Transverse Momentum Dependent Nucleon Structure from Pions Impinged on a Transversely Polarized Proton Target

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April 30, 2019

Outline

Theory

- Proton Structure

Data Collection

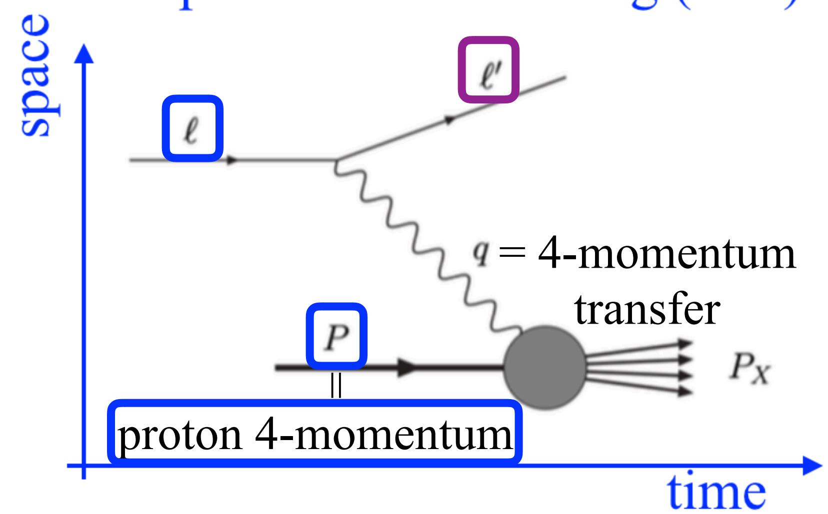
- The COMPASS experiment at CERN (2015)
- Drift Chamber 05
- Spectrometer alignment

Analysis

- Drell-Yan
- J/Ψ production

Proton Structure

Deep Inelastic Scattering (DIS)



Cross-section

$$\sigma \propto L^{\mu\nu} W_{\mu\nu}$$

Lepton Tensor

QED => Perturbation Theory

Hadron Tensor

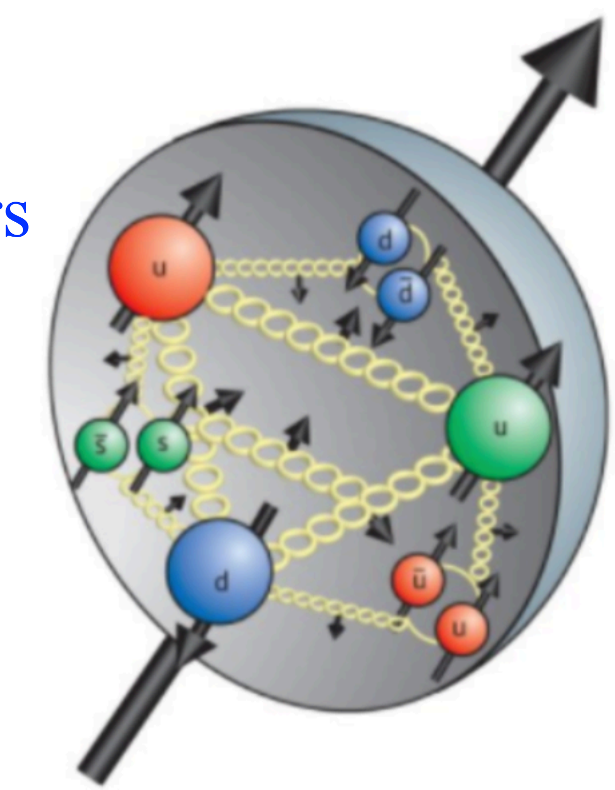
QCD => unable to determine with Perturbation Theory

Parameterize and measure parameters

- Spin 1/2 hadron parameterization (spin-independent)

$$W_{\mu\nu} \propto \sum_{q=u,\, d,\, s} e_q^2 \boxed{f_1^q}$$

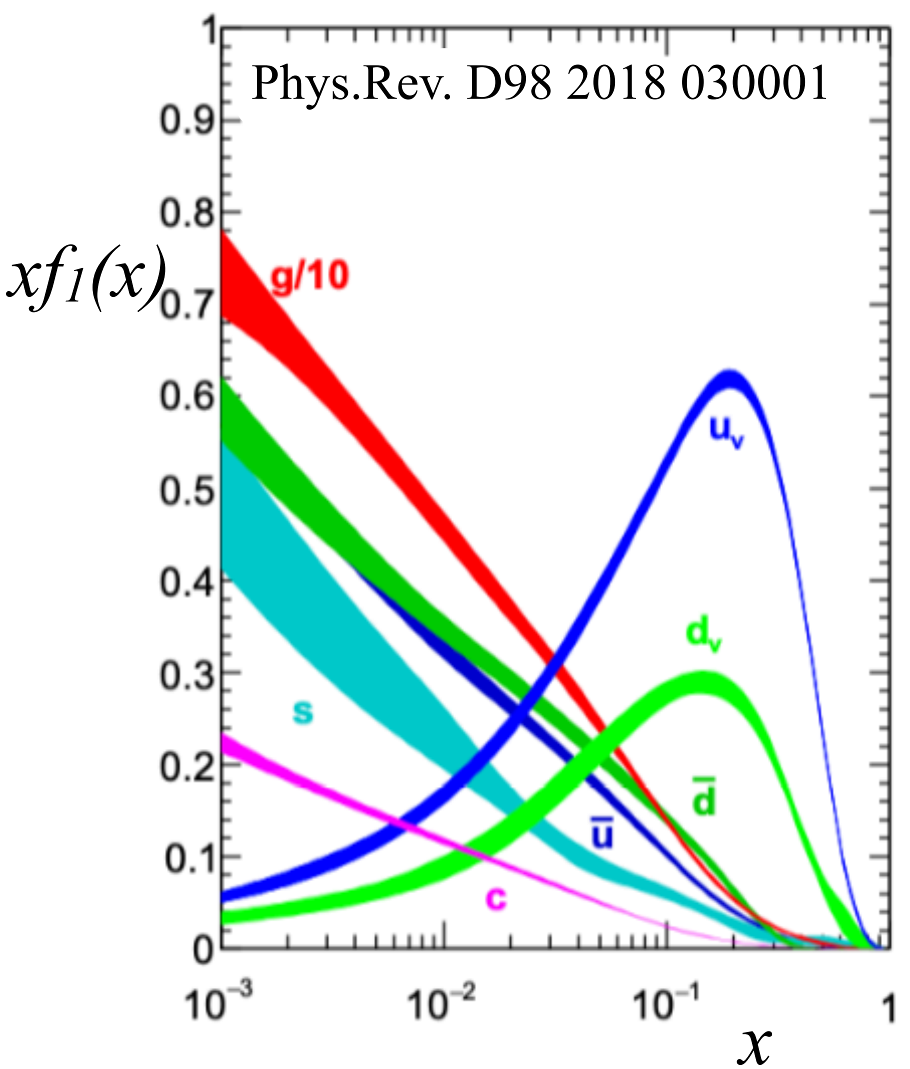
- Proton
  valence quarks up/up/down
  sea quarks in quark/anti-quark pairs
  gluons bind valence/sea quarks



Longitudinal Proton Structure

$$W_{\mu\nu} \propto \sum_{q=u,\,d,\,s} e_q^2 \boxed{f_1^q}$$

- Proton
  - partons (quarks/gluon)
  - longitudinal momentum parallel to the proton's momentum *P*
  - Parton Distribution Functions (PDF) describe bound partons (*f*)



Experimental Observable:

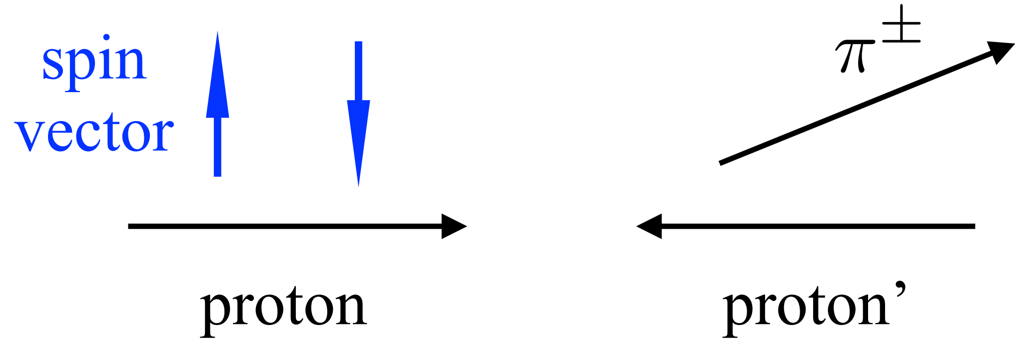
Bjorken x
parton longitudinal momentum fraction

$$x = \frac{|q^2|}{2P\cdot q} \qquad 0 < x < 1$$

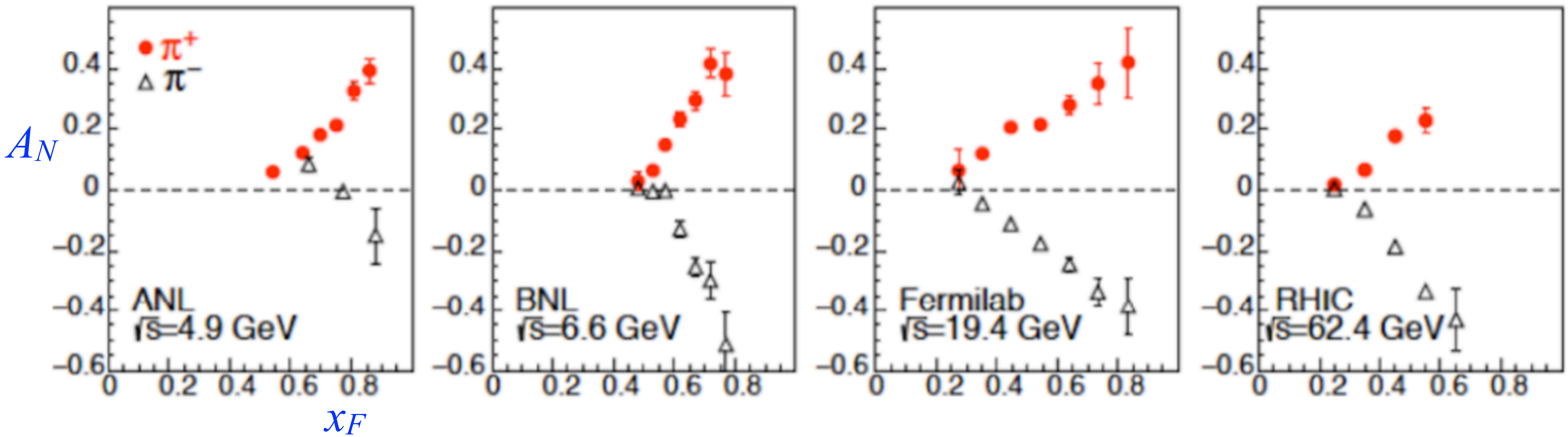
x > ~ 0.1 Valence quarks

Transverse Proton Structure

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$



- Under collinear parton momentum assumption
  Analyzing power (A_N) predicted to be ~ 10^{-4}



Experimental Observable:

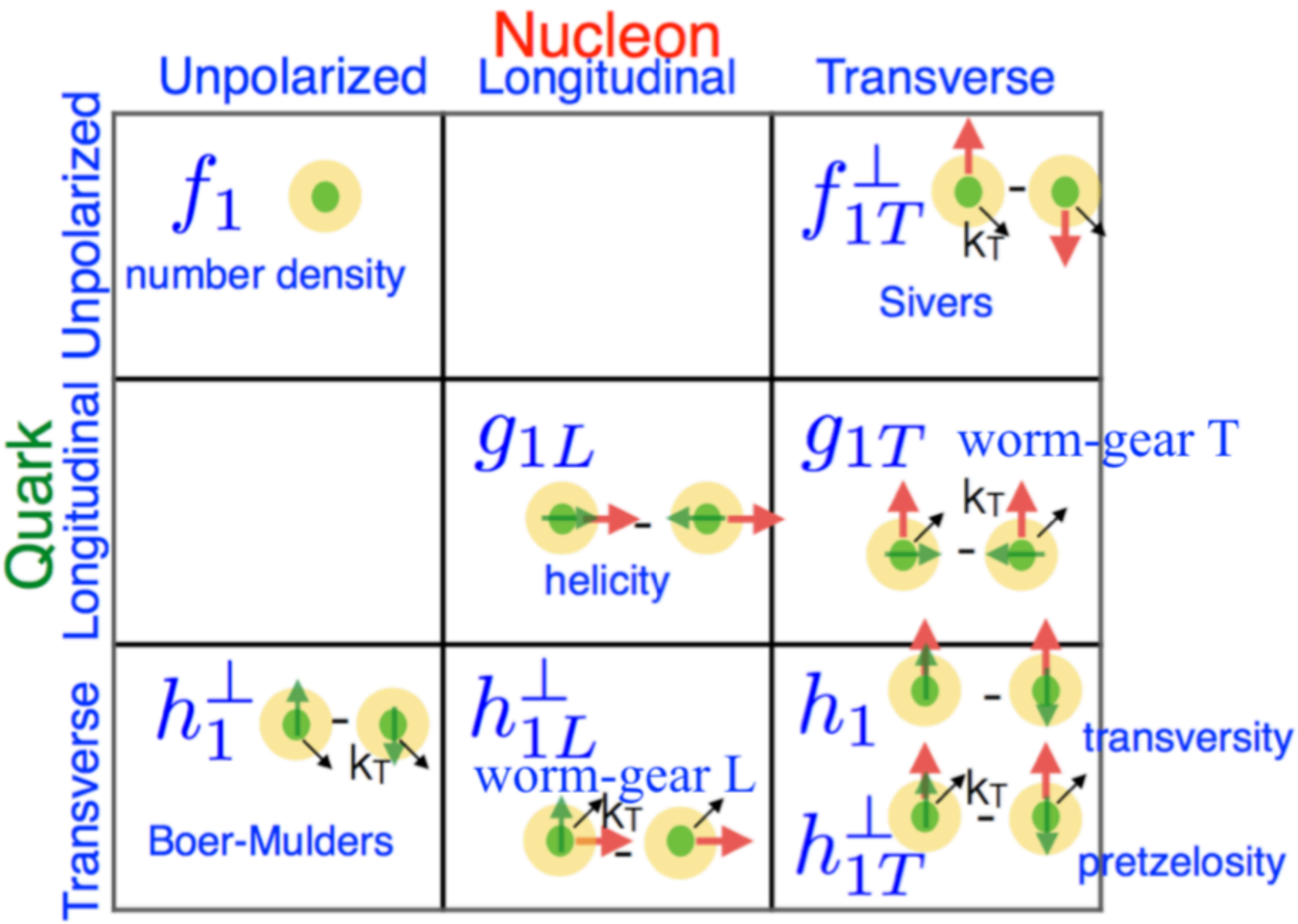
x-Feynman = longitudinal momentum / maximum longitudinal momentum

$$x_F = x_{beam} - x_{target} \qquad -1 < x_F < 1$$

Transverse Momentum Dependent (TMD) Parton Distribution Functions

- Distributions depend on parton transverse momentum k_T and longitudinal momentum fraction x

- Spin 1/2 hadron tensor ($W^{\mu\nu}$) is parametrized by 8 TMDs



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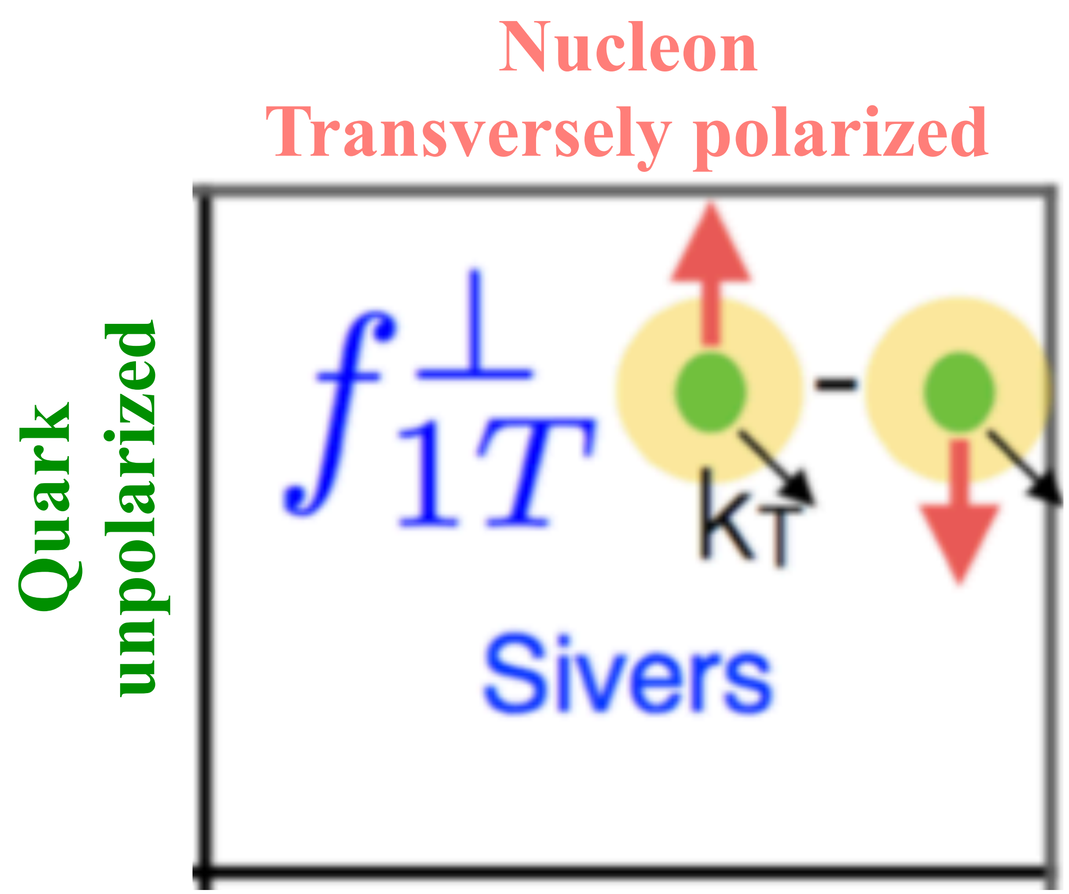
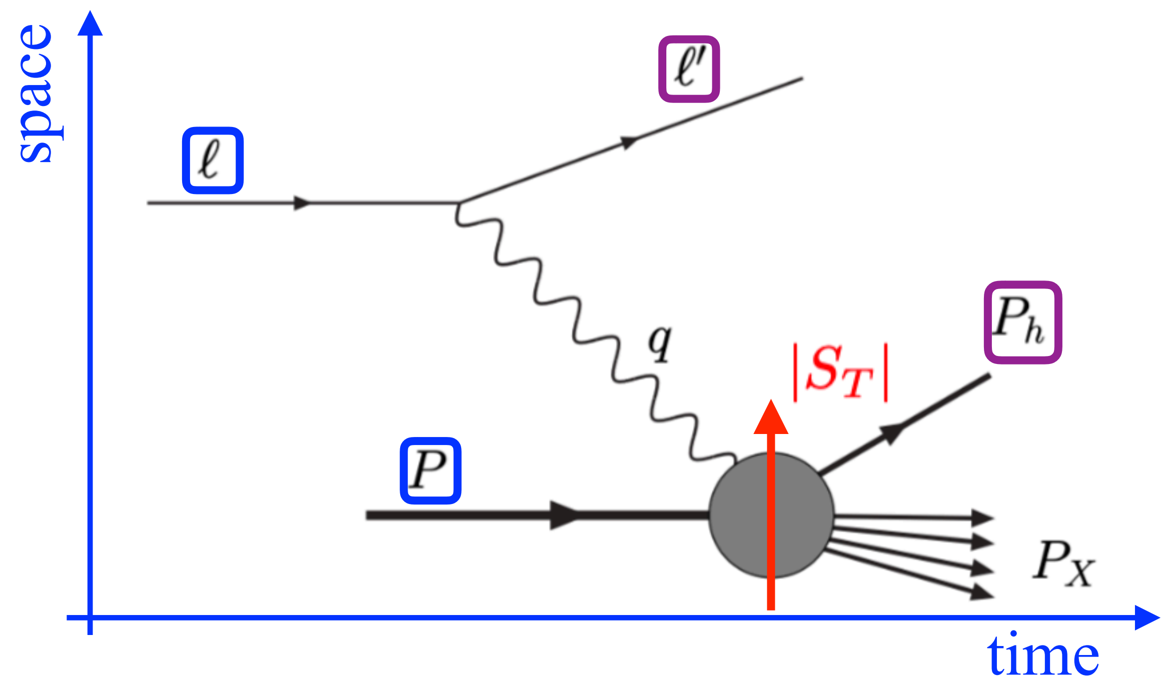
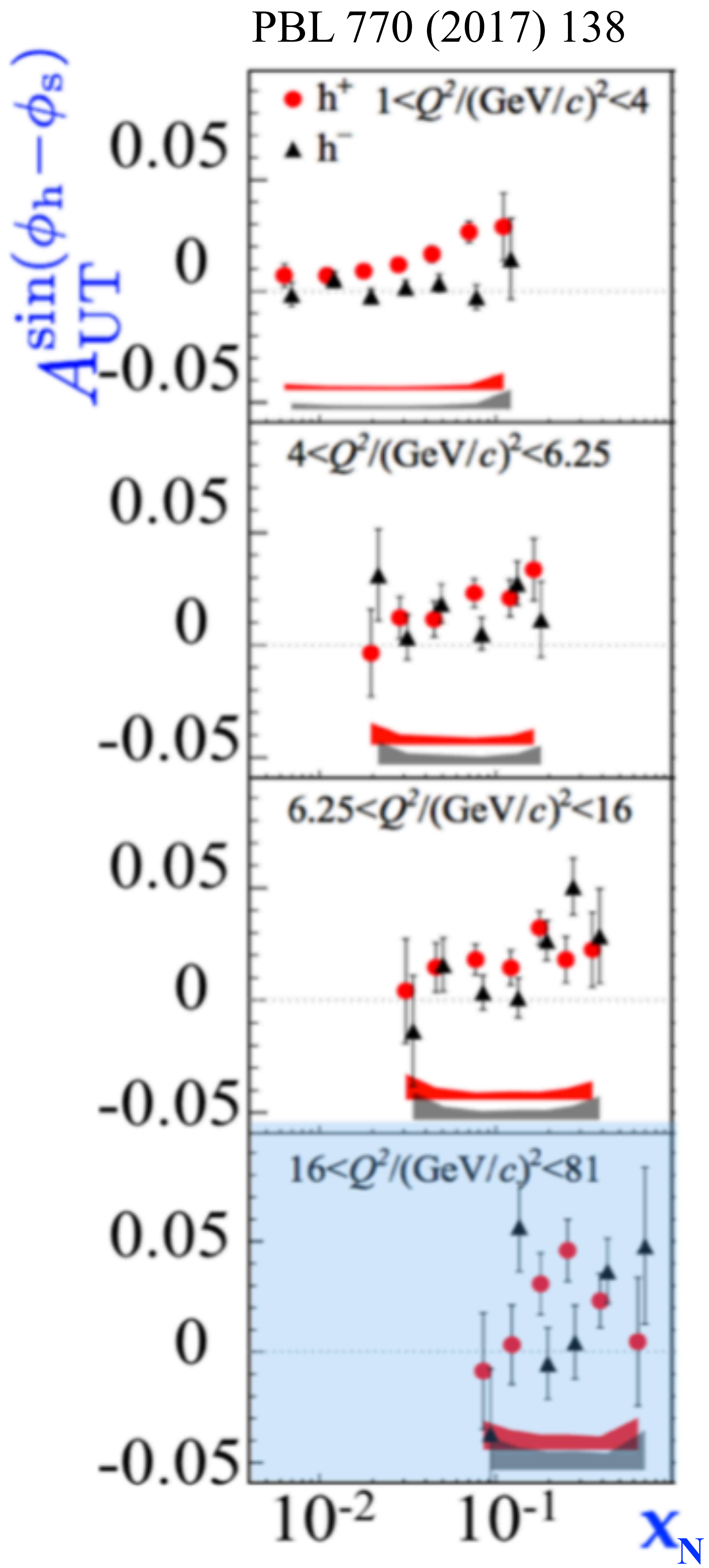


Sivers: Correlation between the *transverse parton momentum* and the *parent hadron's transverse spin*

$$f_{1T}^{\perp q}|_{Drell-Yan} = -f_{1T}^{\perp q}|_{SIDIS}$$

Semi-Inclusive Deep Inelastic Scattering (SIDIS)





$$\frac{d\sigma^{SIDIS}}{dx\,d\phi_S\,d\phi_h} \propto |S_T| \sin(\phi_h - \phi_S) A_{UT}^{\sin(\phi_h-\phi_S)}$$

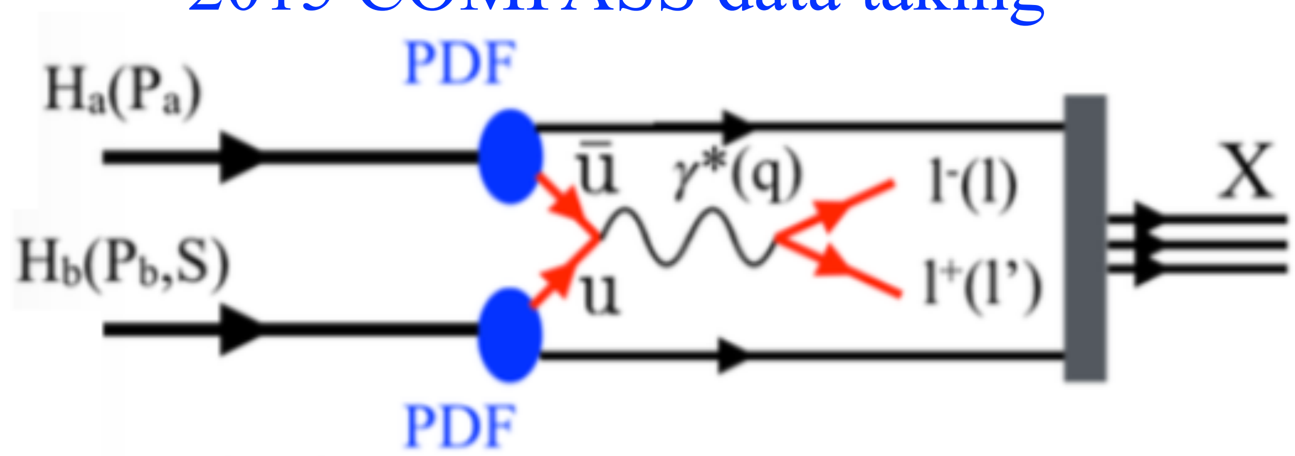
Sivers amplitude   Sivers function

$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

- A Sivers amplitude has been measured from the SIDIS process on a transversely polarized proton target at COMPASS

Drell-Yan

2015 COMPASS data taking



$$\pi^-(P_\pi) + p(P_p,\ S_T) \to \gamma^* + X \to \mu^-(\ell) + \mu^+(\ell') + X$$

- ūu annihilation
- Measured final states is two oppositely charged muons (di-muon pair)

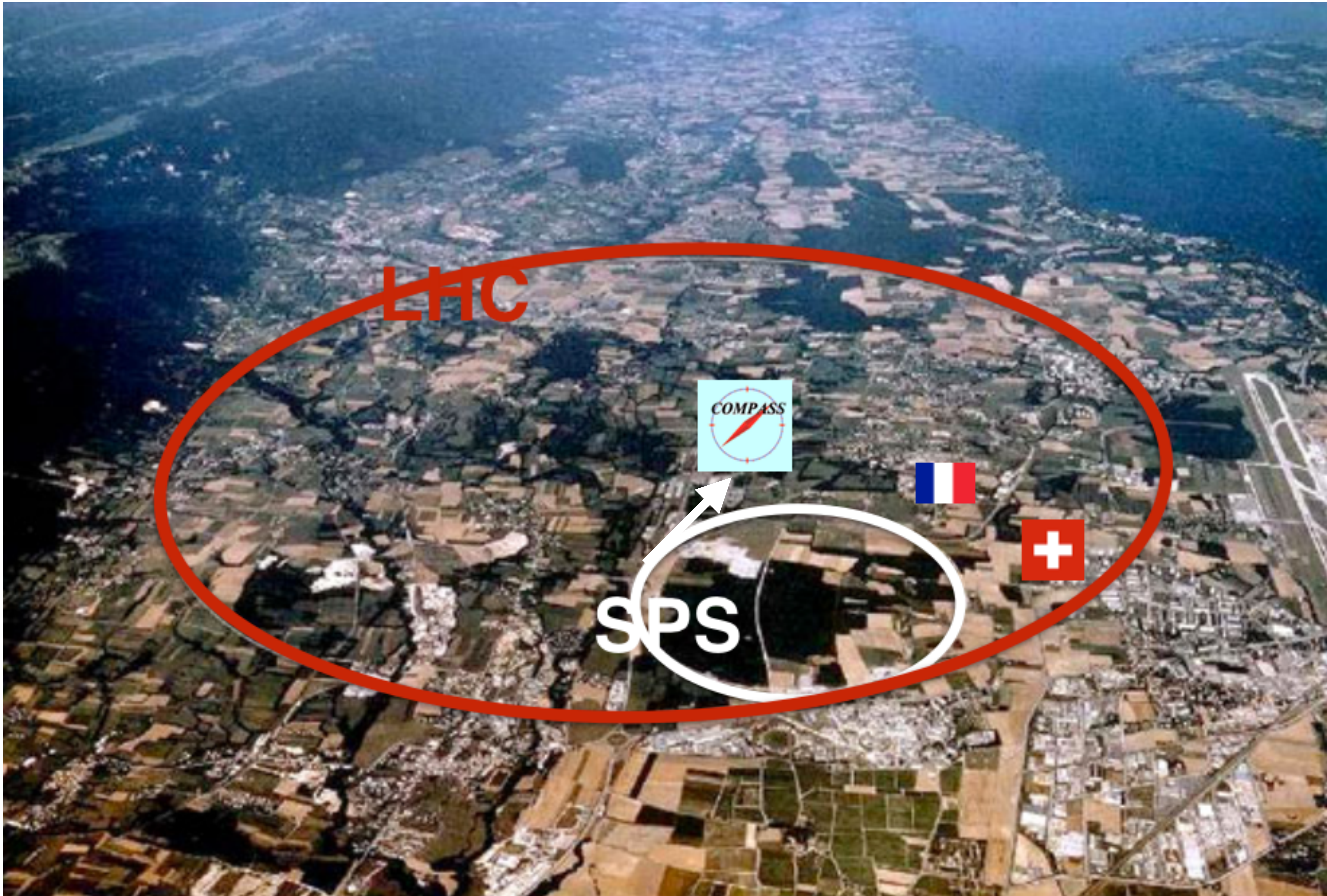
Experimental Observables:

Bjorken x	x-Feynman	di-muon invariant mass
$x = \dfrac{\lvert q^2 \rvert}{2P \cdot q}$	$x_F = x_{beam} - x_{target}$	$\sqrt{q^2} = M_{\mu\mu}$

Goal is to measure a Sivers amplitude!

