An introduction to EIC Physics

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Outline:

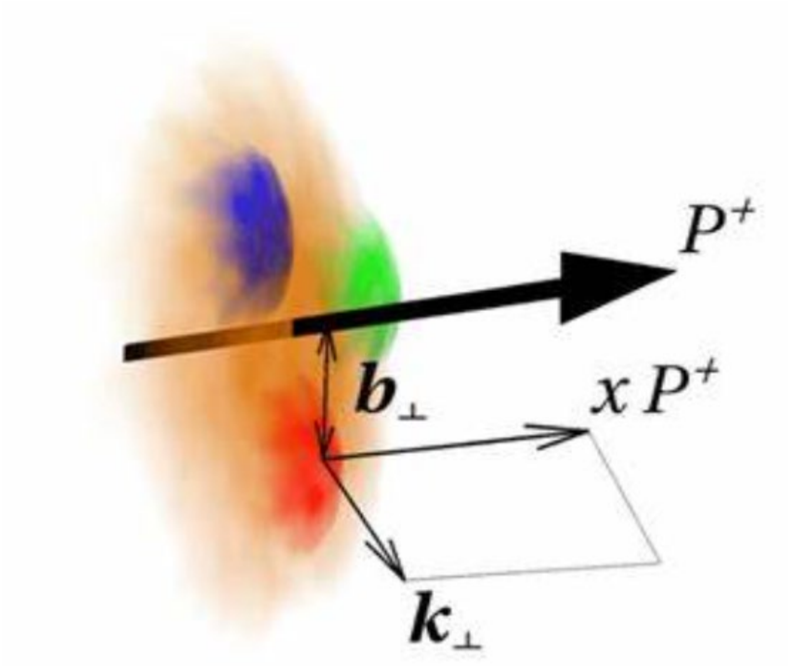
- 3D imaging of proton
- Origin of proton mass and spin
- Small x physics

Disclaimer : Many interesting topics not covered: proton radius puzzle, Quasi PDFs…

3D imaging of proton

3D imaging in momentum space: TMDs

- The "simplest" TMD is the unpolarized function $f_1(x; k_T)$, 8 leading power TMDs



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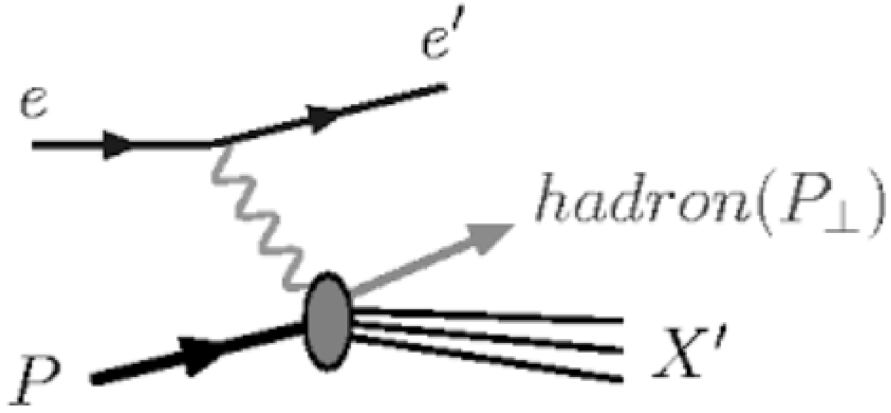


$$\int \frac{dy^- d^2 y_\perp}{(2\pi)^3} e^{-ixP^+ \cdot y^- + i\vec{k}_\perp \cdot \vec{y}_\perp} \langle PS | \overline{\psi}_\beta(y^-, y_\perp) \mathcal{L}_v^\dagger(y^-, y_\perp) \mathcal{L}_v(0) \psi_\alpha(0) | PS \rangle$$

- TMD factorization: Collins-Soper 1981, Collins-Soper-Sterman 1985 , kt<<Q

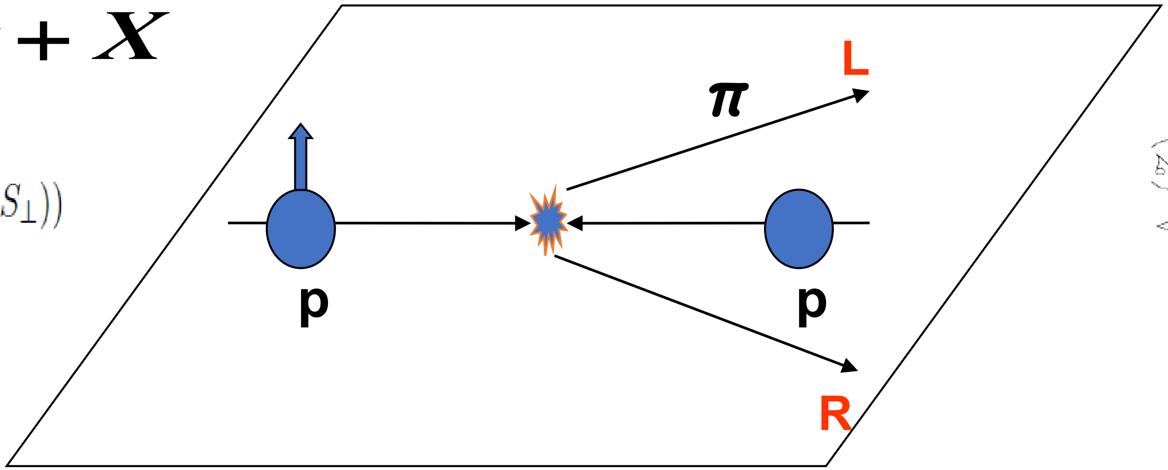
Why TMDs?

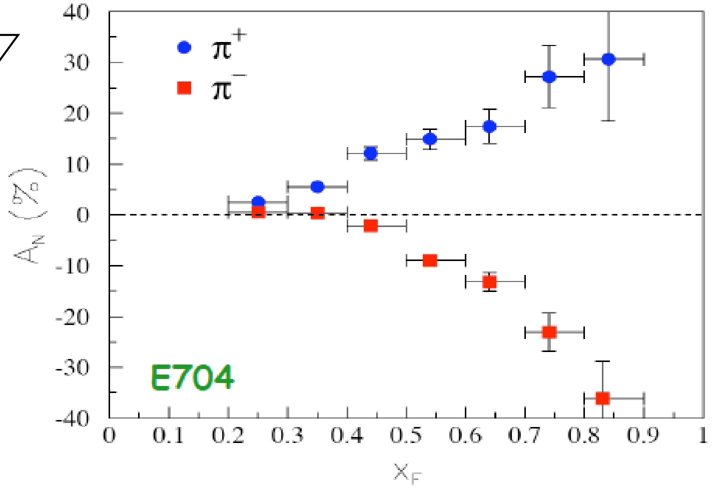
- Phenomenogical needs
- Confined motion of partons inside proton
- Access to orbital angular momentum
- Universality issue, QCD factorization

Transverse single spin asymmetry

$$p(\uparrow) + p \rightarrow \pi + X$$

$$A_N \equiv (\sigma(S_\perp) - \sigma(-S_\perp))/(\sigma(S_\perp) + \sigma(-S_\perp))$$

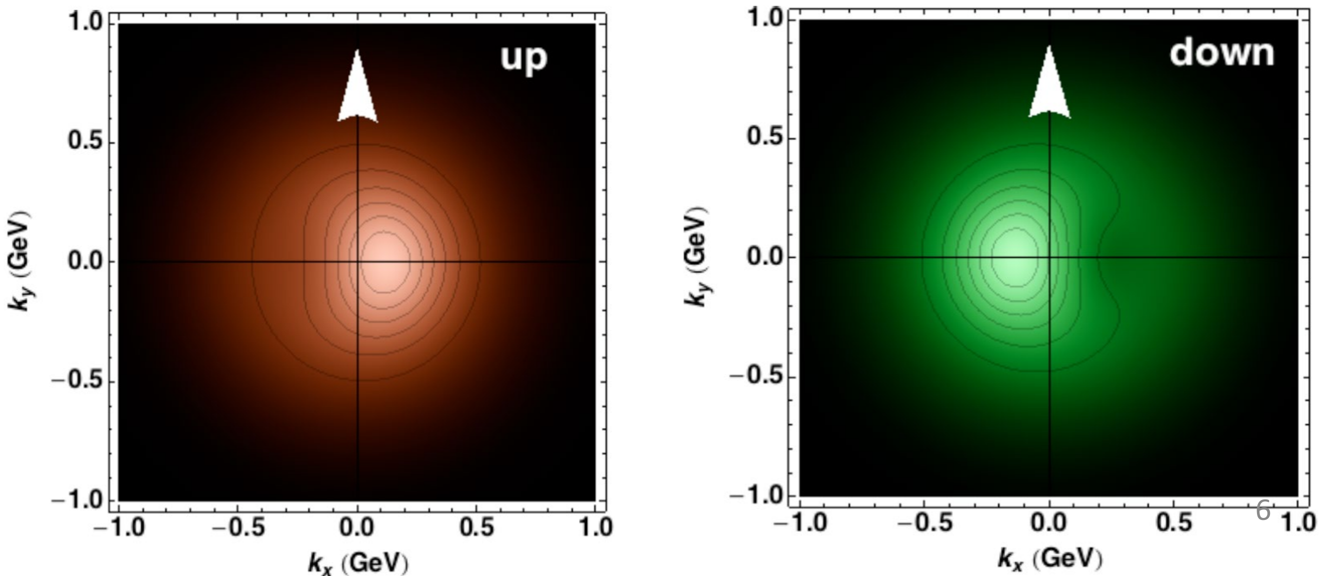




- **The Sivers function** $f_{1T}^{\perp}(x, k_T)$

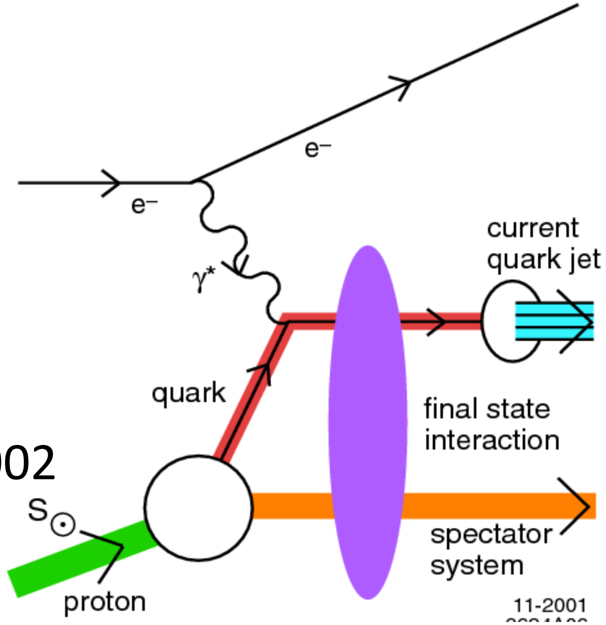
描述夸克横动量与质子横向自旋的关联

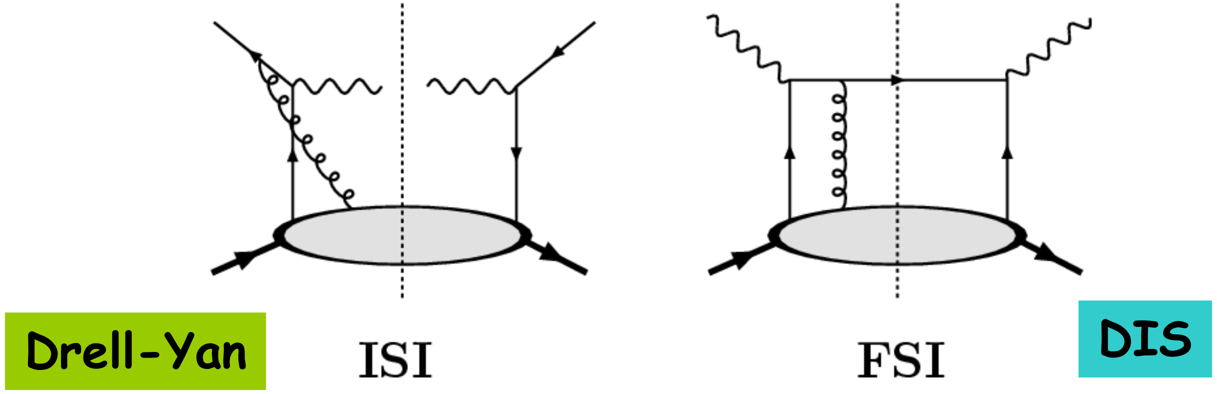
$$k_\perp \times S_\perp$$



The legend of the Sivers function

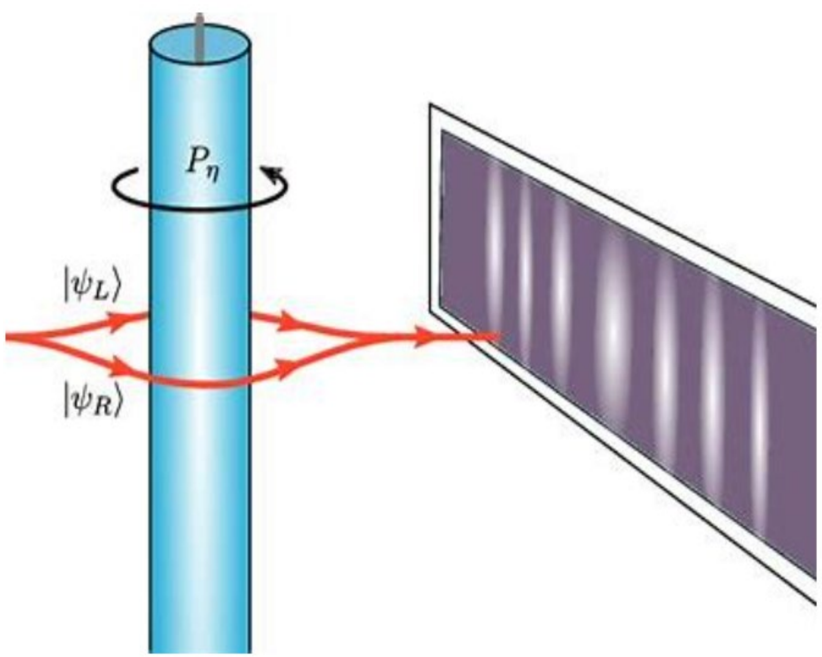
- The introduction of the Sivers function
  Sivers 1990
- Proof it is zero using time&parity invariance of QCD,
  Collins 1993
- Non-vanishing Sivers function in a model calculation,
  Brodsky-Hwang-Schmidt 2002
- Including gauge link contribution, prove :
  Collins 2002

