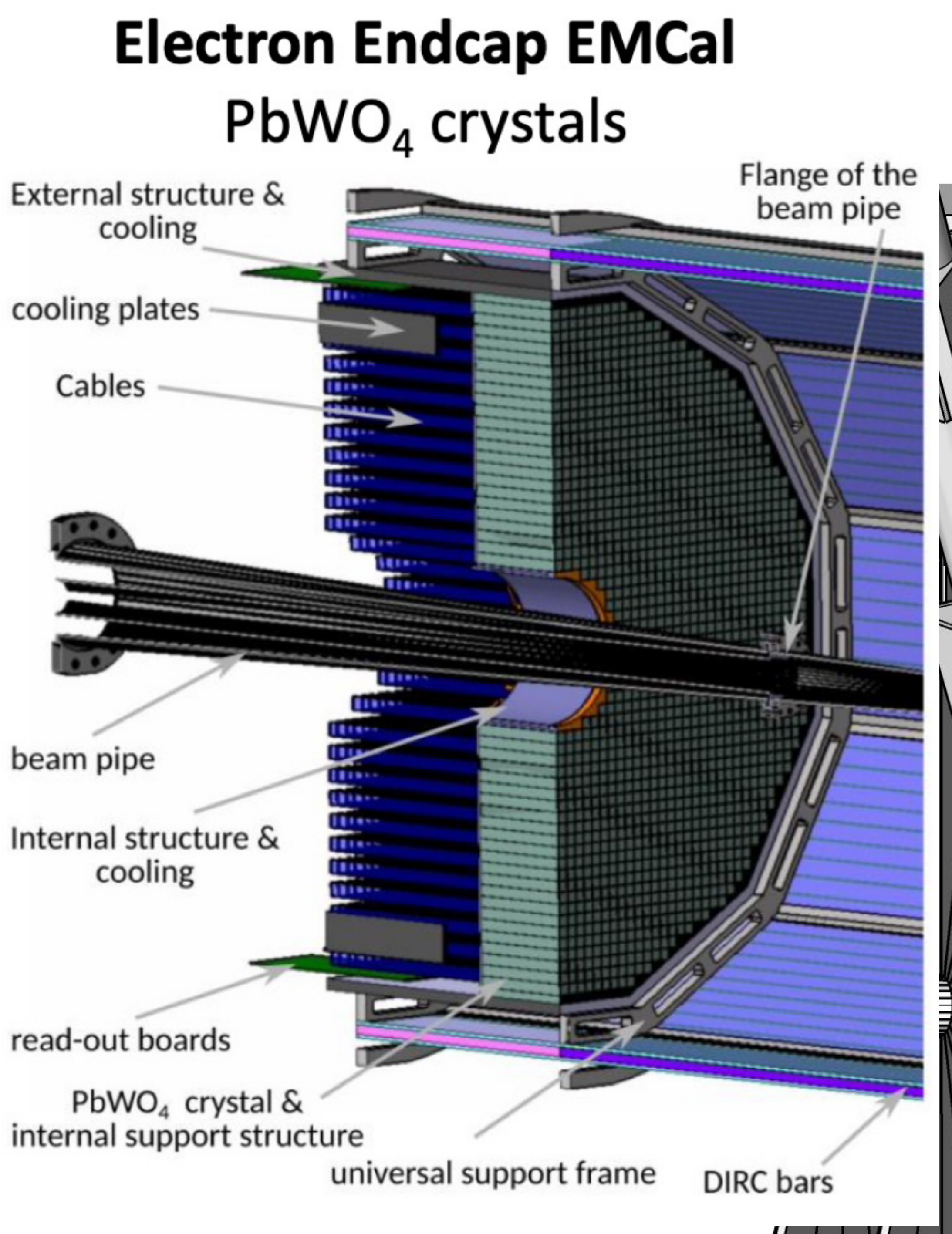
Electromagnetic calorimeter

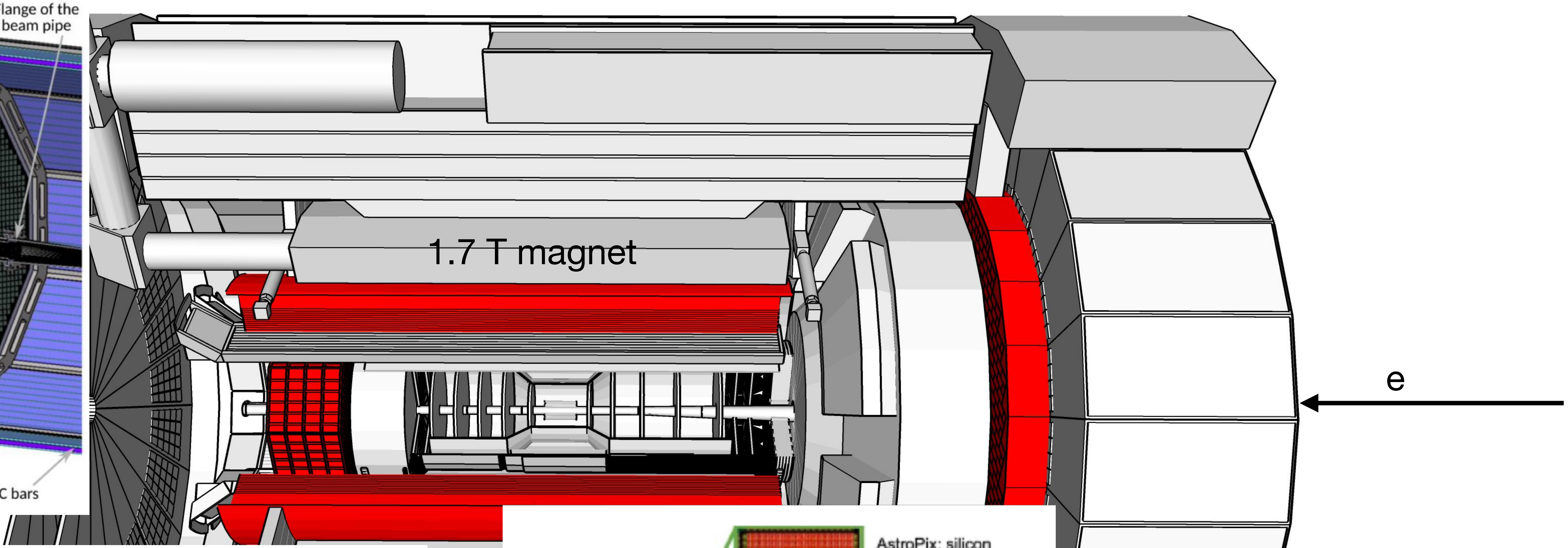


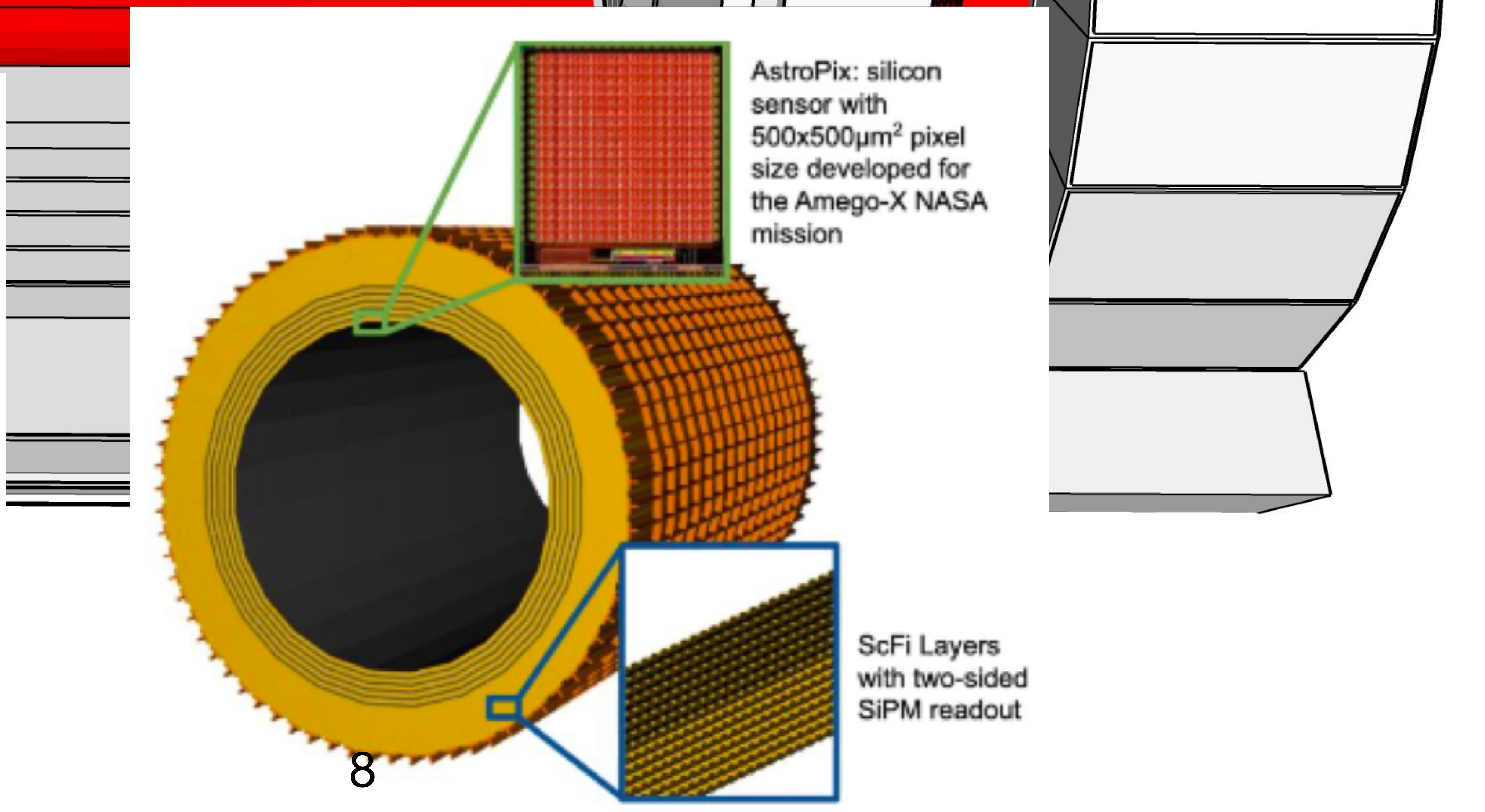


- Backward EMCAL:
  high-precision $PbWO_4$ + Si sensors

Electromagnetic calorimeter

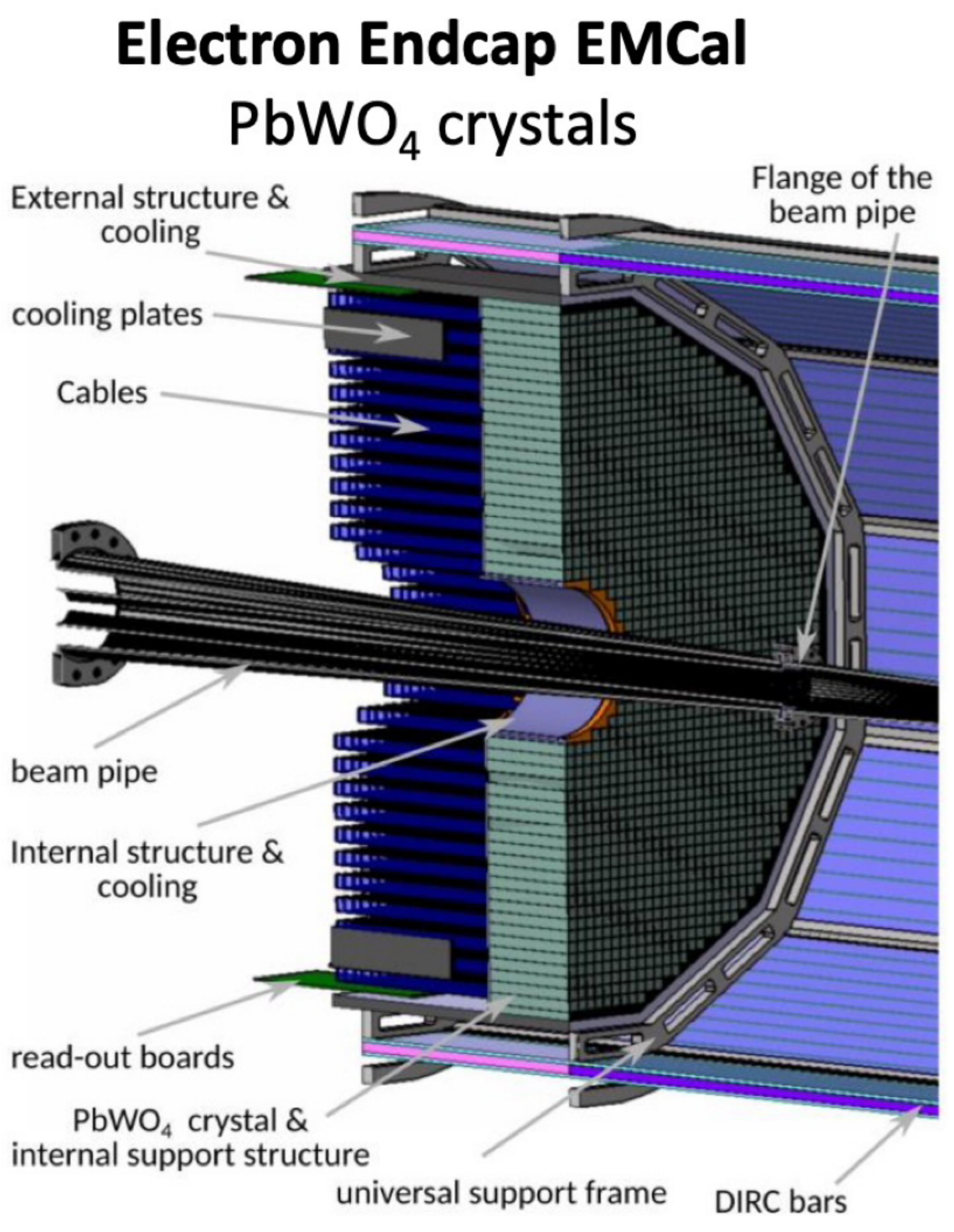


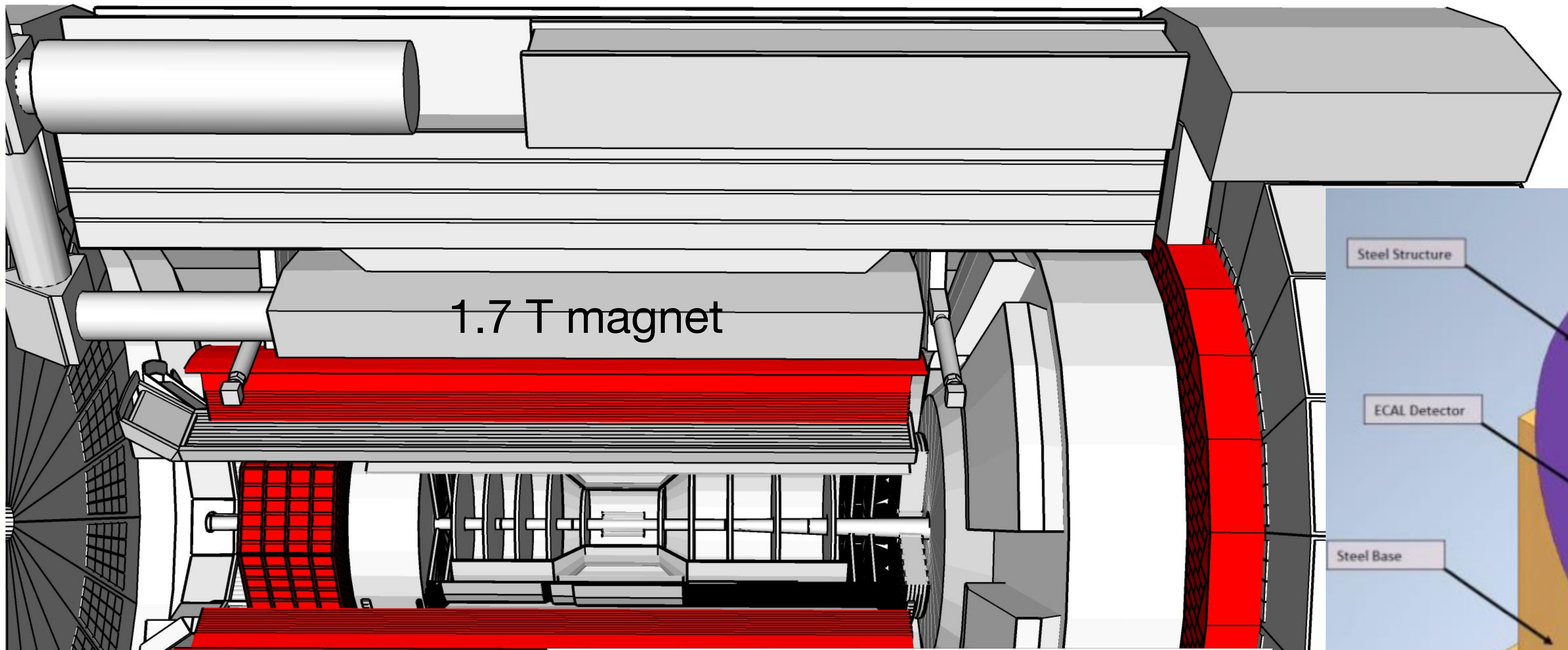


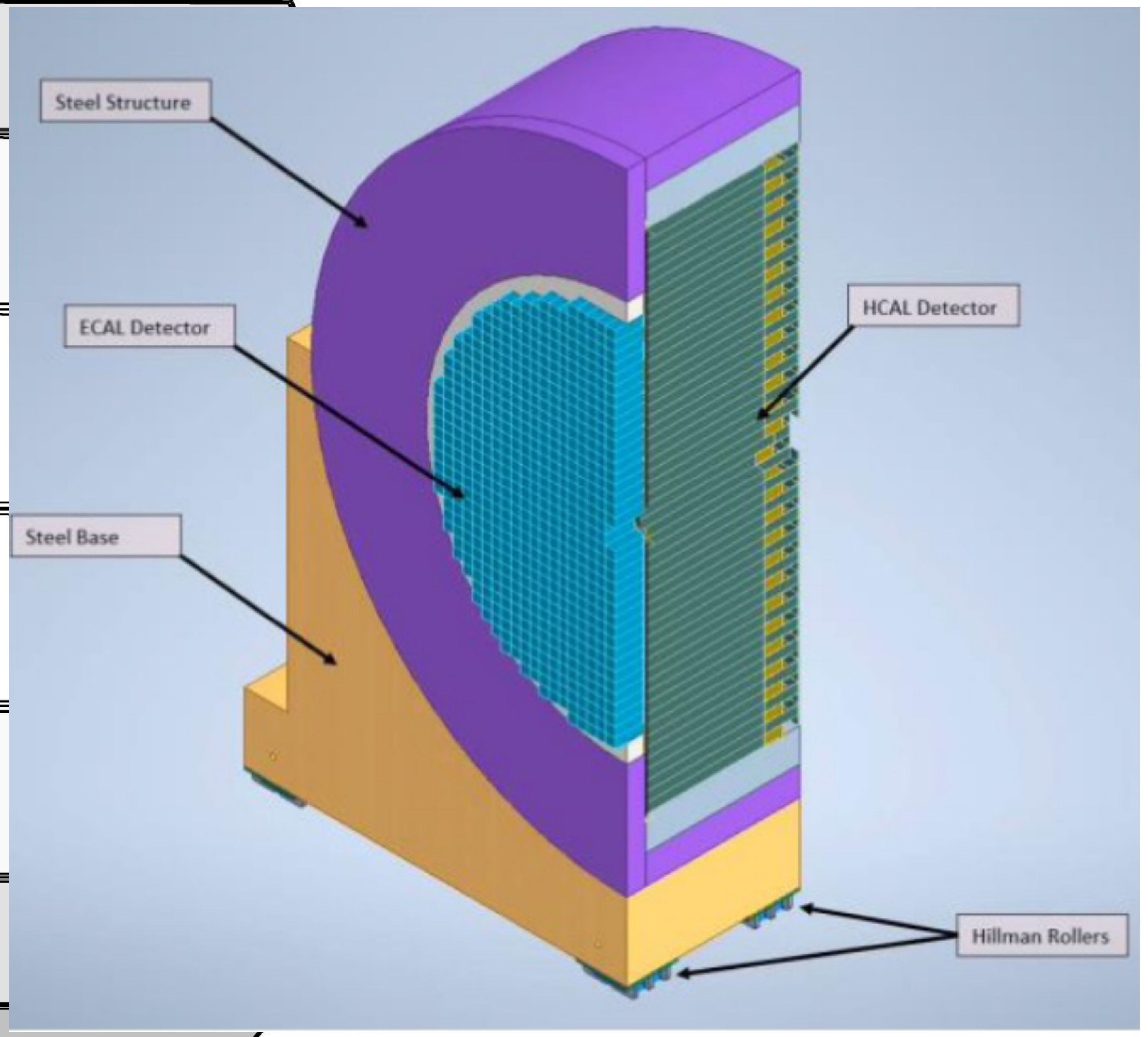


- Backward EMCAL:
  high-precision $PbWO_4$ + Si sensors
- Barrel EMCAL:
  3D imaging with MAPS and sampling Pb/ scintillating fibres with Si sensors

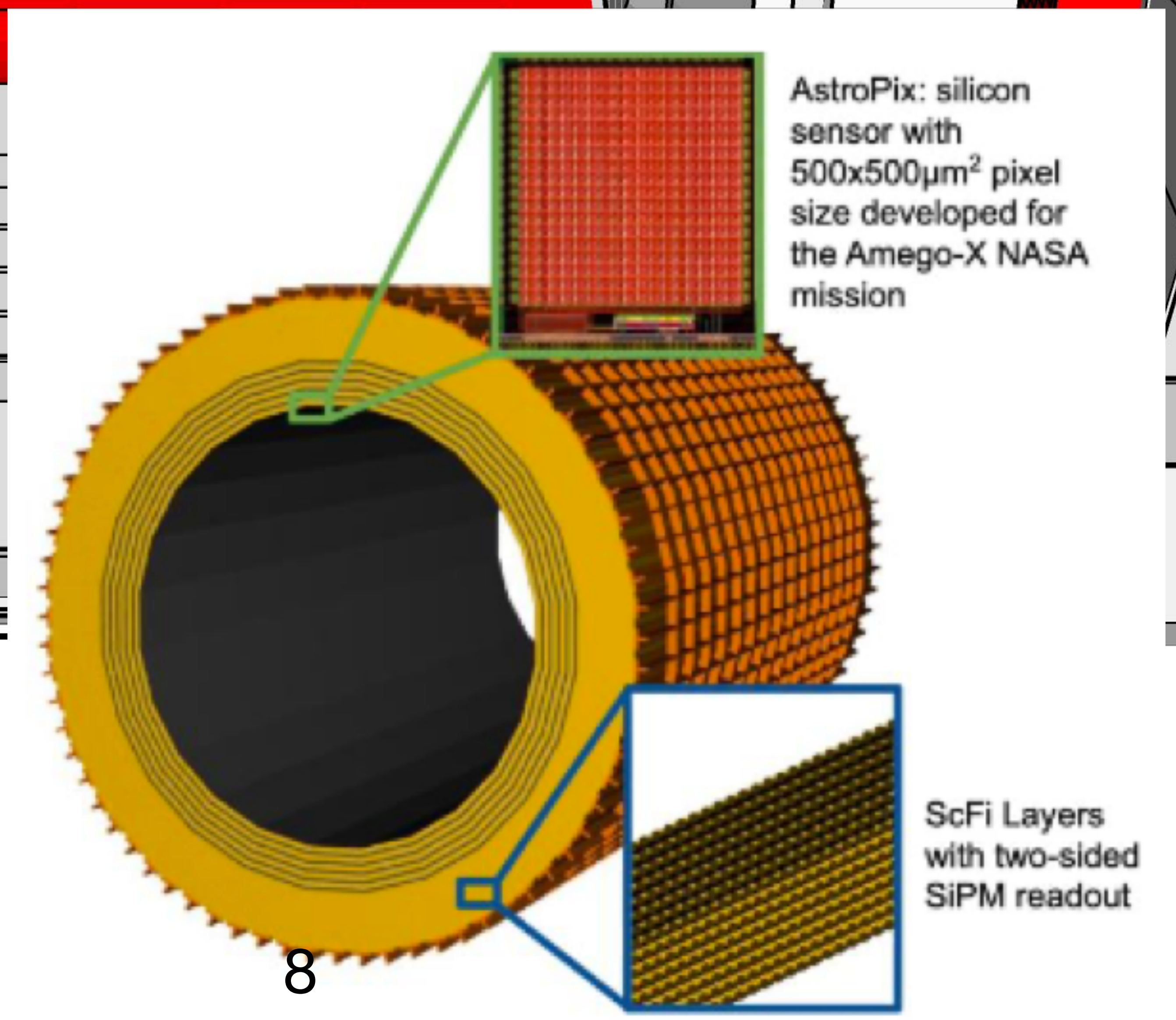
Electromagnetic calorimeter



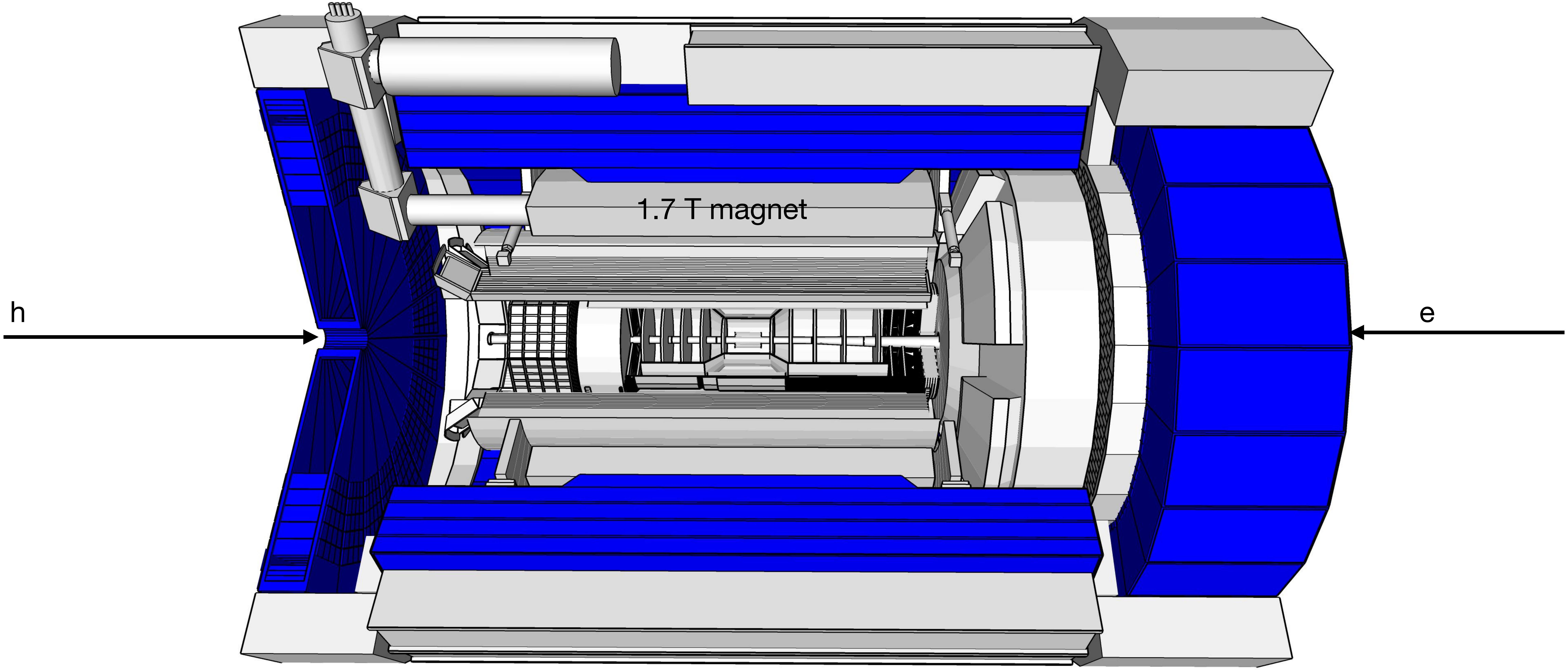




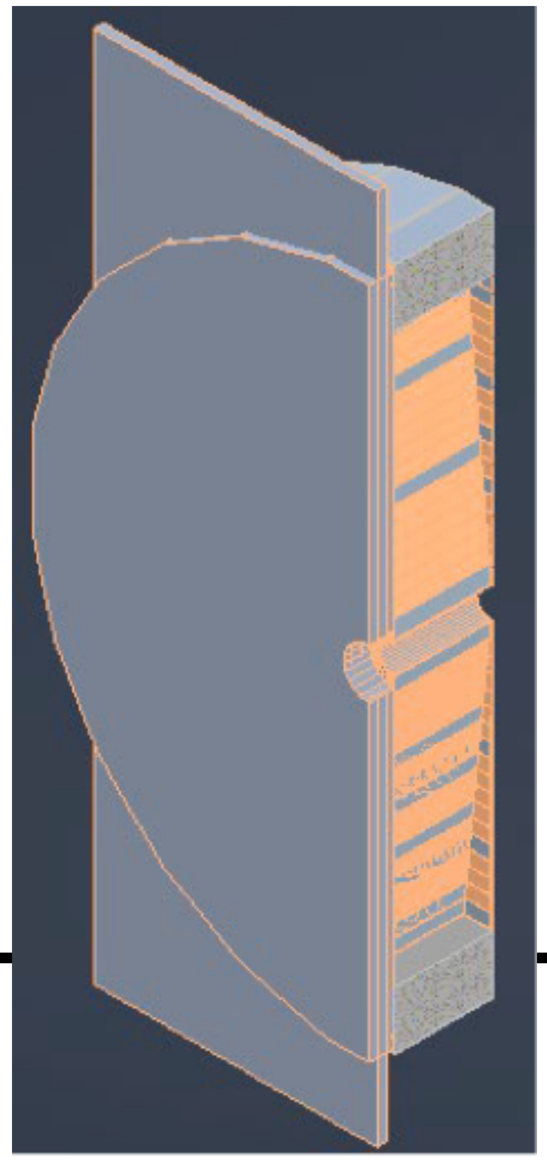
- Backward EMCAL:
  high-precision $PbWO_4$ + Si sensors
- Barrel EMCAL:
  3D imaging with MAPS and sampling Pb/scintillating fibres with Si sensors
- Forward EMCAL:
  finely segmented W powder/scintillating fibres

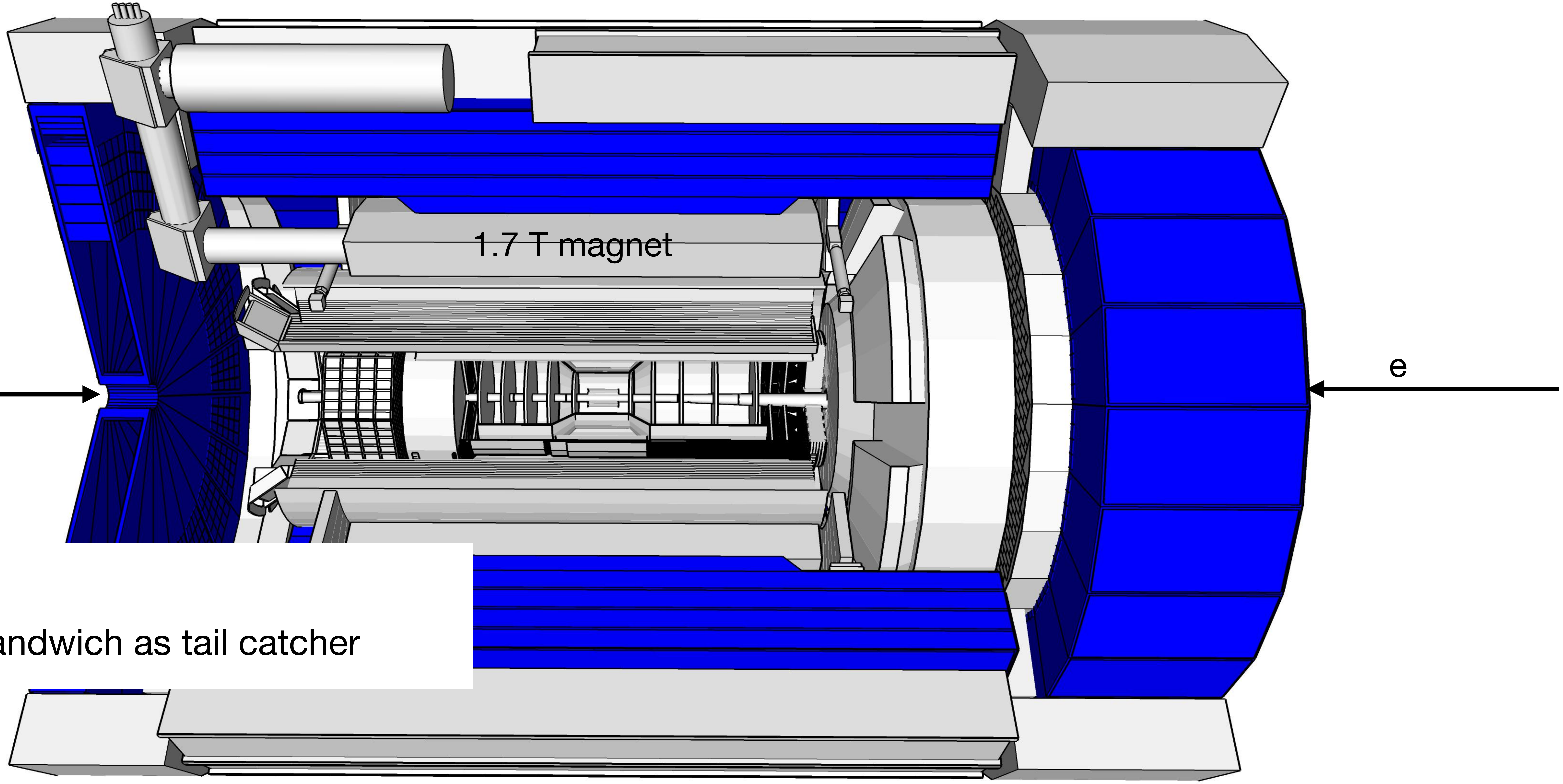


Hadronic calorimeter



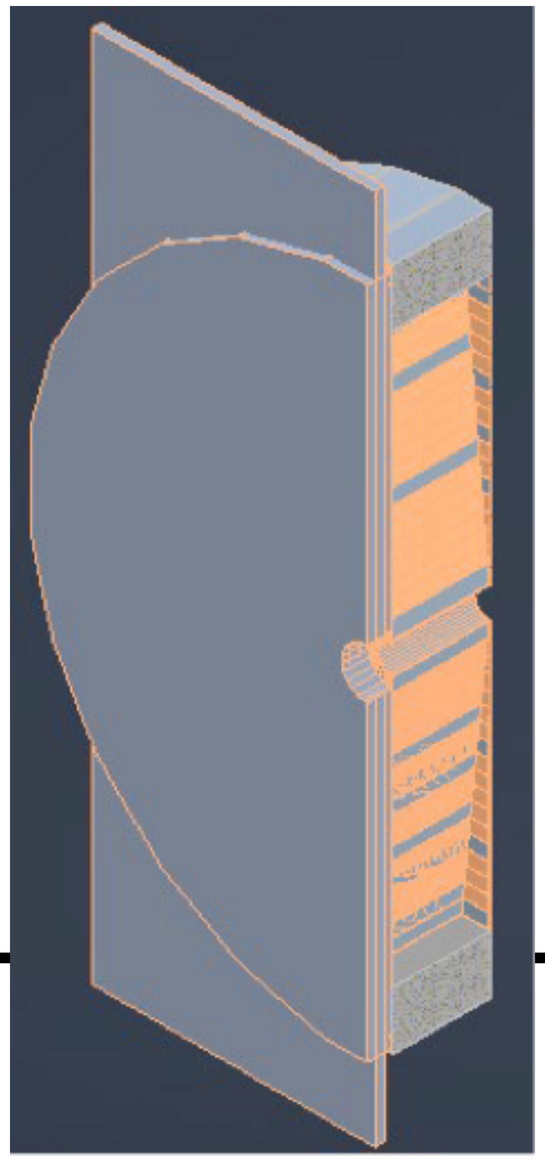
Hadronic calorimeter

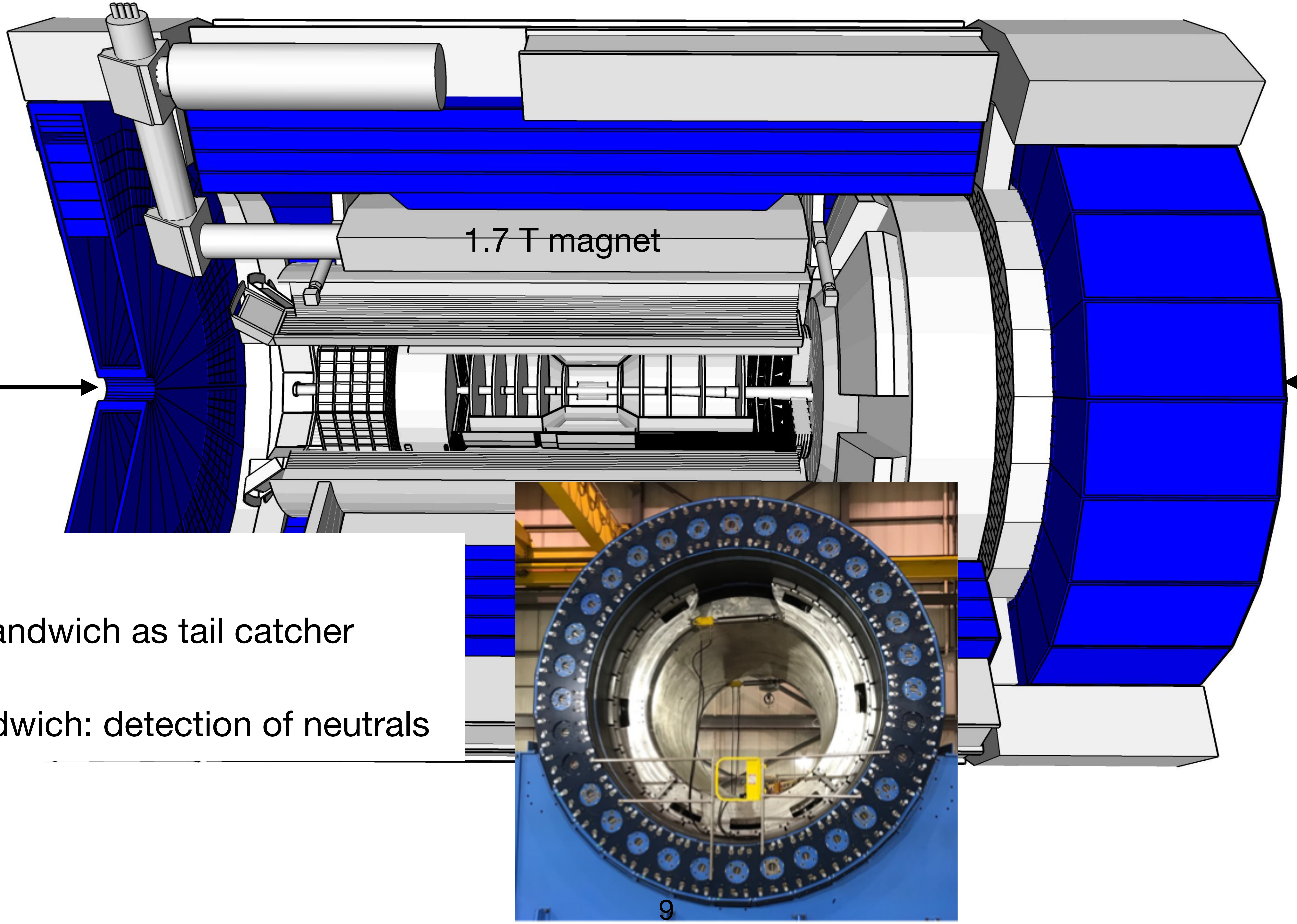




- Backward HCAL:
  steel/scintillator sandwich as tail catcher

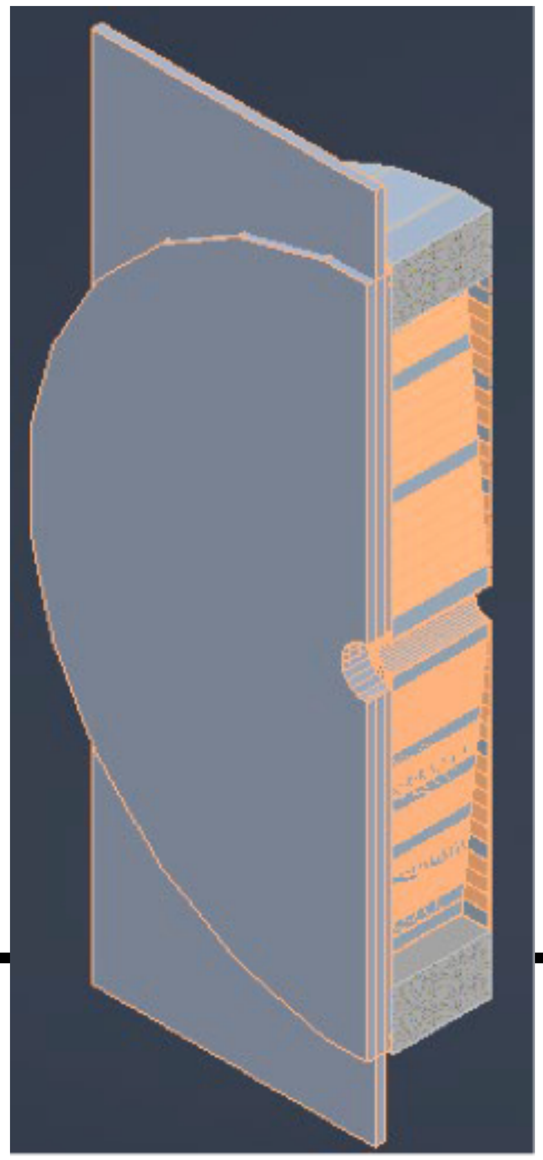
Hadronic calorimeter

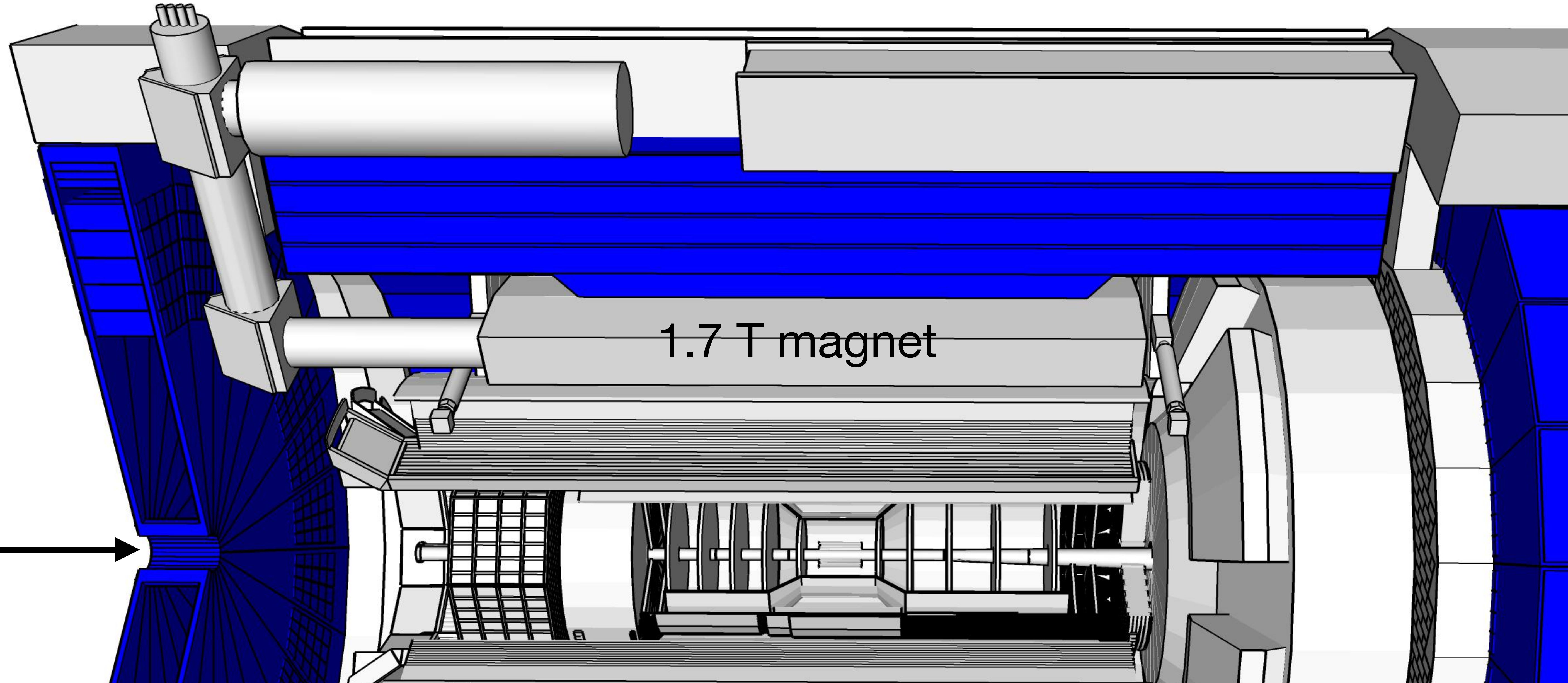




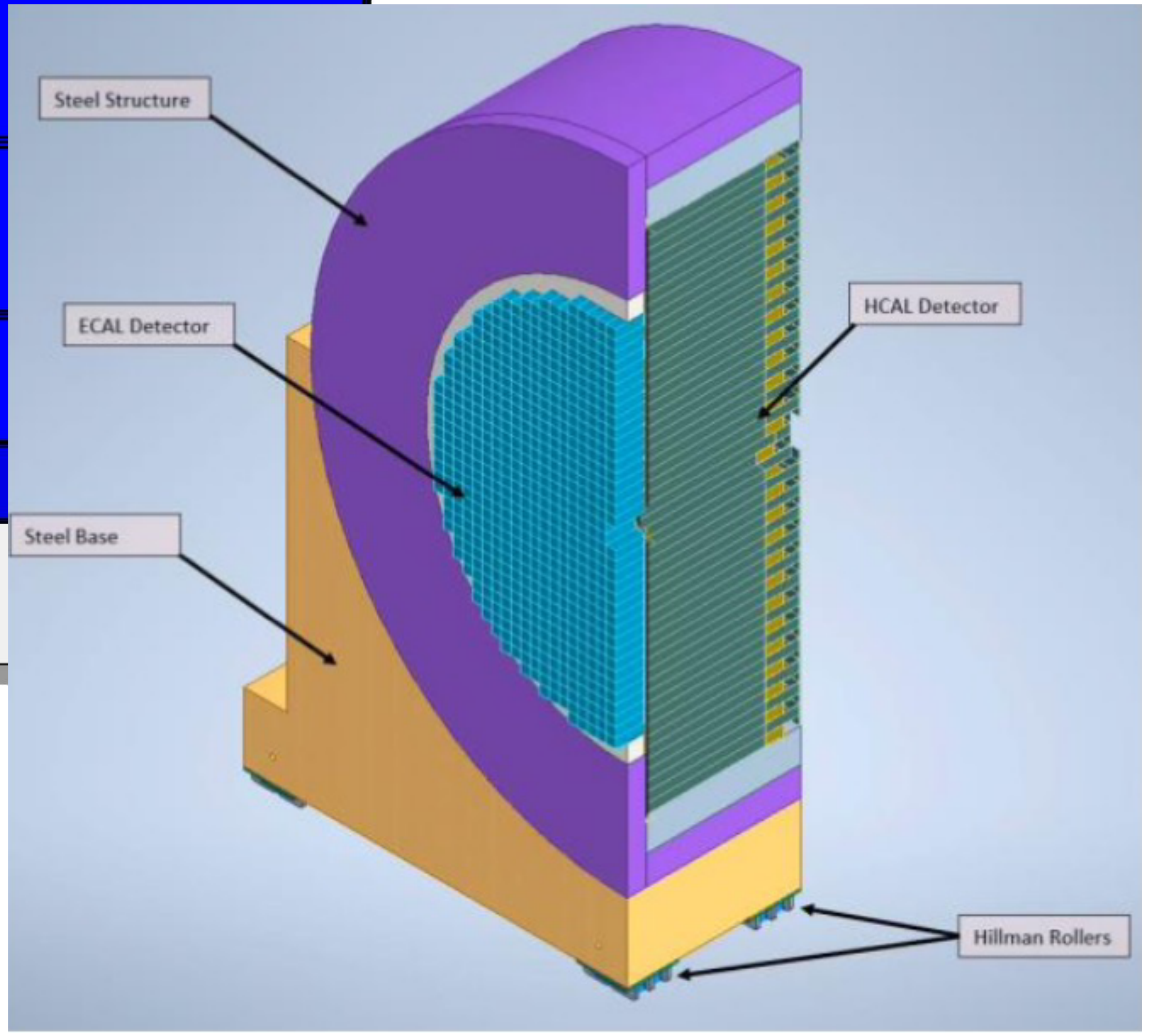
- Backward HCAL:
  steel/scintillator sandwich as tail catcher
- Barrel HCAL:
  Fe/scintillator sandwich: detection of neutrals

Hadronic calorimeter

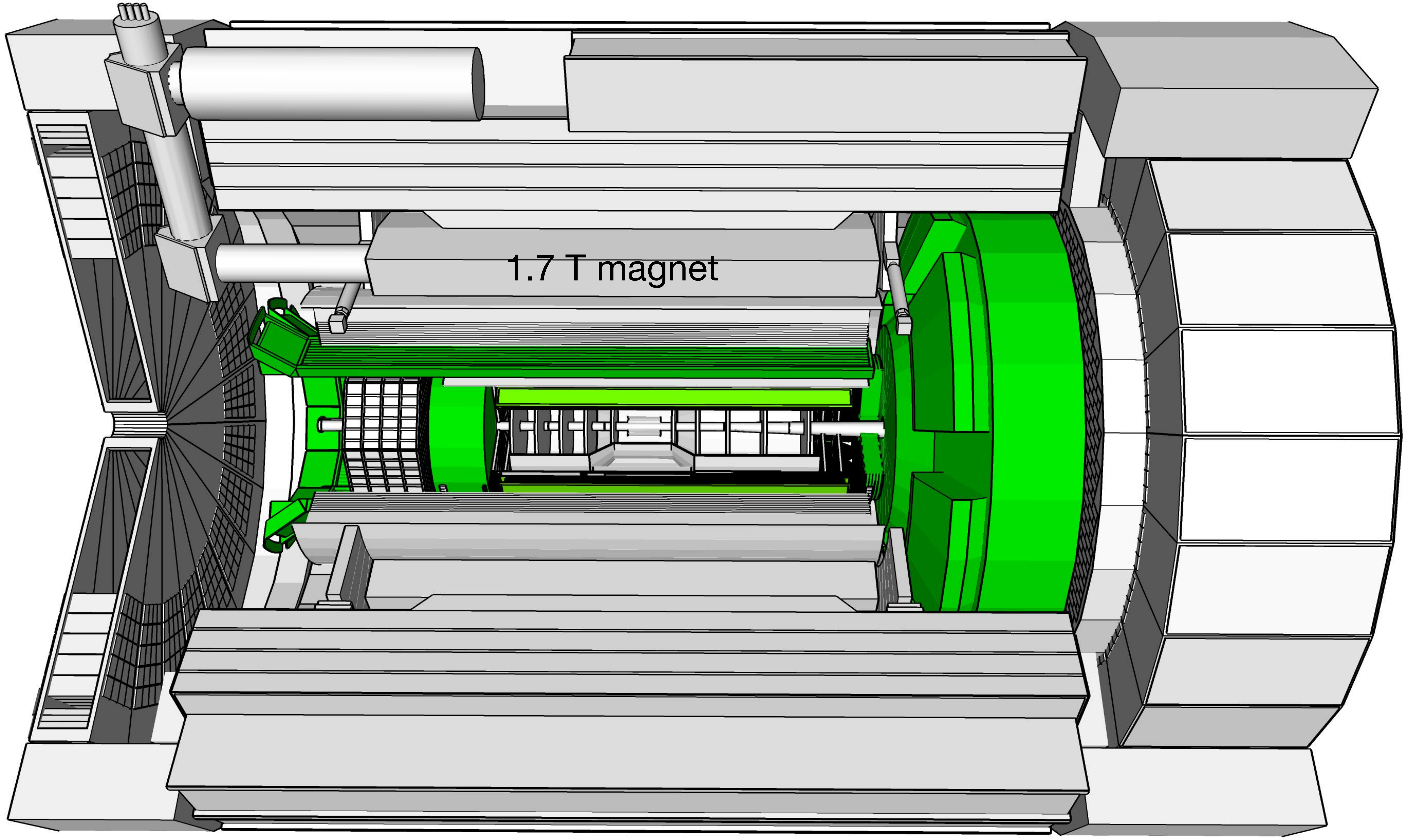




- Backward HCAL:
  steel/scintillator sandwich as tail catcher
- Barrel HCAL:
  Fe/scintillator sandwich: detection of neutrals
- Forward HCAL:
  W/scintillator sandwich longitudinally segmented, high granularity: good E resolution

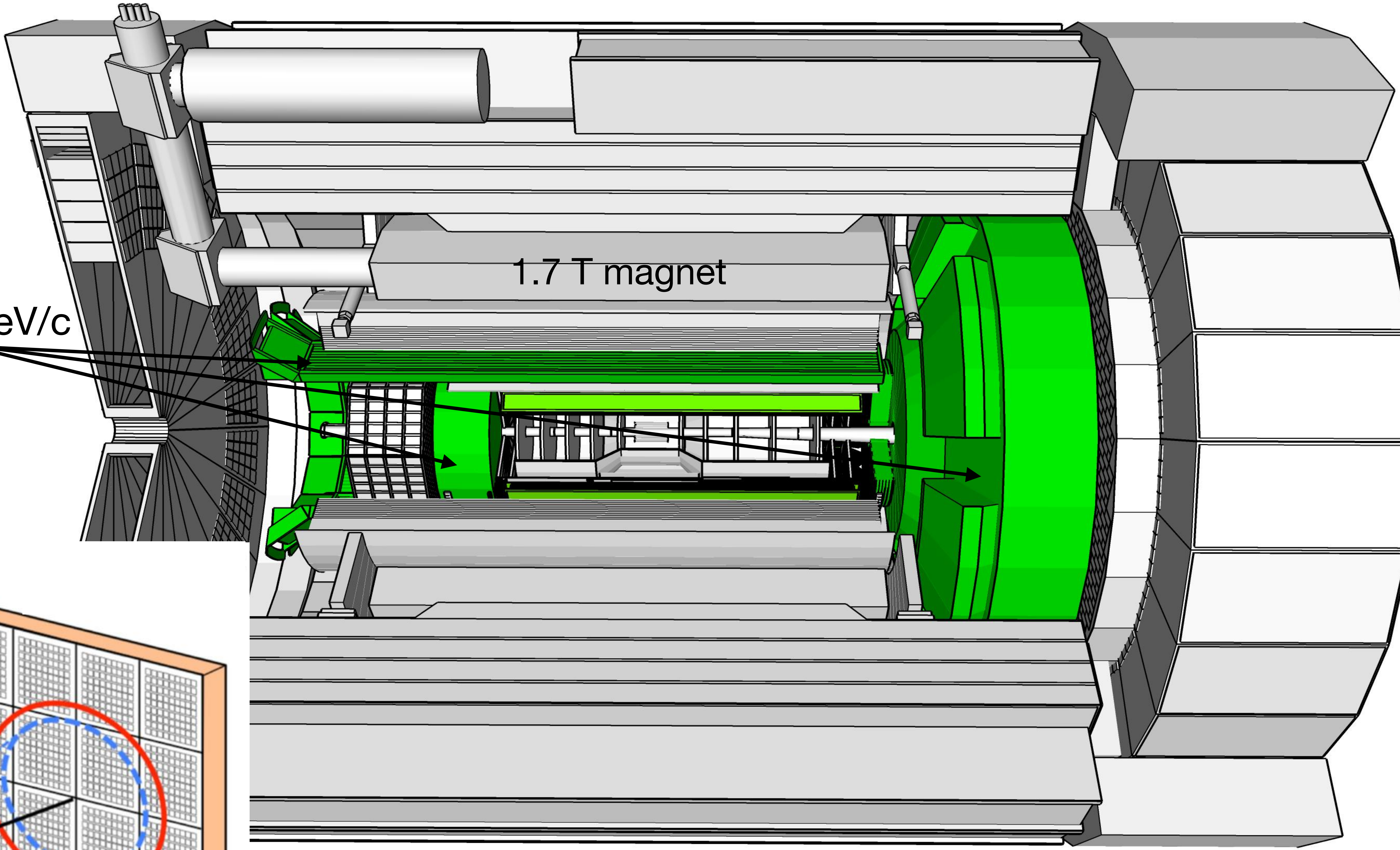


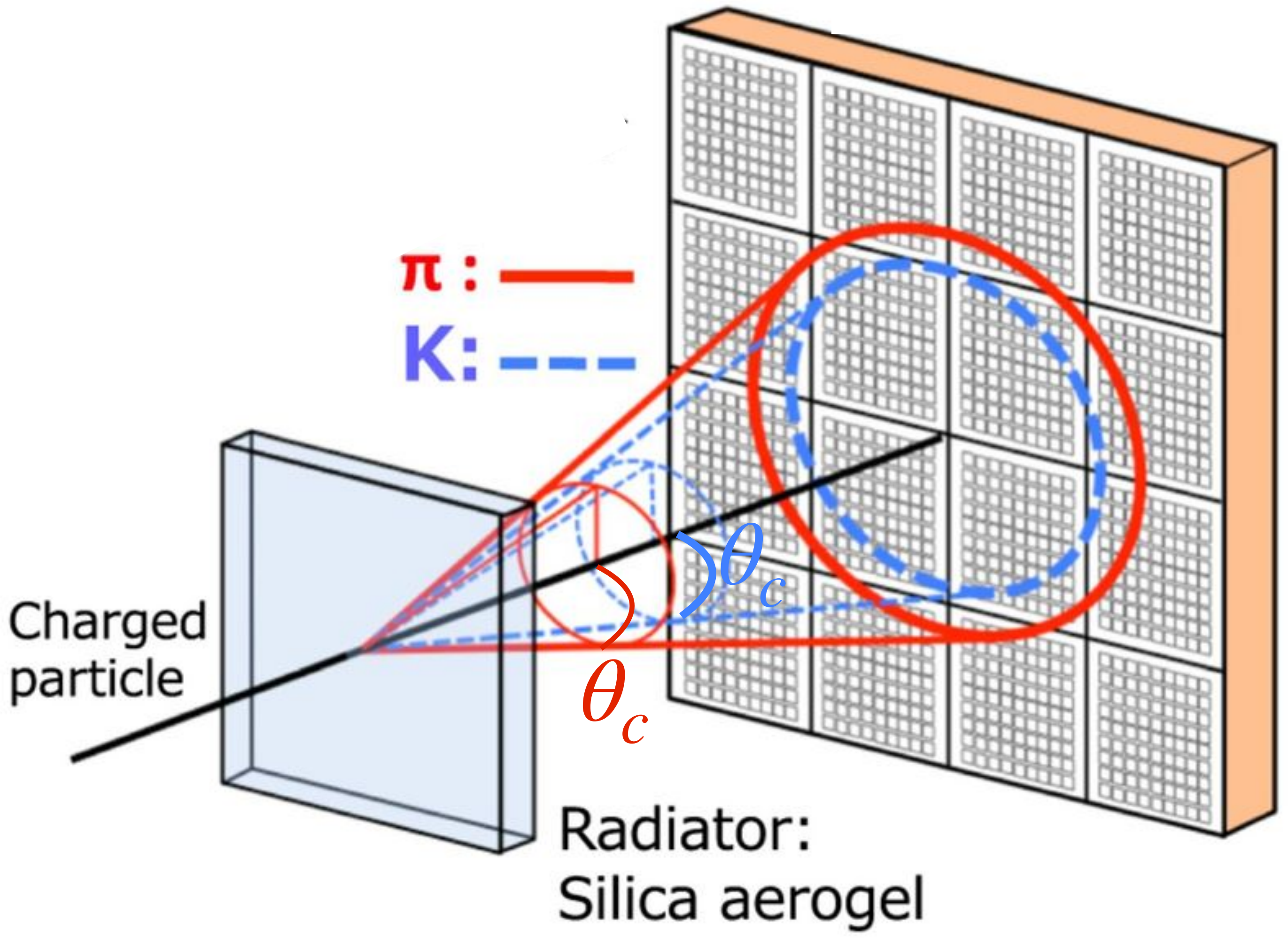
Particle identification



Particle identification

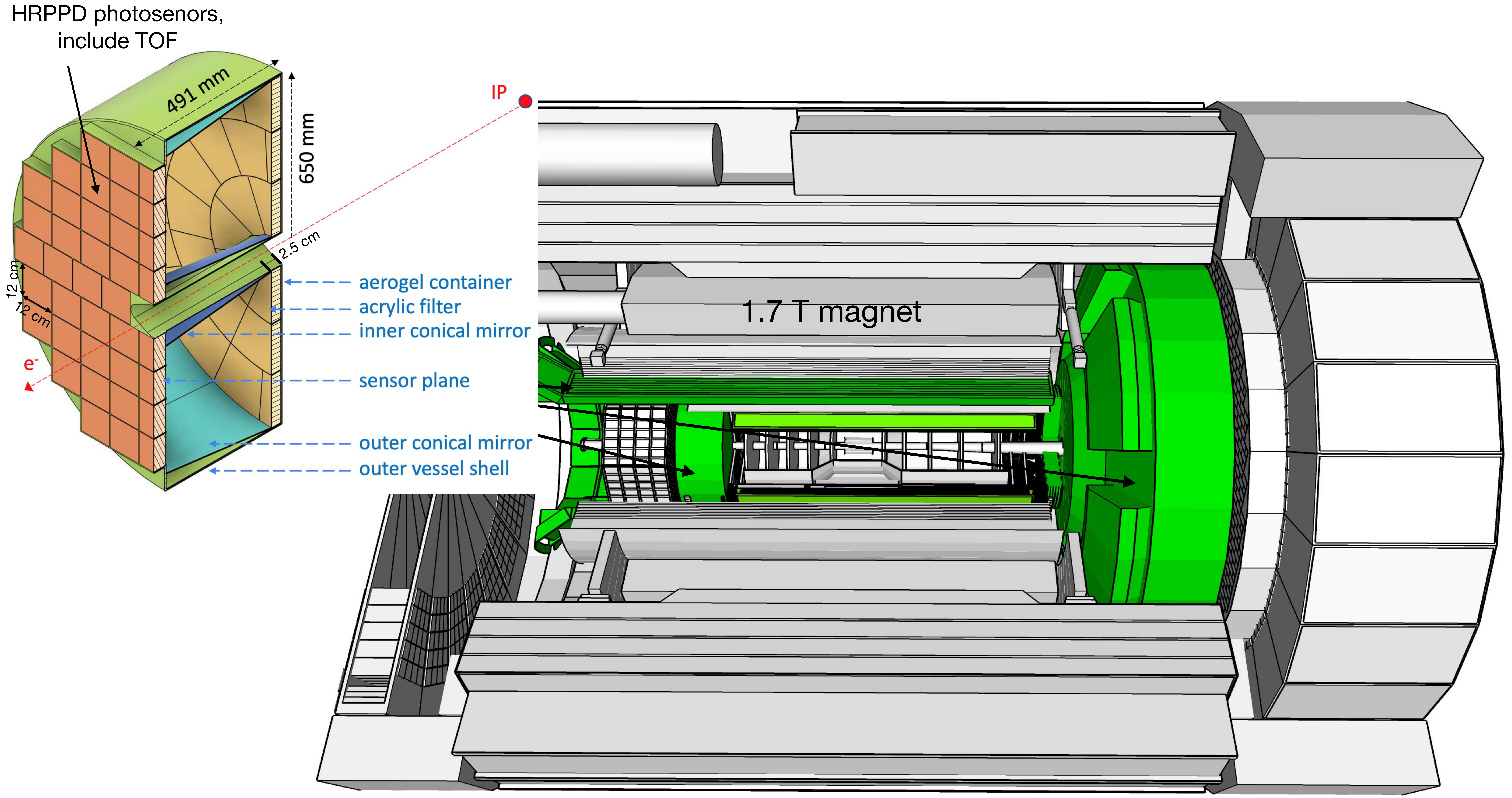
detectors based on
Cherenkov radiation
for 1 GeV/c<p<50 GeV/c



