Brief introduction about polarized DY analysis in COMPASS at CERN

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  - Depolarization factor
  - Asymmetry extraction
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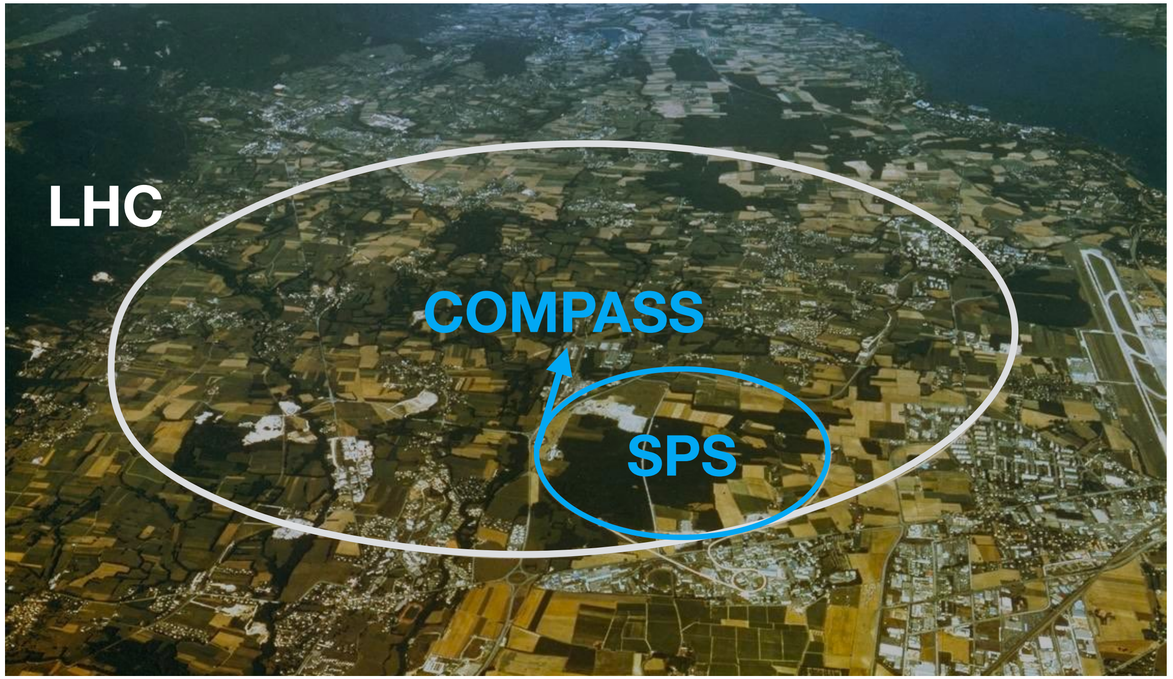
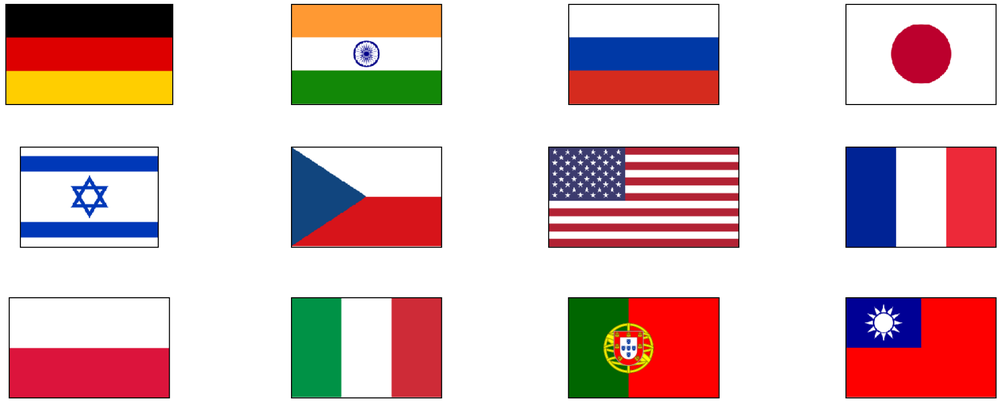
About COMPASS



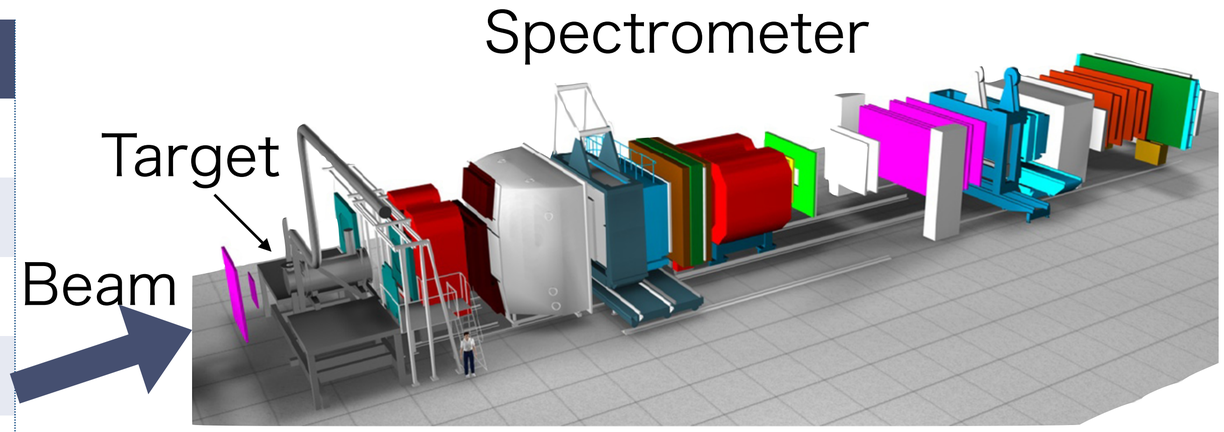
COmmon**M**uon**P**roton**A**pparatus for **S**tructure and **S**pectroscopy

- More than 200 physicists + students
- Hadron structure and spectroscopy
- The first physics data taking in 2002
- The last data taking in 2021



History

Year	Physics	Beam (GeV/c)	Target
02 - 04	SIDIS	$\mu^{\pm}$, 160	^{6}LiD, long. &
06	SIDIS	$\mu^{\pm}$, 160	^{6}LiD, long.
07	SIDIS	$\mu^{\pm}$, 160	NH_3, long. &
08 - 09	Hadron Spectroscopy		
10	SIDIS	μ^{+}, 160	NH_3, trans.
11	SIDIS	μ^{+}, 200	NH_3, long.
12	DVCS pilot run	$\mu^{\pm}$, 160	Liq. H_2
14	DY pilot run	π^{-}, 190	NH_3
15	**DY**	**π^{-}, 190**	**NH_3, trans.**
16 - 17	DVCS	$\mu^{\pm}$, 160	Liq. H_2
18	DY	π^{-}, 190	NH_3, trans.
19-20	Shutdown		
21	SIDIS	$\mu^{\pm}$, 160	^{6}LiD, trans.



Typical setup

Beam : Polarized μ, hadron

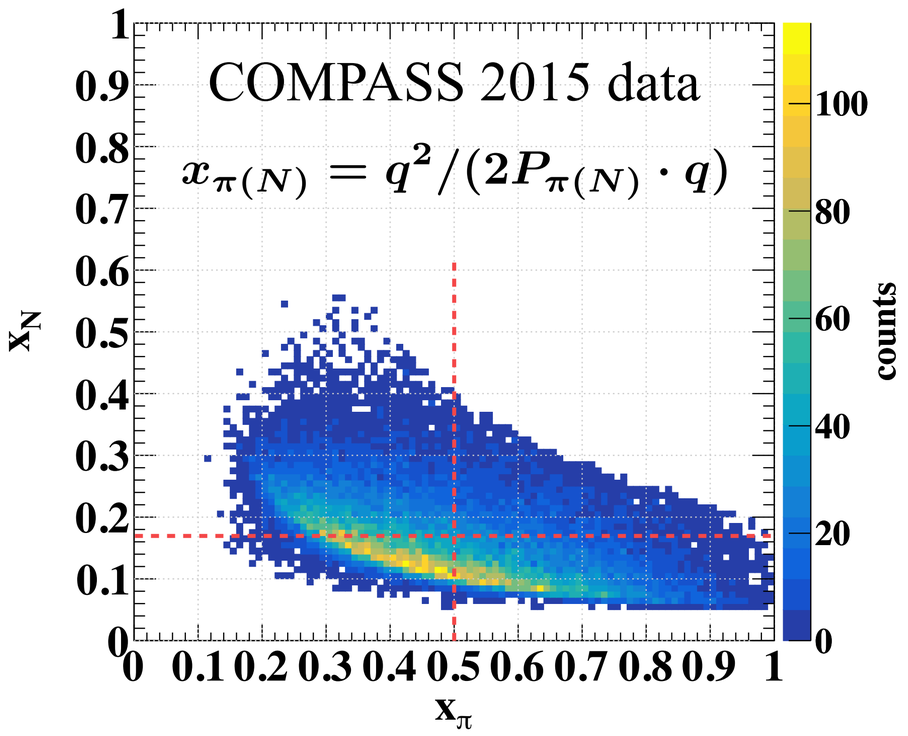
Target : Polarized p or d, Liq. H_2, Ni, Pb, W, ⋯

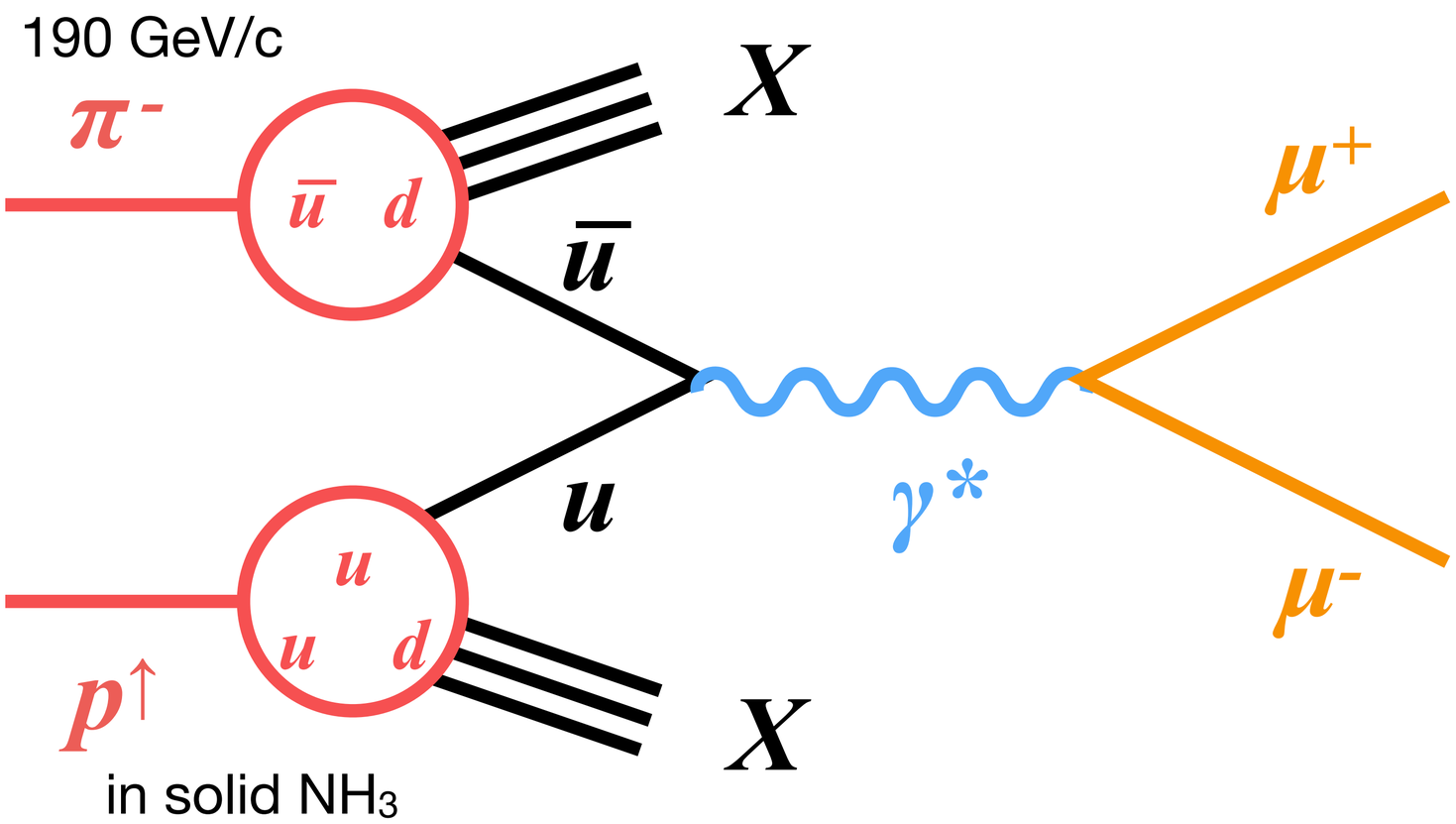
Spectrometer

- About 350 tracking planes
- ECAL & HCAL
- RICH
- μ wall

Polarized DY experiment at COMPASS

$$\langle x_\pi \rangle \sim 0.5$$
$$\langle x_N \rangle \sim 0.17$$





Dominant acceptance of COMPASS spectrometer is valence regions
→ DY by u(p) ū(π⁻) is dominant.

