The electron-ion collider

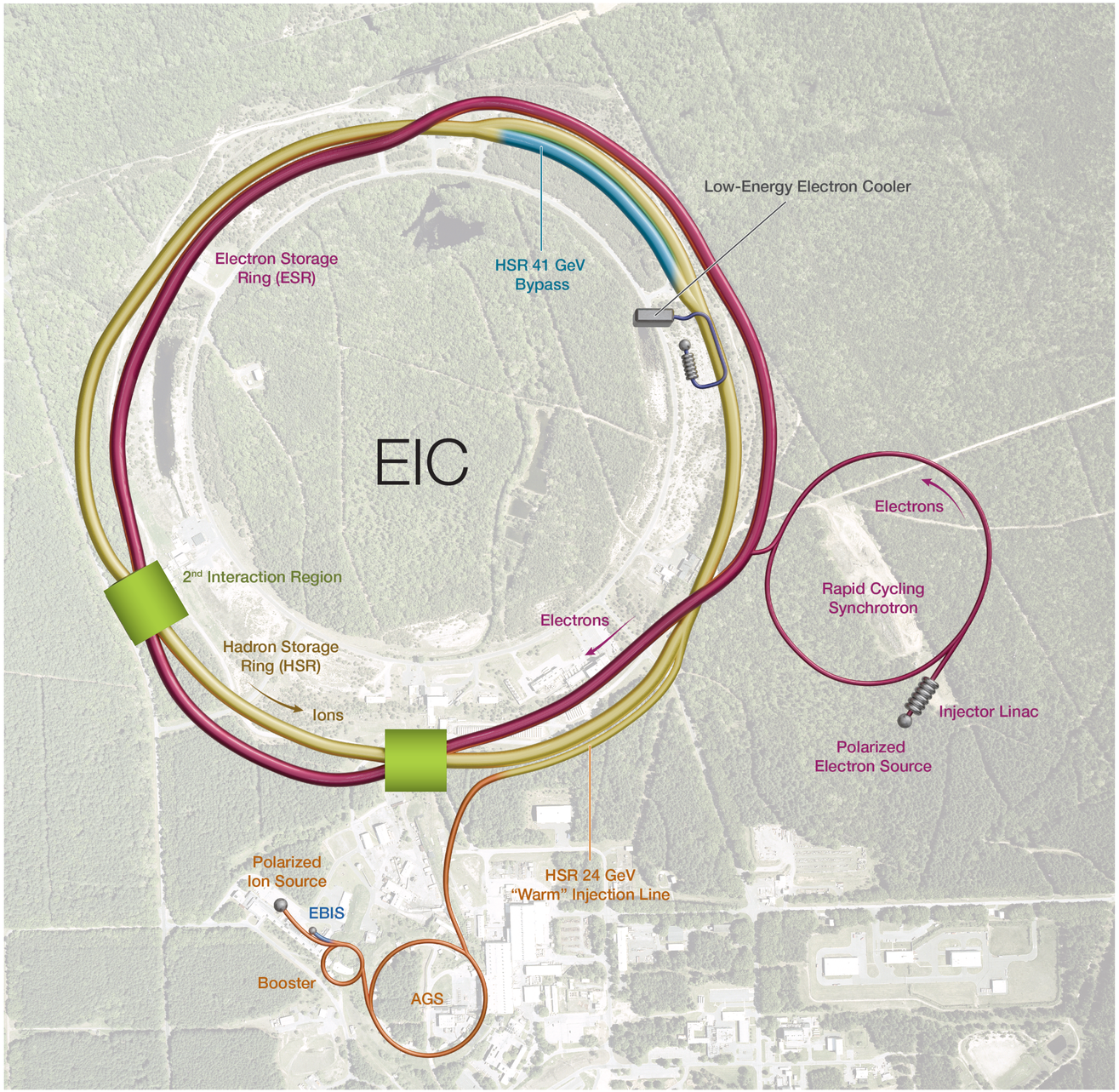
AdT

Charlotte Van Hulse
University of Alcalá

HSF-India/ePIC Workshop
Mumbai, India
May 13–17, 2025

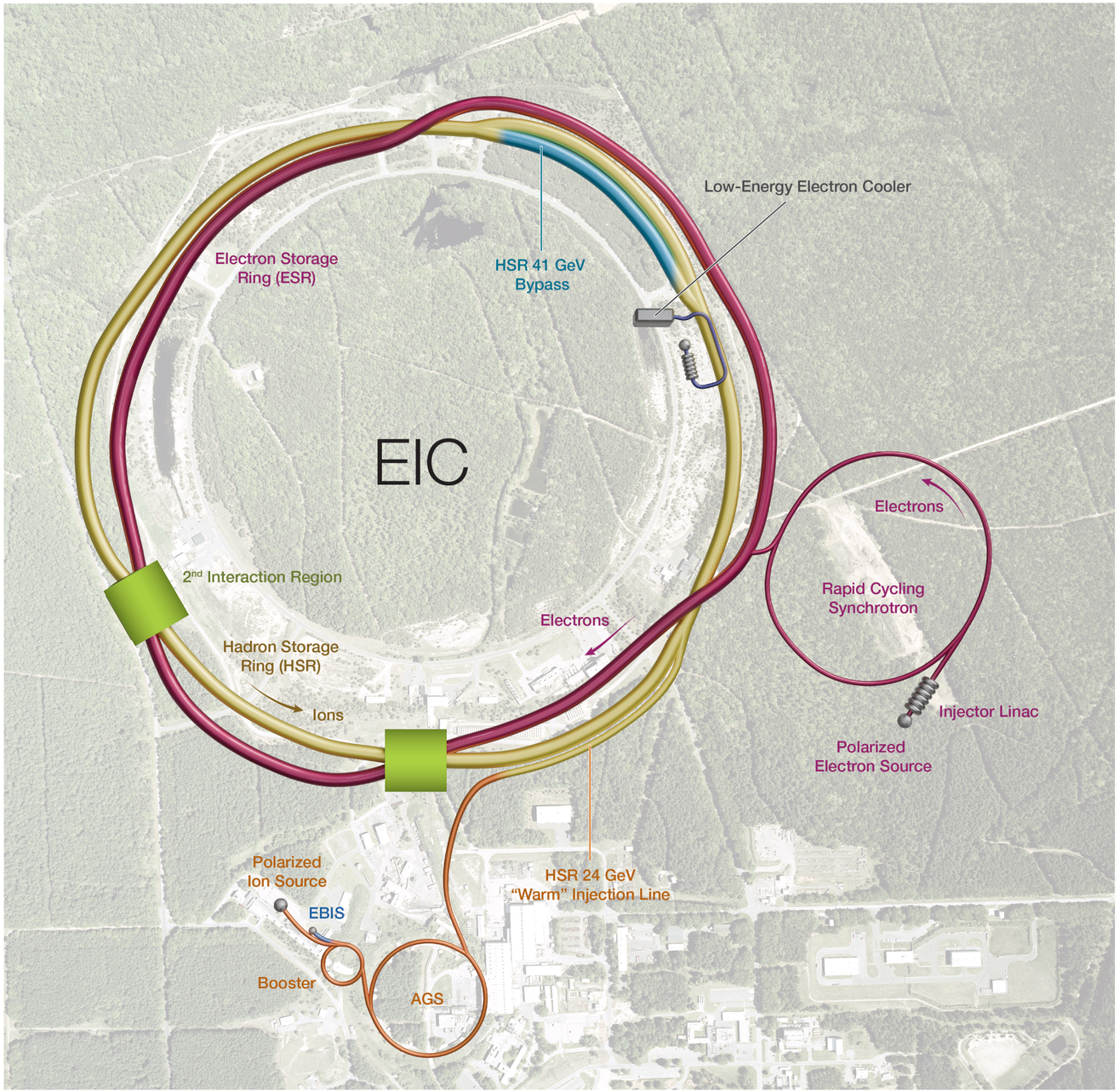
The electron-ion collider (EIC)

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

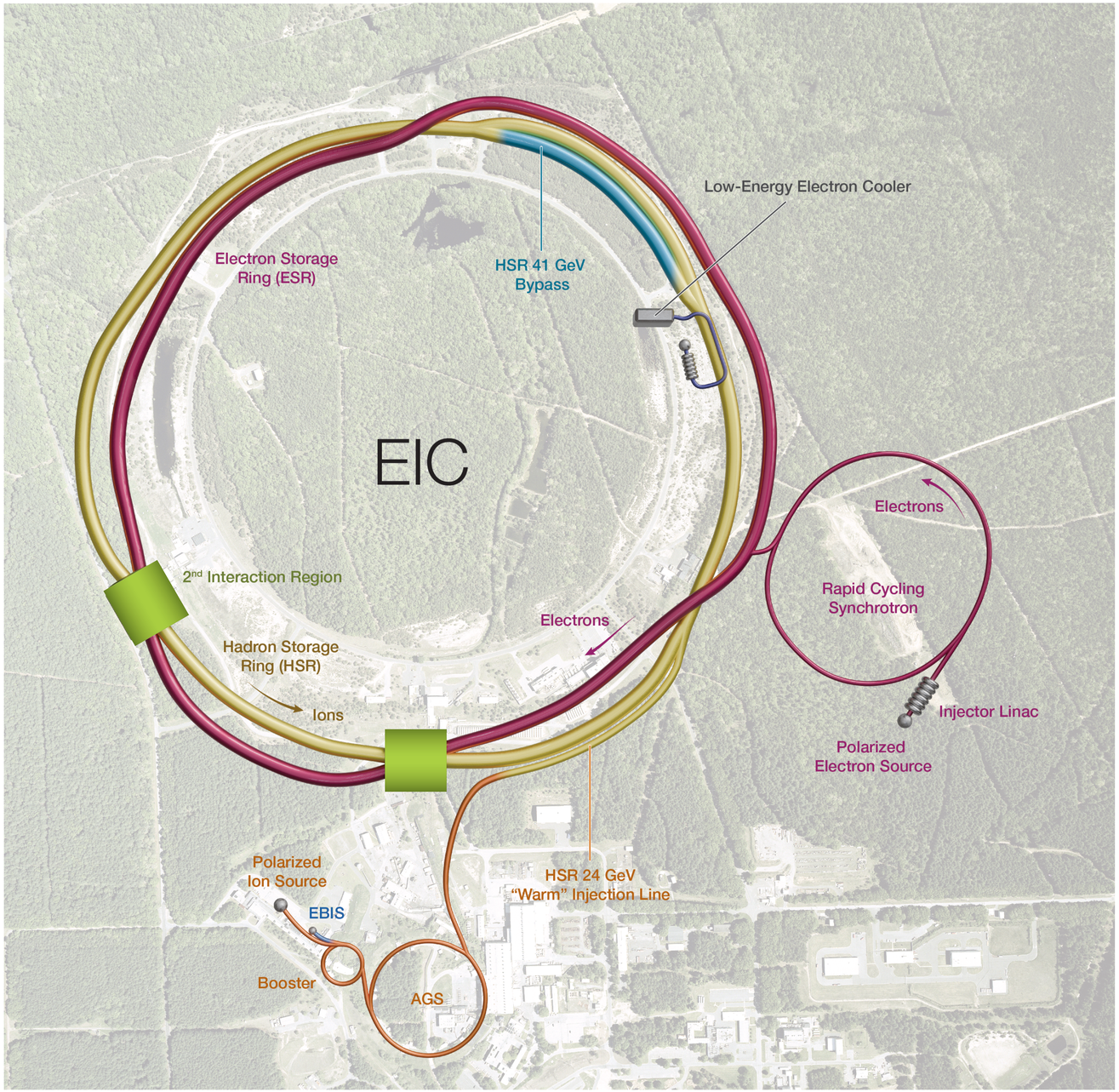
The electron-ion collider (EIC)



- 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)

The electron-ion collider (EIC)



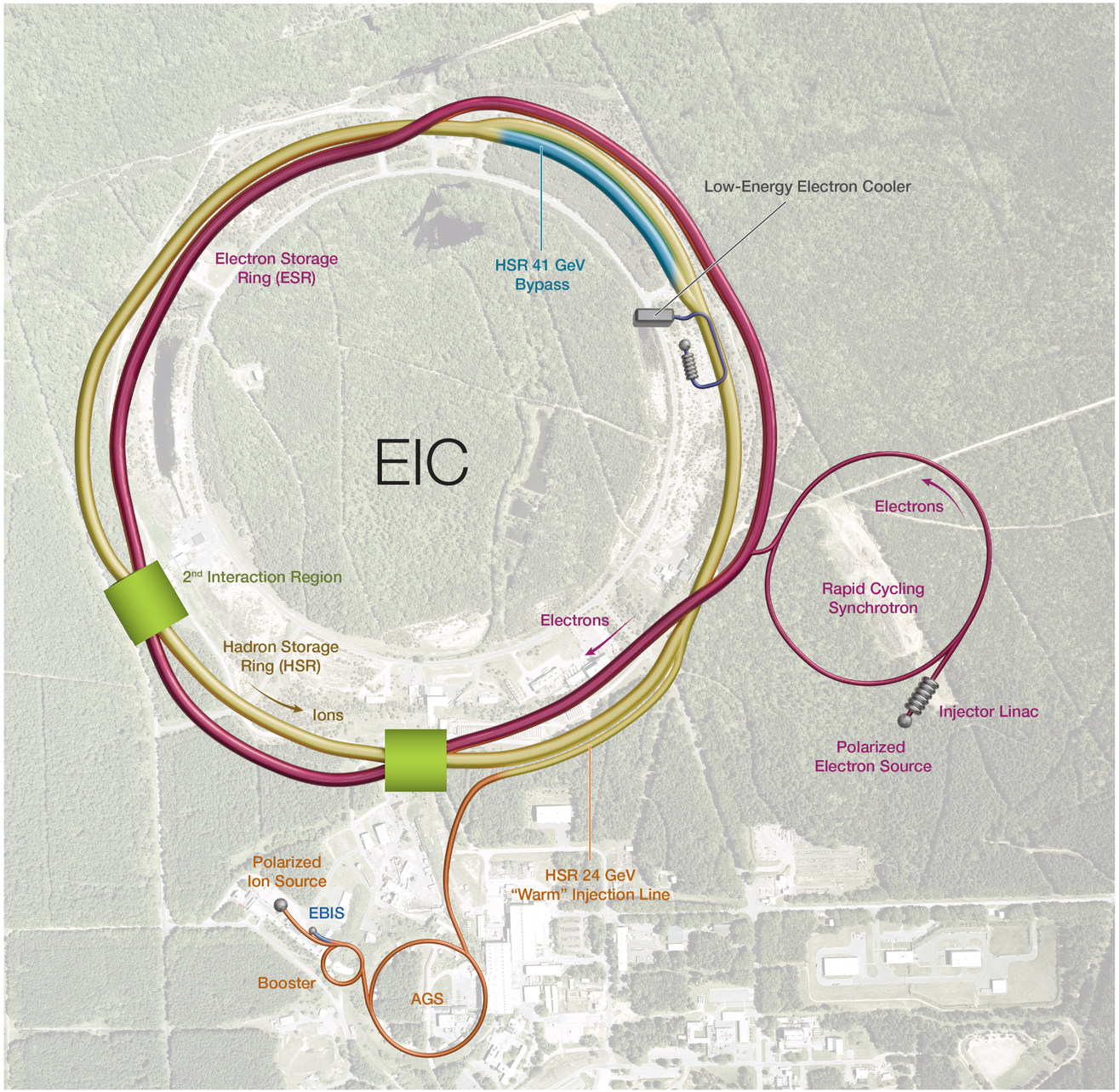
- Based on RHIC:
  - use exiting hadron storage ring
    energy: 41–275 GeV
  - add electron storage ring in RHIC tunnel
    energy: 5–18 GeV

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

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

  ~ 70% polarisation

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

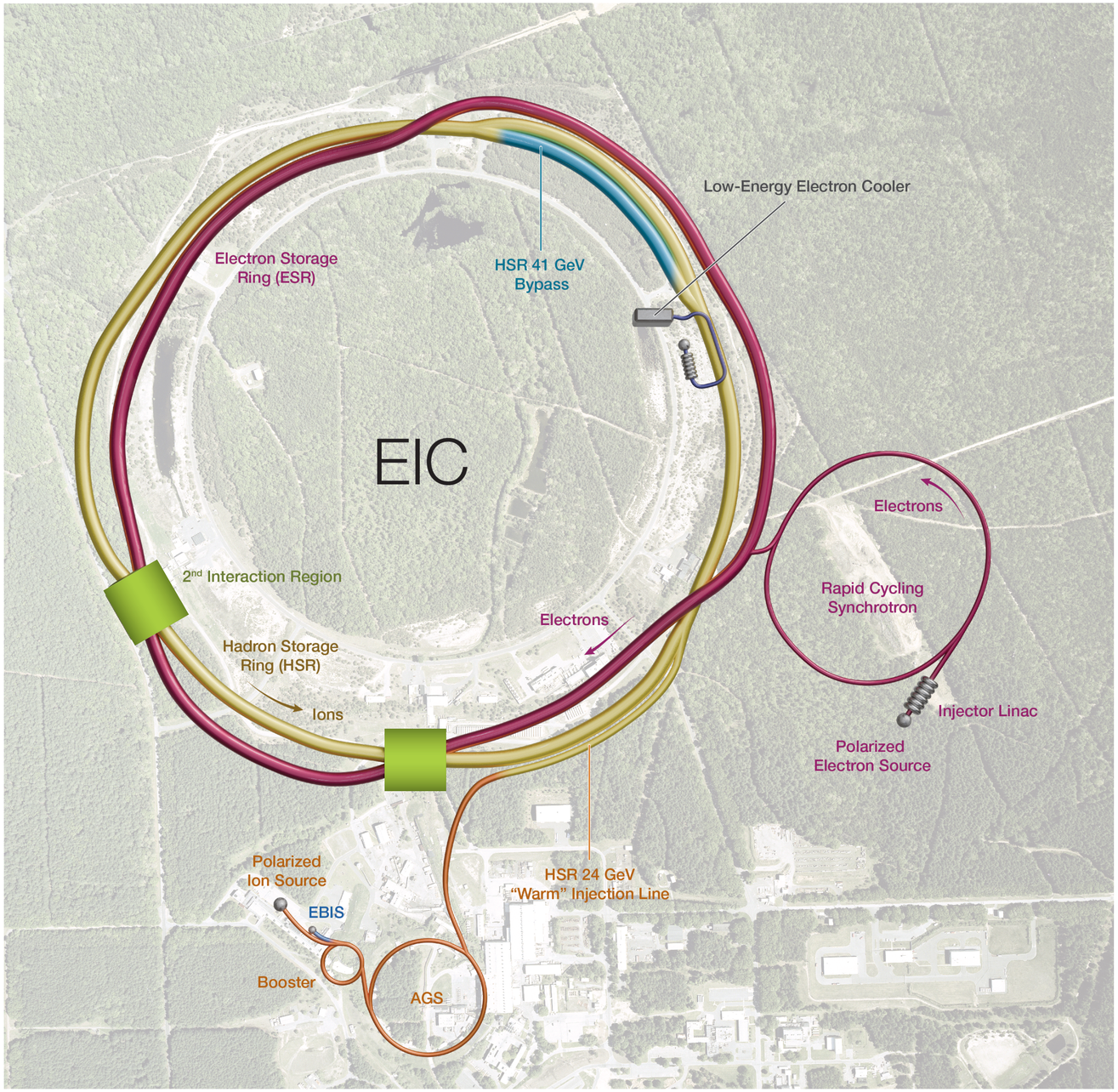
  $\rightarrow \sqrt{s} = 29 - 141$ GeV (per nucleon)

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

  ~ 70% polarisation

  + heavier, unpolarised ions, up to Uranium

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)

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

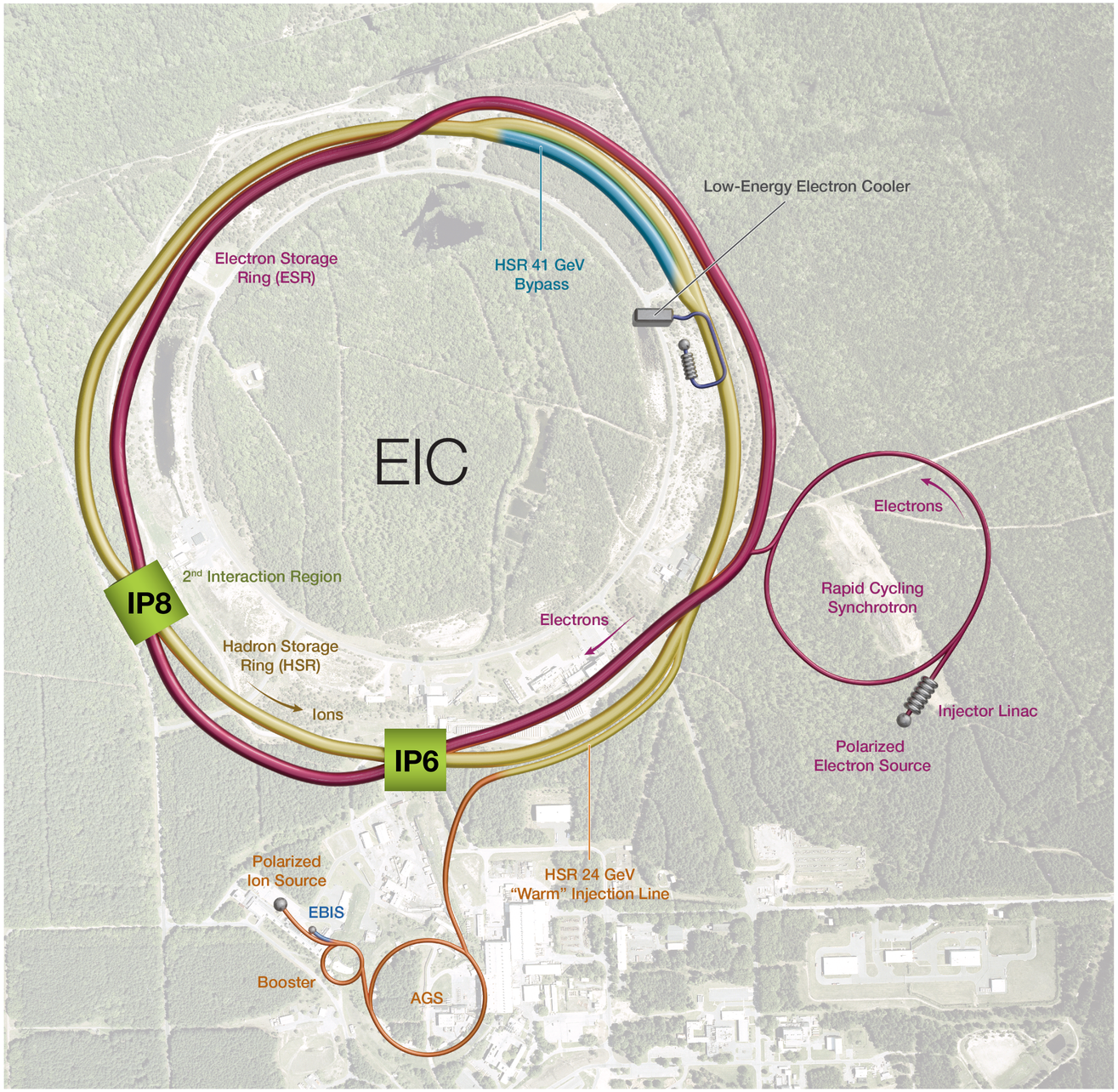
  ~ 70% polarisation

  + heavier, unpolarised ions, up to Uranium

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

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

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)

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

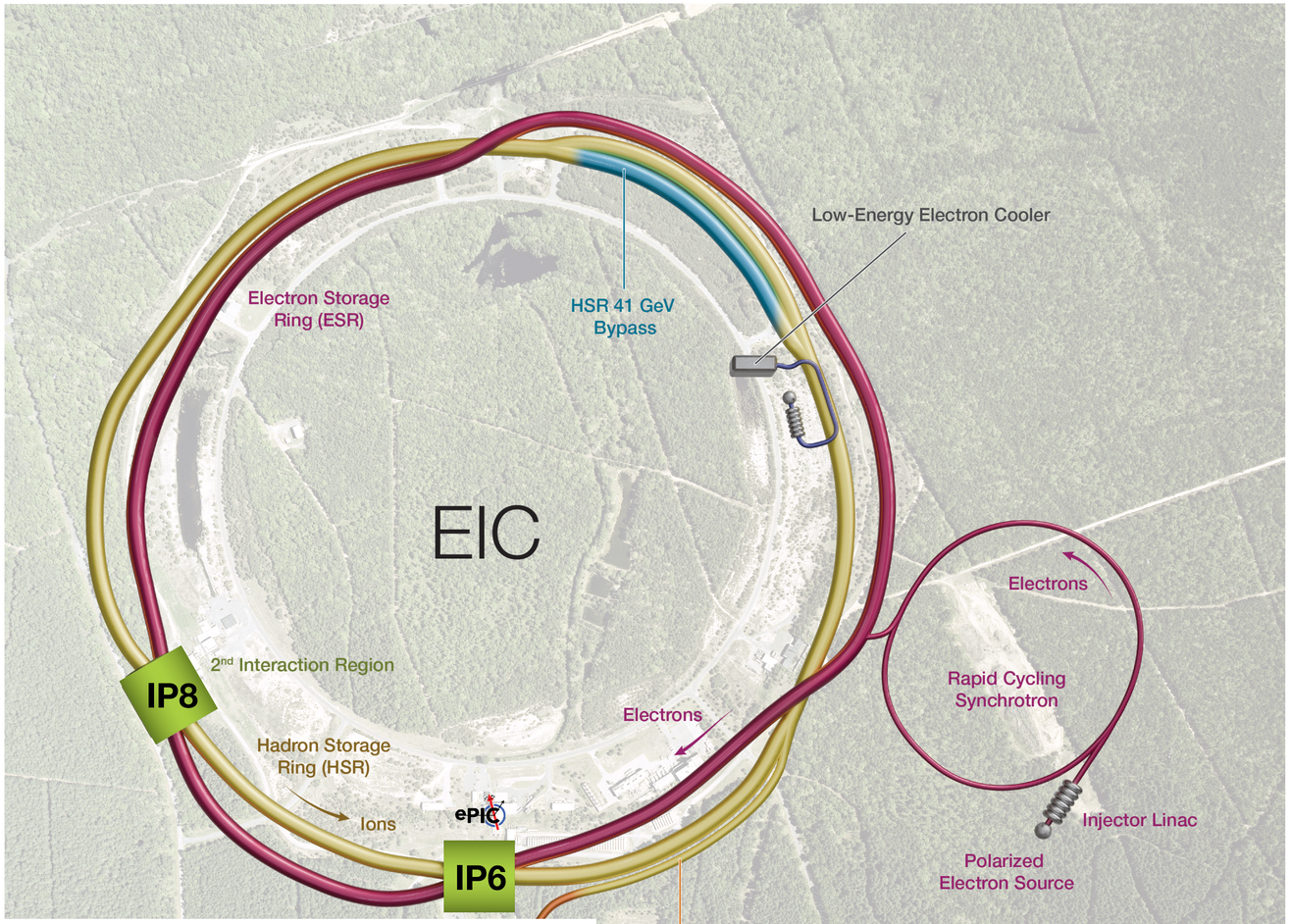
  ~ 70% polarisation

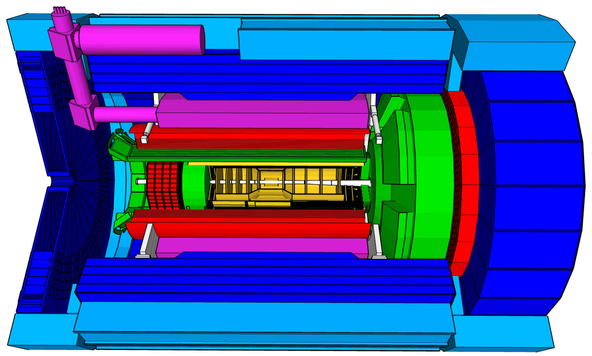
  + heavier, unpolarised ions, up to Uranium

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

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

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)

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

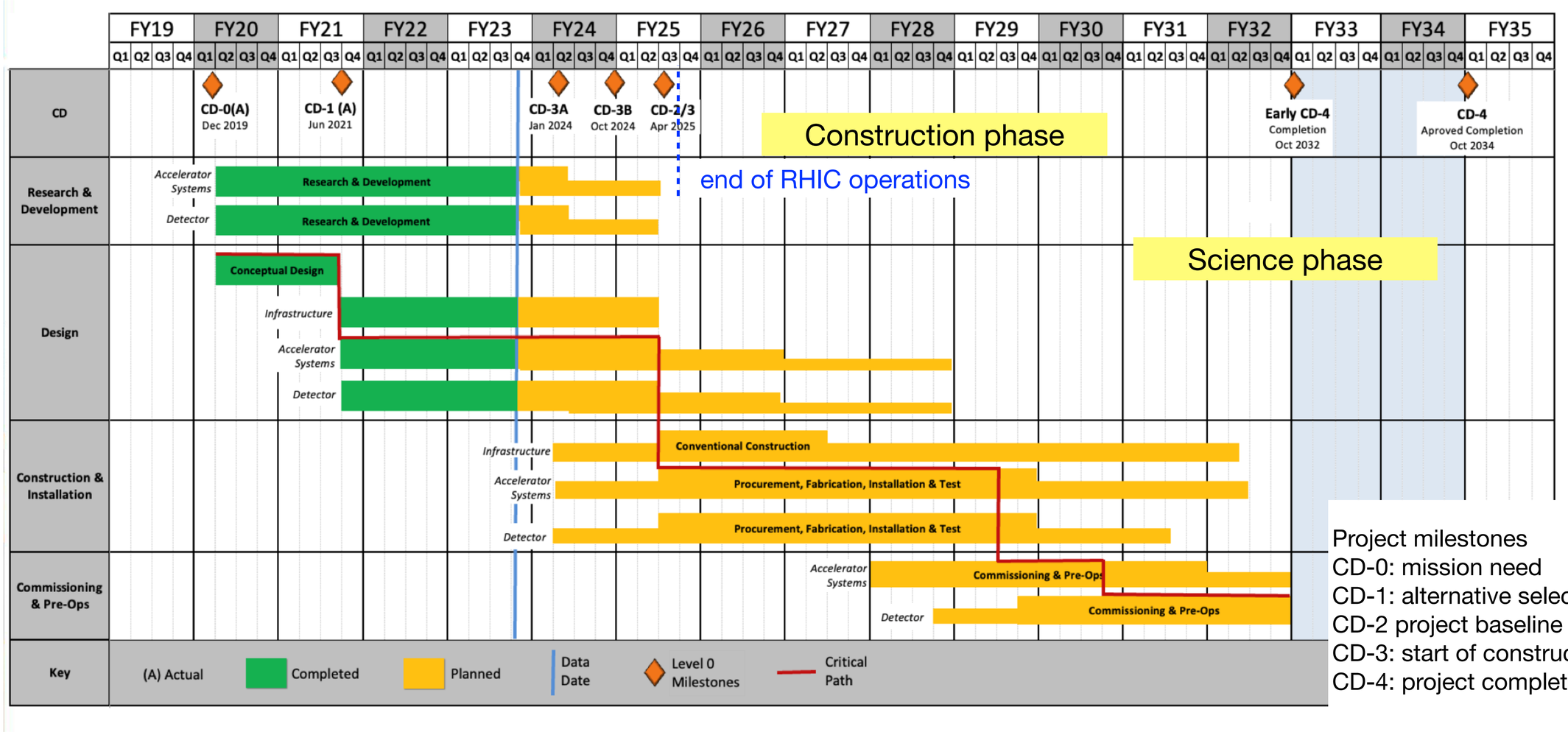
  ~ 70% polarisation

  + heavier, unpolarised ions, up to Uranium

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

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

Timeline

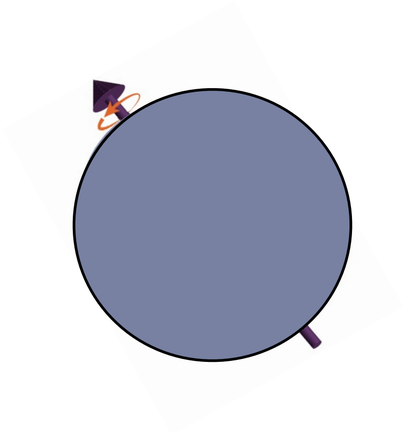


Project milestones
CD-0: mission need
CD-1: alternative selection, cost range
CD-2 project baseline
CD-3: start of construction
CD-4: project completion, start of operation

Why an EIC?

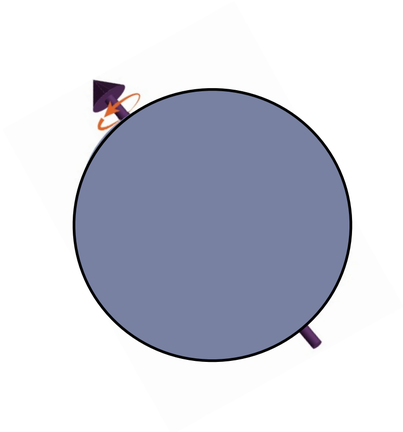
Why an EIC?

Nucleon spin structure

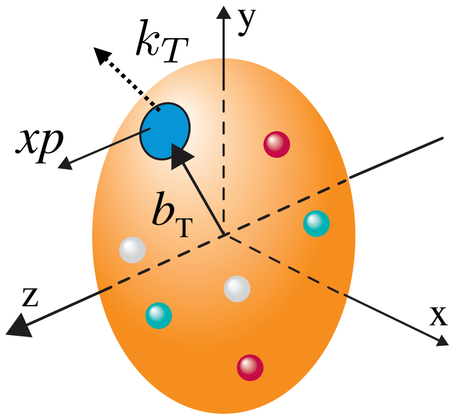


Why an EIC?

Nucleon spin structure

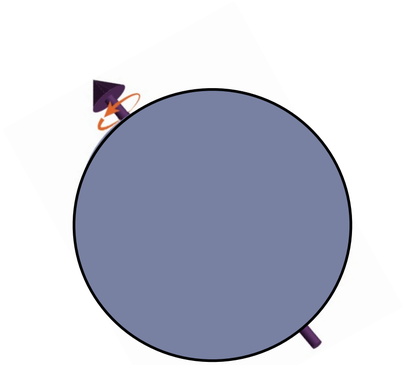


Nucleon multi-dimensional structure

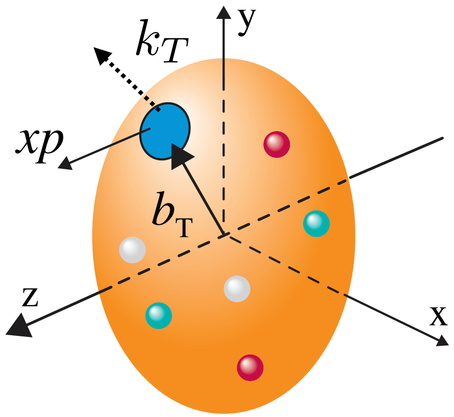


Why an EIC?

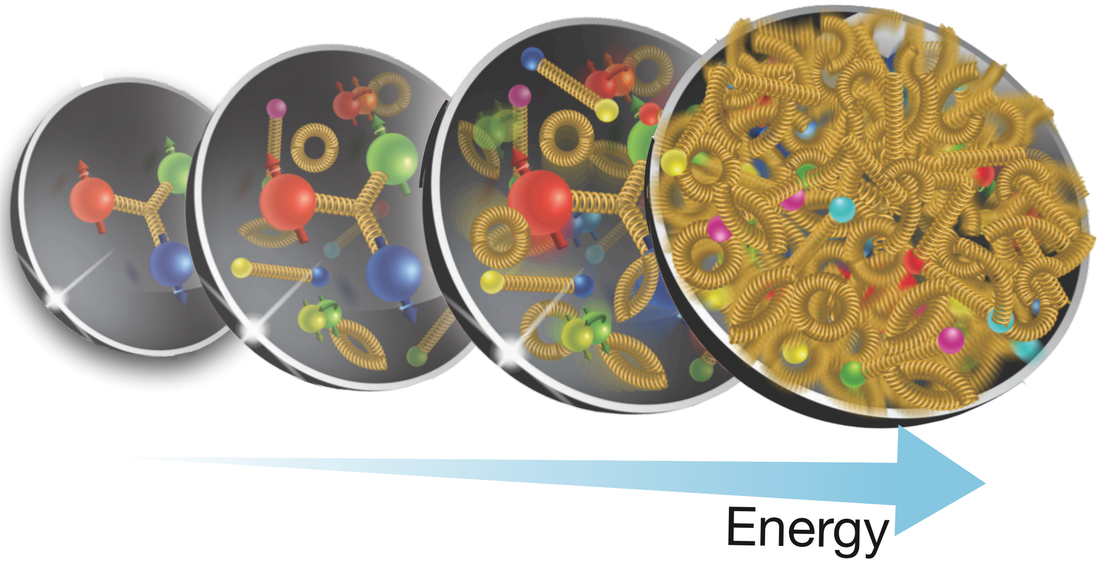
Nucleon spin structure



Nucleon multi-dimensional structure

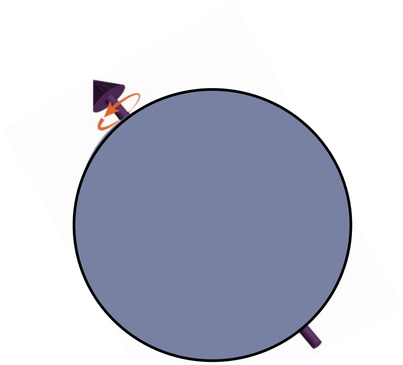


Gluon saturation

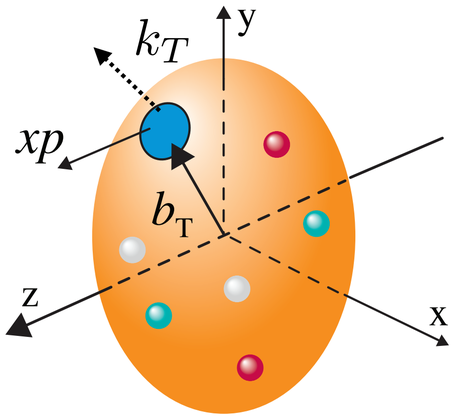


Why an EIC?

