Drell-Yan angular coefficients measurements with the CMS experiment at the LHC

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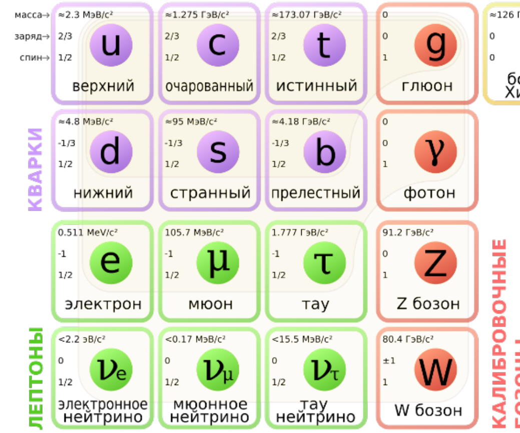
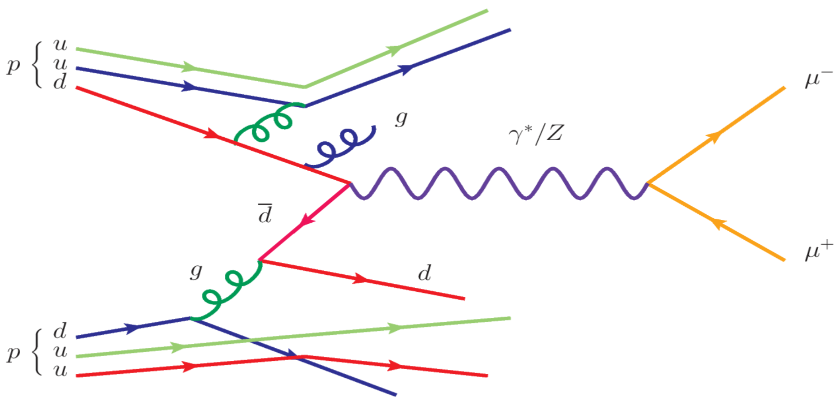
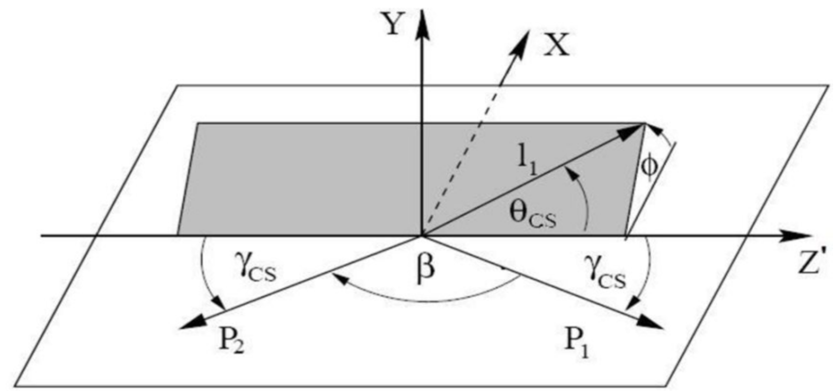
The Drell-Yan Process and Angular Coefficients

Why study dimuons at CMS?

- Important Standard model benchmark channel
- Search for new physic
- Can be used to explore proton inner structure
- Important background source for many BSM processes



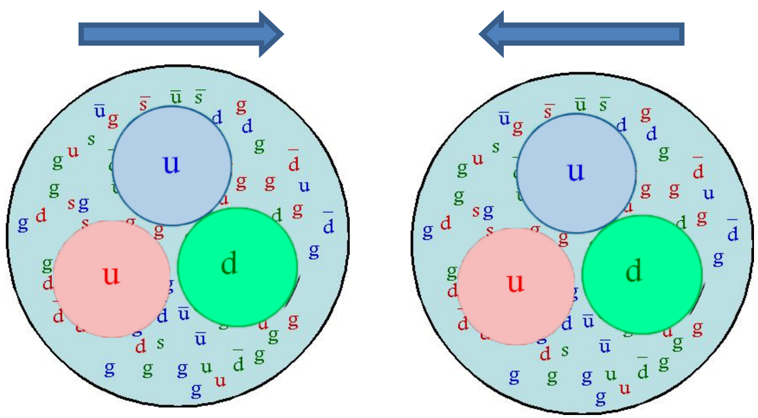


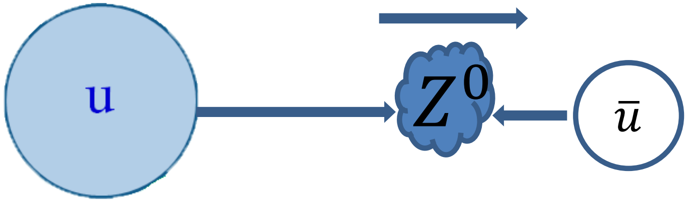


$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \Big[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)$$
$$+A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\Big].$$

where θ^* and φ^* are the polar and azimuthal angles of l^- (e^- or μ^-) in the rest frame of γ^*/Z (Collins-Soper) and coefficients $A_0 - A_7$ are functions of p_T , Y , M kinematic variables, polarised and unpolorised cross sections

What really happens?





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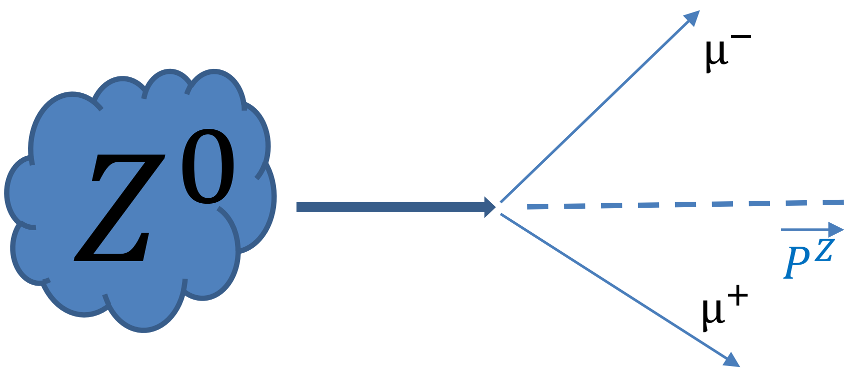
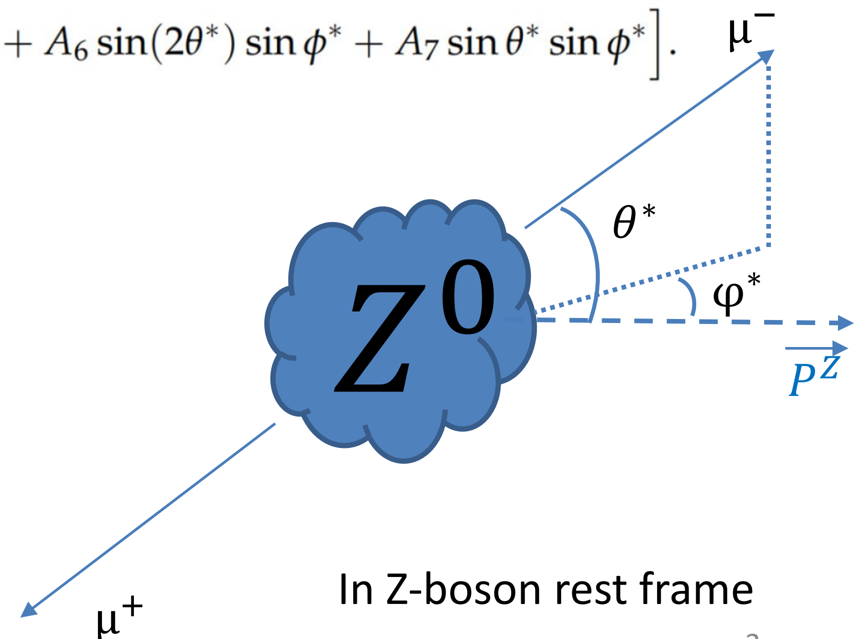
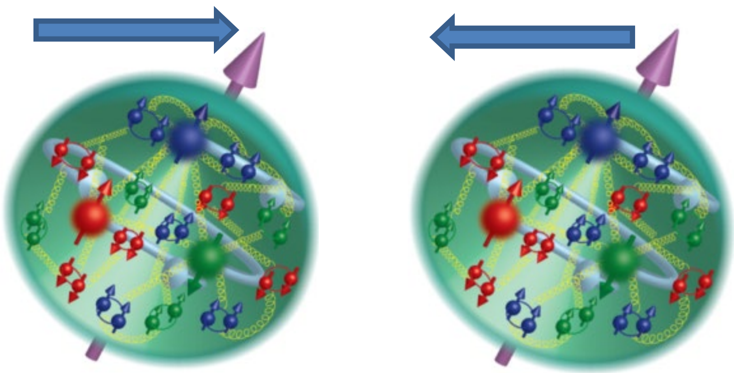




