The 11th Circum-Pan-Pacific Symposium on High Energy Spin Physics

Pion-induced Drell-Yan measurements with transversely polarized proton target in COMPASS at CERN

Genki NUKAZUKA, Yamagata Univ
on behalf of the COMPASS Collaboration

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  - Nucleon structure
  - Sign change of Sivers and Boer-Mulders functions
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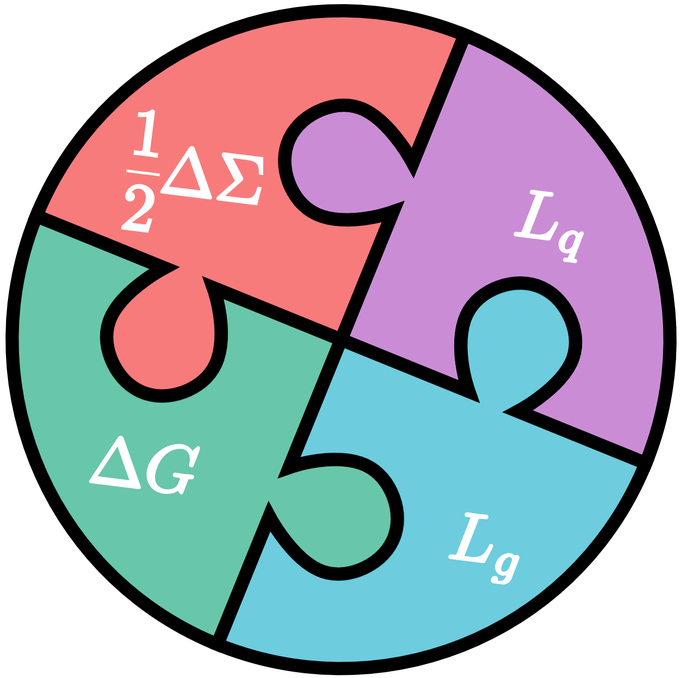
  - Polarized DY process
  - Setup, Spectrometer
  - Polarized target
- **Analysis**
  - Selection of DY events
  - Kinematic distributions
  - Transverse spin asymmetries

Proton spin puzzle

Nucleon spin $\frac{1}{2} =$



Proton spin puzzle

Quark spin

20～30%

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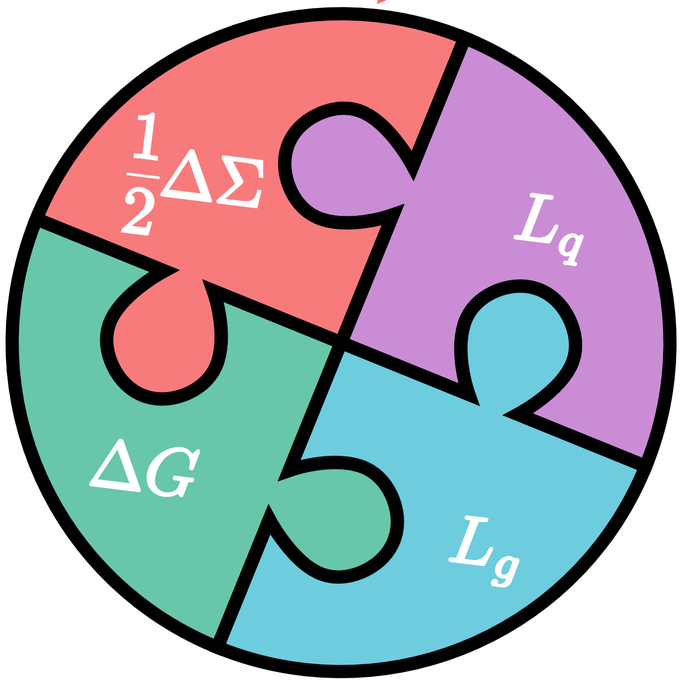

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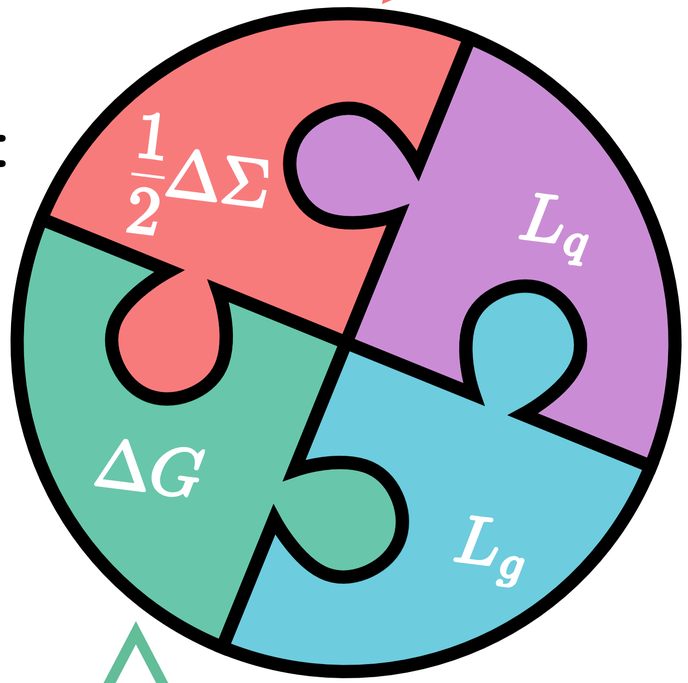

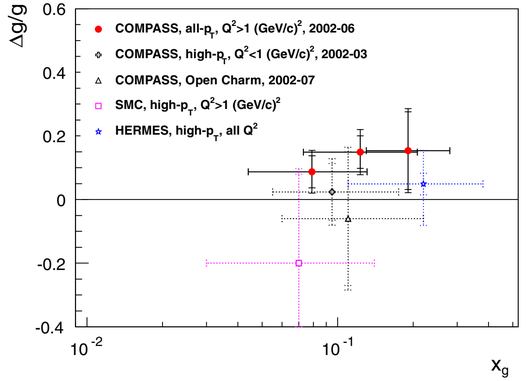

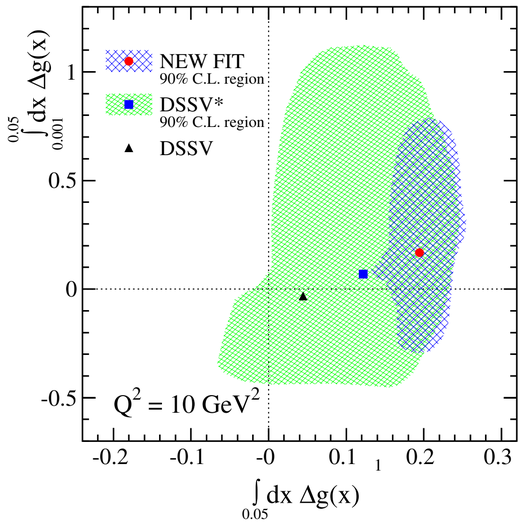

Gluon spin

Some estimations by global fit are available:

e.g.） -20% - +90% (PRL113(2014)012001)

+30% - +50% (PRD93(2016)114024)

Proton spin puzzle

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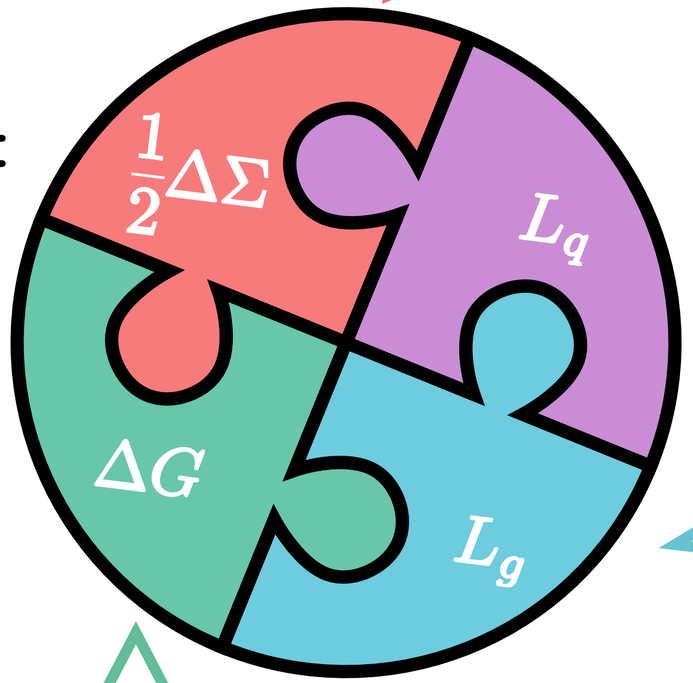
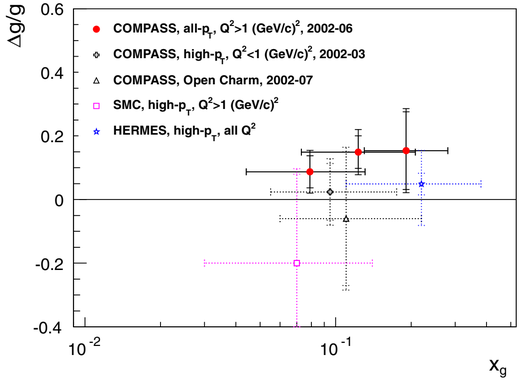
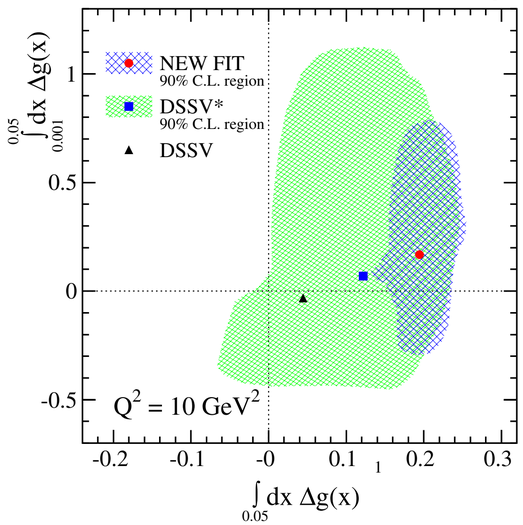


Orbital angular momentum from quarks and gluons

Unknown

Does it exist or not?





Gluon spin

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e.g.) -20% - +90% (PRL113(2014)012001)

+30% - +50% (PRD93(2016)114024)

Polarized DY at COMPASS can help to understand it.

Nucleon structure

Spin state of parton \ Spin state of nucleon	No pol.	Long.	Trans.
No pol.	Number density f_1		Sivers $f_{1T}^{\perp}$
Long.		Helicity g_{1L}	Worm-Gear g_{1T}
Trans.	Boer-Mulders $h_1^{\perp}$	Worm-Gear $h_{1L}^{\perp}$	Transversity h_1
			Pretzelosity $h_{1T}^{\perp}$

At leading twist, nucleon structure is described 8 transverse momentum dependent PDFs

- Colinear PDFs:
  $f_1(x)$ number density, $g_1(x)$ helicity, $h_1(x)$ transversity
- TMD PDF: depend on x and modulus $|k_T|$

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- TMD PDF:
  depend on x and modulus $|\mathbf{k_T}|$

Sivers function :

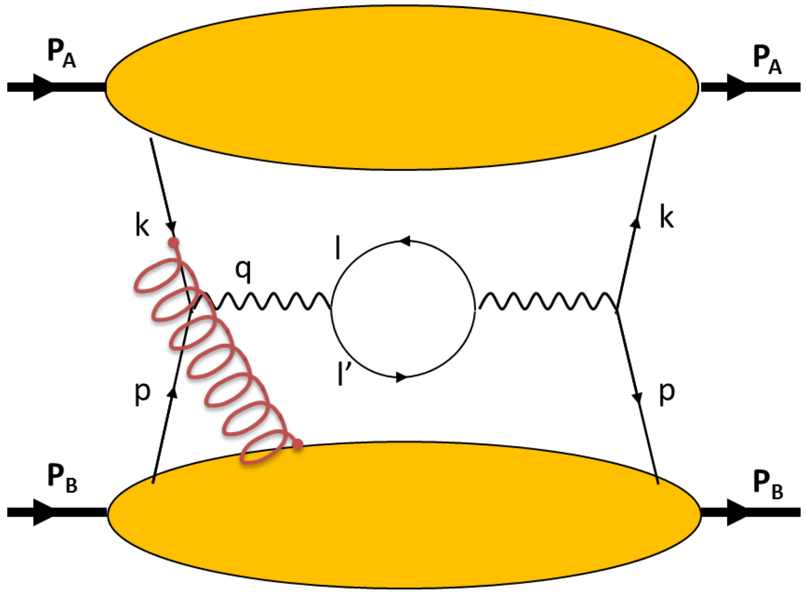
Correlation between transv. spin of the nucleon $\mathbf{S_T}$ and $\mathbf{k_T}$

If the value is 0, it suggests that there is no orbital angular momentum of the parton.

Sivers and Boer-Mulders functions

Sivers and Boer-Mulders funcs. are expected to be naïve time reversal odd (PLB536(2002)43)

→ Sign measured via DY and SIDIS should be opposite!