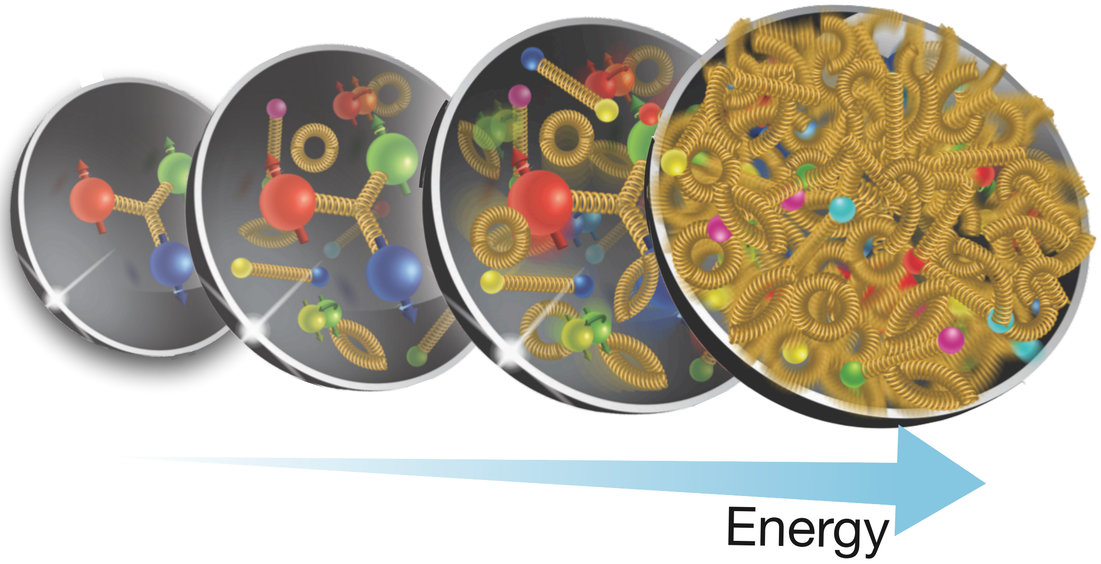
Nucleon spin structure



Nucleon multi-dimensional structure

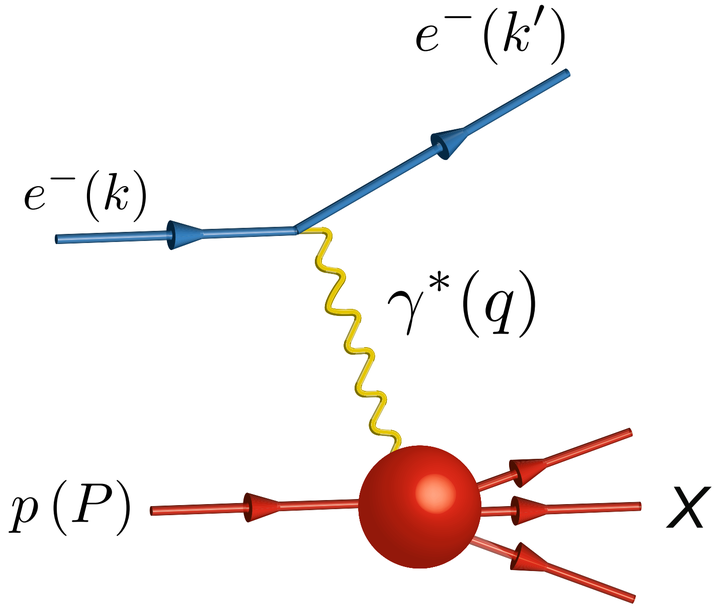


Gluon saturation

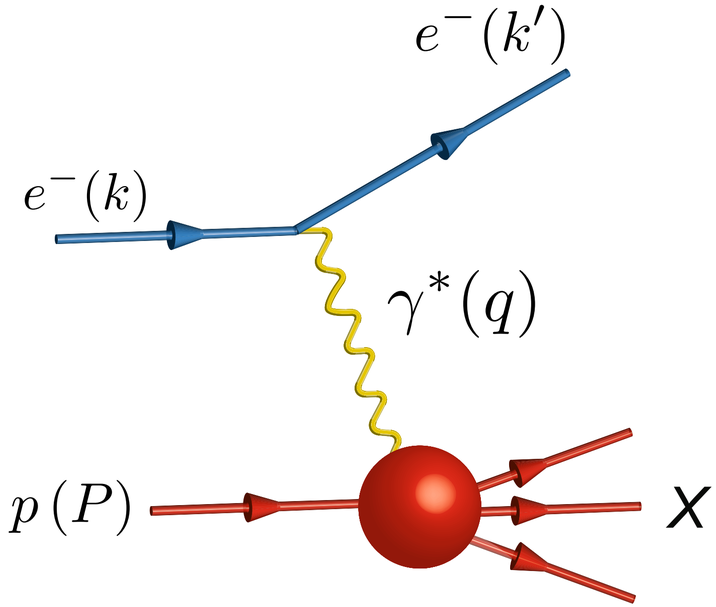


Hadronisation

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



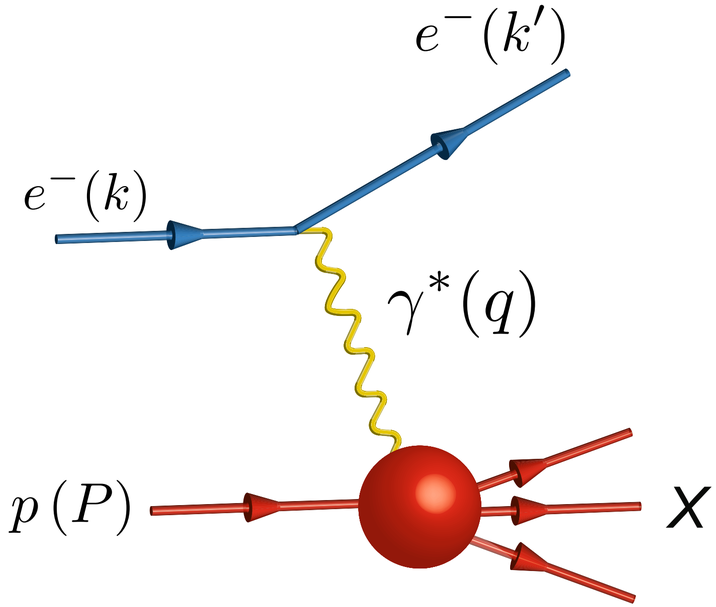
Deep-inelastic scattering (DIS) of electrons and nucleons/nuclei



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

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

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

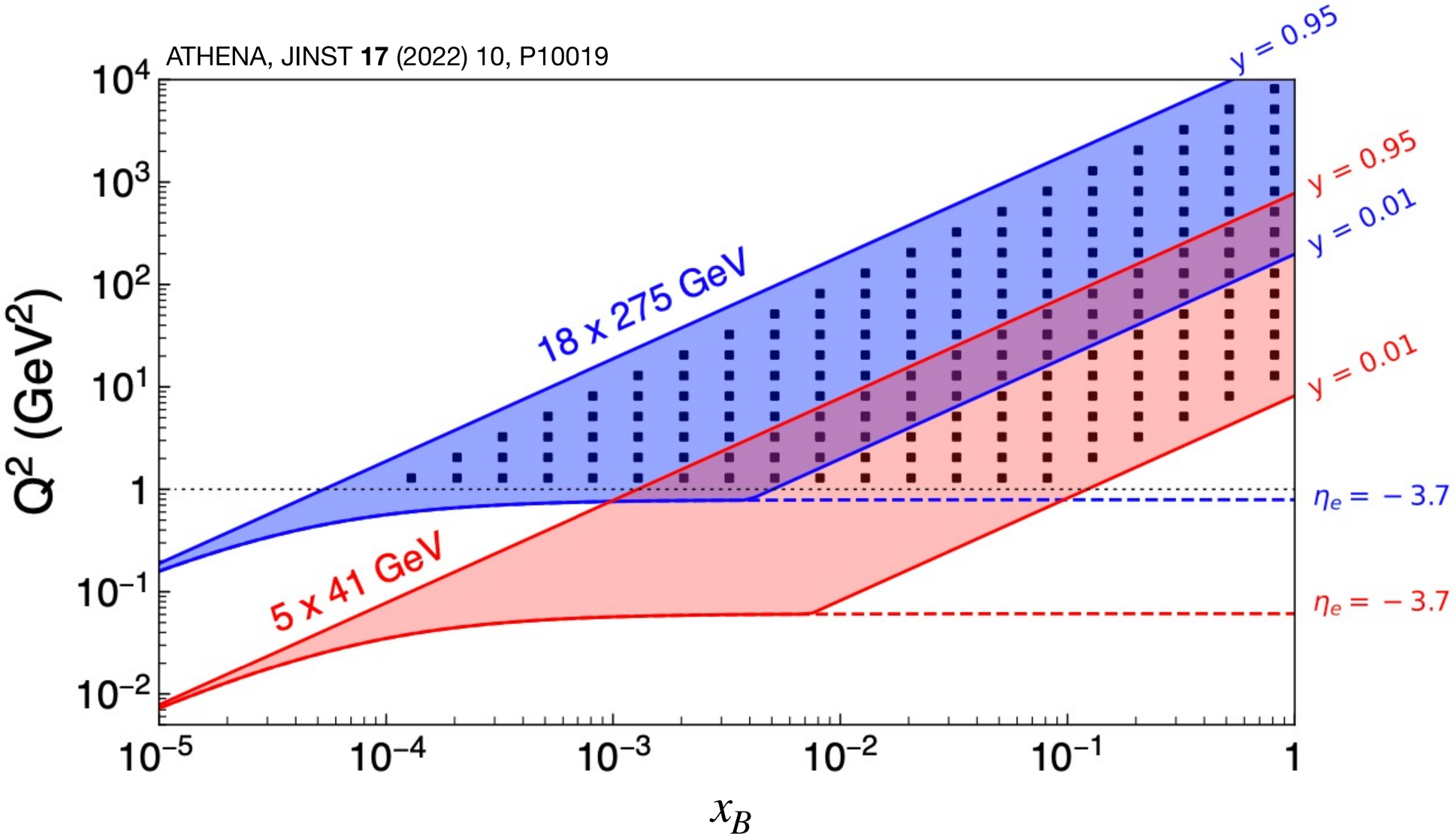


$$Q^2 = -q^2$$

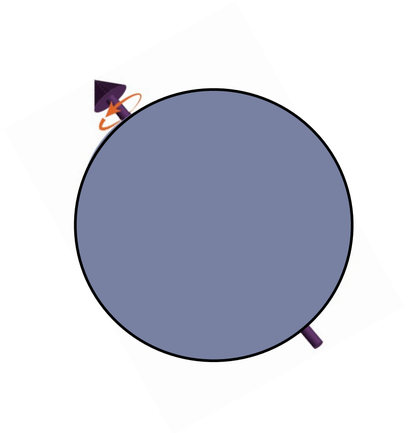
Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

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

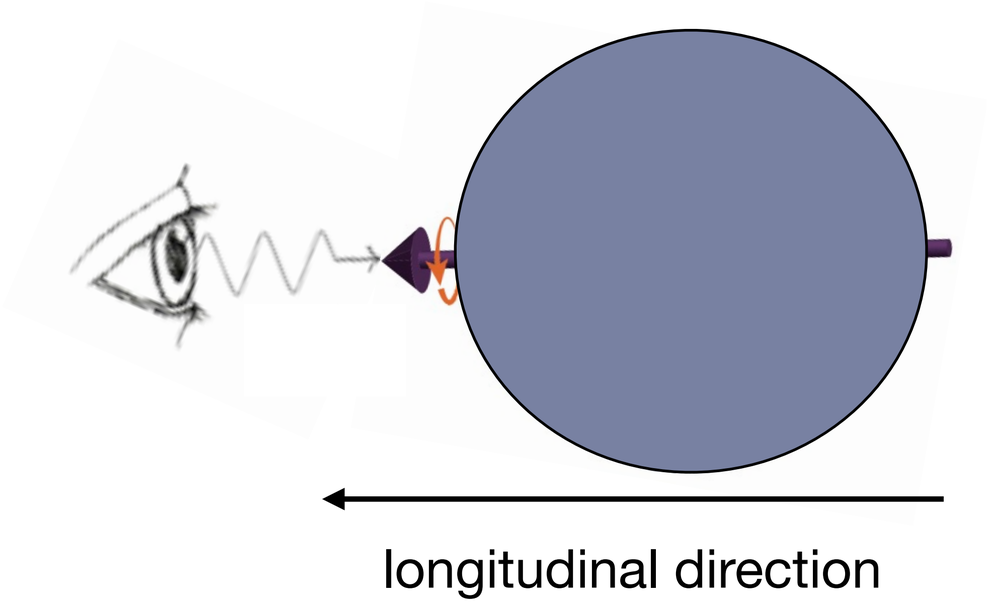
Kinematic coverage at the EIC



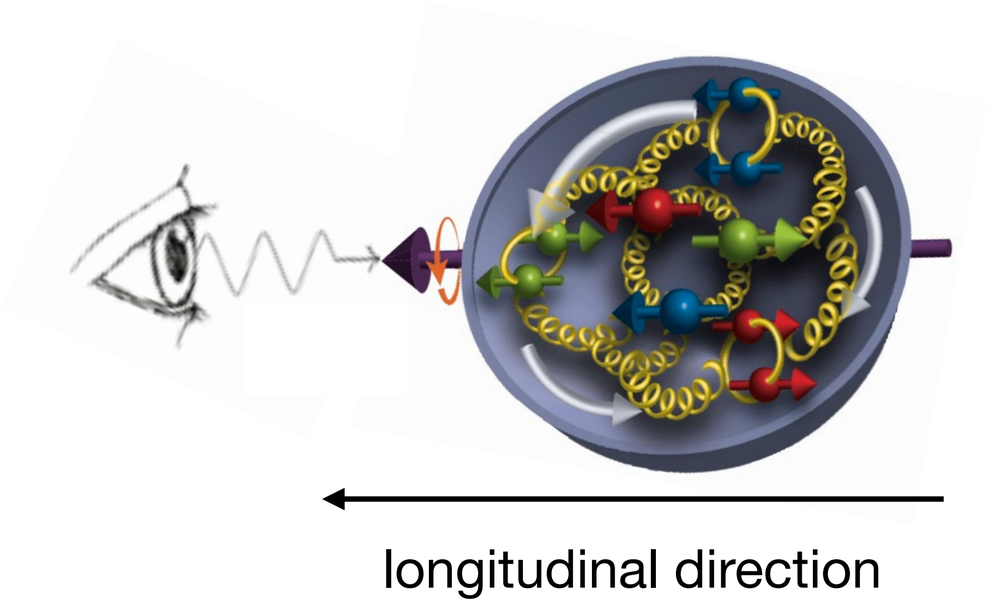
Nucleon spin structure



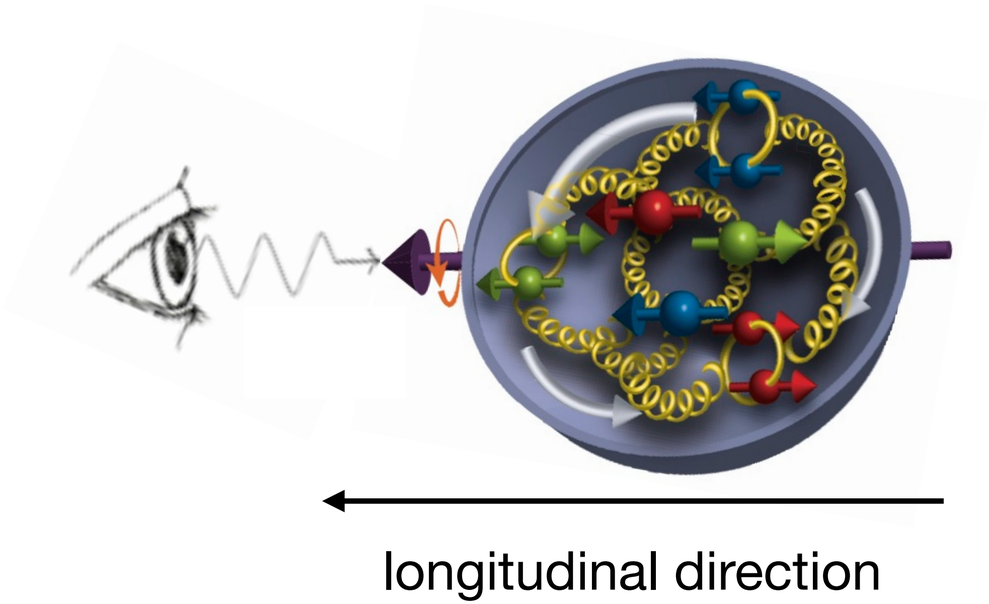
The nucleon spin



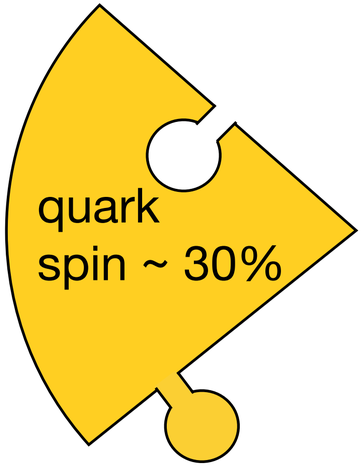
The nucleon spin



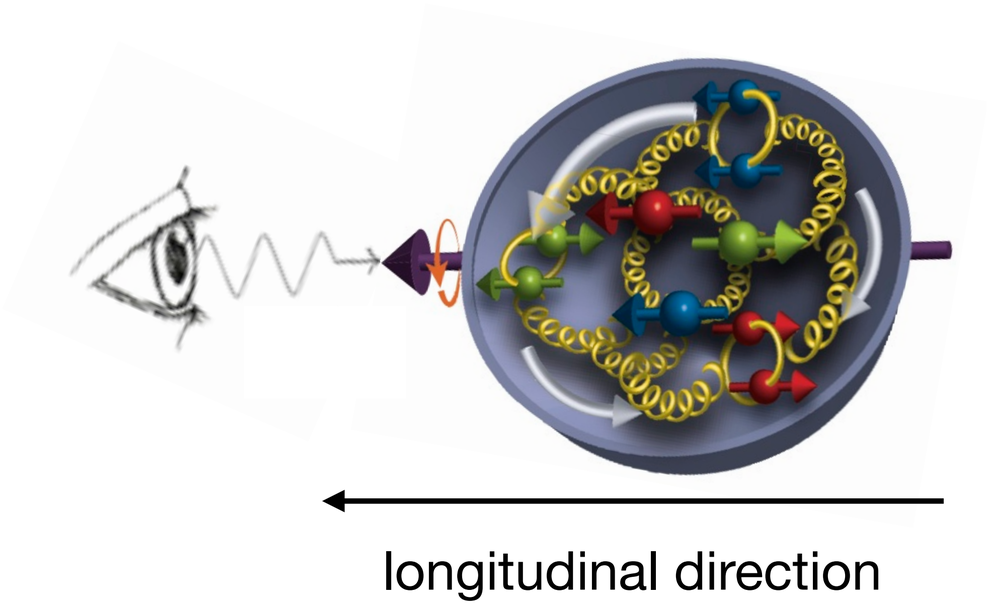
The nucleon spin



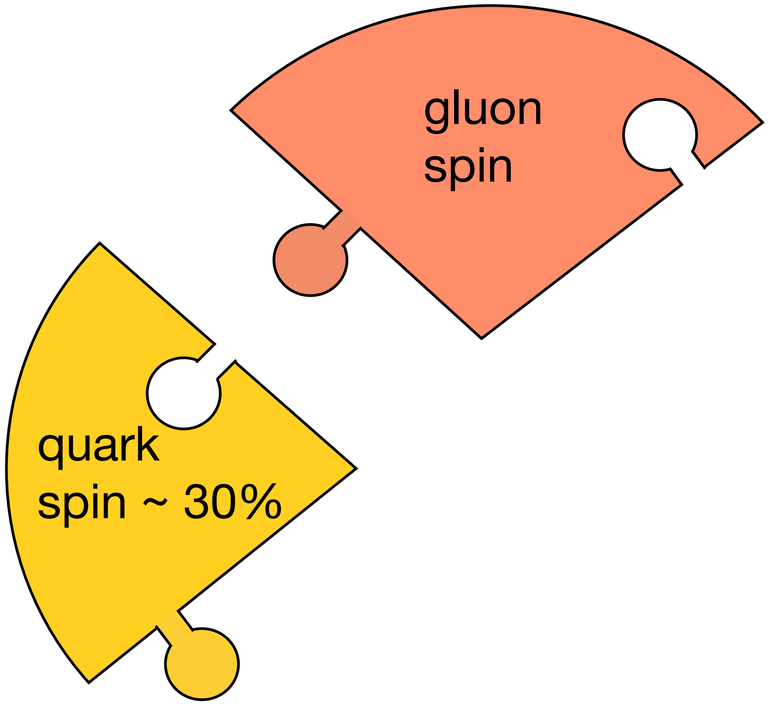
longitudinal direction



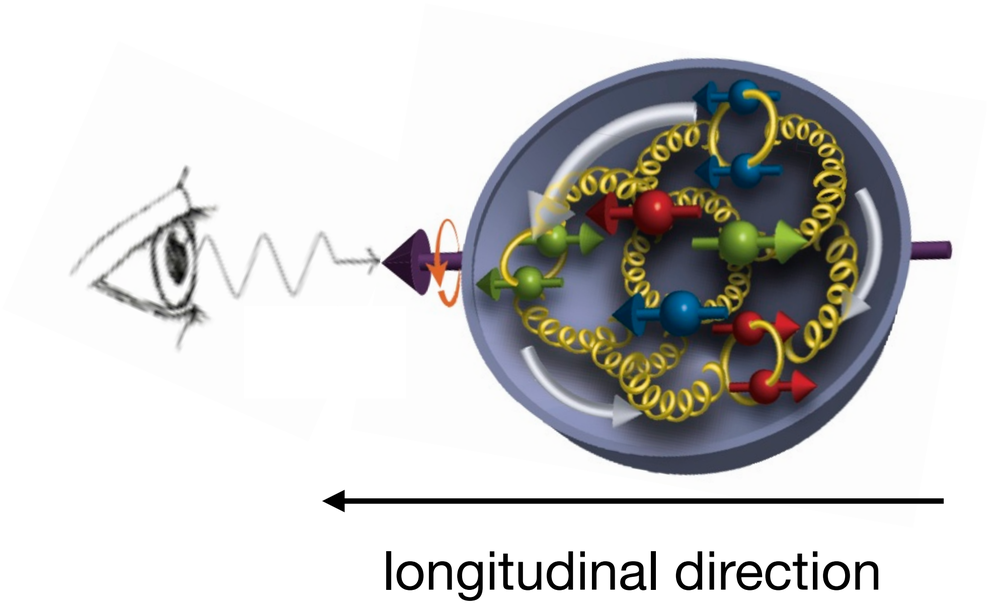
The nucleon spin

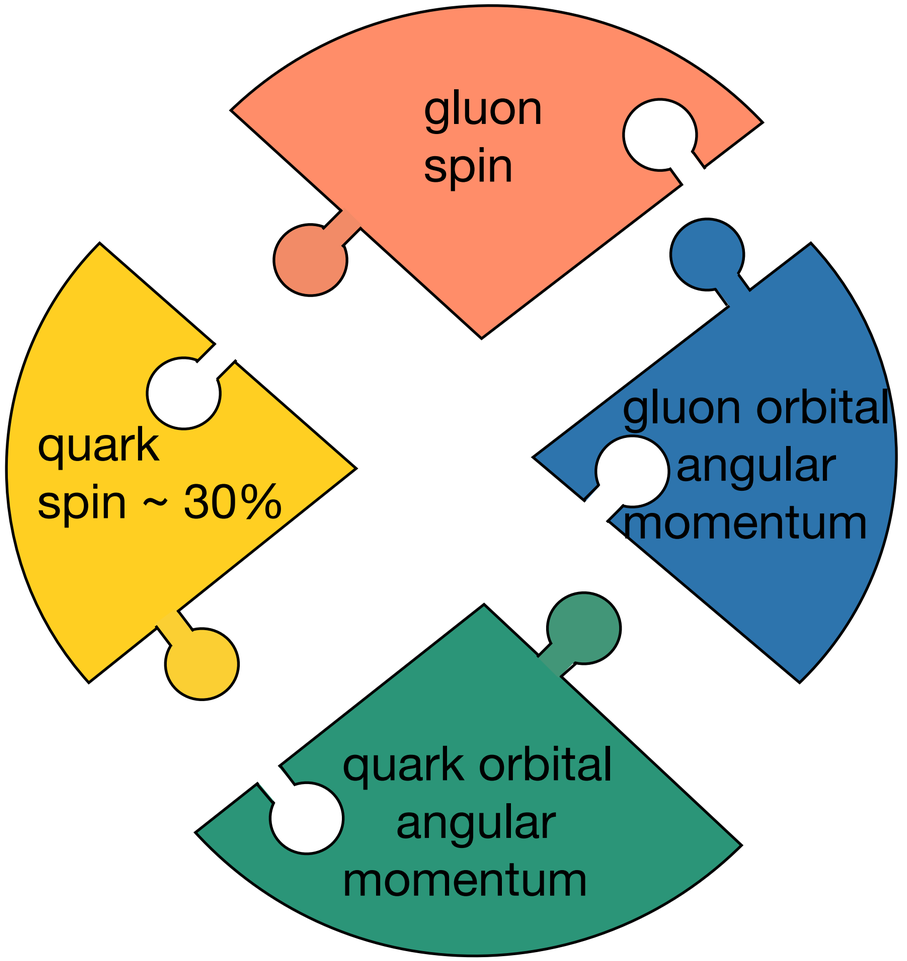


longitudinal direction

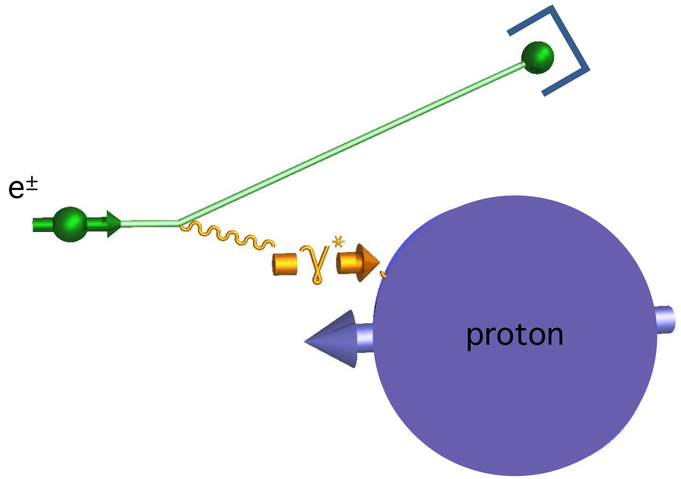


The nucleon spin



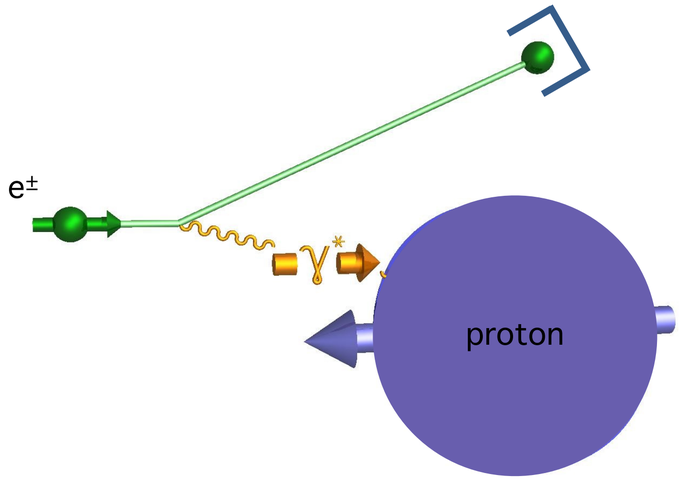


Helicity structure of the nucleon

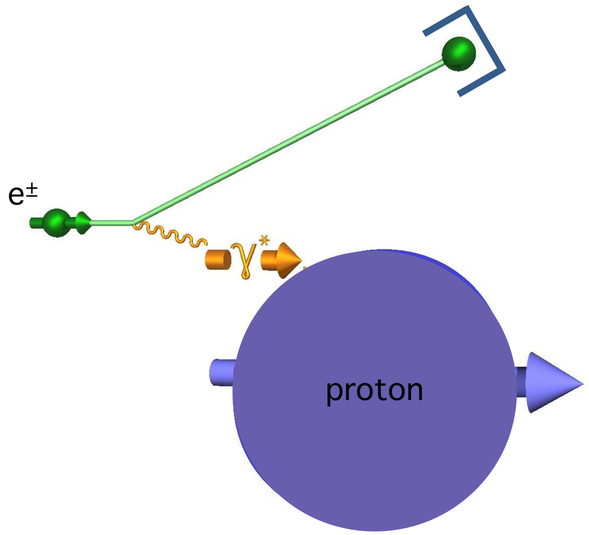


- longitudinally polarised proton
- longitudinally polarised e± beam
- count… 0 2 4 6 8 10

Helicity structure of the nucleon

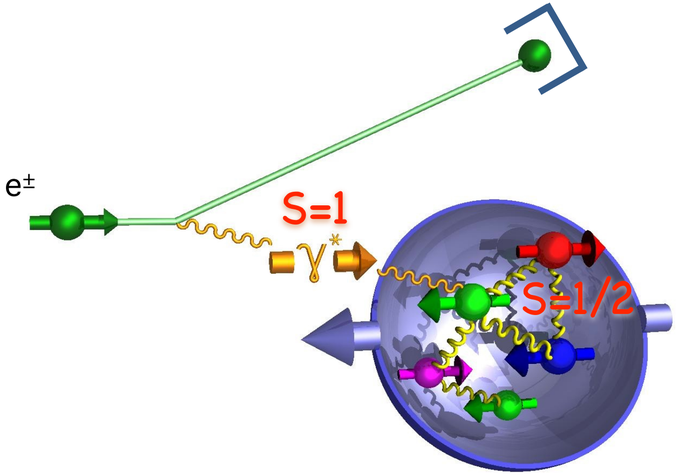


- longitudinally polarised proton
- longitudinally polarised e± beam
- count…

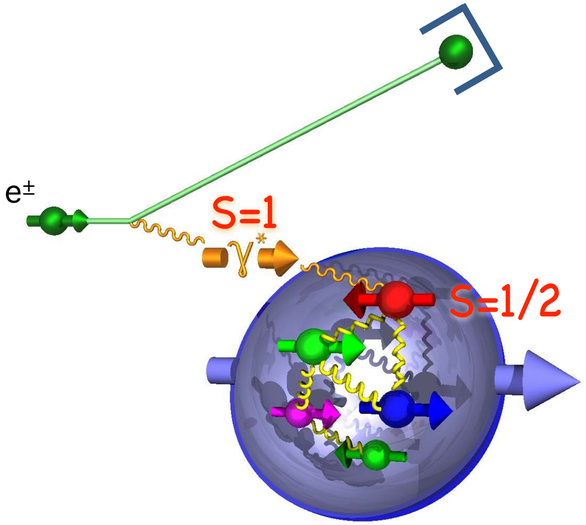


- flip proton spin and count…

Helicity structure of the nucleon

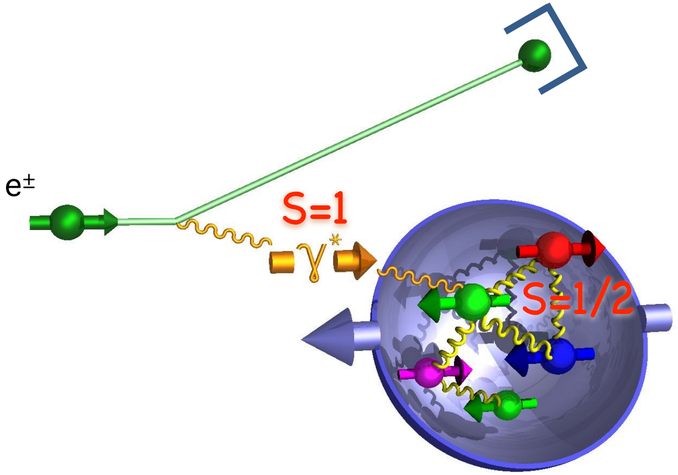


- longitudinally polarised proton
- longitudinally polarised $e^{\pm}$ beam
- count…



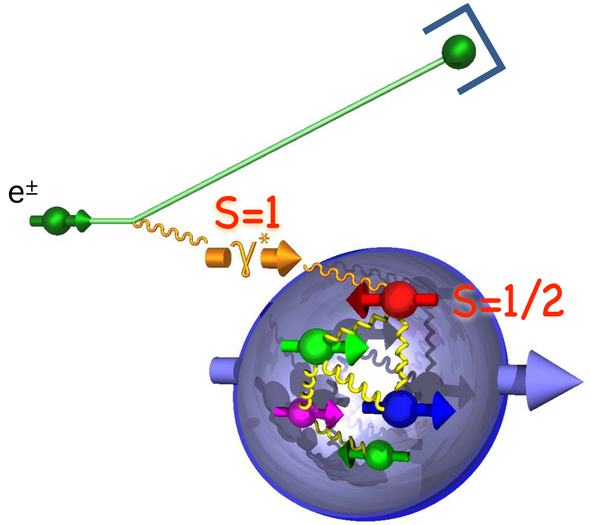
- flip proton spin and count…

Helicity structure of the nucleon



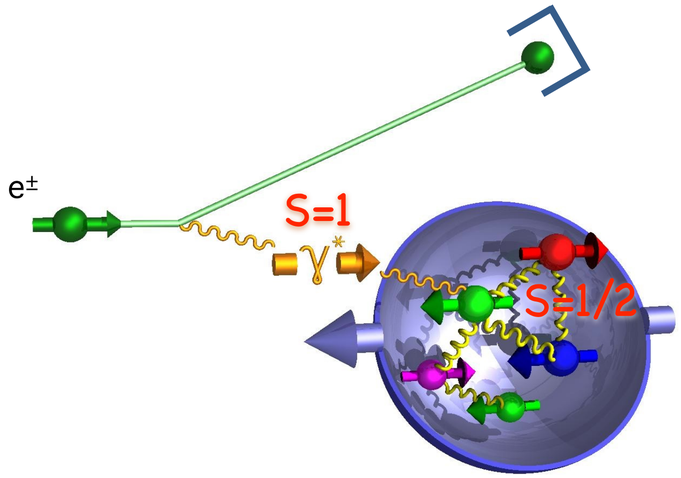
- longitudinally polarised proton
- longitudinally polarised e± beam
- count…

$$\frac{\overleftarrow{\rightarrow}\sigma - \overrightarrow{\rightarrow}\sigma}{\overleftarrow{\rightarrow}\sigma + \overrightarrow{\rightarrow}\sigma}$$

