Lam-Tung relation breaking as a probe of gluon TMD

Workshop on resummation, evolution and factorisation
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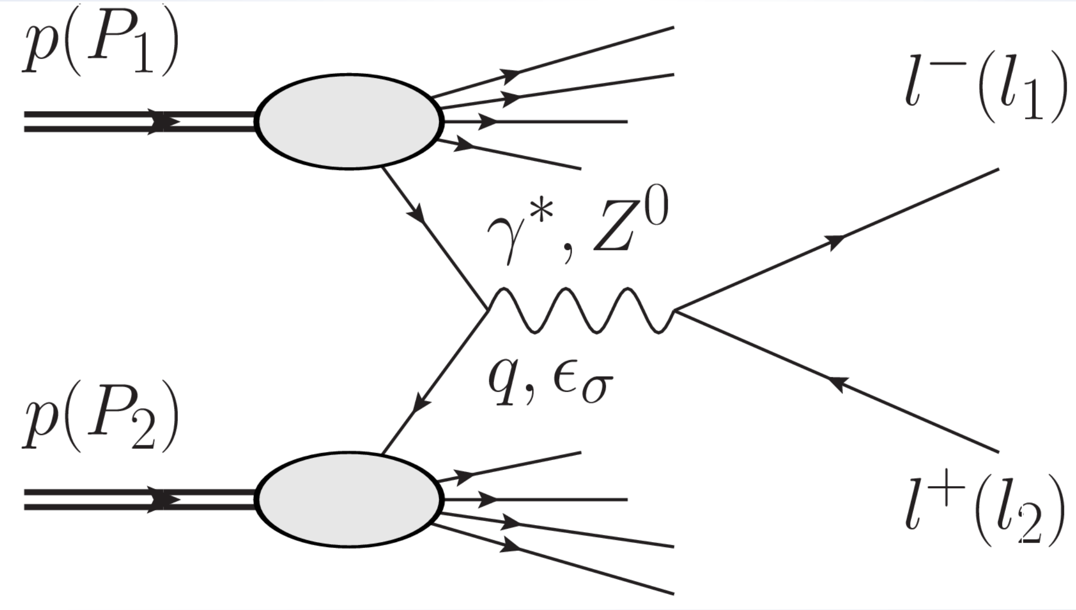
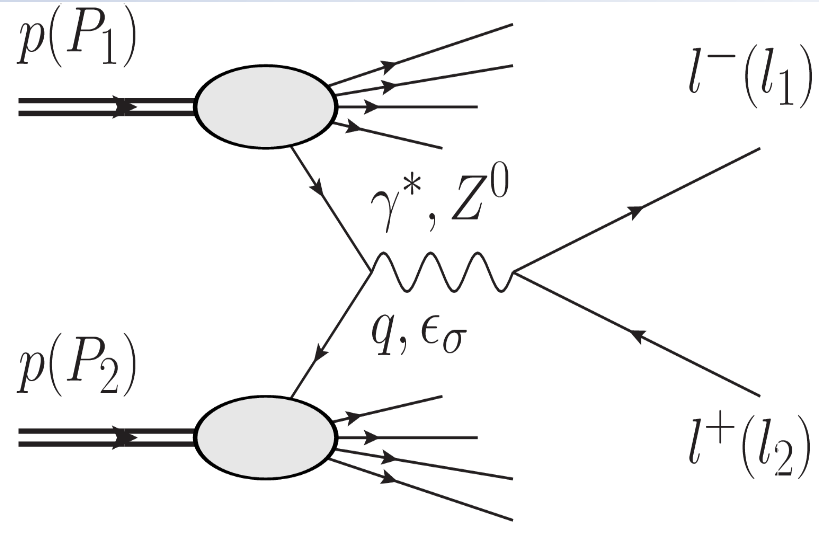
Overview:

- Drell-Yan / Z^0 production
  in pp collisions at the LHC



- Recent ATLAS measurement: precise data on dilepton $l^+ l^-$ angular distributions from Z^0 decays and problems of collinear QCD at NNLO
  [JHEP 1608 (2016) 159 arXiv:1606.00689]
- **This talk:** k_T factorisation approach and inclusion of the g*g* channel → improved description of the data + demonstration of essential sensitivity of the DY dilepton angular distibutions to the shape of gluon TMD
  [Based on recent results obtained with **Mariusz Sadzikowski** and **Tomasz Stebel**, arXive:1609.04300]

Drell-Yan process at the LHC: measured are dileptons
Intermediate: γ^* or Z^0 boson



- Measured are four-momenta of the lepton and antilepton
- Full information about the pair kinematics: invariant mass M, transverse momentum q_T, rapidity Y, and dilepton angular distribution
- **9 independent structure functions** describe dilepton angular distribution for Z^0
- **4 independent structure** functions for γ^* and even parity Z^0 component
  => 3 angular coefficients A_0, A_1 and A_2

$$\left[\frac{d\sigma}{dY\,dM^2\,d^2q_T}\right]^{-1} \frac{d\sigma}{dY\,dM^2\,d^2q_T\,d\Omega_l} = \frac{3}{16\pi}\left[(1+\cos^2\theta) + \frac{1}{2}A_0\,(1-3\cos^2\theta) + A_1\,\sin 2\theta\cos\phi + \frac{1}{2}A_2\,\sin^2\theta\cos 2\phi\right]$$

Lam-Tung combination of angular coefficients

- Lam and Tung: In Collins-Soper frame the difference of angular coefficients

$$A_{LT} = A_0 - A_2$$

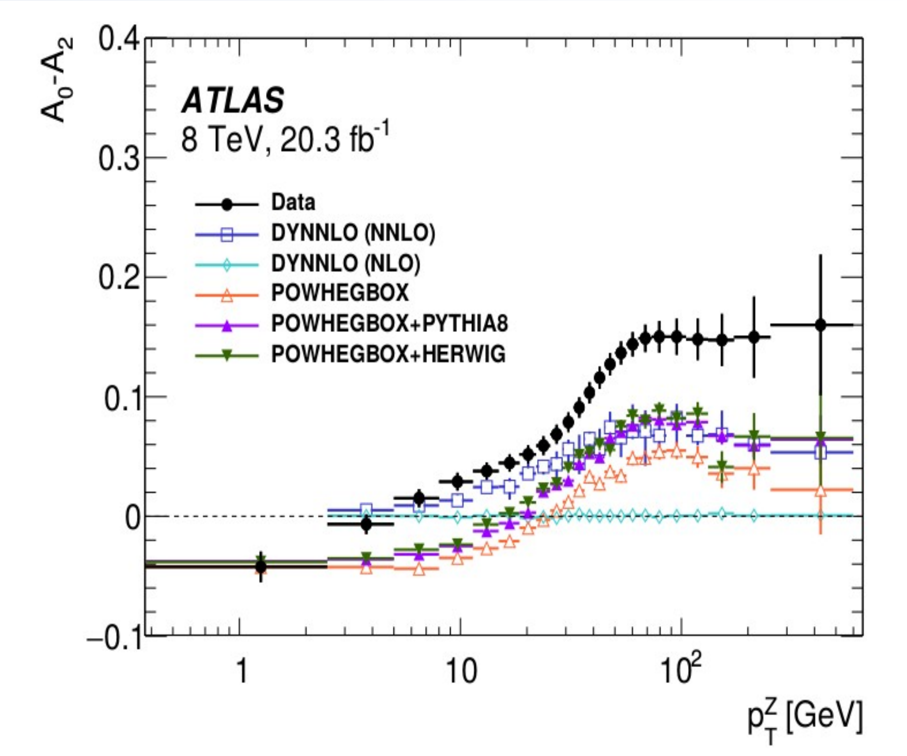
vanishes in the collinear QCD approximation at the leading twist, up to the NNLO

