New probes of the proton internal structures

刘晓辉

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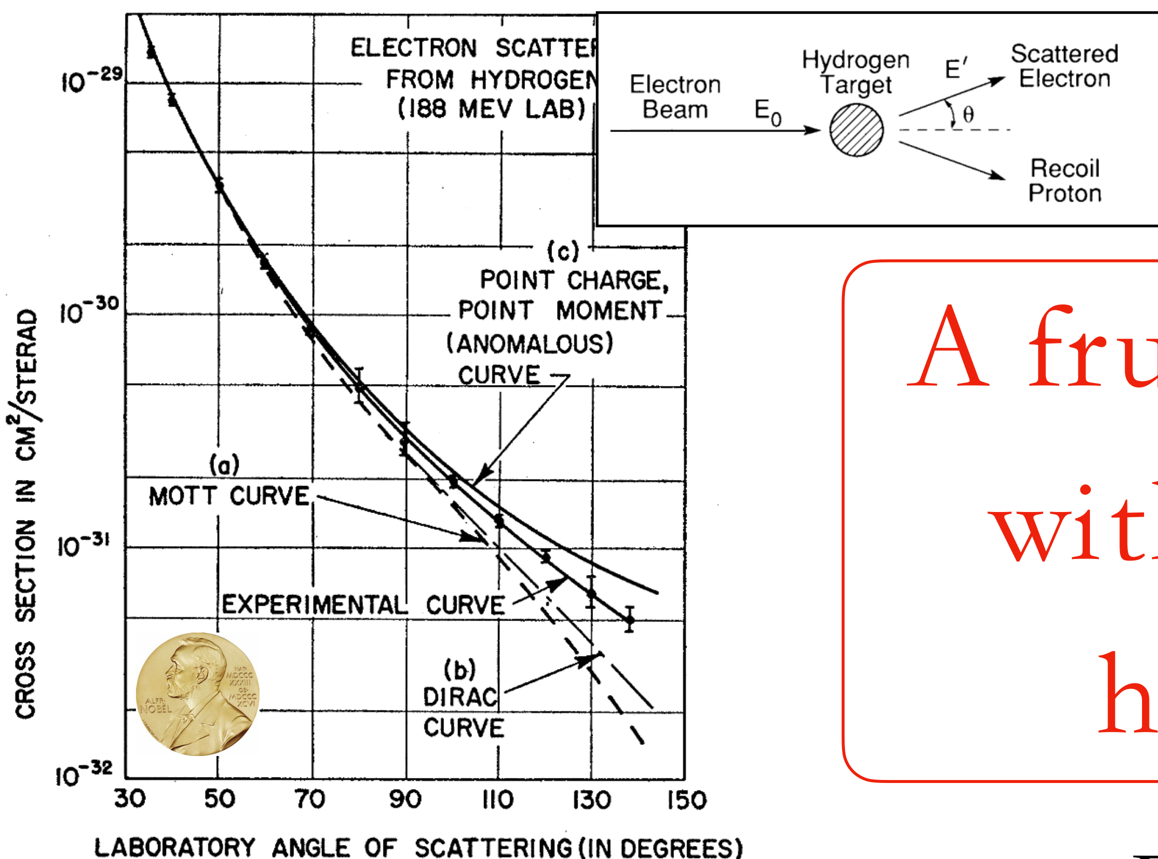
北京師範大學
BEIJING NORMAL UNIVERSITY

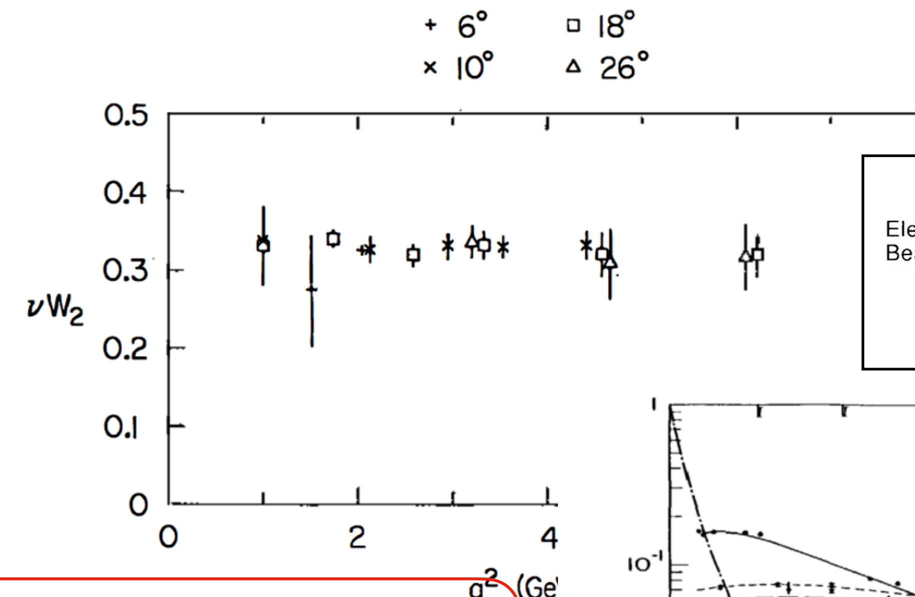
Outline

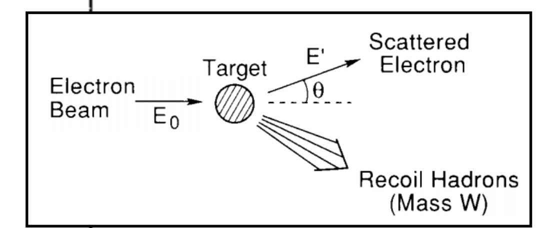
- Proton structure studies (basic ideas)
  - By jet probes
  - By quantum simulation (toy model)
- Conclusion

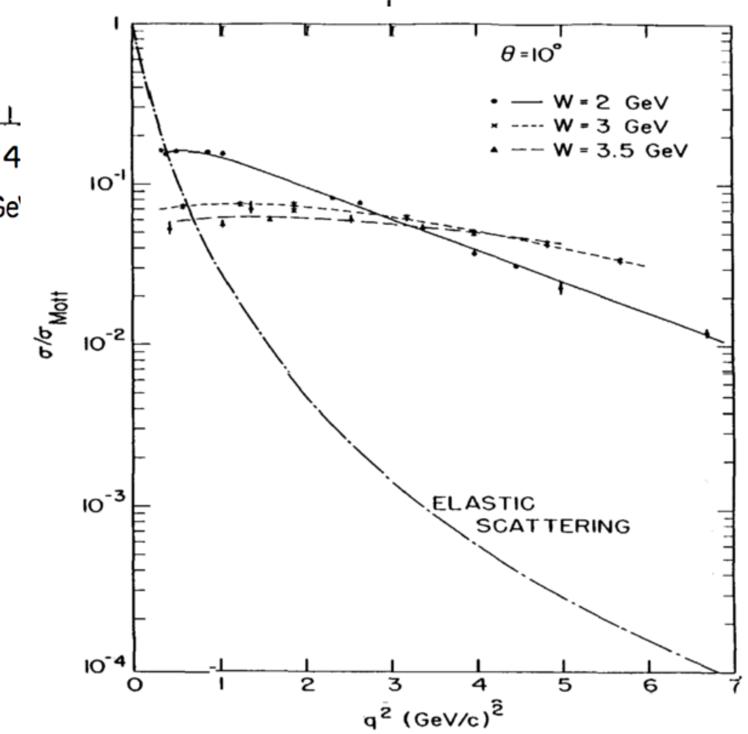
Proton Structure Studies

McAllister, Hofstadter, 1956









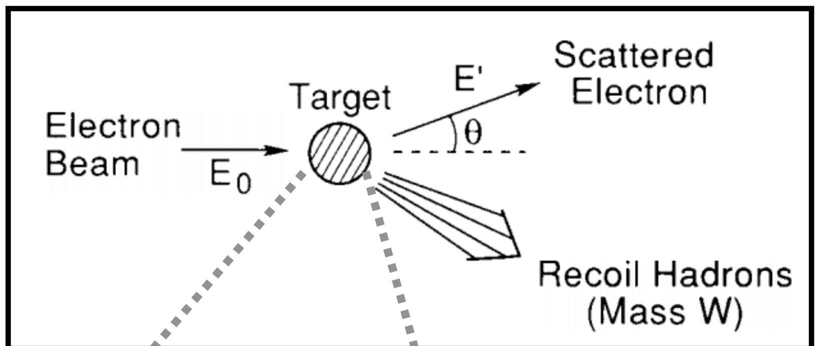
A fruitful field with a long history

Proton is not elementary

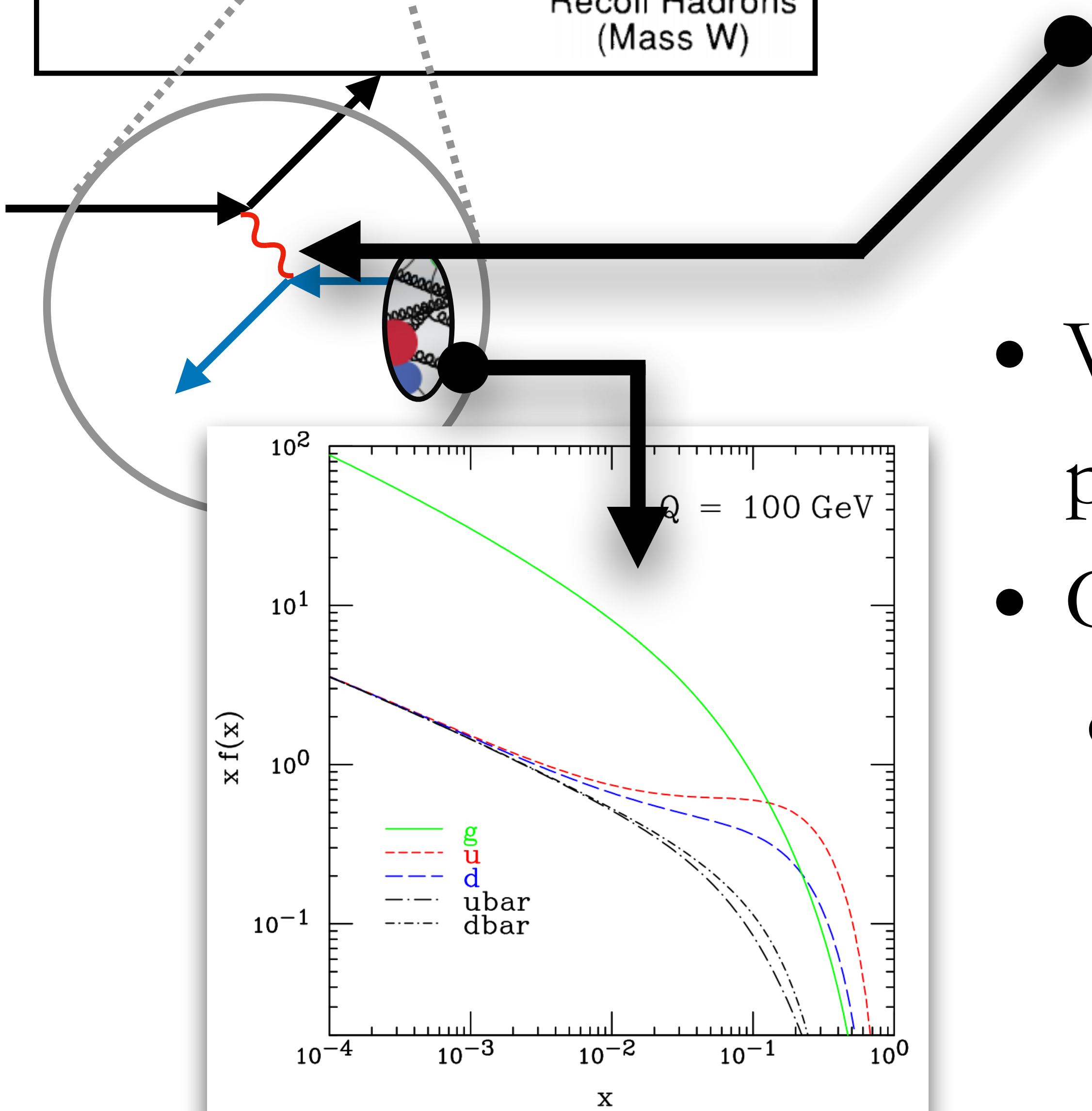
- Feynman Parton Model
- Confirm the existence of quarks
- Asymptotic free
- Discovery of QCD

Proton Structure Studies

- Experimentally: Hard probes



$$\sigma = \hat{\sigma}_i \, f_{i/P}(x) \, , \quad f_{i/P}(x) = \hat{\sigma}_i / \sigma$$

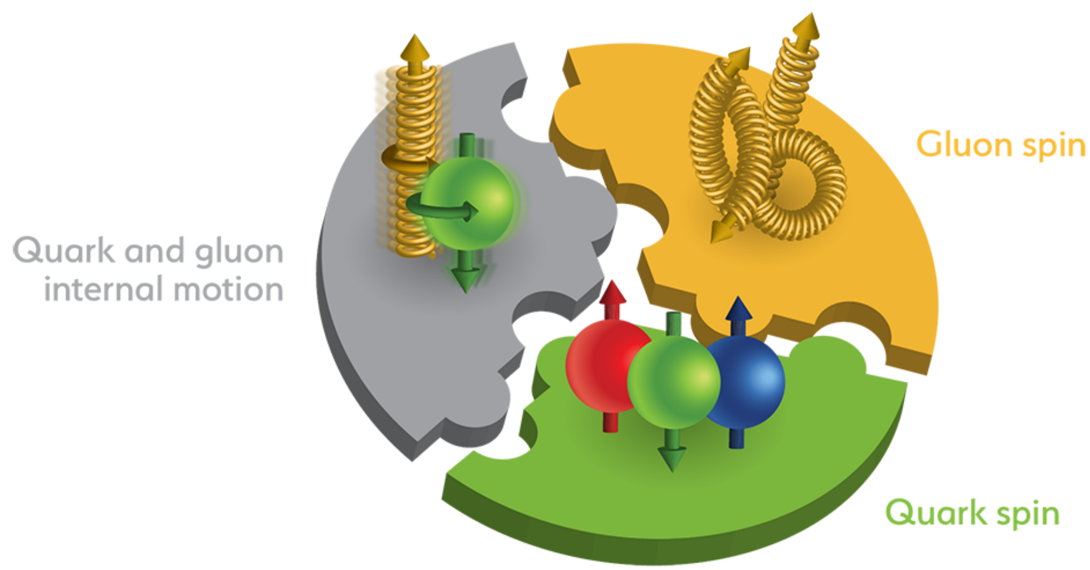


- Very good understanding of the proton longitudinal component
- Crucial for the LHC physics

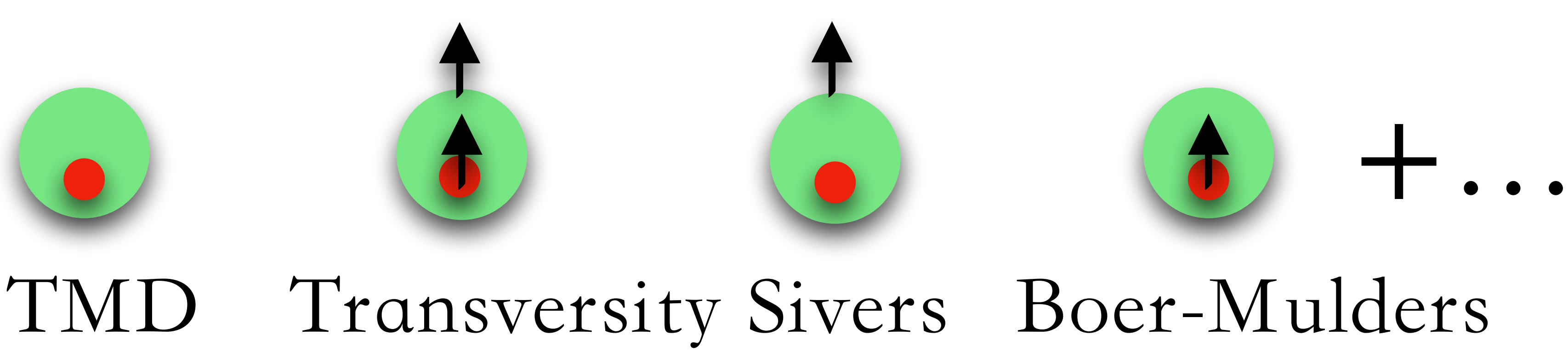
e.g., $\sigma_{ggH} = 48.58\,\mathrm{pb}^{+4.56\%}_{-6.72\%}(\mathrm{theory}) \pm 3.2\%(\mathrm{PDF} + \alpha_s)$

