QCD Effects in Lepton Angular Distributions of Drell-Yan/Z Production and Jet Discrimination

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collaborating with

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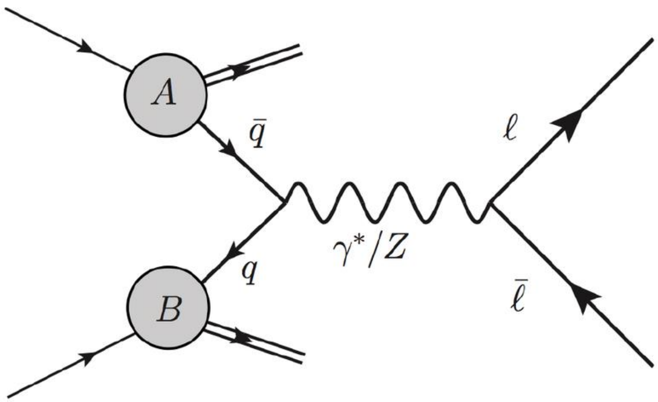
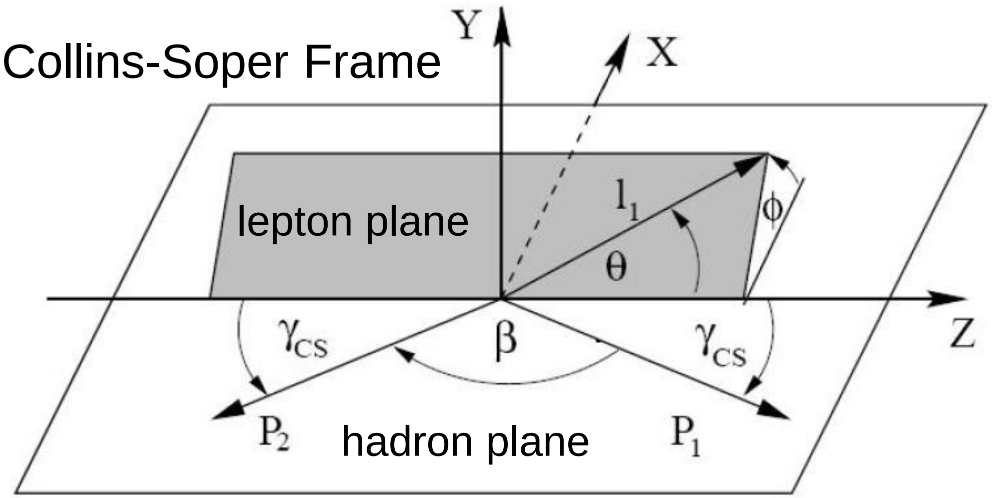
Lepton angular distributions of Drell-Yan process





$$\frac{d\sigma}{d\Omega} \propto (1+\lambda\cos^2\theta+\mu\sin2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos2\phi)$$

$$\propto [(1+\cos^2\theta)+\frac{A_0}{2}(1-3\cos^2\theta)+A_1\sin2\theta\cos\phi+\frac{A_2}{2}\sin^2\theta\cos2\phi]$$

LO $q\bar{q}$ annilation parton model: $O(\alpha_s^0)$ $\lambda=1,\ \mu=\nu=0$; $A_0=A_1=A_2=0$

$$\lambda=\frac{2-3A_0}{2+A_0} \qquad \mu=\frac{2A_1}{2+A_0} \qquad \nu=\frac{2A_2}{2+A_0}$$

Angular Distributions of Lepton Pairs from Z/γ^*

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

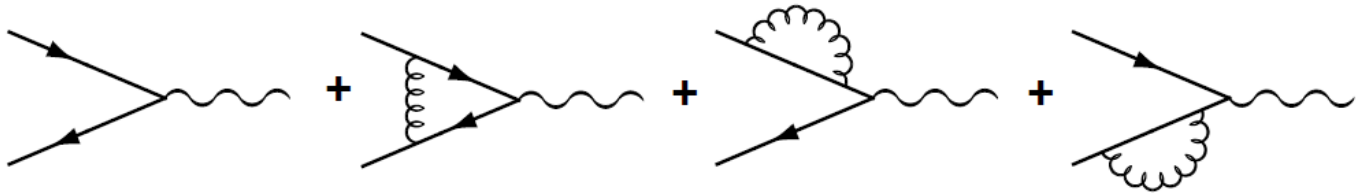
$$+ A_3 \sin\theta\cos\phi + A_4\cos\theta$$

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

$A_3, A_4 : \gamma^* / Z$ interference, sensitive to $\sin^2\theta_W$

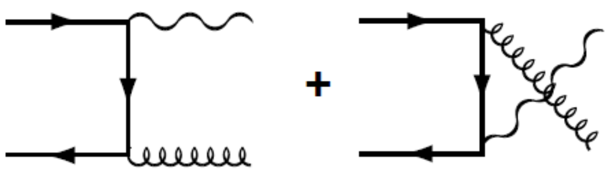
$A_5, A_6, A_7 := 0$, up to $O(\alpha_s^1)$

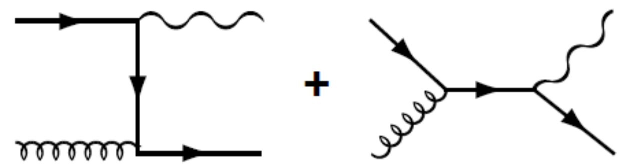
Drell-Yan Process with $O(\alpha_s^1)$ QCD Effect



(a) $q\bar{q} \to \gamma^*$

Quark-antiquark ($q\bar{q}$) annihilation with the virtual gluon correction





(b) $q\bar{q} \to G\gamma^*$

Quark-antiquark ($q\bar{q}$) annihilation with one real gluon

(c) $qG \to q\gamma^*$

Quark-gluon (qG) Compton scattering

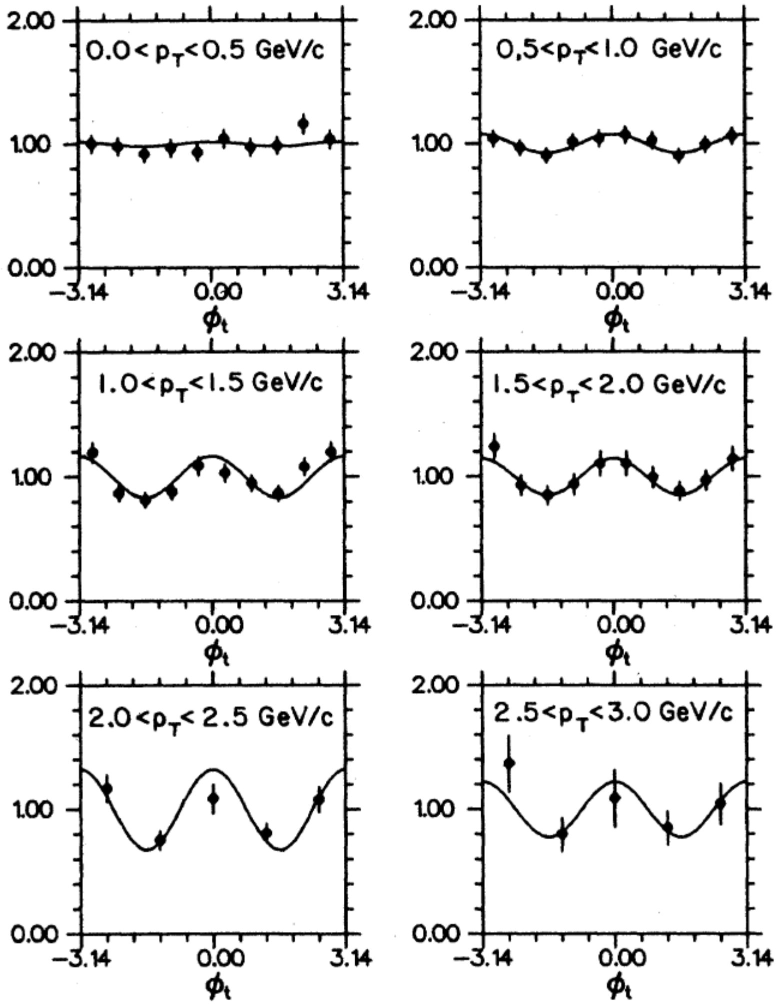
pQCD: $O(\alpha_s^1)$, ; $1-\lambda-2\nu = \dfrac{4(A_0 - A_2)}{2 + A_0} = 0$; $A_0 = A_2$