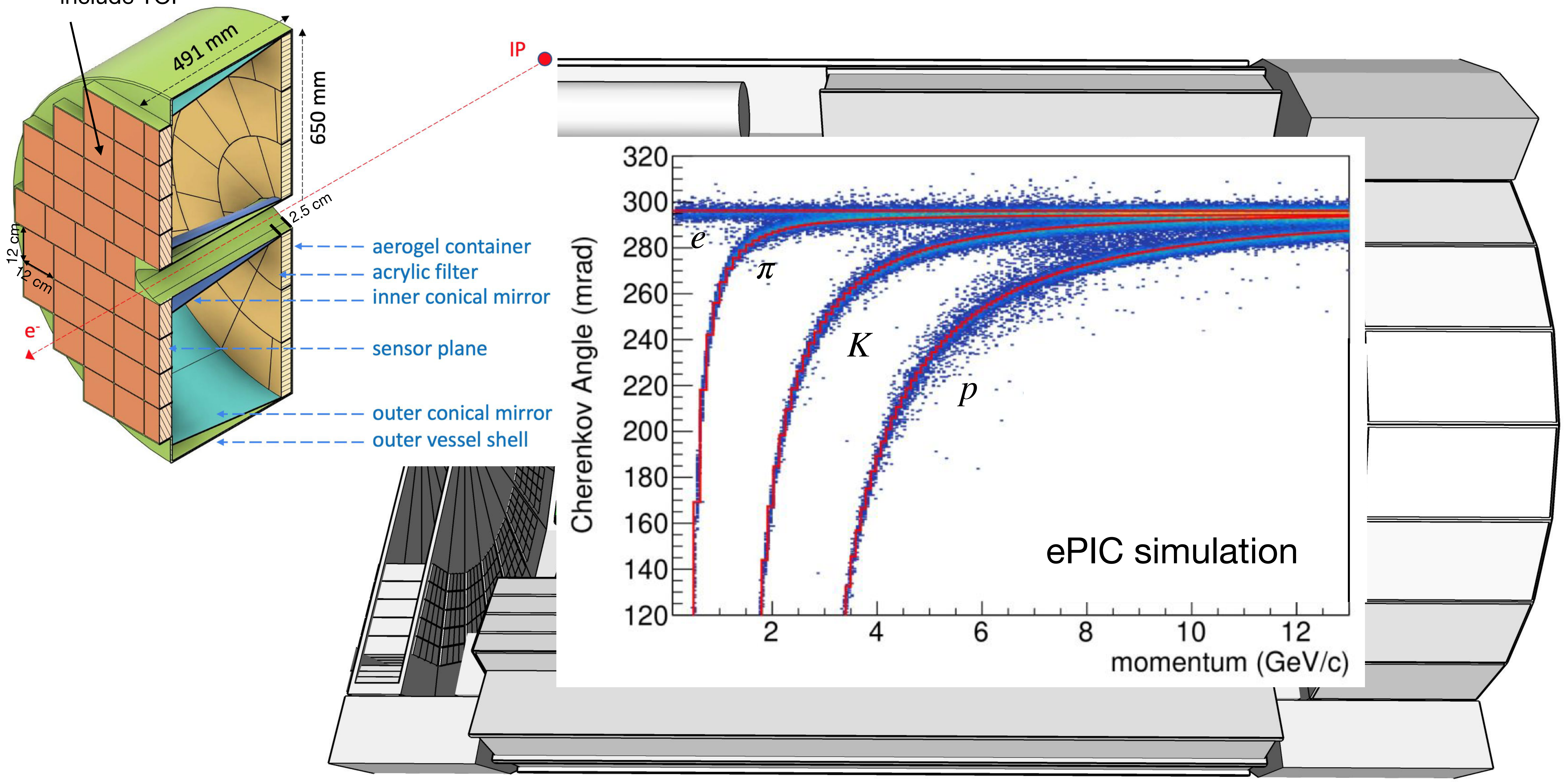


$$\cos\theta_c \propto \frac{1}{v}$$

Particle identification

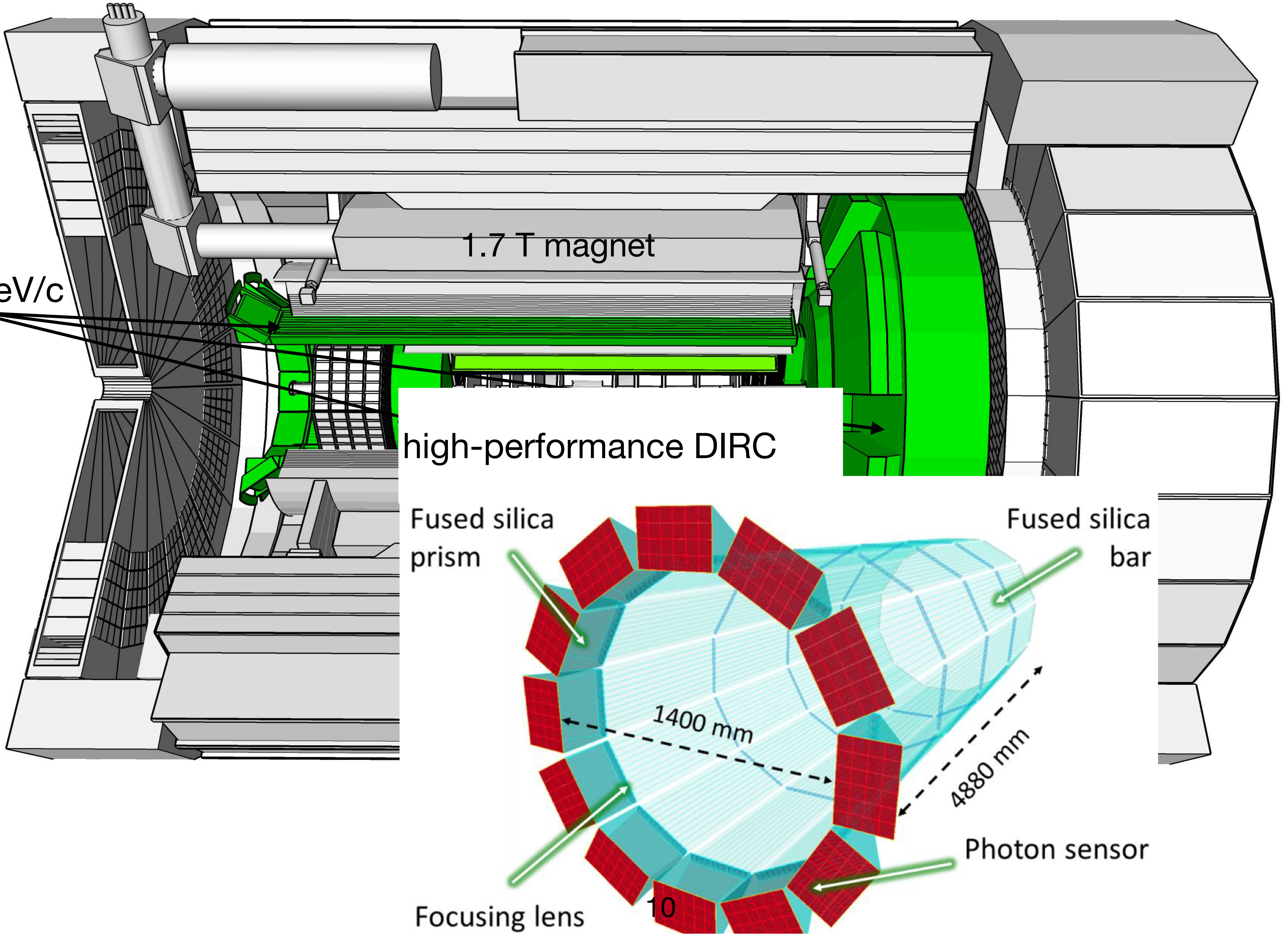


Particle identification



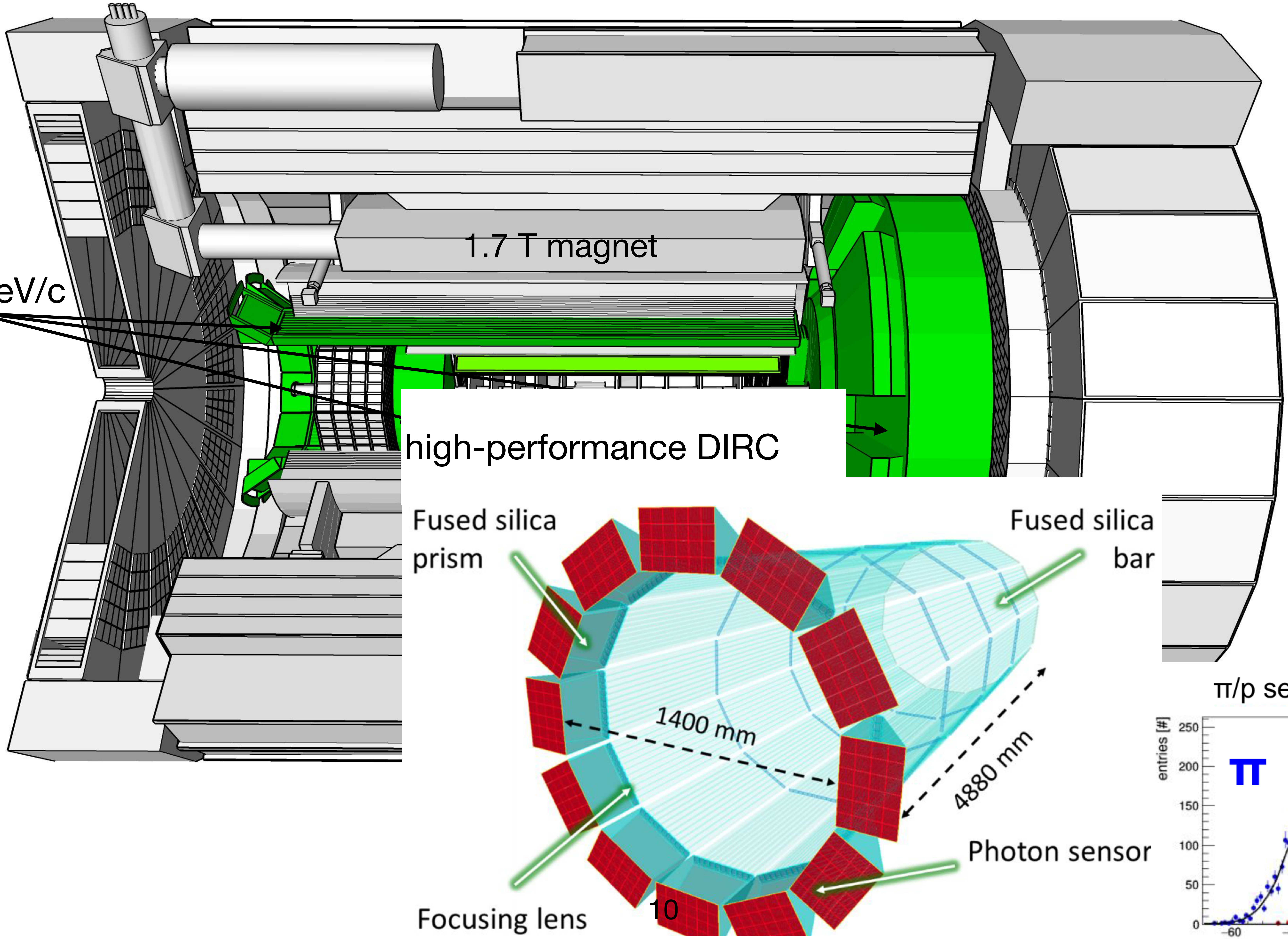
Particle identification

detectors based on
Cherenkov radiation
for 1 GeV/c<p<50 GeV/c

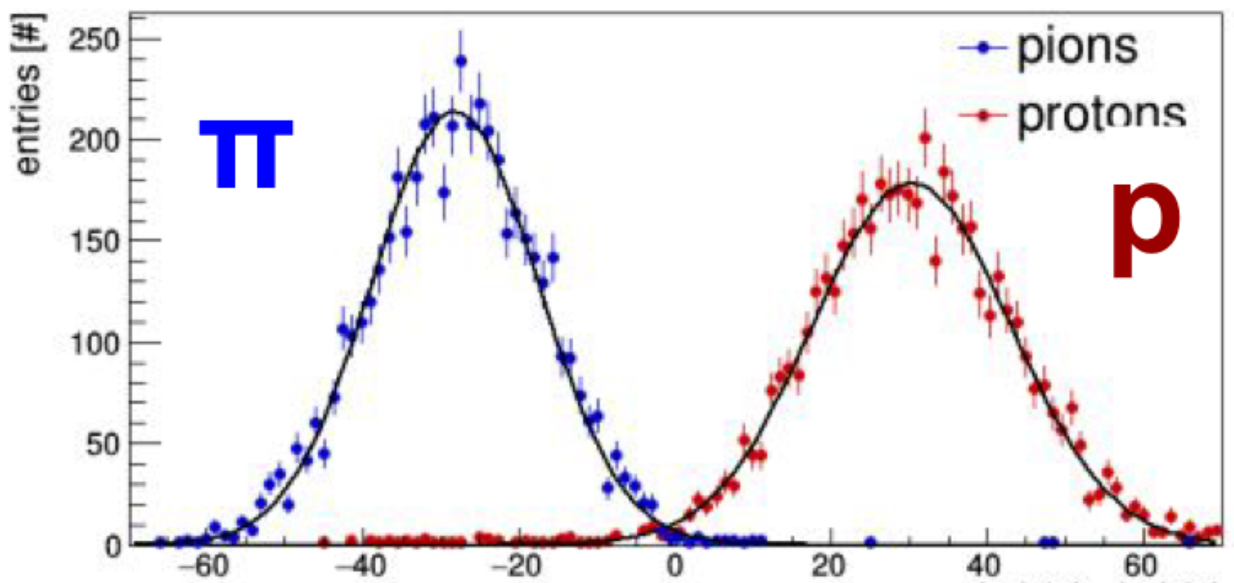


Particle identification

detectors based on
Cherenkov radiation
for 1 GeV/c<p<50 GeV/c

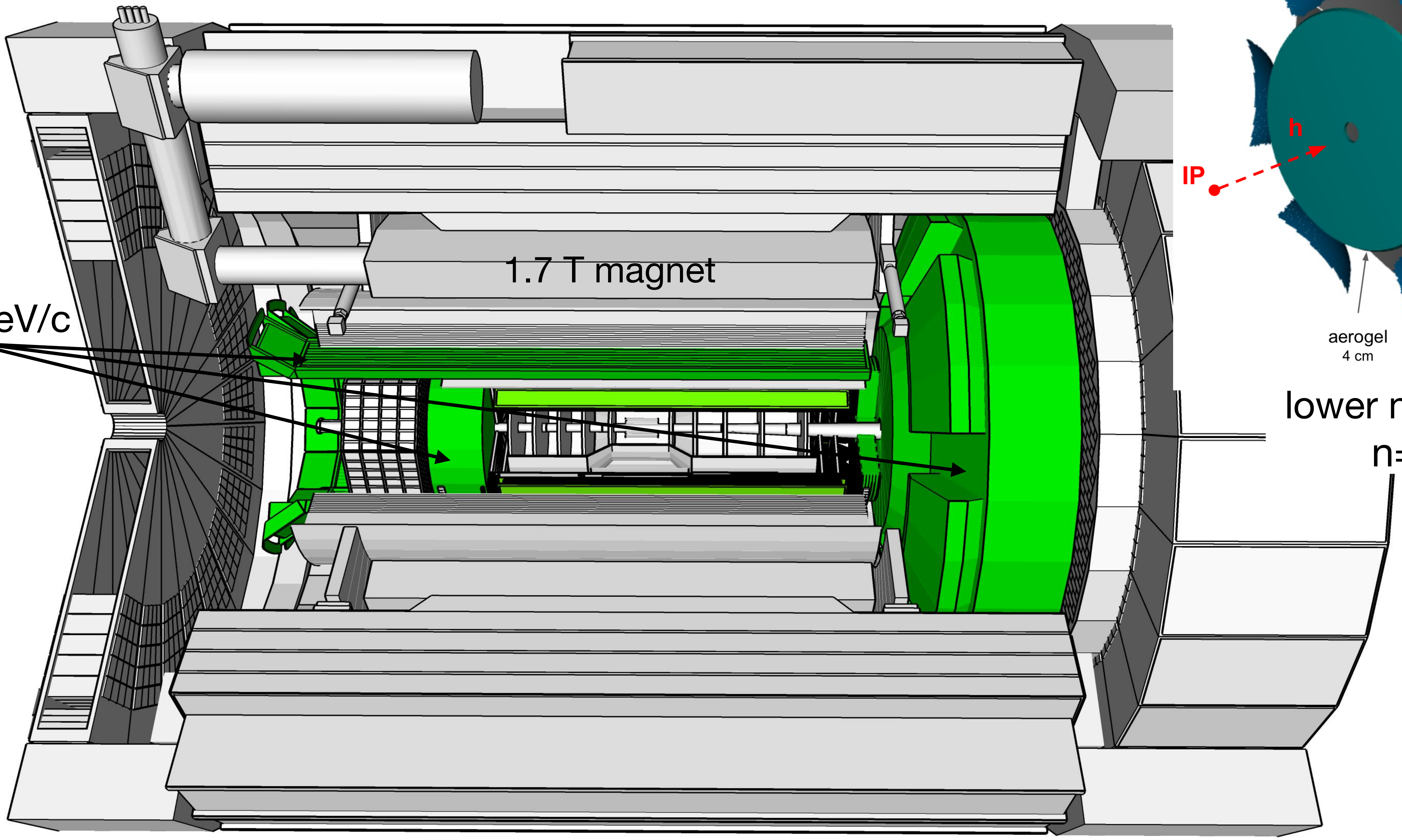


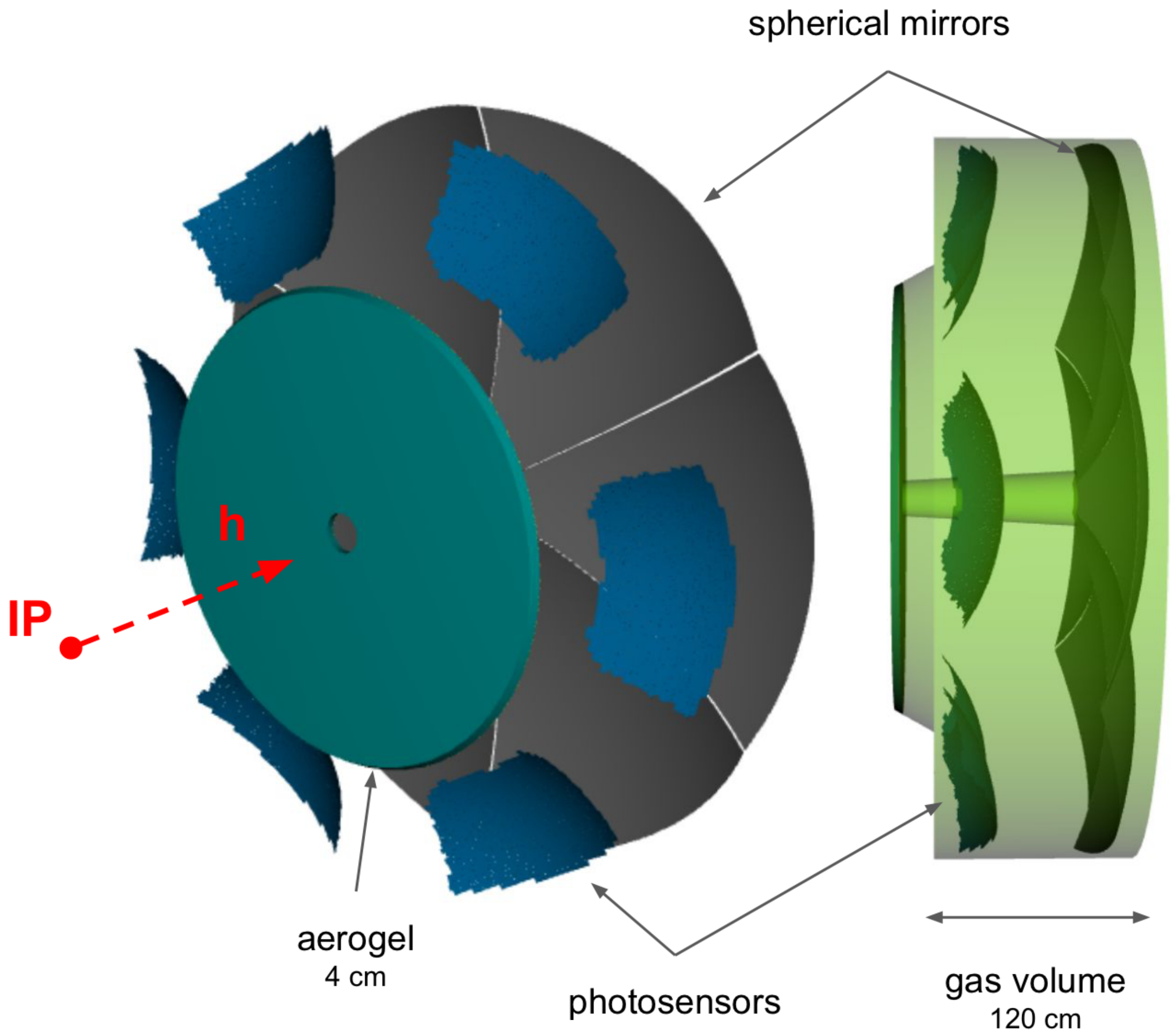
π/p separation power at 7 GeV/c



Particle identification

detectors based on
Cherenkov radiation
for 1 GeV/c<p<50 GeV/c



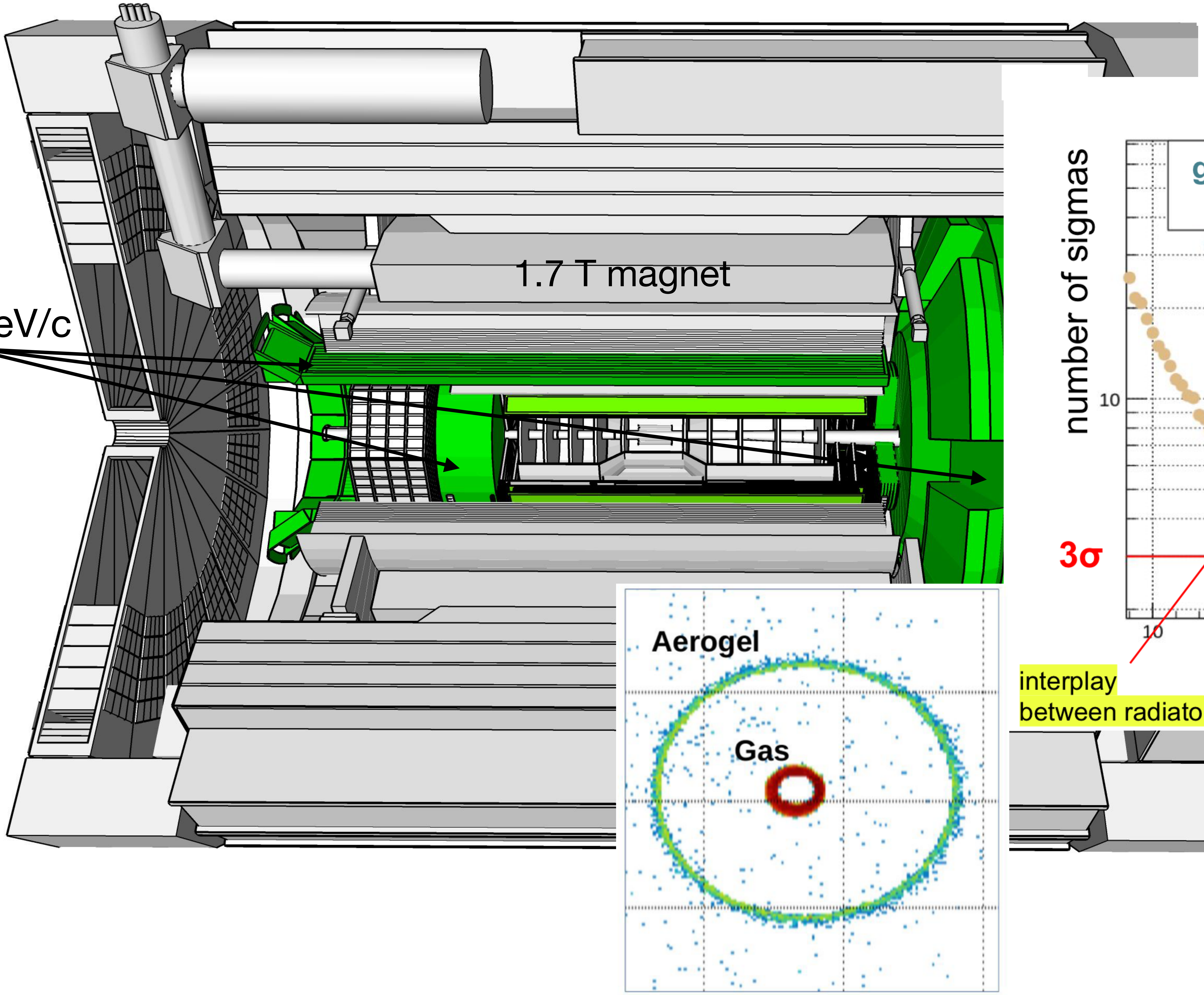


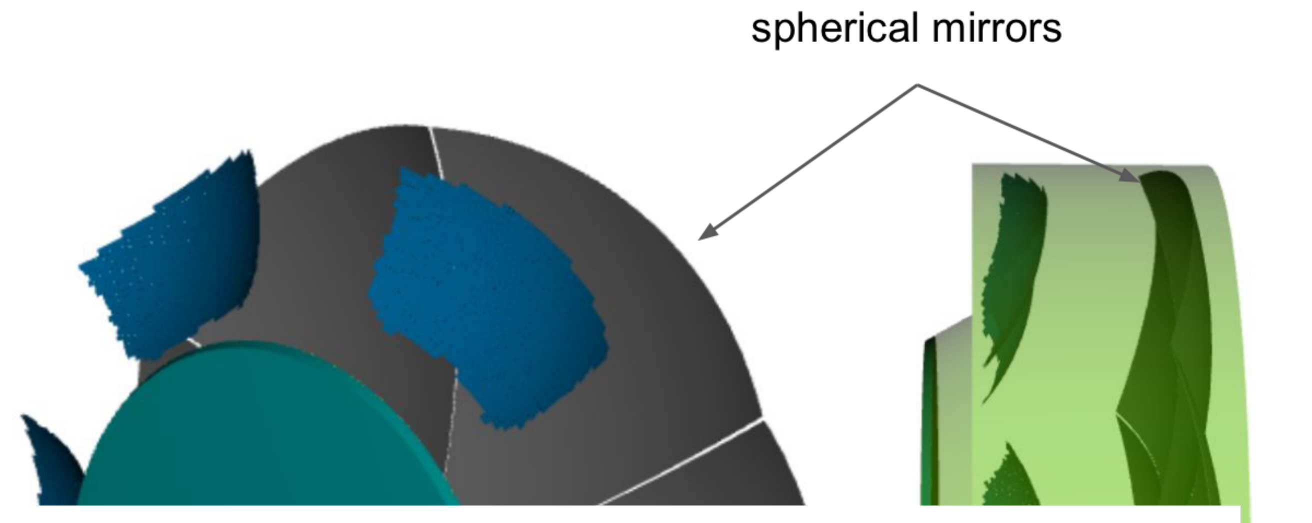
lower momentum
n=1.02

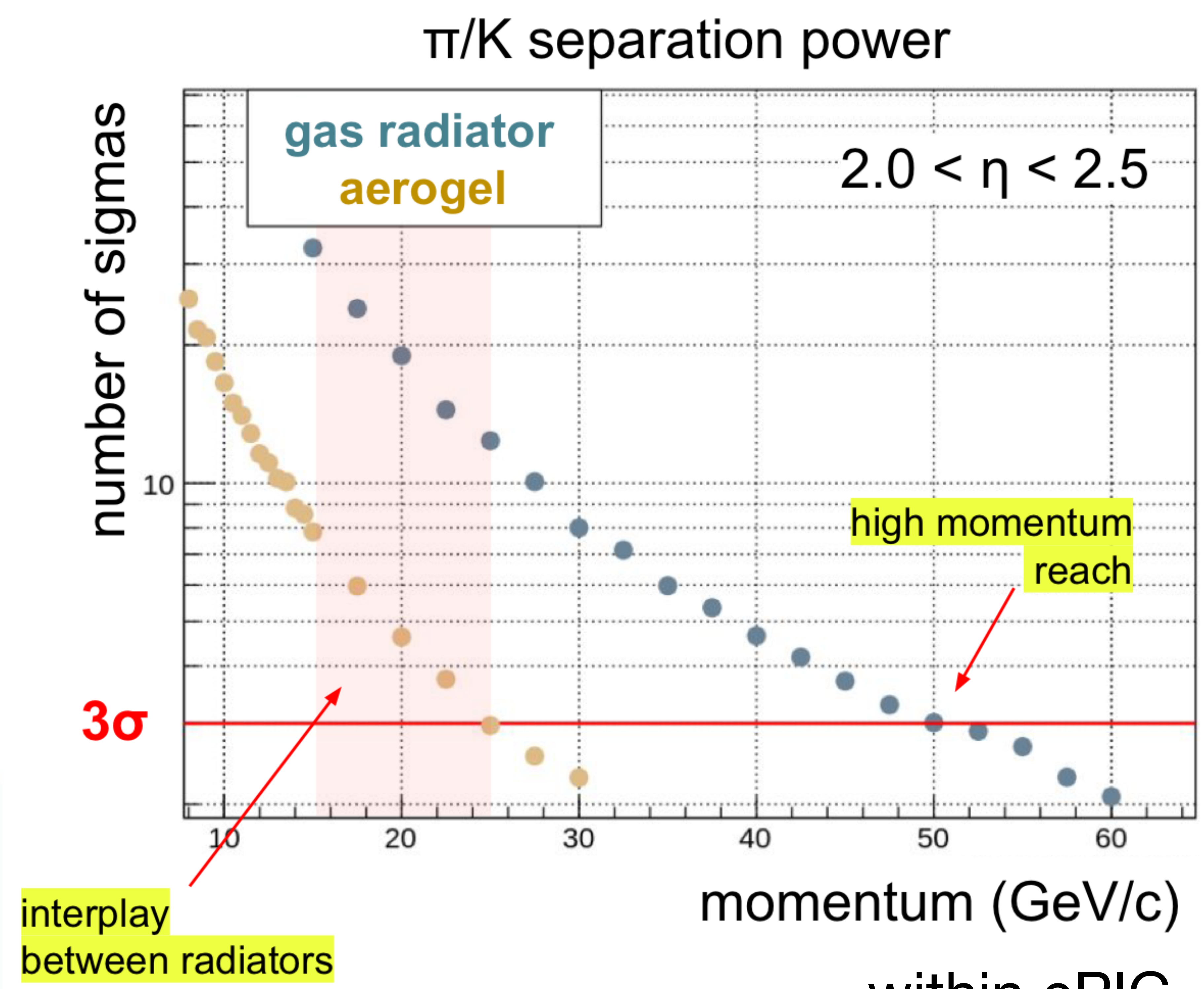
C_4F_{10}
high
momentum
n=1.0008

Particle identification

detectors based on
Cherenkov radiation
for 1 GeV/c<p<50 GeV/c





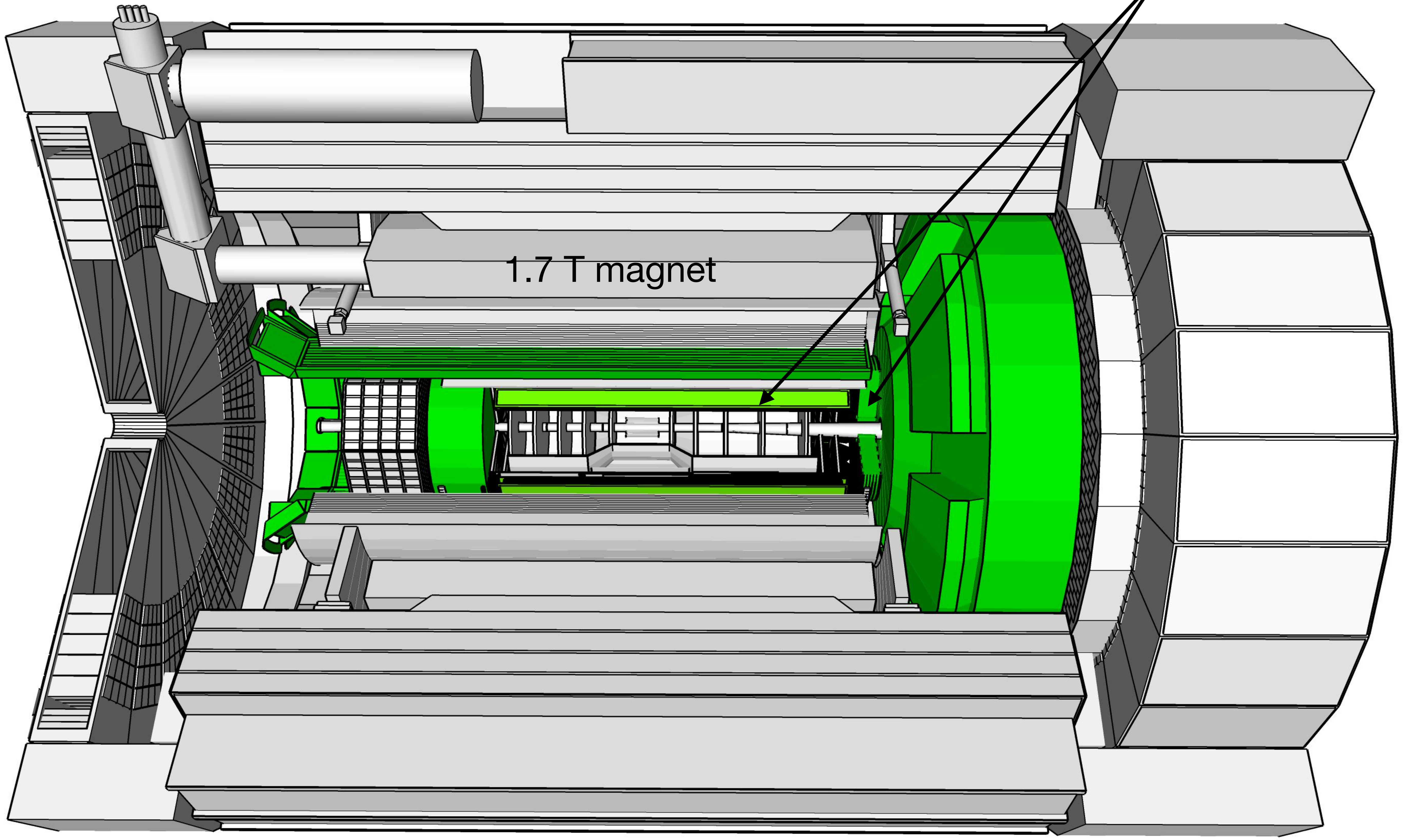


within ePIC
simulation framework

Particle identification

AC-LGAD based TOF, for p < 0.5 – 3 GeV/c

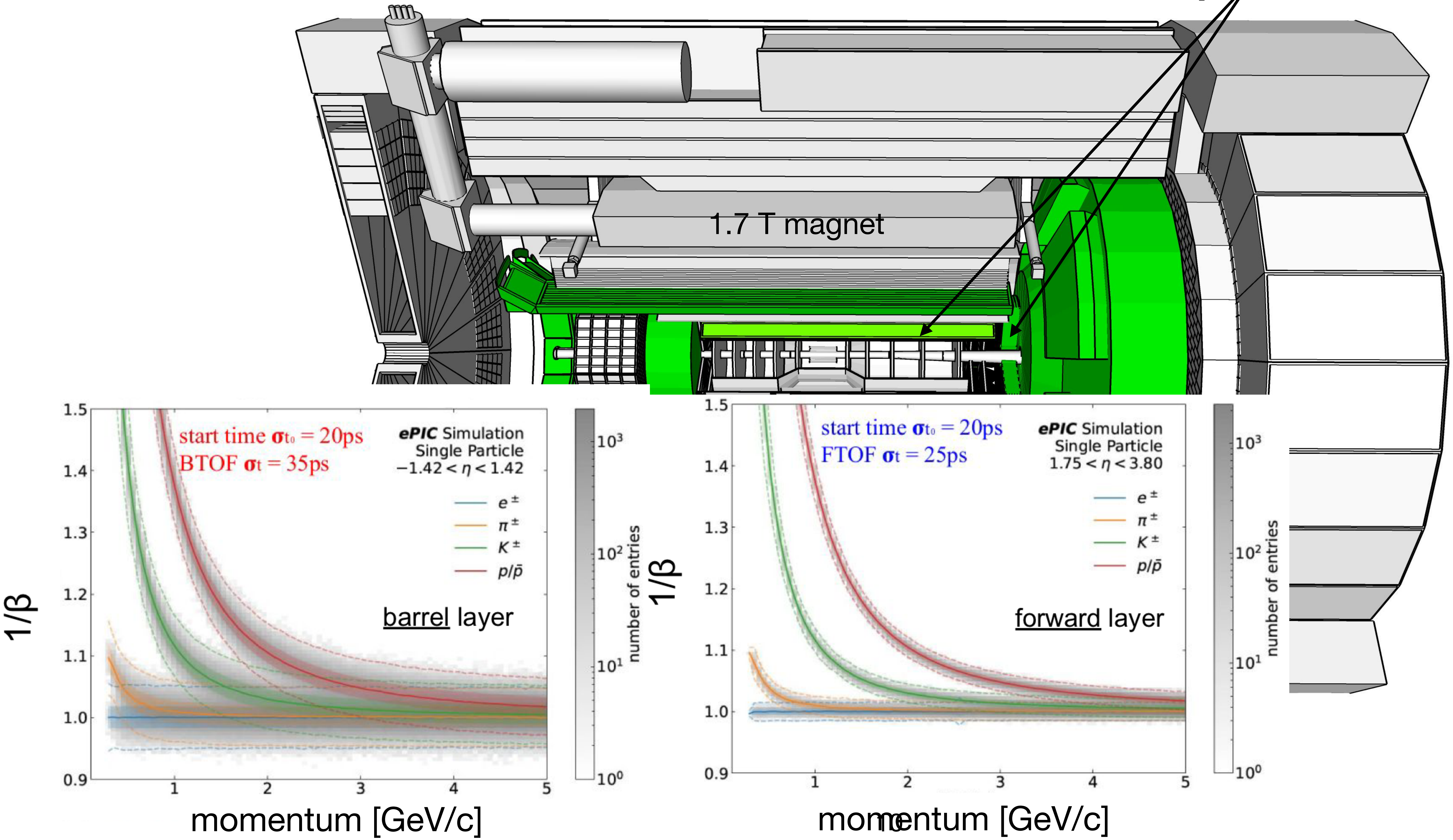
$$v = \frac{L}{t_{stop} - t_{start}}$$



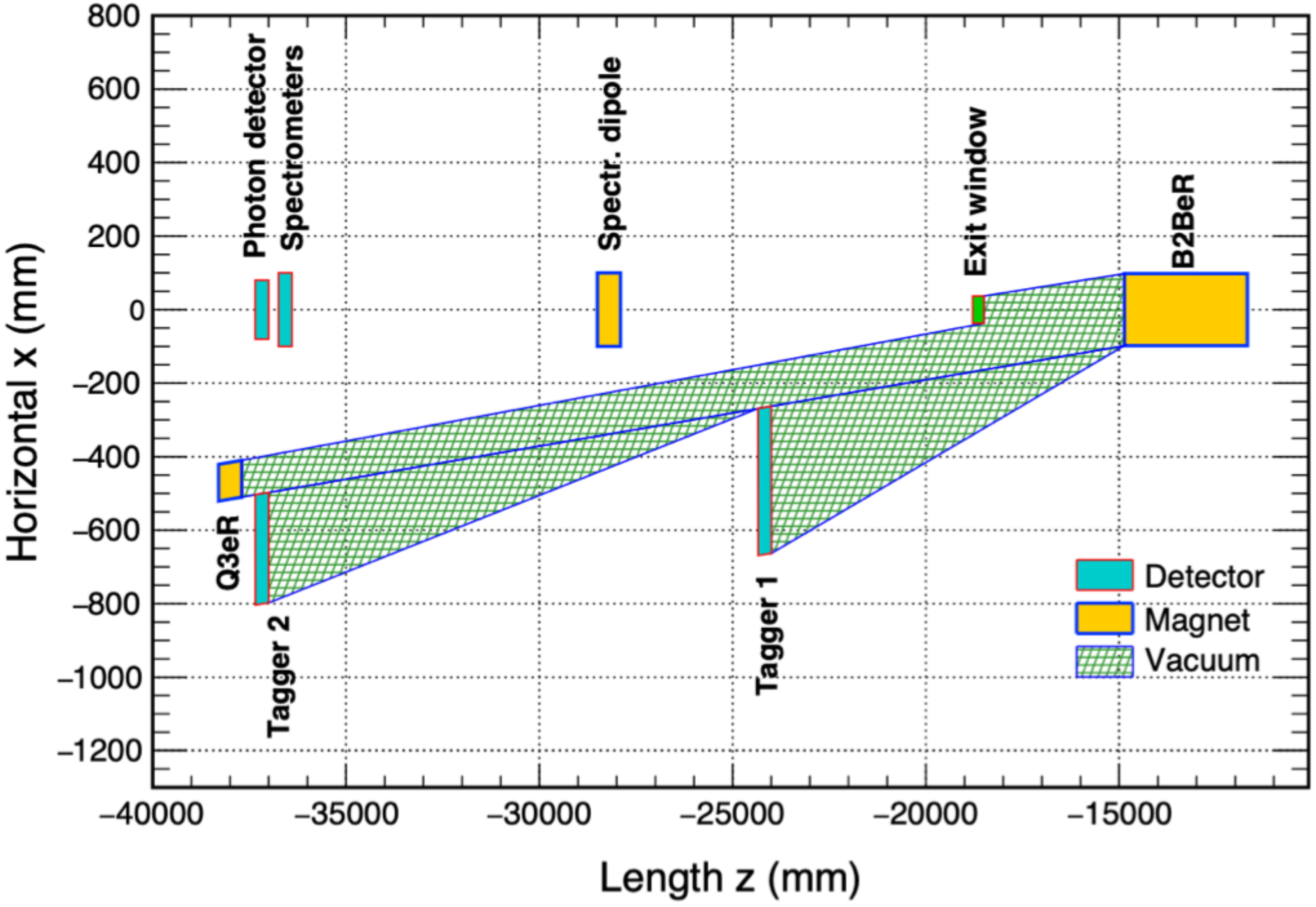
Particle identification

AC-LGAD based TOF, for p < 0.5 – 3 GeV/c

$$v = \frac{L}{t_{stop} - t_{start}}$$

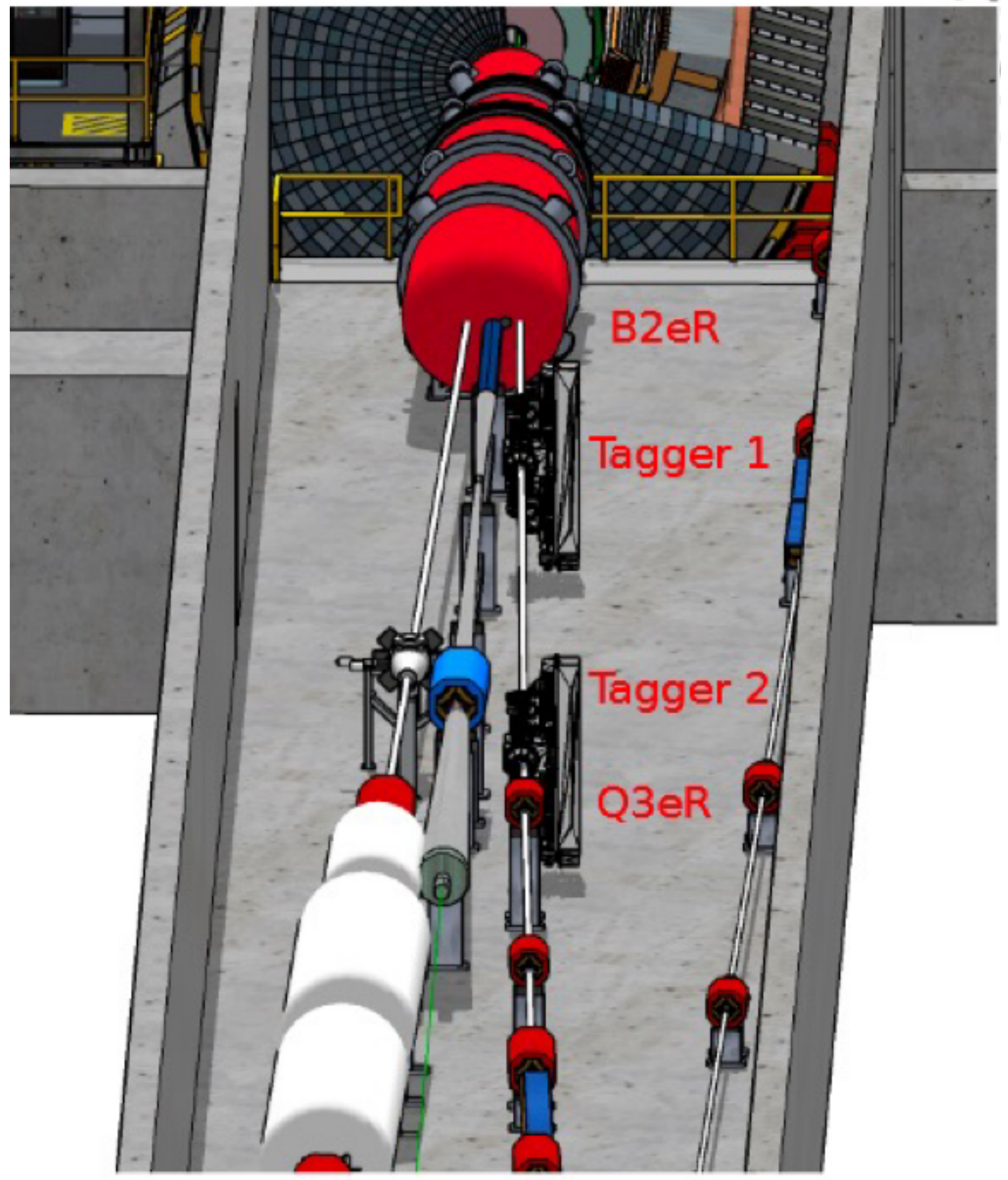


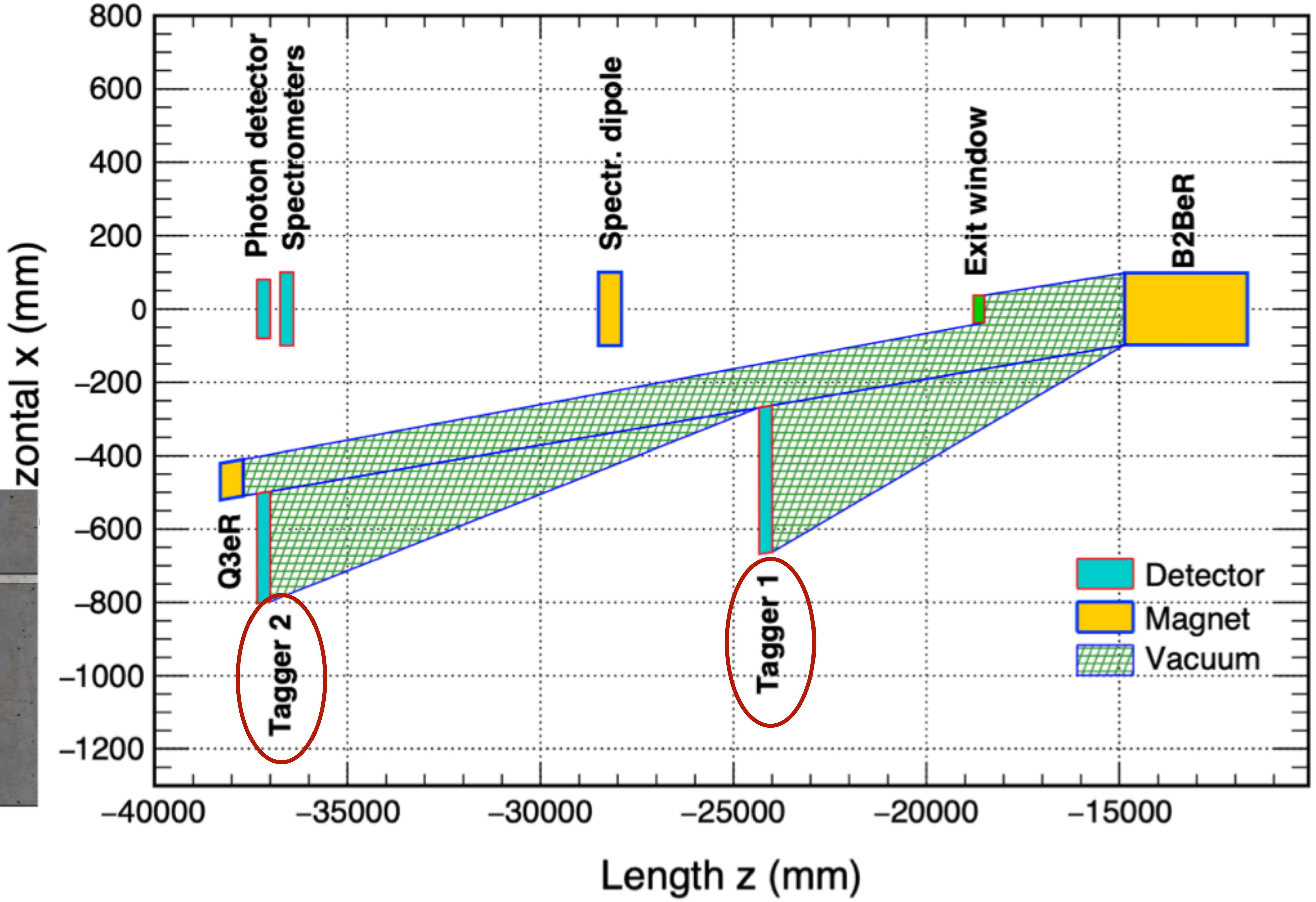
Far-backward region



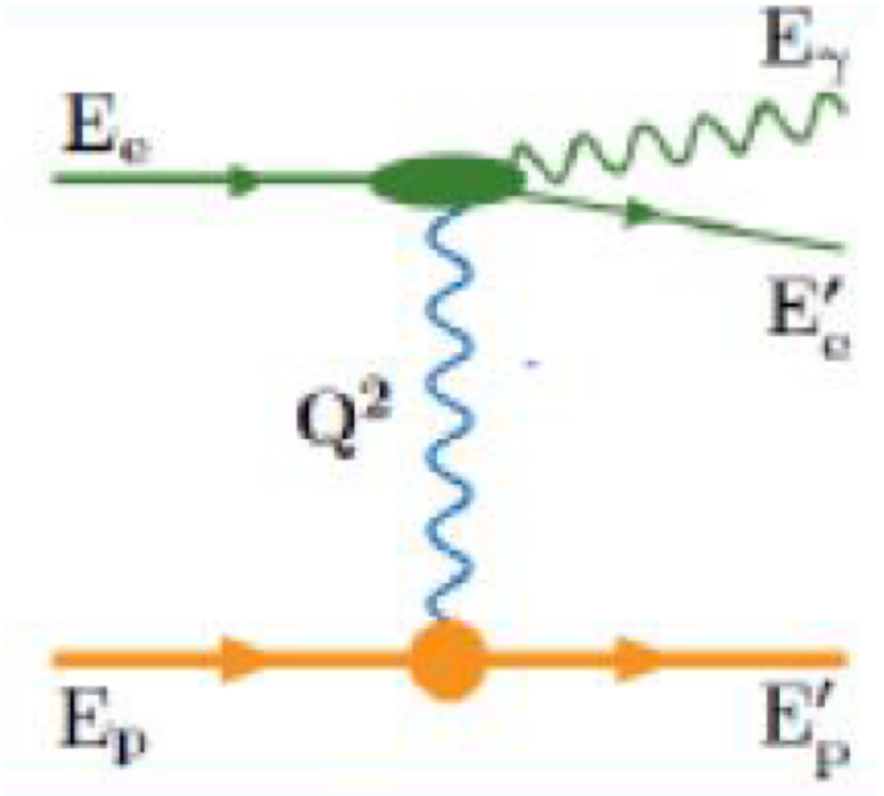
Far-backward region

low-Q² taggers

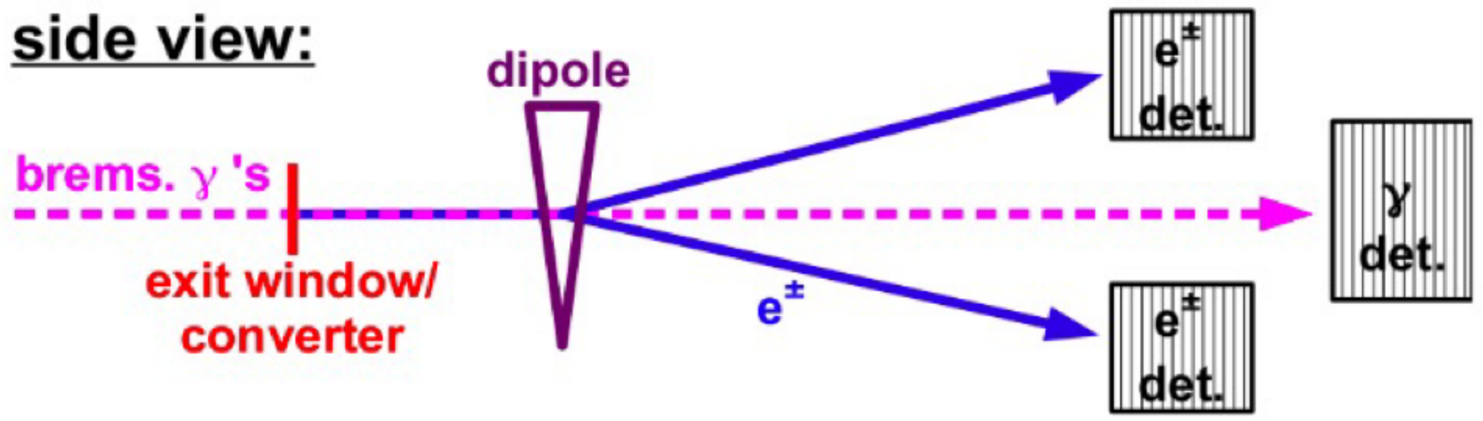




Far-backward region

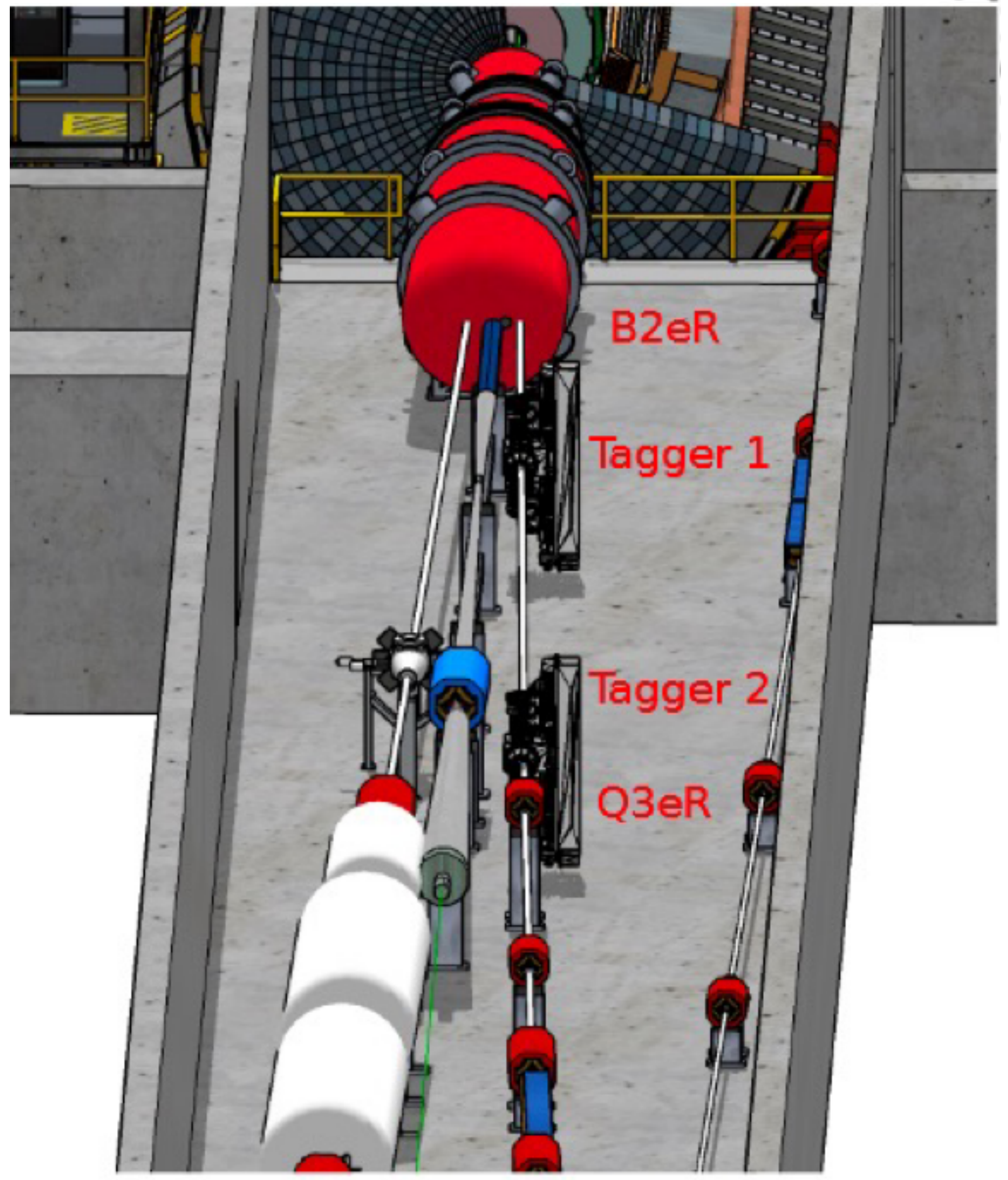


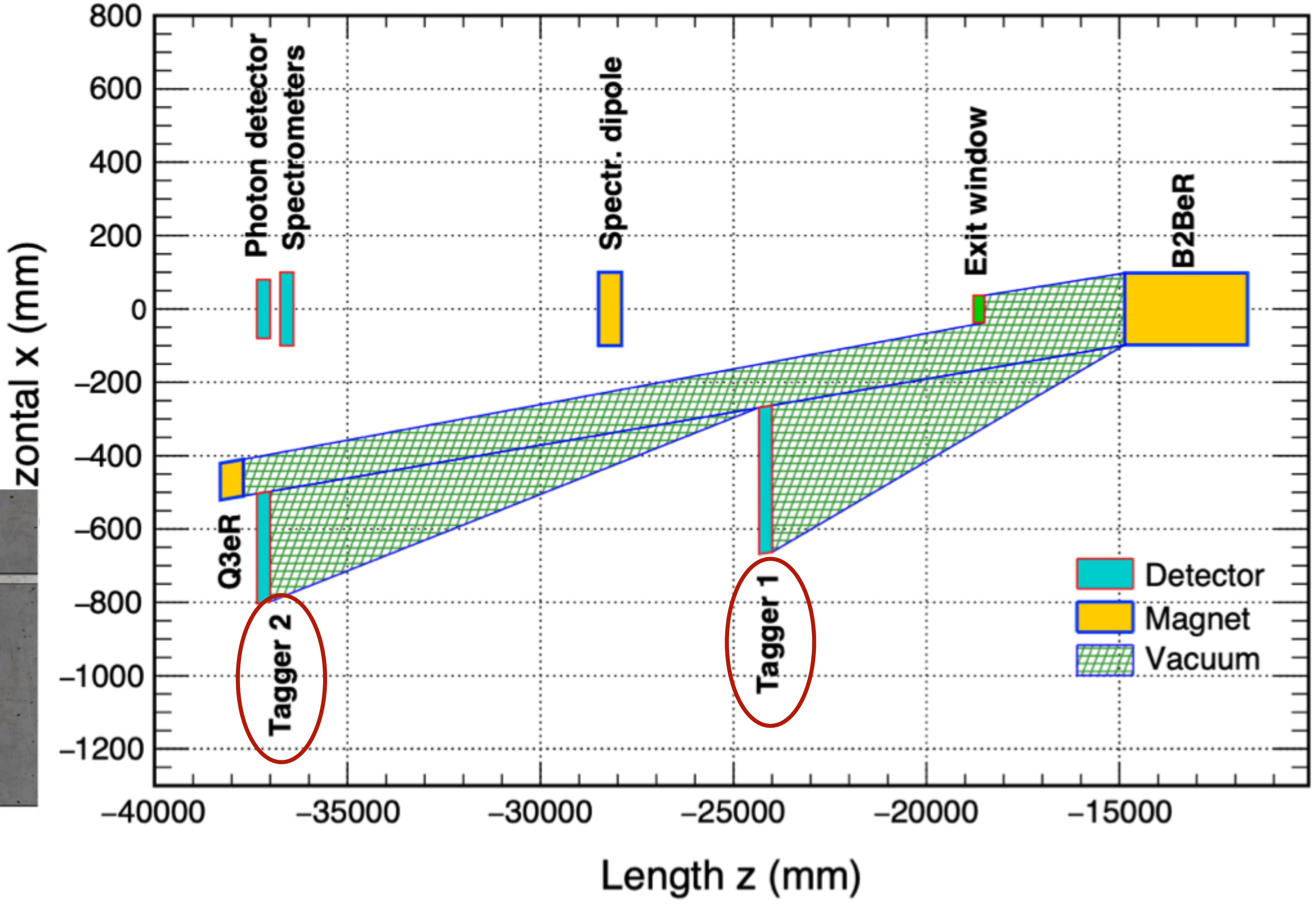
luminosity monitor



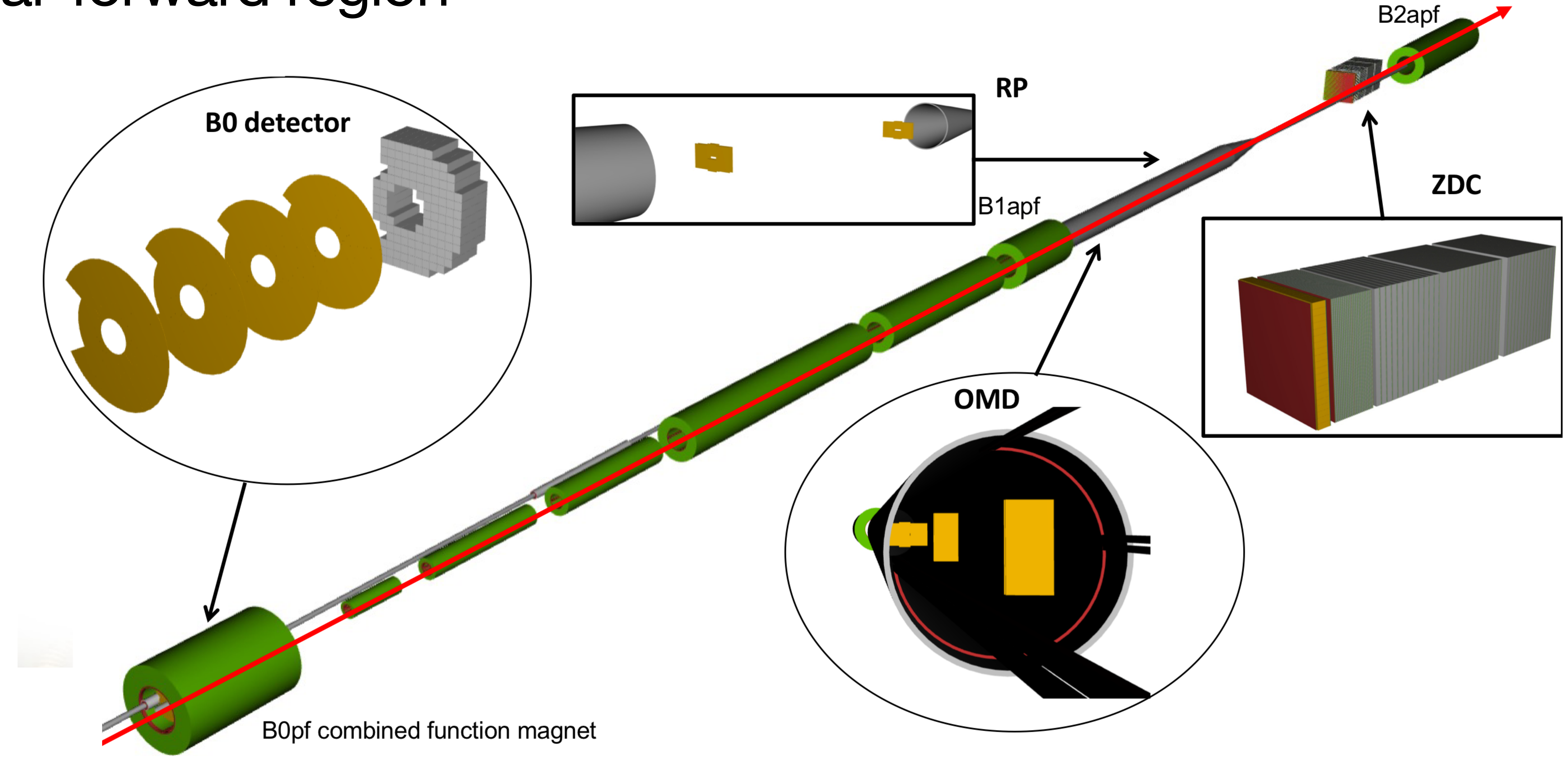
required absolute precision: 1%
required relative precision: 0.01%

low-Q² taggers

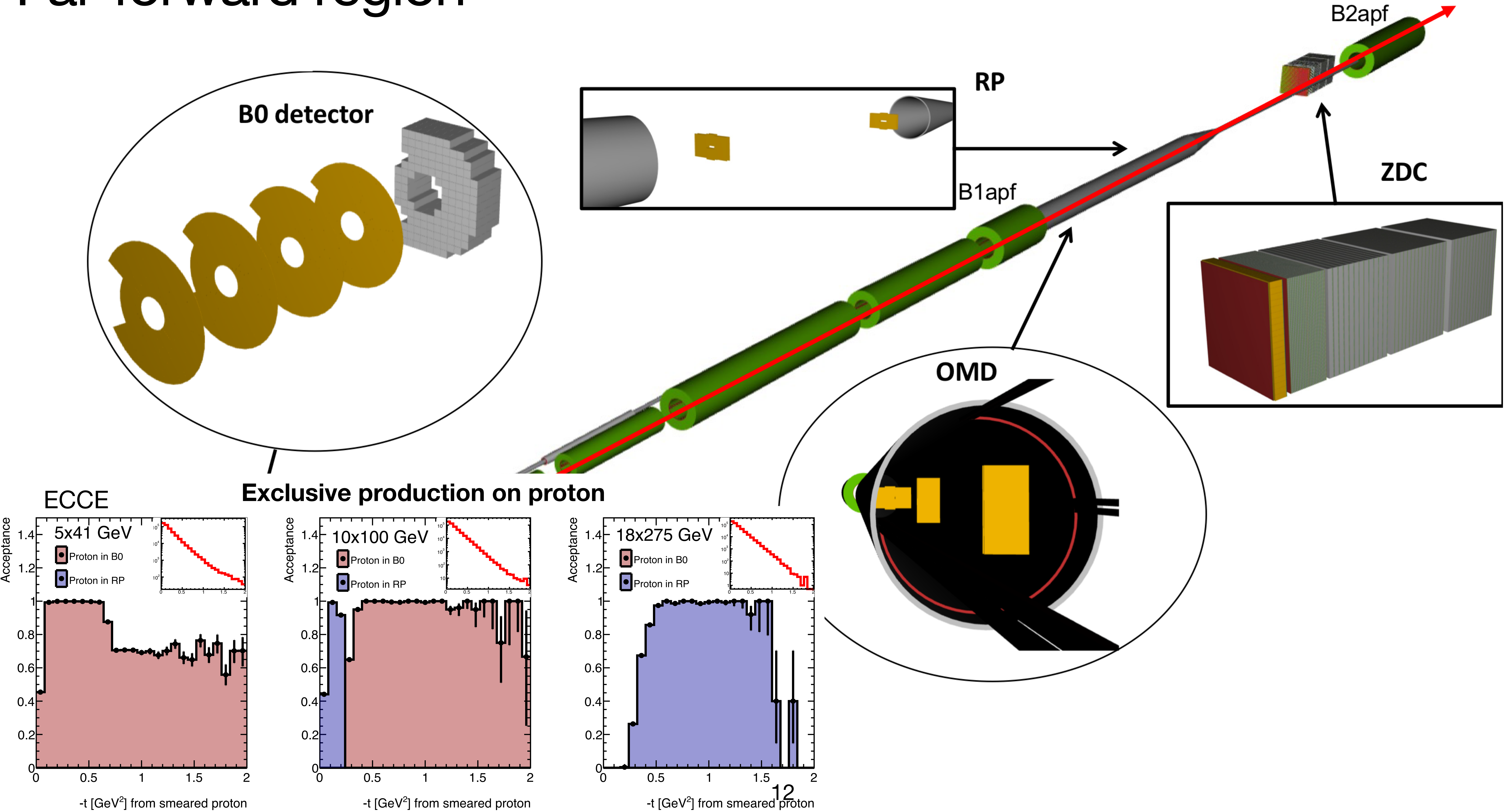




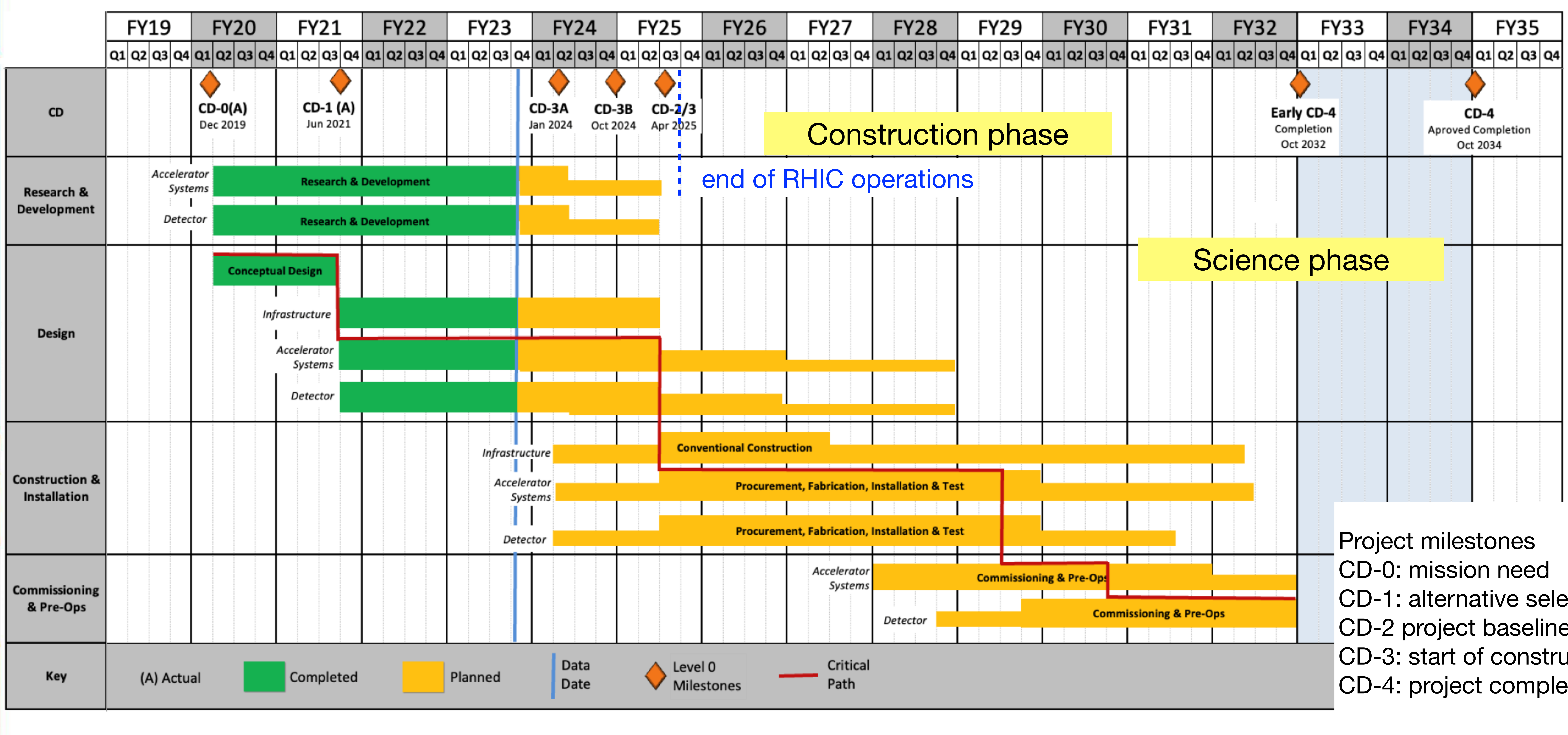
Far-forward region



Far-forward region



Timeline

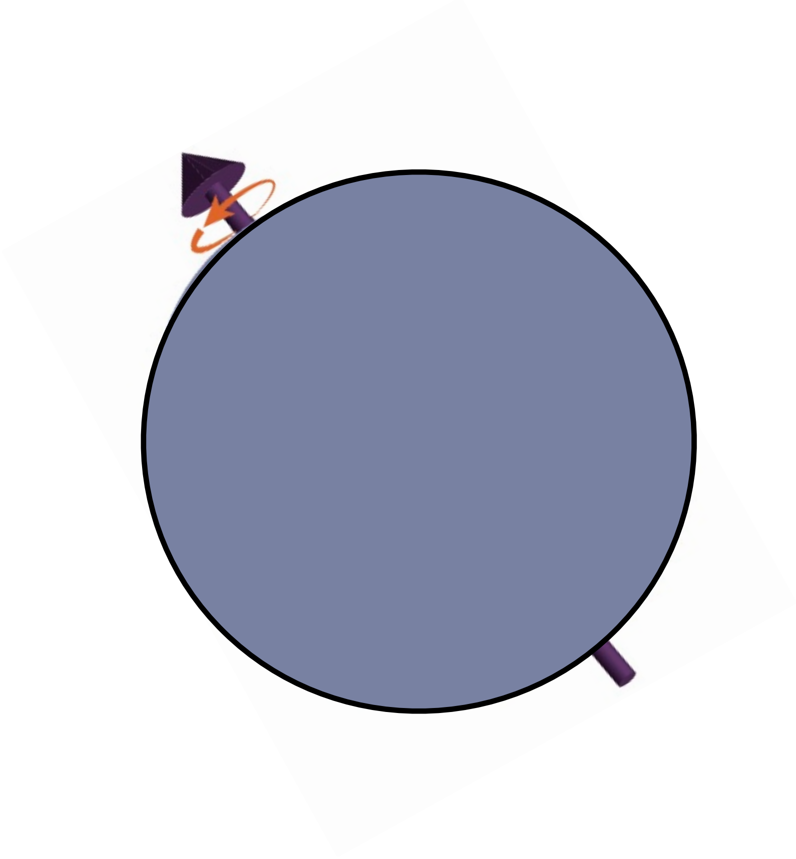


Project milestones
CD-0: mission need
CD-1: alternative selection, cost range
CD-2 project baseline
CD-3: start of construction
CD-4: project completion, start of operation

Why an EIC?

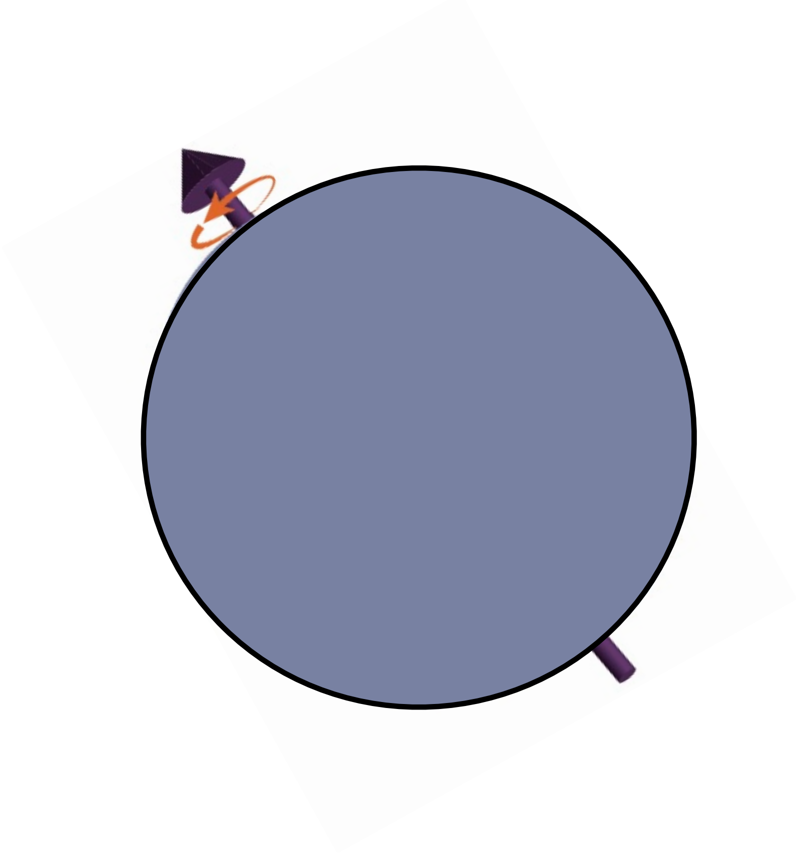
Why an EIC?

Nucleon spin structure

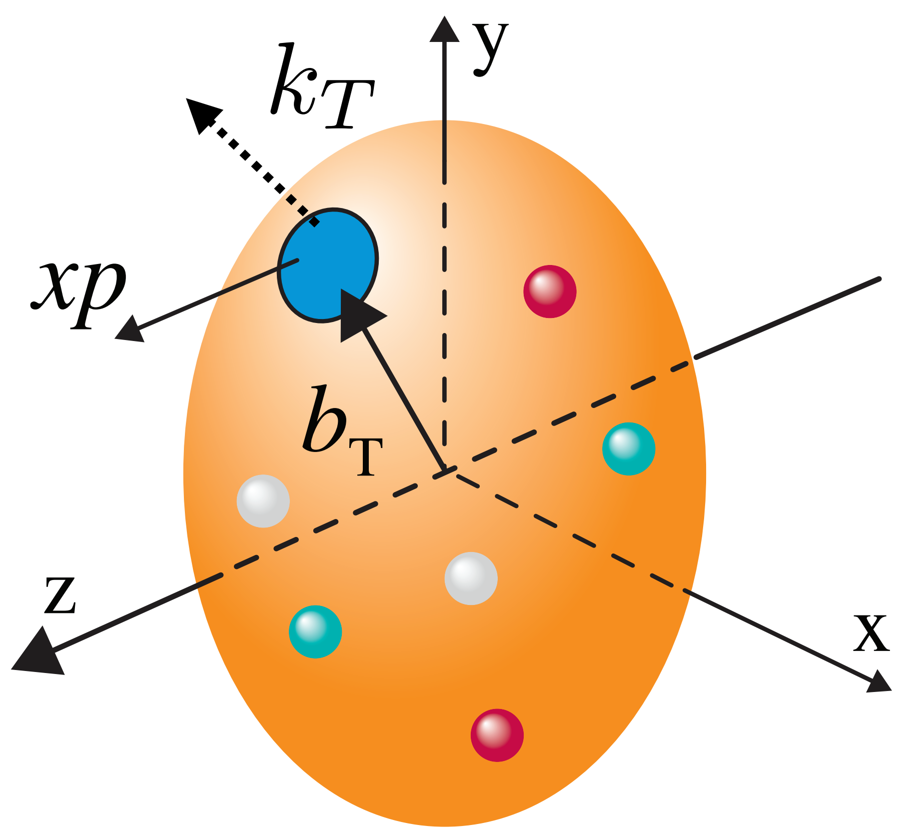


Why an EIC?

Nucleon spin structure

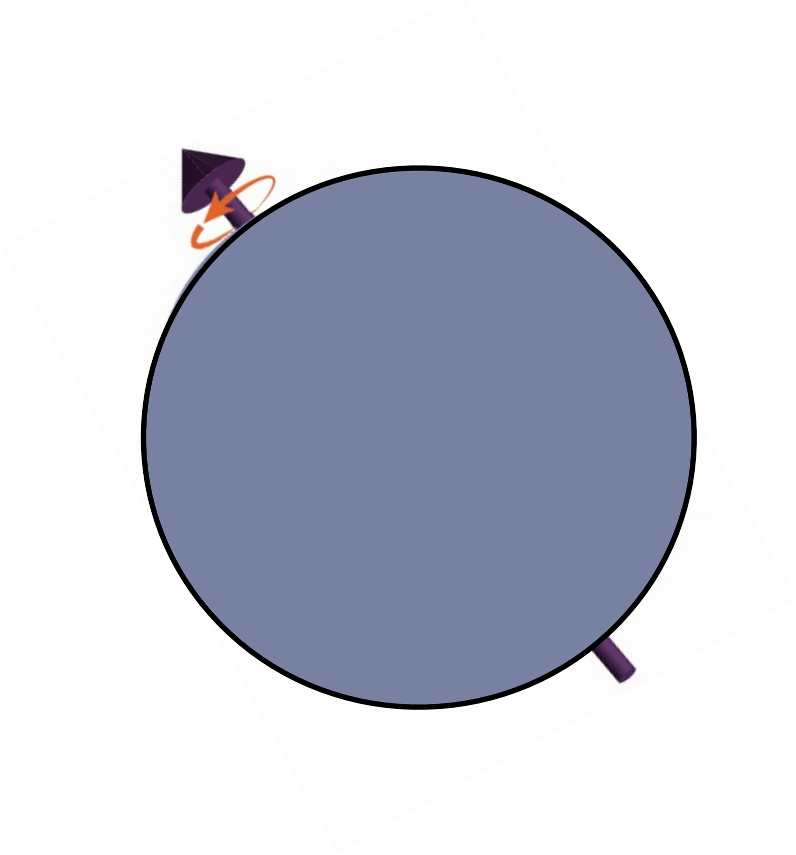


Nucleon multi-dimensional structure

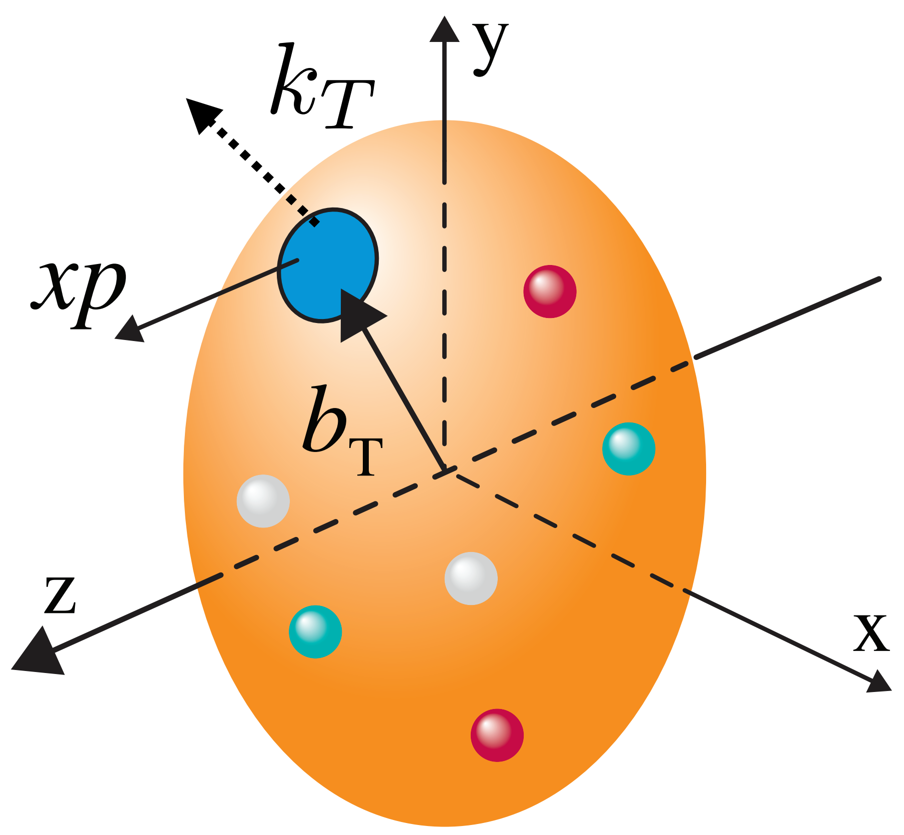


Why an EIC?

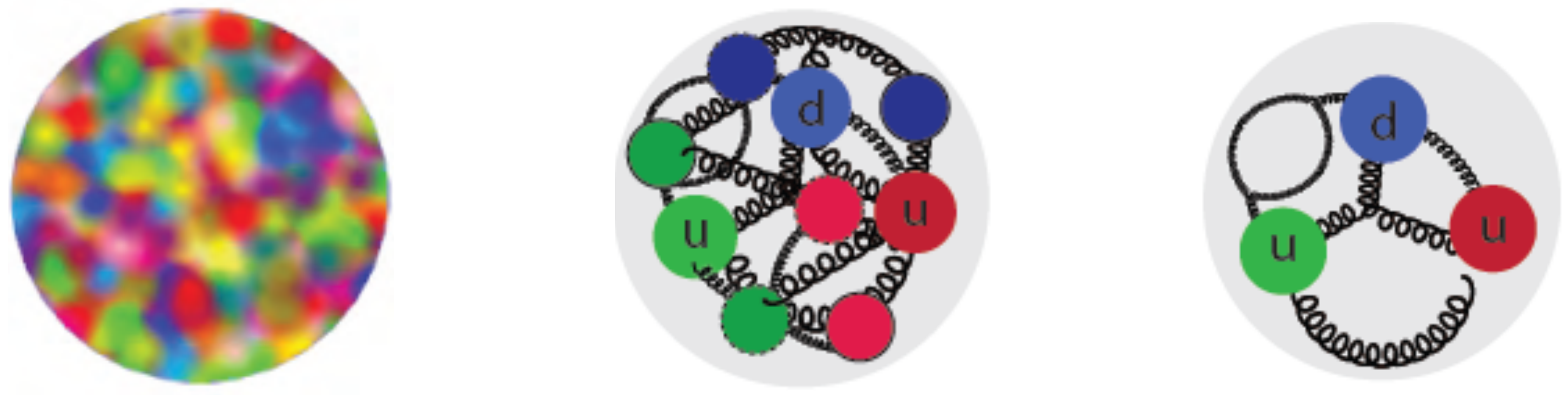
Nucleon spin structure



Nucleon multi-dimensional structure

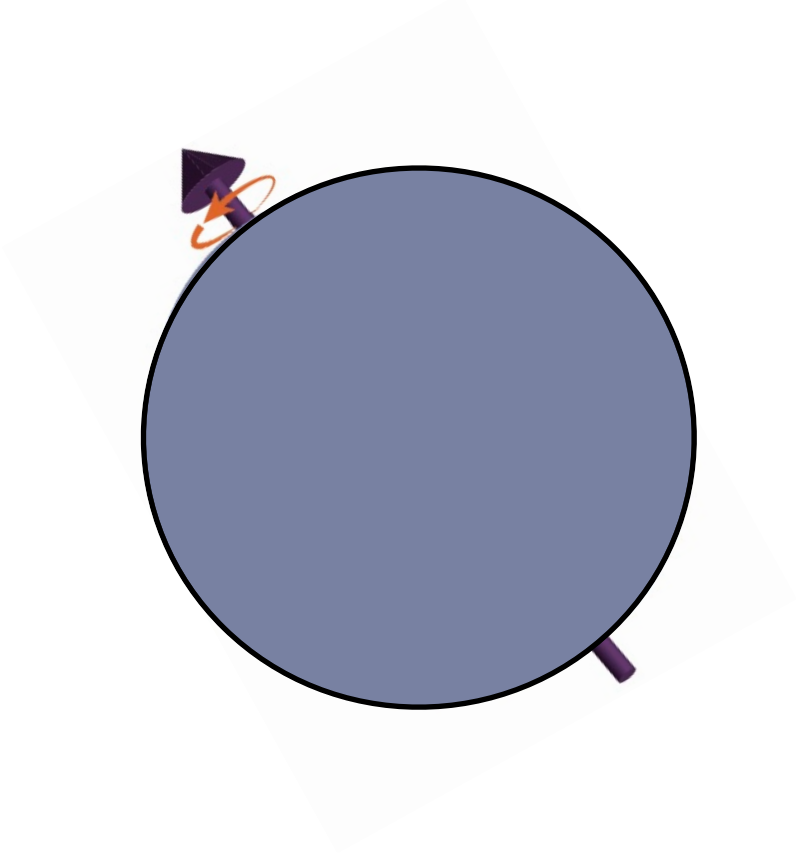


Gluon saturation

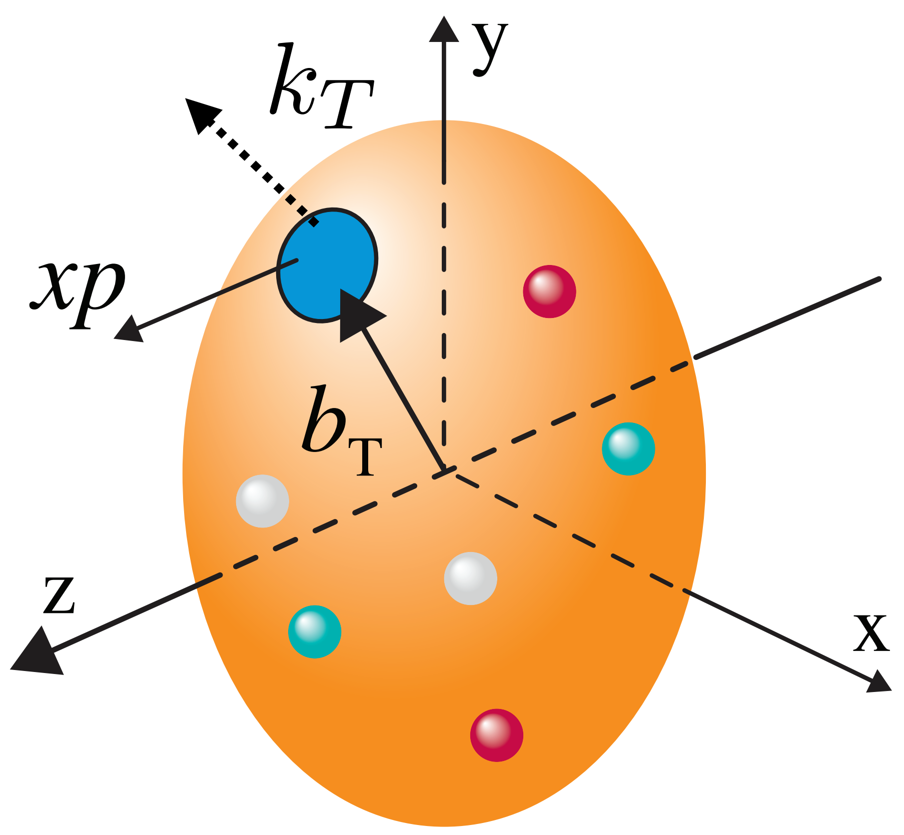


Why an EIC?

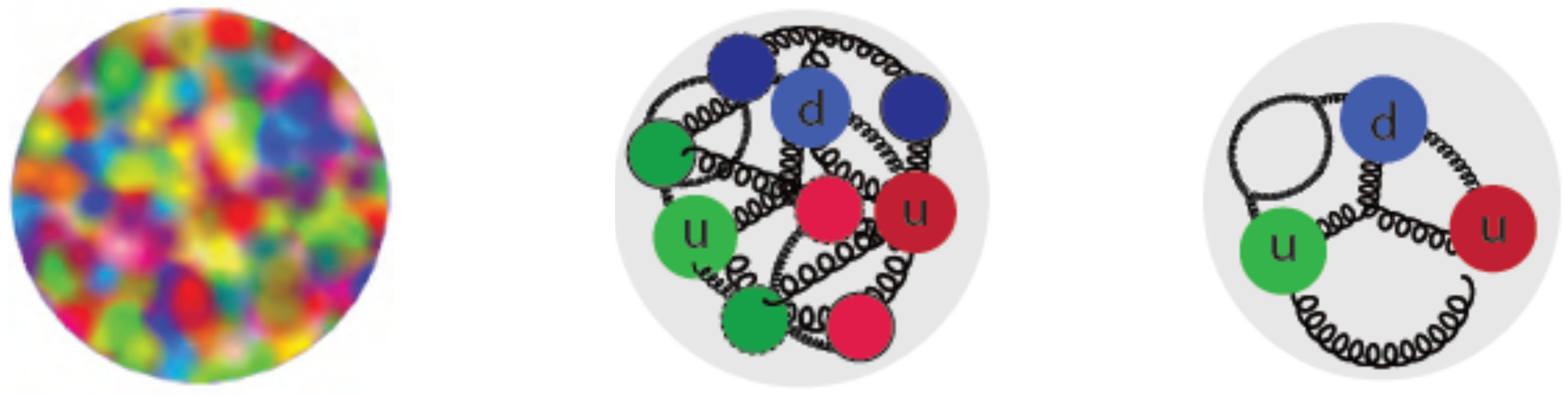
Nucleon spin structure



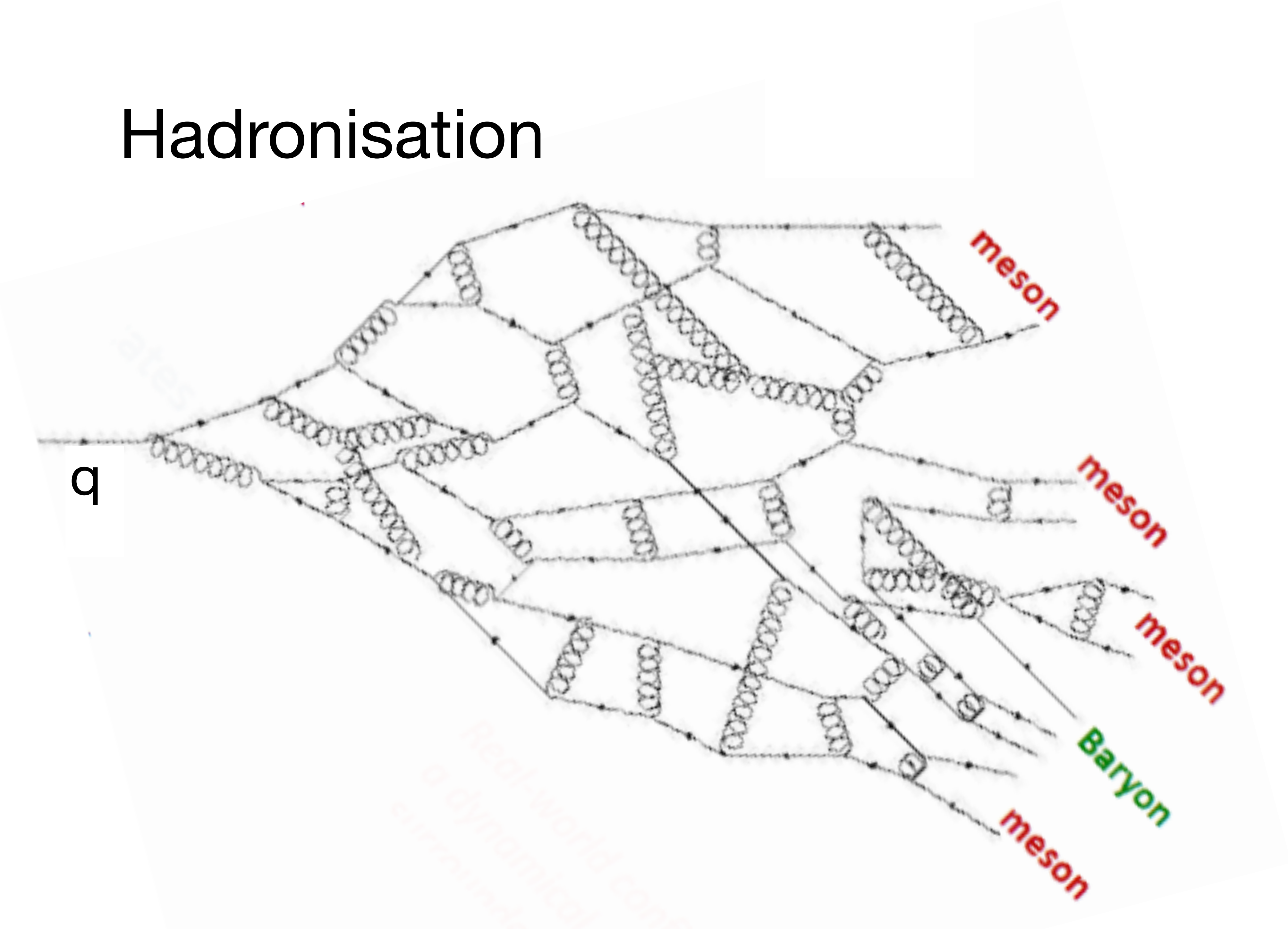
Nucleon multi-dimensional structure



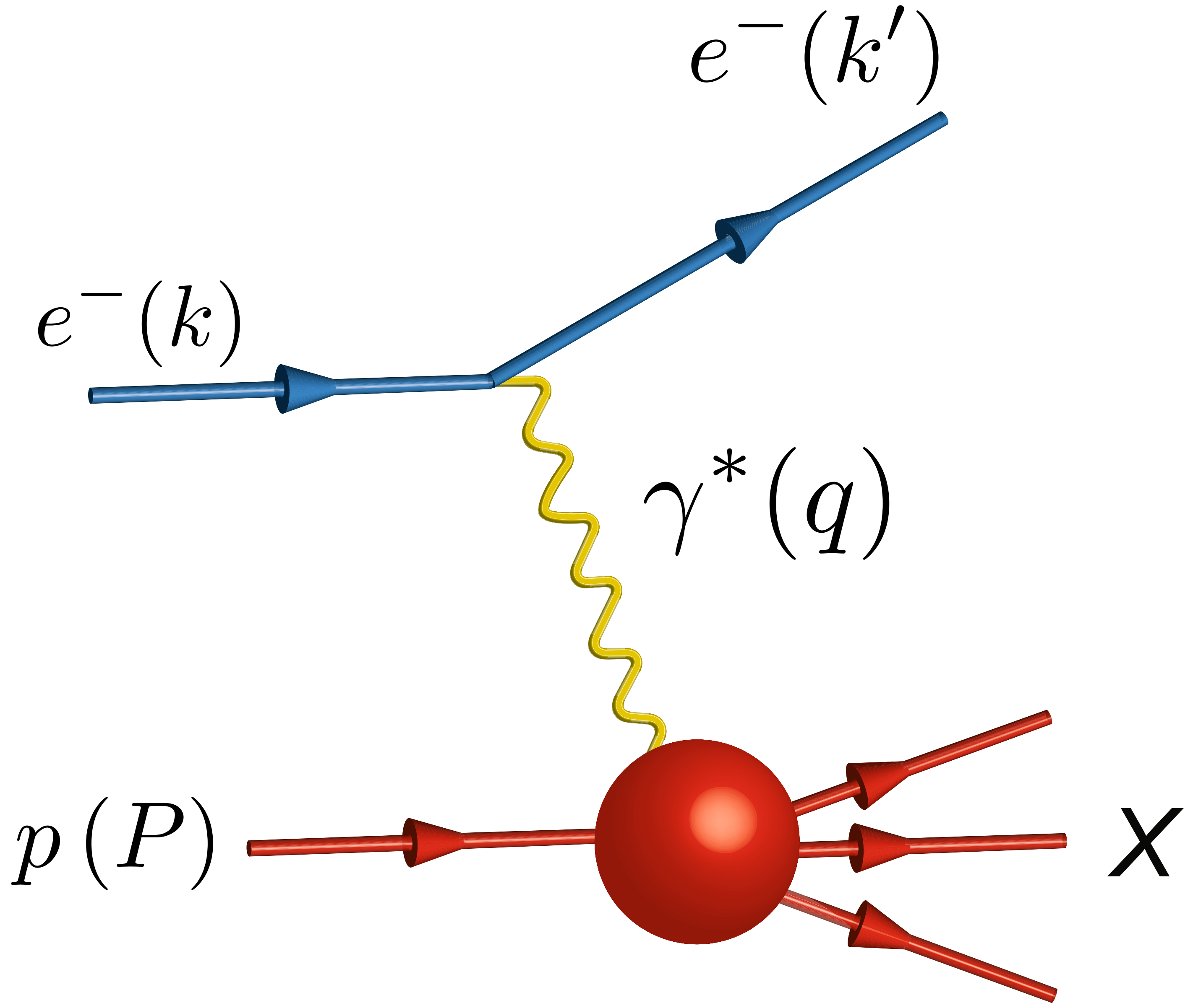
Gluon saturation



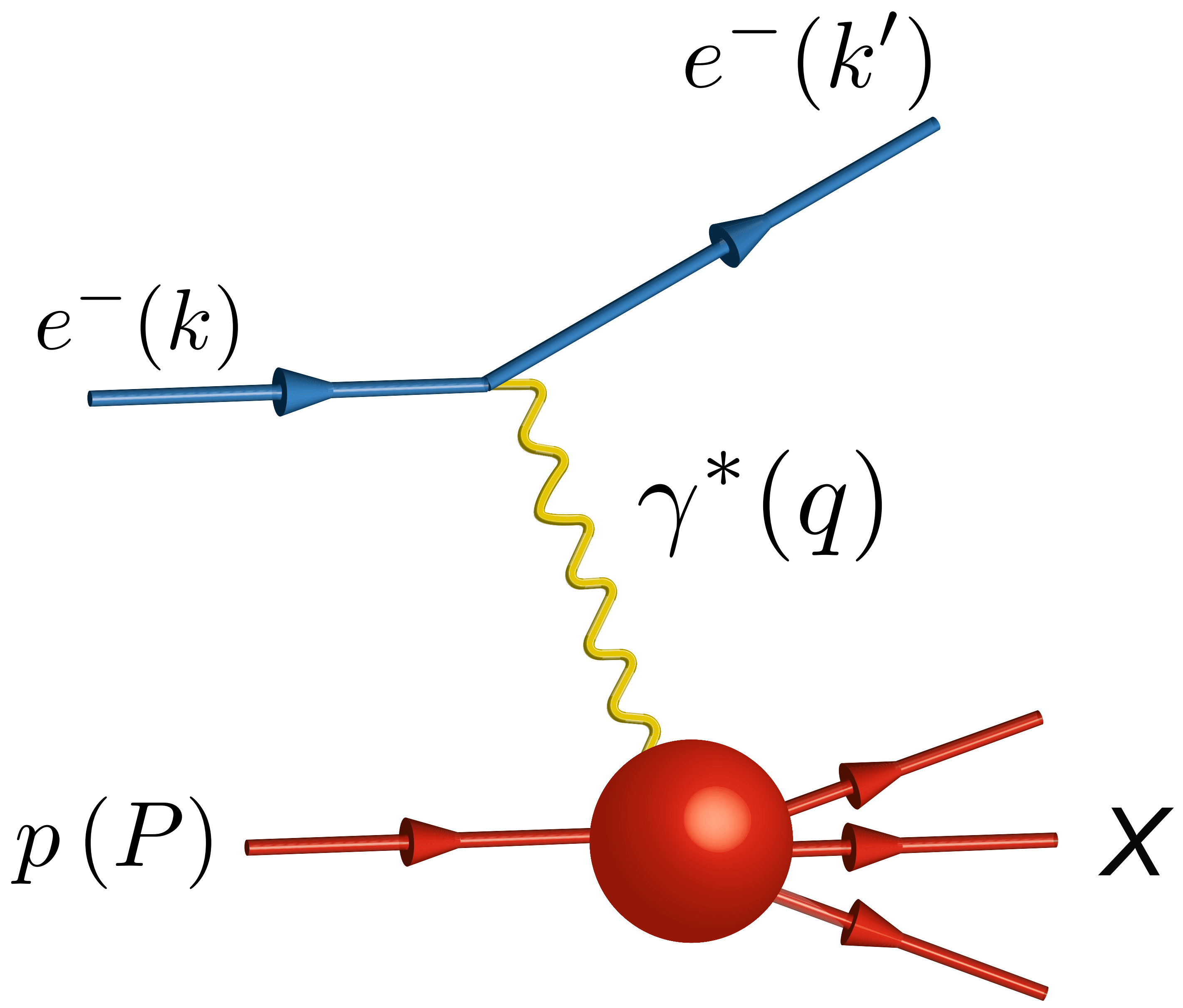
Hadronisation



Deep-inelastic scattering (DIS) of electrons and nucleons/nuclei

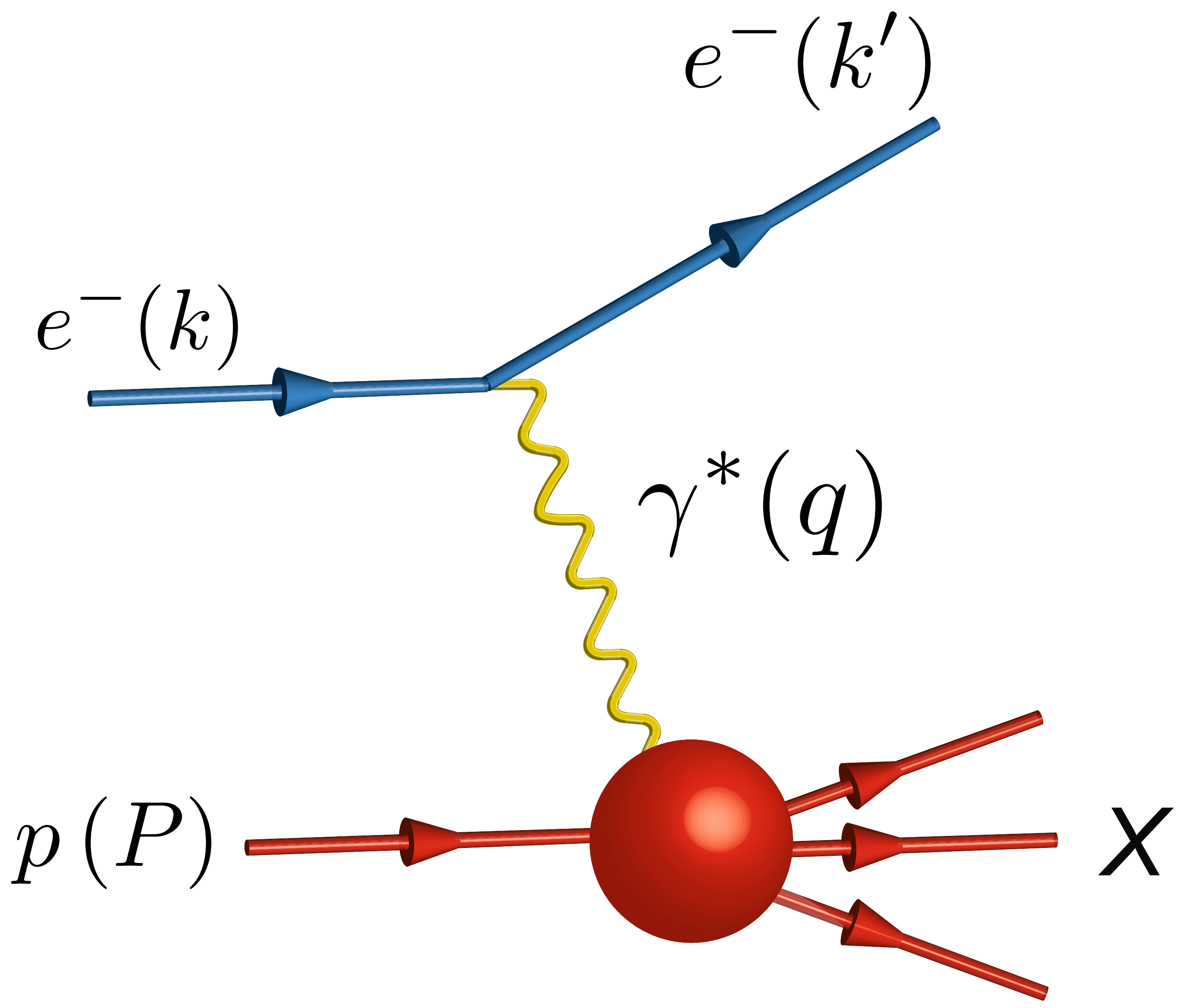


Deep-inelastic scattering (DIS) of electrons and nucleons/nuclei



$$Q^2 = -q^2$$

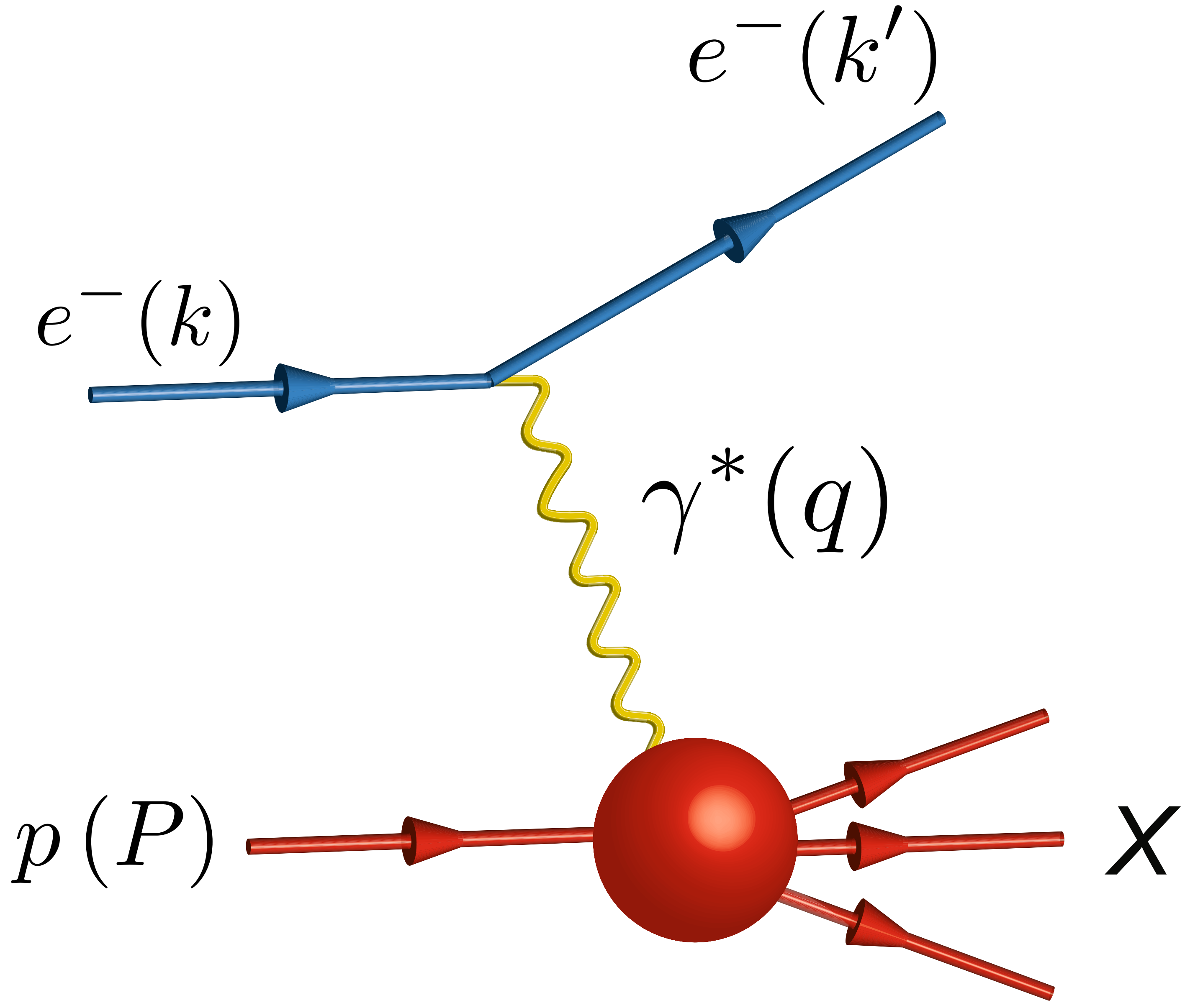
Deep-inelastic scattering (DIS) of electrons and nucleons/nuclei



$$Q^2 = -q^2$$

Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

Deep-inelastic scattering (DIS) of electrons and nucleons/nuclei

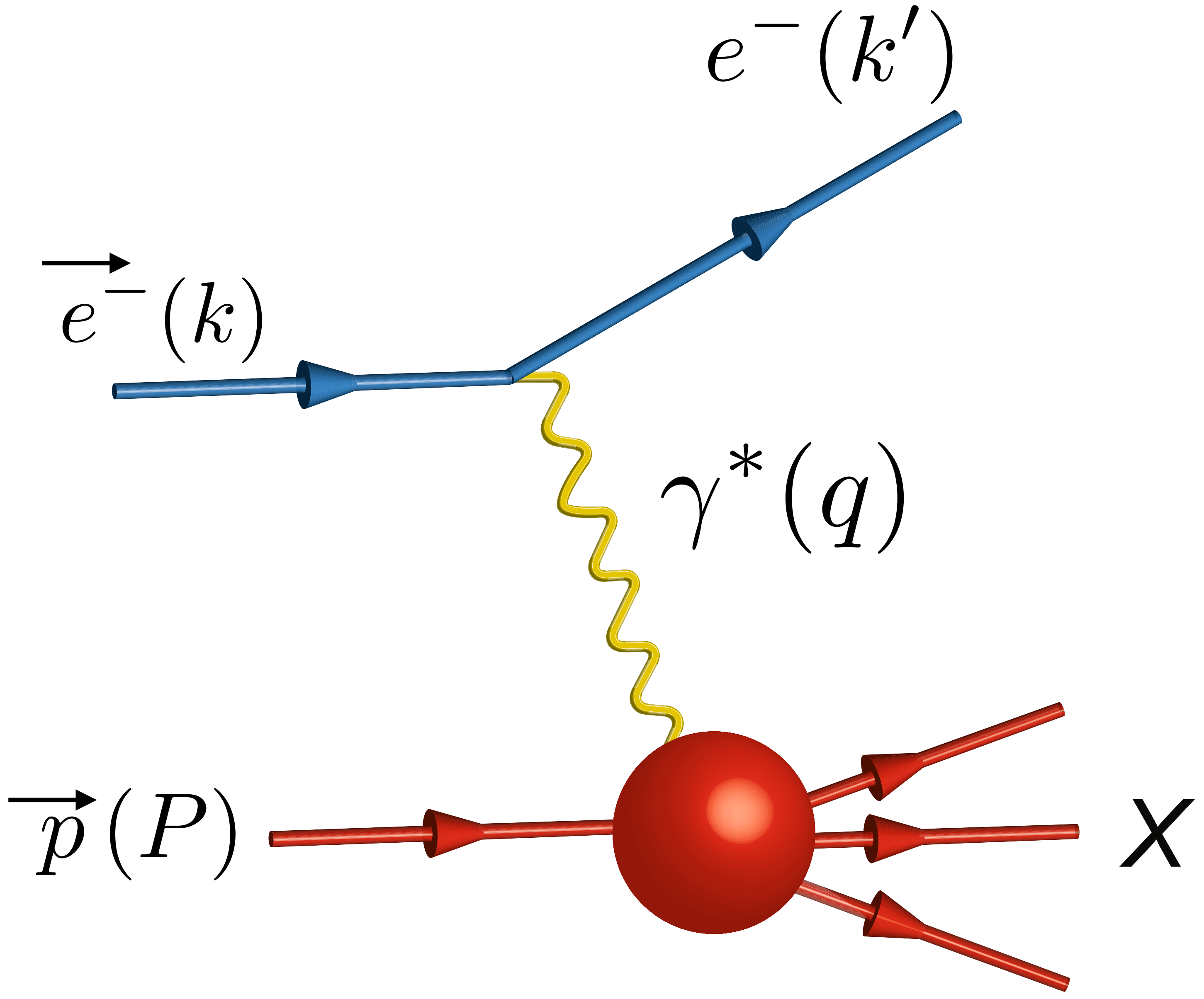


$$Q^2 = -q^2$$

Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

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

Deep-inelastic scattering (DIS) of electrons and nucleons/nuclei

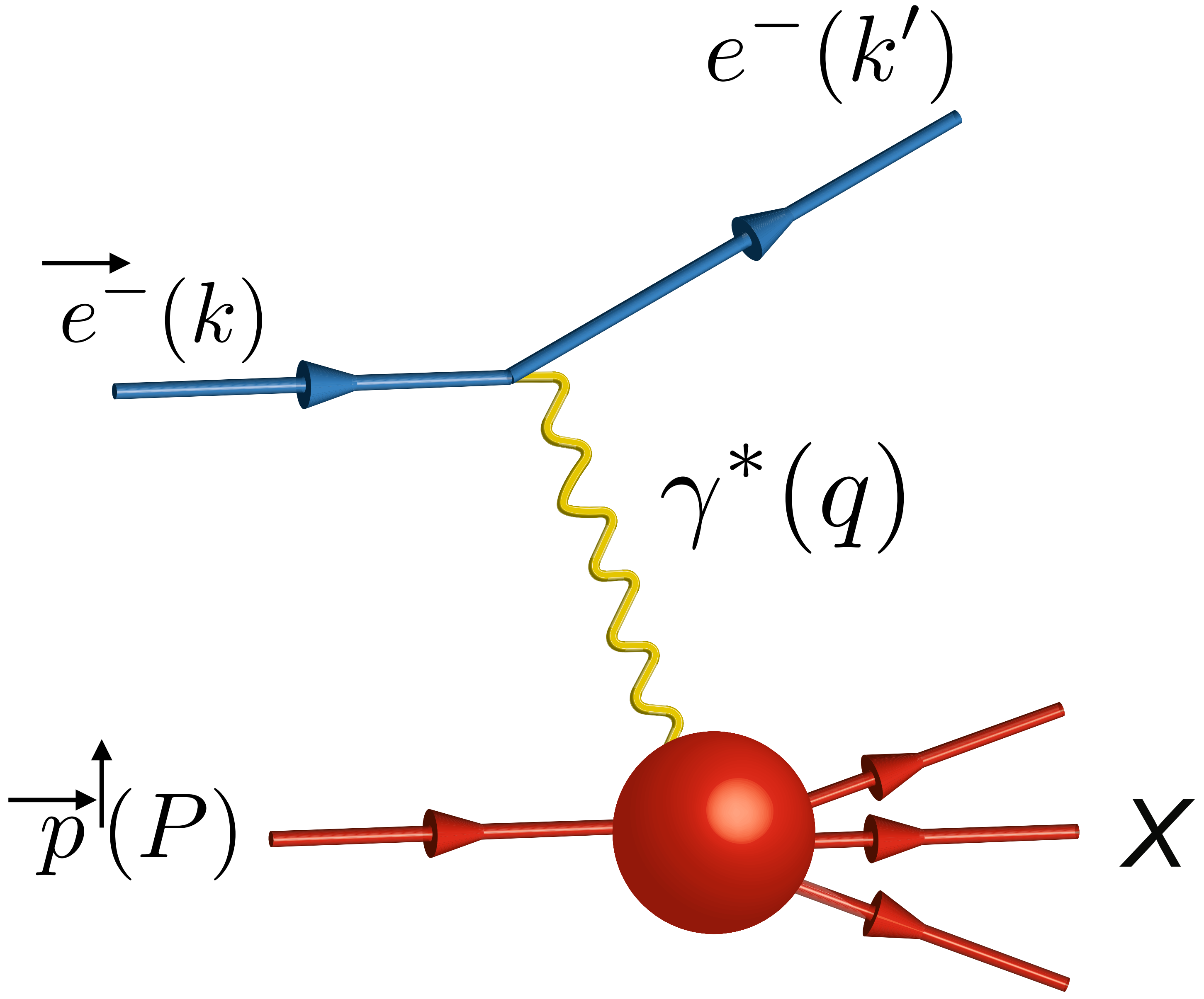


$$Q^2 = -q^2$$

Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

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

Deep-inelastic scattering (DIS) of electrons and nucleons/nuclei



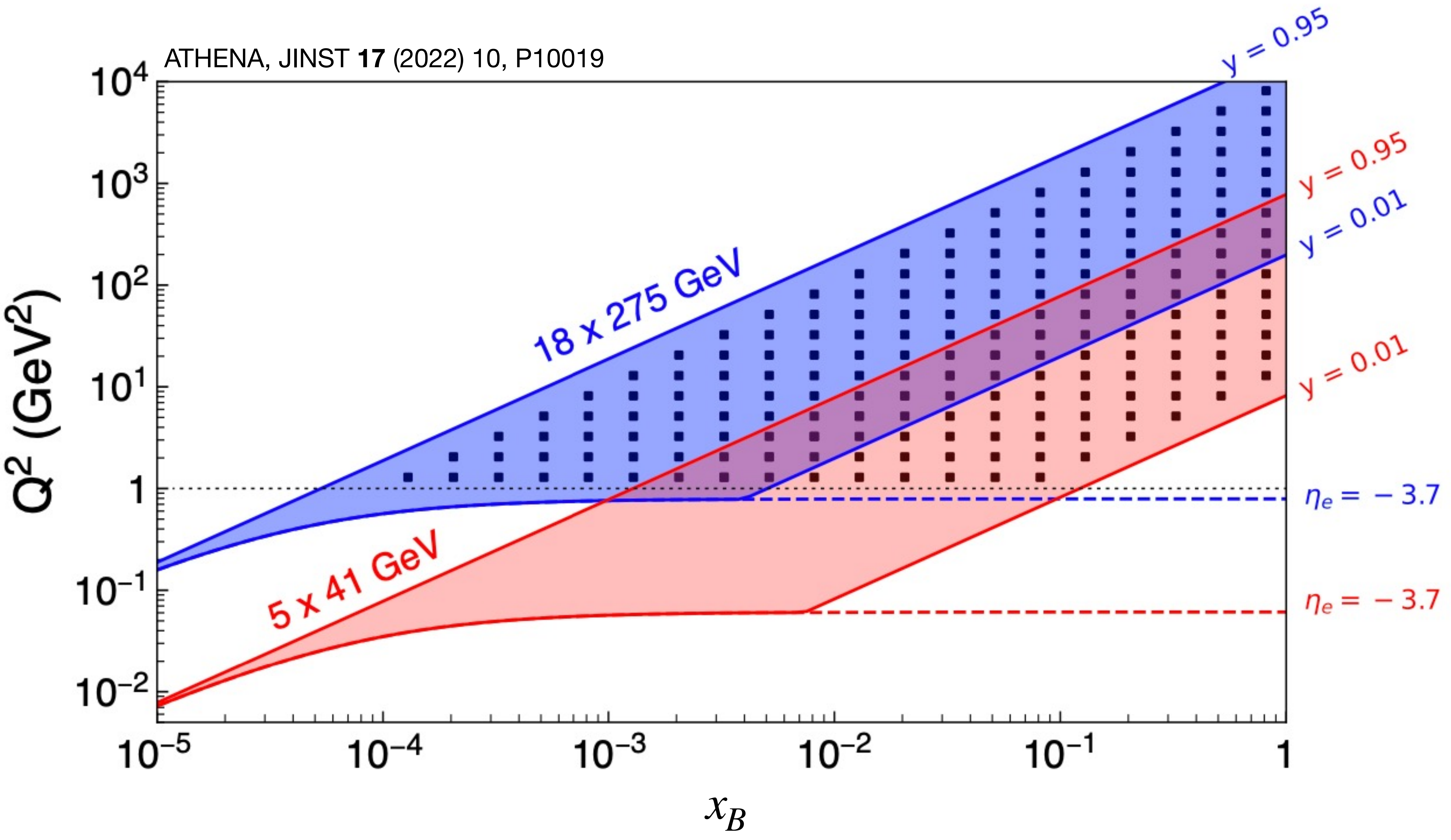
$$Q^2 = -q^2$$

Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

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

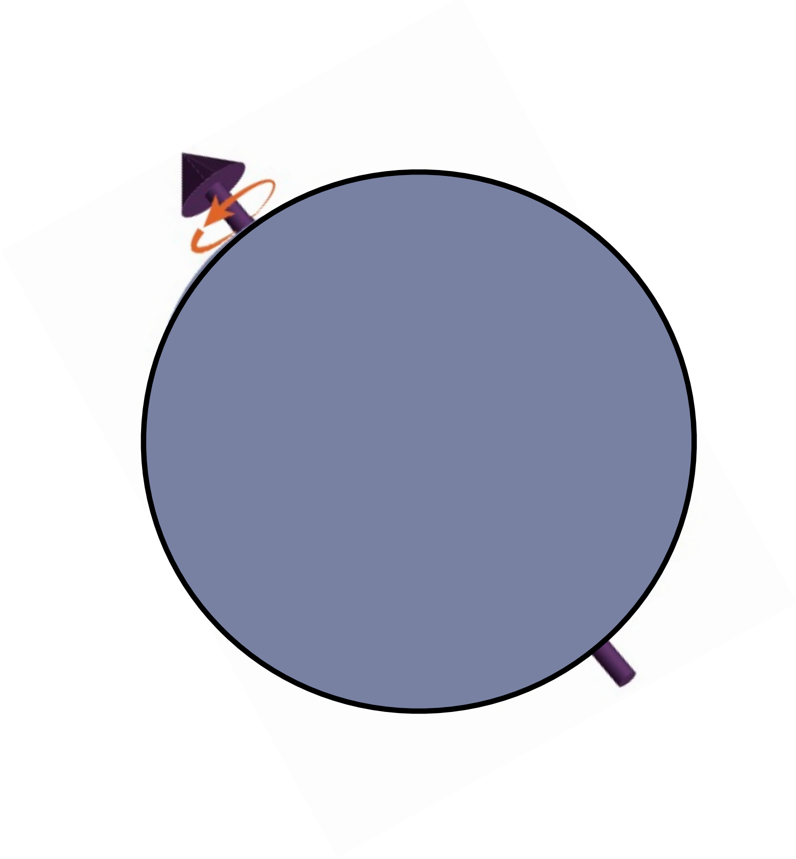
Kinematic coverage at the EIC

ATHENA, JINST **17** (2022) 10, P10019

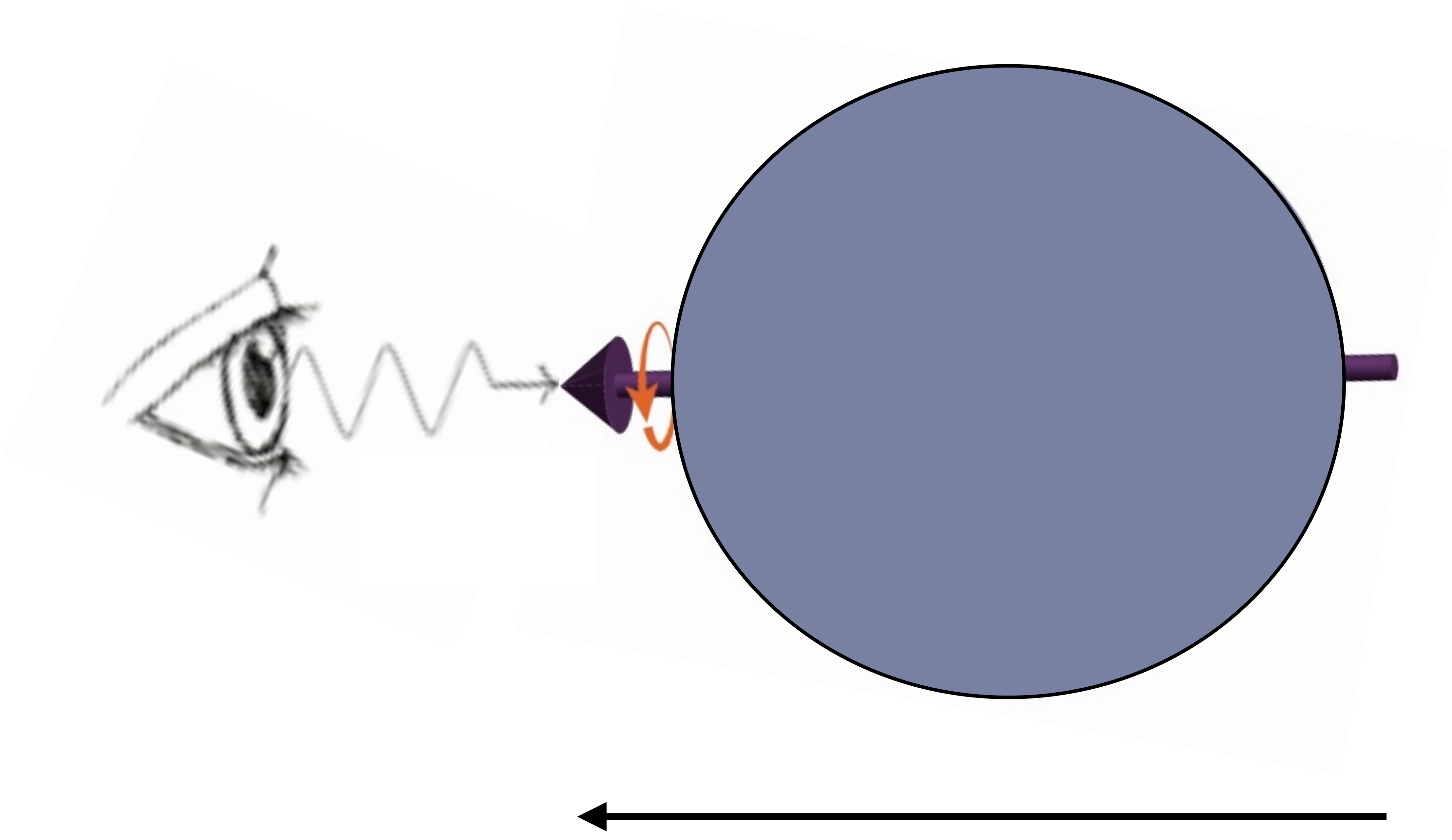


Why an EIC?

