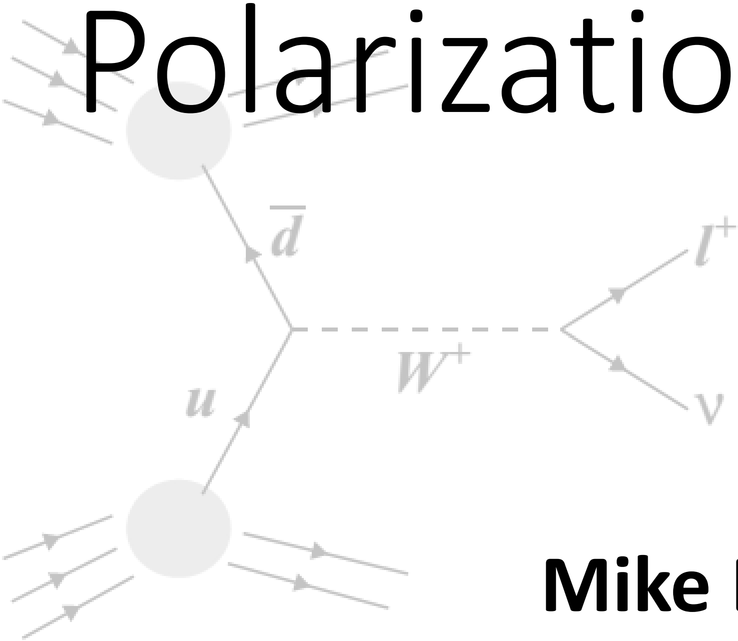
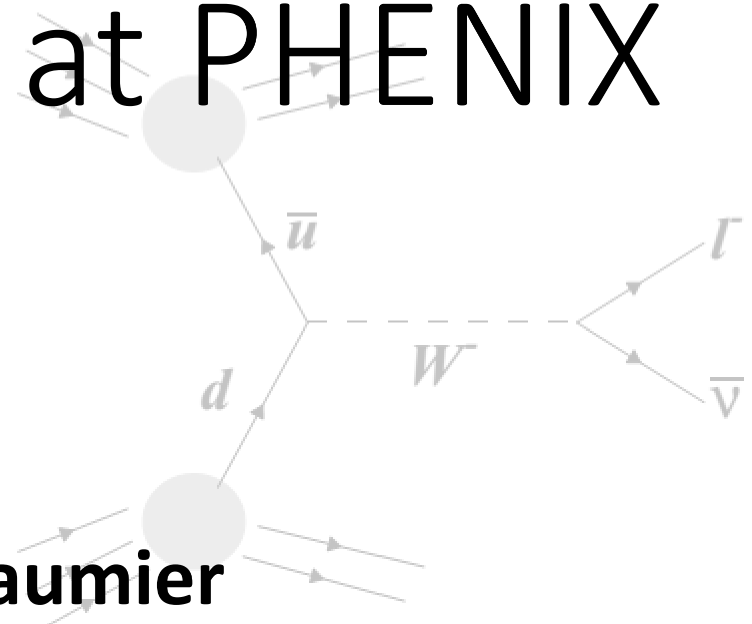
Probing Sea Quark Polarization at PHENIX





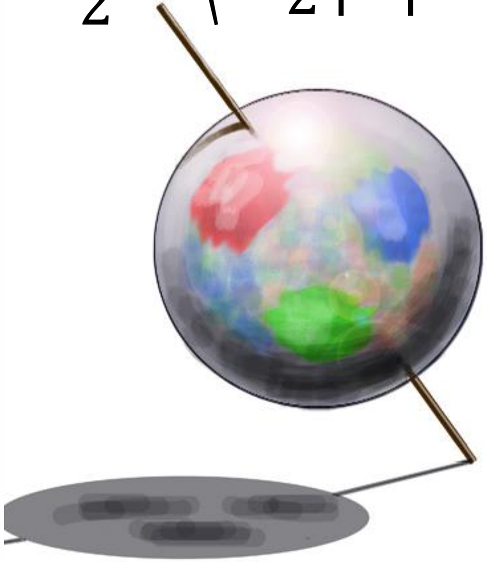
Mike Beaumier

UC RIVERSIDE
UNIVERSITY OF CALIFORNIA

PHENIX

Proton Spin Structure

$$\frac{1}{2} = \left\langle P, \frac{1}{2} \middle| \hat{J_z} \middle| P, \frac{1}{2} \right\rangle$$



Studied for over 20 years – we're still working to understand substructure contribution to "1/2"

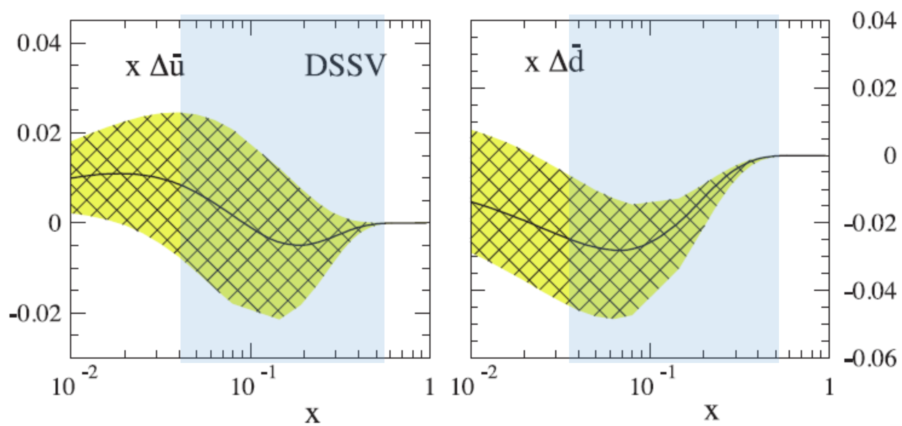
$$\frac{1}{2} = \underbrace{\Delta\Sigma}_{} + \Delta L_q + J_g$$

$$\Delta\Sigma = (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s})$$

Large Uncertainty In Sea Quark Polarization

Quark Polarization measured to be ~30% of Proton Spin at DIS

Semi-inclusive deep inelastic scattering constrains P.D.F.s – they are limited by large uncertainties from dealing with fragmentation functions

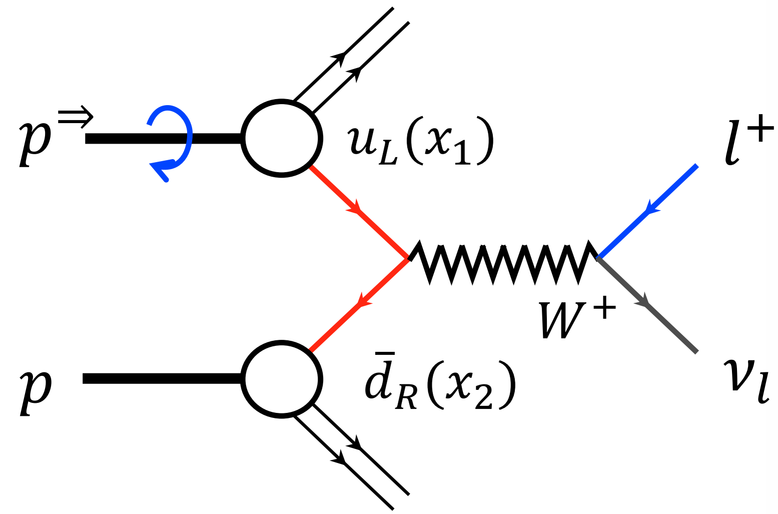


Spin dependent PDF's for $\bar{u}$, $\bar{d}$ from DSSV global fit

PHENIX rapidity sensitivity range

Probing Sea Quark Polarization

$$\boldsymbol{p + p^{\Rightarrow} \rightarrow W^+ \rightarrow l^+ + \nu_l}$$



- W bosons couple to:
  - Left Handed Particles
  - Right Handed Antiparticles
- For $y_l \ll 0$ and $y_l \gg 0$ W charge fixes parent quark flavor

$$\bar{d} + u \rightarrow W^+ \rightarrow \mu^+ + \nu_l$$
$$\bar{u} + d \rightarrow W^- \rightarrow \mu^- + \bar{\nu_l}$$

$$A_L^{W\rightarrow\mu} = \frac{d\sigma^{\Rightarrow} - d\sigma^{\Leftarrow}}{d\sigma^{\Rightarrow} + \mathrm{d}\sigma^{\Leftarrow}}$$

$$A_L^{W^-\rightarrow\mu^-} \frac{\Delta\bar{u}(x_1)}{u(x_1)}, y_L \gg 0$$

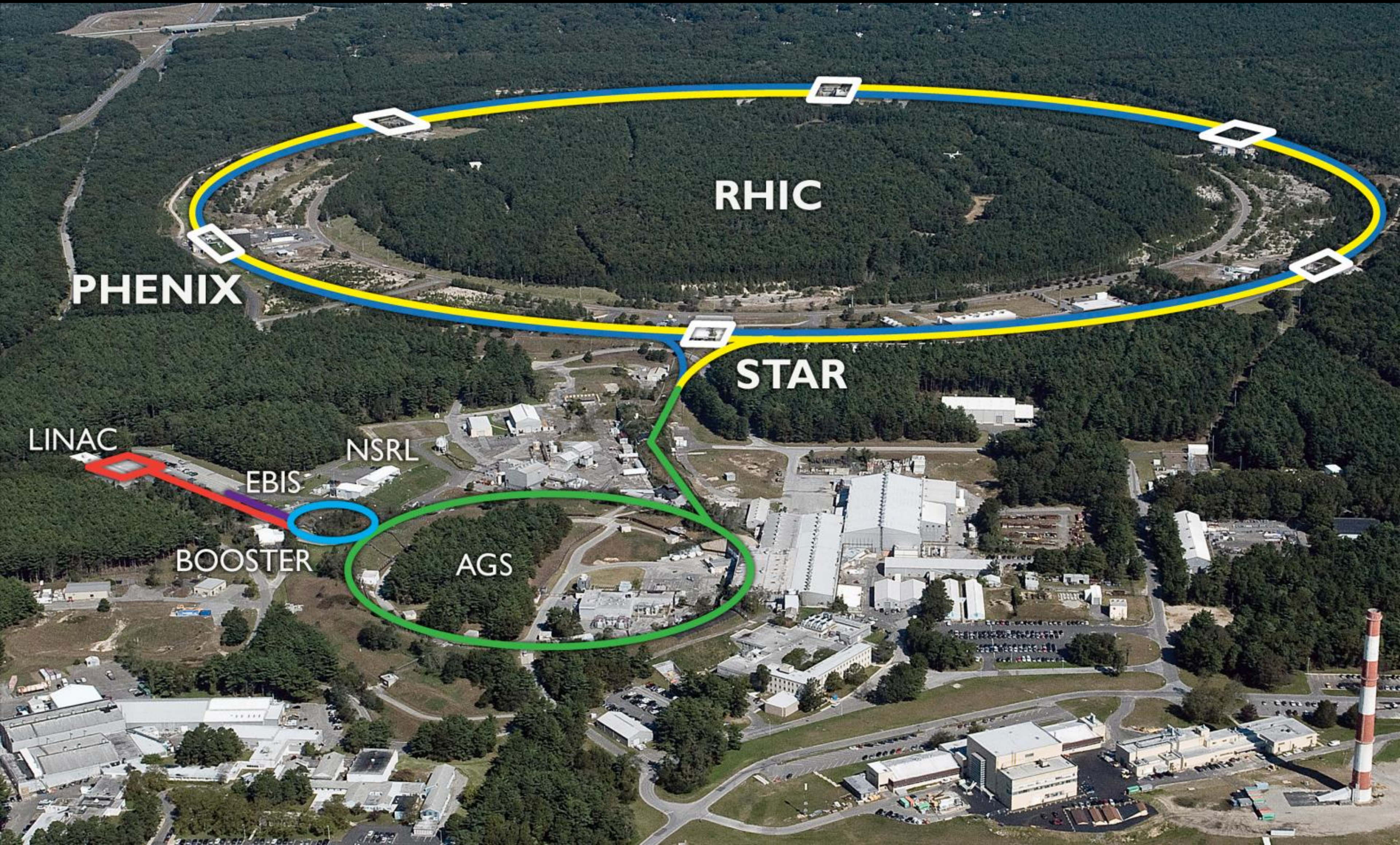
$$A_L^{W^+\rightarrow\mu^+} \frac{\Delta\bar{d}(x_1)}{d(x_1)}, y_L \ll 0$$

Observable: Count of μ's from W decay for different proton helicity configurations