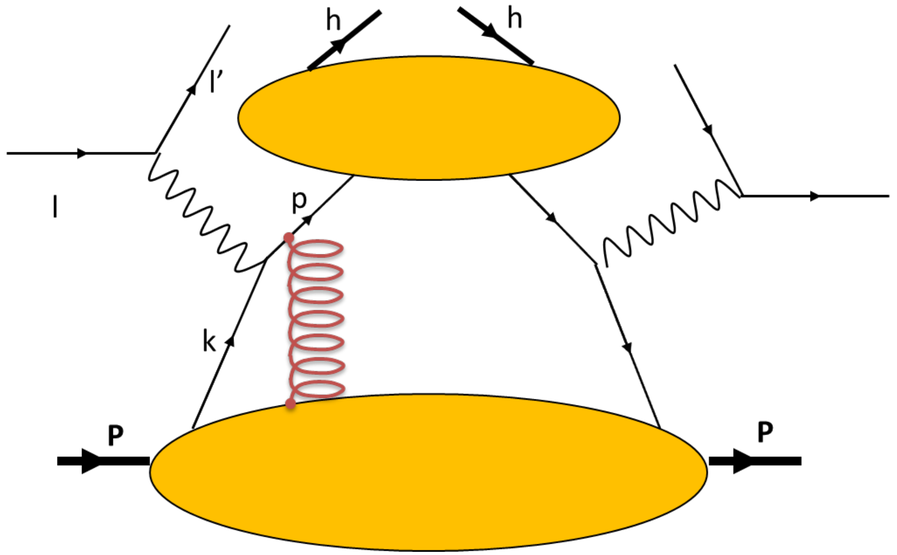


DY

QCD gluon gauge link in the initial state

$$f_{1T,DY}^{\perp} = -f_{1T,SIDIS}^{\perp}$$

$$h_{1,DY}^{\perp} = -h_{1,SIDIS}^{\perp}$$

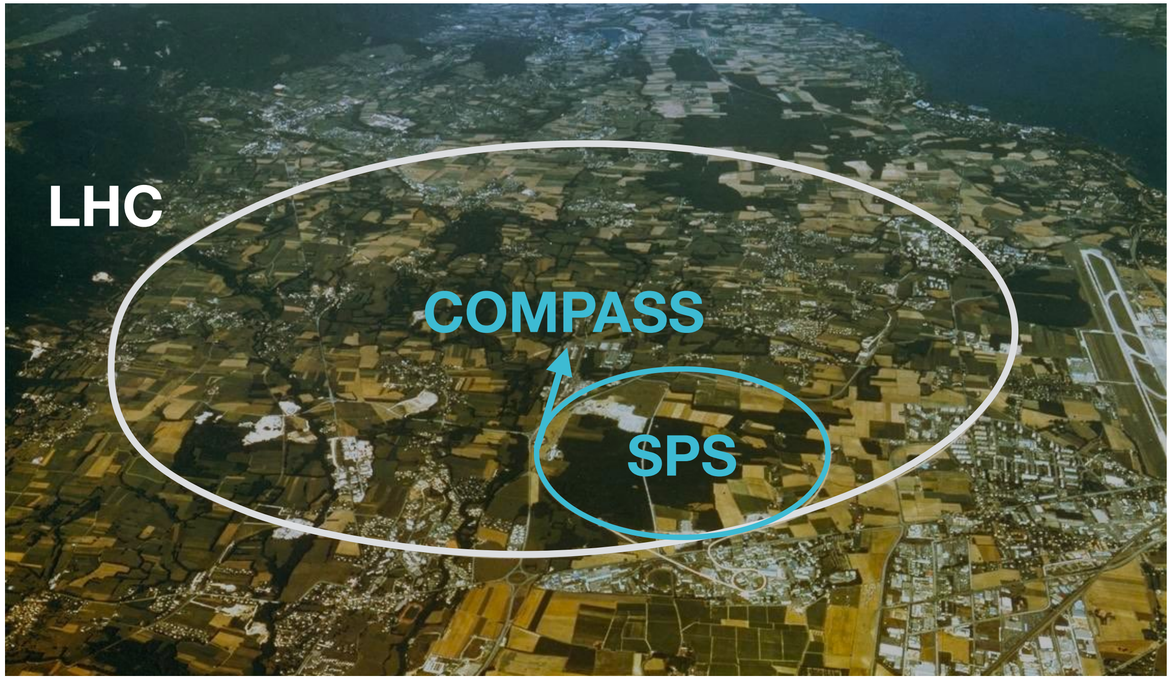


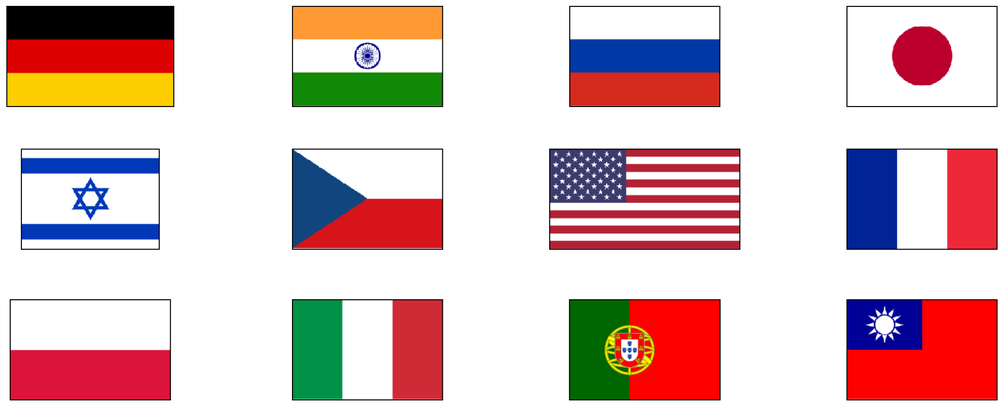
SIDIS

that in the final state

Confirmation of the sign change is a crucial test of QCD TMD framework!!

COMPASS collaboration



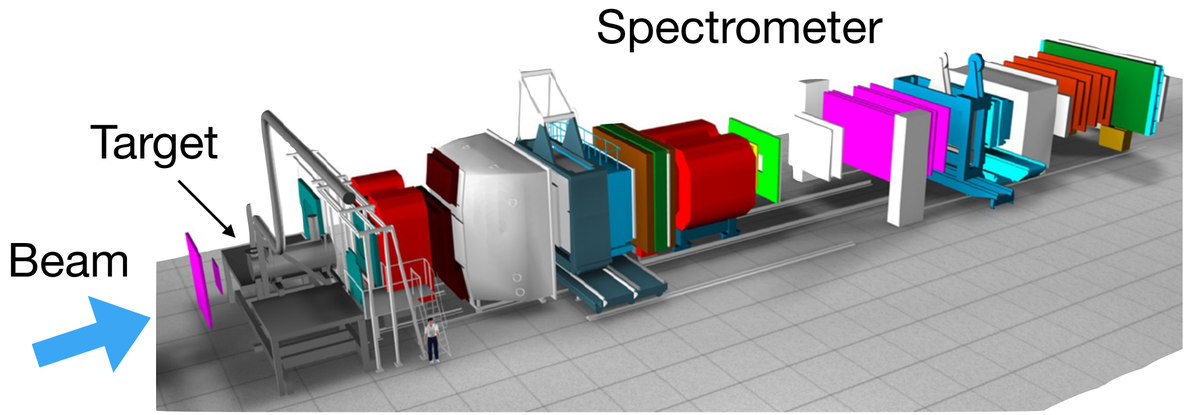


COmmon**M**uon**P**roton**A**pparatus for **S**tructure and **S**pectroscopy

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

History of COMPASS data taking

Year	Physics	Beam (GeV/c)	Target
02 - 04	SIDIS	$\mu^{\pm}$, 160	^{6}LiD, long. & trans.
06	SIDIS	μ^{+}, 160	^{6}LiD, long.
07	SIDIS	μ^{+}, 160	NH_3, long. & trans.
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	Liquid H_2
14	DY pilot run	π^{-}, 190	NH_3
15	DY	π^{-}, 190	NH_3, trans.
16 - 17	DVCS	$\mu^{\pm}$, 160	Liquid H_2
18	DY	π^{-}, 190	NH_3, trans.
19-20	CERN Long Shutdown 2		
21	SIDIS	μ^{+}, 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

Muon beam runs are covered by A. Bressan's talk.

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15	**DY**	**π^{-}, 190**	**NH_3, trans.**
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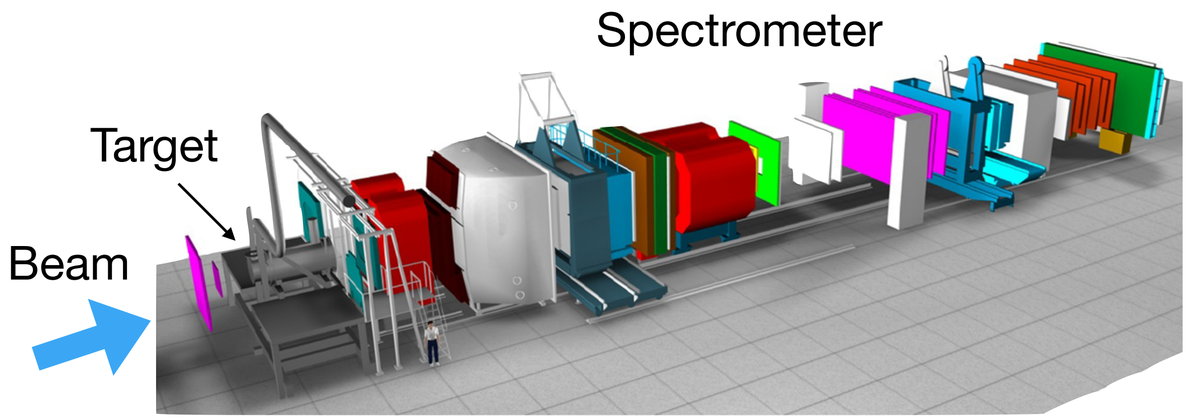


Typical setup

Beam：Polarized μ, hadron

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

Spectrometer

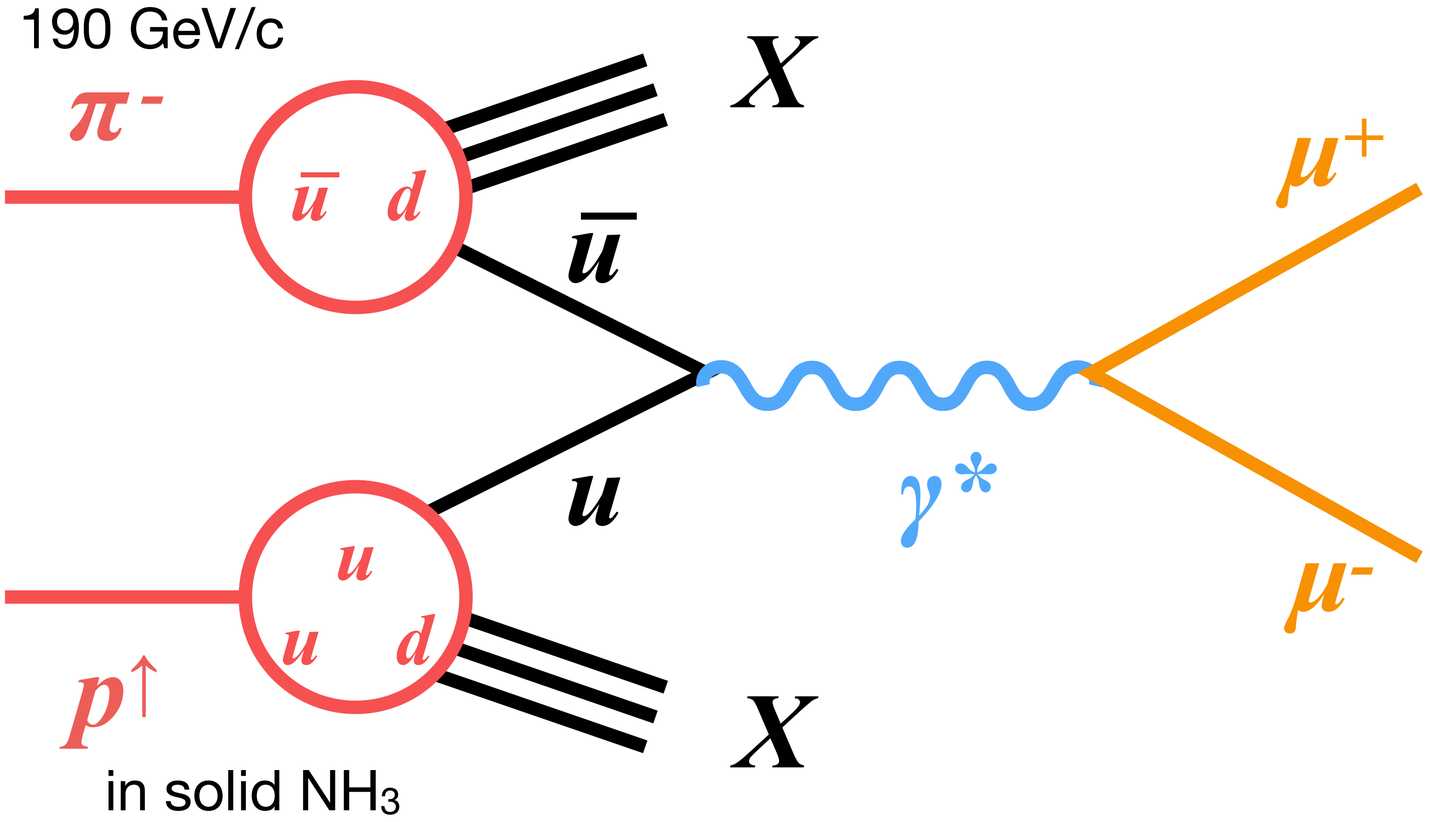
- μ wall

Analysis results were already published from PRL119 (2017) 112002

Half of data had already been analyzed.

