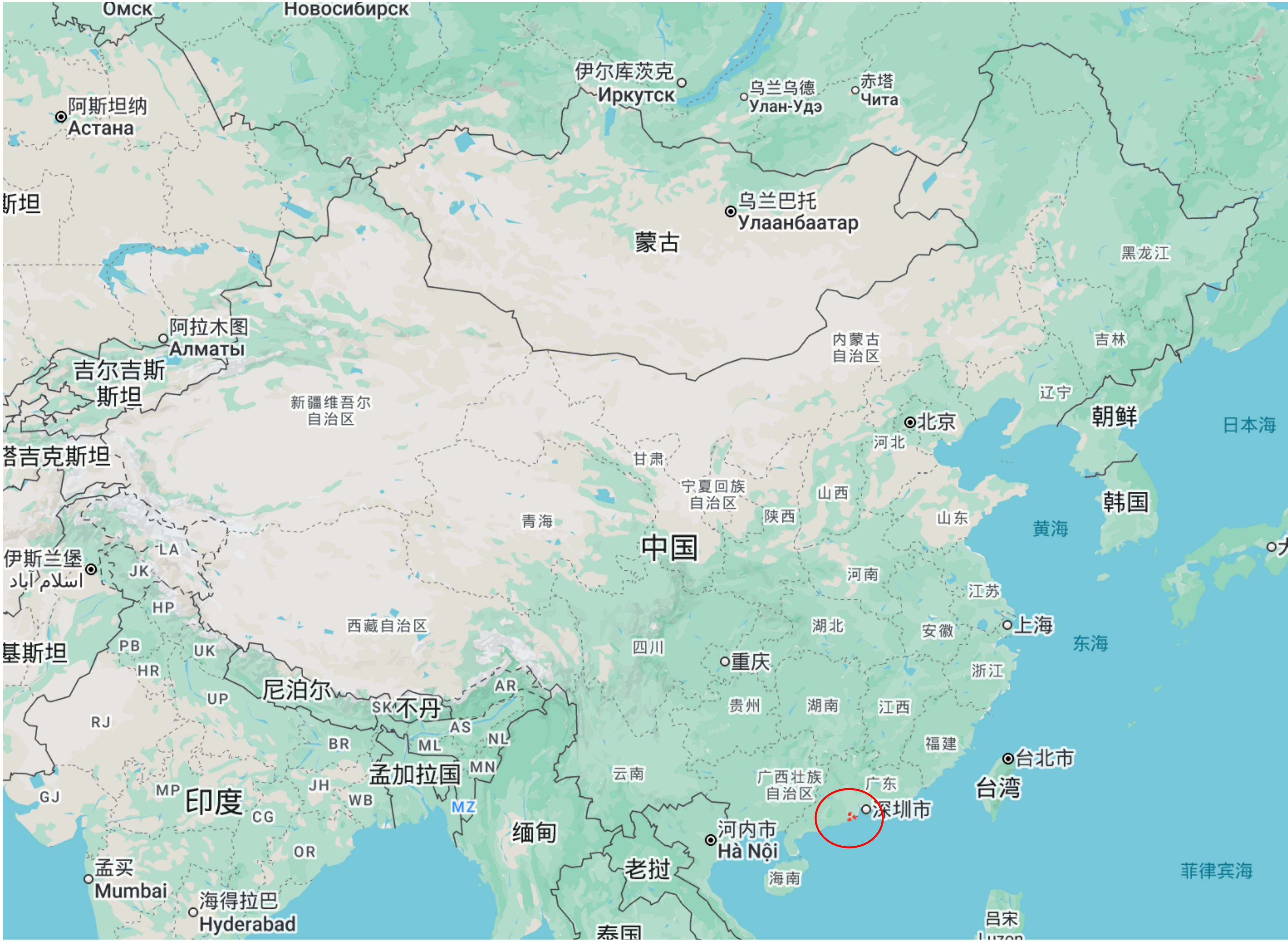
Proton Spin and twist particles

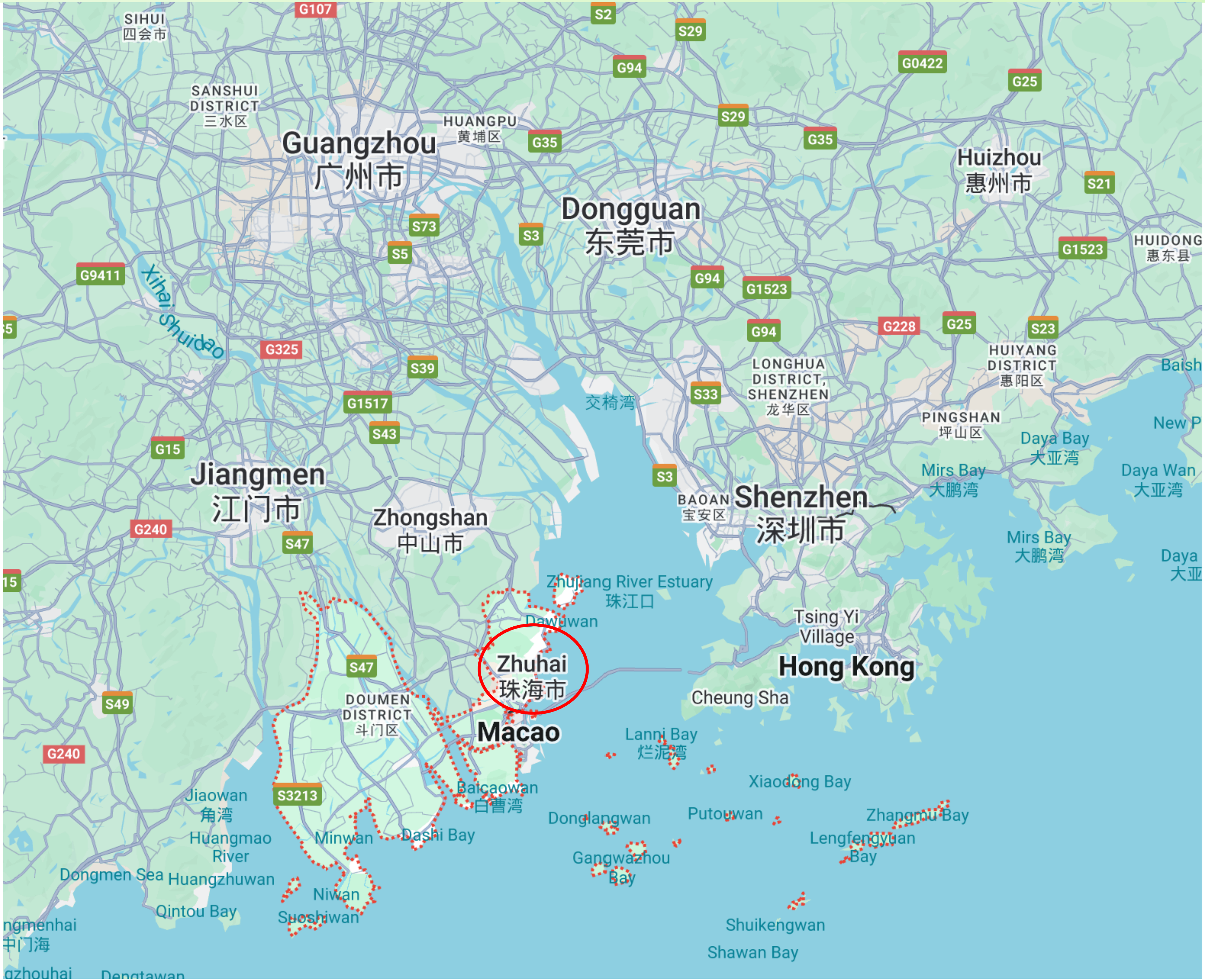
Pengming Zhang (SYSU)

Aug. 29, 2024

Guangdong-Hong Kong-Macao Greater Bay Area



Zhuhai



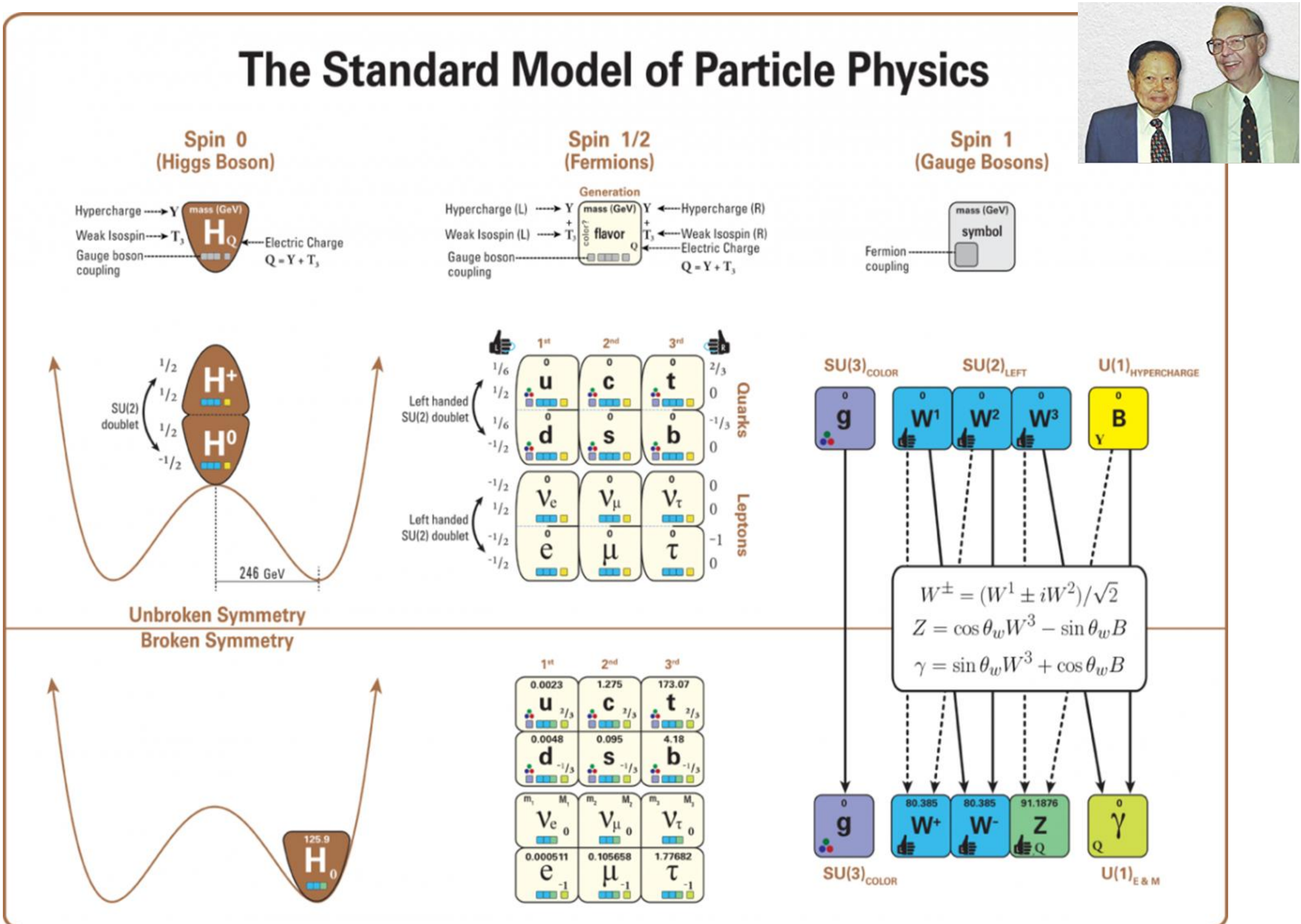
Guangzhou
广州市
Dongguan
东莞市
Huizhou
惠州市
Jiangmen
江门市
Zhongshan
中山市
Shenzhen
深圳市
Zhuhai
珠海市
Macao
Hong Kong
Zhujiang River Estuary
珠江口
DOUMEN DISTRICT
斗门区
Tsing Yi Village
Cheung Sha
Lanni Bay
Xiaodong Bay
Putouwan
Donglangwan
Gangwazhou Bay
Baicaowan
白曹湾
Dashi Bay
Minwan
Niwan
Suoshiwan
Jiaowan
角湾
Huangmao River
Huangzhuwan
Dongmen Sea
Qintou Bay
Zhangmu Bay
Lengfengyuan Bay
Shuikengwan
Shawan Bay
Daya Bay
大亚湾
Mirs Bay
大鹏湾