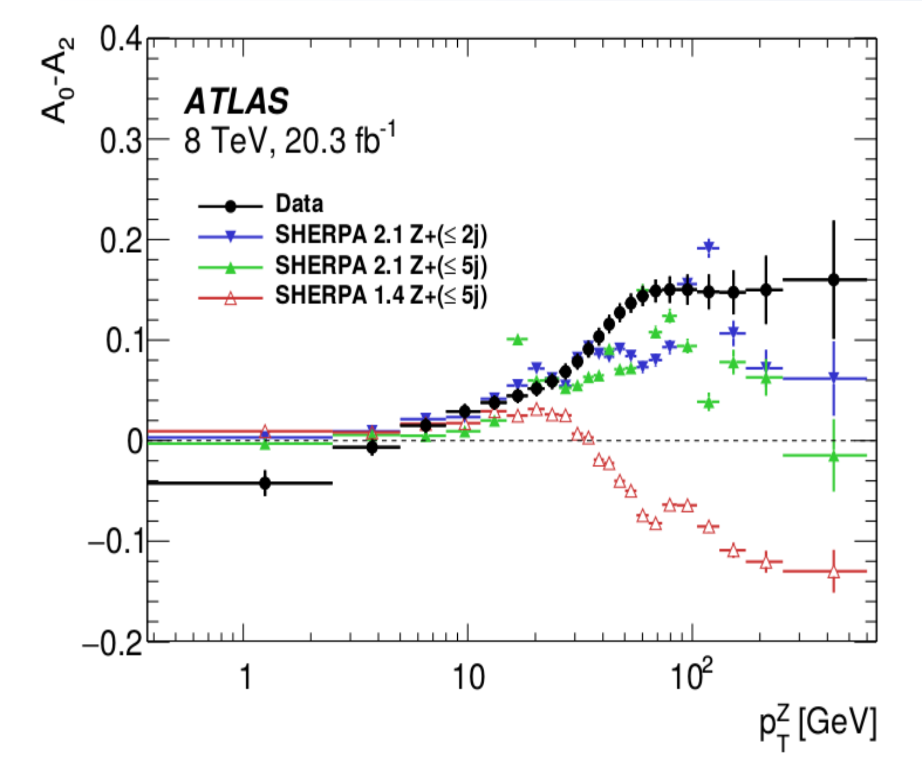
- A_{LT} is invariant under rotations in the XZ plane of the frame – that is under rotations w.r.t. the Y axis – perpendicular to beams and boson momenta

- Enhanced sensitivity of A_{LT} to subtle effects: higher orders, higher twists, parton tranverse momentum

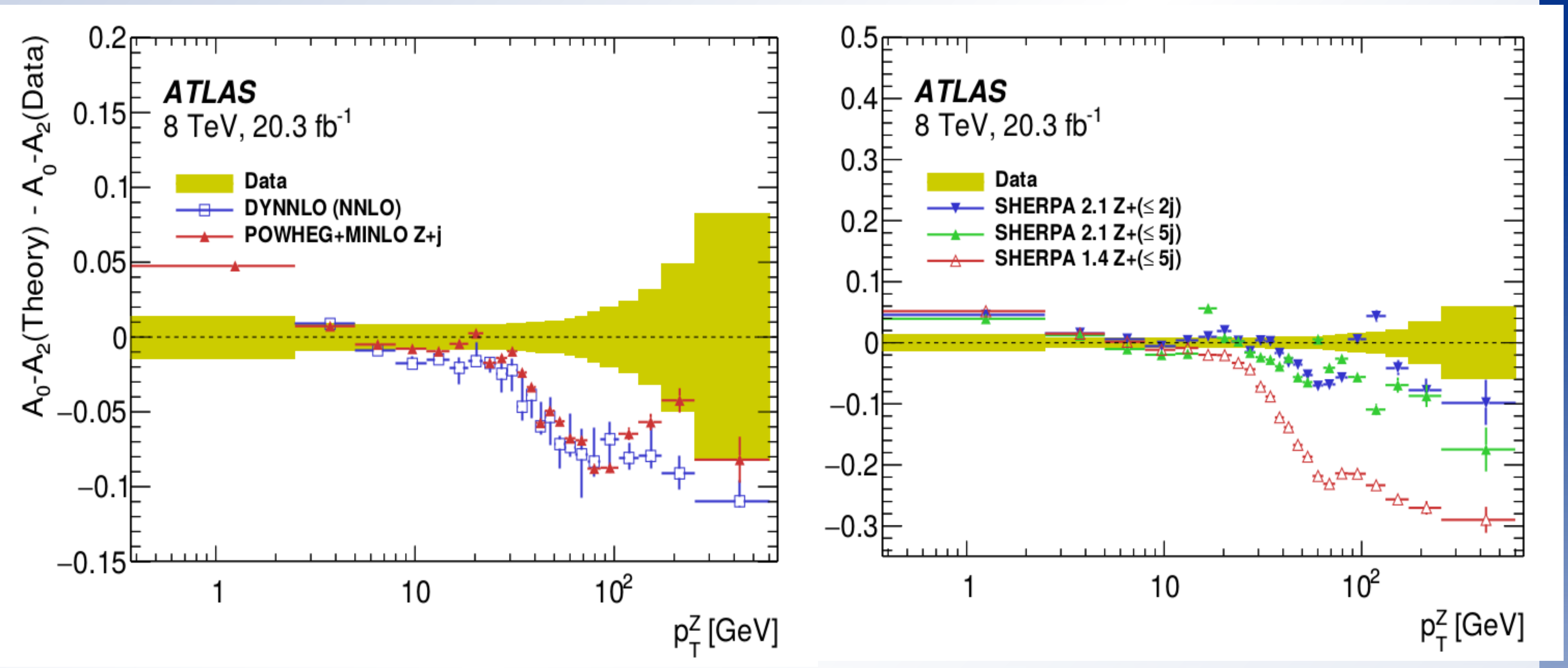
ATLAS measurement of Lam-Tung relation breaking A_{LT}

