Drell-Yan lepton angular distributions in perturbative QCD

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Outline:

- Angular coefficients in pQCD
- Extraction of coefficients at NLO
- Numerical results
- New ATLAS results

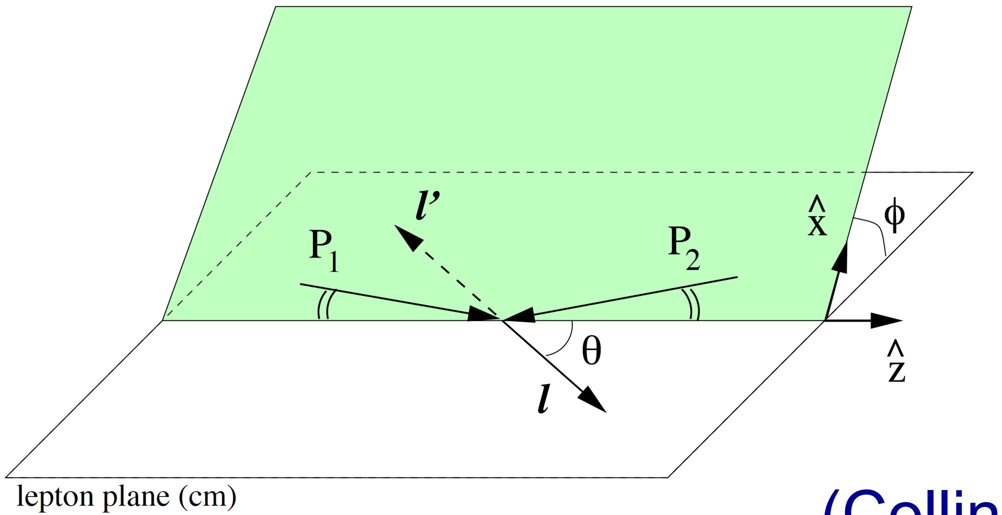
in collaboration with Martin Lambertsen

Introduction / Motivation

Lepton angular distribution in Drell-Yan (photon ex.):

$$\frac{d\sigma}{d^4q\, d\Omega} = \frac{\alpha^2}{2\pi N_c Q^2 s^2}\Big(W_T\,(1+\cos^2\theta) + W_L\,(1-\cos^2\theta)$$

$$+W_\Delta \sin 2\theta \cos\phi + W_{\Delta\Delta} \sin^2\theta \cos 2\phi\Big)$$



(Collins-Soper frame)

$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha^2}{2\pi N_c Q^2 s^2}\Big(W_T\,(1+\cos^2\theta) + W_L\,(1-\cos^2\theta)$$

$$+W_\Delta \sin 2\theta\cos\phi + W_{\Delta\Delta}\sin^2\theta\cos 2\phi\Big)$$

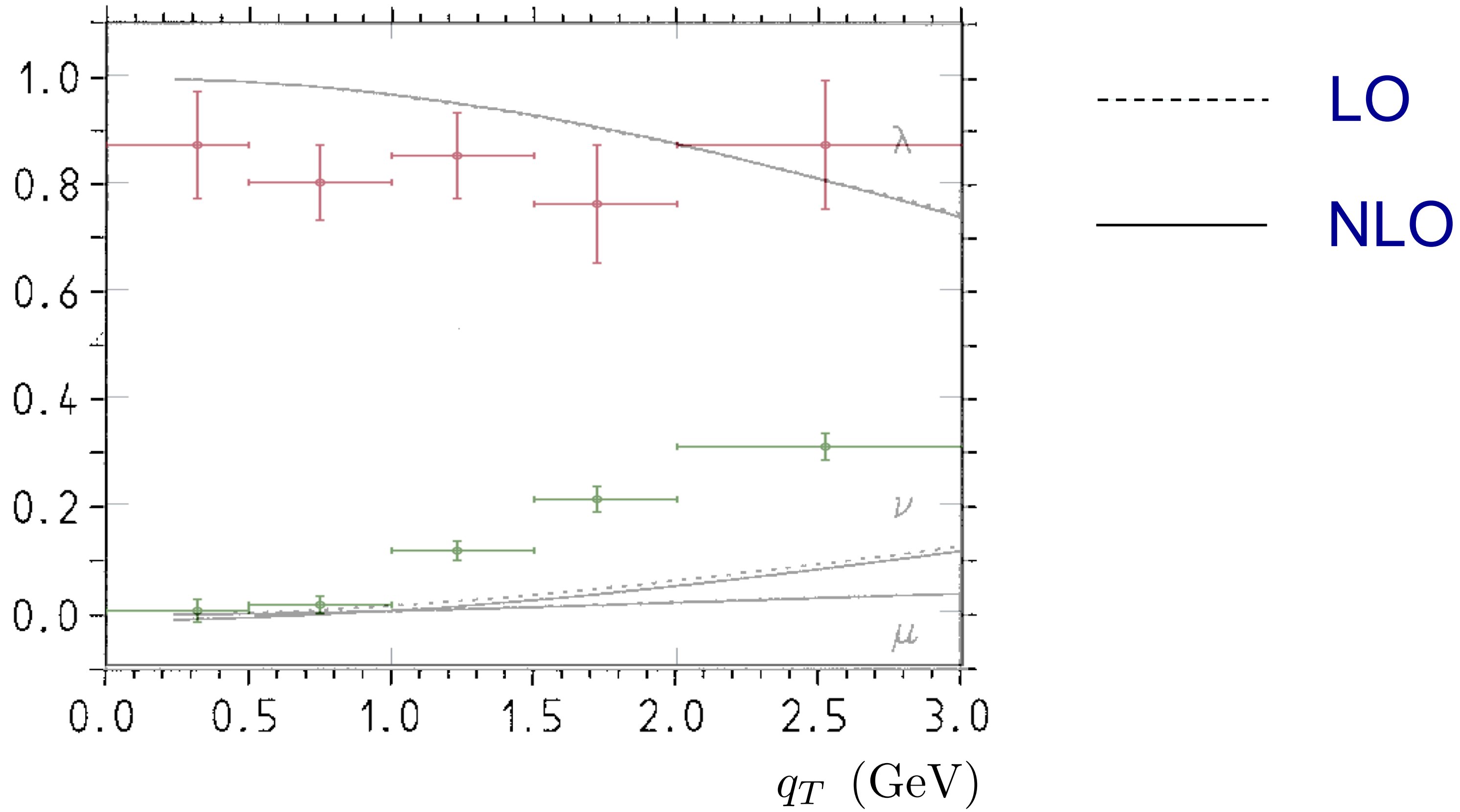
$$\frac{dN}{d\Omega} \equiv \left(\frac{d\sigma}{d^4q}\right)^{-1}\frac{d\sigma}{d\Omega d^4q}$$

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

where:

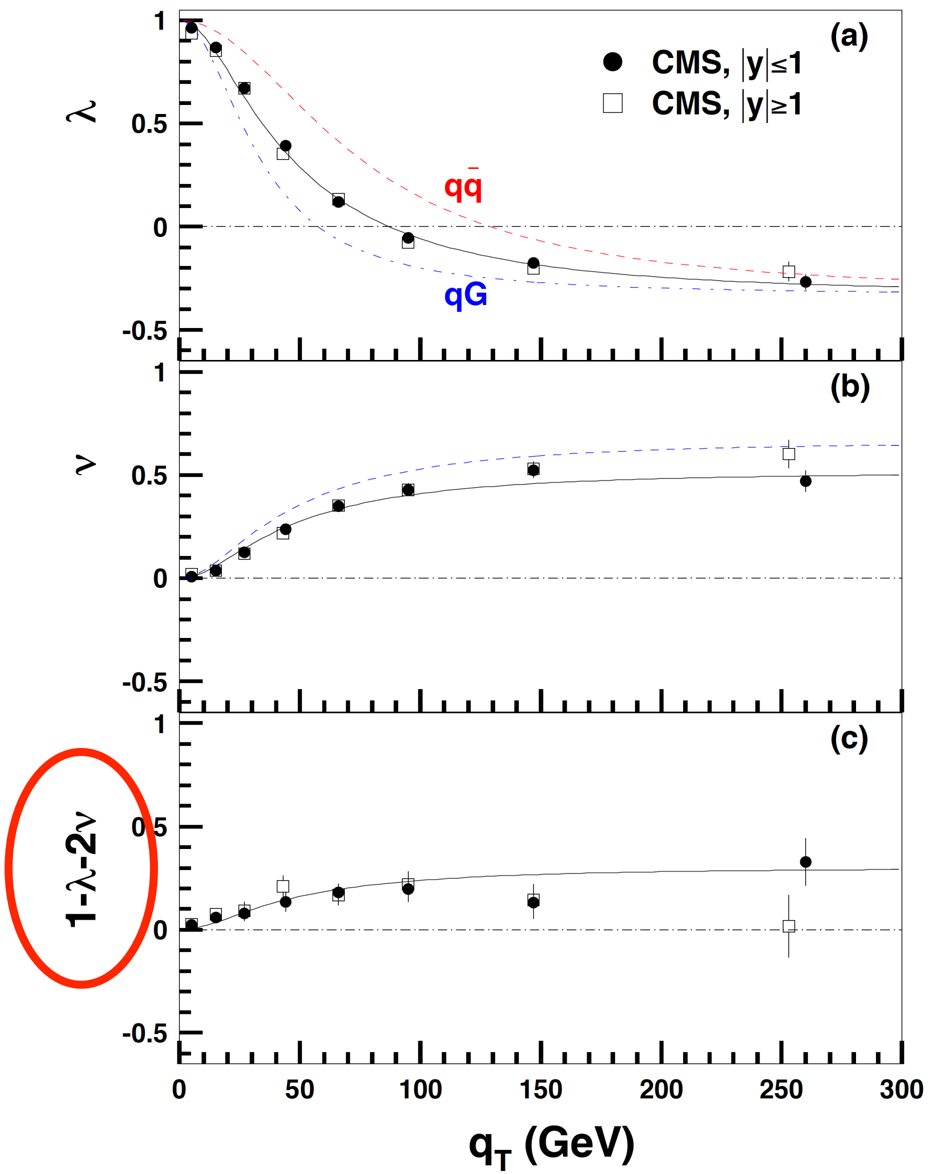
$$\lambda = \frac{W_T - W_L}{W_T + W_L}\,, \quad \mu = \frac{W_\Delta}{W_T + W_L}\,, \quad \nu = \frac{2W_{\Delta\Delta}}{W_T + W_L}$$

