



DETECTOR
 Total weight : 14,000 tonnes
 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T

STEEL RETURN YOKE
 12,500 tonnes

SILICON TRACKERS
 Pixel (100x150 μm) $\sim 16\text{m}^2$ $\sim 66\text{M}$ channels
 Microstrips (80x180 μm) $\sim 200\text{m}^2$ $\sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
 Central solenoid for tracking $\sim 18,000\text{A}$

MUON CHAMBERS
 Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
 Endcaps: 468 Cathode Strip, 12 Resistive Plate Chambers

PRESHOWER
 Silicon strips $\sim 16\text{m}^2$ $\sim 137,000$ channels

FORWARD CALORIMETER
 Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
 76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
 Brass + Plastic scintillator $\sim 7,000$ channels

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

V. Shalaev, S. Shmatov

10.06.2022





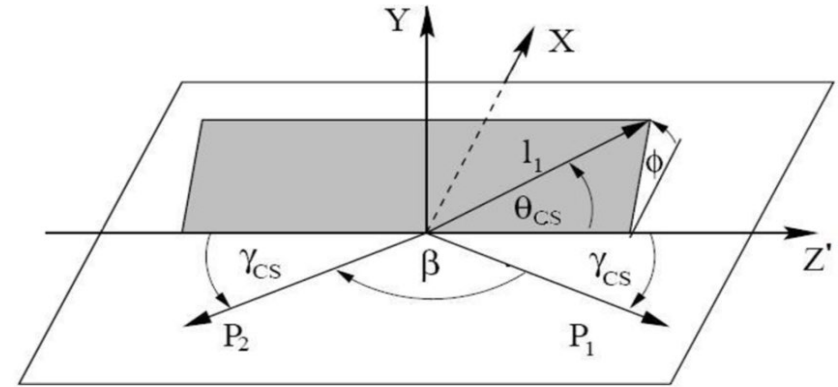
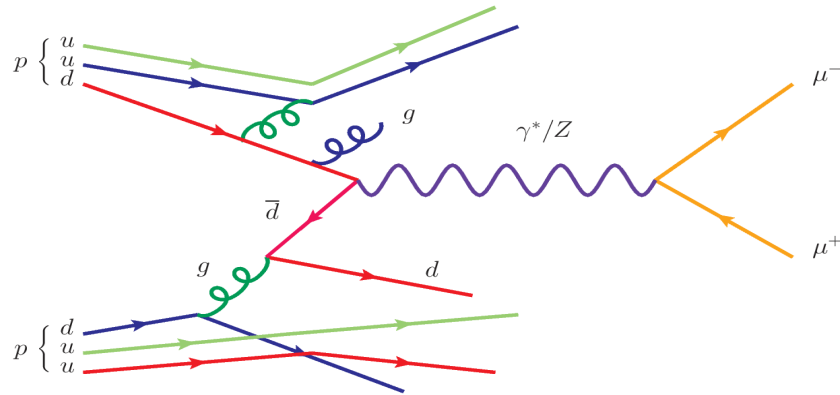
The Drell-Yan Process and Angular Coefficients



Why study dimuons at CMS?

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

масса → заряд → спин →	≈2.3 МэВ/c² 2/3 1/2 u верхний	≈1.275 ГэВ/c² 2/3 1/2 c очарованный	≈173.07 ГэВ/c² 2/3 1/2 t истинный	0 0 0 g глюон	≈126 ГэВ/c² 0 0 H бозон Хиггса
КВАРКИ	≈4.8 МэВ/c² -1/3 1/2 d нижний	≈95 МэВ/c² -1/3 1/2 s странный	≈4.18 ГэВ/c² -1/3 1/2 b прелестный	0 0 1 γ фотон	
ЛЕПТОНЫ	0.511 MeV/c² -1 1/2 e электрон	105.7 МэВ/c² -1 1/2 μ мюон	1.777 ГэВ/c² -1 1/2 τ тау	91.2 ГэВ/c² 0 0 Z Z бозон	КАЛИБРОВОЧНЫЕ БОЗОНЫ
	<2.2 эВ/c² 0 1/2 ν_e электронное нейтрино	<0.17 МэВ/c² 0 1/2 ν_μ мюонное нейтрино	<15.5 МэВ/c² 0 1/2 ν_τ тау нейтрино	80.4 ГэВ/c² ±1 1 W W бозон	

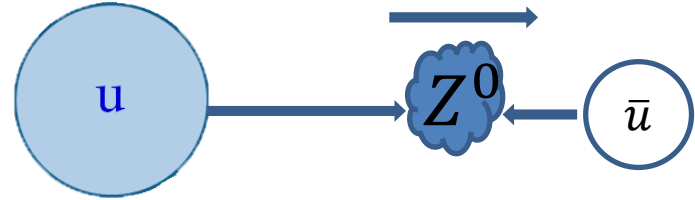
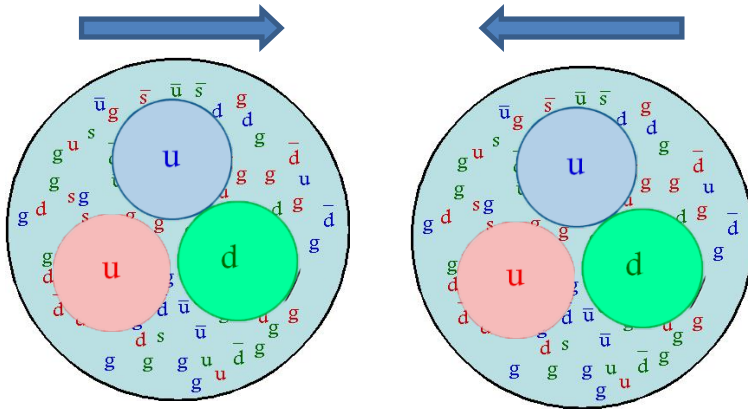


$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \left[(1 + \cos^2\theta^*) + A_0 \frac{1}{2} (1 - 3\cos^2\theta^*) + A_1 \sin(2\theta^*) \cos\phi^* + A_2 \frac{1}{2} \sin^2\theta^* \cos(2\phi^*) + A_3 \sin\theta^* \cos\phi^* + A_4 \cos\theta^* + A_5 \sin^2\theta^* \sin(2\phi^*) + A_6 \sin(2\theta^*)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

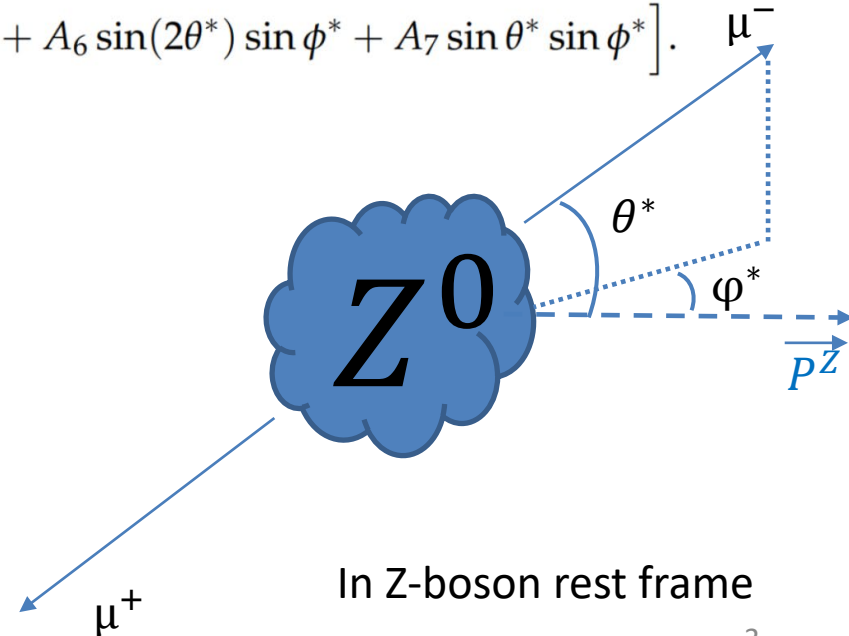
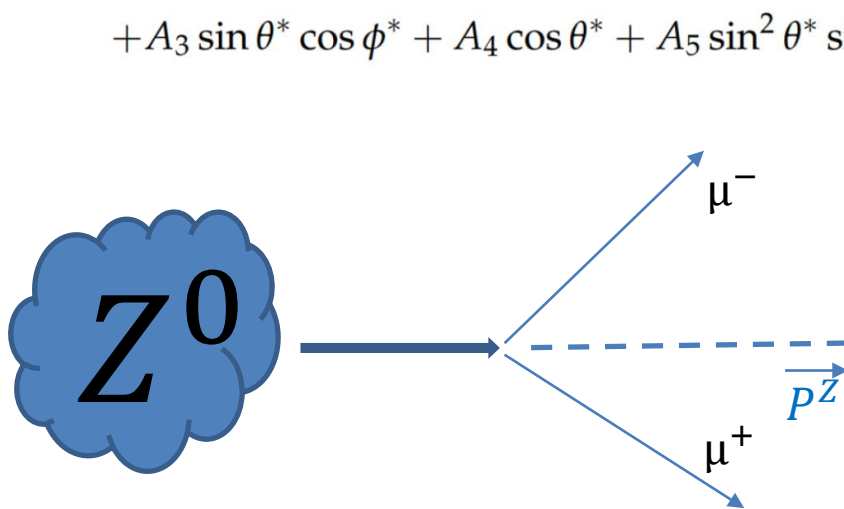
where θ^* and ϕ^* are the polar and azimuthal angles of l^- (e^- or μ^-) in the rest frame of γ^*/Z (Collins-Soper) and coefficients $A_0 - A_7$ are functions of p_T, Y, M kinematic variables, polarised and unpolarised cross sections



What really happens?



