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

Robert Heitz

April 30, 2019

Outline

- Proton Structure

  Longitudinal Structure
  Spin Structure
  Transverse momentum dependent parton distribution functions (TMD PDFs)

- The COMPASS experiment at CERN (2015)

  Negatively charge pion beam
  Transversely polarized proton target

- Drift Chamber 05

  Critical tracking detector

- Spectrometer alignment

  Essential prepossessing step for data quality

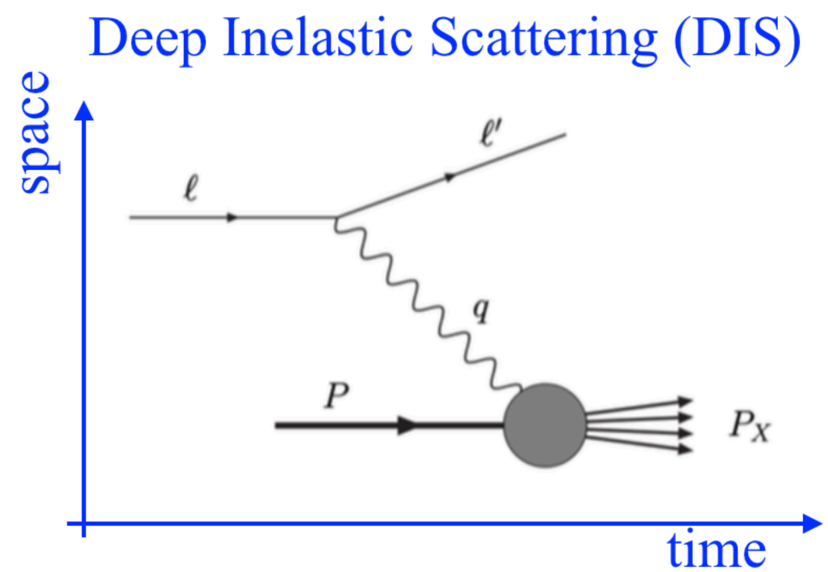
- Drell-Yan analysis

  Left-Right asymmetry to determine the Sivers amplitude

- J/Ψ analysis

  Left-Right asymmetry to determine the Sivers amplitude

Proton Structure



Cross-section

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

Lepton Tensor

- Perturbation Theory

Hadron Tensor

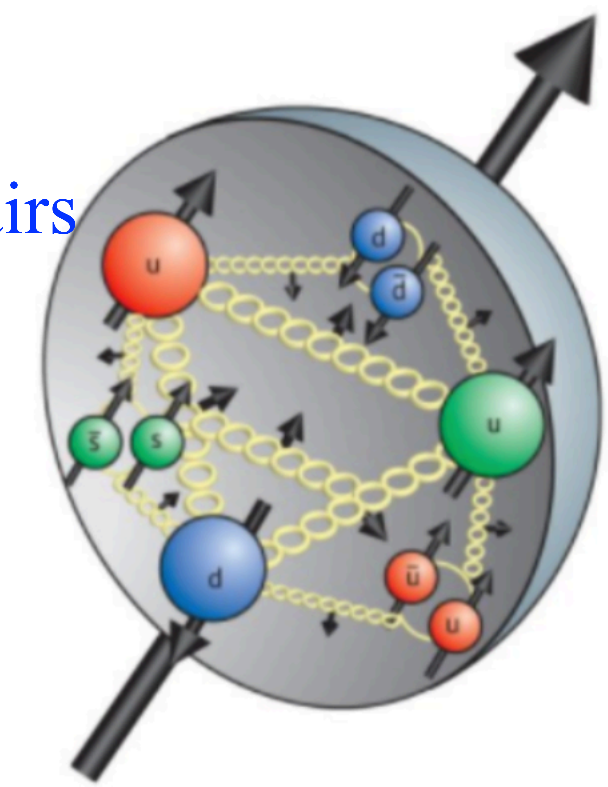
- not able to determine with Perturbation Theory
- Parameterize and measure parameters

- Spin 1/2 hadron
  parameterization
  spin-independent

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

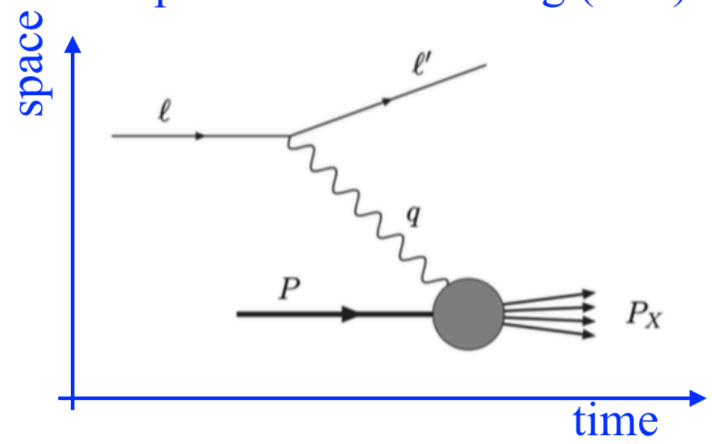
$$\frac{1}{P \cdot q} \sum_q e_q^2 \Big[(k_\mu + q_\mu) P_\nu + (k_\nu + q_\nu) P_\mu - g_{\mu\nu} \Big] f_1^q(x)$$

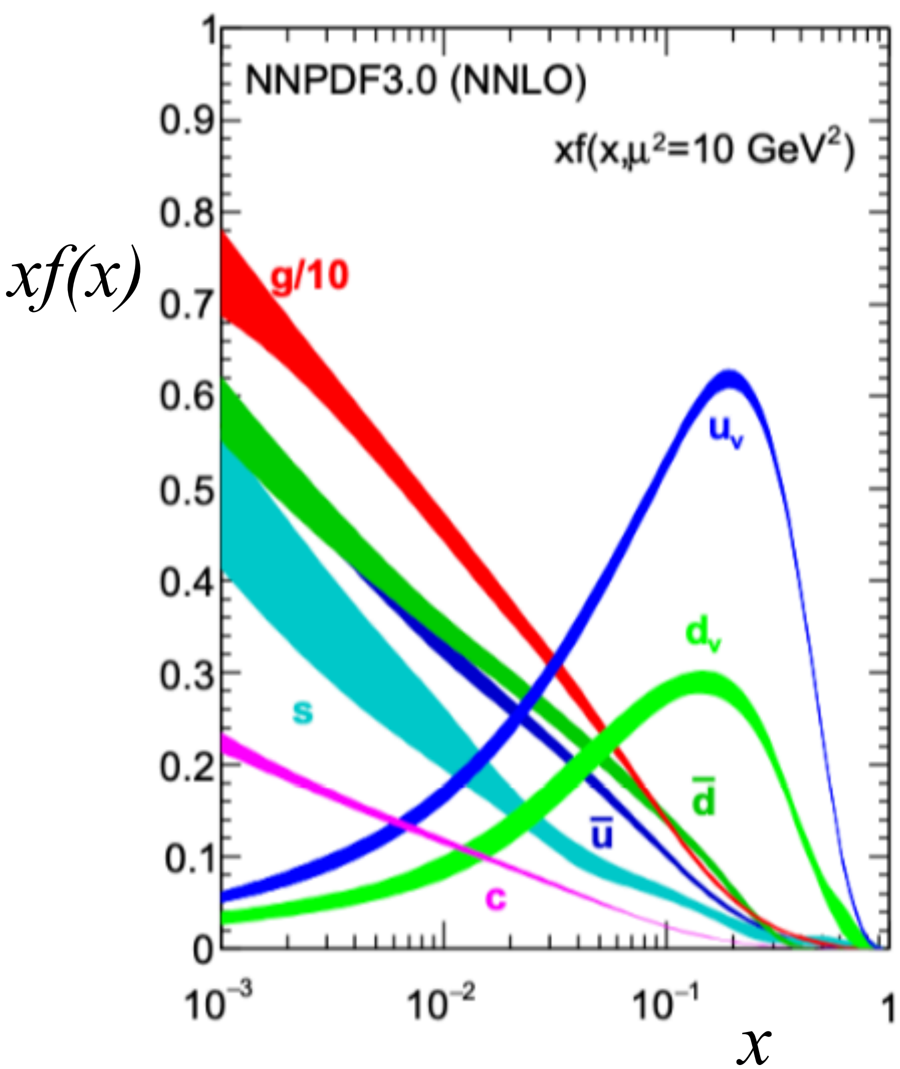
- Proton
  valence quarks up/up/down
  sea quarks in quark/anti-quark pairs
  gluons bind valence/sea quarks



Longitudinal Proton Structure

Deep Inelastic Scattering (DIS)





- 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

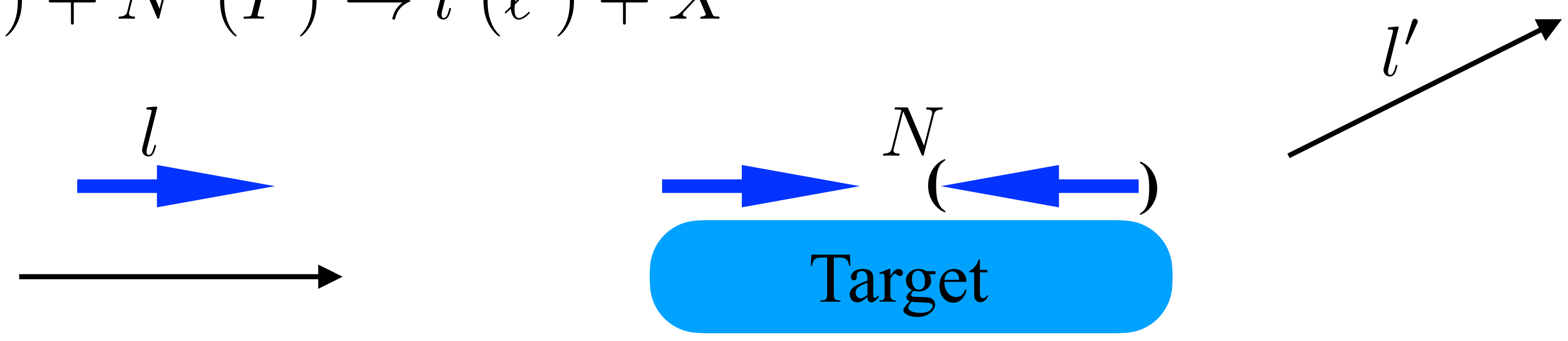
  parton longitudinal momentum fraction

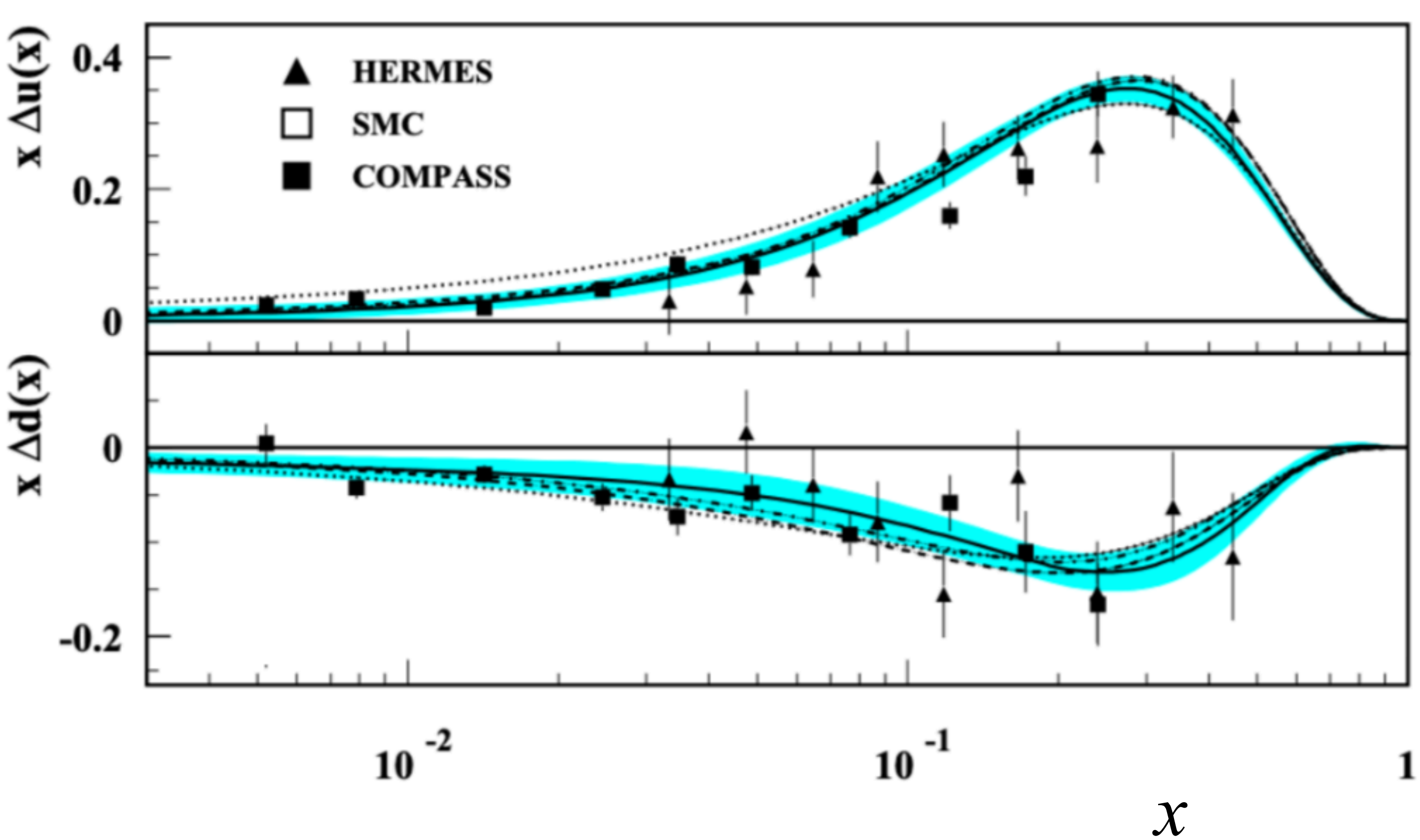
$$x = \frac{|q^2|}{2P \cdot q} \qquad 0 < x < 1$$

x > ~ 0.1 Valence quarks

Longitudinal Proton *Spin*-Structure

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





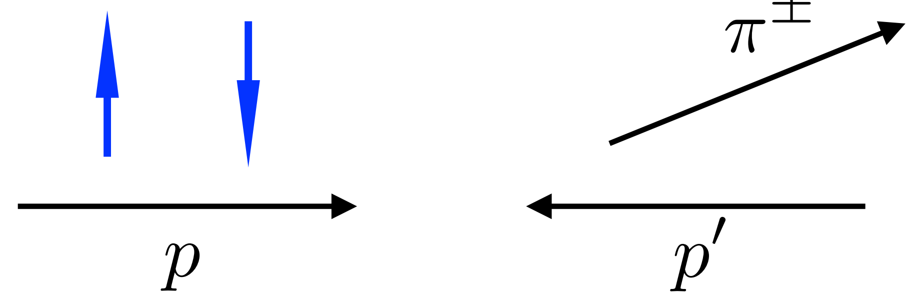
- Spin 1/2 hadron parameterization spin-dependent

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

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

Transverse Proton Spin-Structure

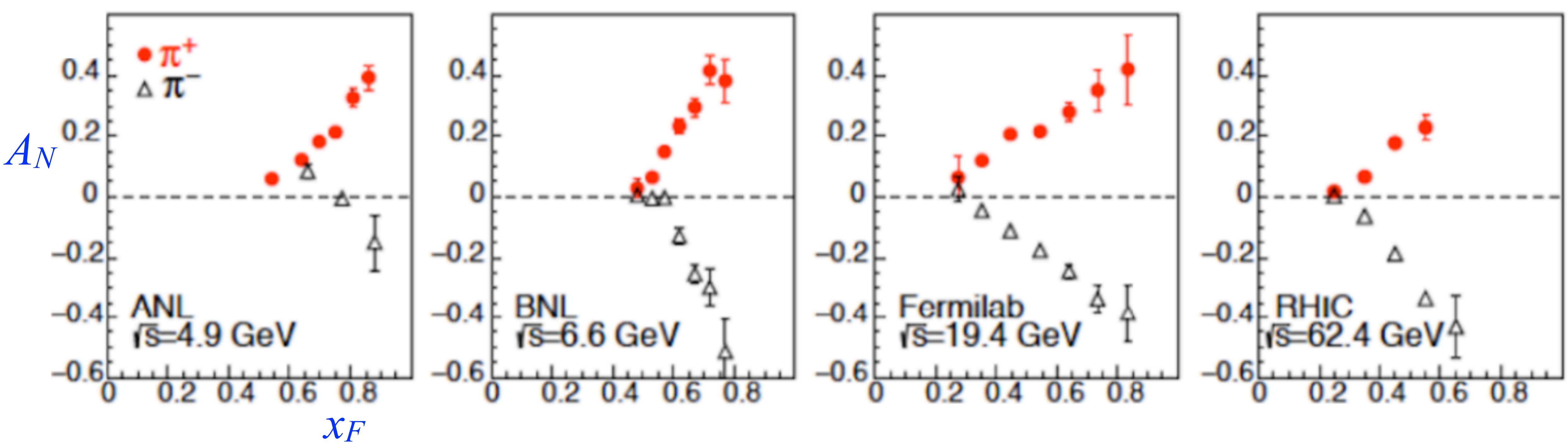
$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$



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

-Experimental Observable
  x-Feynman = longitudinal momentum / maximum longitudinal momentum
  $x_F = x_{beam} - x_{target}$ $\quad -1 < x_F < 1$

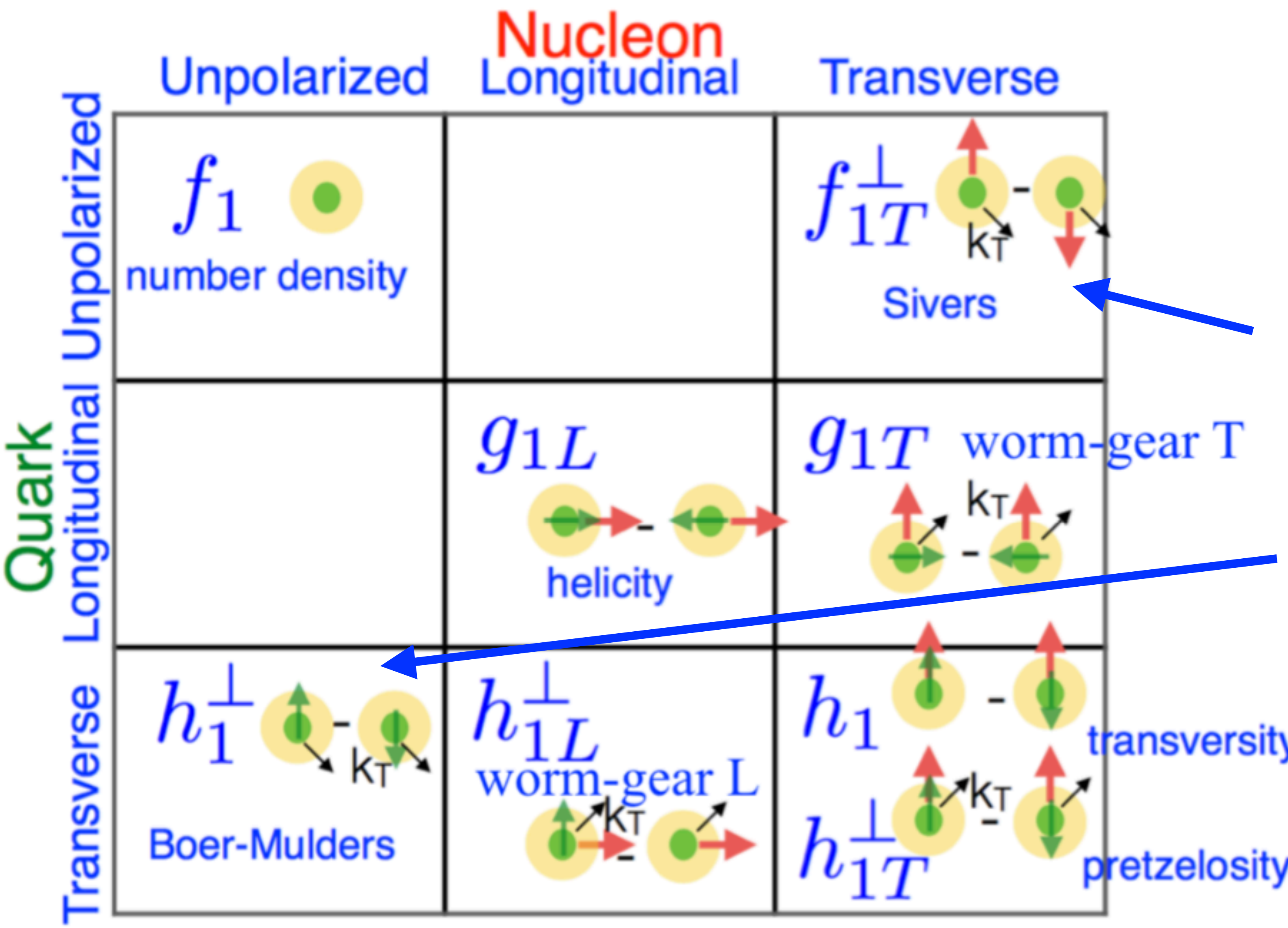
(1976) **(2002)** **(1991)** **(2008)**



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



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

Boer-Mulders: Correlation between the *transverse parton momentum* and the *transverse parton's spin*

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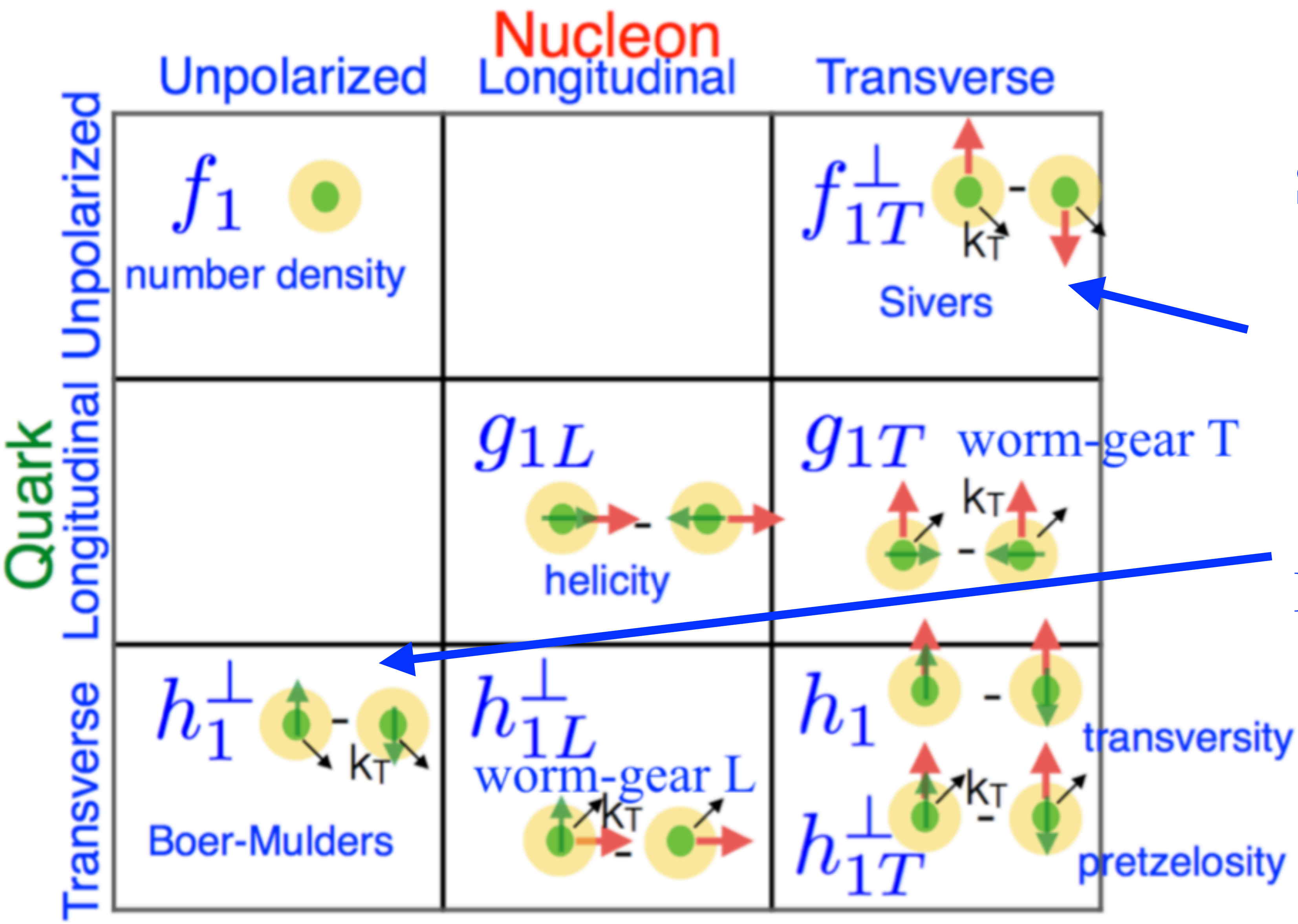


Sivers:

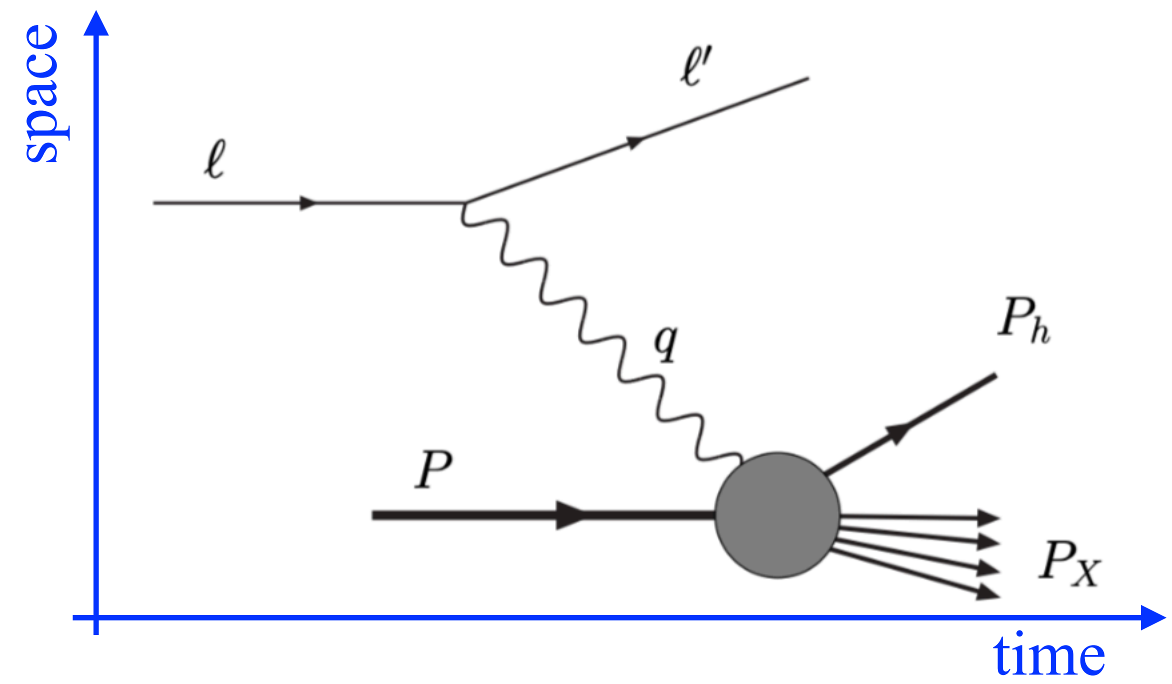
$$f_{1T}^{\perp q}|_{Drell-Yan} = -f_{1T}^{\perp q}|_{SIDIS}$$

T-odd functions

Boer-Mulders:

$$h_1^{\perp q}|_{Drell-Yan} = -h_1^{\perp q}|_{SIDIS}$$

Semi-Inclusive Deep Inelastic Scattering (SIDIS)



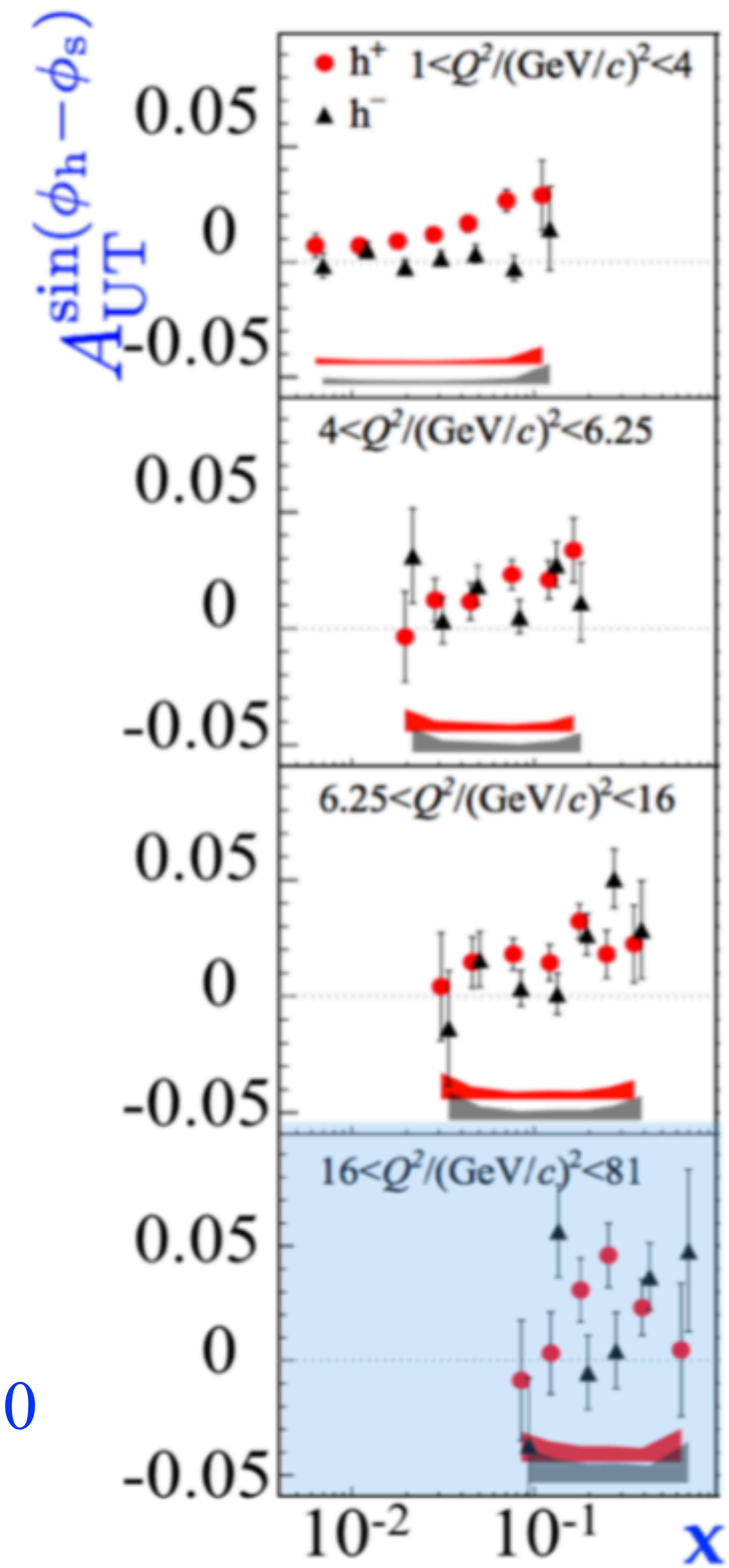
$$\frac{d\sigma_{SIDIS}}{dx d\Omega} \propto |S_T| \sin(\phi_h - \phi_S) A_{UT}^{\sin(\phi_h - \phi_S)}$$

