Anomaly in pion-induced Drell-Yan processes

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Outlines

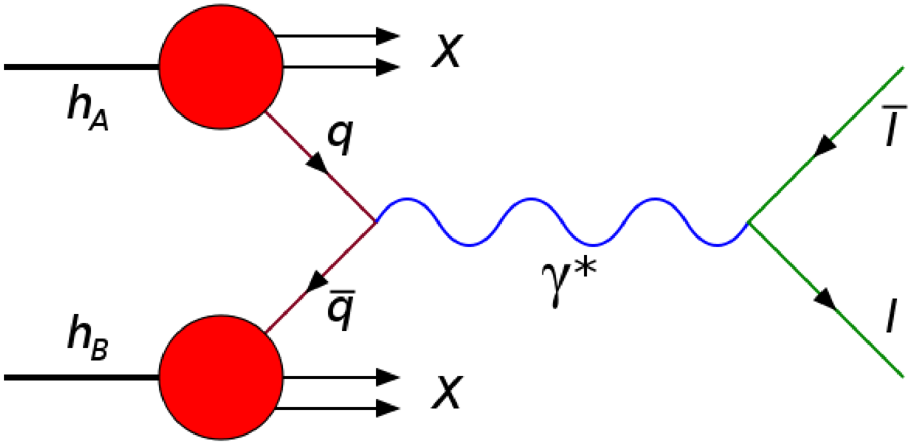
- Introduction
- Violation of Lam-Tung relation
- Resolutions in the literature
- More relevant observations
- Pion-induced Drell-Yan processes
- Summary

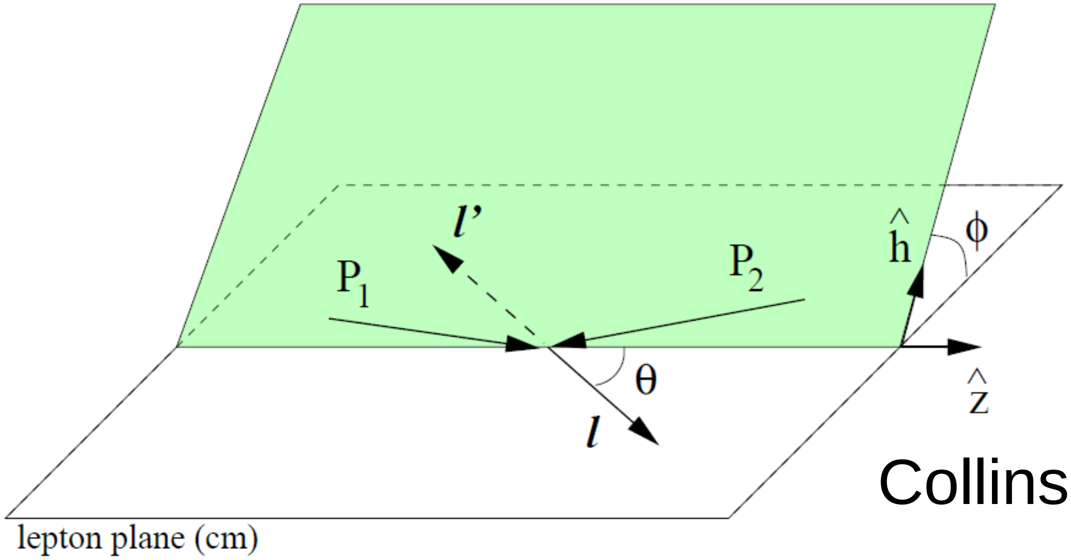
Introduction

- Drell-Yan is one of most intensively studied processes in QCD
- Data have been used to extract various PDF, TMD (unpolarized and polarized)
- But anomaly still exists since 80’s:
- Lam-Tung relation, supposed to be obeyed by lepton angular distributions, is violated in pion-induced Drell-Yan

Violation of Lam-Tung relation

Lepton pair angular distribution





Collins-Soper Frame

Lam-Tung Relation

$$\frac{d\sigma}{d\Omega} \propto [W_T(1+\cos^2\theta) + W_L(1-\cos^2\theta) + W_\Delta \sin 2\theta \cos\phi + W_{\Delta\Delta} \sin^2\theta \cos 2\phi]$$

$$\frac{d\sigma}{d\Omega} \propto (1+\lambda\cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi)$$

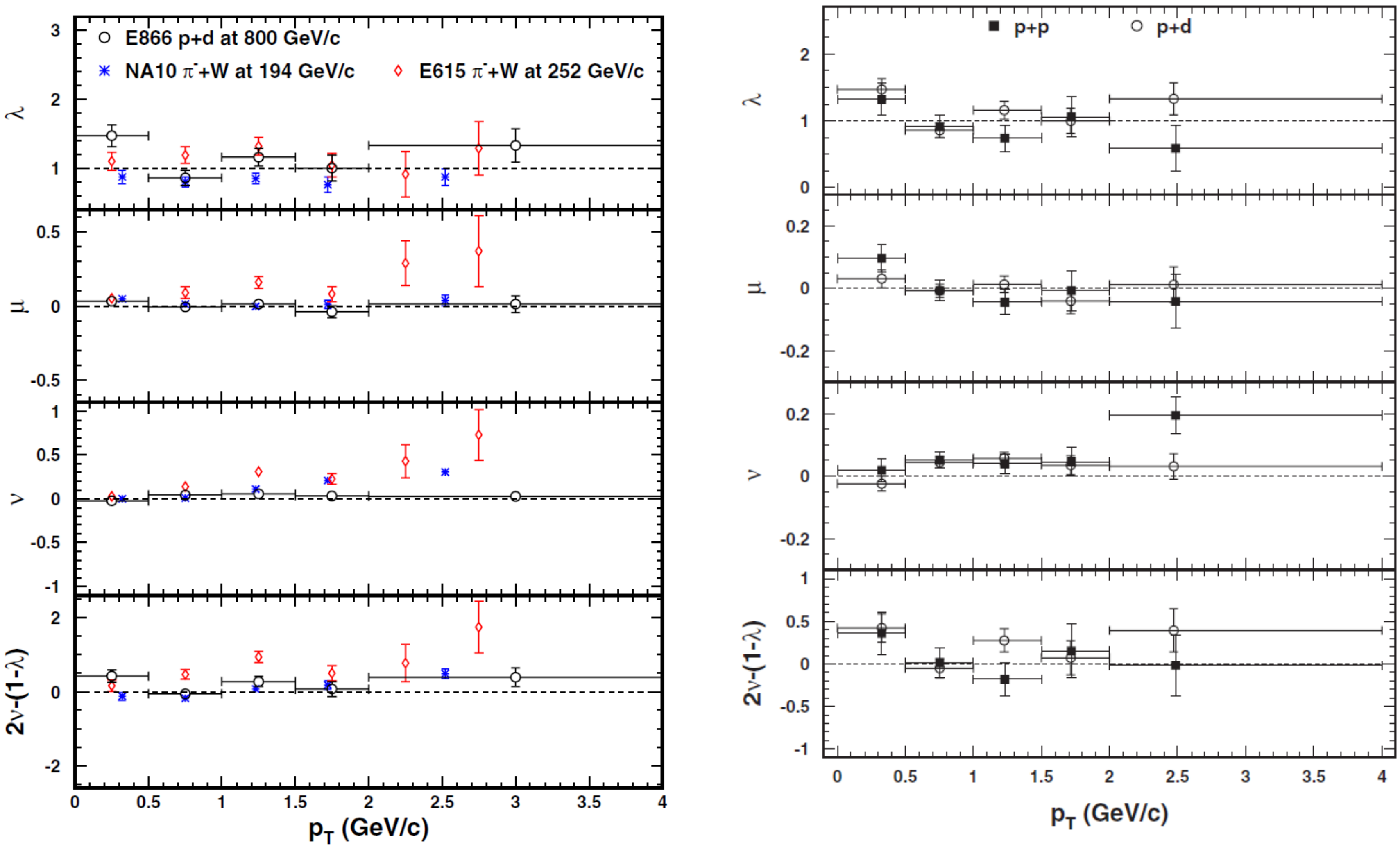
$q\bar{q}$ annilation parton model:

$\mathrm{O}(\alpha_s^0)$ λ=1, $\mu=\nu$=0; $\mathrm{W}_T = 1, \mathrm{W}_L = 0$

pQCD: $\mathrm{O}(\alpha_s^1), W_L = 2W_{\Delta\Delta}; 1-\lambda-2\nu=0$

Lam and Tung (PRD 18, 2447, 1978)

LT relation holds in pp, pd DY



E866 (PRL 99, 082301, 2007; PRL 102, 182001, 2009)

Pion-induced DY

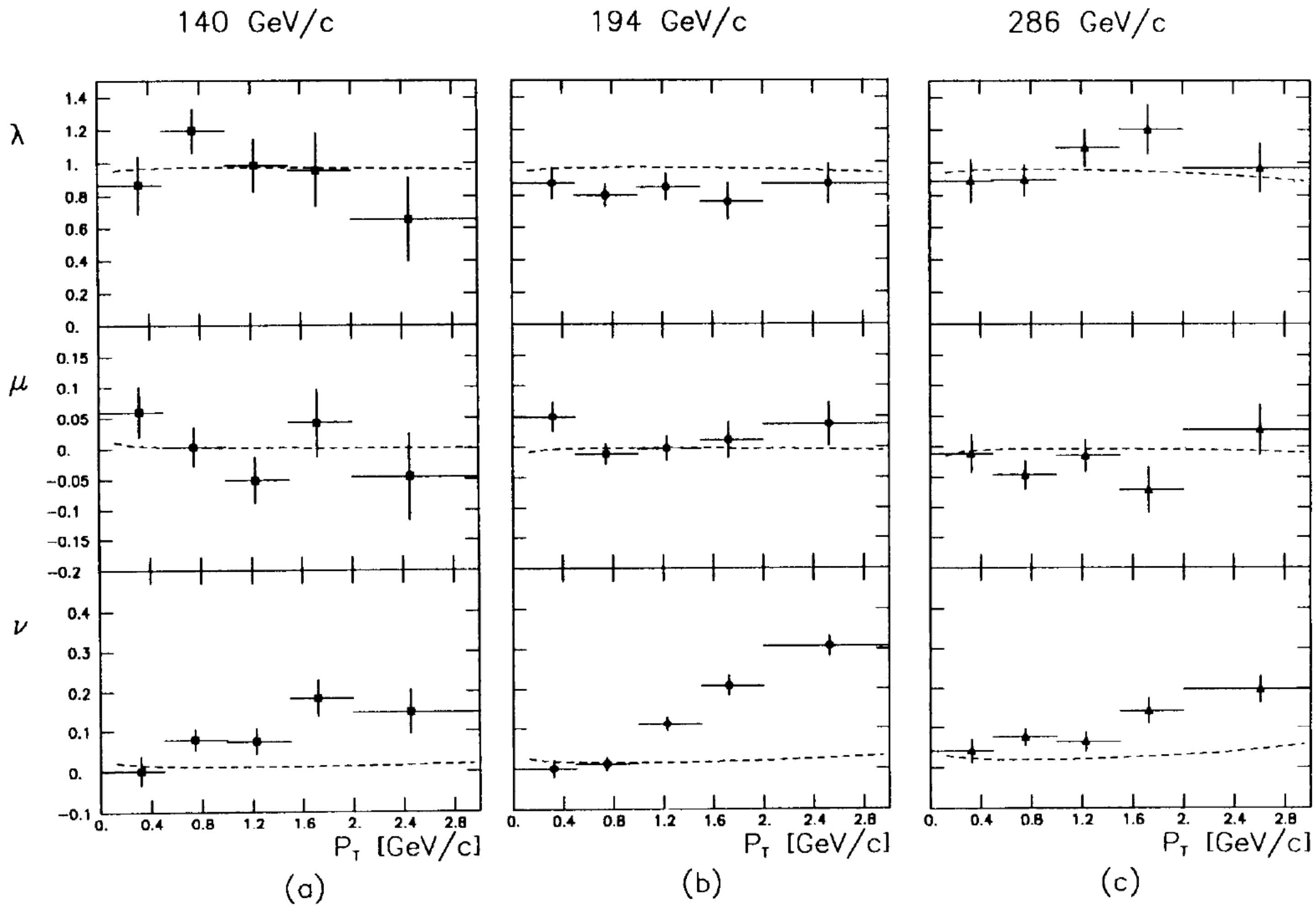
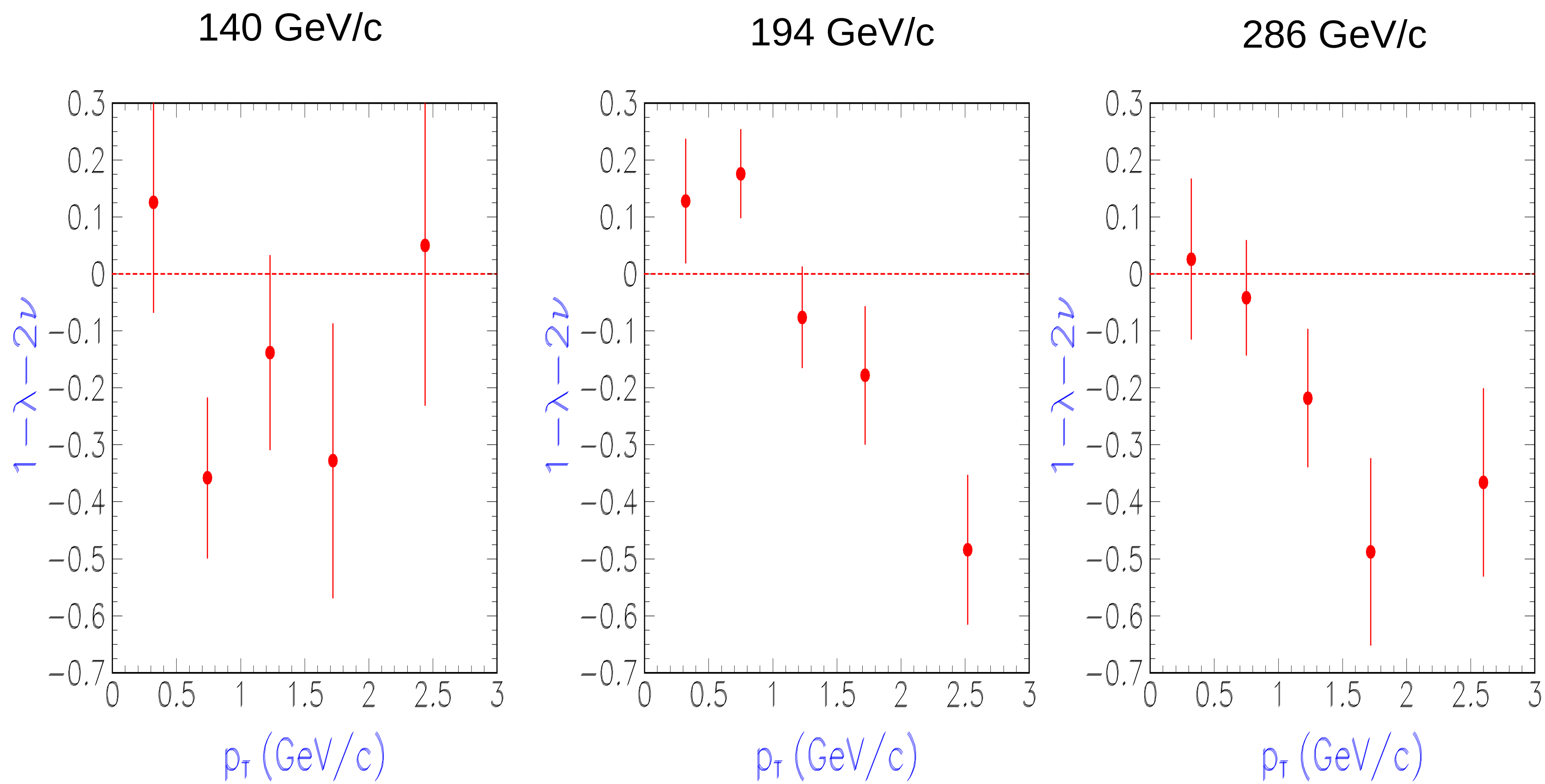


