Interpretation of Angular Distributions of Z-boson Production at Colliders

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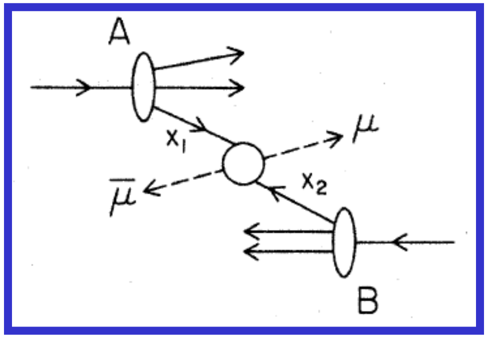
PHENO 2018 Symposium
University of Pittsburgh
May 7-9, 2018

Based on the paper of JCP, Wen-Chen Chang, Evan McClellan, Oleg Teryaev, Phys. Lett. B758 (2016) 384, PRD 96 (2017) 054020, and preprints

Angular Distribution in the "Naïve" Drell-Yan

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

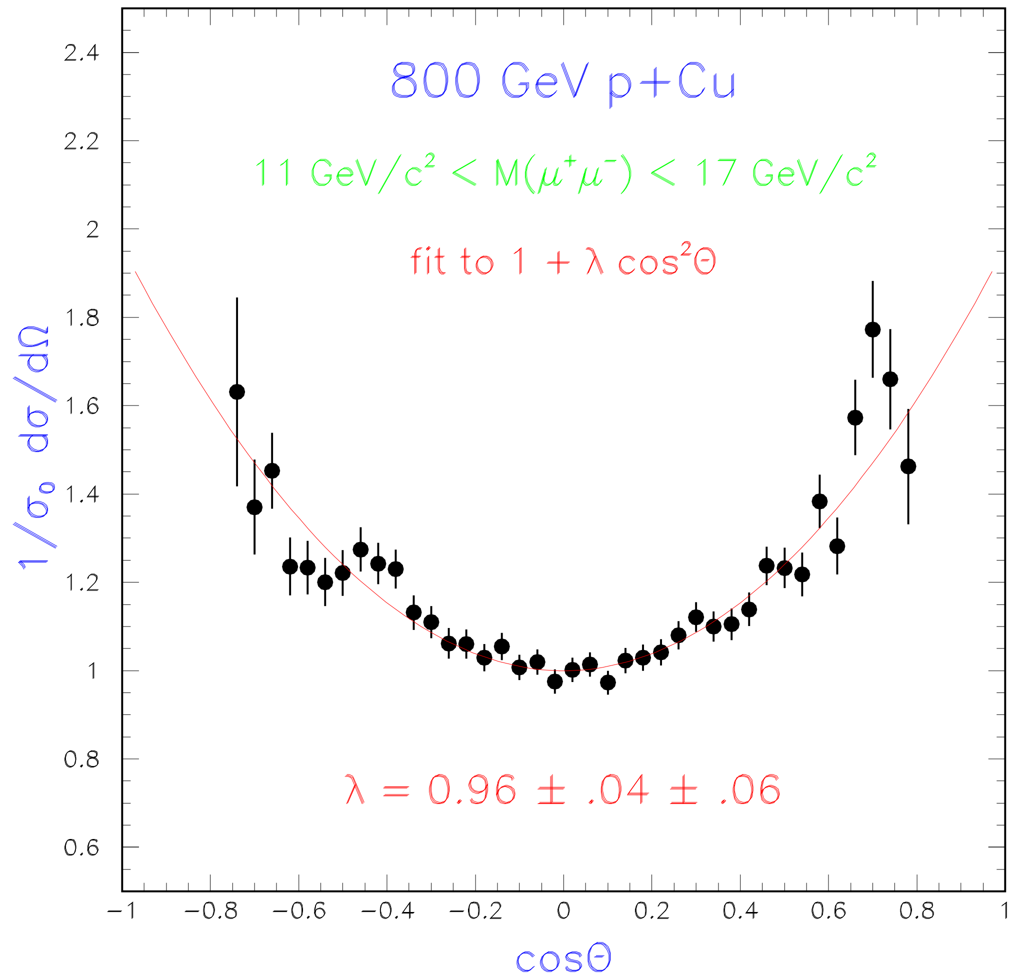


(3) The virtual photon will be predominantly transversely polarized if it is formed by annihilation of spin-$\frac{1}{2}$ parton-antiparton pairs. This means a distribution in the di-muon rest system varying as $(1+\cos^2\theta)$ rather than $\sin^2\theta$ as found in Sakurai's[10] vector-dominance model, where θ is the angle of the muon with respect to the time-like photon momentum. The model used in Fig.

Drell-Yan angular distribution

Lepton Angular Distribution of "naïve" Drell-Yan:

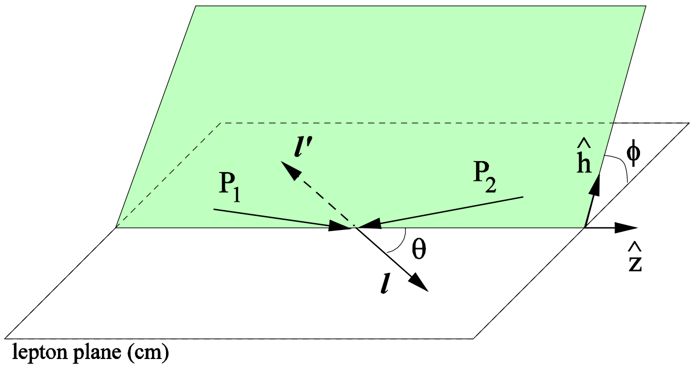
$$\frac{d\sigma}{d\Omega} = \sigma_0 (1 + \lambda \cos^2 \theta); \quad \lambda = 1$$



Data from Fermilab E772

(Ann. Rev. Nucl. Part. Sci. 49 (1999) 217-253)

Drell-Yan lepton angular distributions



Θ and Φ are the decay polar and azimuthal angles of the μ^- in the dilepton rest-frame

Collins-Soper frame

A general expression for Drell-Yan decay angular distributions:

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

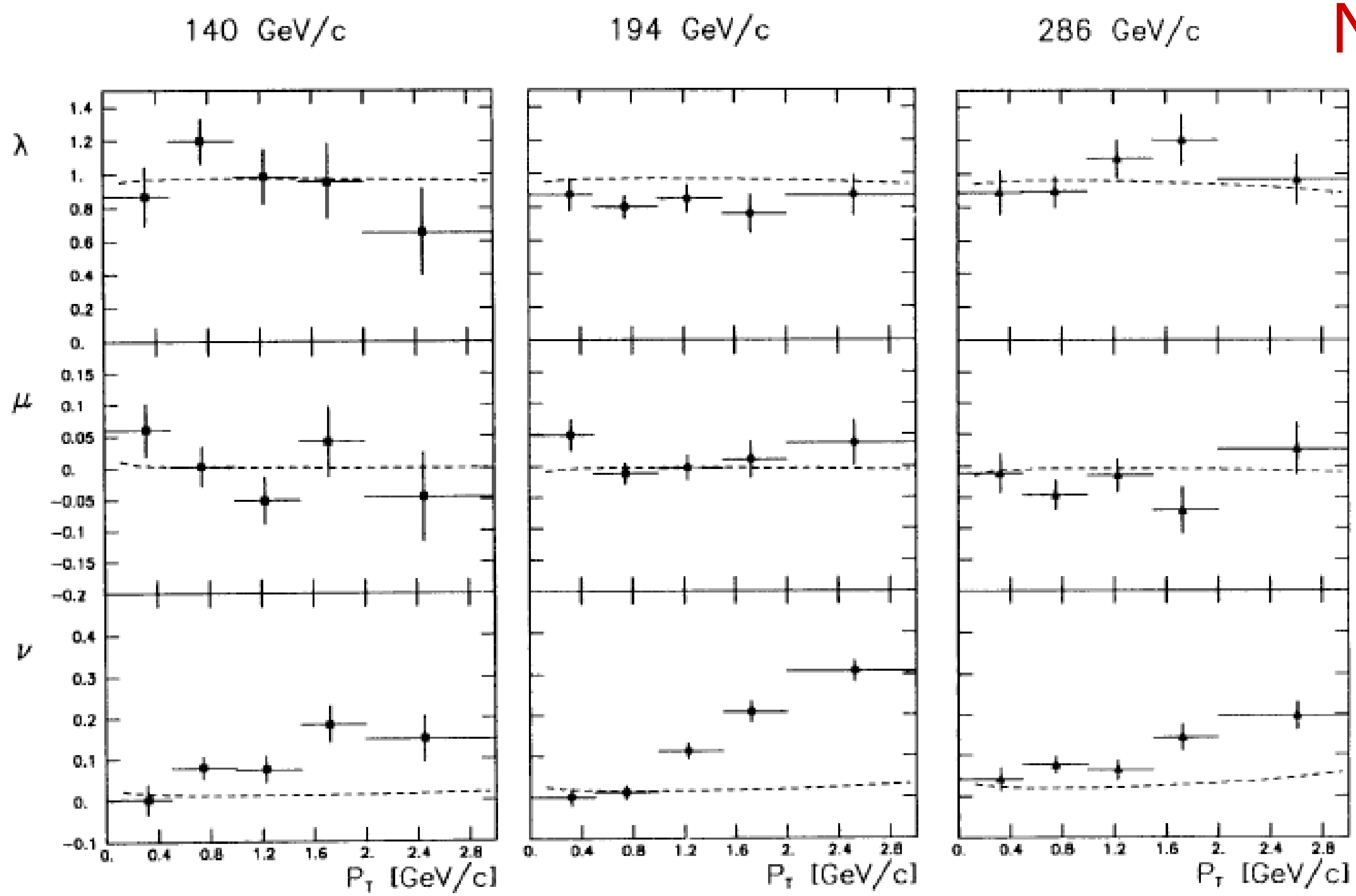
Lam-Tung relation: $1-\lambda=2\nu$

- Reflect the spin-1/2 nature of quarks (analog of the Callan-Gross relation in DIS)
- Insensitive to QCD - corrections

Decay angular distributions in pion-induced Drell-Yan

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

NA10 $\pi^- + W$



Z. Phys.

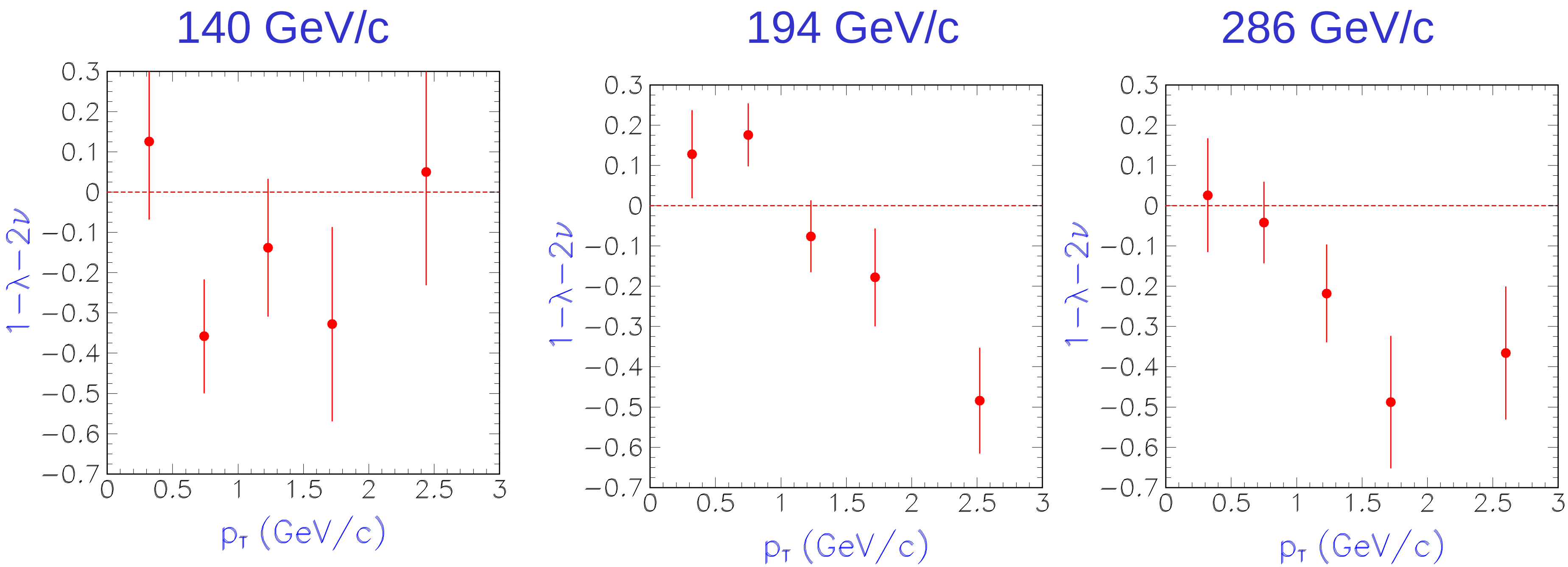
37 (1988) 545

Dashed curves are from pQCD calculations

$\nu \neq 0$ and ν increases with p_T

Decay angular distributions in pion-induced Drell-Yan

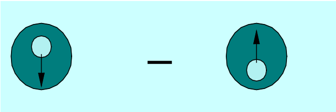
Is the Lam-Tung relation (1-λ-2ν=0) violated?



Data from NA10 (Z. Phys. 37 (1988) 545)

Violation of the Lam-Tung relation suggests interesting new origins (Brandenburg, Nachtmann, Mirkes, Brodsky, Khoze, Müller, Eskolar, Hoyer,Väntinnen, Vogt, etc.)

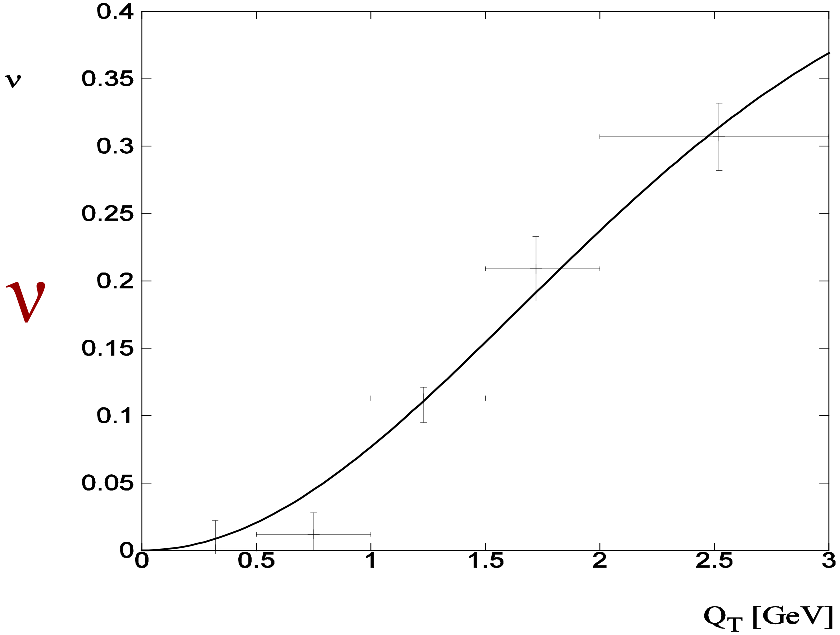
Boer-Mulders function $h_1^{\perp}$



- Boer pointed out that the cos2ϕ dependence can be caused by the presence of the Boer-Mulders function.