Sivers amplitude Sivers function

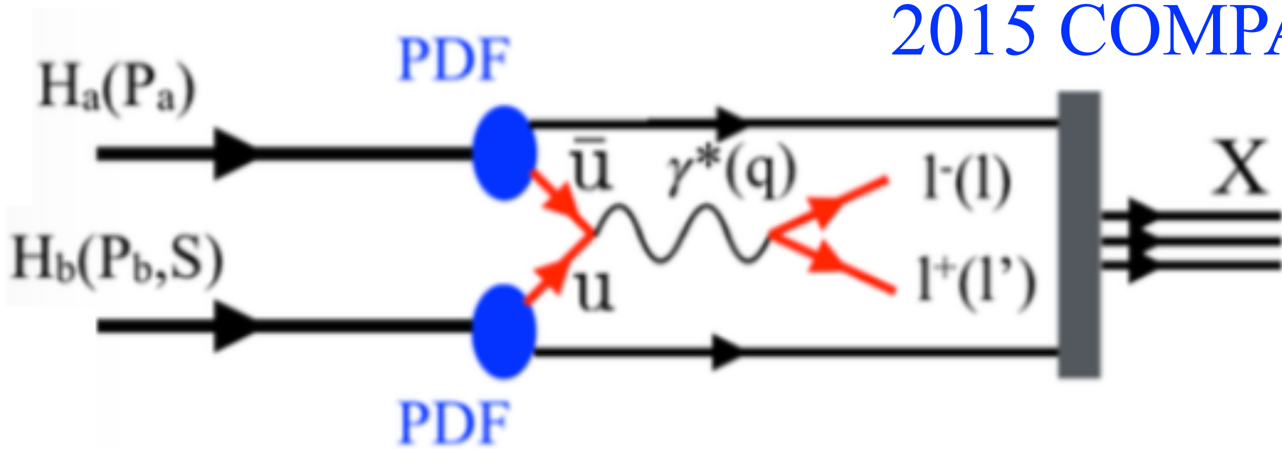
$$A_{UT}^{\sin(\phi_h - \phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$$

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

- u-quark Sivers function > 0, d-quark Sivers function < 0



Drell-Yan



2015 COMPASS data taking

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

- Measured final states is two oppositely charged muons
- Proton target is transversely polarized

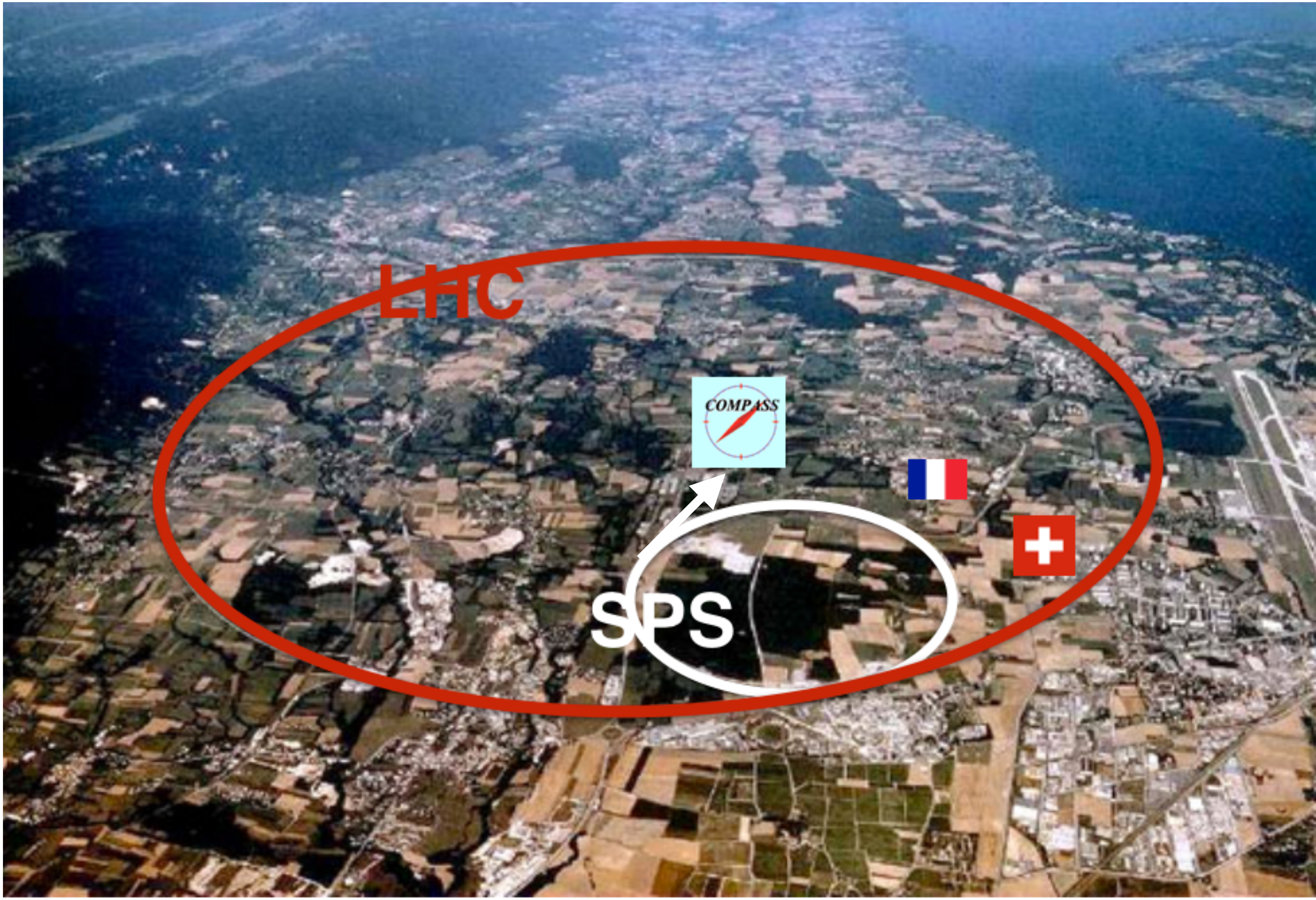
- Negatively charged pion beam (ūd) is advantageous for Drell-Yan ūu annihilation
- Valence quarks from pion and proton

-Experimental Observables

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

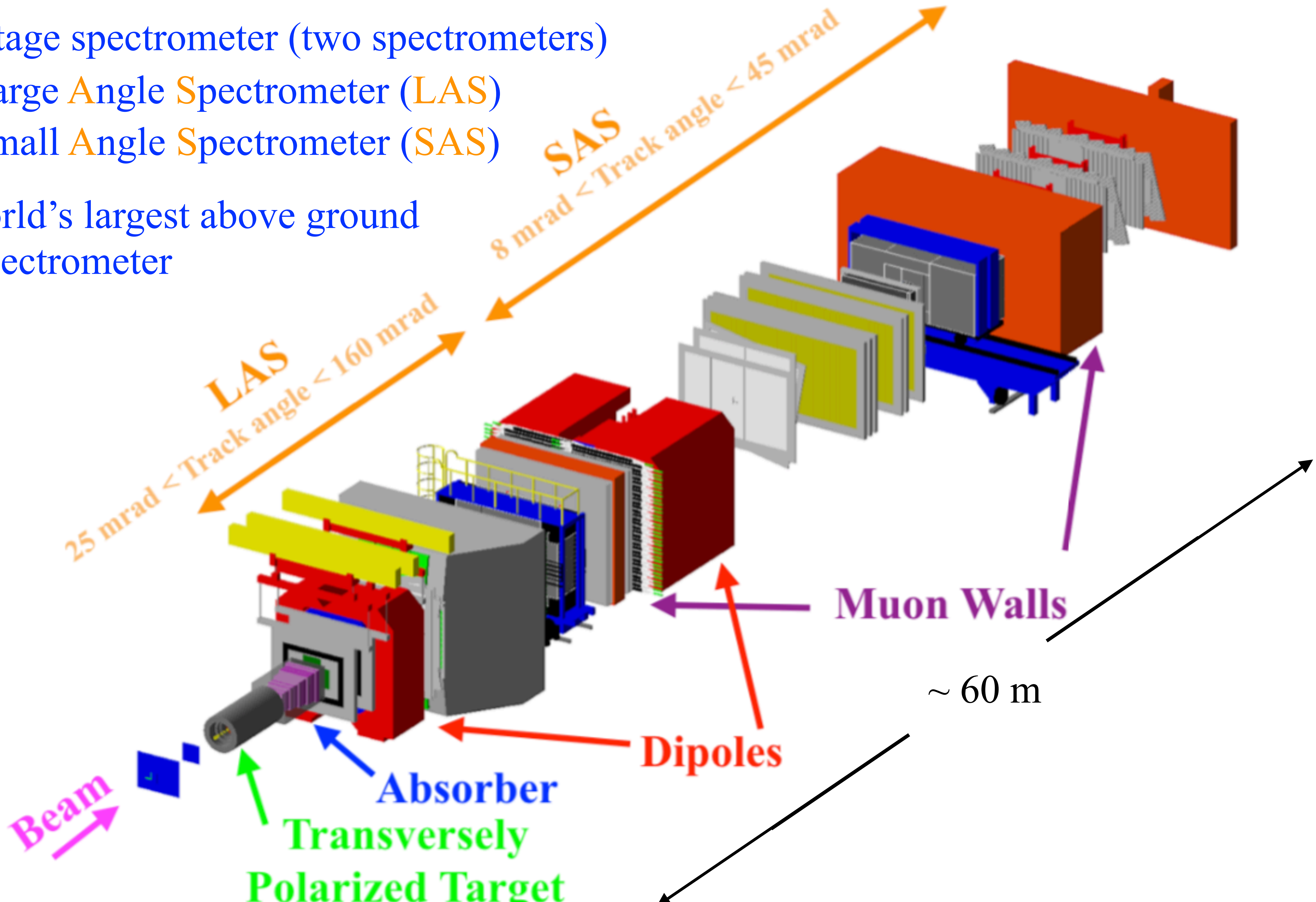
COMPASS

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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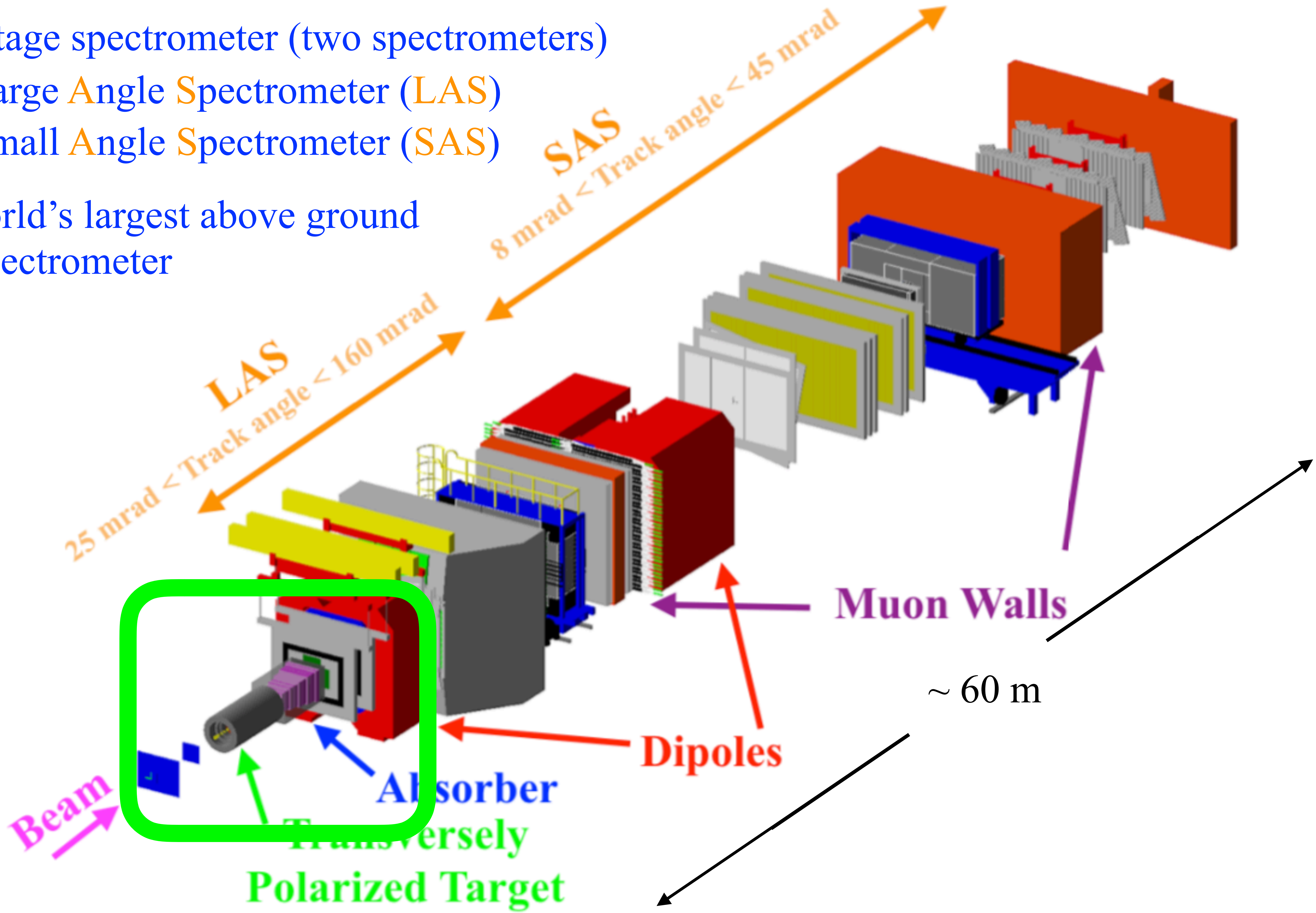


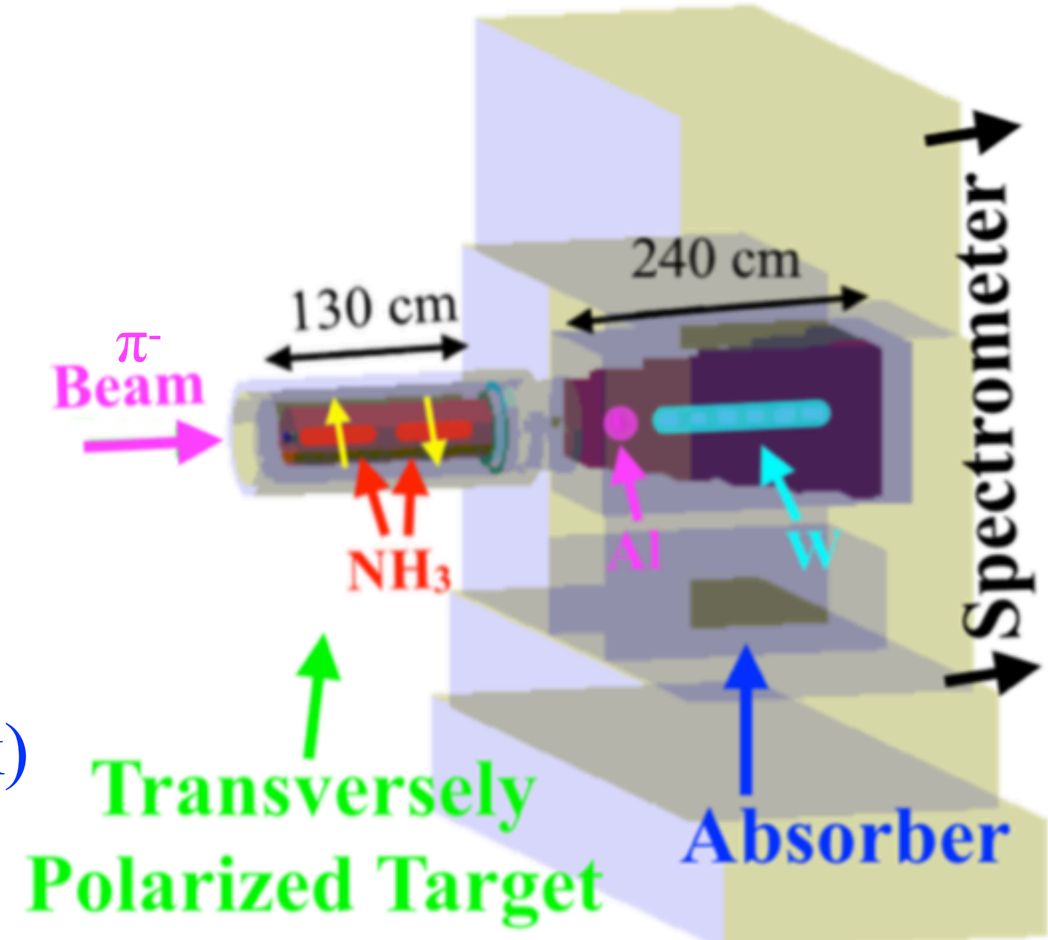
2015 COMPASS Data Taking

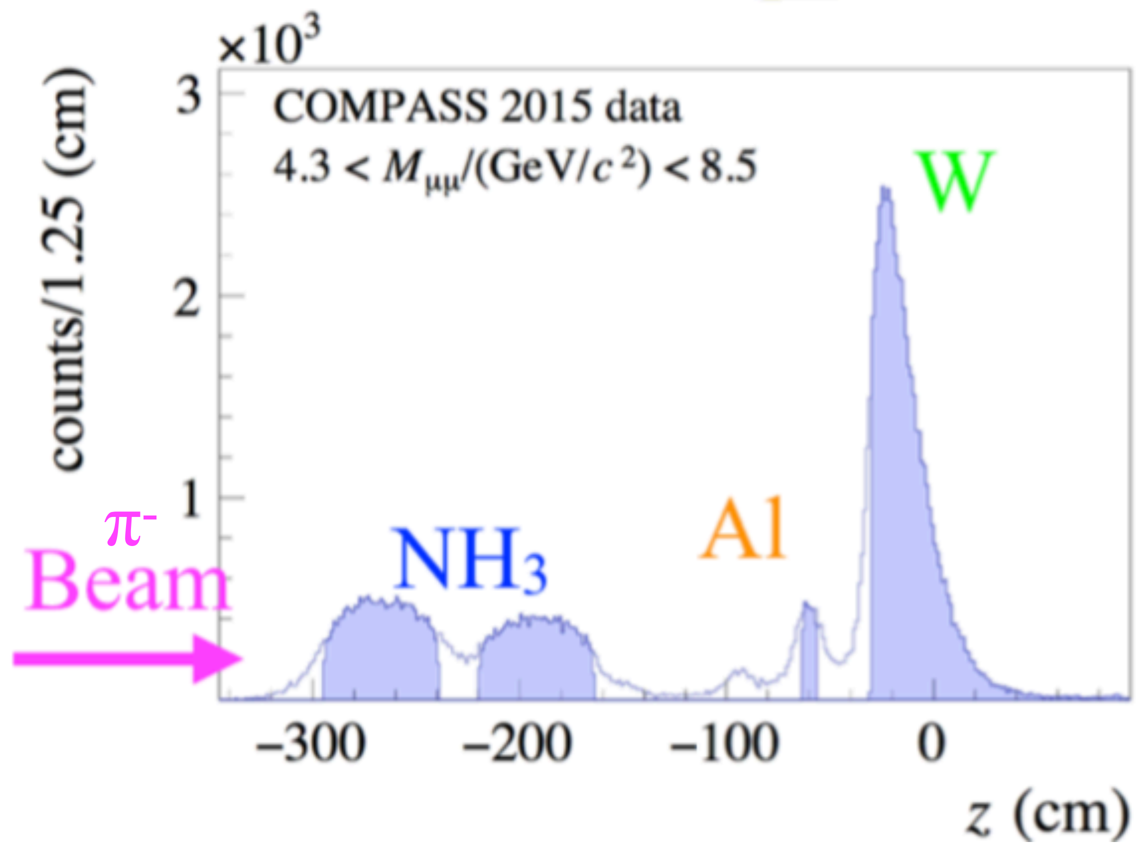
- Negatively charged pion beam
  π^- 190 GeV

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

- Data recorded in periods (1 period = ~2 week)
  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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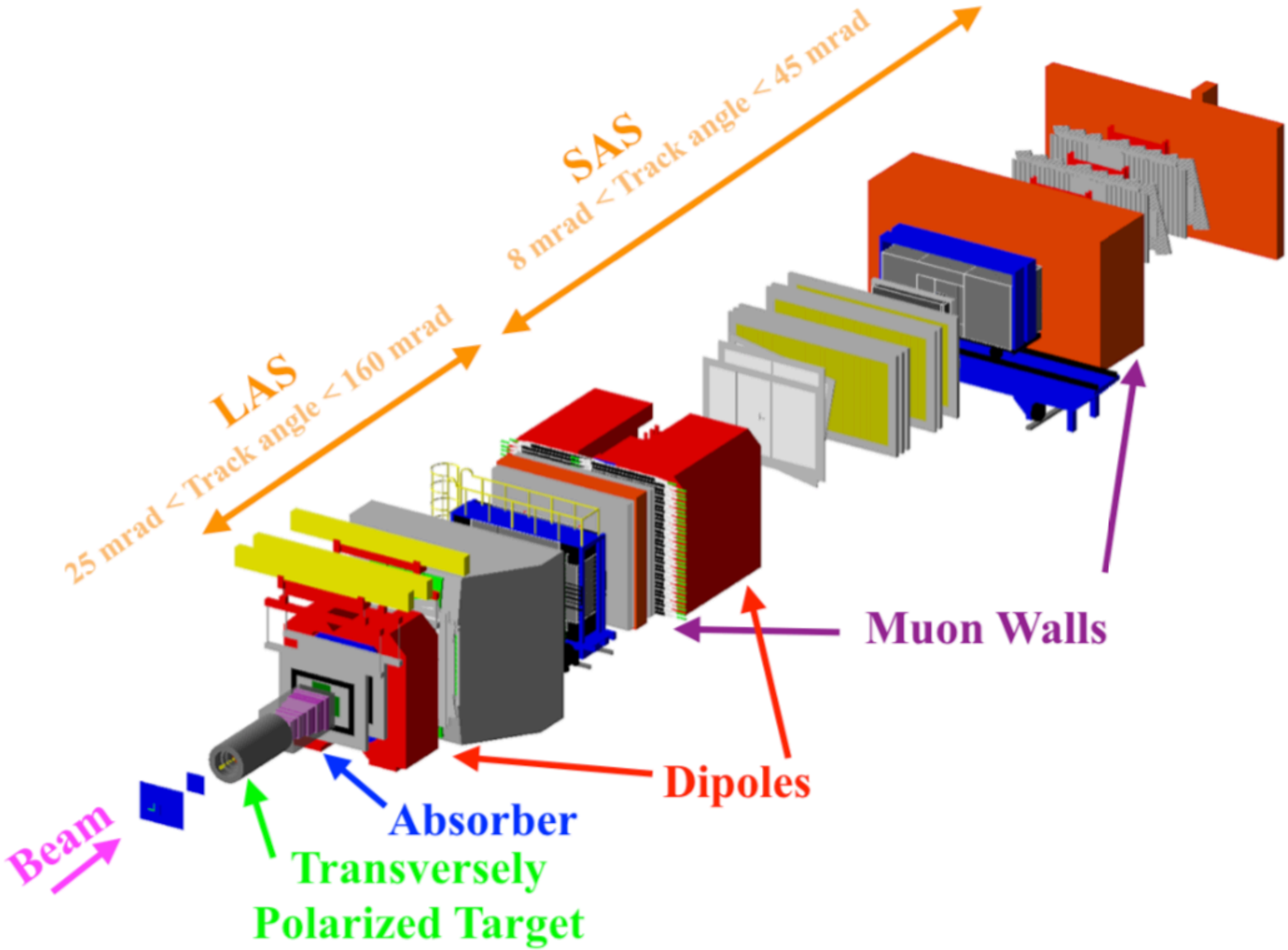

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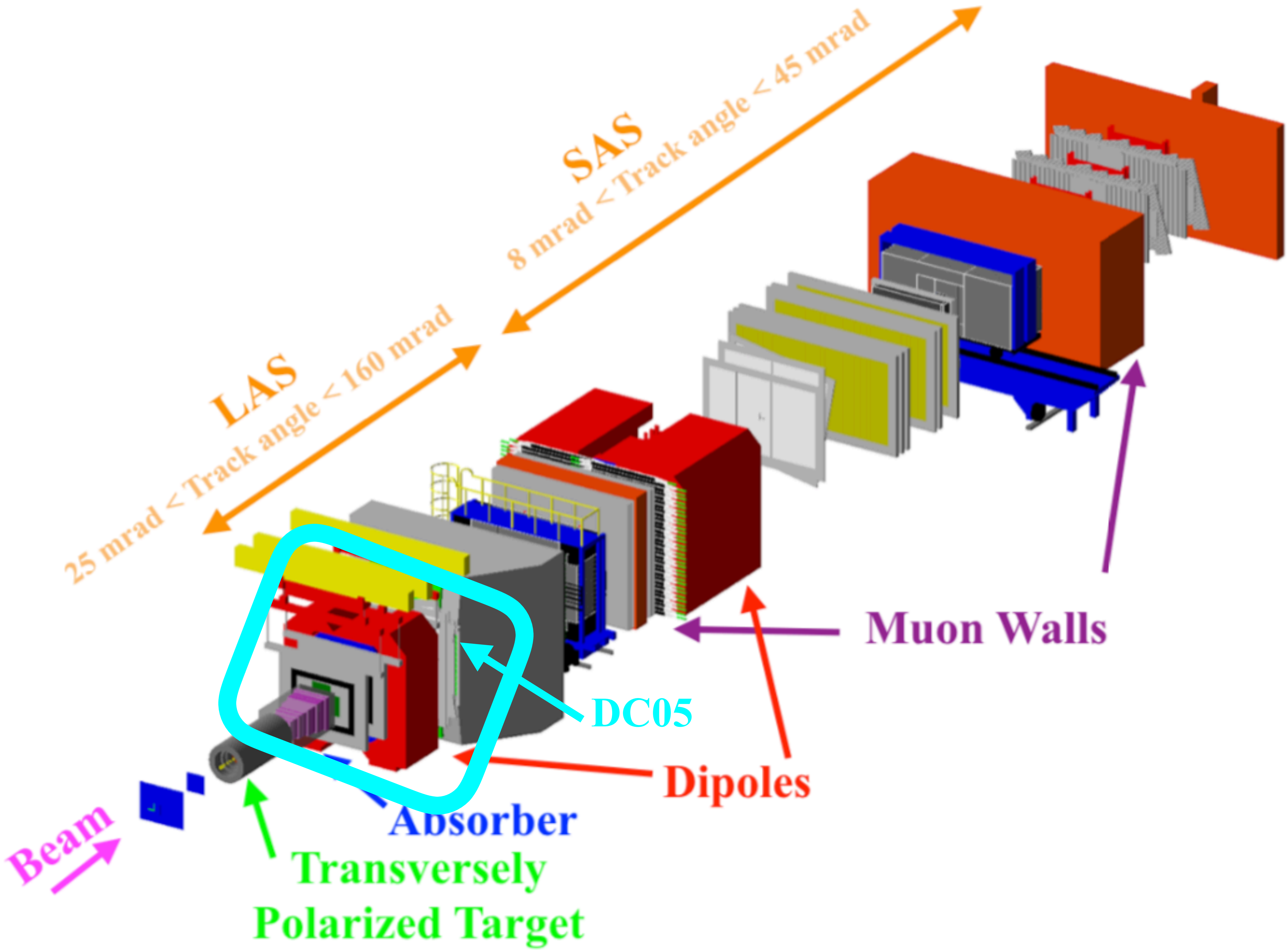
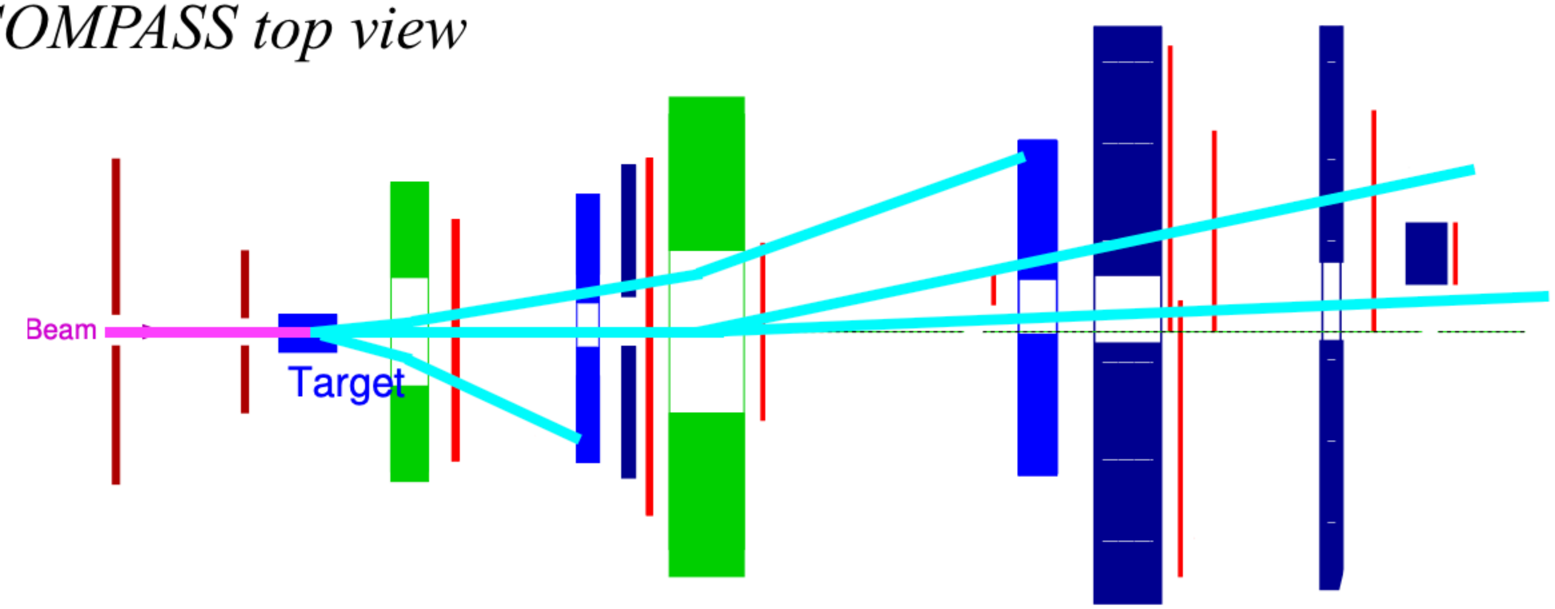