Sun Yat-sen University

- **Gauge field and Proton spin**
- **Orbital angular momentum**
- **Twist state**

Gauge field theory

Standard model：YM gauge field



Gauge potential decomposition

- Gauge potential can be decomposed (Cho, Duan, Ge, Faddeev, Niemi)

$$\vec{A}_\mu = A_\mu \vec{n} + \frac{1}{g} \partial_\mu \vec{n} \times \vec{n} + \vec{X}_\mu = \hat{A}_\mu + \vec{X}_\mu, \qquad \hat{D}_\mu \vec{n} = \left(\partial_\mu + g\hat{A}_\mu \times\right)\vec{n} = 0$$

- Gauge field

$$\vec{F}_{\mu\nu}\left(\vec{A}\right) = \left(F_{\mu\nu} + H_{\mu\nu}\right)\vec{n} + \vec{G}_{\mu\nu}\left(\vec{X}\right)$$

where

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \qquad H_{\mu\nu} = \frac{1}{g}\vec{n} \cdot \left(\partial_\mu \vec{n} \times \partial_\nu \vec{n}\right) = \partial_\mu C_\nu - \partial_\nu C_\mu$$

- Two types of gluons : $\hat{A}_\mu$ (neutral) and $\vec{X}_\mu$ (colored)
- Abelian dominance and Confinement : $\hat{A}_\mu$

Proton spin crisis

- European Muon Collaboration at CERN discovered that only a small part of the proton spin is carried by quarks (1987)
- Up to now, the experiments data show

  quark contribution 30%

  gluon contribution 20% (?)
- Other ?

Proton spin decomposition - I

- **Jaffe-Manohar sum rule (NPB 337 (1990) 509)：canonical form**

$$\vec{J} = \underbrace{\int d^3x \psi^\dagger \frac{1}{2}\vec{\Sigma}\psi}_{S_q} + \underbrace{\int d^3x \psi^\dagger \vec{x} \times \frac{1}{i}\vec{\nabla}\psi}_{L_q} + \underbrace{\int d^3x \vec{E} \times \vec{A}}_{S_g} + \underbrace{\int d^3x E^i \vec{x} \times \vec{\nabla} A^i}_{L_g}$$

- **Ji sum rule(97)：no separated gluon spin and OAM**

$$\vec{J} = \underbrace{\int d^3x \psi^\dagger \vec{\gamma}\gamma^5\psi}_{S_q} + \underbrace{\int d^3x \psi^\dagger (\vec{x} \times i\vec{D})\psi}_{L'_q} + \underbrace{\int d^3x [\vec{x} \times (\vec{E} \times \vec{B})]}_{J'_g}$$

Gauge-Invariant Decomposition of Nucleon Spin

Xiangdong Ji
Phys. Rev. Lett. **78**, 610 – Published 27 January 1997

Article | References | Citing Articles (1,300) | PDF | Export Citation

Proton spin decomposition - II

- **Flat connection (Chen et al. PRL 100 (2008) 232002)**

$$\vec{A} = \vec{A}_{pure} + \vec{A}_{phys}, \qquad \vec{F}_{pure}\left(\vec{A}_{pure}\right) = 0$$

- **gauge inv. Spin and OAM**

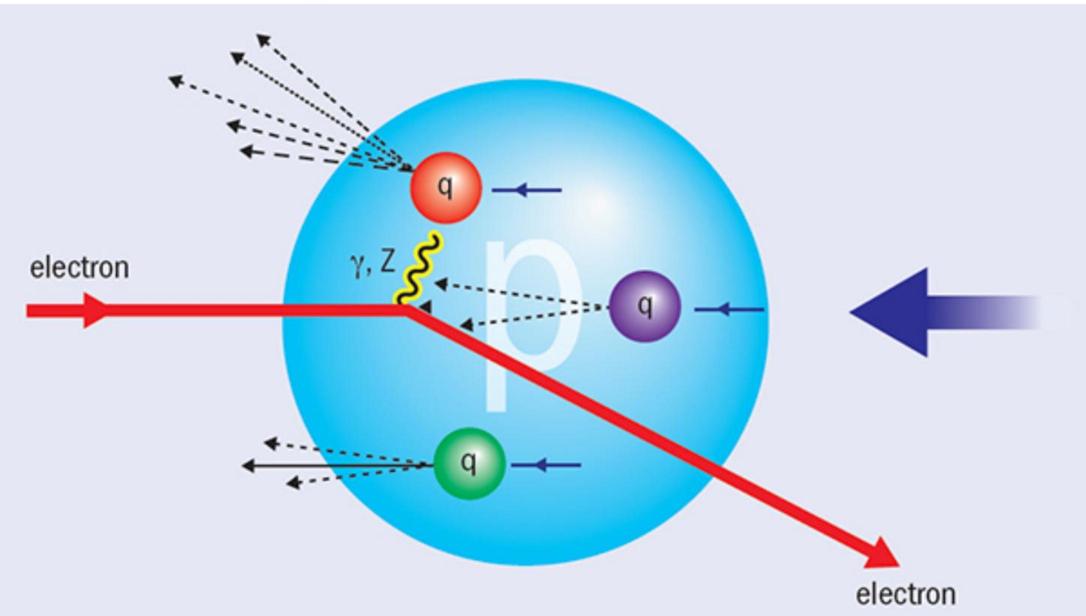
$$\vec{J} = \underbrace{\int d^3x \psi^\dagger \frac{1}{2} \vec{\Sigma} \psi}_{S_q} + \underbrace{\int d^3x \psi^\dagger \vec{x} \times \frac{1}{i} \vec{D}_{pure} \psi}_{L''_q} + \underbrace{\int d^3x \vec{E} \times \vec{A}_{phys}}_{S''_g} + \underbrace{\int d^3x E^i \vec{x} \times \vec{\nabla} A^i_{phys}}_{L''_g}$$

Nucleon structure： mass & spin

Nucleon structure

Modern Rutherford Exp：DIS（Deep Inelastic Scattering） **from J.W.Qiu slide**

SLAC 1968: $e(p) + h(P) \rightarrow e'(p') + X$

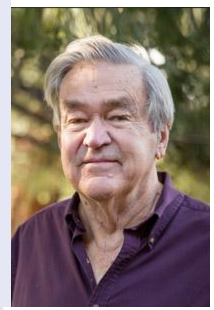


✧ **Localized probe:**

$$Q^2 = -(p - p')^2 \gg 1\ \text{fm}^{-2}$$

$$\Rightarrow \quad \frac{1}{Q} \ll 1\ \text{fm}$$

✧ **Two variables:**



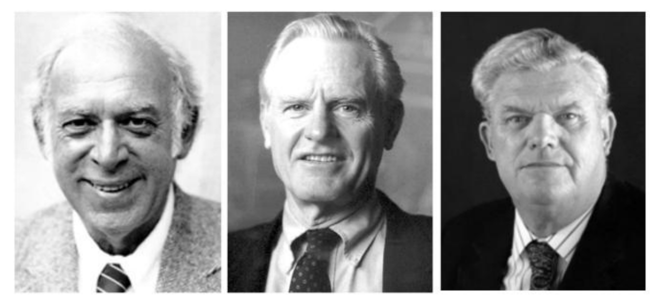
$$Q^2 = 4EE' \sin^2(\theta/2)$$

$$x_B = \frac{Q^2}{2m_N \nu} \quad \text{Bjorken x}$$

$$\nu = E - E'$$

→ **Discovery of spin ½ quarks, and partonic structure!**

What holds the quarks together?