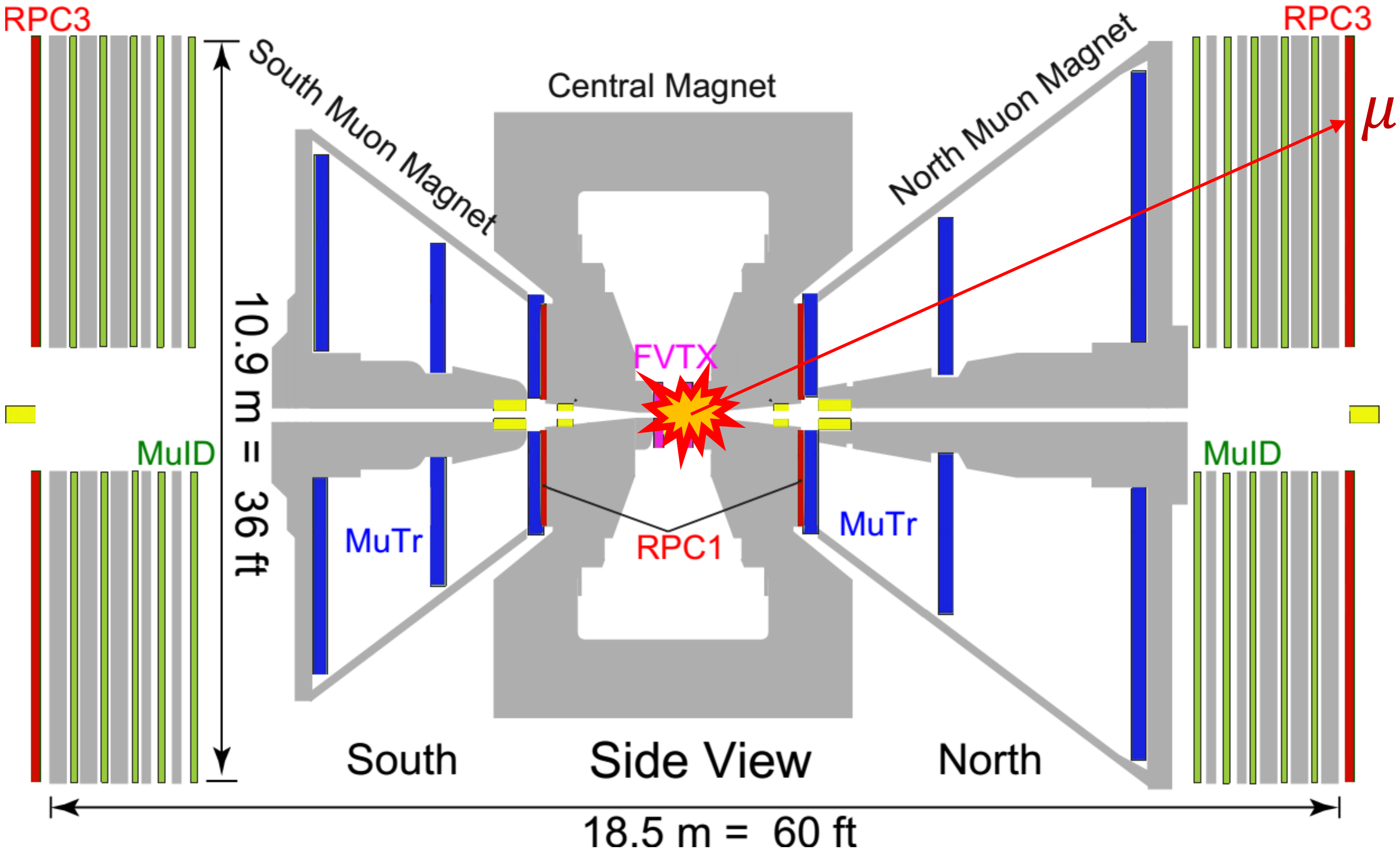
$$\boldsymbol{A_L^+ = \frac{1}{P} \times \frac{N(W^+)^{p^{\Leftarrow}} - N(W^+)^{p^{\Rightarrow}}}{N(W^+)^{p^{\Leftarrow}} + N(W^+)^{p^{\Rightarrow}}}}$$

2013-10-19

W Physics Program at RHIC



PHENIX Muon Arms: $W \to \mu$



Acceptance

1.2 < $|\eta| < 2.4$ North

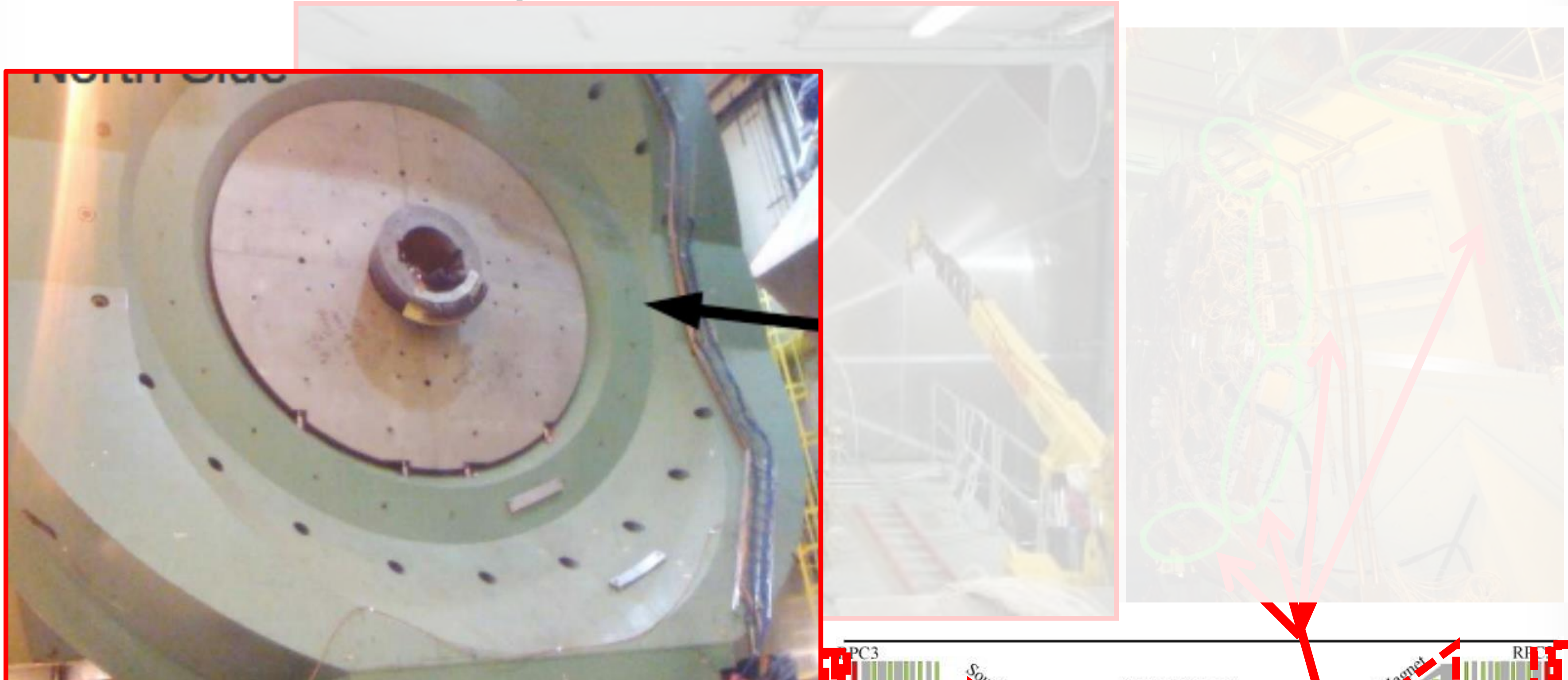
1.2 < $|\eta| < 2.2$ South

$\Delta\phi = 2\pi$

Subsystems

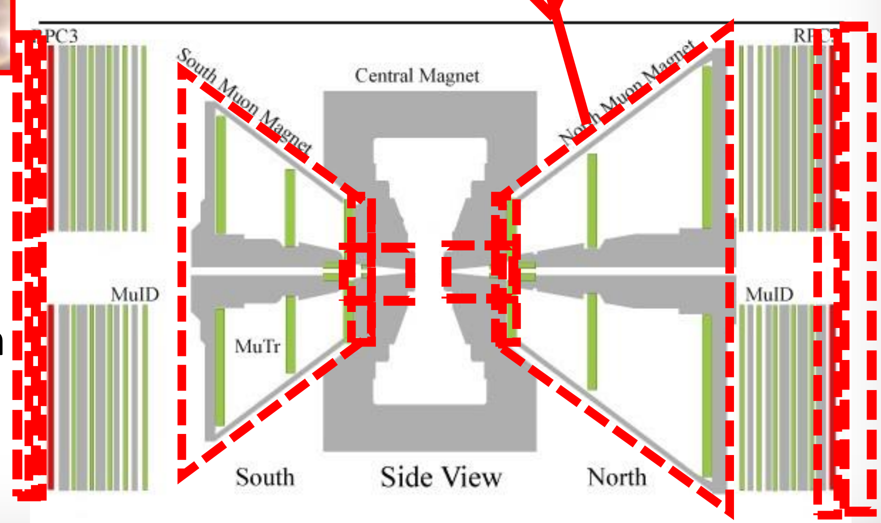
- **Muon Tracker (MuTr)** – Momentum Selection
- **Muon Identifier** – Particle ID
- **Resistive Plate Chambers (RPC)** - Timing
- **Forward Silicon Vertex Detector (FVTX)** – secondary vertex and hadron rejection

Forward W Physics With The Muon Arms

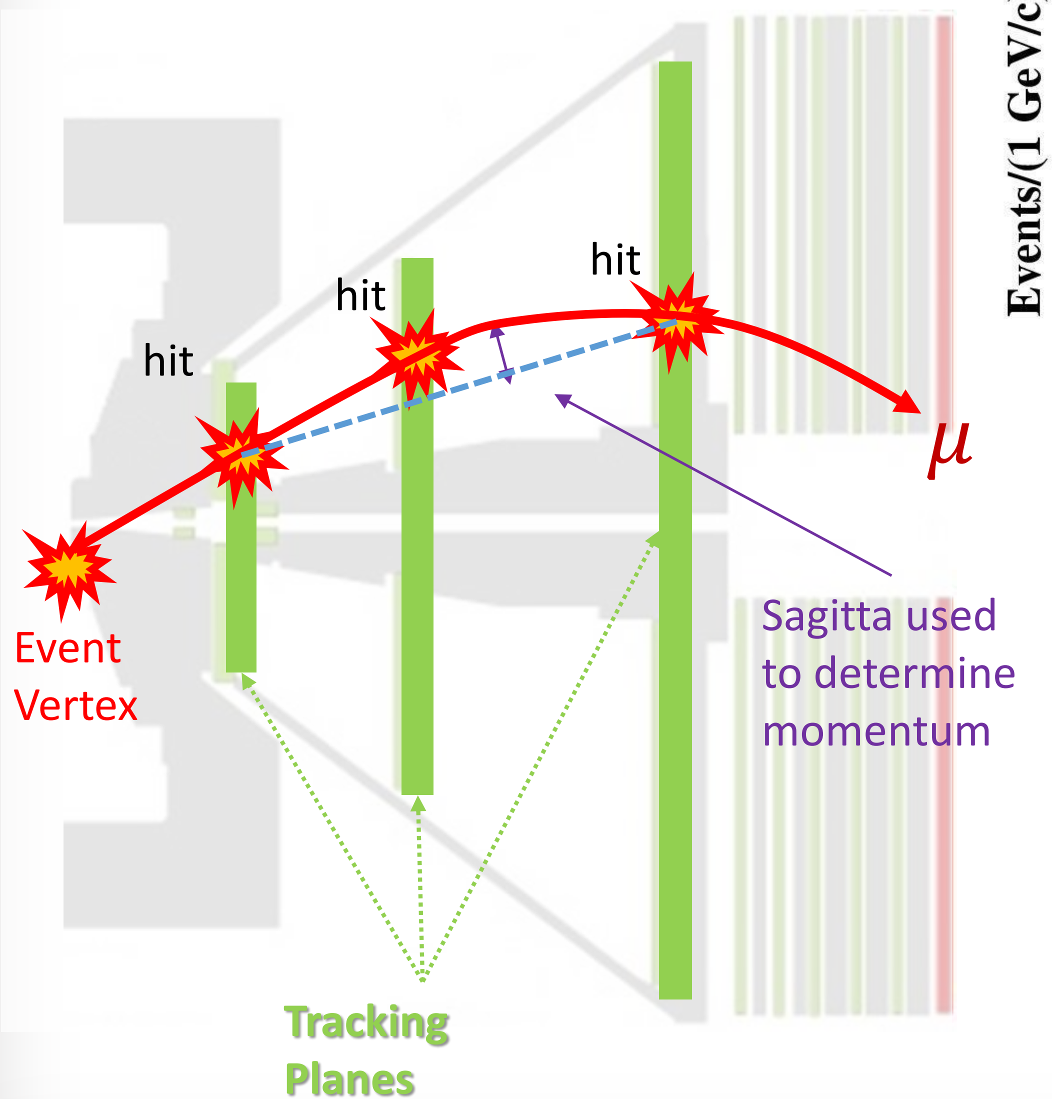


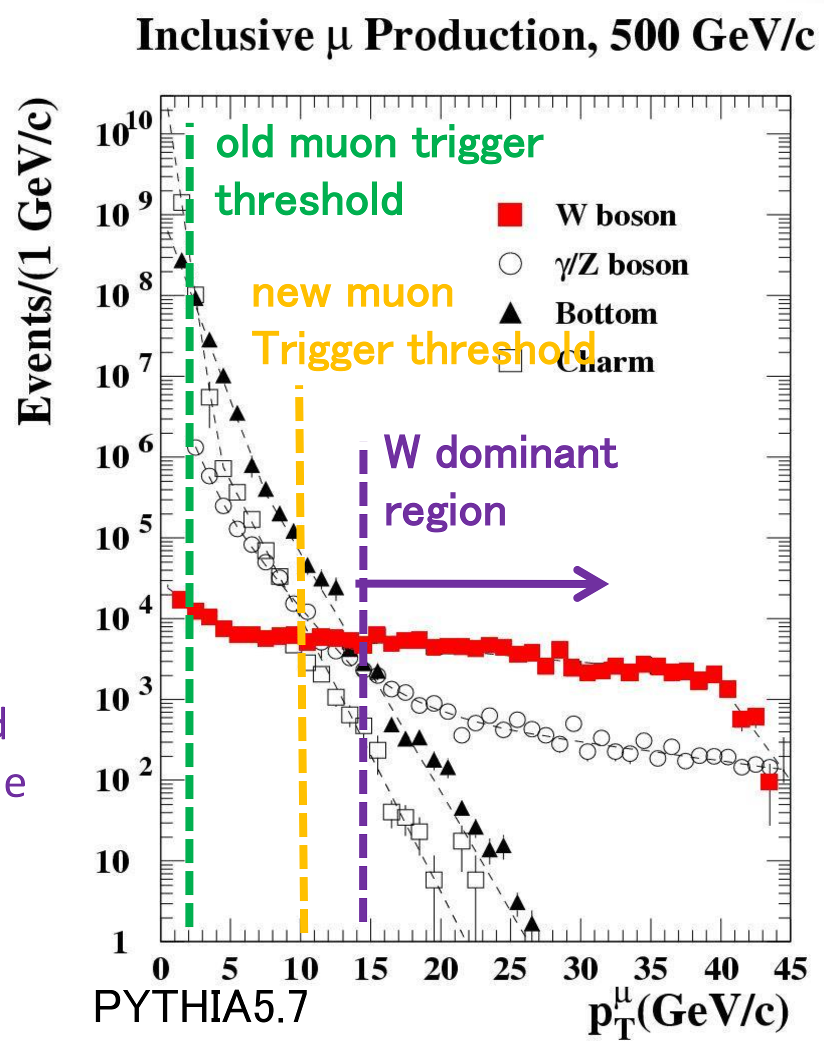
Upgrades required to properly trigger on $W \rightarrow \mu$ events:

- An electronics upgrade in the MuTr to allow for momentum-triggering
- The addition of RPCs for background rejection and timing improvements
- The addition of steel shielding to reduce Hadronic background and beam background



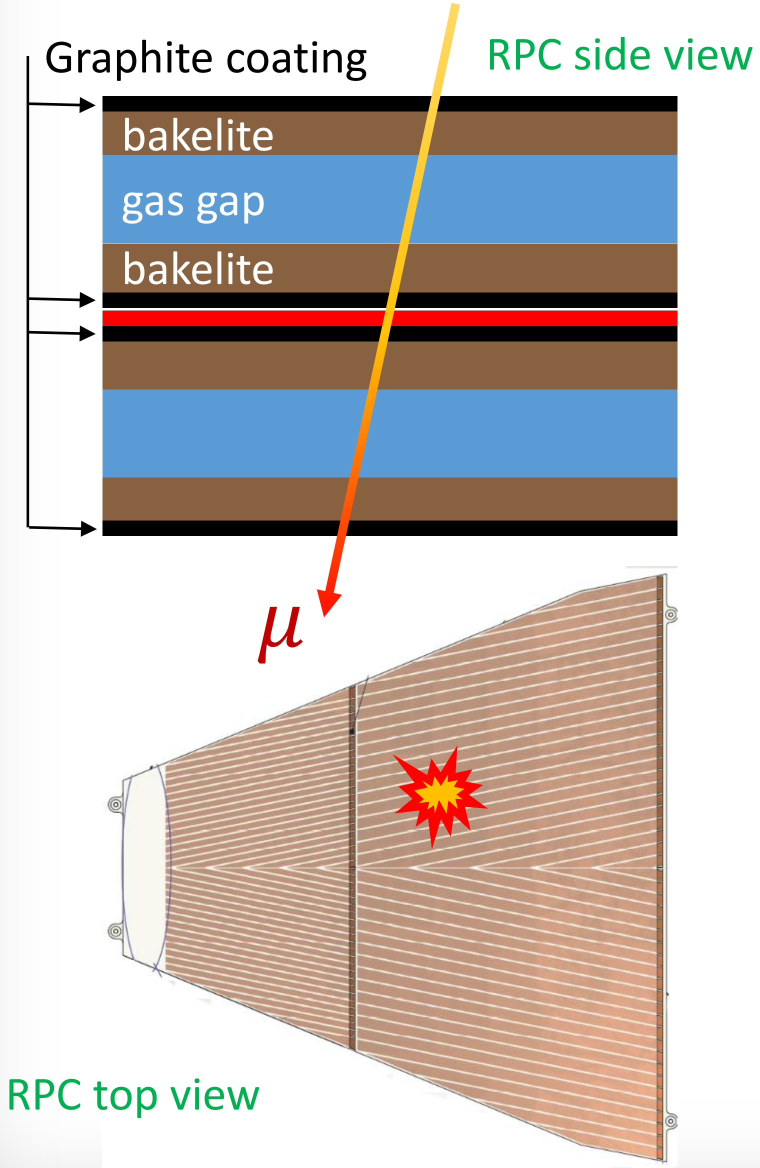
MuTr Upgrade





We can record ALL $W \rightarrow \mu$ event without pre-scaling recorded events

RPC Anatomy

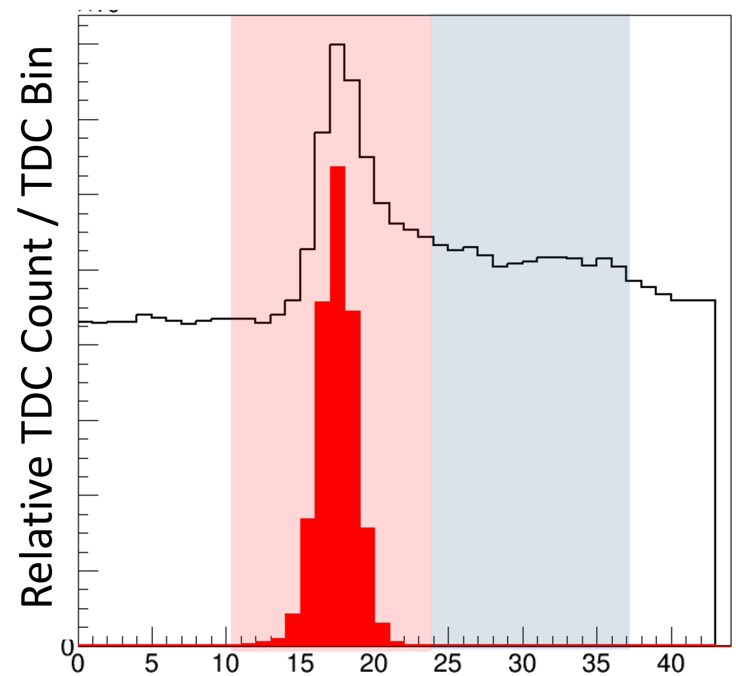


- A passing muon **ionizes the gas** in the **Bakelite gaps**
- Charge Distribution Induced on gaps from applied bias
- Image distributions induced on **copper strips** & read out
- Timing from RPC hit combined with sagitta information from MuTr for new muon trigger
- RPCs also provide azimuthal information

RPC Timing Performance

- Fast timing from RPC TDCs allow for:
  - Sub-beam clock timing resolution
  - Correlation of MuTr Track with crossing pair
  - Distinguishing a Muon Track from beam backgrounds

RPC Timing Resolution

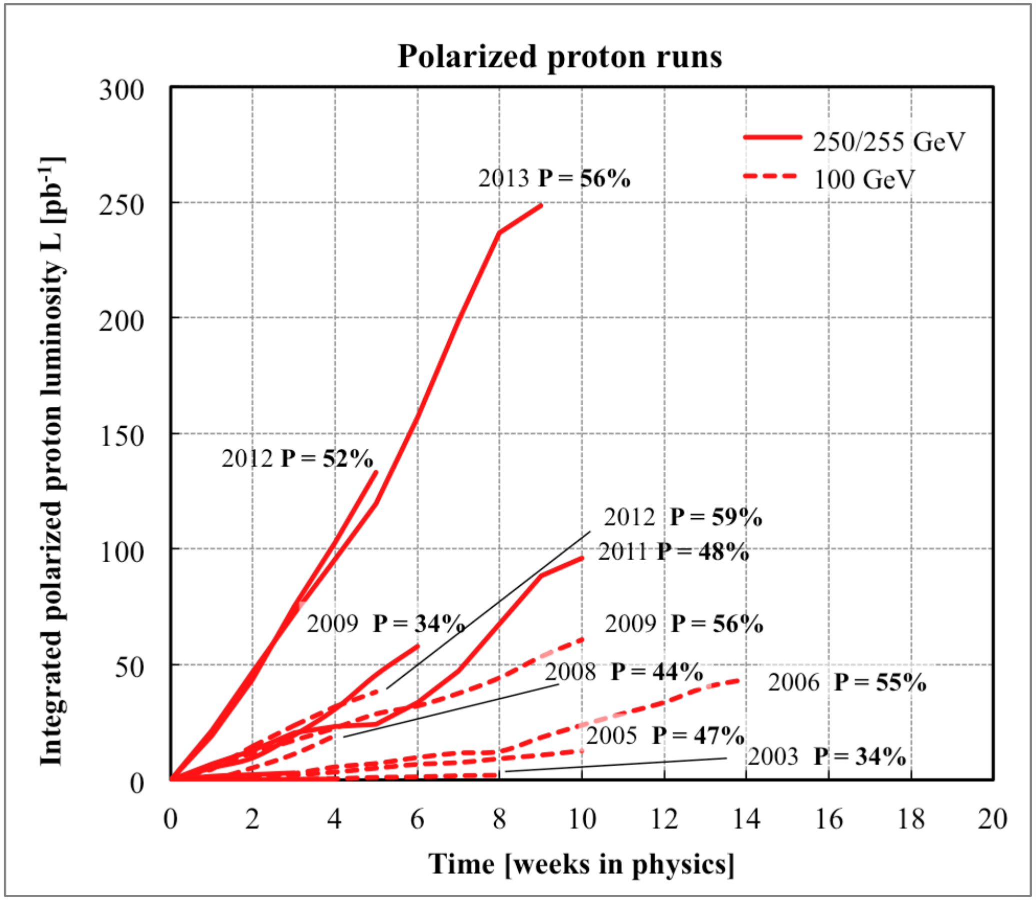


TDC Count – subdividing one beam clock
(1 TDC Count = 106 ns / 44)

TDC Track Matched Region
Incoming Beam Background Timing Region

Summary And Outlook

- Upgrades allow us to capture all $\boldsymbol{W} \rightarrow \boldsymbol{\mu}$ events
- We have about 350 pb^{-1} integrated luminosity from 2012 and 2013
- New statistical analysis methods have been implemented to extract $\boldsymbol{W} \rightarrow \boldsymbol{\mu}$ events
- See Daniel's Talk!



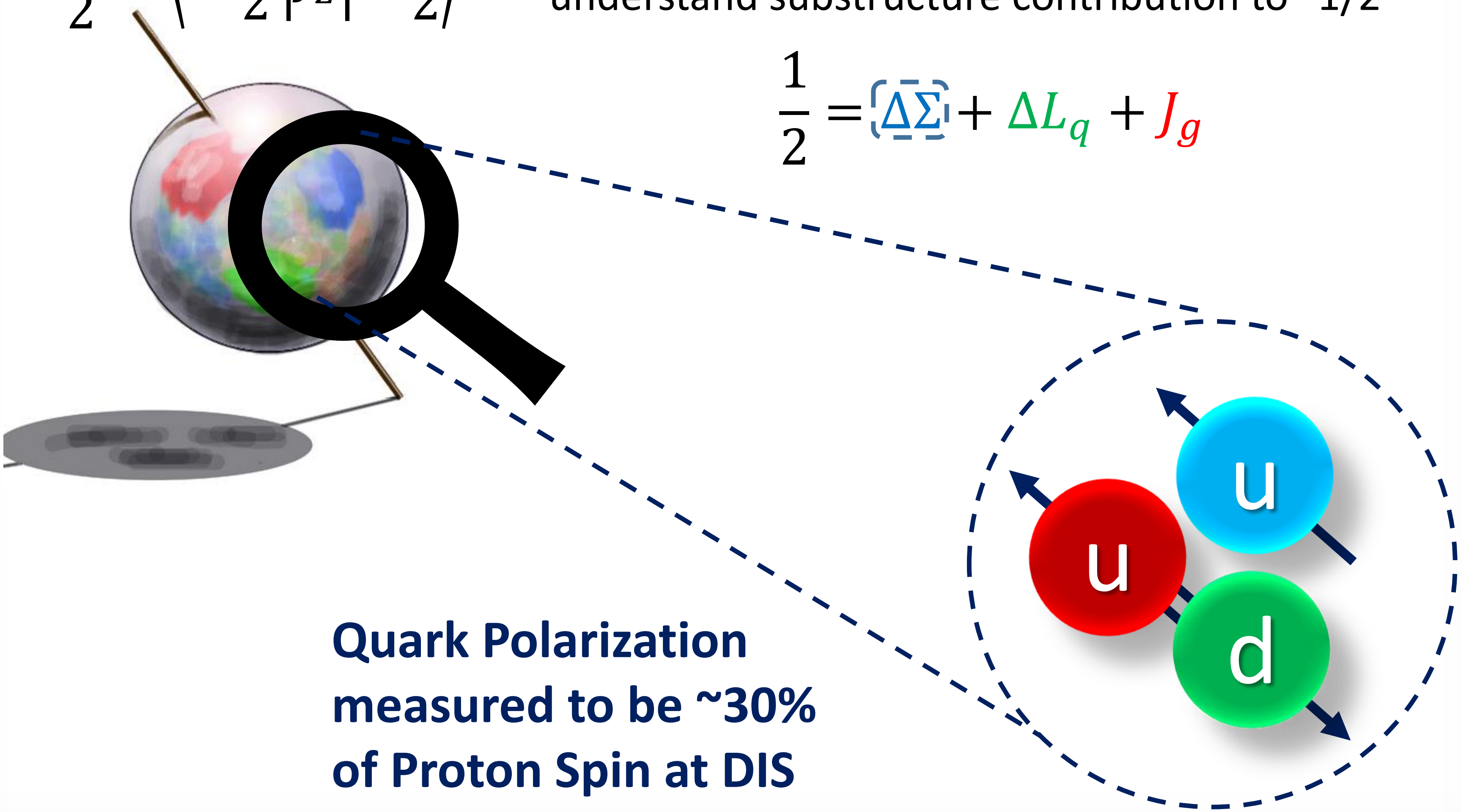
Backup

Proton Spin Structure

$$\frac{1}{2} = \left\langle P, \frac{1}{2} \middle| \widehat{J_z} \middle| P, \frac{1}{2} \right\rangle$$