- $h_1^{\perp}$ can lead to an azimuthal dependence with $\nu \propto \left(\frac{h_1^{\perp}}{f_1}\right)\left(\frac{\overline{h}_1^{\perp}}{\overline{f}_1}\right)$

ν



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

$$\nu = 16\kappa_1 \frac{Q_T^2 M_C^2}{(Q_T^2 + 4M_C^2)^2}$$

Boer, PRD 60 (1999) 014012

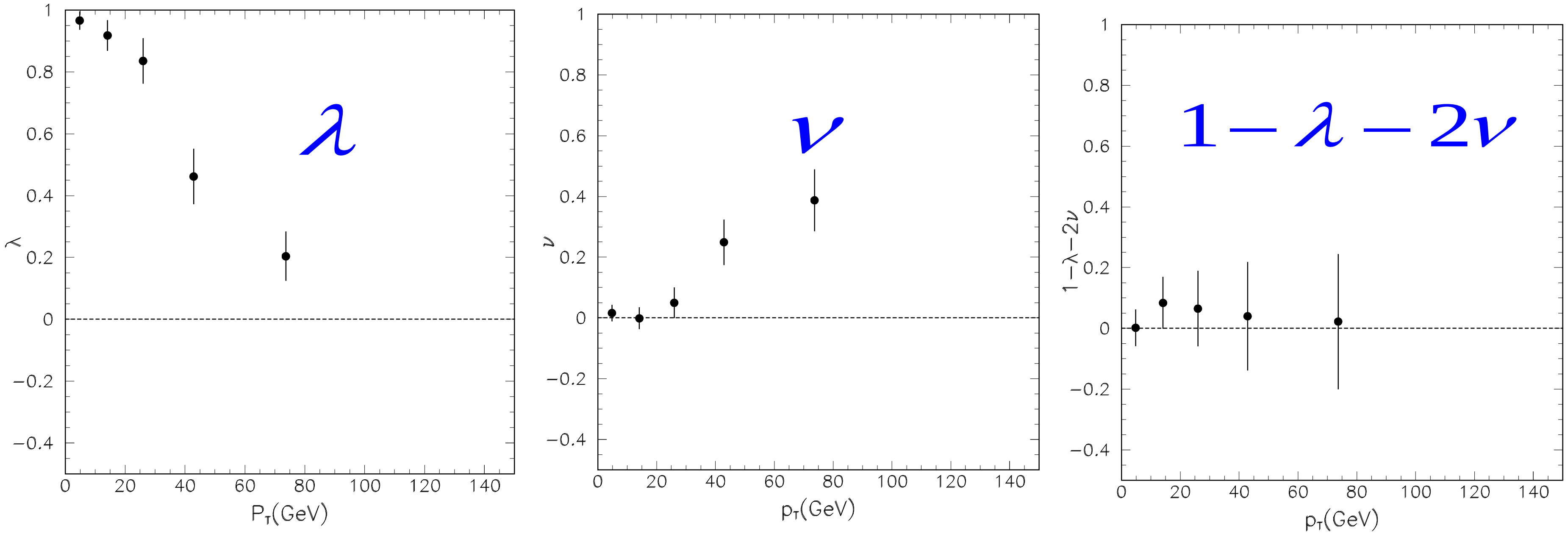
κ_1=0.47, M_C=2.3 GeV

ν>0 implies valence BM functions for pion and nucleon have same signs

Lam-Tung relation from CDF Z-production

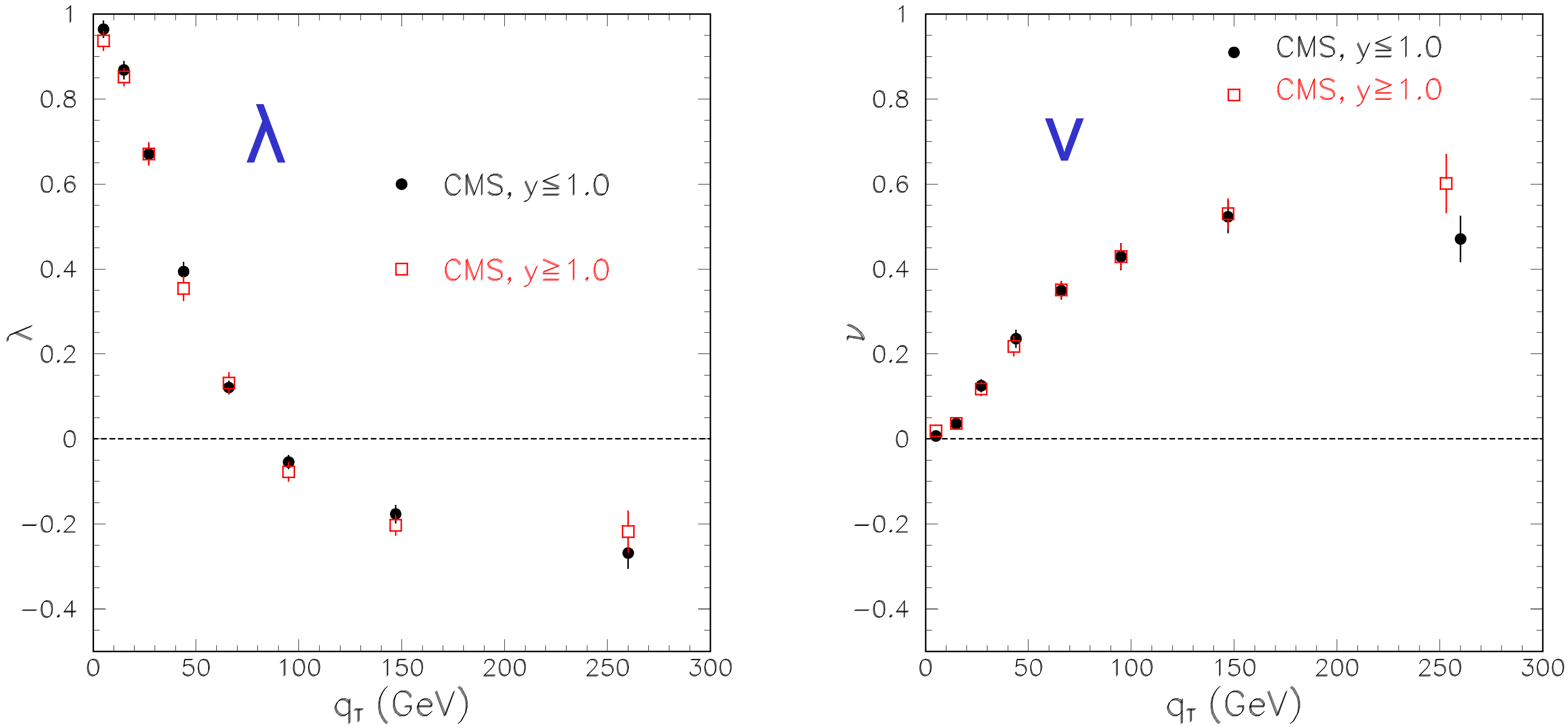
$$p + \overline{p} \rightarrow e^{+} + e^{-} + X \;\; \text{at} \sqrt{s} = 1.96\,\text{TeV}$$

arXiv:1103.5699 (PRL 106 (2011) 241801)



- Strong p_T (q_T) dependence of λ and ν
- Lam-Tung relation (1-λ = 2ν) is satisfied within experimental uncertainties (TMD is not expected to be important at large p_T)