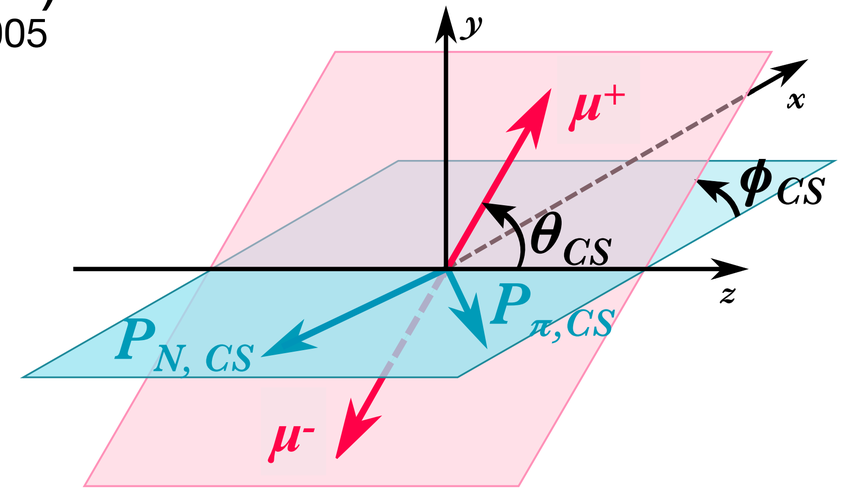
Asymmetries

In the case of unpol. beam and trans. pol. target (twist-2):

PRD79(2009)034005

$$\frac{d\sigma}{dq^4 d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U \times$$

$$\left[\left(1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS}\right) + |S_T| \left\{ A_T^{\sin\phi_S} \sin\phi_S + D_{[\sin^2\theta]} \left(A_T^{\sin(2\phi_{CS}+\phi_S)} \sin(2\phi_{CS}+\phi_S) + A_T^{\sin(2\phi_{CS}-\phi_S)} \sin(2\phi_{CS}-\phi_S) \right) \right\} \right]$$



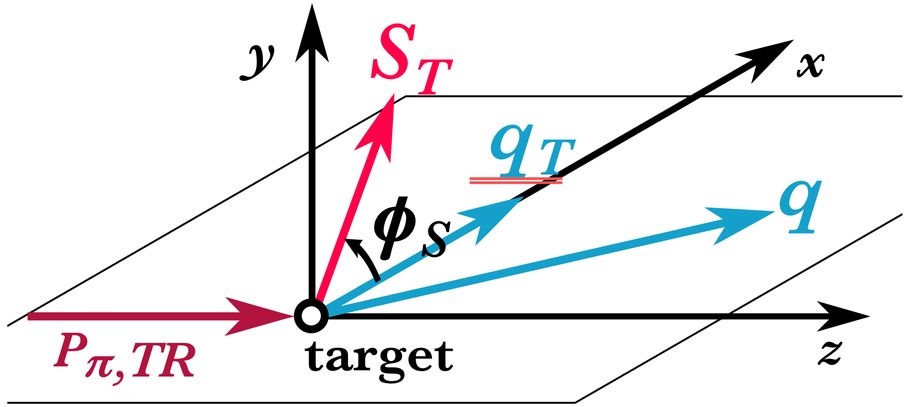
Collins-Soper frame

$$A_{U,T}^{W(\phi_{CS},\phi_S)} = \frac{F_{U,T}^{W(\phi_{CS},\phi_S)}}{F_U^1 + F_U^2}$$: Asymmetry

$F_{U,T}^{W(\phi_{CS},\phi_S)}$: Structure function

$F = 4\sqrt{(P_\pi \cdot P_N)^2 - M_\pi^2 M_N^2}$: Hadron flux

$\hat{\sigma}_U = (F_U^1 + F_U^2)(1 + A_U^1 \cos^2\theta_{CS})$: survives after integration over ϕ_{CS}



Target rest frame

Asymmetries

In the case of unpol. beam and trans. pol. target (twist-2):

PRD79(2009)034005

$$\frac{d\sigma}{dq^4 d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U \times$$

$$\left[\left(1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS}\right) + |S_T| \left\{ A_T^{\sin\phi_S} \sin\phi_S + D_{[\sin^2\theta]} \left(A_T^{\sin(2\phi_{CS}+\phi_S)} \sin(2\phi_{CS}+\phi_S) + A_T^{\sin(2\phi_{CS}-\phi_S)} \sin(2\phi_{CS}-\phi_S) \right) \right\} \right]$$

BM($\bar{u}$ in π) × BM(u in N)

f_1($\bar{u}$ in π) × Sivers(u in N)

BM($\bar{u}$ in π) × Pretzelosity(u in N)

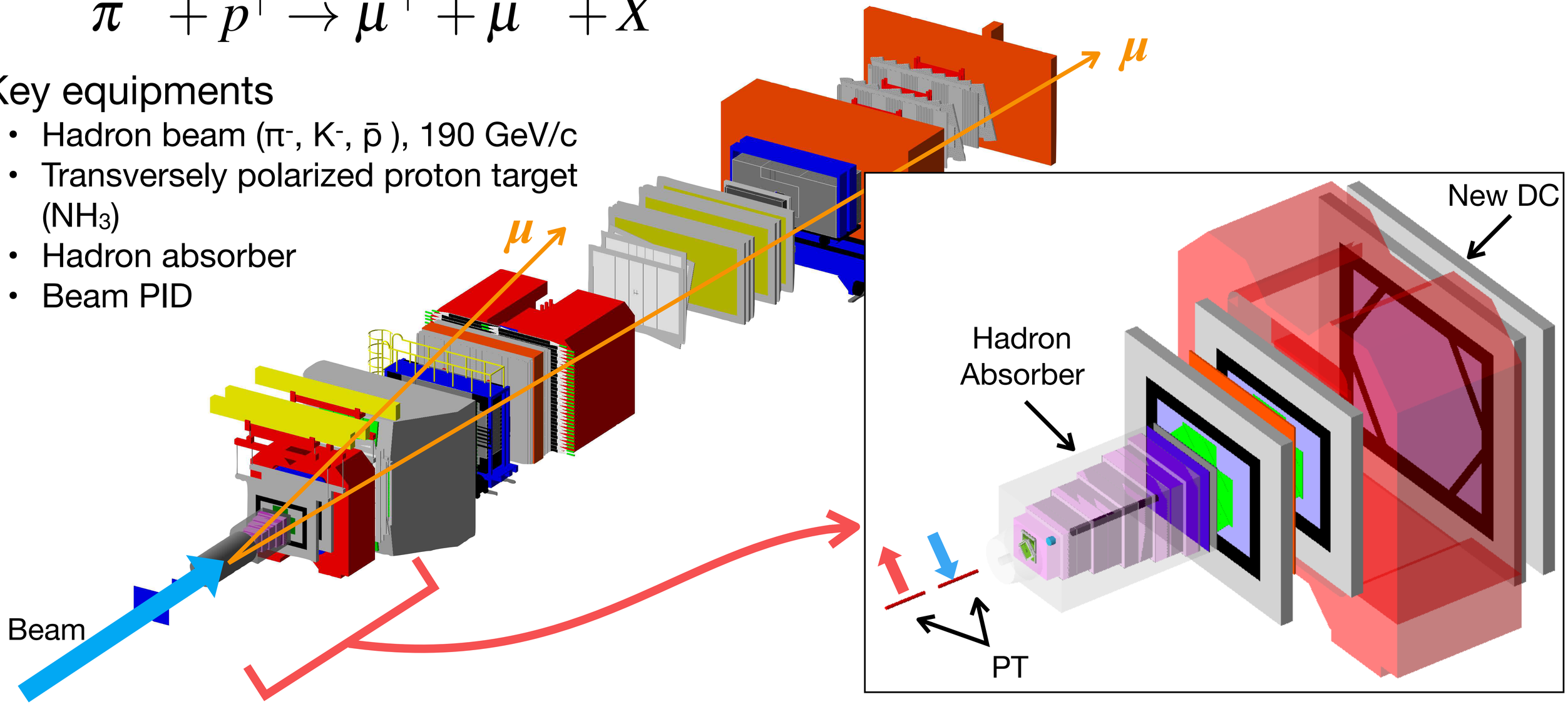
BM($\bar{u}$ in π) × Transversity(u in N)

Setup

$$\pi^- + p^\uparrow \rightarrow \mu^+ + \mu^- + X$$

Key equipments

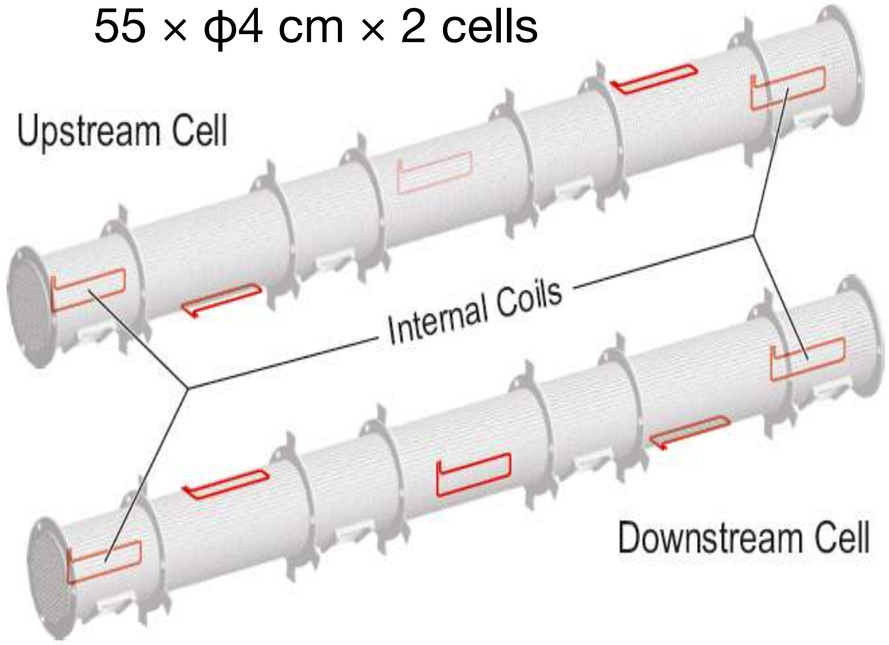
- Hadron beam (π^-, K^-, $\bar{p}$), 190 GeV/c
- Transversely polarized proton target (NH_3)
- Hadron absorber
- Beam PID