Brandenburg, Mirkes, Nachtmann '93



$\pi^- N$ at 194 GeV (NA10) Q = 8 GeV

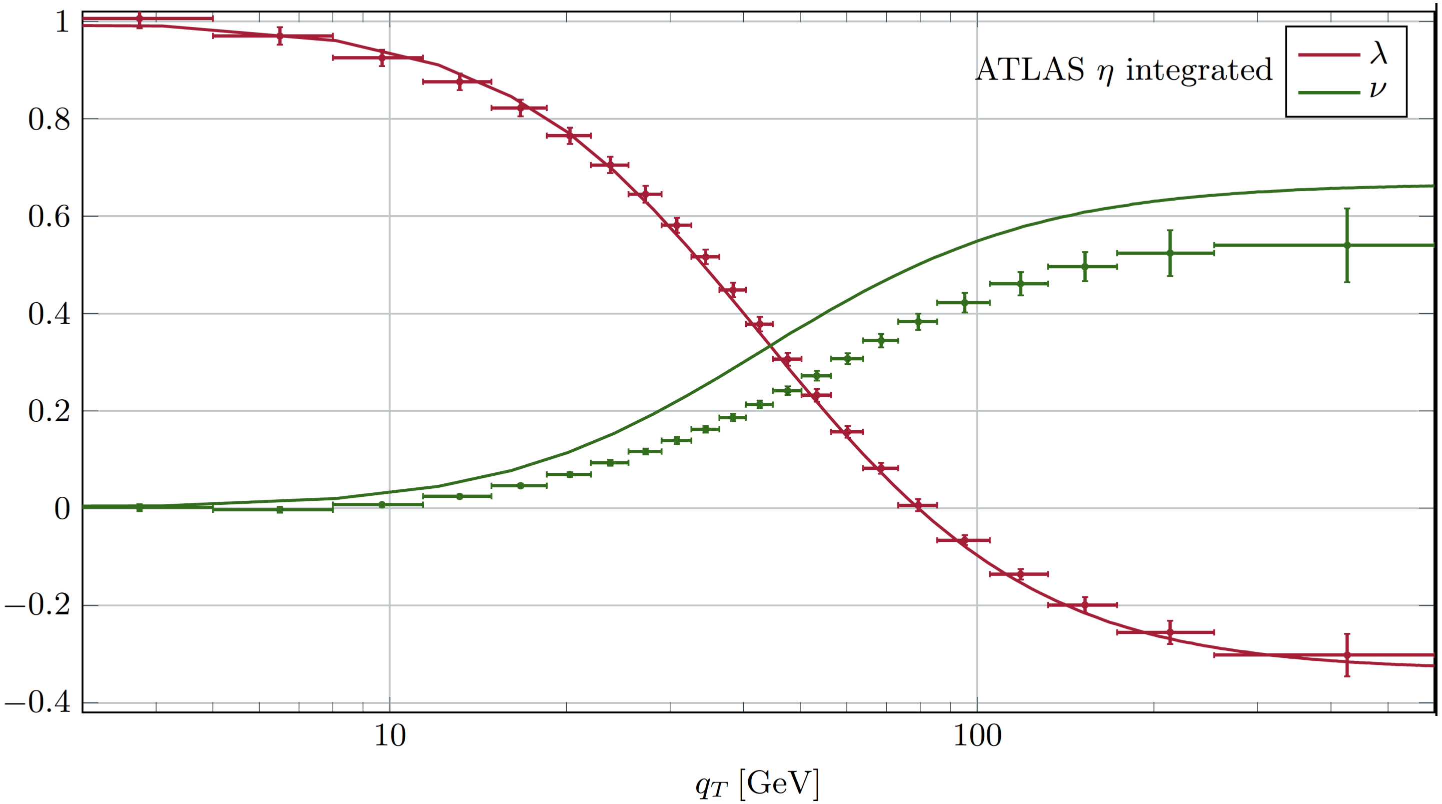
- clearly a relevant issue for extraction of Boer-Mulders fct.



(Z bosons)

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

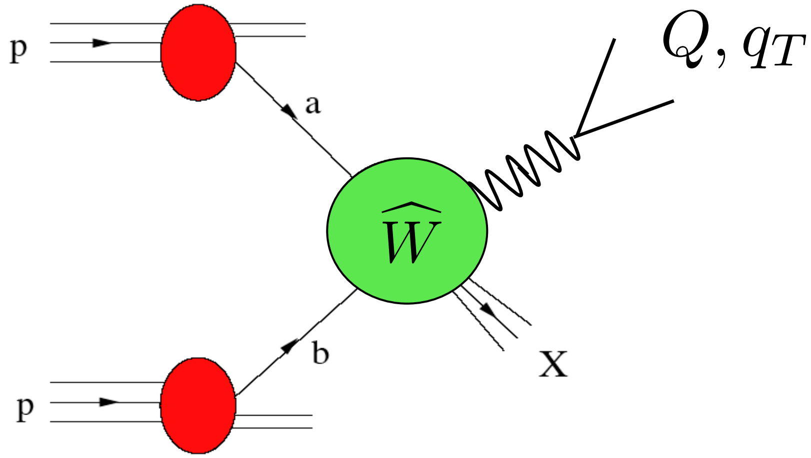
ATLAS 2016



(LO)

Angular coefficients in pQCD

Collinear factorization:



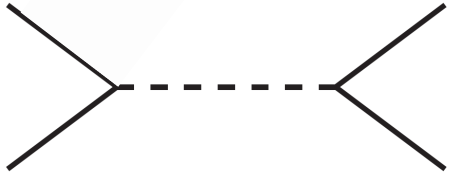
$$W_P = \sum_{a,b} \int dx_a dx_b \, f_a(x_a,\mu) \, f_b(x_b,\mu) \, \widehat{W}_{P,ab}(x_a P_a, x_b P_b, q, \alpha_s(\mu), \mu)$$

$$(P = T, L, \Delta, \Delta\Delta)$$

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

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

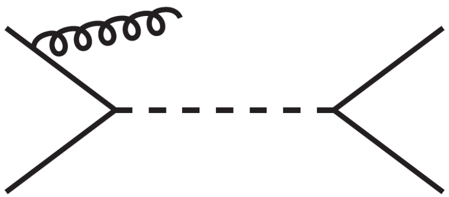
- zeroth order $q\bar{q} \to V \to \ell^+\ell^-$:

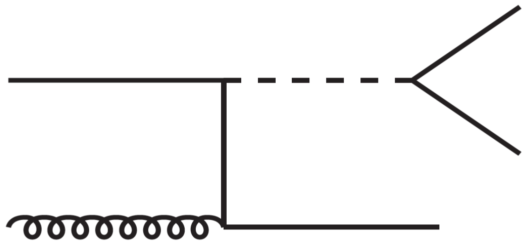


$$\lambda = 1,\ \mu = \nu = 0$$

- however, has $q_T = 0$

- first non-trivial order (= LO)