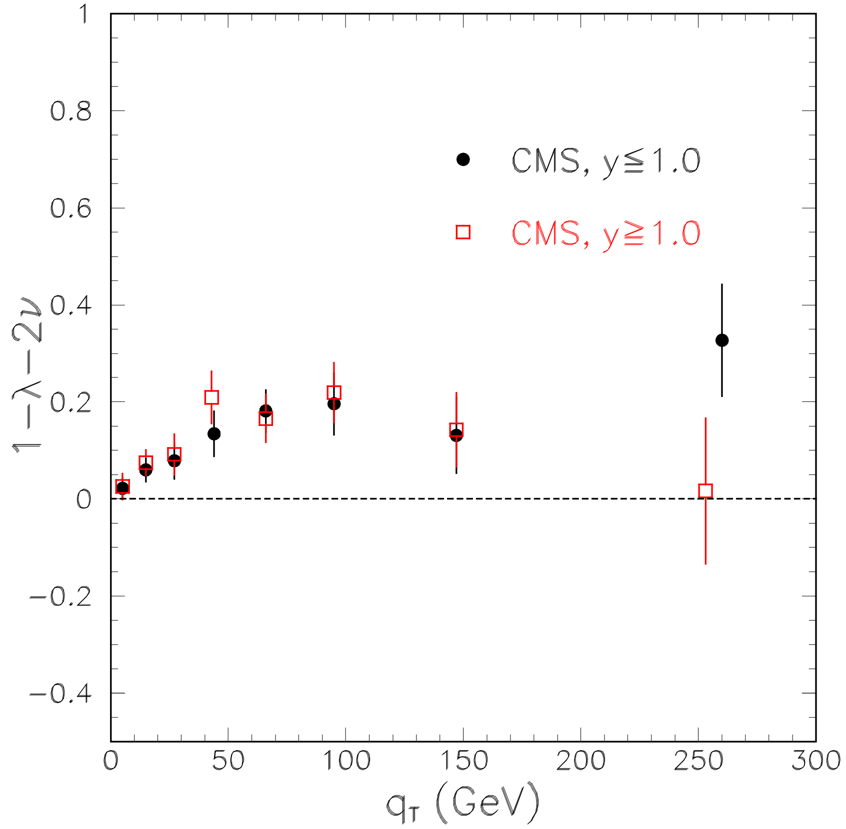
Recent CMS (ATLAS) data for *Z*-boson production in *p*+*p* collision at 8 TeV



(arXiv:1504.03512, PL B 750 (2015) 154)

- Striking q_T dependencies for λ and ν were observed at two rapidity regions
- Is Lam-Tung relation violated?

Recent data from CMS for *Z*-boson production in *p*+*p* collision at 8 TeV



- Yes, the Lam-Tung relation is violated (1-λ > 2ν)!
- Can one understand the origin of the violation of the Lam-Tung relation?

Interpretation of the CMS Z-production results

$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$

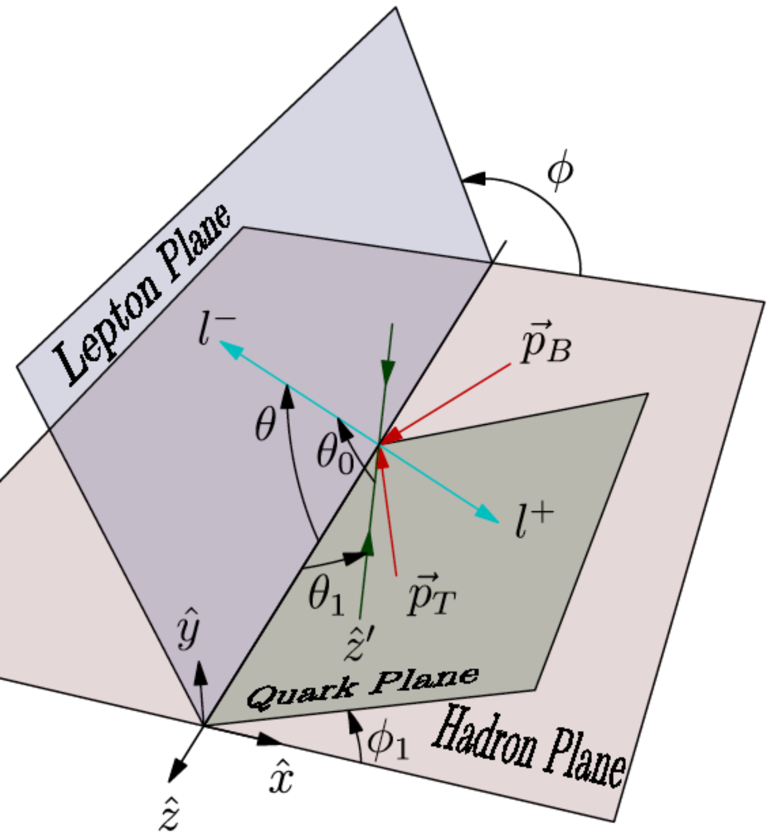
$$+ \frac{A_2}{2}\sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta$$

$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi$$

Questions:

- How is the above expression derived?
- Can one express $A_0 - A_7$ in terms of some quantities?
- Can one understand the q_T dependence of $A_0, A_1, A_2,$ etc?
- Can one understand the origin of the violation of Lam-Tung relation?

How is the angular distribution expression derived?



Define three planes in the Collins-Soper frame

1) Hadron Plane

- Contains the beam $\vec{P}_B$ and target $\vec{P}_T$ momenta
- Angle β satisfies the relation $\tan\beta = q_T / Q$

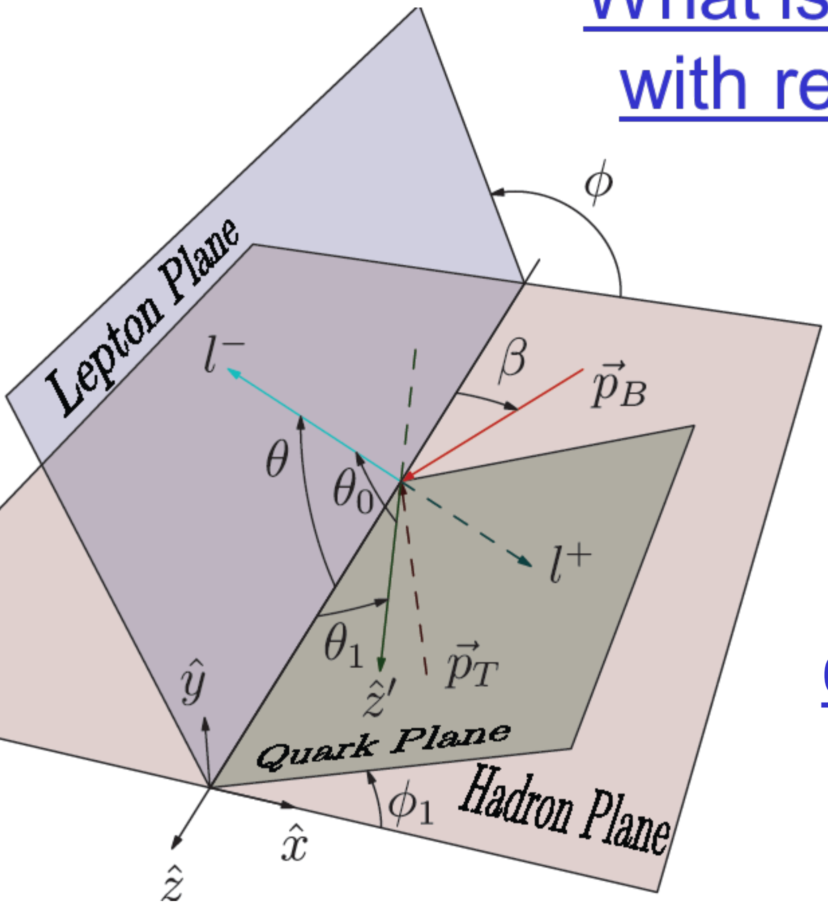
2) Quark Plane

- q and $\overline{q}$ have head-on collision along the $\hat{z}'$ axis
- $\hat{z}'$ axis has angles θ_1 and ϕ_1 in the C-S frame

3) Lepton Plane

- l^- and l^+ are emitted back-to-back with equal $|\vec{P}|$
- l^- and $\hat{z}$ form the lepton plane
- l^- is emitted at angle θ and ϕ in the C-S frame

How is the angular distribution expression derived?