Around PT

PT (NH_3)：

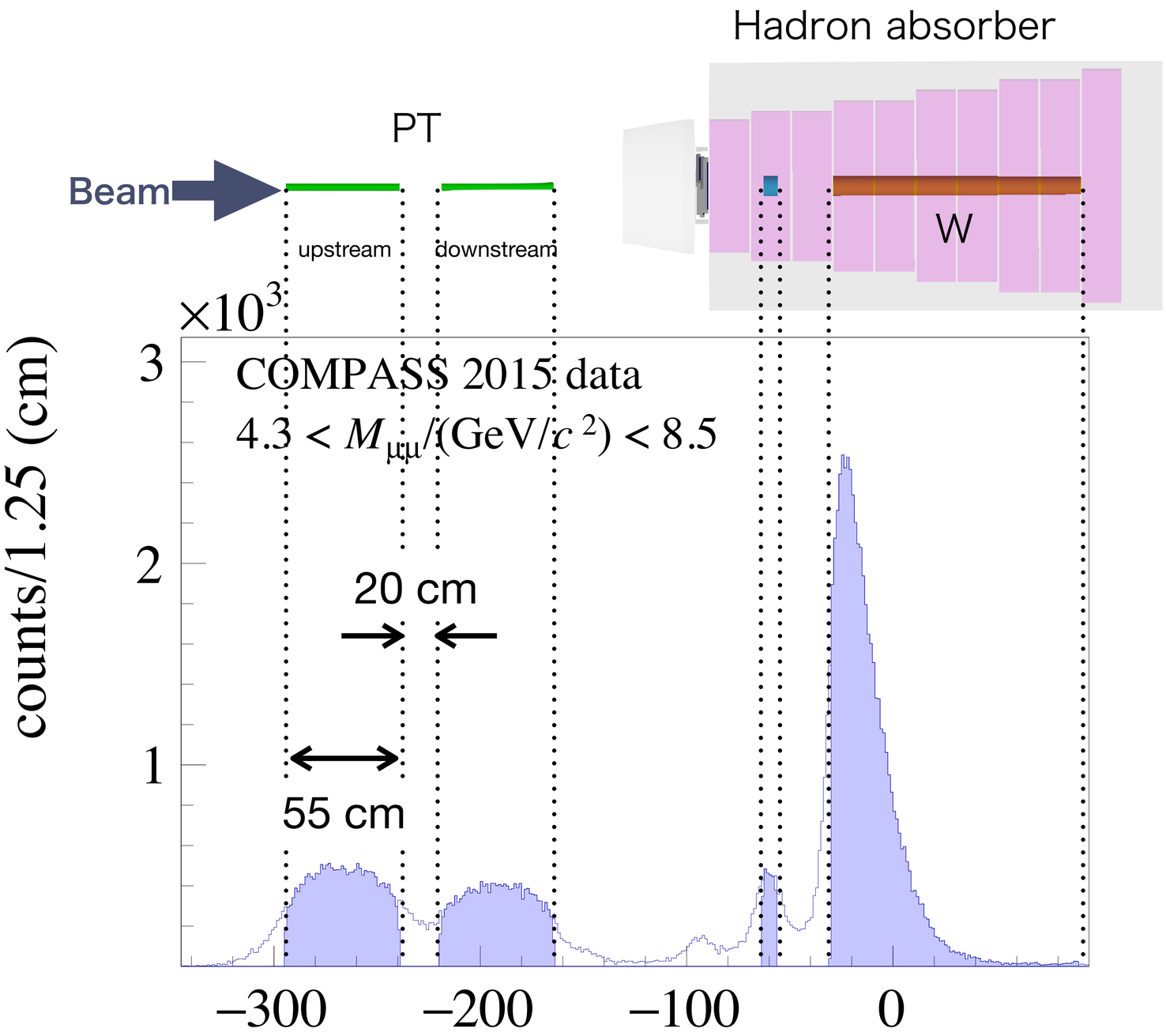
55 × ϕ4 cm × 2 cells

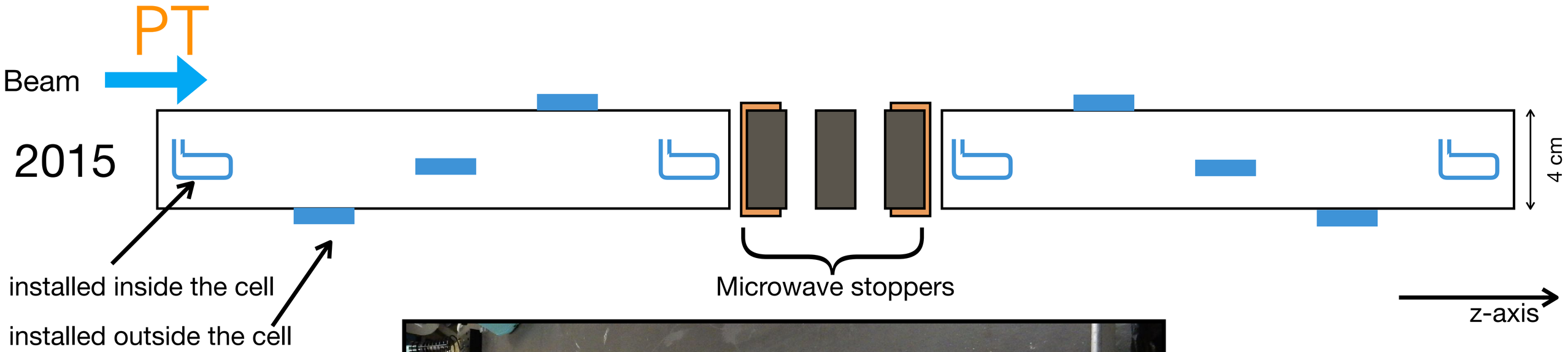


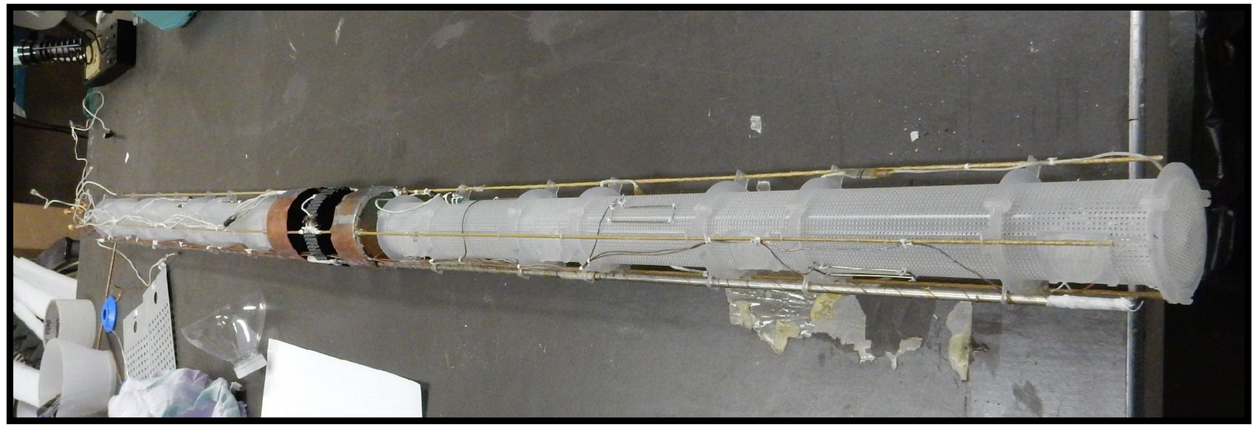
Al target：7 × ϕ 9.4 cm

Tungsten beam dump (W)：

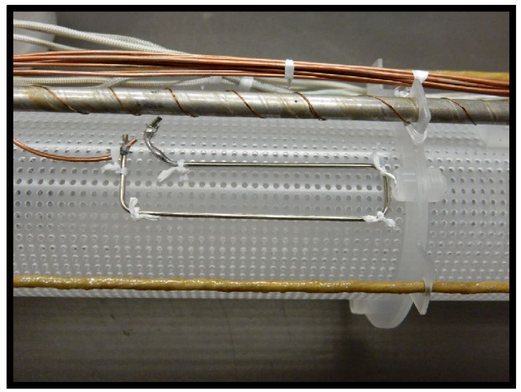
120 ×ϕ9 cm

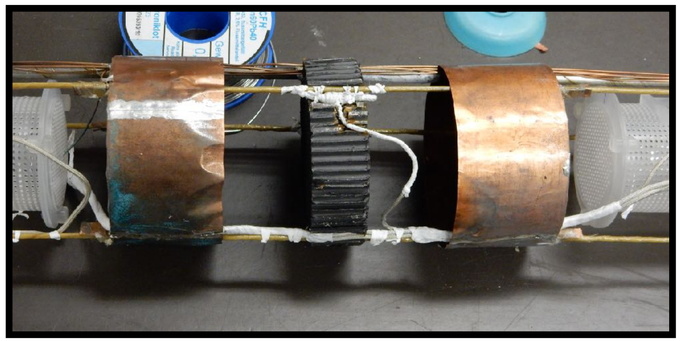






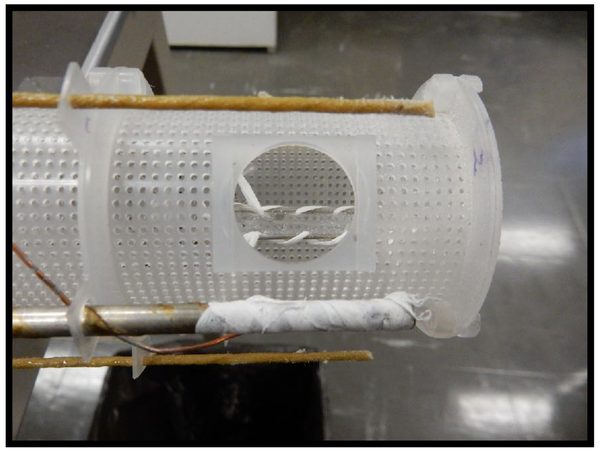
Outer Coil



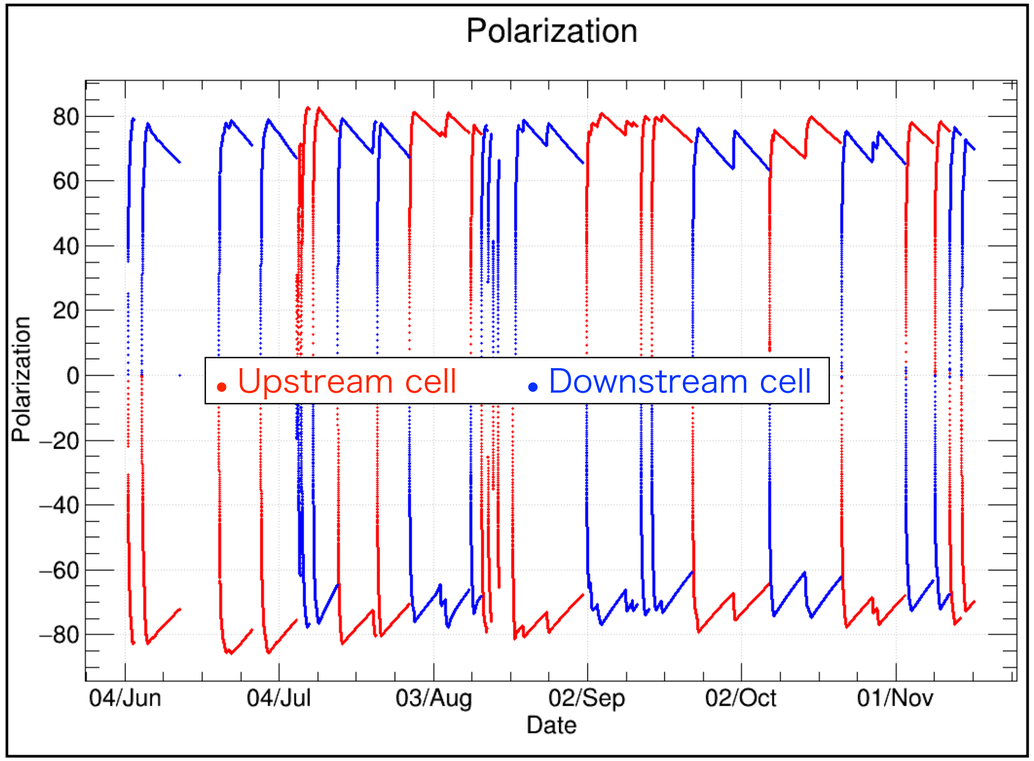


Microwave Stopper

Inner Coil

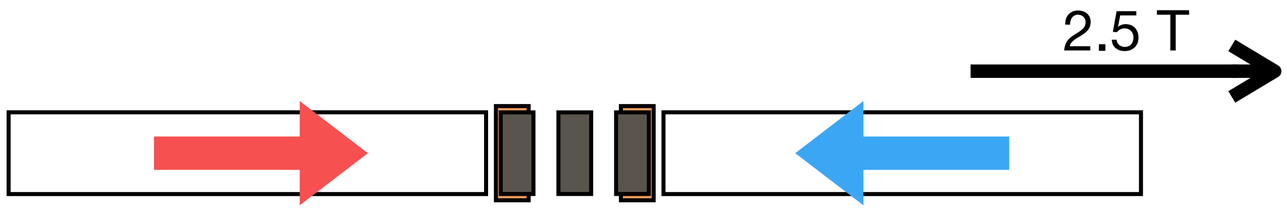


PT, Polarization

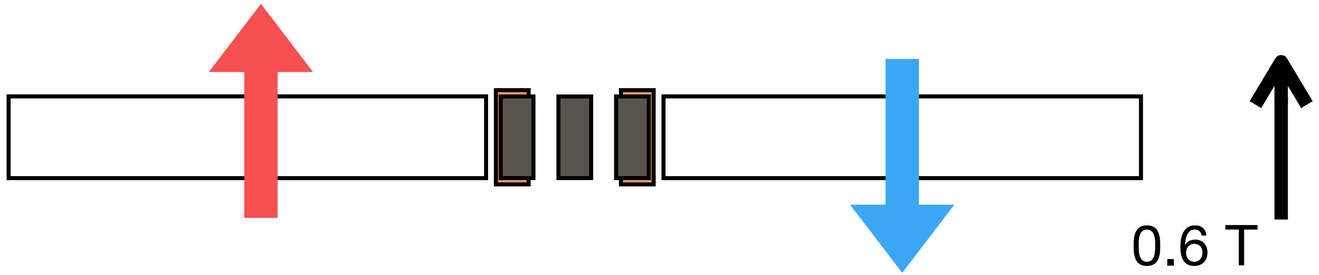


	Max		Average	
	Positive	Negative	Positive	Negative
Upstream	0.83	-0.86	0.74	-0.71
Downstream	0.79	-0.78	0.69	-0.67

- One cell is polarized to positive direction and the other one to negative direction at the same time under the 2.5 T solenoid magnetic field longitudinally.



- Polarization is rotated to transverse direction using the solenoid & dipole magnets.
- Polarization is kept under the 0.6 T dipole magnetic field, and physics data taking begins.



PT, Dilution factor

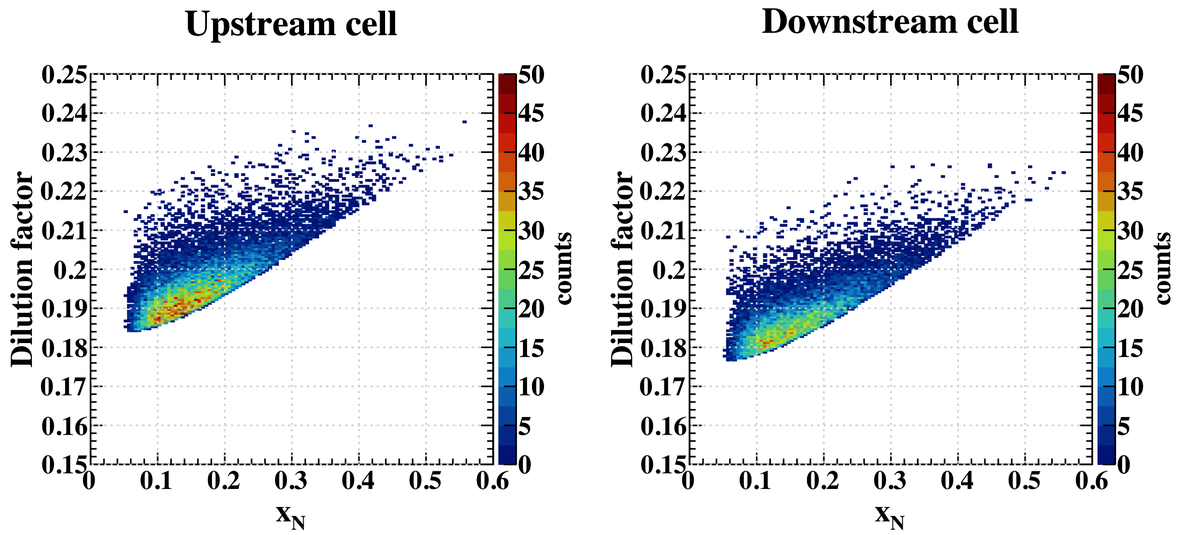
- Target material consists of polarizable particle (target) and unpolarizable particle.
- Naive case for NH_3:
  - N: p×7 + n×7, unpolarizable
  - H×3 : p, polarizable

$$f \equiv \frac{N_{p,polarizable}}{N_p + N_n} = \frac{p \times 3}{p \times (7+3) + n \times 7} = \frac{3}{17}$$

In COMPASS, the difference of proton's and neutron's cross section is taken into account:

$$f \equiv \frac{N_{p,polarizable}\ \sigma_{\pi p}^{DY}}{N_p \sigma_{\pi p}^{DY} + N_n \sigma_{\pi n}^{DY}}$$