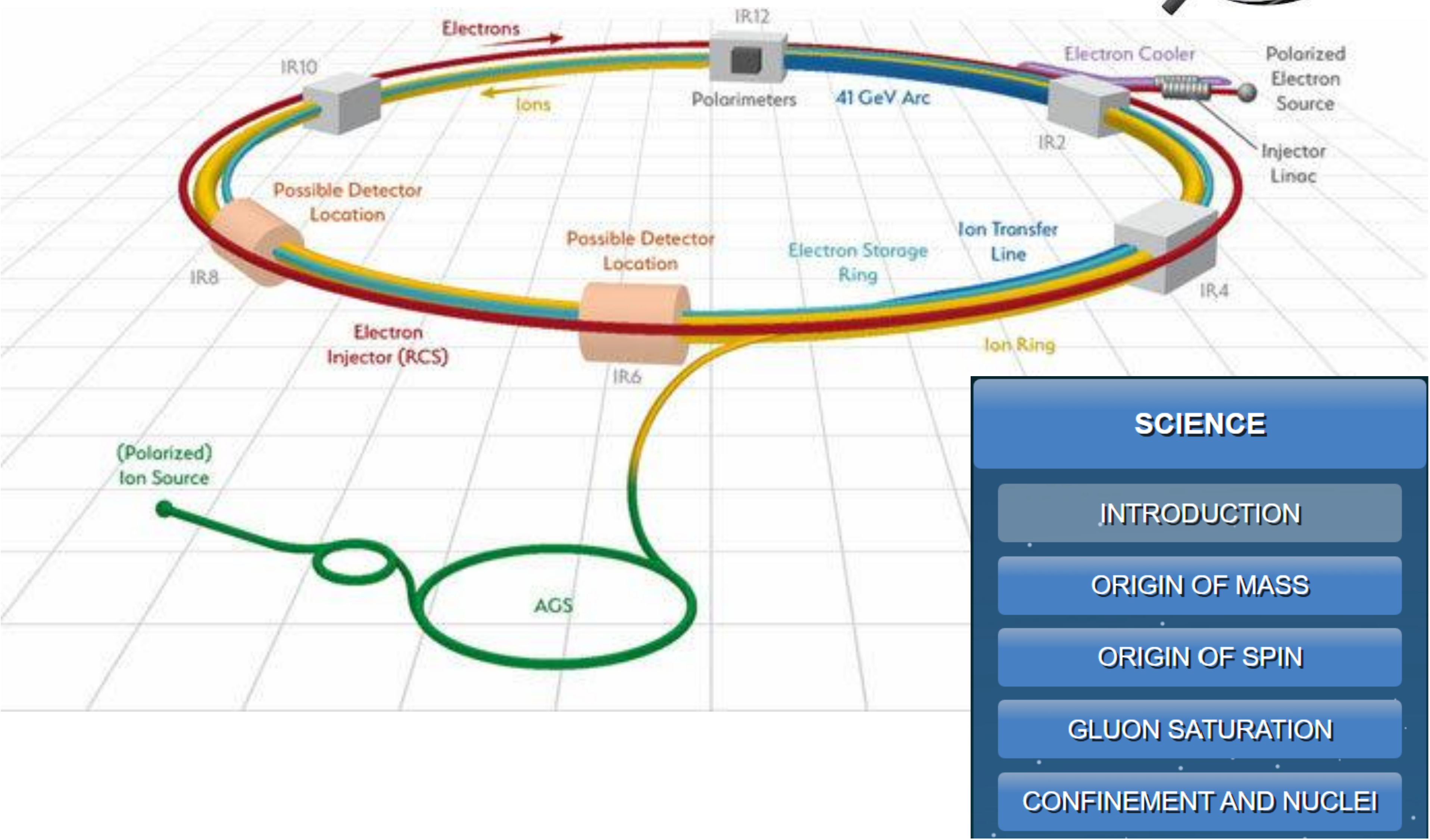


Nobel Prize, 1990
Frierdman Kendall Taylor

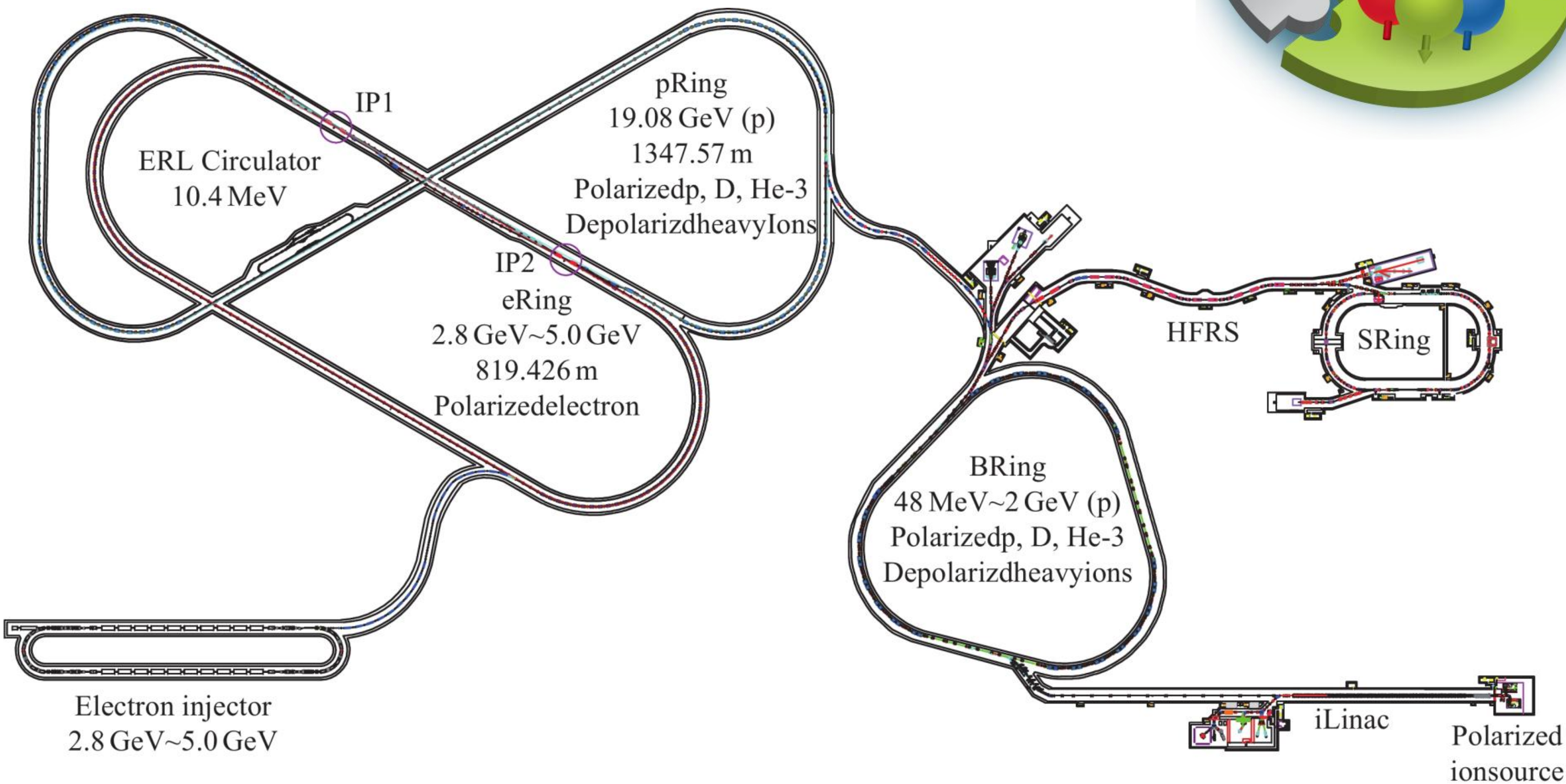
➡ **The birth of QCD (1973)**

– Quark Model + Yang-Mill gauge theory

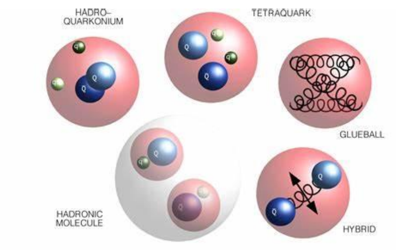
Electron-ion collider @ BNL



Electron-ion collider @ IMP

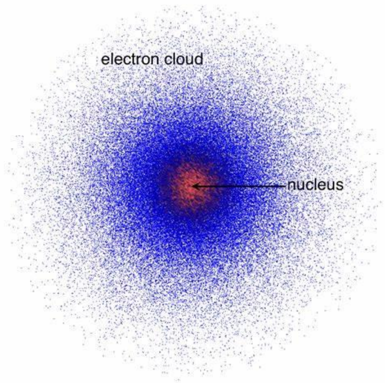


Spin physics



- **QCD**

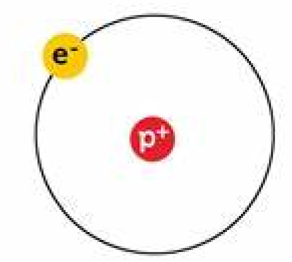
$$\mathcal{L}_{QCD} = -\frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a} + \bar{\psi}(x)\left(i\gamma^{\mu}D_{\mu} - m\right)\psi$$



- **QED**

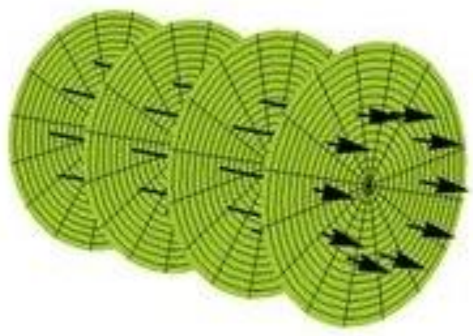
$$\mathcal{L}_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(x)\left(i\gamma^{\mu}D_{\mu} - m\right)\psi$$

- **Free electromagnetic field**



$$\mathcal{L}_{\gamma} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

OAM of free photon ?



- Angular momentum of photon : spin and OAM

$$\vec{J} = \int d^3x \left[\vec{x} \times \left(\vec{E} \times \vec{B}\right)\right] = \underbrace{\int d^3x \ \vec{E} \times \vec{A}}_{\vec{S}} + \underbrace{\int d^3x \ E^i \, \vec{x} \times \vec{\nabla} A^i}_{\vec{L}}$$

- Usually $\vec{L} = 0$, free photon as plane wave $\psi(x, y, z, t) = Ae^{i(kz-\omega t)}$

$$\vec{J} = \vec{S}$$

- Are there free photon carrying nontrivial OAM?

OAM photon/twist photon/vortex light

- **1992，Les Allen （1936-2016）proposed the photo carrying OAM**

Featured in Physics | Milestone

Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes

L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman

Phys. Rev. A **45**, 8185 – Published 1 June 1992

Physics See Feature: 50 Years of *Physical Review A*: The Legacy of Three Classics

An article within the collection: *Physical Review A* 50th Anniversary Milestones

Article | References | Citing Articles (7,488) | PDF | Export Citation

Twist light

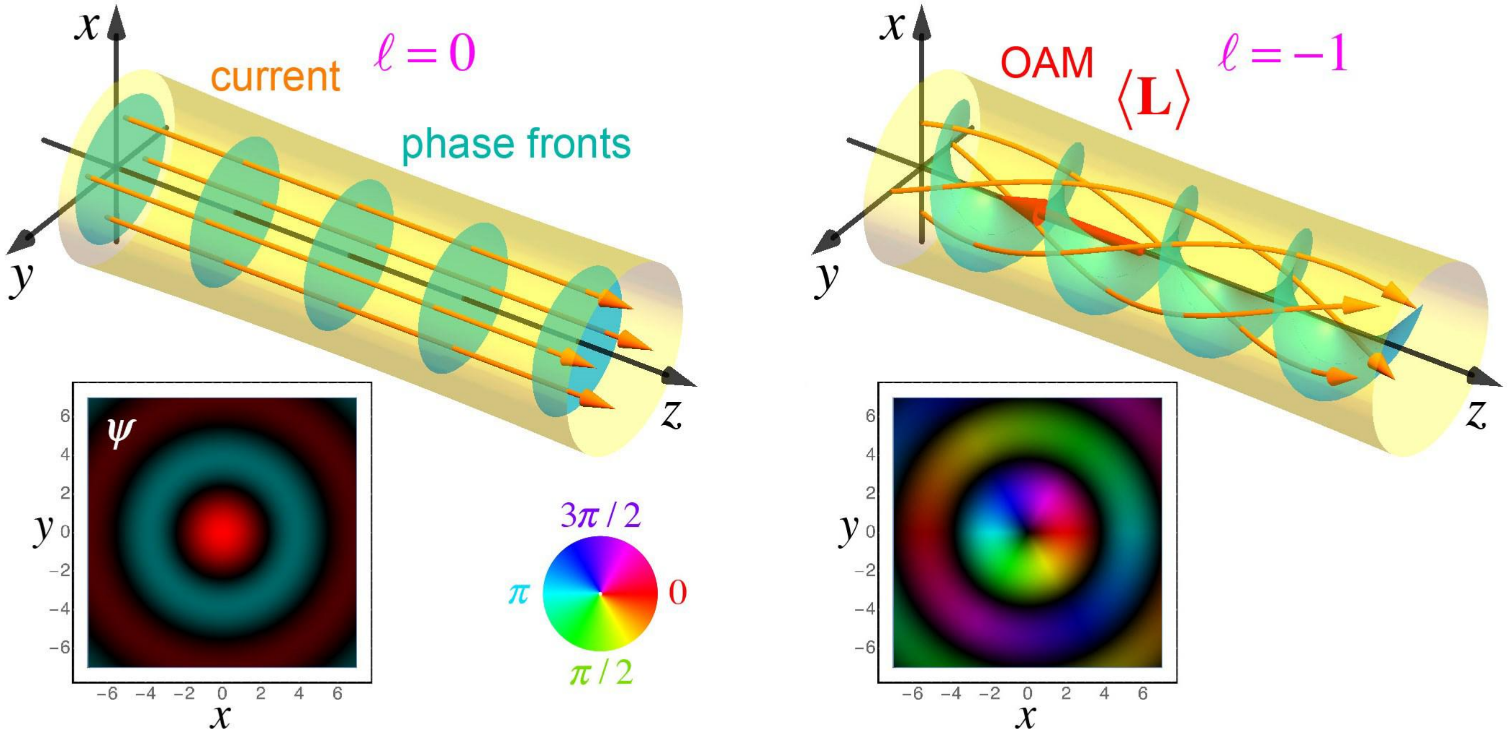
- **Wave function**

3 main melodies of 20-th century physics (C.N.Yang)
quantization, symmetry and phases

