PHENIX W Measurements in polarized p+p collisions

22nd International Spin Symposium
Hosted by: University of Illinois and Indiana University
September 25-30, 2016 at UIUC

Sanghwa Park
(Stony Brook University)
for the PHENIX collaboration

Proton Spin Structure

Haiwang Yu

Quark & gluon orbital angular momentum

Quarks Gluon

$$< S_z >= \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

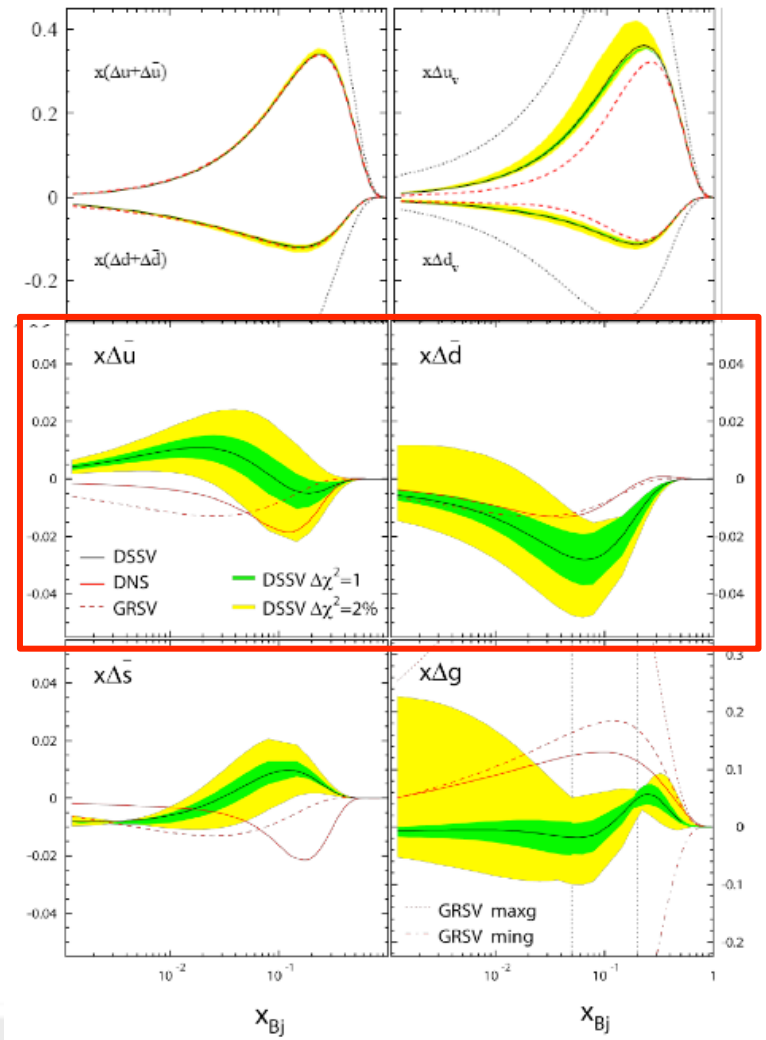
- Sum of quark contributions to the proton spin is measured to be ~30%

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

- Well known combined quark PDFs via DIS
- SIDIS sensitive to flavor separated quark and anti-quark PDFs

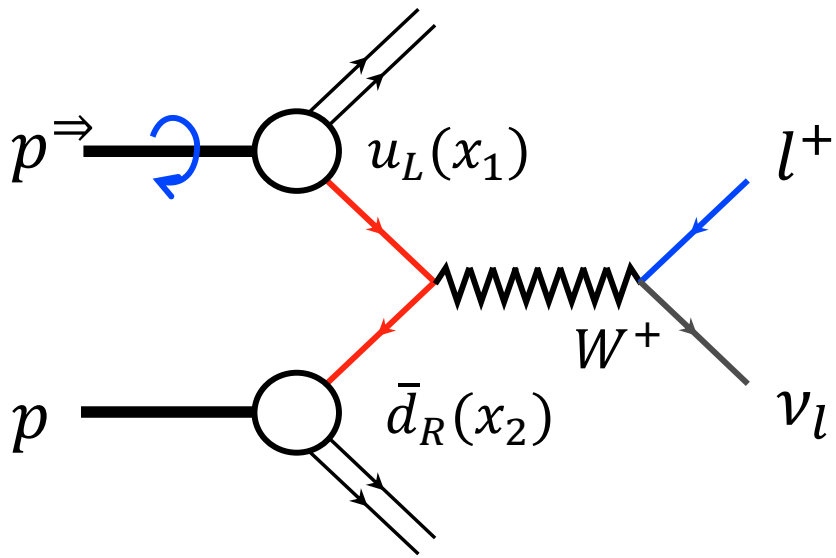
  → limited by the knowledge of fragmentation functions and their uncertainties

De Florian et al. PRL 101, 072001 (2008)



A_L^W Measurement

- Probing light quark sea via maximally parity violating W production and its lepton decay
- W couples only to left-handed quarks and right-handed anti-quarks
- W^+/W^- distinguishes between quarks and anti-quarks
- No fragmentation needed
- High Q^2 set by W mass



$$u_L \bar{d}_R \rightarrow W^+$$

$$d_L \bar{u}_R \rightarrow W^-$$

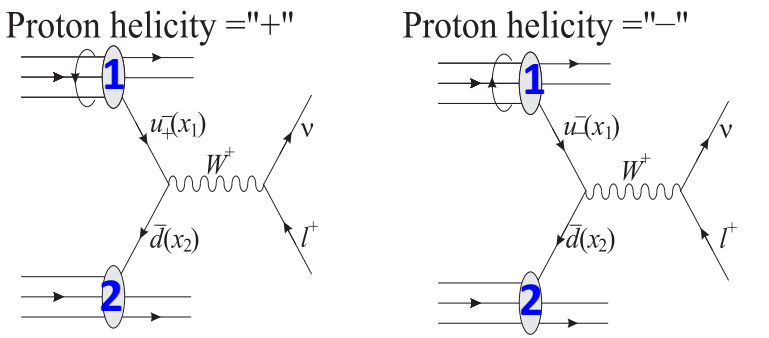
A_L^W Measurement

- Longitudinal single spin asymmetry direct access to quark helicity PDFs

$$A_L \equiv \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

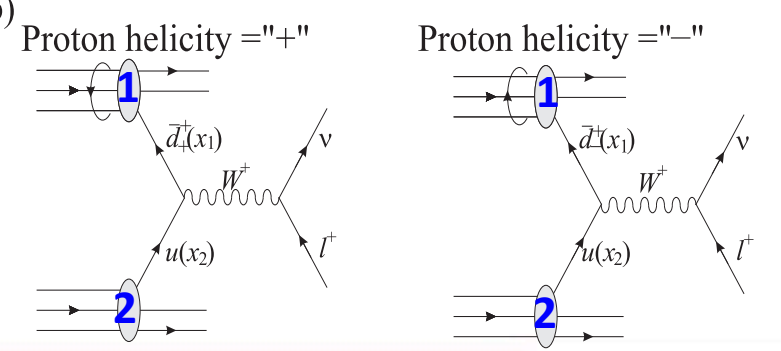
$$A_L^{W^+} = \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

(a)



$$-\frac{\Delta u(x_1)}{u(x_1)}$$

(b)



$$\frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}$$

$A_L^{W\to\ell}$ Measurement

- Longitudinal single spin asymmetry direct access to quark helicity PDFs

$$A_L \equiv \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

- Combined with weak decay kinematics
  - quark flavor mixed at mid-rapidity
  - sensitive to anti-quark polarization at forward/backward rapidity measurement

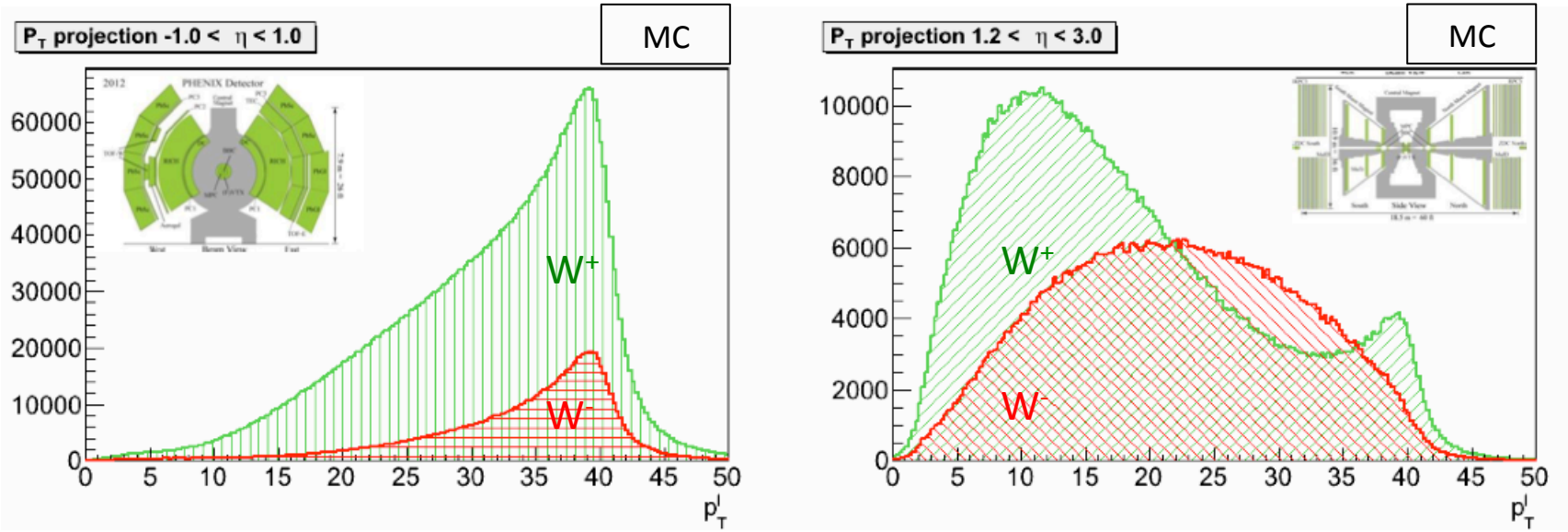
$$A_L^{W^+} = \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)}$$

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

$$A_L^{W^-\to\ell^-} \approx \frac{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}{\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}$$

$$A_L^{W^+\to\ell^+} \approx \frac{\Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2}{\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 + u(x_1)\bar{d}(x_2)(1-\cos\theta)^2}$$

$W^{\pm} \rightarrow \ell^{\pm}$ Kinematics

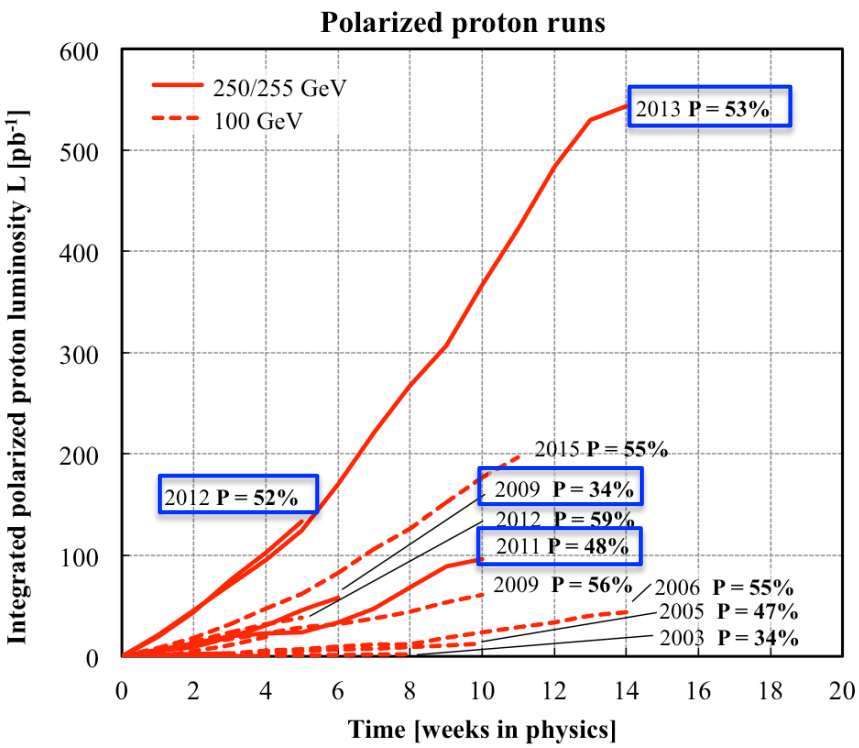


- Different kinematics at mid-rapidity and forward rapidity
- Jacobian peak at mid-rapidity
- Suppressed/no Jacobian peak at forward rapididty
- Access via two decay channels: electrons at mid-rapidity and muons at forward rapidity
- Different analyses to identify W signals in mid- and forward rapidities

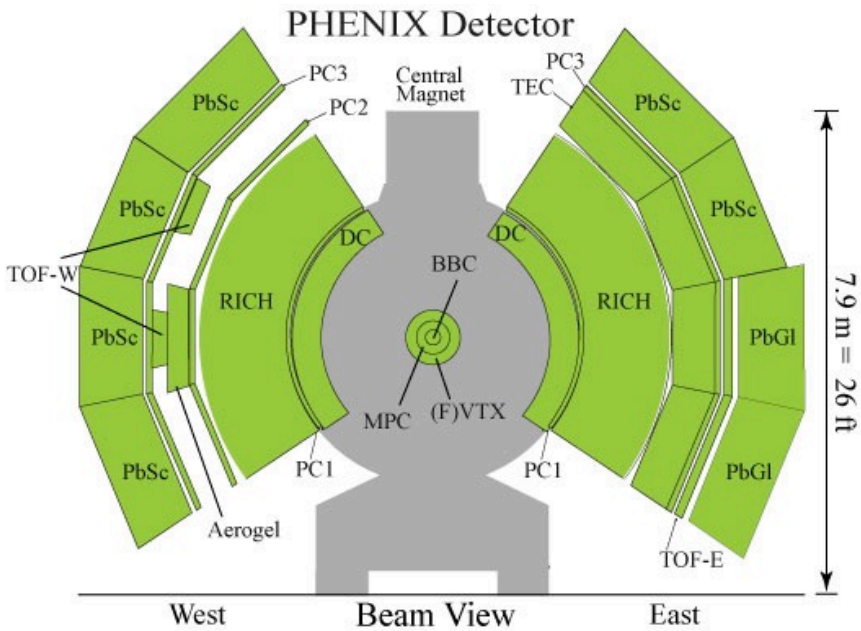
PHENIX

Polarized Proton Data

- First mid-rapidity A_L measurement at 500 GeV in 2009
- Followed by over 300 pb^{-1} data taken with higher beam polarization (2011-2013)
- 2011-2013 mid-rapidity results published this year!
- Forward rapidity preliminary results
  → Results being finalized