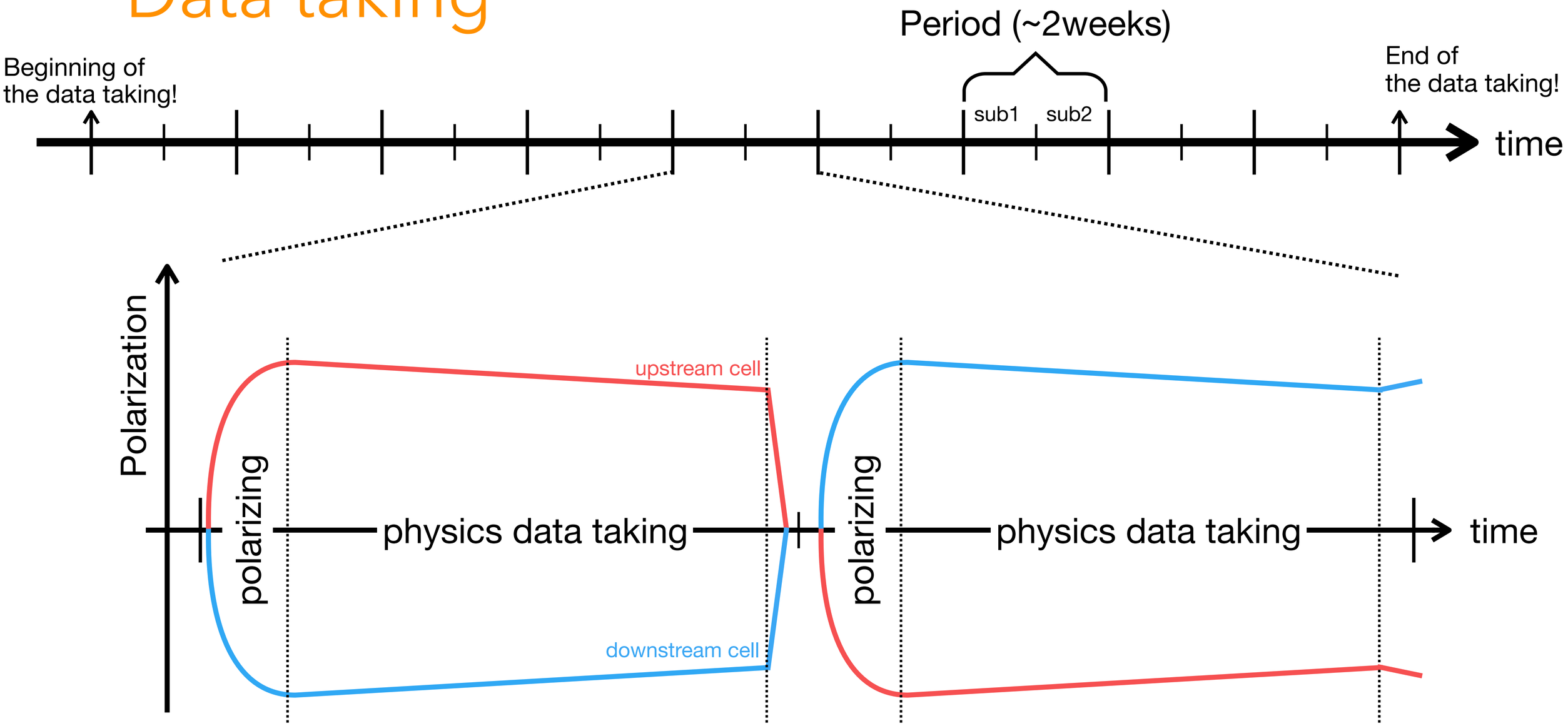
σ_{DY} is estimated using a parton-level Monte-Carlo program MCFM, performing calculation up to NNLO. It's provided to physics data analysis event by event.



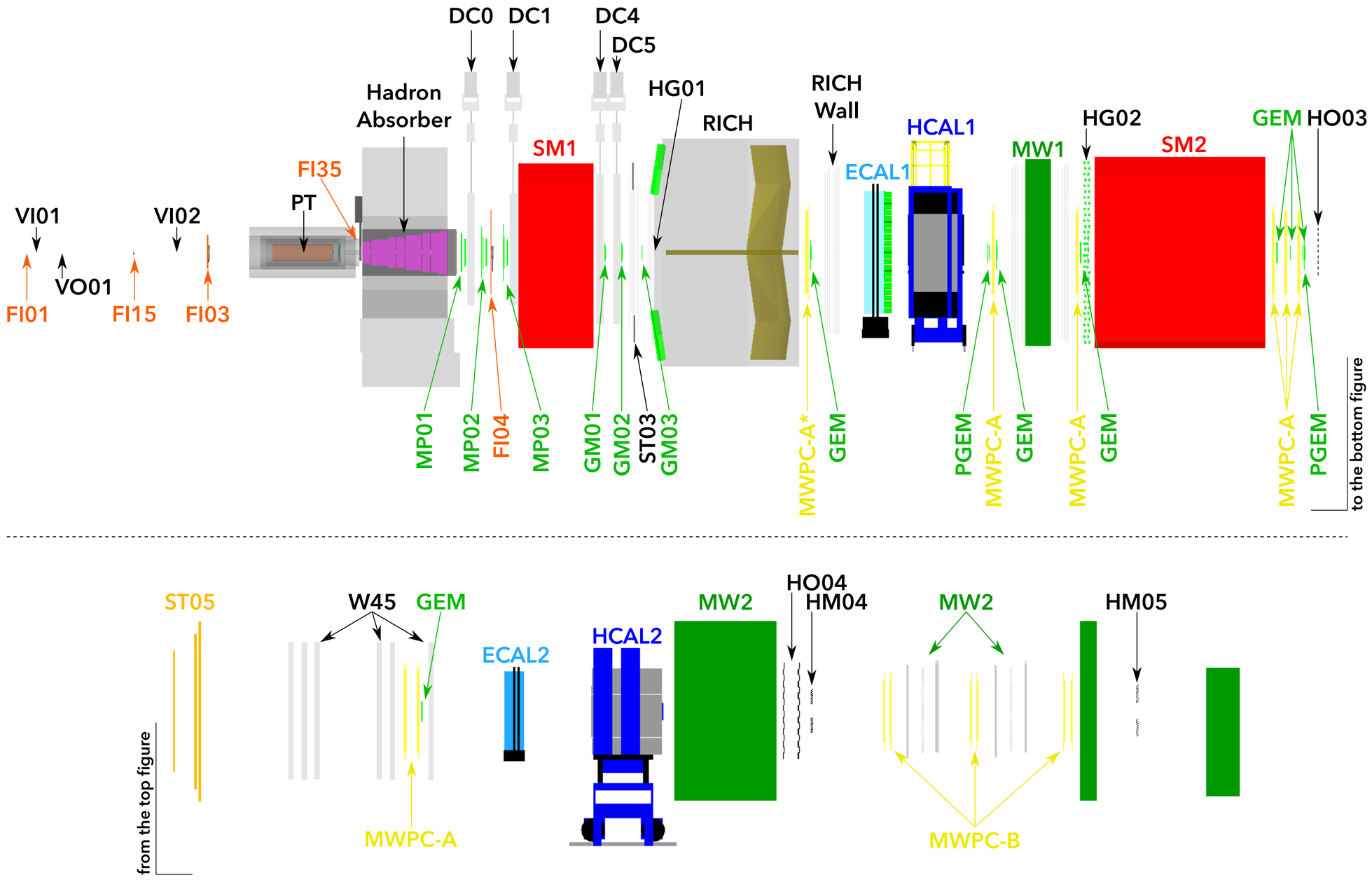
Dilution factor using measured Bjorken-x for each cell.

MCFM: https://doi.org/10.1140/epjc/s10052-016-4558-y

Data taking

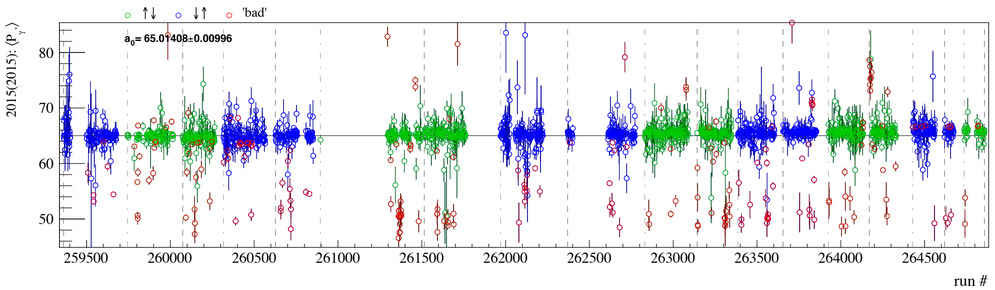


Targets are polarized

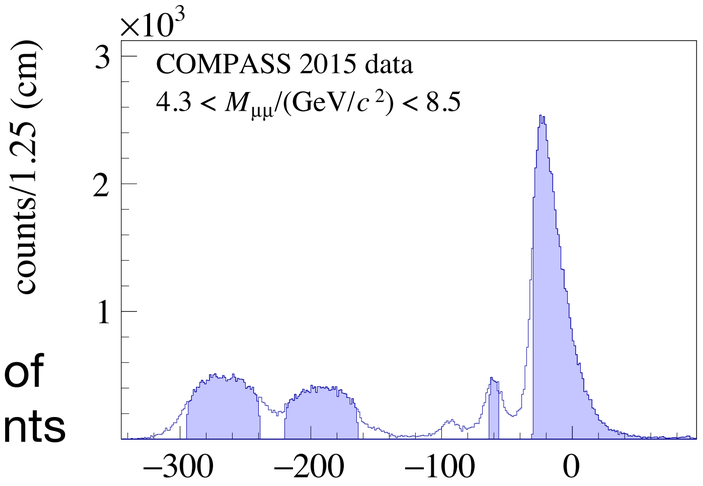

DC0
DC1
DC4
DC5
Hadron Absorber
HG01
RICH
RICH Wall
HCAL1
HG02
GEM
HO03
SM1
MW1
SM2
FI35
ECAL1
PT
VI01
VI02
VO01
FI01
FI15
FI03
MP01
MP02
FI04
MP03
GM01
GM02
ST03
GM03
MWPC-A*
GEM
PGEM
MWPC-A
GEM
MWPC-A
GEM
MWPC-A
PGEM
to the bottom figure
ST05
W45
GEM
ECAL2
HCAL2
MW2
HO04
HM04
MW2
HM05
from the top figure
MWPC-A
MWPC-B

Analysis

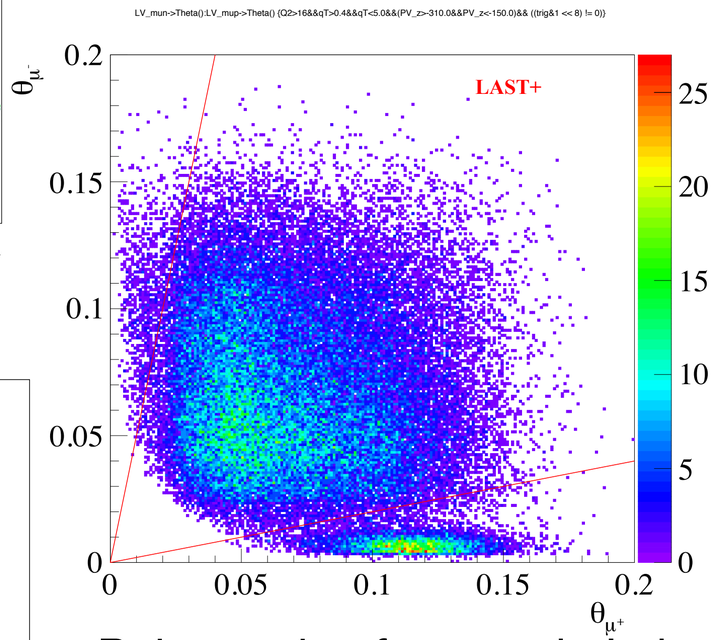
- Pre-step of data analysis (decoding, reconstructions, etc.) is done by a dedicated software using the cluster at CERN (LXPLUS) and UIUC (Bluewaters).
- As a first step of analysis, dimuon events from PT are selected.



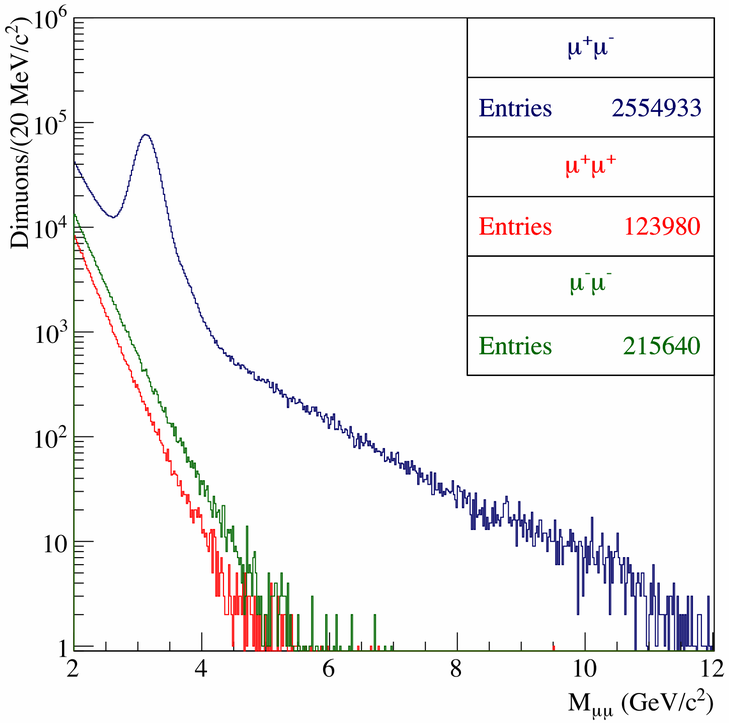
Stability check of data taking.



z-coordinate of interaction points



Polar angle of muons in Lab frame. The small island is from beam-decay muons



Dimuon mass distribution after selection of dimuon events.

Analysis: Monte-Carlo

- Event generation by Pythia8
- Simulation of the passage of generated particles by Geant4
- The same reconstruction program as real data's is used for MC data
- Analysis by the same software as real data

Physics process used in Pythia:

DY

- $f + f \rightarrow \gamma^* \rightarrow \mu^+ \mu^-$

Open Charm

- Production of $c\bar{c}$ pair and dimuon in the final state
- $g + g \rightarrow c + \bar{c}$ and $q + \bar{q} \rightarrow c + \bar{c}$
- only $c + \bar{c} \rightarrow \mu^+ \mu^-$ is used.

J/ψ, ψ'

- $g + g \rightarrow c\bar{c}[3S1(1)] + g$, etc.
- only $J/\psi(\psi') \rightarrow \mu^+ \mu^-$ is used.