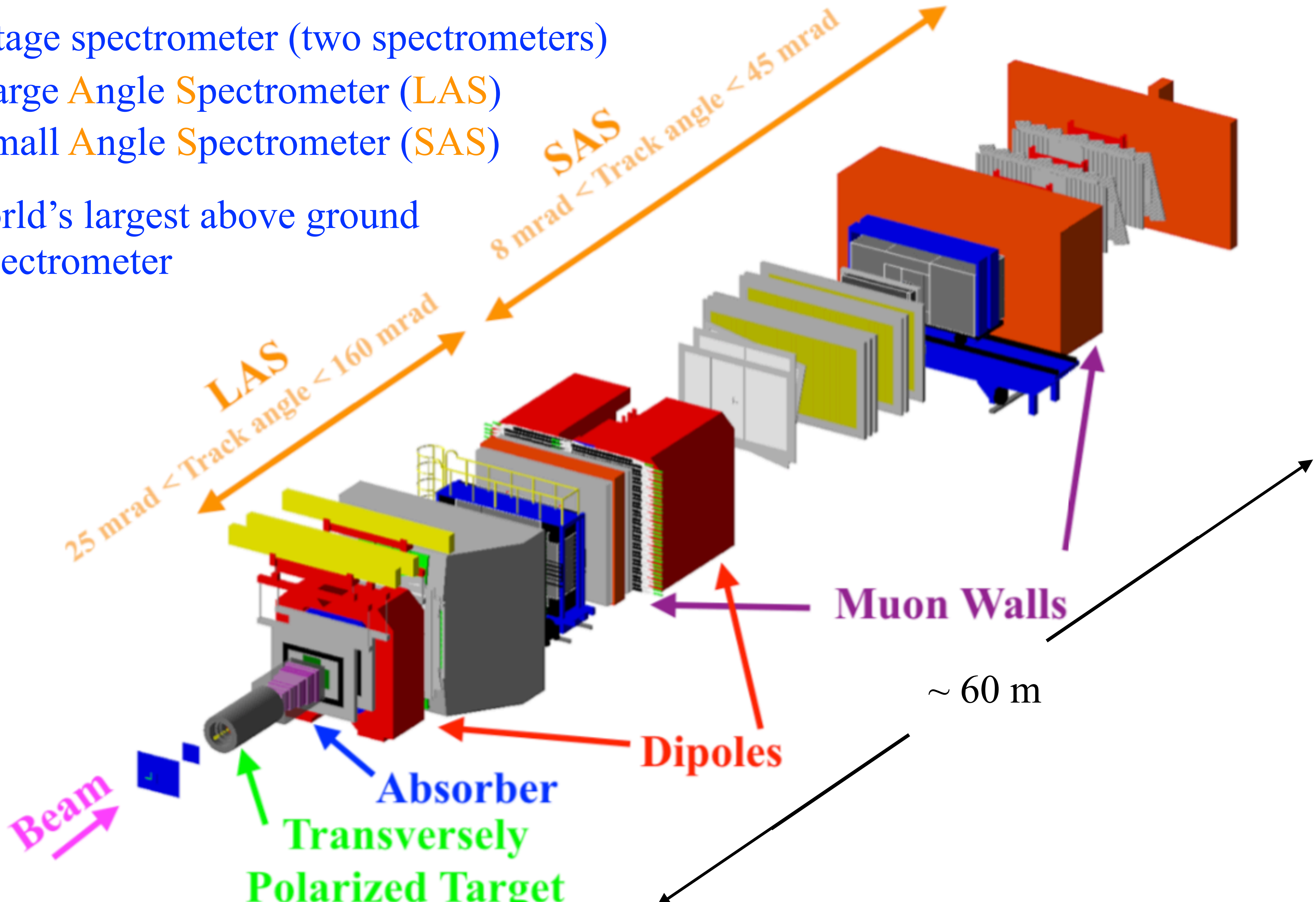
COMPASS

COmmon Muon Proton Apparatus for Structure and Spectroscopy



COMPASS Spectrometer

- 2 stage spectrometer (two spectrometers)
  Large Angle Spectrometer (LAS)
  Small Angle Spectrometer (SAS)
- World's largest above ground spectrometer



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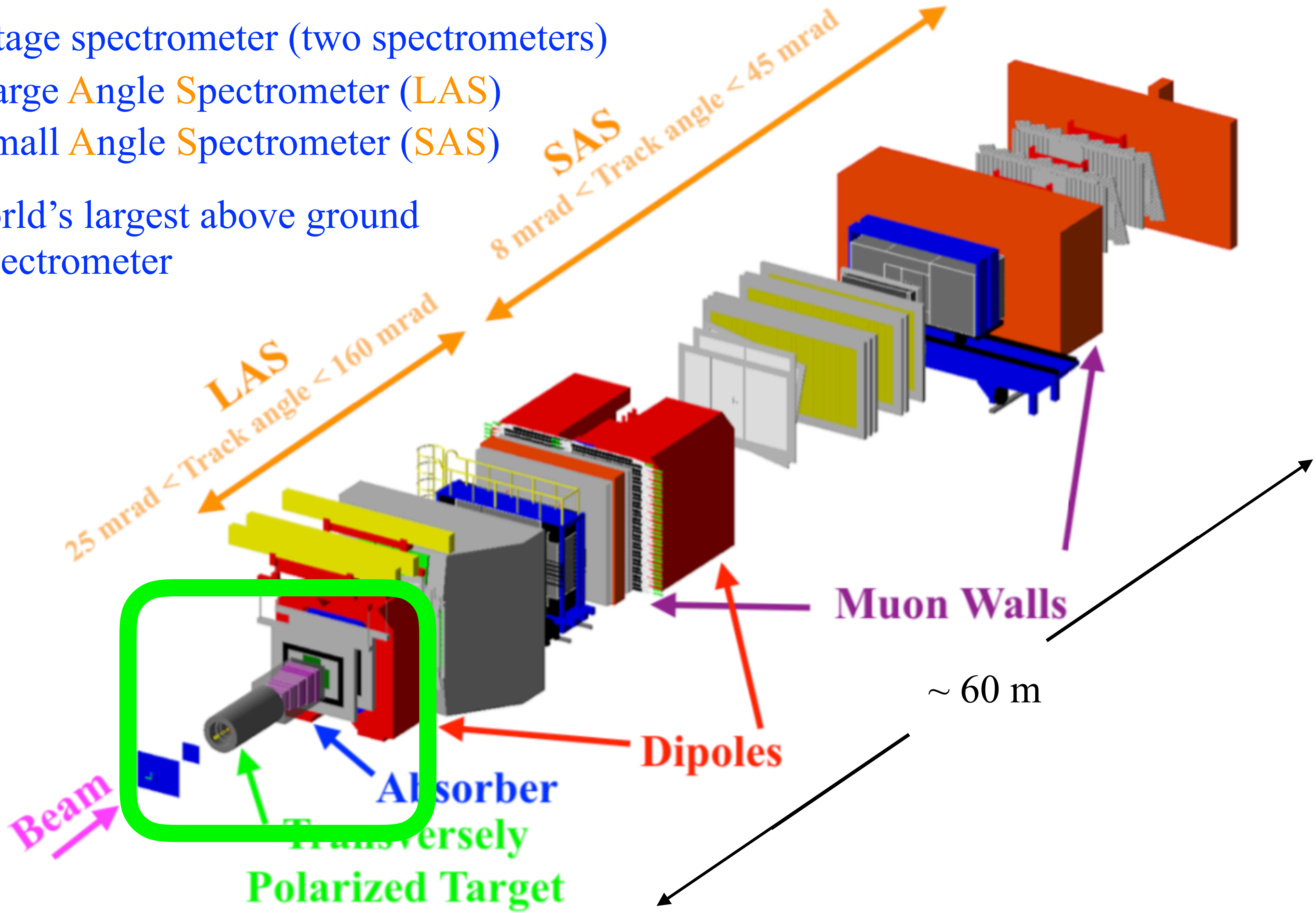


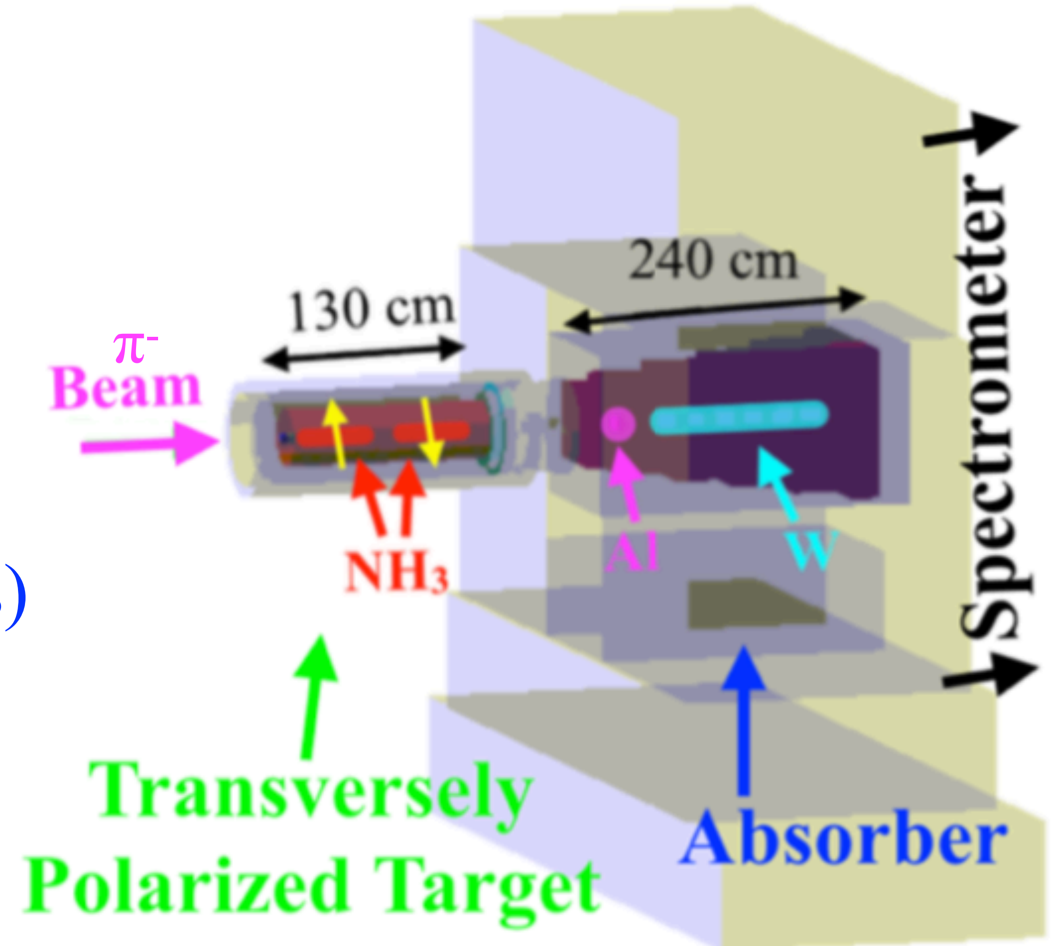
2015 COMPASS Data Taking

- Negatively charged pion beam
  π^- 190 GeV/c momentum

- Transversely polarized NH_3 target
  2 target cells
  Polarized in opposite directions
  ~70% polarization

- Data recorded in periods (1 period = ~2 weeks)
  Target polarization flipped in the middle of each period
  Ensures reduced systematic effects from acceptance

- Hadron absorber
  Ensures majority of detected particles are muons
  Includes 2 nuclear targets (Al, W)



Drift Chamber 05

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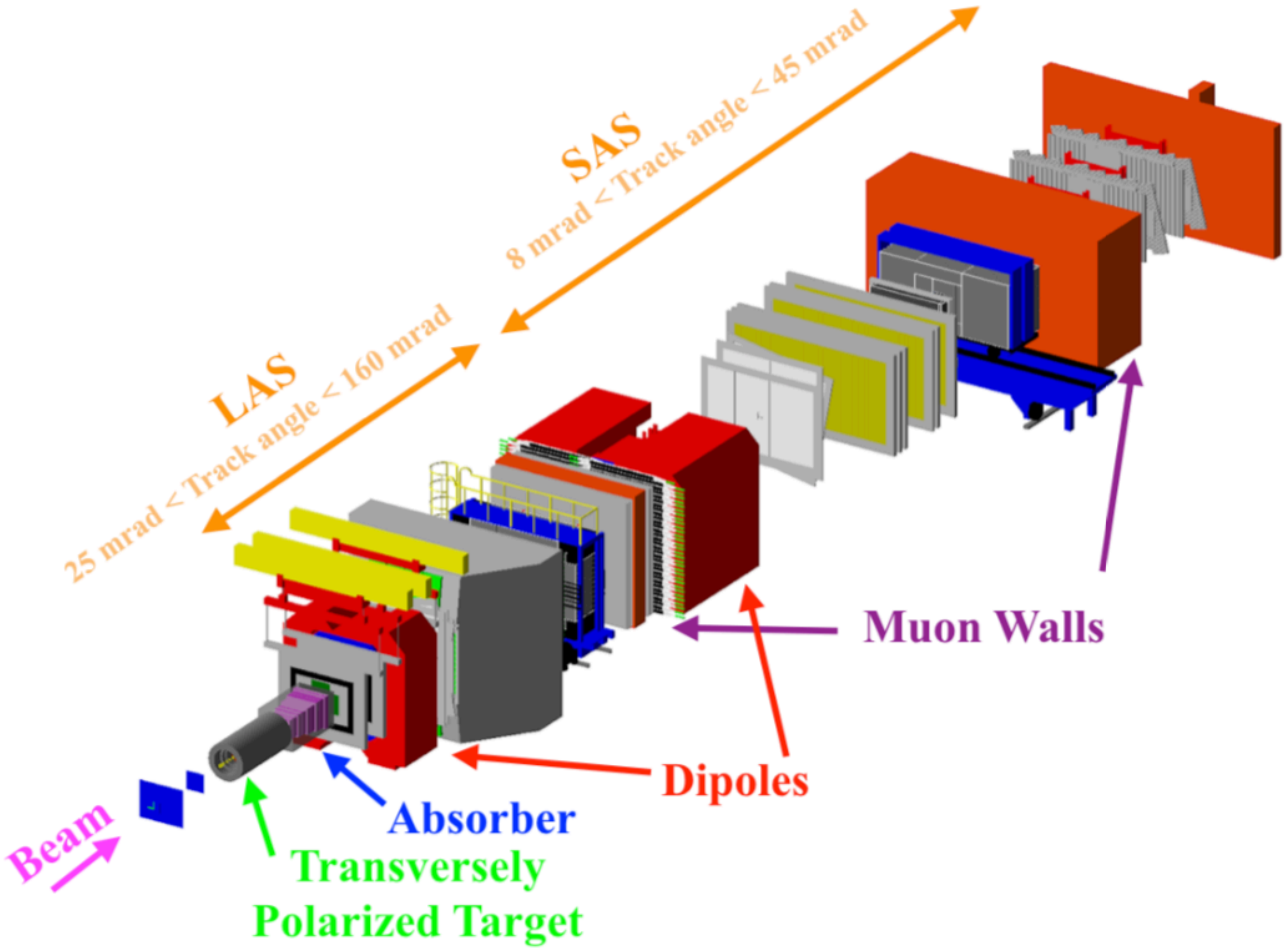

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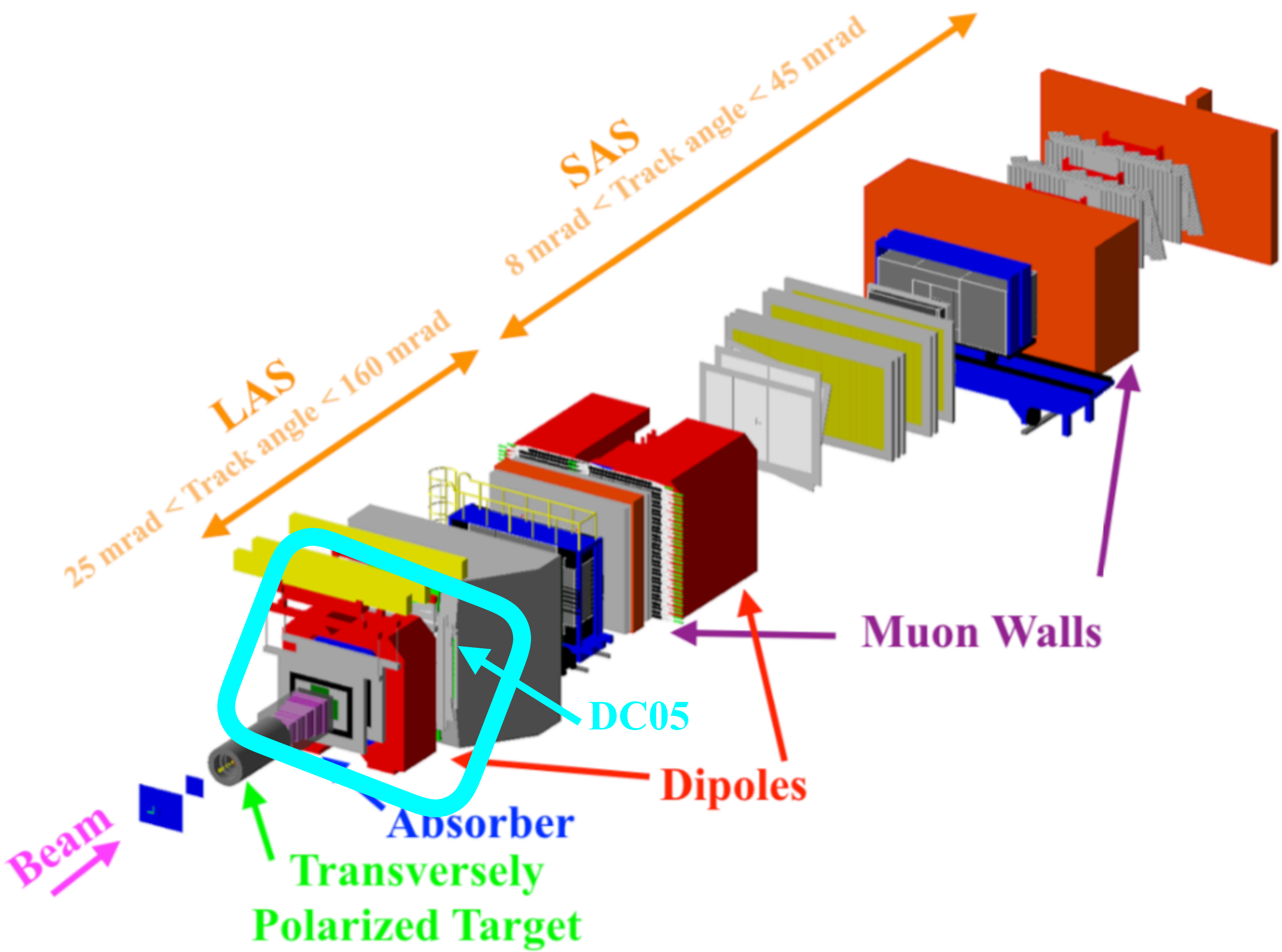
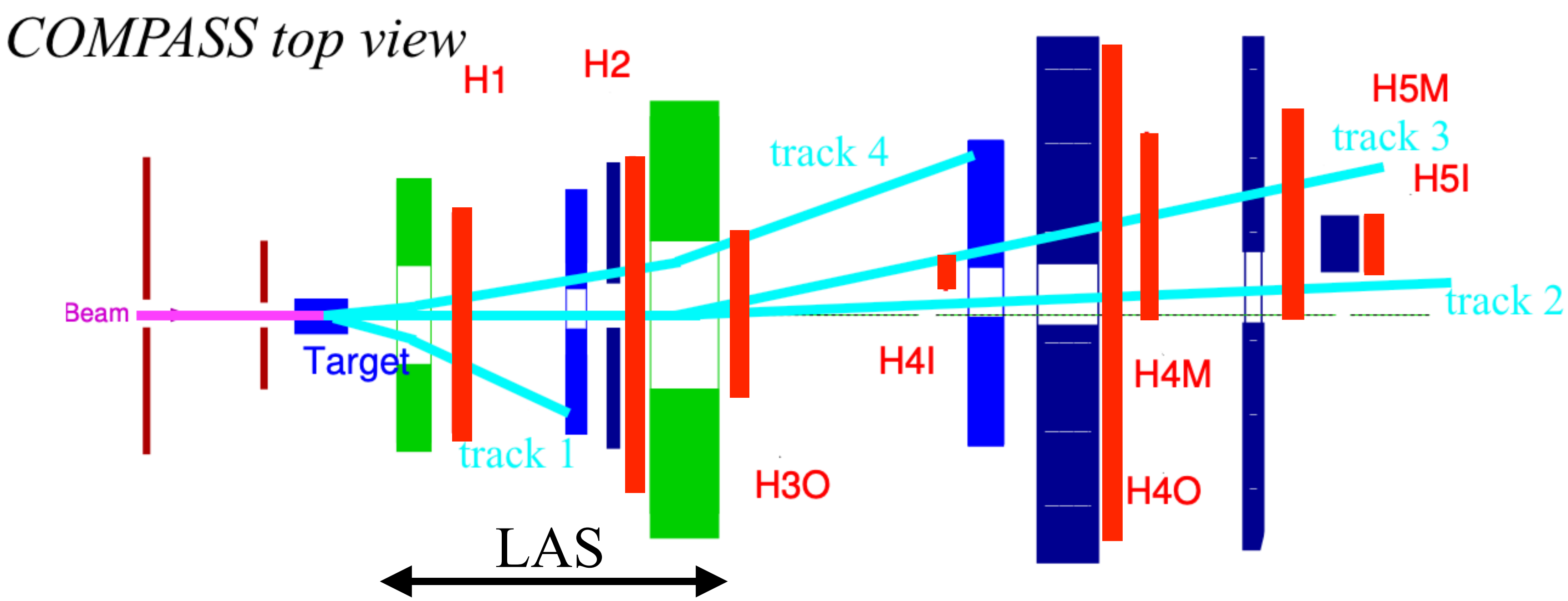


DC05 Motivation



- All 2015 analysis events include a track in the Large Angle Spectrometer (LAS)

- LAS tracking is critical for reconstruction efficiency!

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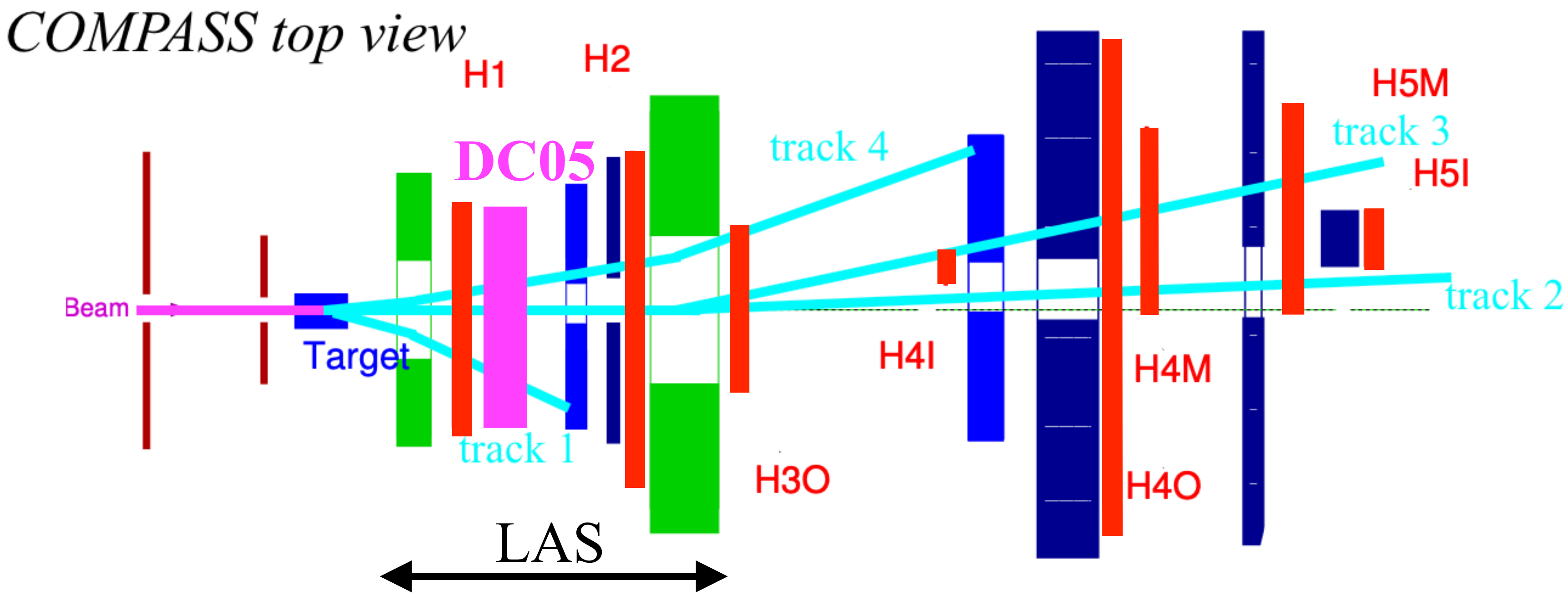

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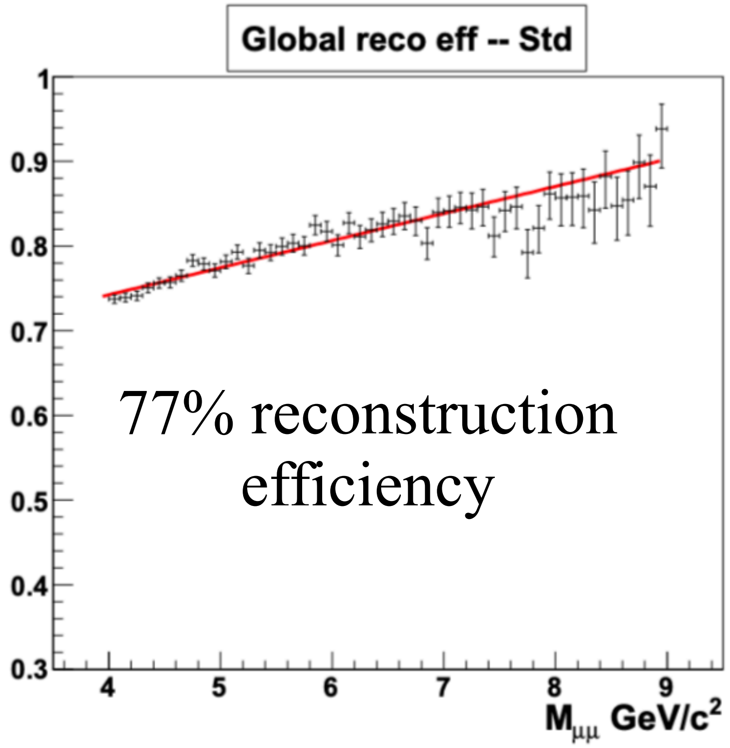
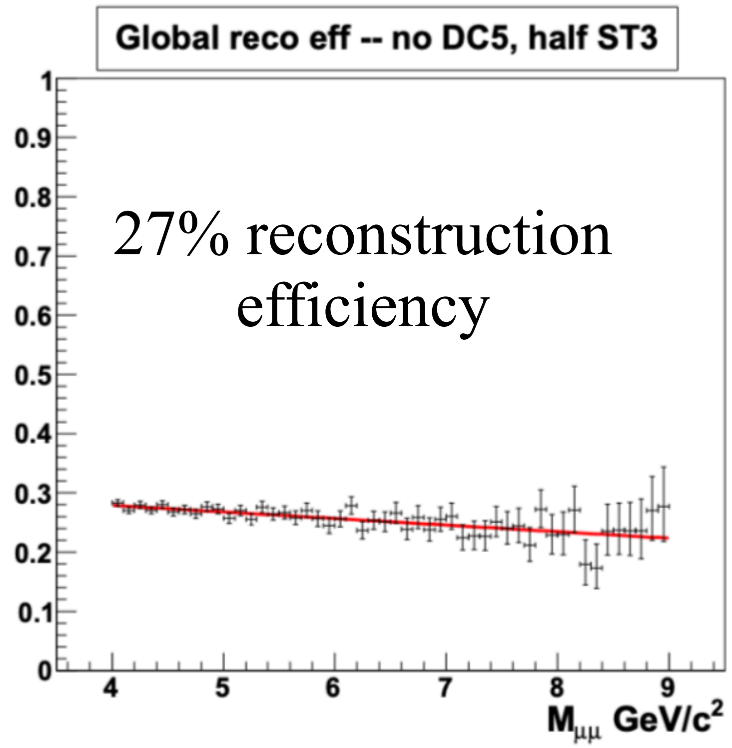
- LAS tracking is critical for reconstruction efficiency!

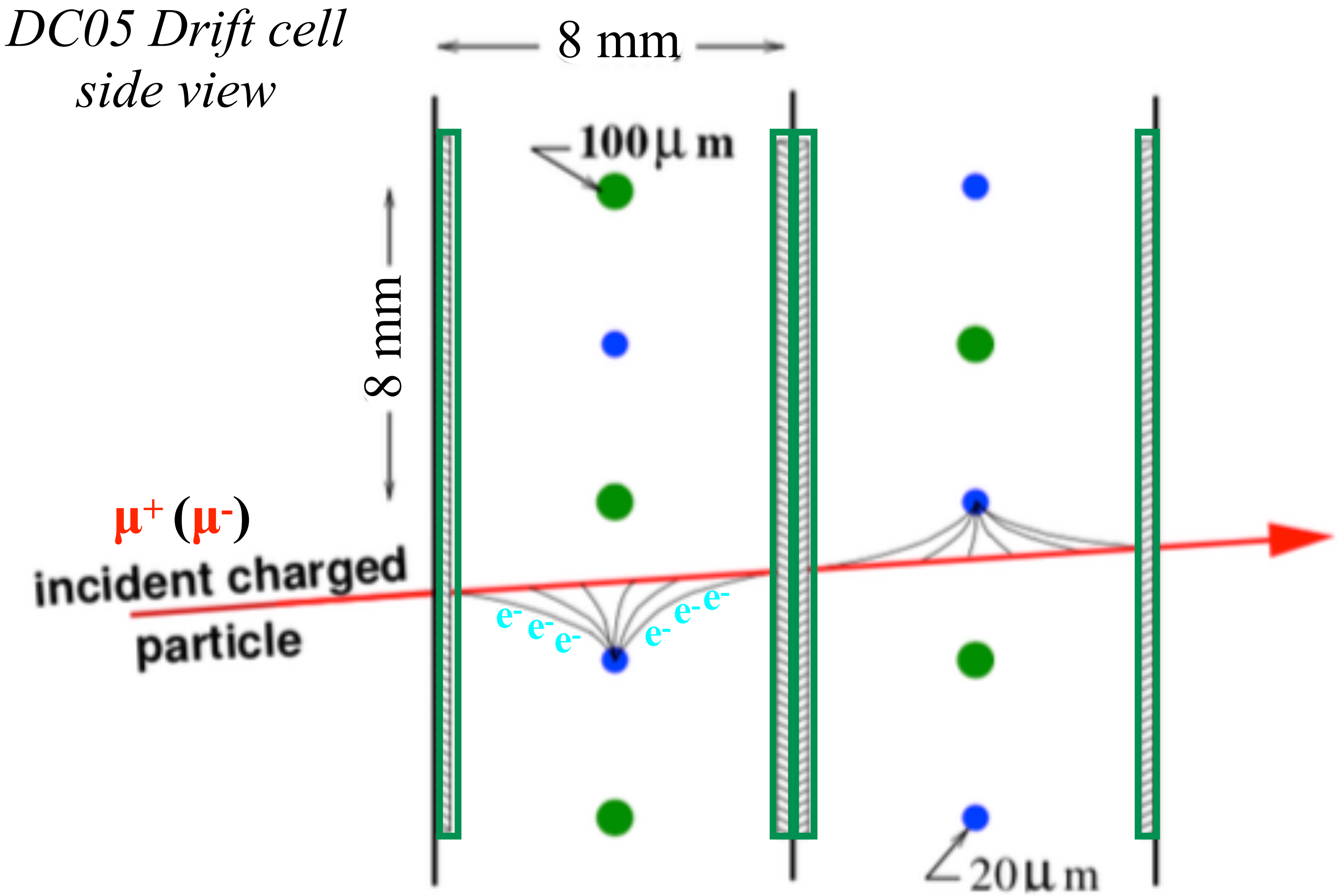




- Drift Chamber 05 is absolutely necessary

DC05 Operational Principle

DC05 Drift cell side view



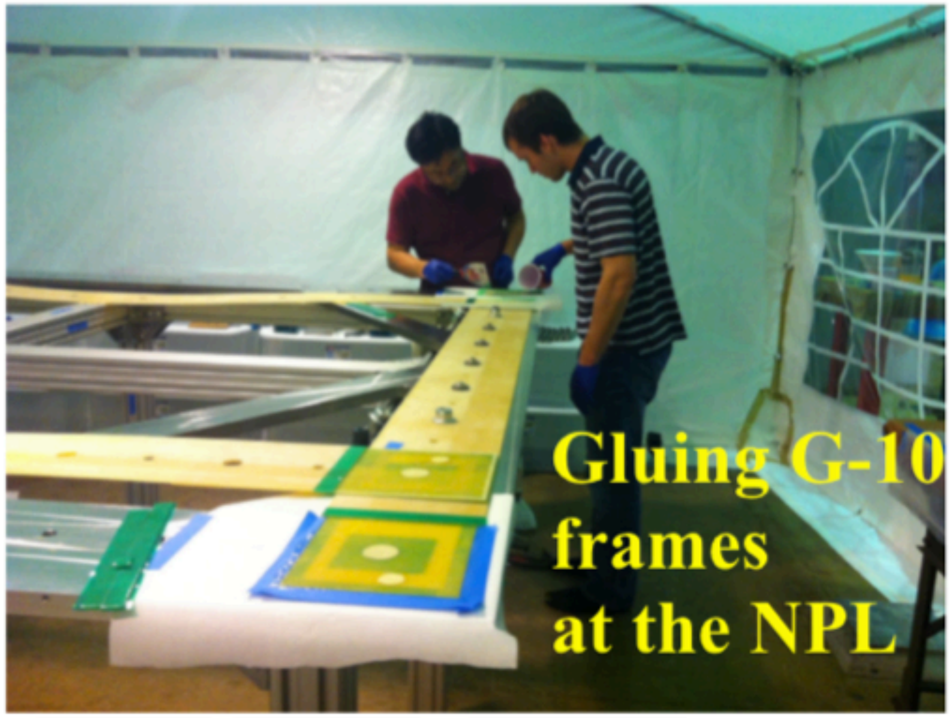
High Voltage:

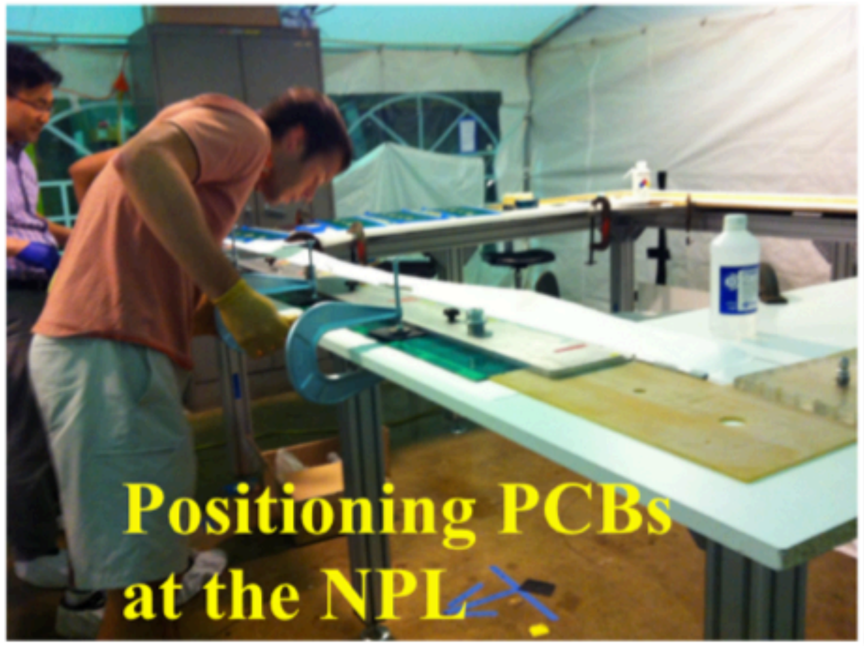
Sense wires 0V
Field wires -1650V
Cathodes -1650V

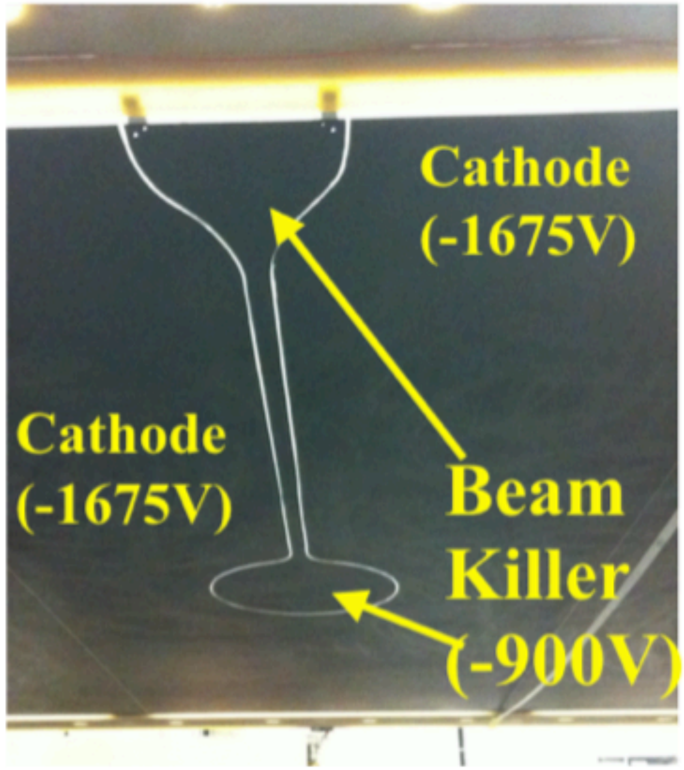
Gas Components:

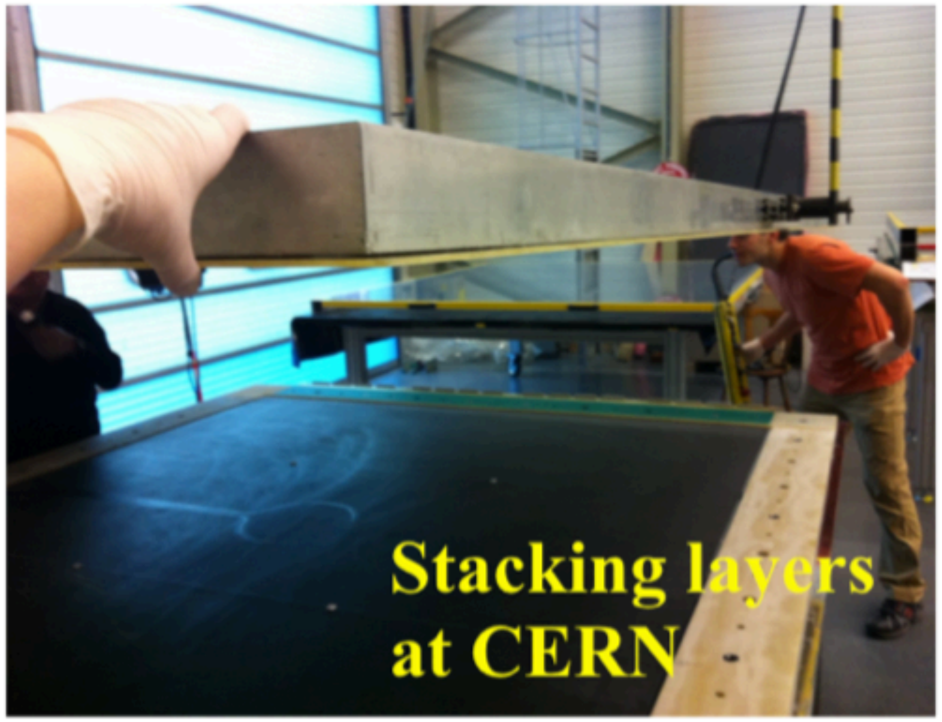
Argon	45%
Ethane	45%
CF_4	10%

DC05 Construction

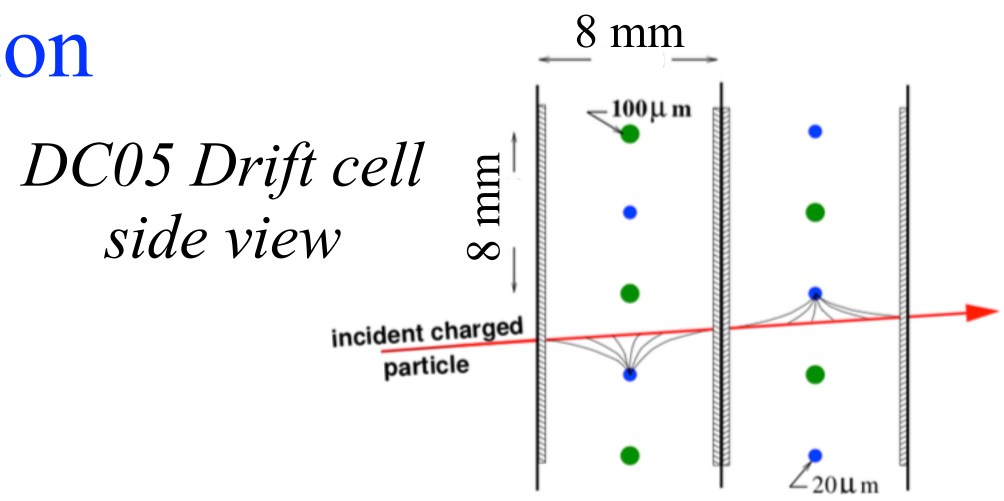






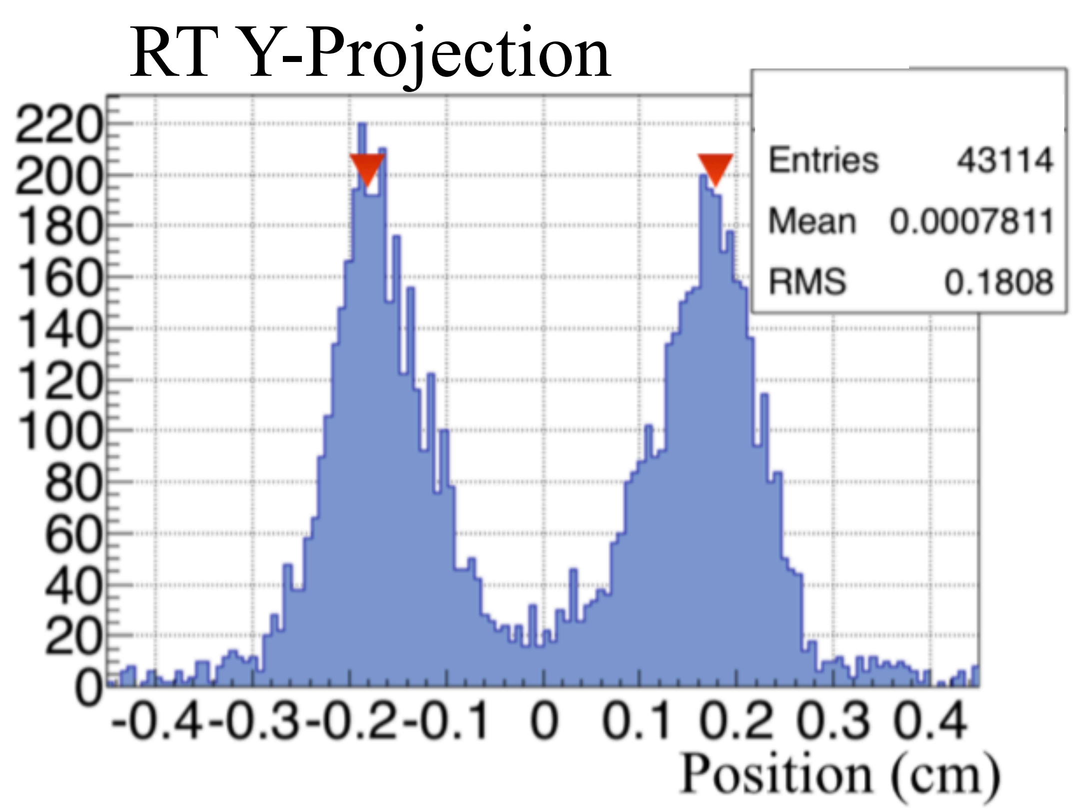


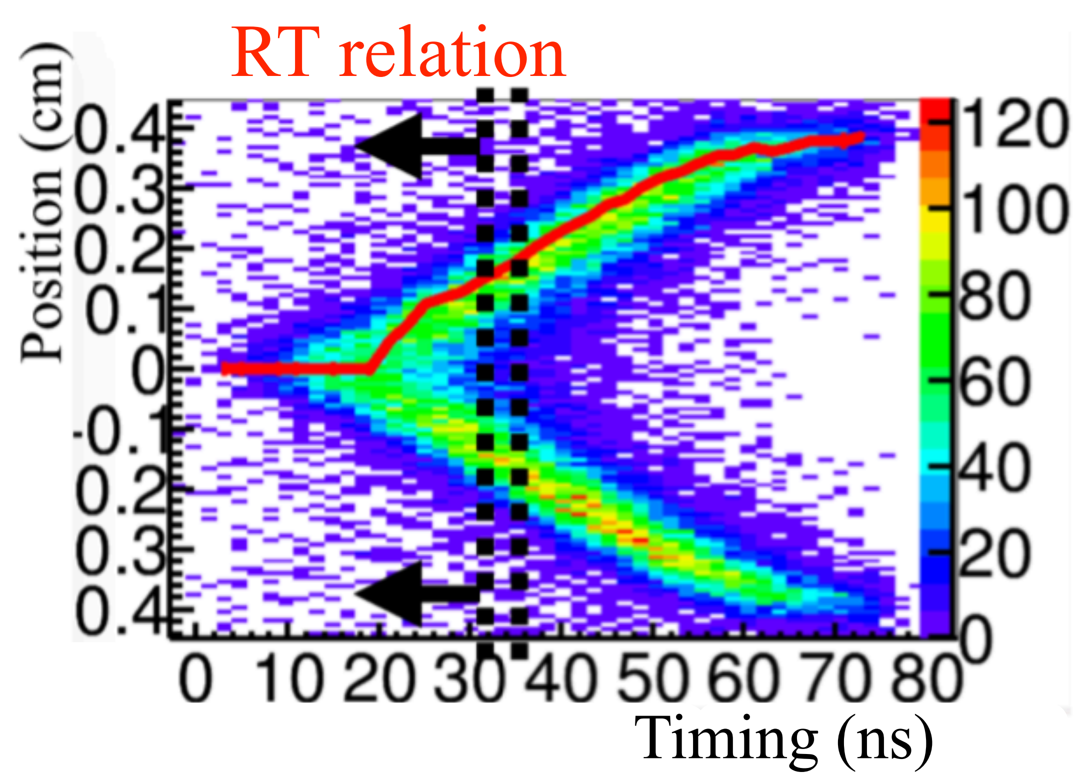
DC05 Calibration



- Reconstruct events to determine an RT relation
    - Calibration plane is excluded from reconstruction
    - Timing information determined from DC05 plane
    - Spatial information determined reconstruction

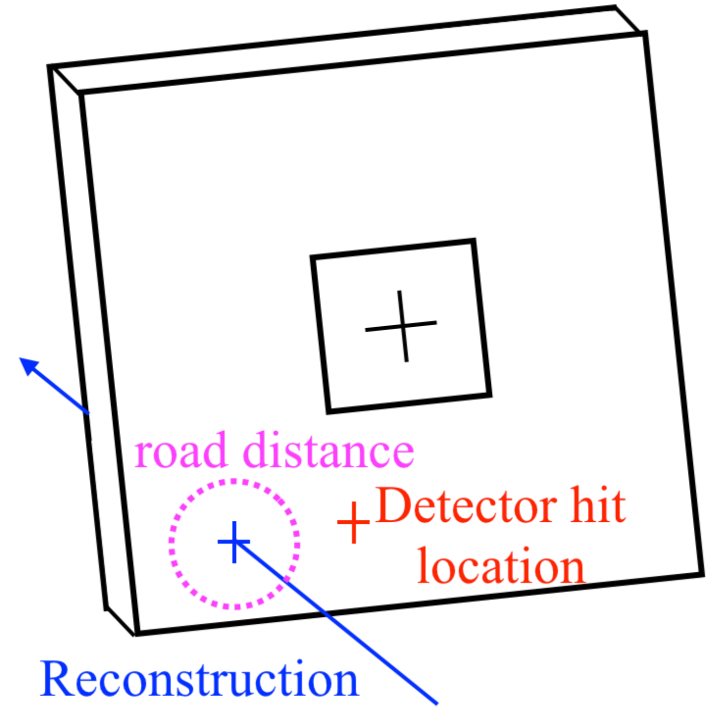
- RT relation improves position resolution





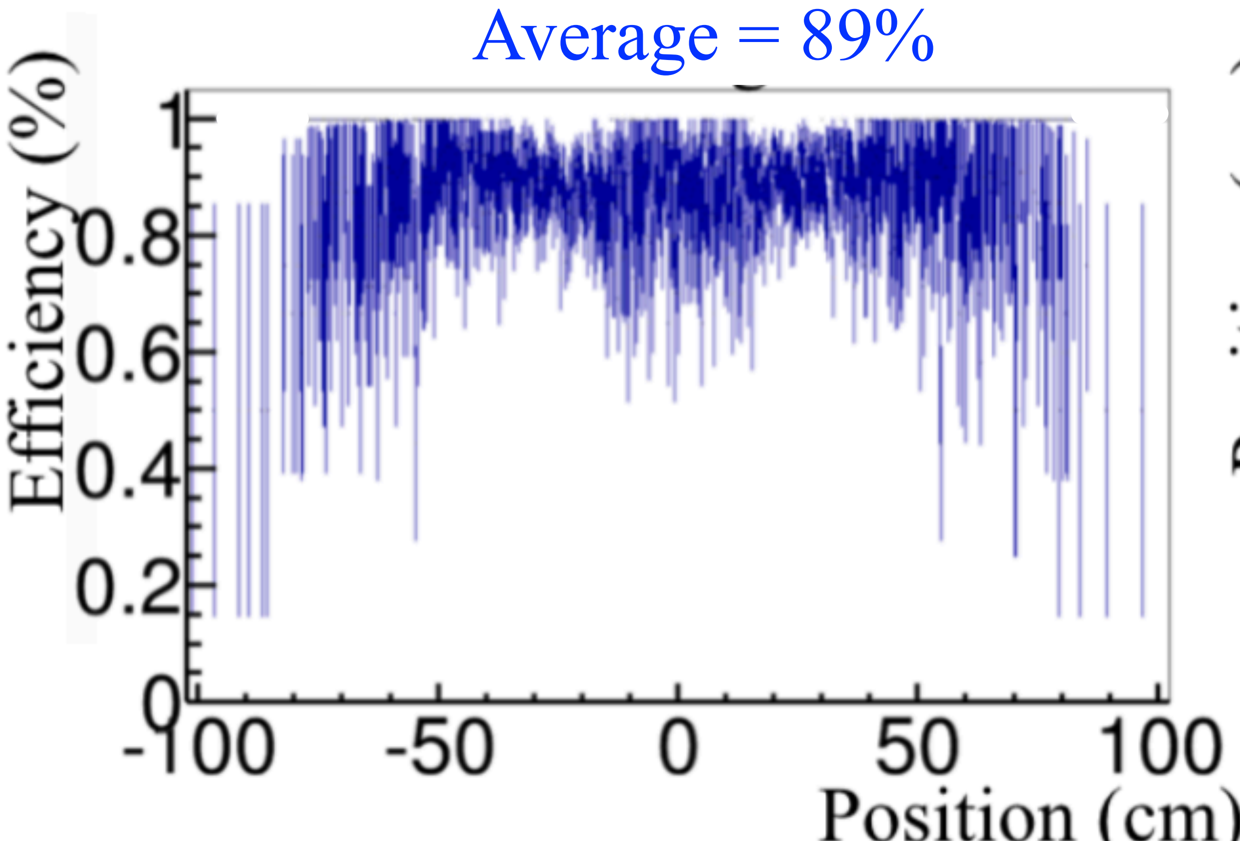
DC05 Efficiency

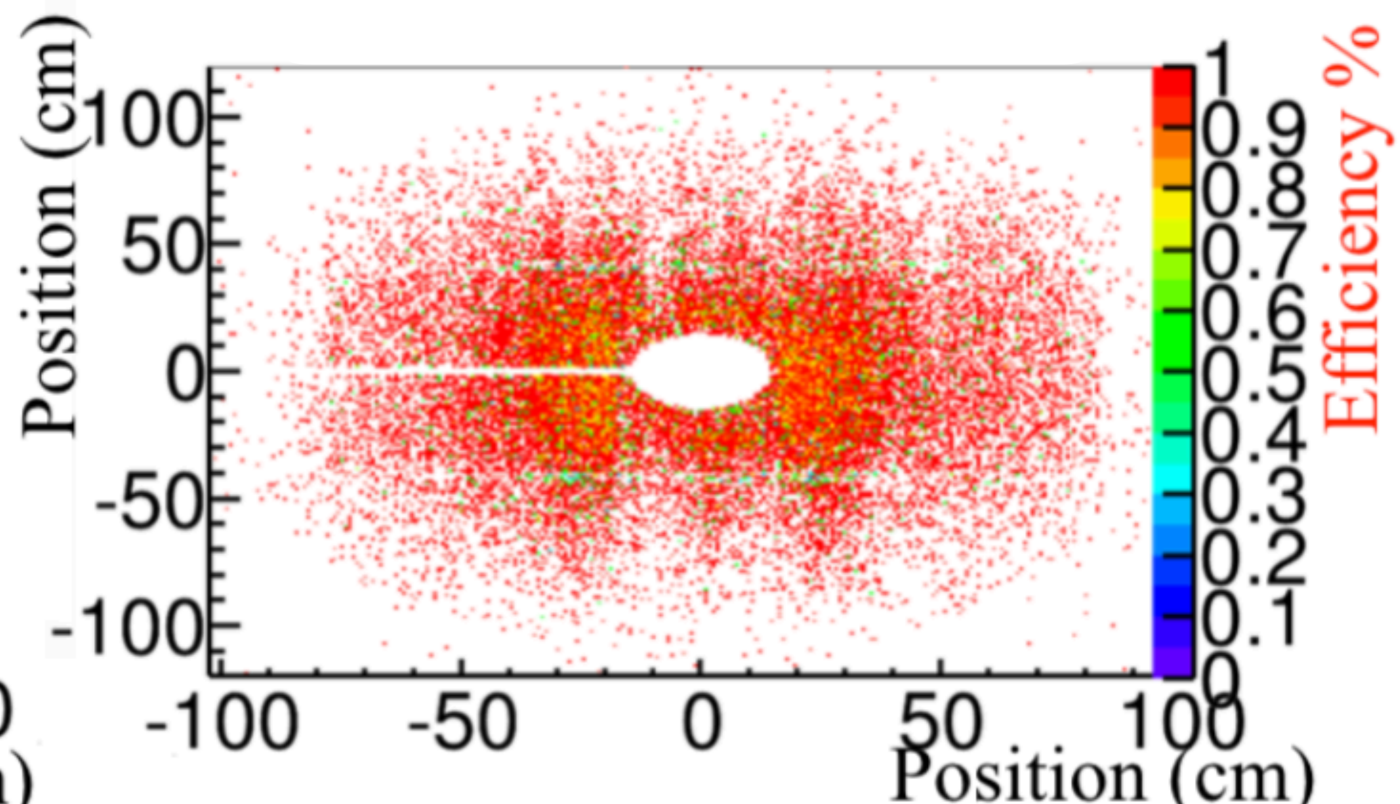
- Detector hit search within ~1mm of reconstruction position
  - Plane of interest is excluded from reconstruction (limits bias)



- In 2015 DC05 achieved an efficiency of > 85%
  - Uniform efficiency throughout the detector

Average = 89%



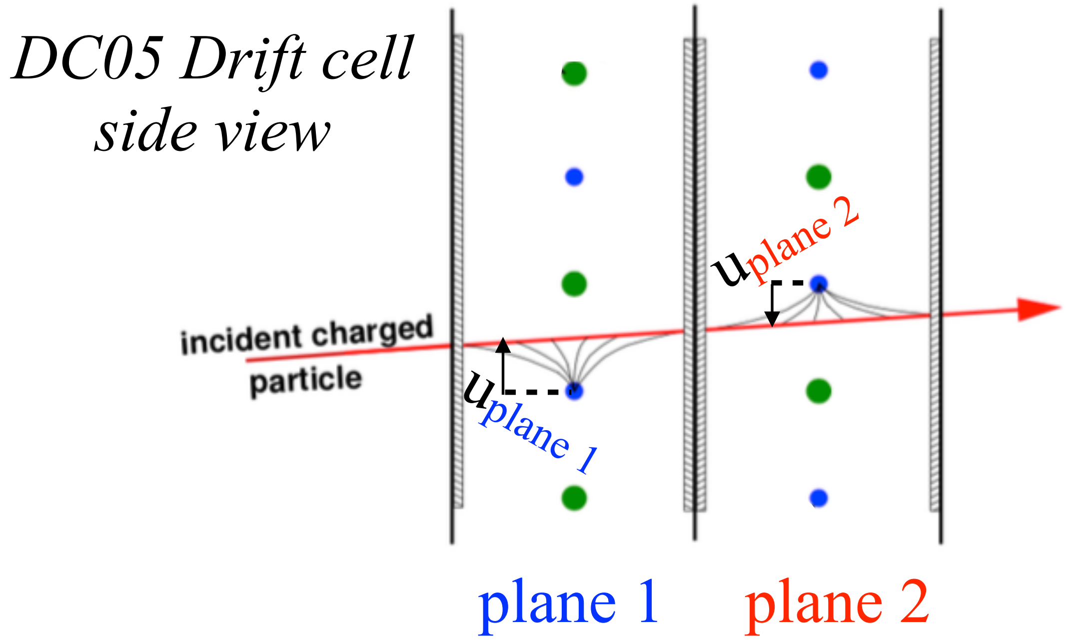


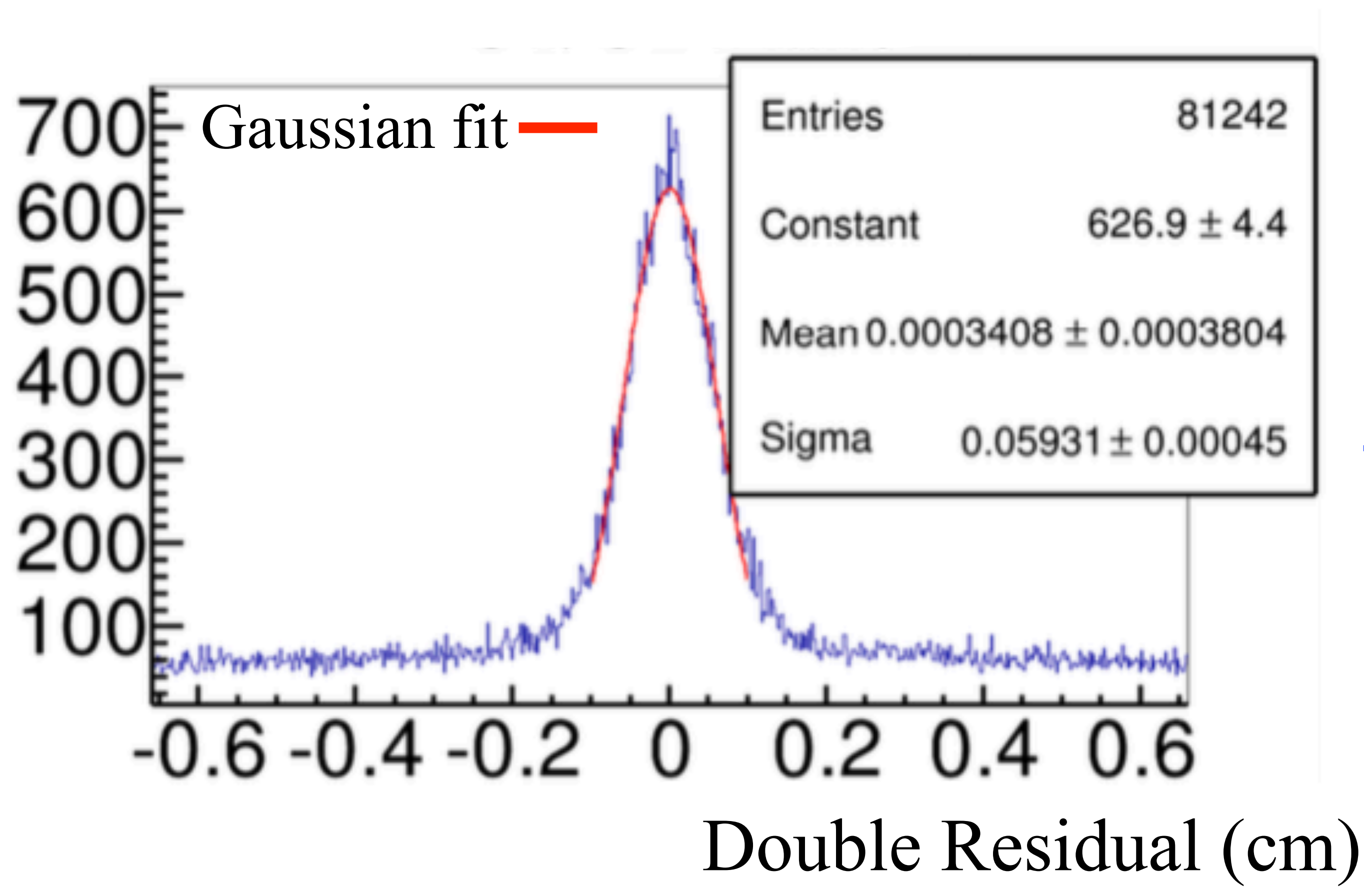
DC05 Position Resolution

Double Residual

DR $=$ u$_{\text{plane 2}}$ - u$_{\text{plane 1}}$

$$\sigma^2_{\mathrm{DR}} = \sigma^2_{\mathrm{u_{plane\ 1}}} + \sigma^2_{\mathrm{u_{plane\ 2}}} = 2\sigma^2_{\mathrm{u_{plane\ 1/2}}}$$





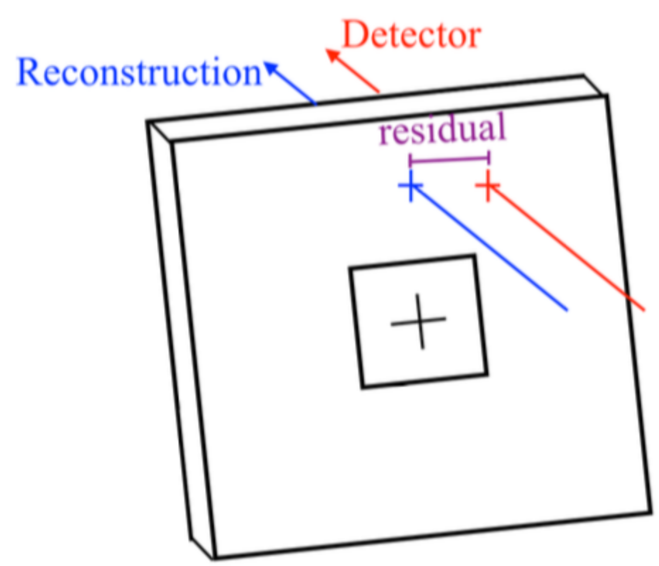
- Gaussian fit determines σ^2_{DR}

  Position resolution $= \frac{\sigma_{DR}}{\sqrt{2}}$

- Achieved a position resolution of ~450 μm

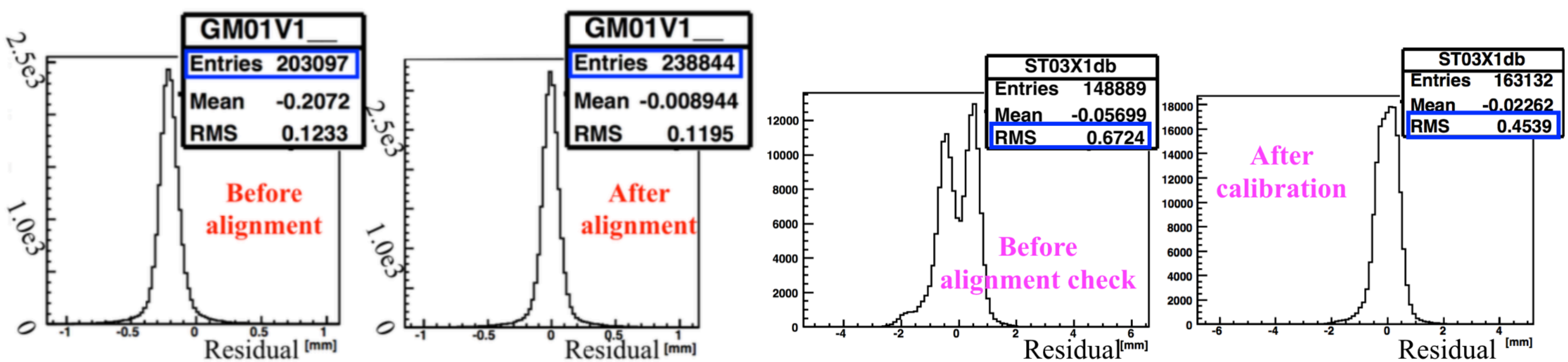
Detector Alignment

- Important preprocessing data step
- Over 300 detector planes in the COMPASS spectrometer
- Survey equipment can only position detectors within ~ 2mm
  track resolutions should be <100 μm