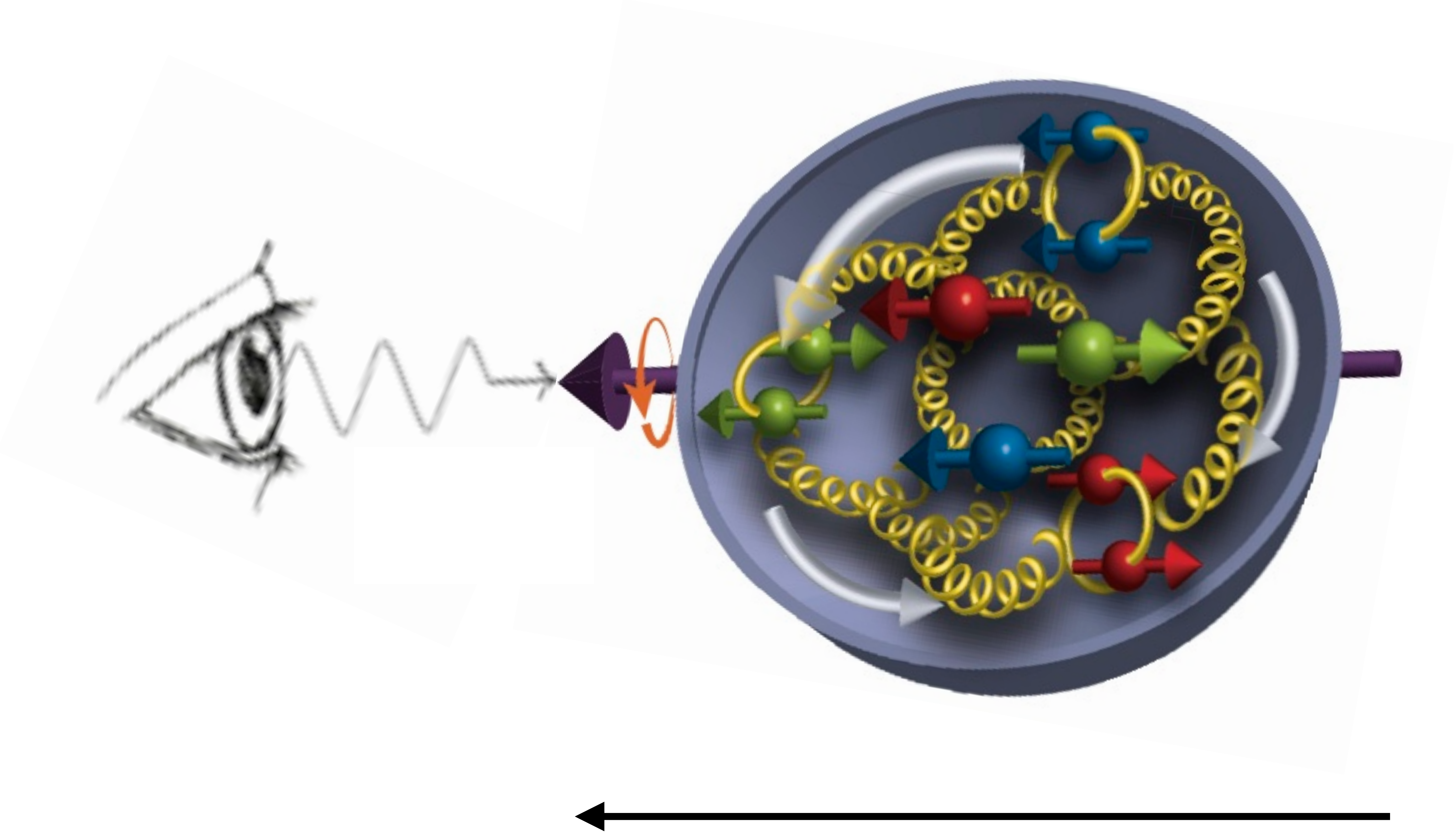
Nucleon spin structure



The nucleon spin

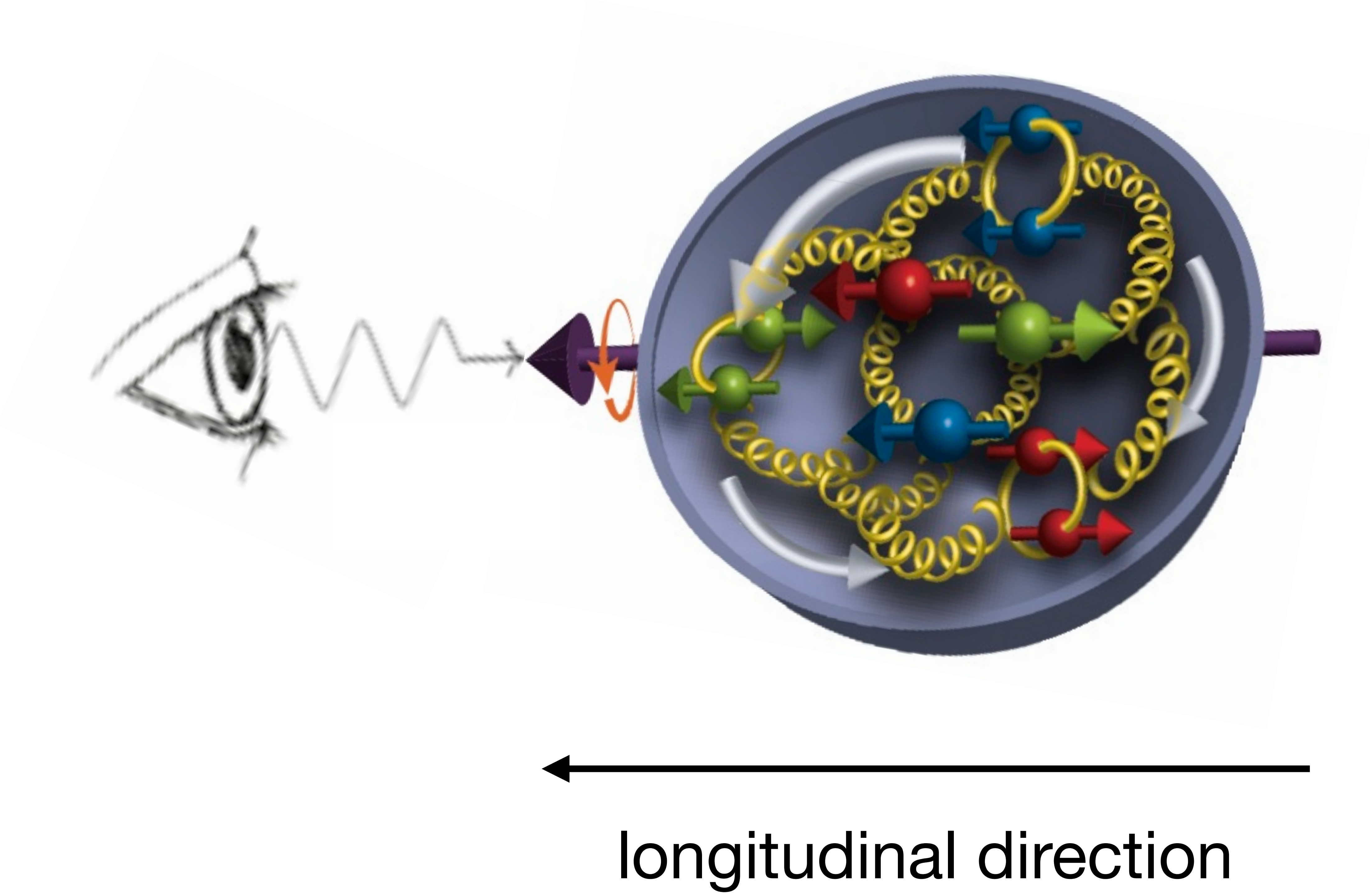


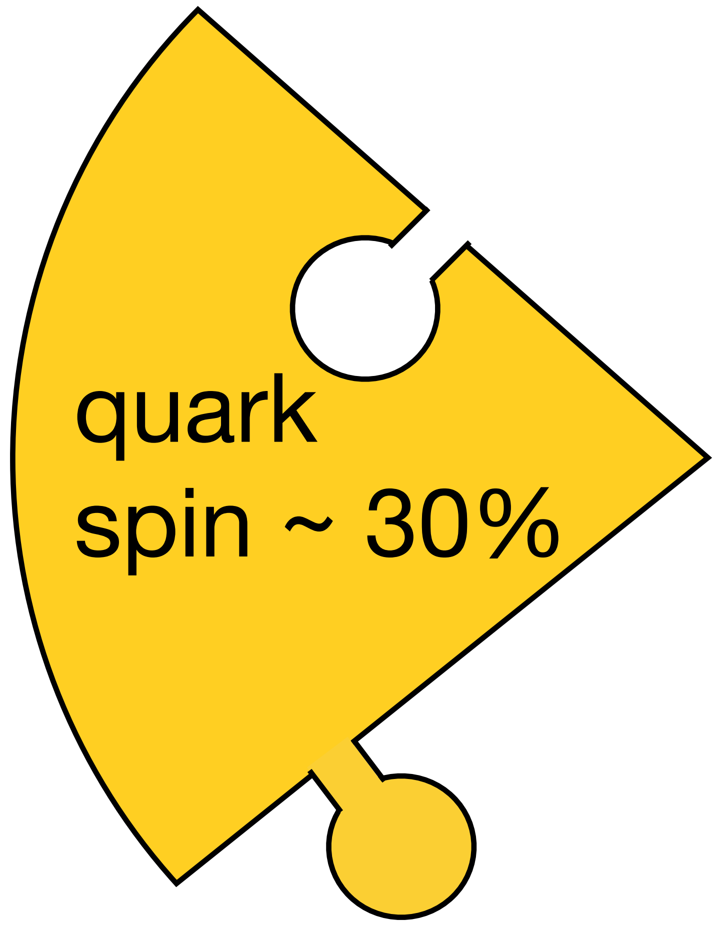
The nucleon spin



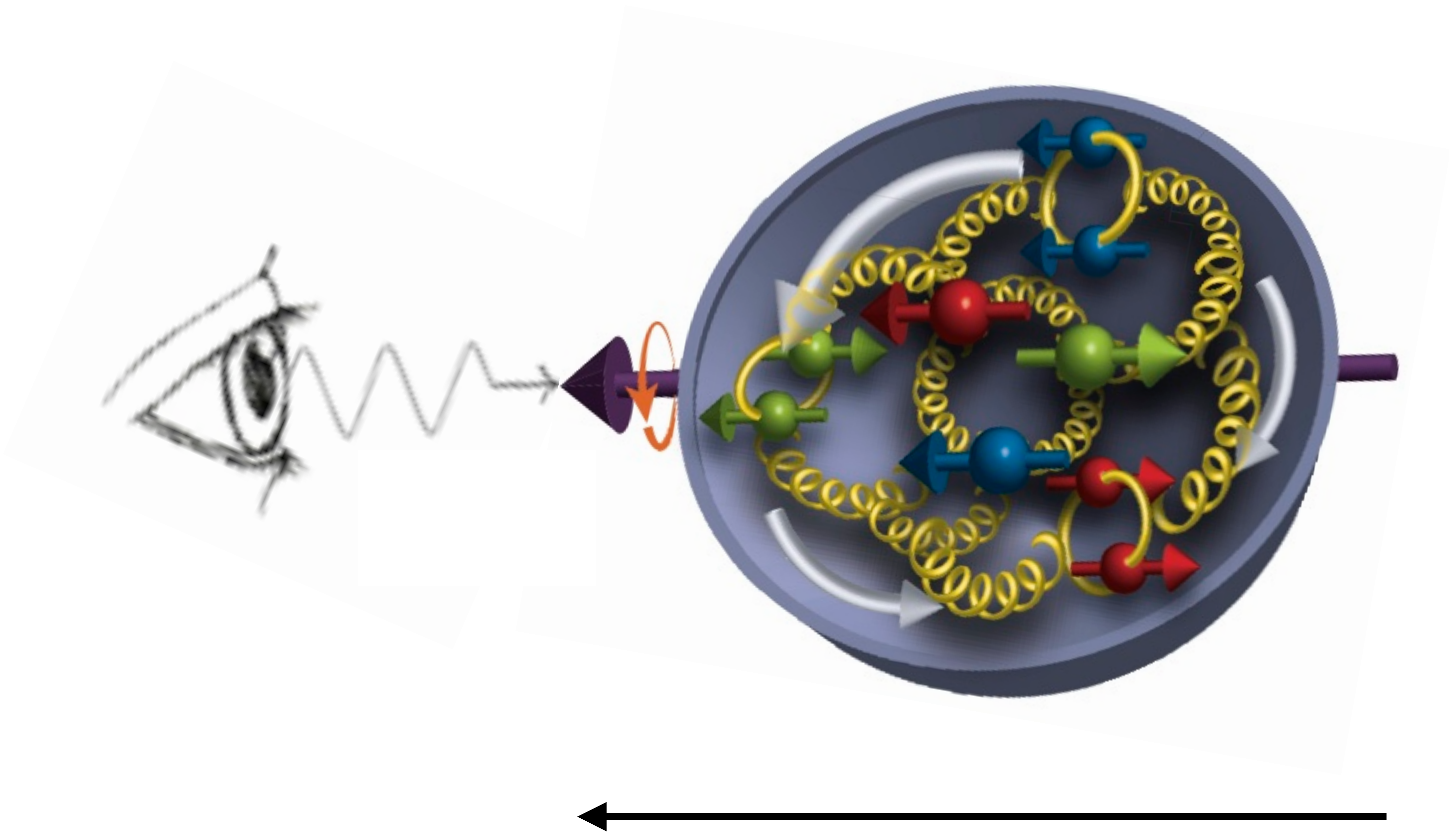
longitudinal direction

The nucleon spin

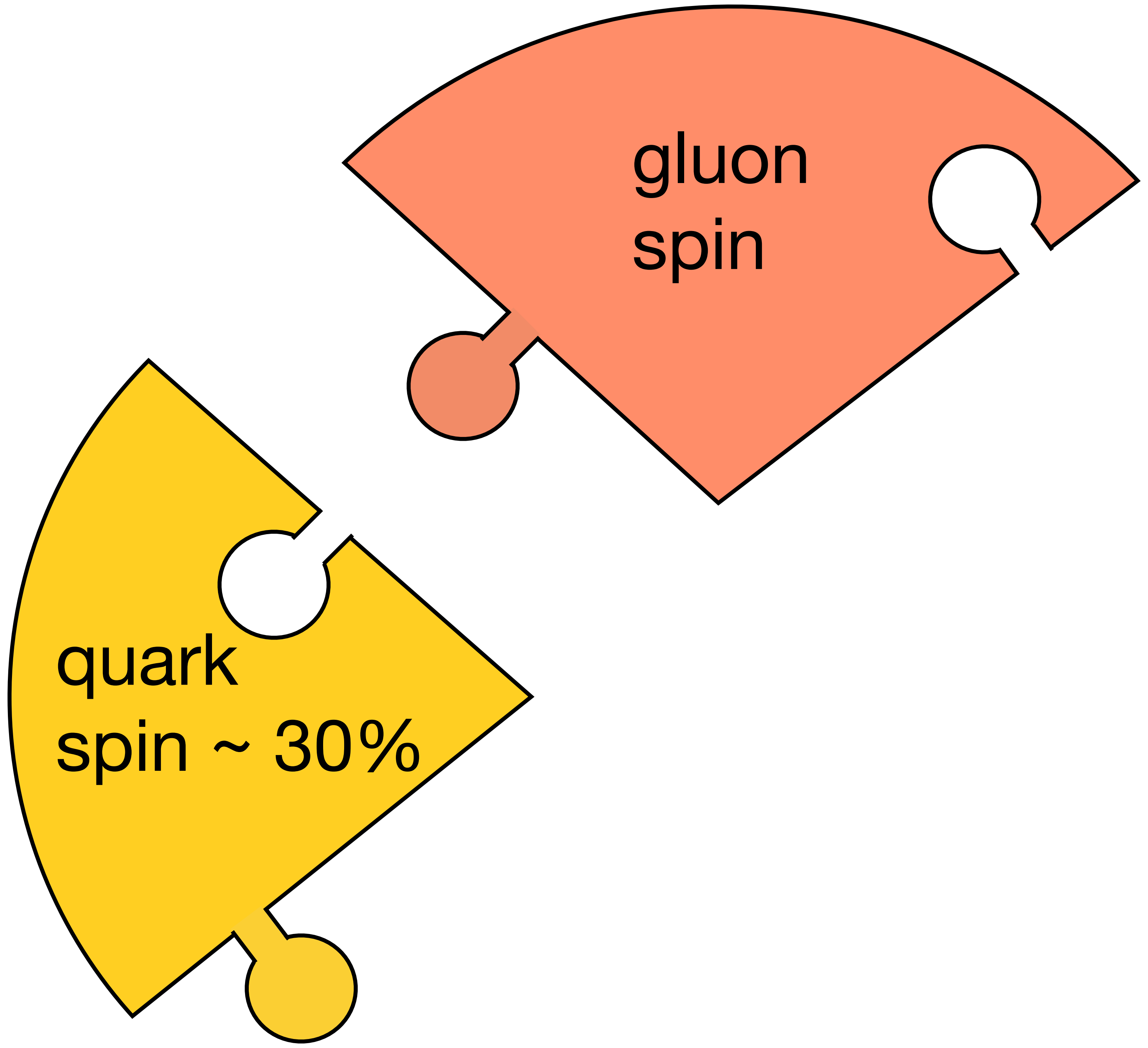




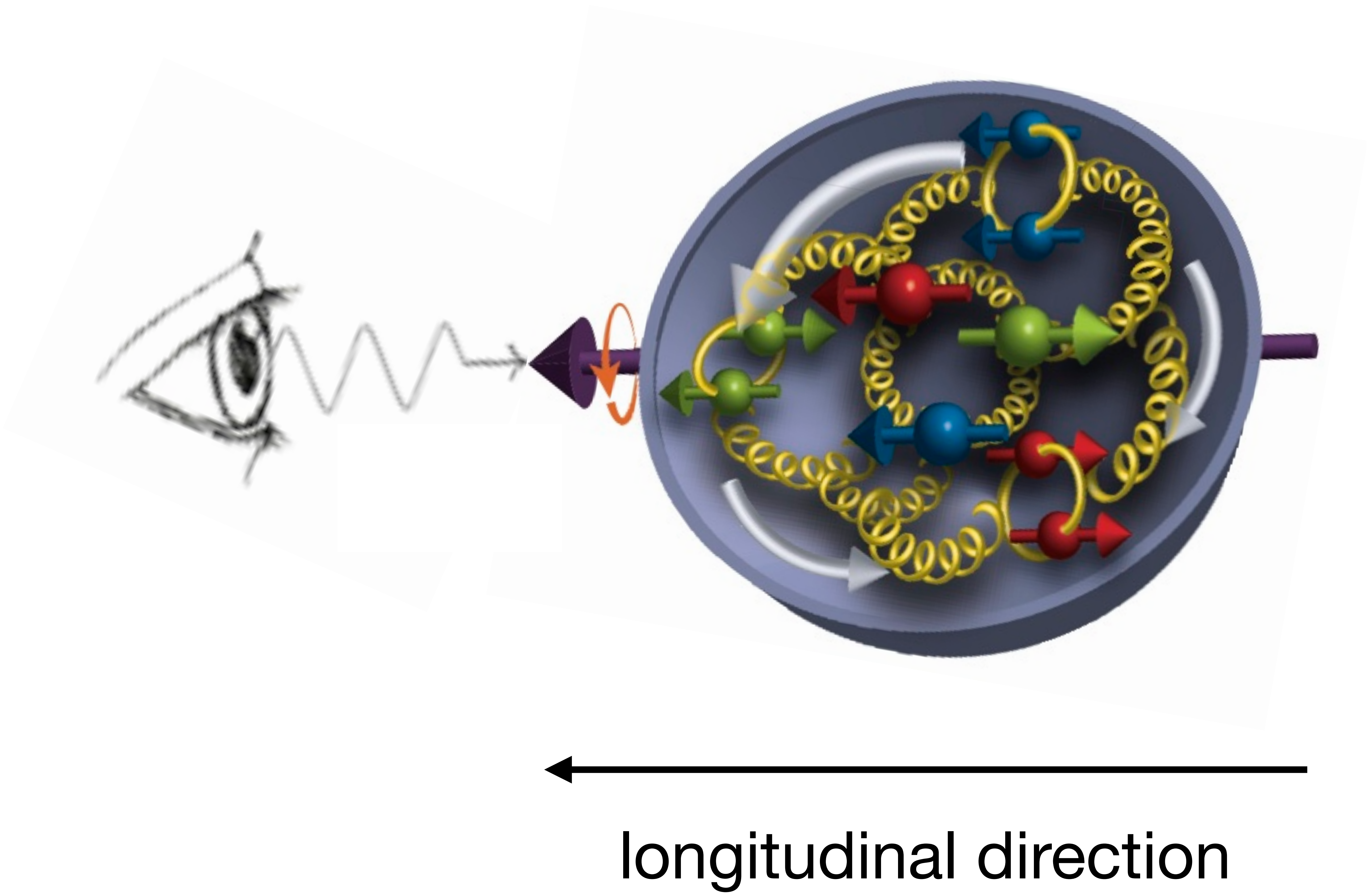
The nucleon spin

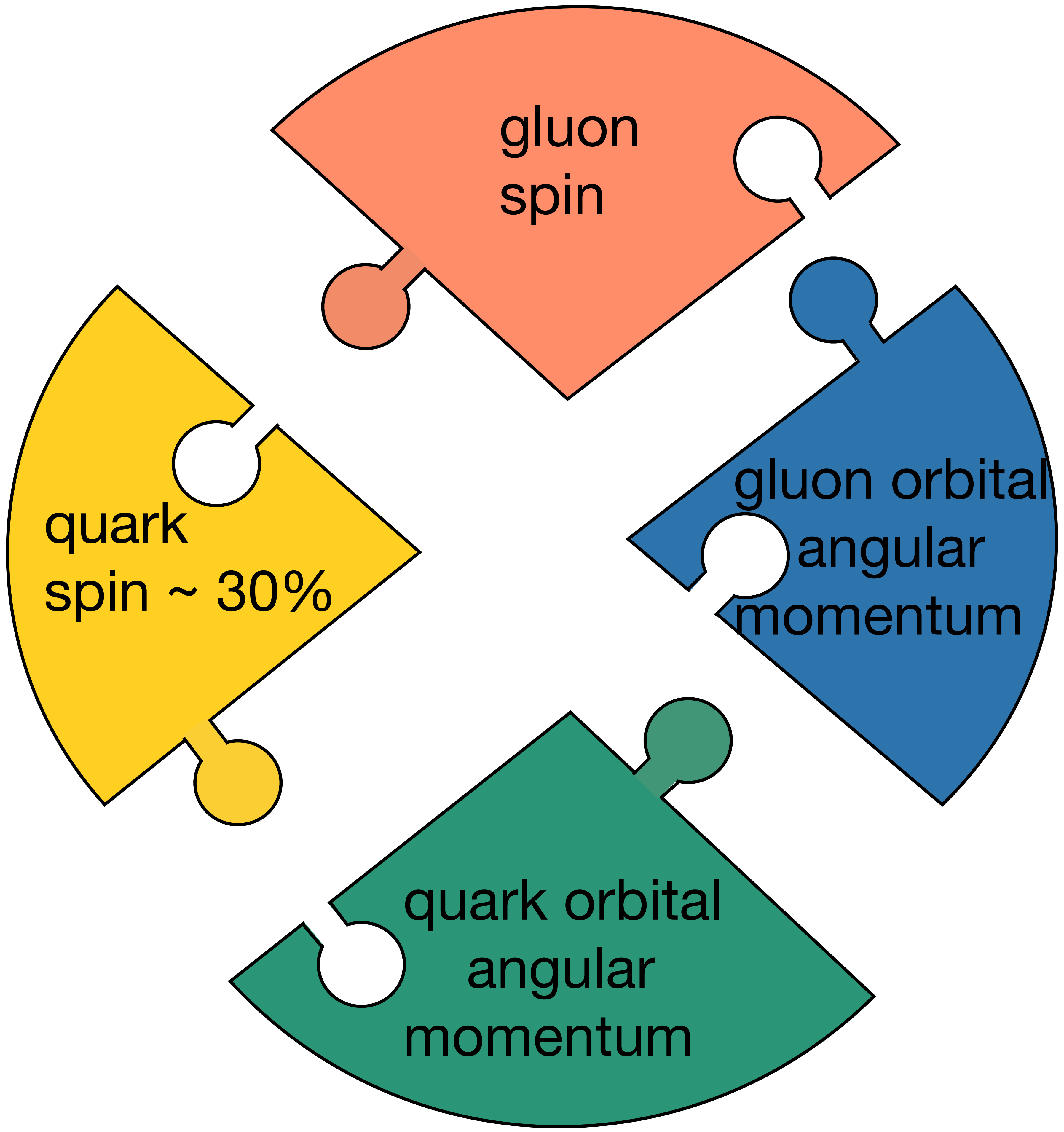


longitudinal direction

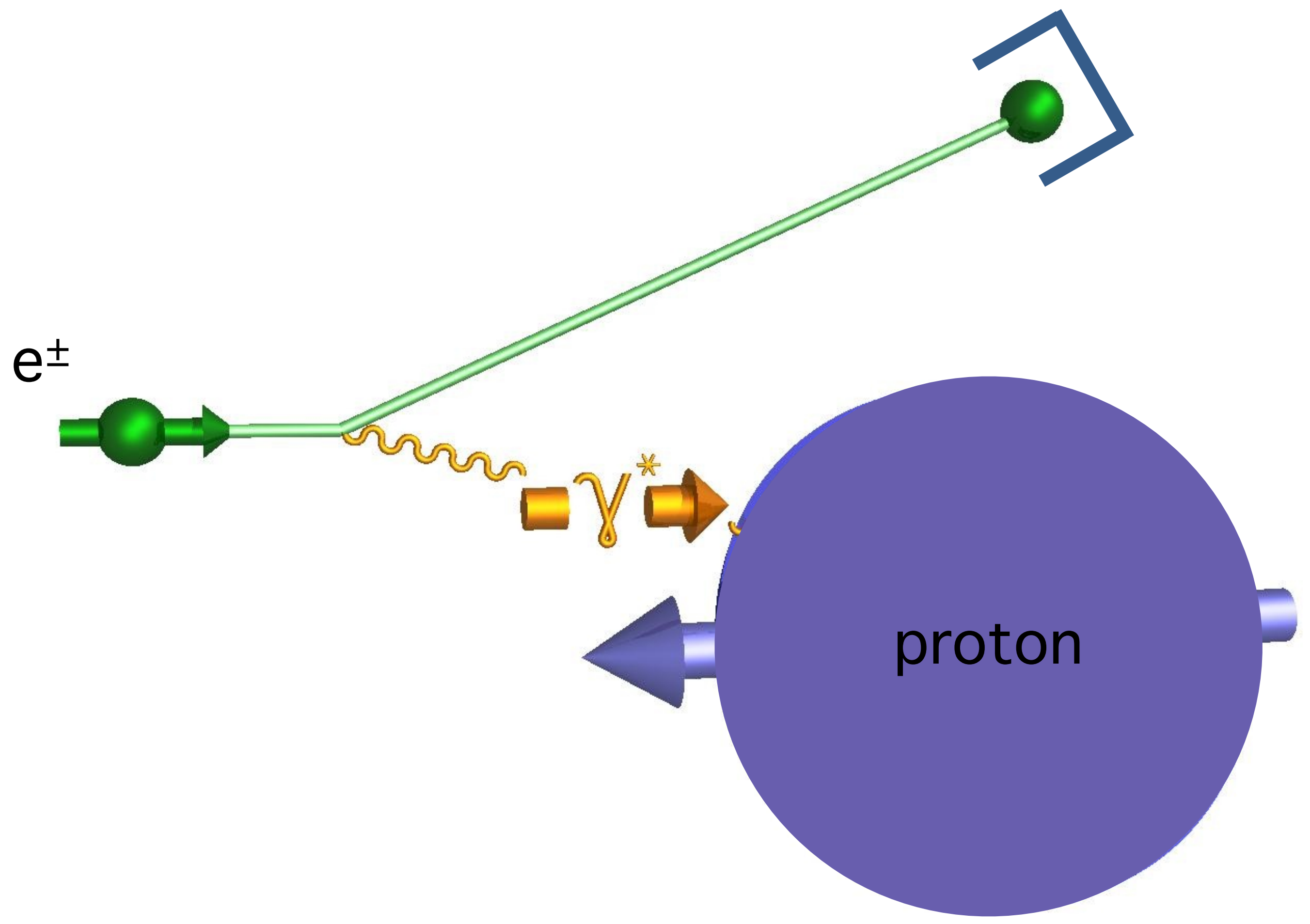


The nucleon spin



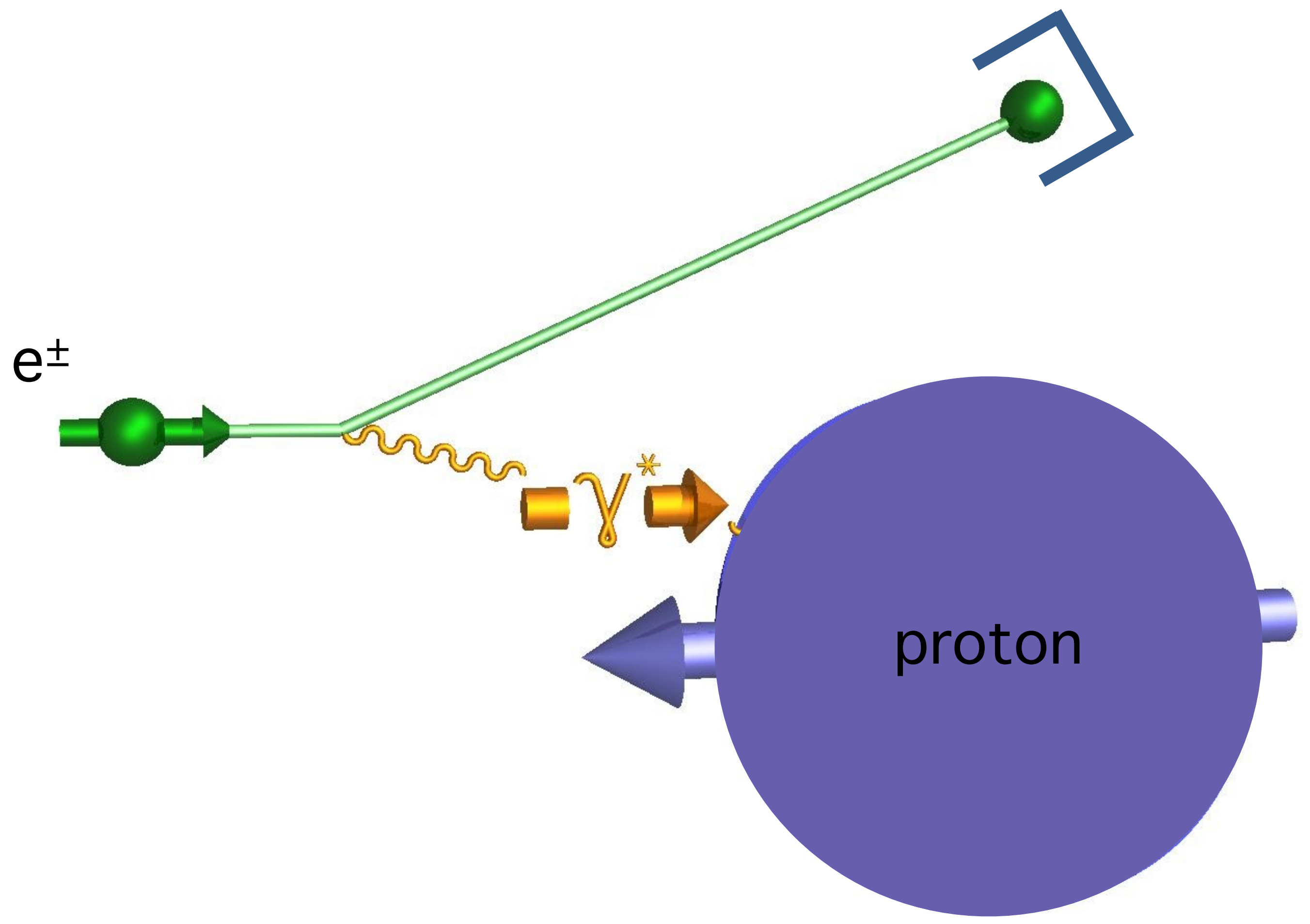


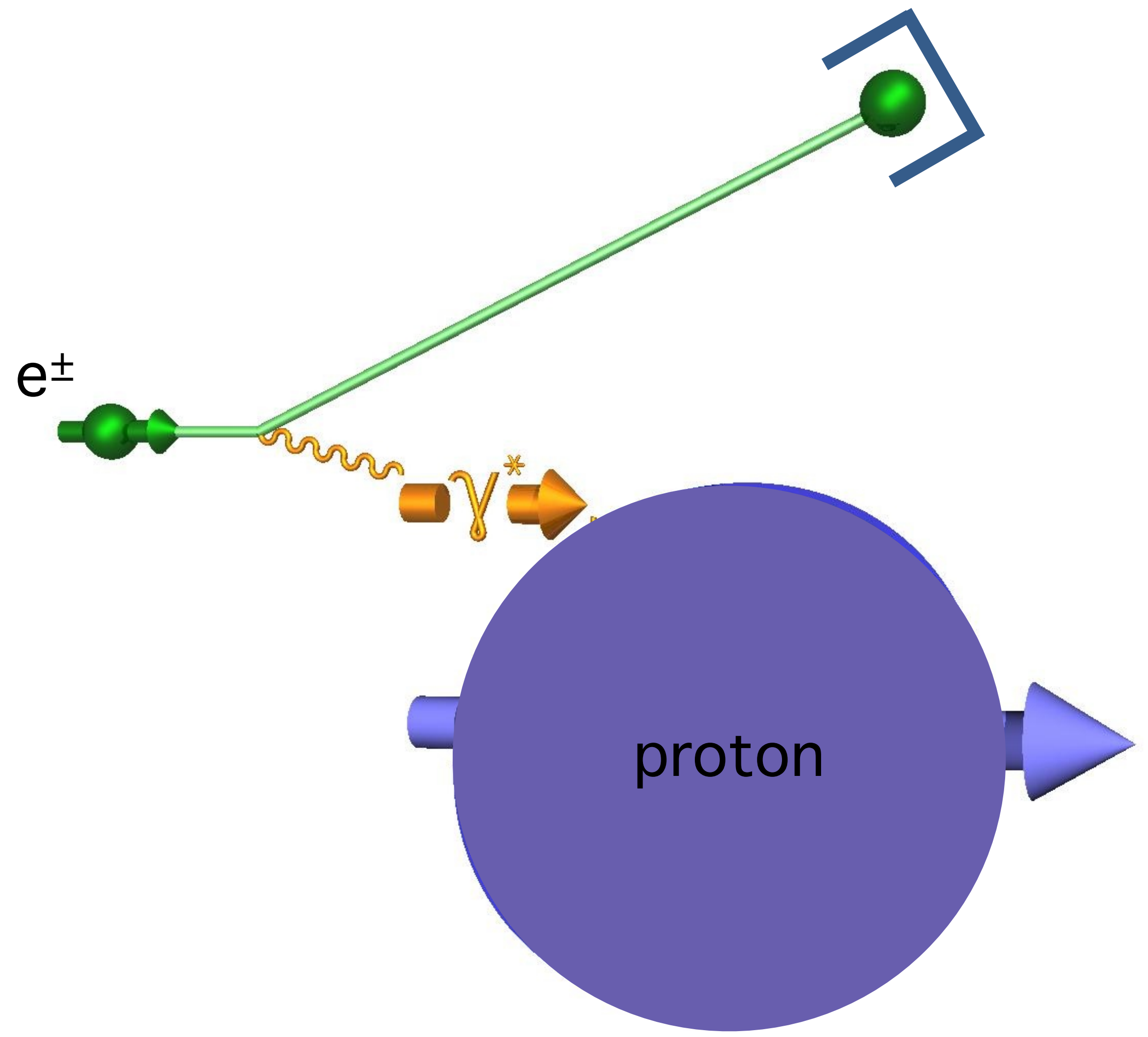
Helicity structure of the nucleon



- longitudinally polarised proton
- longitudinally polarised $e^{\pm}$ beam
- count… 

Helicity structure of the nucleon

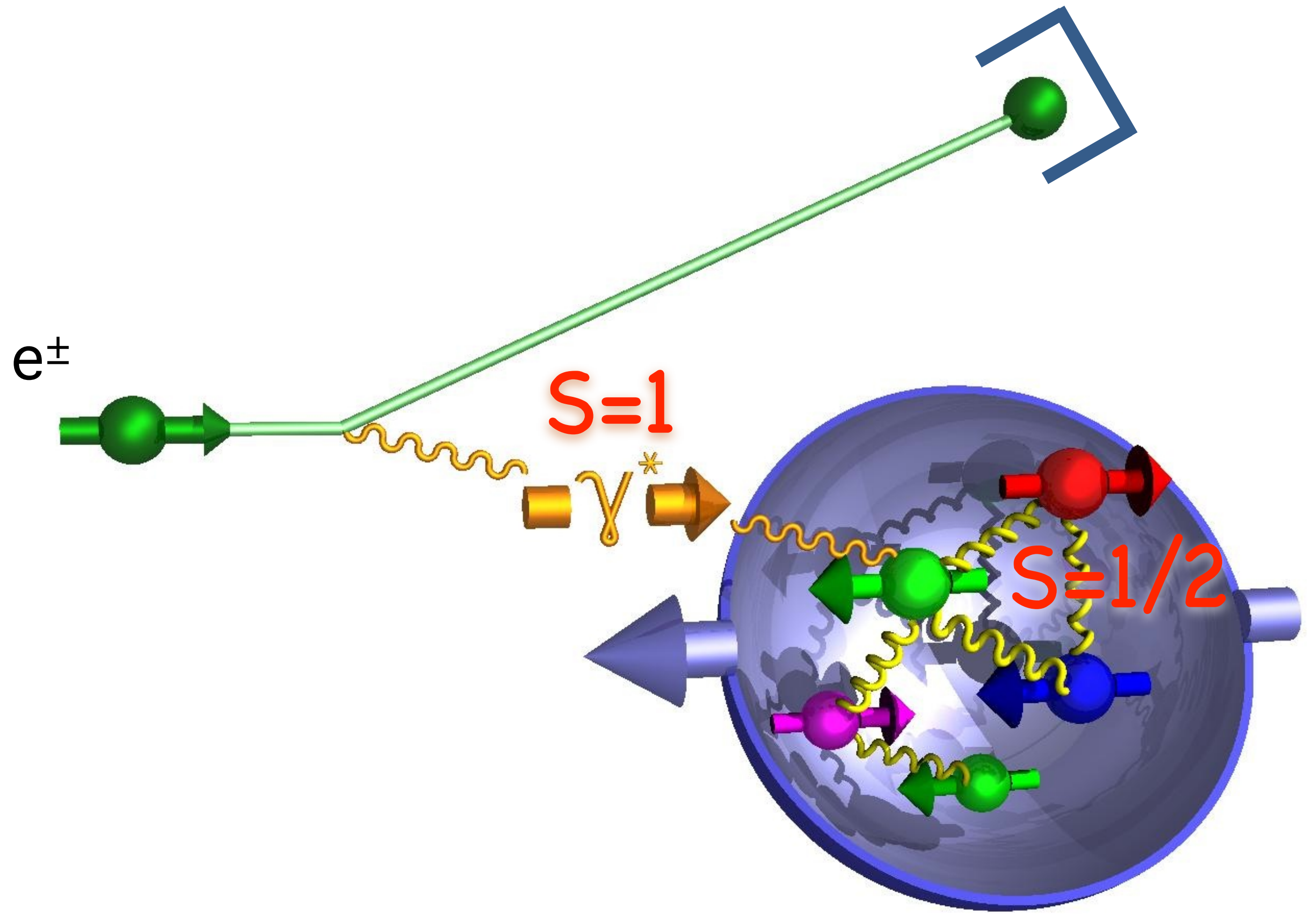




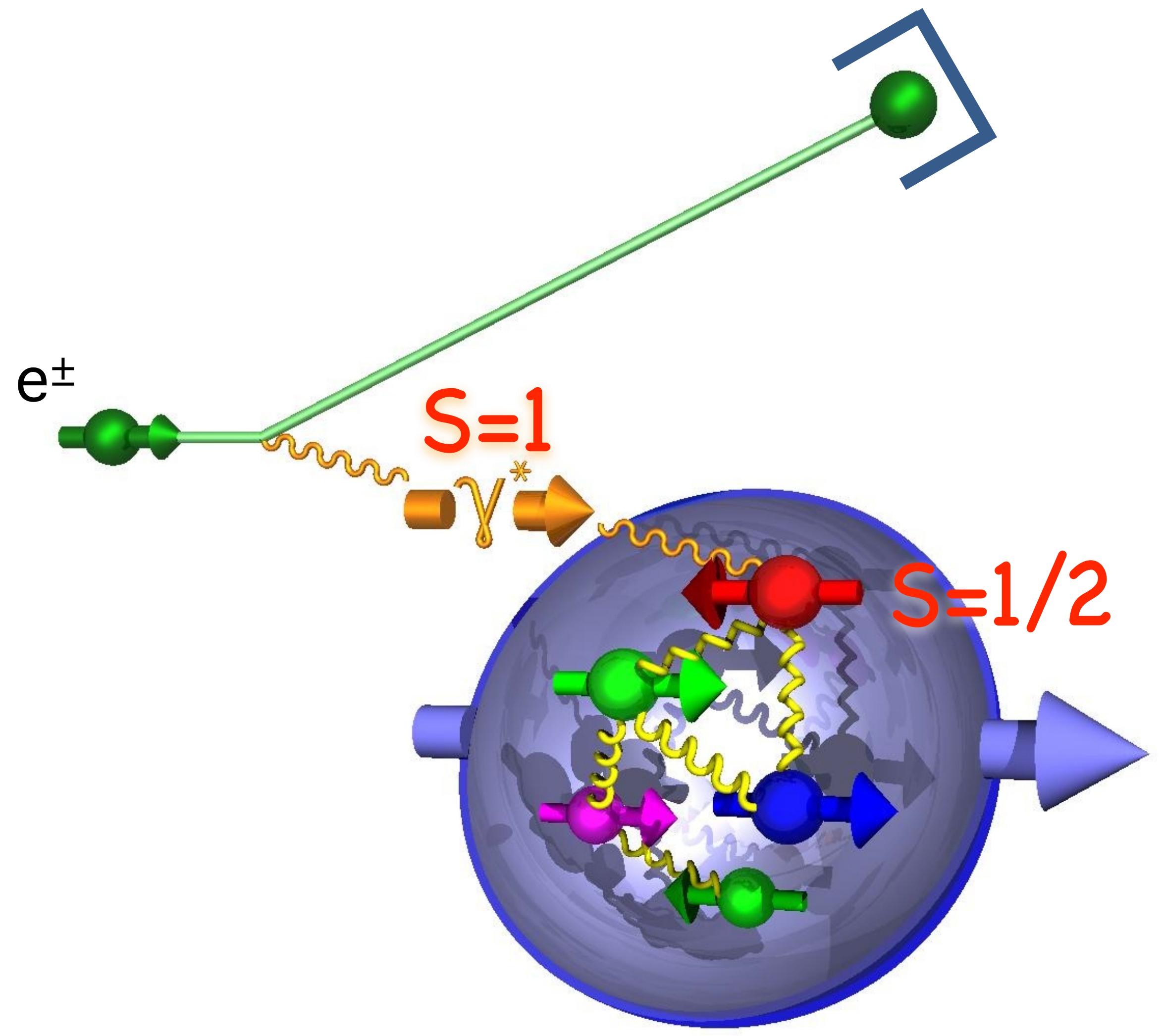
- longitudinally polarised proton
- longitudinally polarised e± beam
- count… 

- flip proton spin and count… 

Helicity structure of the nucleon

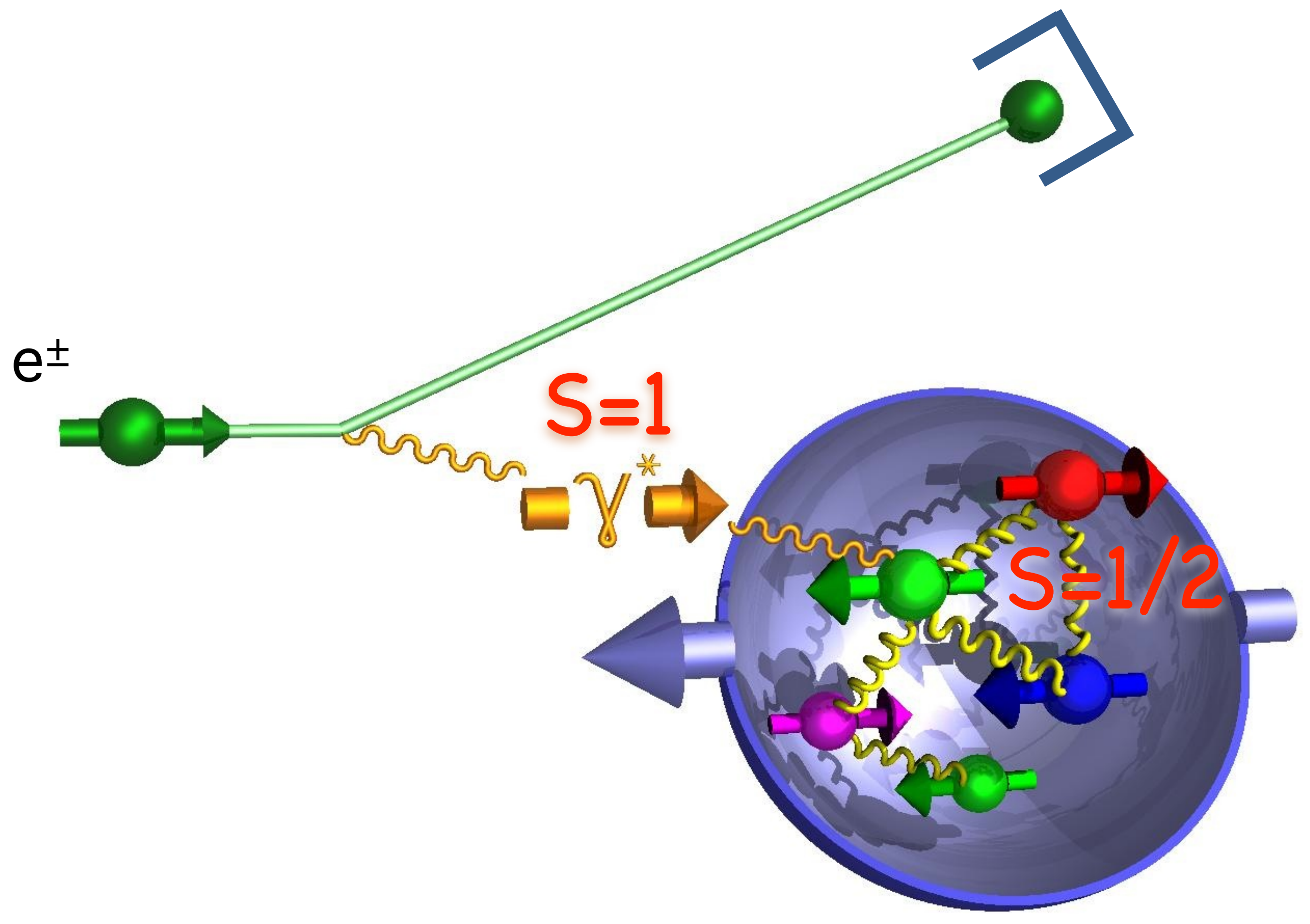


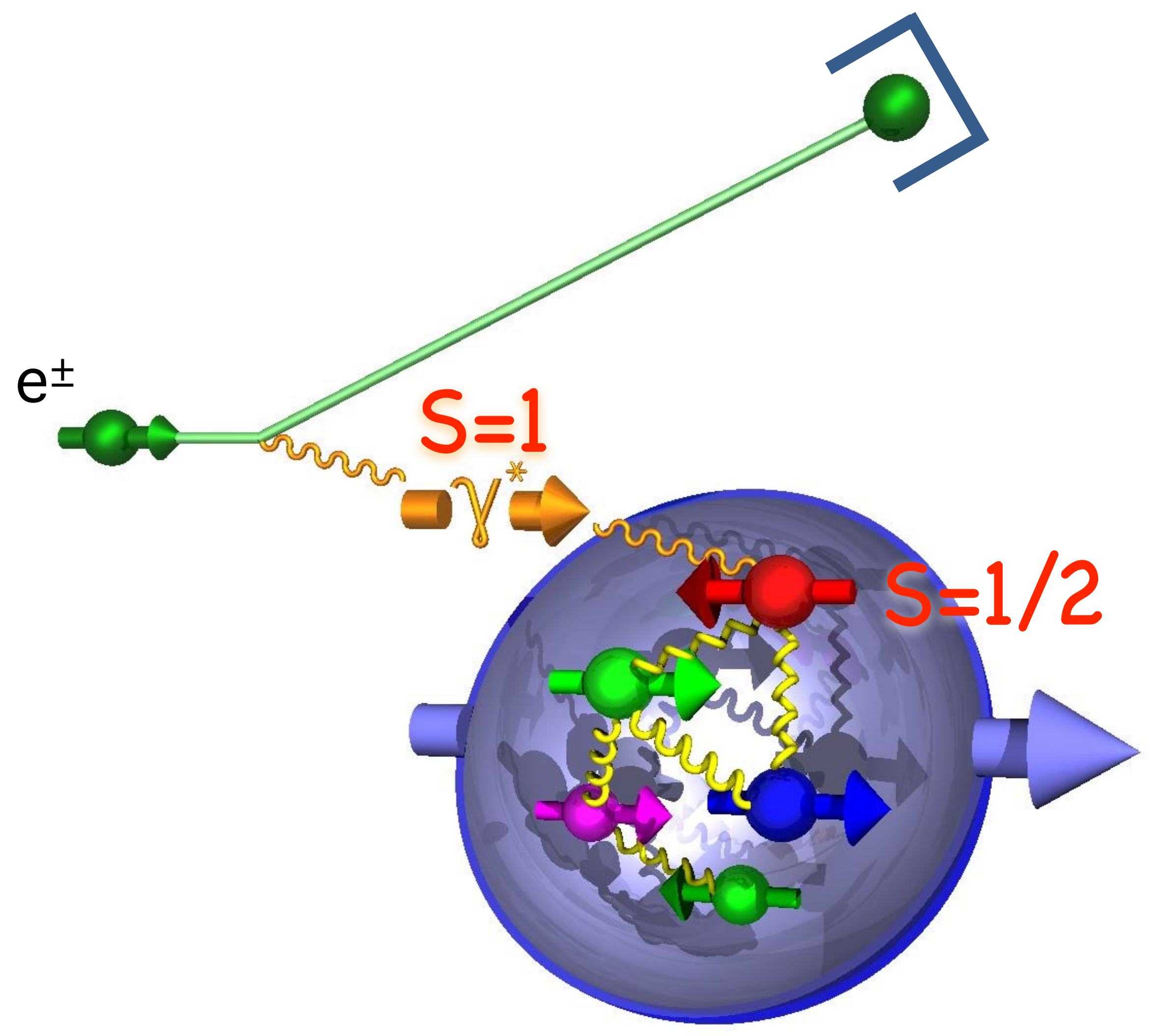
- longitudinally polarised proton
- longitudinally polarised $e^{\pm}$ beam
- count…



- flip proton spin and count…

Helicity structure of the nucleon





- longitudinally polarised proton
- longitudinally polarised e± beam
- count… 

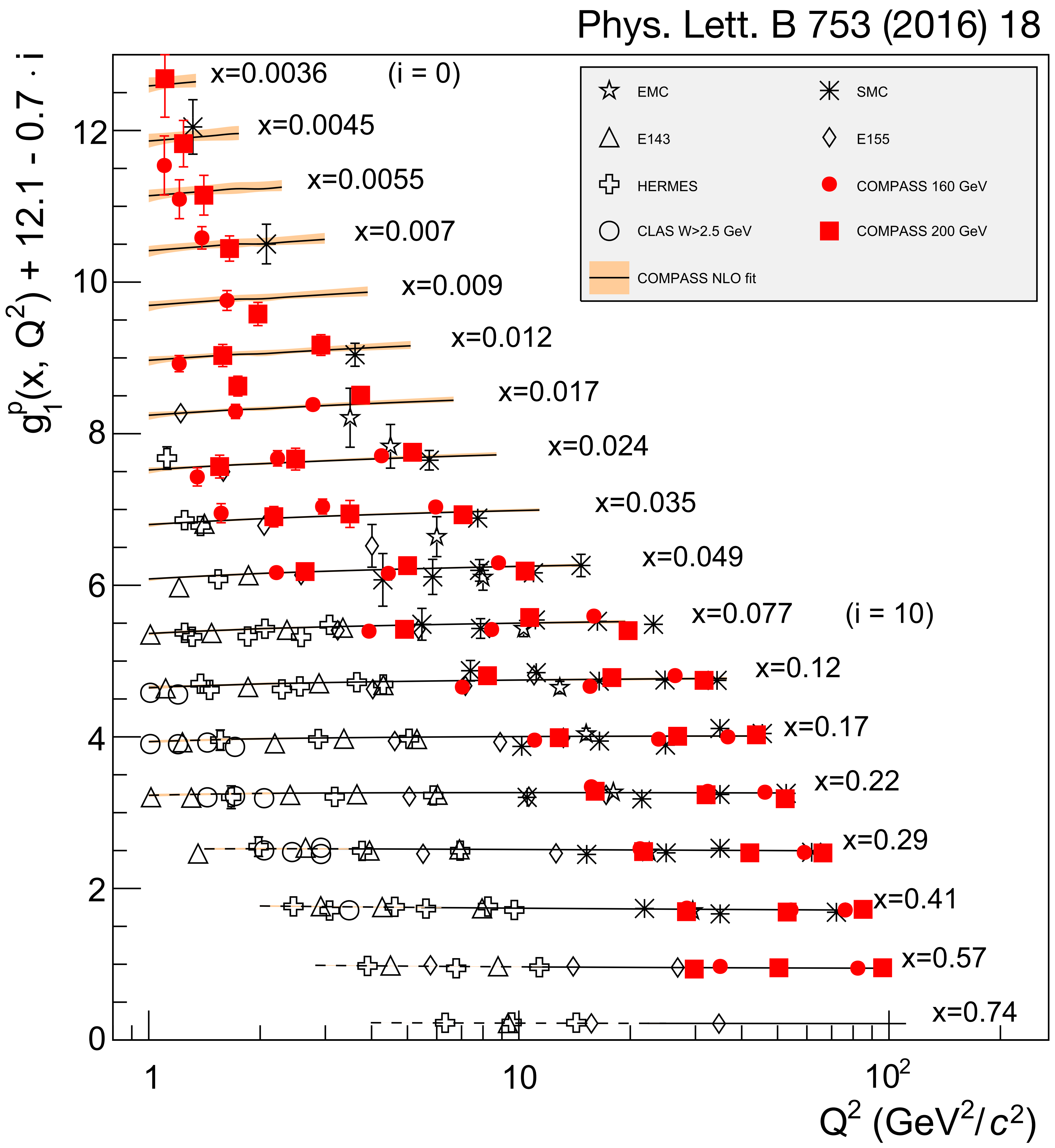
- flip proton spin and count… 

$$\frac{\overset{\Leftarrow}{\vec{\sigma}} - \overset{\Rightarrow}{\vec{\sigma}}}{\overset{\Leftarrow}{\vec{\sigma}} + \overset{\Rightarrow}{\vec{\sigma}}} \propto g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta q(x) = \frac{1}{2}\sum_q e_q^2 \left(\overset{\Leftarrow}{\overleftarrow{q}}(x) - \overset{\rightleftarrows}{q}(x)\right)$$

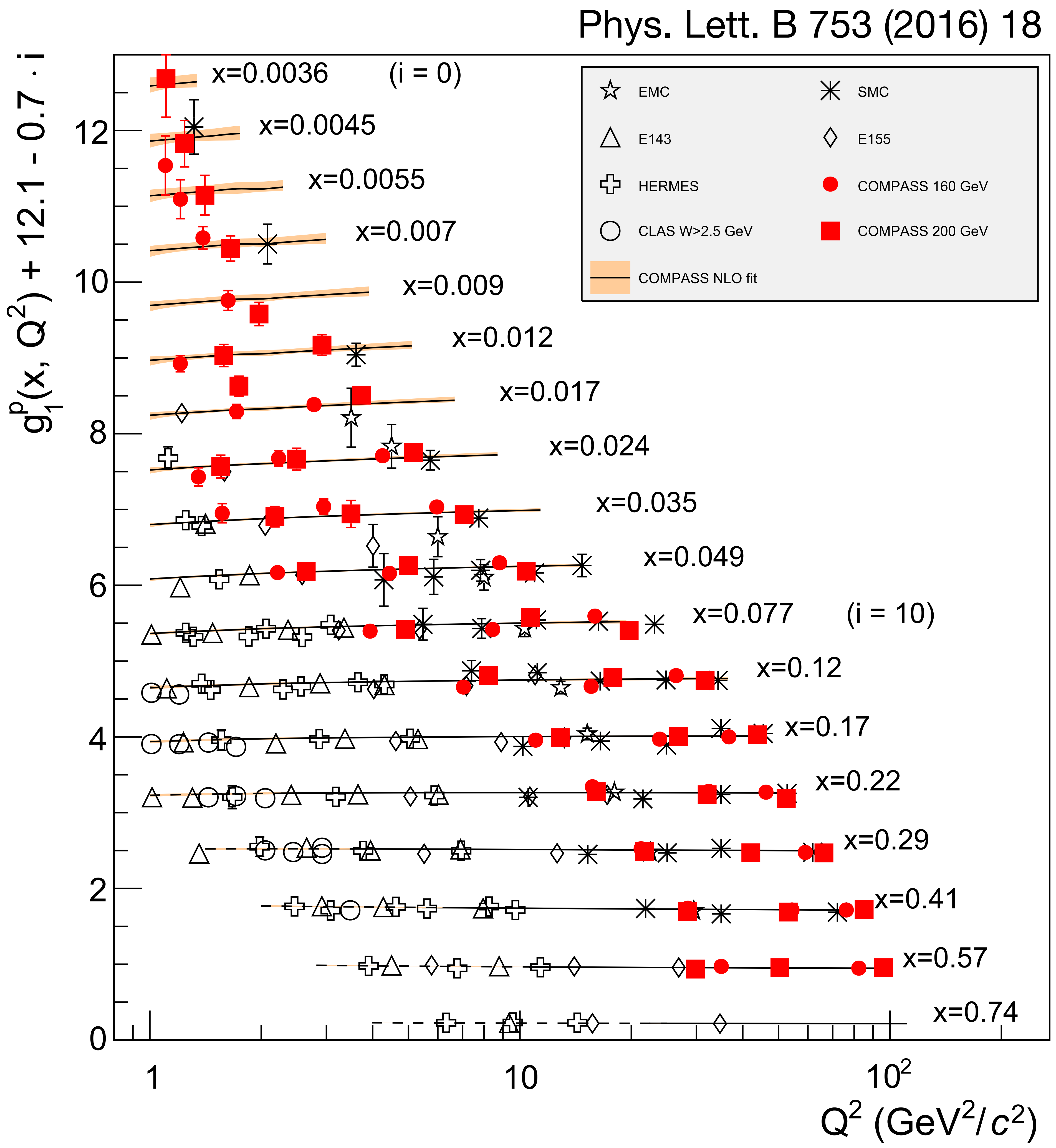
helicity parton distribution function (PDF)

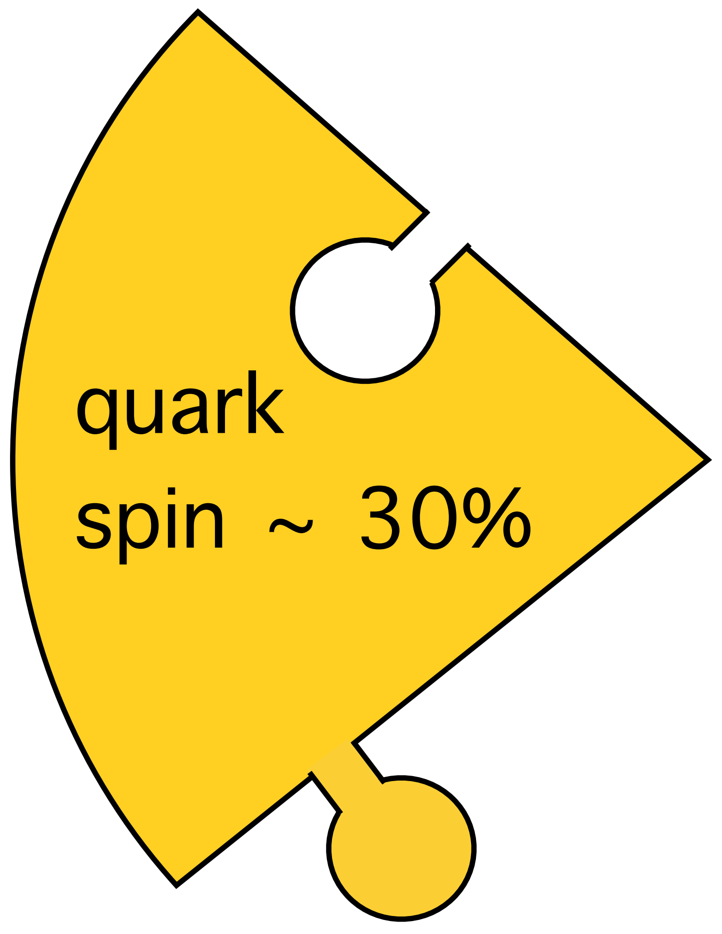
parton fractional longitudinal momentum: x_B

Helicity structure of the nucleon: existing measurements



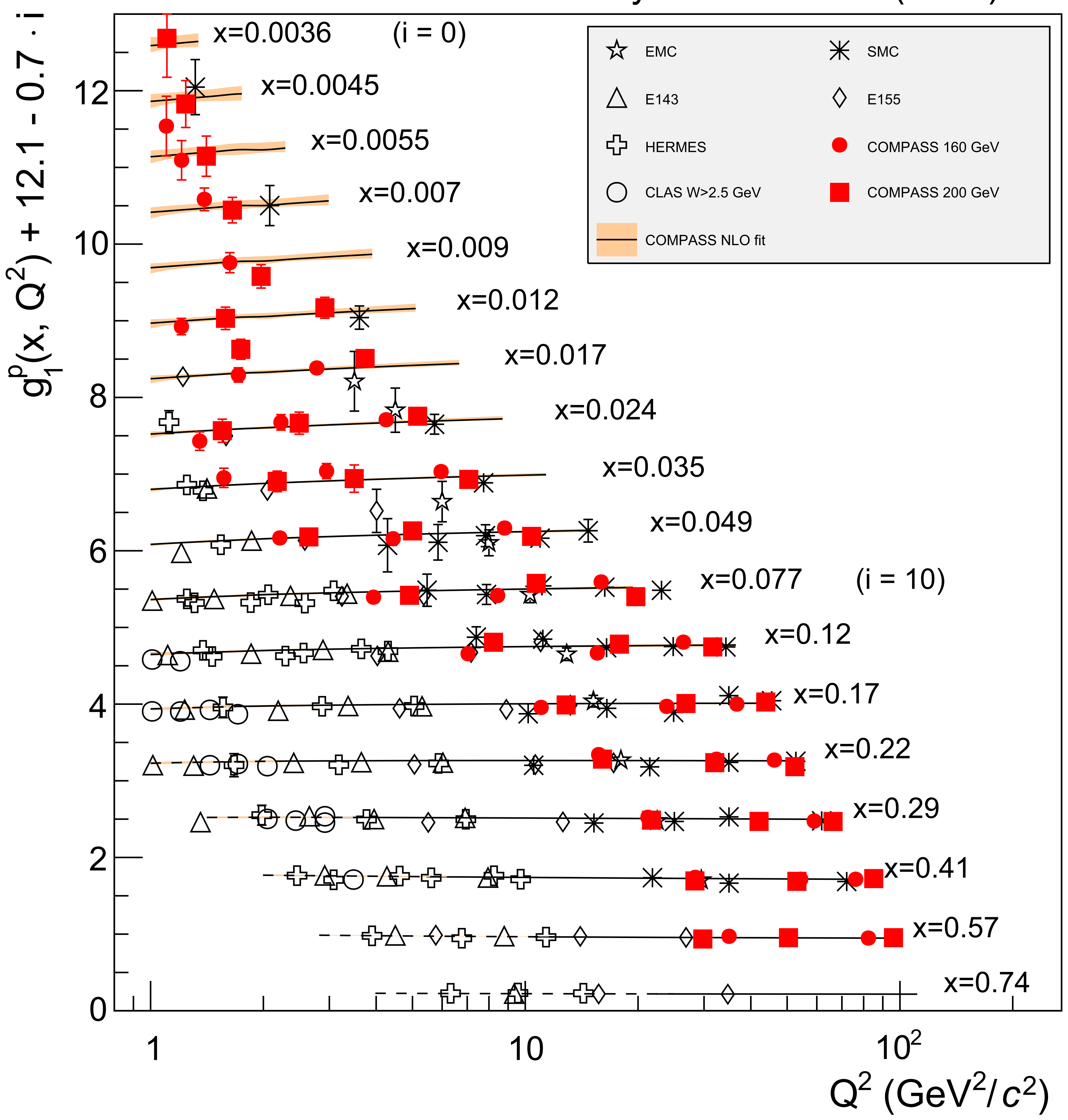
Helicity structure of the nucleon: existing measurements

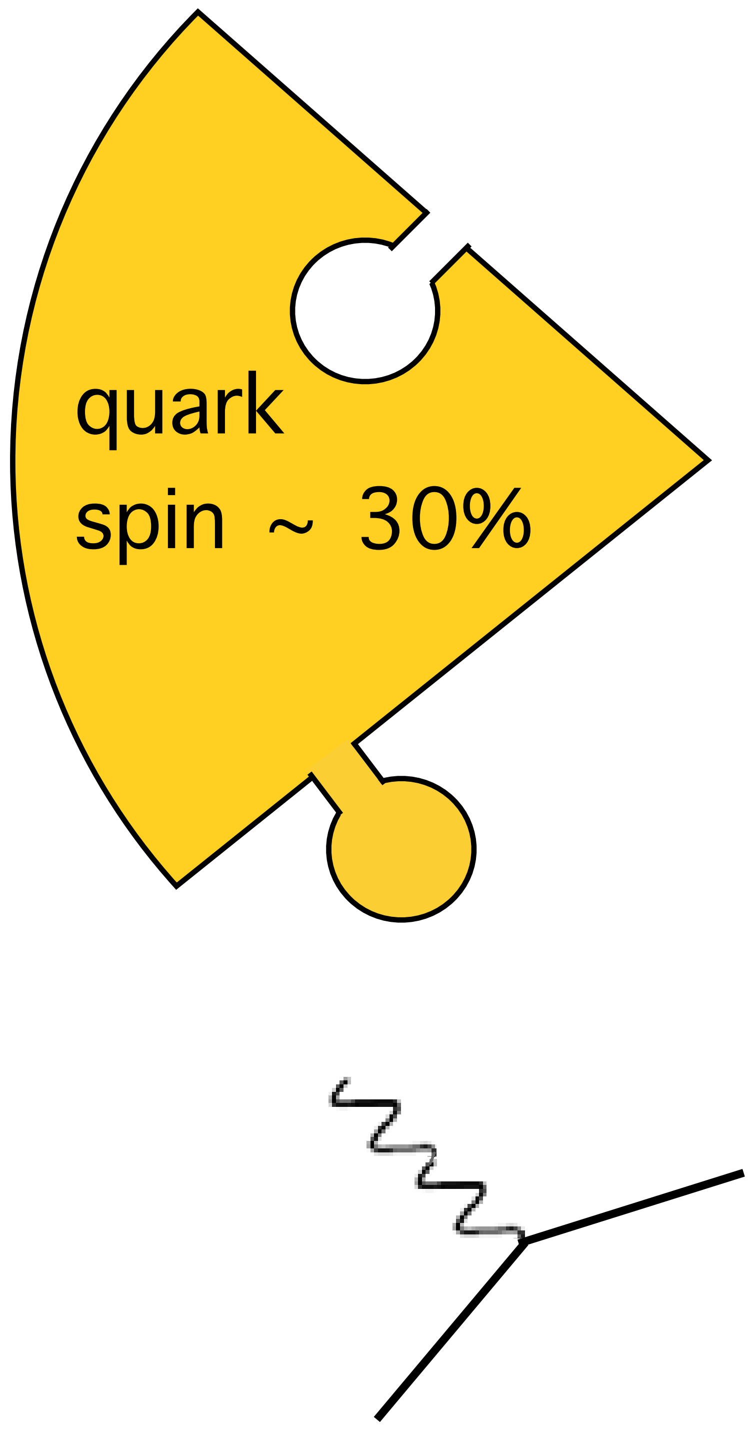




Helicity structure of the nucleon: existing measurements

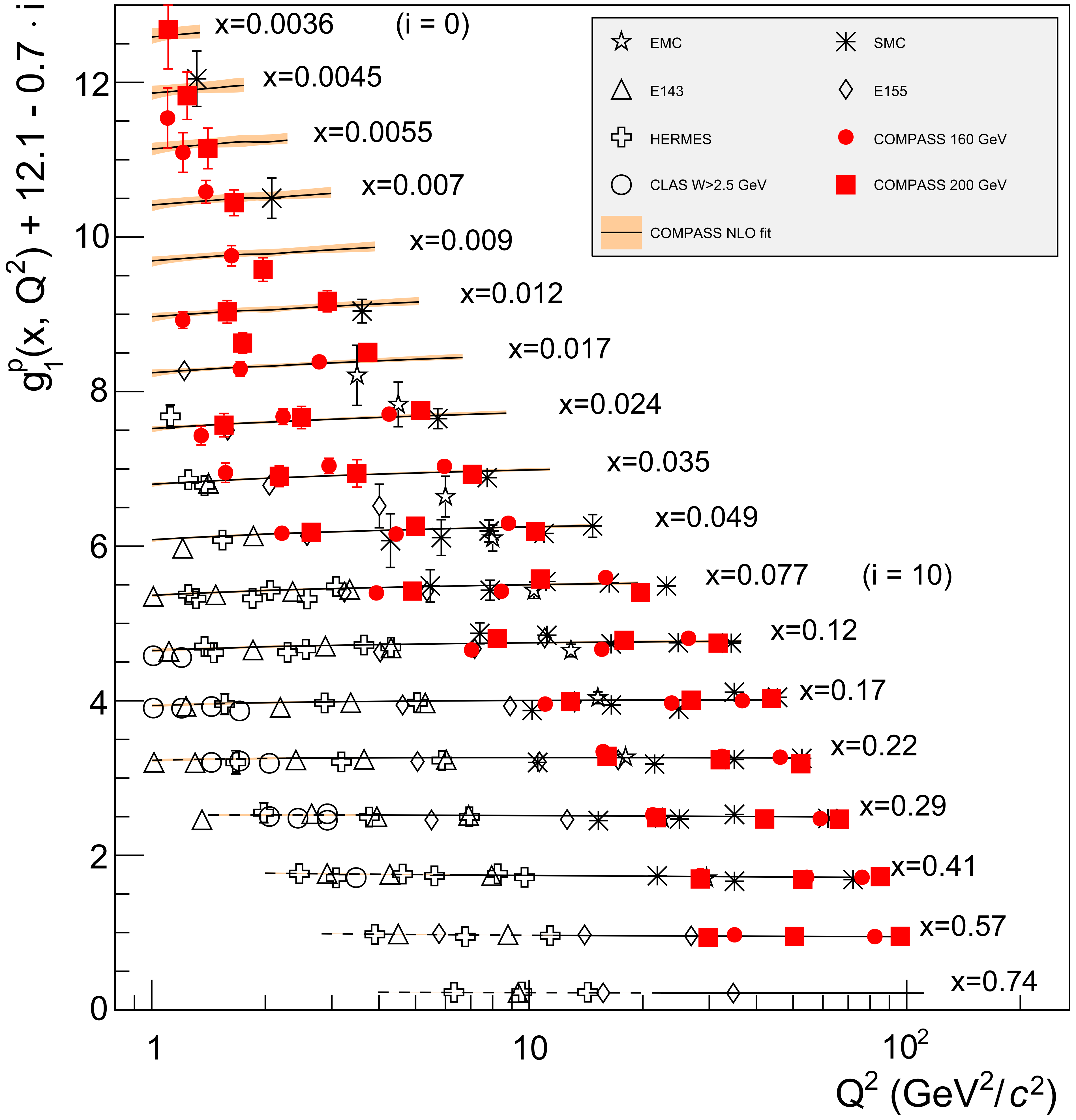
Phys. Lett. B 753 (2016) 18

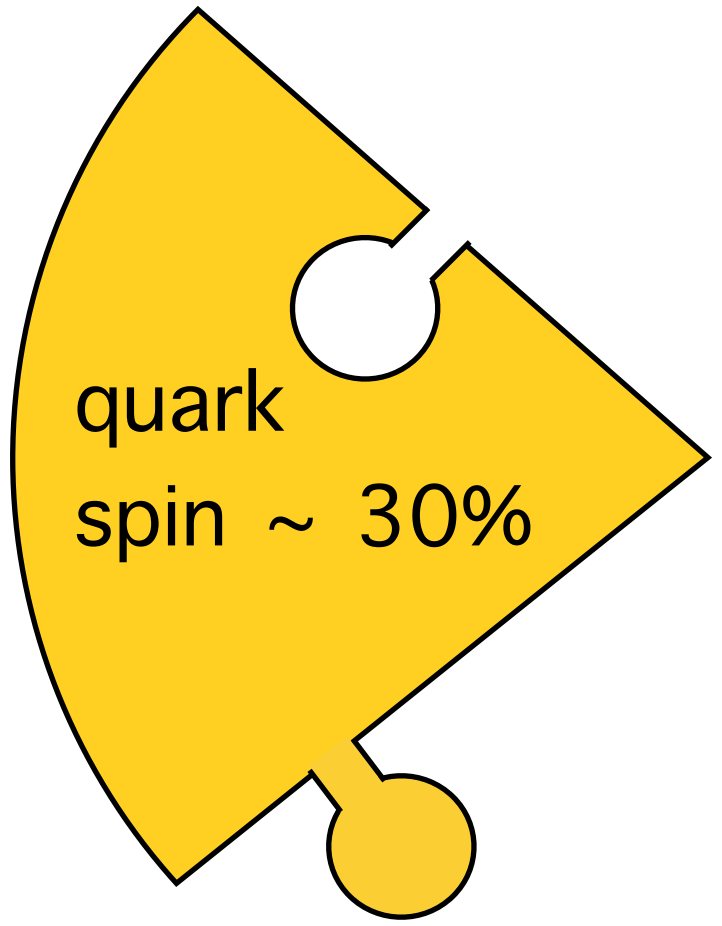




Helicity structure of the nucleon: existing measurements

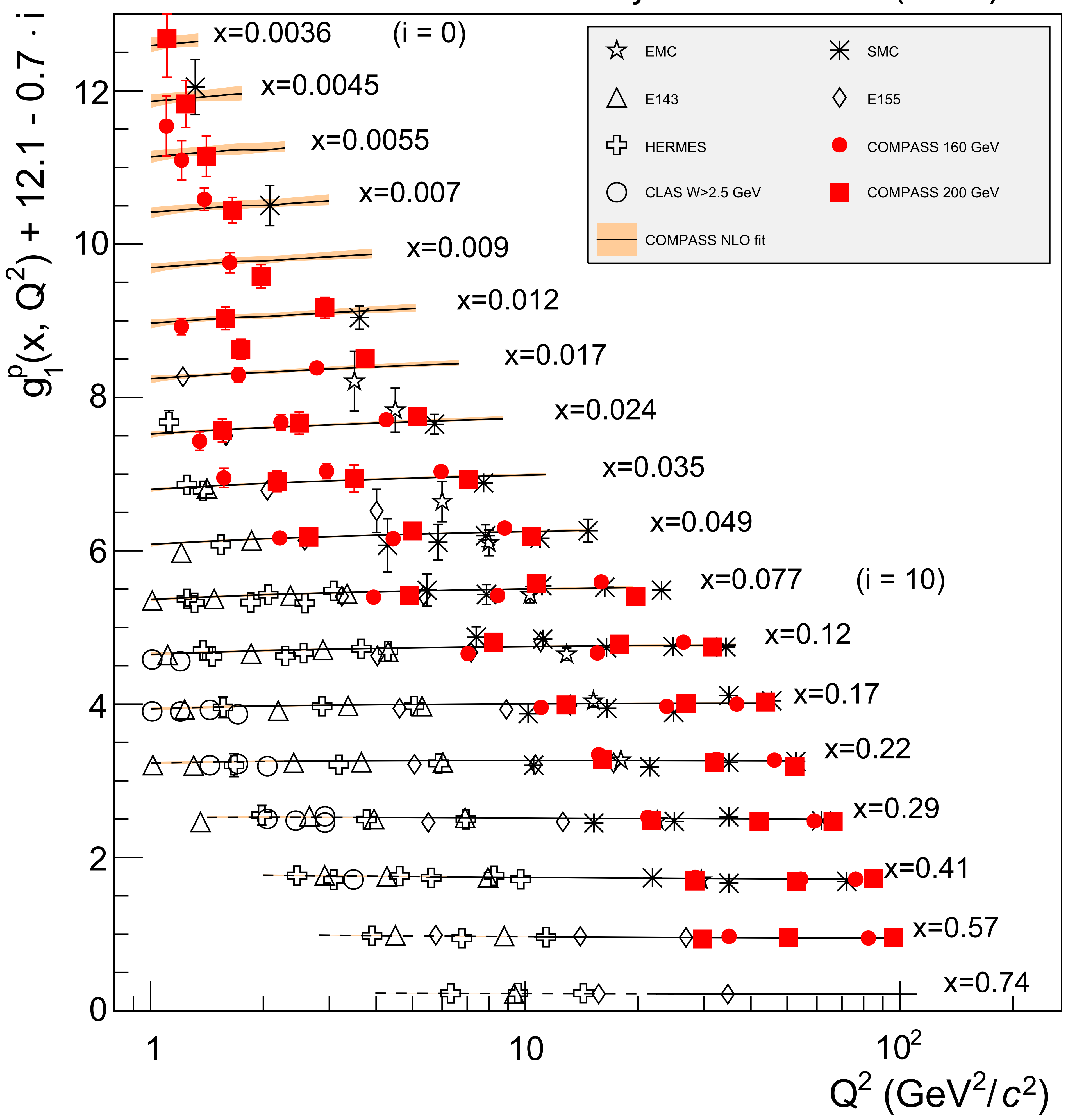
Phys. Lett. B 753 (2016) 18

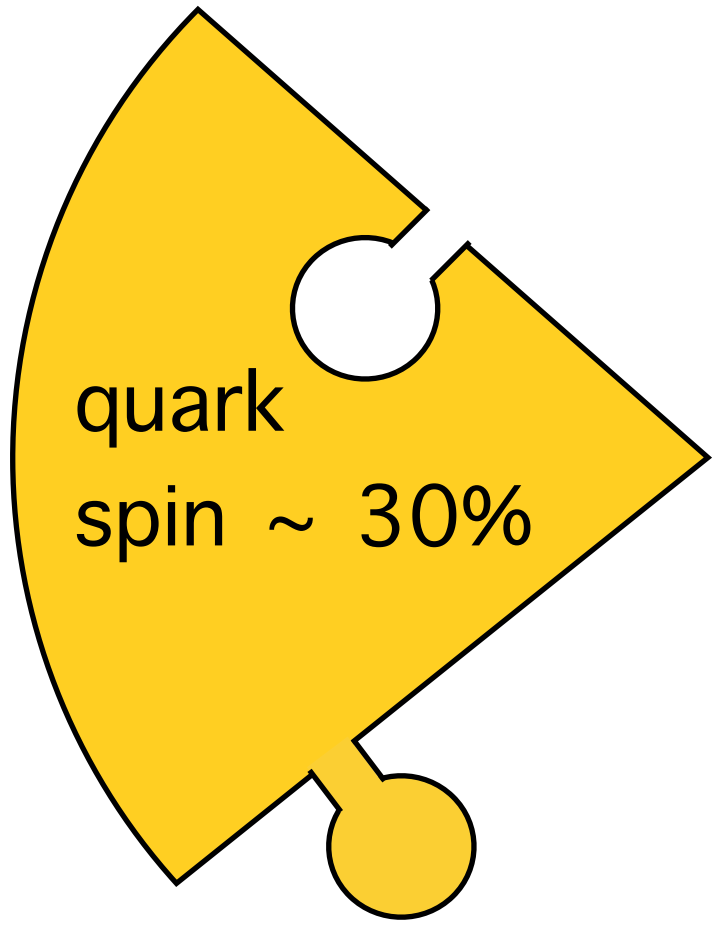




Helicity structure of the nucleon: existing measurements

Phys. Lett. B 753 (2016) 18



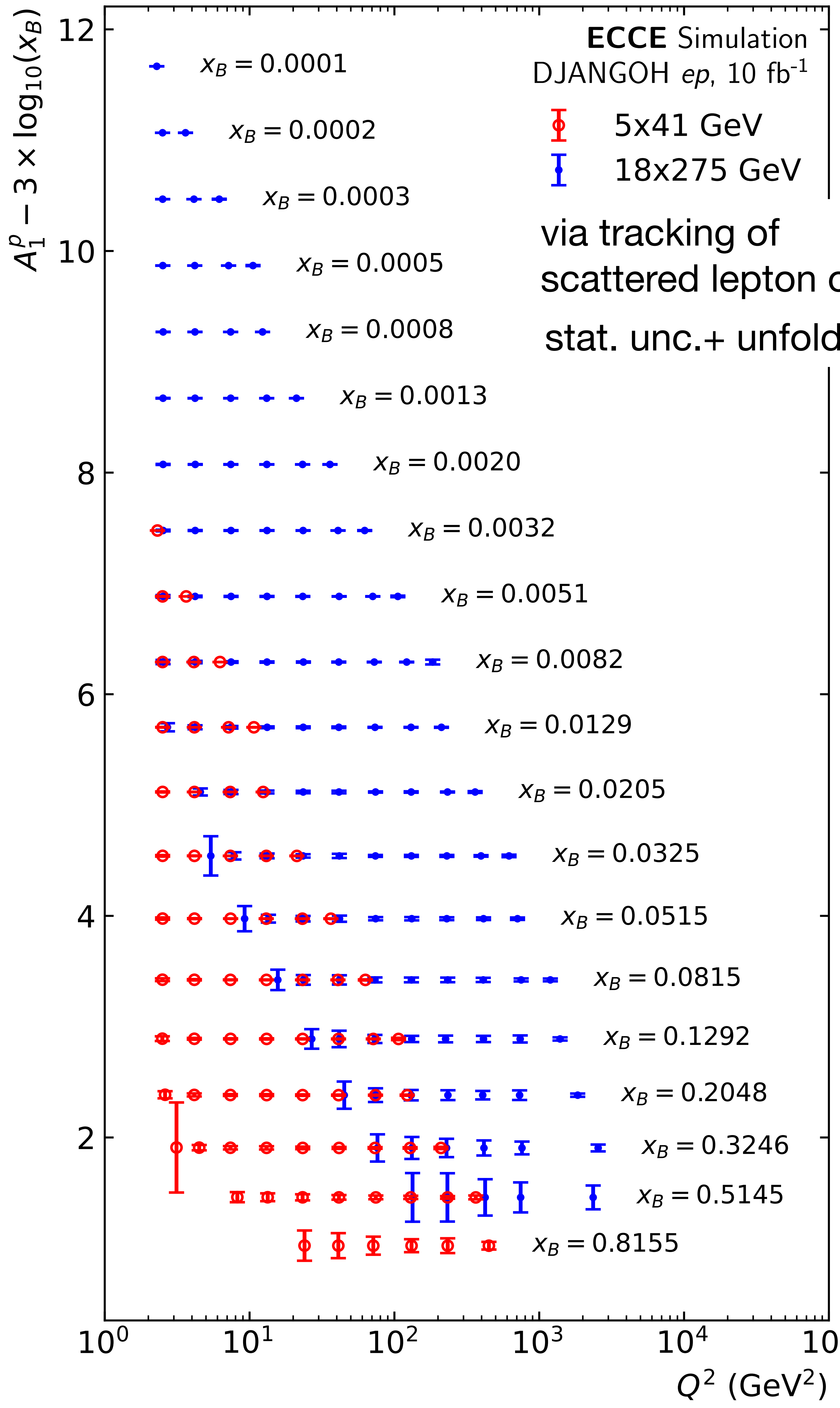


$$\frac{dg_1(x,Q^2)}{d\ln Q^2} \propto -\Delta g(x,Q^2)$$

⟶ gluon spin

Gluon helicity distribution at the EIC

ECCE consortium, 10.5281/zenodo.6537587

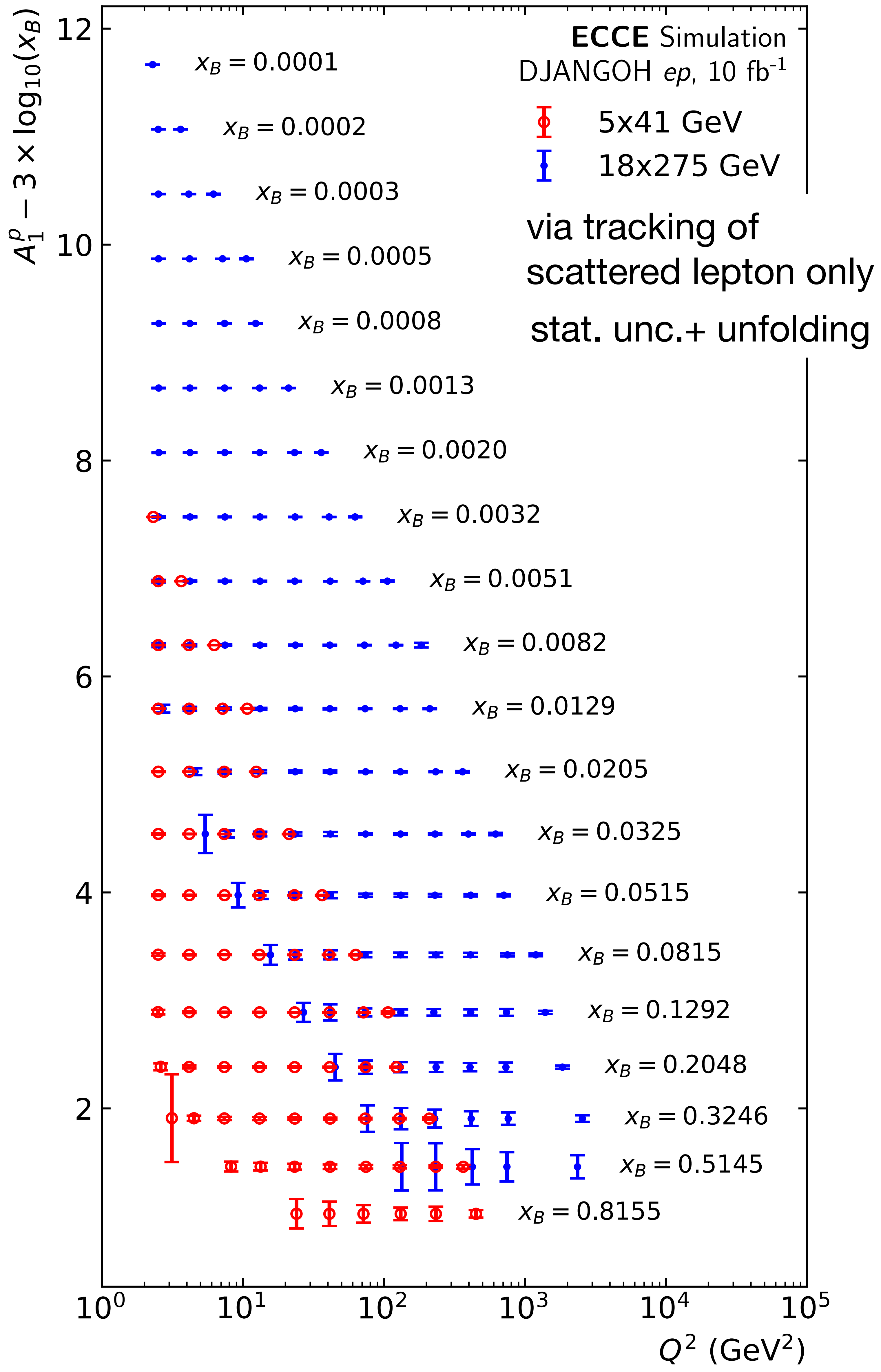


via tracking of
scattered lepton only

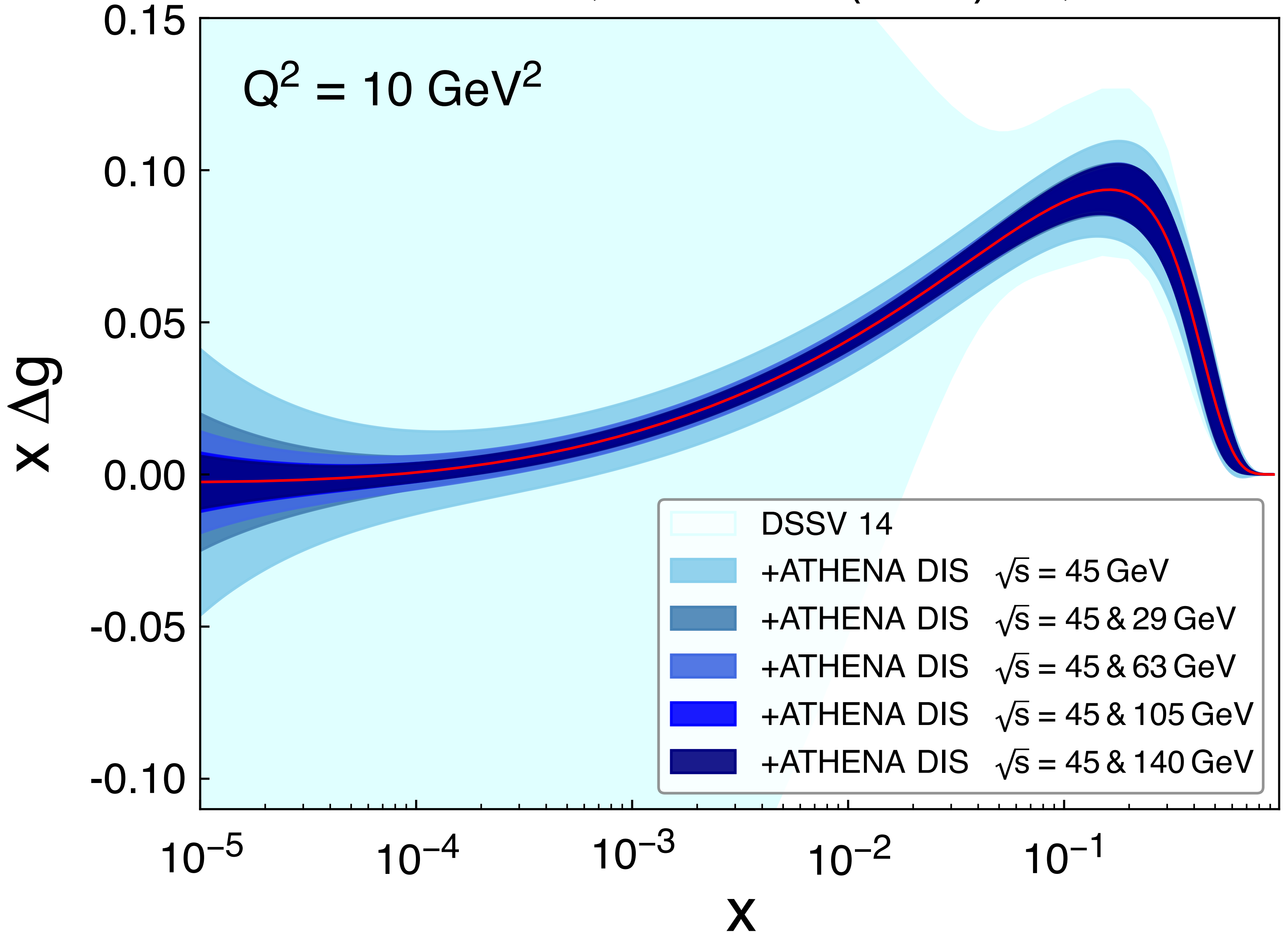
stat. unc.+ unfolding

Gluon helicity distribution at the EIC

ECCE consortium, 10.5281/zenodo.6537587



ATHENA, JINST **17** (2022) 10, P10019

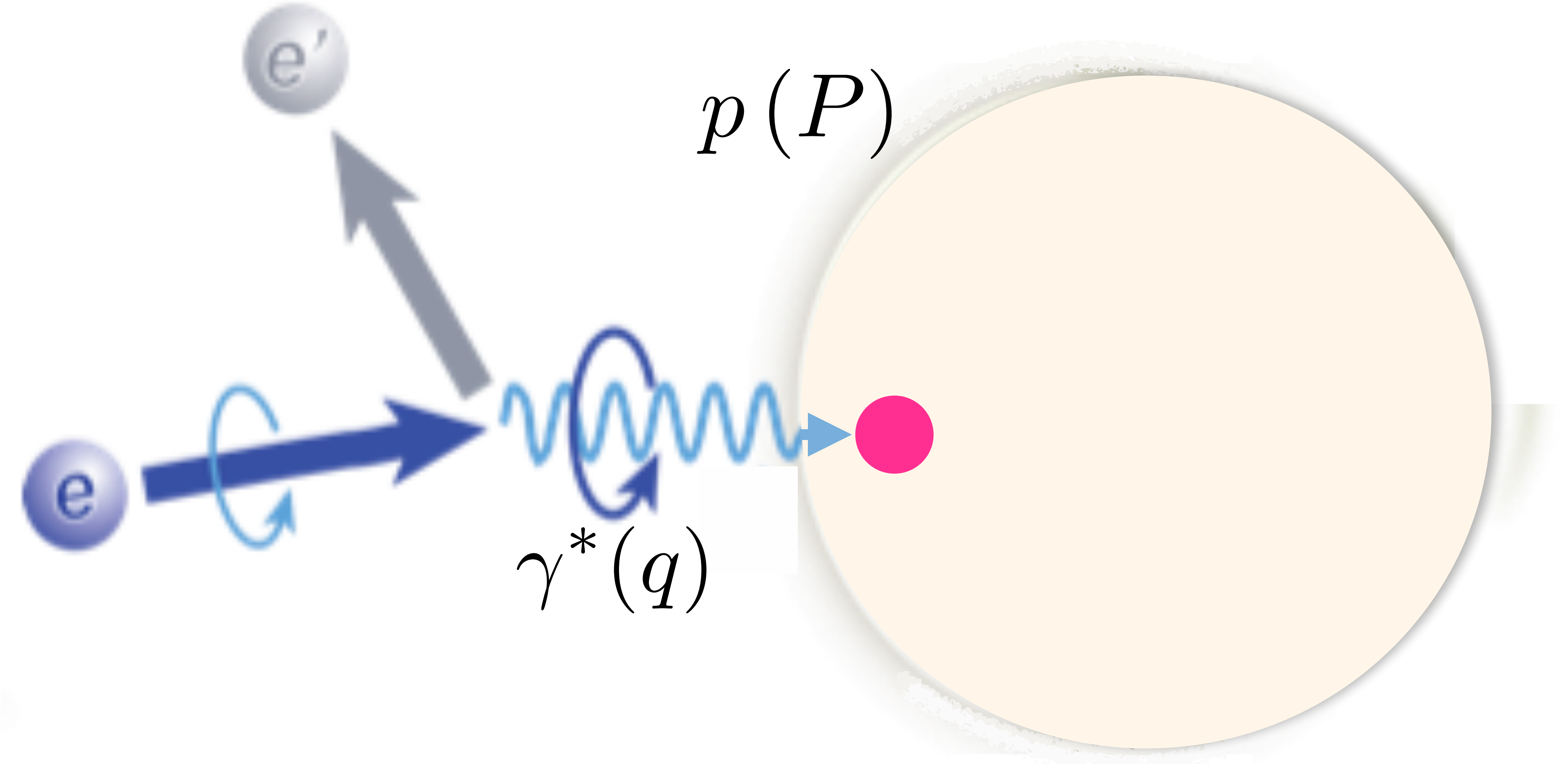


scaling violation from $g_1(x,Q^2)$

Single-hadron production in semi-inclusive DIS

$Q^2 = -q^2$

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

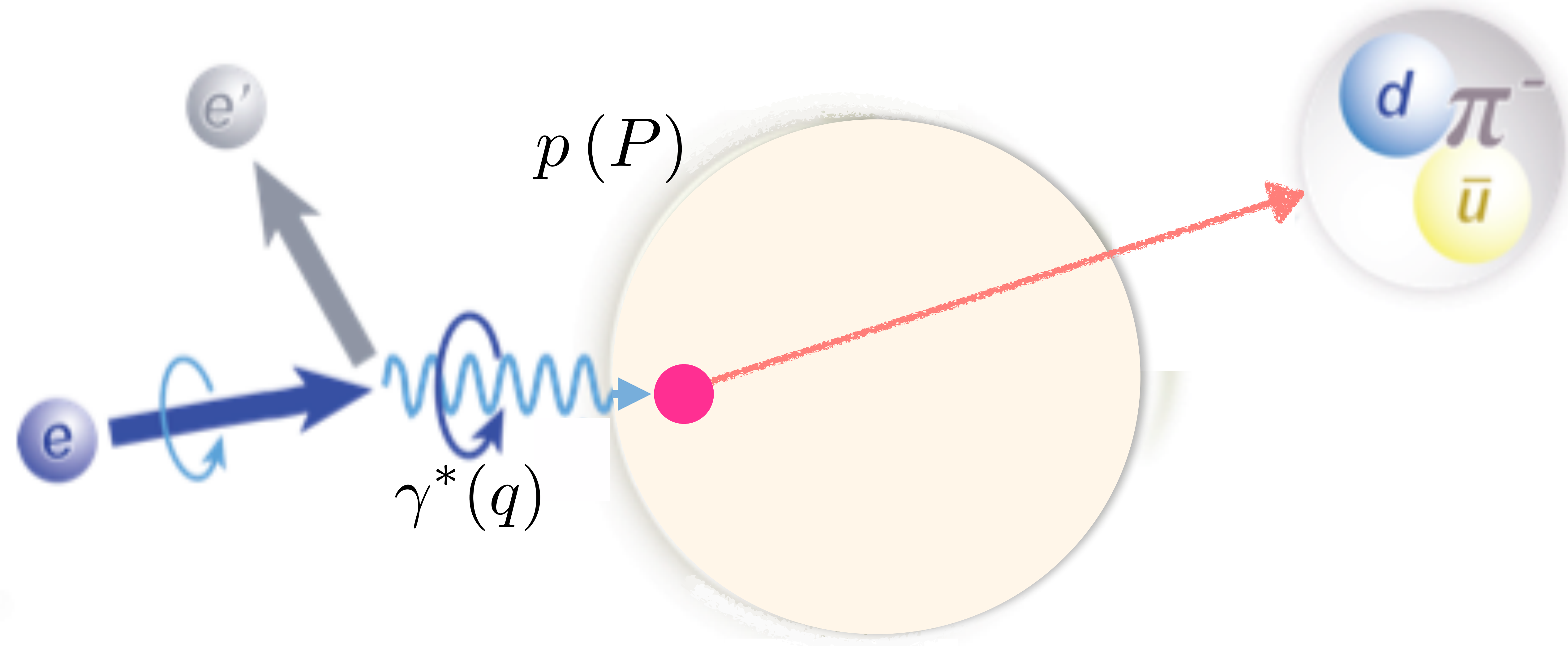


Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

Single-hadron production in semi-inclusive DIS

$$Q^2 = -q^2$$

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



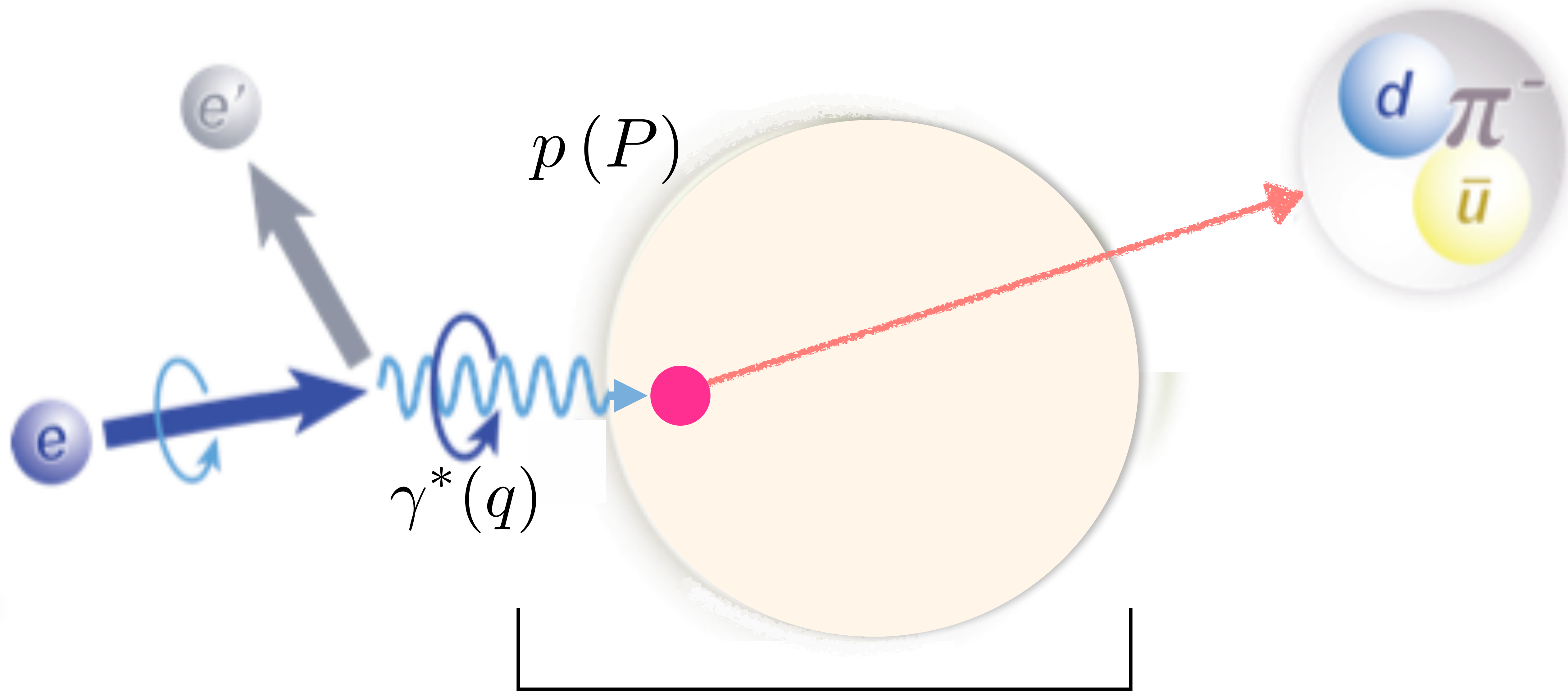
Detect a hadron!

Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

Single-hadron production in semi-inclusive DIS

$Q^2 = -q^2$

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



Detect a hadron!

parton distribution function $PDF(x_B)$

Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

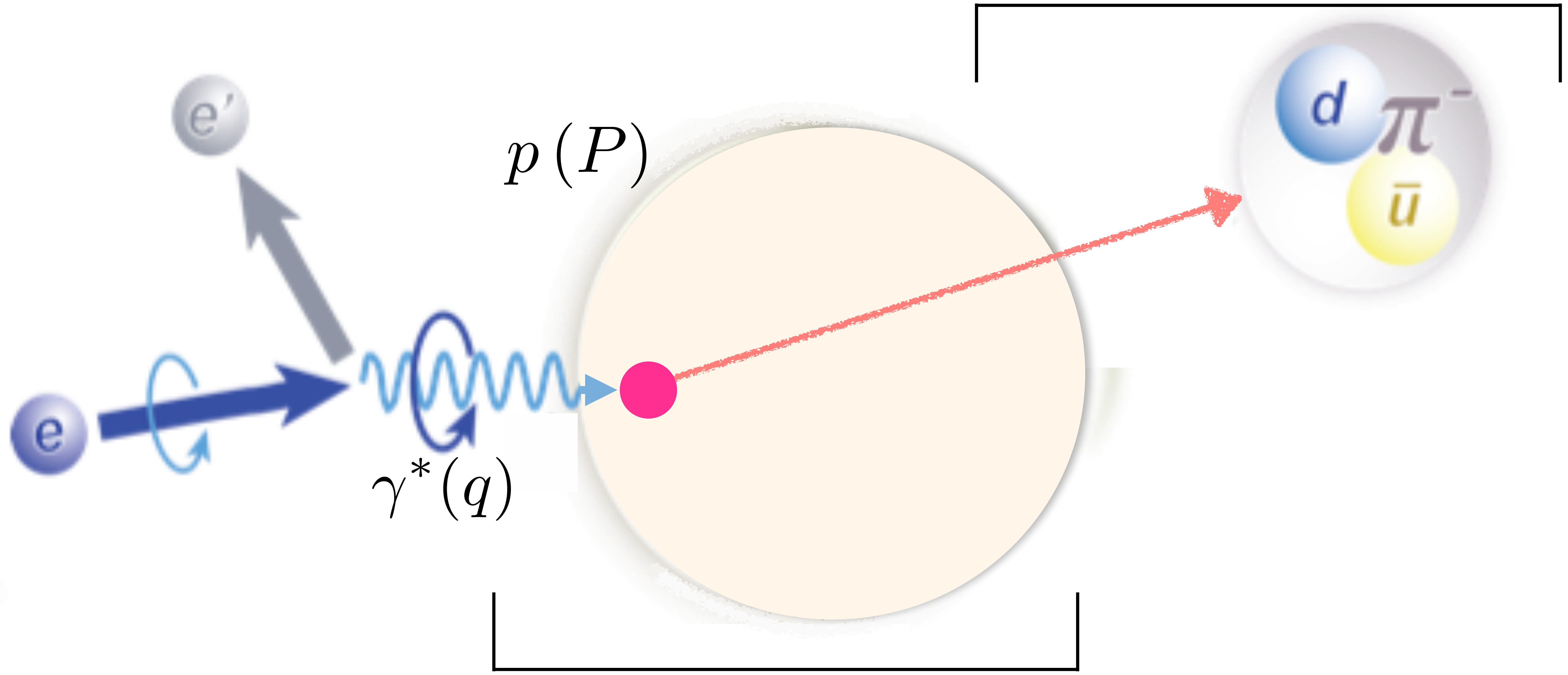
Single-hadron production in semi-inclusive DIS

fragmentation function $FF(z)$

$$Q^2 = -q^2$$

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

$$z \overset{\text{lab}}{=} \frac{E_h}{E_{\gamma *}}$$



Detect a hadron!

parton distribution function $PDF(x_B)$

Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

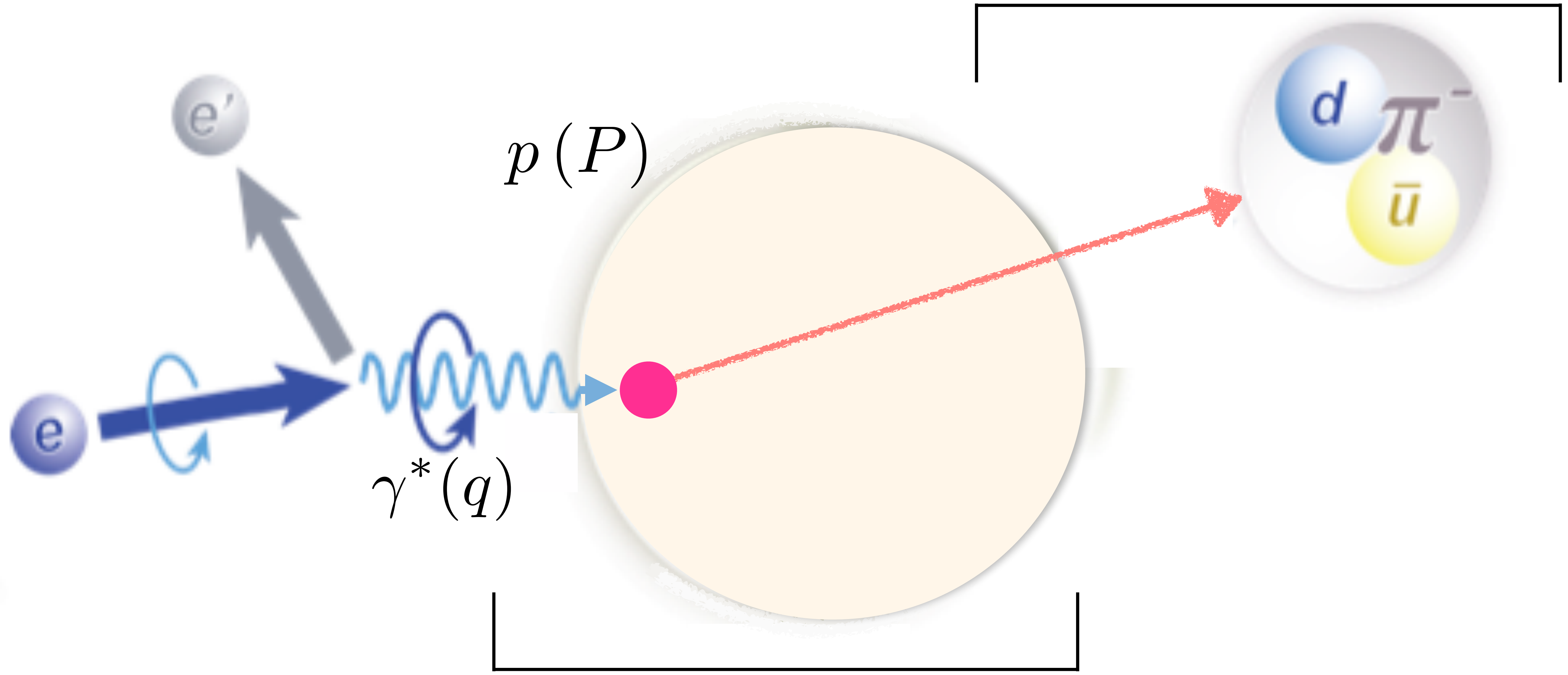
Single-hadron production in semi-inclusive DIS

fragmentation function $FF(z, Q^2)$

$Q^2 = -q^2$

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

$z \overset{\text{lab}}{=} \frac{E_h}{E_{\gamma*}}$



Detect a hadron!

parton distribution function $PDF(x_B, Q^2)$

Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

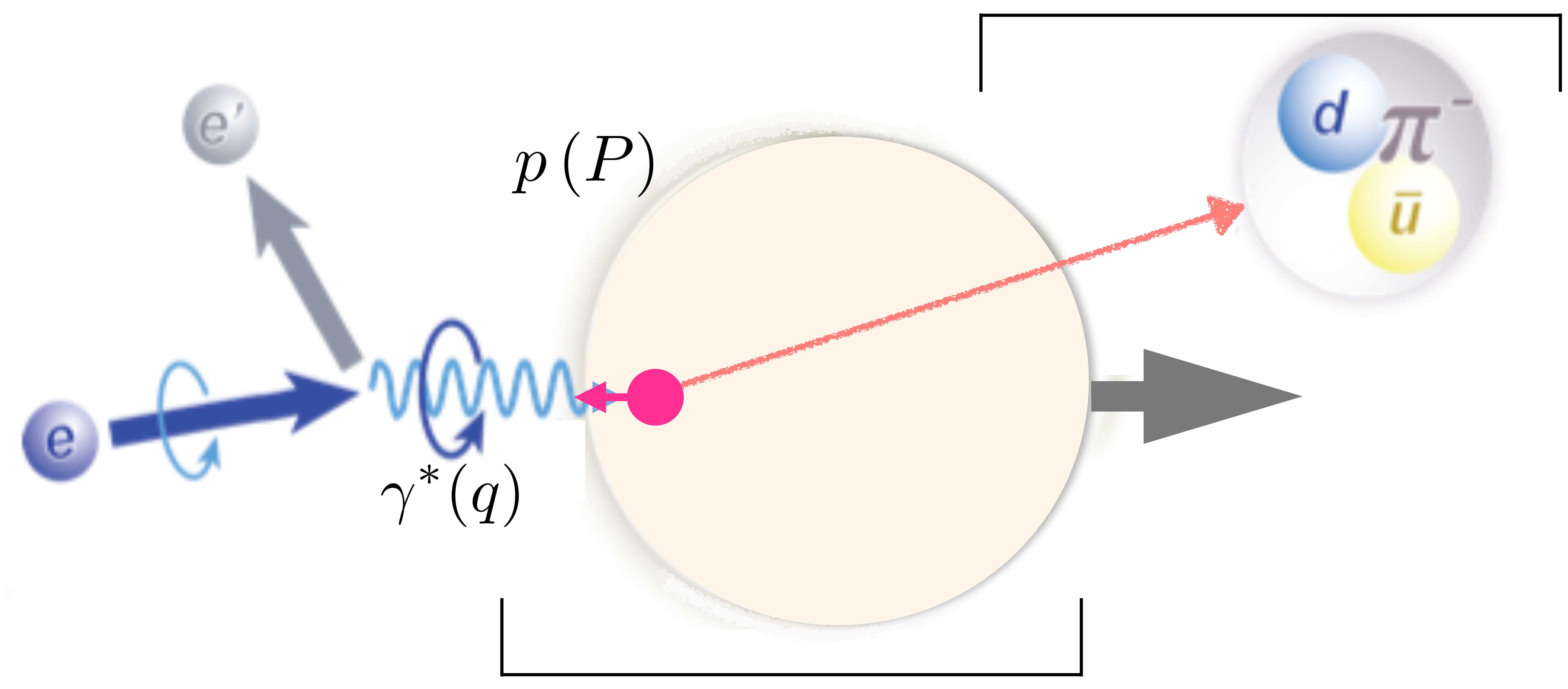
Single-hadron production in semi-inclusive DIS

$Q^2 = -q^2$

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

$z \stackrel{\text{lab}}{=} \frac{E_h}{E_{\gamma*}}$

fragmentation function $FF(z, Q^2)$

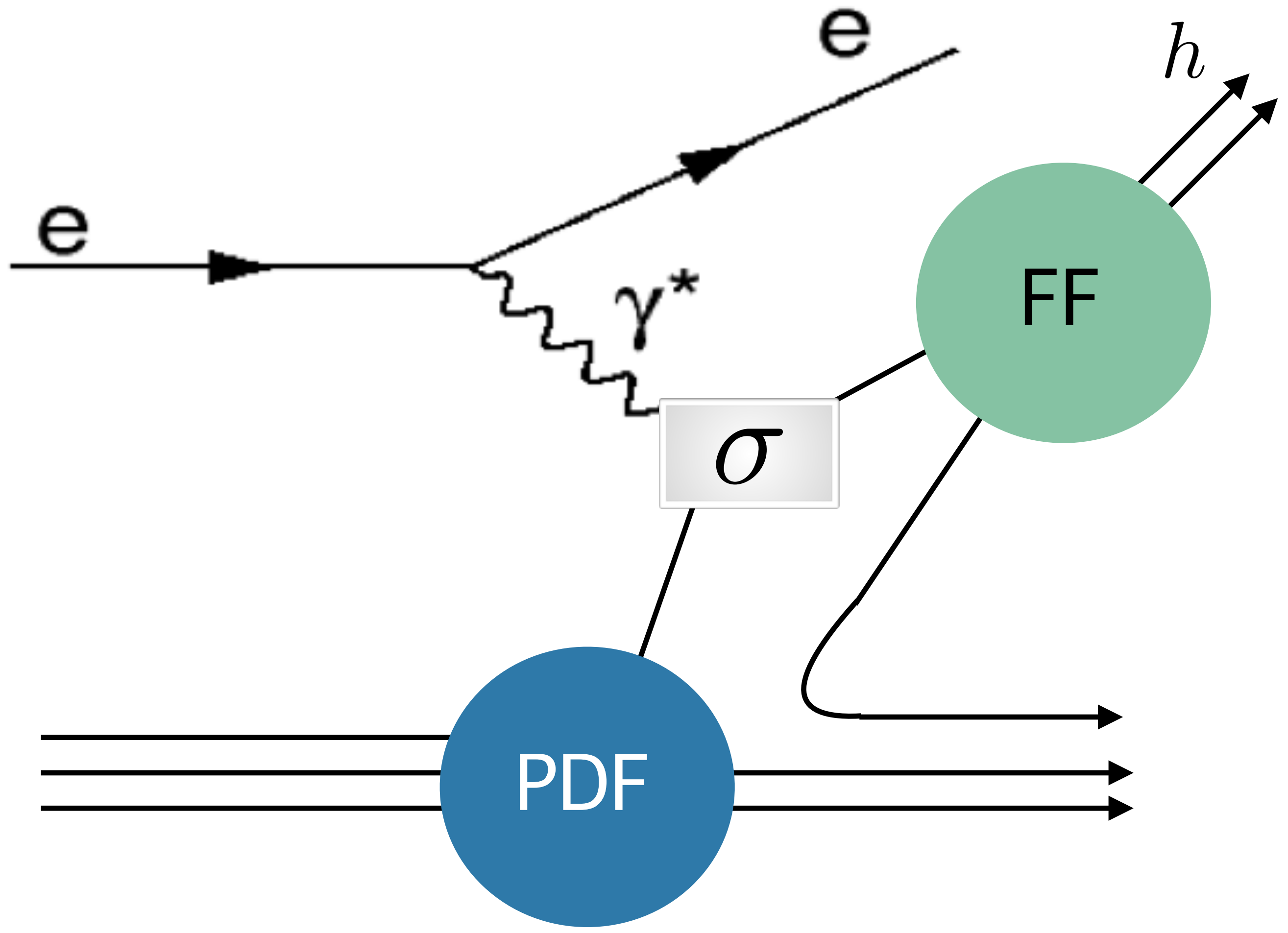


Detect a hadron!