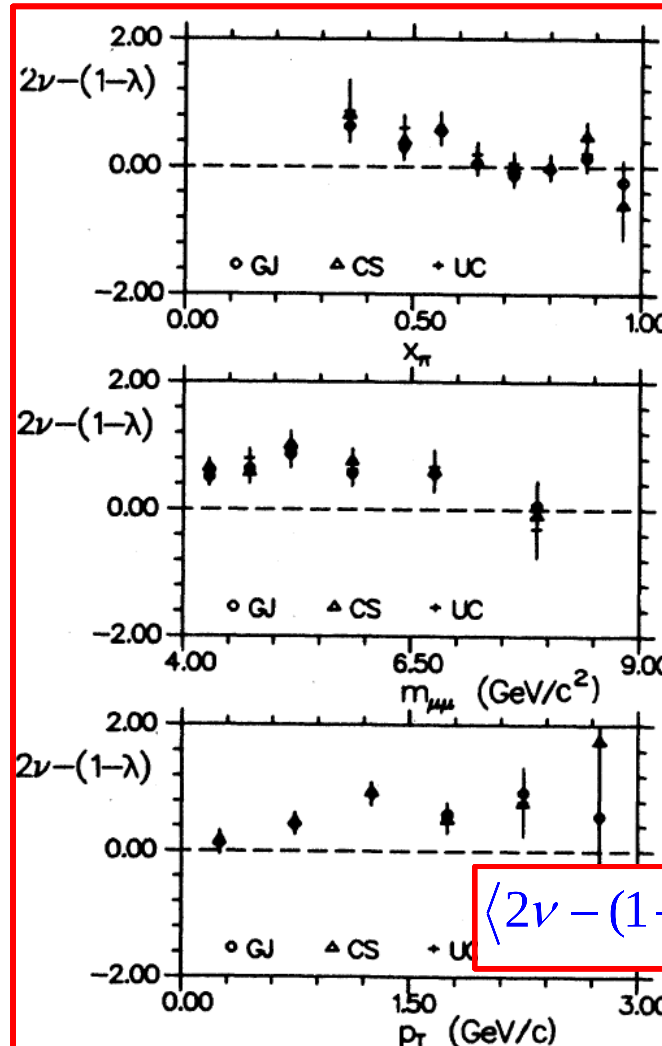
Lam-Tung Relation [PRD 18 (1978) 2447]

252-GeV π^-+W (fixed-target)

E615 @ FNAL: Violation of LT Relation

PRD 39, 92 (1989)



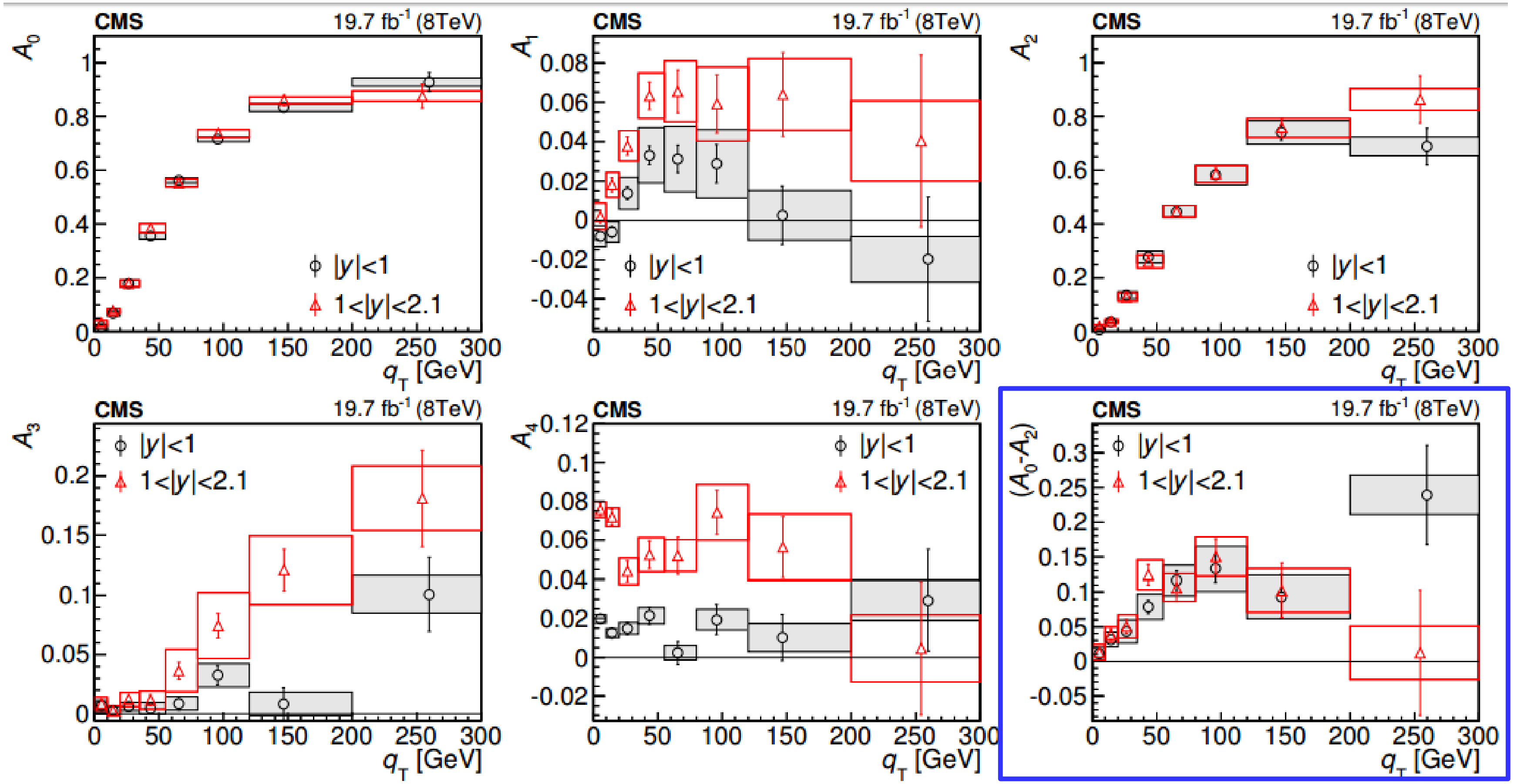


$$\langle 2\nu-(1-\lambda)\rangle_{\pi+p} > 0$$

$\cos 2\phi$ modulation at large p_T

Angular Distributions of Z Production

CMS, PLB750, 154 (2015)