- Measured are dilepton distributions at the Z^0 peak
- All DY structure functions are measured and overall agreement is found with NNLO QCD predictions except of ...
- … **puzzling failure of NNLO QCD for the Lam-Tung combination**
- MC codes at NNLO: DYNNLO, POWHEGBOX-PYTHIA and SHERPA fail to describe A_{LT}





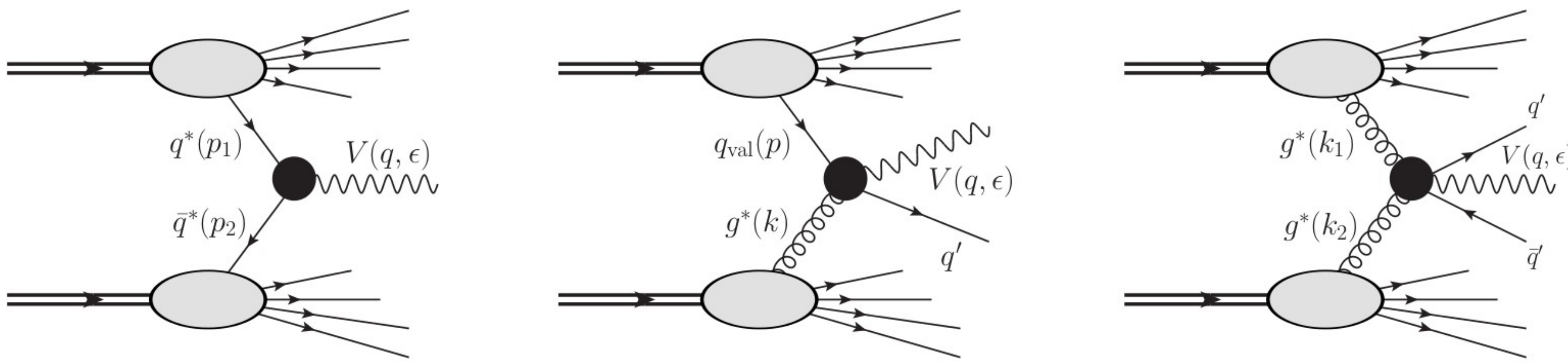
Closer look at A_{LT} – what could be the source of discrepancy?



- At Z^0 peak higher twists are irrelevant
- NNNLO calculation in collinear QCD – rather long term project
- Teryaev et al. → parton p_T as a possible source of Lam-Tung relation breaking → **let us try to use the k_T factorization framework**

Theoretical framework: k_T factorization

- Off-shell quarks and gluons → quark and gluon TMDs
- Channels: $q^*\bar{q}^*$ (from LO), q^*g^*, $\bar{q}^*g^*$ (from NLO) and g^*g^* (from NNLO)



- Relation of angular distribution coeff-s to boson spin density matrix elements: L: 00, T: ++, - - ;   LT: 0+, 0-, -0, +0; TT: +-, -+

$$A_0 = \frac{\sigma_L}{\sigma_T + \sigma_L/2} \qquad A_1 = \frac{\sigma_{LT}}{\sigma_T + \sigma_L/2} \qquad A_2 = \frac{2\sigma_{TT}}{\sigma_T + \sigma_L/2}$$

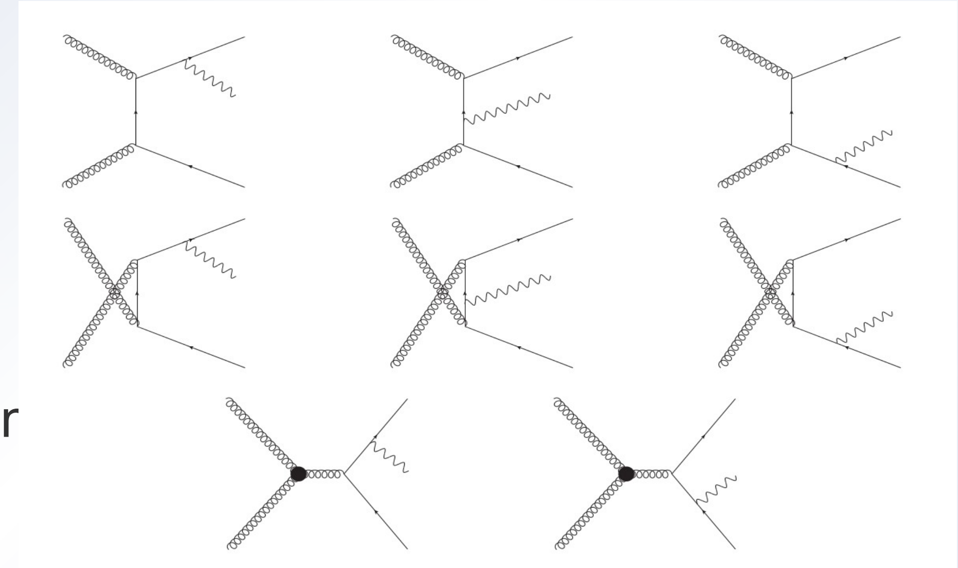
High energy approximation

- In high energy limit sea quarks come from gluons at the last splitting
- Valence quarks should be treated separately
- For pp collisions there are only valence quarks, no valence antiquarks: $\rightarrow$ $q_{val}\ \bar{q}_{val}$ channel does not contribute
- Left are: $q_{val}^*\ g^*$ and g^*g^* channels
- Valence quarks carry moderate transverse momentum as compared to gluons and sea quarks $\rightarrow$ we neglect the valence quarks TM and treat the $q_{val}^*\ g^*$ ME as the known $q_{val}g^*$ ME

g*g* channel

[S. Baranov, A. Lipatov, N. Zotov, Eur.Phys.J. C56 (2008) 371]
[M. Deak, F. Schwennsen, JHEP 0809 (2008) 035]

- High energy limit for gluon polarizations
- The effective triple gluon vertex
- Gauge invariance of the amplitude verified
- Dependence of the DY structure fur on gluon TMD F(x, k_T^2, μ)



$$d\sigma^{(g^* g^*)}_{\sigma\sigma'} = \int dx_1 \int \frac{d^2\boldsymbol{k}_1}{\pi \boldsymbol{k}_1^2} \mathcal{F}(x_1, \boldsymbol{k}_1^2, \mu_F) \int dx_2 \int \frac{d^2\boldsymbol{k}_2}{\pi \boldsymbol{k}_2^2} \mathcal{F}(x_2, \boldsymbol{k}_2^2, \mu_F)$$

$$\times \frac{(2\pi)^4 \mathcal{H}_{\sigma\sigma'}}{2S} dPS_3(k_1 + k_2 \to p_3 + p_4 + q)$$

Models of gluon Transverse Momentum Distributions (TMDs)