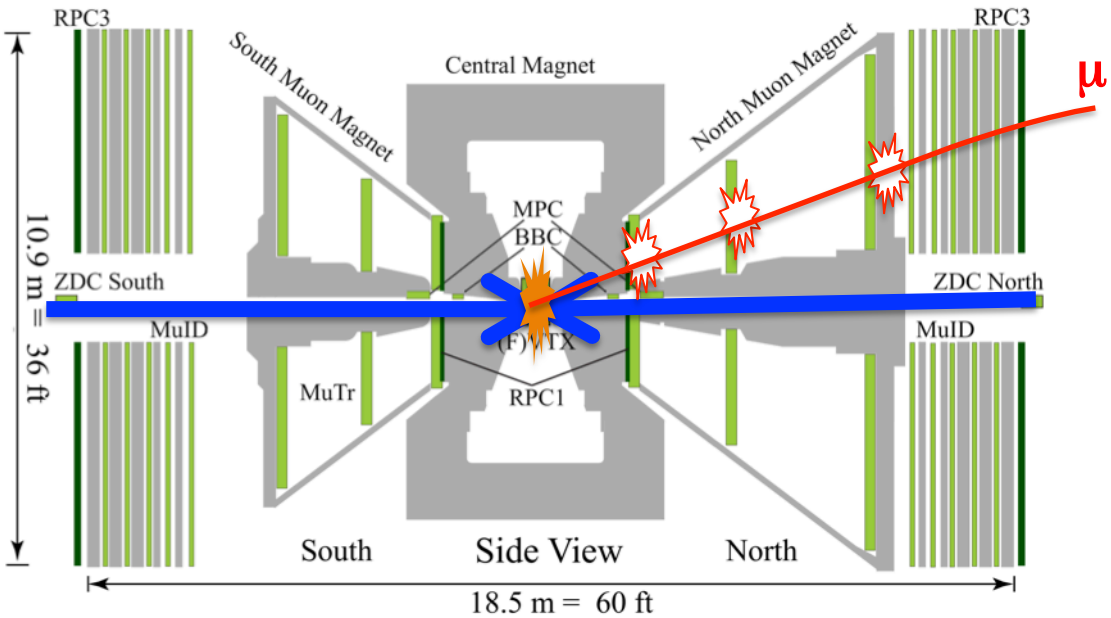


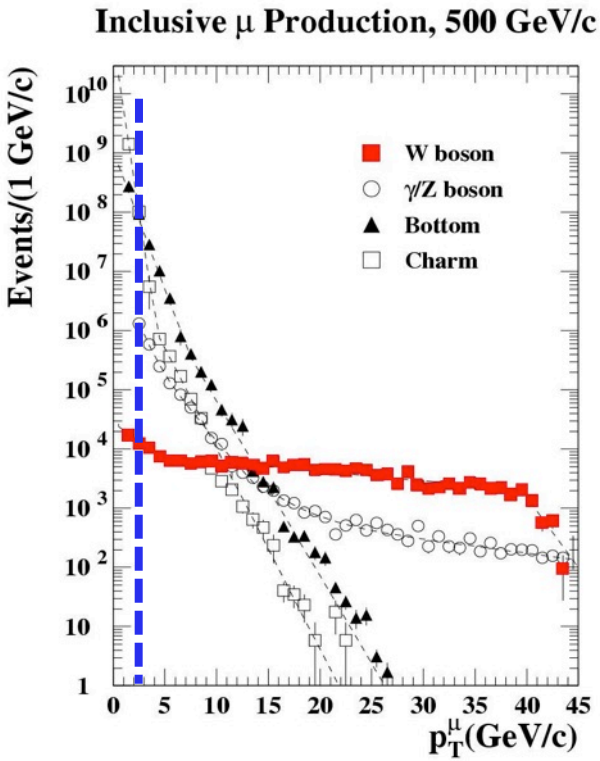
PHENIX Central Arm Detector



- $W^{\pm} \rightarrow e^{\pm} + \nu_e$ channel
- Two arm detector
  - $\Delta\phi = (\pi/2)\times 2$
  - $|\eta| < 0.35$
- High energy electron trigger by Electromagnetic Calorimeter (PbSc, PbGl)
- Drift chamber (DC) and Pad chamber (PC) for tracking and charge separation

PHENIX Forward Arm Detector





- $W^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$ channel
- Two arm detector
  - $1.2 < |\eta| < 2.4$
  - Full azimuthal coverage
- Fully upgraded in 2012
  - high pT trigger, Resisitve Plate Chambers (RPC), Forward Silicon Trackers (FVTX)

- Muon tracking chamber (MuTr)
- Muon Identifier (MuID)
- High-p_T trigger:
  small bending in magnetic field
  + timing (BBC/ RPC)
- RPCs, FVTX: Additional BG rejection

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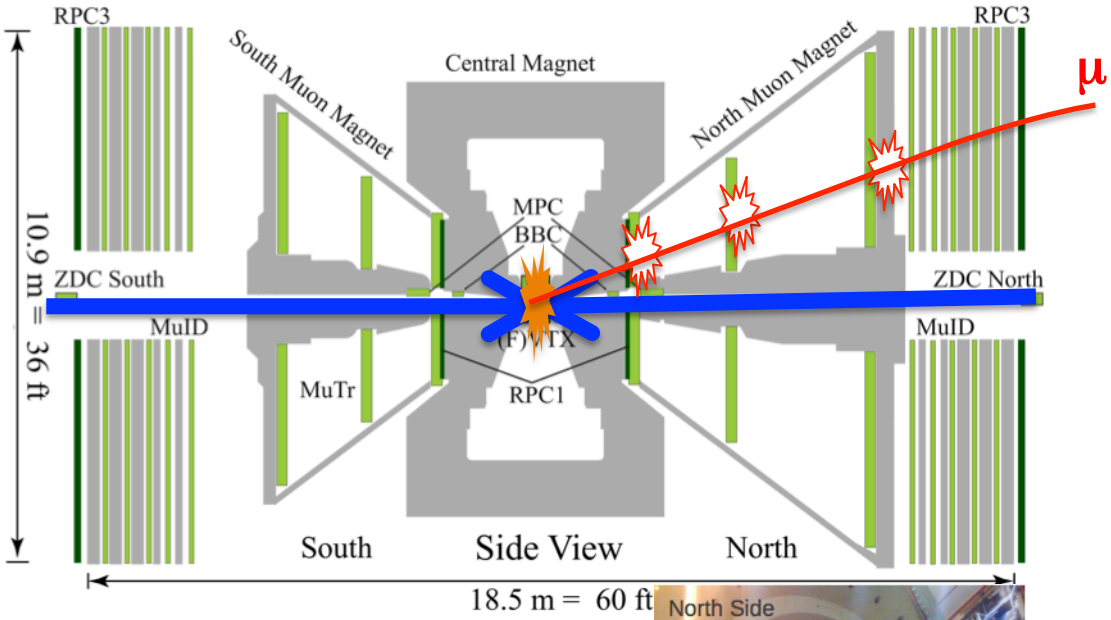

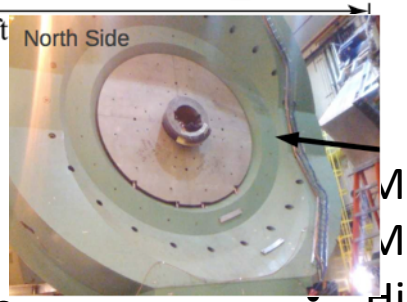

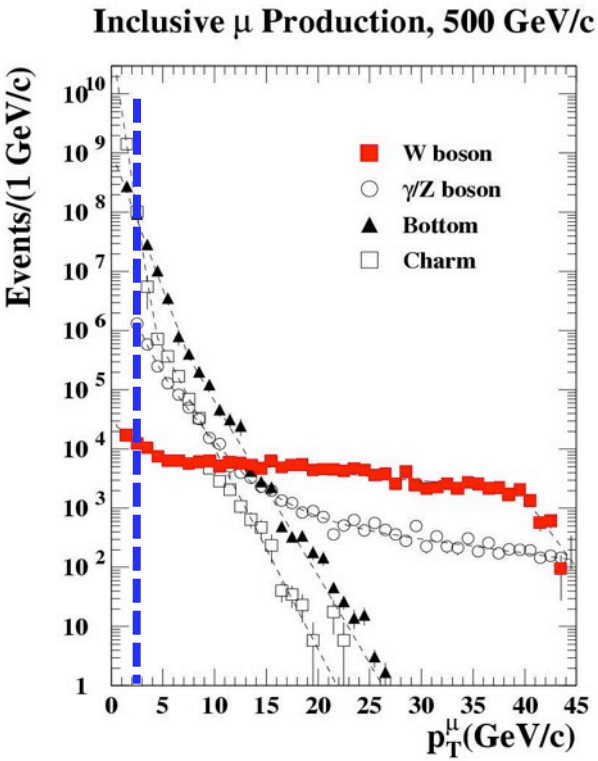

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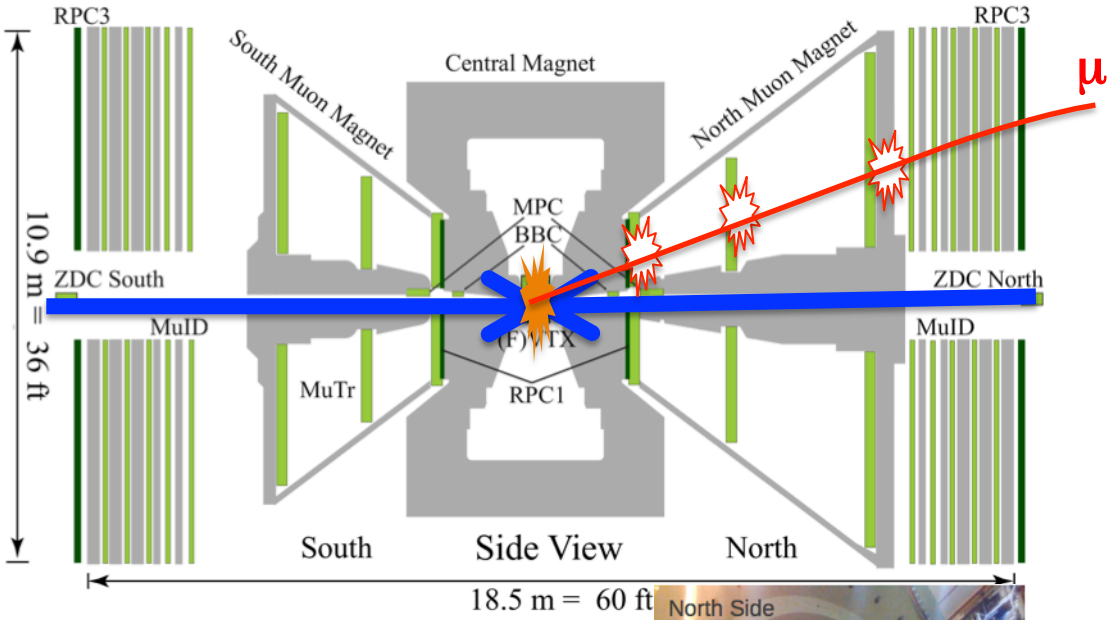

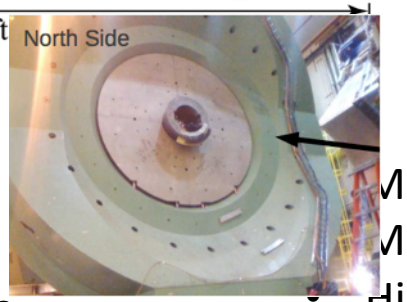

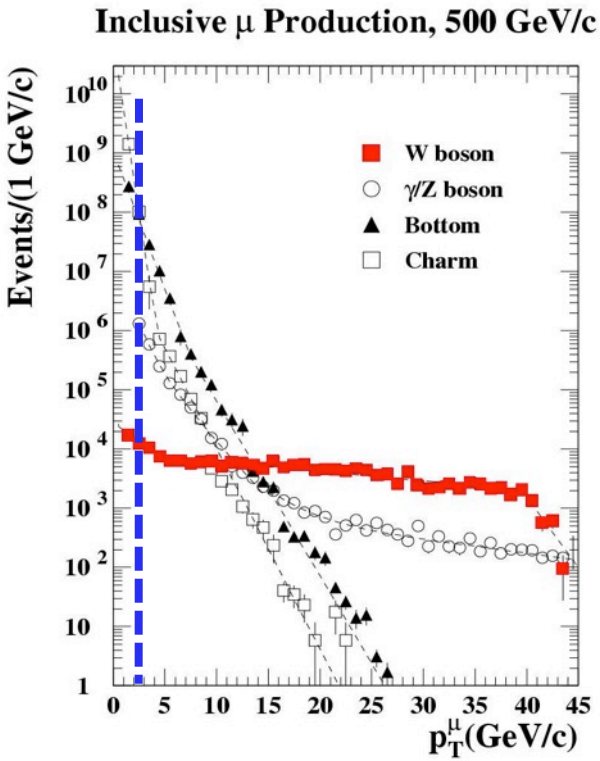

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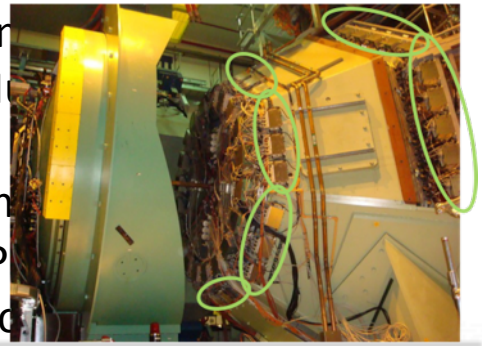

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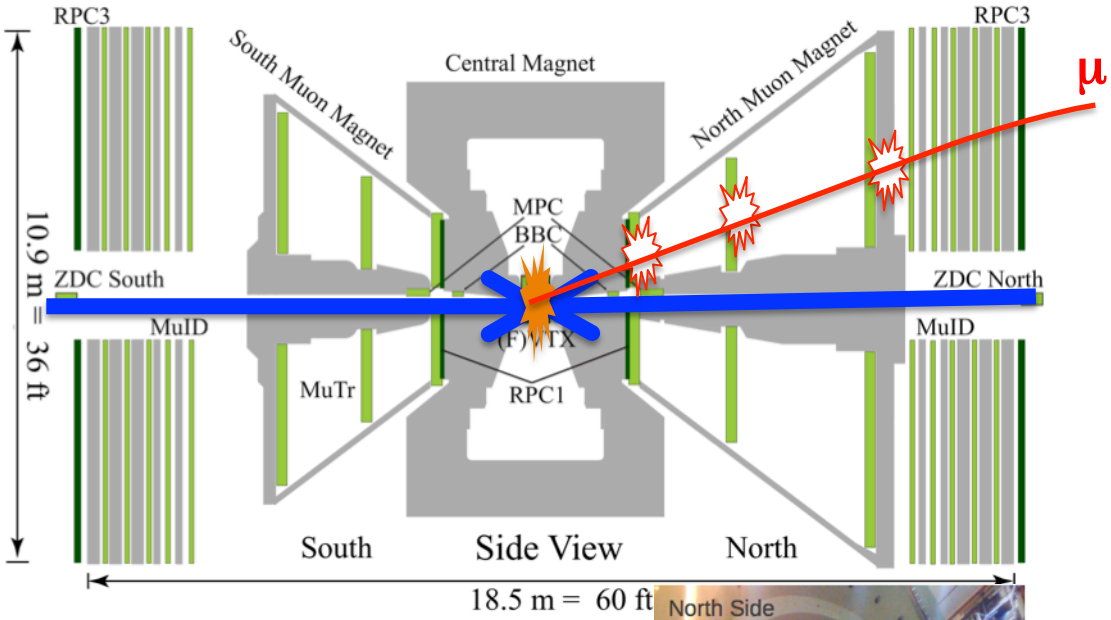