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

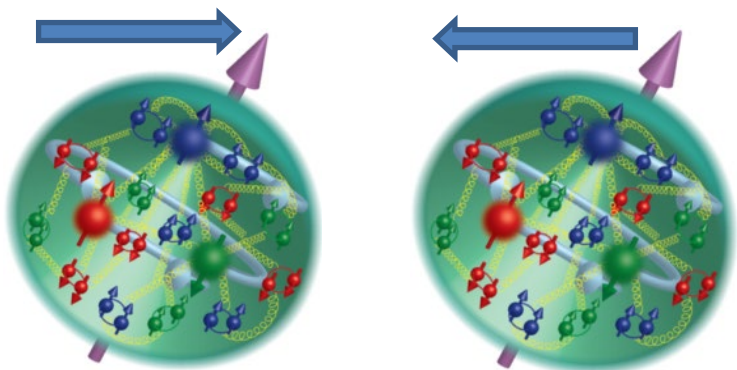




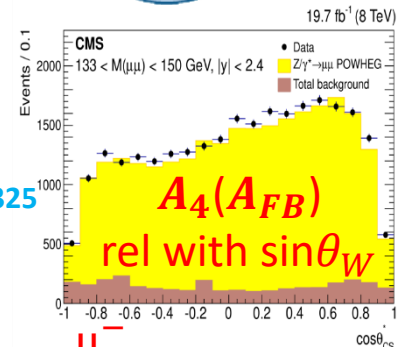
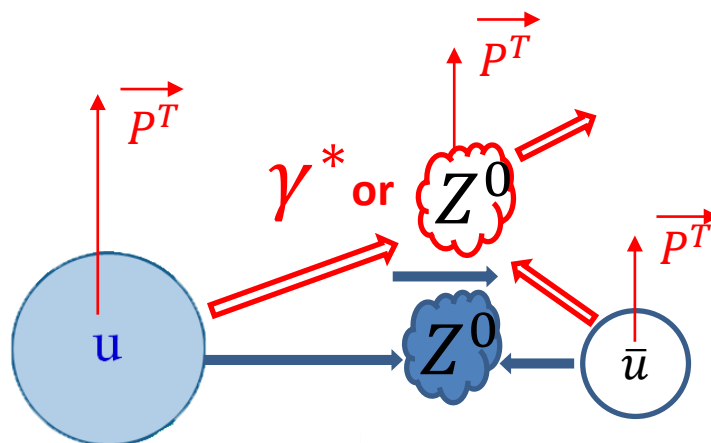
What really happens?



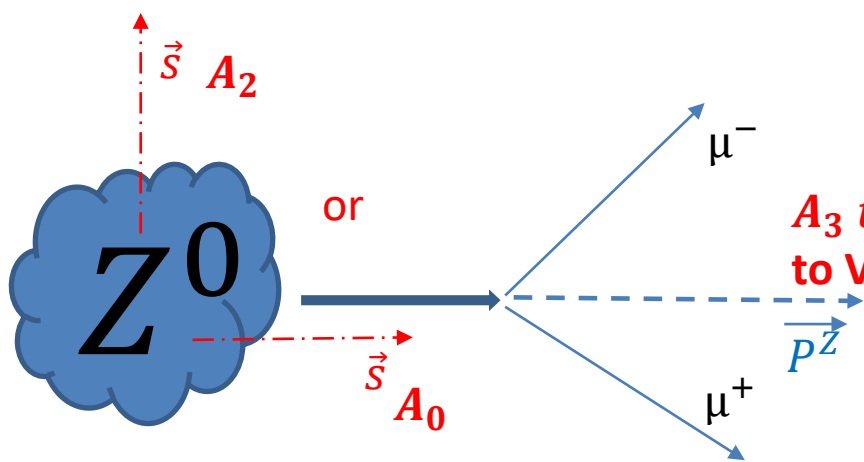
- Non zero partons transverse momentum
- Correlations between spin and parton transverse momentum



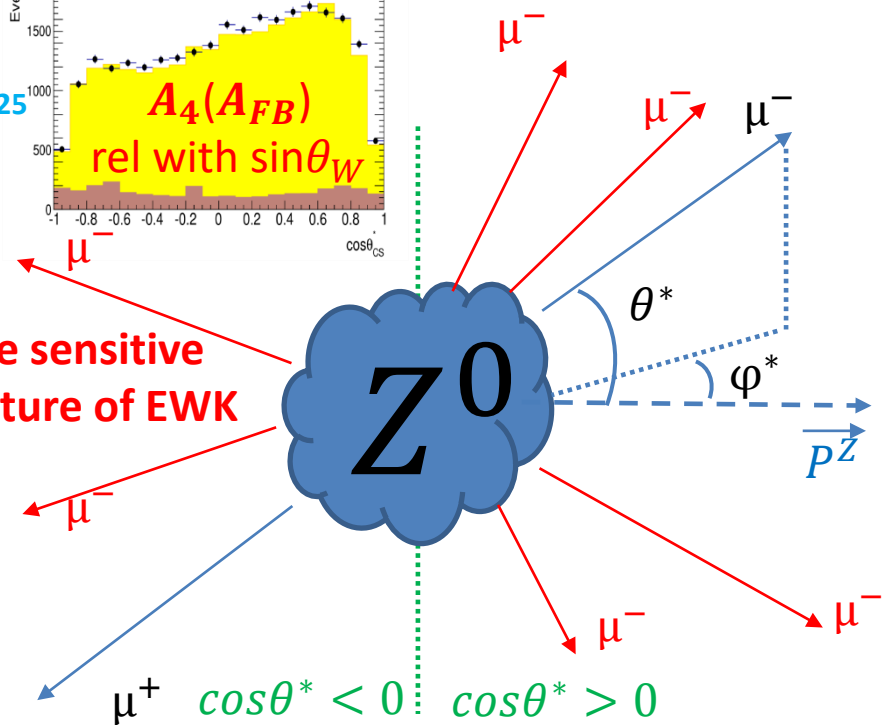
All A_i depends on PDF's



EPJ C 76 (2016) 325



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



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

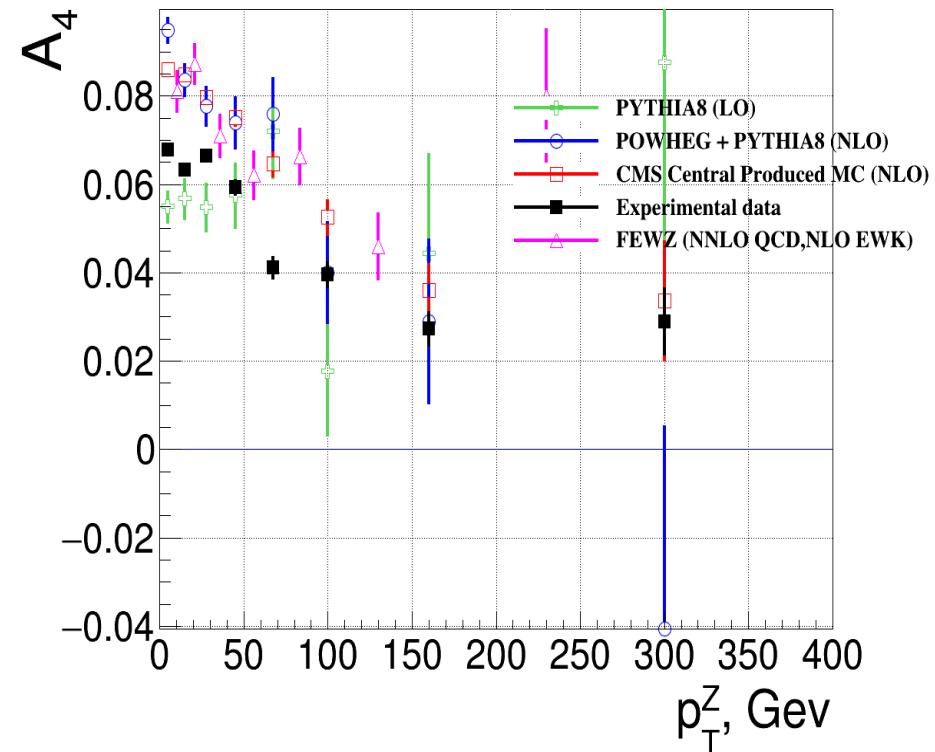
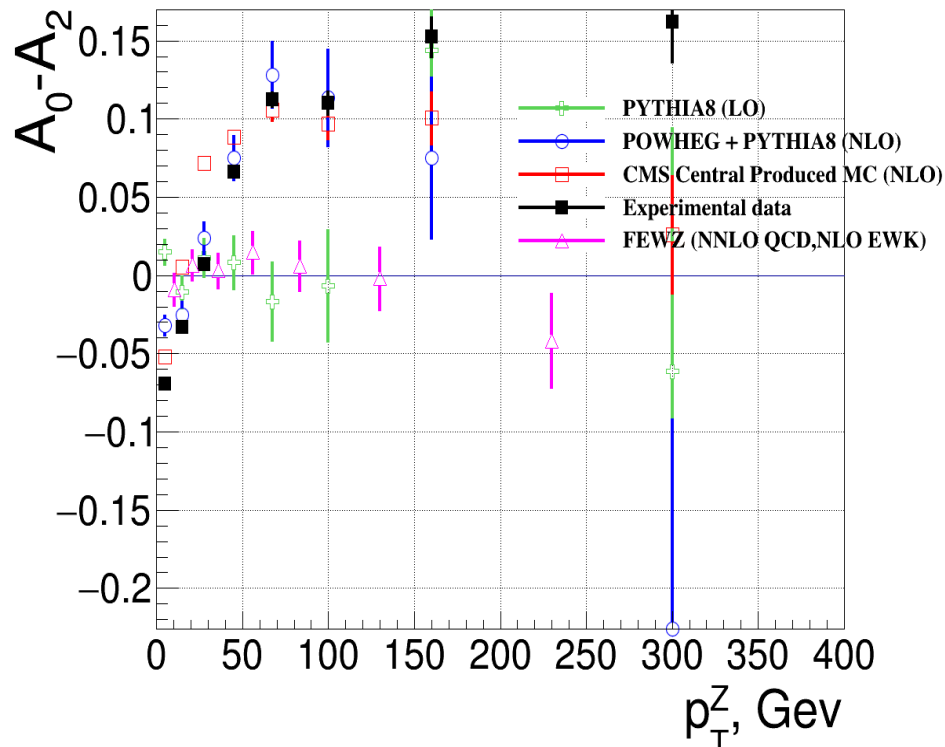
More details in report of Alexey Guskov 6.06.2022

