Polarization Effects in Processes of Dimuon Production

V. Shalaev and S. Shmatov

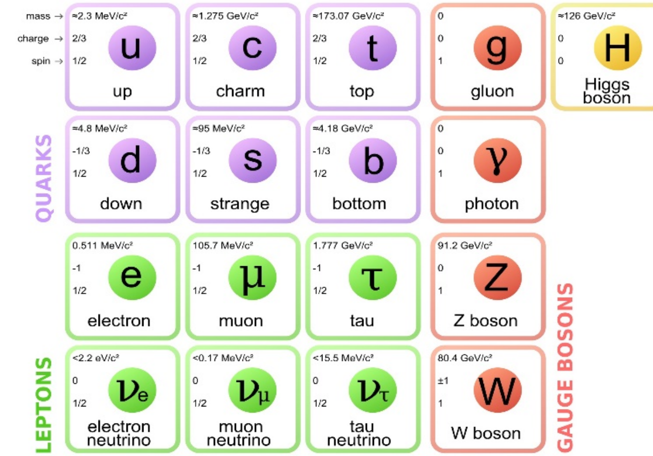
Budapest. 07.12.2023

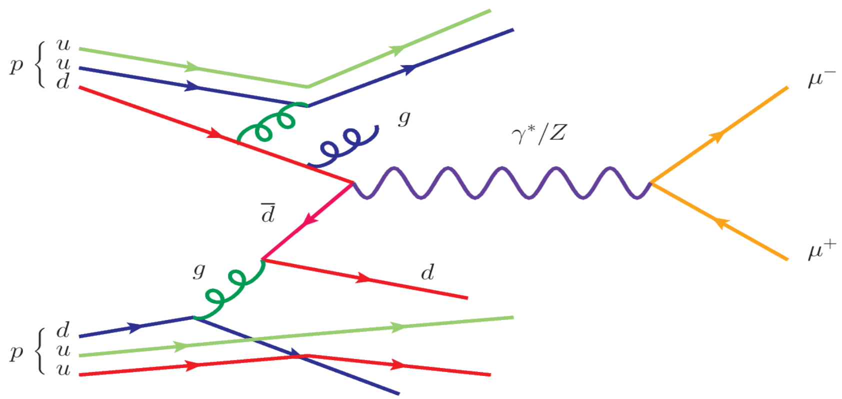
Zimany School 2023

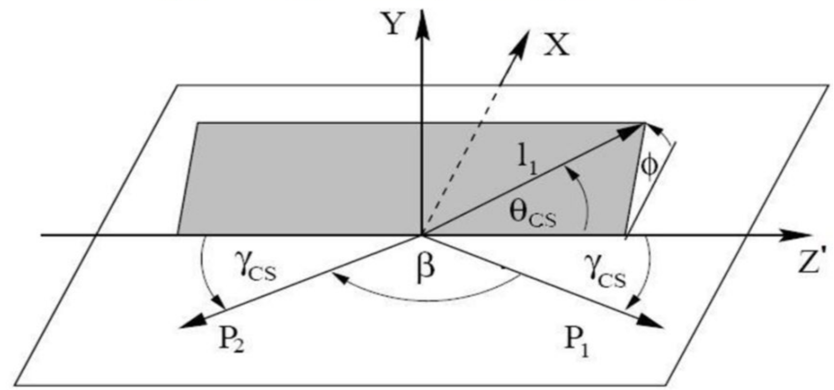
The Drell-Yan Process and Angular Coefficients

Why study dimuons at LHC?

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



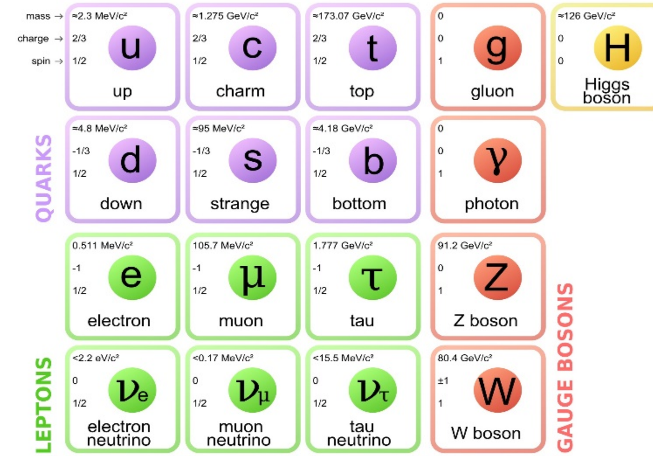




$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \Big[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)$$
$$+A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\Big].$$

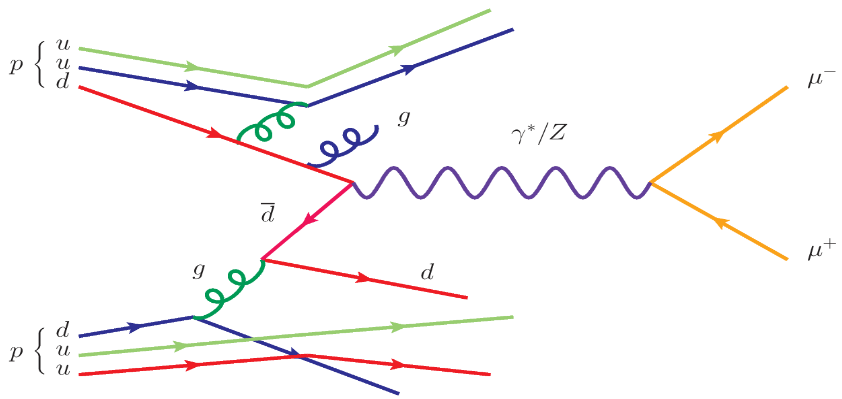
where θ^* and φ^* are the polar and azimuthal angles of l^- (e^- or μ^-) in the rest frame of γ^*/Z (Collins-Soper) and coefficients $A_0 - A_7$ are functions of p_T , Y , M kinematic variables, polarised and unpolorized cross sections

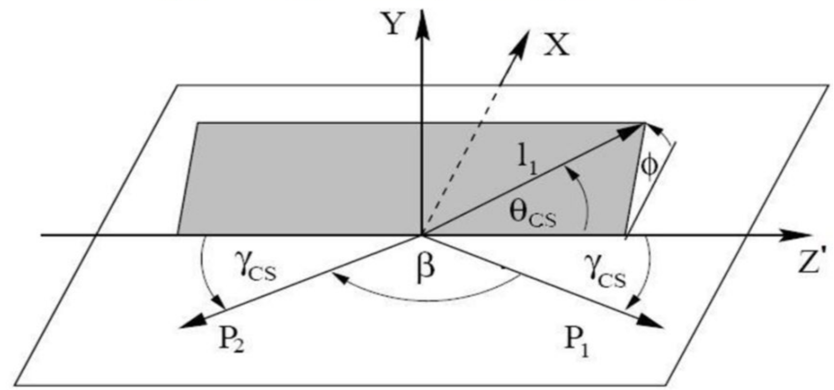
The Drell-Yan Process and Angular Coefficients



Why study dimuons at LHC?

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



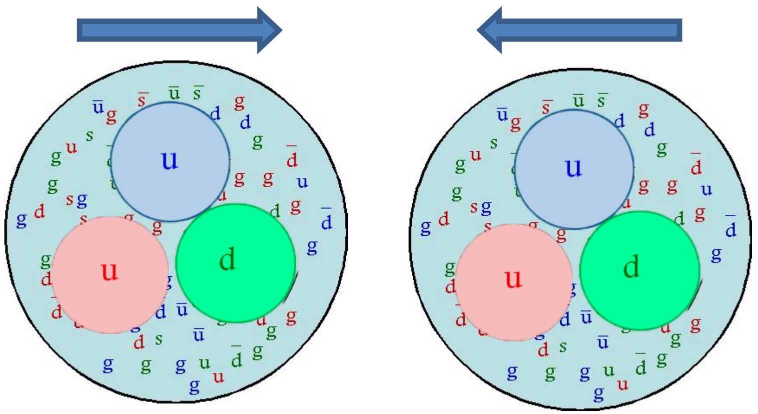


$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \Big[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)$$

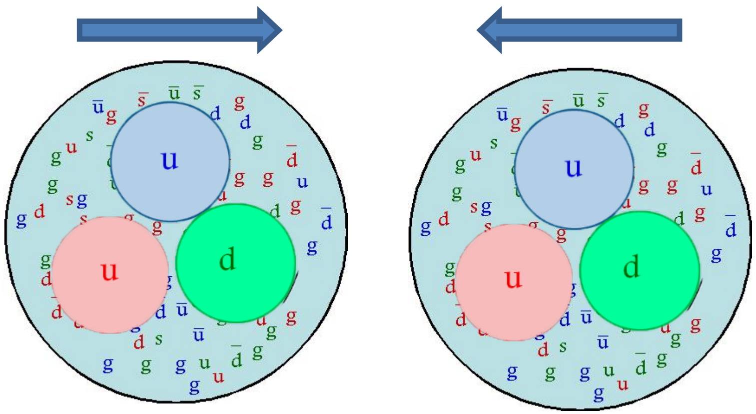
$$+A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\Big].$$

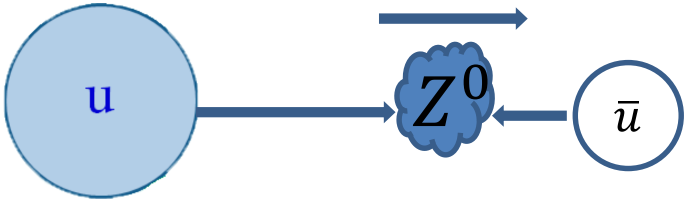
where θ^* and φ^* are the polar and azimuthal angles of l^- (e^- or μ^-) in the rest frame of γ^*/Z (Collins-Soper) and coefficients $A_0 - A_7$ are functions of p_T , Y , M kinematic variables, polarised and unpolorized cross sections