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. **a** 140 GeV/c; **b** 194 GeV/c; **c** 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

NA10 (Z. Phys. C 37, 545,1988)

------- pQCD

LT violation in pion-induced DY



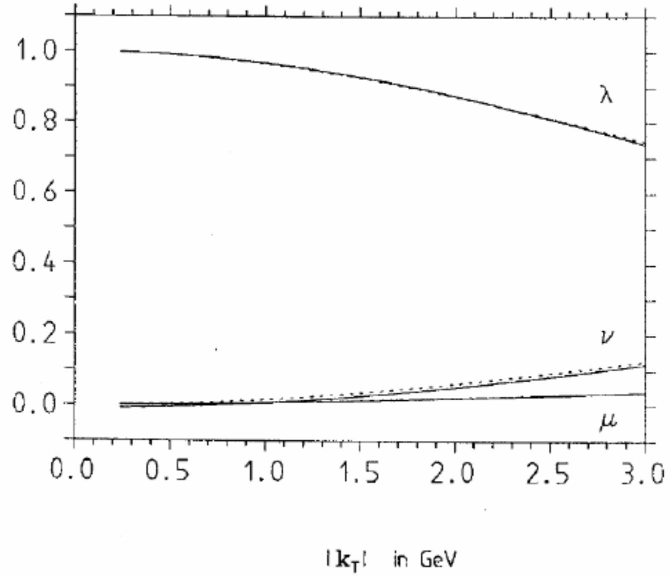
NA10 (Z. Phys. C 37, 545,1988)

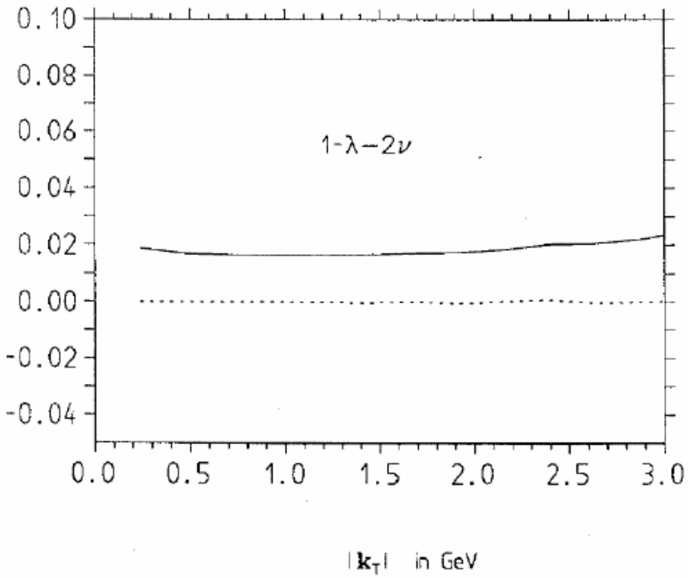
Resolutions in the literature

Vacuum effect;

Boer-Mulders function

Angular asymmetries in Drell-Yan in theory





Dashed lines: $\mathcal{O}(\alpha_s)$; Solid lines: $\mathcal{O}(\alpha_s^2)$; $Q = 8$ GeV

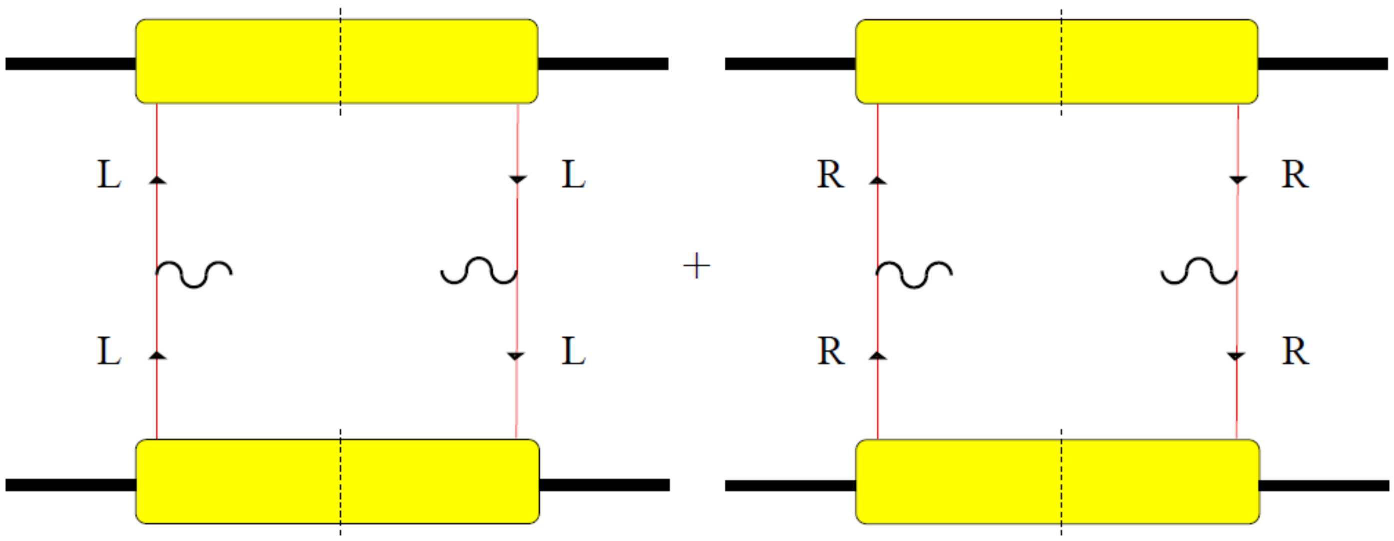
Brandenburg, Nachtmann & Mirkes, ZPC 60 (1993) 697

need nonperturbative dynamics

Collinear factorization

Collinear quarks ($p_{\text{quark}} = xP_{\text{hadron}}$) inside unpolarized hadrons are unpolarized too

$$\rho^{(q,\bar{q})} = \frac{1}{4}\{\mathbf{1} \otimes \mathbf{1}\}$$



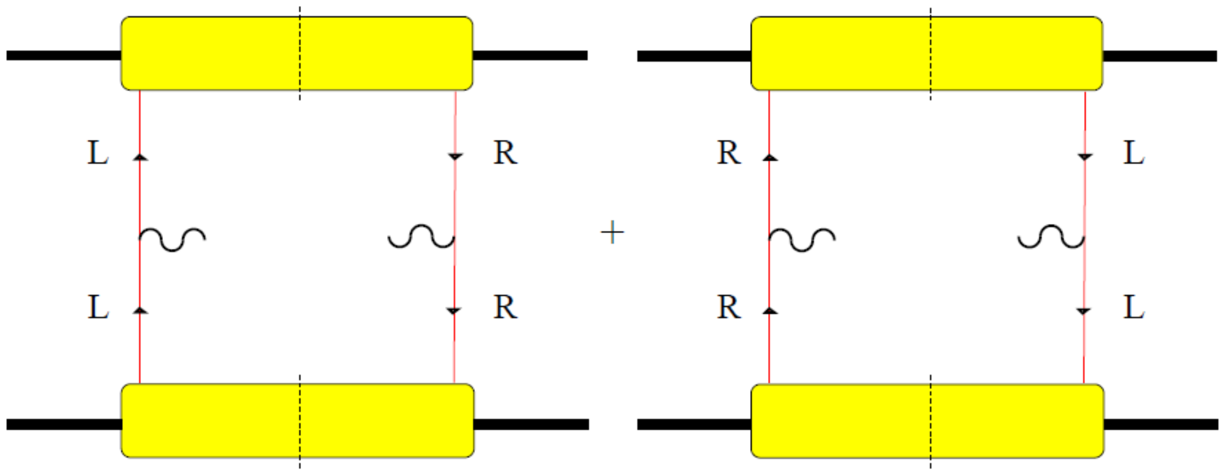
transversely polarized photon, structure W_T only

D. Boer

Angular asymmetry requires helicity flip

The $\cos 2\phi$ asymmetry arises from an interference between $+1$ and -1 photon helicities

$\nu \neq 0$



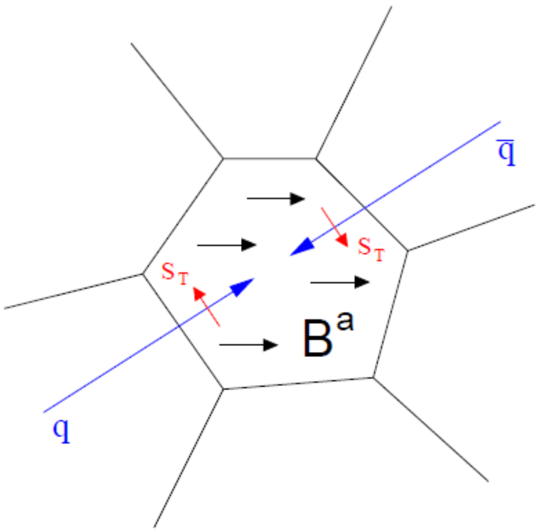
$$|S_x = +1/2\rangle \propto |S_z = +1/2\rangle + |S_z = -1/2\rangle$$

This requires transversely polarized quark-antiquark annihilation

then parton transverse d.o.f comes in to play
sine term appears, which breaks LT relation

D. Boer

Explanation as a QCD vacuum effect



The QCD vacuum can induce a spin correlation between an annihilating $q\,\bar{q}$

Chromo-magnetic Sokolov-Ternov effect: spin-flip gluon synchrotron emission leading to a correlated polarization of q and qbar.

The spin density matrix becomes:

$$\rho^{(q,\bar{q})} = \frac{1}{4}\{\mathbf{1}\otimes\mathbf{1} + F_j\,\boldsymbol{\sigma}_j\otimes\mathbf{1} + G_j\,\mathbf{1}\otimes\boldsymbol{\sigma}_j + H_{ij}\,\boldsymbol{\sigma}_i\otimes\boldsymbol{\sigma}_j\}$$

Lam-Tung relation could be violated

$$1-\lambda-2\nu = -4\kappa = -4\frac{H_{22}-H_{11}}{1+H_{33}}$$

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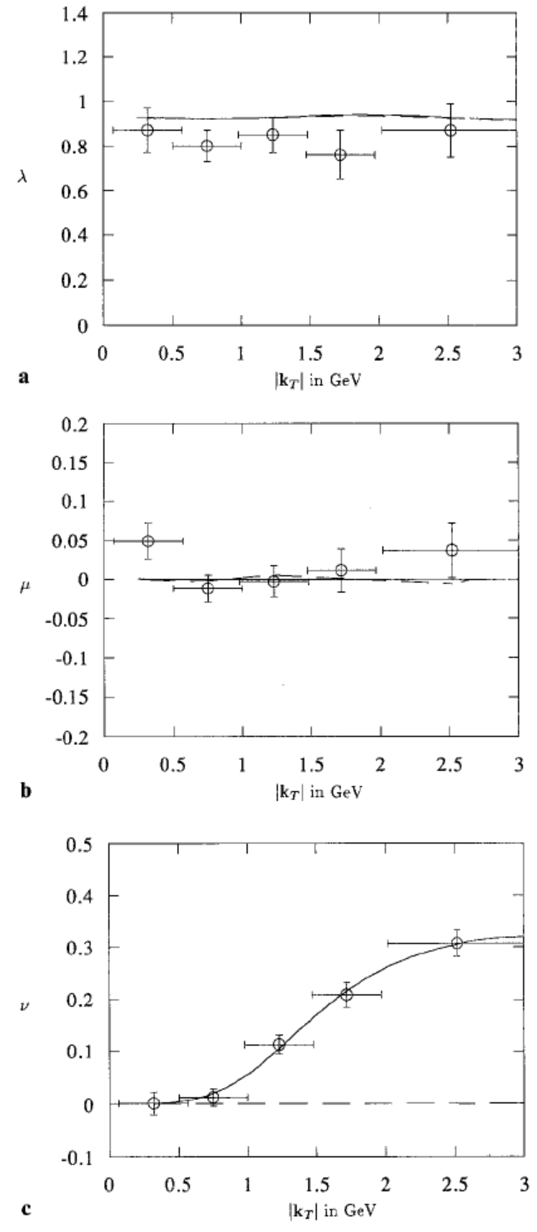
Resolution via vacuum Effect

parameterize the effect and fit to data

$$\kappa = \kappa_0 \frac{|q_T|^4}{|q_T|^4 + m_T^4},$$

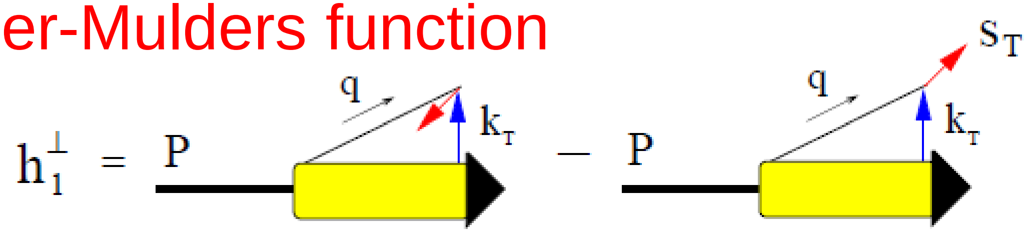
$$\kappa_0 = 0.17, m_T = 1.5 GeV$$

Brandenburg, et. al
(Z. Phy. C60,697, 1993)



