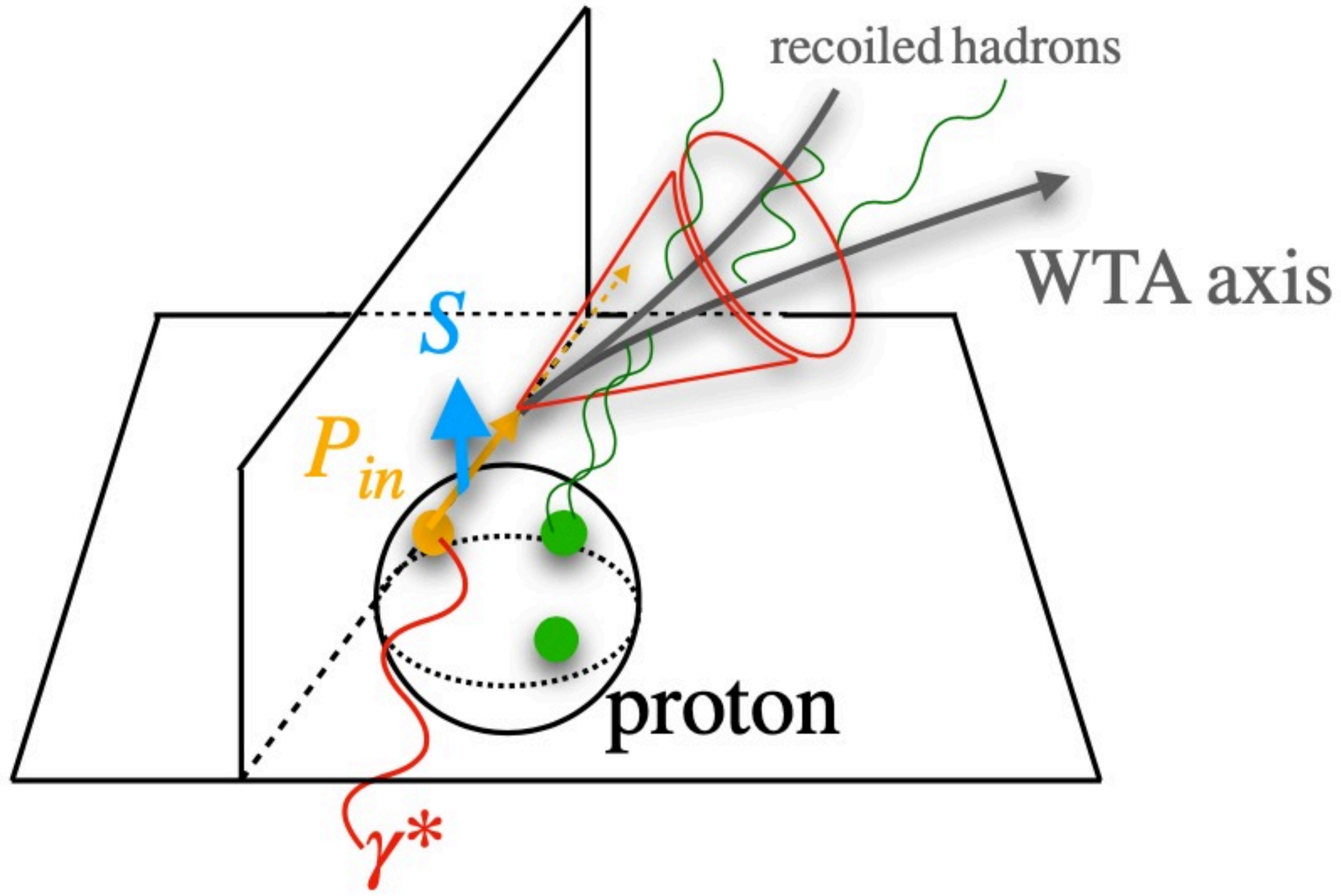
The time reversal odd side of a jet

Hongxi Xing

(South China Normal University)



微扰量子场论研讨会@上海，5.15-16

Outline

- Motivation - the role of jets
- The T-odd jet in DIS and e^+e^- collisions
- Summary

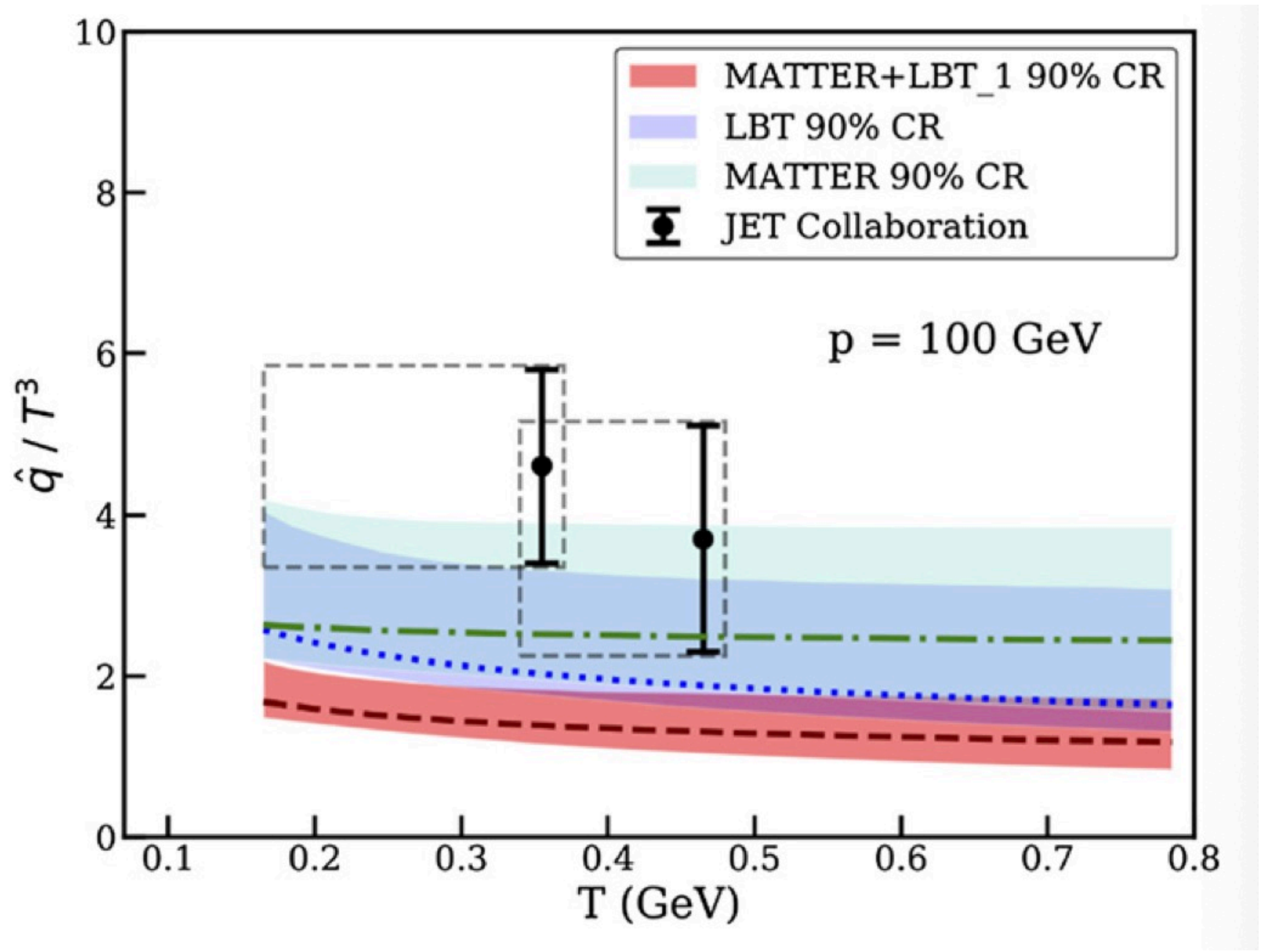
Liu, HX, 2104.03328, 2021

Liu, HX, Zhang, 2021

Lai, Liu, Wang, HX, 2021

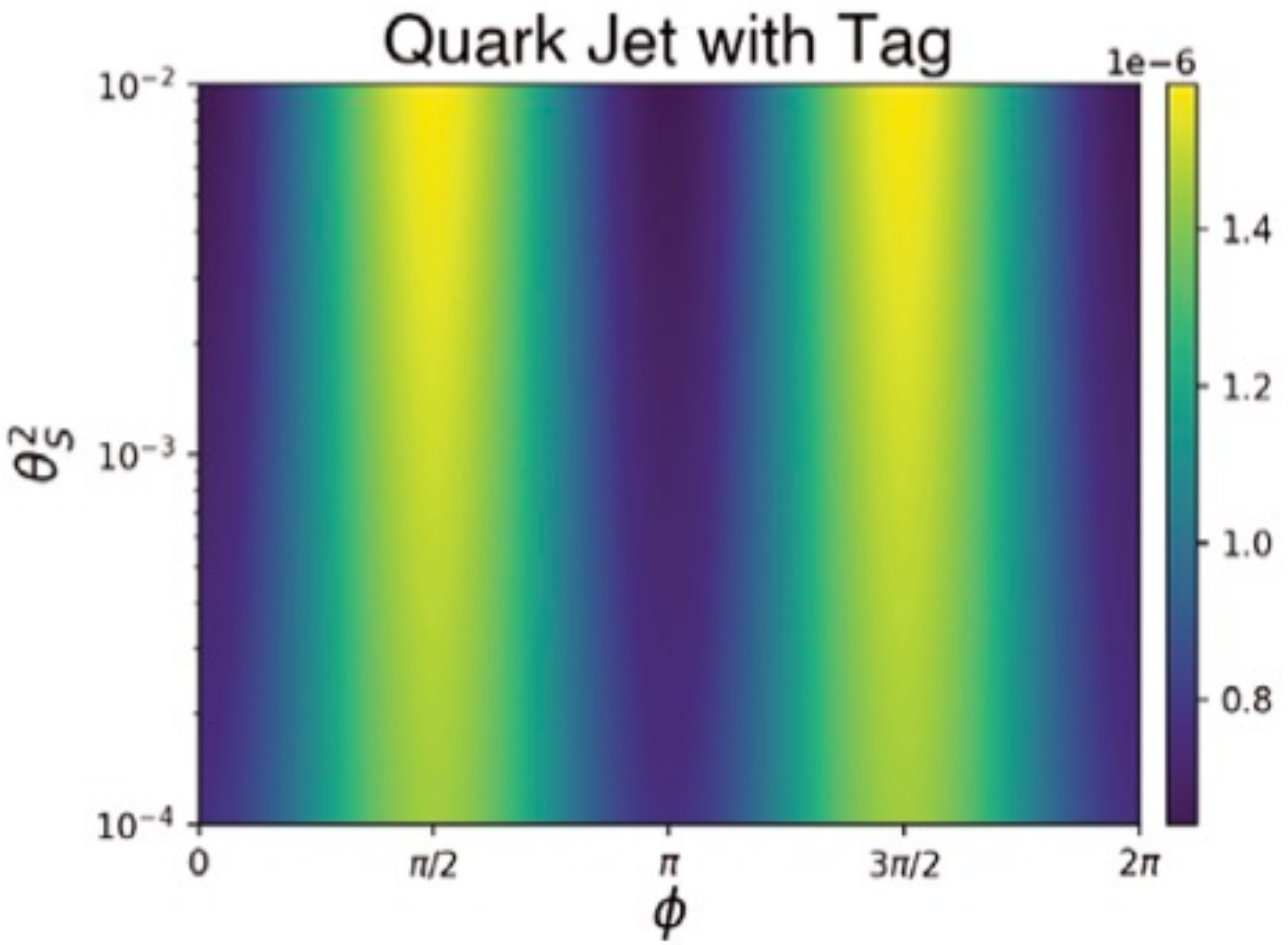
Motivation - jet is powerful in many fields

- Jet as a tool for QGP tomography



See e.g., review by Cao, Wang, Rept.Prog.Phys 2021

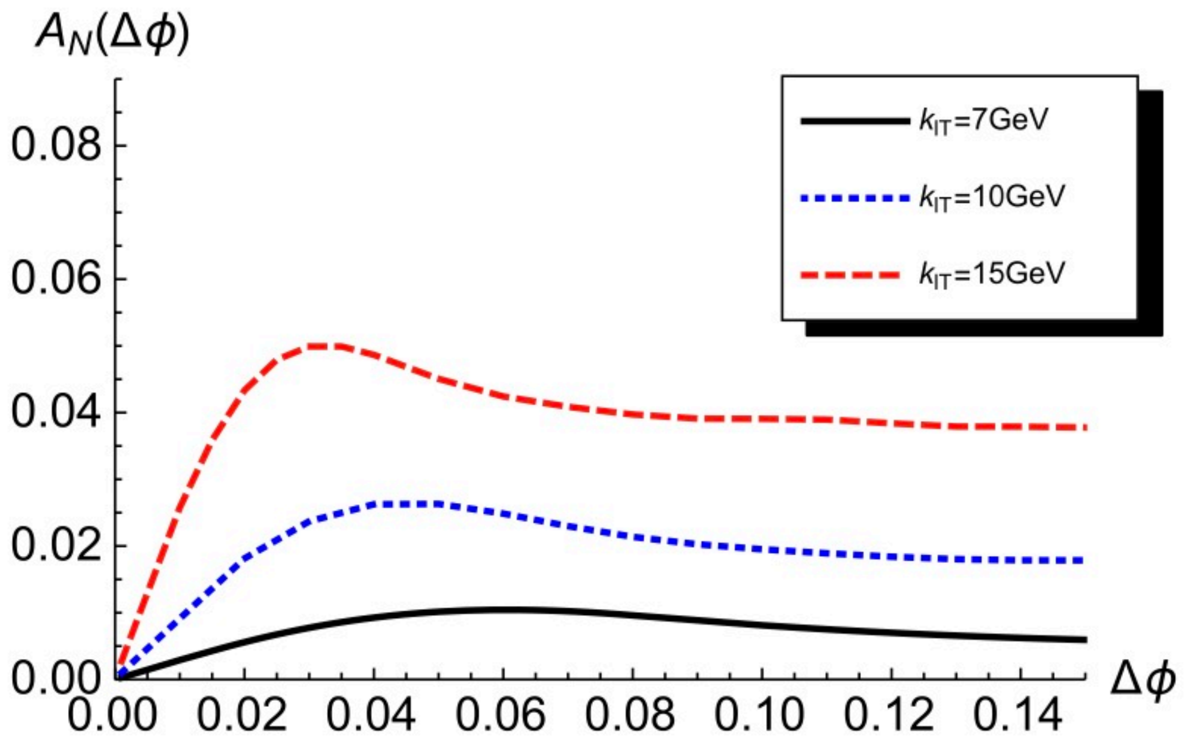
- Quantum interference in jet substructure