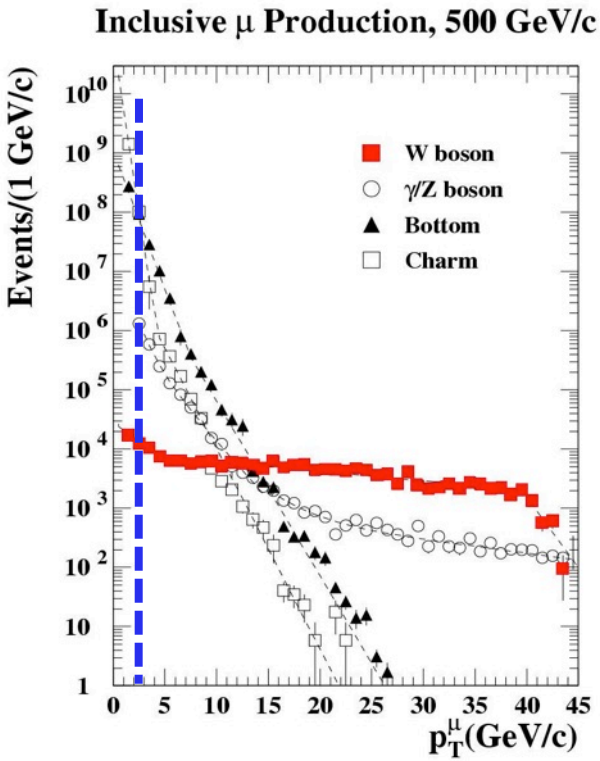

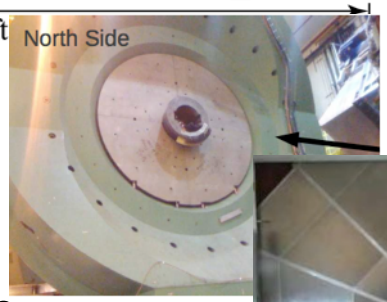

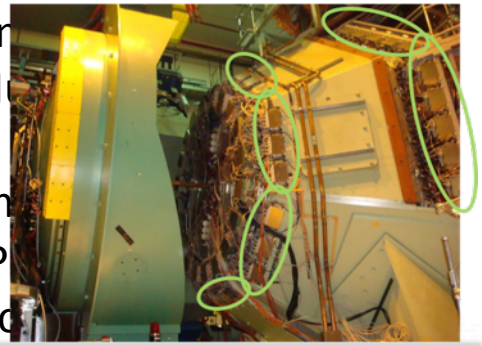

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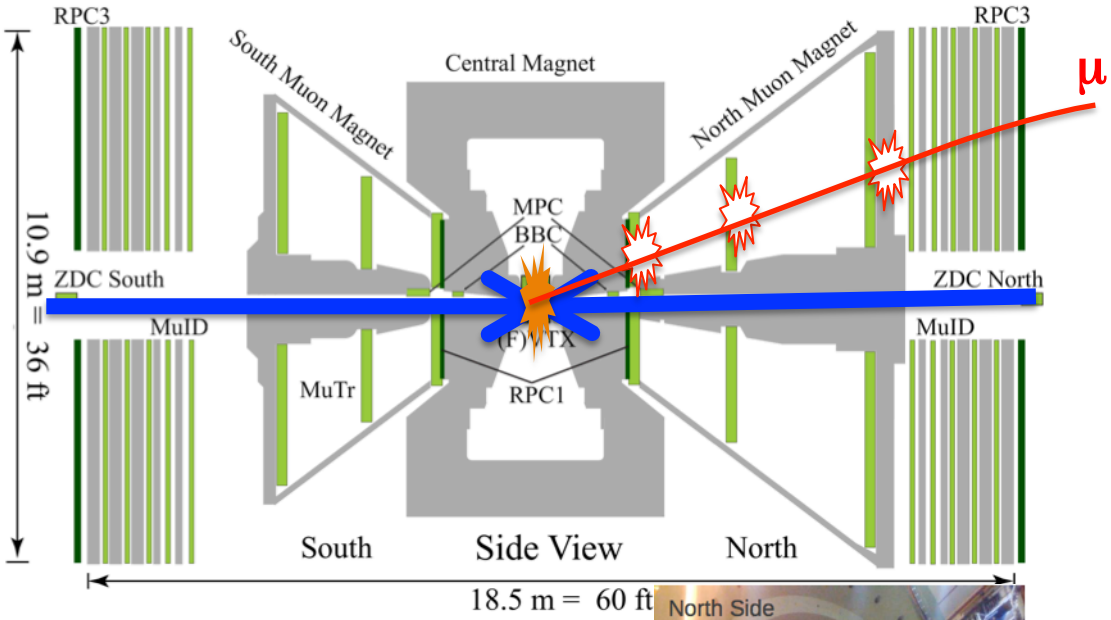

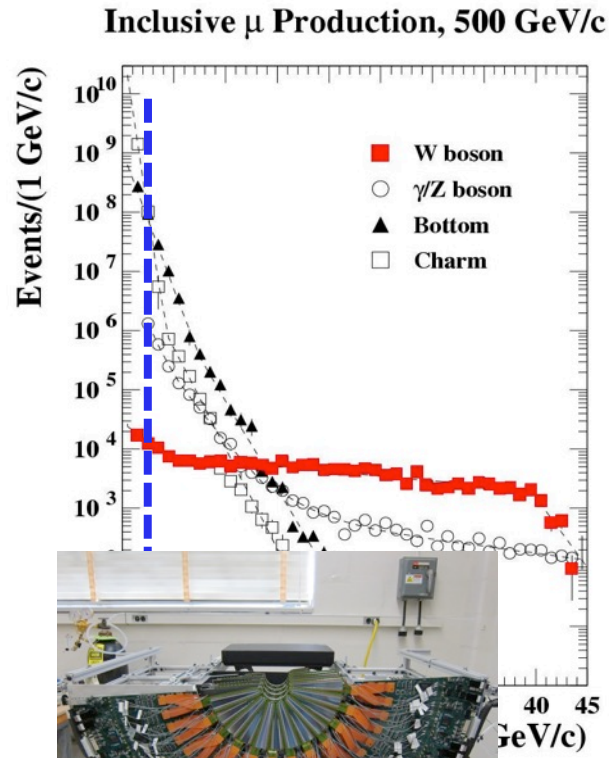

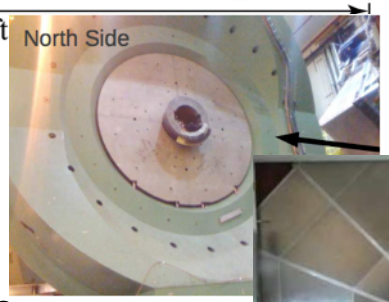

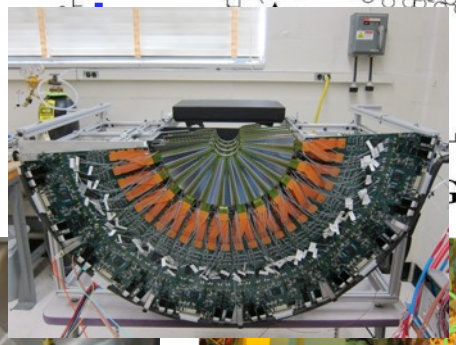

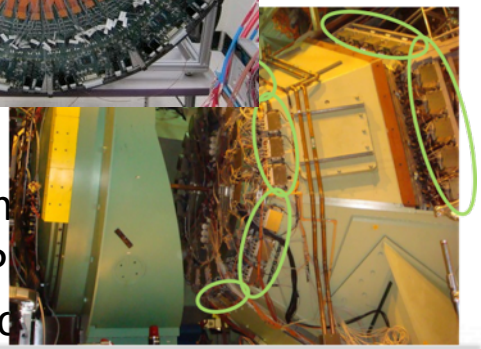

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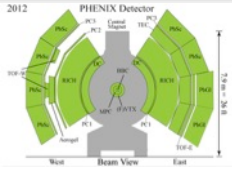
Mid-rapidity Measurement



- Jacobian peak at pT ~ $M_W/2$
- Backgrounds (BG):

  Reducible:

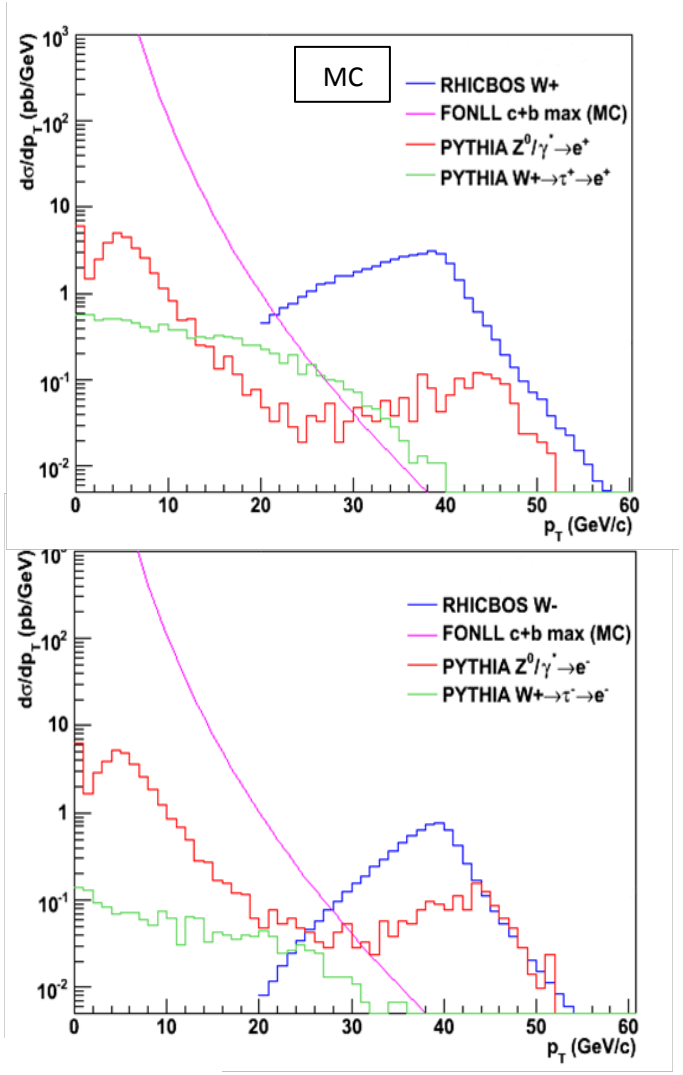
  - Photons from neutral pion/eta decays followed by $e^{\pm}$ pair production

  - Cosmic rays

  - Beam related backgrounds

  Irreducible:

  - Z, charm and bottom, other W decay



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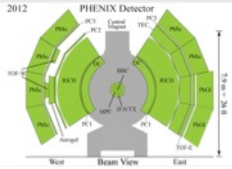
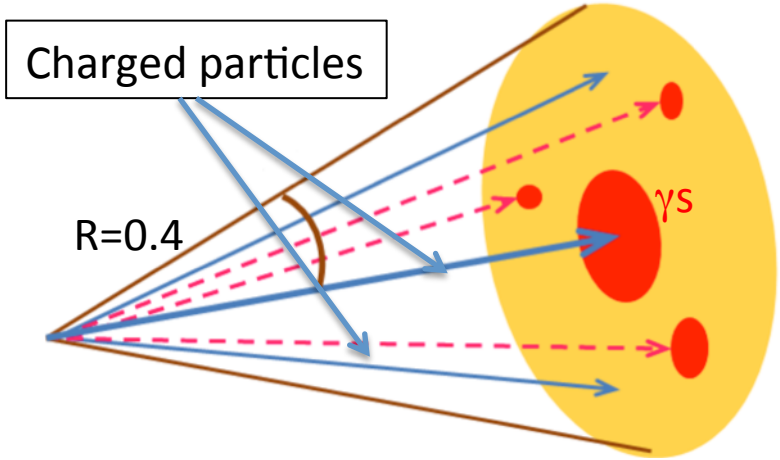
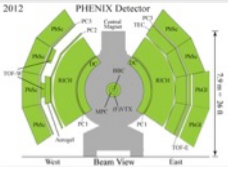


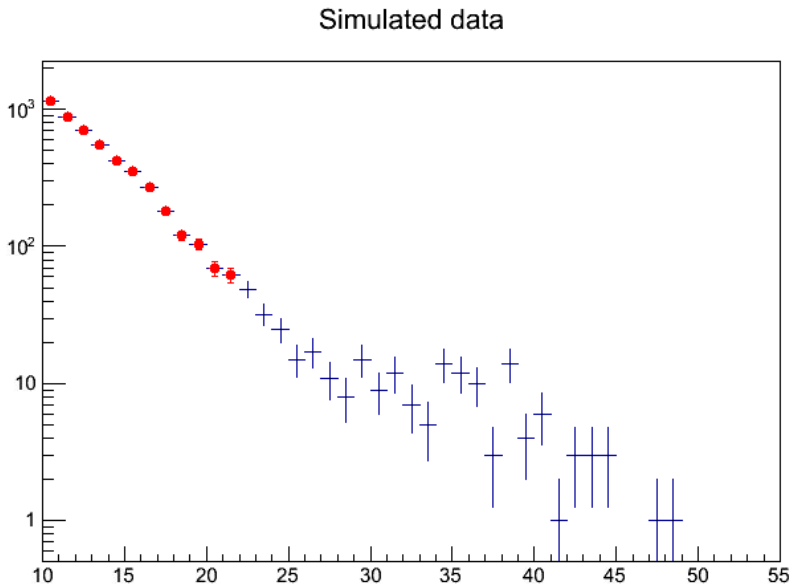
- Jacobian peak at pT ~ $M_W/2$
- Reduce background and estimate contribution between 30 and 50 GeV/c

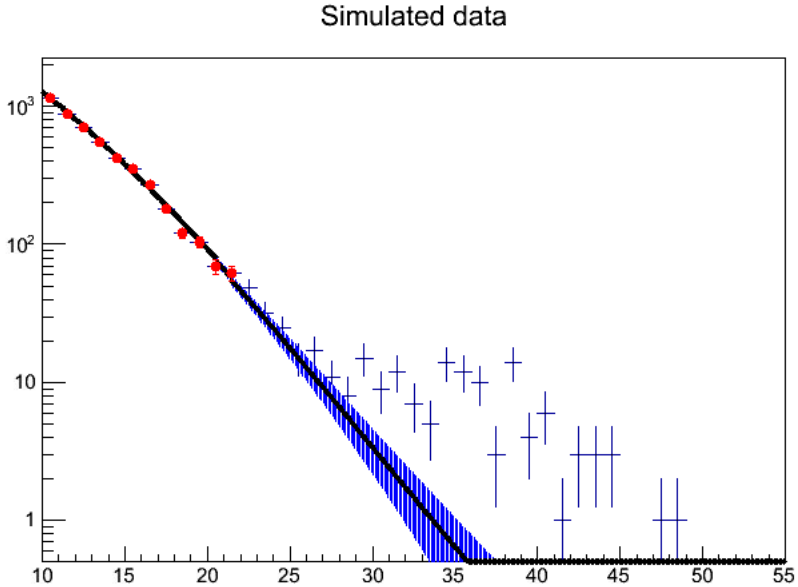
- Measure high pT electrons using EMCal
- DC-EMCal matching ($\Delta\phi<0.01$ rad)
- Relative isolation cut - Main BG discriminator
  - Energy in a cone of R=0.4 devided by energy of the candidate
  - Reduces background by a factor of 10



Gaussian Process Regression

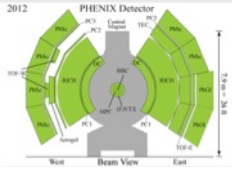


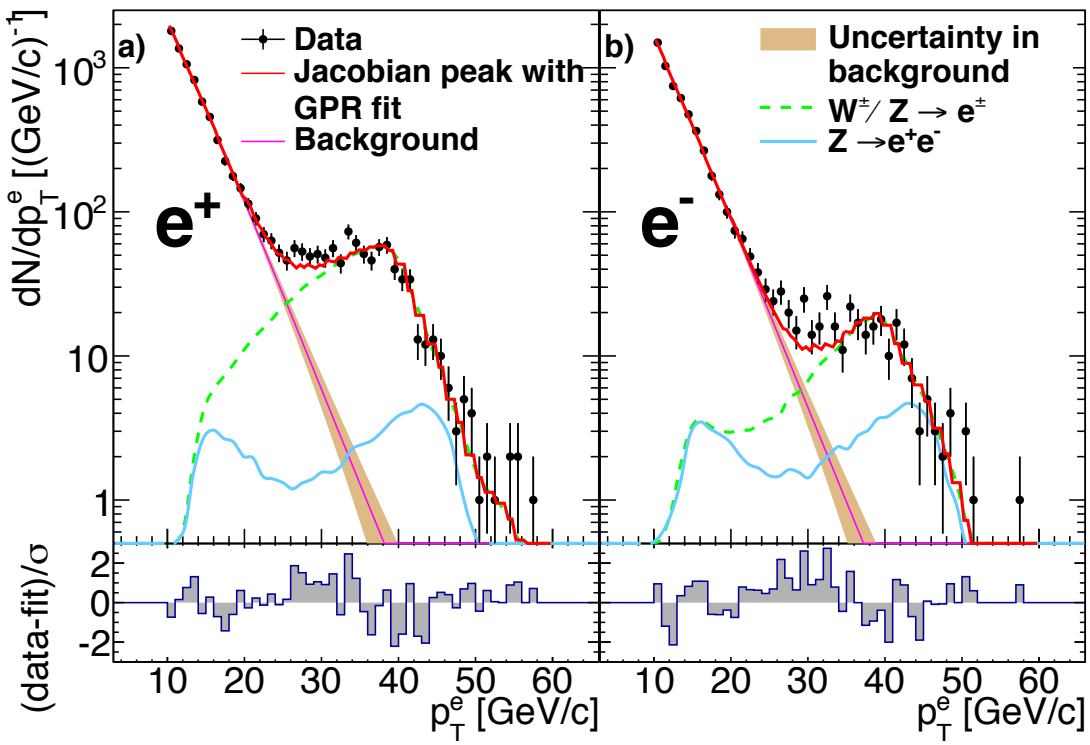




- Use background control region to extrapolate a shape in the signal region (30 to 50 GeV/c)
- The GPR gives a background contribution and uncertainty
- Cross check with a classical functional form (modified power law) showed good agreement