In Z-boson rest frame



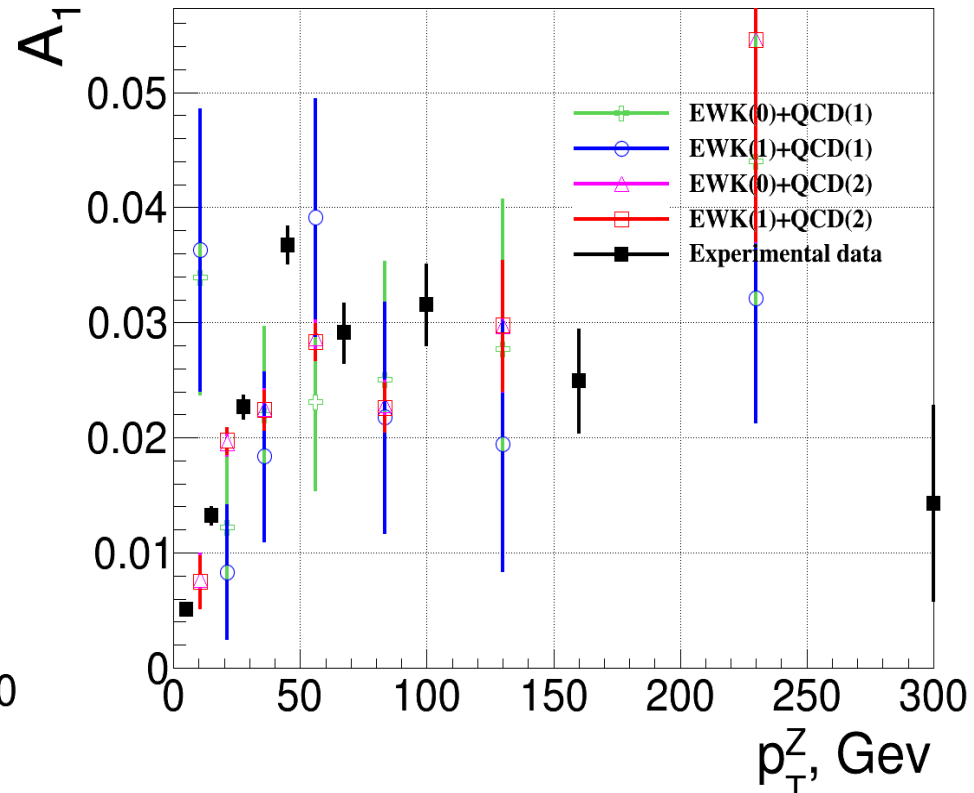
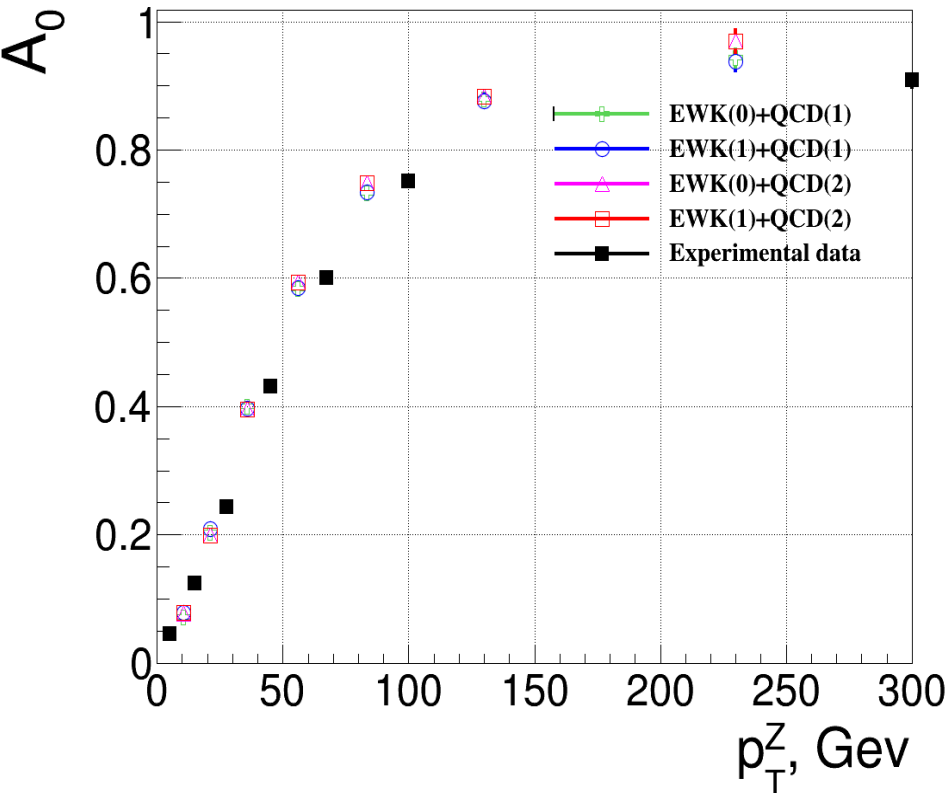
Calculation of Angular Coefficients with MC Generators

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 $\cos\theta^*$, φ^* 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)