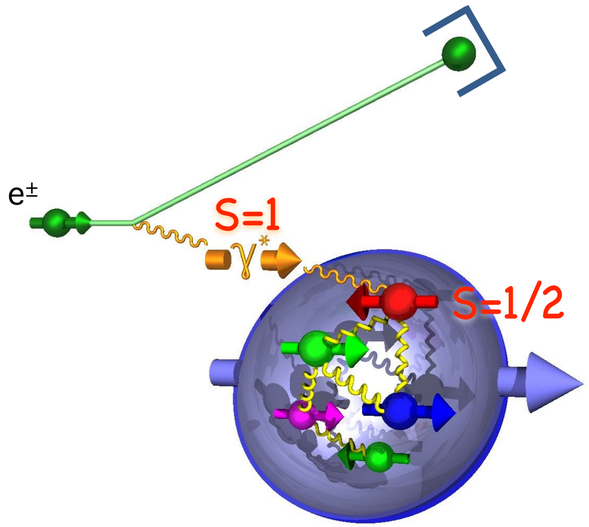


- flip proton spin and count…

Helicity structure of the nucleon



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

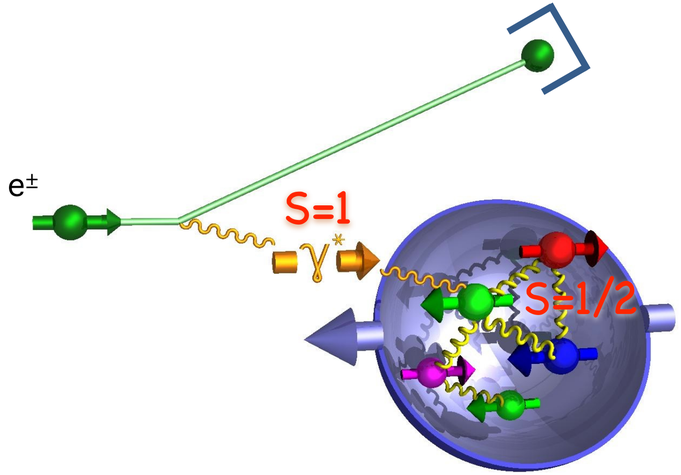


- flip proton spin and count…

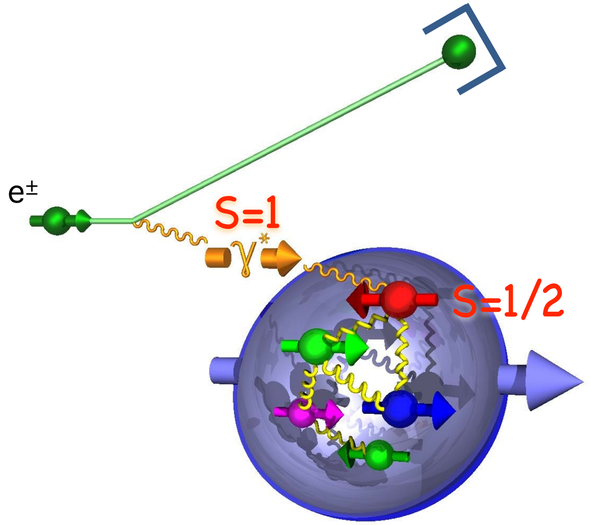
$$\frac{\overleftarrow{\overrightarrow{\sigma}} - \overrightarrow{\overrightarrow{\sigma}}}{\overleftarrow{\overrightarrow{\sigma}} + \overrightarrow{\overrightarrow{\sigma}}} \propto g_1(x) = \frac{1}{2}\sum_q e_q^2 \left(\overrightarrow{\overrightarrow{q}}(x) - \overleftarrow{\overrightarrow{q}}(x) \right)$$

parton fractional longitudinal momentum: x_B

Helicity structure of the nucleon



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



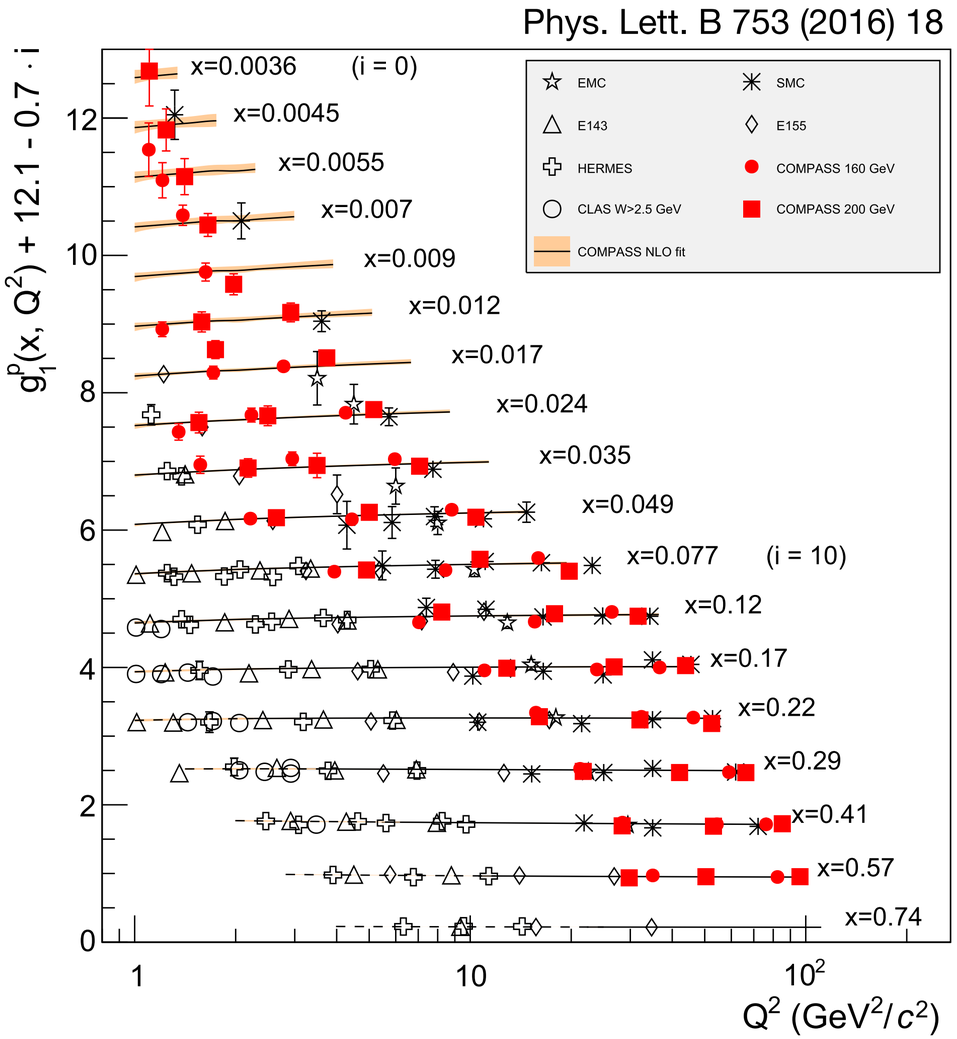
- flip proton spin and count…

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

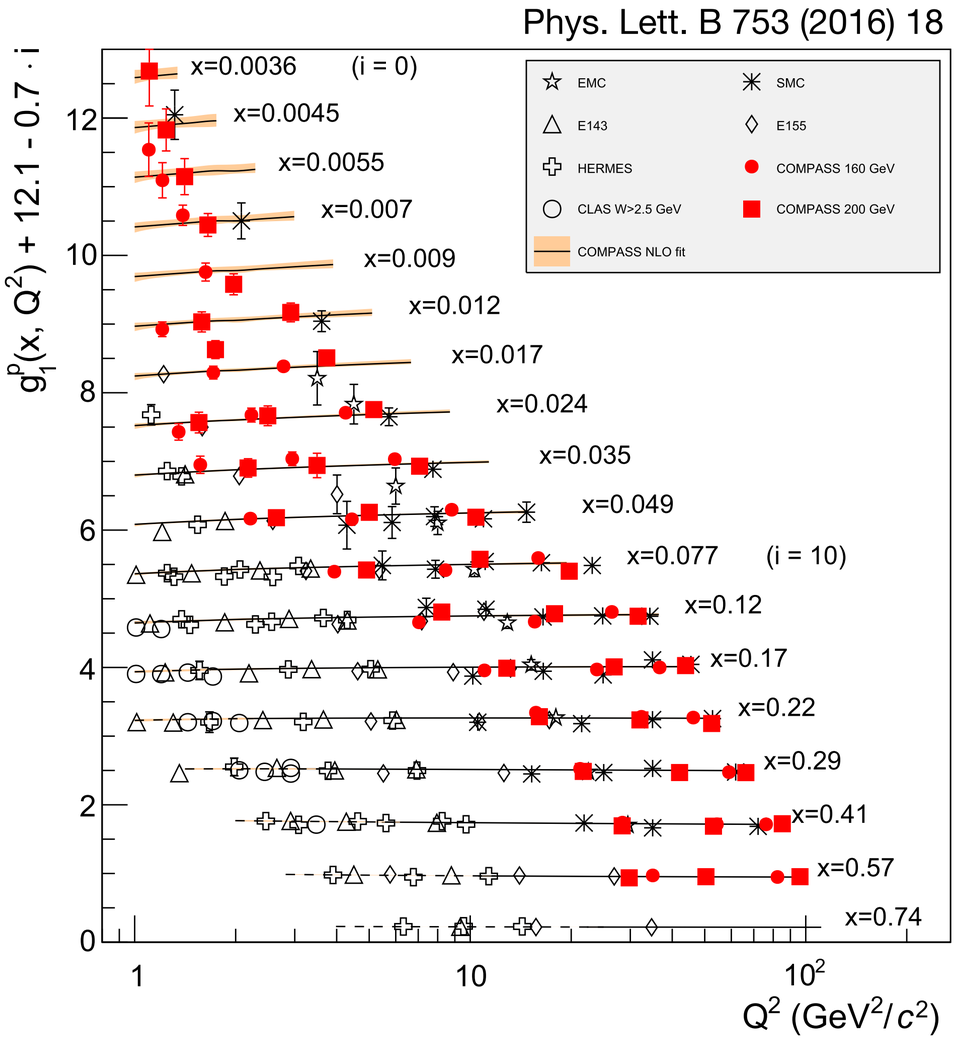
parton fractional longitudinal momentum: x_B

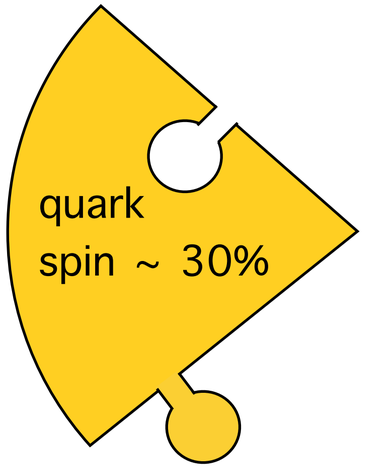
helicity parton distribution function (PDF)

Helicity structure of the nucleon: existing measurements

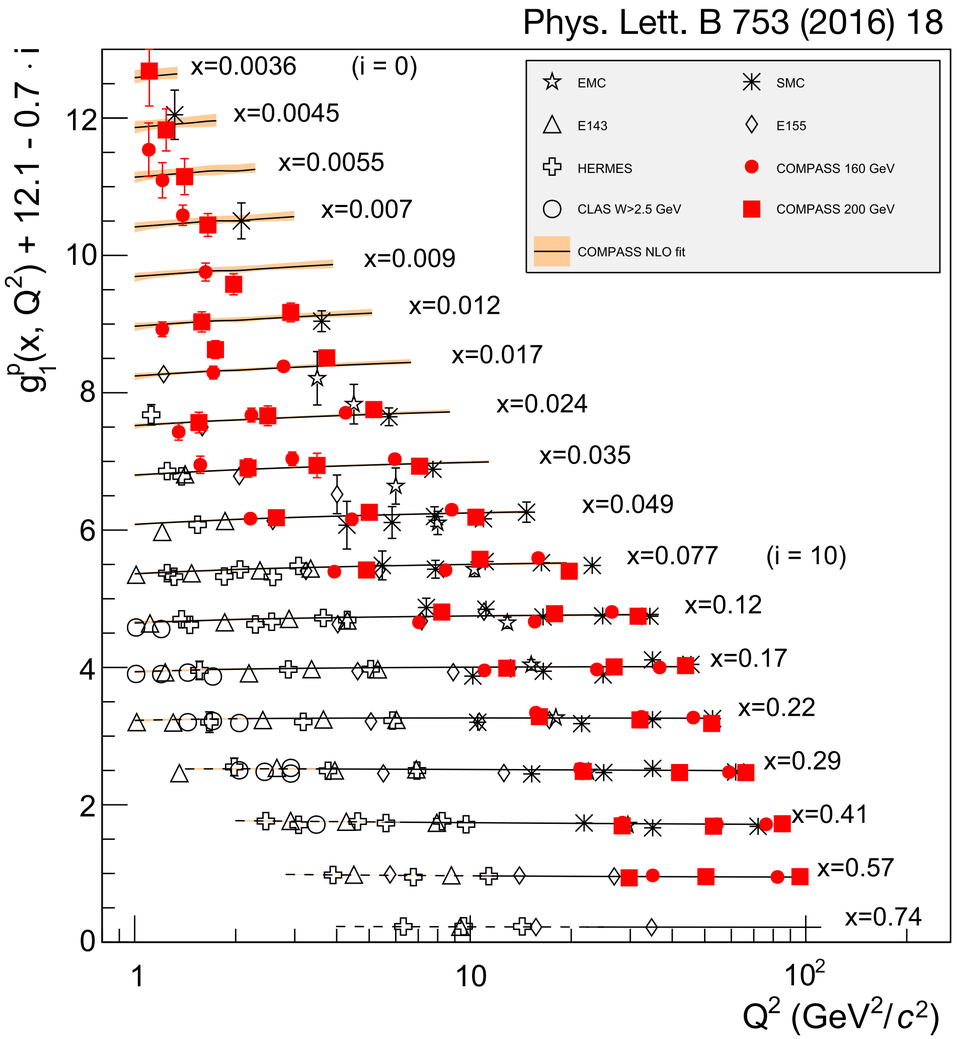


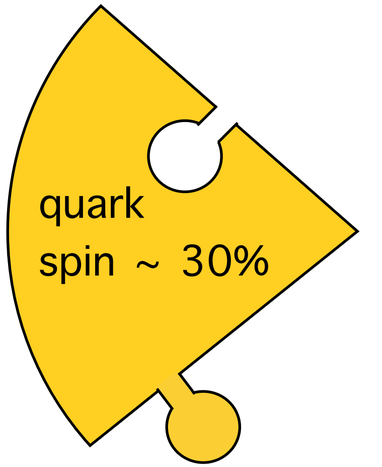
Helicity structure of the nucleon: existing measurements

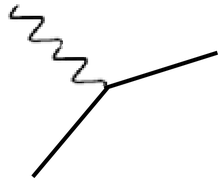




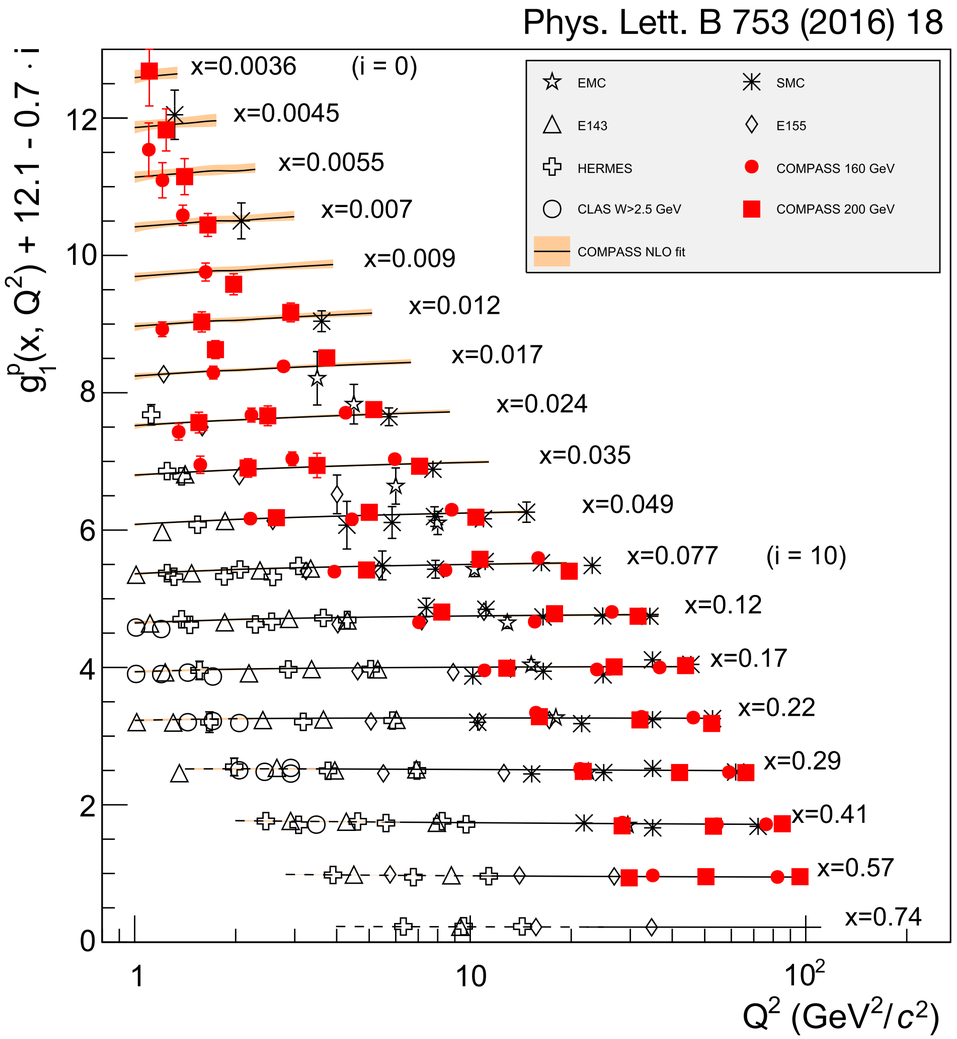
Helicity structure of the nucleon: existing measurements

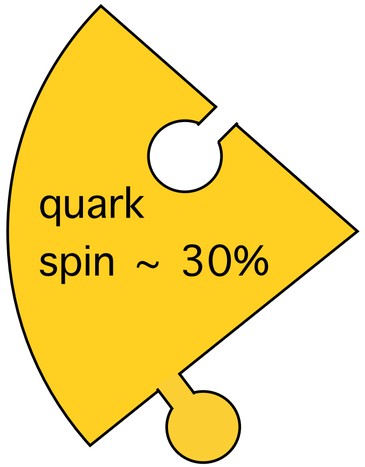




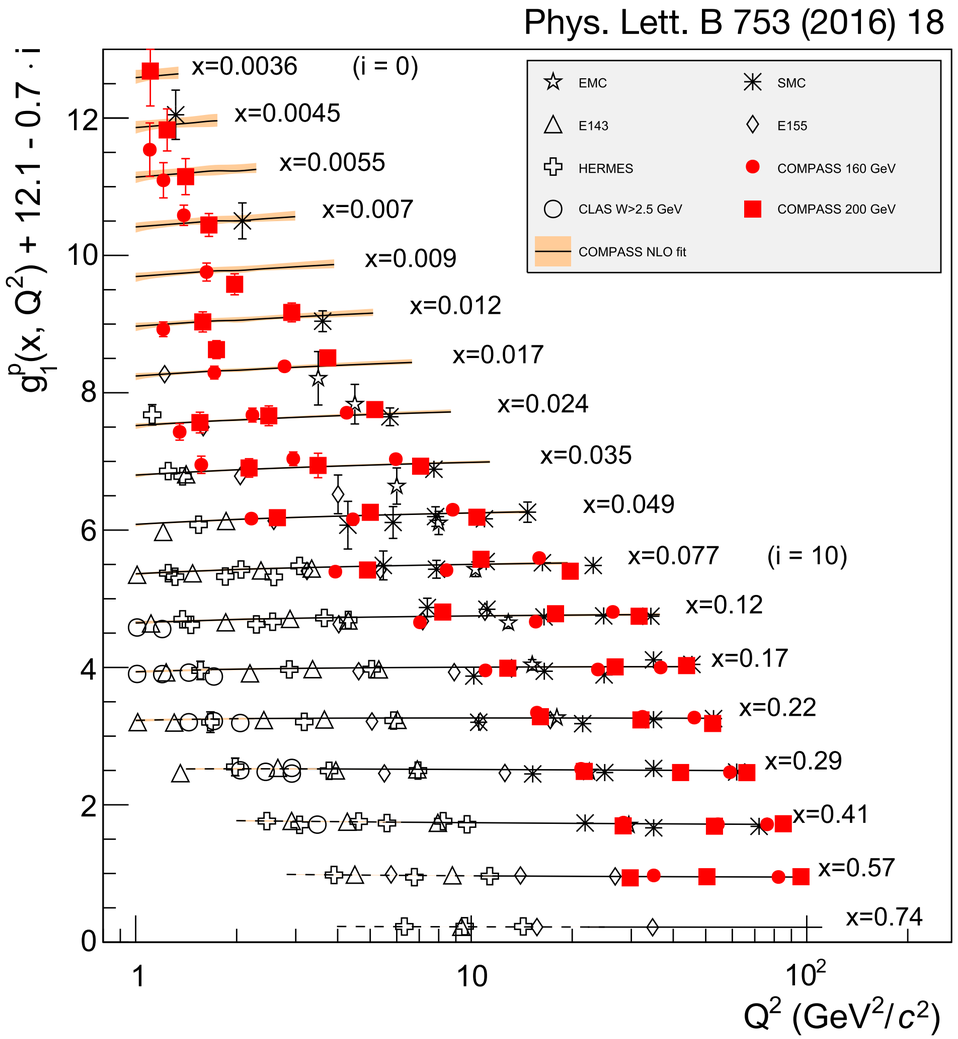


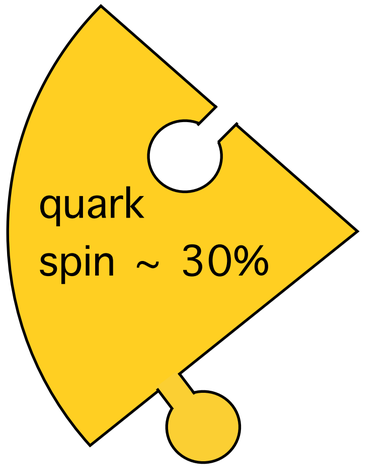
Helicity structure of the nucleon: existing measurements





Helicity structure of the nucleon: existing measurements

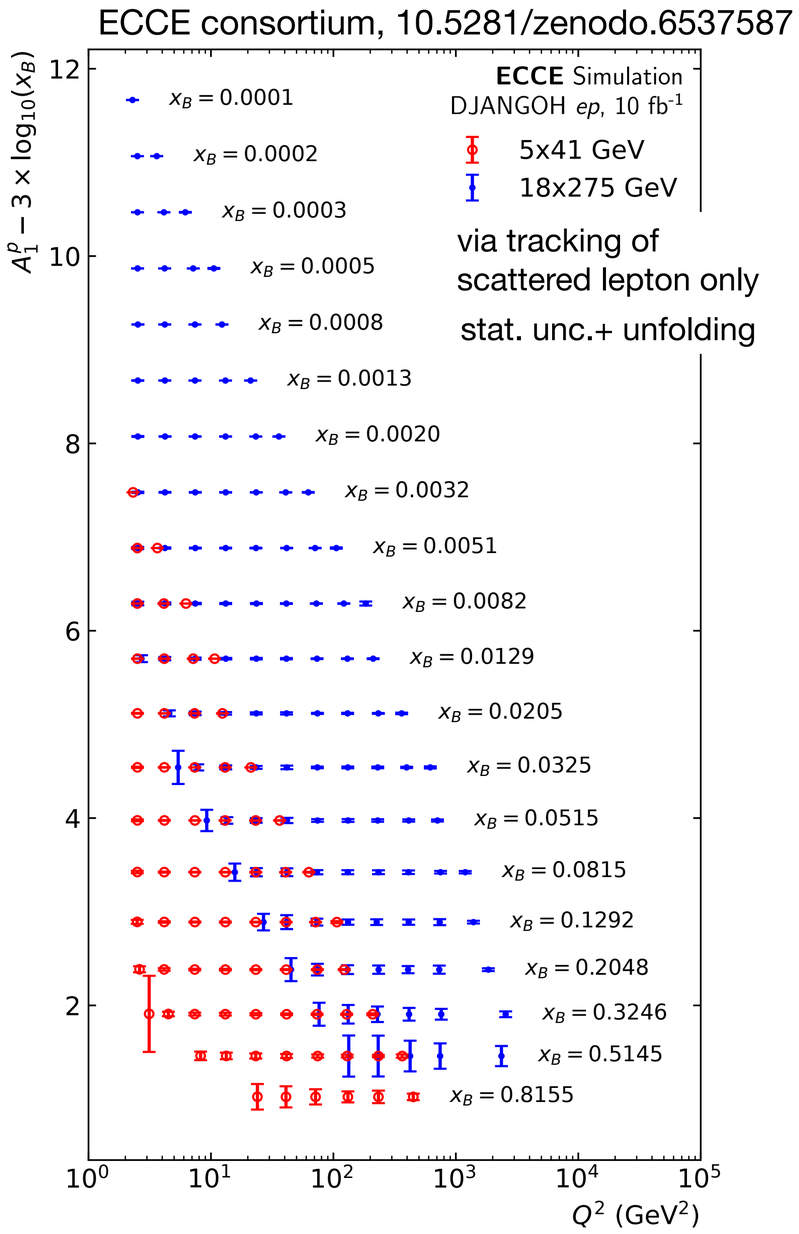




$$\frac{dg_1(x,Q^2)}{d\ln Q^2} \propto -\Delta g(x,Q^2)$$

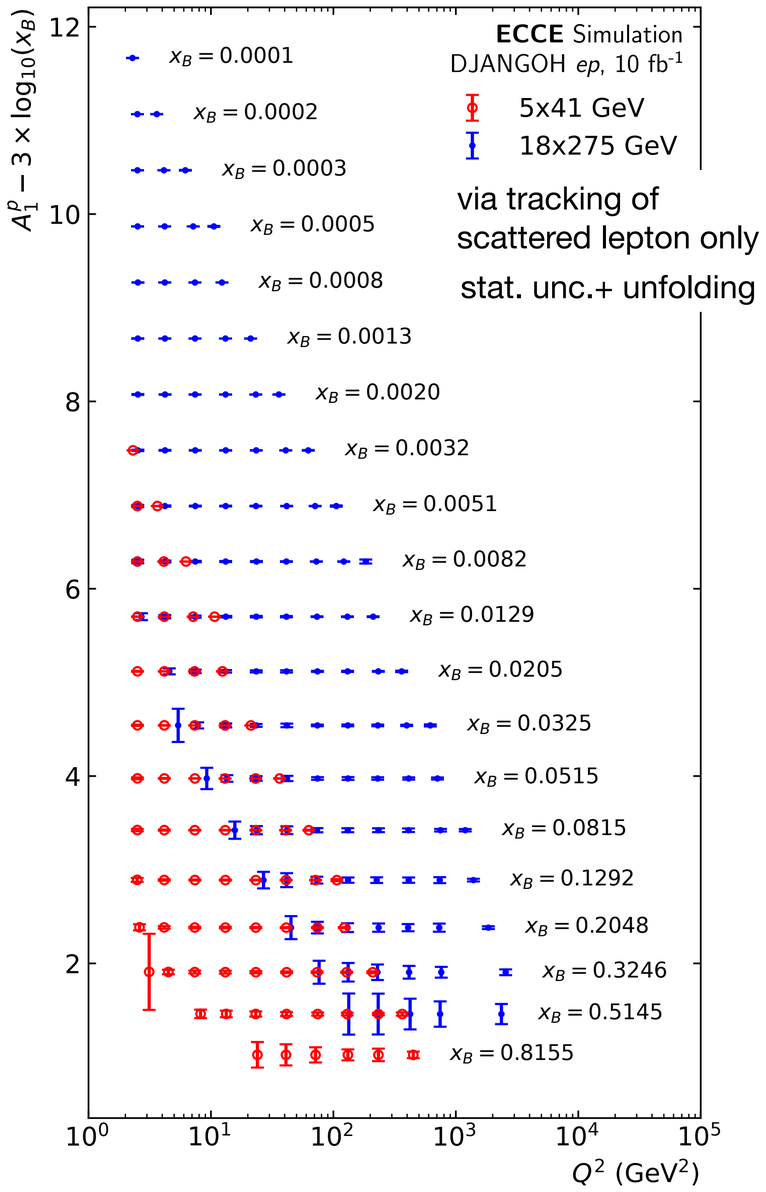
⟶ gluon spin

Gluon helicity distribution at the EIC

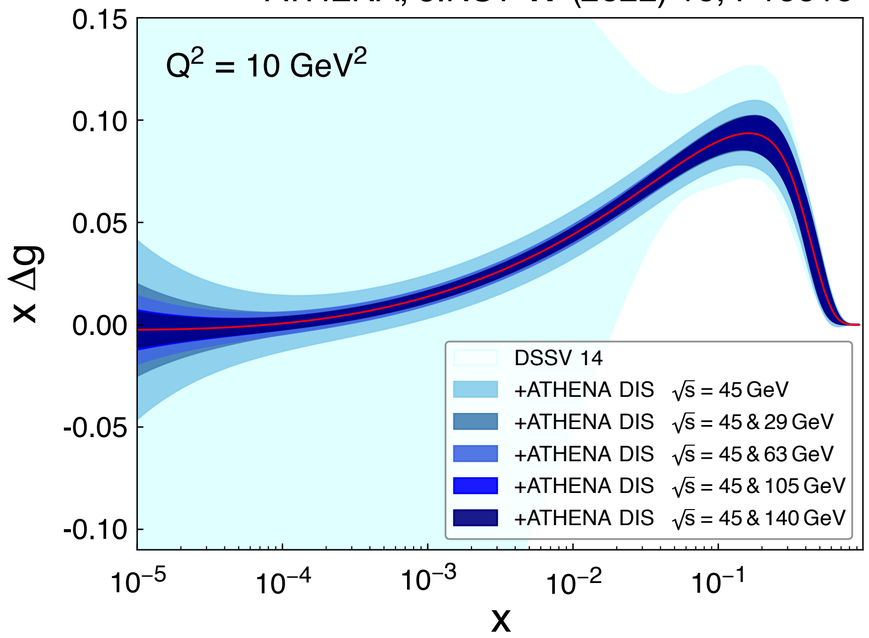


Gluon helicity distribution at the EIC

ECCE consortium, 10.5281/zenodo.6537587



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

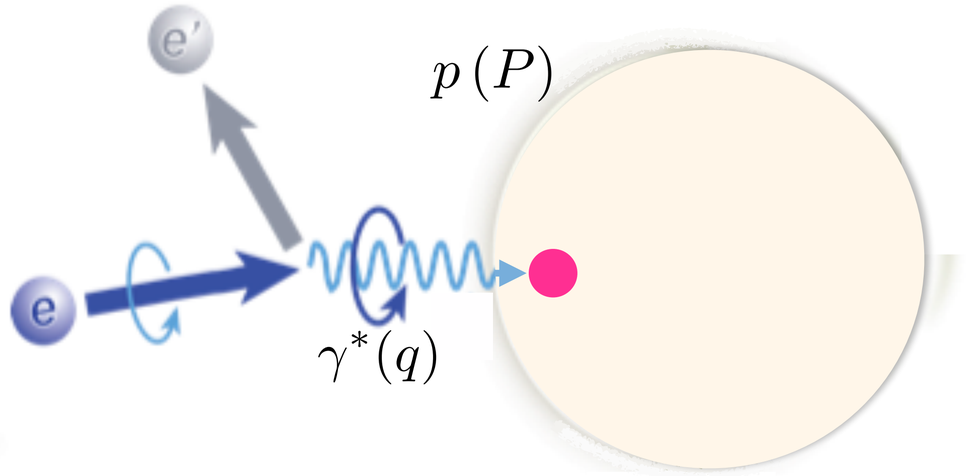


scaling violation from $g_1(x,Q^2)$

Single-hadron production in semi-inclusive DIS

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

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

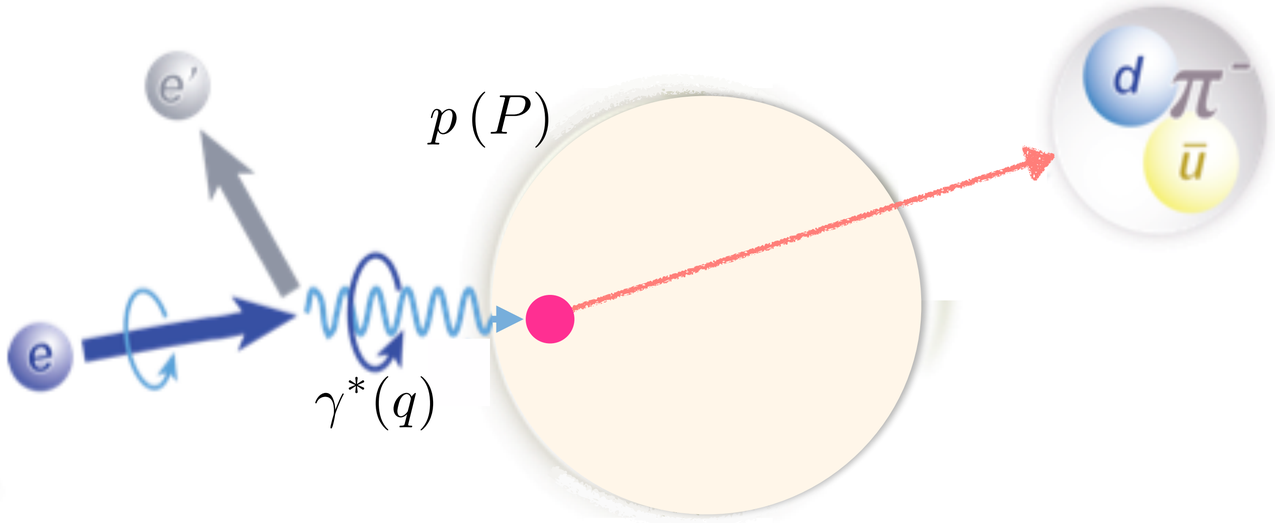


Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

Single-hadron production in semi-inclusive DIS

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

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



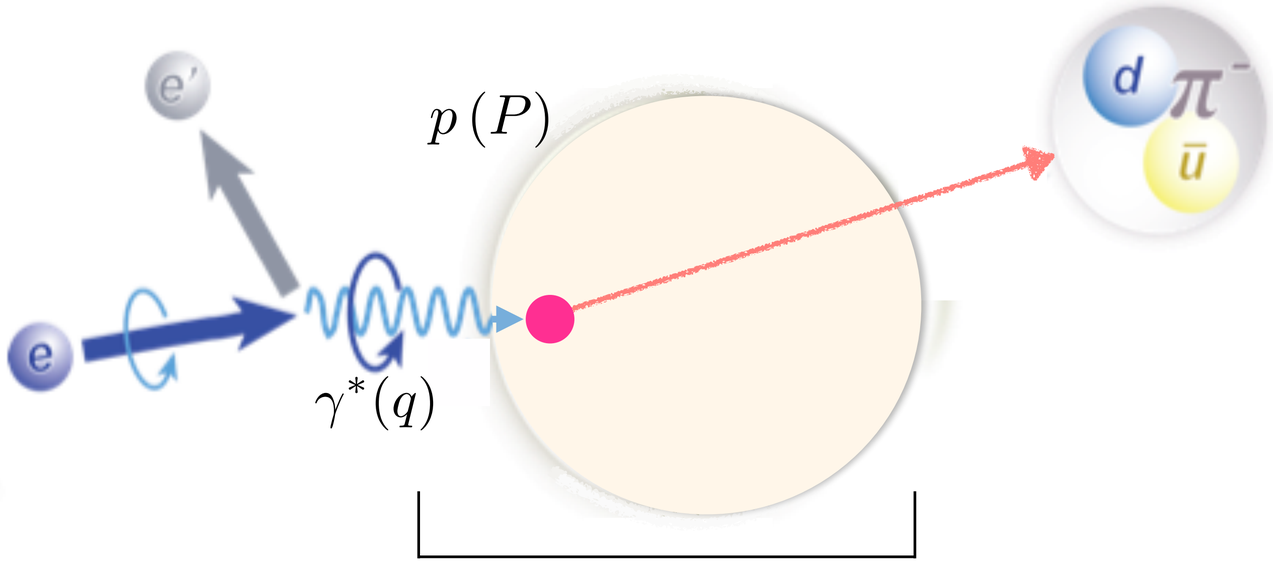
Detect a hadron!

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 $PDF(x_B)$

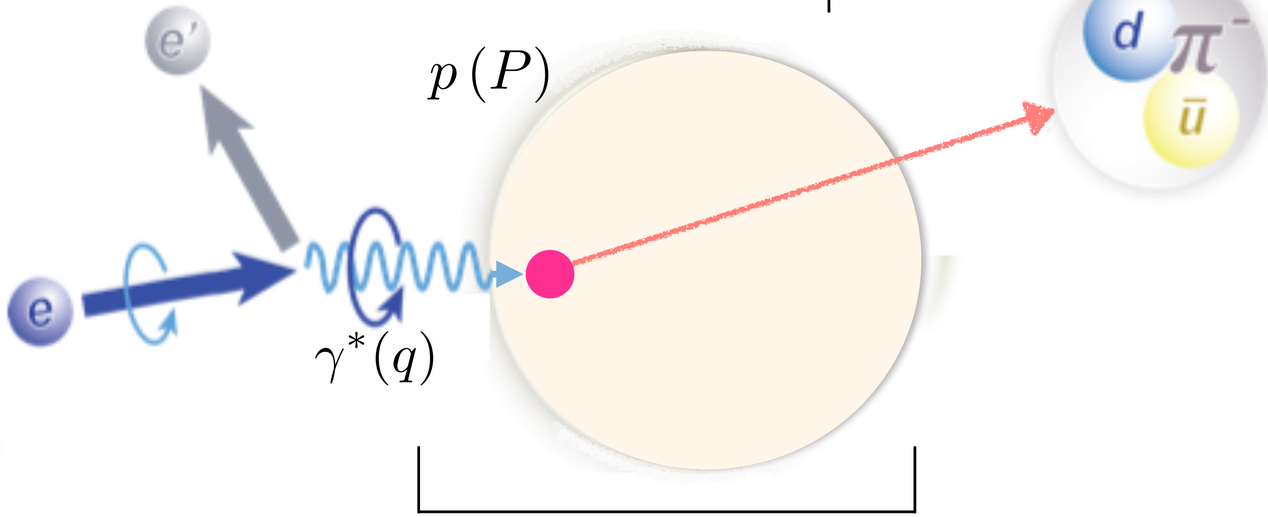
Highly virtual photon:
$Q^2 \gg 1$ GeV^2
provides hard
scale of process

Single-hadron production in semi-inclusive DIS

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

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

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



Detect a hadron!

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

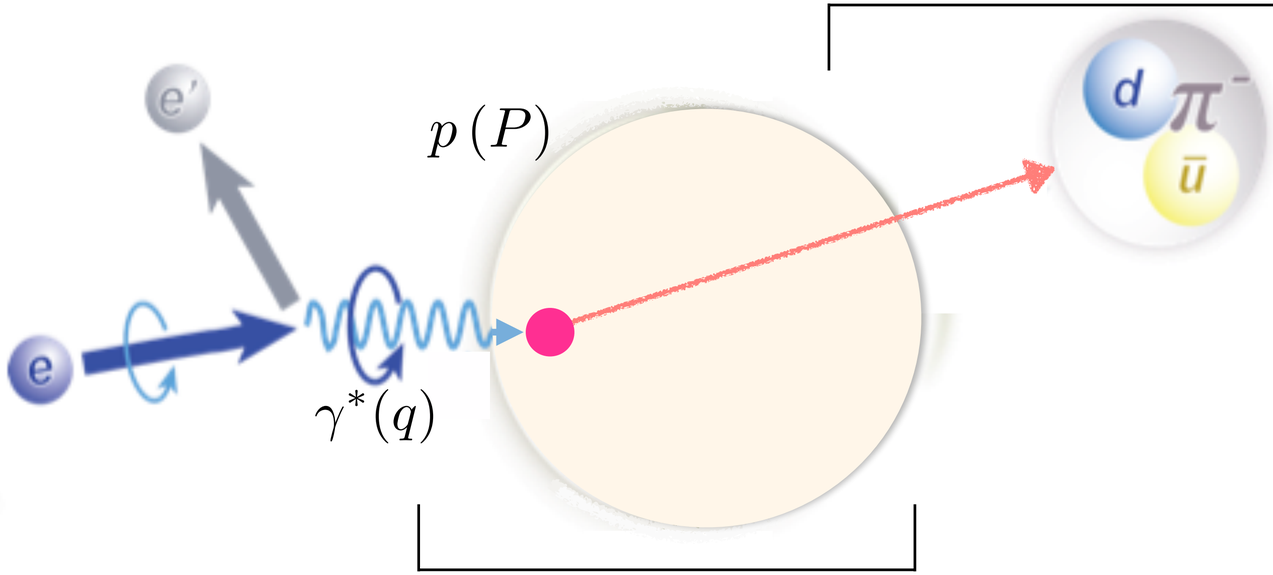
Single-hadron production in semi-inclusive DIS

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

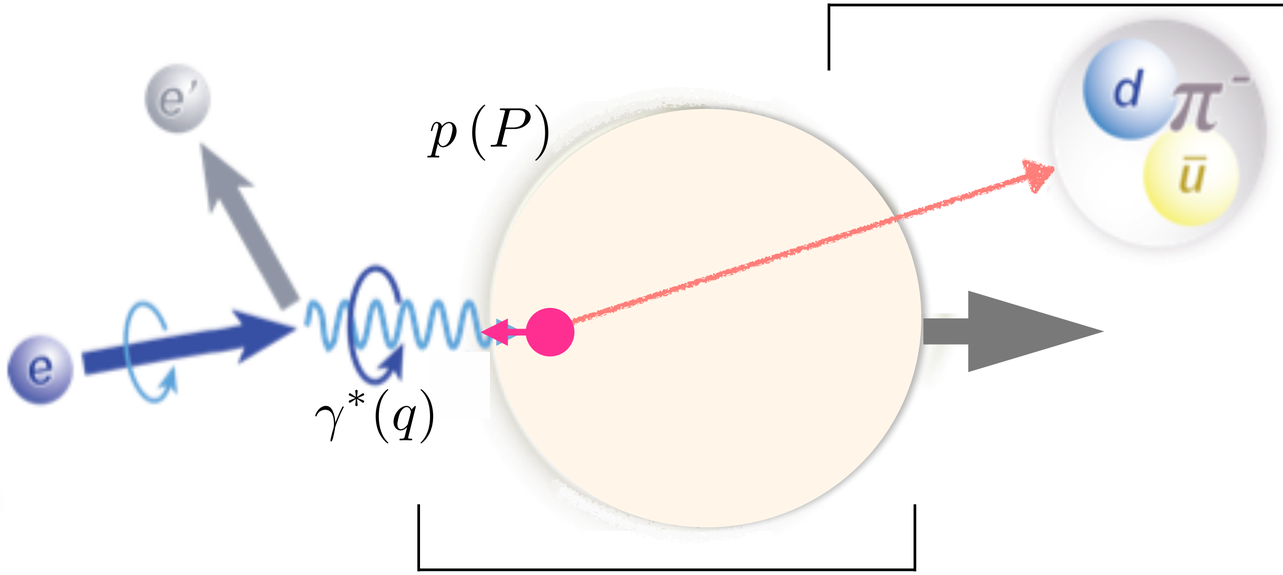
Single-hadron production in semi-inclusive DIS

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

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

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

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

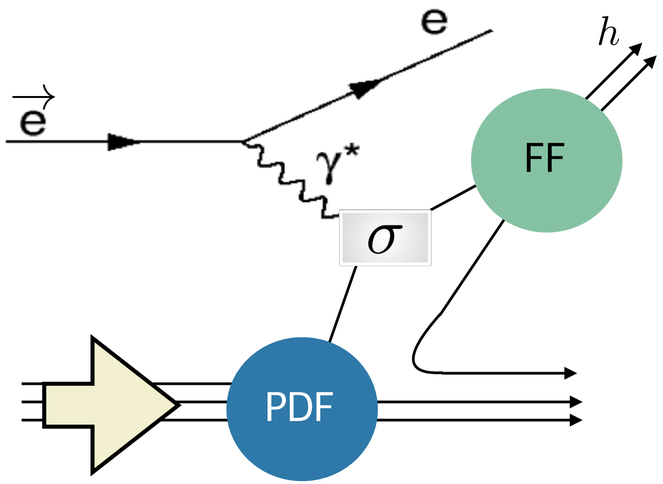


Detect a hadron!