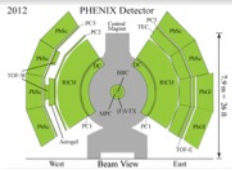
Mid-rapidity Measurement





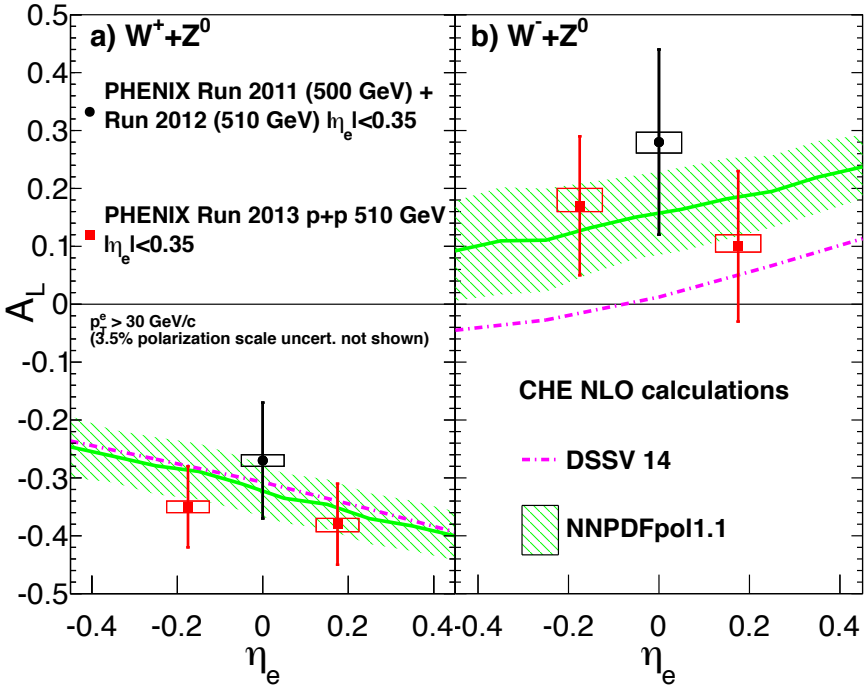
- Fitting with simulated Jacobian peak and GPR background shape produced good agreement with data
- Estimate the signal-to-background ratio in the signal region (30-50 GeV/c)
- 97% (94%) of signal remains for e^+ (e^-)

Mid-rapidity Measurement



- 2011-2013 combined results published!
- 27 times more statistics compared to the previous published result
- Our data is consistent with the STAR data and compares well with the theoretical calculation

$$A_L^{\text{Corrected}} = \frac{1}{P}\frac{N^+ - N^-}{N^+ + N^-}\left(1 + BG/Sig\right)$$



Phys. Rev. D 93, 051103(R)

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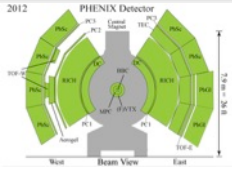

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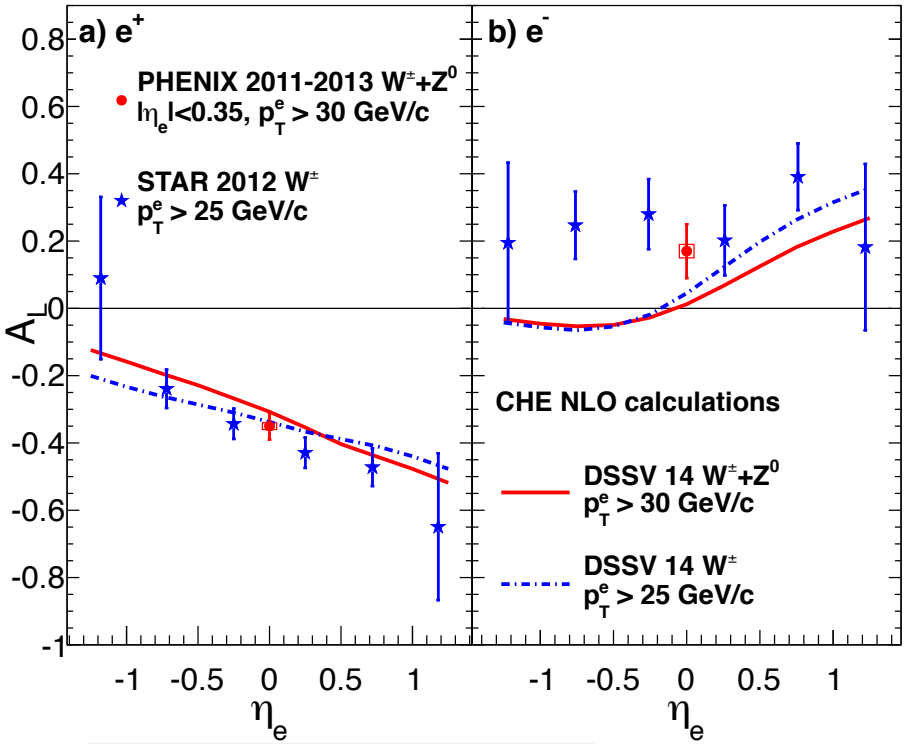
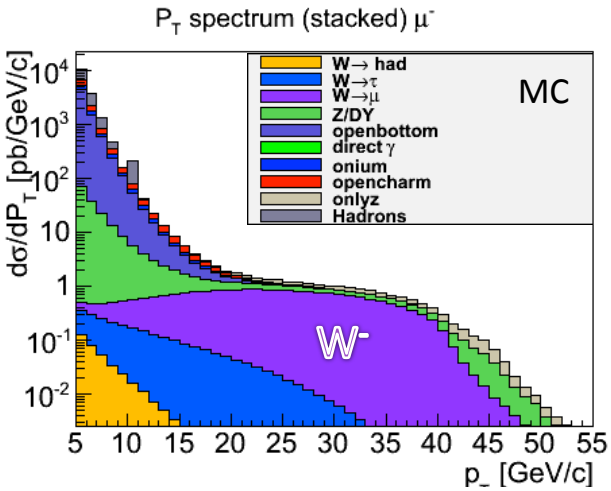
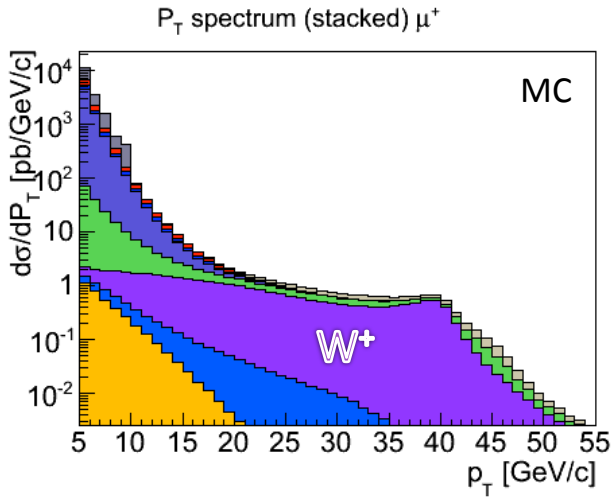


Phys. Rev. D 93, 051103(R)

Forward rapidity Measurement

- Suppressed/no Jacobian peak
- Real muon decays from Heavy flavour and Drell-Yan get smeared into high pT region.
- Large hadron BG contamination (low pT charged kaons, pions)
  - Punch through hadrons
  - Decay-in-flight
- Looking for W at pT > 16 GeV/c





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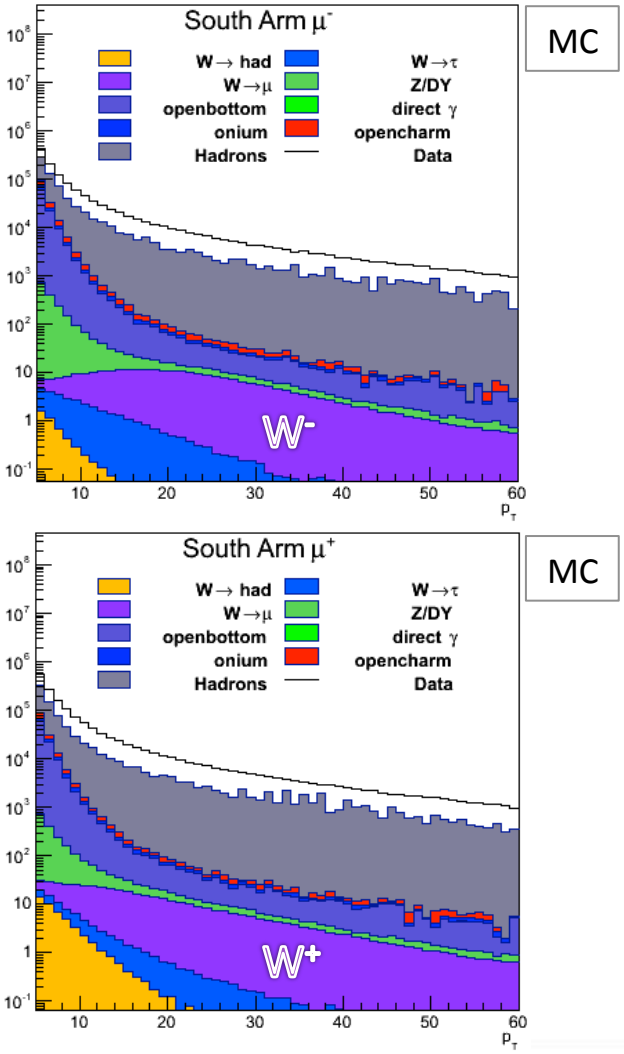

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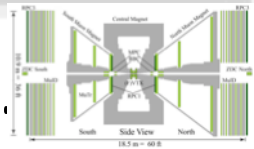
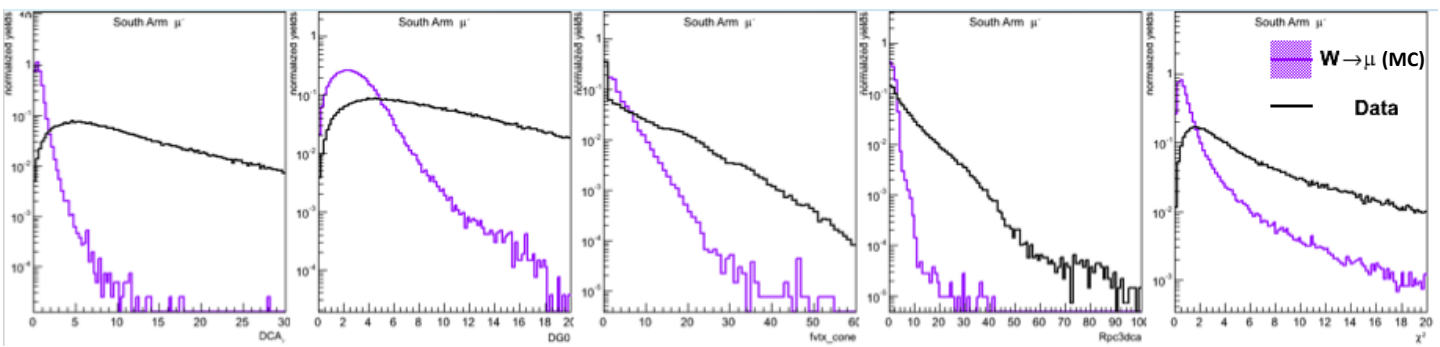
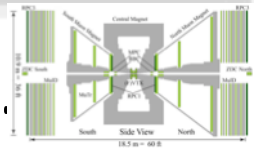


- Reduce BG by likelihood based pre-selection
- Construct likelihood λ_{sig}, λ_{BG} using 5-9 signal/BG sensitive kinematic variables
- Very low signal purity: use real data as background shape at the initial stage
- Define likelihood ratio (W-ness) based on signal (MC) and BG shapes (data)

$$W-ness \equiv \frac{\lambda_{sig}(x)}{\lambda_{sig}(x)+\lambda_{BGs}(x)}$$



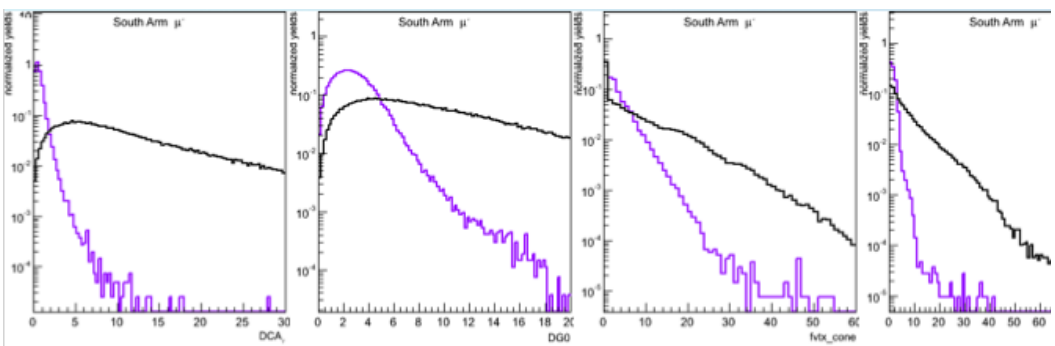
Forward rapidity Measurement

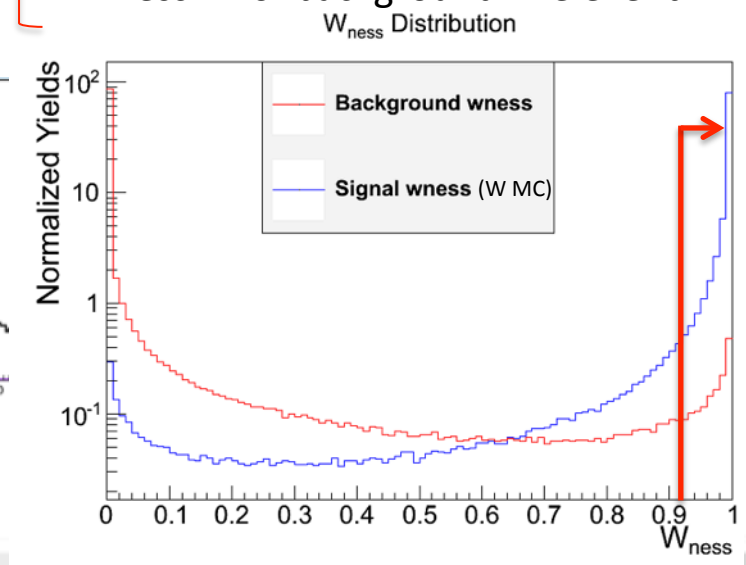


- Reduce BG by likelihood based pre-selection
- Construct likelihood λ_{sig}, λ_{BG} using 5-9 signal/BG sensitive kinematic variables
- Very low signal purity: use real data as background shape at the initial stage
- Define likelihood ratio (W-ness) based on signal (MC) and BG shapes (data)

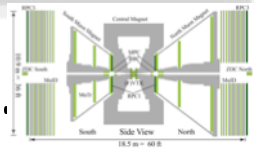
$$\mathrm{W-ness} \equiv \frac{\lambda_{sig}(x)}{\lambda_{sig}(x) + \lambda_{BGs}(x)}$$