- Jung-Hautmann – from the CCFM equation
- Golec-Biernat – Wusthoff – as a quasi-collinear model
- LO BFKL from GBW input at x_{in} = 0.1

$$\mathcal{F}_{\rm BFKL}(x,k^2) = \frac{(1-x)^7}{k^2}\int_{1/2-i\infty}^{1/2+i\infty}\frac{ds}{2\pi i}k^{2s}\exp[\bar{\alpha}_{\rm s}\chi(s)\log(x_{\rm in}/x)]\tilde{f}_0(s)$$

- Simple Weizsaecker-Williams-like model F ~ $1/k^2$ for large k^2 :

$$\mathcal{F}_{\rm WW}(x,k^2) = \begin{cases} (N_1/k_0^2)(1-x)^7\,(x^\lambda k^2/k_0^2)^{-b} & \text{for} \quad k^2 \geq k_0^2 \\ (N_1/k_0^2)(1-x)^7\,x^{-\lambda b} & \text{for} \quad k^2 < k_0^2 \end{cases}$$

The central choice b=1, variations of b to test sensitivity of observabels to shape of gluon TMD

Reggeized Quark Parton Model approximation

- Instead of computing g*g* → q $\bar{q}$ V, approximation may be adopted of g* → q* splitting followed by off-shell quark – antiquark fusion into the electroweak boson
- Jung-Hautmann → sea quark TMD:
  [F. Hautmann, M.Hentschinski, H. Jung, Nucl.Phys. B865 (2012) 54]

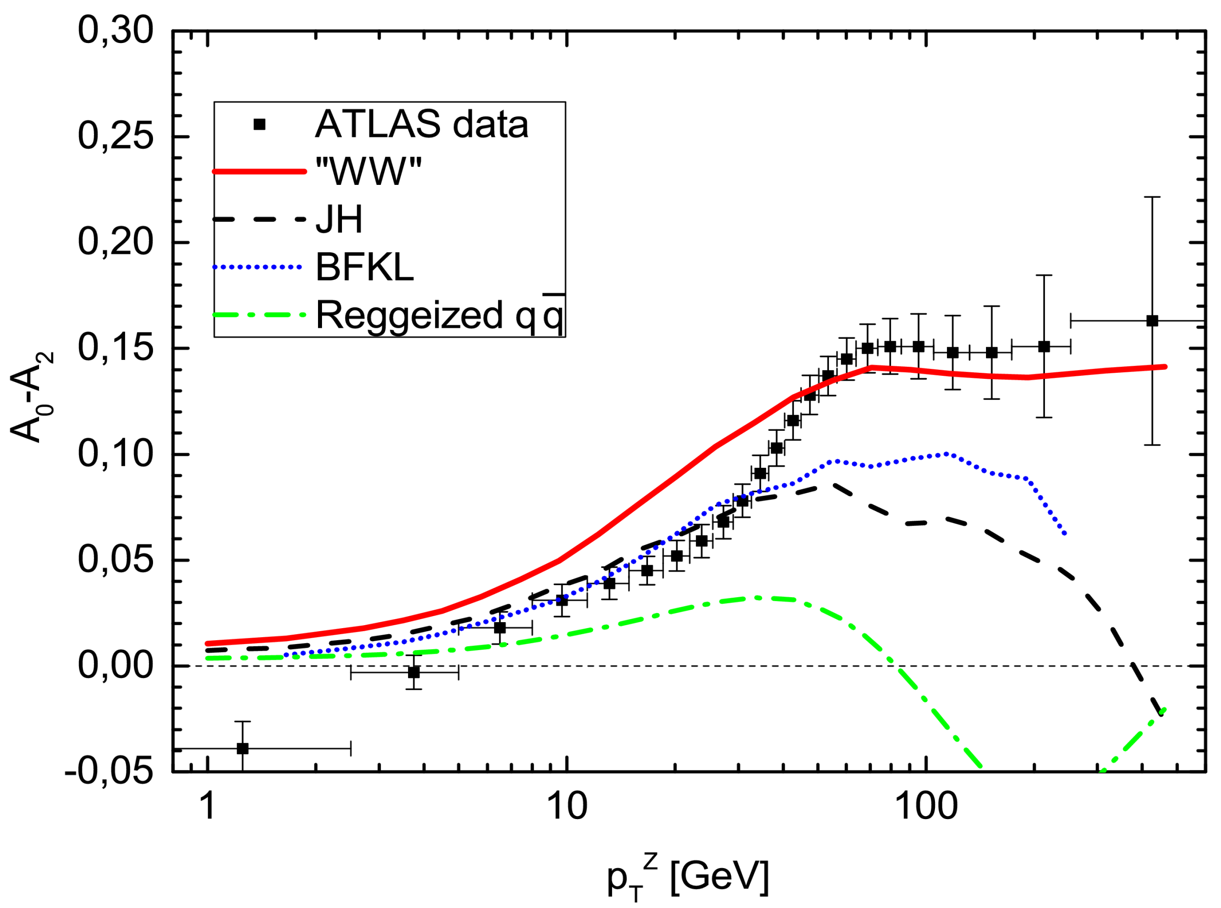
$$\mathcal{Q}_{\mathrm{sea}}(x, \boldsymbol{p}_T^2, \mu_F) = \frac{1}{\boldsymbol{p}_T^2} \int_x^1 \frac{dz}{z} \int dk_T^2 \, \Theta\left(\mu_F^2 - \frac{\boldsymbol{p}_T^2 + z(1-z)\boldsymbol{k}_T^2}{1-z}\right) \times \frac{\alpha_s(\mu_F)}{2\pi} P_{q^*g^*}(z, \boldsymbol{p}_T^2, \boldsymbol{k}_T^2)\, \mathcal{F}(x, \boldsymbol{k}_T^2, \mu_F)$$

where the TM dependent splitting function:

$$P_{q^*g^*}(z, \boldsymbol{p}_T^2, \boldsymbol{k}_T^2) = T_R \left(\frac{\boldsymbol{p}_T^2}{\boldsymbol{p}_T^2 + z(1-z)\boldsymbol{k}_T^2}\right)^2 \left[(1-z)^2 + z^2 + 4z^2(1-z)^2 \frac{\boldsymbol{k}_T^2}{\boldsymbol{p}_T^2}\right]$$

- We shall also test this approximation to g*g* contribution (Reggeized quark approximation)