$$\psi(\vec{r}) \propto e^{il\varphi}$$

- **Intrinsic orbital angular momentum (OAM)**

$$\langle L_z \rangle = \hbar l$$



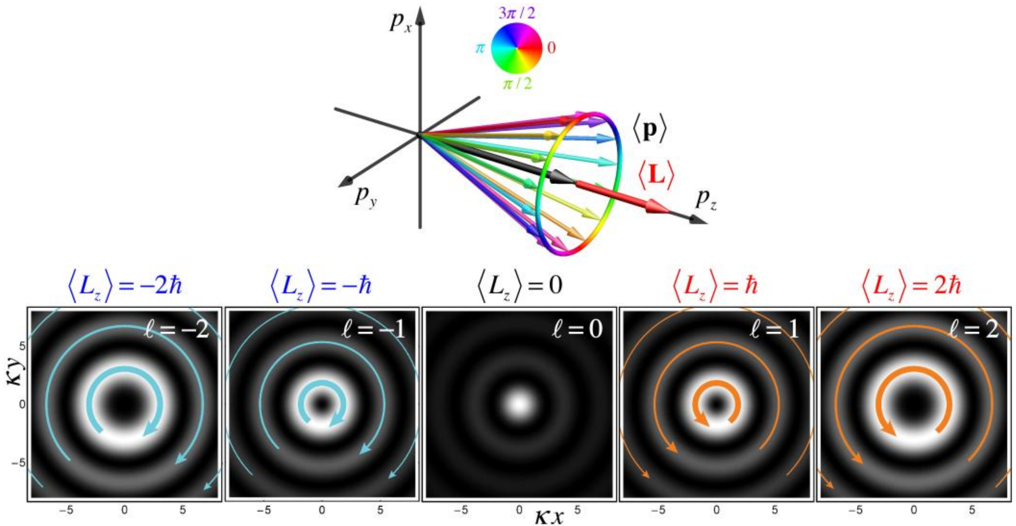
Twist states

- **Plane wave (PW): Given momentum $\vec{k}$**

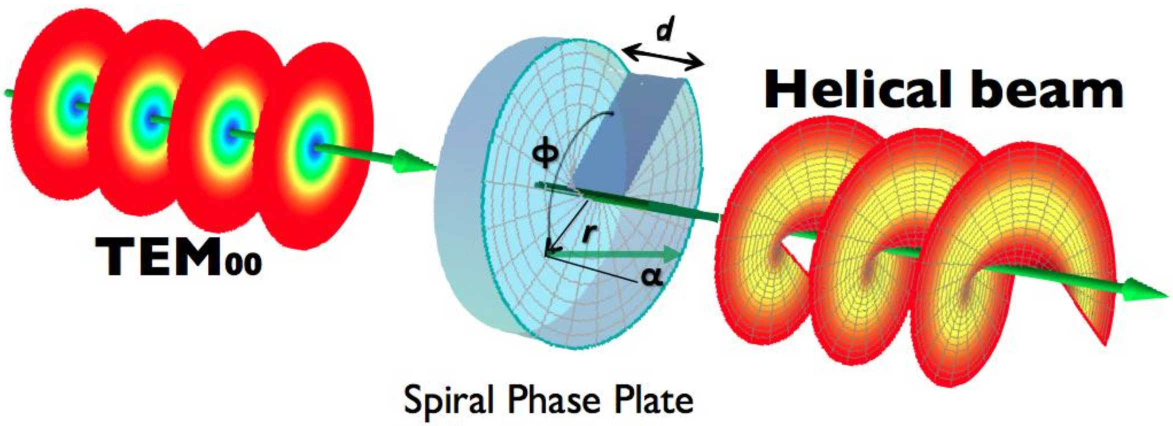
$$\phi\left(\vec{k}\right) \propto \delta^3\left(\vec{k}-\vec{k}_0\right), \qquad \psi(\vec{r}) \propto \int d^3k\, \phi\left(\vec{k}\right) e^{i\vec{k}\cdot\vec{r}} = e^{i\vec{k}_0\cdot\vec{r}}$$

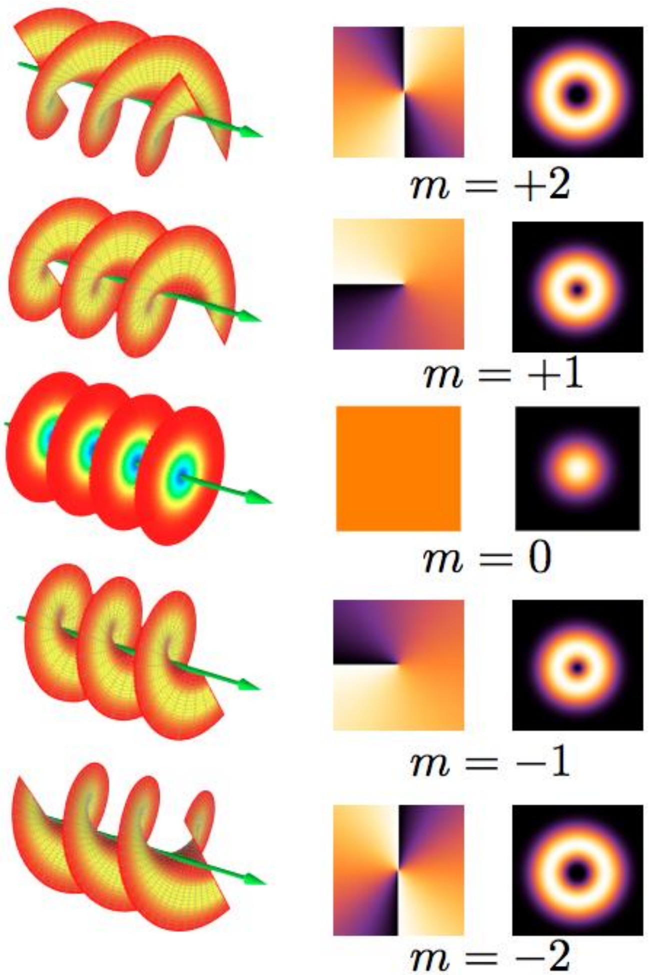
- **Twisted state : fixed longitudinal k_z and transverse module $k_\perp = \sqrt{k_x^2 + k_y^2}$**

$$\phi\left(\vec{k}\right) \propto \delta(k_z - k_{0z})\delta(k_\perp - \kappa)e^{il\varphi_k}, \qquad \psi(\vec{r}) \propto \int d^3k\, \phi\left(\vec{k}\right) e^{i\vec{k}\cdot\vec{r}} = e^{ik_{0z}z}e^{il\varphi_r}J_l(\kappa r_\perp)$$



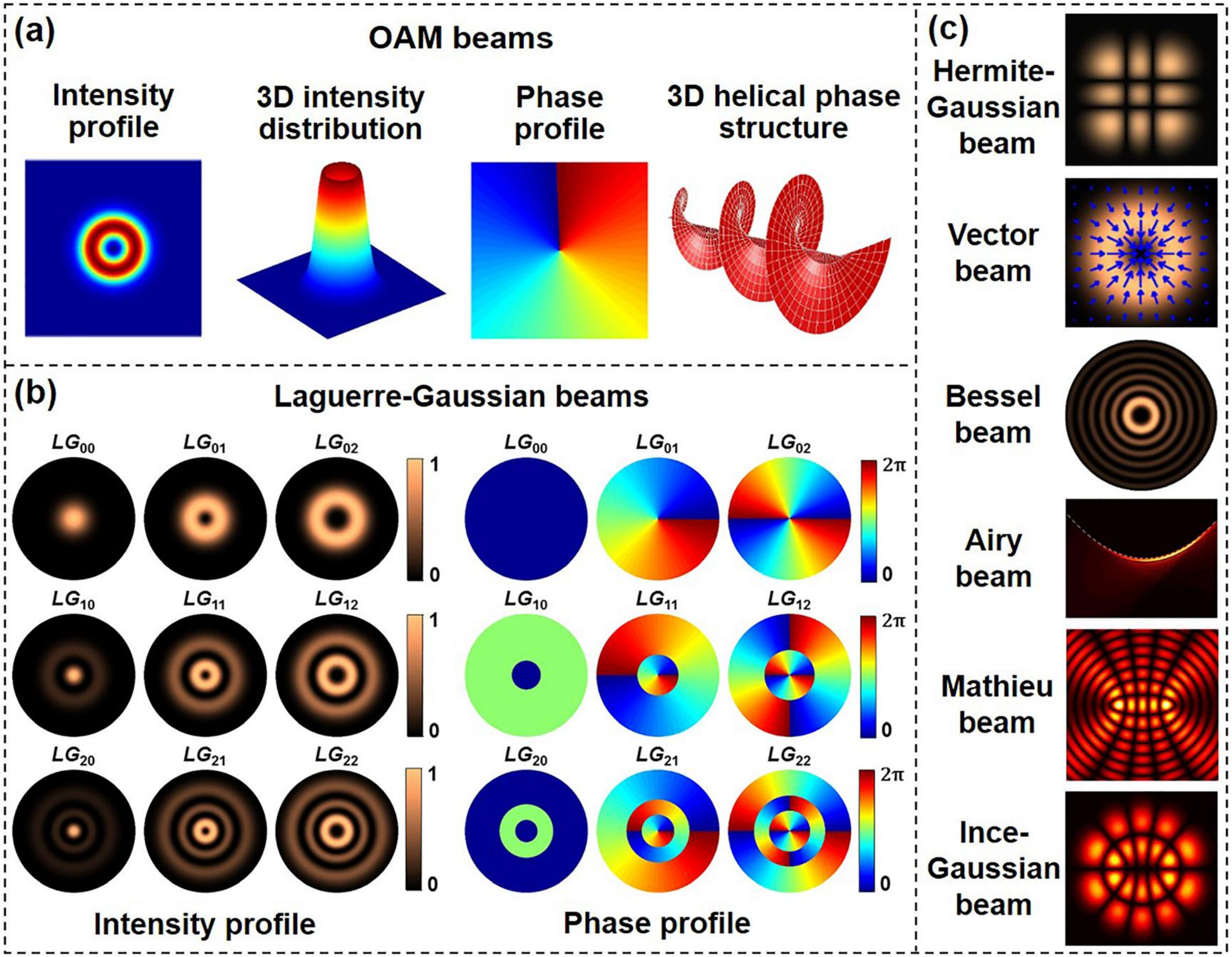
- **Spiral phase plate**





Twist light

- $l = 10000$ (Fickler et al, PNAS 113, 13642 (2016))