W-ness
- W-ness → 1: signal-like event
- W-ness → 0: background-like event

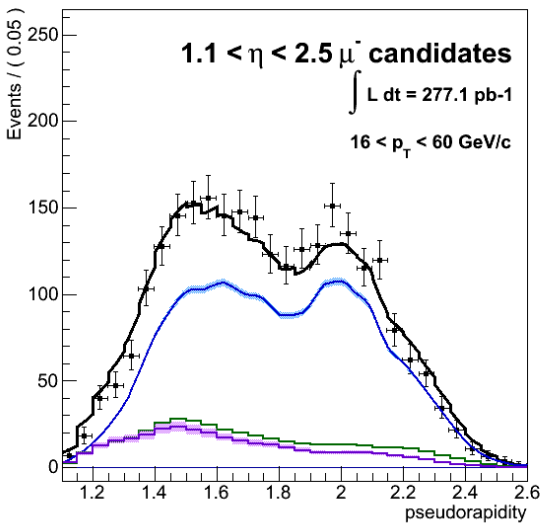


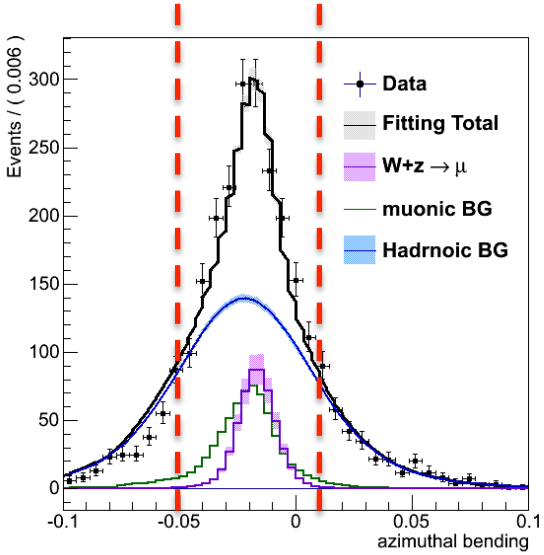


Forward rapidity Measurement



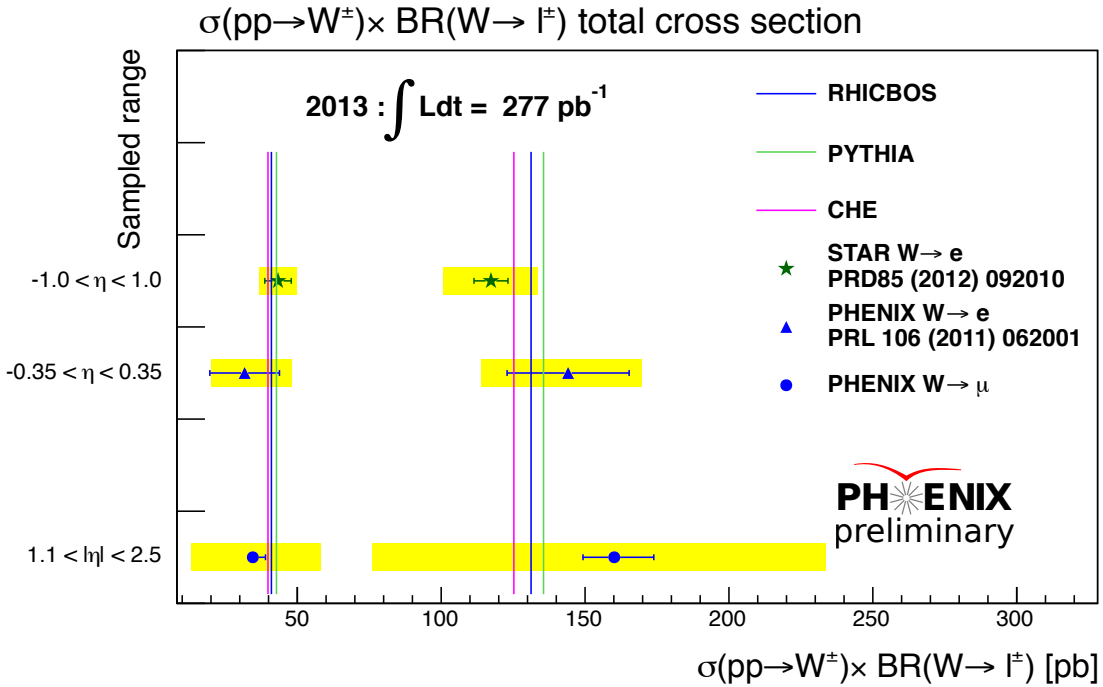
- After the pre-selection, perform 2D unbinned maximum likelihood fit in two independent variables: rapidity(η), effective azimuthal bending angle (dw23)
- Extract shapes for the fit
- Improvement on the pre-selection, S/BG fit underway

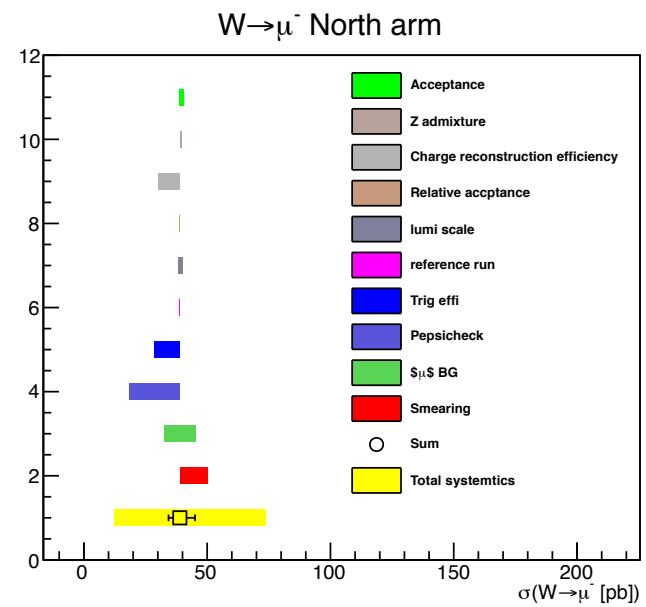




Estimated S/B ratio: ~30%-50% depending on arm and charge

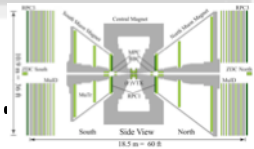
Forward rapidity Measurement



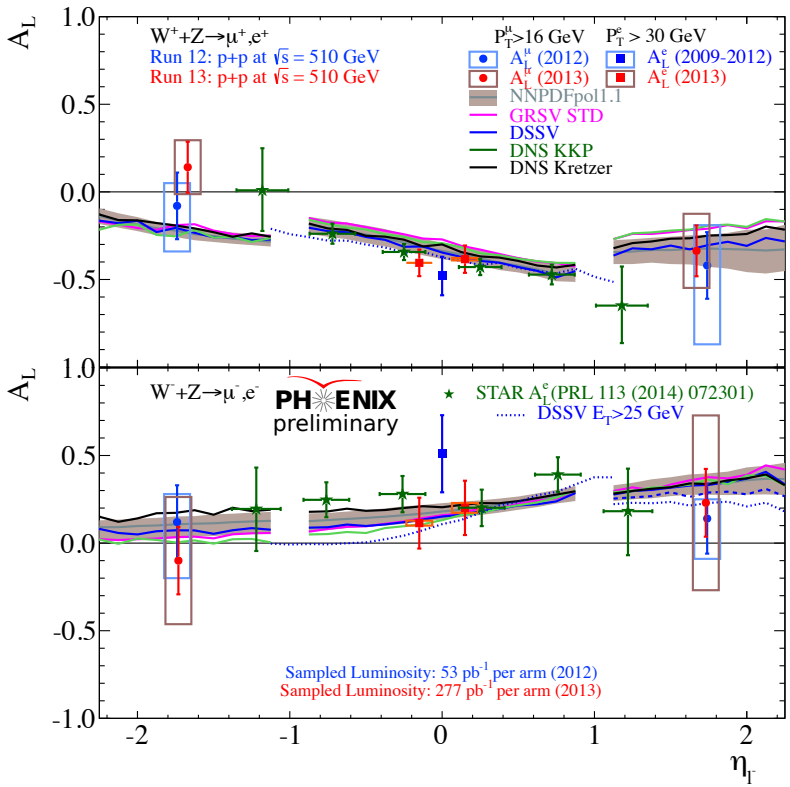


- Preliminary result of cross section measurement with 2013 data
- Consistent with theoretical calculation within large systematic uncertainties
- A lot of effort has been made to reduce systematic uncertainties

Forward rapidity Measurement



- Preliminary results at forward/backward rapidities
- Asymmetries consistent with theoretical calculation
- For W^+, A_L at backward rapidity tends to be smaller/ positive
- Result is being finalized.

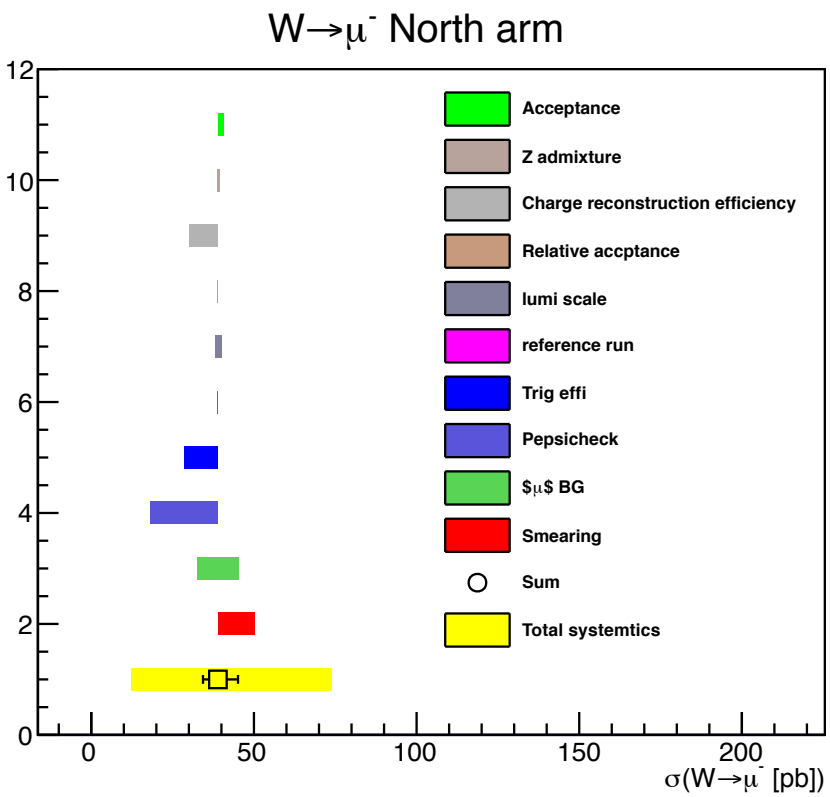


Summary

- PHENIX W measurement provides clean access to light sea quark PDFs and naturally distinguishes between quarks and anti-quarks.
- W cross section, single spin asymmetry A_L are measured using all available data collected at PHENIX.
- PHENIX W results will be an important constraint on the extraction of light sea quark PDFs.
- 2011-2013 combined mid-rapidity results have been published (Phys. Rev. D 93, 051103(R)).
- Forward rapidity analysis is being finalized.

Backup

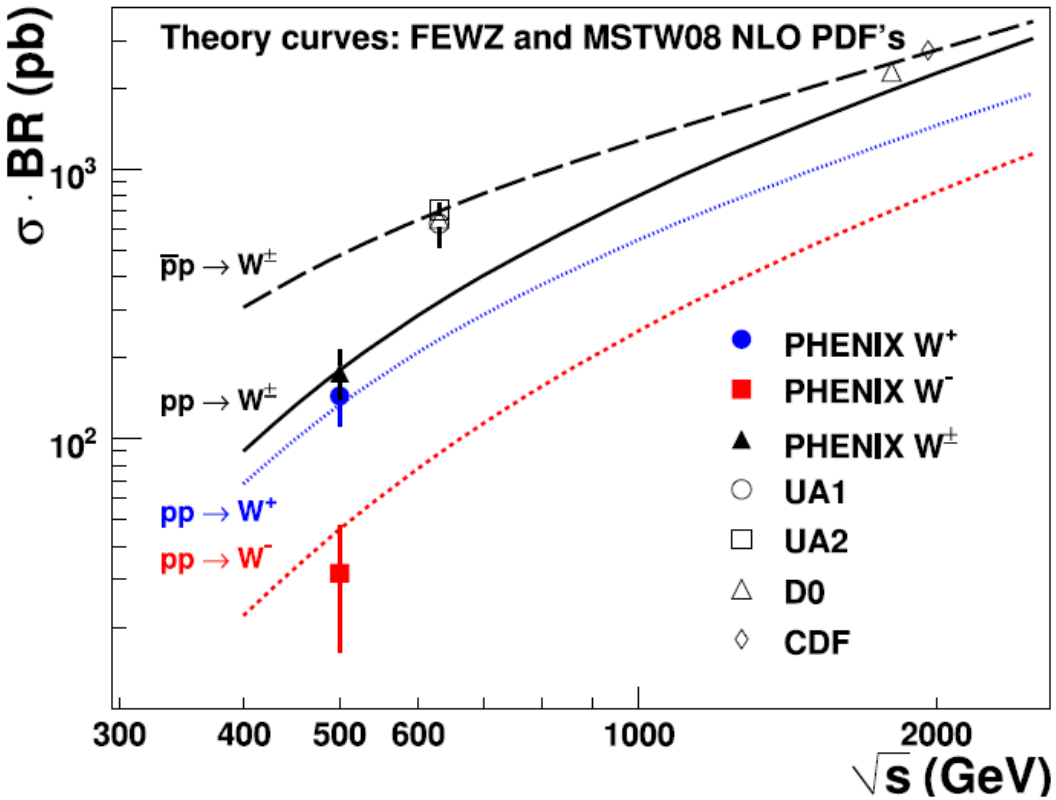
Forward rapidity Measurement



- Trigger efficiency
  → rapidity dependence trigger efficiency
- Muon background
  → Conservative systematic uncertainty assigned for the preliminary. Uncertainty estimated from the correlation matrix between processes for the final result
- Momentum smearing
  → Conservative systematic uncertainty assigned for the preliminary. Updated with cosmic data analysis.
- S/BG ratio
  → Dominant systematic source. Improving S/BG fit.

- Progress to reduce main systematic sources for the final result.

Cross section (Mid-rapidity, 2009 data)