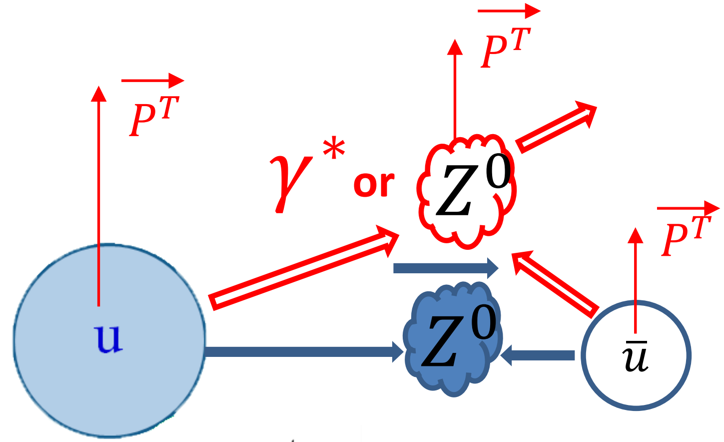
In Z-boson rest frame

What really happens?

- Non zero partons transverse momentum
- Correlations between spin and parton transverse momentum



All A_i depends on PDF's



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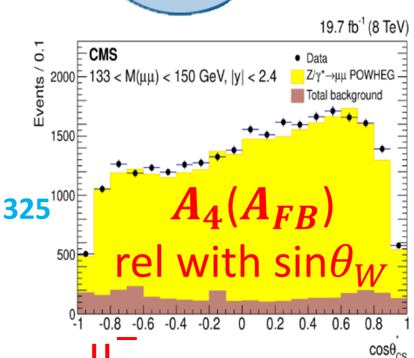
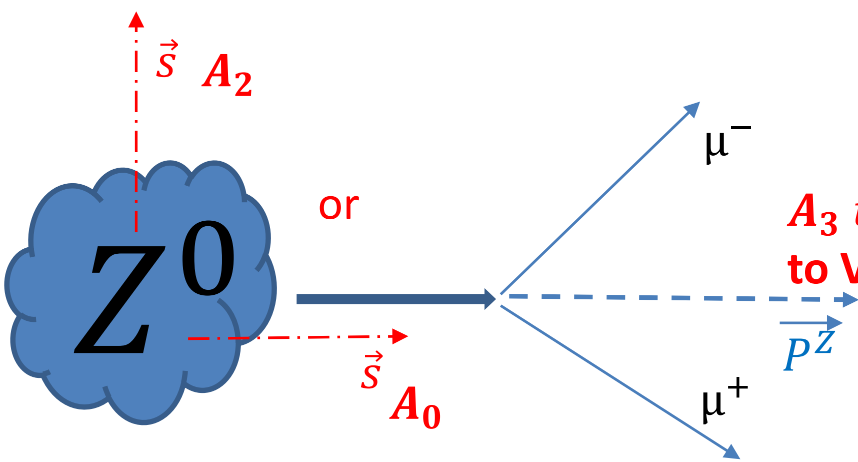
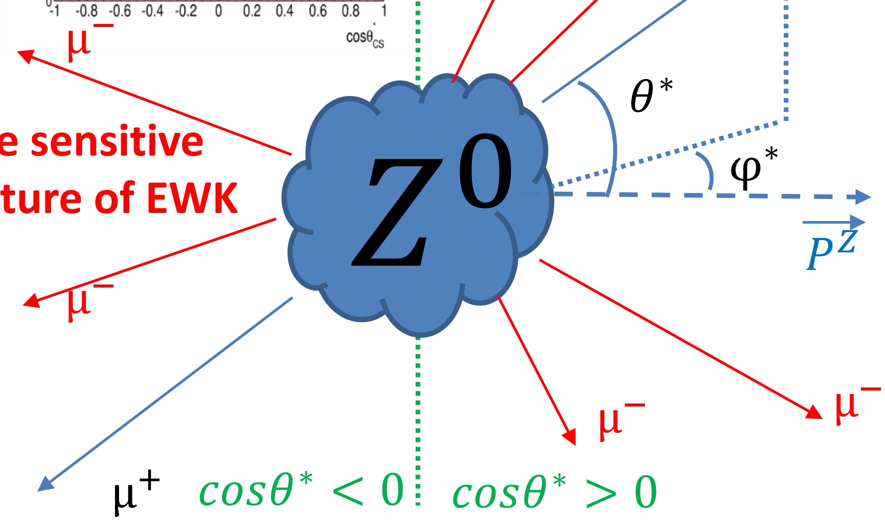




