SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

International Workshop on J-PARC hadron physics in 2016
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POLARIZED QUARK HADRONIZATION

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CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

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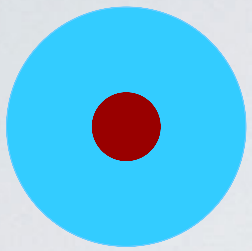
SUB CRUCE LUMEN

Outlook

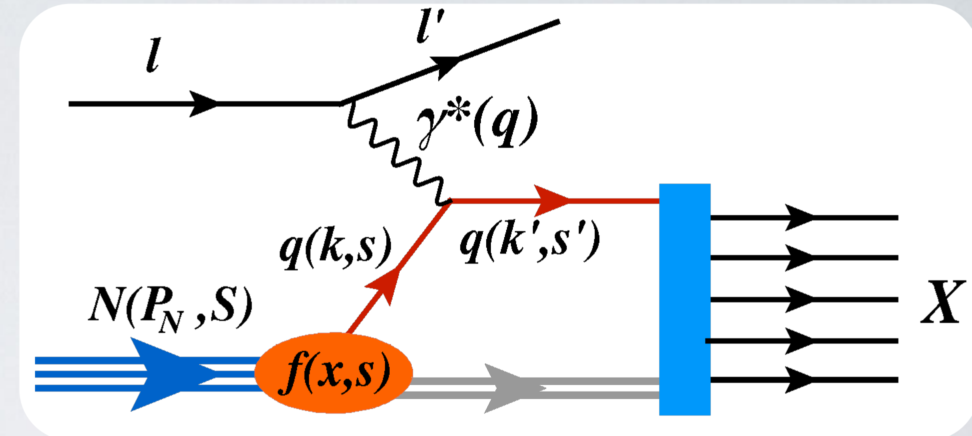
- *Introduction and Motivation.*
- *Brief overview of NJL-jet and the MC implementation.*
- *The recent progress on modelling polarised quark hadronisation.*
- *Conclusions.*

NUCLEON PARTON DISTRIBUTION FUNCTIONS

- *Unpolarized* quark in *Unpolarized* nucleon.

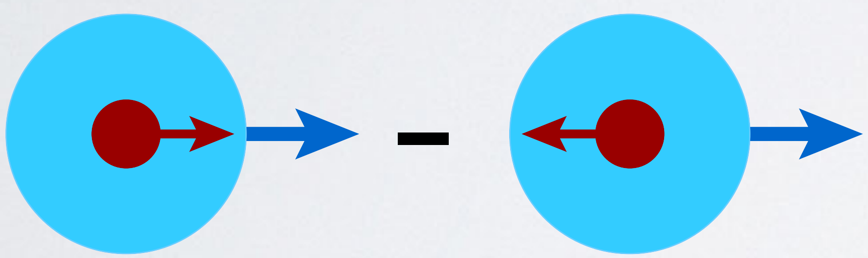


$$f_1^q(x, Q^2)$$



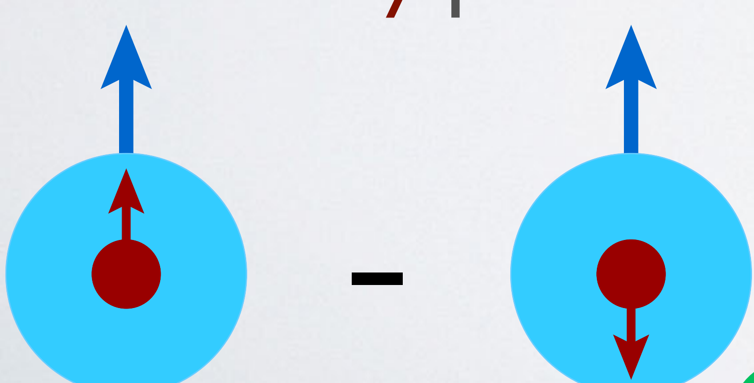
- ***The momentum and the spin of the partons are correlated with the polarization of the nucleon!***

- *Longitudinally* polarized quark in *Longitudinally* polarized nucleon.



$$g_{1L}^q(x, Q^2)$$

- *Transversely* polarized quark in *Transversely* polarized nucleon.



$$h_{1T}^q(x, Q^2)$$

Only for quarks (leading twist)!

Chiral-odd: Suppressed in Inclusive DIS: not well known!

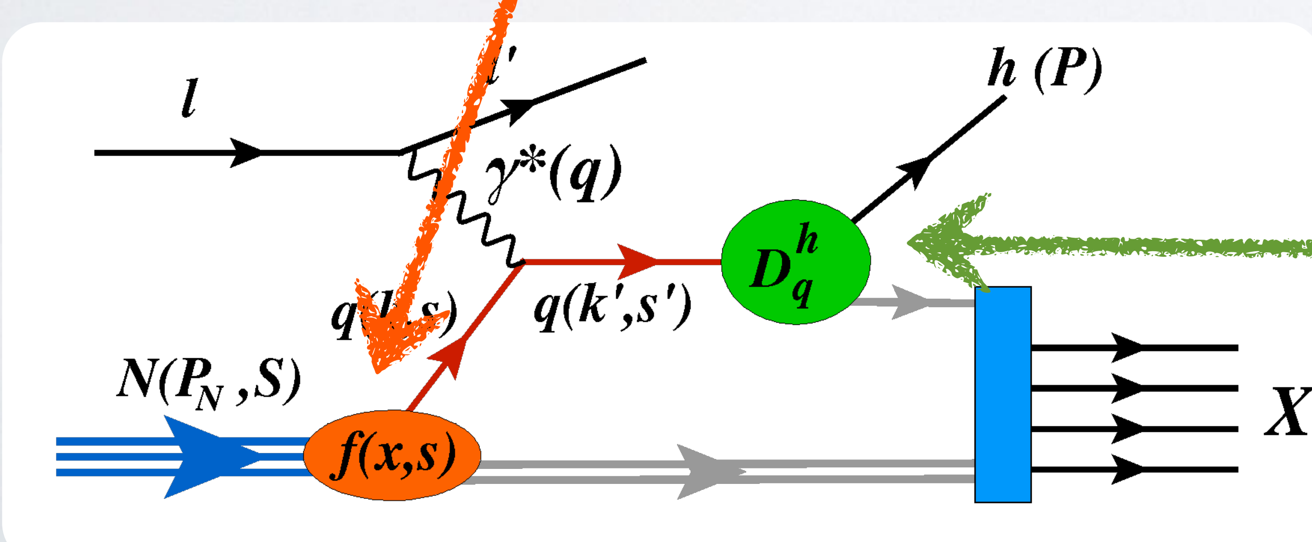
PDFS WITH TRANSVERSE MOMENTUM DEPENDENCE

- ***The transverse momentum (TM) of the parton can couple with both its own spin and the spin of the nucleon:***
- ***TMD PDFs***

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

✦ Survive after TM integration!

- ***Accessible in SIDIS Process***



- ***NEED TMD Fragmentation Functions***

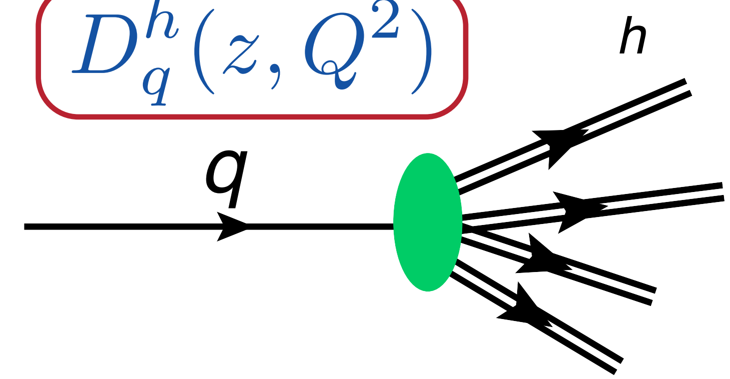
q/h	U
U	D_1
L	
T	$H_1^\perp$

✳unpol/spinless h!

Collinear Fragmentation Functions (FFs)

- **Unpolarized FF is the number density of hadron h with LC momentum fraction z, produced by quark q:**

$$D_q^h(z, Q^2)$$



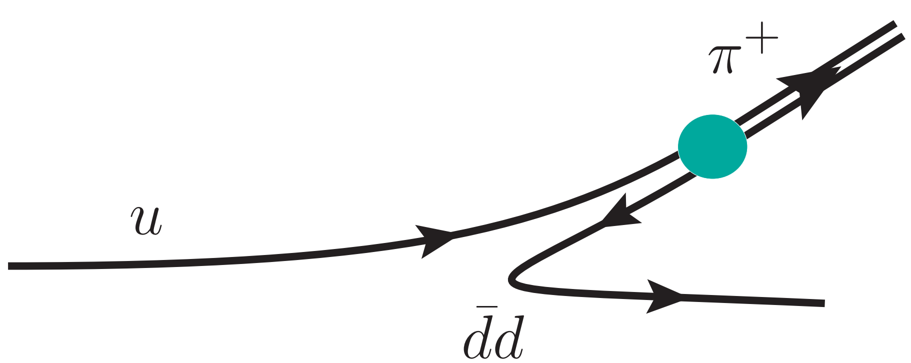
- **Favoured**: the produced hadron has a valence quark of the same flavour.

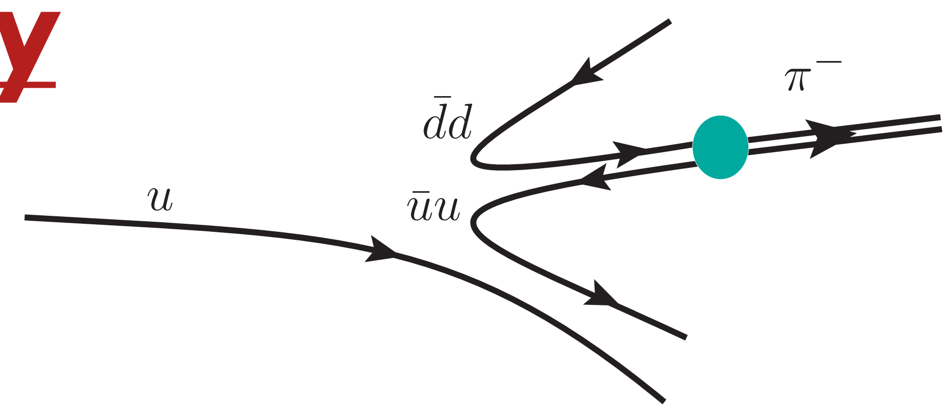
$$u \to \pi^+(u\bar{d}) \quad u \to K^+(u\bar{s})$$

- **Unfavoured** (disfavoured): NO valence quark of the same flavour.

$$u \to \pi^-(\bar{u}d) \quad u \to K^-(\bar{u}s)$$

Naively





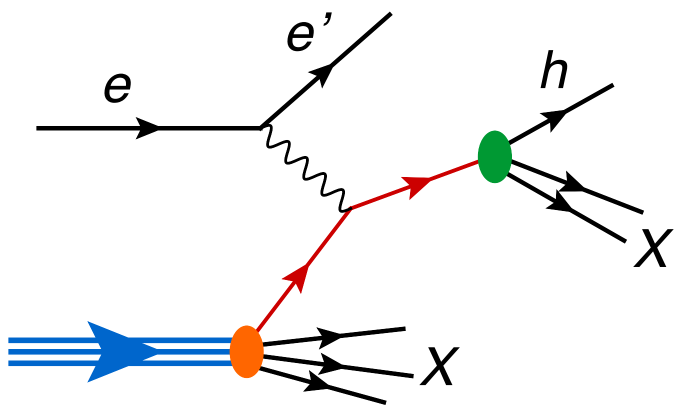
- **Symmetries:**
  - ✦ Charge Conjugation: $q \Leftrightarrow \bar{q}$

$$D_u^{\pi^+} = D_{\bar{u}}^{\pi^-}$$
$$D_s^{K^-} = D_{\bar{s}}^{K^+}$$

  - ✦ Isospin: $u \Leftrightarrow d$

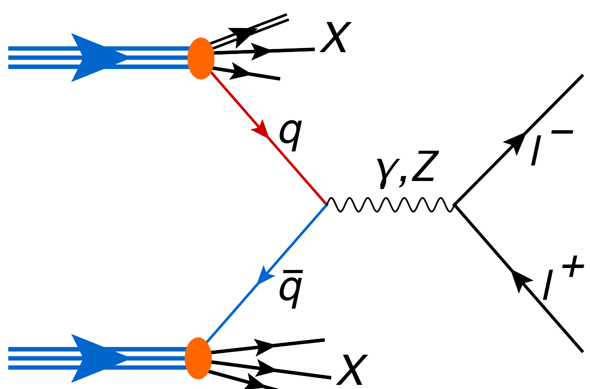
$$D_u^{\pi^+} = D_d^{\pi^-}$$
$$D_u^{K^+} = D_d^{K^0}$$

