

Drell-Yan lepton angular distributions in perturbative QCD

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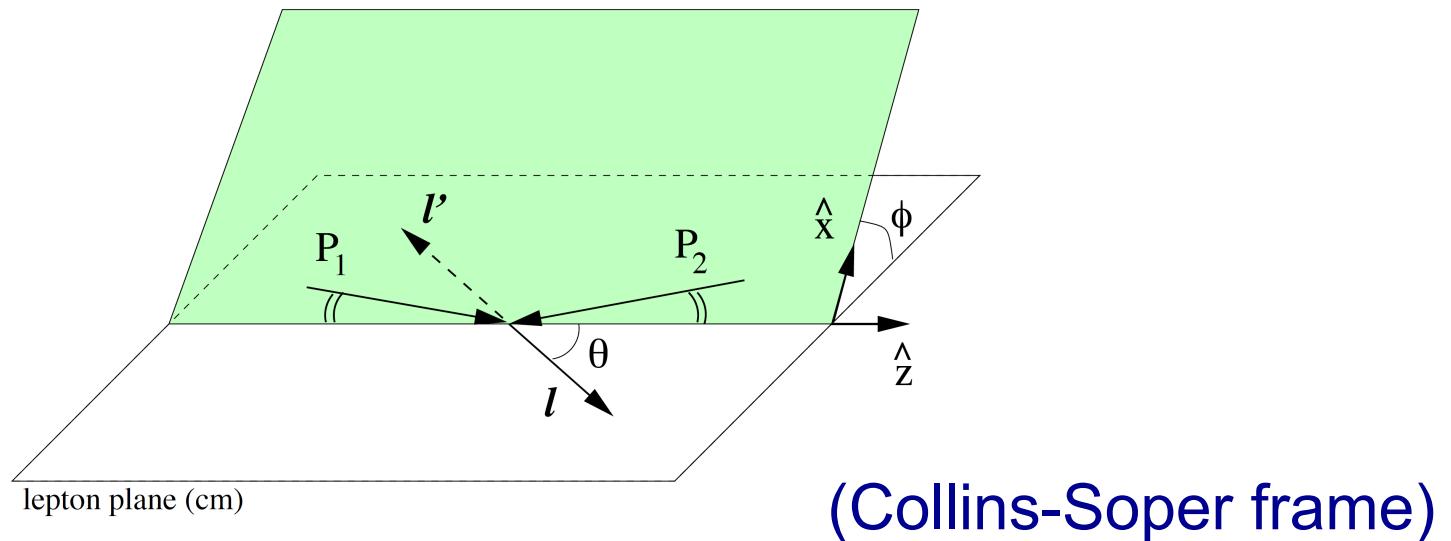
Outline:

- Introduction / Motivation
- Angular coefficients in pQCD
- Extraction of coefficients at NLO
- Numerical results
- Conclusions and outlook

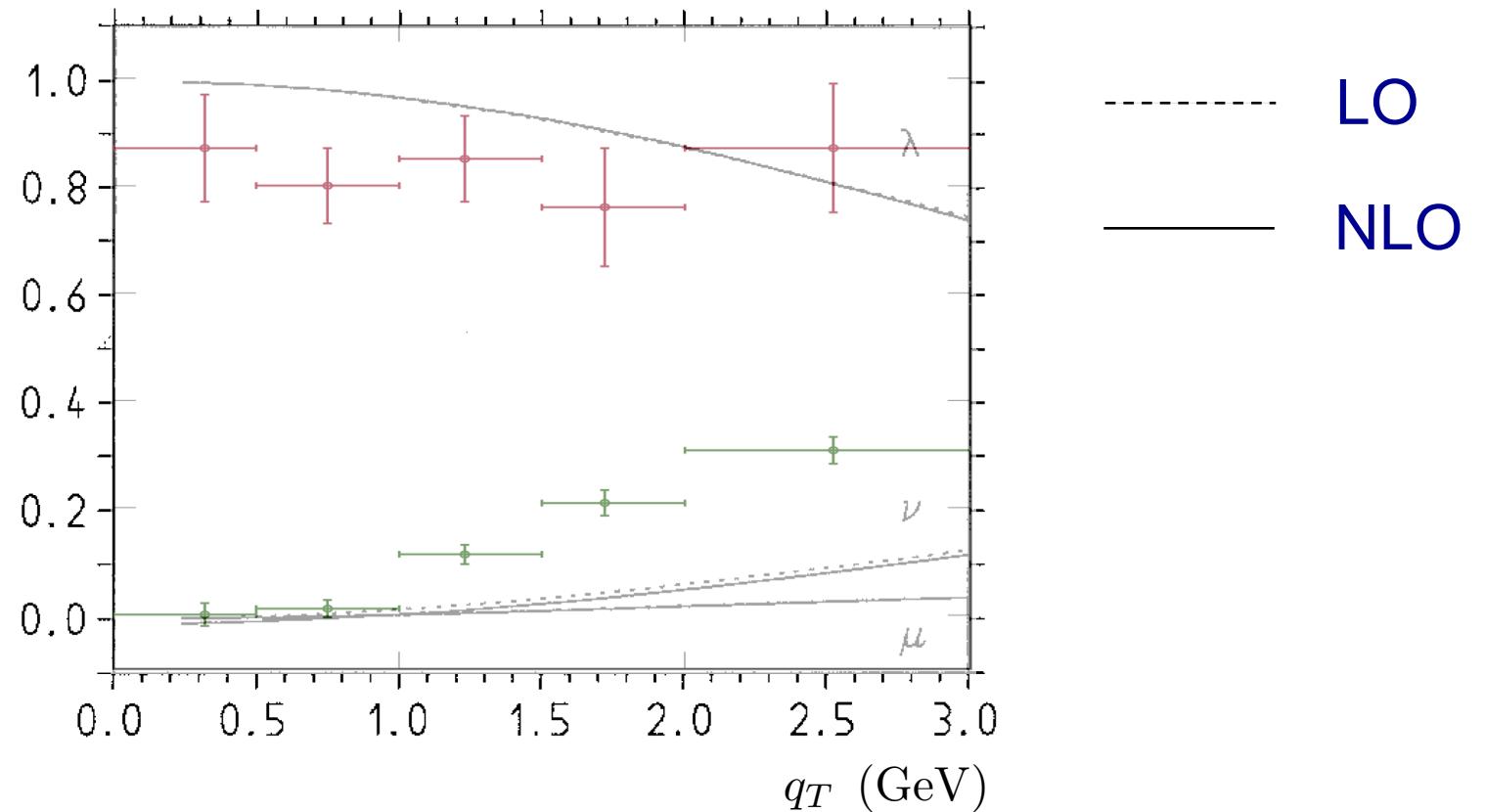
Introduction / Motivation

Lepton angular distribution in Drell-Yan:

$$\frac{d\sigma}{d^4 q d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi$$

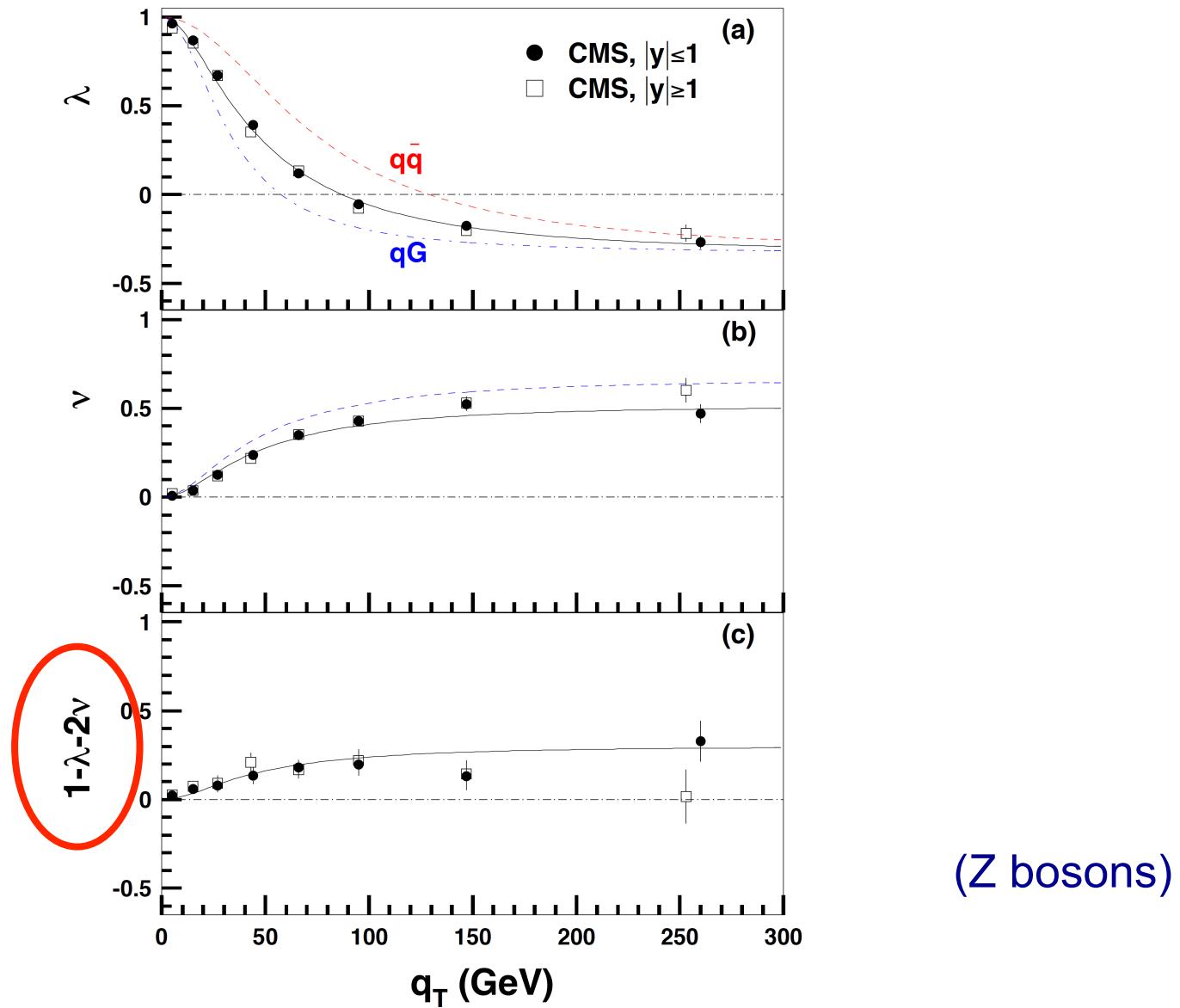


Brandenburg, Mirkes, Nachtmann '93



$\pi^- N$ at 194 GeV (NA10)

$Q = 8$ GeV



Peng, Chang, McClellan, Teryaev 2015; (CMS 2015)

Angular coefficients in pQCD

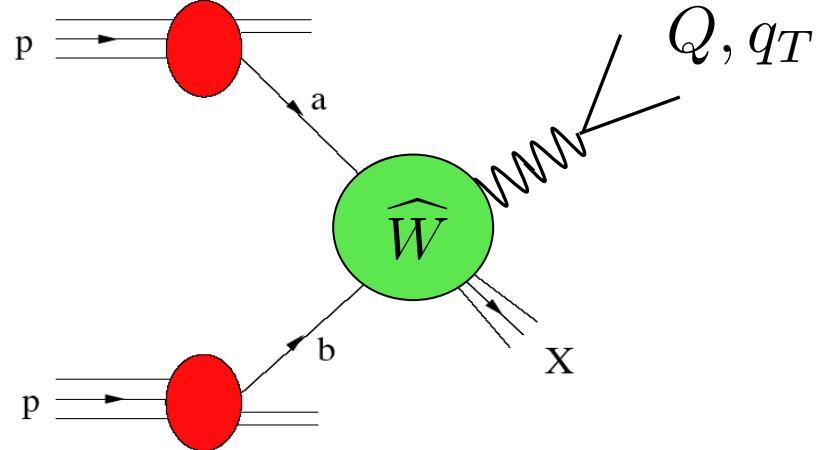
$$\begin{aligned} \frac{d\sigma}{d^4 q d\Omega} &= \frac{\alpha^2}{2\pi N_c Q^2 s^2} \left(W_T (1 + \cos^2 \theta) + W_L (1 - \cos^2 \theta) \right. \\ &\quad \left. + W_\Delta \sin 2\theta \cos \phi + W_{\Delta\Delta} \sin^2 \theta \cos 2\phi \right) \end{aligned}$$

$$\begin{aligned} \frac{dN}{d\Omega} &\equiv \left(\frac{d\sigma}{d^4 q} \right)^{-1} \frac{d\sigma}{d\Omega d^4 q} \\ &= \frac{3}{8\pi} \frac{W_T(1 + \cos^2 \theta) + W_L(1 - \cos^2 \theta) + W_\Delta \sin 2\theta \cos \phi + W_{\Delta\Delta} \sin^2 \theta \cos 2\phi}{2W_T + W_L} \\ &= \frac{3}{4\pi} \frac{1}{\lambda + 3} \left[1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \right] \end{aligned}$$

where:

$$\lambda = \frac{W_T - W_L}{W_T + W_L}, \quad \mu = \frac{W_\Delta}{W_T + W_L}, \quad \nu = \frac{2W_{\Delta\Delta}}{W_T + W_L}$$

Collinear factorization:



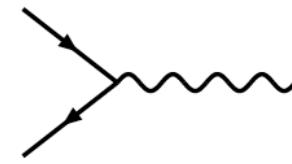
$$W_P = \sum_{a,b} \int dx_a dx_b f_a(x_a, \mu) f_b(x_b, \mu) \widehat{W}_{P,ab}(x_a P_a, x_b P_b, q, \alpha_s(\mu), \mu) \quad (P = T, L, \Delta, \Delta\Delta)$$

- \widehat{W}_P partonic structure fcts.: **perturbative**

$$\widehat{W}_P = \frac{\alpha_s}{\pi} \widehat{W}_P^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 \widehat{W}_P^{(2)} + \dots$$

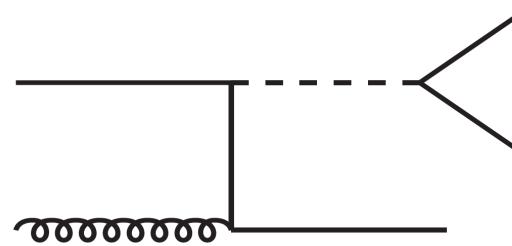
- $\mu \sim Q$ factorization / renormalization scale