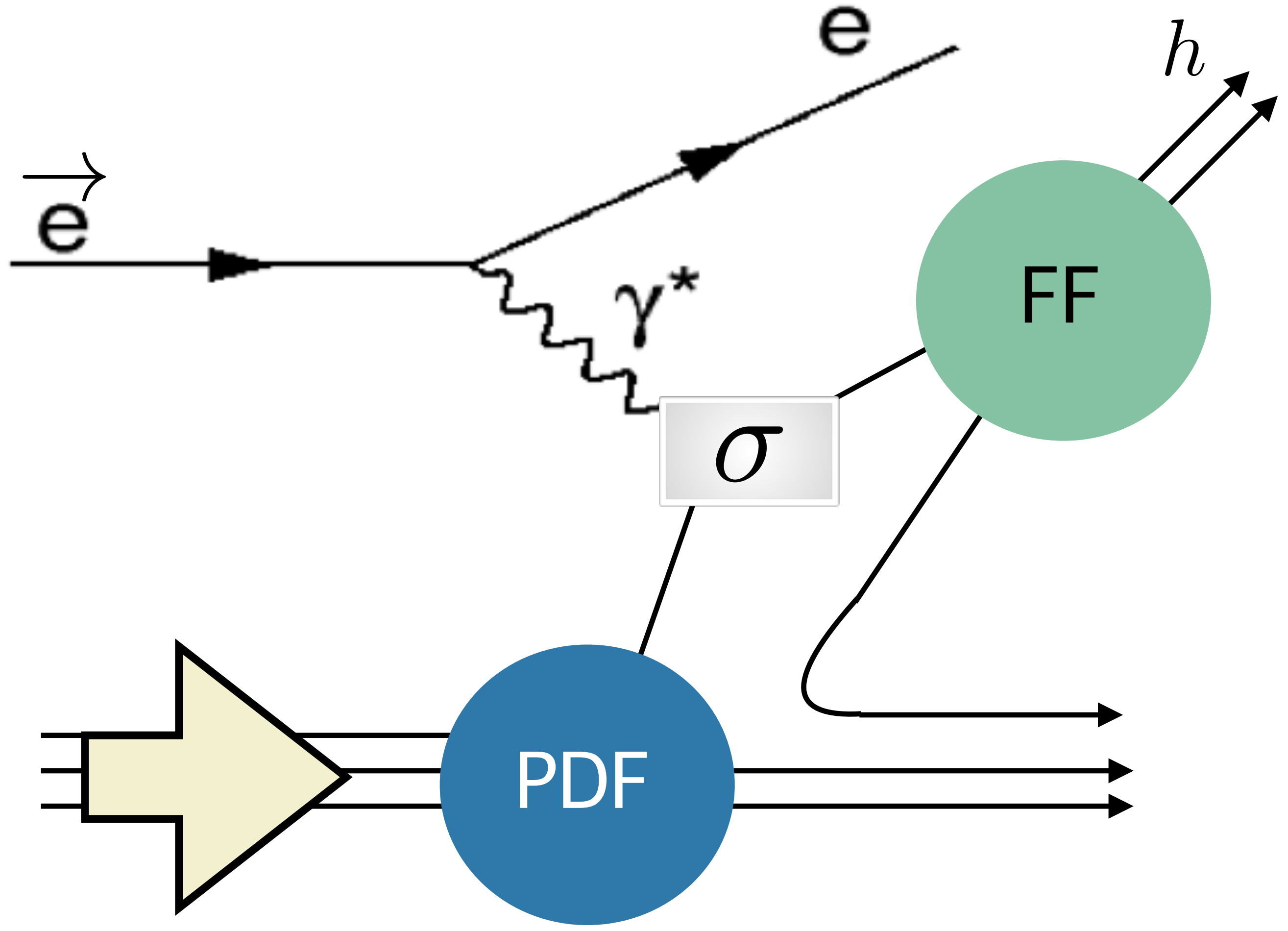
parton distribution function $PDF(x_B, Q^2)$

Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

Sea-quark helicity distributions



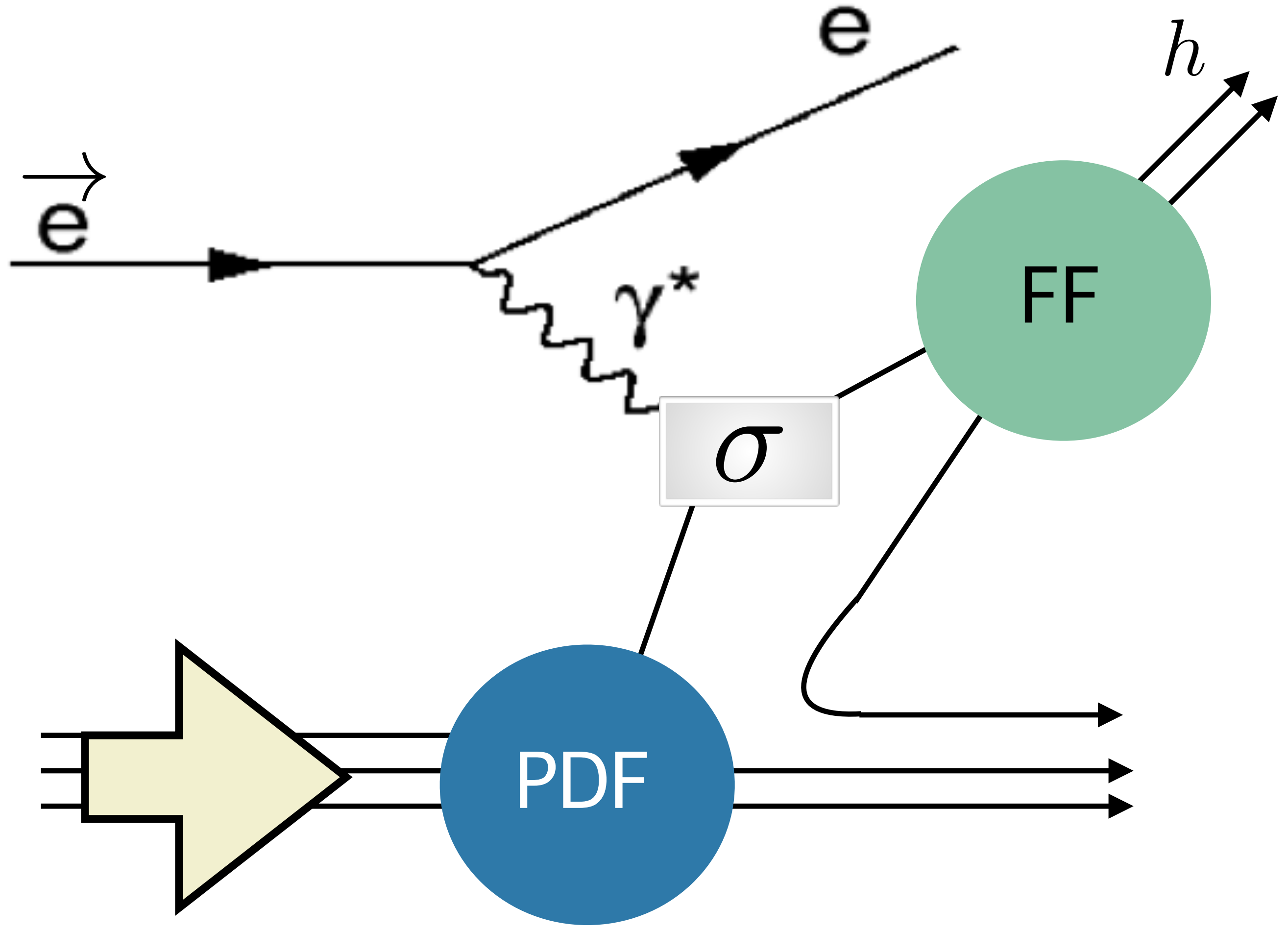
Sea-quark helicity distributions



$$A_{\parallel}^{h}(x_B, Q^2, z) = \frac{1}{P_e P_p} \frac{\frac{\overrightarrow{\Rightarrow}{N}^h}{\overrightarrow{\Rightarrow}{L}} - \frac{\overleftarrow{\Rightarrow}{N}^h}{\overleftarrow{\Rightarrow}{L}}}{\frac{\overrightarrow{\Rightarrow}{N}^h}{\overrightarrow{\Rightarrow}{L}} + \frac{\overleftarrow{\Rightarrow}{N}^h}{\overleftarrow{\Rightarrow}{L}}}(x_B, Q^2, z)$$

$$= D(y) A_1^h(x_B, Q^2, z)$$

Sea-quark helicity distributions



$$A^h_{\parallel}(x_B, Q^2, z) = \frac{1}{P_e\,P_p}\,\frac{\frac{\overset{\rightrightarrows}{N^h}}{\overset{\rightrightarrows}{L}} - \frac{\overset{\leftrightarrows}{N^h}}{\overset{\leftrightarrows}{L}}}{\frac{\overset{\rightrightarrows}{N^h}}{\overset{\rightrightarrows}{L}} + \frac{\overset{\leftrightarrows}{N^h}}{\overset{\leftrightarrows}{L}}}(x_B, Q^2, z)$$

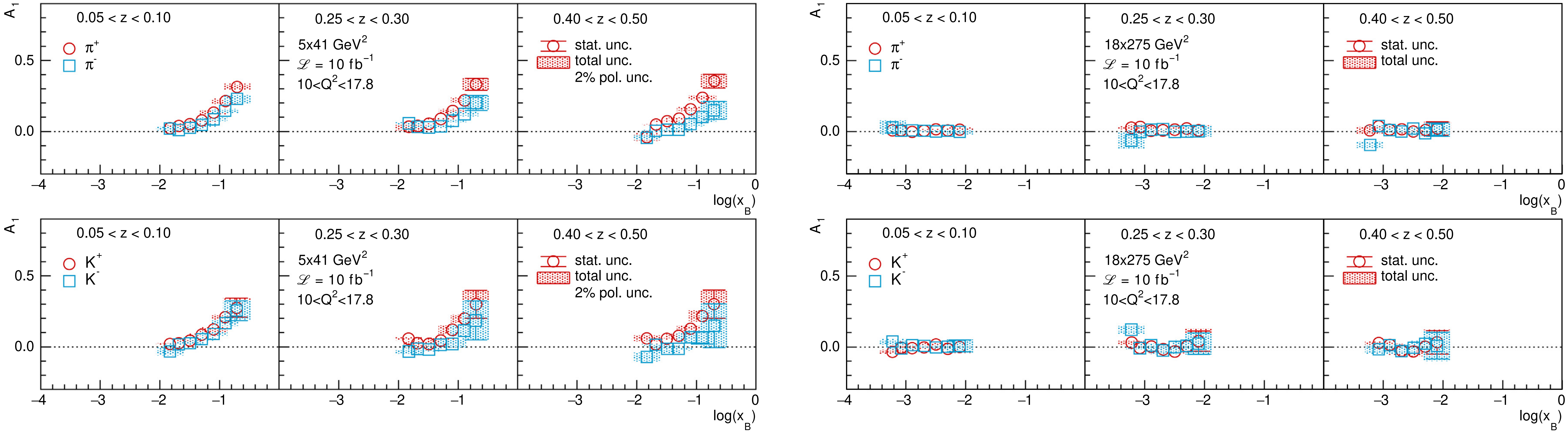
$$= D(y)\,A^h_1(x_B, Q^2, z)$$

$$\propto \sum_q e_q^2 \left[\Delta q \otimes w_1\, D_1^{q\to h}\right]$$

Semi-inclusive measurements
→ access to sea-quark spin

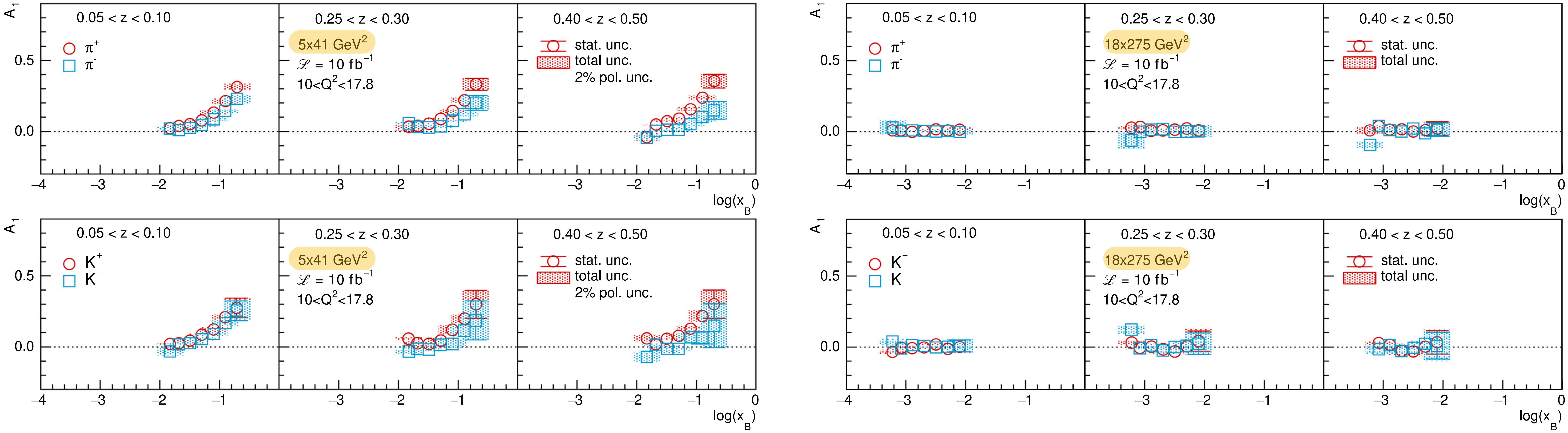
Sea-quark helicity distributions at the EIC

CVH et al., NIM A 1056 (2023) 168563



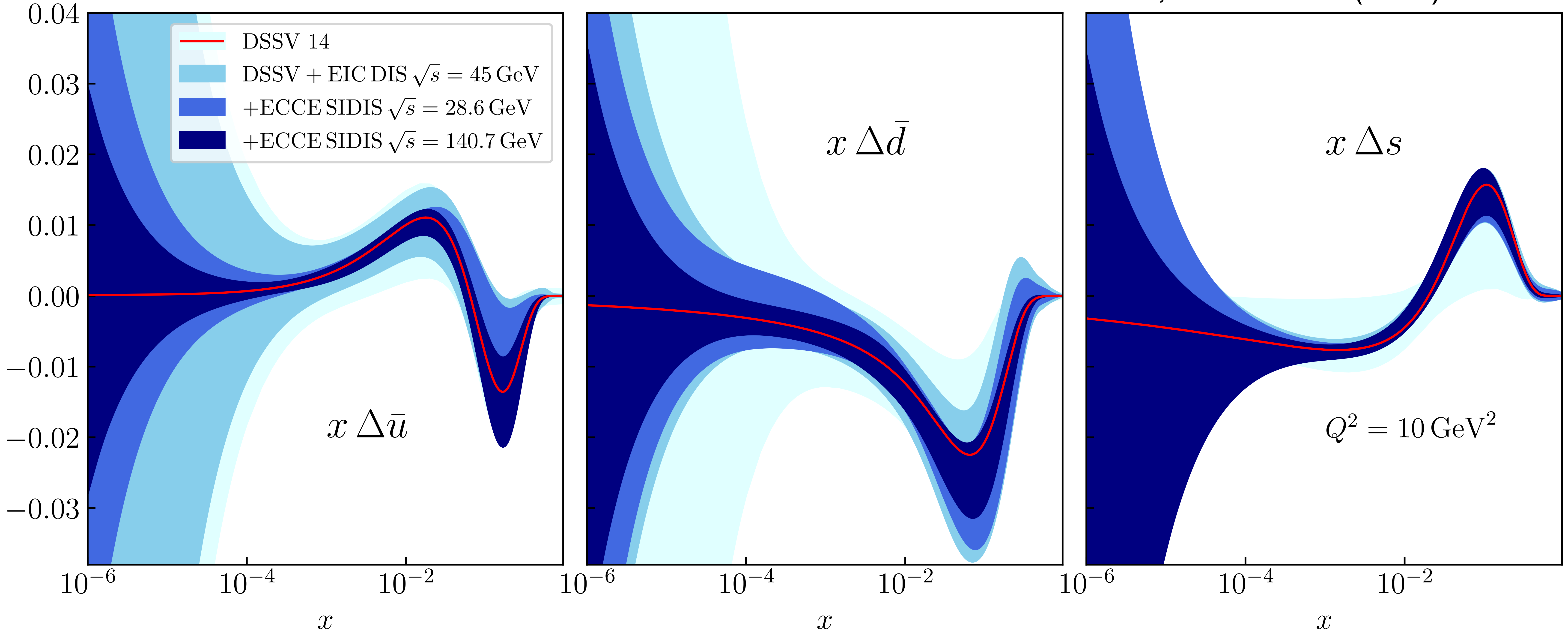
Sea-quark helicity distributions at the EIC

CVH et al., NIM A 1056 (2023) 168563



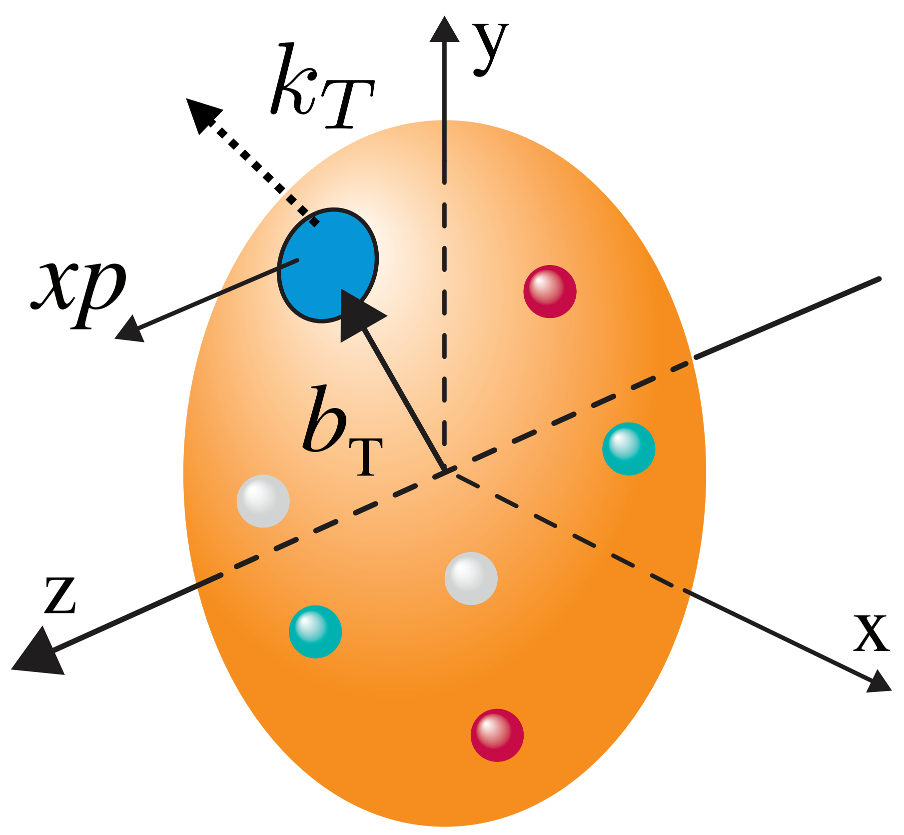
Sea-quark helicity distributions at the EIC

CVH et al., NIM A 1056 (2023) 168563



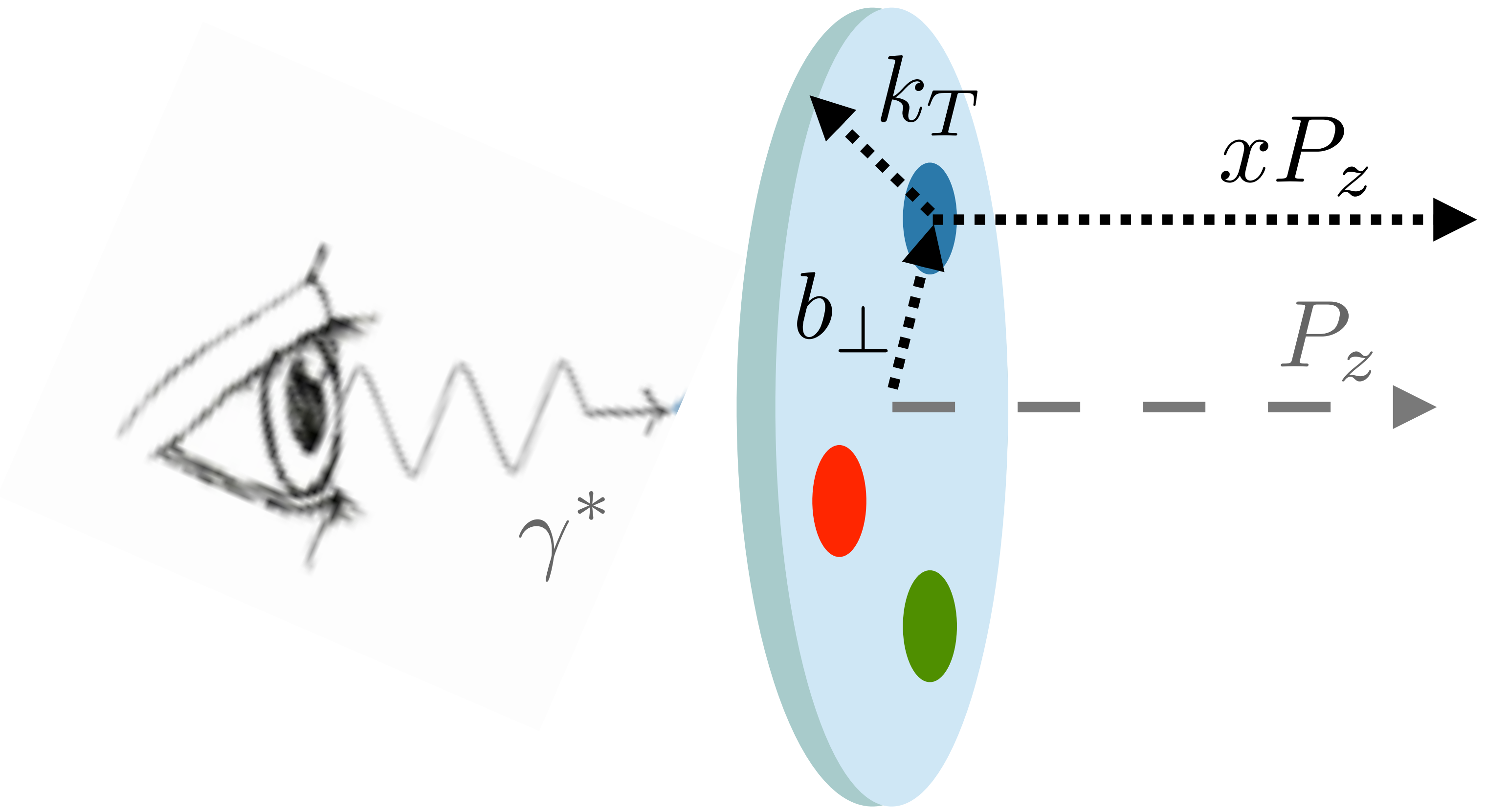
Why an EIC?

Nucleon multi-dimensional structure



The nucleon multi-dimensional structure

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

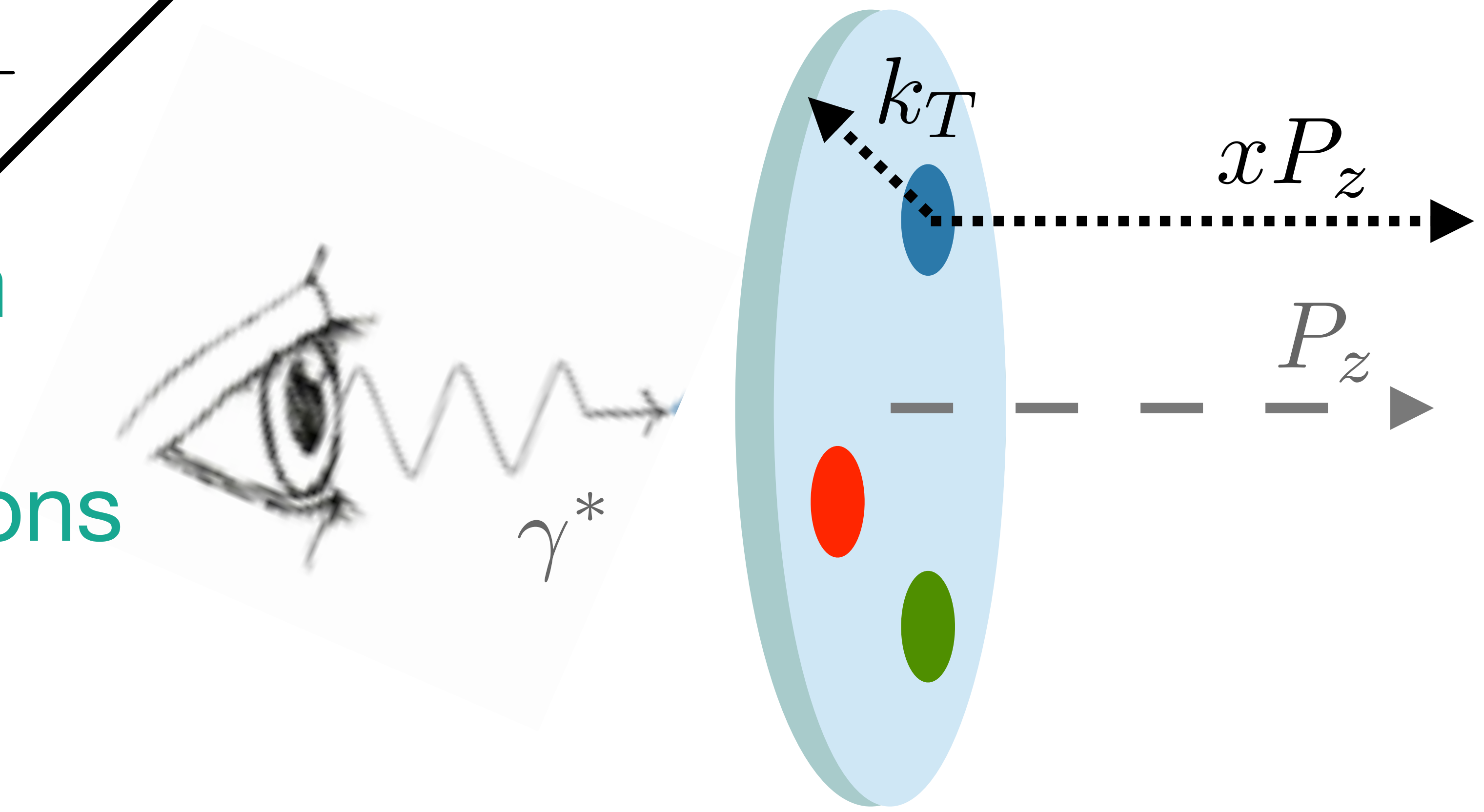


The nucleon multi-dimensional structure

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

transverse-momentum dependent (TMD) parton distribution functions (PDFs)

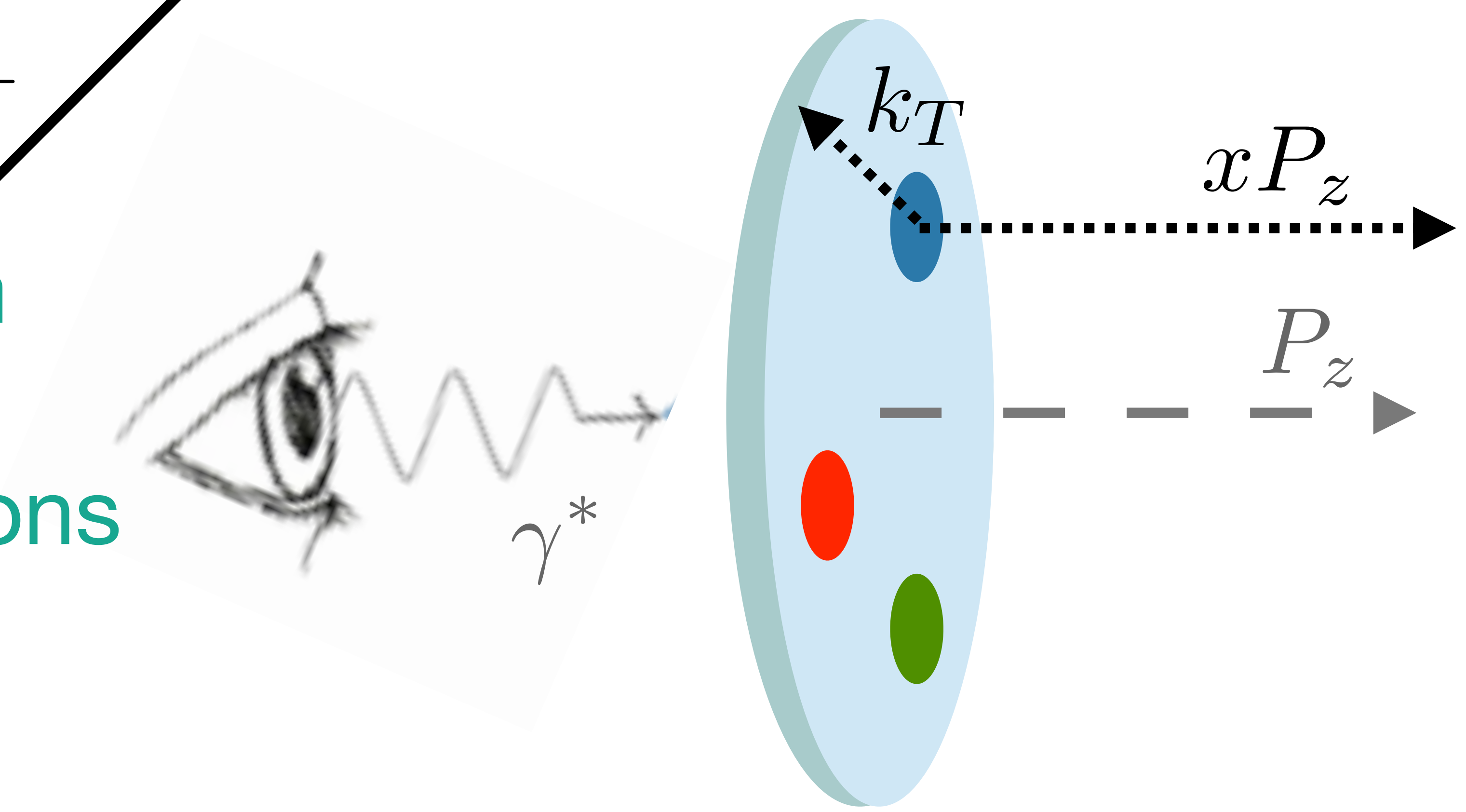


The nucleon multi-dimensional structure

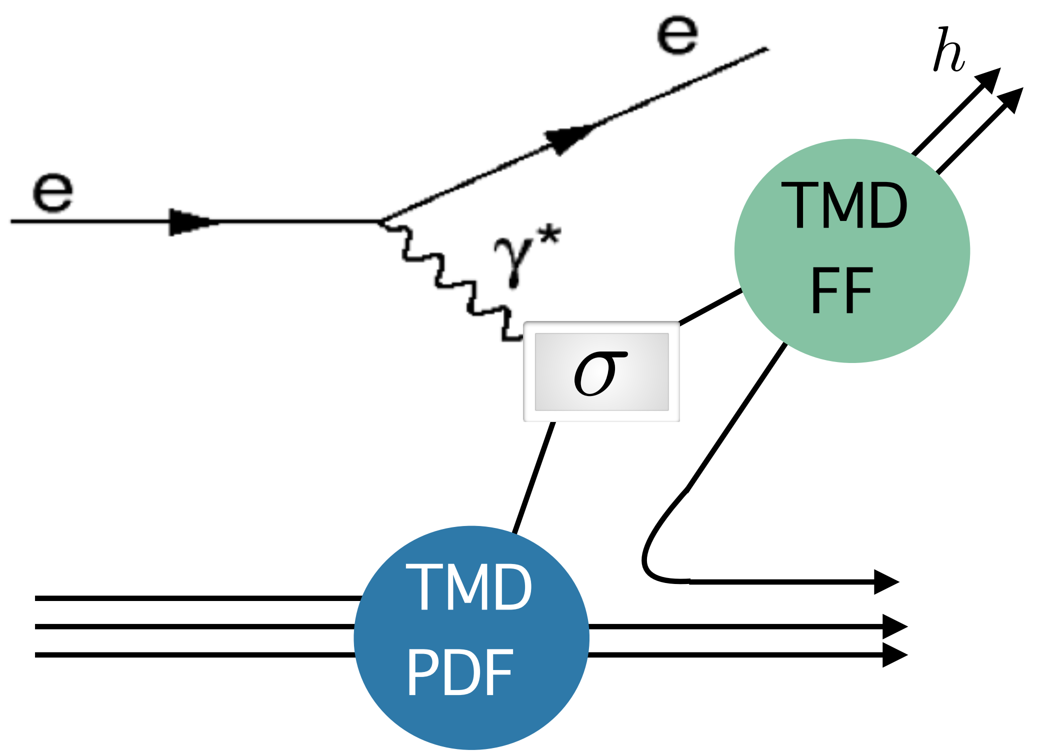
Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

transverse-momentum dependent (TMD) parton distribution functions (PDFs)



Semi-inclusive production

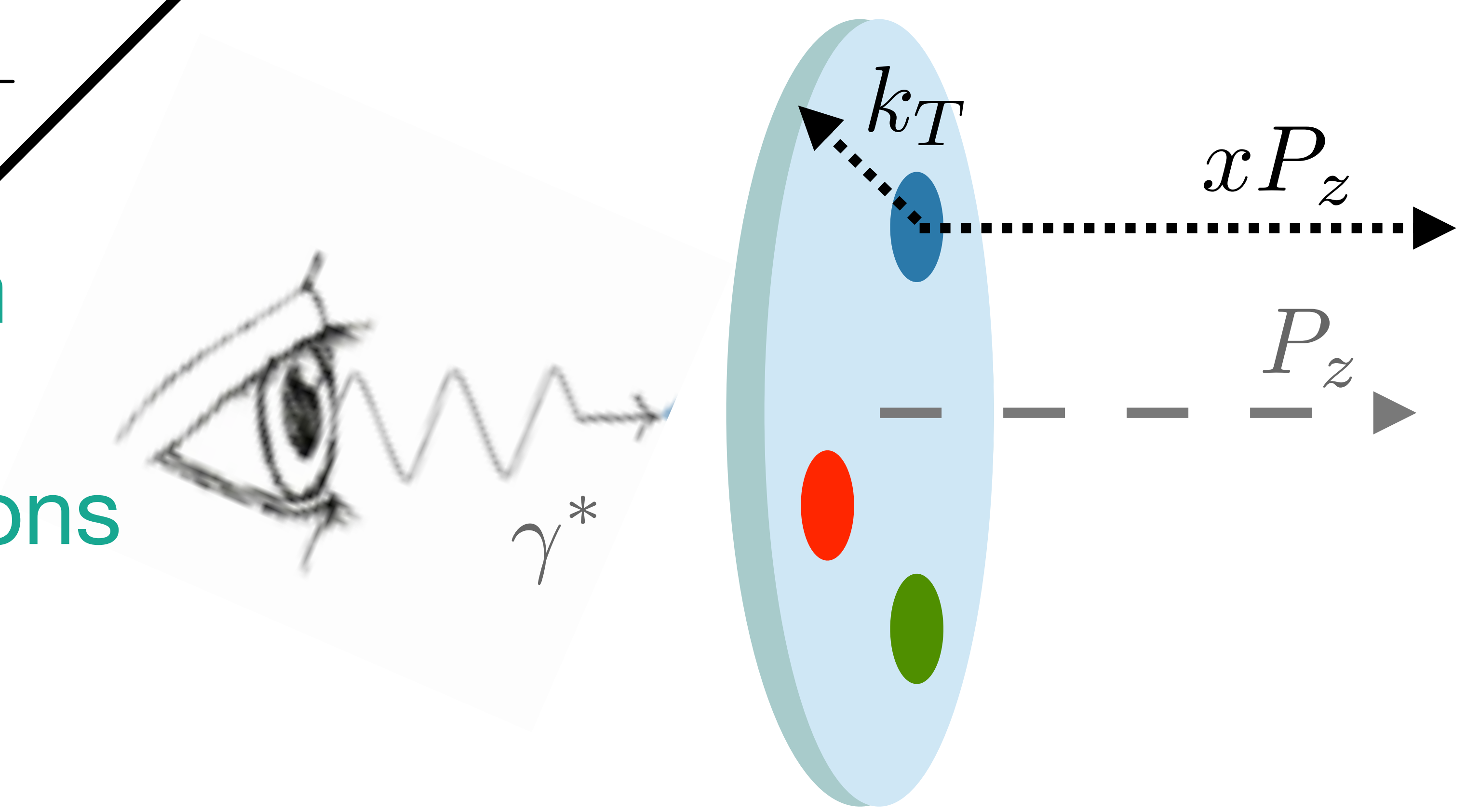


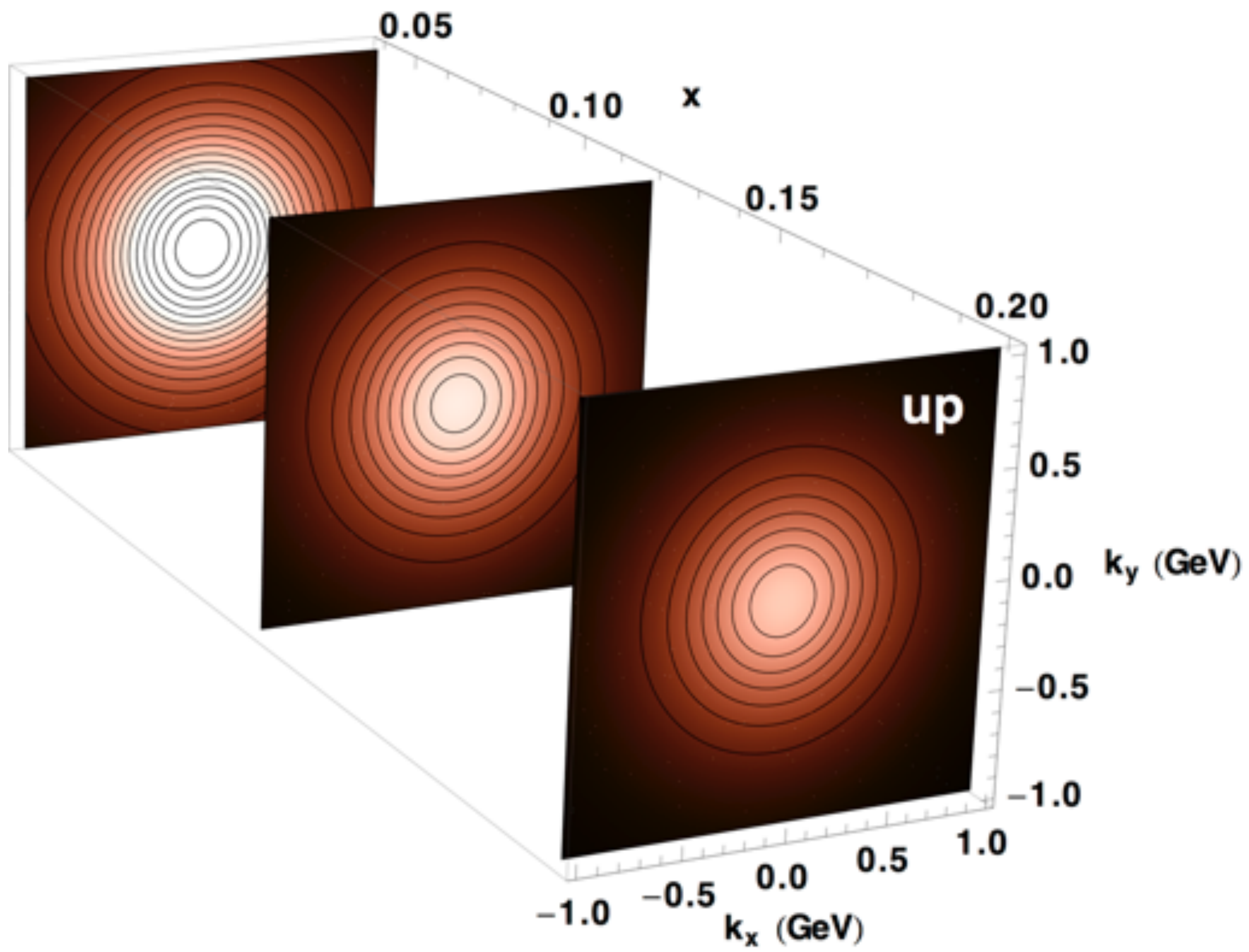
The nucleon multi-dimensional structure

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

transverse-momentum dependent (TMD) parton distribution functions (PDFs)



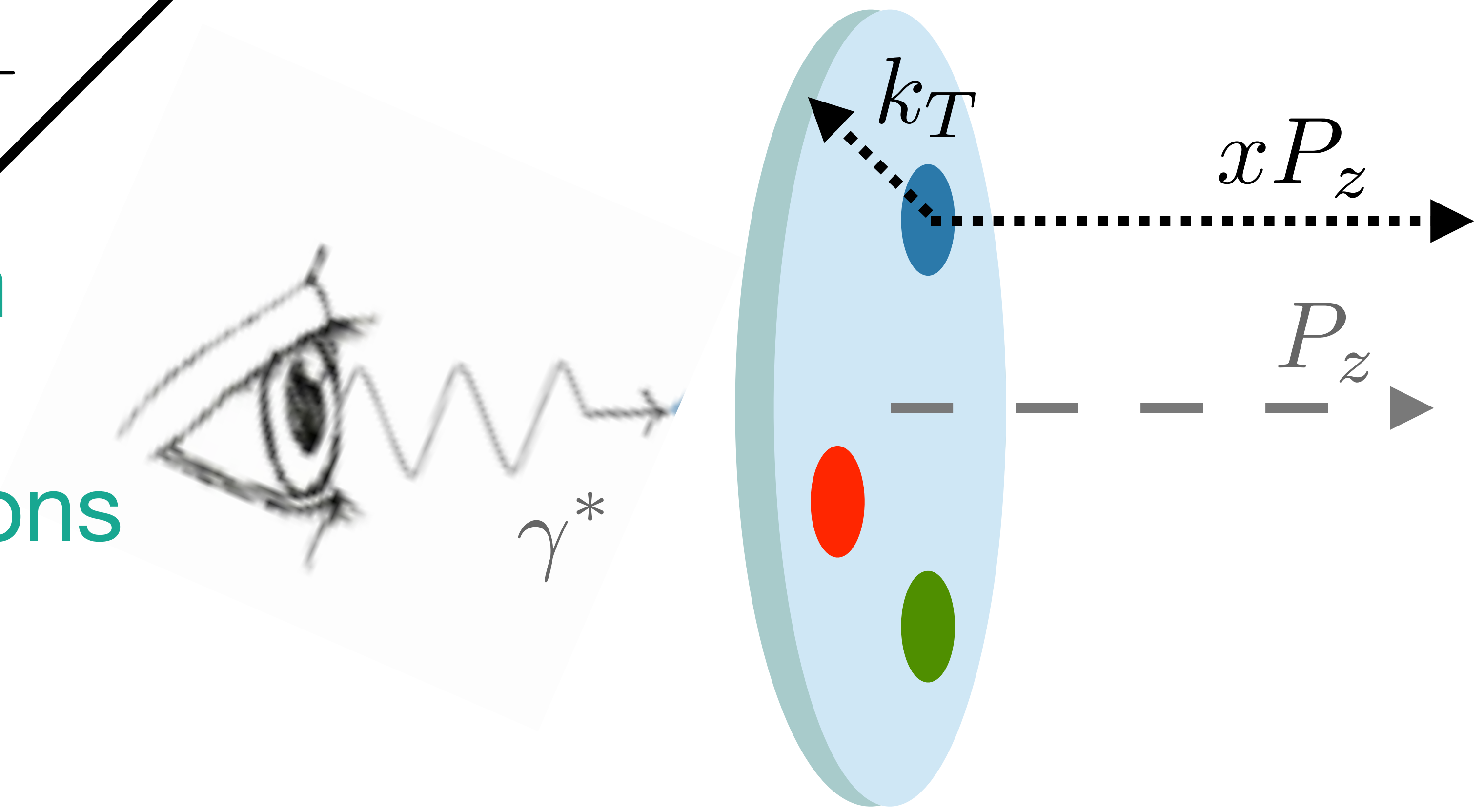


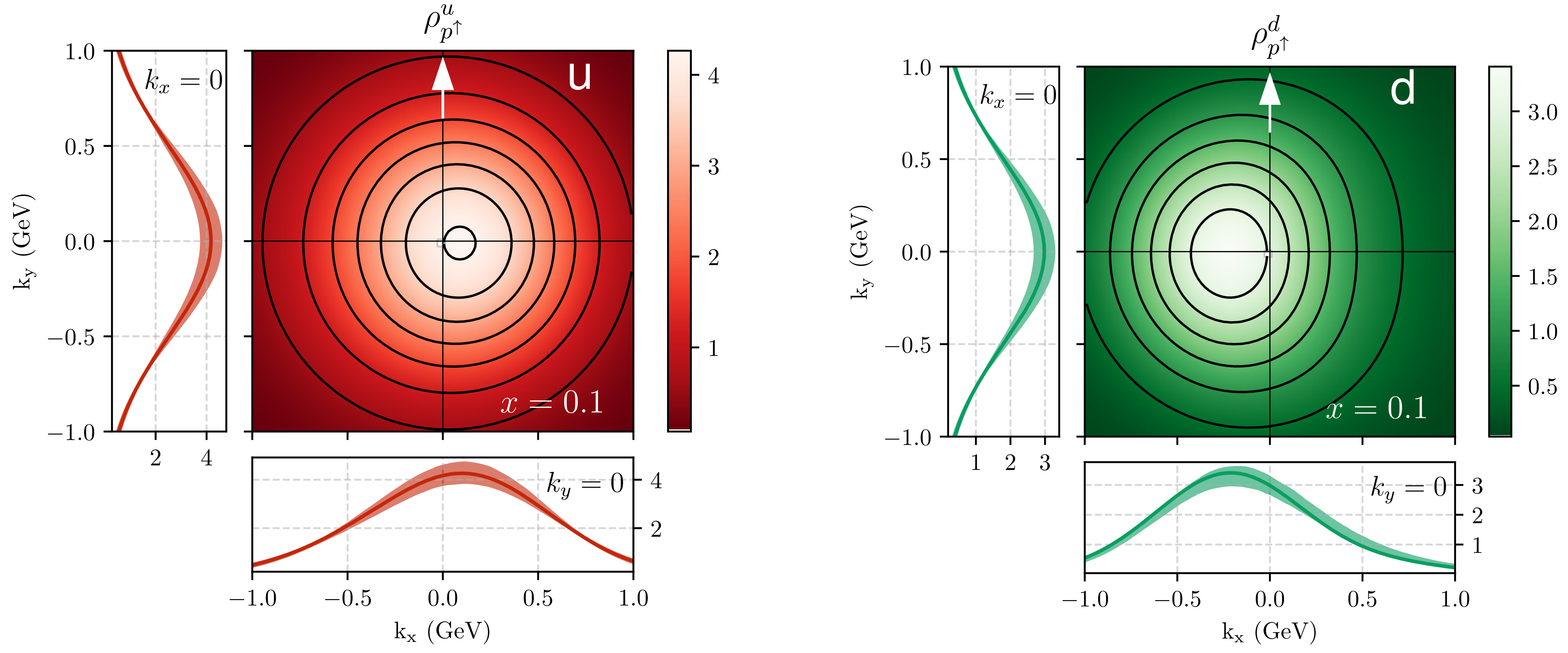
The nucleon multi-dimensional structure

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

transverse-momentum
dependent (TMD)
parton distribution functions
(PDFs)



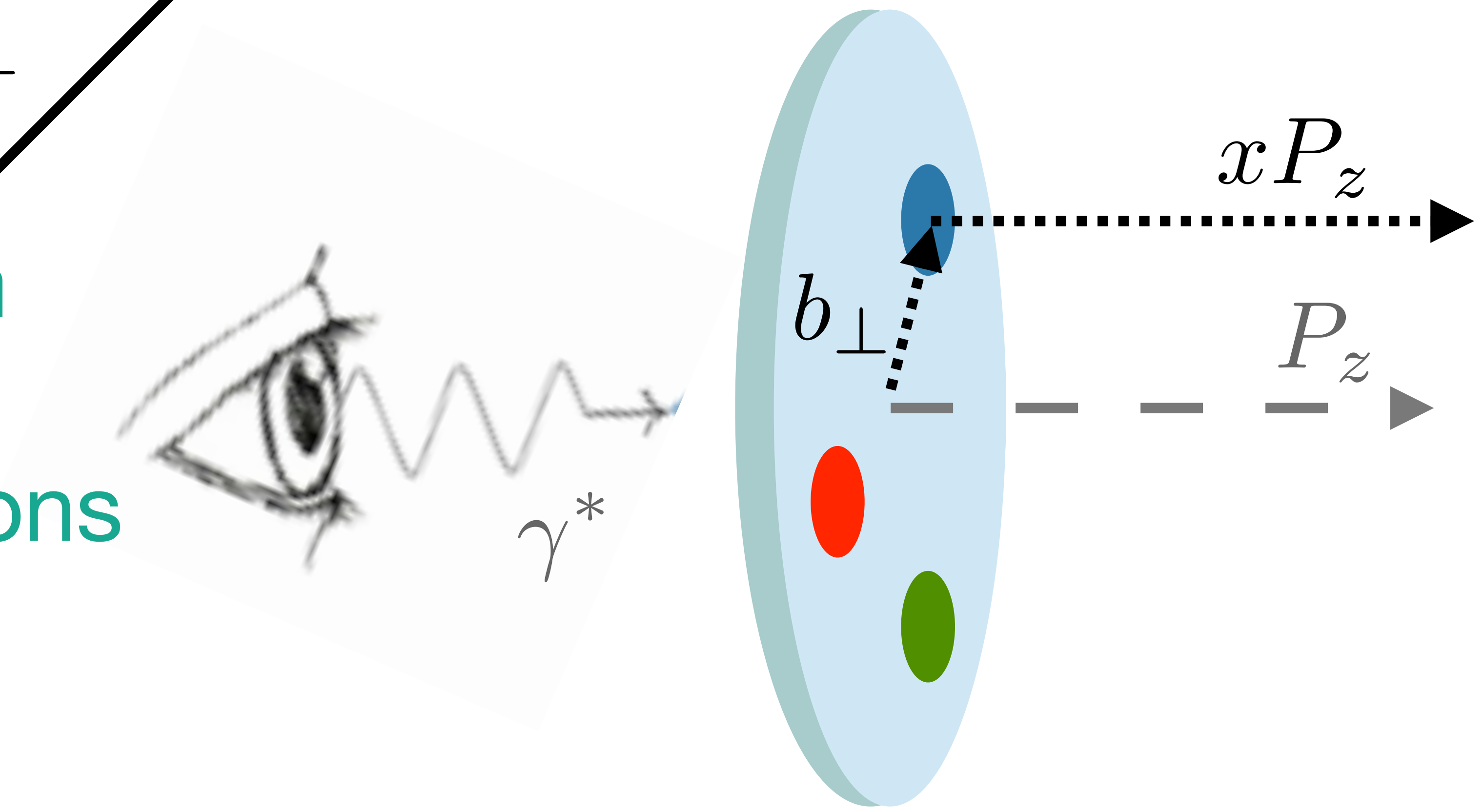


The nucleon multi-dimensional structure

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

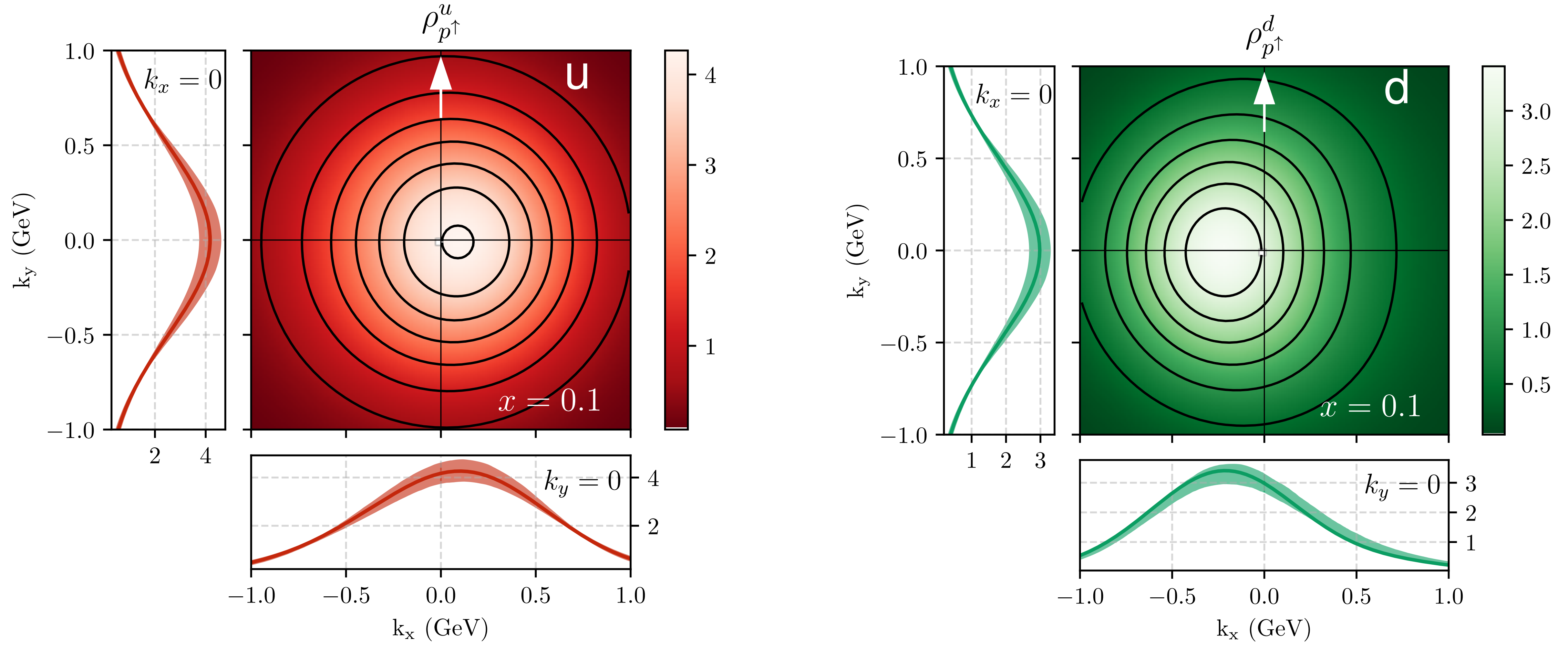
$\int d^2\vec{b}_\perp$

transverse-momentum
dependent (TMD)
parton distribution functions
(PDFs)



$\int d^2\vec{k}_T$

impact-parameter
dependent PDFs

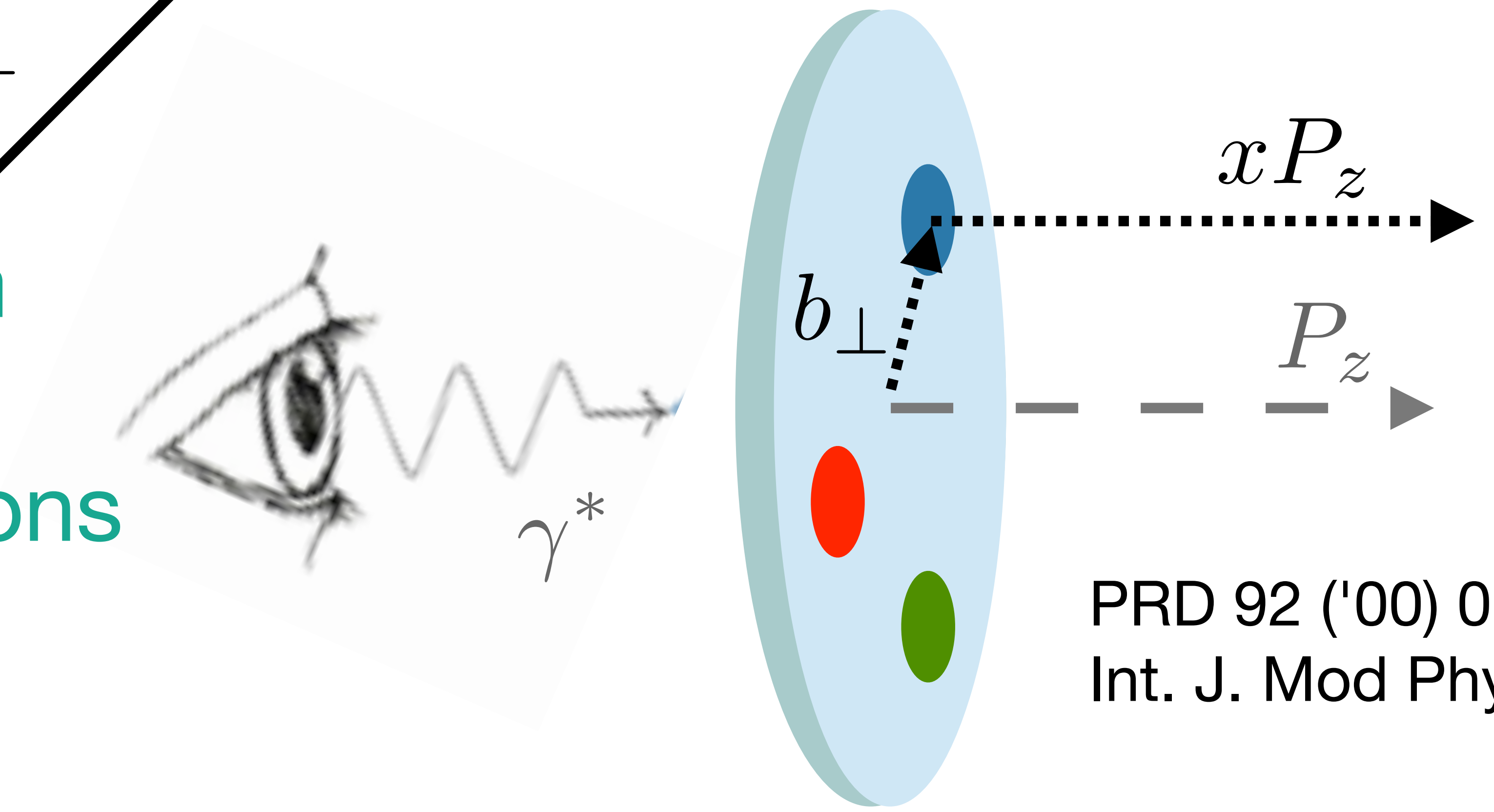


The nucleon multi-dimensional structure

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

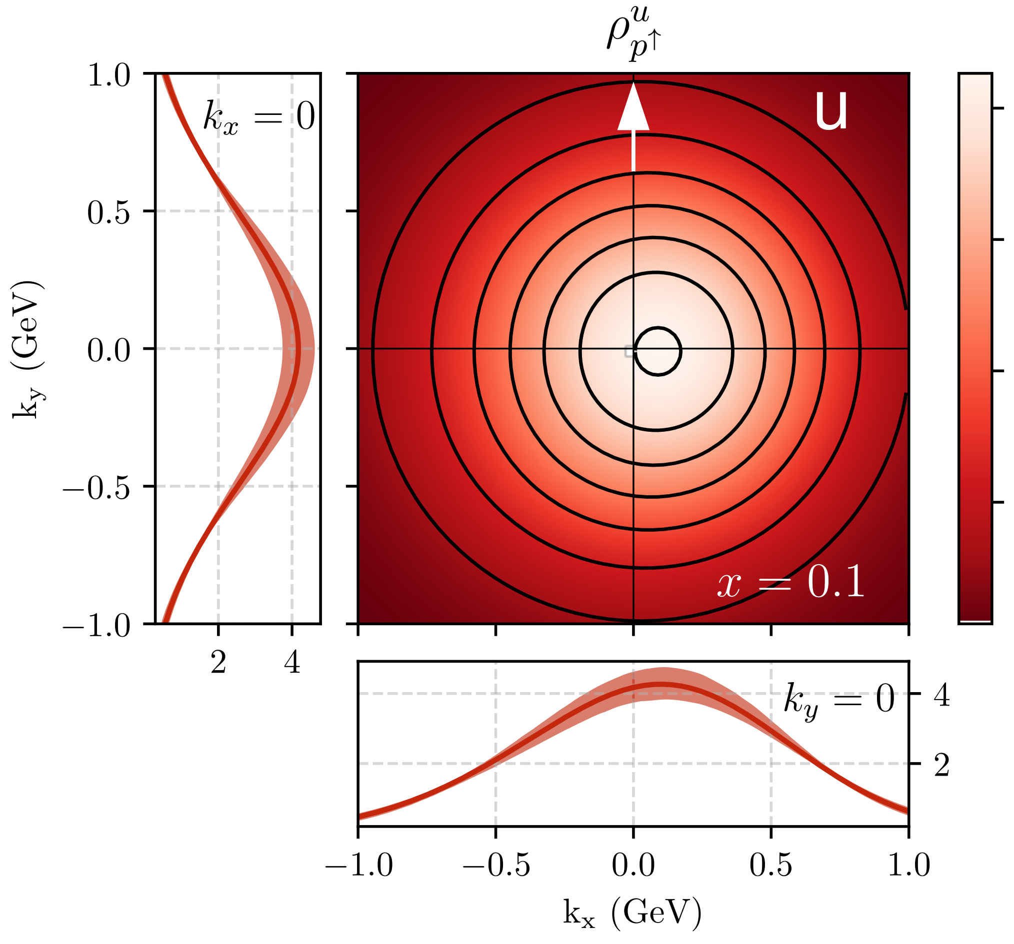
$\int d^2\vec{b}_\perp$ → transverse-momentum dependent (TMD) parton distribution functions (PDFs)

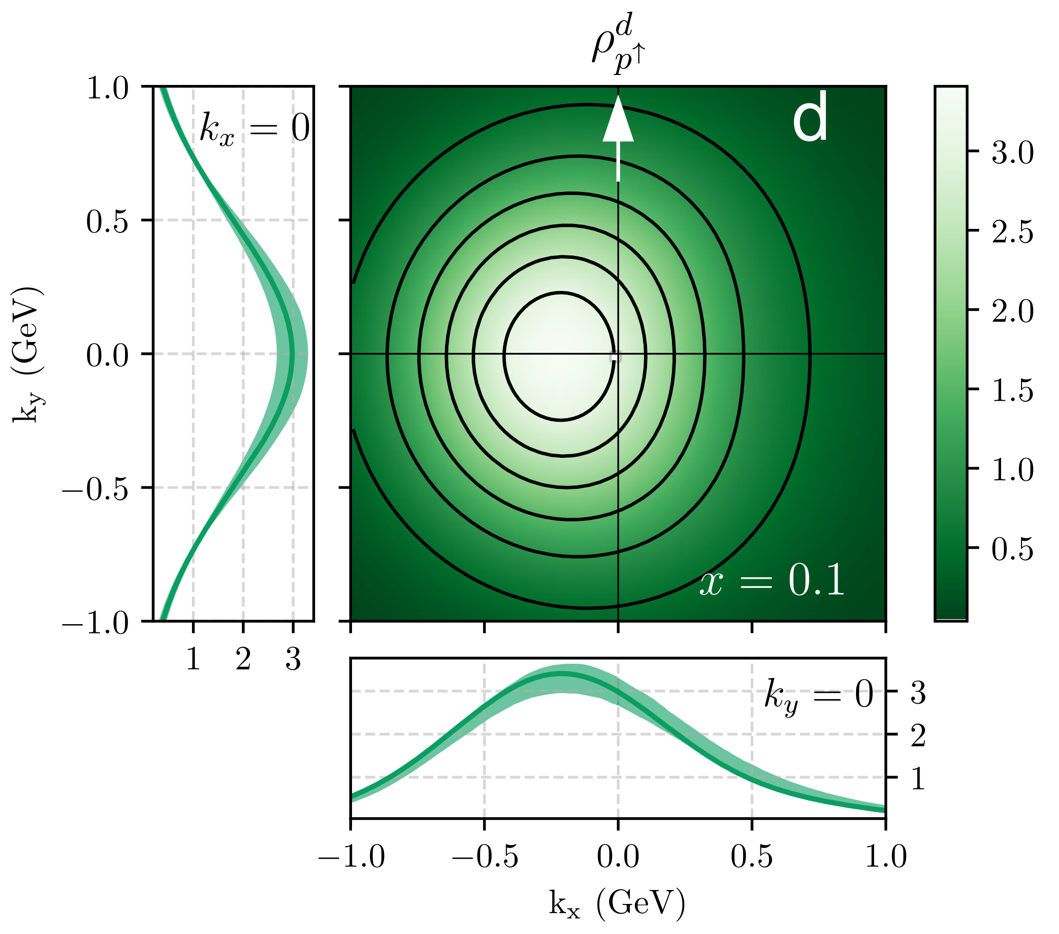
$\int d^2\vec{k}_T$ → impact-parameter dependent PDFs



PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

impact-parameter dependent PDFs → Fourier transform → generalised parton distributions (GPDs)



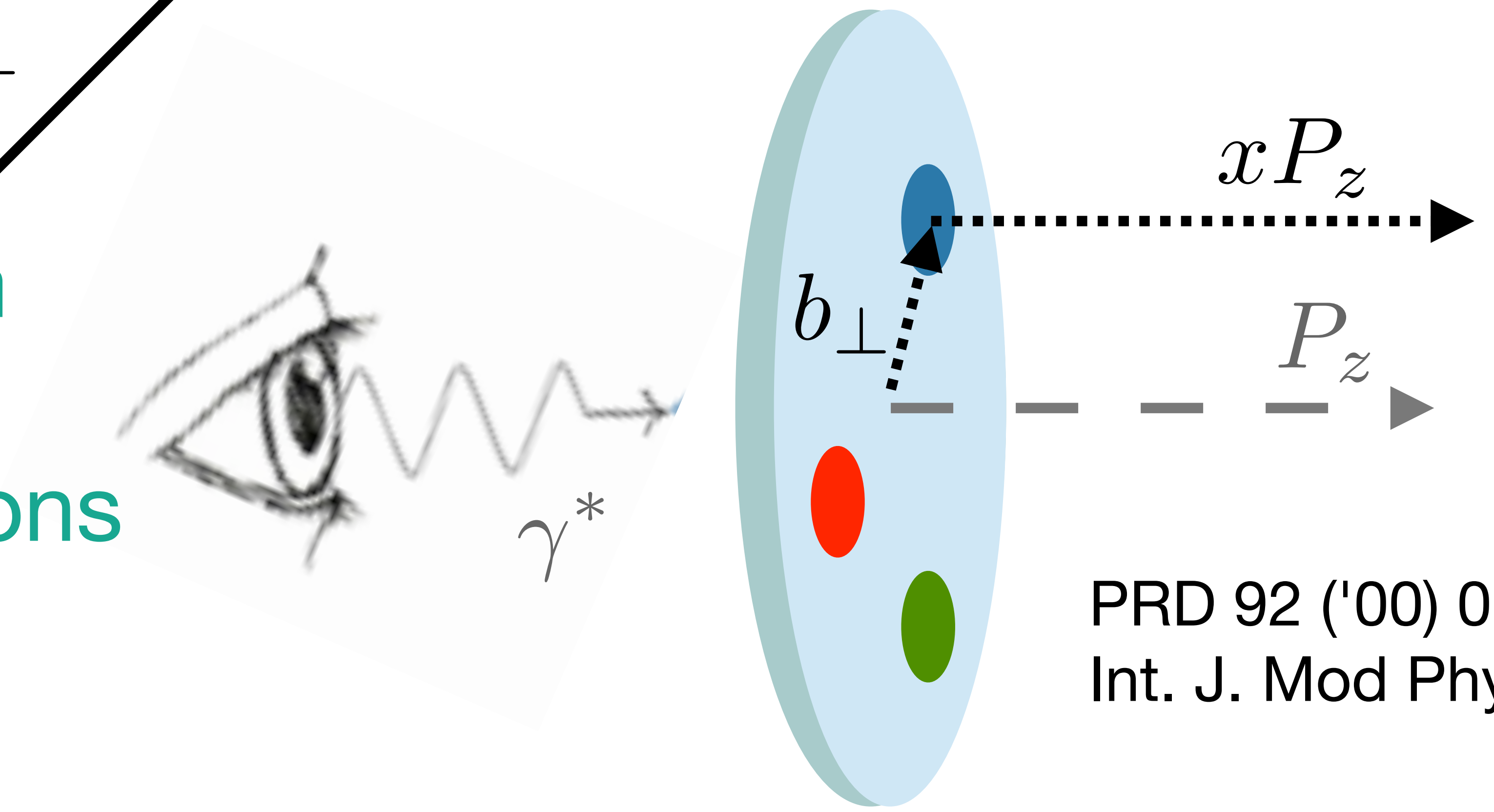


The nucleon multi-dimensional structure

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

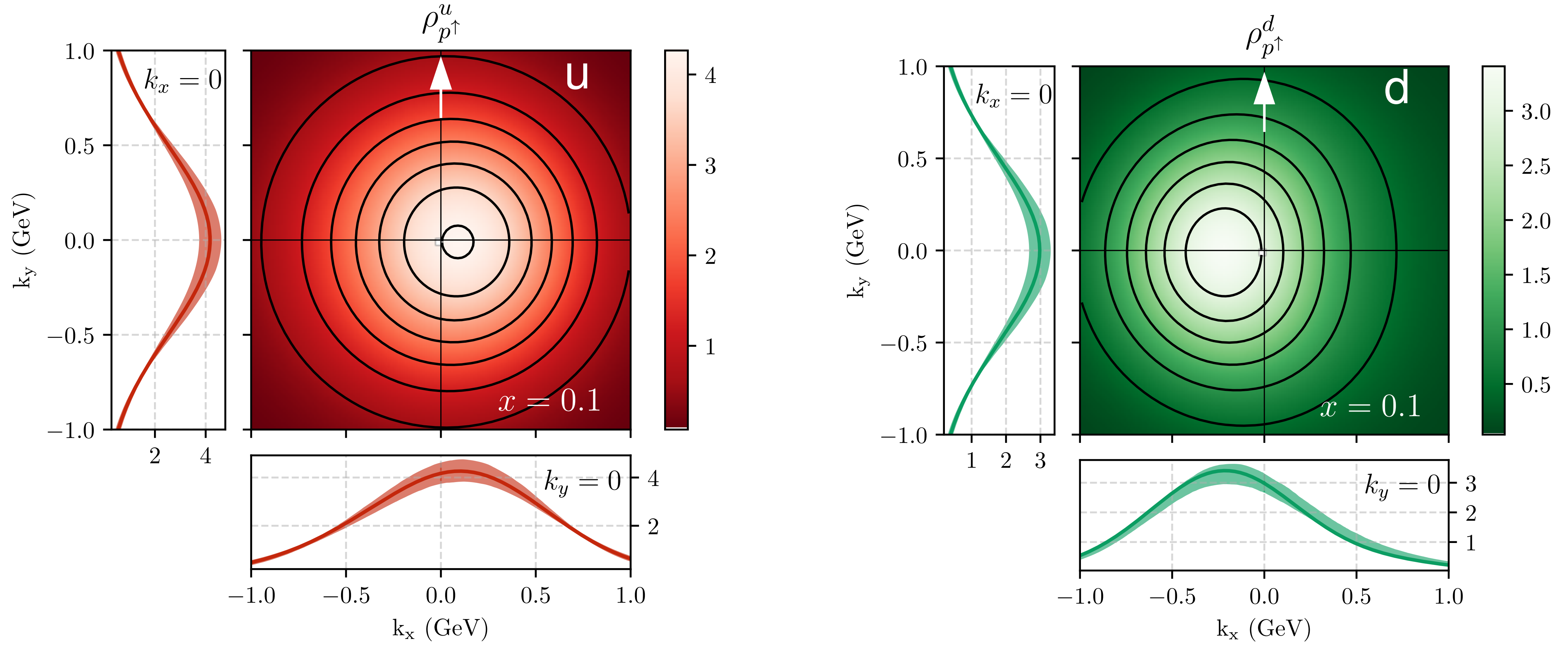
$\int d^2\vec{b}_\perp$ → transverse-momentum dependent (TMD) parton distribution functions (PDFs)

$\int d^2\vec{k}_T$ → impact-parameter dependent PDFs

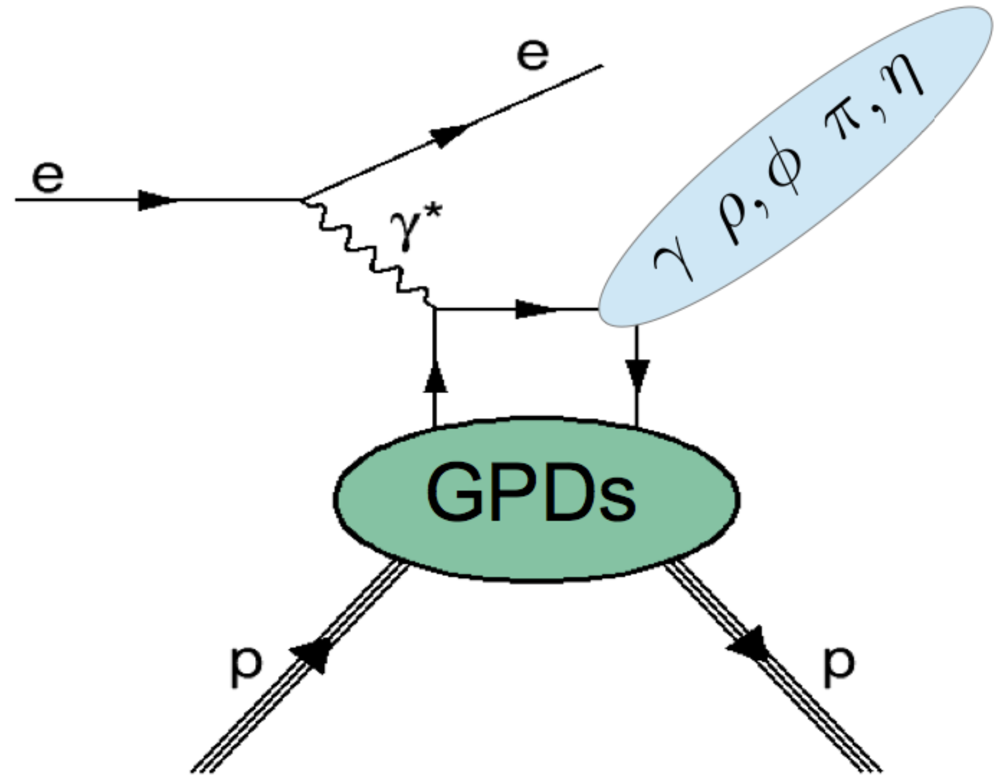


PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

Fourier transform → generalised parton distributions (GPDs)



Exclusive production

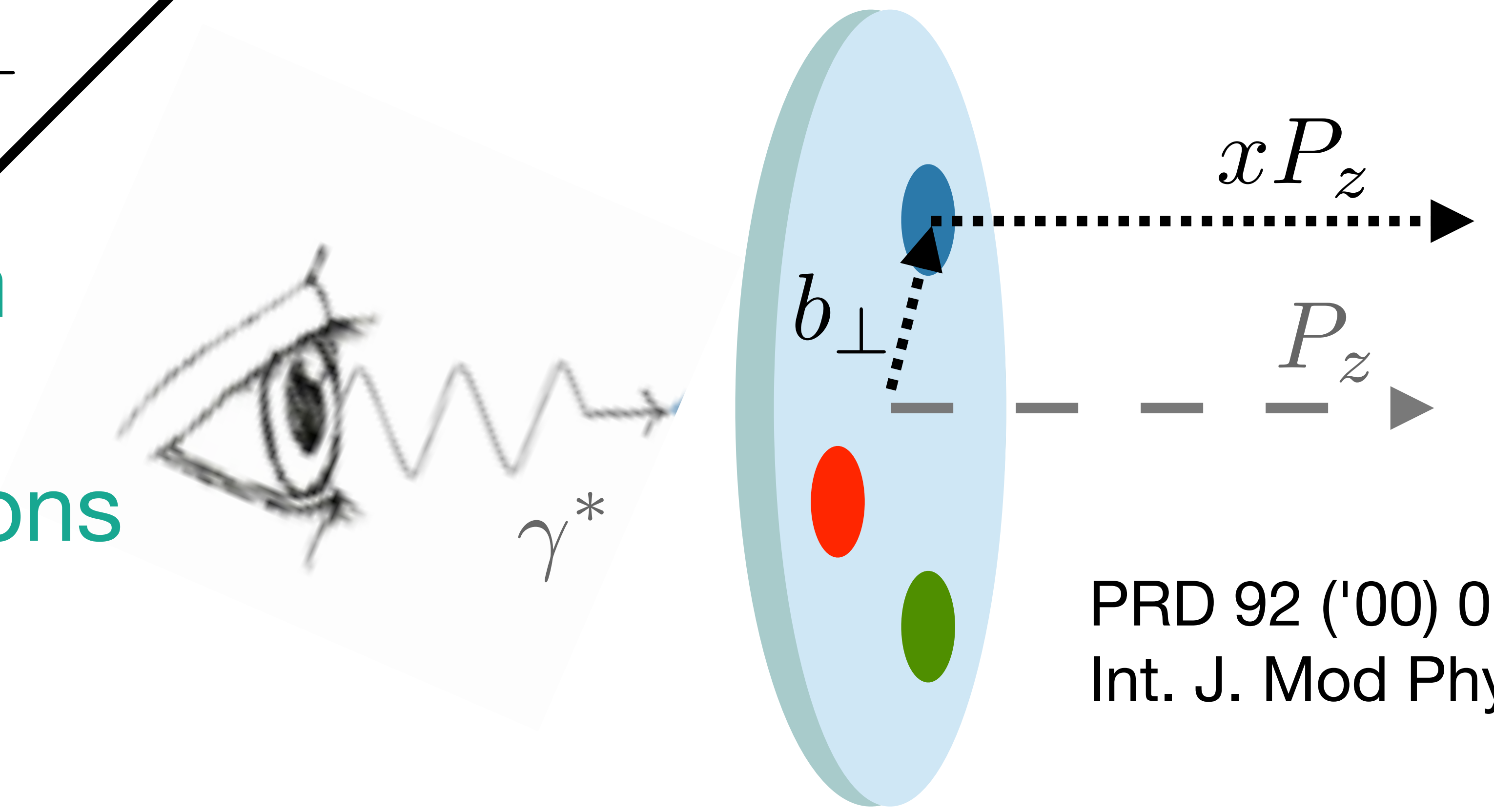


The nucleon multi-dimensional structure

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

transverse-momentum dependent (TMD) parton distribution functions (PDFs)



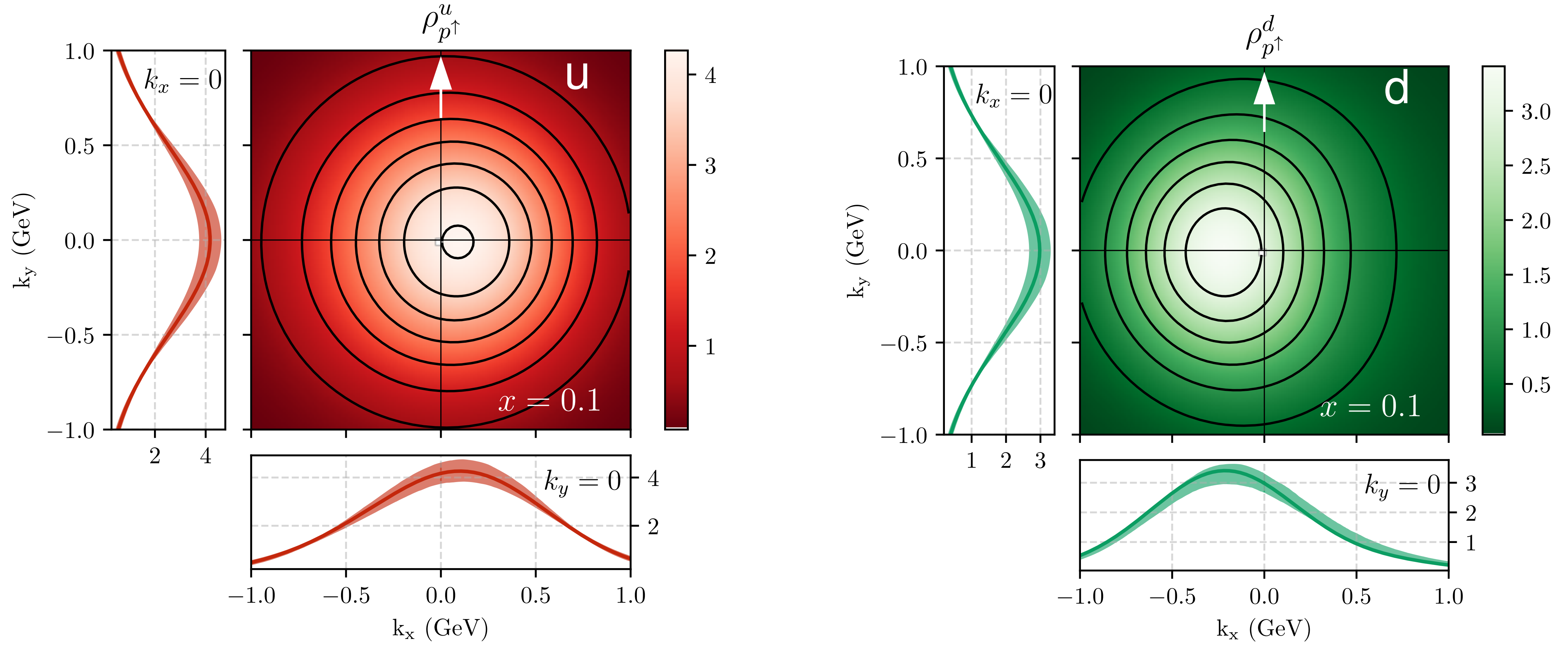
$\int d^2\vec{k}_T$

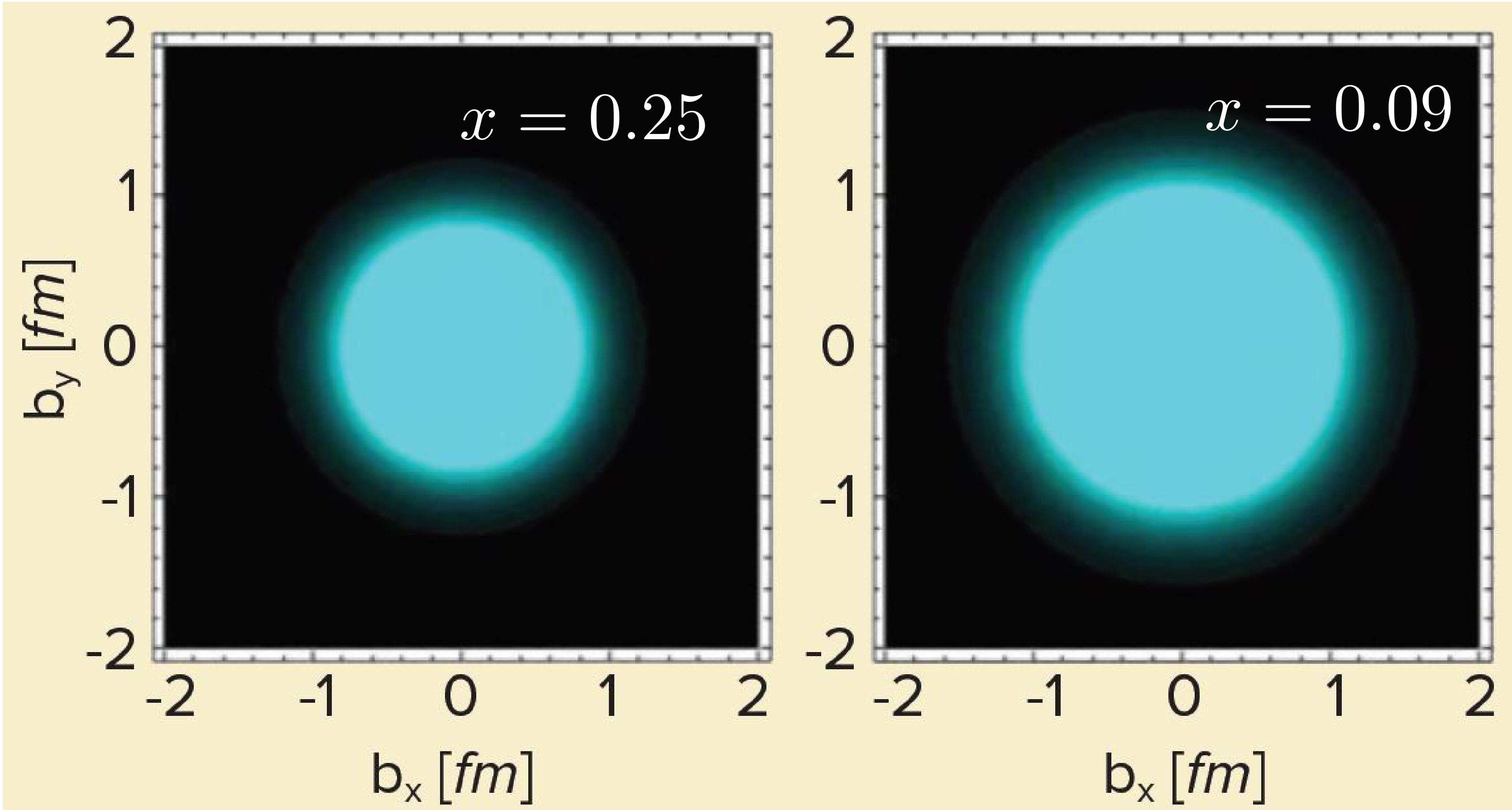
impact-parameter dependent PDFs

PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

Fourier transform

generalised parton distributions (GPDs)



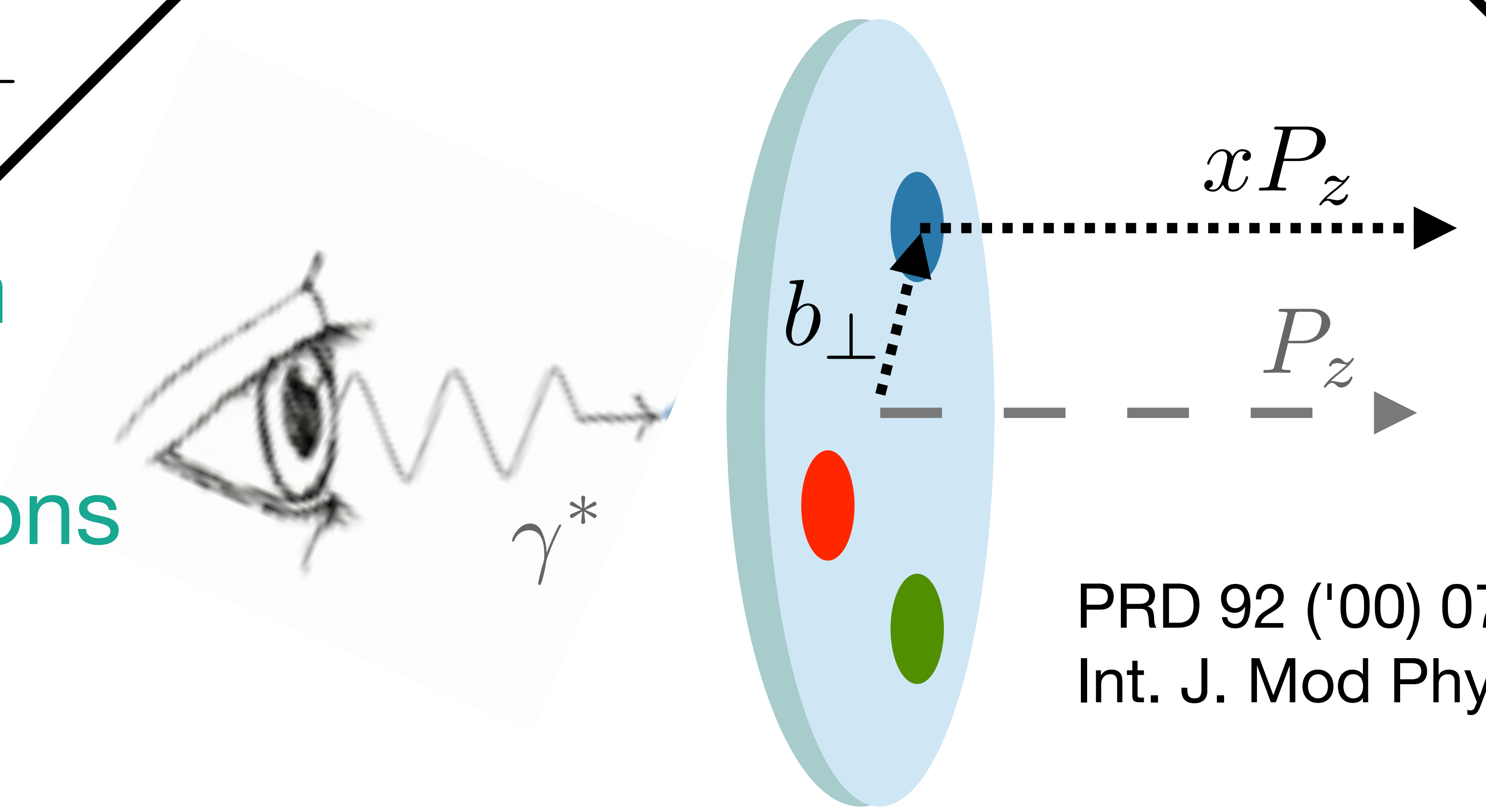


The nucleon multi-dimensional structure

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$ → transverse-momentum dependent (TMD) parton distribution functions (PDFs)

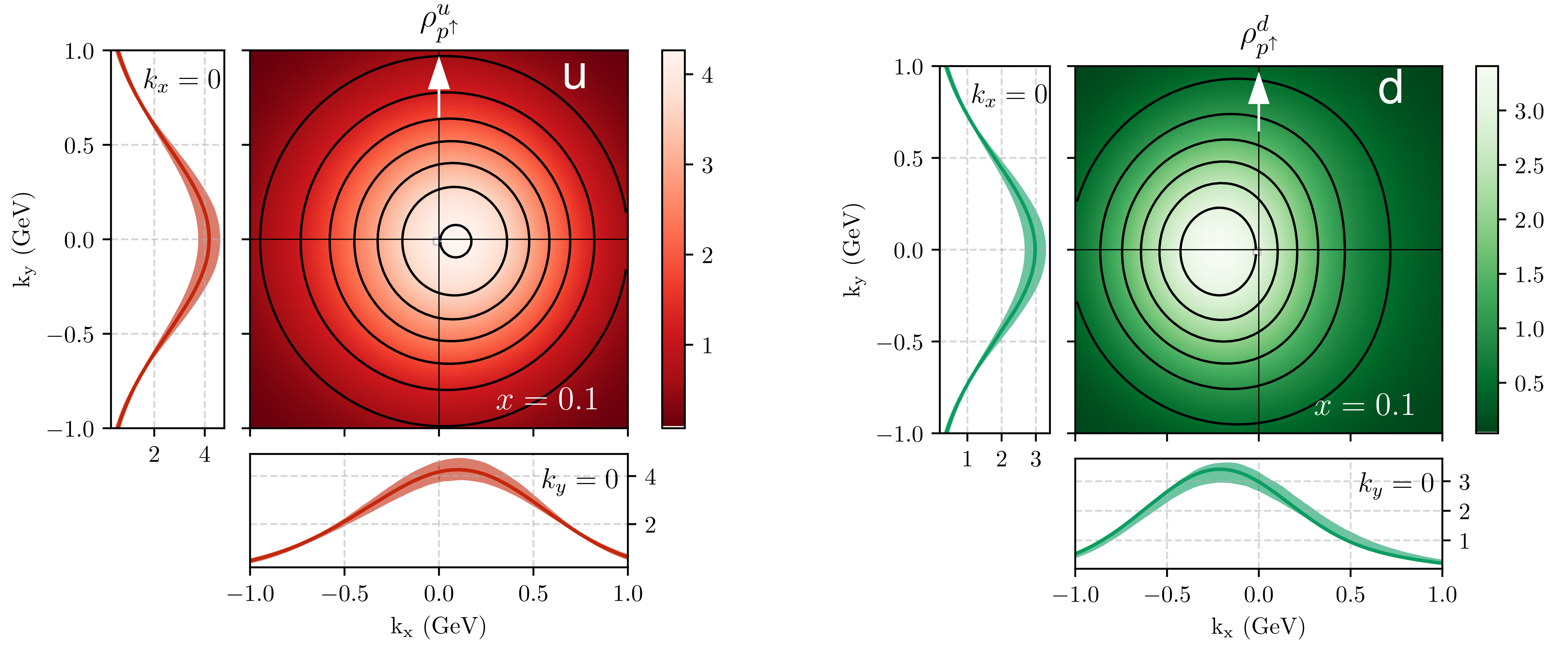
$\int d^2\vec{k}_T$ → impact-parameter dependent PDFs

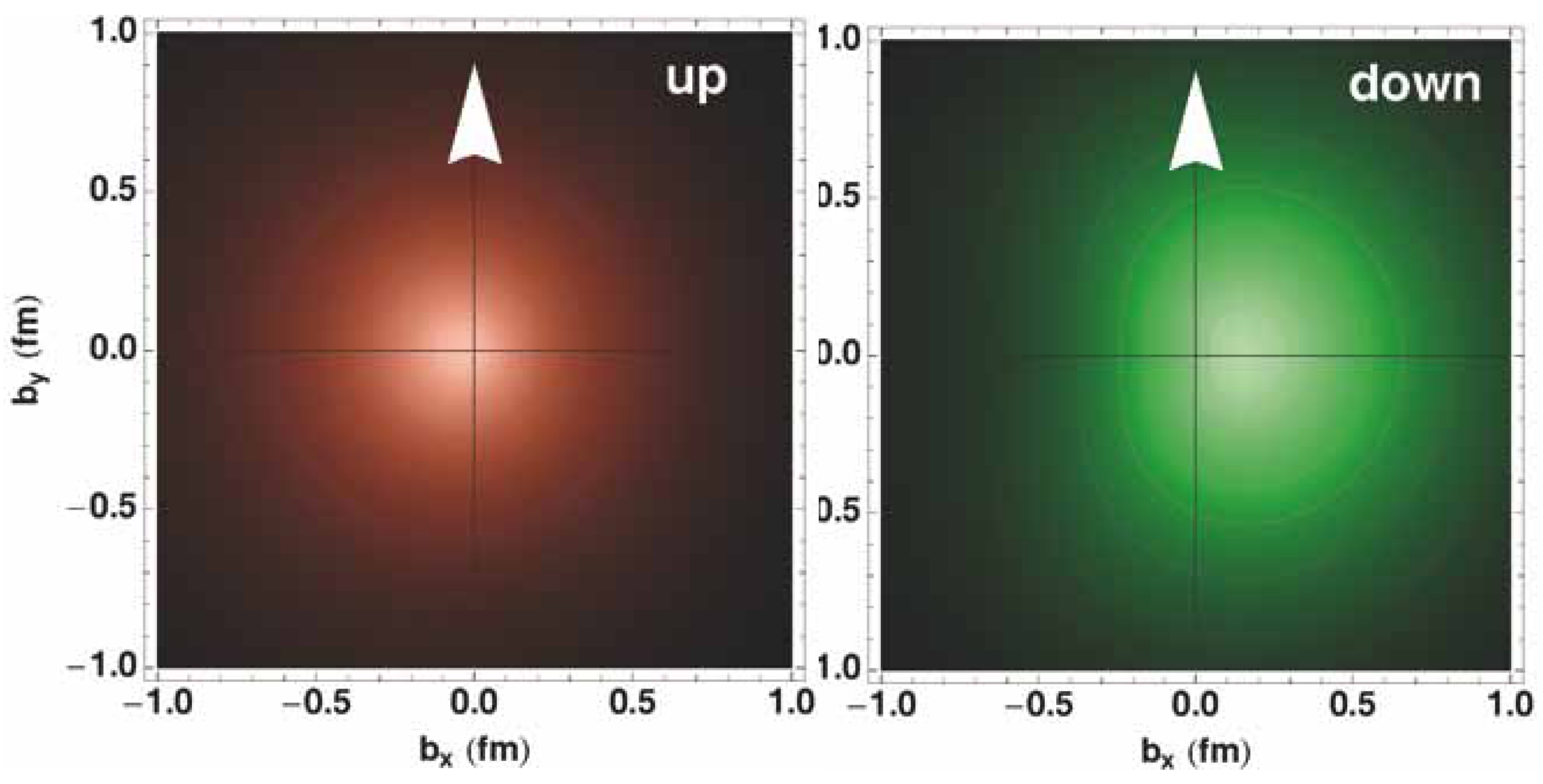


PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

Fourier transform

generalised parton distributions (GPDs)