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

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

Sea-quark helicity distributions

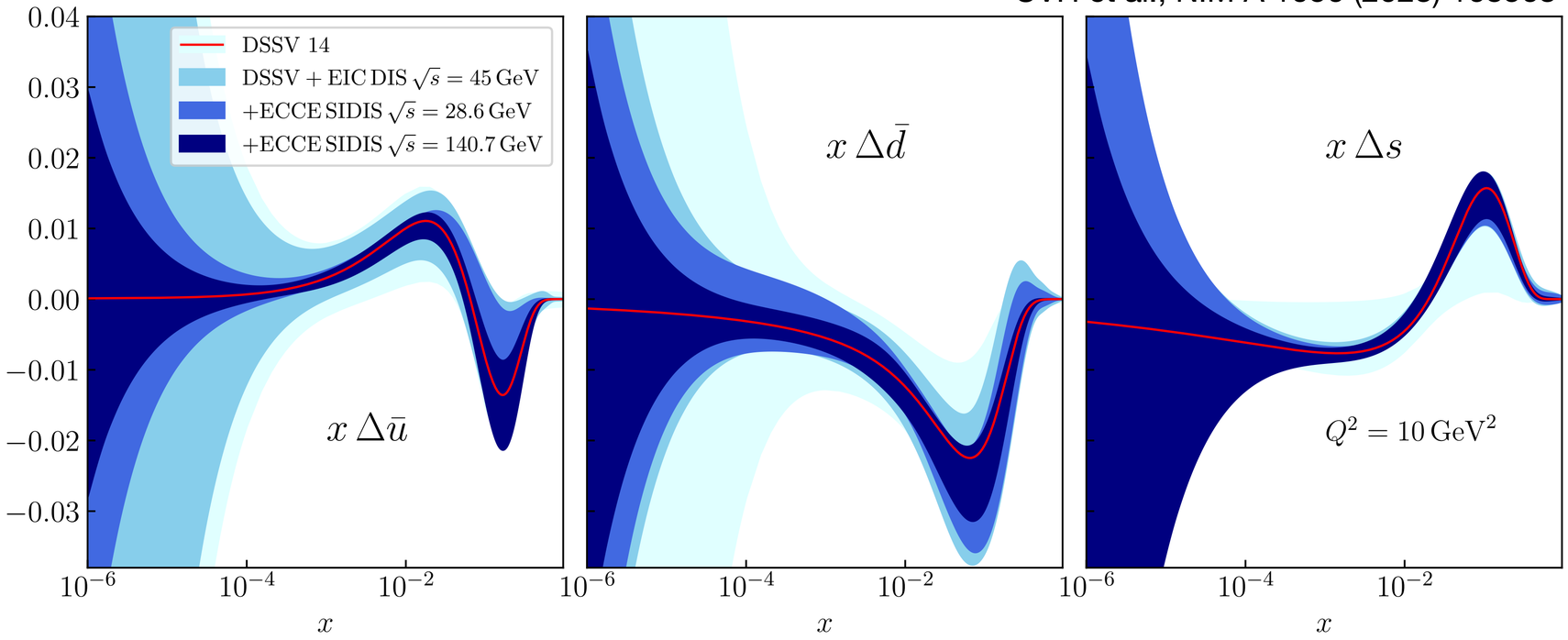


$$\frac{\overleftarrow{\rightarrow}^h - \overrightarrow{\rightarrow}^h}{\overleftarrow{\rightarrow}^h + \overrightarrow{\rightarrow}^h} \propto \sum_q e_q^2 \left[\Delta q \otimes w_1 D_1^{q \to h} \right]$$

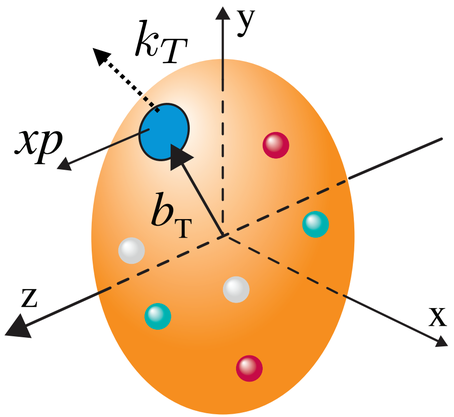
Semi-inclusive measurements
→ access to sea-quark spin

Sea-quark helicity distributions at the EIC

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

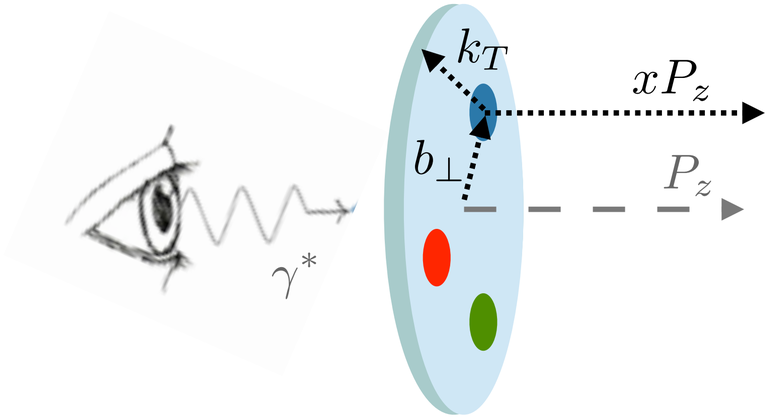


Nucleon multi-dimensional structure



The nucleon multi-dimensional structure

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

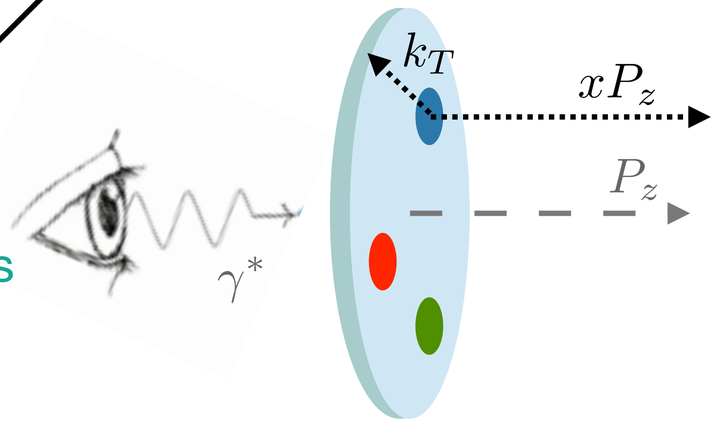


The nucleon multi-dimensional structure

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

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

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

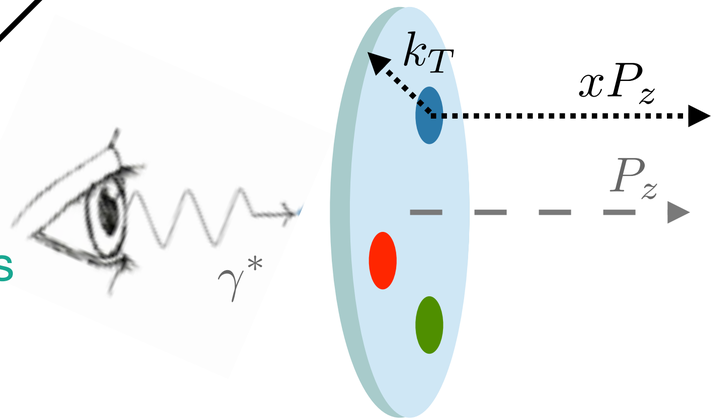


The nucleon multi-dimensional structure

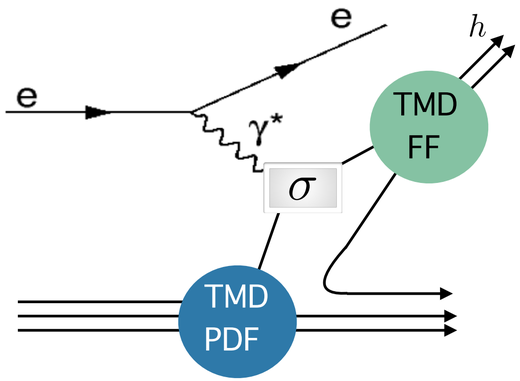
Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

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

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



Semi-inclusive production

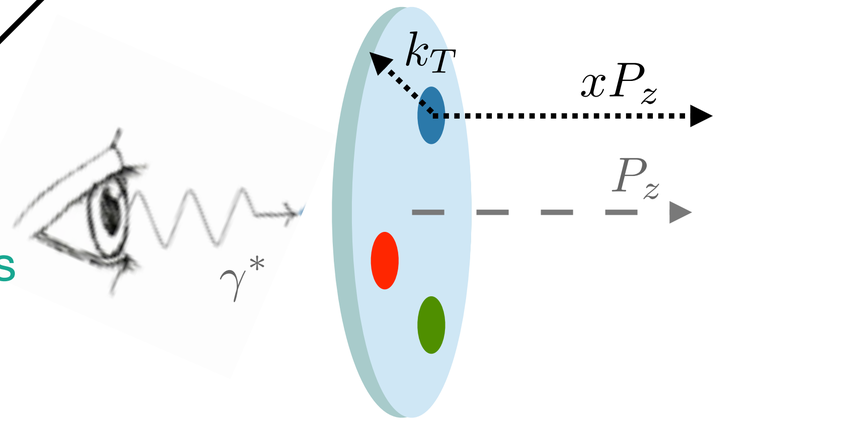


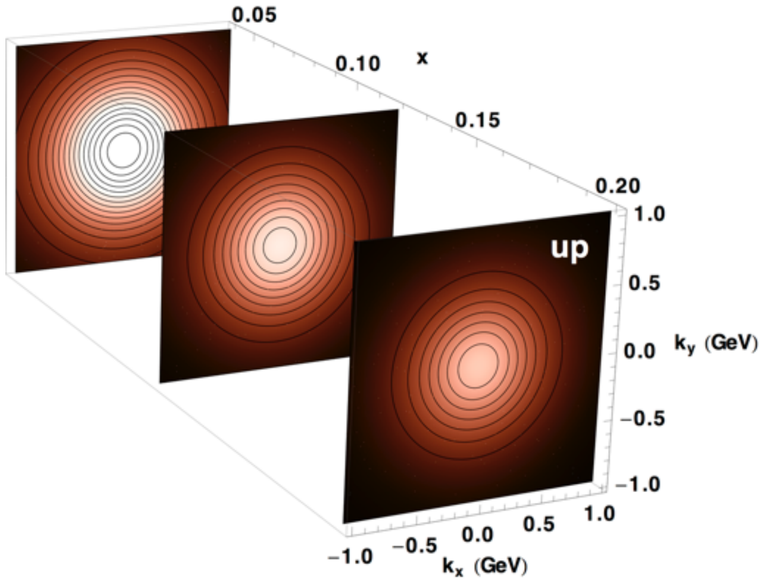
The nucleon multi-dimensional structure

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

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

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



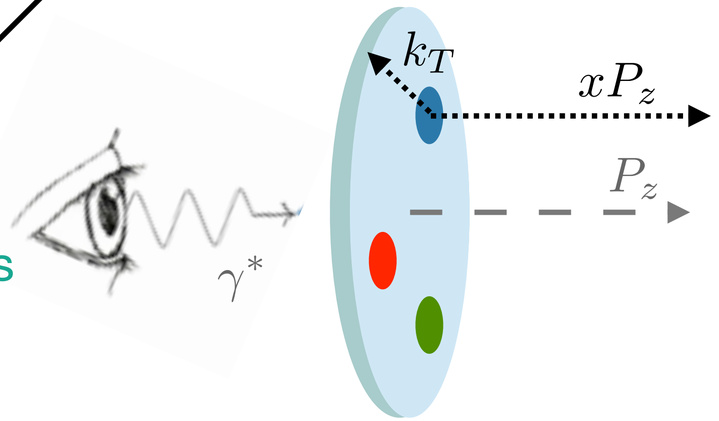


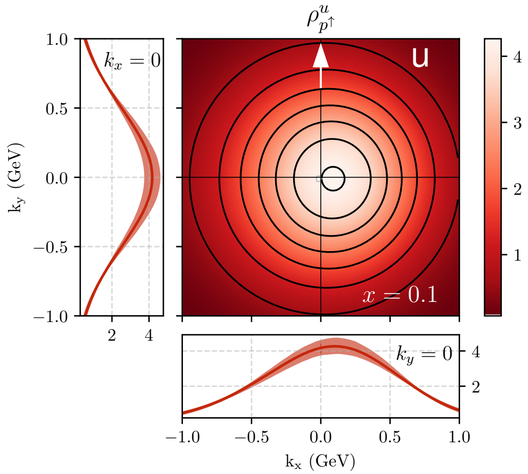
The nucleon multi-dimensional structure

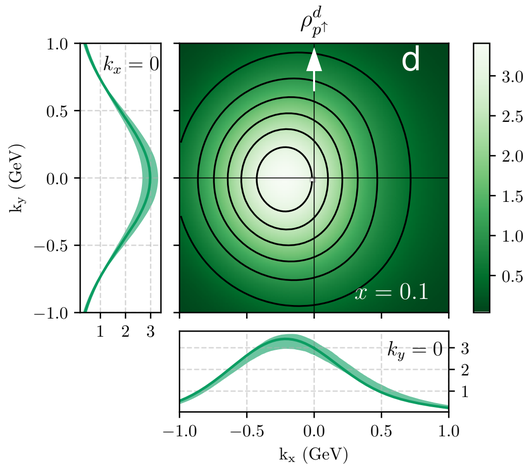
Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

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

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







The nucleon multi-dimensional structure

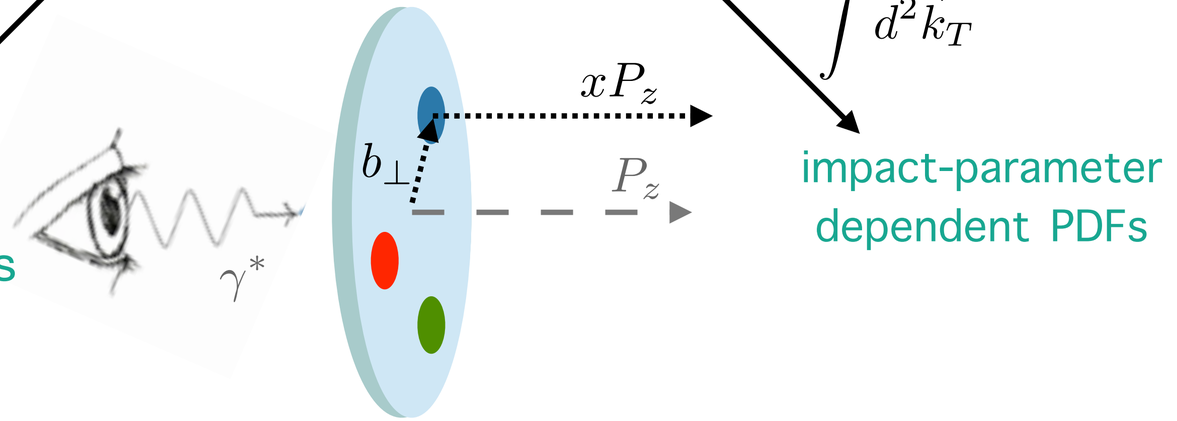
Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

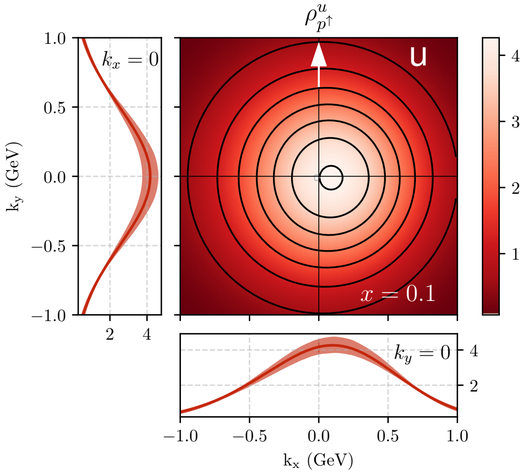
$\int d^2\vec{b}_\perp$

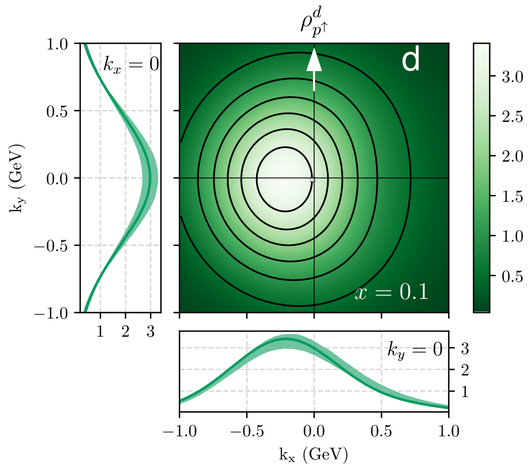
$\int d^2\vec{k}_T$

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

impact-parameter dependent PDFs







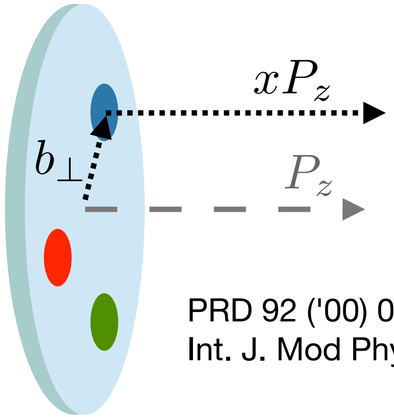
The nucleon multi-dimensional structure

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

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

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

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

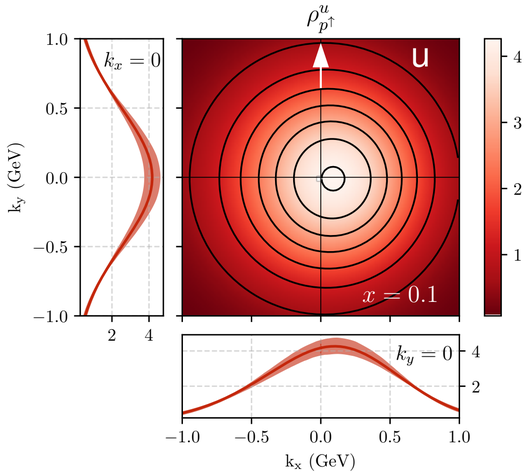


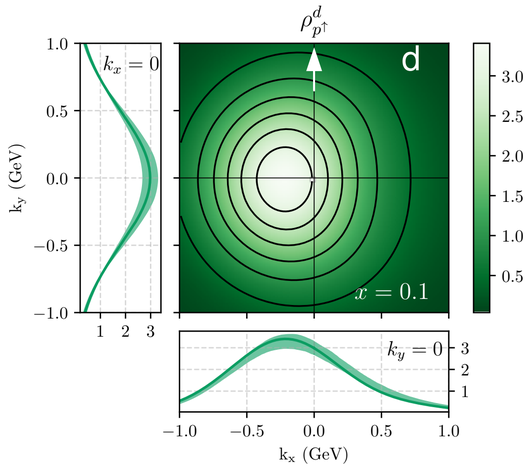
impact-parameter dependent PDFs

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

Fourier transform

generalised parton distributions (GPDs)





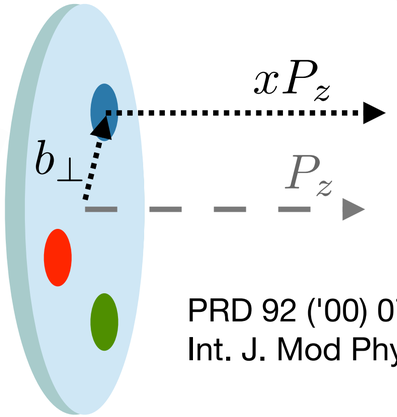
The nucleon multi-dimensional structure

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)

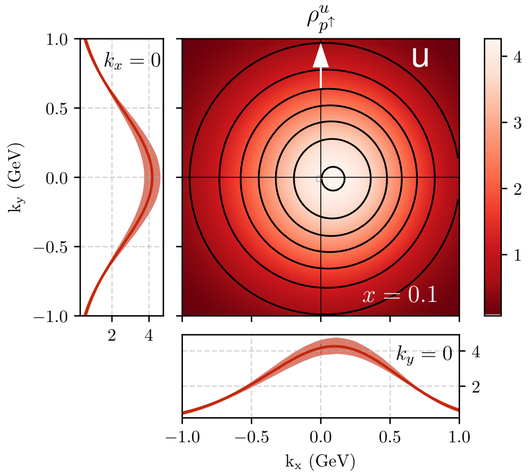


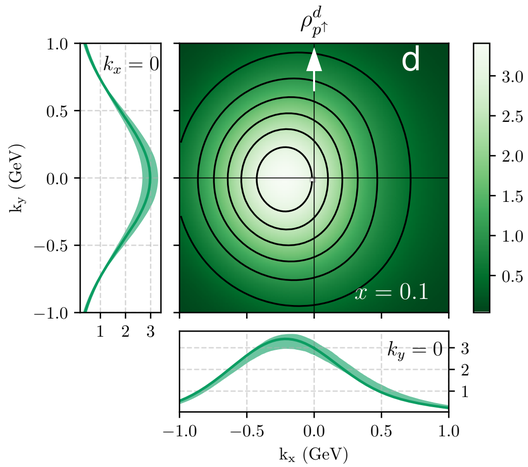
impact-parameter dependent PDFs

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

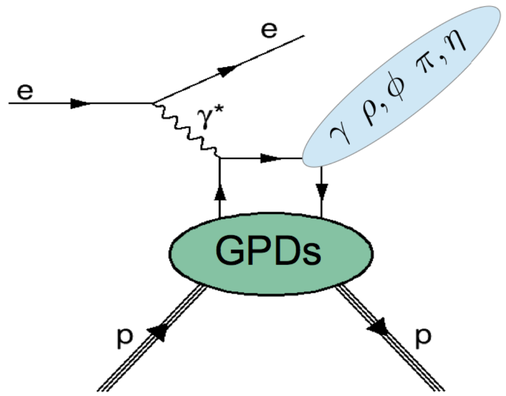
Fourier transform

generalised parton distributions (GPDs)





Exclusive production



The nucleon multi-dimensional structure

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

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

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

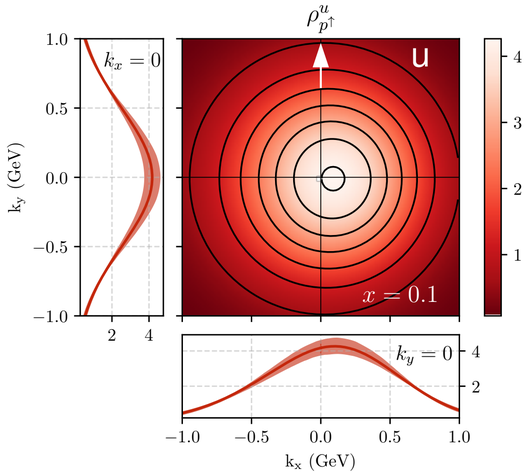
transverse-momentum dependent (TMD) parton distribution functions (PDFs)

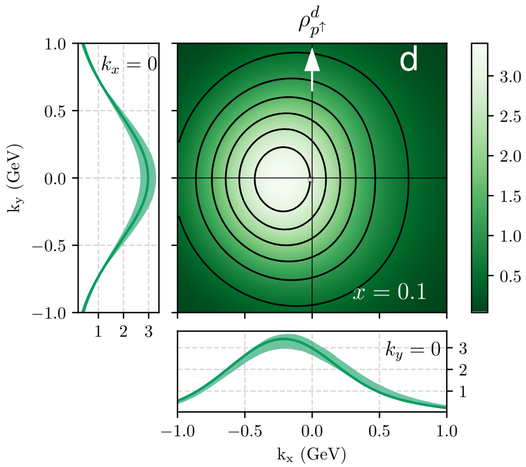
impact-parameter dependent PDFs

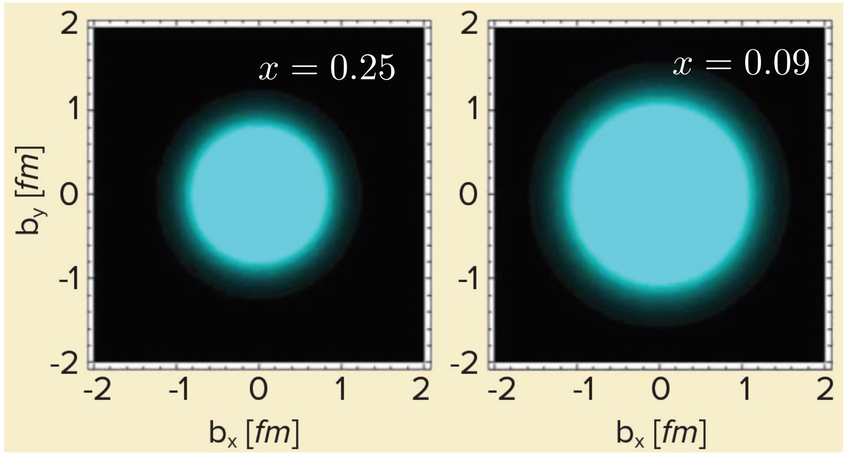
PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

Fourier transform

generalised parton distributions (GPDs)







The nucleon multi-dimensional structure

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

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

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

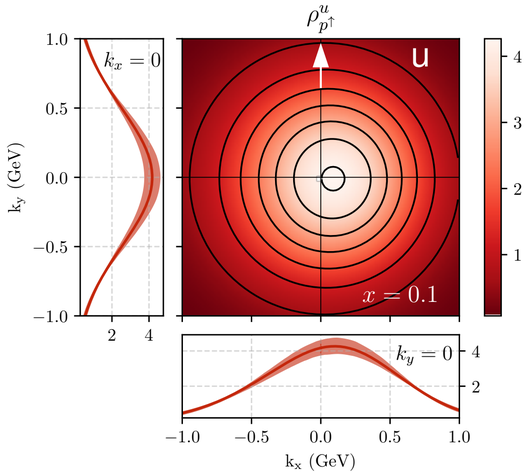
transverse-momentum dependent (TMD) parton distribution functions (PDFs)

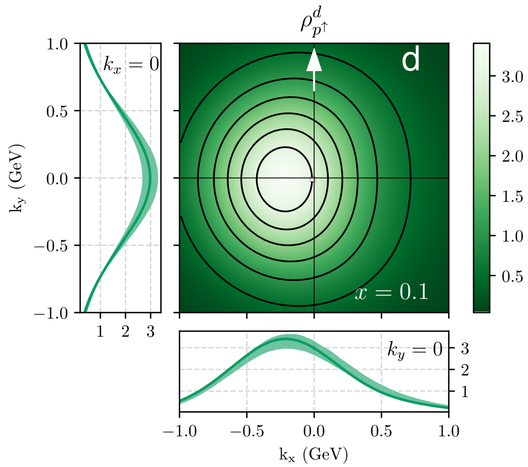
impact-parameter dependent PDFs

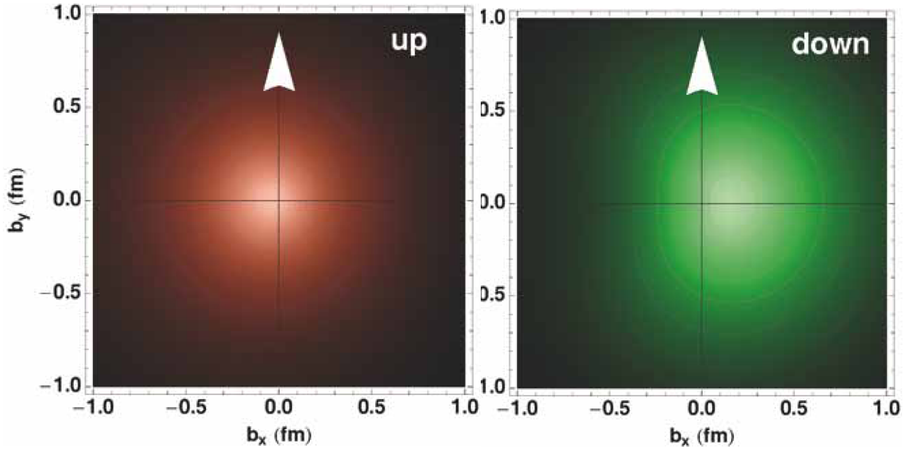
Fourier transform

generalised parton distributions (GPDs)

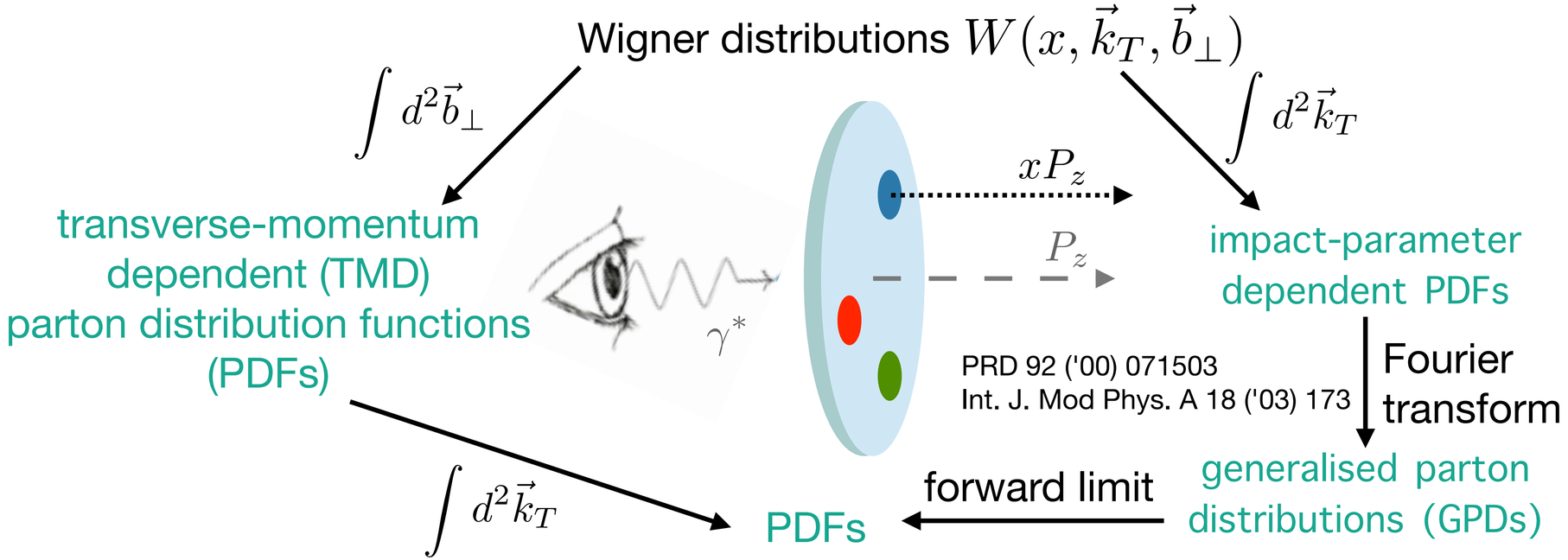
PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

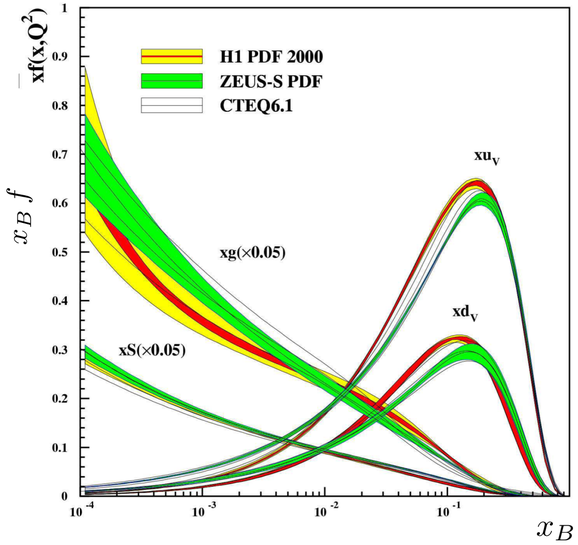






The nucleon multi-dimensional structure



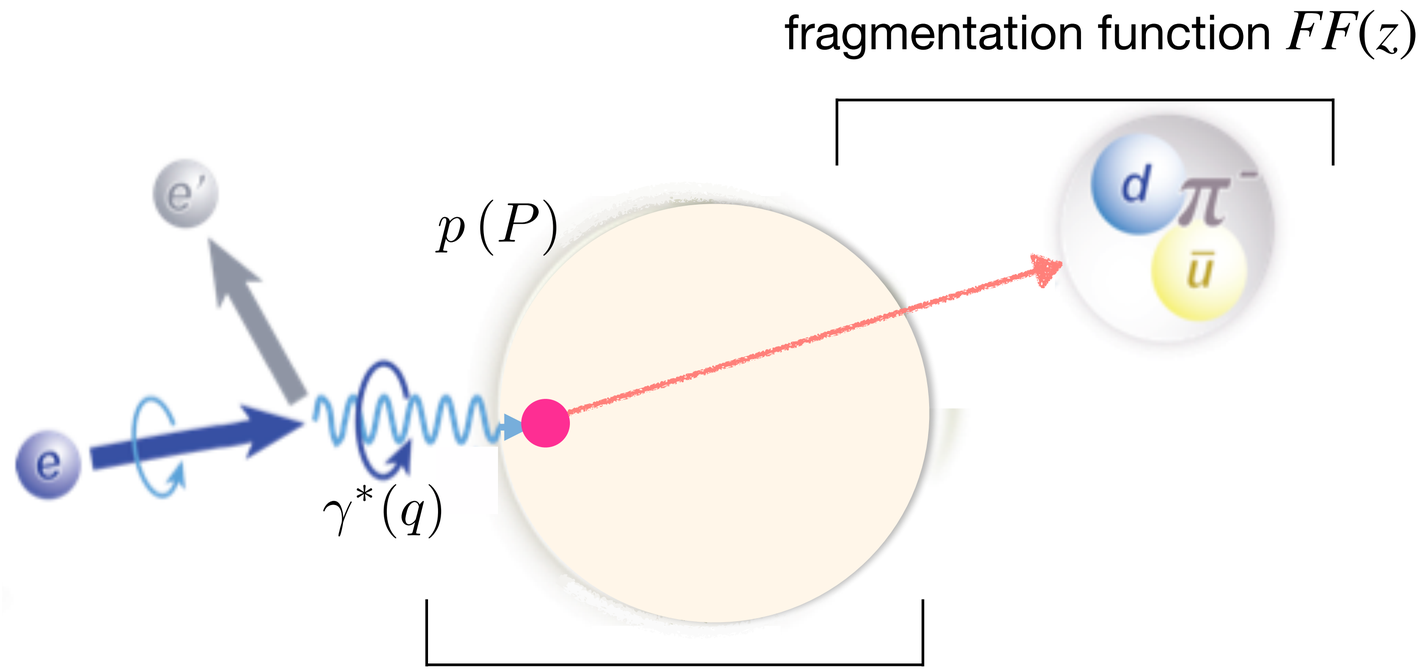


Single-hadron production in semi-inclusive DIS

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

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

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



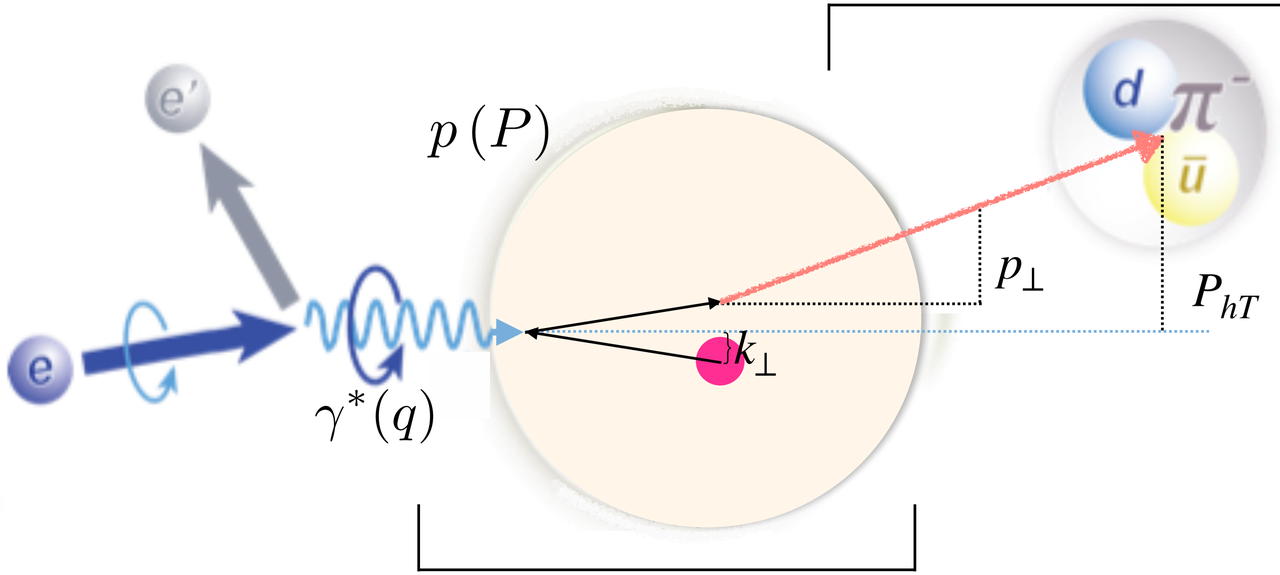
Single-hadron production in semi-inclusive DIS