DC05 Motivation

COMPASS top view



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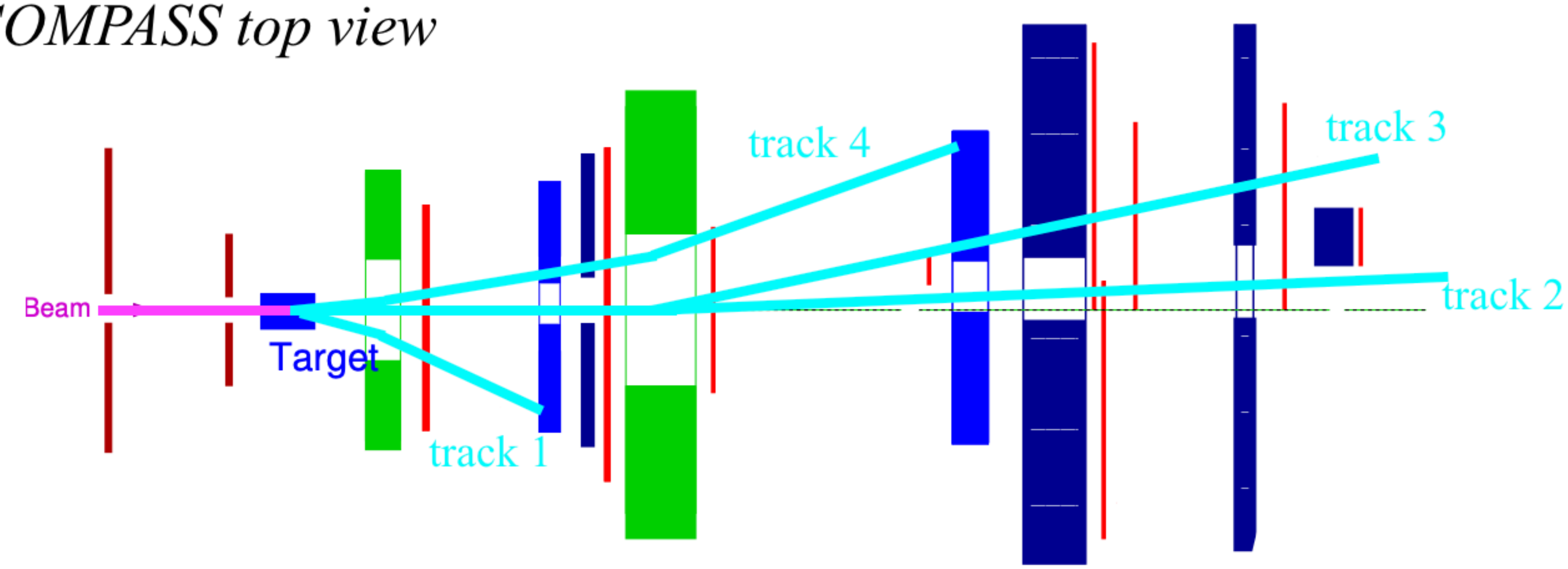

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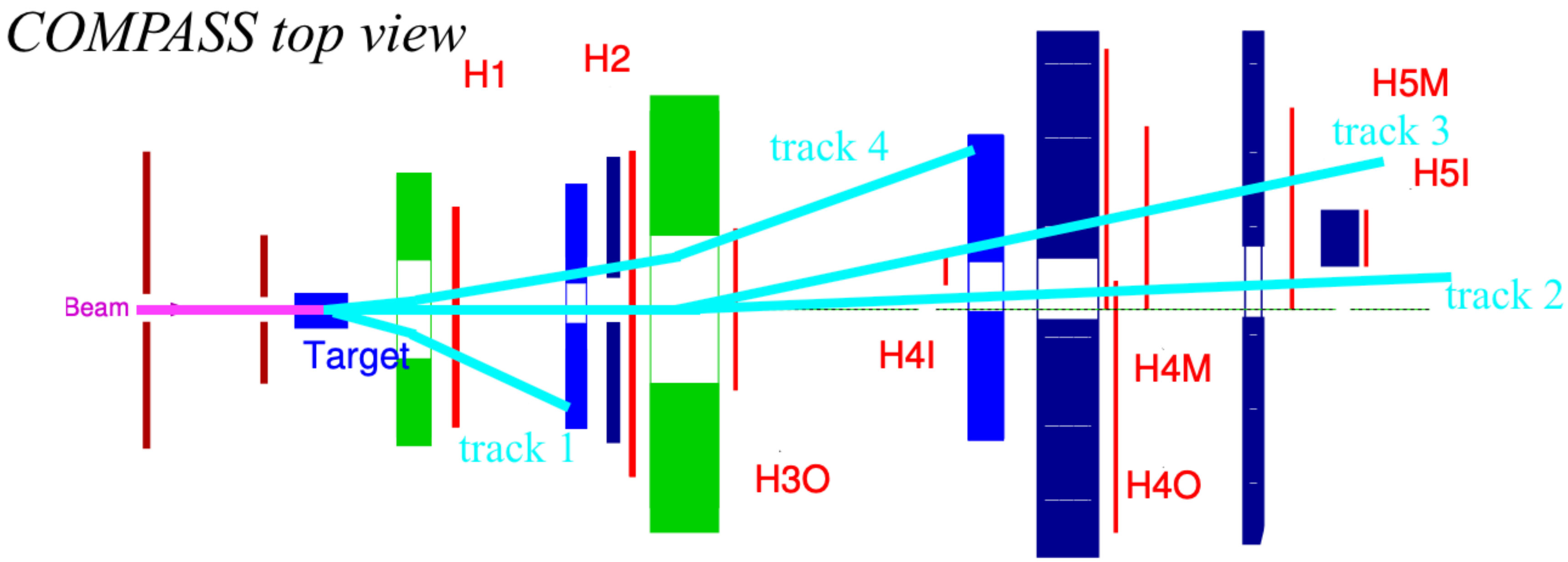

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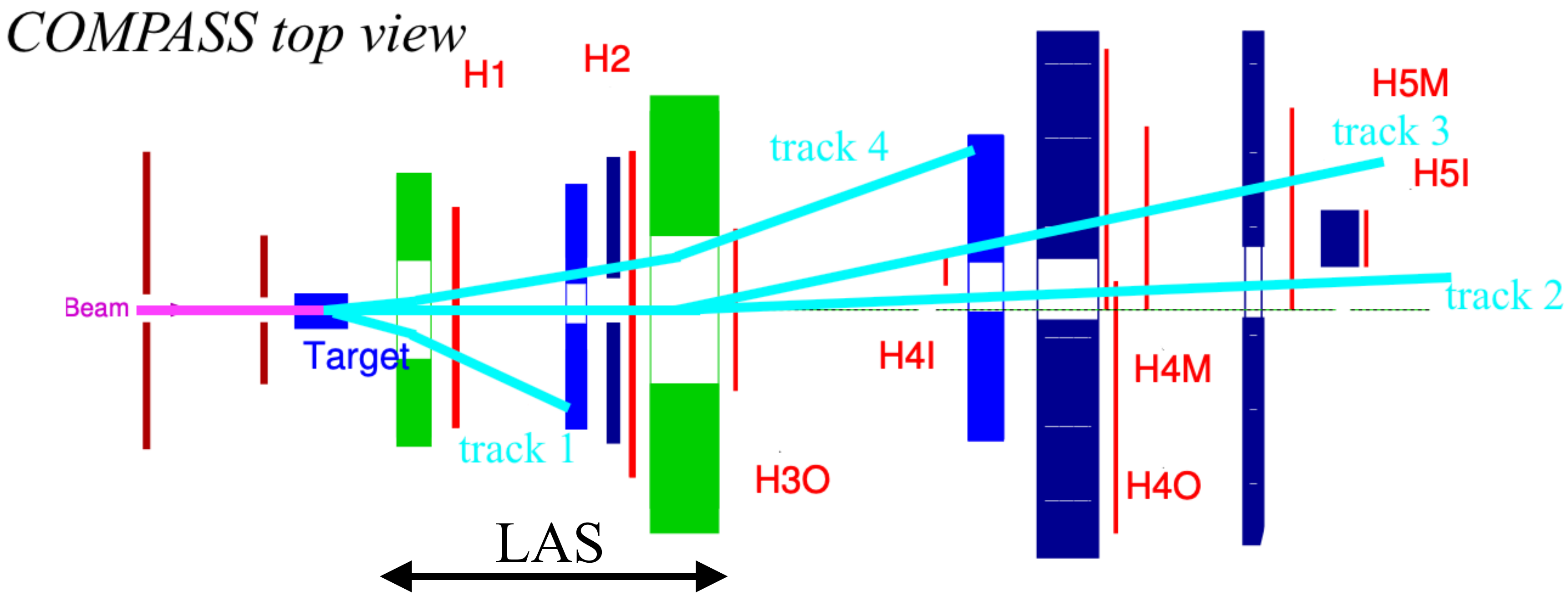

- All 2015 analysis events include a track in the Large Angle Spectrometer (LAS)
- LAS tracking is critical for reconstruction efficiency!

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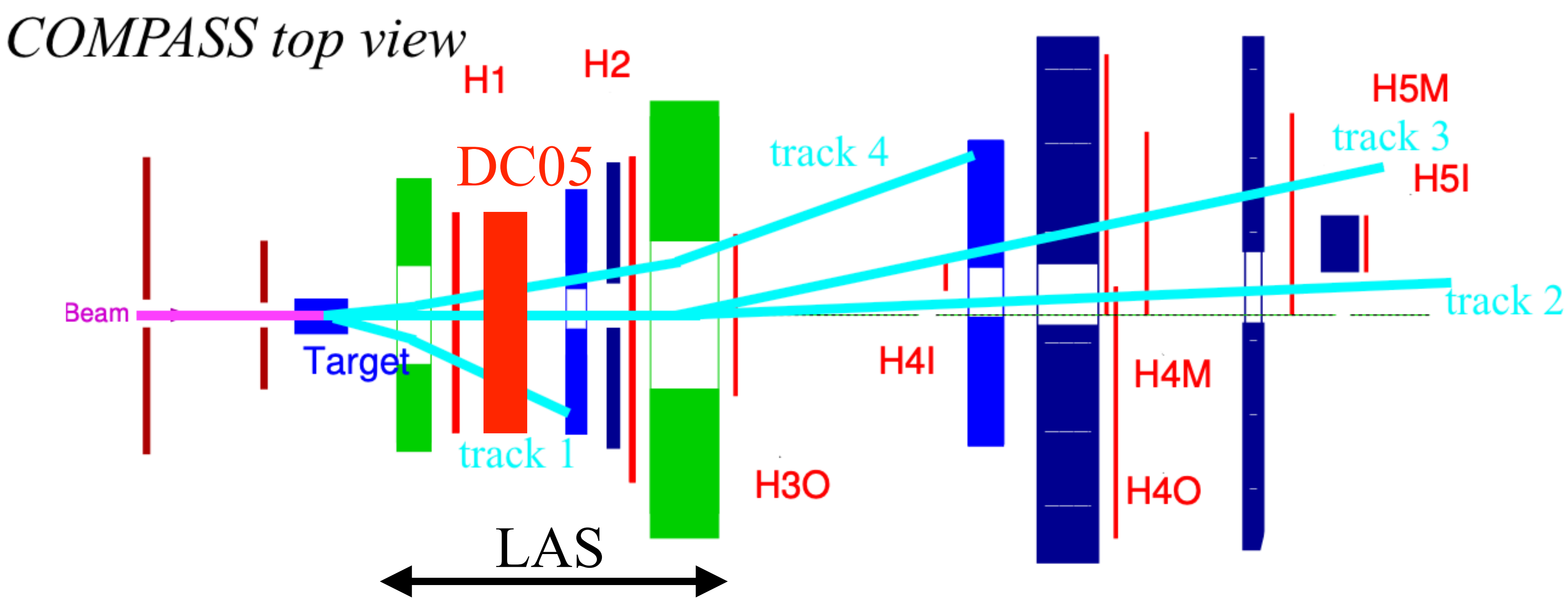

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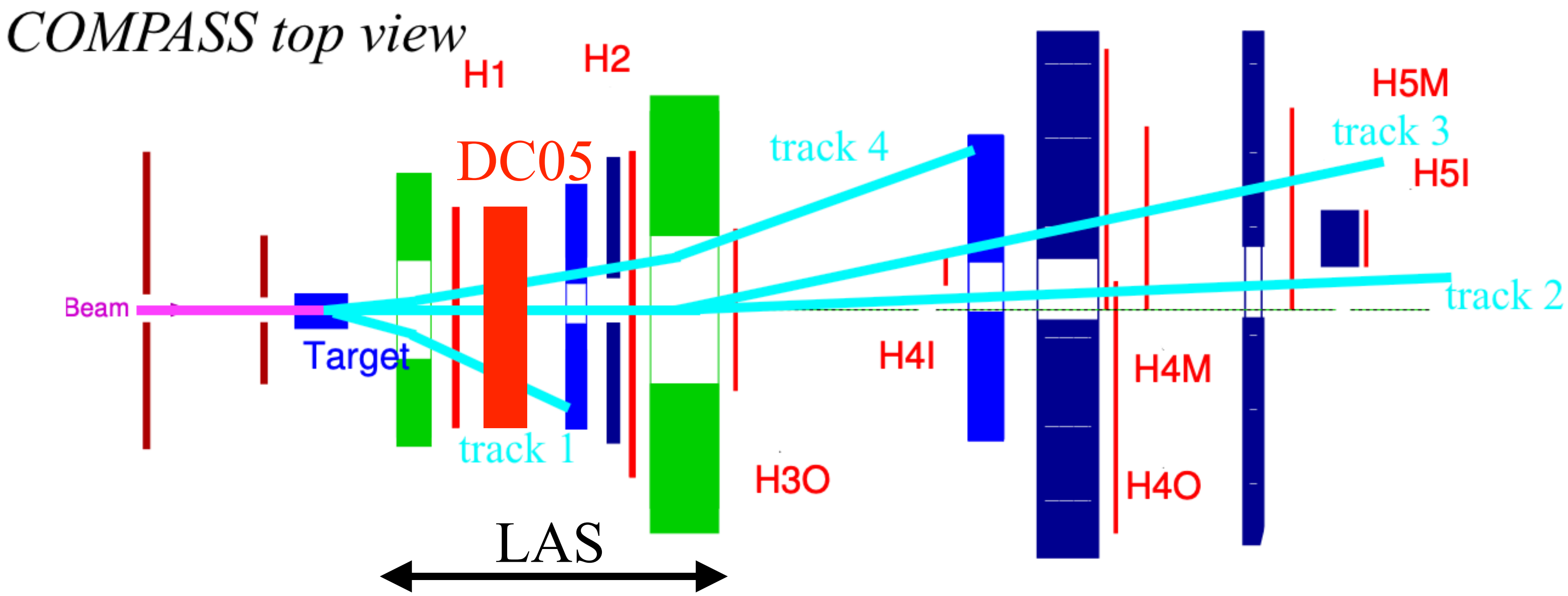

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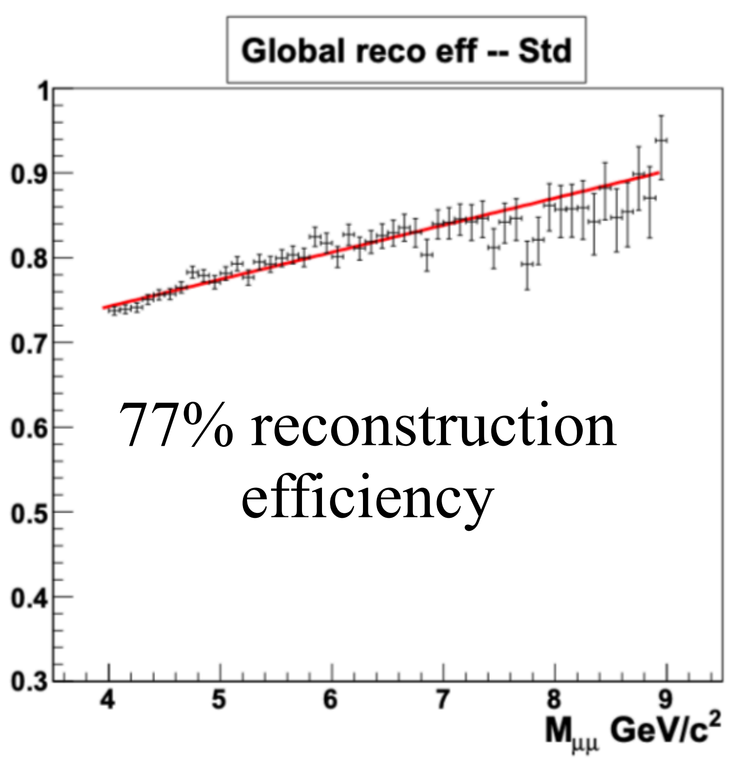
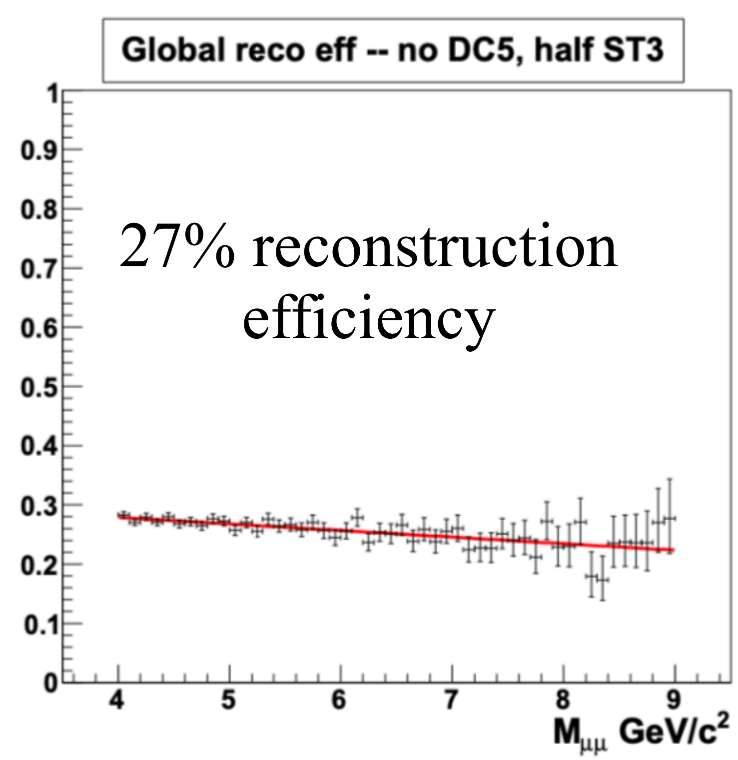
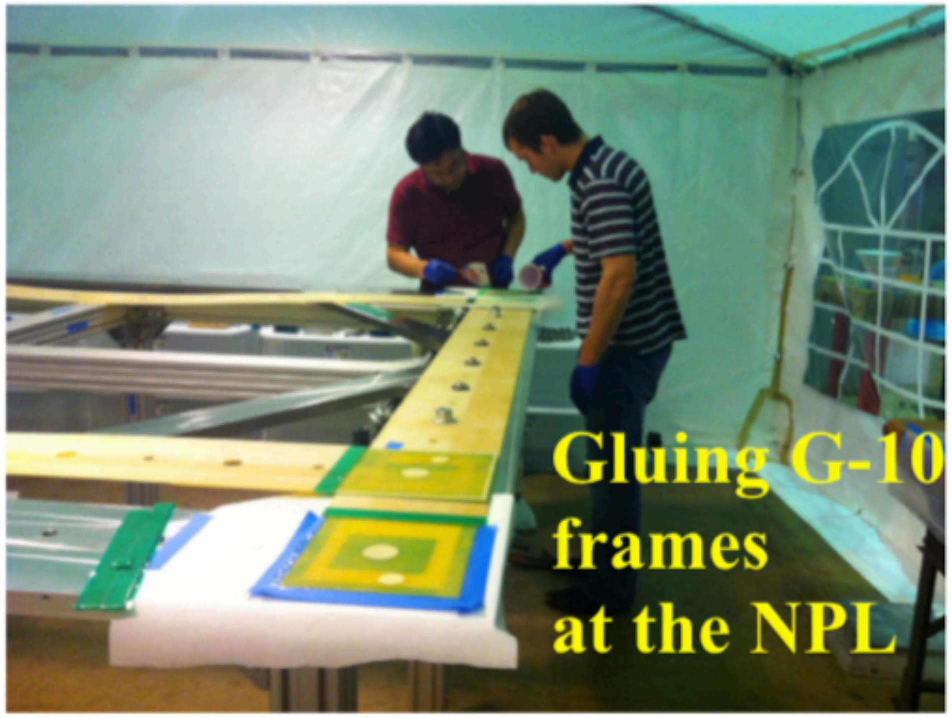
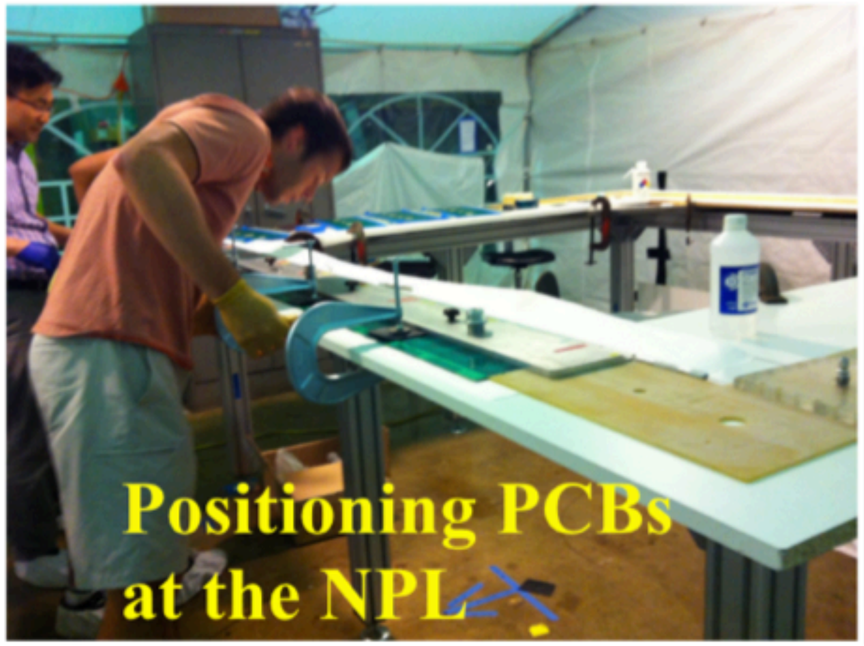


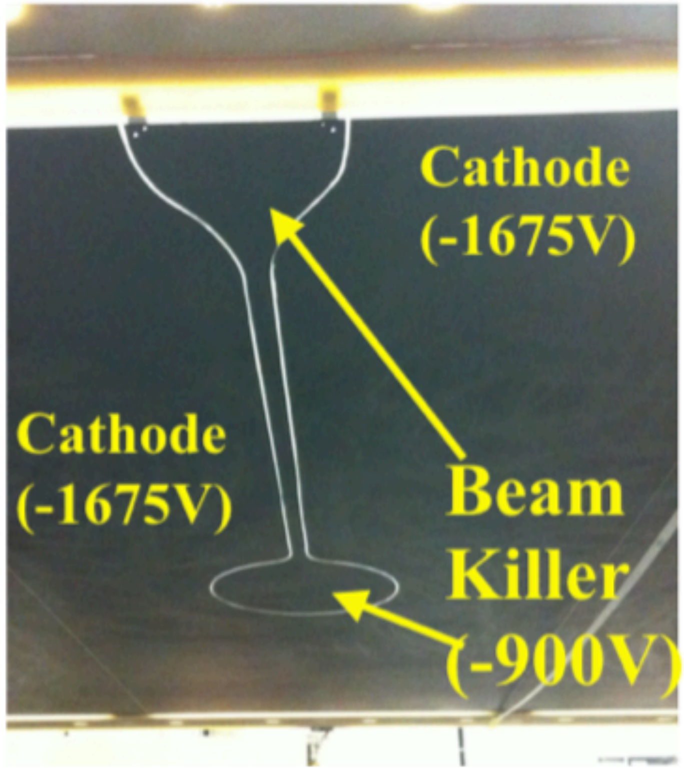


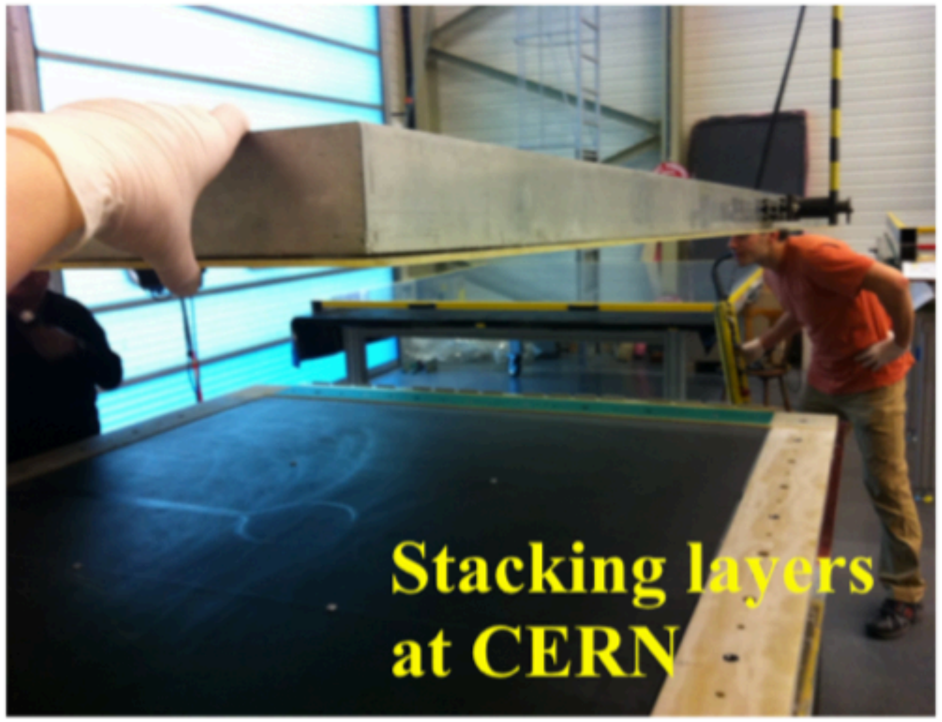
- Drift Chamber 05 is absolutely necessary

