Probing the Sea-Quark Contribution to the Total Proton Spin Via the Weak Interaction at PHENIX

{ *Physical Motivations* }
{ *Experimental Observable* }
{ *RHIC collider and PHENIX apparatus* }
{ *Central Rapidity Analysis* }
{ *Forward Rapidity Analysis* }

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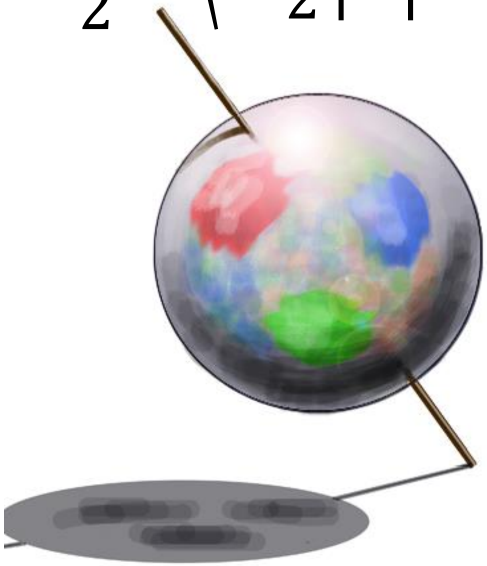
Proton Spin Structure

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

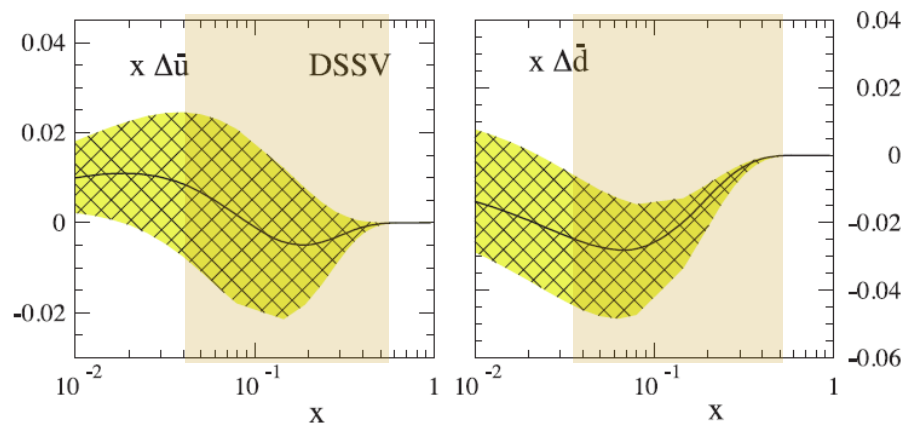


Studied for over 20 years – we're still working to understand substructure contribution to "1/2"

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

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

Large Uncertainty In Sea Quark Polarization



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

PHENIX rapidity sensitivity range

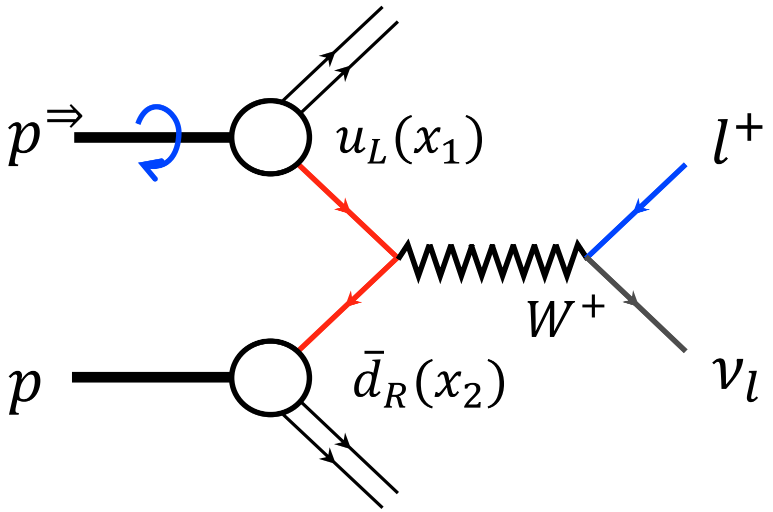
Quark Polarization measured to be ~30% of Proton Spin via DIS

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

Experimental Observable – A_L

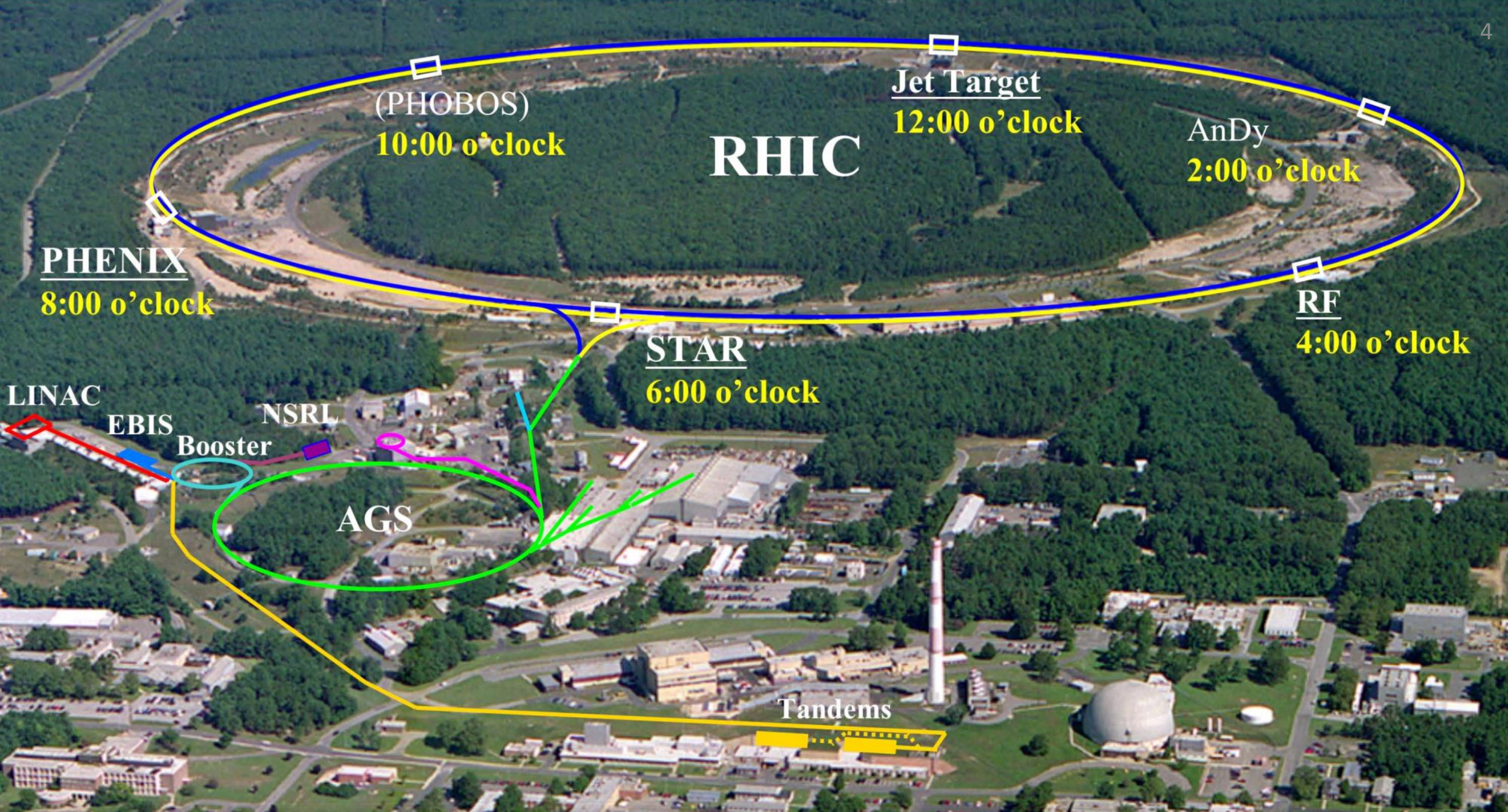
- Collide polarized and unpolarized protons – interactions mediated by P.D.F.s
- $q, \bar{q}$ interaction creates real W. Maximal parity violating interaction
  - $u_L \bar{d}_R \rightarrow W^+$
  - $d_L \bar{u}_R \rightarrow W^-$
  - Count helicity combinations of decay leptons
- Calculate A_L, use knowledge of 'valence quark' polarization to access to sea-quark polarized parton distribution functions.

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



$$A_L^{l+}(y_l) \equiv \frac{1}{P} \times \frac{N(l_{W^+})^{p^{\Leftarrow}} - N(l_{W^+})^{p^{\Rightarrow}}}{N(l_{W^+})^{p^{\Leftarrow}} + N(l_{W^+})^{p^{\Rightarrow}}} \equiv \frac{-\Delta u(x_1)\bar{d}(x_2)\left(1-\cos\hat{\theta}\right)^2 + \Delta\bar{d}(x_1)u(x_2)\left(1+\cos\hat{\theta}\right)^2}{u(x_1)\bar{d}(x_2)\left(1-\cos\hat{\theta}\right)^2 + \bar{d}(x_1)u(x_2)\left(1+\cos\hat{\theta}\right)^2}$$

$$A_L^{l-}(y_l) \equiv \frac{1}{P} \times \frac{N(l_{W^-})^{p^{\Leftarrow}} - N(l_{W^-})^{p^{\Rightarrow}}}{N(l_{W^-})^{p^{\Leftarrow}} + N(l_{W^-})^{p^{\Rightarrow}}} \equiv \frac{\Delta\bar{u}(x_1)d(x_2)\left(1-\cos\hat{\theta}\right)^2 - \Delta d(x_1)\bar{u}(x_2)\left(1+\cos\hat{\theta}\right)^2}{\bar{u}(x_1)d(x_2)\left(1-\cos\hat{\theta}\right)^2 + d(x_1)\bar{u}(x_2)\left(1+\cos\hat{\theta}\right)^2}$$



Experimental Apparatus

RHIC: The **R**elativistic **H**eavy **I**on **C**ollider - World's Only Polarized Proton-Proton Collider

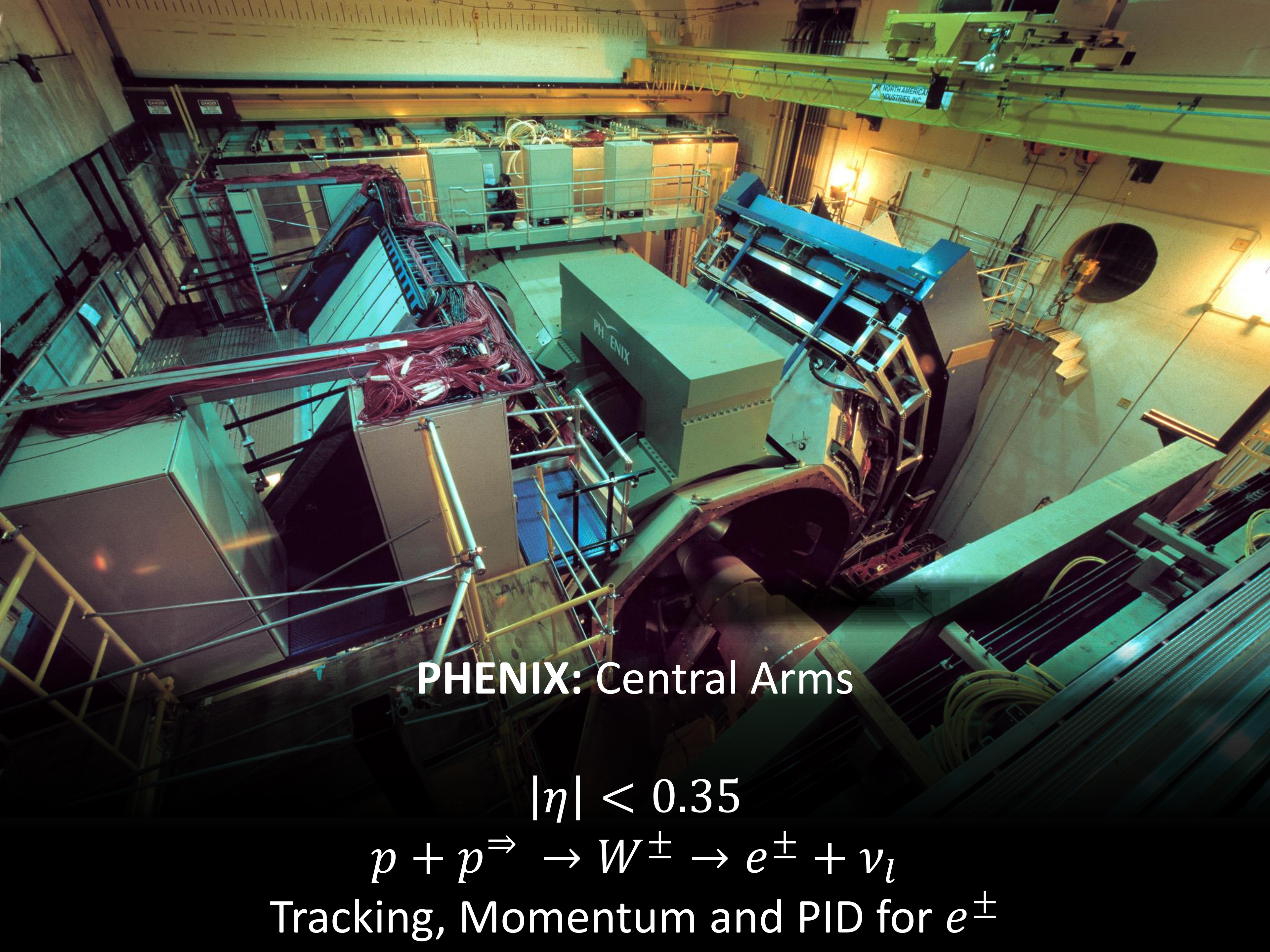
PHENIX: Pioneering **H**igh **E**nergy **N**uclear **I**nteraction e**X**periment