FACTORIZATION AND *UNIVERSALITY*



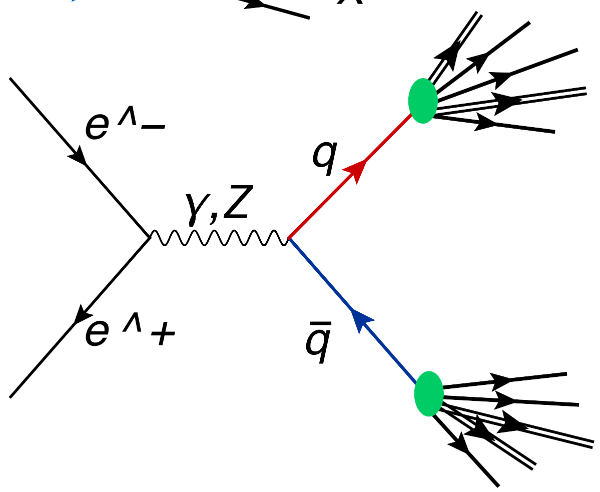
- SEMI INCLUSIVE DIS (SIDIS)

$$\sigma^{eP\to ehX} = \sum_q f_q^P \otimes \sigma^{eq\to eq} \otimes D_q^h$$



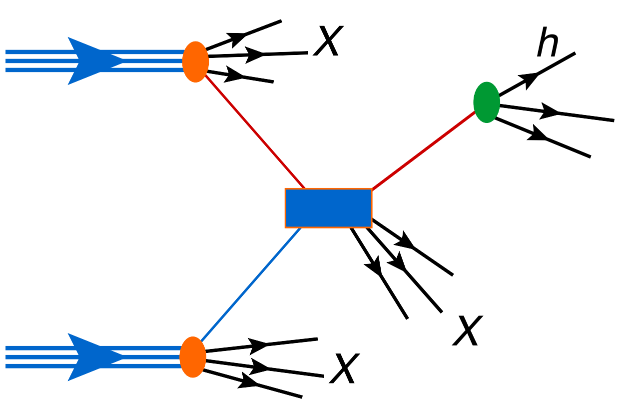
- DRELL-YAN (DY)

$$\sigma^{PP\to l^+l^-X} = \sum_{q,q'} f_q^P \otimes f_{\bar{q}}^P \otimes \sigma^{q\bar{q}\to l^+l^-}$$



- e^+e^-

$$\sigma^{e^+e^-\to hX} = \sum_q \sigma^{e^+e^-\to q\bar{q}} \otimes (D_q^h + D_{\bar{q}}^h)$$



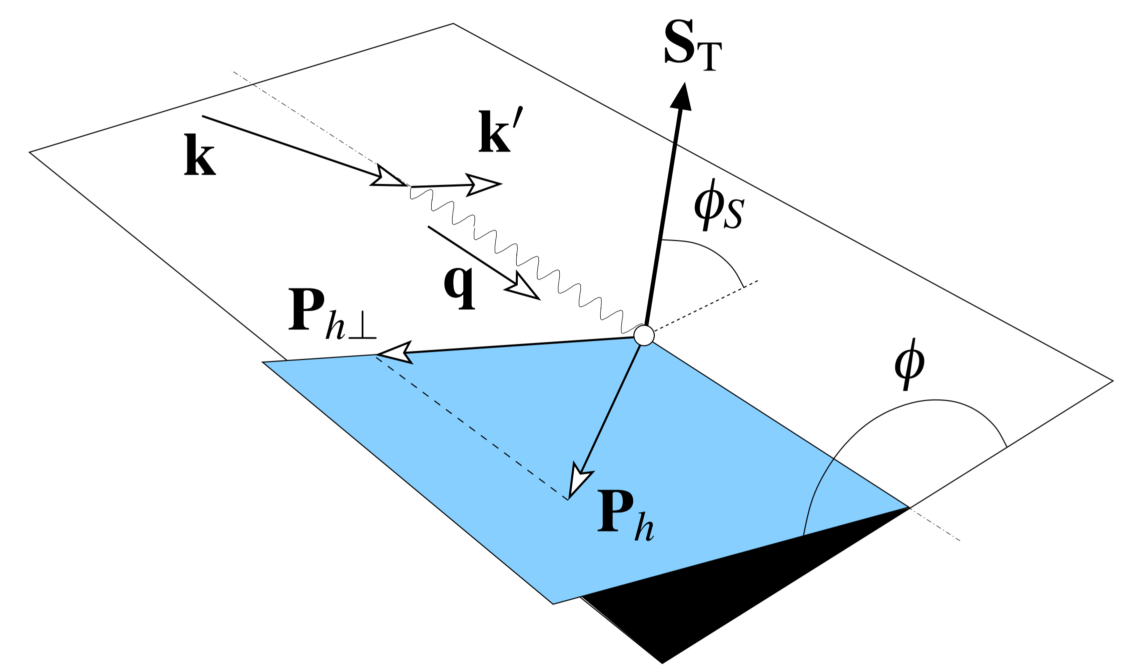
- Hadron Production

$$\sigma^{PP\to hX} = \sum_{q,q'} f_q^P \otimes f_{q'}^P \otimes \sigma^{qq'\to qq'} \otimes D_q^h$$

TMDs from SIDIS $e\,P \to e'\,h\,X$

A. Bacchetta et al., JHEP08 023 (2008).

- *For polarized SIDIS cross-section there are **18 terms** in leading twist expansion:*



$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} \sim F_{UU,T} + \varepsilon F_{UU,L} + \ldots$$

$$+ |\boldsymbol{S}_\perp| \left[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \right) + \varepsilon\, \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + .. \right]$$

Collins term

- Access the structure functions via *specific* modulations.
- LO Matching to *convolutions* of PDFs and FFs: $P_T^2 \ll Q^2$

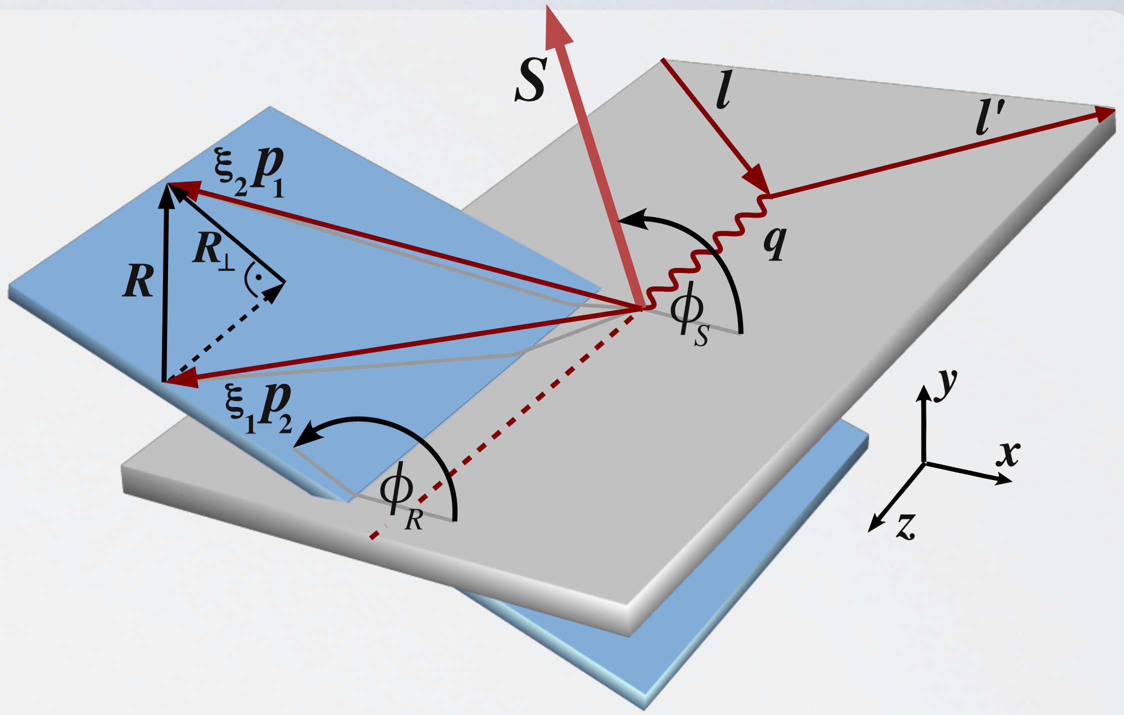
$$F_{UU,T} \sim \mathcal{C}[f_1\ D_1] \qquad F_{UT}^{\sin(\phi_h+\phi_S)} \sim \mathcal{C}[h_1\ H_1^\perp]$$

- ***NEED Collins Fragmentation Function to access Transversity PDF from SIDIS!*** *[BELLE (II) , BaBar]*

ACCESS TO TRANSVERSITY PDF From DiFF in *SIDIS*

M. Radici, et al: PRD 65, 074031 (2002).

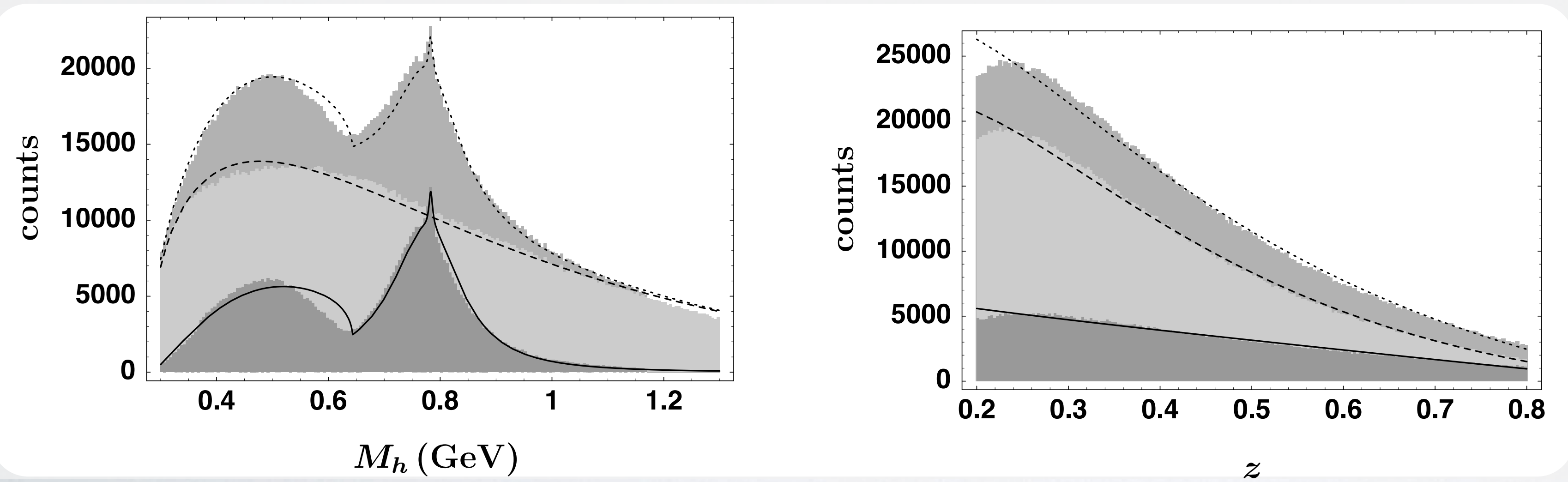
- In two hadron production from polarized target the cross section factorizes ***collinearly* - no TMD!**
- Allows clean access to ***transversity***.
- ***Unpolarized*** and ***Interference*** Dihadron FFs are needed!



$$\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \sin(\phi_R + \phi_S) \frac{\sum_q e_q^2\ h_1^q(x)/x\ H_1^{\sphericalangle q}(z, M_h^2)}{\sum_q e_q^2\ f_1^q(x)/x\ D_1^q(z, M_h^2)}$$

- **Empirical Model for D_1^q has been fitted to PYTHIA simulations.**

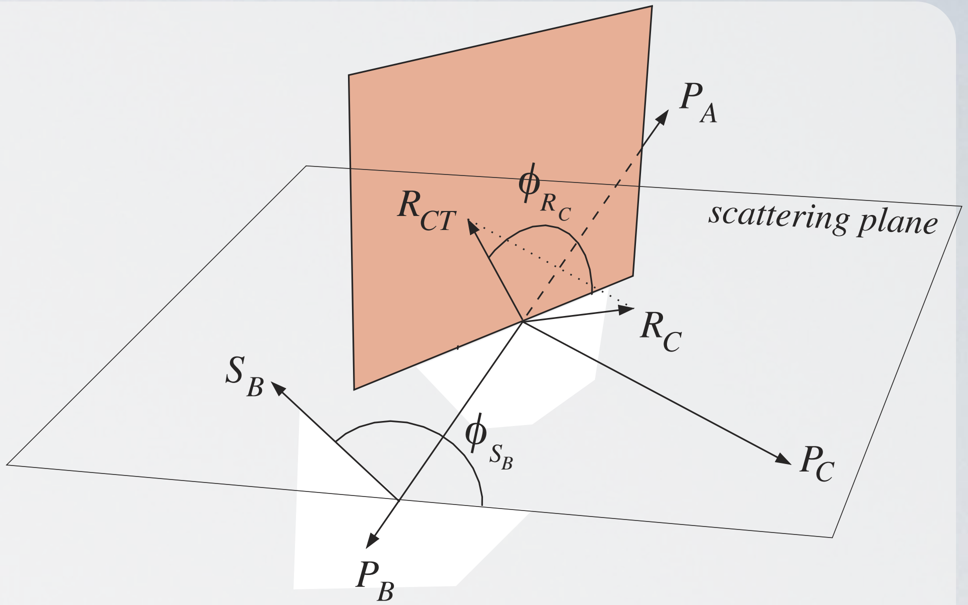
A. Bacchetta and M. Radici, PRD 74, 114007 (2006).



