Properites of Angular Distributions in Drell-Yan/Z Dilepton Production

SPIN2021

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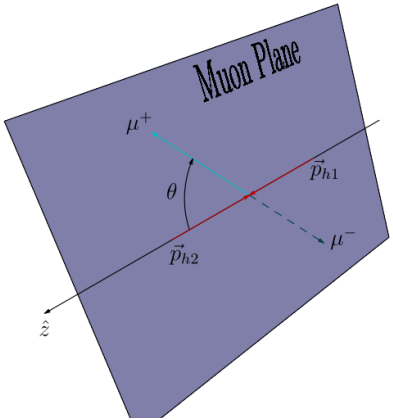
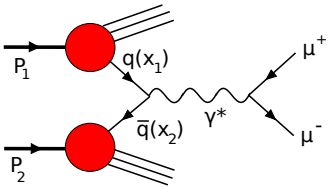
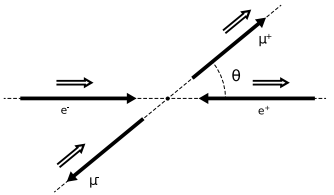
Presented on Behalf of:
Jen-Chieh Peng, Wen-Chen Chang, REM, Oleg Teryaev
(and featuring Daniël Boer and Yang Lyu)

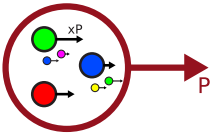
Collinear Drell-Yan Angular Distribution

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta$$

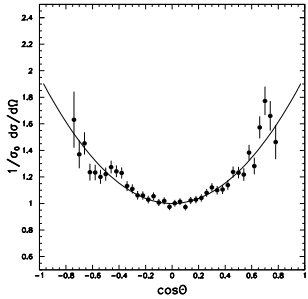








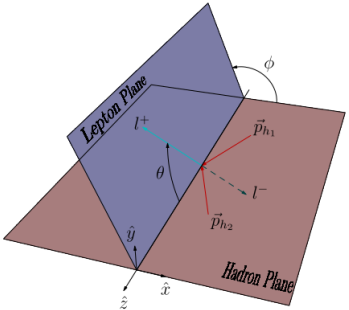
Fermilab E772



$\lambda = 0.96 \pm 0.04 \pm 0.06$

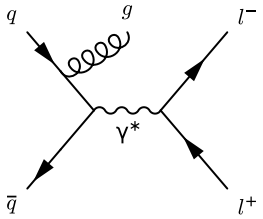
General Drell-Yan Angular Distribution

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



Collins-Soper Frame
(virtual photon rest frame)

- Non-zero photon p_T
- Polar angle: θ
- Azimuthal angle: ϕ



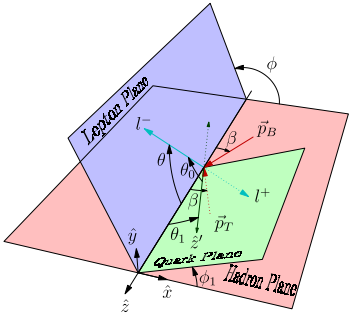
Lam-Tung Relation

$$\boldsymbol{\lambda = 1 - 2\nu}$$

- $\lambda \neq 1$ matched by $\nu \neq 0$
- Remains valid for first-order QCD corrections

Intuitive Geometric Interpretation

$$\frac{d\sigma}{d\Omega} \propto 1 + \cos^2\theta_0 \quad \rightarrow \quad \frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$



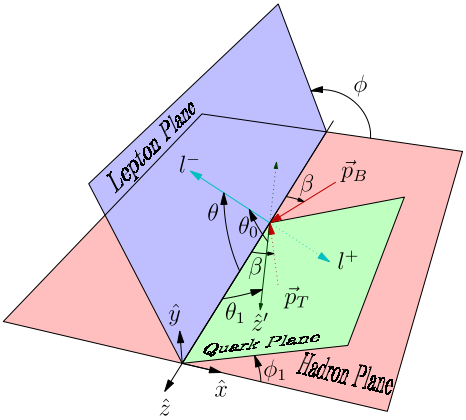
$$\frac{d\sigma}{d\Omega} \propto 1 + \left(\frac{2 - 3\sin^2\theta_1}{2 + \sin^2\theta_1}\right) \cos^2\theta + \left(\frac{\sin 2\theta_1 \cos\phi_1}{2 + \sin^2\theta_1}\right) \sin 2\theta \cos\phi + \left(\frac{\sin^2\theta_1 \cos 2\phi_1}{2 + \sin^2\theta_1}\right) \sin^2\theta \cos 2\phi$$