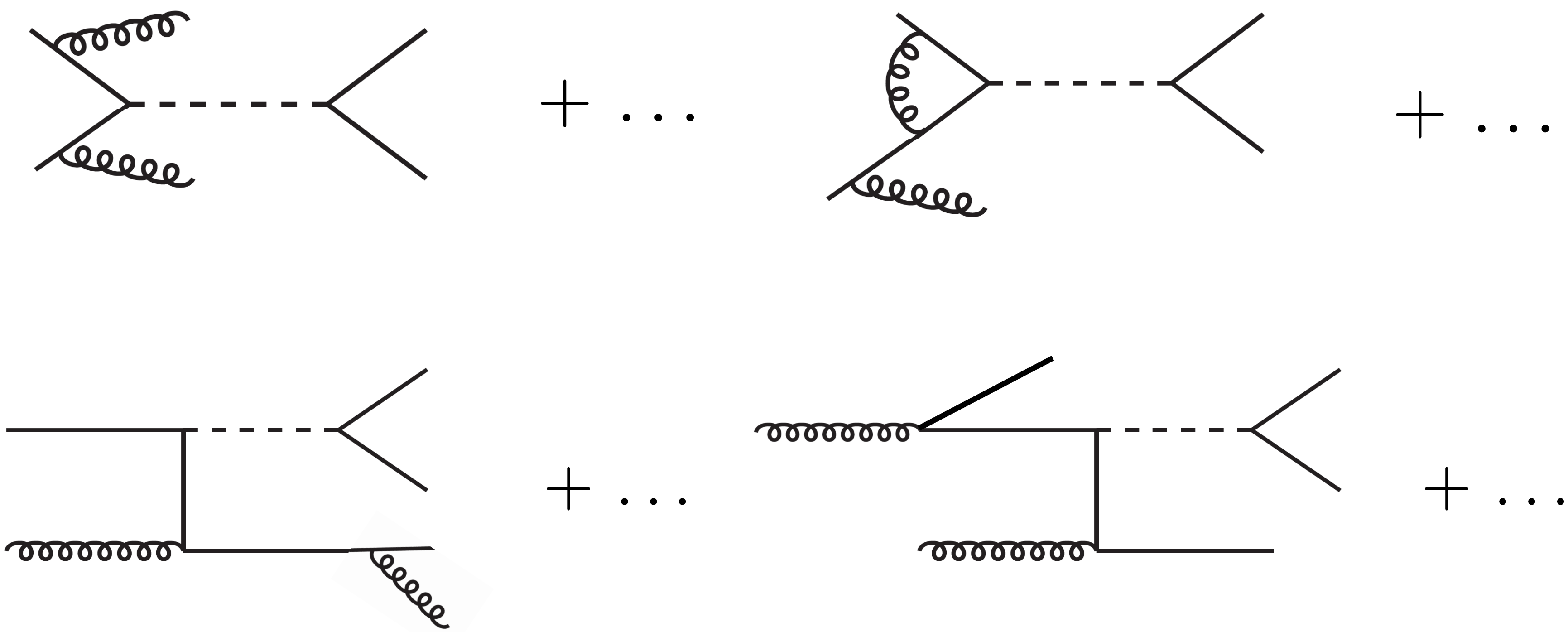




$$\lambda \neq 1,\ \mu \neq 0,\ \nu \neq 0$$

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

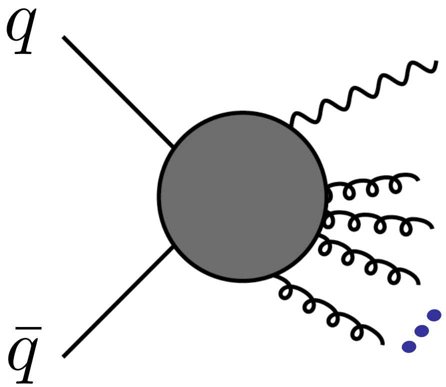
- NLO:



first computed by Mirkes ‘92; Mirkes, Ohnemus ’95

New NLO results Lambertsen, WV

- region $q_T \ll Q$:



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

"q_T logarithms"

- all-order resummation very well understood for W_T
  Collins-Soper-Sterman formalism

- and, of course, TMDs…

Boer, Mulders;
Boer, Brodsky, Hwang;
Lu, Ma;
Pasquini, Schweitzer; …

Bacchetta, Boer, Diehl, Mulders

Extraction of λ, ν at NLO

"How far do we get w/ fixed-order pQCD?"

- a lot of work in recent decade on perturbative corrections for Drell-Yan process

  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:

$$\ell^\mu_{\rm CS} = \frac{Q}{2}\begin{pmatrix} 1 \\ \sin\theta\cos\phi \\ \sin\theta\sin\phi \\ \cos\theta \end{pmatrix} \xrightarrow{\text{Lorentz Tr.}} \ell^\mu_{\rm cm} = \frac{1}{2}\begin{pmatrix} q_0\,(1+\sin\alpha\sin\theta\cos\phi) + q_L\cos\alpha\cos\theta \\ q_T + Q\,\frac{\sin\theta\cos\phi}{\cos\alpha} \\ Q\,\sin\theta\sin\phi \\ q_L\,(1+\sin\alpha\sin\theta\cos\phi) + q_0\cos\alpha\cos\theta \end{pmatrix}$$

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

- from this:

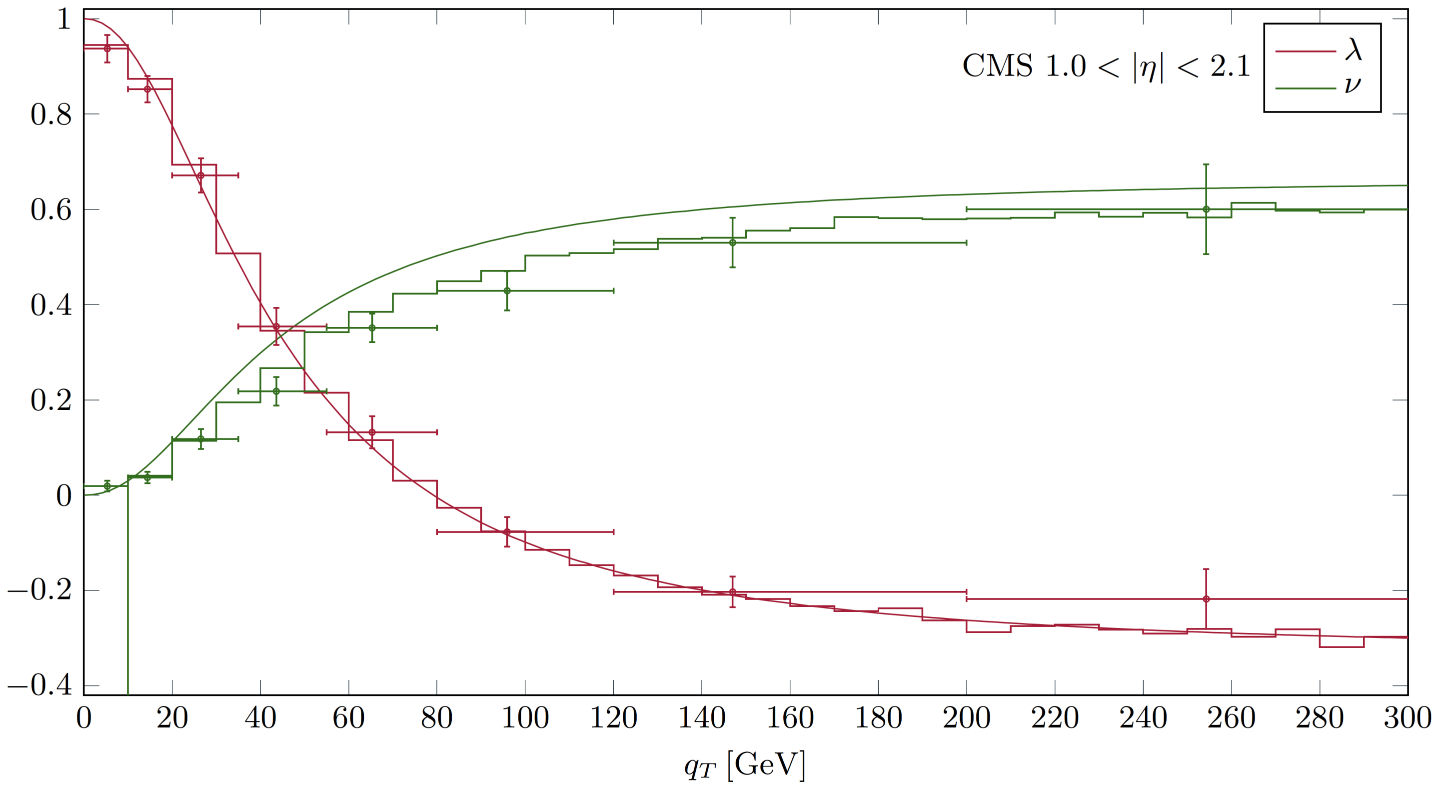
$$\cos\theta = -\frac{2\,\ell_{\rm cm}\cdot\mathcal{P}_1}{(Q^2+q_T^2)\cos\alpha} \qquad \cos 2\phi = 1 - \frac{2\,(\ell_{\rm cm}\cdot\mathcal{P}_2)^2}{q_T^2\left[\frac{Q^2}{4} - \frac{(\ell_{\rm cm}\cdot\mathcal{P}_1)^2}{Q^2+q_T^2}\right]}$$