Resolution via BM Effect

Boer-Mulders function

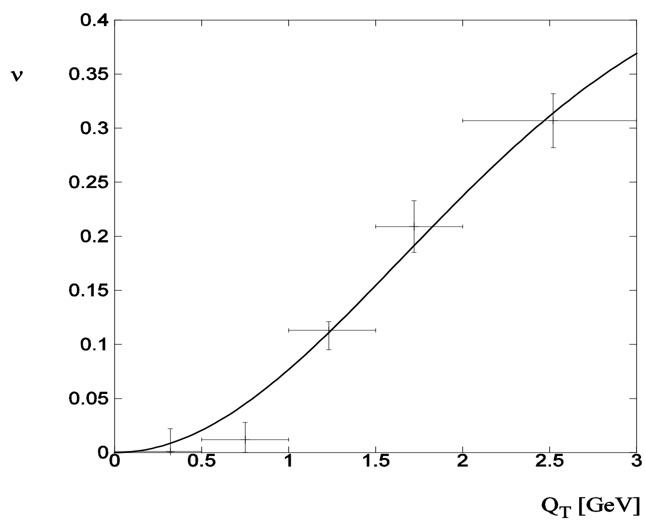


$$\propto \frac{k_T}{M}$$

hadron mass

- $h_1^\perp$ represents a correlation between quark's k_T and transverse spin in an unpolarized hadron

- $h_1^\perp$ can lead to an azimuthal dependence with $\frac{\nu}{2} \propto h_1^\perp(N)\overline{h}_1^\perp(\pi)$



$$h_1^\perp(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x),$$

$$\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2}, \qquad \kappa_1 = C_{H_1} C_{H_2}/2$$

$$\kappa = \frac{\nu}{2} \to 0 \text{ for large } |k_T|$$

Consistency of factorization in term of TMDs

Boer (PRD 60, 014012, 1999)

Remarks

- Vacuum effect is flavor blind, how to differentiate pion-proton and proton-proton DY? The pp DY obeys LT relation.
- BM can explain pp DY by arguing that sea quark is involved, and sea quark BM function is small

More relevant observations

Clue 1:
k_T factorization

k_T factorization

- Collinear and k_T factorizations are fundamental tools in PQCD
- k_T factorization applies to small x (high energy), to final-state spectra at low q_T, to exclusive process with end-point singularity (heavy-quark decays) $xP^+ \approx k_T$, $q_T \approx k_T$
- Keep parton k_T in hard kernel, and k_T is not integrated out in PDF-> TMD
- k_T factorization appropriate for studying low q_T spectra in Drell-Yan processes

Clue 2:
k_T factorization breakdown

Collins, Qiu 07

Vogelsang, Yuan 07

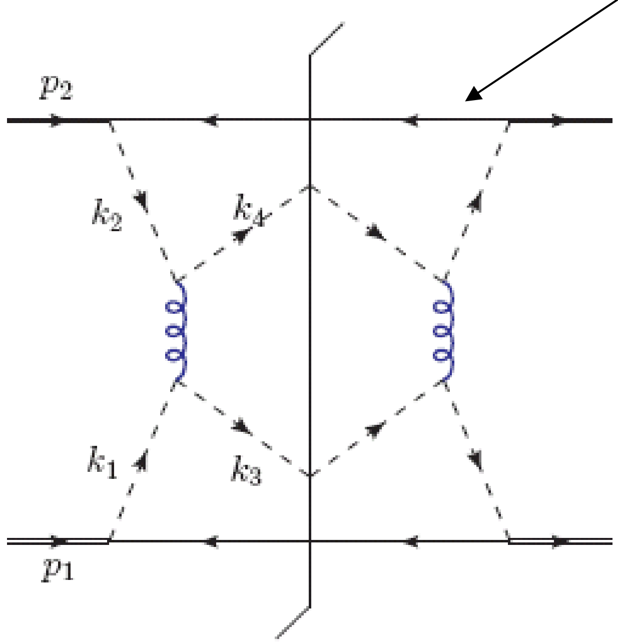
Collins 0708.4410

Hadron hadroproduction

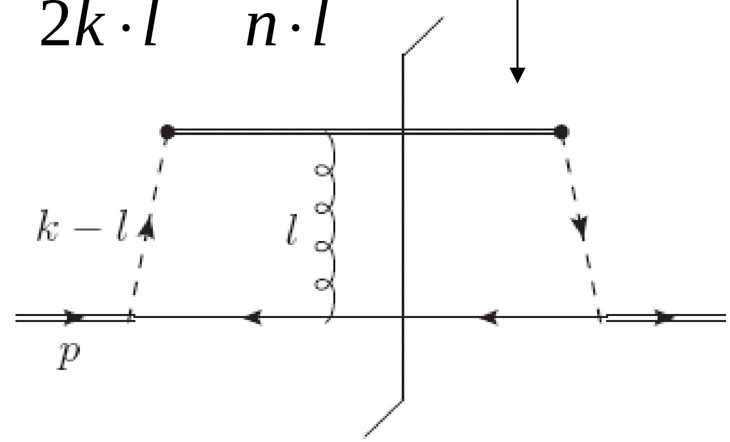
- k_T factorization holds for simple processes like DIS, but breaks down for complicated ones like hadron production $H_1(p_1) + H_2(p_2) \to H_3(p_3) + H_4(p_4) + X$
- Can lower TMD be factorized from the full process?

for illustration,
consider scalar particles

eikonal line
from collinear
approximation

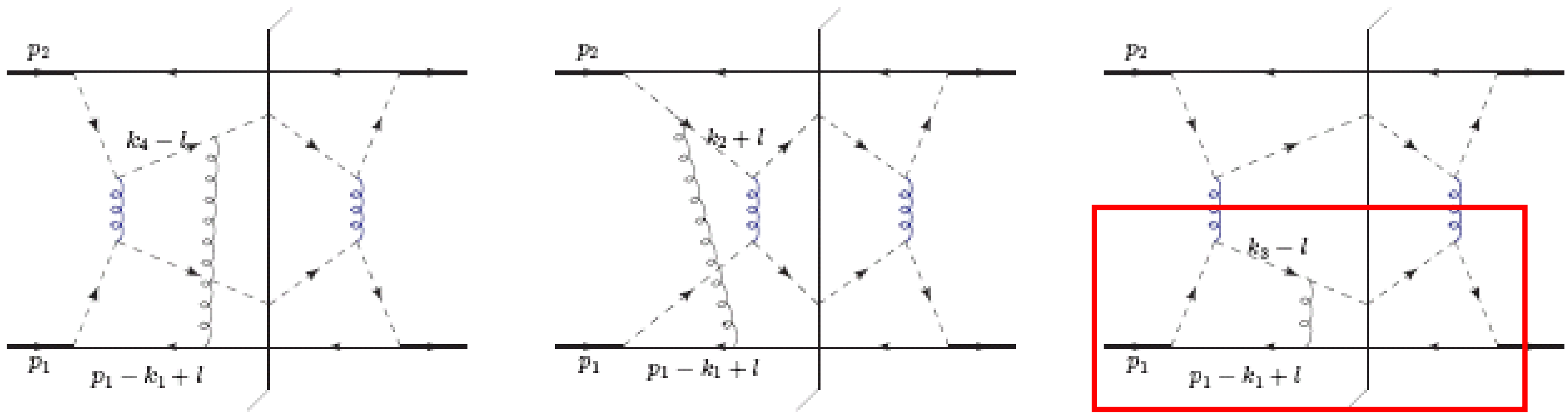


$$\frac{2k^\mu}{(k+l)^2} \approx \frac{2k^\mu}{2k \cdot l} = \frac{n^\mu}{n \cdot l}$$



NLO factorization

- The first two diagrams do not contribute to lower TMD, k_T factorization holds at NLO



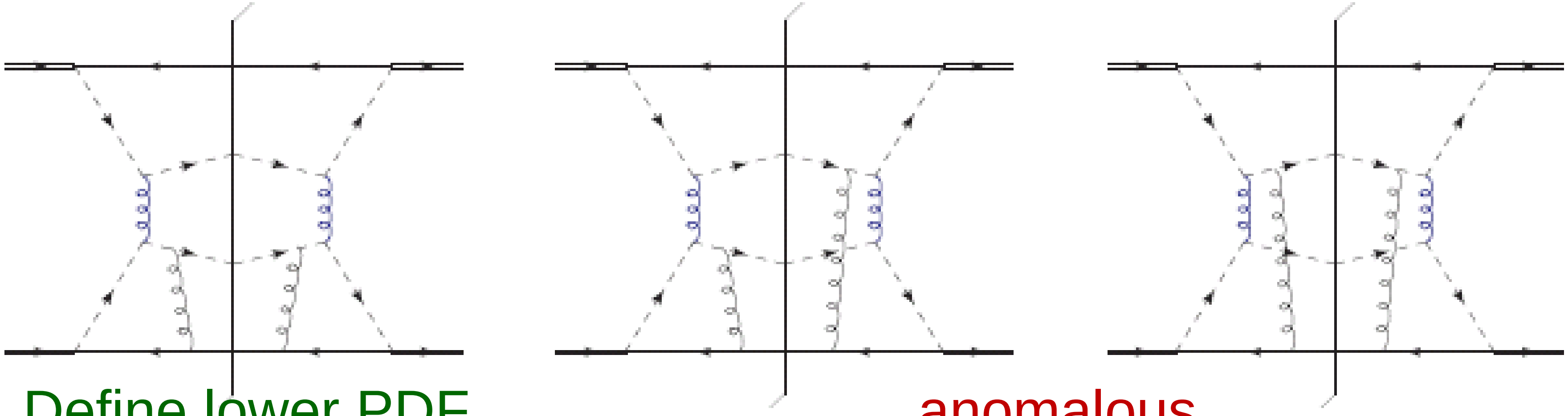
label upper coupling by g_2

$$E(l) = \frac{g_2}{l^+ + i\epsilon} + \frac{g_2}{-l^+ + i\epsilon} + \frac{g_1}{-l^+ + i\epsilon}$$
$$= -2\pi i g_2 \delta(l^+) + \frac{g_1}{-l^+ + i\epsilon}$$

Canceled by gluons on RHS. Cross section must be real.