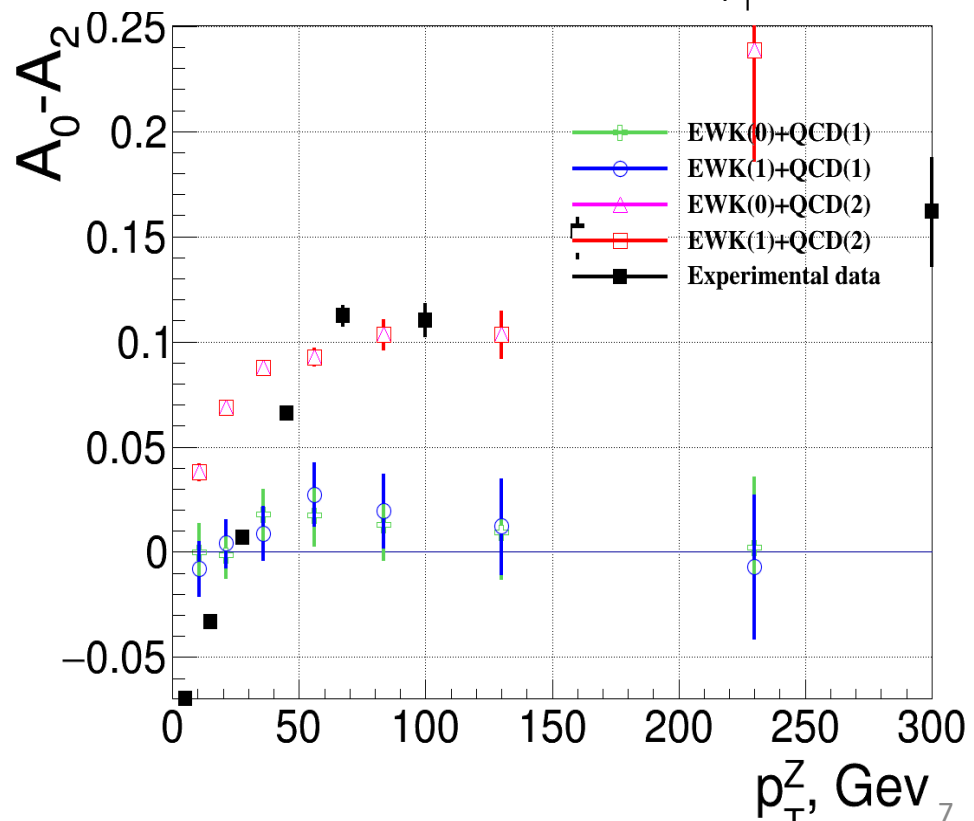
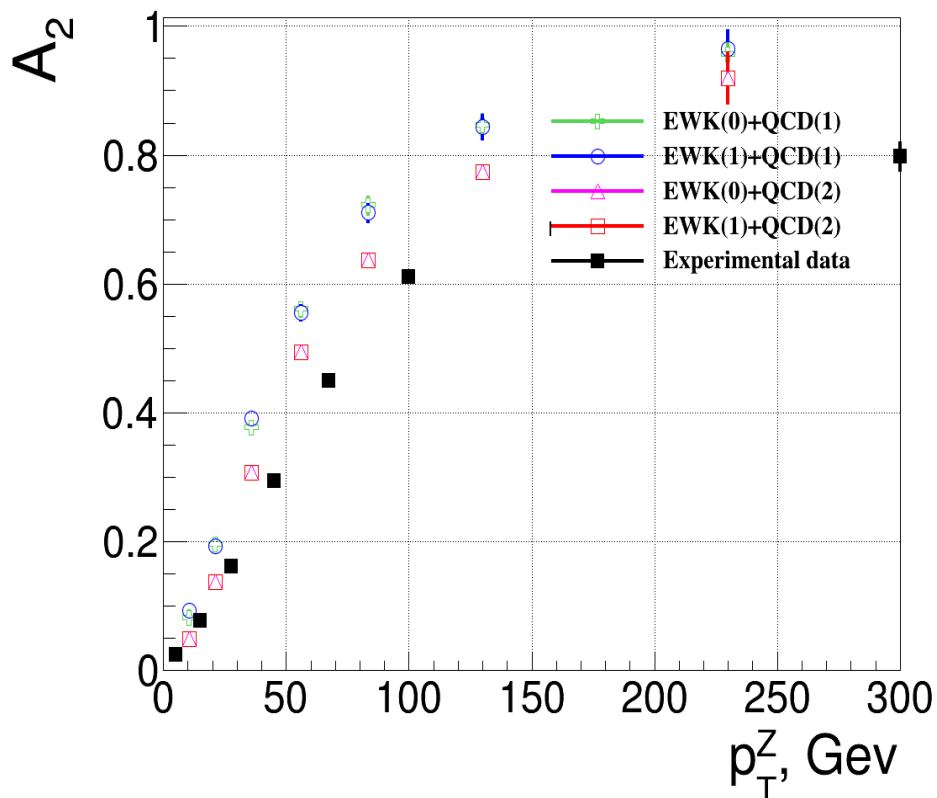
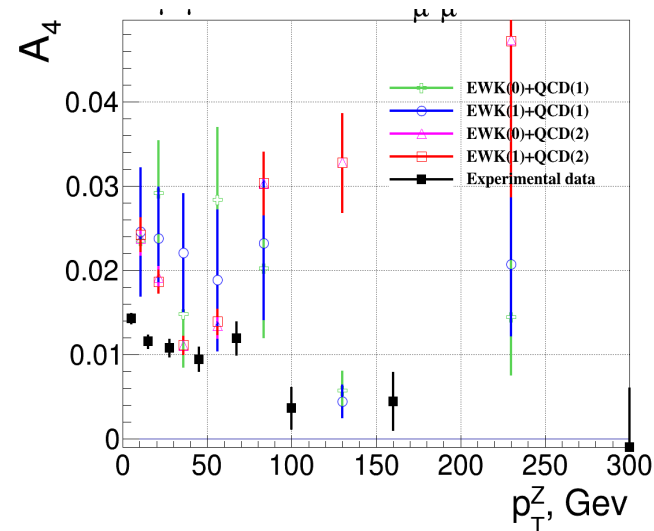
- Good agreement for A_0 and A_1 at all orders
- NNLO results look a bit better at describing of A_1
- Actually zero influence of NLO EWK



let's Focus on FEWZ (II)

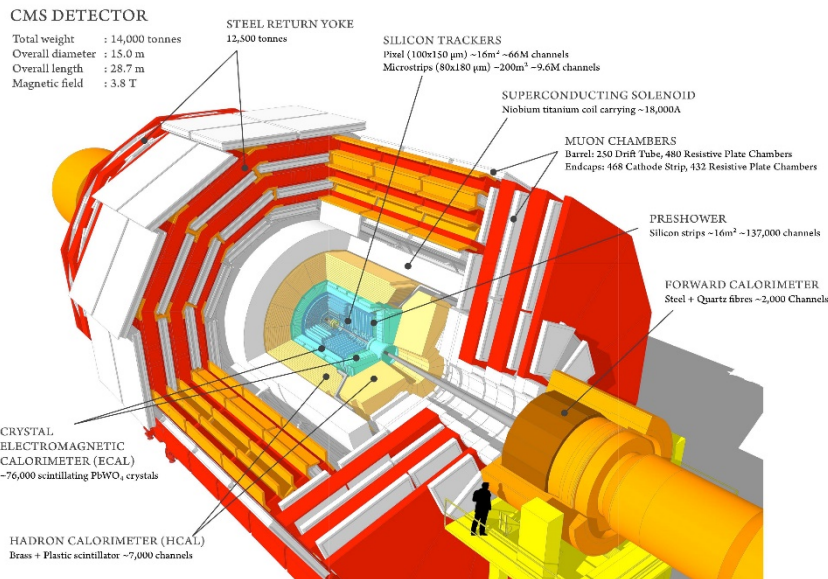


- Overestimation for A_2 , are observed at each orders, but NNLO QCD better at A_2 description
- Actually zero influence of NLO EWK for A_2 and $A_0 - A_2$, but small effect exist for A_4
- “Variable success” of Lum-Tung description for different orders with p_T increasing. Big differences between NLO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



- 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 planned

Differences?



- 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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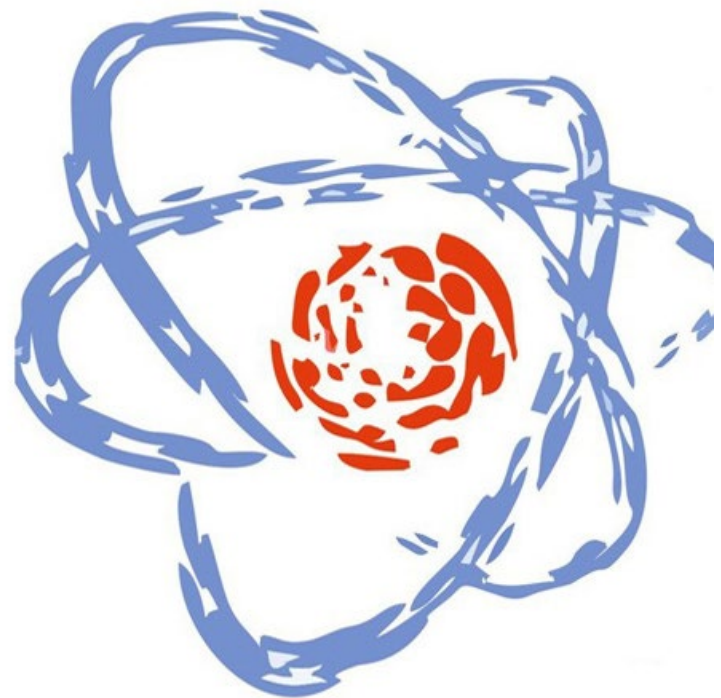
Differences?