Process Dynamics

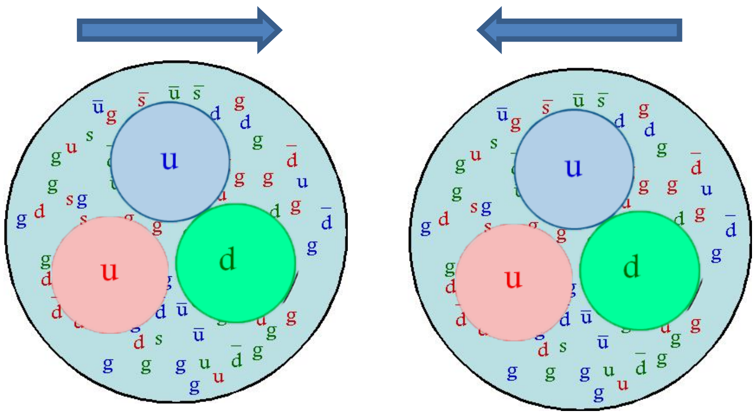


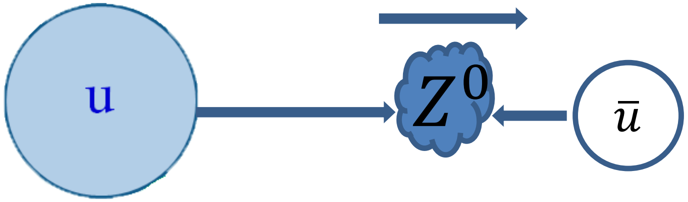
Process Dynamics

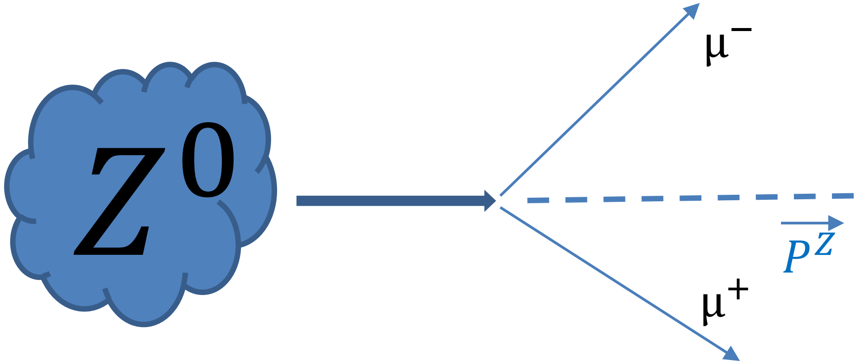




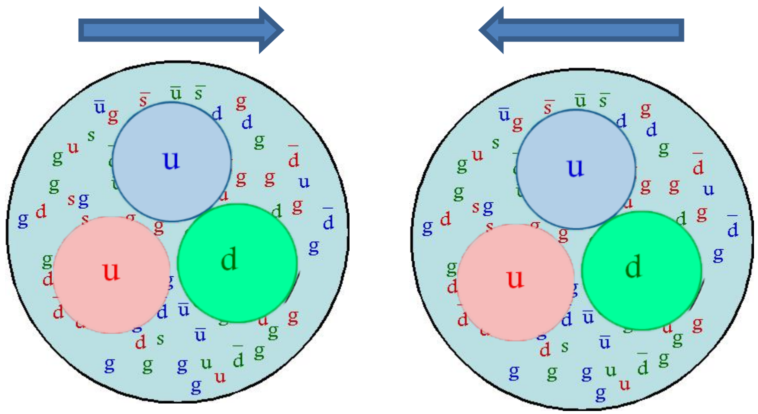
Process Dynamics

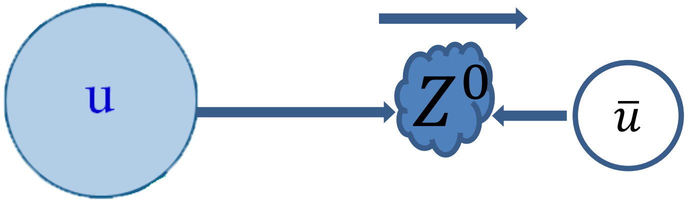


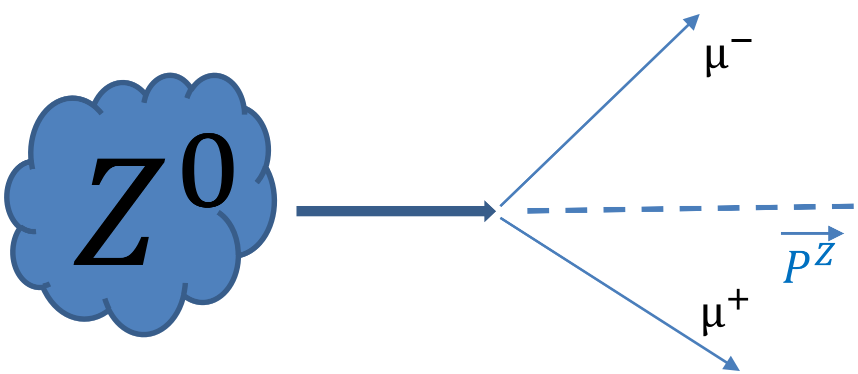


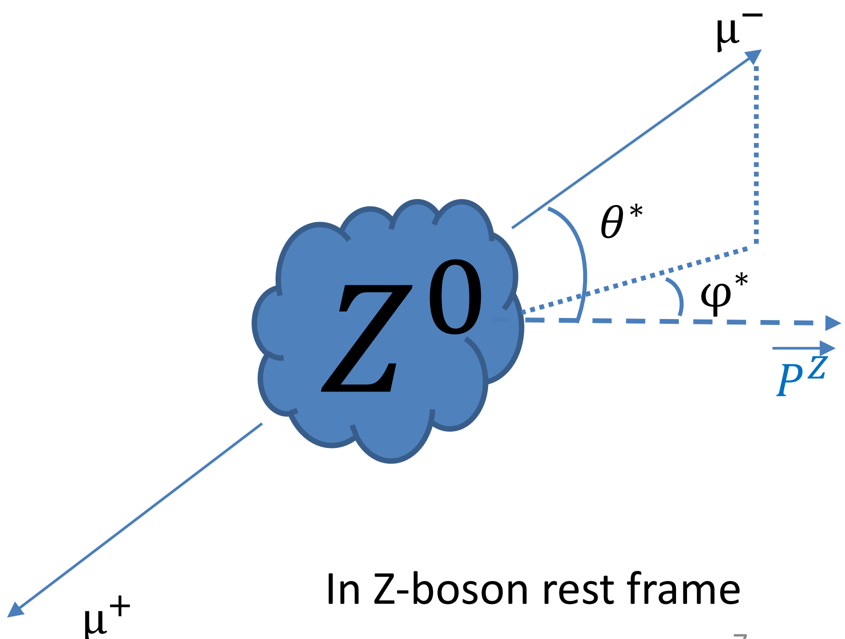


Process Dynamics



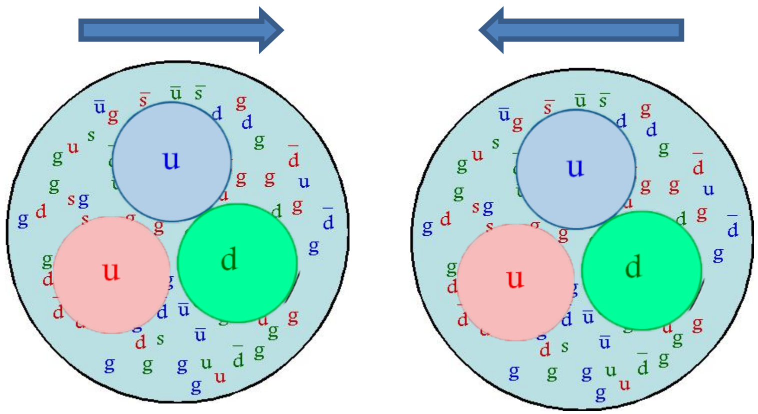


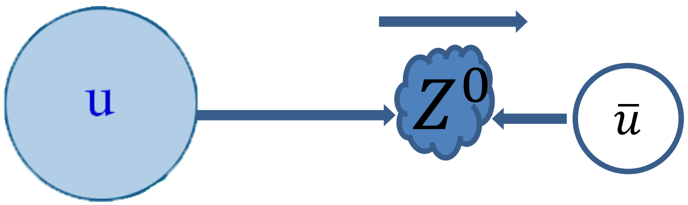




In Z-boson rest frame

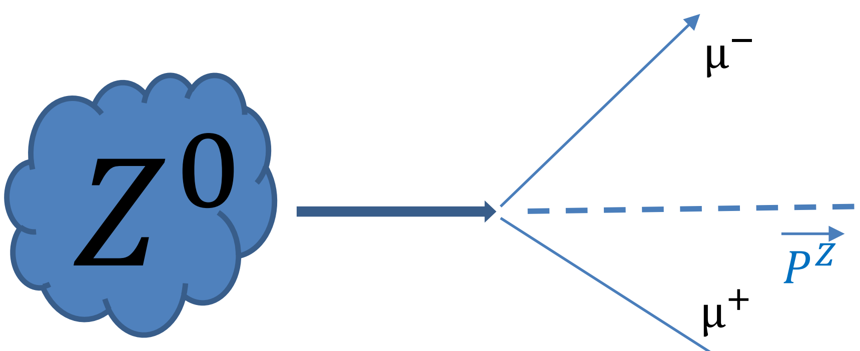
Process Dynamics

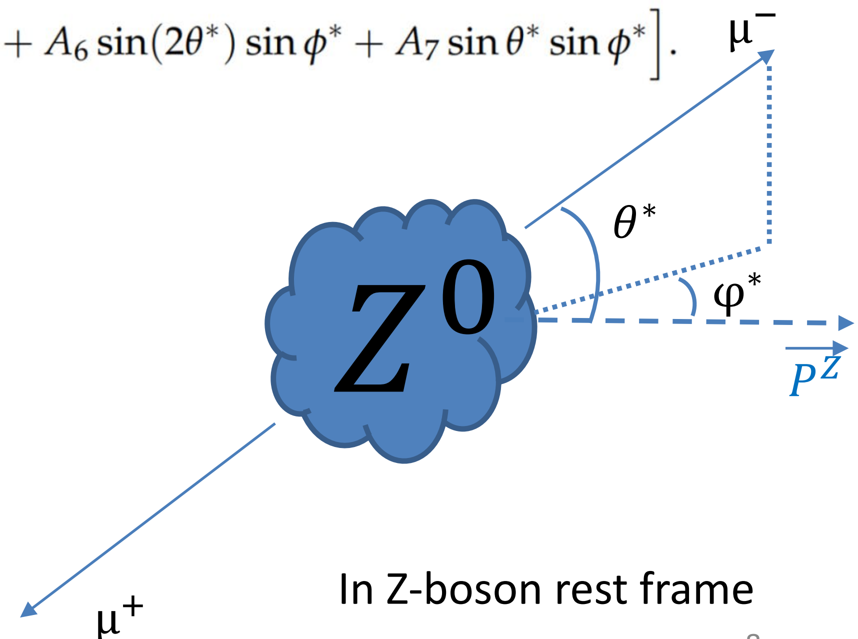




$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \Big[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)$$

$$+A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\Big].$$

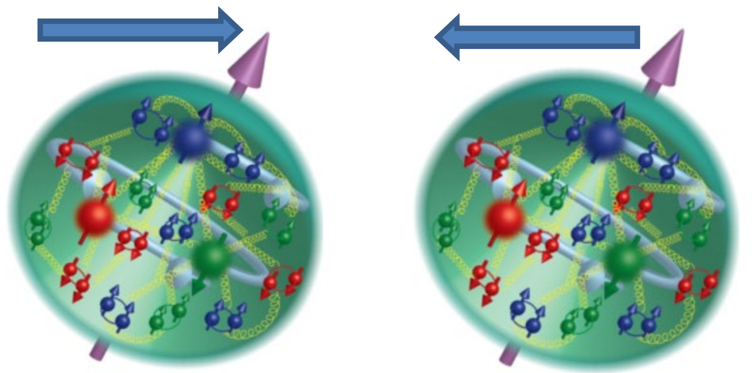




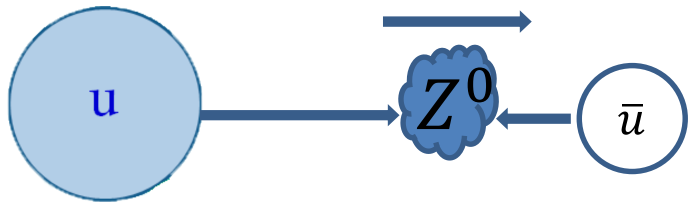
In Z-boson rest frame

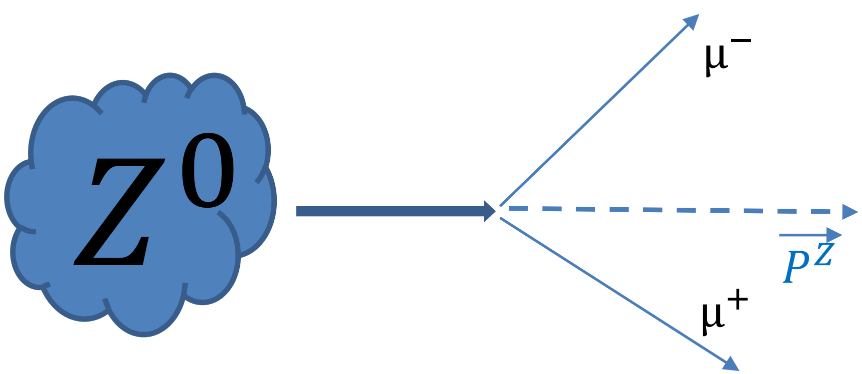
Process Dynamics

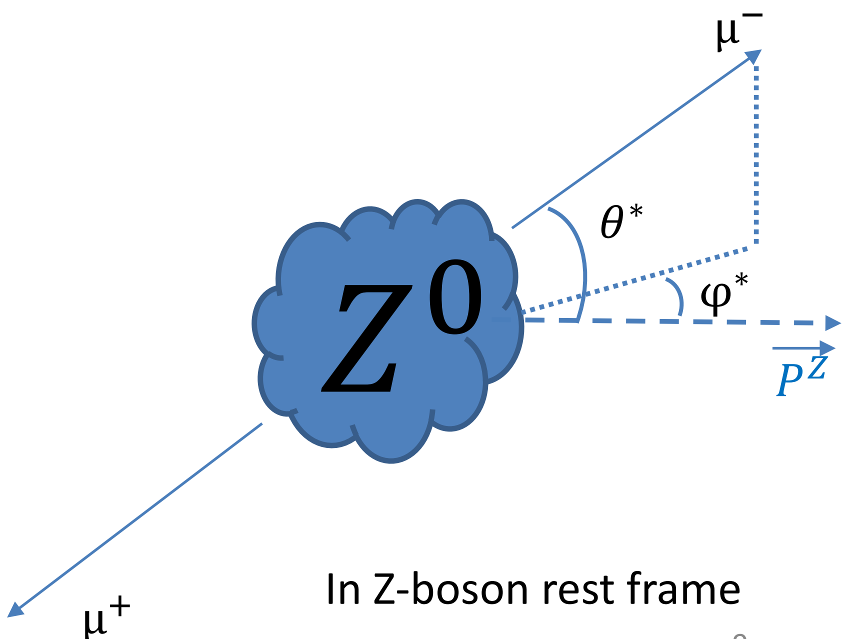
- Non zero partons transverse momentum
- Correlations between spin and parton transverse momentum



All A_i depends on PDF's!