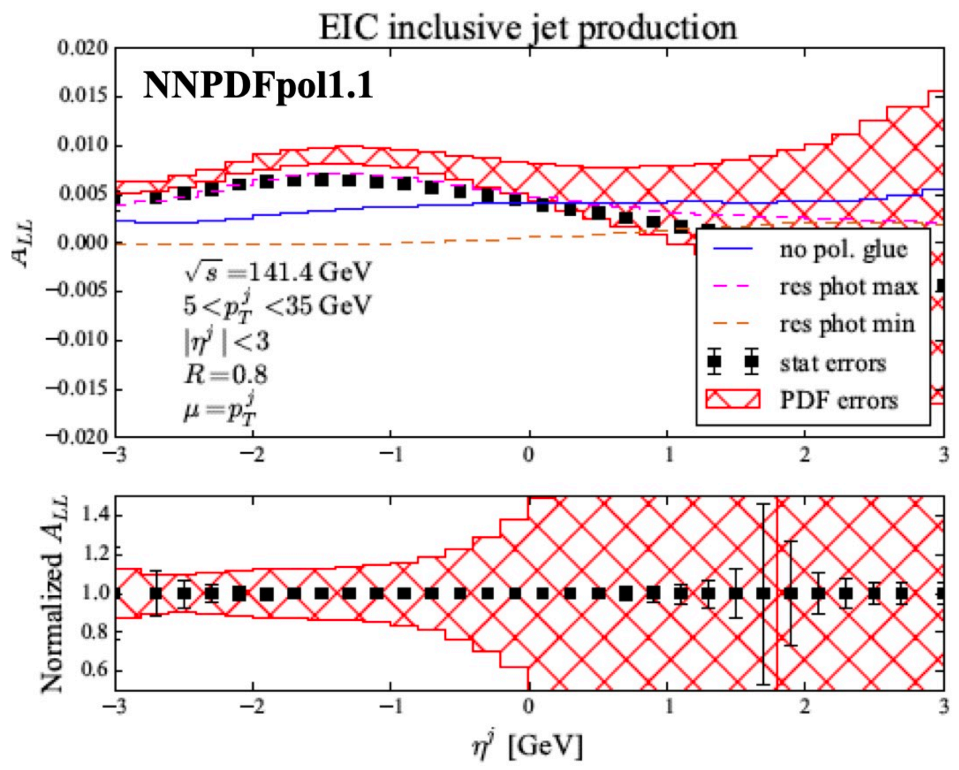
Chen, Moult, Zhu, PRL 2021
talk by H. Chen

Jet for spin related physics

- Jet in DIS for Sivers and helicity distributions

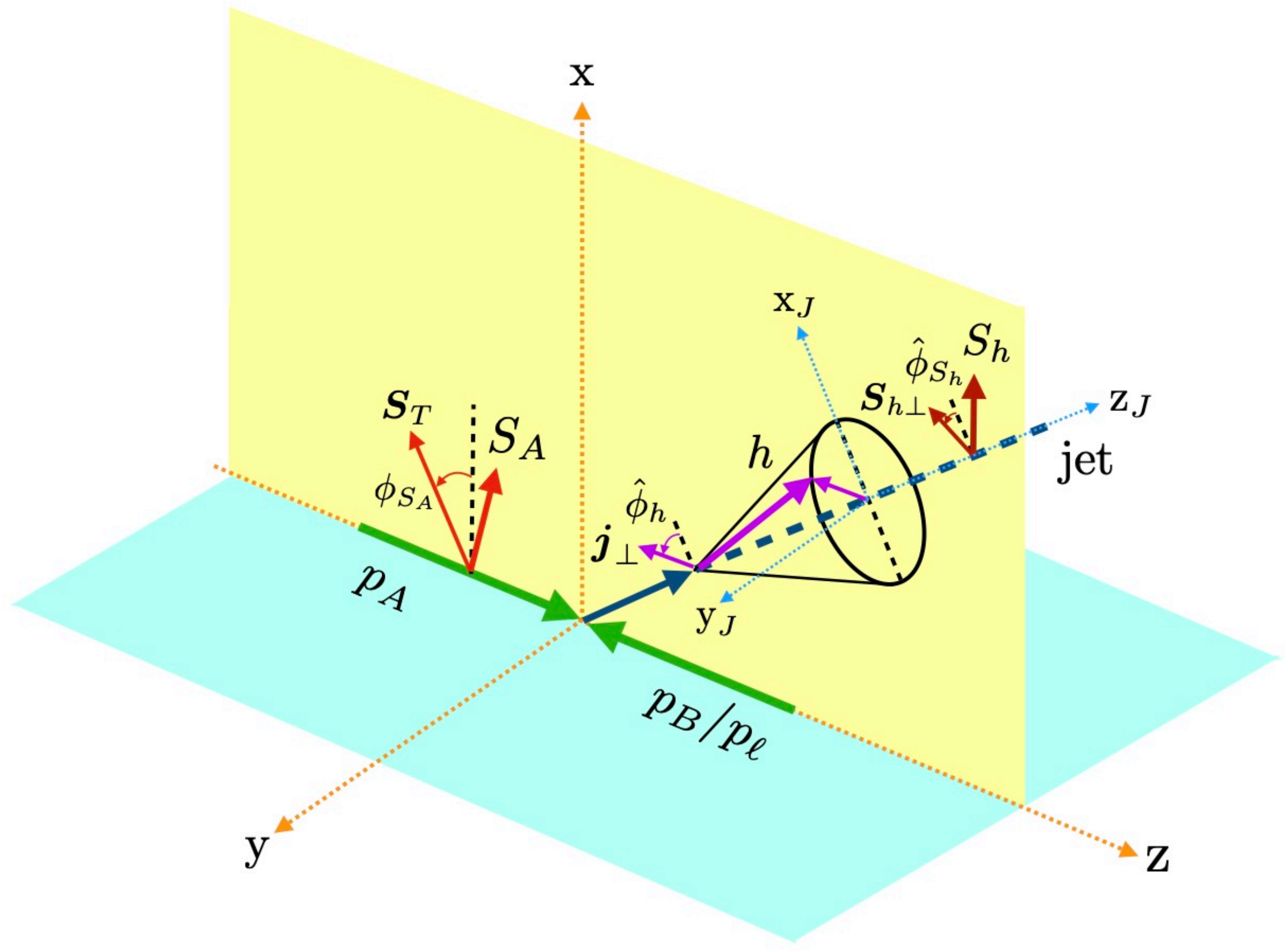


Liu, Ringer, Vogelsang, Yuan, PRL 2019

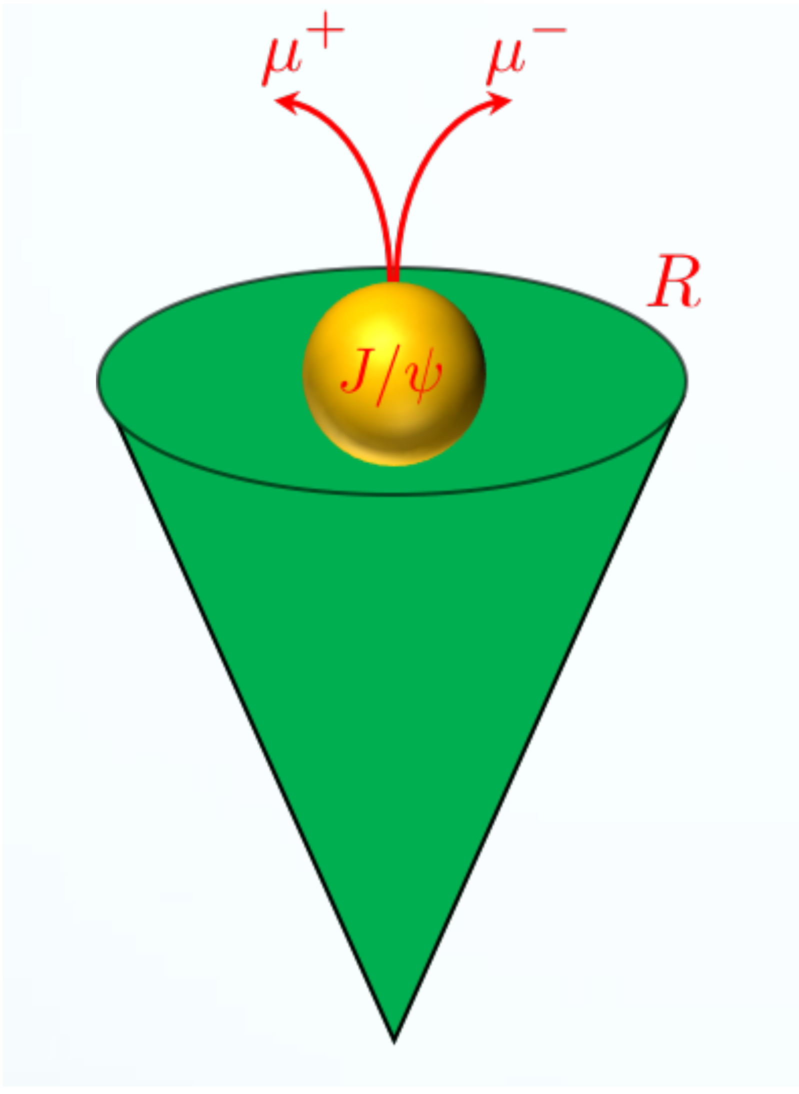


Boughezal, Petriello, HX, PRD 2017

- Jet fragmentation -> polarized fragmentation functions (J/ψ, Λ)

