W Measurements at PHENIX

Chong Kim

University of California at Riverside

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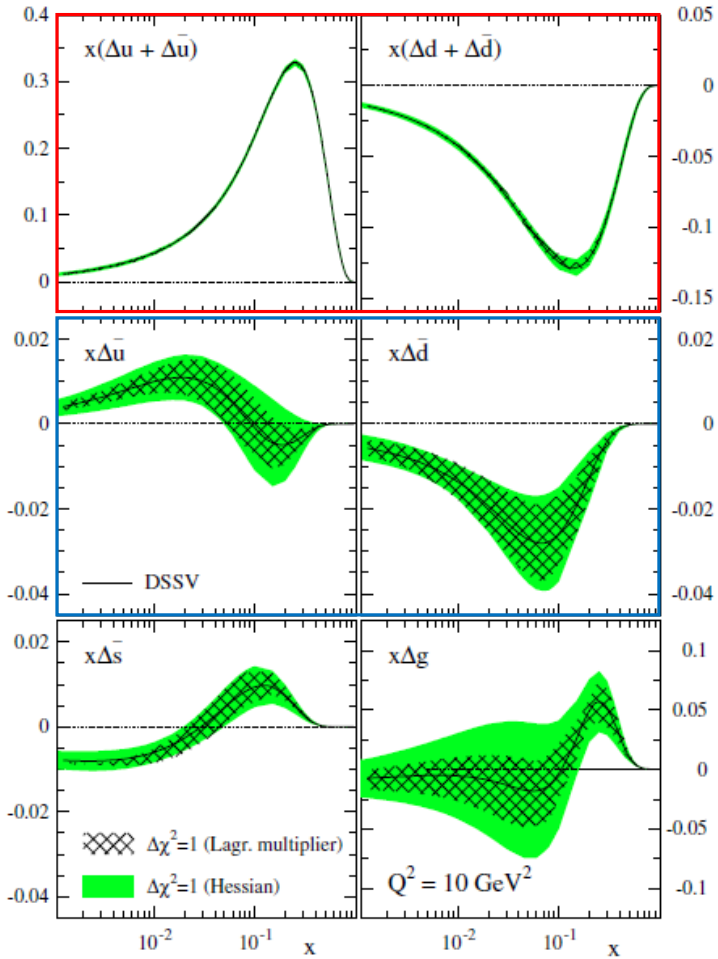
For the PHENIX collaboration

Outline

- **Introduction**
  - Motivation
  - RHIC and PHENIX
  - Recent longitudinal spin runs
- **W Measurements at PHENIX**
  - $W \rightarrow e$ at midrapidity
  - $W \rightarrow \mu$ at forward rapidity
- **Summary**

Introduction Motivation



PRD80. 034030 (2009)

- Jaffe-Manohar spin sum rule
  - $S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$
- $\Delta\Sigma$?
  - $(\Delta q + \Delta\bar{q})$:

    well constrained down to x ~ 10^{-3}, thanks to DIS
  - $\Delta\bar{q}$:

    poorly constrained with large uncertainty,

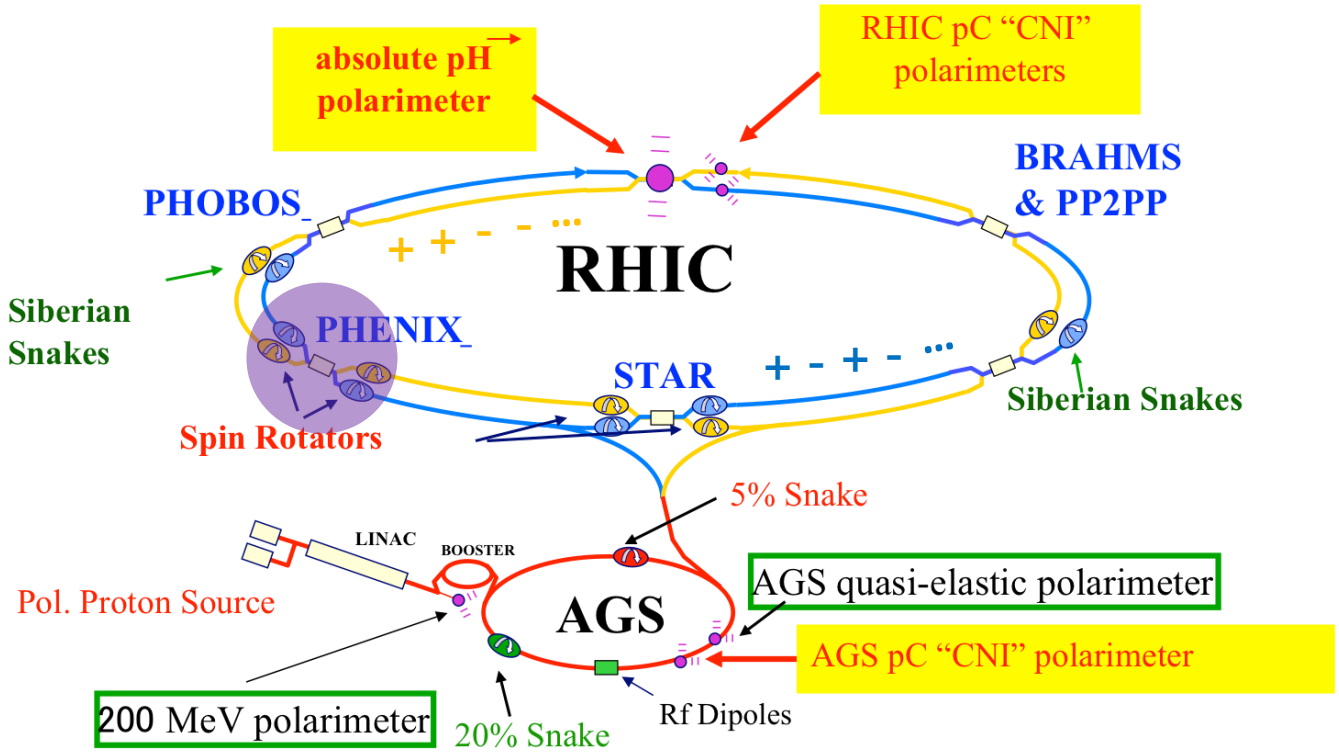
    mainly originated from fragmentation functions

    → RHIC: fragmentation free *W* decay leptons
- ΔG?
  - Barely accessible via DIS / Limited access via SIDIS
  - Substantial non-zero contribution discovered at RHIC:

    a. STAR Jet A_{LL} (PRL115, 092002)

    b. PHENIX midrapidity π^0 A_{LL} (PRD93, 011501)