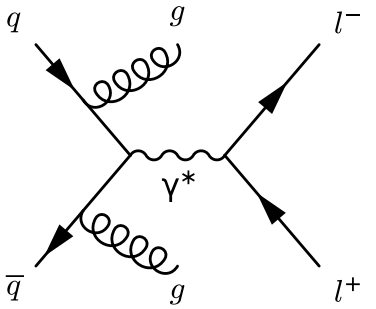
$$\lambda = \left(\frac{2-3\sin^2\theta_1}{2+\sin^2\theta_1}\right) \qquad \mu = \left(\frac{\sin 2\theta_1 \cos\phi_1}{2+\sin^2\theta_1}\right) \qquad \nu = \left(\frac{2\sin^2\theta_1 \cos 2\phi_1}{2+\sin^2\theta_1}\right)$$

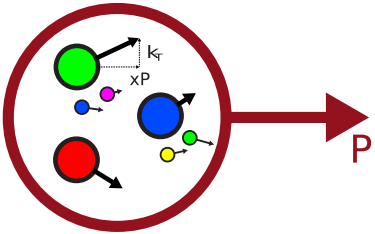
Prediction:
Non-coplanarity modifies ν, not λ

Note: If $\cos 2\phi_1 = 0$ then $\lambda = 1 - 2\nu$

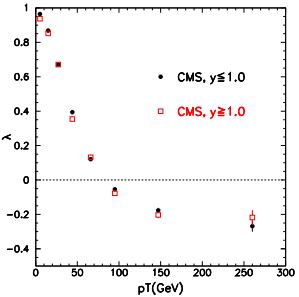
Non-coplanarity and Lam-Tung Violation

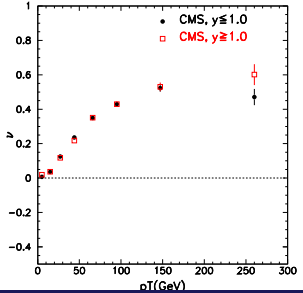




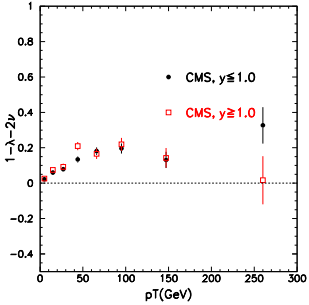


High-p_T, Precise "Drell-Yan" from CMS



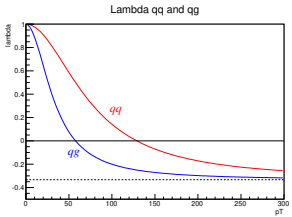


CMS Collaboration, Phys. Lett.B750,154 (2015)
ATLAS Collaboration, JHEP 08 (2016) 159
Z-boson "Drell-Yan" $M = M_Z = 91.2\,\mathrm{GeV}$



- Striking λ and ν p_T-shapes
- Clear Lam-Tung violation
- Boer-Mulders? **No!**
- TMDs only affect low-p_T ($\boldsymbol{p_T \sim k_T}$)

p_T-Dependence of $\mathcal{O}(\alpha_s)$ Processes



Thews (1979), Lindfors (1979)

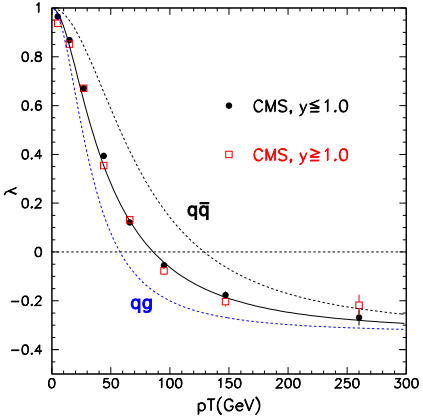
$$\lambda_{q\bar{q}} = \frac{2M_Z^2 - p_T^2}{2M_Z^2 + 3p_T^2} \quad \lambda_{qg} \approx \frac{2M_Z^2 - 5p_T^2}{2M_Z^2 + 15p_T^2}$$

$$\nu_{q\bar{q}} = \frac{2p_T^2}{2M_Z^2 + 3p_T^2} \quad \nu_{qg} \approx \frac{10p_T^2}{2M_Z^2 + 15p_T^2}$$