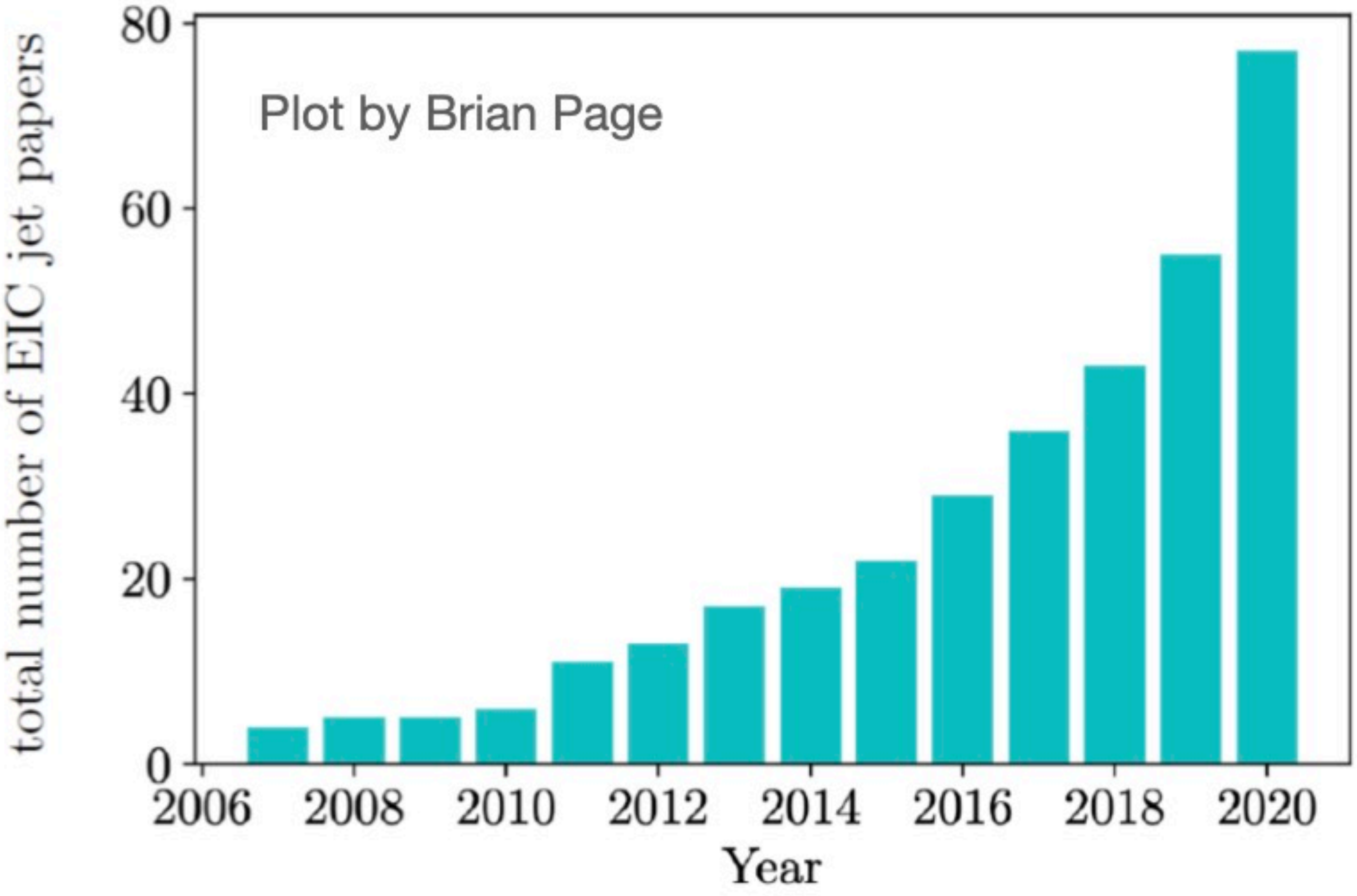


Kang, Lee, Zhao, PLB 2020



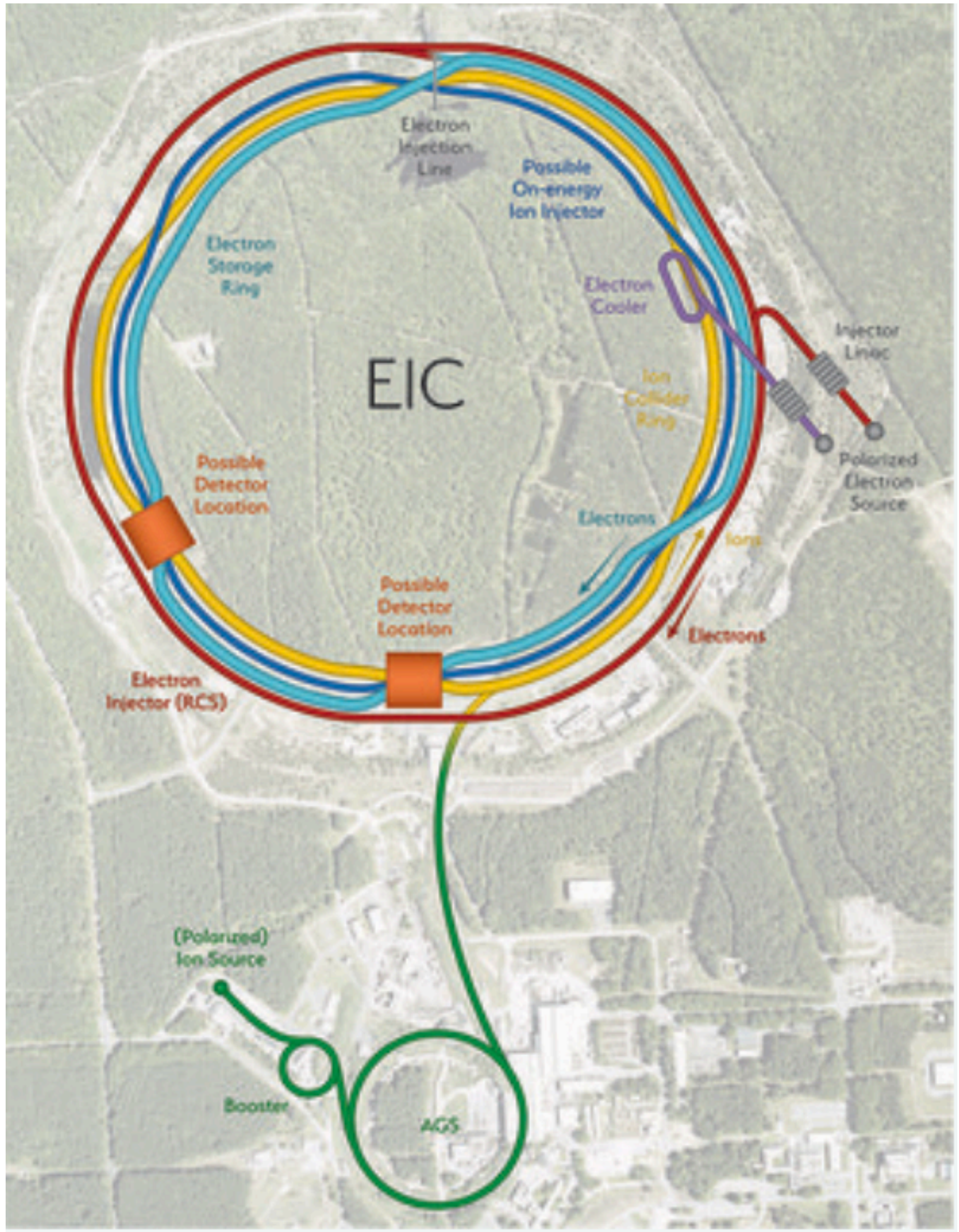
Kang, Qiu, Ringer, HX, Zhang
PRL 2017

Rapid growing interests for jets @ EIC

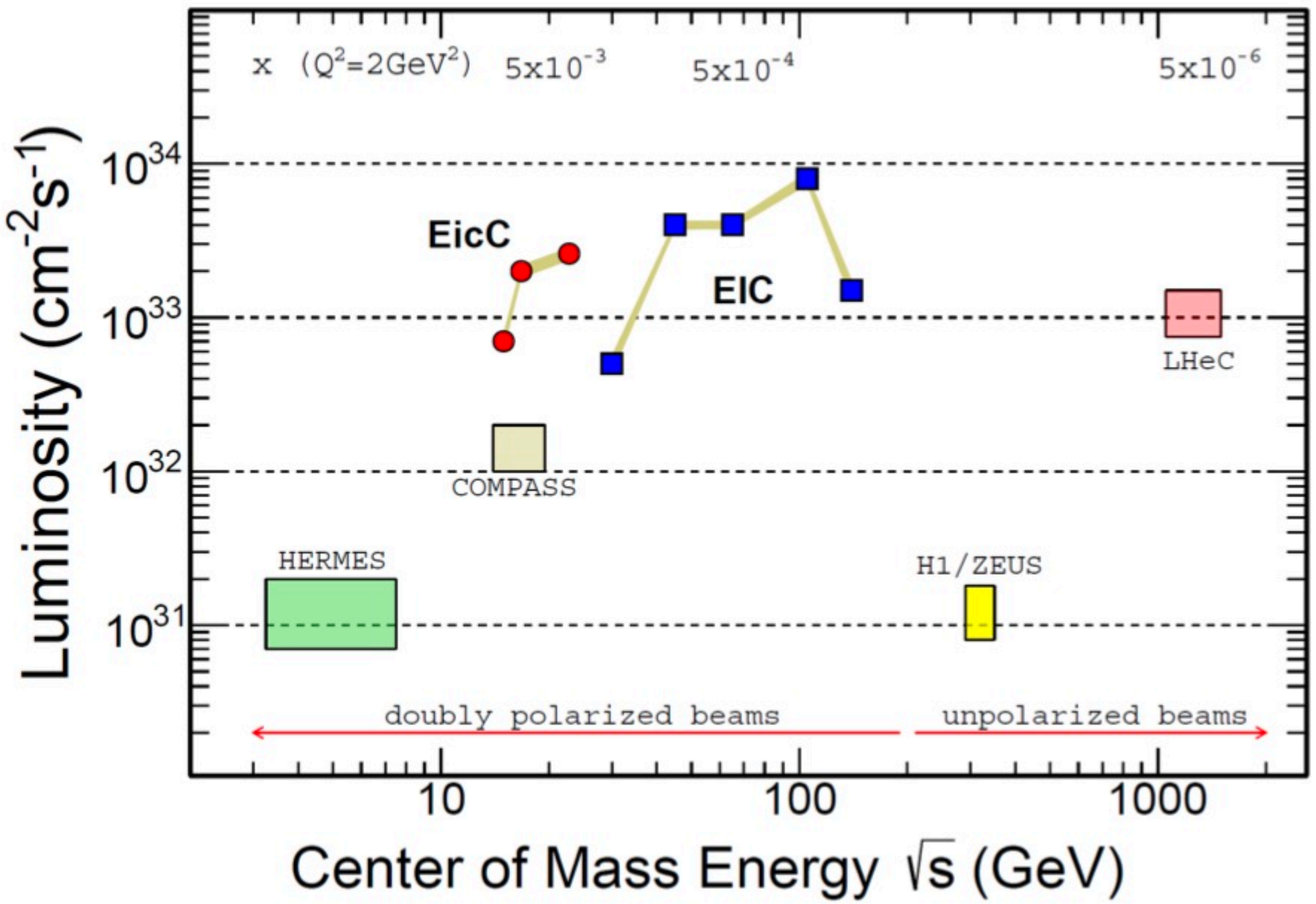


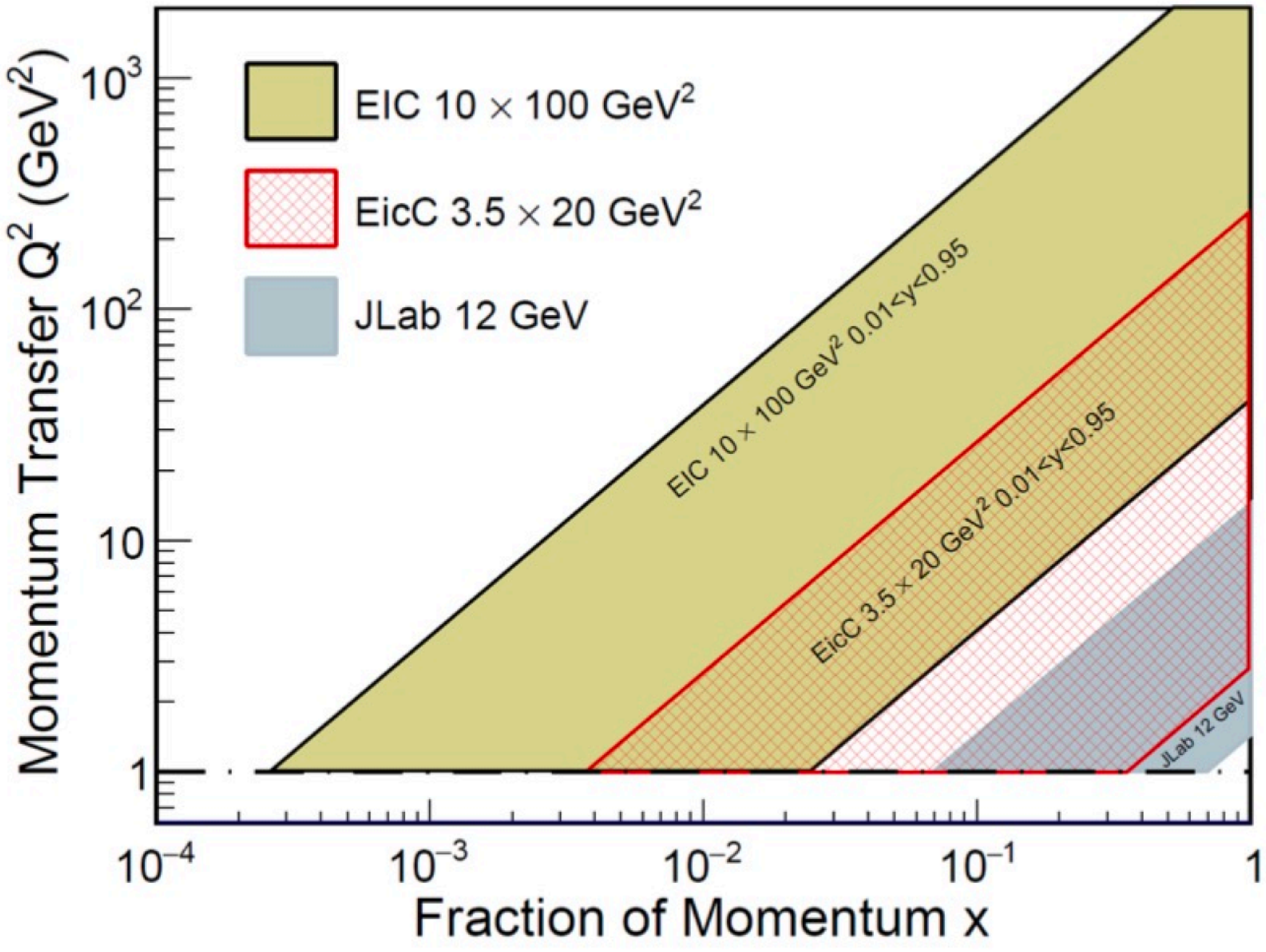
Electron Ion Collider in China, EicC

Electron Ion Collider (US)



Mapping out the nucleon structure via EICs worldwide





EicC white paper (arXiv: 2102.09222)

Also in production in the *Frontiers of Physics* Journal

arXiv.org > nucl-ex > arXiv:2102.09222

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Nuclear Experiment

[Submitted on 18 Feb 2021]

Electron-Ion Collider in China

Daniele P. Anderle, Valerio Bertone, Xu Cao, Lei Chang, Ningbo Chang, Gu Chen, Xurong Chen, Zhuojun Chen, Zhufang Cui, Lingyun Dai, Weitian Deng, Minghui Ding, Xu Feng, Chang Gong, Longcheng Gui, Feng-Kun Guo, Chengdong Han, Jun He, Tie-Jiun Hou, Hongxia Huang, Yin Huang, Krešimir Kumerički, L. P. Kaptari, Demin Li, Hengne Li, Minxiang Li, Xueqian Li, Yutie Liang, Zuotang Liang, Chen Liu, Chuan Liu, Guoming Liu, Jie Liu, Liuming Liu, Xiang Liu, Tianbo Liu, Xiaofeng Luo, Zhun Lyu, Boqiang Ma, Fu Ma, Jianping Ma, Yugang Ma, Lijun Mao, Cédric Mezrag, Hervé Moutarde, Jialun Ping, Sixue Qin, Hang Ren, Craig D. Roberts, Juan Rojo, Guodong Shen, Chao Shi, Qintao Song, Hao Sun, Paweł Sznajder, Enke Wang, Fan Wang, Qian Wang, Rong Wang, Ruiru Wang, Taofeng Wang, Wei Wang, Xiaoyu Wang, Xiaoyun Wang, Jiajun Wu, Xinggang Wu, Lei Xia, Bowen Xiao, Guoqing Xiao, Ju-Jun Xie, Yaping Xie, Hongxi Xing, Hushan Xu, Nu Xu, Shusheng Xu, Mengshi Yan, Wenbiao Yan, Wencheng Yan, Xinhu Yan, Jiancheng Yang, Yi-Bo Yang, Zhi Yang, Deliang Yao, Peilin Yin, C.-P. Yuan, Wenlong Zhan, Jianhui Zhang, Jinlong Zhang, Pengming Zhang, Chao-Hsi Chang, Zhenyu Zhang, Hongwei Zhao, Kuang-Ta Chao, Qiang Zhao, Yuxiang Zhao, Zhengguo Zhao, Liang Zheng, Jian Zhou, Xiang Zhou, Xiaorong Zhou et al. (2 additional authors not shown)

Lepton scattering is an established ideal tool for studying inner structure of small particles such as nucleons as well as nuclei. As a future high energy nuclear physics project, an Electron-ion collider in China (EicC) has been proposed. It will be constructed based on an upgraded heavy-ion accelerator, High Intensity heavy-ion Accelerator Facility (HIAF) which is currently under construction, together with a new electron ring. The proposed collider will provide highly polarized electrons (with a polarization of \sim80%) and protons (with a polarization of \sim70%) with variable center of mass energies from 15 to 20 GeV and the luminosity of (2-3) \times 10^{33} cm^{-2} s^{-1}. Polarized deuterons and Helium-3, as well as unpolarized ion beams from Carbon to Uranium, will be also available at the EicC.

The main foci of the EicC will be precision measurements of the structure of the nucleon in the sea quark region, including 3D tomography of nucleon; the partonic structure of nuclei and the parton interaction with the nuclear environment; the exotic states, especially those with heavy flavor quark contents. In addition, issues fundamental to understanding the origin of mass could be addressed by measurements of heavy quarkonia near-threshold production at the EicC. In order to achieve the above-mentioned physics goals, a hermetical detector system will be constructed with cutting-edge technologies.

This document is the result of collective contributions and valuable inputs from experts across the globe. The EicC physics program complements the ongoing scientific programs at the Jefferson Laboratory and the future EIC project in the United States. The success of this project will also advance both nuclear and particle physics as well as accelerator and detector technology in China.

Comments: EicC white paper, written by the whole EicC working group

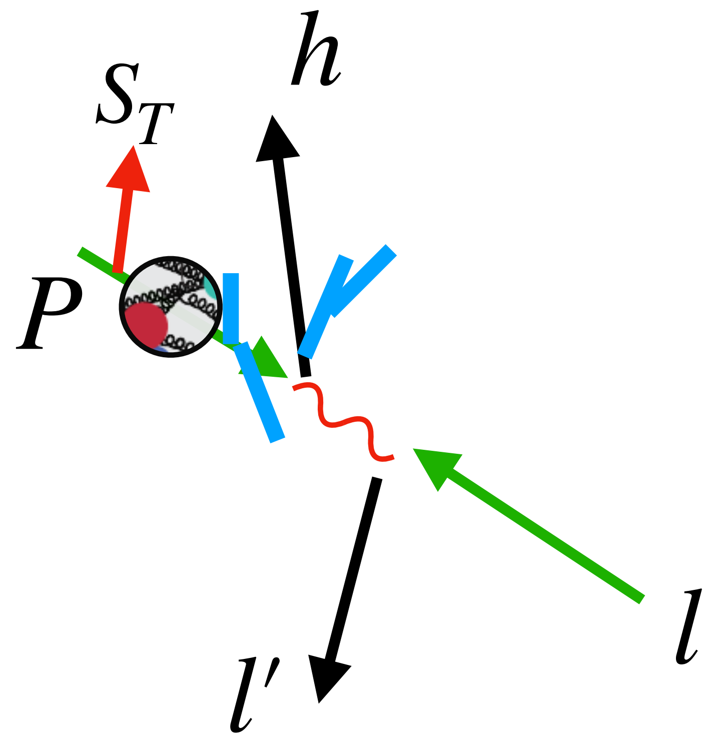
Subjects: **Nuclear Experiment (nucl-ex)**; High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenology (hep-ph); Nuclear Theory (nucl-th)

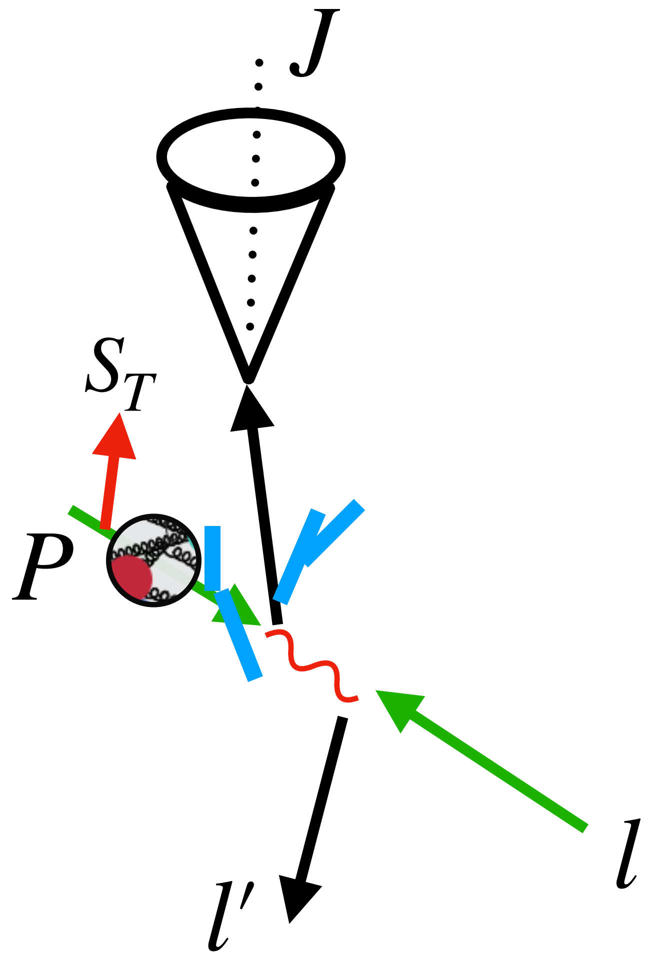
Cite as: arXiv:2102.09222 **[nucl-ex]**

(or arXiv:2102.09222v1 **[nucl-ex]** for this version)