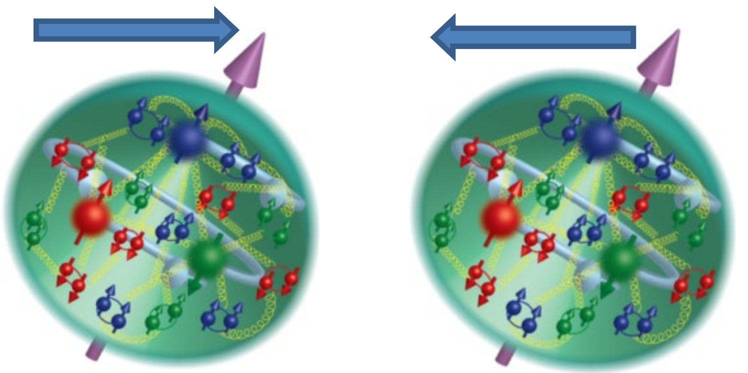




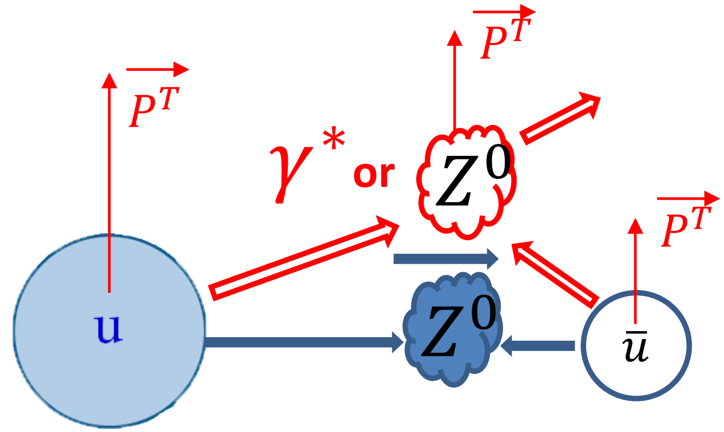


Process Dynamics

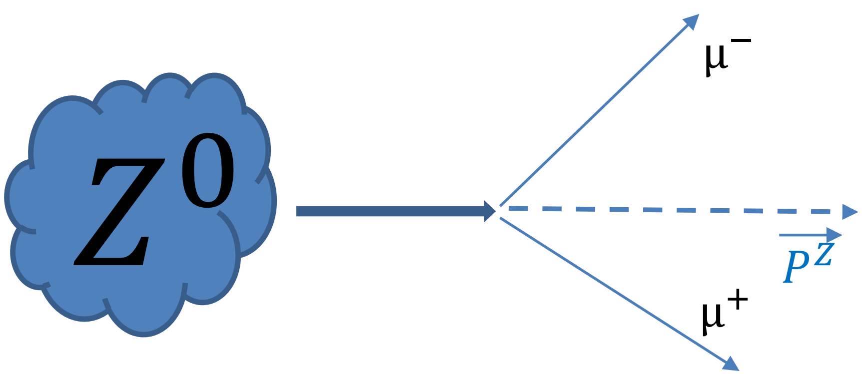
- Non zero partons transverse momentum
- Correlations between spin and parton transverse momentum

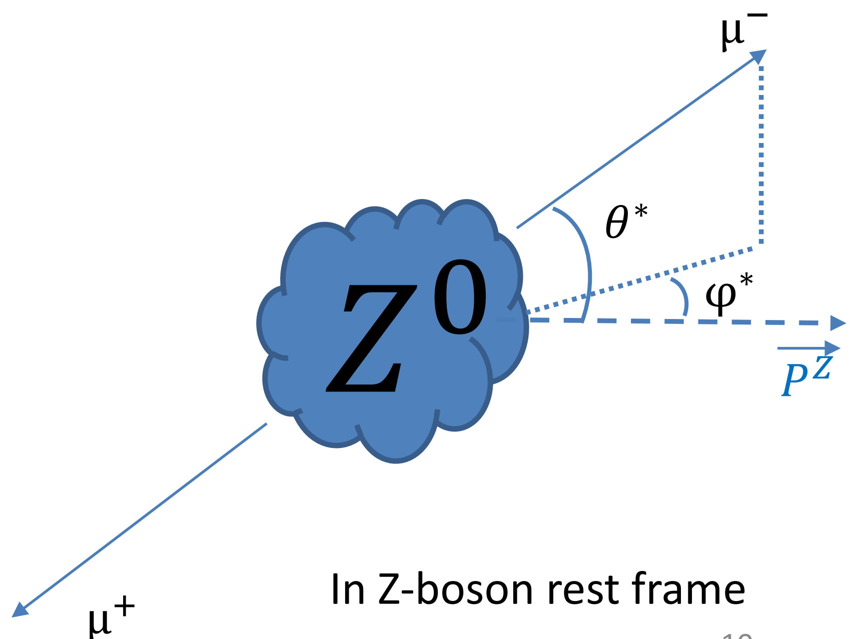


All A_i depends on PDF's!



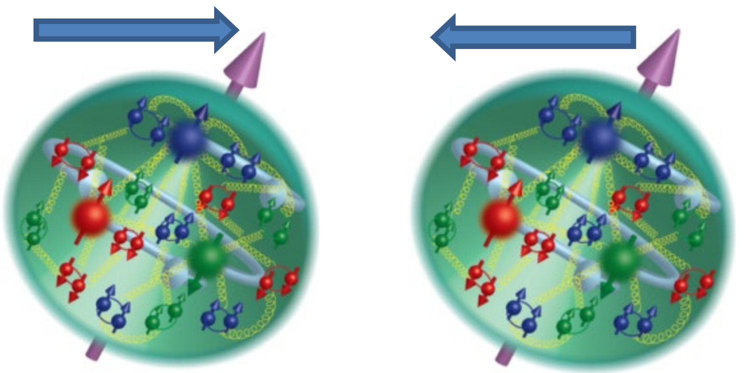
- Higher orders QCD effects produce complicated P^T distribution of partons



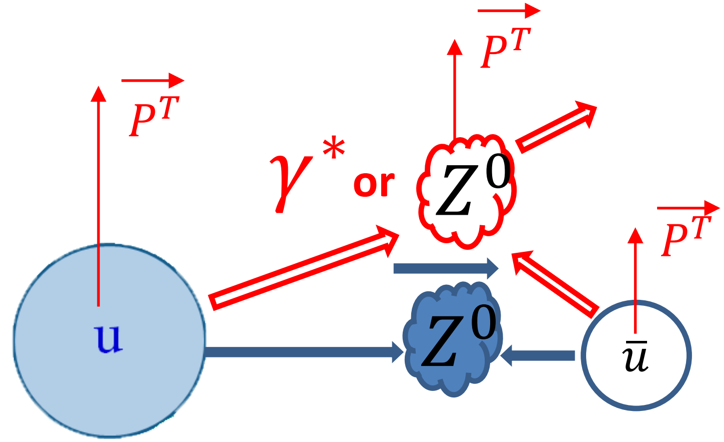


Process Dynamics

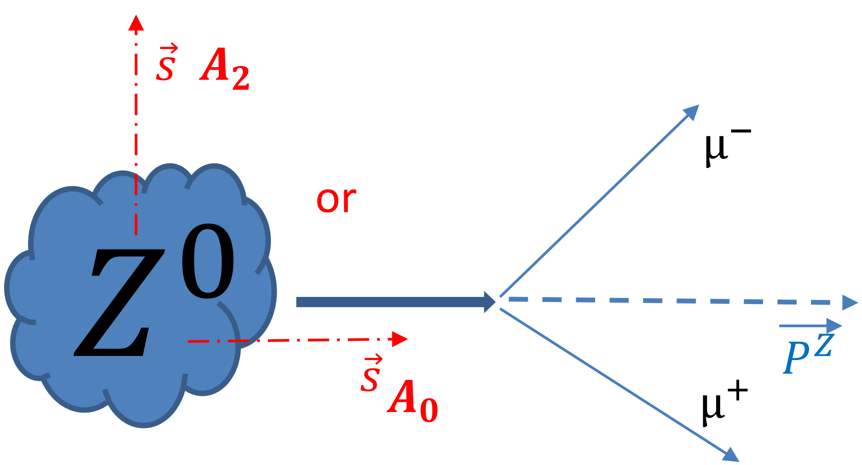
- Non zero partons transverse momentum
- Correlations between spin and parton transverse momentum



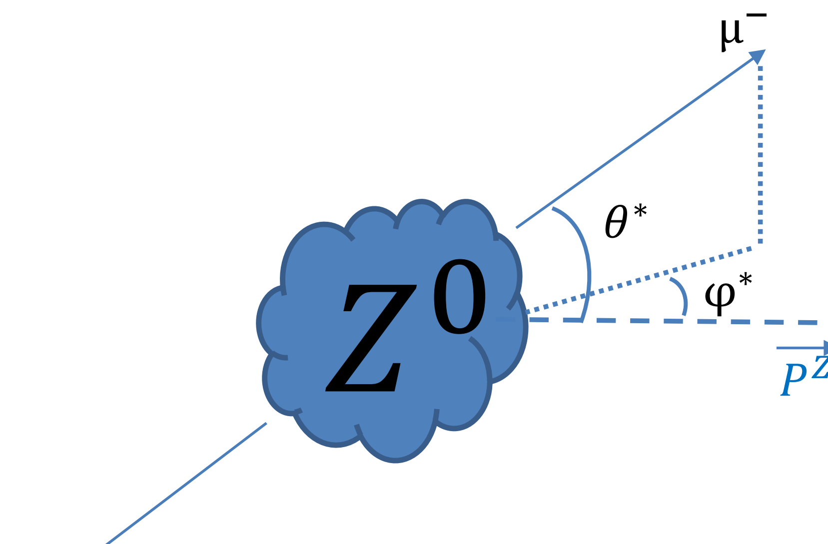
All A_i depends on PDF's!