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

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

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

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



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

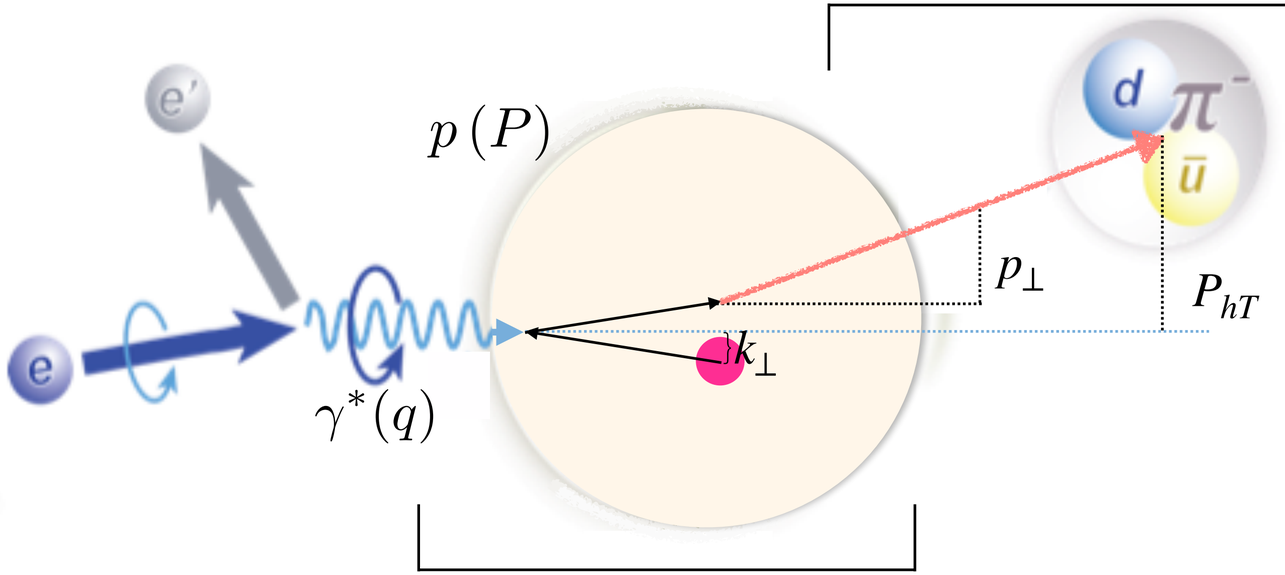
Single-hadron production in semi-inclusive DIS

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

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

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

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



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

TMD evolution

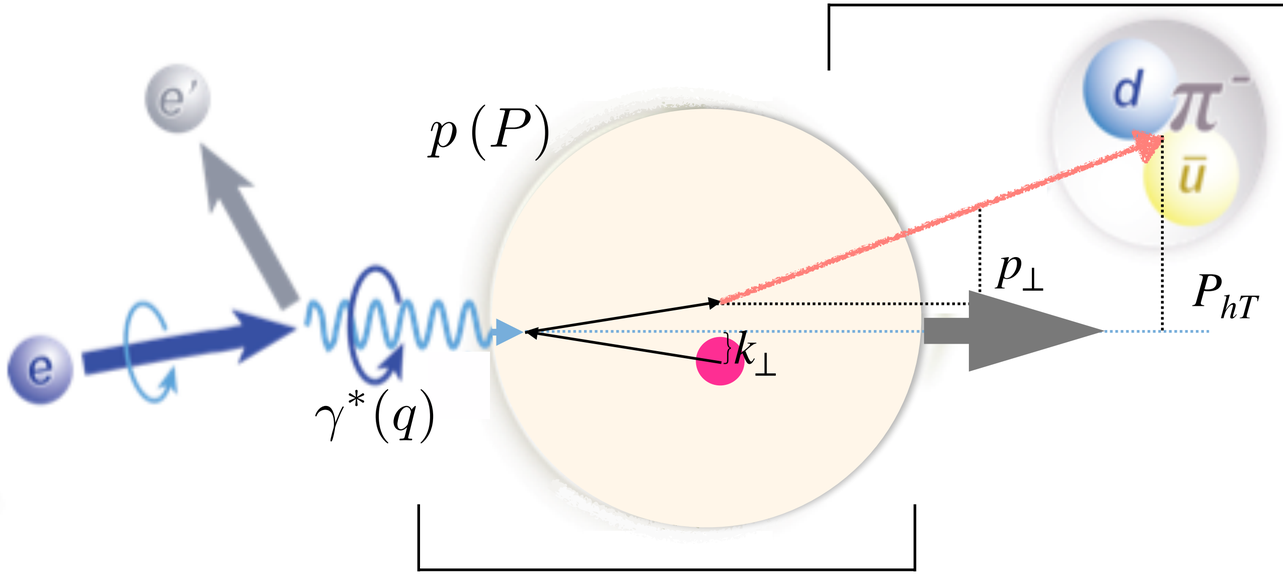
Single-hadron production in semi-inclusive DIS

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

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

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

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



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

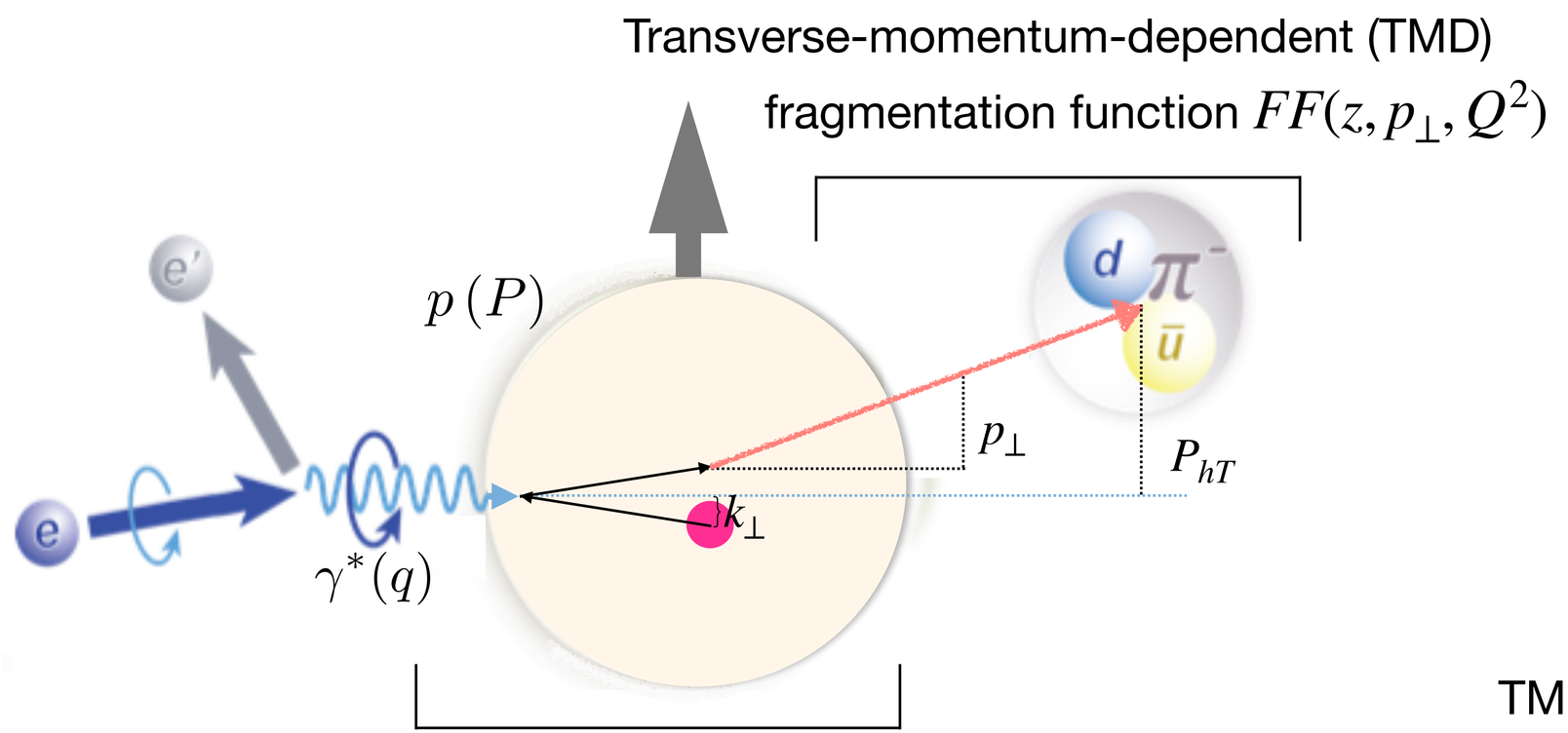
TMD evolution

Single-hadron production in semi-inclusive DIS

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

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

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



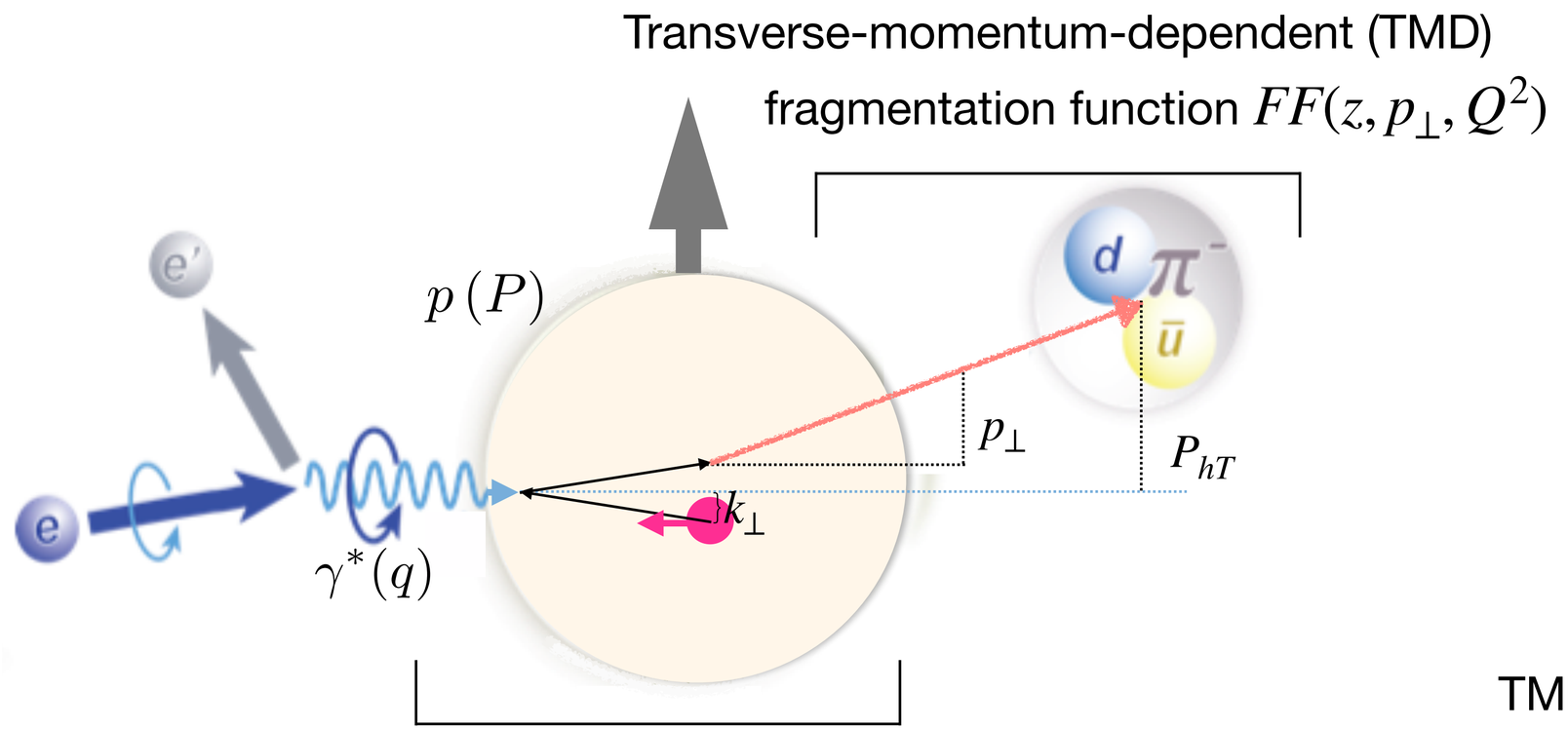
TMD evolution

Single-hadron production in semi-inclusive DIS

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

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

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



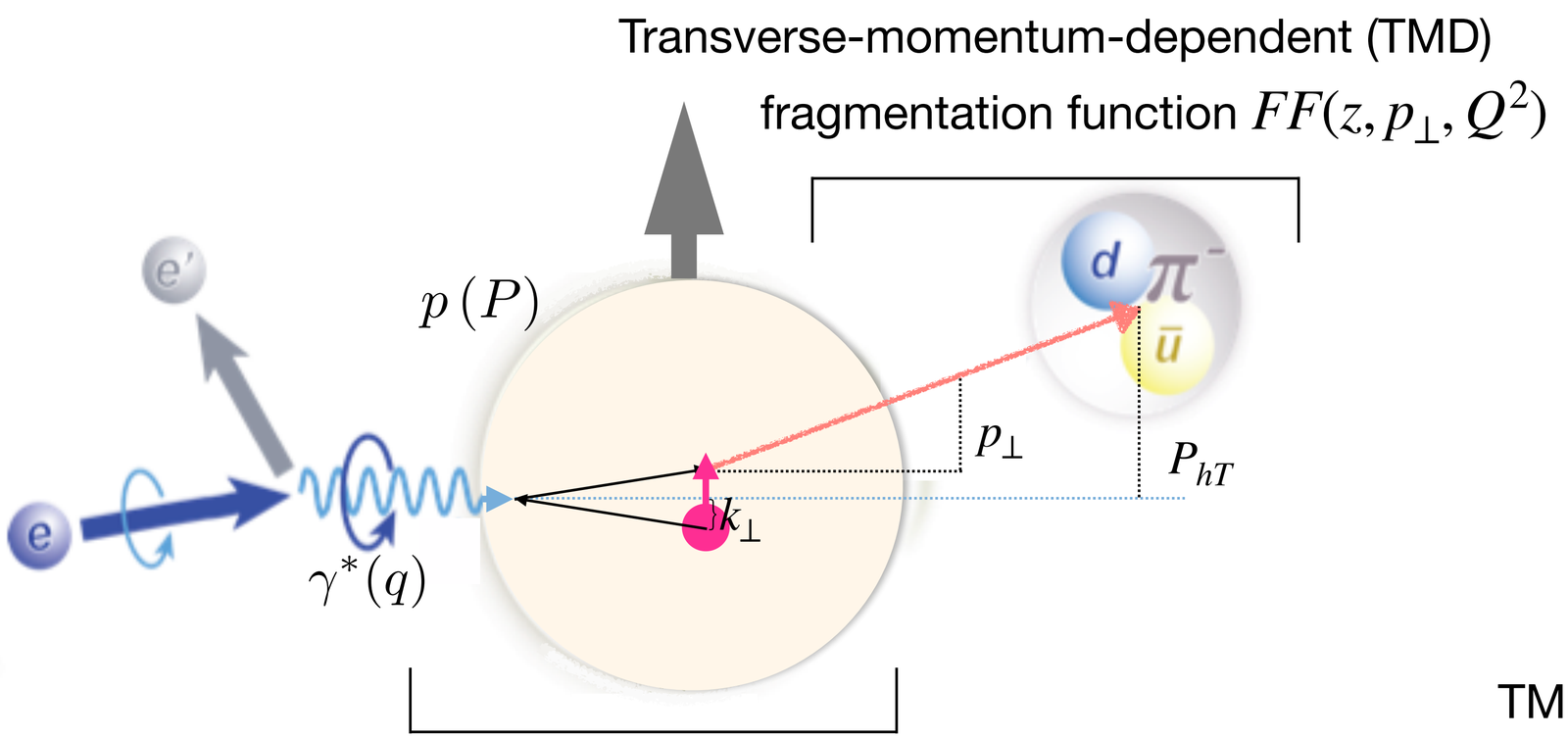
TMD evolution

Single-hadron production in semi-inclusive DIS

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

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

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



TMD evolution

Transverse-momentum-dependent parton distribution functions

quark polarisation

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

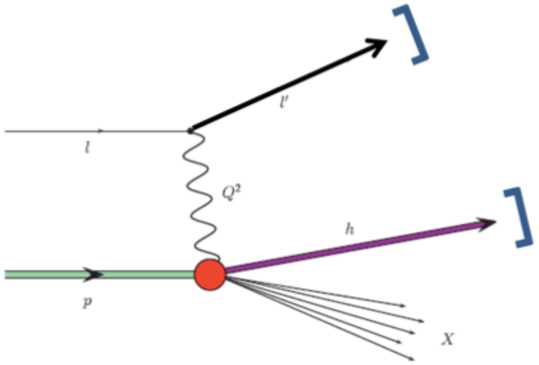
survive integration over parton transverse momentum

Transverse-momentum-dependent parton distribution functions

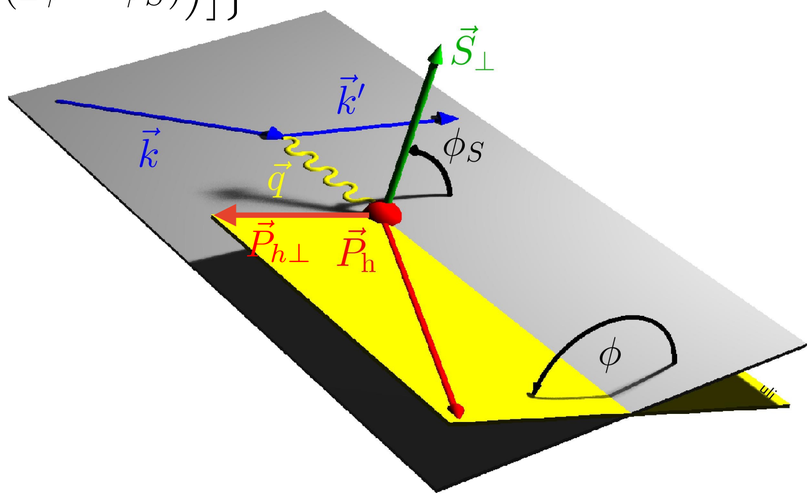
quark polarisation

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

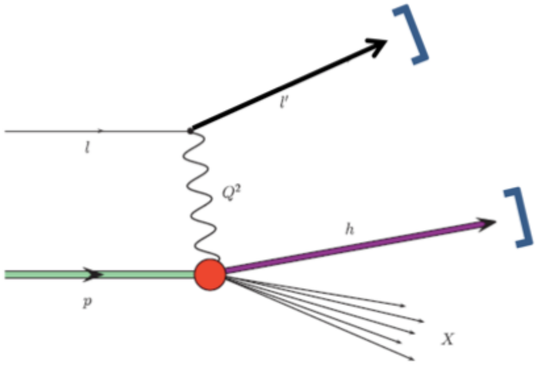
Semi-inclusive DIS cross section



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



Semi-inclusive DIS cross section



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

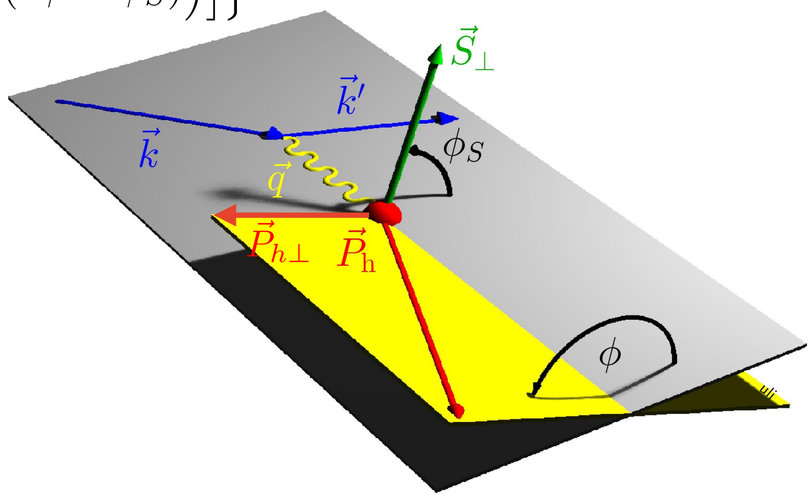
longitudinal target polarisation

transverse target polarisation

beam polarisation

beam polarisation

target polarisation



TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY} :

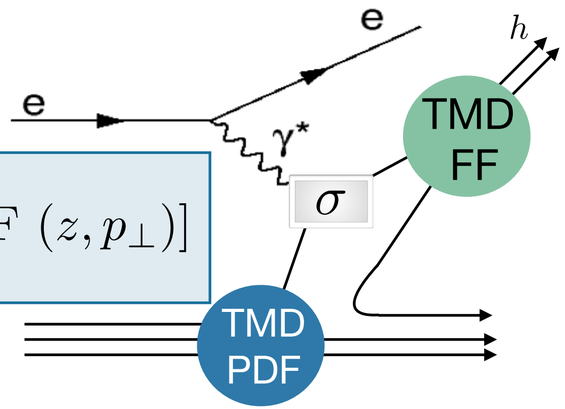
$$2\langle \sin(\phi + \phi_S)\rangle^h_{UT} = \epsilon\, F^{\sin(\phi+\phi_S)}_{UT}$$

TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY} :

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

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

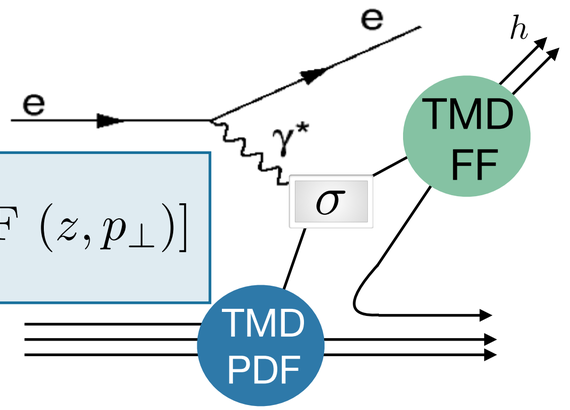


TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY} :

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

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



quark polarisation

nucleon polarisation

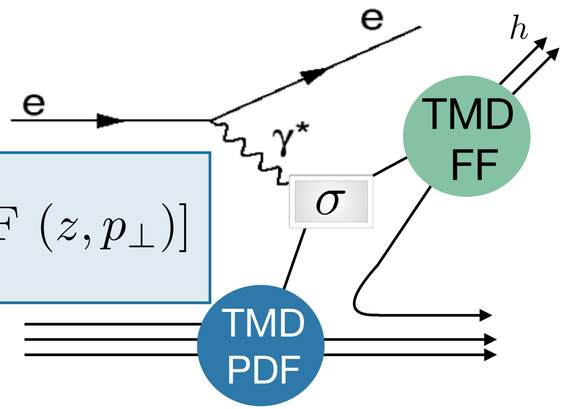
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\, h_{1T}^\perp$

TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY} :

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

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



quark polarisation

nucleon polarisation

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

quark polarisation

hadron polarisation

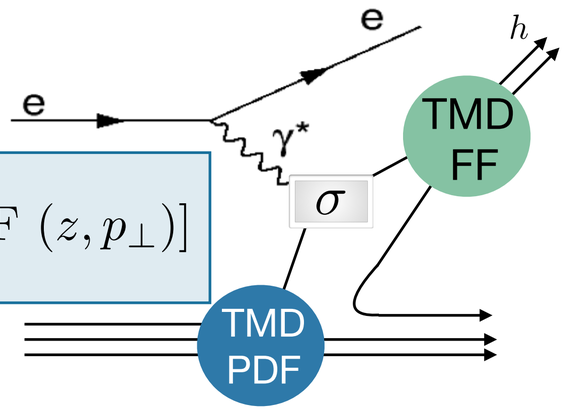
	U	L	T
U	D_1		$H_1^\perp$

TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY} :

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

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



quark polarisation

nucleon polarisation

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

chiral even x chiral even

quark polarisation

hadron polarisation

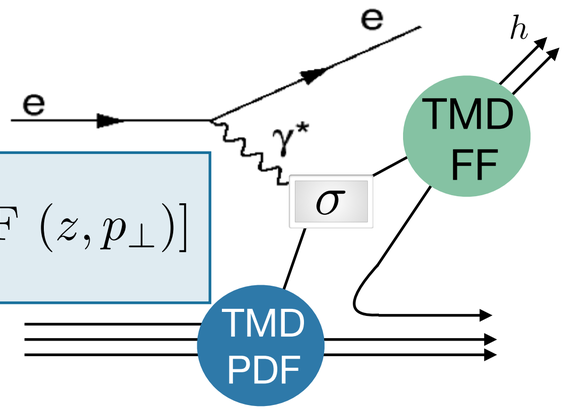
	U	L	T
U	D_1		$H_1^\perp$

TMD PDFs and fragmentation functions (FFs)

Azimuthal amplitudes related to structure functions F_{XY} :

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

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



quark polarisation

nucleon polarisation

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

quark polarisation

hadron polarisation

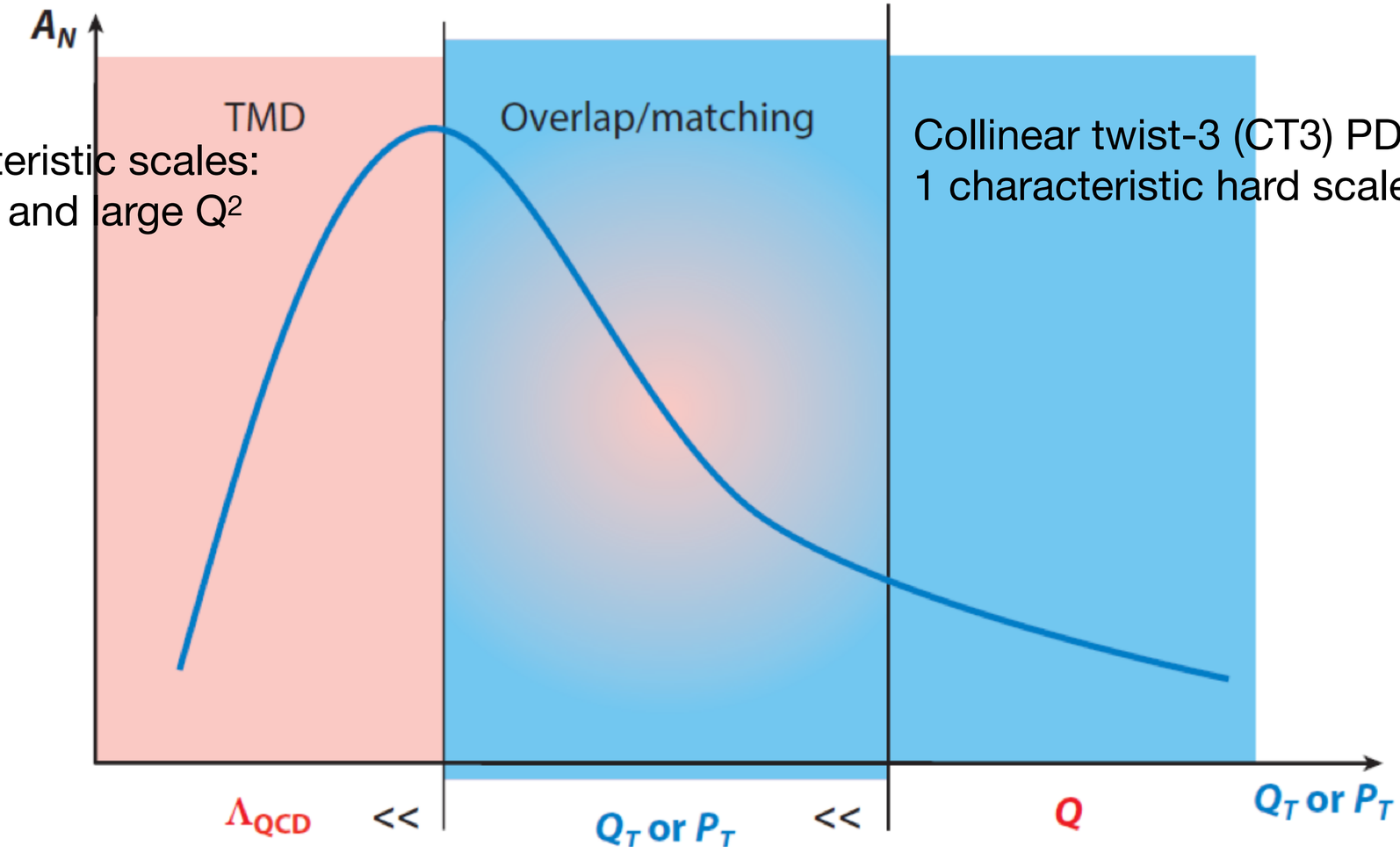
	U	L	T
U	D_1		$H_1^\perp$

chiral even x chiral even

chiral odd x chiral odd

Validity of TMD description

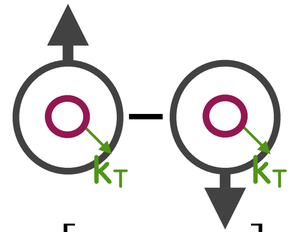
2 characteristic scales:
small P_{hT} and large Q^2



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

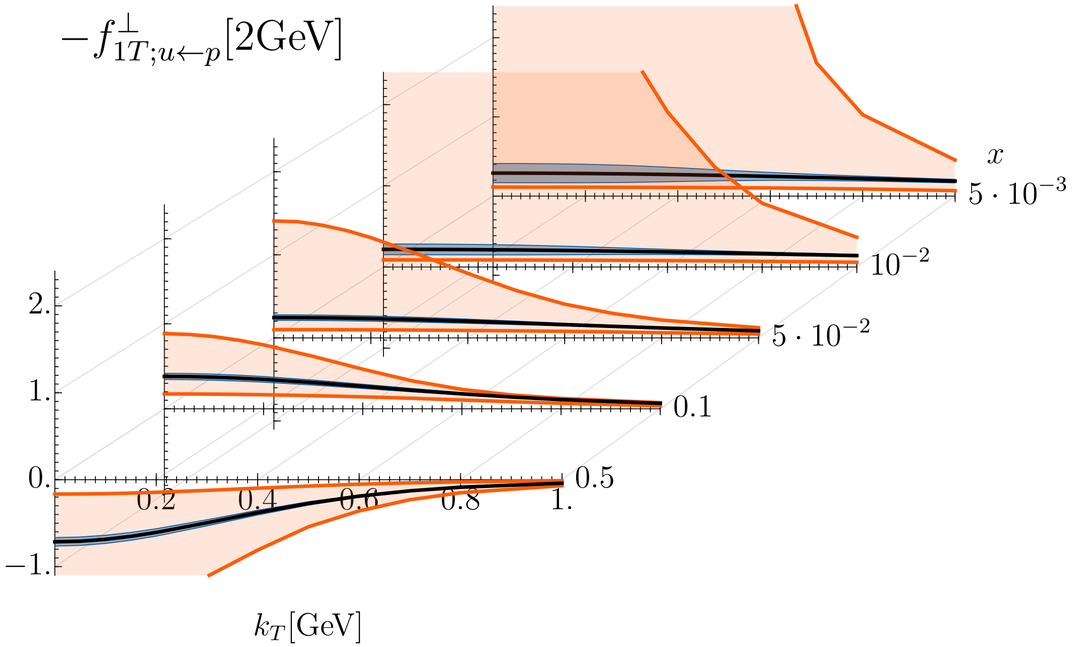
Consistent results for TMD
and CT3 in overlap region

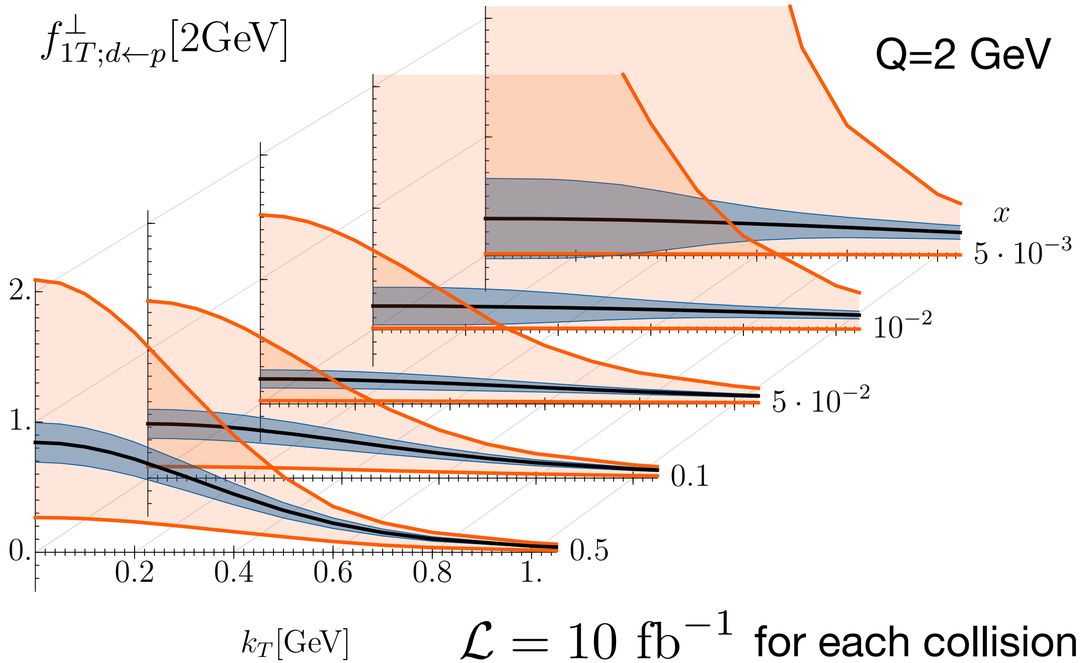
Impact of EIC on Sivers TMD PDFs



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

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





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

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

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

Fourier transform

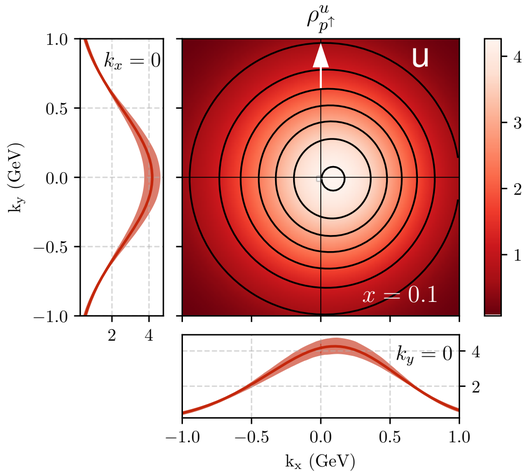
generalised parton distributions (GPDs)

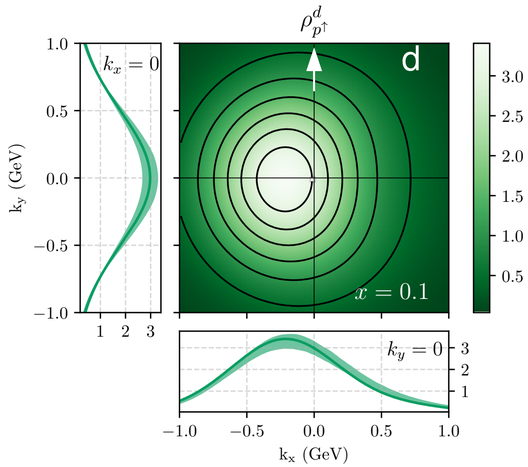
forward limit

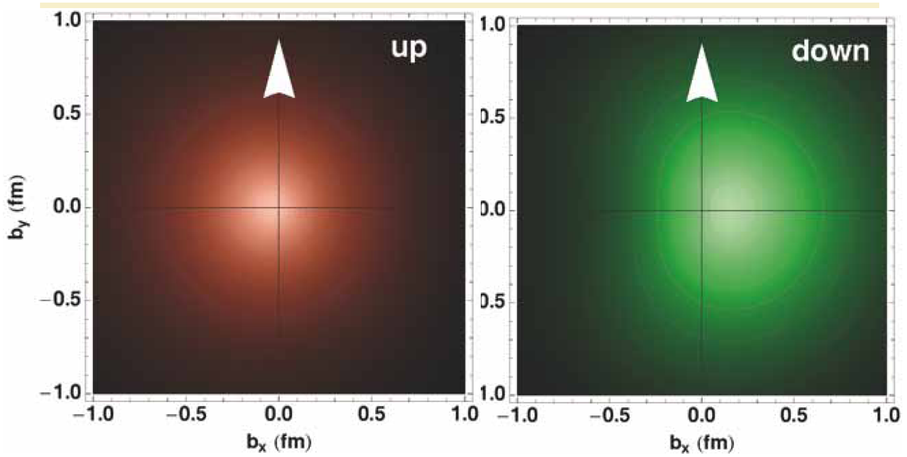
PDFs

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

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







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

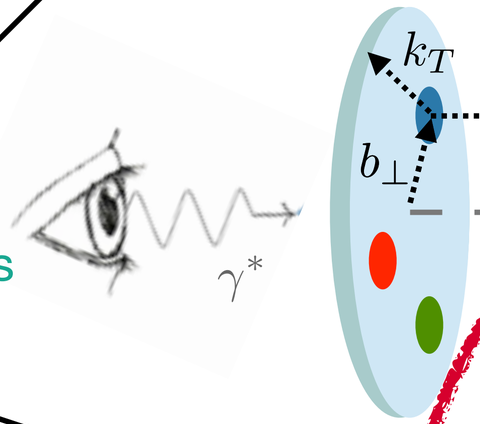
Fourier transform

generalised parton distributions (GPDs)

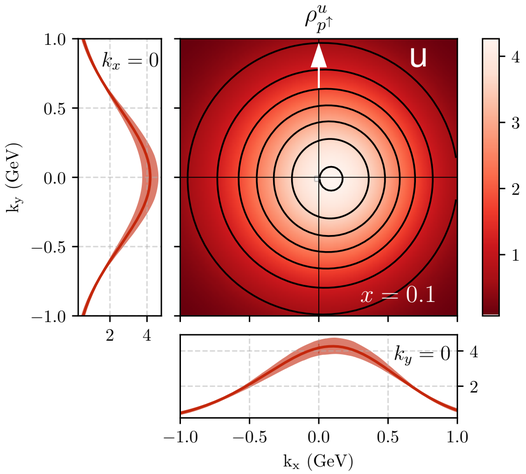
forward limit

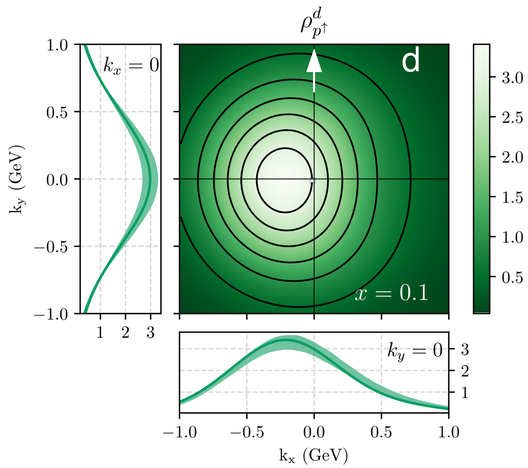
PDFs

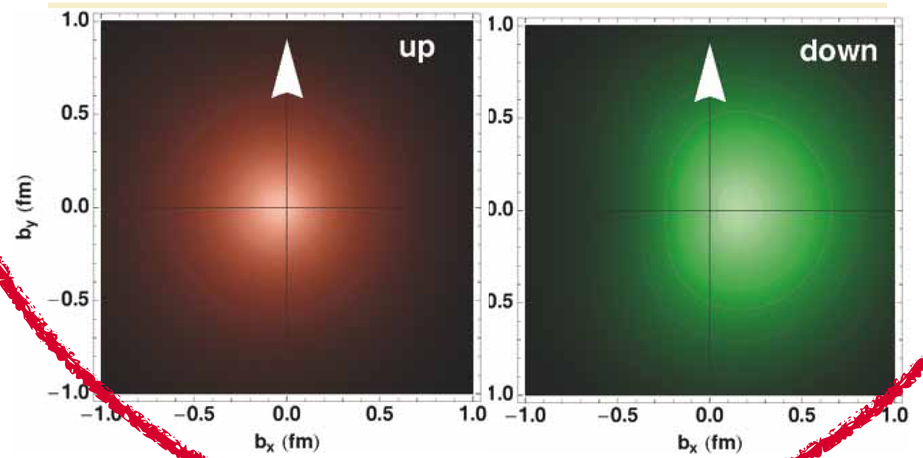
$\int d^2\vec{k}_T$



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

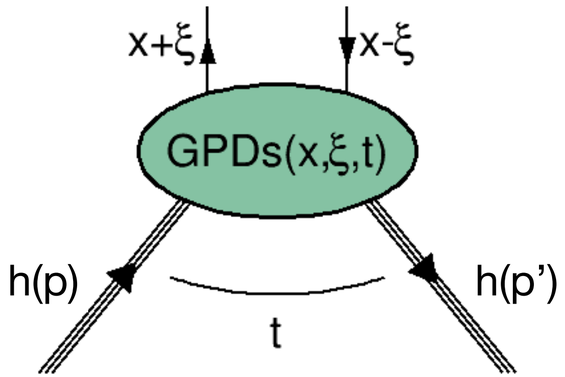






What are generalised parton distributions (GPDs)?