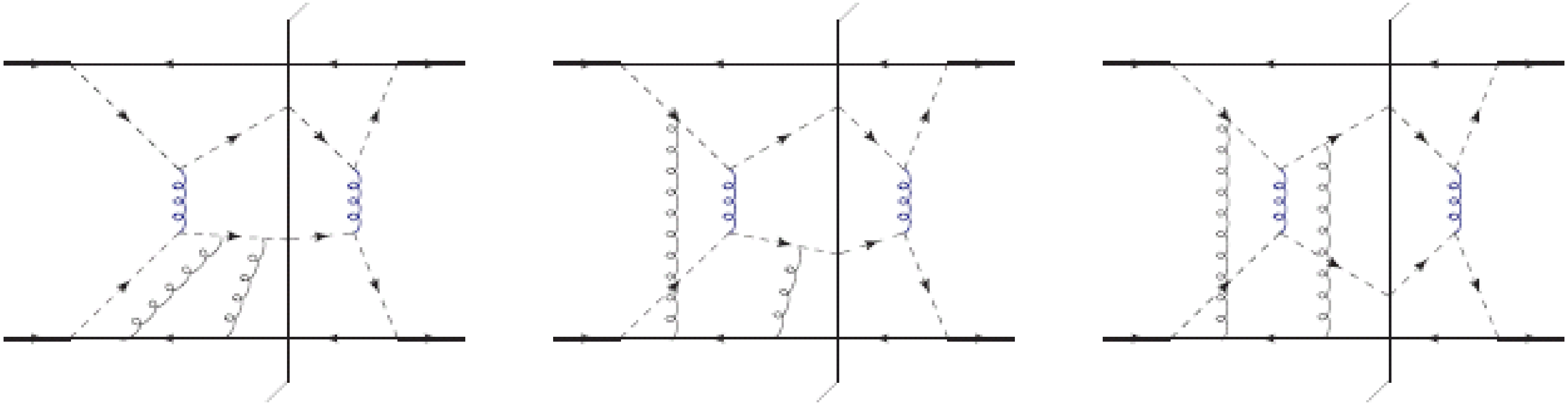
No cancellation at NNLO

- Two gluons on opposite sides

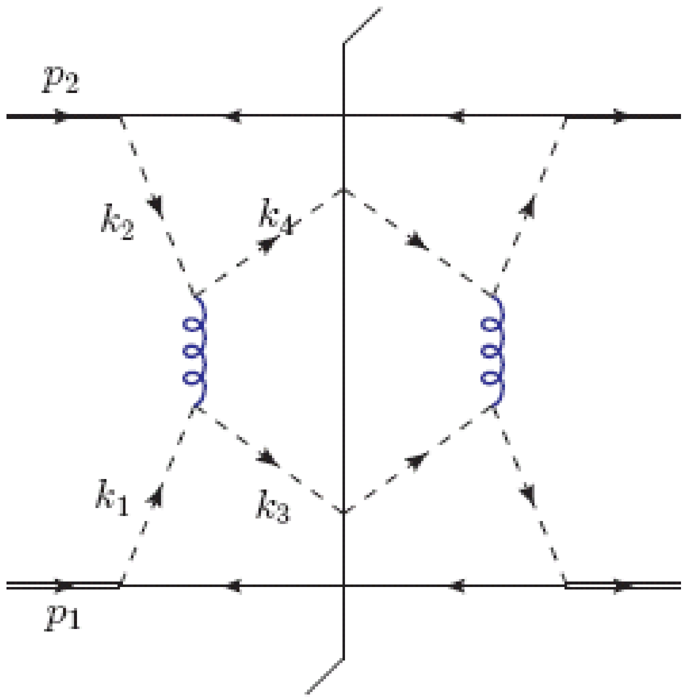


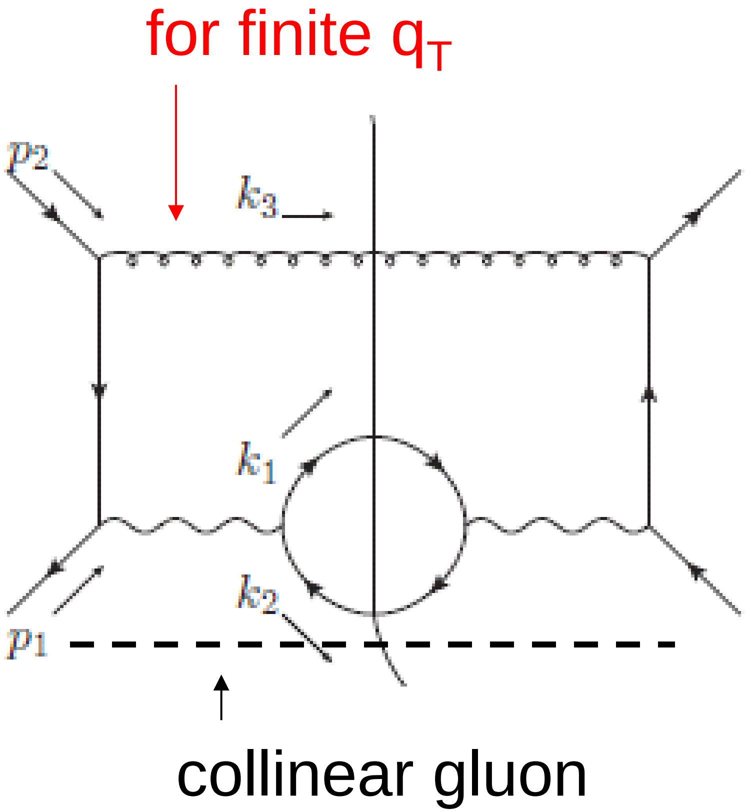
Define lower PDF anomalous

- Two gluons on the same side



Glauber gluons in Drell-Yan





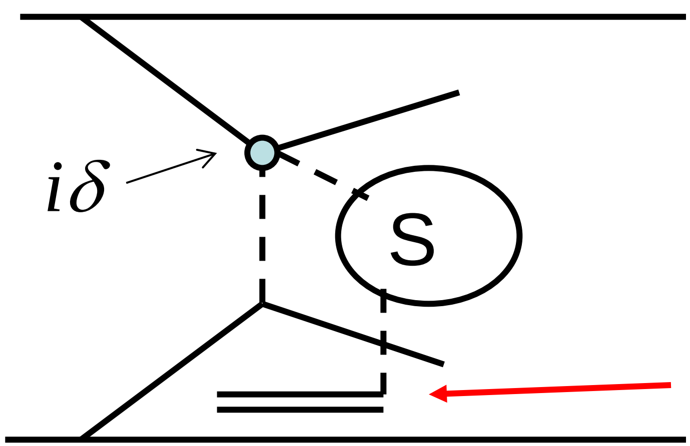
- k_T factorization broken by Glauber gluons in processes involving at least 3 hadrons

Clue 3:
Glauber phase at low q_T

Glauber-gluon factorization

- Eikonal approximation holds at low q_T
- Glauber gluons factorize

one loop~ $i\int\frac{d^2 l_T}{l_T^2}$



all orders~ $\exp(iS_e)$
Se: Glauber phase

Eikonal line

- TMD maintains its universality

Chang, Li 2011

- Generalized k_T factorization applies to Drell-Yan at low q_T

Clue 4:
Other pion-involved puzzles

Puzzles in B decays

- $B(\pi^0\pi^0), B(\pi^0\rho^0)$ much larger than predictions

data [theory]

$$
\begin{aligned}
B(\pi^0\pi^0) &= 1.55 \pm 0.19, \quad [(0.29^{+0.50}_{-0.20})] \\
B(\pi^0\rho^0) &= 2.0 \pm 0.5, \quad [\approx 0.7] \\
B(\rho^0\rho^0) &= 0.74^{+0.30}_{-0.27}, \quad [(0.92^{+1.10}_{-0.56})],
\end{aligned}
$$

~1.91 X 10E-6

- $A_{CP}(\pi^0 K^\pm)$ much different from $A_{CP}(\pi^\mp K^\pm)$
- New physics or QCD effect?
- If new physics, how about $B(\pi^0\pi^0), B(\pi^0\rho^0)$
- If QCD, but $B(\rho^0\rho^0)$ is normal

Puzzles in D decays

	Mode	Representation quark amplitudes	$\mathcal{B}_{\rm exp}$ $(\times 10^{-3})$	$\mathcal{B}_{\rm theory}$ $(\times 10^{-3})$
D^0	$\pi^+\pi^-$	$\lambda_p[(T+E)\delta_{pd}+P^p+PE+PA]$	1.400 ± 0.026	2.24 ± 0.10
	$\pi^0\pi^0$	$\frac{1}{\sqrt{2}}\lambda_p[(-C+E)\delta_{pd}+P^p+PE+PA)]$	0.80 ± 0.05	1.35 ± 0.05
	$\pi^0\eta$	$\lambda_p[-E\delta_{pd}\cos\phi - \frac{1}{\sqrt{2}}C\delta_{ps}\sin\phi + (P^p+PE)\cos\phi]$	0.68 ± 0.07	0.75 ± 0.02
	$\pi^0\eta'$	$\lambda_p[-E\delta_{pd}\sin\phi + \frac{1}{\sqrt{2}}C\delta_{ps}\cos\phi + (P^p+PE)\sin\phi]$	0.89 ± 0.14	0.74 ± 0.02
	$\eta\eta$	$\frac{1}{\sqrt{2}}\lambda_p\{[(C+E)\delta_{pd}+P^p+PE+PA]\cos^2\phi$ $+(-\frac{1}{\sqrt{2}}C\sin 2\phi + 2E\sin^2\phi)\delta_{ps}\}$	1.67 ± 0.20	1.44 ± 0.08
	$\eta\eta'$	$\lambda_p\{\frac{1}{2}[(C+E)\delta_{pd}+P^p+PE+PA]\sin 2\phi$ $+(\frac{1}{\sqrt{2}}C\cos 2\phi - E\sin 2\phi)\delta_{ps}\}$	1.05 ± 0.26	1.19 ± 0.07

Note discrepancy in pi pi

Even including symmetry breaking, pi pi puzzle persists.

See C.D. Lu's talk

Cheng, Chiang 2012

Pion hadroproduction

Bylinkin, Rostovtsev 1112.5734

- Charged particle production in hadron collisions at RHIC and LHC
- Spectrum shape parametrization

$$\frac{d\sigma}{P_T dP_T} = A_e \exp\left(-E_{T\,kin}/T_e\right) + \frac{A}{\left(1 + \frac{P_T^2}{T^2 \cdot n}\right)^n}$$

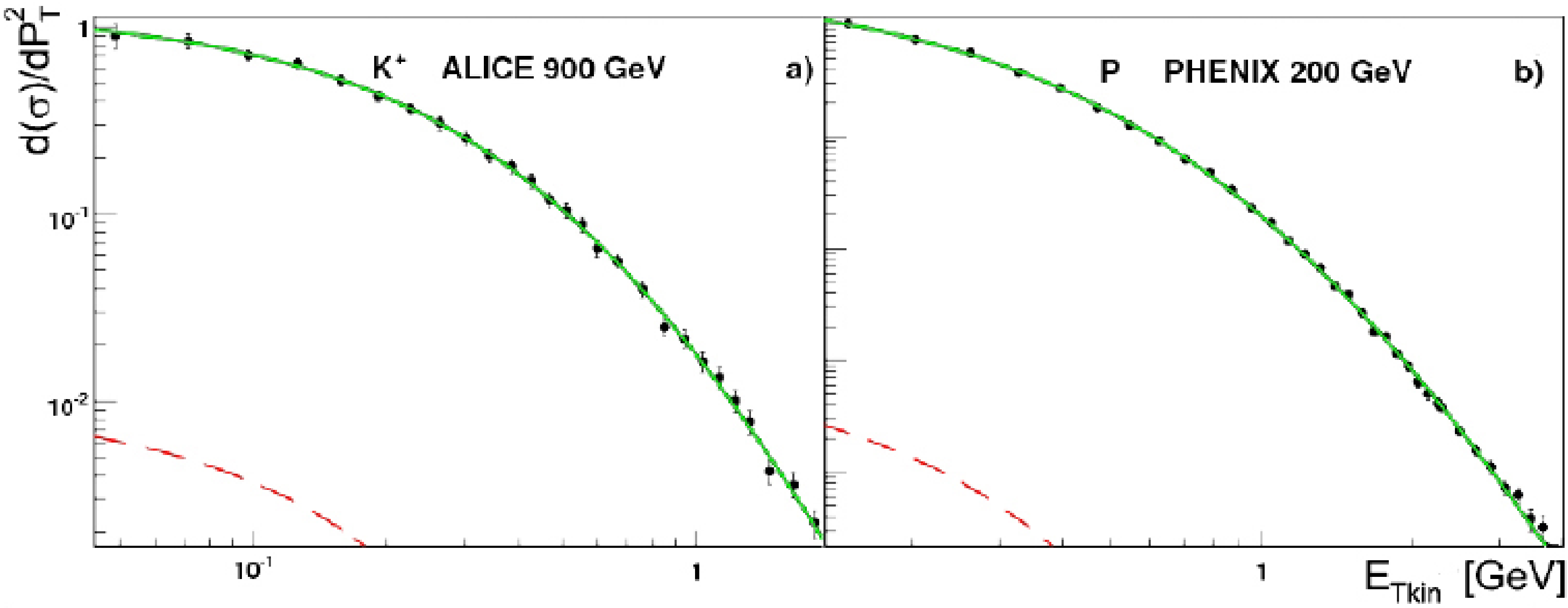
$$E_{T\,kin} = \sqrt{P_T^2 + M^2} - M$$

M: hadron mass

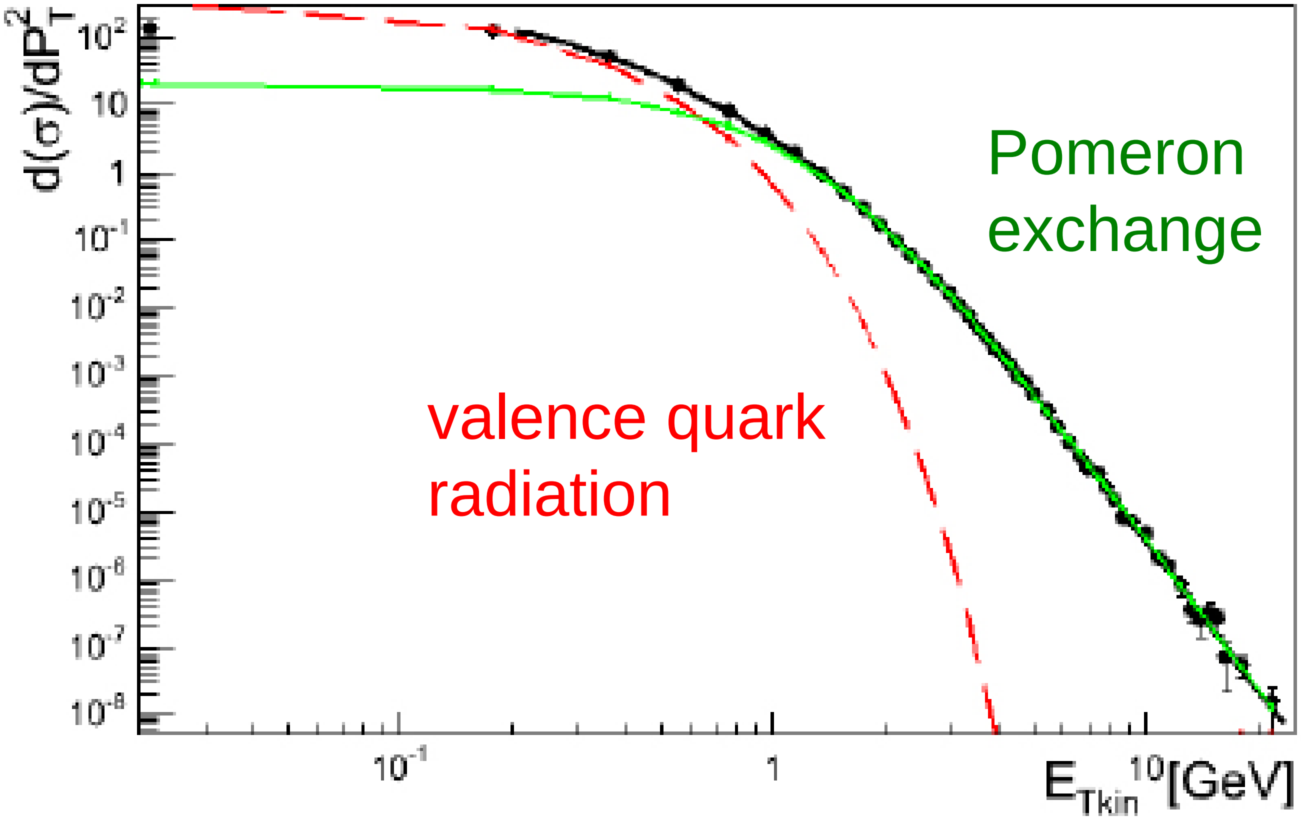
A_e, A, T_e, T and "n" are free parameters