Studied for over 20 years – we're still working to understand substructure contribution to "1/2"

$$\frac{1}{2} = \boxed{\Delta\Sigma} + \Delta L_q + J_g$$



Quark Polarization measured to be ~30% of Proton Spin at DIS

Longitudinal Asymmetries

$$A_L^{l+}(y_l) = \frac{-\Delta u(x_1)\bar{d}(x_2)\left(1-\cos\hat{\theta}\right)^2 + \Delta\bar{d}(x_1)u(x_2)\left(1+\cos\hat{\theta}\right)^2}{u(x_1)\bar{d}(x_2)\left(1-\cos\hat{\theta}\right)^2 + \bar{d}(x_1)u(x_2)\left(1+\cos\hat{\theta}\right)^2}$$

$$A_L^{l-}(y_l) = \frac{-\Delta\bar{u}(x_1)d(x_2)\left(1-\cos\hat{\theta}\right)^2 + \Delta d(x_1)\bar{u}(x_2)\left(1+\cos\hat{\theta}\right)^2}{\bar{u}(x_1)d(x_2)\left(1-\cos\hat{\theta}\right)^2 + d(x_1)\bar{u}(x_2)\left(1+\cos\hat{\theta}\right)^2}$$

Asymmetries in terms of quark helicity distribution functions

$$A_L(\eta_\mu) = \frac{d\sigma^{\Rightarrow} - d\sigma^{\Leftarrow}}{d\sigma^{\Rightarrow} + \mathrm{d}\sigma^{\Leftarrow}}$$

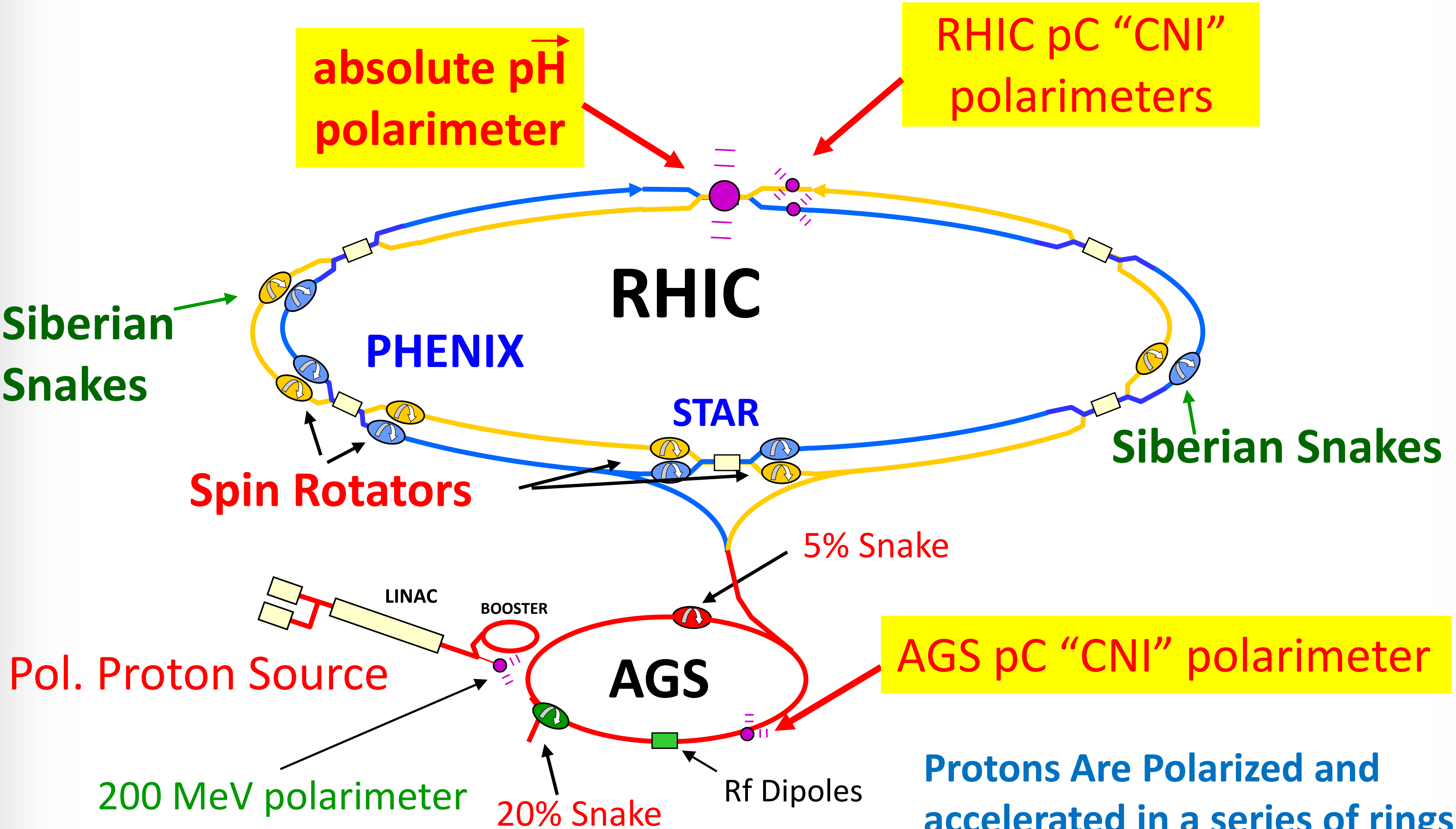
Measured Asymmetry in terms of cross sections for $W \rightarrow \mu$

$$A_{LL}(\eta_\mu) = \left.\frac{d\sigma^{\Rightarrow\Rightarrow} - d\sigma^{\Leftarrow\Rightarrow}}{d\sigma^{\Rightarrow\Rightarrow} + d\sigma^{\Leftarrow\Rightarrow}}\right|_{\eta_\mu}$$

Double spin asymmetry

We build our Asymmetry by counting the number of $W \rightarrow \mu$ events for each arm and charge, and **forming raw asymmetries**, and accommodating any **dilution from the Muon background and the polarization of the beams**

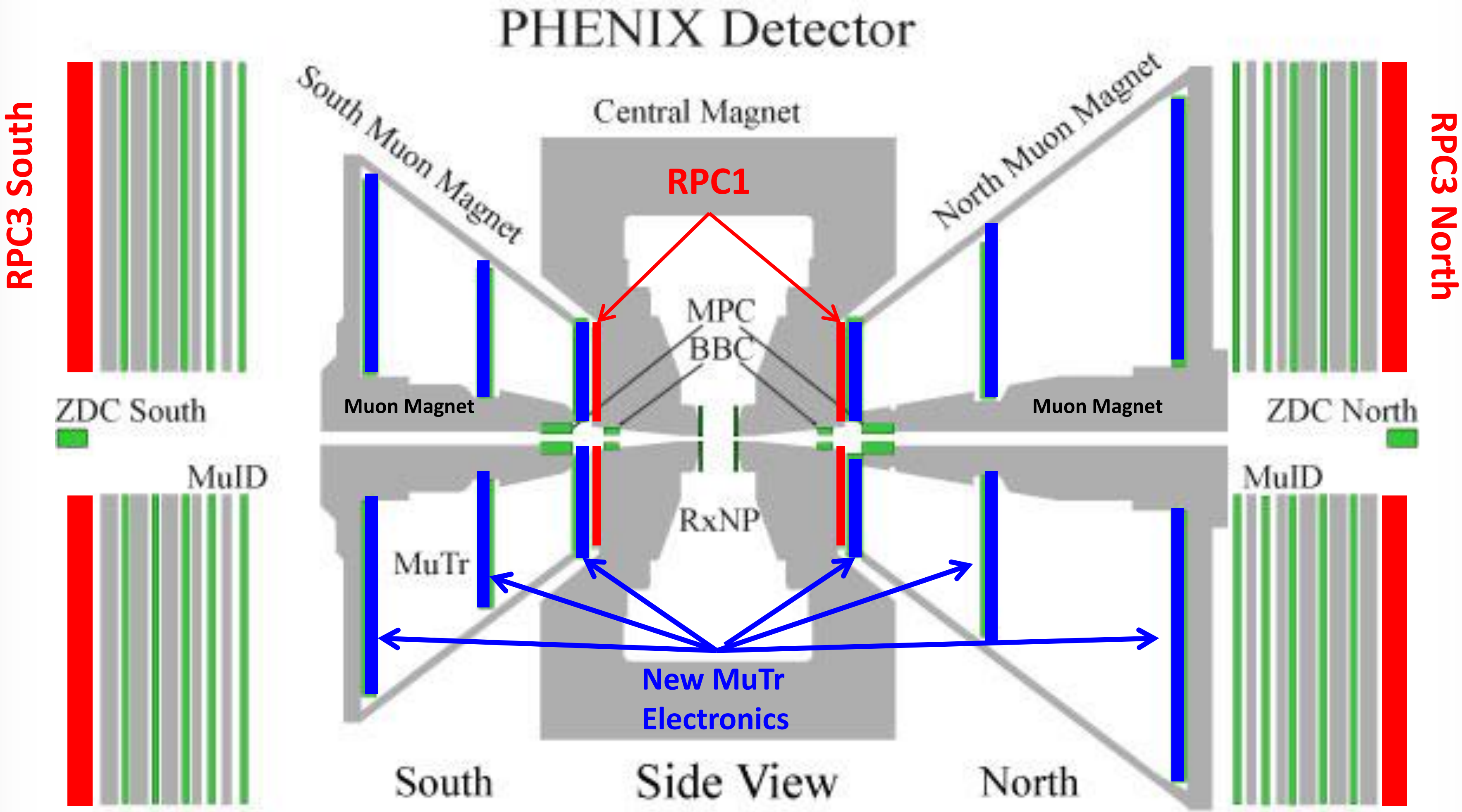
RHIC – Schematic Overview



Protons Are Polarized and accelerated in a series of rings. Polarization typically 55% for 2013 Run, with $\sqrt{s} = 510\ GeV$