The nucleon multi-dimensional structure

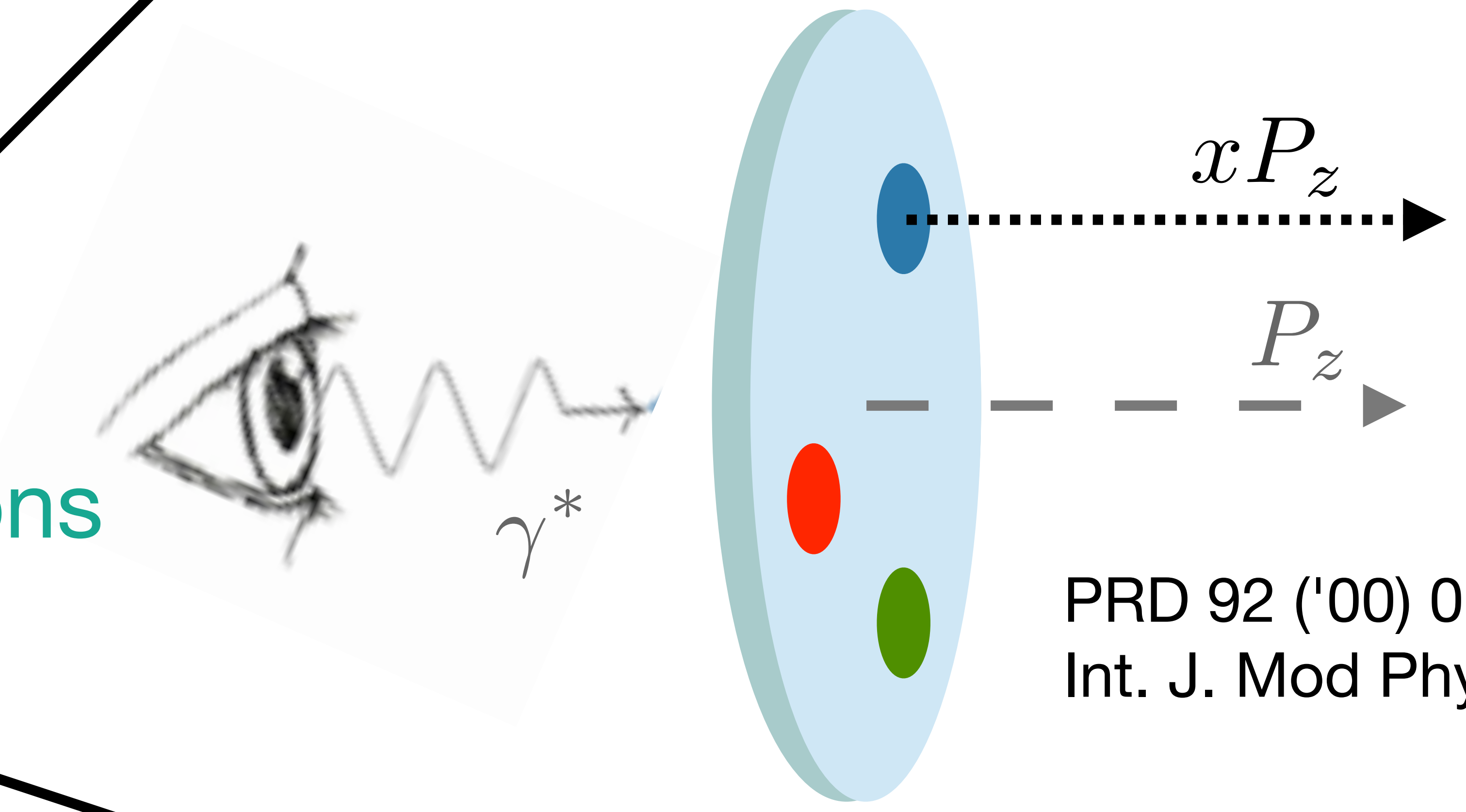
Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

transverse-momentum dependent (TMD) parton distribution functions (PDFs)

$\int d^2\vec{k}_T$

impact-parameter dependent PDFs



PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

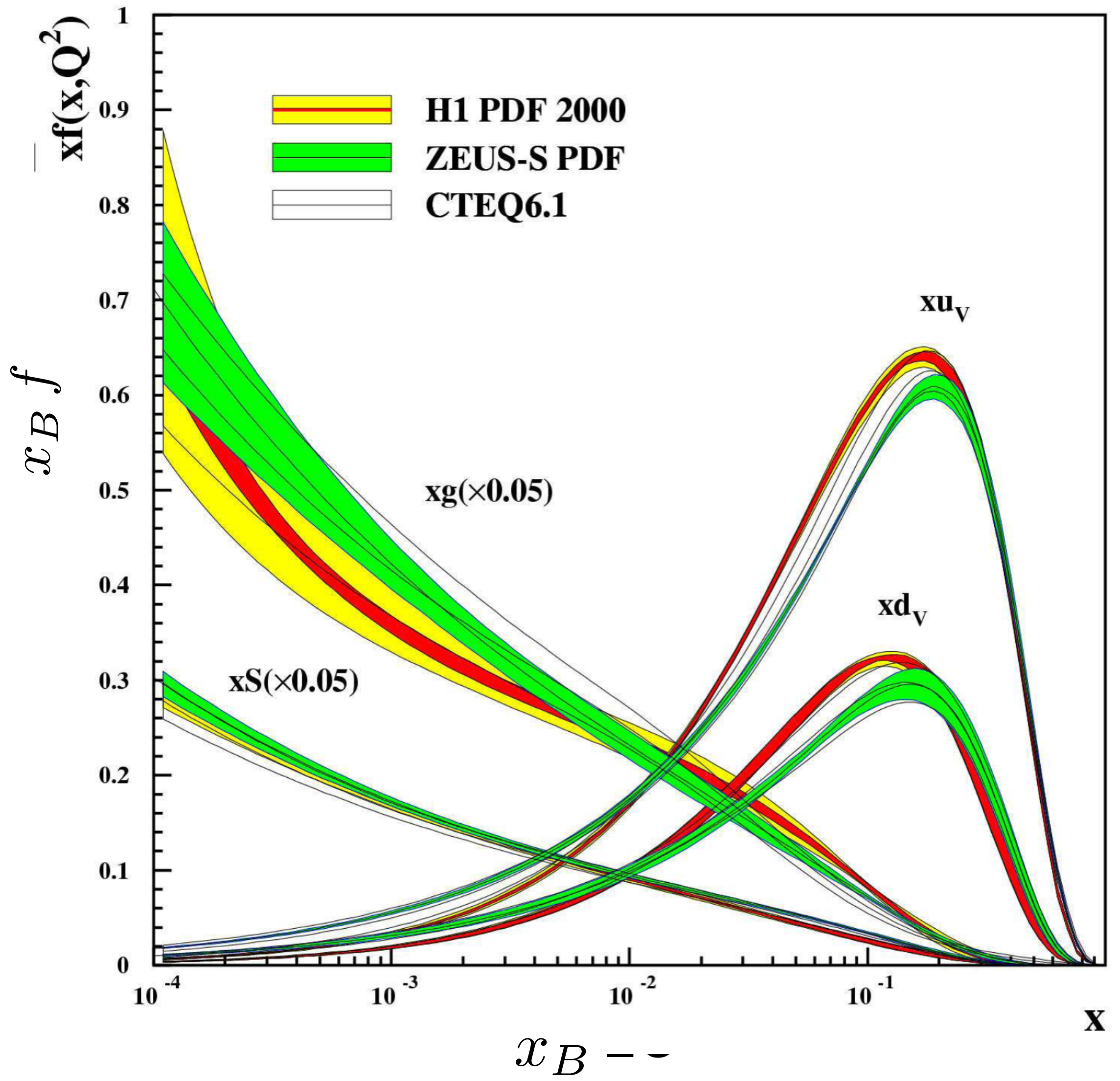
Fourier transform

generalised parton distributions (GPDs)

forward limit

$\int d^2\vec{k}_T$

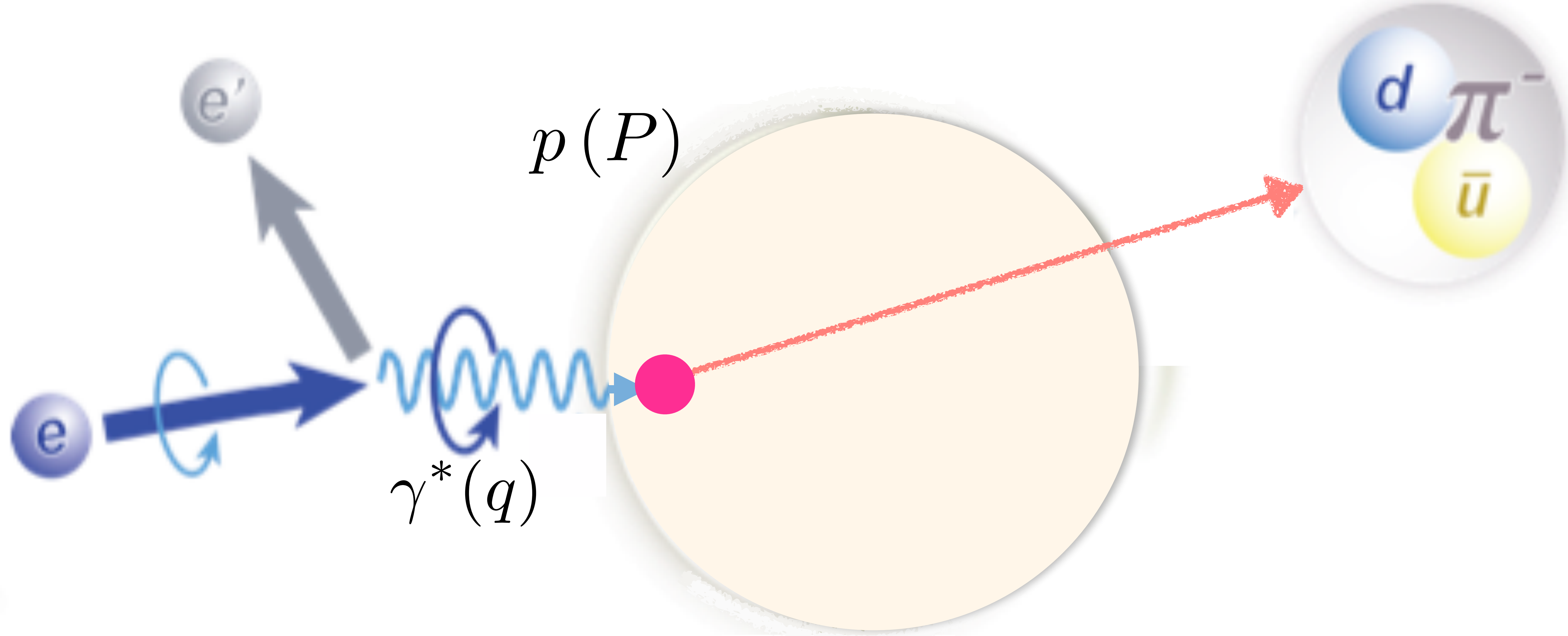
PDFs



Single-hadron production in semi-inclusive DIS

$$Q^2 = -q^2$$

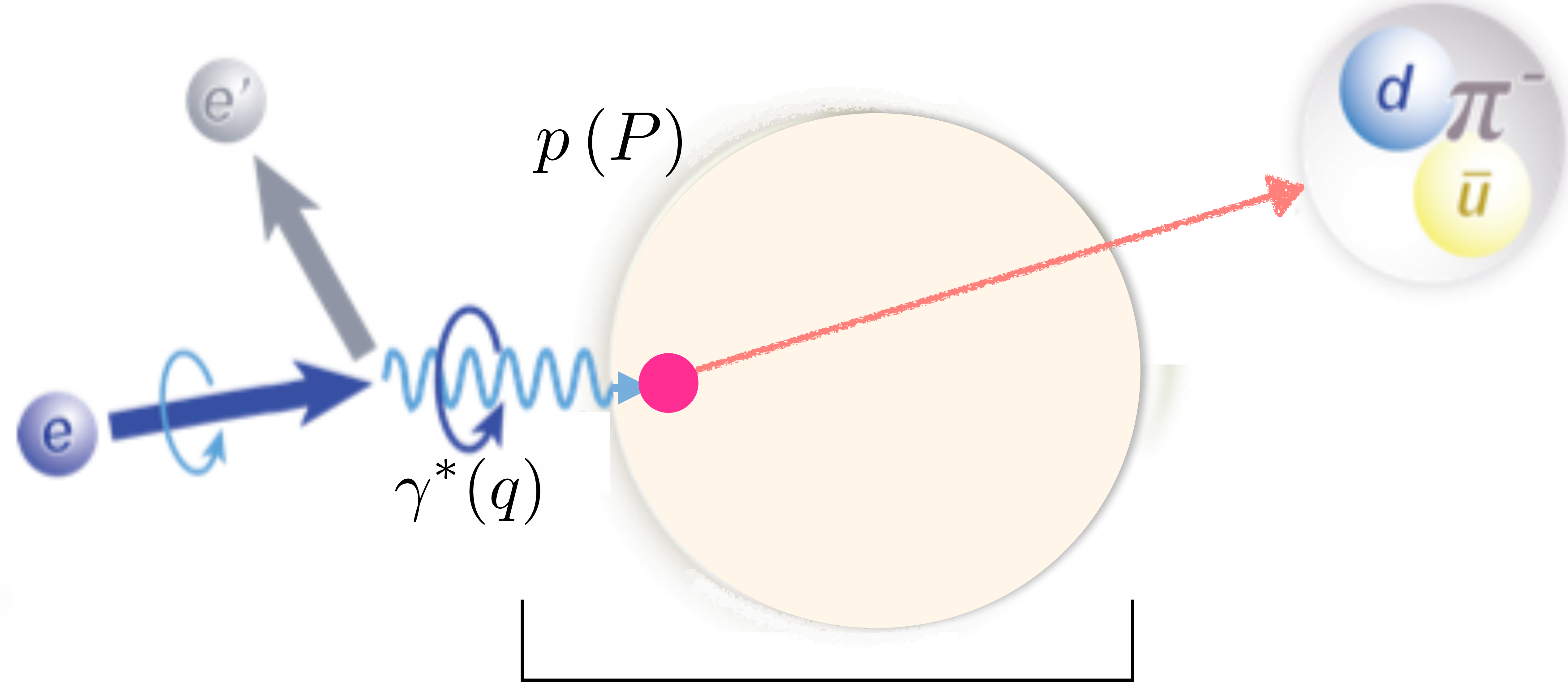
$$x_B = \frac{Q^2}{2P \cdot q}$$



Single-hadron production in semi-inclusive DIS

$$Q^2 = -q^2$$

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



parton distribution function $PDF(x_B)$

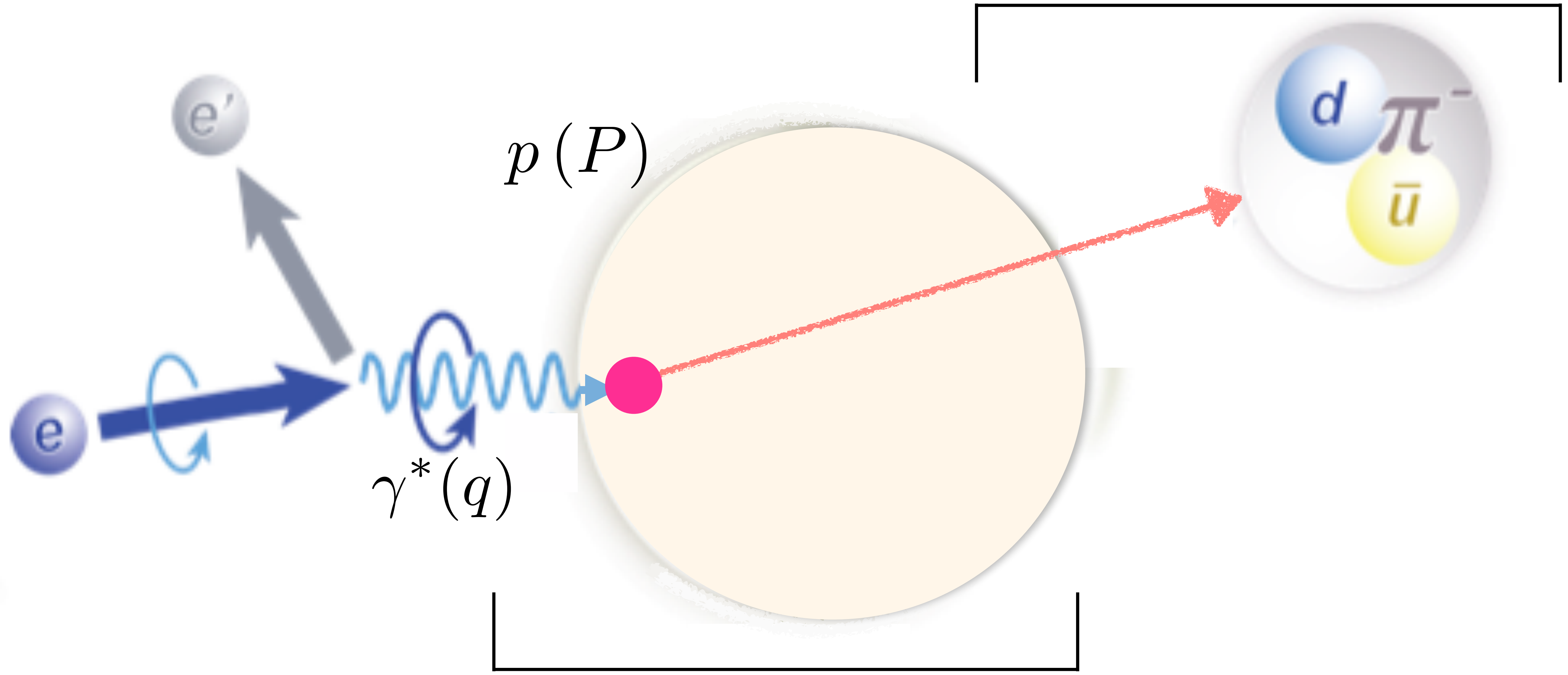
Single-hadron production in semi-inclusive DIS

$Q^2 = -q^2$

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

$z \overset{\text{lab}}{=} \frac{E_h}{E_{\gamma*}}$

fragmentation function $FF(z)$



parton distribution function $PDF(x_B)$

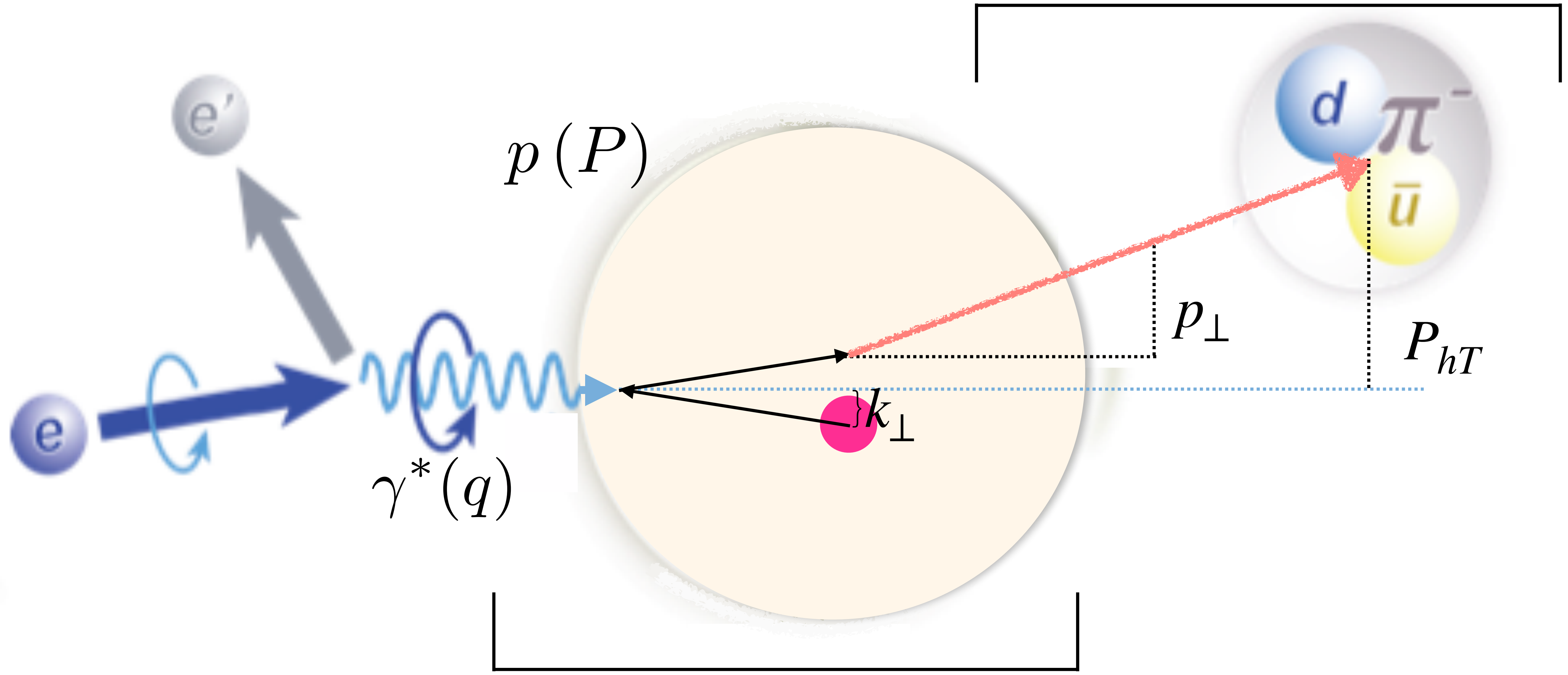
Single-hadron production in semi-inclusive DIS

Transverse-momentum-dependent (TMD)
fragmentation function $FF(z, p_\perp)$

$$Q^2 = -q^2$$

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

$$z \overset{\text{lab}}{=} \frac{E_h}{E_{\gamma*}}$$



Transverse-momentum-dependent (TMD)
parton distribution function $PDF(x_B, k_\perp)$

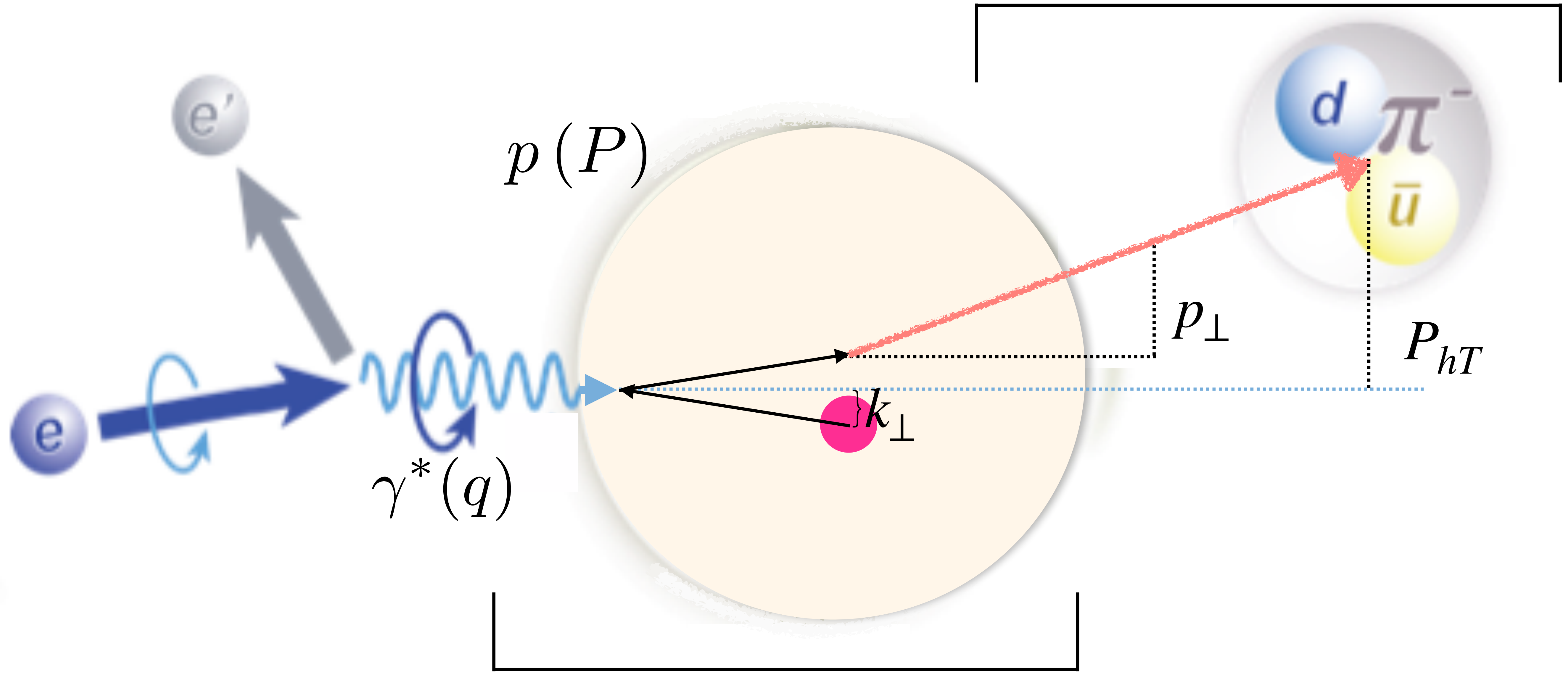
Single-hadron production in semi-inclusive DIS

$Q^2 = -q^2$

$x_B = \dfrac{Q^2}{2P \cdot q}$

$z \overset{\text{lab}}{=} \dfrac{E_h}{E_{\gamma*}}$

Transverse-momentum-dependent (TMD)
fragmentation function $FF(z, p_\perp, Q^2)$



Transverse-momentum-dependent (TMD)
parton distribution function $PDF(x_B, k_\perp, Q^2)$

TMD evolution

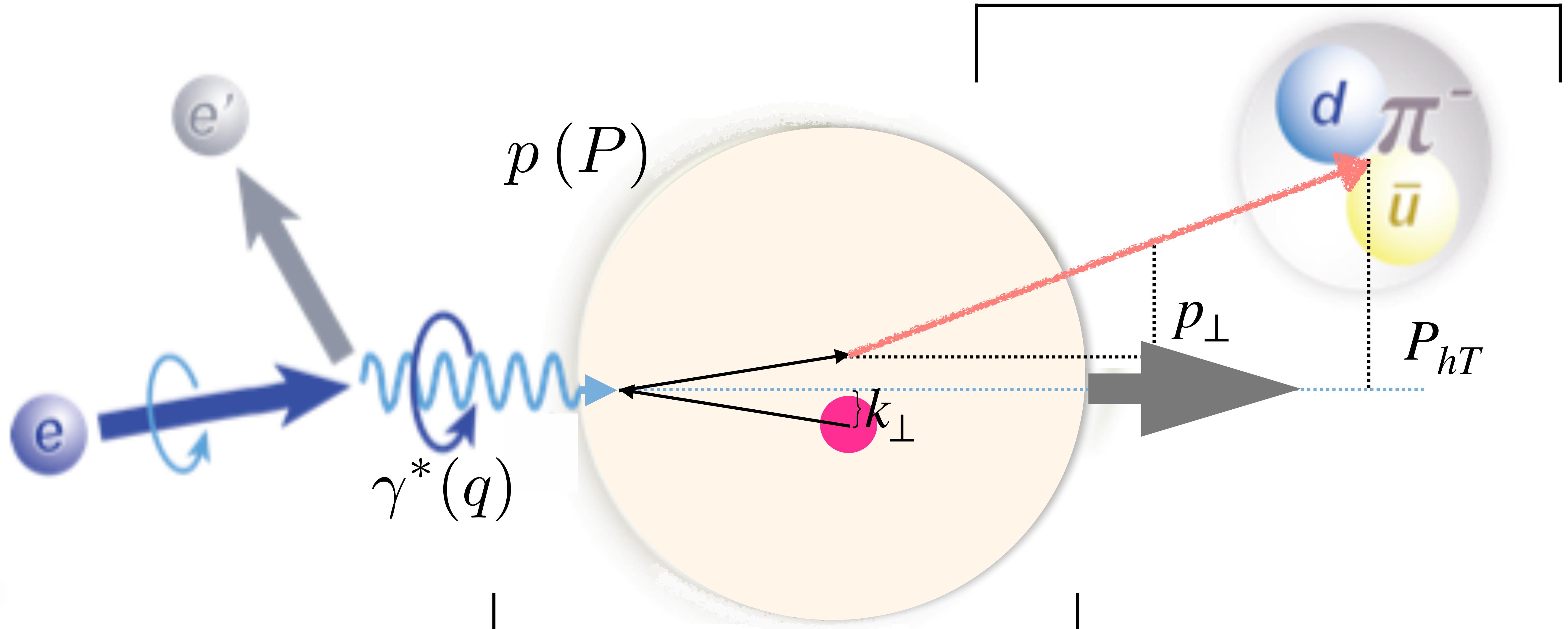
Single-hadron production in semi-inclusive DIS

$$Q^2 = -q^2$$

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

$$z \overset{\text{lab}}{=} \frac{E_h}{E_{\gamma*}}$$

Transverse-momentum-dependent (TMD) fragmentation function $FF(z, p_\perp, Q^2)$



Transverse-momentum-dependent (TMD) parton distribution function $PDF(x_B, k_\perp, Q^2)$

TMD evolution

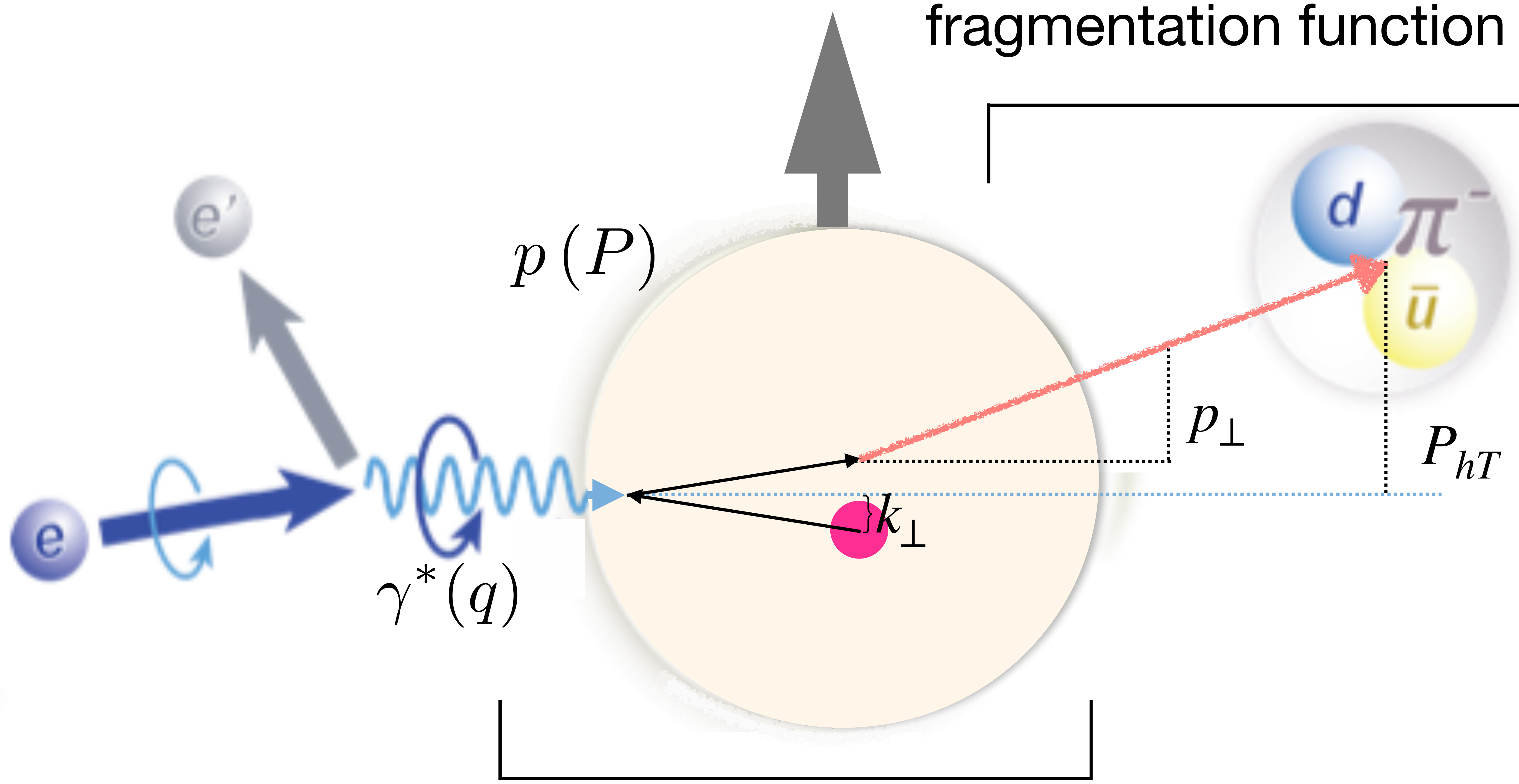
Single-hadron production in semi-inclusive DIS

$$Q^2 = -q^2$$

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

$$z \overset{\text{lab}}{=} \frac{E_h}{E_{\gamma*}}$$

Transverse-momentum-dependent (TMD)
fragmentation function $FF(z, p_\perp, Q^2)$



Transverse-momentum-dependent (TMD)
parton distribution function $PDF(x_B, k_\perp, Q^2)$

TMD evolution

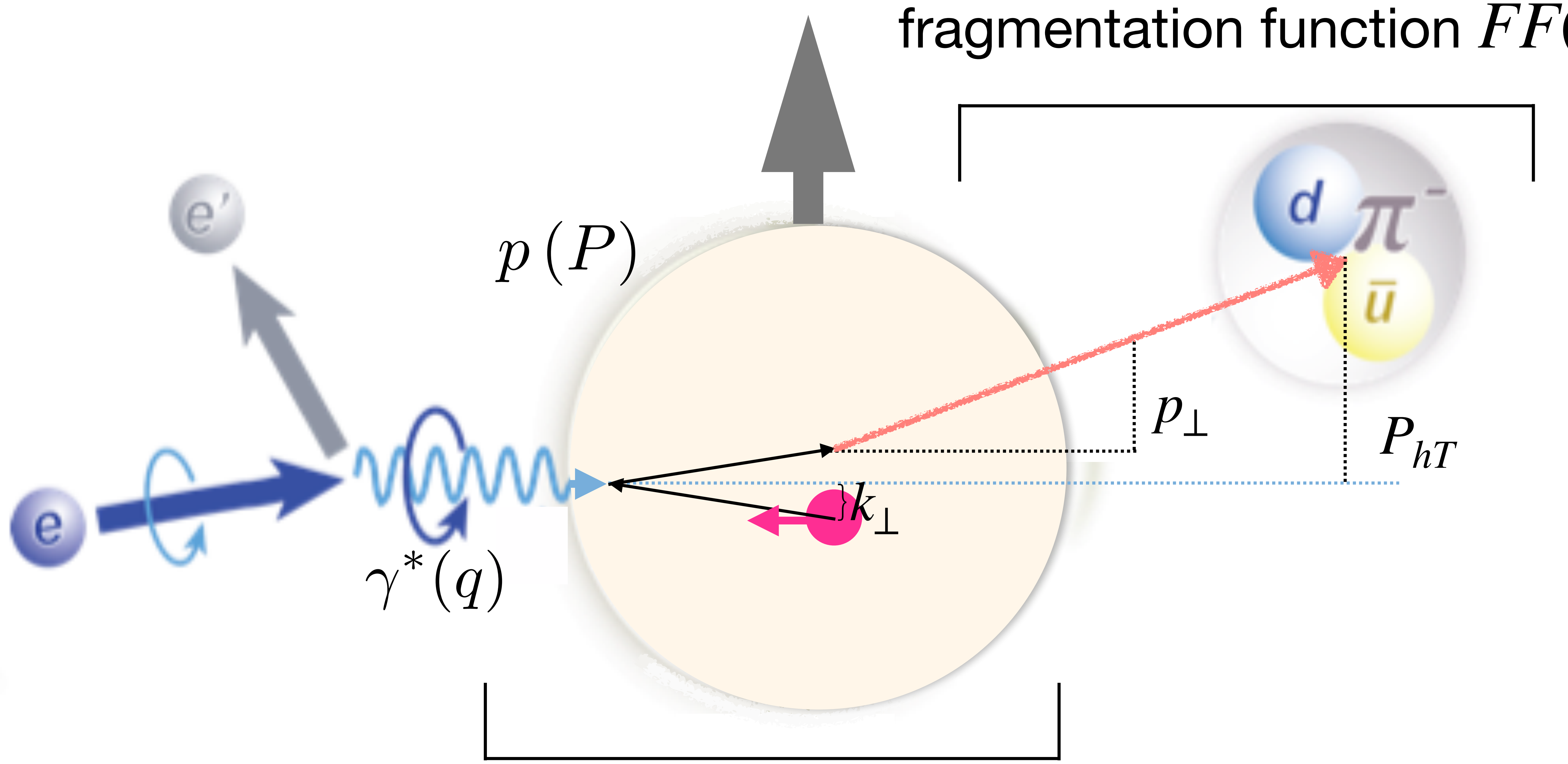
Single-hadron production in semi-inclusive DIS

$Q^2 = -q^2$

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

$z \overset{\text{lab}}{=} \frac{E_h}{E_{\gamma*}}$

Transverse-momentum-dependent (TMD) fragmentation function $FF(z, p_\perp, Q^2)$



Transverse-momentum-dependent (TMD) parton distribution function $PDF(x_B, k_\perp, Q^2)$

TMD evolution

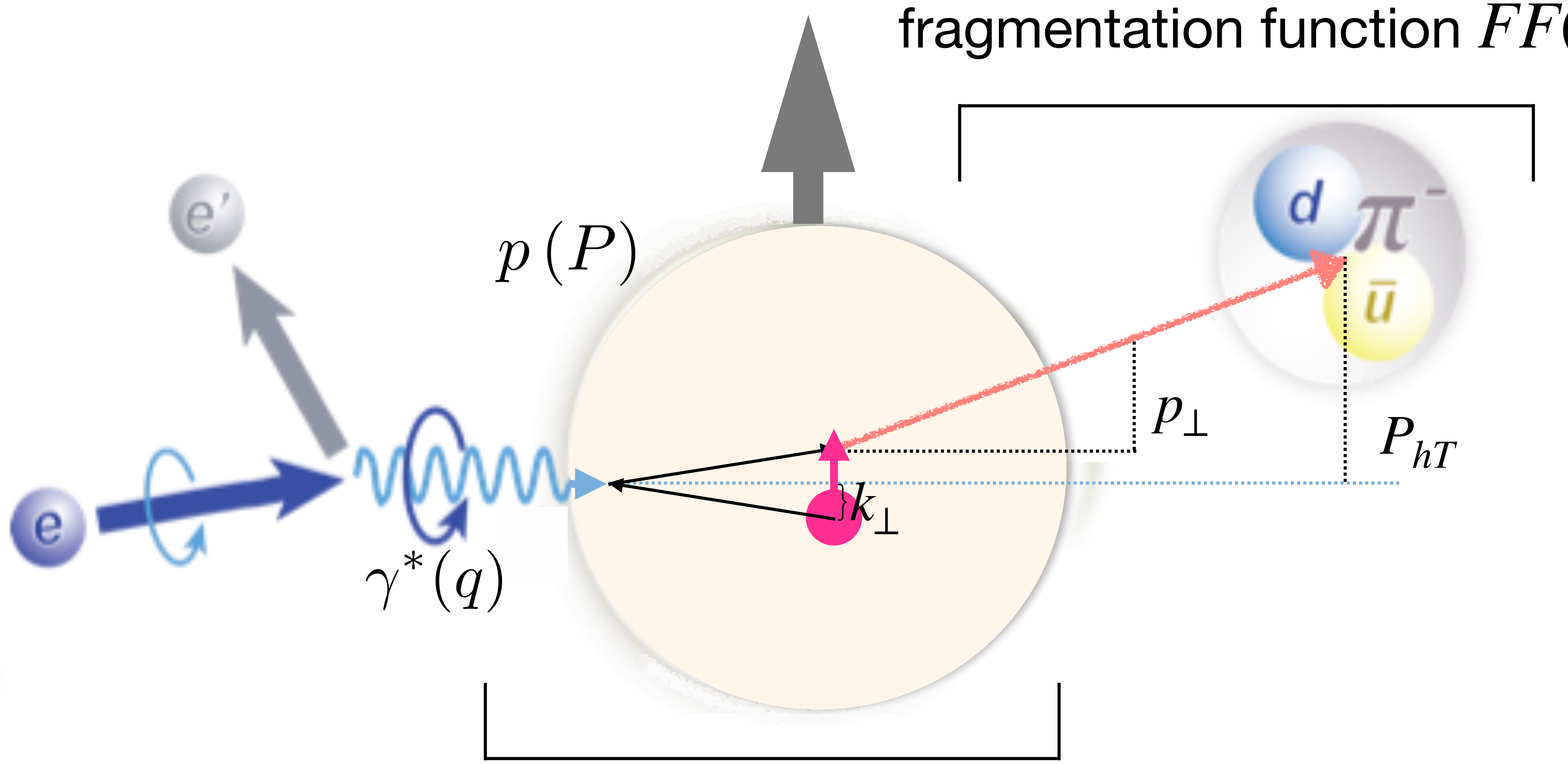
Single-hadron production in semi-inclusive DIS

$Q^2 = -q^2$

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

$z \overset{\text{lab}}{=} \frac{E_h}{E_{\gamma^*}}$

Transverse-momentum-dependent (TMD) fragmentation function $FF(z, p_\perp, Q^2)$



Transverse-momentum-dependent (TMD) parton distribution function $PDF(x_B, k_\perp, Q^2)$

TMD evolution

Transverse momentum dependent parton distribution functions

quark polarisation

nucleon polarisation

	U	L	T
U	f_1		
L		g_{1L}	
T			h_{1T}

survive integration over parton transverse momentum

Transverse momentum dependent parton distribution functions

quark polarisation

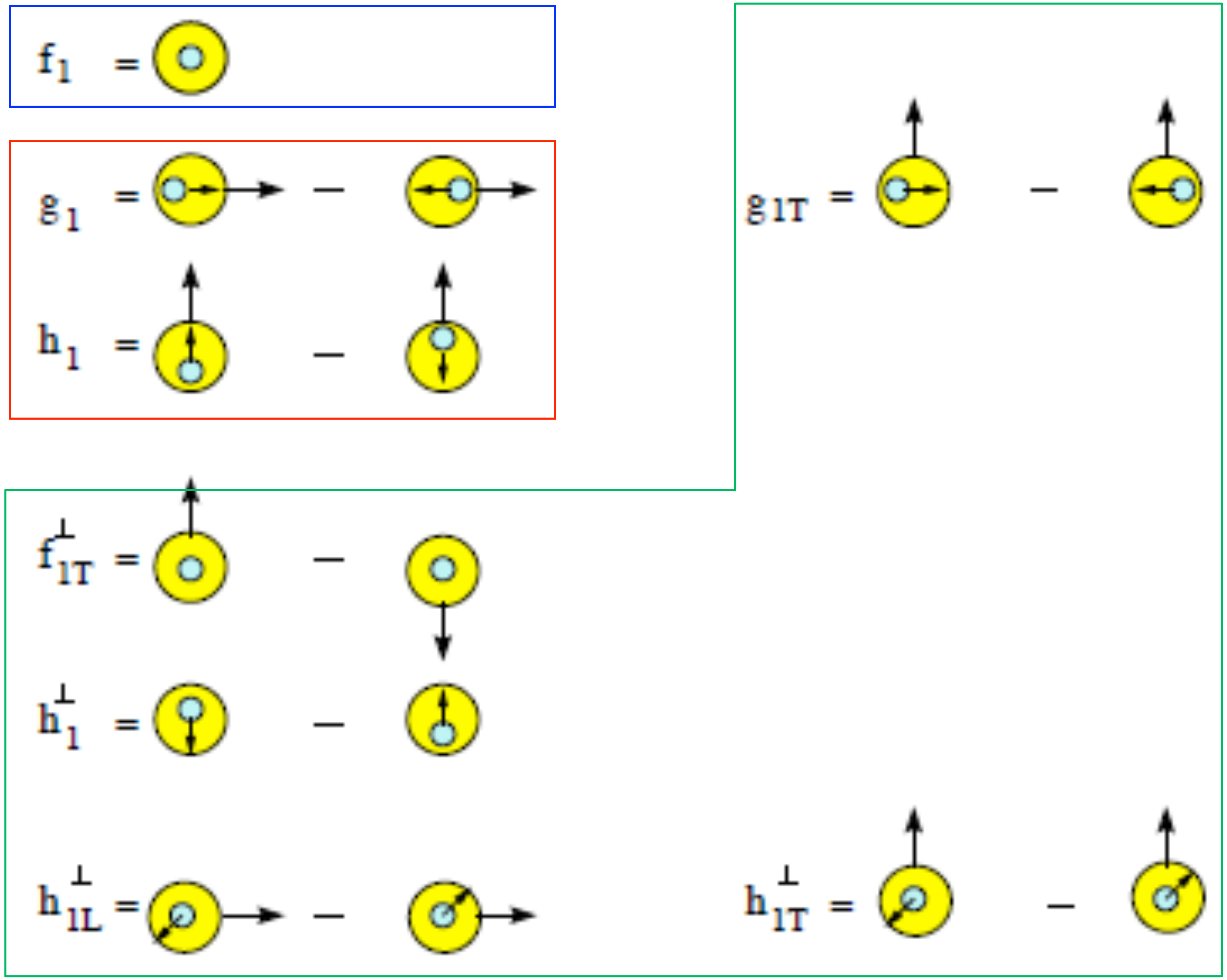
nucleon polarisation	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\, h_{1T}^\perp$

Transverse momentum dependent parton distribution functions

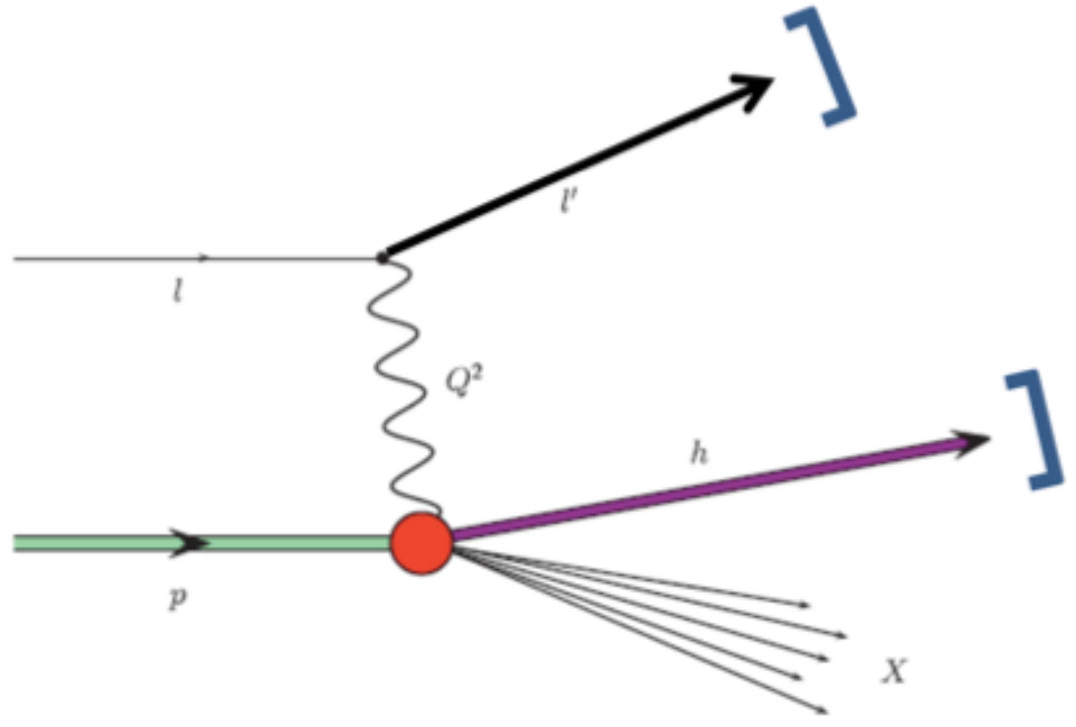
spin-independent

spin-spin
correlations

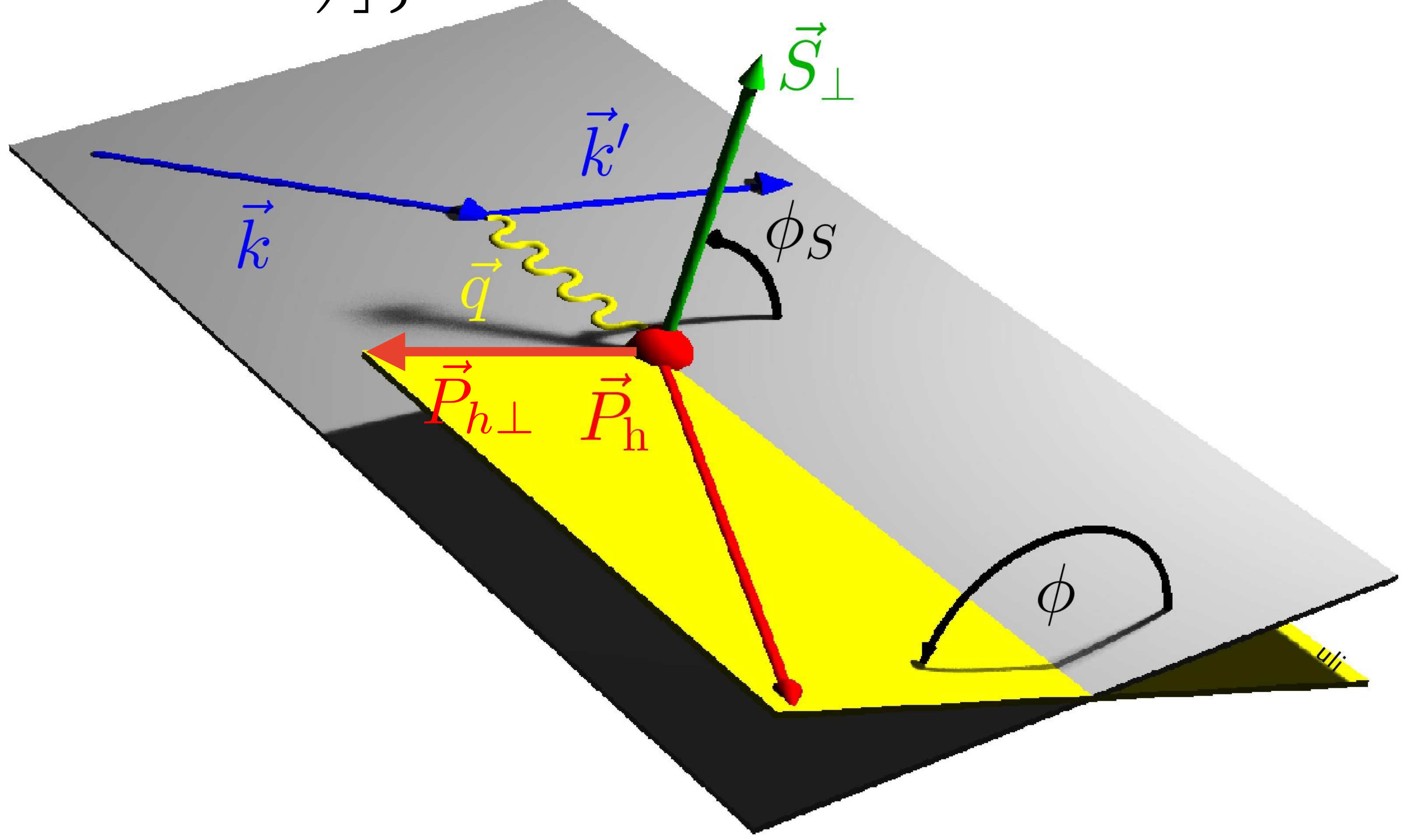
spin-momentum
correlations



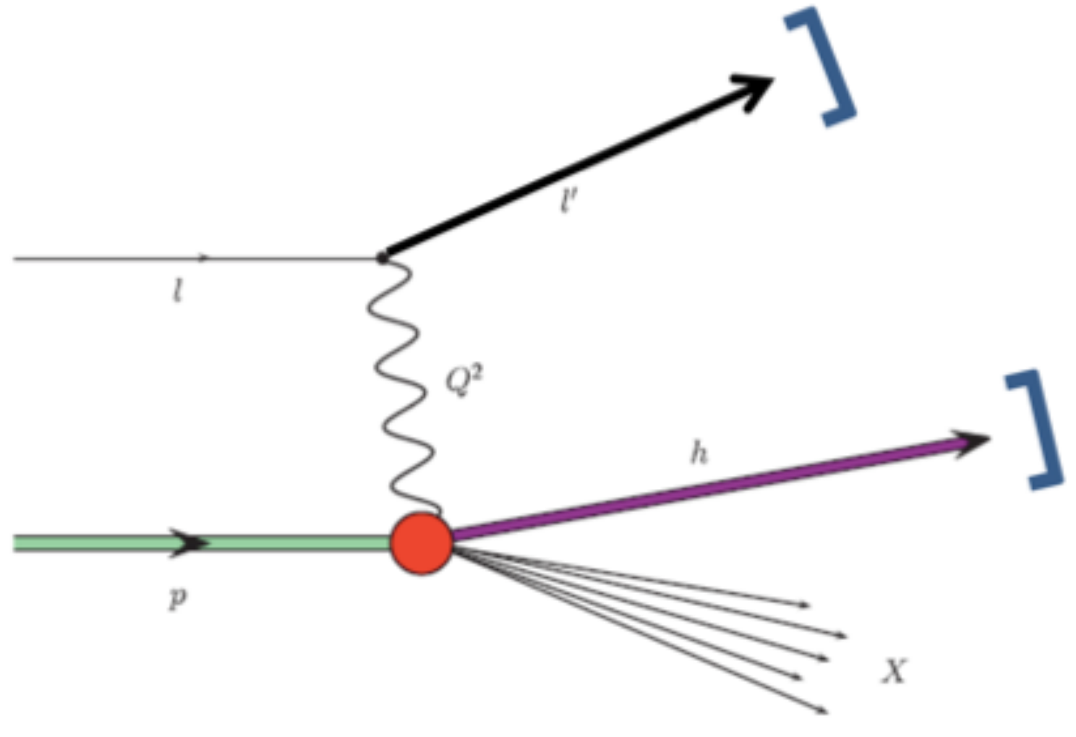
Semi-inclusive DIS cross section



$$
\begin{aligned}
\sigma^h(\phi,\phi_S) &= \sigma^h_{UU}\Big\{1+2\langle\cos(\phi)\rangle^h_{UU}\,\cos(\phi)+2\langle\cos(2\phi)\rangle^h_{UU}\,\cos(2\phi)\\
&+\lambda_l\,2\langle\sin(\phi)\rangle^h_{LU}\,\sin(\phi)\\
&+S_L\Big[2\langle\sin(\phi)\rangle^h_{UL}\,\sin(\phi)+2\langle\sin(2\phi)\rangle^h_{UL}\,\sin(2\phi)\\
&+\lambda_l\Big(2\langle\cos(0\phi)\rangle^h_{LL}\,\cos(0\phi)+2\langle\cos(\phi)\rangle^h_{LL}\,\cos(\phi)\Big)\Big]\\
&+S_T\Big[2\langle\sin(\phi-\phi_S)\rangle^h_{UT}\,\sin(\phi-\phi_S)+2\langle\sin(\phi+\phi_S)\rangle^h_{UT}\,\sin(\phi+\phi_S)\\
&+2\langle\sin(3\phi-\phi_S)\rangle^h_{UT}\,\sin(3\phi-\phi_S)+2\langle\sin(\phi_S)\rangle^h_{UT}\,\sin(\phi_S)\\
&+2\langle\sin(2\phi-\phi_S)\rangle^h_{UT}\,\sin(2\phi-\phi_S)\\
&+\lambda_l\Big(2\langle\cos(\phi-\phi_S)\rangle^h_{LT}\,\cos(\phi-\phi_S)\\
&+\;2\langle\cos(\phi_S)\rangle^h_{LT}\,\cos(\phi_S)+2\langle\cos(2\phi-\phi_S)\rangle^h_{LT}\,\cos(2\phi-\phi_S)\Big)\Big]\Big\}
\end{aligned}
$$



Semi-inclusive DIS cross section



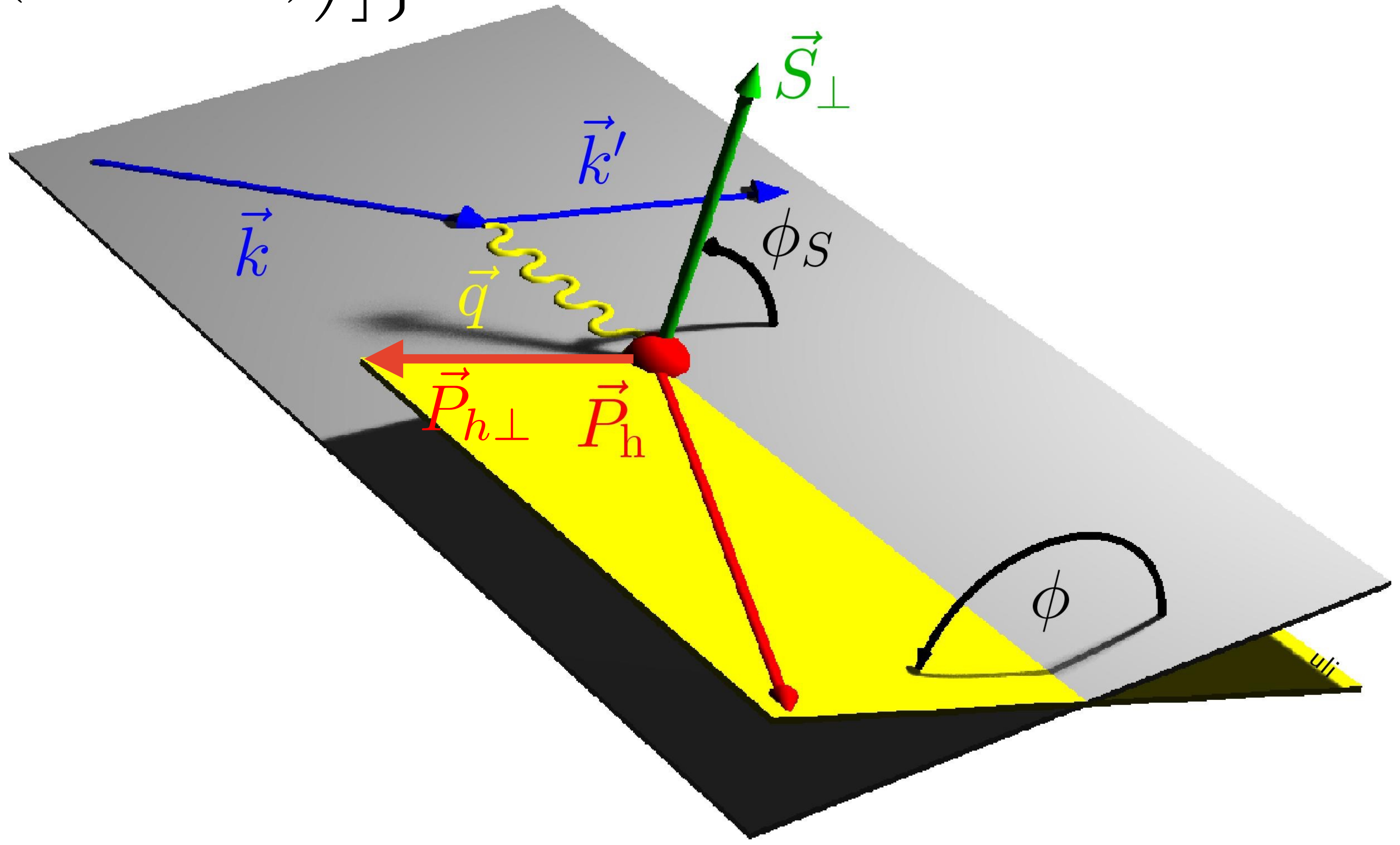
$$
\begin{aligned}
\sigma^h(\phi,\phi_S) &= \sigma^h_{UU}\Big\{1 + 2\langle\cos(\phi)\rangle^h_{UU}\,\cos(\phi) + 2\langle\cos(2\phi)\rangle^h_{UU}\,\cos(2\phi)\\
&+ \lambda_l\, 2\langle\sin(\phi)\rangle^h_{LU}\,\sin(\phi)\\
&+ S_L\Big[2\langle\sin(\phi)\rangle^h_{UL}\,\sin(\phi) + 2\langle\sin(2\phi)\rangle^h_{UL}\,\sin(2\phi)\\
&+ \lambda_l\Big(2\langle\cos(0\phi)\rangle^h_{LL}\,\cos(0\phi) + 2\langle\cos(\phi)\rangle^h_{LL}\,\cos(\phi)\Big)\Big]\\
&+ S_T\Big[2\langle\sin(\phi-\phi_S)\rangle^h_{UT}\,\sin(\phi-\phi_S) + 2\langle\sin(\phi+\phi_S)\rangle^h_{UT}\,\sin(\phi+\phi_S)\\
&+ 2\langle\sin(3\phi-\phi_S)\rangle^h_{UT}\,\sin(3\phi-\phi_S) + 2\langle\sin(\phi_S)\rangle^h_{UT}\,\sin(\phi_S)\\
&+ 2\langle\sin(2\phi-\phi_S)\rangle^h_{UT}\,\sin(2\phi-\phi_S)\\
&+ \lambda_l\Big(2\langle\cos(\phi-\phi_S)\rangle^h_{LT}\,\cos(\phi-\phi_S)\\
&+ 2\langle\cos(\phi_S)\rangle^h_{LT}\,\cos(\phi_S) + 2\langle\cos(2\phi-\phi_S)\rangle^h_{LT}\,\cos(2\phi-\phi_S)\Big)\Big]\Big\}
\end{aligned}
$$

longitudinal target polarisation (S_L)

transverse target polarisation (S_T)

beam polarisation (λ_l)

LT: beam polarisation, target polarisation



TMD PDFs and fragmentation functions (FFs)

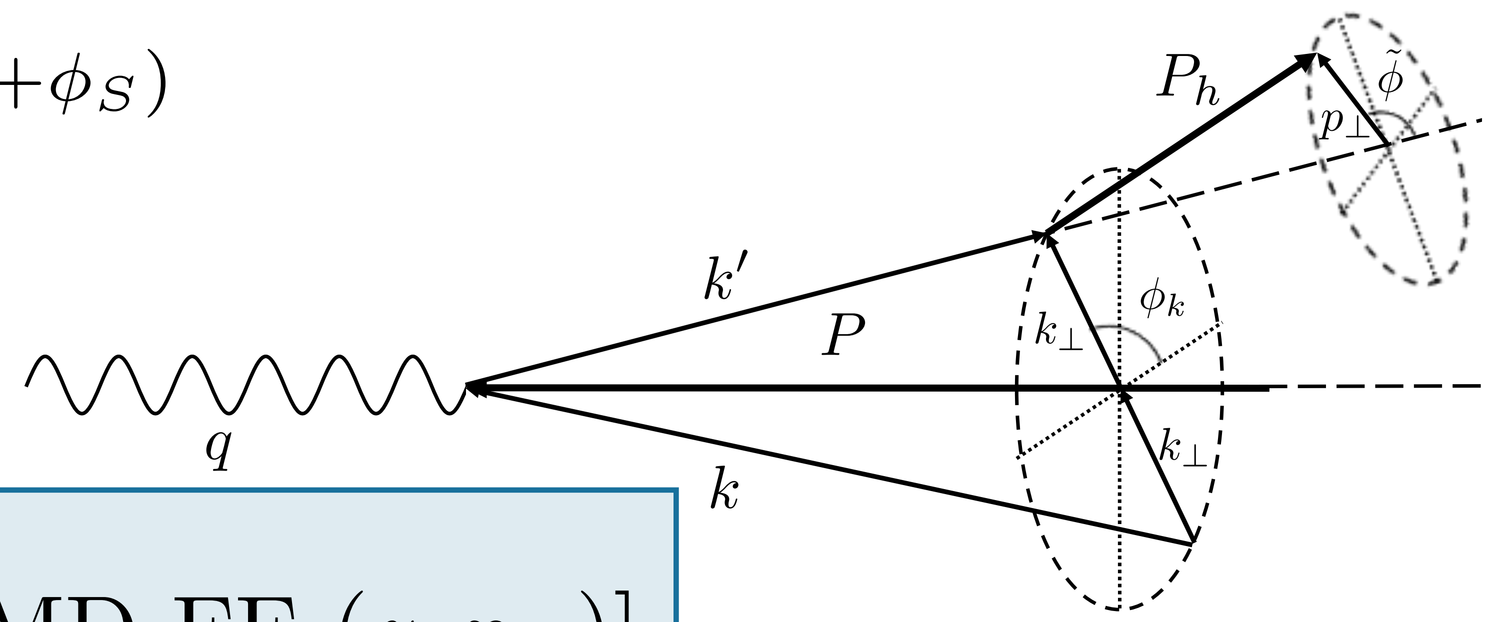
Azimuthal amplitudes related to structure functions F_{XY} :

$$2\langle \sin(\phi + \phi_S) \rangle_{UT}^{h} = \epsilon \, F_{UT}^{\sin(\phi+\phi_S)}$$

TMD PDFs and fragmentation functions (FFs)

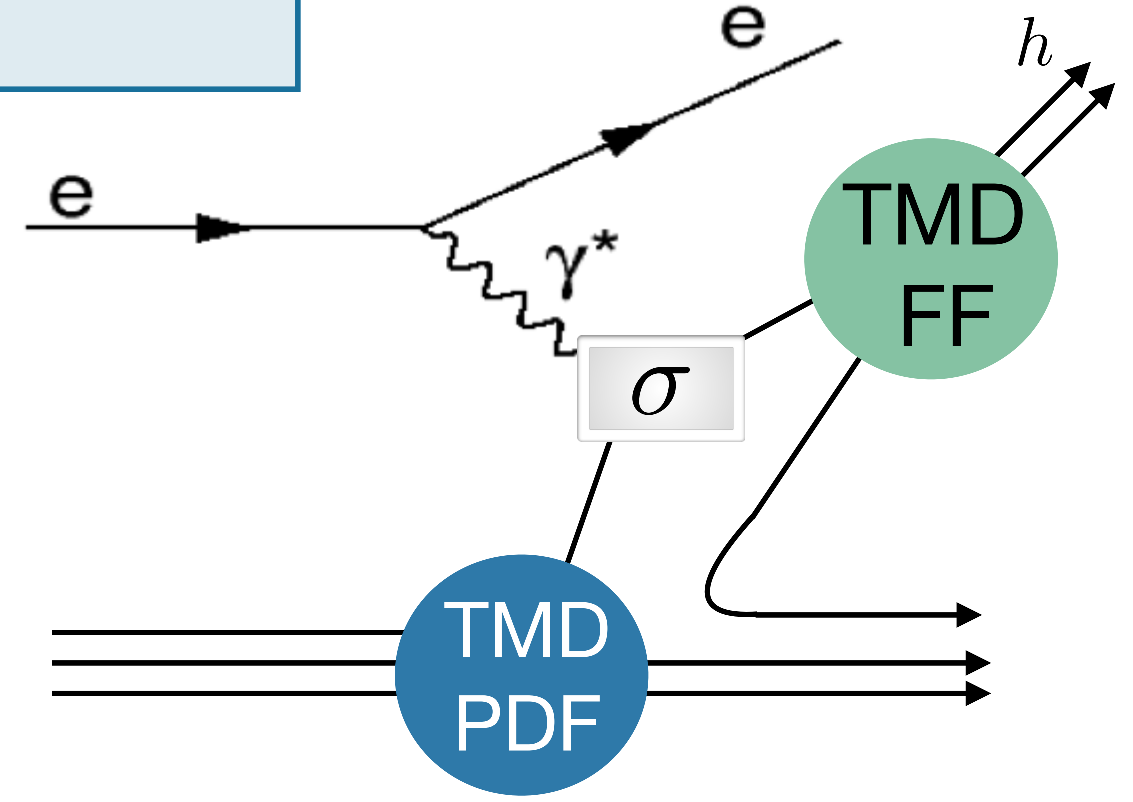
Azimuthal amplitudes related to structure functions F_{XY} :

$$2\langle \sin(\phi + \phi_S)\rangle^h_{UT} = \epsilon\, F^{\sin(\phi+\phi_S)}_{UT}$$



$$F_{XY} \propto \mathcal{C}\,[\text{TMD PDF}(x, k_\perp) \times \ \text{TMD FF}\ (z, p_\perp)]$$

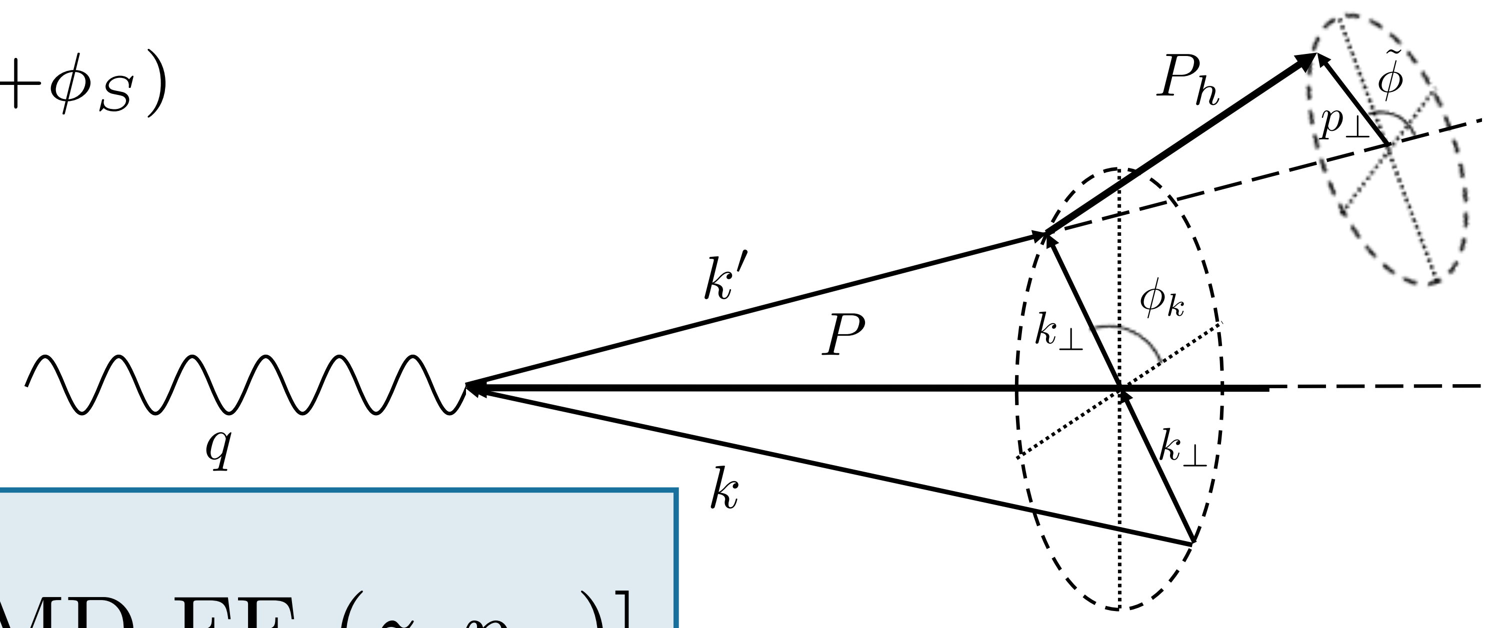
$$z \overset{\text{lab}}{=} \frac{E_h}{E_{\gamma *}}$$



TMD PDFs and fragmentation functions (FFs)

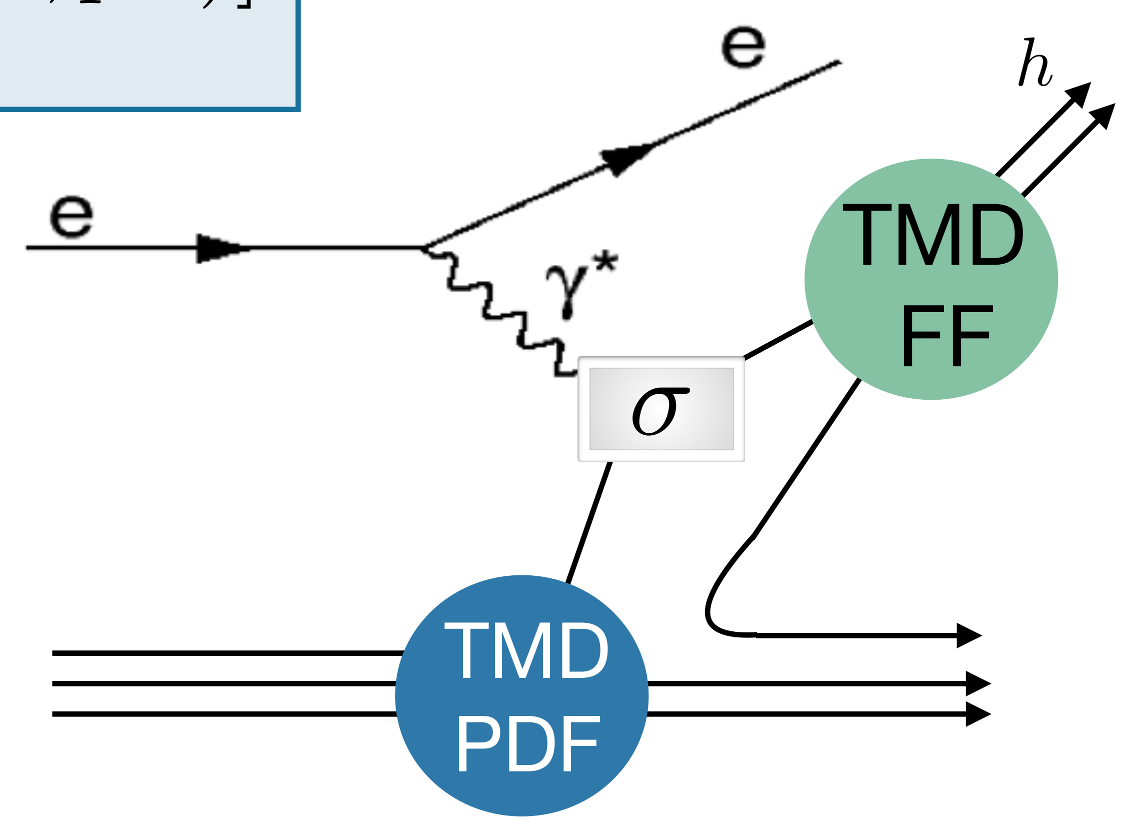
Azimuthal amplitudes related to structure functions F_{XY} :

$$2\langle \sin(\phi+\phi_S)\rangle_{UT}^{h} = \epsilon\, F_{UT}^{\sin(\phi+\phi_S)}$$



$$F_{XY} \propto \mathcal{C}\,[\mathrm{TMD\ PDF}(x,k_\perp) \times\ \mathrm{TMD\ FF}\ (z,p_\perp)]$$

$$z \stackrel{\text{lab}}{=} \frac{E_h}{E_{\gamma*}}$$



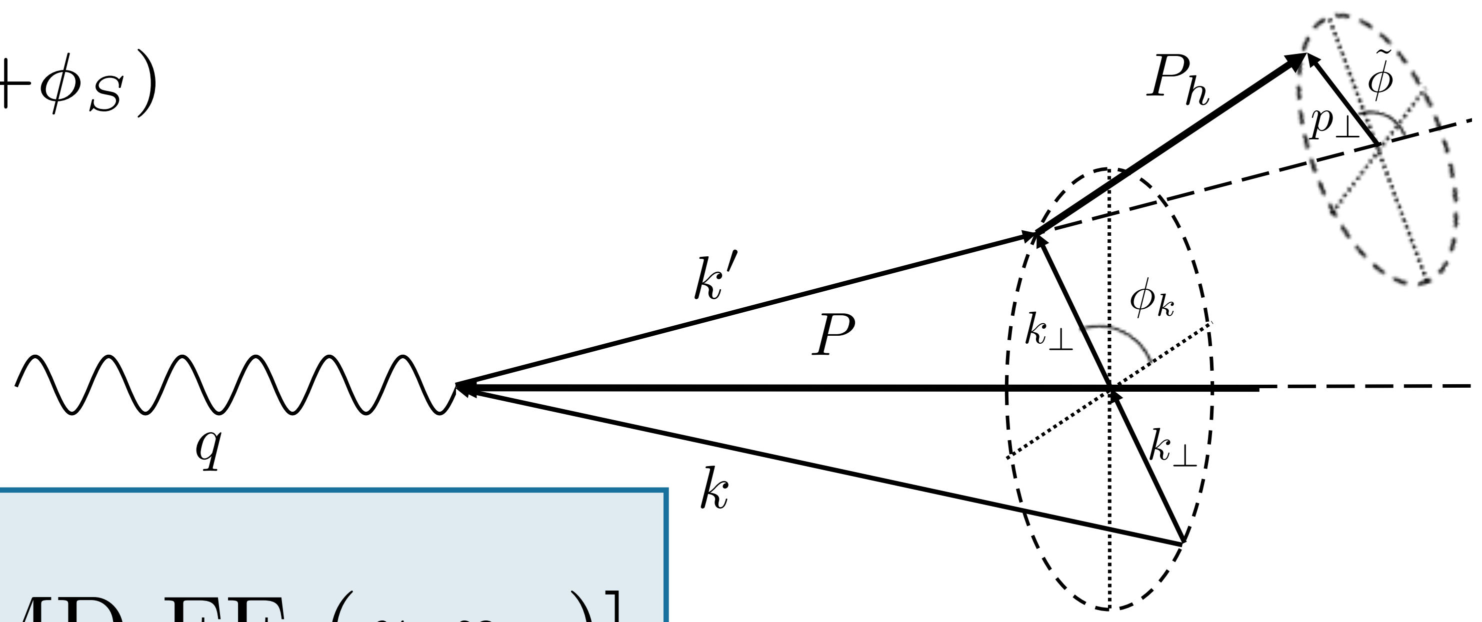
quark polarisation (columns) / nucleon polarisation (rows)

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\,h_{1T}^\perp$

TMD PDFs and fragmentation functions (FFs)

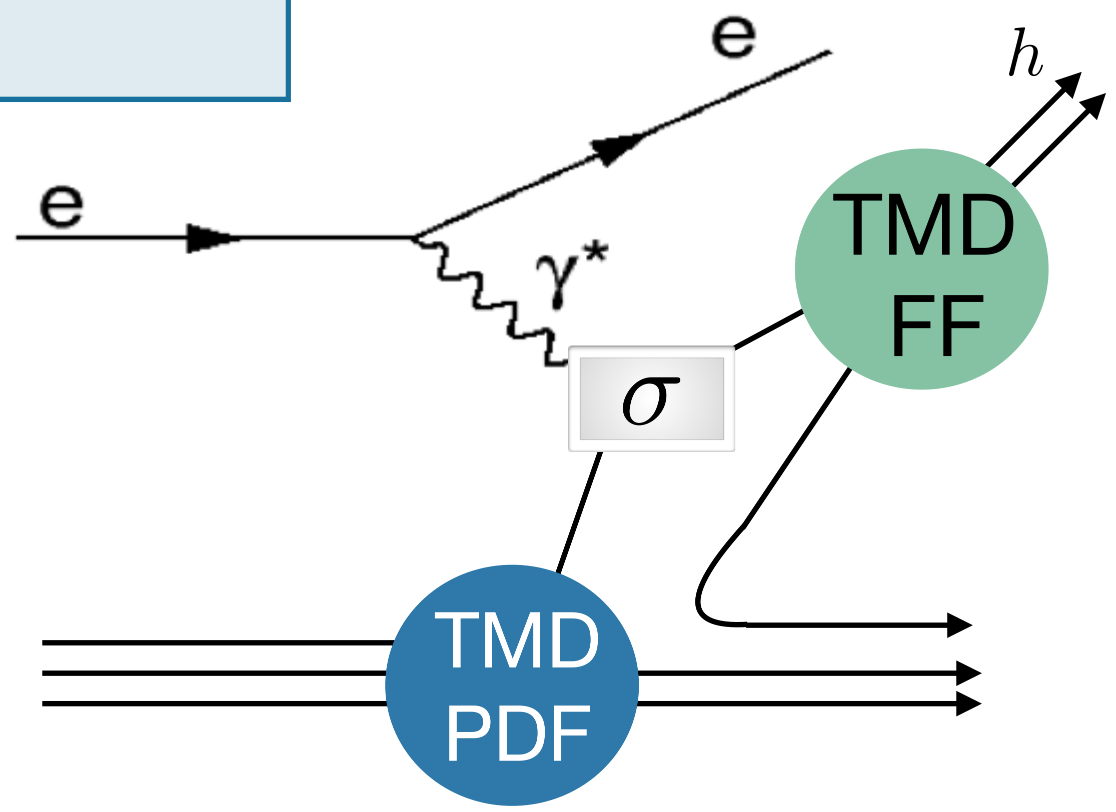
Azimuthal amplitudes related to structure functions F_{XY} :

$$2\langle \sin(\phi+\phi_S)\rangle^h_{UT} = \epsilon\, F^{\sin(\phi+\phi_S)}_{UT}$$



$$F_{XY} \propto \mathcal{C}\,[\text{TMD PDF}(x,k_\perp) \times\ \text{TMD FF}\ (z,p_\perp)]$$

$$z \overset{\text{lab}}{=} \frac{E_h}{E_{\gamma*}}$$



quark polarisation (columns) / nucleon polarisation (rows)

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\,h_{1T}^\perp$

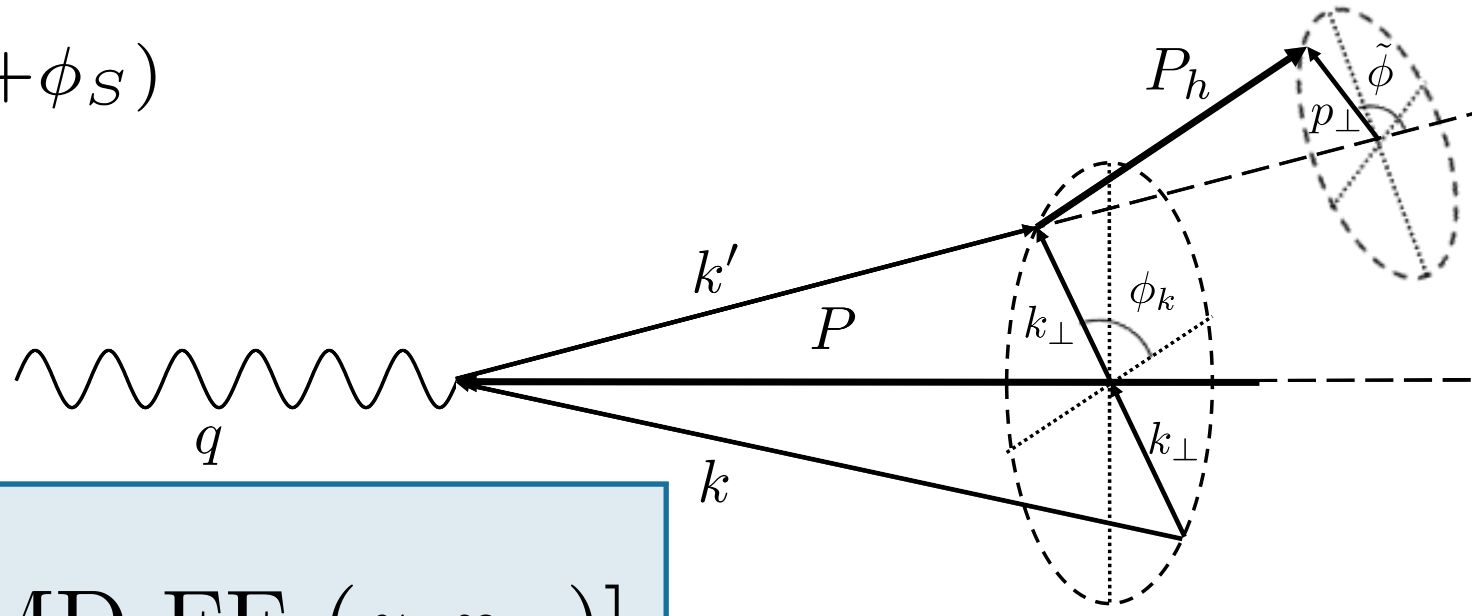
quark polarisation (columns) / hadron polarisation (rows)

	U	L	T
U	D_1		$H_1^\perp$

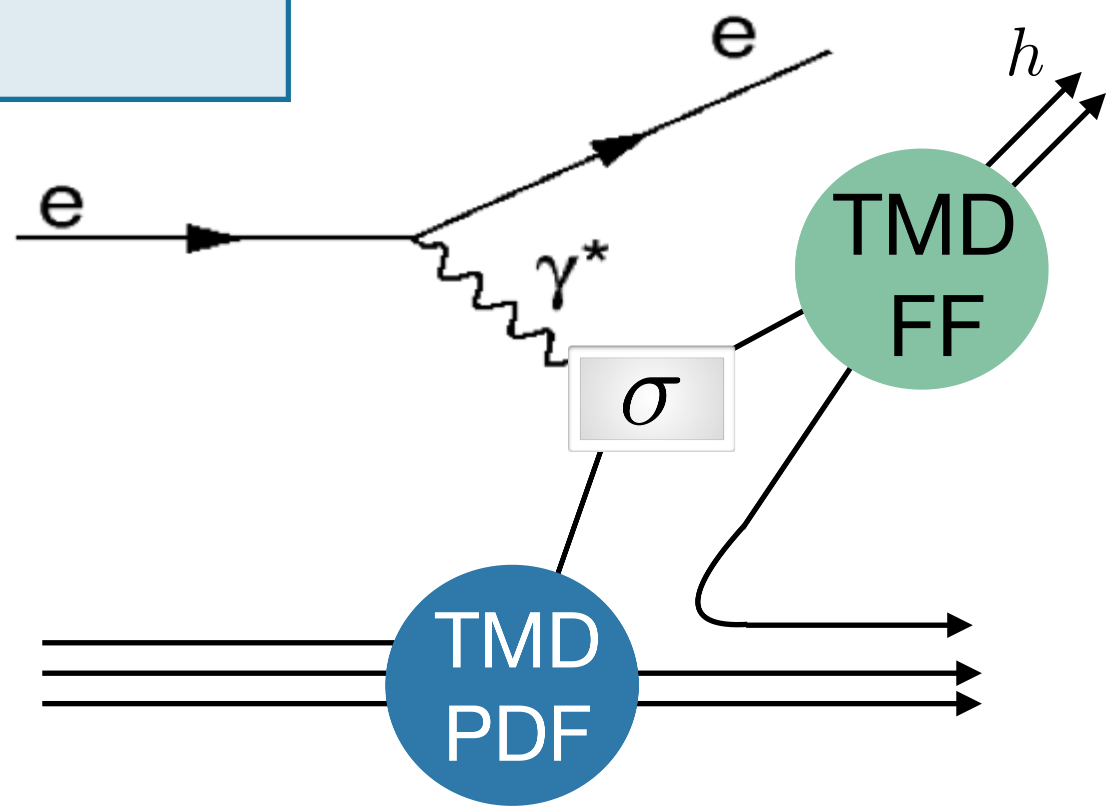
TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY} :

$$2\langle \sin(\phi+\phi_S)\rangle^h_{UT} = \epsilon\, F_{UT}^{\sin(\phi+\phi_S)}$$



$$F_{XY} \propto \mathcal{C}\,[\text{TMD PDF}(x,k_\perp) \times \ \text{TMD FF}\ (z,p_\perp)]$$



$$z \overset{\text{lab}}{=} \frac{E_h}{E_{\gamma*}}$$

quark polarisation (columns) / nucleon polarisation (rows)

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\, h_{1T}^\perp$

quark polarisation (columns) / hadron polarisation (rows)

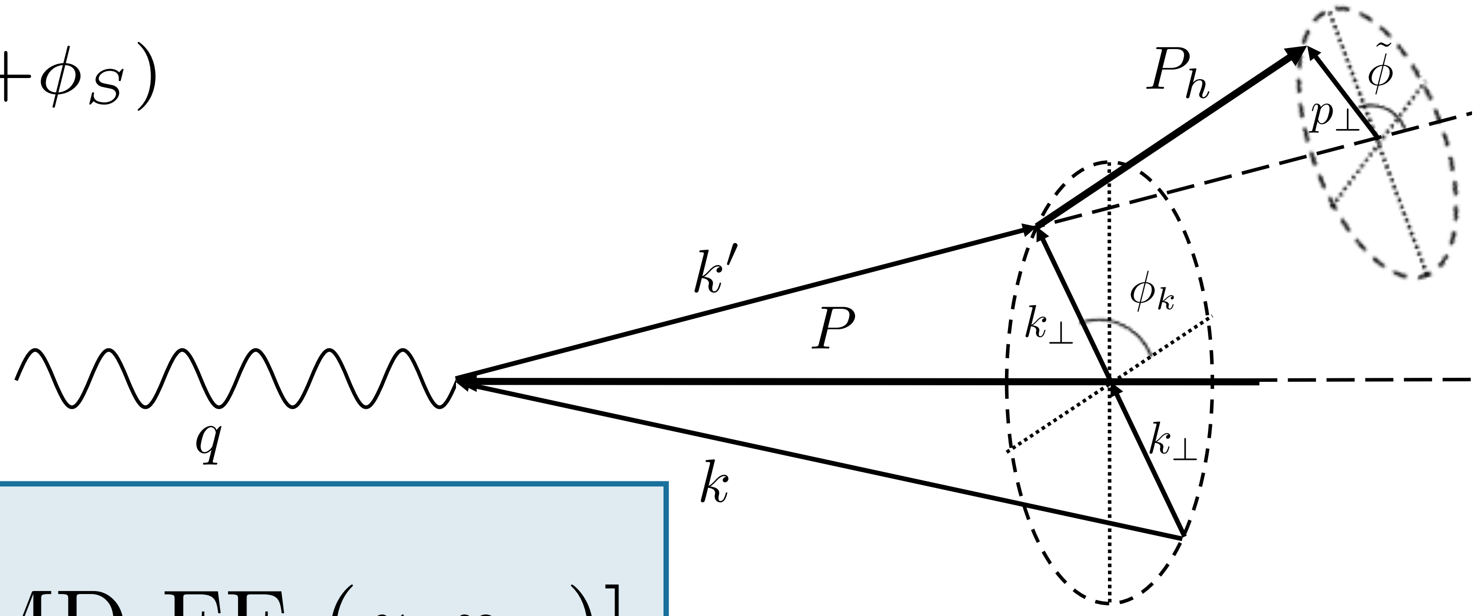
	U	L	T
U	D_1		$H_1^\perp$

Chiral odd

TMD PDFs and fragmentation functions (FFs)

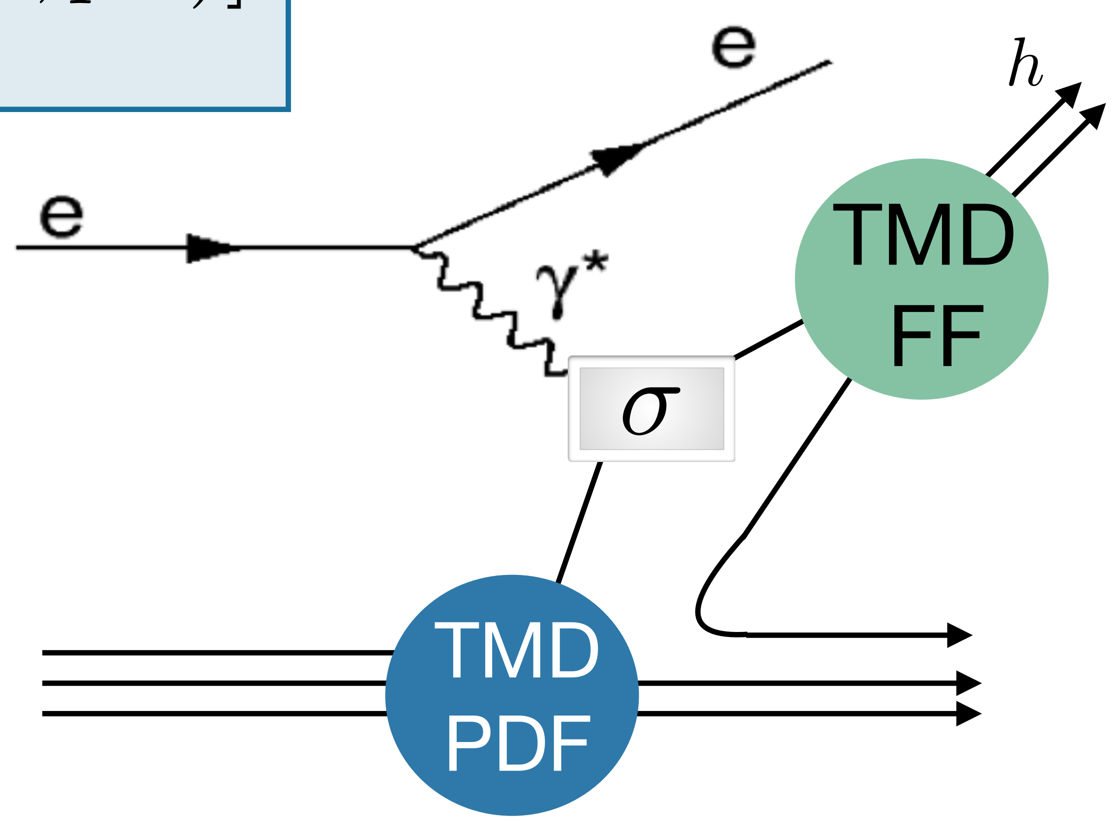
Azimuthal amplitudes related to structure functions F_{XY} :

$$2\langle \sin(\phi + \phi_S) \rangle^h_{UT} = \epsilon\, F_{UT}^{\sin(\phi+\phi_S)}$$



$$F_{XY} \propto \mathcal{C}\,[\text{TMD PDF}(x, k_\perp) \times \ \text{TMD FF}\ (z, p_\perp)]$$

$$z \overset{\text{lab}}{=} \frac{E_h}{E_{\gamma*}}$$



nucleon polarisation / **quark polarisation**

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\, h_{1T}^\perp$

hadron polarisation / **quark polarisation**

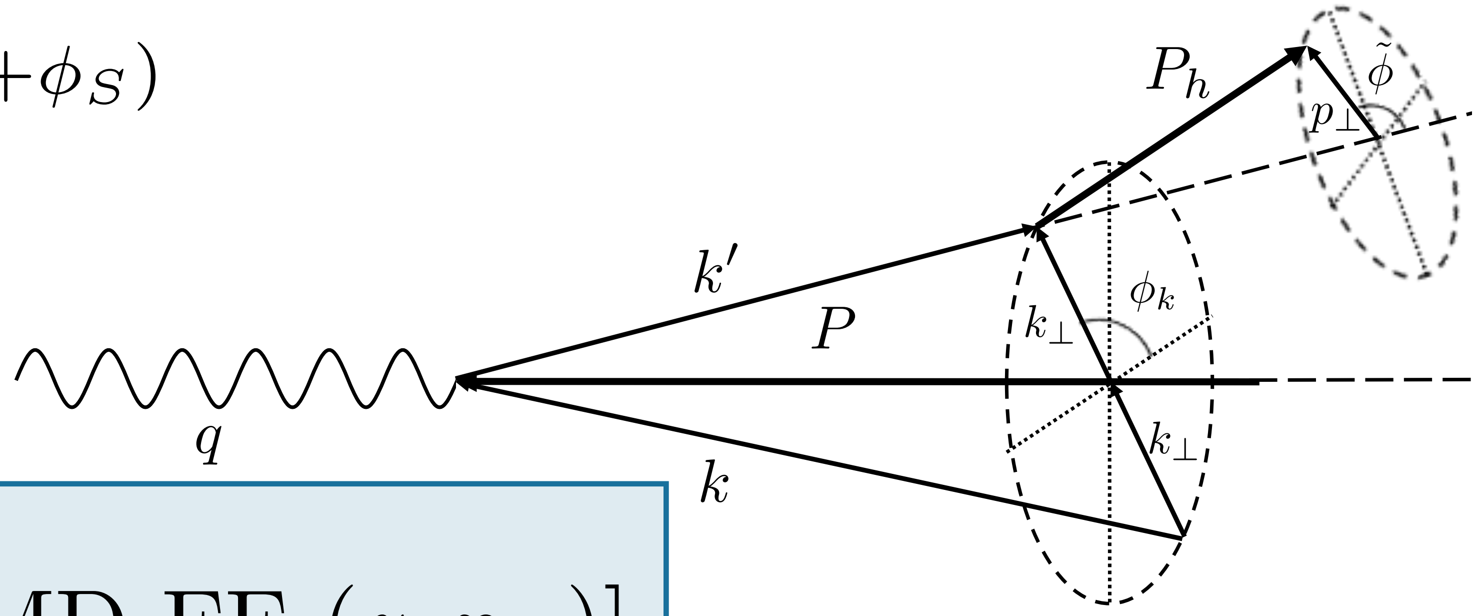
	U	L	T
U	D_1		$H_1^\perp$

Chiral odd

TMD PDFs and fragmentation functions (FFs)

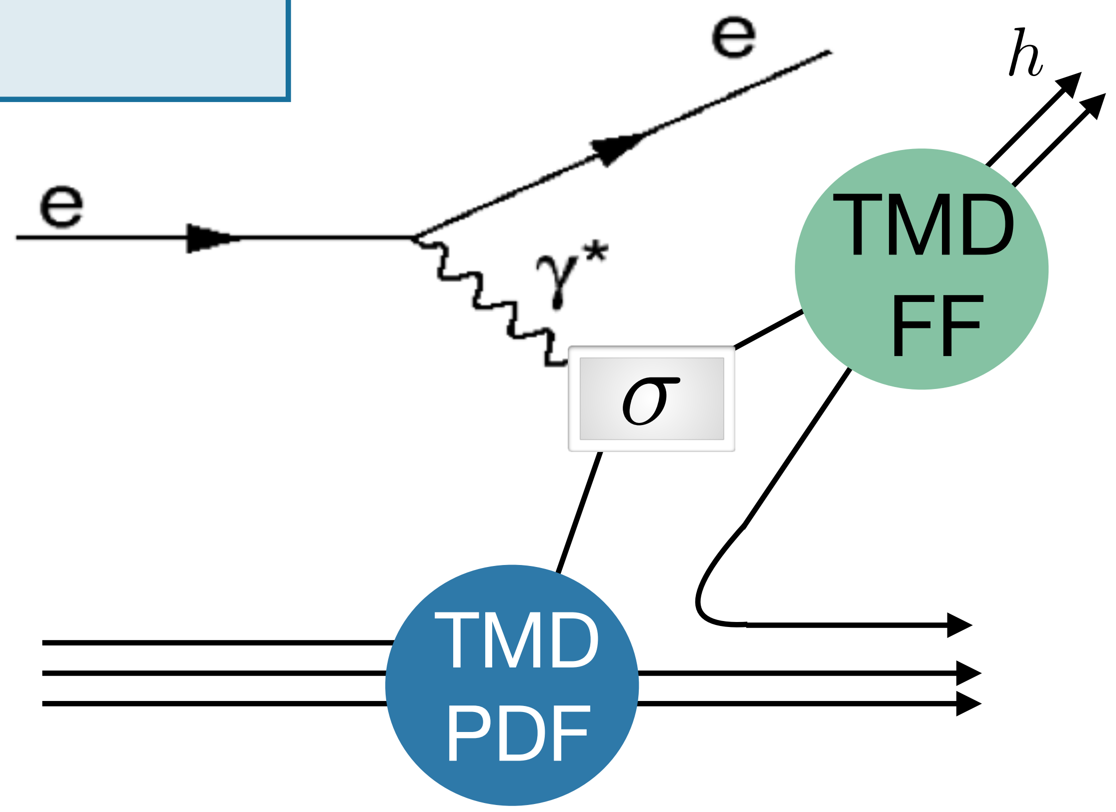
Azimuthal amplitudes related to structure functions F_{XY} :

$$2\langle \sin(\phi + \phi_S)\rangle^h_{UT} = \epsilon\, F^{\sin(\phi+\phi_S)}_{UT}$$



$$F_{XY} \propto \mathcal{C}\,[\mathrm{TMD\ PDF}(x, k_\perp) \times\ \mathrm{TMD\ FF}\ (z, p_\perp)]$$

$$z \overset{\mathrm{lab}}{=} \frac{E_h}{E_{\gamma*}}$$



quark polarisation (columns) / nucleon polarisation (rows)

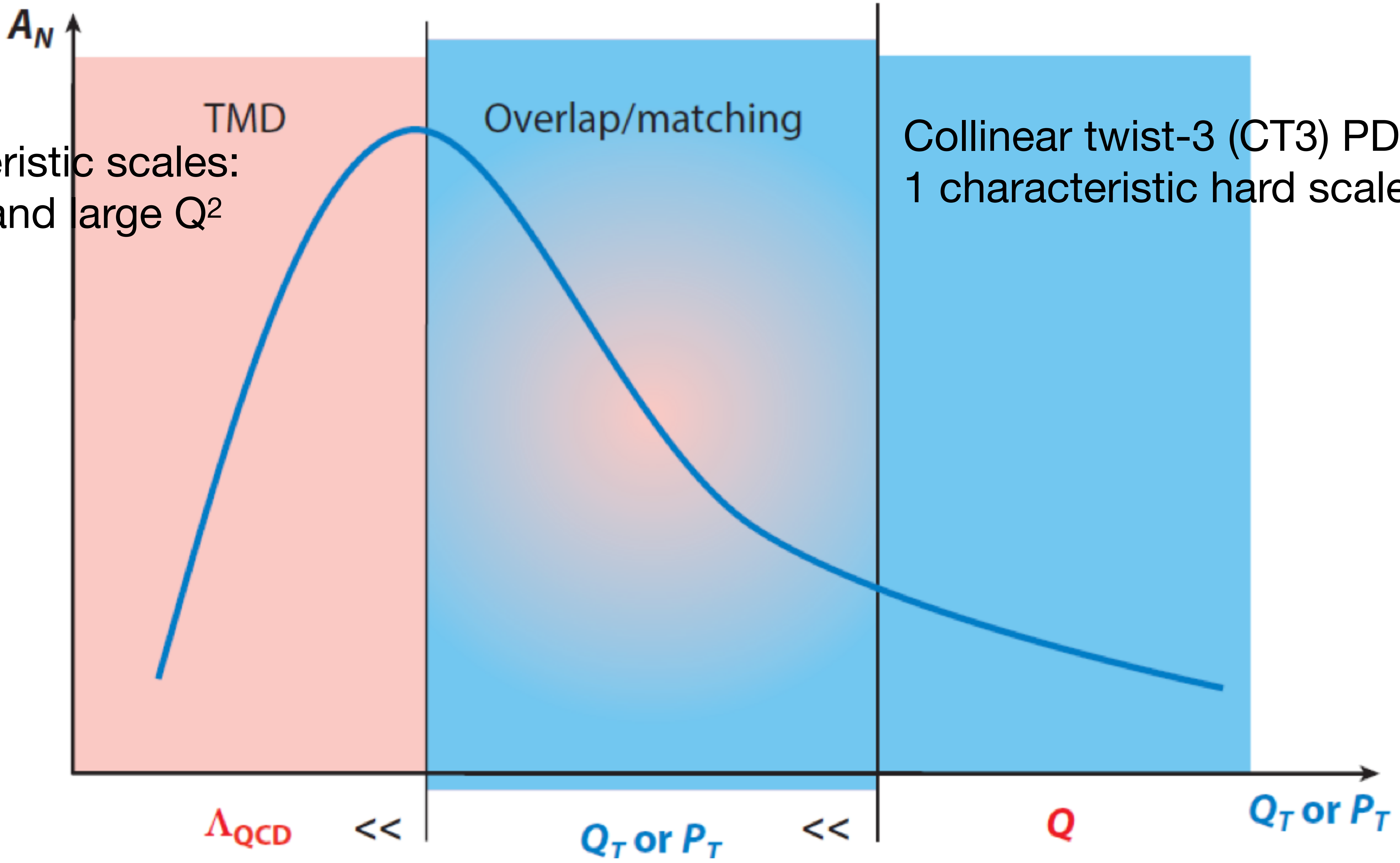
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\, h_{1T}^\perp$

quark polarisation (columns) / hadron polarisation (rows)

	U	L	T
U	D_1		$H_1^\perp$

Chiral odd

Validity of TMD description

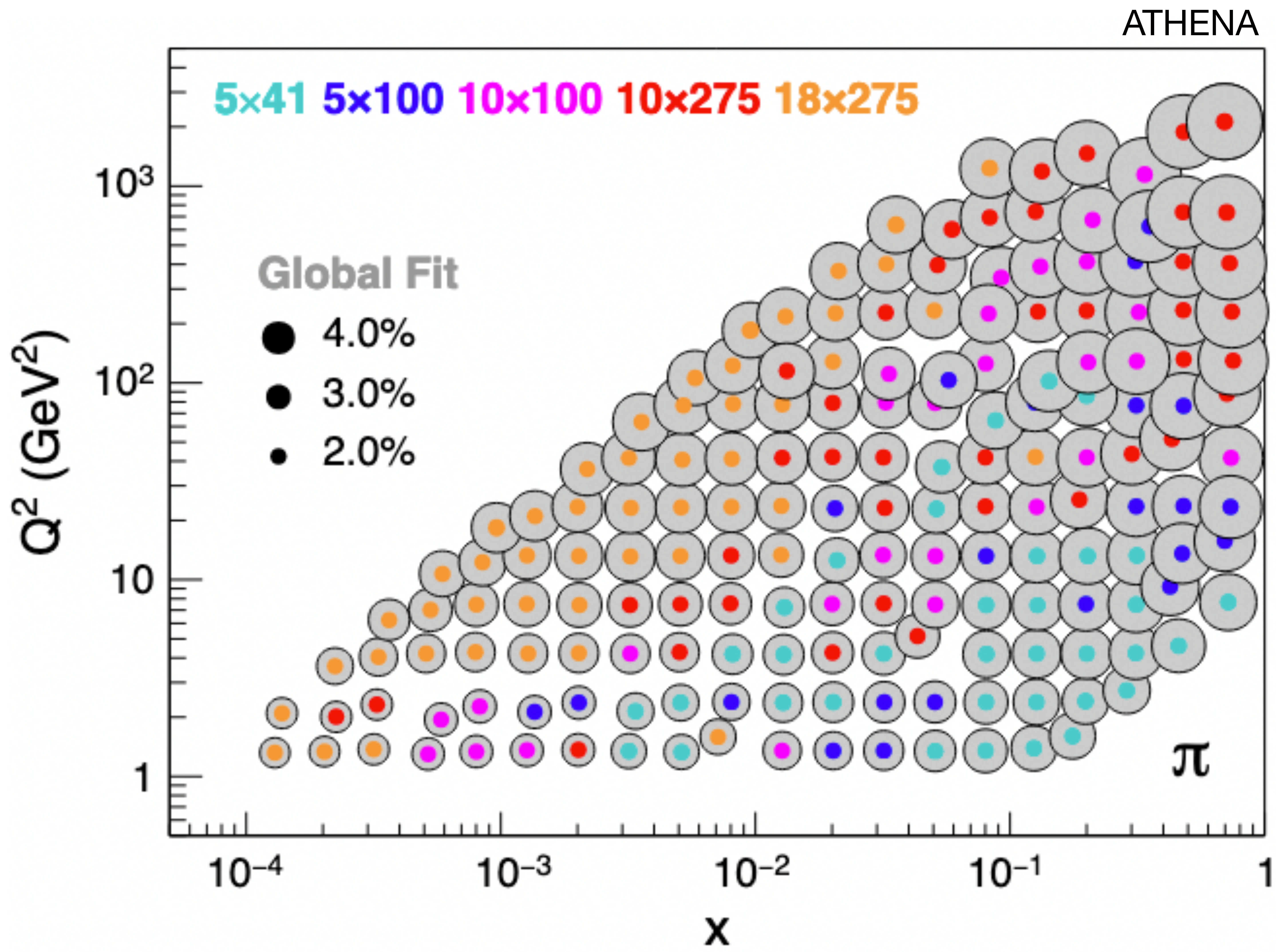


2 characteristic scales:
small P_{hT} and large Q^2

Collinear twist-3 (CT3) PDFs.
1 characteristic hard scale, e.g., P_{hT}

Consistent results for TMD and CT3 in overlap region

Spin-independent TMD PDFs at EIC



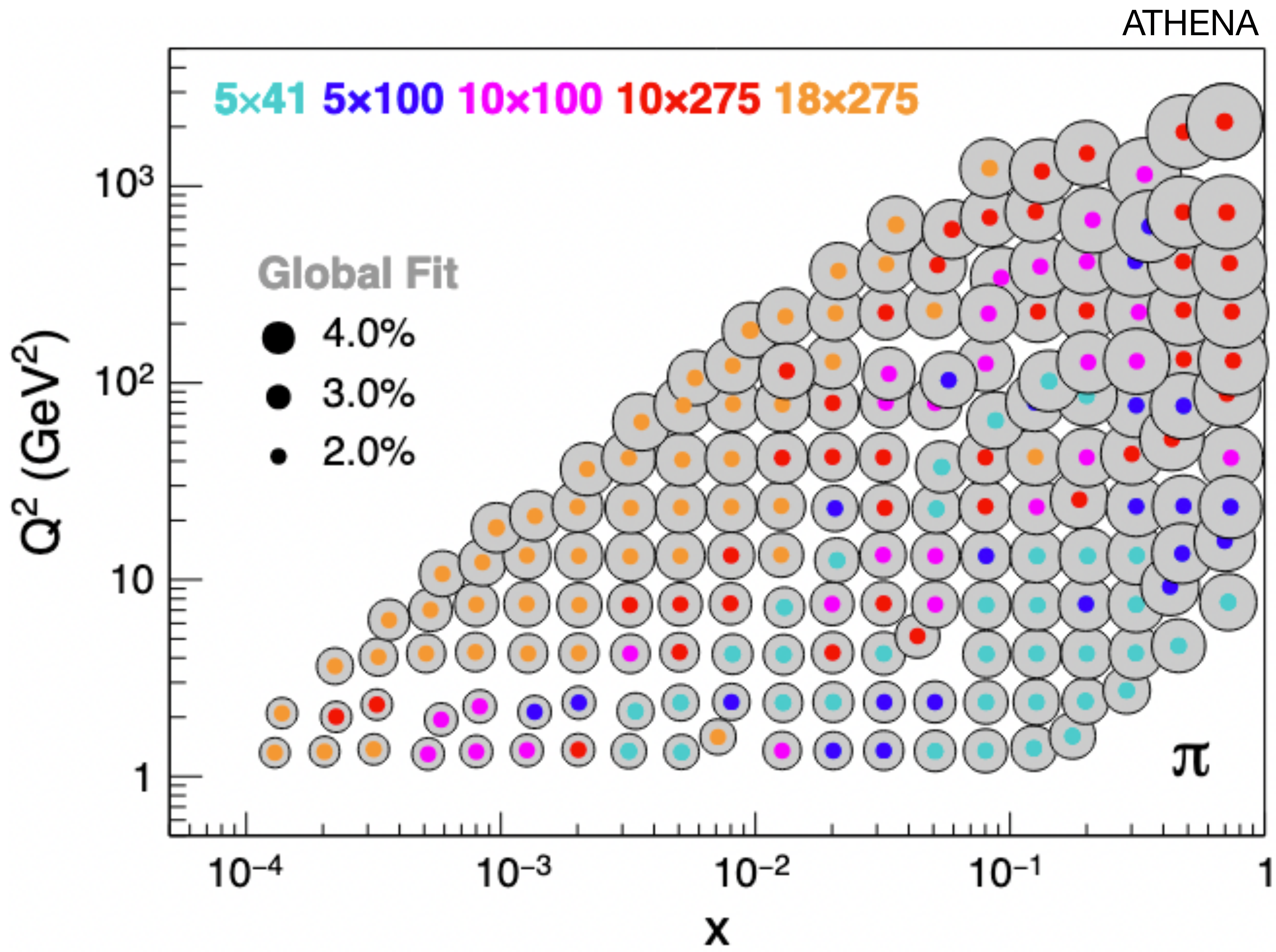
Fit:
A. Bacchetta et al.,
JHEP 06 (2017) 081,
JHEP 06 (2019) 051 (erratum)

EIC uncertainties dominated by assumed
3% point-to-point uncorrelated uncertainty
3% scale uncertainty

Theory uncertainties dominated by TMD evolution.