PHENIX: Muon Arms

$$1.2 < |\eta| < 2.4$$

$$p + \vec{p} \rightarrow W^{\pm} \rightarrow \mu^{\pm} + \nu_l$$

Tracking and Momentum for $\mu^{\pm}$



PHENIX: Central Arms

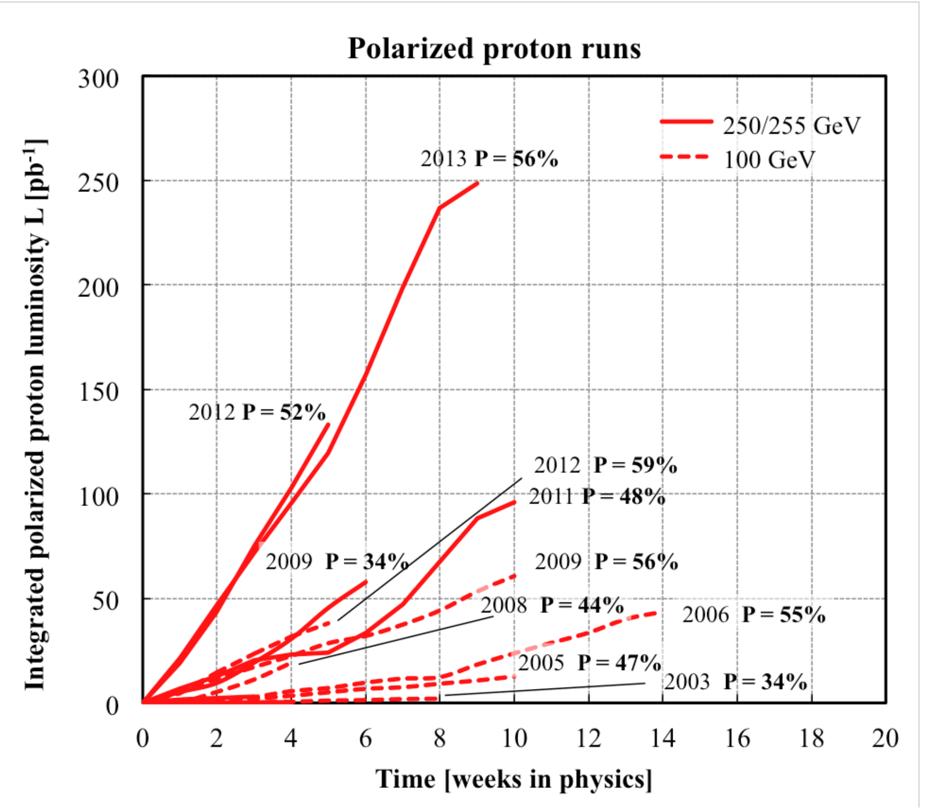
$$|\eta| < 0.35$$

$$p + p^{\Rightarrow} \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu_l$$

Tracking, Momentum and PID for $e^{\pm}$

2013 Data Set – $p + p$ 510 $GeV \sqrt{s}$

- Highest proton polarization (longitudinal) and beam luminosity to date
- $277\ pb^{-1}$ data accumulated
  - Corrected for multiple collisions
- Central analysis status
  - Final results posted to arXiv **today!**
- Forward analysis status
  - Recent preliminary status!



Central Analysis

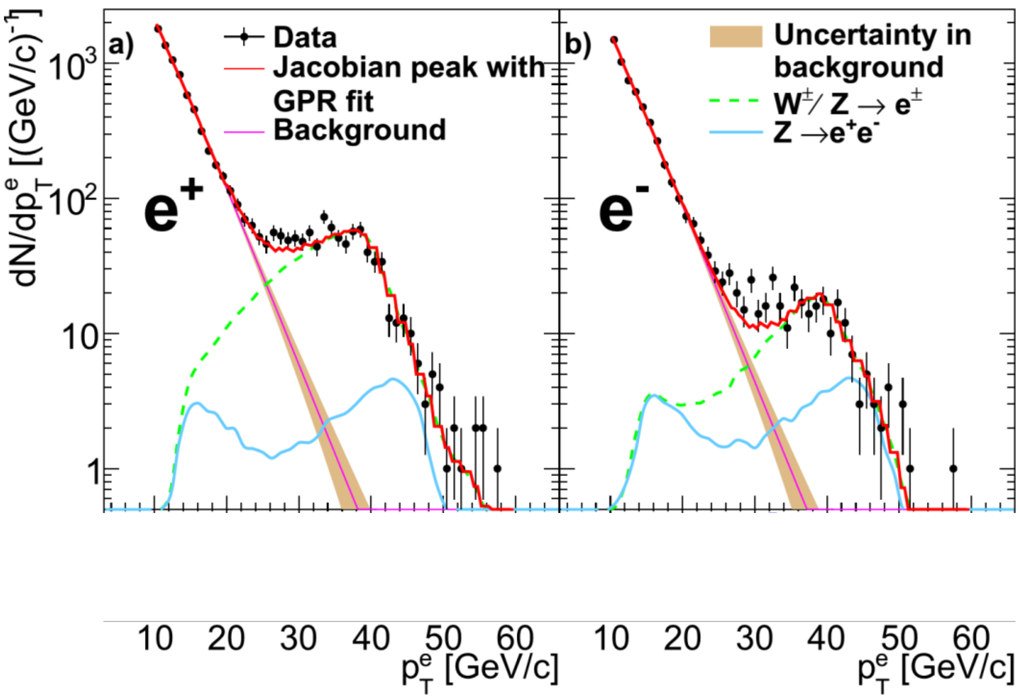
$$W^{\pm} \rightarrow e^{\pm} + \nu_l$$

Central Analysis: $W^{\pm} \rightarrow e^{\pm} + \nu_l$

Analysis Strategy

1. Reduce backgrounds as much as possible with isolation cuts
   - Electron pair production, cosmic rays, beam background, Z/charm/bottom decays
2. Extract the background shape (Gaussian Process Regression) and fit entire spectra with model for background + signal, extracting yields.
   - Use low pT region as a model for background, extrapolate.

- Calculate and evaluate Asymmetries



Jacobian Peaks Visible!

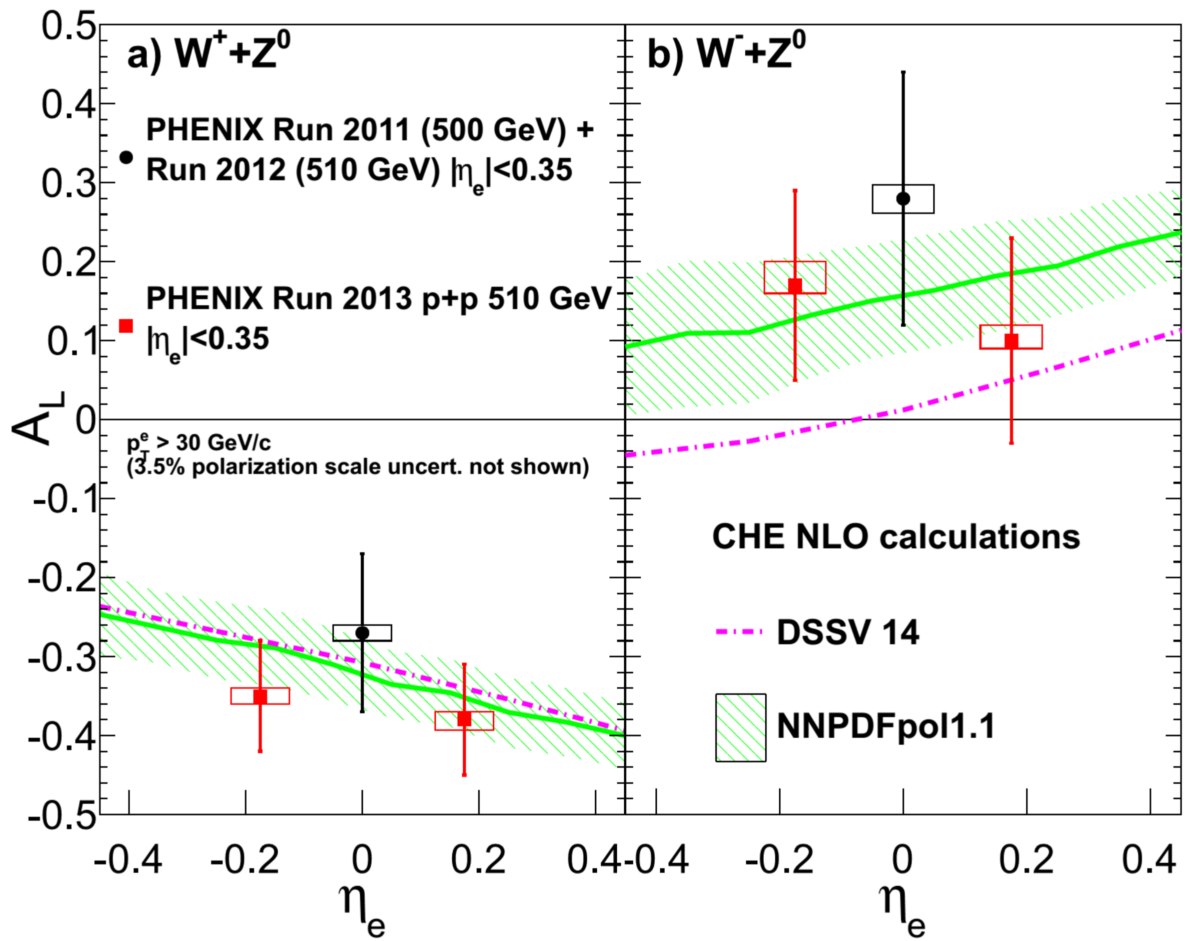
Close Agreement between data and fit!

Central Analysis: $W^{\pm} \rightarrow e^{\pm} + \nu_l$

Asymmetry Results

Good agreement with prediction!

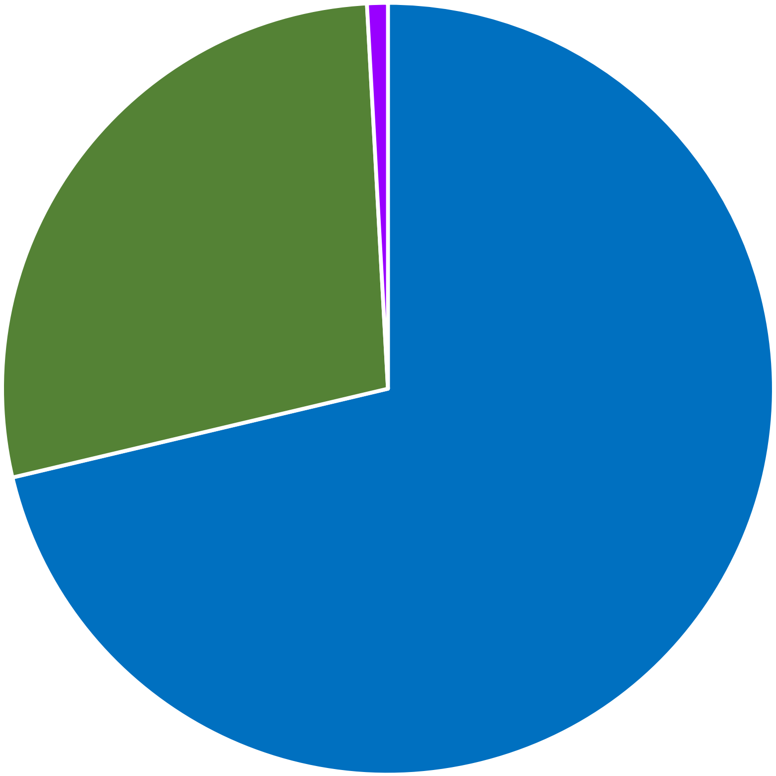
http://arxiv.org/pdf/1504.07451v1.pdf



Forward Analysis

$$W^{\pm} \rightarrow \mu^{\pm} + \nu_l$$

Data Set Composition



Fake Muon Background

Hadronic decay in Muon Tracker reconstructed as high pT muons

Real Muon Background

Other processes which create muons, we model this with simulated data

$W \rightarrow \mu$ Signal

The actual signal data we want to look at. Even with recent hardware upgrades, signal comprises only **4 in 100 million events**

Analysis Strategy

Form PDFs Filter Data

Construct uncorrelated kinematic variables to generate probability density functions which can be used to discriminate between Signal and Background muon tracks

Calculate Likelihood

Use generated PDFs to assign a statistical likelihood ratio to each event. This likelihood ratio is used to cut out background events from total data set

Extract Signal to Background Ratio

Unbinned Maximum Likelihood Fit: Construct new set of PDFs. Fit PDFs representing Fake Muons, Real Background Muons, and W-signal muons to remaining data.

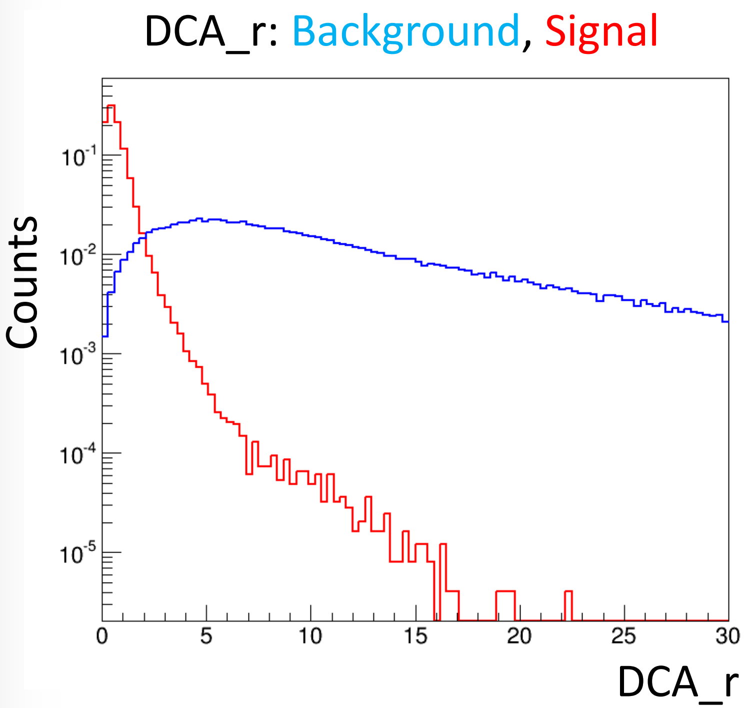
Calculate Asymmetry With Dilution

$$A_{L_{corrected}} = A_{L_{measured}}(1 + \frac{BG}{SIG})$$

Asymmetry is calculated, corrected for SBR dilution

Calculate Likelihood

Use known shape of a kinematic variable to a probability density function. Use these P.D.F.s to calculate likelihood ratio for each event.