DC05 Construction

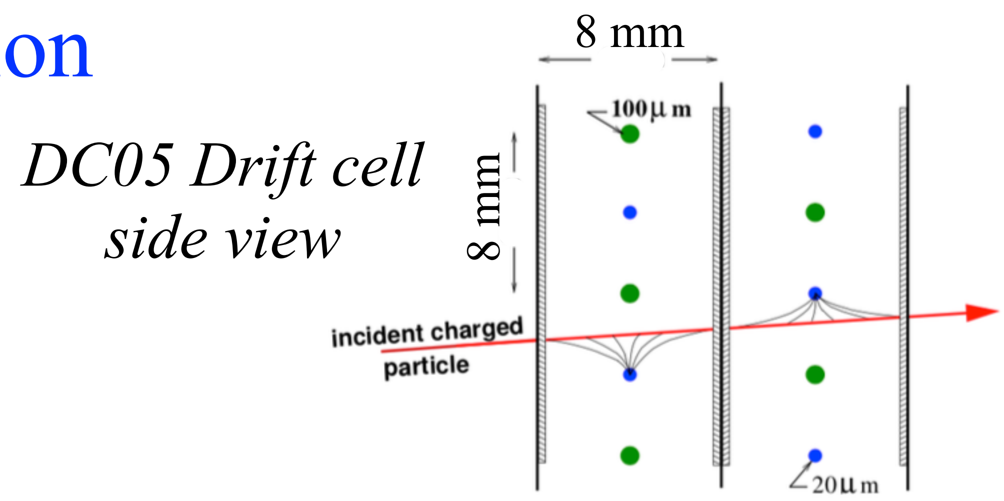




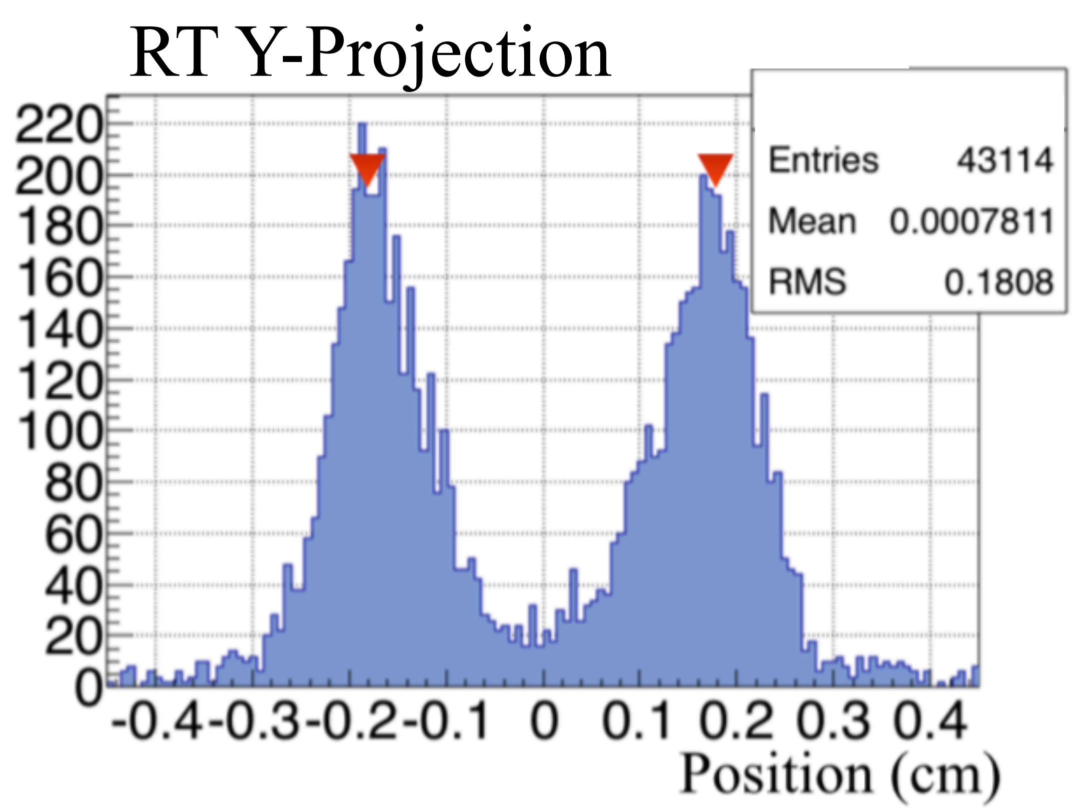


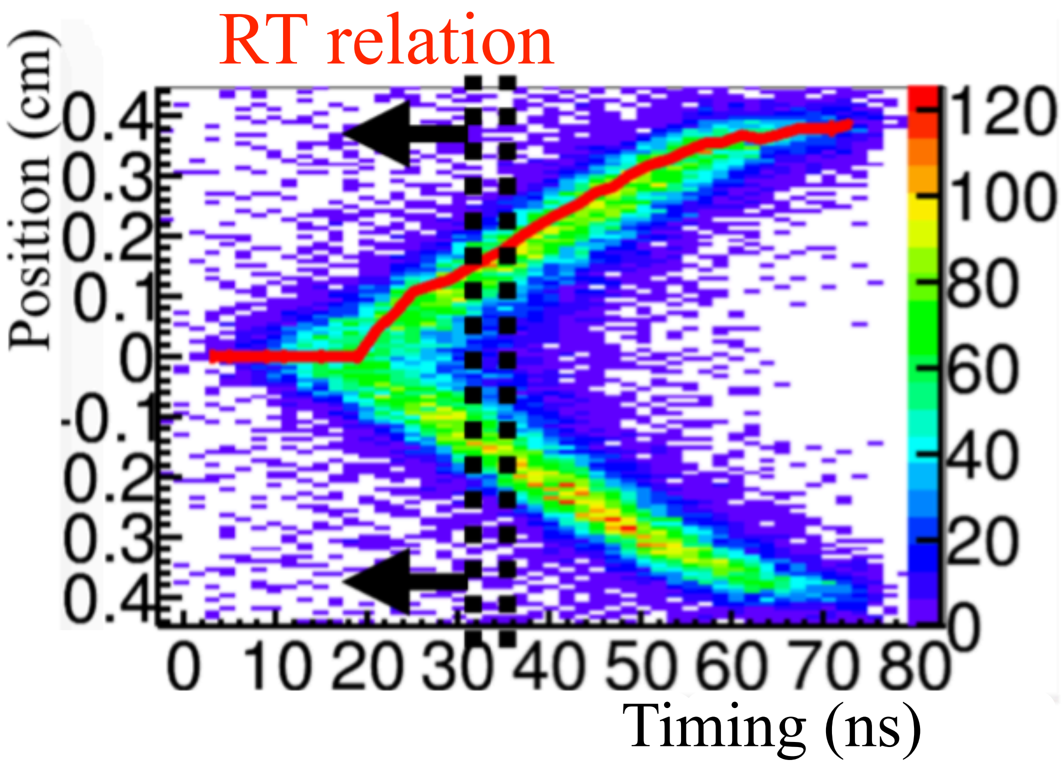


DC05 Calibration



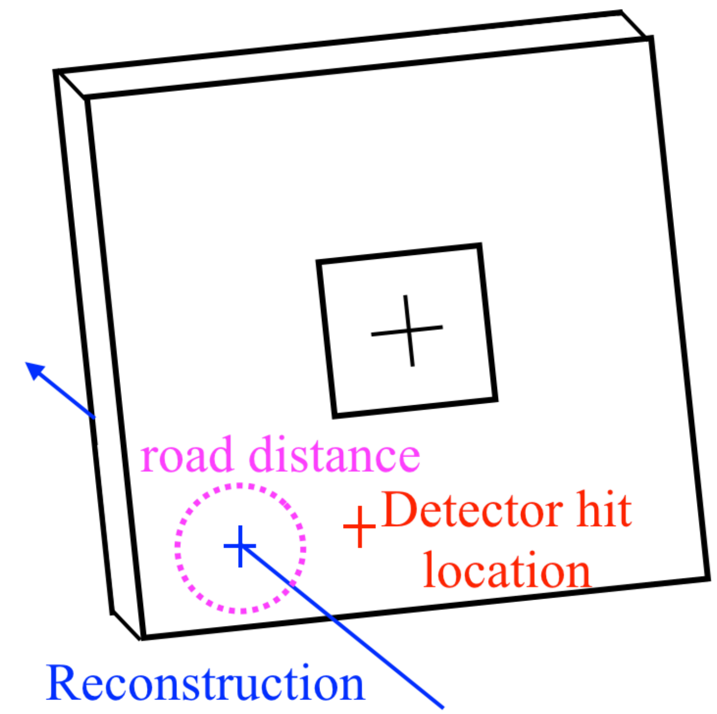
- Reconstruct events to determine an RT relation
  - Calibration plane is excluded from reconstruction
  - Timing information determined from DC05 plane
  - Spacial information determined reconstruction
- RT relation improves position resolution



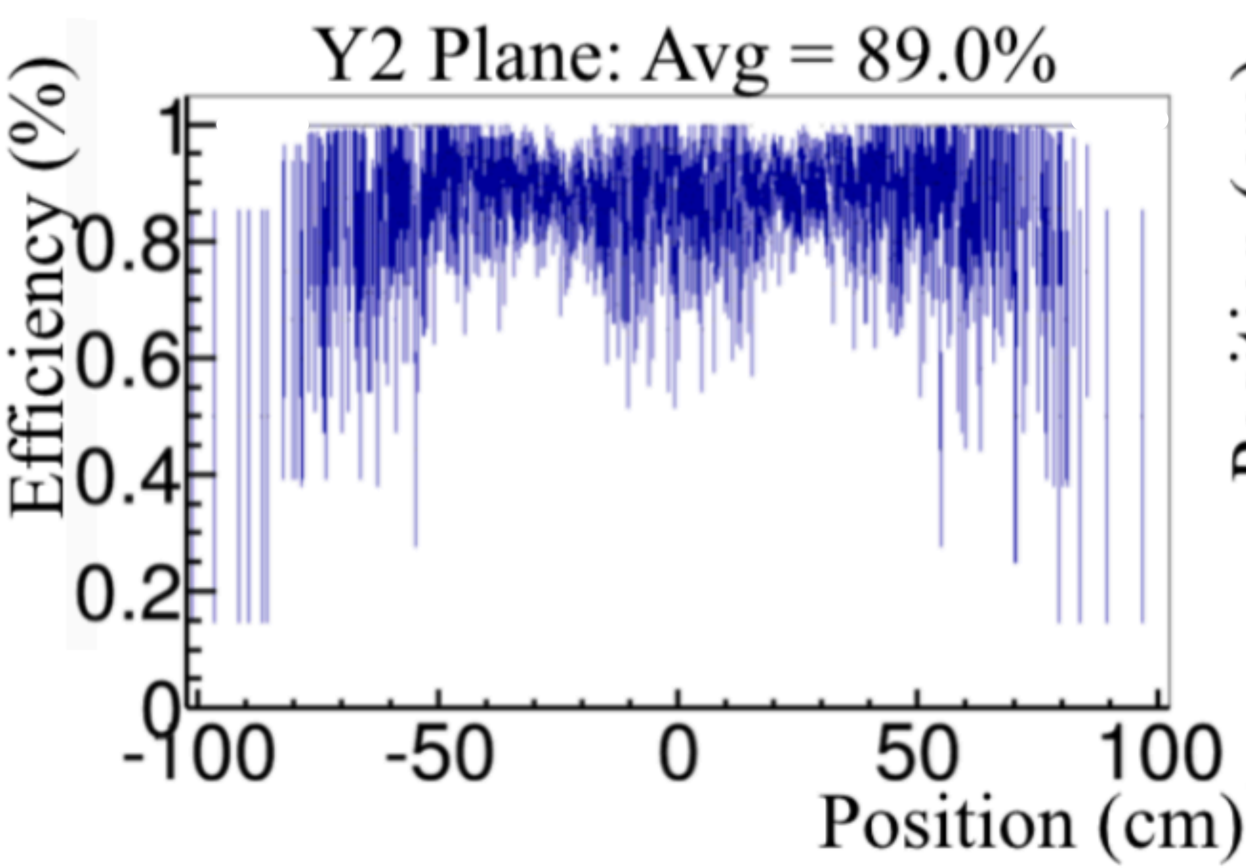


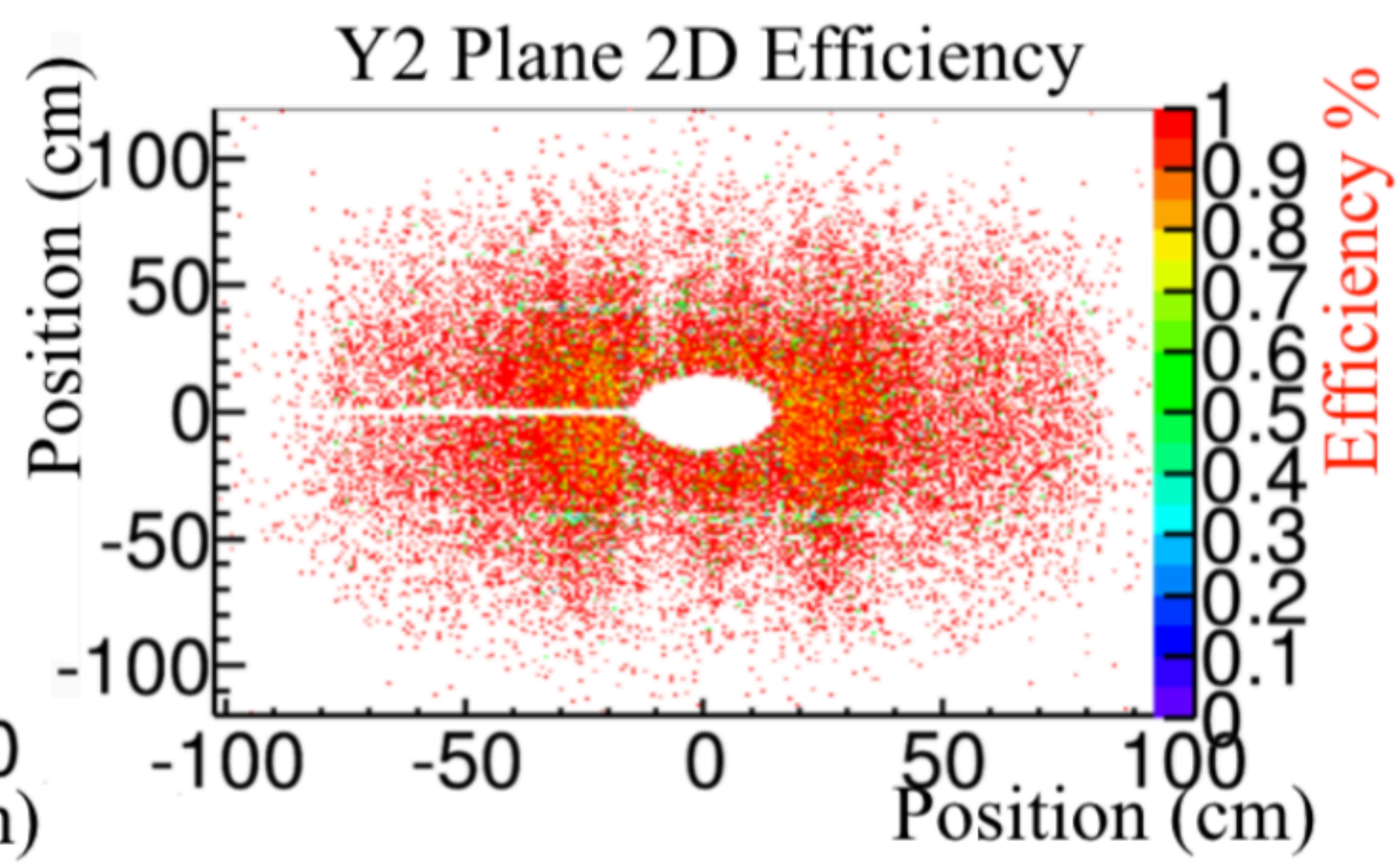
DC05 Efficiency

- 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





DC05 Position Resolution

Residual = u_{track} - u_{det}

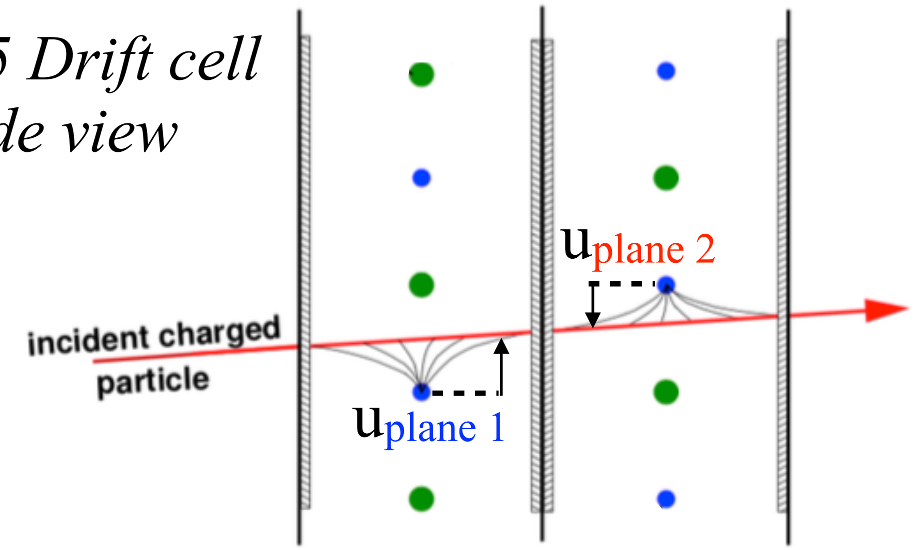
Double Residual

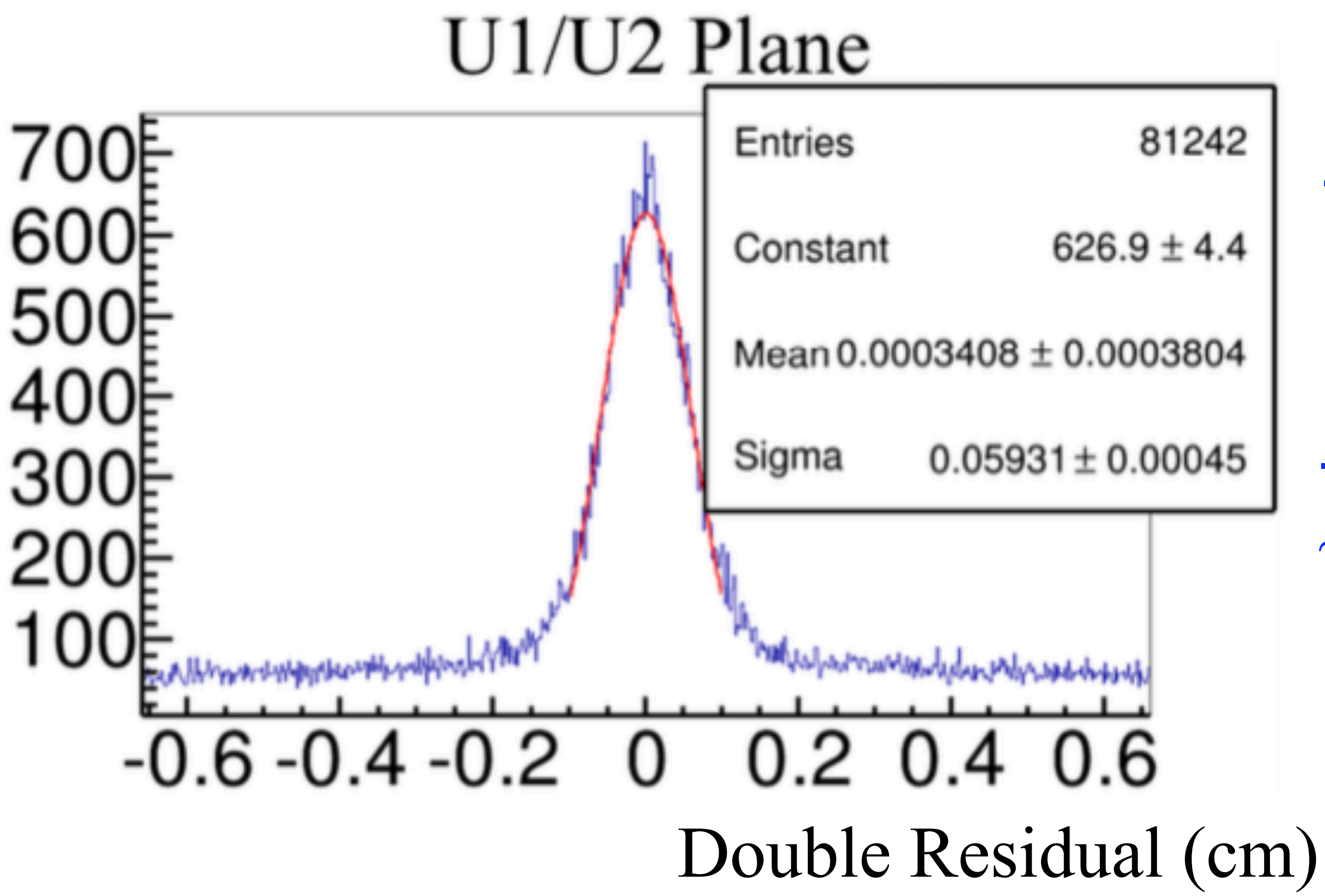
DR = $\text{Residual}_{\text{plane 1}}$ - $\text{Residual}_{\text{plane 2}}$

= $u_{\text{plane 2}}$ - $u_{\text{plane 1}}$

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

DC05 Drift cell side view





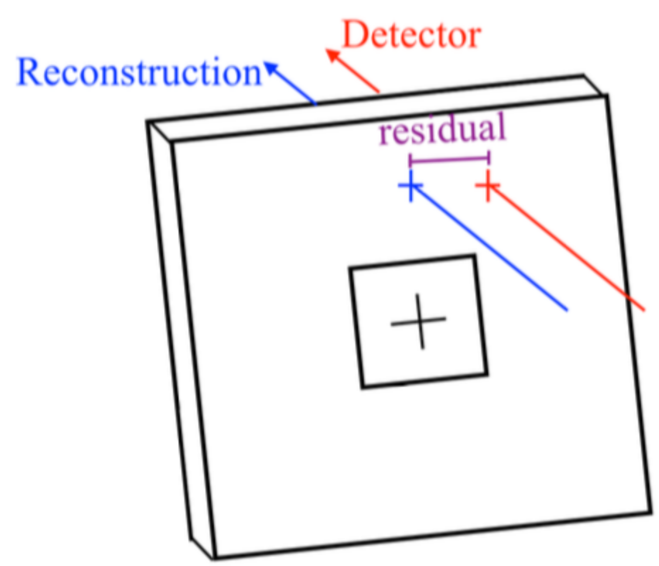
- Gaussian fit determines σ^2_{DR}

  Position resolution = σ_{DR}/sqrt(2)

- Achieved a position resolution of ~450 μm

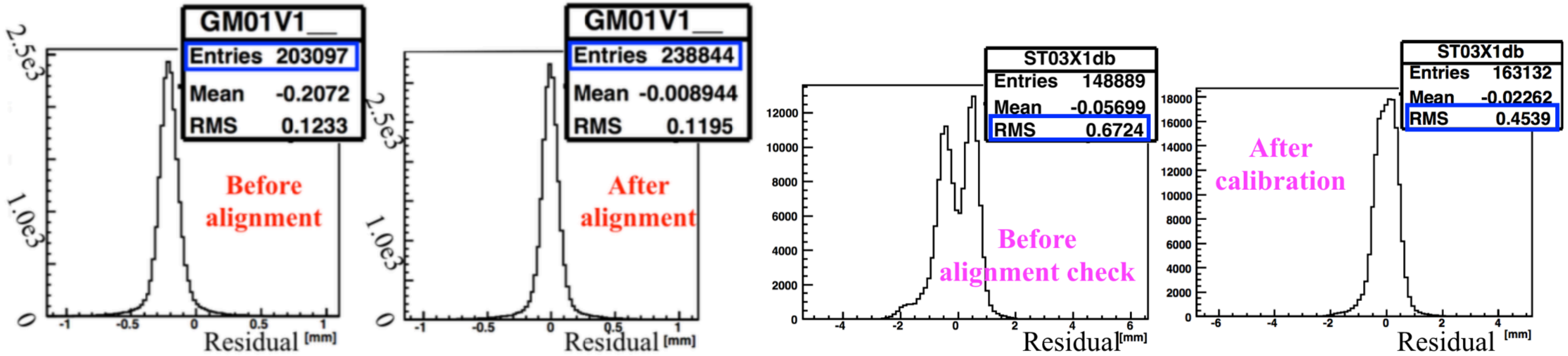
Detector Alignment

- 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



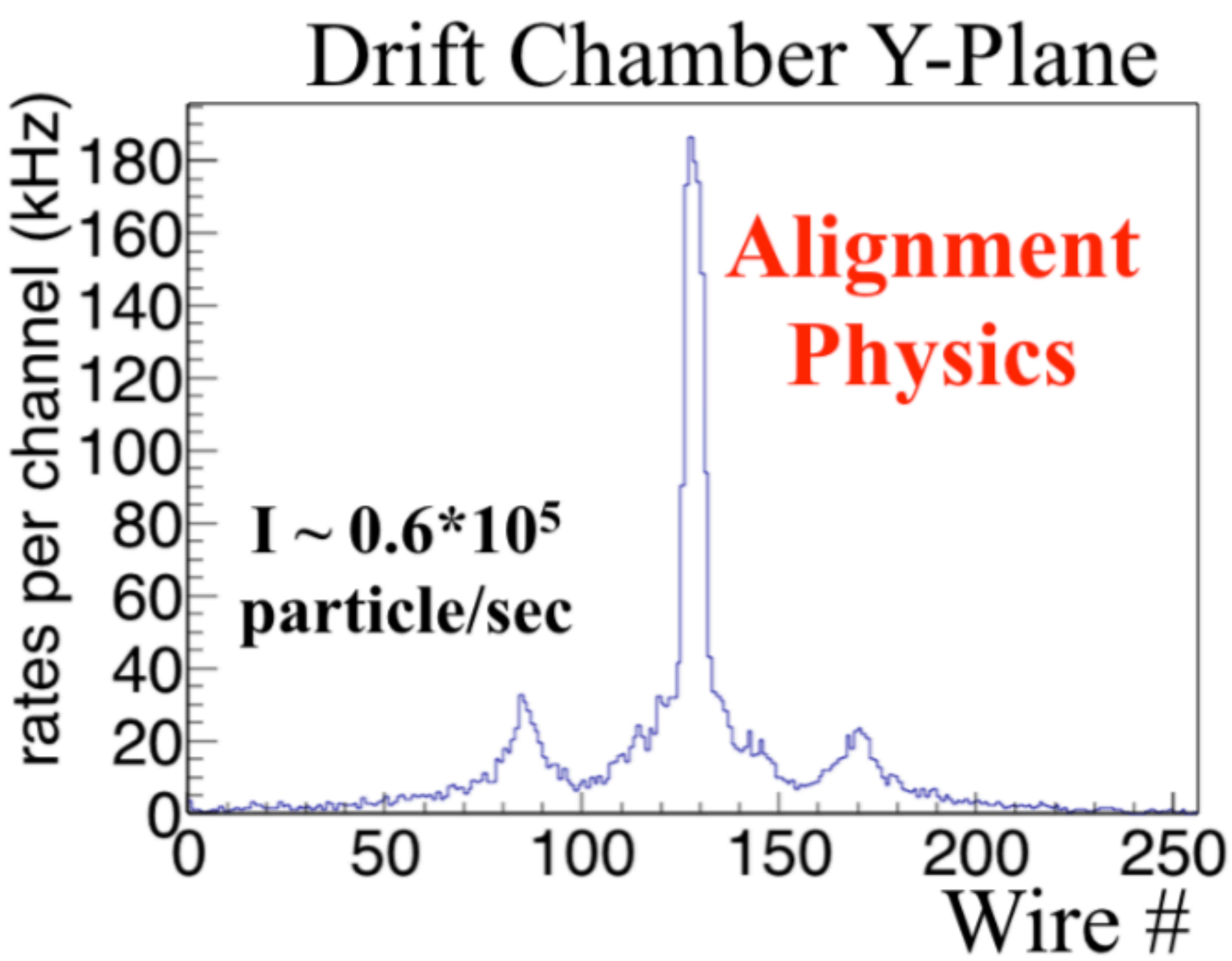
residual = u_{track} - u_{det}

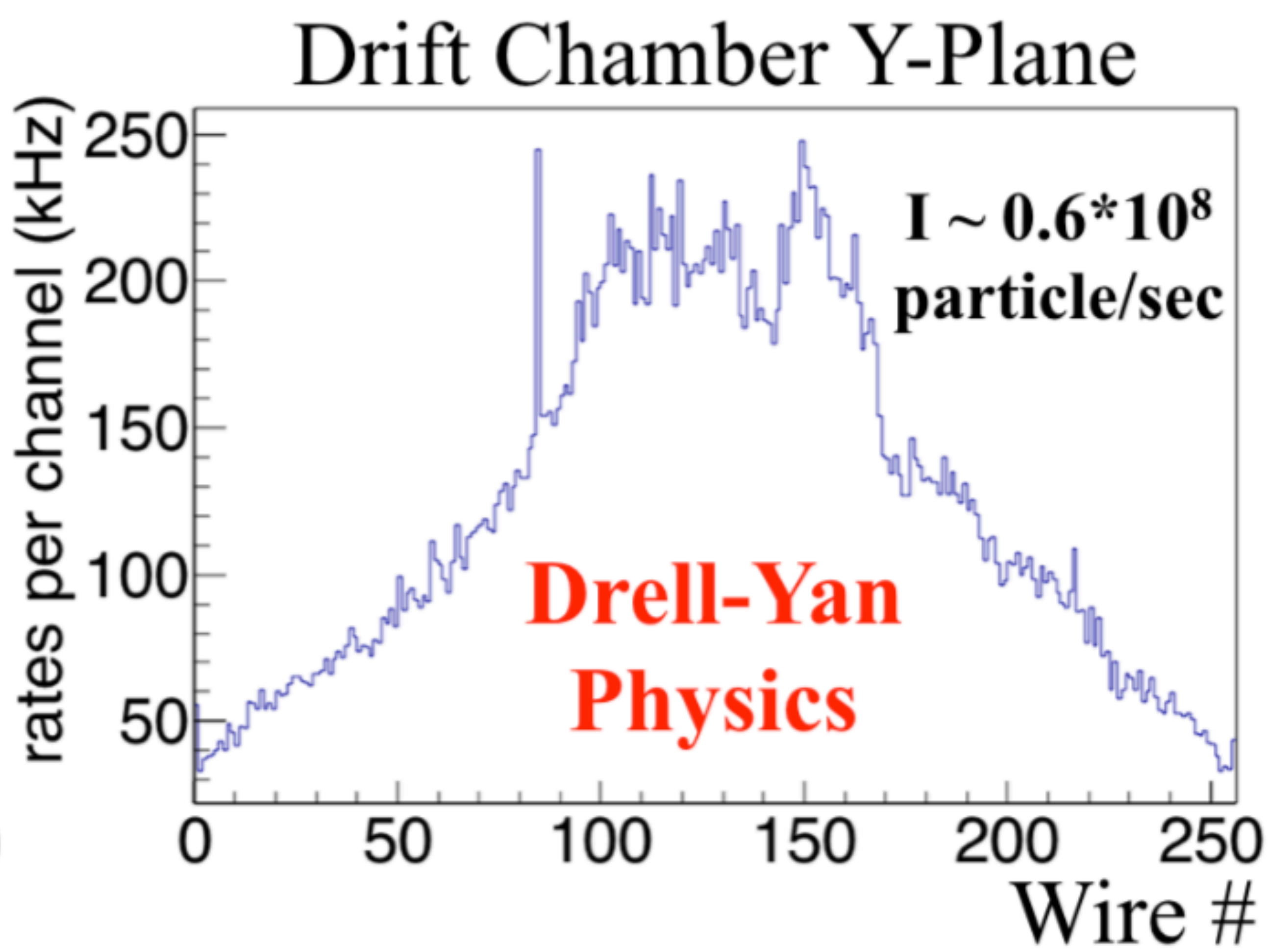
- Detector alignment is a critical before reconstruction