- zeroth order $q\bar{q} \rightarrow V \rightarrow \ell^+ \ell^- :$



$$\lambda = 1, \mu = \nu = 0$$

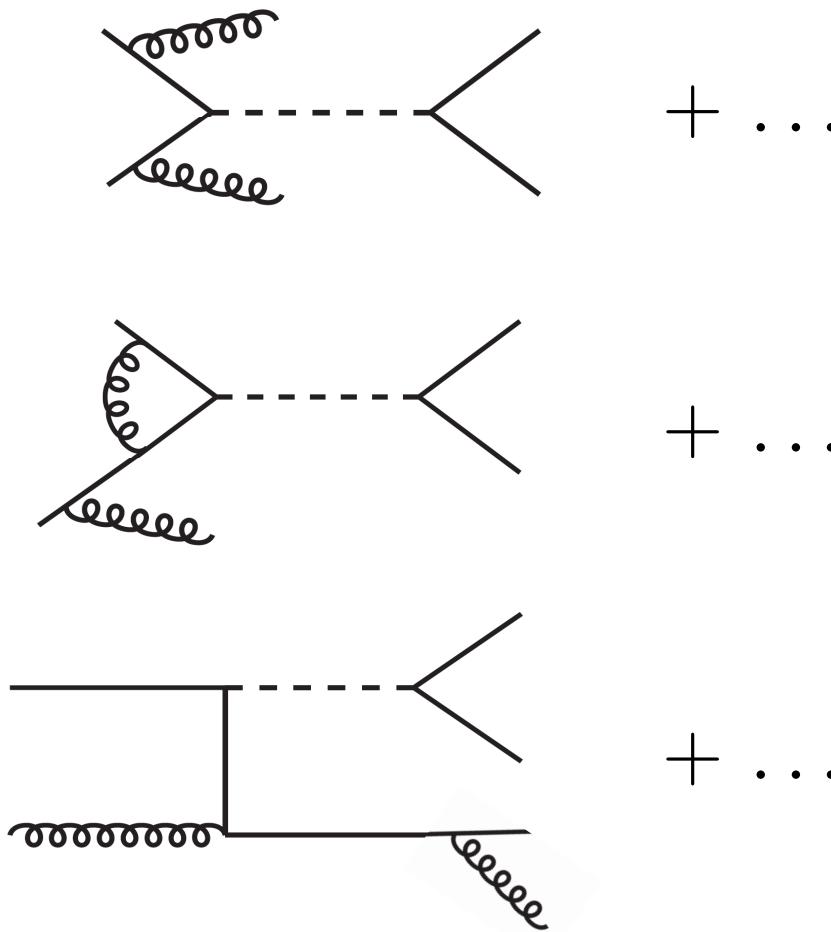
- however, $q_T = 0$
- first non-trivial order (= LO)



$$\lambda \neq 1, \mu \neq 0, \nu \neq 0$$

- but: $1 - \lambda - 2\nu = 0$ (Lam-Tung relation)

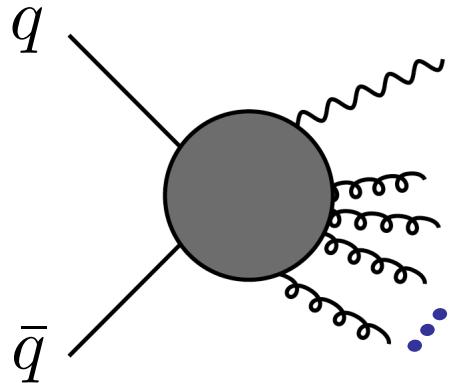
- NLO:



first computed by Mirkes '92; Mirkes, Ohnemus '95

This talk: New NLO results

- region $q_T \ll Q$:



$$\widehat{W}_T^{(k)} \propto \alpha_s^k \left(\frac{\log^{2k-1}(q_T^2/Q^2)}{q_T^2} \right)_+ + \dots$$

“ q_T logarithms”

- all-order resummation very well understood
CSS formalism, TMD evolution

- specifically structure functions at LO (CS frame):

$$\widehat{W}_T^{(1)} = -C_F \frac{\alpha_s}{2\pi} \frac{2 \log(q_T^2/Q^2) + 3}{q_T^2} + \dots$$

$$\widehat{W}_L^{(k)} = 2 \widehat{W}_{\Delta\Delta}^{(k)} = -C_F \frac{\alpha_s}{2\pi} (2 \log(q_T^2/Q^2) + 3) + \dots$$

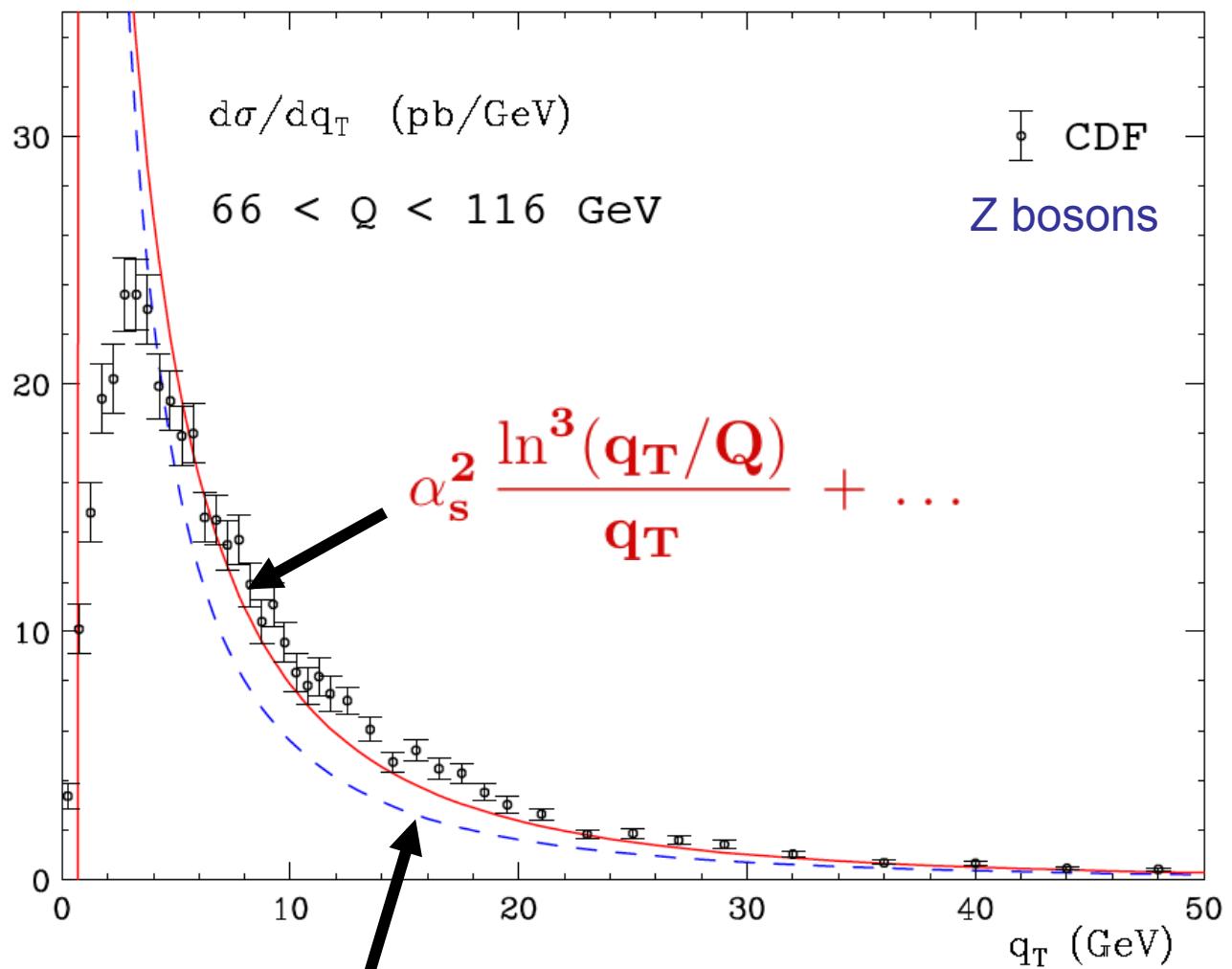
Boer, WV

- leading logs same to all orders in $\widehat{W}_T, \widehat{W}_L, \widehat{W}_{\Delta\Delta}$

Berger, Qiu, Rodriguez

- differences at next-to-leading log Boer, WV

- still, expect small resummation effects for λ, ν



$$\alpha_s \frac{\ln(q_T/Q)}{q_T} + \dots$$

- and, of course, TMDs...
Boer, Mulders;
Boer, Brodsky, Hwang;
Lu, Ma;
Pasquini, Schweitzer;
...
- relation TMD formalism to fixed-order:
Bachhetta, Boer, Diehl, Mulders
- in the following, use NLO perturbation theory and compare to data

Extraction of λ, ν at NLO

- a lot of work in recent decade on perturbative corrections for Drell-Yan process (motivated by LHC / Higgs)

Hamberg, van Neerven, Matsuura; Harlander, Kilgore;
Anastasiou, Dixon, Melnikov, Petriello; Melnikov, Petriello;
Li, Petriello, Quackenbusch; Catani, Cieri, Ferrera, de Florian, Grazzini;
Li, von Manteuffel, Schabinger, Zhu; Anastasiou et al.;

...