Experiments:
BELLE,
HERMES,
COMPASS.

ACCESS TO TRANSVERSITY PDF From DiFF in $P^{\uparrow}P$

Bacchetta, Radici: PRD 70, 094032 (2004).



- In two hadron production from polarized $P^{\uparrow}P$ *assume* the cross section factorizes.
- Access to *transversity* in collinear kinematics in hadron pair from the *same quark jet*.

$$\frac{d\sigma^{PP^{\uparrow}} - d\sigma^{PP^{\downarrow}}}{d\sigma^{PP^{\uparrow}} + d\sigma^{PP^{\downarrow}}} = \frac{d\sigma_{UT}}{d\sigma_{UU}} = \sin(\phi_{RS}) A_{UT}$$

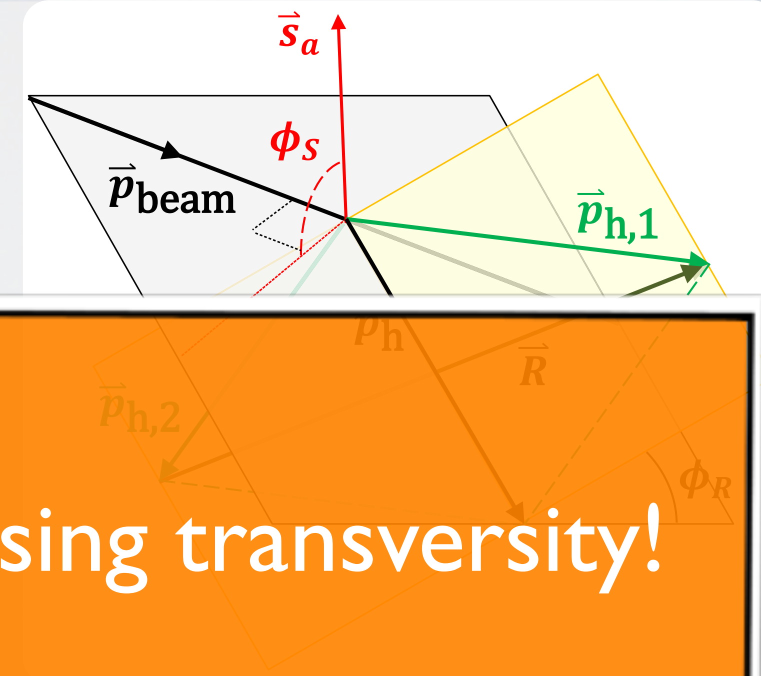
$$A_{UT} \sim \frac{\sum_{a,b,c,d} \int dx_a dx_b \; f_1^{a/P}(x_a) \, h_1^{b^{\uparrow}/P^{\uparrow}}(x_b) \, \frac{d\hat{\sigma}^{ab^{\uparrow} \to c^{\uparrow} d}}{d\hat{t}} \, H_{1,c}^{\sphericalangle}(z, M)}{\sum_{a,b,c,d} \int dx_a dx_b \; f_1^{a/P}(x_a) \, f_1^{b/P}(x_b) \, \frac{d\hat{\sigma}^{ab \to cd}}{d\hat{t}} \, D_{1,c}(z, M)}$$

- Again, we *need DiFFs* to extract transversity!
- No *u dominance for P* (no *charge weighting* like in SIDIS).

Measurements in *STAR for $P^{\uparrow}P$ at* $\sqrt{s} = 200\mathrm{GeV}$

STAR: Phys.Rev.Lett. 115, 242501 (2015).

- First-ever measurements of transversity in *PP.*

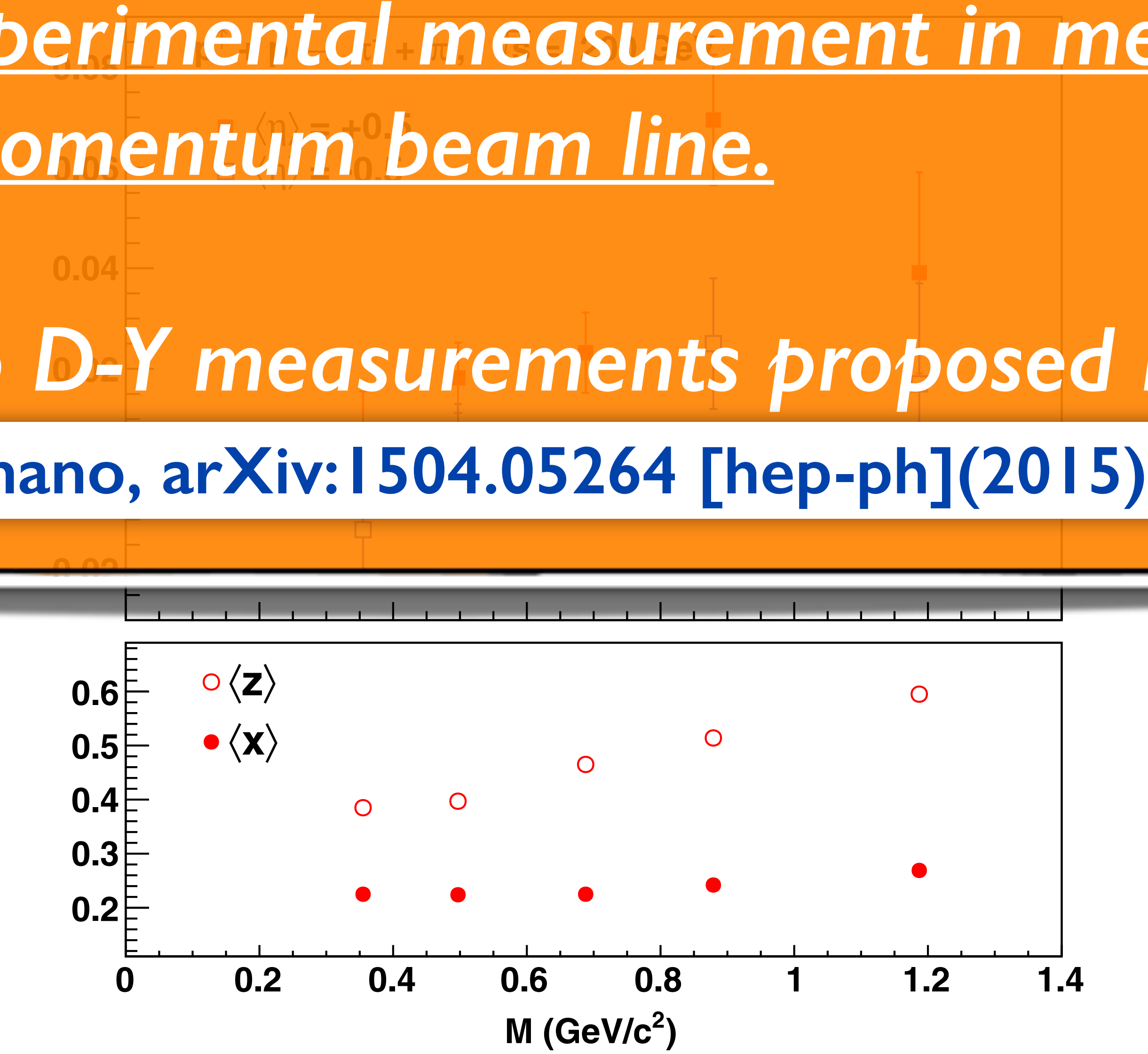


$$\frac{N^{\uparrow}(\phi_{RS}) - r \cdot N^{\downarrow}(\phi_{RS})}{N^{\uparrow}(\phi_{RS}) + r \cdot N^{\downarrow}(\phi_{RS})} = P_{\mathrm{beam}} A_{UT} \sin(\phi_{RS})$$

- Signal in excess of 5σ at high pT, $\eta > 0.5$.

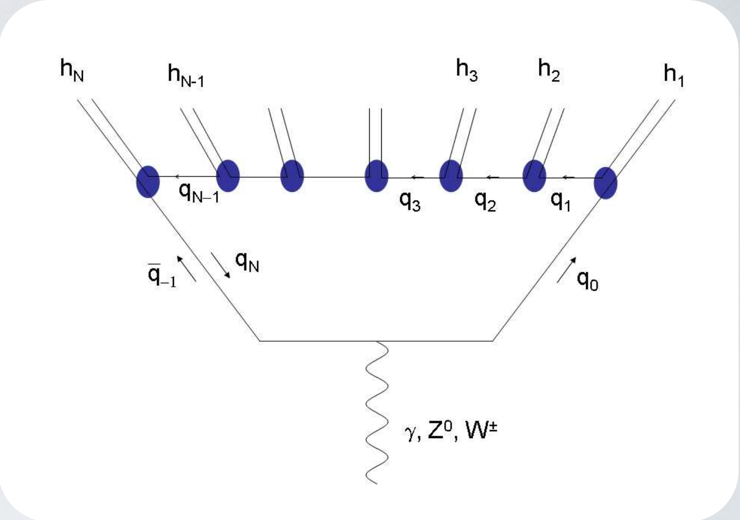
- Hadron - Proton scattering is viable for accessing transversity!
- *Possible future experimental measurement in medium-x region at J-PARC High-Momentum beam line.*
- *Complimentary to D-Y measurements proposed in*

S. Kumano, arXiv:1504.05264 [hep-ph](2015).

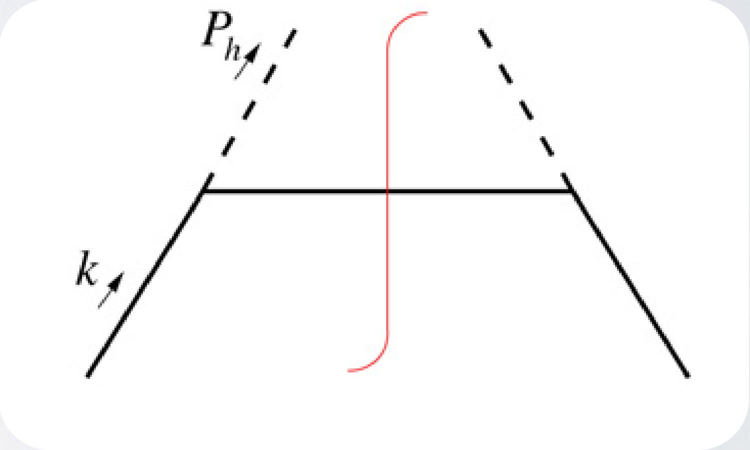


(SOME of the) MODELS FOR FRAGMENTATION

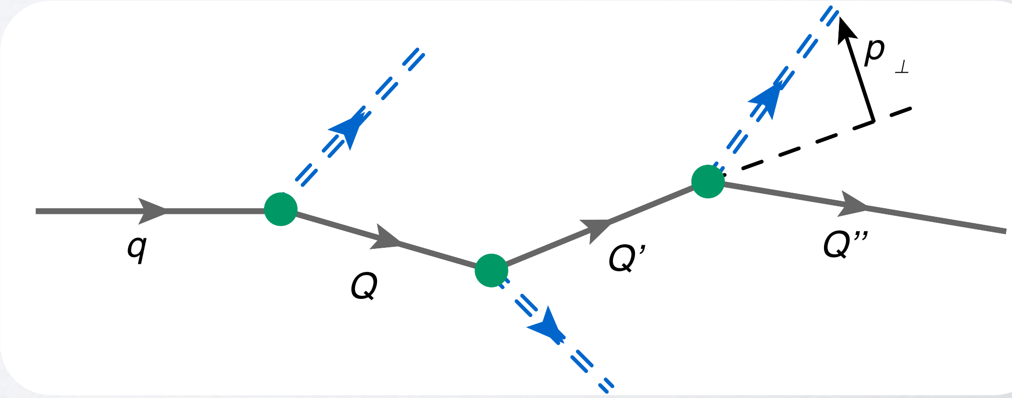
- *Lund String Model*
  - *Very Successful* implementation in *JETSET, PYTHIA*.
  - Highly Tunable - Limited Predictive Power.
  - No Spin Effects - Formal developments by X. Artru et al but no quantitative results!