Fit to kaon and proton data

Negligible exponential term



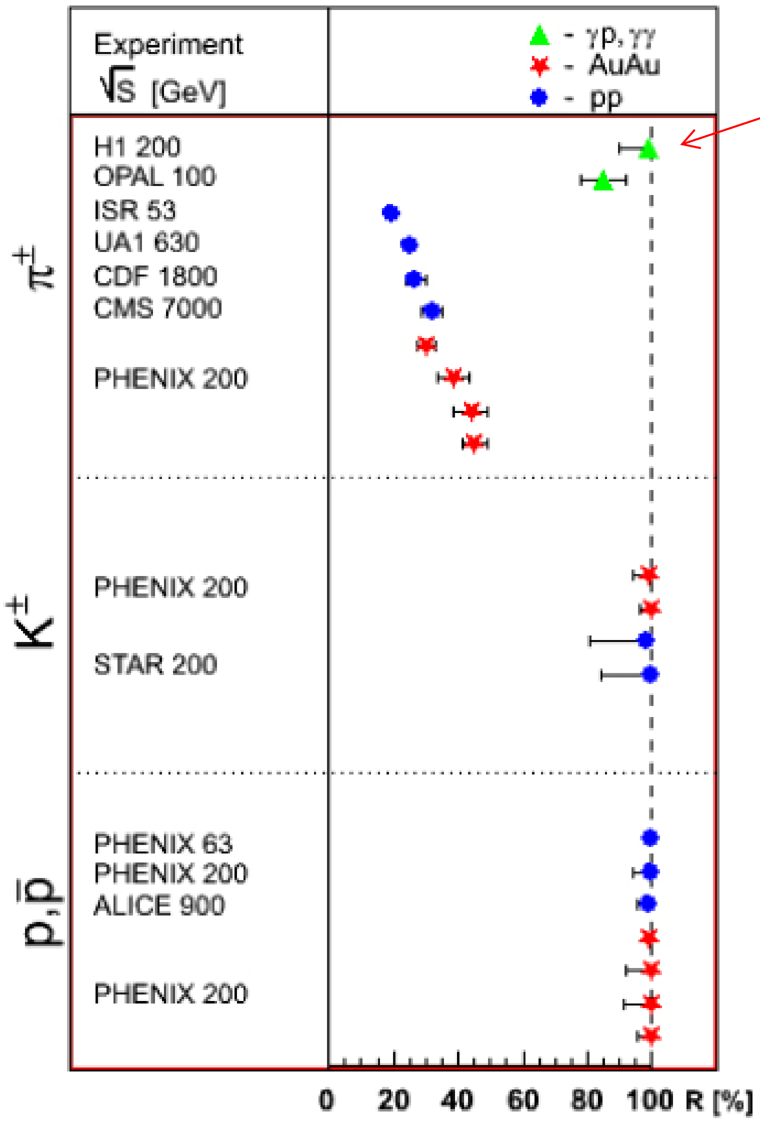
Fit to pion data-sizable exp term



UA1, Phys. Lett. B366, 434 (1996)

FIG. 1. Pion spectrum [9] fitted with a modified Tsallis function (1): the red (dashed) line shows the exponential term and the green (solid) one - the power law.

In terms of ratio R



but not these data
fewer hadrons involved

ratio of power-law contribution with p_T integrated over

$$R = \frac{AnT}{AnT + A_e(2MT_e + 2T_e^2)(n-1)}$$

Common features

- All anomalous processes demand k_T factorization (end-point singularity in heavy-flavor decays, and p_T spectra)
- All anomalous processes involve at least three hadrons
- The above are necessary conditions for Glauber divergences to appear
- All anomalous processes involve pions
- Do we really understand pion?

Clue 5:
Nambu-Goldstone boson

Unique role of pion

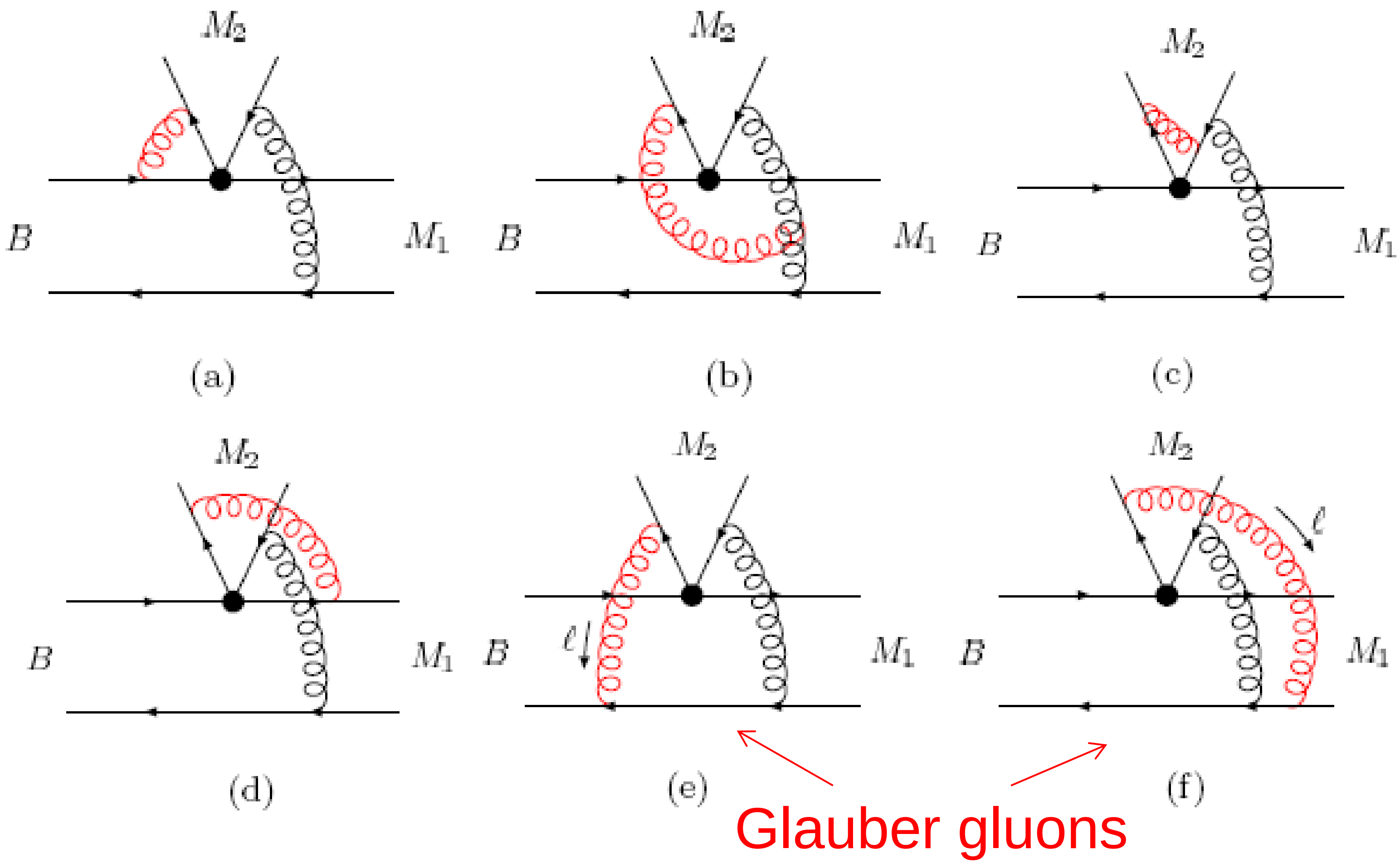
- Due to confinement, ordinary hadron as quark bound state must have finite mass
- No contradiction
- If massless Nambu-Goldstone boson is elementary, no contradiction
- Pion is Nambu-Goldstone boson
- But pion is also $q\bar{q}$ bound state with confinement, which must have finite mass
- How could it be possible?

Reconciliation?

- Use different Fock states to meet different roles of pion
- Leading Fock state $q\bar{q}$ is tight to lower confinement potential, higher Fock state gives soft cloud (Lepage, Brodsky 79; Nussinov, Shrock 08; Duraisamy, Kagan 08)
- But parton model is under approximation of neglect confinement…?
- Anyway, pion is unique.
- Strong Glauber effect from this soft cloud? Are those puzzles due to Glauber phase?

Clue 6:
Resolutions of puzzles
with Glauber phase of pion

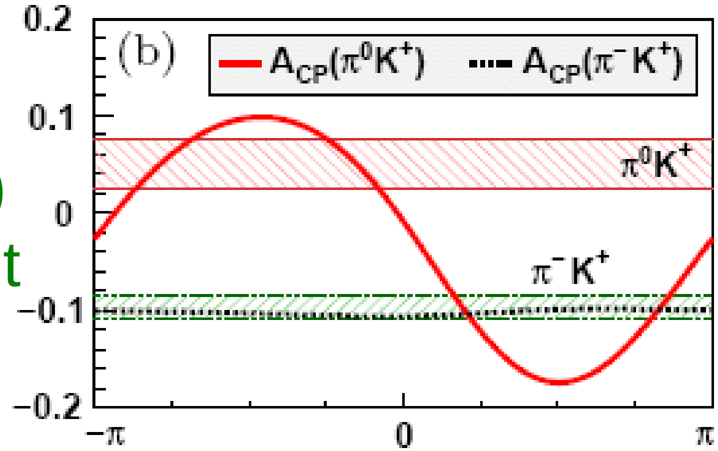
Spectator diagrams involve 3 hadrons

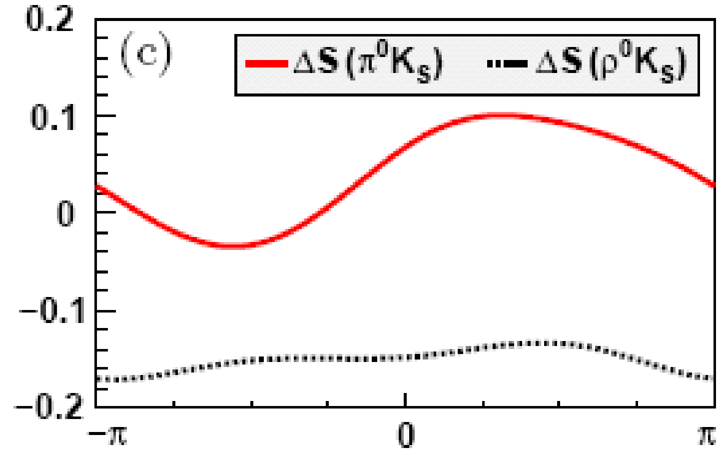


pi K puzzle in B decays

- Treat Glauber phase $\exp(iS_e)$ as a constant
- pi K puzzle resolved for Se ~ -0.5

Sin(Se) relevant here





$$\mathcal{A}_{K\pi} \equiv A_{\rm CP}(B^0 \to K^+\pi^-) = -0.093 \pm 0.015$$

$$\mathcal{A}_{K\pi^0} \equiv A_{\rm CP}(B^+ \to K^+\pi^0) = +0.047 \pm 0.026$$

$$S_{c\bar{c}s} \;=\; 0.672 \pm 0.024 \quad S_{\pi^0 K_S} \;=\; 0.57 \pm 0.17$$

$$S_{\rho^0 K_S} = 0.63^{+0.17}_{-0.21}$$

D decay BRs with Se=-0.5

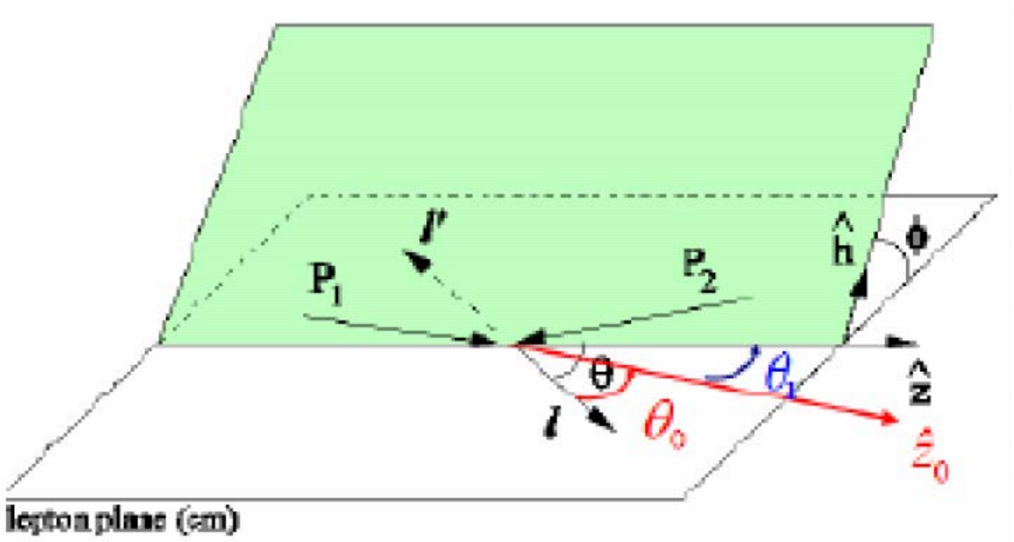
Li, Lu, Yu, 2011

Modes	Br(FSI)	Br(diagram)	Br(pole)	Br(exp)	Br(this work)
$D^0 \to \pi^+\pi^-$	1.59	2.24±0.10	2.2 ± 0.5	1.45±0.05	1.43 ⇦
$D^0 \to K^+K^-$	4.56	1.92±0.08	3.0 ± 0.8	4.07±0.10	4.19
$D^0 \to K^0\overline{K}^0$	0.93	0	0.3 ± 0.1	0.320±0.038	0.36
$D^0 \to \pi^0\pi^0$	1.16	1.35±0.05	0.8 ± 0.2	0.81±0.05	0.57
$D^0 \to \pi^0\eta$	0.58	0.75±0.02	1.1 ± 0.3	0.68±0.07	0.94
$D^0 \to \pi^0\eta'$	1.7	0.74±0.02	0.6 ± 0.2	0.91±0.13	0.65
$D^0 \to \eta\eta$	1.0	1.44±0.08	1.3 ± 0.4	1.67±0.18	1.48
$D^0 \to \eta\eta'$	2.2	1.19±0.07	1.1 ± 0.1	1.05±0.26	1.54
$D^+ \to \pi^+\pi^0$	1.7	0.88±0.10	1.0 ± 0.5	1.18±0.07	0.89
$D^+ \to K^+\overline{K}^0$	8.6	5.46±0.53	8.4 ± 1.6	6.12±0.22	5.95
$D^+ \to \pi^+\eta$	3.6	1.48±0.26	1.6 ± 1.0	3.54±0.21	3.39 ⇦
$D^+ \to \pi^+\eta'$	7.9	3.70±0.37	5.5 ± 0.8	4.68±0.29	4.58
$D_S^+ \to \pi^0K^+$	1.6	0.86±0.09	0.5 ± 0.2	0.62±0.23	0.67
$D_S^+ \to \pi^+K^0$	4.3	2.73±0.26	2.8 ± 0.6	2.52±0.27	2.21
$D_S^+ \to K^+\eta$	2.7	0.78±0.09	0.8 ± 0.5	1.76±0.36	1.00
$D_S^+ \to K^+\eta'$	5.2	1.07±0.17	1.4 ± 0.4	1.8±0.5	1.92