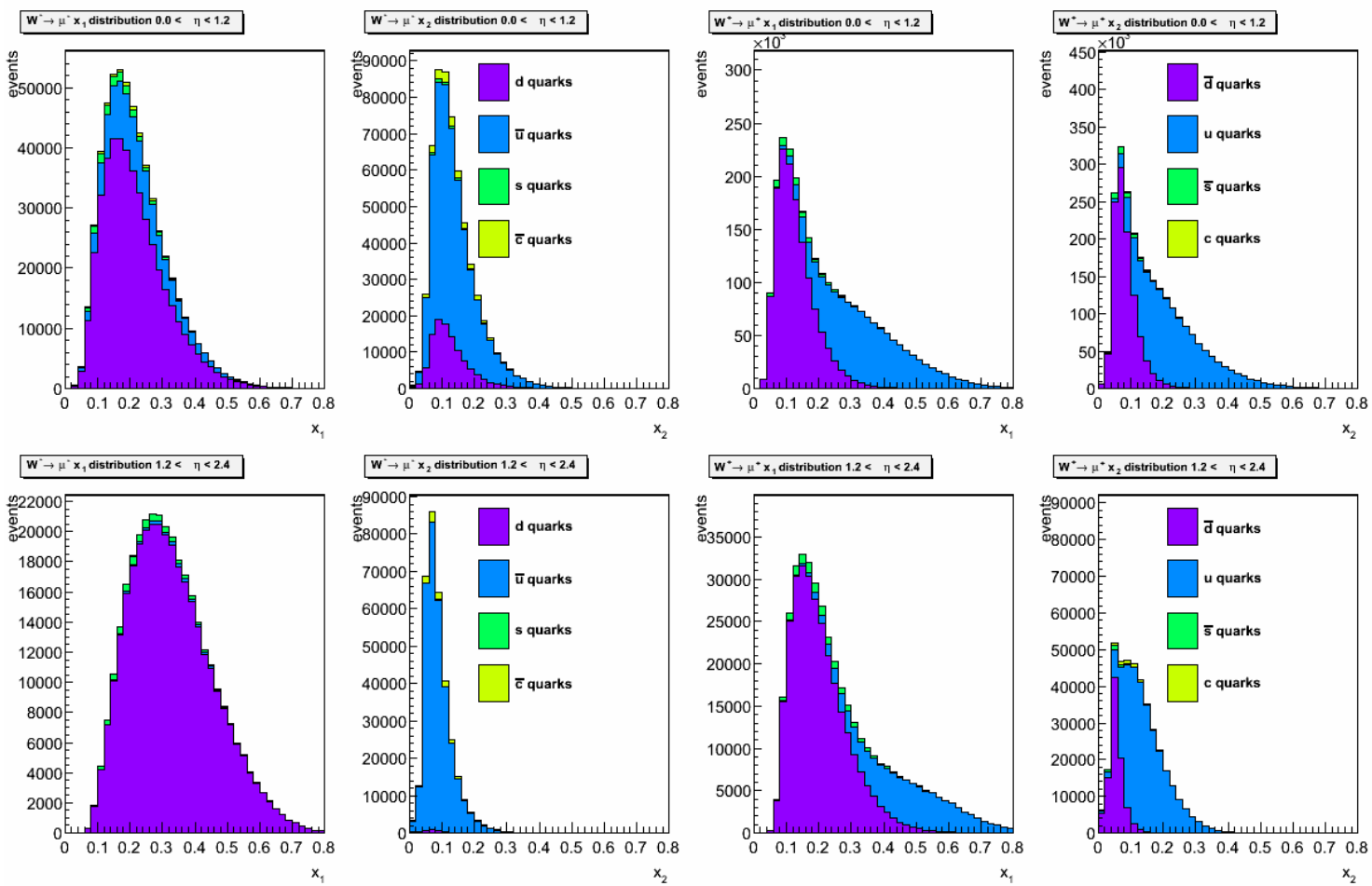
x1, x2

PYTHIA

W⁻ **W⁺**

Central

Forward



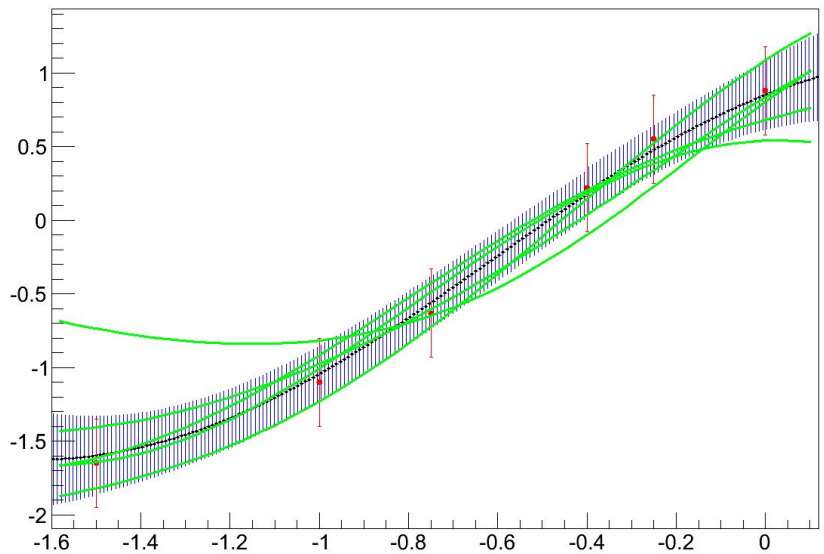
Gaussian Process Regression

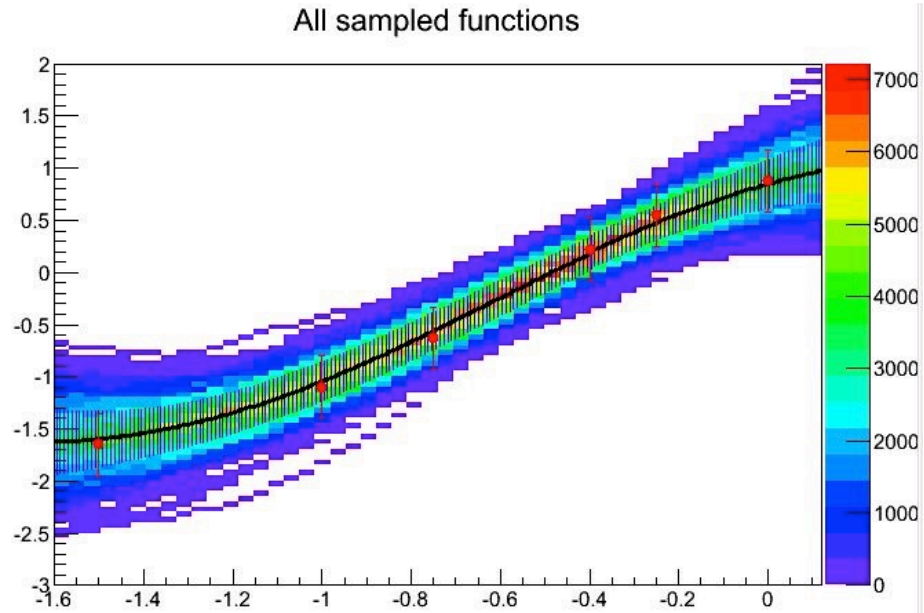
- When functional form is not known apriori
- Shift focus from prior knowledge over parameters to prior over functions (with some minimal constraints)

$$k(x, x') = \sigma_f^2 \exp\left[\frac{-(x - x')^2}{2l^2}\right] + \sigma_n^2 \delta(x, x')$$

- Correlation function encodes how much each data point influences the neighboring points
- Hyperparameters are determined through minimization over data

Function Extraction

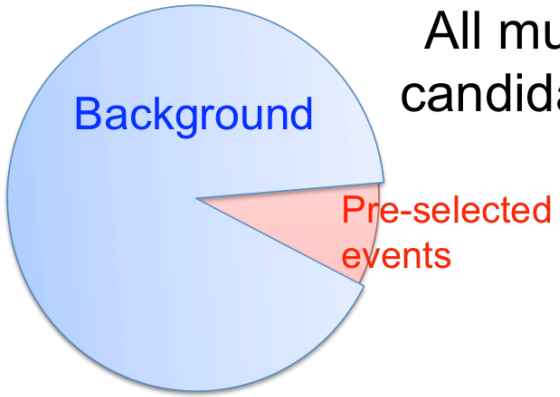




- Sampling over these functions and filling a 2D histogram (as on the right) will give a Gaussian distribution for each prediction point
- The mean of the Gaussian distribution is the prediction and the sigma is the uncertainty

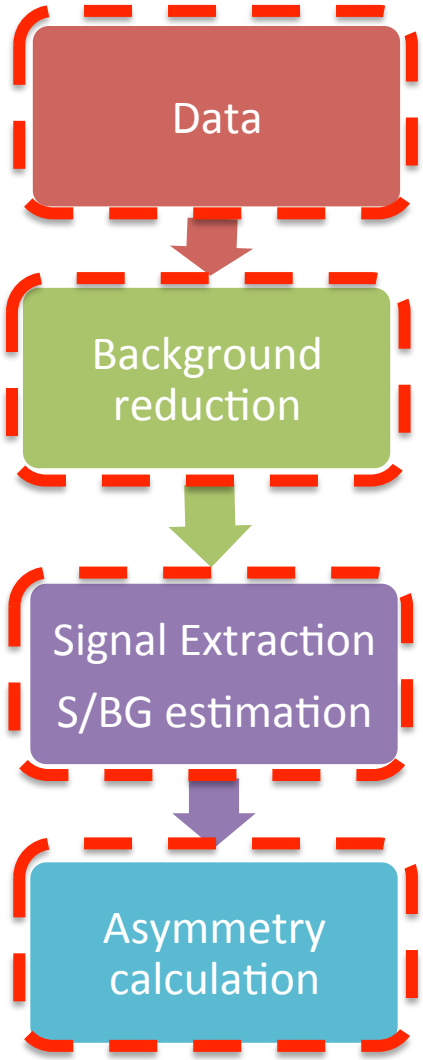
Analysis Flow Chart

- Multi-step background reduction
- Likelihood based approach

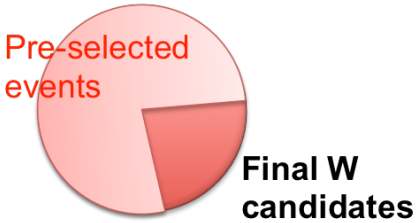


All muon candidates

Multivariate cut using likelihood ratio



- Background dominant
- Signal purity < 1%



Unbinned maximum likelihood fit
+ sideband cutout

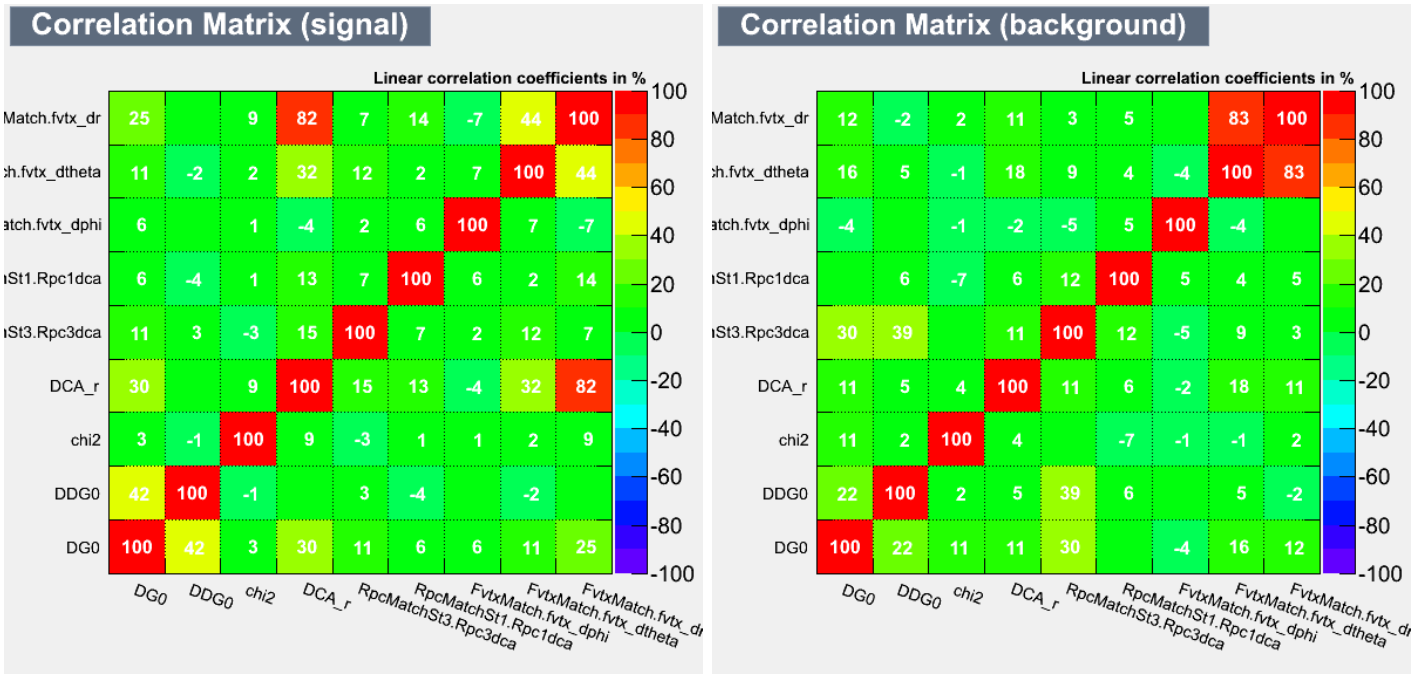
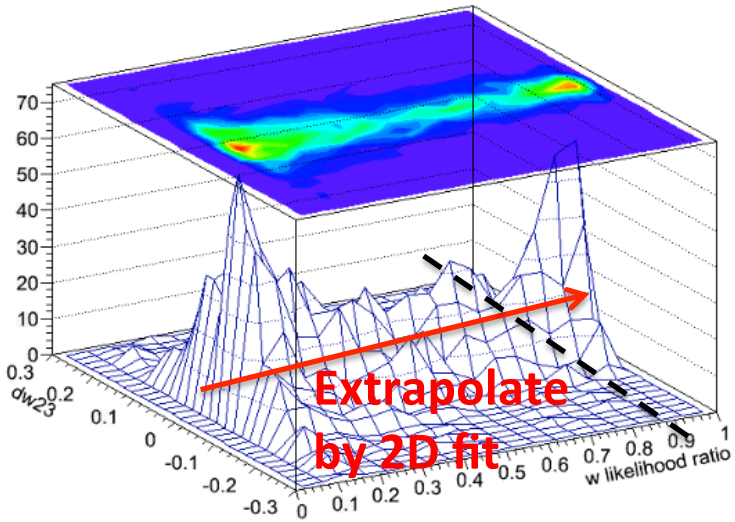


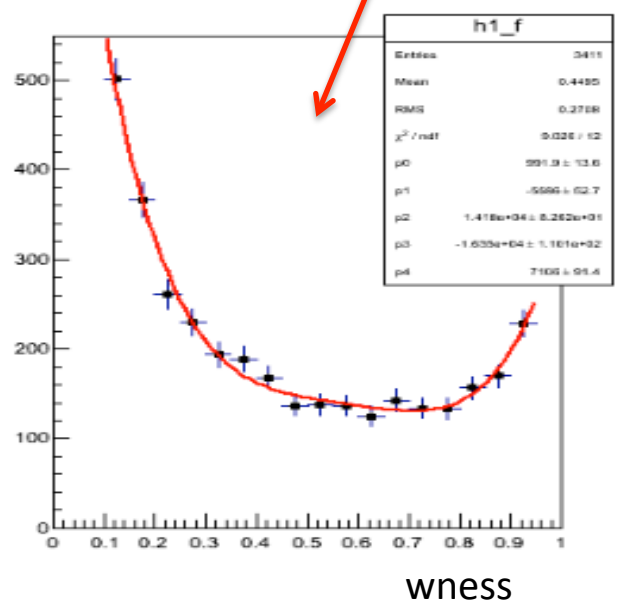
Figure 1.1: Correlation coefficients between various kinematic variables used in the analysis. The left panel shows the MC simulated signal while the other panel show the data.

dw23 for Hadron Background

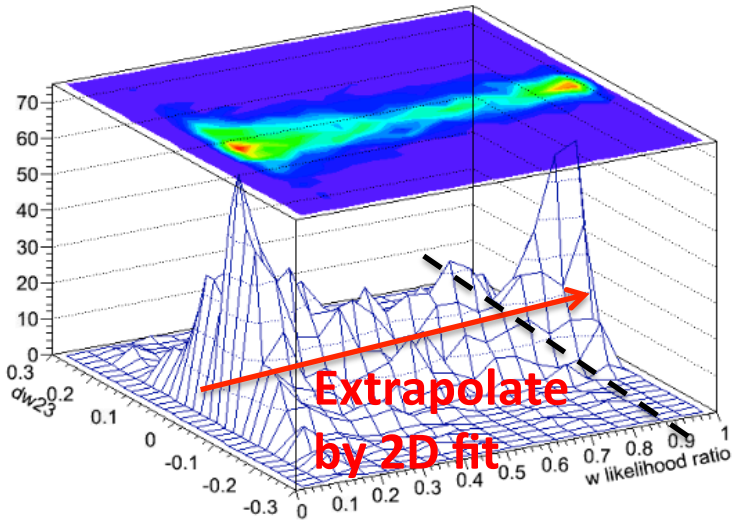


2D model of dw23-wness

$$p(\text{wness}, \text{dw23}) = p(\text{wness}) \cdot p(\text{dw23} \mid \text{wness})$$



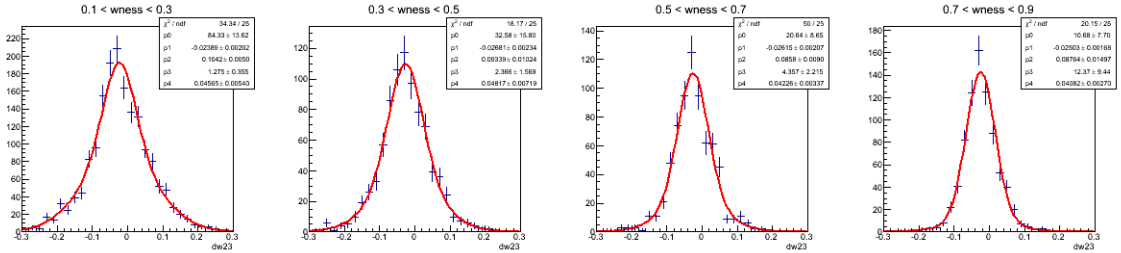
dw23 for Hadron Background



2D model of dw23-wness

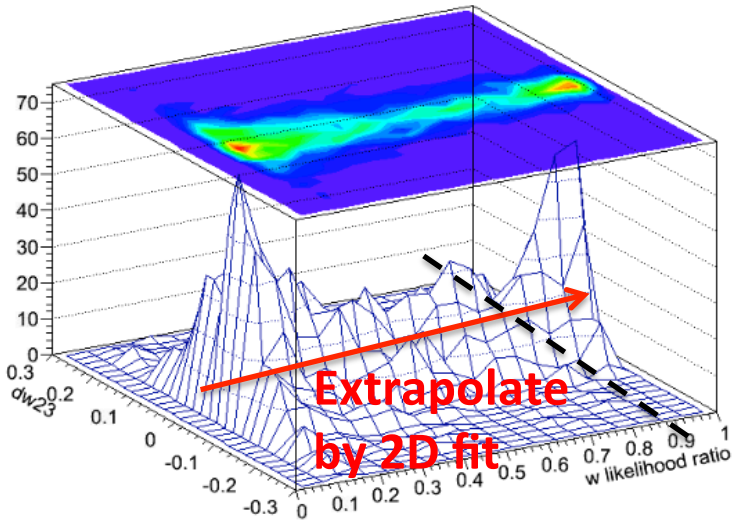
$$p(\text{wness}, \text{dw23}) = p(\text{wness}) \cdot p(\text{dw23} \mid \text{wness})$$