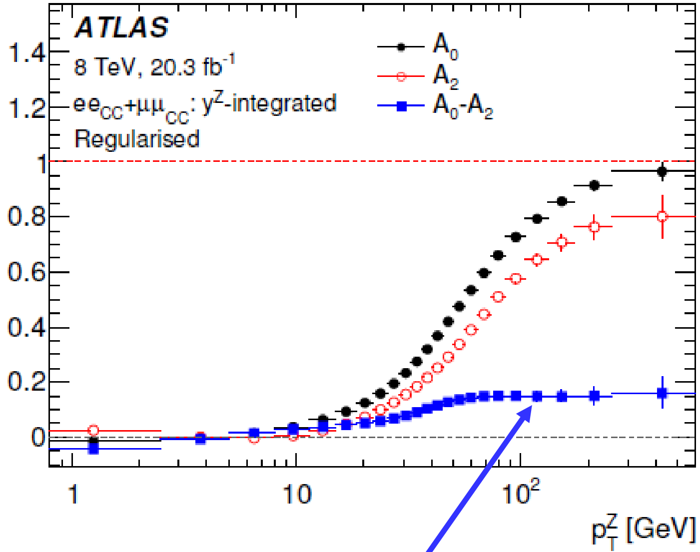
A_1, A_3 and A_4 show y-dependence, but not A_0 and A_2.

Violation of Lam-Tung relation

$A_0 \neq A_2$

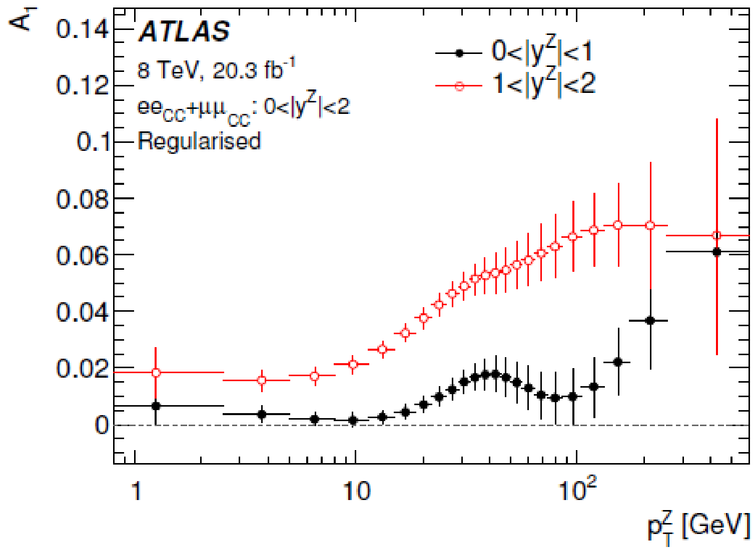
Angular Distributions of Z Production

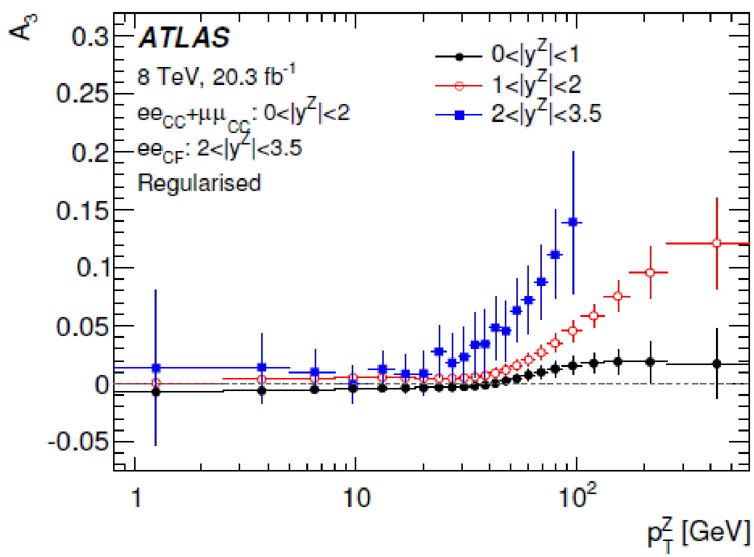
ATLAS, JHEP08, 159 (2016)



Violation of Lam-Tung relation

$$A_0 \neq A_2$$





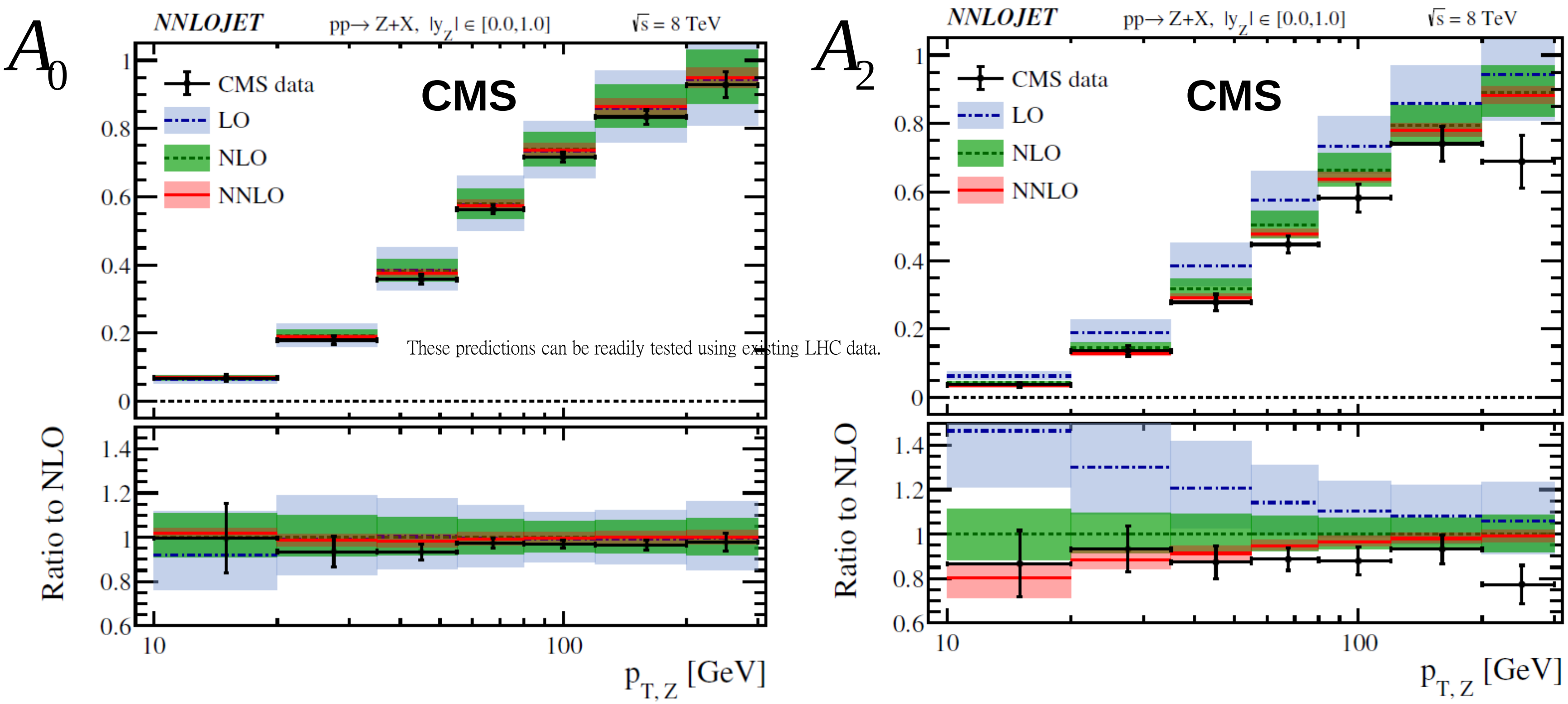
A_1 and A_3 show y-dependence.