…red by A. Bressan's talk.

Polarized DY experiment at COMPASS



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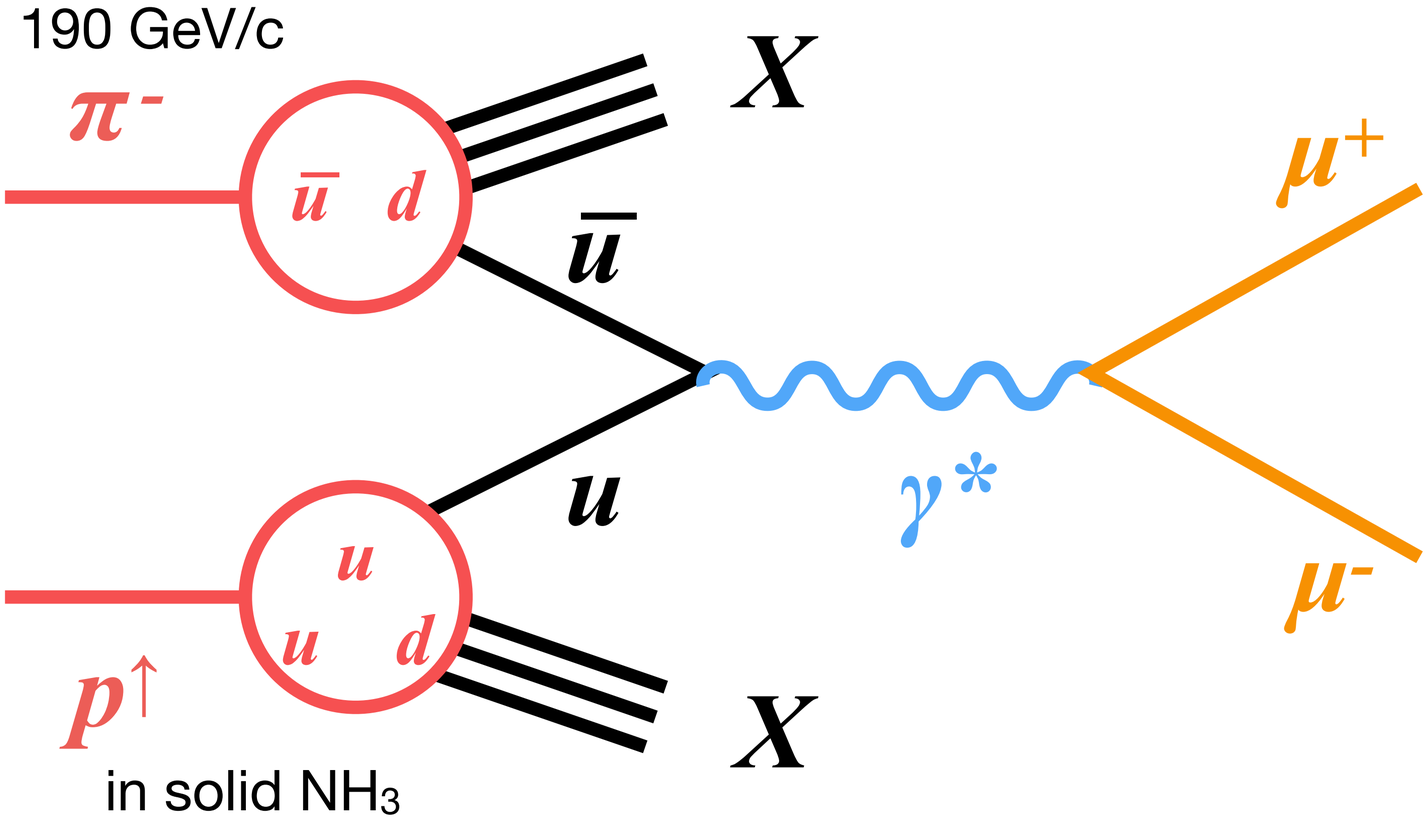
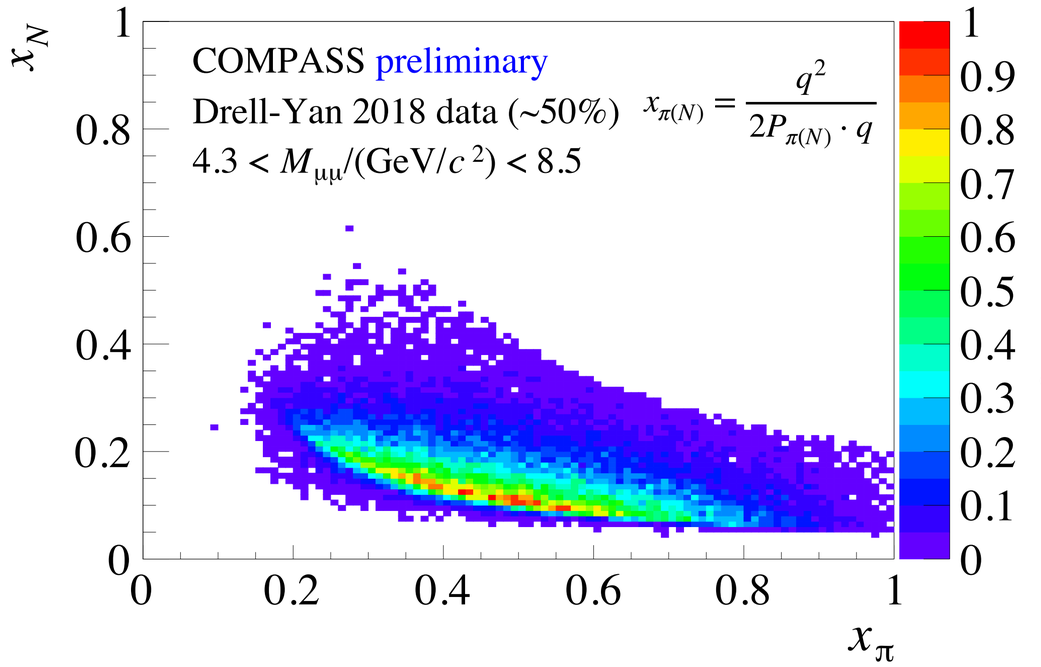




Dominant acceptance of COMPASS spectrometer is valence regions
→ DY by u(p) ū(π⁻) is dominant.

Asymmetries

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

PRD79(2009)034005

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

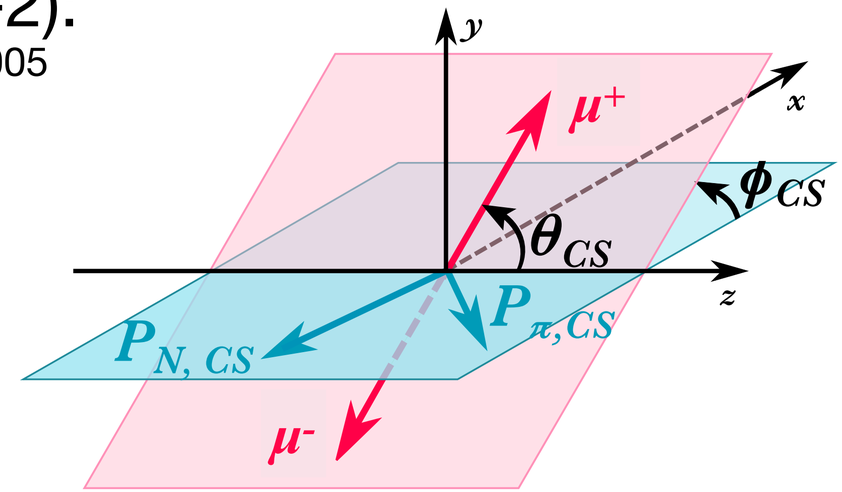
$$\left[\left(1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS}\right) + |S_T| \left\{ A_T^{\sin\phi_S} \sin\phi_S + D_{[\sin^2\theta]} \left(A_T^{\sin(2\phi_{CS}+\phi_S)} \sin(2\phi_{CS}+\phi_S) + A_T^{\sin(2\phi_{CS}-\phi_S)} \sin(2\phi_{CS}-\phi_S) \right) \right\} \right]$$

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

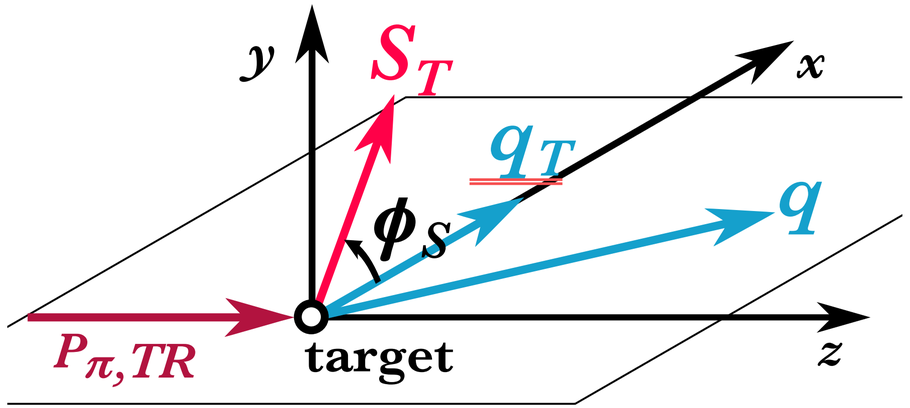
$F_{U,T}^{W(\phi_{CS},\phi_S)}$: Structure function

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



Collins-Soper frame



Target rest frame

Asymmetries

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

PRD79(2009)034005

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

$$A \propto \mathrm{PDF}(\pi) \otimes \mathrm{PDF}(\mathrm{p})$$

8 TMDs at the leading-twist

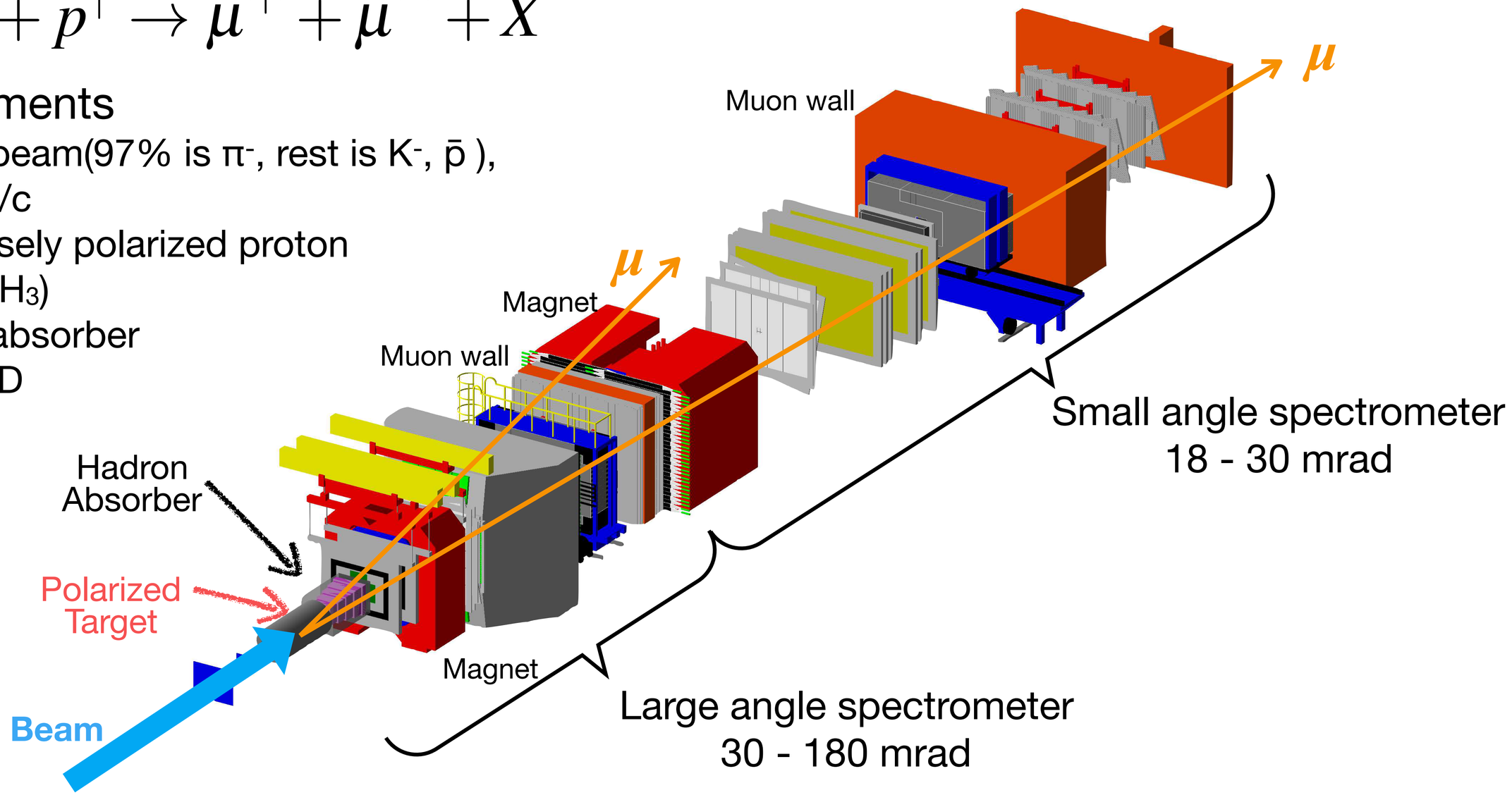
Spin state of parton \ Spin state of nucleon	No pol.	Long.	Trans.
No pol.	Number density f_1		Sivers $f_{1T}^{\perp}$
Long.		Helicity g_{1L}	Worm-Gear g_{1T}
Trans.	Boer-Mulders $h_1^{\perp}$	Worm-Gear $h_{1L}^{\perp}$	Transversity h_1 / Pretzelosity $h_{1T}^{\perp}$