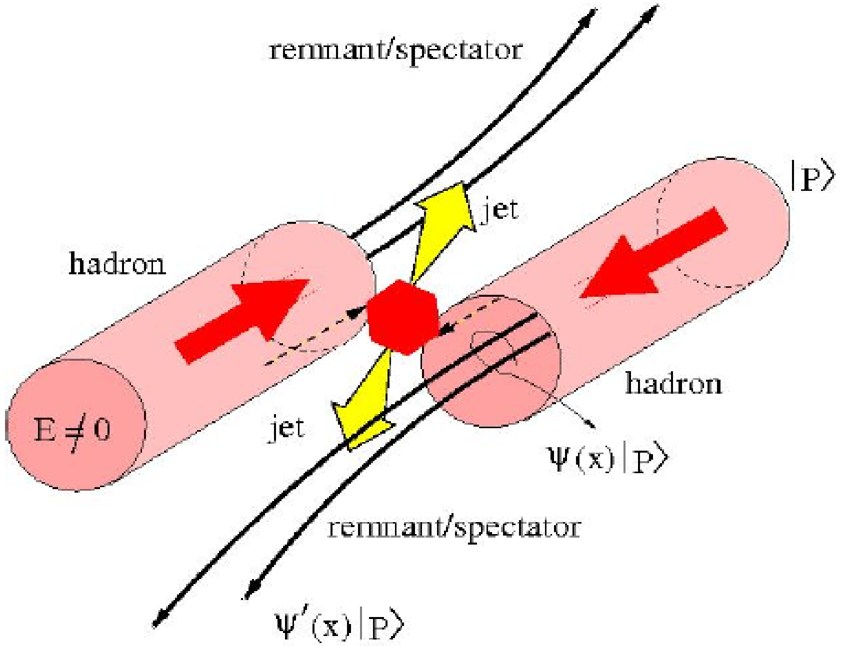




$$\mathrm{Sivers}|_{\mathrm{DY}} = -\mathrm{Sivers}|_{\mathrm{DIS}}$$

QCD Aharonov-Bohm effect





$$\psi' = e^{ie\int ds.A}\psi \qquad \psi_i(x)\left|P\right\rangle = e^{-ig\int_x^{x'} ds_\mu A^\mu}\,\psi_i(x')\left|P\right\rangle$$

Gauge link (Wilson line), pure gauge gluon

- S and P wave interference

Boris, Liang 1993
Belitsky, Ji, Yuan, 2004

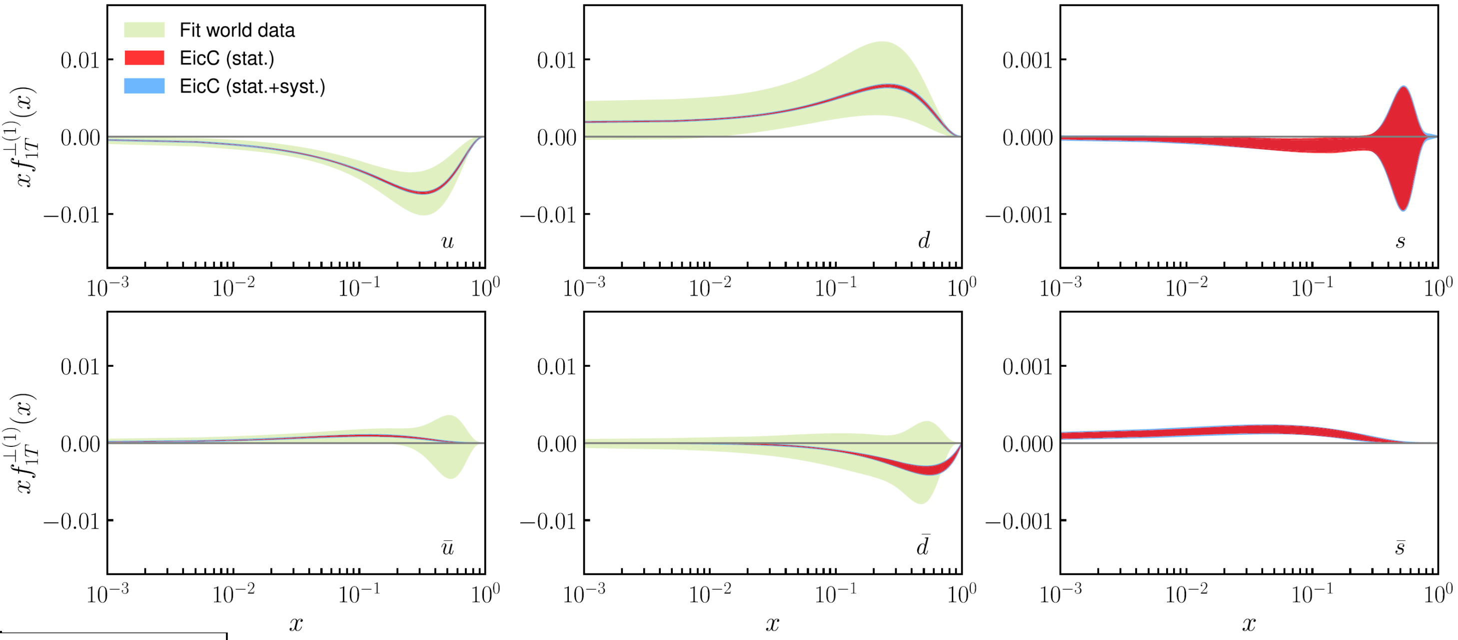
Zoo of TMDs

		Quark Polarization		
		U	L	T
Nucleon Polarization	U	f_1 unpolarized		$h_1^{\perp}$ Boer-Mulders
	L		g_{1L} helicity	$h_{1L}^{\perp}$ longi-transversity (worm-gear)
	T	$f_{1T}^{\perp}$ Sivers	g_{1T} trans-helicity (worm-gear)	h_1 transversity $h_{1T}^{\perp}$ pretzelosity

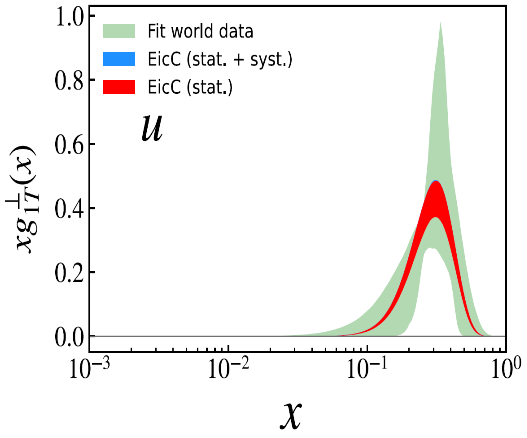
Polarization dependent TMD distributions

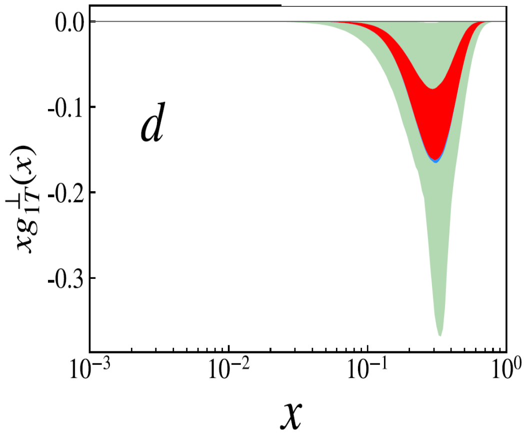
- Each TMD reflects a unique underlying physics and characterizes a facet of proton structure.
- Many accelerator facilities are dedicated to measuring TMDs（HERA, RHIC，JLAB, COMPASS, **EIC, EicC**)

Sivers function

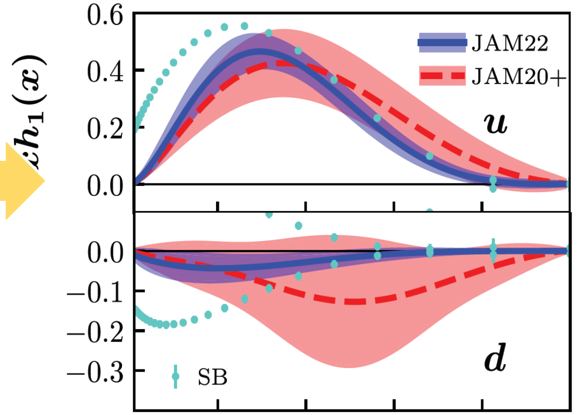


Worm-gear distribution





Transversity distribution

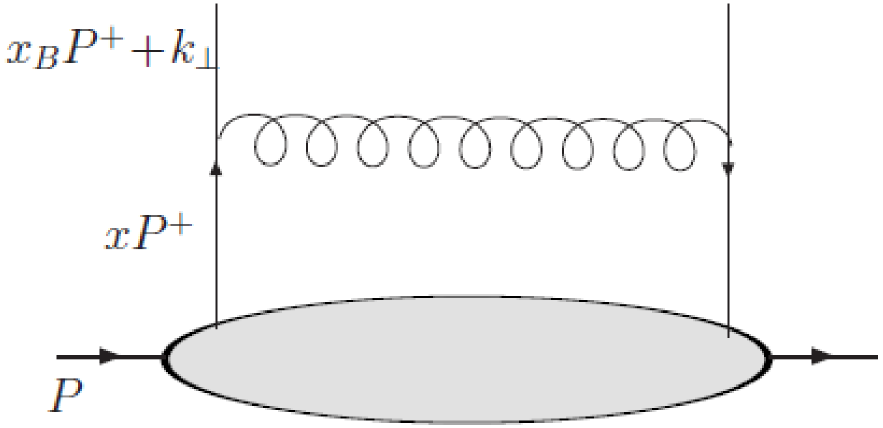


Courtesy of Tianbo Liu

TMD: a PQCD playground

TMD dynamics at large kt

- TMD distributions can be calculated within perturbative QCD at large kt,



radiated gluon generate large transverse momentum,

$$f_1(x_B, k_\perp) = \frac{\alpha_s}{2\pi^2}\frac{1}{\vec{k}_\perp^2}C_F\int\frac{dx}{x}f_1(x)\left[\frac{1+\xi^2}{(1-\xi)_+}+\delta(1-\xi)\left(\ln\frac{x_B^2\zeta^2}{\vec{k}_\perp^2}-1\right)\right]$$

TMD evolution: resum to all orders using the Collins-Soper equation

kt-odd TMD distributions at large Kt at twsit-3

- Sivers and Boer-Mulders

$$f_{1T}^{\perp}|_{\rm DY}(x_B,k_\perp) = \frac{\alpha_s}{\pi}\frac{M^2}{(\vec{k}_\perp^2)^2}\int\frac{dx}{x}\left[A_{f_{1T}^\perp} + C_F T_F(x,x)\delta(1-\xi)\left(\ln\frac{x_B^2\zeta^2}{\vec{k}_\perp^2}-1\right)\right]$$

$$h_1^{\perp}|_{\rm DY}(x_B,k_\perp) = \frac{\alpha_s}{\pi}\frac{M^2}{(\vec{k}_\perp^2)^2}\int\frac{dx}{x}\left[A_{h_1^\perp} + C_F T_F^{(\sigma)}(x,x)\delta(1-\xi)\left(\ln\frac{x_B^2\zeta^2}{\vec{k}_\perp^2}-1\right)\right]$$

Ji, Qiu, Vogelsang, Yuan

ZJ, Yuan, Liang,2009

- g_{1T} and h_{1L}

$$g_{1T}(x_B,k_\perp) = \frac{\alpha_s}{\pi^2}\frac{M^2}{(k_\perp^2)^2}\int\frac{dx}{x}\left\{A_{g_{1T}} + C_F\tilde{g}(x)\delta(\xi-1)\left(\ln\frac{x_B^2\zeta^2}{k_\perp^2}-1\right)\right\}$$

$$h_{1L}(x_B,k_\perp) = \frac{\alpha_s}{\pi^2}\frac{M^2}{(k_\perp^2)^2}\int\frac{dx}{x}\left\{A_{h_{1L}} + C_F\tilde{h}(x)\delta(\xi-1)\left(\ln\frac{x_B^2\zeta^2}{k_\perp^2}-1\right)\right\}$$

ZJ, Yuan, Liang, 2009

$$A_{f_{1T}^\perp} = -\frac{1}{2N_c}T_F(x,x)\frac{1+\xi^2}{(1-\xi)_+} + \frac{C_A}{2}T_F(x,x_B)\frac{1+\xi}{(1-\xi)_+} + \frac{C_A}{2}\tilde{T}_F(x_B,x)$$

$$A_{h_1^\perp} = -\frac{1}{2N_c}T_F^{(\sigma)}(x,x)\frac{2\xi}{(1-\xi)_+} + \frac{C_A}{2}T_F^{(\sigma)}(x,x_B)\frac{2}{(1-\xi)_+} \ .$$

$$\begin{aligned} A_{g_{1T}} = & \int dx_1\left\{\frac{1}{2N_C}\tilde{g}(x)\frac{1+\xi^2}{(1-\xi)_+}\delta(x_1-x)\right. \\ & + \left[C_F\left(\frac{x_B^2}{x^2}+\frac{x_B}{x_1}-\frac{2x_B^2}{x_1 x}-\frac{x_B}{x}-1\right)+\frac{C_A}{2}\frac{(x_B^2+xx_1)(2x_B-x-x_1)}{(x_B-x_1)(x-x_1)x_1}\right]\tilde{G}_D(x,x_1 \\ & + \left.\left[C_F\left(\frac{x_B^2}{x^2}+\frac{x_B}{x_1}-\frac{x_B}{x}-1\right)+\frac{C_A}{2}\frac{x_B^2-xx_1}{(x_1-x_B)x_1}\right]G_D(x,x_1)\right\} \qquad (\end{aligned}$$

$$\begin{aligned} A_{h_{1L}} = & \int dx_1\left\{\frac{1}{2N_C}\tilde{h}(x)\frac{2\xi}{(1-\xi)_+}\delta(x_1-x)\right. \\ & + \left.\left[C_F\frac{2(x-x_1-x_B)}{x_1}+\frac{C_A}{2}\frac{2x_B(x_Bx+x_Bx_1-x^2-x_1^2)}{(x_B-x_1)(x-x_1)x_1}\right]H_D(x,x_1)\right\} \ . \end{aligned}$$