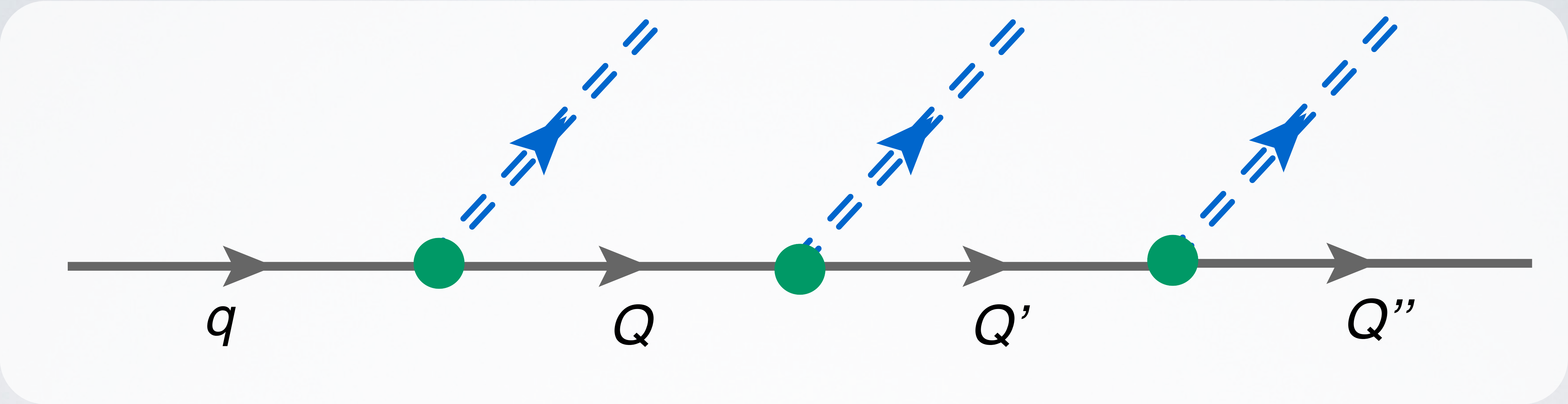


- *Spectator Model*
  - Quark model calculations with empirical form factors.
  - No unfavored fragmentations.
  - Need to tune parameters for small z dependence.



- *NJL-jet Model*
  - *Multi-hadron* emission framework with effective quark model input.
  - *Monte-Carlo framework* allows flexibility in including the transverse momentum, spin effects, two-hadron correlations, etc.



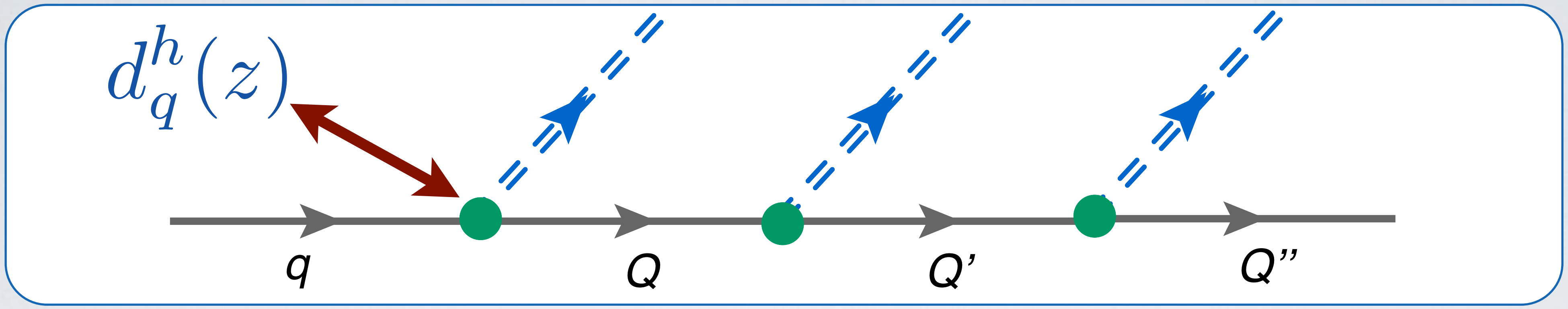


THE NJL-jet MODEL

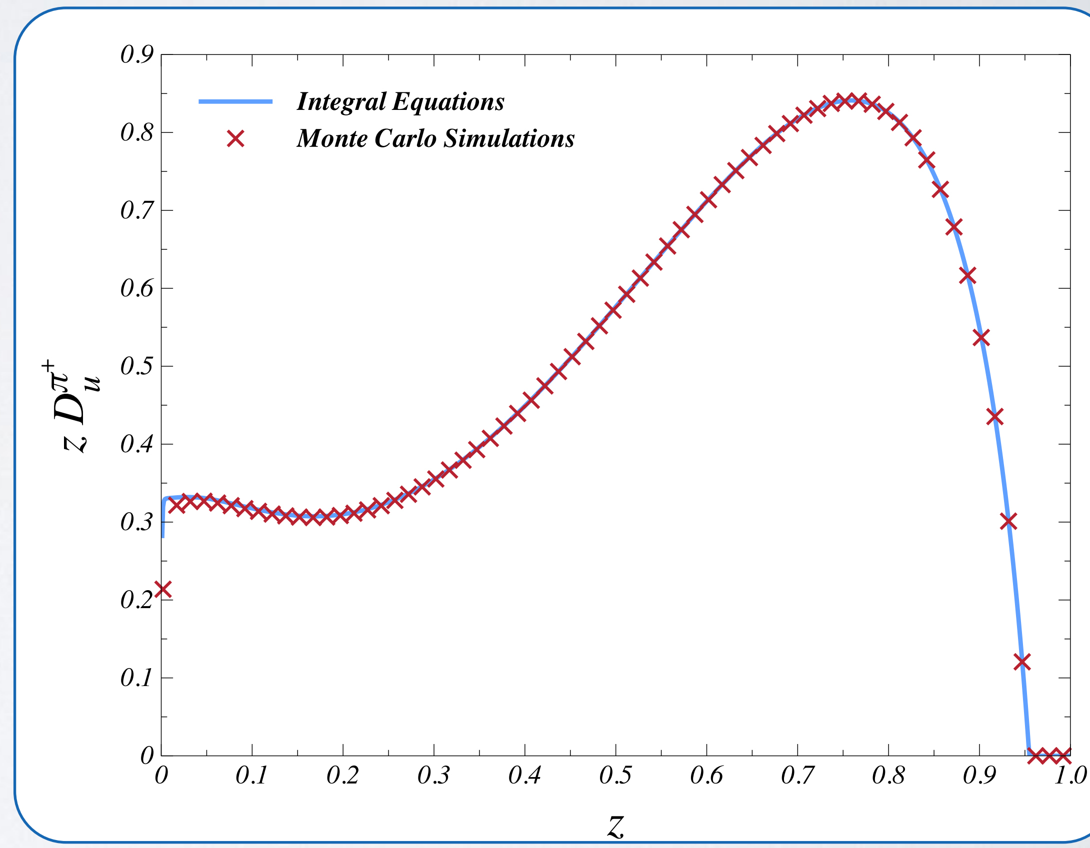
COLLINEAR FRAGMENTATIONS FROM MC

H.M., Thomas, Bentz, PRD. 83:07400; PRD.83:114010, 2011.

- Input: One hadron emission probability



- Sample the emitted hadron type and z according to input splitting.



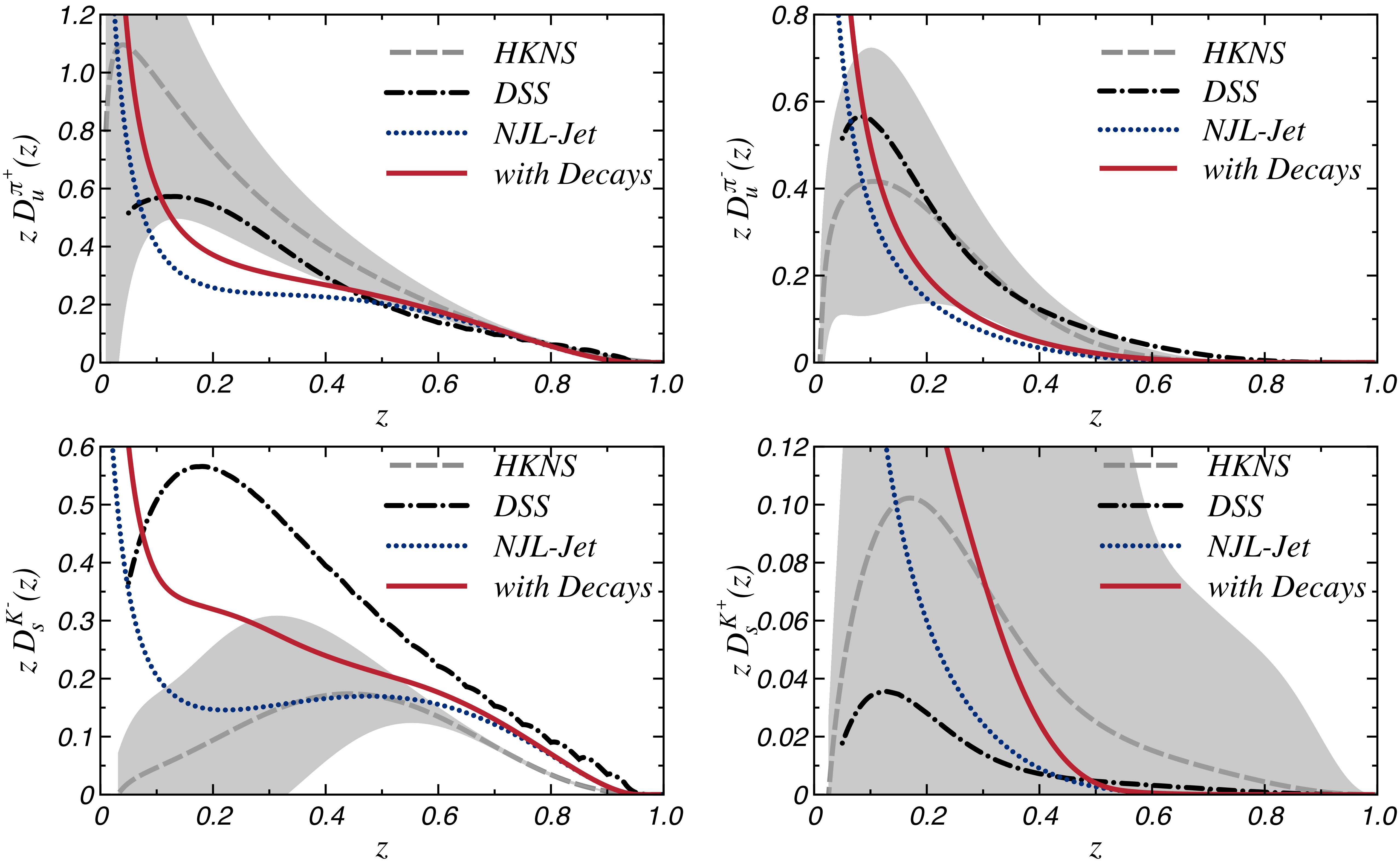
- ***CONSERVE***: Momentum and Quark Flavor in each step.

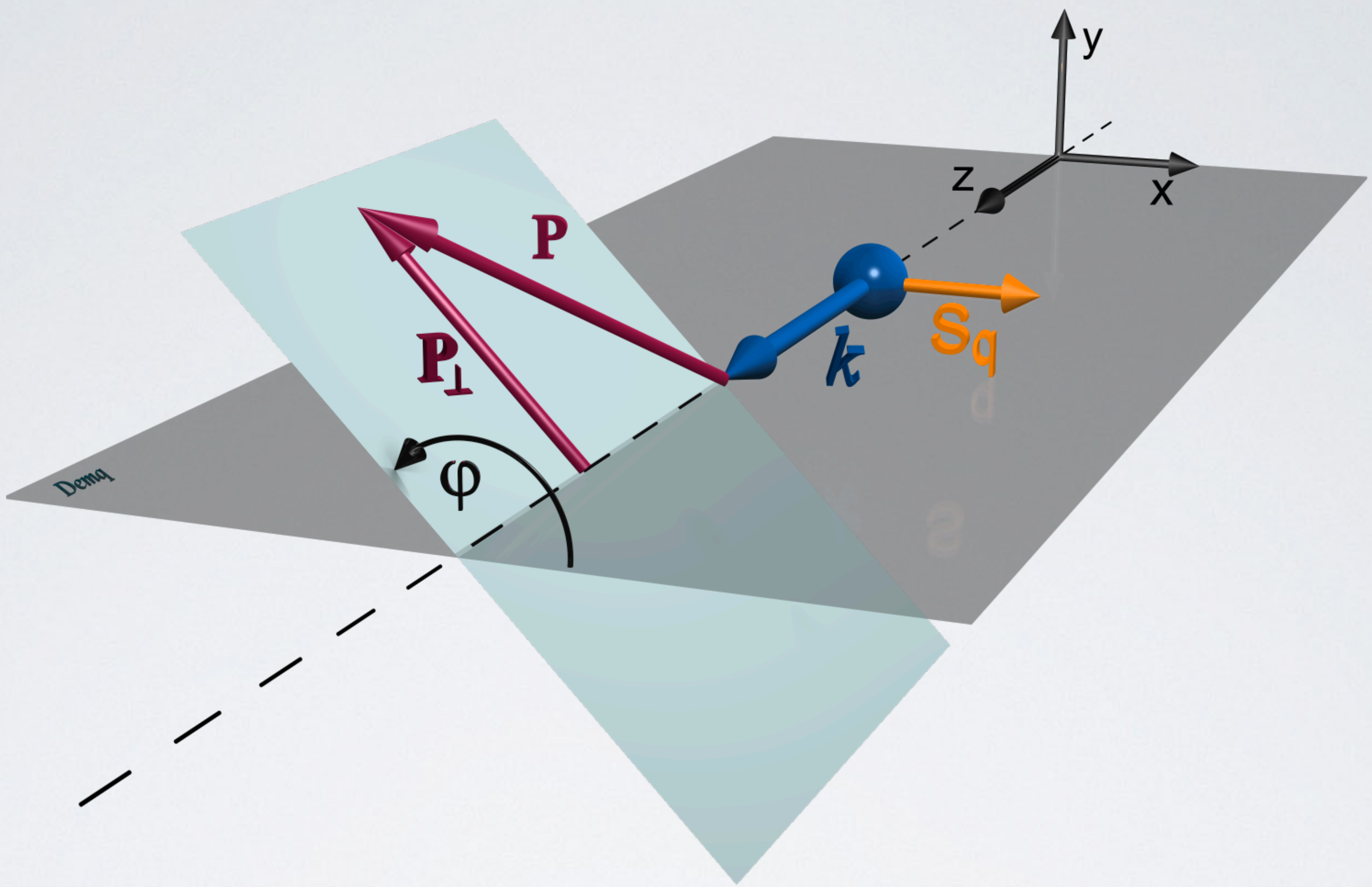
- Repeat for decay chains with the same initial quark.