Anastasou, et.al., PRL 2016

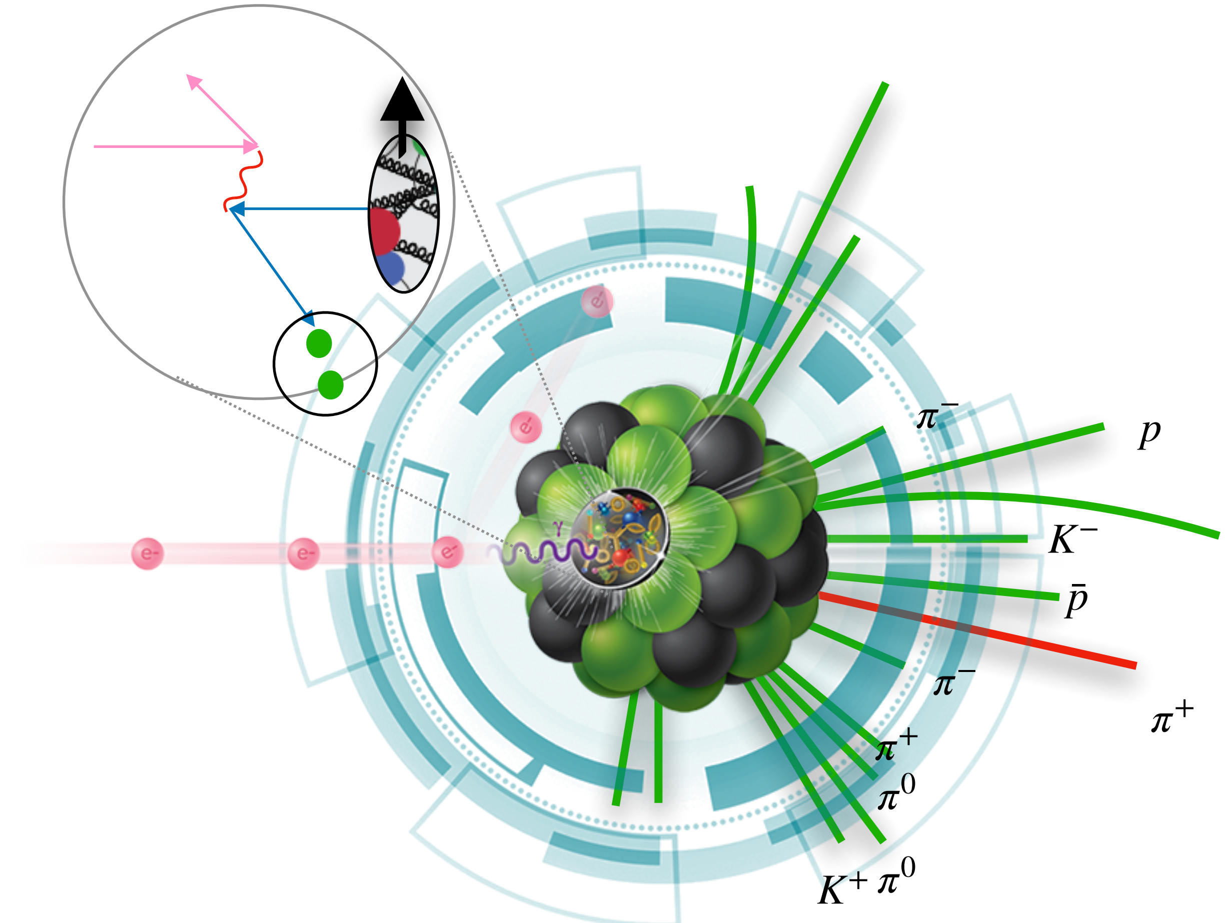
Proton Structure Studies



- A lot to answer @ EicC, EIC
  - Spin components
  - Mass decomposition
  - Proton radius
- 3D Parton distribution functions
  - Longitudinal + transverse
  - Polarization of partons in a (un-) polarized proton

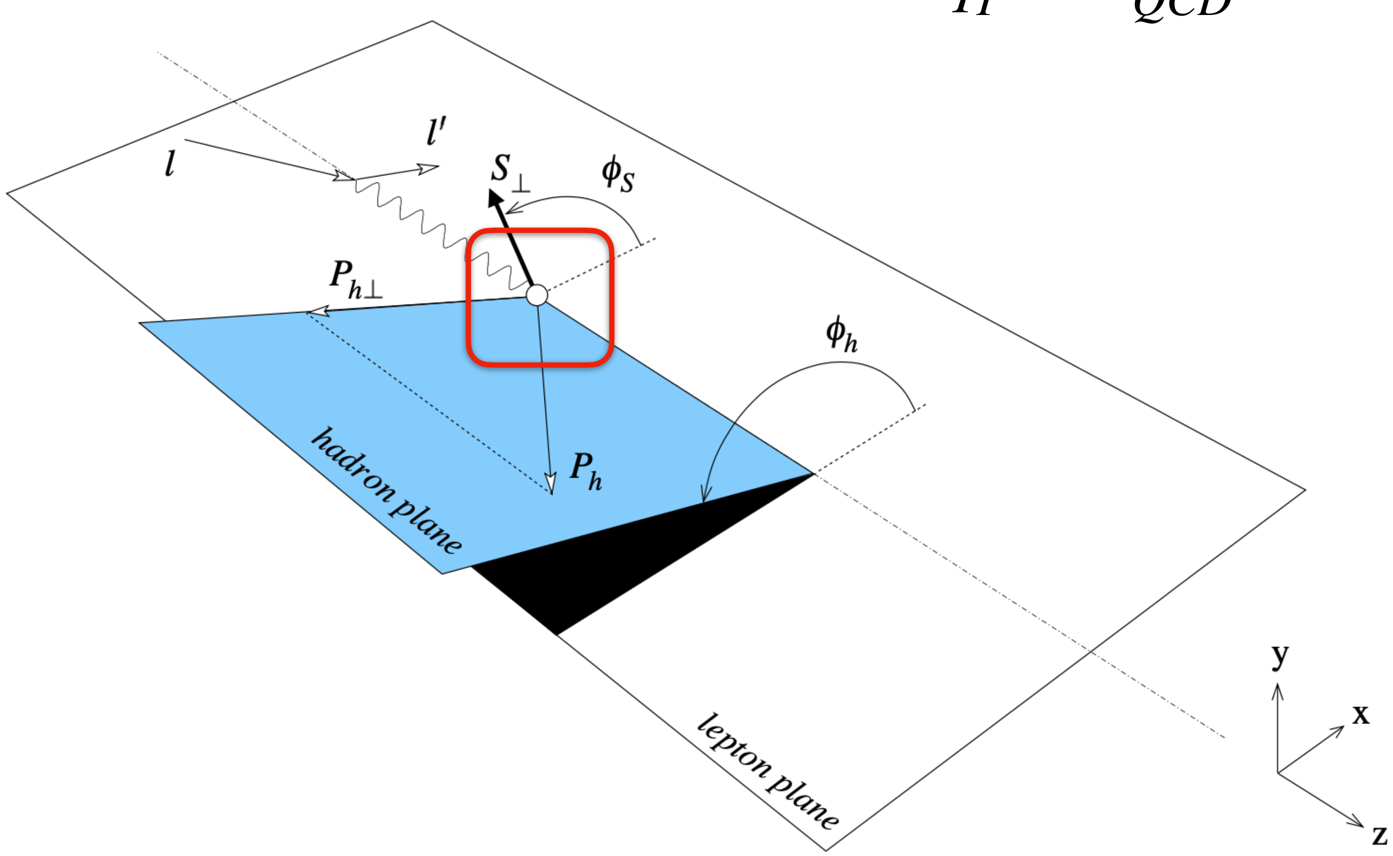


Proton Structure Studies



- Semi Inclusive DIS
  - Tag one hadron, inclusive over others, require $P_{h,\perp}$ (the q_T of the system) small

$$q_T \sim \Lambda_{QCD}$$



- Usually performed in the GNS frame, Breit frame
- TMD factorization

$$\sigma = \hat{\sigma}_{i\to j}\, f_{i/P}(x, k_T, S) \otimes_{q_T} D_{j/H}(z, k'_T)$$

Proton Structure Studies

- Semi Inclusive DIS
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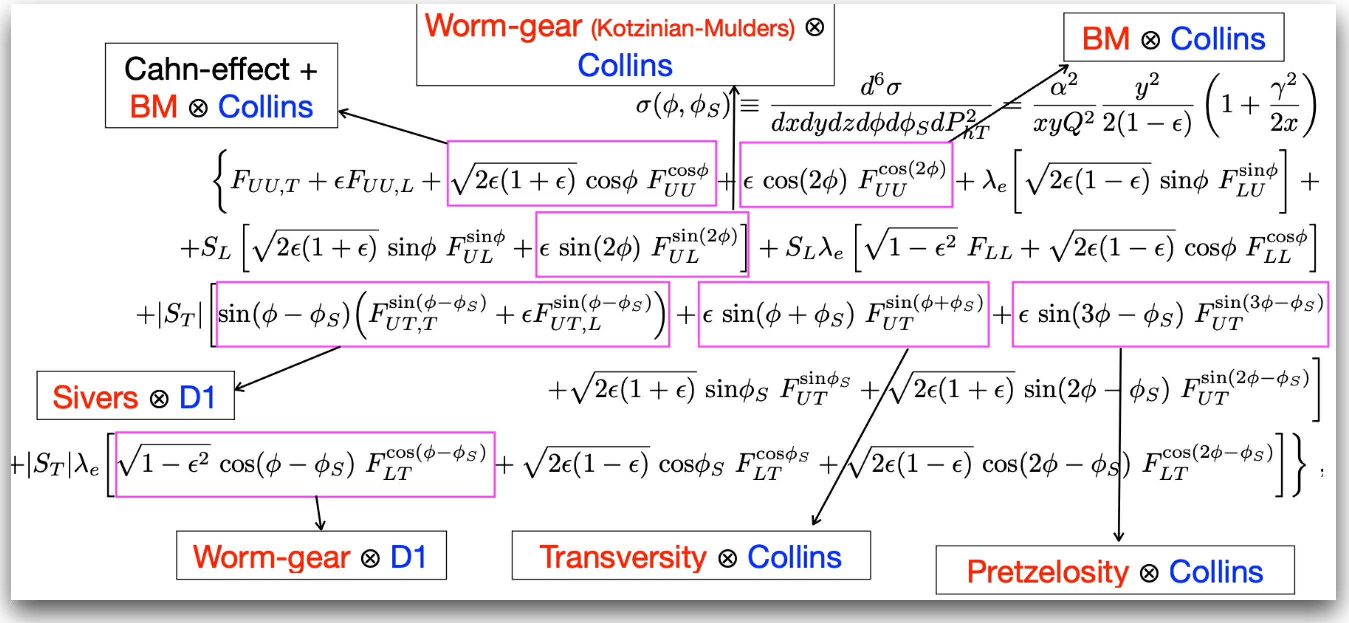
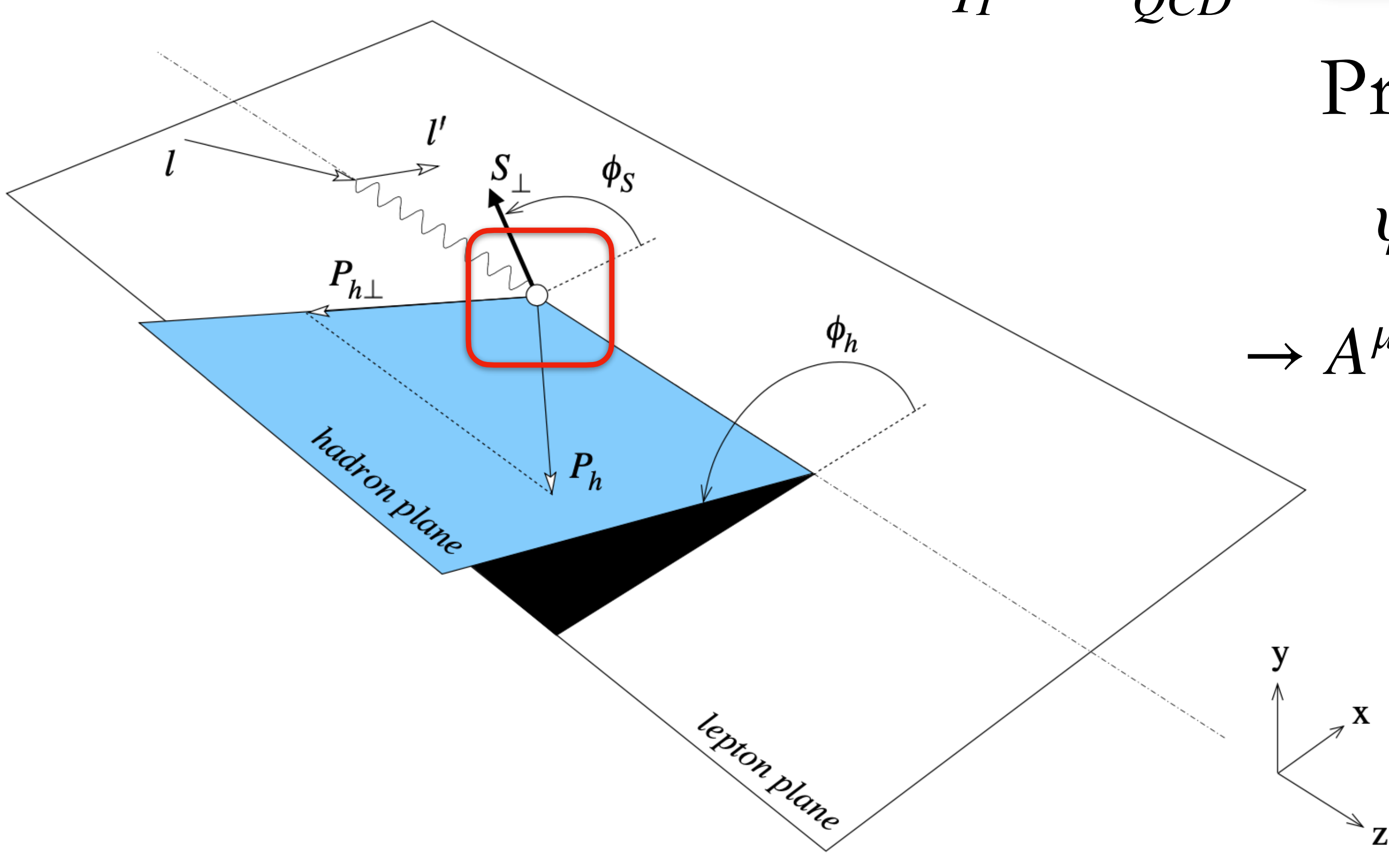




Pro: Abundant structures

$$\bar{\psi}_n \gamma^\mu \psi_{\bar{n}} \bar{\psi}_{\bar{n}} \gamma^\nu \psi_n$$

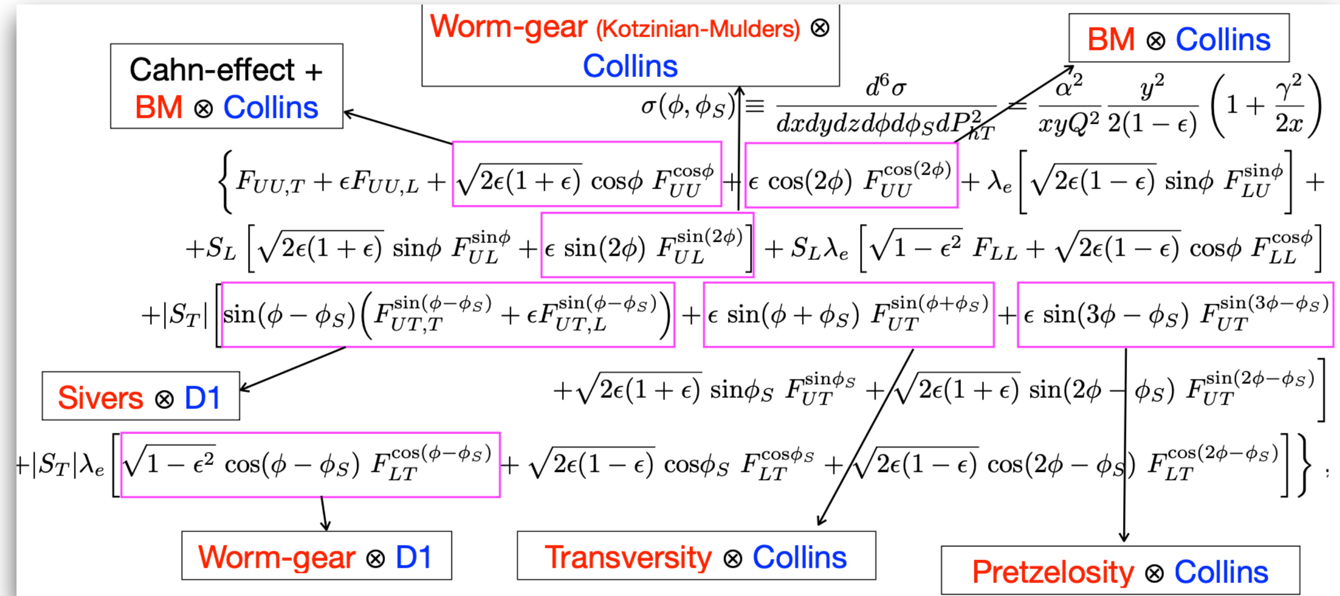
$$\to A^{\mu\nu} \bar{\psi}_n \bar{n}\!\!\!/ \psi_n \; \bar{\psi}_{\bar{n}} n\!\!\!/ \psi_{\bar{n}} + B^{\mu\nu}_{\alpha\beta} \bar{\psi}_n \bar{n}\!\!\!/ \gamma_\perp^\alpha \gamma^5 \psi_n \; \bar{\psi}_{\bar{n}} n\!\!\!/ \gamma_\perp^\beta \gamma^5 \psi_{\bar{n}} + \ldots$$

Possible since non-pert.