$\text{residual} = u_{\text{track}} - u_{\text{det}}$

- Detector alignment is a critical before reconstruction

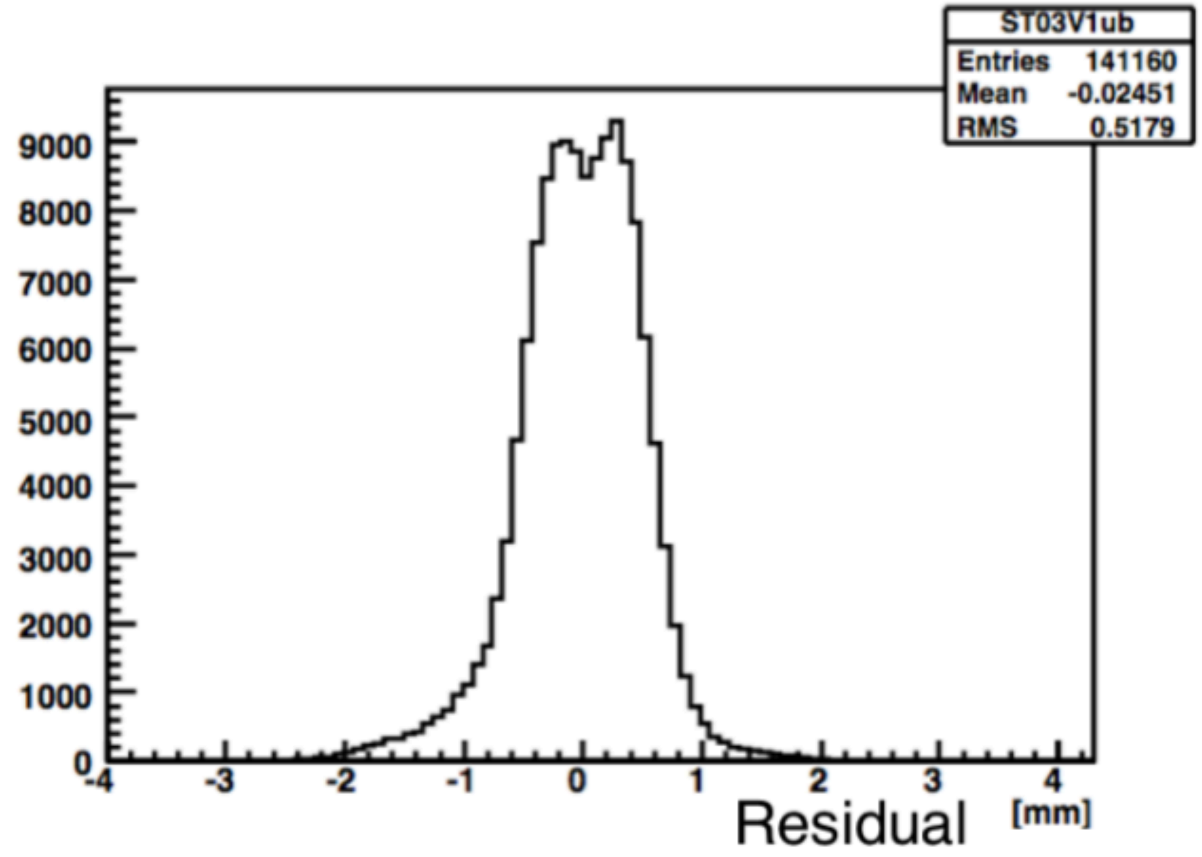


Alignment Quality

- Alignment procedure minimizes χ^2 of all detector residuals from all tracks

$$\chi^2_{det} = \frac{Residual^2_{det}(u,\ \theta,\ pitch)}{\sigma^2_{det}}$$

- All residuals should be 0



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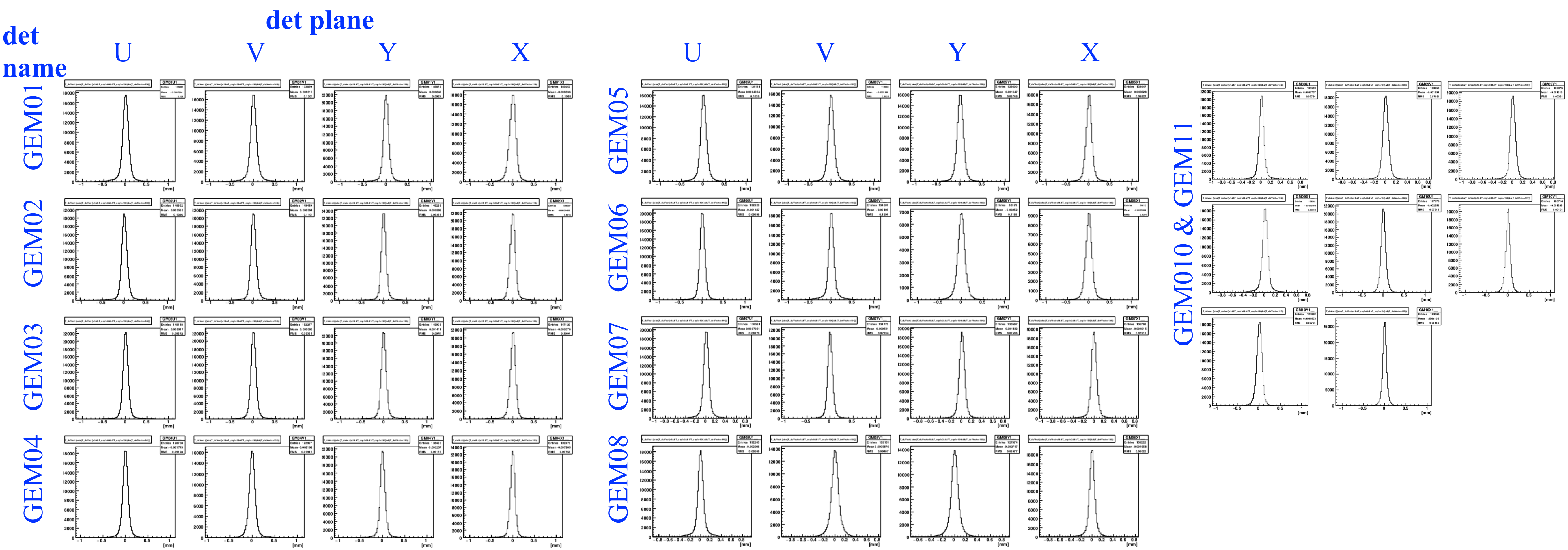
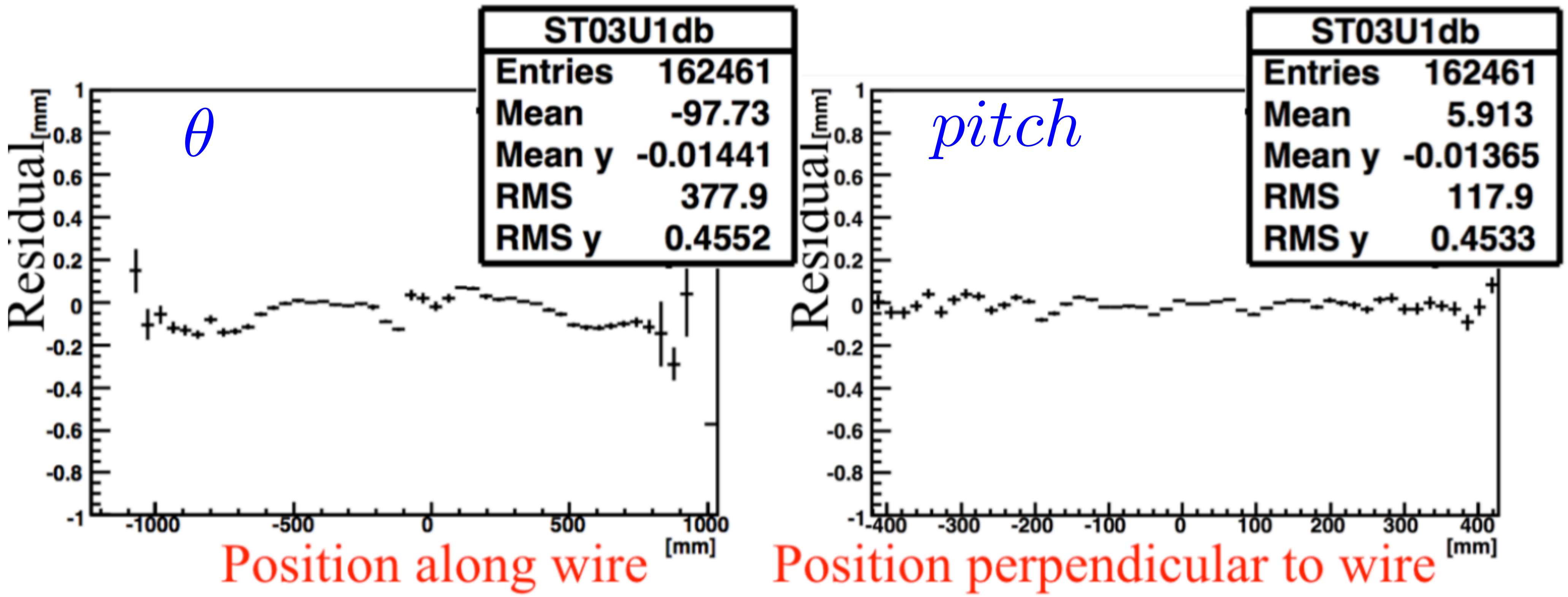


Alignment Quality

- Alignment procedure minimizes χ^2 of all detector residuals from all tracks

$$\chi^2_{det} = \frac{Residual^2_{det}(u,\ \theta,\ pitch)}{\sigma^2_{det}}$$

- All residuals should be 0
  - Residuals should be 0 along wire -> angle alignment
  - Residuals should be 0 perpendicular to wire -> pitch alignment



2015 Drell-Yan Data

Data recording:

- 9 periods lasting ~ two weeks each (W07-W15)
  July - November 2015 (~ 18 weeks)

Data volumes:

- 850 terabytes raw data
  detector timing information

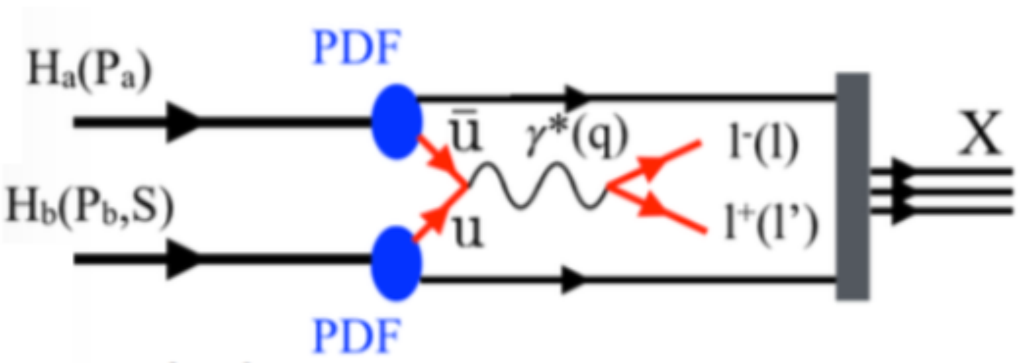
- 100 terabytes reconstructed data
  physics quantities determined (momentum, charge, energy, vertex)

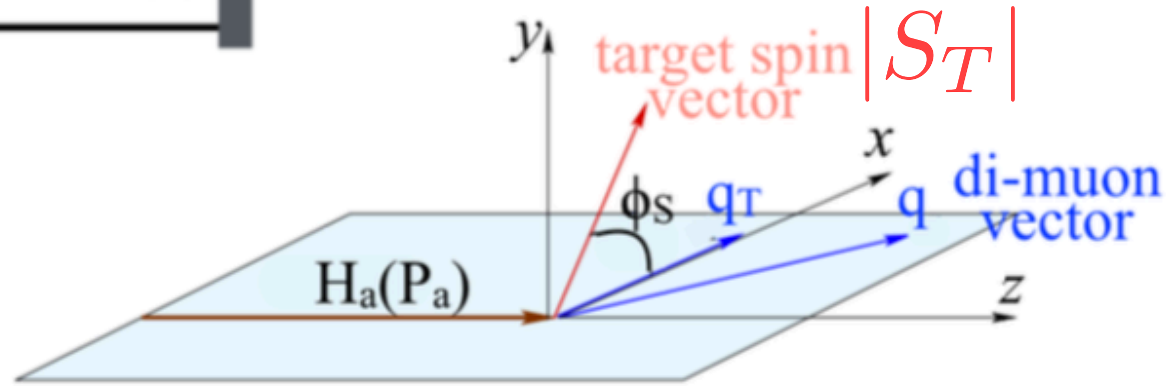
- 7.7 terabytes micro-Data Structured Trees
  events with at least 2 muons (same charge or opposite charge)

Oppositely charge di-muon events:

- 37,921 Drell-Yan (high mass [4.3-8.5 GeV/c^2])
- 1,540,868 JPsi (mass [2.87-3.38 GeV/c^2])

Drell-Yan Target Frame





Target Frame

$$\frac{d\sigma^{DY}}{d\phi_S} \propto |S_T| \; A_T^{\sin(\phi_S)} \; \sin(\phi_S)$$

$$A_T^{\sin(\phi_S)} \propto f_{1,\,\pi^-}^{\bar{u}} \otimes \overset{Sivers}{f_{1,\,T}^{\perp\,u}}$$

- Transverse Momentum Dependent PDF from azimuthal amplitudes

Di-muon Invariant Mass

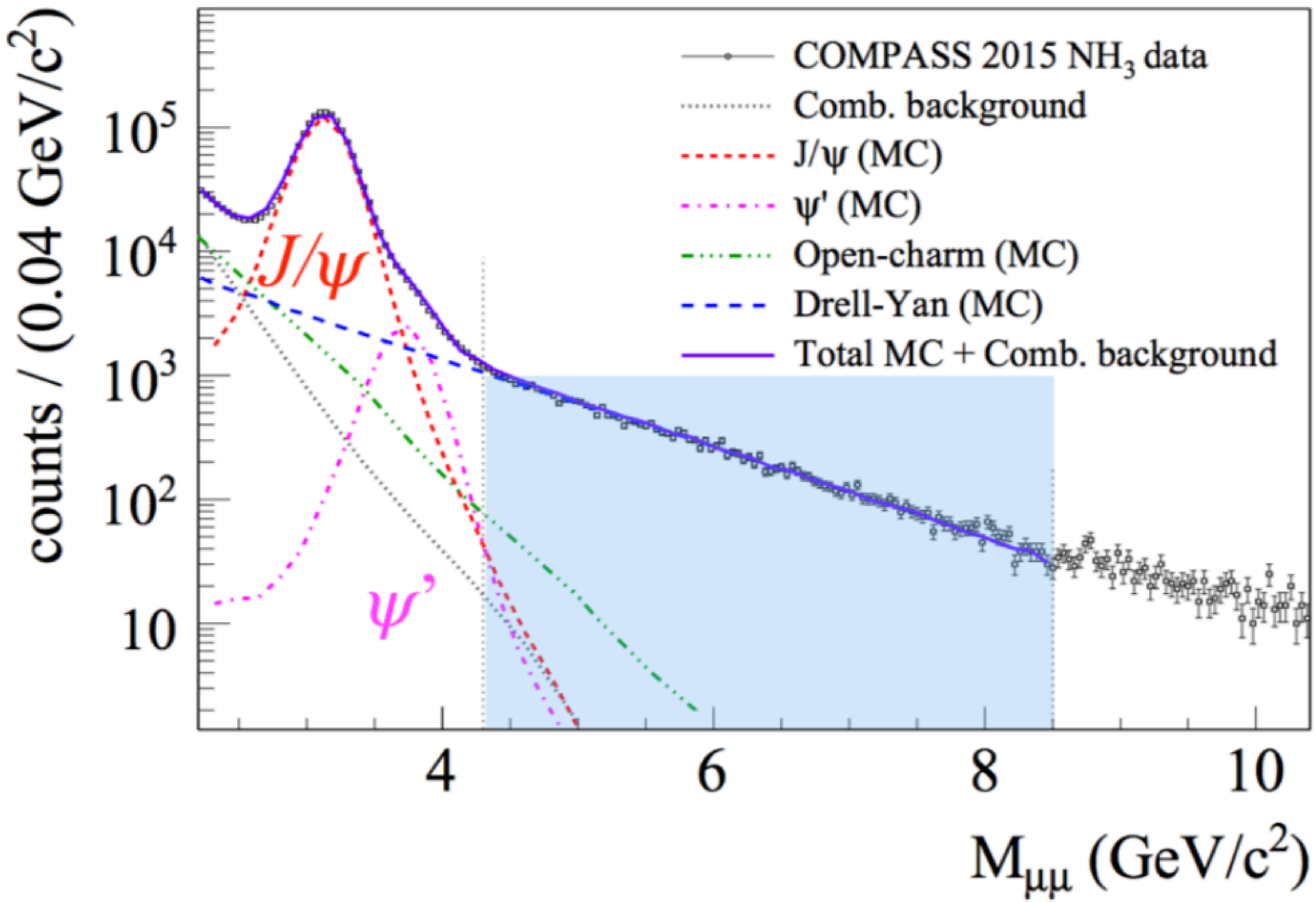
- The Drell-Yan analysis was performed in the invariant mass range 4.3-8.5 GeV/c²

    4% background in this mass range

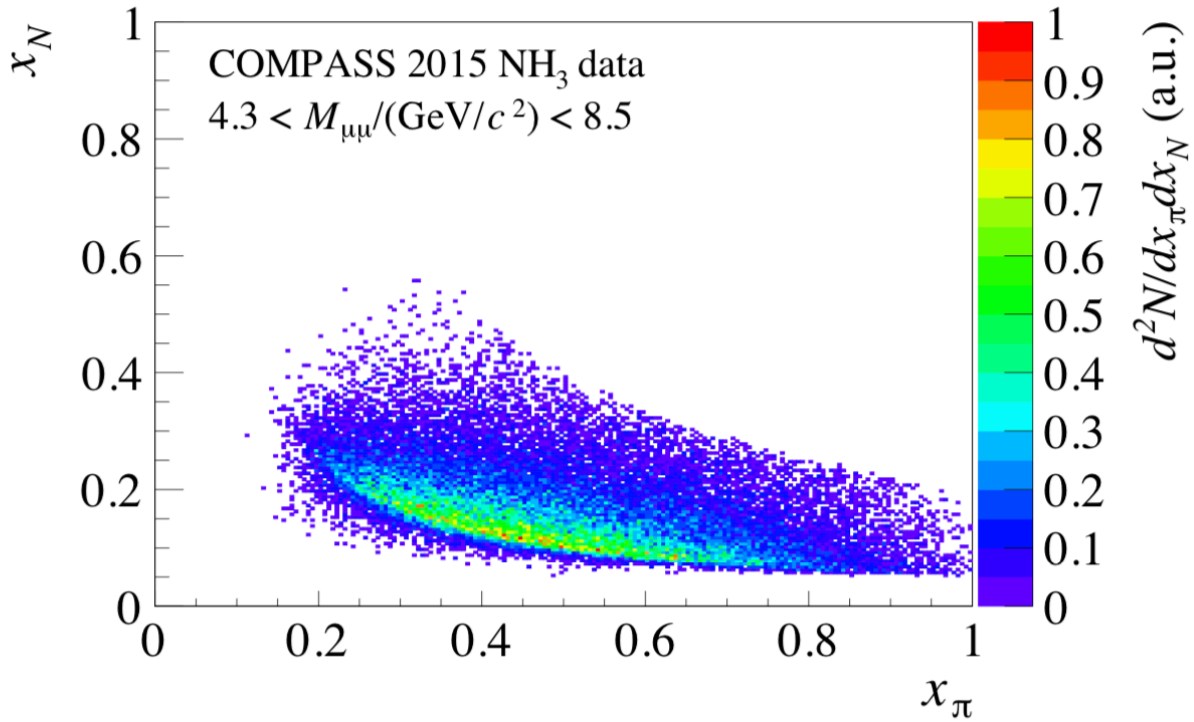
Background includes:

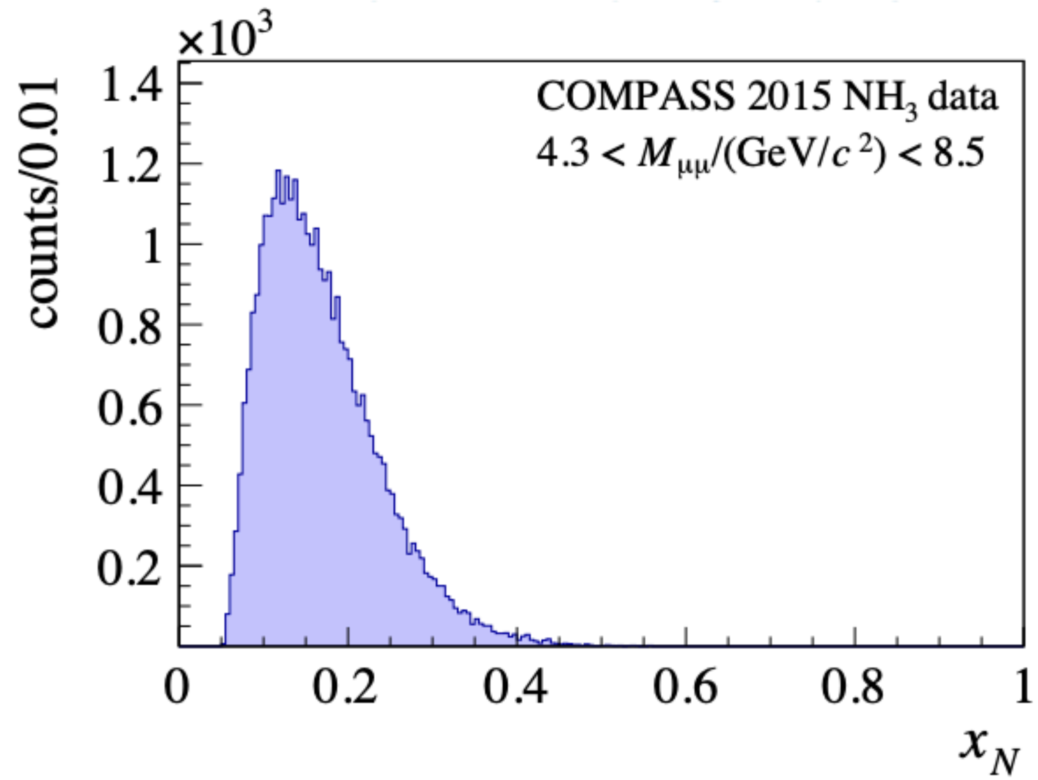
$J/\Psi\ (c\bar{c})$, $\Psi'\ (c\bar{c})$, Open Charm (xc),

Combinatorial background $2\sqrt{N_{\mu^+\mu^+}N_{\mu^-\mu^-}}$ $\left(\begin{matrix}\pi^-(beam) \to \mu^- \\ \pi^+ \to \mu^+\end{matrix}\right)$



Drell-Yan Phase Space





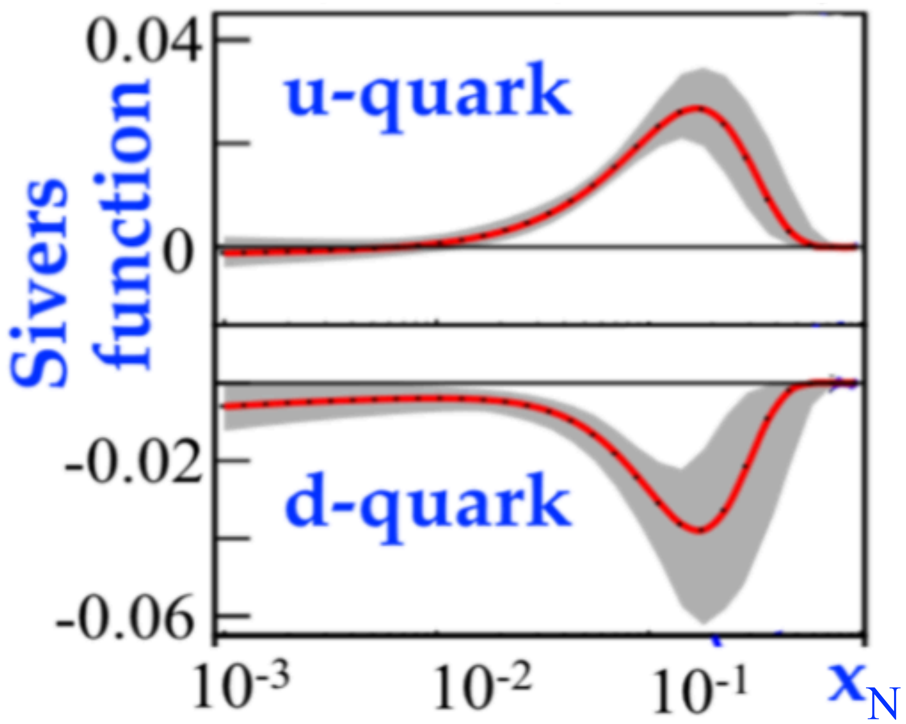
- Valence quark annihilation from both beam and target

$x_N > 0.1$, $x_\pi > 0.2$

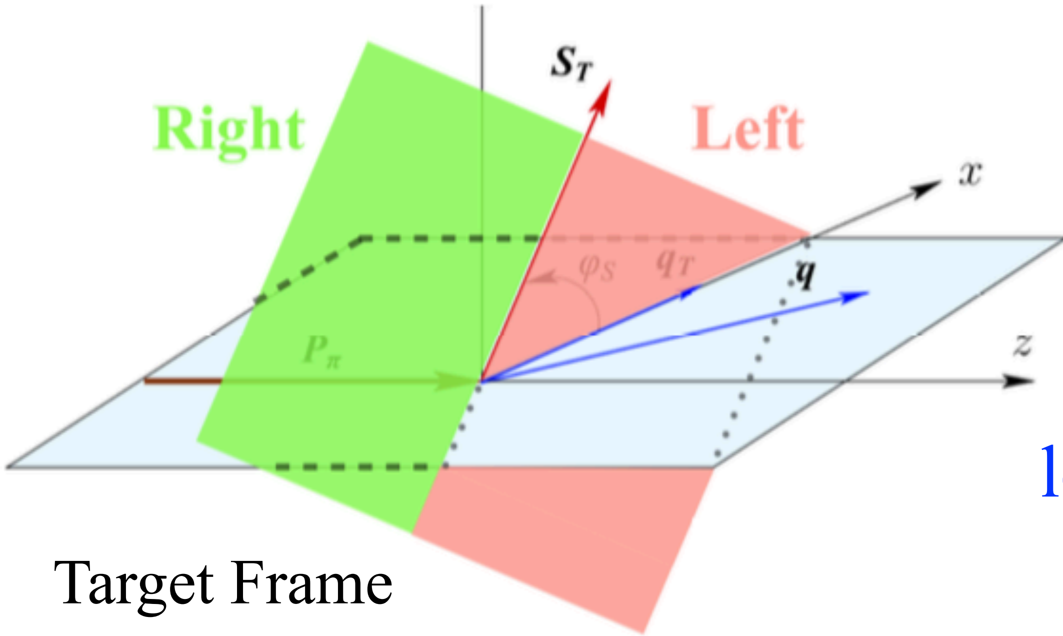
- This is the same region the Sivers function was extracted to reach it's maximum

- Most sensitive region to the Sivers sign flip

Anselmino, Boglione & Alesio
JHEP04 (2017) 046



Left-Right Asymmetry



Target Frame

Left: $0 < \varphi_S < \pi$

Right: $-\pi < \varphi_S < 0$

left and right depend on the transverse spin direction

$$A_{lr} = \frac{1}{|S_T|} \frac{\sigma_{left} - \sigma_{right}}{\sigma_{left} + \sigma_{right}} = \frac{1}{|S_T|} \frac{\int_{\phi_S=0}^{\phi_S=\pi} \frac{d\sigma^{DY}}{d\phi_S} - \int_{\phi_S=\pi}^{\phi_S=2\pi} \frac{d\sigma^{DY}}{d\phi_S}}{\int_{\phi_S=0}^{\phi_S=\pi} \frac{d\sigma^{DY}}{d\phi_S} + \int_{\phi_S=\pi}^{\phi_S=2\pi} \frac{d\sigma^{DY}}{d\phi_S}}$$

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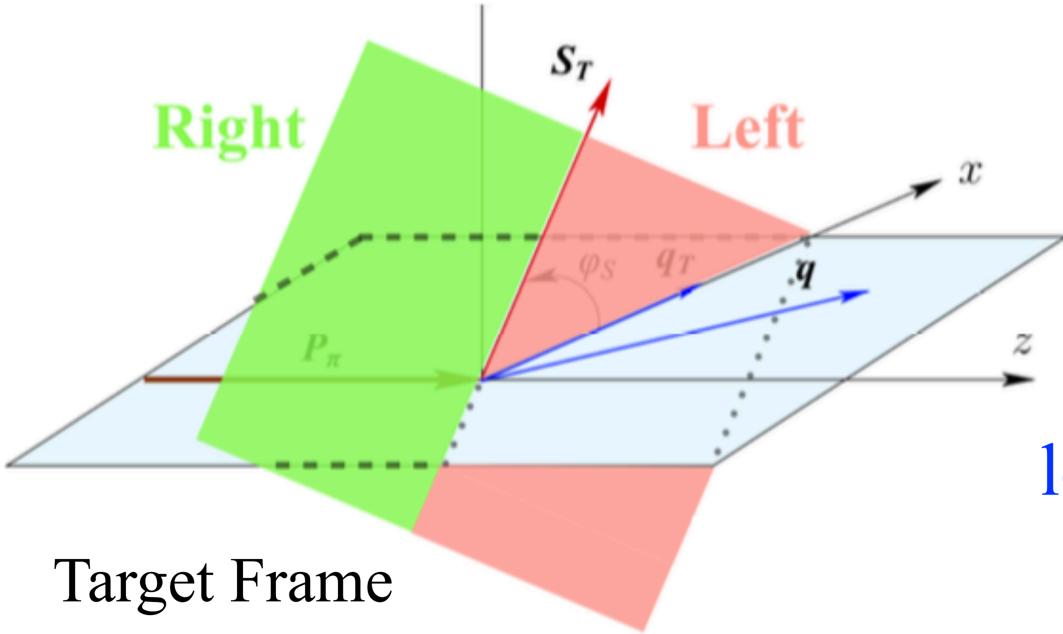

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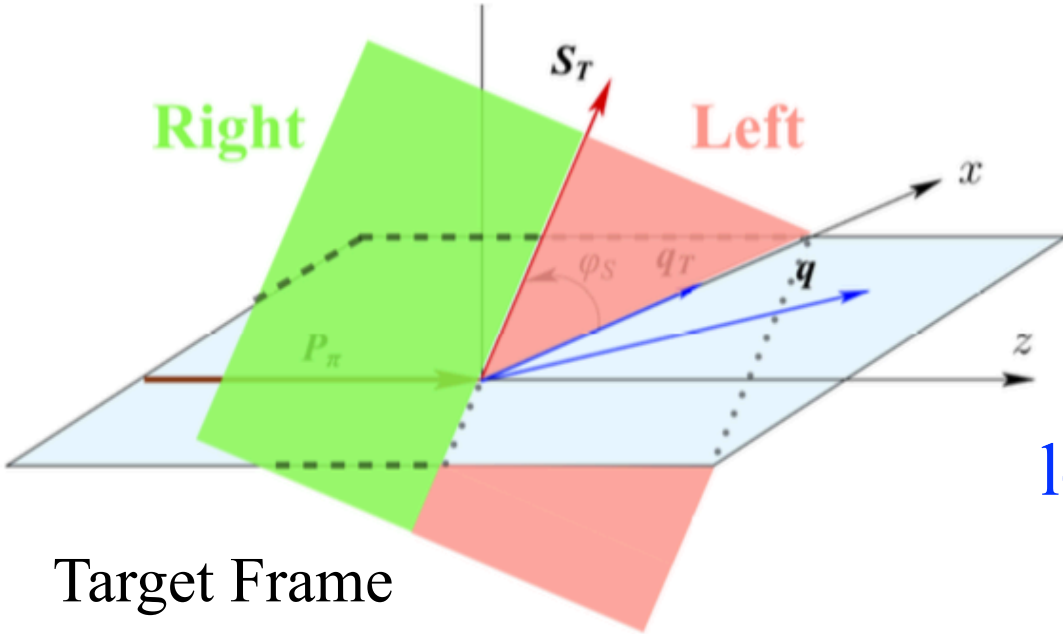
left and right depend on the transverse spin direction

$$A_{lr} = \frac{1}{|S_T|}\frac{\sigma_{left} - \sigma_{right}}{\sigma_{left} + \sigma_{right}} = \frac{2A_T^{\sin(\phi_S)}}{\pi}$$