A_3 to A_7 are sensitive to V-A structure of EWK



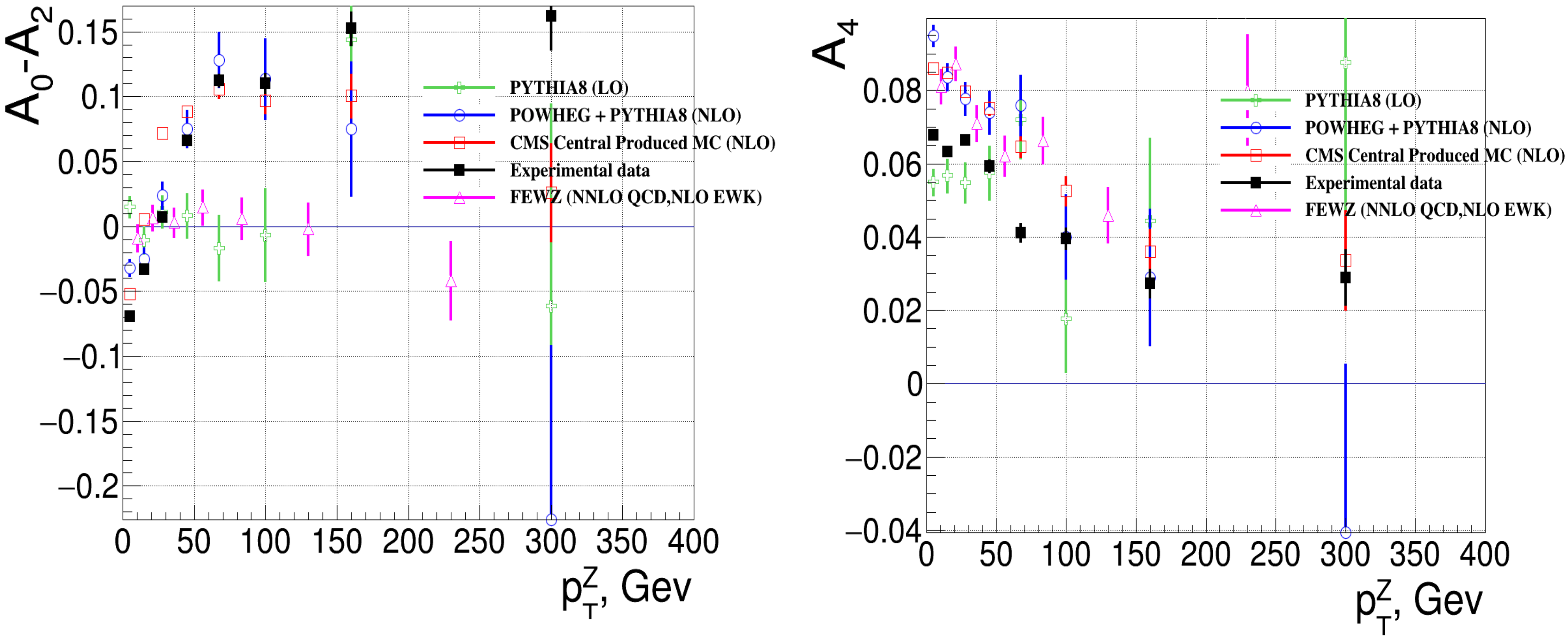
In Z-boson rest frame

- **LO: $A_0 - A_2 = 0$**
- **NLO: $A_0 - A_2 > 0$**

More details in report of Alexey Guskov 6.06.2022

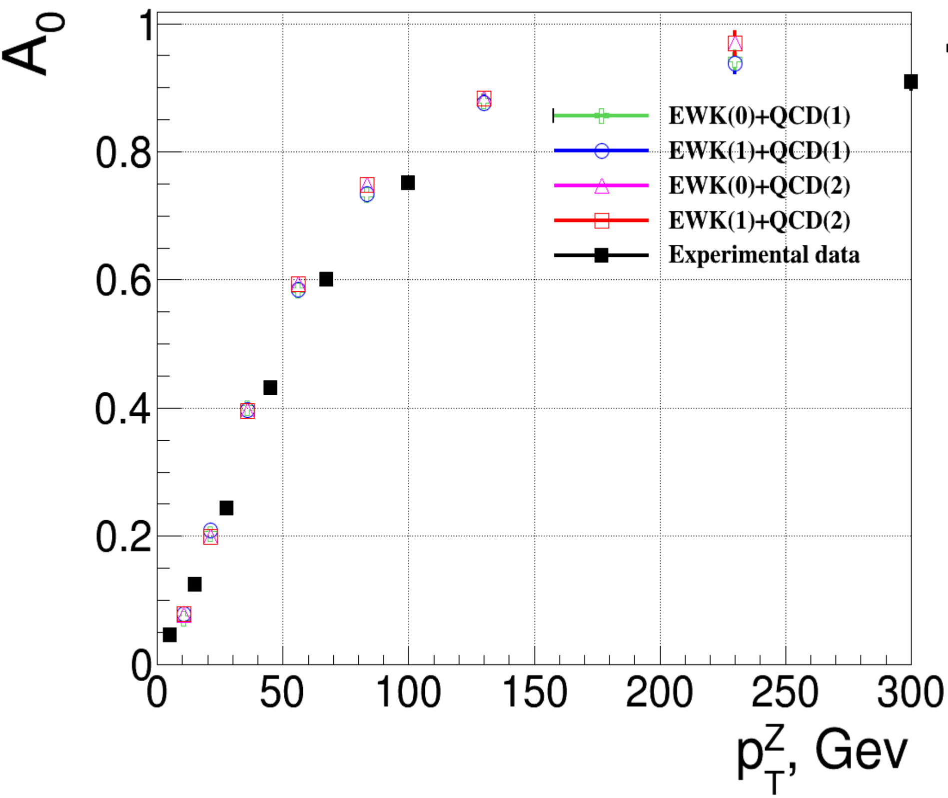
Calculation of Angular Coefficients with MC Generators

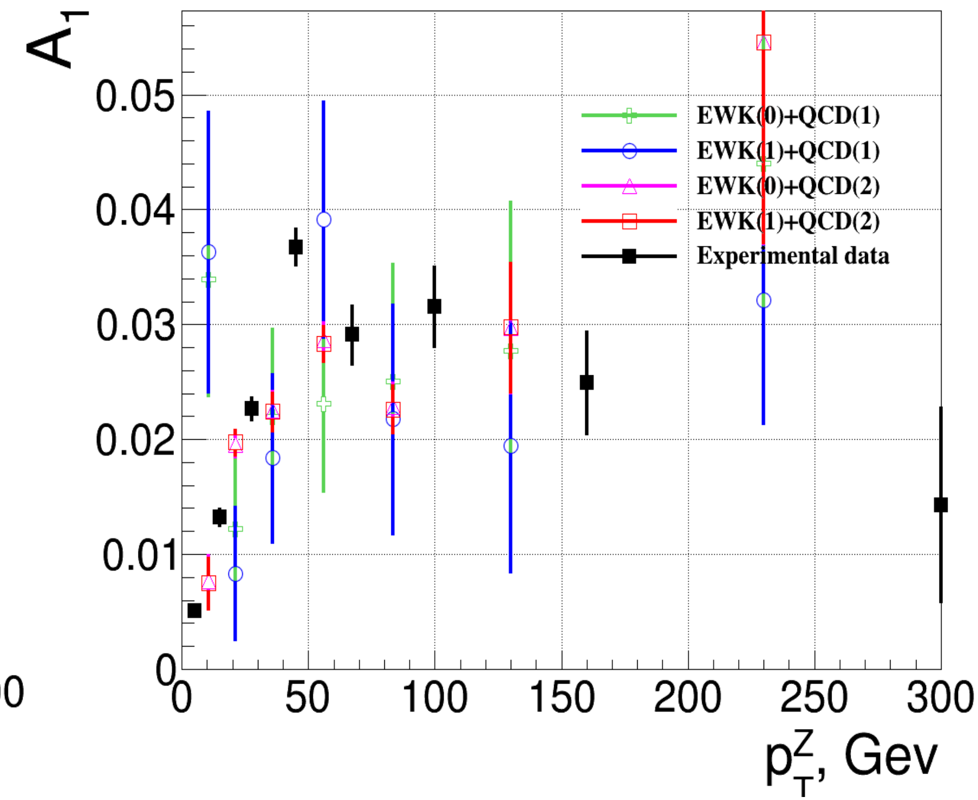
To estimate of QCD higher orders contribution to A_i different MC-generators were used (PYTHIA8, POWHEG и FEWZ). $A_0 - A_7$ were extracted via approximation of $cos\theta^*, \varphi^*$ distribution. Results of the simulation are compared with each other and main analysis results (*rep. of V. Shalaev AYSS-2021, Almaty*).