GPDs are probability <u>amplitudes</u>

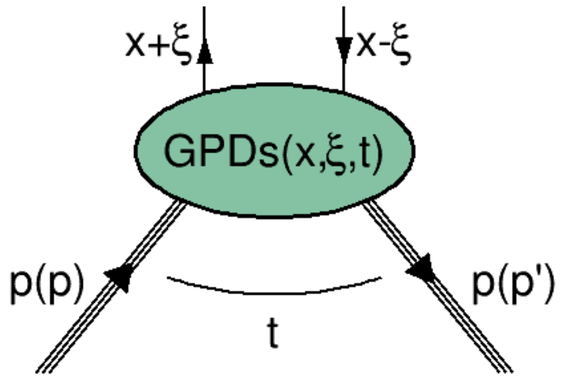


- x=average longitudinal momentum fraction
- 2ξ=longitudinal momentum transfer
- t=squared momentum transfer to hadron

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

What are generalised parton distributions (GPDs)?

GPDs are probability <u>amplitudes</u>



- 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

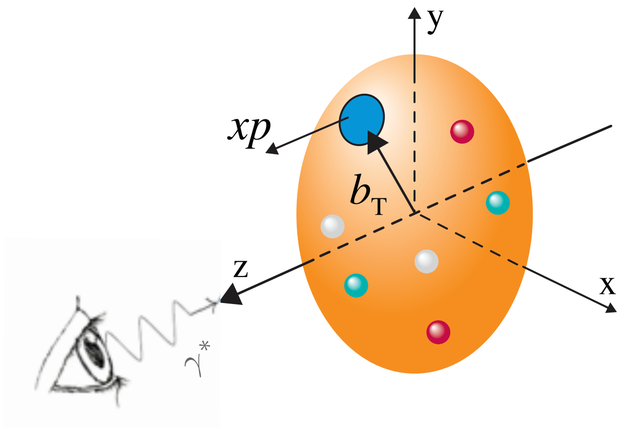
$H(x,\xi,t)$	$E(x,\xi,t)$	parton-spin independent
$\tilde{H}(x,\xi,t)$	$\tilde{E}(x,\xi,t)$	parton-spin dependent
proton helicity non flip	proton helicity flip	

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

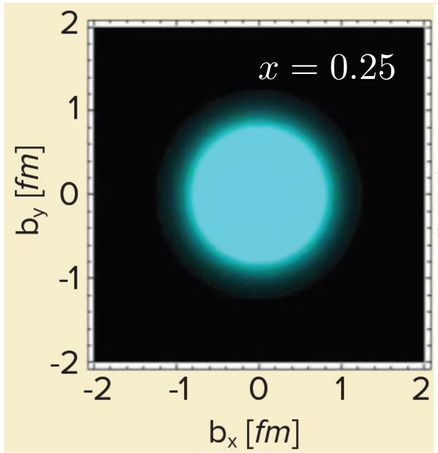


M. Burkardt, PRD **92** ('00) 071503
Int. J. Mod Phys. A **18** ('03) 173

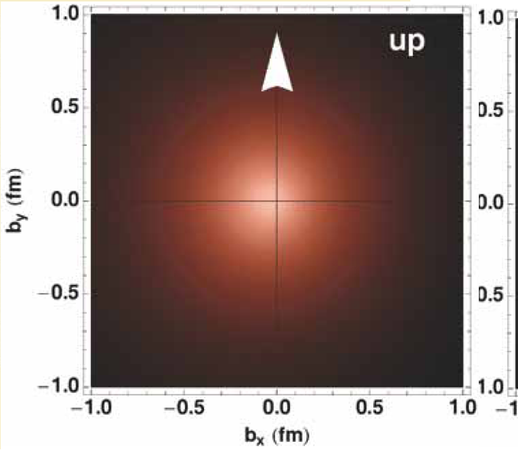
impact-parameter dependent distributions:
probability to find parton (x,b_T)

↑ Fourier transform for ξ=0

GPDs



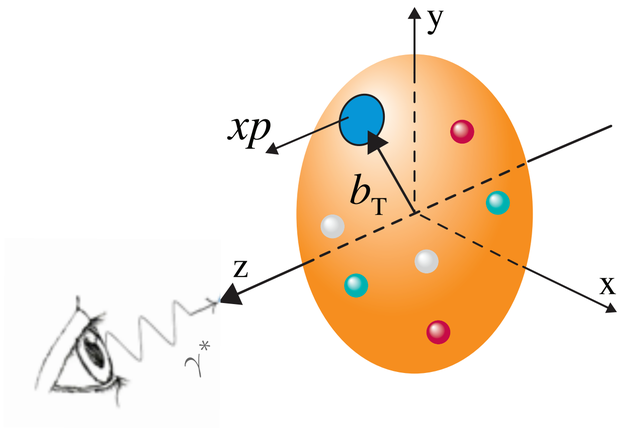
GPD H



GPDs H+E

What GPDs tell us about the nucleon

- 3D parton distributions

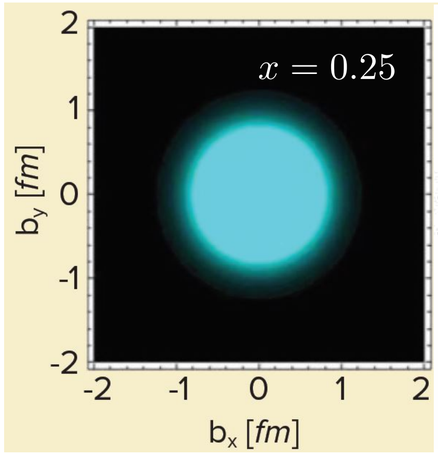


M. Burkardt, PRD **92** ('00) 071503
Int. J. Mod Phys. A **18** ('03) 173

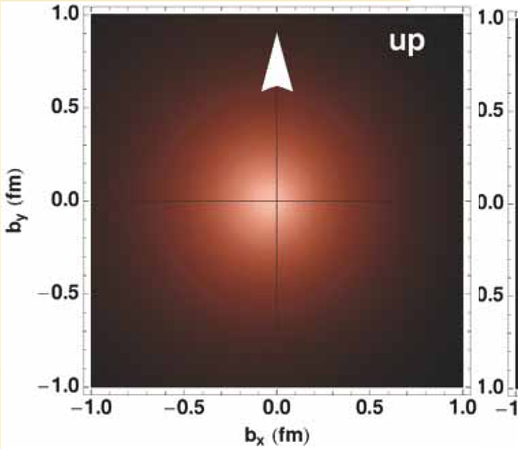
impact-parameter dependent distributions:
probability to find parton (x,b_T)

↑ Fourier transform for ξ=0

GPDs



GPD H



GPDs H+E

- pressure distributions

GPDs

↓ $\int dx\, x$

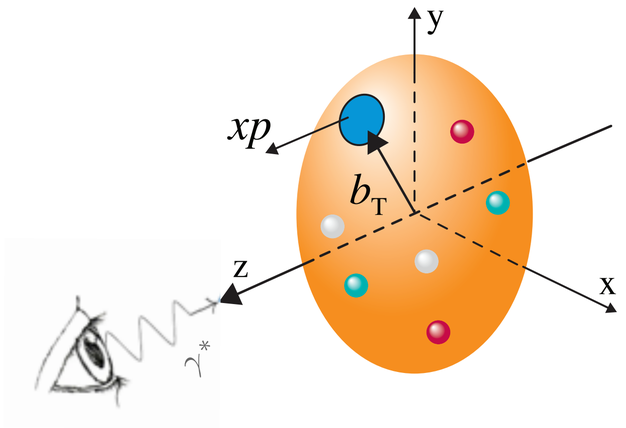
gravitational form factors

↓ Fourier transform

pressure distributions

What GPDs tell us about the nucleon

- 3D parton distributions

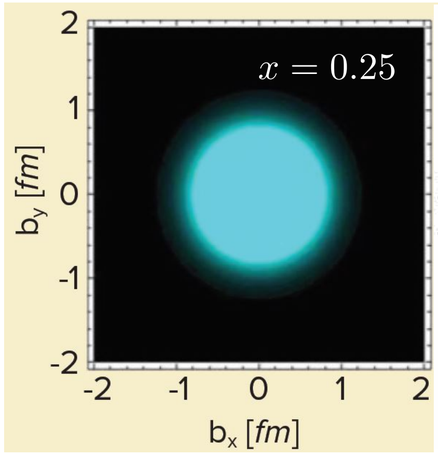


M. Burkardt, PRD **92** ('00) 071503
Int. J. Mod Phys. A **18** ('03) 173

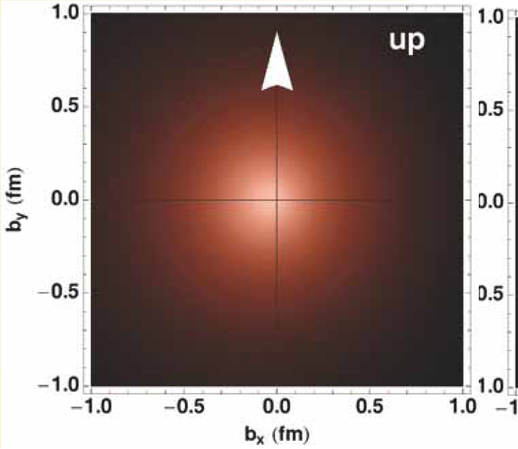
impact-parameter dependent distributions:
probability to find parton (x,b_T)

↑ Fourier transform for ξ=0

GPDs



GPD H



GPDs H+E

- pressure distributions

GPDs

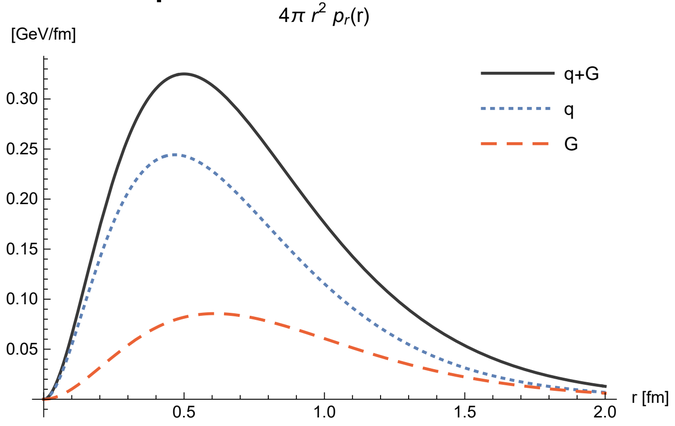
↓ $\int dx\, x$

gravitational form factors

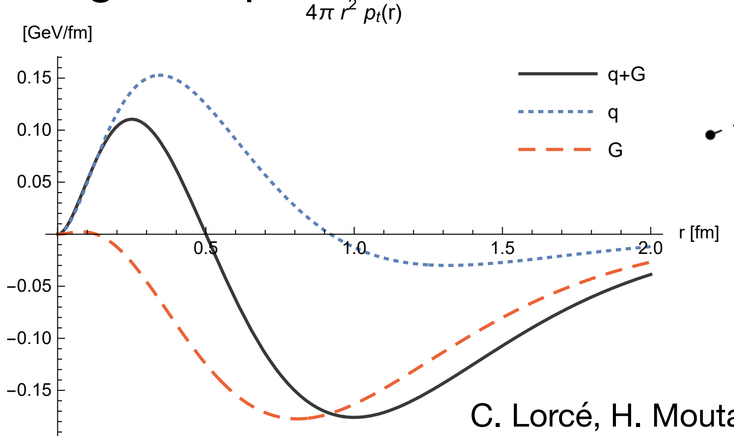
↓ Fourier transform

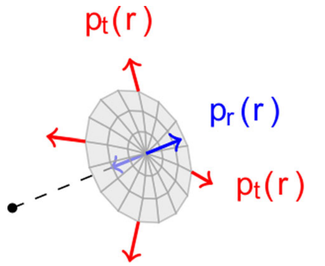
pressure distributions

radial pressure



tangential pressure

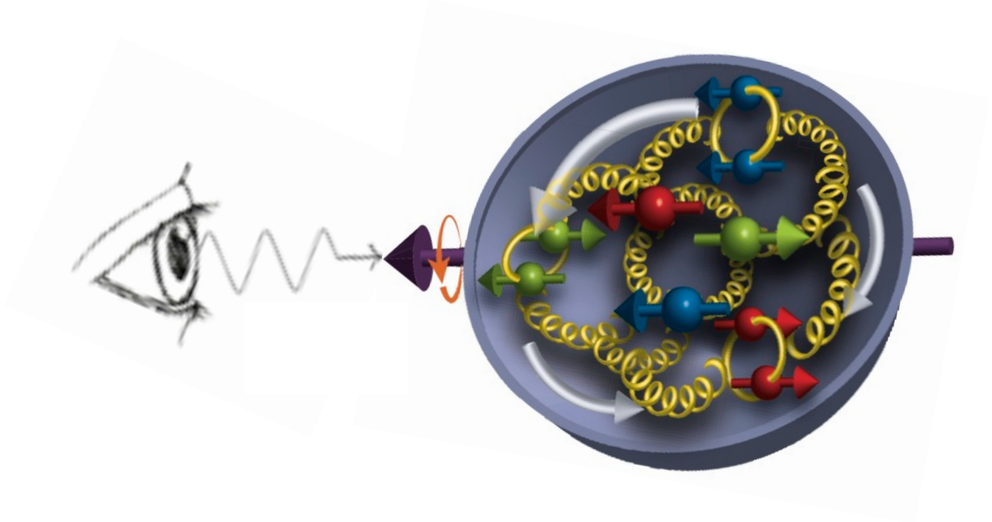




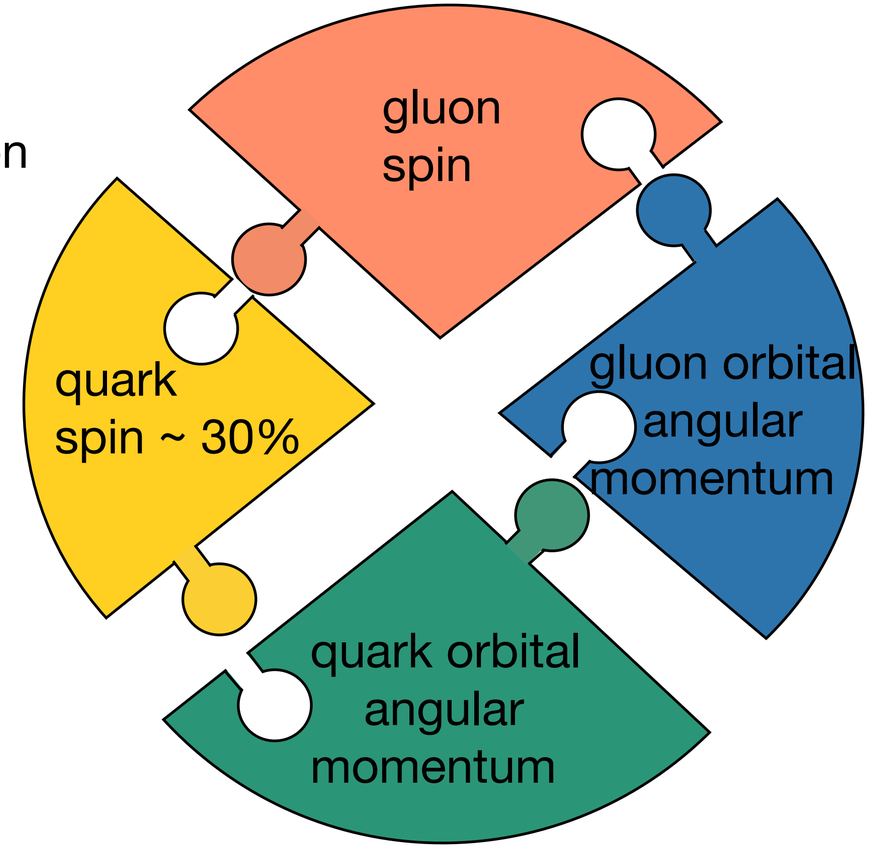
C. Lorcé, H. Moutarde, A. P. Trawiński
Eur. Phys. J. C **79** ('19) 89

… and its spin

longitudinally polarised nucleon

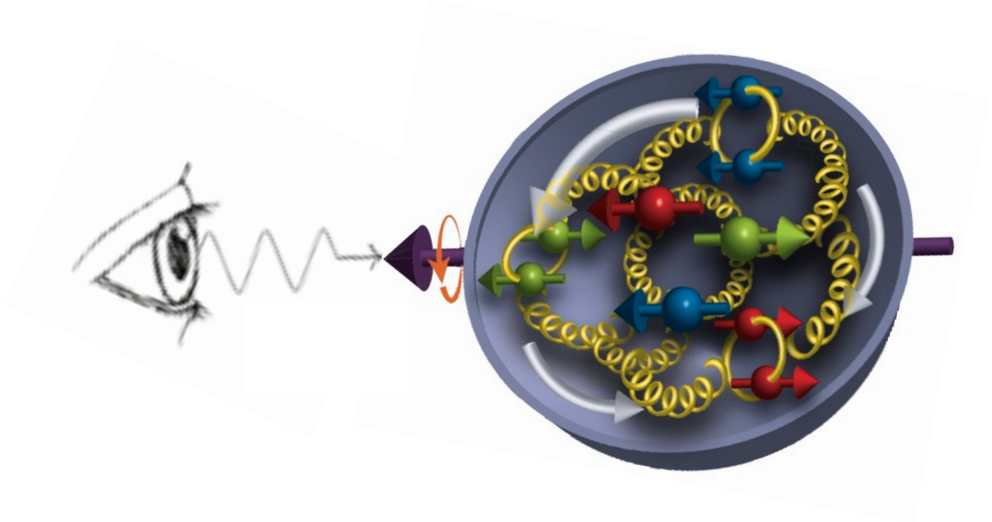


proton spin
decomposition

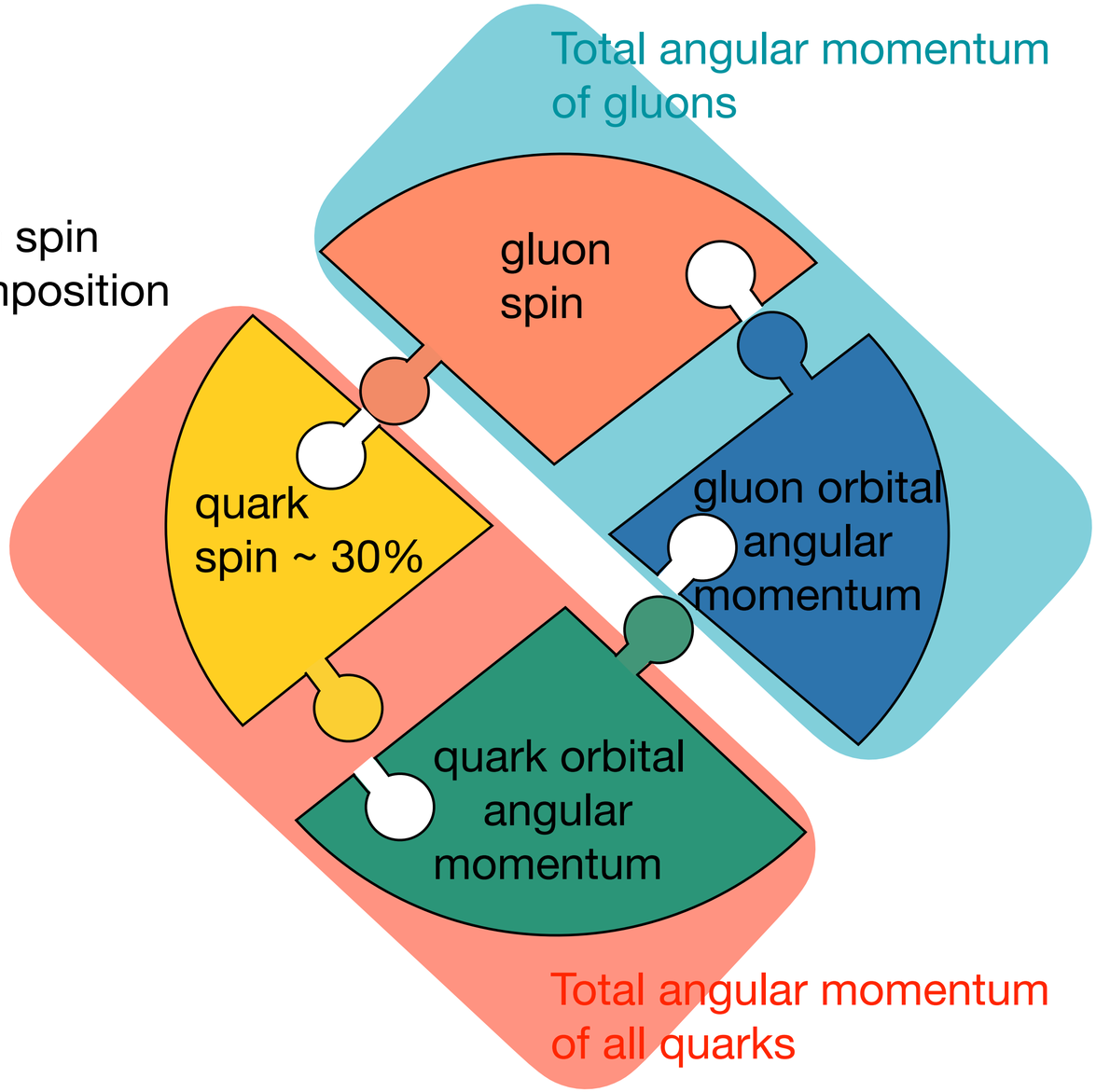


… and its spin

longitudinally polarised nucleon

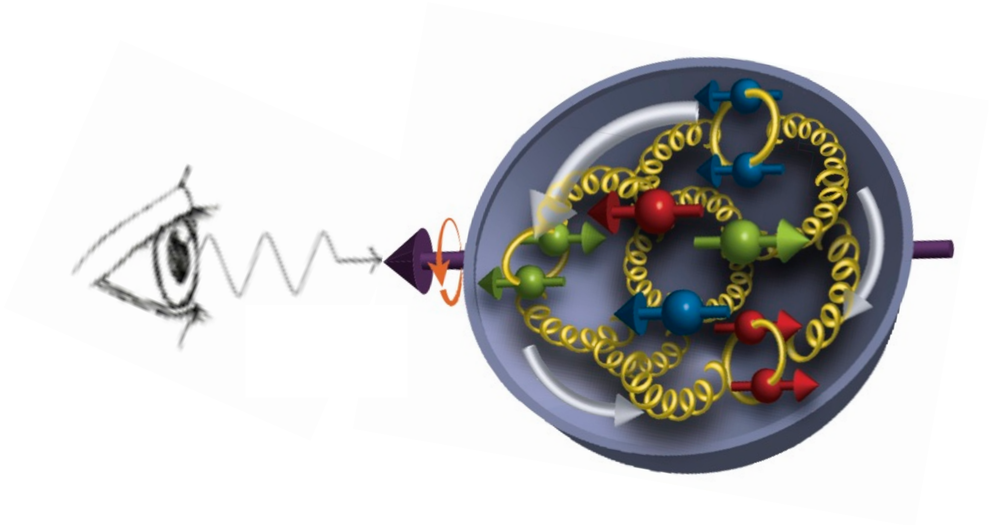


proton spin decomposition

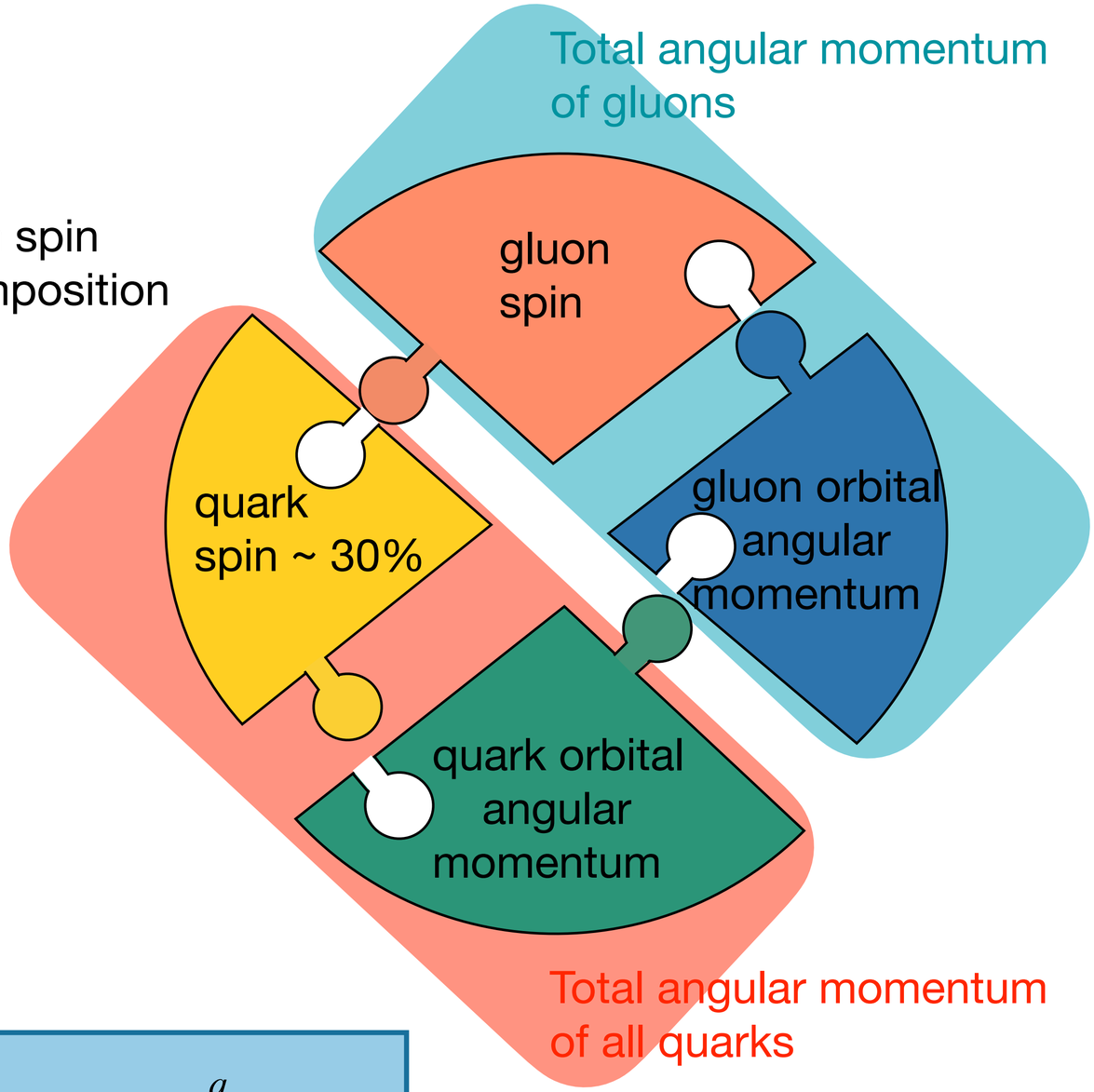


… and its spin

longitudinally polarised nucleon



proton spin decomposition

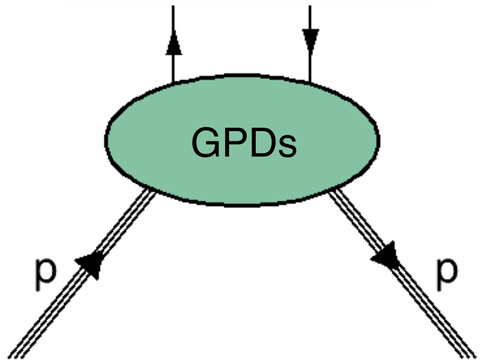


Ji relation

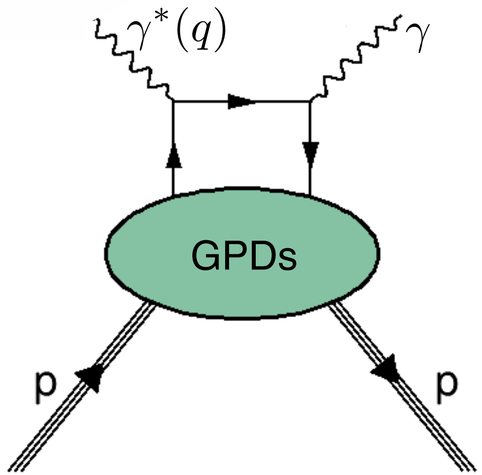
$$J^q = \lim_{t\to 0} \frac{1}{2} \int_{-1}^{1} dx\, x\, [H^q(x,\xi,t) + E^q(x,\xi,t)]$$

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

Experimental access to GPDs

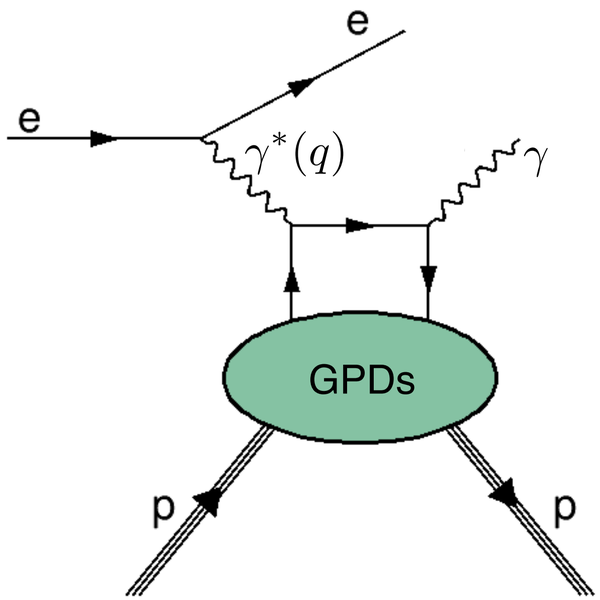


Experimental access to GPDs



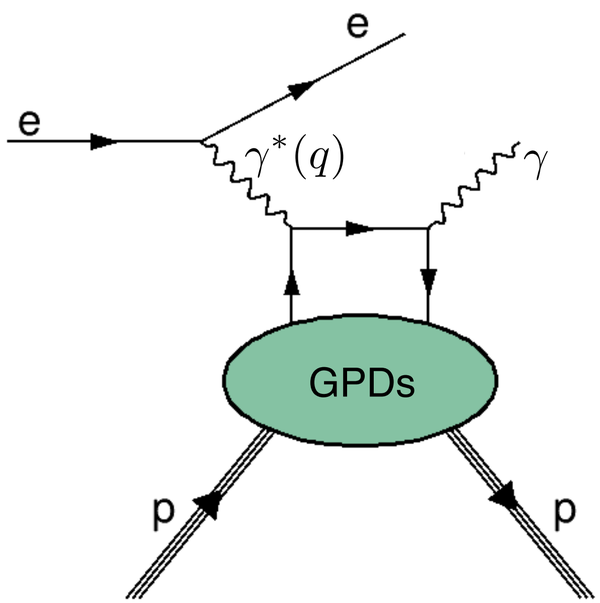
Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$