Example constructed variable: 'DCA_r'. We wish to apply an event selection cut to this variable. Our options are:

1. Side band cut → $[DCA\_r_{min}, DCA\_r_{fix}]$: robust, simple – apply to total spectrum of Signal + Background
2. If we **know** the distribution of DCA_r for signal and background independently, we can do better.
3. We define a likelihood for each event:
$$x_i = \lambda_{sig}(x_i), \lambda_{bg}(x_i)$$

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

We construct a likelihood ratio using all variables which offer this discriminating power.

Calculate Likelihood

Use combined P.D.F.s from many kinematic variables to form total likelihood ratio (likelihood ratio for W event “Wness”). Determine optimum Wness cut to reduce background in data.

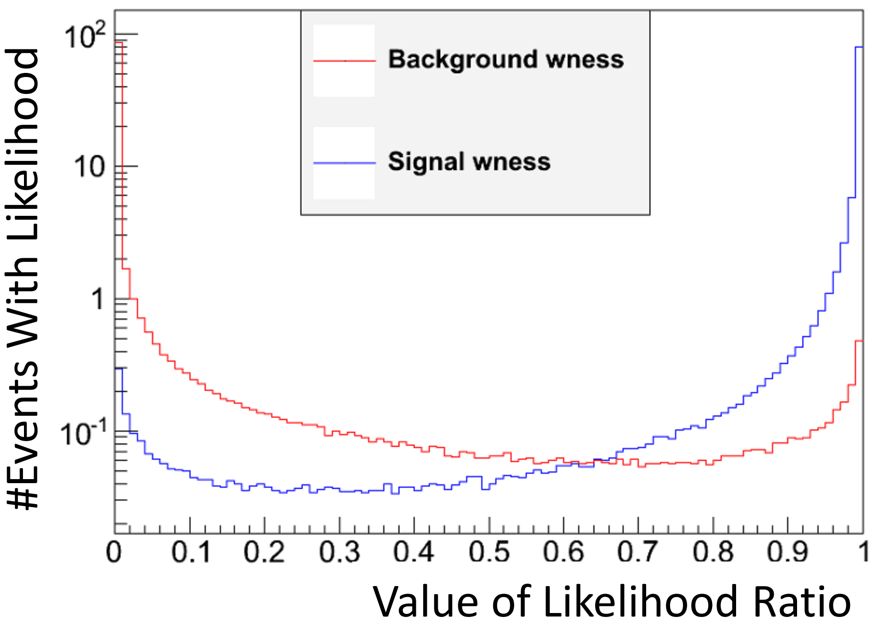
$$W_{ness} \equiv f(x_i) \equiv \frac{\lambda_{sig}(x_i)}{\lambda_{sig}(x_i) + \lambda_{bg}(x_i)}$$

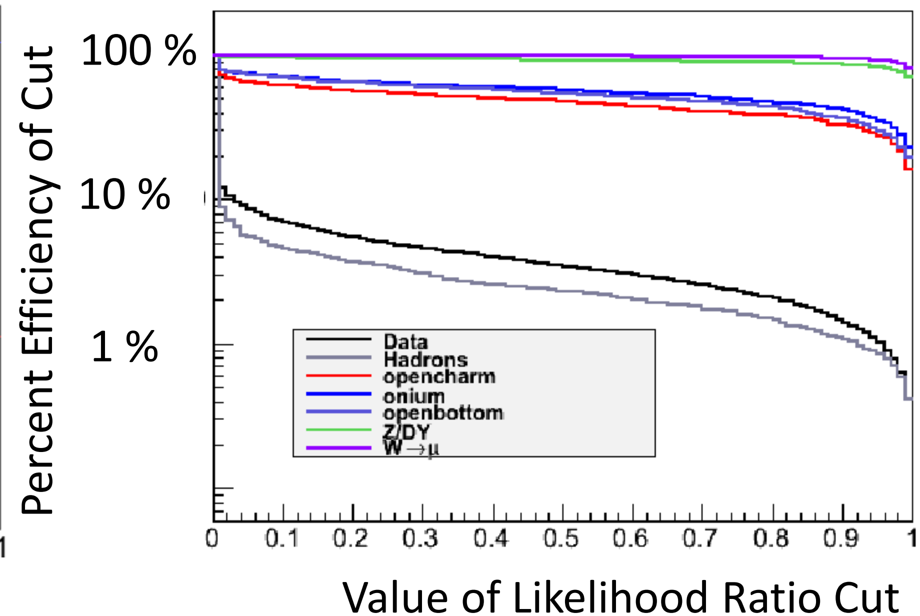
$$W_{ness} \to 0 \Rightarrow W \to \mu \ is\ unlikely$$

$$W_{ness} \to 1 \Rightarrow W \to \mu \ is\ likely$$

Cut data using likelihood

Calculate likelihood for simulated event populations to estimate cut efficiency!





Extract Signal to Background Ratio

Unbinned Maximum Likelihood Fit: Construct new set of PDFs. Fit PDFs representing Fake Muons, Real Background Muons, and W-signal muons to remaining data.

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

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

θ gives the fit parameters, s.t. $\theta = \left(n_{\mu_{signal}}, n_{\mu\_\mu bkgd}, n_{\mu_{hadron}}\right)$

- **Muonic Background (simulation):** obtain P.D.F.s directly from simulation cocktail (fixed)
- **W signal (free parameter, simulation):** obtain P.D.F.s directly from simulation
- **Hadronic Background (free parameter, data) :** Extrapolate P.D.F.s from data

Extract Signal to Background Ratio

Unbinned Maximum Likelihood Fit: Reasonable description of total data set by Muon Background, Hadronic Background and W Signal PDFs.

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

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

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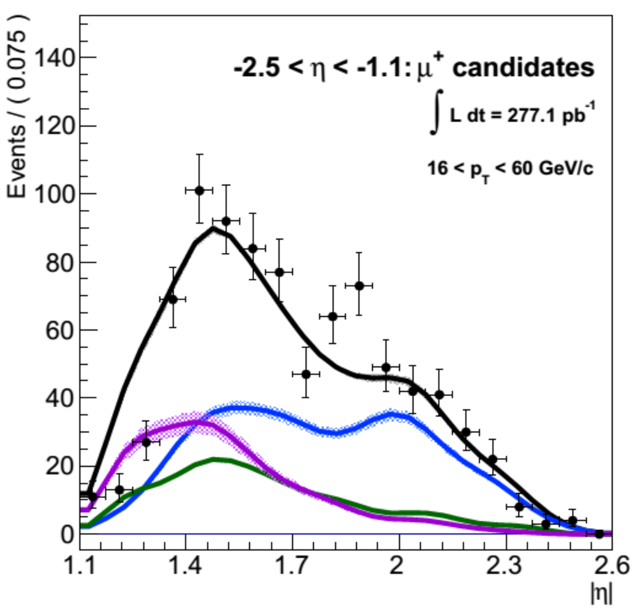
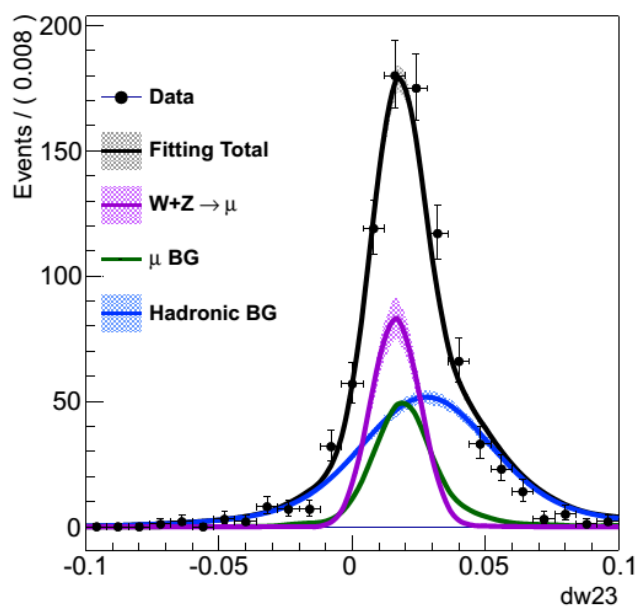




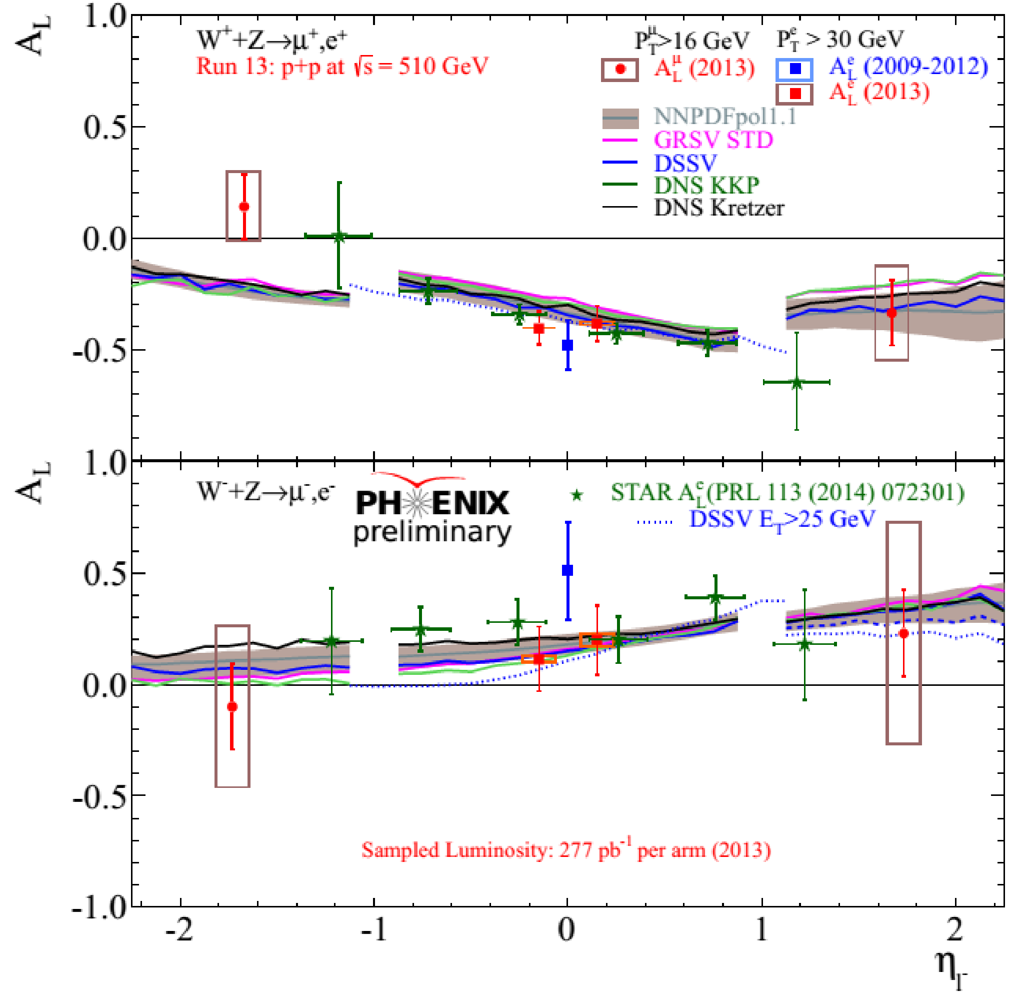
Calculate Asymmetry With Dilution

$$A_{L_{corrected}} = A_{L_{measured}}\left(1+\frac{BG}{SIG}\right) = \frac{1}{P}\frac{N^{+}-N^{-}}{N^{+}+N^{-}}$$