What is the lepton angular distribution with respect to the $\hat{z}'$ (natural) axis?

$$\frac{d\sigma}{d\Omega} \propto 1 + a\cos\theta_0 + \cos^2\theta_0$$

Azimuthally symmetric !

How to express the angular distribution in terms of θ and ϕ?

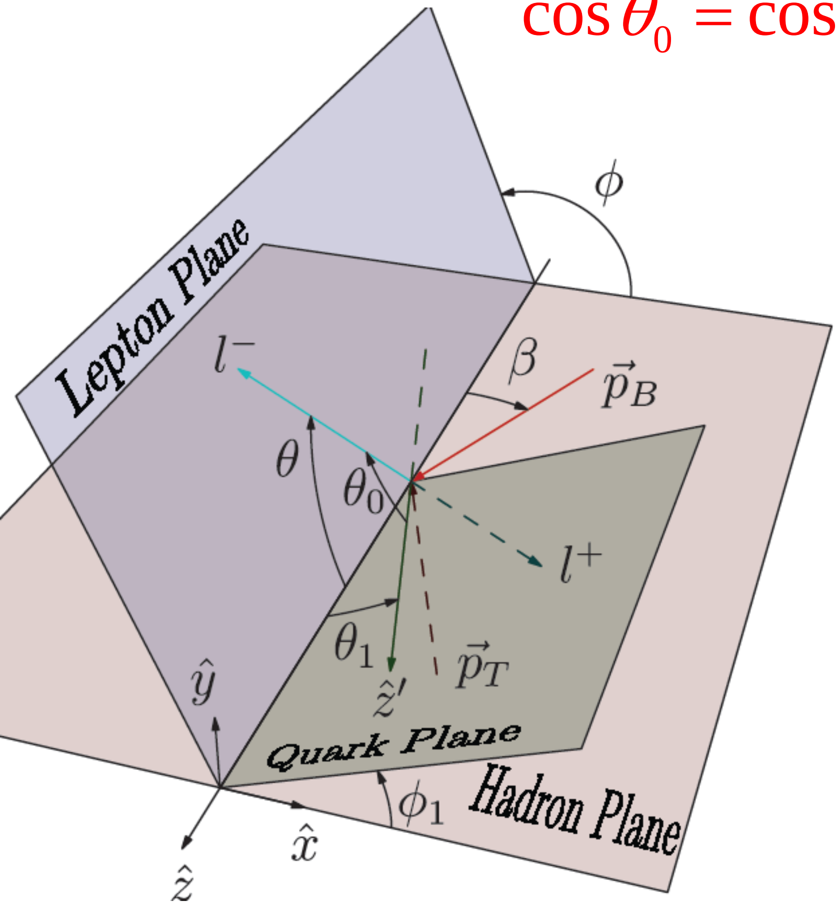
Use the following relation:

$$\cos\theta_0 = \cos\theta\cos\theta_1 + \sin\theta\sin\theta_1\cos(\phi - \phi_1)$$

How is the angular distribution expression derived?

$$\frac{d\sigma}{d\Omega} \propto 1 + a\cos\theta_0 + \cos^2\theta_0$$

$$\cos\theta_0 = \cos\theta\cos\theta_1 + \sin\theta\sin\theta_1\cos(\phi - \phi_1)$$



$$\begin{aligned}\frac{d\sigma}{d\Omega} \propto\ & (1+\cos^2\theta) + \frac{\sin^2\theta_1}{2}(1-3\cos^2\theta) \\ & + (\frac{1}{2}\sin 2\theta_1 \cos\phi_1)\sin 2\theta\cos\phi \\ & + (\frac{1}{2}\sin^2\theta_1\cos 2\phi_1)\sin^2\theta\cos 2\phi \\ & + (a\sin\theta_1\cos\phi_1)\sin\theta\cos\phi + (a\cos\theta_1)\cos\theta \\ & + (\frac{1}{2}\sin^2\theta_1\sin 2\phi_1)\sin^2\theta\sin 2\phi \\ & + (\frac{1}{2}\sin 2\theta_1\sin\phi_1)\sin 2\theta\sin\phi \\ & + (a\sin\theta_1\sin\phi_1)\sin\theta\sin\phi.\end{aligned}$$

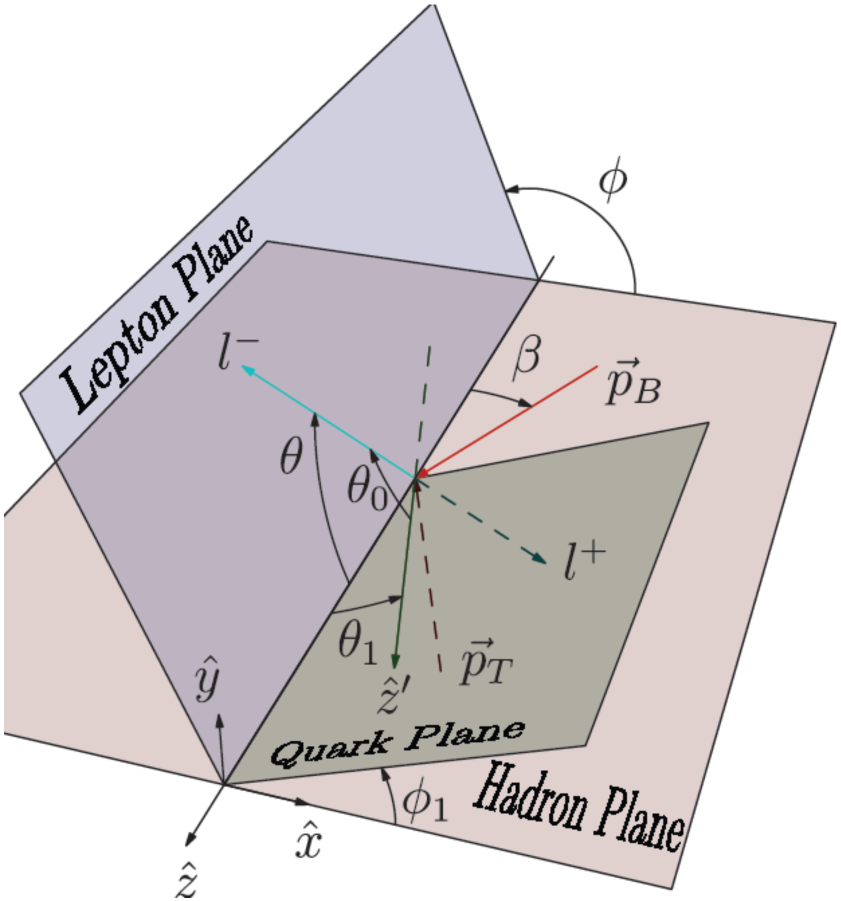
All eight angular distribution terms are obtained!