Lam-Tung still valid

Interpretation of Angular Distributions of Z-boson Production at Colliders

Jen-Chieh Peng,[1] Wen-Chen Chang,[2] Randall Evan McClellan,[1] and Oleg Teryaev[3]

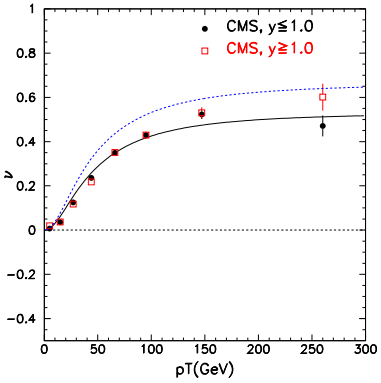


$$q\bar{q} = 41.5 \pm 1.6\%$$
$$qg = 58.5 \pm 1.6\%$$

$$\lambda = \left\langle \frac{2 - 3\sin^2\theta_1}{2 + \sin^2\theta_1} \right\rangle$$

- Data lies between $q\bar{q}$ and qg curves
- Combination explains p_T-dependence well

p_T-Dependence of ν



$\frac{\lambda}{1-2\nu} = 1$

$\frac{\lambda}{1-2\nu} = \mathbf{0.77}$

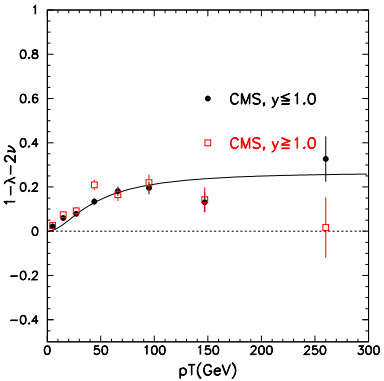
$$\nu = \left\langle \frac{2\sin^2\theta_1 \cos 2\phi_1}{2+\sin^2\theta_1} \right\rangle$$

- $q\bar{q} + qg$ combination alone (blue) doesn't match ν p_T-distribution
- Allowing Lam-Tung violation to reduce ν:

$$\frac{\lambda}{1-2\nu} = \mathbf{0.77 \pm 0.02}$$

Higher-order QCD Contributions

p_T-Dependence of Lam-Tung Violation



$$q\bar{q} = 41.5 \pm 1.6\%$$

$$qg = 58.5 \pm 1.6\%$$

$$\frac{\lambda}{1-2\nu} = 0.77 \pm 0.02$$

- $\mathcal{O}(\alpha_s)$ $q\bar{q}$ and qg, plus reduction of ν due to higher-orders
- Lam-Tung violation in high-p_T Z-boson "Drell-Yan" requires no non-perturbative effects

Follow-up Publications

- p_T and rapidity dependence
- Rotationally Invariant Expressions
- Fixed Target data and Perturbative QCD
- quark vs gluon jet discrimination
- W-boson production

Collider Parameters: A0-A7

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

$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta) + \frac{1}{2}\sin^2\theta_1(1-3\cos^2\theta) + \frac{1}{2}\sin 2\theta_1\cos\phi_1\sin 2\theta\cos\phi + \frac{1}{2}\sin^2\theta_1\cos 2\phi_1\sin^2\theta\cos 2\phi + (A_4...A_5...A_6...A_7)$$

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

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

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

$$\lambda = \frac{2-3A_0}{2+A_0}$$

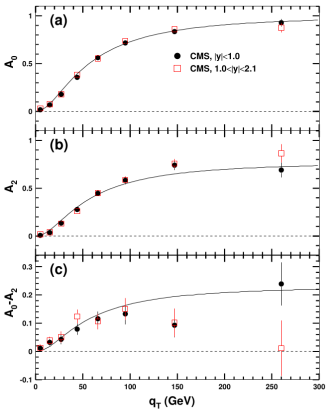
$$\mu = \frac{2A_1}{2+A_0}$$

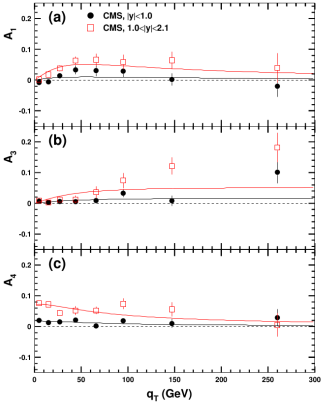
$$\nu = \frac{2A_2}{2+A_0}$$

Rapidity-Dependence

Dependencies of lepton angular distribution coefficients on the transverse momentum and rapidity of Z bosons produced in pp collisions at the LHC