Asymmetry is calculated, corrected for SBR dilution

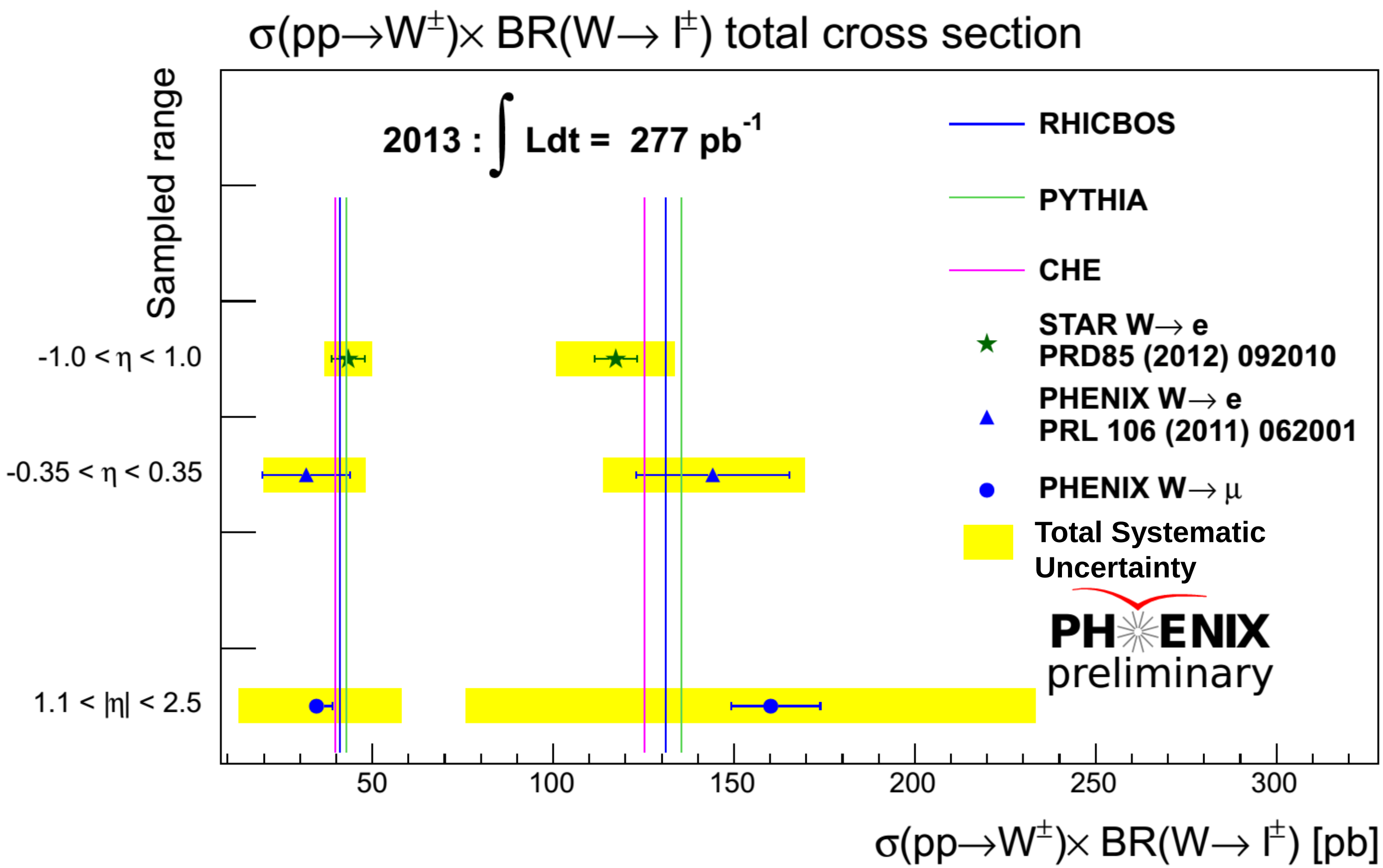
PHENIX Preliminary Results:

Asymmetries tend to be small, and consistent with predictions.



Calculate Asymmetry With Dilution

Cross section may also be calculated from data as a consistency check



Summary

$W^{\pm} \rightarrow e^{\pm} + \nu_l$

- Final results and paper in advanced stage, and will be submitted for publication imminently

$W^{\pm} \rightarrow \mu^{\pm} + \nu_l$

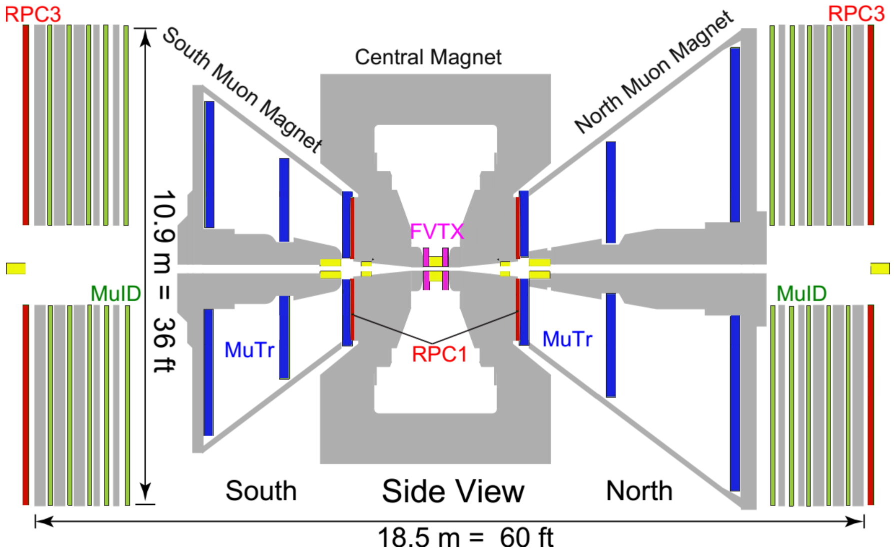
Preliminary results for run 2013 presented for first time at DIS

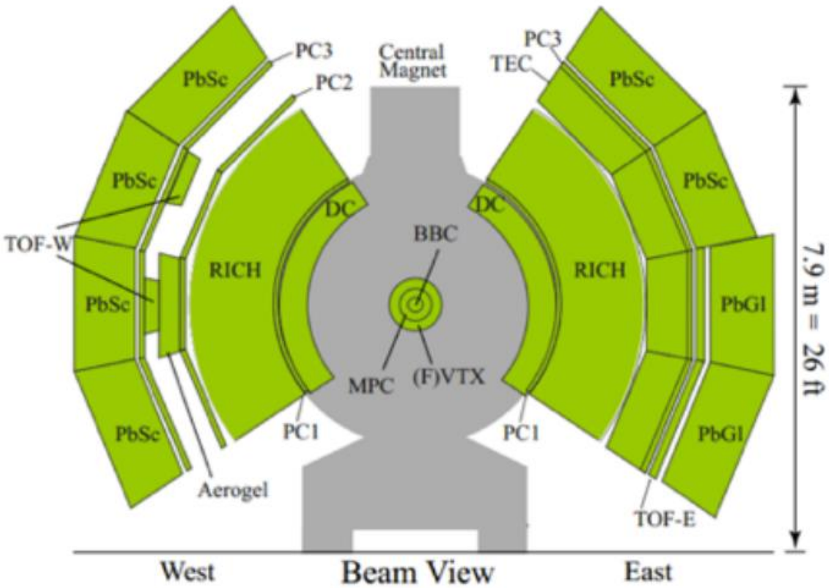
Work in progress to reduce systematics:

- Improve signal to background extraction
- New data production to correct alignment between detector subsystems, improving momentum smearing and charge reconstruction

Backup

The PHENIX Apparatus





Forward Muon Arms

$1.2 < |\eta| < 2.4$

$p + p^{\Rightarrow} \rightarrow W^{\pm} \rightarrow \mu^{\pm} + \nu_l$

Tracking and Momentum for $\mu^{\pm}$

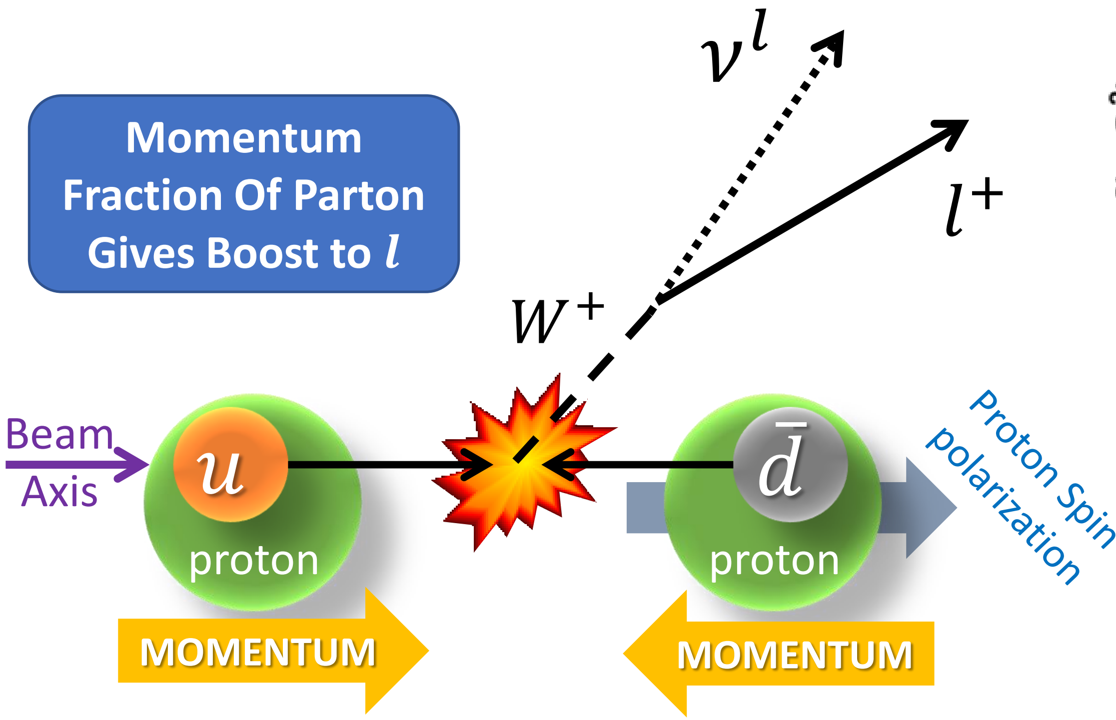
Central Arms

$|\eta| < 0.35$

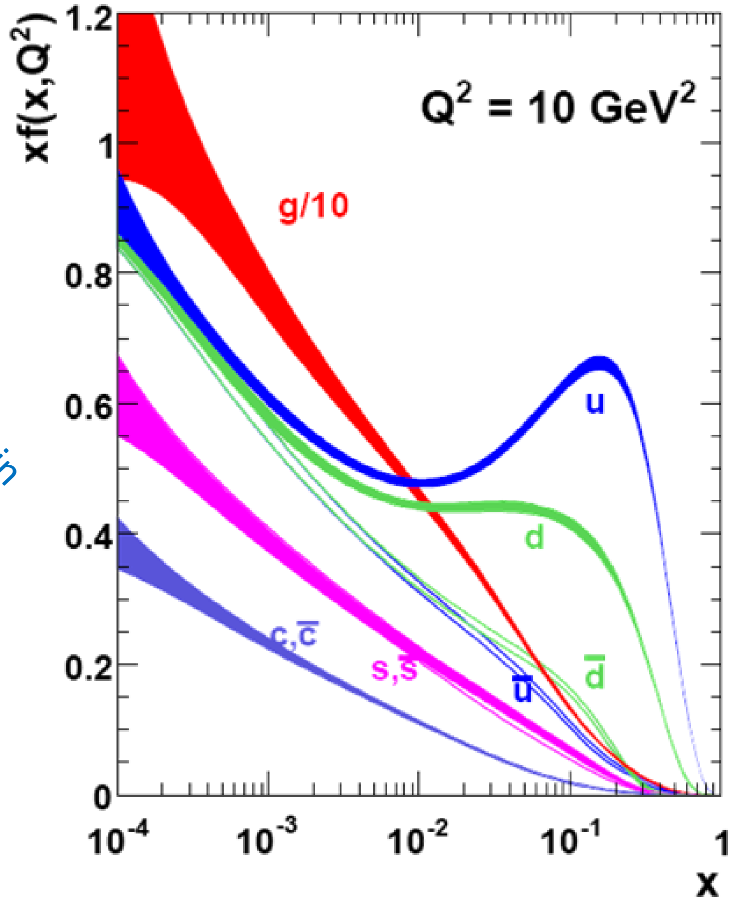
$p + p^{\Rightarrow} \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu_l$

Tracking, Momentum and PID for $e^{\pm}$

Experimental Observable – A_L



Partonic Momentum Fraction



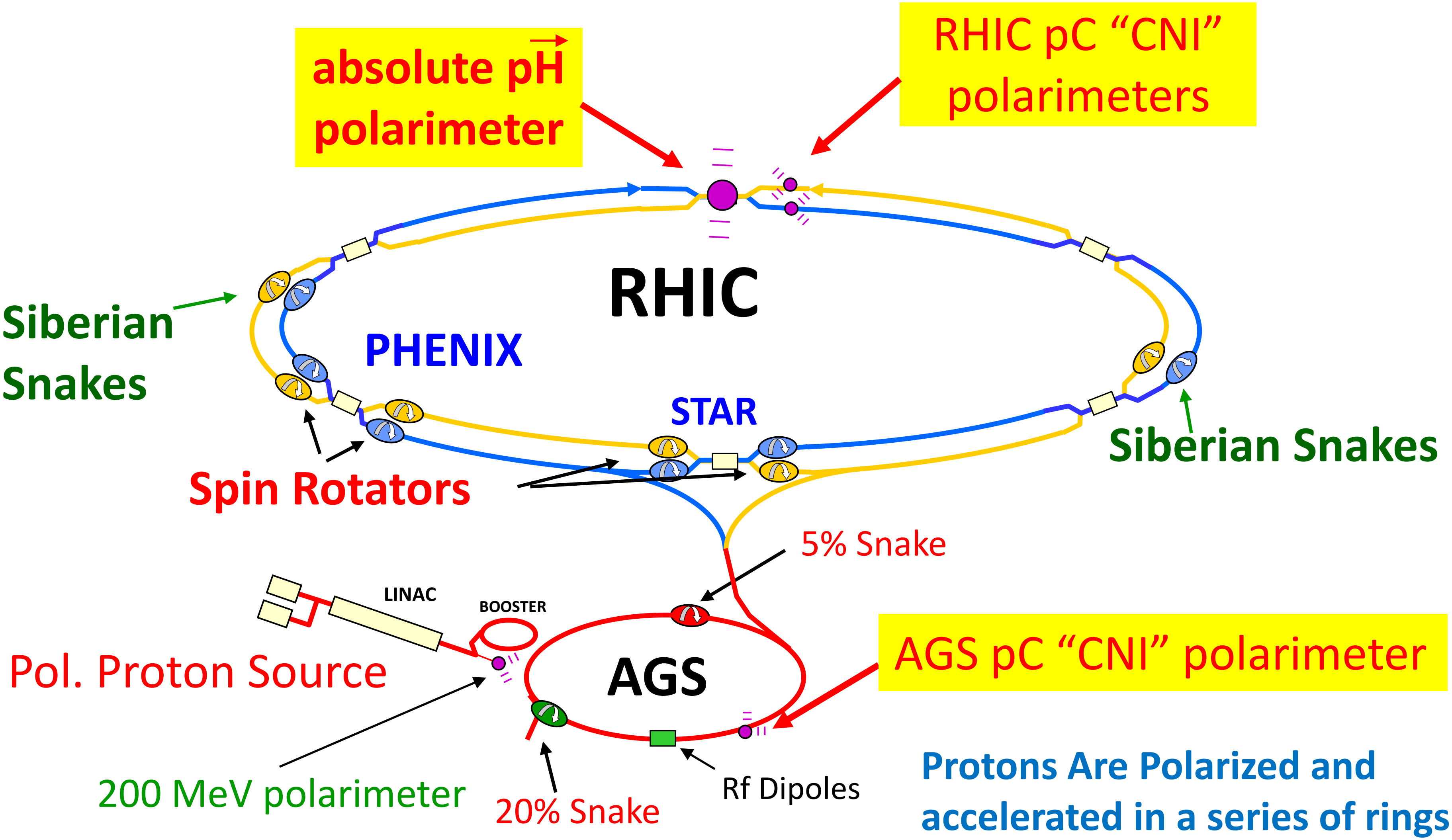
$$A_L^{W^+\to\mu^+} = \frac{1}{P} \times \frac{N(l_{W^+})^{p^{\Leftarrow}} - N(l_{W^+})^{p^{\Rightarrow}}}{N(l_{W^+})^{p^{\Leftarrow}} + N(l_{W^+})^{p^{\Rightarrow}}}$$