Schematic Courtesy of Kiyoshi Tanida

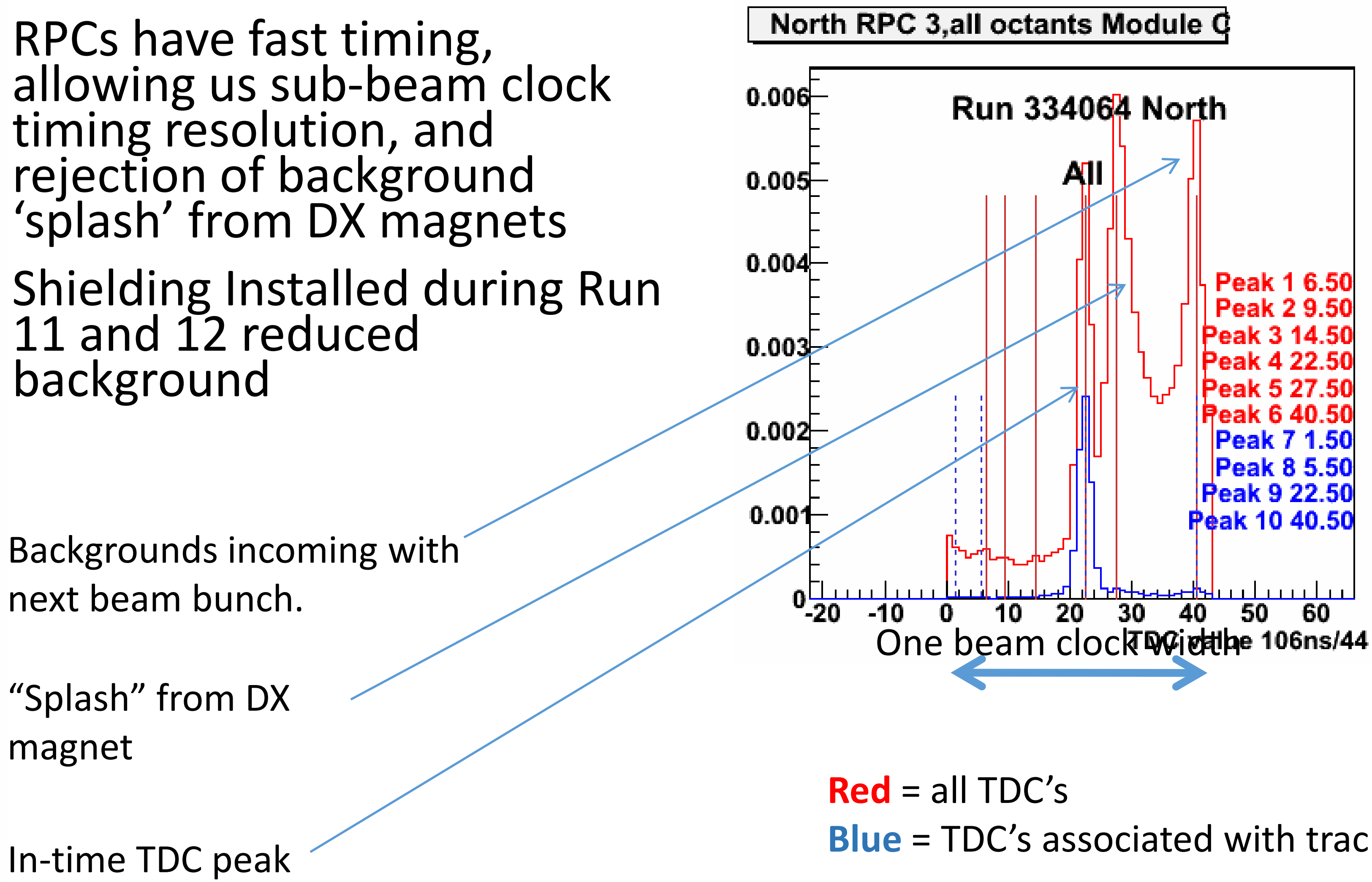
W Detection Summary



1) Muon Tracker (MuTr): Fast Electronics, Slow Muon Triggering
2) Resistive Plate Chambers (RPCs) 1&3 + MuTr: High pT muons, fast triggering

RPCs – Run 12 Pre Shielding

- RPCs have fast timing, allowing us sub-beam clock timing resolution, and rejection of background 'splash' from DX magnets
- Shielding Installed during Run 11 and 12 reduced background



Red = all TDC's
Blue = TDC's associated with tracks

Analysis Overview

Phase 1

- Pass over the Run 13 data and Monte Carlo $W \rightarrow \mu$ simulation, selecting kinematic variables which offer discriminating power between $W \rightarrow \mu$ events, $X \rightarrow \mu_{\mathrm{fake}}$ background events

Phase 2

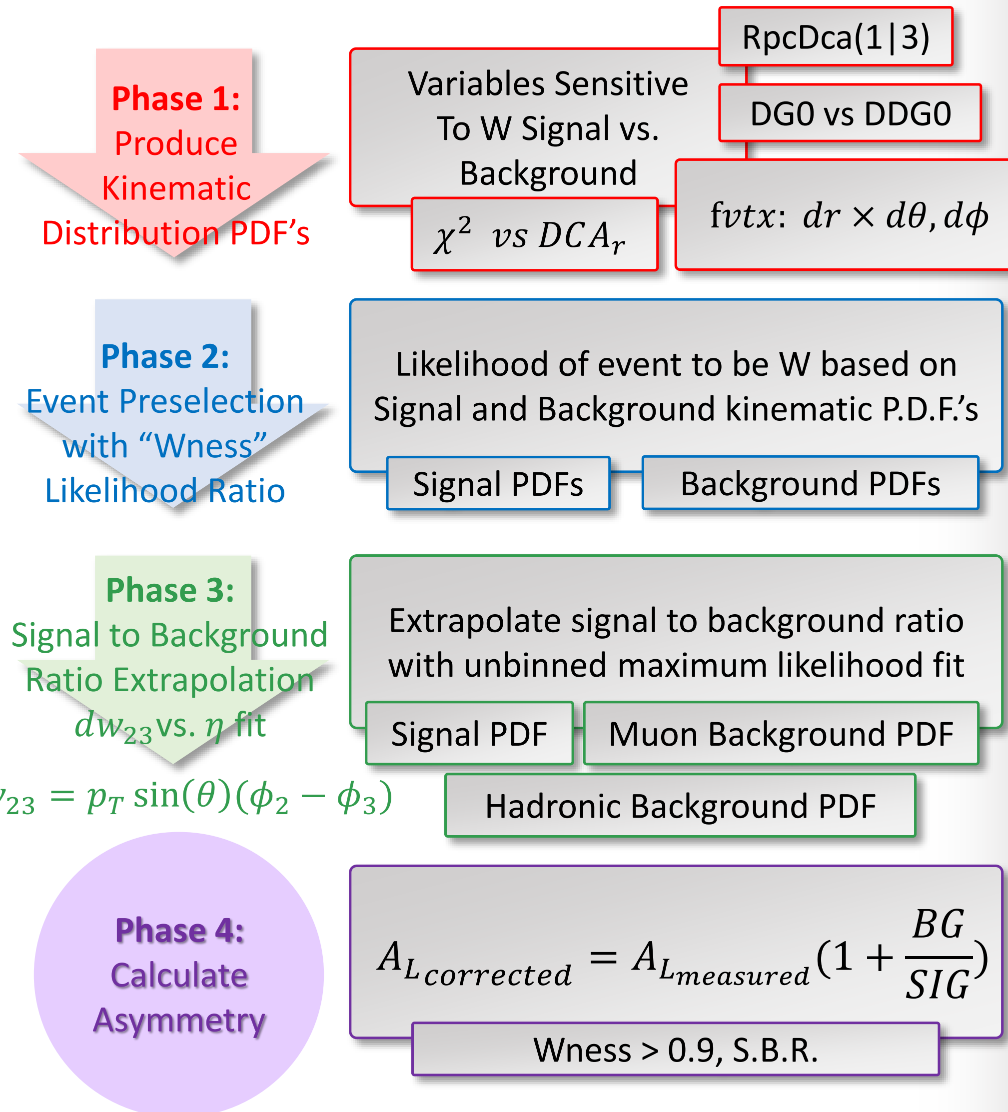
- Use the discriminating kinematic variables to create Probability Density Functions, which can assign a $W \rightarrow \mu$ likelihood (Wness) to each μ track in the Run 13 Data.

Phase 3

- Perform an unbinned maximum likelihood fit on the data, to extract the signal to background ratio, using Muonic background simulation, W simulation, and data

Phase 4

- Calculate A_L from the signal to background ratio



Discriminating Kinematic Variables

Variable	Definition
η	Pseudorapidity – we use this variable to perform secondary likelihood cuts
χ^2_{track}	This variable is the chi-squared value from the track fitting + Kalman fitter during reconstruction
$DG0, DDG0$	Roads are generated through MUID + MuTr planes. These roads are compared to tracks fit through the same hits. DG0 is the distance between the first gap's road and track. DDG0 is the opening angle between the road and track
DCA_r, DCA_z	Distance of closest approach between the track and beam axis (DCA_r). DCA_z is the distance between the track's intersection with the z axis, and the event vertex.
$RpcDca\ 1,3$	Distance between extrapolated track at RPC 1 or 3 and the hit-cluster at RPC 1 or 3.
dw_{23}	Reduced azimuthal bending – the magnitude of this variable corresponds to the bending of the particle in the azimuthal direction. $dw_{23} = p_T \sin(\theta)(\phi_2 - \phi_3)$
$fvtx\_d\phi$, $fvtx\_d\theta$, $fvtx\_dr$	Fvtx residuals for phi, theta and radius. The FVTX has a separate tracking system from the Muon Tracker, so these residuals are the result of matching.

Schematic Representation of Discriminating Variables

$$dw_{23} = p_T \sin(\theta)(\phi_2 - \phi_3)$$

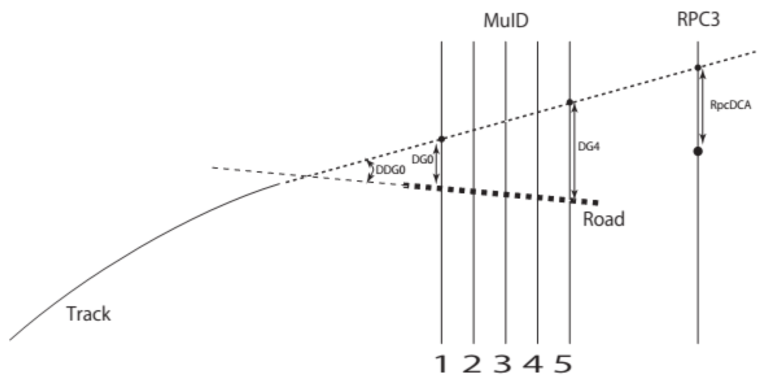


Figure 4.6: Schematic illustration of the definitions of DG0, DG4, DDG0 and RpcDCA in side view.

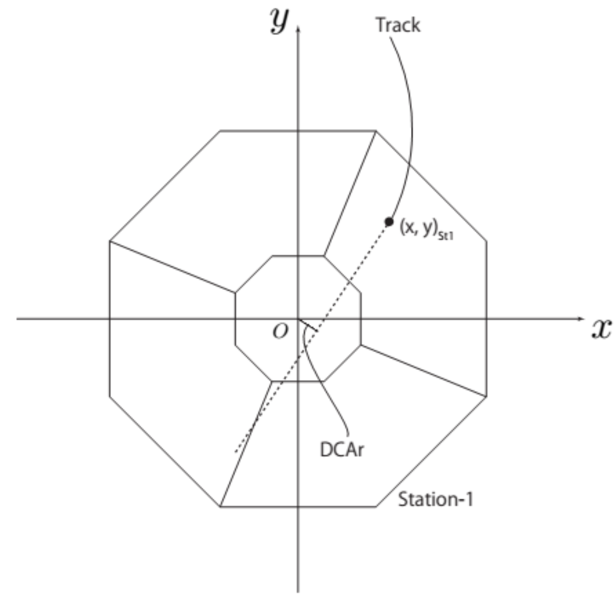


Figure 4.7: Definition of DCA_r.

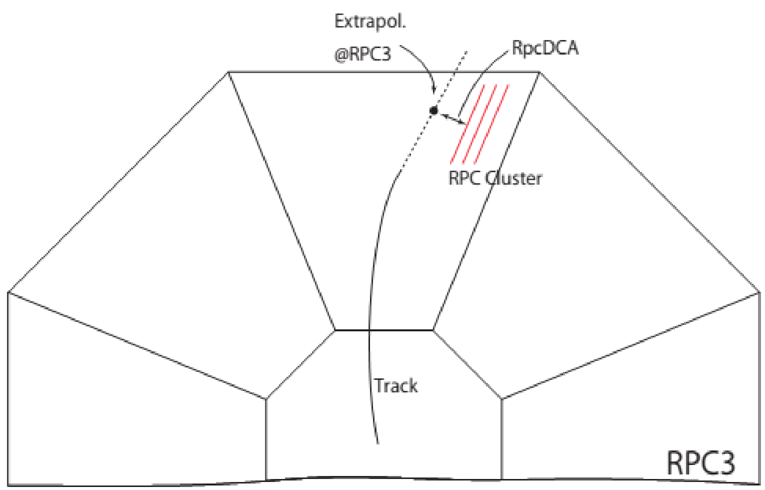


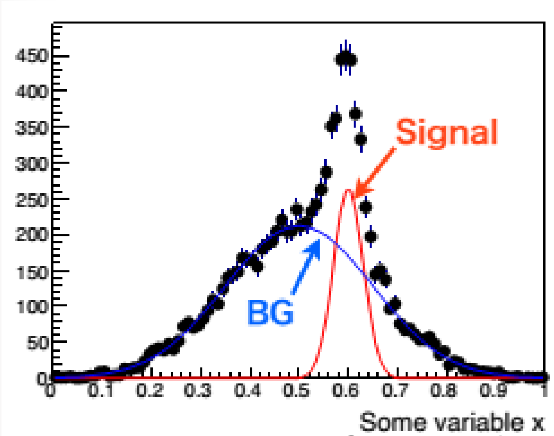
Figure 4.8: Illustration of RpcDCA in beam view.