Setup

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

Key equipments

- Hadron beam(97% is π^-, rest is K^-, $\bar{p}$), 190 GeV/c
- Transversely polarized proton target (NH_3)
- Hadron absorber
- Beam PID

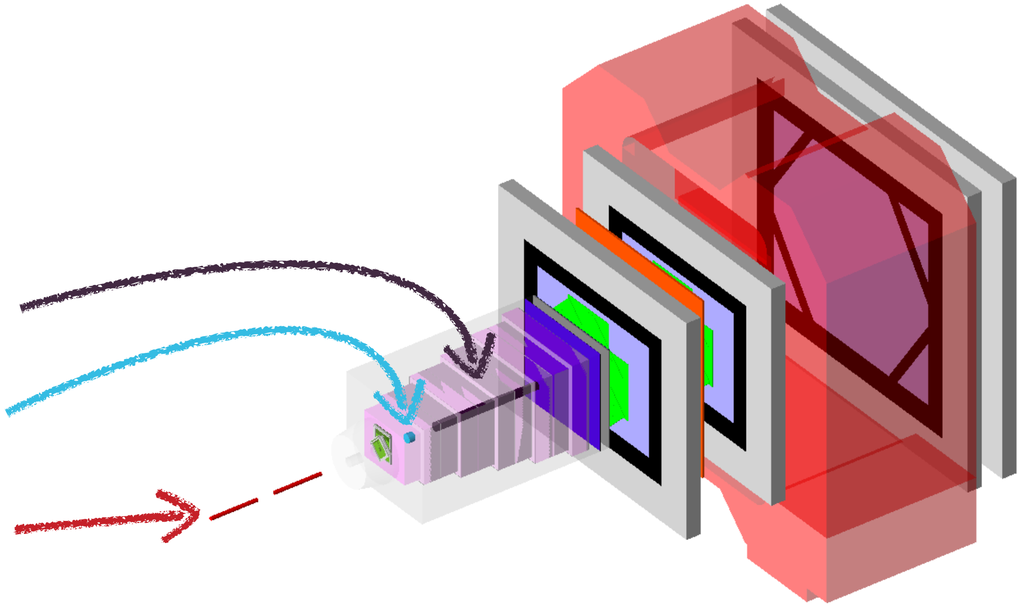


Setup, the targets

Tungsten beam dump (W) : L=120 cm, D=9 cm

Al target : L=7 cm, D= 9.4 cm

PT (NH_3) : L=55cm, D=4 cm, 2 cells



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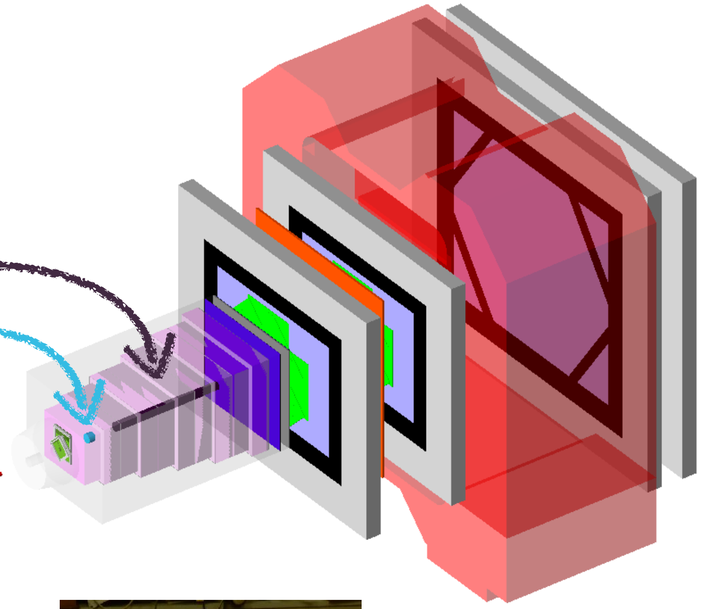

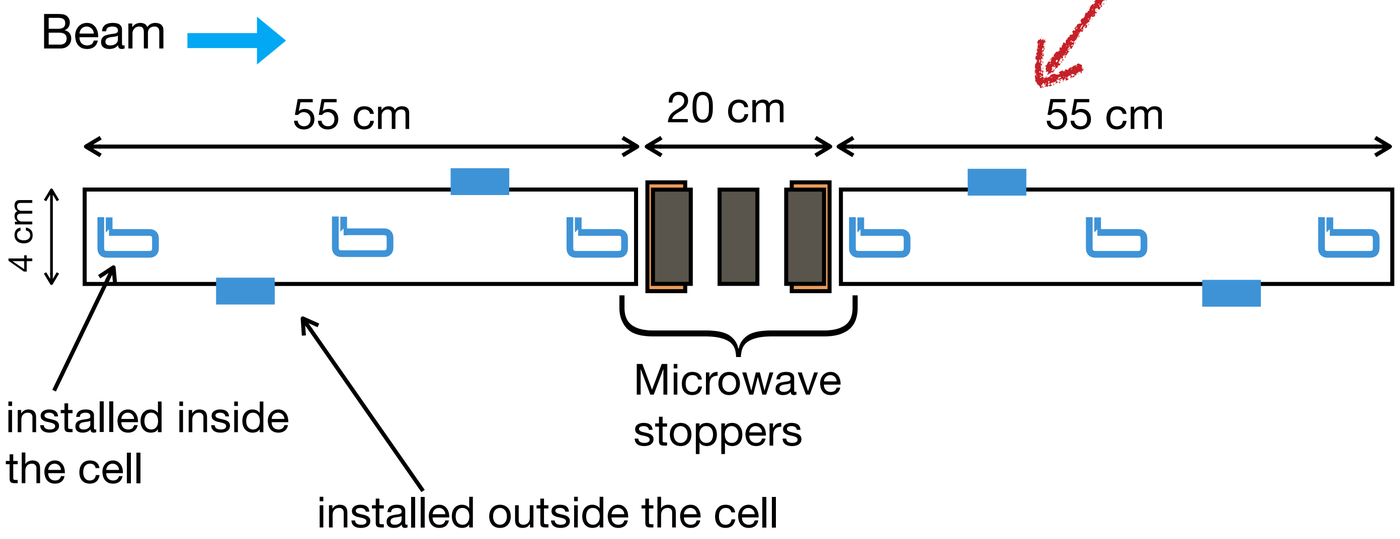

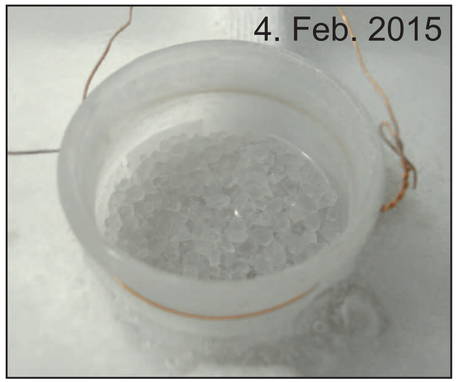

Polarizable NH_3 by DNP method.

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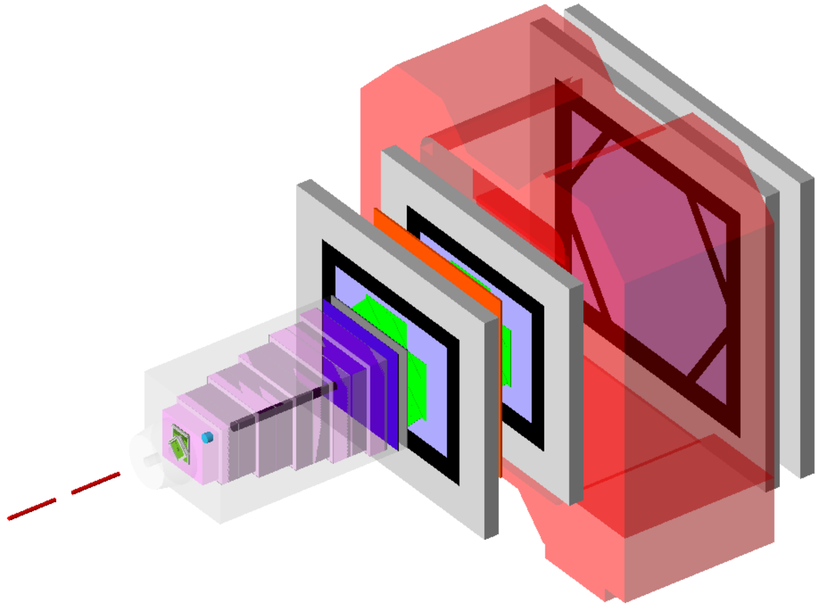
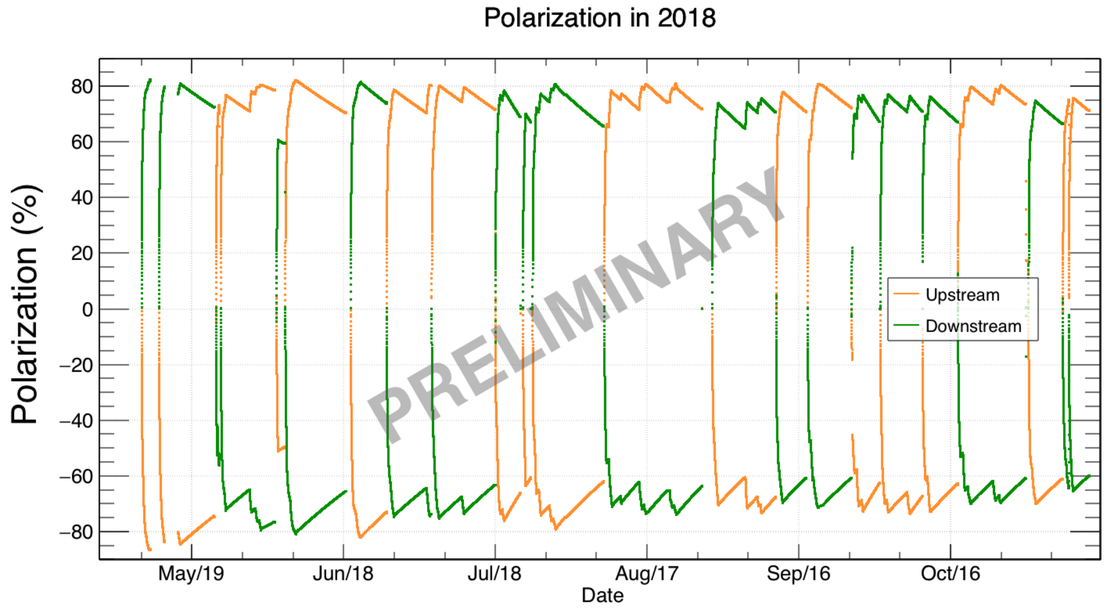


		Max		Average	
		Positive	Negative	Positive	Negative
2015	Upstream	0.83	-0.86	0.74	-0.71
	Downstream	0.79	-0.78	0.69	-0.67
2018	Upstream	0.82	-0.87	0.76	-0.68
	Downstream	0.82	-0.81	0.72	-0.70