- A_{lr} is proportional to the Sivers amplitude using the leading order TMD model

Left-Right Asymmetry



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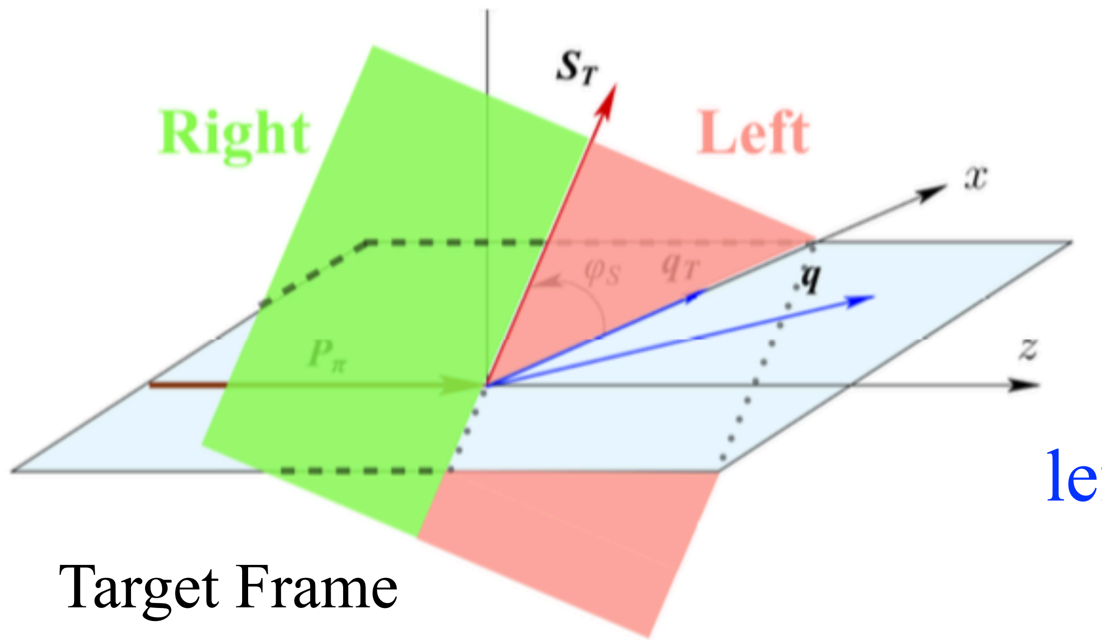
left and right depend on the transverse spin direction

Experimental observable:

$$A_{lr} = \frac{1}{|S_T|}\frac{\sigma_{left} - \sigma_{right}}{\sigma_{left} + \sigma_{right}} = \frac{1}{|S_T|}\frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

- A_{lr} model independent

Left-Right Asymmetry



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left and right depend on the transverse spin direction

Experimental observable:

$$A_{lr} = \frac{1}{|S_T|}\frac{\sigma_{left} - \sigma_{right}}{\sigma_{left} + \sigma_{right}} = \frac{1}{|S_T|}\frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

$$= \frac{2A_T^{\sin(\phi_S)}}{\pi}$$

- A_{lr} model independent

- A_{lr} is proportional to the Sivers amplitude using the leading order TMD model

Acceptance

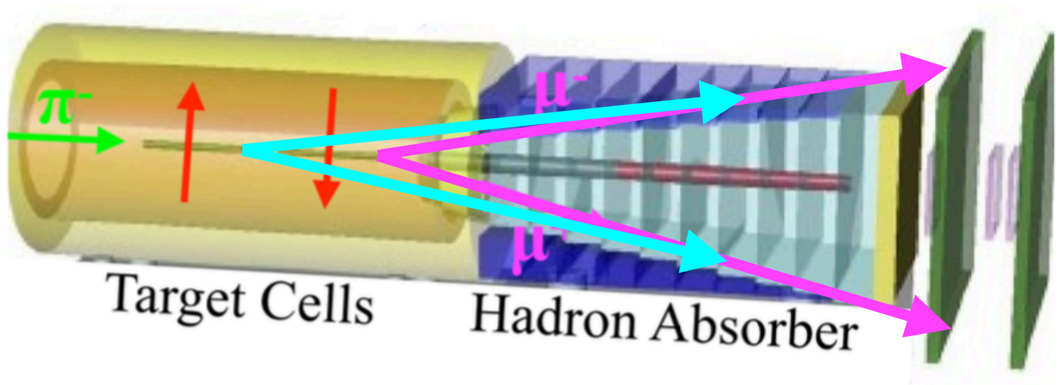
Experimental observable:

$$A_{lr} = \frac{1}{|S_T|} \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

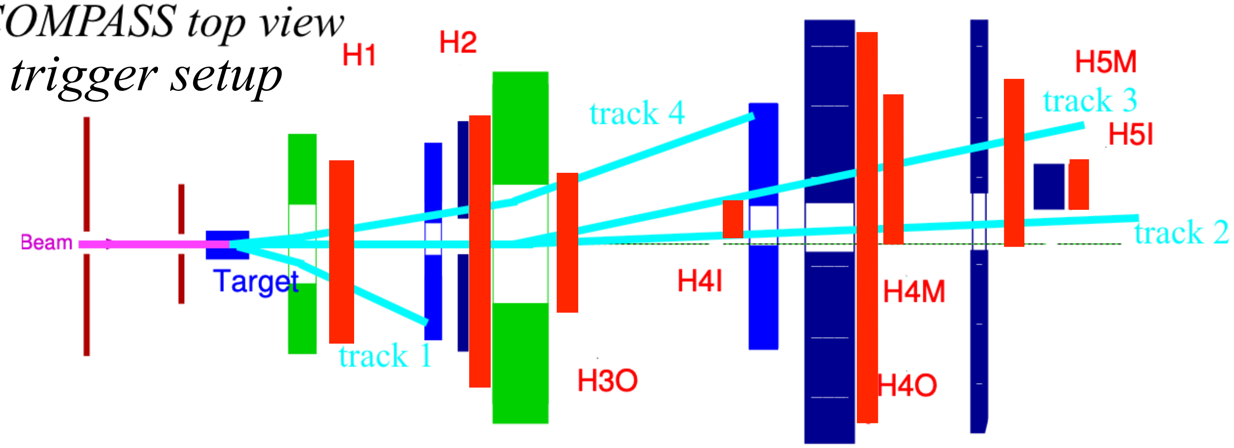
- Depends on acceptance

$$\underbrace{N(\Phi) = \overset{\textbf{acceptance}}{a(\Phi)}\ \underbrace{\sigma(\Phi)}_{\text{cross-section}}\ \overset{\text{luminosity}}{L}}$$

upstream vs. downstream



COMPASS top view
trigger setup



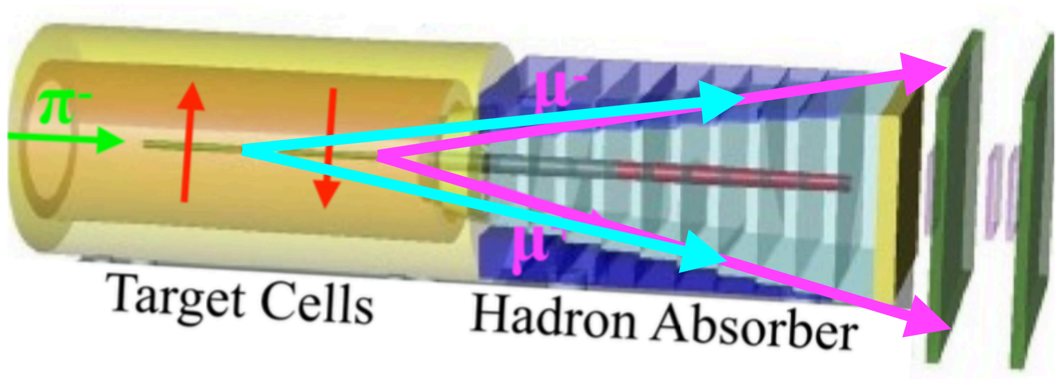
Acceptance

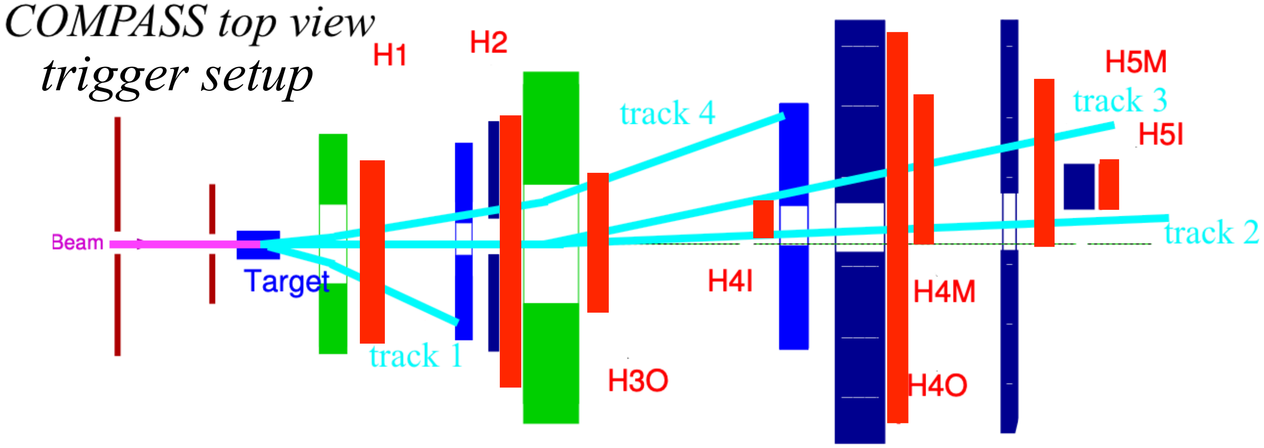
Experimental observable:

$$A_{lr} = \frac{1}{|S_T|} \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

- Depends on acceptance

$$N(\Phi) = \underbrace{a(\Phi)}_{\text{acceptance}} \, \underbrace{\sigma(\Phi)}_{\text{cross-section}} \, \underbrace{L}_{\text{luminosity}}$$





$$A_{lr} = \frac{1}{|S_T|} \frac{\sqrt[4]{N^{\uparrow}_{1,\,left} N^{\downarrow}_{1,\,left} N^{\uparrow}_{2,\,left} N^{\downarrow}_{2,\,left}} - \sqrt[4]{N^{\uparrow}_{1,\,right} N^{\downarrow}_{1,\,right} N^{\uparrow}_{2,\,right} N^{\downarrow}_{2,\,right}}}{\sqrt[4]{N^{\uparrow}_{1,\,left} N^{\downarrow}_{1,\,left} N^{\uparrow}_{2,\,left} N^{\downarrow}_{2,\,left}} + \sqrt[4]{N^{\uparrow}_{1,\,right} N^{\downarrow}_{1,\,right} N^{\uparrow}_{2,\,right} N^{\downarrow}_{2,\,right}}}$$

- Acceptance effects reduced

Left-Right Asymmetry Systematics

Left/Right

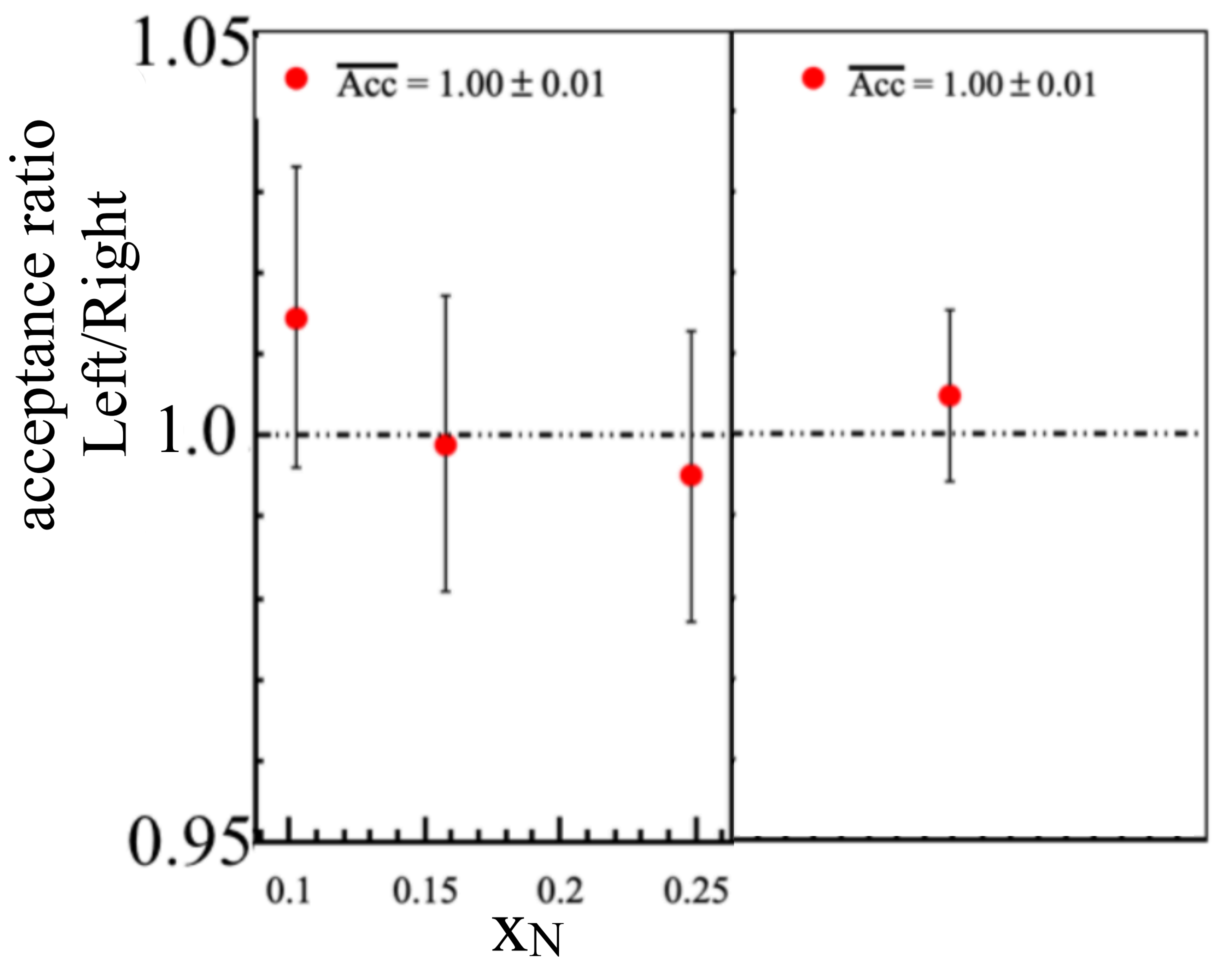
$$A_{lr,\ false} = \frac{1}{|S_T|}\frac{\sqrt[4]{N^{\uparrow}_{1,\ right}N^{\downarrow}_{1,\ left}N^{\uparrow}_{2,\ left}N^{\downarrow}_{2,\ right}} - \sqrt[4]{N^{\uparrow}_{1,\ left}N^{\downarrow}_{1,\ right}N^{\uparrow}_{2,\ right}N^{\downarrow}_{2,\ left}}}{\sqrt[4]{N^{\uparrow}_{1,\ right}N^{\downarrow}_{1,\ left}N^{\uparrow}_{2,\ left}N^{\downarrow}_{2,\ right}} + \sqrt[4]{N^{\uparrow}_{1,\ left}N^{\downarrow}_{1,\ right}N^{\uparrow}_{2,\ right}N^{\downarrow}_{2,\ left}}}$$

False asymmetry:
- independent of differential cross-section
- Only non-zero from spectrometer acceptance effects

Left-Right Asymmetry Systematics

$$A_{lr,\ false} = A_{lr,\ false}(acceptance)$$

False asymmetry:
- independent of differential cross-section
- Only non-zero from spectrometer acceptance effects

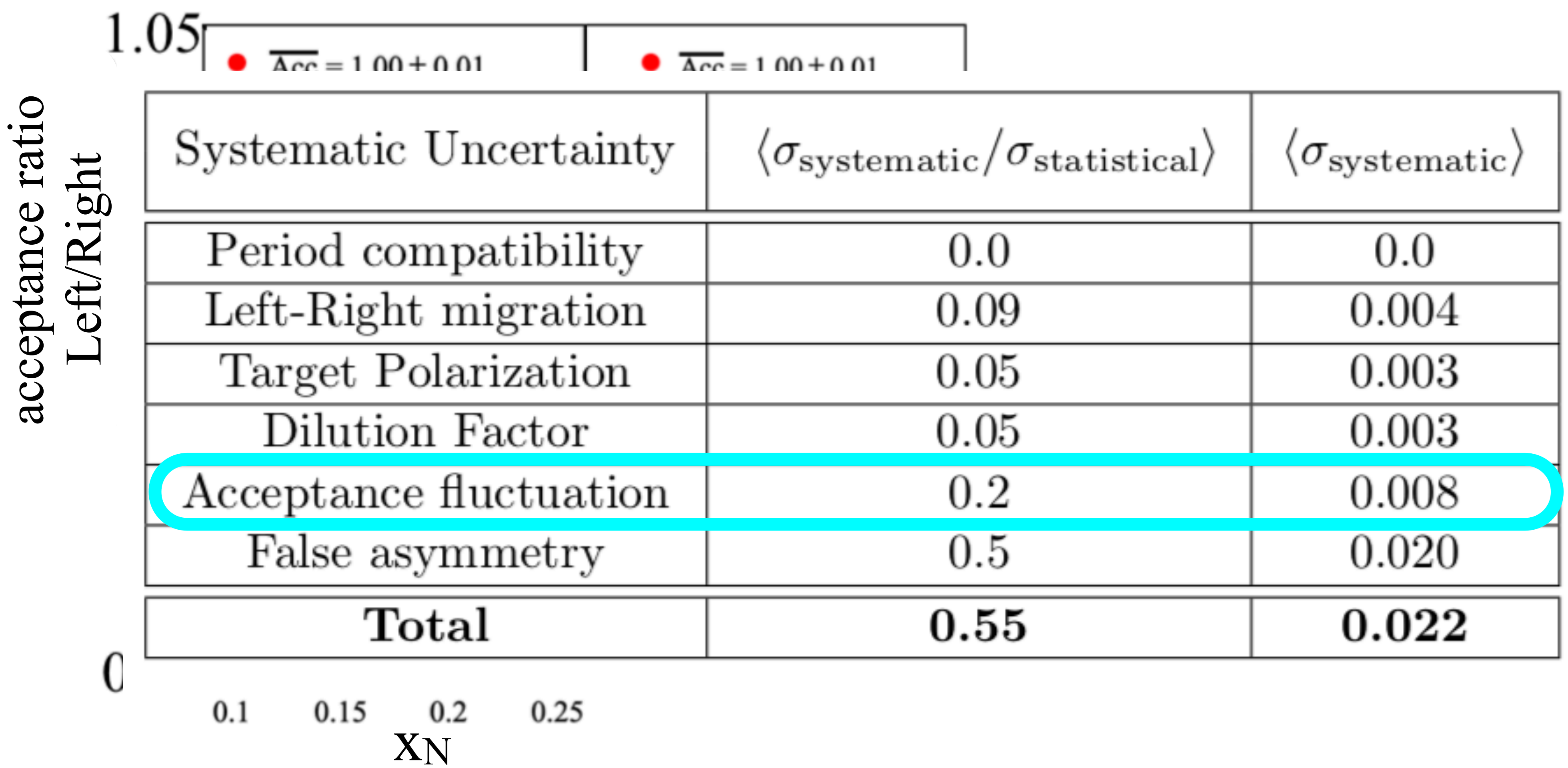


- Left/Right acceptance used to estimate systematic uncertainty

Left-Right Asymmetry Systematics

$$A_{lr,\ false} = A_{lr,\ false}(acceptance)$$

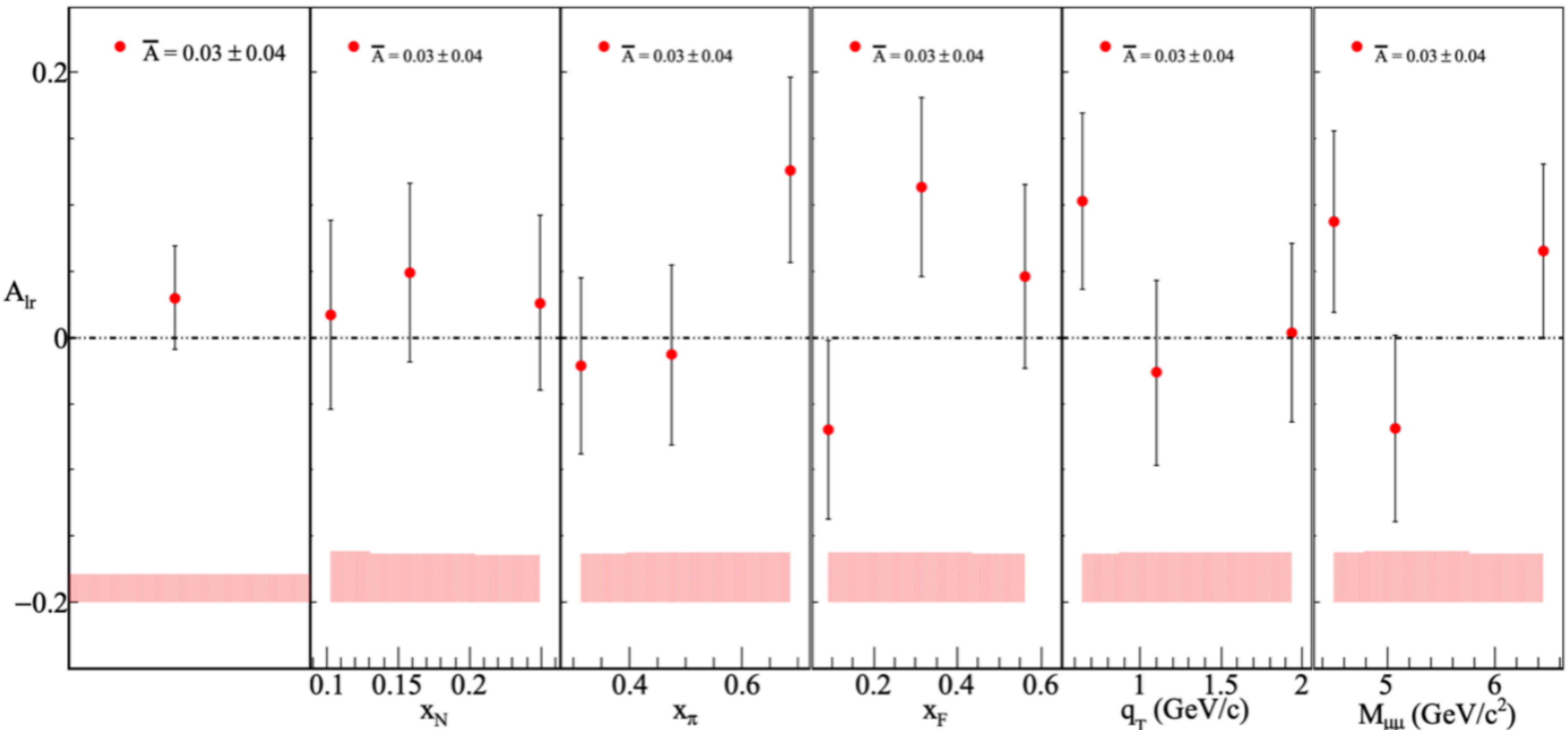
False asymmetry:
- independent of differential cross-section
- Only non-zero from spectrometer acceptance effects



Systematic Uncertainty	$\langle \sigma_{systematic}/\sigma_{statistical} \rangle$	$\langle \sigma_{systematic} \rangle$
Period compatibility	0.0	0.0
Left-Right migration	0.09	0.004
Target Polarization	0.05	0.003
Dilution Factor	0.05	0.003
Acceptance fluctuation	0.2	0.008
False asymmetry	0.5	0.020
Total	**0.55**	**0.022**

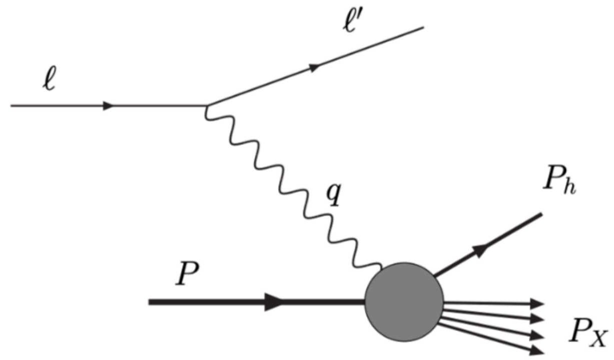
ce used to
uncertainty

Left-Right Asymmetry Results

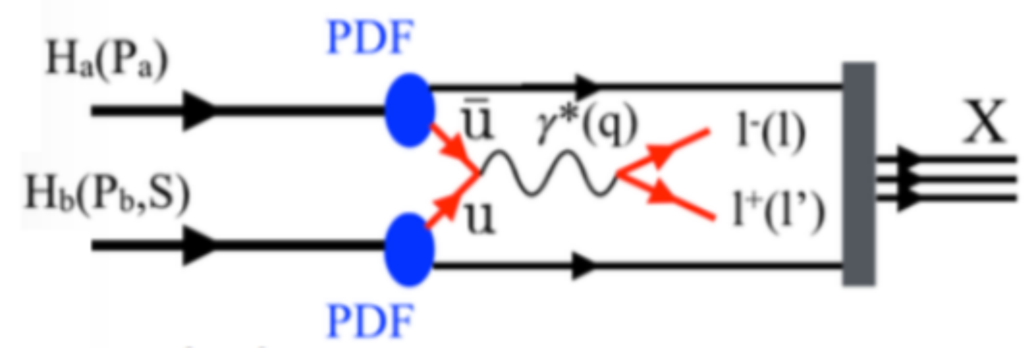


- Integrated asymmetry is positive by ~1 sigma
  still compatible with zero
- Need more statistics to determine trends in kinematic variables
- **New knowledge related to proton structure!**

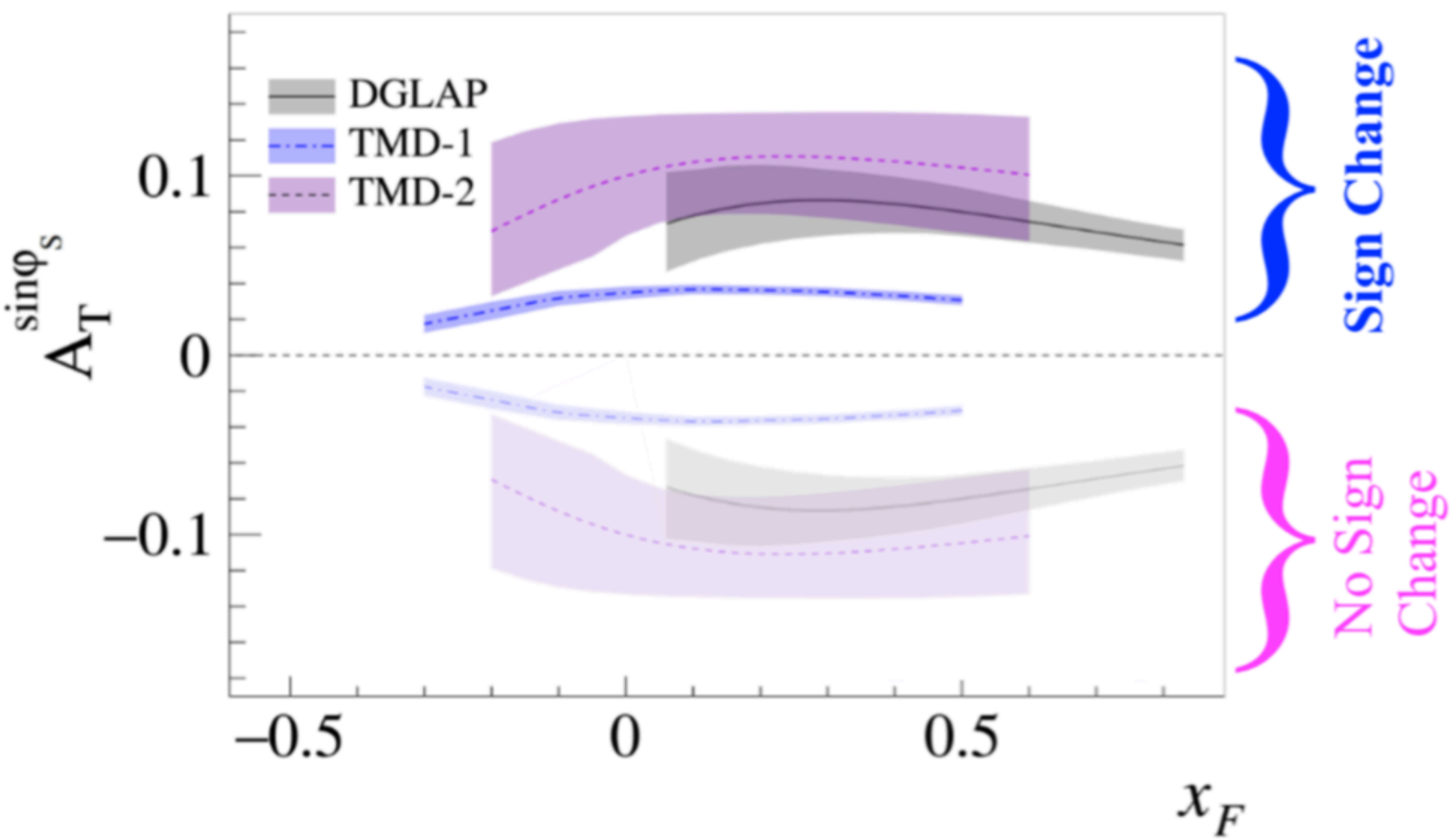
Sivers Sign Flip



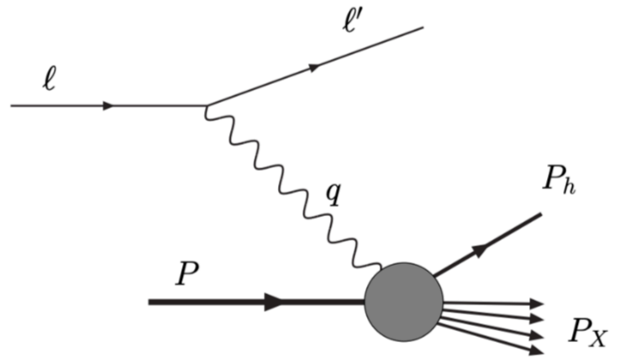
Semi-Inclusive Deep Inelastic Scattering (SIDIS)