Count l's from Protons with Positive Helicity

Count l's from Protons with Negative Helicity

Calculate Asymmetry

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

Analysis Variables - P.D.F. Seeds – Section 1.1 AN1195

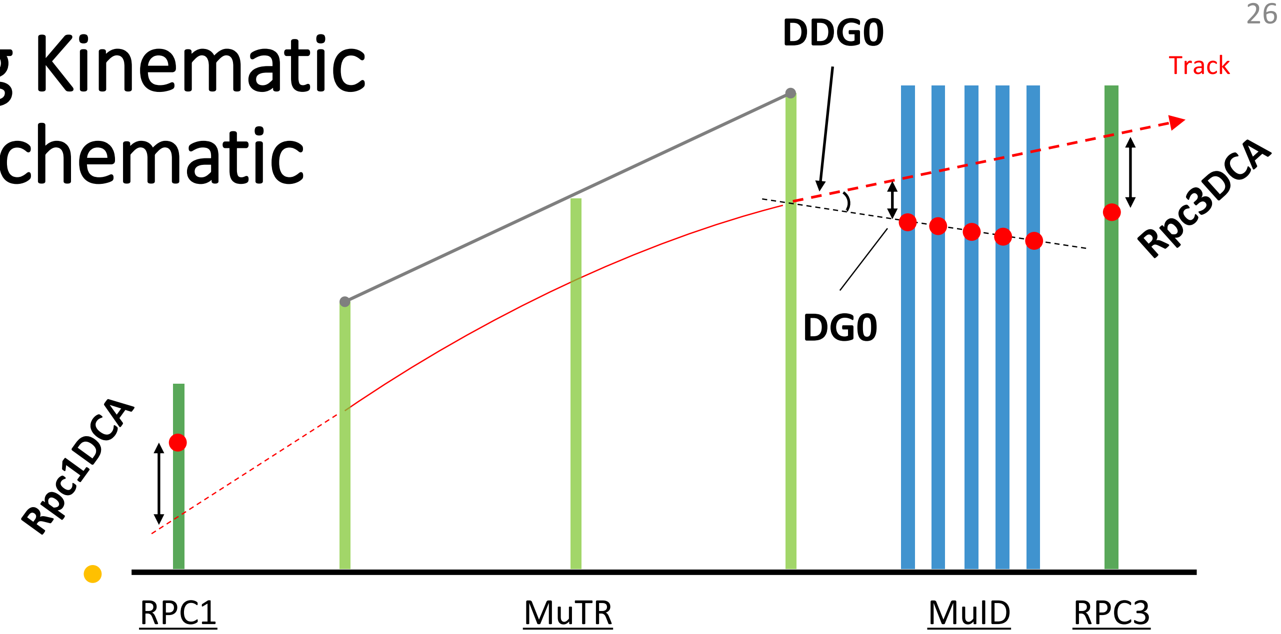
η	Pseudorapidity – we use this variable to perform secondary likelihood cuts
χ^2_{track}	This variable is the chi-squared value from the track fitting + Kalman fitter during reconstruction
$DG0, DDG0$	Roads are generated through MUID + MuTr planes. These roads are compared to tracks fit through the same 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.
Rpc_1DCA Rpc_3DCA	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 between MuTr and FVTX track at Z=+/-40cm
$fvtx\_cone$	FVTX clusters in a cone or fvtx_cone: Number of FVTX clusters inside a cone around the track defined by 0.04 rad < dR < 0.52 rad, where dR = sqrt(dEta^2 + dPhi^2)

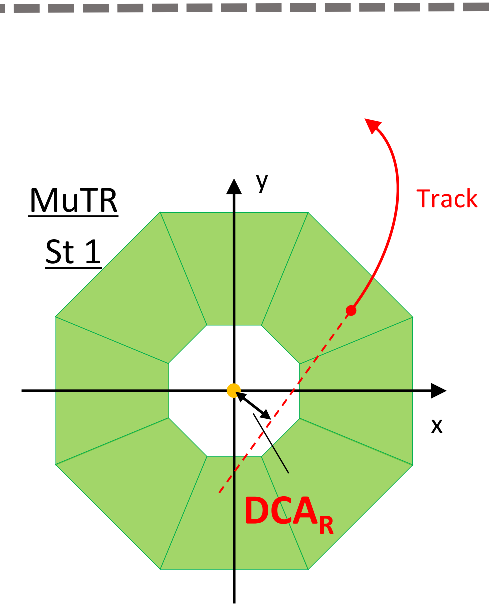
Used in W_{ness} Calculation ← Uncorrelated → **Used in EUMLF, SBR Extraction**

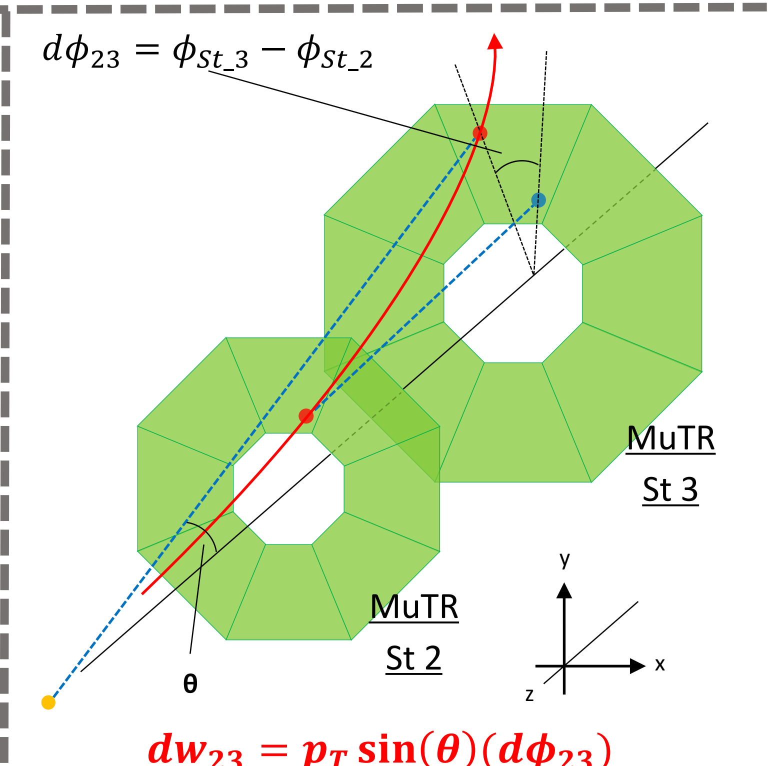
Discriminating Kinematic Variables - Schematic

Each Discriminating Variable is Chosen because:

1. Its distribution can be **meaningfully normalized**
2. Its distribution has a **shape depending on the data set** composition