Combinatorial Background

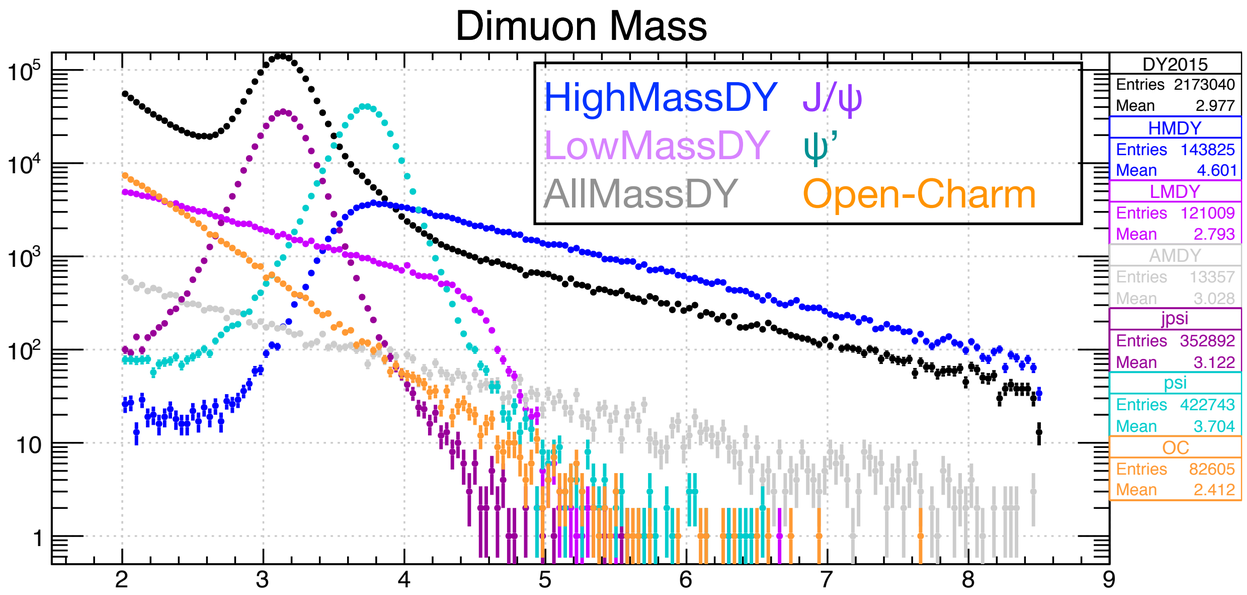
- Forming dimuon from uncorrelated μ^+ and μ^-
- Estimated from real data

Analysis: Monte-Carlo

How to reproduce real data

Some processes are needed to reproduce real data by MC data for long range of $M_{\mu\mu}$

1. MC is done process by process
   - LowMassDY (1.5-3.5 GeV)
   - HighMassDY (3.5-9 GeV)
   - AllMassDY (1.5-9 GeV)
   - J/ψ
   - ψ'
   - Open-charm



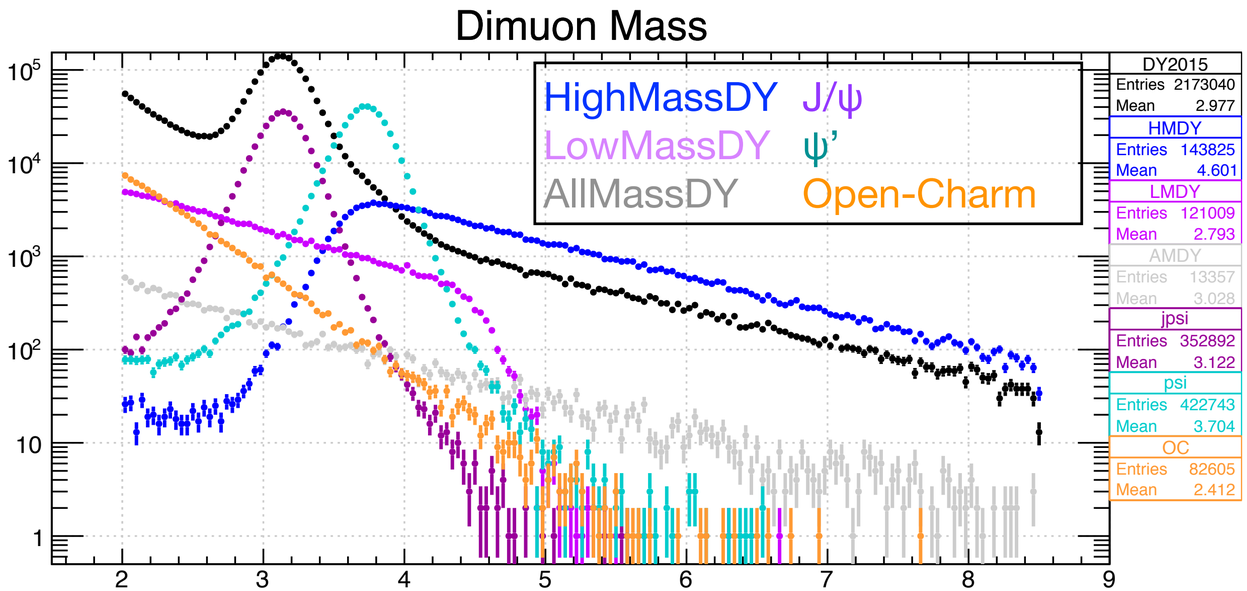
Dimuon mass distribution from real and MC data.
MC data need to be scaled to reproduce read data.

Analysis: Monte-Carlo

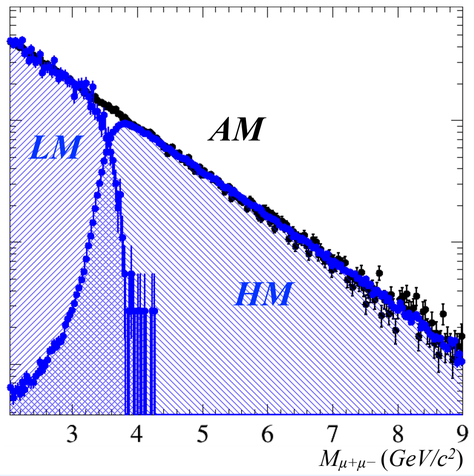
How to reproduce real data

Some processes are needed to reproduce real data by MC data for long range of $M_{\mu\mu}$

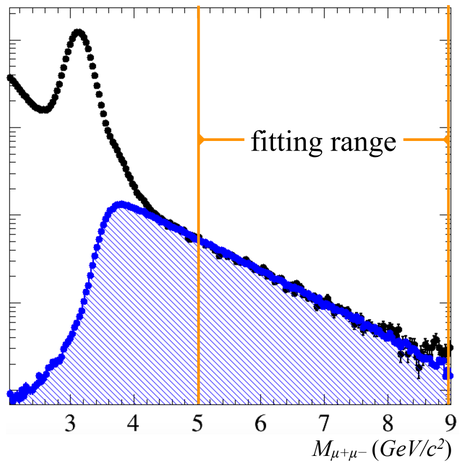
1. MC is done process by process
   - LowMassDY (1.5-3.5 GeV)
   - HighMassDY (3.5-9 GeV)
   - AllMassDY (1.5-9 GeV)
   - J/ψ
   - ψ'
   - Open-charm
2. Scaling of DY simulations
   1. Fitting to AMDY by LMDAY and HMDY
   2. Fitting to real data in 5- 9 GeV by HMDY



Dimuon mass distribution from real and MC data.
MC data need to be scaled to reproduce read data.



Example of 2.1



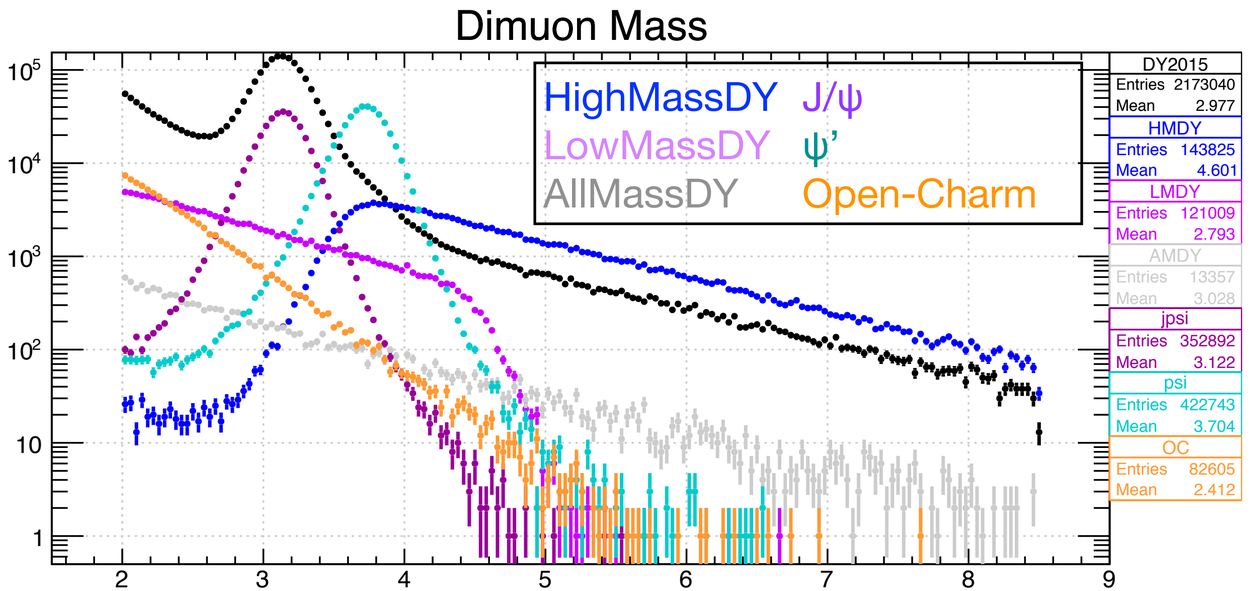
Example of 2.2

Analysis: Monte-Carlo

How to reproduce real data

Some processes are needed to reproduce real data by MC data for long range of $M_{\mu\mu}$

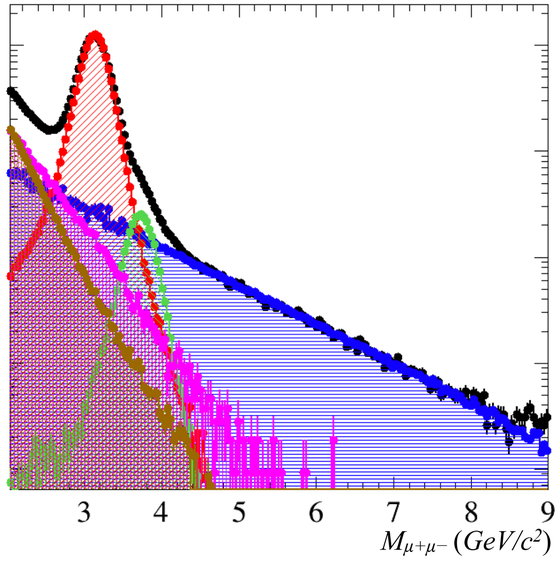
1. MC is done process by process
   - LowMassDY (1.5-3.5 GeV)
   - HighMassDY (3.5-9 GeV)
   - AllMassDY (1.5-9 GeV)
   - J/ψ
   - ψ'
   - Open-charm
2. Scaling of DY simulations
   1. Fitting to AMDY by LMDAY and HMDY
   2. Fitting to real data in 5- 9 GeV by HMDY
3. Scaling of MC events except DY
   - Fitting to real data by MC data
   - (LMDY + HMDY) is used as a fixed parameter
   - Combinatorial background estimated from real data is also included as a fixed parameter



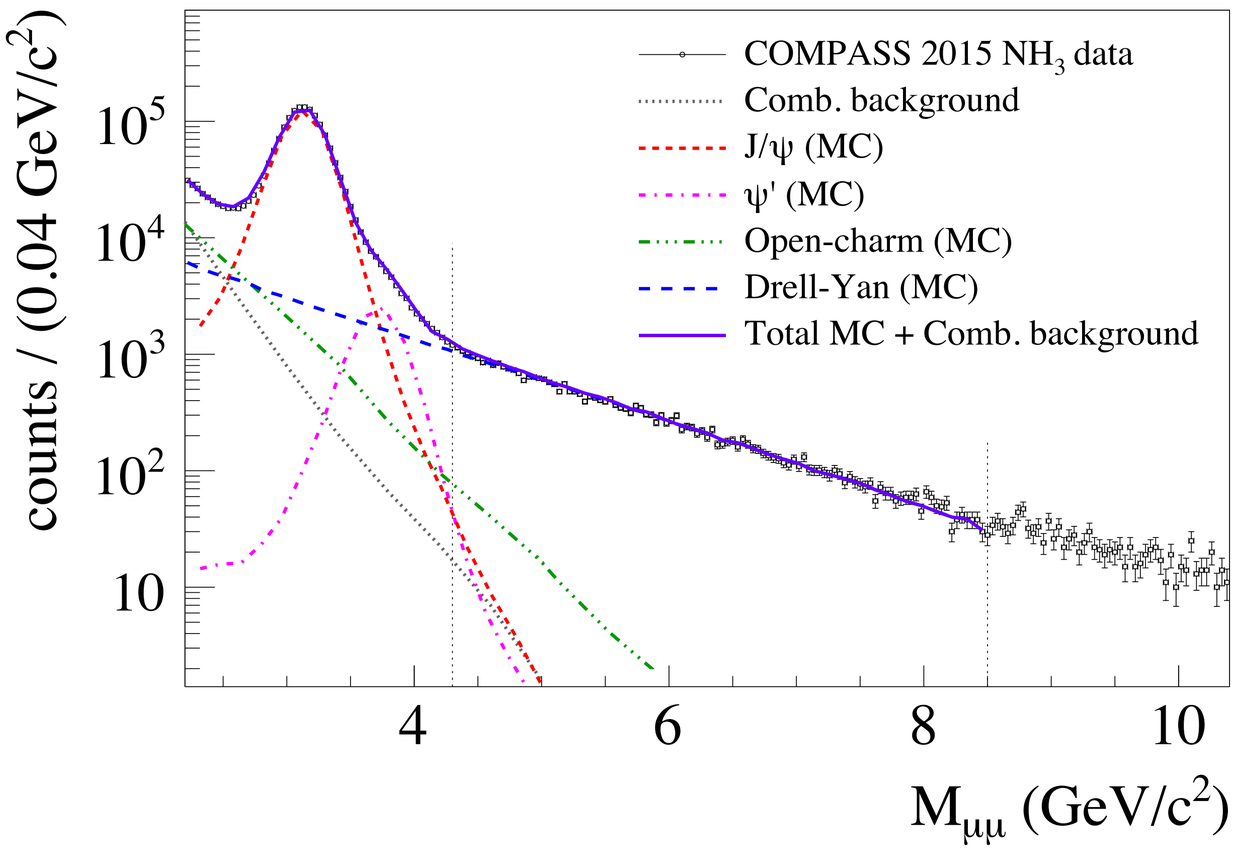
Dimuon mass distribution from real and MC data.
MC data need to be scaled to reproduce read data.