Now we have 46 institutes and >100 physicists

Jet vs hadron





- Semi-inclusive DIS

$$\sigma^h \sim \sum_{i,j} \hat{\sigma}_{ei\to e'j}\ f_{i/p}(x, k_T) \otimes D_{j/h}(z, k'_T) \otimes S(k_T)$$

The nonperturbative fragmentation functions -> extra uncertainty

Identified hadrons can be used as flavor separation

- Jet production in DIS

$$\sigma^J = \sum_{i,j} \hat{\sigma}_{ei\to e'j}\ f_{i/p}(x, k_T) \otimes J(p_T, R) \otimes S(k_T, p_T R)$$

Jet functions can be calculated perturbatively -> controllable uncertainty

Sum all hadrons within jet, hard for flavor separation

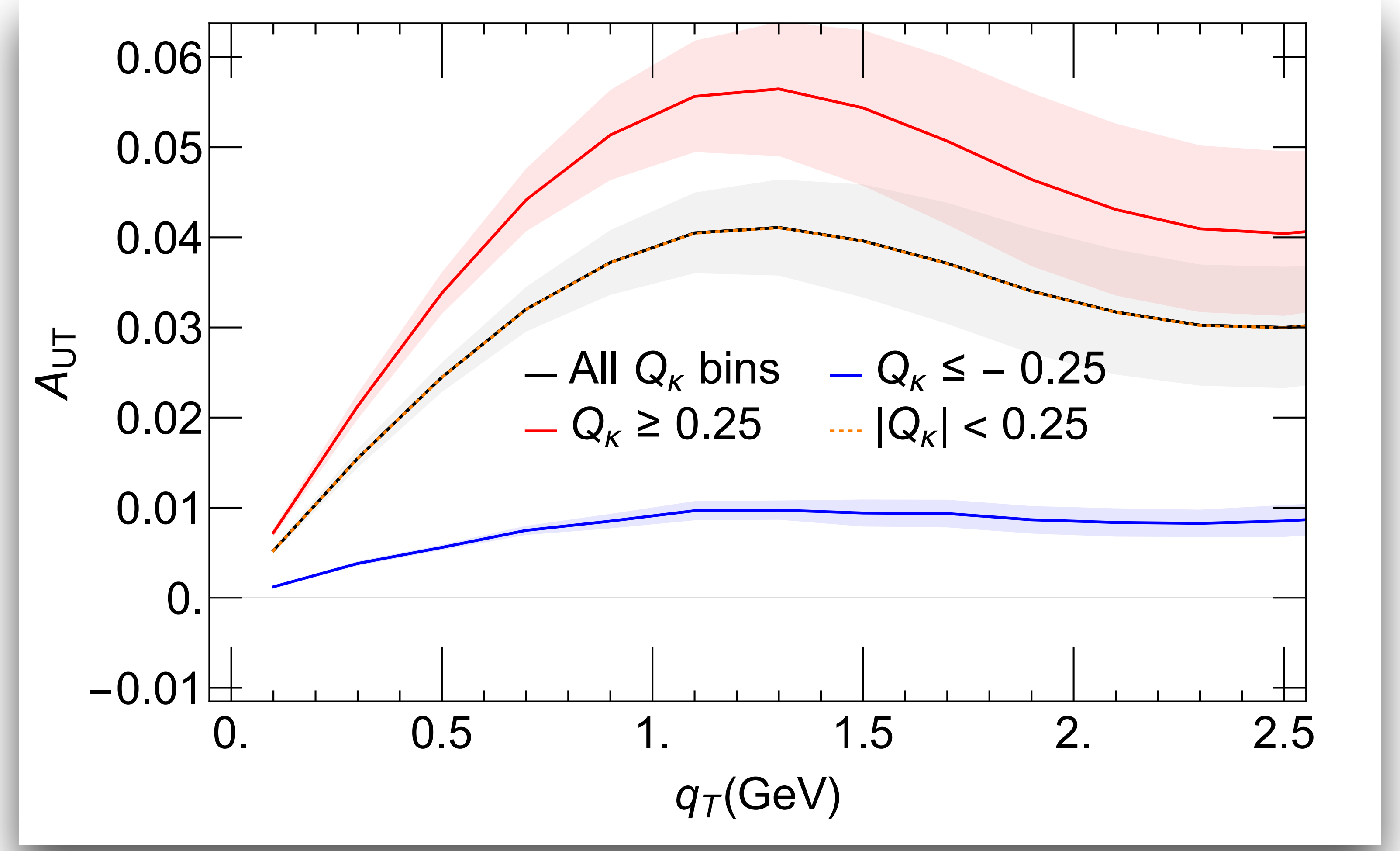
Jet charge for nucleon/nucleus flavor separation

Definition:

$$Q_\kappa = \sum_h \left(\frac{p_{h,T}}{p_J}\right)^\kappa Q_h$$

Field, Feynman, 1978

Krohn, Schwartz, Lin, Waalewijn, 2013

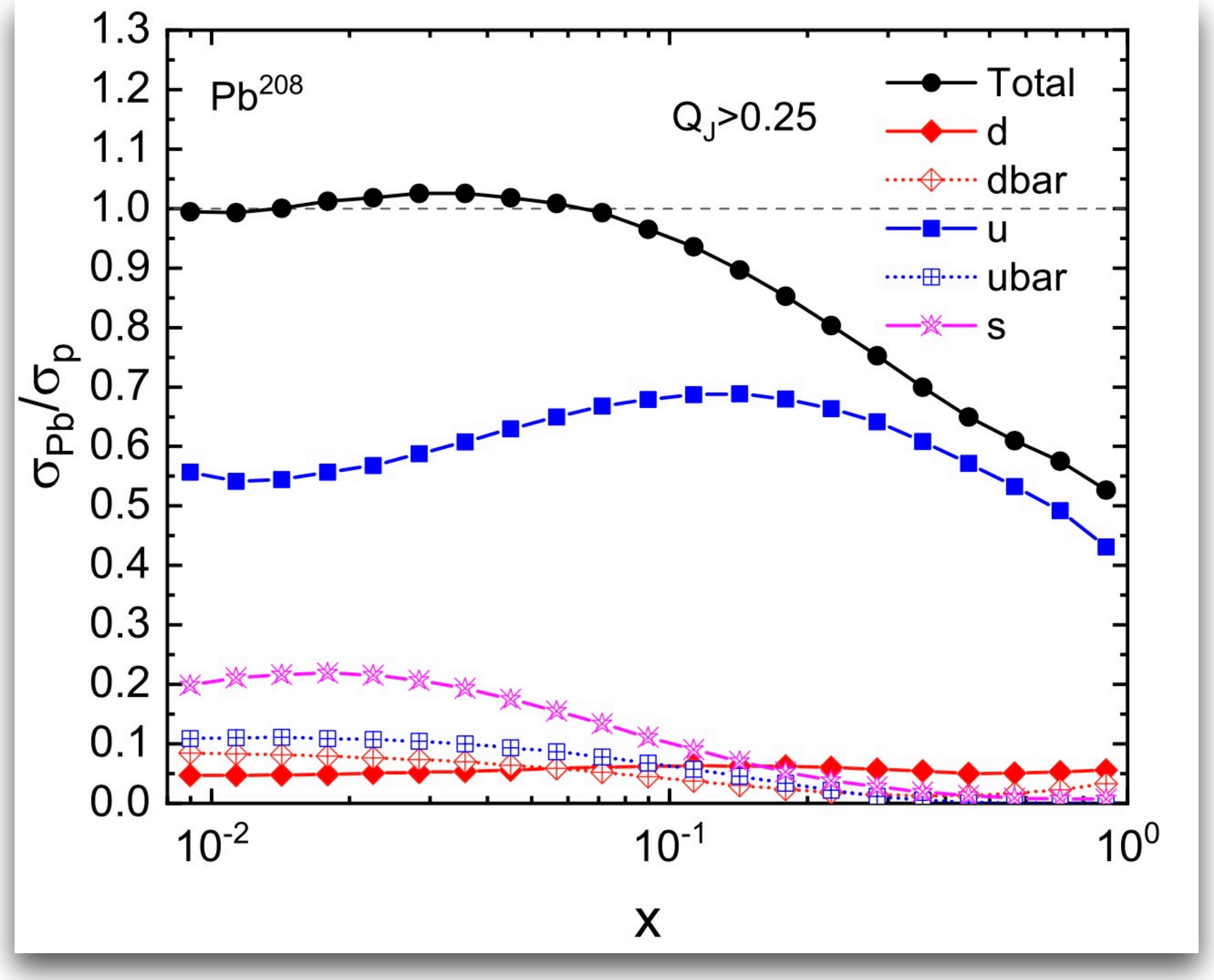


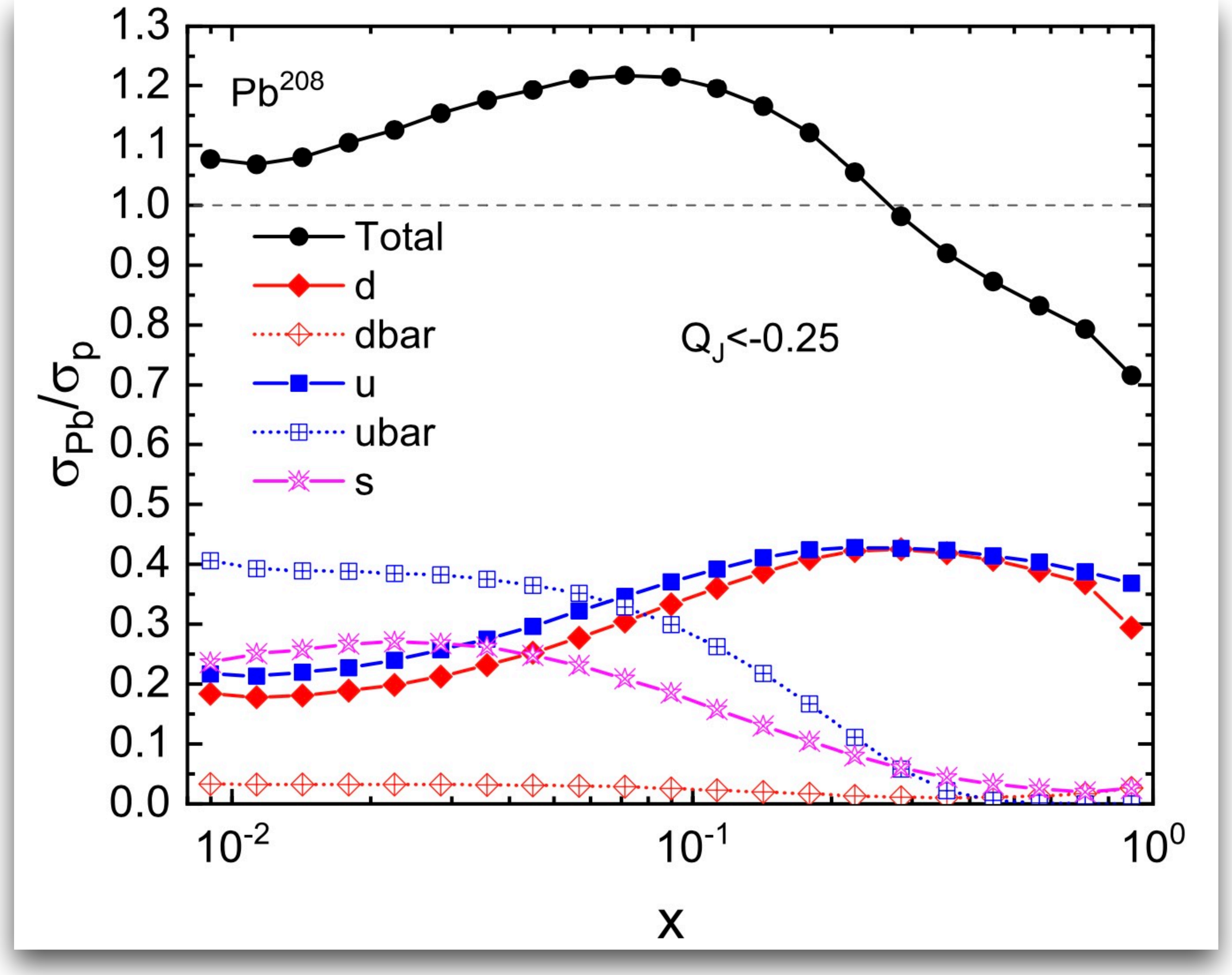
Flavor dependent Sivers effect

Positive charge: u

Negative charge: d

Kang, Liu, Mantry, Shao, PRL 2020





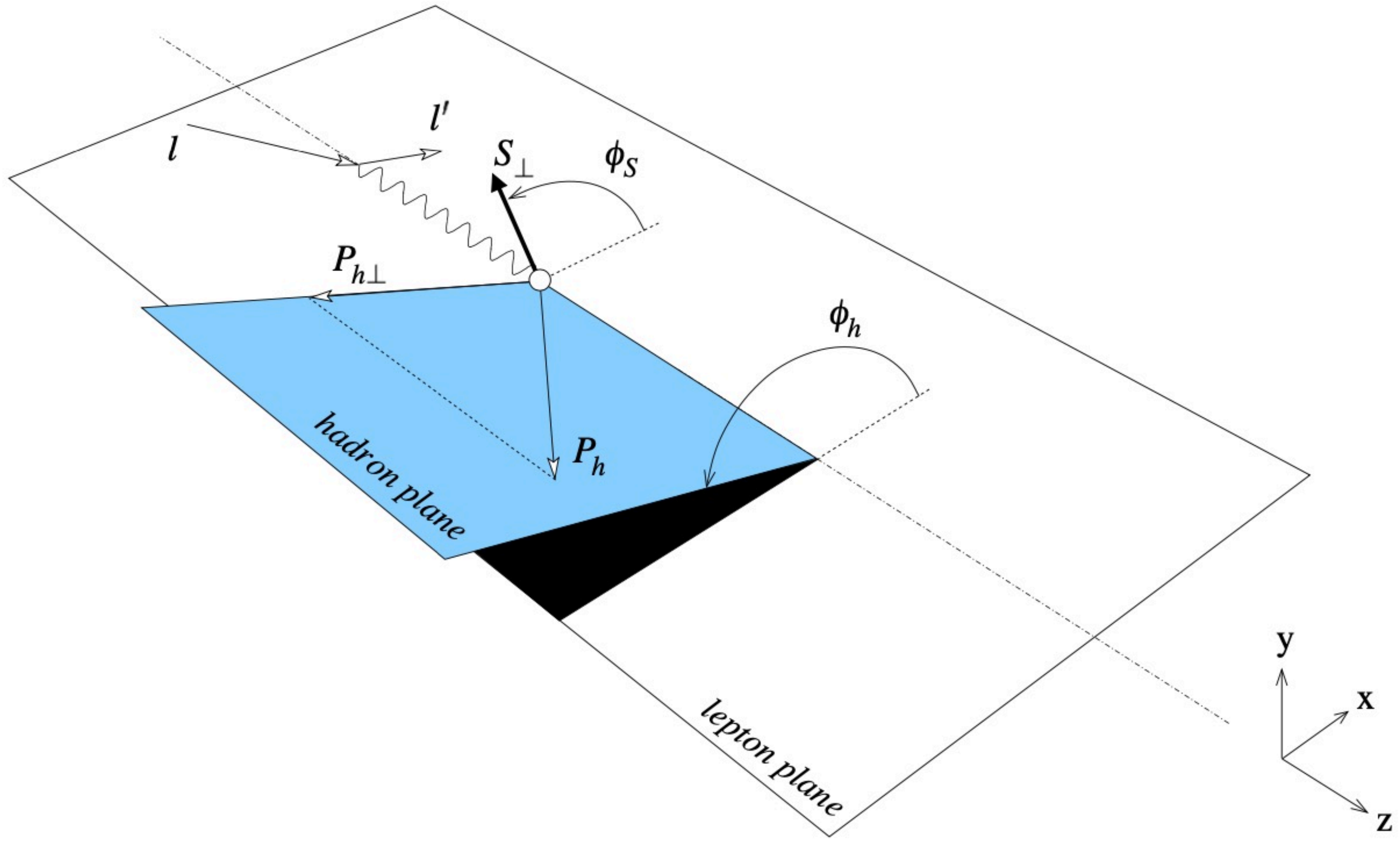
Flavor dependent nuclear PDFs

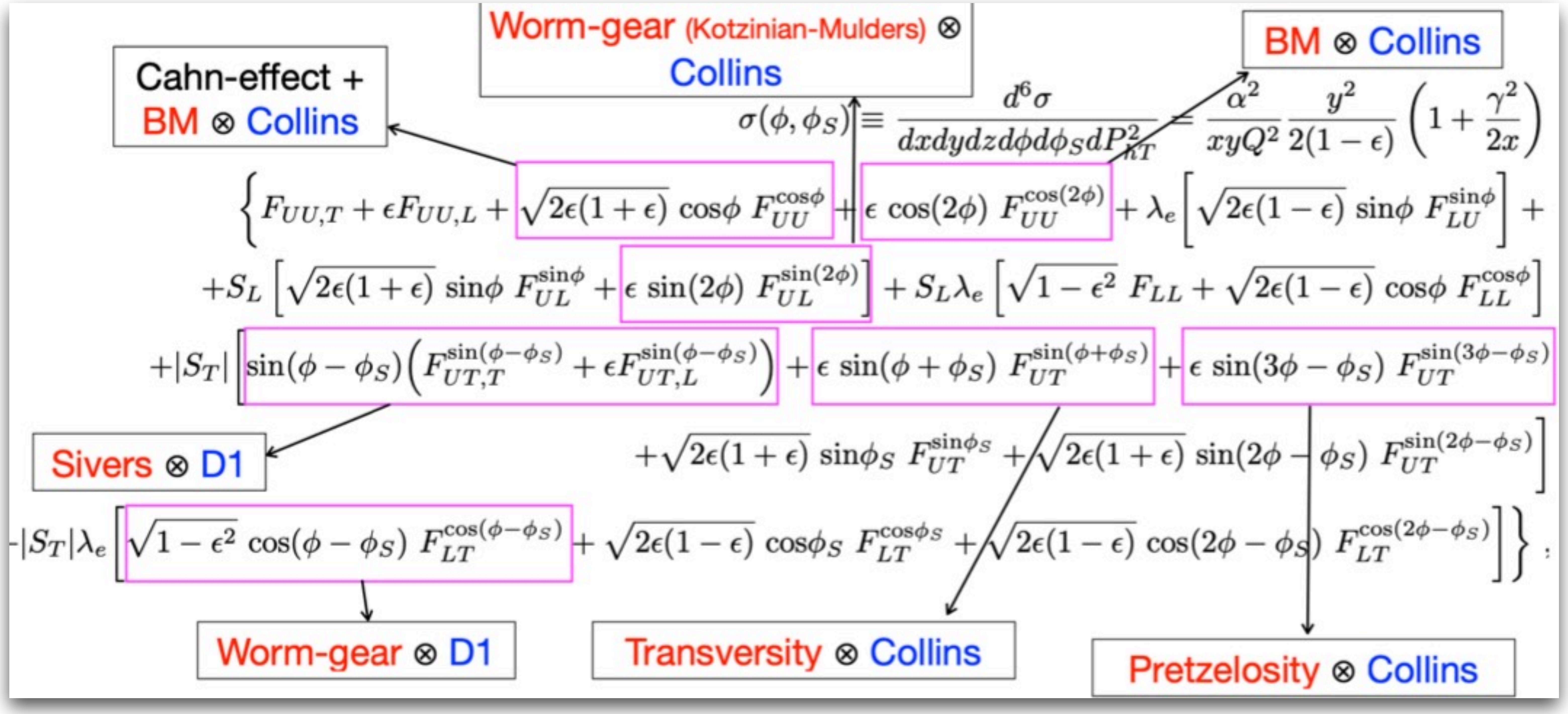
Positive charge: u

Negative charge: u, d, sea

Liu, HX, Zhang, in preparation, 2021

The role of T-odd fragmentation functions



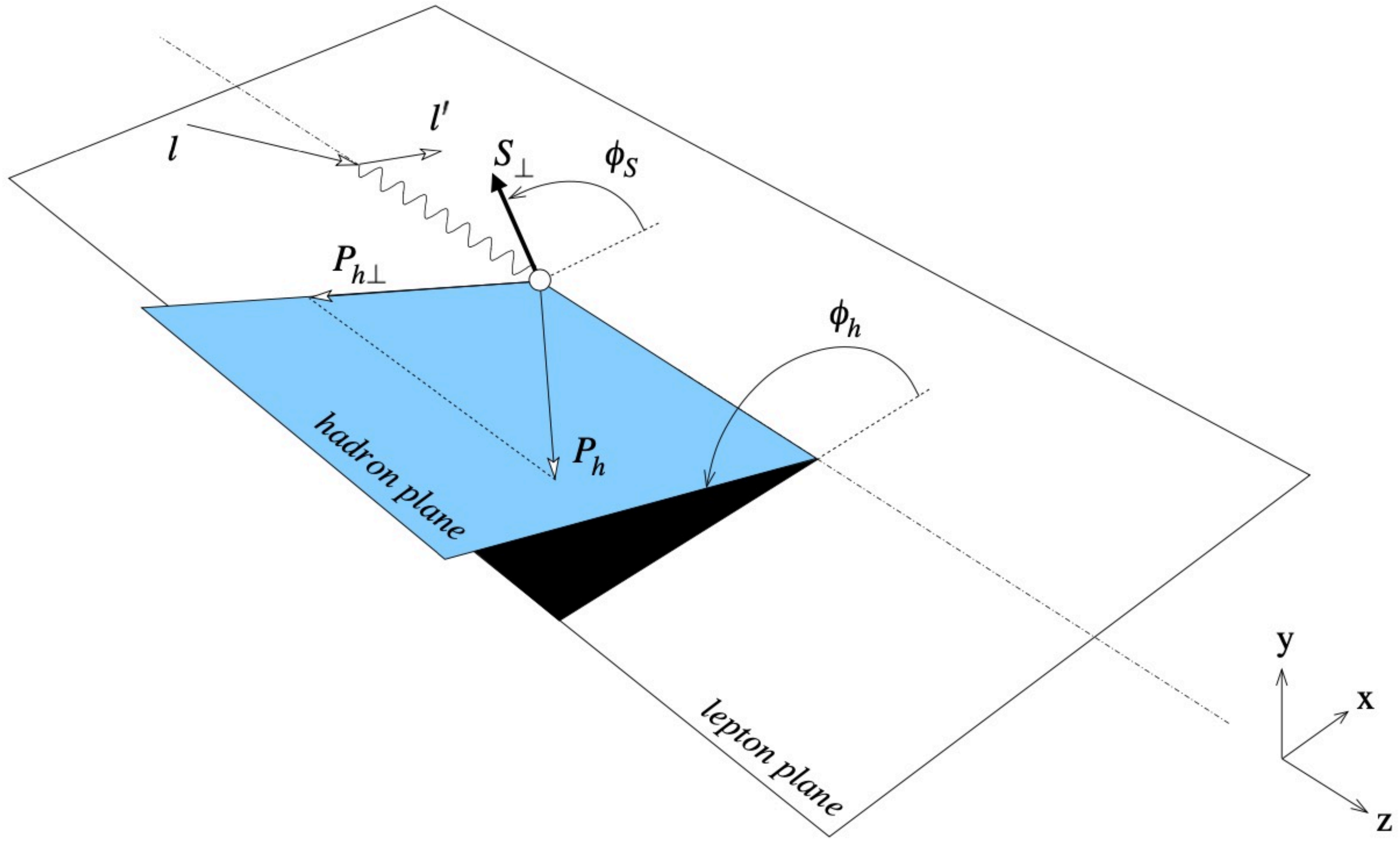


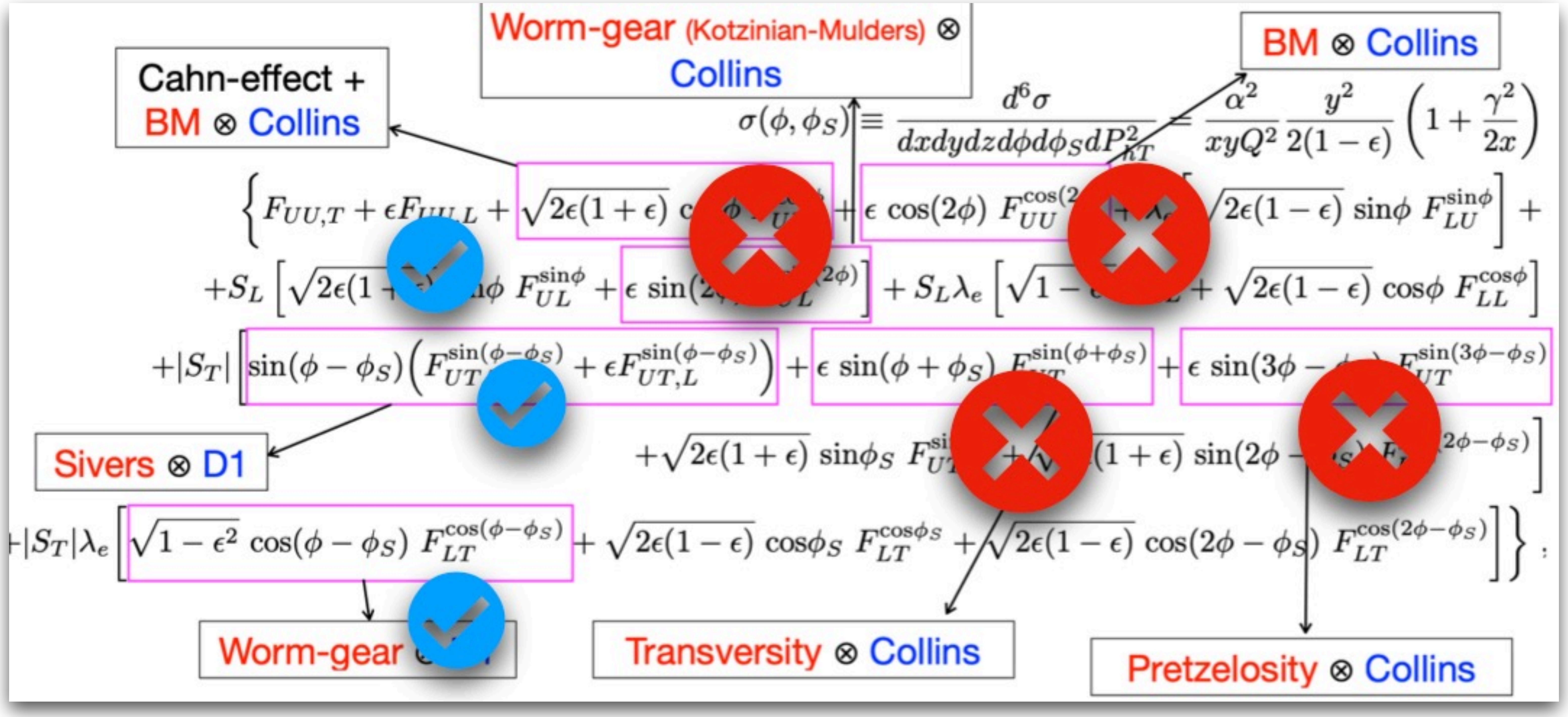
Bacchetta, Diehl, Goeke, Metz, Mulders, Schlegel, JHEP 2007

QCD requires all physical observables should preserve time reversal invariance!

The T-odd FFs provide us abundant opportunities to probe nucleon structure.

Limited power of jet probing - conventional wisdom





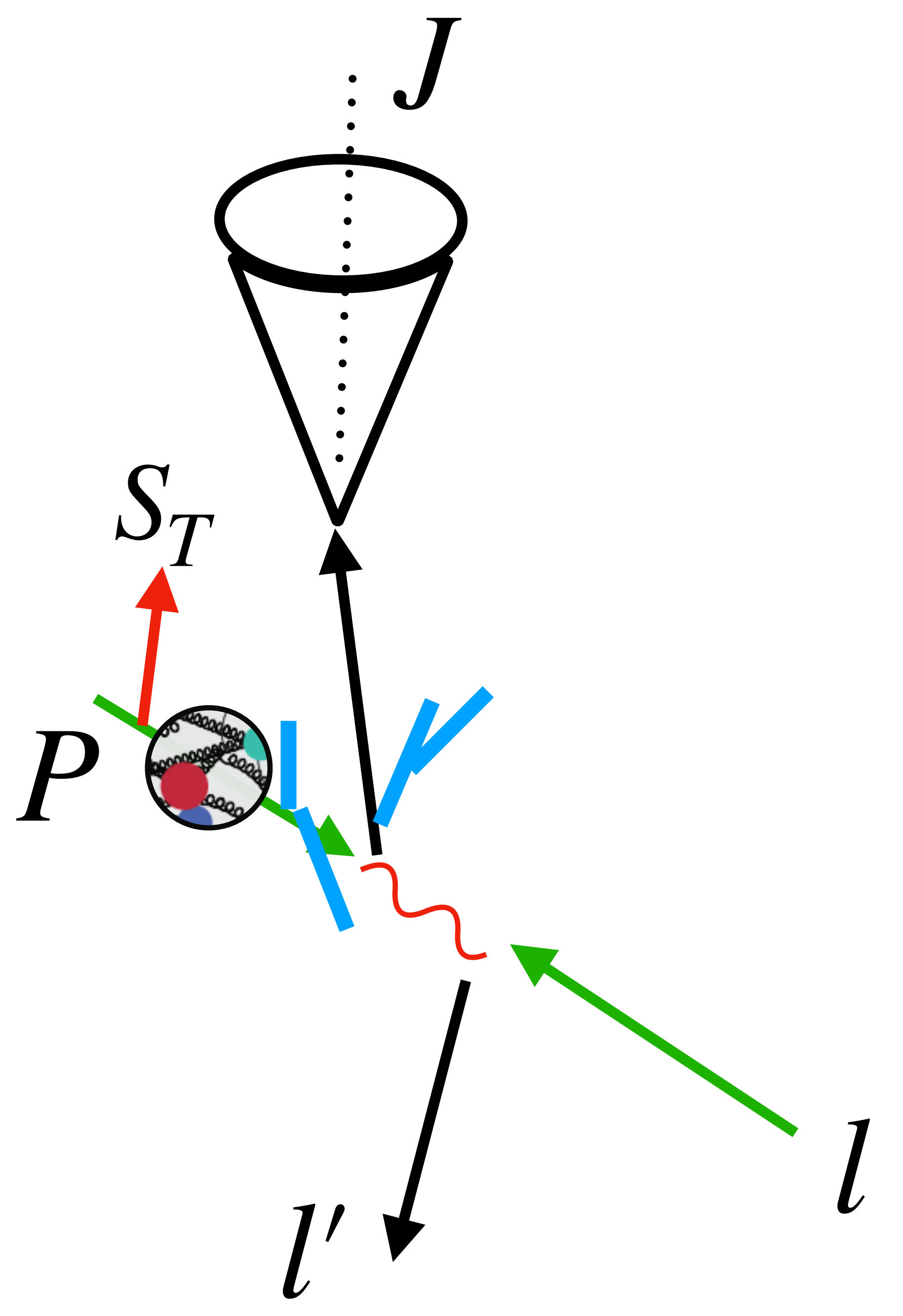
In conventional wisdom, perturbative jet is T-even, thus many spin structures vanish.