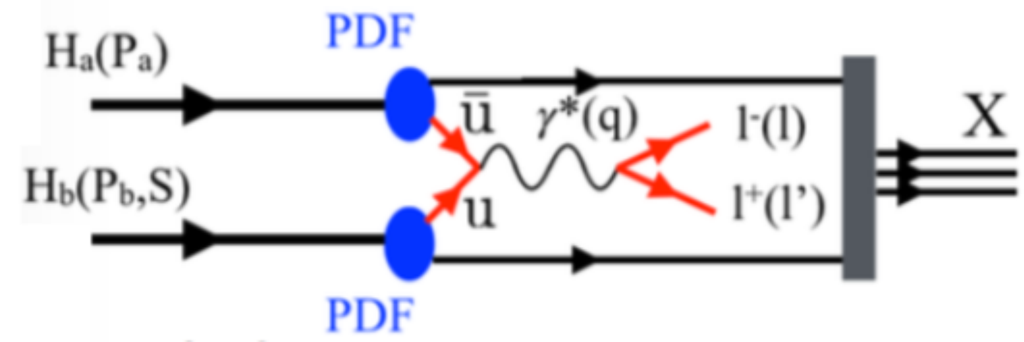
Drell-Yan



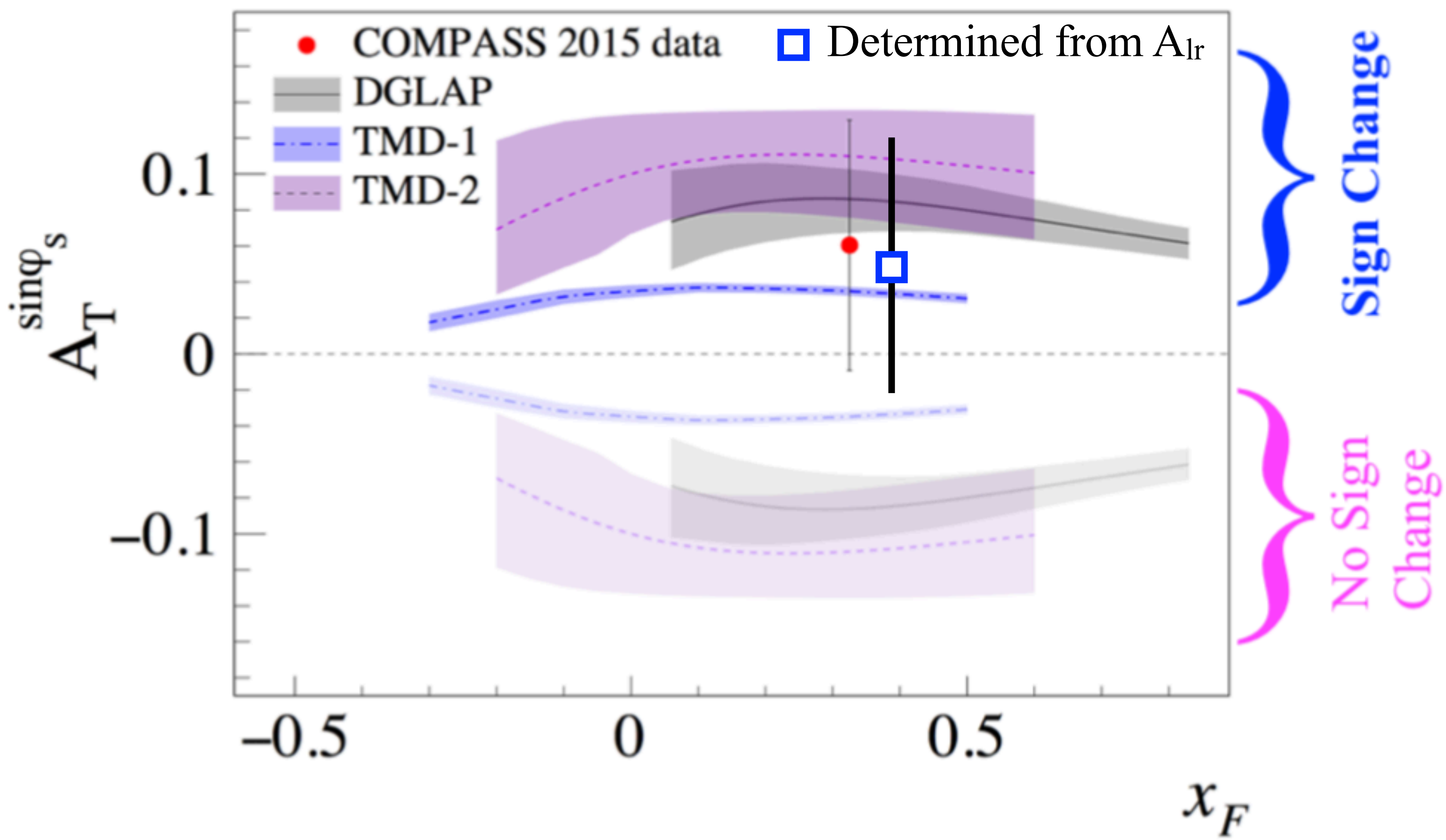
Sivers Sign Flip



Semi-Inclusive Deep Inelastic Scattering (SIDIS)



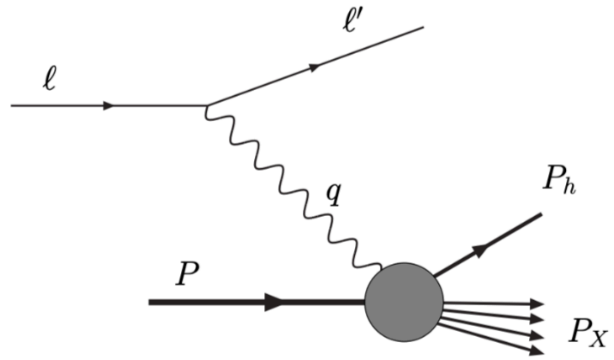
Drell-Yan



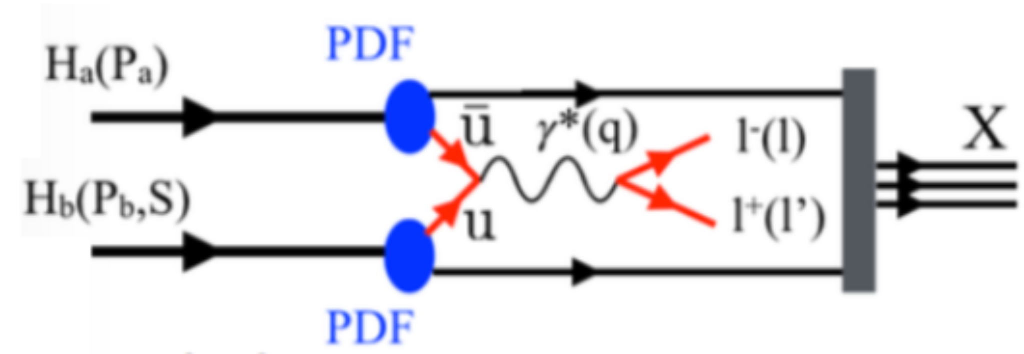
- The sign of the Sivers is consistent with a sign change between SIDIS and Drell-Yan

- The Sivers amplitude is 1-sigma greater than zero and 2-sigma greater than no-sign flip

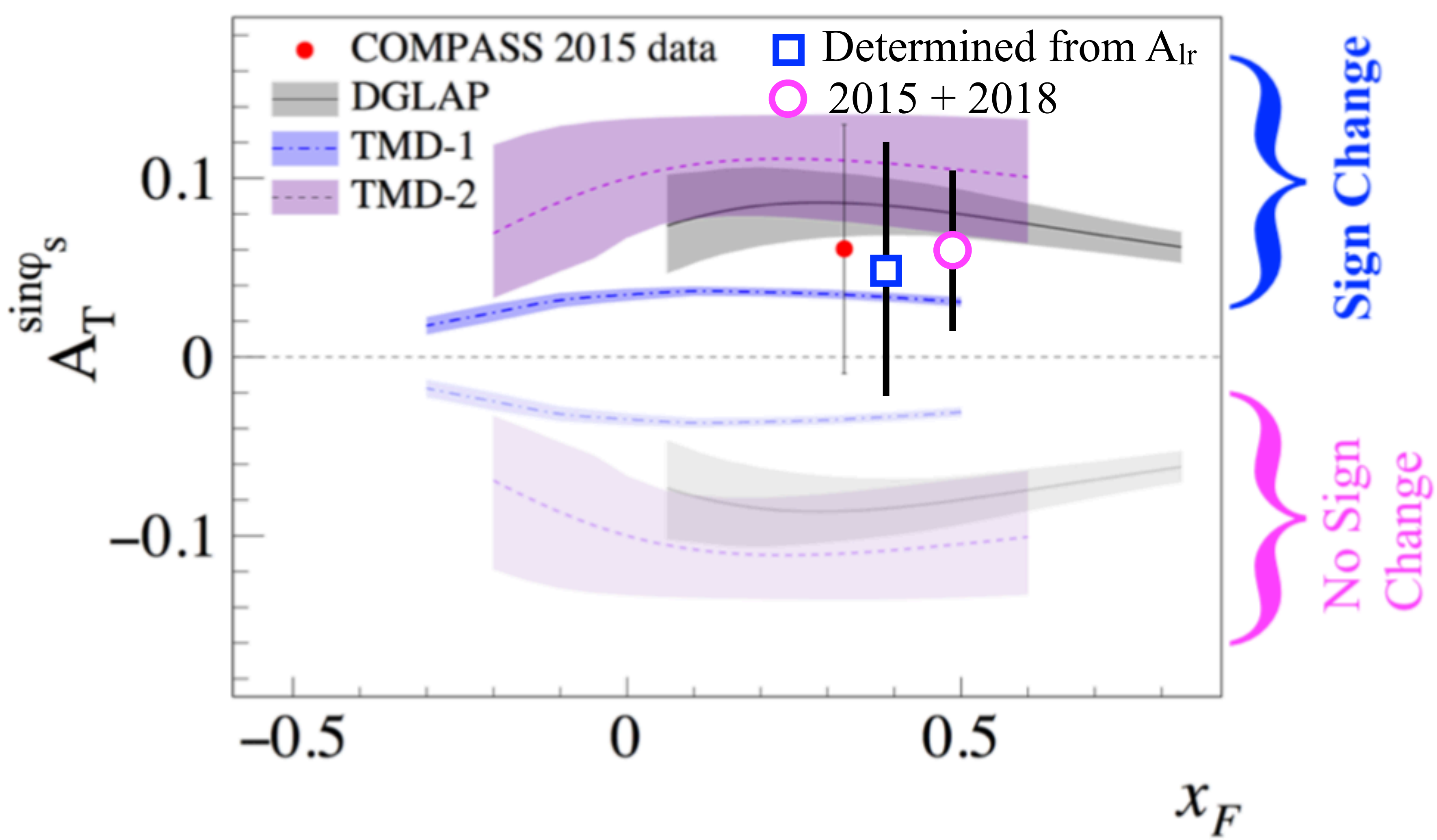
Sivers Sign Flip



Semi-Inclusive Deep
Inelastic Scattering (SIDIS)



Drell-Yan

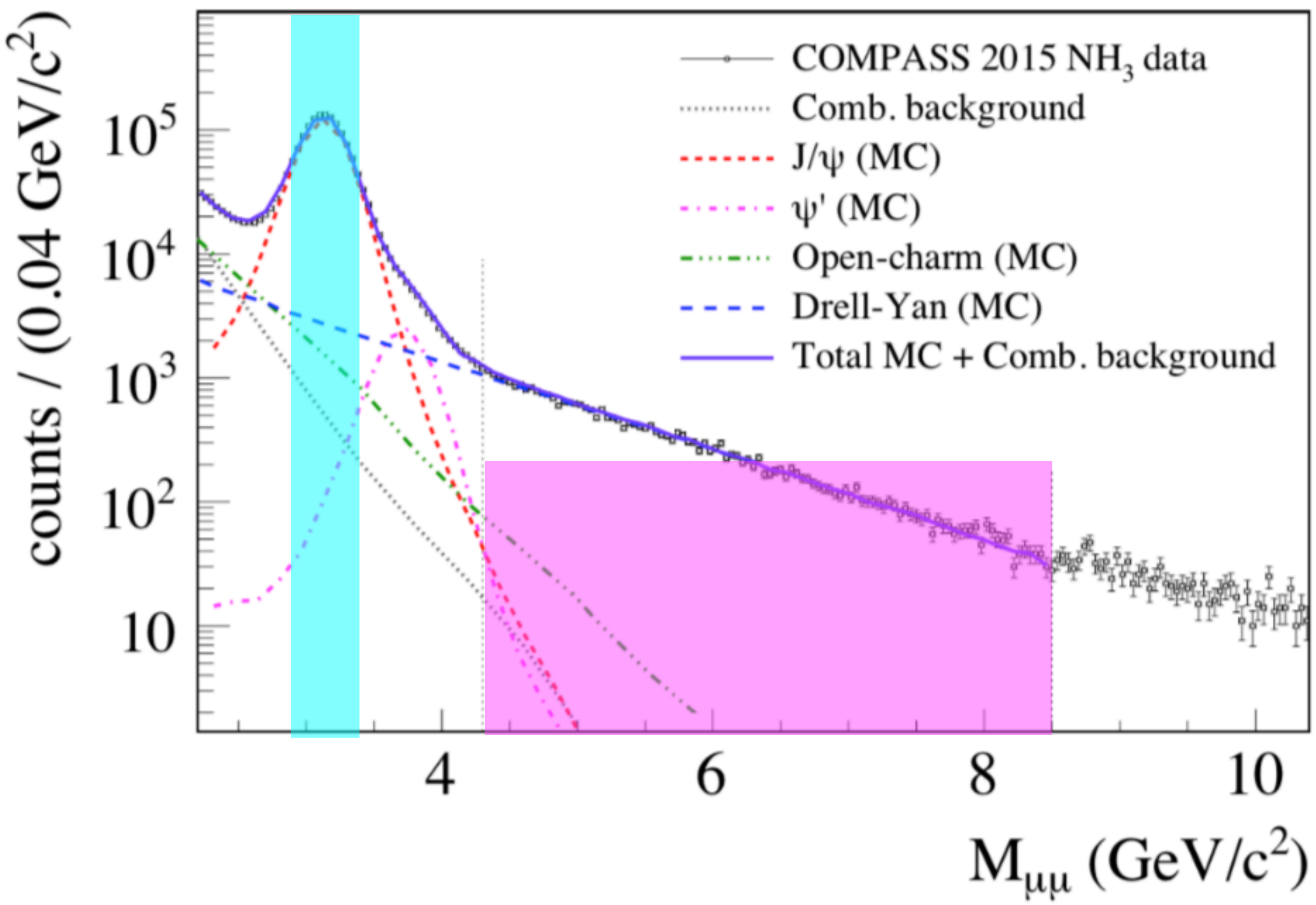


- The sign of the Sivers is consistent with a sign change between SIDIS and Drell-Yan

- The Sivers amplitude is 1-sigma greater than zero and 2-sigma greater than no-sign flip

- COMPASS performed an additional Drell-Yan measurement in 2018. Future results will shrink the statistical error bars

J/Ψ Production



Oppositely charge di-muon events:

37,921 high mass [4.3-8.5 GeV/c²]

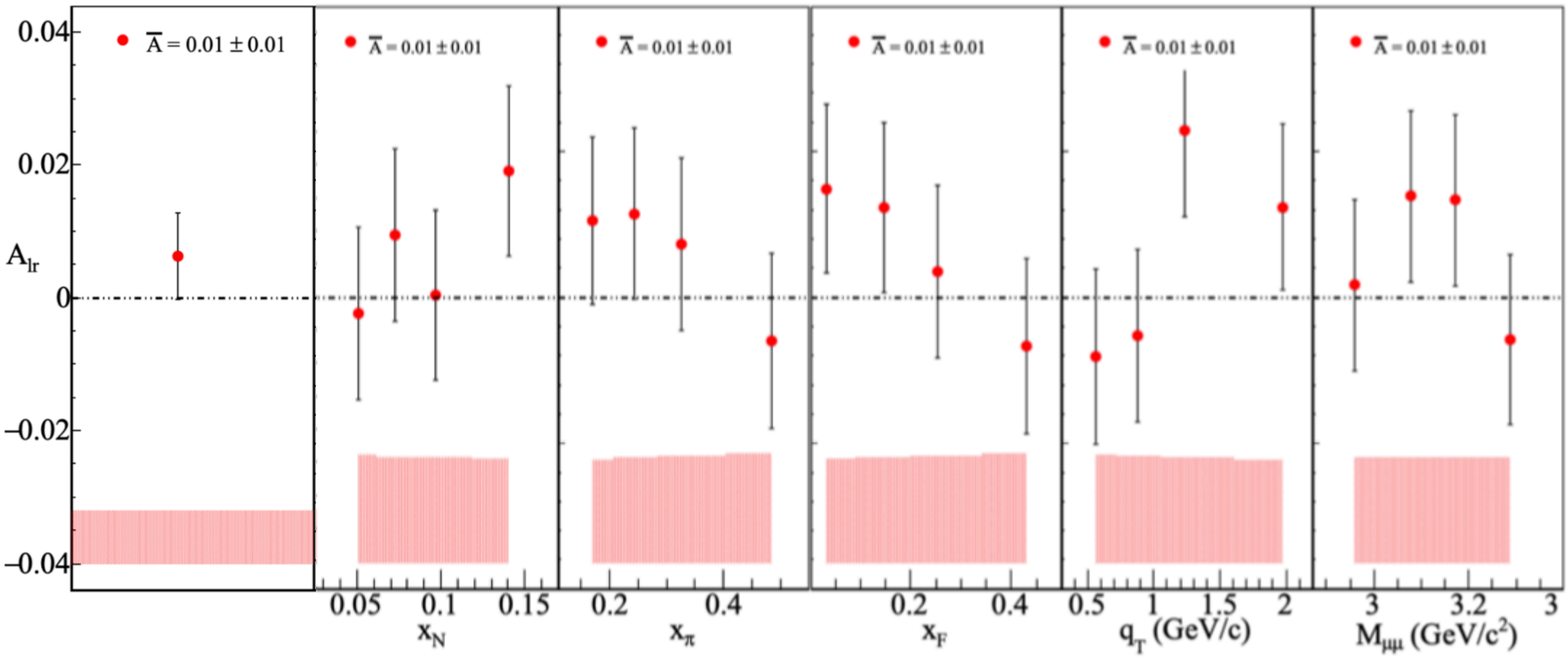
1,540,868 JPsi [2.87-3.38 GeV/c²]

Statistical gain: JPsi mass vs. high mass

40x more events

$\sim \frac{1}{\sqrt{N}}$ Asymmetry uncertainty => 6.4x statistical error reduction

J/Ψ Results



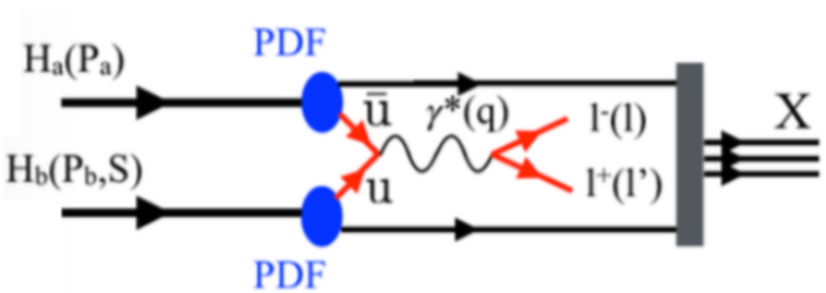
- Integrated asymmetry is positive by ~1 sigma
- Possible inverse dependence on x_F
- **New knowledge related to J/Ψ production!**

J/Ψ Mechanism

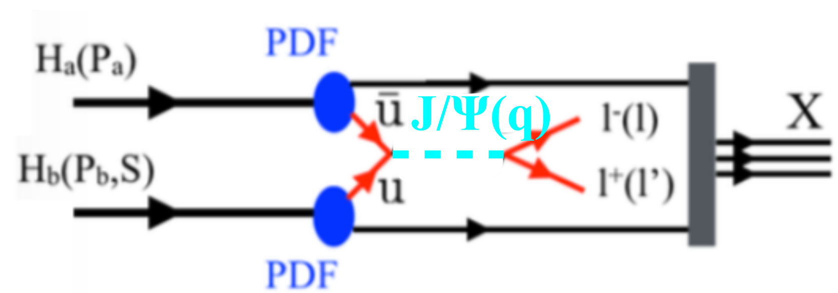
- J/Ψ coupling strength unknown

Quantum numbers J^P (Spin^{Parity})

Virtual Photon: $J^P = 1^{-1}$



J/Ψ: $J^P = 1^{-1}$



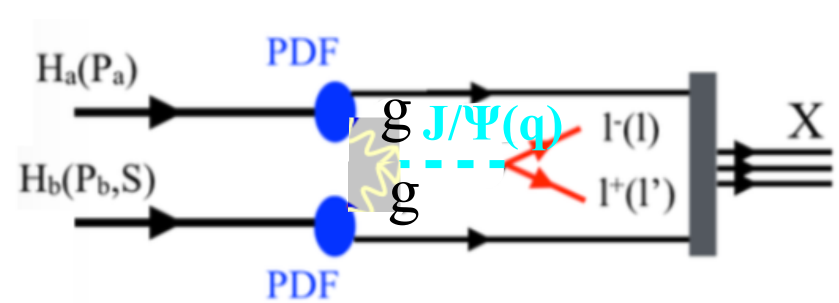
Same cross-section but new coupling strength & propagator

Drell−Yan Production		J/Ψ Production
$16\pi^2\alpha^2 e_q^2$	$\rightarrow$	$(g_q^{J/\Psi})^2(g_l^{J/\Psi})^2$
$\frac{1}{M^4}$	$\rightarrow$	$\frac{1}{(M^2 - M_{J/\Psi}^2)^2 + M_{J/\Psi}^2\Gamma_{J/\Psi}^2}$

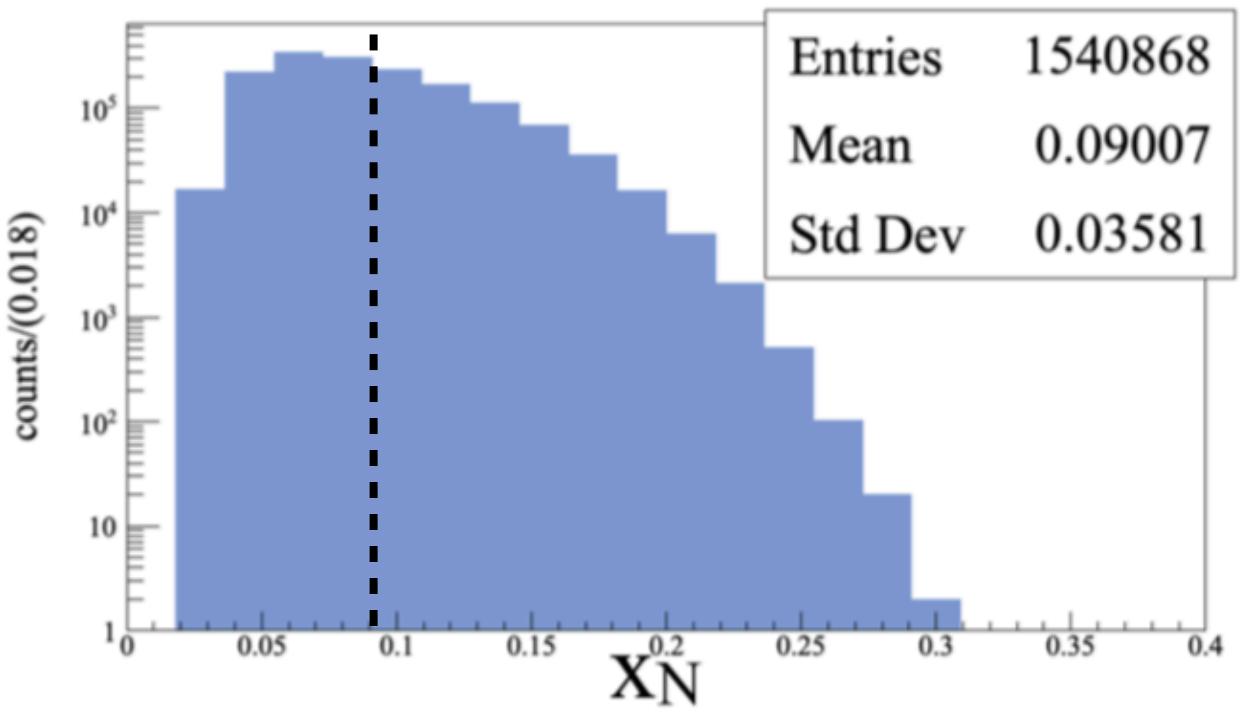
- Asymmetry is independent of coupling strength/propagator

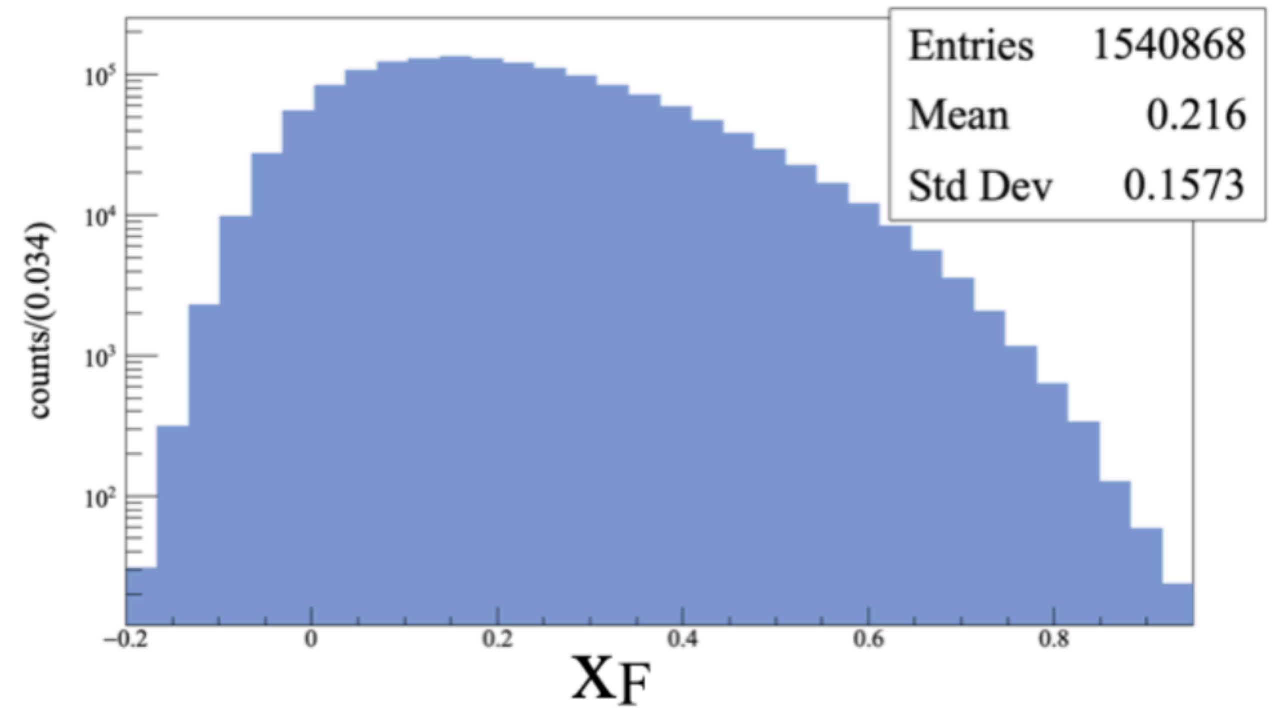
$$A_{lr} = \frac{1}{|S_T|}\frac{\sigma_{left} - \sigma_{right}}{\sigma_{left} + \sigma_{right}}$$

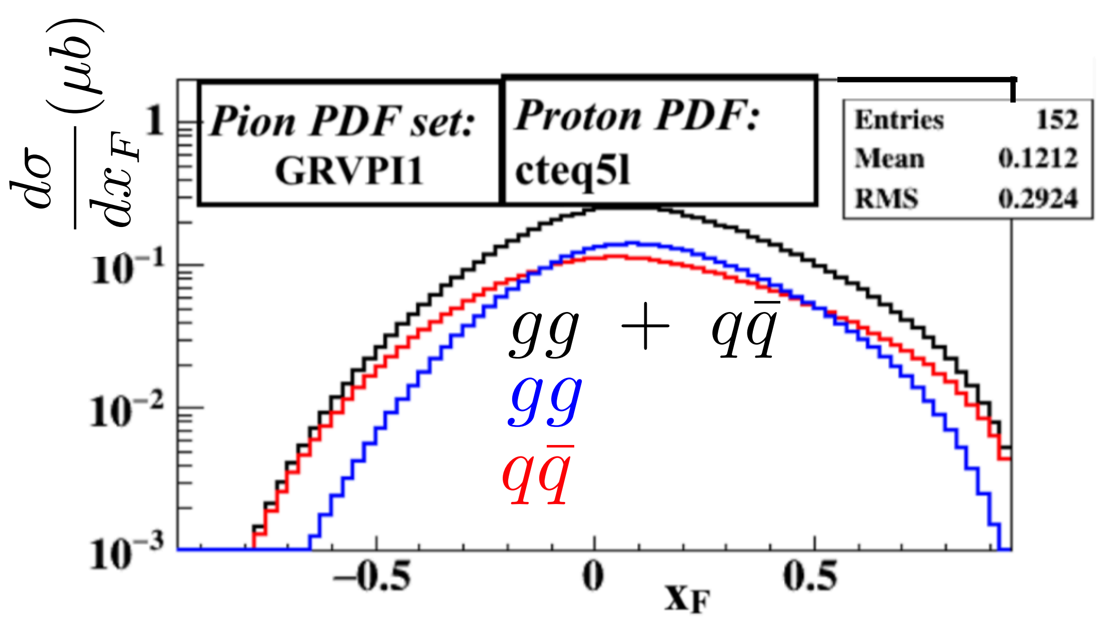
- J/Ψ Sivers effect diluted by gluon fusion



J/Ψ Kinematic Variables





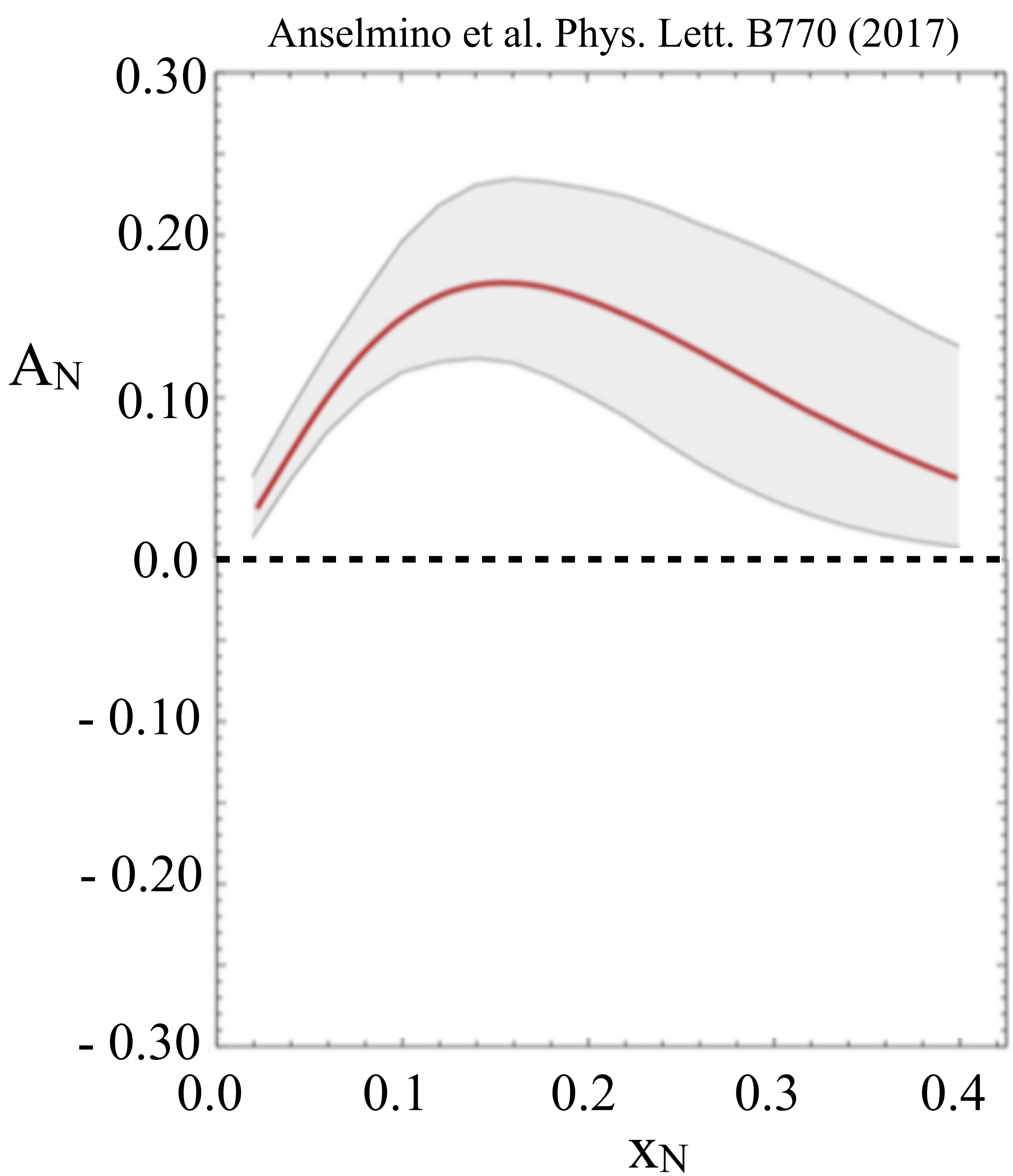


- Dilutions determined using weighted average of the COMPASS x_F distribution

Pion PDFs	SMRS	OW	GRV	ABFKW
Dilution $q\bar{q}$/**gg**	0.96	0.58	0.80	0.72

- Mixture of quark-quark annihilation and gluon-gluon fusion
- Not enough known about the pion to determine the correct production ratio