TMD evolution

Two scales problem(formulated in bt space):

$$\frac{d\ln \tilde{f}(x,b;\zeta,\mu)}{d\ln\sqrt{\zeta}} = \tilde{K}(b;\mu), \qquad \frac{d\ln \tilde{f}(x,b;\zeta,\mu)}{d\ln\mu} = \gamma_F(g(\mu);\zeta/\mu^2)$$

Collins Soper(CS) equation

Renormalization group equation

J. Collins, D. Soper , 1982; J. Collins, D. Soper, G. Sterman 1985

Recent developments:

- Joint small x & TMD resummation, ZJ, 2016, Xiao, Yuan, ZJ 2017, ZJ 2019

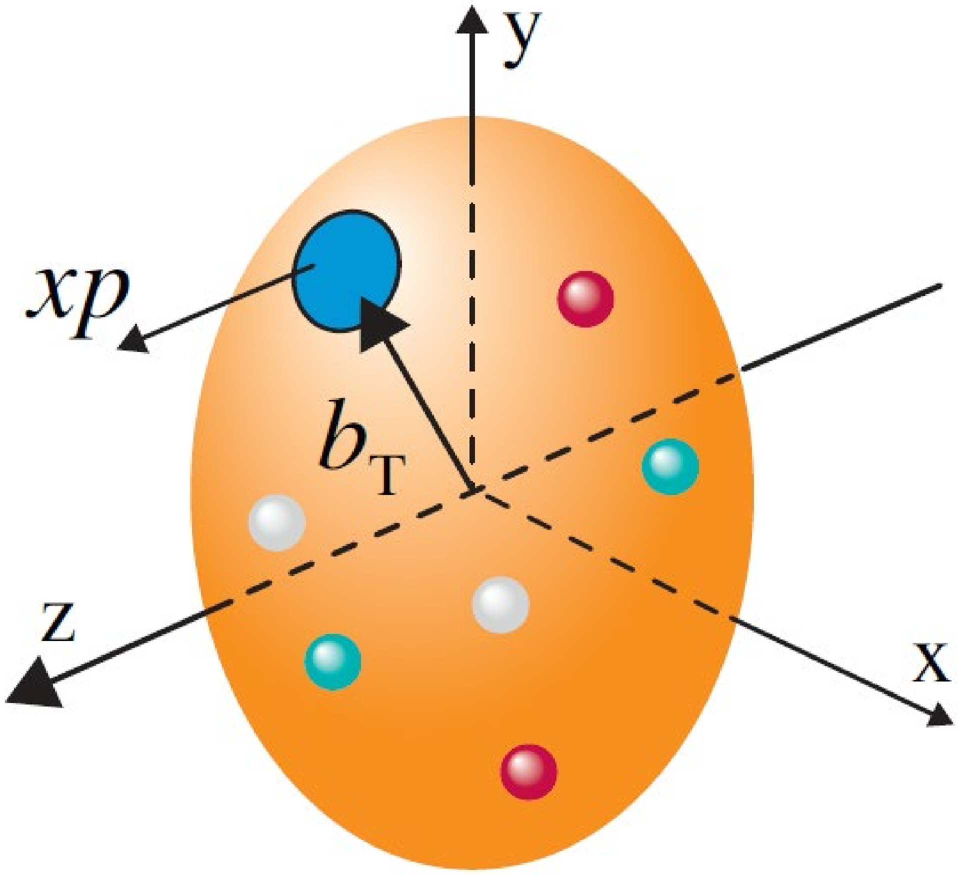
$$xG^{(1)}(x,k_\perp,\zeta) = -\frac{2}{\alpha_S}\int \frac{d^2x_\perp d^2y_\perp}{(2\pi)^4} e^{ik_\perp\cdot r_\perp}\mathcal{H}^{WW}(\alpha_s(Q))e^{-S_{sud}(Q^2,r_\perp^2)}\mathcal{F}^{WW}_{Y=\ln 1/x}(x_\perp,y_\perp)$$

- Joint threshold & TMD resummation Kang, Lee, Shao, Zhao 2023

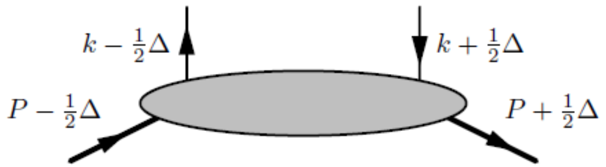
Spatial imaging of Quarks and Gluons

- Longitudinal momentum distribution + transverse spatial distribution: $f(x,b_T)$

- Remark: $f(x,b_T)$ and $f(x,k_T)$ are not related to each other by a Fourier transform



Generalized Parton Distributions(GPDs)



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

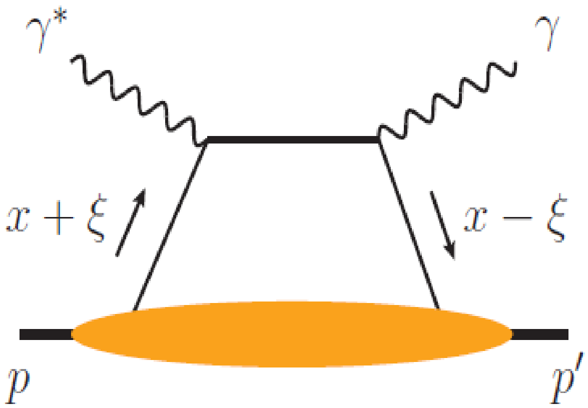
$$x, \zeta, t$$

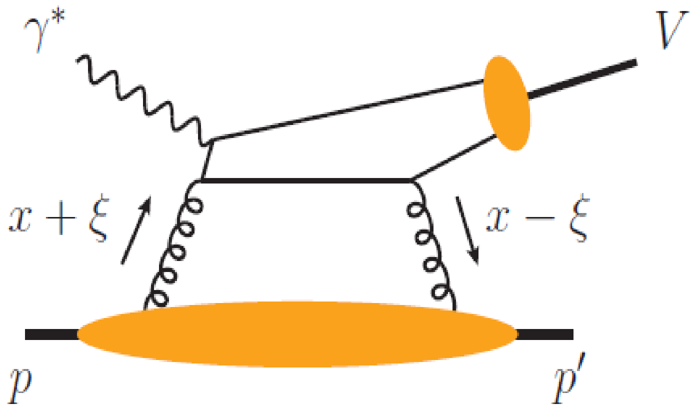
D. Muller, 94
X. D. Ji, 97
A. V. Radushkin, 97

$$\int \frac{d\lambda}{2\pi} e^{ix(Pz)} n_{-\alpha} n_{-\beta} \langle p' | G^{\alpha\mu}\left(-\frac{z}{2}\right) G^{\beta}_{\mu}\left(\frac{z}{2}\right) | p \rangle \Big|_{z=\lambda n_-} = \frac{1}{2}\left[H^g\, \bar{u}(p')\, \not{n}_- u(p) + E^g\, \bar{u}(p') \frac{i\sigma^{\alpha\beta} n_{-\alpha} \Delta_\beta}{2\, m_N} u(p) \right]$$

- Transverse spatial distribution $\mathcal{H}^q(x, \vec{b}_T^2) = \int \frac{d^2 \vec{\Delta}_T}{(2\pi)^2} e^{-i\vec{\Delta}_T \cdot \vec{b}_T} H^q(x, 0, -\vec{\Delta}_T^2)$ Soper 77 & Burkardt 2000

DVCS





5D imaging of proton

Parton Wigner distributions

In quantum mechanics:

$$\widehat{W}^{[\Gamma]}(\vec{b}_\perp,\vec{k}_\perp,x)\equiv\frac{1}{2}\int\frac{\mathrm{d}z^-\,\mathrm{d}^2z_\perp}{(2\pi)^3}\,e^{i(xp^+z^- - \vec{k}_\perp\cdot\vec{z}_\perp)}\,\overline{\psi}(\vec{b}_\perp - \tfrac{z}{2})\Gamma\mathcal{W}\,\psi(\vec{b}_\perp + \tfrac{z}{2})\big|_{z^+=0}$$

Operator definition:

$$\rho^{[\Gamma]}(\vec{b}_\perp,\vec{k}_\perp,x,\vec{S})\equiv\int\frac{\mathrm{d}^2\Delta_\perp}{(2\pi)^2}\,\langle p^+,\tfrac{\vec{\Delta}_\perp}{2},\vec{S}|\widehat{W}^{[\Gamma]}(\vec{b}_\perp,\vec{k}_\perp,x)|p^+,-\tfrac{\vec{\Delta}_\perp}{2},\vec{S}\rangle.$$

A. Belitisky, X. D. Ji and F. Yuan, 2003

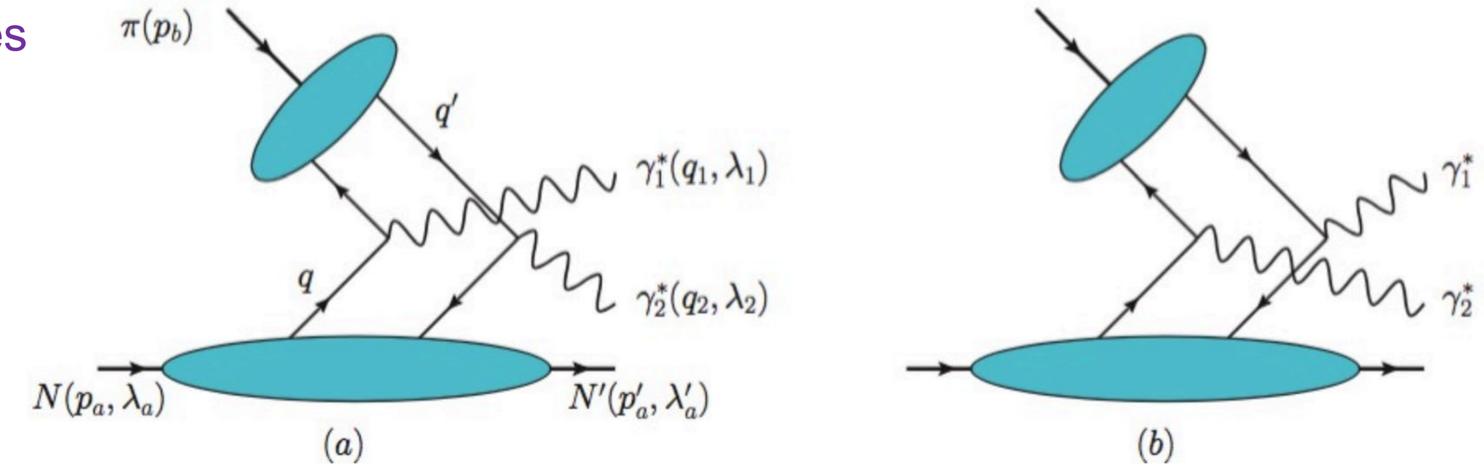
Motivations of studying parton Wigner distributions:

- tomography picture of nucleon
- encode information on parton OAM

Are they measurable?