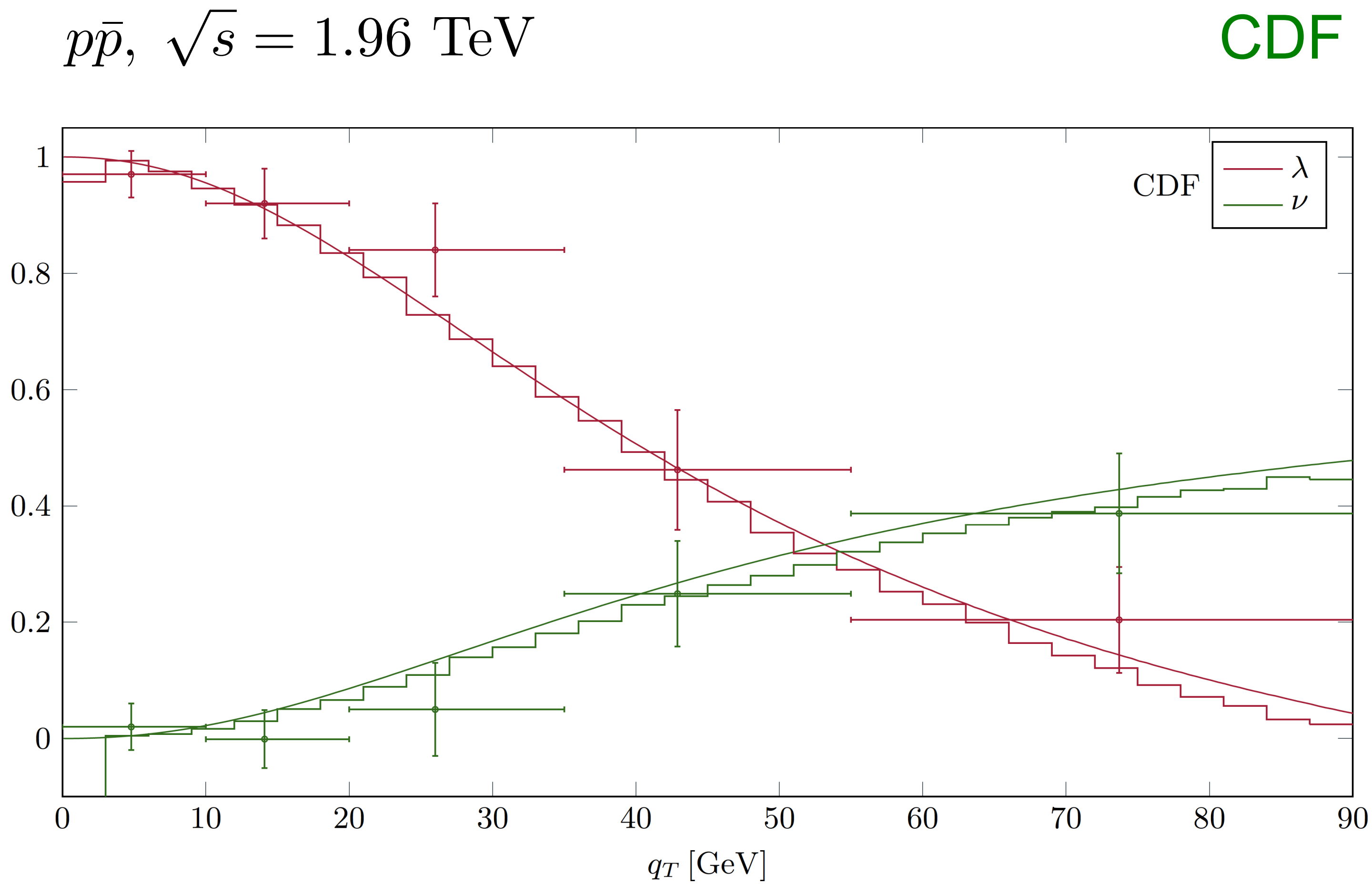
where $\mathcal{P}_1^\mu \equiv \begin{pmatrix} q_L \\ 0 \\ 0 \\ q_0 \end{pmatrix}$ $\qquad \mathcal{P}_2^\mu \equiv q_T\begin{pmatrix} 0 \\ 0 \\ -1 \\ 0 \end{pmatrix}$

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 weak
- NLO computationally very demanding