T-odd distributions involved

But Perturbative Jet is (almost) T-even

Revisit jet production in DIS

$$l\,p(P,s_T) \to \gamma^*(q) \to l'\,J(P_J) + X$$



- Factorization frame

$$P^\mu = \frac{P^-}{2}(1,0,0,1) = \frac{P^-}{2}n^\mu \qquad P_J^\mu = \frac{P_J^+}{2}(1,0,0,-1) = \frac{P_J^+}{2}\bar{n}^\mu$$

$$q_T = q - \frac{q\cdot n}{2}\bar{n} - \frac{q\cdot \bar{n}}{2}n \qquad q_T \ll Q$$

- Winner-take-all jet

$$\text{SJA}: \quad E_{(12)} = E_1 + E_2, \quad \vec{p}_{(12)} = \vec{p}_1 + \vec{p}_2\,,$$

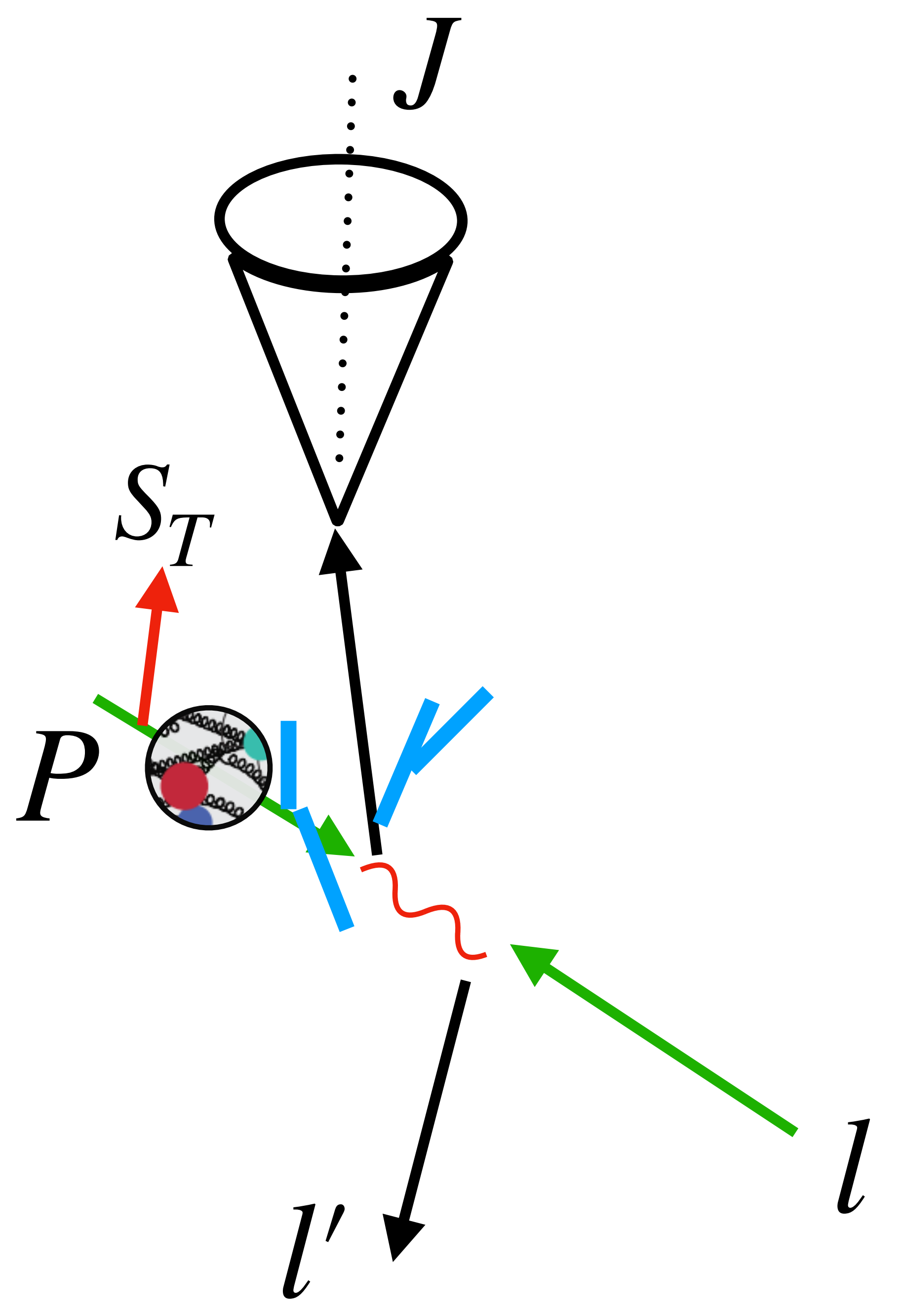
$$\text{WTA}: \quad E_{(12)} = E_1 + E_2, \quad \vec{p}_{(12)} = E_{(12)}\left[\frac{\vec{p}_1}{|\vec{p}_1|}\theta(E_1 - E_2) + \frac{\vec{p}_2}{|\vec{p}_2|}\theta(E_2 - E_1)\right]$$

WTA jet TMD has the same RG as TMD FFs

Bertolini, Chan, Thaler, JHEP 2014

Reyes, Scimemi, Waalewijn, Zoppi, PRL 2018

Revisit jet production in DIS



$$l\,p(P, s_T) \to \gamma^*(q) \to l'\,J(P_J) + X$$

In small q_T limit

$$\sigma = \frac{1}{2s}\int [dl']\frac{e^4 e_q^2}{Q^4}\frac{1}{2}L_{\mu\nu}\frac{1}{2N_c}\int d^2x_T\, e^{iq_T\cdot x_T}\gamma^{\mu}_{\alpha\beta}\gamma^{\nu}_{\beta'\alpha'}$$
$$\times \int dx^- e^{iq^+x^-}\langle P, s_T|\xi_n(0)\xi_n^\dagger(x^-, x_T)|P, s_T\rangle_{\alpha'\alpha}$$
$$\times \int [dP_J]\int dx^+ e^{iq^-x^+}\langle 0|\xi_{\bar n}(x^+, x_T)|JX_{\bar n}\rangle_\beta \langle JX_{\bar n}|\xi_{\bar n}^\dagger(0)|0\rangle_{\beta'}$$

- Only consider photon exchange
- $L_{\mu\nu}$ is leptonic tensor

SCET quark field: $\xi_{n(\bar n)} = W^\dagger_{n(\bar n)}\chi_{n(\bar n)}$

Decomposition Φ into different Dirac structures

$$\Phi(\zeta, p_T) = \frac{1}{2}\left\{ f_1 \not{n} - f_{1T}^{\perp} \frac{\epsilon_T^{\rho\sigma} p_{T\sigma} s_{T\sigma}}{M} \not{n} + g_{1s}\gamma_5 \not{n} \right.$$

$$\left. + h_{1T}\frac{[\not{s}_T, \not{n}]\gamma_5}{2} + h_{1s}^{\perp}\frac{[\not{p}_T, \not{n}]\gamma_5}{2M} + i h_1^{\perp}\frac{[\not{p}_T, \not{n}]}{2M} \right\} + \dots$$

TMDs		Quark polarization		
		Unpolarized (U)	Longitudinally polarized (L)	Transversely polarized (T)
Nucleon polarization	U	f_1 Unpolarized		$h_1^{\perp}$ Boer–Mulders
	L		g_{1L} Helicity	$h_{1L}^{\perp}$ Longi-transversity
	T	$f_{1T}^{\perp}$ Sivers	g_{1T} Trans-helicity	h_1 Transversity $h_{1T}^{\perp}$ Pretzelosity

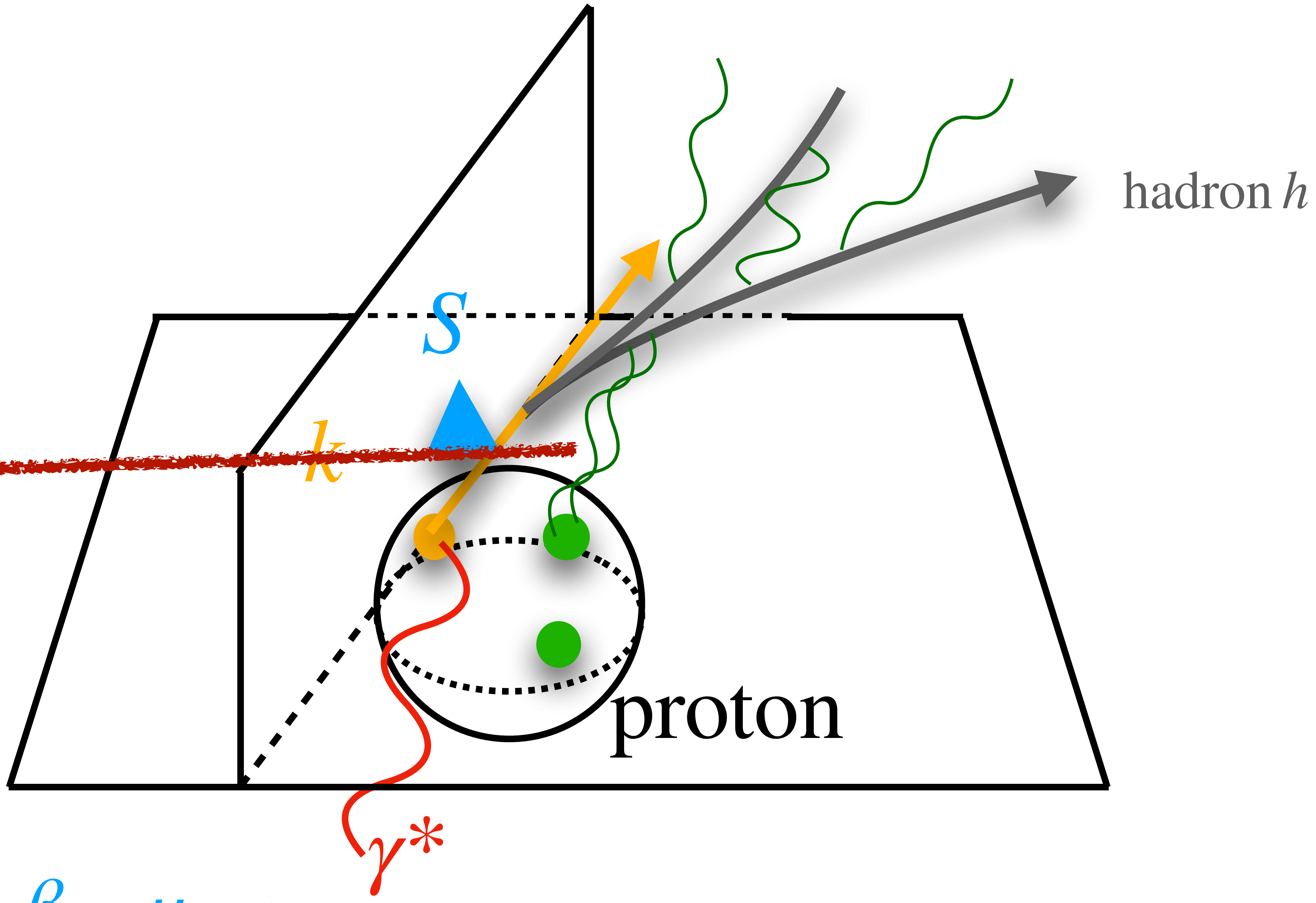
Decomposition of Δ into different Dirac structures

For single hadron production:

Collins function -> T-odd

$$\Delta(z, k_T) = \frac{1}{2}\left\{ D_1 \not{n} + i H_1^{\perp} \frac{[\not{k}_T, \not{n}]}{2M_h} \right\} + \ldots$$

Final state interactions generate an asymmetry



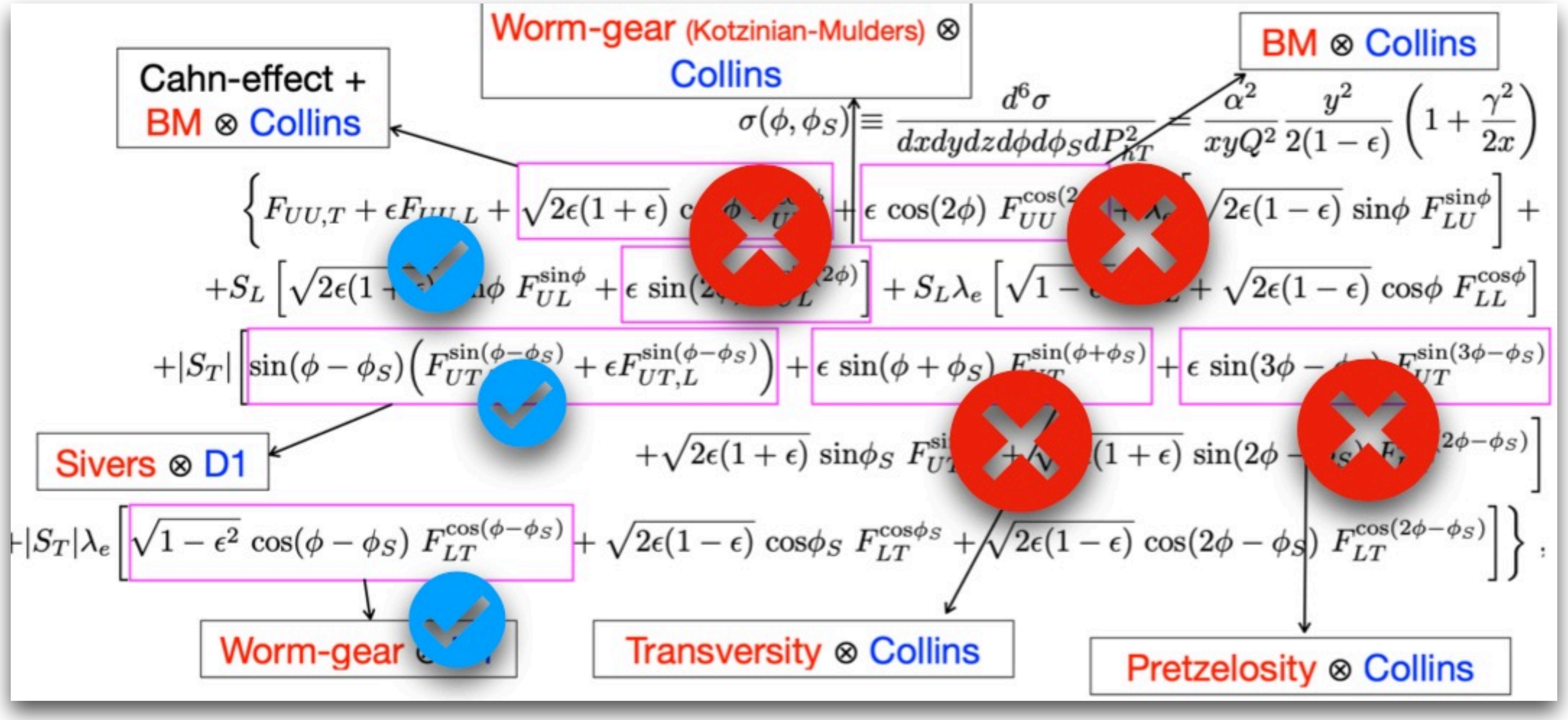
To observe the asymmetry (Collins 2002):