Drell-Yan Angular Distributions

- Features:
  - Distinctive q_T dependence.
  - Lam-Tung violation:
    - $1 - \lambda - 2\nu \neq 0$ for fixed-target experiments
    - $A_0 - A_2 \neq 0$ for collider experiments.
  - Rapidity dependence for A_1, A_3, and A_4.
- Can these features be understood by pQCD?
- Is there any simple picture for interpretation?

CMS vs. NNLO:$O(\alpha_s^3)$

$LO:O(\alpha_s^1)$; $NLO:O(\alpha_s^2)$; $NNLO:O(\alpha_s^3)$

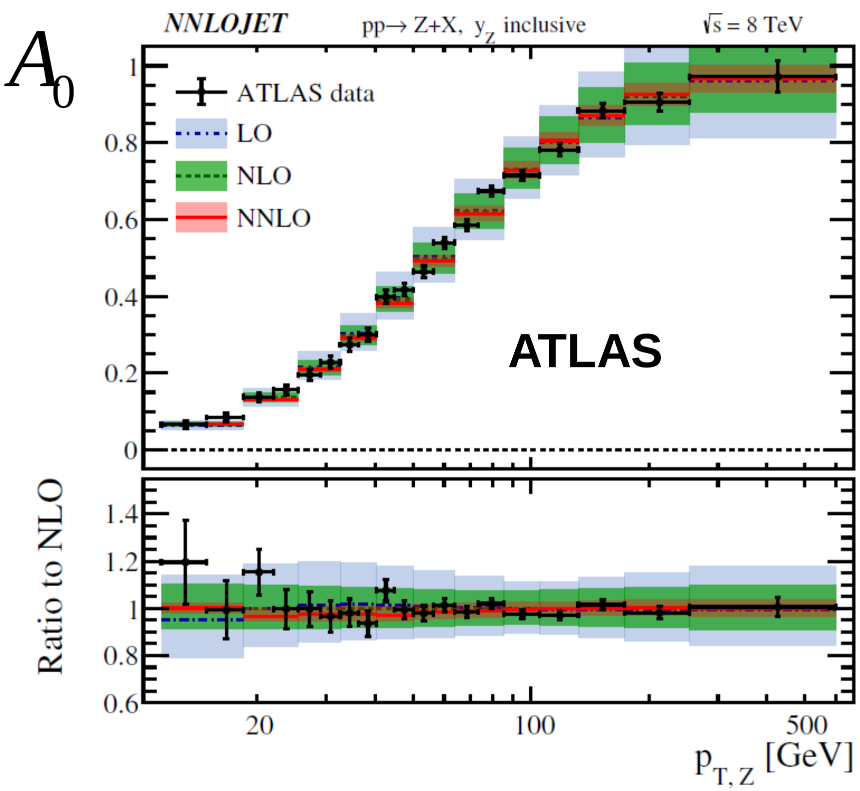


$A_0(LO) \approx A_0(NLO) \approx A_0(NNLO)$ $A_2(LO) > A_2(NLO) > A_2(NNLO)$

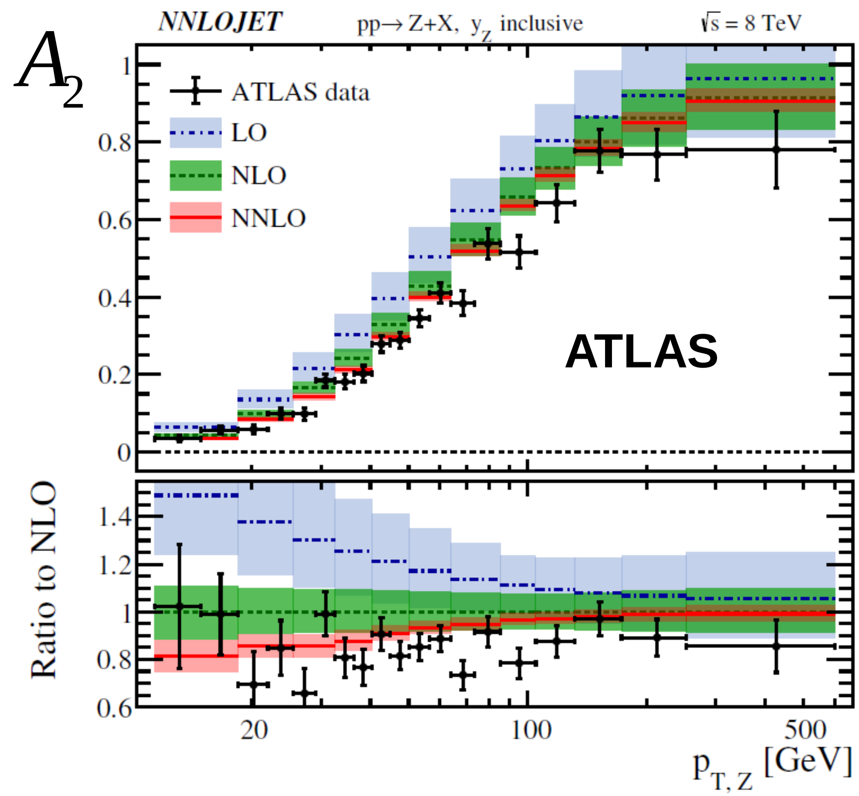
JHEP11(2017)003

ATLAS vs. NNLO:$O(\alpha_s^3)$