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

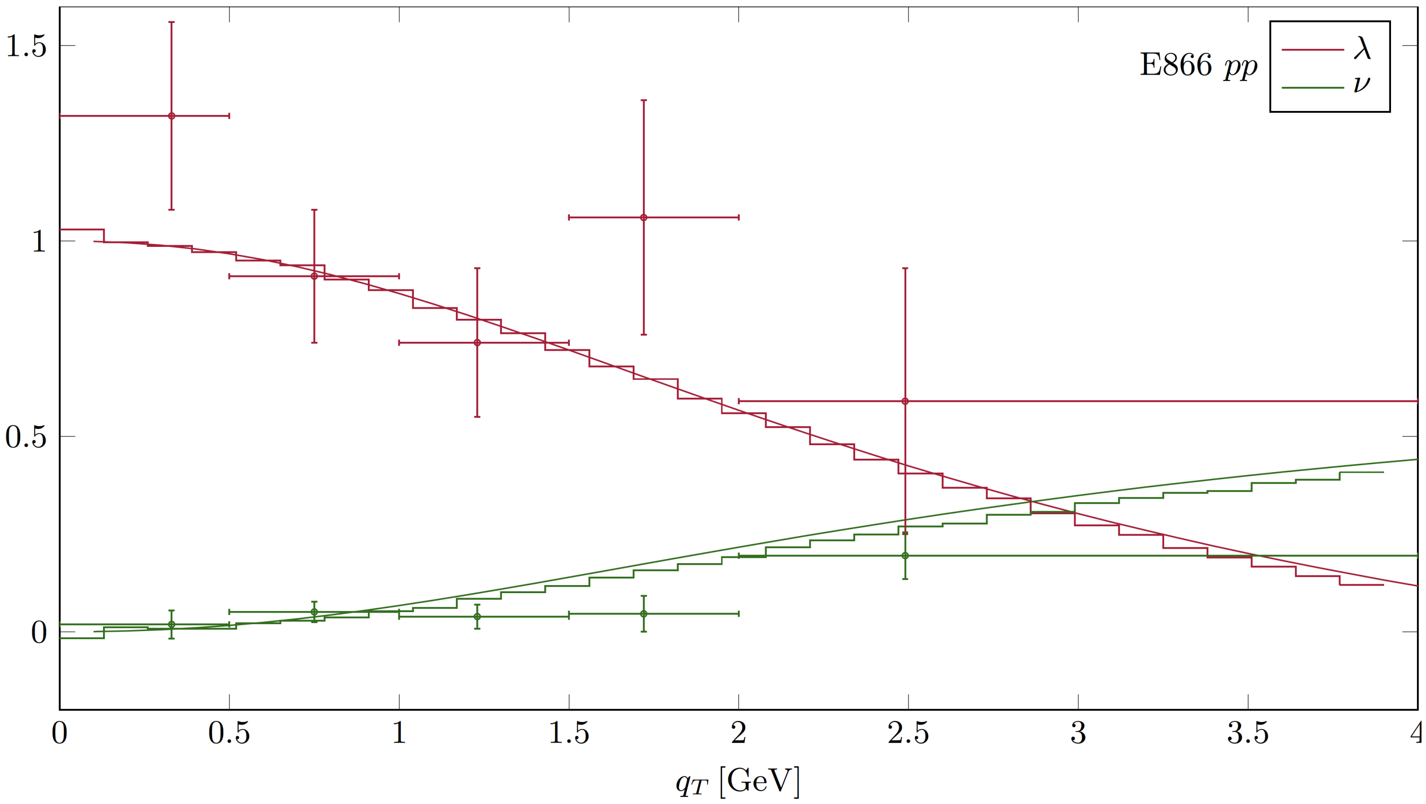




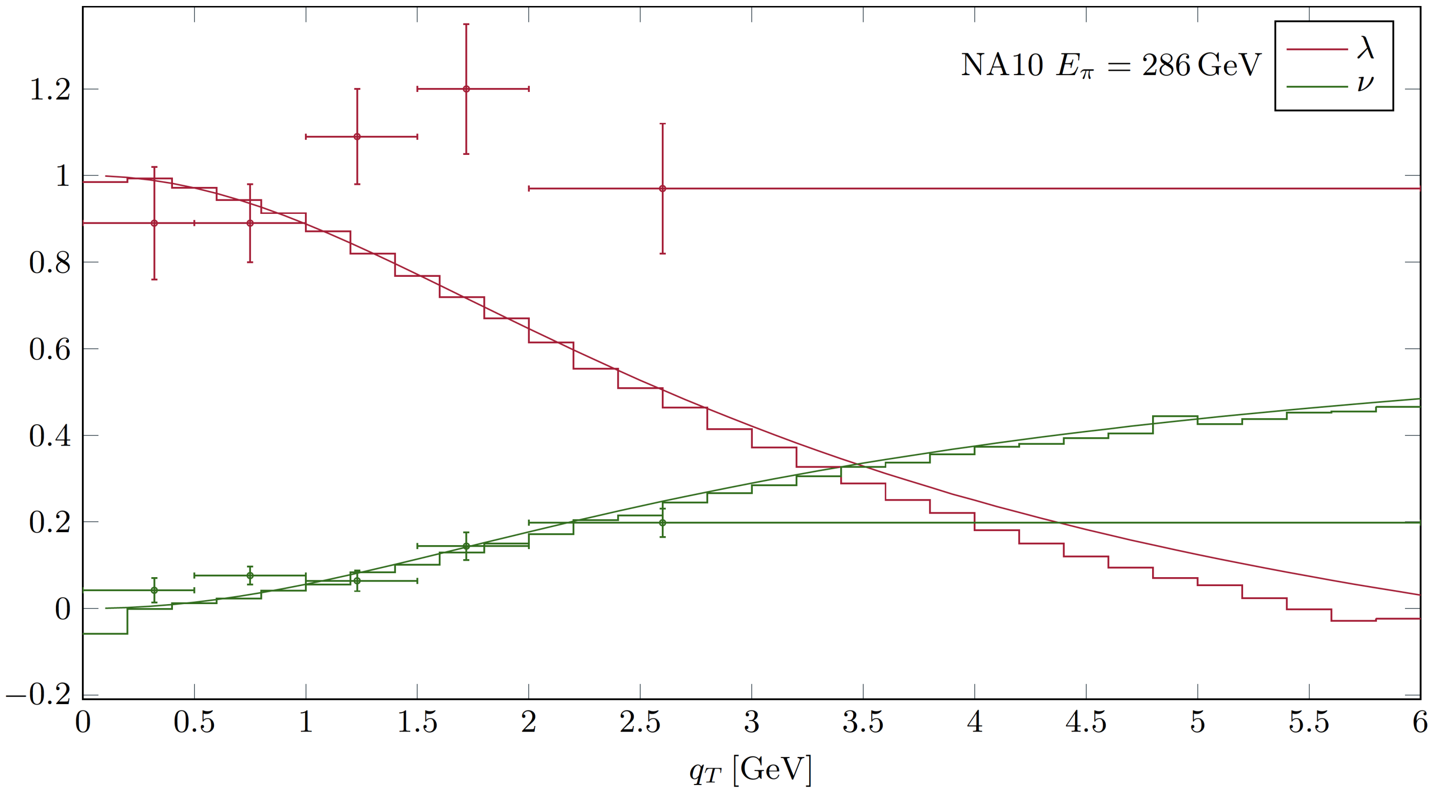
$p\bar{p},\ \sqrt{s} = 1.96\ \text{TeV}$
CDF
CDF
λ
ν
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
80
90
q_T [GeV]