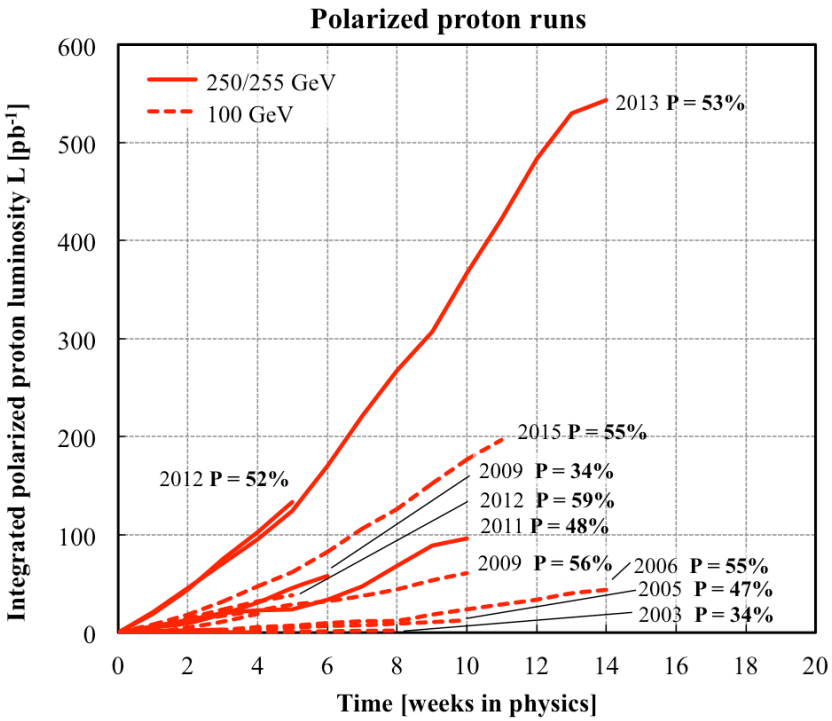
Introduction RHIC and PHENIX



- **RHIC @ Brookhaven Lab., NY**
  - Polarized p + p @ √s = 62.5 to 510 (GeV)
  - Maximum average polarization ($\langle P \rangle$) ≈ 60 (%)

Introduction

Recent longitudinal p + p runs at RHIC



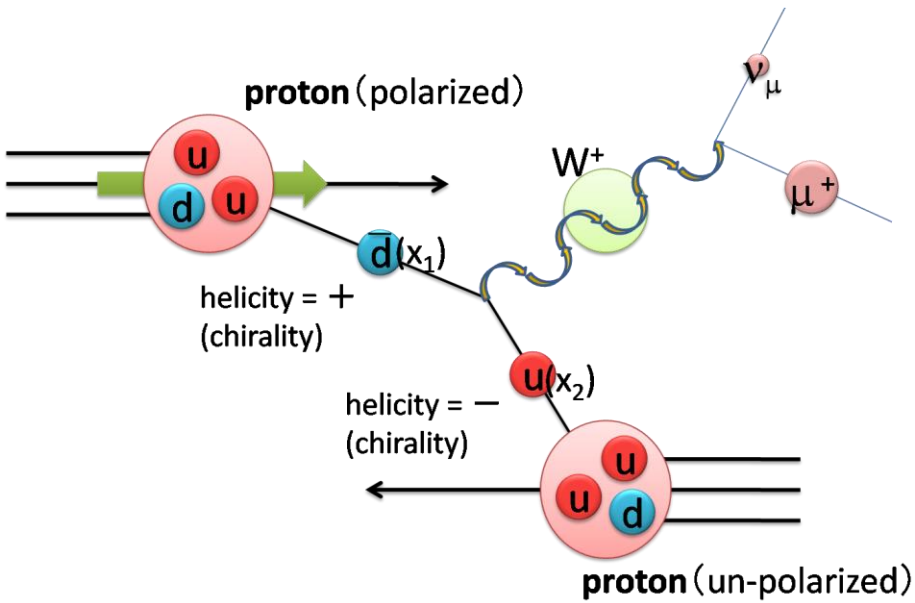
Year	√s (GeV)	Int. L (pb^{-1})	$\langle P \rangle$ (%)	FoM ($L \cdot \langle P \rangle^2$)
09	200	15.6	56 / 57	4.98
	500	14.0	33 / 36	1.66
11	500	27.6	48 / 48	6.36
12	510	53	56 / 58	17.21
13	510	285	54 / 55	84.65

* Int. L: MinBias with no vertex cut at PHENIX

- **PHENIX RUN11 - RUN13**
  - Top 3 highest FoM years for all longitudinal spin runs in RHIC history
  - PHENIX forward detector upgrade completed at 2012