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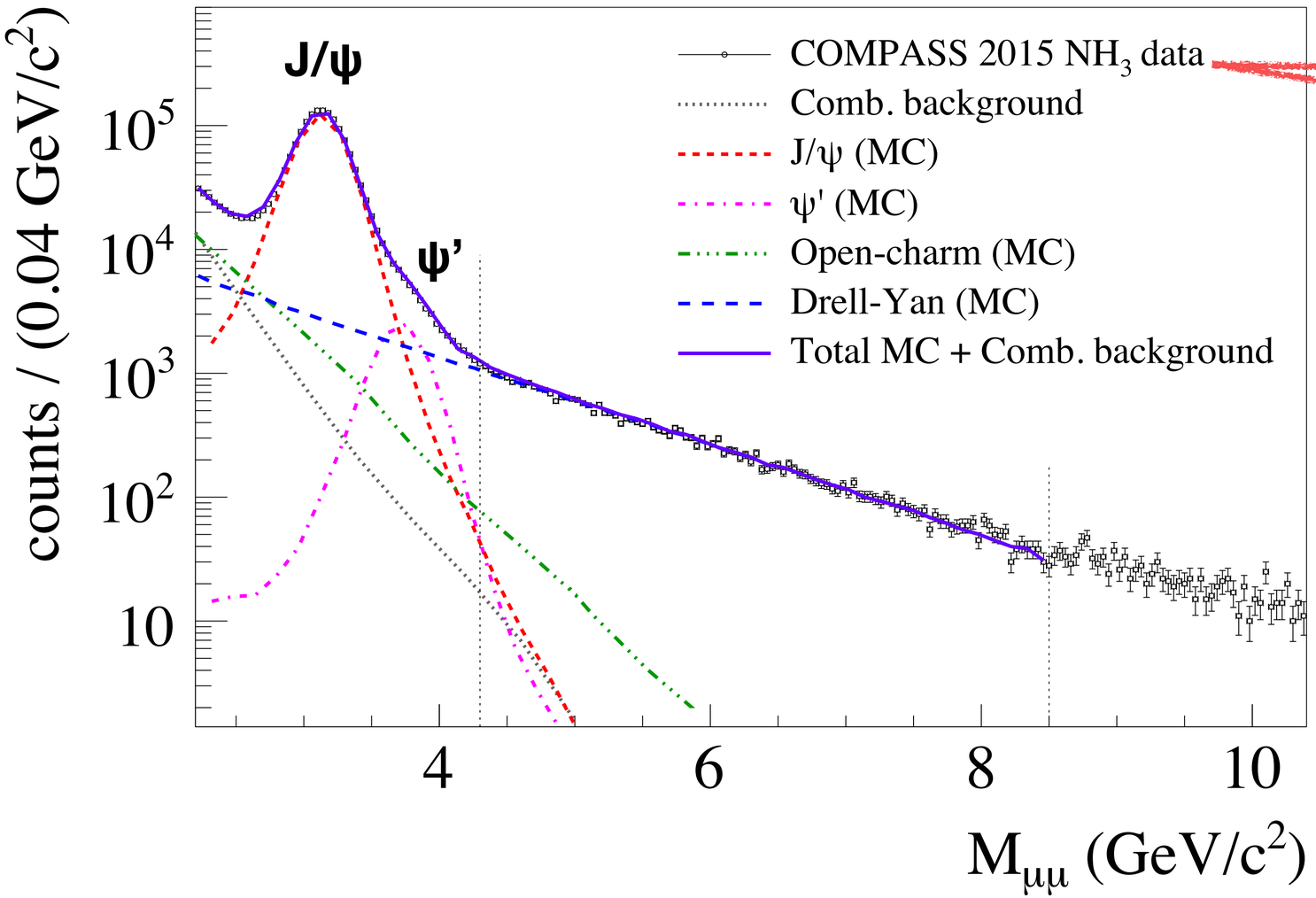
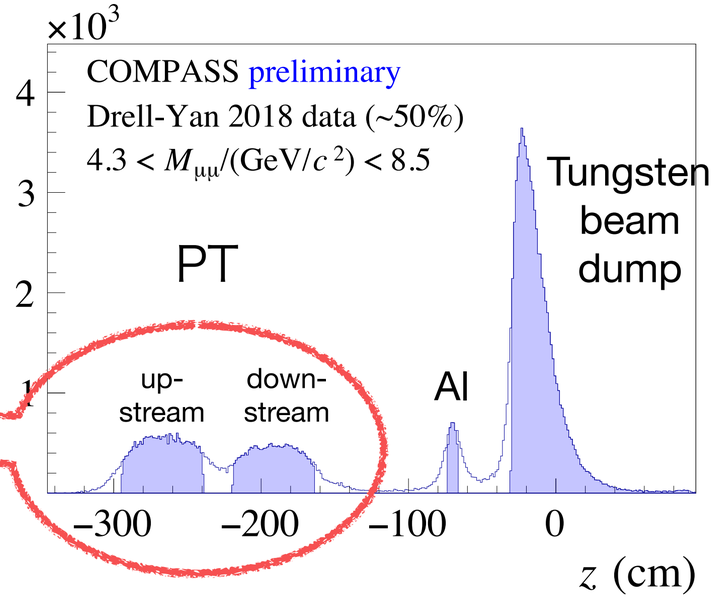
Analysis, Selection of DY events

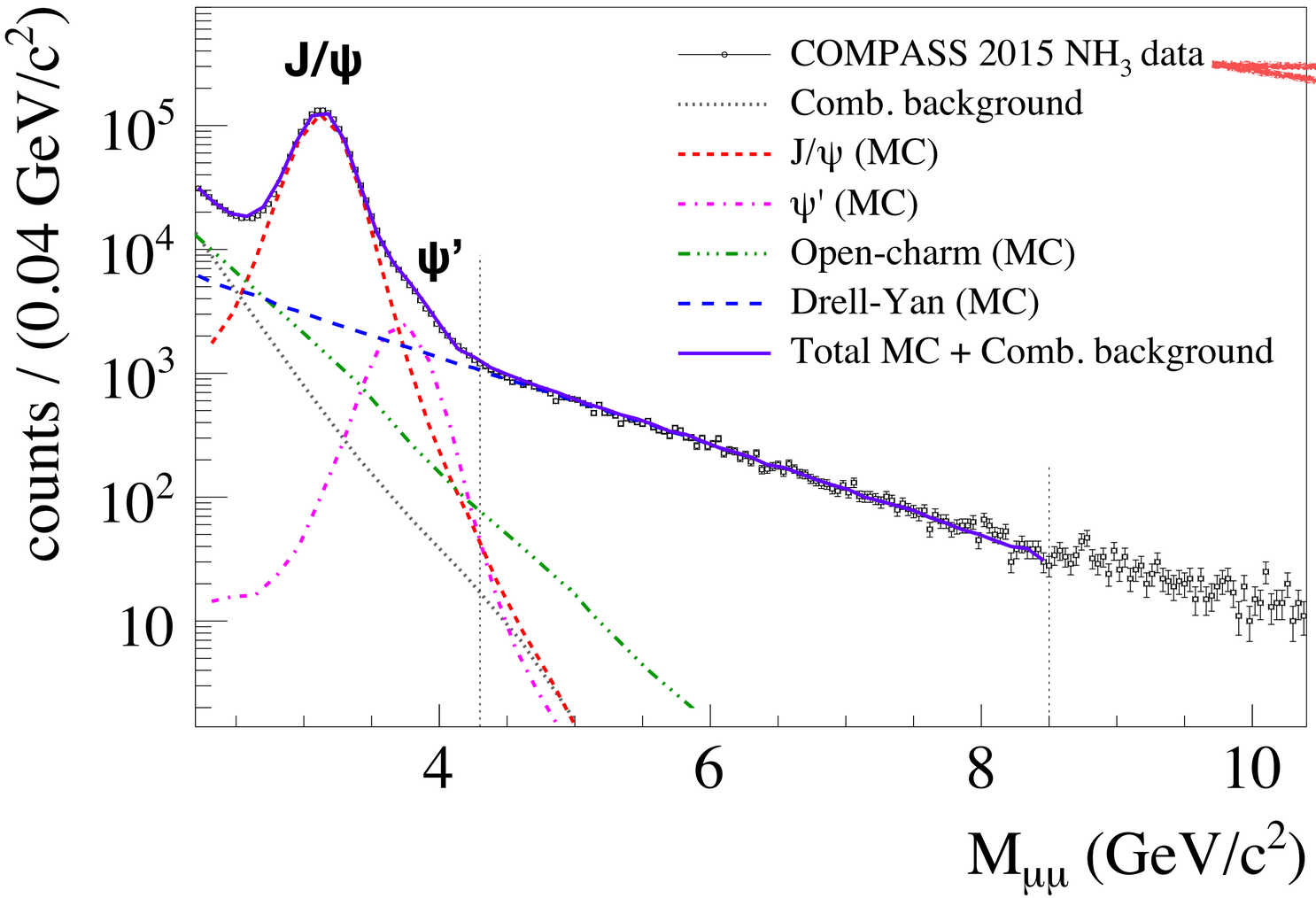


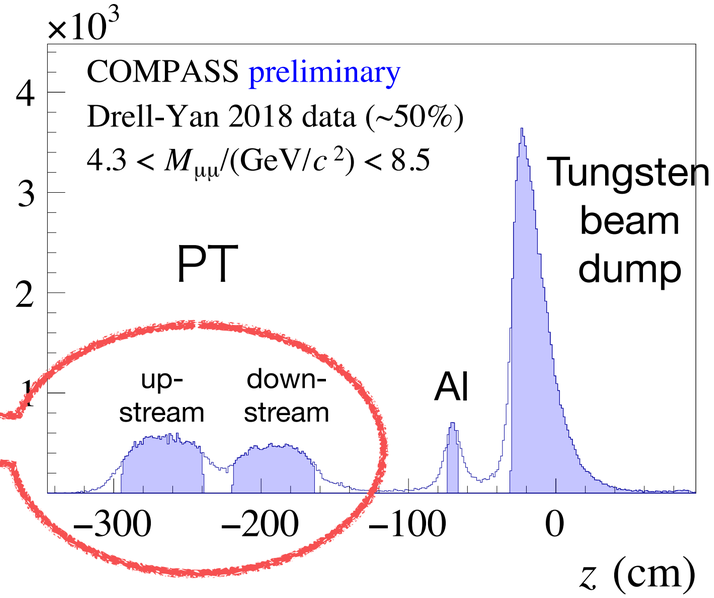


- Dimuon events from 2015 data

To reduce background as mush as possible, we need to select an appropriate invariant mass region.

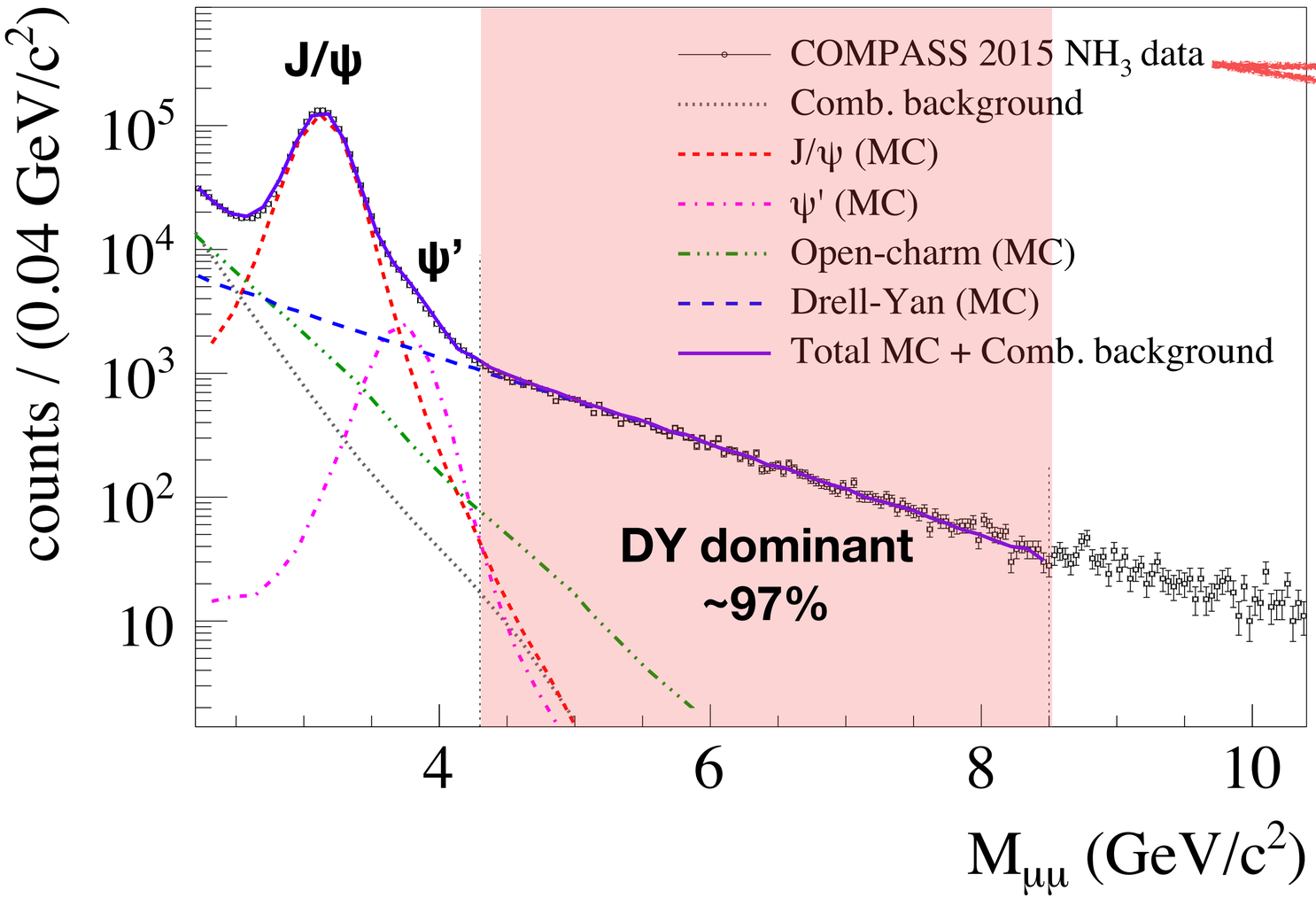
Analysis, Selection of DY events

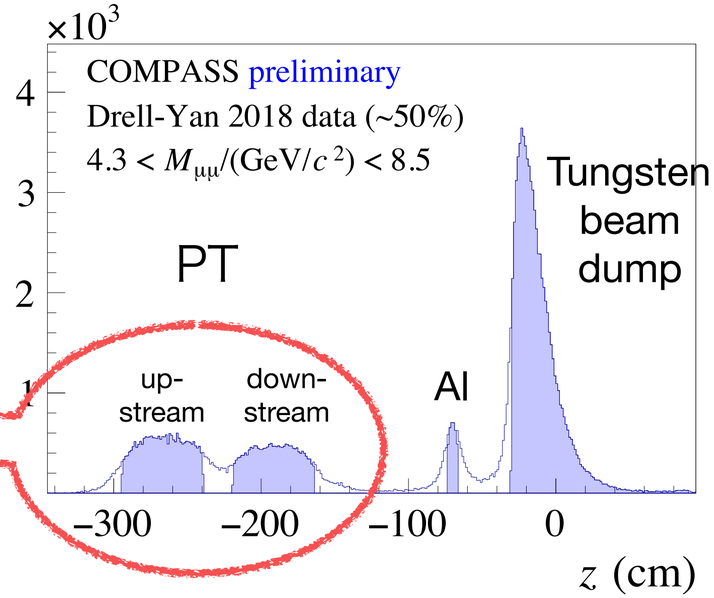




- Dimuon events from 2015 data
- Simulation
  - DY, J/ψ, ψ', Open-Charm were simulated.
  - Analysis were done in the same way as in real data.
  - Combinatorial background (gray dashed) was estimated by like-sign method from real data.