- Significant difference between LO and higher orders (NLO and NNLO) are observed
- More accurate PDF tuning for NNLO is required

let's Focus on FEWZ (I)

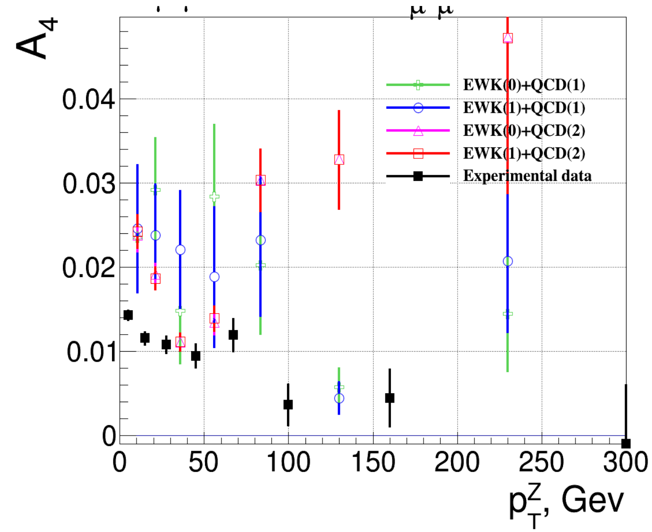


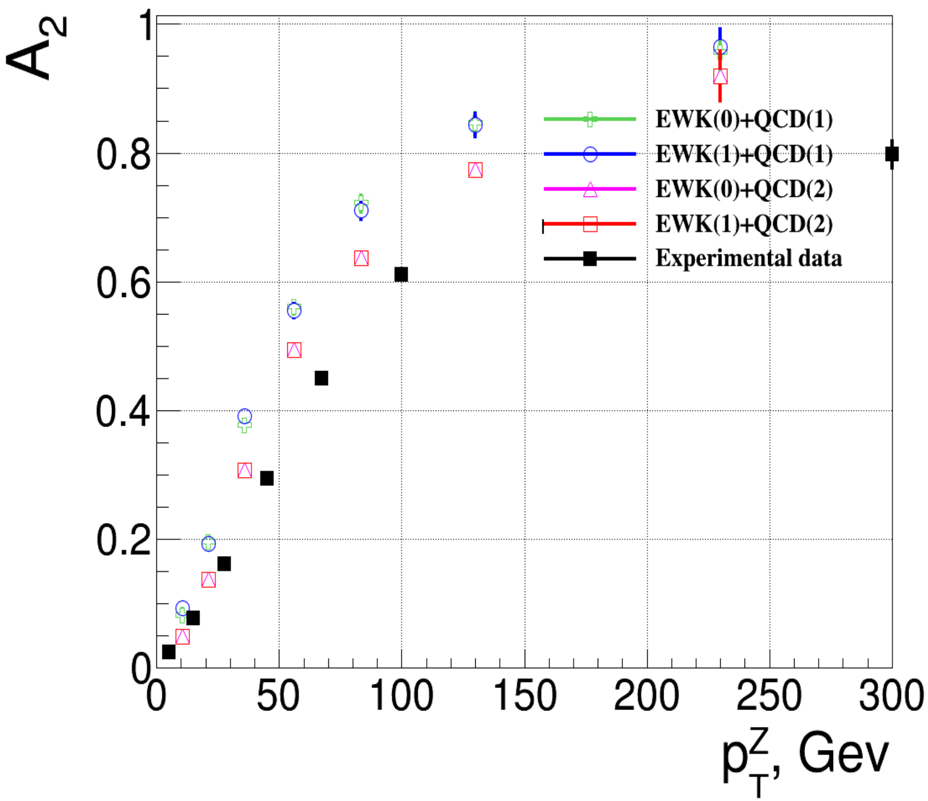


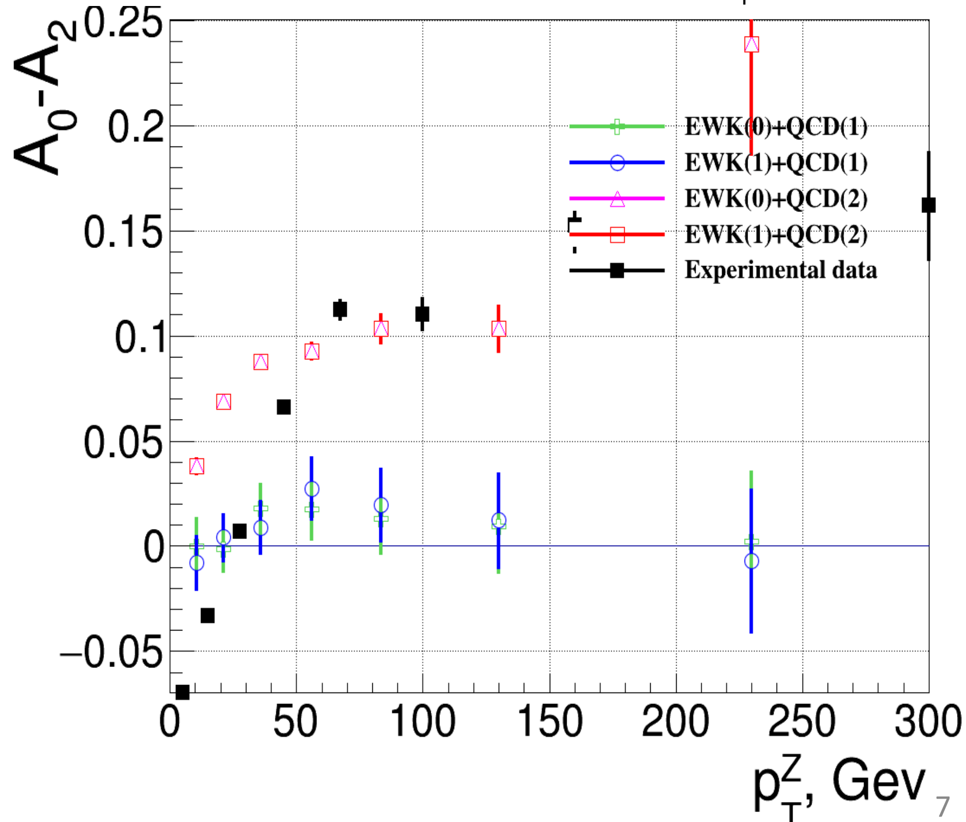
- Good agreement for A_0 and A_1 at all orders
- NNLO results look a bit better at describing of A_1
- Actually zero influence of NLO EWK

let's Focus on FEWZ (II)

- Overestimation for A_2, are observed at each orders, but NNLO QCD better at A_2 description
- Actually zero influence of NLO EWK for A_2 and $A_0 - A_2$, but small effect exist for A_4
- "Variable success" of Lum-Tung description for different orders with p_T increasing. Big differences between NLO and NNLO for Lum-Tung violation



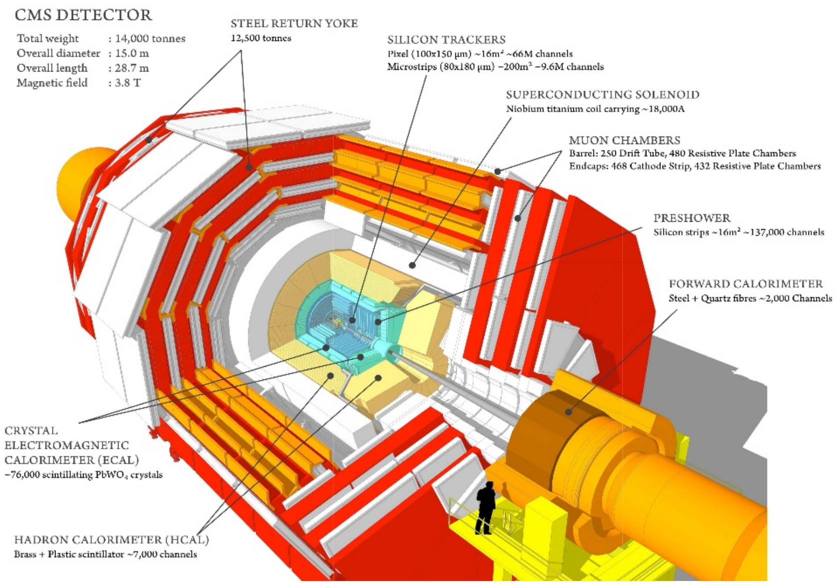




Conclusions

- Studying of angular coefficients with MC simulation is a huge task which could be extended out of scope of the main analysis
- Obtained results are already used to estimate of A_i measurement of systematic uncertainty related with generator selection in the analysis
- Now the work with generators is also ongoing (increase statistics, test more generators like READY, ReneSANCe)
- An independent publication based on results of this activity is planed

Differences?