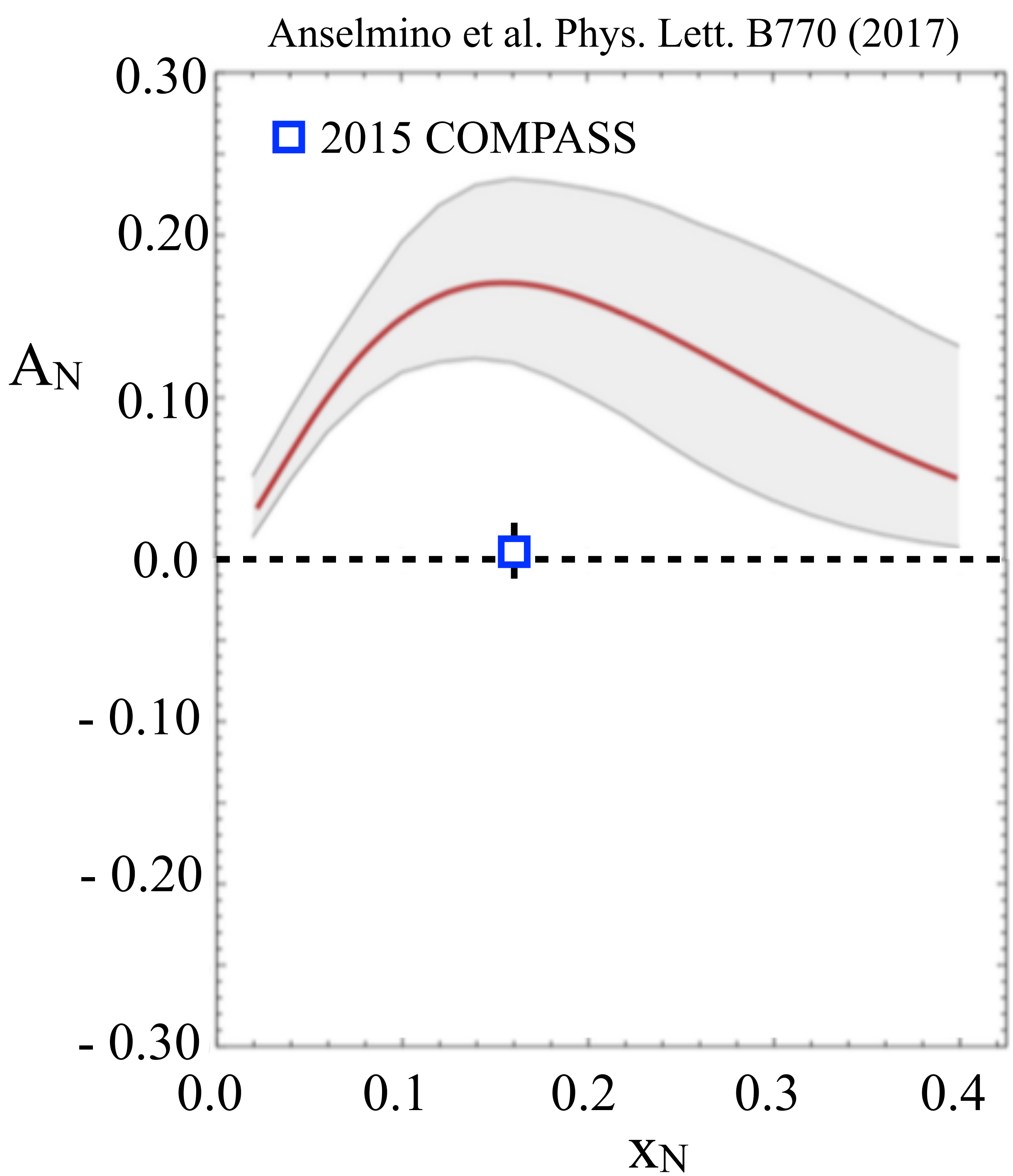
J/Ψ Sivers



A_N prediction for:

$\bar{u}u$ -> J/Ψ -> $\mu^+ + \mu^-$

J/Ψ Sivers



A_N prediction for:

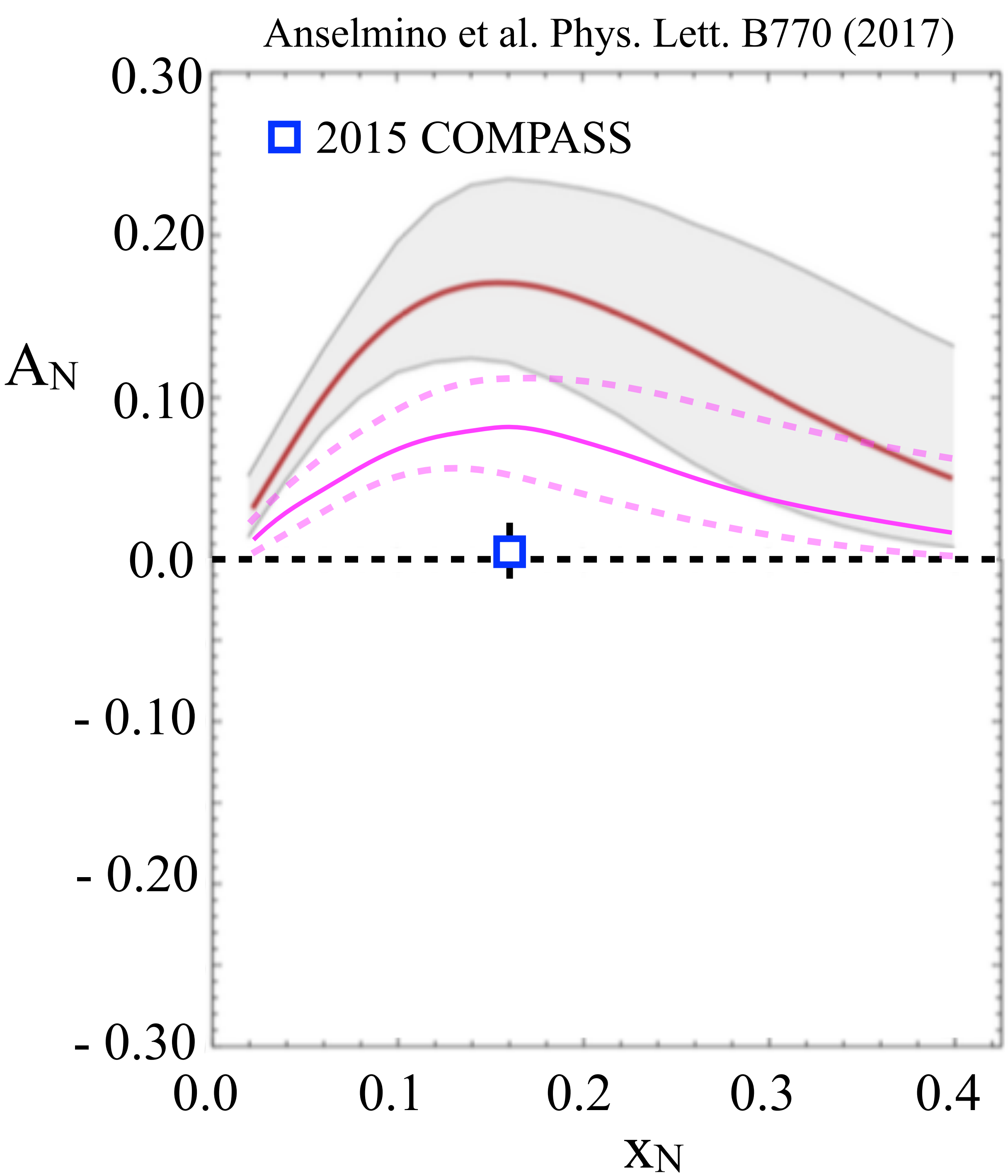
$\bar{u}u \rightarrow J/\Psi \rightarrow \mu^+ + \mu^-$

Quark annihilation vs. Gluon fusion:

$0.58 < q\bar{q}/gg < 0.96$

$37\% = q\bar{q} = 49\%$

J/Ψ Sivers



A_N prediction for:

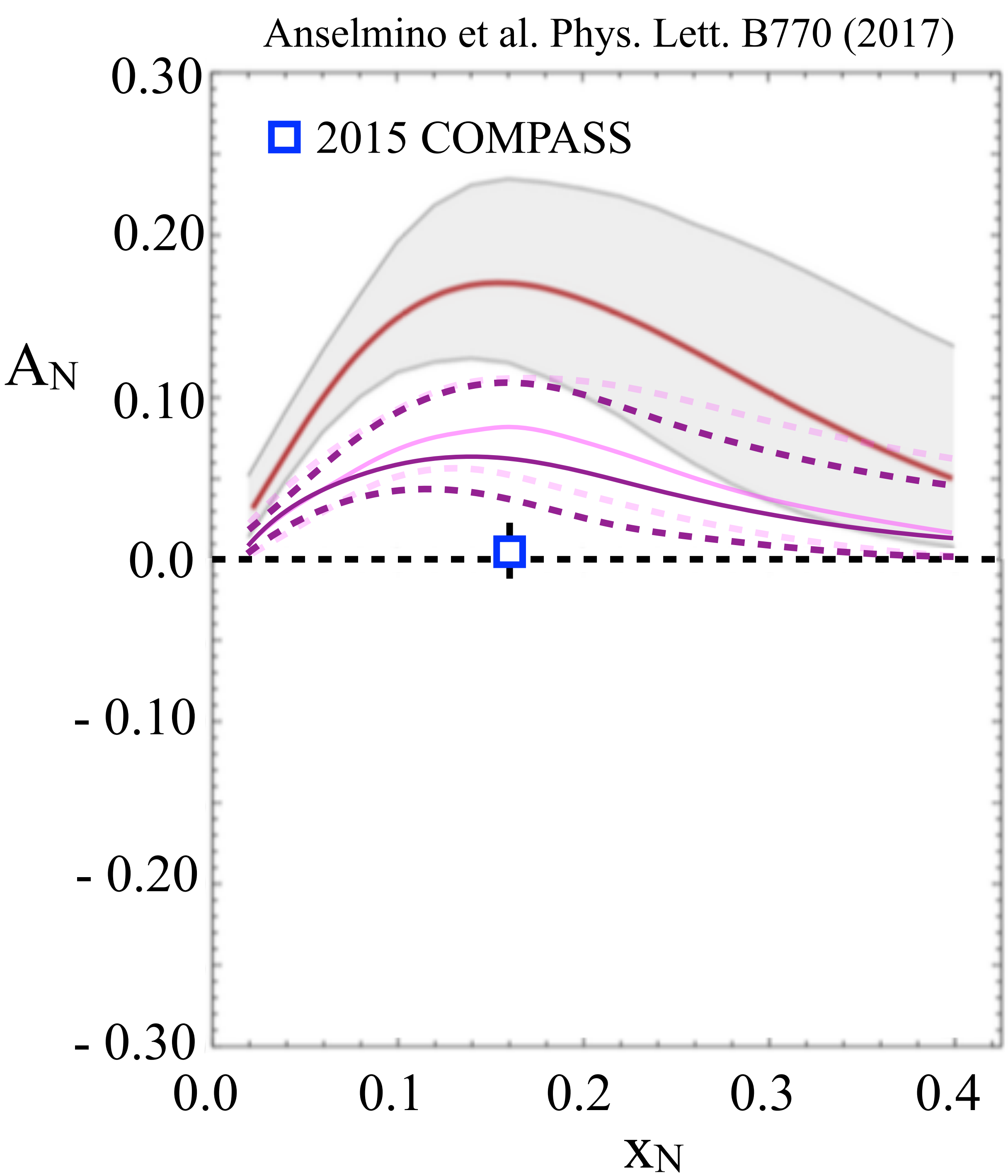
ūu -> J/Ψ -> $\mu^+ + \mu^-$

Quark annihilation vs. Gluon fusion:

$0.58 < q\bar{q}/gg < 0.96$

$37\% = q\bar{q} = 49\%$

J/Ψ Sivers



A_N prediction for:

$\bar{u}u$ -> J/Ψ -> $\mu^+ + \mu^-$

Quark annihilation vs. Gluon fusion:

$0.58 < q\bar{q}/gg < 0.96$

$37\% = q\bar{q} = 49\%$

Interpretation and Future Measurements:

- J/Ψ mechanism model is incorrect
- SIDIS asymmetry amplitudes are from higher twist effects
  => SIDIS measurements at higher Q^2 (EIC)
- Pion gluon density is larger
  => direct photon production from πp scattering (COMPASS)

Summary and Outlook

- The COMPASS spectrometer recorded data from oppositely charged di-muon events resulting from pions on a transversely polarized proton target

- The Sivers amplitude was measured to be consistent with a sign flip between Drell-Yan and SIDIS

  2018 Drell-Yan data from COMPASS will reduce the statistical error bar of the Sivers amplitude

- The Sivers like amplitude from J/Ψ production was measured to be 1-sigma positive

- The J/Ψ Sivers amplitude is inconsistent with a quark annihilation theory

  Pion gluon density is larger

  => Future COMPASS pion beam measurements

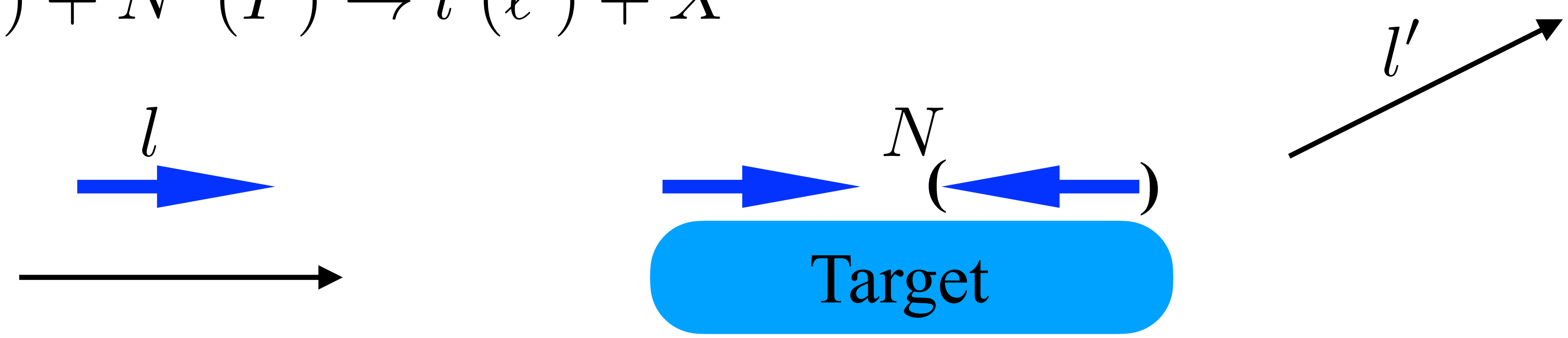
  Sivers function from SIDIS from higher twist

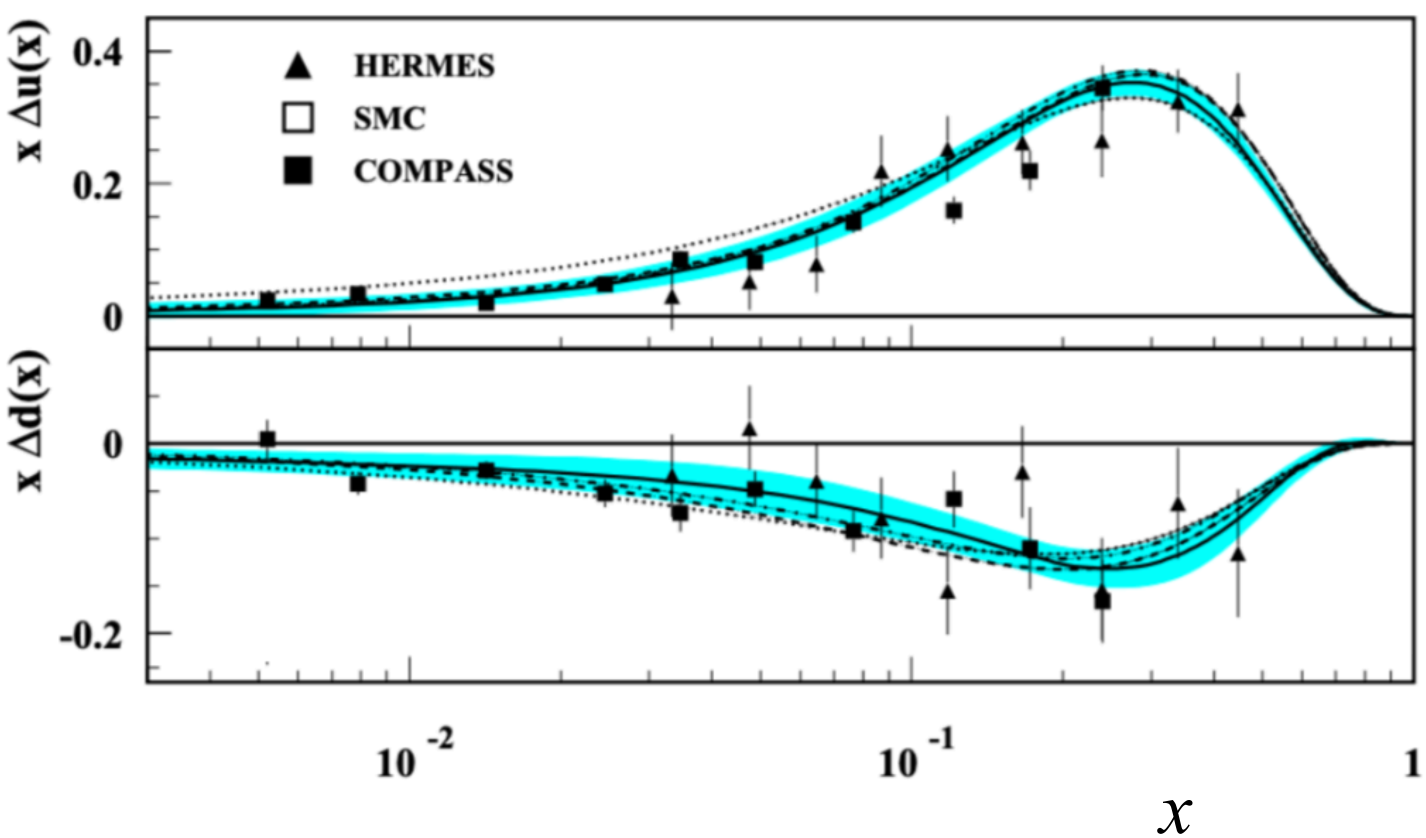
  => Future EIC measurements

Backup

Longitudinal Proton *Spin*-Structure

$$l^{\uparrow}(\ell) + N^{\uparrow}(P) \rightarrow l'(\ell') + X$$





- Spin 1/2 hadron parameterization
  spin-dependent

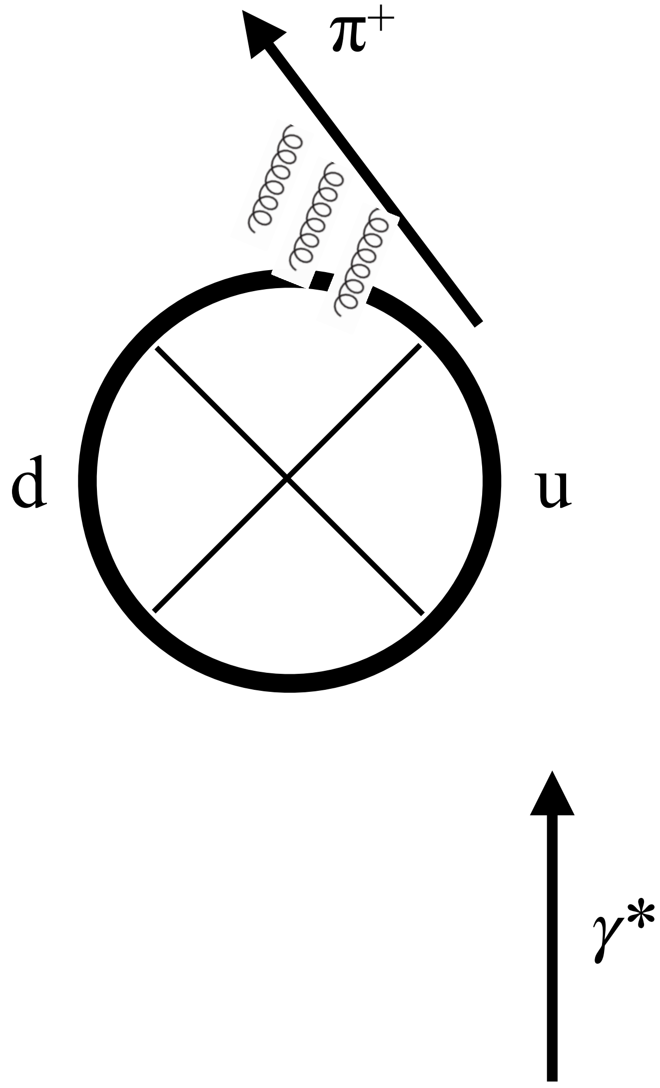
$$W_{\mu\nu}(x) =$$

$$\epsilon_{\mu\nu\rho\sigma} \frac{q^{\rho}}{2P \cdot q} \lambda^{\sigma} \sum_q e_q^2 \Delta f^q(x)$$

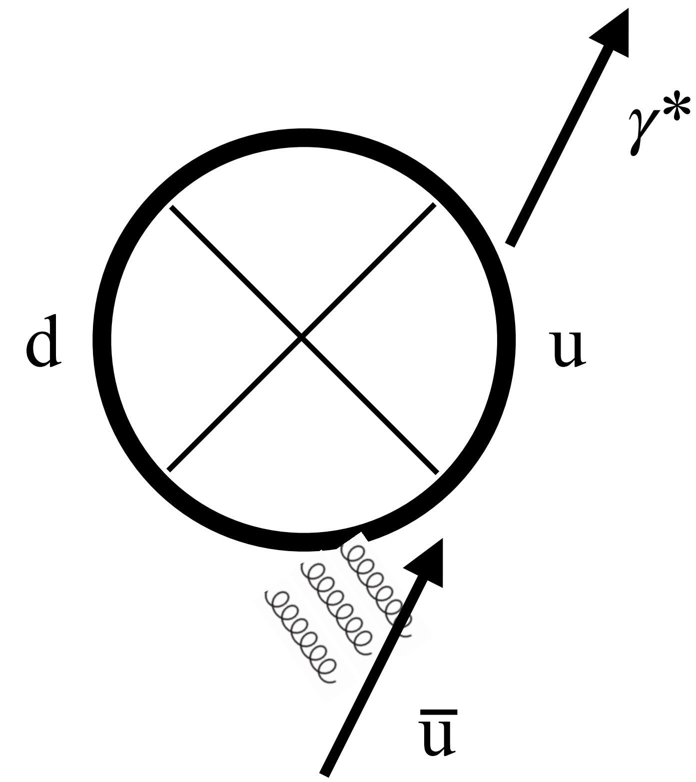
$$\Delta f_1(x) = f_1^{+}(x) - f_1^{-}(x)$$

Sign Flip

SIDIS



Drell-Yan

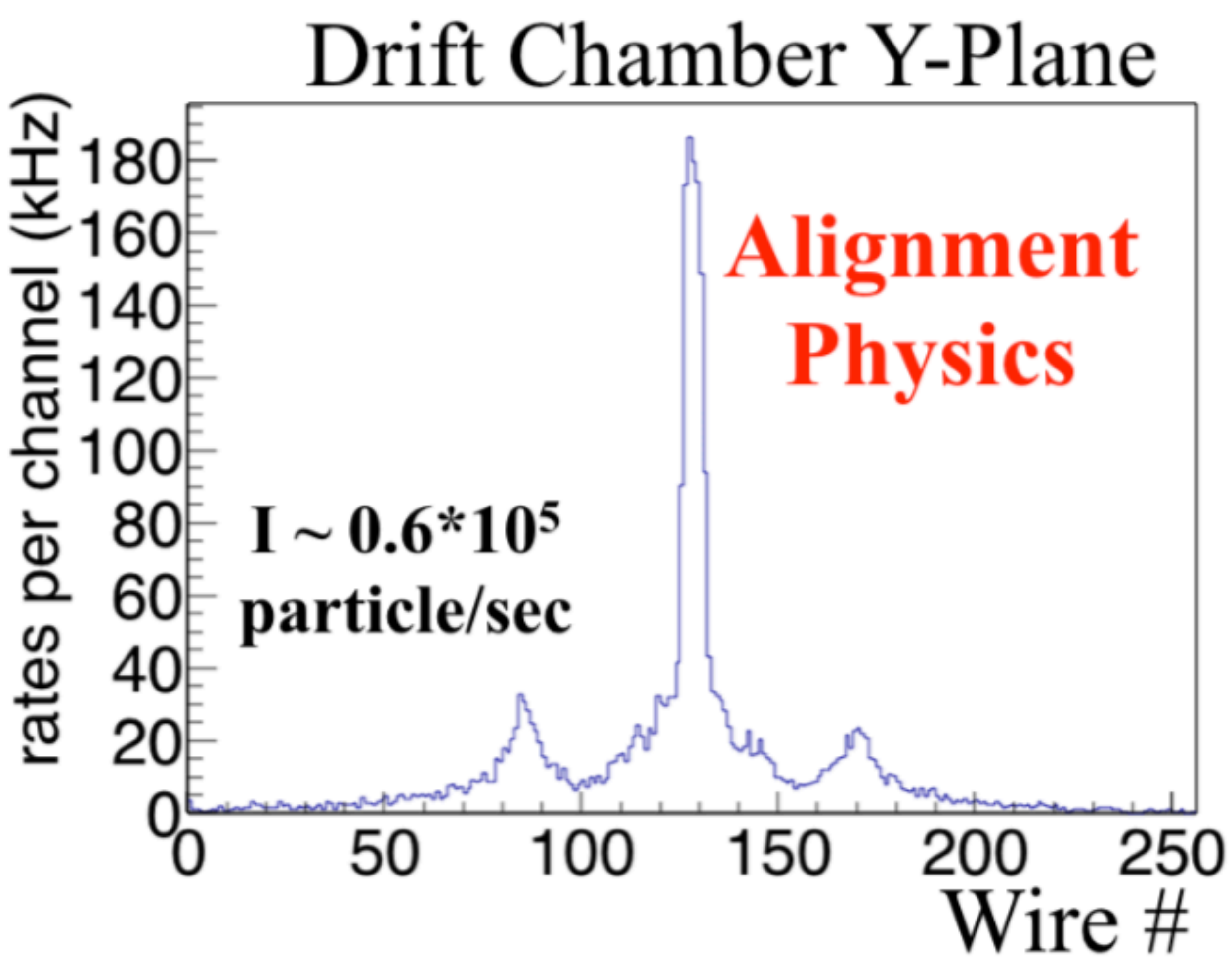


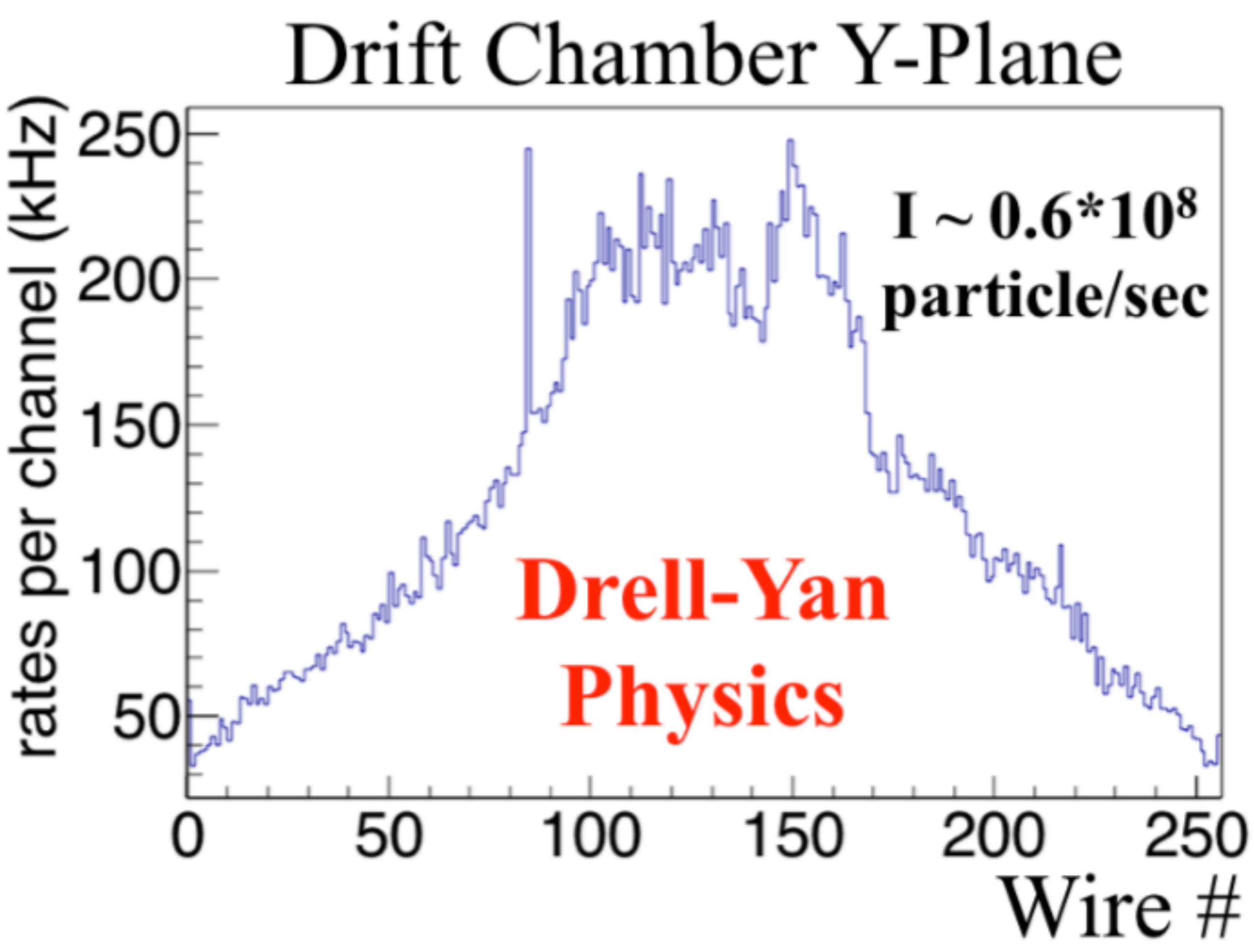
Alignment Data

- Alignment runs performed for each data taking period
  Detectors are not allowed to be changed within a data taking period

- Lower intensity, negatively charged muon beam
  Tracks are assumed to be straight