Analysis, Selection of DY events





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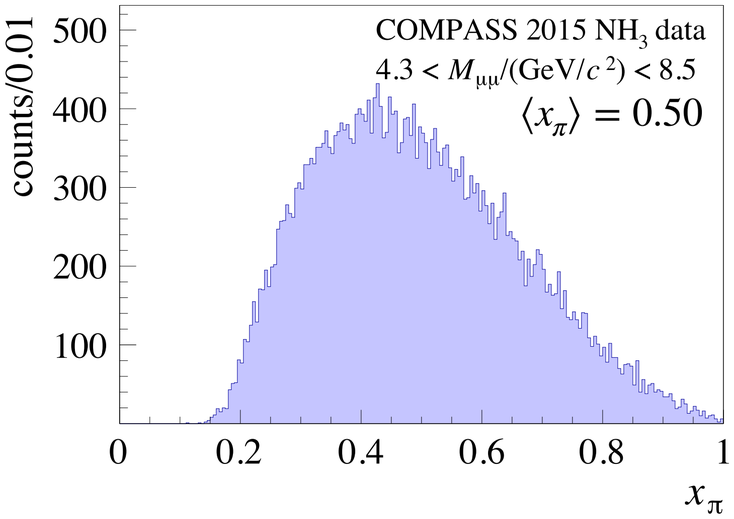
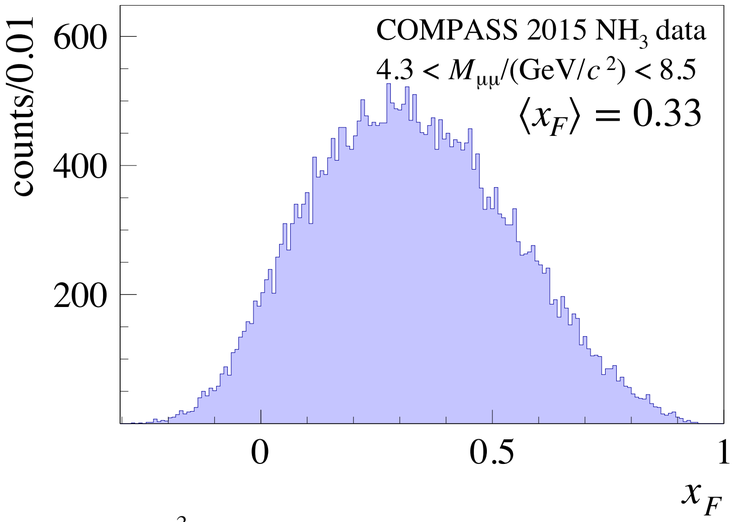
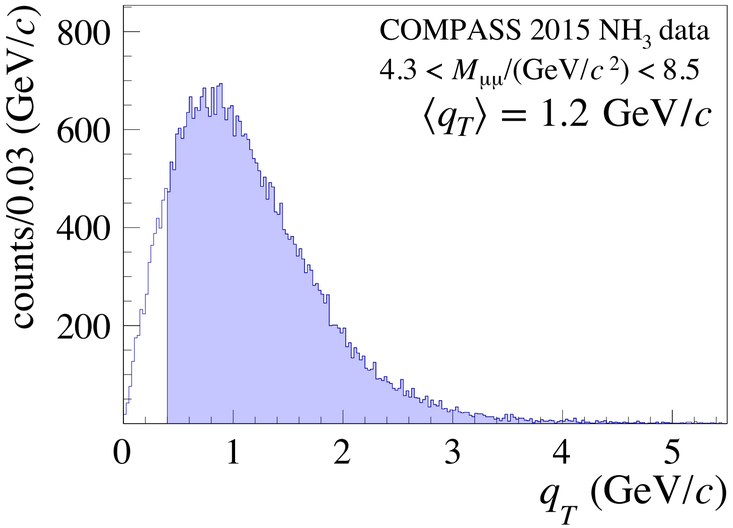
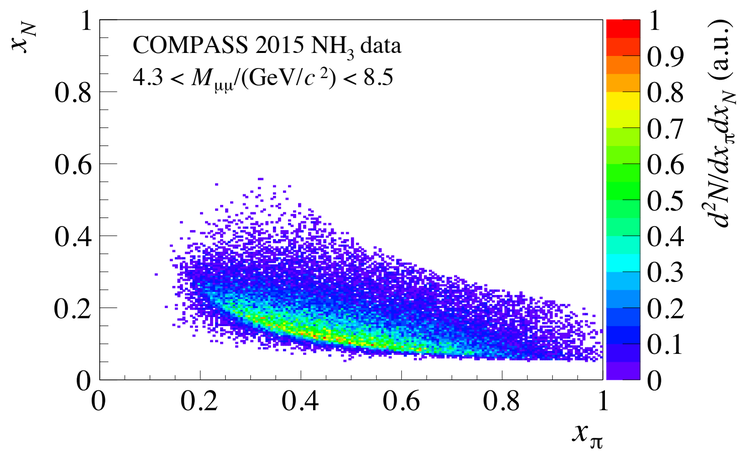
The background to DY is only 3% in the dimuon mass range 4.3-8.5 GeV/c²

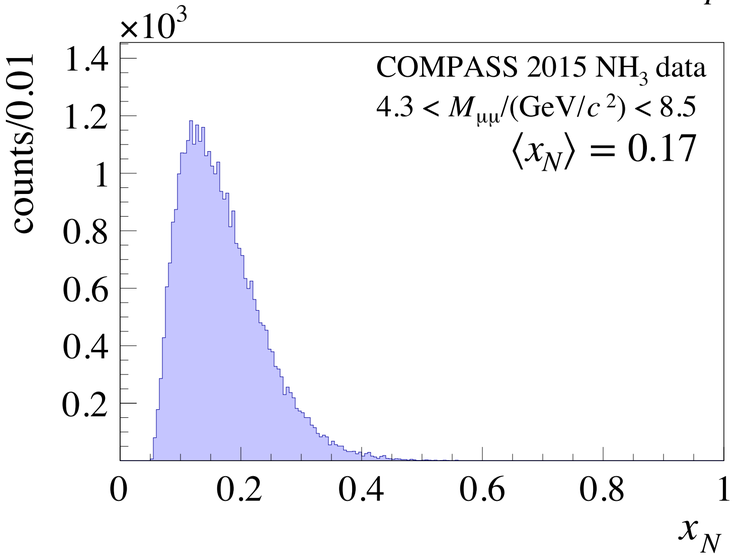
Analysis, Kinematics from **2015** Data

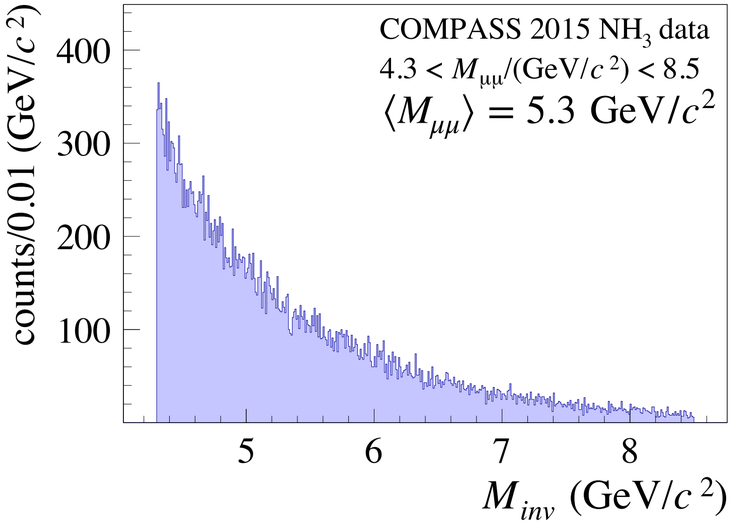






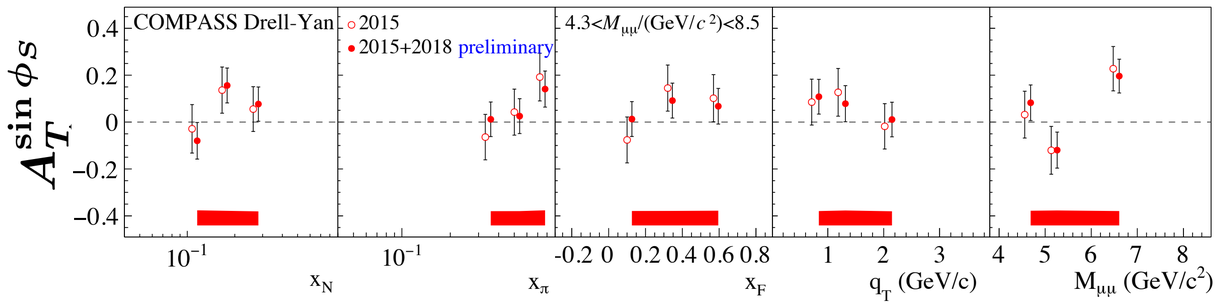




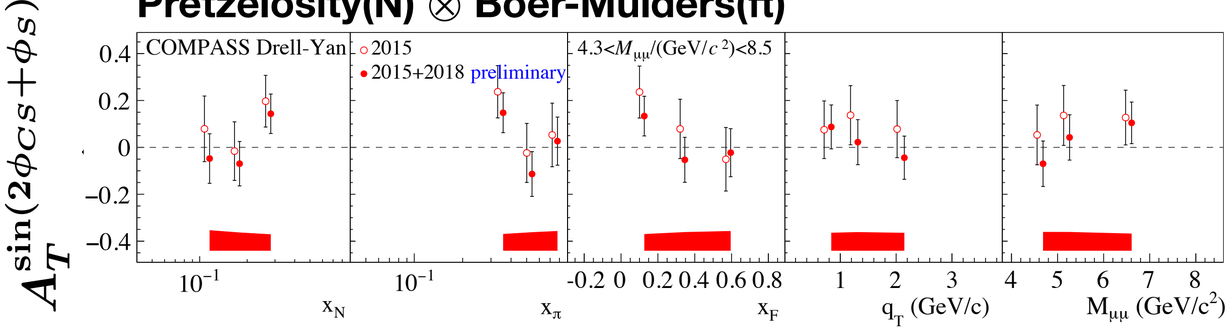


Asymmetry, 2015 & half of 2018

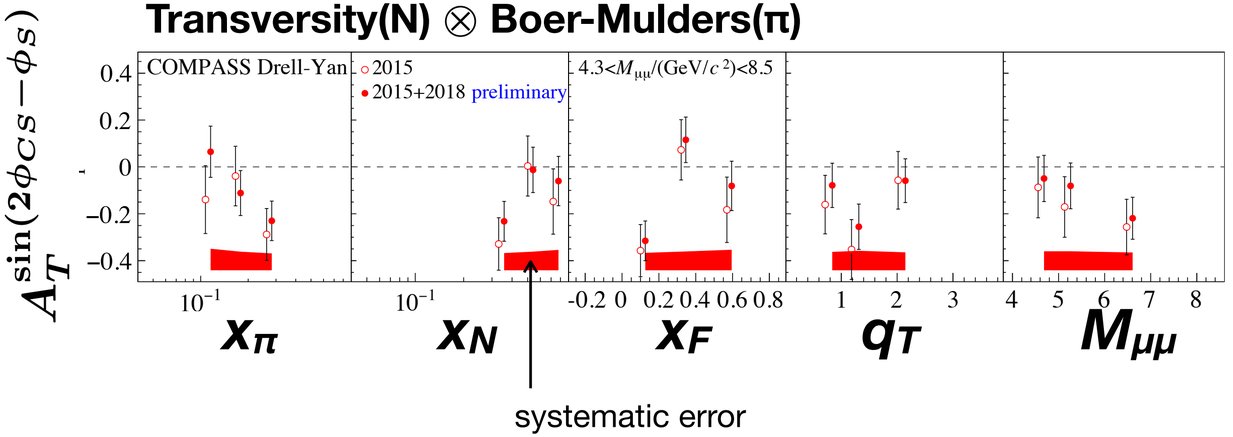
Sivers(N) ⊗ Number density(π)