$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta) + \frac{\sin^2\theta_1}{2}(1-3\cos^2\theta)$$
$$+ (\frac{1}{2}\sin 2\theta_1 \cos\phi_1)\sin 2\theta\cos\phi$$
$$+ (\frac{1}{2}\sin^2\theta_1 \cos 2\phi_1)\sin^2\theta\cos 2\phi$$
$$+ (a\sin\theta_1\cos\phi_1)\sin\theta\cos\phi + (a\cos\theta_1)\cos\theta$$
$$+ (\frac{1}{2}\sin^2\theta_1 \sin 2\phi_1)\sin^2\theta\sin 2\phi$$
$$+ (\frac{1}{2}\sin 2\theta_1 \sin\phi_1)\sin 2\theta\sin\phi$$
$$+ (a\sin\theta_1\sin\phi_1)\sin\theta\sin\phi.$$

$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta)$$
$$+ A_1\sin 2\theta\cos\phi$$
$$+ \frac{A_2}{2}\sin^2\theta\cos 2\phi$$
$$+ A_3\sin\theta\cos\phi + A_4\cos\theta$$
$$+ A_5\sin^2\theta\sin 2\phi$$
$$+ A_6\sin 2\theta\sin\phi$$
$$+ A_7\sin\theta\sin\phi$$

$A_0 - A_7$ are entirely described by θ_1, ϕ_1 and a

Angular distribution coefficients $A_0 - A_7$



$$A_0 = \langle \sin^2\theta_1 \rangle$$

$$A_1 = \frac{1}{2}\langle \sin 2\theta_1 \cos\phi_1 \rangle$$

$$A_2 = \langle \sin^2\theta_1 \cos 2\phi_1 \rangle$$

$$A_3 = a\langle \sin\theta_1 \cos\phi_1 \rangle$$

$$A_4 = a\langle \cos\theta_1 \rangle$$

$$A_5 = \frac{1}{2}\langle \sin^2\theta_1 \sin 2\phi_1 \rangle$$

$$A_6 = \frac{1}{2}\langle \sin 2\theta_1 \sin\phi_1 \rangle$$

$$A_7 = a\langle \sin\theta_1 \sin\phi_1 \rangle$$

Some implications of the angular distribution coefficients $A_0 - A_7$

$$A_0 = \langle \sin^2\theta_1 \rangle$$

$$A_1 = \frac{1}{2}\langle \sin 2\theta_1 \cos\phi_1 \rangle$$

$$A_2 = \langle \sin^2\theta_1 \cos 2\phi_1 \rangle$$

$$A_3 = a\langle \sin\theta_1 \cos\phi_1 \rangle$$

$$A_4 = a\langle \cos\theta_1 \rangle$$

$$A_5 = \frac{1}{2}\langle \sin^2\theta_1 \sin 2\phi_1 \rangle$$

$$A_6 = \frac{1}{2}\langle \sin 2\theta_1 \sin\phi_1 \rangle$$

$$A_7 = a\langle \sin\theta_1 \sin\phi_1 \rangle$$

- $A_0 \geq A_2$ (or $1 - \lambda - 2\nu \geq 0$)
- Lam-Tung relation ($A_0 = A_2$) is satisfied when $\phi_1 = 0$
- Forward-backward asymmetry, a, is reduced by a factor of $\langle \cos\theta_1 \rangle$ for A_4
- A_5, A_6, A_7 are odd function of ϕ_1 and must vanish from symmetry consideration
- Some equality and inequality relations among $A_0 - A_7$ can be obatined

Some implications of the angular distribution coefficients $A_0 - A_7$

$$A_0 = \left\langle \sin^2\theta_1 \right\rangle$$

$$A_1 = \frac{1}{2}\left\langle \sin 2\theta_1 \cos\phi_1 \right\rangle$$

$$A_2 = \left\langle \sin^2\theta_1 \cos 2\phi_1 \right\rangle$$

$$A_3 = a\left\langle \sin\theta_1 \cos\phi_1 \right\rangle$$

$$A_4 = a\left\langle \cos\theta_1 \right\rangle$$

$$A_5 = \frac{1}{2}\left\langle \sin^2\theta_1 \sin 2\phi_1 \right\rangle$$

$$A_6 = \frac{1}{2}\left\langle \sin 2\theta_1 \sin\phi_1 \right\rangle$$

$$A_7 = a\left\langle \sin\theta_1 \sin\phi_1 \right\rangle$$

Some bounds on the coefficients can be obtained

$$0 < A_0 < 1$$

$$-1/2 < A_1 < 1/2$$

$$-1 < A_2 < 1$$

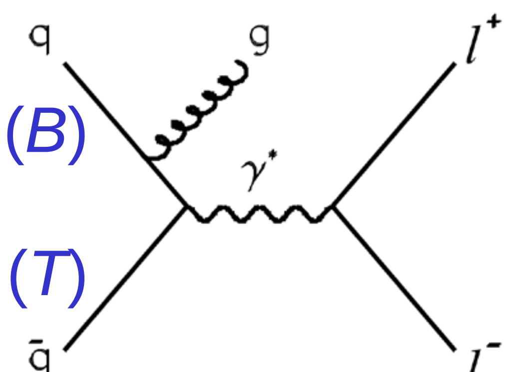
$$-a < A_3 < a$$

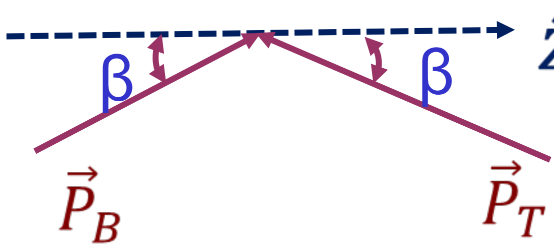
$$-a < A_4 < a$$

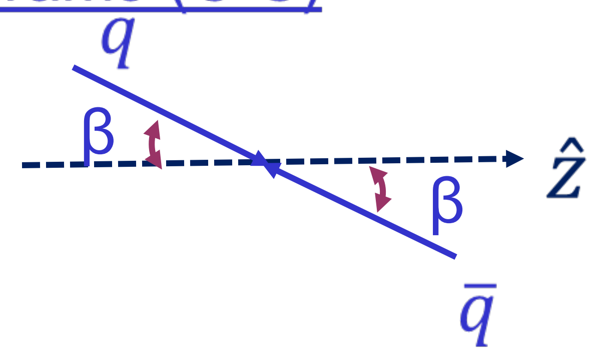
What are the values of θ_1 and ϕ_1 at order α_s?

1) $q\bar{q} \to \gamma^*(Z^0)g$

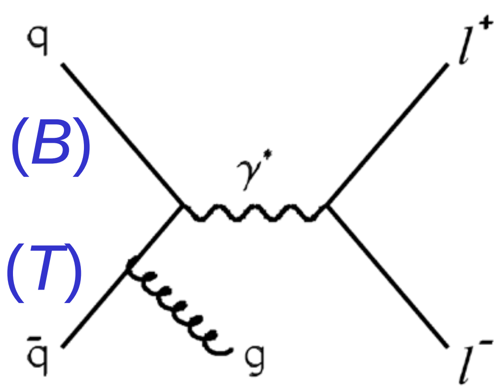
In γ^* rest frame (C-S)