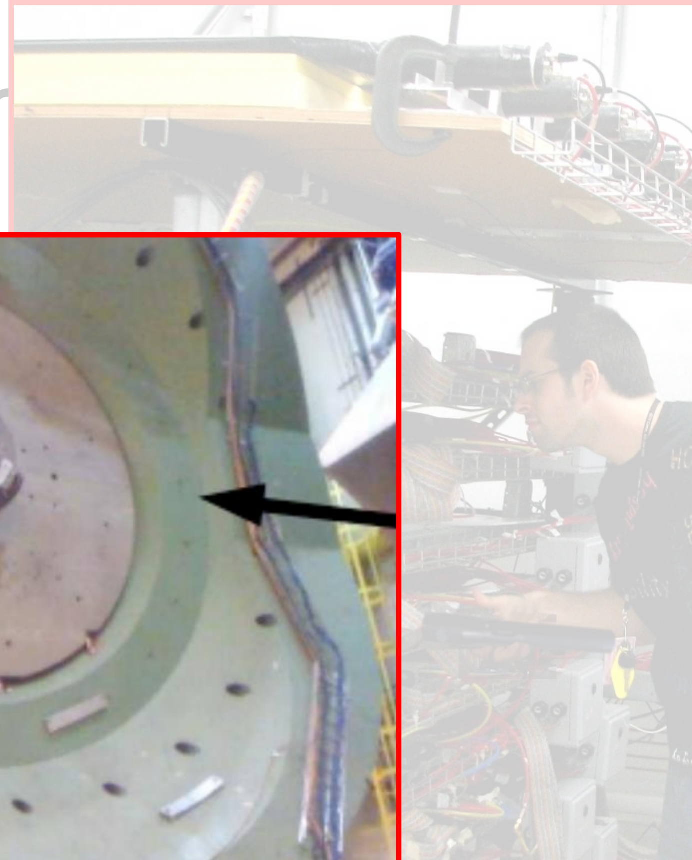


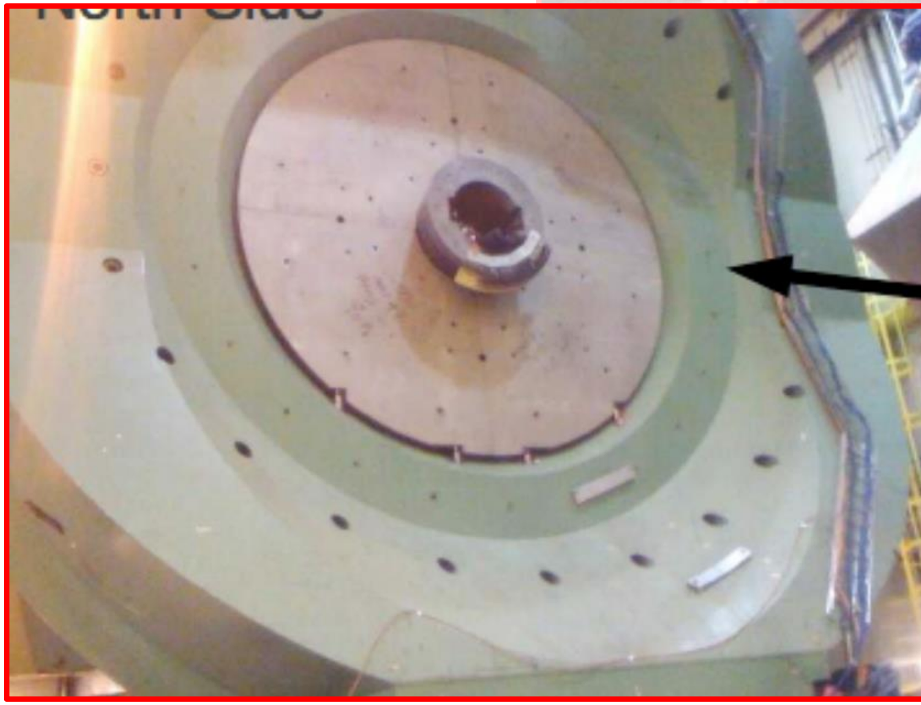




Graphics By Chong Kim

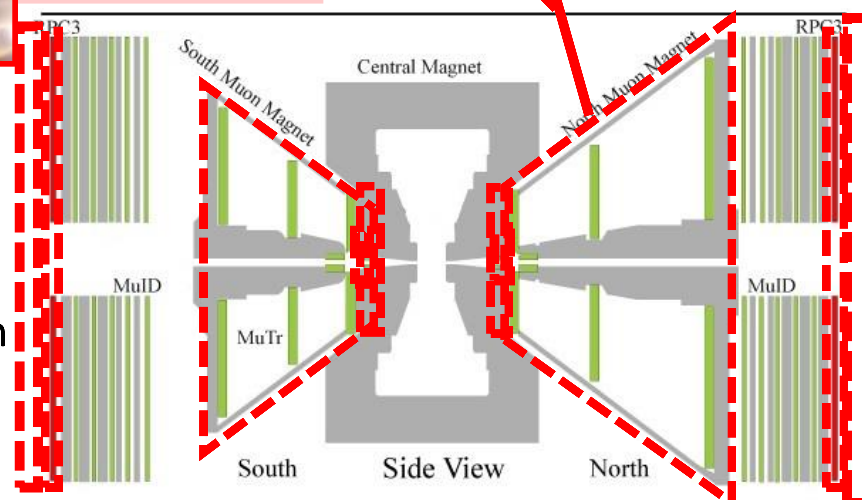
Forward W Pl luon Arms



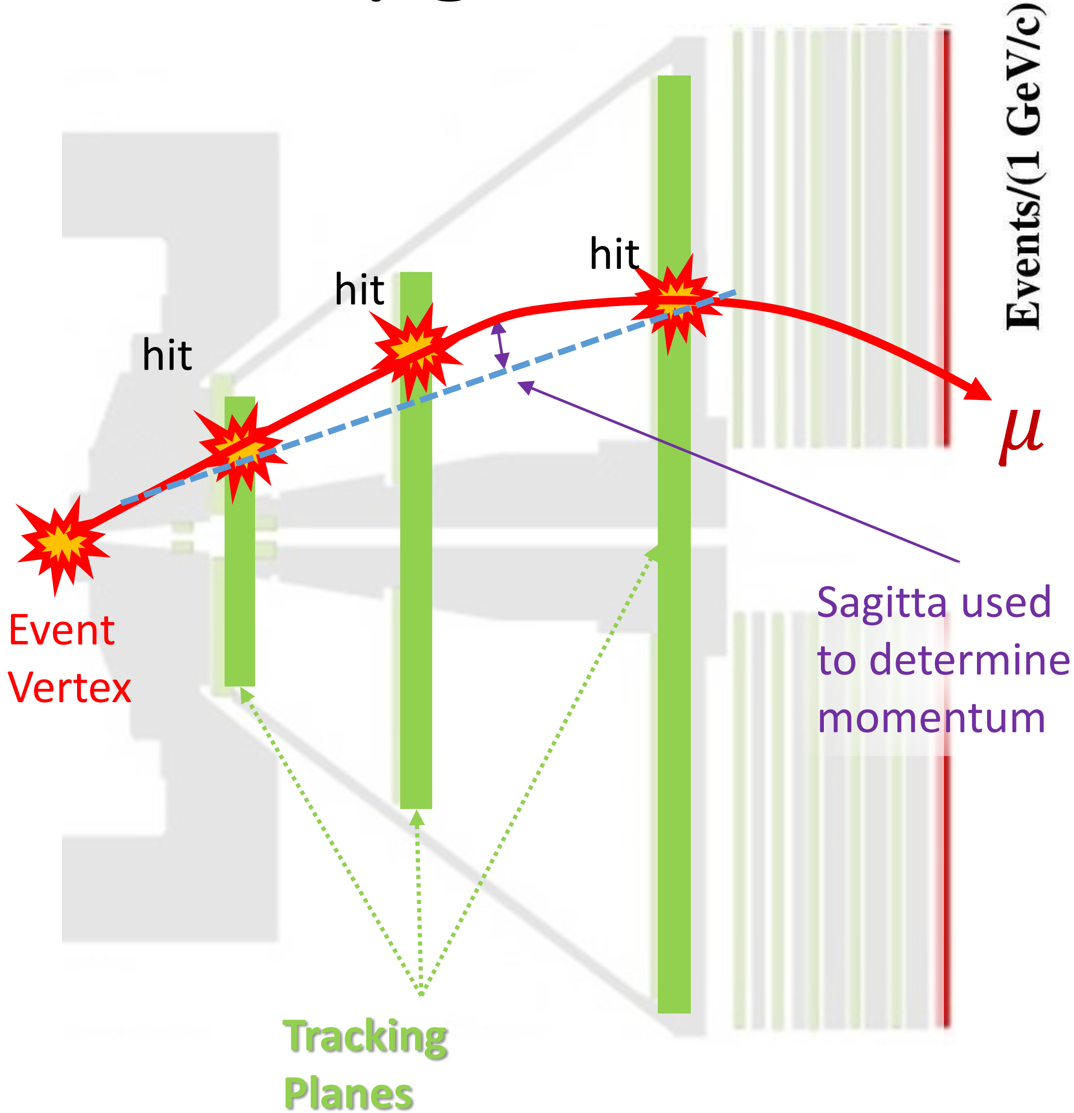


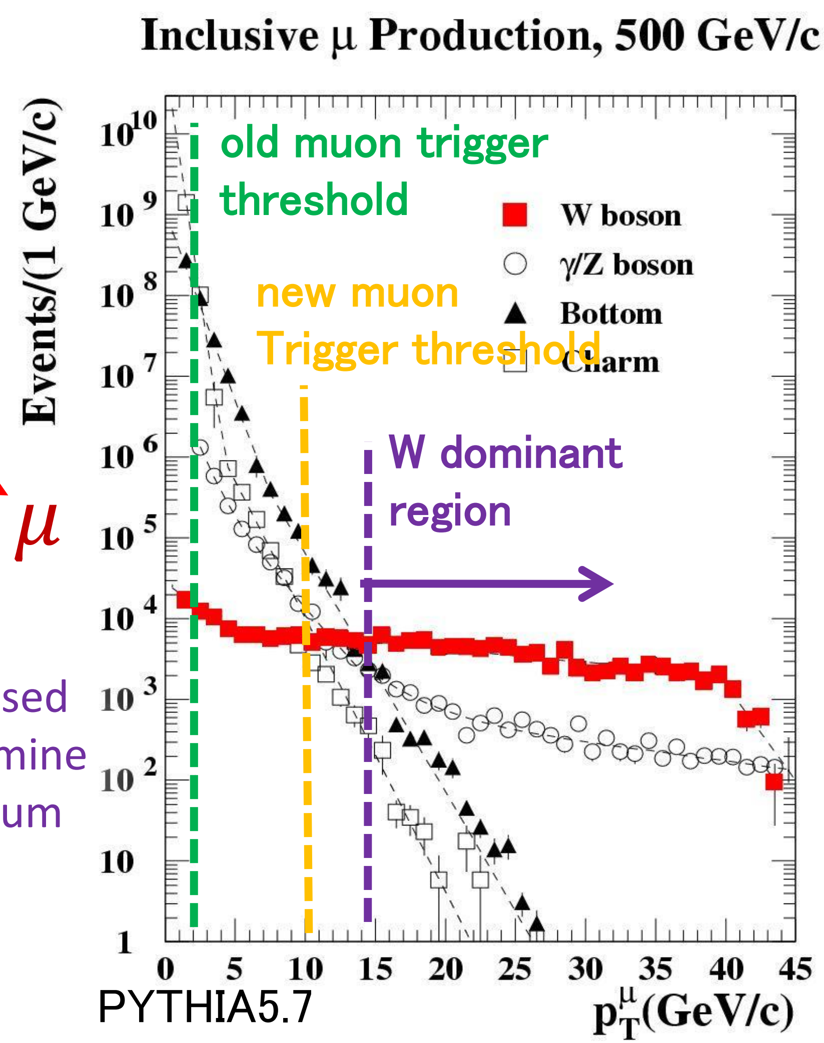
Upgrades required to properly trigger on $W \rightarrow \mu$ events:

- 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



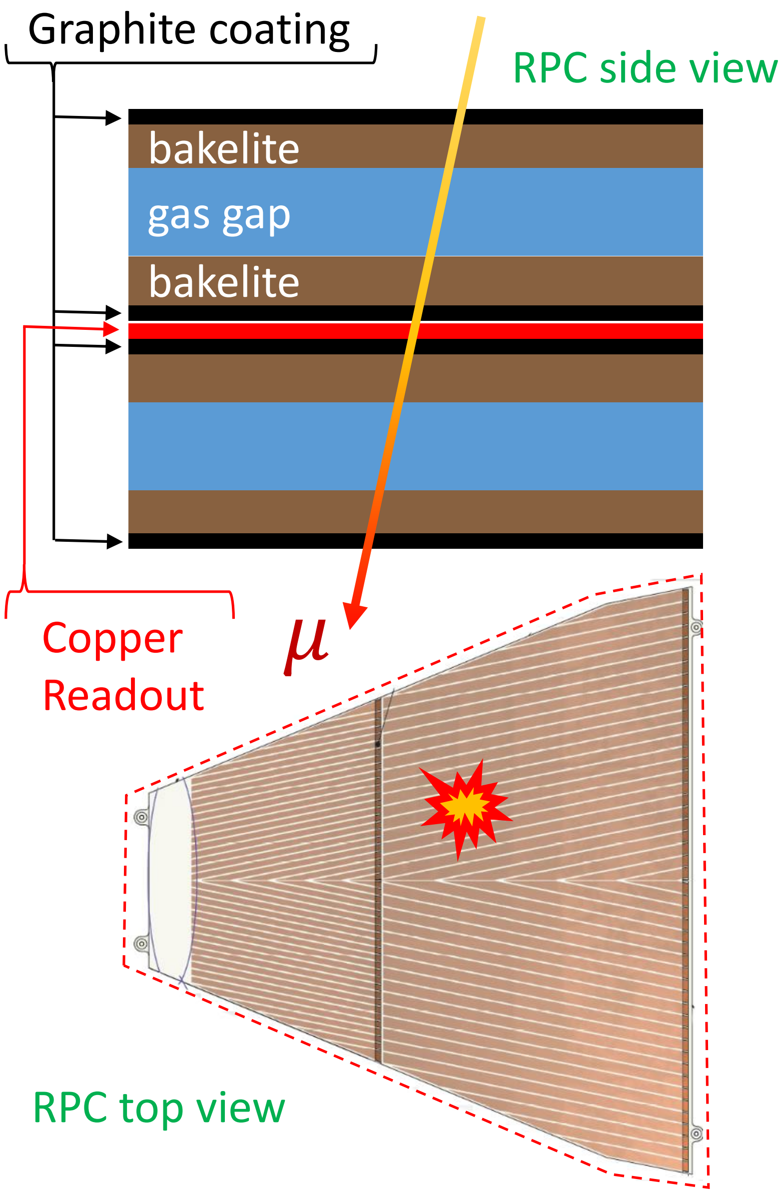
MuTr Upgrade





We can record ALL $W \to \mu$ 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

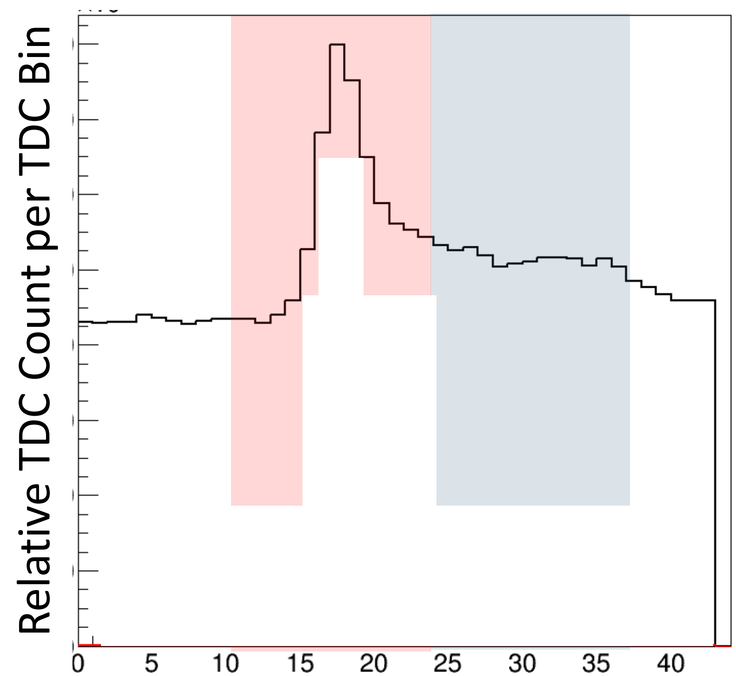
Hardware Support

I built and tested the RPC hardware

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)

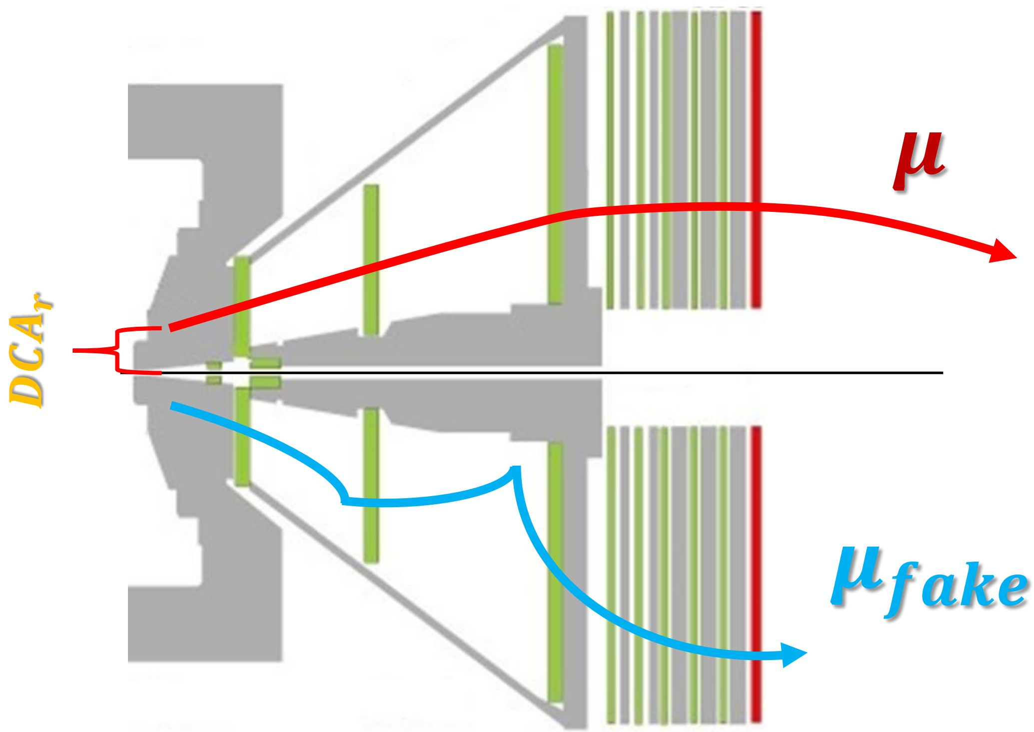
TDC Track Matched Region (scaled for comparison)

Incoming Beam Background Timing Region

PHASE 2- Forming P.D.F.s For Wness

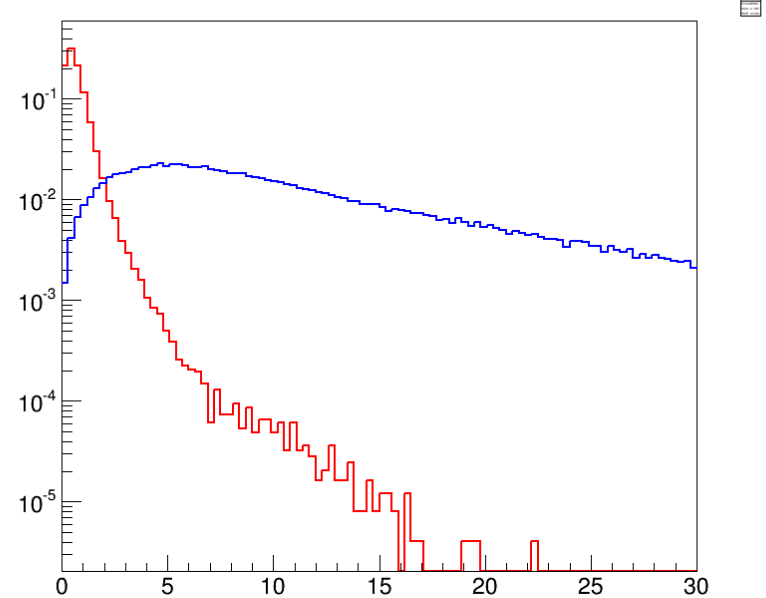
Calculate Likelihood

Example: forming P.D.F.s for kinematic variables used to calculate the Wness of an event



- Real Muons
- Fake Muons

Relative DCA_r distribution Shapes for $W \to \mu$ and **data**



Some kinematic variables are highly correlated – in which case 2D distributions are utilized.