- Higher orders QCD effects produce complicated P^T distribution of partons



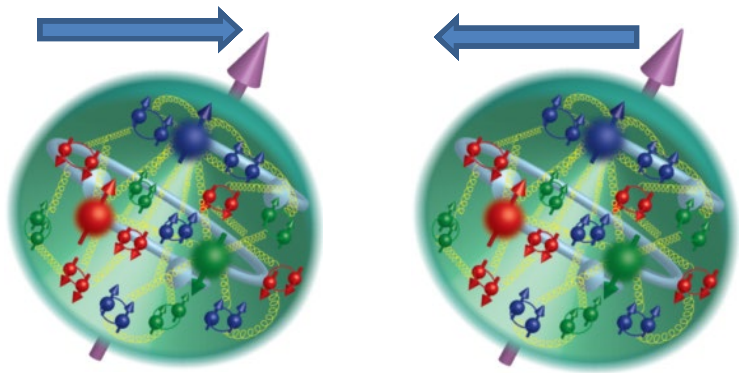
- **LO: $A_0 - A_2 = 0$**
- **NLO: $A_0 - A_2 > 0$**

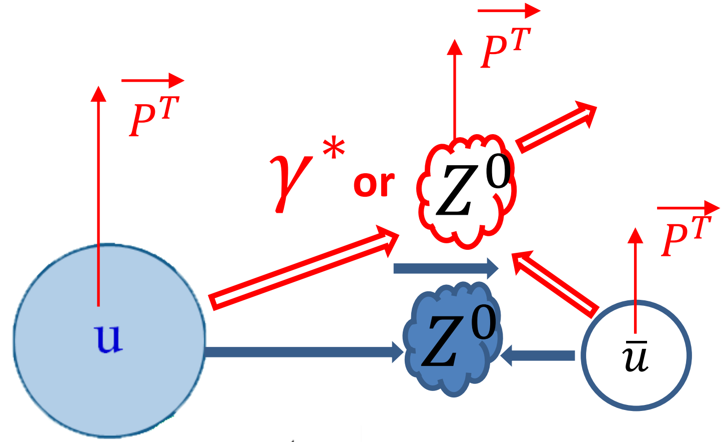


In Z-boson rest frame

Process Dynamics

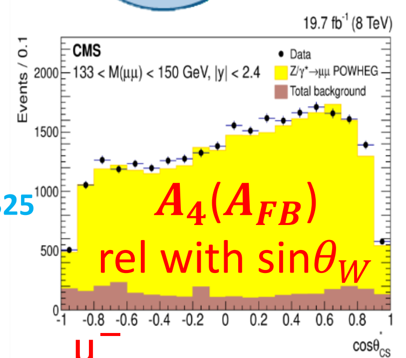
- Non zero partons transverse momentum
- Correlations between spin and parton transverse momentum

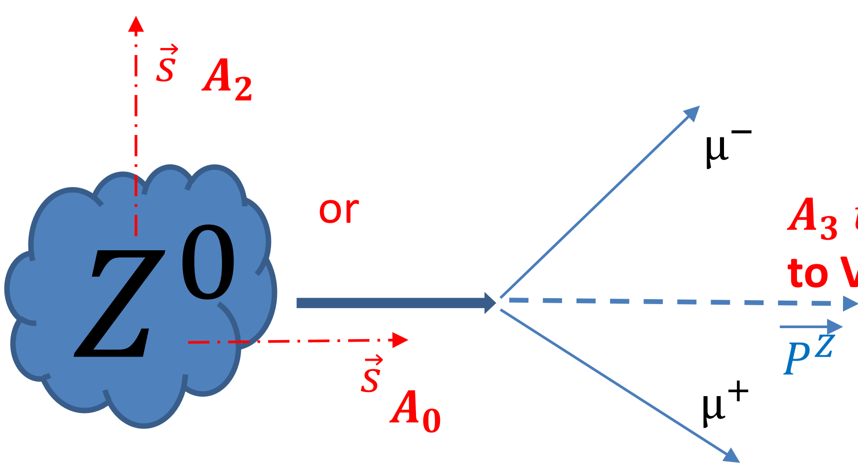




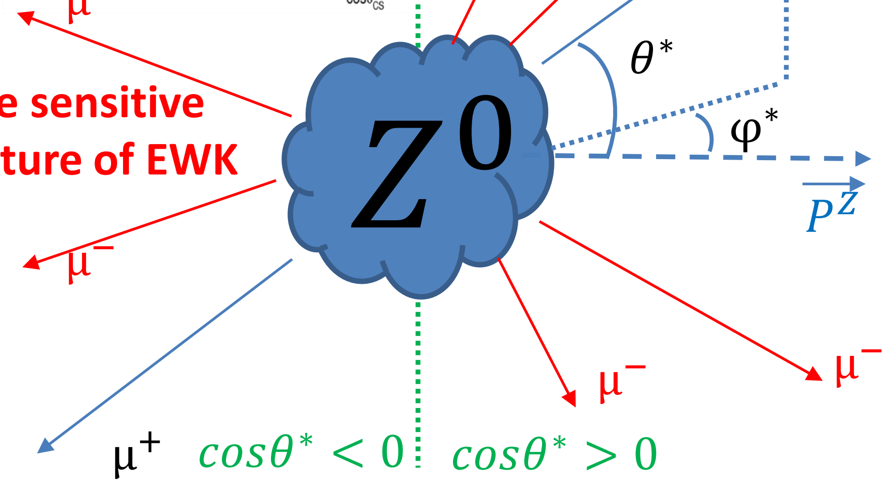
All A_i depends on PDF's

EPJ C 76 (2016) 325





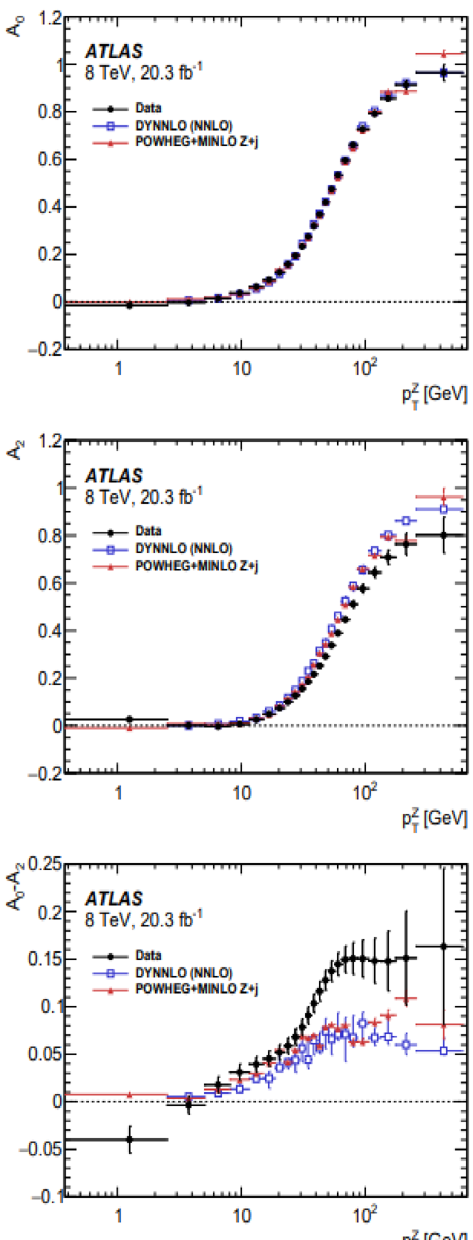
***A_3 to A_7* are sensitive to V-A structure of EWK**