Conclusions

- Studying of angular coefficients with MC simulation is a huge task which could be extended out of scope of the main analysis
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Differences?

Thanks for
your attention!

Thanks Organising
Committee for this
nice event!^^

Angular Coefficients Calculated with different generators

To estimate the contribution of higher orders to A_i PYTHIA8, POWHEG and FEWZ MC generators were used. $A_0 - A_7$ were extracted via $cos\theta^*, \varphi^*$ distribution fit. Results are compared with MC (Gen-level) is used in analysis and data as well

Generators were used:

- PYTHIA8 (LO QCD, LO EWK, CTEQ6)
  - 3 mln. of events were generated
- POWHEG+PYTHIA8 (NLO QCD, LO EWK, nCTEQ15_1_1)
  - 4.5 mln. Of events were generated
- FEWZ(NNLO QCD, NLO EWK, CTEQ10)
  - Not really flexible, binning differs from analysis
  - Just A_0, A_1, A_2, A_3, A_4 were measured

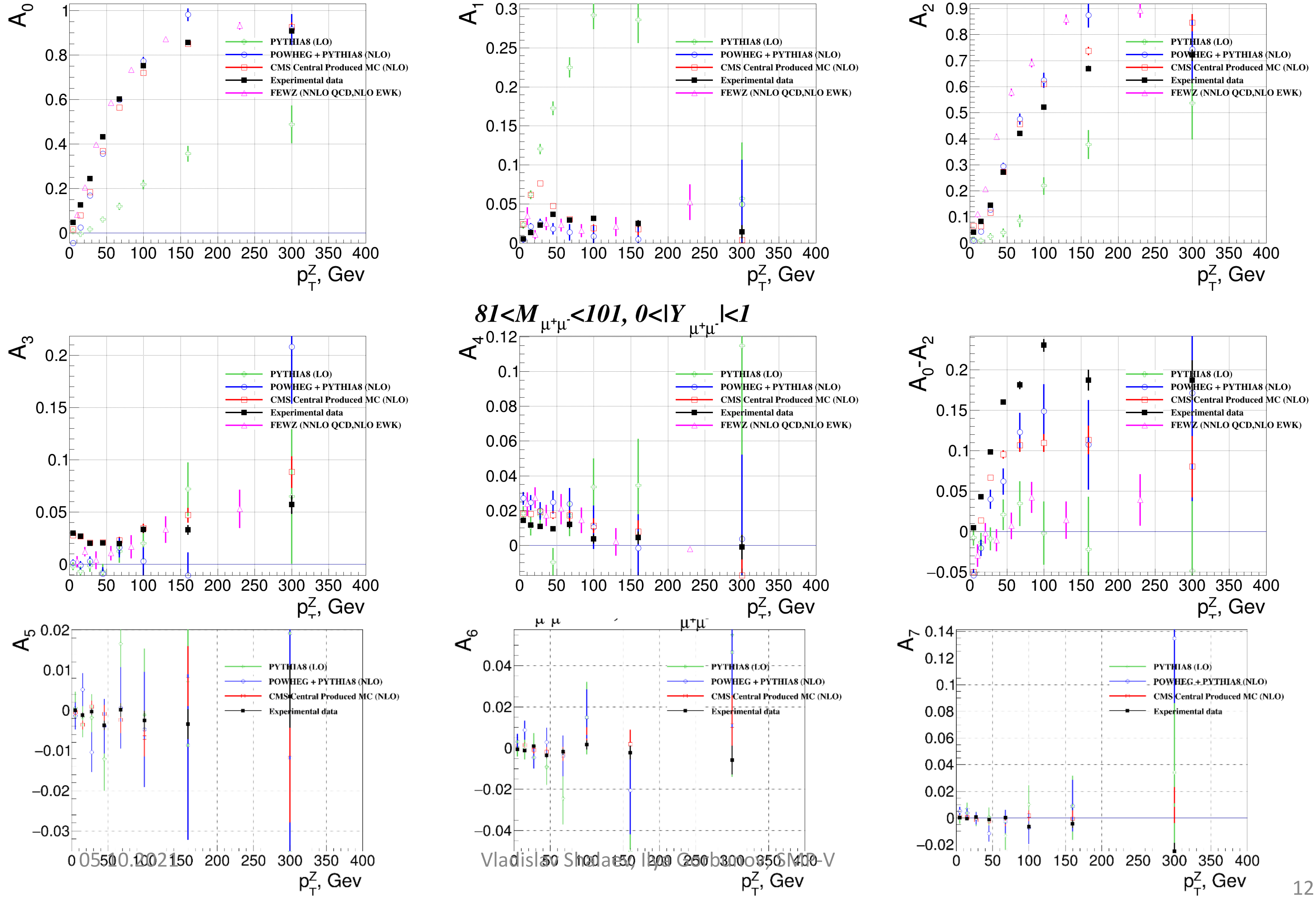
$$M = 81 - 101$$
$$|Y_Z| = 0, 1, 2.4$$

No detector simulation yet!

Compared with:

- CMS central produced MC (NLO QCD, LO EWK)
  - Generator level
- Experimental data (13 TeV)
  - Full Run 2 statistic (corrected)

PYTHIA8 (LO QCD, LO EWK, CTEQ6) & POWHEG+PYTHIA8 (NLO QCD, LO EWK, nCTEQ15.1.1) & & FEWZ & central produced MC & Data