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 aluminate detectors



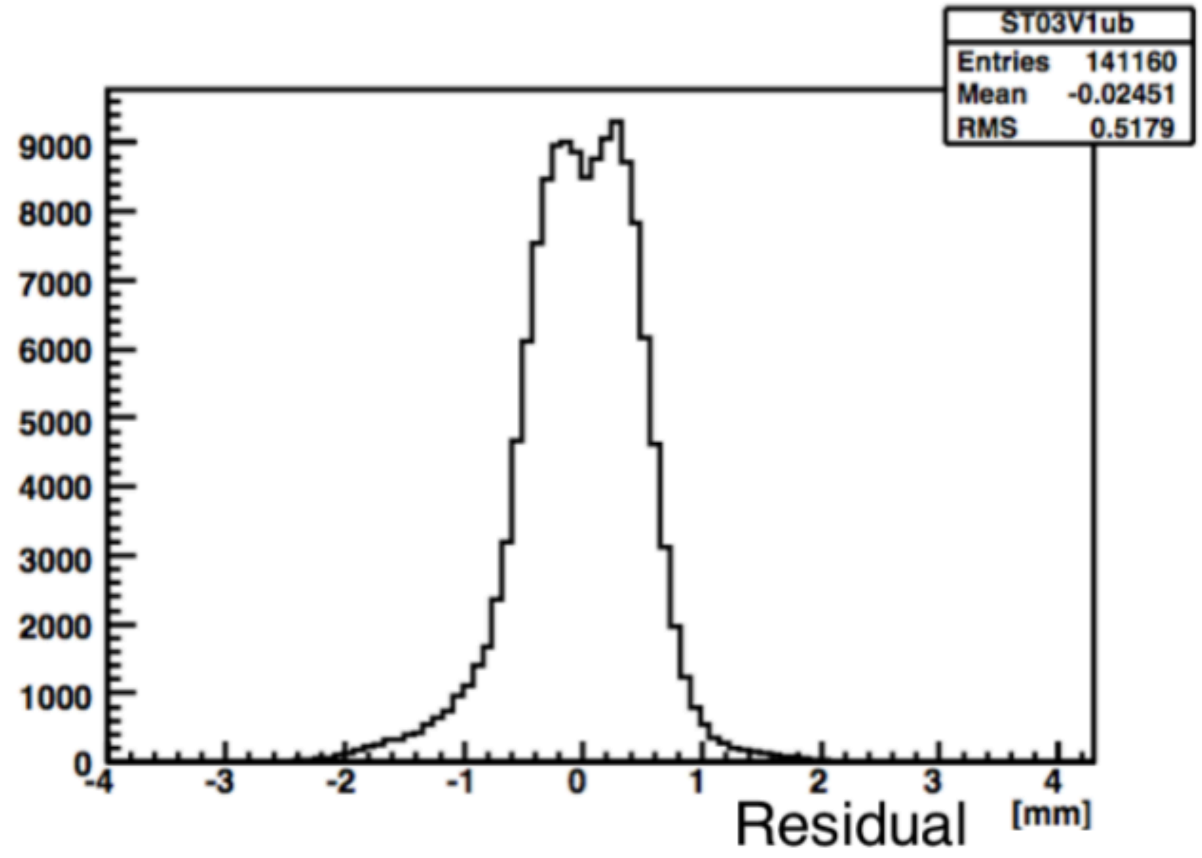


Alignment Quality

- 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



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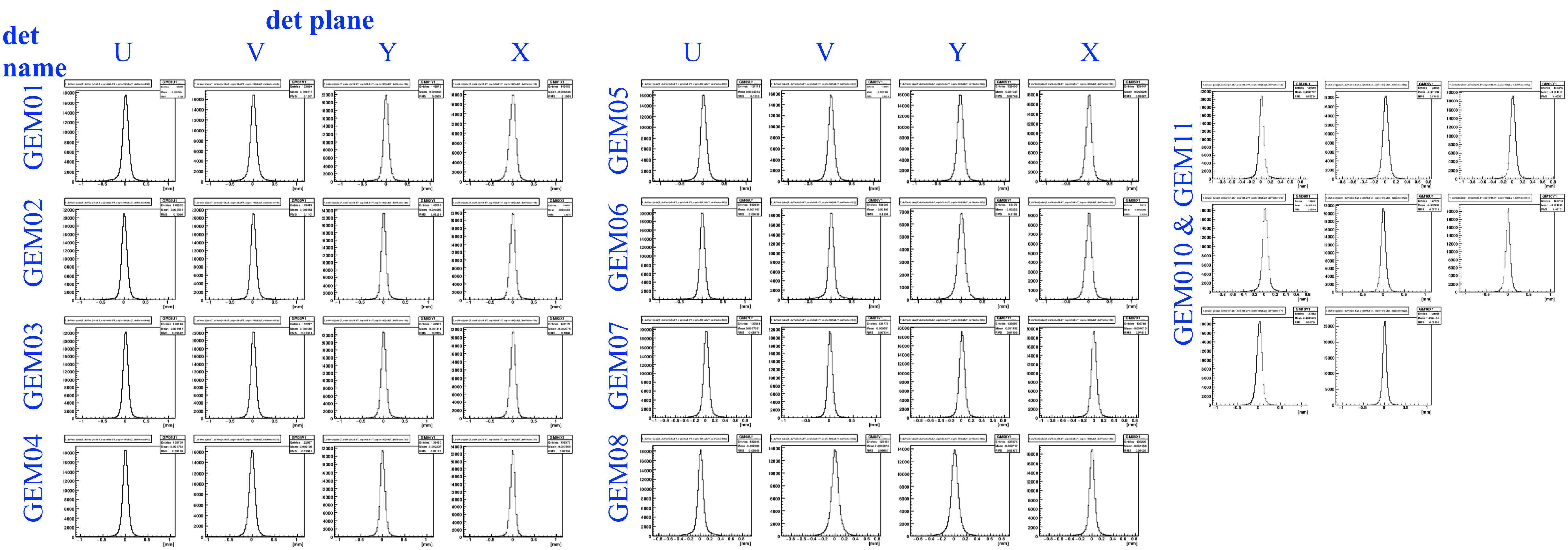

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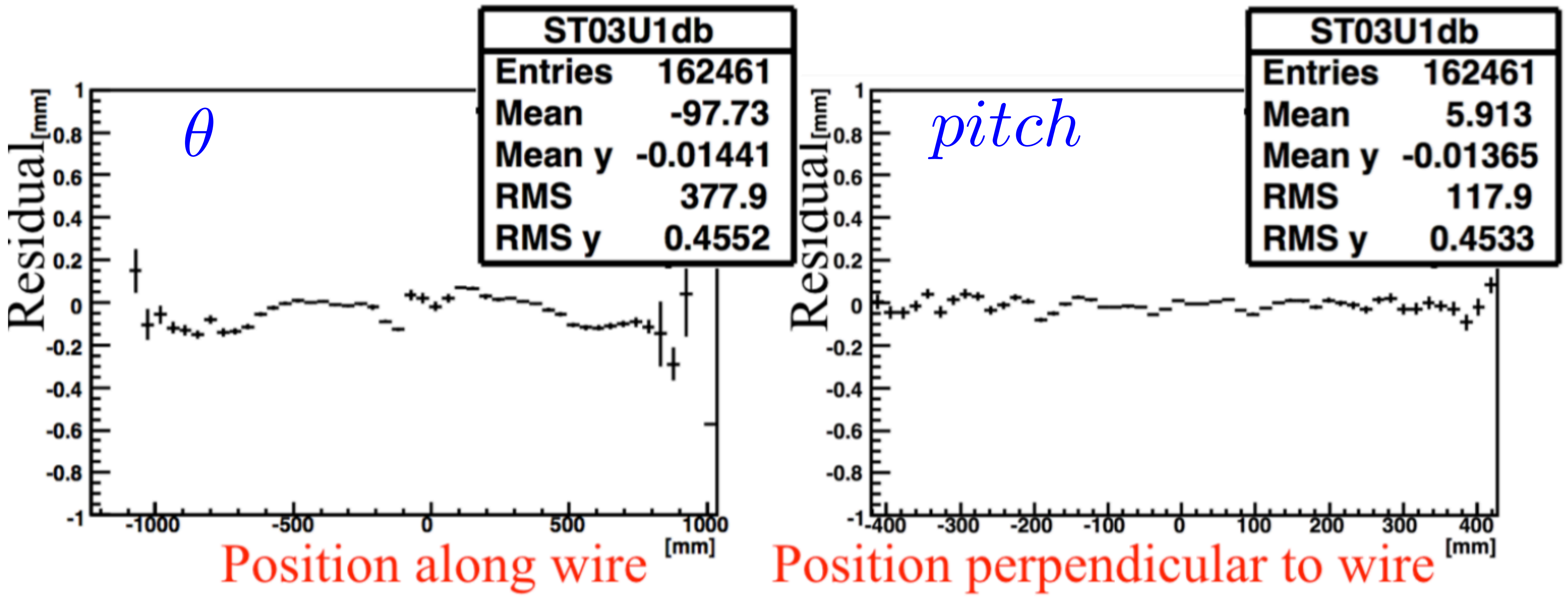
$$\chi^2_{det} = \frac{{\color{red}Residual}^2_{det}(u,\ \theta,\ pitch)}{\sigma^2_{det}}$$

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



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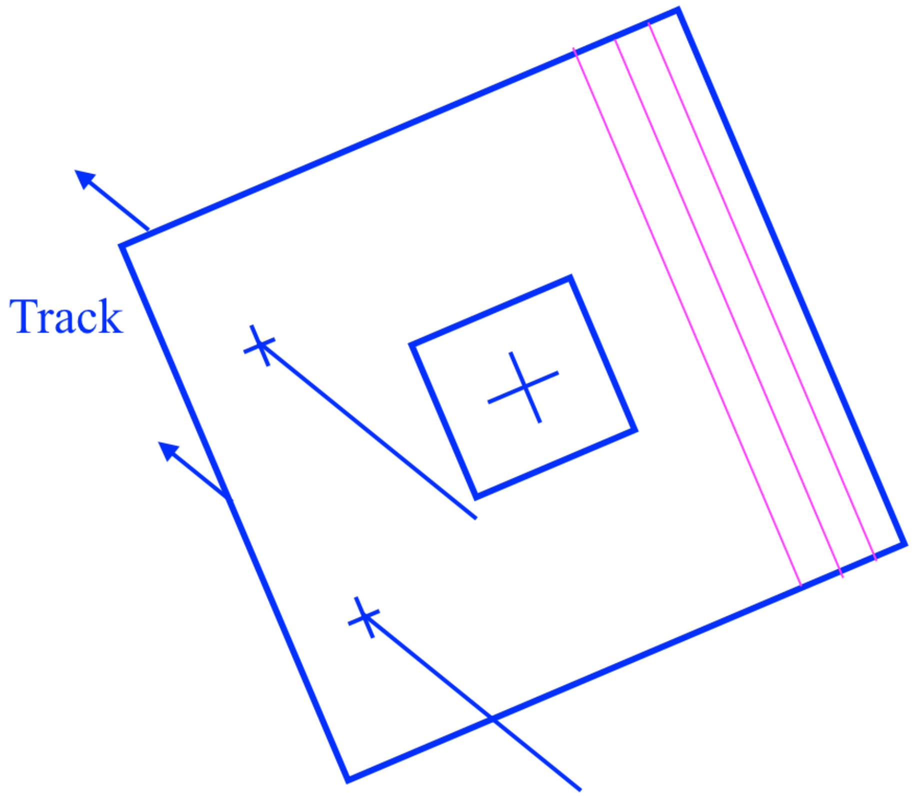

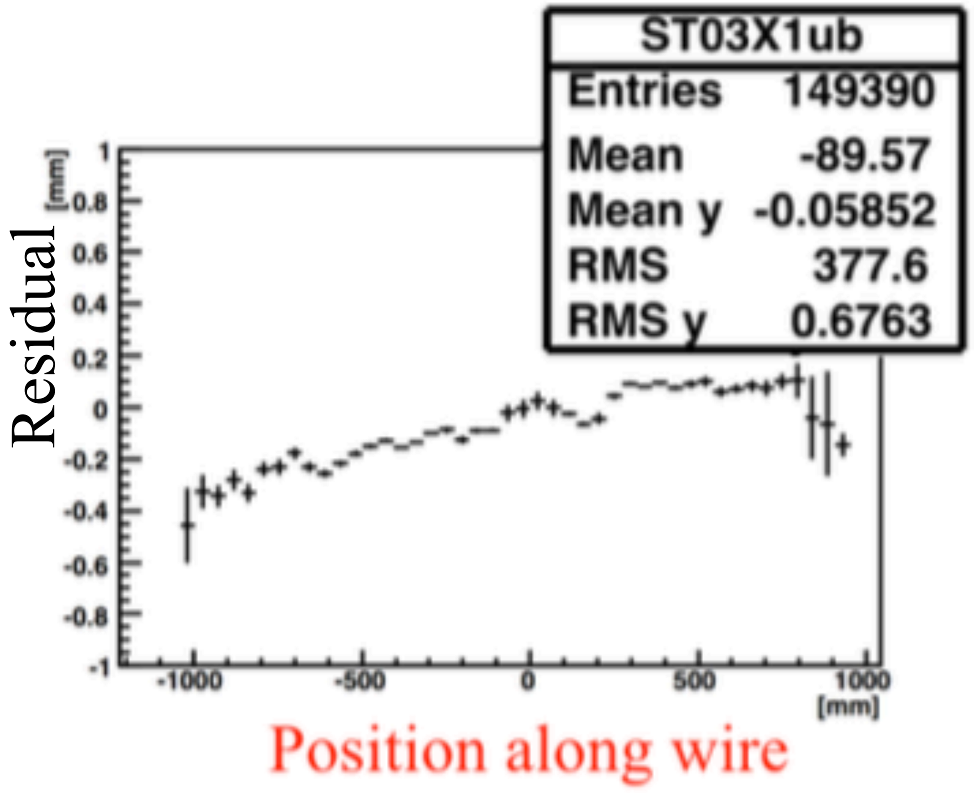

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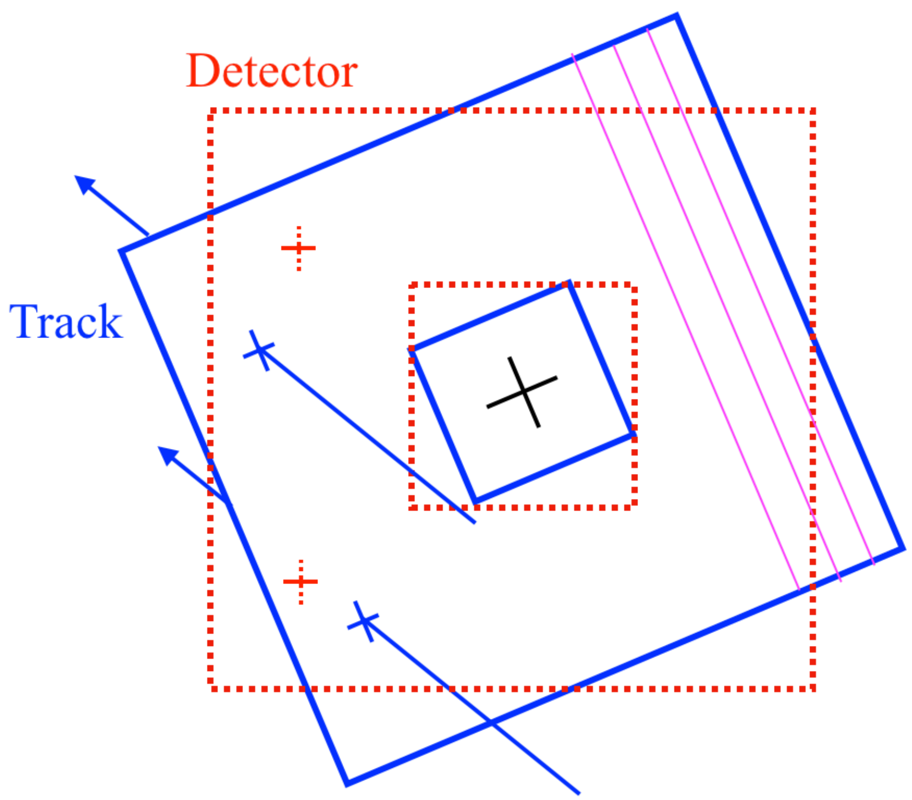

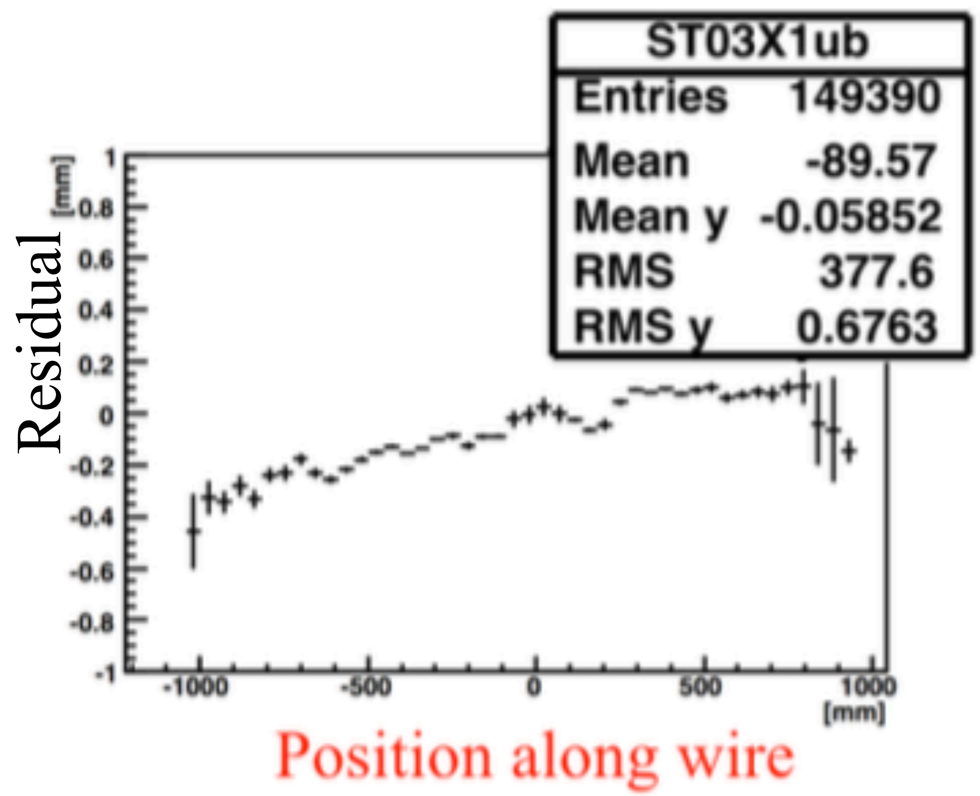

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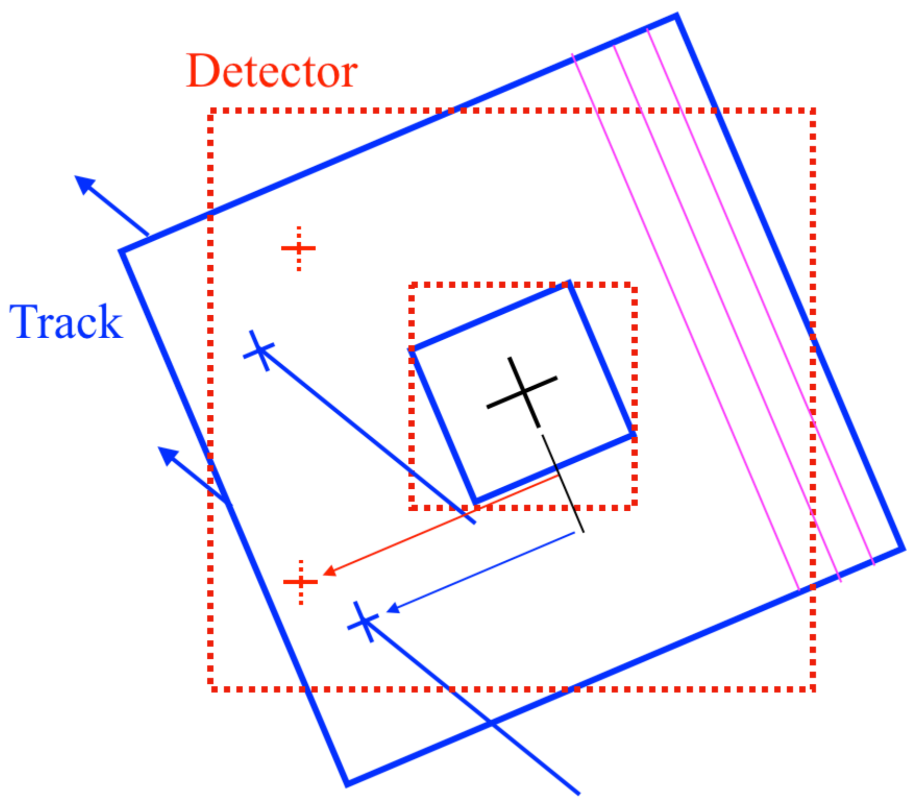
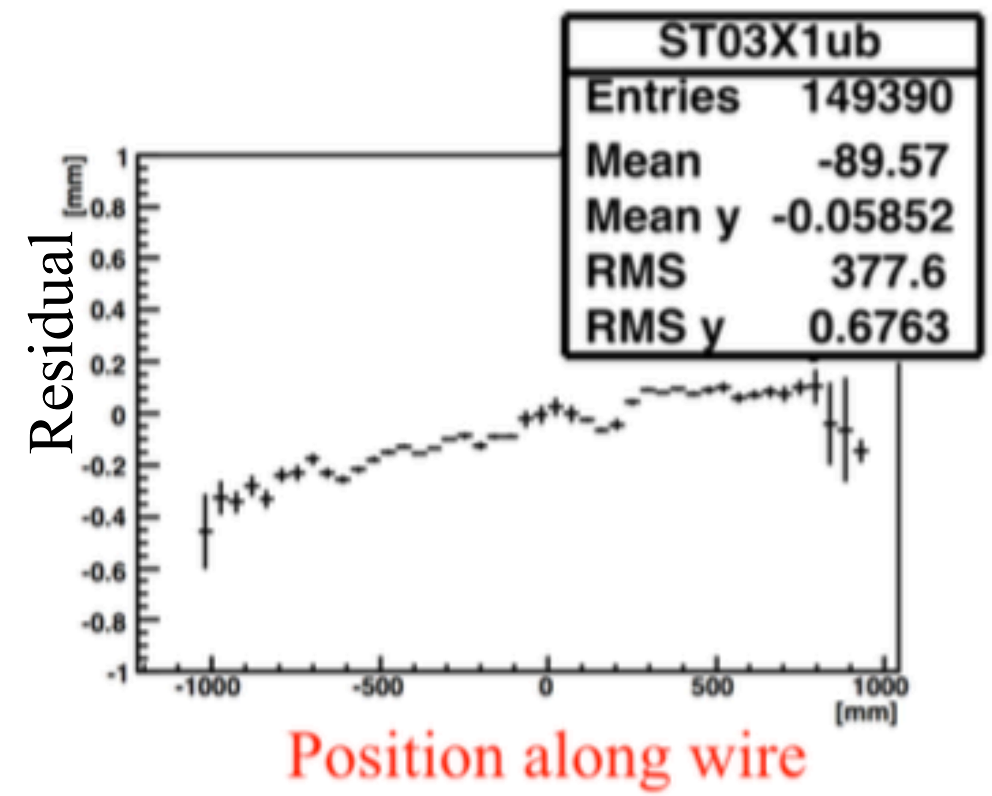


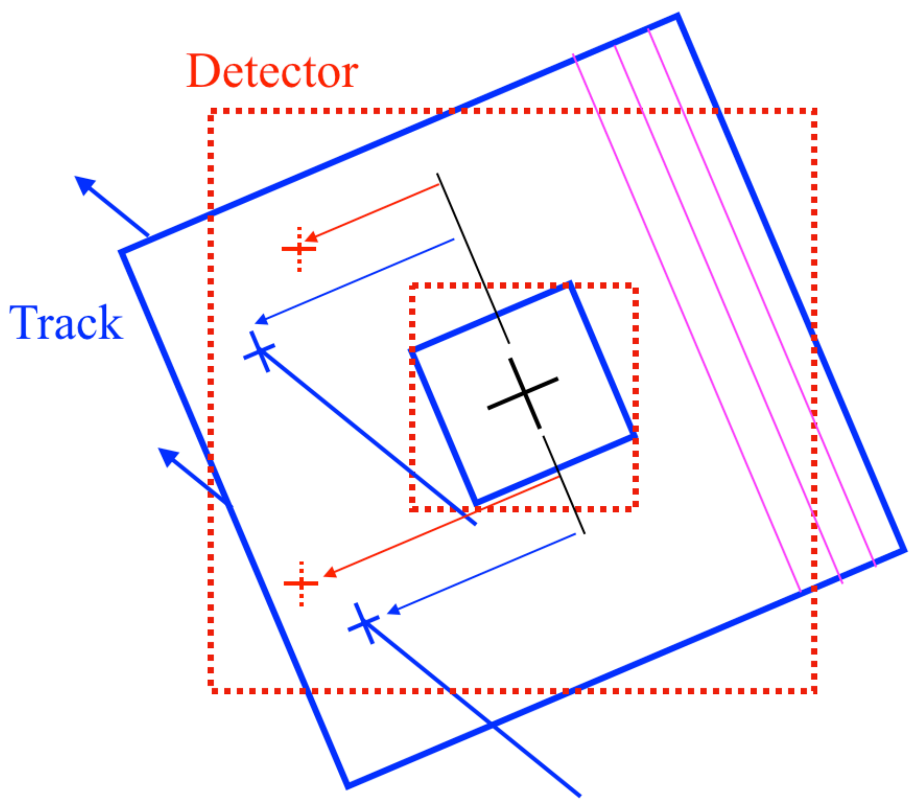


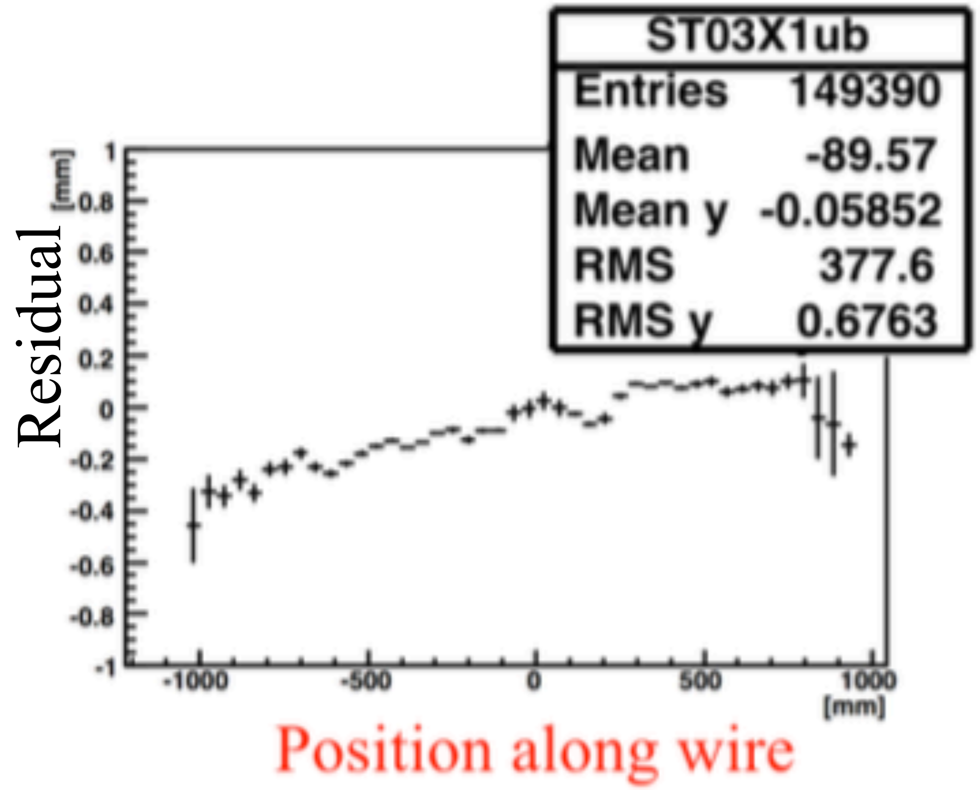
Alignment Quality

- 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)

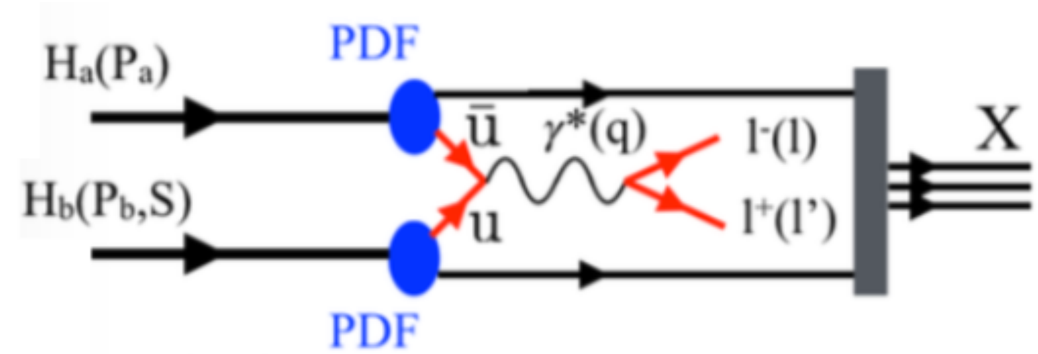
- 7.7 terabytes micro-Data Structured Trees
  events with at least 2 muons (same charge or opposite charge)

Oppositely charge di-muon events:

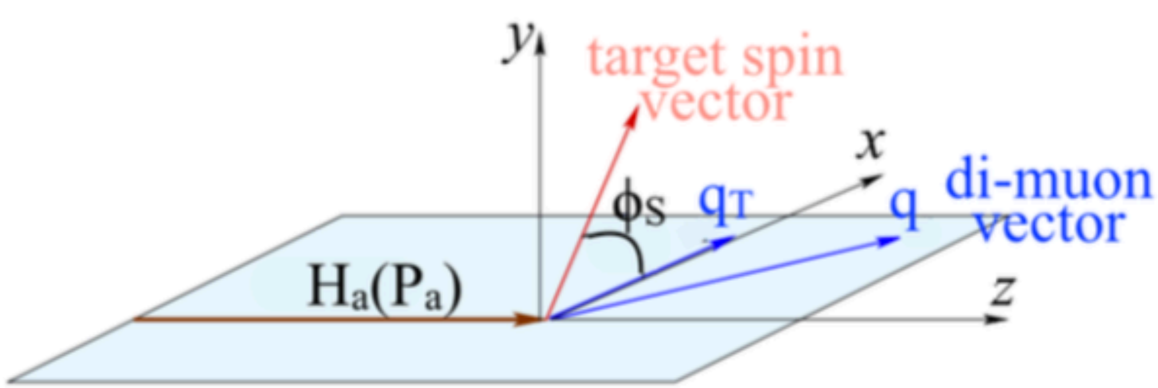
- 37,921 high mass [4.3-8.5 GeV/c^2]
- 1,540,868 JPsi mass [2.87-3.38 GeV/c^2]