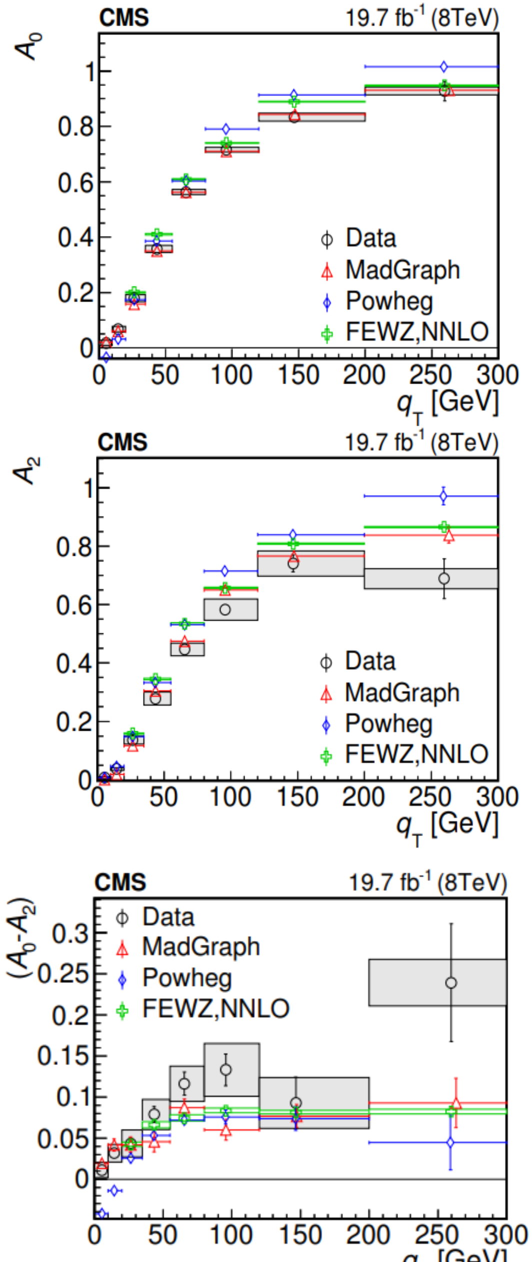
In Z-boson rest frame

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

Measurements of Drell-Yan Angular Coefficients at the LHC



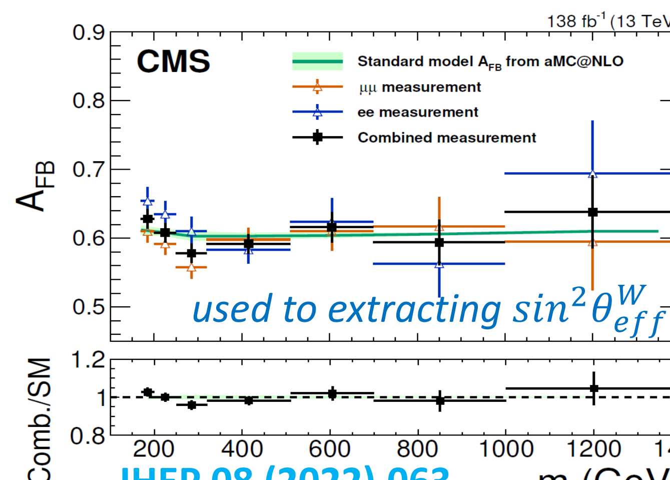
JHEP 08 (2016) 159



PLB 750 (2015) 154

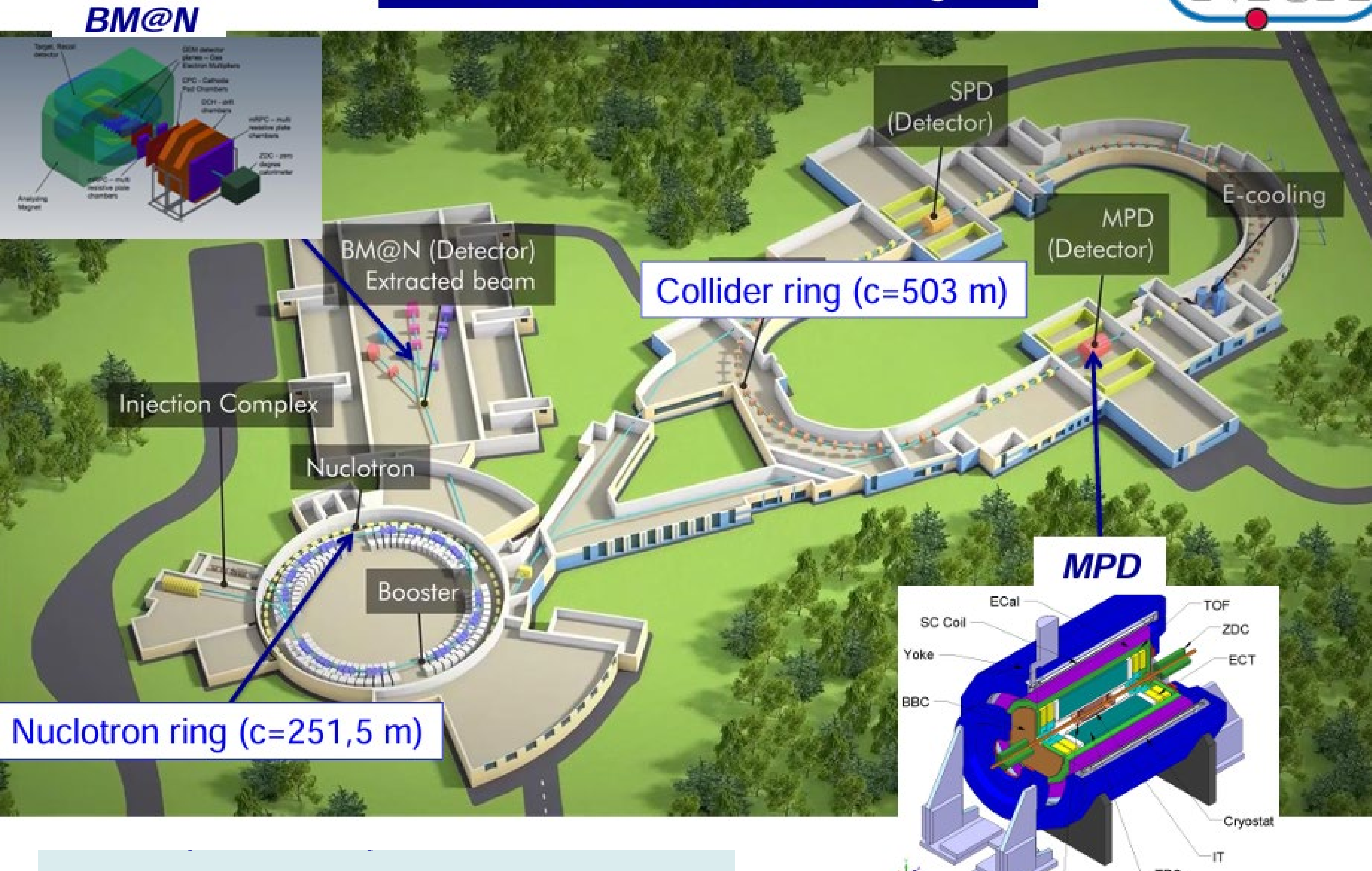
Angular coefficients A_{0-7} (A_{0-4}) are obtained in bins of dilepton (dimuon) transverse momentum and rapidity 80 < $M_{\mu^+\mu^-}$< 100 GeV by ATLAS (CMS) collaboration at 8 TeV

- ✓ Lam-Tung relation $A_0 = A_2$ (related with rotation invariance) violation was observed
- ✓ Forward-Backward Asymmetry A_{FB} was also measured at 7, 8, and 13 TeV
- ✓ Experimental data of CMS and ATLAS experiments are in agreement with each other and with SM NNLO predictions, but some deviations are exist at high p_T^Z
- ✓ A_{0-7} measurements at 13 TeV are in progress (CMS)



JHEP 08 (2022) 063

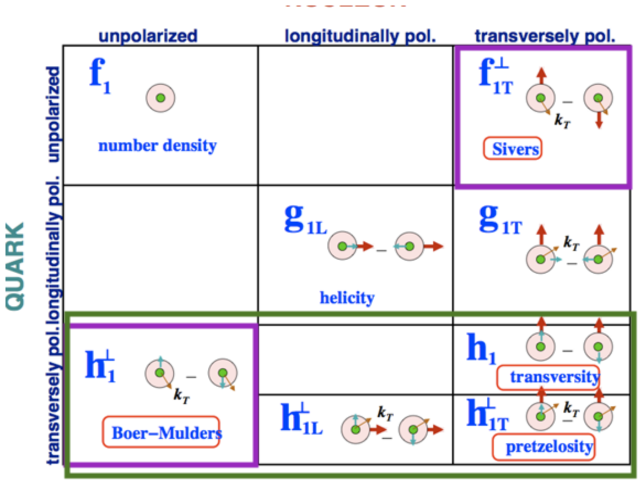
The NICA basic facility



$\sqrt{S_{NN}}$= **11** GeV (Au^{79+}) and =**27** GeV (p)

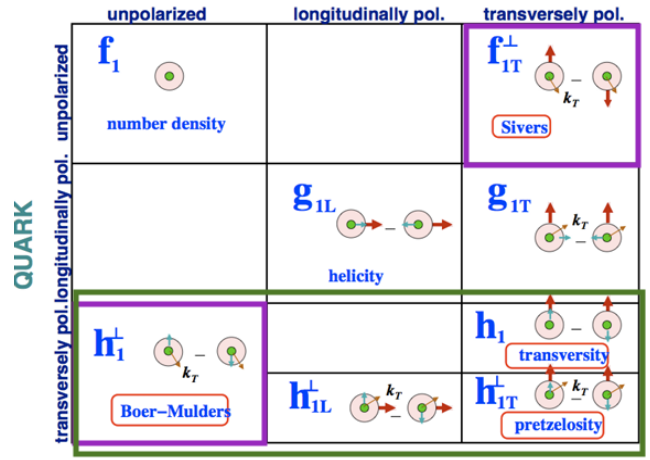
Polarization Study with the SPD NICA (Nuclotron based Ion Colider fAcility)

- $\sqrt{s_{pp}} = 27\ GeV$ is not really well known region
- QCD sub-processes not well-described at this energy range
- Polorized beams give a possibility to study Transverse Momentum Dependent PDFs



Polarization Study with the SPD NICA

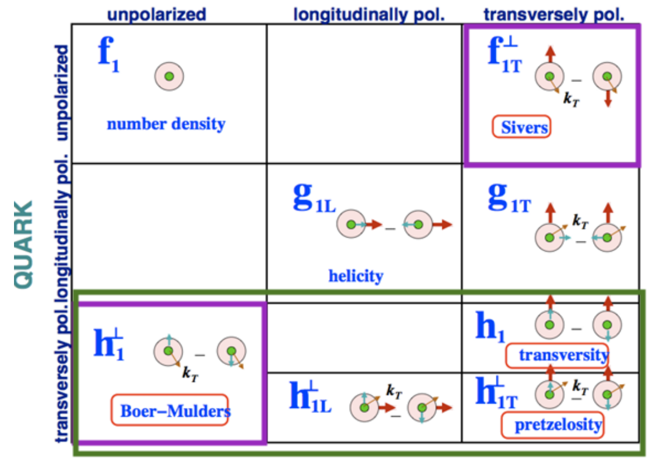
- $\sqrt{s_{pp}} = 27\ GeV$ is not really well known region
- QCD sub-processes not well-described at this energy range
- Polorized beams give a possibility to study Transverse Momentum Dependent PDFs



Study of Drell – Yan process at NICA energies is inefficient: **S/B≈ 4.6 x 10^{-4}** (before cuts)
The SPD Collaboration made a decision to suspend the study of such reactions *(A. Skachkova Report 31.08.23 Minsk)*

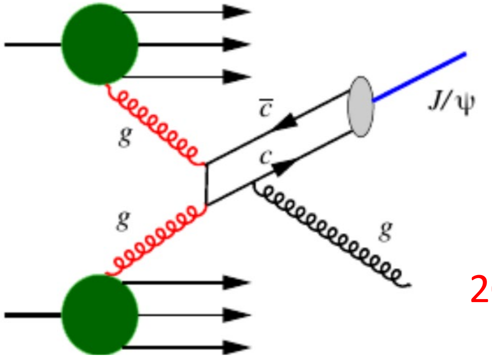
Polarization Study with the SPD NICA

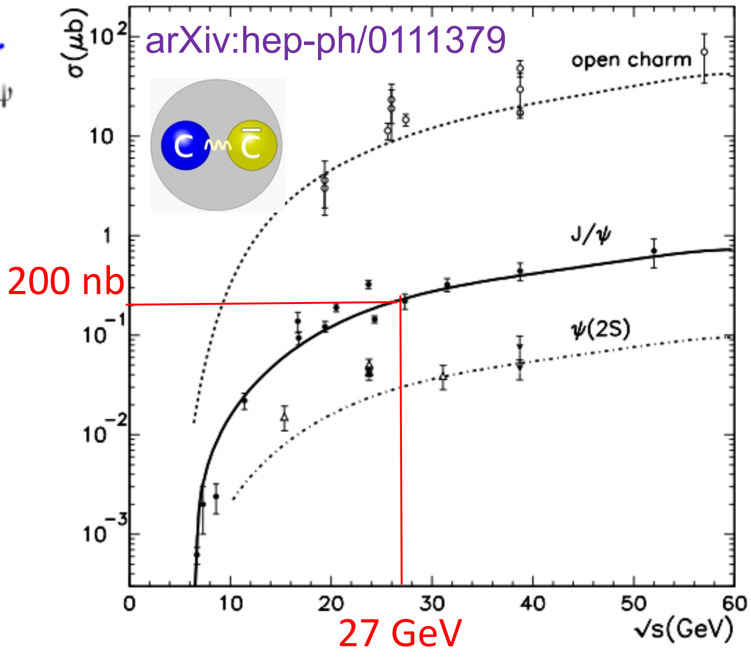
- $\sqrt{s_{pp}} = 27\ GeV$ is not really well known region
- QCD sub-processes not well-described at this energy range
- Polorized beams give a possibility to study Transverse Momentum Dependent PDFs



Study of Drell – Yan process at NICA energies is inefficient: **S/B≈ 4.6 x 10^{-4}** (before cuts)
The SPD Collaboration made a decision to suspend the study of such reactions *(A. Skachkova Report 31.08. Minsk)*

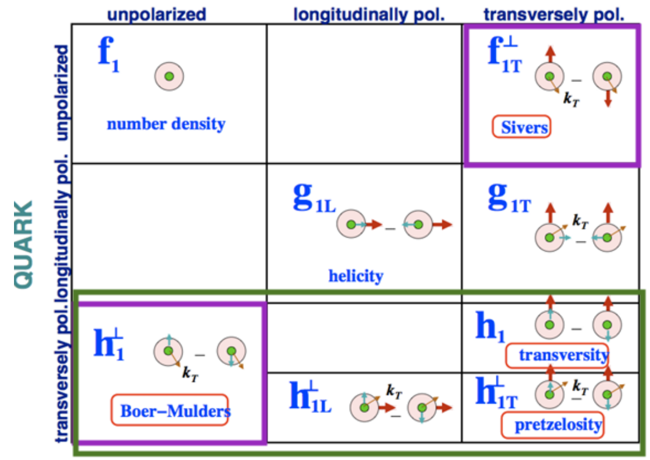
- ✓ Dominated by gluon-gluon fusion
- ✓ High cross-section
- ✓ J/ψ can be easily reconstructed from the $\mu^+\mu^-$ - decay
- ✓ Factorization of $c\bar{c}$ pair is not well understood theoretically





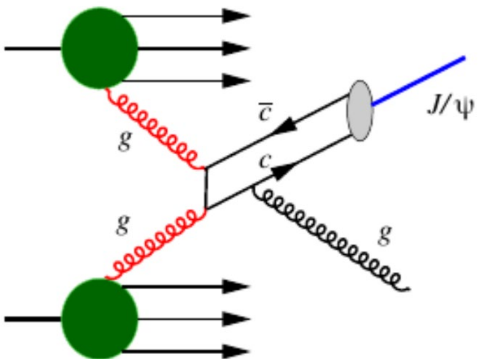
Polarization Study with the SPD NICA

- $\sqrt{s_{pp}} = 27\ GeV$ is not really well known region
- QCD sub-processes not well-described at this energy range
- Polorized beams give a possibility to study Transverse Momentum Dependent PDFs



Study of Drell – Yan process at NICA energies is inefficient: **S/B≈ 4.6 x 10^{-4}** (before cuts)
The SPD Collaboration made a decision to suspend the study of such reactions *(A. Skachkova Report 31.08. Minsk)*