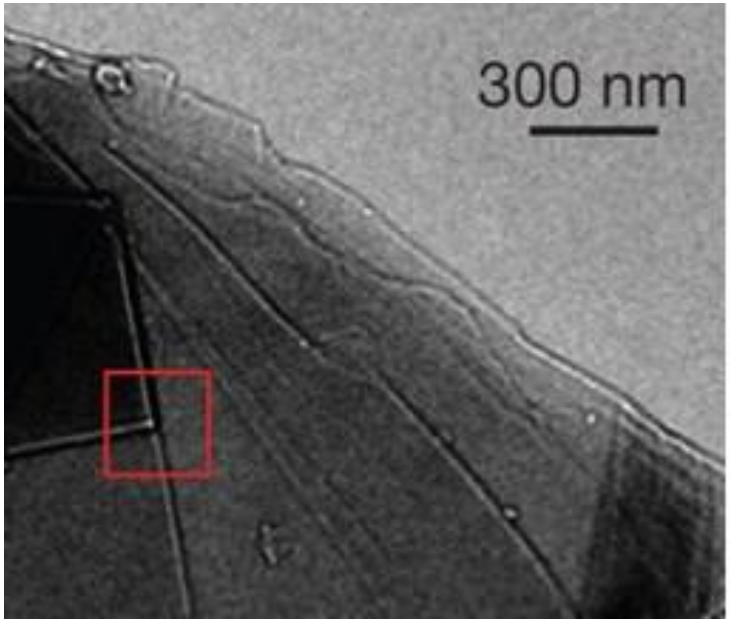
Twist electron

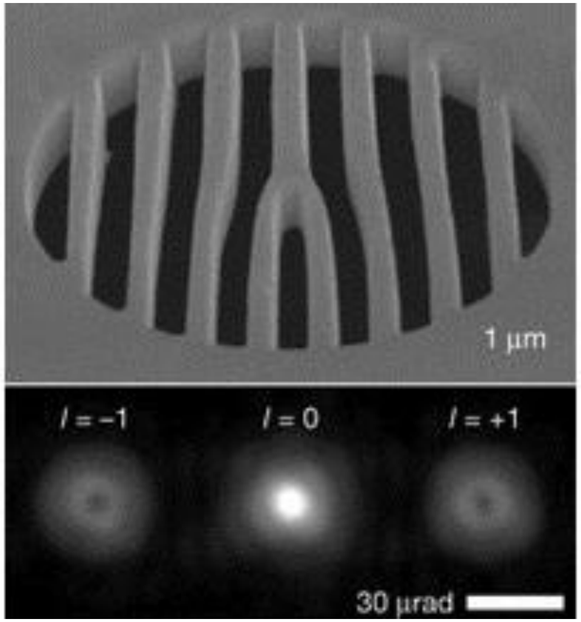
Twist electron

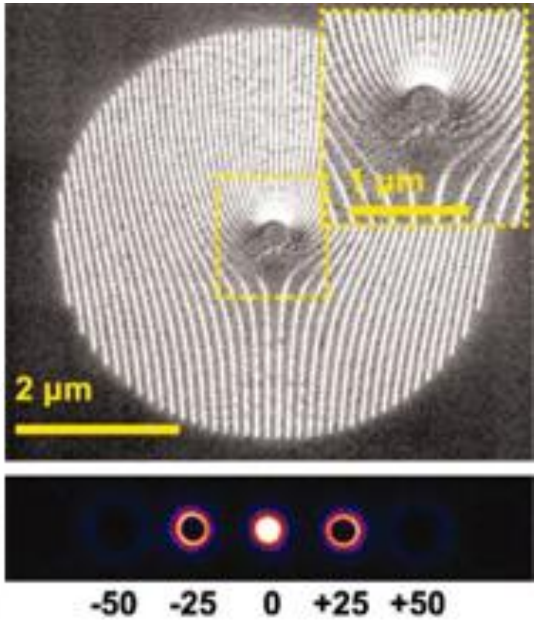
- **Theory:** Bliokh et al, PRL99, 190404 (2007)
- **Exps:** Uchida, Tonomura, Nature 464, 737 (2010);

  Verbeeck, Tian, Schattschneider, Nature 467, 301 (2010);

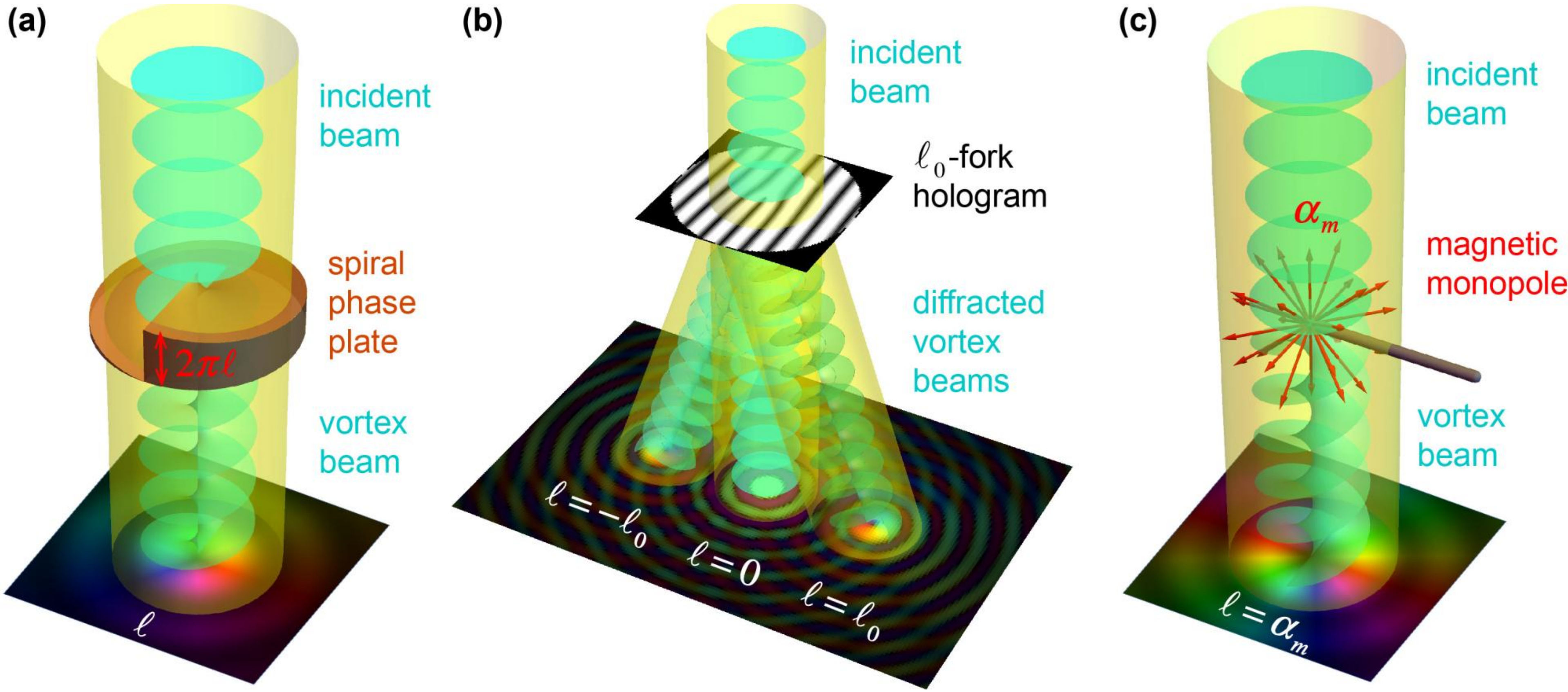
  McMorran et al, Science 331, 192 (2011)
- **Typical value:** $E = 300$ keV, $l \sim 1000$







Experimental set up for twist electrons



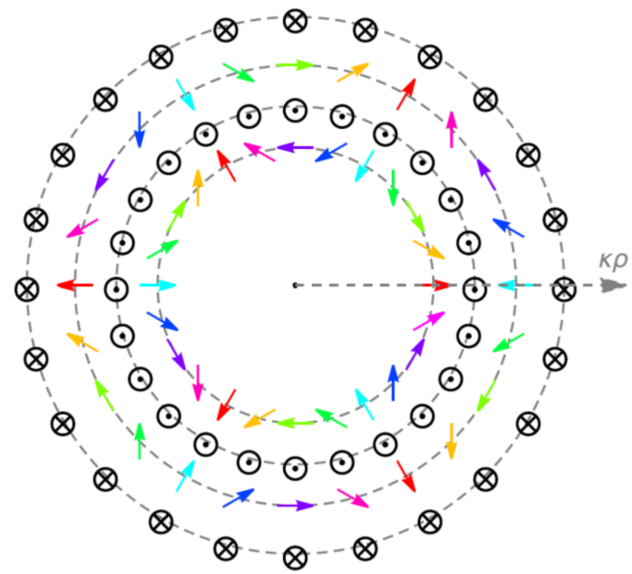
Bliokh et al, Phys. Reports 690 (2017) 1; Lloyd et al, RMP 89 (2017) 035004

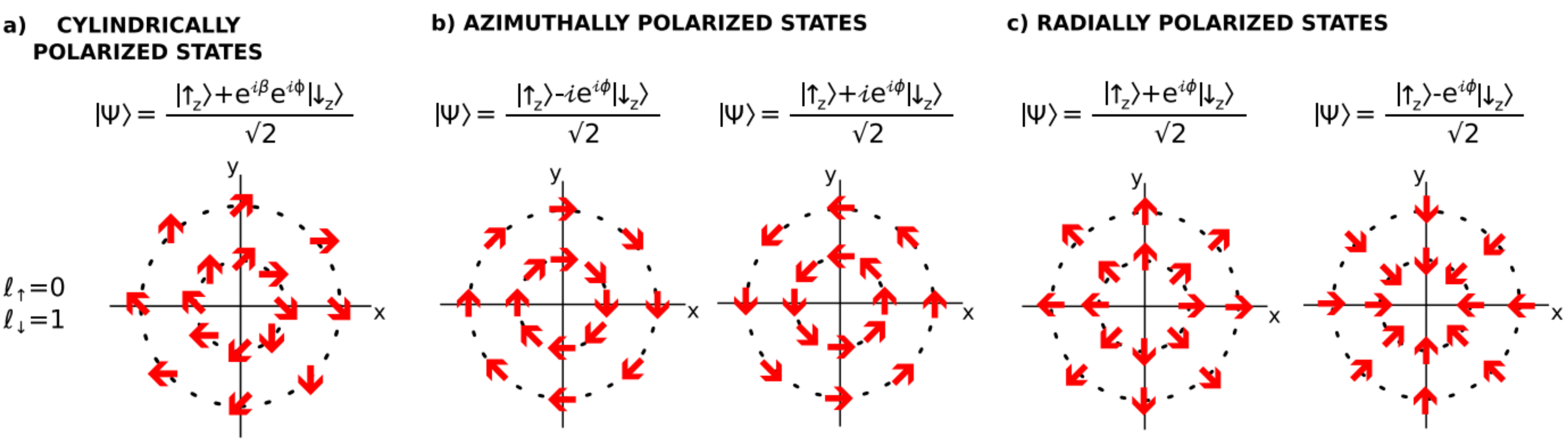
Novel properties of twist electron

- **Manipulate with electromagnetic field (PRL 119 (2017) 243903)**
- **Orbital Sokolov-Ternov effect (PRL 121 (2018) 043202)**
- **Electric Quadrupole Moment and the Tensor Magnetic Polarizability (PRL 122 (2019) 063201)**
- **OAM Hall effect (2312.14391)**
- **……**

Spin-orbit states

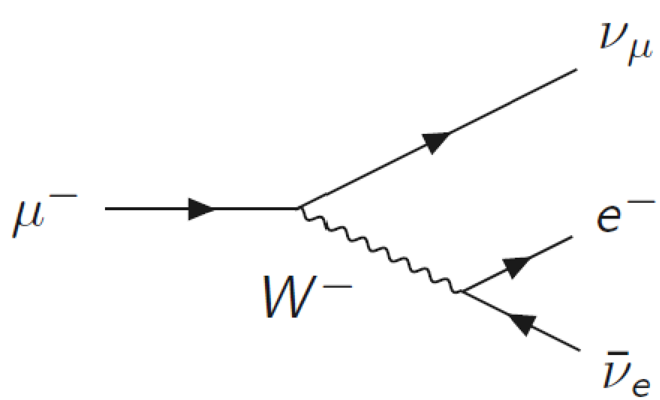
- **Spin-orbit pattern (J. Phys. G 50 (2023) 015006)**





[Sarenac et al, New J. Phys. 20 (2018) 103012]