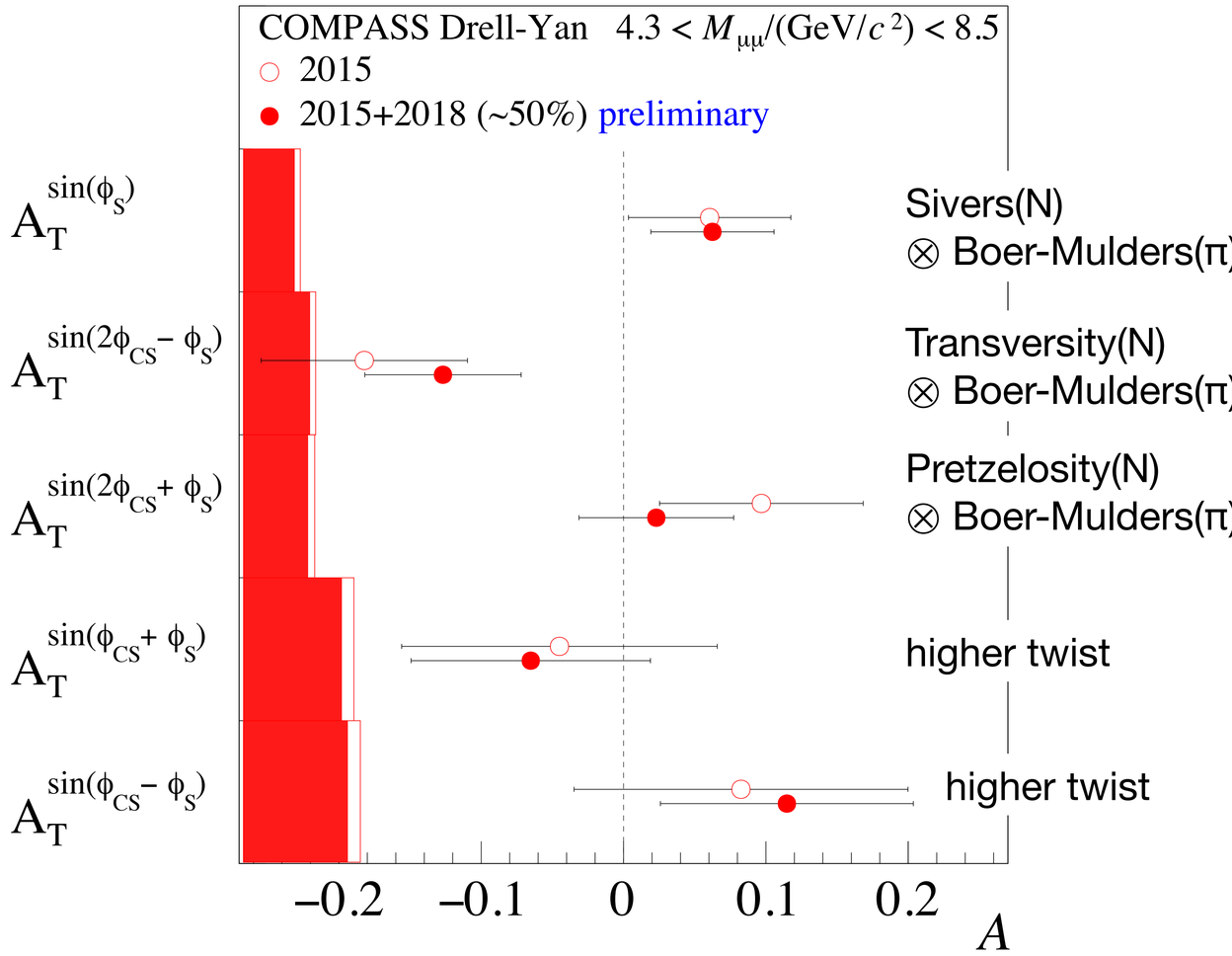


Pretzelosity(N) ⊗ Boer-Mulders(π)



Transversity(N) ⊗ Boer-Mulders(π)

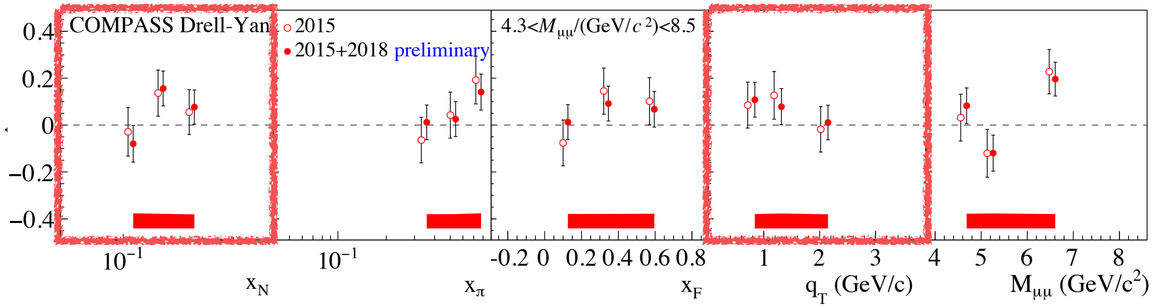




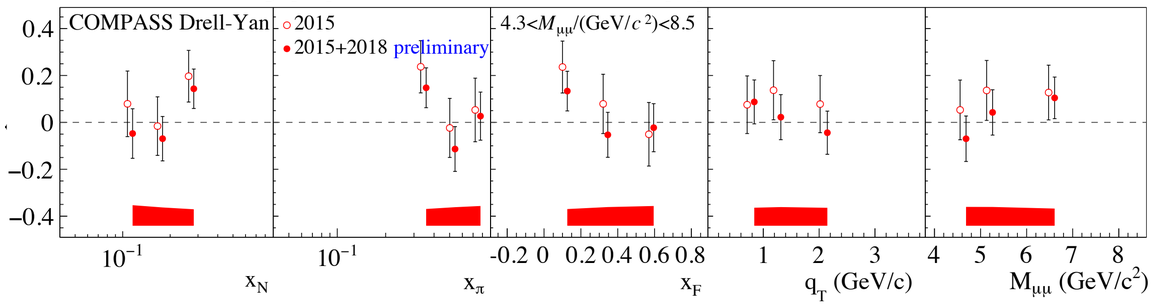
Asymmetries integrated over all variables.

Asymmetry, 2015 & half of 2018

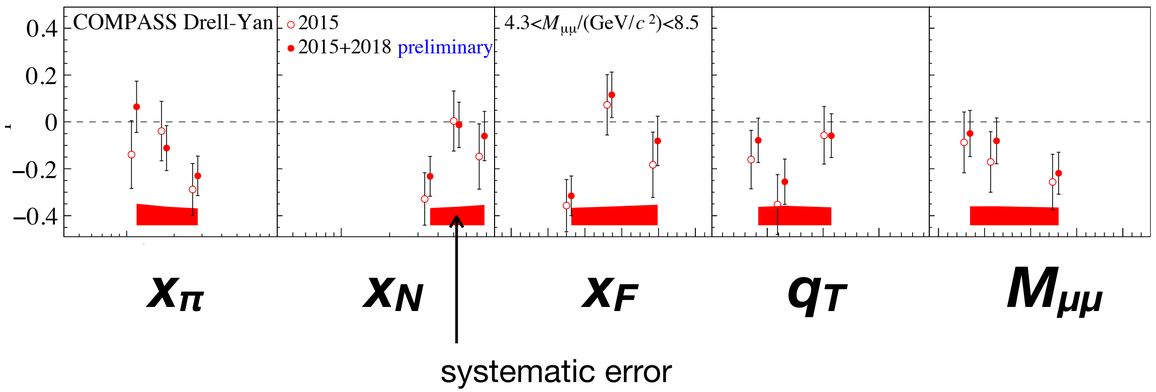
Sivers(N) ⊗ Number density(π)



Pretzelosity(N) ⊗ Boer-Mulders(π)



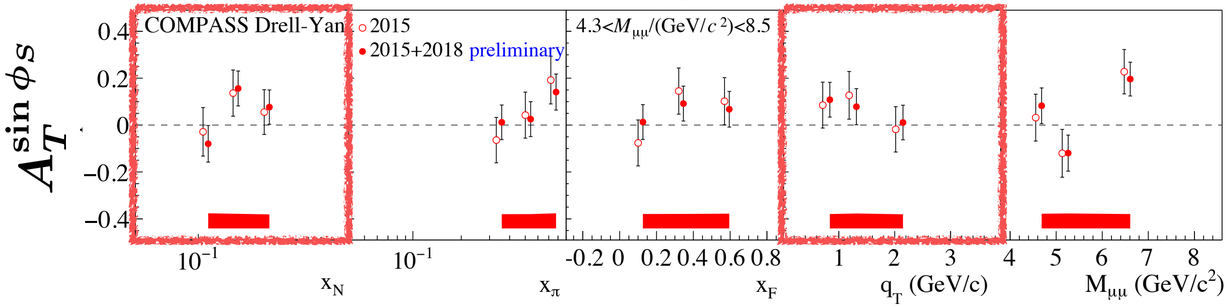
Transversity(N) ⊗ Boer-Mulders(π)



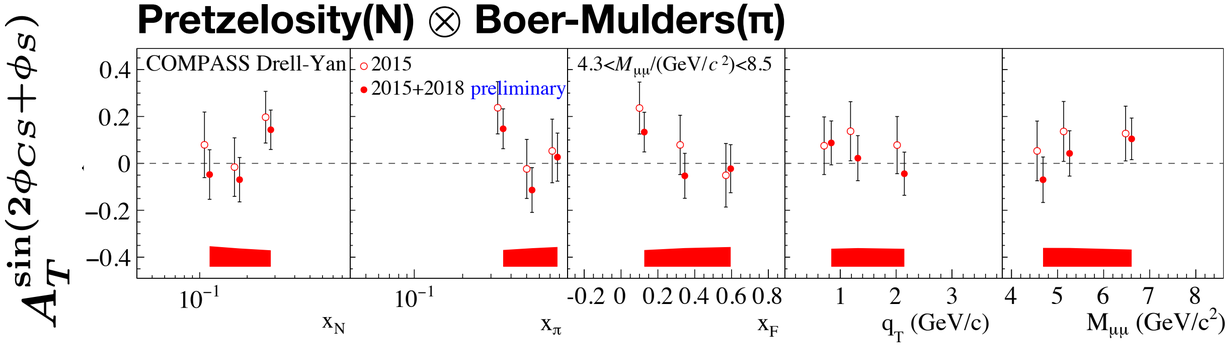
DY: positive trend

Asymmetry, 2015 & half of 2018 SIDIS, $A_{UT}^{\sin(\phi_h-\phi_S)}$: Sivers ⊗ F.F.

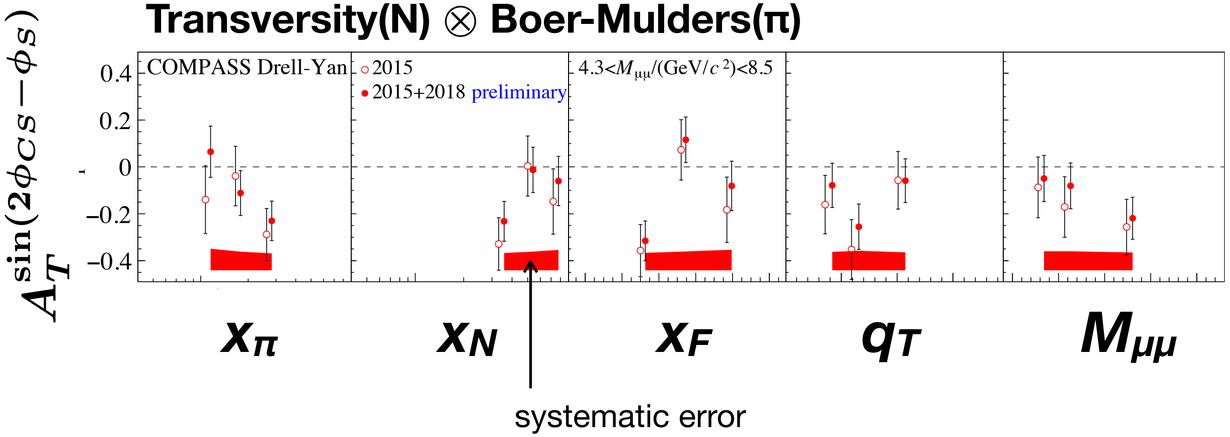
Sivers(N) ⊗ Number density(π)

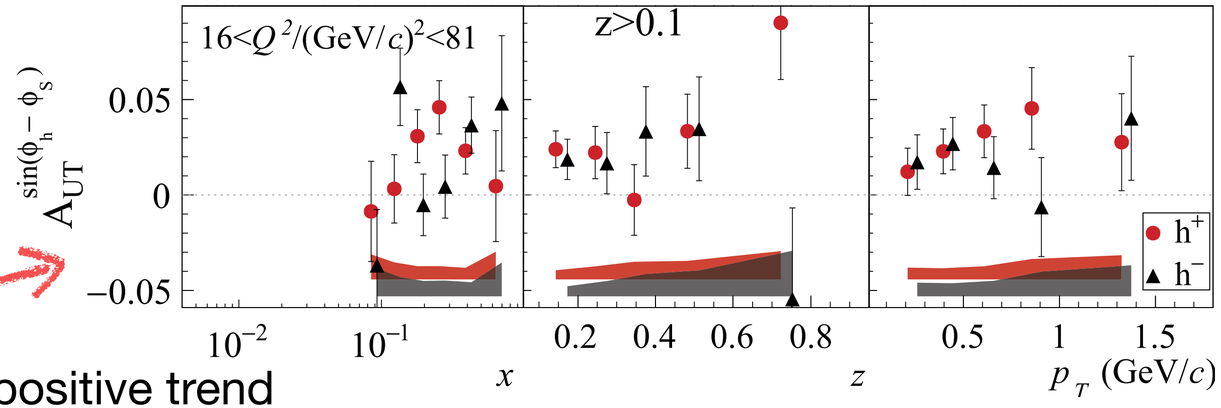


Pretzelosity(N) ⊗ Boer-Mulders(π)