- ✓ Dominated by gluon-gluon fusion
- ✓ High cross-section
- ✓ J/ψ can be easily reconstructed from the $\mu^+\mu^-$ - decay
- ✓ Factorization of $c\bar{c}$ pair is not well understood theoretically

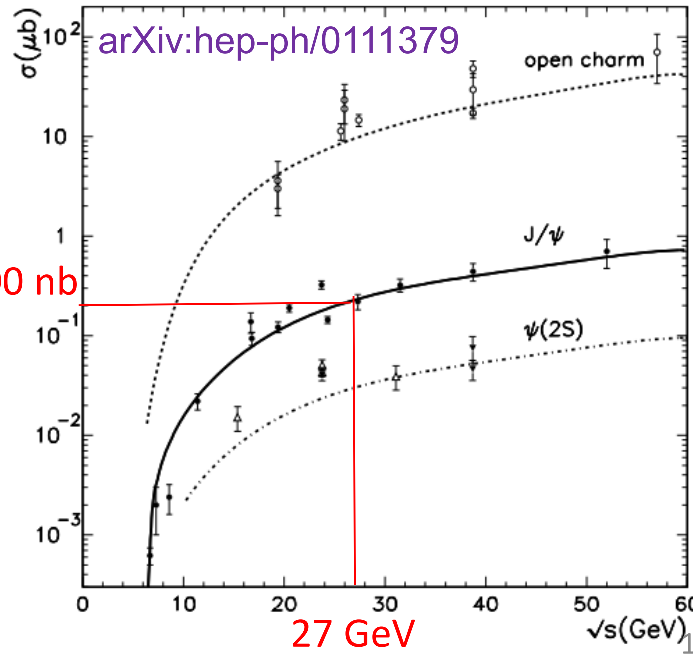


$\sigma_{\sqrt{s_{pp}}=27\ GeV}(J/\psi)$ = 200 nb

Br: $J/\psi \longrightarrow \mu^+\mu^-$ = 0.05961

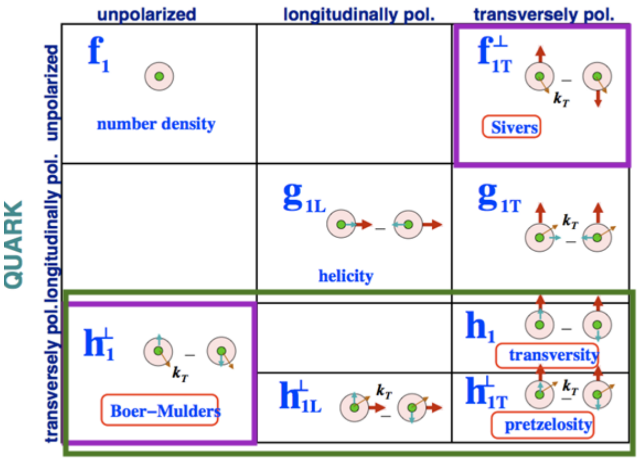
σ ($J/\psi \longrightarrow \mu^+\mu^-$) = 12 nb

Main background: $\pi^+\pi^- \longrightarrow \mu^+\mu^-$

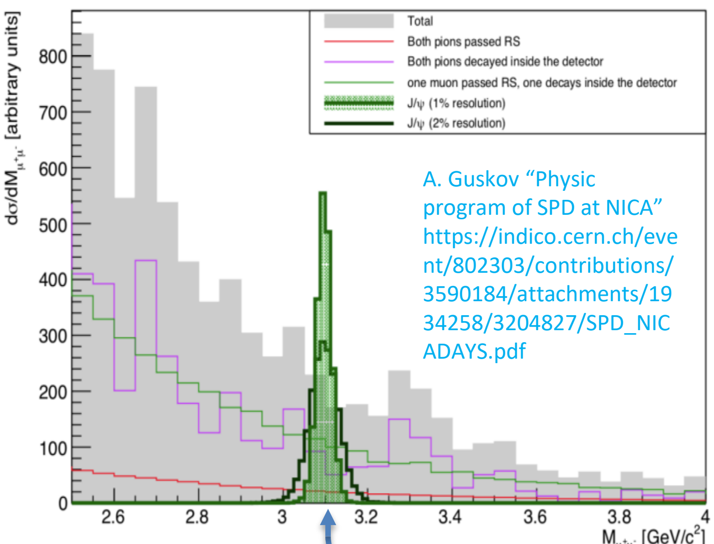


Polarization Study with the SPD NICA

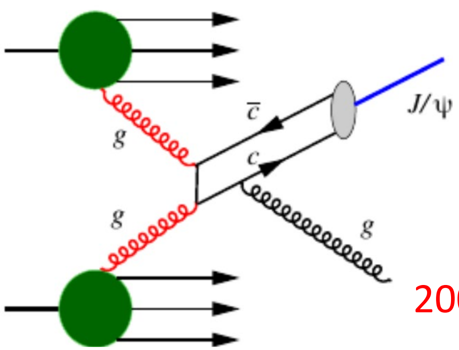
- $\sqrt{s_{pp}} = 27\ GeV$ is not really well known region
- QCD sub-processes not well-described at this energy range
- Polorized beams give a possibility to study Transverse Momentum Dependent PDFs



Study of Drell – Yan process at NICA energies is inefficient: **S/B≈ 4.6 x 10^{-4}** (before cuts)
The SPD Collaboration made a decision to suspend the study of such reactions *(A. Skachkova Report 31.08. Minsk)*



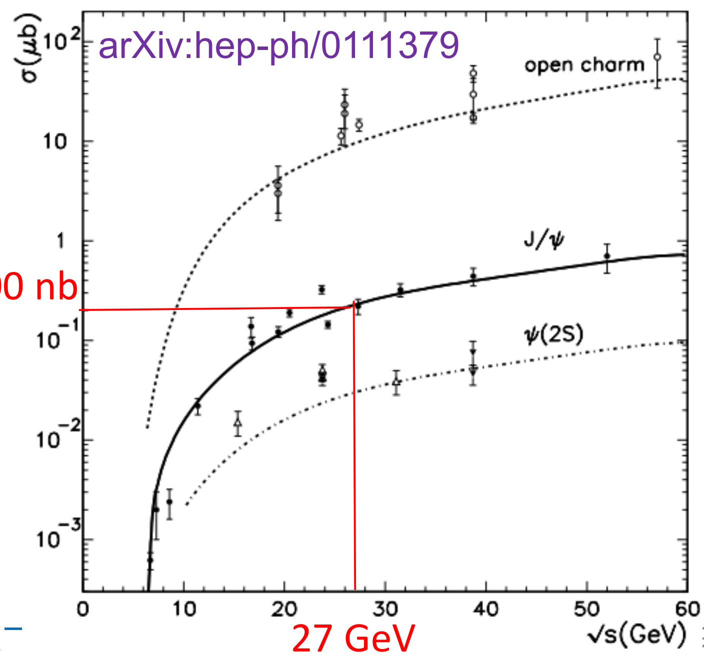
Could be suppressed with selection conditions!



$\sigma_{\sqrt{s_{pp}}=27\ GeV}(J/\psi)$ = 200 nb

Br: $J/\psi \rightarrow \mu^+\mu^-$ = 0.05961

σ ($J/\psi \rightarrow \mu^+\mu^-$) = 12 nb



Main background: $\pi^+\pi^- \rightarrow \mu^+\mu^-$

Conclusions

Results:

- ✓ Full set o angular polarization coefficients A_{0-7} was measured in Z-peak by ATLAS and CMS (A_{0-4}) in pp-collisions at 8 TeV
- ✓ A_{0-7} measurements at 13 TeV with the CMS is almost done. Estimation of higher order effects is under the process

All measurements (8, 13 TeV) are in a good agreement with a Standard model predictions!

- ✓ Studying of J/ψ production under SPD conditions is started with MC modeling. Possibility to perform this kind of research at NICA is approved

Prospects:

- ❑ Publish 13 TeV A_i measurements results
- ❑ Studying of J/ψ production with simulation of SPD detector response

---

Thanks for your attention!

CMS Draft Analysis Note

The content of this note is intended for CMS internal use and distribution only

2021/10/02
Archive Hash: 9583ef3-D
Archive Date: 2021/08/27

The Drell-Yan Angular Coefficients Measurement at 13 TeV

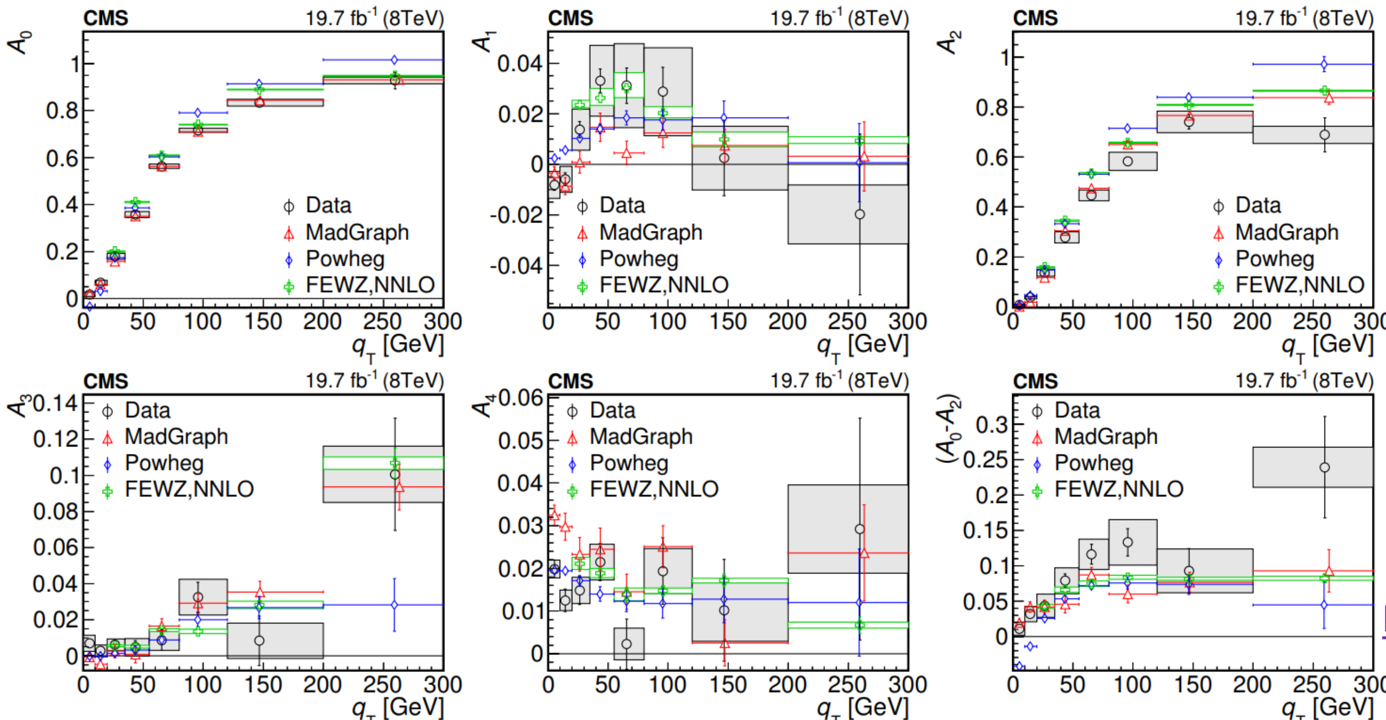
the CMS Collaboration
CERN

Abstract

The polarization of the Z-boson is presented triple differentially, in bins of Z-boson rapidity, transverse momentum and dilepton invariant mass. A data set of Z-bosons decaying to muons at a pp collision energy of 13 TeV and with an integrated luminosity of 138.7 fb^{-1} is used. The polarization of the Z-boson does affect the acceptance for precision measurements and is important for the modeling of the kinematics of leptons, as the polarization governs the Z-boson decay. The seven polarization coefficients that are measured in the Collins-Soper frame. Fair agreement is observed between the data and simulation.