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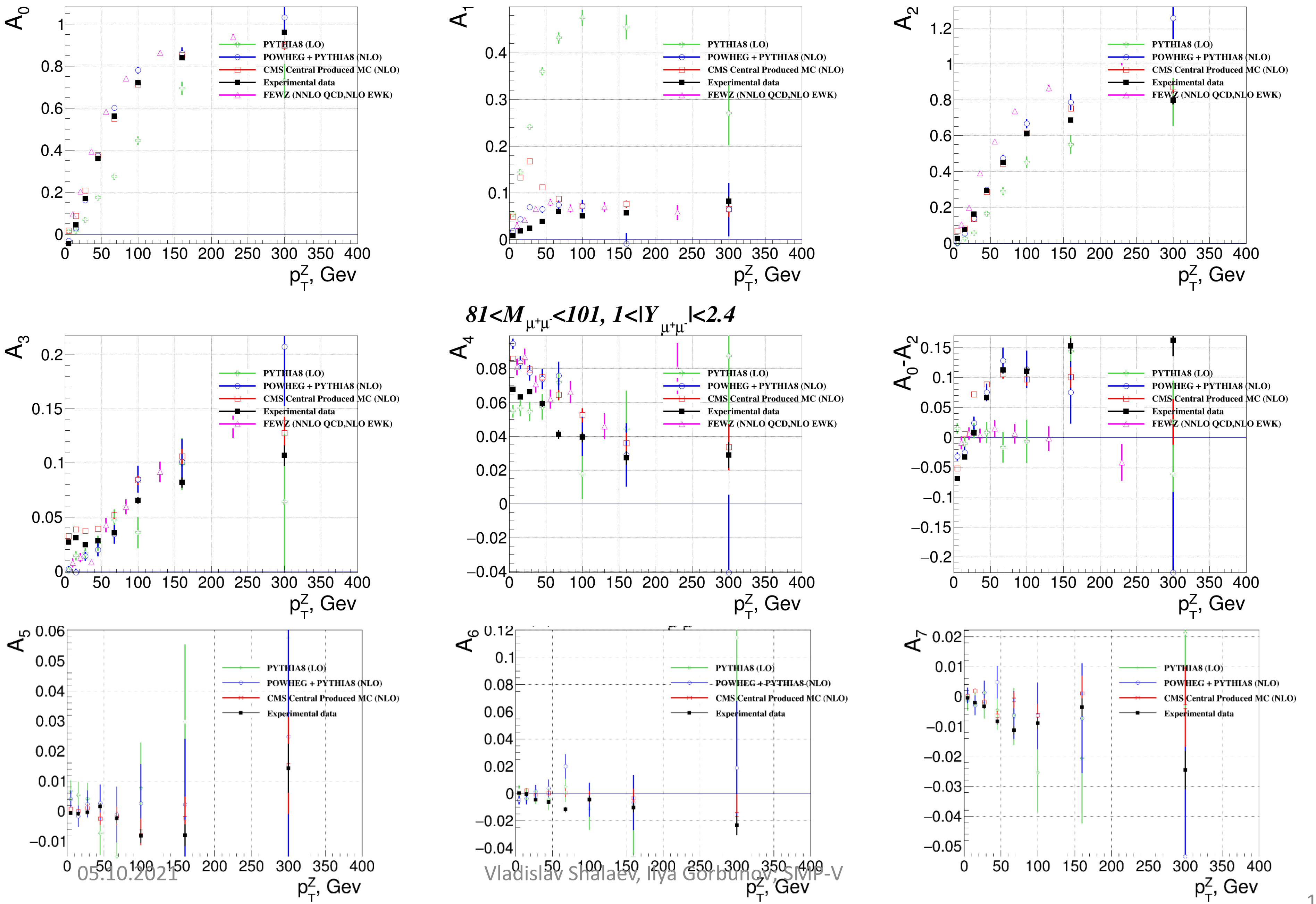

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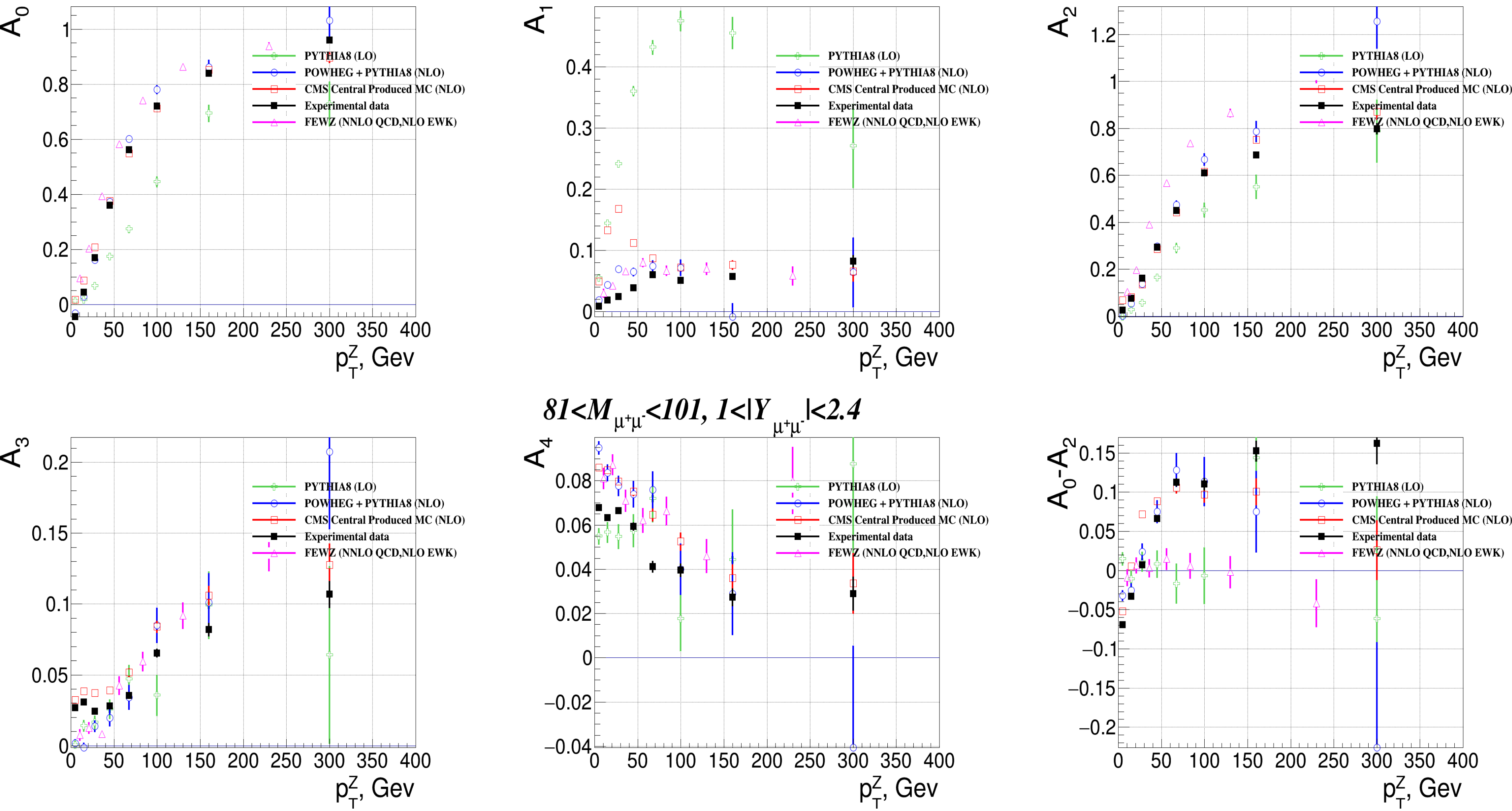


- Significant differences between LO and NLO (NNLO) for A_0, A_1, A_2, are observed
- FEWZ overshoots A_2, so Lum-Tung violation is quite small
- POWHEG and FEWZ looks better at describing A_1 than analysis MC
- POWHEG looks better at describing Lum-Tung violation than analysis MC

Angular Coefficients Calculated with FEWZ

To estimate the contribution of higher orders to A_i FEWZ MC generator were used. $A_0 - A_7$ were calculated at different orders. Results are compared with data is used in analysis

Features:

- FEWZ (LO QCD, LO EWK) – *CAN'T BE GENERATED!*
- FEWZ (NLO QCD, LO EWK, NNPDF2.1_NLO)
- FEWZ (NLO QCD, NLO EWK, NNPDF2.1_NLO)
- FEWZ(NNLO QCD, LO EWK, NNPDF2.1_NNLO)
- FEWZ(NNLO QCD, NLO EWK, NNPDF2.1_NNLO)
  - Not really flexible, binning differs from analysis
  - Just A_0, A_1, A_2, A_3, A_4 were measured