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

E866

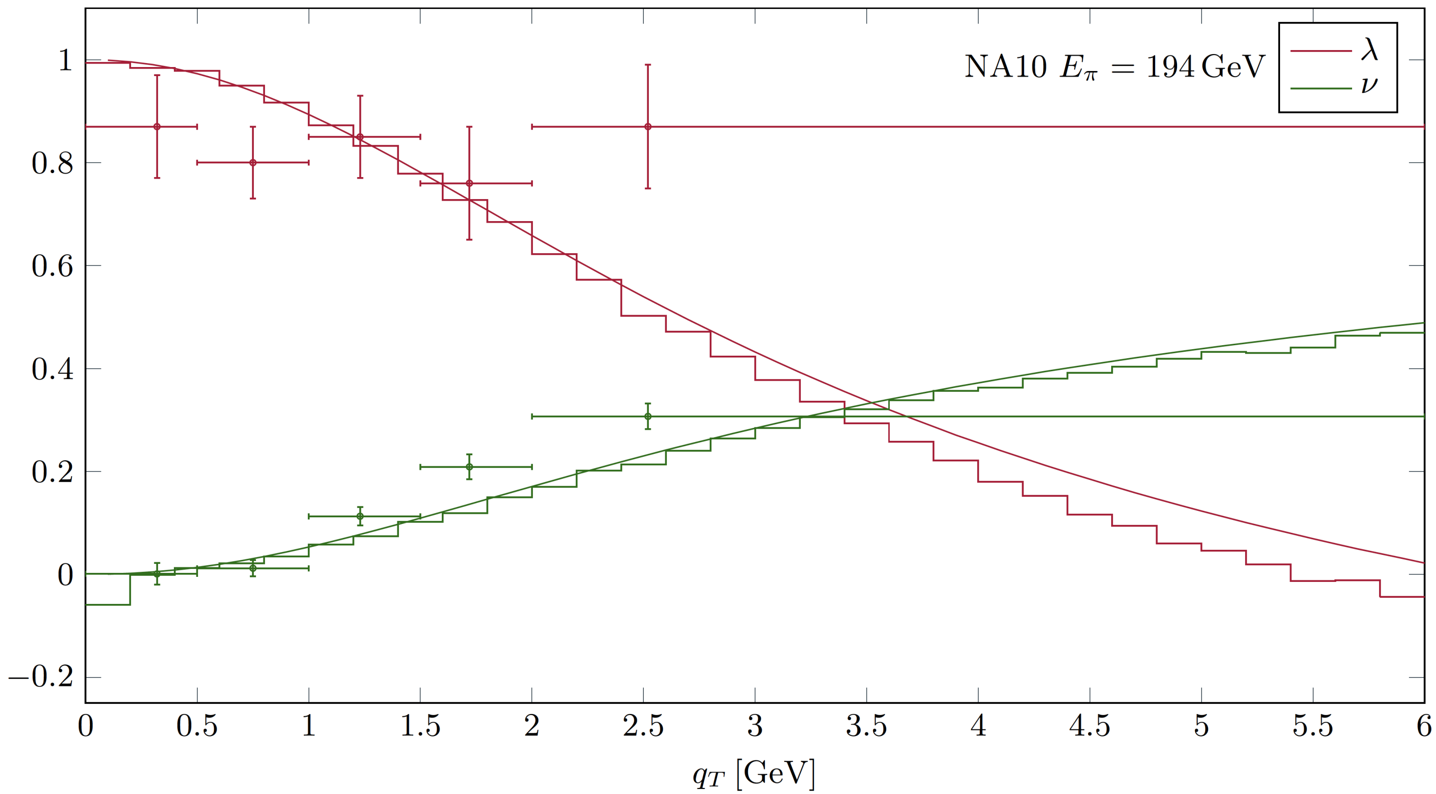


$\pi W,\ E_\pi = 286\,\mathrm{GeV}$ NA10

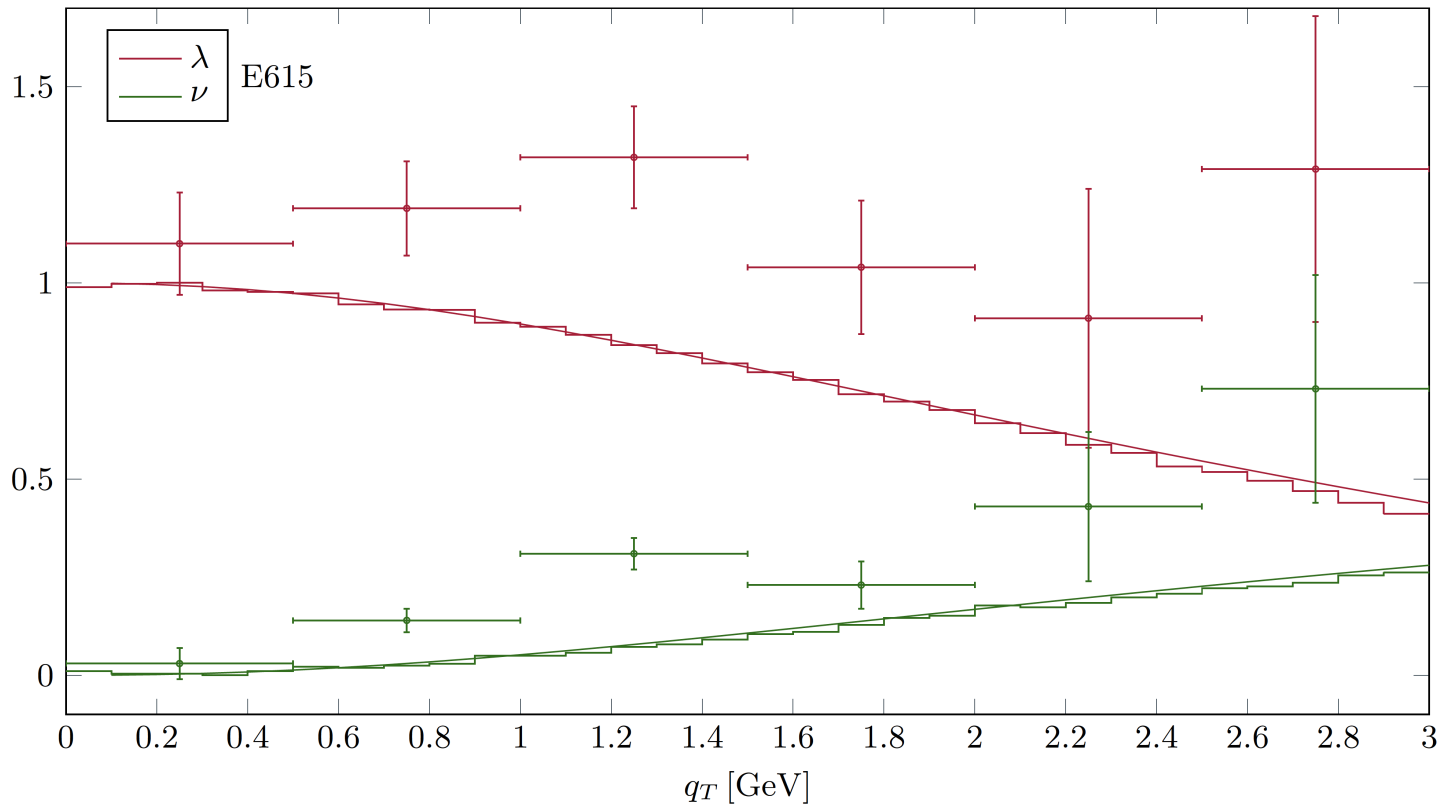


$\pi W,\ E_\pi = 194\,\mathrm{GeV}$

NA10



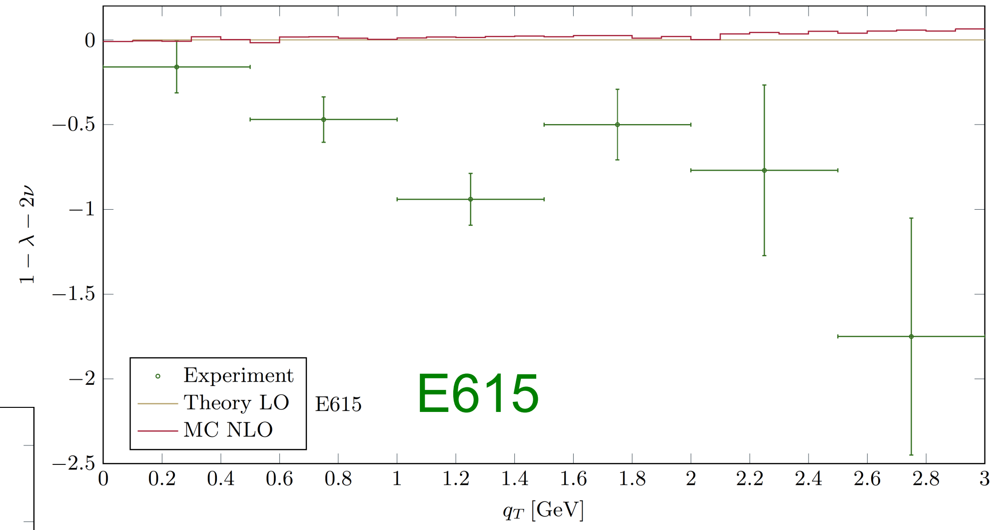
$\pi W,\ E_\pi = 252\,\mathrm{GeV}$ E615

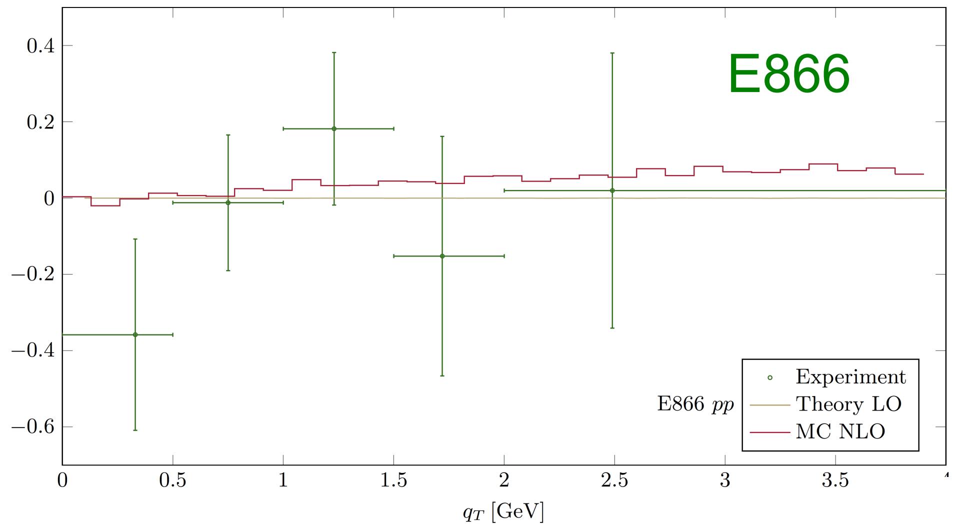


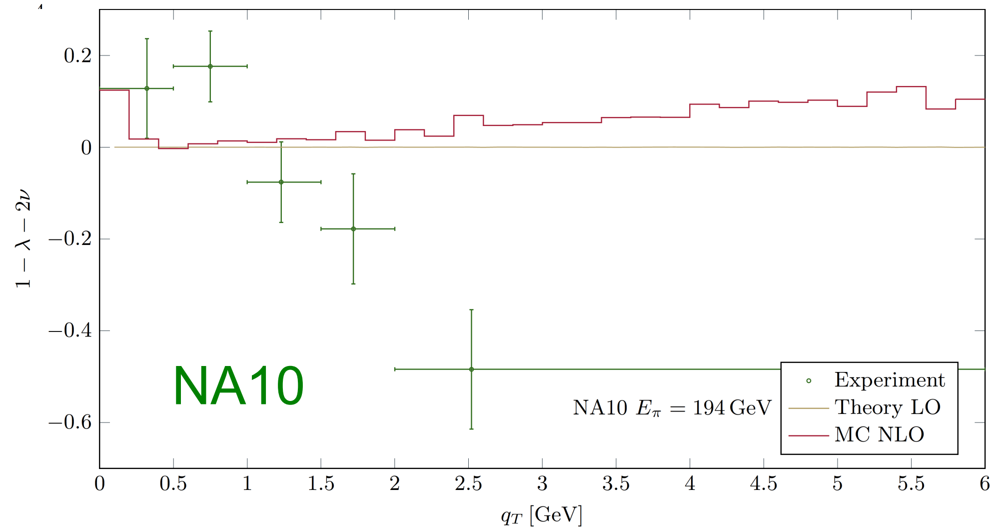
- note: $$\lambda = \frac{W_T - W_L}{W_T + W_L}$$