A_i Measurement at *8 TeV* *for* $|Y| < 1$

Comparison of the five angular coefficients A_i *and* $A_0 - A_2$
measured in the Collins– Soper frame in bins of p_T *for* $|Y| < 1$

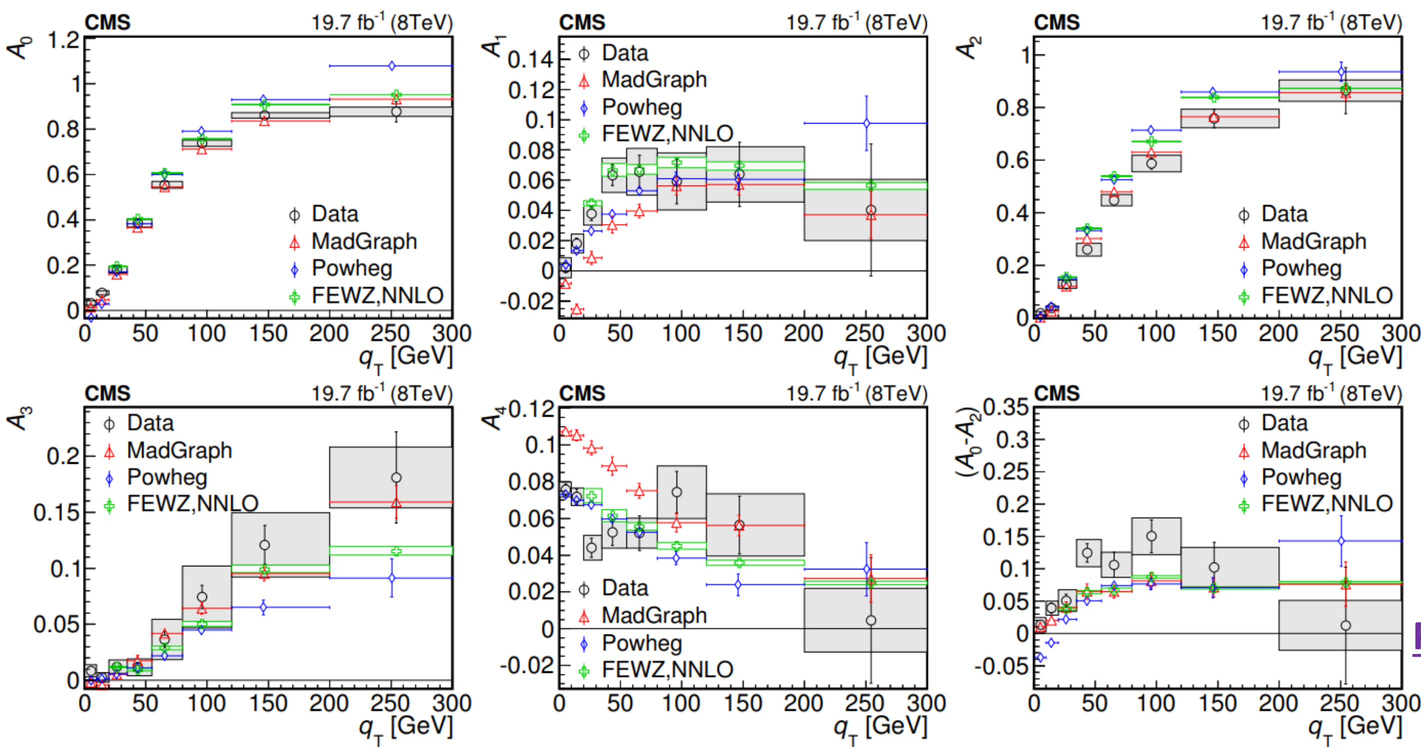


PLB 750 (2015) 154

- A_i increasing with p_T enlargement (except A_4)
- $A_0 \approx A_2$ as it is predicted
- Lum—Tung violation are presented
- Well described by theory
- But…

A_i Measurement at *8 TeV for* $1 < |Y| < 2.1$

Comparison of the five angular coefficients A_i and $A_0 - A_2$ measured in the Collins– Soper frame in bins of p_T for $1 < |Y| < 2.1$



PLB 750 (2015) 154

- … some deviations between data and MC at high p_T!

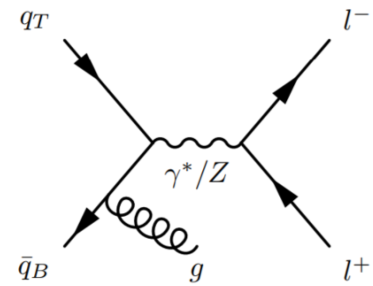
A_i well described by Standard Model but we should get more precise information about NLO (NNLO) effects at high p_T!

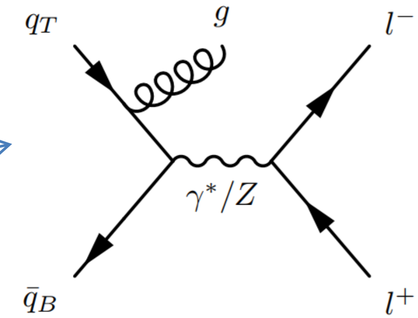
Angular Coefficients Values

- At LO only A_4 is non-zero
- $A_0 = A_2$ at LO QCD (Lum-Tung relation) but it is violated at higher orders

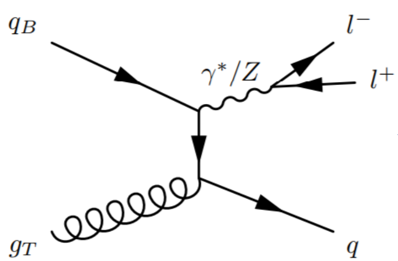
Lum-Tung relation can be violated for non-zero p_T of Z-bosons due to:

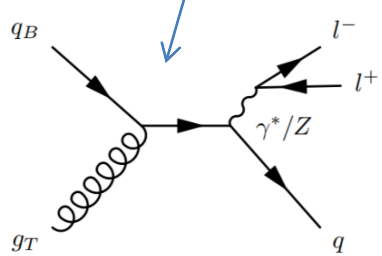
- higher orders and twists
- QCD vacuum structure





$q\bar{q}$ annihilation





qg scattering

$A_0 - A_2$ related to the Z-boson polarisation
$A_3 - A_6$ sensetive V-A structure of the couplings in parity violation terms

- A_i is dependent on PDF
- A_4 related to the forward-backward asymmetry.
- A_5 - A_7 are expected to become non-zero only NNLO, but are small for NLO processes, usually taken to be zero.

Datasets for Data

Experimental data at $\sqrt{s}$ = *13 TeV*. Results for 2016 data ($\sim 37.2\ fb^{-1}$) are presented. Work with the full Run-2 statistic is ongoing

Year	Dataset
2016	/SingleMuon/Run2016B-05Feb2018_ver2-v1/MINIAOD /SingleMuon/Run2016C-05Feb2018-v1/NANOAOD /SingleMuon/Run2016D-05Feb2018-v1/NANOAOD /SingleMuon/Run2016E-05Feb2018-v1/NANOAOD /SingleMuon/Run2016F-05Feb2018-v1/NANOAOD /SingleMuon/Run2016G-05Feb2018-v1/NANOAOD /SingleMuon/Run2016H-05Feb2018_ver2-v1/NANOAOD /SingleMuon/Run2016H-05Feb2018_ver3-v1/NANOAOD
2017	/SingleMuon/Run2017B-31Mar2018-v1/NANOAOD /SingleMuon/Run2017C-31Mar2018-v1/NANOAOD /SingleMuon/Run2017D-31Mar2018-v1/NANOAOD /SingleMuon/Run2017E-31Mar2018-v1/NANOAOD /SingleMuon/Run2017F-31Mar2018-v1/NANOAOD /SingleMuon/Run2017H-31Mar2018-v1/NANOAOD
2018	/SingleMuon/Run2018A-14Sep2018_ver3-v1/NANOAOD /SingleMuon/Run2018B-14Sep2018_ver2-v1/NANOAOD /SingleMuon/Run2018C-14Sep2018_ver1-v1/NANOAOD /SingleMuon/Run2018D-14Sep2018_ver2-v1/NANOAOD

Year	Dataset
2016	/DYJetsToLL_M-50....to Inf_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/RunIISummer16NanoAOD-PUMoriond17_05Feb2018_94X_mcRun2_asymptotic_v2_ext2-v1/NANOAODSIM

Events Selection conditions:

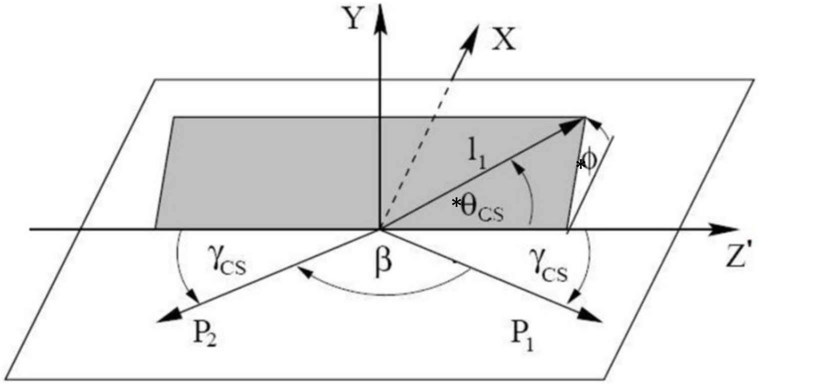
- $p_T^{\mu} > 20\ GeV, |\eta| < 2.4$
- Tight Muon Selection
- Isolation: RelIso < 0.15, R=0.4
- HLT_IsoTkMu24 || HLT_IsoMu24

Binning

- Z region
  - $p_T = 0, 10, 20, 35, 55, 80, 120, 200, 400, inf.$
  - $|Y| = 0, 1, 2.4$
  - $M = 81 - 101$
- 50toInf
  - $p_T = 0, 10, 20, 40, 600.$
  - $|Y|$ =0, 0.35, 0.9, 1.35, 2.4
  - $M = 50, 81, 101, inf$

Angular Coefficients

The Collins-Soper coordinate system is chosen in such a way that the Z-axis bisects the angle between the interacting quarks



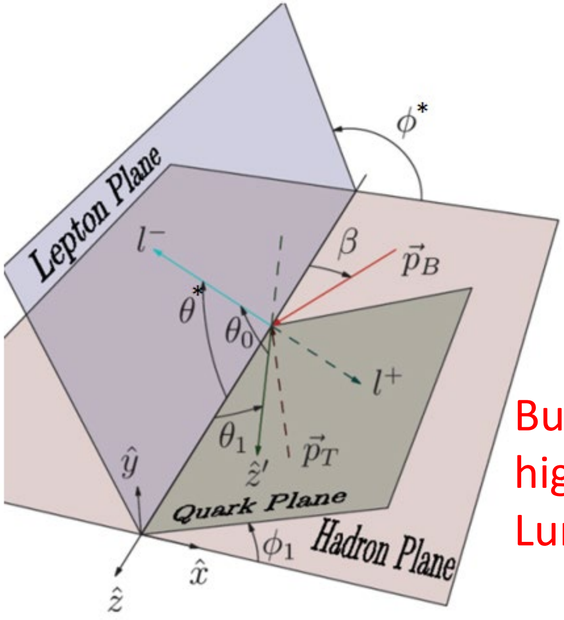
$$\cos\theta^* = \frac{p_z^{(\ell^+\ell^-)}}{|p_z^{(\ell^+\ell^-)}|}\frac{2}{m(Z/\gamma^*)\sqrt{m(Z/\gamma^*)^2 + p_T(Z/\gamma^*)^2}}(P_1^+P_2^- - P_1^-P_2^+)$$

$$P_i^{\pm} = \frac{1}{\sqrt{2}}(E_i \pm p_{z,i}),$$

$$\tan\varphi^* = \frac{\sqrt{M_{l^+l^-}^2 + (p_T^{l^+l^-})^2}}{M_{l^+l^-}} \cdot \frac{\overrightarrow{\Delta_r}\cdot\widehat{R_T}}{\overrightarrow{\Delta_r}\cdot\hat{h}}$$

Where $M_{l^+l^-}$ is the dilepton invariant mass, $\overrightarrow{\Delta_r} = l^- - l^+$, where $l^-$and $l^+$are the respective four-momenta of the particle (electron, muon) and antiparticle (positron, antimuon), $\hat{h}$ is a transverse unit vector in the direction of $p_T^{l^+l^-}$ and $\widehat{R_T}$ is a transverse unit vector in the direction $\overrightarrow{P_A} \times \vec{Q}$, $\overrightarrow{P_A}$ is a vector pointing along the negative z-axis, $\overrightarrow{P_A}$ = (0, 0, −1), and $\vec{Q}$ is the four-momentum of the dilepton pair.