PHASE 2 – Calculation of Wness

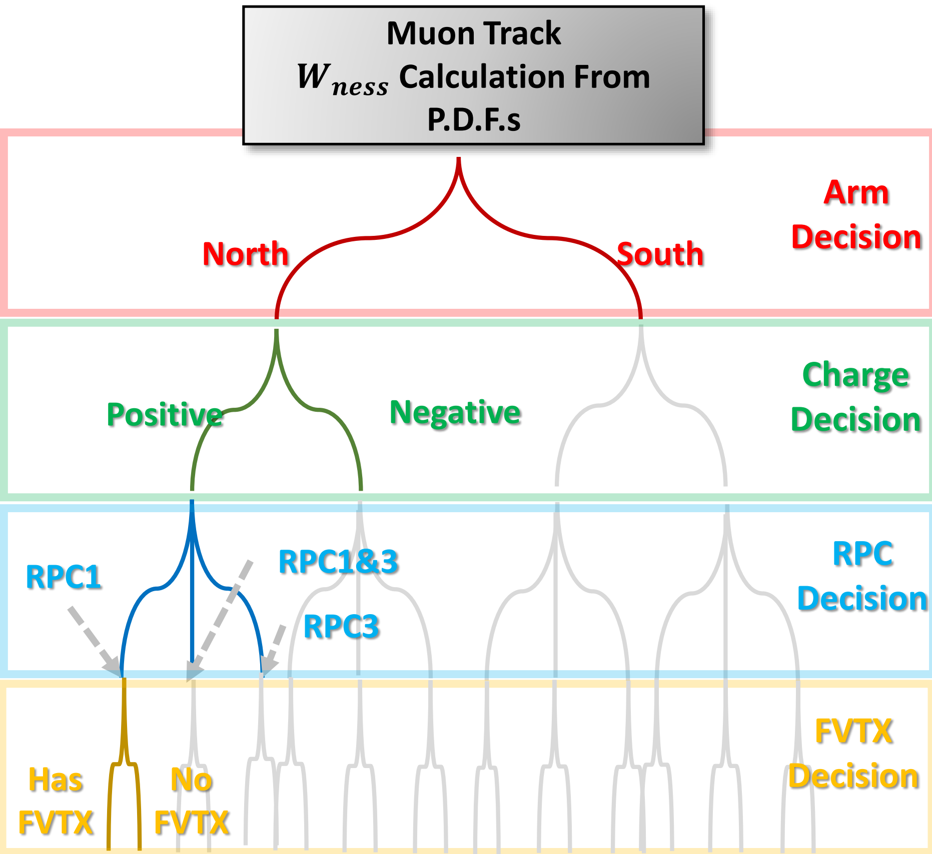
Calculate Likelihood

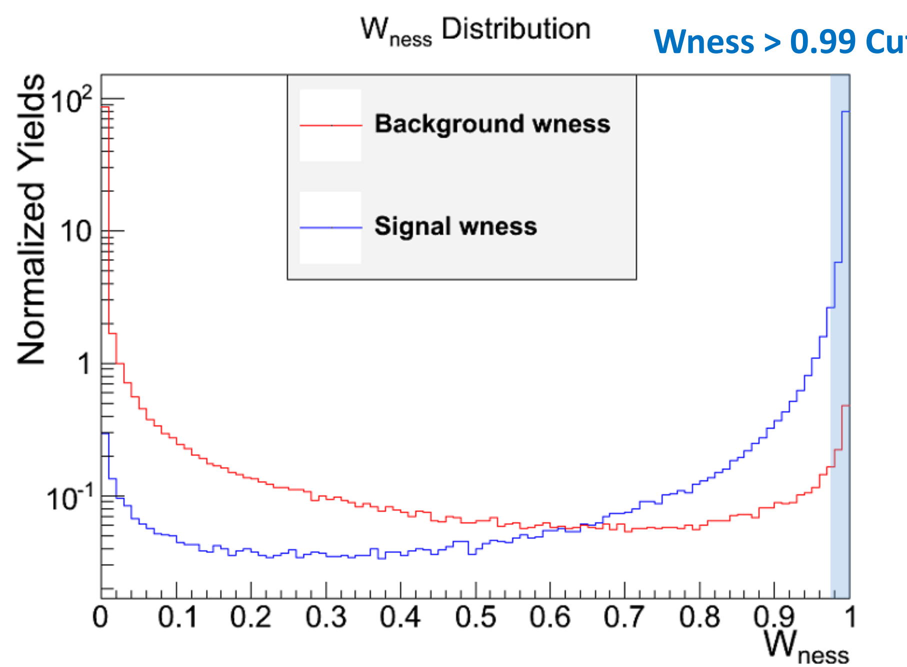
Constructing a set of unique P.D.F.s to calculate Wness each event, characterized by each event's properties

$$W_{ness} \equiv f(x_i) \equiv \frac{\lambda_{sig}(x_i)}{\lambda_{sig}(x_i) + \lambda_{bg}(x_i)}$$

$$W_{ness} \rightarrow 0 \Rightarrow W \rightarrow \mu \; is \; unlikely$$

$$W_{ness} \rightarrow 1 \Rightarrow W \rightarrow \mu \; is \; likely$$

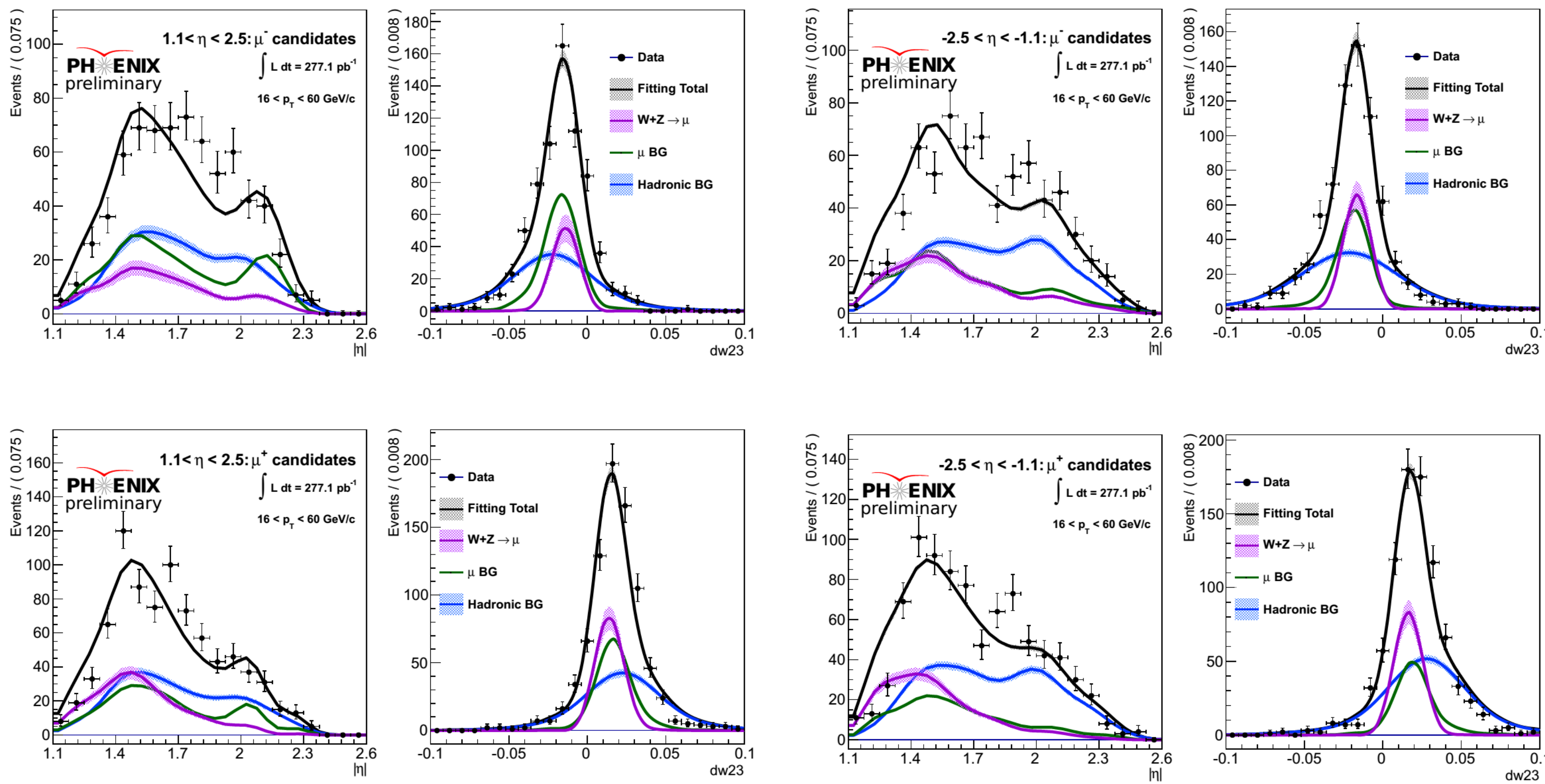




Unbinned Maximum Likelihood Fit

Extract Signal to Background Ratio

Unbinned Maximum Likelihood: New PDFs fit to data sensitive to differences in Fake Muons, Real Background Muons, and W-signal muons are fit to data.



Modeling dw23 with Wness Dependence

- We fit the dw23 vs Wness region from 0.1 < Wness < 0.9 in order to extrapolate its value in high Wness, in order to seed the Hadronic Background PDF

$$\mu = P_0 + P_1 W_{ness} \qquad \sigma_2 = P_4 + P_5 W_{ness}$$

$$\sigma_1 = P_2 + P_3 W_{ness} \qquad C_g = P_6 + P_7 W_{ness}$$

$$g(W_{ness}, dw_{23}) = C_w \times \left(\left(\frac{1}{\sqrt{2\pi}\sigma_1 + C_g\sqrt{2\pi}\sigma_2} \right) \times \left(\left(e^{-\frac{1}{2}\left(\frac{dw_{23}-\mu}{\sigma_1}\right)^2} + C_g e^{-\frac{1}{2}\left(\frac{dw_{23}-\mu}{\sigma_2}\right)^2} \right) \right) \right)$$

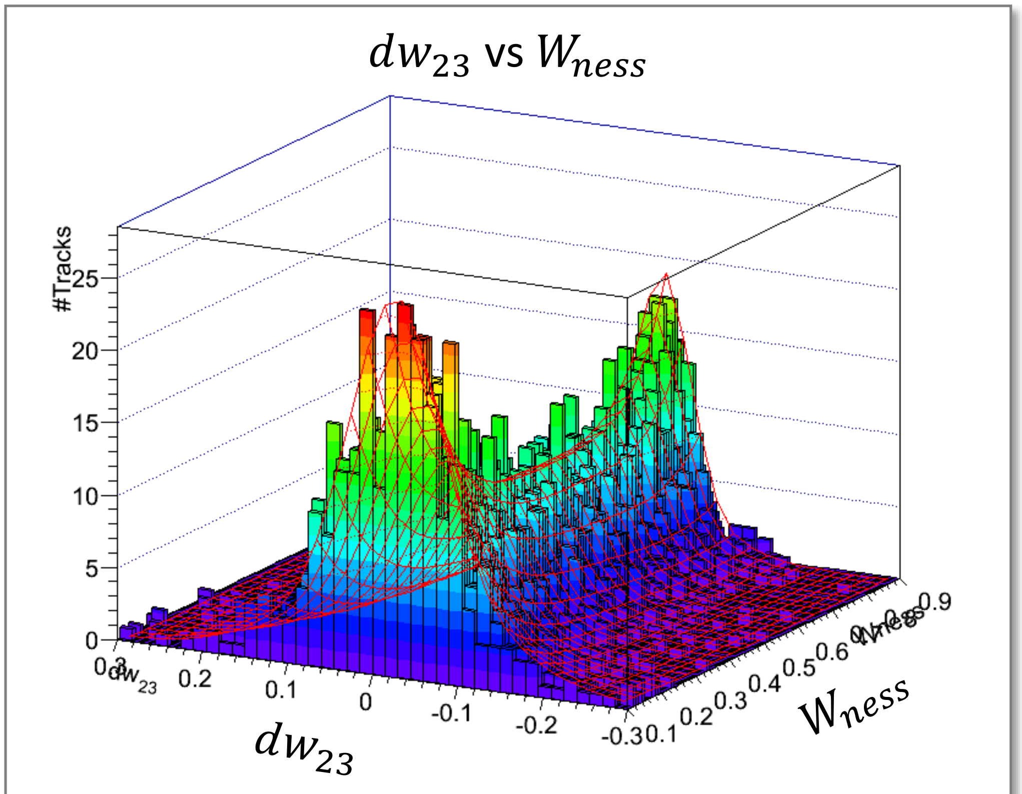
$$f(W_{ness}) = P_8 + P_9 W_{ness} + P_{10} W_{ness}^2 + P_{11} W_{ness}^3 + P_{12} W_{ness}^4$$

$$\boldsymbol{F(W_{ness}, dw_{23}) = f(W_{ness}) \times g(W_{ness}, dw_{23})}$$

PHASE 3 - Improving dw_{23} Extraction

Extract Signal to Background Ratio

Our ability to extract *only* the hadronic background P.D.F.s from the combined data set directly affects our ability to create a signal to background ratio. Can this be improved?