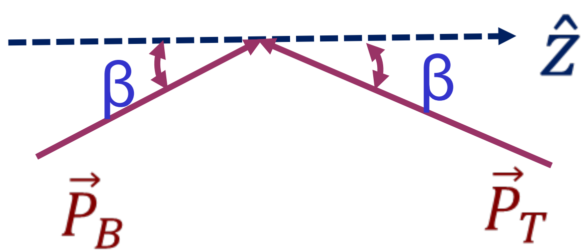


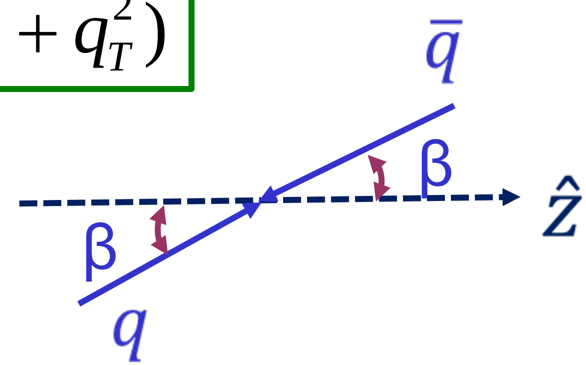




$$\sin^2\beta = q_T^2/(Q^2 + q_T^2)$$





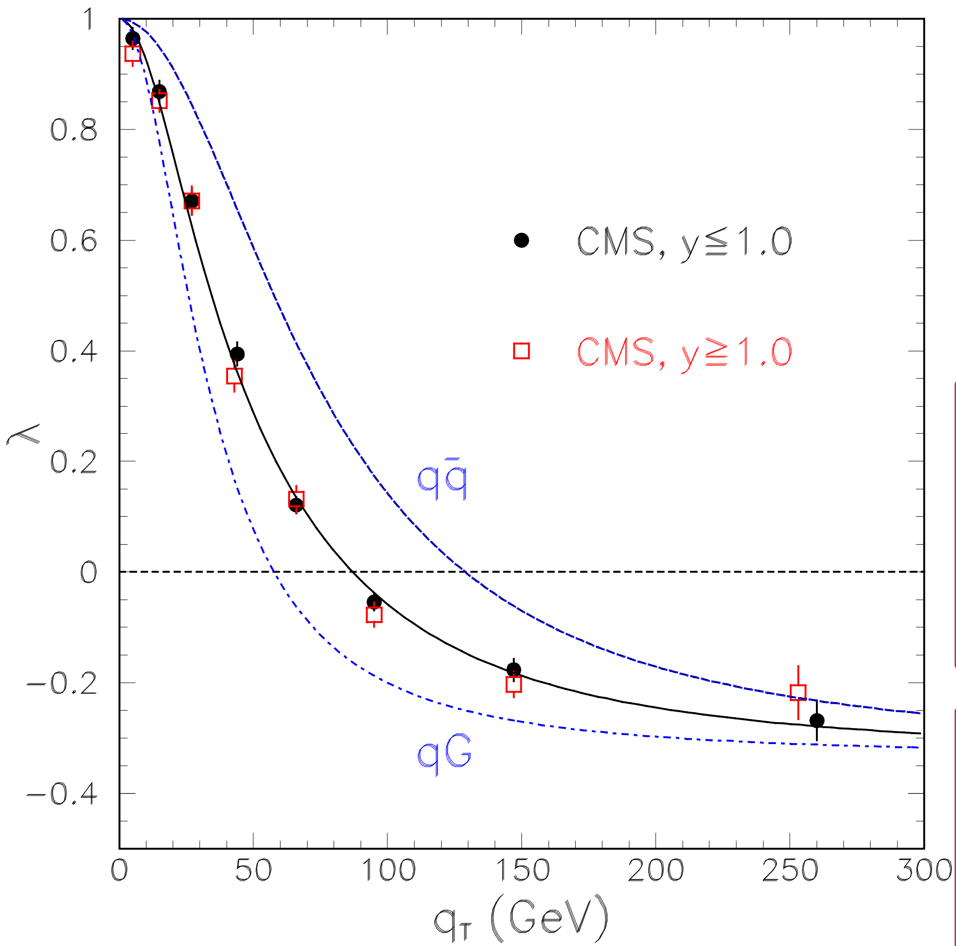


$\theta_1 = \beta$ and $\phi_1 = 0$; $A_0 = A_2 = \sin^2\beta$

$$\lambda = \frac{2-3A_0}{2+A_0} = \frac{2Q^2 - q_T^2}{2Q^2 + 3q_T^2}; \qquad \nu = \frac{2A_2}{2+A_0} = \frac{2q_T^2}{2Q^2 + 3q_T^2}$$

Compare with CMS data on λ

(*Z* production in *p*+*p* collision at 8 TeV)



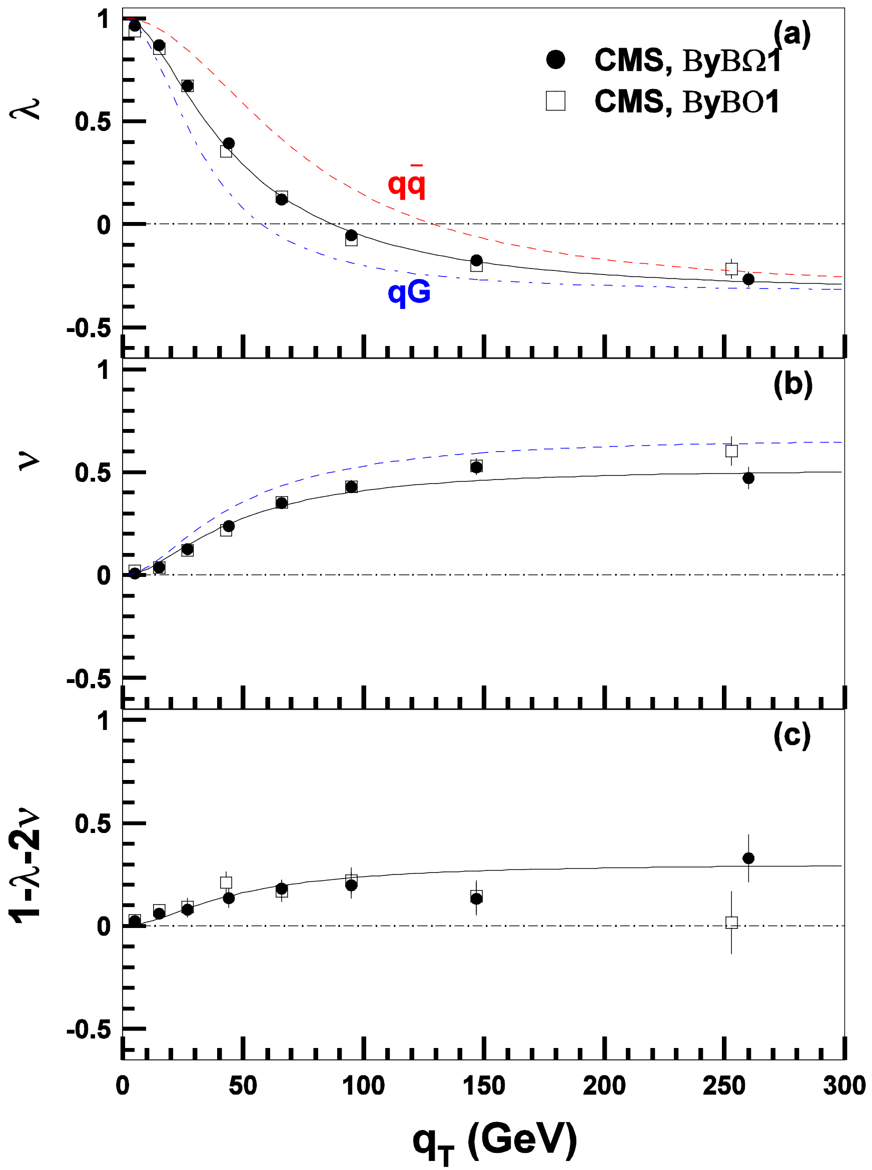
$$\lambda = \frac{2Q^2 - q_T^2}{2Q^2 + 3q_T^2} \quad \text{for} \quad q\bar{q} \to Zg$$

$$\lambda = \frac{2Q^2 - 5q_T^2}{2Q^2 + 15q_T^2} \quad \text{for} \quad qG \to Zq$$

For both processes
$\lambda = 1$ at $q_T = 0$ ($\theta_1 = 0^o$)
$\lambda = -1/3$ at $q_T = \infty$ ($\theta_1 = 90^o$)

Data can be well described with a mixture of 58.5% qG and 41.5% $q\bar{q}$ processes