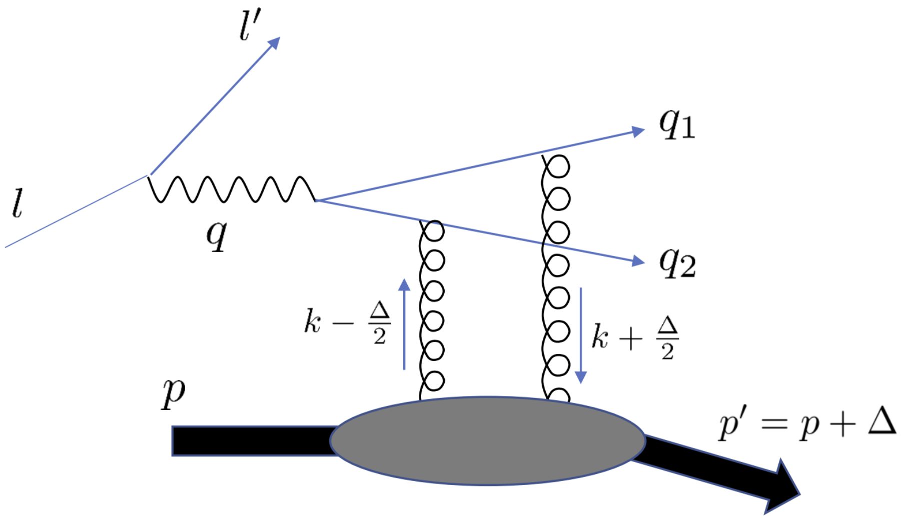
Exclusive double Drell-Yan process

Quark case: exclusive double DY proces

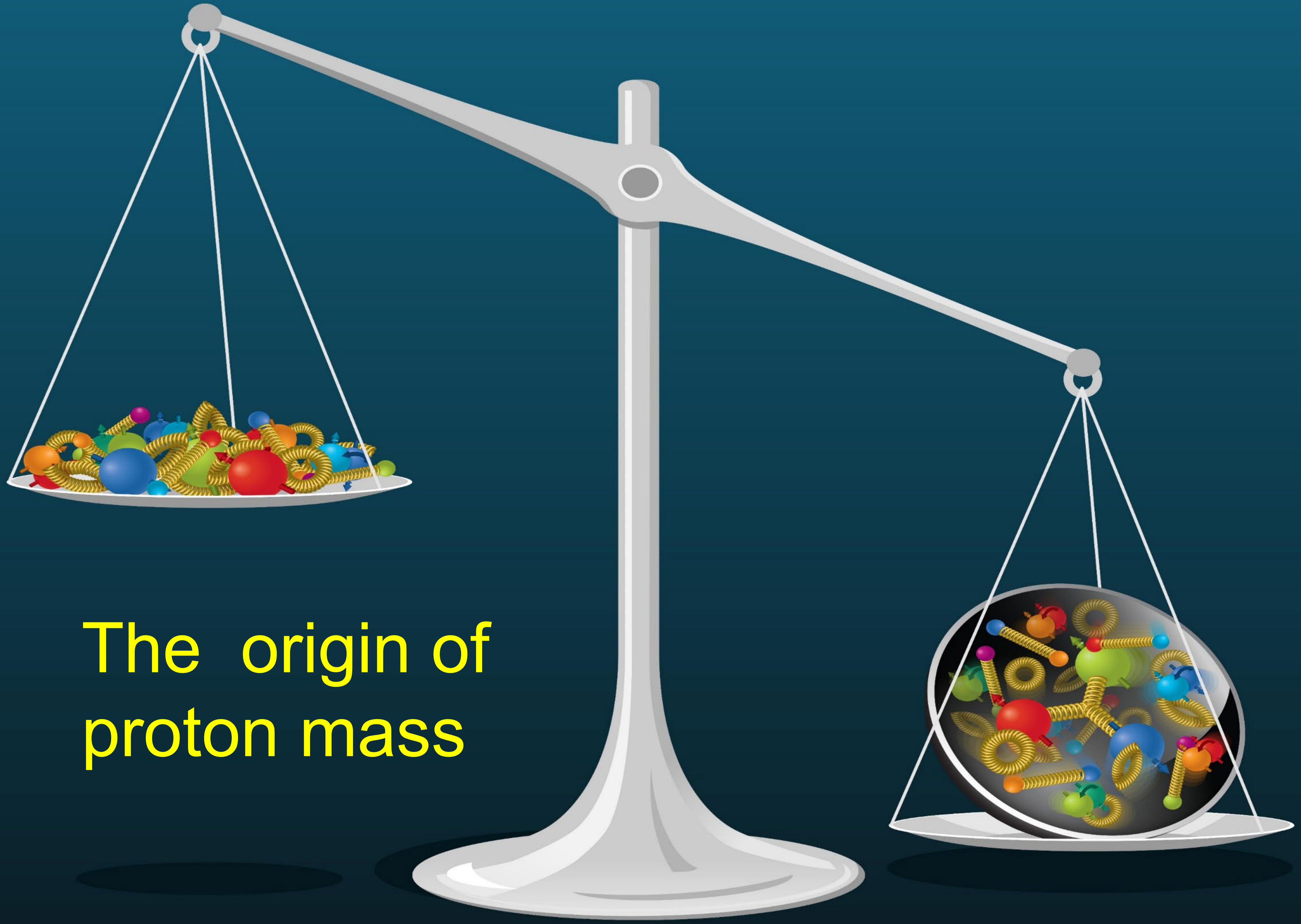


Bhattacharya, Metz, ZJ 2017

Gluon case: diffractive di-jet production

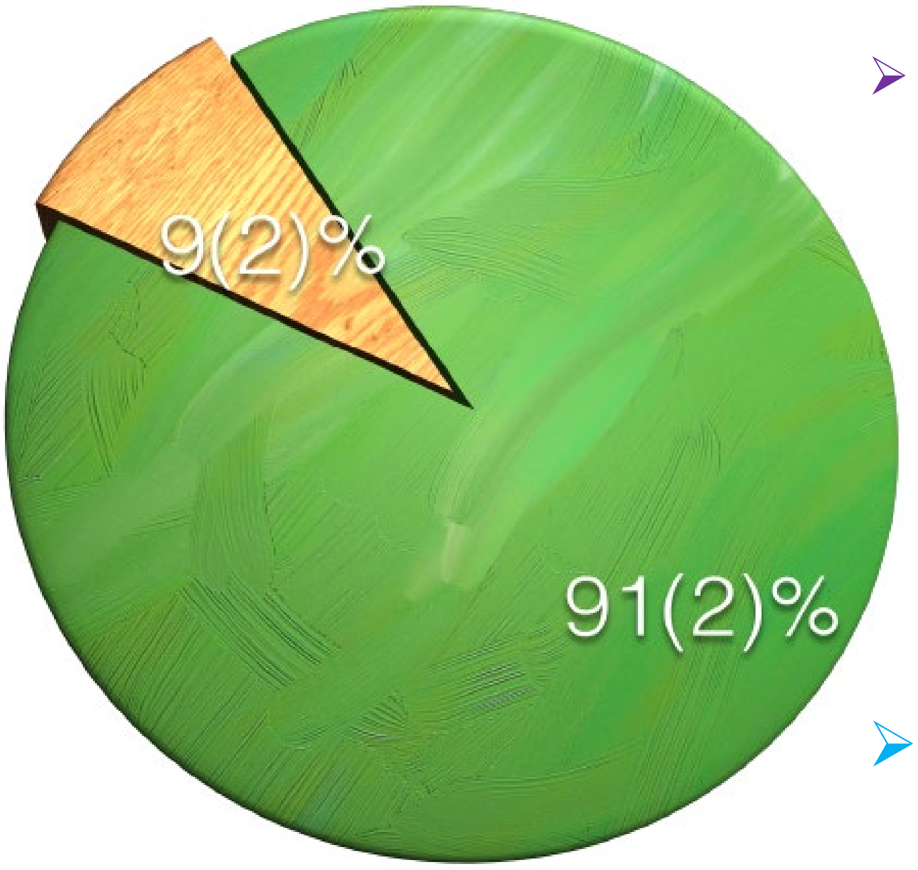


Hatta-Nakagawa-Yuan-Zhao-Xiao, 2017



The origin of proton mass

Proton mass budget



Lattice result

- Mass from Quark and gluon kinetic energy accessible via PDF

$$\int_0^1 dx\, xq(x) \qquad \int_0^1 dx\, xg(x)$$

◆ In the massless limit: m_q=0:

- Quark&Gluon kinetic energy make up ¾ proton mass.
- Trace anomaly contributes to another ¼ proton mass.

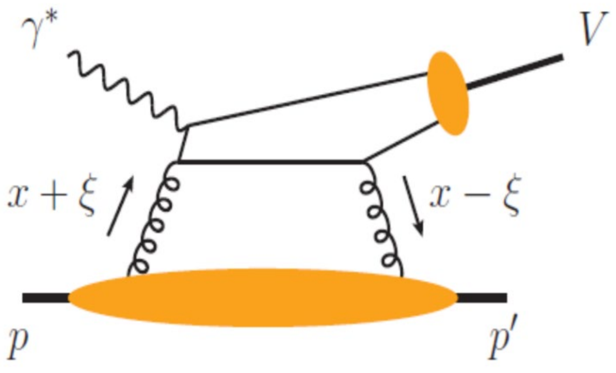
Collins, Duncan, Joglekar, 1977
Nielsen, 1977

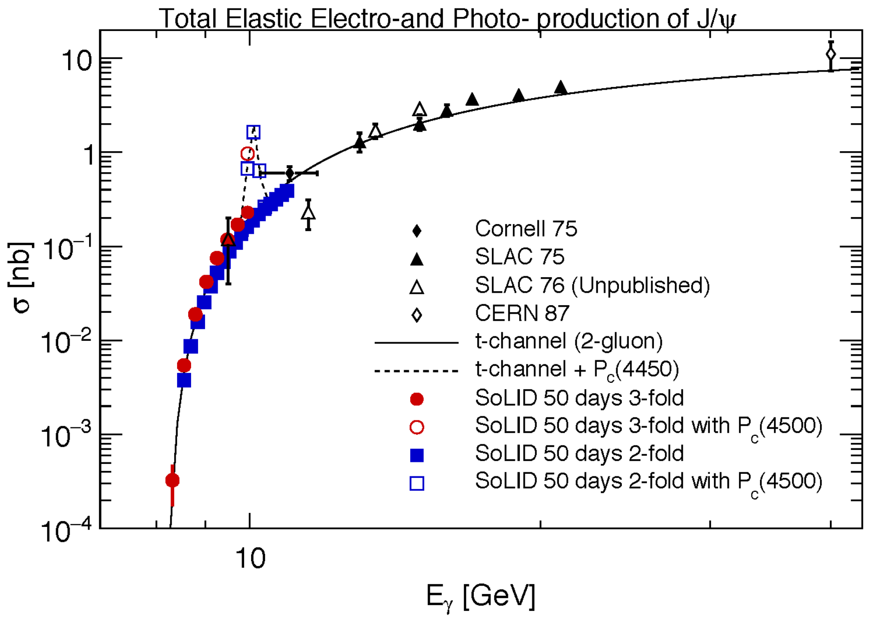
How to measure trace anomaly

- Twist-4 operator: $\langle P'|F^{\mu\nu}F_{\mu\nu}|P\rangle$

- Threshold J/psi production

Kharzeev,Satz,Syamtomov, 1998





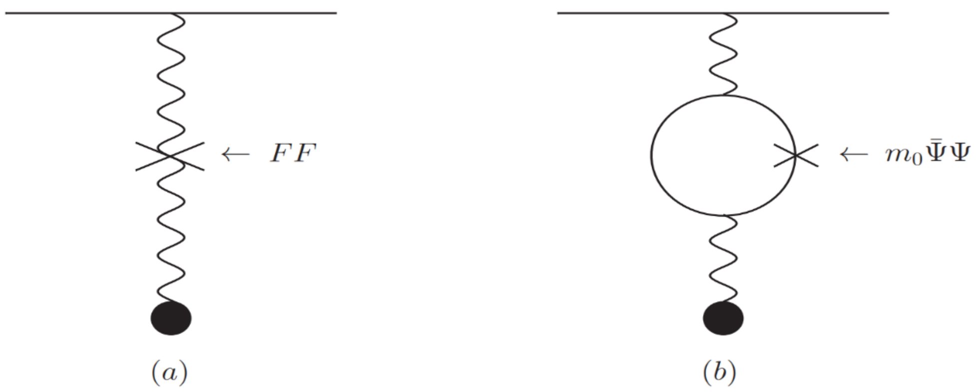
- Extractions: Xu-Xie-Wang-Chen, 2020
  Wang-Bu-Zeng, 2022

- Intense debates:

  Hatta, Ji, Ma, Sun, Tong, Yuan.....

Perturbative calculation of trace anomaly

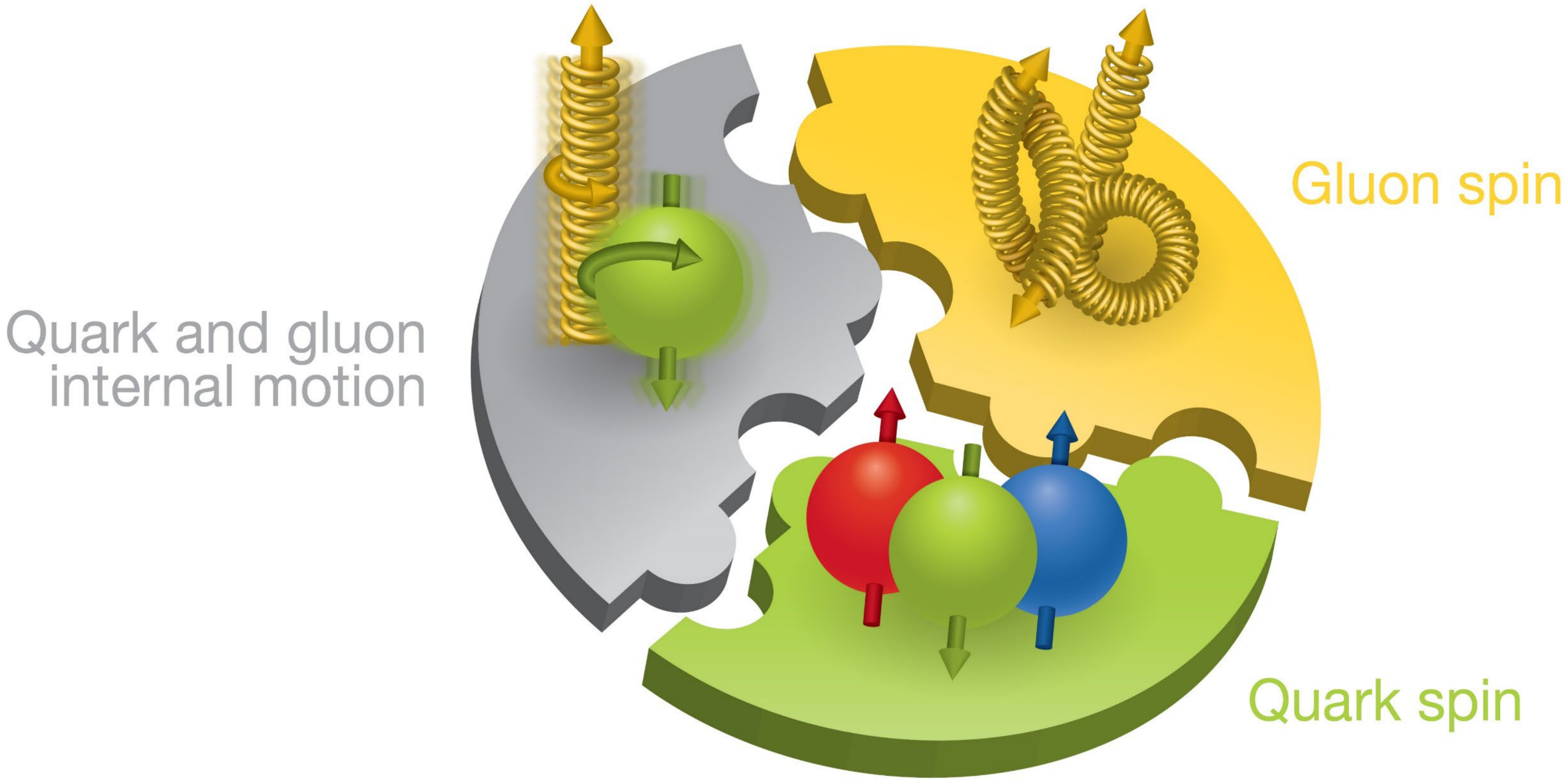
- Trace anomaly contribution to hydrogen atom mass



$$8\alpha_{em}^2\int d^3y\int\frac{d^3q}{(2\pi)^3}e^{i\vec{q}\cdot\vec{y}}\int_0^1 da\frac{a^2(1-a)^2}{m^2}\varphi_0^\dagger(y)\varphi_0\,(y)=\frac{-4\alpha_{em}^2}{15m^2}\varphi_0^\dagger(0)\varphi_0\,(0)$$