$LO : O(\alpha_s^1)$; $NLO : O(\alpha_s^2)$; $NNLO : O(\alpha_s^3)$



$A_0(LO) \approx A_0(NLO) \approx A_0(NNLO)$



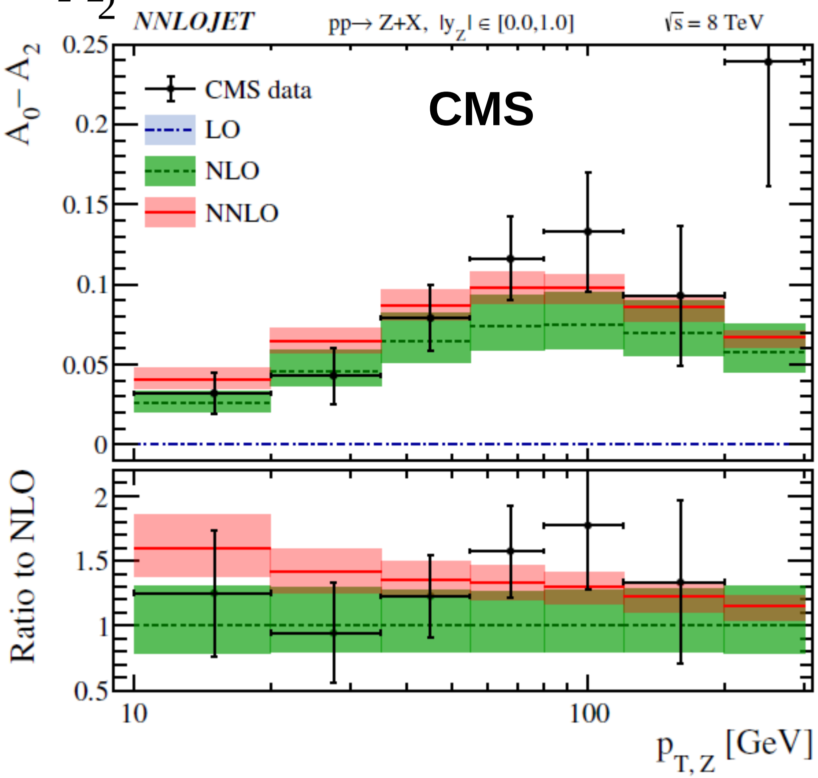
$A_2(LO) > A_2(NLO) > A_2(NNLO)$

JHEP11(2017)003

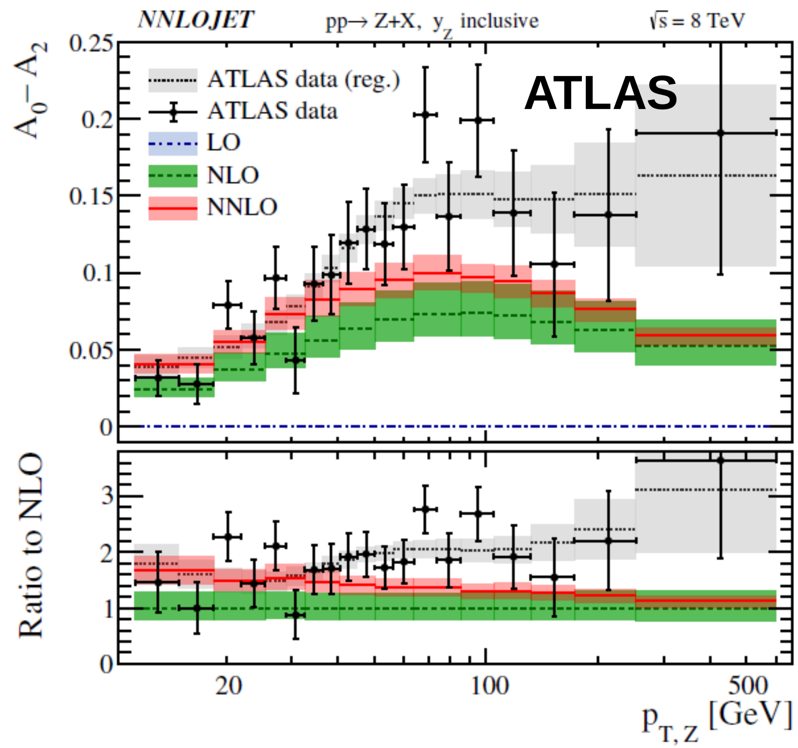
Lam-Tung Violation: $A_0 - A_2$

$LO: O(\alpha_s^1)$; $NLO: O(\alpha_s^2)$; $NNLO: O(\alpha_s^3)$

$A_0 - A_2$



$A_0 - A_2$

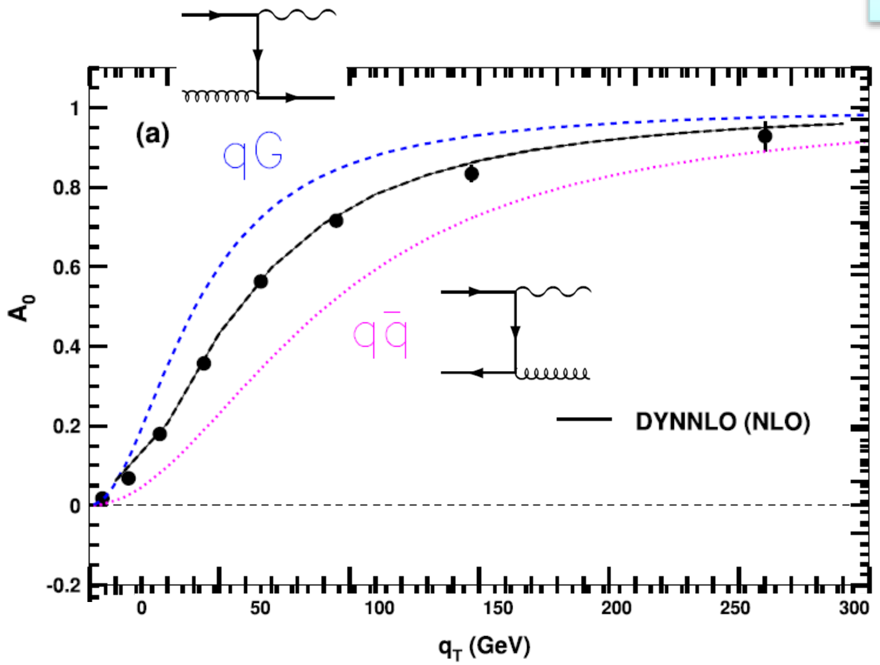


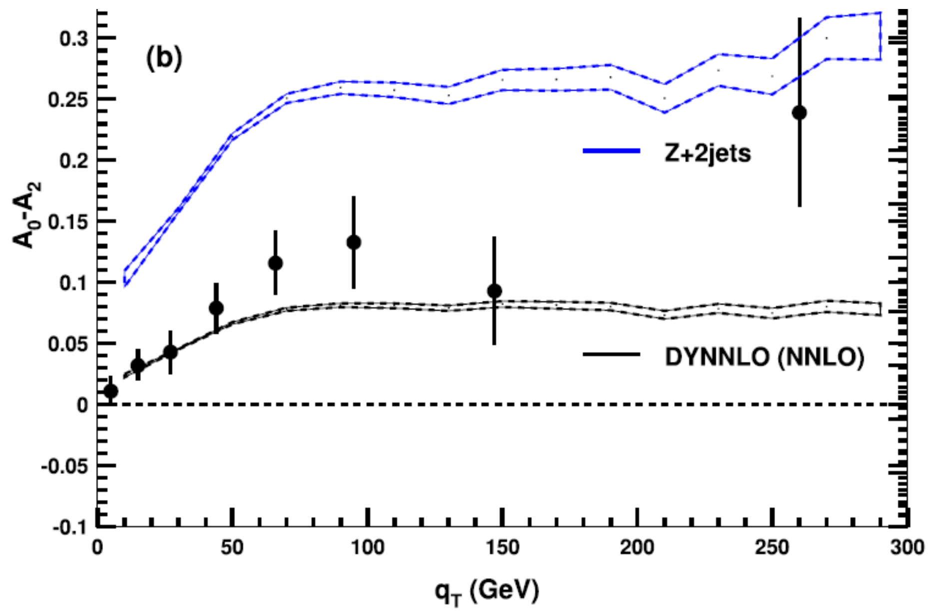
NLO (CMS):	$\chi^2/N_{\rm data} = 24.5/14 = 1.75$	NLO (ATLAS):	$\chi^2/N_{\rm data} = 185.8/38 = 4.89$
NNLO (CMS):	$\chi^2/N_{\rm data} = 14.2/14 = 1.01$	NNLO (ATLAS):	$\chi^2/N_{\rm data} = 68.3/38 = 1.80$.