We produce distributions of these variables to server as seeds to Probability Density Functions. Criteria for choosing the variables are:

1. **The distribution can be meaningfully normalized** (i.e. it converges to zero in asymptotic regions)
2. **The distribution has a shape depending on the data set composition** (i.e., rich in W events, rich in Hadronic background, rich in Muonic background)

The Likelihood Ratio Event Selection Method

- Suppose we have a variable, 'x' and we wish to apply a cut for event selection. Our options are:



1. Side band cut → $[\mathrm{x_{min}}, \mathrm{x_{fix}} = 1]$: robust, simple
2. We can do better, if we **know** the distribution of signal and background, in x.
3. We define a likelihood for each event:

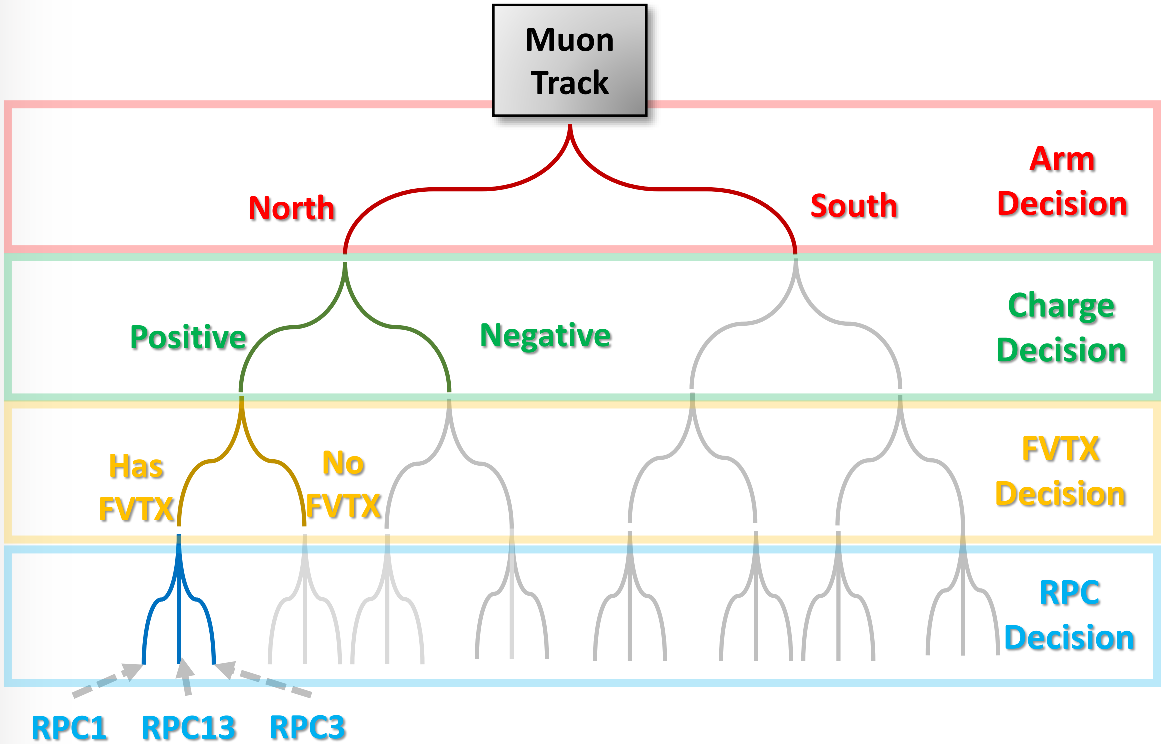
$$x_i = \lambda_{sig}(x_i), \lambda_{bg}(x_i)$$

We may define this likelihood ratio: $f(x_i) \equiv \frac{\lambda_{sig}(x_i)}{\lambda_{sig}(x_i)+\lambda_{bg}(x_i)}$

We construct the likelihood ratio (Wness) from our discriminating variables.

$$\lambda = p(DG0, DDG0)p(chi2)p(DCA_r)p(Rpc1/3dca)p\left(dr_{fvtx} * d\theta_{fvtx}\right)p\left(d\phi_{fvtx}\right)$$

Constructing Probability Density Functions & Wness

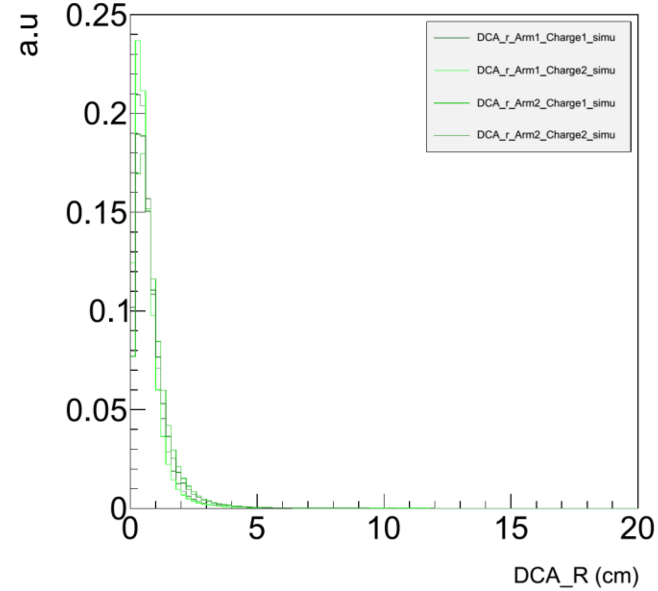


For Each Track, we traverse this decision tree to decide which combination of Probability Density Functions to use in calculating the "Wness" of that event. Each event has one "Wness"

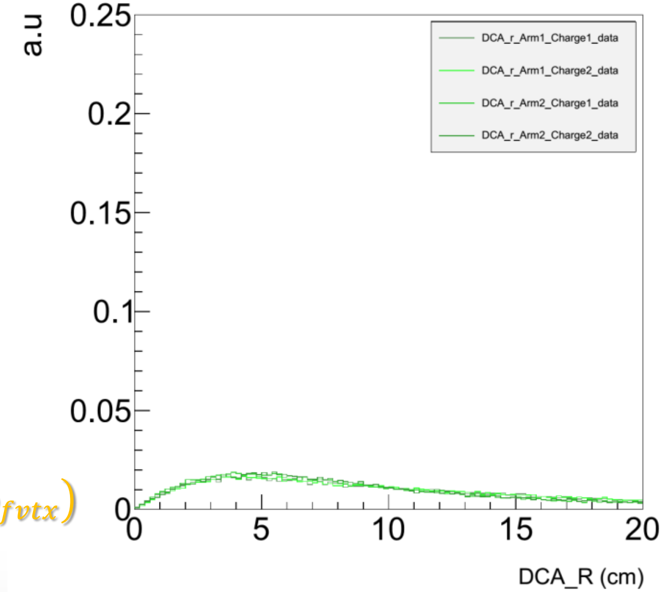
$$\lambda: p(DG0, DDG0)p(chi2) \times p(DCA_r)p(Rpc1/3dca)p(dr_{fvtx} * d\theta_{fvtx})p(d\phi_{fvtx})$$

$$\frac{\lambda_{sig}(x_i)}{\lambda_{sig}(x_i) + \lambda_{bg}(x_i)}$$

P.D.F - Simulation (W Signal Simulation)

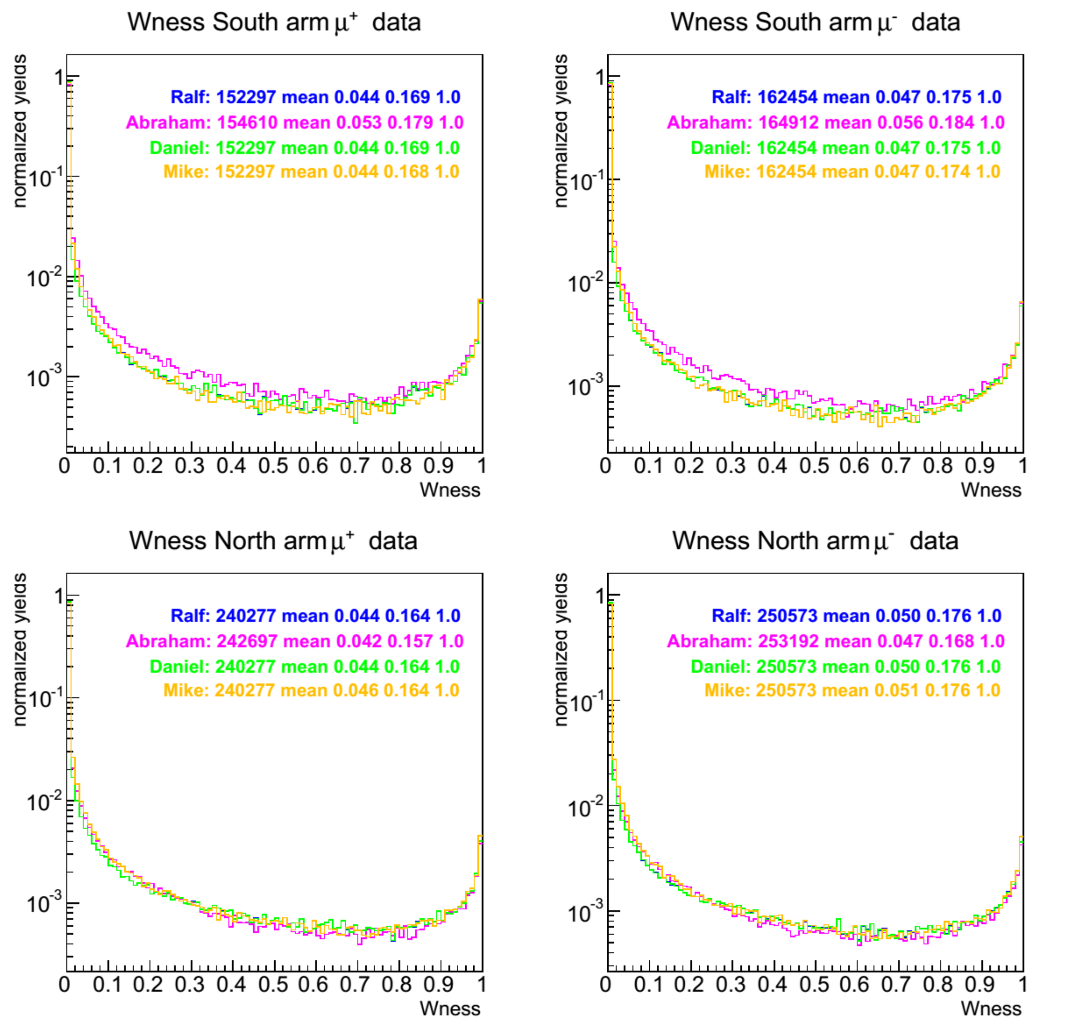


P.D.F. - Data (W + Hadronic Background)



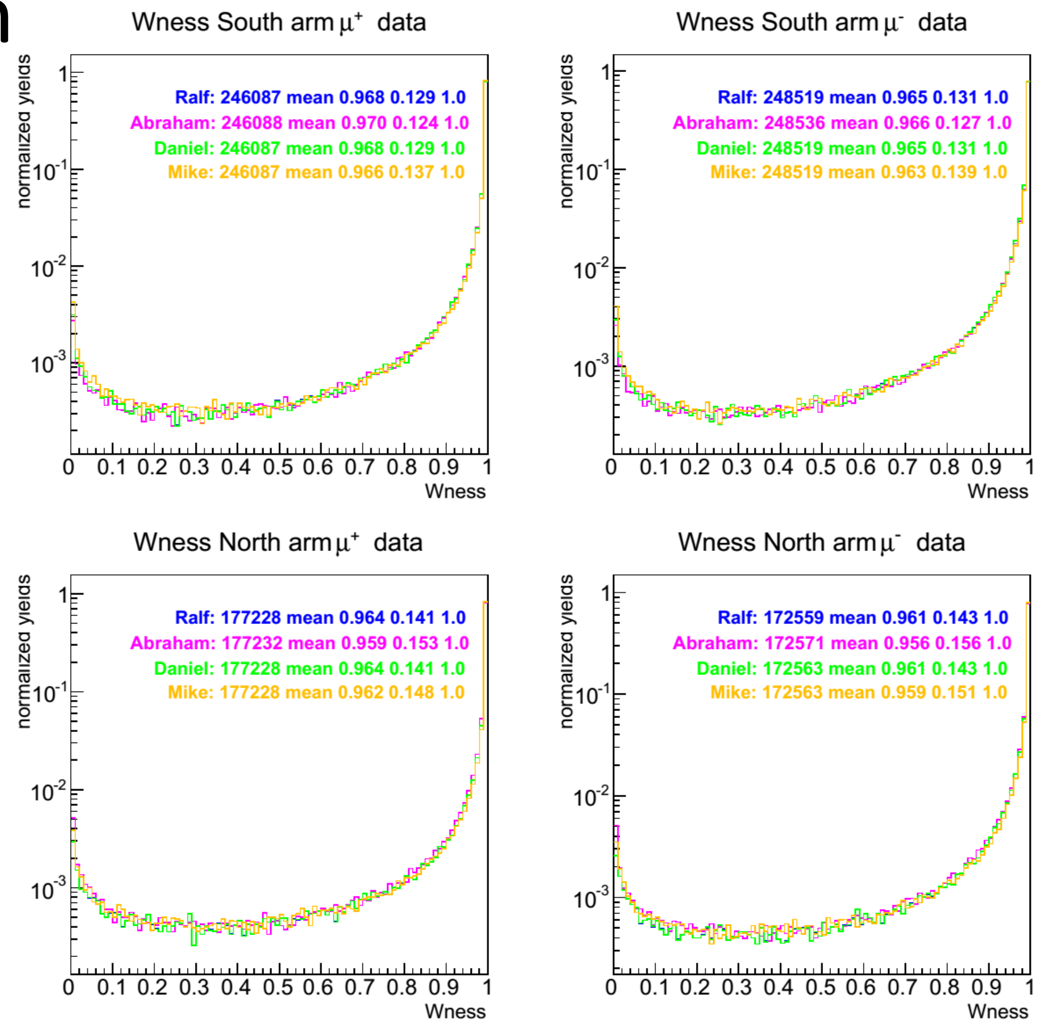
Wness Comparison Run 13 Data

- Figures produced by running over all Run 13 data.
- Unique Wness distributions are produced for each arm and charge configuration.
- Agreement is very good between analyzers. Differences stem currently from using two separate productions (muon & fvtx), as well as a minor bug in Mike's code