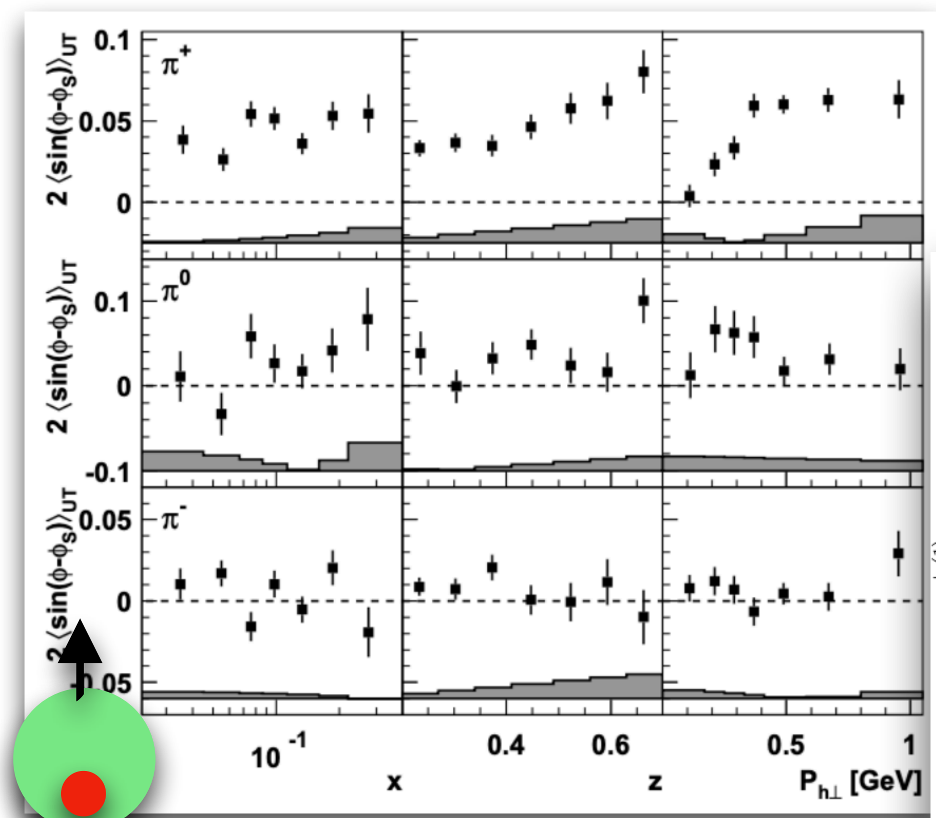
$$\sigma = \hat{\sigma}_{i\to j} \, f_{i/P}(x, k_T, S) \otimes_{q_T} D_{j/H}(z, k'_T)$$

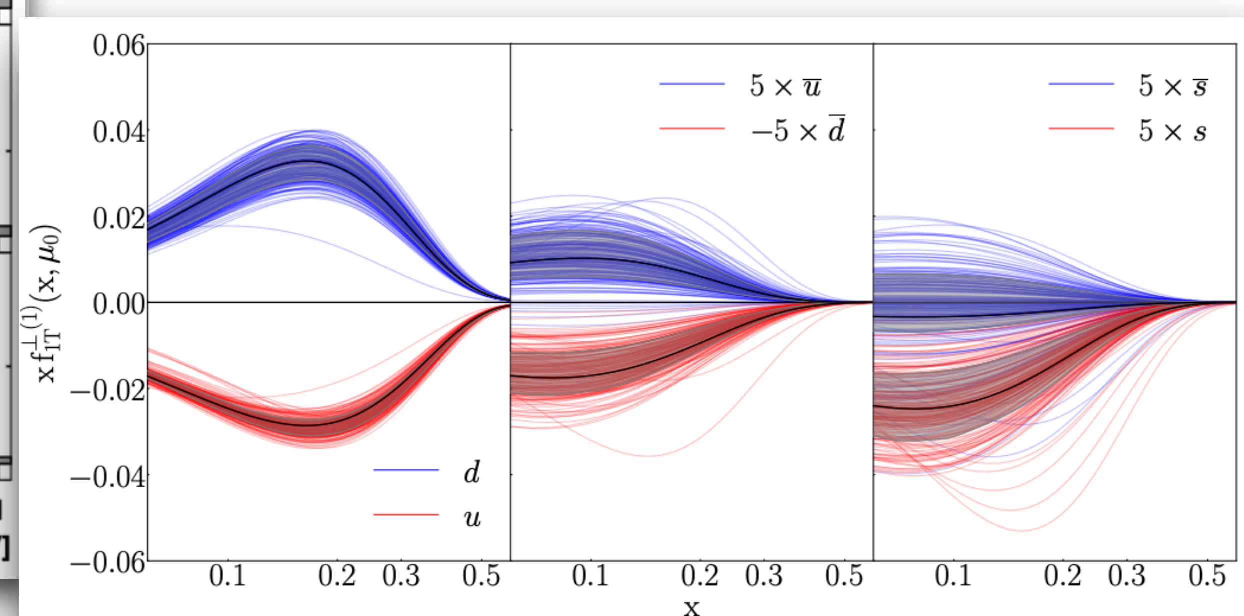
Proton Structure Studies

- Semi Inclusive DIS
  - Tag one hadron, inclusive over others, require $P_{h,\perp}$ (the q_T of the system) small $\sim \Lambda_{QCD}$



Pro: Abundant structures





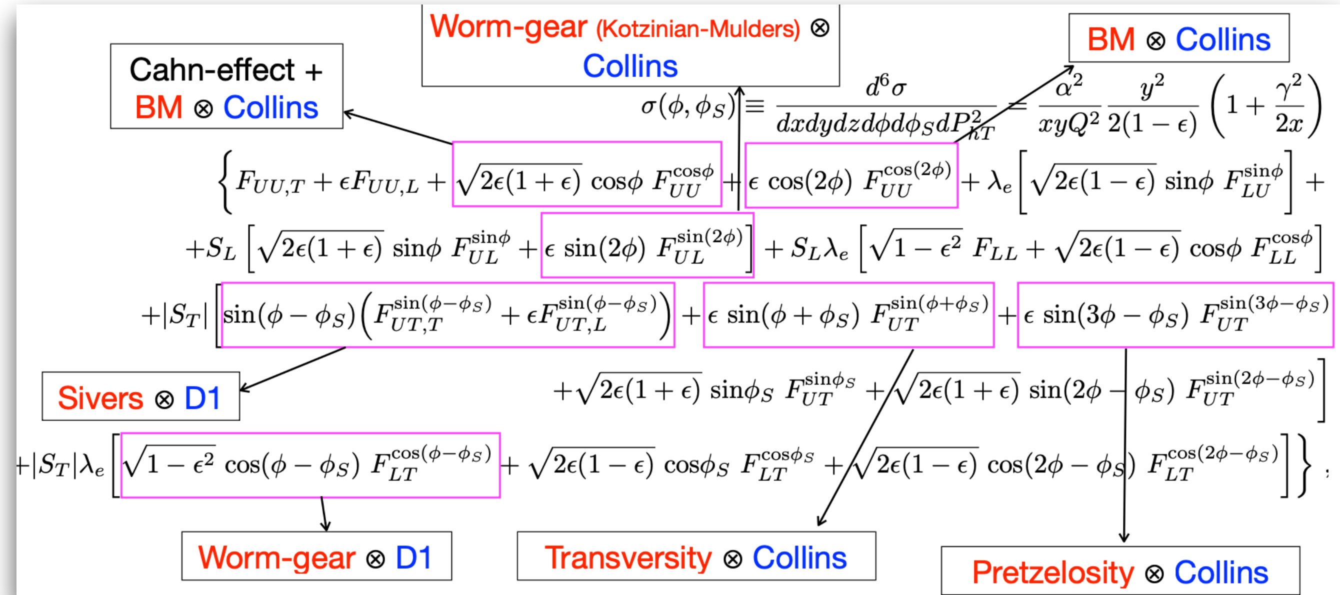
$q_T\ D_{j/H}(z, k'_T)$

HERMES collaboration, 2009

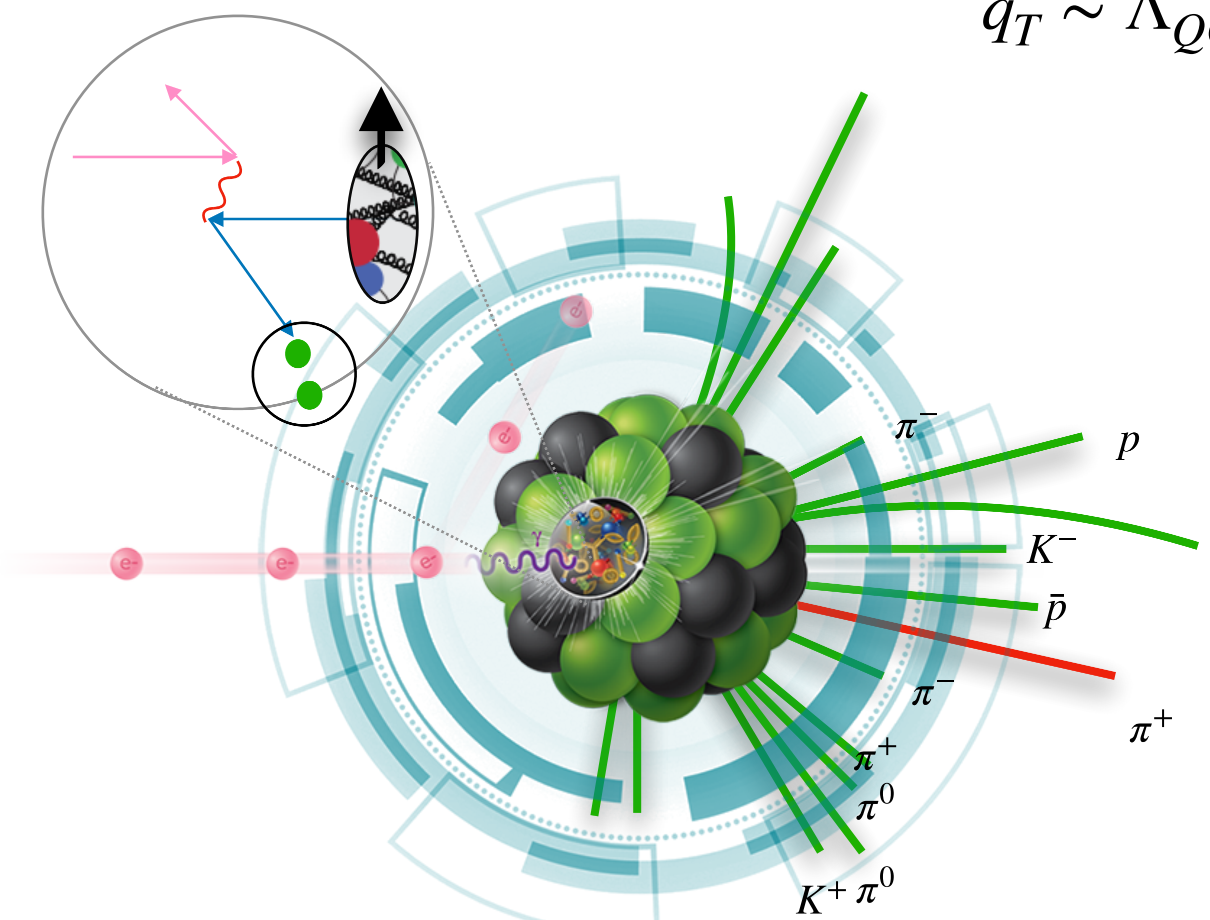
Kang et al., JHEP 2021

Proton Structure Studies

- Semi Inclusive DIS
  - Tag one hadron, inclusive over others, require $P_{h,\perp}$ (the q_T of the system) small



$q_T \sim \Lambda_{QCD}$



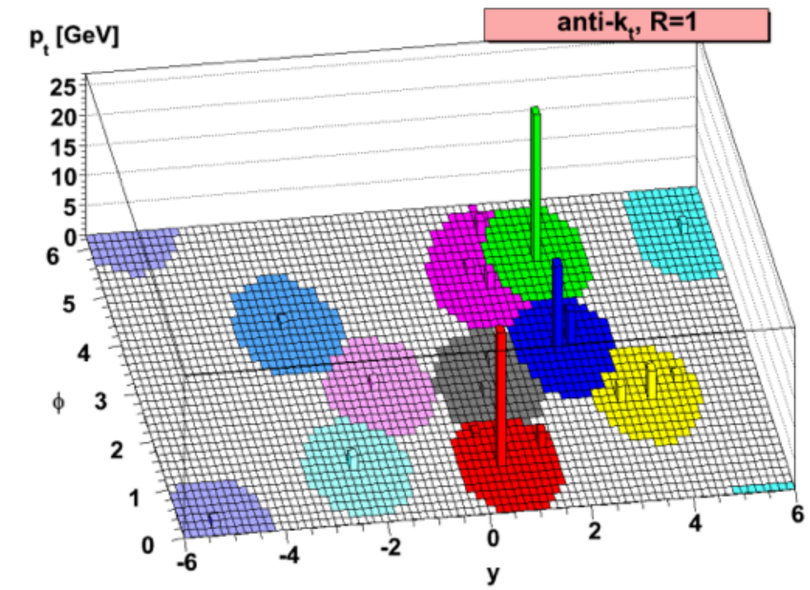
Pro: Abundant structures

Con: $D_{j/H}(z, k_T)$ is non-perturbative, hard to extract. Alternatives ?

$$\sigma = \hat{\sigma}_{i\to j}\, f_{i/P}(x, k_T, S) \otimes_{q_T} D_{j/H}(z, k_T')$$

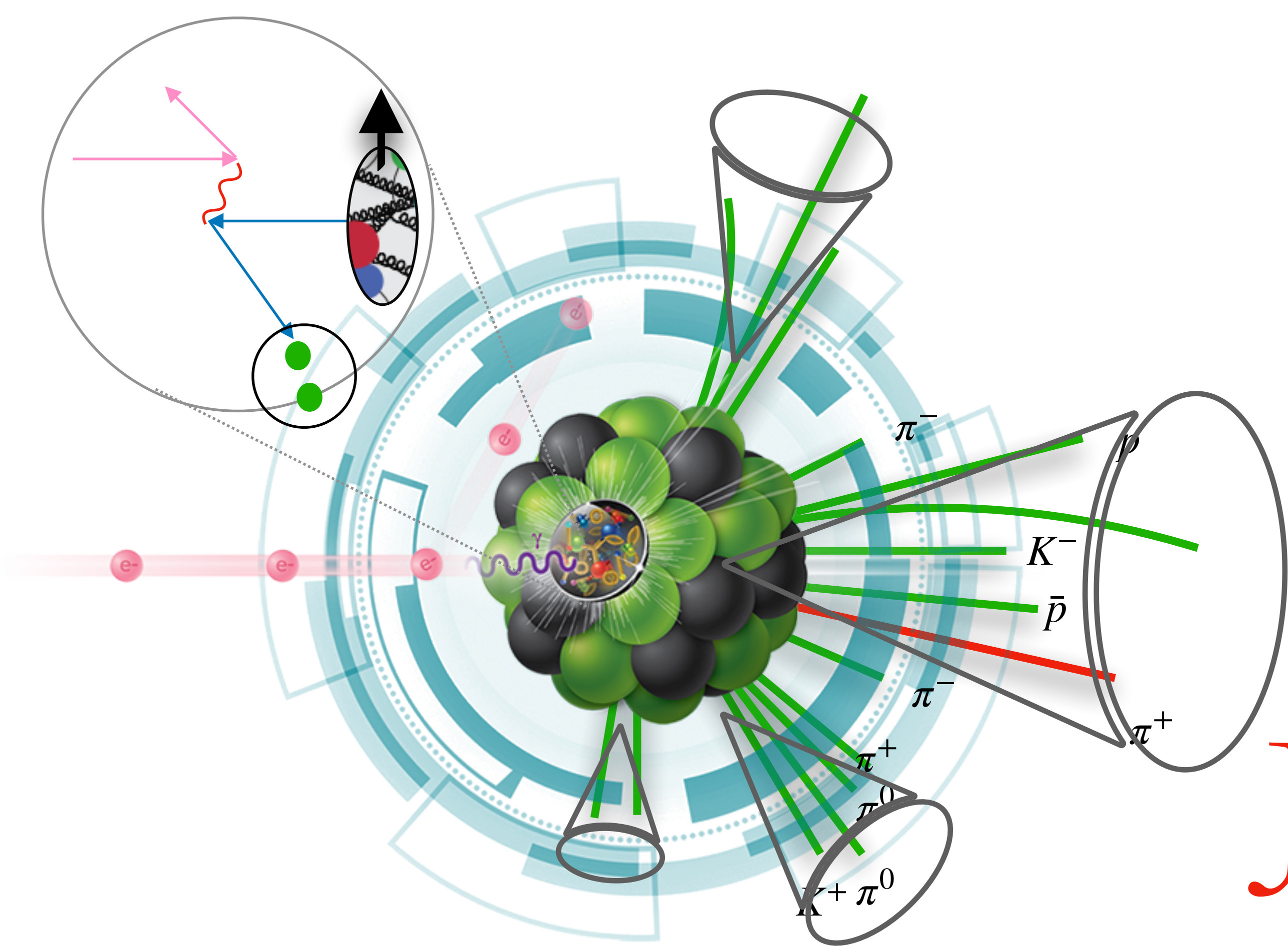
Jet Probes

- Jets
    - Sprays of hadrons,
    - Man-made objects, by algorithms
    - perturbative (?)



$$d_{ij} = \min(p_{ti}^{-2}, p_{tj}^{-2})\frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = p_{ti}^{-2}$$

$$\Delta R_{ij}^2 = \Delta^2\phi_{ij} + \Delta^2\eta_{ij}$$

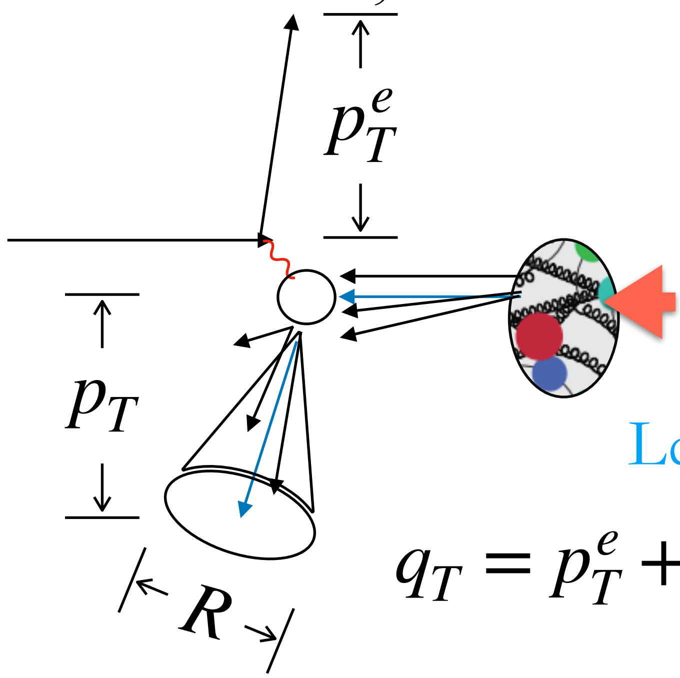


Jets

- Find the minimum of d_{iB} and d_{ij}
- If d_{ij} is the smallest, combine i, j
- If d_{iB} is the smallest, then i is a jet and remove from the list
- Iterate till all partons fall into jets