Decay of twist muon

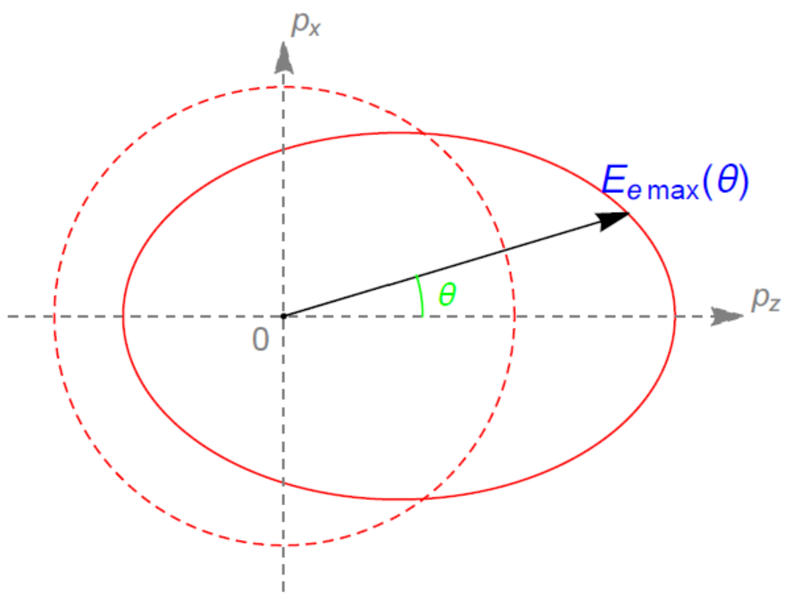


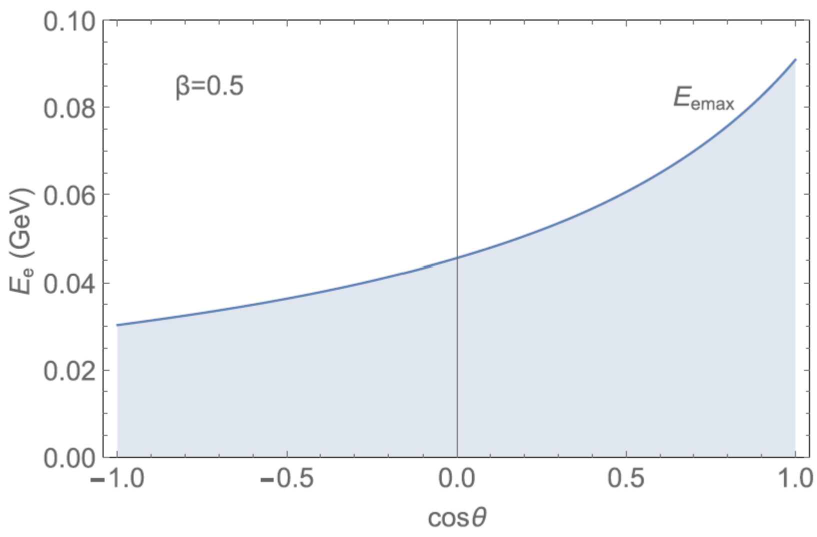
Decay of polarized muon

- **1957, Garwin et al. and Friedman et al. measure parity violation of muon decay**

- **For outgoing angle θ, one threshold :**

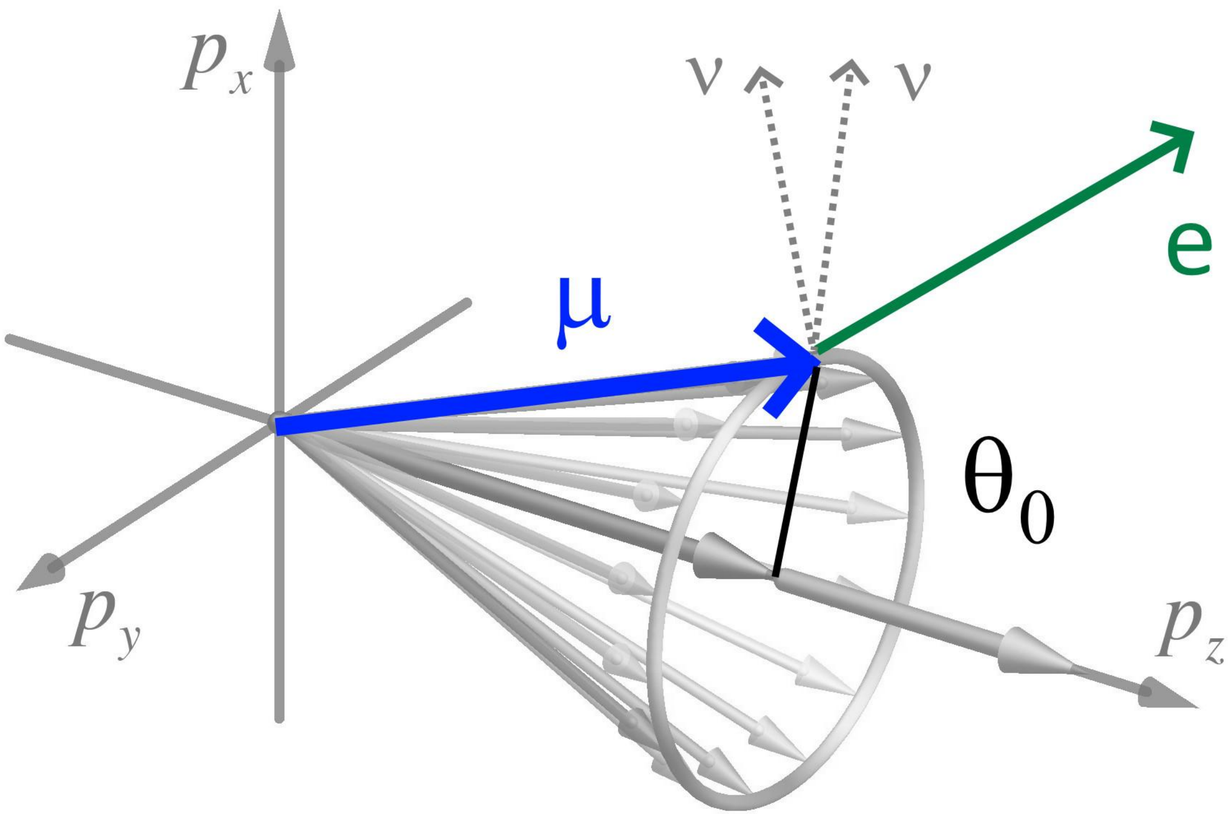
$$E_e < E_{e\,max} = \frac{m^2}{2E(1-\beta\cos\theta)}$$





Decay of twist muon

- **OAM muon :** $d\Gamma_{twist} = \int \frac{d\varphi_p}{2\pi} d\Gamma_{PW}(\vec{p})$



Decay of twist muon

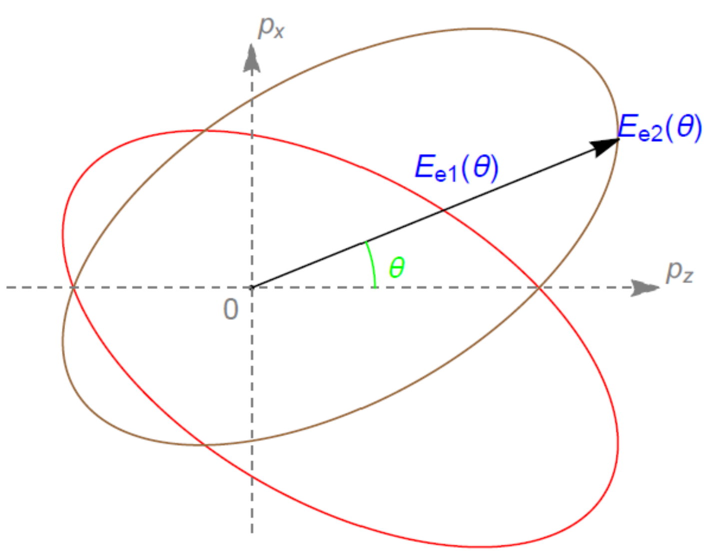
- **OAM muon : there are two thresholds**

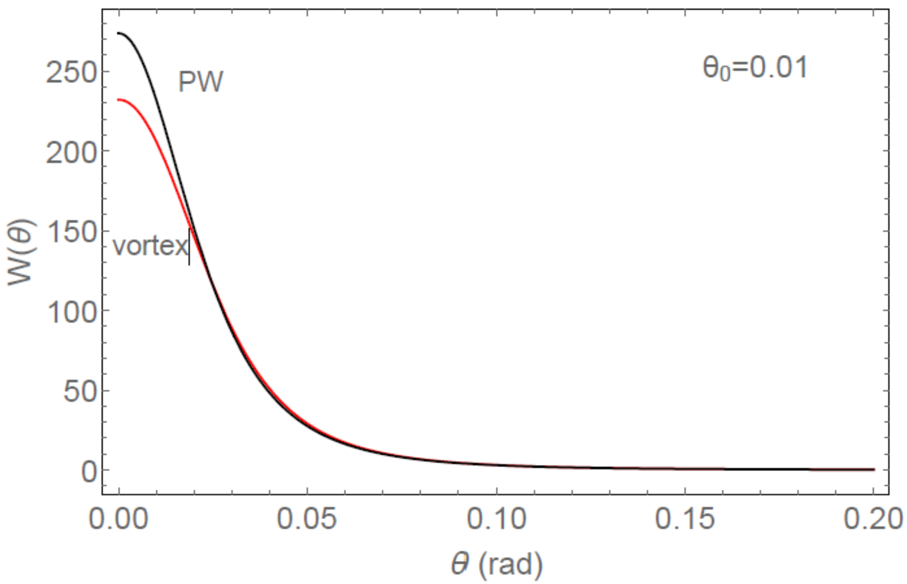
$$E_{e1} = \frac{m^2}{2E(1-\beta cos(\theta+\theta_0))}, \qquad E_{e2} = \frac{m^2}{2E(1-\beta cos(\theta-\theta_0))}$$