JHEP11(2017)003

CMS: Z + jet(s)

$(A_0 - A_2)_{Z+2jets} \gg (A_0 - A_2)_{Z+X}$



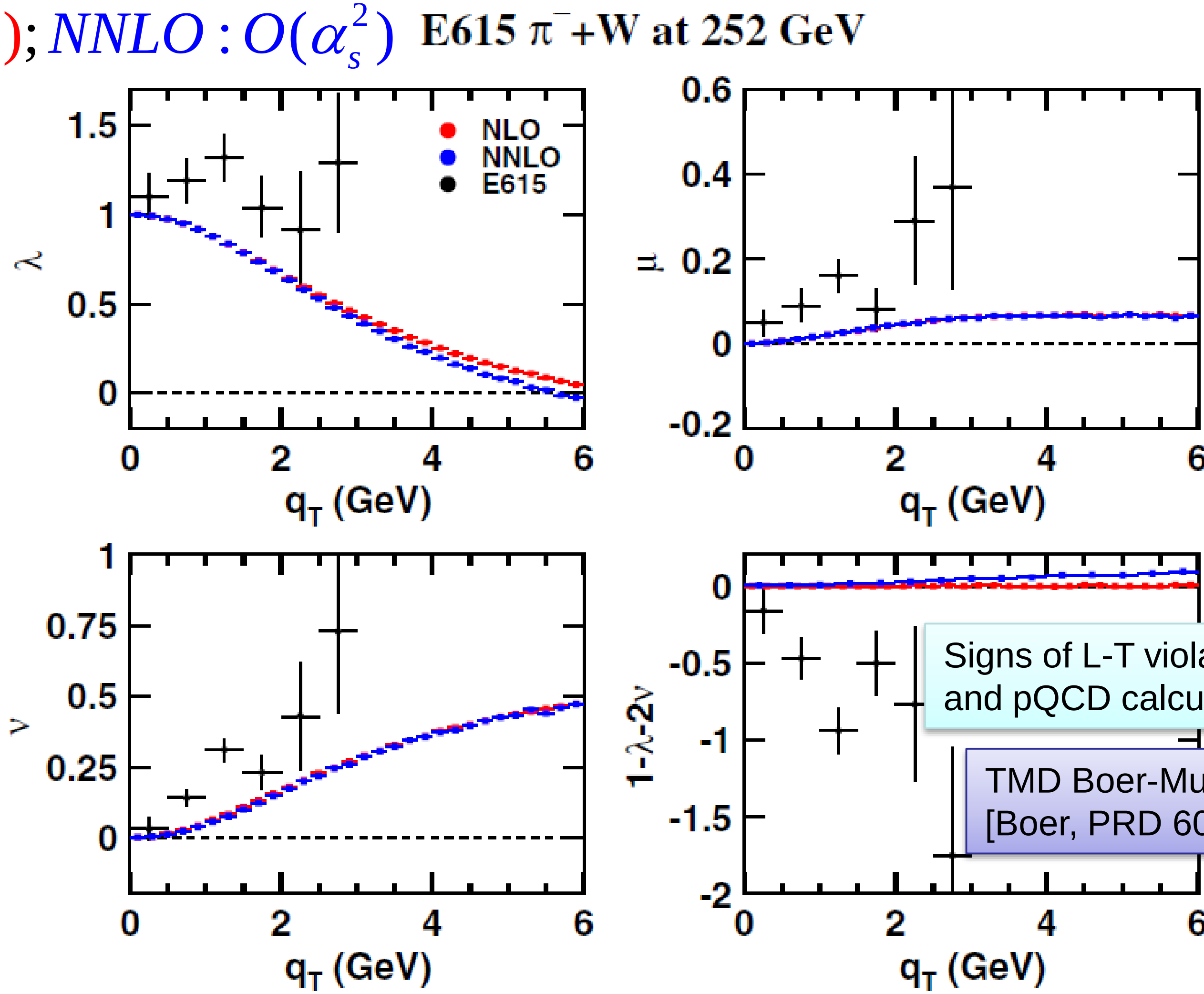


$A_0^{Z+\,q-jet} \neq A_0^{Z+\,G-jet}$

J.C. Peng et al., PLB 797, 134895 (2019)

E615 vs. NNLO: $O(\alpha_s^2)$

$NLO : O(\alpha_s^1)$; $NNLO : O(\alpha_s^2)$



Signs of L-T violation for the data and pQCD calculations are opposite!

TMD Boer-Mulders Effect [Boer, PRD 60, 014012 (1999)]

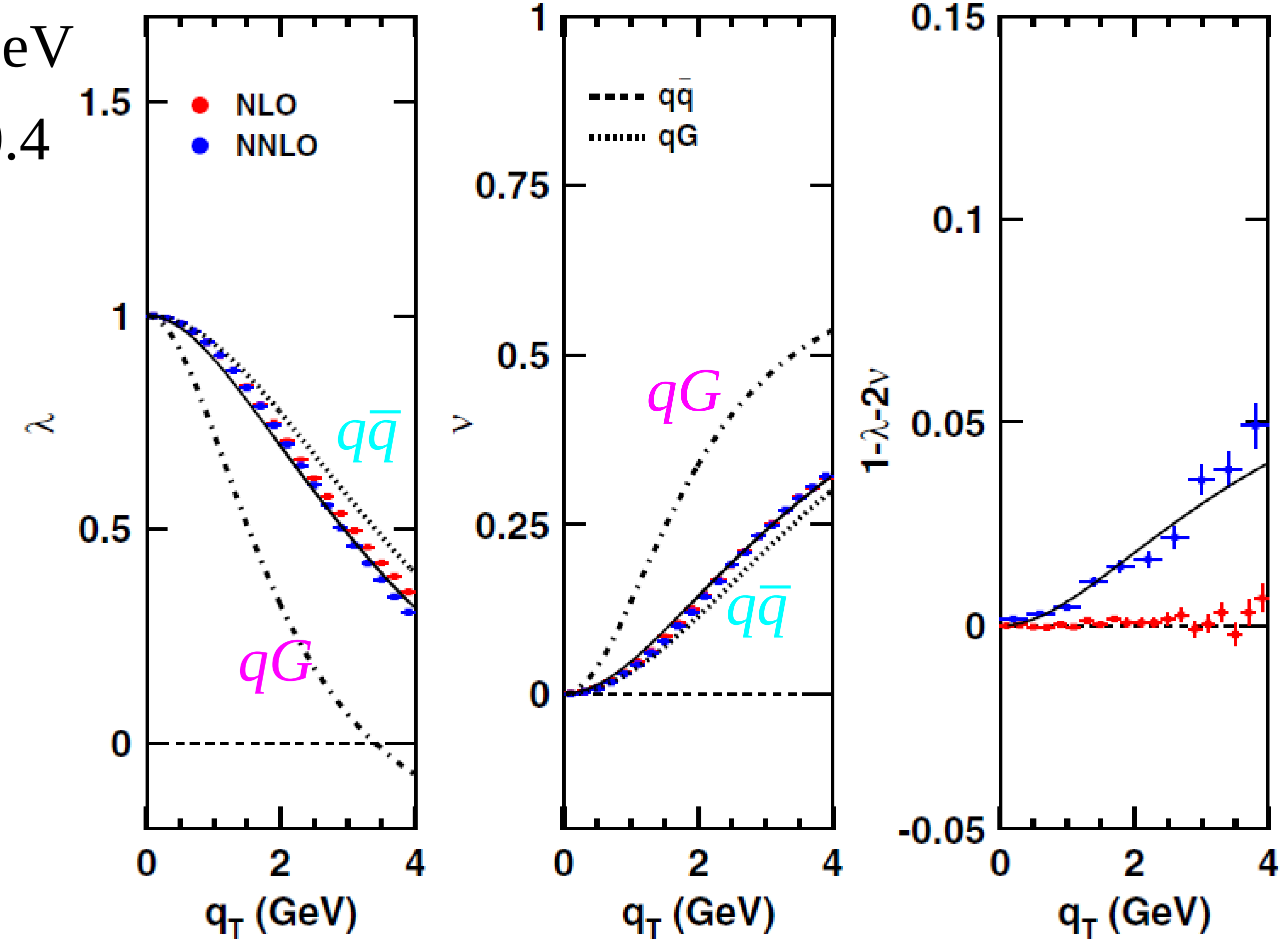
W.C. Chang et al., PRD 99, 014032 (2019)