W Measurements at RHIC

A_L via *W* decay leptons



$$A_L = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

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

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

technically,

$$A_L^{W} = \frac{1}{P}\frac{N_+ - RN_-}{N_+ + RN_-}$$

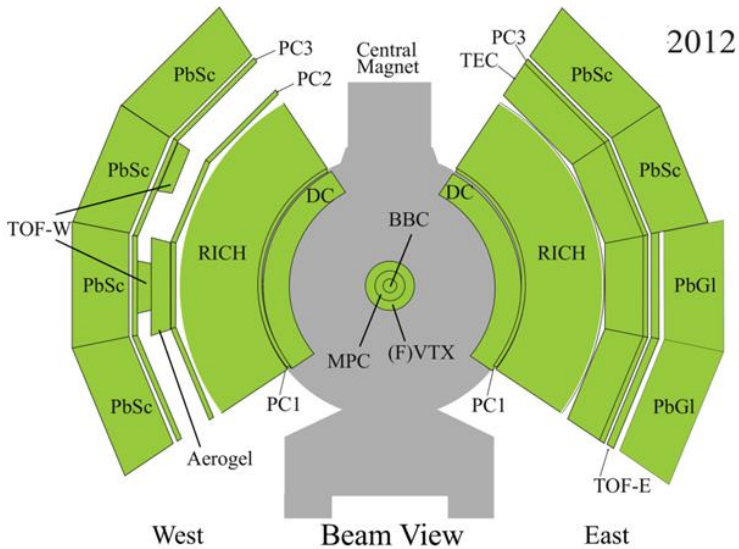
- *P* : avg. polarization of each beam
- *N*+ (*N*-) : yields in same (opposite) helicity
- *R* ($\frac{L++}{L+-}$) : relative luminosity

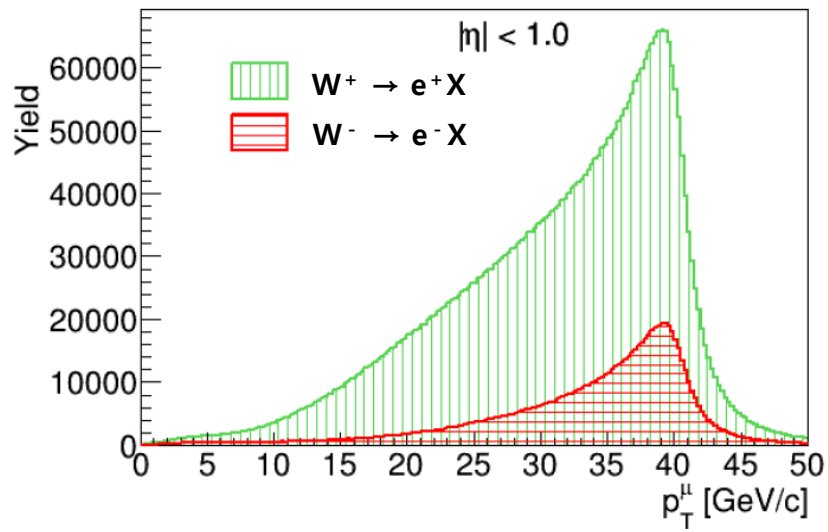
- **A_L (single longitudinal spin asymmetry) measurement at RHIC**
  - Natural flavor separation: couple with only positive helicity anti-quark + negative helicity quark
  - Fragmentation free measurement: uses directly decay lepton as probe

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

@ Central Arms ($|\eta| < 0.35$)

$W^{\pm} \rightarrow e^{\pm}$ PHENIX Midrapidity



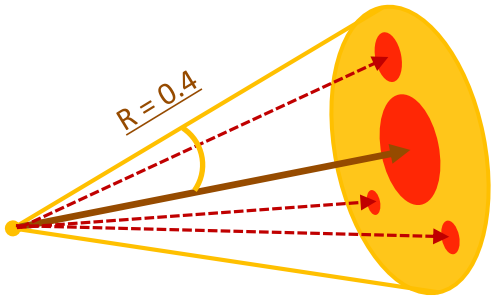


- **Central Arms**
  - $|\eta| < 0.35$, $\Delta\phi = \frac{\pi}{2} \times 2$
  - Tracking: DC, PC
  - pID: RICH, ToF
  - EMCal: PbGl, PbSc