- Fit model: Coaxial double gaussian
- Vary parameters linearly



Slice of dw23 distributions

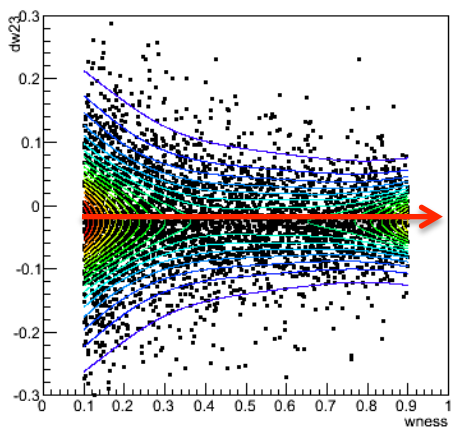
dw23 for Hadron Background



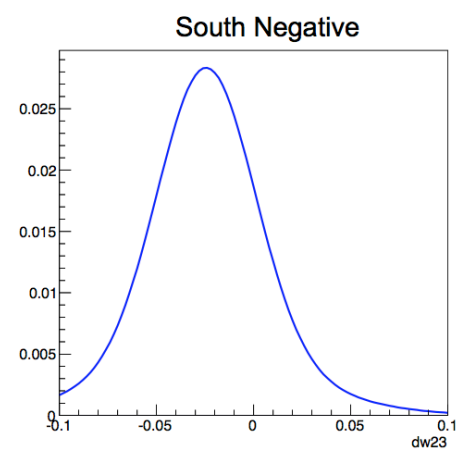
2D model of dw23-wness

$$p(\text{wness}, \text{dw23}) = p(\text{wness}) \cdot p(\text{dw23} \mid \text{wness})$$

2D fit result

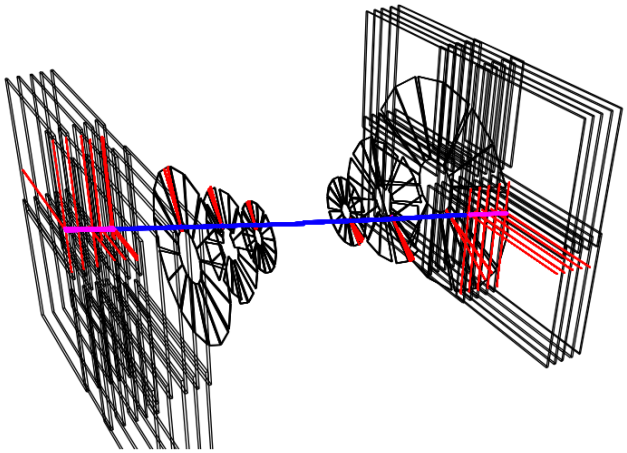


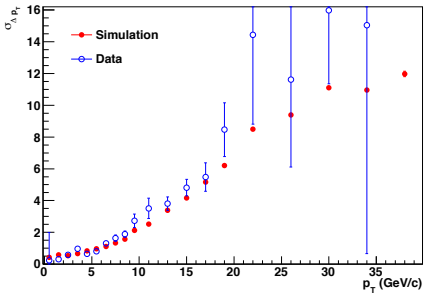
Extrapolate the fit function to the target wness region.

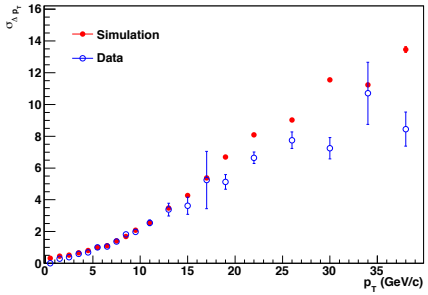


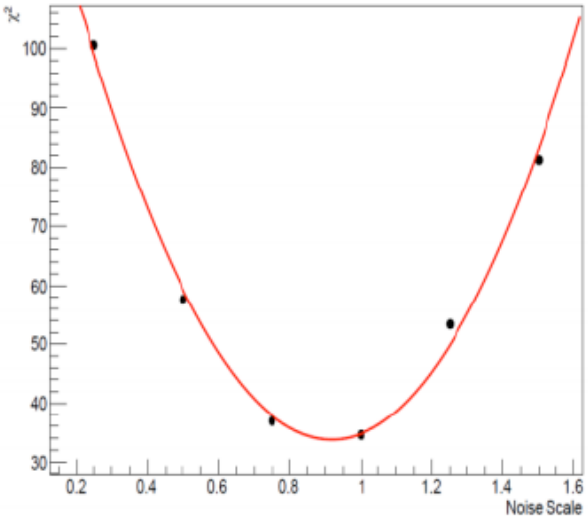
MuTr position resolution

- Using the cosmic data
  - Measure momentum for incoming and outgoing tracks
  - Compare data with MC
  - Noise RMS to be tuned



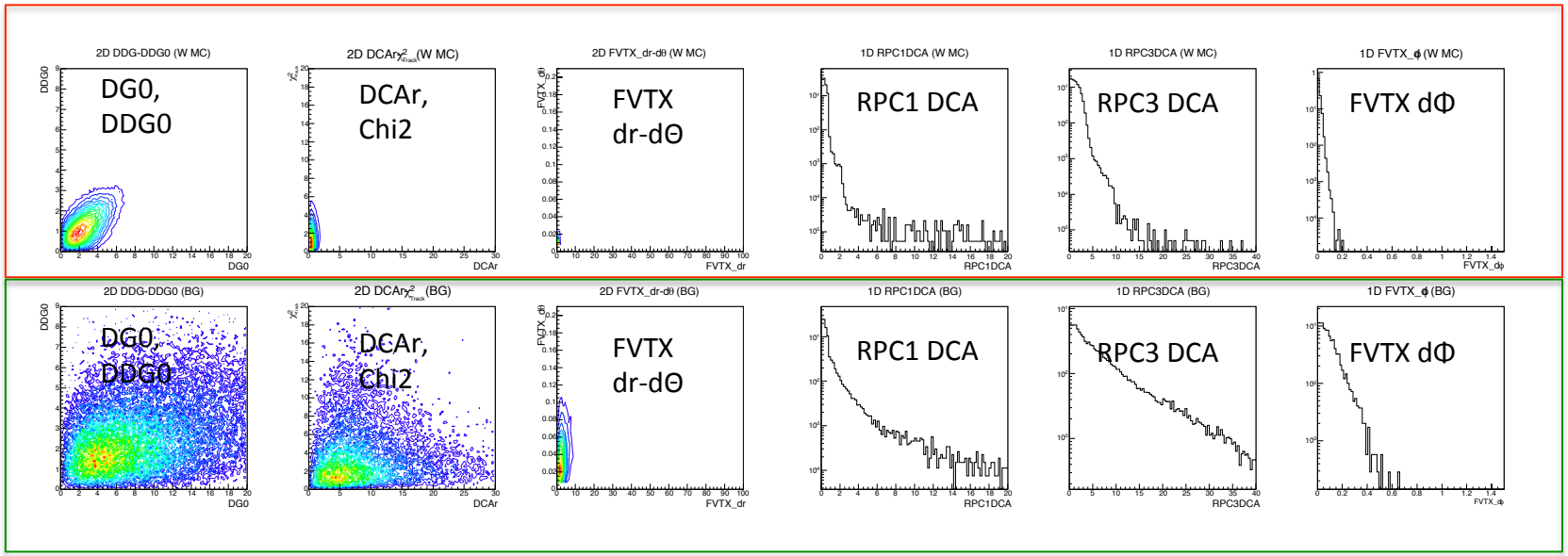






Pre-selection variables

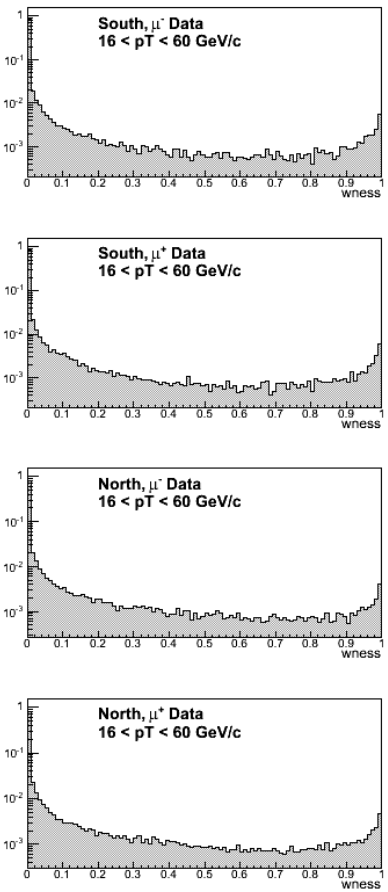
Kinematic variable distributions of Signal MC



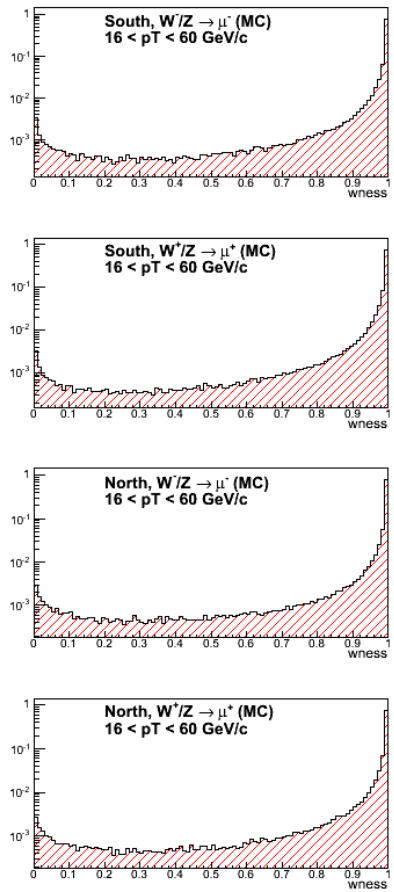
Kinematic variable distributions of BG

Likelihood ratio (wness) distributions

Data
(BG dominant)

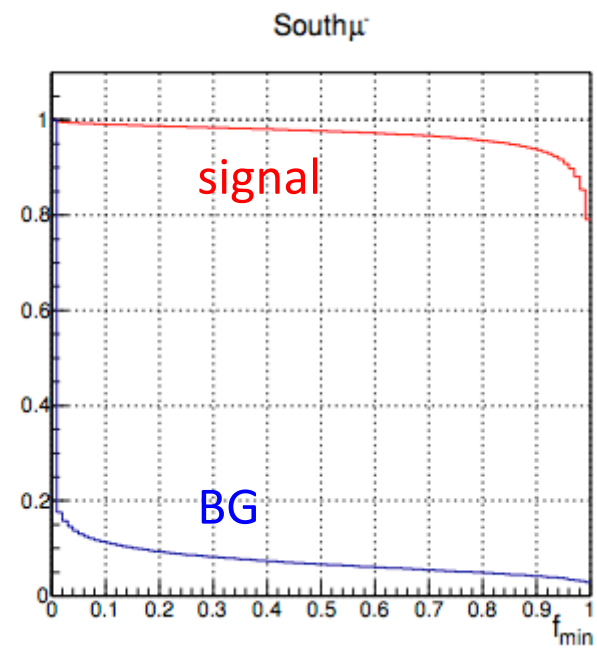


Signal MC



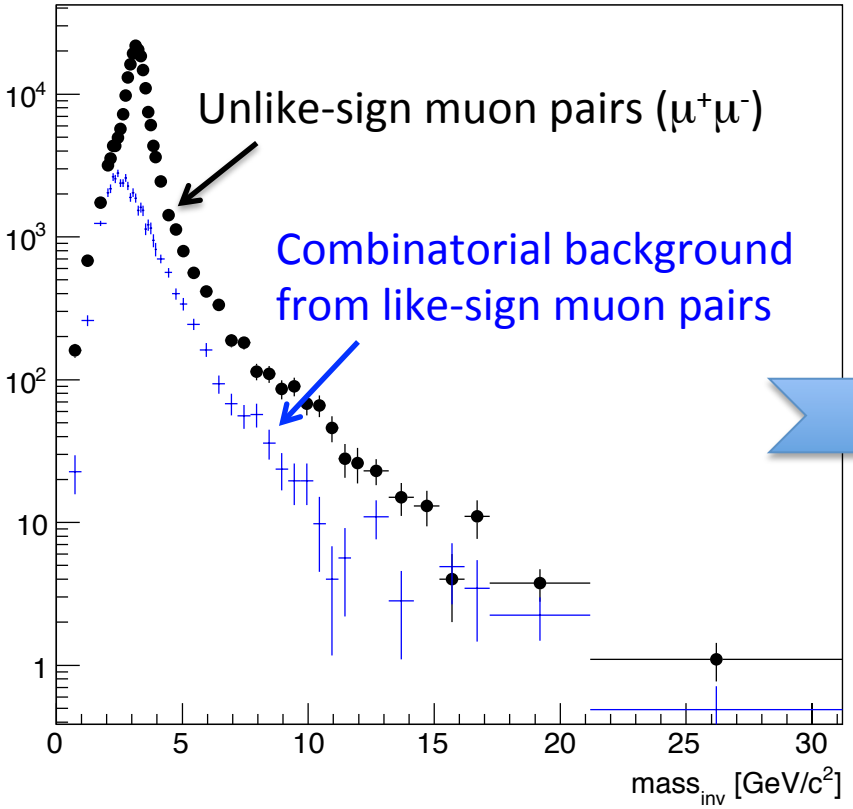
- Signal efficiency:

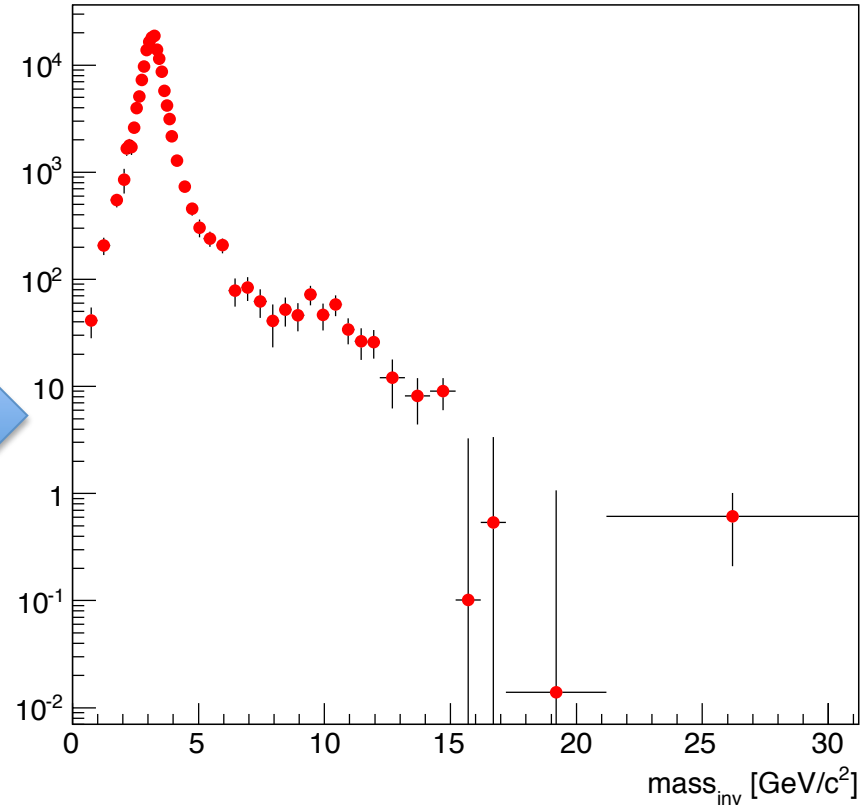
$$Efficiency(f_{min}) = \frac{\int_{f_{min}}^{1} f(wness)\ dwness}{\int_{0}^{1} f(wness)\ dwness}$$