Drell-Yan Analysis Frames

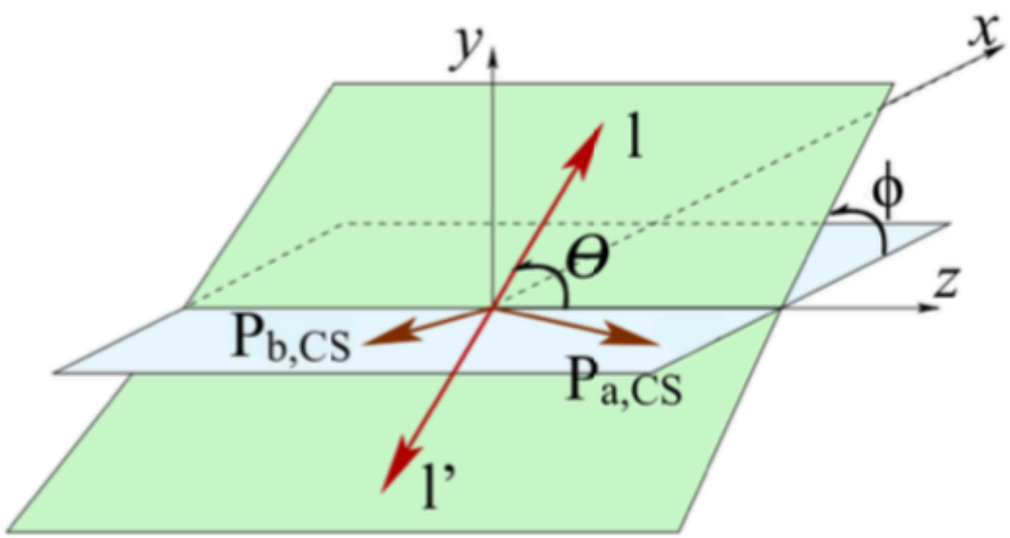
- Transverse Momentum Dependent PDF
  from azimuthal amplitudes



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



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

Di-muon Invariant Mass

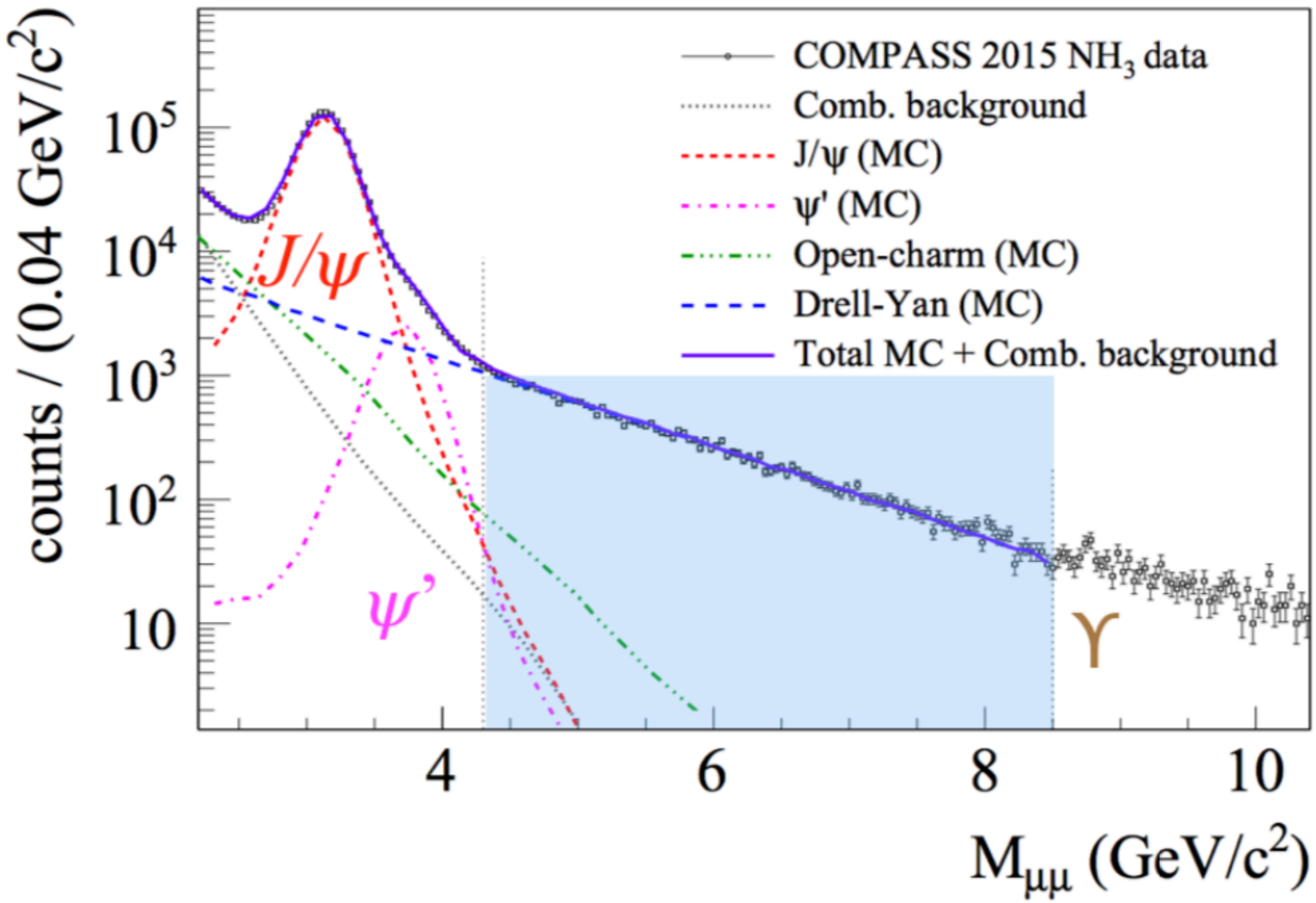
- The Drell-Yan analysis was performed in the invariant mass range 4.3-8.5 GeV/c²

  4% background in this mass range

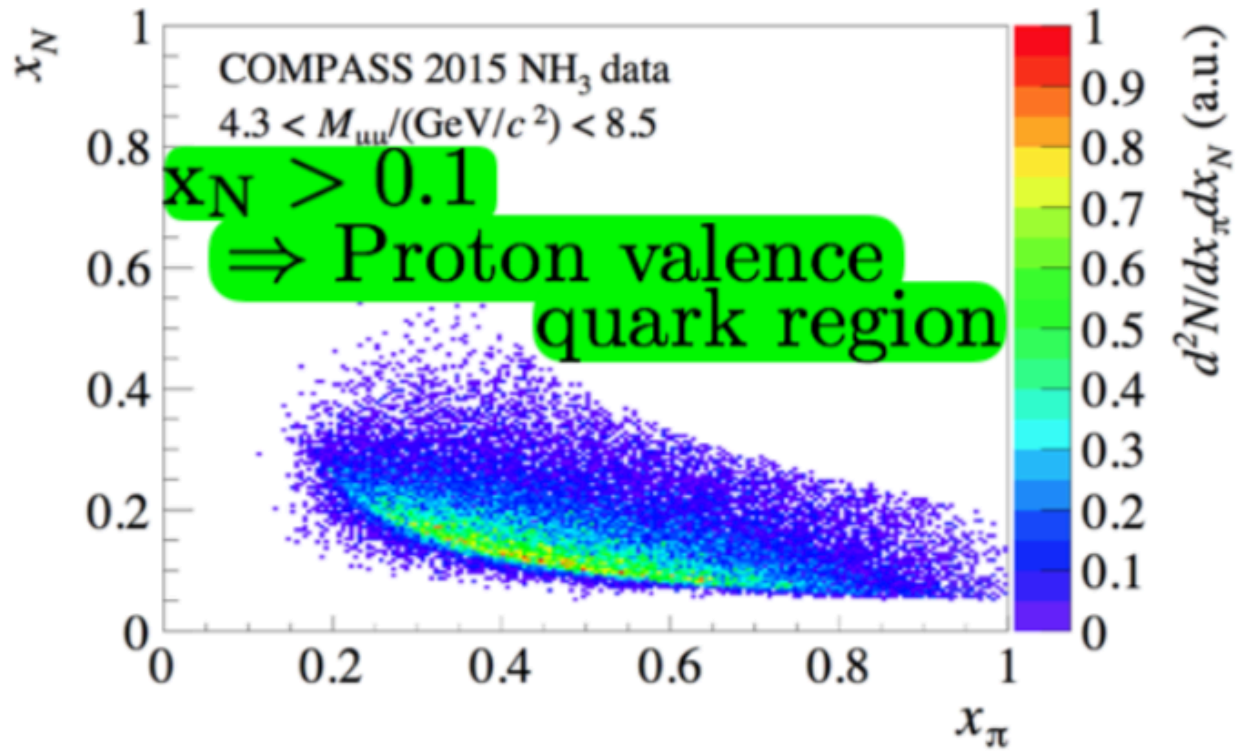
Background includes:

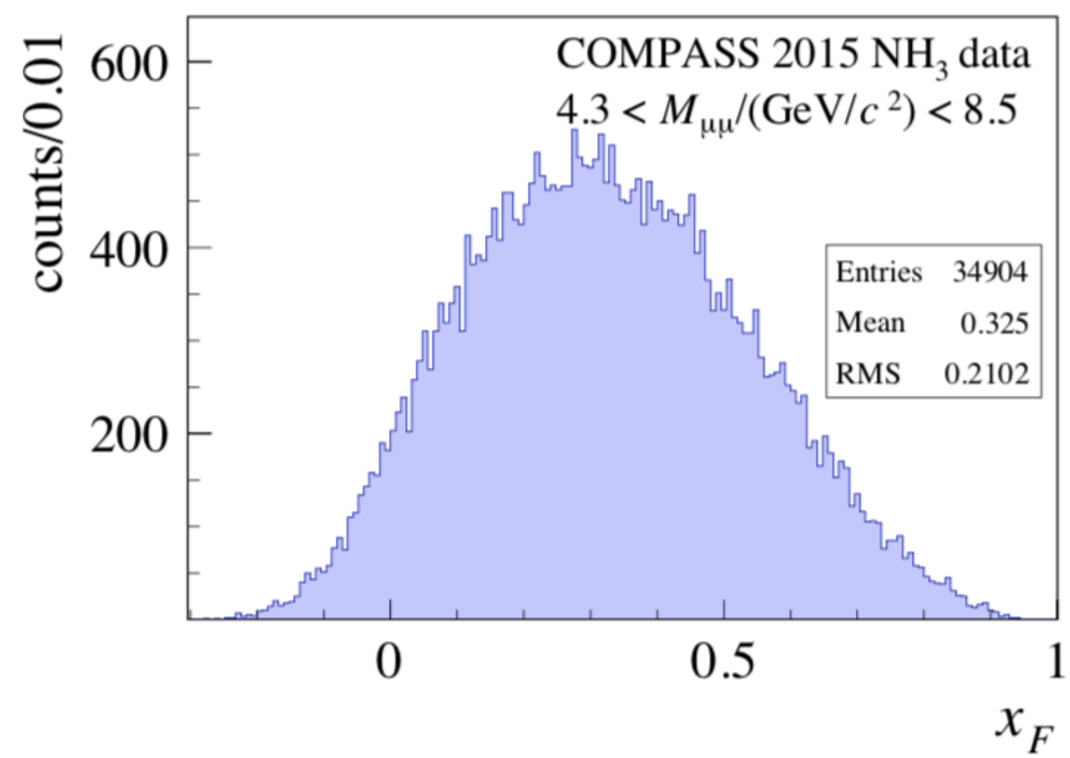
J/Ψ ($c\bar{c}$), Ψ' ($c\bar{c}$), Open Charm (xc),

Combinatorial background $2\sqrt{N_{\mu^+\mu^+}N_{\mu^-\mu^-}}$



Drell-Yan Phase Space

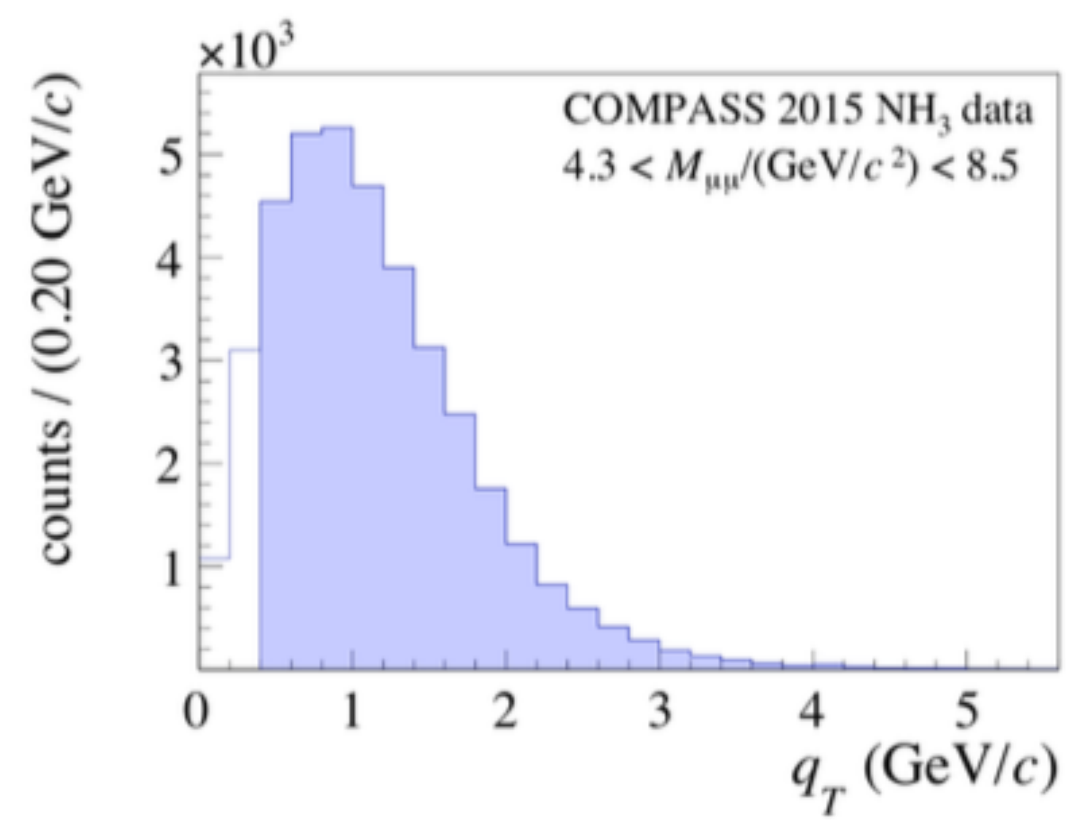




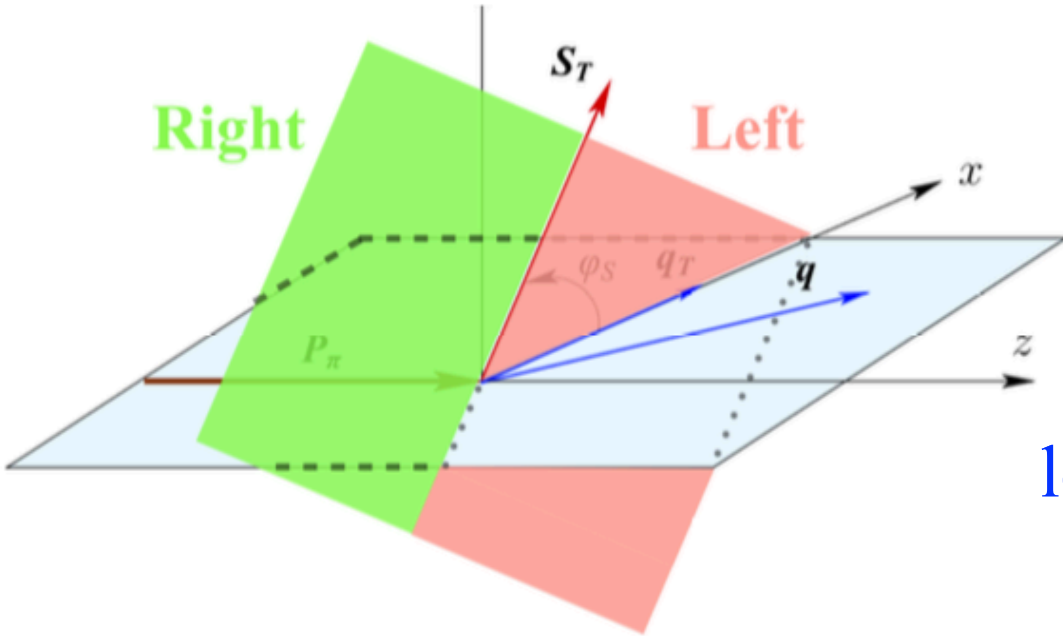
- Valence quark annihilation from both beam and target
  $x_N > 0.1$, $x_\pi > 0.2$

- 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



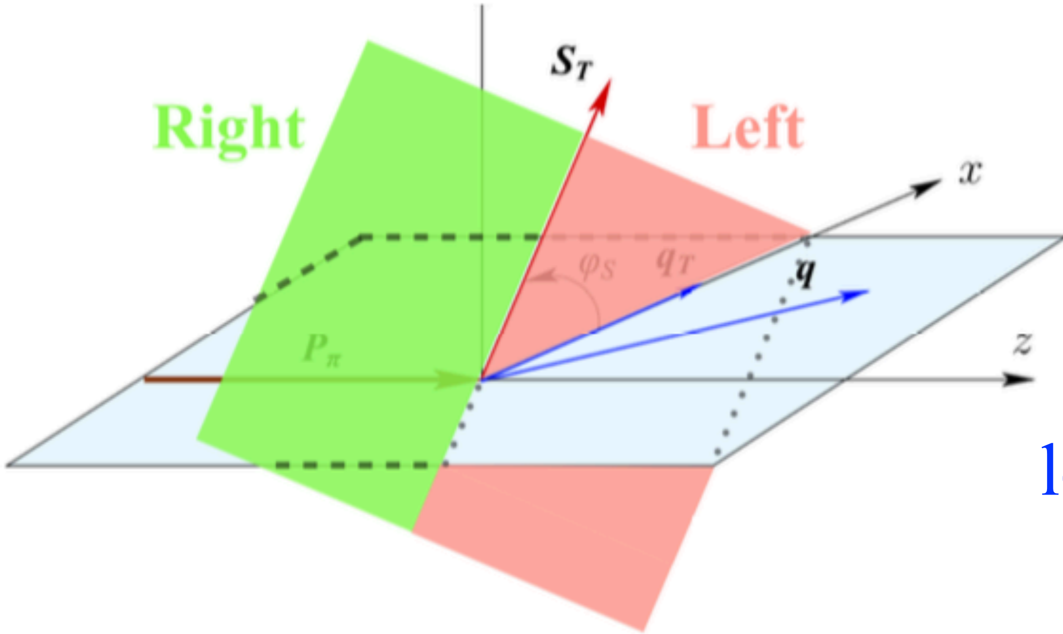
Left: $0 < \varphi_S < \pi$

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

left and right depend on the transverse spin direction

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

Left-Right Asymmetry



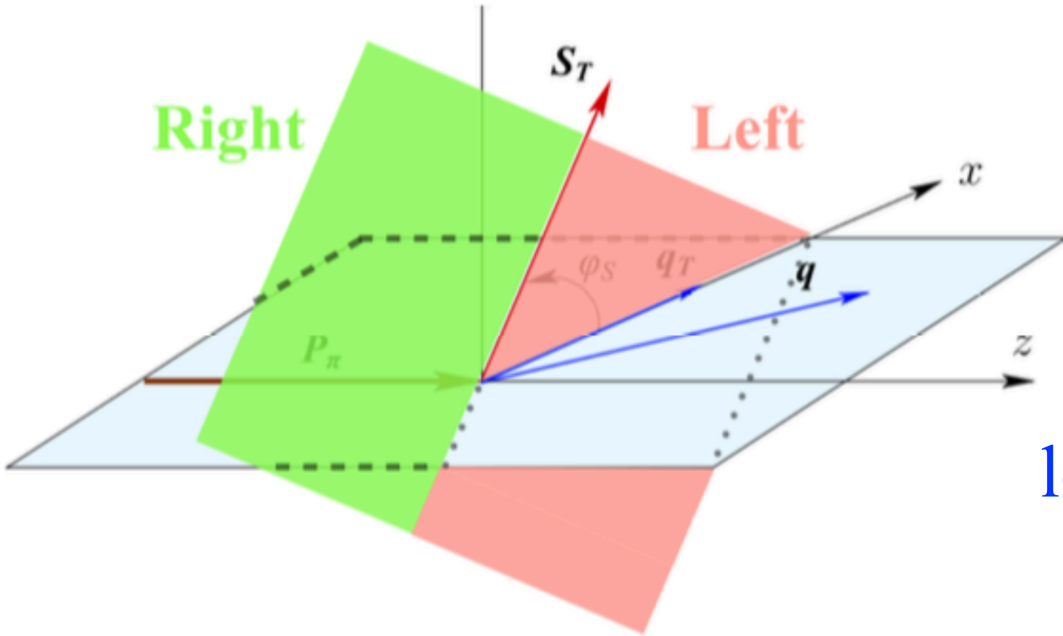
Left: $0 < \varphi_S < \pi$

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

left and right depend on the transverse spin direction

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

Left-Right Asymmetry



Left: $0 < \varphi_S < \pi$

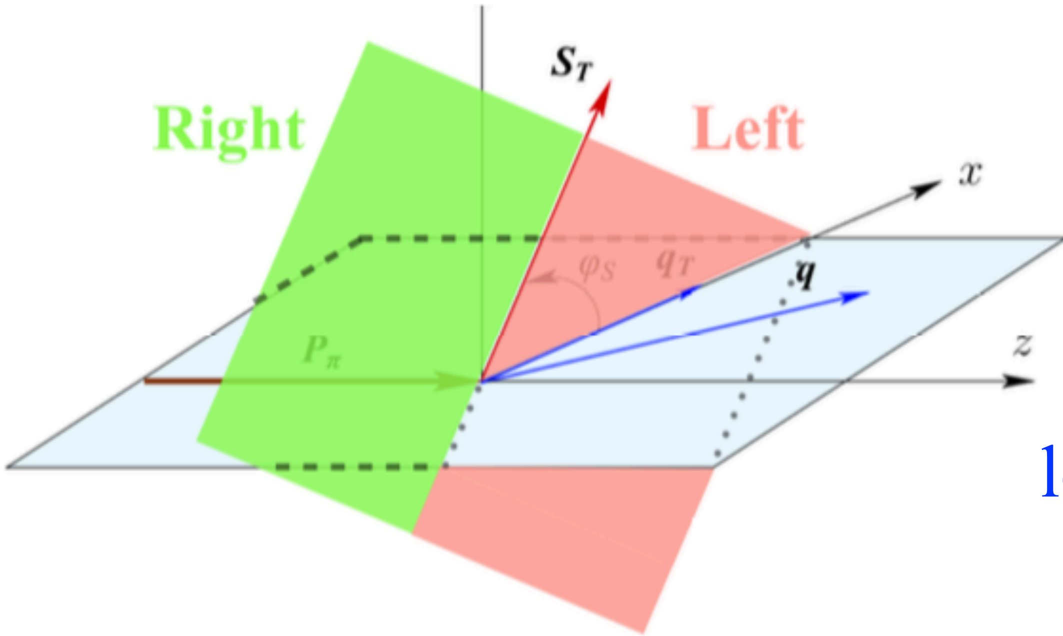
Right: $-\pi < \varphi_S < 0$

left and right depend on the transverse spin direction

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

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

Left-Right Asymmetry



Left: $0 < \varphi_S < \pi$

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

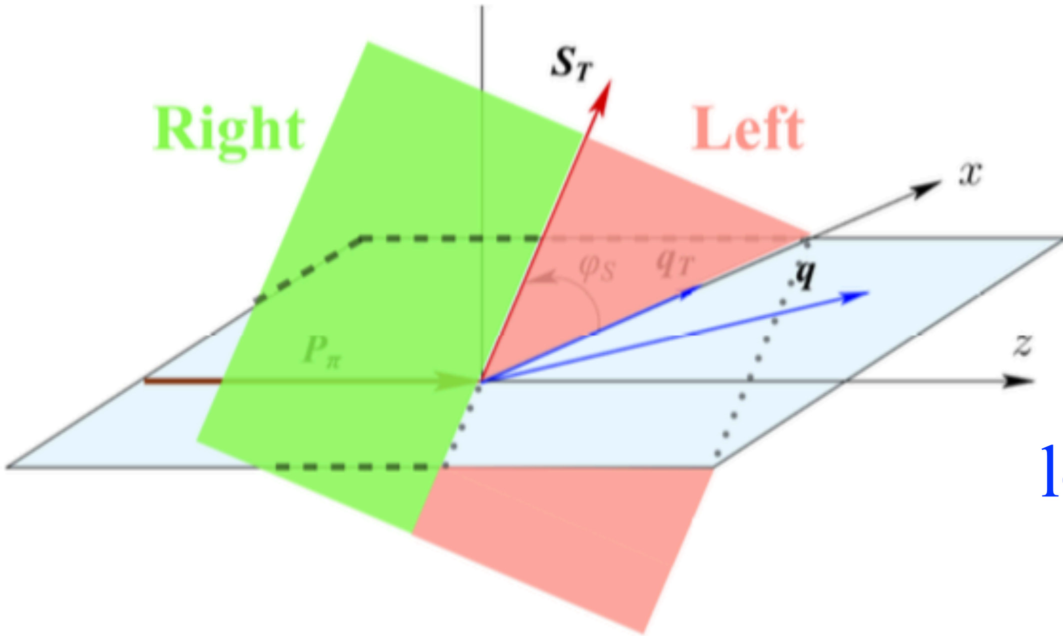
left and right depend on the transverse spin direction

Experimental observable:

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

- A_{lr} model independent

Left-Right Asymmetry



Left: $0 < \varphi_S < \pi$

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left and right depend on the transverse spin direction

Experimental observable:

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

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

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

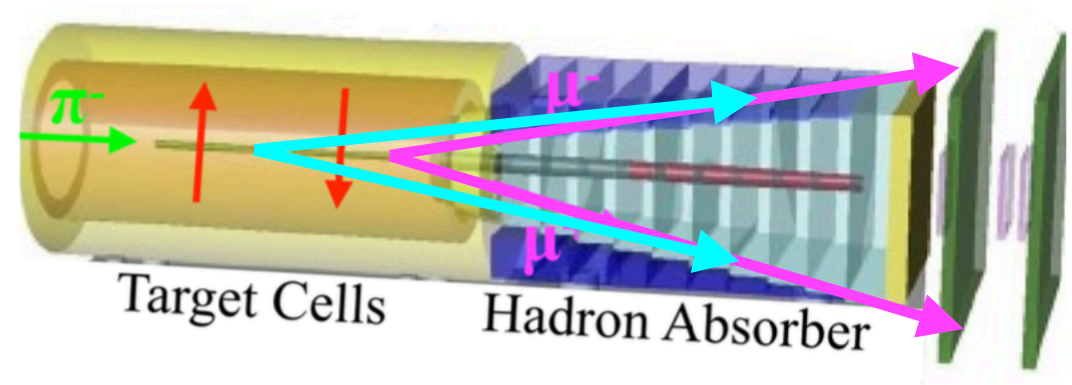
Left-Right Asymmetry Measurement

Experimental observable:

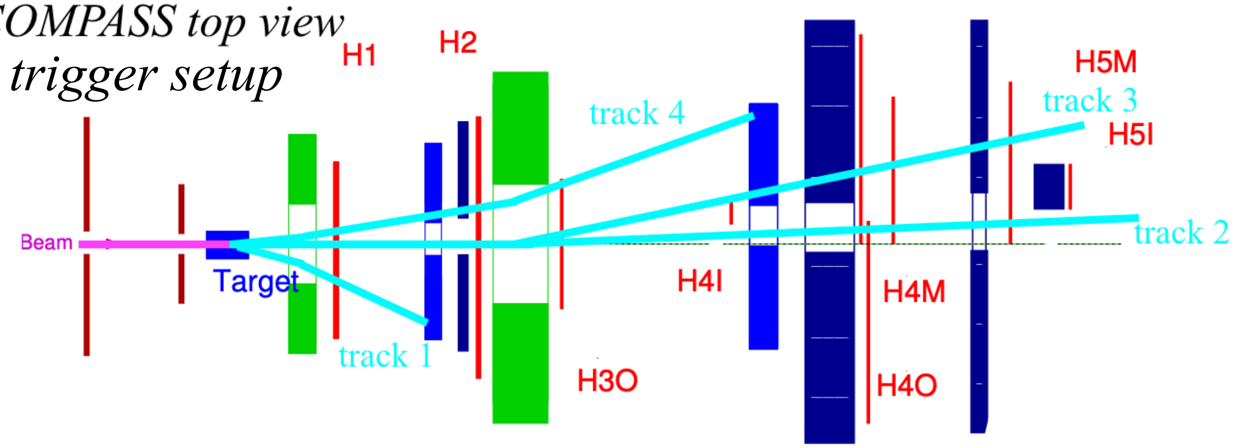
$$A_{lr} = \frac{1}{|S_T|} \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

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

upstream vs. downstream



COMPASS top view trigger setup



Left-Right Asymmetry Measurement

Experimental observable:

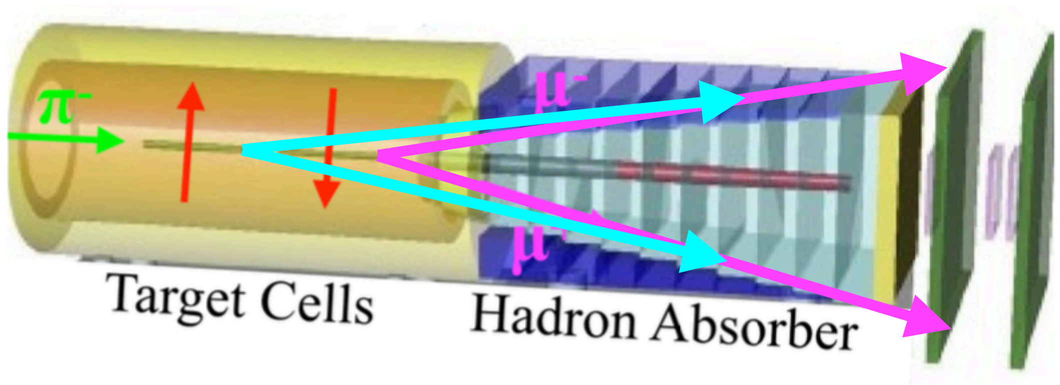
$$A_{lr} = \frac{1}{|S_T|} \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