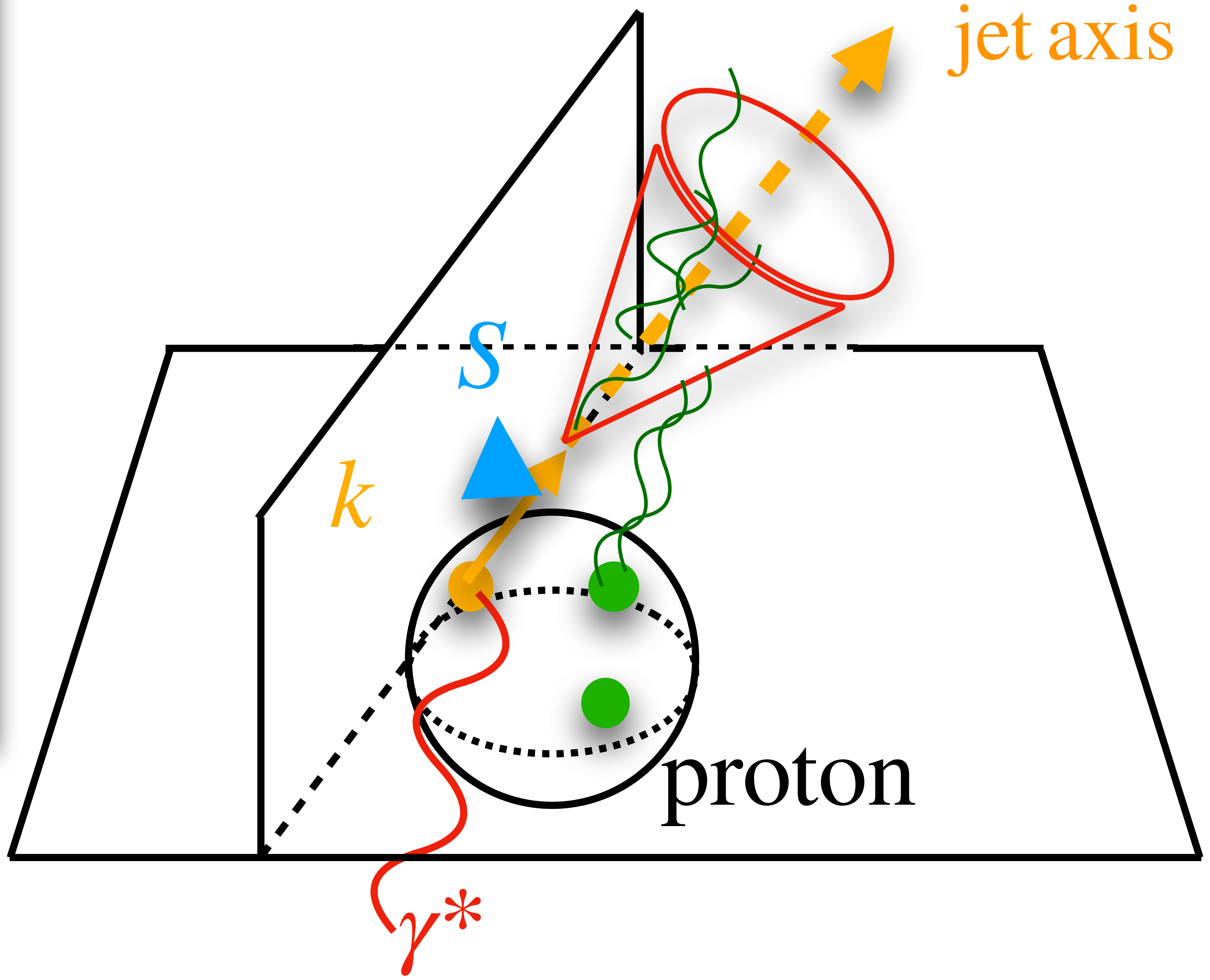
- h is not in the k-S plane
- Non-perturbative

$$\propto \epsilon_{\alpha\beta\mu\nu} k_\perp^\alpha s_\perp^\beta P_h^\mu n^\nu$$

Decomposition of $\mathcal{J}$ into different Dirac structures

$$\mathcal{J}(z,k_T) = \frac{1}{4}\left\{ J_1 \not{\bar{n}} + i J_T \frac{[\not{k}_T, \not{\bar{n}}]}{2M_h} \right\} + \dots$$





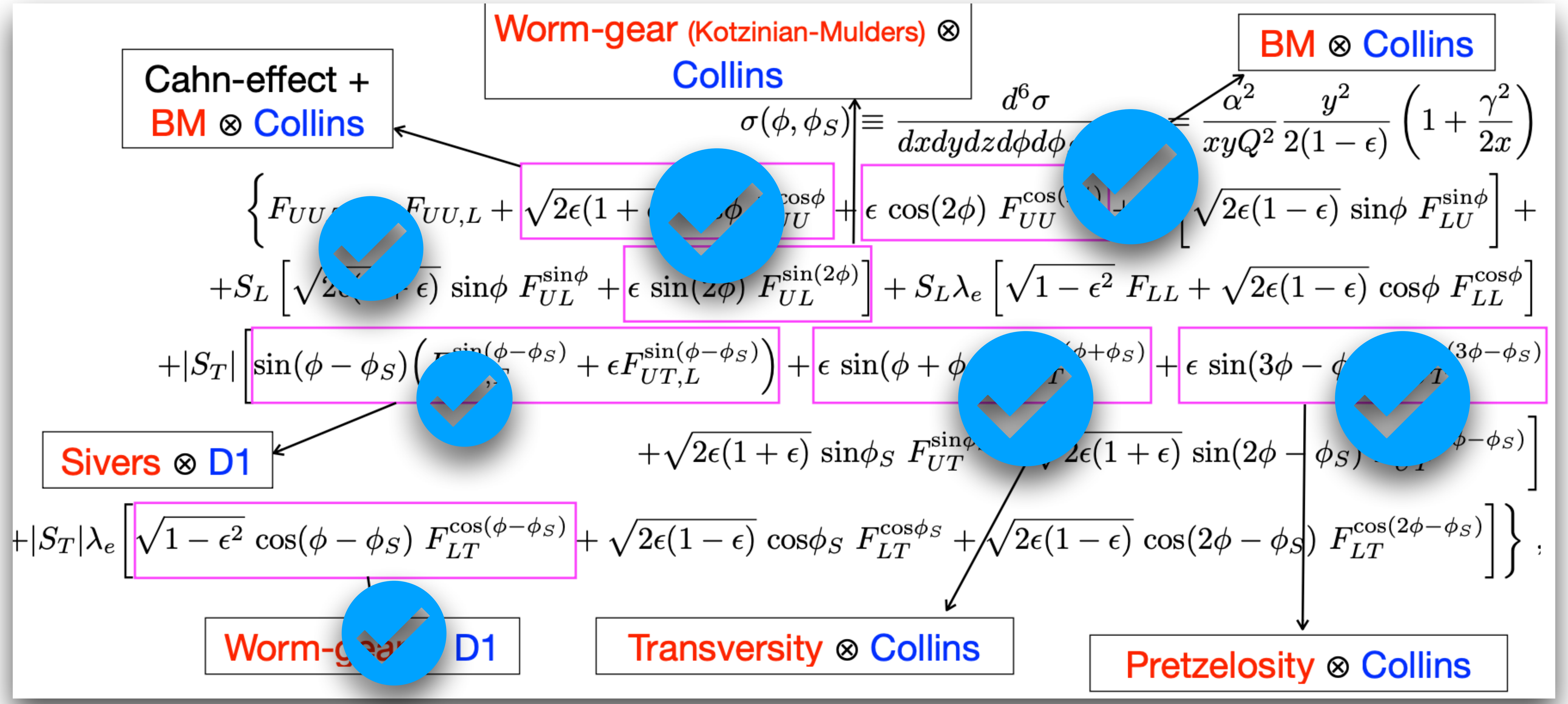
- Jet is in the k-S plane
- perturbative

T-even jets limit the power of jet probe!

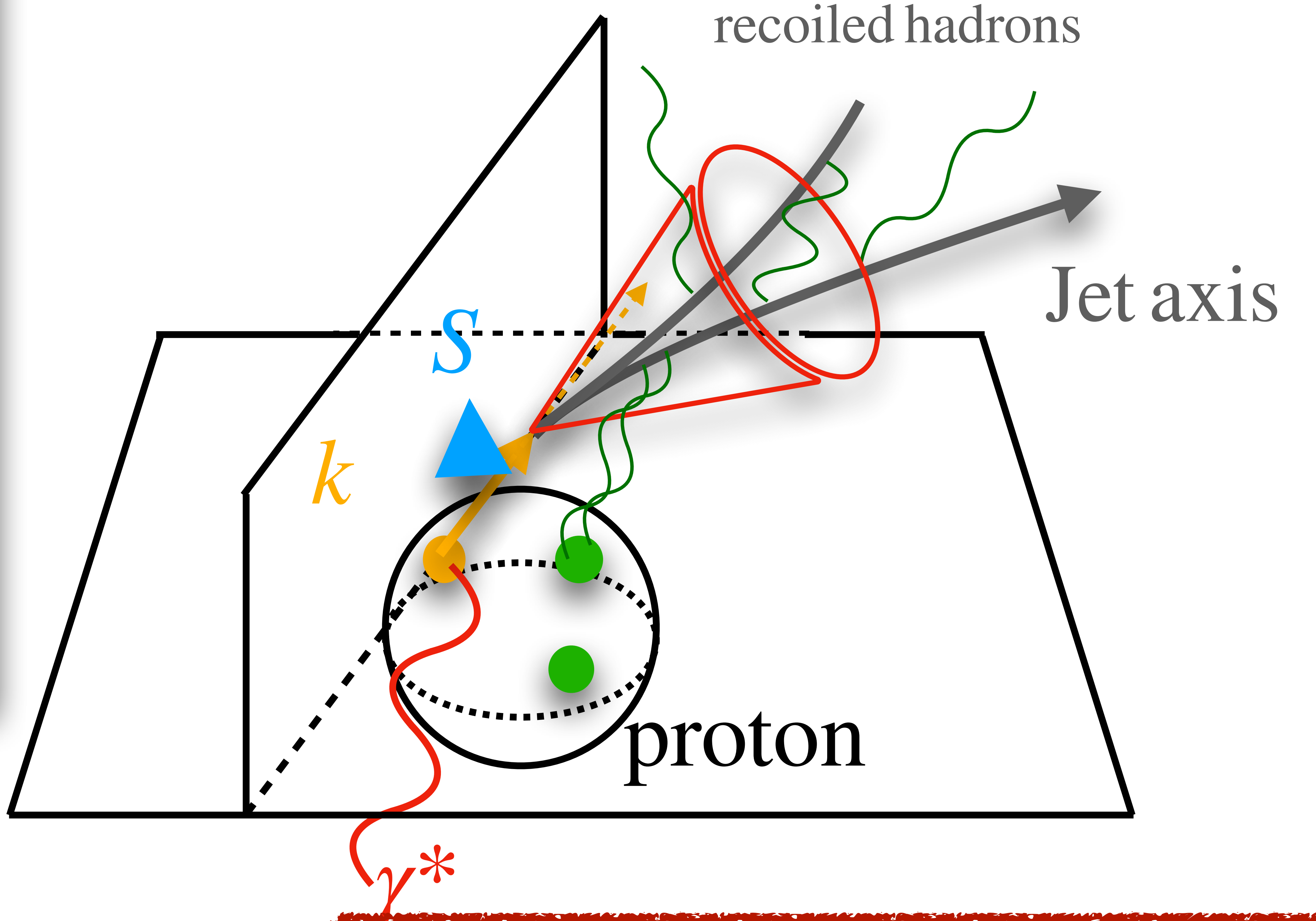
Decompose quark field correlation functions into different Dirac structures

$$\mathcal{J}(z, k_T) = \frac{1}{4}\left\{ J_1 \not{n} + iJ_T \frac{[\not{k}_T, \not{n}]}{2M_h} \right\} + \dots$$

Not true -> existence of T-odd jet component



Lai, Liu, Wang, HX, 2021

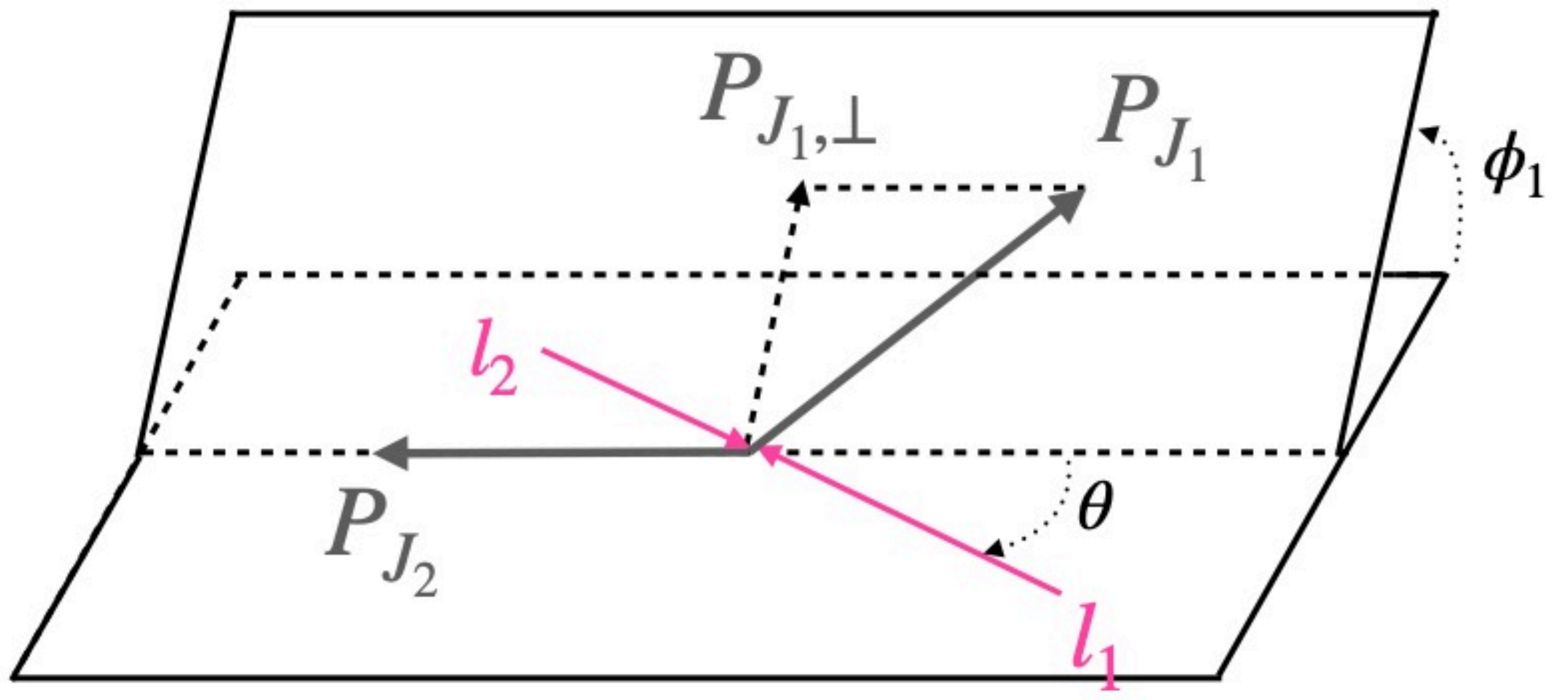


Jet axes can be different with different artificial algorithms

- Jet is not in the k-S plane
- Can be non-perturbative

Cal, Neill, Ringer, Waalewijn, JHEP 2020

Constrain T-odd jet in e^+e^- collisions



Azimuthal asymmetry:

$$R^{J_1J_2} = 1 + \cos(2\phi_1)\frac{\sin^2\theta}{1+\cos^2\theta}\frac{F_T(q_T)}{F_U(q_T)}$$