Muon Background Estimation

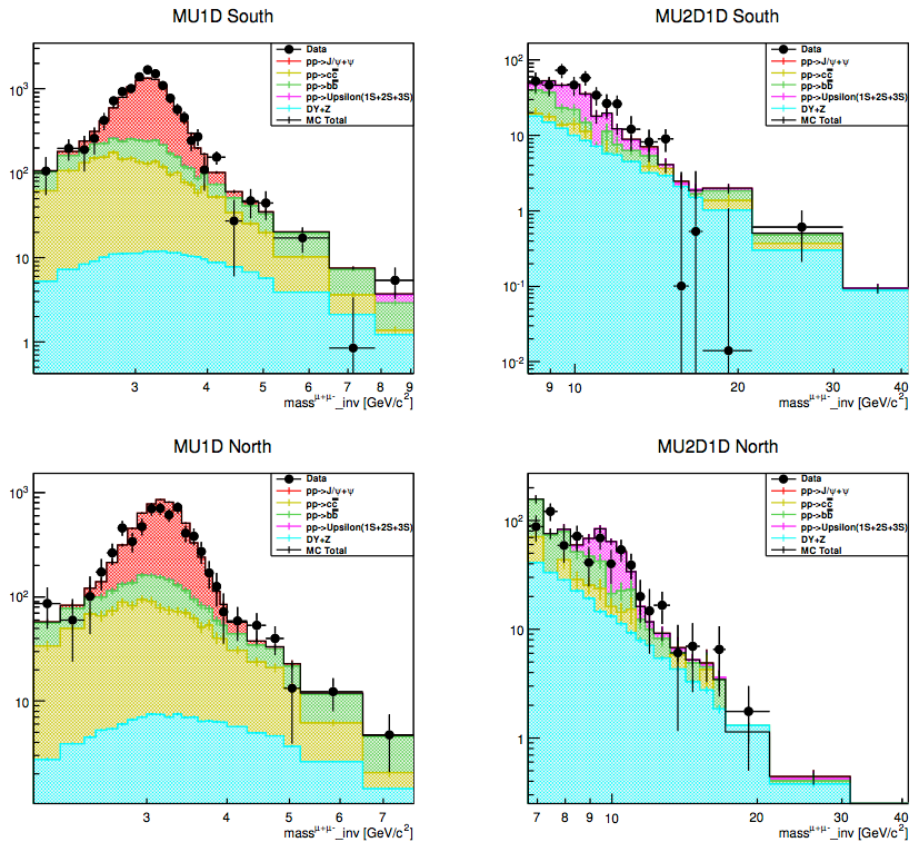
Invariant mass (real collision data)



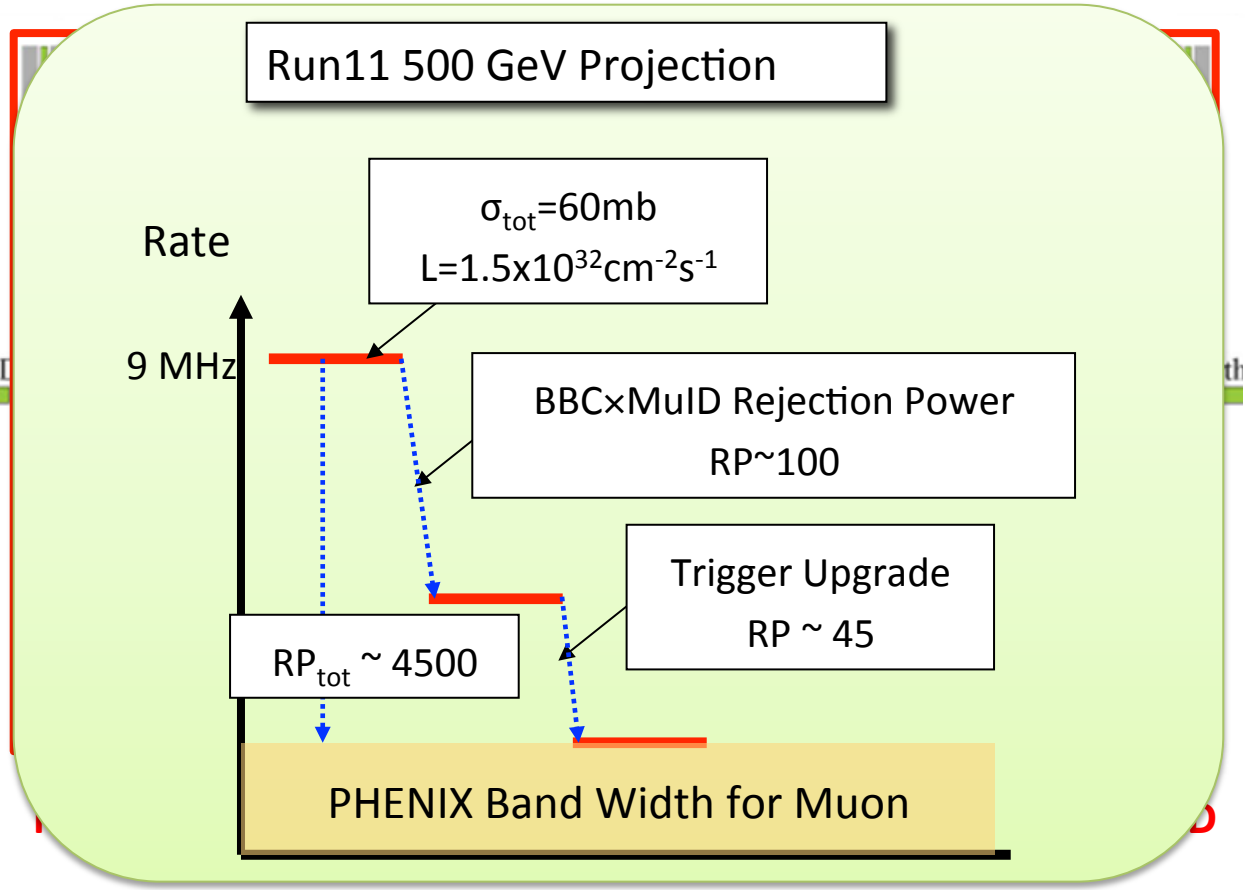


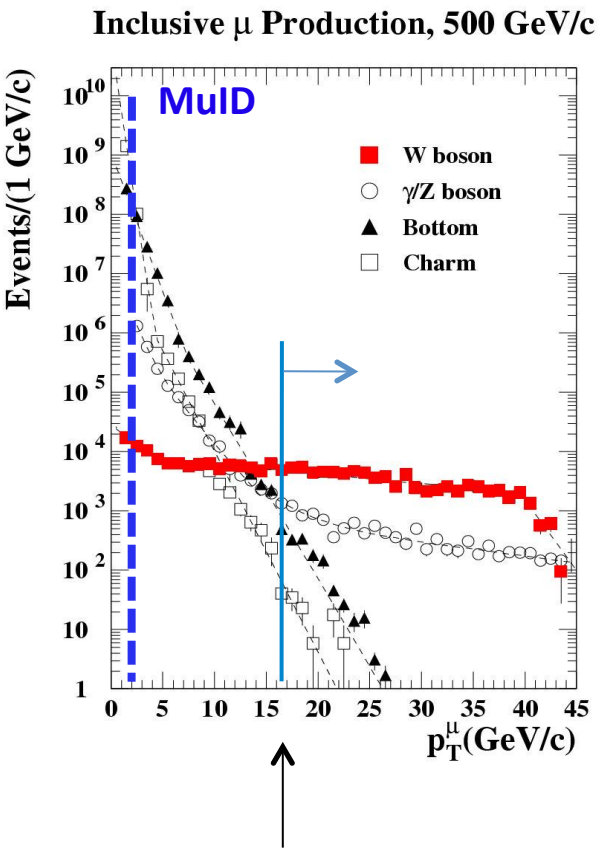
Muon Background Estimation

- Muon background: Open heavy flavor, quarkonia, Drell-Yan/Z
- Various muon background processes are combined together before constructing probability density functions.
- Relative contributions → scale factors.



PHENIX Detector System (in the past)

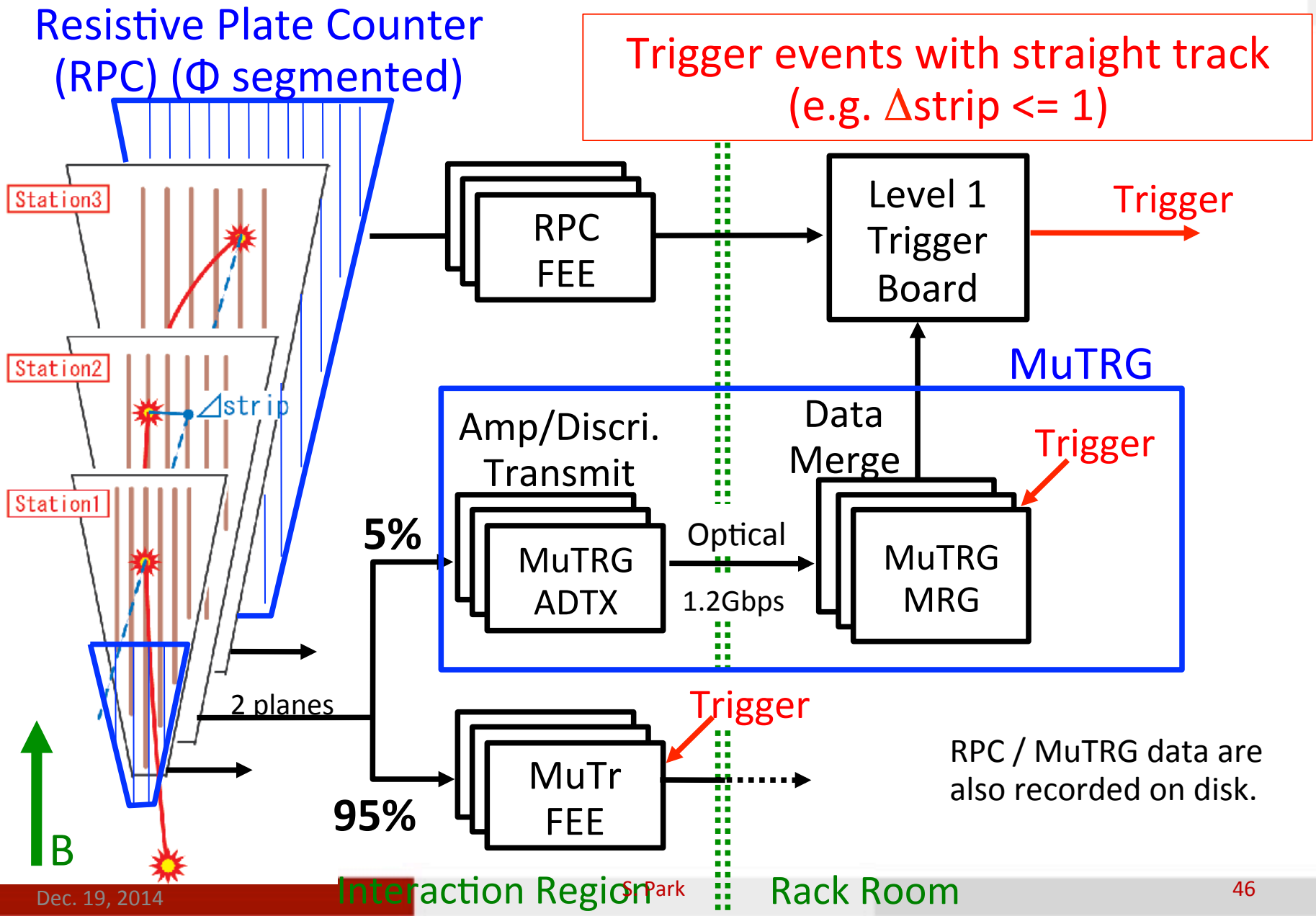




W dominant region

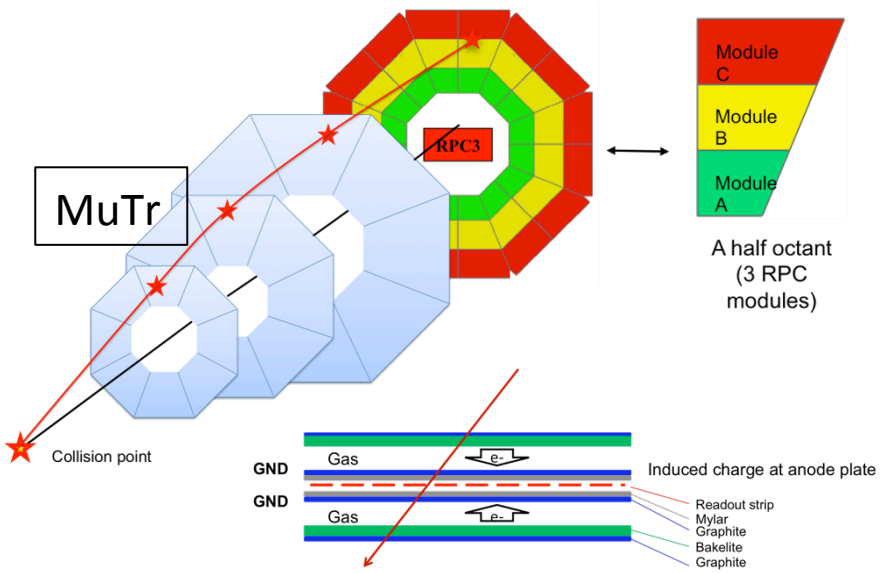
- **Data acquisition system limit (< 2 KHz)**
- **Low momentum threshold of MuID (~2 GeV)**
  - **MuID rejection power ~100**
  - **Collision rate ~9 MHz at designed luminosity**
  - **Required rejection power ~ 4500**

W Trigger System



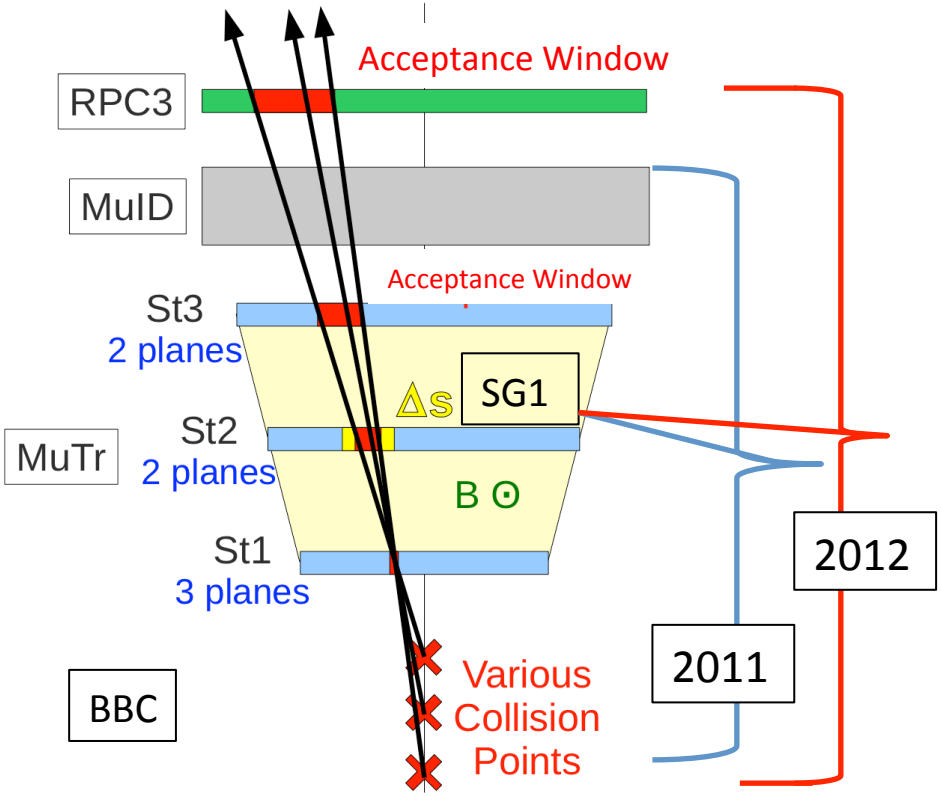
Introduction of New W Trigger in 2012

- **RPC (Resistive Plate Chamber)**



- RPC has good timing resolution (< 3ns).
  → align events with correct beam crossing.
- Better online tracking than MuID
- Provides additional hit information.
- Background rejection in offline analysis

→ **New W Trigger gives higher rejection power**



2011: SG1xMUIDxBBC trigger
2012: SG1xRPC3xBBC trigger (main)
SG1xMUIDxBBC trigger (backup)