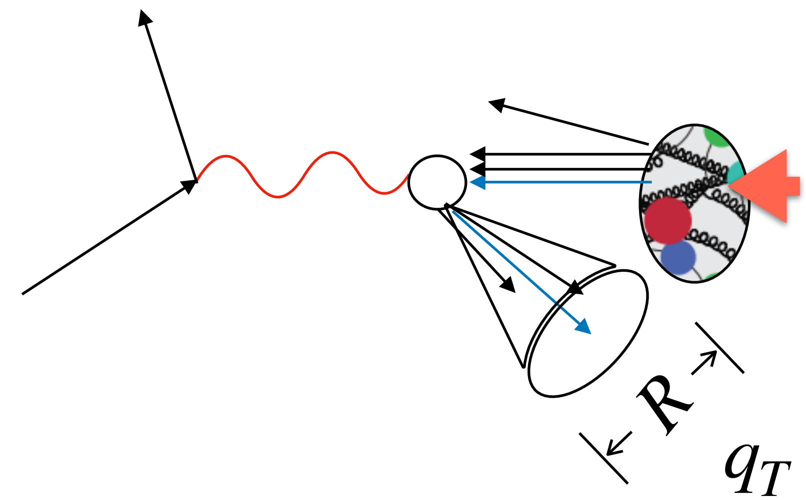
Jet Probes

- Frame choice, flexibility



Lab frame

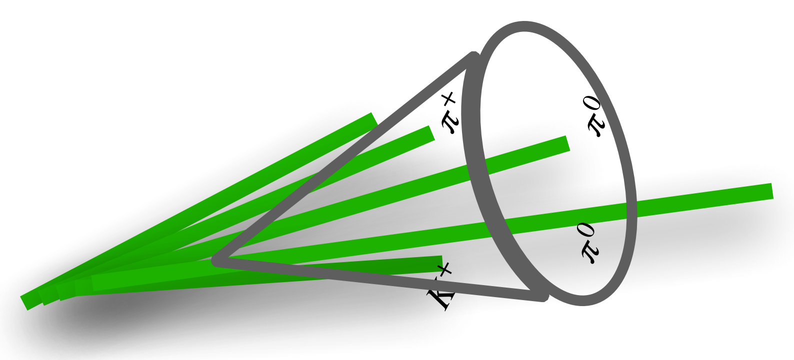
$$q_T = p_T^e + p_T \ll Q$$



GNS or Breit

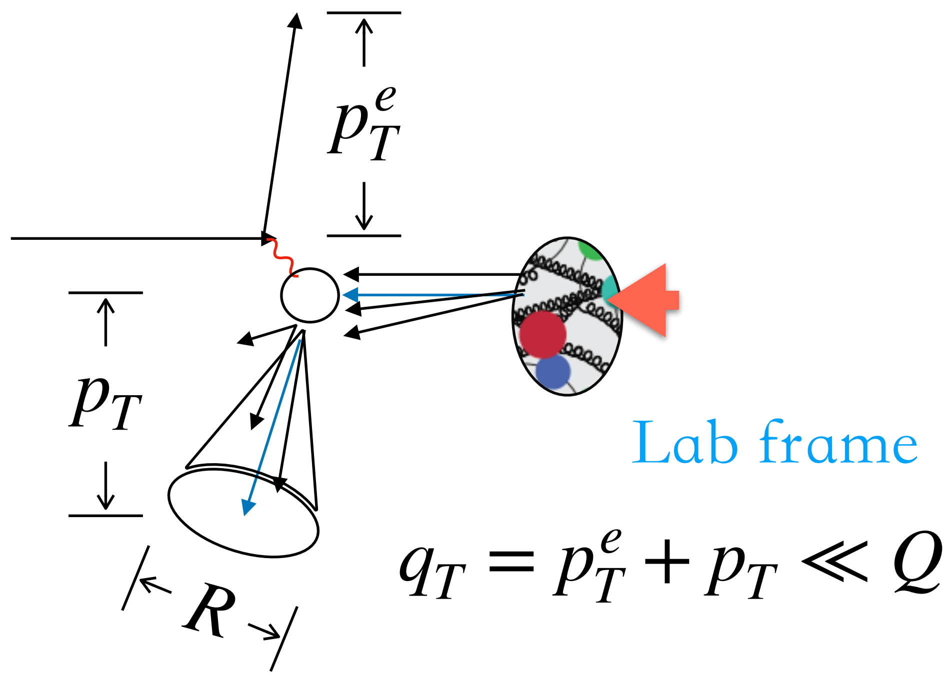
$$q_T = p_T / z_J \ll Q$$

- LHC-like
  - anti-k_T
  - Migrate LHC techniques
- New jet play-ground ⋯
  - Centauro jet, WTA jet ⋯
  - Jet physics possible for low energy machine?

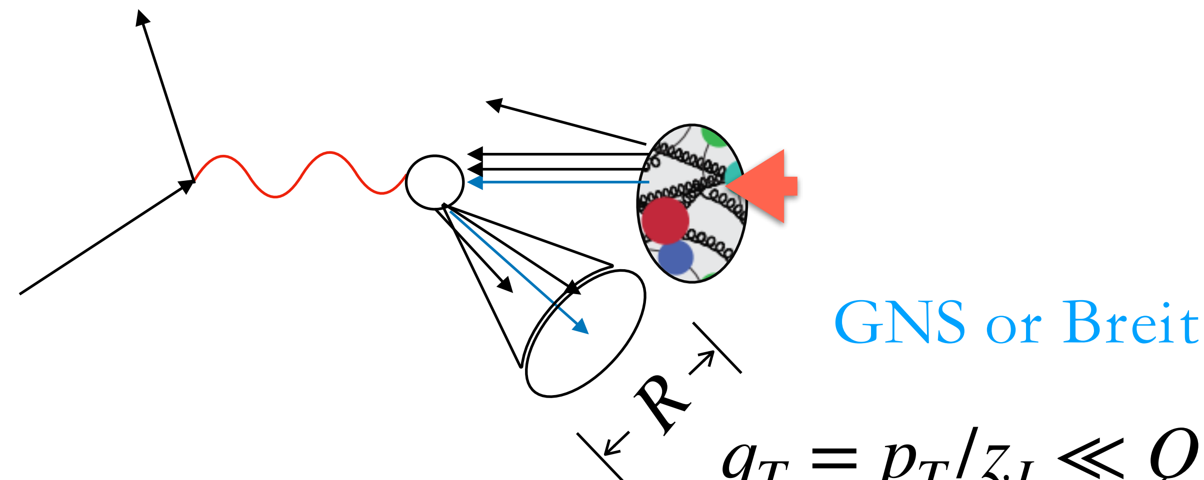


Jet Probes

- Precision



$q_T = p_T^e + p_T \ll Q$



$q_T = p_T/z_J \ll Q$

- LHC-like

$\sigma(q_T) \sim f(x, k_T) \otimes_{q_T} S_C(k_T'', R) \otimes_\Omega J(P_T R)$

Known to NLL XL et al., PRL 2019

Efforts to go beyond NLL:

$J(p_T R)$ @ 2-loops Liu, XL, Moch, PRD 2021

- New jet play-ground ⋯

$\sigma(q_T) \sim f(x, k_T) \otimes_{q_T} J_{WTA}(P_T R, k_T')$

$\to_{R \gg q_T/p_T} f(x, k_T) \otimes_{q_T} J_{WTA}(k_T')$

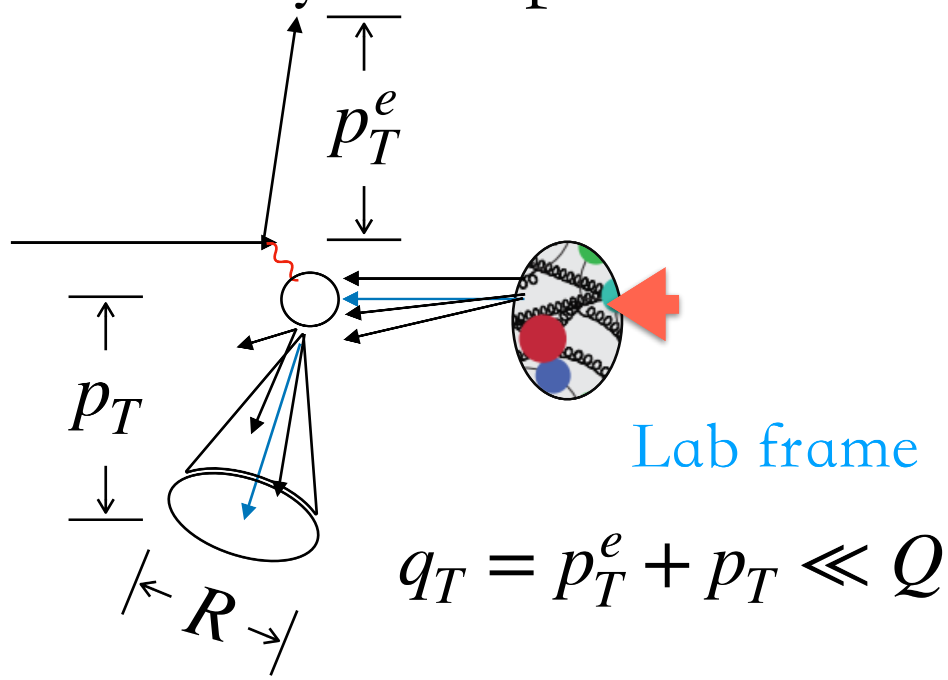
Known to NNLL

Gutierrez-Reyes et al., PRL 2018

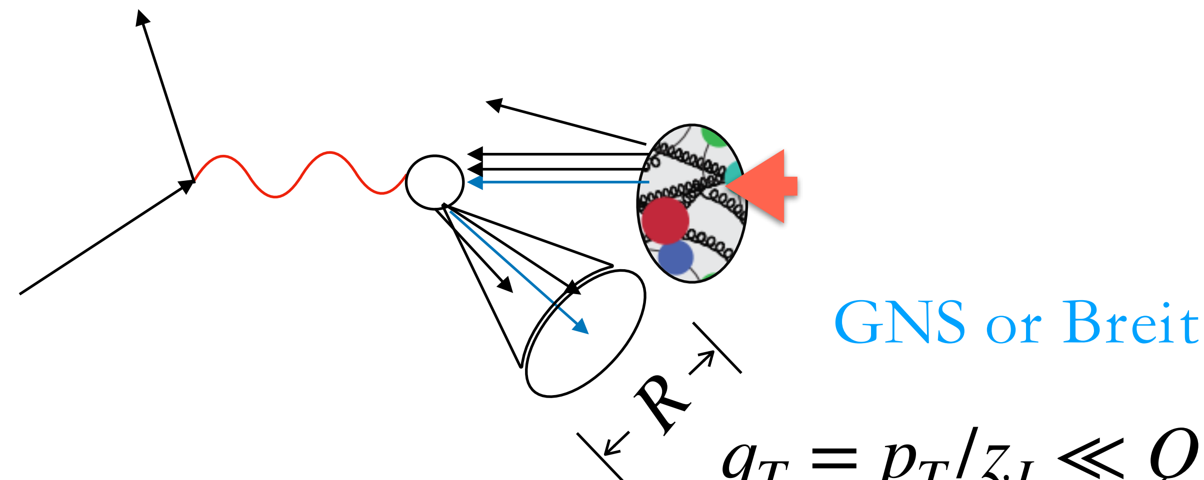
Challenging due to complicated clustering procedure

Jet Probes

- Intrinsically non-perturbative when $q_T \sim \Lambda_{QCD}$



$q_T = p_T^e + p_T \ll Q$



$q_T = p_T / z_J \ll Q$

- LHC-like

$$\sigma(q_T) \sim f(x, k_T) \otimes_{q_T} S_C(k_T'', R) \otimes_\Omega J(P_T R)$$

- New jet play-ground $\cdots$

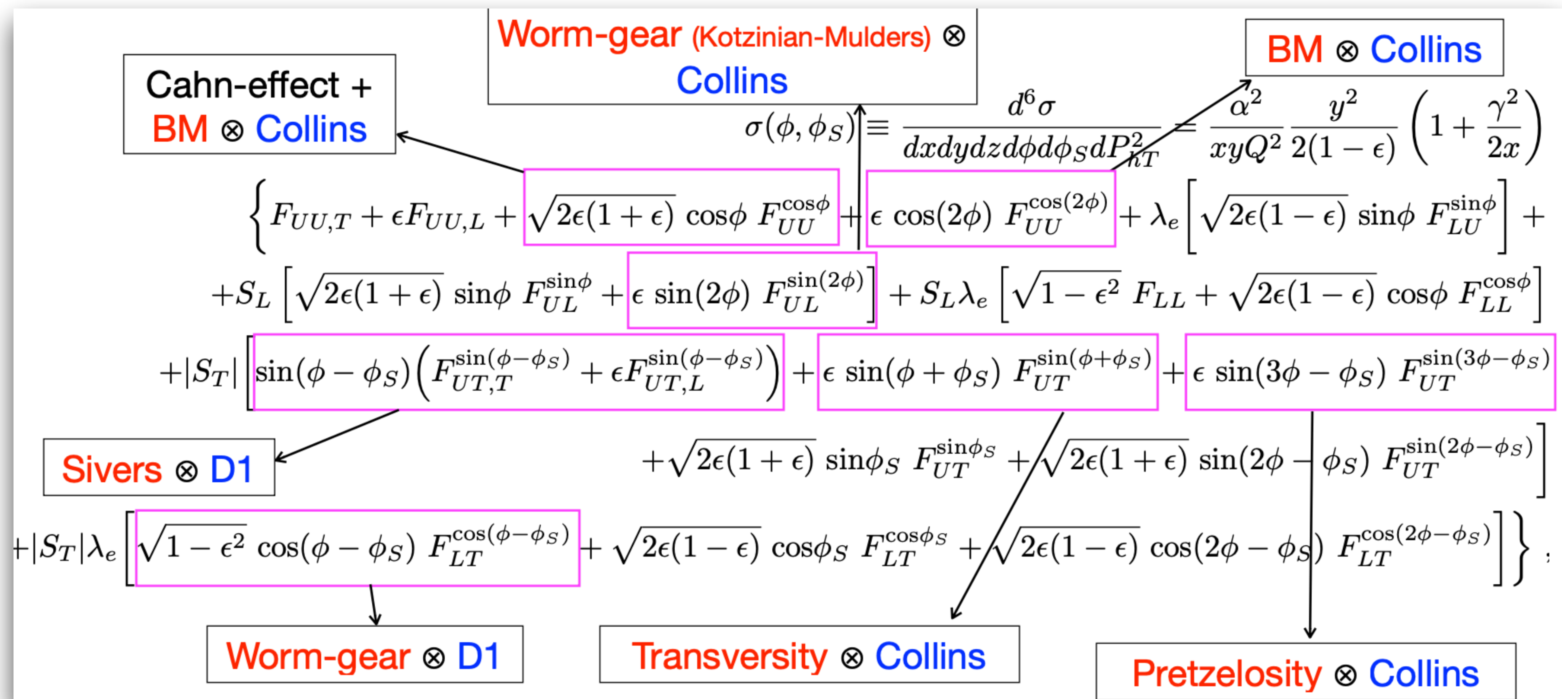
$$\sigma(q_T) \sim f(x, k_T) \otimes_{q_T} J_{WTA}(P_T R, k_T')$$

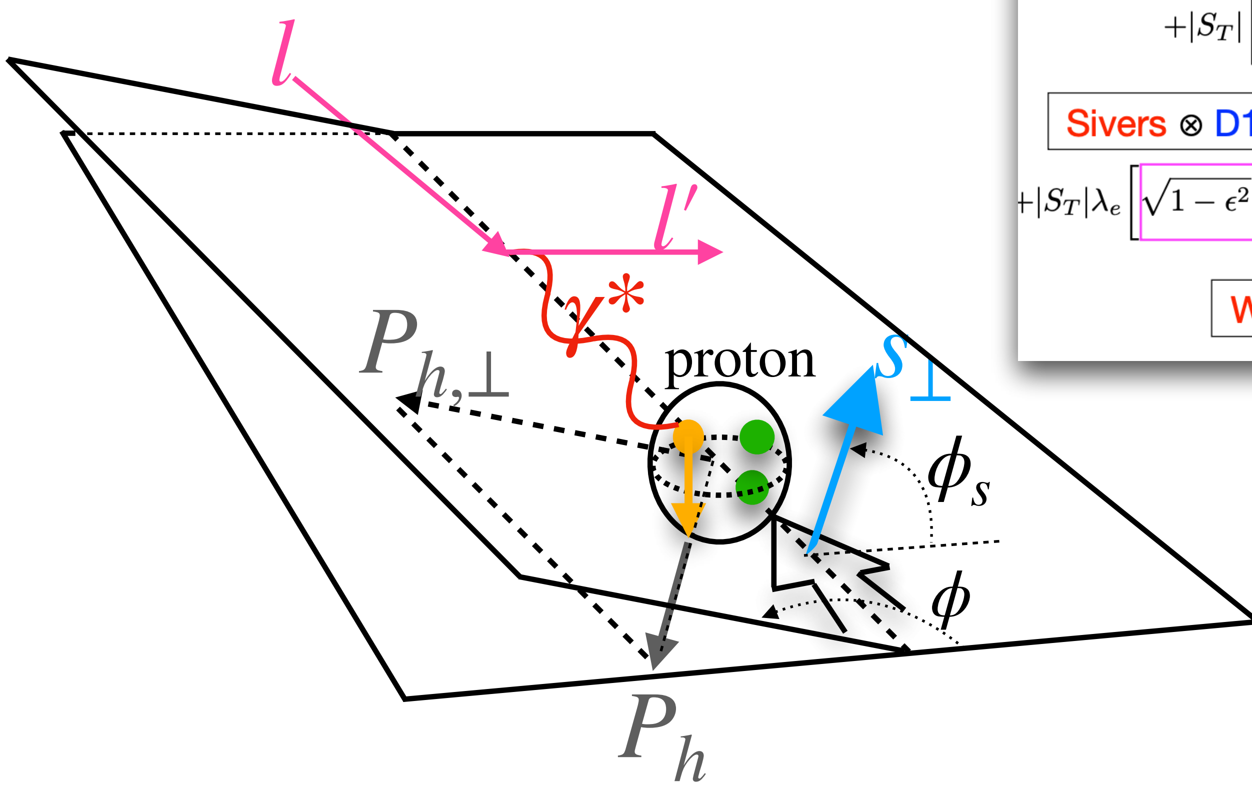
$$\to_{R \gg q_T/p_T} f(x, k_T) \otimes_{q_T} J_{WTA}(k_T')$$