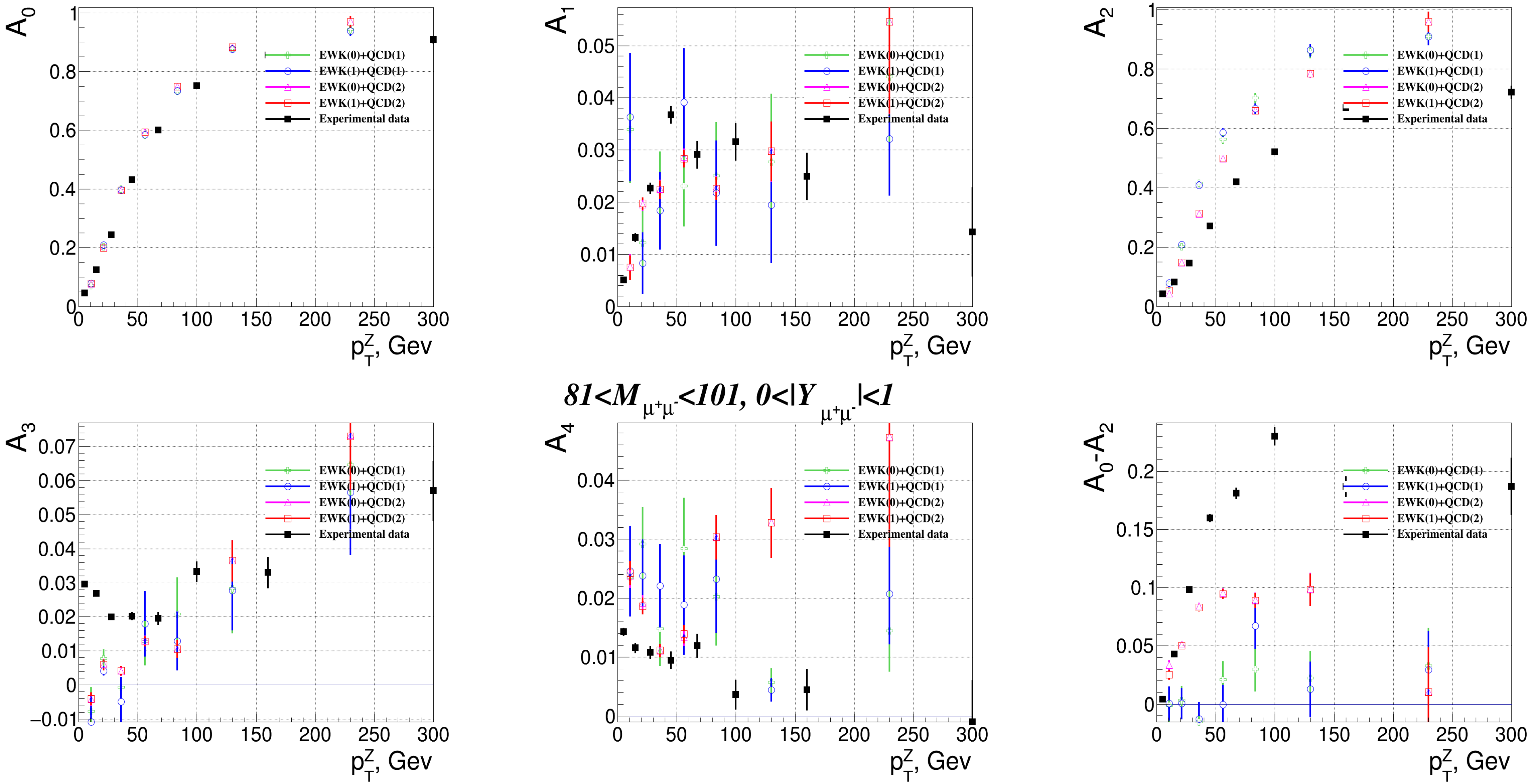
$$M = 81 - 101$$
$$|Y_Z| = 0, 1, 2.4$$

No detector simulation yet!

Compared with:

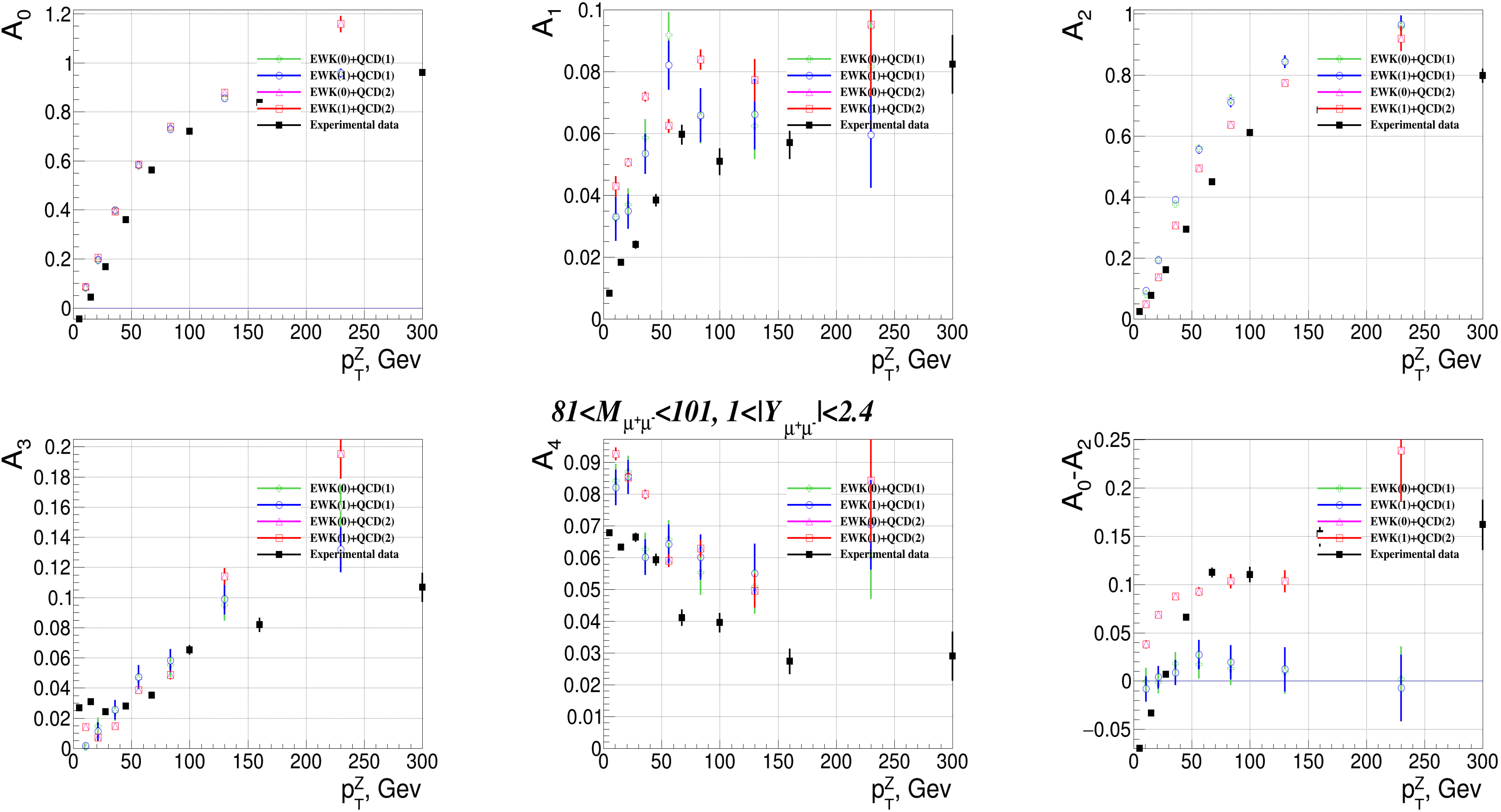
- Experimental data (13 TeV)
  - Full Run 2 statistic (corrected)

FEWZ & RUN2 Data (I)