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 $\cos\theta^*$, φ^* 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

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

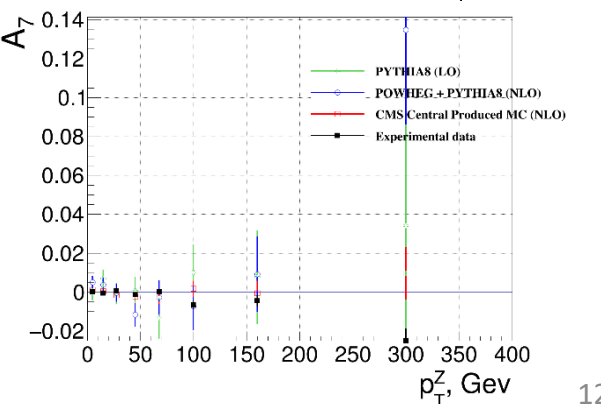
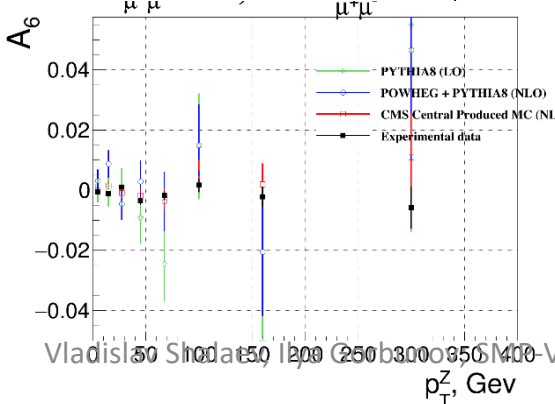
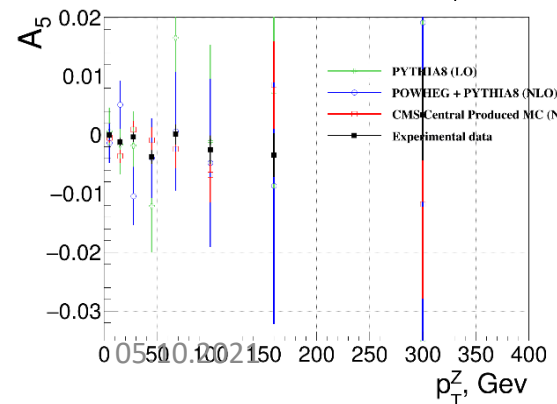
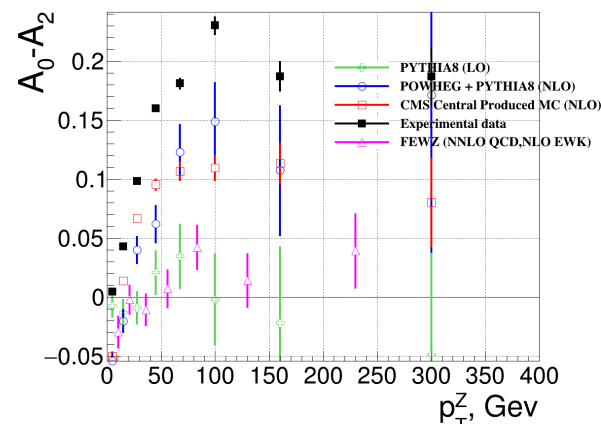
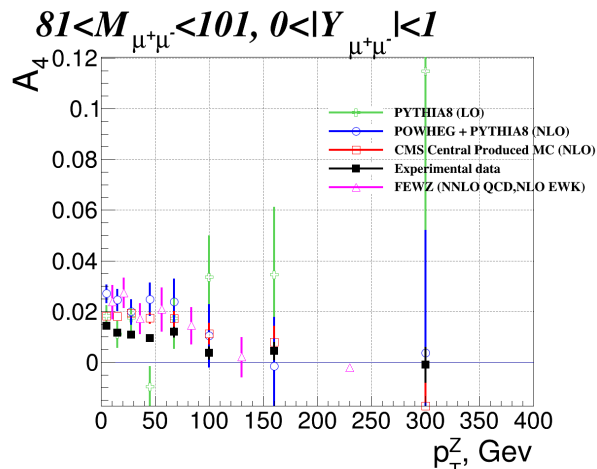
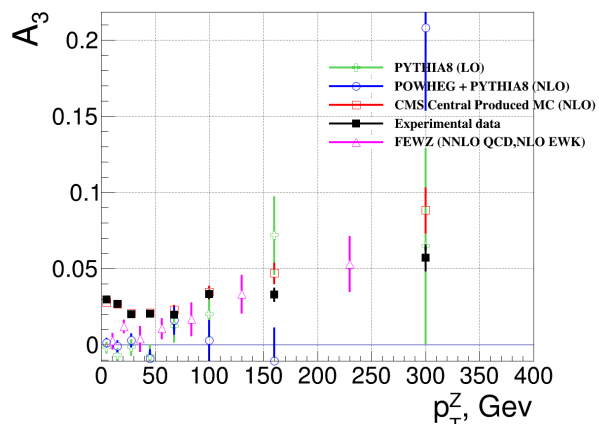
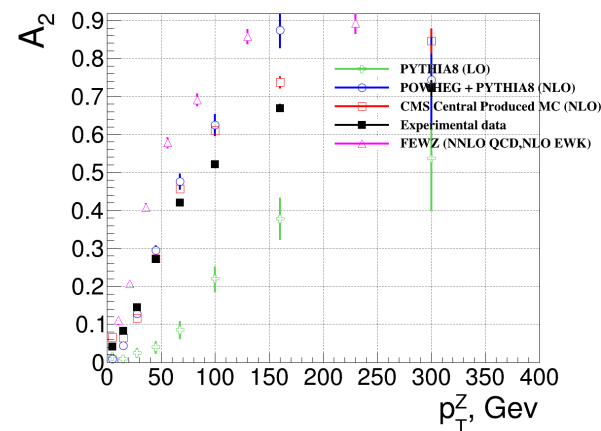
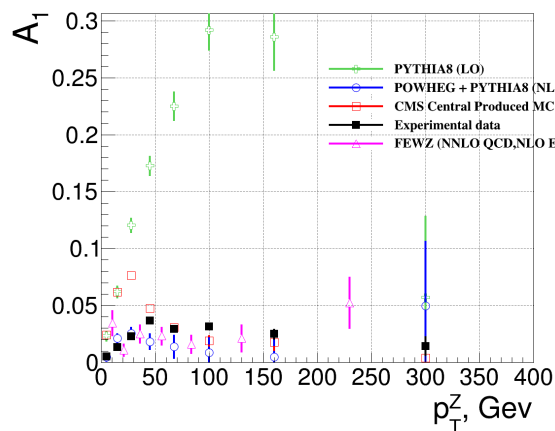
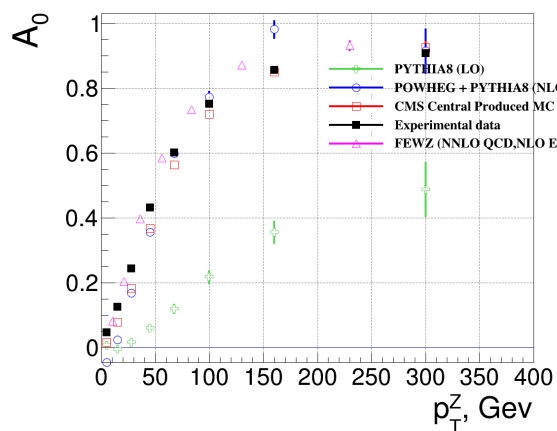
No detector simulation yet!

Compared with:

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



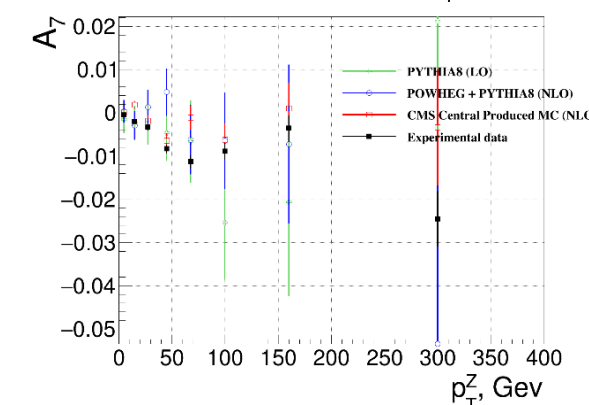
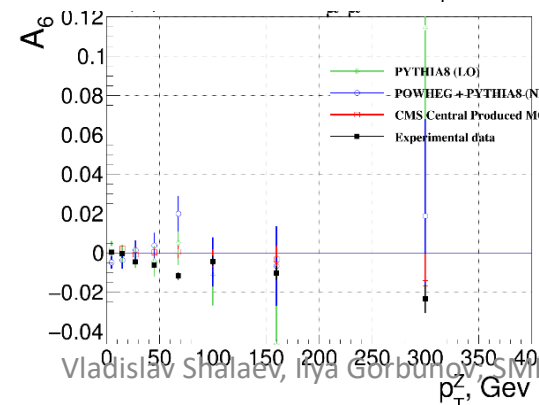
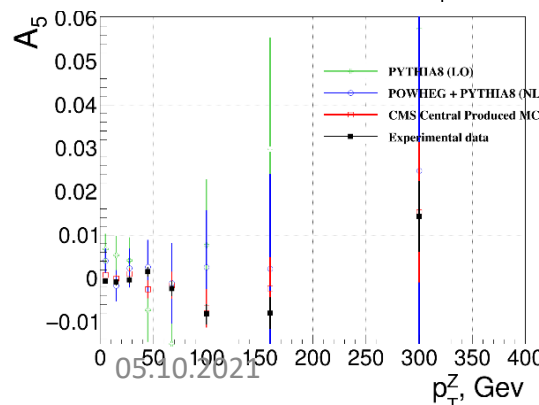
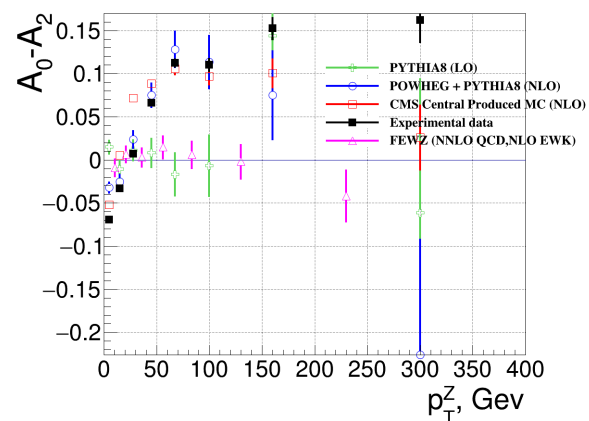
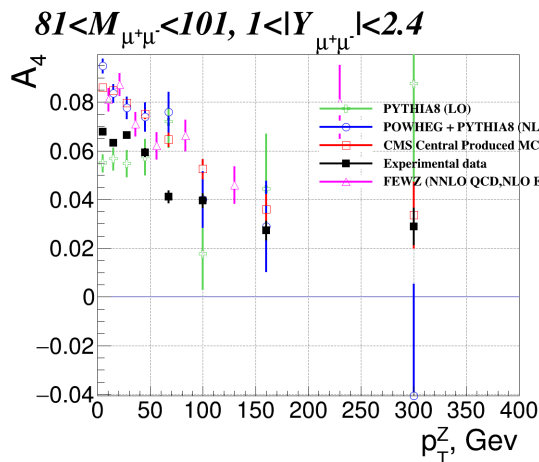
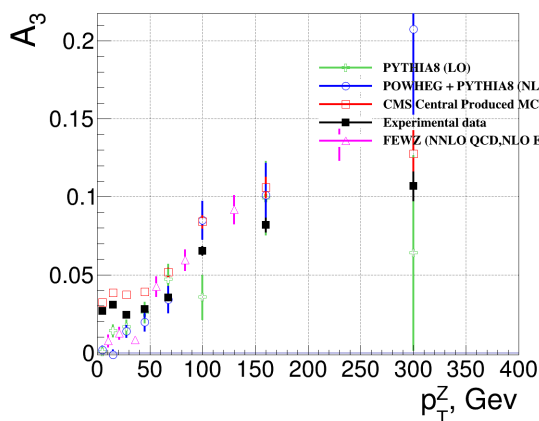
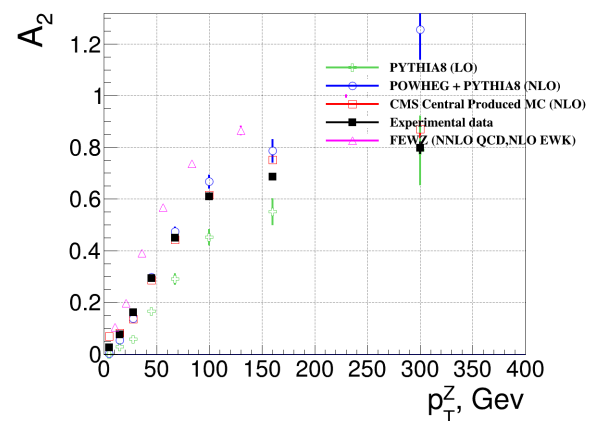
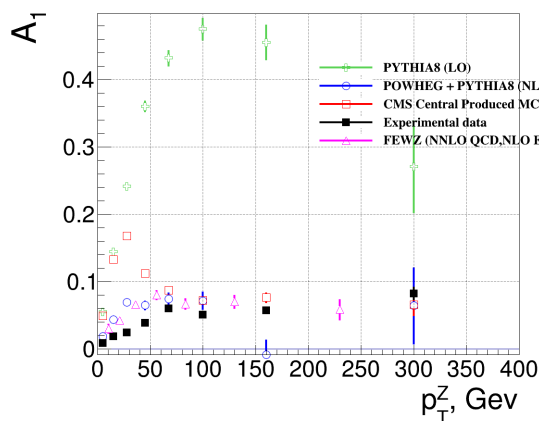
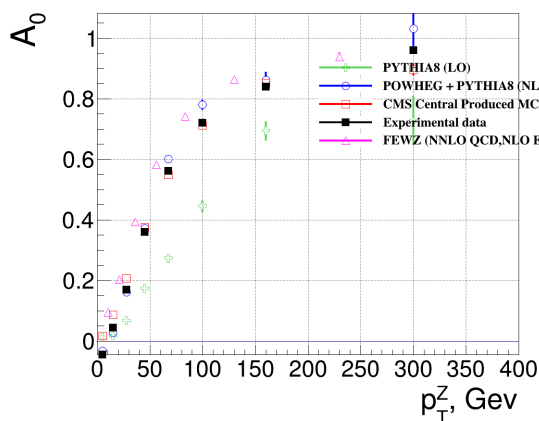
PYTHIA8 (LO QCD, LO EWK, CTEQ6) & POWHEG+PYTHIA8 (NLO QCD, LO EWK, nCTEQ15.1.1) & FEWZ & central produced MC & Data



Vladislav Shatalov, hep-ph/0605285



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

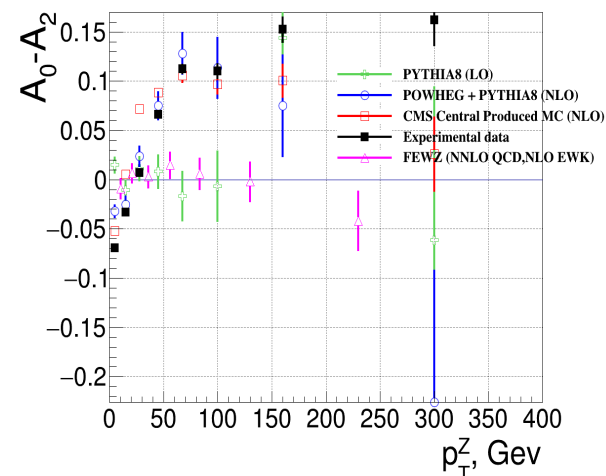
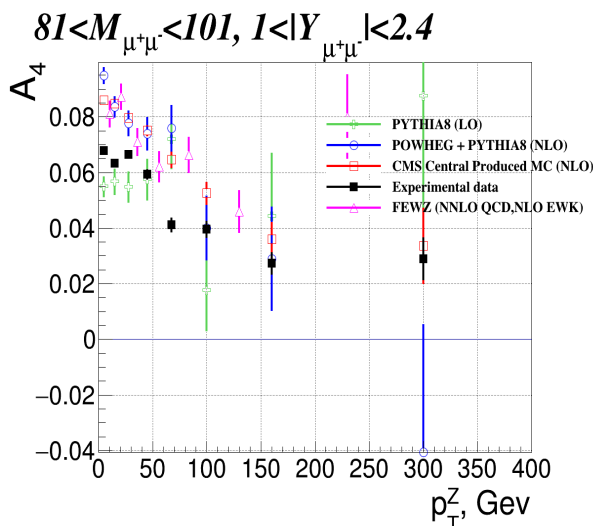
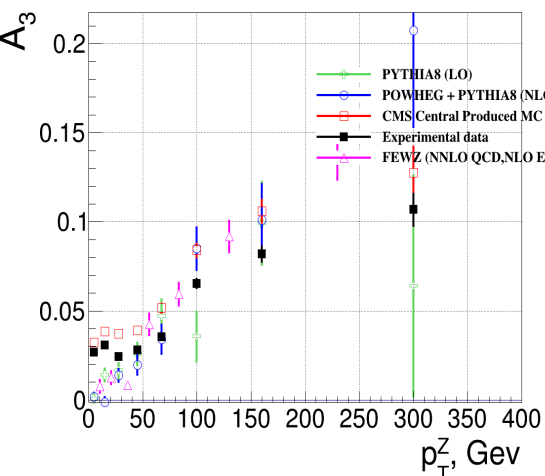
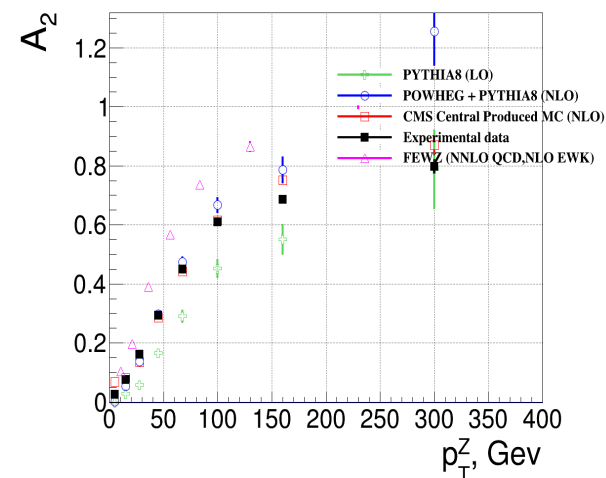
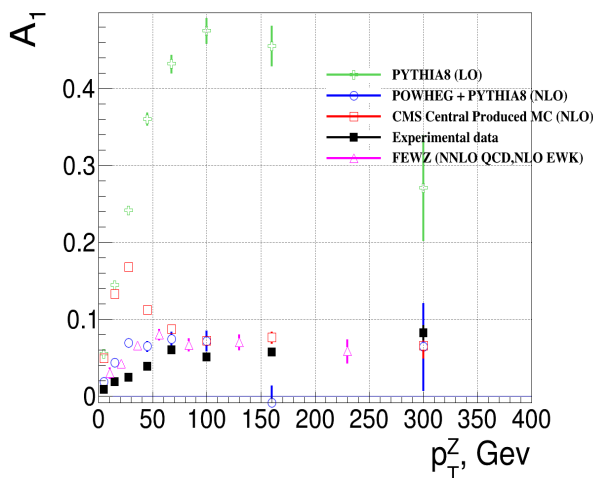
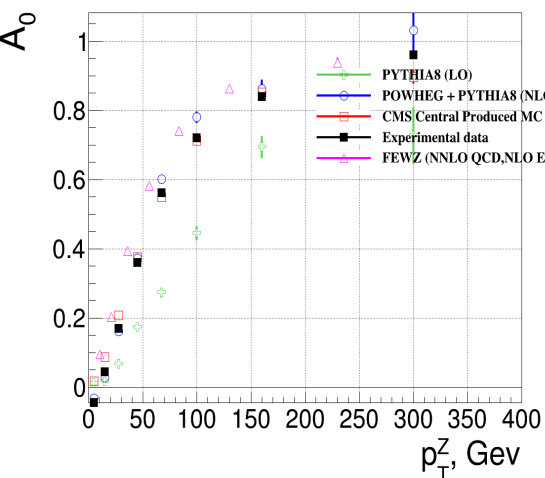