Factorization for WTA jet

$$\mathcal{J}^q_{\beta\beta'}(z,k_T,R) = \delta(1-z)J^q_{\beta\beta'}(k_T) + \mathcal{O}\left(\frac{k_T^2}{p_J^2R^2}\right)$$

$$F_U = q_T\sum_q e_q^2\int\frac{\mathrm{d}b\, b}{2\pi}J_0(q_Tb)J^q(b)\bar{J}^{\bar{q}}(b)$$

Reyes, Scimemi, Waalewijn, Zoppi, PRL 2018

$$F_T = q_T\sum_q e_q^2\int\frac{\mathrm{d}^2b}{(2\pi)^2}e^{-iq_T\cdot b}\left(2\frac{q_T^\alpha}{q_T}\frac{q_T^\beta}{q_T} + g^{\alpha\beta}\right)\partial_{b^\alpha}J_T^q(b)\partial_{b^\beta}\bar{J}_T^{\bar{q}}(b)$$

Liu, HX, 2104.03328, 2021

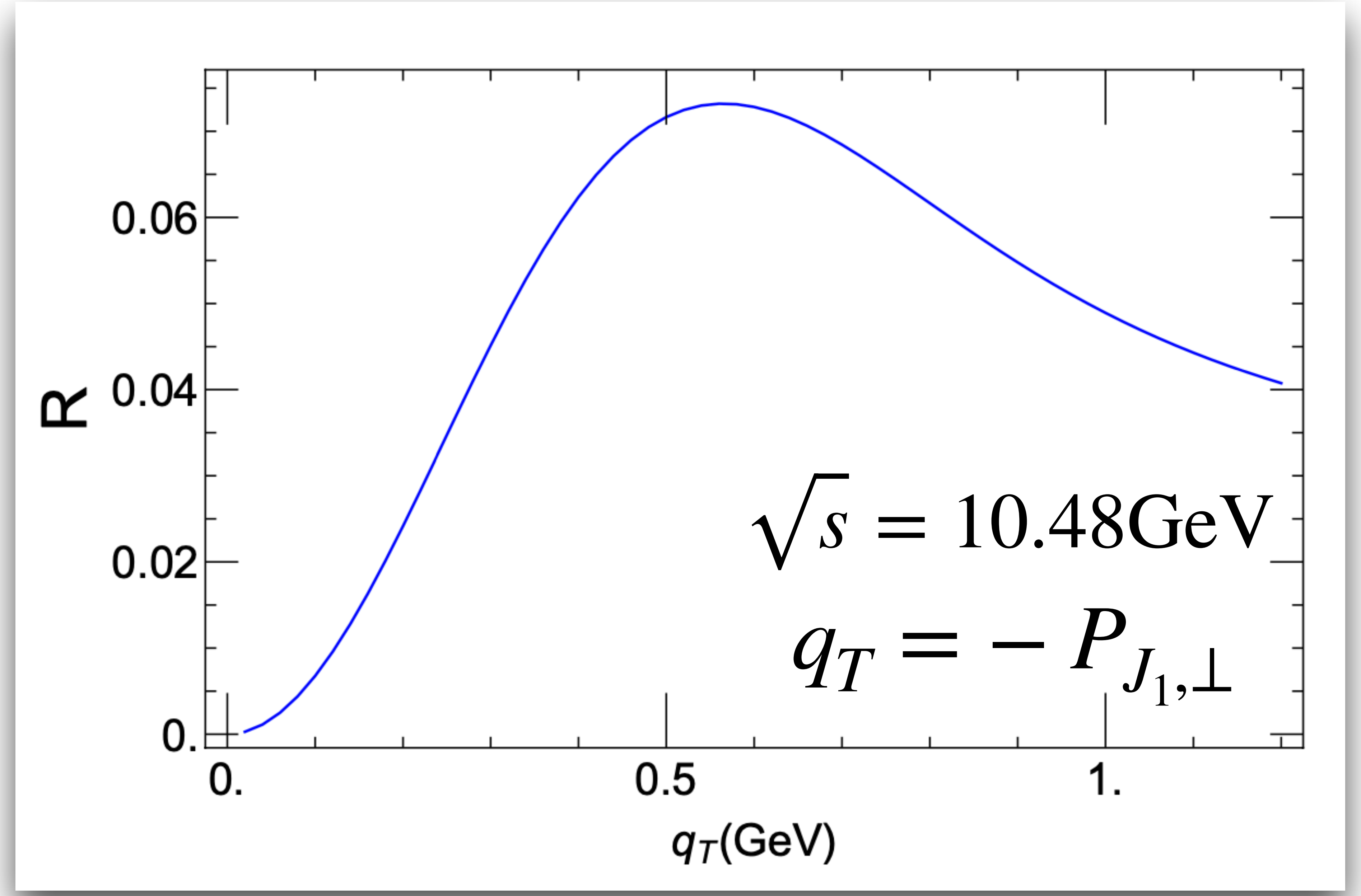
Azimuthal asymmetry in e^+e^-

$$R = 2\int d\cos\theta \frac{d\phi_1}{\pi}\cos(2\phi_1)R^{J_1J_2}$$

$$J(b)\bar{J}(b) = e^{-S_{pert.}-S^J_{NP}}\left(1+\mathcal{O}(\alpha_s)\right) r_q(Q_{J_{h_1}}) r_{\bar{q}}(Q_{J_{h_2}})$$

$$S_{pert.} = \int_{\mu_b^2}^{s}\frac{d\mu^2}{\mu^2}\left(A\log\frac{s}{\mu^2}+B\right)$$

$$\partial_{b^\alpha} J_T^q \partial_{b^\beta} \bar{J}_T^{\bar{q}} = e^{-S_{pert.}-S^T_{NP}}\frac{b^\alpha b^\beta}{4}\mathcal{N}_q^h(b)\mathcal{N}_{\bar{q}}^h(b)$$



- Follow the parametrization for Collins TMD (Kang, Prokudin, Sun, Yuan, 2015)
- This is for illustration only, because the non-perturbative T-odd jet functions are yet to be determined.

Can be extracted directly from BELLE or BaBar data

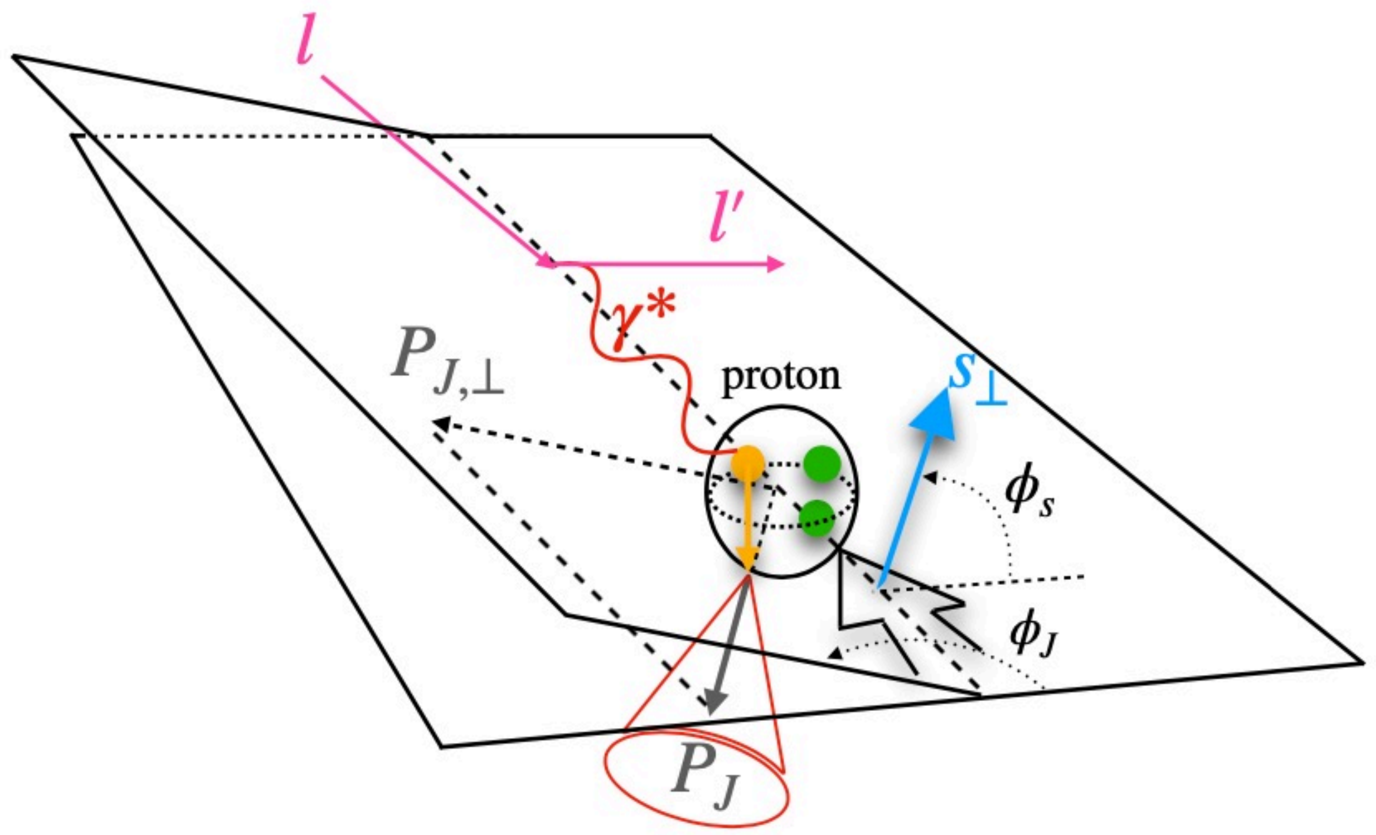
The lower the jet energy the better (if statistics guaranteed)

Using T-odd jets to constrain the nucleon tensor charge

Factorization in DIS

$$A(\zeta, y, \phi_s, \phi_J, P_{J\perp}) = 1 + \epsilon|s_\perp|\sin(\phi_J + \phi_s)\frac{F_{UT}}{F_{UU}}$$

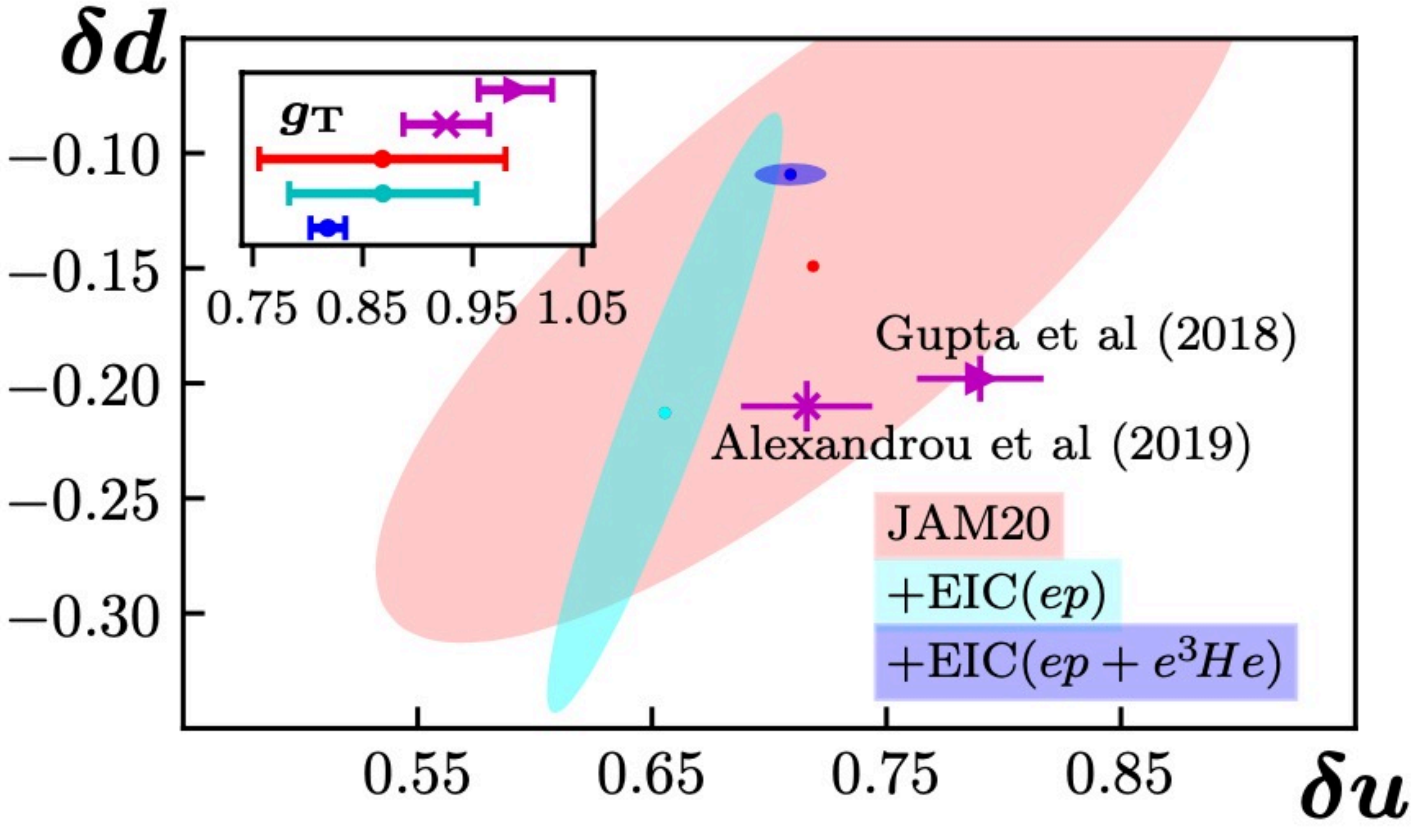
$$F_{UT} = \sum_q e_q^2 \int \frac{d^2b}{4\pi^2} e^{-iP_{J\perp}\cdot b} i \frac{P_{J\perp}^\alpha}{P_{J\perp}} \zeta\, h_1^q(\zeta, b)\, \partial_{b^\alpha} J_T^q(b)$$



Nucleon tensor charge: $g_T = \delta u - \delta d$

$$\delta u = \int_0^1 dx\,(h_1^u(x) - h_1^{\bar{u}}(x)), \quad \delta d = \int_0^1 dx\,(h_1^d(x) - h_1^{\bar{d}}(x))$$

T-odd jet with jet charge measurement can serve as a fantastic probe for nucleon tensor charge.



Gamberg, Kang, Pitonyak, Prokudin, Sato, PLB 2021

Conclusion

- Jet is a powerful tool in many fields.
- Two fundamental difficulties in conventional jet

  Flavor separation -> Jet charge

  Limited power of jet probing on nucleon spin structure -> T-odd jet

- More comprehensive and precise analyses will come soon - stay tuned!

Conclusion

- Jet is a powerful tool in many fields.
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Thanks for your attention!