Experimental access to GPDs

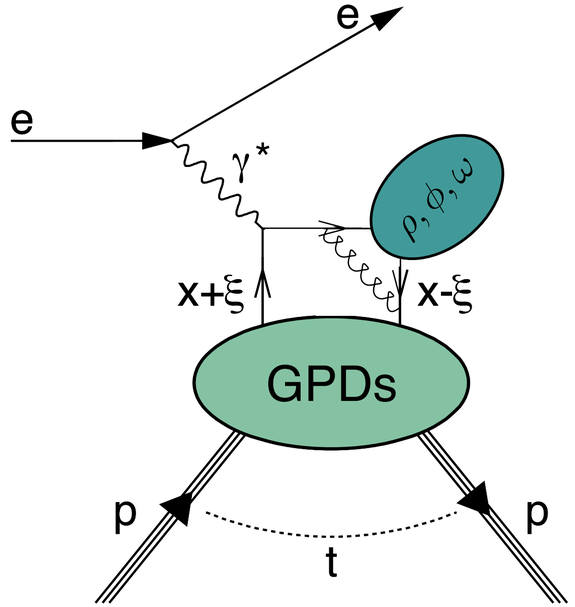


Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$

Experimental access to GPDs

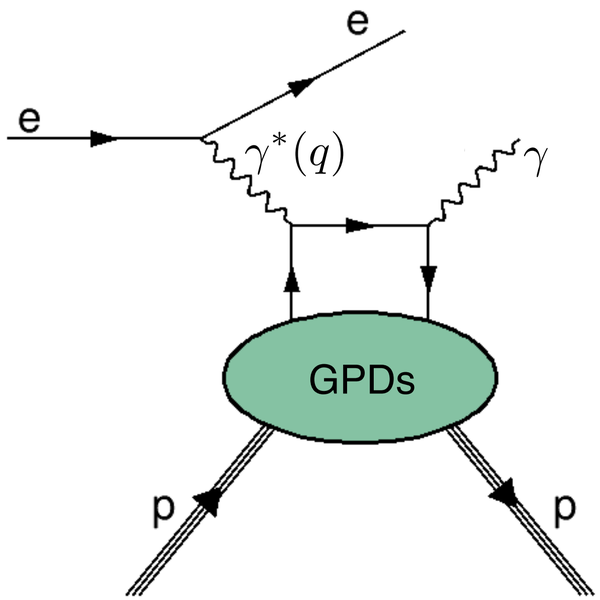


Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$

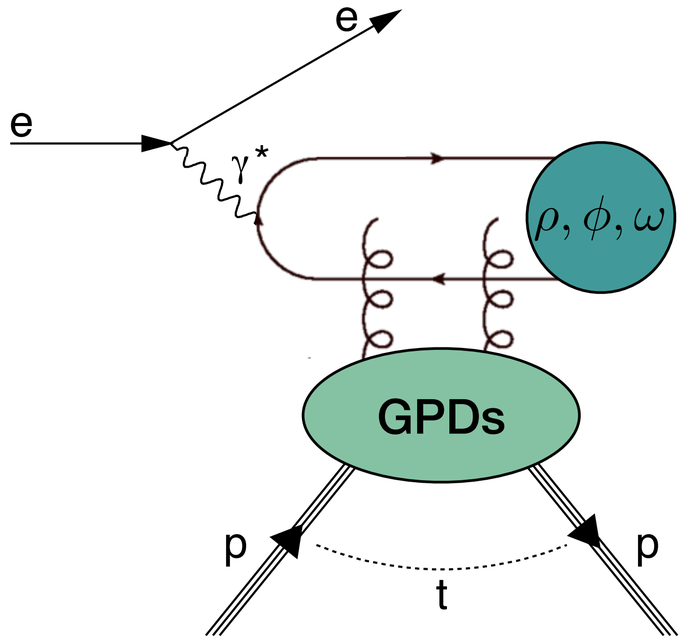


Hard exclusive meson production
Hard scale=large Q^2

Experimental access to GPDs

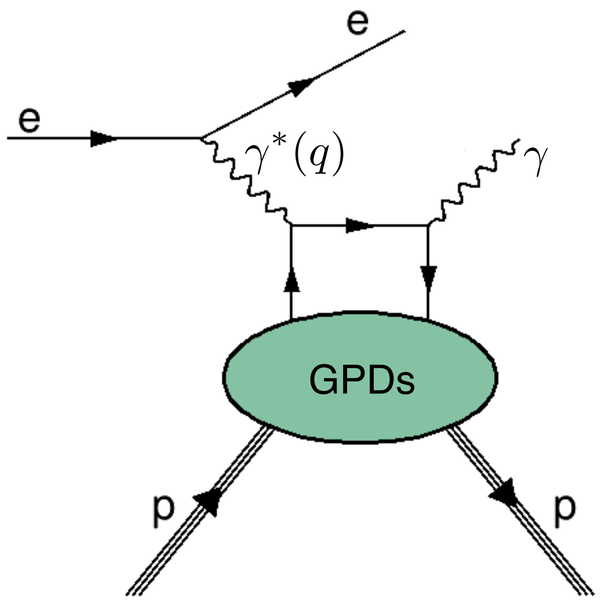


Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$

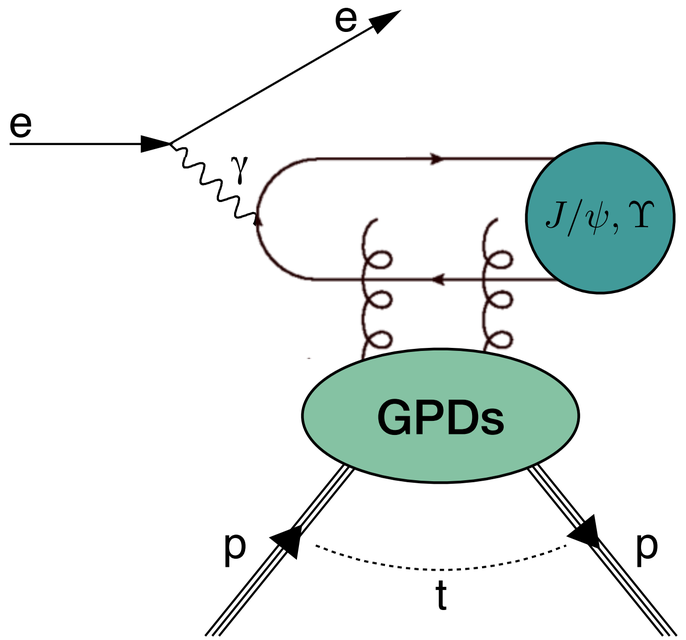


Hard exclusive meson production
Hard scale=large Q^2

Experimental access to GPDs

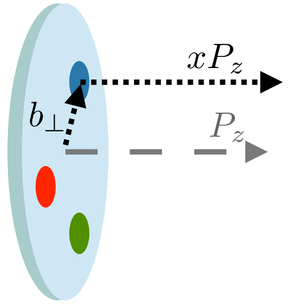


Deeply virtual Compton scattering (DVCS)
Hard scale=large $Q^2=-q^2$



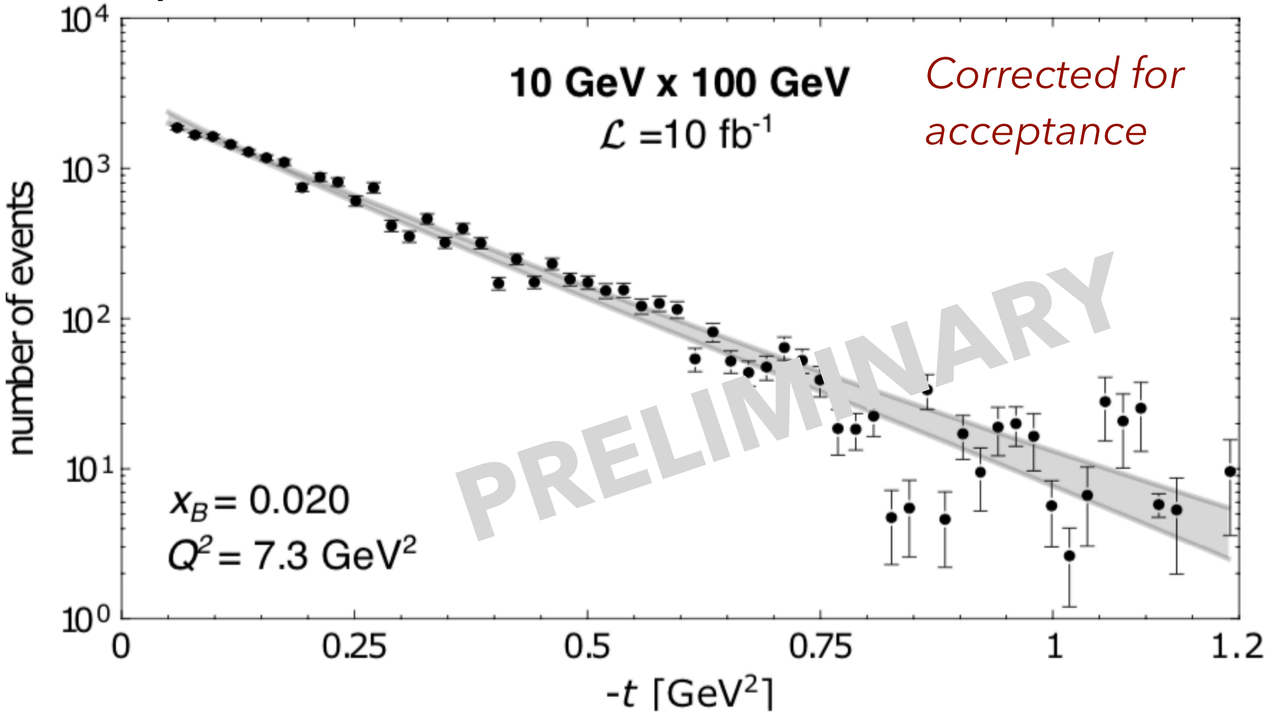
Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass

Exclusive measurements on p with the EIC

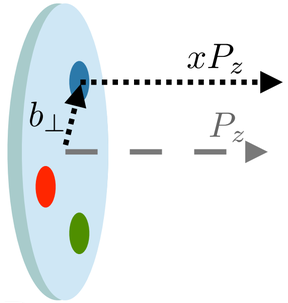


Deeply virtual Compton scattering
→ sensitive to quarks (and gluons)

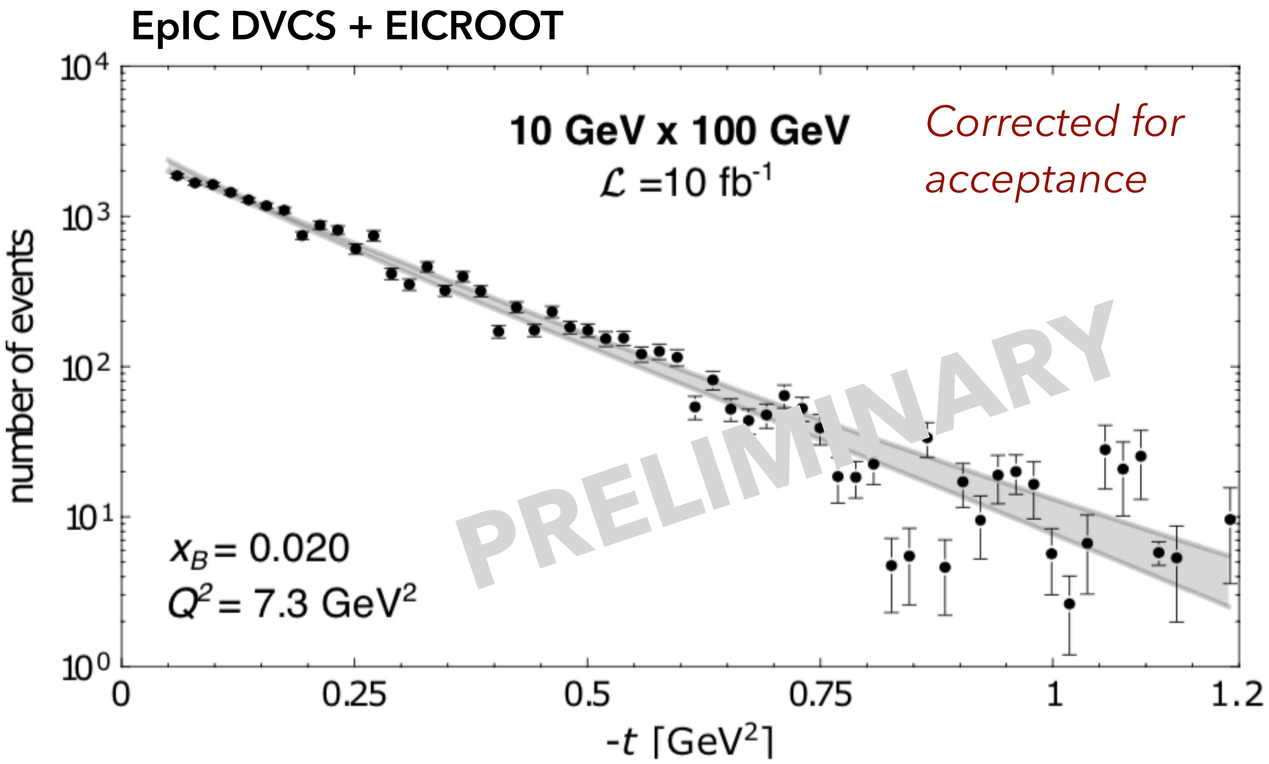
EpIC DVCS + EICROOT



Exclusive measurements on p with the EIC

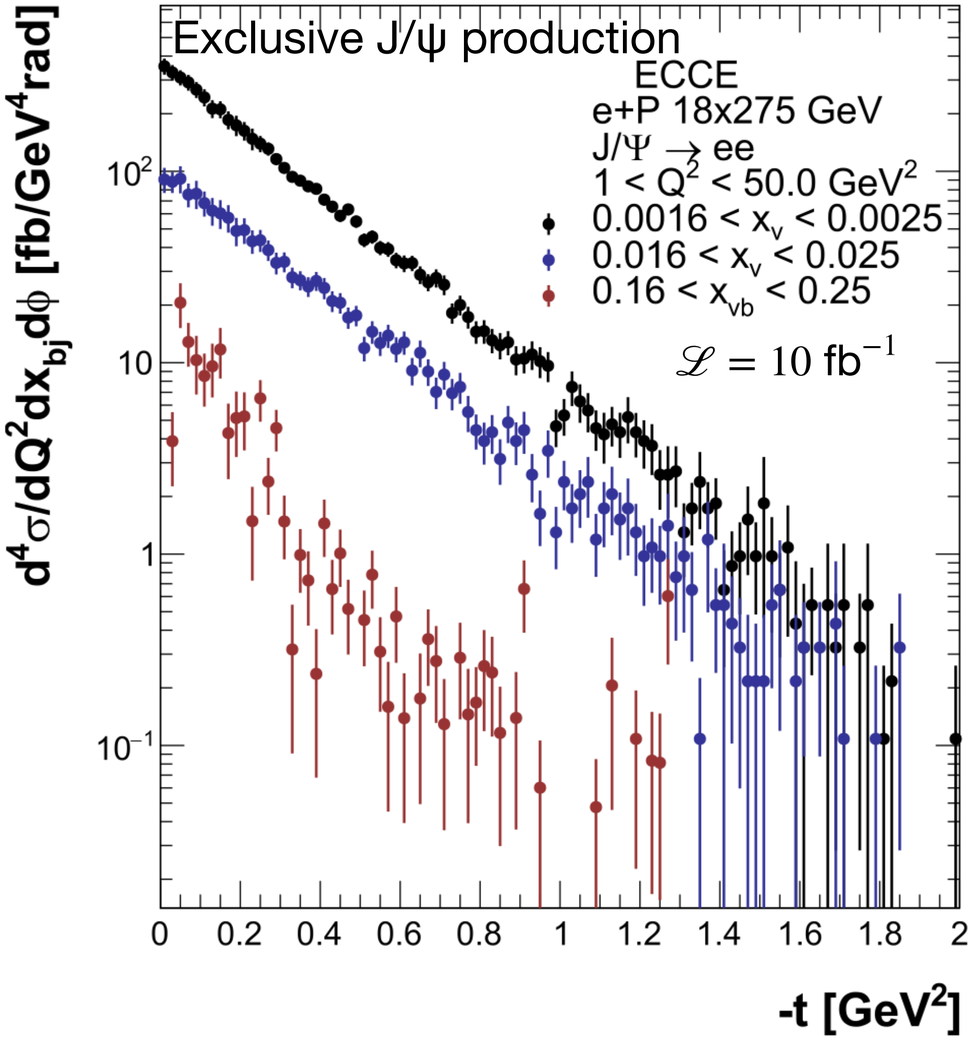


Deeply virtual Compton scattering
→ sensitive to quarks (and gluons)

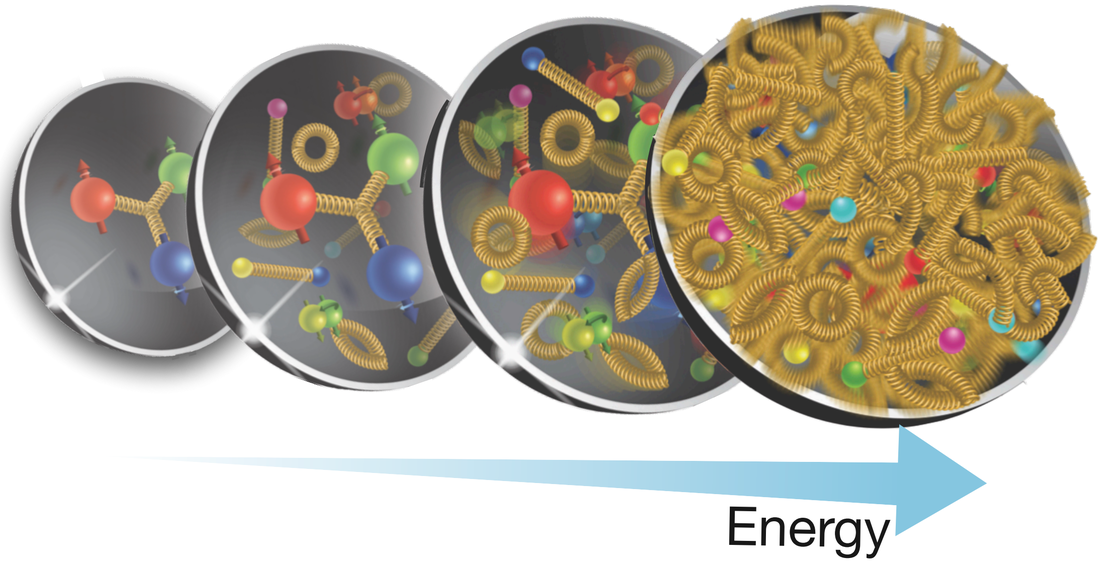


Exclusive J/ψ production
→ excellent to probe gluon GPDs

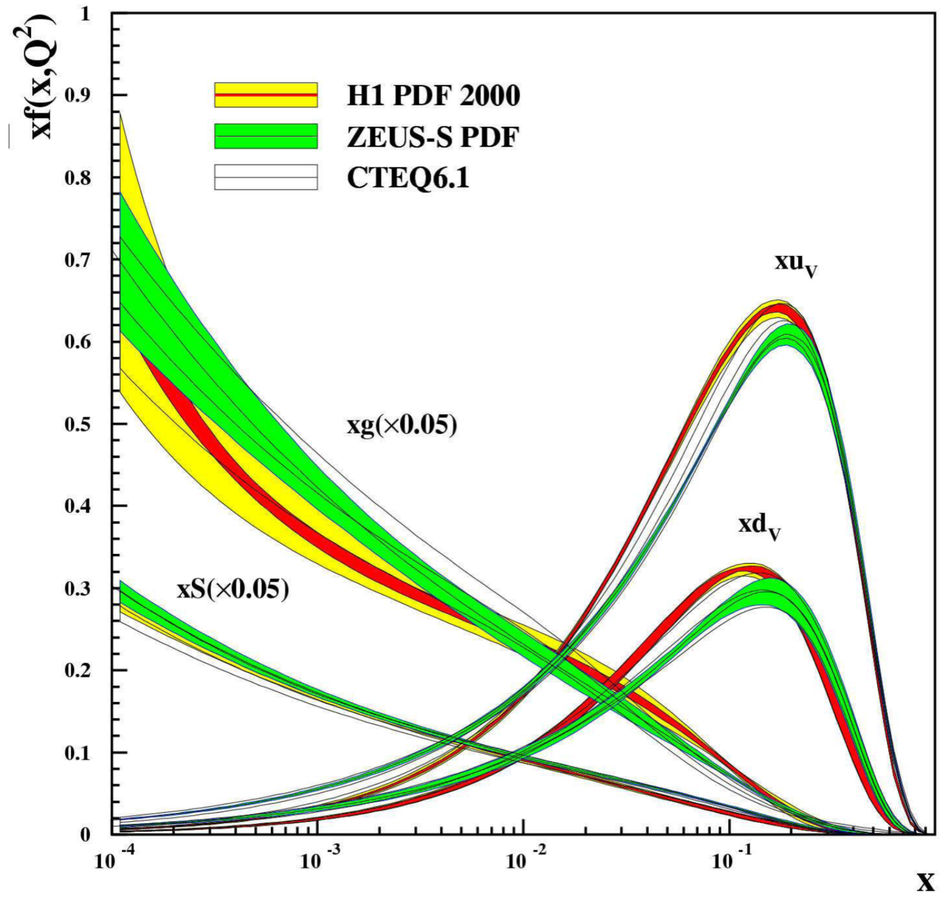
ECCE, NIMA **1052** (2023) 168238



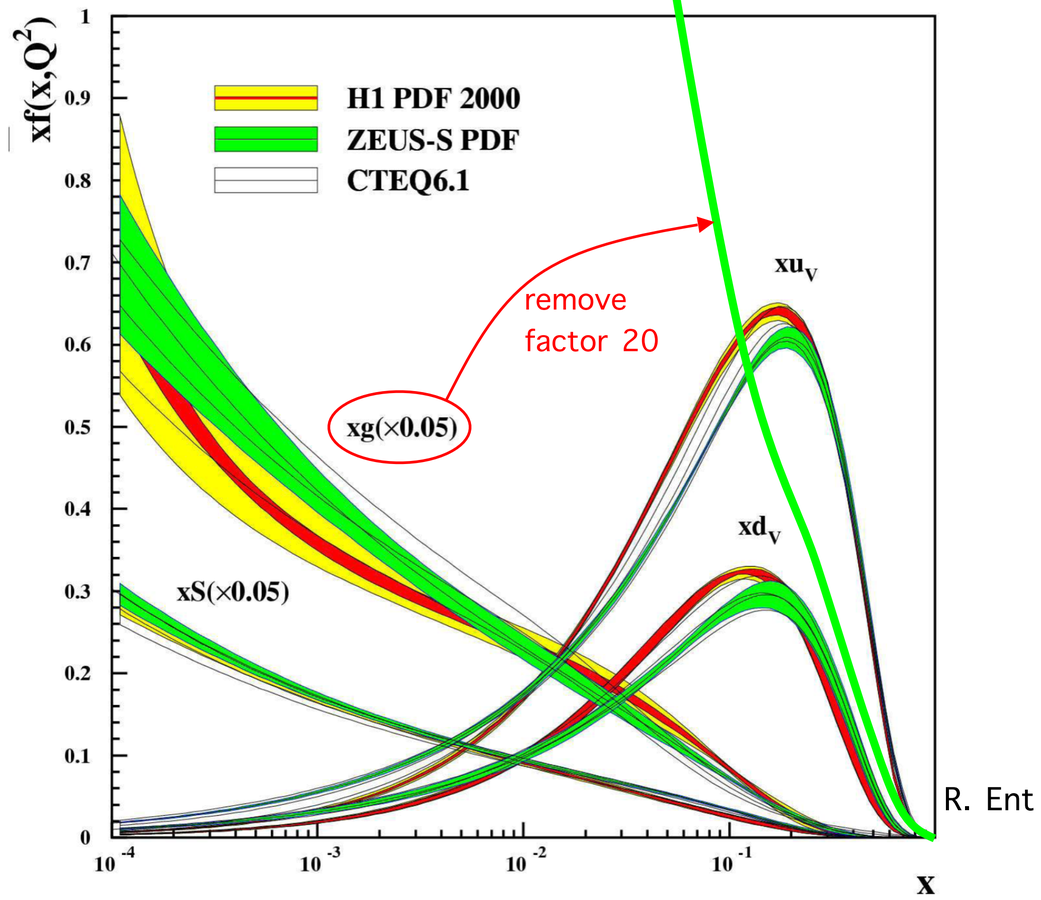
Gluon saturation



Spin-independent parton distributions

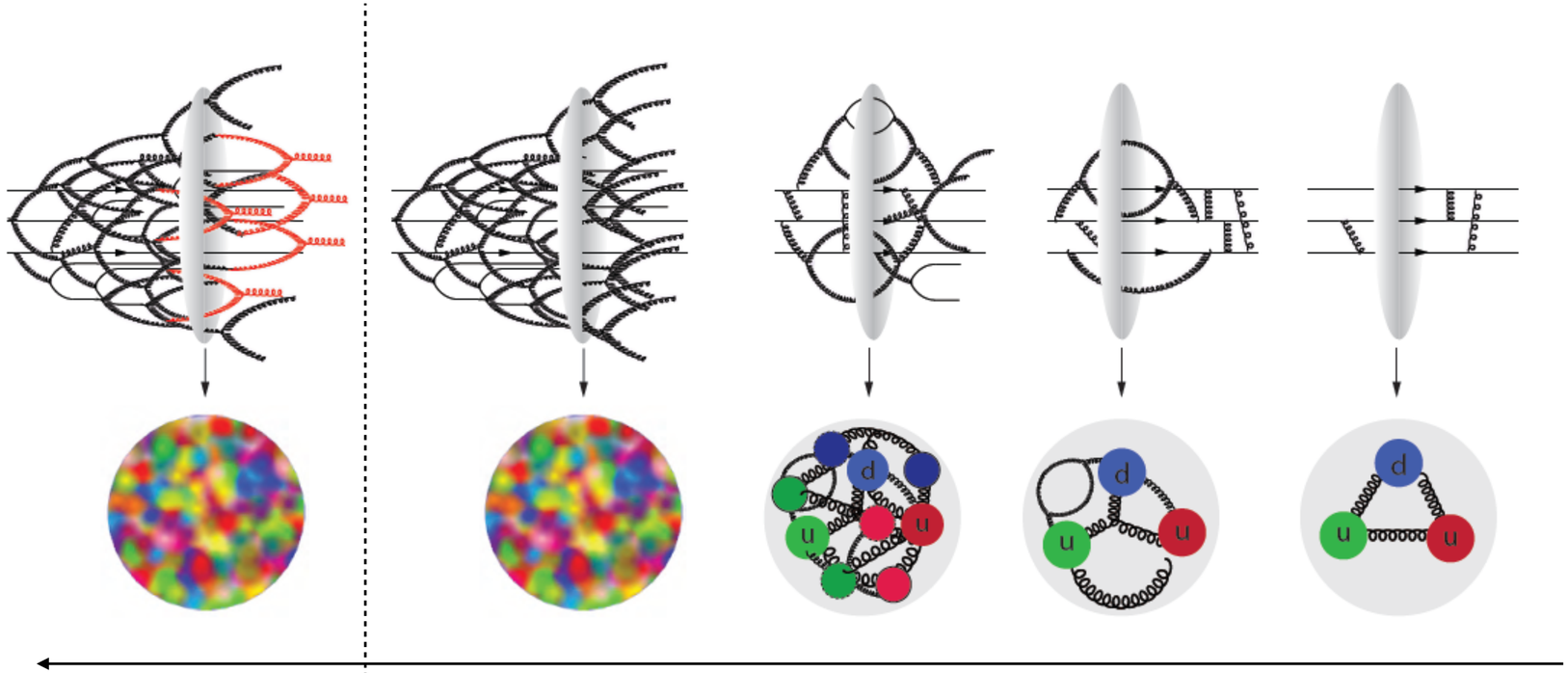


Spin-independent parton distributions

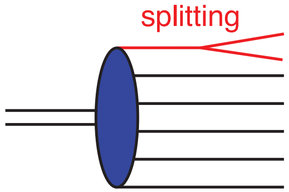


R. Ent

Gluon splitting and recombination

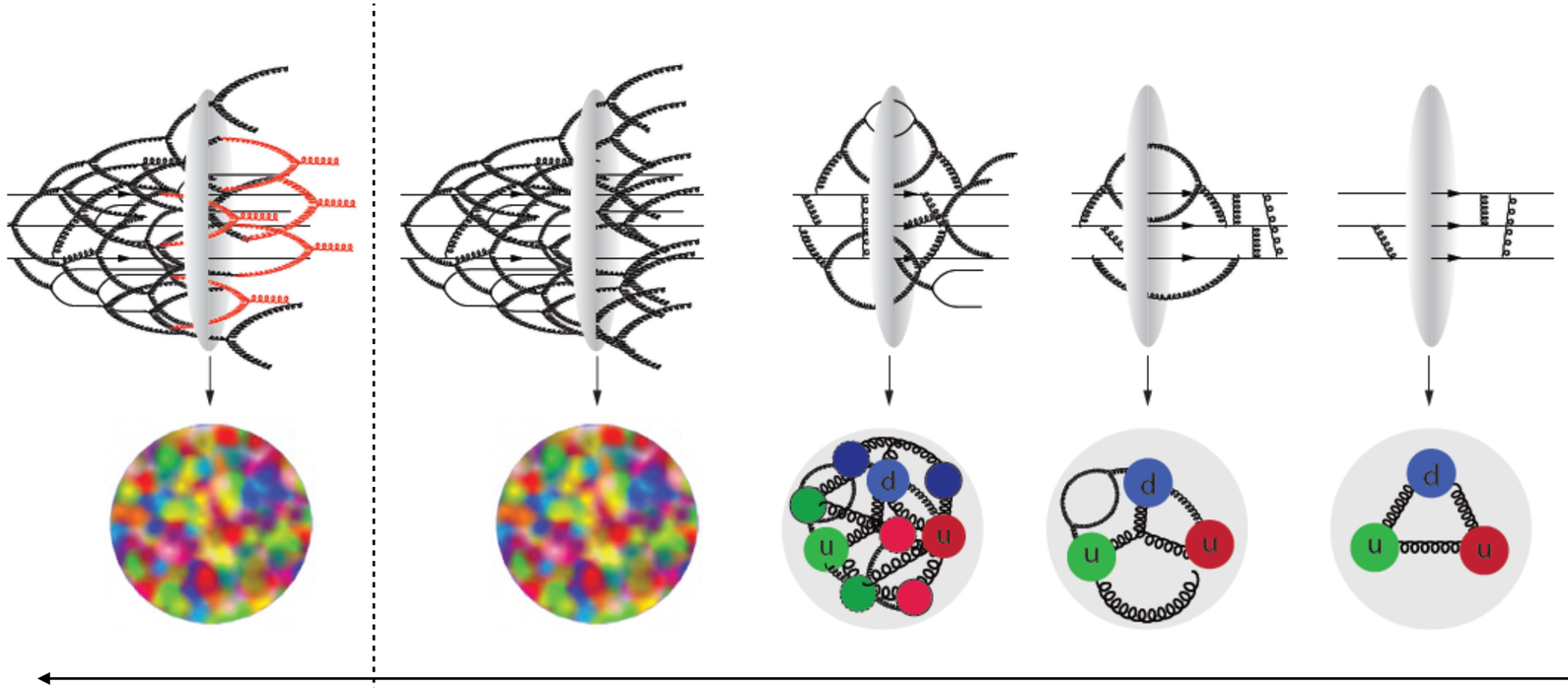


ln(1/x)



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

Gluon splitting and recombination



ln(1/x)

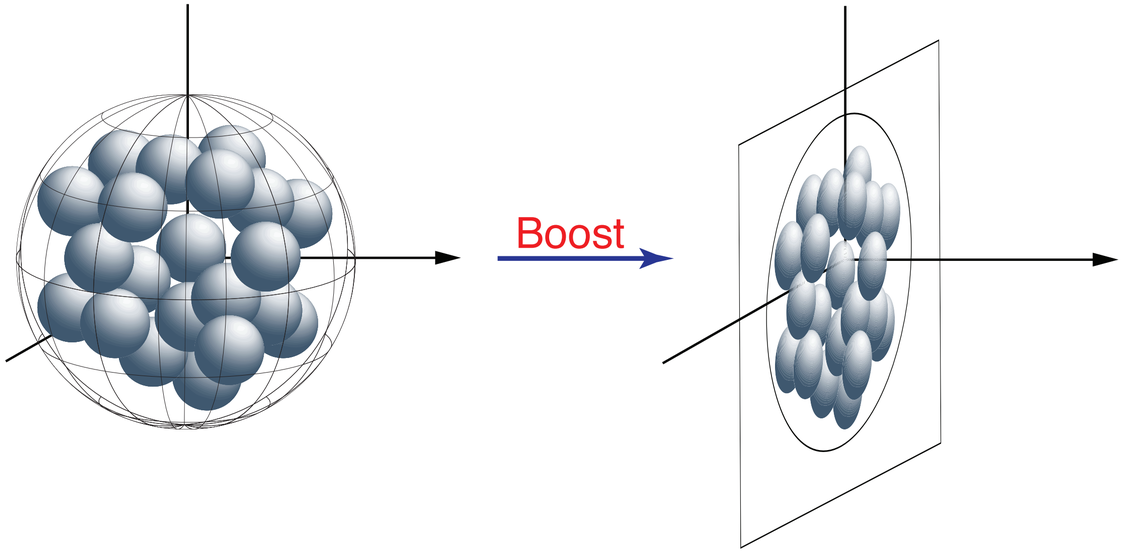
recombination

splitting

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

saturation

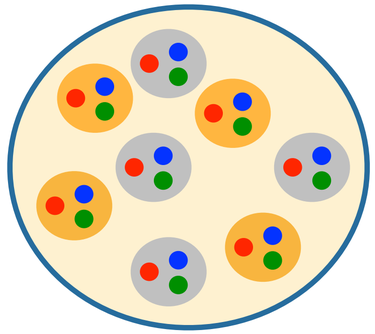
The Oomph factor



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

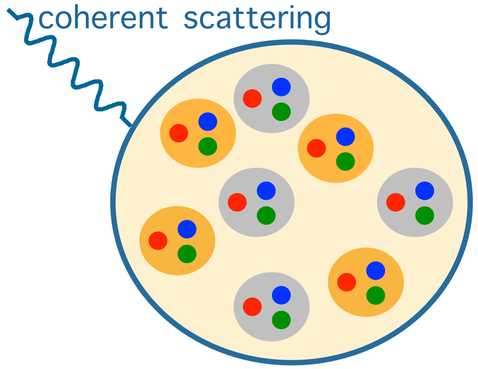
Exclusive/diffractive measurements on nuclei

What object are we probing?



Exclusive/diffractive measurements on nuclei

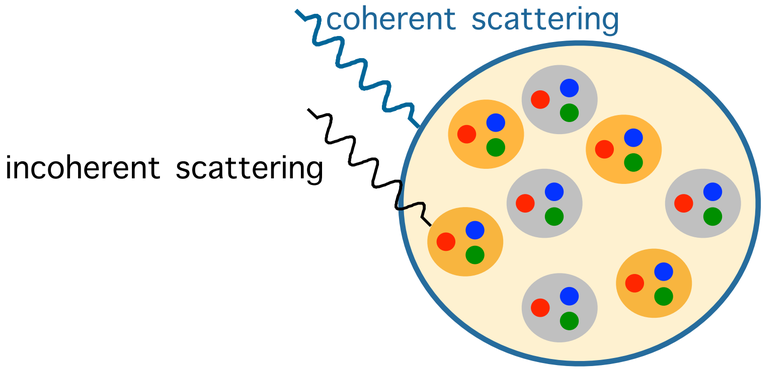
What object are we probing?



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

Exclusive/diffractive measurements on nuclei

What object are we probing?

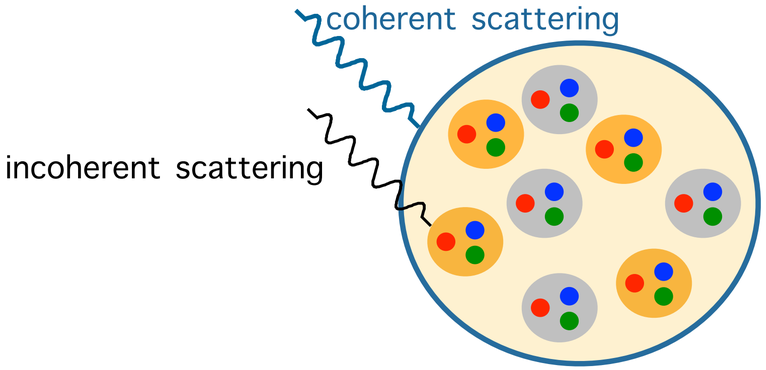


Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

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

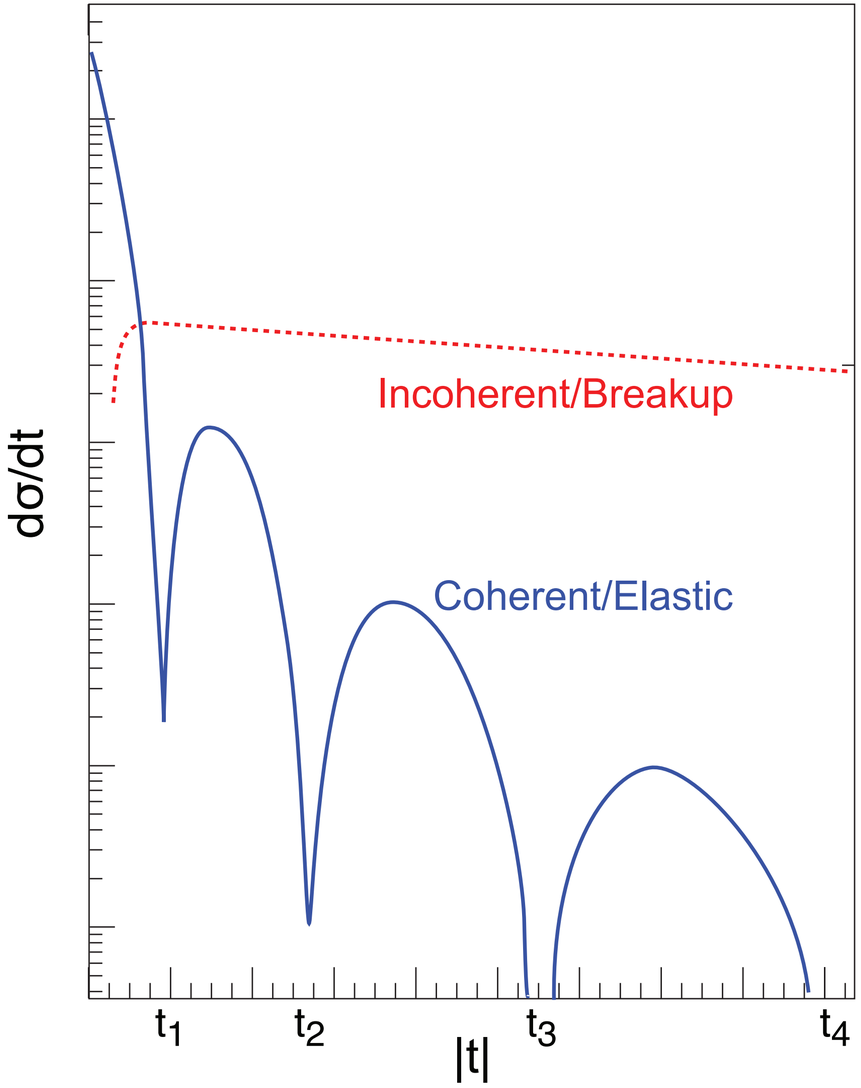
Exclusive/diffractive measurements on nuclei

What object are we probing?