Compare with CMS data on Lam-Tung relation

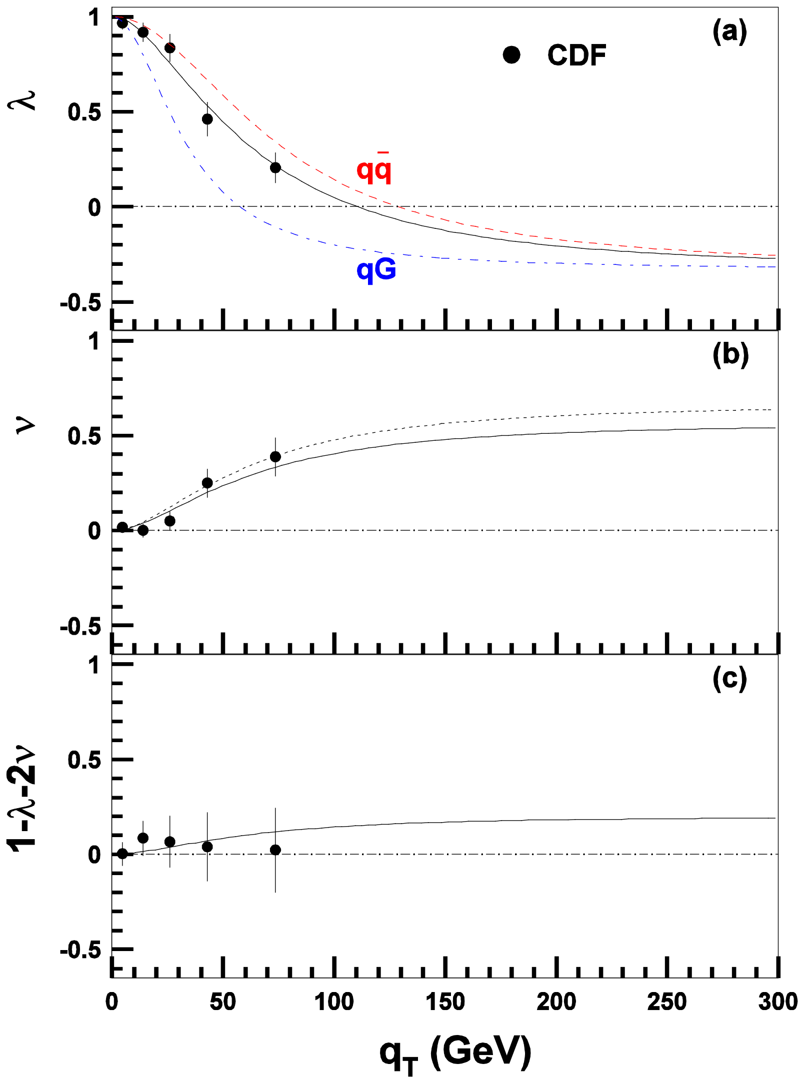


Solid curves correspond to a mixture of 58.5% qG and 41.5% $q\bar{q}$ processes, and $\langle \sin^2\theta_1 \cos 2\phi_1 \rangle / \langle \sin^2\theta_1 \rangle = 0.77$

Violation of Lam-Tung relation is well described

Compare with CDF data

(Z production in $p + \bar{p}$ collision at 1.96 TeV)

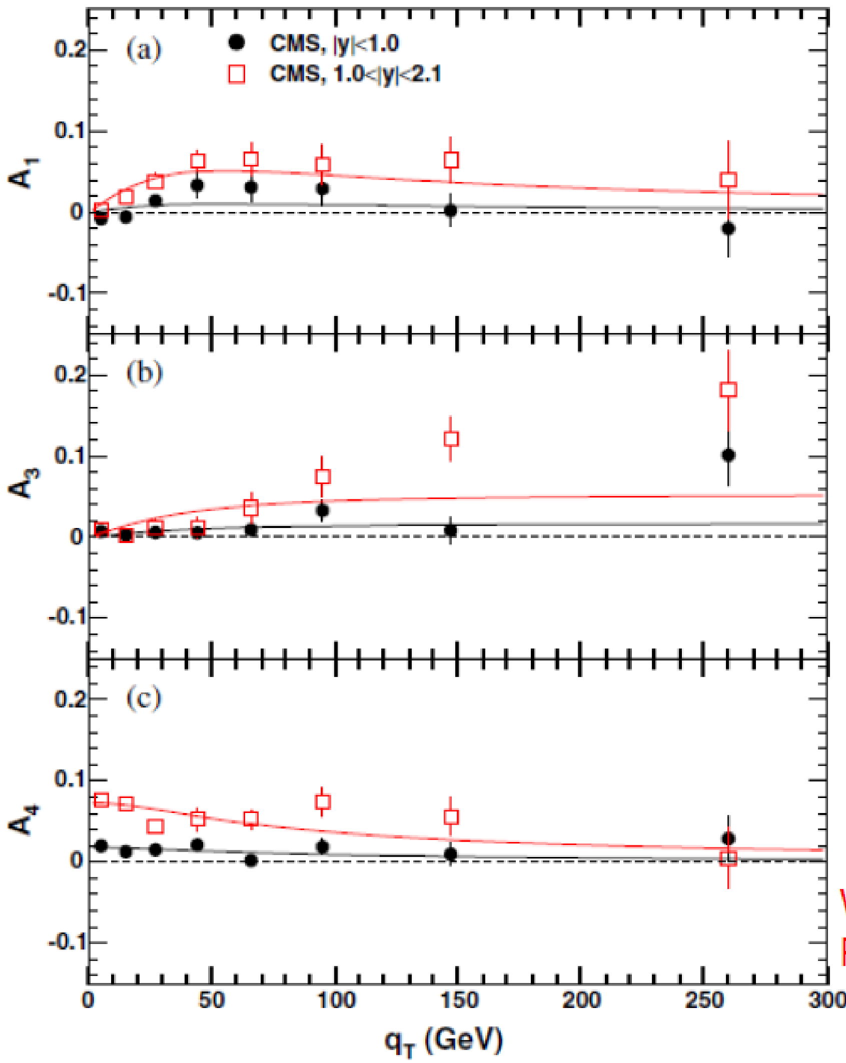


Solid curves correspond to a mixture of 27.5% qG and 72.5% $q\bar{q}$ processes, and

$$\left\langle \sin^2\theta_1 \cos 2\phi_1 \right\rangle / \left\langle \sin^2\theta_1 \right\rangle = 0.85$$

Violation of Lam-Tung relation is not ruled out

Compare with CMS data on A_1, A_3 and A_4



$$A_1 = r_1\left[f\frac{q_T Q}{Q^2+q_T^2} + (1-f)\frac{\sqrt{5}q_T Q}{Q^2+5q_T^2}\right]$$

$$A_3 = r_3\left[f\frac{q_T}{\sqrt{Q^2+q_T^2}} + (1-f)\frac{\sqrt{5}q_T}{\sqrt{Q^2+5q_T^2}}\right]$$

$$A_4 = r_4\left[f\frac{Q}{\sqrt{Q^2+q_T^2}} + (1-f)\frac{Q}{\sqrt{Q^2+5q_T^2}}\right]$$

Rapidity of A_1, A_3 and A_4 are well described

W.C. Chang, R.E. McClellan, J.C. Peng, O. Teryaev
Phys. Rev. D 96, 054020 (2017)

Future prospects

- Extend this study to W-boson production
  - Preliminary results show that the data can be well described
- Extend this study to fixed-target Drell-Yan data
  - Extraction of Boer-Mulders functions must take into account the QCD effects
- Extend this study to dihadron production in $e^- e^+$ collision (inverse of the Drell-Yan)
  - Analogous angular distribution coefficients and analogous Lam-Tung relation