Lum-Tung relation ($A_0 = A_2$) is satisfied when $\varphi_1 = 0$!



But $\varphi_1 \neq 0$ at NLO and higher!
Lum-Tung violated

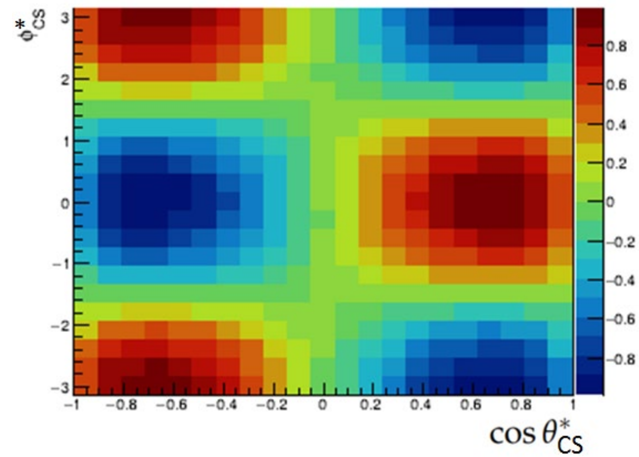
Template Method

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



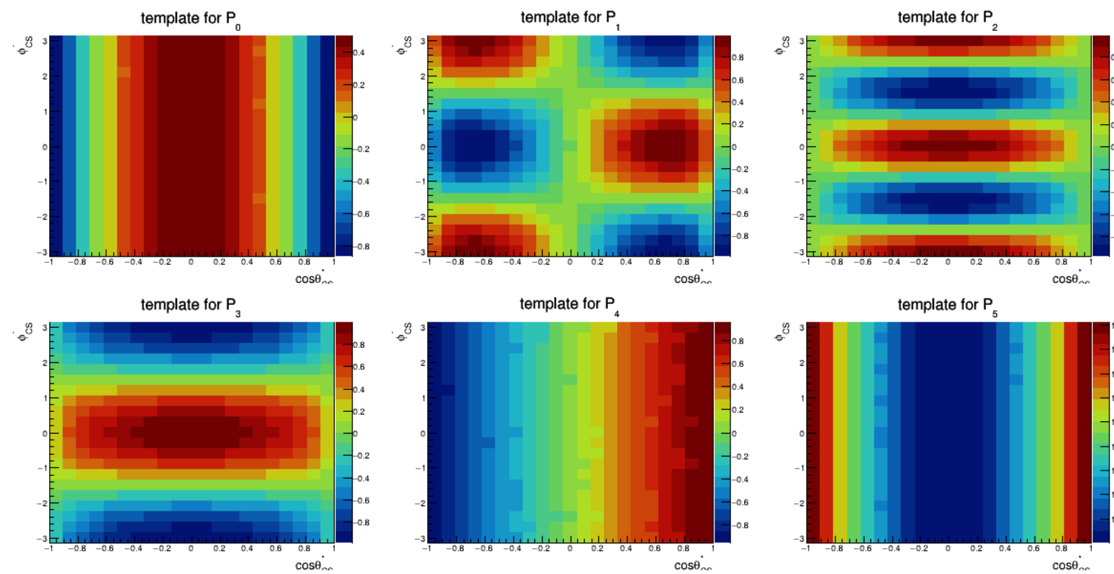
- Angular coefficients can be directly obtained by minimizing the objective function:

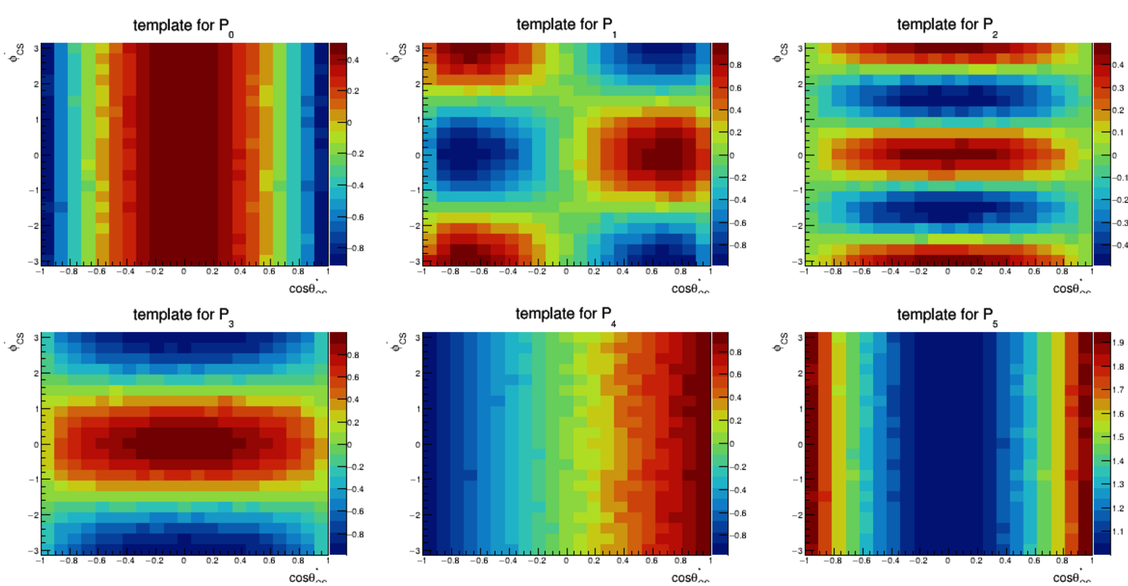
$$\chi^2 = \frac{\left(\mathrm{data}^{j,k} - \left(\sum_{i=0}^{5} P_i H_i^{j,k} + H_{Bkg}^{j,k}\right)\right)^2}{\mathrm{data}^{j,k}}$$

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





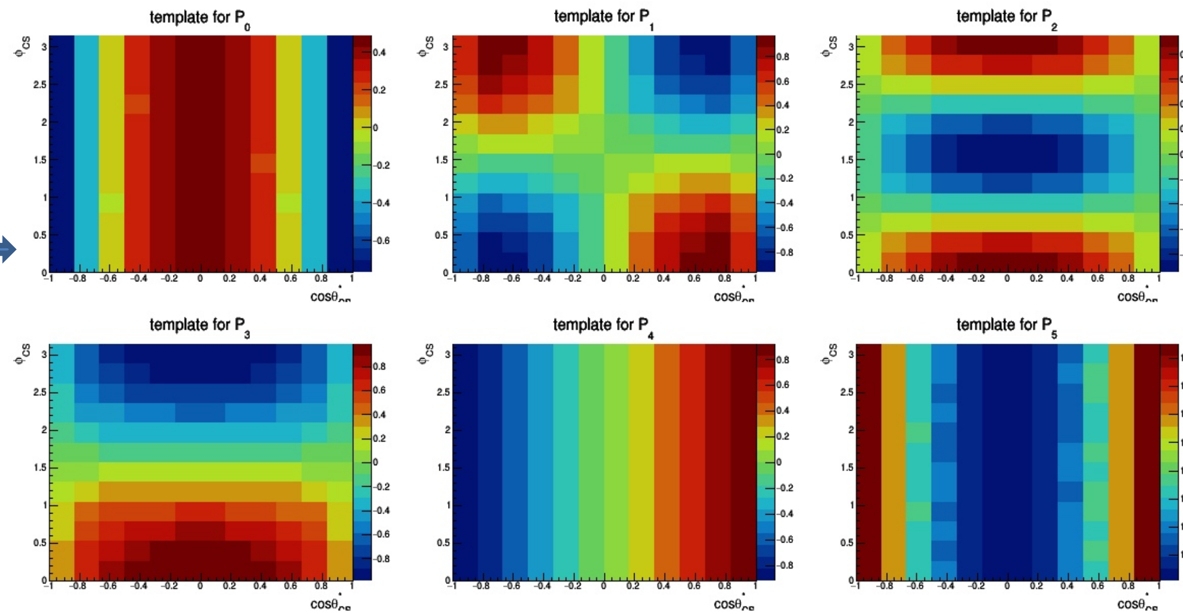
Templates for the six fit parameters P_0-P_5 on generator level obtained for the first bin of p_T (200-400 GeV) bin for the rapidity bin 1 < |Y| < 2.4.

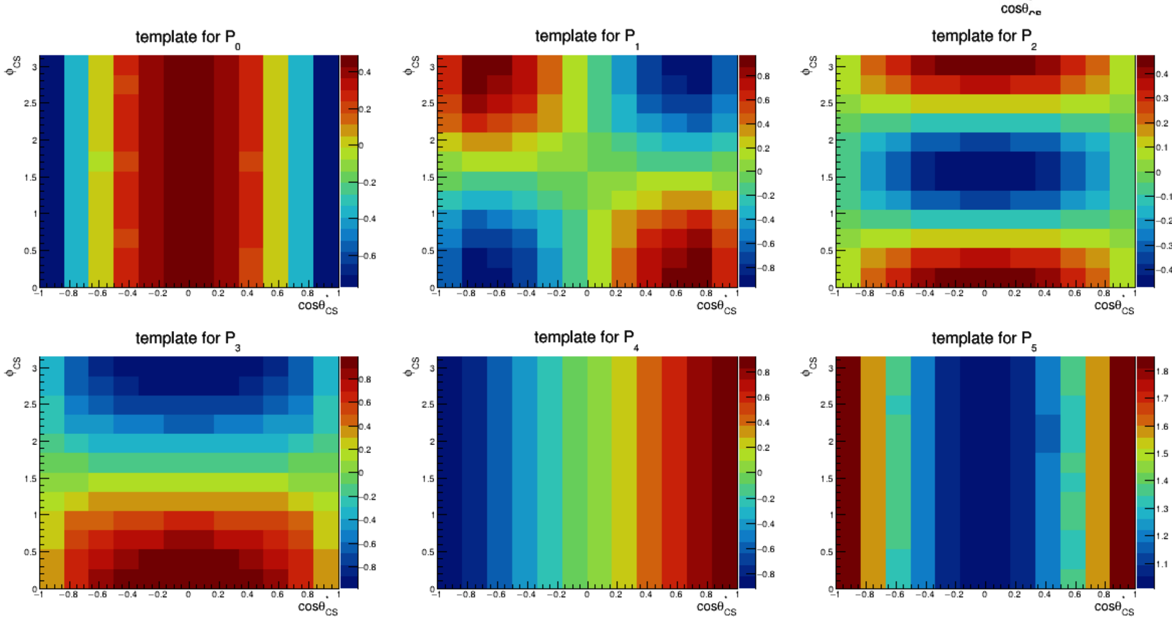
Шаблоны получены в восьми бинах p_T и двух бинах быстроты!

Templates at *13 TeV (Generator Level)*

(MADGRAPH+PYTHIA8, CUETP8M1)

Templates for the six fit parameters P_0-P_5 on generator level obtained for the first bin of p_T (0-10 GeV) bin for the rapidity bin 1 < |Y| < 2.4.





Templates for the six fit parameters P_0-P_5 on generator level at $\sqrt{s}$ = 13 TeV for the same p_T bin and |Y| < 1.

Templates obtained for eight p_T and two rapidity bins!