- especially useful: NNLO $\mathcal{O}(\alpha_s^2)$ Monte-Carlo codes
 - FEWZ: Melnikov, Petriello; Melnikov, Petriello;
Li, Petriello, Quackenbusch
 - DYNNLO: Catani, Cieri, Ferrera, de Florian, Grazzini
- full control over 4-momenta of produced particles, including leptonic decay

$$\lambda = \frac{W_T - W_L}{W_T + W_L} , \quad \nu = \frac{2W_{\Delta\Delta}}{W_T + W_L}$$

Lam, Tung '78:

$$2W_T + W_L = \mathcal{N} \frac{d\sigma}{d^4q}$$

$$W_T - W_L = \frac{8}{3} \mathcal{N} \left[\frac{d\sigma}{d^4q} \left(|\cos \theta| > \frac{1}{2} \right) - \frac{d\sigma}{d^4q} \left(|\cos \theta| < \frac{1}{2} \right) \right]$$

$$W_{\Delta\Delta} = \frac{\pi}{2} \mathcal{N} \left[\frac{d\sigma}{d^4q} (\cos 2\phi > 0) - \frac{d\sigma}{d^4q} (\cos 2\phi < 0) \right]$$

- lepton momentum:

$$\ell_{\text{CS}}^\mu = \frac{Q}{2} \begin{pmatrix} 1 \\ \sin \theta \cos \phi \\ \sin \theta \sin \phi \\ \cos \theta \end{pmatrix} \xrightarrow{\text{Lorentz}} \ell_{\text{cm}}^\mu = \frac{1}{2} \begin{pmatrix} q_0 (1 + \sin \alpha \sin \theta \cos \phi) + q_L \cos \alpha \cos \theta \\ q_T + Q \frac{\sin \theta \cos \phi}{\cos \alpha} \\ Q \sin \theta \sin \phi \\ q_L (1 + \sin \alpha \sin \theta \cos \phi) + q_0 \cos \alpha \cos \theta \end{pmatrix}$$

$$\sin \alpha \equiv \frac{q_T/Q}{\sqrt{1 + (q_T/Q)^2}}, \quad \cos \alpha \equiv \frac{1}{\sqrt{1 + (q_T/Q)^2}}$$

- from this:

$$\cos \theta = -\frac{2 \ell_{\text{cm}} \cdot \mathcal{P}_1}{(Q^2 + q_T^2) \cos \alpha}$$

where $\mathcal{P}_1^\mu \equiv \begin{pmatrix} q_L \\ 0 \\ 0 \\ q_0 \end{pmatrix}$

$$\cos 2\phi = 1 - \frac{2 (\ell_{\text{cm}} \cdot \mathcal{P}_2)^2}{q_T^2 \left[\frac{Q^2}{4} - \frac{(\ell_{\text{cm}} \cdot \mathcal{P}_1)^2}{Q^2 + q_T^2} \right]}$$

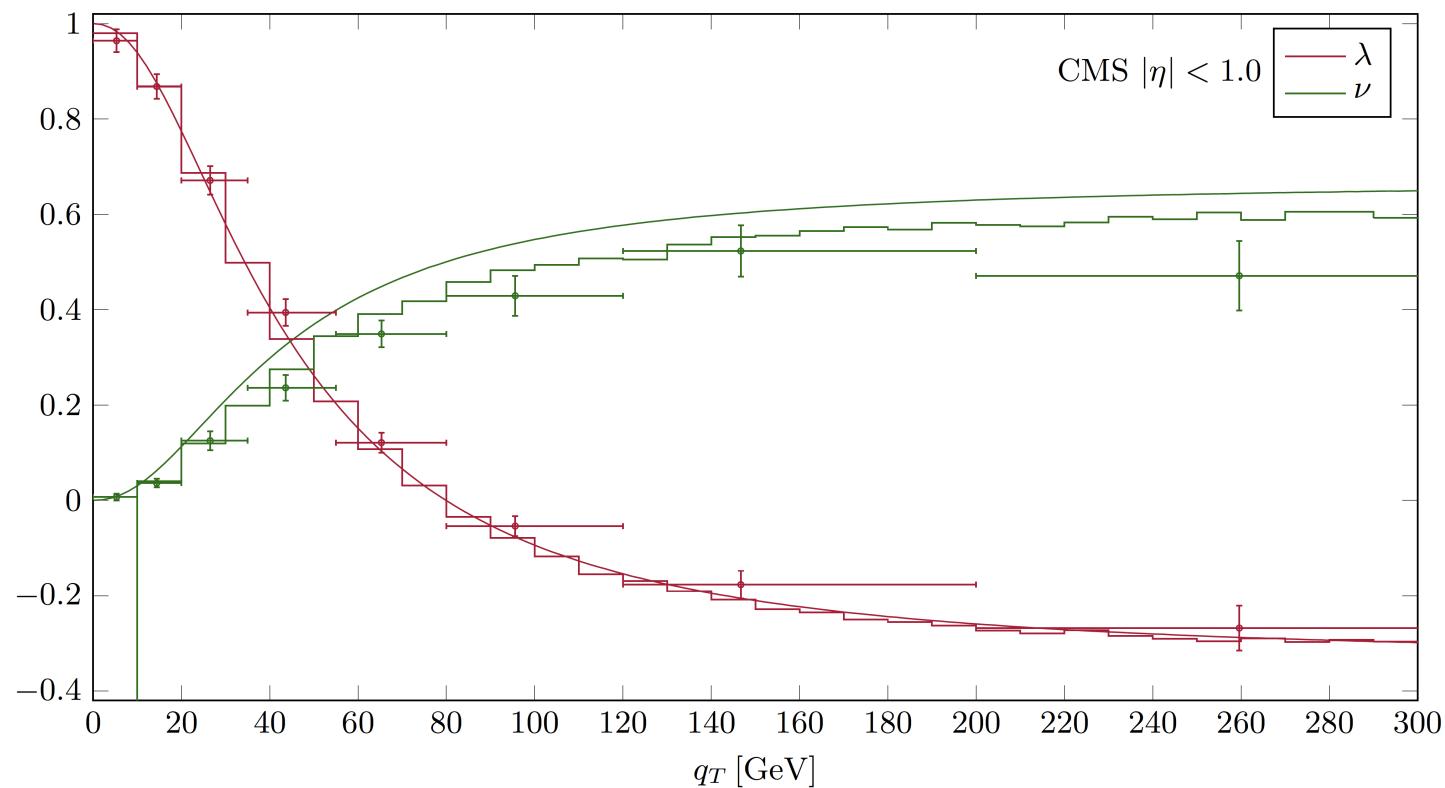
$$\mathcal{P}_2^\mu \equiv q_T \begin{pmatrix} 0 \\ 0 \\ -1 \\ 0 \end{pmatrix}$$

Numerical results

- use **FEWZ** and **DYNNLO** codes
- excellent agreement. NLO results below are for **FEWZ**
- benchmark against our own LO code
- **MSTW** proton PDFs
GRV pion PDFs
no genuine nuclear effects (other than isospin)
- choose scale $\mu = Q$; scale dependence really weak
- NLO computationally very demanding:
Results below > 2 years on single quad-core CPU
- results in order of *decreasing energy*