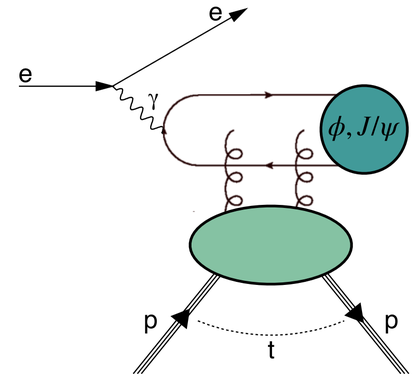


Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

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



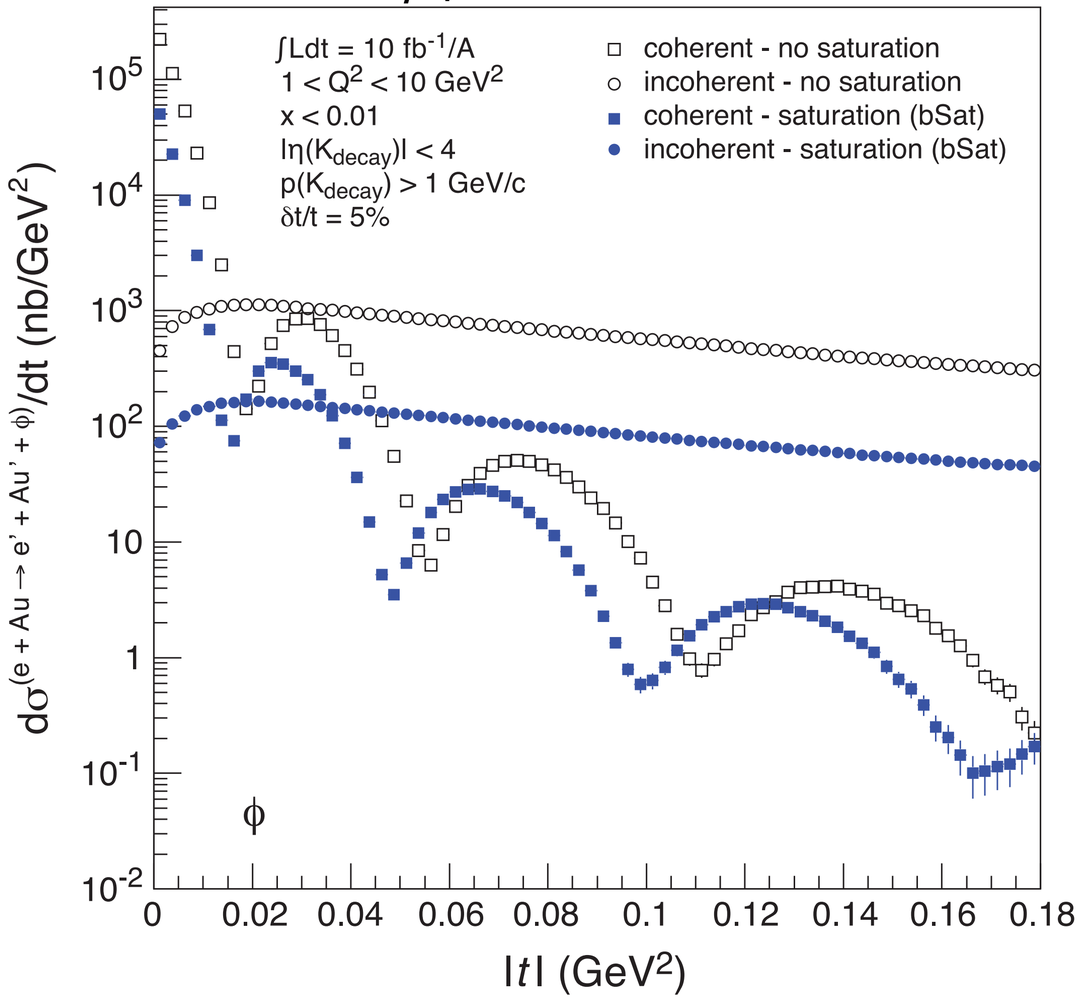
Diffractive measurements and saturation

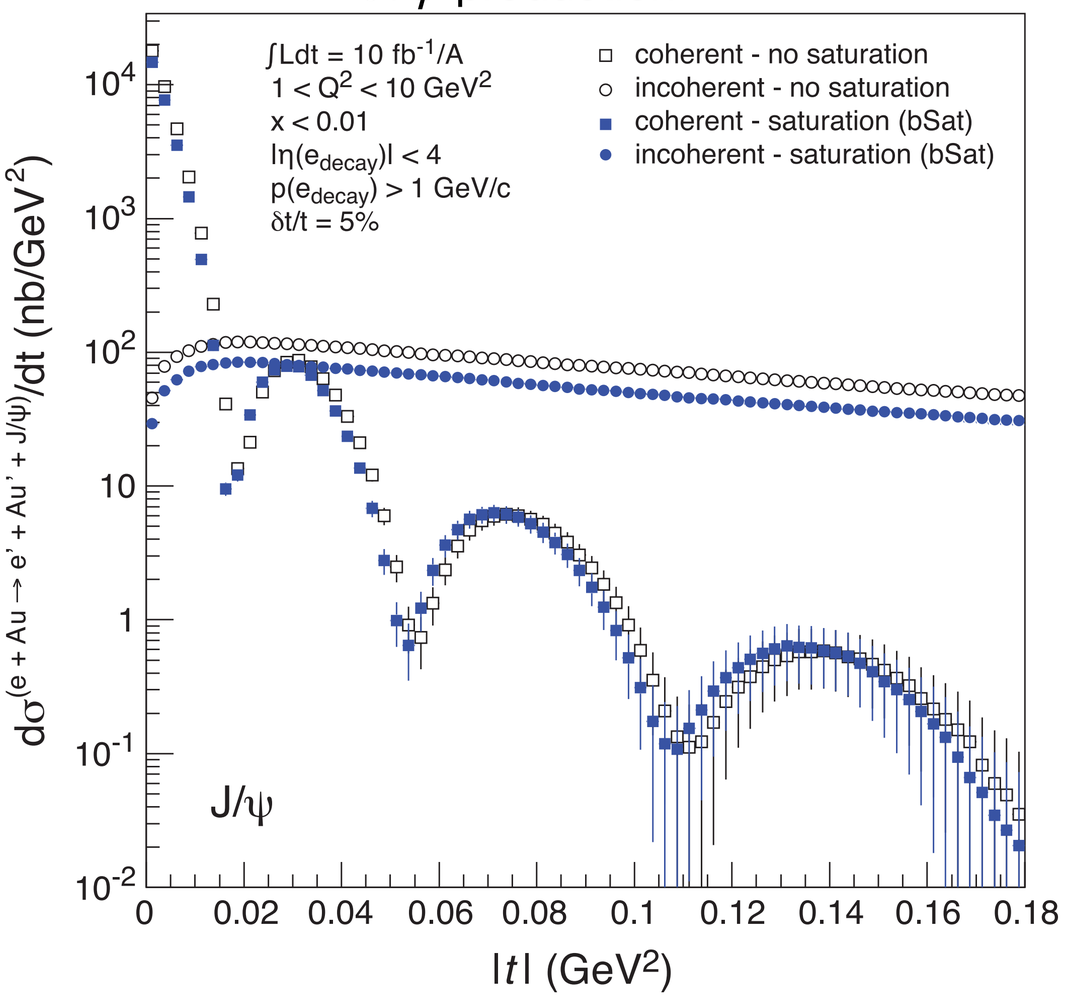


ϕ production

A. Accardi et al., arXiv:1212.1701

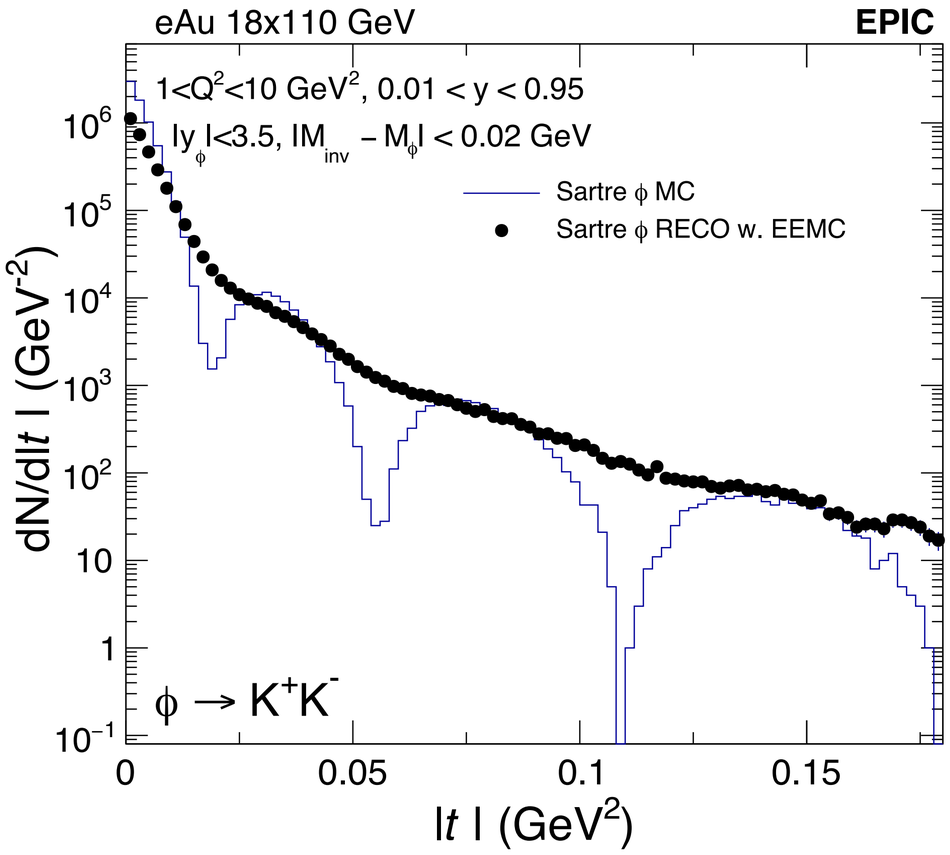
J/ψ production





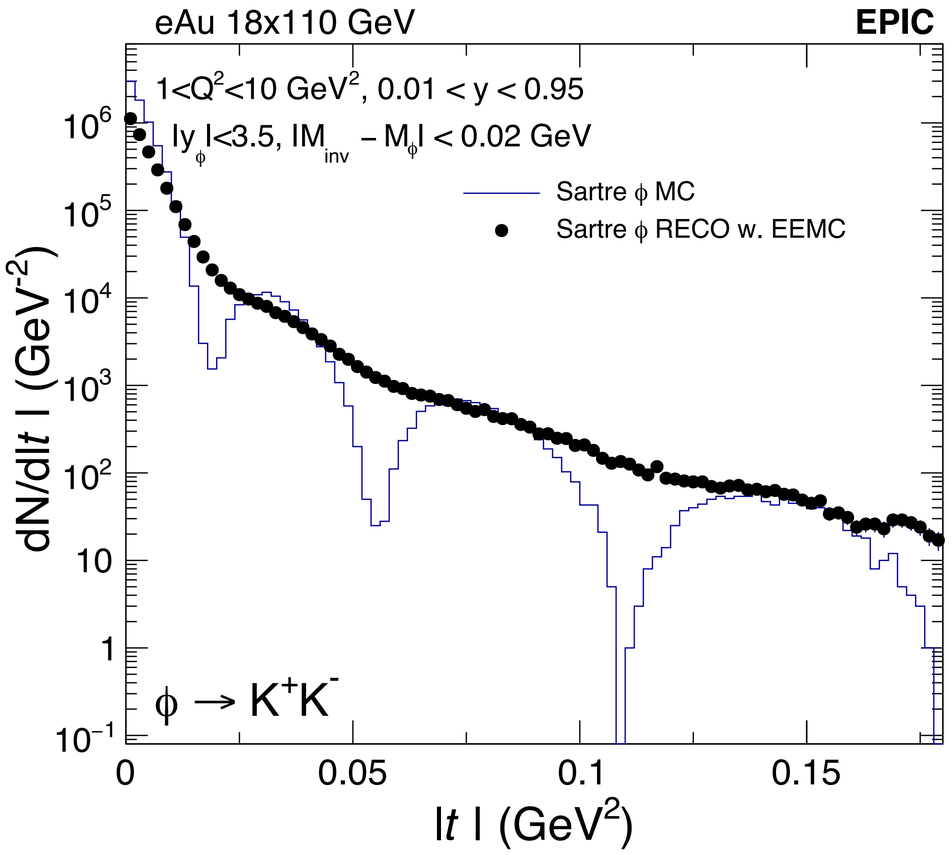
Exclusive measurements on nuclear targets with the EIC

Reconstruction of the coherent signal

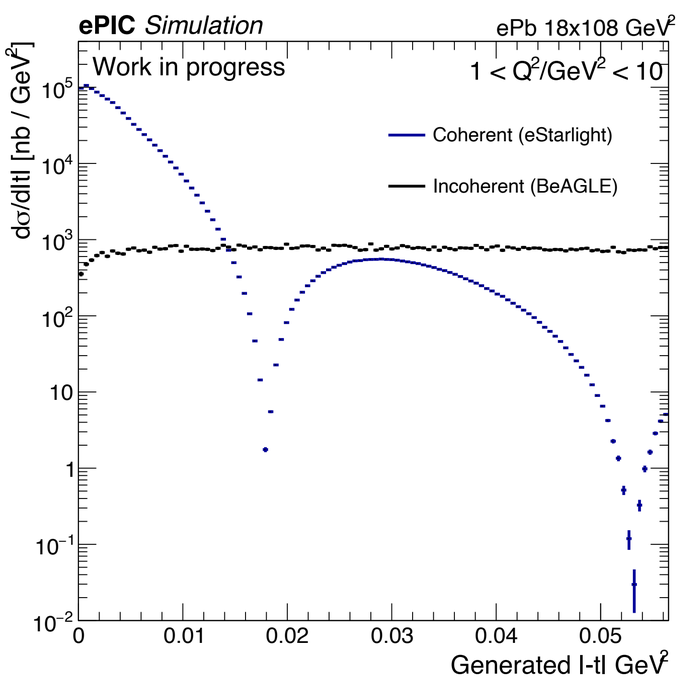


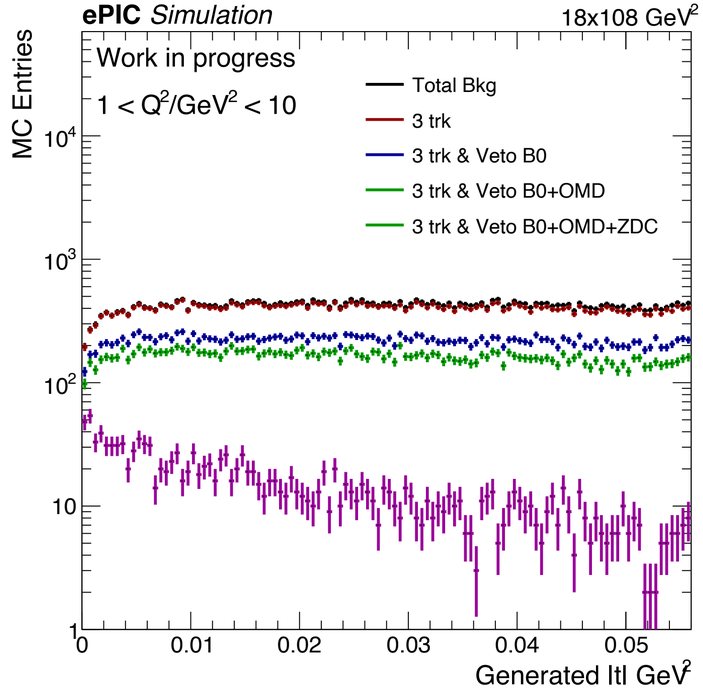
Exclusive measurements on nuclear targets with the EIC

Reconstruction of the coherent signal



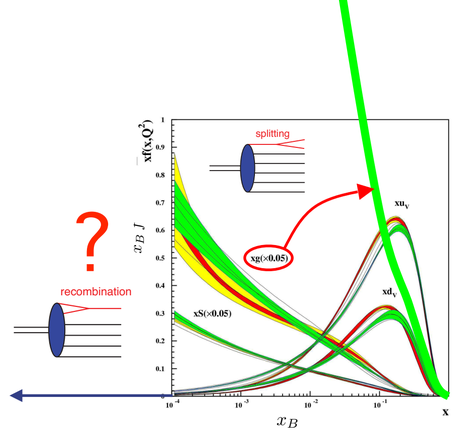
Suppression of the incoherent signal





Di-hadron production in eA collisions

- Complementarity region covered by dihadron and jet production

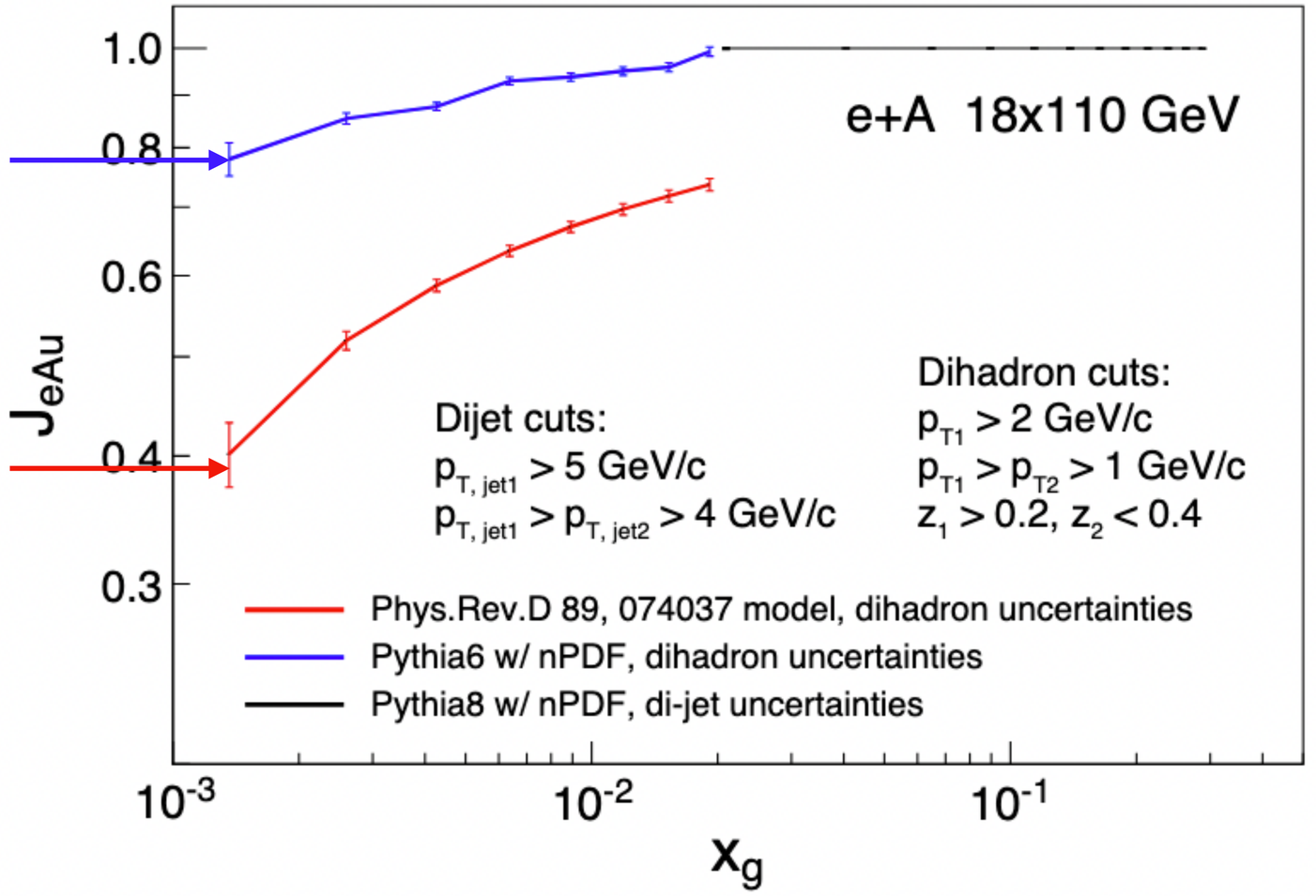


correlated back-to-back hadron pairs in e+Au/e+p scaled by $A^{1/3}$
Away-side suppression

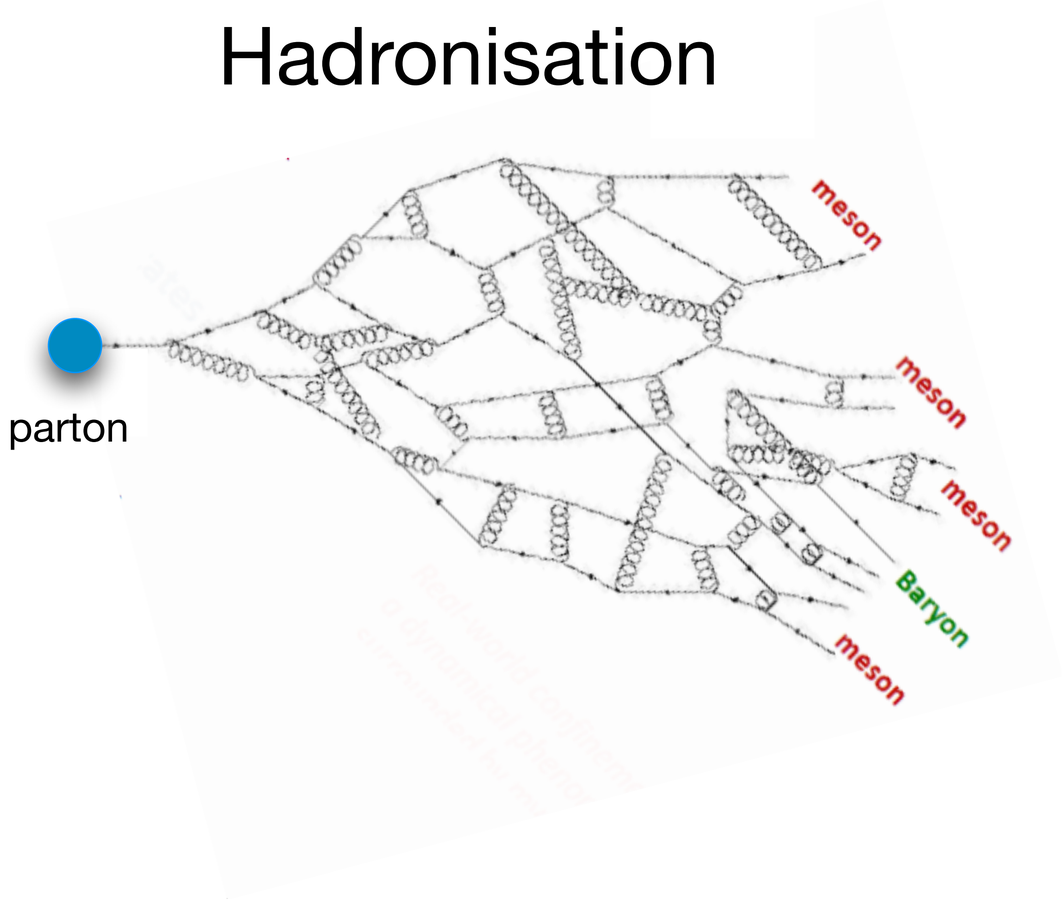
ATHENA

No saturation

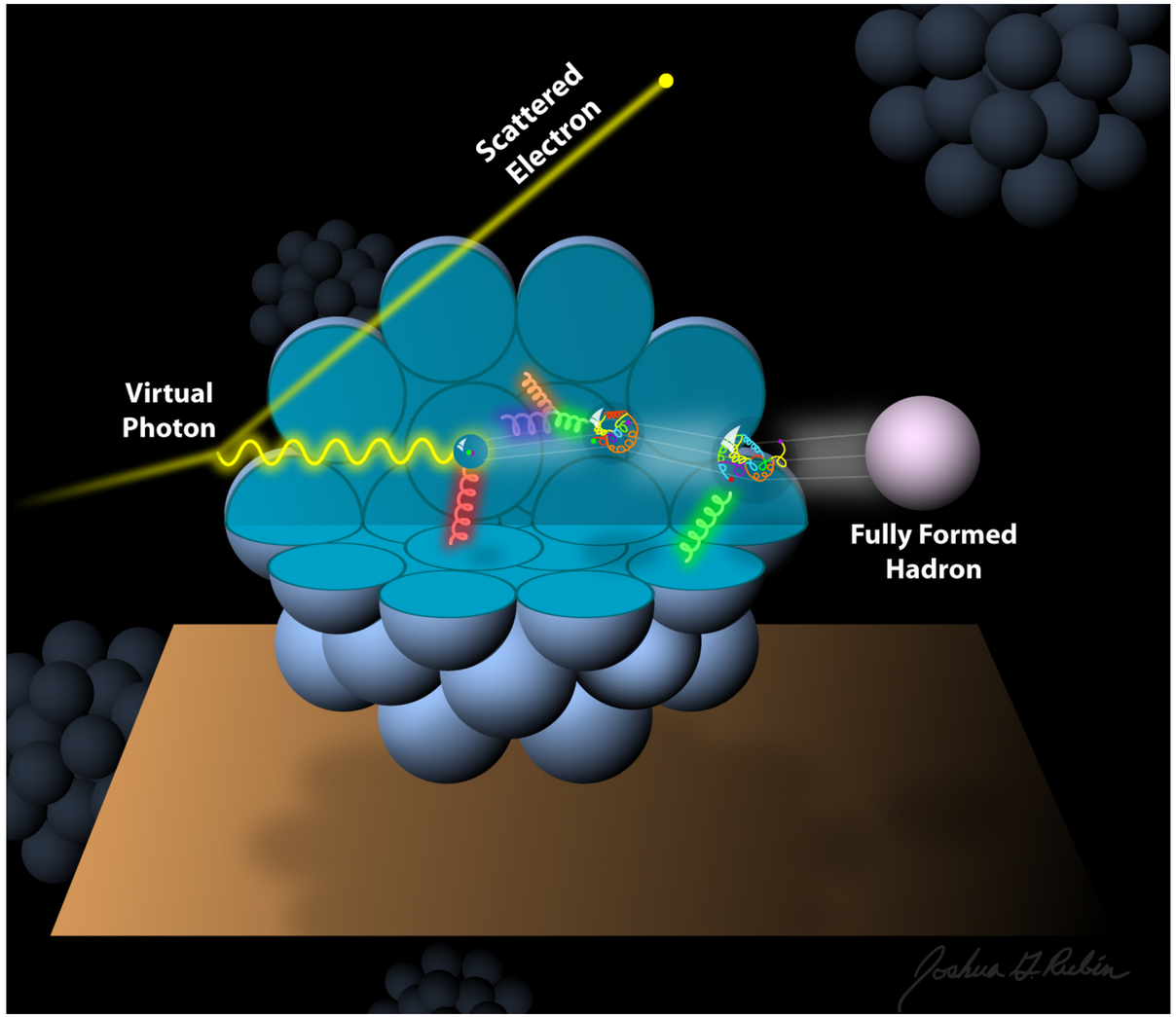
Saturation



Hadronisation



Probing space-time evolution of hadronisation



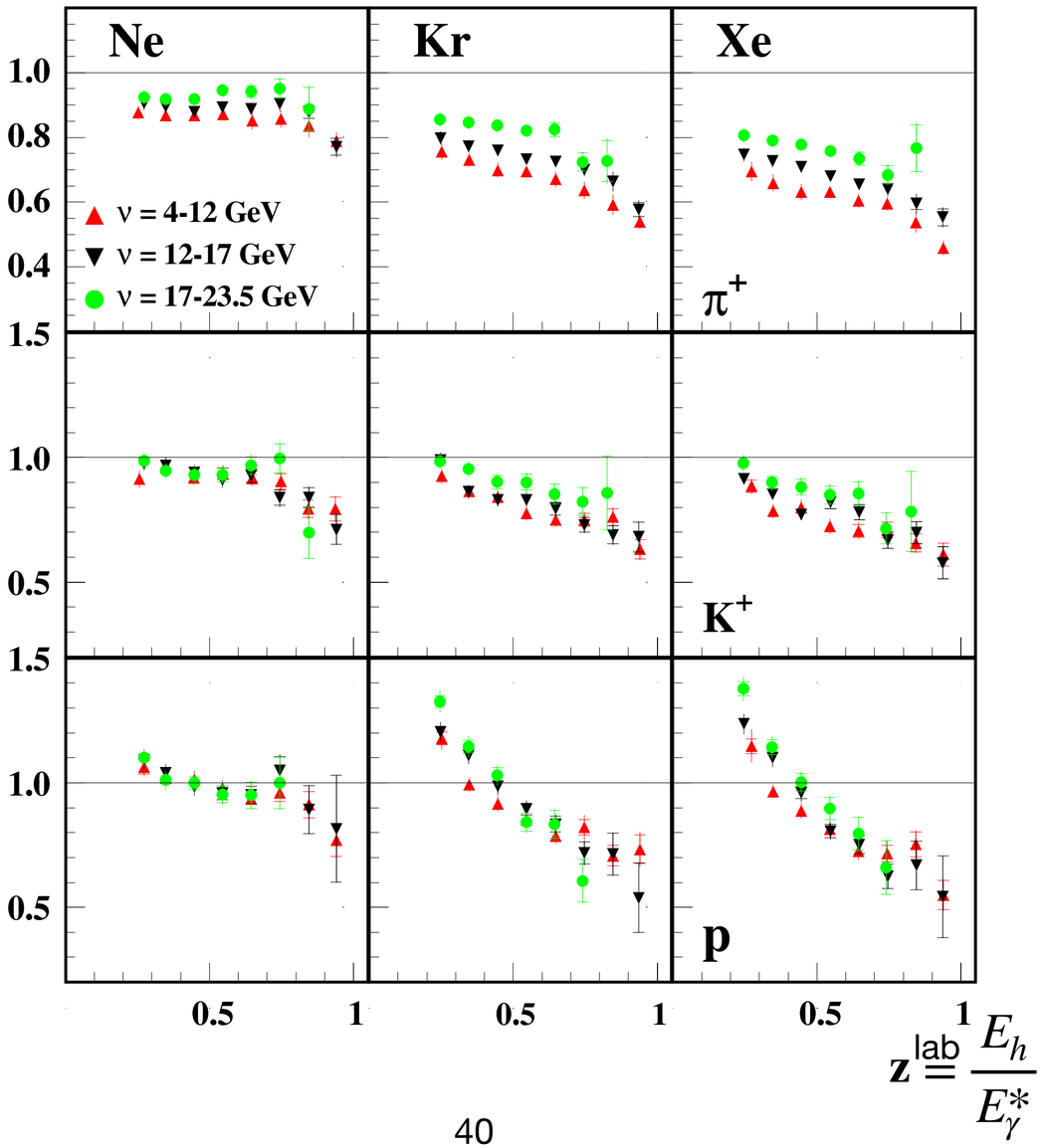
- Energy loss of parton by medium-induced gluon radiation
- Energy loss of (pre-)hadrons
  - absorption
  - rescattering (small)
- Partonic and hadronic processes: different signature

→ probe space-time evolution of hadron formation

Multiplicity ratios

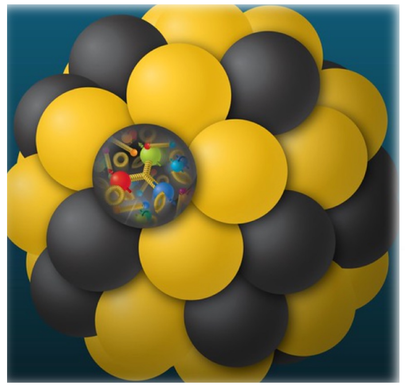
$$R_A^h = \frac{\left(\frac{N^h}{N_{DIS}}\right)_A}{\left(\frac{N^h}{N_{DIS}}\right)_D}$$

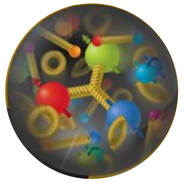
HERMES, Eur. Phys. J. A **47** (2011) 113

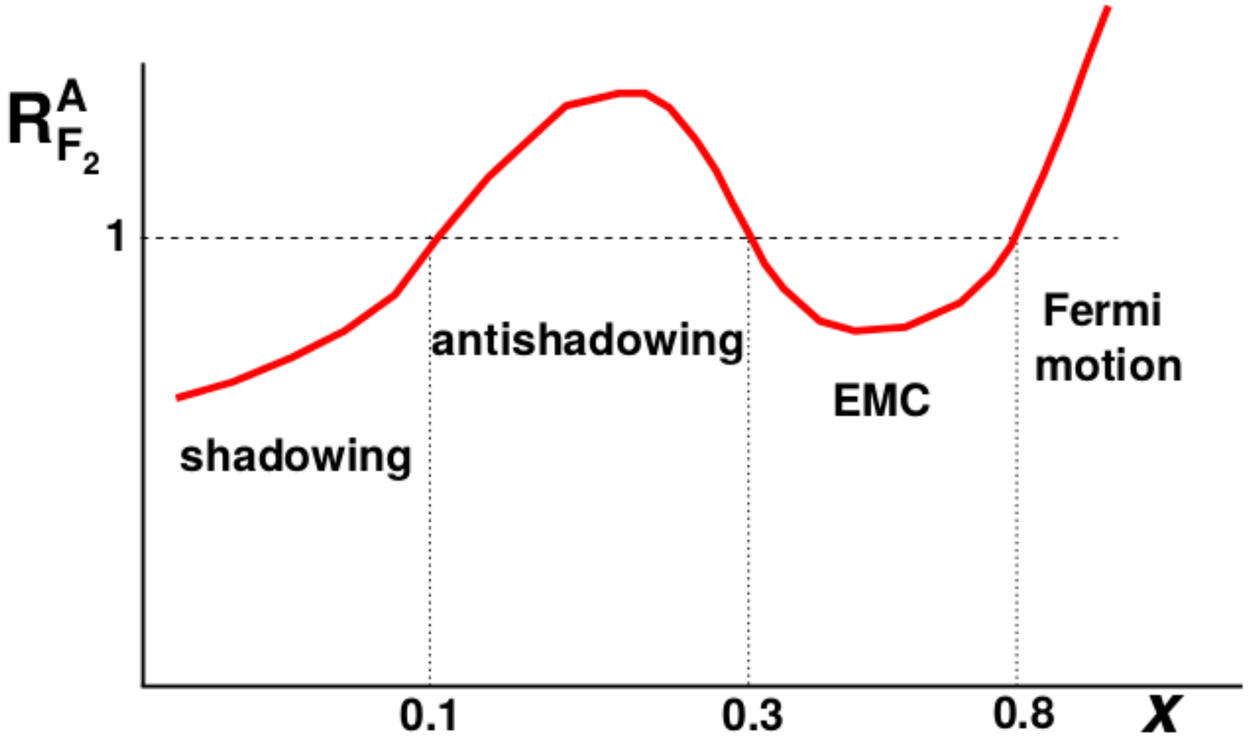


At highest z:
hadronic absorption

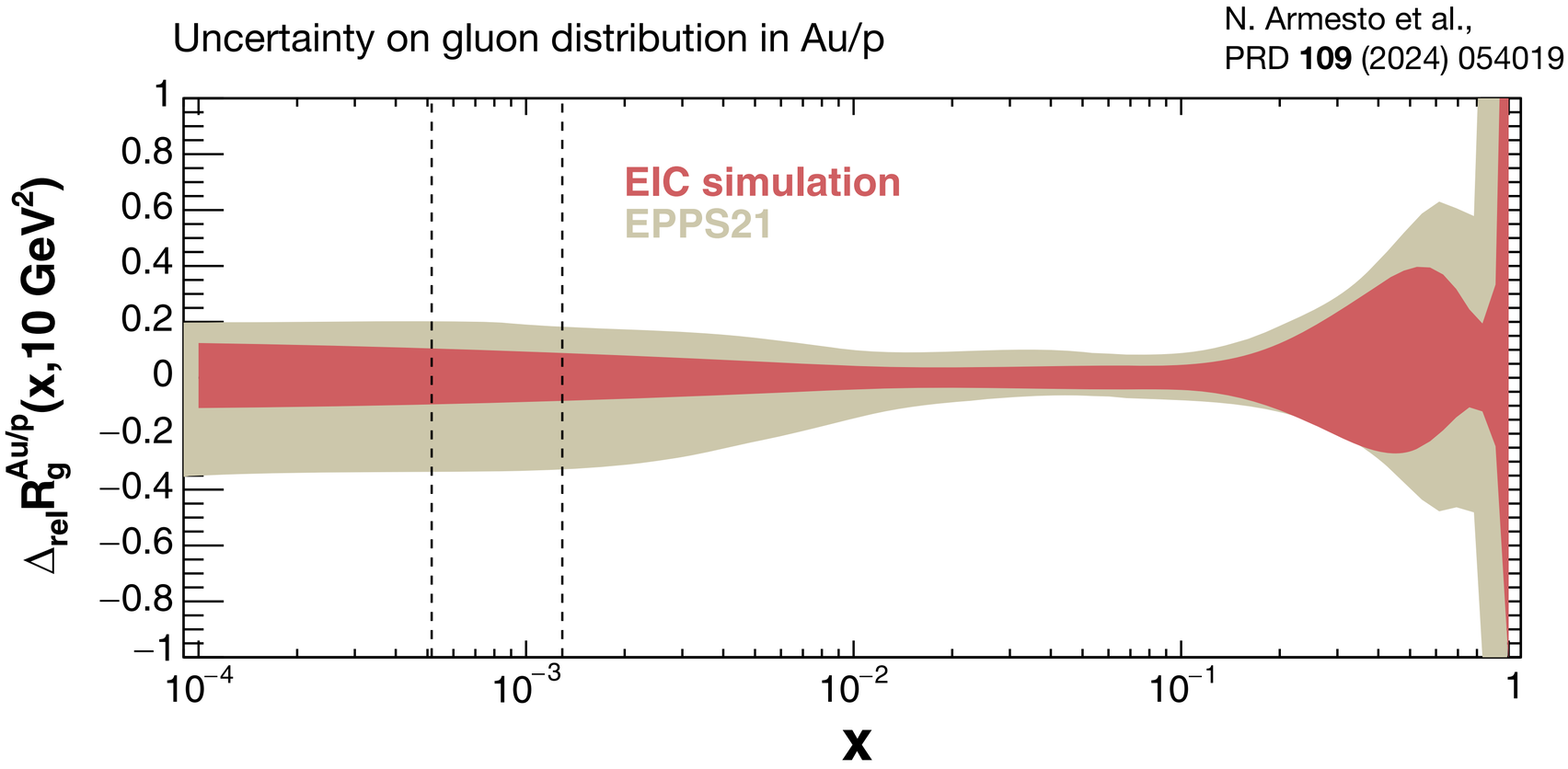
Nuclear PDFs







Nuclear PDFs at EIC



Inclusive e-Au data only:
constrain of nuclear PDF one single nucleus!

Early science programme

	Species	Energy (GeV)	Luminosity/nucleon per year (fb^{-1})	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG

J. Lajoie,
Early Science Workshop
April 24–25, 2025

Summary

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

- Precise inclusive and semi-inclusive DIS measurements to probe the parton spin contribution to the nucleon spin.
- Measurements for 3D (spin-dependent) tomography in momentum space and position space.
- Measurements on a large variety of nuclei:
  - understand nuclear structure
  - probe gluon saturation
  - study the space-time evolution of hadron formation.