- $0 < E_e < E_{e1}$, **all plane wave components have contribution**

- $E_{e1} < E_e < E_{e2}$, **part plane wave components have contribution**

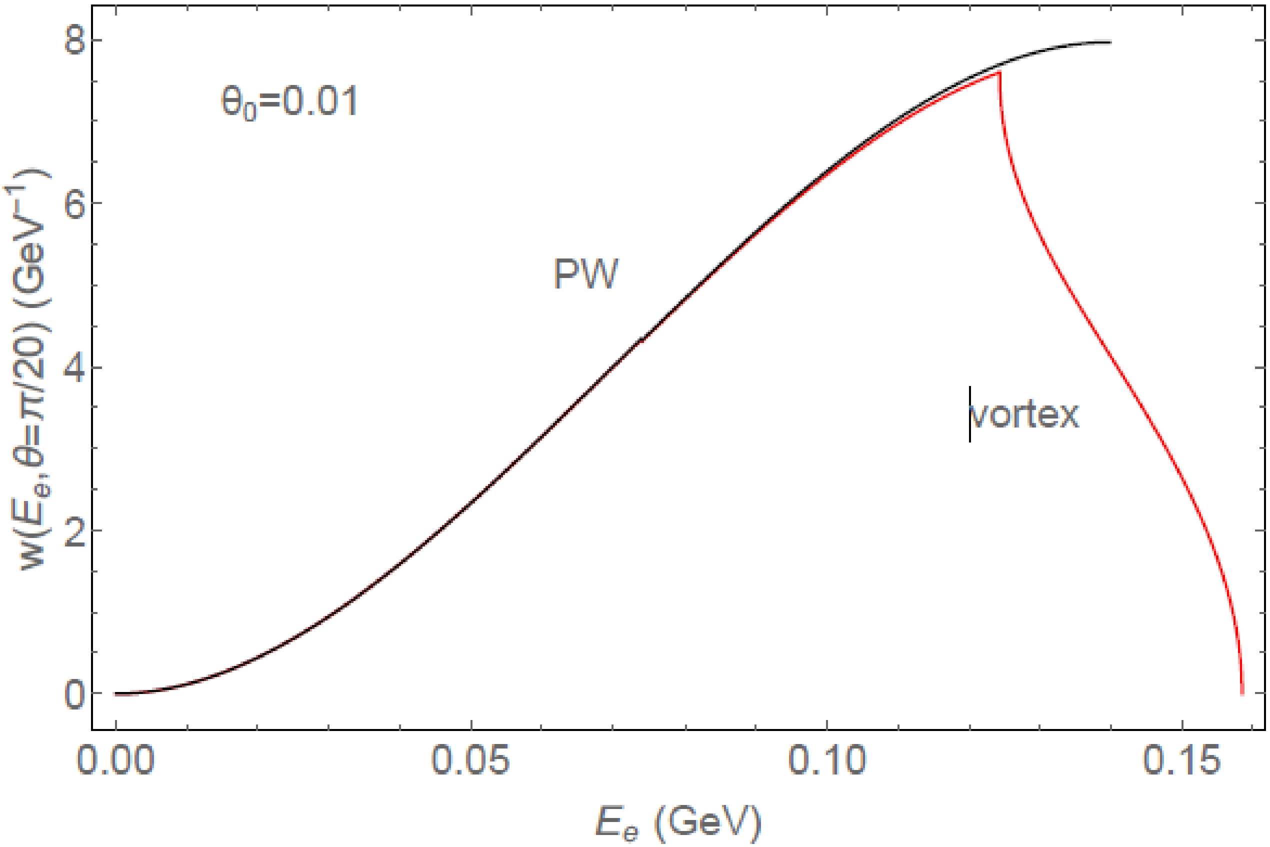
- **electron angular distribution similar**





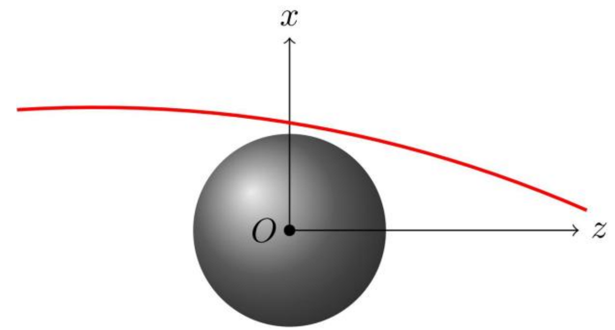
Decay of twist muon

- **Electron energy spectrum (2106.0034)**



Twist photon in gravitational field

Gravitational spin Hall effect



- **Spinless particle : geodesic equation**

$$\frac{d^2x^\mu}{ds^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{ds}\frac{dx^\beta}{ds} = 0$$

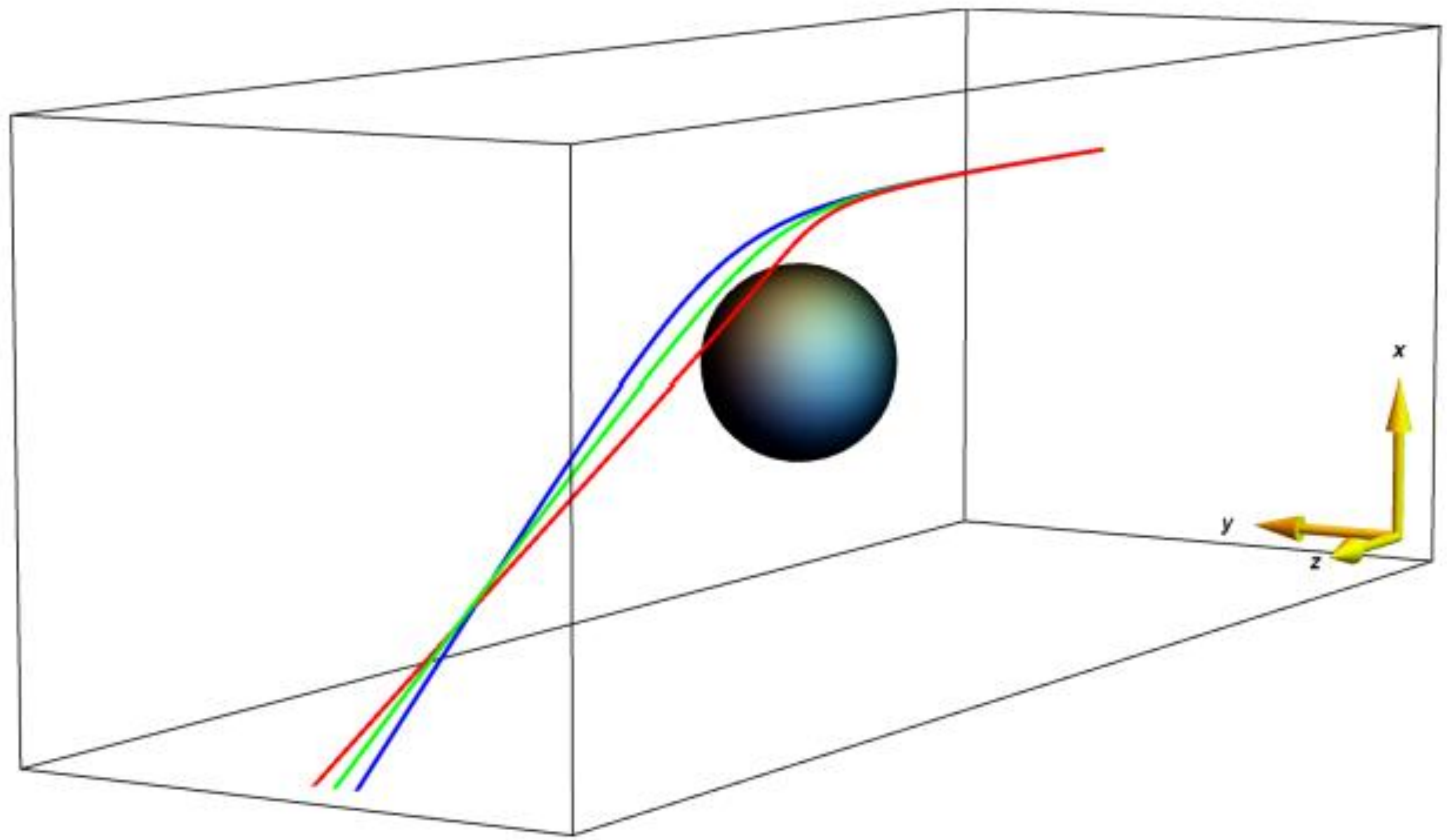
- **Spinning particle : MPD equation (Andersson, Harte, Oancea, Shoom, ...)**

$$\dot{p}^\mu = -\frac{1}{2}R^\mu_{\nu\alpha\beta}u^\nu S^{\alpha\beta}, \qquad \dot{S}^{\alpha\beta} = p^{[\alpha}u^{\beta]}$$

- **Deflection angle between trajectory and geodesic plane (Duval, Marsot, ...)**

$$\beta \sim -\left(1 - \frac{2GM}{r_0}\right)\frac{\chi\lambda_0}{2\pi r_0}$$

- **Spin effect (Harte, Oancea)**



Gravitational orbital Hall effect

- **Evolution of wave function in gravitational field**

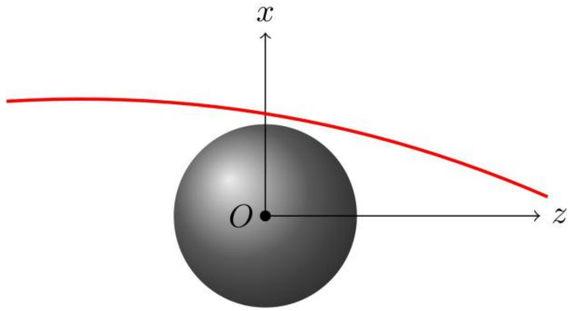
$$\nabla_\alpha \nabla^\alpha \phi = 0$$

- **Position is defined by energy-momentum tensor**

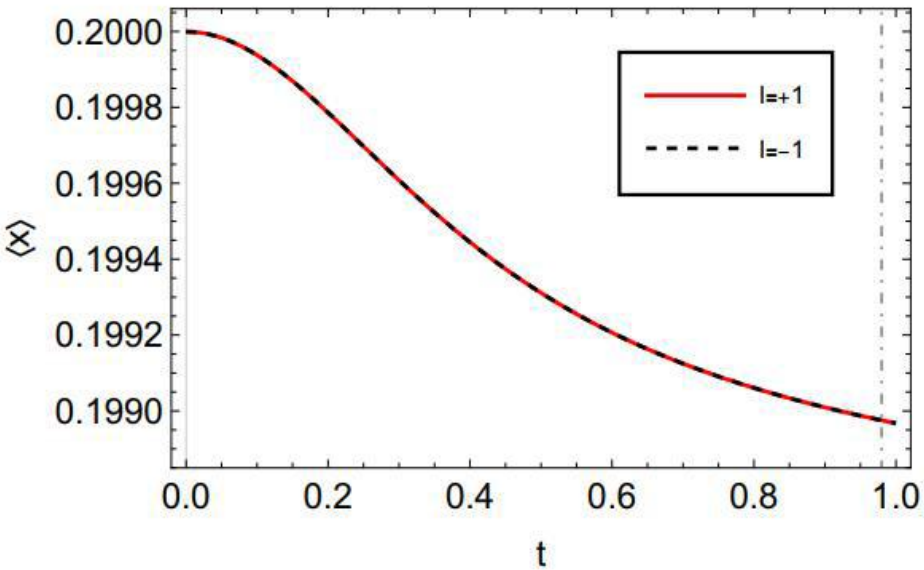
$$\langle x^i \rangle = \frac{\int \sqrt{g} x^i T^{00} dx^3}{\int \sqrt{g} T^{00} dx^3}$$