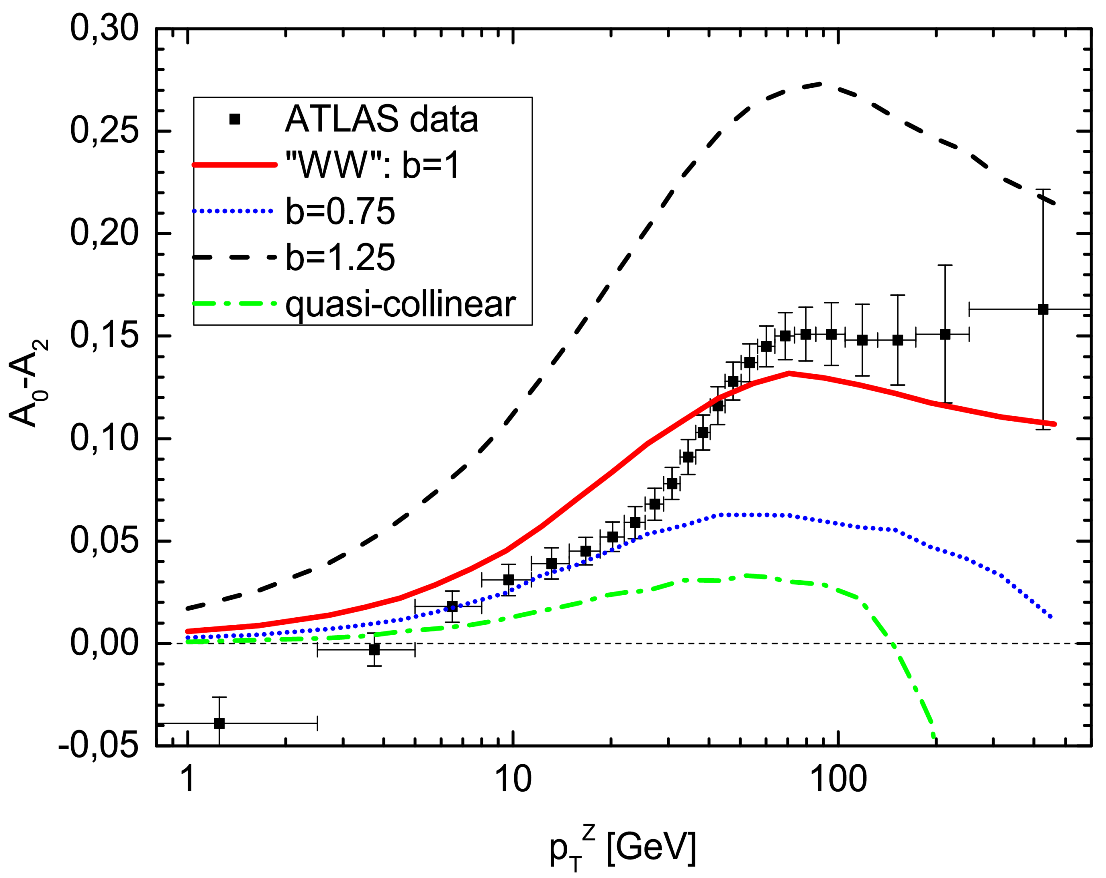
Results: Lam-Tung relation breaking in physical models



- Best description of large p_T data in the "WW" model with $1/k_T^2$ dependence of gluon TMD for large k_T a
- Reggeized quark model does not describe the data well

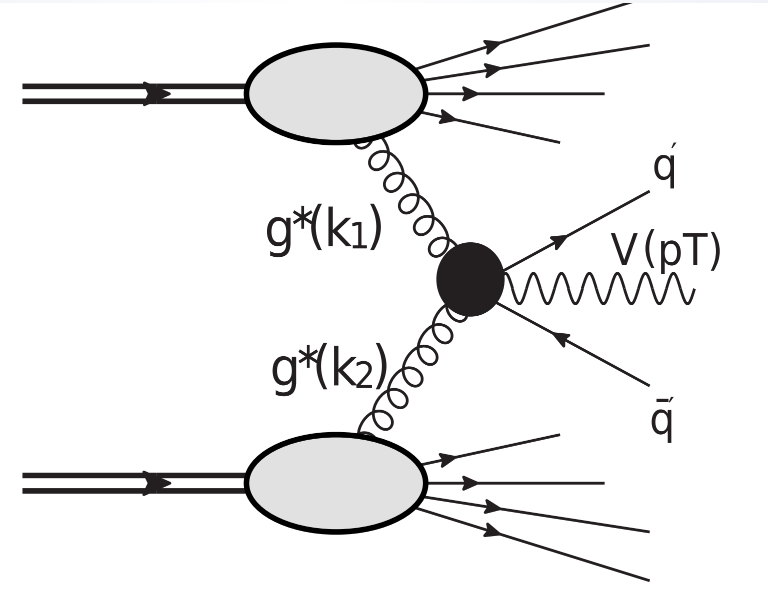
Results: Lam-Tung relation breaking in simplified models

- Model of gluon TMD with power-like behaviour: $(1 / k_T^2)^b$: b=1 (central), b=0.75 and b=1.25



- Quasi-collinear model of gluon TMD, Gaussian with O(1 GeV) width
- Strong sensitivity to the shape of gluon TMD
- Quasi-collinear model far below the data → generation of quark transverse momenta in the hard matrix elements is not sufficient → consistent with failure of collinear QCD at NNLO for A_{LT}
- **High sensitivity of to g* transverse momentum distribution**

Range of kinematic relevance



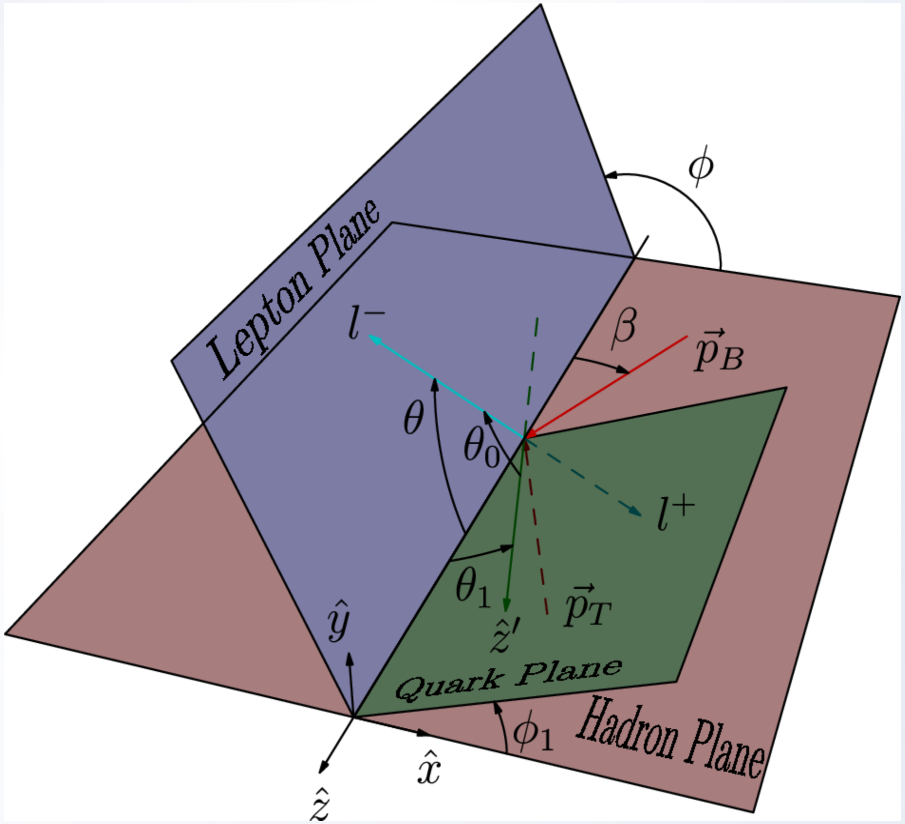
- ATLAS measurements performed at 8 TeV
- The transverse mass of Z^0 boson from M_T to about 0.5 TeV
- For central production and typical p_T ~100 GeV: $\mathbf{x_Z \sim 0.02}$
- In dominant g* g* channel recoil by light quarks → $M_{inv}(Z^0\, q\, \bar{q}) >> M_T$ → gluon $\mathbf{x_g >> x_Z}$
- **At moderate p_T : $x_g \sim$ 0.03 – 0.01 and at large $p_T \sim$ 0.5 TeV typical $x_g > 0.1$**
- **This is x_g -range that is still highly sensitive to the k_T profile of gluon input for evolution towards smaller values of x_g**