Pion-induced Drell-Yan processes

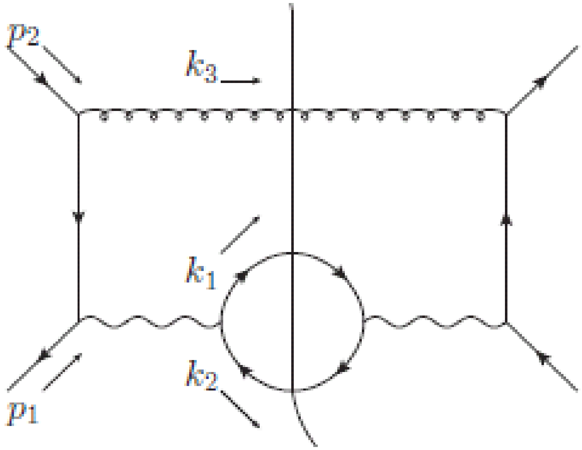
Put all clues together…

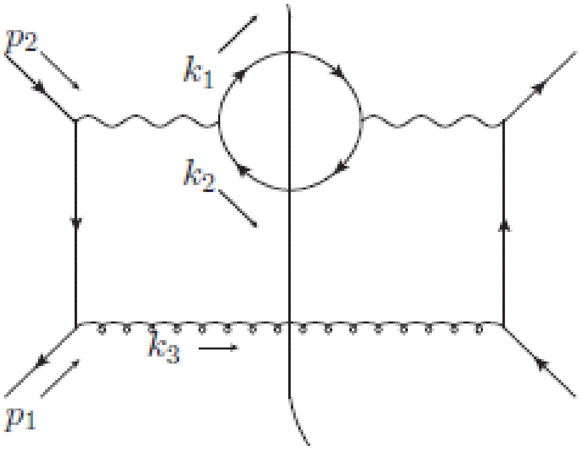
Collins-Soper frame

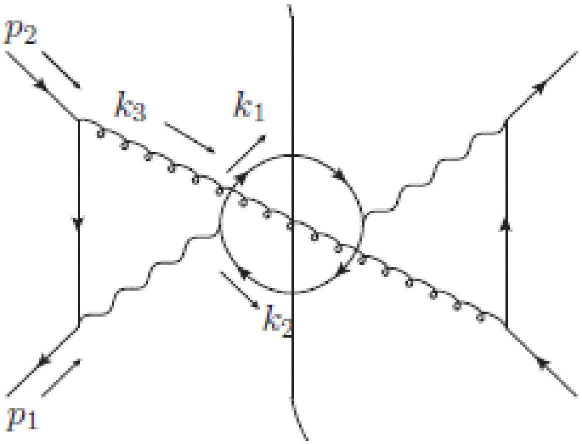


- q_T : lepton-pair transverse momentum
- Q: lepton-pair invariant mass
- θ_1 : related to boost of Collins-Soper frame

LO diagrams for finite q_T



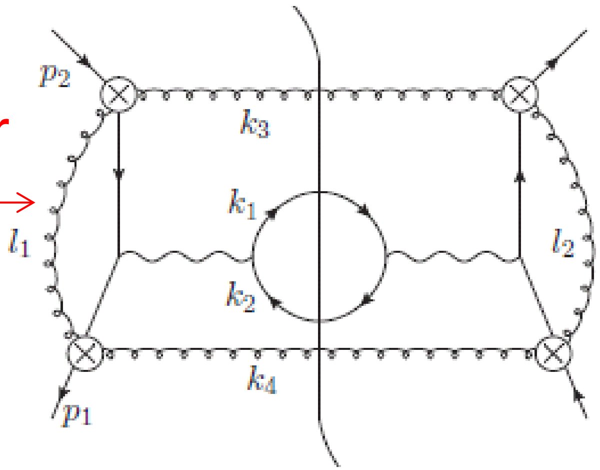


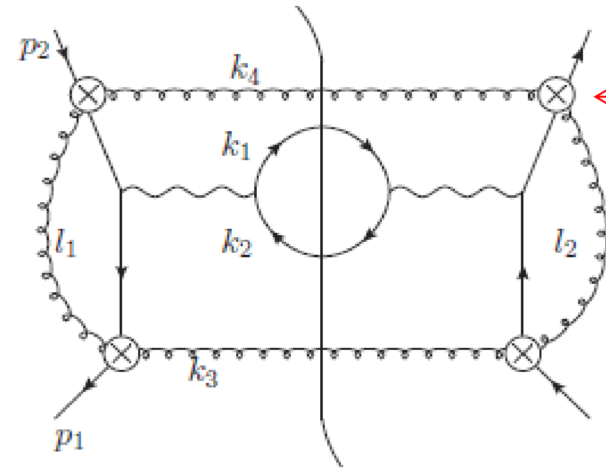


Glauber gluons

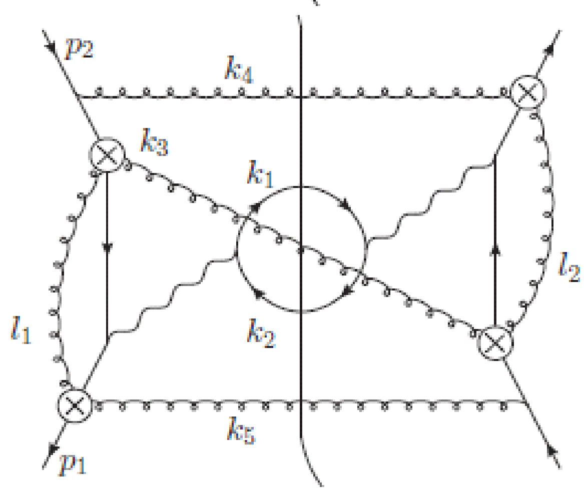
- Sum over Glauber-gluon attachments to ladder diagrams

Glauber gluon $\longrightarrow$





$\leftarrow i\delta$



one more collinear gluon is needed

next-to-leading logarithm

Glauber phase

- Assign exp(iSe) and exp(-iSe) to first two diagrams, coefficient of each angular term

$$\hat{\sigma}_0 = \left(\frac{E_1}{E_2}+\frac{E_2}{E_1}\right)\left(1+\frac{1}{2}s_1^2\right)+\underline{(c_e-1)}$$

$$\boxed{c_e \equiv \cos S_e}$$

$$\times\left\{2\left[\frac{E_1E_2}{k^2}c_1^2+\frac{k}{E_1}+\frac{k}{E_2}-\frac{1}{2}\left(\frac{E_1}{E_2}+\frac{E_2}{E_1}\right)-2\right]\right.$$
$$\left.-\left[\frac{E_1E_2}{k^2}c_1^2-\frac{1}{2}\left(\frac{E_1}{E_2}+\frac{E_2}{E_1}\right)\right]s_1^2\right\}, \qquad (3)$$

$$\hat{\sigma}_1 = \left(\frac{E_1}{E_2}+\frac{E_2}{E_1}\right)\left(c_1^2-\frac{1}{2}s_1^2\right)+(c_e-1)$$
$$\times\left\{\left(\frac{E_1}{E_2}+\frac{E_2}{E_1}-2\right)c_1^2\right.$$
$$\left.+\left[\frac{E_1E_2}{k^2}c_1^2-\frac{1}{2}\left(\frac{E_1}{E_2}+\frac{E_2}{E_1}\right)\right]s_1^2\right\}$$

E1: hadron 1 energy
E2: hadron 2 energy
k: lepton energy
in CS frame

More formulas

$$\hat{\sigma}_2 = \left(\frac{E_1}{E_2} - \frac{E_2}{E_1}\right) c_1 s_1 + (c_e - 1) \times \left(\frac{E_2 - E_1}{k} + \frac{E_1}{E_2} - \frac{E_2}{E_1}\right) c_1 s_1$$

$$\hat{\sigma}_3 = \left(\frac{E_1}{E_2} + \frac{E_2}{E_1}\right) s_1^2 - (c_e - 1) \times 2\left[\frac{E_1 E_2}{k^2} c_1^2 - \frac{1}{2}\left(\frac{E_1}{E_2} + \frac{E_2}{E_1}\right)\right] s_1^2,$$

$$\sin^2\theta_1 = \frac{q_T^2}{Q^2 + q_T^2}$$

corresponding to boost in Collins-Soper frame

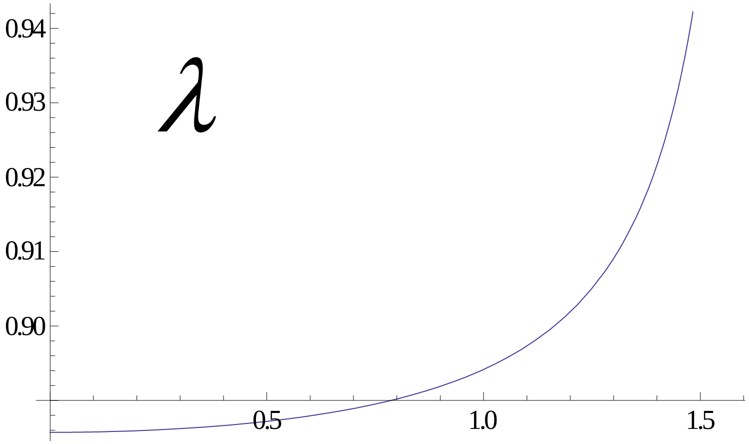
$$\lambda \sim \hat{\sigma}_1 / \hat{\sigma}_0 \qquad \mu \sim \hat{\sigma}_2 / \hat{\sigma}_0 \qquad \nu \sim \hat{\sigma}_3 / \hat{\sigma}_0$$

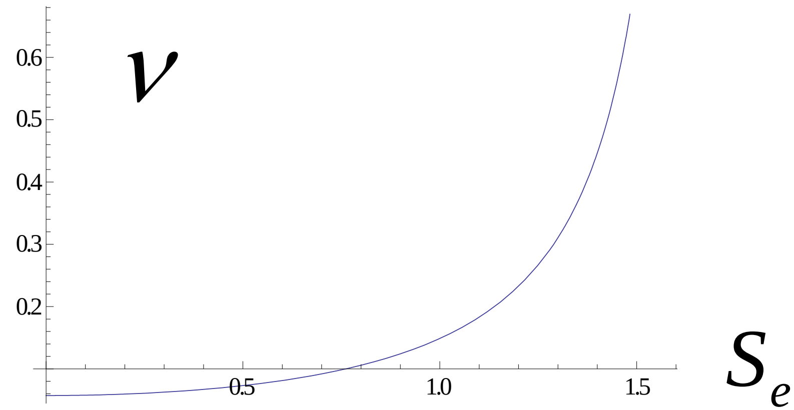
- As Se->0

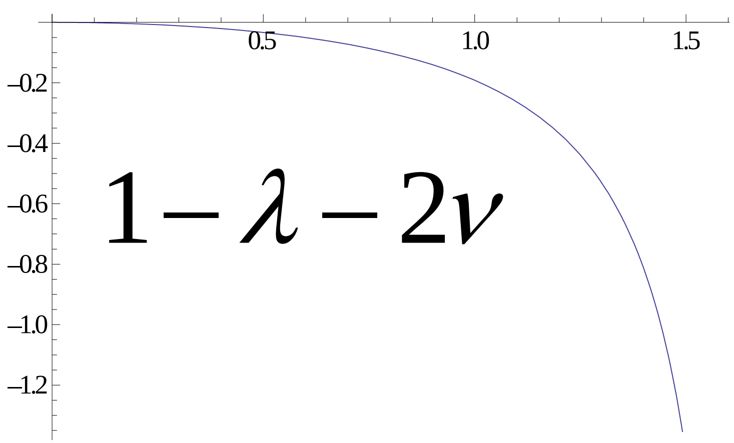
$$\lambda = \frac{c_1^2 - \frac{1}{2}s_1^2}{1 + \frac{1}{2}s_1^2}, \quad \mu = \frac{\frac{E_1}{E_2} - \frac{E_2}{E_1}}{\frac{E_1}{E_2} + \frac{E_2}{E_1}} \frac{c_1 s_1}{1 + \frac{1}{2}s_1^2}, \quad \nu = \frac{s_1^2}{1 + \frac{1}{2}s_1^2}$$