$$D_q^h(z)\Delta z = \langle N_q^h(z, z+\Delta z)\rangle \equiv \frac{\sum_{N_{Sims}} N_q^h(z, z+\Delta z)}{N_{Sims}}$$

Results with VM decays: $Q^2 = 4\ \mathrm{GeV}^2$

Favored | **Unfavored**





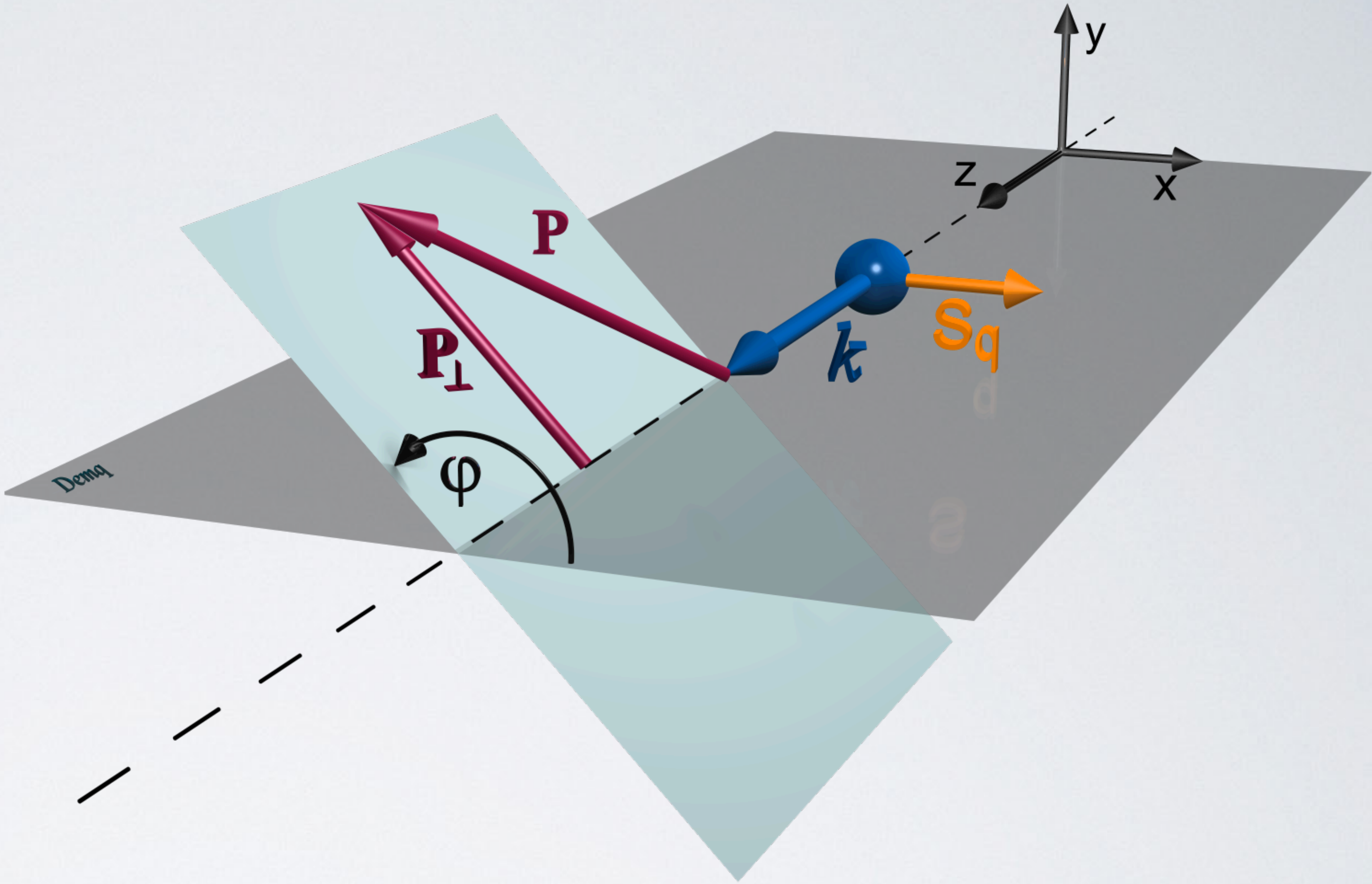
TRANSVERSELY POLARIZED QUARK FRAGMENTATION:

COLLINS EFFECT AND TWO-HADRON CORRELATIONS

COLLINS FRAGMENTATION FUNCTION

- **Collins Effect:**

  Azimuthal Modulation of Transversely Polarized Quark' Fragmentation Function.



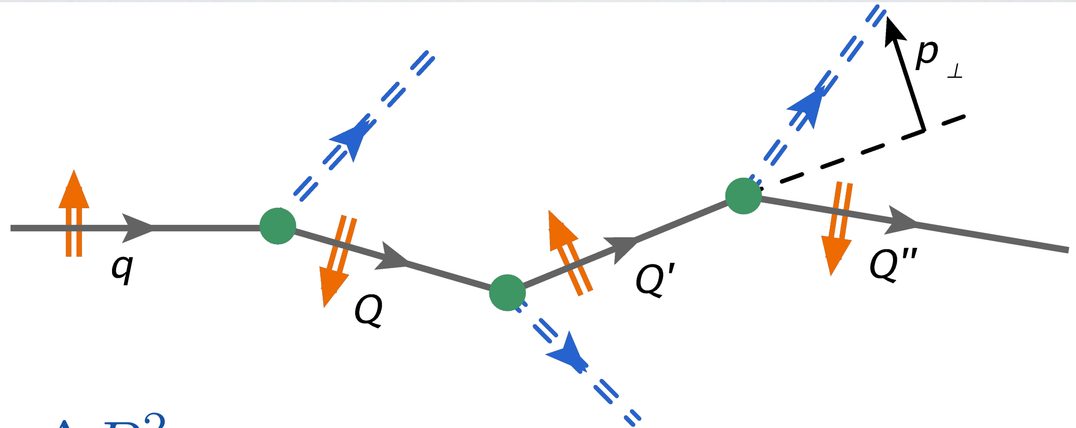
Unpolarized

$$D_{h/q^{\uparrow}}(z, P_{\perp}^{2}, \varphi) = D_{1}^{h/q}(z, P_{\perp}^{2}) - H_{1}^{\perp h/q}(z, P_{\perp}^{2}) \frac{P_{\perp} S_{q}}{z m_{h}} \sin(\varphi)$$

Collins

- **Chiral-ODD**: Needs to be coupled with another chiral-odd quantity to be observed.

COLLINS EFFECT - NJL-jet MKII

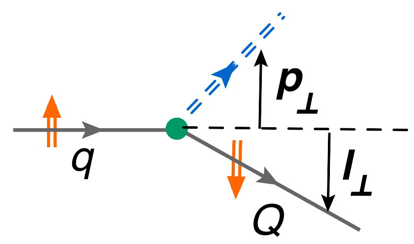


$$D_{h/q^\uparrow}(z, P_\perp^2, \varphi)\, \Delta z\, \frac{\Delta P_\perp^2}{2}\, \Delta\varphi = \left\langle N_{q^\uparrow}^h(z, z+\Delta z; P_\perp^2, P_\perp^2 + \Delta P^2; \varphi, \varphi + \Delta\varphi) \right\rangle$$

MKII Model Assumptions:

H.M., Kotzinian, Thomas, PLB731 208-216 (2014).

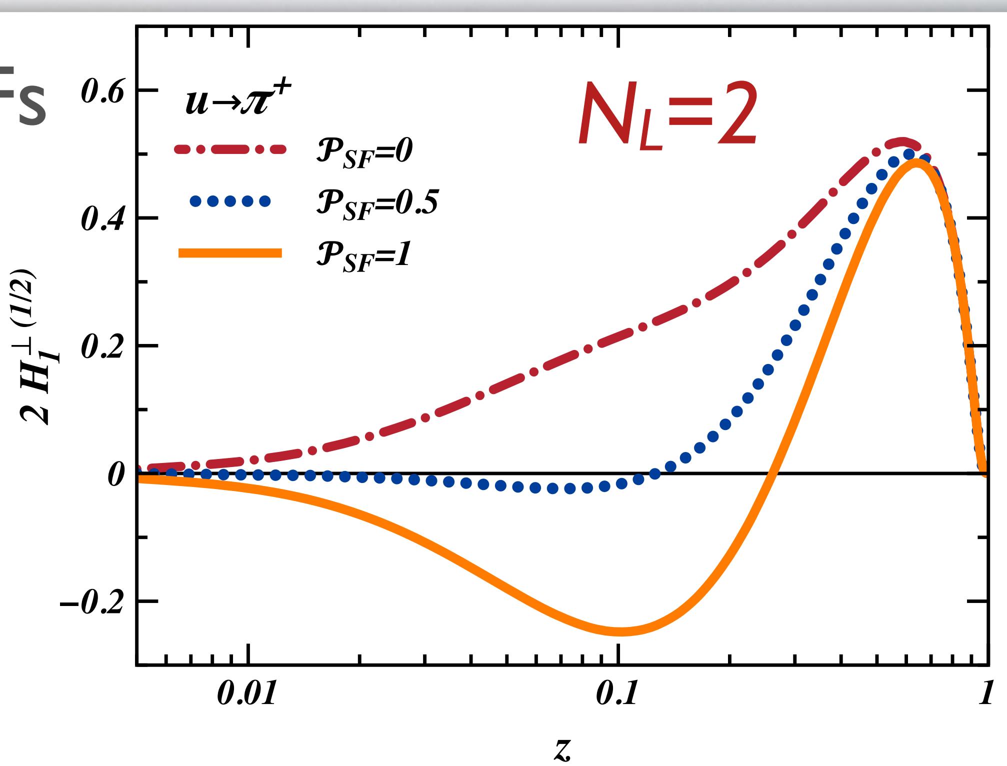
1. Allow for Collins Effect only in a SINGLE emission vertex (N_L^{-1} scaling of the resulting Collins function).
2. Use constant values for spin flip probability: $\mathcal{P}_{SF}$.



- ✦ Use fit form to extract unpol. and Collins FFs from $D_{h/q^\uparrow}$.

$$F(c_0, c_1) = c_0 - c_1 \sin(\varphi)$$

- ✦ The results for N_L=2, $\mathcal{P}_{SF} = 1$.