- Modified trigger to illuminate detectors



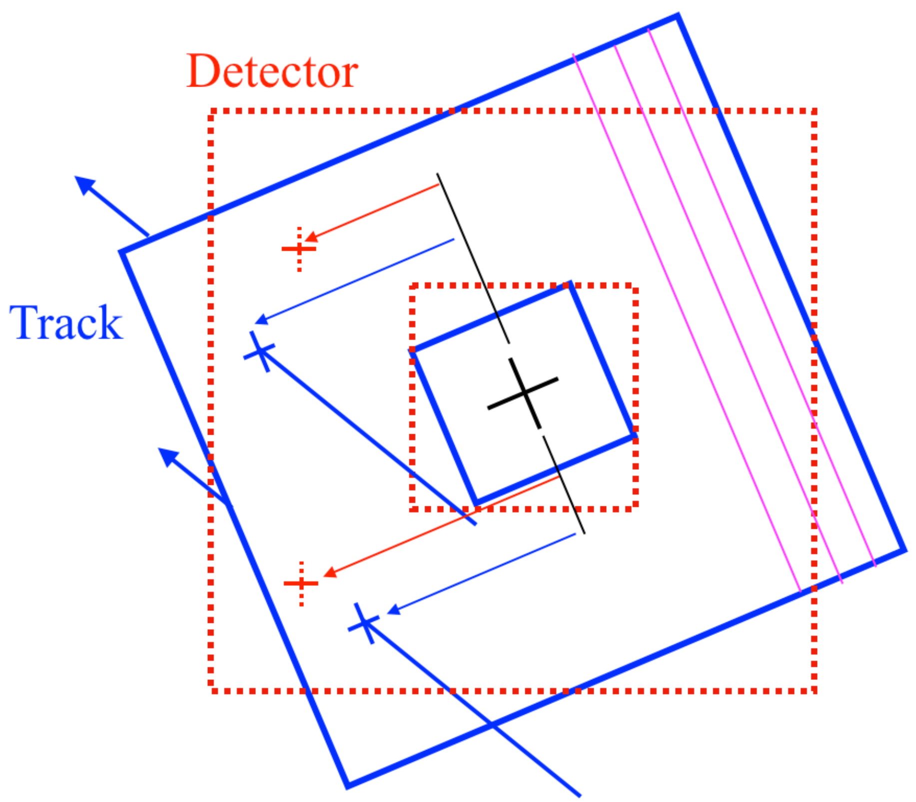


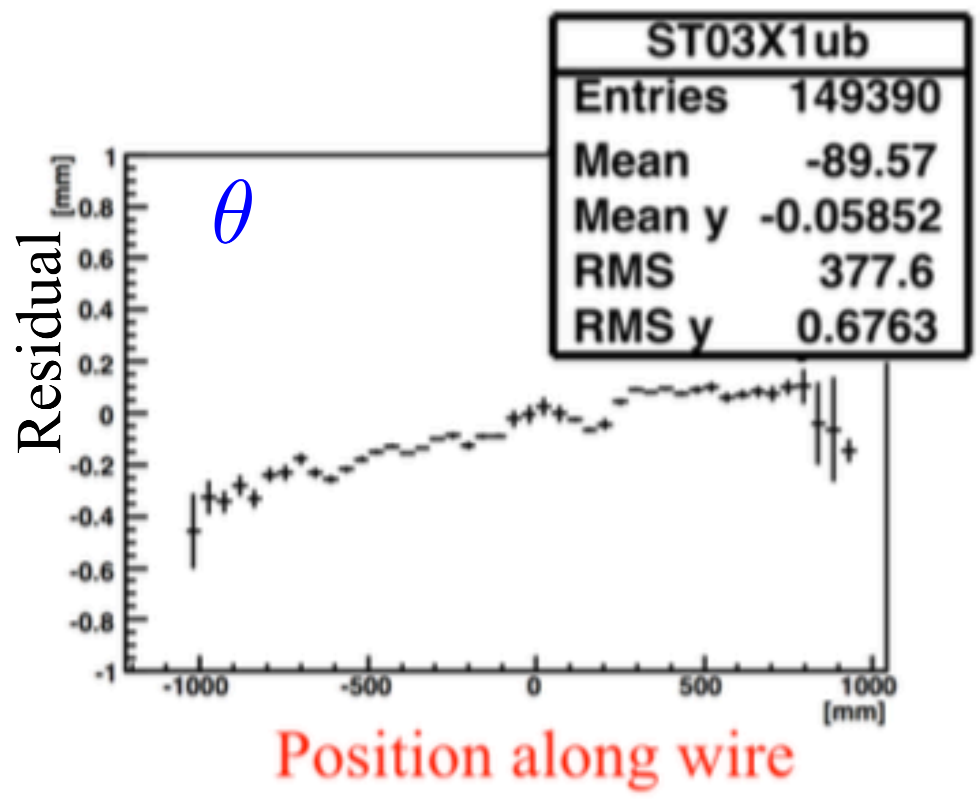
Alignment Quality

- Alignment procedure minimizes χ^2 of all detector residuals from all tracks

$$\chi^2_{det} = \frac{Residual^2_{det}(u,\ \theta,\ pitch)}{\sigma^2_{det}}$$

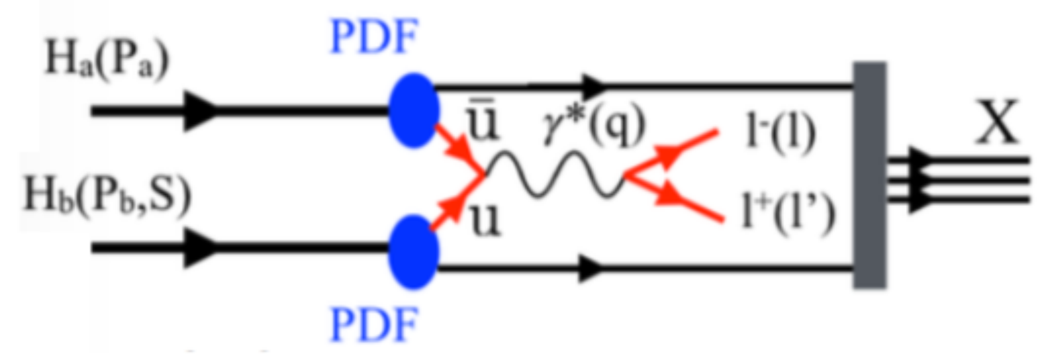
- All residuals should be 0
  - Residuals should be 0 along wire -> angle alignment
  - Residuals should be 0 perpendicular to wire -> pitch alignment



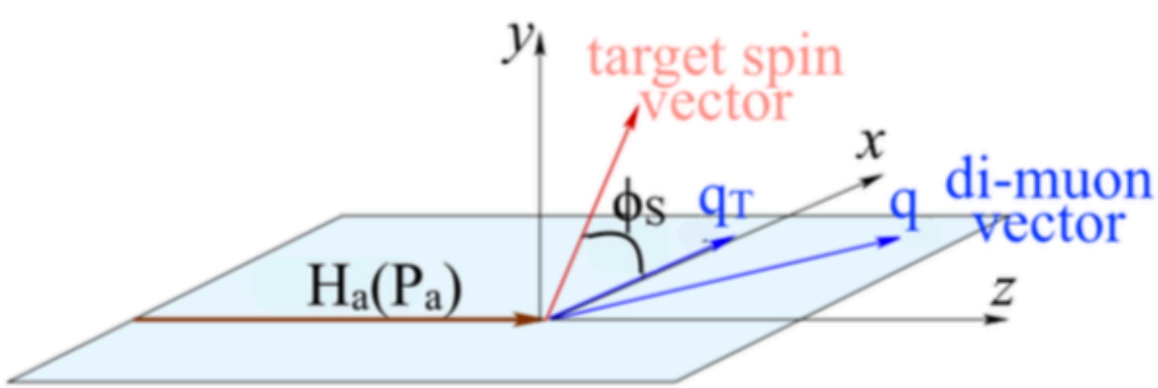


Drell-Yan Analysis Frames

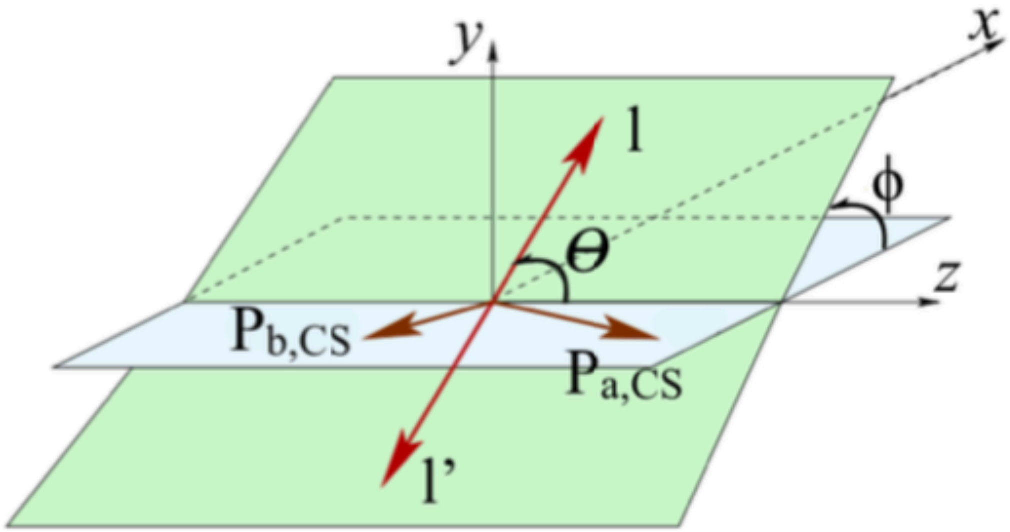
- Transverse Momentum Dependent PDF
  from azimuthal amplitudes



$$d\sigma^{DY} \propto \left[1 + A_U^{\cos(2\phi)} \cos(2\phi)\right] + \|S_T\| \Big\{ A_T^{\sin(\phi_S)} \sin(\phi_S)$$
$$+ \left[A_T^{\sin(2\phi+\phi_S)} \sin(2\phi + \phi_S) + A_T^{\sin(2\phi-\phi_S)} \sin(2\phi - \phi_S) \right] \Big\}$$



Target reference frame



Collins-Soper center of momentum frame

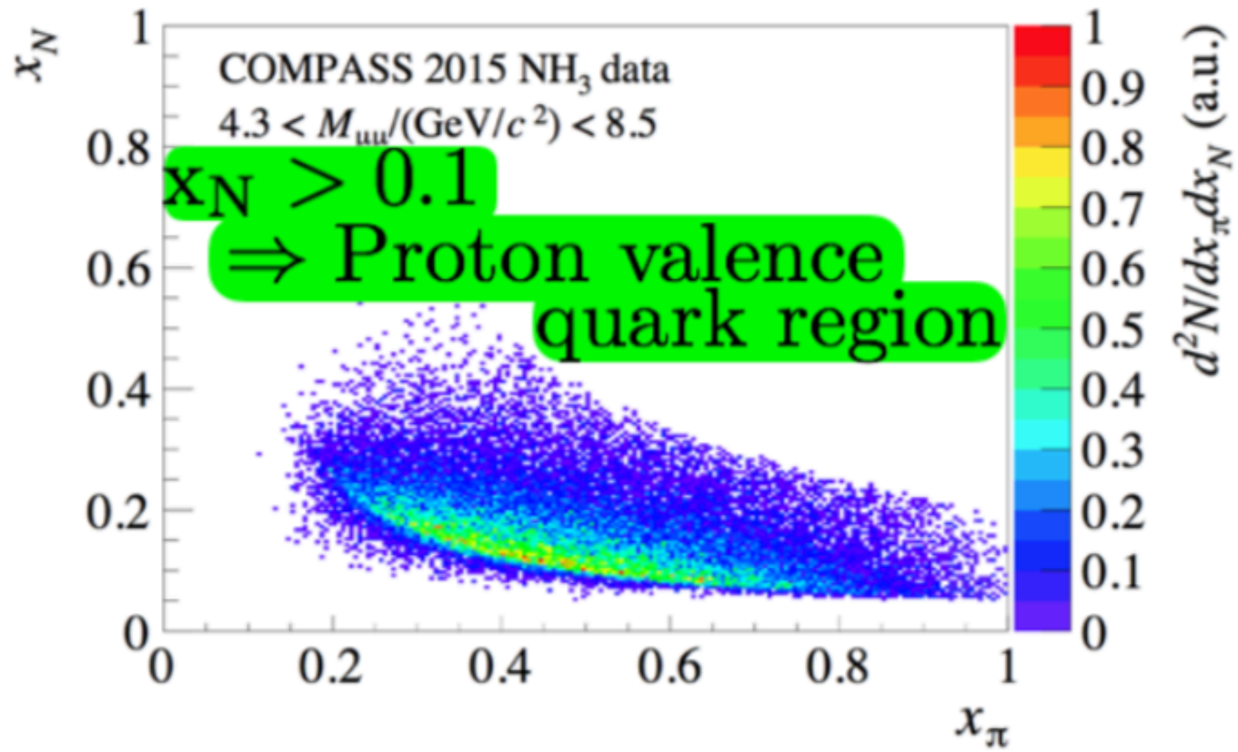
$A_U^{\cos(2\phi)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$ Boer-Mulders

$A_T^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$ Sivers

$A_T^{\sin(2\phi-\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$ transversity

$A_T^{\sin(2\phi+\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp}$ pretzelosity

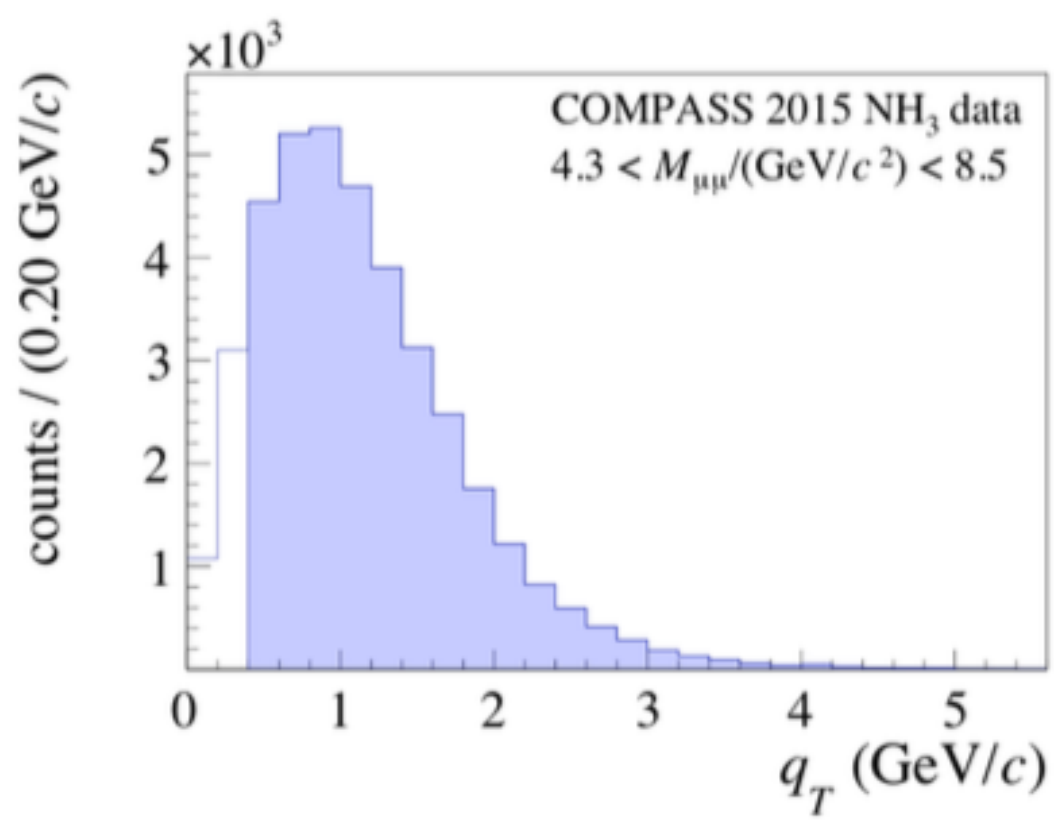
Drell-Yan Phase Space



- Valence quark annihilation from both beam and target
  $x_N > 0.1$, $x_\pi > 0.2$

- Average transverse photon momentum
  $\langle q_T \rangle = 1.2$ GeV/c
  Average invariant mass $\langle M_{\mu\mu} \rangle = 5.3$ GeV/c^2

- q_T cut ensures better angular resolution



Left-Right Asymmetry Systematics

Left/Right ***Right/Left***

$$A_{lr,\ false} = \frac{1}{|S_T|}\frac{\sqrt[4]{N^{\uparrow}_{1,\ left}N^{\downarrow}_{1,\ right}N^{\uparrow}_{2,\ left}N^{\downarrow}_{2,\ right}} - \sqrt[4]{N^{\uparrow}_{1,\ right}N^{\downarrow}_{1,\ left}N^{\uparrow}_{2,\ right}N^{\downarrow}_{2,\ left}}}{\sqrt[4]{N^{\uparrow}_{1,\ left}N^{\downarrow}_{1,\ right}N^{\uparrow}_{2,\ left}N^{\downarrow}_{2,\ right}} + \sqrt[4]{N^{\uparrow}_{1,\ right}N^{\downarrow}_{1,\ left}N^{\uparrow}_{2,\ right}N^{\downarrow}_{2,\ left}}}$$

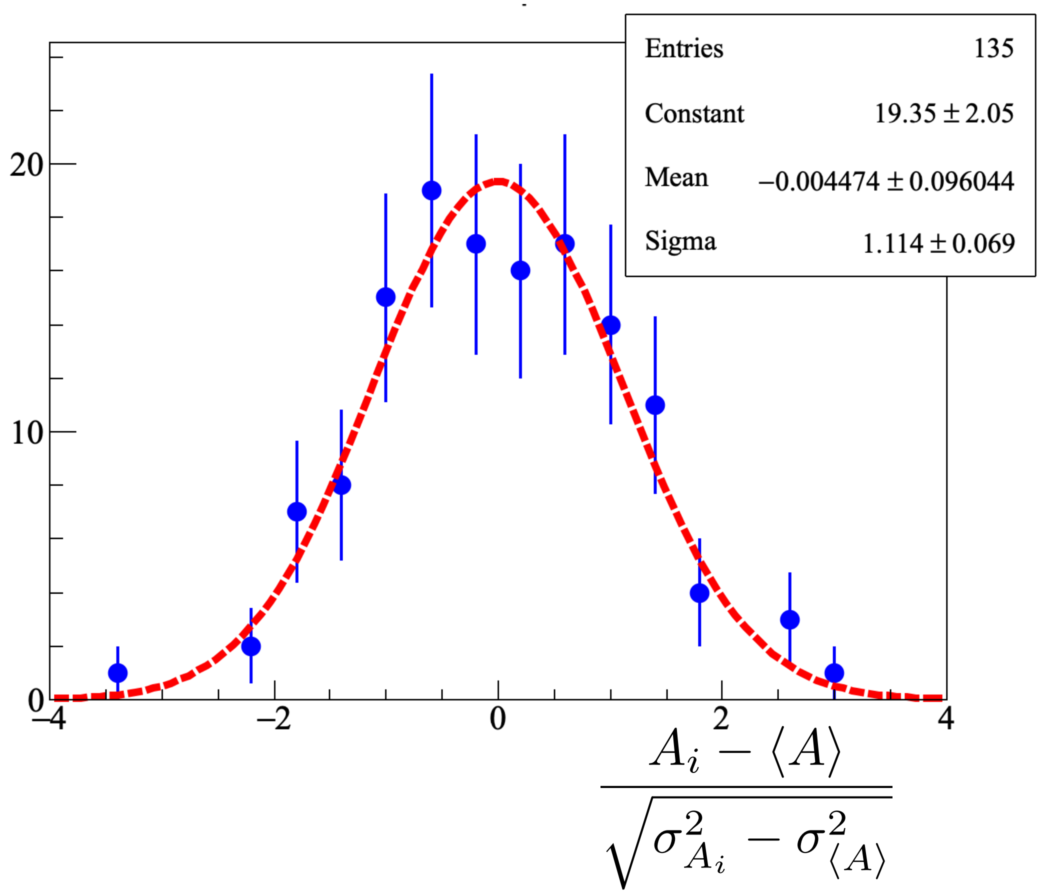
False asymmetry:

- independent of differential cross-section
- dependent on spectrometer acceptance => $A_{lr,\ false} \neq 0$
- time dependence => systematic uncertainty

Left-Right Asymmetry Systematics

$$A_{lr,\ false} = A_{lr,\ false}(\textcolor{red}{acceptance,\ systematic\ uncertainty})$$

False asymmetry:
- independent of differential cross-section
- dependent on spectrometer acceptance => $A_{lr,\ false} \neq 0$
- time dependence => systematic uncertainty



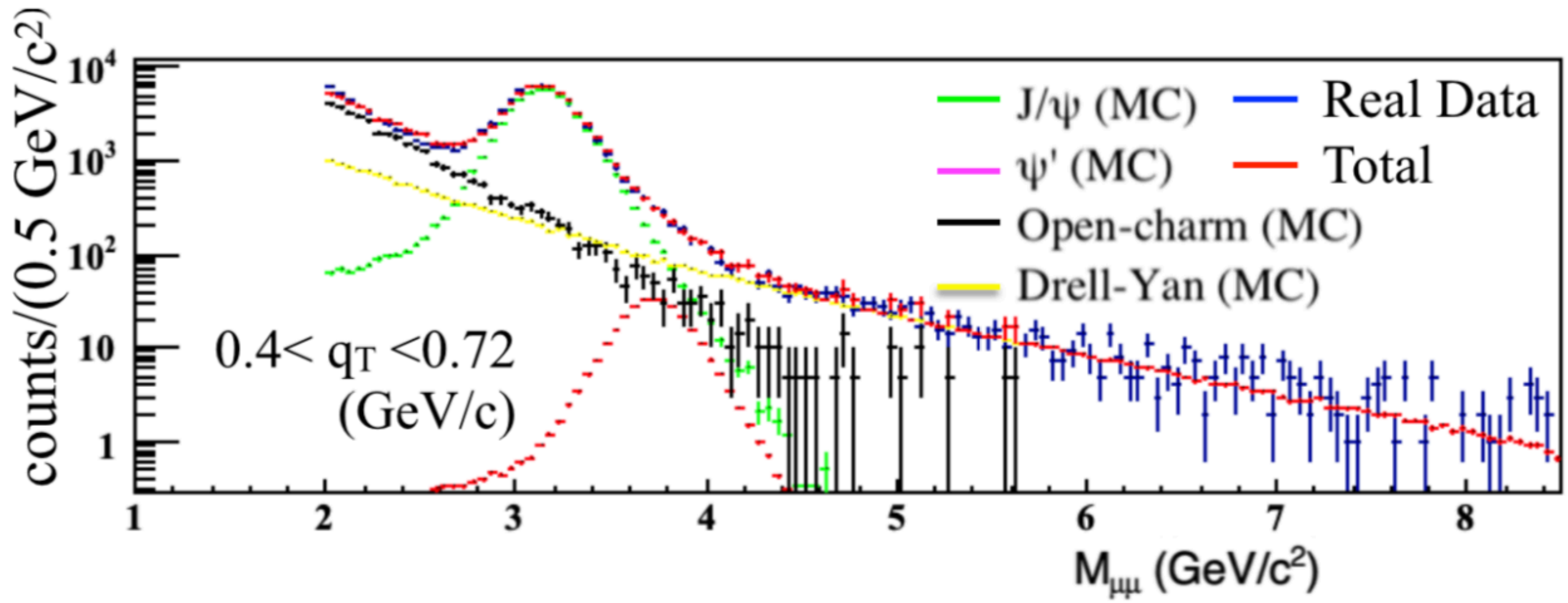
- Estimate systematic uncertainty with students t-test

Mean	should =	0
Sigma	should =	1

JPsi Purity

$$\frac{\sigma_{systematic}}{\sigma_{statistical}} = \frac{(1-p)}{p}$$

Criteria for mass range chosen: >90 % J/Ψ purity demanded

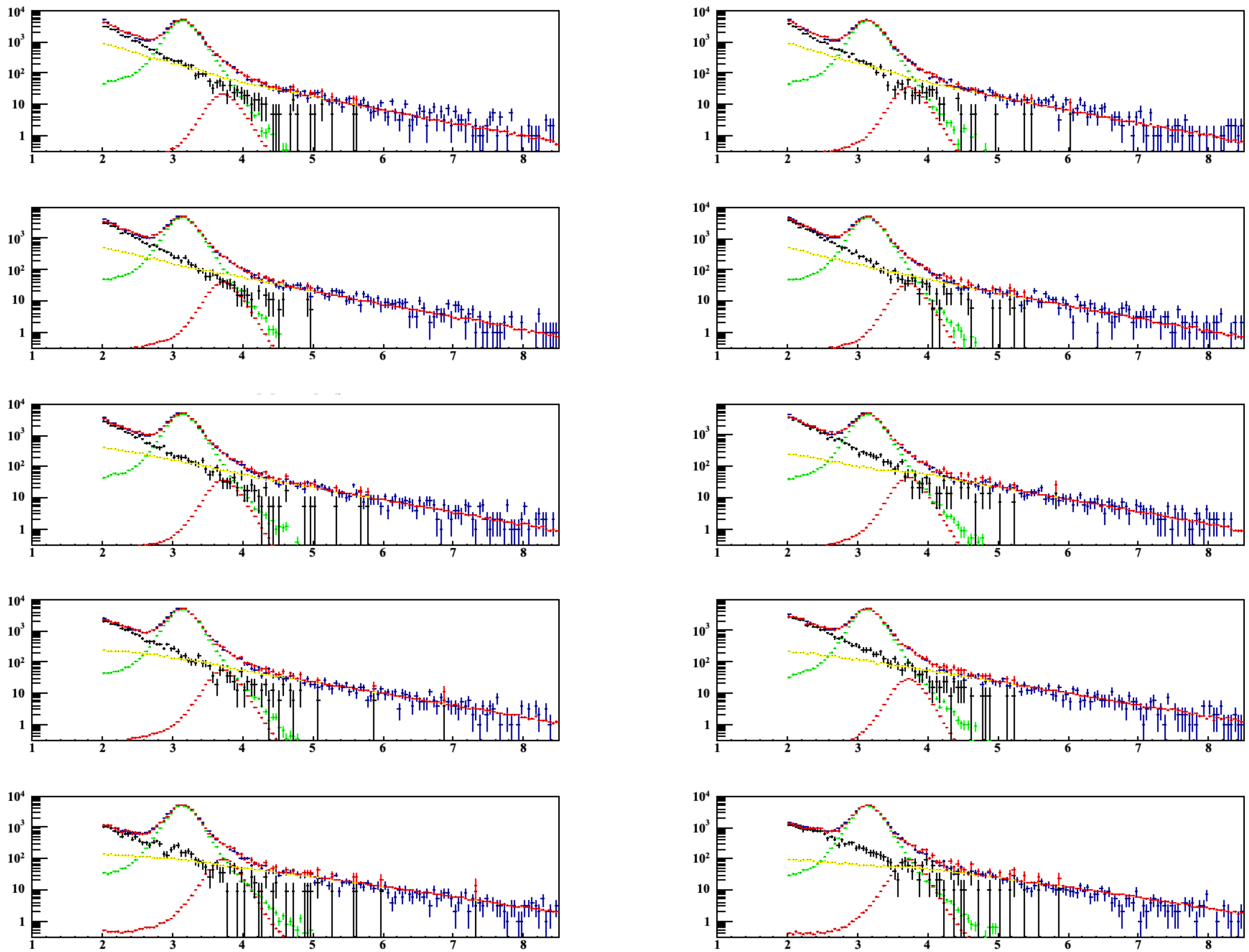


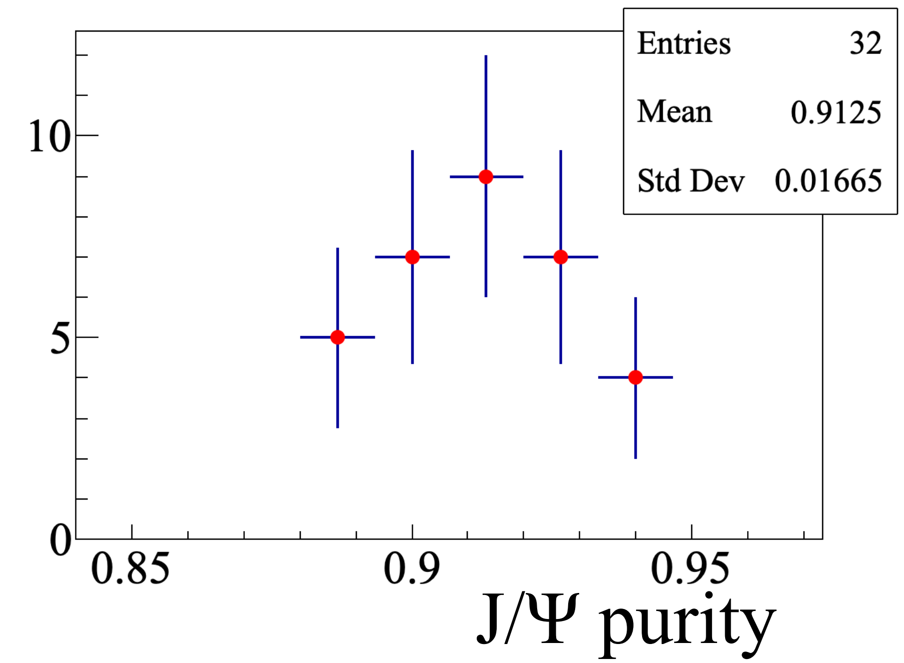
- Monte-Carlo sample used to get invariant mass distribution

JPsi Purity

$$\frac{\sigma_{systematic}}{\sigma_{statistical}} = \frac{(1-p)}{p}$$

Criteria for mass range chosen: >90 % J/Ψ purity demanded

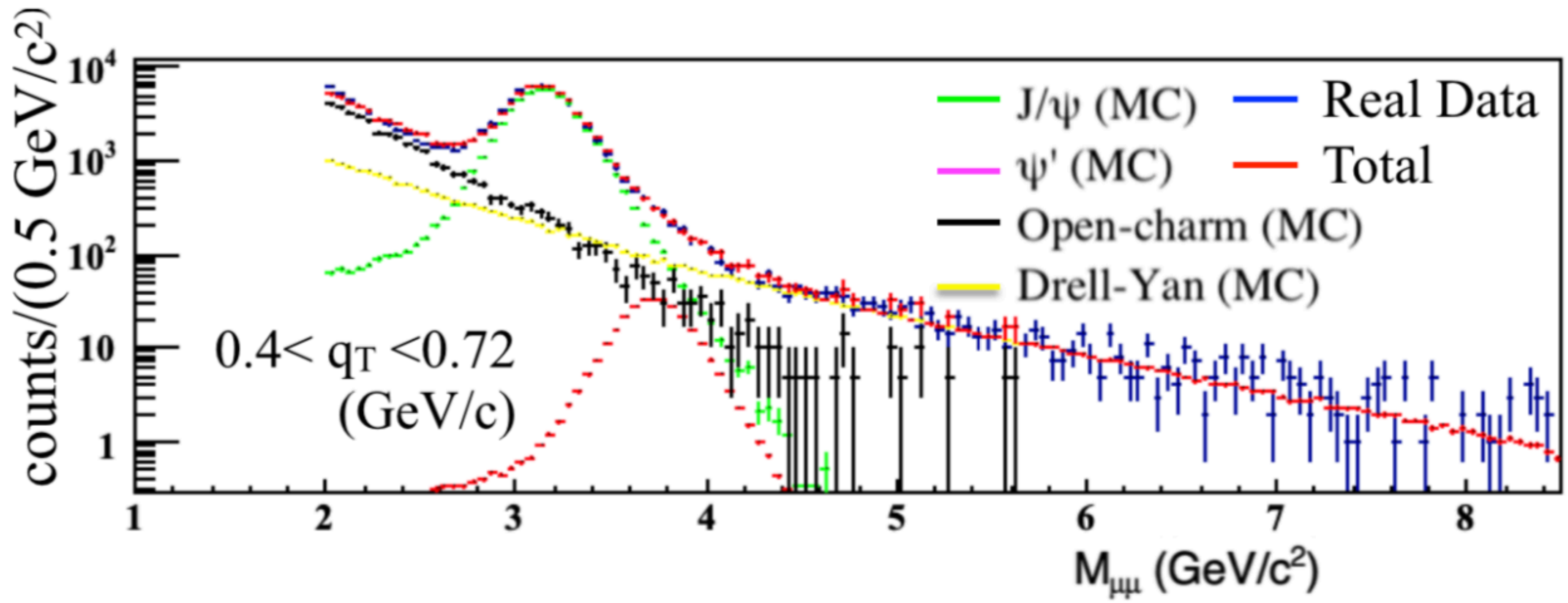




JPsi Purity

$$\frac{\sigma_{systematic}}{\sigma_{statistical}} = \frac{(1-p)}{p}$$

Criteria for mass range chosen: >90 % J/Ψ purity demanded



Mass range GeV/c^2	J/Ψ Purity %
2.5-4.3	79.7 ± 2.9
2.78-3.46	88.9 ± 2.0
2.87-3.38	**91.3 ± 1.5**
2.95-3.29	92.9 ± 1.0
3.08-3.17	94.0 ± 1.0

$$\frac{\sigma_{systematic}}{\sigma_{statistical}} = 9.5\%$$

JPsi Purity

$$\frac{\sigma_{systematic}}{\sigma_{statistical}} = \frac{(1-p)}{p}$$

Criteria for mass range chosen: >90 % J/Ψ purity demanded

Systematic error	$\langle \sigma_{\text{systematic}} / \sigma_{\text{statistical}} \rangle$	$\langle \sigma_{\text{systematic}} \rangle$
Period compatibility	0.16	0.001
Left-Right migration	0.044	0.0003
J/Ψ purity	0.095	0.0006
Target Polarization	0.05	0.0003
Dilution Factor	0.05	0.0003
Acceptance fluctuation	0.23	0.001
False asymmetry	1.2	0.008
Total	**1.24**	**0.008**

2.95-3.29	92.9 ± 1.0
3.08-3.17	94.0 ± 1.0

JPsi Sivers

Quark annihilation vs. Gluon fusion

$0.58 < q\bar{q}/gg < 0.96$