05.10.2021

Vladislav Shalaev, Ilya Gorbunov, SMP-V



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



- 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

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

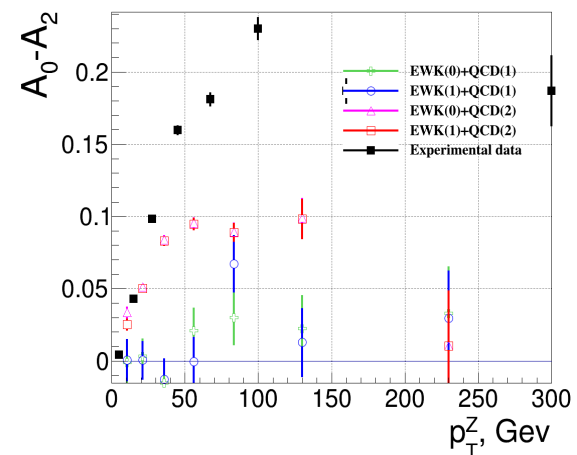
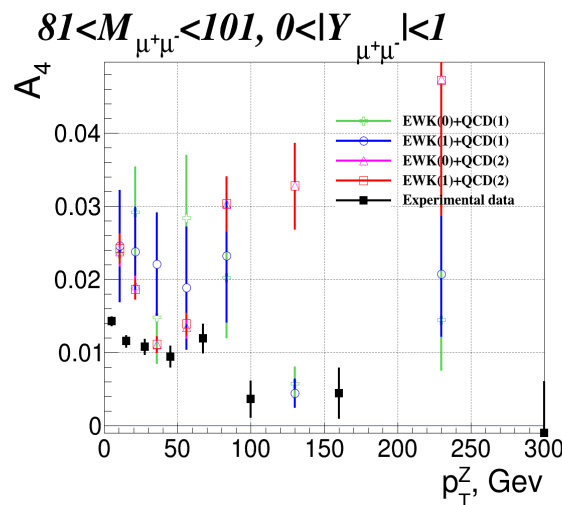
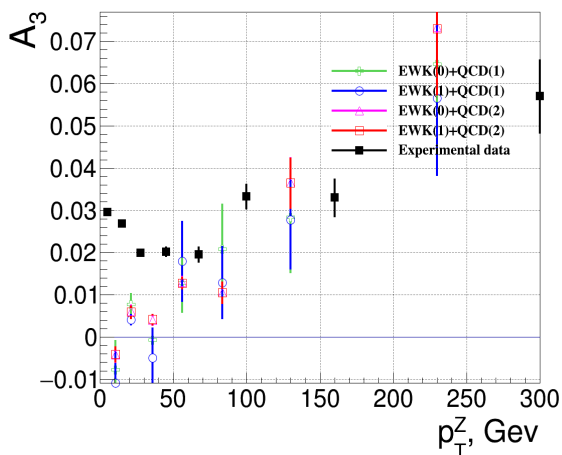
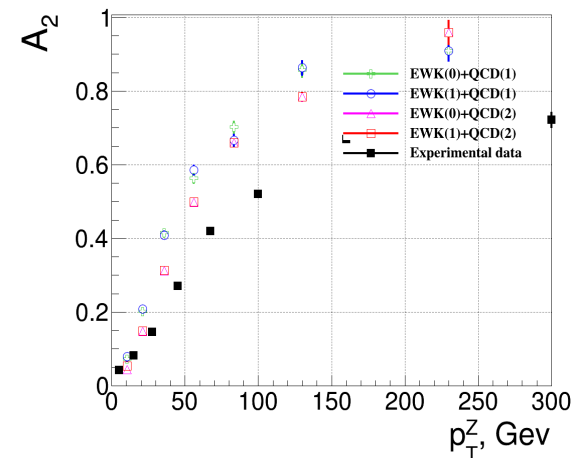
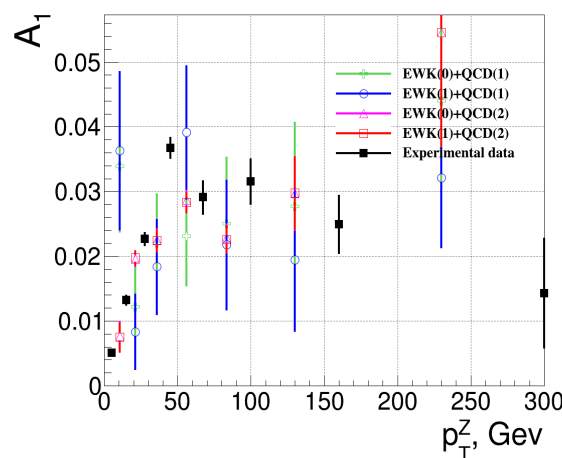
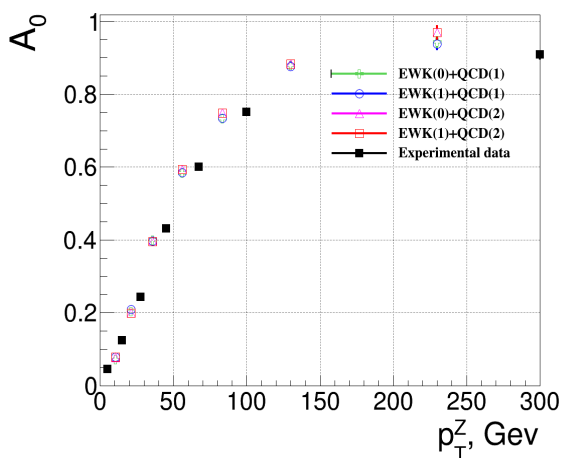
No detector
simulation yet!

Compared with:

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



FEWZ & RUN2 Data (I)