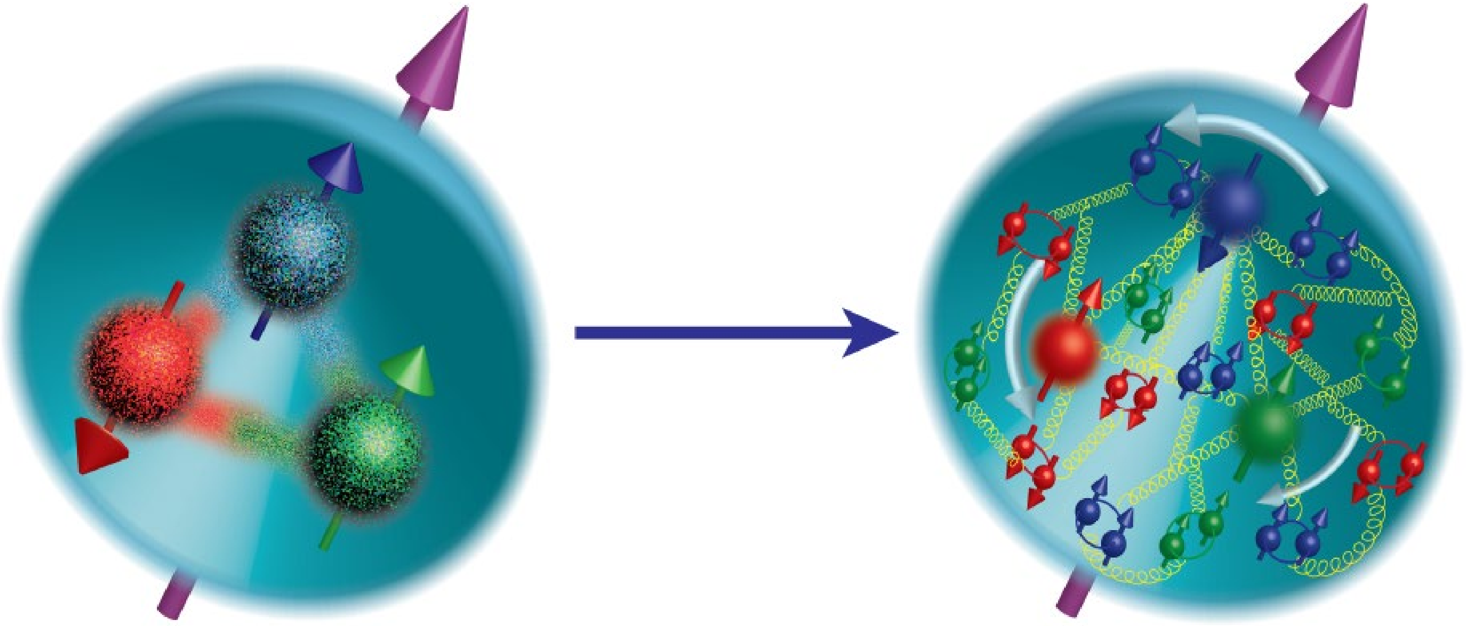
- Related to the **Lamb shift.** Sun-Sun-ZJ, 2020

Proton spin decomposition



Proton spin sum rule

$$J = \frac{1}{2}\Delta\Sigma(Q^2) + \mathrm{L}_q(Q^2) + \Delta G(Q^2) + \mathrm{L}_g(Q^2) = \frac{1}{2}$$



Parton orbital angular momentum

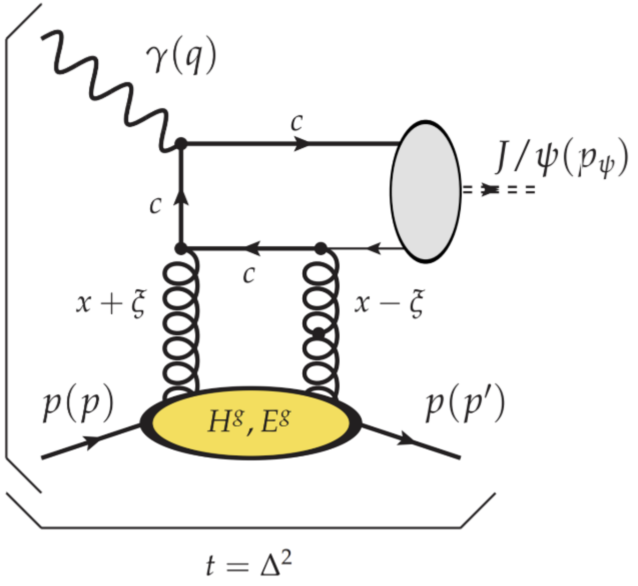
- The total angular momentum is related to the GPD:

$$J_q = \lim_{t\to 0} \frac{1}{2}\int_0^1 dx x[H_q(x,t,\xi) + E_q(x,t,\xi)]$$

Ji, 1997

- SSA in exclusive process

$$A_N^\gamma = \frac{\frac{1}{2m_N}(1+\xi)|\Delta_T|\sin(\phi_{\vec{\Delta}})\,\Im(\mathcal{H}^g\mathcal{E}^{g\star})}{(1-\xi^2)|\mathcal{H}^g|^2 + \frac{\xi^4}{1-\xi^2}|\mathcal{E}^g|^2 - 2\xi^2\Re(\mathcal{H}^g\mathcal{E}^{g\star})}$$



Koempel, Kroll, Metz, ZJ, 2012

Small x asymptotic behavior of gluon OAM

- Never can reach x=0 at any experiment, how to extrapolate down to x=0

- Small x evolution equation for Eg(x)

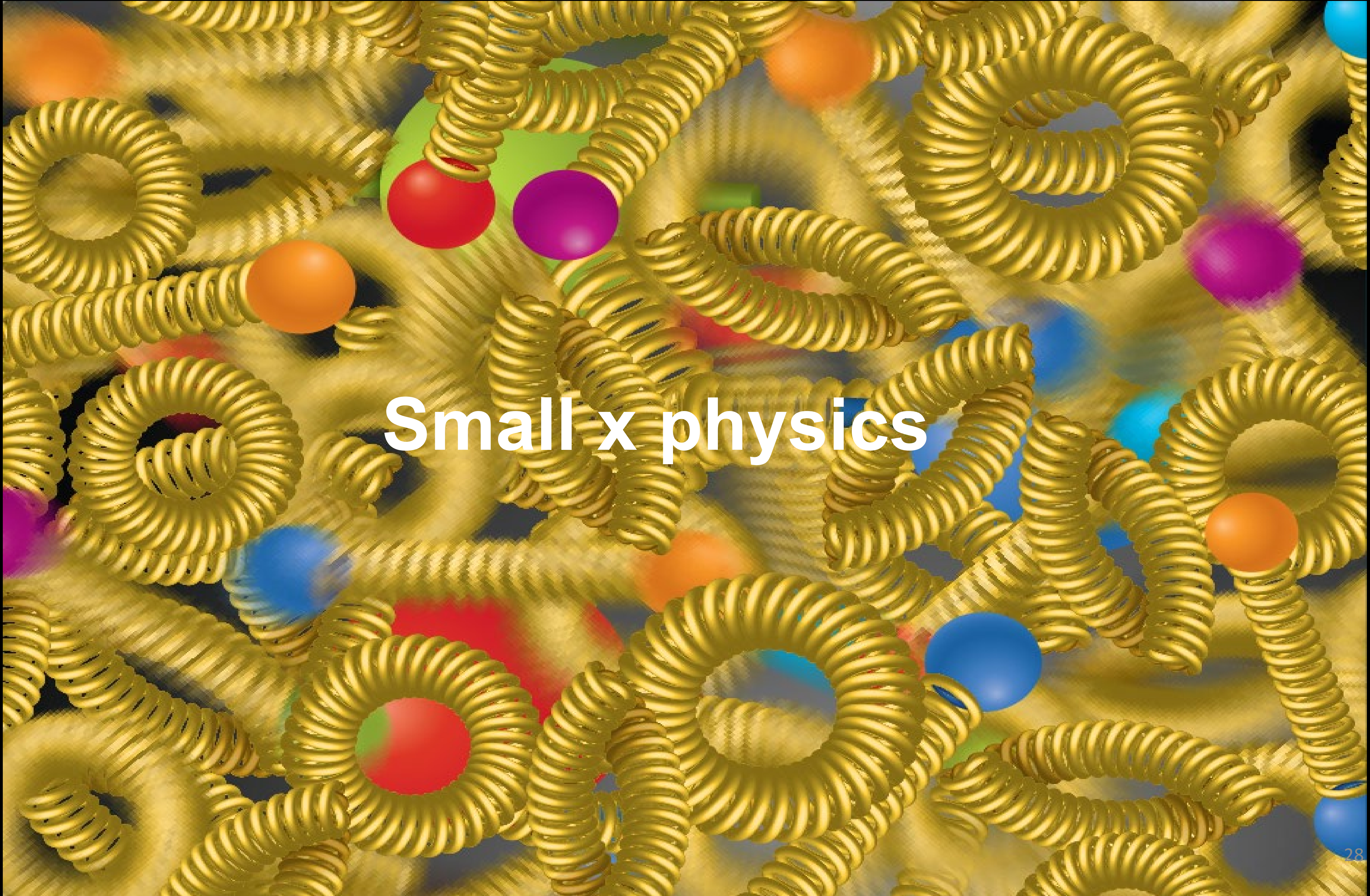
$$\partial_Y \mathcal{E}(k_\perp) = \frac{\bar{\alpha}_s}{\pi} \int \frac{d^2 k'_\perp}{(k_\perp - k'_\perp)^2} \left[\mathcal{E}(k'_\perp) - \frac{k_\perp^2}{2k'^2_\perp} \mathcal{E}(k_\perp) \right] - 4\pi^2 \alpha_s^2 \overline{\mathcal{F}}_{1,1}(k_\perp) \mathcal{E}(k_\perp)$$

Hatta, ZJ, 2022

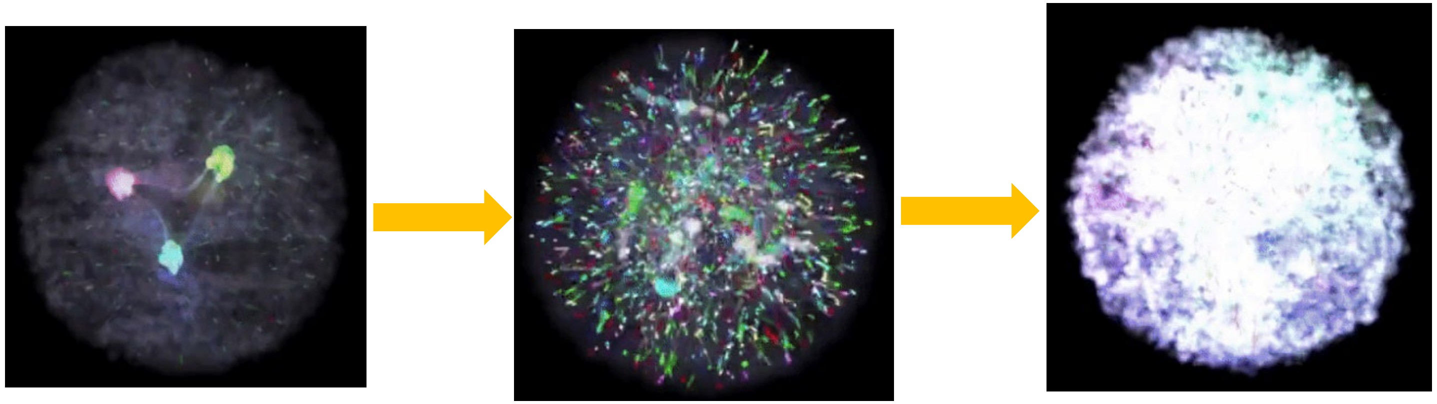
Conclusion: Eg(x) rises as rapidly as the normal unpolarized gluon distribution!