$pp, \sqrt{s} = 8 \text{ TeV} \quad |\eta| < 1$

CMS



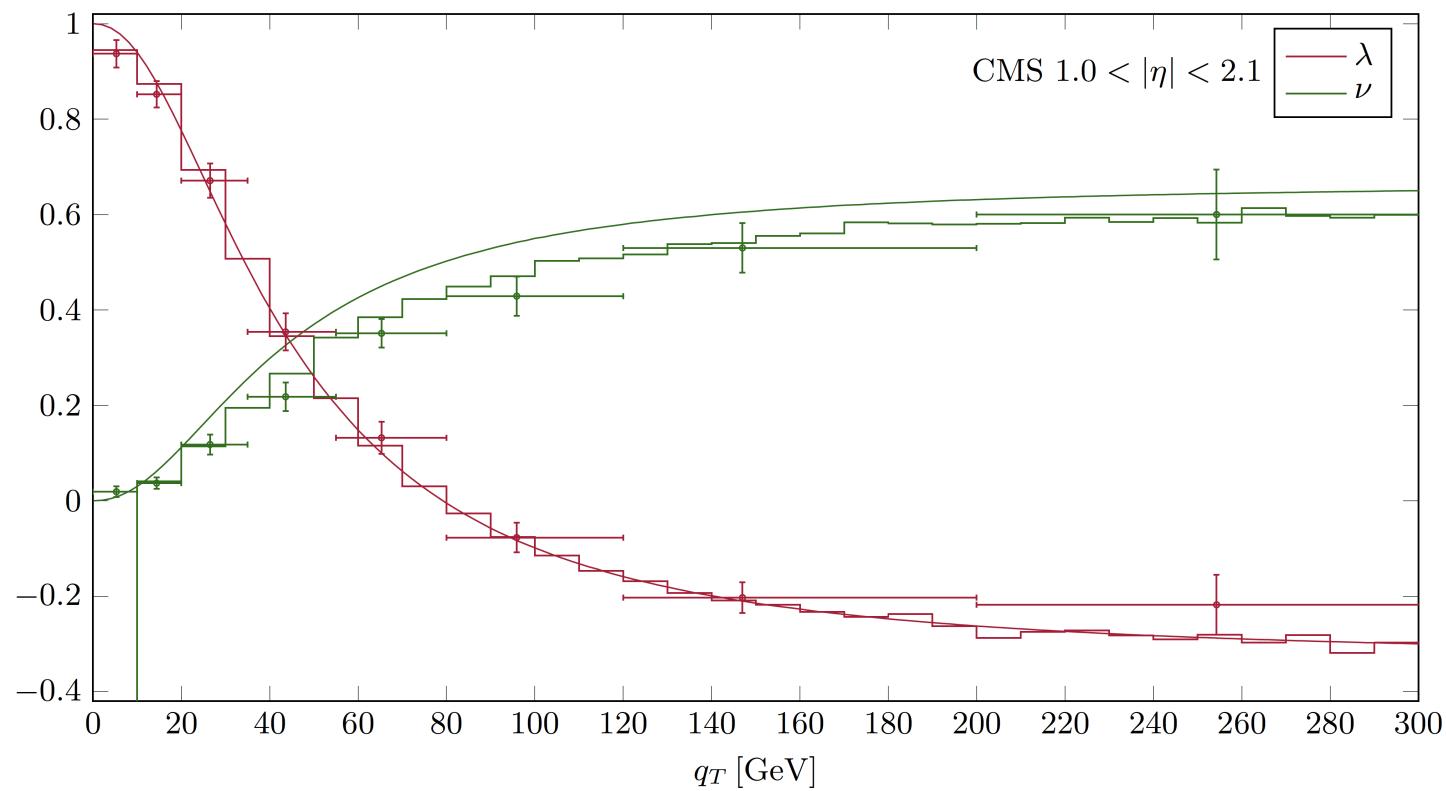
lines: LO

histograms: NLO

Lambertsen, WV

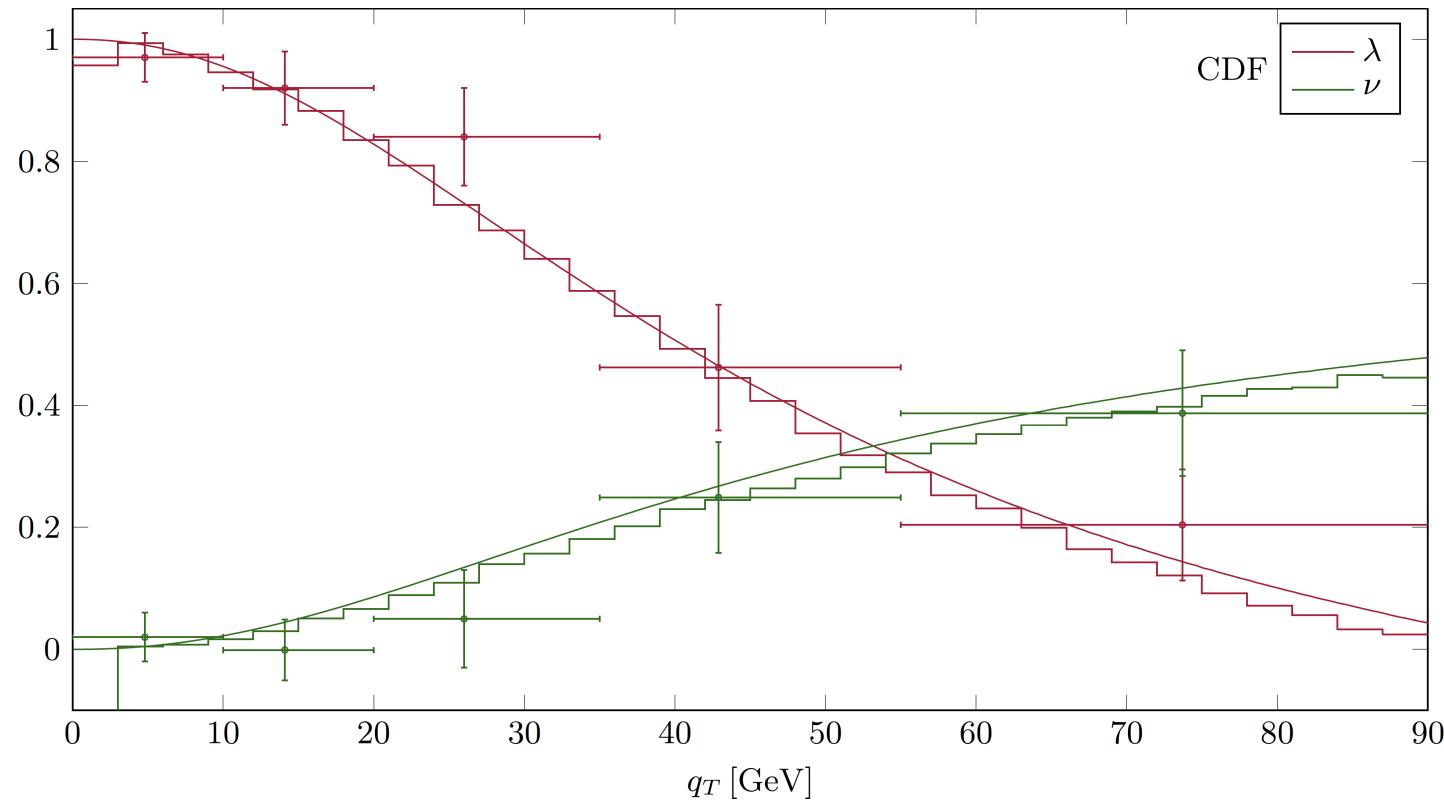
$pp, \sqrt{s} = 8 \text{ TeV}$ $1 < |\eta| < 2.1$