COMPASS: pQCD calculations

$NLO : O(\alpha_s^1)$; $NNLO : O(\alpha_s^2)$ COMPASS π^-+W at 190 GeV

$4 < Q < 9$ GeV

$0.2 < x_F < 0.4$



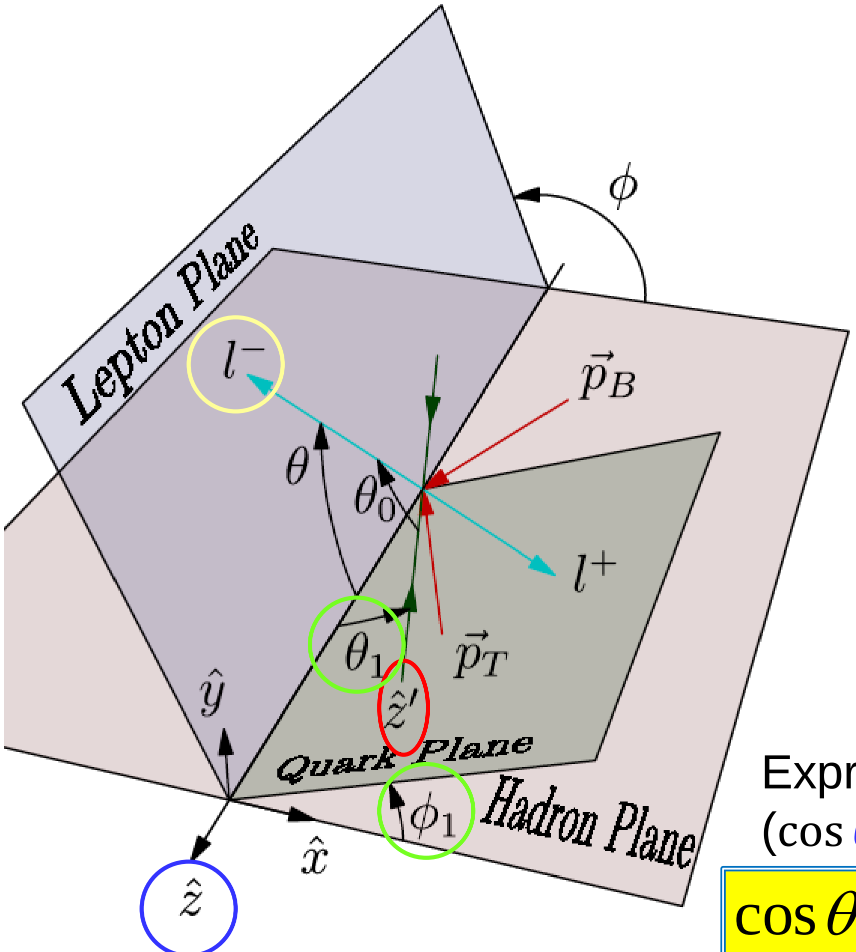
W.C. Chang et al., PRD 99, 014032 (2019)

Drell-Yan Angular Distributions

- Features:
  - Distinctive q_T dependence.
  - Lam-Tung violation:
    - $1 - \lambda - 2\nu \neq 0$ for fixed-target experiments
    - $A_0 - A_2 \neq 0$ for collider experiments.
  - Rapidity dependence for A_1, A_3, and A_4.
- Can these features be understood by pQCD? **Partially YES!**
- Is there any simple picture for interpretation?

A geometric picture:
J.C. Peng, W.C. Chang, R.E. McClellan, O. Teryaev, PLB 758, 394 (2016)
W.C. Chang, R.E. McClellan, J.C. Peng, O. Teryaev, PRD 96, 054020 (2017)

Natural Axis $\hat{z}'$



Lepton angular distributions with respect to the natural axis $\hat{z}'$:

$$\frac{d\sigma}{d\Omega} \propto 1 + a\cos\theta_0 + \lambda_0 \cos^2\theta_0$$

- Drell-Yan, trans. polarized quarkonium: λ_0=+1
- Unpolarized quarkonium: λ_0= 0
- Longi. polarized quarkonium: λ_0= –1

Express the measured lepton angular distributions ($\cos\theta$, ϕ) with respect to the natural axis $\hat{z}'$:

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

Intrinsic k_T, non-collinear effects: $\theta_1, \phi_1 \neq 0$

Quantization axis: Faccioli et al., PRD 83, 056008 (2011)

Lepton angular distributions w.r.t. the natural axis $\hat{z}'$

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

=

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

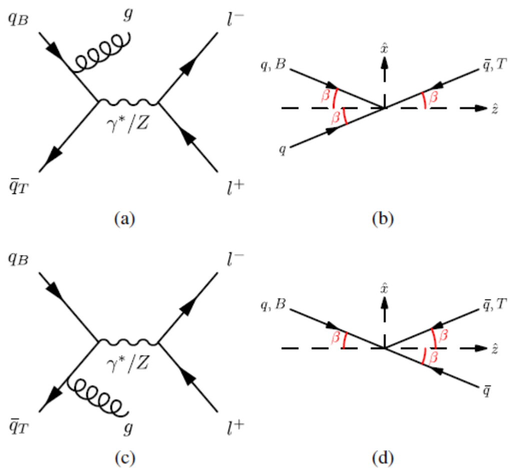
$A_0 - A_7$ are entirely described by θ_1, φ_1 and a.

$$A_0 = \langle \sin^2\theta_1 \rangle$$
$$A_1 = \frac{1}{2}\langle \sin 2\theta_1 \cos\phi_1 \rangle$$
$$A_2 = \langle \sin^2\theta_1 \cos 2\phi_1 \rangle$$
$$A_3 = a\langle \sin\theta_1 \cos\phi_1 \rangle$$
$$A_4 = a\langle \cos\theta_1 \rangle$$
$$A_5 = \frac{1}{2}\langle \sin^2\theta_1 \sin 2\phi_1 \rangle$$
$$A_6 = \frac{1}{2}\langle \sin 2\theta_1 \sin\phi_1 \rangle$$
$$A_7 = a\langle \sin\theta_1 \sin\phi_1 \rangle$$

(Non-)Coplanarity of Quark Plane and Hadron Plane

$A_0 = \langle \sin^2\theta_1 \rangle$ $A_2 = \langle \sin^2\theta_1 \cos 2\phi_1 \rangle$