$x^{-0.3}$

Small x physics



色玻璃凝聚态（Color glass condensate）



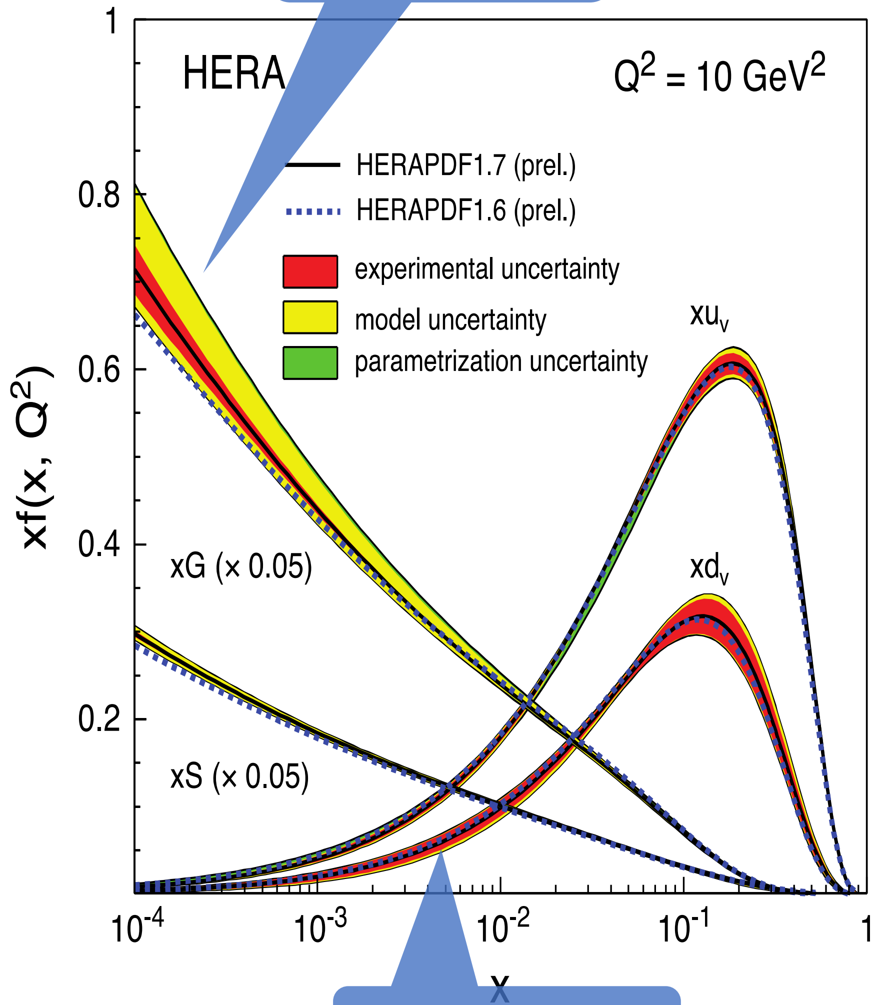
x=0.3　　x=0.01　　x=0.0001

$$P_{gg}(x) \sim \frac{1}{x} \text{ for } x \to 0$$

- 极高密度胶子物质，新的物质形态
- 微扰QCD在小x区有更强的预言力

◆ LHC、RHIC的重要物理研究内容，EIC的核心科学目标

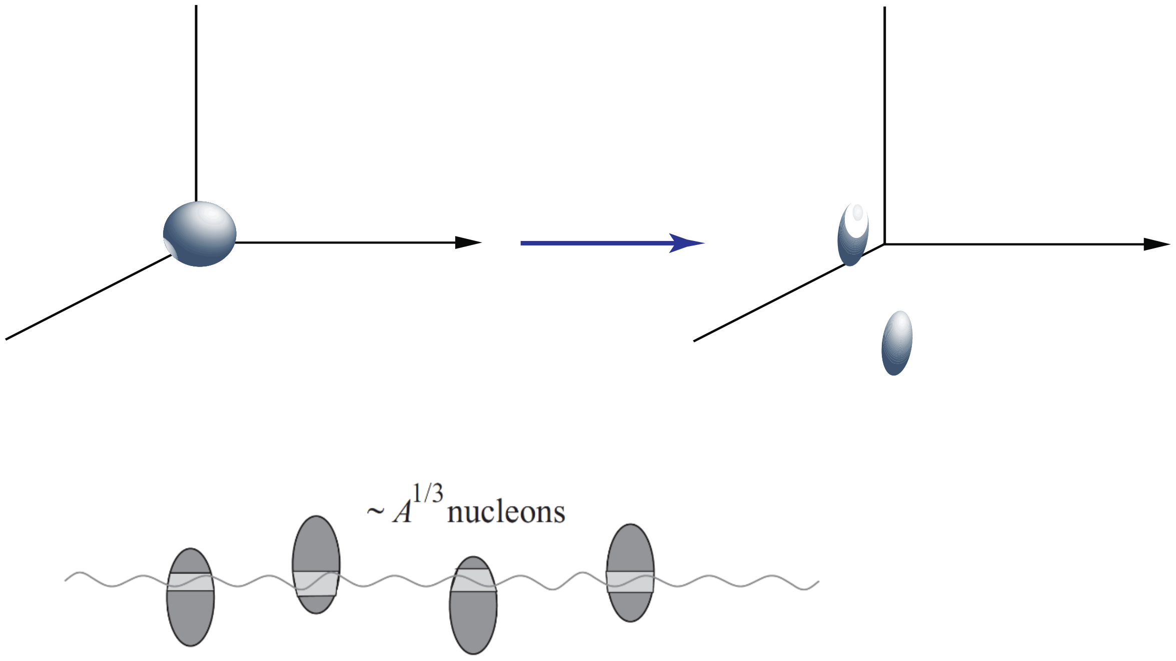
缩小20倍的胶子分布函数

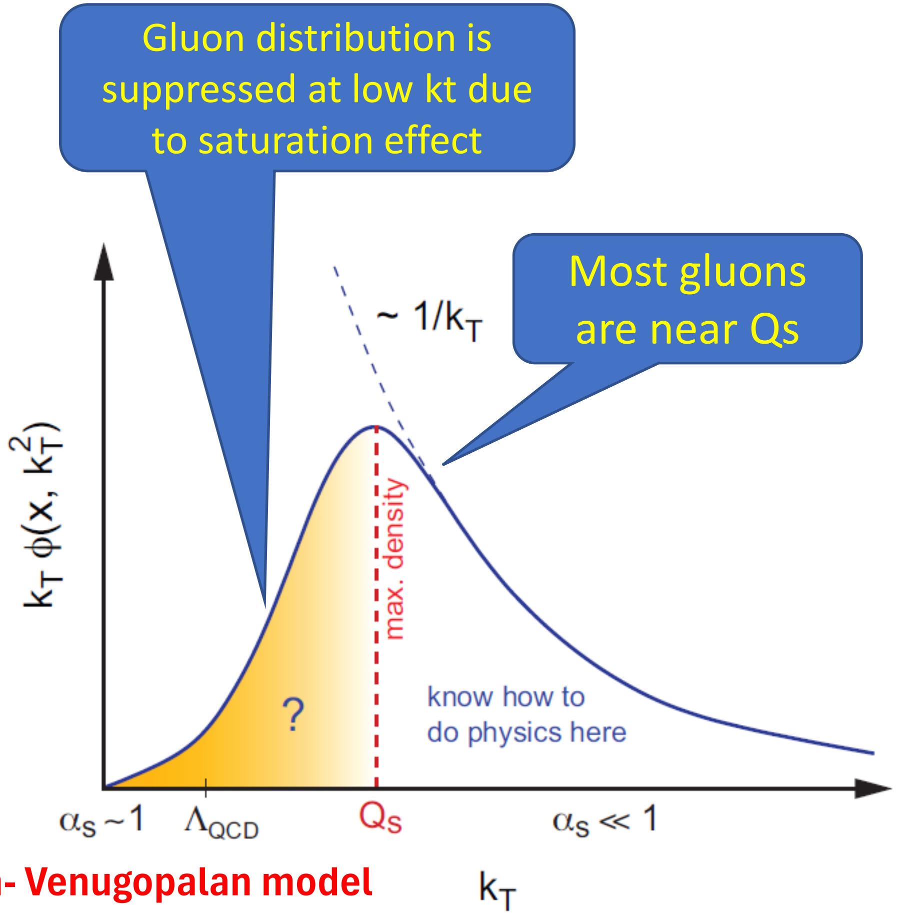


夸克分布函数

Saturation scale

- To reach high gluon density: very small x & large nucleus





McLerran- Venugopalan model

- Small x gluons(with long wave length) from different nucleons overlap with each other!

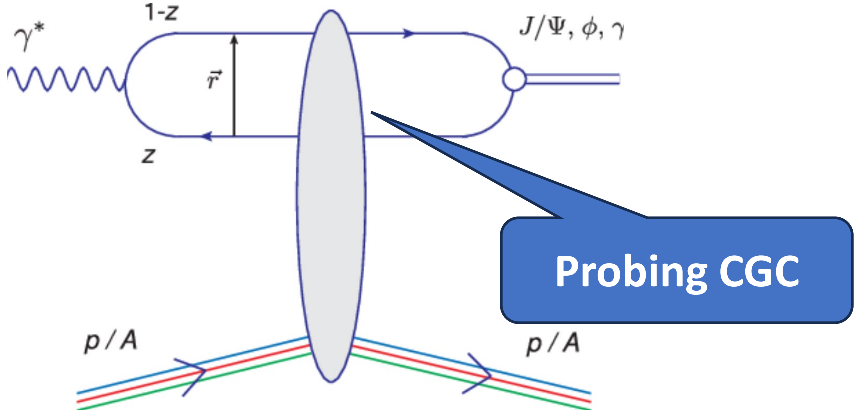
$$Q_s^2(x) \sim \left(\frac{A}{x}\right)^{1/3}$$

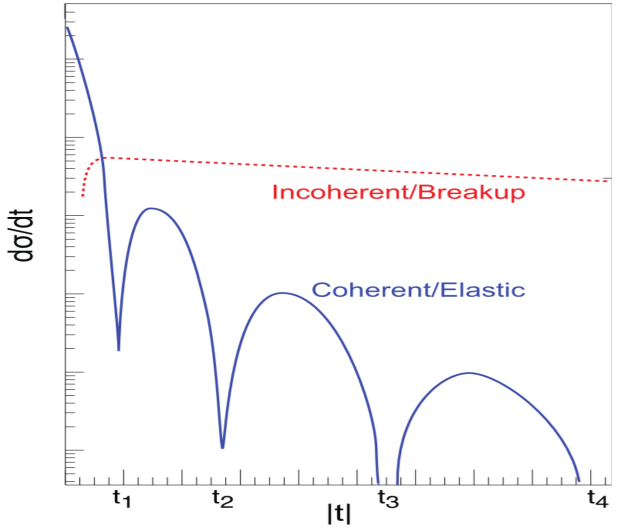
rcBK

Balitsky, 1996;Kovchegov, 1997

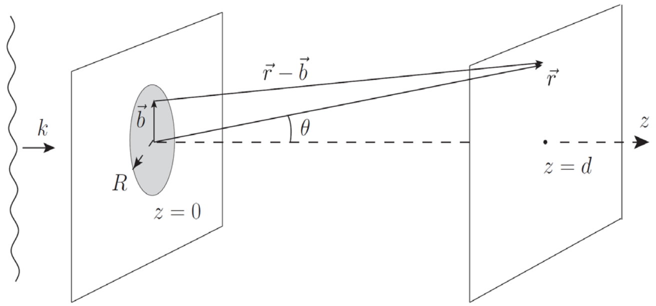
The probe of saturation effect at EIC I

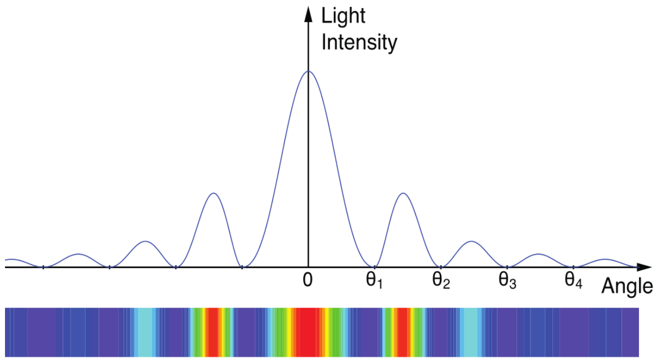
◆ Diffractive vector meson production：





◆ Optical analogy ：

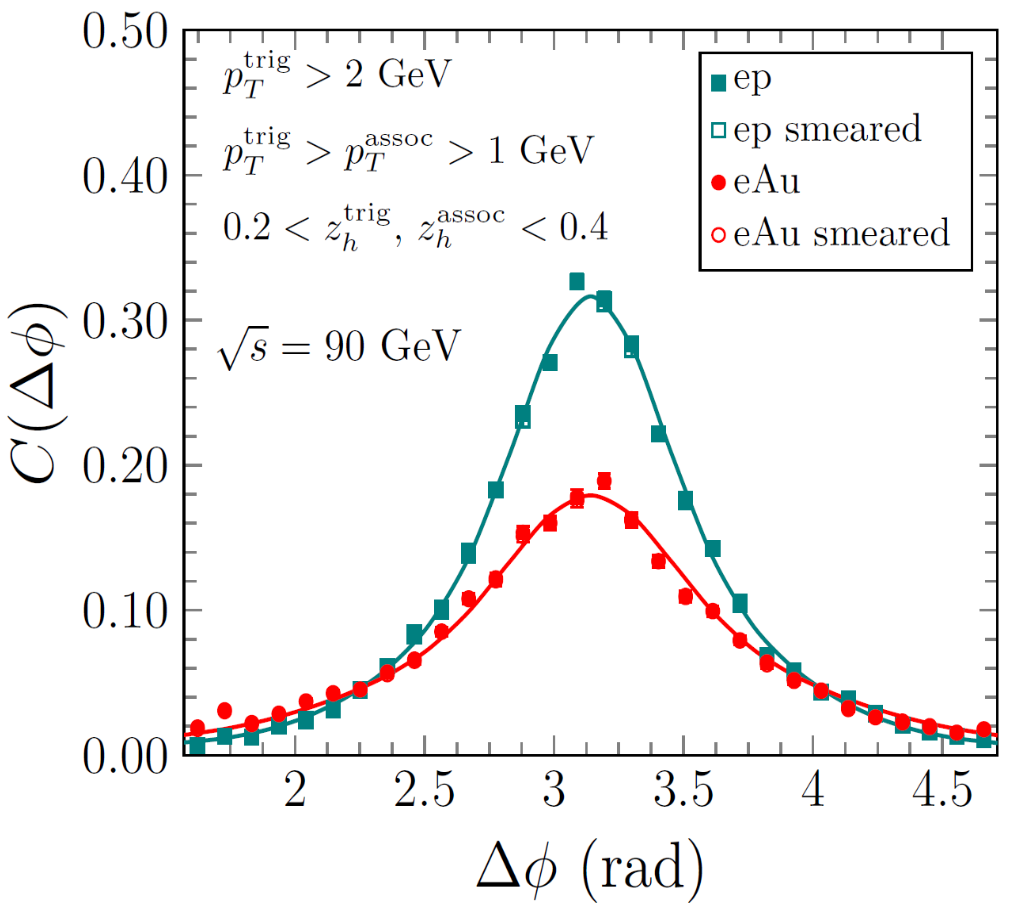




➢ Reconstruct the size R of the obstacle and the optical “blackness” of the obstacle from the diffractive pattern.

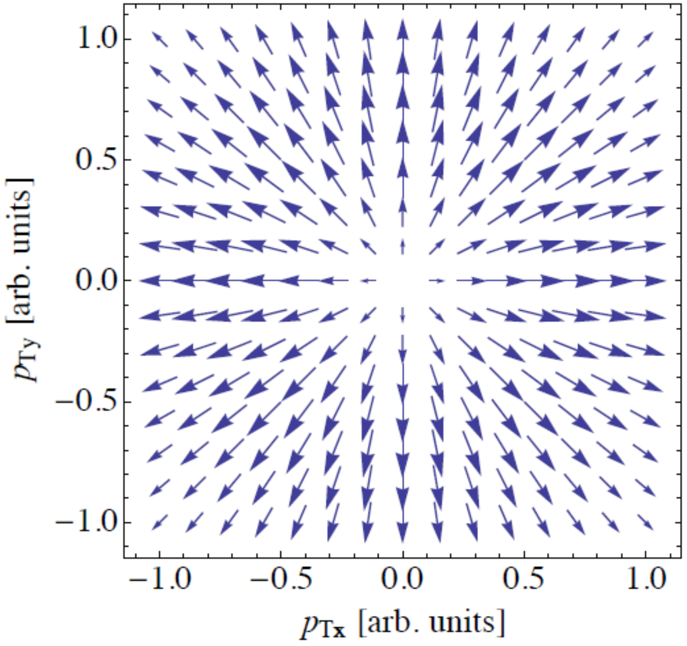
The probe of saturation effect at EIC II