Spin-independent TMD PDFs at EIC

Large lever-arm in Q^2 over large x range
→ Q^2 evolution of TMD PDF

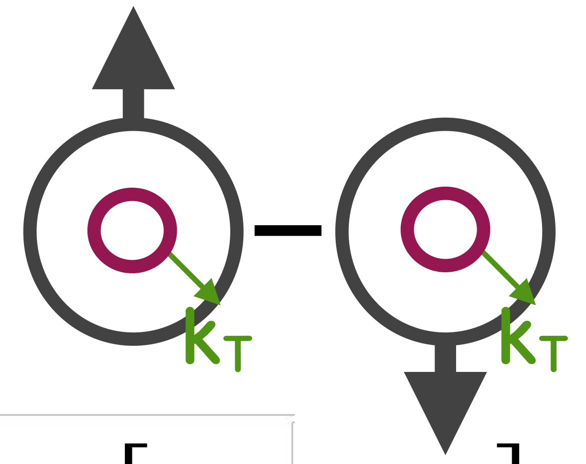


Fit:
A. Bacchetta et al.,
JHEP 06 (2017) 081,
JHEP 06 (2019) 051 (erratum)

EIC uncertainties dominated by assumed
3% point-to-point uncorrelated uncertainty
3% scale uncertainty

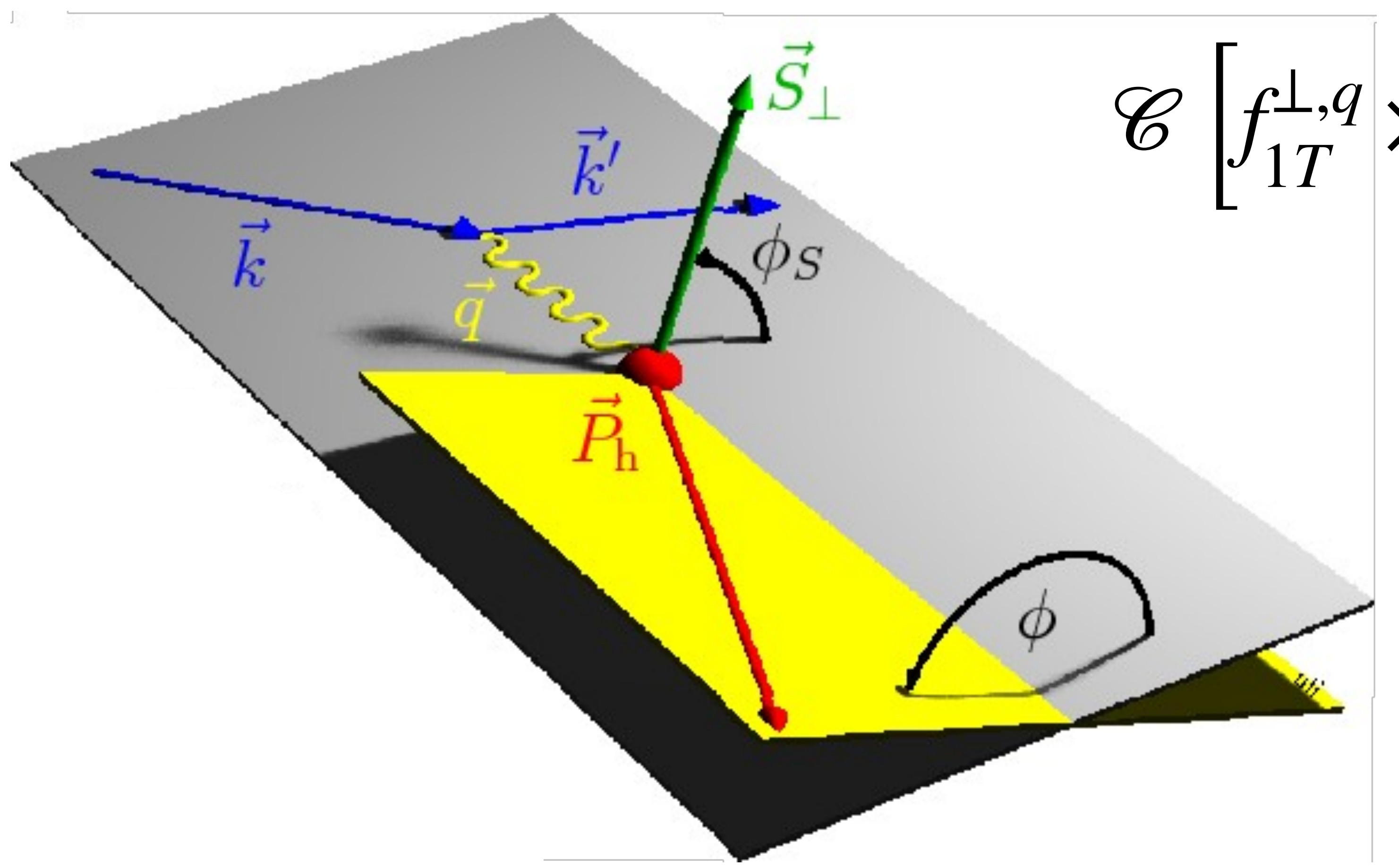
Theory uncertainties dominated by TMD evolution.

Sivers amplitudes: measurement

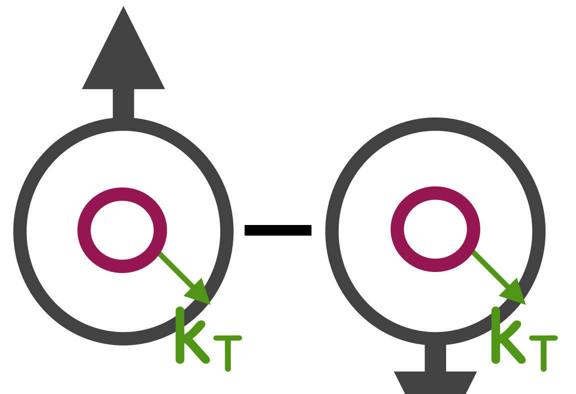


$\mathscr{C}\left[f_{1T}^{\perp,q} \times D_1^q\right]$

$$A_{UT} = \frac{1}{\langle |S_T| \rangle} \frac{N^{\uparrow}(\phi,\phi_S) - N^{\downarrow}(\phi,\phi_S)}{N^{\uparrow}(\phi,\phi_S) + N^{\downarrow}(\phi,\phi_S)}$$

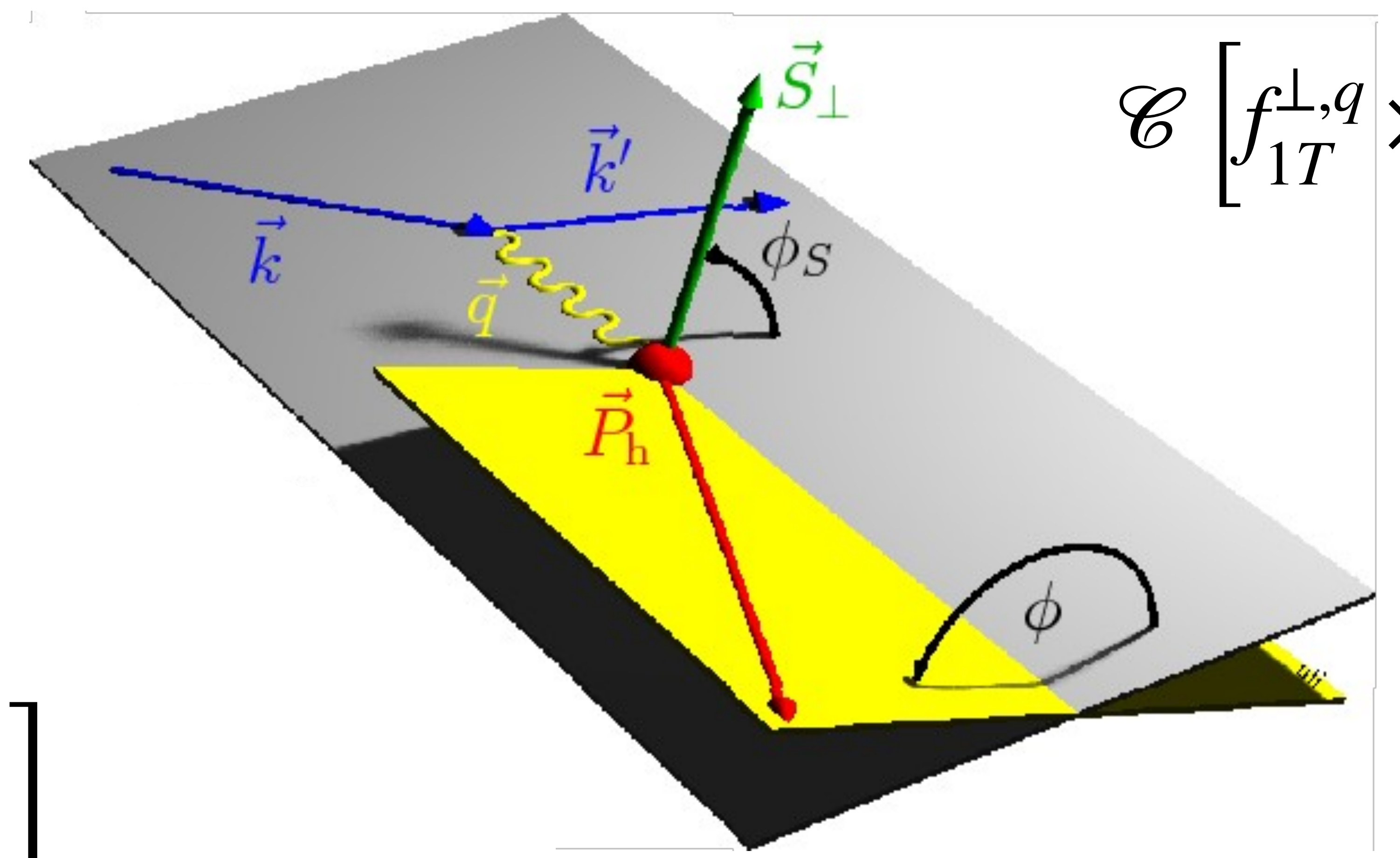


Sivers amplitudes: measurement



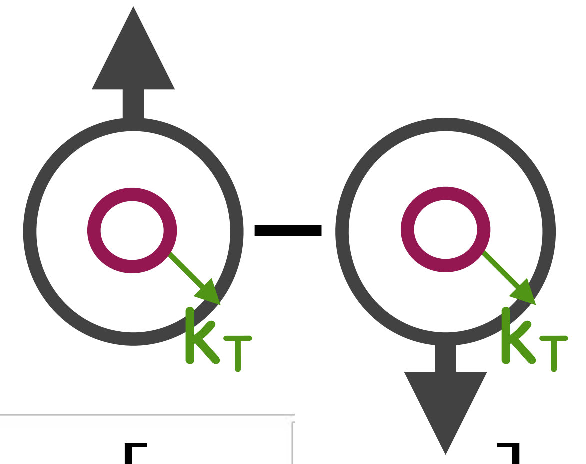
$\mathscr{C}\left[f_{1T}^{\perp,q} \times D_1^q\right]$

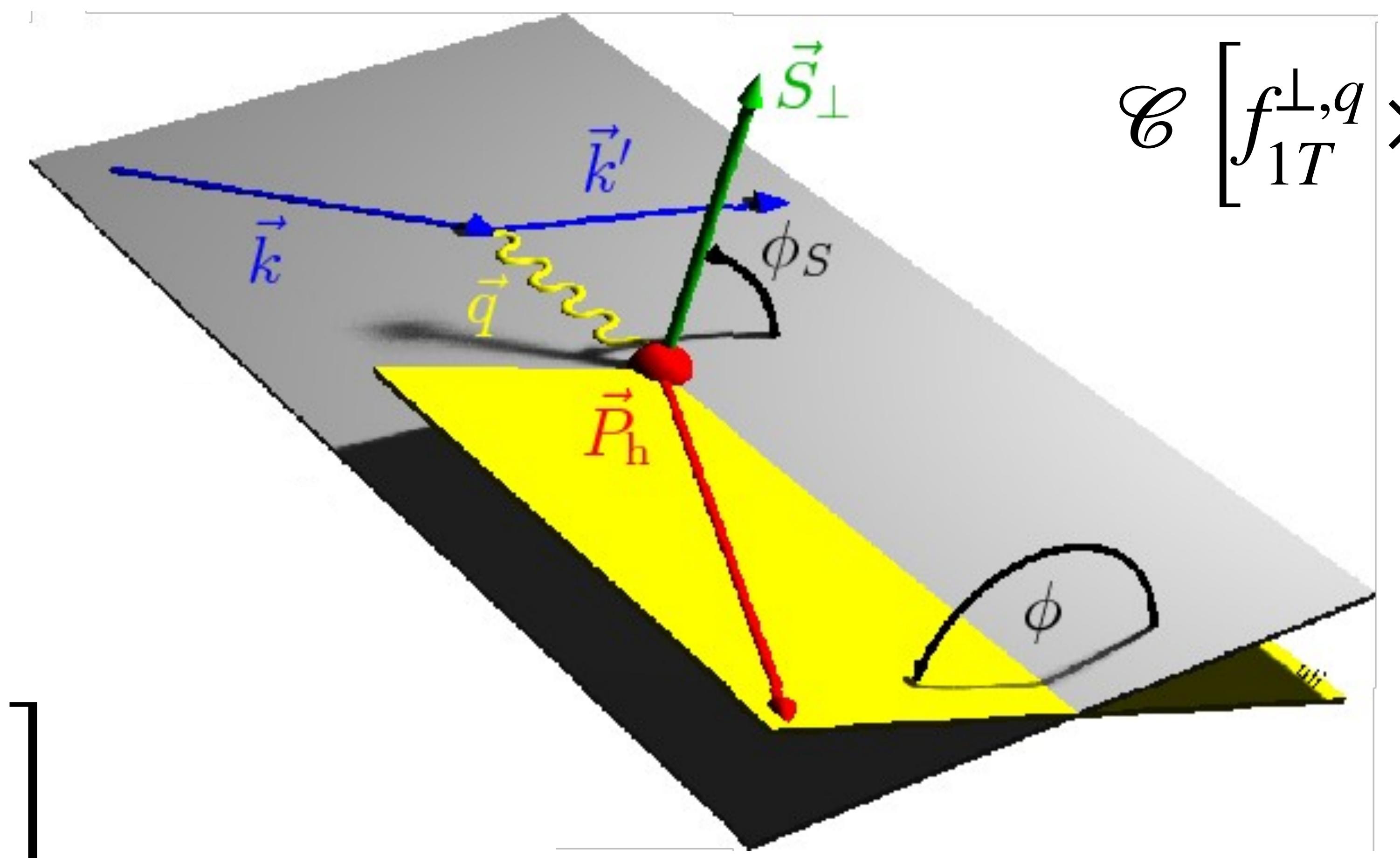
$$A_{UT} = \frac{1}{\langle|S_T|\rangle} \frac{N^{\uparrow}(\phi,\phi_S) - N^{\downarrow}(\phi,\phi_S)}{N^{\uparrow}(\phi,\phi_S) + N^{\downarrow}(\phi,\phi_S)}$$



$$\sim \sin(\phi - \phi_S) \sum_q e_q^2\, \mathscr{C}\left[f_{1T}^{\perp,q}(x,k_\perp) \times D_1^q(z,p_\perp)\right]$$

Sivers amplitudes: measurement

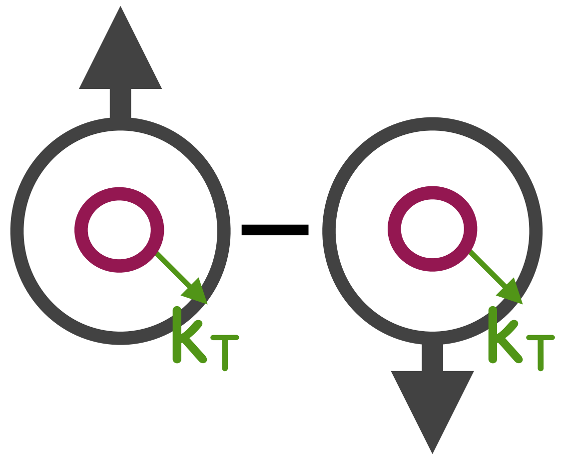




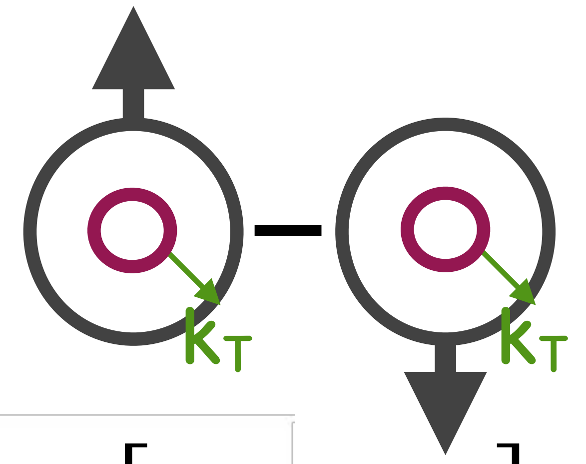
$$A_{UT} = \frac{1}{\langle |S_T| \rangle} \frac{N^\uparrow(\phi,\phi_S) - N^\downarrow(\phi,\phi_S)}{N^\uparrow(\phi,\phi_S) + N^\downarrow(\phi,\phi_S)}$$

$$\sim \sin(\phi - \phi_S) \sum_q e_q^2 \mathscr{C}\left[f_{1T}^{\perp,q}(x,k_\perp) \times D_1^q(z,p_\perp)\right]$$

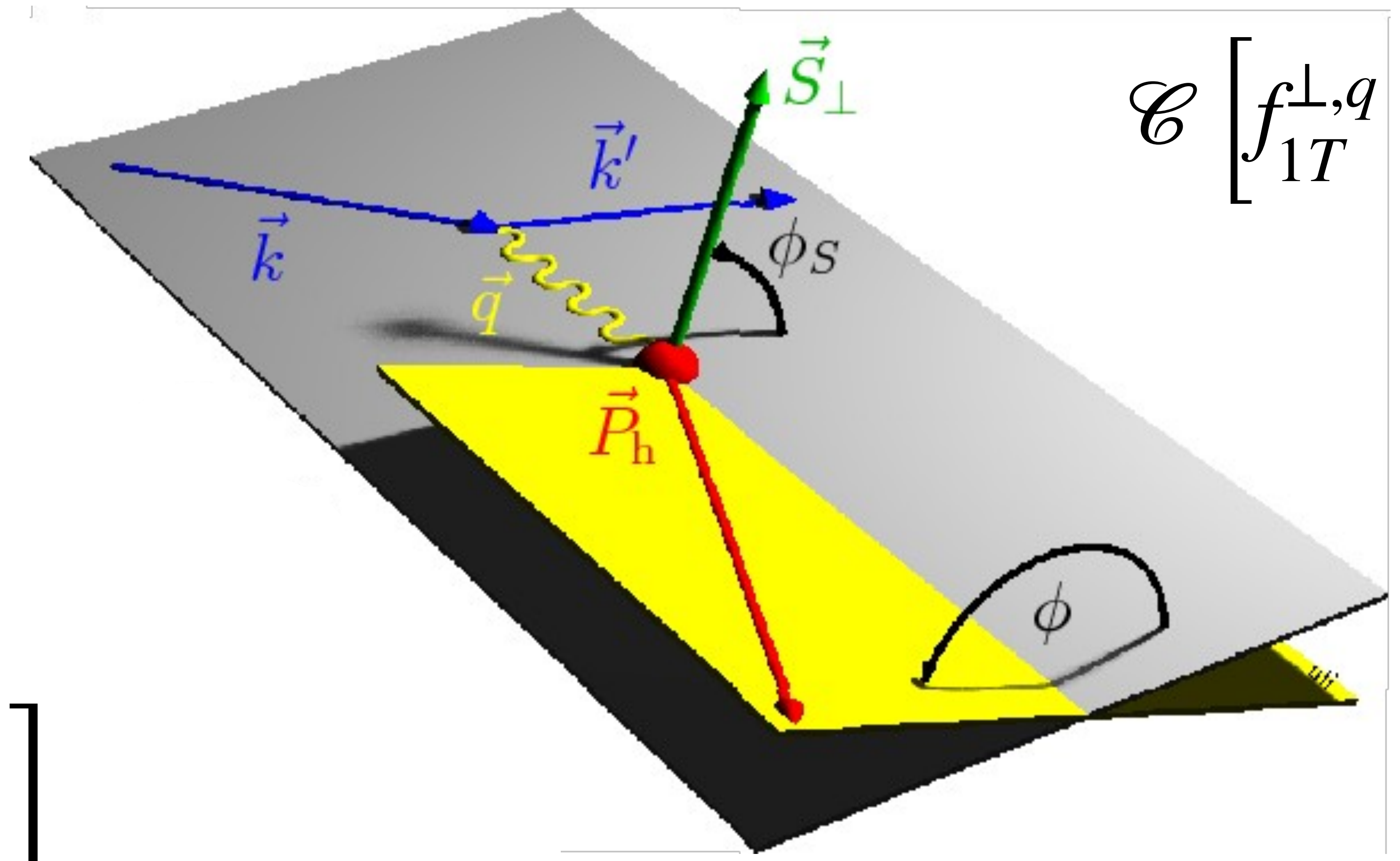
$f_{1T}^{\perp,q}(x,k_\perp)$: Sivers function



Sivers amplitudes: measurement



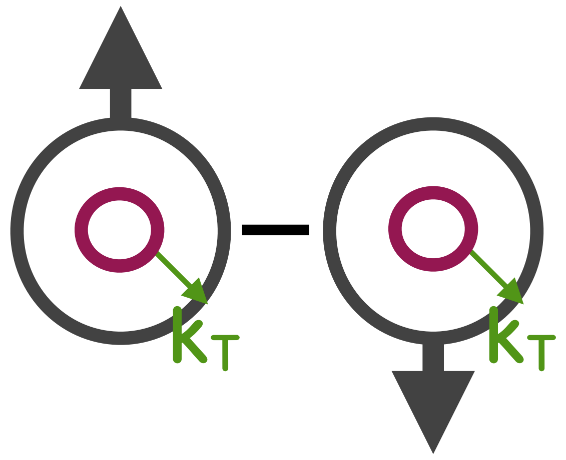
$\mathscr{C}\left[f_{1T}^{\perp,q} \times D_1^q\right]$



$$A_{UT} = \frac{1}{\langle |S_T| \rangle} \frac{N^{\uparrow}(\phi, \phi_S) - N^{\downarrow}(\phi, \phi_S)}{N^{\uparrow}(\phi, \phi_S) + N^{\downarrow}(\phi, \phi_S)}$$

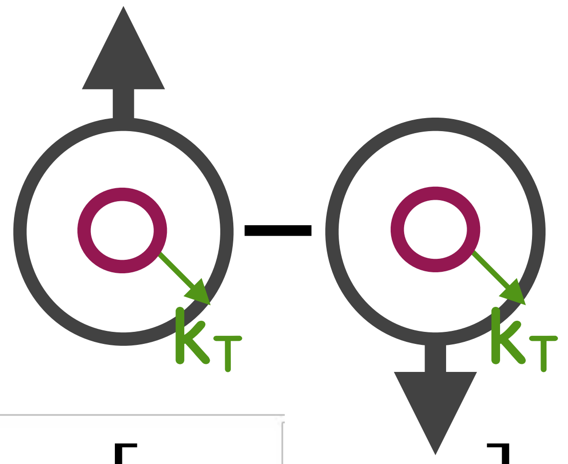
$$\sim \sin(\phi - \phi_S) \sum_q e_q^2 \mathscr{C}\left[f_{1T}^{\perp,q}(x, k_\perp) \times D_1^q(z, p_\perp)\right]$$

$f_{1T}^{\perp,q}(x, k_\perp)$: Sivers function

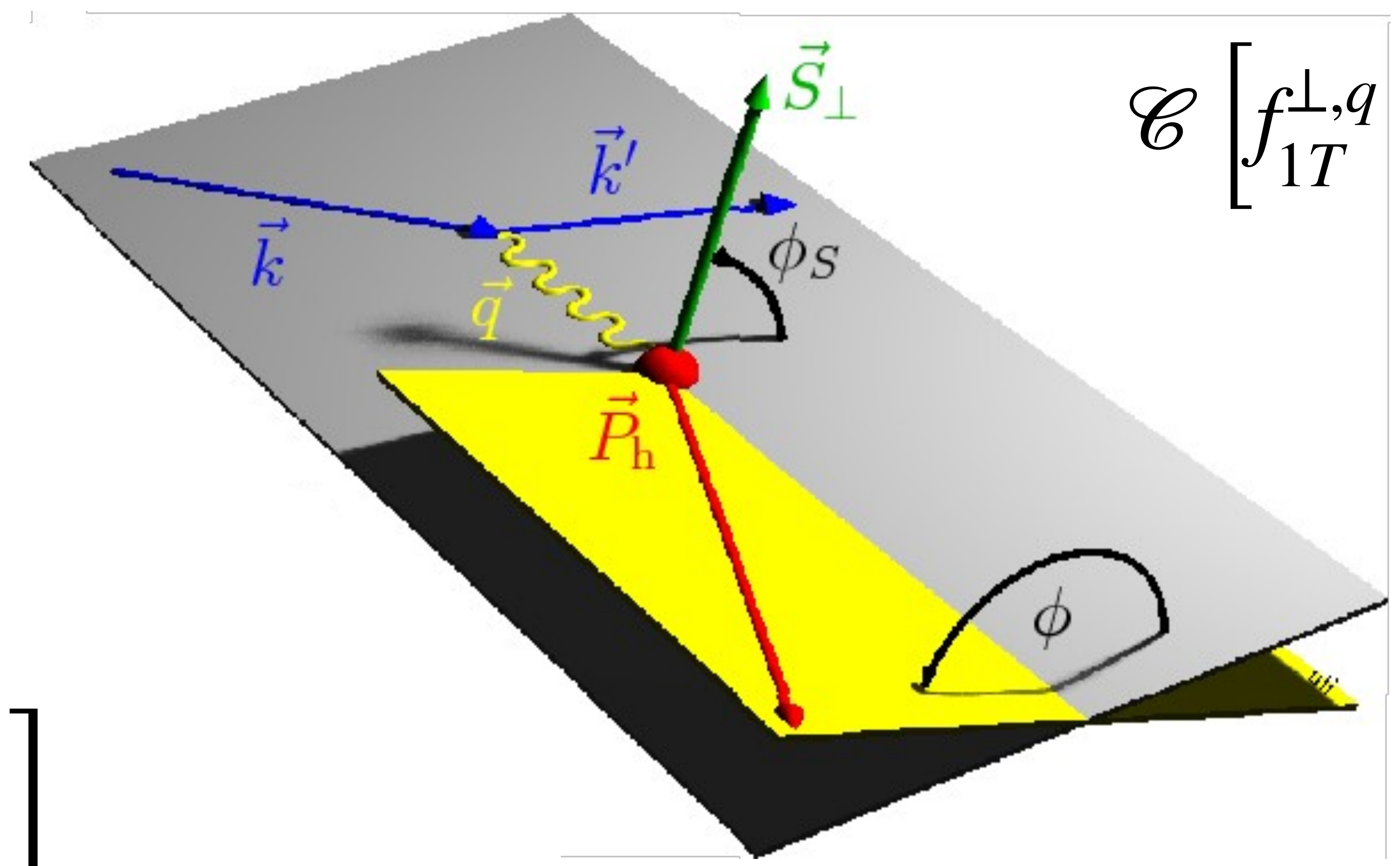


$D_1^q(z, p_\perp)$: spin-independent fragmentation function

Sivers amplitudes: measurement



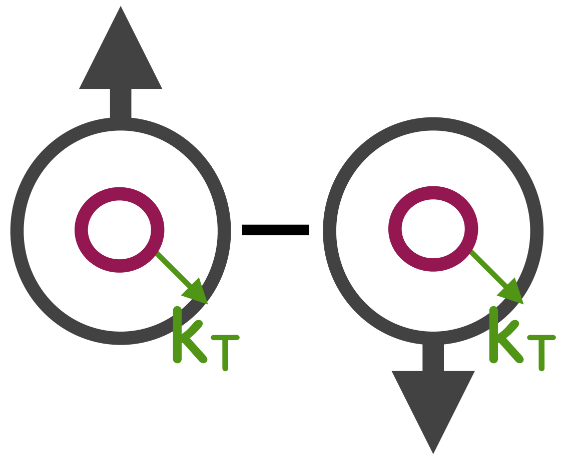
$\mathscr{C}\left[f_{1T}^{\perp,q} \times D_1^q\right]$



$$A_{UT} = \frac{1}{\langle |S_T| \rangle} \frac{N^\uparrow(\phi, \phi_S) - N^\downarrow(\phi, \phi_S)}{N^\uparrow(\phi, \phi_S) + N^\downarrow(\phi, \phi_S)}$$

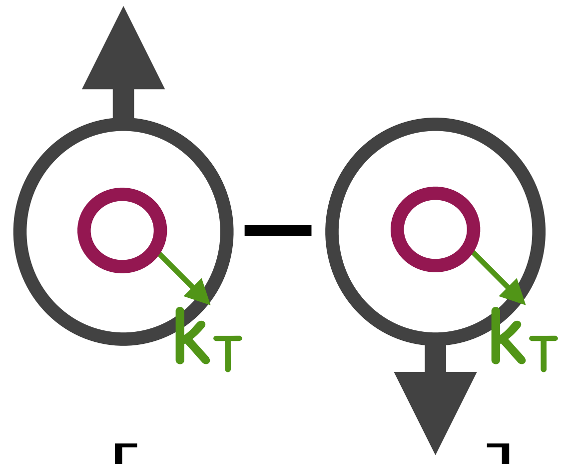
$$\sim \sin(\phi - \phi_S) \sum_q e_q^2 \mathscr{C}\left[f_{1T}^{\perp,q}(x, k_\perp) \times D_1^q(z, p_\perp)\right]$$

$f_{1T}^{\perp,q}(x, k_\perp)$: Sivers function



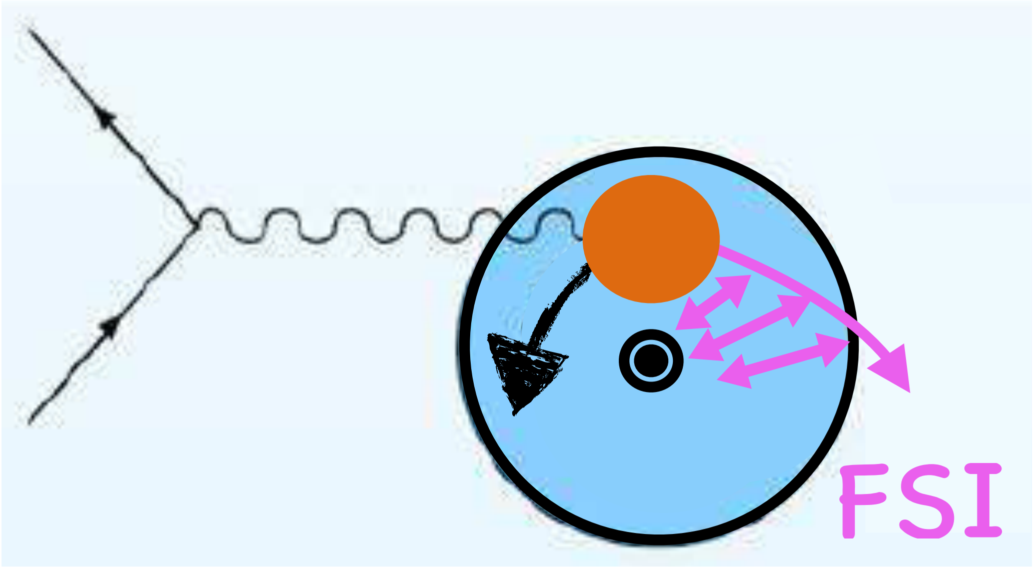
$D_1^q(z, p_\perp)$: spin-independent fragmentation function

Sivers amplitudes

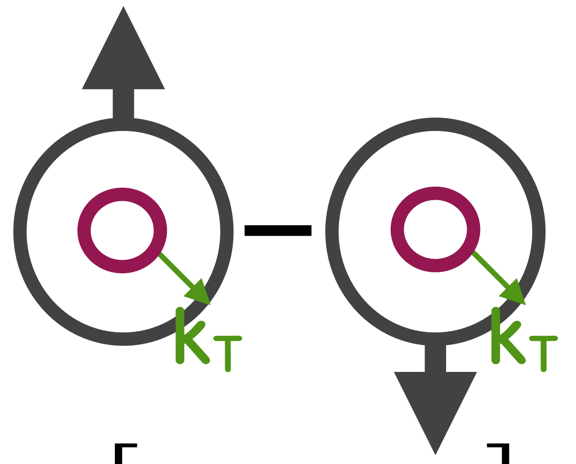


$\mathscr{C}\left[f_{1T}^{\perp,q} \times D_1^q\right]$

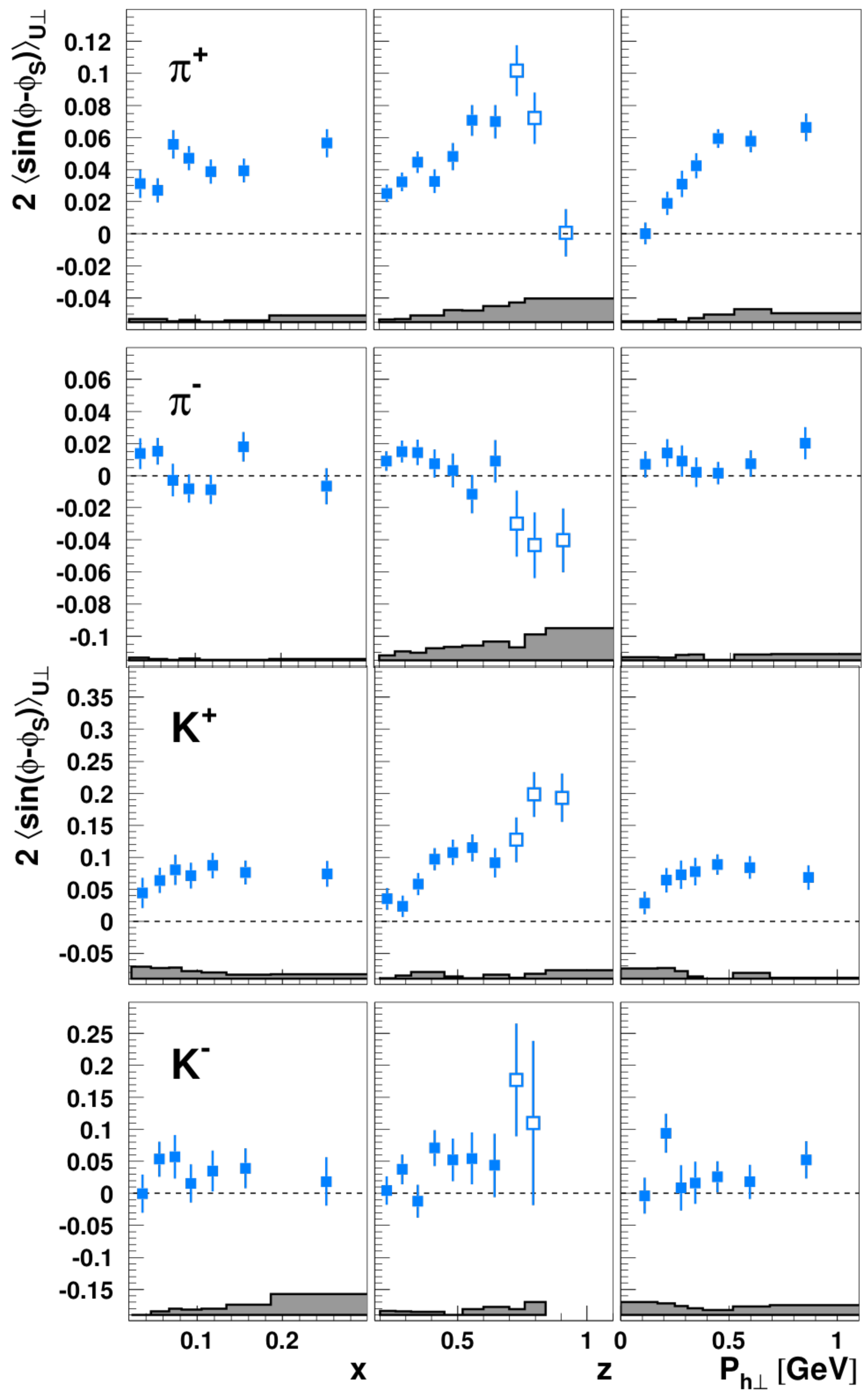
- Sivers function:
  - requires non-zero orbital angular momentum
  - final-state interactions ⟶ azimuthal asymmetries



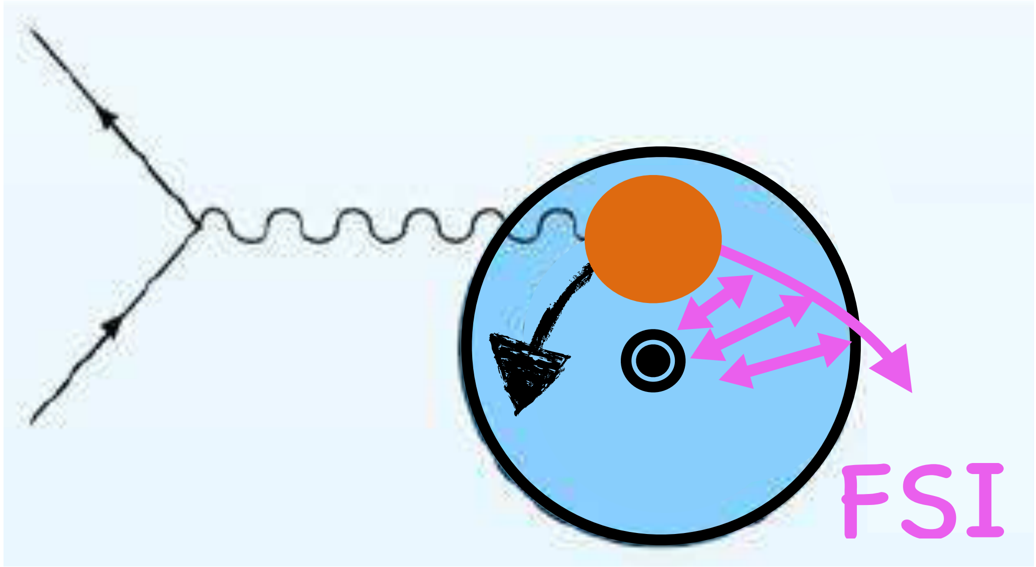
Sivers amplitudes



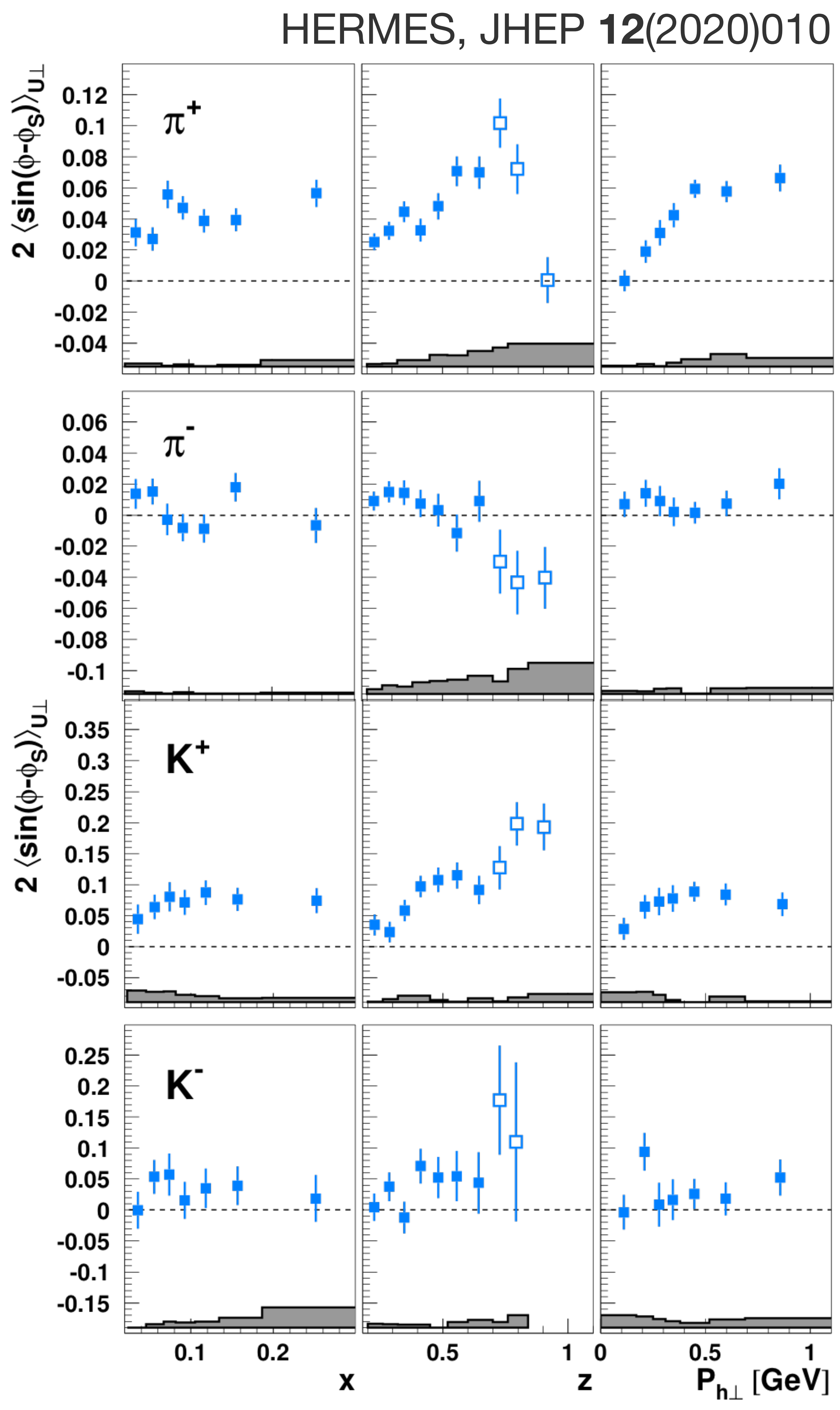
HERMES, JHEP **12**(2020)010

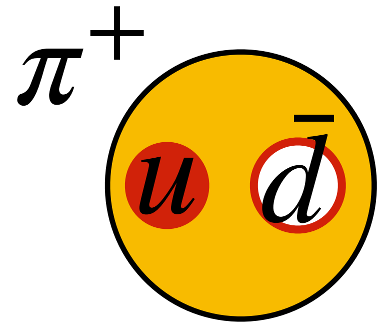


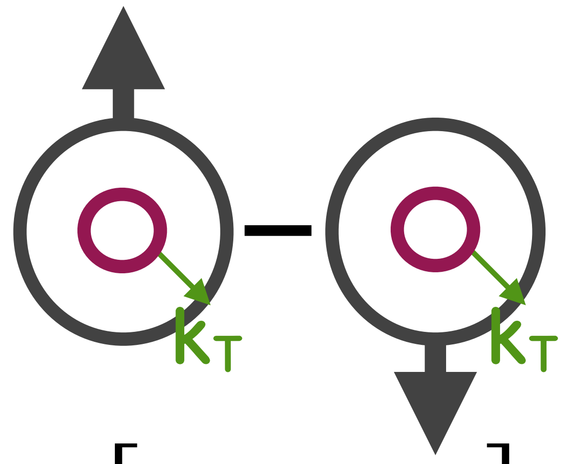
- Sivers function:
  - requires non-zero orbital angular momentum
  - final-state interactions ⟶ azimuthal asymmetries



Sivers amplitudes

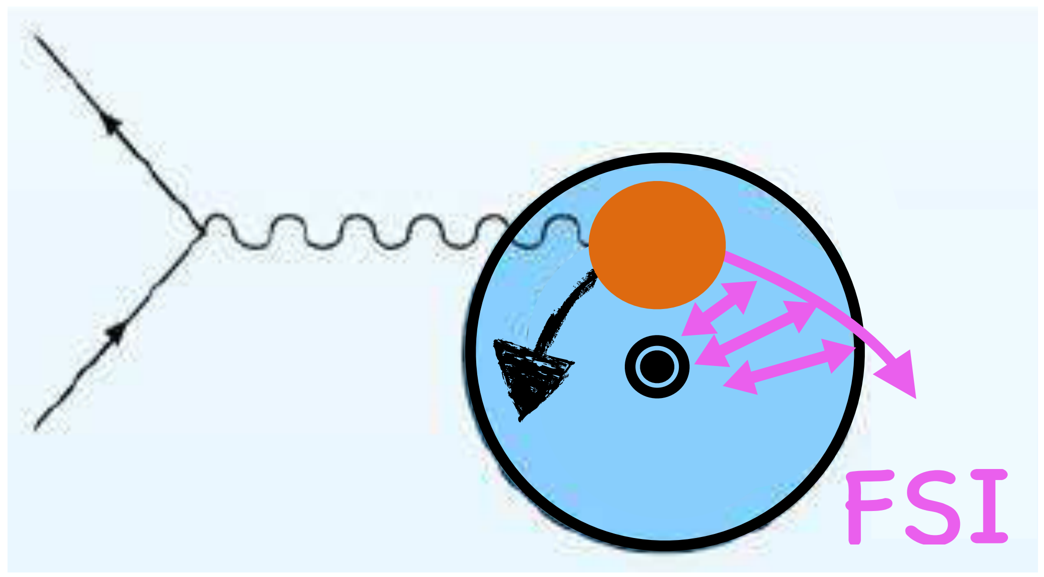




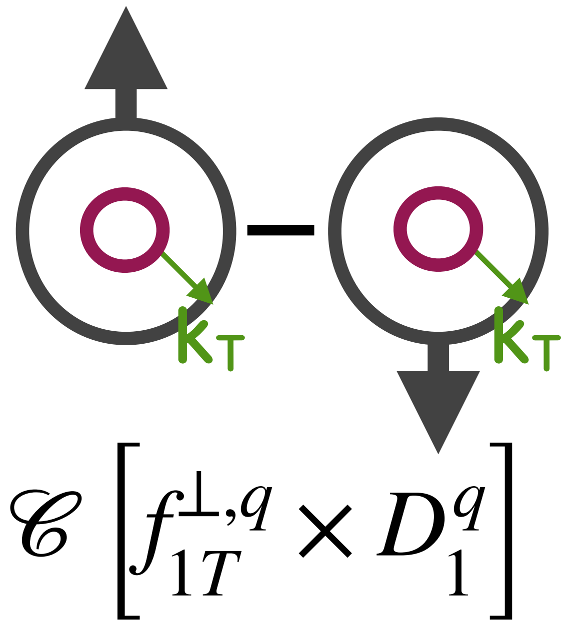


$\mathscr{C}\left[f_{1T}^{\perp,q} \times D_1^q\right]$

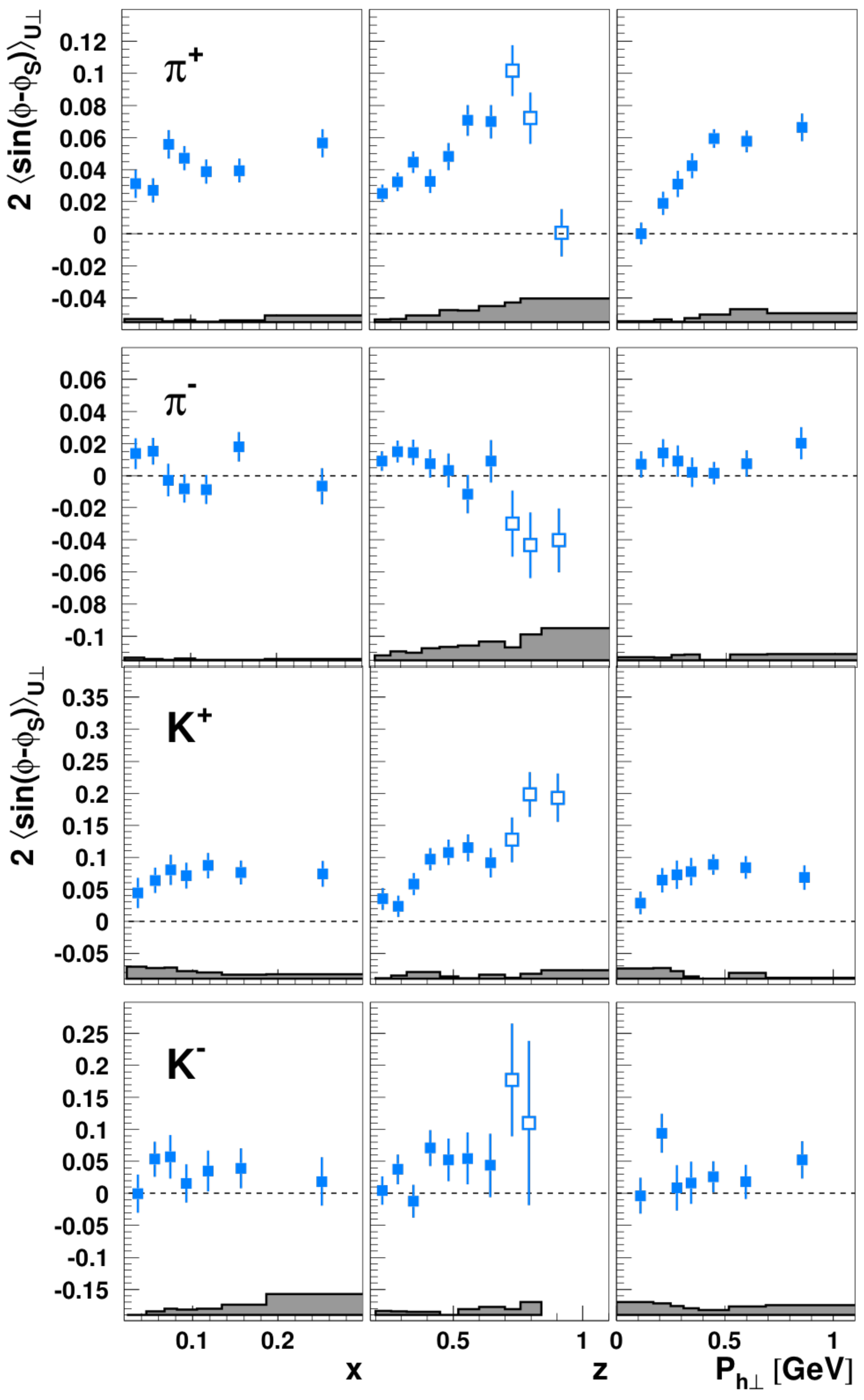
- Sivers function:
  - requires non-zero orbital angular momentum
  - final-state interactions ⟶ azimuthal asymmetries

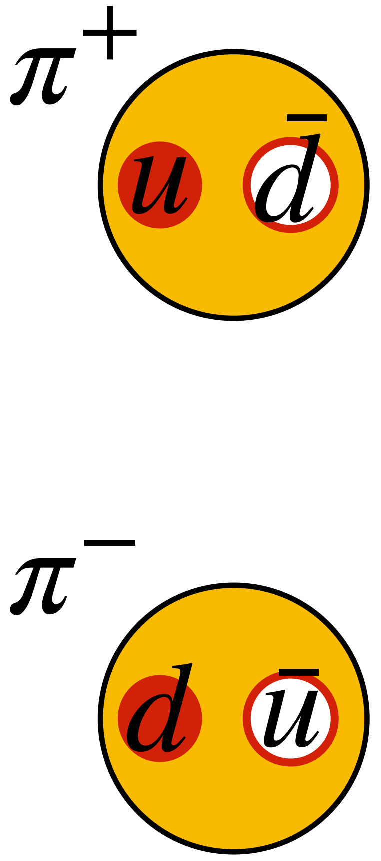


Sivers amplitudes

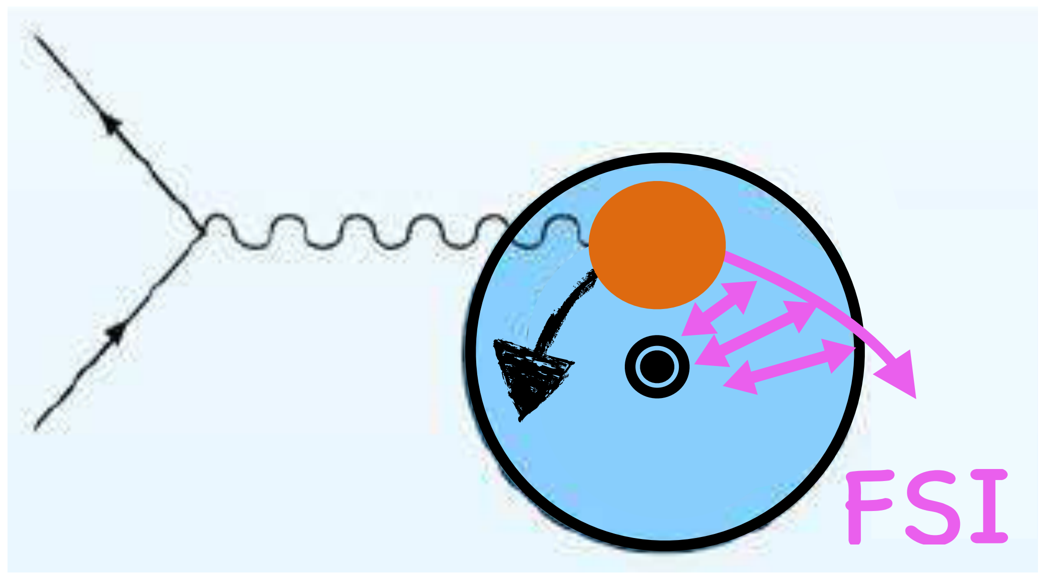


HERMES, JHEP **12**(2020)010

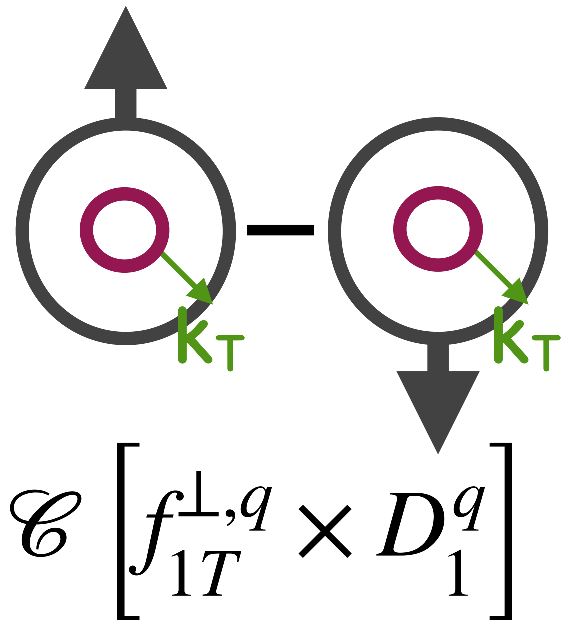




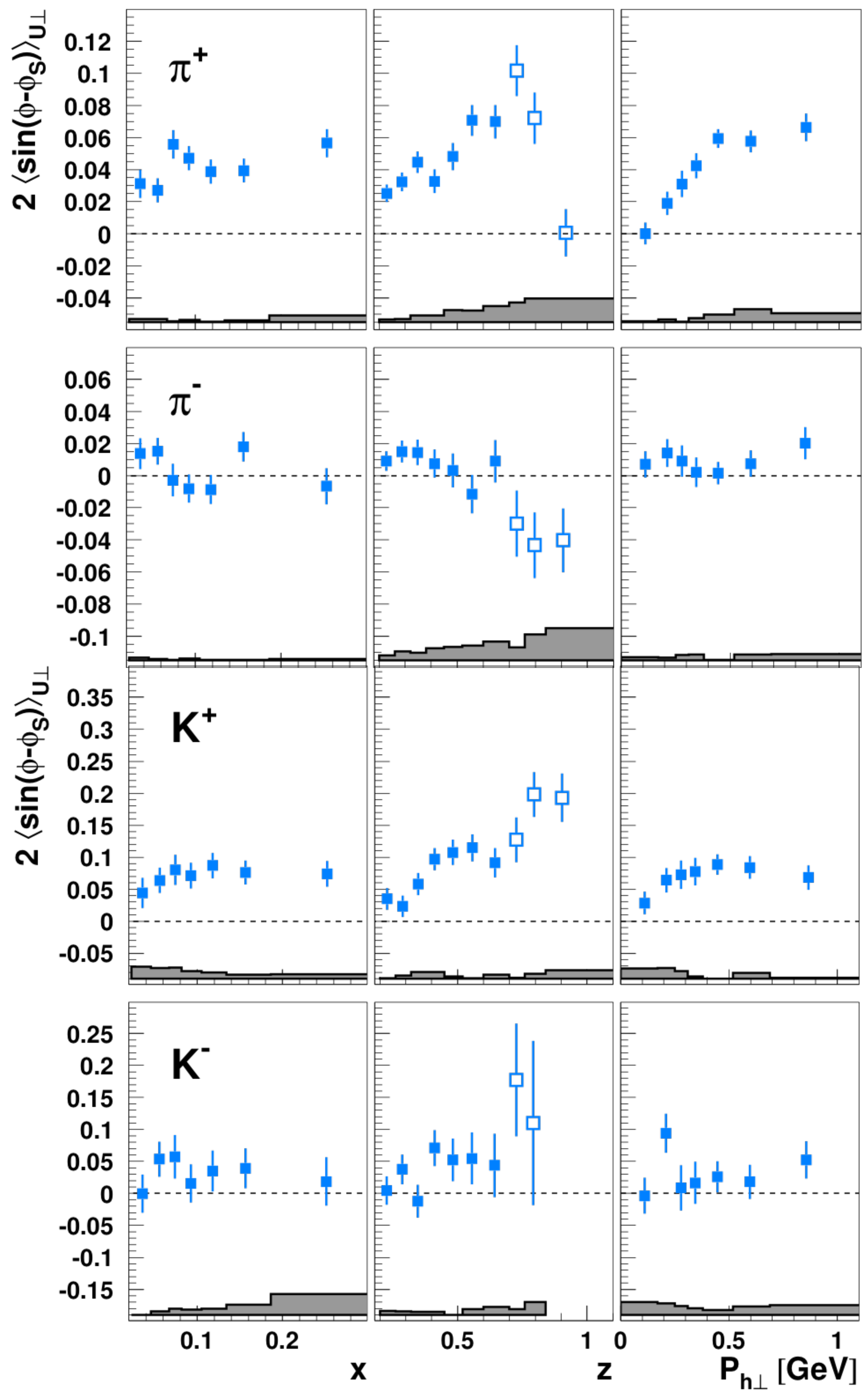
- Sivers function:
  - requires non-zero orbital angular momentum
  - final-state interactions ⟶ azimuthal asymmetries

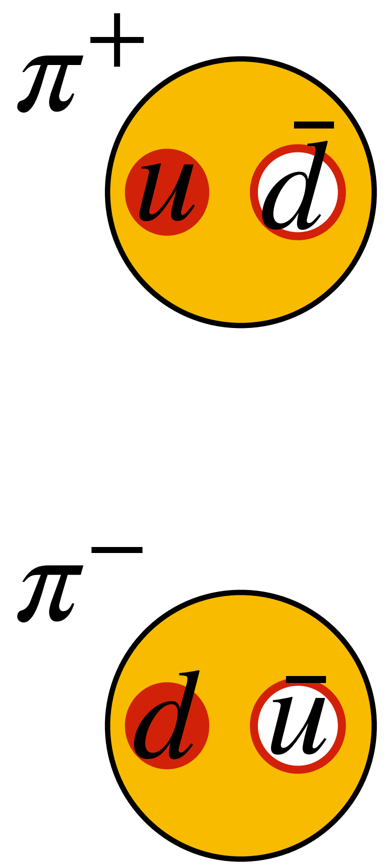


Sivers amplitudes

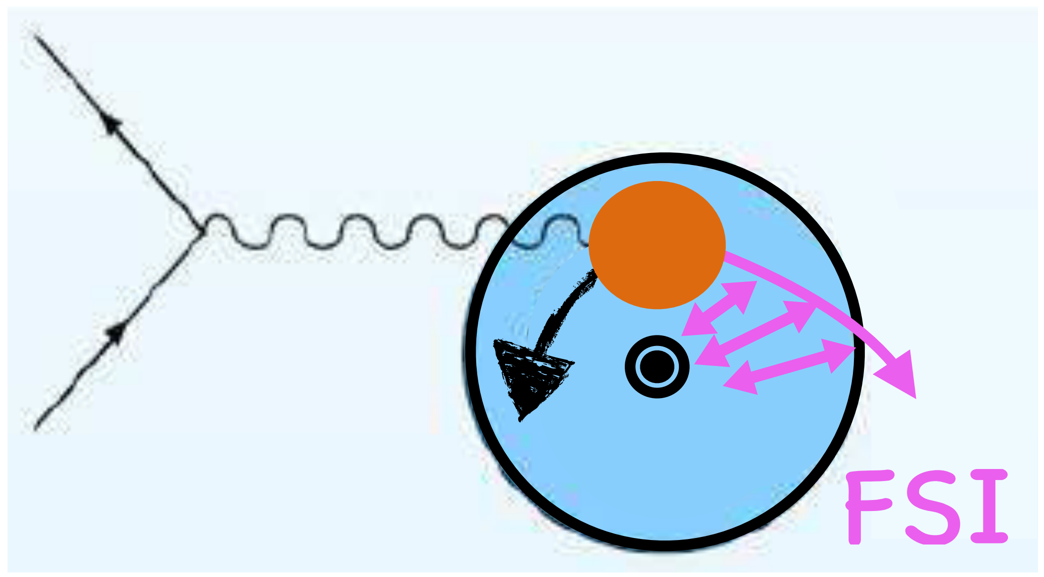


HERMES, JHEP **12**(2020)010





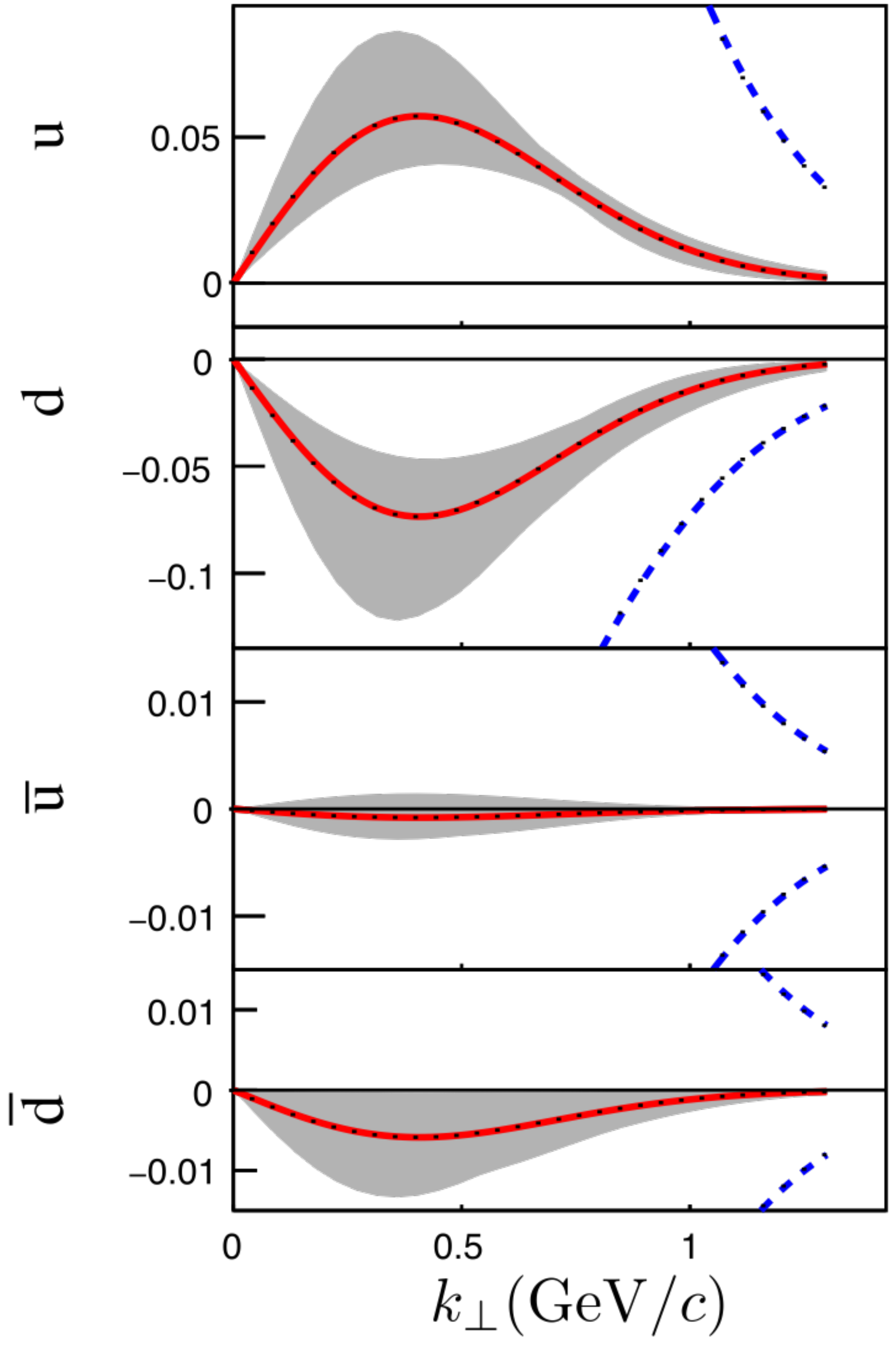
- Sivers function:
  - requires non-zero orbital angular momentum
  - final-state interactions ⟶ azimuthal asymmetries

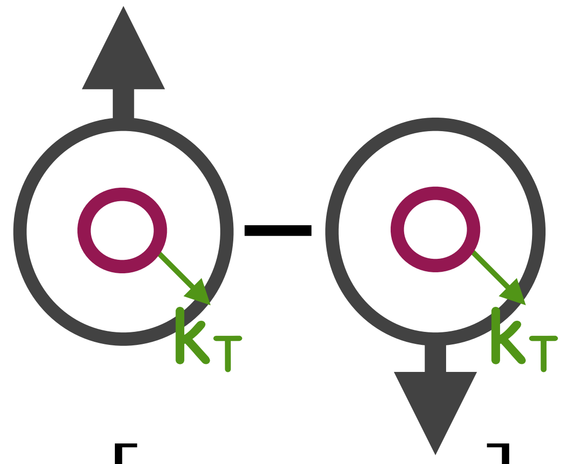


- π^+:
  - positive -> non-zero orbital angular momentum
- π^-:
  - consistent with zero → u and d quark cancelation

Sivers function

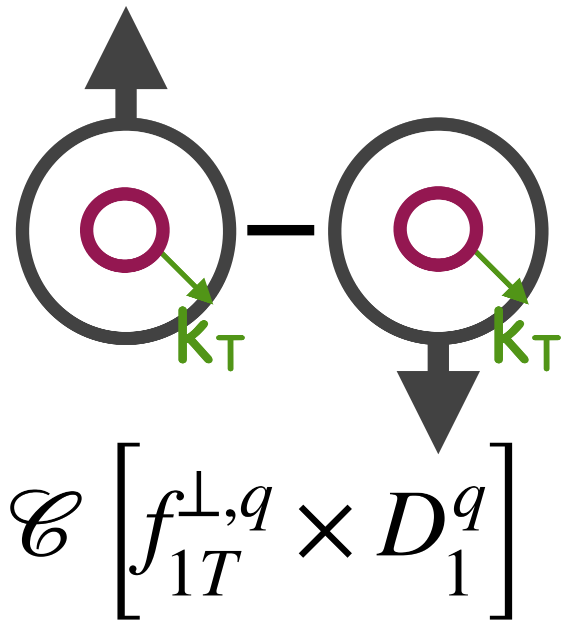
M. Anselmino et al., JHEP **04** (2017) 046





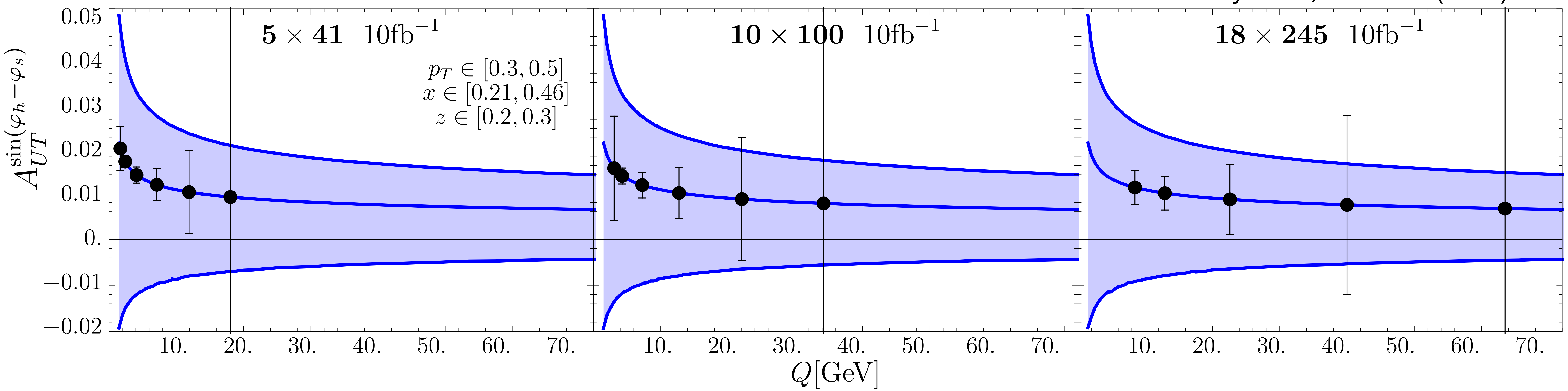
$\mathscr{C}\left[f_{1T}^{\perp,q} \times D_1^q\right]$

Sivers amplitude and Q²



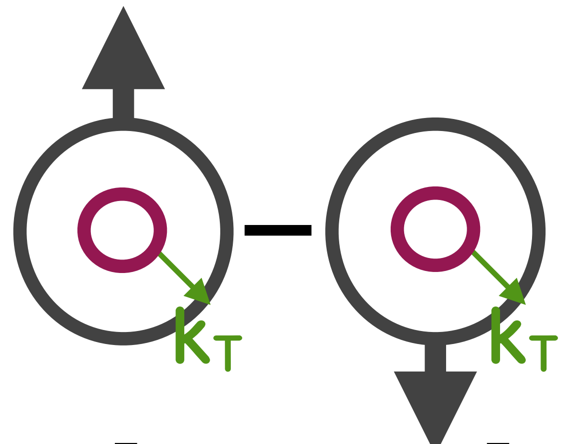
R. Seidl, A. Vladimirov et al., NIM A **1055** (2023) 168458

Parametrisation: M. Bury et al., JHEP **05** (2021)151



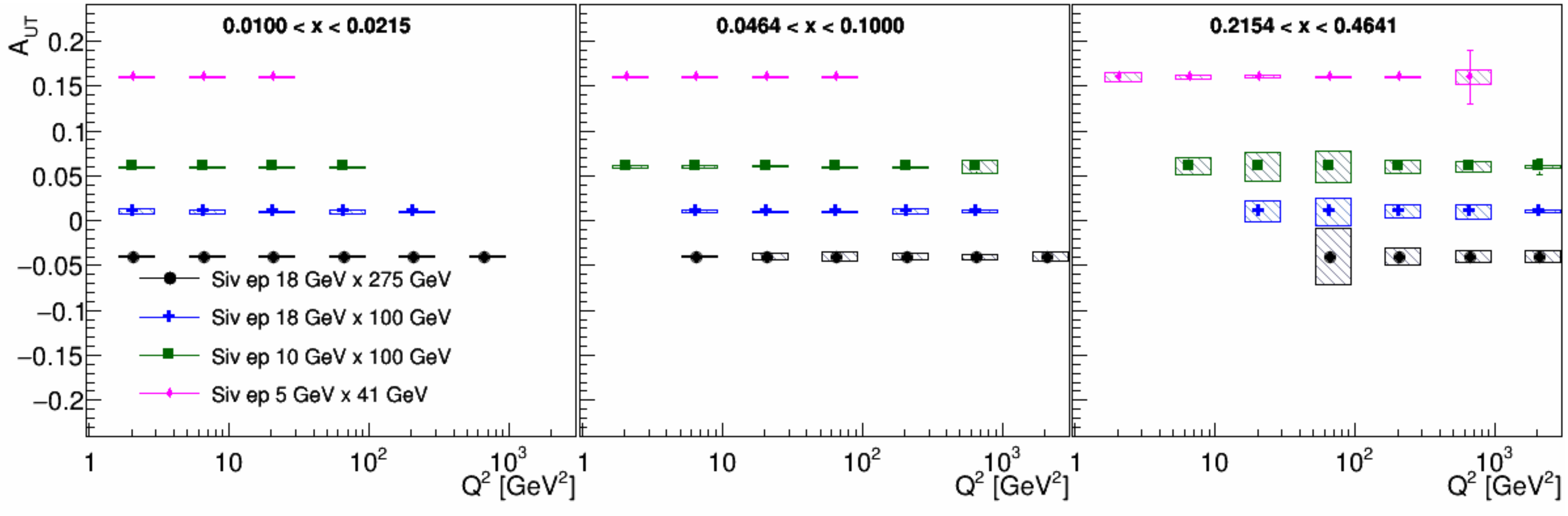
Decrease of asymmetry with increasing Q² → need high precision (<1%) to measure asymmetry at high Q²

Impact of EIC on Sivers TMD PDFs

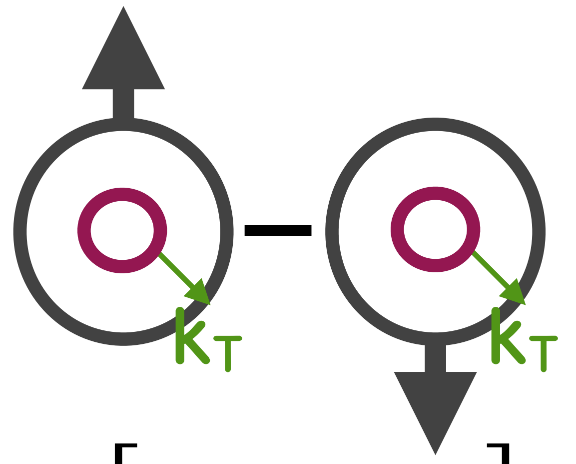


$$\mathscr{C}\left[f_{1T}^{\perp,q} \times D_1^q\right]$$

R. Seidl, A. Vladimirov et al., NIM A **1055** (2023) 168458

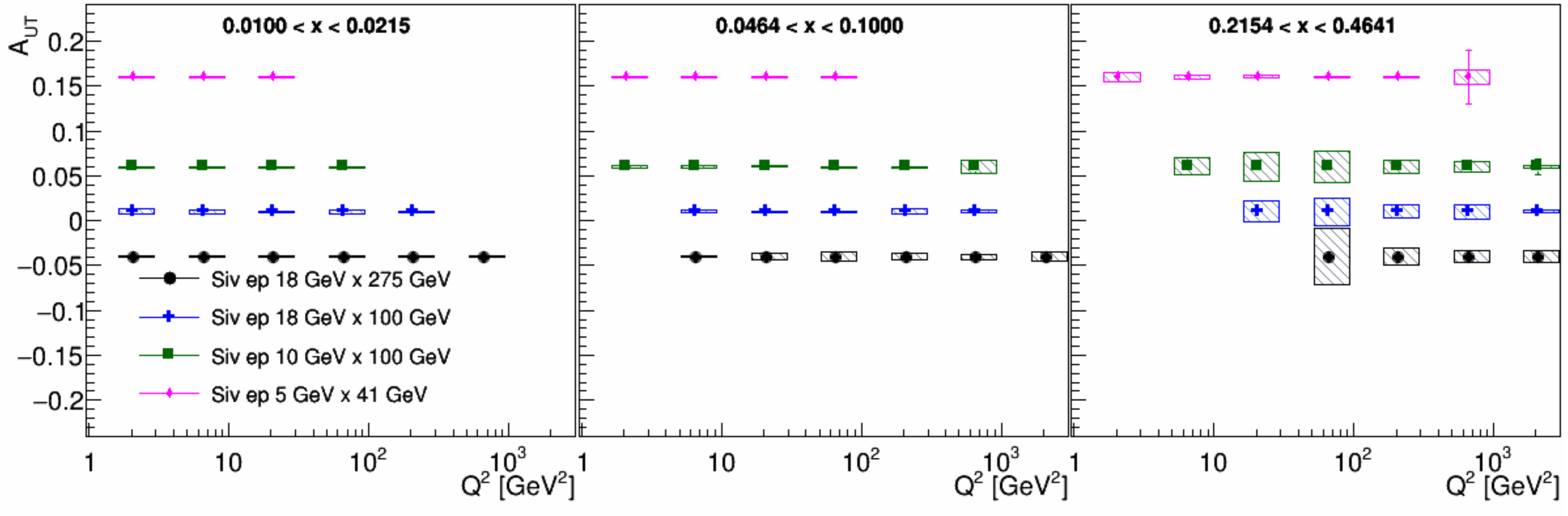


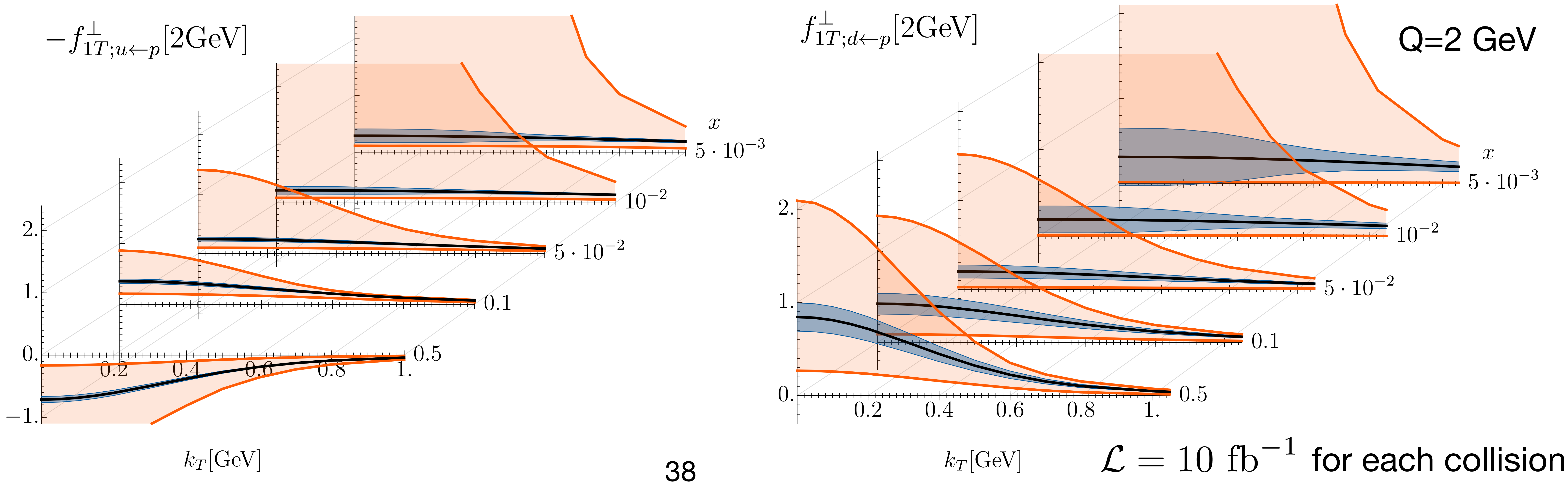
Impact of EIC on Sivers TMD PDFs



$\mathscr{C}\left[f_{1T}^{\perp,q} \times D_1^q\right]$

R. Seidl, A. Vladimirov et al., NIM A **1055** (2023) 168458





Q=2 GeV

$\mathcal{L} = 10\ \mathrm{fb}^{-1}$ for each collision energy

Gluon TMDs

GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g,\ h_{1T}^{\perp g}$

- In contrast to quark TMDs, gluon TMDs are almost unknown
- Accessible through production of dijets, high-P_T hadron pairs, quarkonia

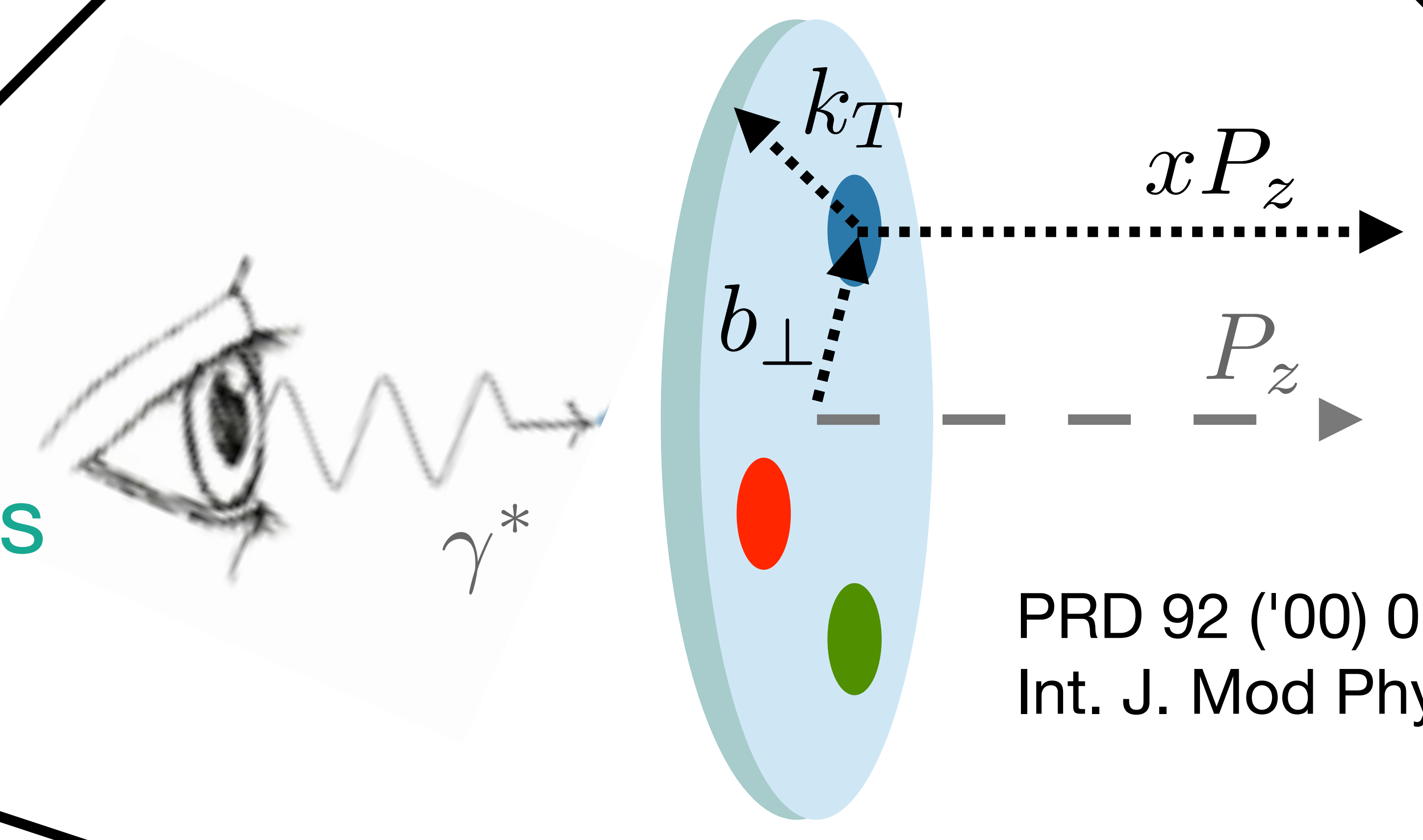
The various dimensions of the nucleon structure

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

$\int d^2\vec{k}_T$

transverse-momentum dependent (TMD) parton distribution functions (PDFs)



impact-parameter dependent PDFs

PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

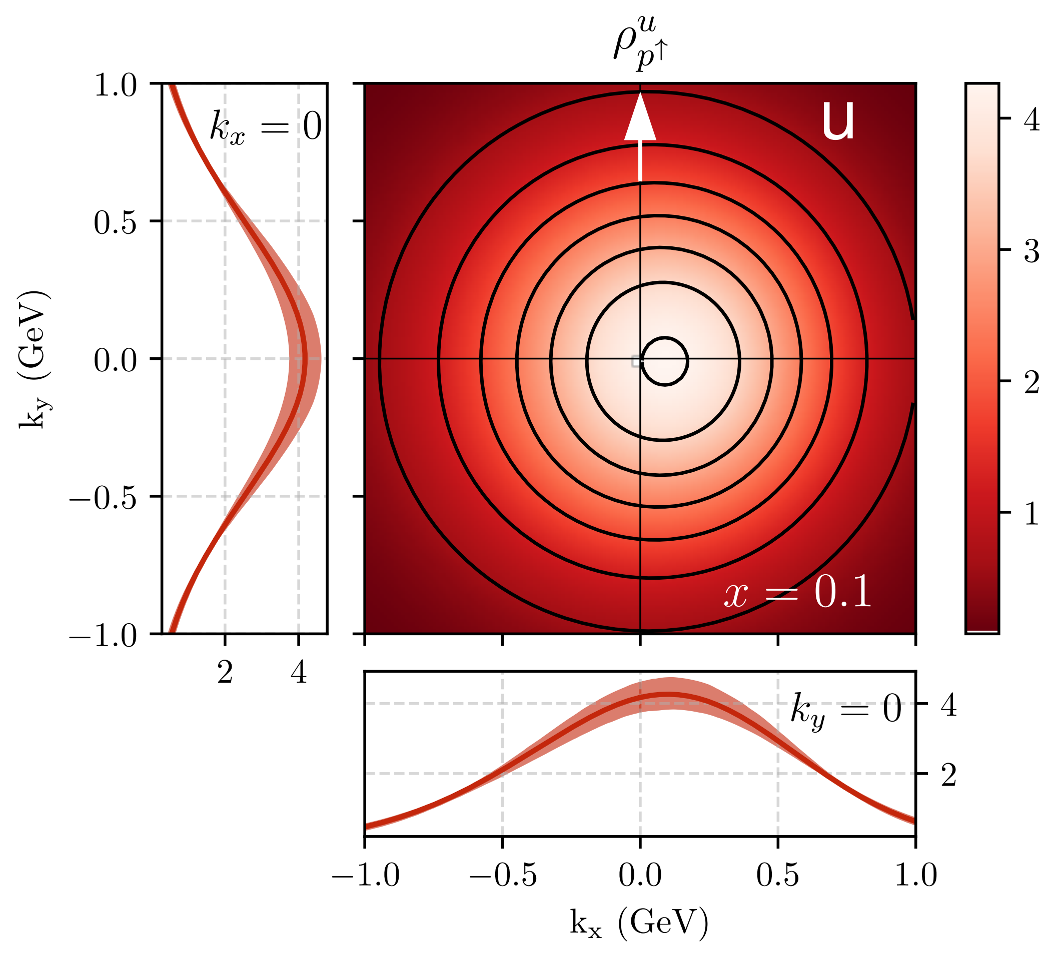
Fourier transform

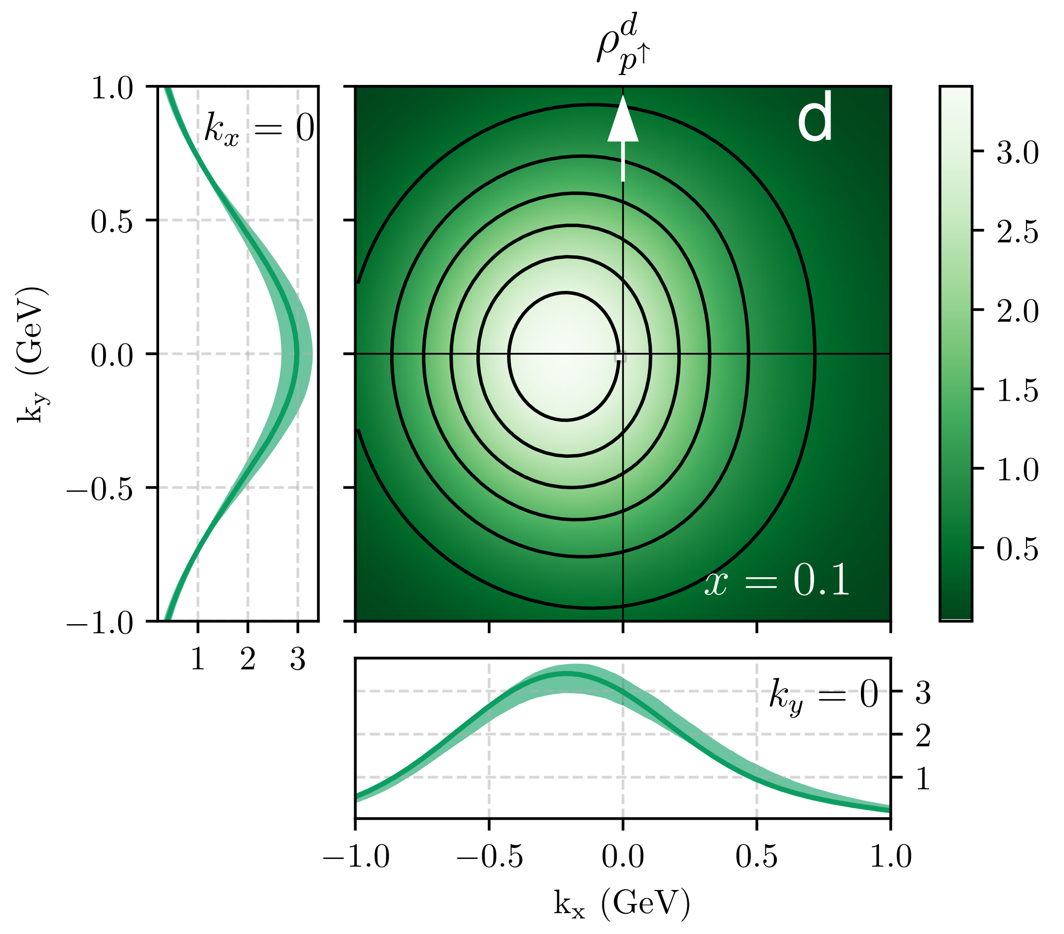
generalised parton distributions (GPDs)