Wen-Chen Chang,[1] Randall Evan McClellan,[2,3] Jen-Chieh Peng,[2] and Oleg Teryaev[4]





Phys.Rev.D 96 (2017) 5, 054020
arXiv:1708.05807

- Qualitatively describe the rapidity-dependence of A_1, A_3, and A_4

Rotational Invariance and Non-Invariance

On the Rotational Invariance and Non-Invariance of Lepton Angular Distributions in Drell-Yan and Quarkonium Production

Jen-Chieh Peng[a], Daniël Boer[b], Wen-Chen Chang[c], Randall Evan McClellan[a,d], Oleg Teryaev[e]

- Angular Parameters are *frame-dependent*
- Magnitude of Lam-Tung violation is also
- Center of Mass frames:
  - Collins-Soper
  - Gottfried-Jackson
  - Helicity
- All frames share a common y-axis
- Can express results in terms of rotation invariants

(Faccioli et al 2010, 2011)

$$F = \frac{1+\lambda+\nu}{3+\lambda} = \frac{1+\lambda_0-2\lambda_0 y_1^2}{3+\lambda_0}$$

$$\tilde{\lambda} = \frac{2\lambda+3\nu}{2-\nu} = \frac{\lambda_0-3\lambda_0 y_1^2}{1+\lambda_0 y_1^2}$$

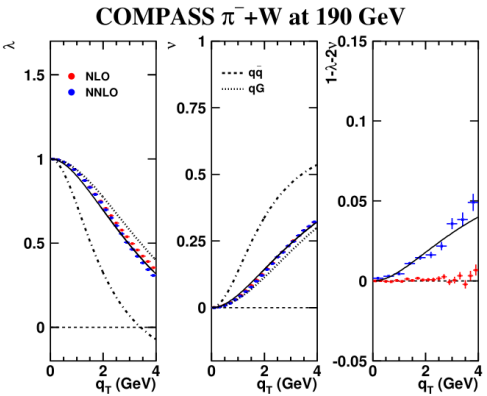
$$\tilde{\lambda}' = \frac{(\lambda-\nu/2)^2+4\mu^2}{(3+\lambda)^2} = \frac{\lambda_0^2(1-y_1^2)^2}{(3+\lambda_0)^2}$$

Phys.Lett.B 789 (2019) 356-359, arXiv:1808.04398

Compare with Perturbative QCD

Lepton angular distributions of fixed-target Drell-Yan experiments in perturbative QCD and a geometric approach

Wen-Chen Chang,[1] Randall Evan McClellan,[2,3] Jen-Chieh Peng,[3] and Oleg Teryaev[4]

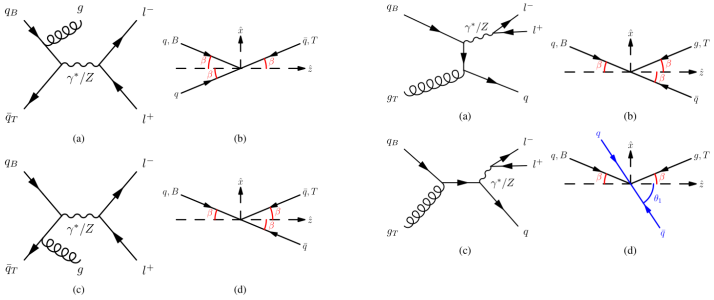


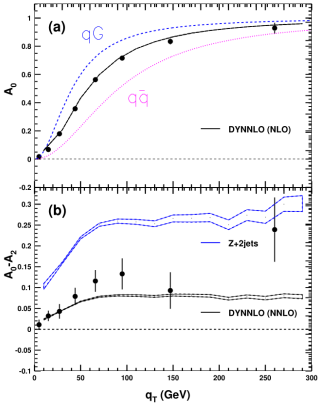
Phys.Rev.D 99 (2019) 1, 014032
arXiv:1811.03256

- Fixed-Target Kinematics
- Zero Lam-Tung violation for NLO
- Large Lam-Tung violation for NNLO
- This Lam-Tung violation is *purely perturbative*