→ positivity constraint $\lambda \leq 1$ Lam, Tung '78

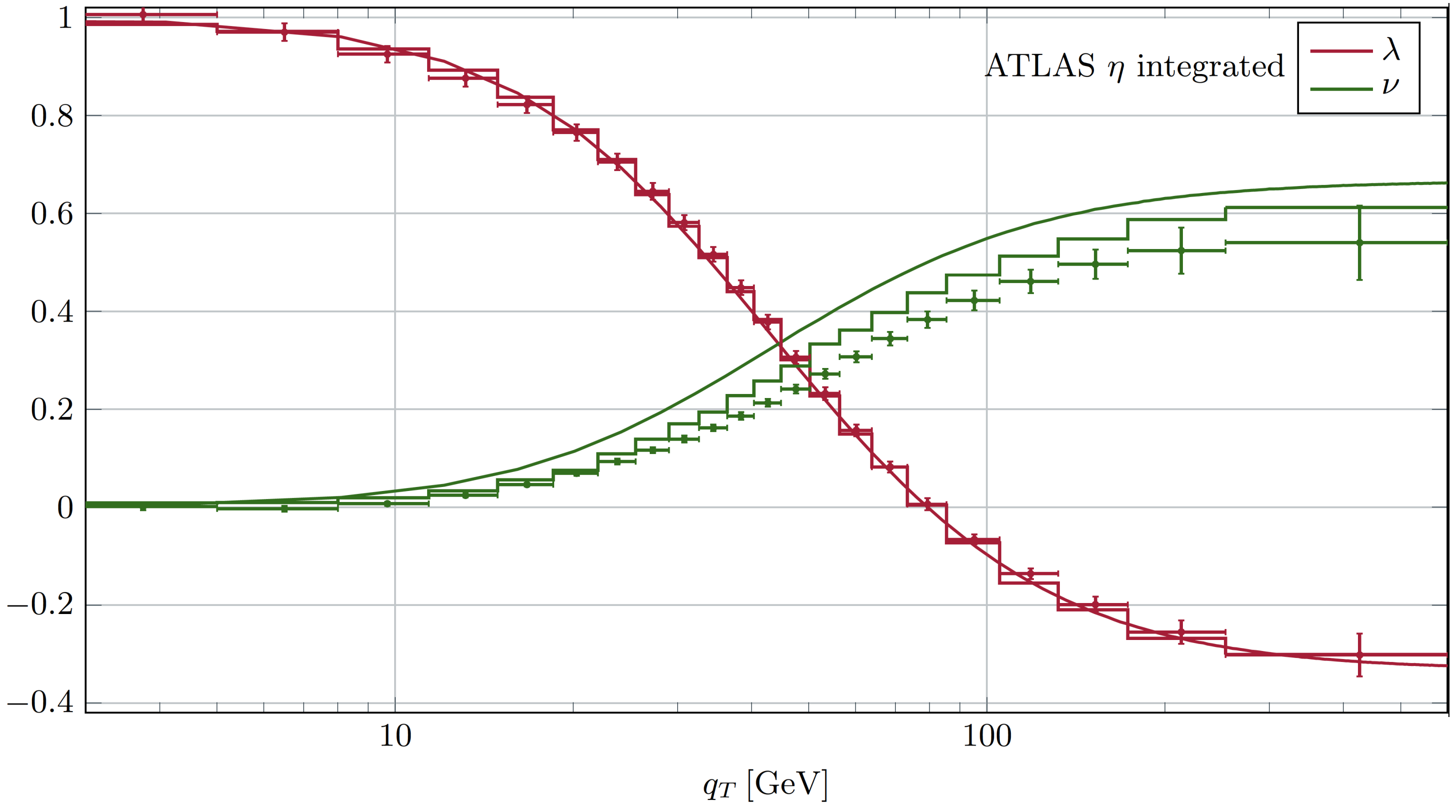
Lam-Tung $1 - \lambda - 2\nu$







New ATLAS results



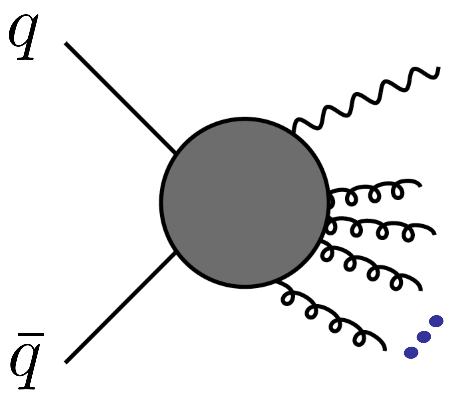
ATLAS η integrated
λ
ν
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
10
100
q_T [GeV]

- dependence on scales and PDFs is small

- do not expect TMD effects to be relevant beyond q_T=10 GeV

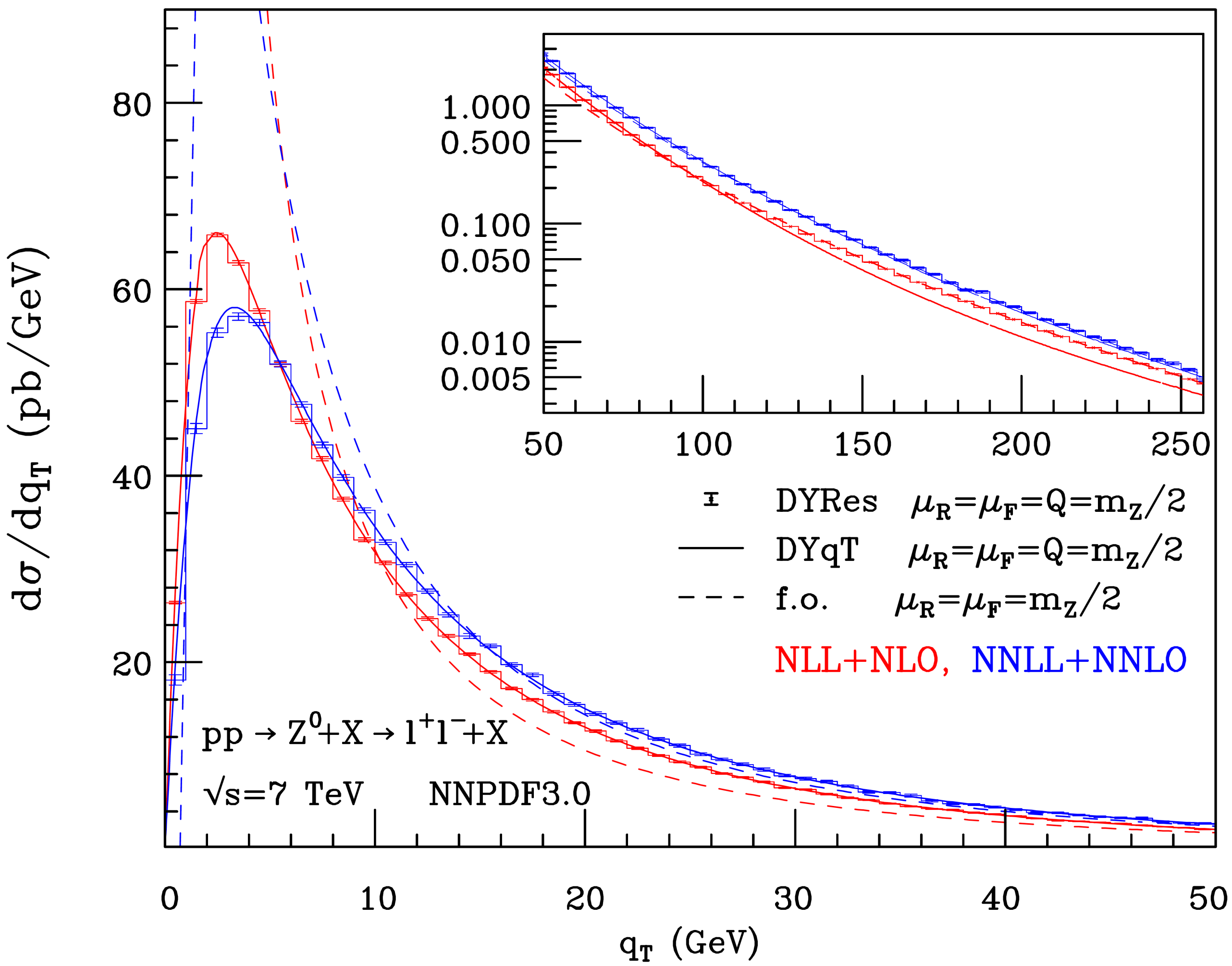
- a regime where log(q_T/Q) is not particularly large

- region $q_T \ll Q$:



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

Catani, de Florian,
Ferrera, Grazzini ‘15



- low-q_T structure functions at $\mathcal{O}(\alpha_s)$ (CS frame):

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

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

Boer, WV

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

Berger, Qiu, Rodriguez

- to leading log:

Berger, Qiu, Rodriguez

$$W_T^{\rm Resum} = \left(1 - \frac{1}{2}\frac{Q_\perp^2/Q^2}{1+Q_\perp^2/Q^2}\right)\frac{W^{\rm Resum}}{2}$$

$$W_L^{\rm Resum} = \frac{Q_\perp^2/Q^2}{1+Q_\perp^2/Q^2}\,\frac{W^{\rm Resum}}{2}$$

$$W_{\Delta\Delta}^{\rm Resum} = \frac{1}{2}\,\frac{Q_\perp^2/Q^2}{1+Q_\perp^2/Q^2}\,\frac{W^{\rm Resum}}{2}$$

(up to matching)

- differences at next-to-leading log

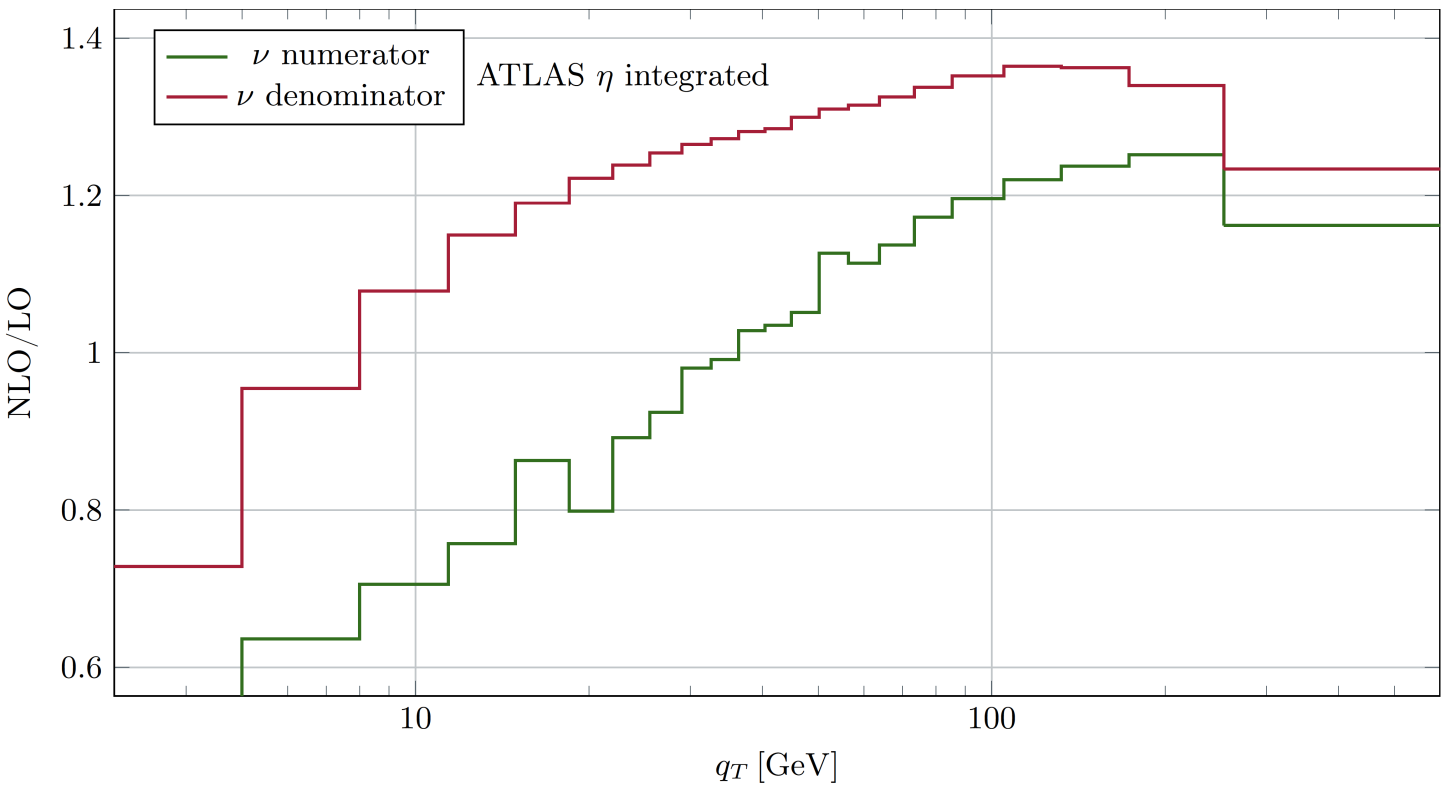
Boer, WV

- still, expect small resummation effects for $\lambda,\ \nu$

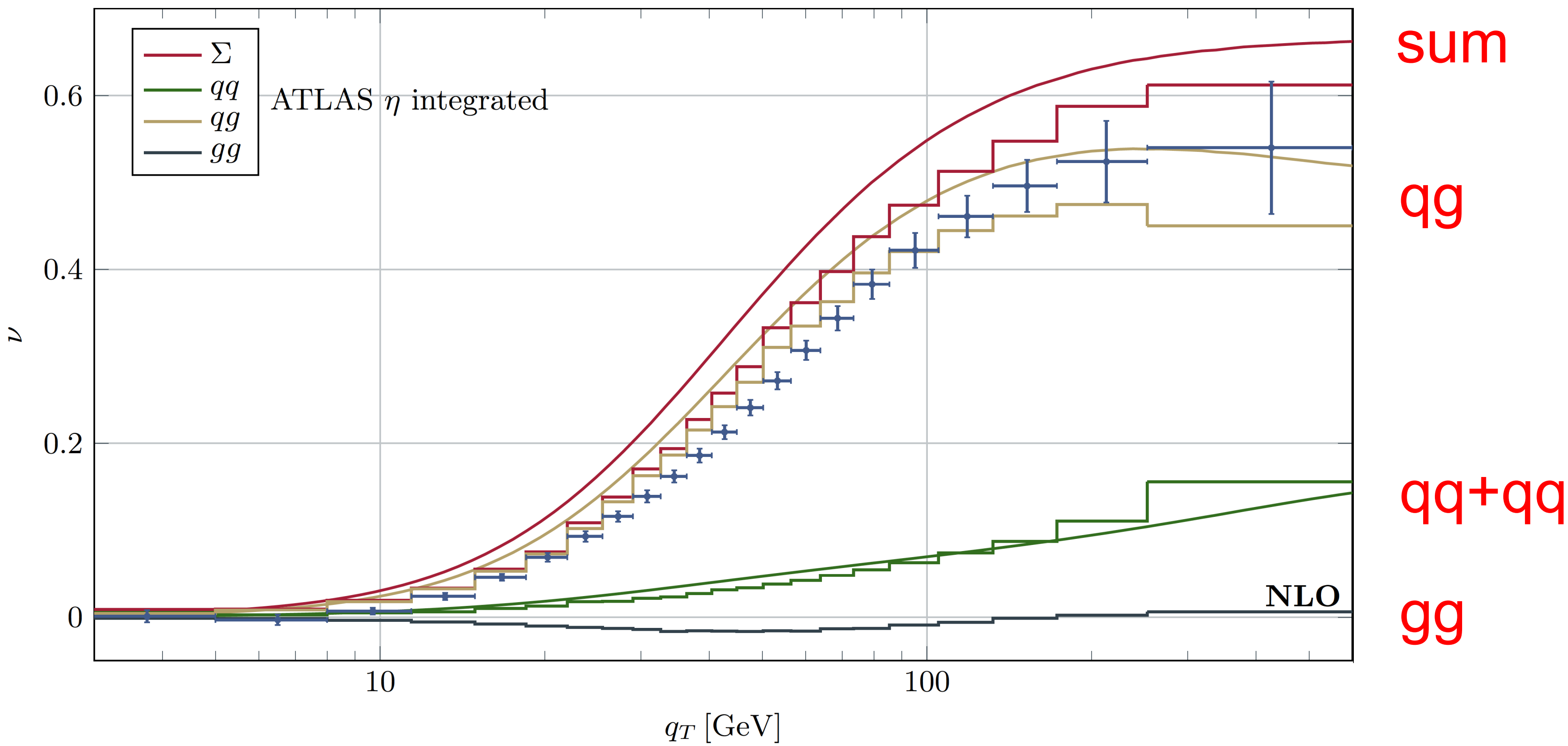
$$\nu = \frac{2W_{\Delta\Delta}}{W_T + W_L}$$

K factors

denominator / numerator



LO/NLO partonic channels for ν :



NNLO effect? We'll know soon…

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The NNLO QCD corrections to Z boson production at large transverse momentum

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and T.A. Morgan[d]

Conclusions and outlook:

- have extracted coefficients λ, ν at NLO from FEWZ and DYNNLO codes
- "dispel myth" that pQCD cannot describe data: overall reasonable description
- *not* meant to argue that there are no effects beyond fixed-order pQCD
- serious studies of Boer-Mulders should include pQCD radiative effects (including resummation)
- clear call for better data in fixed-target regime