- Well control via operator studies, reduced parameters
- Interesting phenomenologies different from the LHC jets could arise

Jet Probes

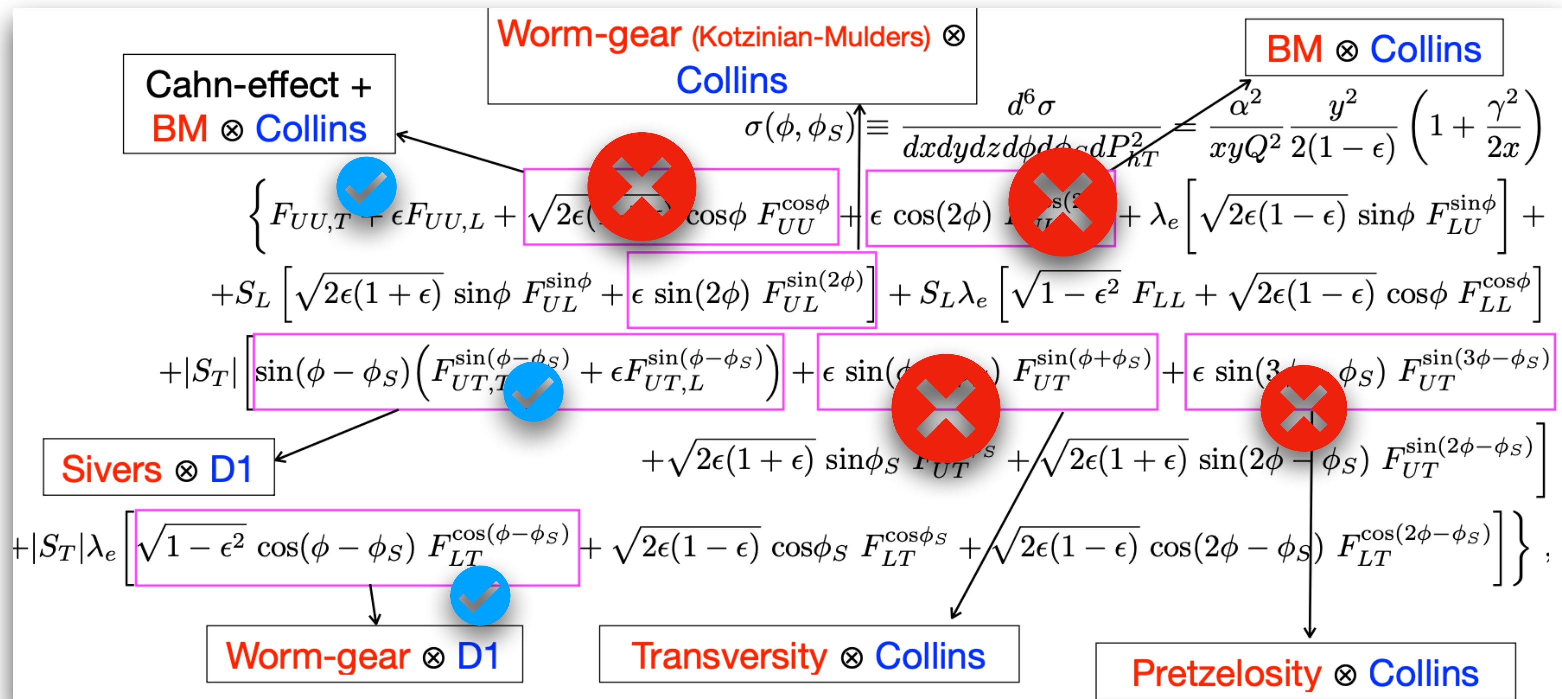
- Abundant structures for hadron probes

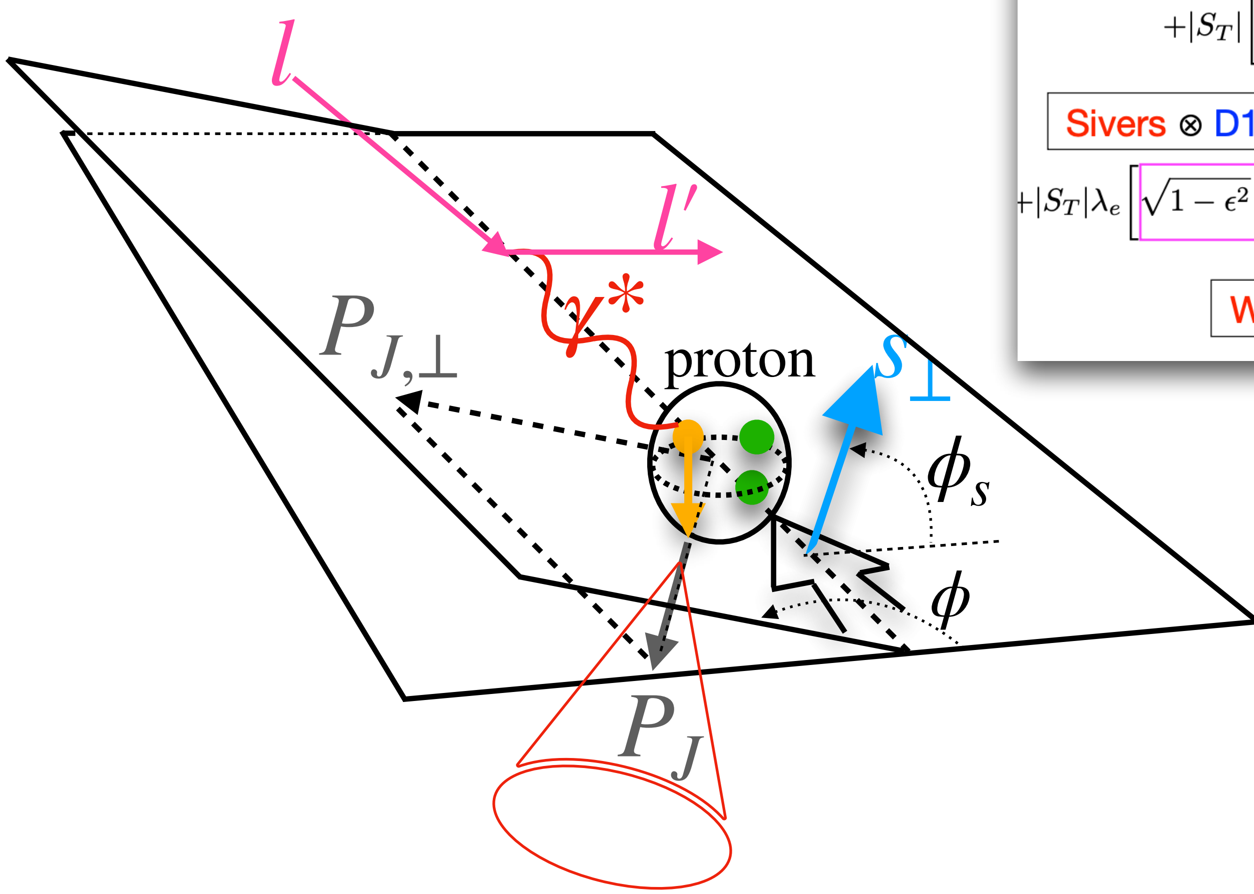




Jet Probes

- Extremely limited structures for jet probes



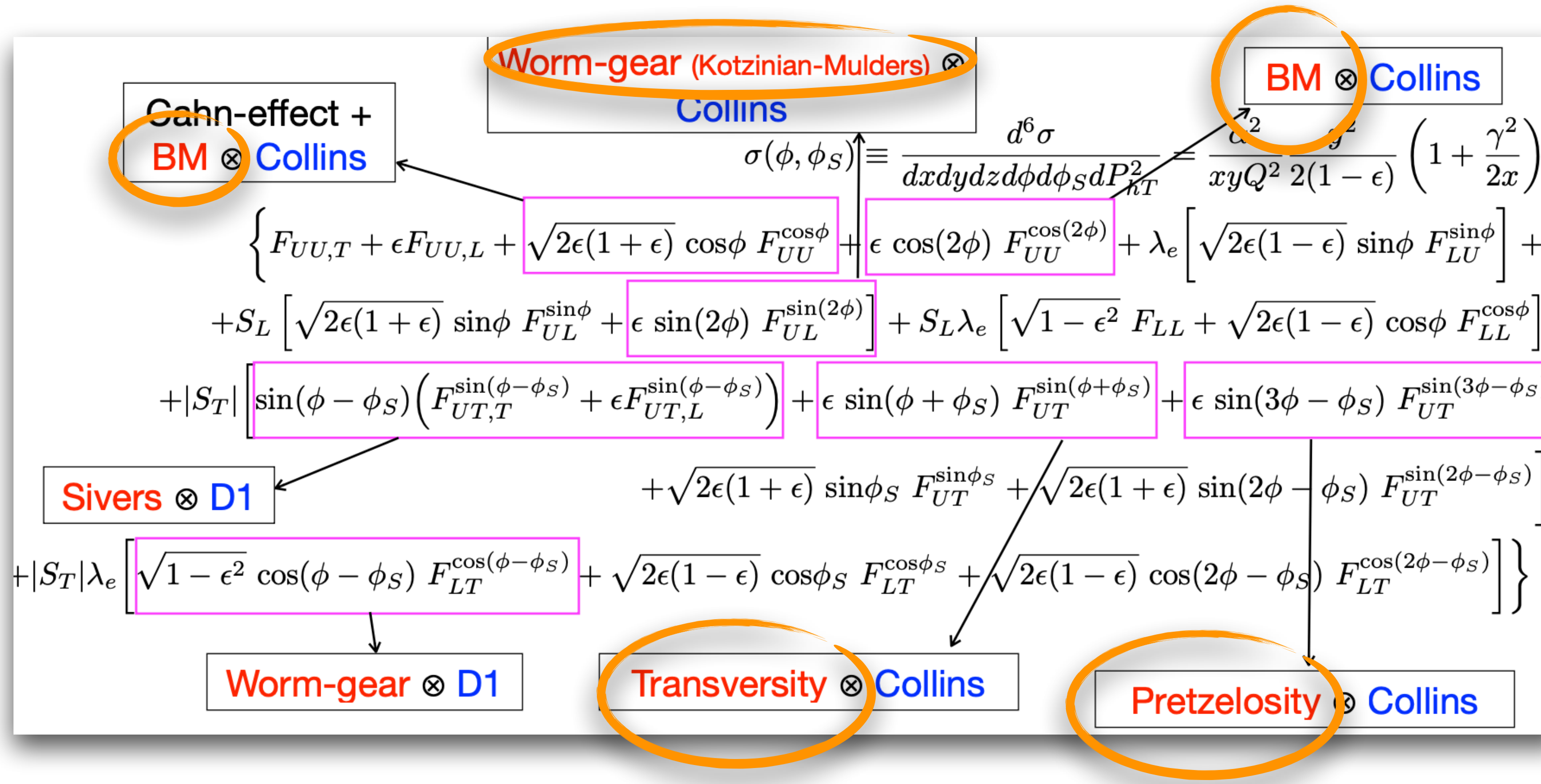


Needs 2 polarized beams for jet probes, highly inefficient

Jet Probes

- Non-perturbative phase

Chiral-odd TMDs



$$\sigma(\phi,\phi_S) \equiv \frac{d^6\sigma}{dx\,dy\,dz\,d\phi\,d\phi_S\,dP_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\epsilon F_{UU,L}+\sqrt{2\epsilon(1+\epsilon)}\cos\phi\,F_{UU}^{\cos\phi}+\epsilon\cos(2\phi)\,F_{UU}^{\cos(2\phi)}+\lambda_e\left[\sqrt{2\epsilon(1-\epsilon)}\sin\phi\,F_{LU}^{\sin\phi}\right]+$$
$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi\,F_{UL}^{\sin\phi}+\epsilon\sin(2\phi)\,F_{UL}^{\sin(2\phi)}\right]+S_L\lambda_e\left[\sqrt{1-\epsilon^2}\,F_{LL}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi\,F_{LL}^{\cos\phi}\right]$$
$$+|S_T|\Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)}+\epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right)+\epsilon\sin(\phi+\phi_S)\,F_{UT}^{\sin(\phi+\phi_S)}+\epsilon\sin(3\phi-\phi_S)\,F_{UT}^{\sin(3\phi-\phi_S)}$$
$$+\sqrt{2\epsilon(1+\epsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)\,F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$
$$+|S_T|\lambda_e\left[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)\,F_{LT}^{\cos(\phi-\phi_S)}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S}+\sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)\,F_{LT}^{\cos(2\phi-\phi_S)}\right]\Big\},$$

(Collins) Chiral-odd FFs

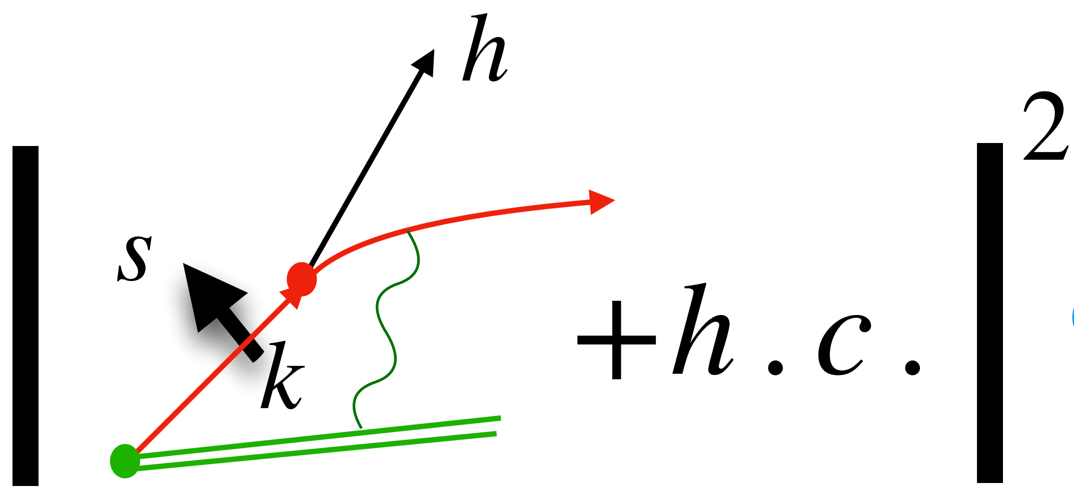
$$\propto \int e^{ik^+x^-}e^{-k_\perp\cdot x_\perp}\gamma^5\gamma^+ s_\perp\cdot\gamma_\perp\langle 0|\psi(x^-,x_\perp)|hX\rangle\langle hX|\bar\psi|0\rangle$$

$$\bar\psi_n\gamma^\mu\psi_{\bar n}\bar\psi_{\bar n}\gamma^\nu\psi_n$$

$$\to A^{\mu\nu}\bar\psi_n\bar{n}\!\!\!/\,\psi_n\;\bar\psi_{\bar n}n\!\!\!/\,\psi_{\bar n}+B^{\mu\nu}_{\alpha\beta}\bar\psi_n\bar{n}\!\!\!/\,\gamma_\perp^\alpha\gamma^5\psi_n\;\bar\psi_{\bar n}n\!\!\!/\,\gamma_\perp^\beta\gamma^5\psi_{\bar n}+\dots$$

Jet Probes

- Non-perturbative phase

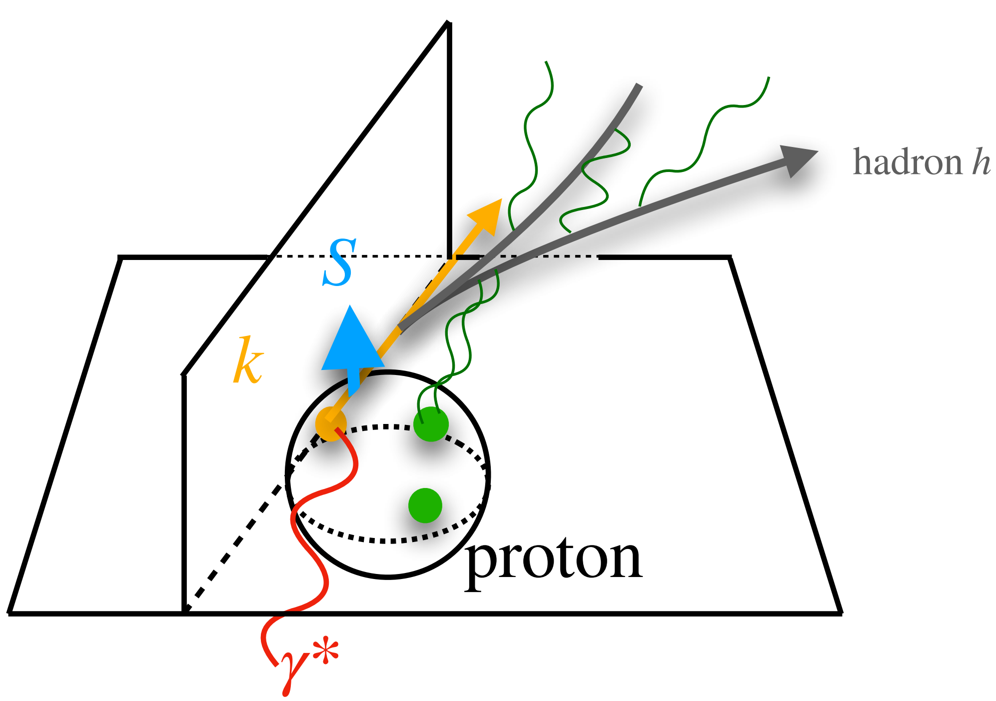


$\propto M\, Im(\sigma)\, \epsilon_{\alpha\beta\mu\nu} k_\perp^\alpha s_\perp^\beta P_h^\mu n^\nu$