Kinematic sources of Lam-Tung relation breaking

[J.-C. Peng, W.-C. Chang, R. McClellan, O. Teryaev, Phys.Lett. B758 (2016) 384]

- In dilepton rest frame with Z-axis set by quark momentum the lepton angular distribution:

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

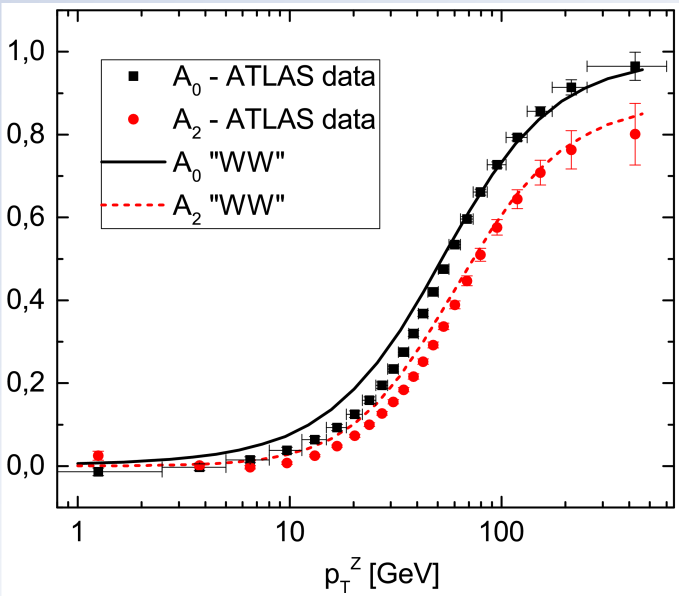


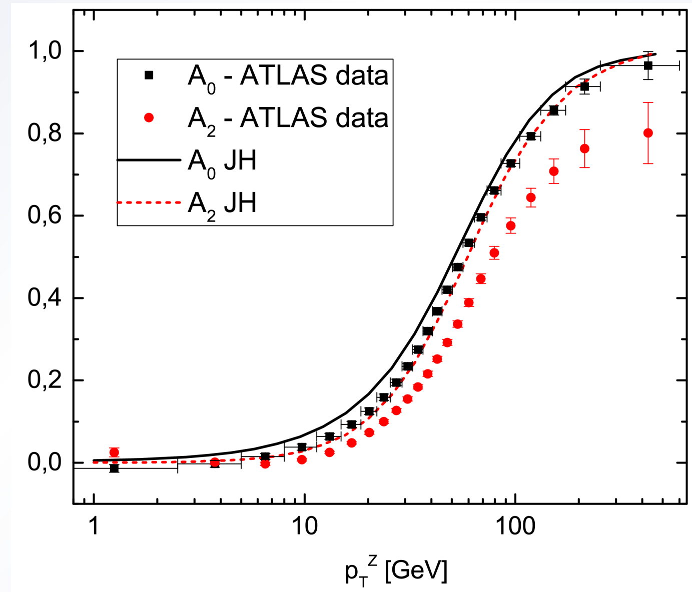
- **LT relation is preserved in this frame**

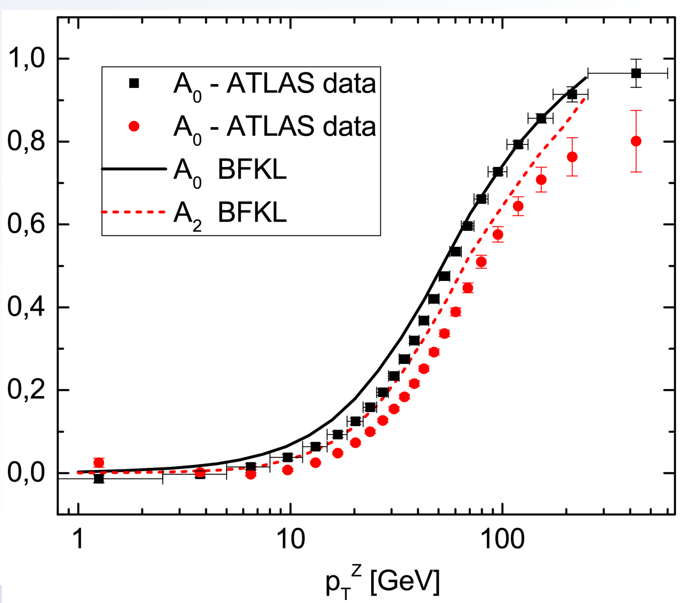
- LT observable is invariant uder rotations with respect to Y axis
  → LT relation may be broken
  if quark-antiquark boson plane is not parallel to beam-beam-boson plane

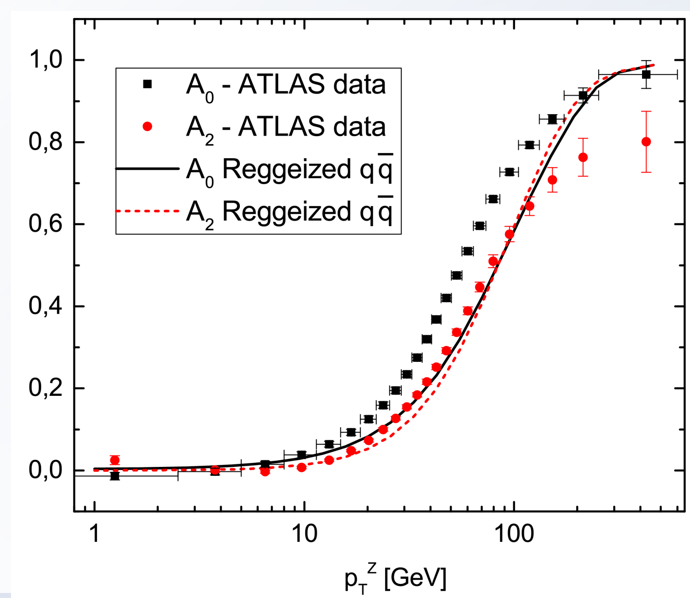
- **Indeed, quark / antiquark kT in the Y direction leads to Lam-Tung relation breaking**