obey Lam-Tung relation

Numerical results







$$\sqrt{S} = 194\, GeV$$

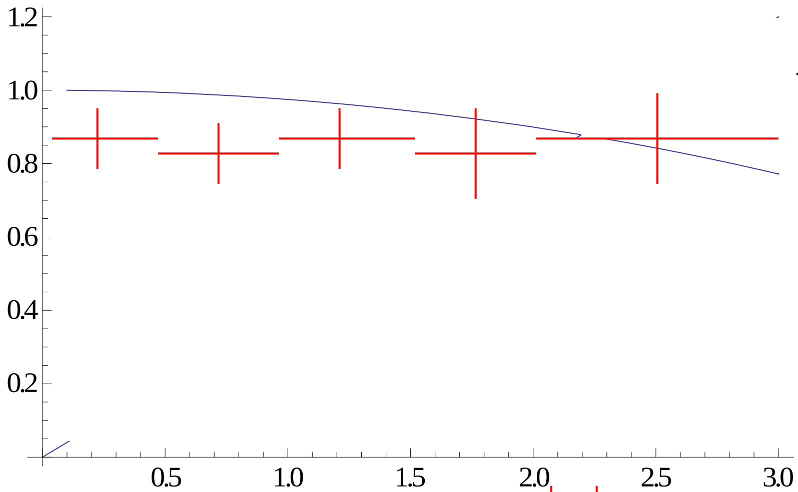
$$q_T = 2\, GeV, \quad Q = 8\, GeV$$

$$Se = 1.15, \quad \lambda \sim 0.9, \quad \nu \sim 0.2$$

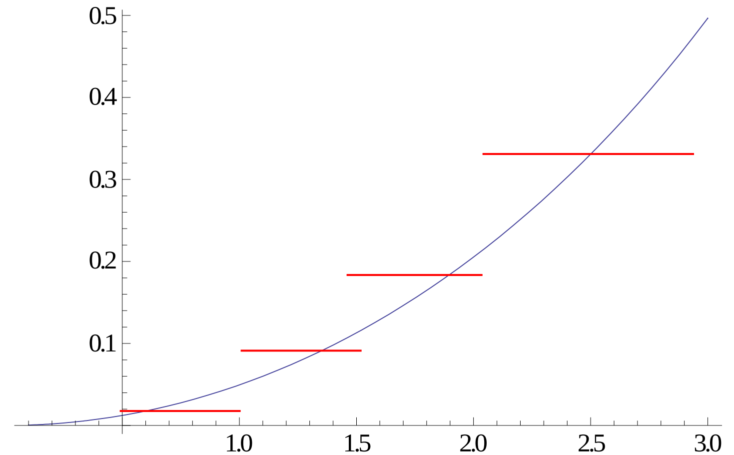
$$1-\lambda-2\nu \sim -0.3$$

q_T dependence

λ

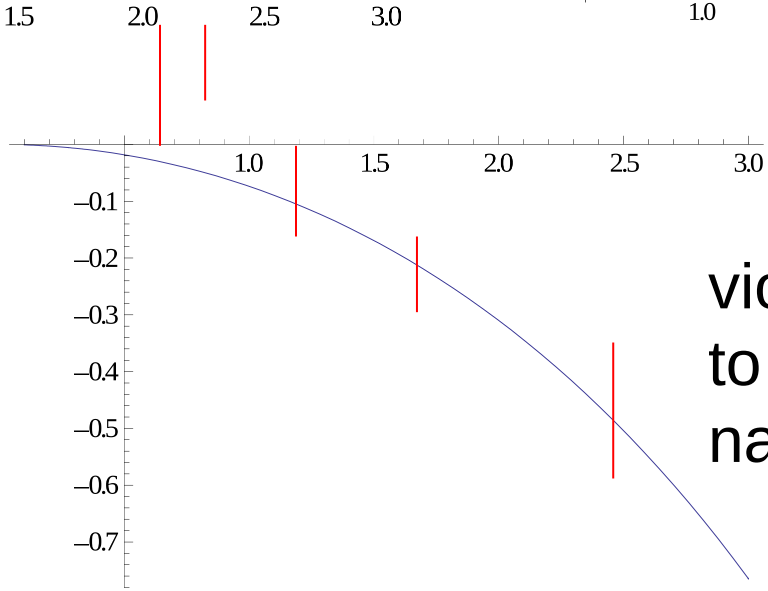


ν



q_T

$1-\lambda-2\nu$



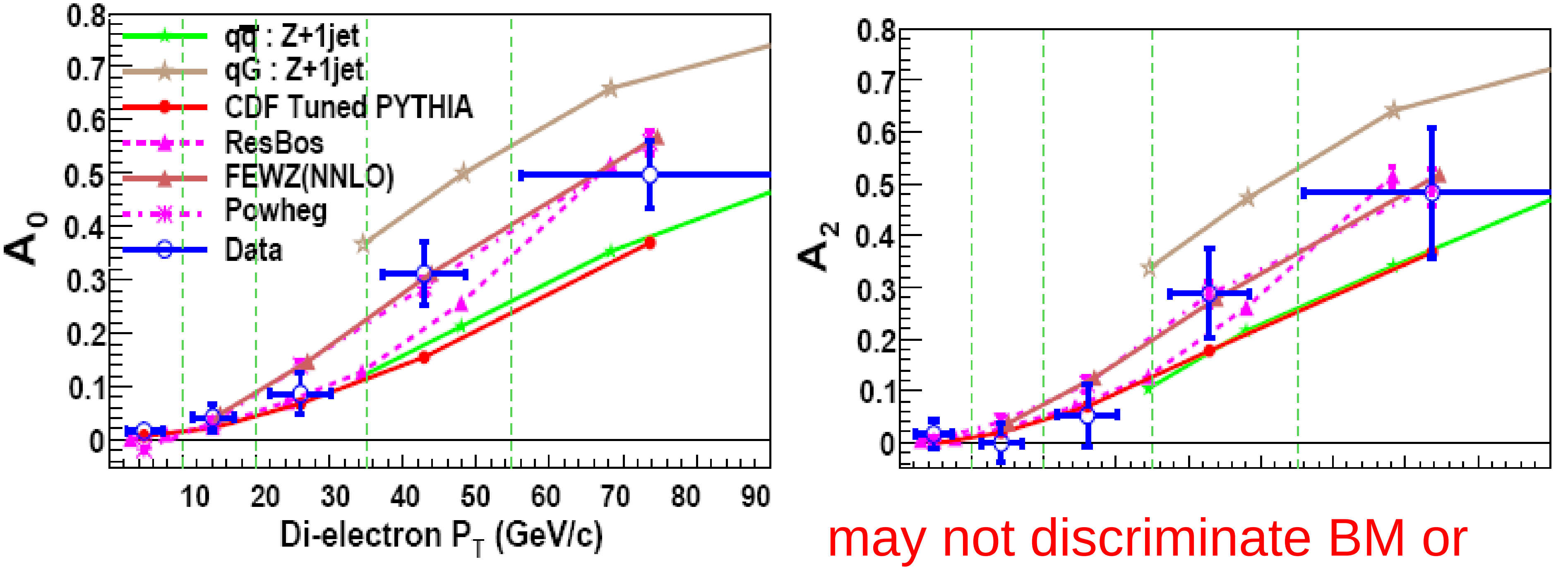
violation proportional to $\sin^2\theta_1$, vanishes naturally as q_T -> 0

Comparison

- Like vacuum effect, Glauber gluon causes fact. breakdown (but from soft cloud)
- Vacuum effect is flavor blind, but Glauber effect is strong only from pion
- Compared to BM function, parton transverse d.o.f introduced by small q_T
- Glauber gluon: Nambu-Goldstone nature
- BM or Nambu-Goldstone nature?
  Discriminated by measuring $\bar{p}p$ Drell-Yan (valence anti-quark from $\bar{p}$)

CDF $\bar{p}p$ data

- Lam-Tung relation is respected: $A_0 = A_2$
- at large Q=mZ, consistent with LT
- p_T/Q not small, support Glauber gluons



CDF, 1103.5699

may not discriminate BM or Glauber gluons due to high p_T

Summary

- Violation of Lam-Tung relation is one of pion-involved anomalous data
- Glauber-gluon effect leads to phase factor in k_T factorization, which could resolve several pion-involved puzzles
- Propose to measure anti-proton-proton Drell-Yan process to discriminate the BM or Nambu-Goldstone nature
- Next target: can pion hadroproduction be resolved by Glauber gluons?

Back-up slides

Total NNLO

- Two gluons on opposite sides

$$I_1(k_T) = \frac{\lambda^2 g_1^2 g_2 (g_2+g_1)}{(2\pi)^{12}} x p^+ \int dk^-\, d^4 l_1\, d^4 l_2 \, \frac{[2(p^+-k^+)+l_1^+]\,[2(p^+-k^+)+l_2^+]}{(l_1^2-m_g^2)\,(l_2^2-m_g^2)\,[(k-l_1)-m_q^2+i\epsilon]\,[(k-l_2)-m_q^2+i\epsilon]}$$
$$\times \frac{(2\pi)^2\delta(l_1^+)\delta(l_2^+)\; 2\pi\delta\big((p-k)^2-m_q^2\big)}{[(p-k+l_1)-m_q^2+i\epsilon]\,[(p-k+l_2)-m_q^2+i\epsilon]}$$
$$= \frac{\lambda^2 g_1^2 g_2 (g_2+g_1) x(1-x)}{256\pi^7} \int d^2 l_{1T}\, d^2 l_{2T} \prod_{j=1,2} \frac{1}{(l_{jT}^2+m_g^2)\,[(k_T-l_{jT})^2+m_q^2]}.$$

- Two gluons on the same sides

$$I_2(k_T) = \frac{-\lambda^2 g_1^2 g_2 (g_2+g_1) x(1-x)}{256\pi^7} \int d^2 l_{1T}\, d^2 l_{2T} \, \frac{1}{(l_{1T}^2+m_g^2)\,(l_{2T}^2+m_g^2)\,[(k_T-l_{1T}-l_{2T})^2+m_q^2]\,(k_T^2+m_q^2)}$$

- No cancellation. Lower TMD is not universal. k_T fact. fails. Integrated over k_T, they cancel. Collinear factorization holds.

Glauber region

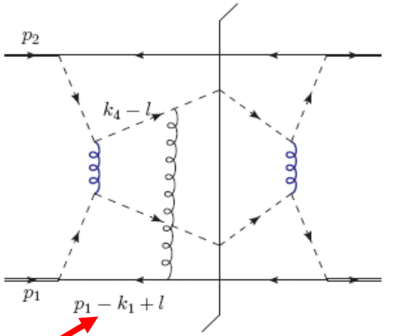
- Collinear region $(l^+, l^-, l_T) \sim (E, m^2/E, m)$
- Soft region ~ (m,m,m)
- Breakdown appears in Glauber region $(0, m^2/E, m)$ due to $\delta(l^+)$, $l^2 = - l_T^2$
- Consider spectator propagator $(p_1\text{-}k_1\text{+}l)^2\text{=}2(p_1 \text{-}k_1)^+l^- + (k_{1T} + l_T)^2$
- Two terms are of the same order of m^2

$\Rightarrow$ $(k_{1T} + l_T)^2$ is not negligible

$\Rightarrow$ Eikonal approximation does not hold

- IR gluons usually not factorized in Glauber region. Universality of TMD is lost

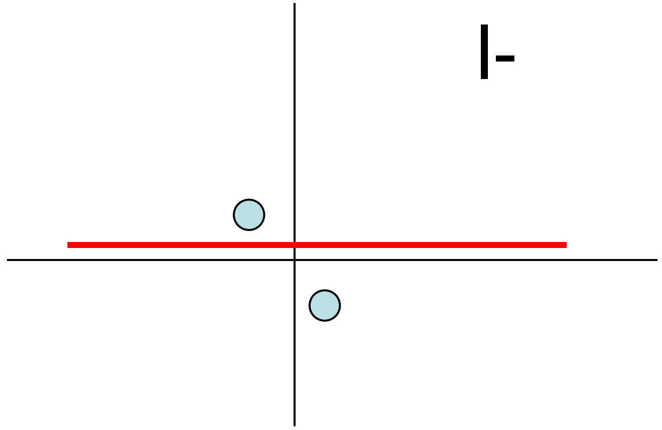
Contour deformation

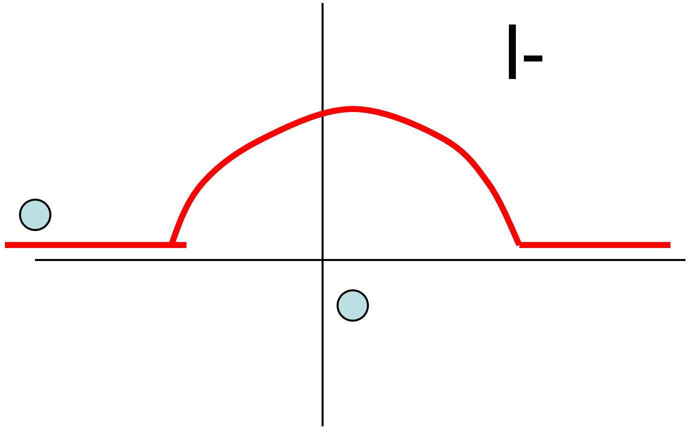


- Poles of loop momentum

$$l^- = k_1^- - \frac{|l_T - k_{1T}|^2}{2k_1^+} + i\epsilon, \quad l^- = k_1^- + \frac{|l_T - k_{1T}|^2}{2(p_1^+ - k_1^+)} - i\epsilon,$$

- For high q_T (large k_1^+), for low q_T (small k_1^+)





- l^- is of order m^2/E and m, respectively
- For latter, $2(p_1 - k_1)^+ l^- \gg (k_{1T} + l_T)^2$

Reconciliation?

- As r decreases, interaction decreases, m decreases, but quarks not allowed to move freely
- To reconcile pion's role, need to create state "no interaction, no free motion"
- Namely, short distance, low mass
- As r decreases, k_T must be frozen
- Pion has large soft cloud in this sense, $k_T << 1/r$
- Violation of uncertainty principle?