CMS



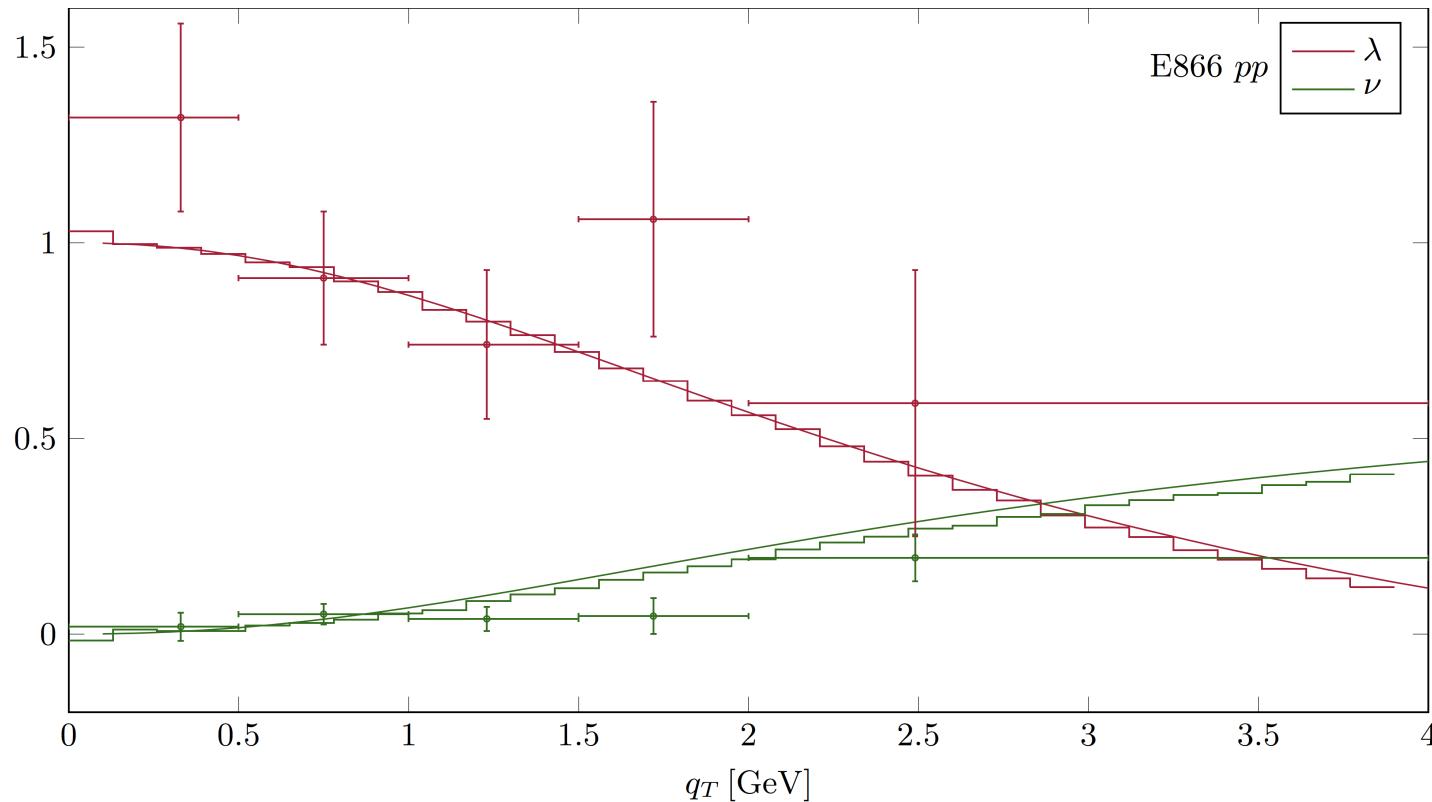
$p\bar{p}$, $\sqrt{s} = 1.96$ TeV

CDF



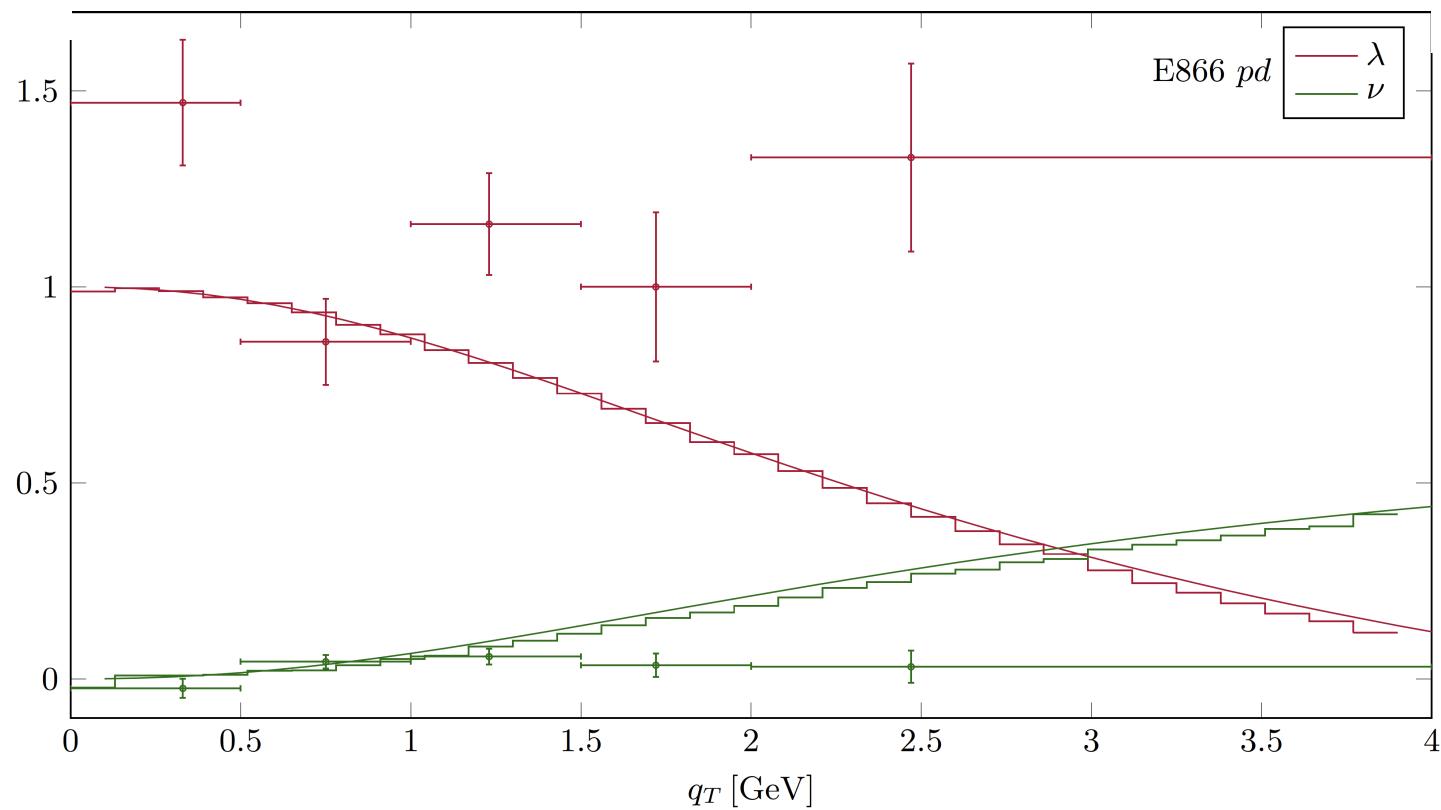
$pp, E = 800 \text{ GeV}$

E866



$pd, E = 800 \text{ GeV}$

E866



- recall:

$$\lambda = \frac{W_T - W_L}{W_T + W_L}$$

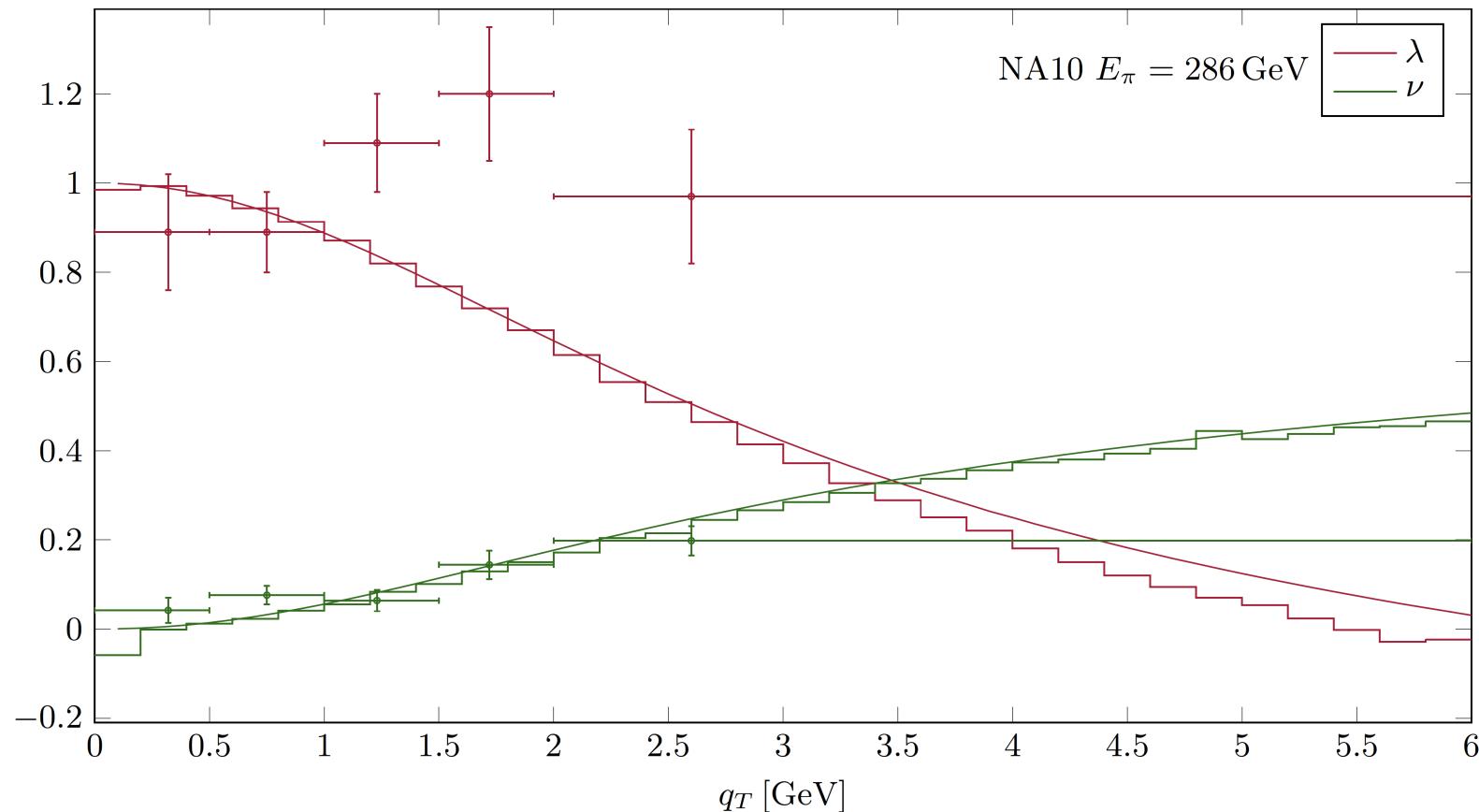
Lam, Tung '78:

positivity constraint $W_L \geq 0 \quad \Rightarrow \quad \lambda \leq 1$

(from $V_\mu W^{\mu\nu} V_\nu^* \geq 0$ for any 4-vector V)