Lepton angular distribution of Z boson production and jet discrimination

Jen-Chieh Peng,[1] Wen-Chen Chang,[2] Randall Evan McClellan,[1,3] and Oleg Teryaev[4]

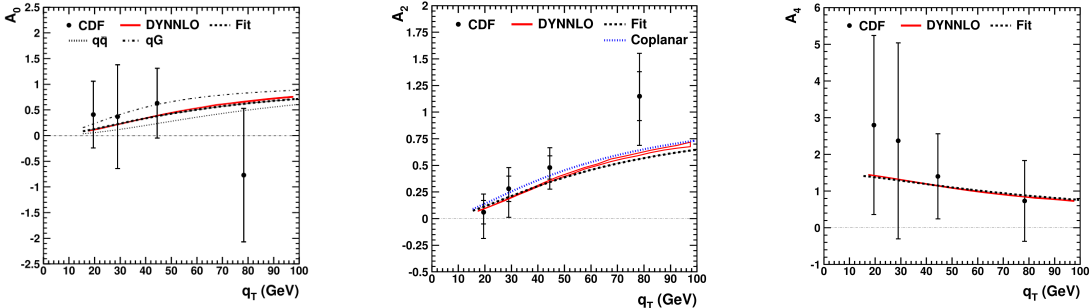




Phys.Lett.B 979 (2019) 134895, arXiv:1907.10483

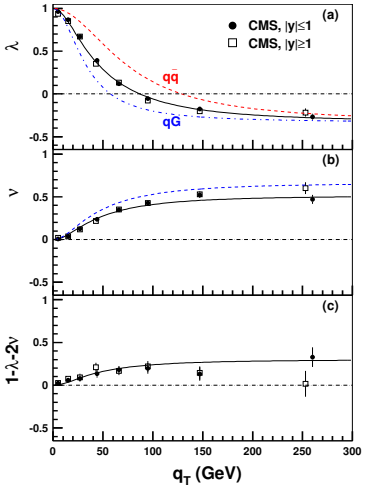
Lepton angular distribution of W boson productions

Yang Lyu,[1,2] Wen-Chen Chang,[3] Randall Evan McClellan,[1,4] Jen-Chieh Peng,[1] and Oleg Teryaev[5]



Phys.Rev.D 103 (2021) 3, 034011, arXiv:2010.01826

Recap and Outlook



Recap

- Contribution of $\mathcal{O}(\alpha_s^2)$ and higher can cause Lam-Tung violation
- p_T-dependence
- Rapidity-dependence, pQCD comparison
- Rotation-invariant parameter expressions
- quark-jet vs gluon-jet discrimination
- Describe W-boson production

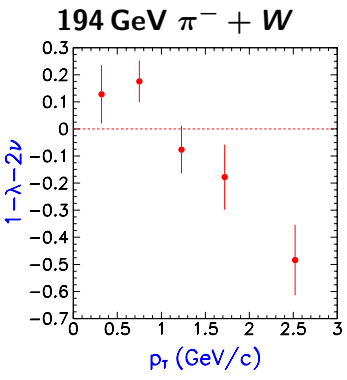
Outlook

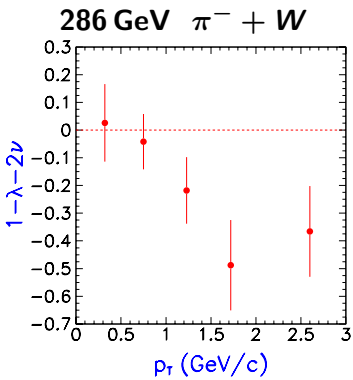
- Extend to DIS, SIDIS
- Non-coplanar parameter equalities/inequalities
- Single-jet vs Multi-jet discrimination
- Intrinsic-k_T, TMD implications

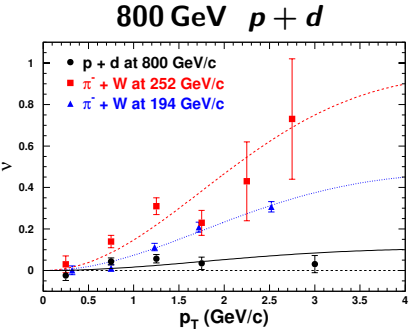
Backup

Lam-Tung Violation

CERN NA10, pion-induced Drell-Yan







$$1 - \lambda - 2\nu \neq 0$$

Evidence of Non-Perturbative effects in Drell-Yan angular distributions