Large soft cloud in pion

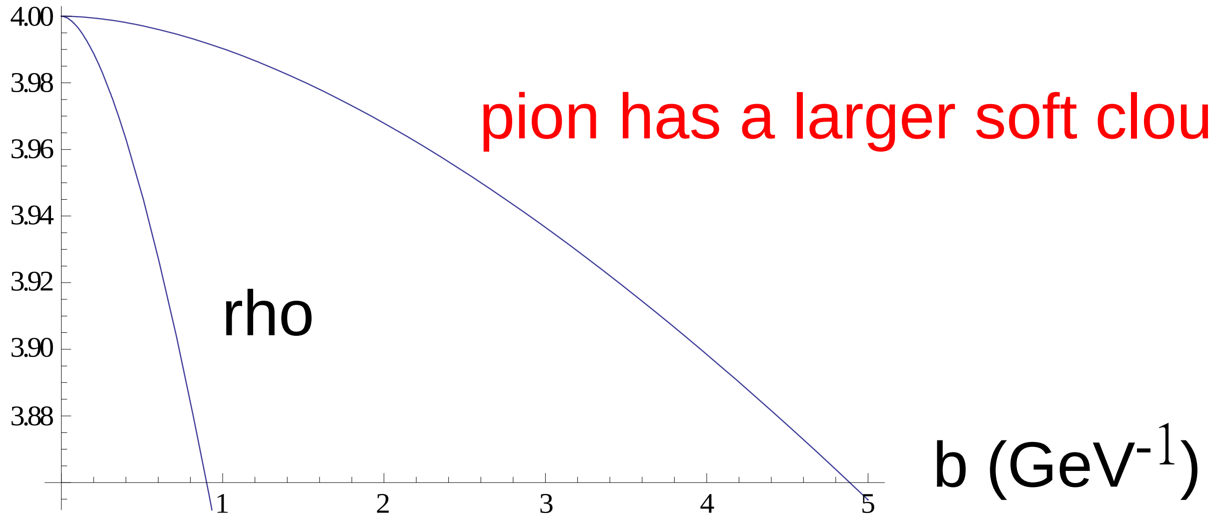
- Model of Brodsky et al. (1980)

$$\phi_p(x, k_T) = \frac{4\pi m_p^2}{[m_p^2 + k_T^2/x + k_T^2/(1-x)]^2}$$

carried by quark

carried by anti-quark

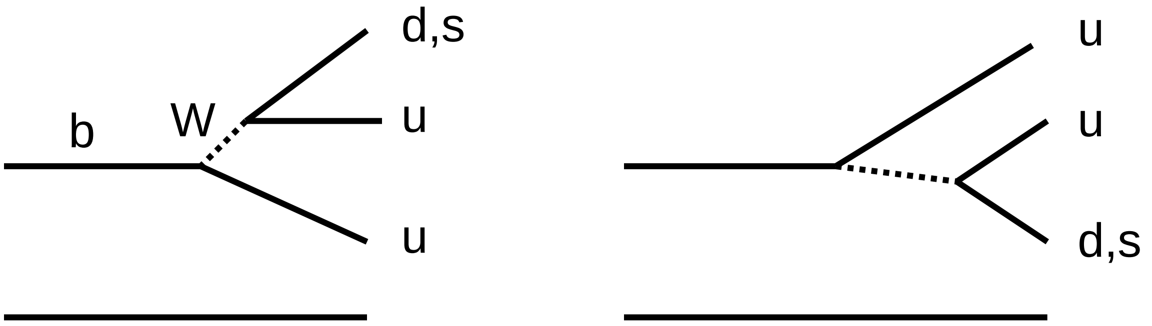
- m_p : meson mass
- Distribution in b space



Clue 6:
Glauber phase from pion

Color-suppressed tree

- $B(\pi^0\pi^0), B(\rho^0\rho^0)$ both depend on color-suppressed tree amplitude C



Color-allowed tree T Color-suppressed tree C

- C is an important but least understood quantity in B decays

Glauber phase factor

- Glauber factor is factorized and universal. How is it different between π, ρ?
- Though Glauber gluons are factorized, loop momentum l_T flows through mesons
- If mesons have different intrinsic k_T dependence, Glauber effects are different
- Consider Glauber factor

$$G_2(l_T) = \int d^2b' \exp(il_T \cdot b') \exp[iS(b')]$$

parametrization $S(b) = \alpha b^2$

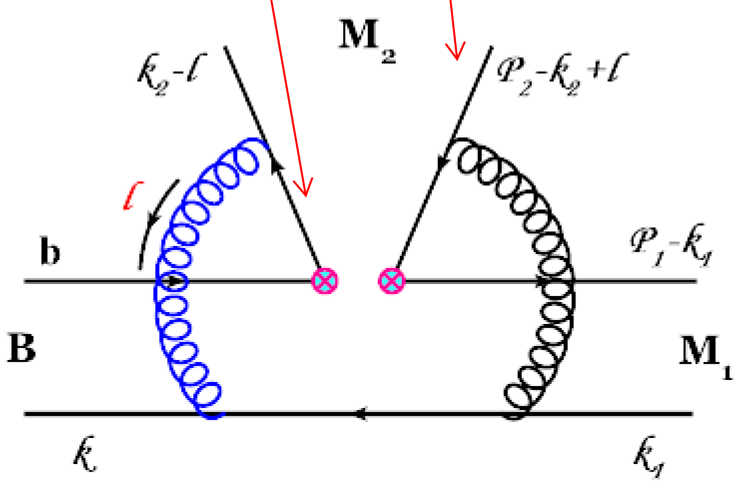
Convolution in k_T space

- Consider intrinsic k_T dependence

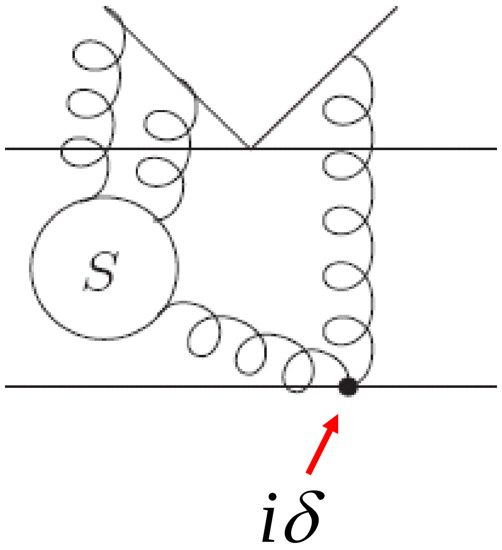
$$\int \frac{d^2k_T}{(2\pi)^2}\frac{d^2k_{1T}}{(2\pi)^2}\frac{d^2k_{2T}}{(2\pi)^2}\int\frac{d^2l_T}{(2\pi)^2}\phi_B(k_T)\phi_1(k_{1T})$$

$$\bar{\phi}_2(k_{2T},-k_{2T}+l_T)G_2(l_T)H_a(k_T,k_{1T},k_{2T},l_T)$$

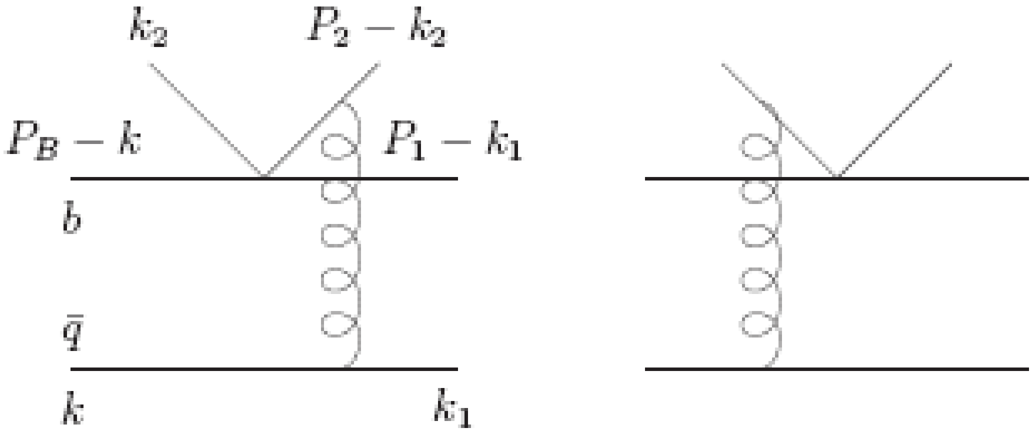
Brodsky model



Glauber effect



- Resum Glauber divergence to all orders, like summing collinear divergence into meson wave function



minus sign due to radiation from anti-quark

$$I_a \approx e^{iS_e} \mathcal{M}_a^{(0)} \qquad I_b \approx e^{-iS_e} \mathcal{M}_b^{(0)}$$

- like $1-1 \Rightarrow e^{iS_e} - e^{-iS_e}$, large imaginary C

Numerical results

depend on T

- With $\alpha = -0.42$ for all followng

Mode	Data [1]	NLO [4]	NLO (this work)
$B^0 \to \pi^+\pi^-$	5.11 ± 0.22	$6.5^{+\ 6.7\,(+\ 2.7)}_{-\ 3.8\,(-\ 1.8)}$	$6.58^{+2.21}_{-1.62}(\omega_B)^{+0.24}_{-0.19}(a_2^\pi)$
$B^+ \to \pi^+\pi^0$	$5.48^{+0.35}_{-0.34}$	$4.0^{+\ 3.4\,(+\ 1.7)}_{-\ 1.9\,(-\ 1.2)}$	$5.60^{+0.00}_{-1.90}(\omega_B)^{+0.00}_{-2.39}(a_2^\pi)$
$B^0 \to \pi^0\pi^0$	$1.91^{+0.22}_{-0.23}$	$0.29^{+0.50\,(+0.13)}_{-0.20\,(-0.08)}$	$1.10^{+0.00}_{-0.88}(\omega_B)^{+0.00}_{-0.65}(a_2^\pi)$
$B^0 \to \rho^0\rho^0$	$0.73^{+0.27}_{-0.28}$	$0.92^{+1.10\,(+0.64)}_{-0.56\,(-0.40)}$	$0.61^{+1.02}_{-0.00}(\omega_B)^{+0.15}_{-0.06}(a_2^\rho)$

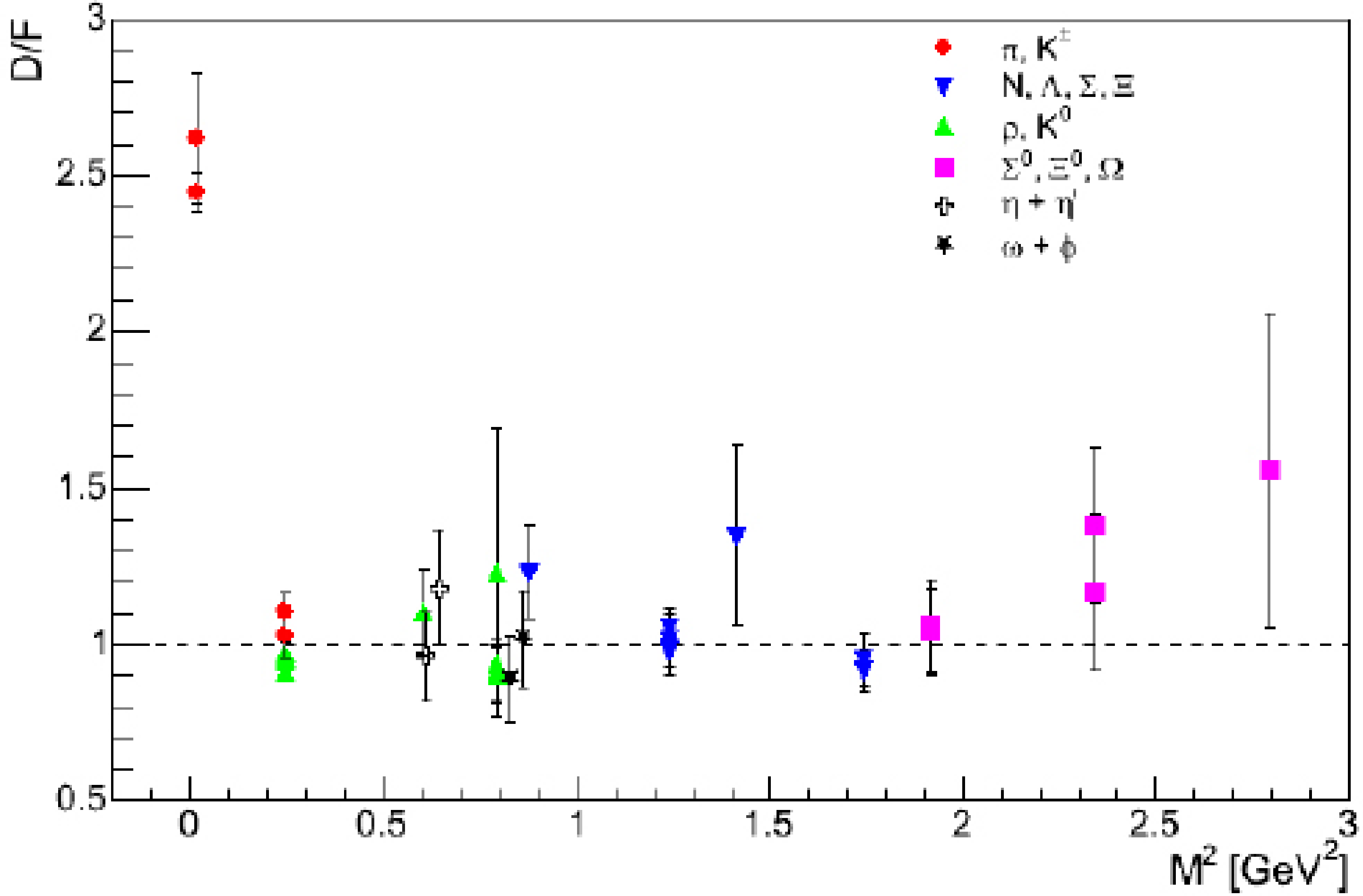
Li, Liu, Xiao, to appear

- Pion indeed shows stronger Glauber effect than rho

Pion multiplicity in e+e- anni.

- Hadron productions at Z pole

$$\langle N(\text{particle})\rangle = \frac{2J+1}{2I_m+1} a \exp(-bM^2)$$



BM, vacuum effect, and Glauber gluons

	$h_1^\perp \neq 0$	QCD vacuum effect	Glauber gluon
$\rho^{(q,\bar{q})}$	$\rho^{(q)} \otimes \rho^{(\bar{q})}$	possibly entangled	possibly entangled
Q dependence	$\kappa \sim 1/Q$	?	$1/Q^2$
large Q_T limit	$\kappa \to 0$	need not disappear ($\kappa \to \kappa_0$)	should disappear
flavor dependence	yes	flavor blind	yes
x dependence	yes	if yes, then not hadron blind	yes

D.B., Brandenburg, Nachtmann & Utermann, EPJC 40 (2005) 55

Different experiments ($\pi^\pm, p, \bar{p}, \ldots$ beams) are needed in different kinematical regimes

CDF data at Q=mZ, consistent with LT,
may not discriminate BM or Glauber gluons (1103.5699)