Wness Comparison Run 13 W Simulation

- Figures produced by running over all Run 12 W simulation
- Unique Wness distributions are produced for each arm and charge configuration.
- Agreement is very good between analyzers. Differences stem currently from using two separate productions (muon & fvtx), as well as a minor bug in Mike's code



Extended Unbinned Maximum Likelihood Fit

- Choose variables to seed P.D.F.s, fit P.D.F.s to data
- Variables: dw_{23}, η

$$L(\theta|X) = \frac{n^N e^{-n}}{N!} \prod_{x, \epsilon X}^{N} \sum_c \frac{n_c}{n} p_c(x_i), with\, n = \sum_x n_c$$

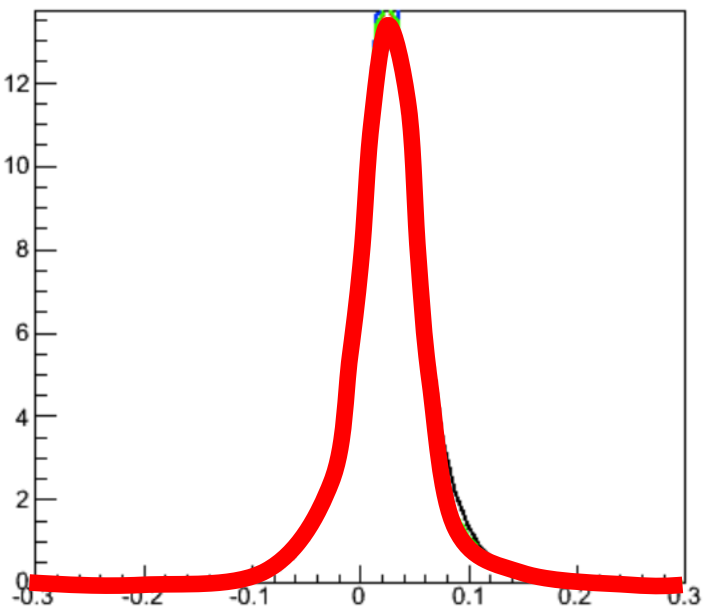
X is the sample of N total events, $x_i = (\eta_i, dw_{23,i})$

θ gives the fit parameters, s.t. $\theta = (n_{\mu sig}, n_{\mu W}, n_{\mu fake})$

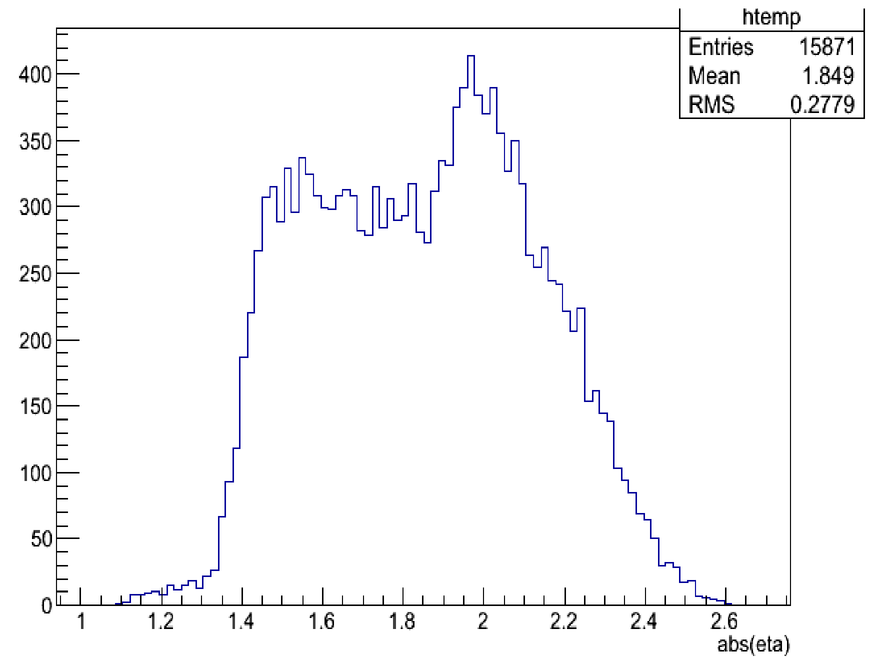
- **Muonic Background:** obtain PDF directly from simulation
- **W signal:** obtain PDF directly from simulation
- **Hadronic (fake μ) background:** PDF requires extrapolation…

Data – $|\eta|$ and dw23 P.D.Fs

dw_{23}



$|\eta|$



Our goal is to select a portion of high-Wness data and fit P.D.F.s for each muon source the data, so as to extract a signal to background ratio.

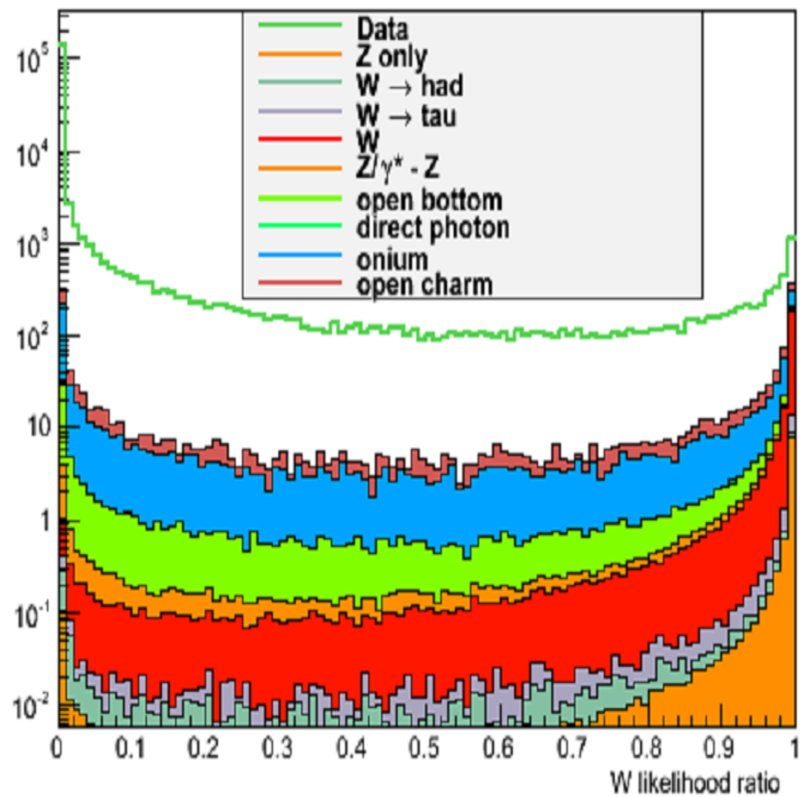
Because the high Wness region contains a mixture of Muonic background, Hadronic background, and w signal, we extrapolate the shape of dw23 from low Wness into high Wness. $|\eta|$ shape varies very little over the range of Wness.

Muon Background PDFs

Before we can utilize the muon backgrounds simulation, we must weight each simulation appropriately

Process	Generated k events * 10 ^3	$\sigma\ (mb)$	$L = \#\frac{Events}{\sigma}\sigma$ (pb-1)	Scale Factor
Direct γ	6400	5.32 x 10^2	120.30	0.771367
onium	55470	0.14	410.89	0.209710
Z Only	106.5	(-)1.33 x 10^{-7}	-800751.88	-0.000083
Open bottom	4003	7.3 x 10^{-3}	548.36	0.093074
Open charm	134220	0.571000	235.06	0.960310
W had	81	1.66 x 10^{-6}	48795.18	0.001358
W tau	82	1.66 x 10^{-6}	49397.59	0.001342
Z	245.2	1.59 x 10^{-5}	15421.38	0.009456

W simulation and Data are shown below relative to muon backgrounds, stacked and weighted, Wness distriubiton used for comparison, for S, μ^+



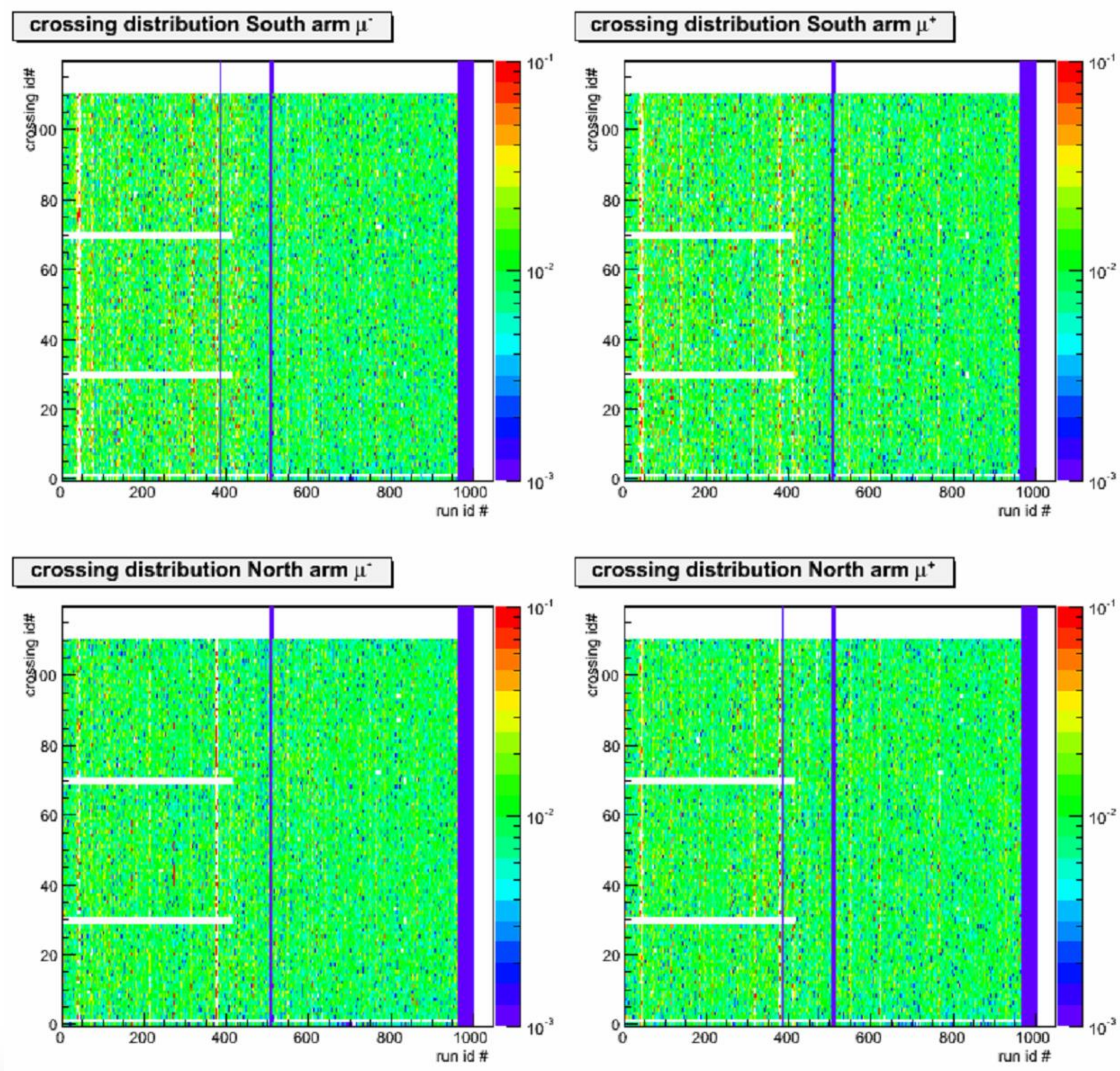
$$Scale\ Factor = \frac{228}{L(pb-1)} \times k\_factor \times detector\_eff$$