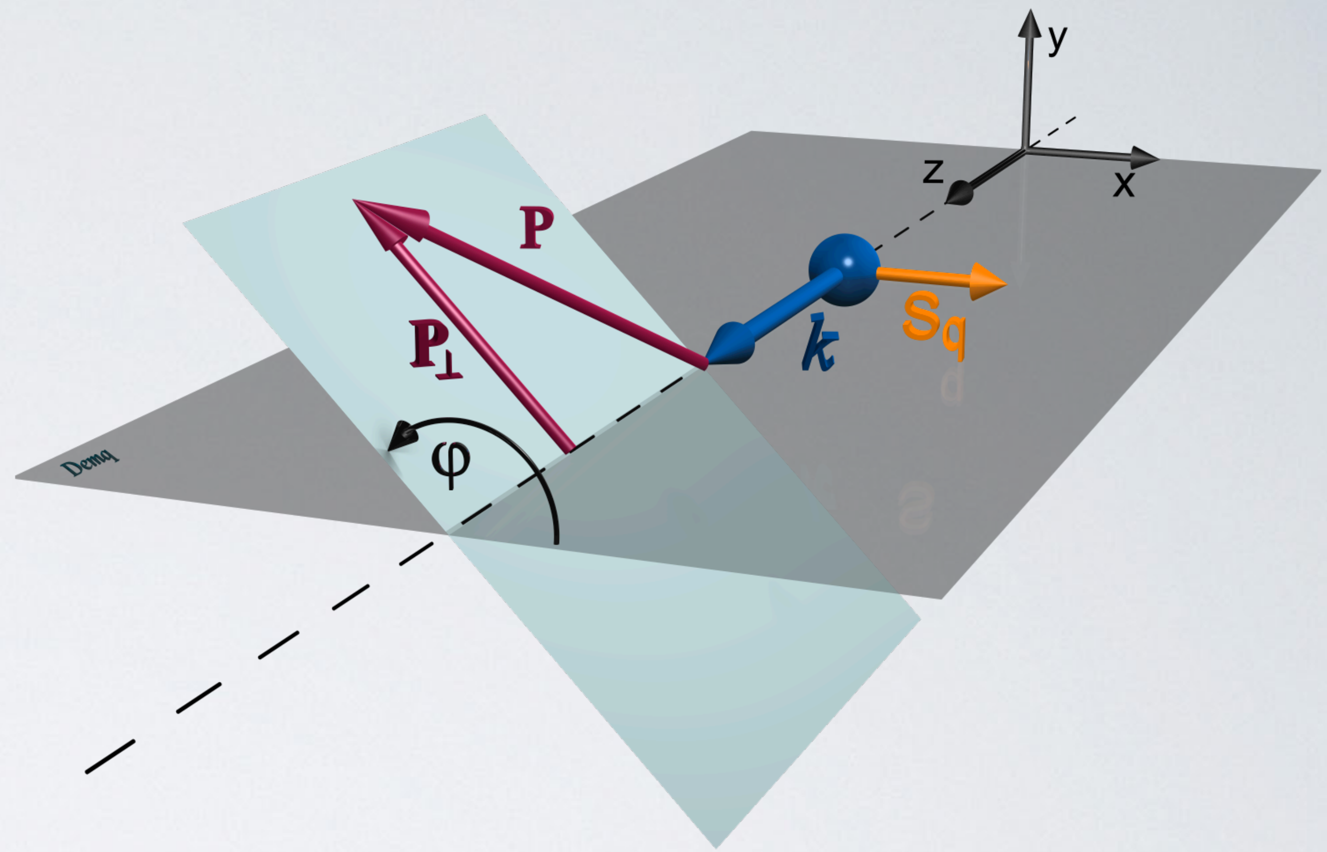


TWO-HADRON FRAGMENTATION

- **Transformation to frame $\mathbf{k}_T = 0$**

$$k = (k^-, k^+, \mathbf{0})$$
$$\mathbf{k}_T = -\mathbf{P}_T / z_h$$

$$\mathbf{P}_T = \mathbf{P}^{\perp}_{h_1} + \mathbf{P}^{\perp}_{h_2}$$
$$\mathbf{R} = (\mathbf{P}^{\perp}_{h_1} - \mathbf{P}^{\perp}_{h_2})/2$$



- **Integrate over one or other momentum:**

$$D_{q^\uparrow}^{h_1 h_2}(\varphi_R) = D_{1,q}^{h_1 h_2} + \sin(\varphi_R - \varphi_S)\mathcal{F}[H_1^{\sphericalangle}, H_1^{\perp}]$$

$$D_{q^\uparrow}^{h_1 h_2}(\varphi_T) = D_{1,q}^{h_1 h_2} + \sin(\varphi_T - \varphi_S)\mathcal{F}'[H_1^{\sphericalangle}, H_1^{\perp}]$$

- The IFF surviving after $\mathbf{k}_T$ integration is redefined as

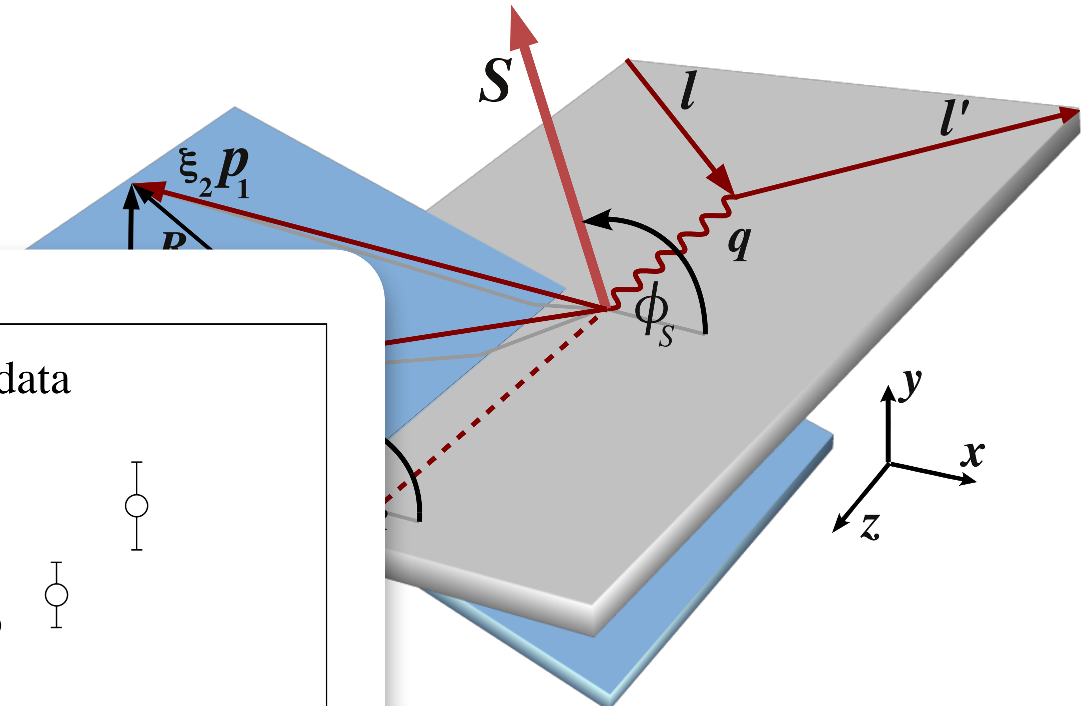
A. Bacchetta, M. Radici: PRD 69, 074026 (2004).

$$H_1^{\sphericalangle}(z_h, \xi, M_h^2) \equiv \int d^2\mathbf{k}_T \left[H_1^{\sphericalangle\,' e}(z_h, \xi, M_h^2, k_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) + \frac{k_T^2}{2M_h^2} H_1^{\perp o}(z_h, \xi, k_T^2, R_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \right]$$

RECENT COMPASS RESULTS

COMPASS, PLB736, 124-131 (2014).

✦ SIDIS with transversely polarized target.



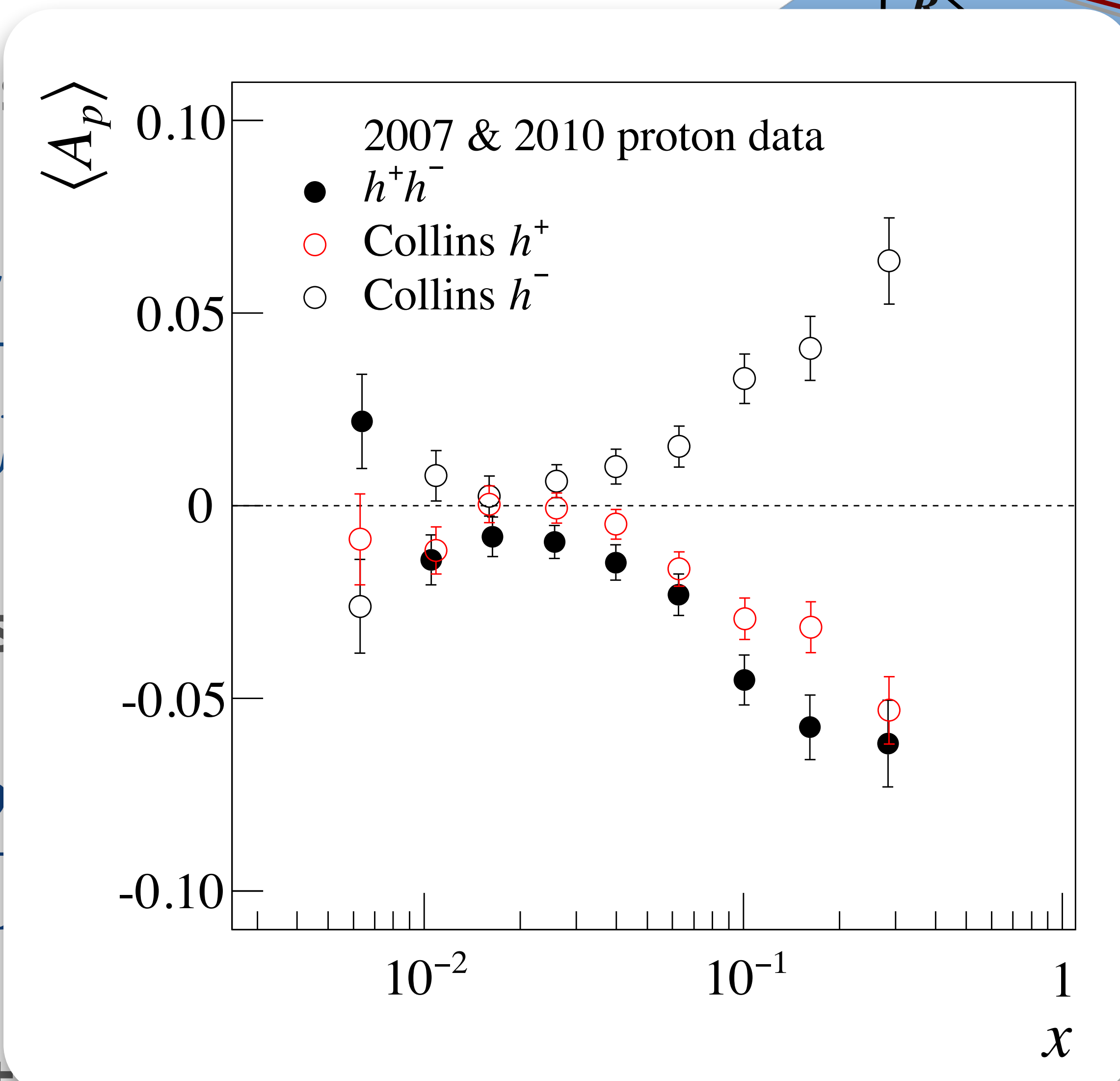
✦ Collins single spin a

$$A_{Coll} = \frac{\sum_q e_q^2\ h}{\sum_q e_q^2\ j}$$

✦ Two hadron single s

$$A_{UT}^{\sin\phi_{RS}} = \frac{|p}{2} \quad M_{h^+h^-}^2, \cos\theta) \quad M_{h^+h^-}^2, \cos\theta)$$

✦ Note the choice of the vector

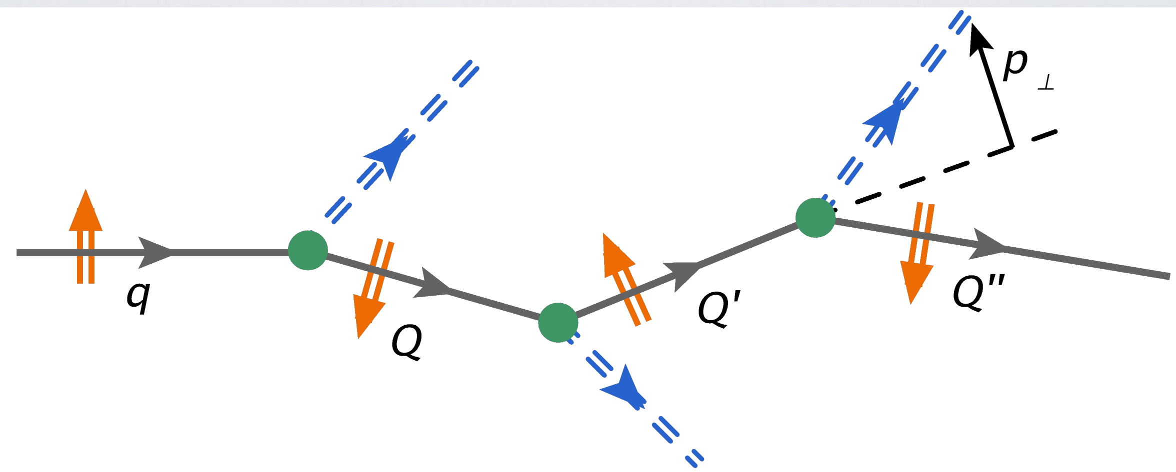


$$\boldsymbol{R}_{Artru} = \frac{z_2\boldsymbol{P}_1 - z_1\boldsymbol{P}_2}{z_1 + z_2}$$

POLARIZED QUARK DIFF IN QUARK-JET.