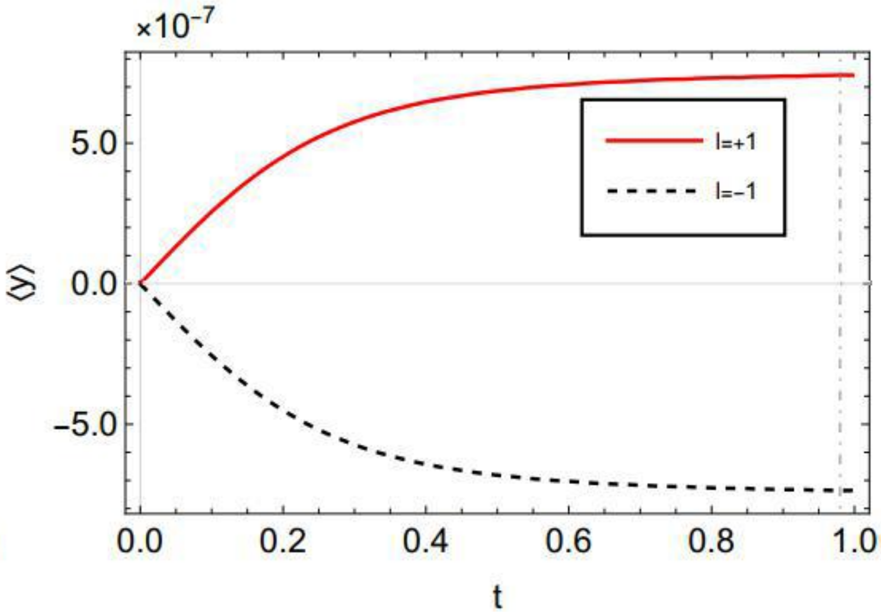
Gravitational orbital Hall effect

- **Geodesic plane (x-z)**



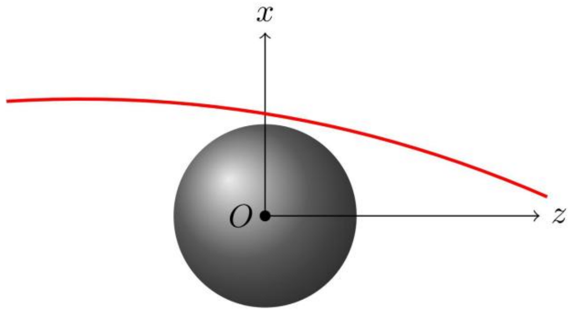
$$\langle y \rangle \propto l$$



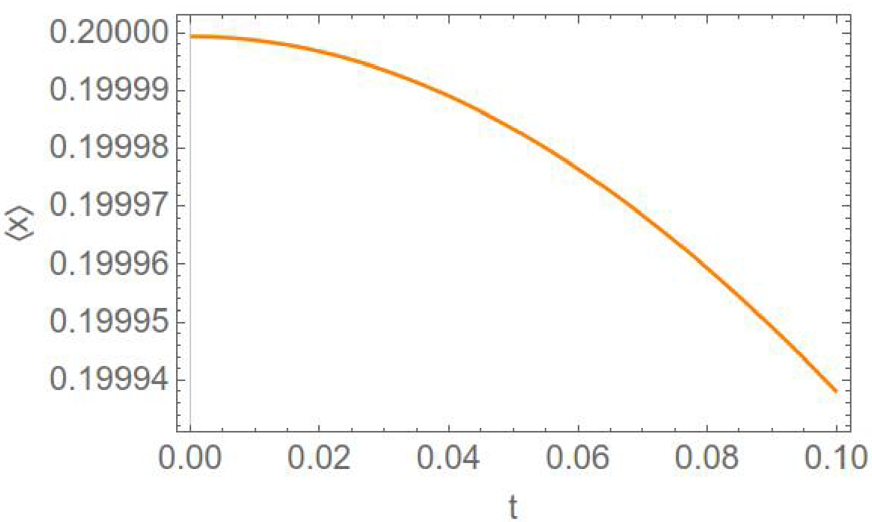


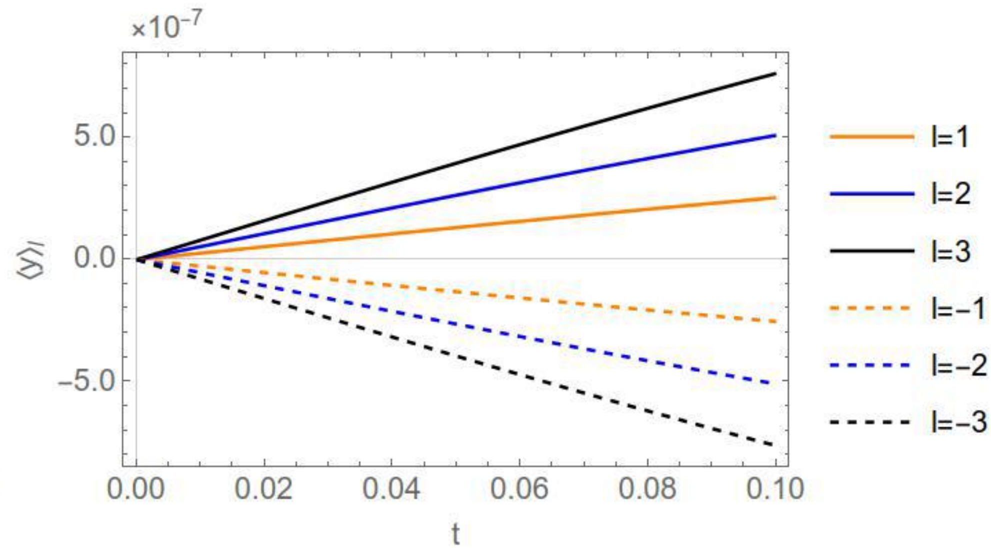
Gravitational orbital Hall effect

- **Geodesic plane (x-z)**



$$\langle y \rangle \propto l$$



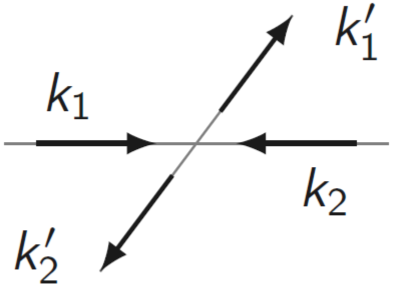


arXiv: 2312.14391

Scattering between twisted states

scattering

- **Plane wave： fixed momentums $|\boldsymbol{k_1}\rangle + |\boldsymbol{k_2}\rangle \to |\boldsymbol{k_1}'\rangle + |\boldsymbol{k_2}'\rangle$**

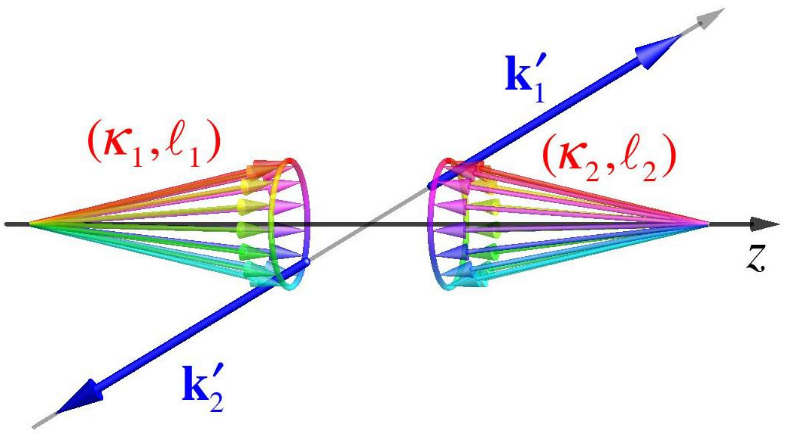


  total momentum c.o.m $\vec{K} = \vec{k}_1' + \vec{k}_2' = 0 \implies \vec{k}_1'$ ($\vec{k}_2'$) fixed

- **Twist states： $|\boldsymbol{\kappa_1}, \boldsymbol{l_1}\rangle + |\boldsymbol{\kappa_2}, \boldsymbol{l_2}\rangle \to |\boldsymbol{k_1}'\rangle + |\boldsymbol{k_2}'\rangle$**

  distribution of total momentum $\vec{K} = \vec{k}_1' + \vec{k}_2'$

- **a new tool to study spin physics (PRL 124, 192001 (2020))**



Electron-ion collide with polarized particles

Spin Structure of the Nucleons

three quark distribution functions (DF) are necessary to describe the structure of the nucleon at LO

$q(x)$

$f_1^q(x)$

unpolarised DF

quark with momentum *xP* in a nucleon

well known – unpolarised DIS

$\Delta q(x)$

$g_1^q(x)$

helicity DF

quark with spin parallel to the nucleon spin in a longitudinally polarised nucleon

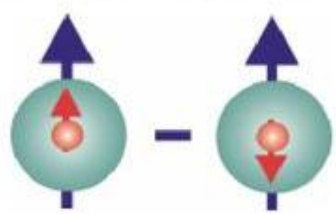
known – polarised DIS

$\Delta_T q(x) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)$

$h_1^q(x)$,

$\delta q(x)$,

$\delta_T q(x)$



transversity DF

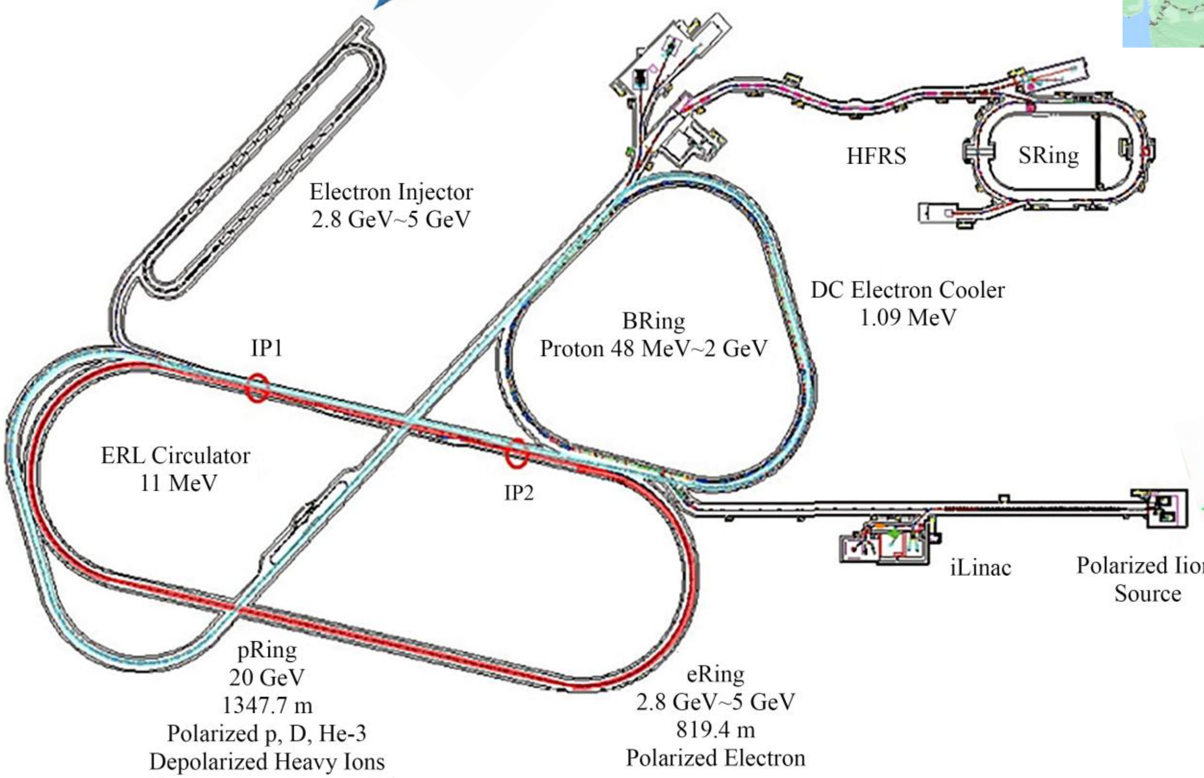
quark with spin parallel to the nucleon spin in a transversely polarised nucleon

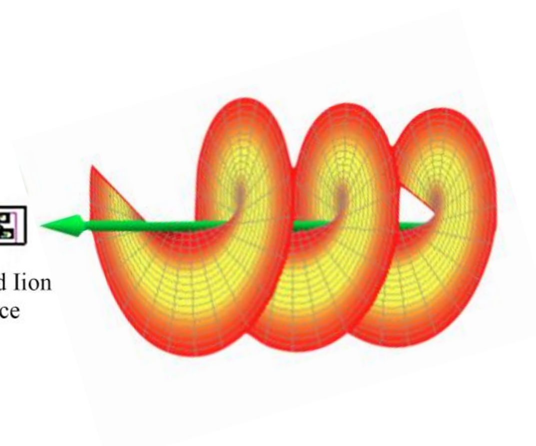
still unkown

Anna Martin

Electron-ion collider with twist states（TEIC)

- **EIC with twist electrons and twist ions**





Thanks !