- Semi-inclusive di-jet production in eA collisions

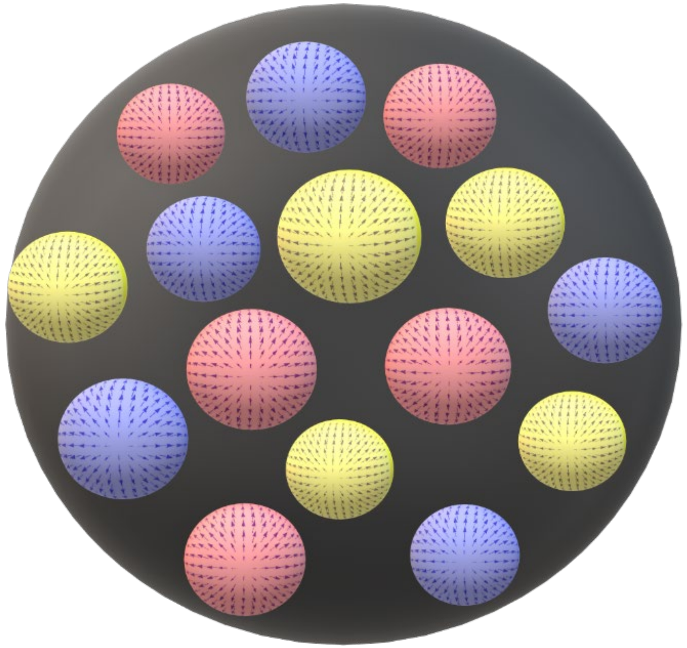


Linearly polarized gluons at small x

Transverse momentum space

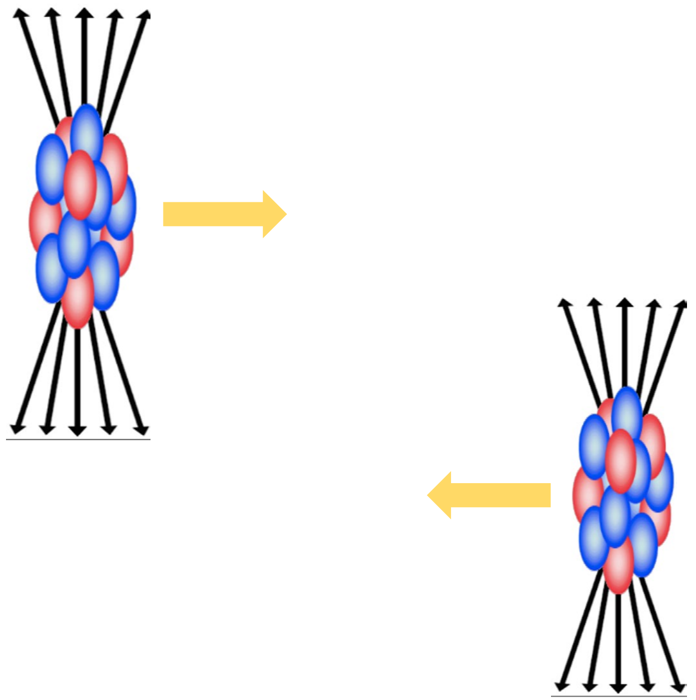


Transverse coordinate space

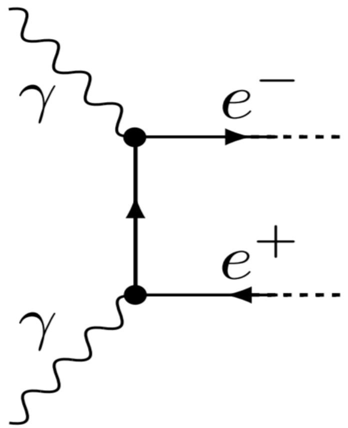


A. Metz, ZJ; 2011

Ultra-peripheral heavy collisions(UPCs) : a portal to small x physics



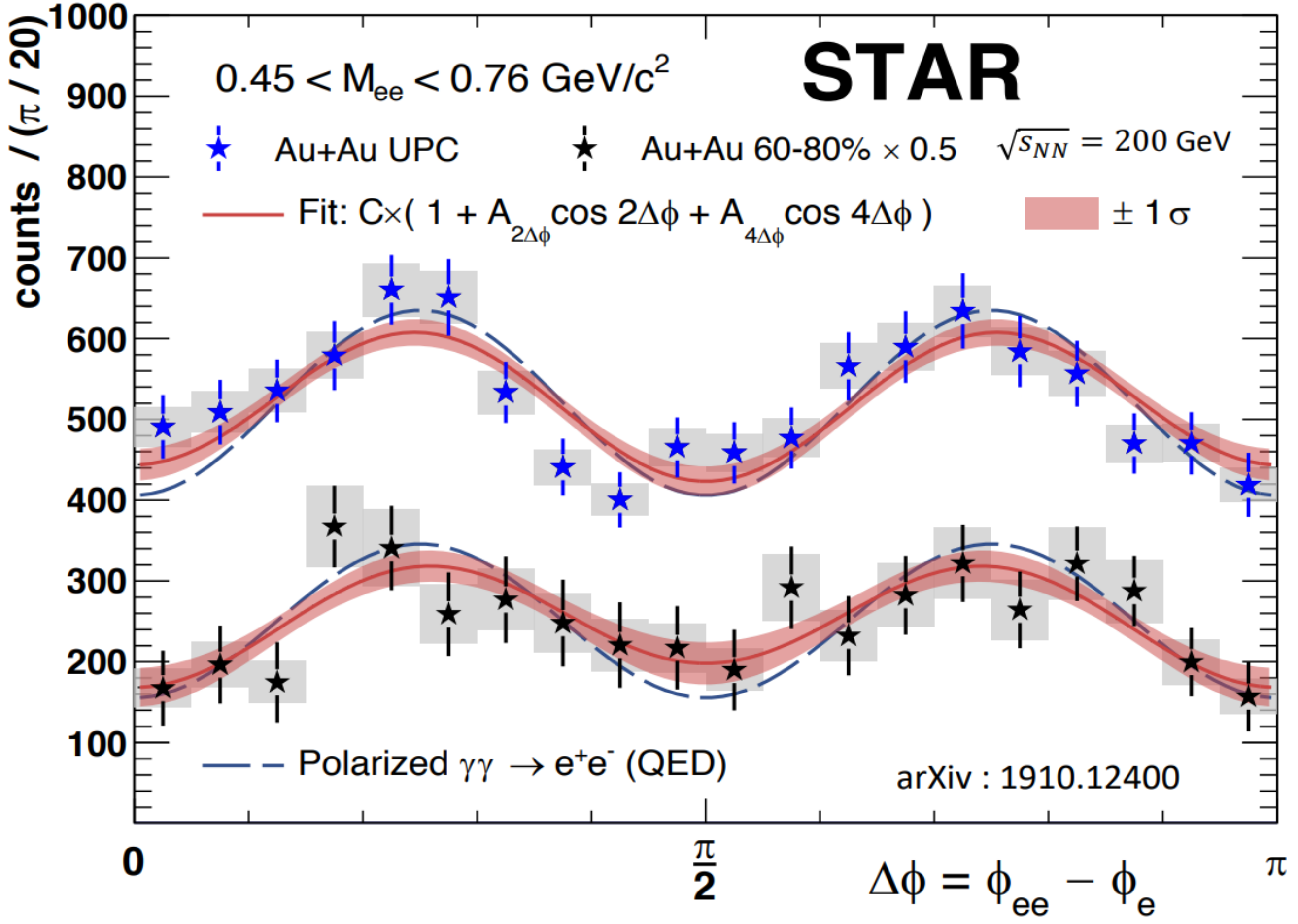
Verified by STAR experiment



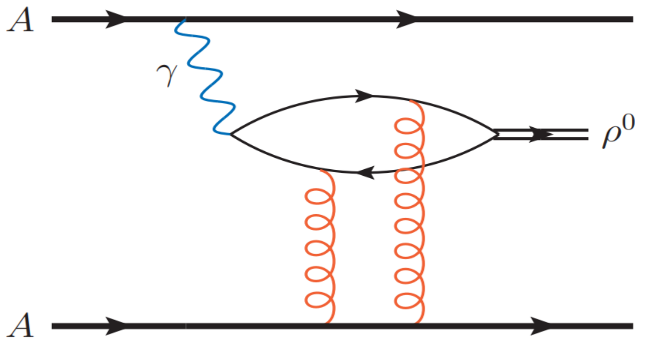
	Measured	QED calculation
Tagged UPC	**16.8%±2.5%**	**16.5%**
60%-80%	27%±6%	34.5%

Li-JZ-Zhou, 2020

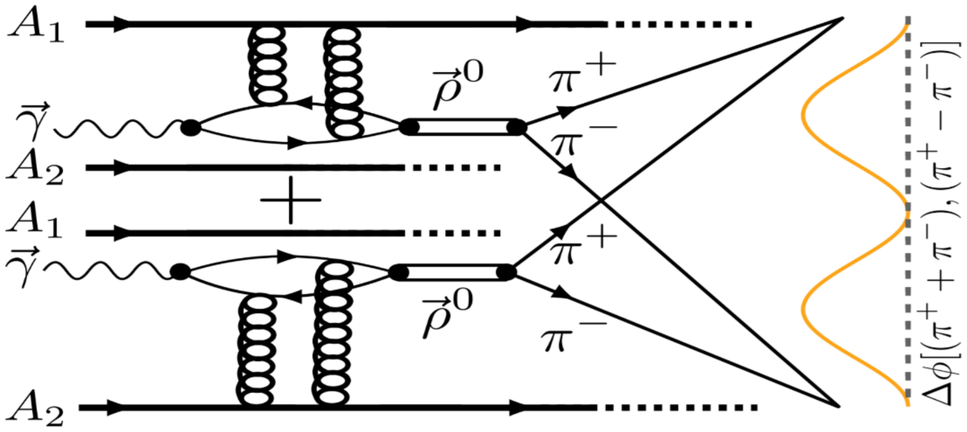
STAR collaboration, PRL，2021

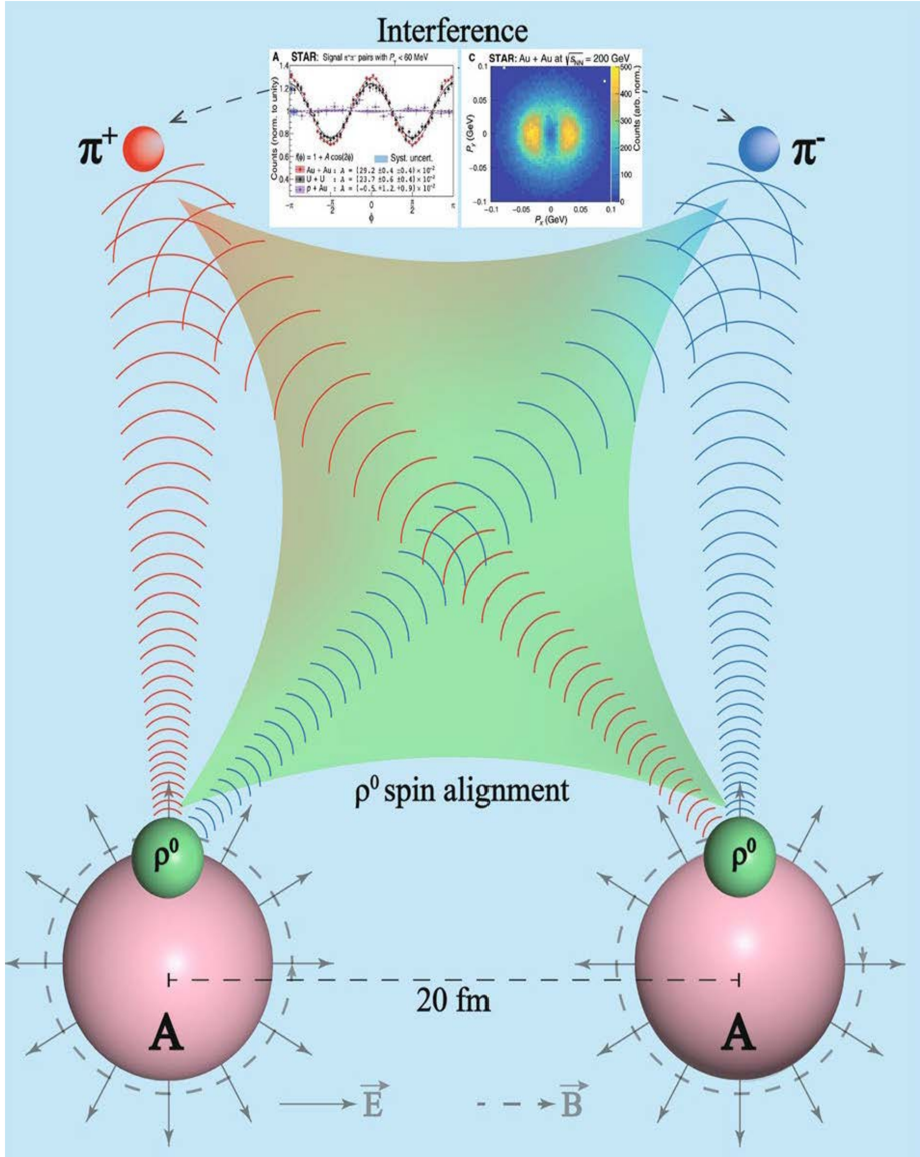


- Diffractive vector meson production



- double-slit experiment in UPCs





Taken from Prof. Ma's review paper

Joint $\tilde{b}_\perp$ & $q_\perp$ dependent cross section III

- **Full cross section:** $k_\perp + \Delta_\perp = k'_\perp + \Delta'_\perp$

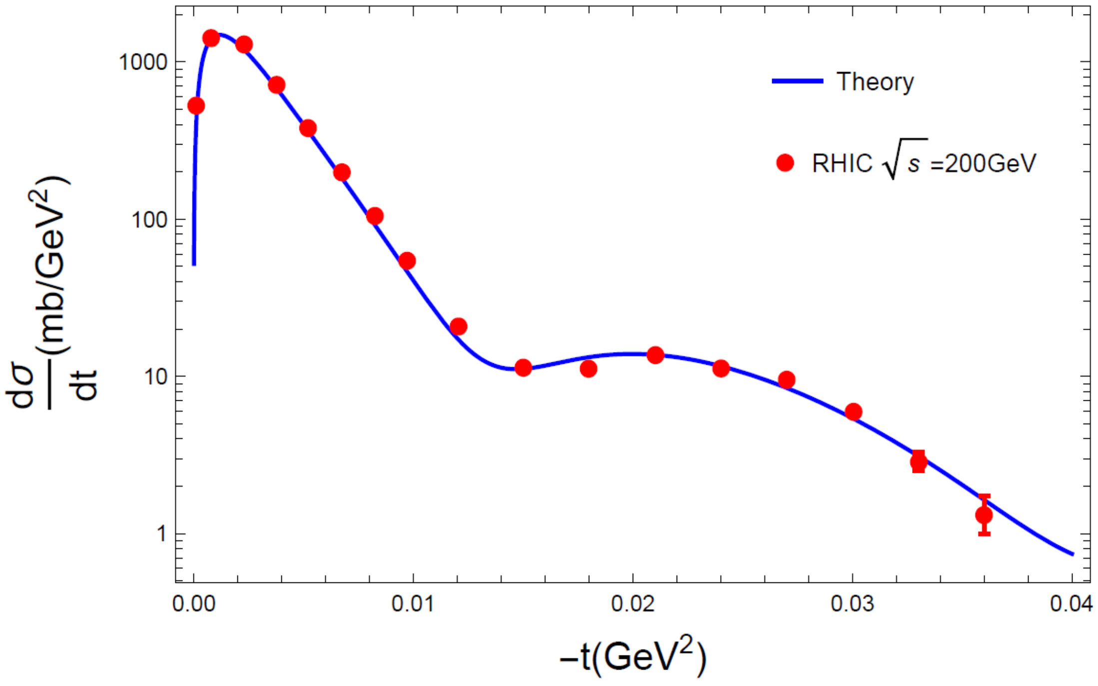
$$\frac{d\sigma}{d^2q_\perp dY d^2\tilde{b}_\perp} = \frac{1}{(2\pi)^4}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp + \Delta_\perp - q_\perp)(\epsilon_\perp^{V*}\cdot\hat{k}_\perp)(\epsilon_\perp^V\cdot\hat{k}'_\perp)\Big\{\int d^2b_\perp$$
$$\times e^{i\tilde{b}_\perp\cdot(k'_\perp - k_\perp)}\left[T_A(b_\perp)\mathcal{A}_{in}(Y,\Delta_\perp)\mathcal{A}^*_{in}(Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp) + (A\leftrightarrow B)\right]$$
$$+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp - k_\perp)}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp)\right]$$
$$+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp - \Delta_\perp)}\mathcal{A}_{co}(-Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right]$$
$$+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp - k_\perp)}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right]$$
$$+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp - \Delta_\perp)}\mathcal{A}_{co}(-Y,\Delta_\perp)\mathcal{A}^*_{co}(Y,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(Y,k'_\perp)\right]\Big\}, \quad (2.14)$$