Tests of the models with other observables: A_0 and A_2





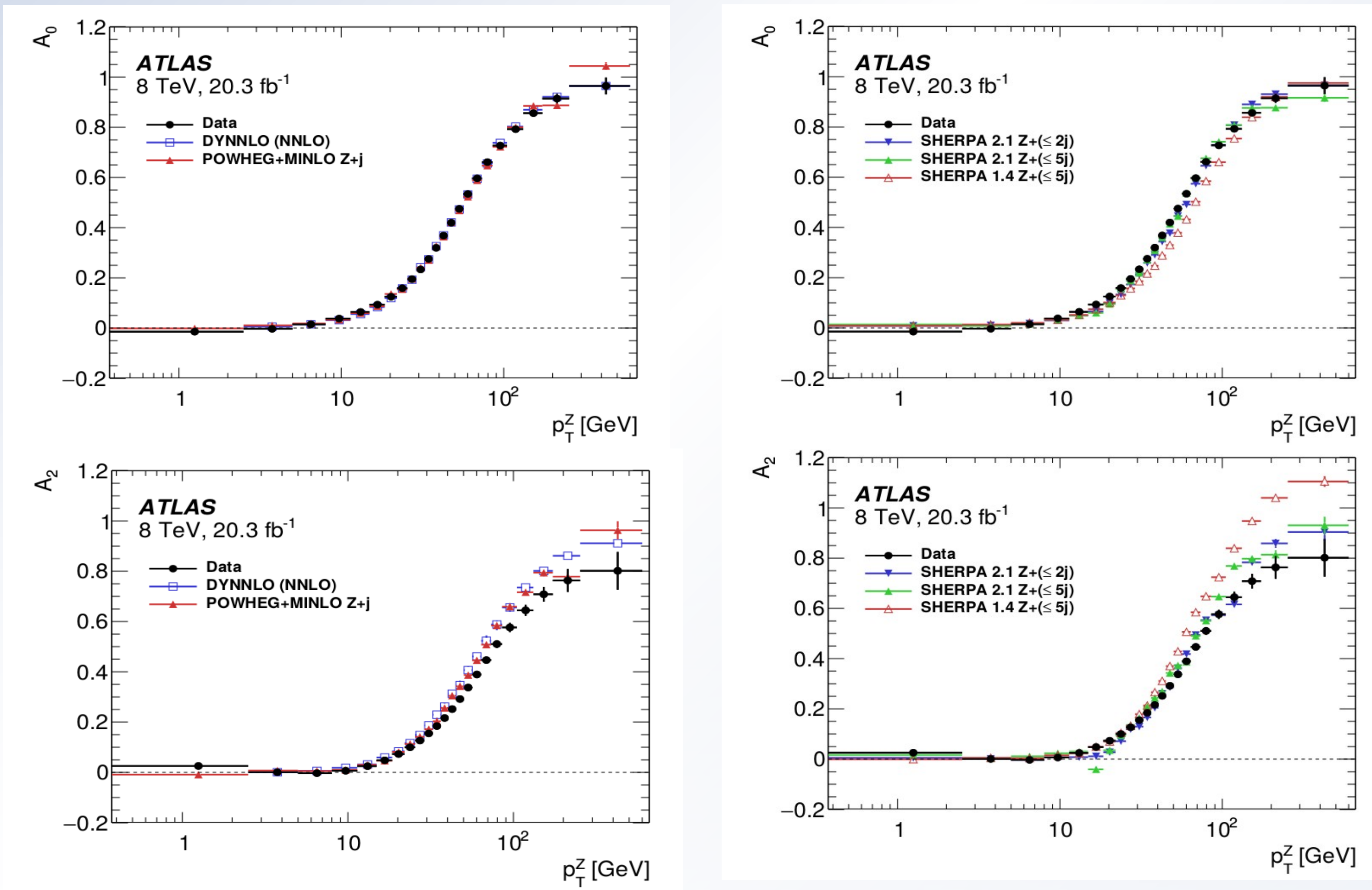




Comparison to NNLO collinear QCD Monte Carlos

DYNNLO / POWHEG-BOX SHERPA

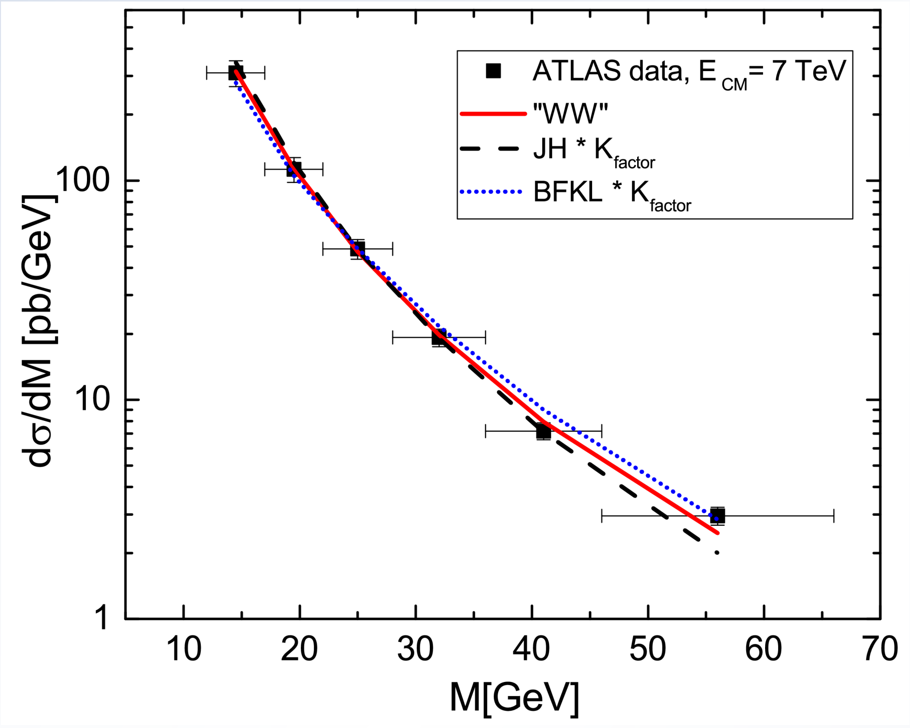
- A_0
- A_2

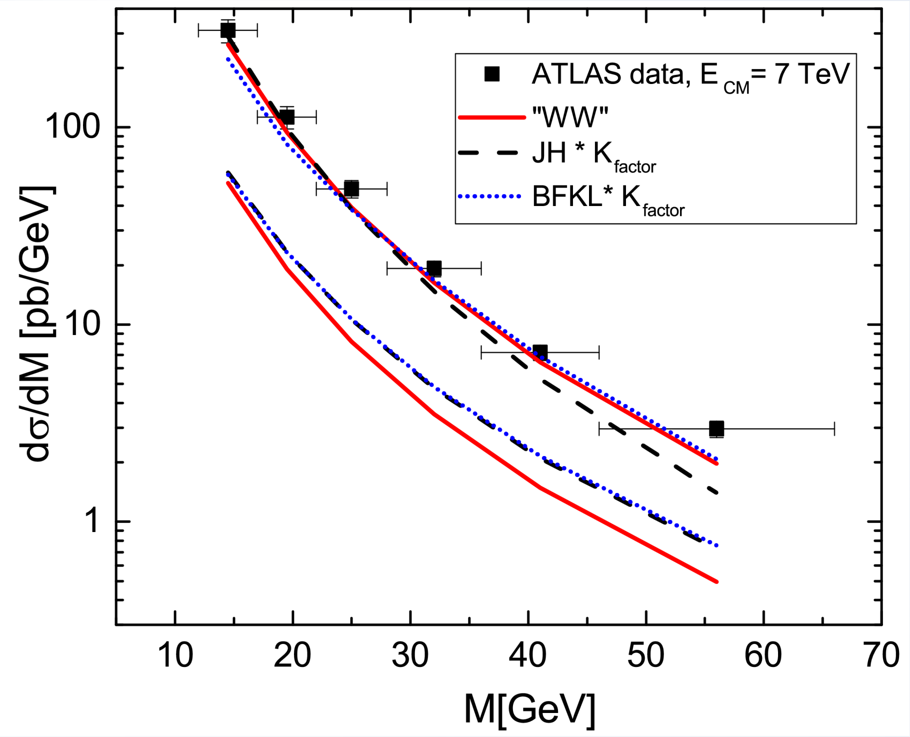


- A_2 is the difficult observable responsible for the puzzle of the large Lam-Tung relation breaking

A check of the approach: DY pair mass distribution at lower masses (γ^* exchange region)

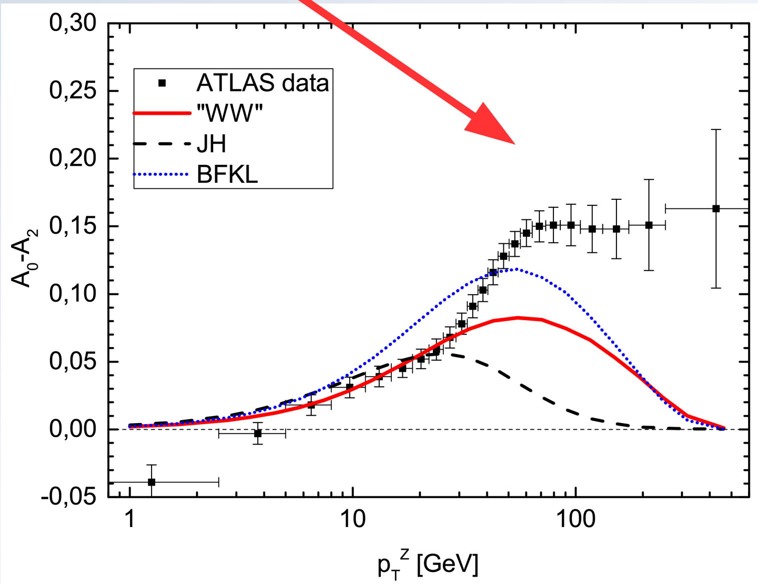
- Good agreement with data of the WW model assuming $q_{val}g^*$ + g^*g^* channels
- Dominance of the g^*g^* channel

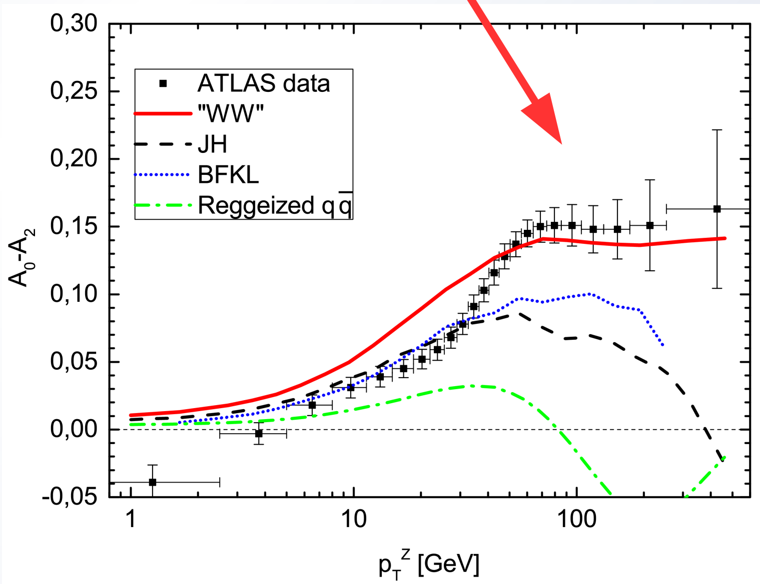




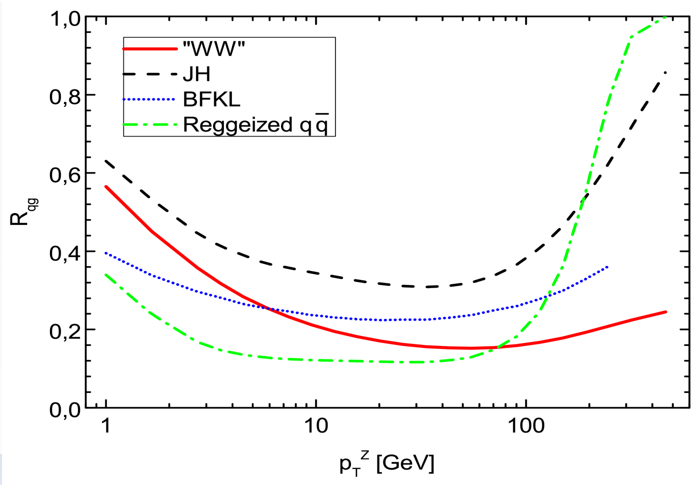
Contributions of parton channels to Lam-Tung relation breaking

- LT relation breaking at large p_T comes from the dominant g*g* channel; the q_{val} g* channel does not lead to significant LT breaking at large p_T





Ratio R_{qg} of the q_{val} g* contribution to the total cross-section shows dominance of the g*g* channel



Conclusions

- Collinear QCD at NNLO fails to describe Lam-Tung relation breaking $A_{LT} = A_0 - A_2$ in Z^0 production at the LHC. It is mostly due to inaccurate description of A_2 coefficient of the lepton angular distribution

- In k_T factorization framework with g*g* channel is taken into accout, A_{LT} at large p_T may be well described with a simple Weizsaecker-Williams: $\sim 1/k_T^{\ 2}$ shape of gluon TMD

- The WW model describes well also other DY observables

- A_{LT} exhibits strong sensitivity to the shape of gluon TMD and may be used as a sensitive probe to constrain / measure gluon TMDs

THANK YOU!