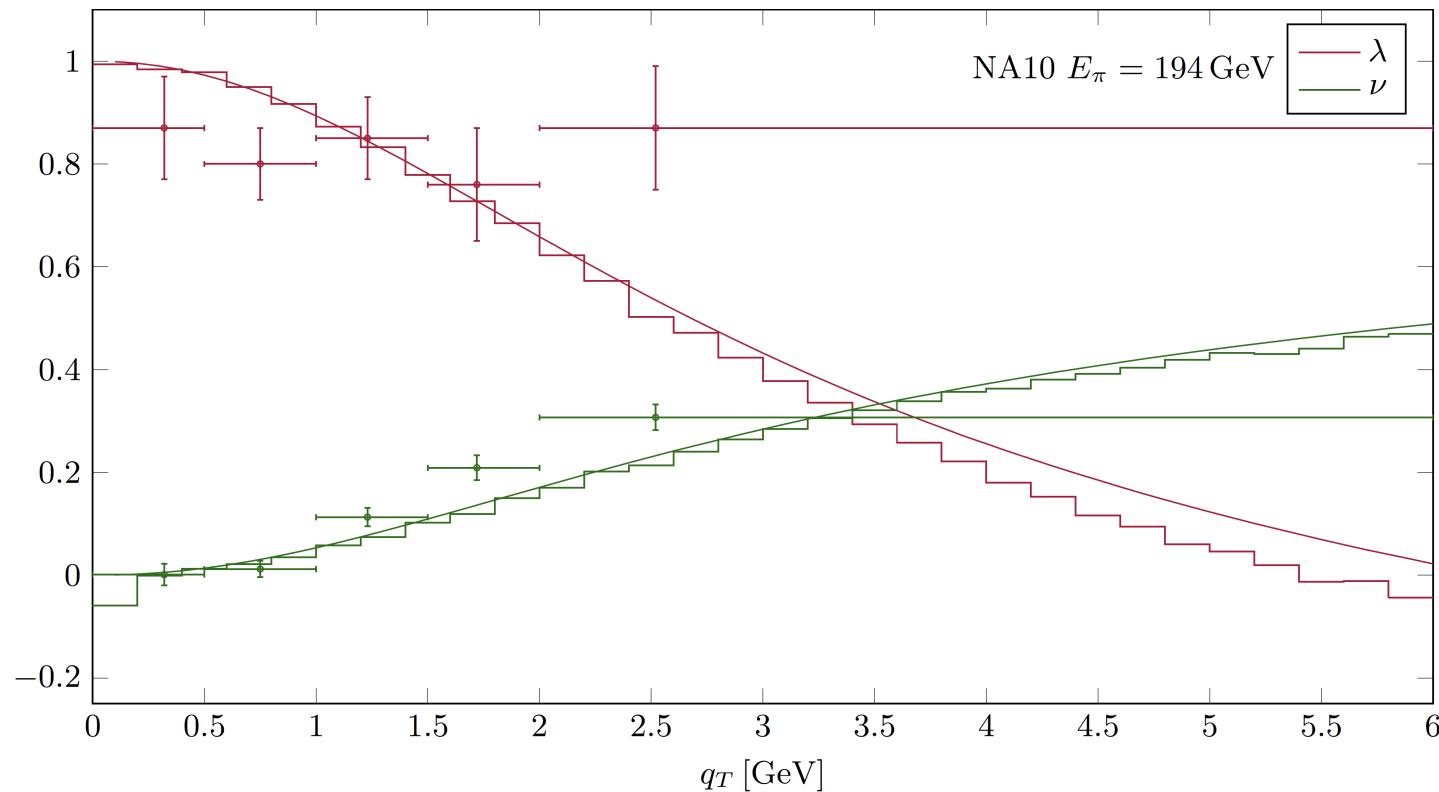
$\pi W, E_\pi = 286 \text{ GeV}$

NA10



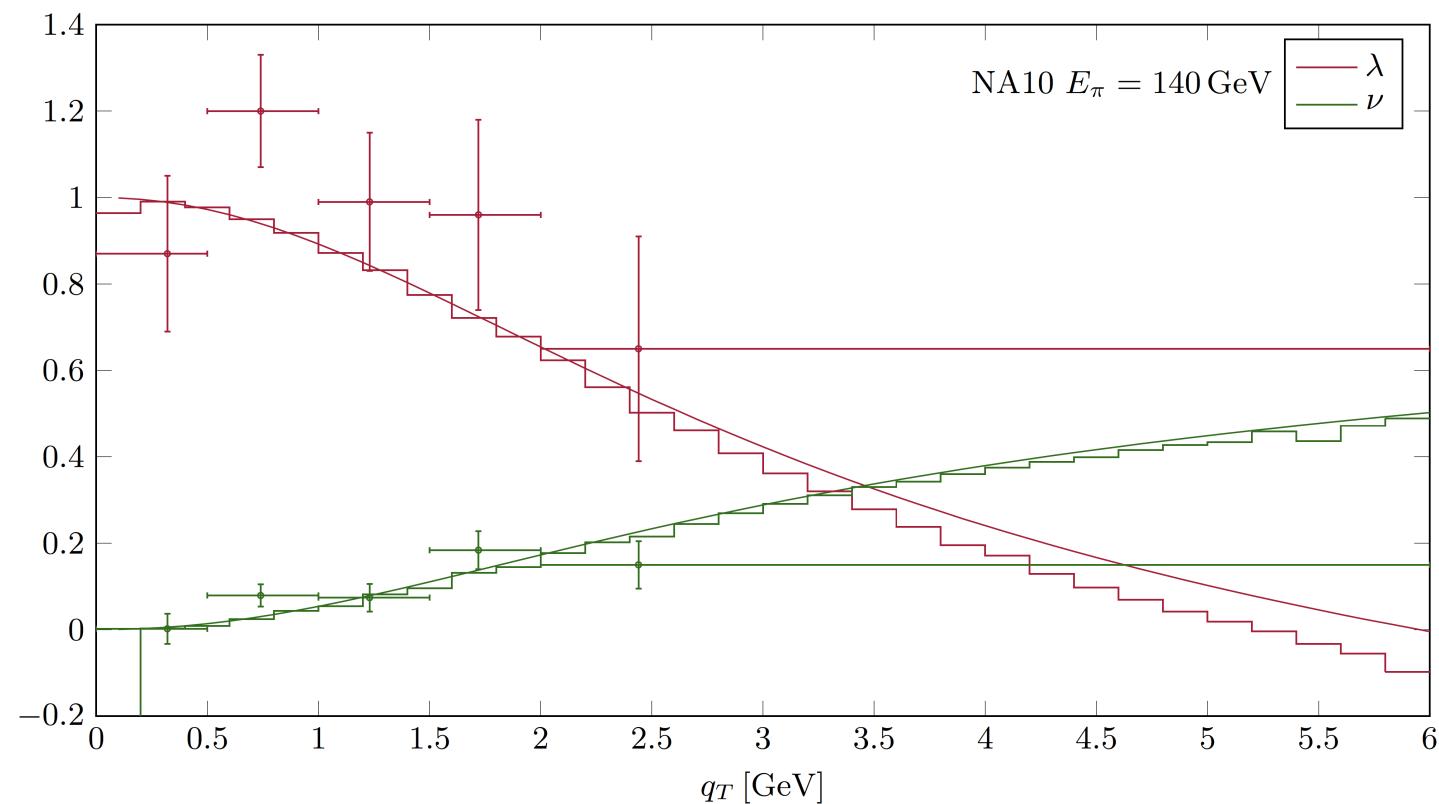
$\pi W, E_\pi = 194 \text{ GeV}$

NA10



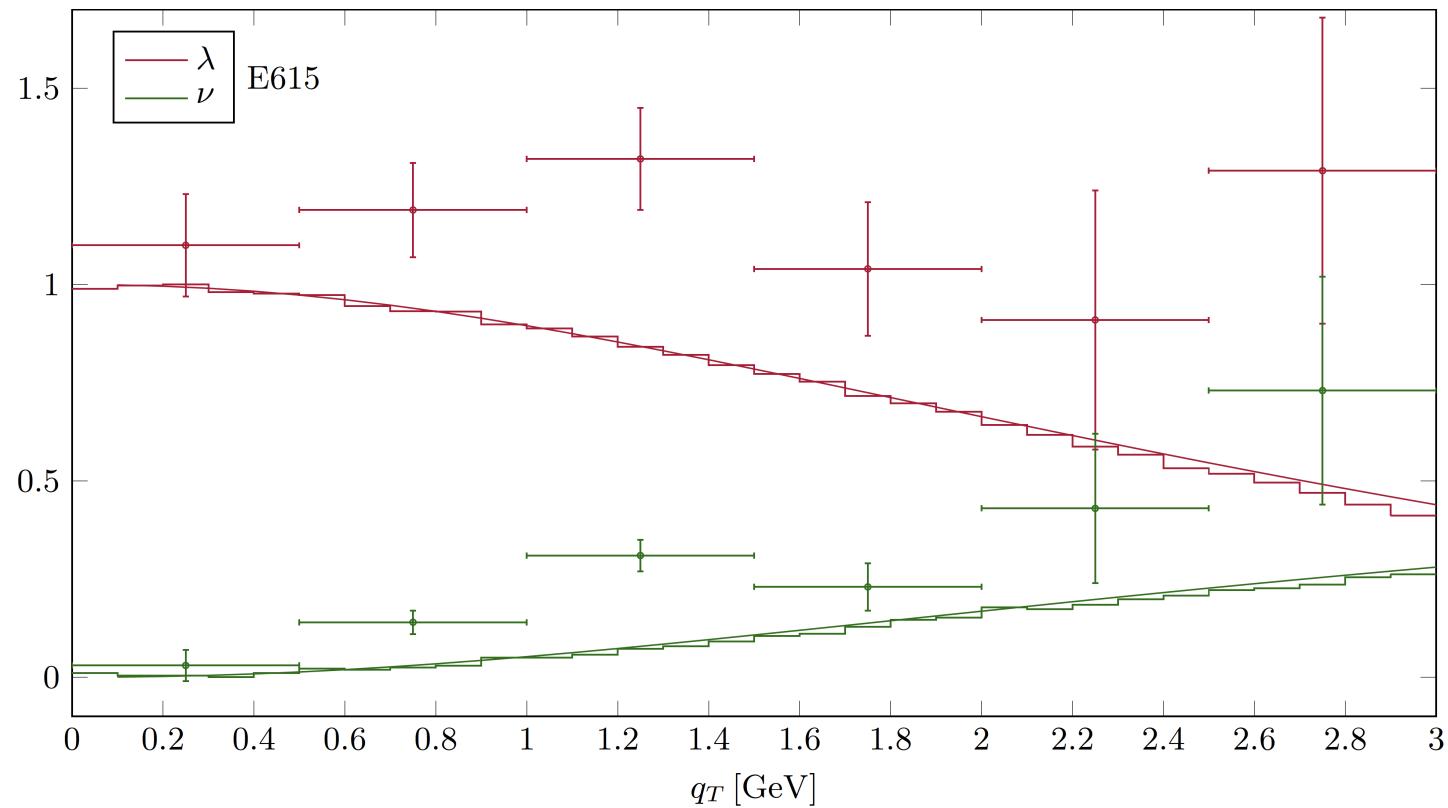
$\pi W, E_\pi = 140 \text{ GeV}$

NA10



$\pi W, E_\pi = 252 \text{ GeV}$

E615



Conclusions and outlook:

- have extracted coefficients λ, ν at NLO from **FEWZ** and **DYNNLO** codes
- “dispel myth” that pQCD cannot describe data:
overall good description
 - excellent for LHC & Tevatron
 - reasonable even in fixed-target regime
- we do *not* argue that there are no effects beyond fixed-order pQCD
- serious studies of Boer-Mulders should include pQCD radiative effects (including resummation)