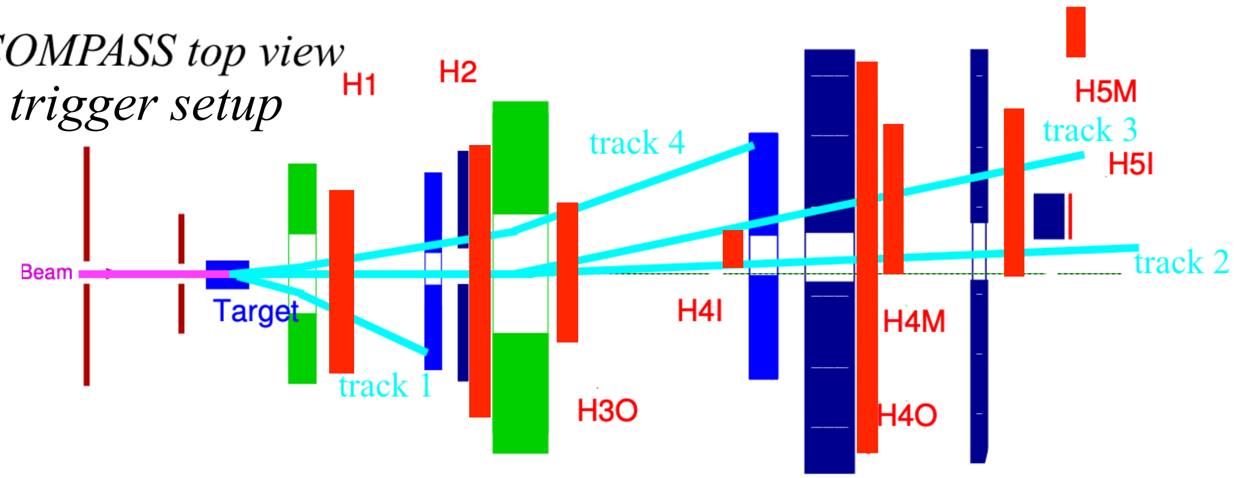
acceptance luminosity

$$N(\Phi) = a(\Phi)\,\sigma(\Phi)\,L$$

cross-section

upstream vs. downstream





Left-Right Asymmetry Measurement

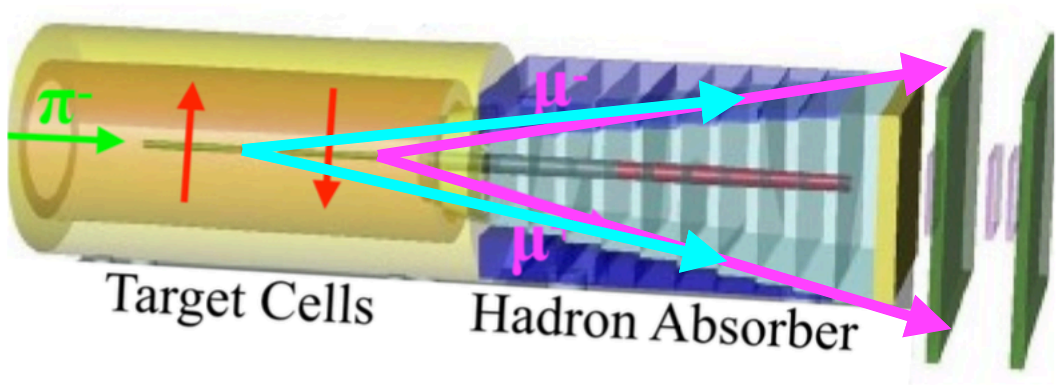
Experimental observable:

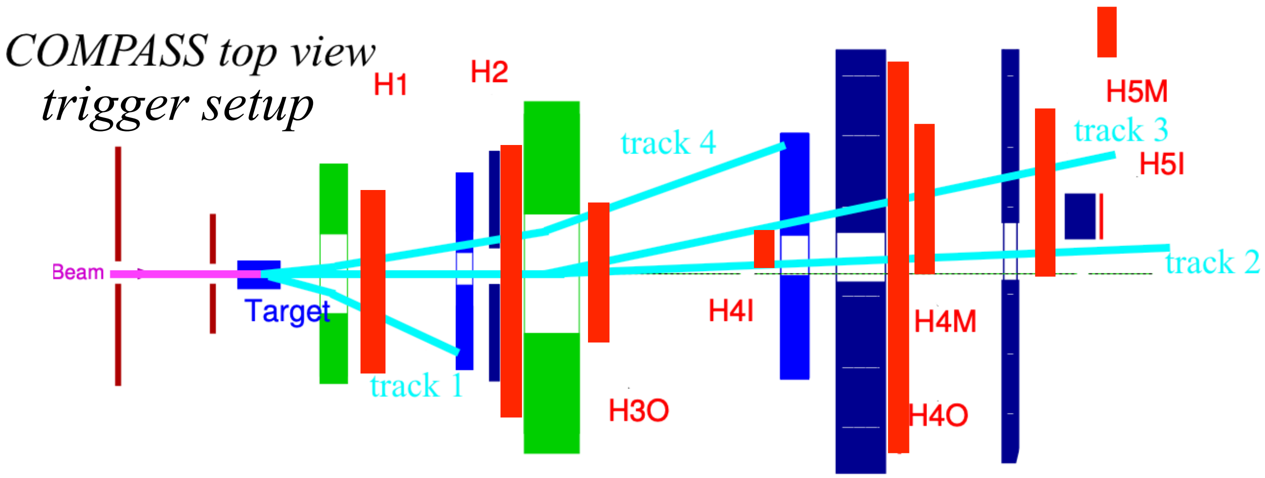
$$A_{lr} = \frac{1}{|S_T|} \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

acceptance luminosity

$$N(\Phi) = a(\Phi)\, \sigma(\Phi)\, L$$

cross-section





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

Left-Right Asymmetry Systematics

Left **Right**

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

Left-Right Asymmetry Systematics

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

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

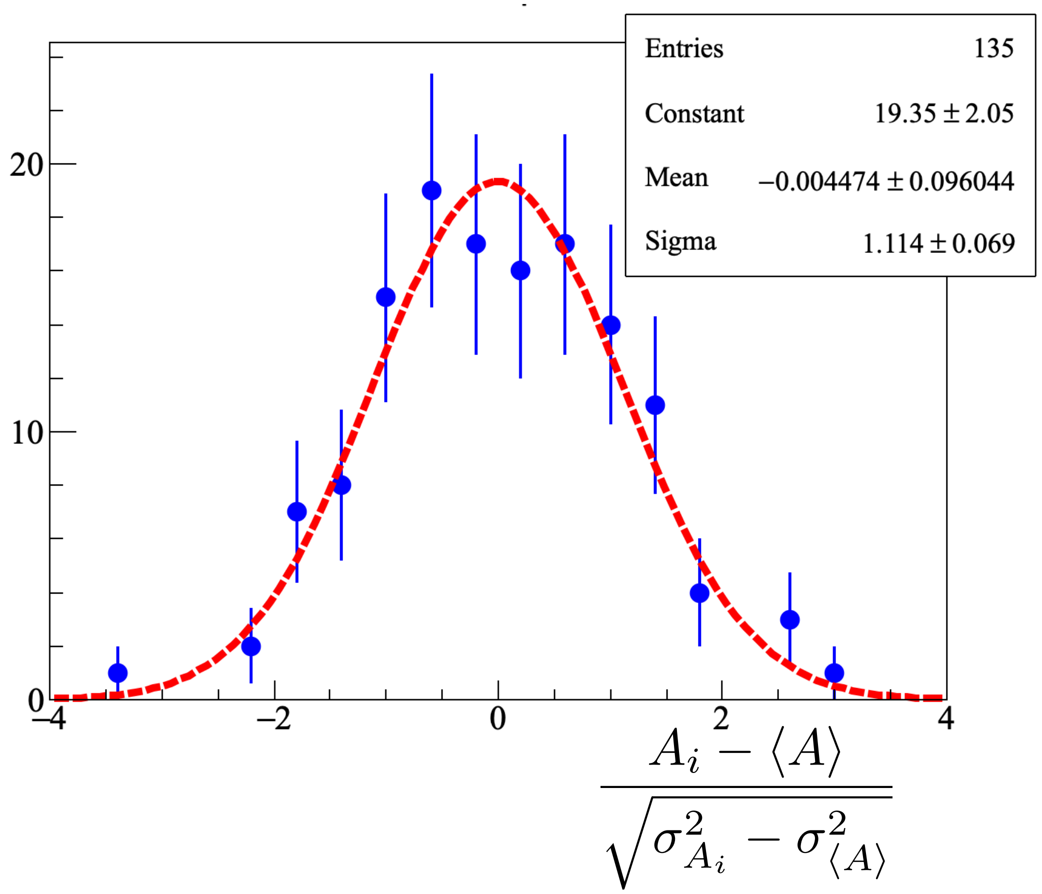
False asymmetry:

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

Left-Right Asymmetry Systematics

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

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



- Estimate systematic uncertainty with students t-test

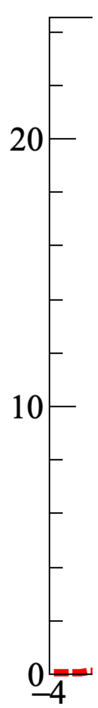
Mean should = 0
Sigma should = 1

Left-Right Asymmetry Systematics

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

False asymmetry:

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

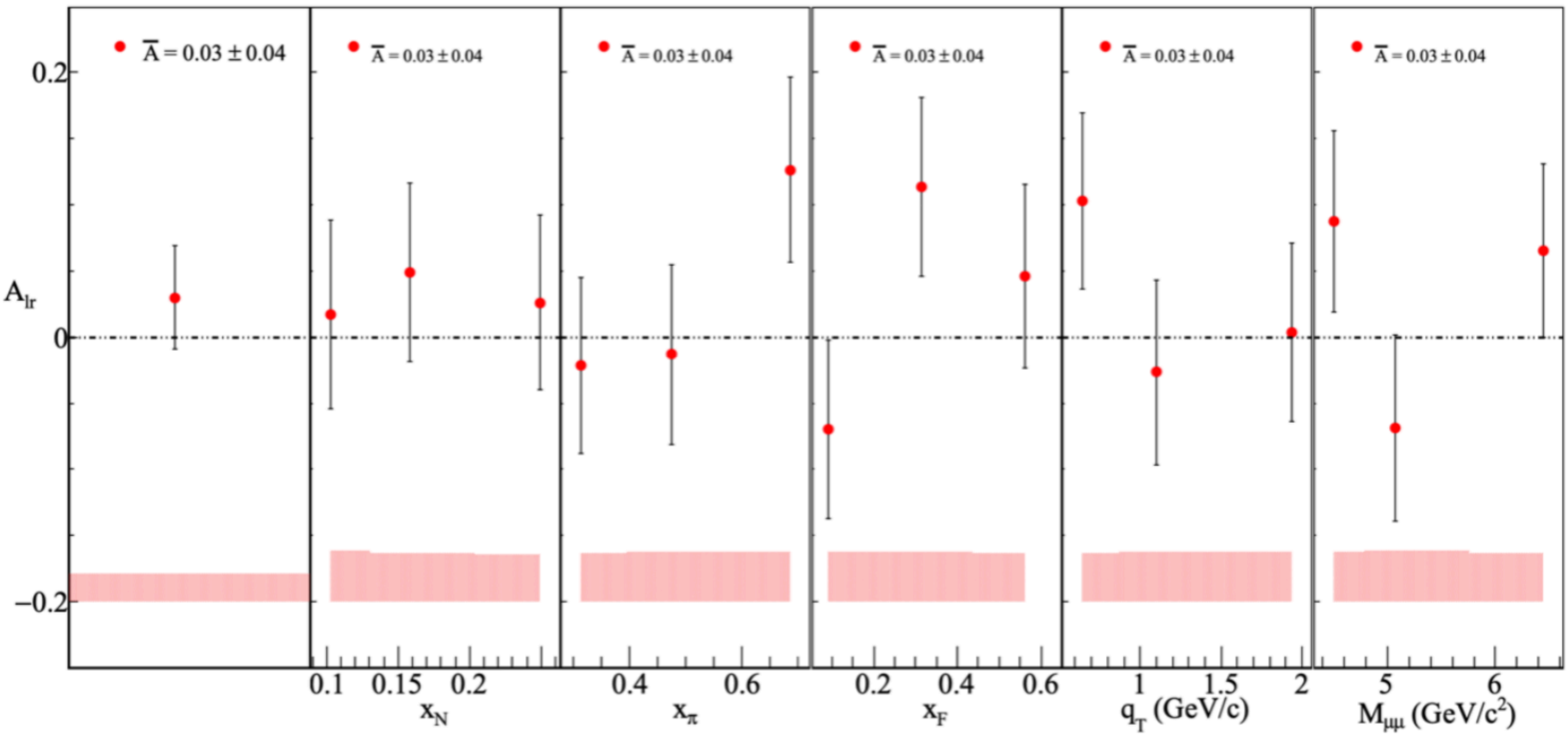


Systematic Uncertainty	$\langle \sigma_{\mathrm{systematic}} / \sigma_{\mathrm{statistical}} \rangle$	$\langle \sigma_{\mathrm{systematic}} \rangle$
Period compatibility	0.0	0.0
Left-Right migration	0.09	0.004
Target Polarization	0.05	0.003
Dilution Factor	0.05	0.003
Acceptance fluctuation	0.2	0.008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

rtainty with

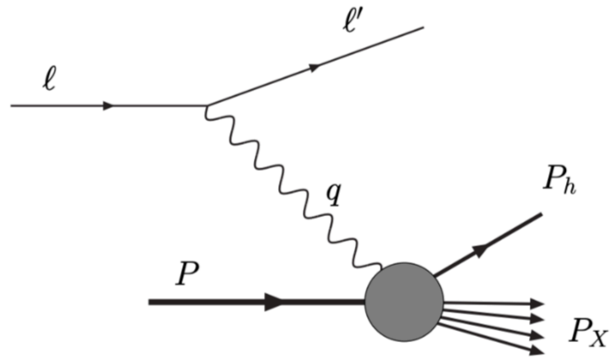
$$\sqrt{\sigma^2_{A_i} - \sigma^2_{\langle A \rangle}}$$

Left-Right Asymmetry Results

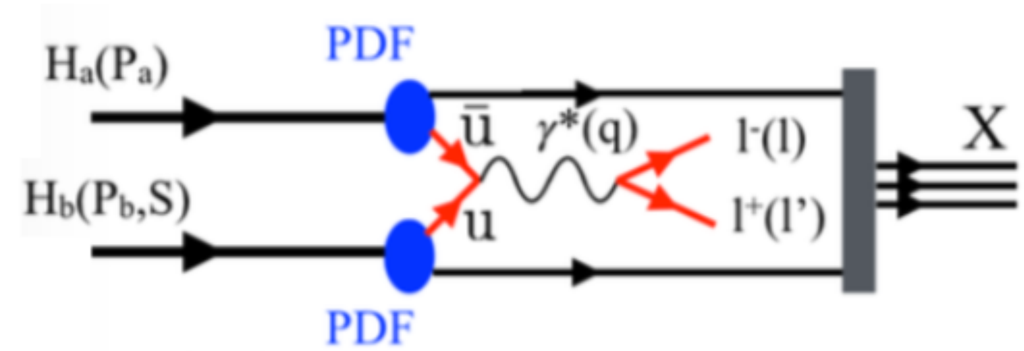


- Integrated asymmetry is positive by ~1 sigma
- Need more statistics to determine trends in kinematic variables
- **New knowledge related to proton structure!**

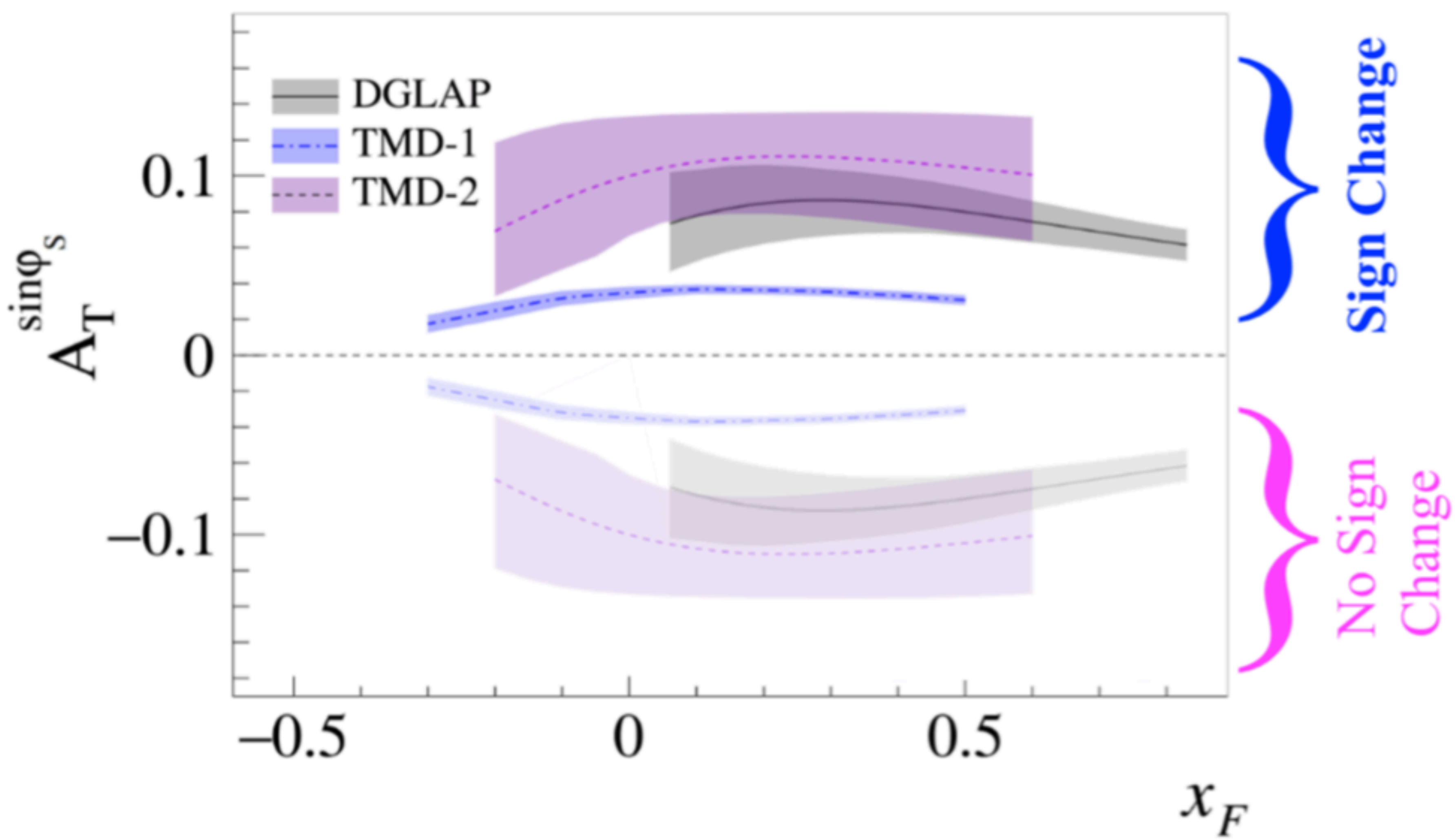
Sign Flip



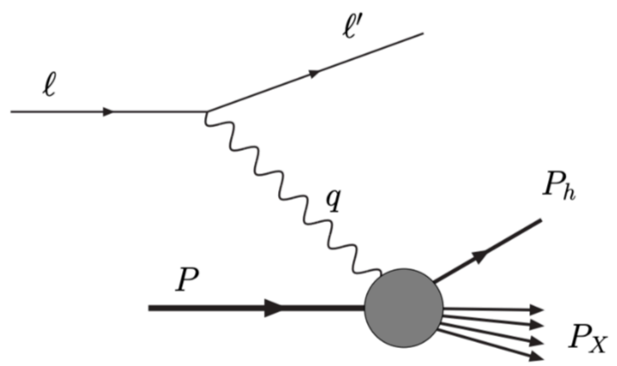
Semi-Inclusive Deep Inelastic Scattering (SIDIS)



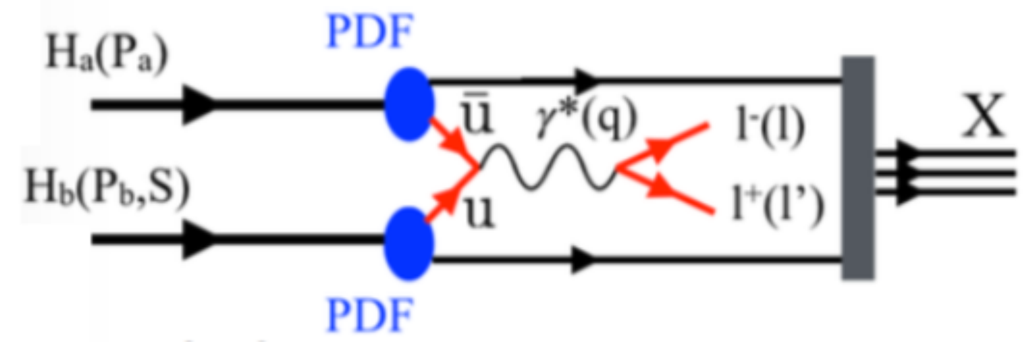
Drell-Yan



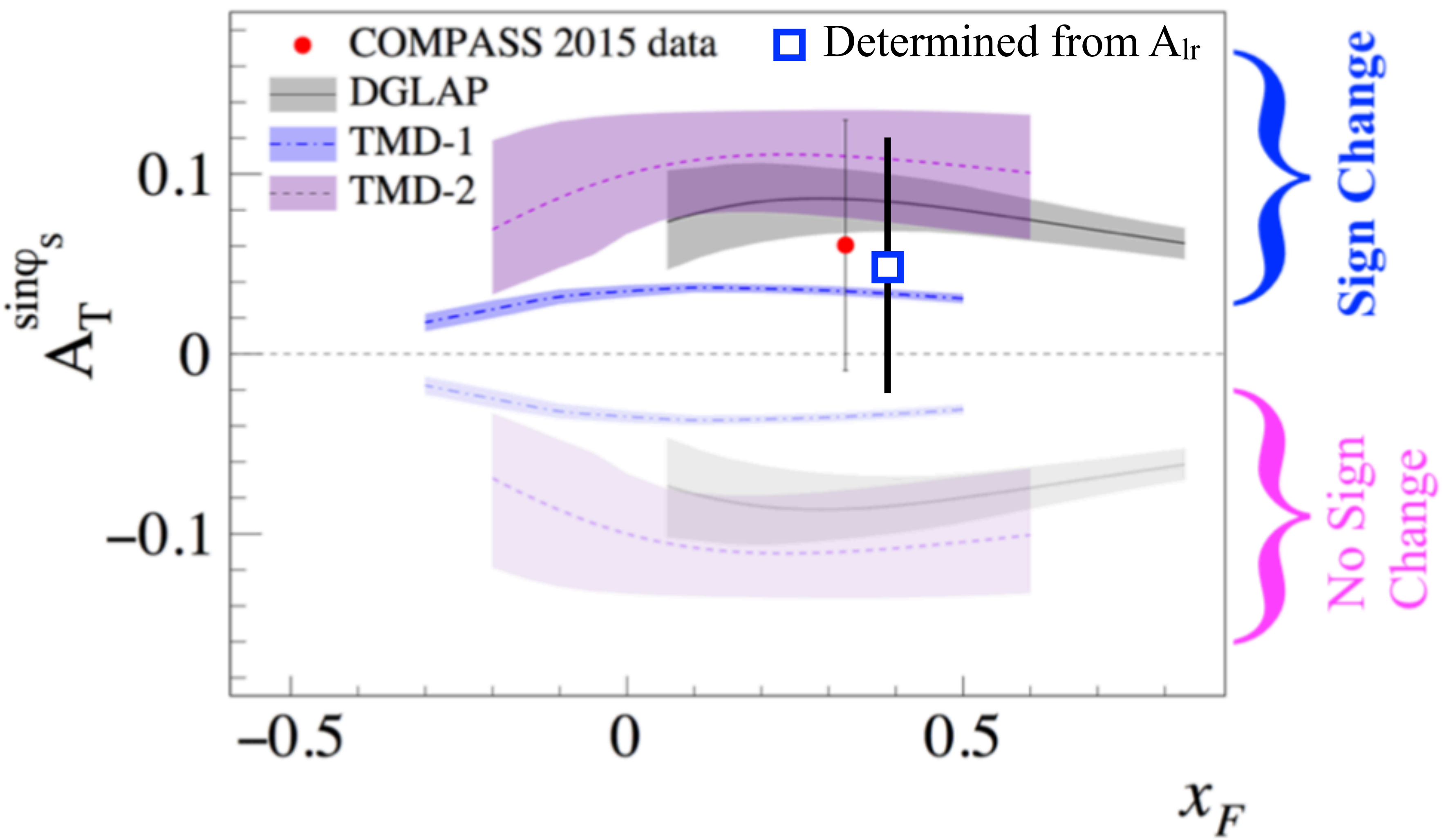
Sign Flip



Semi-Inclusive Deep Inelastic Scattering (SIDIS)

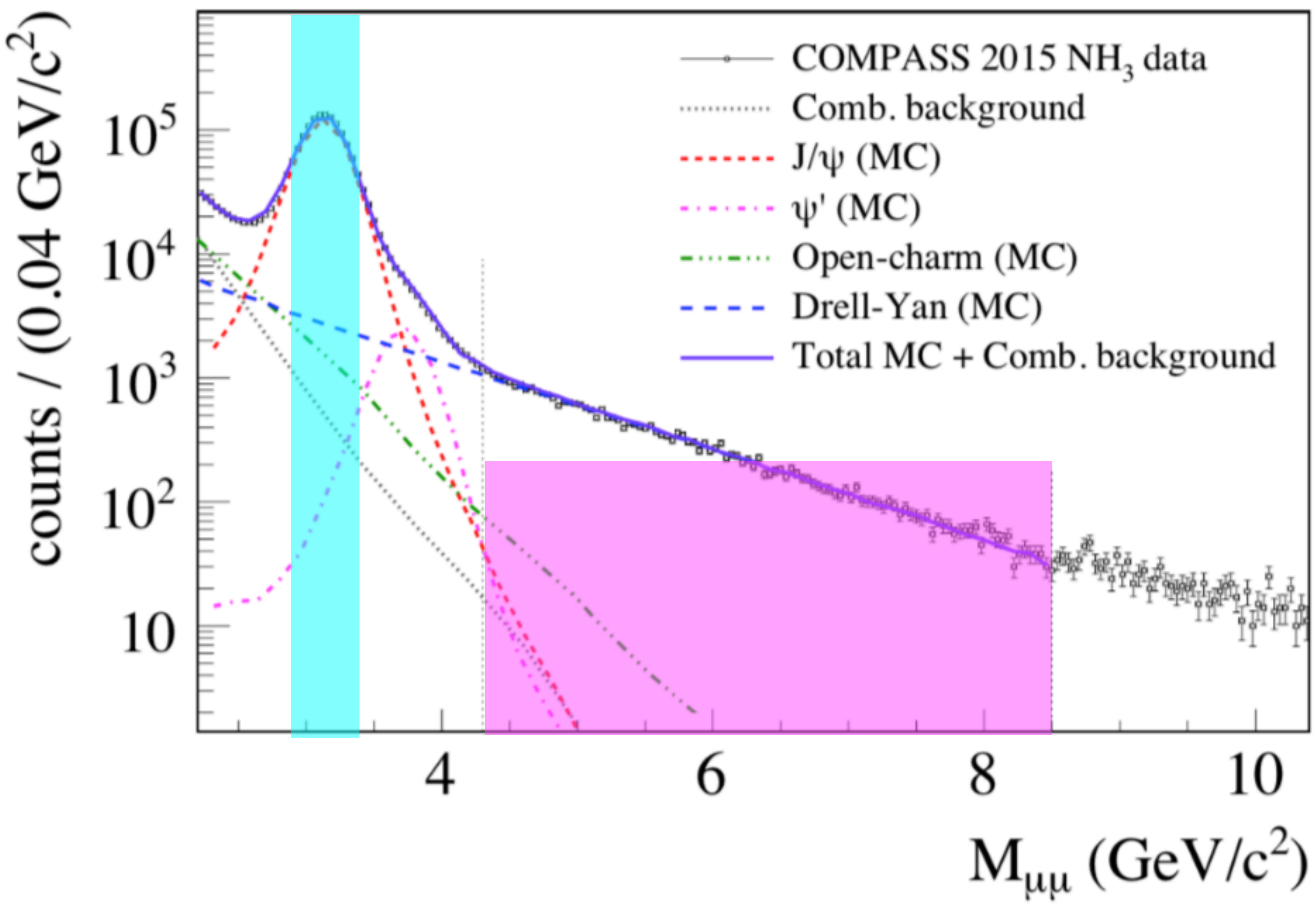


Drell-Yan



- 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

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

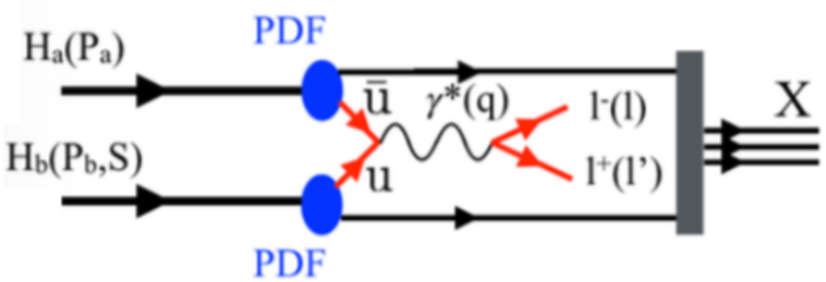
J/Ψ Mechanism

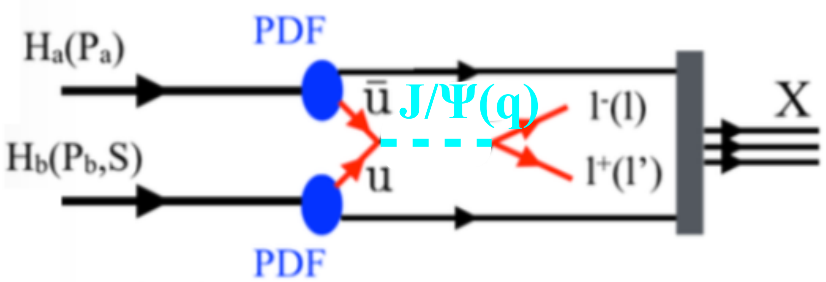
- J/Ψ coupling strength unknown

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

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

J/Ψ: $J^P = 1^{-1}$





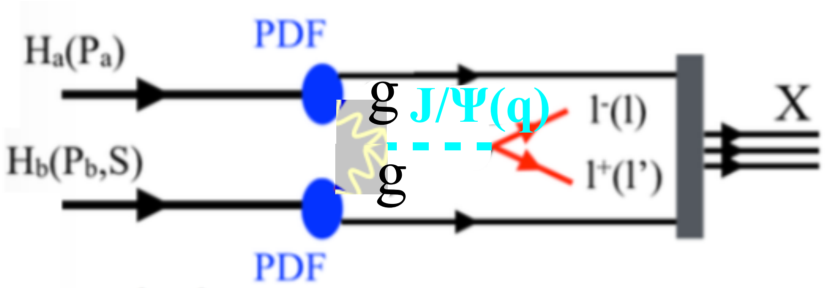
Same cross-section but new coupling strength & propagator

$$\begin{array}{ccc} \text{Drell–Yan Production} & & J/\Psi \text{ Production} \\ 16\pi^2\alpha^2 e_q^2 & \rightarrow & (g_q^{J/\Psi})^2 (g_l^{J/\Psi})^2 \\ \frac{1}{M^4} & \rightarrow & \frac{1}{(M^2 - M_{J/\Psi}^2)^2 + M_{J/\Psi}^2 \Gamma_{J/\Psi}^2} \end{array}$$