Collins, Metz + $\cdots$

Final state interactions

generate an asymmetry

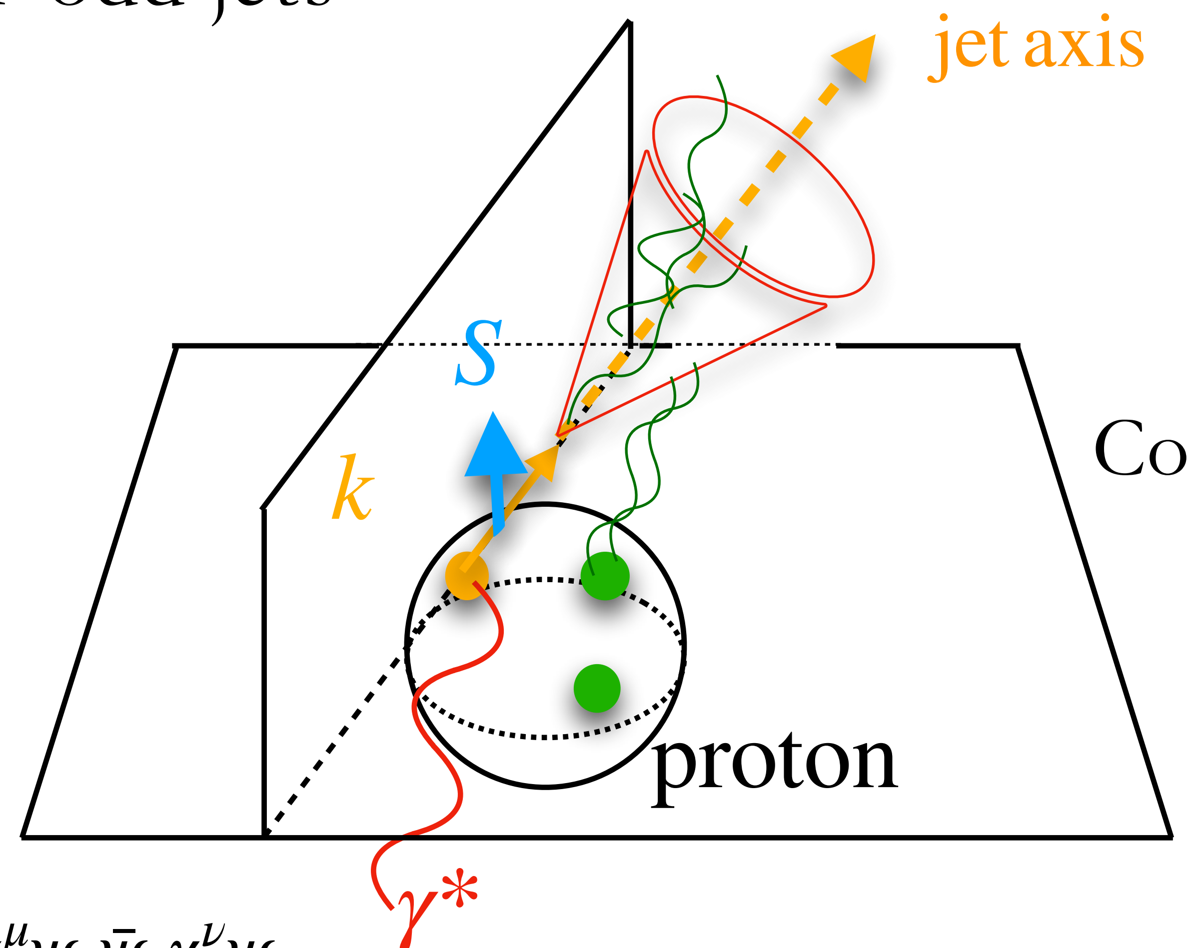


To observe the asymmetry :

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

Jet Probes

- The T-odd jets



Conventional wisdom:

- Jet is perturbative
- Jet axis is in the k-S plane

$$\bar\psi_n \gamma^\mu \psi_{\bar n} \bar\psi_{\bar n} \gamma^\nu \psi_n$$

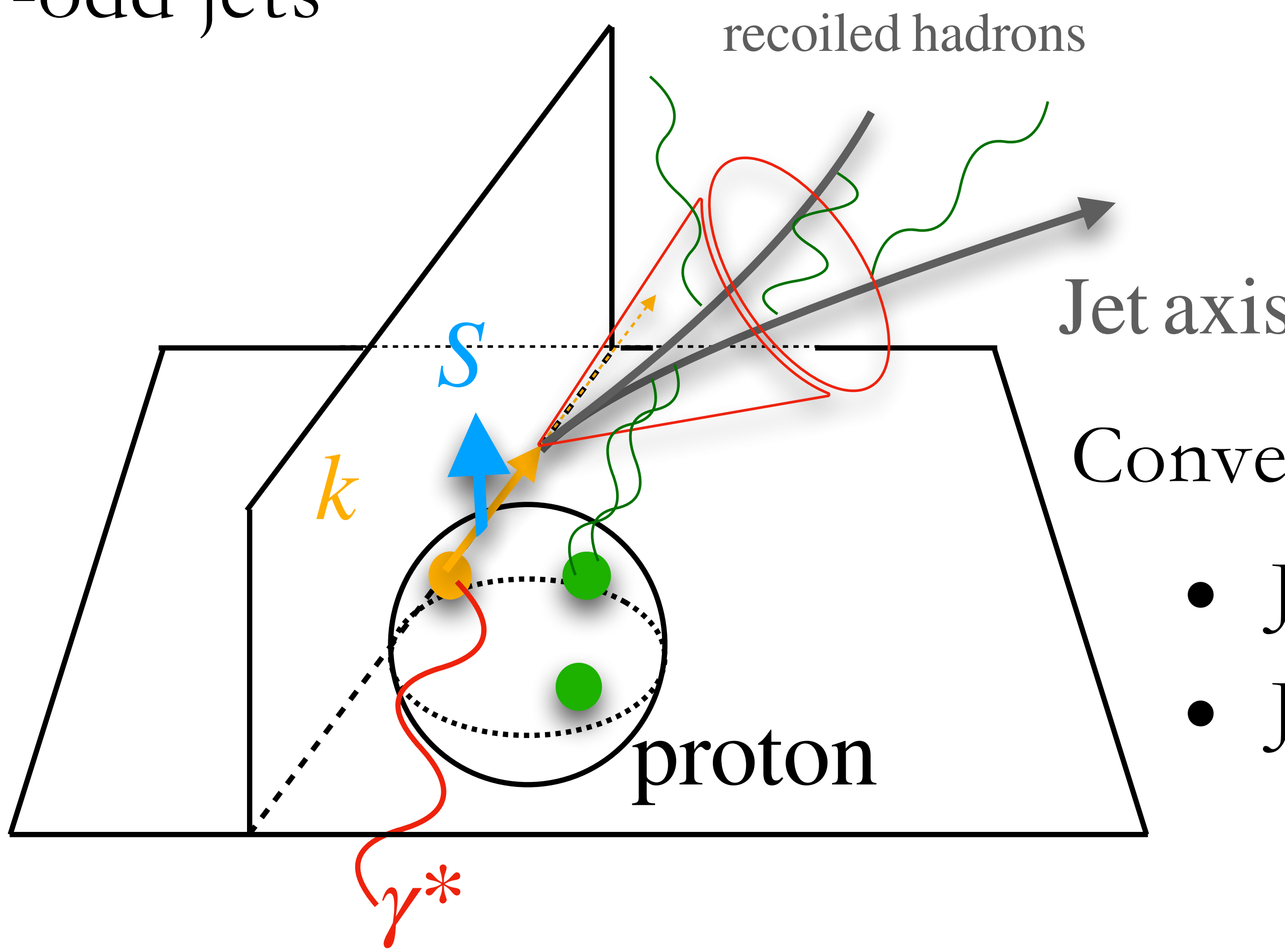
$$\to A^{\mu\nu} \bar\psi_n \not{\bar n} \psi_n \; \bar\psi_{\bar n} \not{n} \psi_{\bar n} + B^{\mu\nu}_{\alpha\beta} \bar\psi_n \not{\bar n} \gamma_\perp^\alpha \gamma^5 \psi_n \; \boxed{\bar\psi_{\bar n} \not{n} \gamma_\perp^\beta \gamma^5 \psi_{\bar n}} + \dots$$

$$\langle 0 | \bar\psi(x) | JX \rangle \langle JX | \psi | 0 \rangle \propto \frac{\not{\bar n}}{2} J + i \frac{\not{k}_T \not{\bar n} \gamma_5}{2} J_T$$

Conventional jet function

Jet Probes

- The T-odd jets



Conventional wisdom:

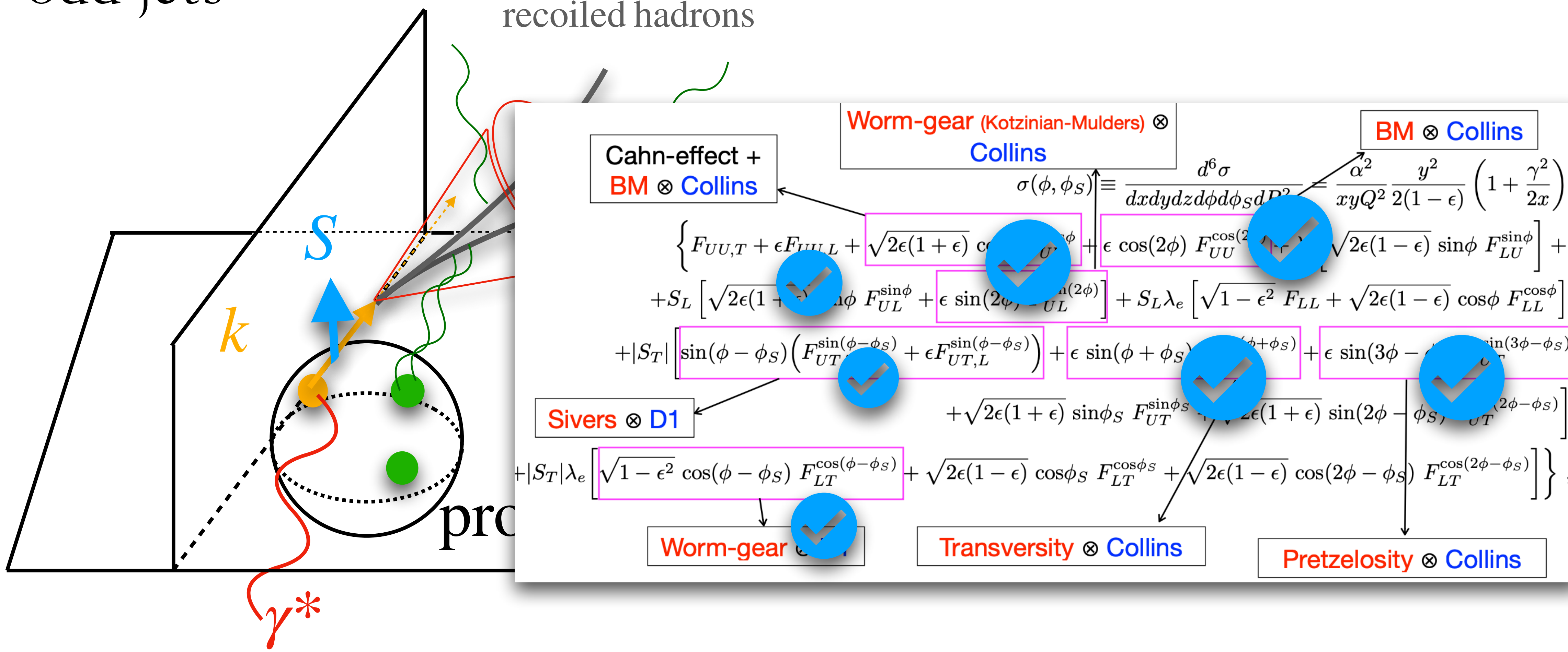
- Jet is perturbative — Depends on observable!
- Jet axis is in the k-S plane — Not true

$$\langle 0|\bar{\xi}_\alpha(x)|JX\rangle\langle JX|\xi_\beta|0\rangle \propto \frac{\not{n}}{2}J + i\frac{\not{k}_T\not{n}\gamma_5}{2}J_T$$

XL, Xing, 2104.03328, 2021

Jet Probes

- The T-odd jets



$$\langle 0|\bar{\xi}_\alpha(x)|JX\rangle\langle JX|\xi_\beta|0\rangle \propto \frac{\not{n}}{2}J + i\frac{\not{k}_T\not{n}\gamma_5}{2}J_T$$

Unlock almost all possibilities

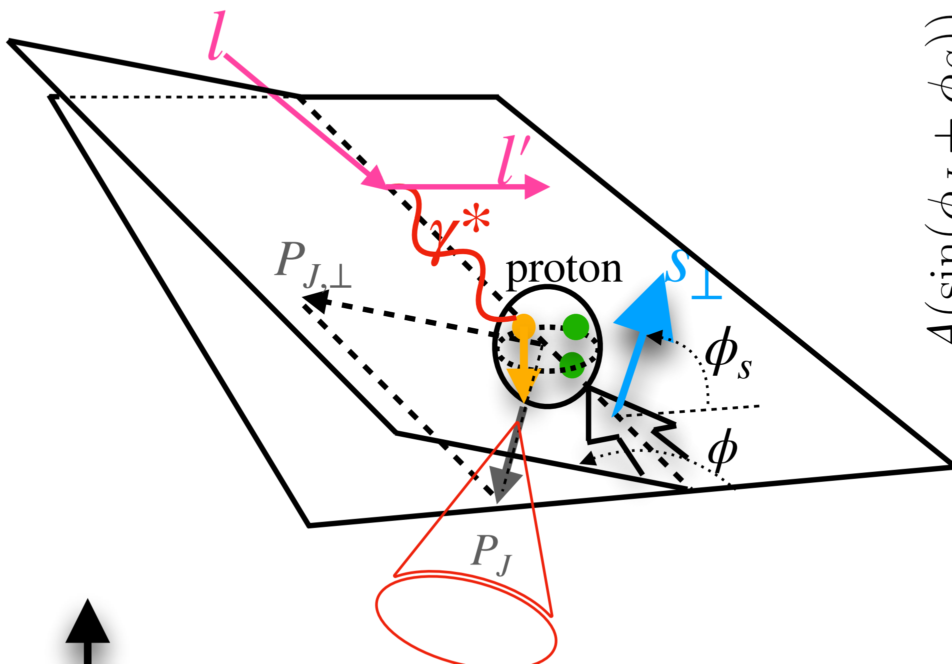
Only need one polarized beam

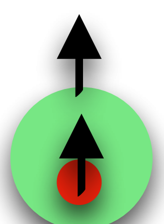
With reduced d.o.f.s and more flexibility