- Good agreement for A_0 and A_1 at all orders
- Overestimation for A_2, are observed at each orders, but NNLO QCD better at A_2 description
- Actually zero influence of NLO EWK
- More than twice underestimation of Lum-Tung for NNLO QCD. Big differences between NLO and NNLO for Lum-Tung violation

FEWZ & RUN2 Data (II)



- Overestimation for A_0, A_1, A_2, are observed at each orders, but NNLO QCD better at A_2 description
- Actually zero influence of NLO EWK
- “Variable success” of Lum-Tung description for different orders with p_T increasing. Big differences between NLO and NNLO for Lum-Tung violation

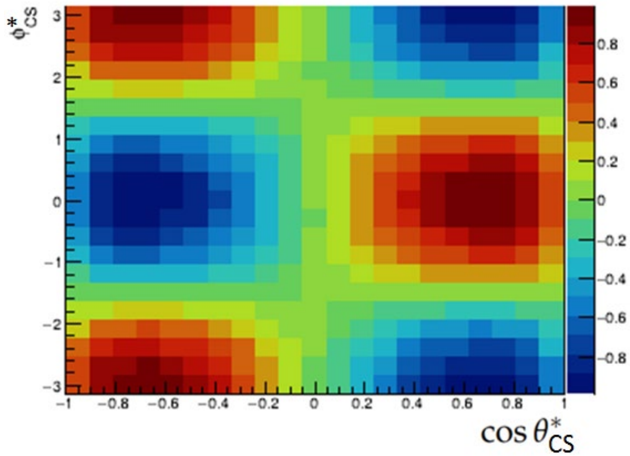
Template Method

CMS measured only first five coefficients (while ATLAS measured all 8 coefficients):

$$\frac{d^2\sigma}{d\theta^* d\phi^*} = \sum_{i=0}^{5} \sigma^i = P_5(1+\cos^2\theta^*) + P_0\frac{1}{2}(1-3\cos^2\theta^*) + P_1\sin(2\theta^*)\cos\phi^* + P_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*) + P_3\sin\theta^*\cos\phi^* + P_4\cos\theta^*$$

P_i coefficients relates with A_i as: $A_i = \frac{P_i}{P_5}$

- Fill $cos\theta^*, \varphi^*$ histogram at gen and reco level
- Reweight Reco events by $\frac{1+\cos^2\theta^*}{N_{gen}(\cos\theta^*,\varphi^*)}$, $\frac{1-3\cos^2\theta^*}{2\,N_{gen}(\cos\theta^*,\varphi^*)}$,... to get templates H_i for all of the coefficients. Here we divide by $N_{gen}(\cos\theta^*,\varphi^*)$ to get rid of polarization



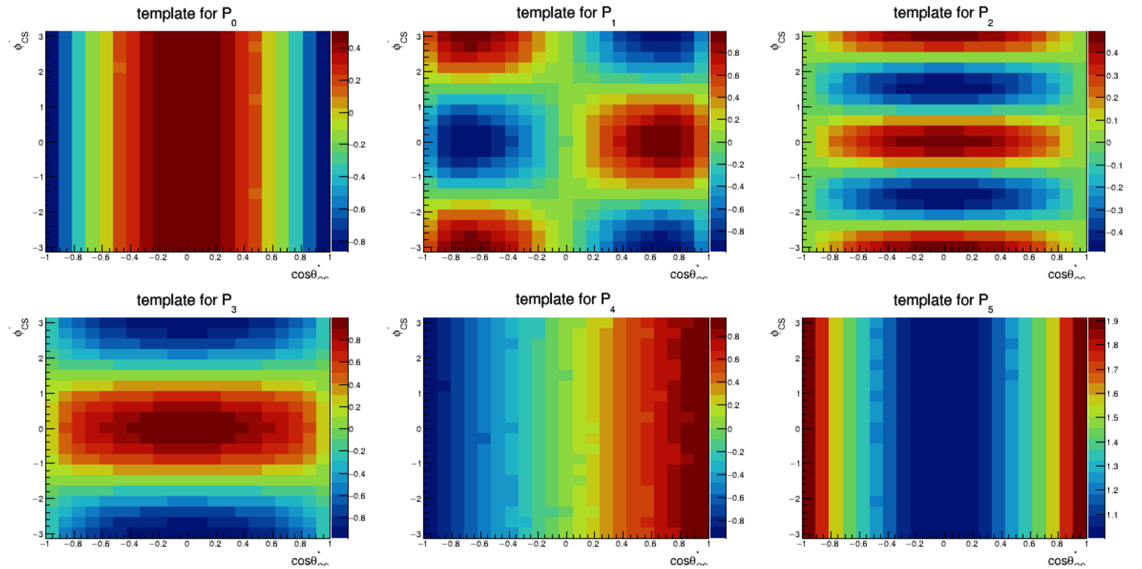
- Angular coefficients can be directly obtained by minimizing the objective function:

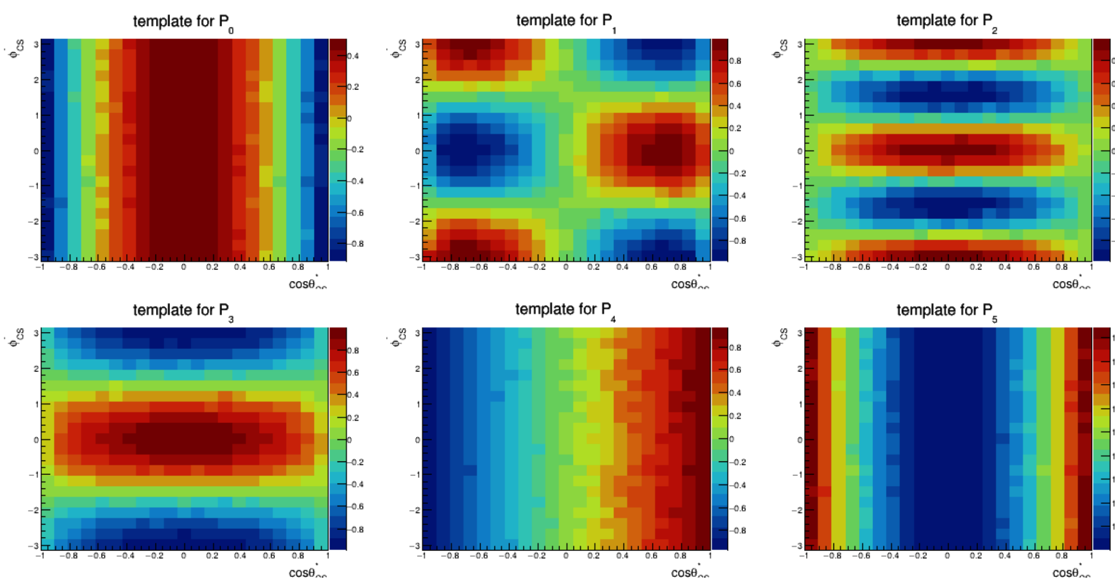
$$\chi^2 = \frac{\left(\text{data}^{j,k} - \left(\sum_{i=0}^{5} P_i H_i^{j,k} + H_{Bkg}^{j,k}\right)\right)^2}{\text{data}^{j,k}}$$

Templates at *13 TeV (Generator Level)*

(MADGRAPH+PYTHIA8, CUETP8M1,NLO)

Templates for the six fit parameters P_0-P_5 on generator level obtained for the first bin of p_T (10-20 GeV) bin for the rapidity bin |Y| < 1





Templates for the six fit parameters P_0-P_5 on generator level obtained for the first bin of p_T (200-400 GeV) bin for the rapidity bin 1 < |Y| < 2.4.

Шаблоны получены в восьми бинах p_T и двух бинах быстроты!