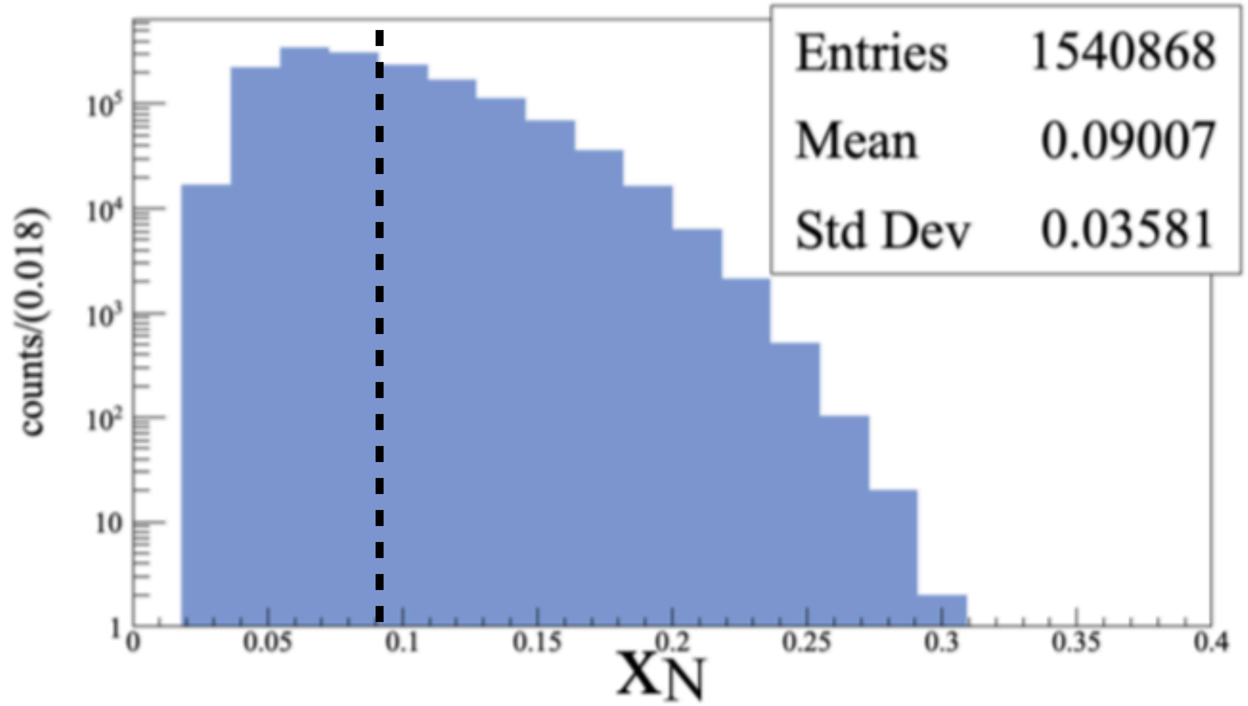
- Asymmetry is independent of coupling strength/propagator

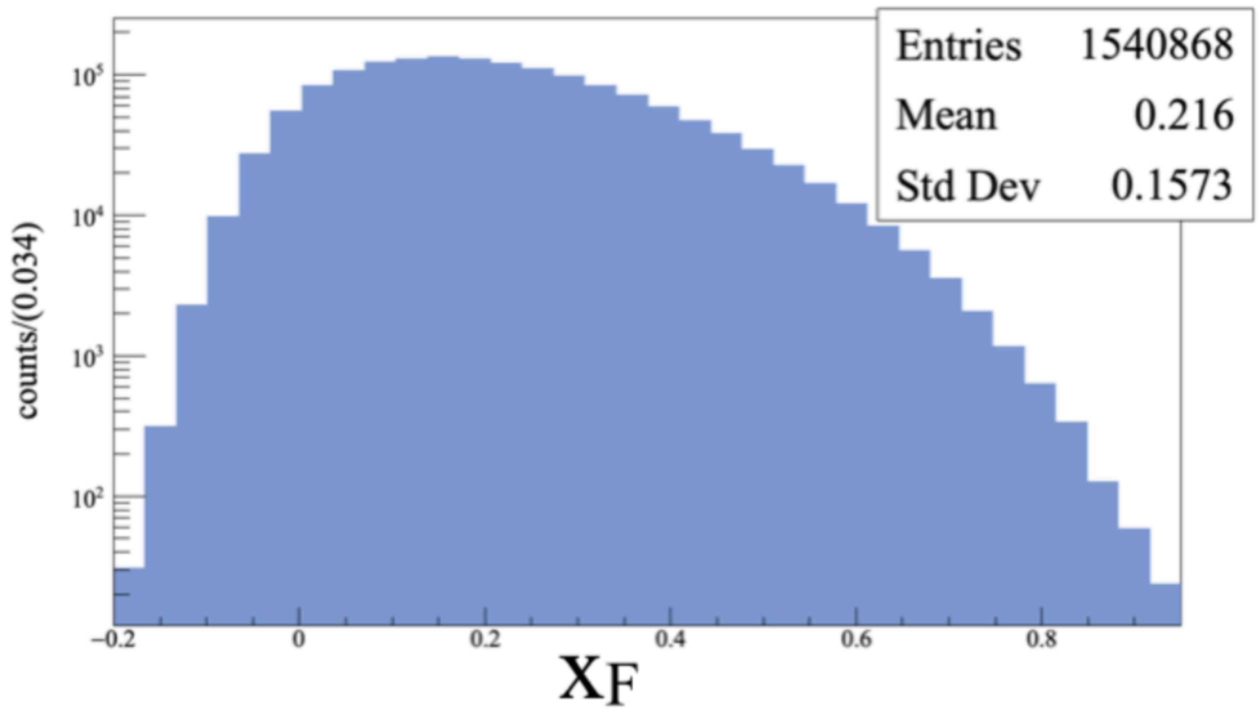
$$A_{lr} = \frac{1}{|S_T|} \frac{\sigma_{left} - \sigma_{right}}{\sigma_{left} + \sigma_{right}}$$

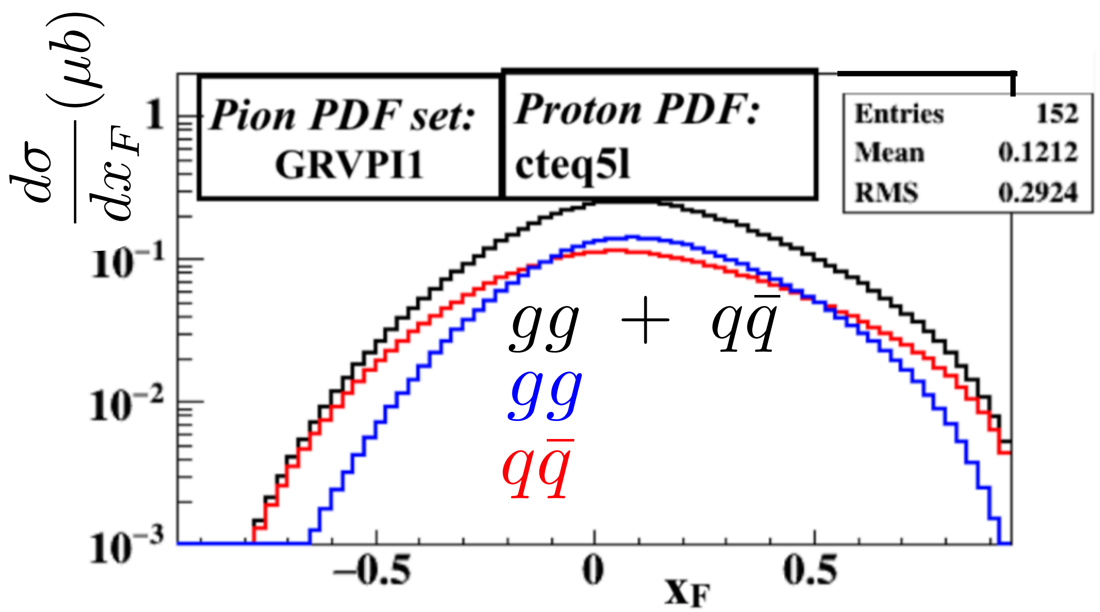
- J/Ψ Sivers effect diluted by gluon fusion



JPsi Kinematic Variables







- Dilutions determined using weighted average of the COMPASS x_F distribution

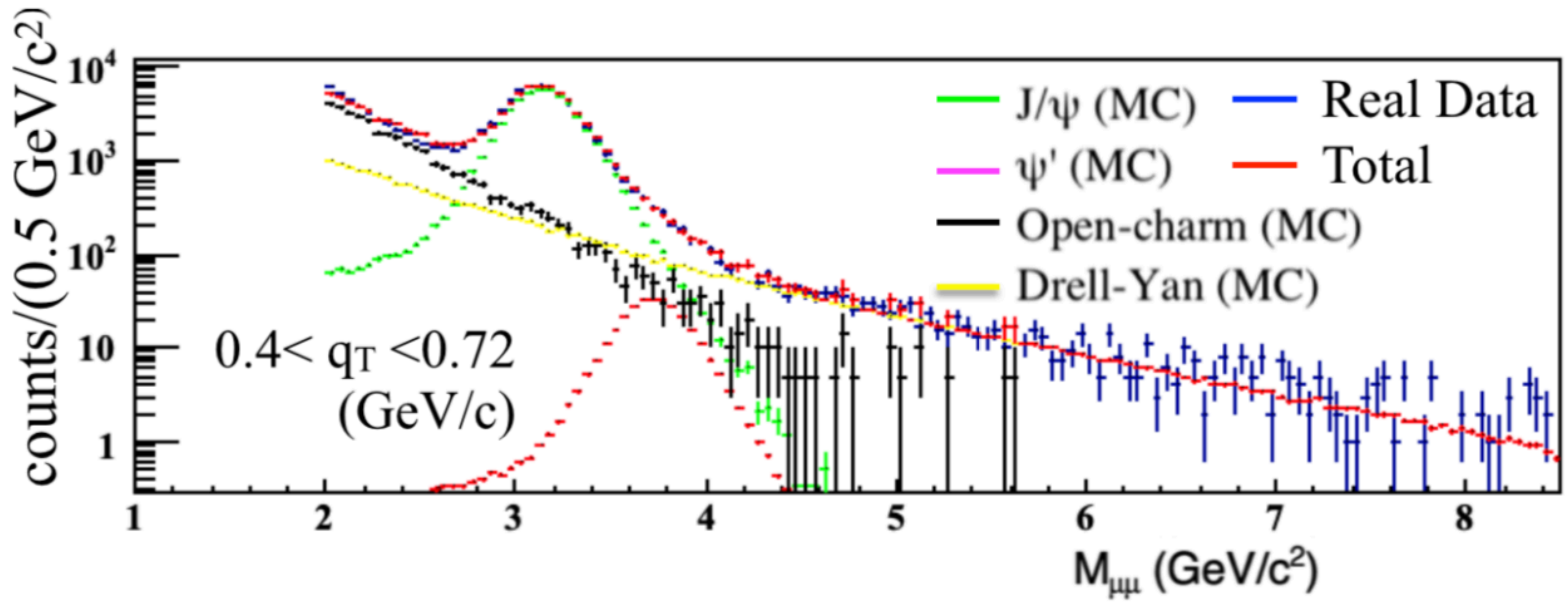
	SMRS	OW	GRV	ABFKW
Dilution $q\bar{q}$/**gg**	0.96	0.58	0.80	0.72

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

JPsi Purity

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

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

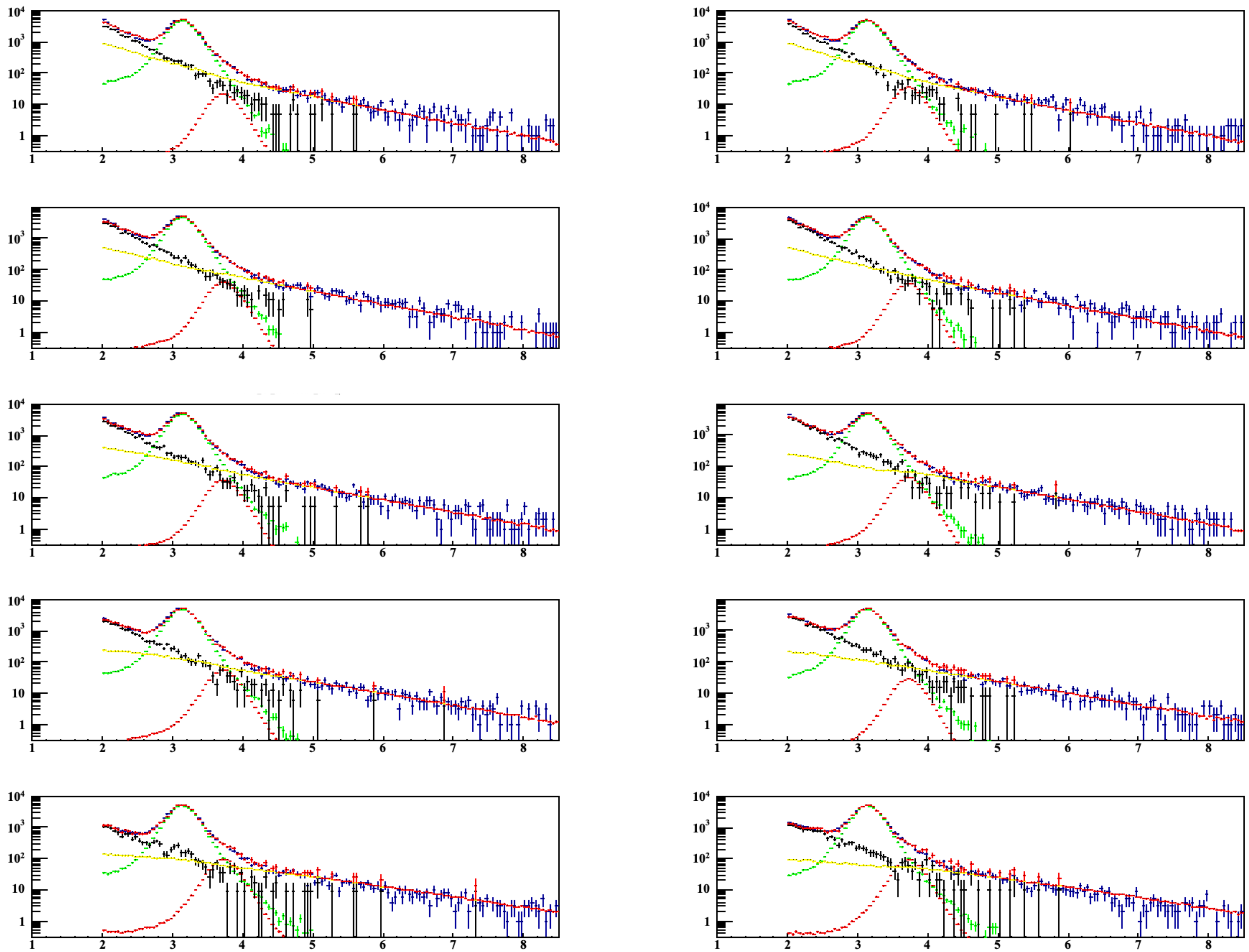


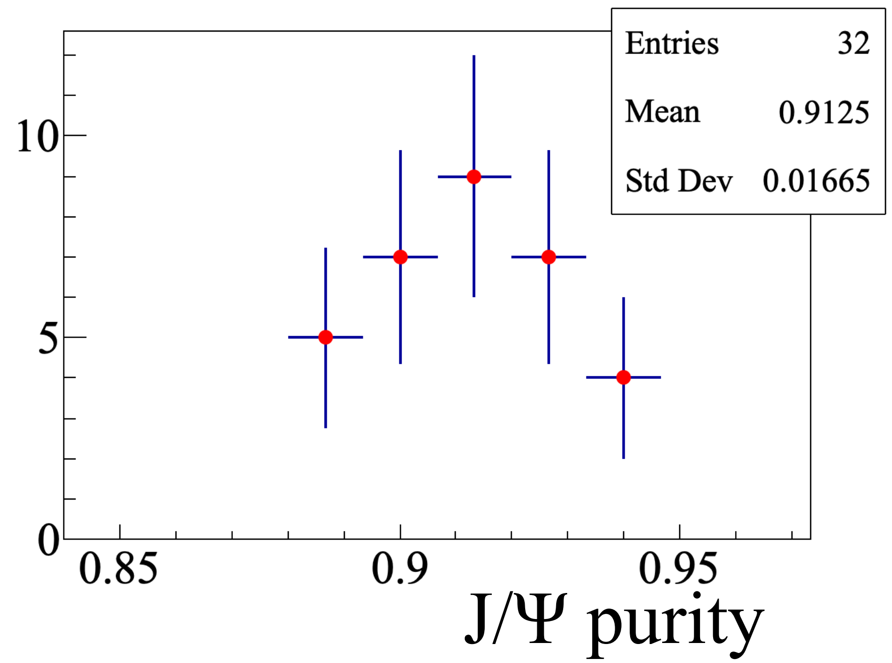
- Monte-Carlo sample used to get invariant mass distribution

JPsi Purity

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

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





JPsi Purity

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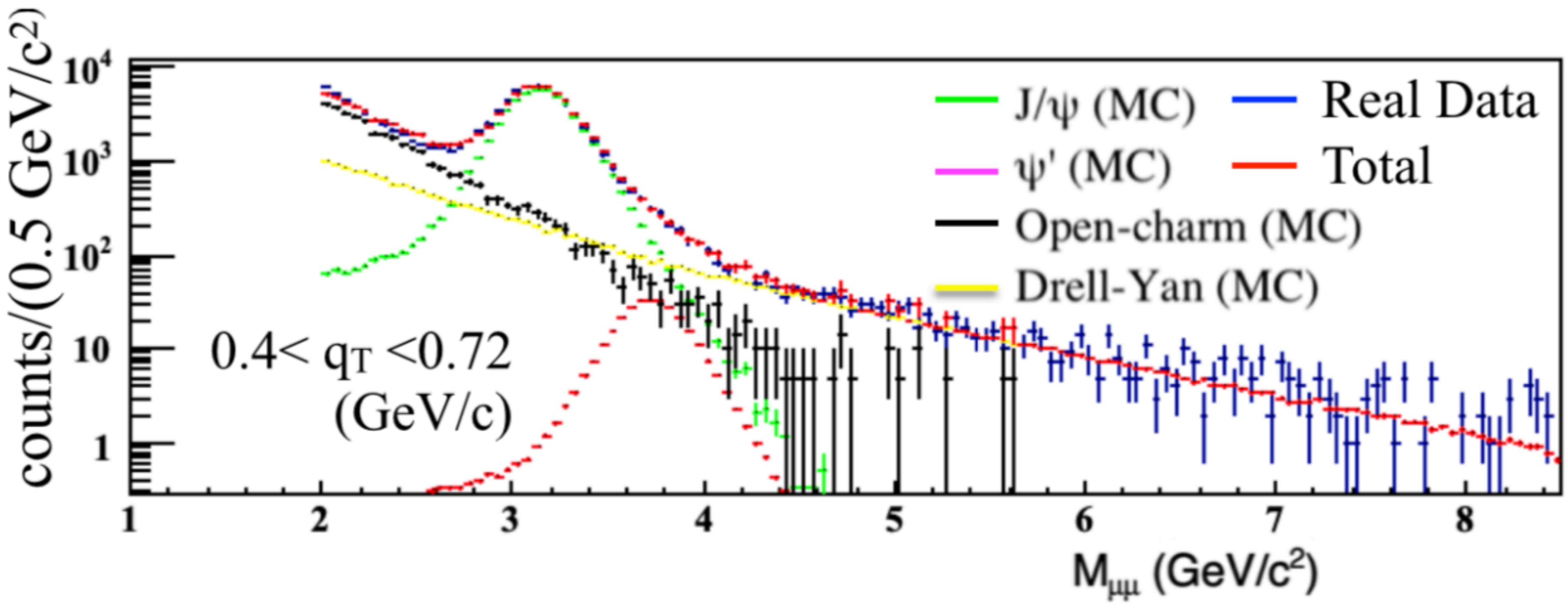


Mass range GeV/c^2	J/Ψ Purity %
2.5-4.3	79.7 ± 2.9
2.78-3.46	88.9 ± 2.0
2.87-3.38	**91.3 ± 1.5**
2.95-3.29	92.9 ± 1.0
3.08-3.17	94.0 ± 1.0

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

JPsi Purity

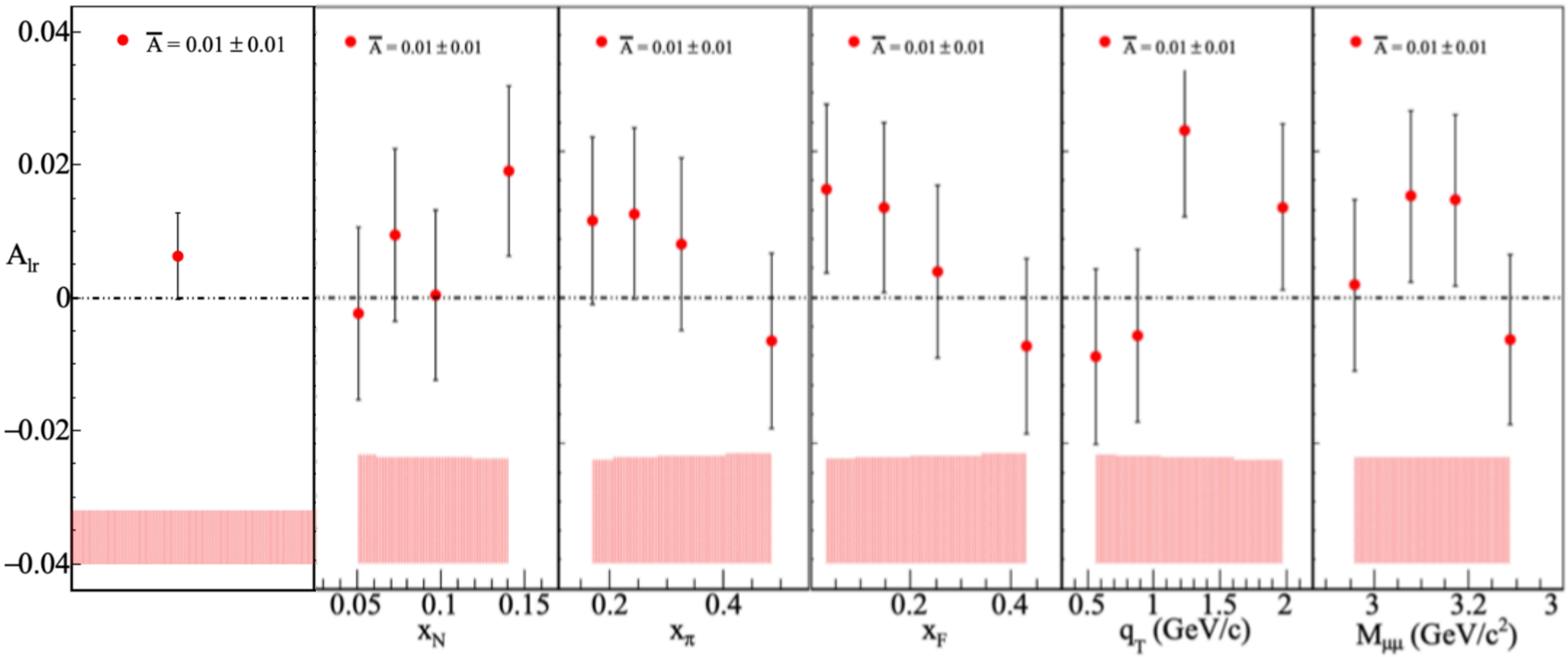
$$\frac{\sigma_{systematic}}{\sigma_{statistical}} = \frac{(1-p)}{p}$$

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**

3.08-3.17	94.0 ± 1.0

JPsi Results



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

Conclusion

- The COMPASS spectrometer recorded data from oppositely di-muon events resulting from pions on a transversely polarized NH_3 target

- The UIUC group (in collaboration with out institutes) built Drift Chamber 05 which is an important component for track reconstruction

- The alignment of the COMPASS spectrometer is critical for data reconstruction

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

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

Backup

Planned Outline

Theory (7) Proton structure, SIDIS, DY

COMPASS (5)
Experimental setup, target (absorber),

DC05 (7)
Motivation, construction, calibration, performance

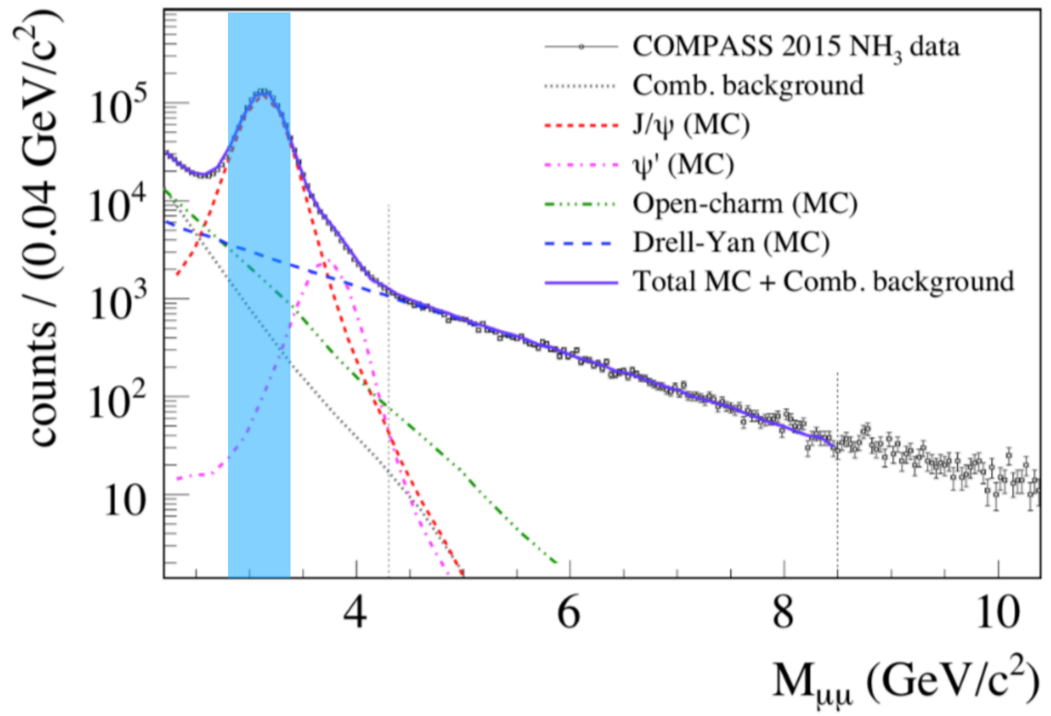
Alignment (5)

HM analysis (10)
x-section (1), distributions (2), left/right asymmetry (1), l/r systematics (1), l/r results (1), standard analysis sign flip (1)

JPsi (5)

Conclusion (1)

J/Ψ Production



Oppositely charge di-muon events:

37,921 high mass [4.3-8.5 GeV/c²]

1,540,868 JPsi mass [2.87-3.38 GeV/c²]

Statistical gain: JPsi mass vs. high mass

40x more events

$\sim \frac{1}{\sqrt{N}}$ Asymmetry uncertainty

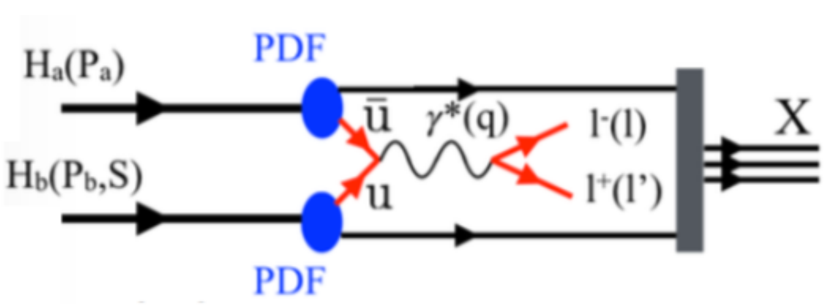
=> 6.4x statistical error reduction

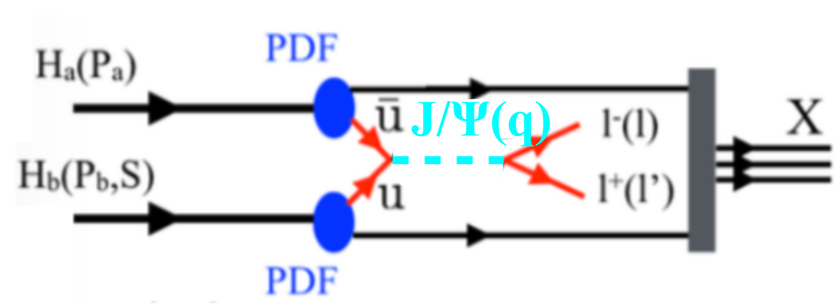
- J/Ψ coupling strength unknown

Quantum numbers (J^P)

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

J/Ψ: $J^P = 1^{-1}$





- Asymmetry is independent of coupling strength/propagator

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