XL, Xing, 2104.03328, 2021

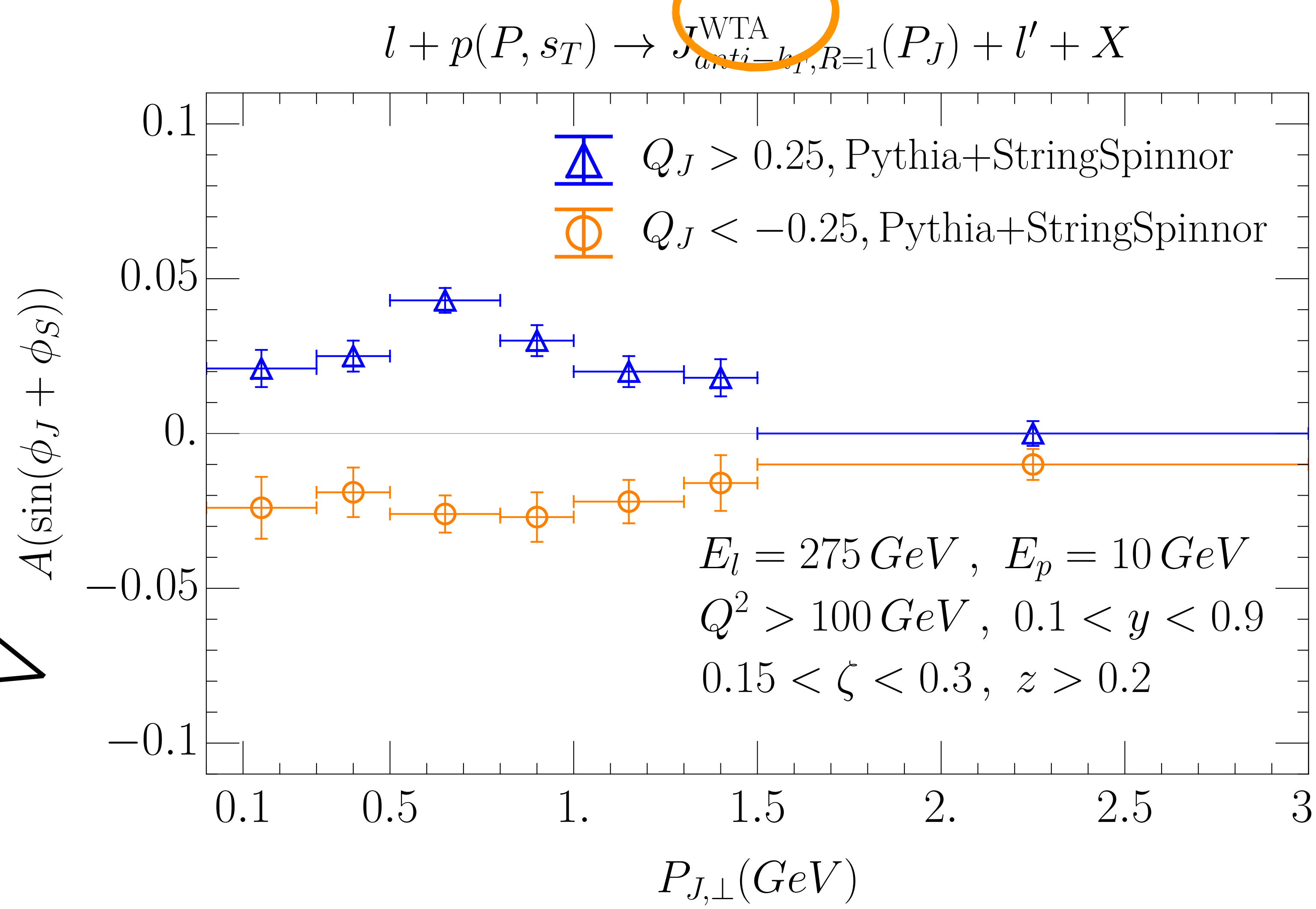
Jet Probes

- The T-odd jets





Transversity



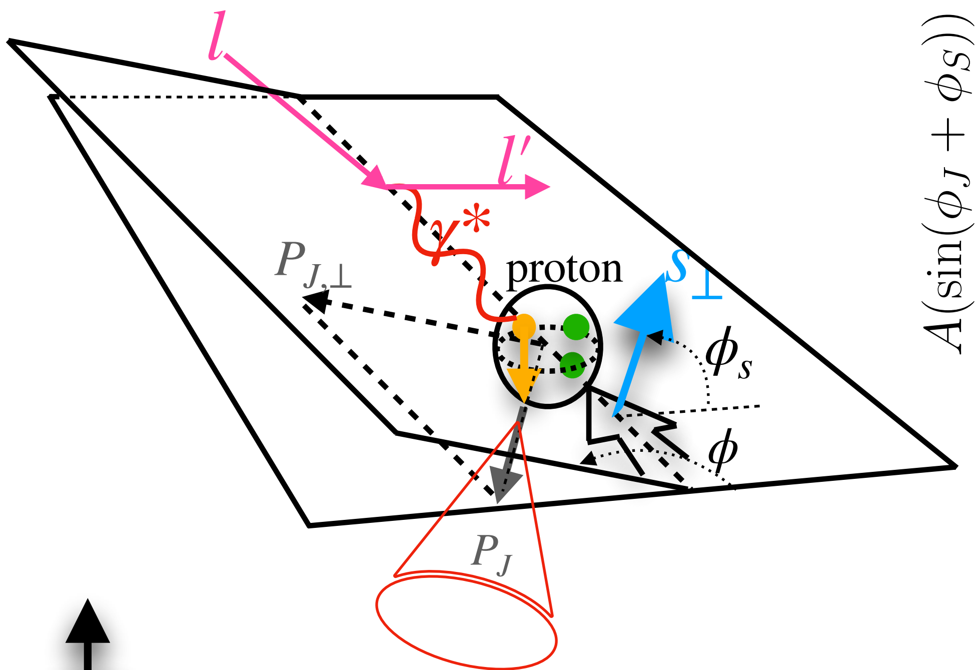
$$A = 1 + \epsilon\,|s_\perp|\sin(\phi_J + \phi_s)\frac{F_{UT}}{F_{UU}}$$

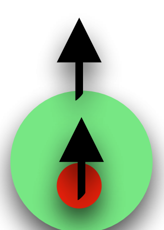
$$F_{UT} = \sum_q e_q^2 \int \frac{d^2b}{4\pi^2} e^{-iP_{J\perp}\cdot b_\perp} i\frac{P^\alpha_{J\perp}}{P_{J\perp}} \zeta\, h_1^q(\zeta, b)\, \partial_{b^\alpha} J_T^q(b)$$

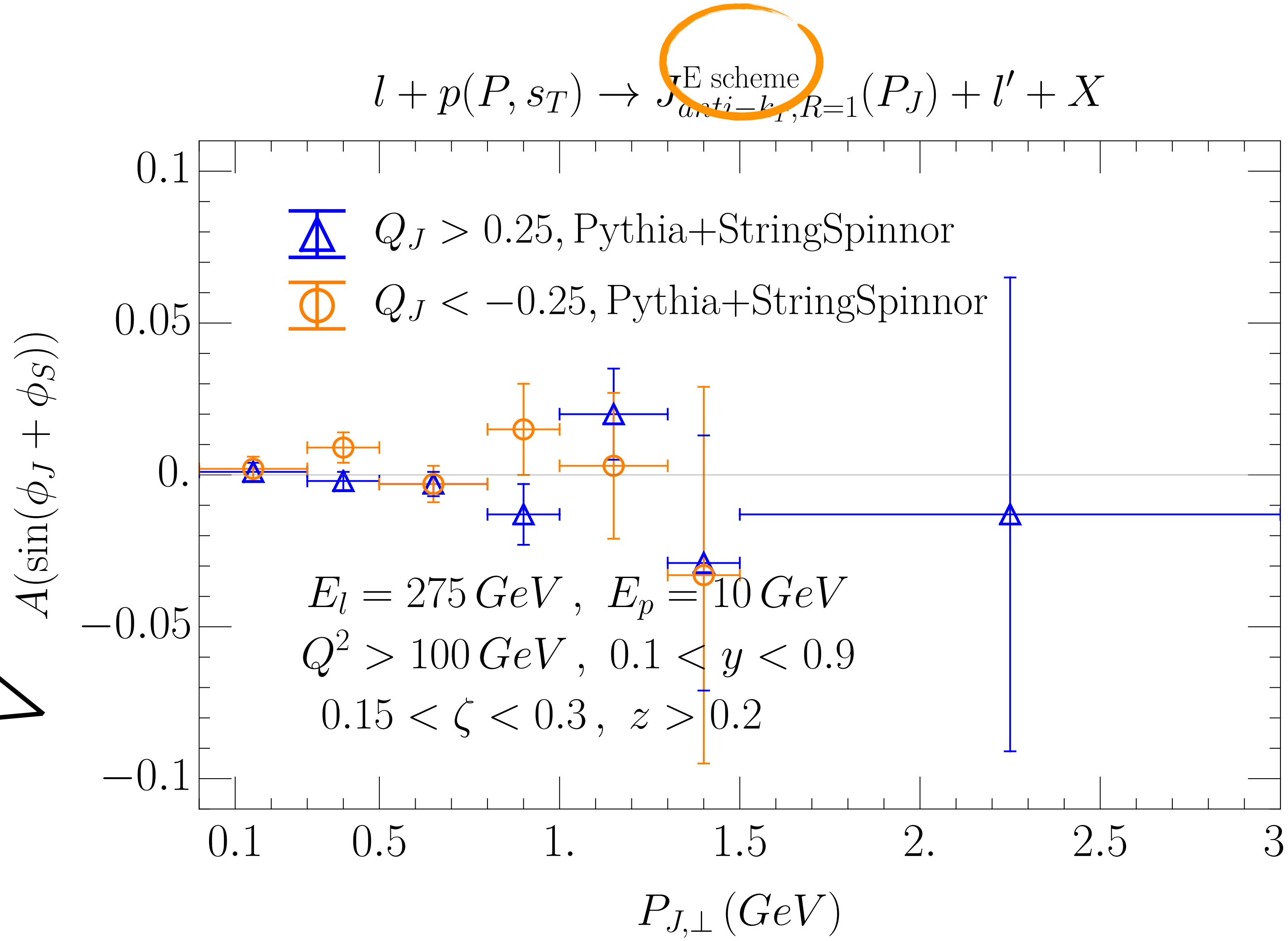
XL, Xing, 2104.03328, 2021

Jet Probes

- The T-odd jets







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

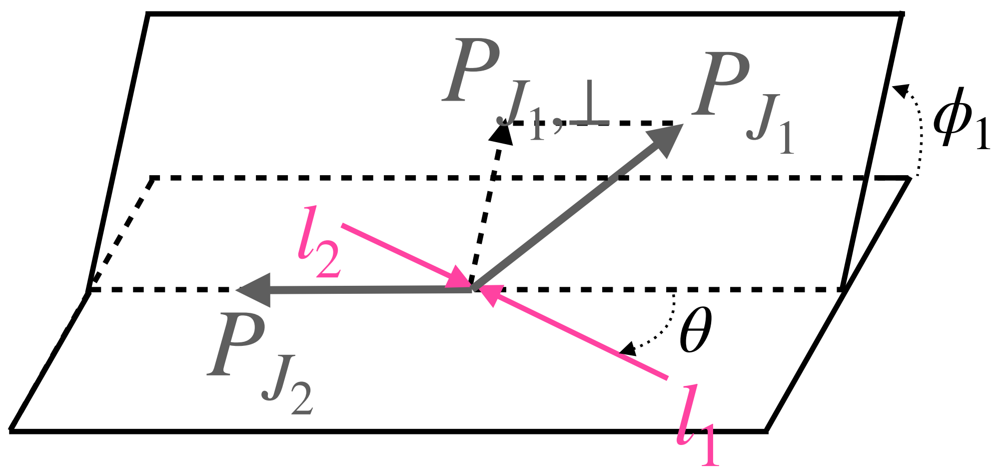
Different jet axis leads to different sensitivity

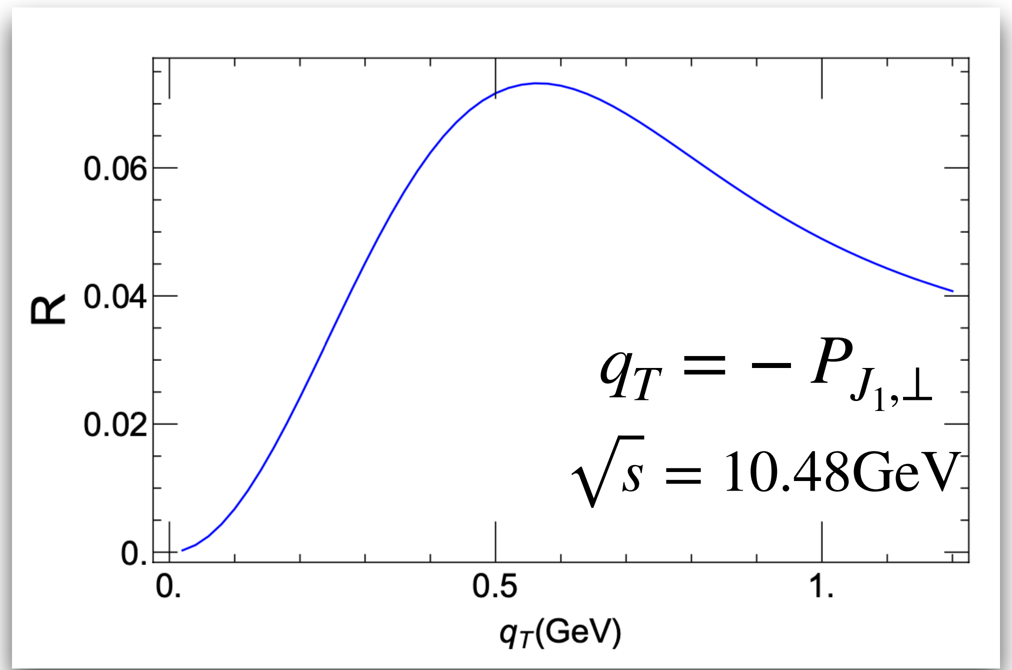
$$F_{UT} = \sum_q e_q^2 \int \frac{d^2b}{4\pi^2} e^{-iP_{J\perp}\cdot b_\perp} i\frac{P^\alpha_{J\perp}}{P_{J\perp}} \zeta\, h_1^q(\zeta, b)\, \partial_{b^\alpha} J_T^q(b)$$

Lai, XL, Xing, Wang in preparation

Jet Probes

- The T-odd jets





Can be extracted directly from BELLE or BaBar data

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

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

XL, Xing, 2104.03328, 2021

$$F_T = q_T \sum_q e_q^2 \int \frac{d^2b}{4\pi^2} e^{-iq_T\cdot b}\left(2\frac{q_T^\alpha q_T^\beta}{q_T^2} + g^{\alpha\beta}\right)\partial_{b^\alpha} J_T^q(b)\partial_{b^\beta} J_T^{\bar{q}}(b)$$

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

Quantum Simulation

Li, Guo, Lai, XL, Wang, Xing, Zhang, Zhu, 2021

$$f(x) = \int dz^- e^{-ixM_h xz^-} \langle h | \bar{\psi}(z^-)\gamma^+\psi(0) | h \rangle \qquad z^- = (z, 0, 0, -z)$$

Now it can be calculated by lattice QCD

Same IR

See Wei's talk in this series.

$$f(x) = C \otimes f_{quasi} + \mathcal{O}\left(\frac{1}{P_z}\right)$$

Ji, PRL, 2013, Ma and Qiu, PRL 2018, Lian et al., PRD 2020, Lin, Chen, Wang, Yang, Yong, J. Zhang, + a long list

$$f_{quasi}(x) = \int dz^- e^{-ixM_h xz^-} \langle h | \bar{\psi}(0, -z)\gamma^+\psi(0) | h \rangle$$

$$\langle \Omega | \mathcal{O}_h \bar{\psi}\gamma^+\psi\mathcal{O}_h | \Omega \rangle$$

Path integral on Lattice

virtual time

Quantum Simulation

Li, Guo, Lai, XL, Wang, Xing, Zhang, Zhu, 2021

$$f(x) = \int dz^- e^{-ixM_h xz^-} \langle h | \bar{\psi}(z^-) \gamma^+ \psi(0) | h \rangle \qquad z^- = (z,0,0,-z)$$

$$= \int dz^- e^{-ixM_h xz^-} \langle h | e^{iHz} \bar{\psi}(0,-z) e^{-iHz} \gamma^+ \psi(0) | h \rangle$$

$$e^{-iHz} \approx \lim_{\delta z \to 0, N \to \infty} \left[e^{-iH\delta z} \right]_N$$

Trotter, 1959

Classically: diagonalize Costy, hard

Quantum Simulation

Li, Guo, Lai, XL, Wang, Xing, Zhang, Zhu, 2021

$$f(x) = \int dz^- e^{-ixM_h x z^-} \langle h | \bar{\psi}(z^-) \gamma^+ \psi(0) | h \rangle \qquad z^- = (z, 0, 0, -z)$$

$$= \int dz^- e^{-ixM_h x z^-} \langle h | e^{iHz} \bar{\psi}(0, -z) e^{-iHz} \gamma^+ \psi(0) | h \rangle$$

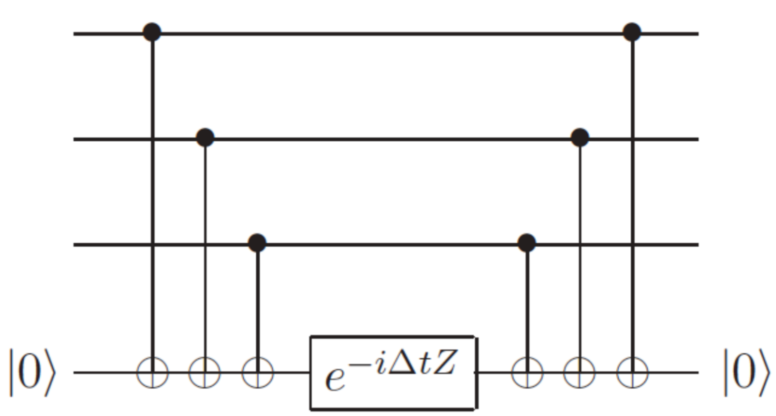
$$e^{-iHz} \approx \lim_{\delta z \to 0, N \to \infty} \left[e^{-iH\delta z} \right]_N$$

Trotter, 1959

Quantum: decompose to set of gates

e.g. Local $e^{-i\sigma_x t} = HXR_z(-t)XR_z(t)H$

non-Local $H = Z_1 \otimes Z_2 \otimes Z_3$ $\quad e^{-iH\Delta t} =$



Quantum Simulation

Li, Guo, Lai, XL, Wang, Xing, Zhang, Zhu, 2021

- A toy model

$$\mathscr{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi + g(\bar{\psi}\psi)^2 \quad \text{(no gauge, 1+1)}$$

Gross, Neveu, 1974

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \to \begin{pmatrix} \phi_{2n} \\ \phi_{2n+1} \end{pmatrix}$$

Staggered fermion

$$\phi_n = \prod_{i<n} \sigma_i^3 \sigma_n^+$$

Jordan-Wigner

$$f(x) \to \sum_{i,j} \sum_{z} \frac{1}{4\pi} e^{-ixM_h z} \langle h | e^{iHz} \phi^\dagger_{-2z+i} e^{-iHz} \phi_j | h \rangle$$

$$H_1 = \sum_{n=\text{even}} \frac{1}{4} \left[\sigma_n^1 \sigma_{n+1}^2 - \sigma_n^2 \sigma_{n+1}^1 \right] + H_2 + H_3 + H_4$$