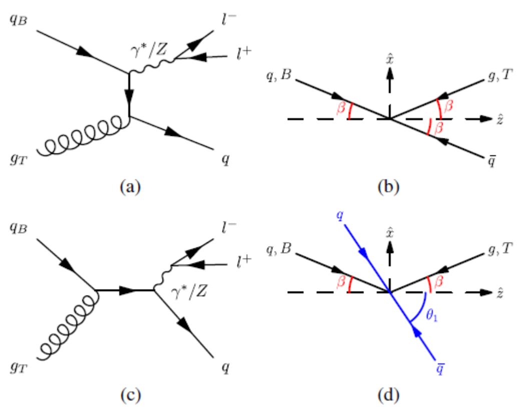
- $O(\alpha_s^1)$: $\phi_1 = 0, \pi$. $A_0 = A_2$



$\theta_1 = \beta;\ \phi_1 = 0$

$q\bar{q} \to G\gamma^*$

$\theta_1 = \beta;\ \phi_1 = \pi$

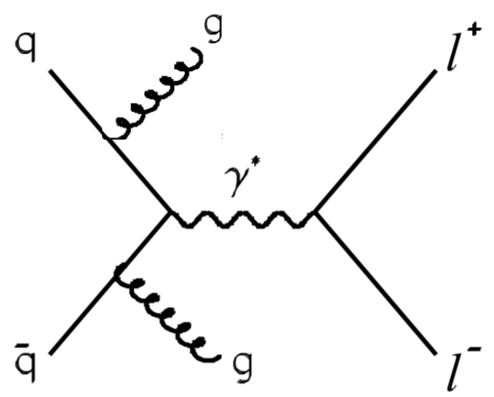


$\theta_1 = \beta;\ \phi_1 = 0$

$qG \to q\gamma^*$

$\theta_1 > \beta;\ \phi_1 = 0$

- $O(\alpha_s^2)$ or higher:
  $\phi_1 \neq 0, \pi$
  → $A_0 > A_2\ (1 - \lambda - 2\nu > 0)$



- Intrinsic k_T of interacting partons:
  $\phi_1 \neq 0, \pi$
  → $A_0 > A_2\ (1 - \lambda - 2\nu > 0)$

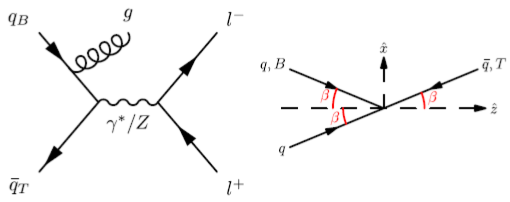
Cancelation Effect for $A_1(\nu)$, A_3 and A_4

- $O(\alpha_s^1)$: $\theta_1 = \beta, \pi - \beta$; $\phi_1 = 0, \pi$

$$A_0 = \langle \sin^2 \theta_1 \rangle \qquad A_1 = \frac{1}{2}\langle \sin 2\theta_1 \cos \phi_1 \rangle$$

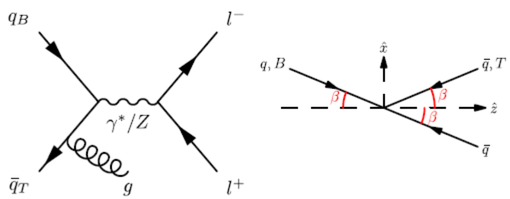
$$A_2 = \langle \sin^2 \theta_1 \cos 2\phi_1 \rangle \qquad A_3 = a\langle \sin \theta_1 \cos \phi_1 \rangle$$

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



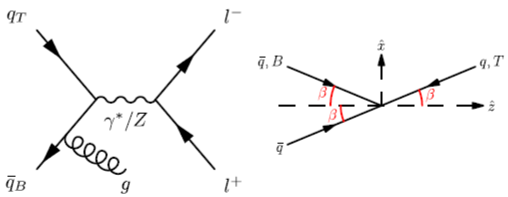
(a) (b)

$$\theta_1 = \beta;\ \phi_1 = 0$$



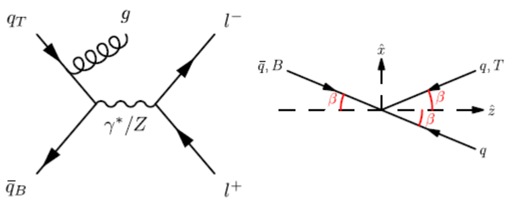
(c) (d)

$$\theta_1 = \beta;\ \phi_1 = \pi$$



(a) (b)

$$\theta_1 = \pi - \beta;\ \phi_1 = 0$$



(c) (d)

$$\theta_1 = \pi - \beta;\ \phi_1 = \pi$$

TABLE I. Angles θ_1 and ϕ_1 for four cases of gluon emission in the $q - \bar{q}$ annihilation process at order-α_s. The signs of A_0 to A_4 for the four cases are also listed.

Case	Gluon emitted from	θ_1	ϕ_1	A_0	A_1	A_2	A_3	A_4
1	Beam quark	β	0	+	+	+	+	+
2	Target antiquark	β	π	+	−	+	−	+
3	Beam antiquark	$\pi - \beta$	0	+	−	+	+	−
4	Target quark	$\pi - \beta$	π	+	+	+	−	−

A cancelation effect leads to a strong rapidity-dependence of $A_1(\nu)$, A_3 and A_4.

Summary

- pQCD calculations describe the Drell-Yan angular distributions from colliders at large q_T. Deviation seen in the fixed-target data.
- Angular distributions of Z+jets are different for the quark and gluon jets.
- Features of the data and pQCD calculations could be interpreted by a geometric picture of the natural $q - \bar{q}$ axis:
  - Violation of the Lam-Tung relation ($A_0 \neq A_2$) is caused by the non-coplanarity between the quark plane and the hadron plane. $A_0 > A_2$ from NNLO.
  - A cancelation effect leads to strong rapidity dependence of A_1, A_3 and A_4 (or μ).

References

- "*Interpretation of Angular Distributions of Z-boson Production at Colliders*", J.C. Peng, W.C. Chang, R.E. McClellan, and O. Teryaev, Phys. Lett. B 758, 394 (2016) [arXiv:1511.08932].
- "*Dependencies of lepton angular distribution coefficients on the transverse momentum and rapidity of Z bosons produced in pp collisions at the LHC*", W.C. Chang, R.E. McClellan, J.C. Peng, and O. Teryaev, Phys. Rev. D 96, 054020 (2017) [arXiv:1708.05807].
- "*On the Rotational Invariance and Non-Invariance of Lepton Angular Distributions in Drell-Yan and Quarkonium Production* ", J.C. Peng, D. Boer, W.C. Chang, R.E. McClellan and O. Teryaev, Phys. Lett. B 789, 356 (2019) [arXiv:1808.04398].
- "*Lepton Angular Distributions of Fixed-target Drell-Yan Experiments in Perturbative QCD and a Geometric Approach*", W.C. Chang, R.E. McClellan, J.C. Peng, and O. Teryaev, Phys. Rev. D 99, 014032 (2019) [arXiv:1811.03256].
- "*Lepton angular distribution of Z boson production and jet discrimination*", J.C. Peng, W.C. Chang, R.E. McClellan and O. Teryaev, Phys. Lett. B 797, 134895 (2019) [arXiv:1907.10483].

Thanks for your attention!