H.M., Kotzinian, Thomas, PLB731 208-216 (2014).

- **Use the NJL-jet Model including Collins effect (MKII) to study DiFFs.**



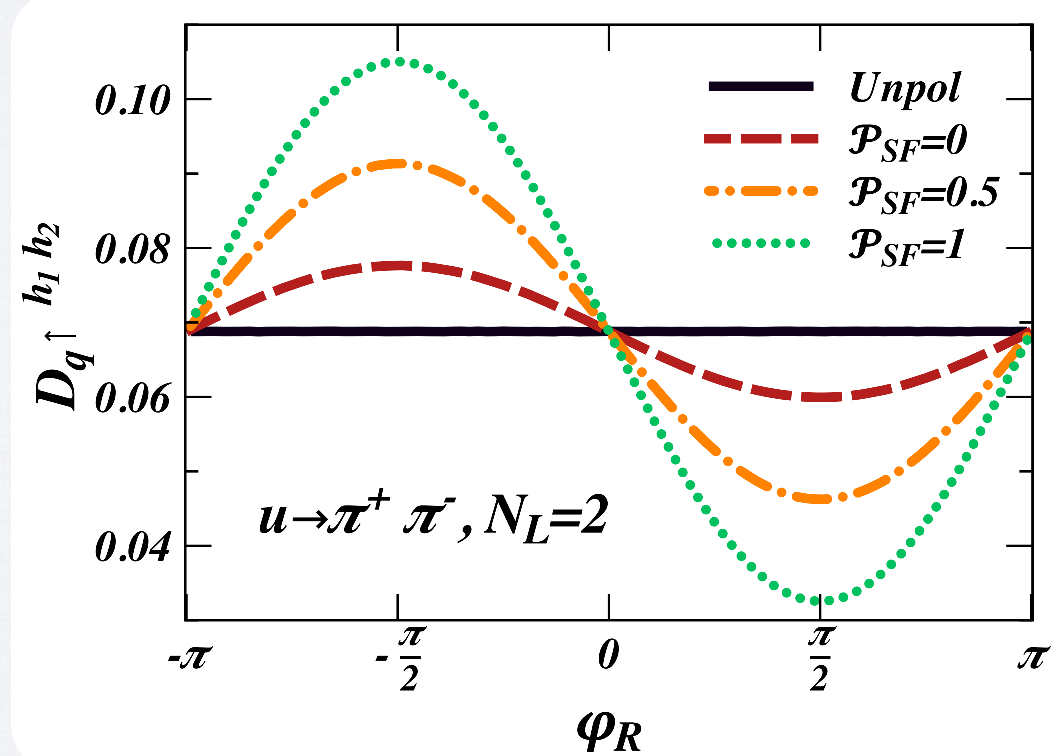
$$D_{q^\uparrow}^{h_1 h_2}(z, M_h^2, \varphi_R)\ \Delta z\ \Delta M_h^2\ \Delta\varphi_R = \left\langle N_{q^\uparrow}^{h_1 h_2}(z, z+\Delta z; M_h^2, M_h^2+\Delta M_h^2; \varphi_R, \varphi_R+\Delta\varphi_R)\right\rangle .$$

- ***Choose a constant Spin flip probability:*** $\mathcal{P}_{SF}$

- ***Simple model to start with:***

  Only pions and extreme ansatz for the Collins term in elementary function.

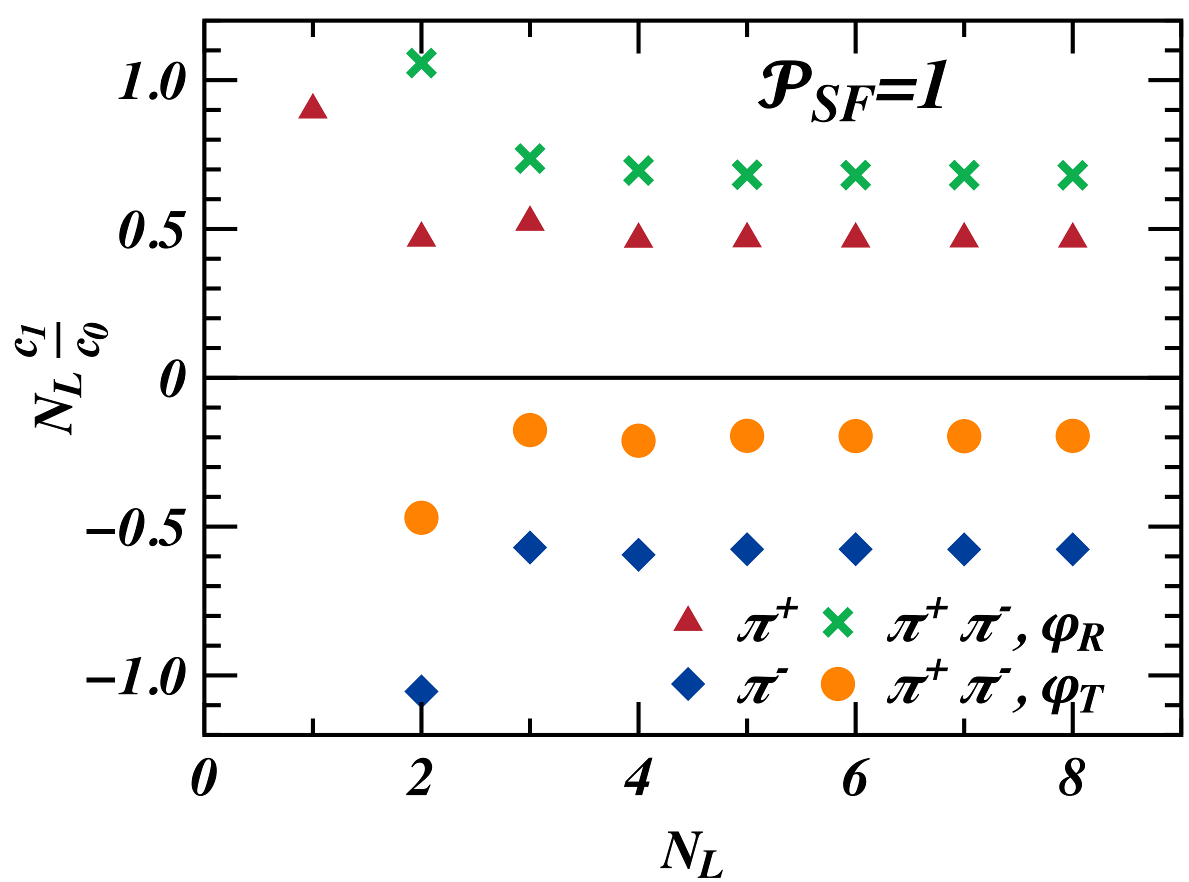
$$d_{h/q^\uparrow}(z, \mathbf{p}_\perp) = d_1^{h/q}(z, p_\perp^2)(1 - 0.9\sin\varphi)$$

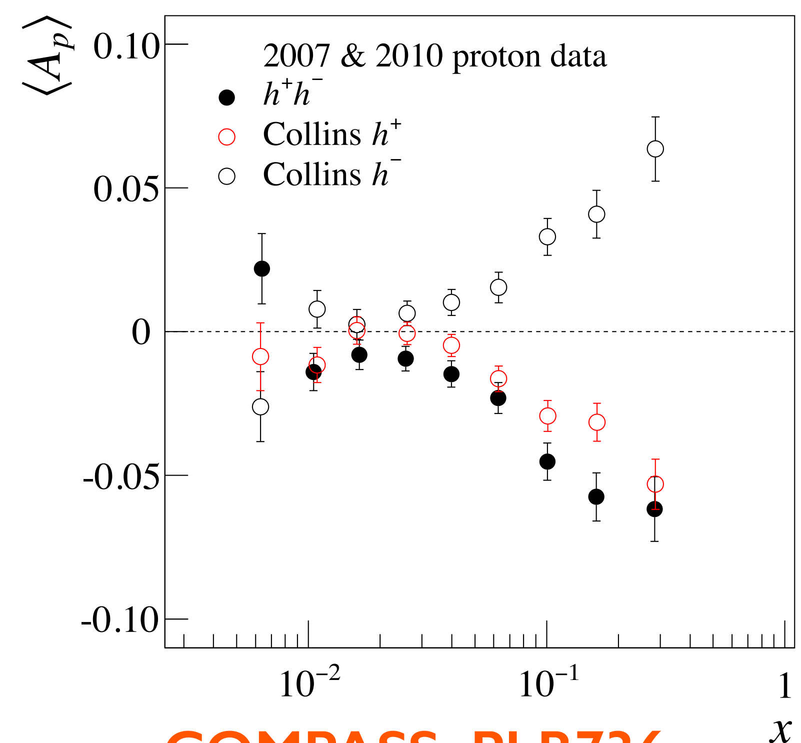


INTEGRATED ANALYZING POWERS

H.M., Kotzinian, Thomas, PLB731 208-216 (2014).

$z_{1,2} > 0.2, z > 0.2$



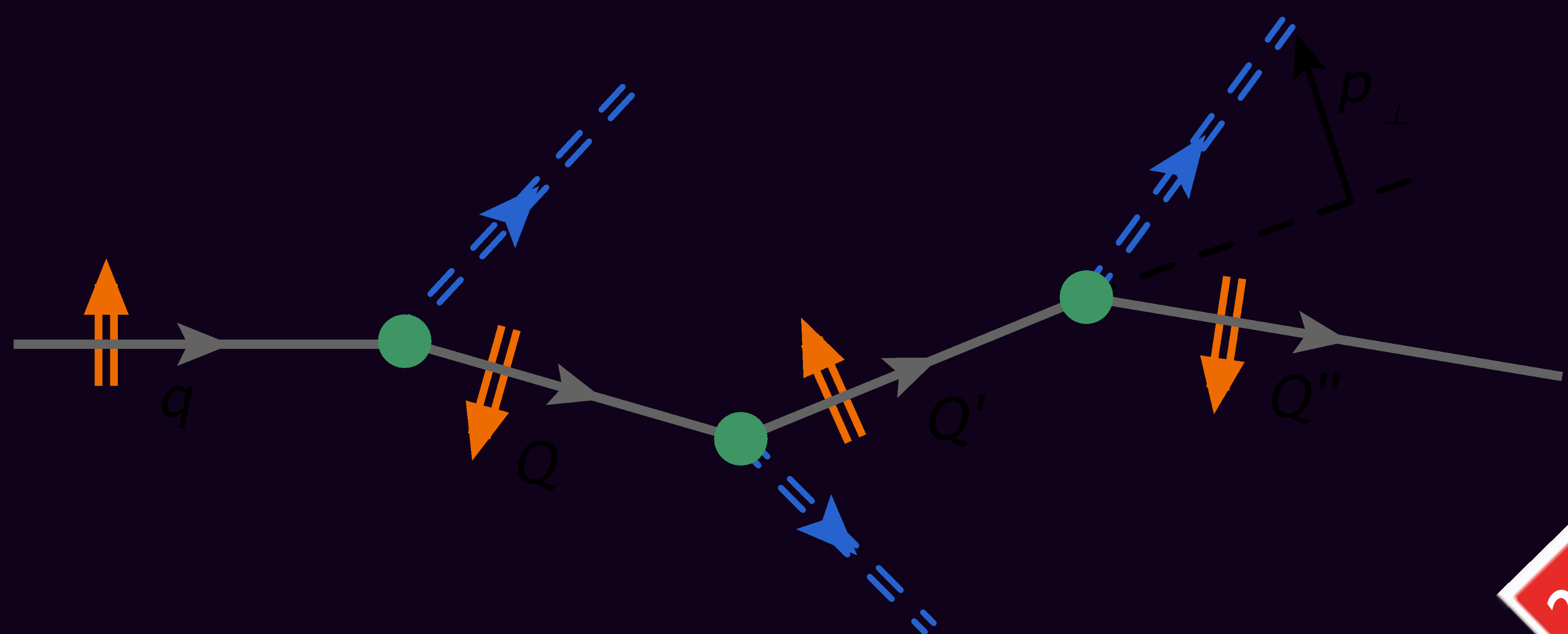


COMPASS: PLB736, 124-131 (2014).

✓ ***NJL-jet** model results are **consistent** with **COMPASS** measurements on interplay between one- and two- hadron SSAs.*

NJL-jet MKIII

New Developments



27.3% Extra Free!

What's Inside the Green BoX?

✦ TMD Polarized Fragmentation Functions at LO.