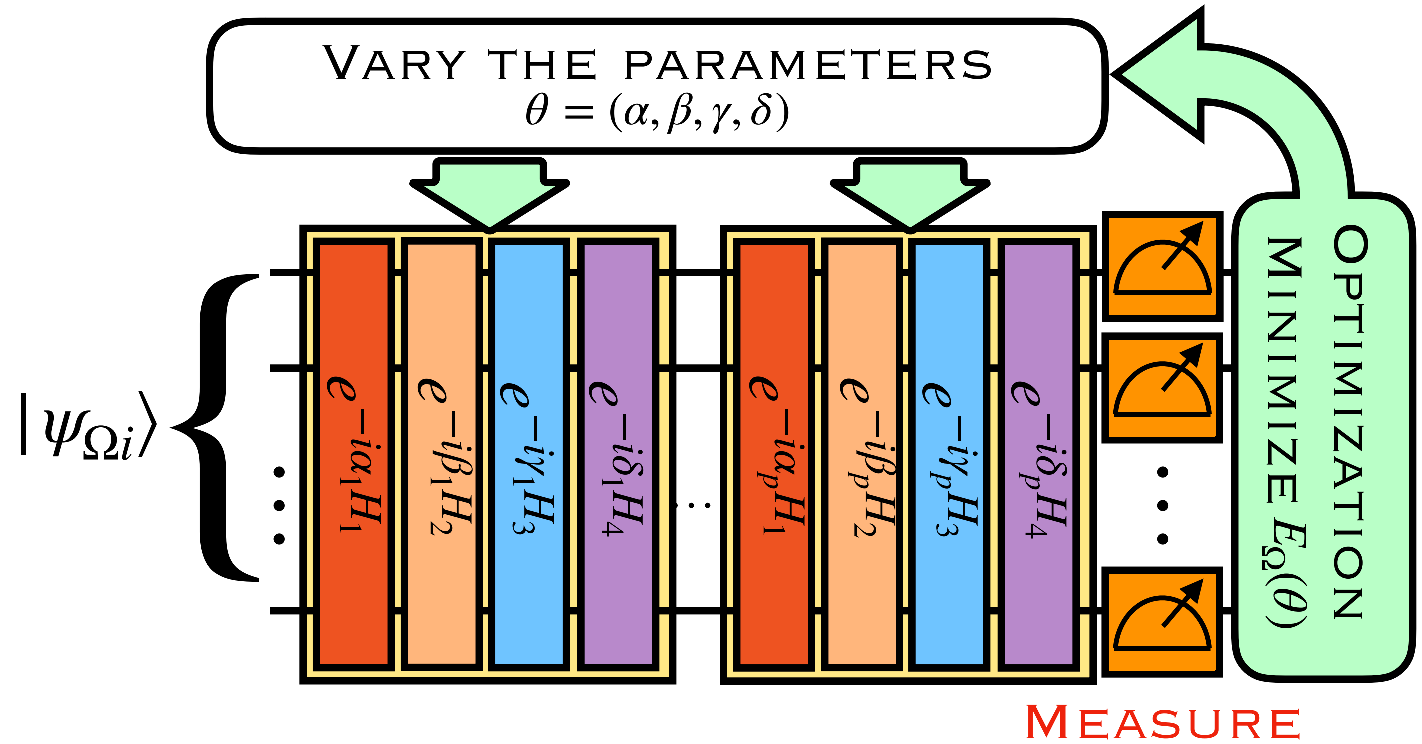
Quantum Simulation

Li, Guo, Lai, XL, Wang, Xing, Zhang, Zhu, 2021

- A toy model

Prepare the state by QAOA

Farhi et al., 411.4028, 2014



$$\psi_i(\theta)\rangle = \prod e^{iH_i\theta_i}|\psi_i\rangle \qquad [H_i, H_{i+1}] \neq 0$$

$$E(\theta) = \sum_i^k w_i \langle \psi_i(\theta) | H | \psi_i(\theta) \rangle$$ Minimize

$$|\psi_\Omega\rangle = |0101\ldots01\rangle$$

$$|\psi_h\rangle = |1001\ldots01\rangle + |0110\ldots01\rangle + \ldots$$

$$f(x) \rightarrow \sum_{i,j} \sum_z \frac{1}{4\pi} e^{-ixM_h z} \langle h | e^{iHz} \phi^\dagger_{-2z+i} e^{-iHz} \phi_j | h \rangle$$

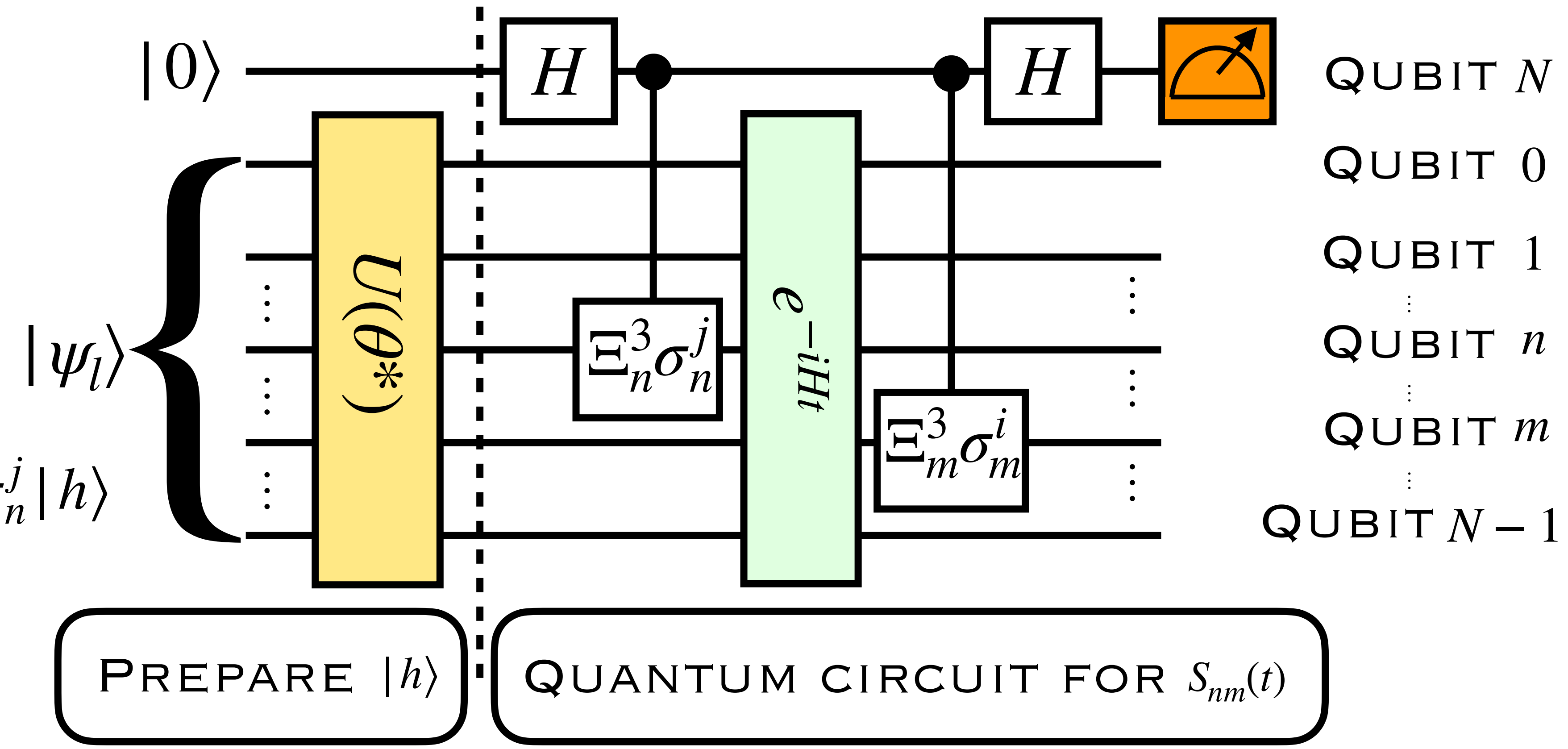
$$H_1 = \sum_{n=\text{even}} \frac{1}{4} \left[\sigma_n^1 \sigma_{n+1}^2 - \sigma_n^2 \sigma_{n+1}^1 \right] + H_2 + H_3 + H_4$$

Quantum Simulation

Li, Guo, Lai, XL, Wang, Xing, Zhang, Zhu, 2021

- A toy model

Evaluate evolution



$$S_{mn}(t) = \langle h | e^{iHt}\Xi_m^3\sigma_m^i e^{-iHt}\Xi_n^3\sigma_n^j | h\rangle$$

$$S_{mn}(t) = \frac{1}{2}p_{mn}(t) - \frac{1}{2}$$

Pedernales et al., PRL, 2014

$$f(x) \to \sum_{i,j}\sum_{z}\frac{1}{4\pi}e^{-ixM_h z}\langle h | e^{iHz}\phi^\dagger_{-2z+i}e^{-iHz}\phi_j | h\rangle$$

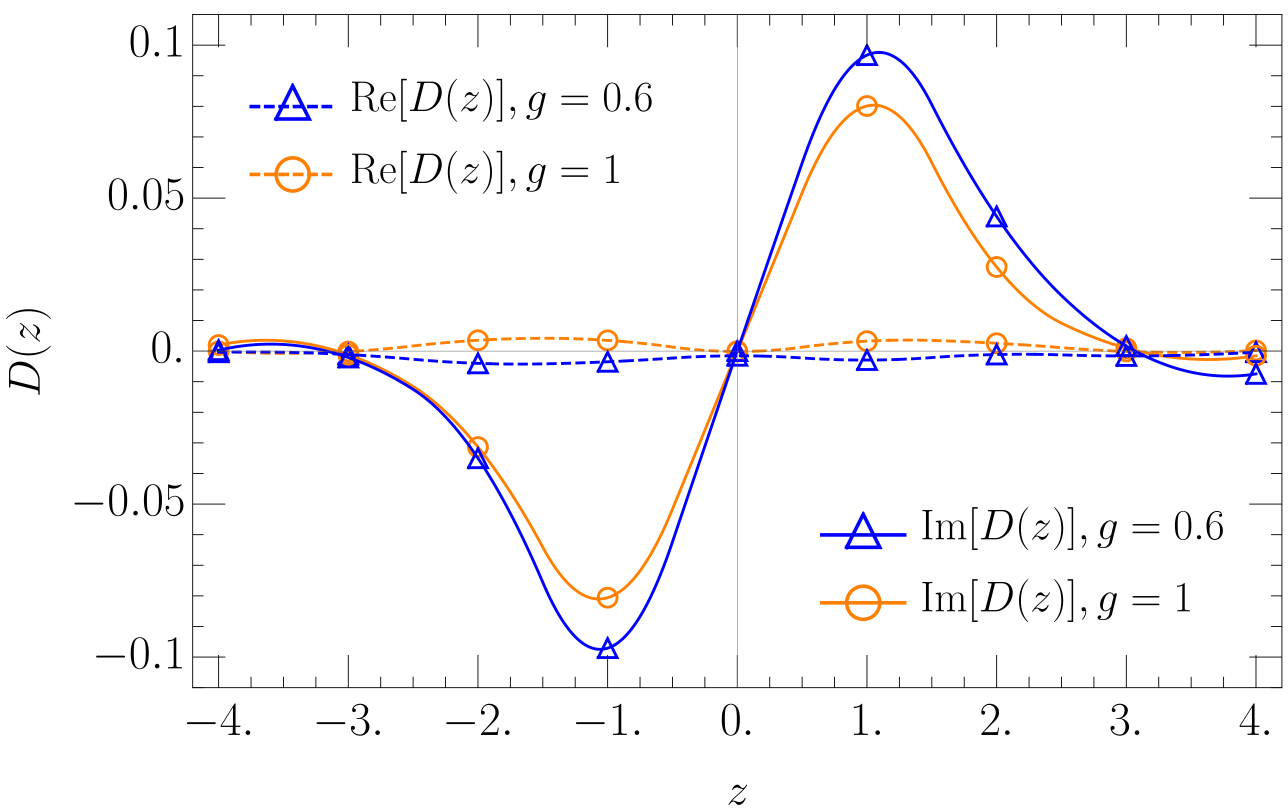
$$H_1 = \sum_{n=\text{even}}\frac{1}{4}\left[\sigma_n^1\sigma_{n+1}^2 - \sigma_n^2\sigma_{n+1}^1\right] + H_2 + H_3 + H_4$$

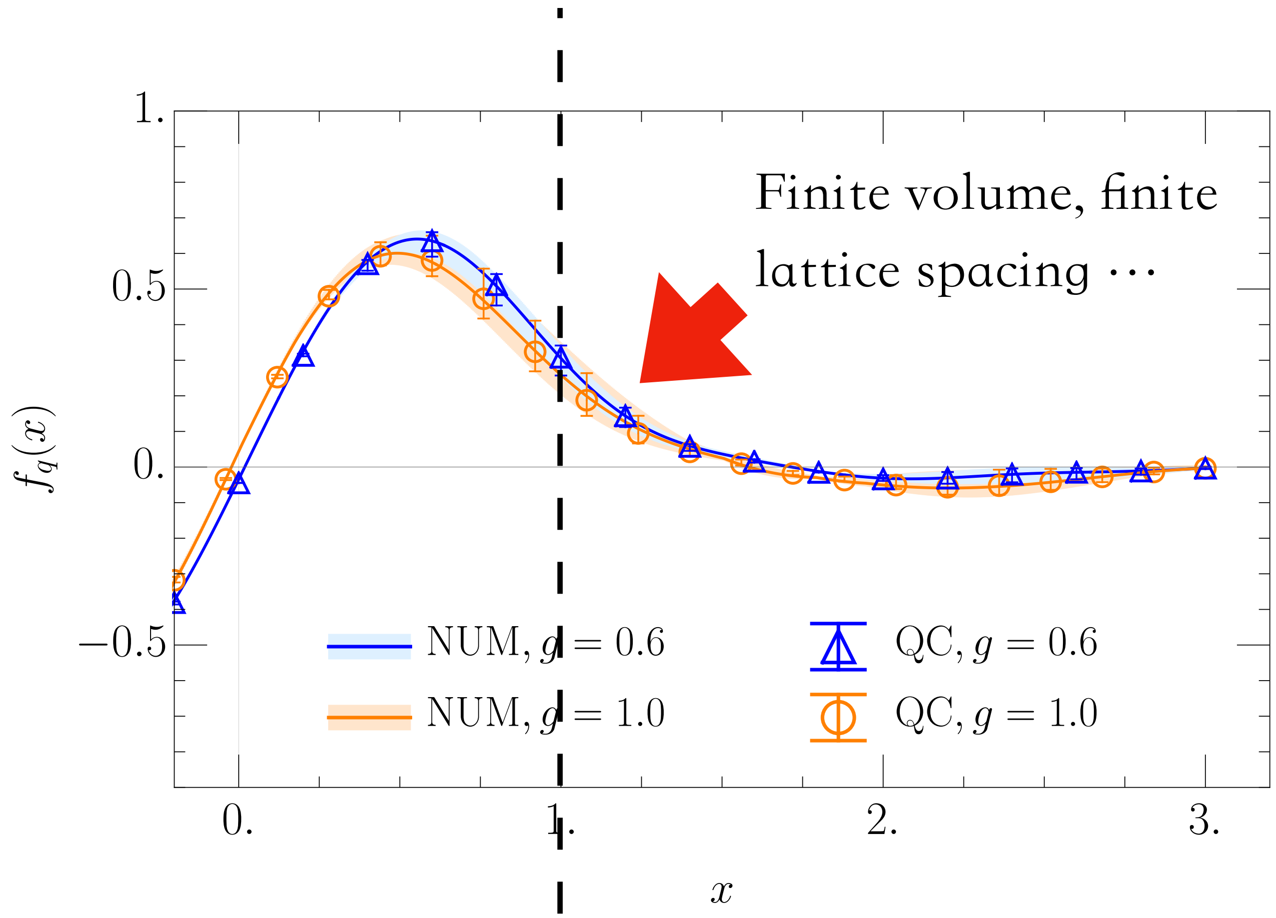
Quantum Simulation

Li, Guo, Lai, XL, Wang, Xing, Zhang, Zhu, 2021

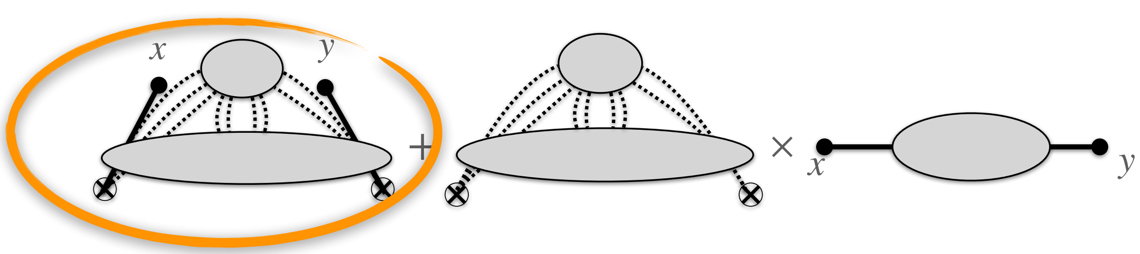
- A toy model

Results





$_H\langle h\,|\,T[\psi_H(x)\,\psi_H(y)]\,|\,h\rangle_H =$



$$f(x) \to \sum_{i,j}\sum_{z}\frac{1}{4\pi}e^{-ixM_h z}\langle h\,|\,e^{iHz}\phi^\dagger_{-2z+i}e^{-iHz}\phi_j\,|\,h\rangle$$

Summary

- Jet probe
  - an active direction for hard probes of the nucleon intrinsic information.
  - New avenue to QCD strong dynamics
- Quantum Computation
  - Future direction to explore
  - The system and applications are still limited

Thanks