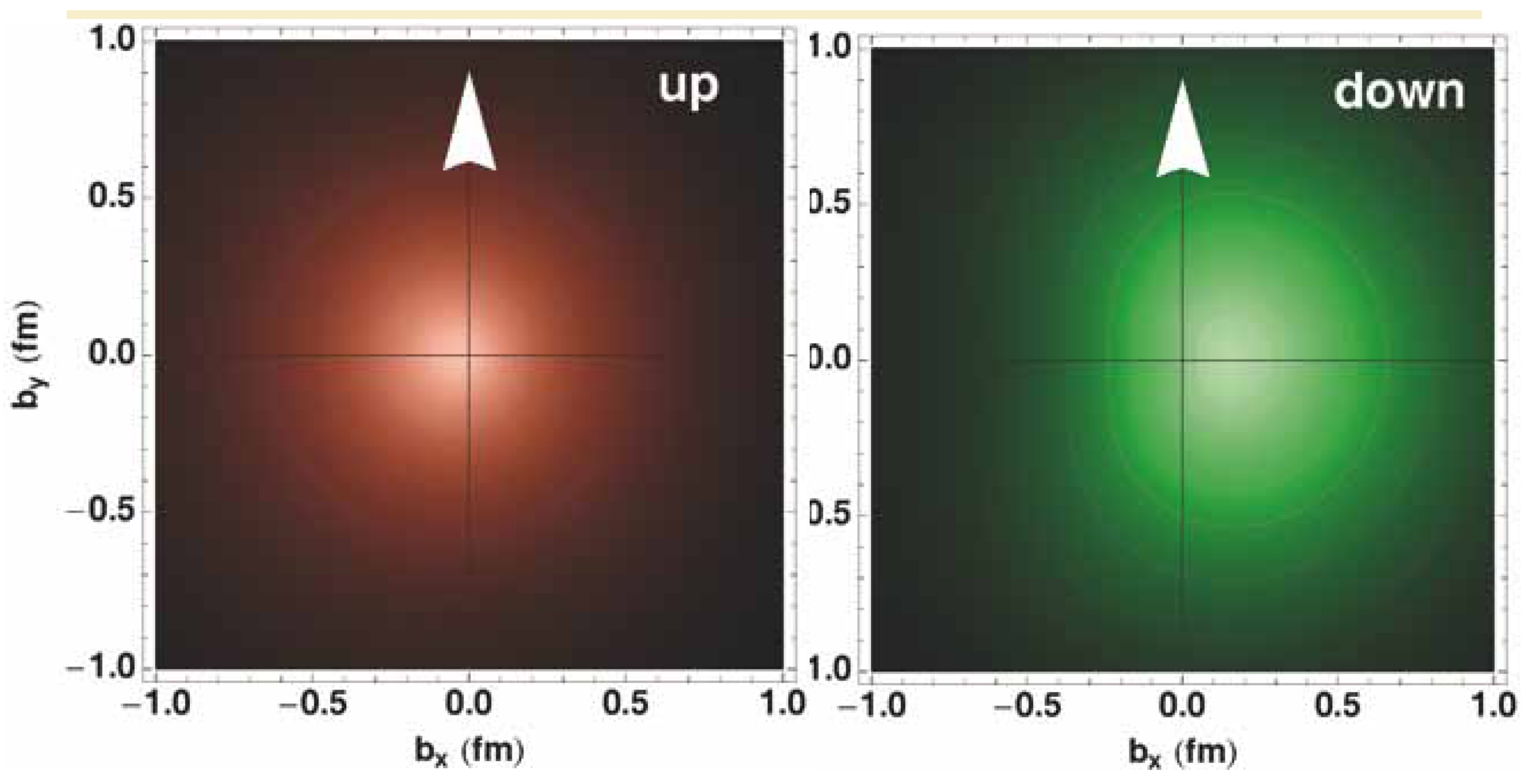
forward limit

$\int d^2\vec{k}_T$

PDFs





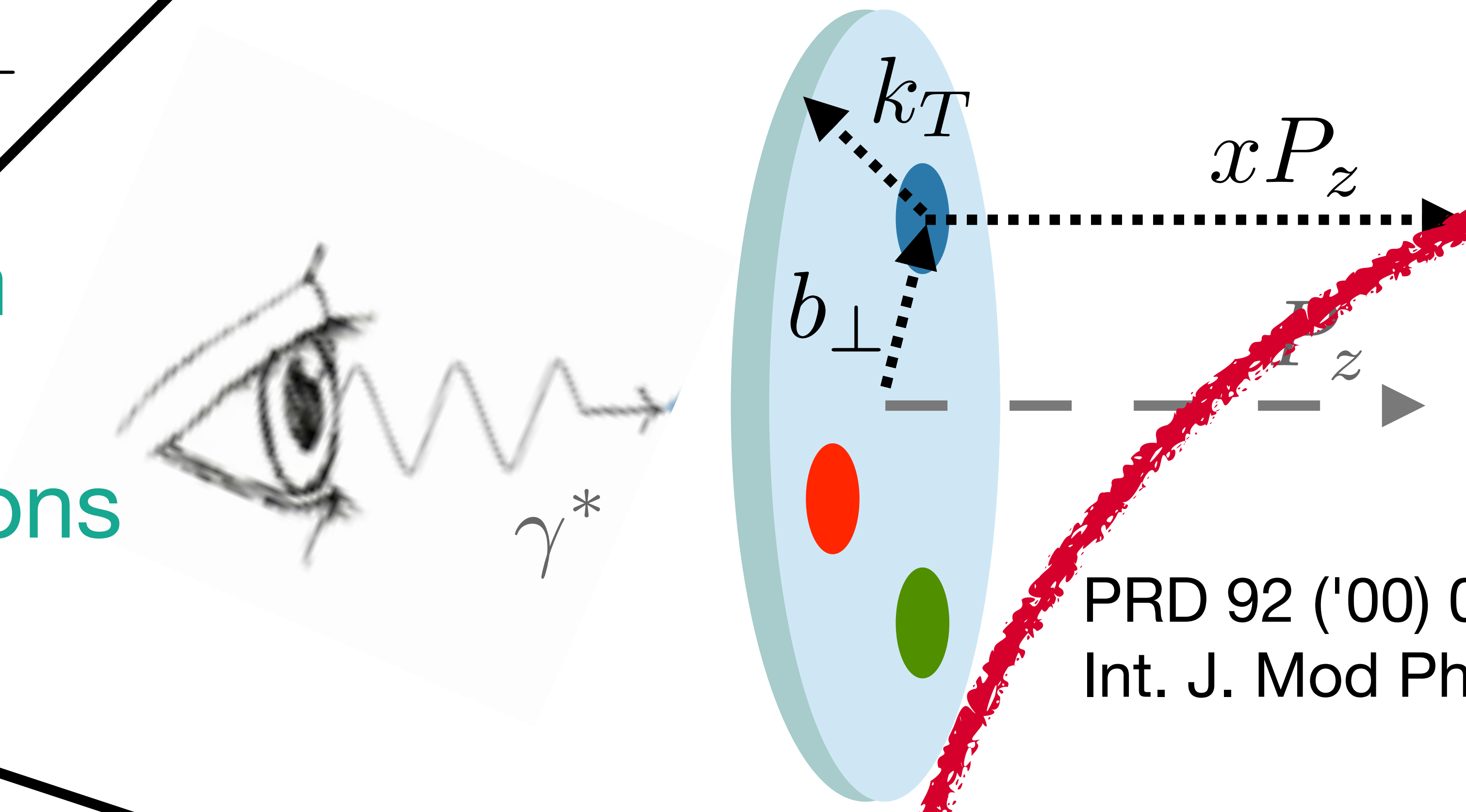


The various dimensions of the nucleon structure

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$ → transverse-momentum dependent (TMD) parton distribution functions (PDFs)

$\int d^2\vec{k}_T$ → impact-parameter dependent PDFs

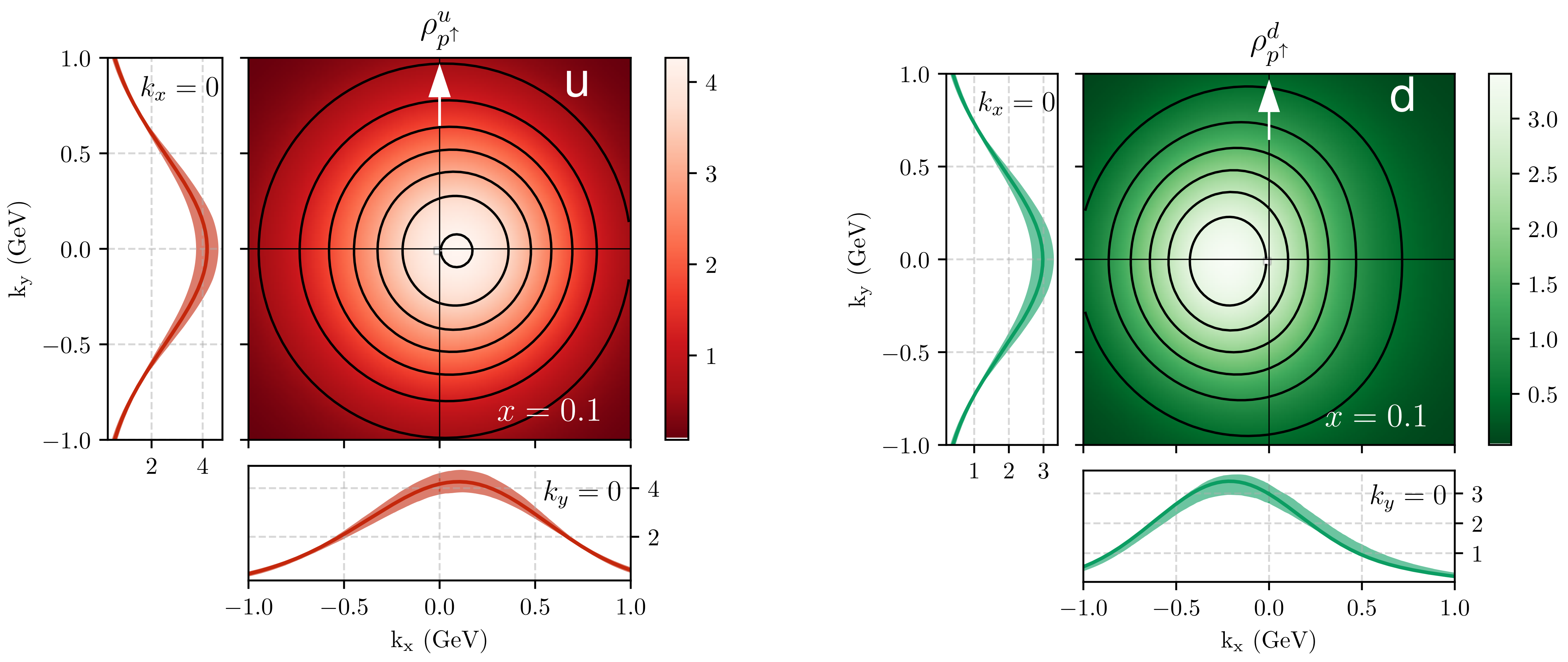


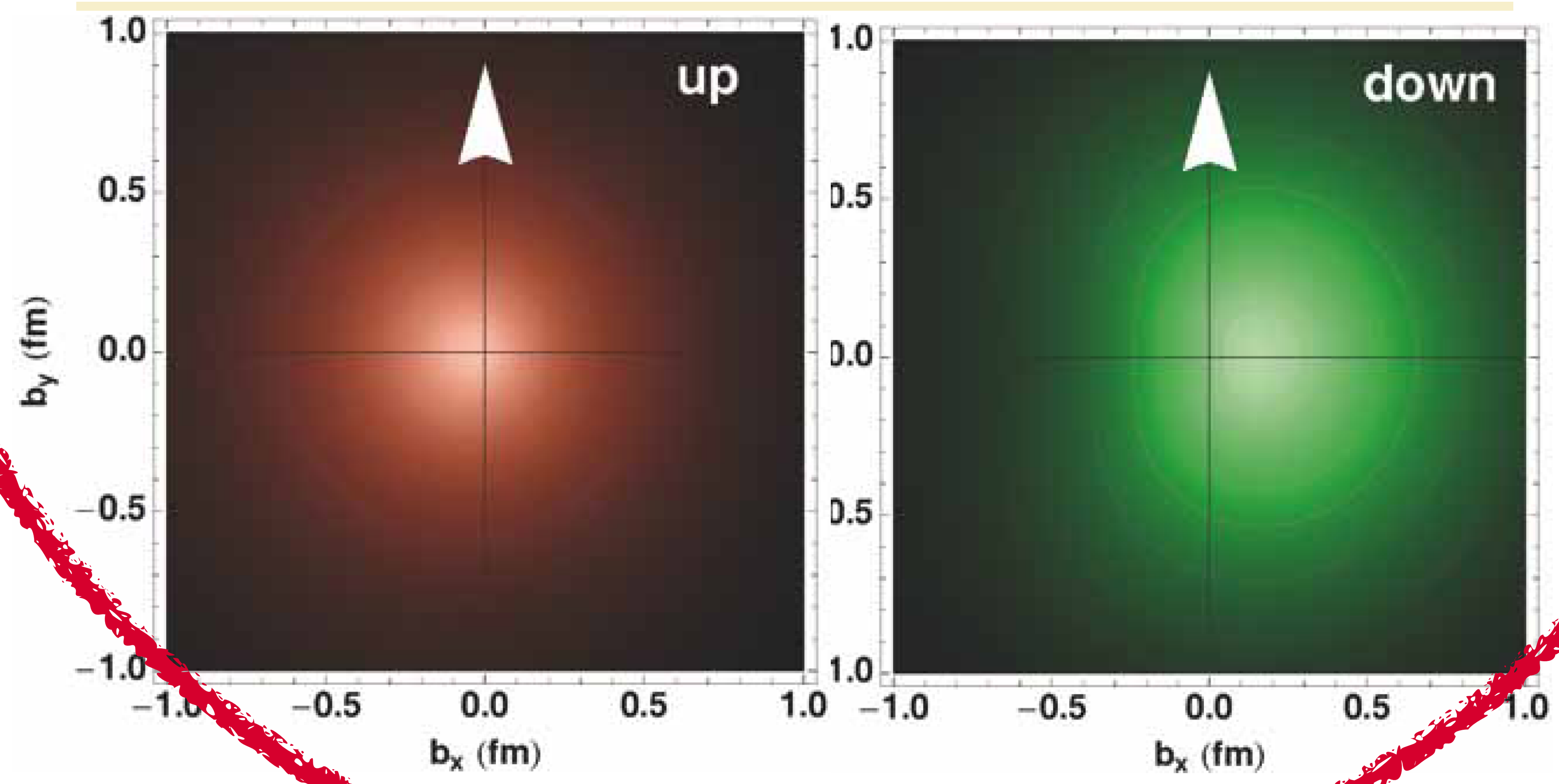
PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

impact-parameter dependent PDFs ↓ Fourier transform → generalised parton distributions (GPDs)

generalised parton distributions (GPDs) → forward limit → PDFs

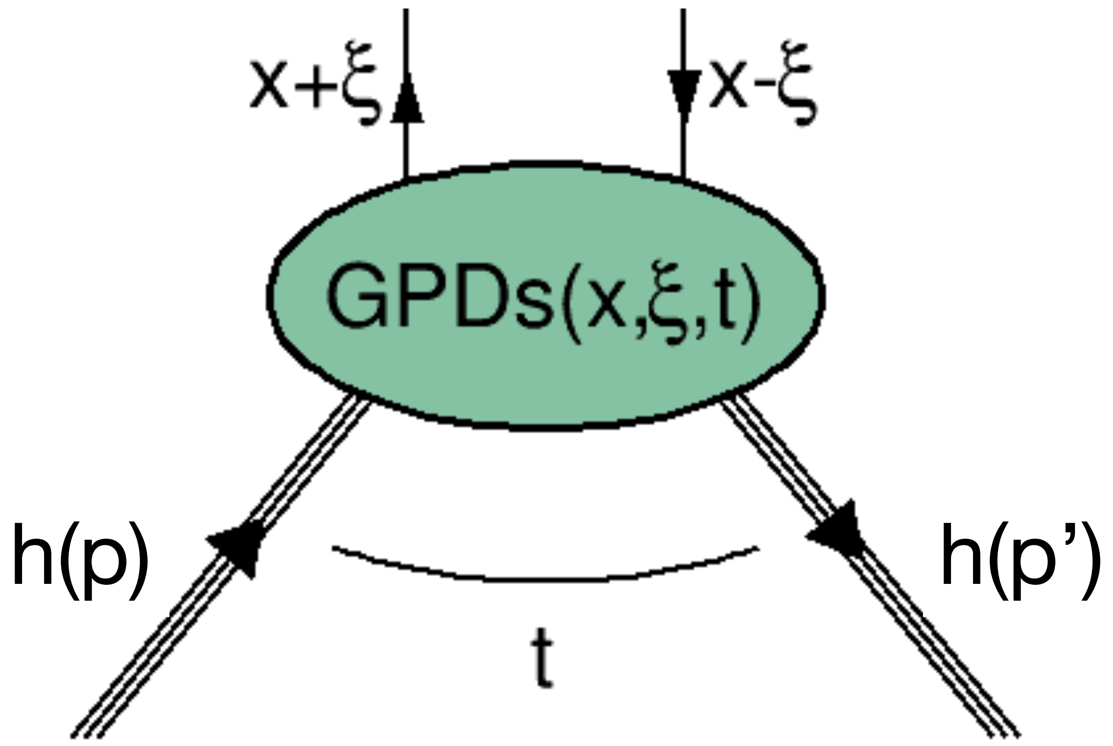
TMD PDFs → $\int d^2\vec{k}_T$ → PDFs





What are generalised parton distributions (GPDs)?

GPDs are probability amplitudes

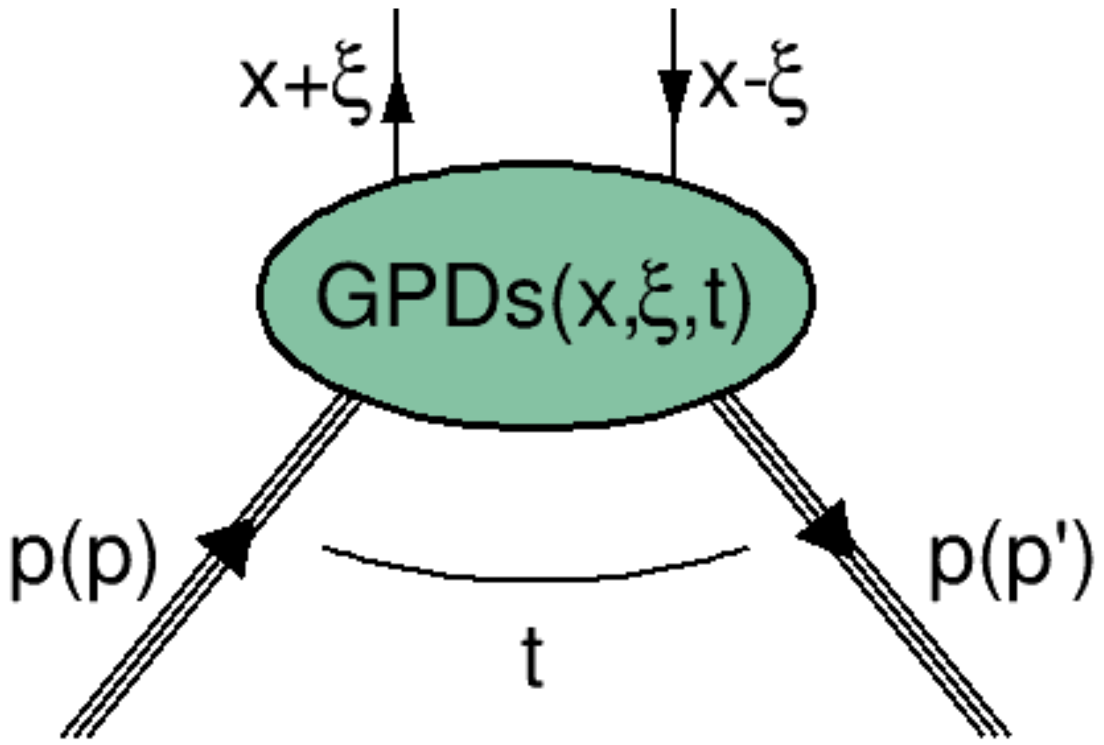


- x=average longitudinal momentum fraction
- 2ξ=longitudinal momentum transfer
- t=squared momentum transfer to hadron

- experimental access to t and ξ
- in general: no experimental access to x

What are generalised parton distributions (GPDs)?

GPDs are probability amplitudes



- x=average longitudinal momentum fraction
- 2ξ=longitudinal momentum transfer
- t=squared momentum transfer to hadron

- experimental access to t and ξ
- in general: no experimental access to x

- for spin-1/2 hadron:

Four parton helicity-conserving twist-2 GPDs

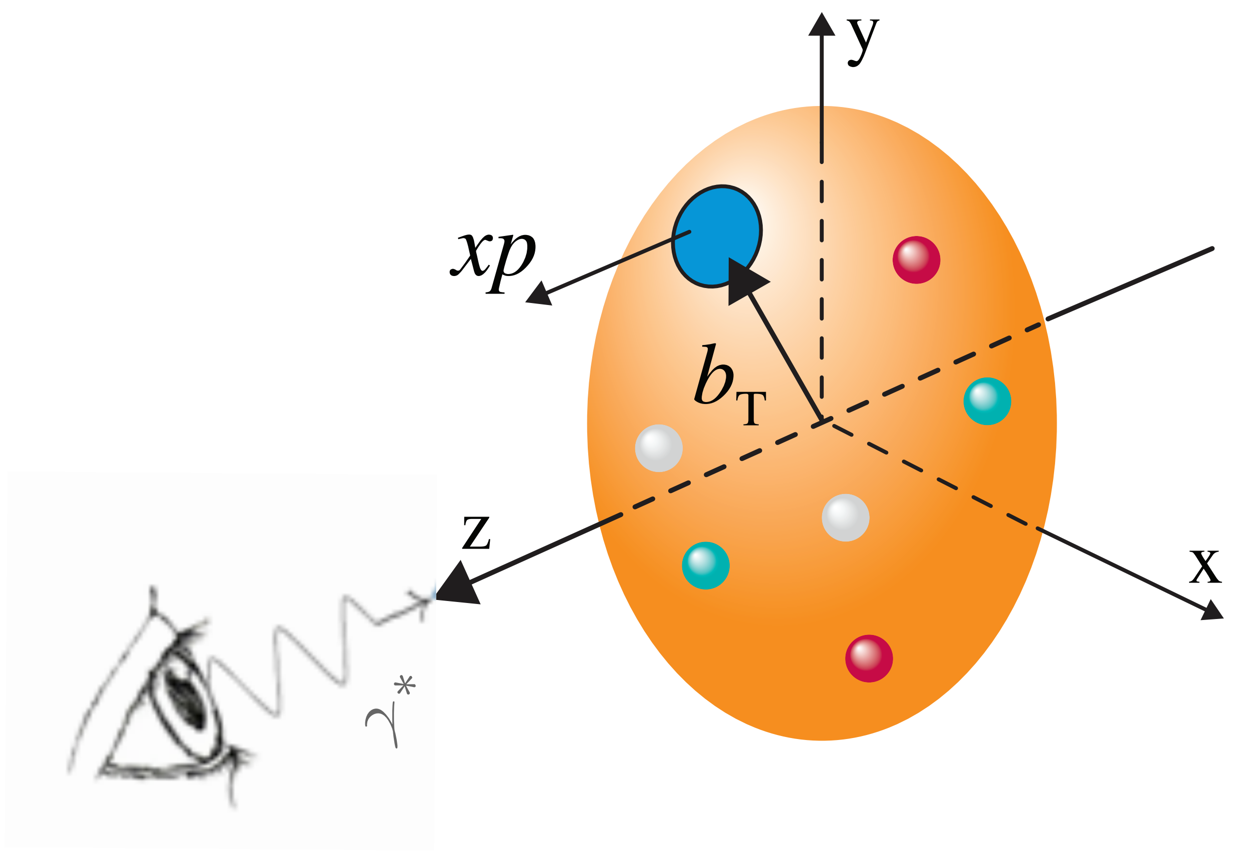
$H(x,\xi,t)$	$E(x,\xi,t)$	parton-spin independent
$\tilde{H}(x,\xi,t)$	$\tilde{E}(x,\xi,t)$	parton-spin dependent
proton helicity non flip	proton helicity flip	

Four parton helicity-flip twist-2 GPDs

$H_T(x,\xi,t)$	$E_T(x,\xi,t)$
$\tilde{H}_T(x,\xi,t)$	$\tilde{E}_T(x,\xi,t)$

What GPDs tell us about the nucleon

- 3D parton distributions

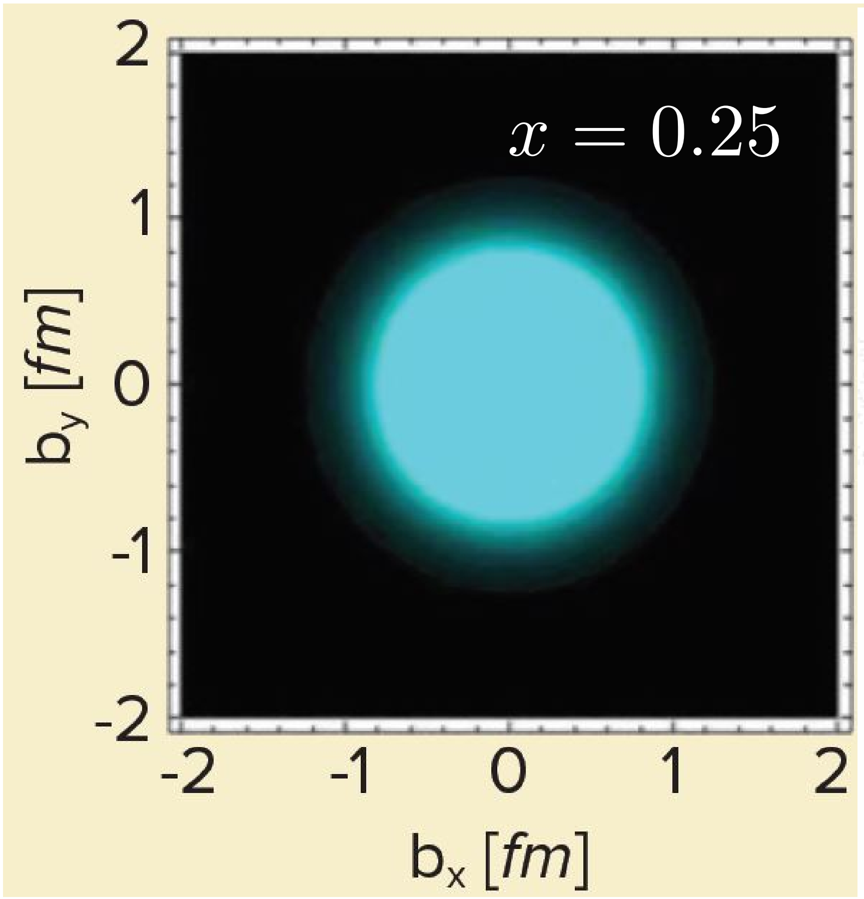


M. Burkardt, PRD **92** ('00) 071503
Int. J. Mod Phys. A **18** ('03) 173

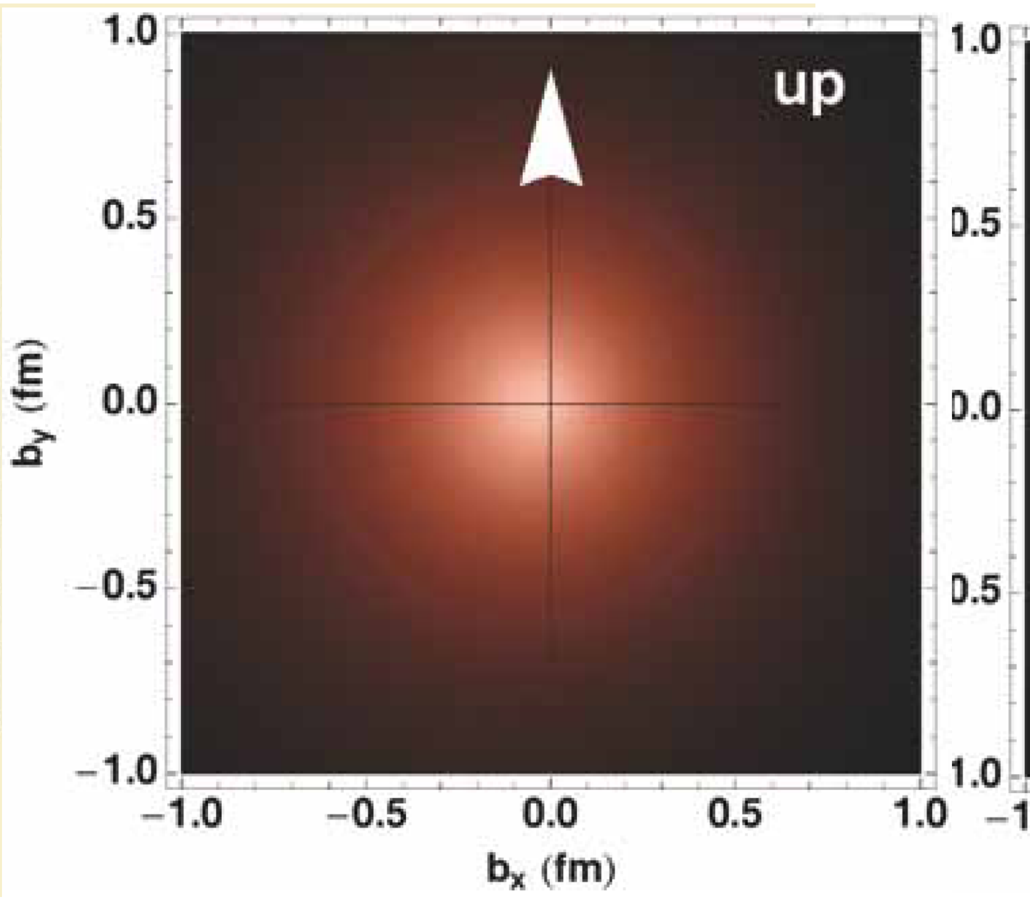
impact-parameter dependent distributions:
probability to find parton (x, b_T)

↑ Fourier transform for ξ=0

GPDs



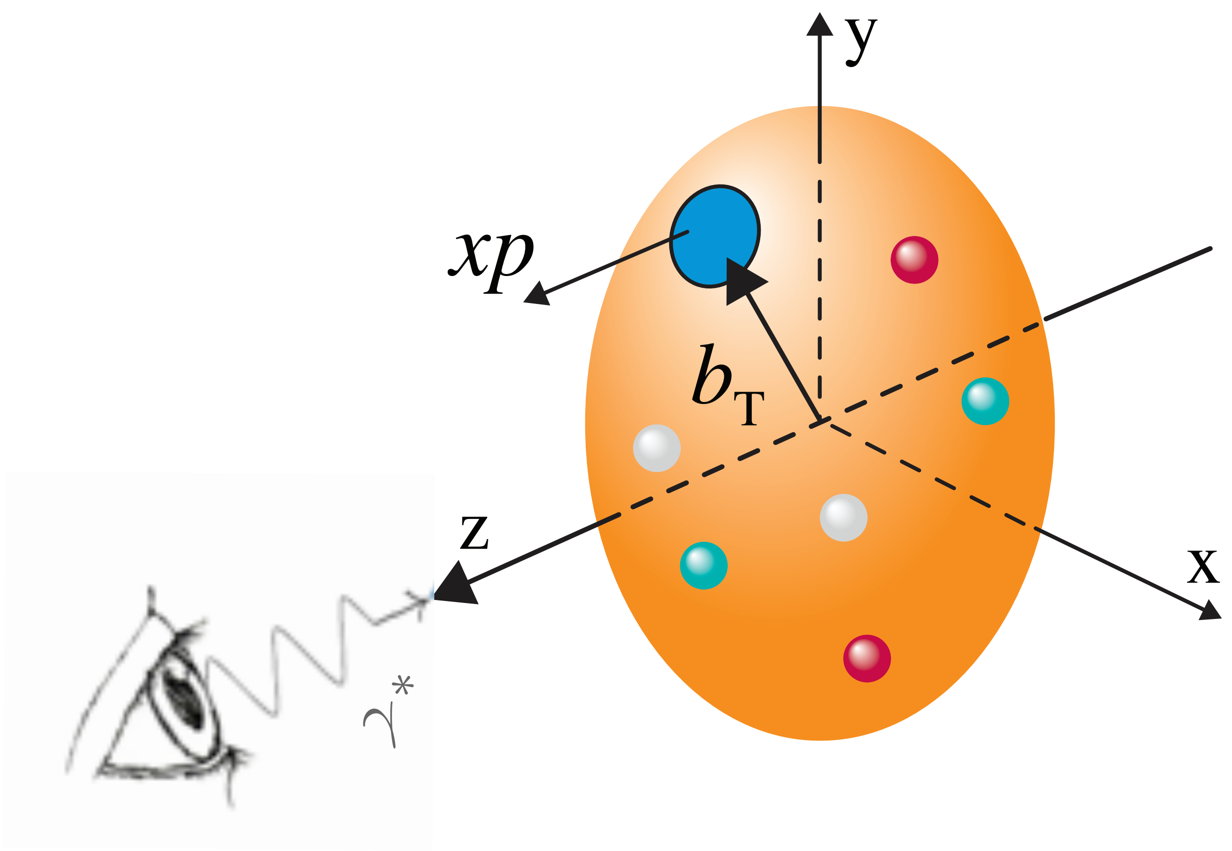
GPD H



GPDs H+E

What GPDs tell us about the nucleon

- 3D parton distributions

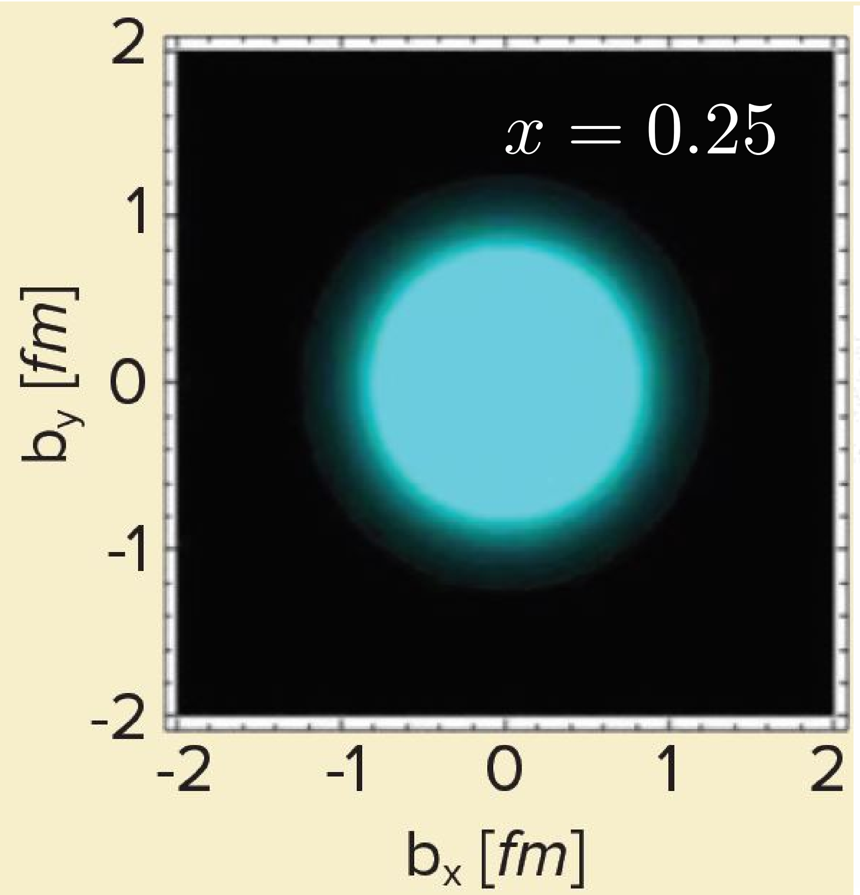


M. Burkardt, PRD **92** ('00) 071503
Int. J. Mod Phys. A **18** ('03) 173

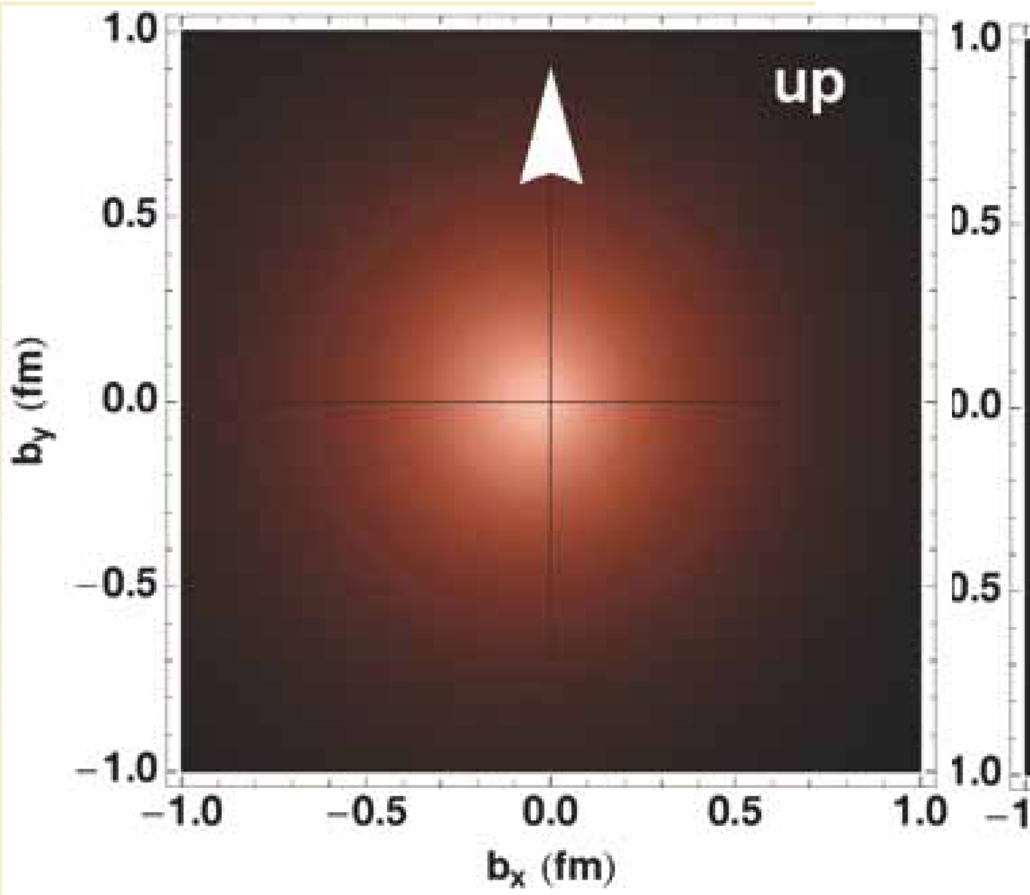
impact-parameter dependent distributions:
probability to find parton (x,b_T)

↑ Fourier transform for ξ=0

GPDs



GPD H



GPDs H+E

- pressure distributions

GPDs

↓ $\int dx\, x$

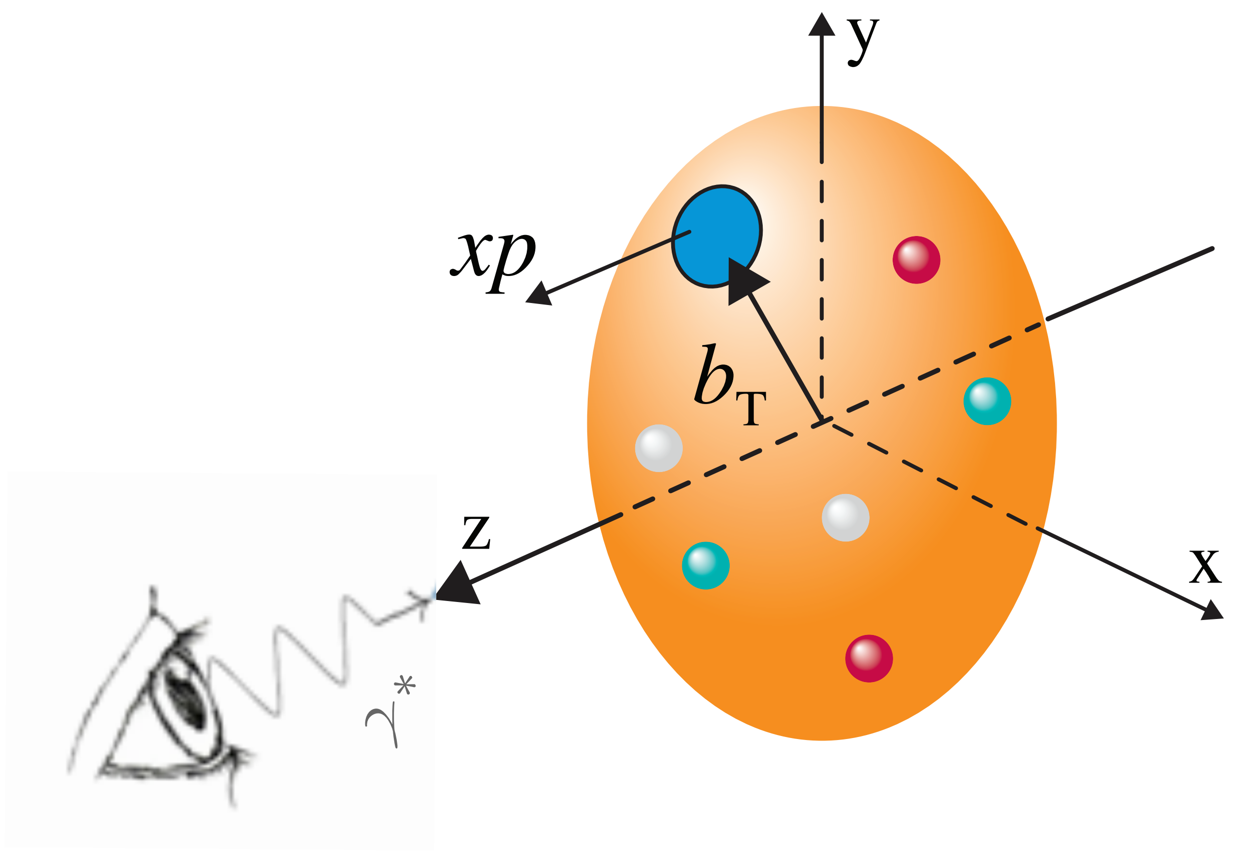
gravitational form factors

↓ Fourier transform

pressure distributions

What GPDs tell us about the nucleon

- 3D parton distributions

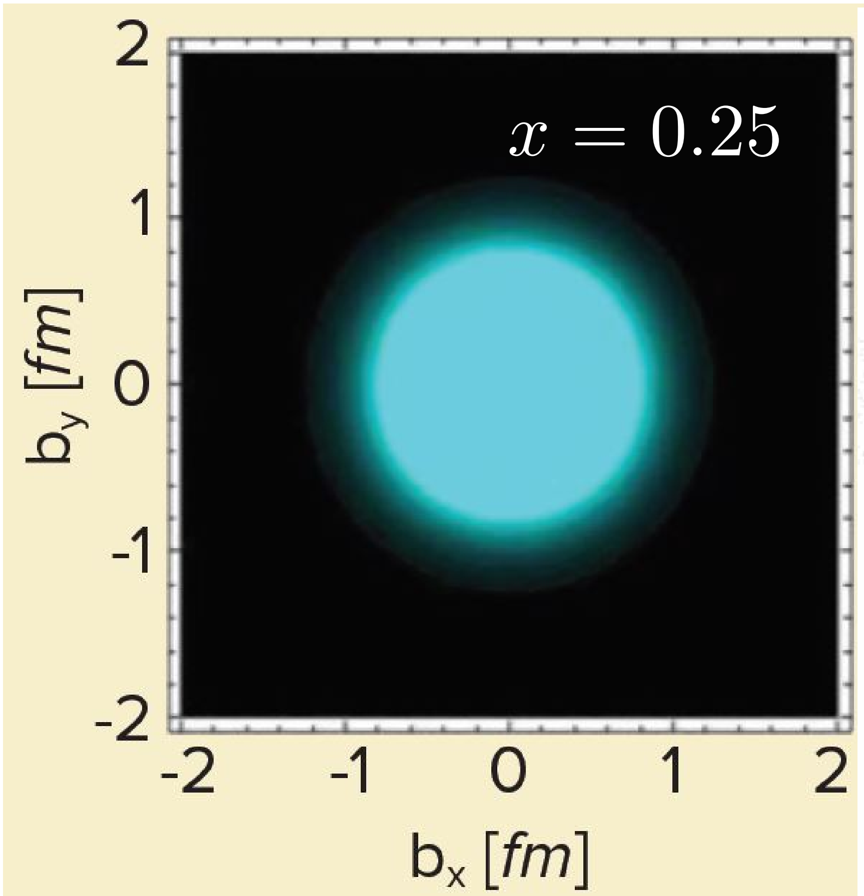


M. Burkardt, PRD **92** ('00) 071503
Int. J. Mod Phys. A **18** ('03) 173

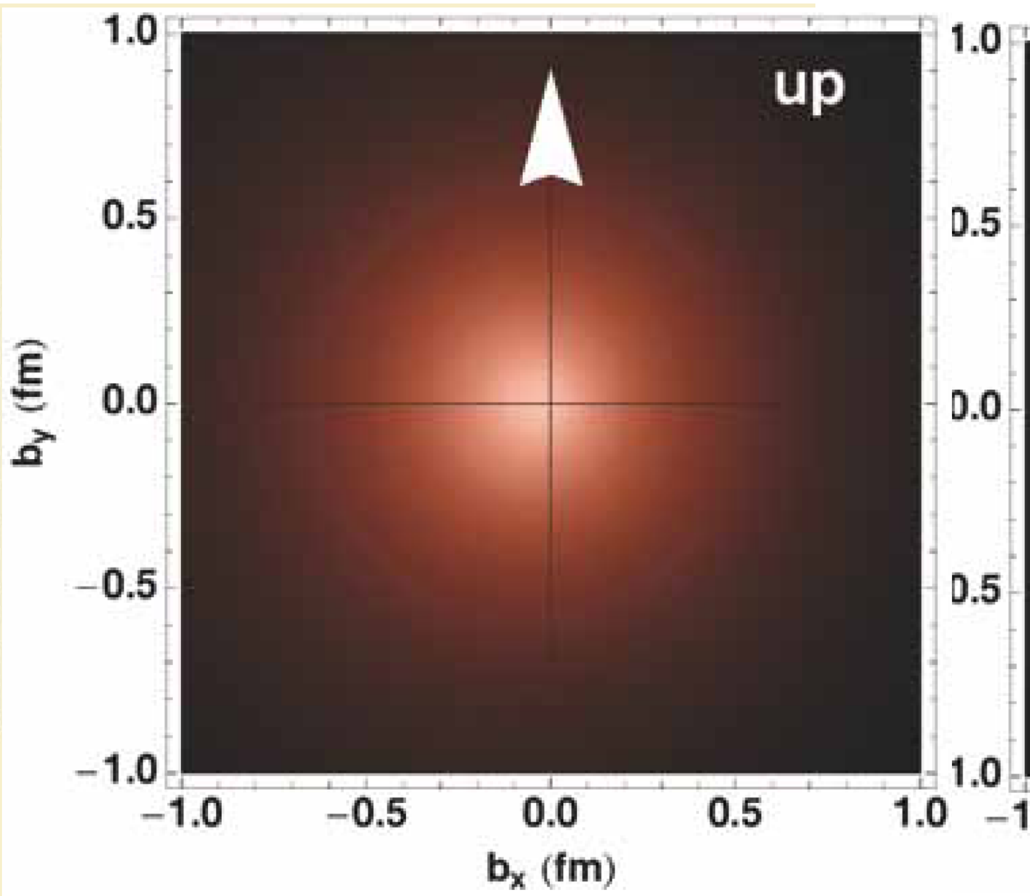
impact-parameter dependent distributions:
probability to find parton (x,b_T)

↑ Fourier transform for ξ=0

GPDs



GPD H



GPDs H+E

- pressure distributions

GPDs

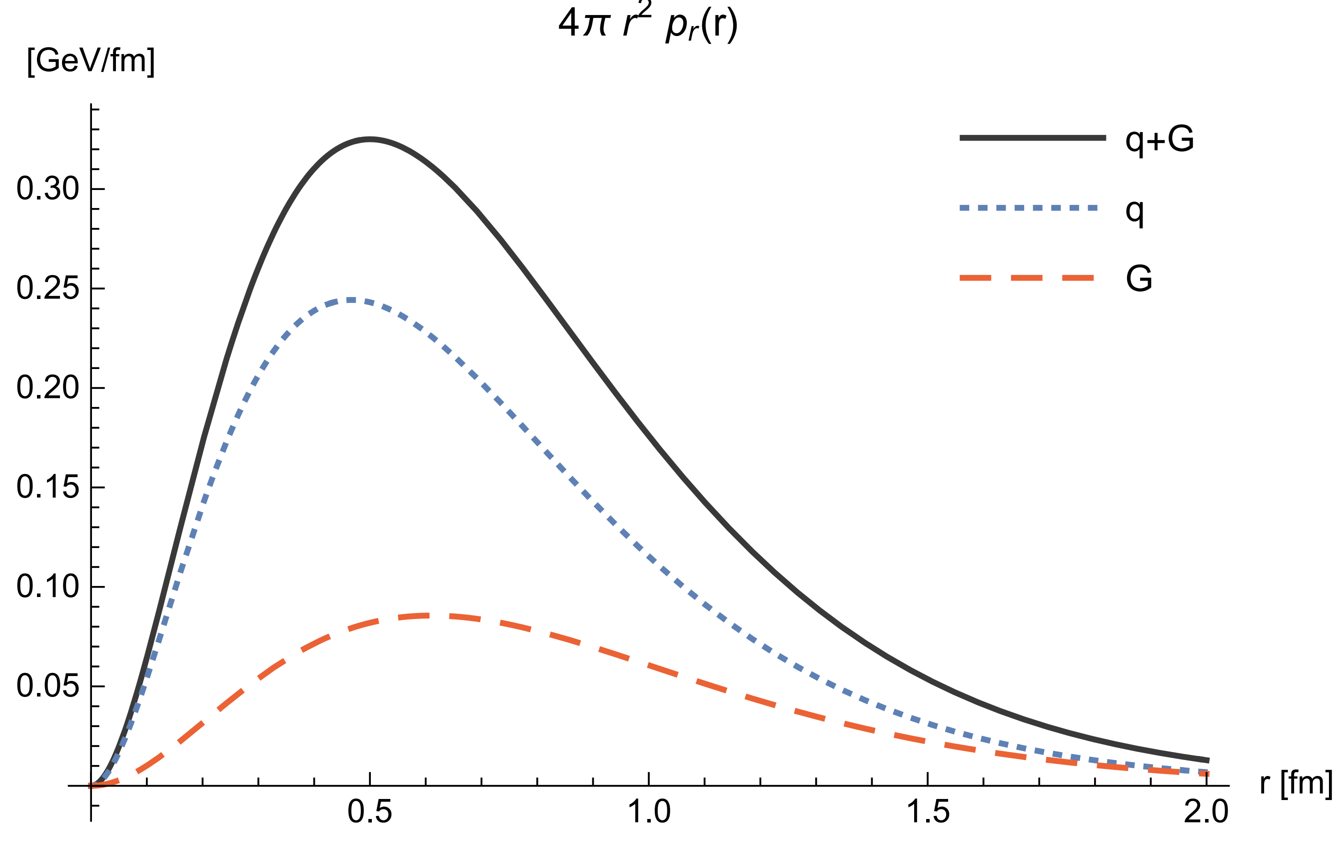
↓ $\int dx\, x$

gravitational form factors

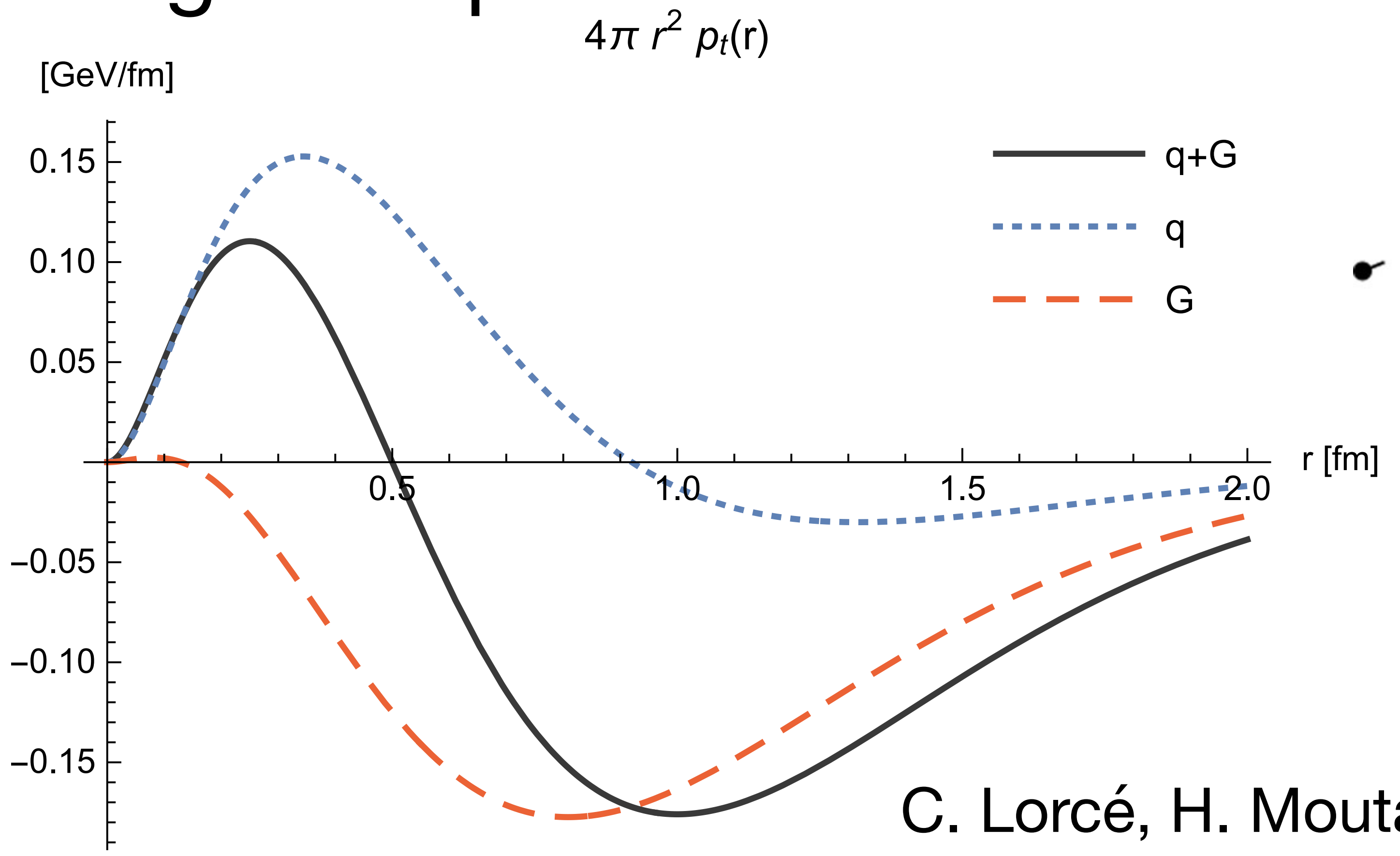
↓ Fourier transform

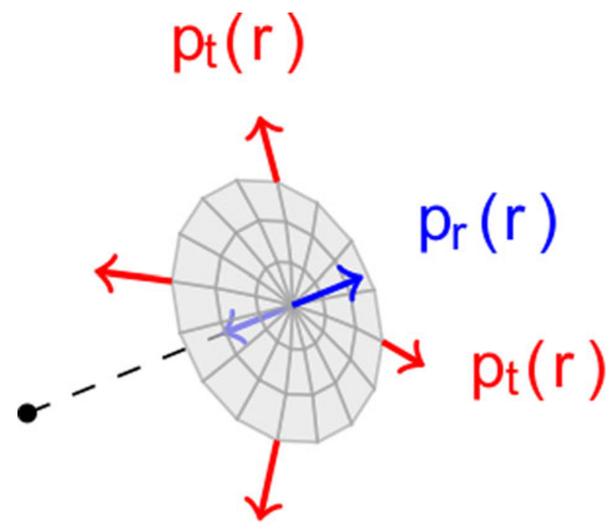
pressure distributions

radial pressure



tangential pressure

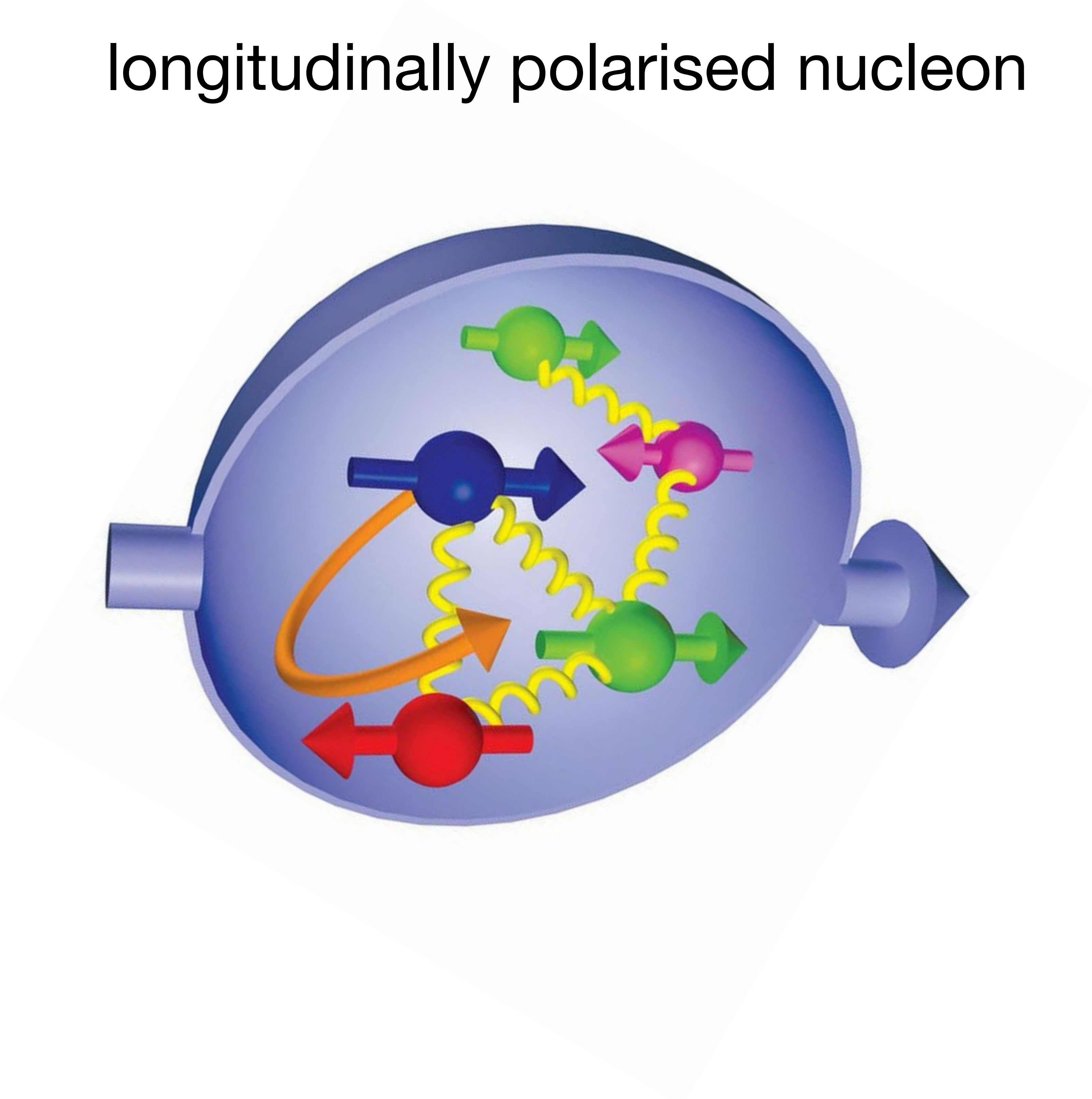




C. Lorcé, H. Moutarde, A. P. Trawiński
Eur. Phys. J. C **79** ('19) 89

… and its spin

longitudinally polarised nucleon



proton spin

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \sum_q L^q + J^G$$

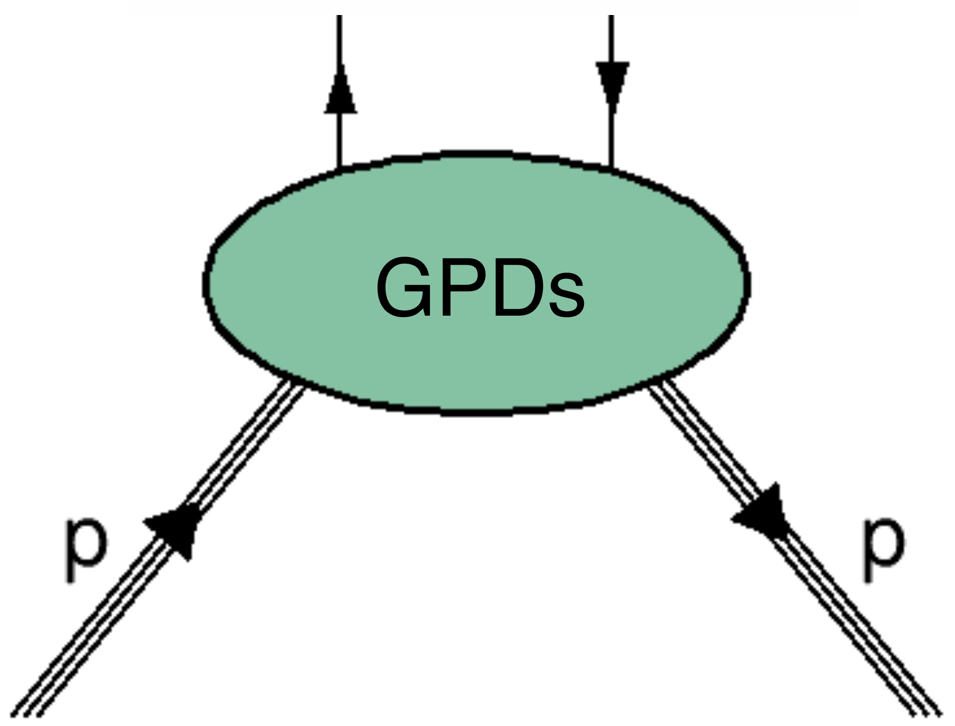
quark spin — quark orbital angular momentum — gluon angular momentum

30% — ? — ?

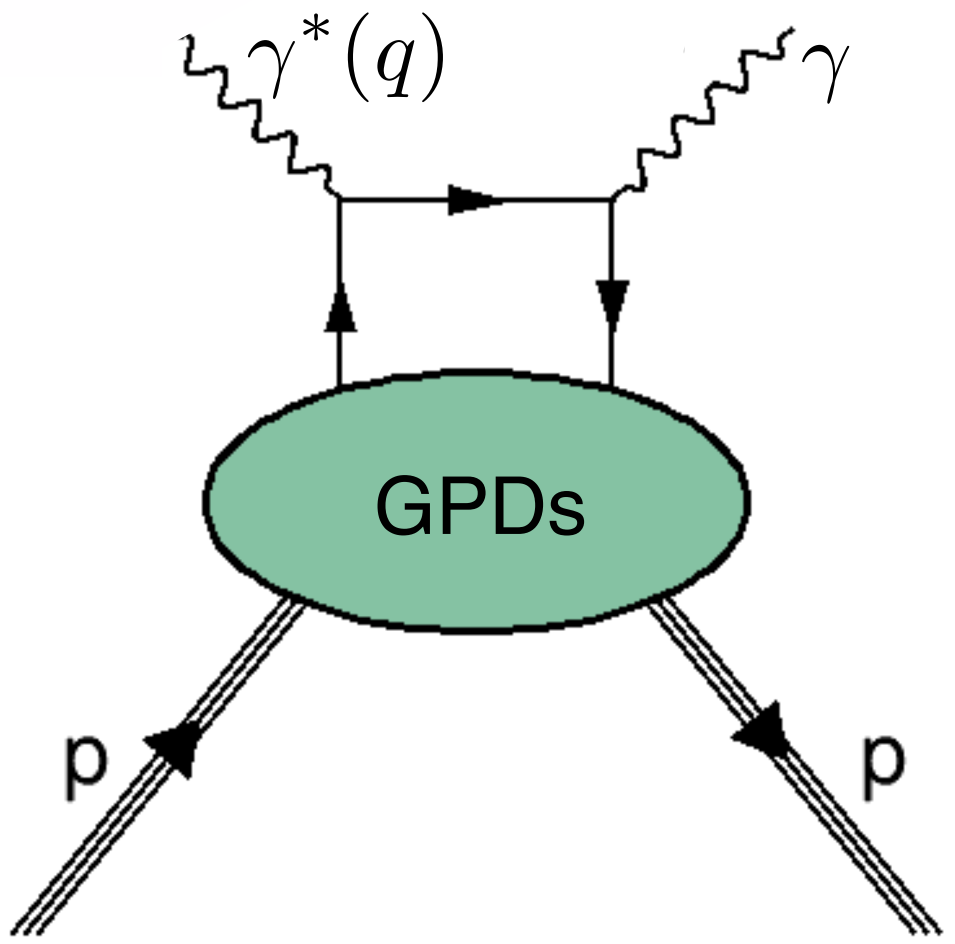
$$J = \lim_{t\to 0} \frac{1}{2}\int_{-1}^{1} dx\, x\, [H(x,\xi,t) + E(x,\xi,t)]$$

X. Ji, Phys. Rev. Lett. 78 (1997) 610

Experimental access to GPDs

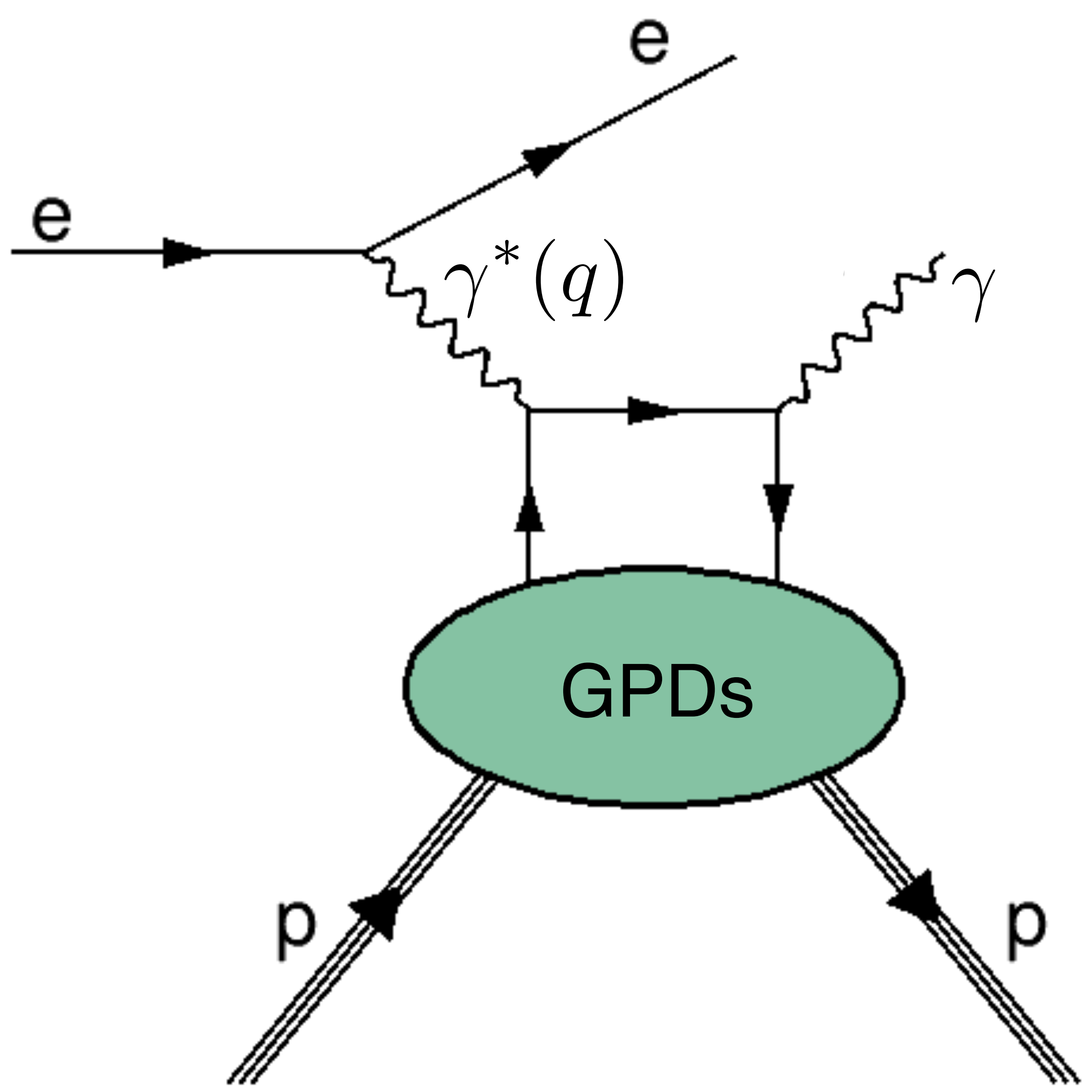


Experimental access to GPDs



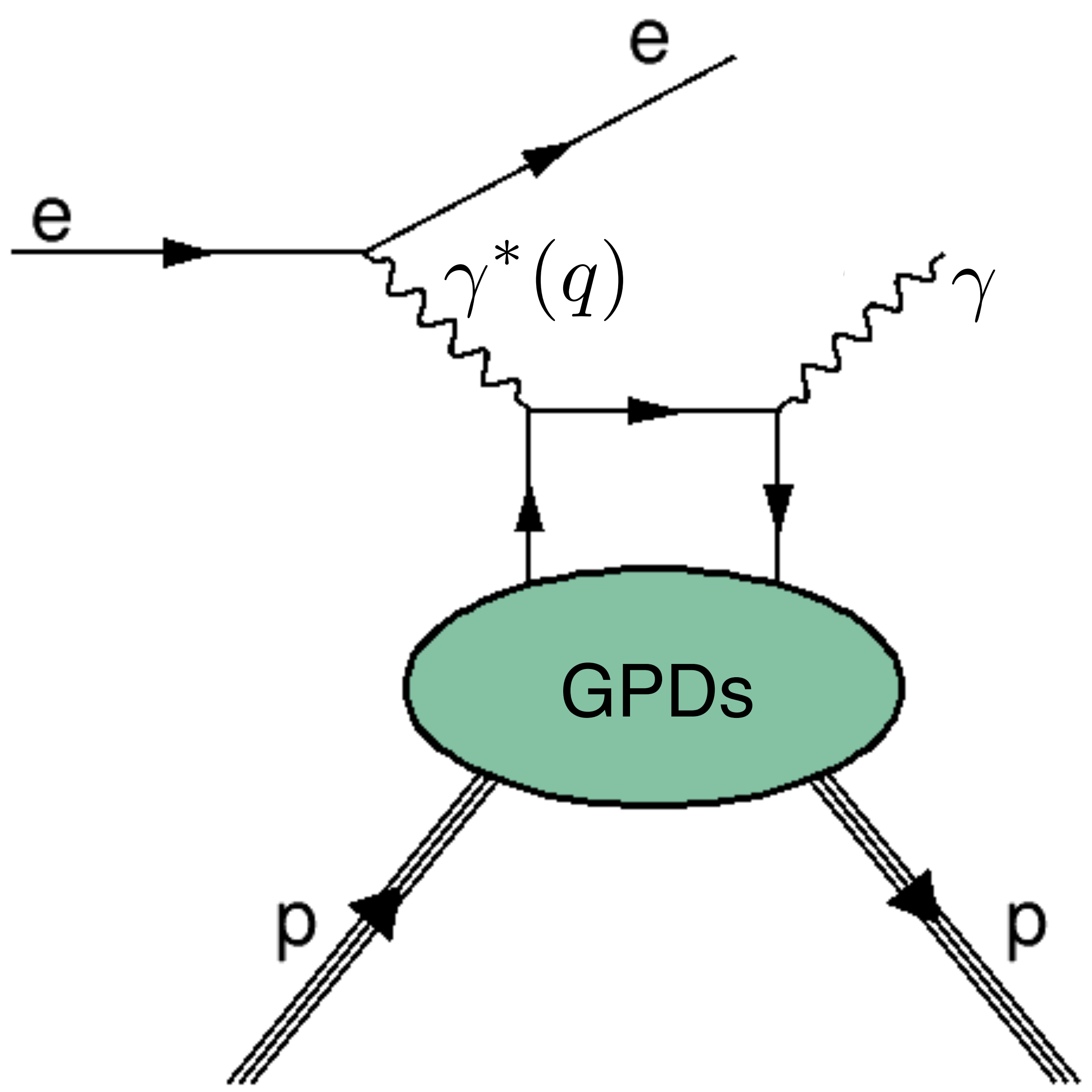
Deeply virtual Compton scattering (DVCS)
Hard scale=large Q^2=-q^2

Experimental access to GPDs



Deeply virtual Compton scattering (DVCS)
Hard scale=large Q^2=-q^2

Experimental access to GPDs



Deeply virtual Compton scattering (DVCS)
Hard scale=large Q^2=-q^2

CLAS – PRC 80 ('09) 035206; PRL 87 ('01) 182002; 100 ('08) 162002

COMPASS – arXiv:1702.06315

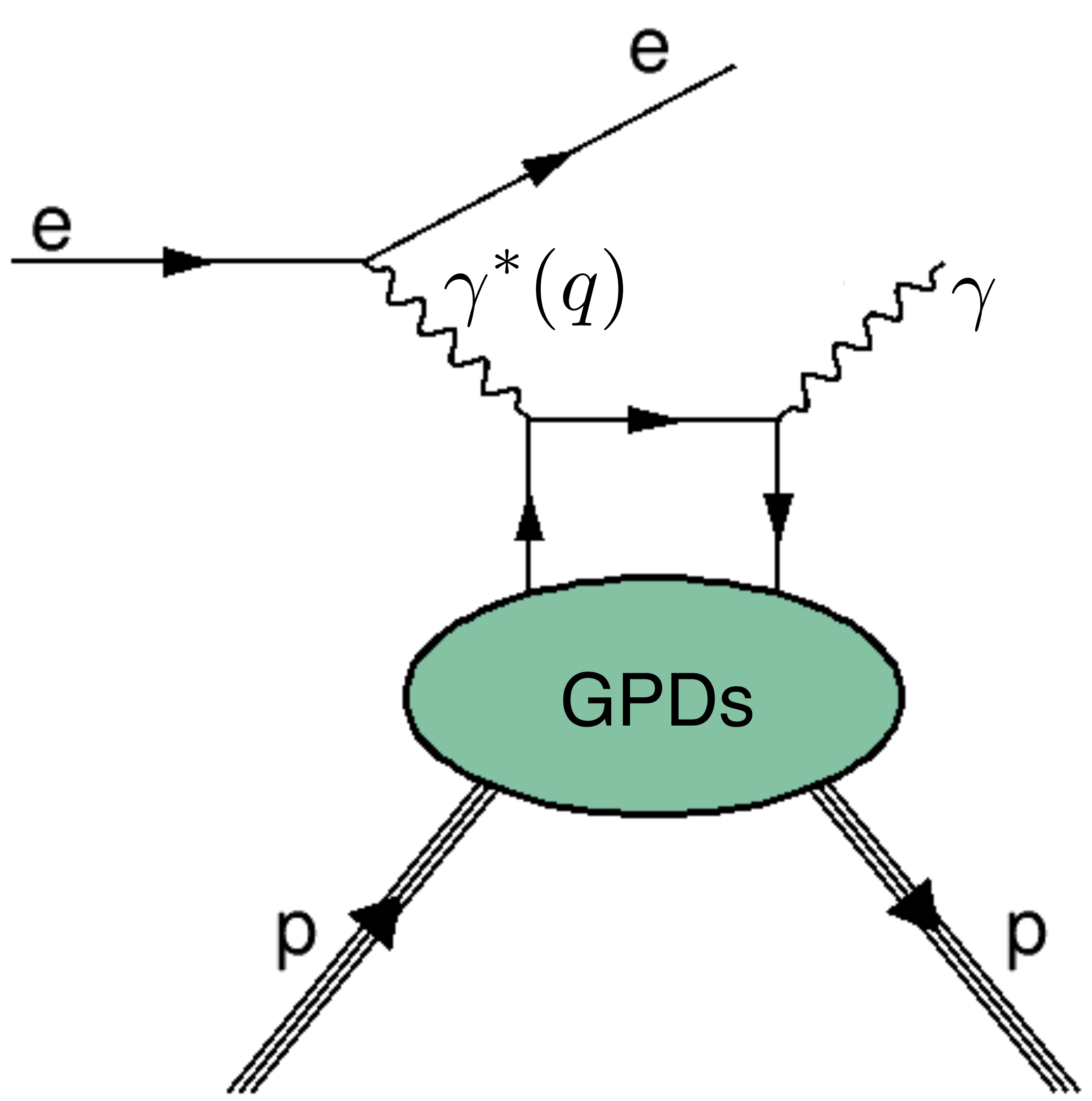
JLab Hall A Collaboration – PRL 99 ('07) 242501; PRC 92 ('15) 055202; Nat. Com. **8** (’17) 1408

HERMES – JHEP 10 (’12) 042; PLB 704 ('11) 15; NPB 842 ('11) 265

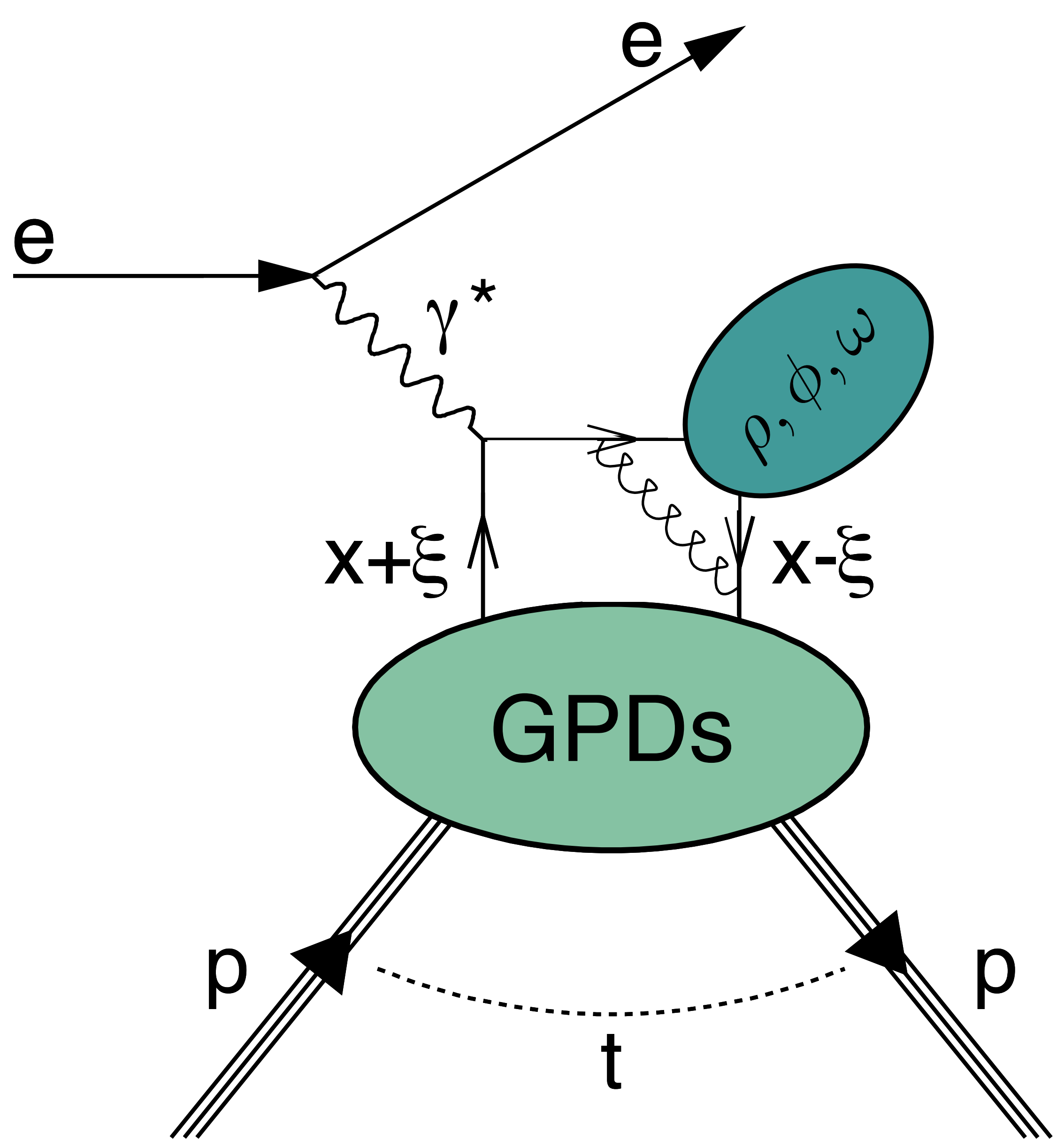
H1 – PLB 681 ('09) 391; 659 ('07) 796; EPJ C 44 ('05) 1

ZEUS – PLB 573 (2003) 46; JHEP 05 ('09) 108

Experimental access to GPDs



Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$



Hard exclusive meson production
Hard scale=large Q^2

CLAS – PRC 80 ('09) 035206; PRL 87 ('01) 182002; 100 ('08) 162002

COMPASS – arXiv:1702.06315

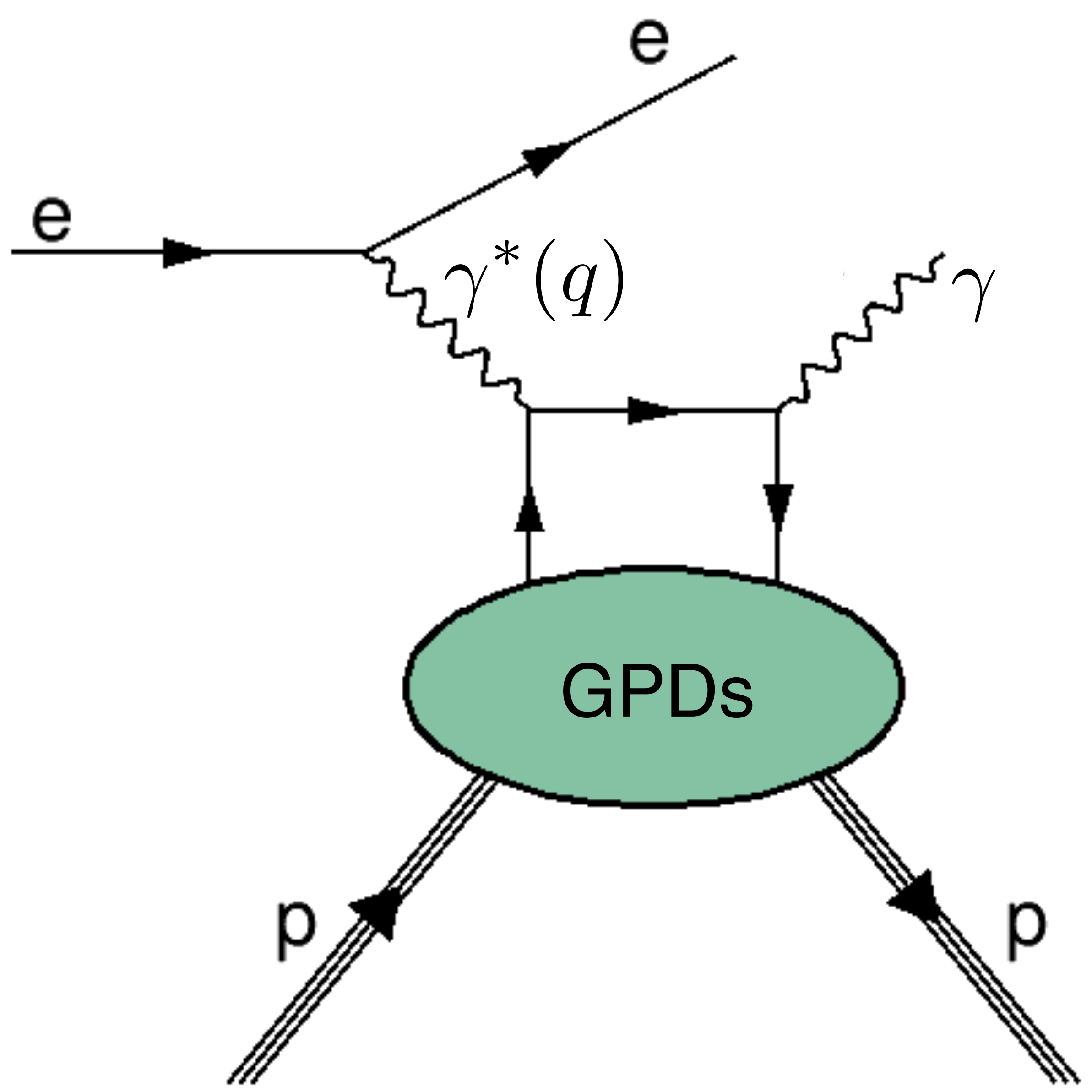
JLab Hall A Collaboration – PRL 99 ('07) 242501; PRC 92 ('15) 055202; Nat. Com. **8** ('17) 1408

HERMES – JHEP 10 ('12) 042; PLB 704 ('11) 15; NPB 842 ('11) 265

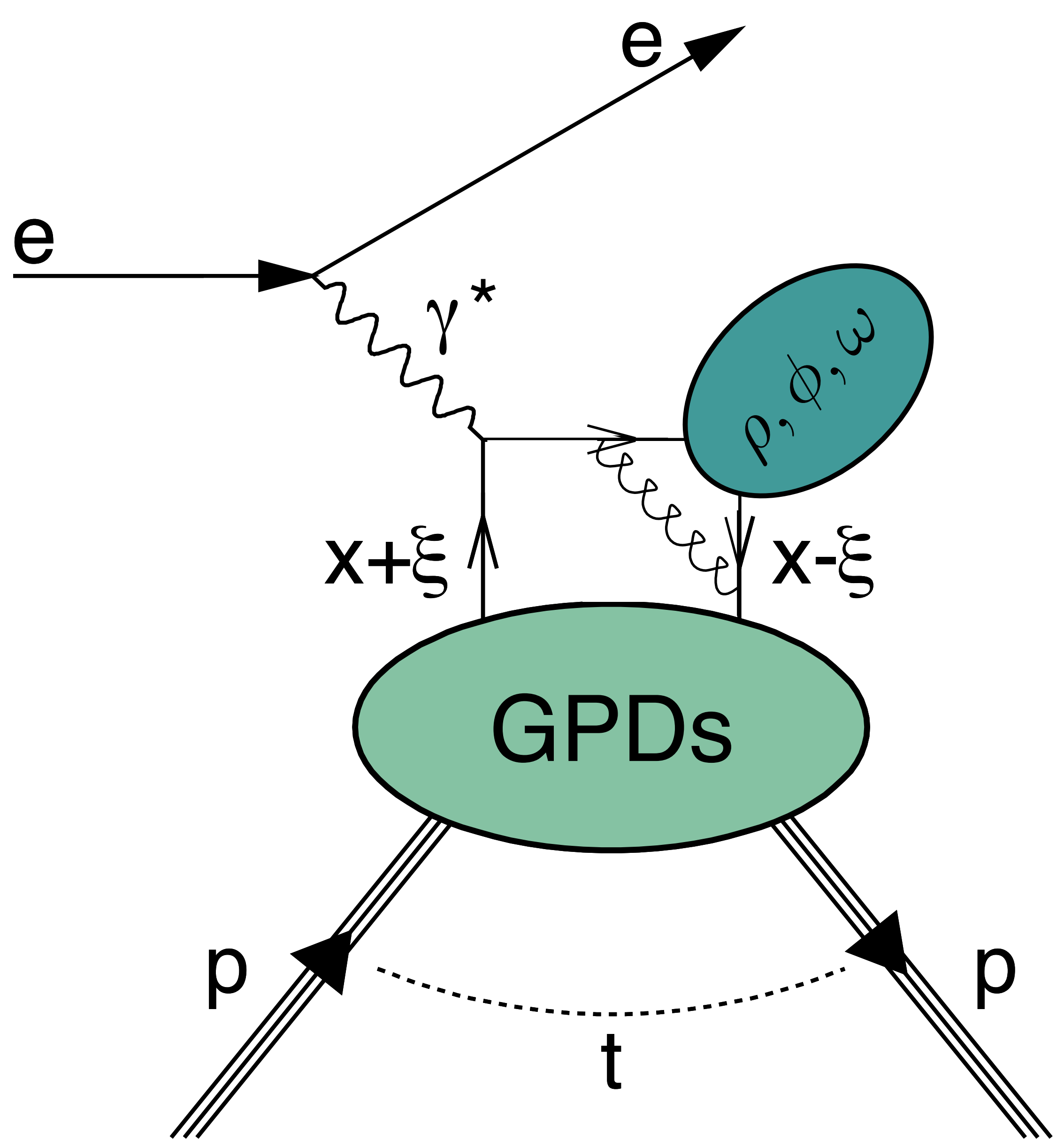
H1 – PLB 681 ('09) 391; 659 ('07) 796; EPJ C 44 ('05) 1

ZEUS – PLB 573 (2003) 46; JHEP 05 ('09) 108

Experimental access to GPDs



Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$

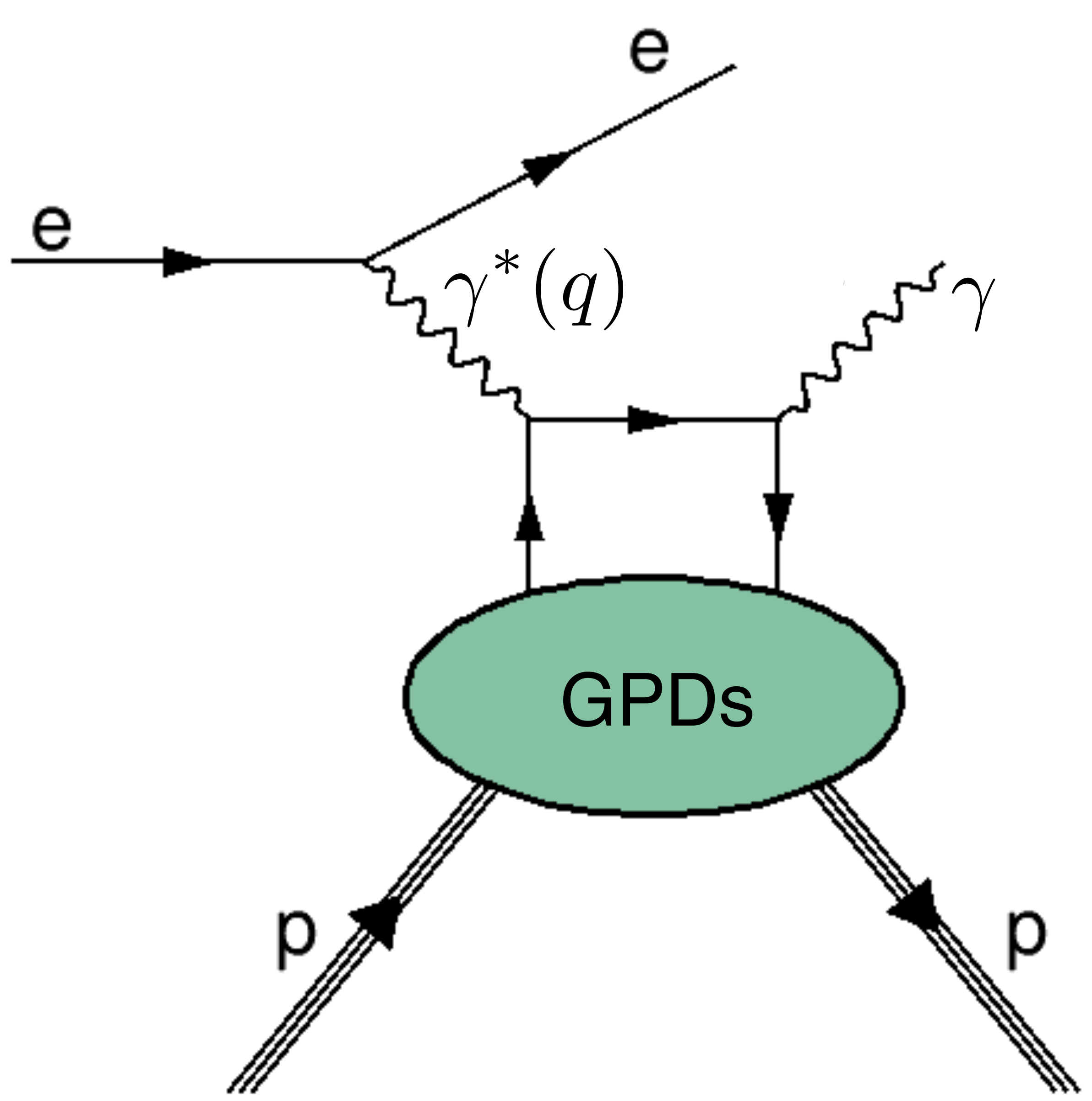


Hard exclusive meson production
Hard scale=large Q^2

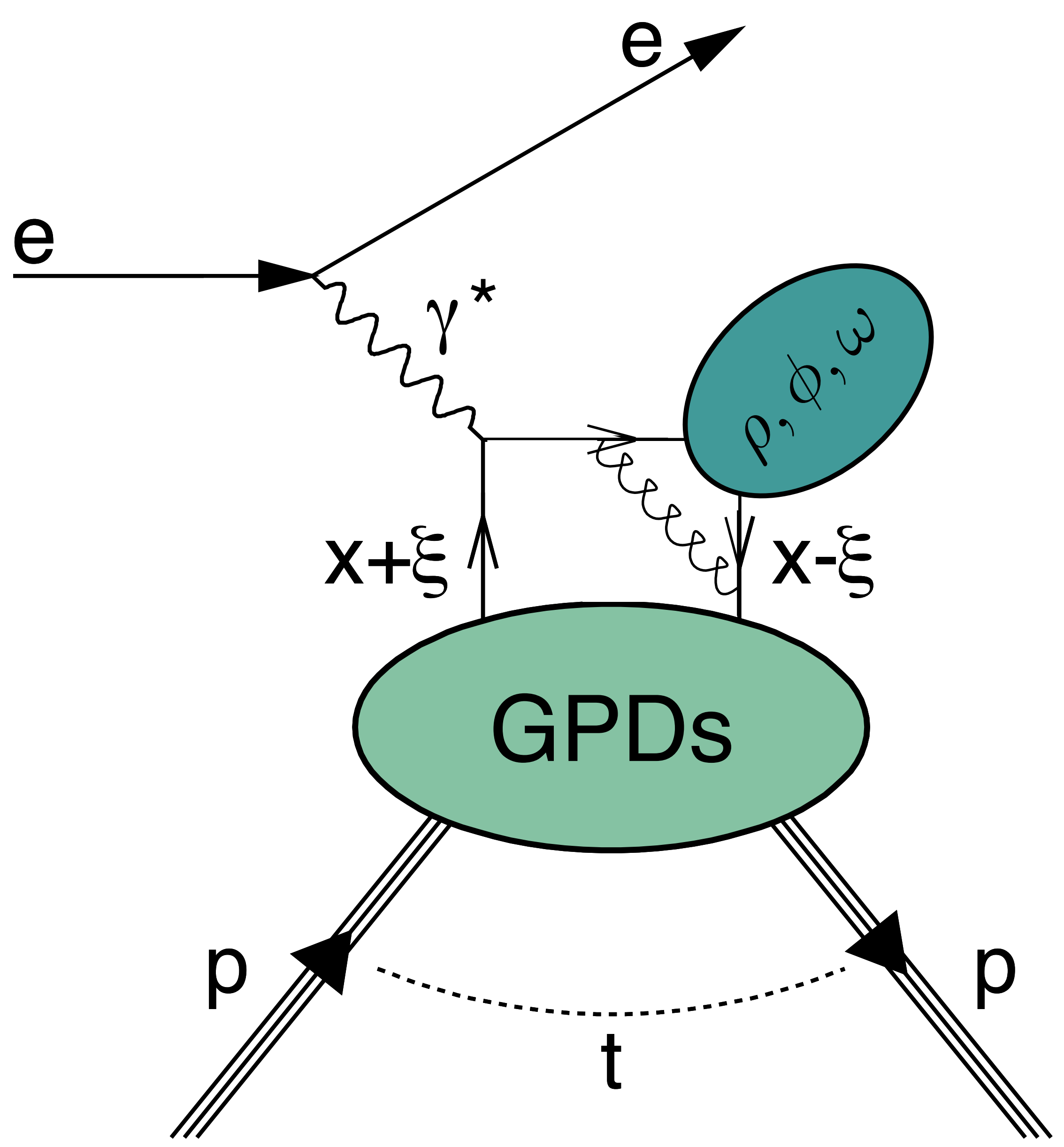
CLAS – PRC 80 ('09) 035206; PRL 87 ('01) 182002; 100 ('08) 162002
COMPASS – arXiv:1702.06315
JLab Hall A Collaboration – PRL 99 ('07) 242501; PRC 92 ('15) 055202; Nat. Com. **8** ('17) 1408
HERMES – JHEP 10 ('12) 042; PLB 704 ('11) 15; NPB 842 ('11) 265
H1 – PLB 681 ('09) 391; 659 ('07) 796; EPJ C 44 ('05) 1
ZEUS – PLB 573 (2003) 46; JHEP 05 ('09) 108

CLAS – PRC 95 ('17) 035207; 95 (2017) 035202
COMPASS – PLB 731 ('14) 19; NPB 915 ('17) 454
JLab Hall A Collaboration – PRC 83 ('11) 025201
HERMES – EPJ C 74 ('14) 3110; 75 ('15) 600; 77 ('17) 378

Experimental access to GPDs



Deeply virtual Compton scattering (DVCS)
Hard scale=large Q^2=-q^2



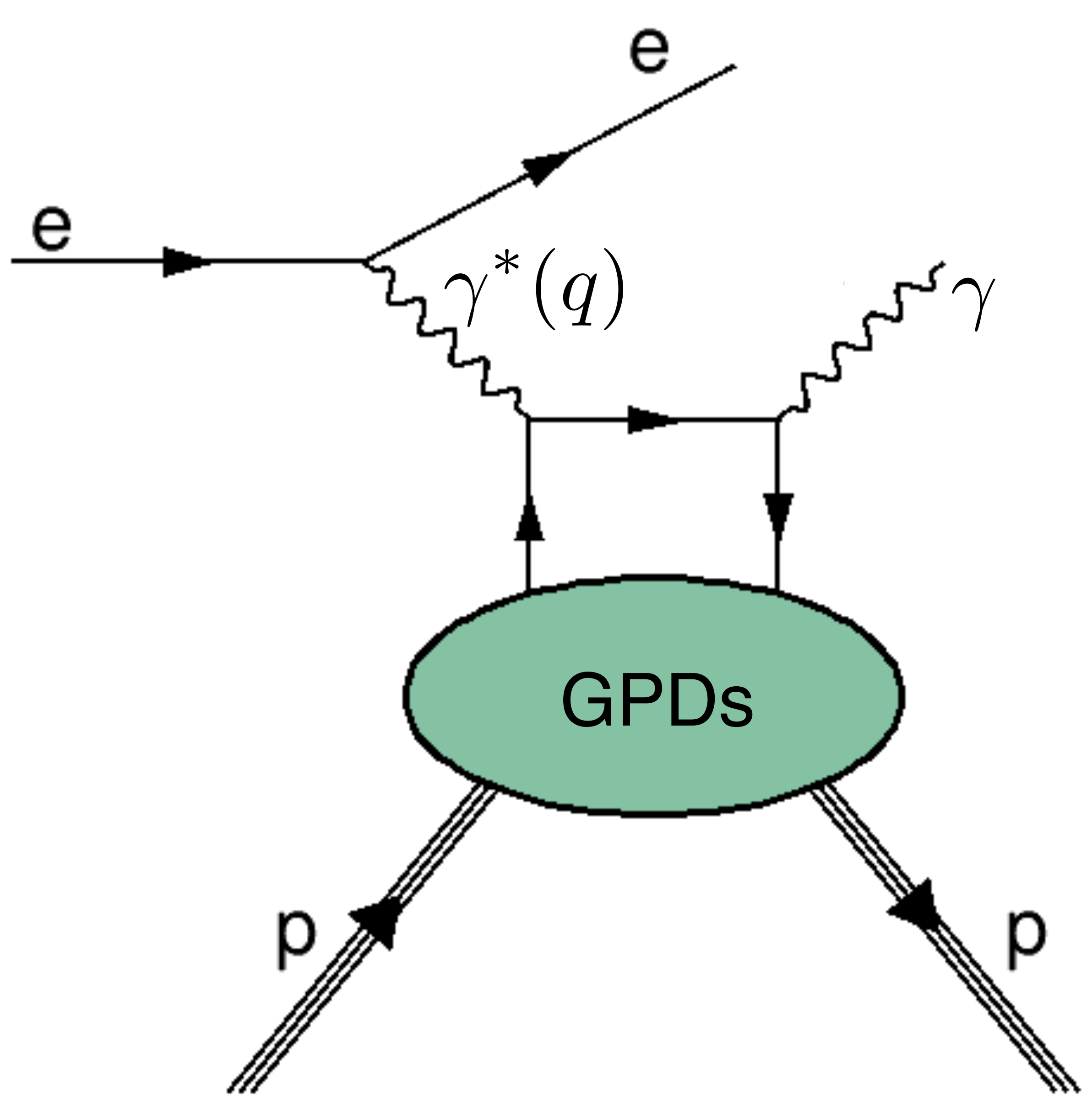
Hard exclusive meson production
Hard scale=large Q^2

CLAS – PRC 80 ('09) 035206; PRL 87 ('01) 182002; 100 ('08) 162002
COMPASS – arXiv:1702.06315
JLab Hall A Collaboration – PRL 99 ('07) 242501; PRC 92 ('15) 055202; Nat. Com. **8** ('17) 1408
HERMES – JHEP 10 ('12) 042; PLB 704 ('11) 15; NPB 842 ('11) 265
H1 – PLB 681 ('09) 391; 659 ('07) 796; EPJ C 44 ('05) 1
ZEUS – PLB 573 (2003) 46; JHEP 05 ('09) 108

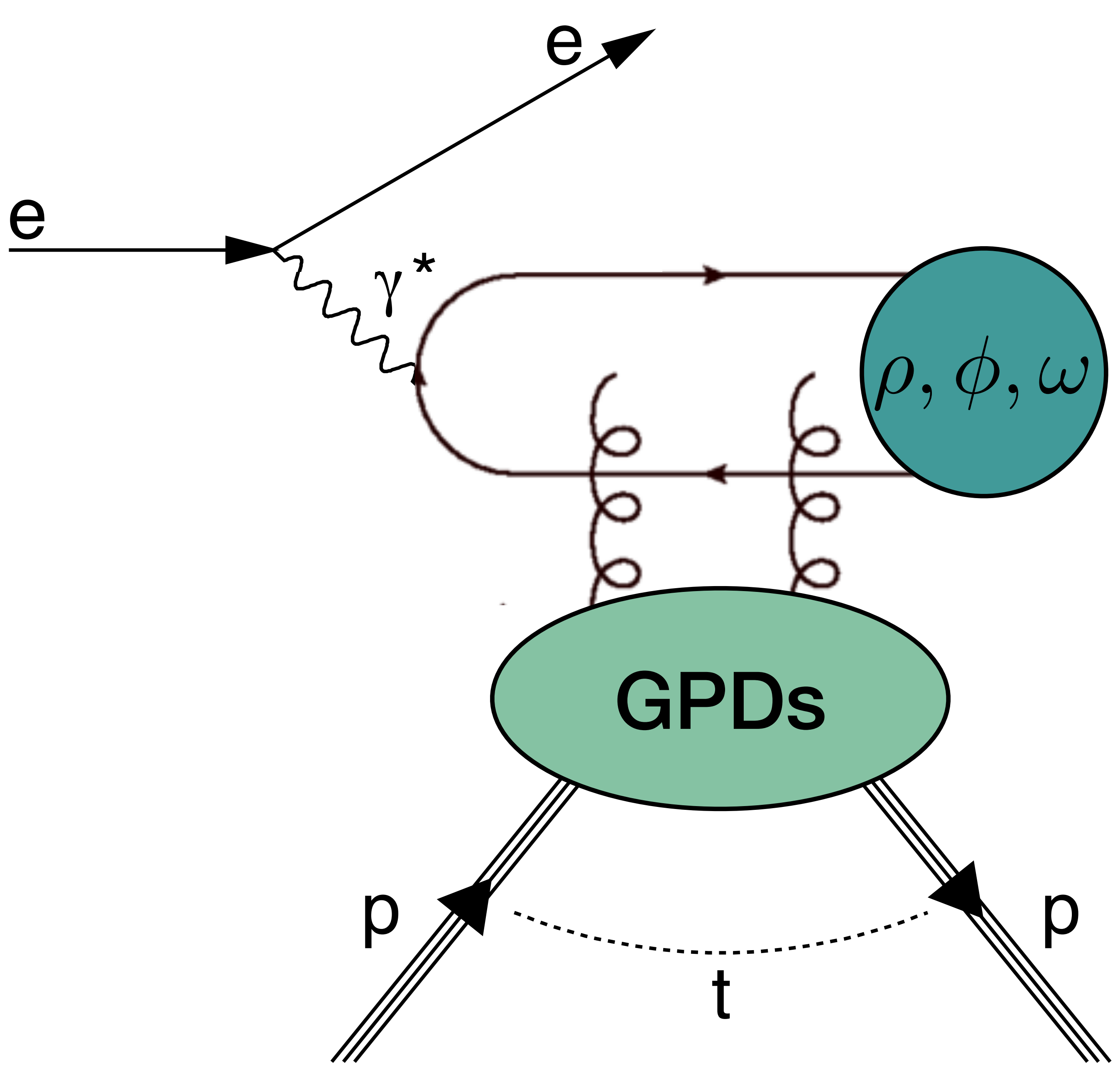
CLAS – PRC 95 ('17) 035207; 95 (2017) 035202
COMPASS – PLB 731 ('14) 19; NPB 915 ('17) 454
JLab Hall A Collaboration – PRC 83 ('11) 025201
HERMES – EPJ C 74 ('14) 3110; 75 ('15) 600; 77 ('17) 378

fixed target: medium/large x_B , quarks

Experimental access to GPDs



Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$



Hard exclusive meson production
Hard scale=large Q^2

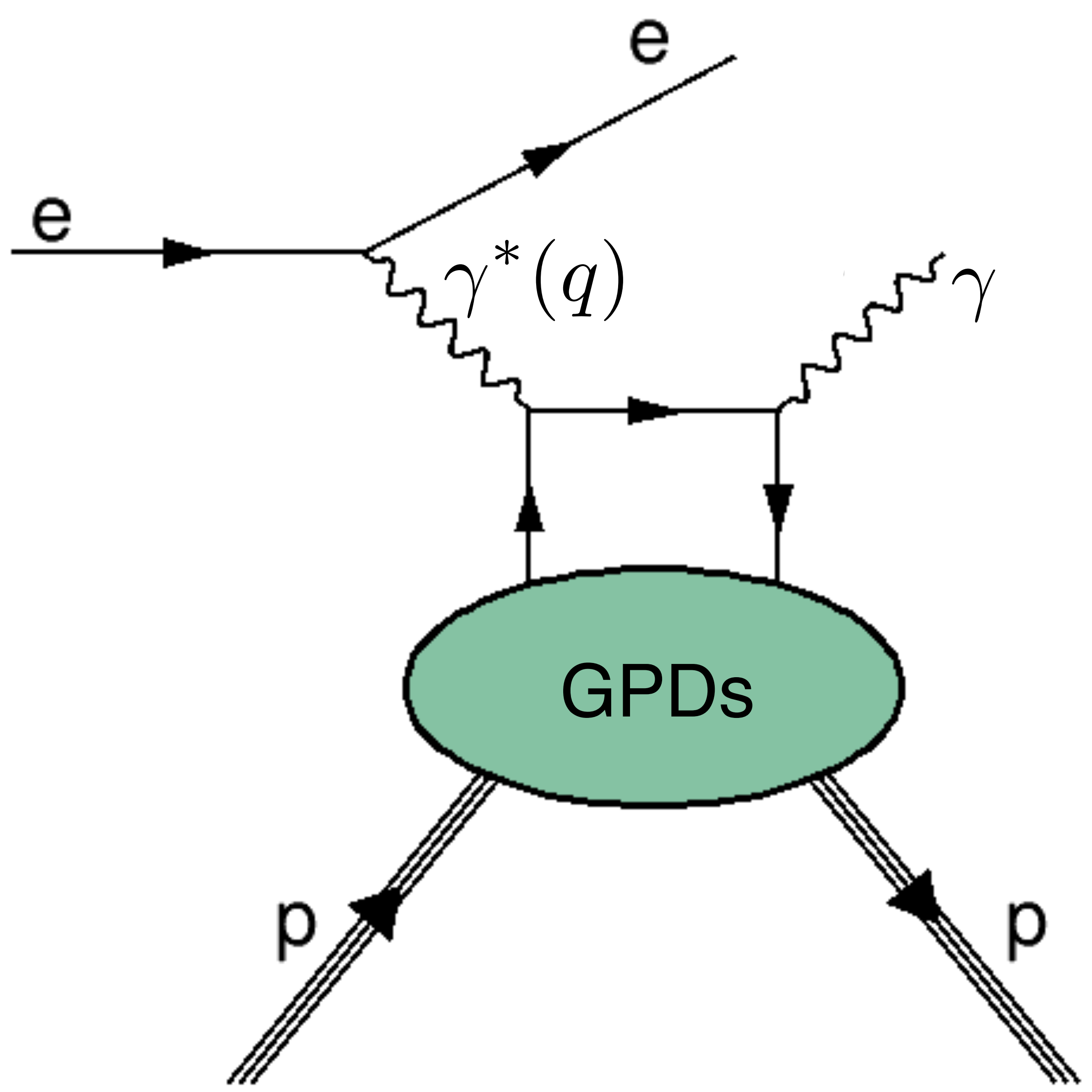
CLAS – PRC 80 ('09) 035206; PRL 87 ('01) 182002; 100 ('08) 162002
COMPASS – arXiv:1702.06315
JLab Hall A Collaboration – PRL 99 ('07) 242501; PRC 92 ('15) 055202; Nat. Com. **8** ('17) 1408
HERMES – JHEP 10 ('12) 042; PLB 704 ('11) 15; NPB 842 ('11) 265
H1 – PLB 681 ('09) 391; 659 ('07) 796; EPJ C 44 ('05) 1
ZEUS – PLB 573 (2003) 46; JHEP 05 ('09) 108

CLAS – PRC 95 ('17) 035207; 95 (2017) 035202
COMPASS – PLB 731 ('14) 19; NPB 915 ('17) 454
JLab Hall A Collaboration – PRC 83 ('11) 025201
HERMES – EPJ C 74 ('14) 3110; 75 ('15) 600; 77 ('17) 378
H1 – JHEP 05('10)032; EPJ C 46 ('06) 585
ZEUS – PMC Phys. A1 ('07) 6; NPB 695 ('04) 3

colliders, small x_B, gluons

fixed target: medium/large x_B, quarks

Experimental access to GPDs



Deeply virtual Compton scattering (DVCS)
Hard scale=large Q^2=-q^2

CLAS – PRC 80 ('09) 035206; PRL 87 ('01) 182002; 100 ('08) 162002

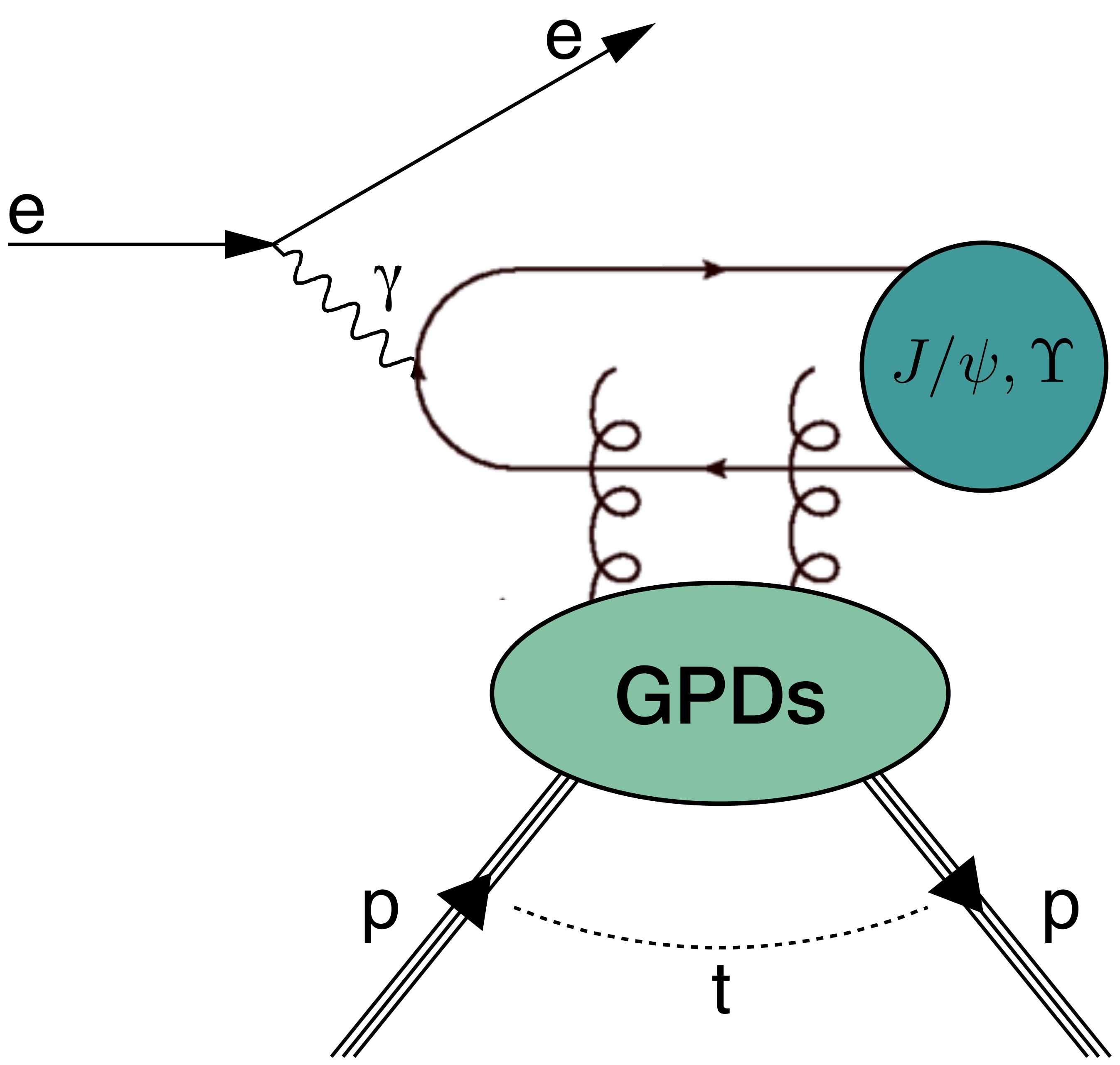
COMPASS – arXiv:1702.06315

JLab Hall A Collaboration – PRL 99 ('07) 242501; PRC 92 ('15) 055202; Nat. Com. **8** ('17) 1408

HERMES – JHEP 10 ('12) 042; PLB 704 ('11) 15; NPB 842 ('11) 265

H1 – PLB 681 ('09) 391; 659 ('07) 796; EPJ C 44 ('05) 1

ZEUS – PLB 573 (2003) 46; JHEP 05 ('09) 108

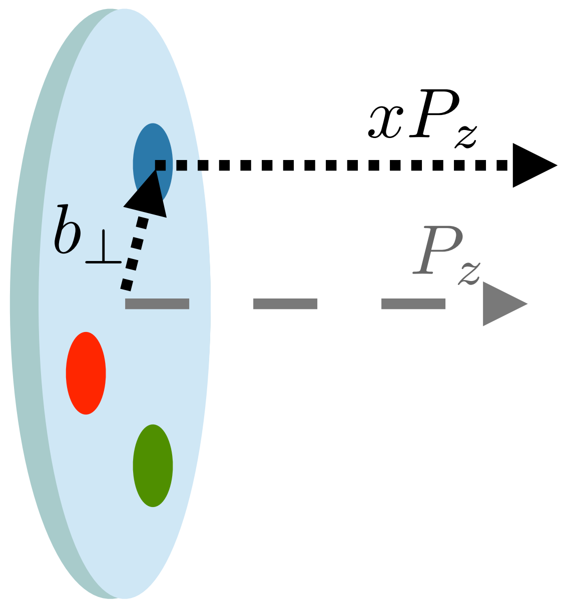


gluons!