Transversity(N) ⊗ Boer-Mulders(π)





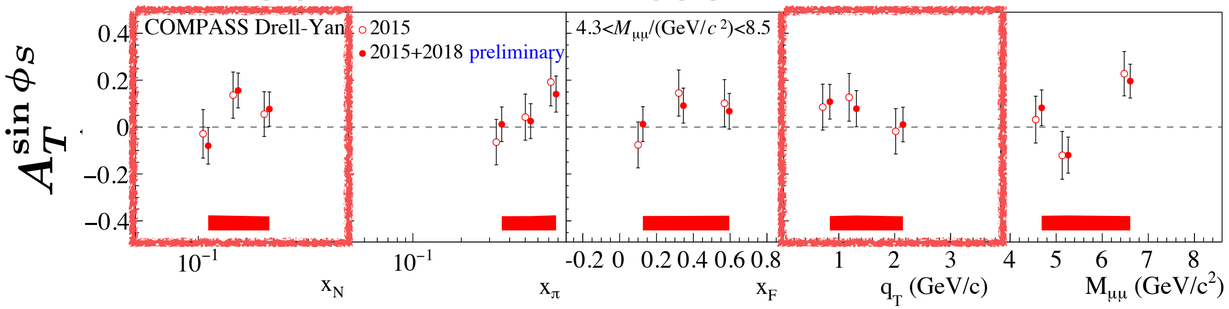
DY: positive trend
SIDIS: positive trend

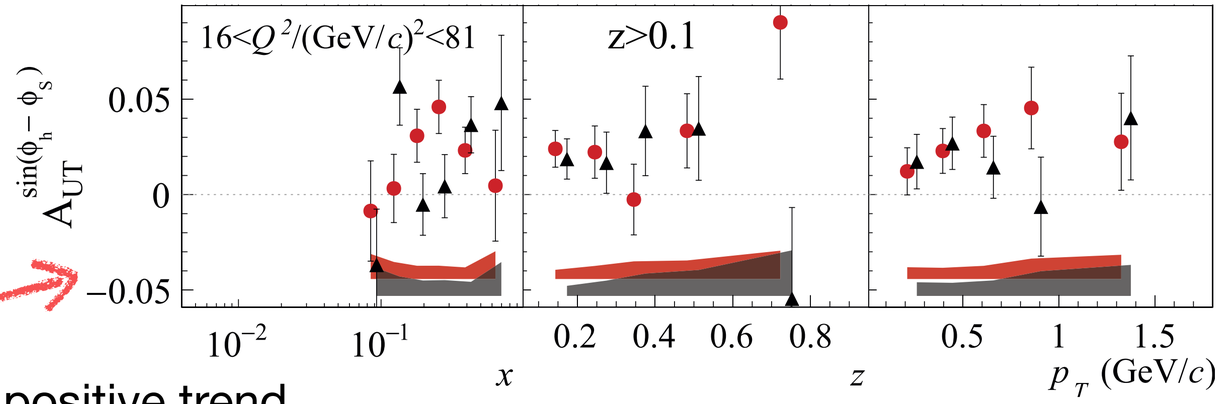
PLB770(2017)138, COMPASS

NB. Sign change of Sivers should give the same sign of asymmetry due to different definition of asymmetries in DY and SIDIS.

Asymmetry, 2015 & half of 2018 SIDIS, $A_{UT}^{\sin(\phi_h-\phi_S)}$: Sivers ⊗ F.F.

Sivers(N) ⊗ Number density(π)

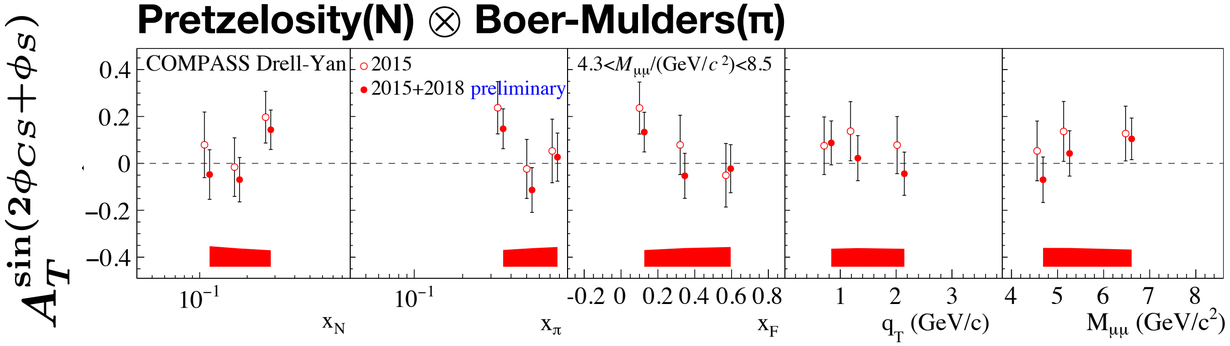




DY: positive trend
SIDIS: positive trend

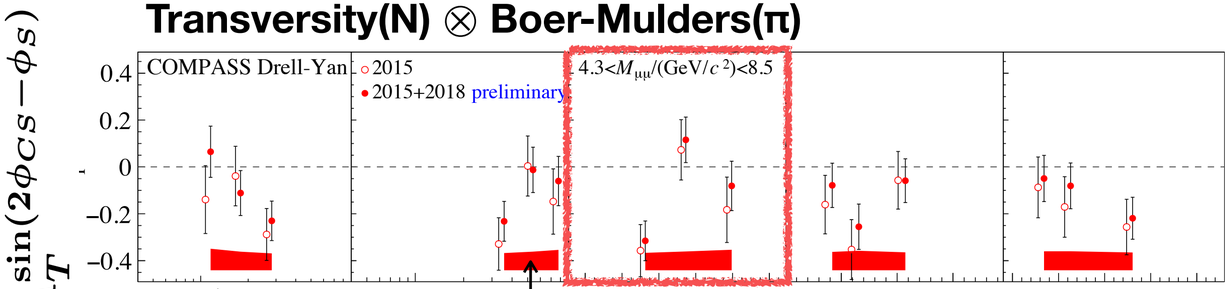
PLB770(2017)138, COMPASS

Pretzelosity(N) ⊗ Boer-Mulders(π)



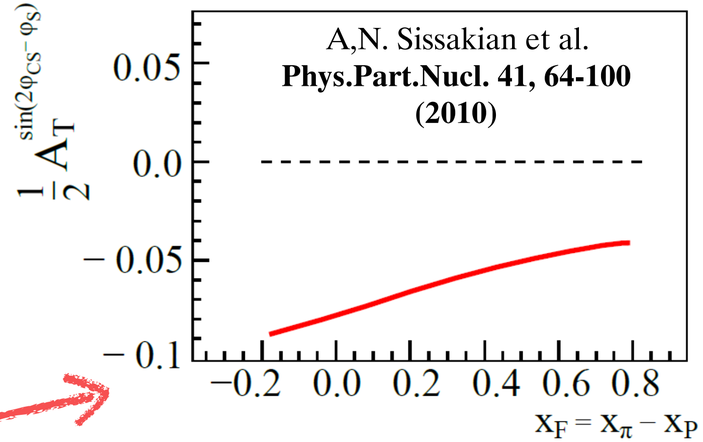
NB. Sign change of Sivers should give the same sign of asymmetry due to different definition of asymmetries in DY and SIDIS.

Transversity(N) ⊗ Boer-Mulders(π)



systematic error

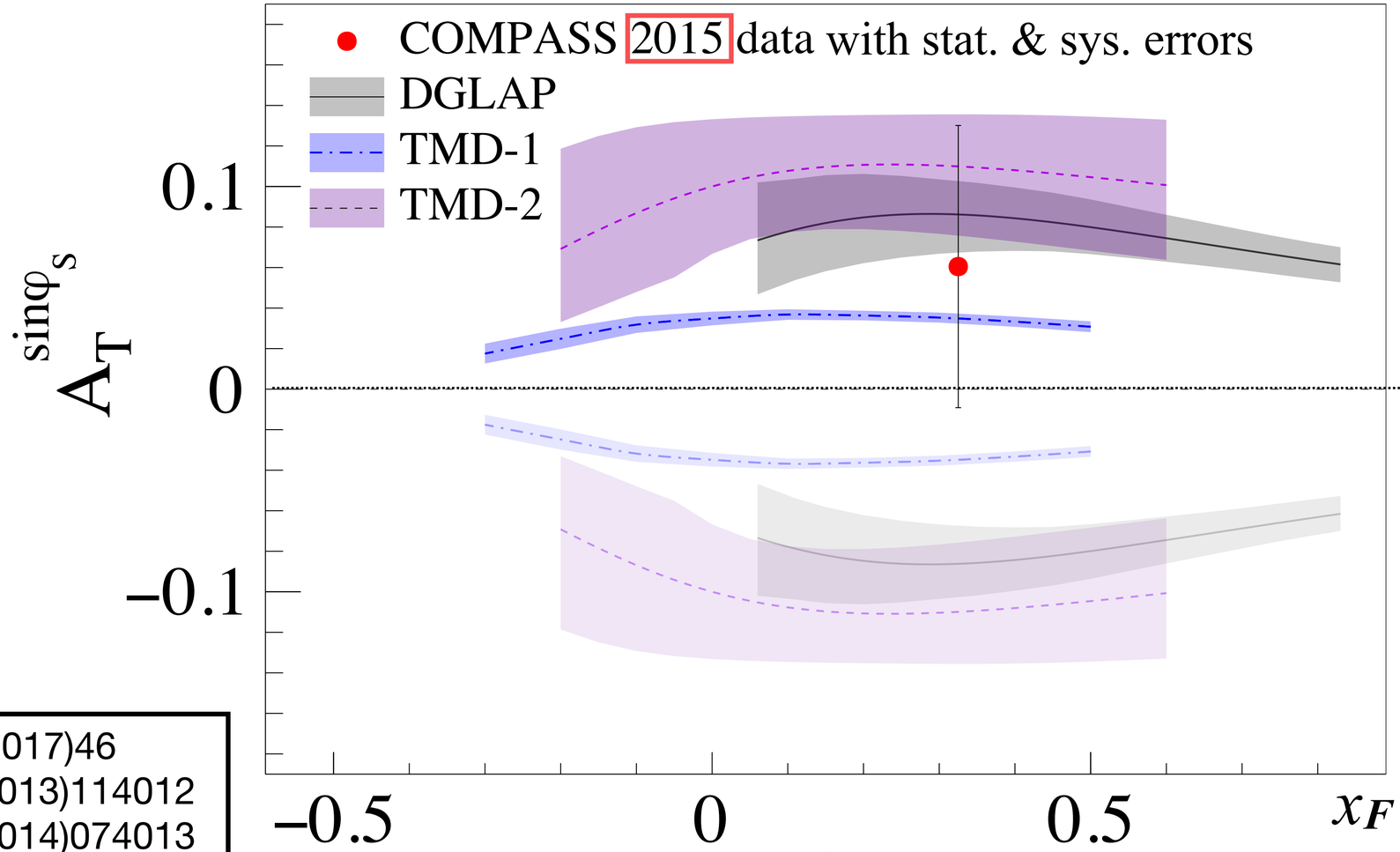
DY: negative trend
Theory: negative trend



Theoretical estimation the asymmetry from DY.

Comparison of $A_T^{\sin\phi_S}$ to theoretical estimation

$A_T^{\sin\phi_S}$ obtained from COMPASS DY and from global fits to **SIDIS** data



Sign change?

YES!

NO!

DGLAP : JHEP4(2017)46
TMD-1 : PRD88(2013)114012
TMD-2 : PRD89(2014)074013

$\langle A_T^{\sin\phi_S} \rangle = 0.060 \pm 0.057(stat.) \pm 0.040(sys.)$

PRL119 (2017) 112002

Summary

- The contribution of quarks' OAM to the nucleon spin is almost unknown.
  Study of TMDs helps to understand partons' OAM.
- COMPASS measured polarized DY process in 2015 and 2018.
  - Beam: π- with 190 GeV/c
  - Target: Transversely polarized protons in solid NH_3
  - Final 2015 sample: about 35000 dimuon events in the mass range from 4.3 to 8.5 GeV/c^2.
    Results were published in PRL119 (2017) 112002
  - Half of data taken in 2018 was already analyzed.
- All transverse spin dependent asymmetries were extracted.
  - $A_T^{\sin\phi_S}$: Sivers(N)⊗NumberDensity(π), 0.060 ± 0.057(stat.) ± 0.040 (sys.) from 2015 data suggests the sign change in comparison to the SIDIS asymmetry from COMPASS.
  - $A_T^{\sin(2\phi_{CS}+\phi_S)}$: Pretzelosity(N)⊗BM(π), consistent with 0 within errors.
  - $A_T^{\sin(2\phi_{CS}-\phi_S)}$: Transversity(N)⊗BM(π), showing negative trend as theorists obtained.