H.X. Xing, Z. Zhang, ZJ, Y.J. Zhou, 2020

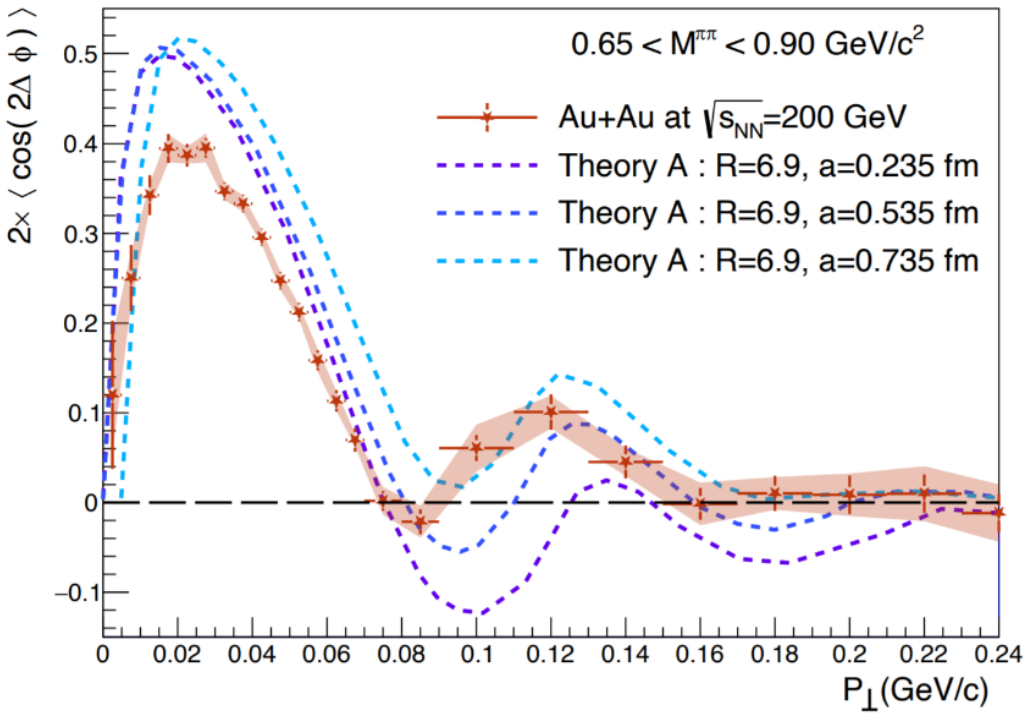
- **EM potential:** $\mathcal{F}(Y,k_\perp) = \frac{Z\sqrt{\alpha_e}}{\pi}|k_\perp|\frac{F(k_\perp^2 + x^2M_p^2)}{(k_\perp^2 + x^2M_p^2)}$

ρ^0 production in UPCs

Azimuthal averaged cross section



Cos2ϕ azimuthal asymmetry



Xing, Zhang, ZJ, Zhou 2020, Zha, Brandenburg, Ruan,Tang,2021

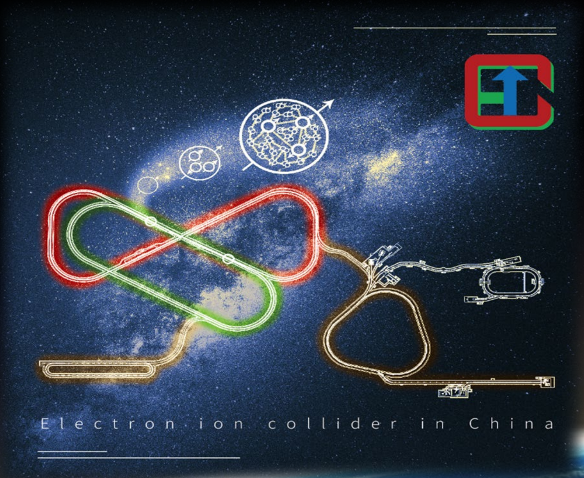
The Scope of EIC/EicC physics

- 3D imaging of proton
- Origin of proton mass and spin
- Small x physics

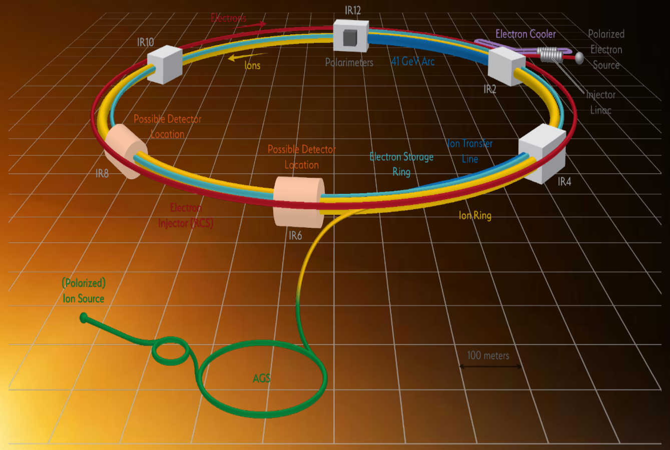
- The global properties of proton:
  proton radius, EM form factors, axial/tensor charge
- Fragmentation processes
- Double parton distributions
- Jet physics
- The lattice study, Quasi-PDFs, form factors…
- Exotic hadronic states
- Short range correlations
- Beyond standard model physics: axion, dark photon.
- ……

The dawn of EIC era

EicC(17GeV), sea quark region



EIC(140GeV) , gluonic matter



Thank you for your attention!

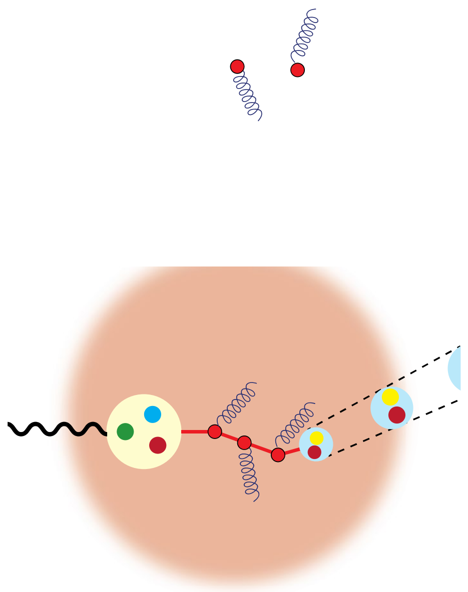
山东大学(青岛)
SHANDONG UNIVERSITY, QINGDAO

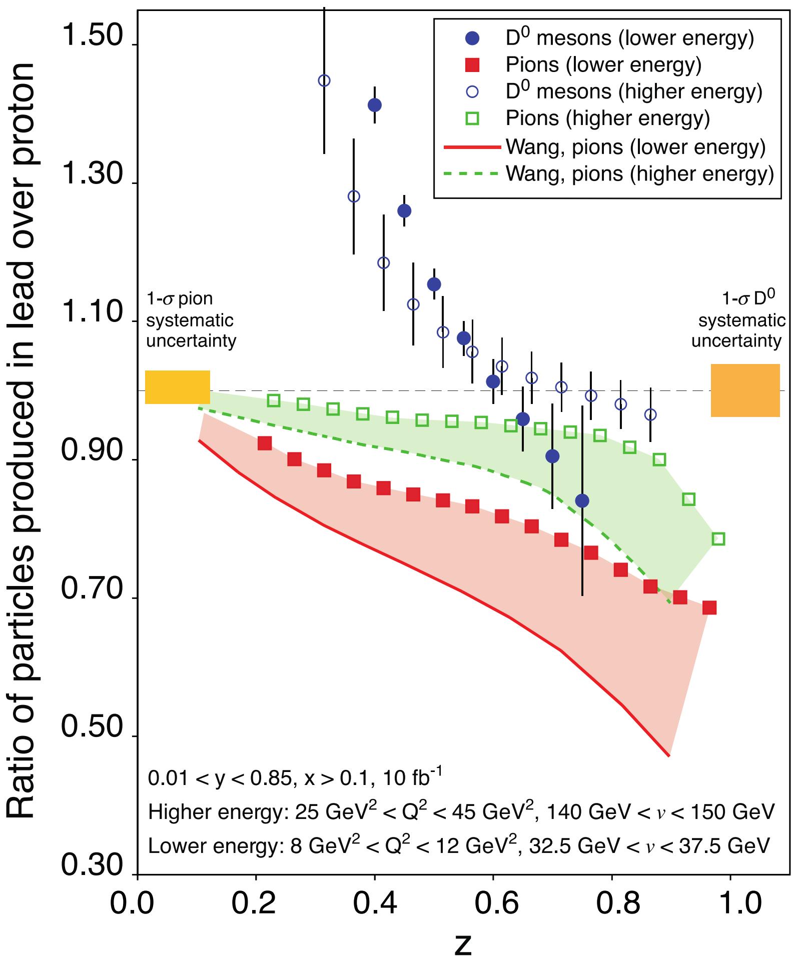
Thank you for your attention!

SHANDONG UNIVERSITY, QINGDAO

Energy Loss in Cold Nuclear Matter

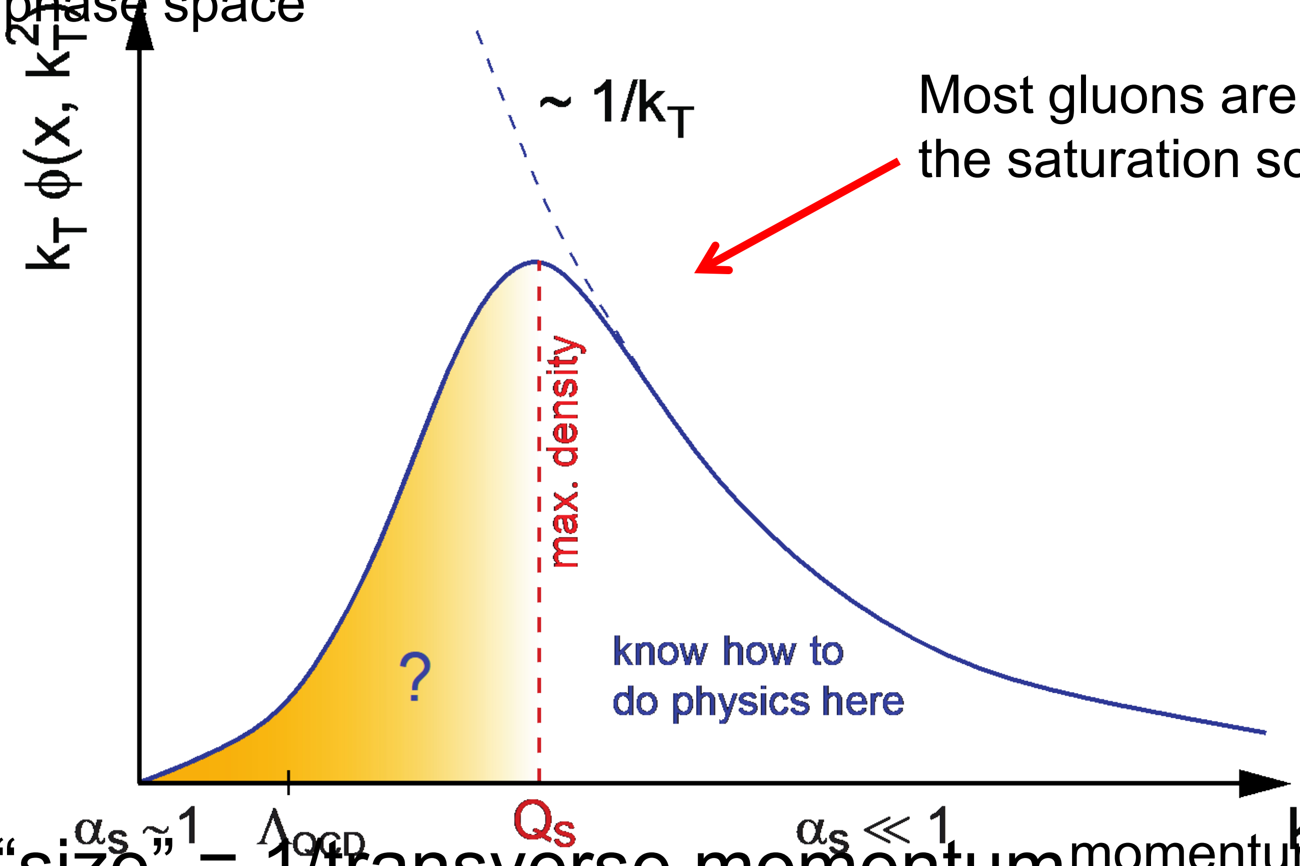
- By studying quark propagation in cold nuclear matter we can learn important information about hadronization and may even measure qhat in the cold nuclear medium:





Typical gluon "size"

Number of gluons (gluon TMD) times the phase space



Most gluons are near the saturation scale Q_s.

momentum transverse to the beam

Gluon "size" = 1/transverse momentum = $1/Q_s$