A number of like sign pair N_{++} and N_{--} and combinatorial background N_{CB} are :

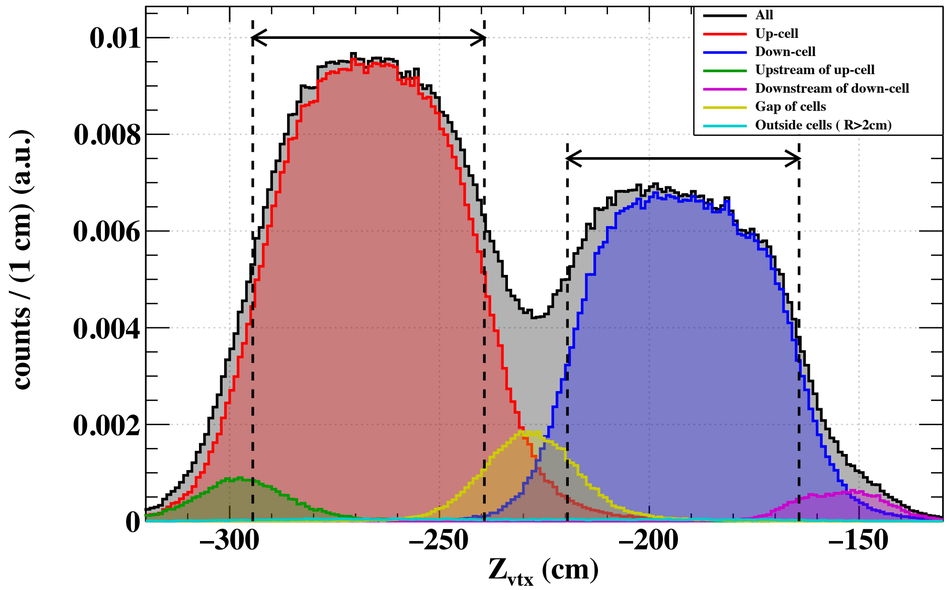
$$N_{CB} = 2\sqrt{N_{++}N_{--}}$$



Analysis: Monte-Carlo



Dimuon mass distribution from real data(black) and MC(blue).
In the range 4.3-8.5 GeV, 96% of events are from DY.



Study of vertex reconstruction by MC.
Contamination from one cell to the other estimated about 2%

Asymmetry extraction

$$\frac{d\sigma}{dq^4 d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U \times$$

$$\left[\begin{array}{l} \left(1 + D_{[\sin^2\theta]} A_U^{\cos 2\phi} \cos 2\phi + D_{[\sin 2\theta]} A_U^{\cos\phi} \cos\phi\right) \\ + |S_T| \left\{ \begin{array}{l} A_T^{\sin\phi_S} \sin\phi_S \\ + D_{[\sin^2\theta]} \left(\begin{array}{l} A_T^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) \\ + A_T^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) \end{array} \right) \\ + D_{[\sin 2\theta]} \left(\begin{array}{l} A_T^{\sin(\phi+\phi_S)} \sin(\phi+\phi_S) \\ + A_T^{\sin(\phi-\phi_S)} \sin(\phi-\phi_S) \end{array} \right) \end{array} \right\} \end{array}\right]$$

- Extended Unbanned Maximum Likelihood (NIMA297(1990)496) with weights of dilution factor and depolarization factor extracts all asymmetries at the same time.
- Asymmetries are extracted from each data taking period. Final results are obtained by averaging over them.
- Averaged polarization over a sub-period is applied.
- Dilution factor and depolarization factor are calculated for each event.

Likelihood estimator:

$$\mathcal{L} = \prod_{cell=1}^{n_{cell}=2} \left[\prod_{pol=1}^{n_{pol}=2} \left\{ \left(e^{-I_{cell}^{pol}} \prod_{n=1}^{N_{cell}^{pol}} P^{pol}(\phi_{CS,n}, \phi_{S,n}; a_{cell}^{pol}, \vec{A}) \right)^{\frac{\bar{N}}{N_{cell}^{pol}}} \right\} \right]$$

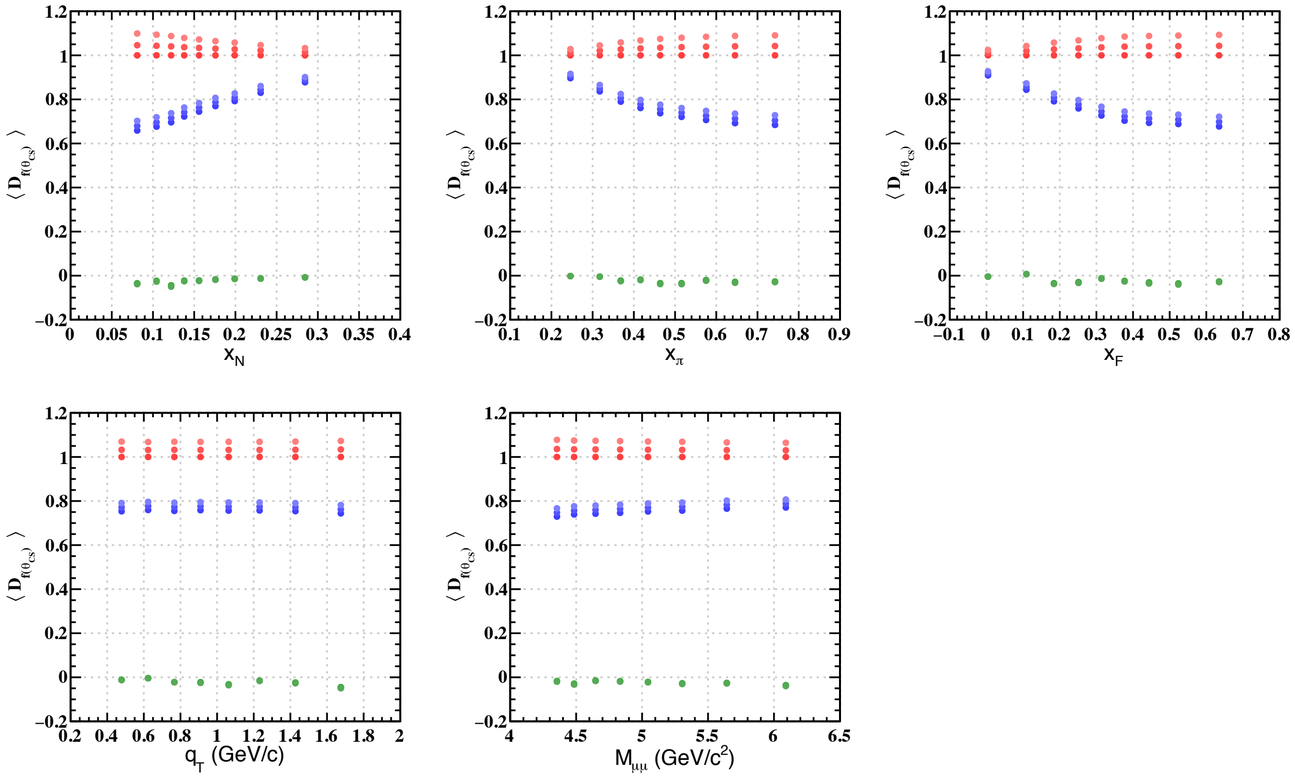
Probability density function: $P^{\pm}(\varphi_{CS}, \varphi_S; a_c^{\pm}, \vec{A}) = a_c^{\pm}(\varphi_{CS}, \varphi_S; \vec{A}) \cdot \sigma^{\pm}(\varphi_{CS}, \varphi_S; \vec{A}),$

Cross-section: $\sigma^{\pm}(\varphi_{CS}, \varphi_S; \vec{A}) = 1 + A_U^{\cos\varphi_{CS}} + A_U^{\cos 2\varphi_{CS}} \pm \sum_{i=1}^{3} \langle P_T \rangle f D(\theta_{CS})^{w_i(\varphi_{CS},\varphi_S)} A_T^{w_i(\varphi_{CS},\varphi_S)}$

Depolarization factor

$$D_{[f(\theta)]} = \frac{f(\theta)}{1 + \lambda \cos^2\theta}$$

$$f(\theta) = 1 + \cos^2\theta_{CS},\ \ \sin^2\theta_{CS},\ \ \sin 2\theta_{CS}$$



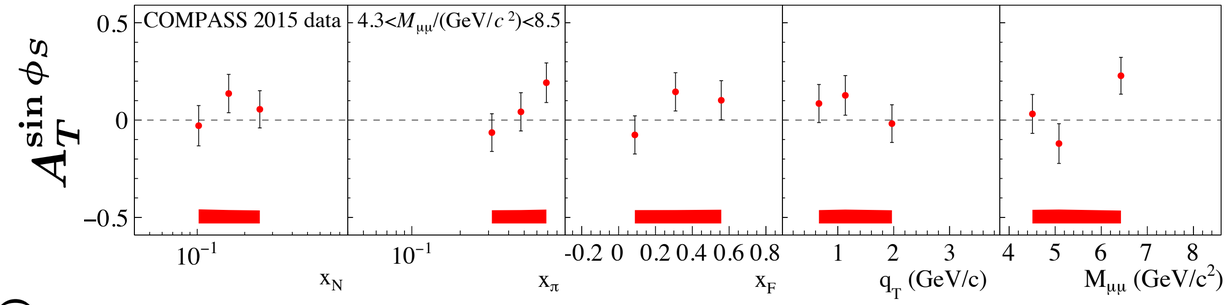
$$\frac{1 + \cos^2\theta_{CS}}{1 + \lambda \cos^2\theta_{CS}} \qquad \frac{\sin^2\theta_{CS}}{1 + \lambda \cos^2\theta_{CS}} \qquad \frac{\sin 2\theta_{CS}}{1 + \lambda \cos^2\theta_{CS}}$$

- λ = 1 is used in the extraction.
- λ can be differ from 1.
- Difference of D with λ = 0.5 - 1 from D with λ = 1 is included to the systematic error.

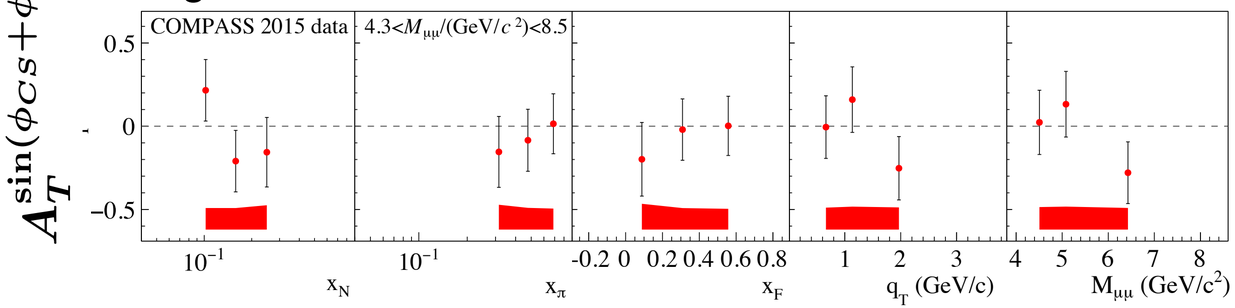
- The maximum difference is about 10%.
- The difference of 5% is hired for the systematic error.

Asymmetry

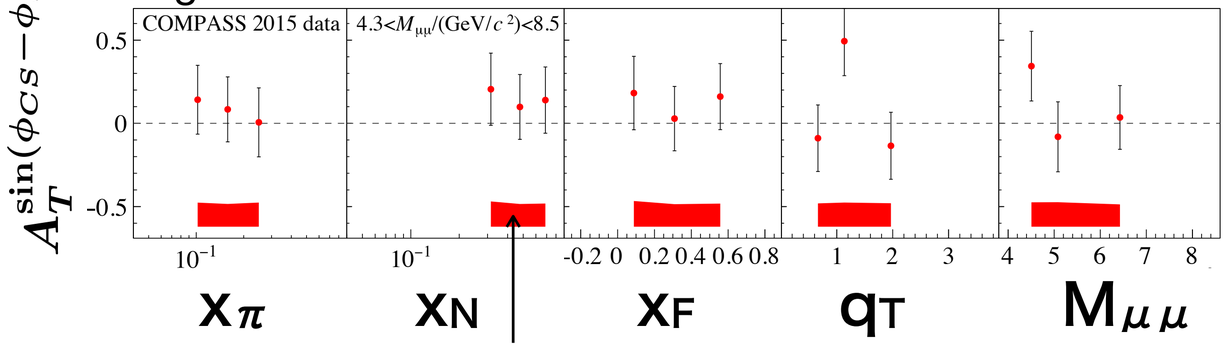
Sivers(N) ⊗ Boer-Mulders(π)