Detector_eff = 0.407

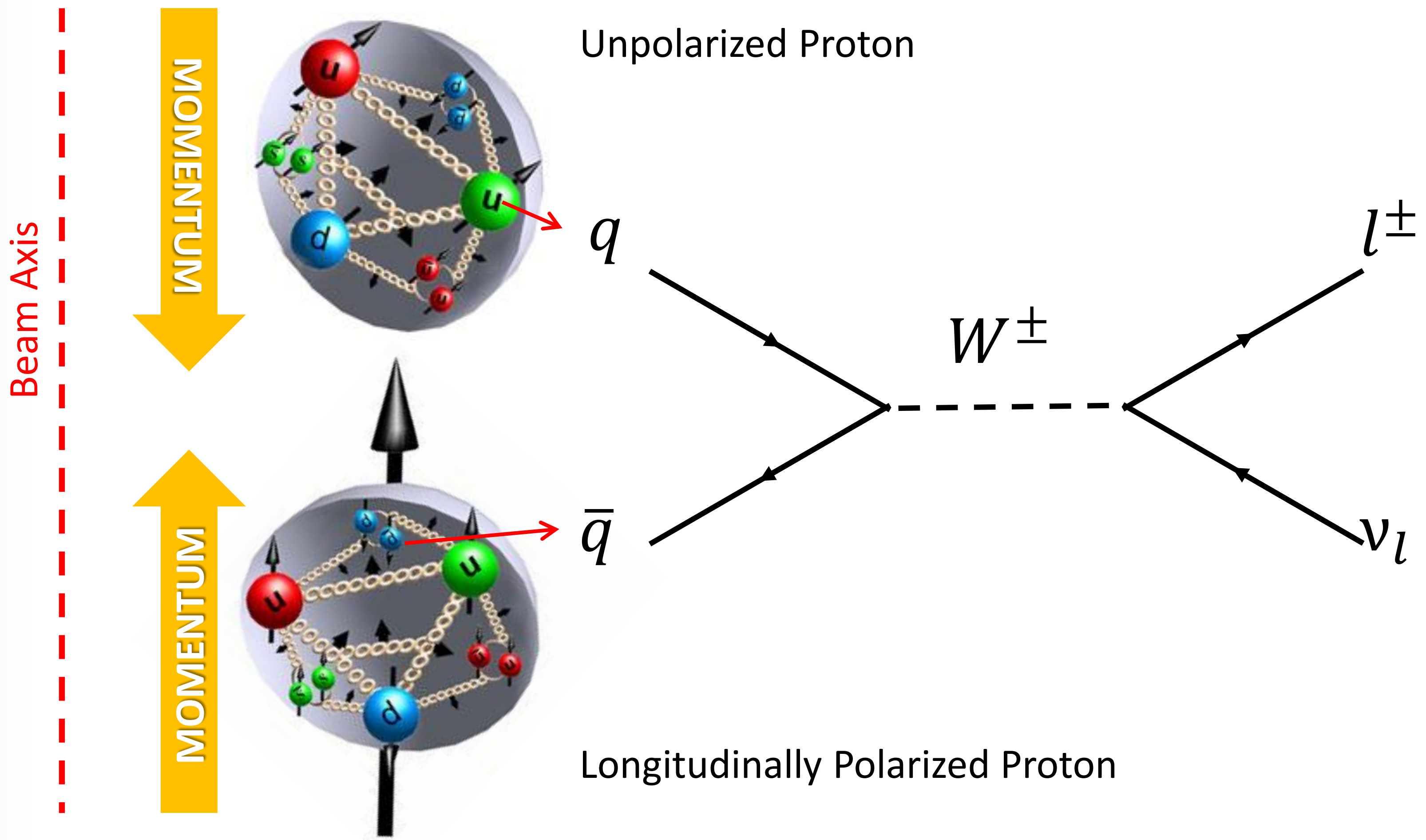
Spin Information

We must match spin information at each crossing in the data.

The spin database has been updated with latest crossing shift information (see AN1125)

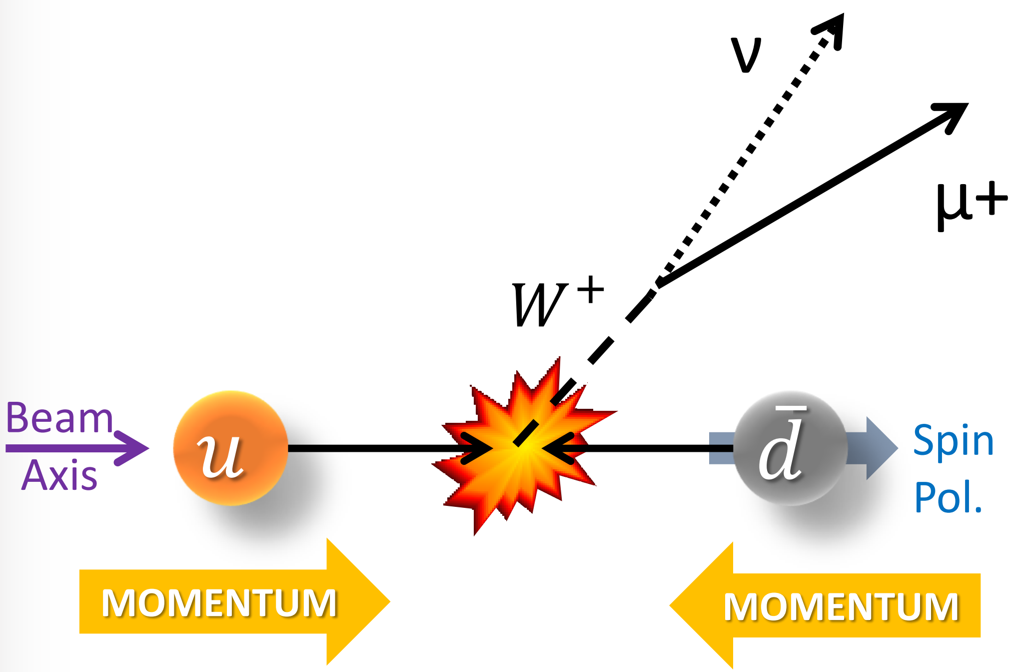


Inside the $W^{\pm} \rightarrow l^{\pm} + \nu_l$ interaction



Shown: $u\bar{d} \rightarrow W^{+} + \nu_l$

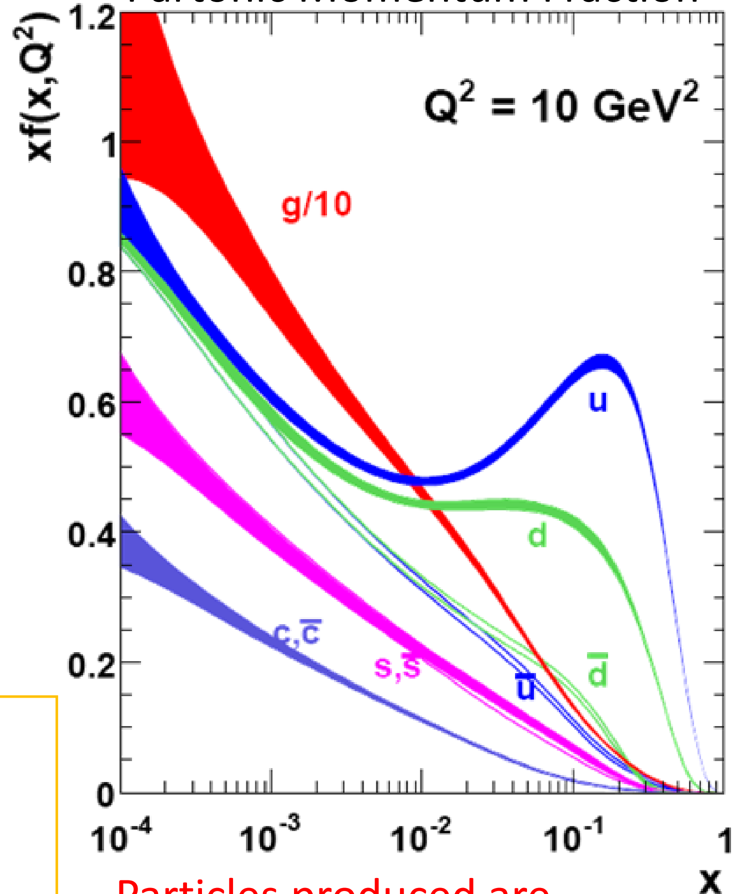
Inside the $W^{\pm} \rightarrow l^{\pm} + \nu_l$ interaction



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

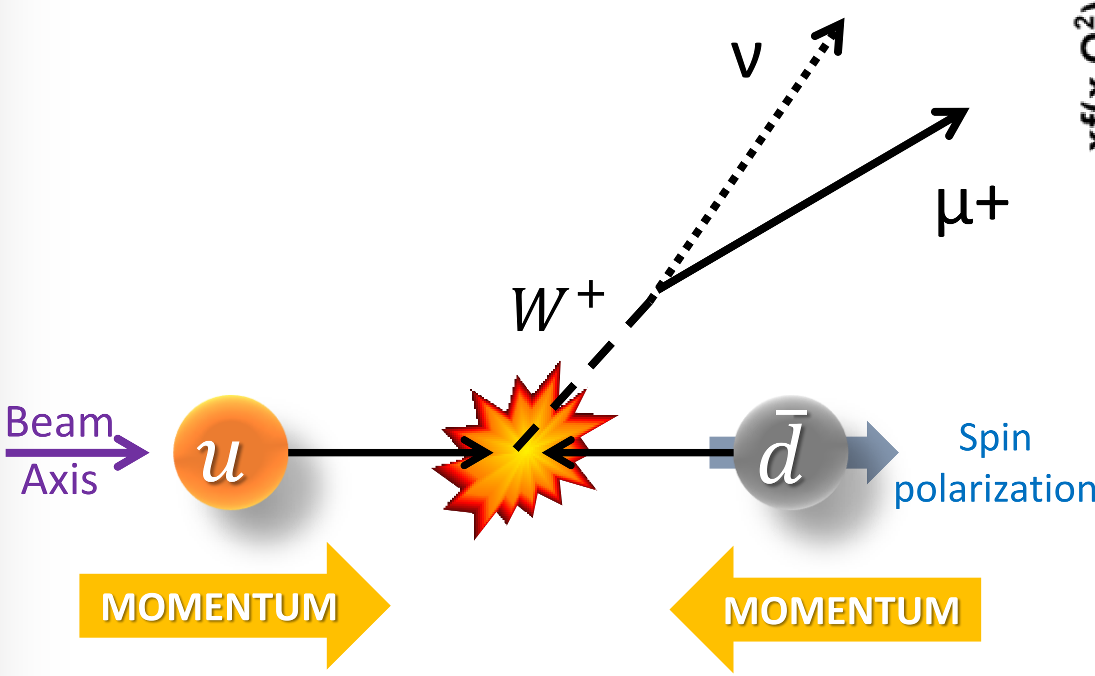
$$A_L^{W^+} = -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

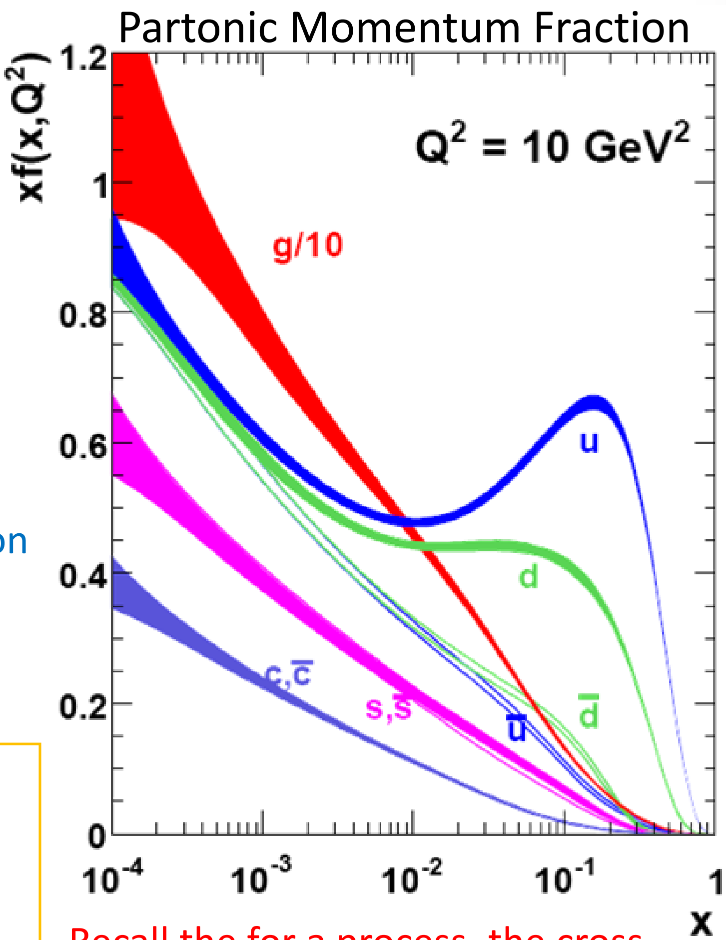
Partonic Momentum Fraction



Particles produced are boosted according to the momentum fraction carried by the interacting partons.

Inside the $W^{\pm} \rightarrow l^{\pm} + \nu_l$ interaction





$$A_L^{W^+} = \frac{1}{P} \times \frac{\boxed{N^+(W)} - \boxed{N^-(W)}}{N^+(W) + N^-(W)}$$

Count W's from Protons with Positive Helicity

Count W's from Protons with Negative Helicity

*detecting muons

Recall the for a process, the cross section is proportional to the number of particles produced $\left(N = \frac{\sigma}{L}\right)$

Measuring $W \rightarrow l + \nu$ at PHENIX

- PHENIX is not hermetic; missing energy carried away by neutrinos causes some smearing of $q, \bar{q}$ distribution.
  - Smearing is due to fixed helicity of neutrinos, but additional kinematic smearing is introduced in central regions because of θ modulation to $A_L^{W^\pm}$ terms in W center of mass frame.
    - θ is polar angle μ makes with the beam axis

Full form $A_L^{W^\pm}$ in terms of parton distribution functions:

$$\begin{aligned} A_L(p^{\Rightarrow} p \rightarrow W^+ \rightarrow \ell^+ \nu_\ell) &= \frac{\int dx_1 dx_2 \sum_{i,j} (-\Delta q_i(x_1)\bar{q}_j(x_2) + \Delta\bar{q}_j(x_1)q_i(x_2)) \cdot d\hat{\sigma}}{\int dx_1 dx_2 \sum_{i,j} (q_i(x_1)\bar{q}_j(x_2) + \bar{q}_j(x_1)q_i(x_2)) \cdot d\hat{\sigma}} \\ &\approx \frac{\int dx_1 dx_2 \left(-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)\right) \cdot d\hat{\sigma}}{\int dx_1 dx_2 \left(u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)\right) \cdot d\hat{\sigma}} \qquad (2.89) \end{aligned}$$