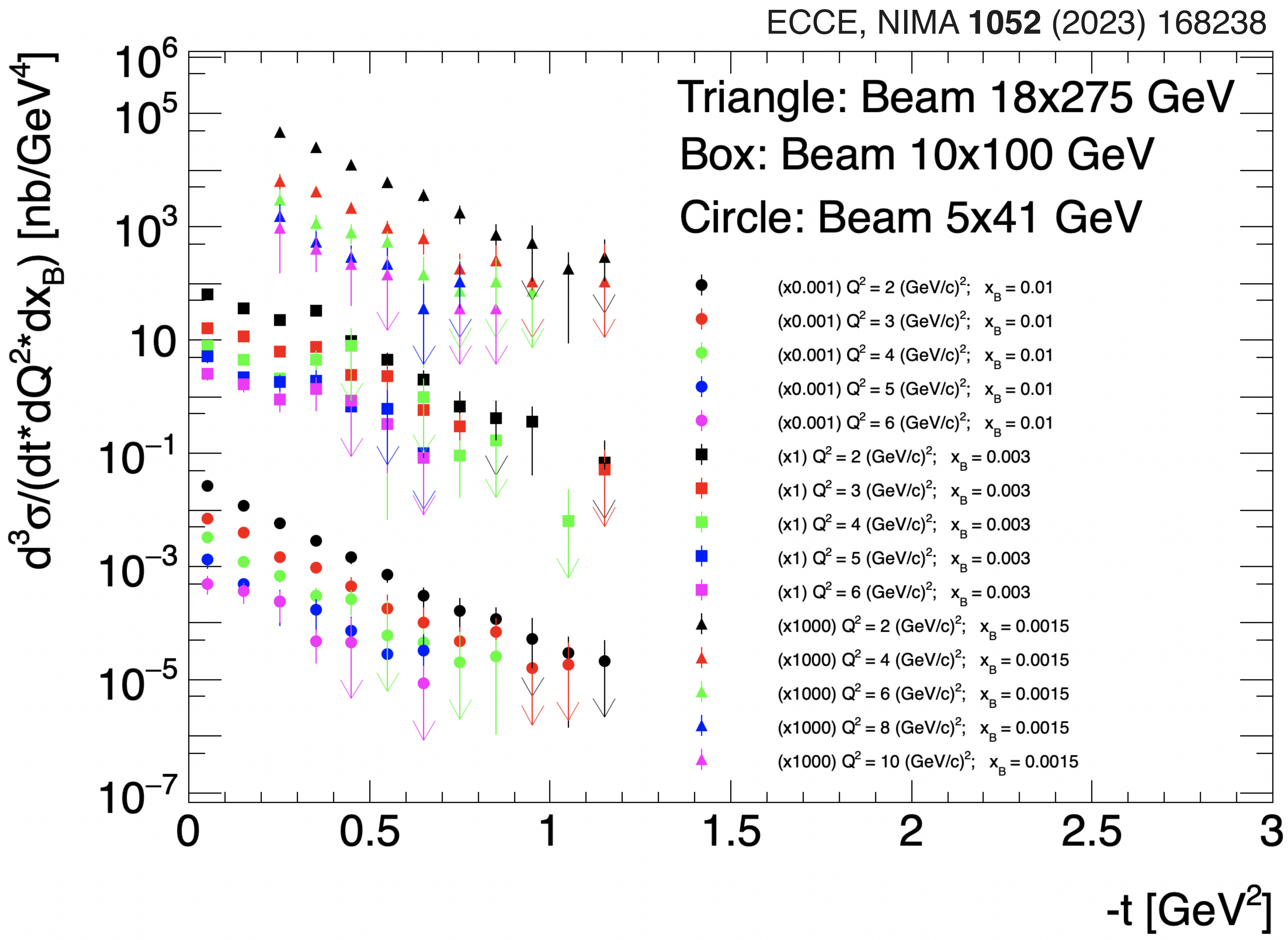
Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass

H1 – EPJ C 46 ('06) 585; 73 ('13) 2466; PLB 541 ('02) 251
ZEUS – Nucl. Phys. B 695 ('04) 3; PLB 680 ('09) 4

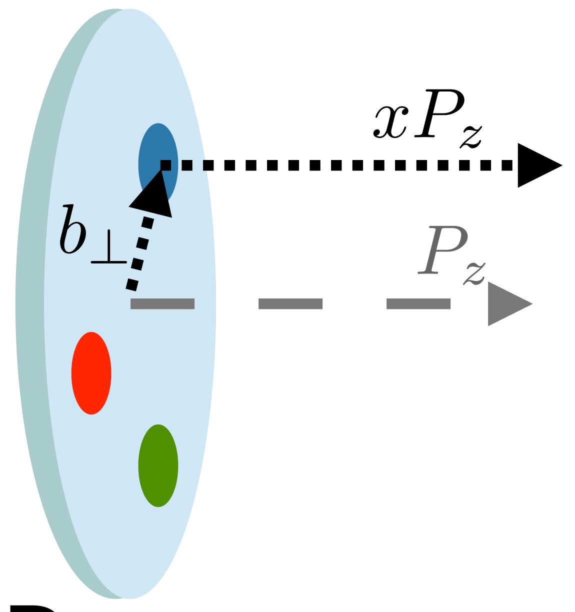
Exclusive measurements on p with the EIC



Deeply virtual Compton scattering
→ sensitive to quarks (and gluons)

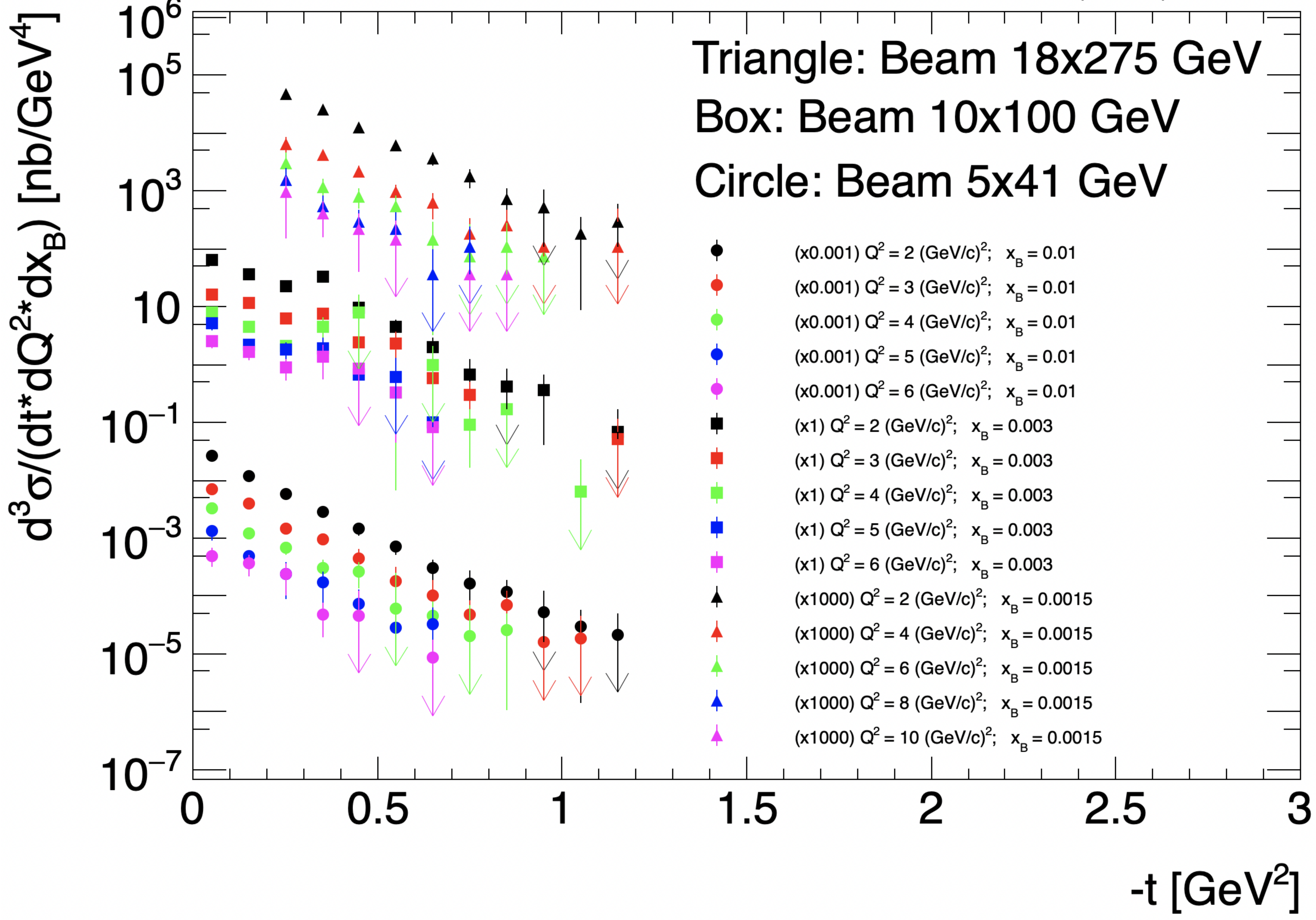


Exclusive measurements on p with the EIC



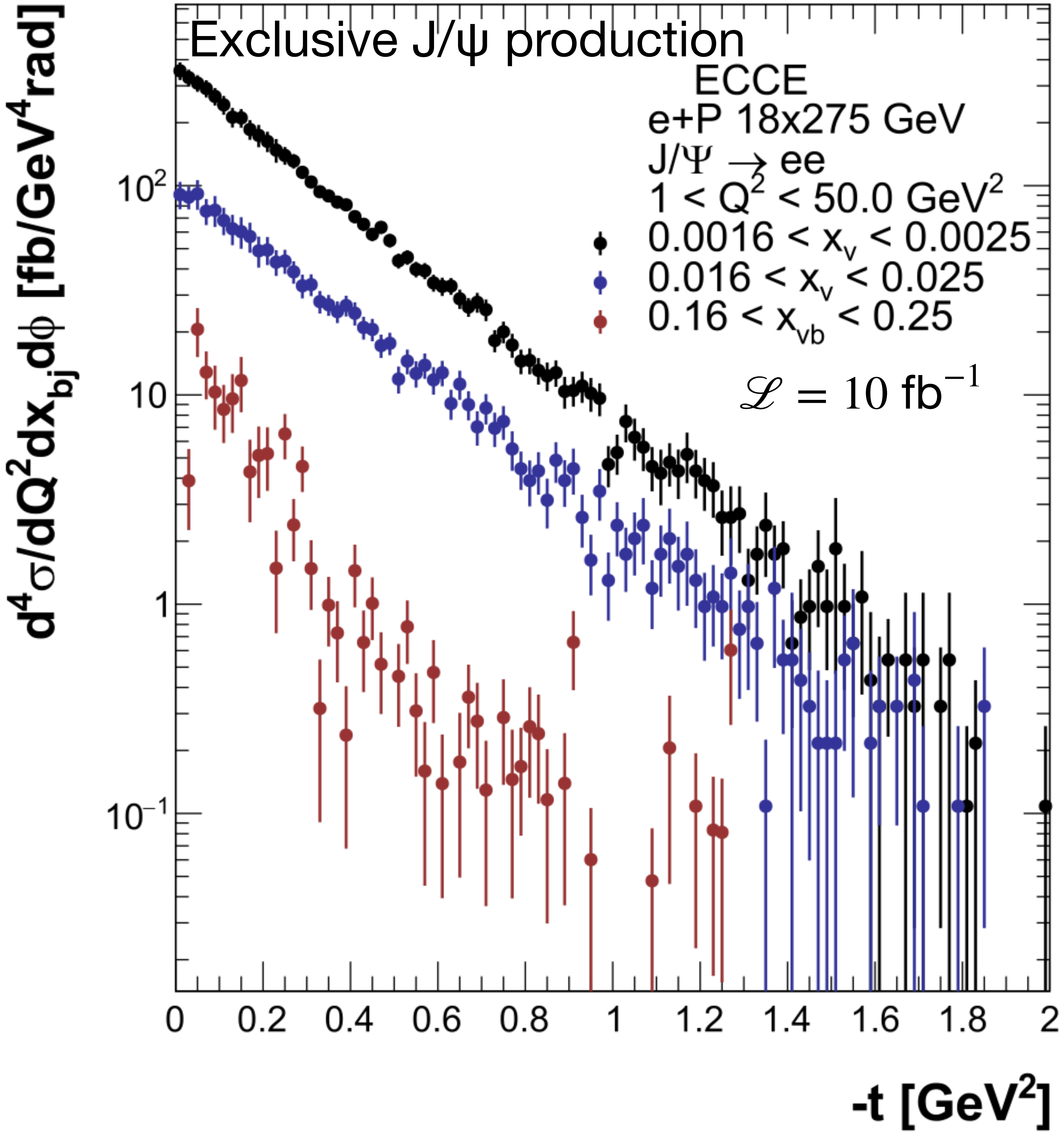
Deeply virtual Compton scattering
→ sensitive to quarks (and gluons)

ECCE, NIMA **1052** (2023) 168238



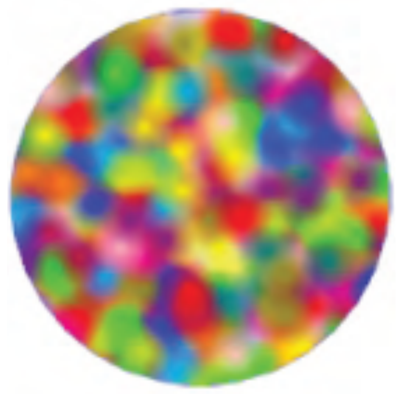
Exclusive J/ψ production
→ excellent to probe gluon GPDs

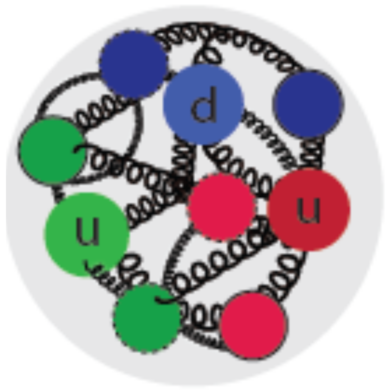
ECCE, NIMA **1052** (2023) 168238

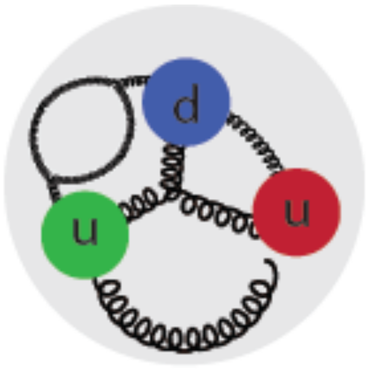


Why an EIC?

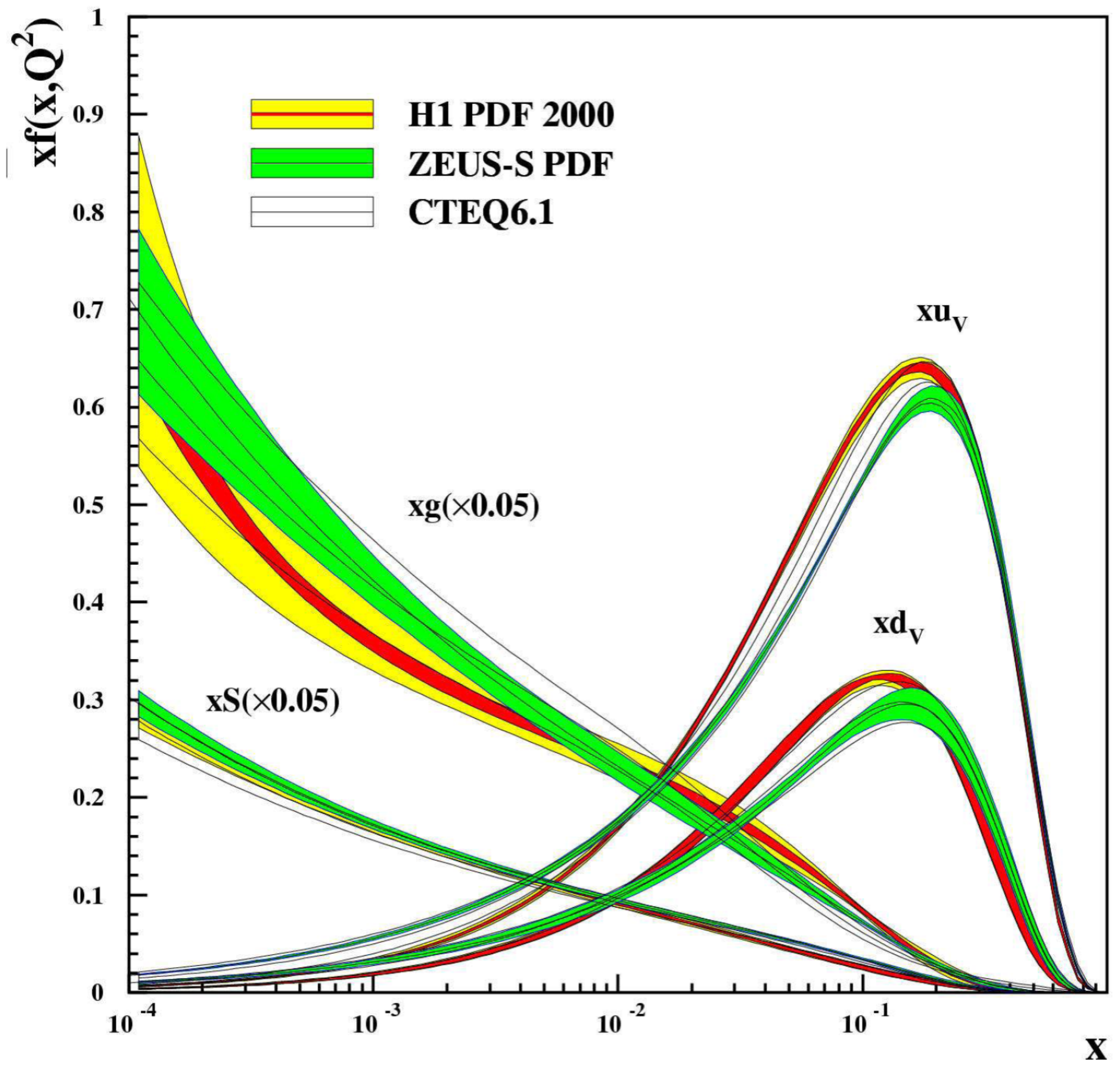
Gluon saturation



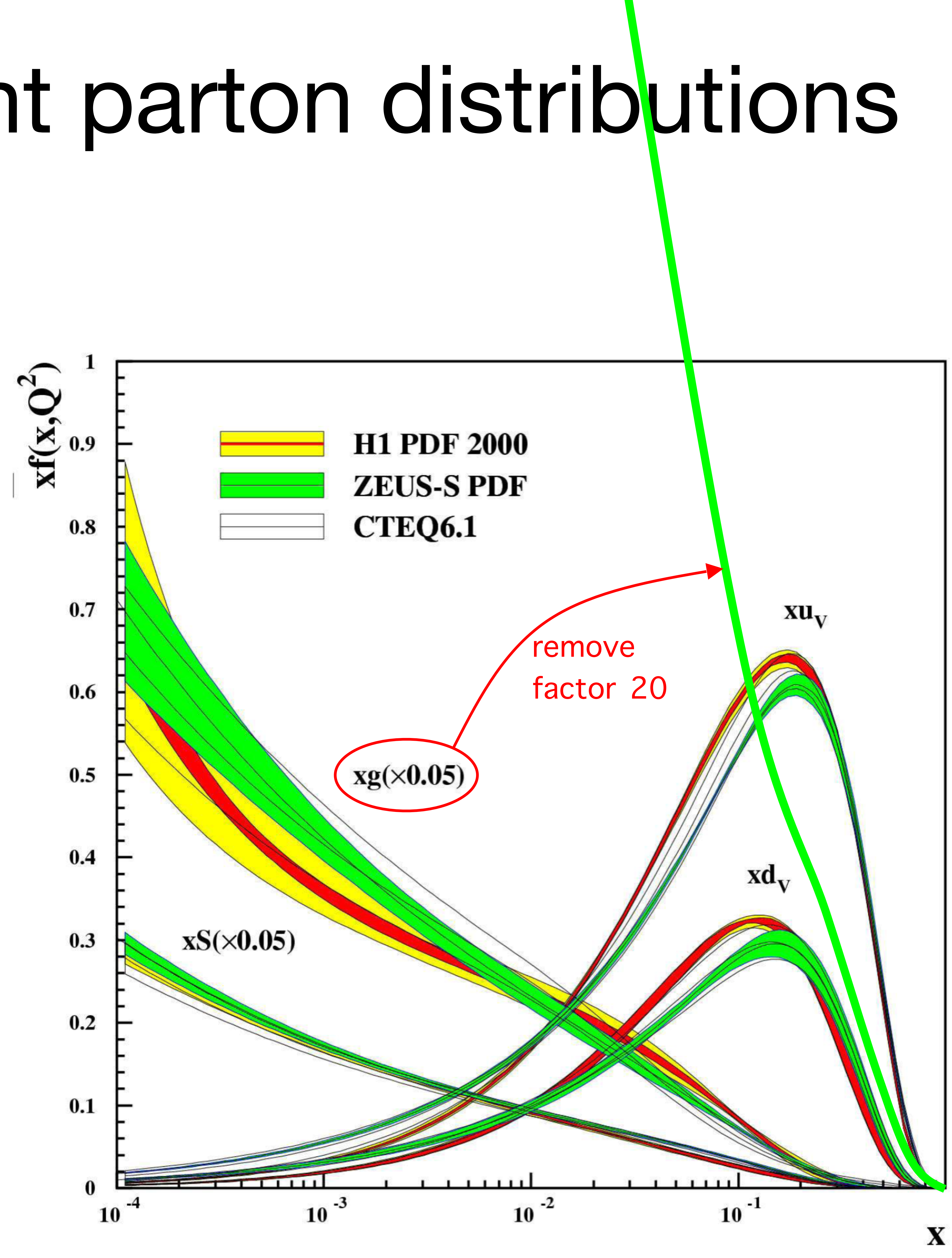




Spin-independent parton distributions

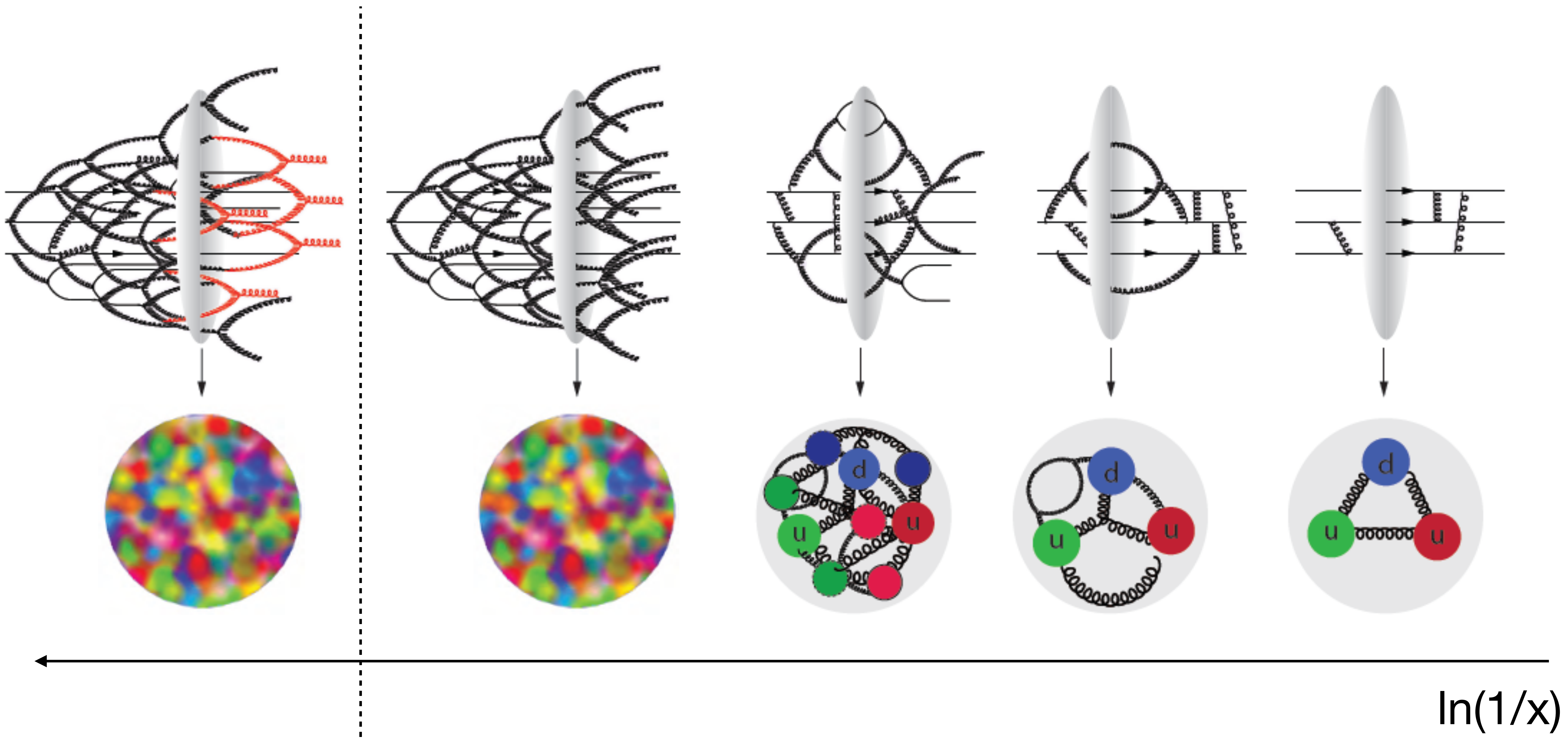


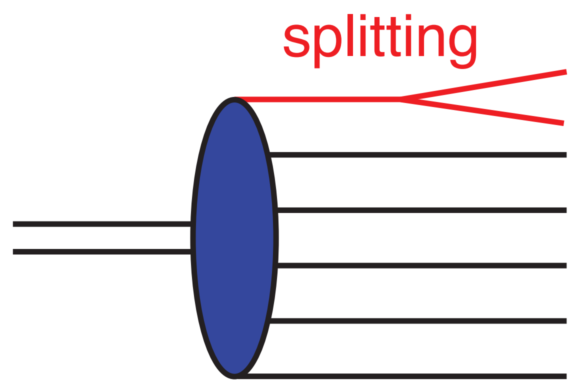
Spin-independent parton distributions



R. Ent

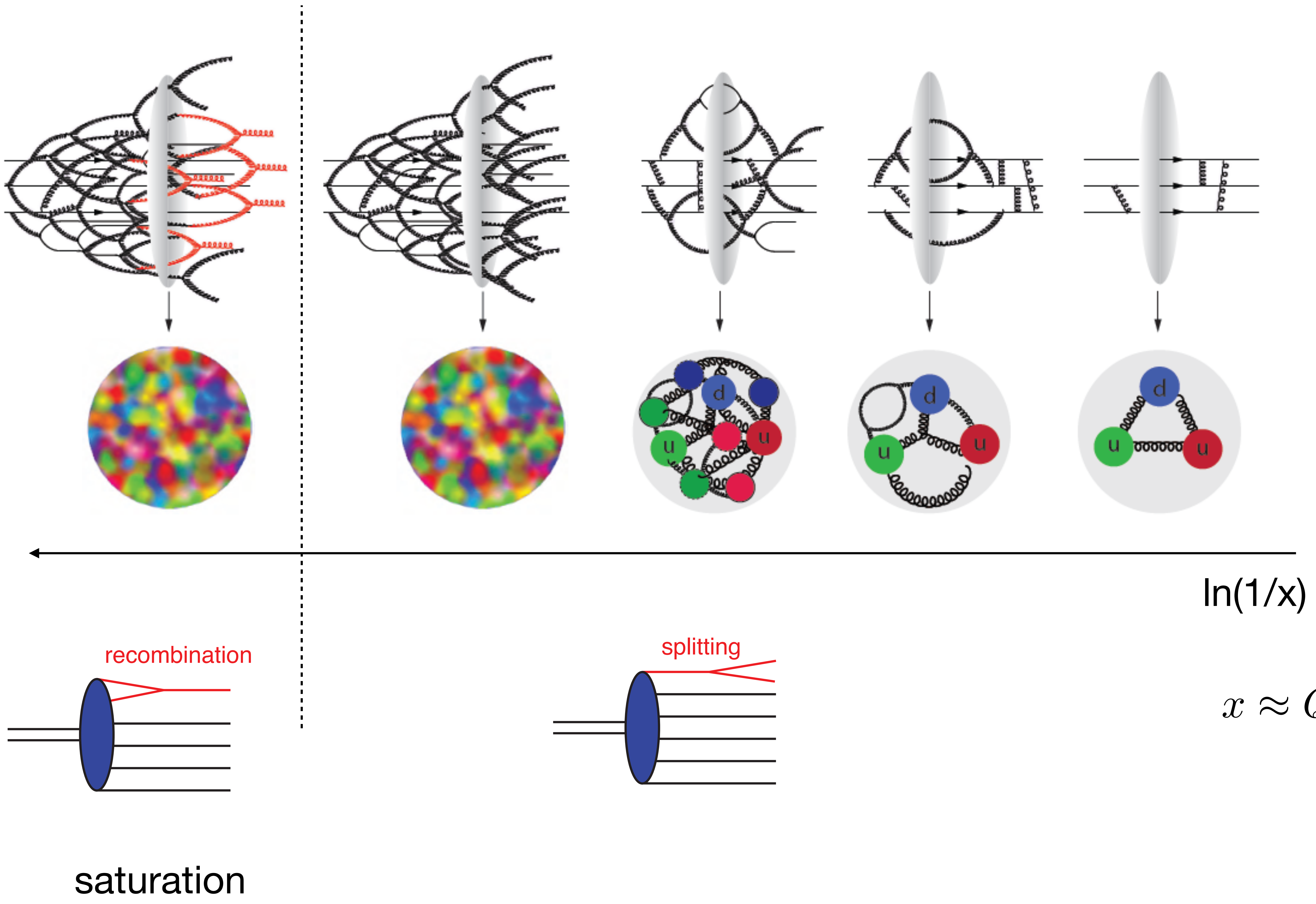
Gluon splitting and recombination





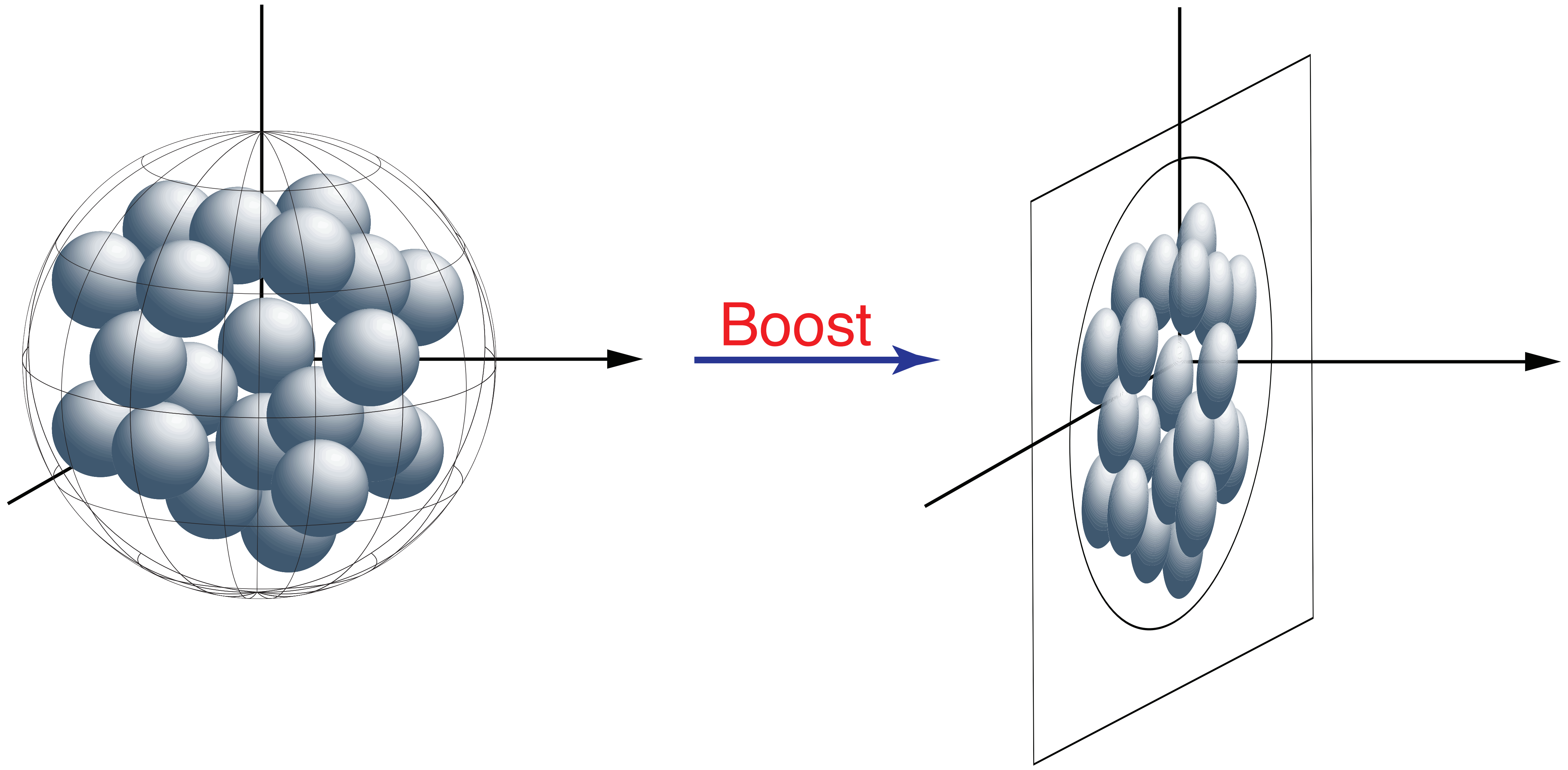
$$x \approx Q^2/W^2$$

Gluon splitting and recombination

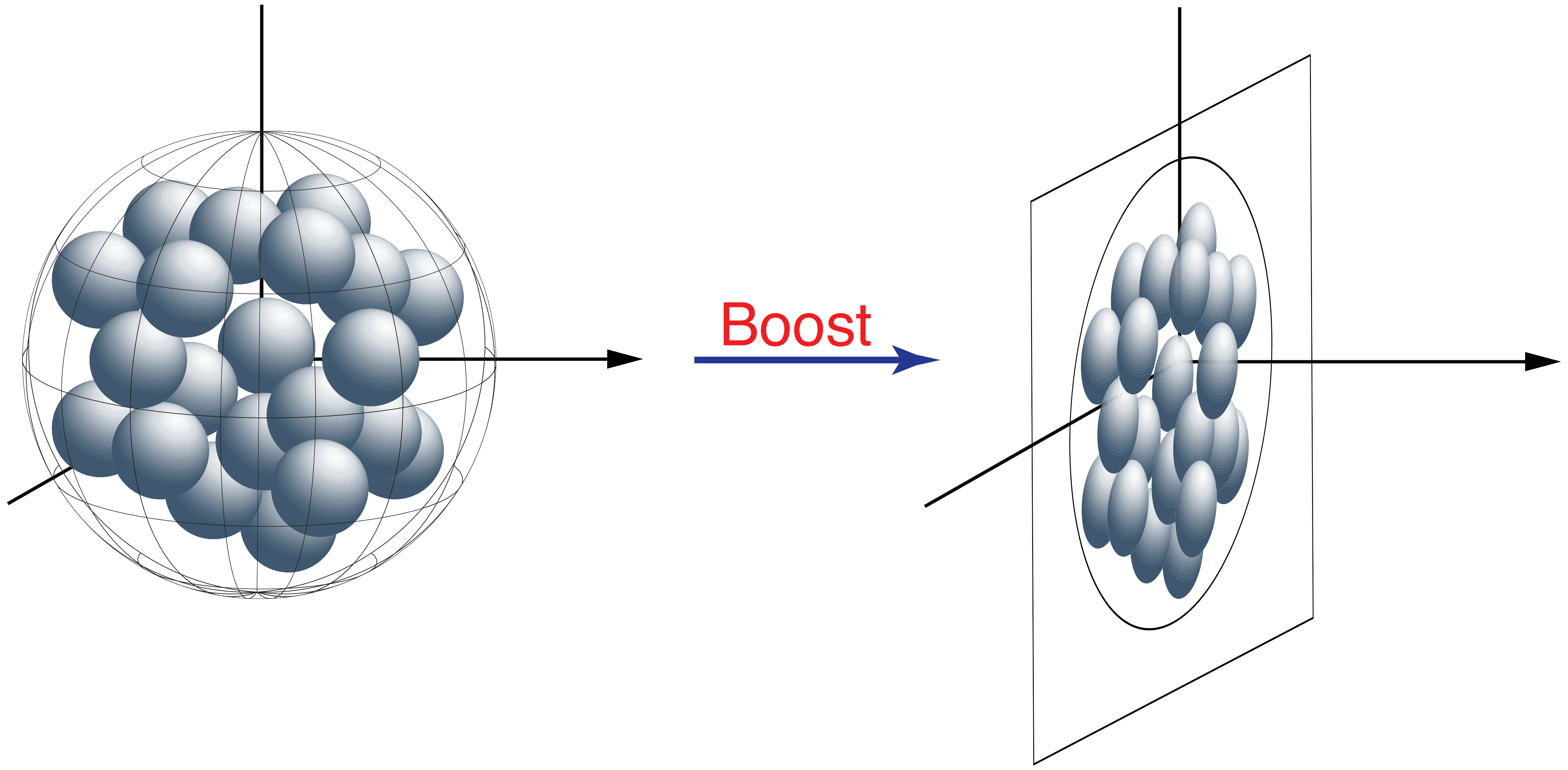


$x \approx Q^2/W^2$

The Oomph factor



The Oomph factor



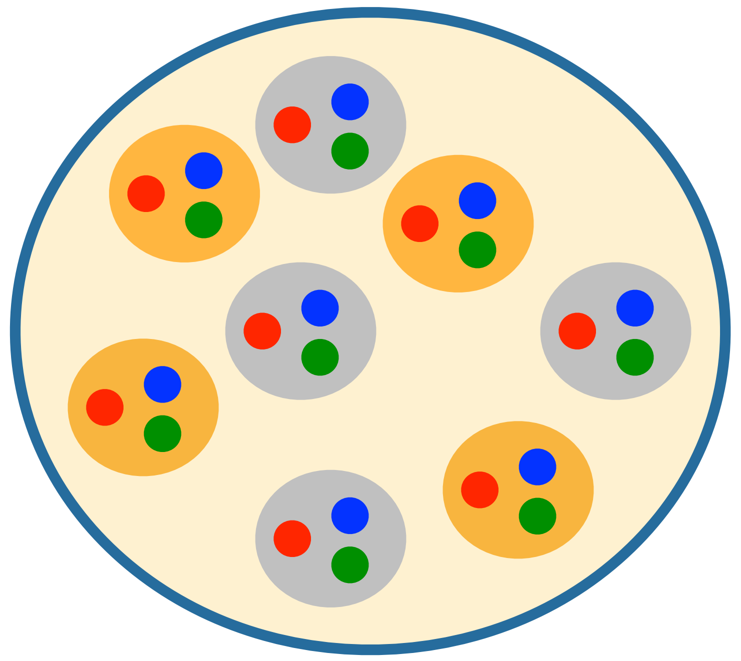
Oomph factor: $A^{1/3}$ enhancement of saturation effect

Exclusive/diffractive measurements on nuclei

What object are we probing?

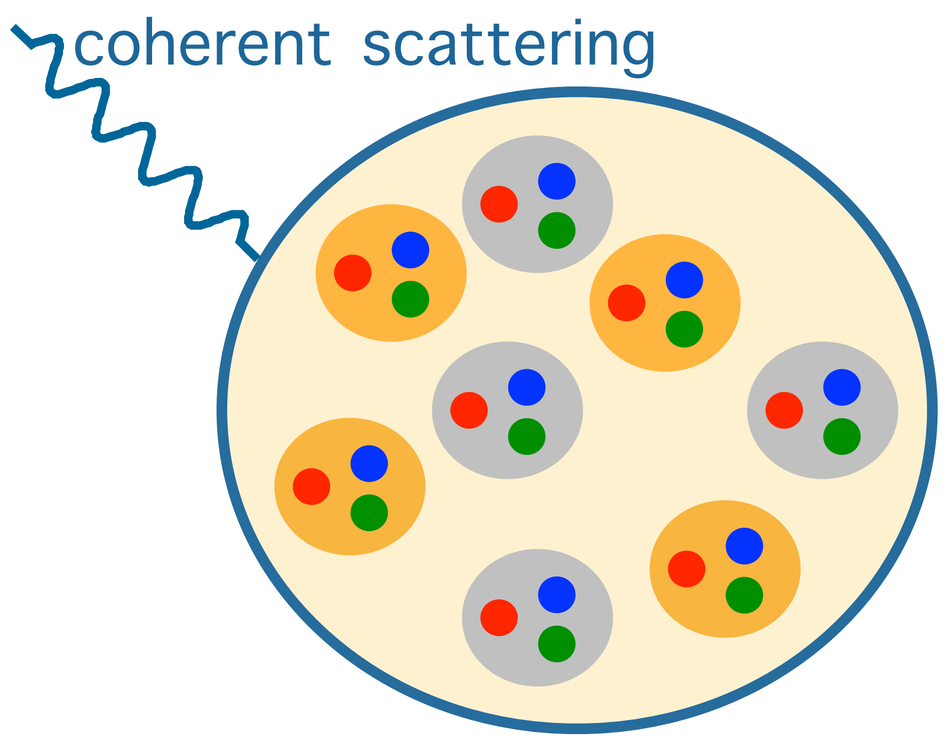
Exclusive/diffractive measurements on nuclei

What object are we probing?



Exclusive/diffractive measurements on nuclei

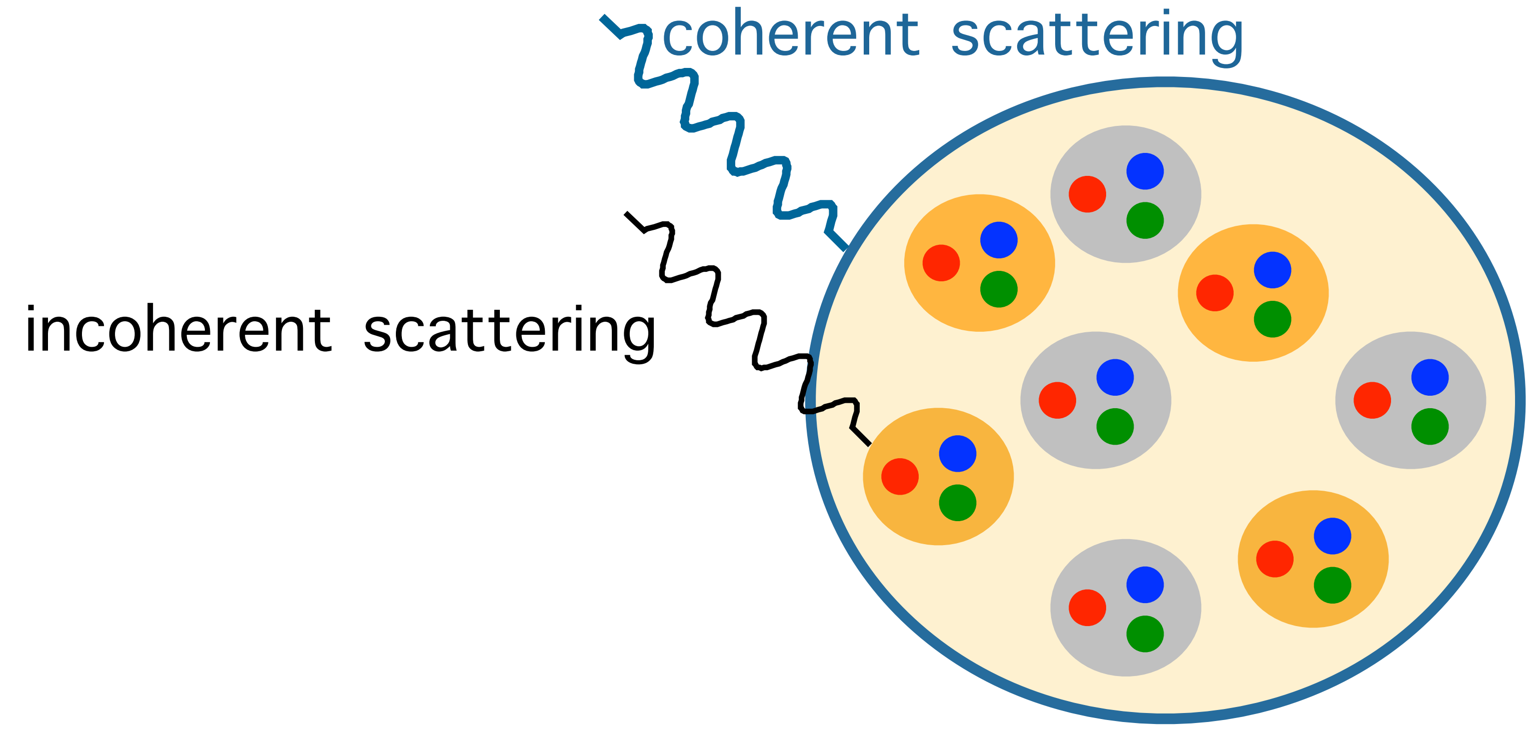
What object are we probing?



Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

Exclusive/diffractive measurements on nuclei

What object are we probing?

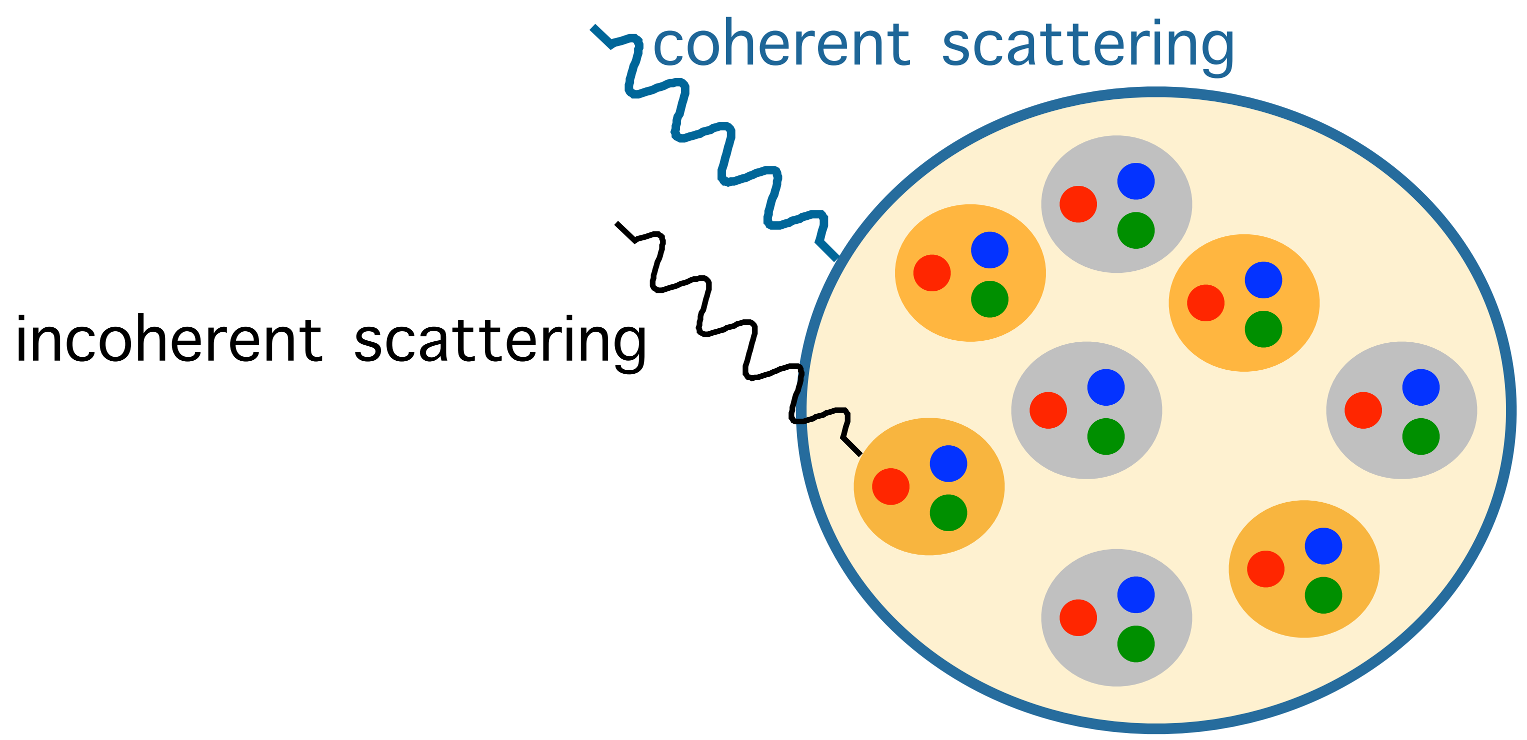


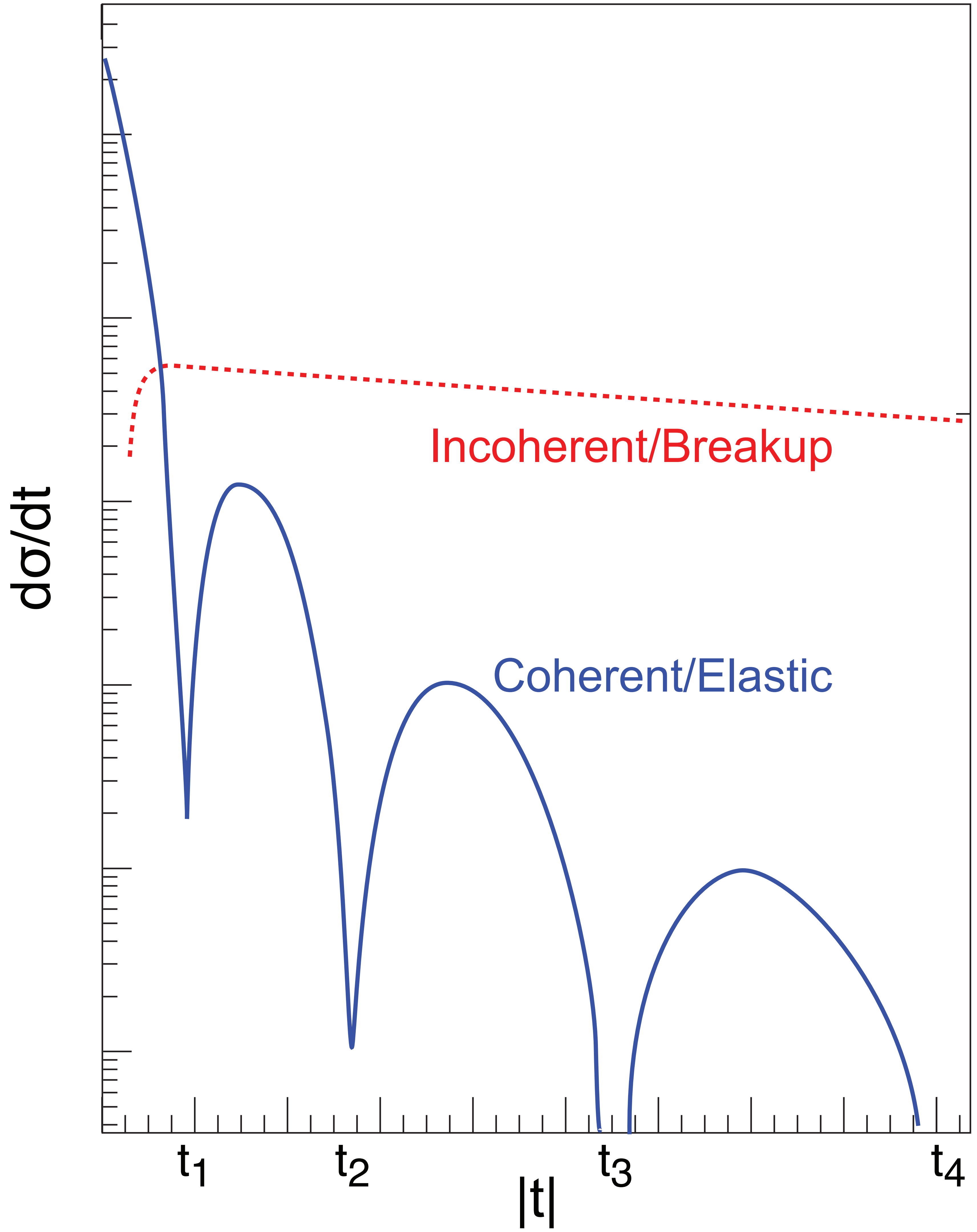
Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

Incoherent interaction: interaction with constituents inside target.
~ target does not remain in same quantum state.
Ex.: target dissociation, excitation

Exclusive/diffractive measurements on nuclei

What object are we probing?

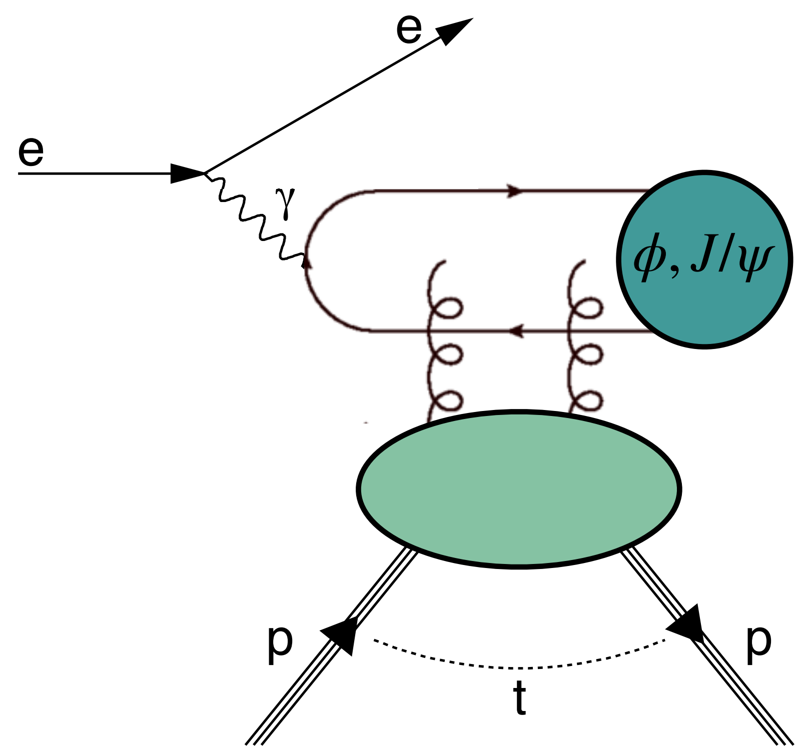




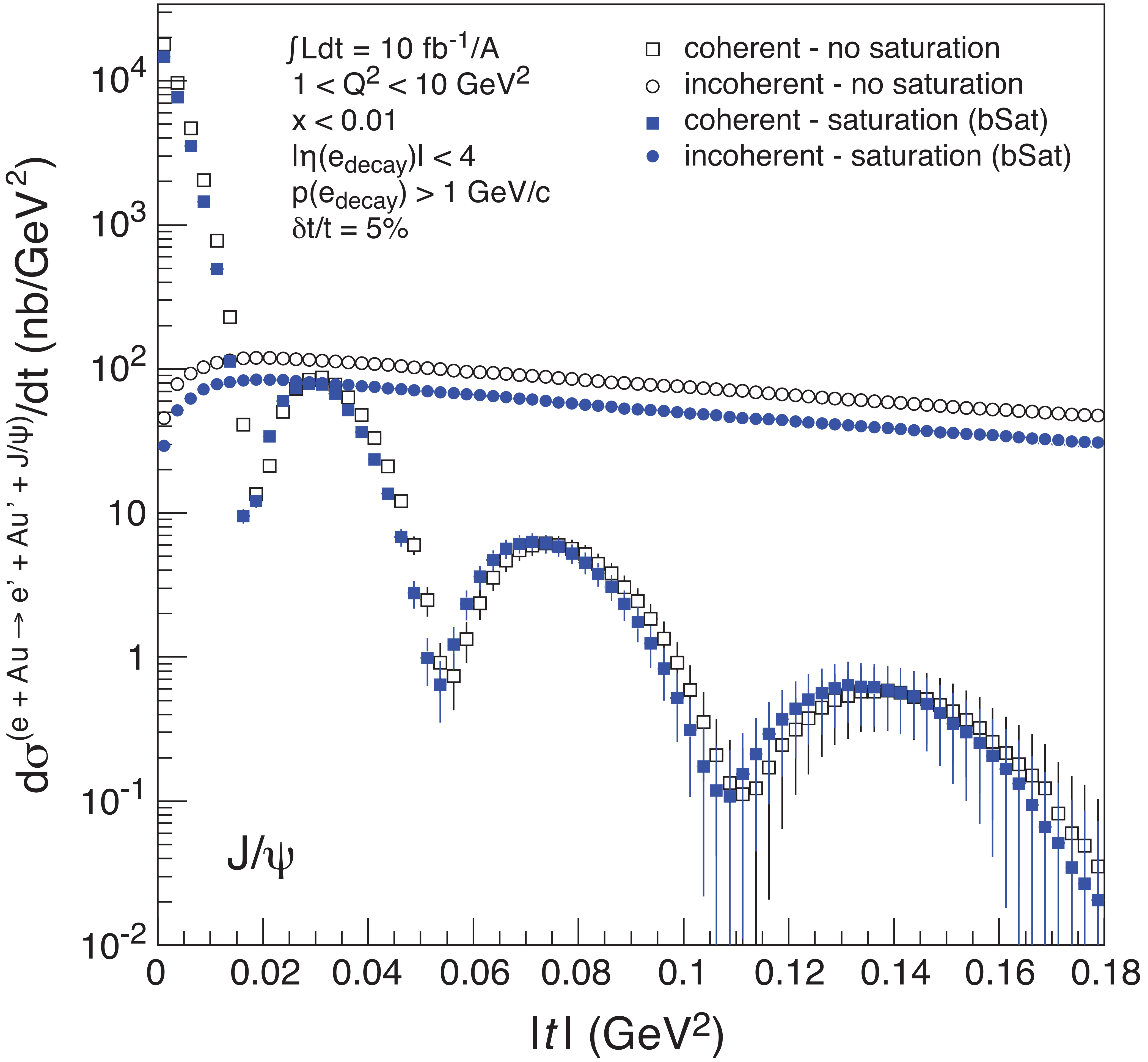
Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

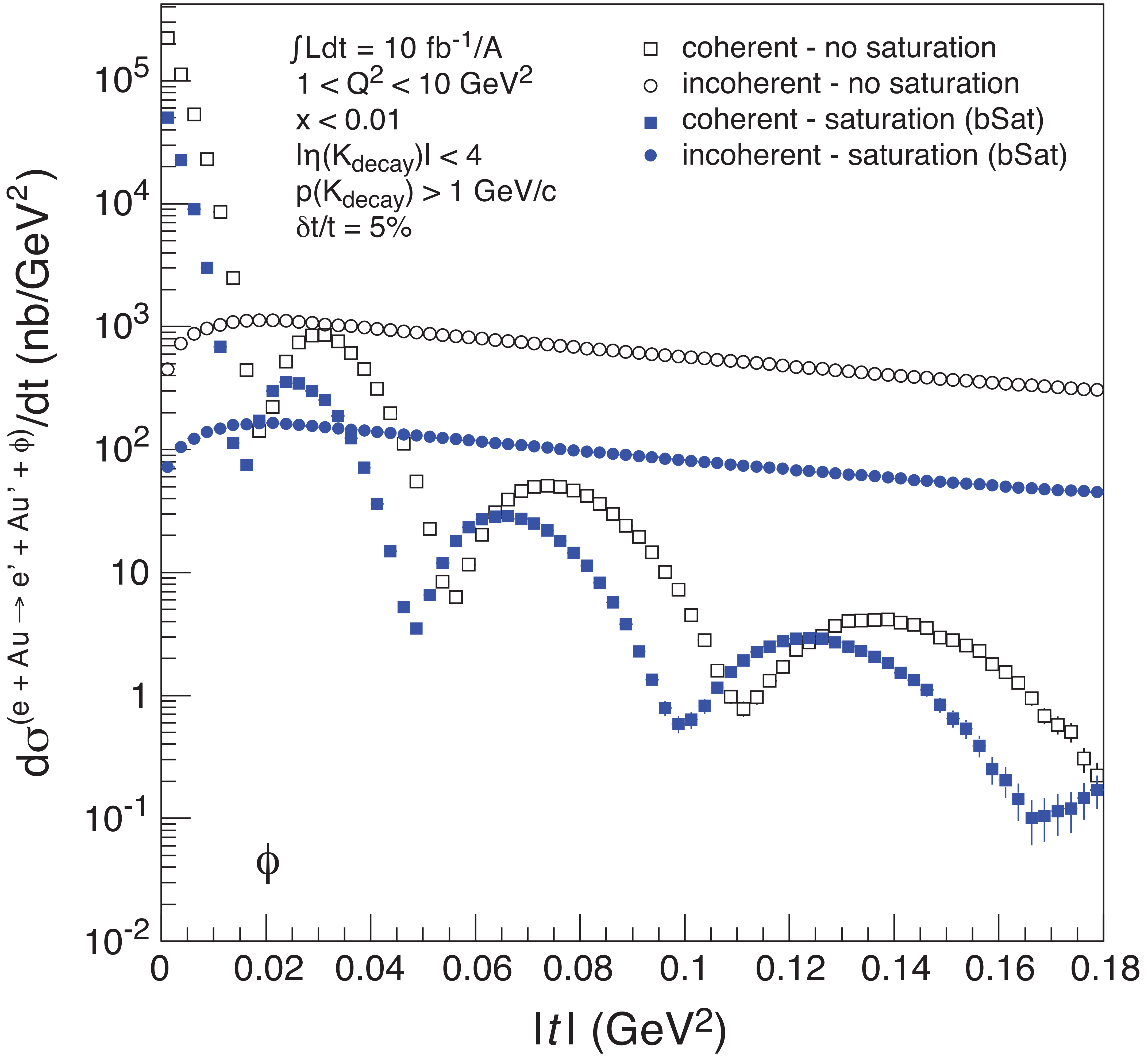
Incoherent interaction: interaction with constituents inside target.
~ target does not remain in same quantum state.
Ex.: target dissociation, excitation

Diffractive measurements at the EIC



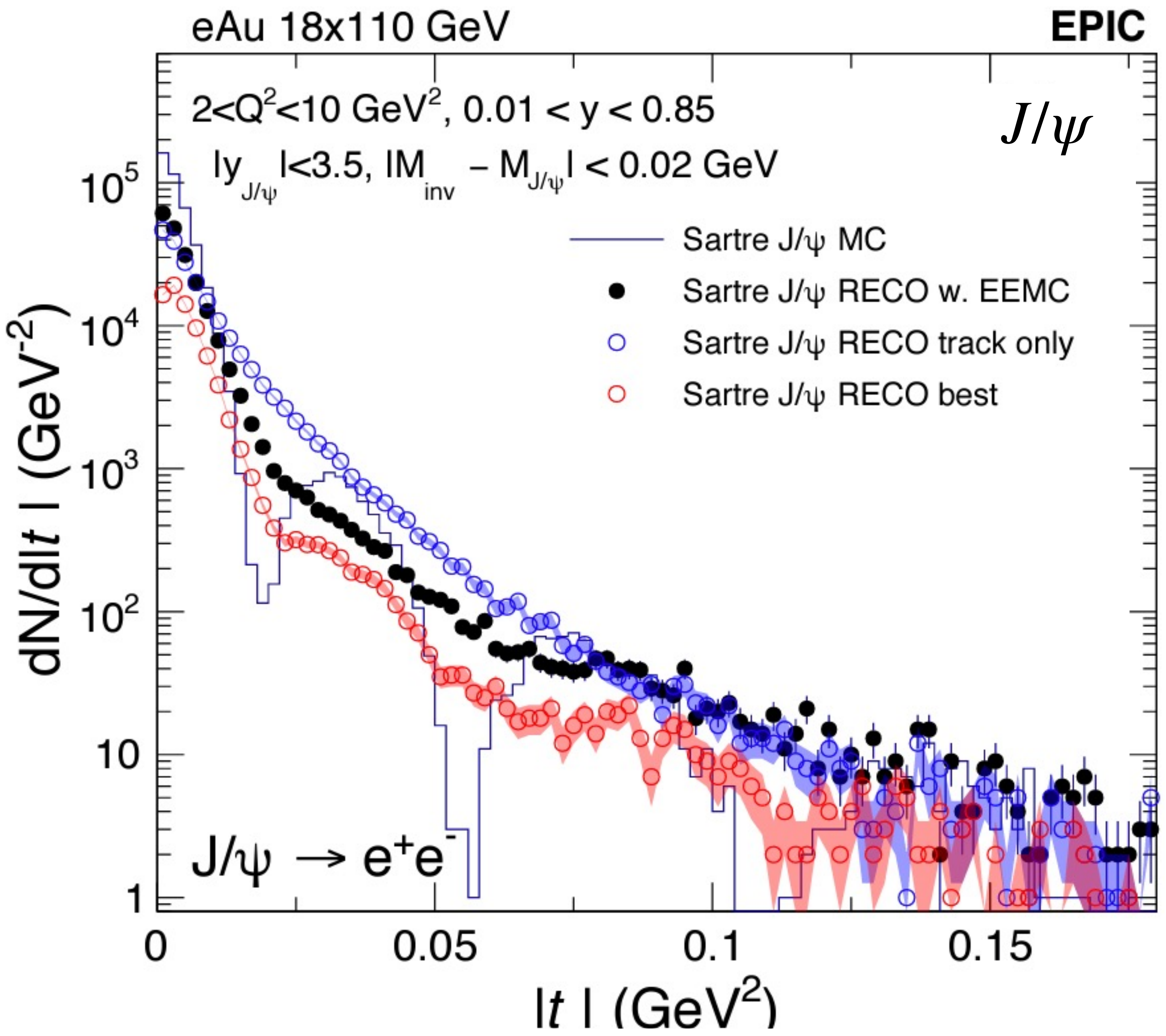
A. Accardi et al., arXiv:1212.1701

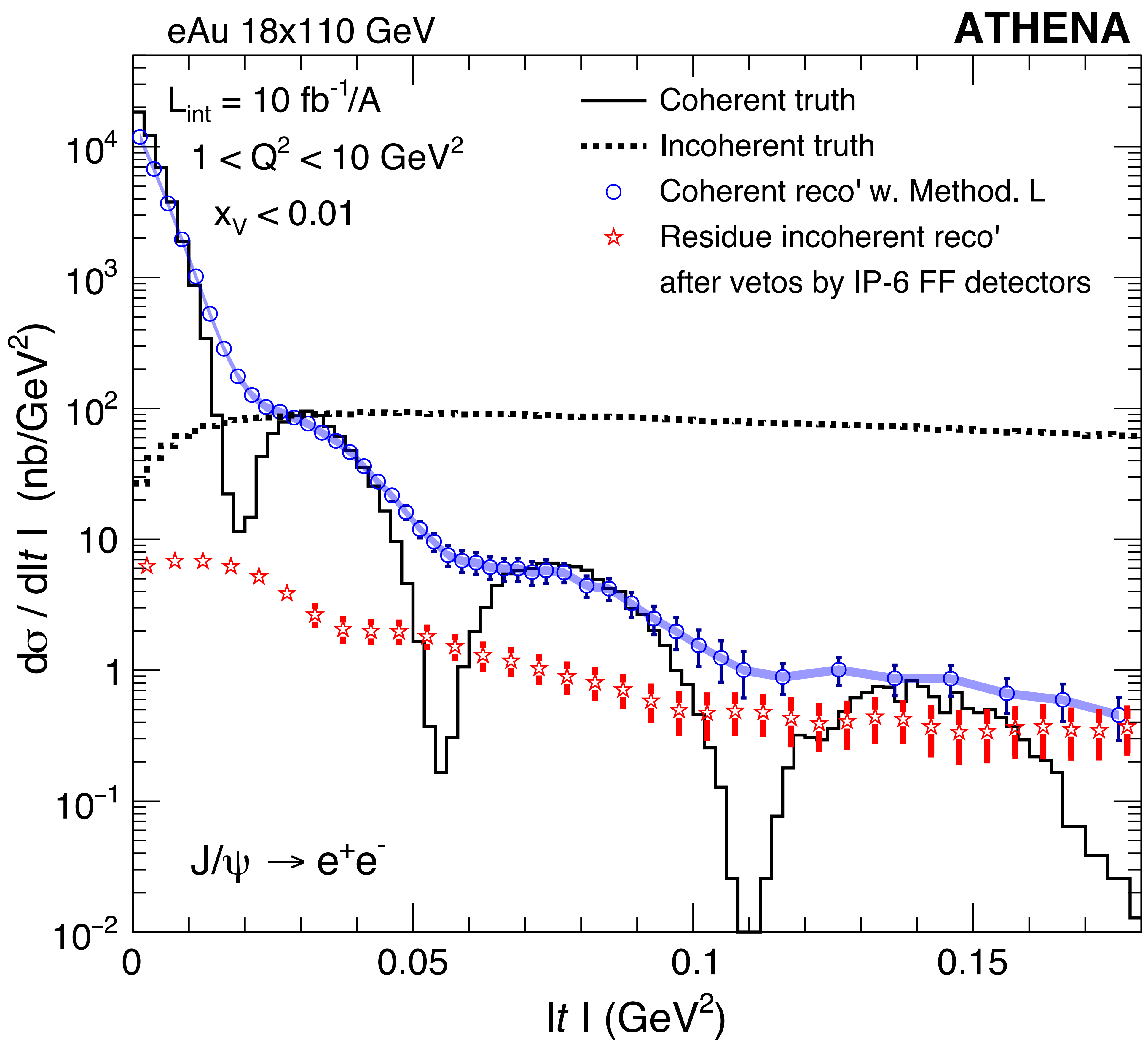




Exclusive measurements on nuclear targets with the EIC

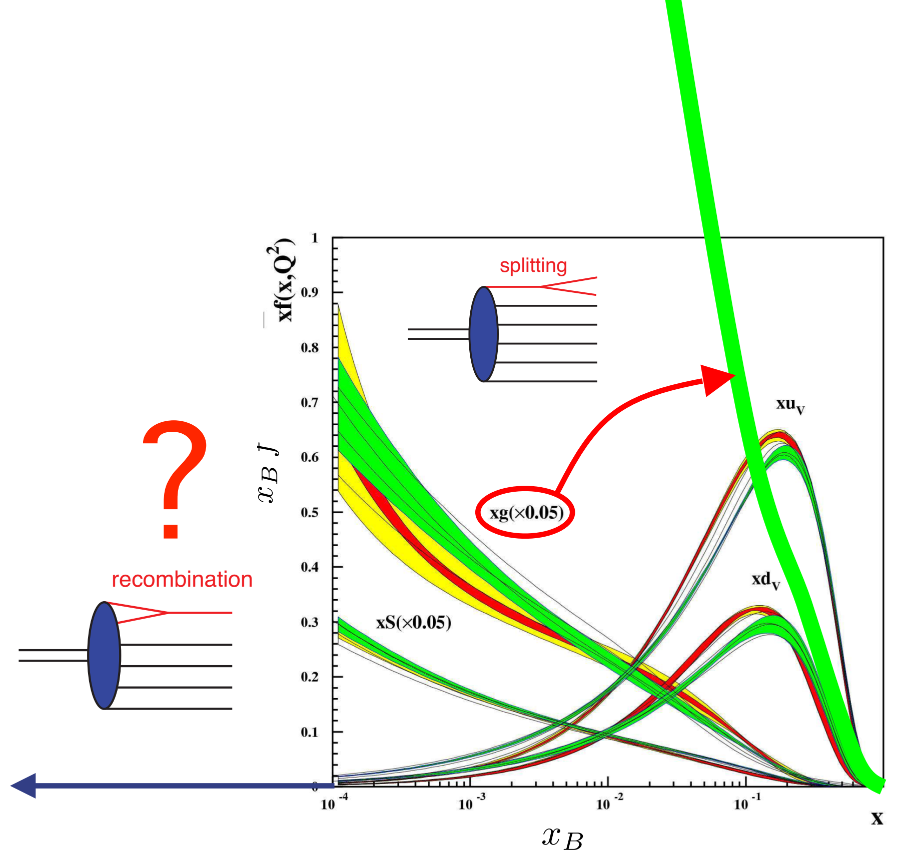
K. Tu, DIS 2023



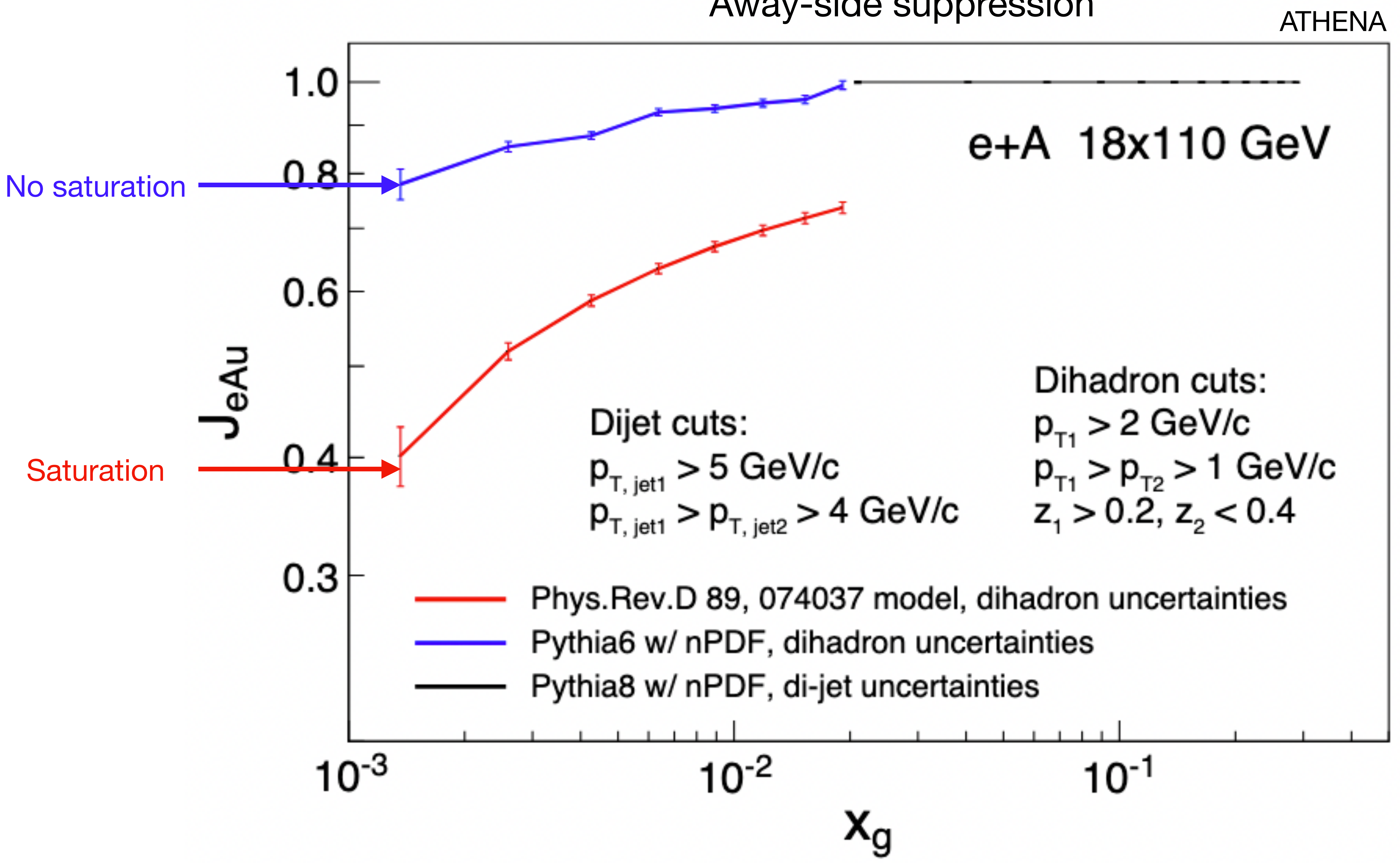


Di-hadron production and jets in eA

- Complementarity region covered by dihadron and jet production

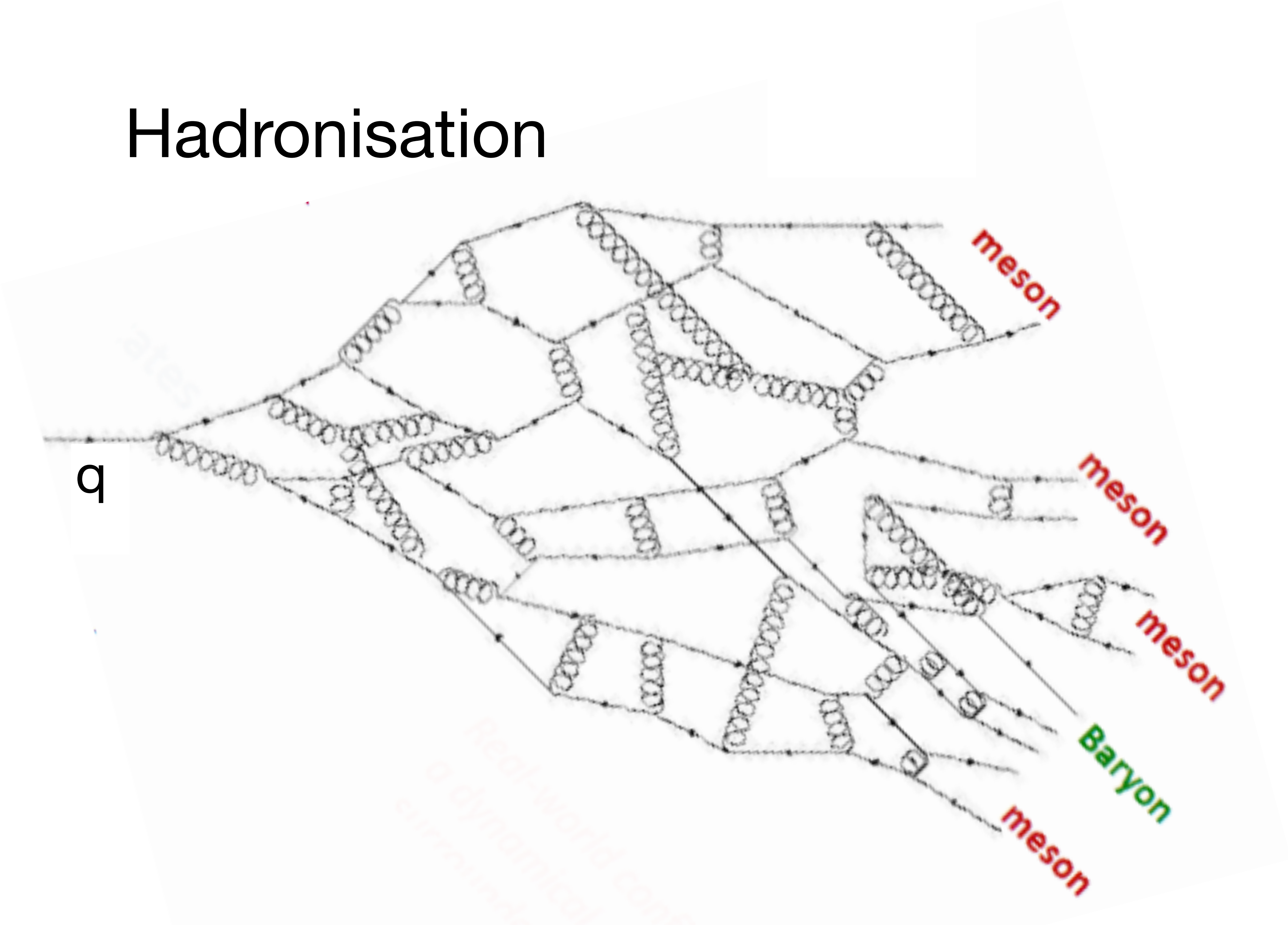


correlated back-to-back hadron pairs in e+Au/e+p scaled by $A^{1/3}$
Away-side suppression

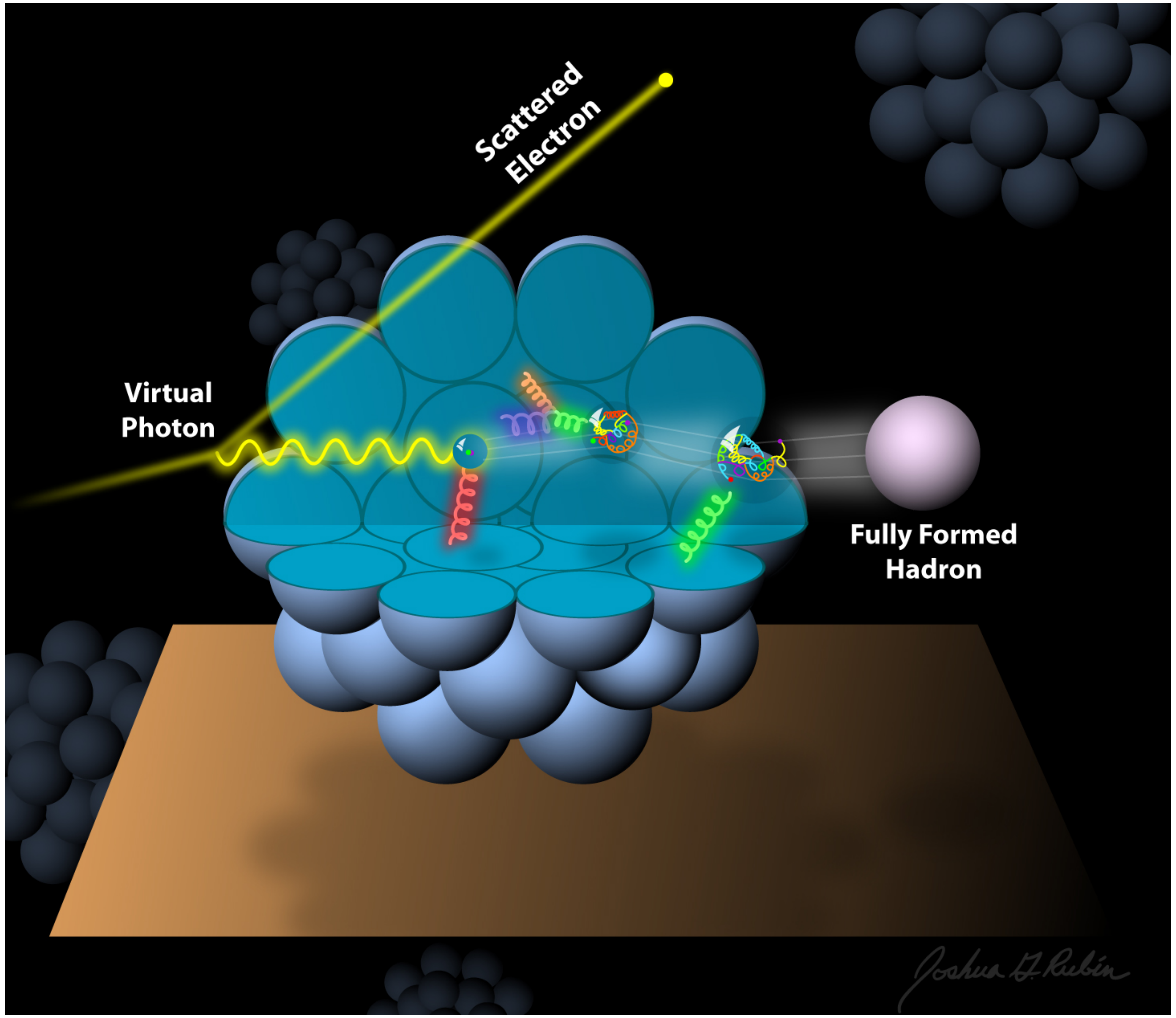


Why an EIC?

Hadronisation



Probing space-time evolution of hadronisation



- Energy loss of parton by medium-induced gluon radiation

- Energy loss of (pre-)hadrons
  - absorption
  - rescattering (small)

- Partonic and hadronic processes: different signature

→ probe space-time evolution of hadron formation

- PDFs modified by nuclear medium

Multiplicity ratios

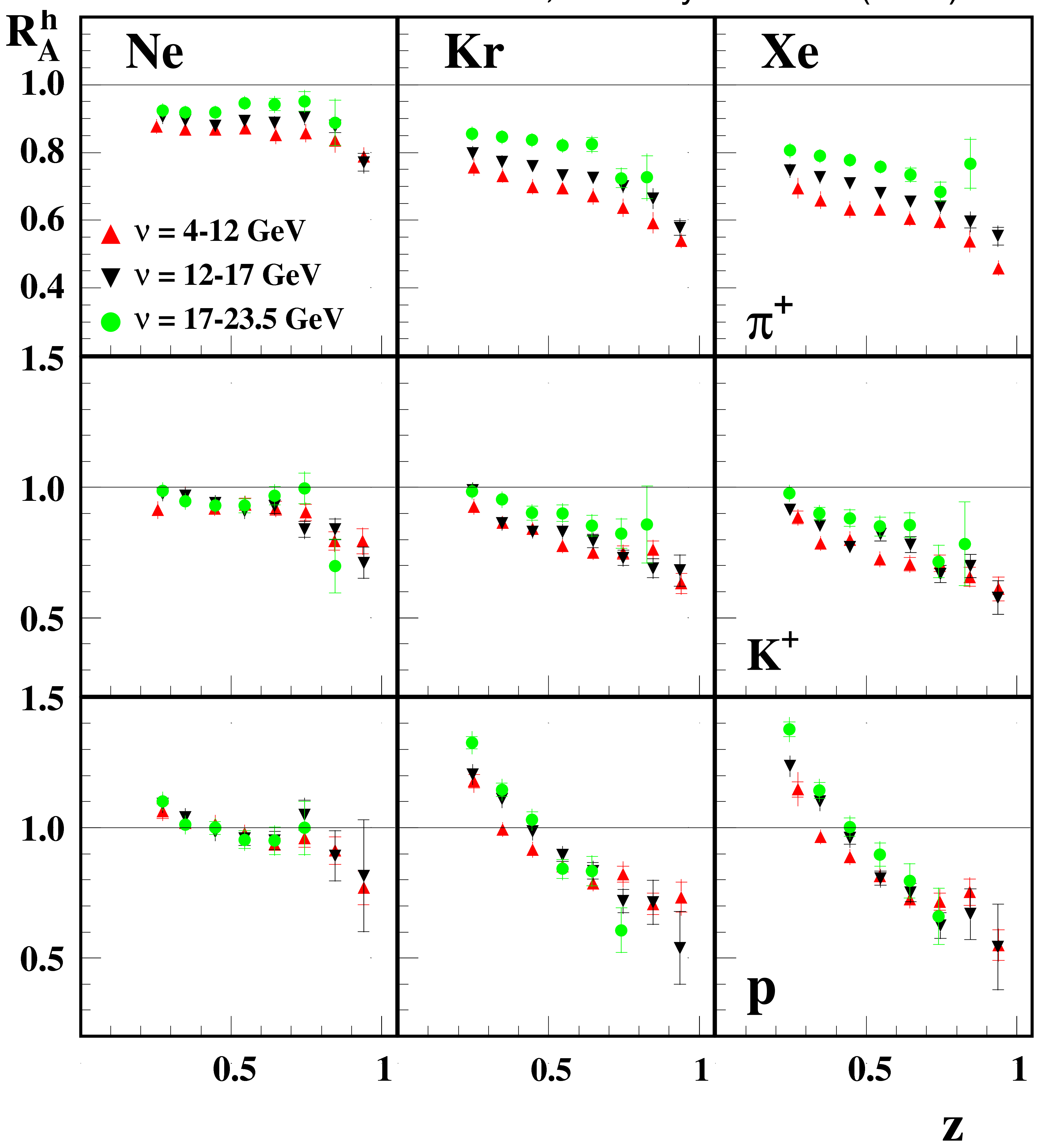
Multiplicity ratios:

$$R_A^h = \frac{\left(\frac{N^h}{N_{DIS}}\right)_A}{\left(\frac{N^h}{N_{DIS}}\right)_D}$$

Ratios → approximate cancelation of

- QED radiative effects
- limited detector acceptance and resolution

HERMES, Eur. Phys. J. A **47** (2011) 113



At highest z: hadronic absorption

Summary

EIC with ePIC can address various aspects of the nucleon and nuclear structure through:

- Precise inclusive and semi-inclusive (spin-dependent) DIS measurements via high-resolution EM calorimeters.
- Measurements for 3D (spin-dependent) tomography in momentum space provided by good Cherenkov-based and TOF AC-LGAD hadron PID detectors and tracking.
- Exclusive measurements on protons, using the far-forward detector system.
- Diffractive and exclusive measurements with coherent/incoherent separation via very precise EM calorimeters and far-forward detector system.
- Measurements on a large variety of nuclei: probe gluon saturation and study the space-time evolution of hadron formation.