higher-twist



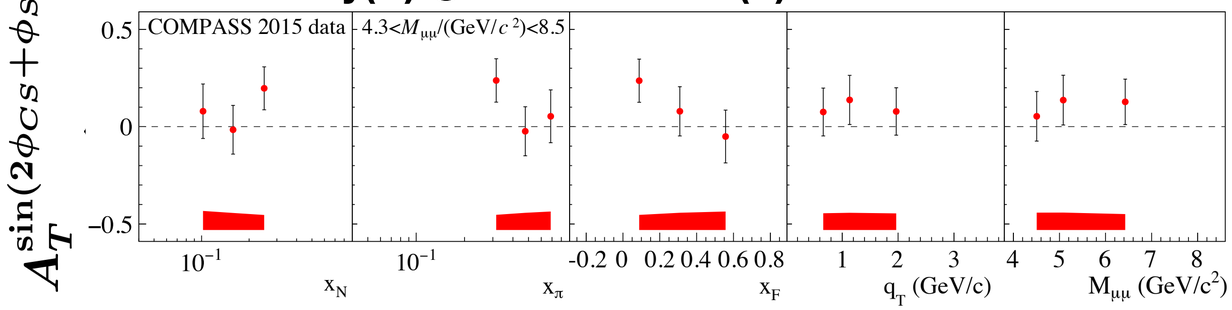
higher-twist



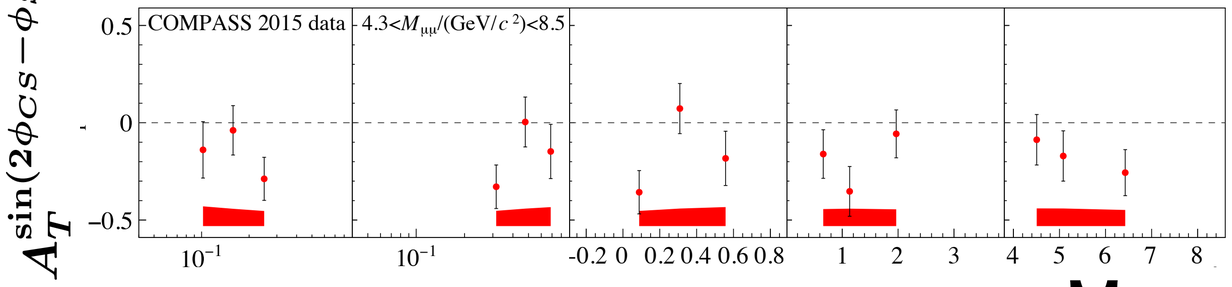
x_π x_N x_F q_T $M_{\mu\mu}$

systematic error

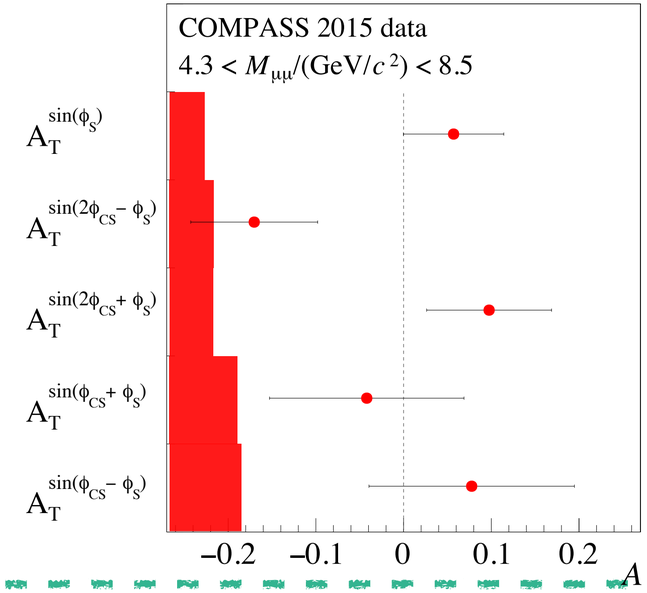
Pretzelosity(N) ⊗ Boer-Mulders(π)



Transversity(N) ⊗ Boer-Mulders(π)



x_π x_N x_F q_T $M_{\mu\mu}$



Systematic study

Compatibility check of periods

- Comparison 9 data taking periods

Cut studies

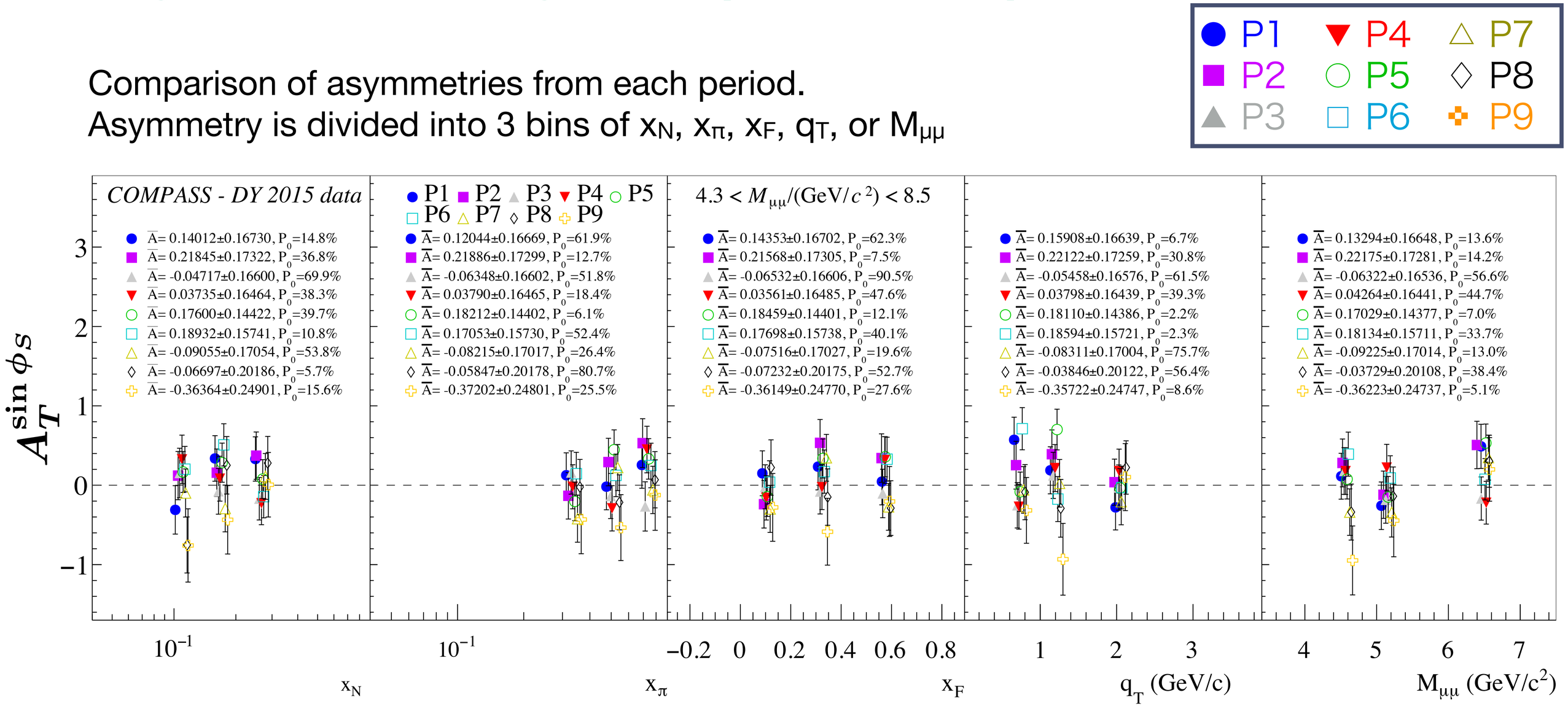
- Asymmetries with/without bad spills and bad runs
- tight cut for target
- tight cut for dimuon transverse momentum
- etc.

Misc

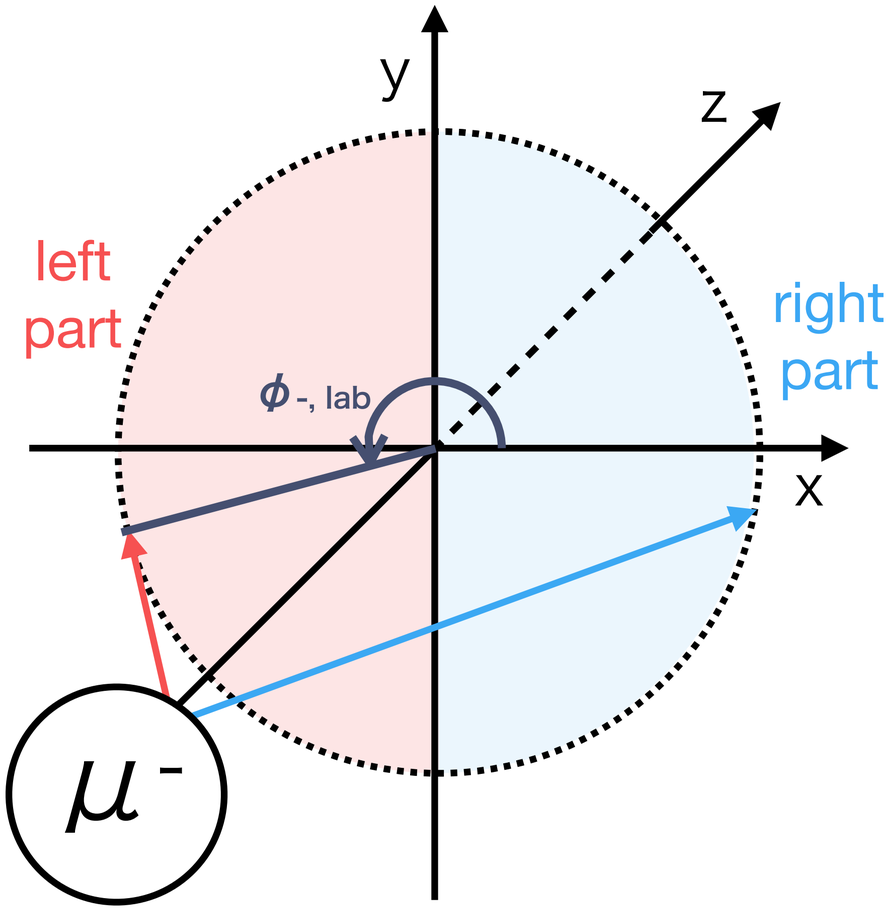
- Bias check if spectrometer is divided into left/right or up/down geometrically.
- False asymmetries from fake data sets
- Comparison of asymmetry extraction method to Unbanned Maximum Likelihood

Systematic study, Comparison of periods

Comparison of asymmetries from each period.
Asymmetry is divided into 3 bins of x_N, x_π, x_F, q_T, or $M_{\mu\mu}$



Systematic study, top/bottom and left/right asymmetries

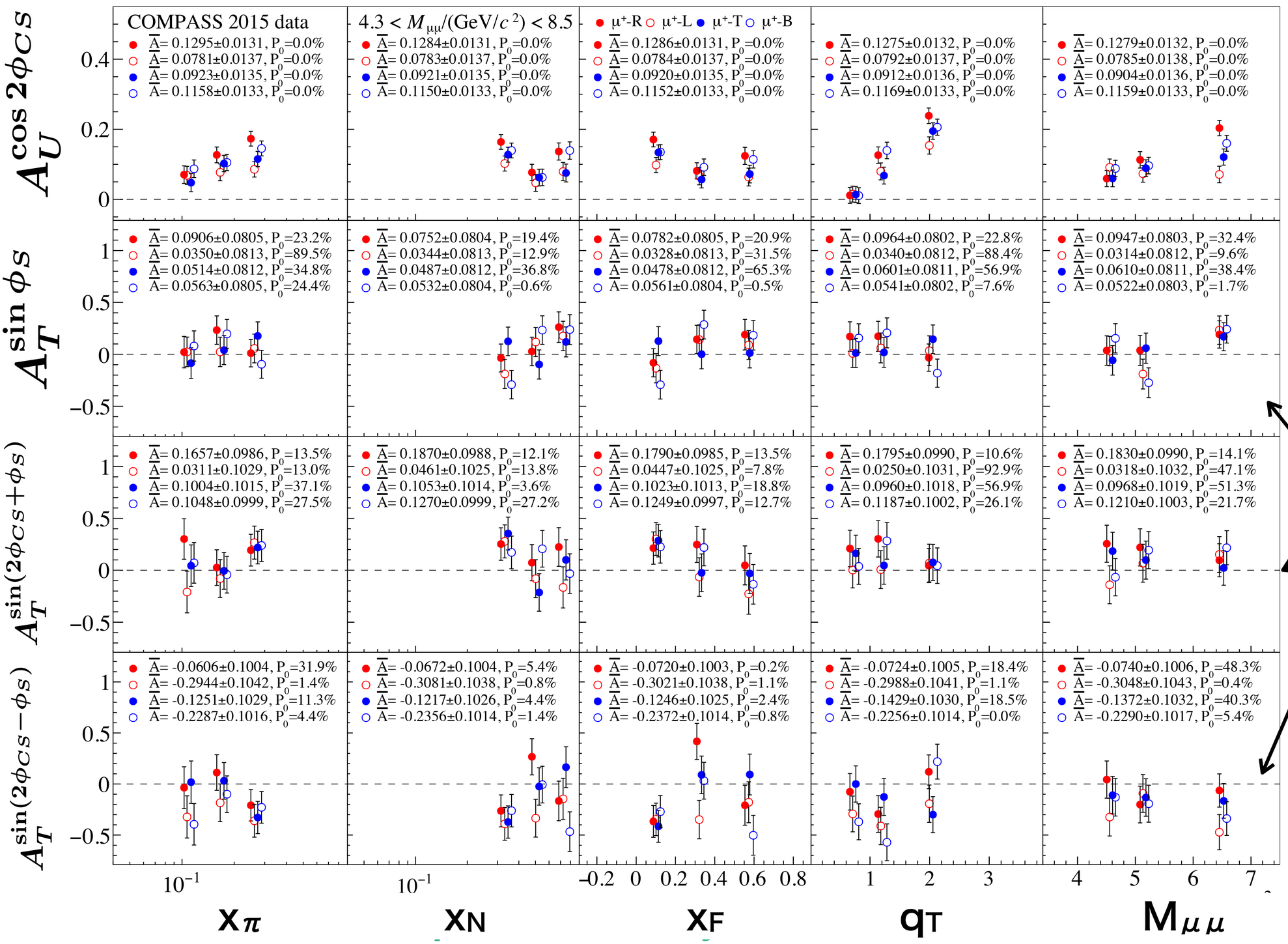


COMPASS spectrometer is not symmetric vertically and horizontally with respect to dimuons. Bias coming from this asymmetric structure need to be checked.

Dimuon events are divided into

- top/bottom parts ($\Phi_{\mu^-,\,lab}$: [0°, 180] and [180°, 360°]) or
- left/right parts ($\Phi_{\mu^-,\,lab}$: [-90°, 90°] and [90°, 270°]).