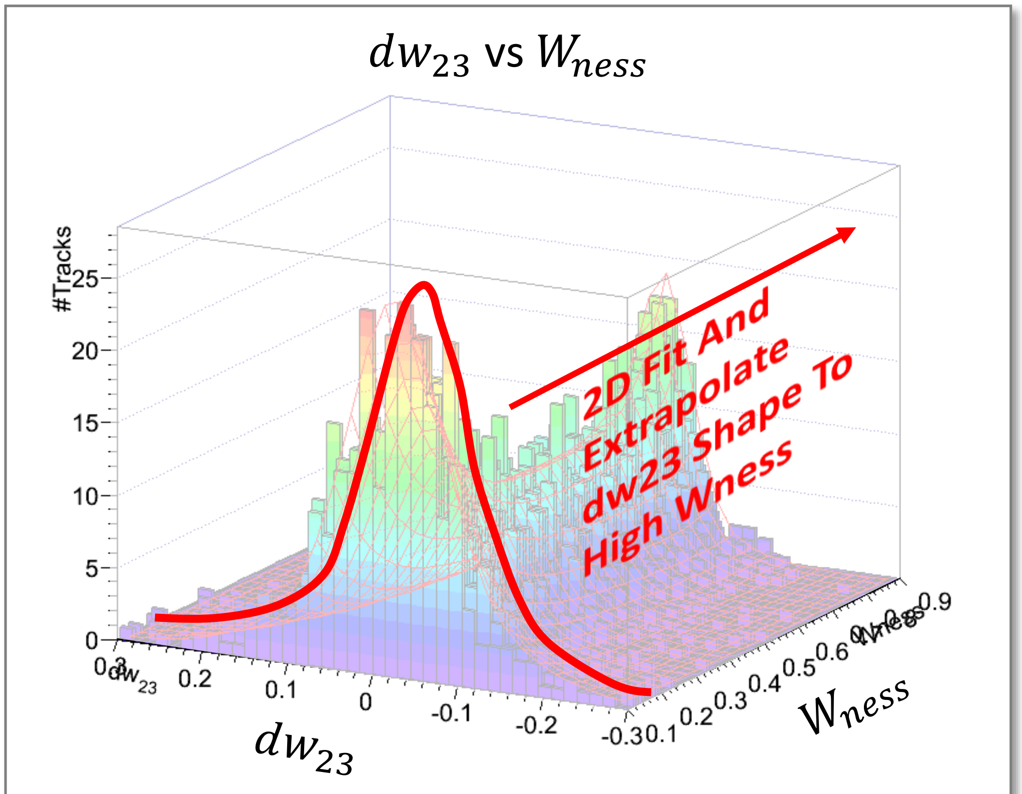
dw_{23} varies width with Wness – so we fit dw_{23} vs W_{ness} in order to extrapolate shape of dw_{23} Hadronic background P.D.F. in high Wness range

$$dw_{23}\colon 0.1 < W_{ness} < 0.9 \rightarrow$$
$$dw_{23}\colon W_{ness} = 0.92$$

PHASE 3 - Improving dw_{23} Extraction

Extract Signal to Background Ratio

Our ability to extract *only* the hadronic background P.D.F.s from the combined data set directly affects our ability to create a signal to background ratio. Can this be improved?



The shape of dw23, and its dependence on Wness is determined in the low-signal region of the dw23 vs Wness distribution.

The shape of dw23 is then extrapolated into the high Wness region so as to approximate the P.D.F. for hadronic background events in the high-Wness region.

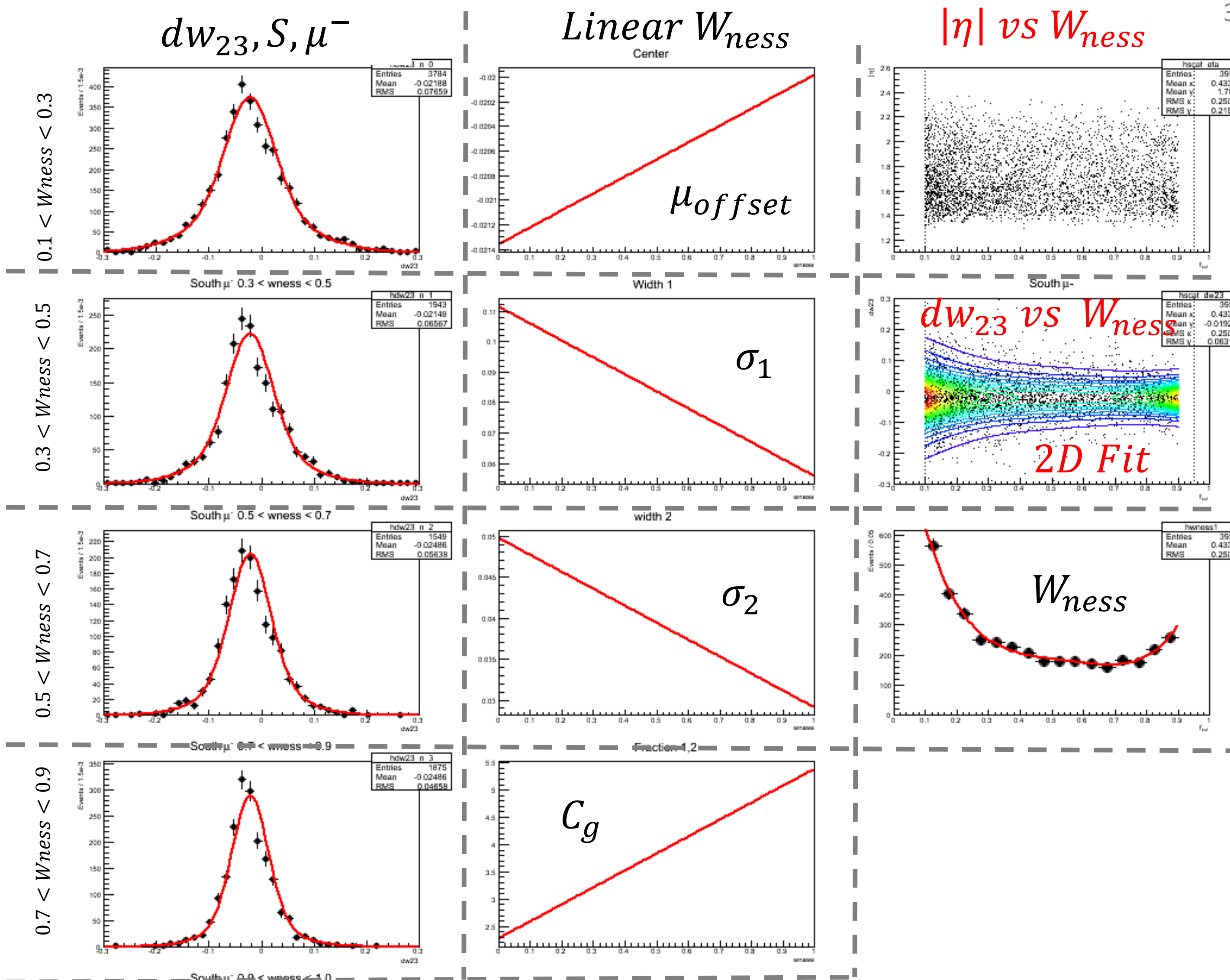
However, due to lower than expected asymmetries, we need to understand how well our P.D.F.s perform in extracting the real distributions of data in the high Wness region.

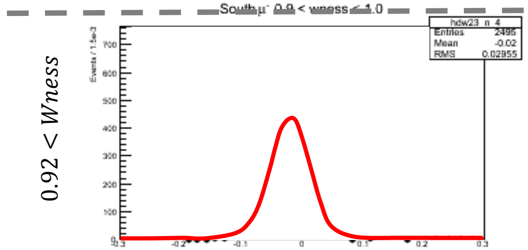
Hadronic Background P.D.F. – dw23

We extrapolate dw23 into high Wness to obtain shape for P.D.F

Similar extrapolations are performed for other arm/charge configurations with good results.

Red Curve is projection of 2D fit

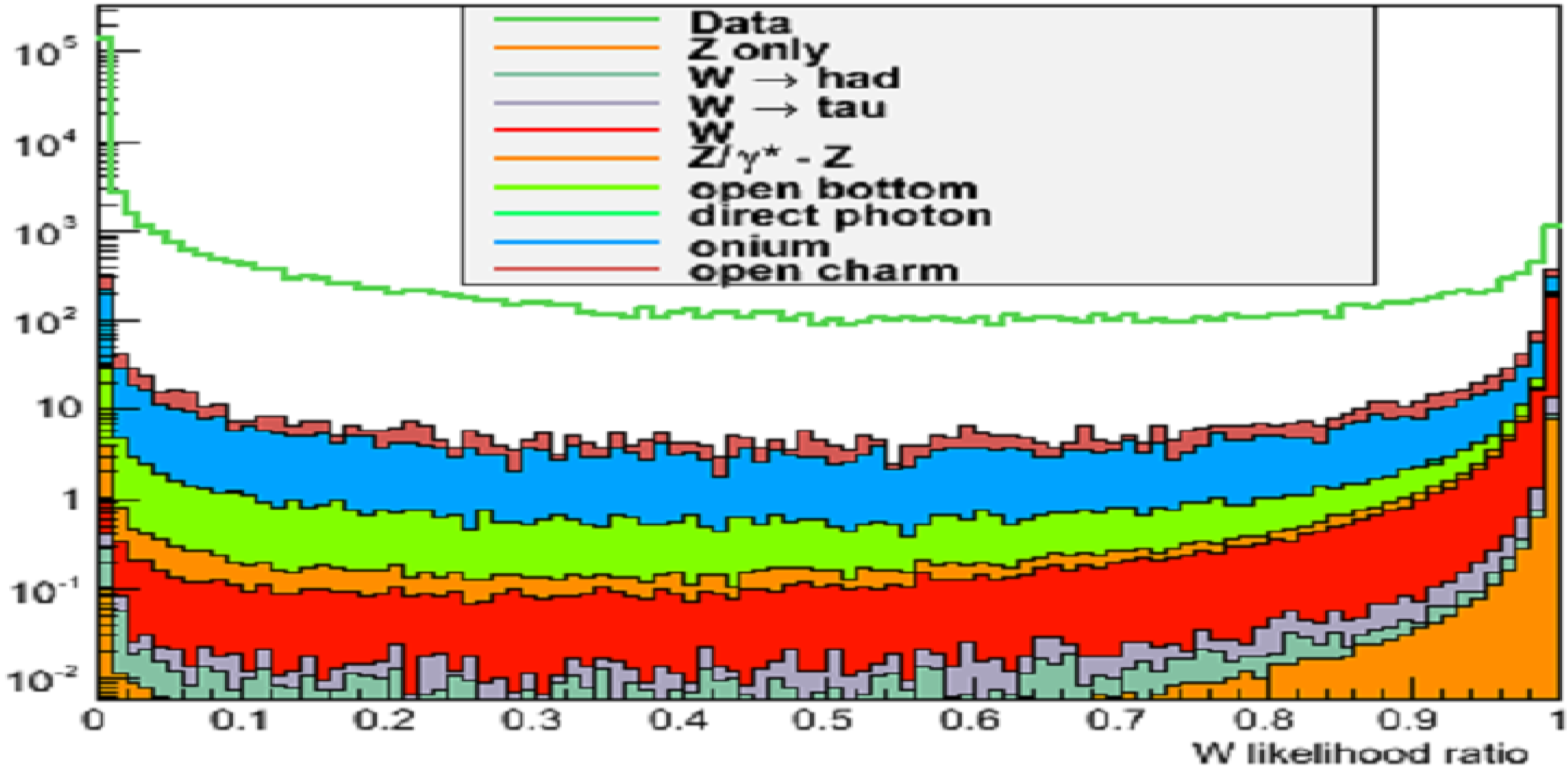




High Wness Region – we extrapolate the shape of Hadronic background into this region – which also contains W signal and muon background.

Merging Muon Background Simulation

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

Muon Background Cocktail

	final yield	generatd events	luminosity correction	correction factor
Charm	84.54	5.85e+11	2.23e-01	5.40e-01
Onium	89.16	1.50e+11	2.05e-01	1.90e-01
direct γ	0.21	5.84e+10	2.08e-01	2.08e-01
Bottom	48.38	7.36e+09	2.26e-01	1.24e-01
Z+DY	87.8	2.93e+08	1.24e-02	1.94e-02
$W \rightarrow \tau$	5.12	3.43e+08	1.10e-03	7.88e-04
$W \rightarrow hadrons$	0.09	3.42e+08	1.11e-03	7.90e-04
Z	46.61	1.73e+08	4.44e-04	7.00e-04

Table 3.1: Muon background factors used for weighting/scaling various muon backgrounds before adding to generate muon background distributions. This particular table shows values for the south arm, negative charge.

Signal To Background Ratios

	South μ^-	South μ^+	North μ^-	North μ^+
Total events	708	810	704	845
Signal events	$143^{+26.95}_{--26.49}$	$237^{+28.49}_{--27.86}$	$180^{+25.38}_{--24.77}$	$235^{+26.57}_{--25.83}$
Hadron events	$298^{+28.50}_{--27.21}$	$334^{+29.53}_{--28.39}$	$326^{+26.41}_{--25.34}$	$429^{+29.23}_{--28.27}$
Muon events	267	239	197	181
Signal/BG	$0.25^{+0.06}_{-0.06}$	$0.41^{+0.07}_{-0.07}$	$0.34^{+0.07}_{-0.06}$	$0.38^{+0.06}_{-0.06}$
old S/BG	0.38	0.30	0.37	0.26

Data subject to Wness cut of 0.95