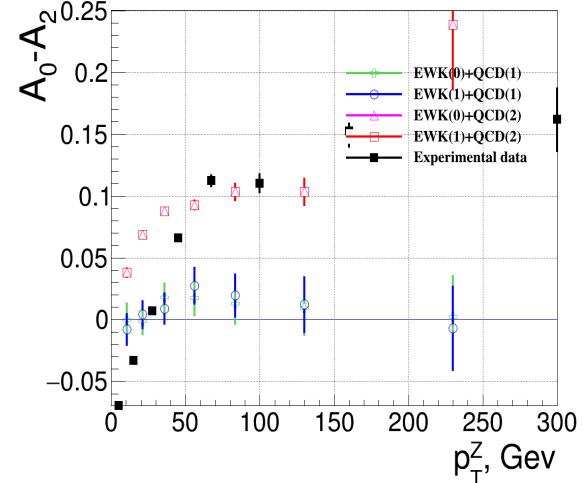
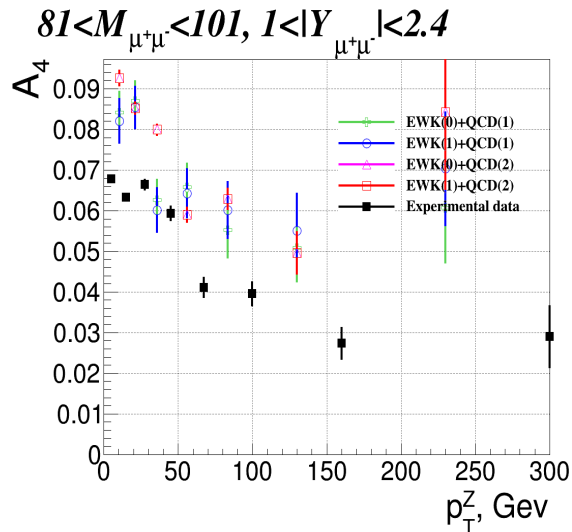
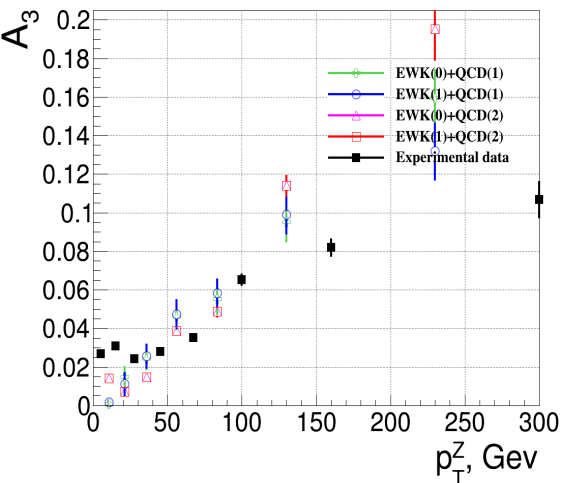
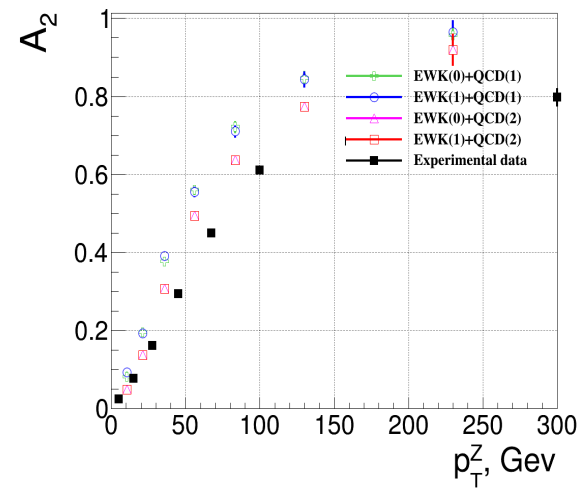
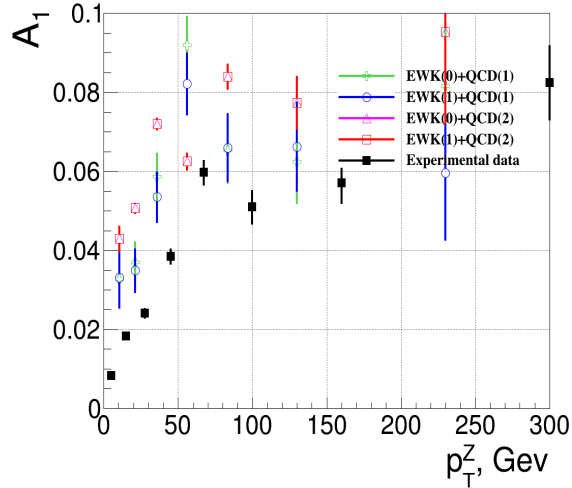
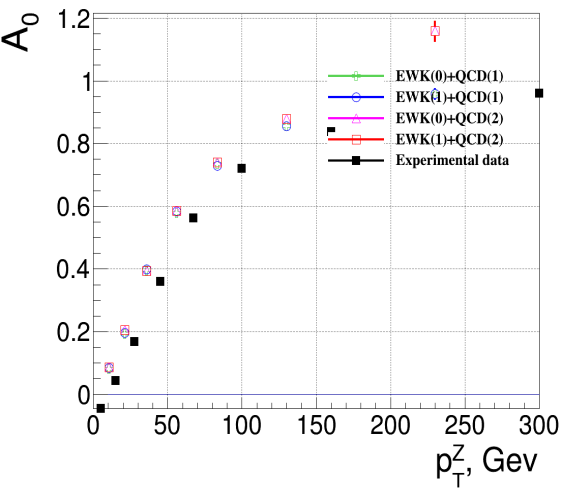


$81 < M_{\mu^+\mu^-} < 101, 0 < |Y_{\mu^+\mu^-}| < 1$

- 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)



$81 < M_{\mu^+\mu^-} < 101, 1 < |Y_{\mu^+\mu^-}| < 2.4$

- 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

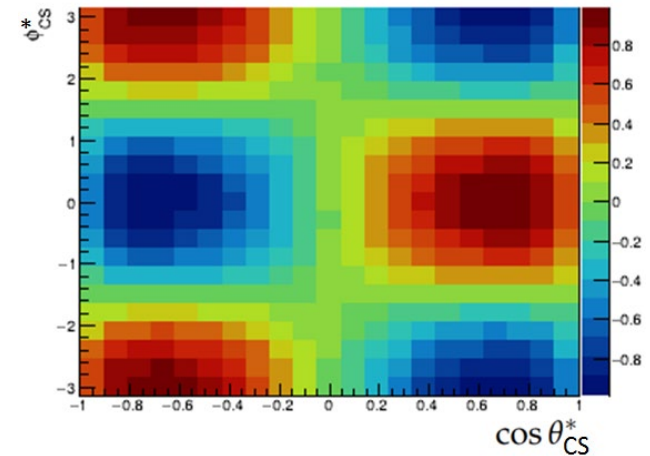


CMS measured only first five coefficients (while ATLAS measured all 8 coefficients):

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

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:

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

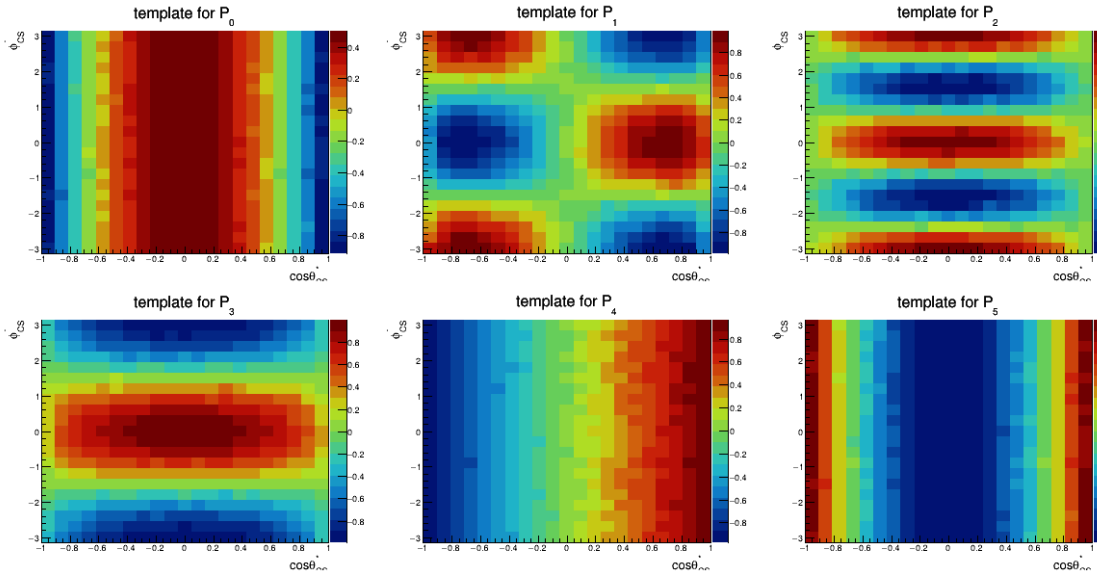
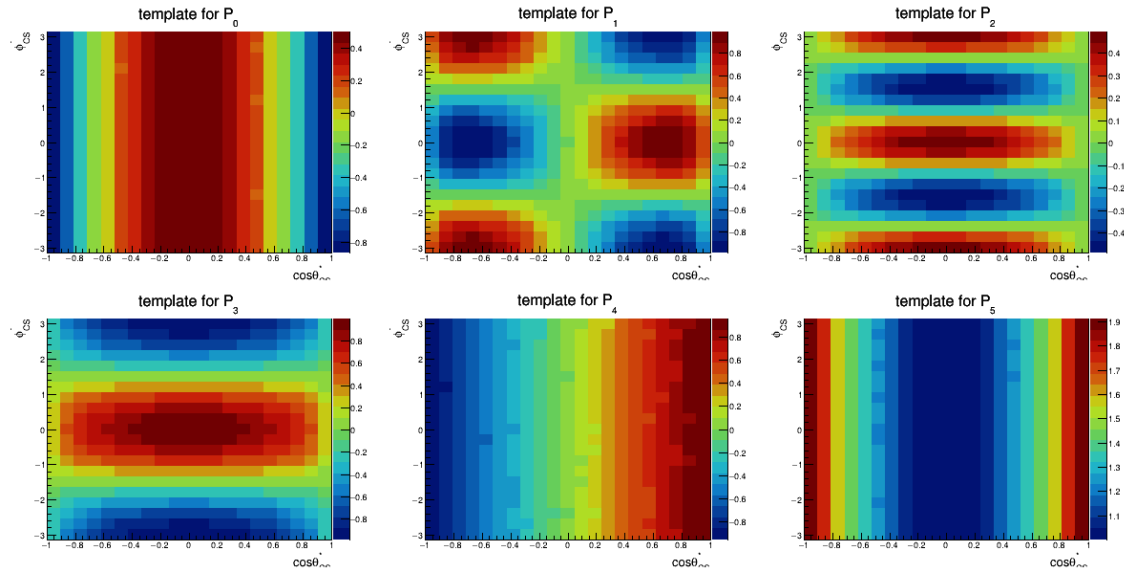


Templates at 13 TeV (Generator Level)

(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!