- *Only* ***two*** *for unpolarised final state hadrons.*

PDFs

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

Fragment. Functions

h/q	U	L	T
U	D_1		$H_1^\perp$

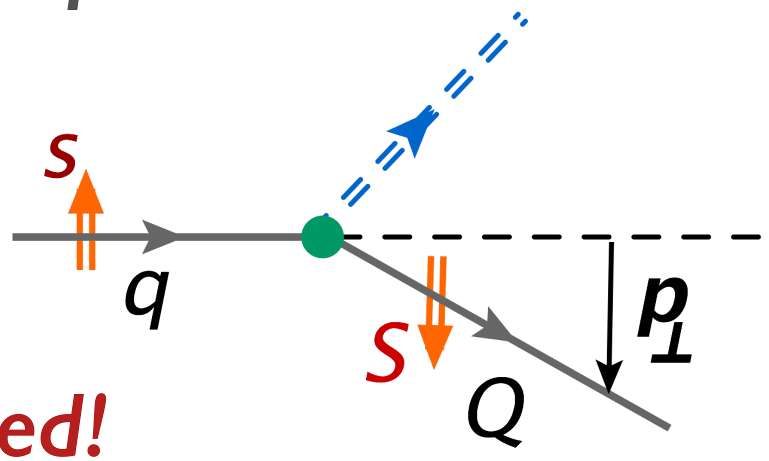
- ***8 for spin 1/2 final state (including quark). Similar to TMD PDFs.***

Spin Transfer in quark-jet Framework.

✦NJL-jet MKIII:

- *The probability for the process* $q \to Q$, *initial spin* $\mathbf{s}$ *to* $\mathbf{S}$

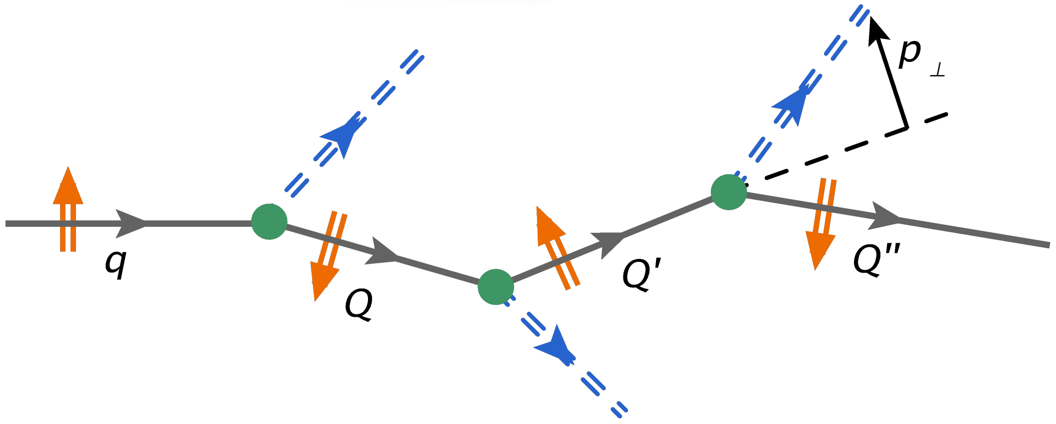
$$F^{q\to Q}(z, \mathbf{p}_\perp; \mathbf{s}, \mathbf{S}) = \alpha_s + \beta_\mathbf{s} \cdot \mathbf{S}$$



- ***Intermediate** quarks in quark-jet are **unobserved!***

Berestetskii, E. M. Lifshitz, and L. P. Pitaevskii: **QUANTUM ELECTRODYNAMICS (1982).**

$$\mathbf{S}_{unob} = \frac{\beta_\mathbf{s}}{\alpha_\mathbf{s}}$$



- *Remnant quark's **S uniquely determined by** $z, \mathbf{p}_\perp$ **and** $\mathbf{s}$ **!***

- *Process probability is **the same** as transition to **unpolarized state.***

$$F^{q\to Q}(z, \mathbf{p}_\perp; \mathbf{s}, \mathbf{0}) = \alpha_s$$

Example: Pion production.

Fragment. Functions

$$F^{q\to Q}(z,\boldsymbol{p}_\perp;\boldsymbol{s},\boldsymbol{S})$$

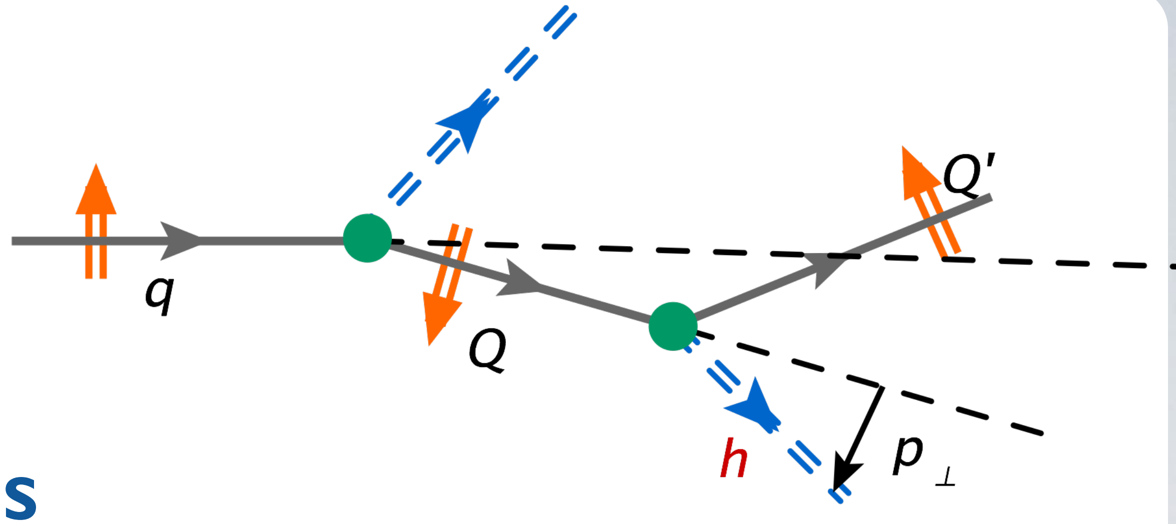
Q/q	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	$H_{1T} H_{1T}^\perp$

$$F^{q\to\pi}(z,\boldsymbol{p}_\perp;\boldsymbol{s})$$

π/q	U	L	T
U	D_1		$H_1^\perp$

Example: Pion prod. up to Rank 2

✦ **Only consider pion produced in the first two emission steps!**



✦ **Then the polarised number density is**

1st rank — 2nd rank

$$F^{(2)q\to\pi} = f^{q\to\pi} + f^{q\to Q} \otimes f^{Q\to\pi}$$

✦ **"Elementary" number densities:** *only favoured types are non-zero.*

$$f^{q\to\pi} = d^{q\to\pi} - \frac{p_\perp}{zM_h} s_T h_1^{\perp q\to\pi}$$

$$f^{u\to\pi^-} = 0$$

✦ *It is shown <u>analytically</u> that only Collins modulations appear!*

$$F^{(2)q\to\pi}(z, p_\perp^2, \varphi_C) = F_0^{(2)}(z, p_\perp^2) - \sin(\varphi_C) F_1^{(2)}(z, p_\perp^2)$$

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$$F^{(2)q\to\pi}(z,p_\perp^2,\varphi_C) = F_0^{(2)}(z,p_\perp^2) - \sin(\varphi_C)F_1^{(2)}(z,p_\perp^2)$$

✦ ***Up to <u>unspecified</u> coefficients, using.***

<u>Unpolarised term:</u>

From TM-induced Spin of intermediate quark

$$F_0^{(2)q\to\pi} = d^{q\to\pi} + (d^{q\to Q}\otimes d^{Q\to\pi} + d_T^{\perp q\to Q}\otimes h^{\perp Q\to\pi})$$

<u>Collins term:</u>

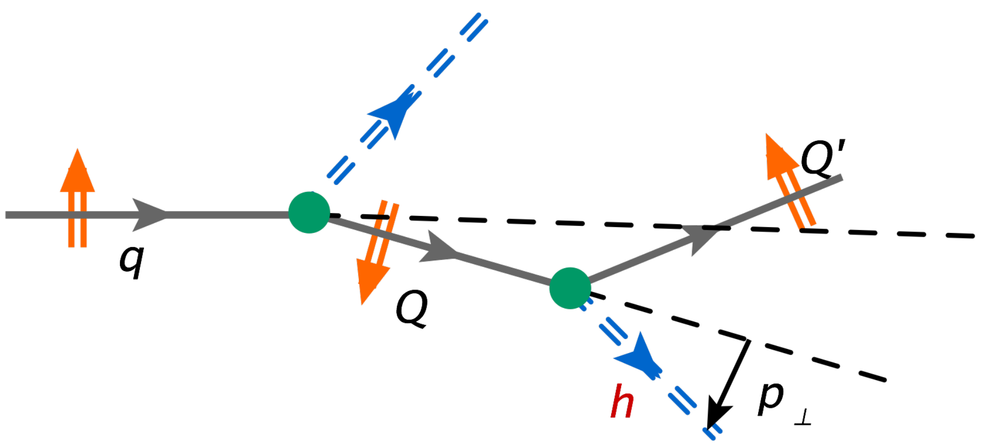
"Recoil" TM contribution

$$F_1^{(2)q\to\pi} \sim h^{\perp q\to\pi} + [h^{\perp q\to Q}\otimes d^{Q\to\pi} + (h_T^{q\to Q} + h_T^{\perp q\to Q})\otimes h^{\perp Q\to\pi}]$$

Transferred Spin of intermediate quark

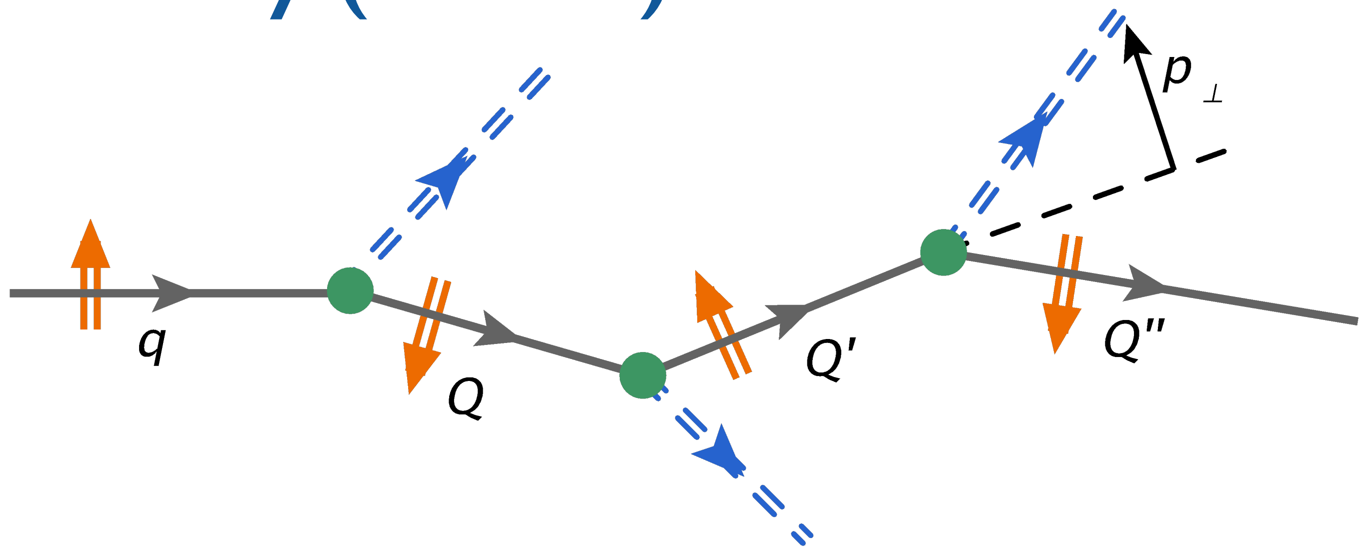
✦ ***Reminder***

Q/q	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	$H_{1T} H_{1T}^\perp$



Full Hadronization

✦ We can consider many (infinite) number of emissions.



✦ Then the polarised number density is

$$F^{q\to h} = f^{q\to h} + f^{q\to Q} \otimes F^{Q\to h}$$

✦ *Again, only Collins modulations appear for unpolarised h!*

$$F^{q\to h}(z, p_\perp^2, \varphi_C) = F_0(z, p_\perp^2) - \sin(\varphi_C) F_1(z, p_\perp^2)$$

✦ Also applicable for *polarised* hadron production.

✦ We can also employ *MC approach*.

✦ We only need the "elementary" splittings.

$$f^{q\to h} \qquad\qquad f^{q\to Q}$$

Conclusions

- ❖ Polarised TMD FFs provide a wealth of information about the *spin-spin* and *spin-momentum* correlations in hadronisation.
- ❖ Modelling Polarised Quark Hadronization is needed for both calculations of polarised FFs and phenomenological studies of various correlations (Collins and IFF, etc).
- ❖ Incorporating polarised parton hadronisation into *MC generators* is needed for *supporting future experiments* in mapping out the 3D structure of nucleon (*JLab12, BELLE II, EIC*).
- ❖ The *NJL-jet* model provides a robust and extendable framework for *microscopic* description of various fragmentation phenomena using MC simulations: *TMD, Collins, DiHadron*.
- ❖ The extension of the underlying *quark-jet* mechanism to include polarisation can be readily incorporated in other MC frameworks.


Thanks!
Photo by Jun Zhang