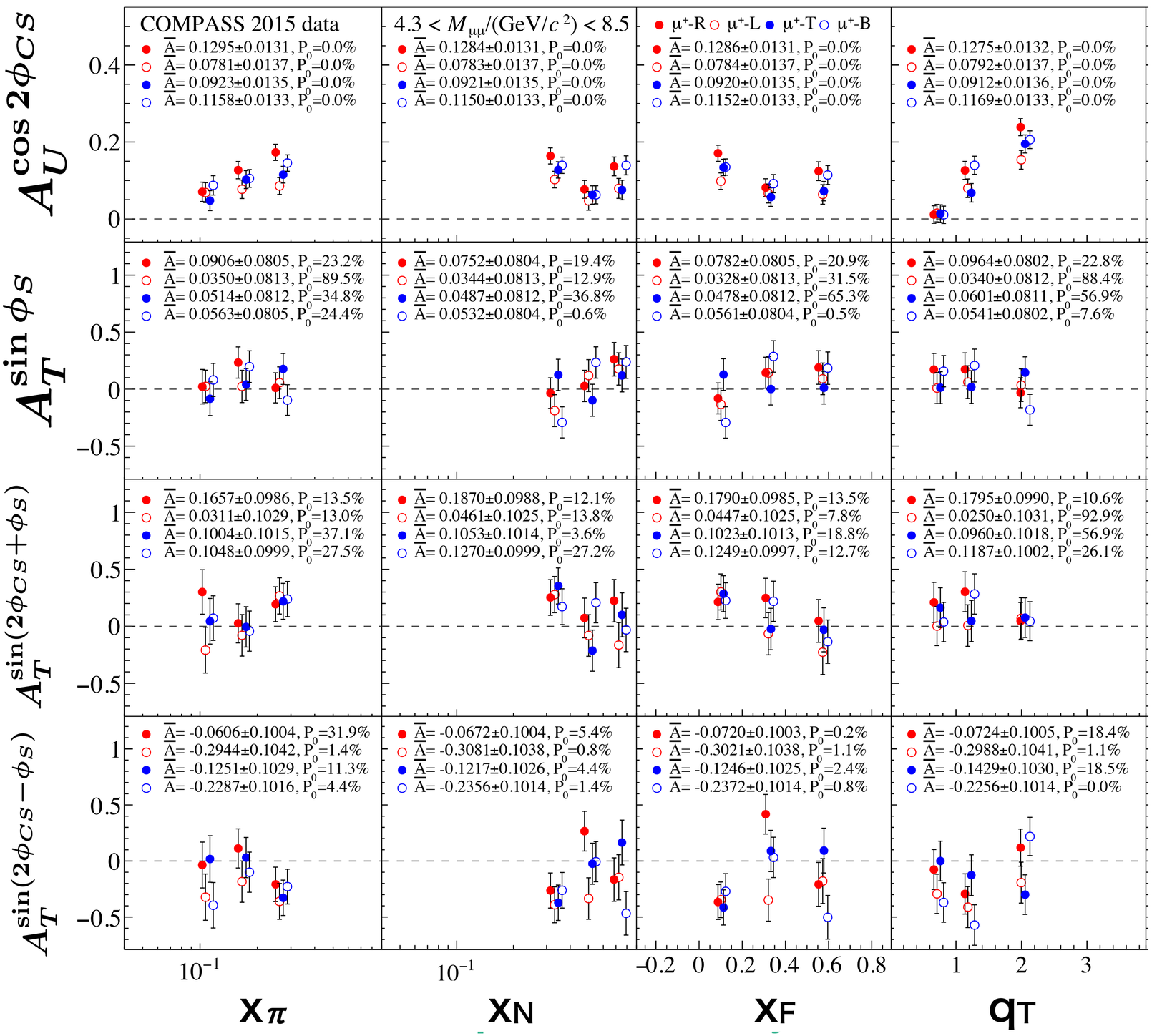
If there is no bias, there is no difference between asymmetries from the parts.



←Asymmetries (top&bottom or left&right) are not consistent. Acceptance correction of Φ_{CS} is necessary.

Asymmetries are consistent

● Top	● Right
○ Bottom	○ Left



Estimated systematic errors

	$A_T^{\sin\phi_S}$	$A_T^{\sin(\phi_{CS}+\phi_S)}$	$A_T^{\sin(\phi_{CS}-\phi_S)}$
T/B	0.79	0.63	0.67
L/R	0.49	0.59	0.51
Mean	0.6	0.6	0.6

	$A_T^{\sin(\phi_{CS}-\phi_S)}$	$A_T^{\sin(2\phi_{CS}+\phi_S)}$	$A_T^{\sin(2\phi_{CS}-\phi_S)}$
T/B	0.67	0.56	0.57
L/R	0.51	0.49	0.58
Mean	0.6	0.5	0.6

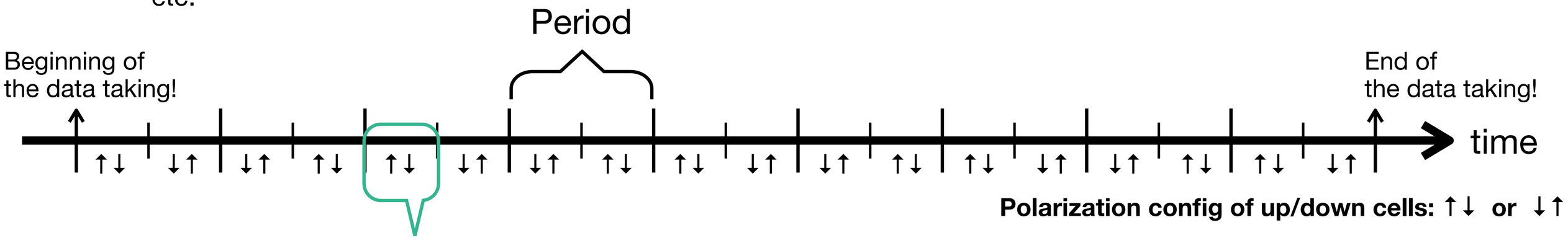
units of σ_{stat}

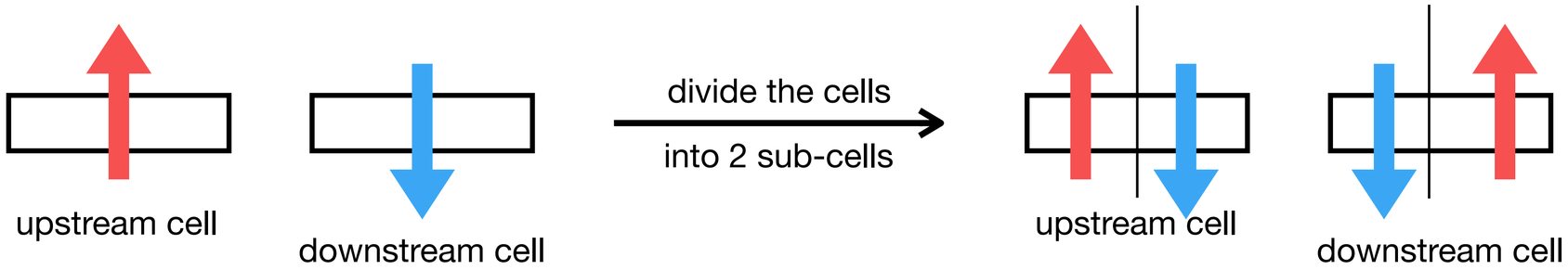
Systematic study, Asymmetries from fake datasets

Normally, asymmetries are extracted from a period, and the final asymmetries are obtained by averaging them.

For systematic study, extraction from fake datasets like:

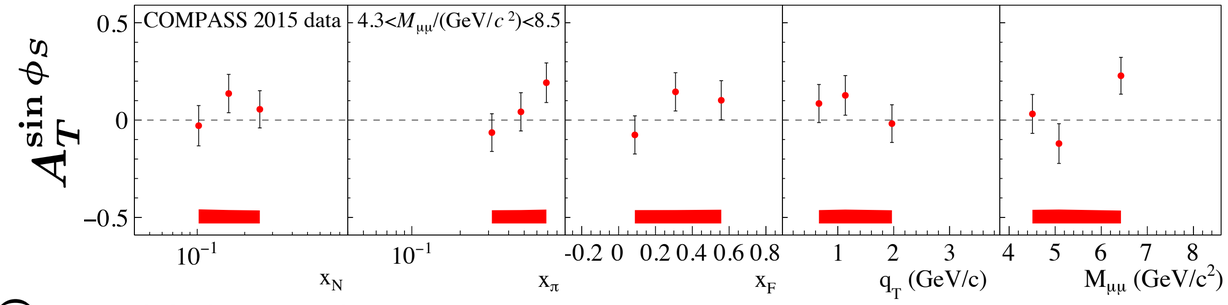
- Polarization flip for one of the cells
- Dividing a cell into 2 fake sub-cell assigning fake polarization
- Runs (units of data taking, ~2 hours) in the given period is randomized into 2 sub-periods, and asymmetries are extracted from them as usual
- etc.



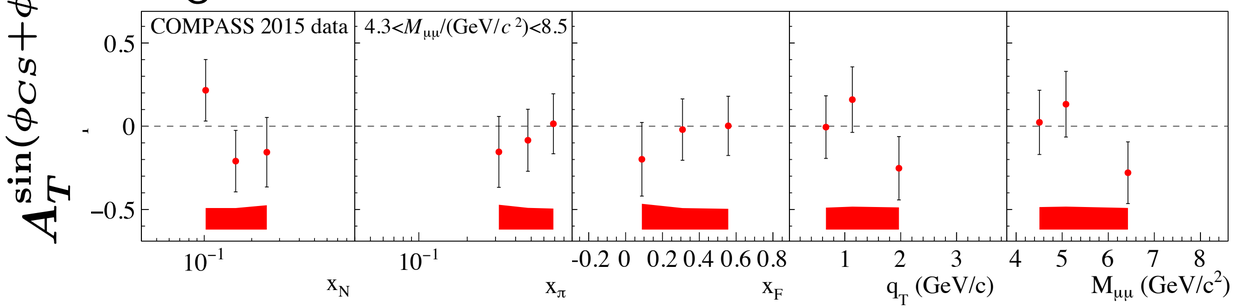


Asymmetry

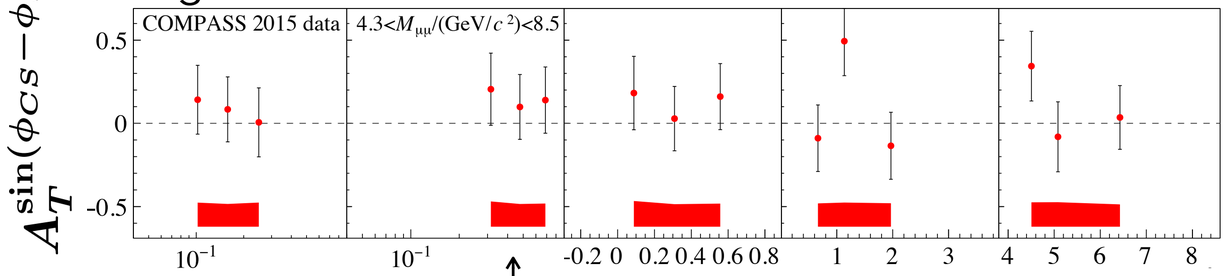
Sivers(N) ⊗ Boer-Mulders(π)



higher-twist



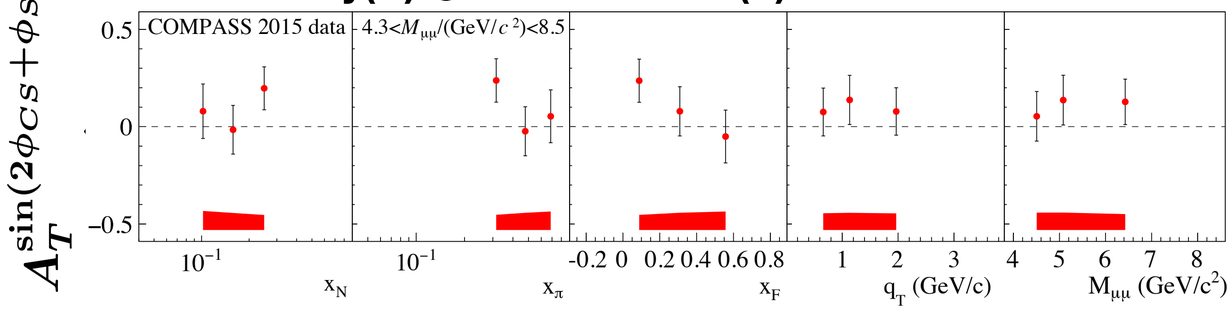
higher-twist



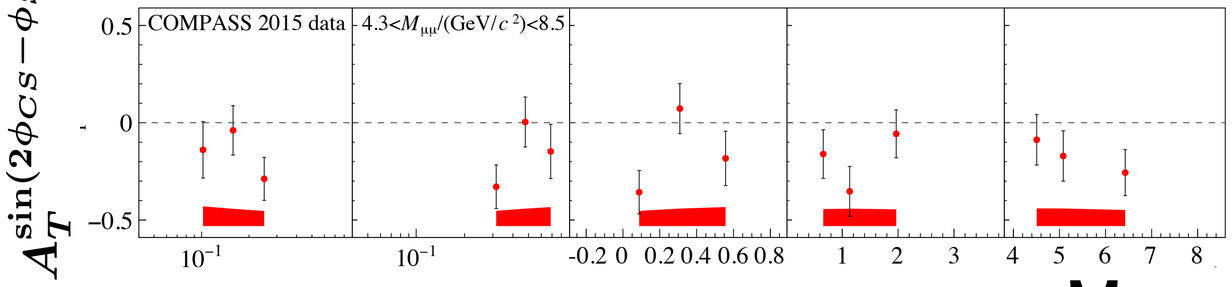
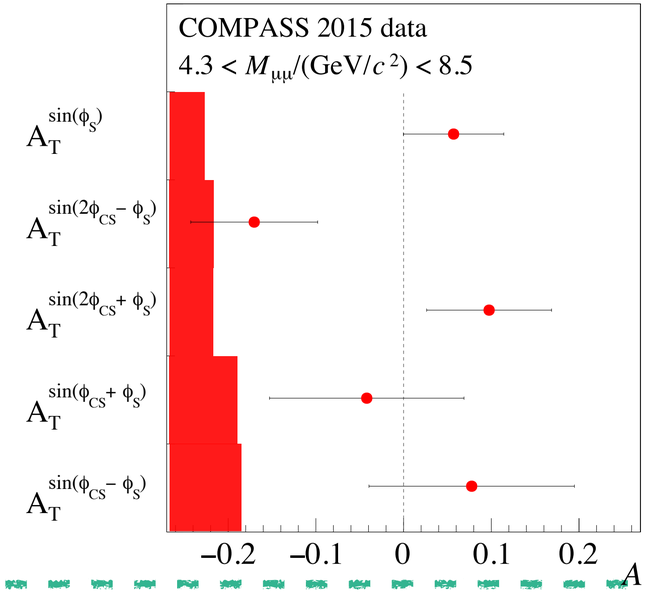
x_π x_N x_F q_T $M_{\mu\mu}$

systematic error

Pretzelosity(N) ⊗ Boer-Mulders(π)



Transversity(N) ⊗ Boer-Mulders(π)



x_π x_N x_F q_T $M_{\mu\mu}$