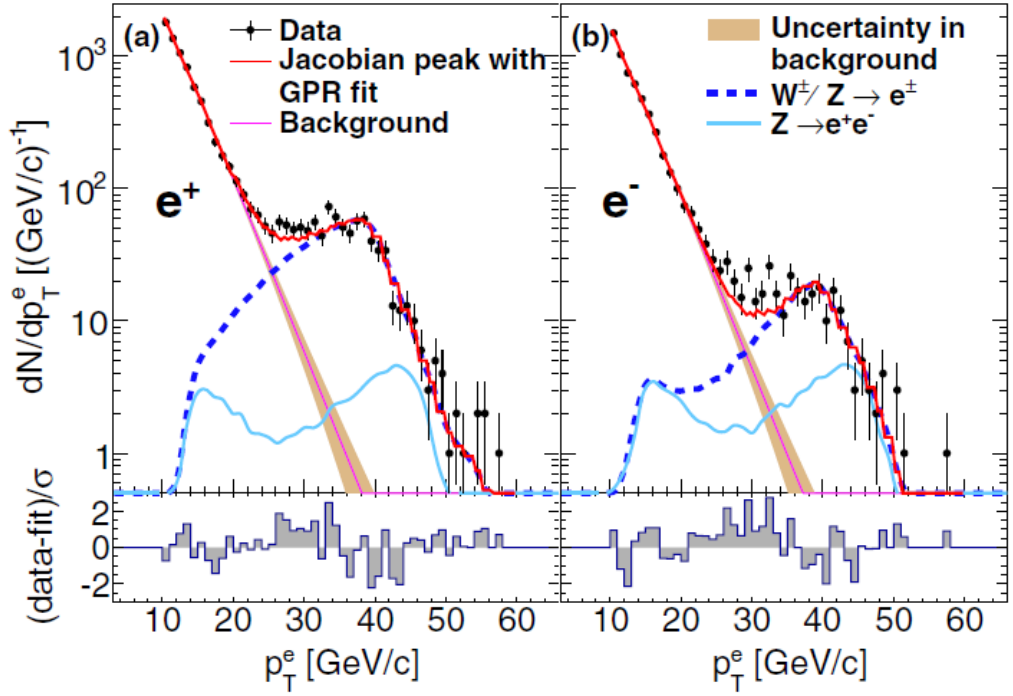
- ***$W^{\pm} \rightarrow e^{\pm}$* at $|\eta| < 0.35$**
  - Distinct Jacobian peak
  - Triggered by energy
  - Momentum measurement by energy
  - Charge determination by tracking in B-field

$W^{\pm} \rightarrow e^{\pm}$ Analysis

PRD93, 051103 (2016)



$$\frac{E_{cone} - E_{candiate}}{E_{candiate}} < 10\ (\%)$$



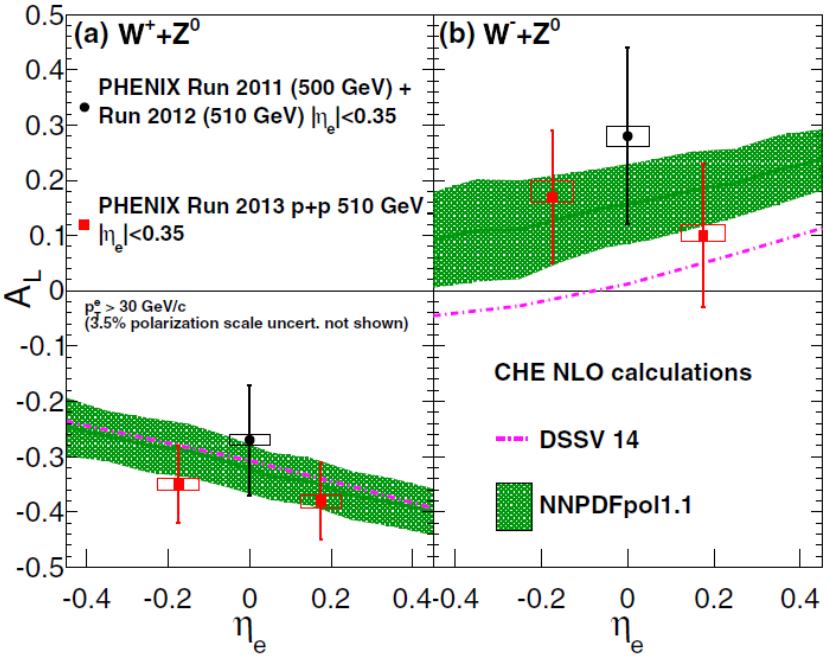
- **Utilize Jacobian peak**
  - | Vtx_Z | < 30 (cm)
  - 1st background suppression by energy isolation cut, with cone R = 0.4 in η and ϕ
  - Estimate remaining backgrounds in signal dominant region (p_T > 30 GeV)

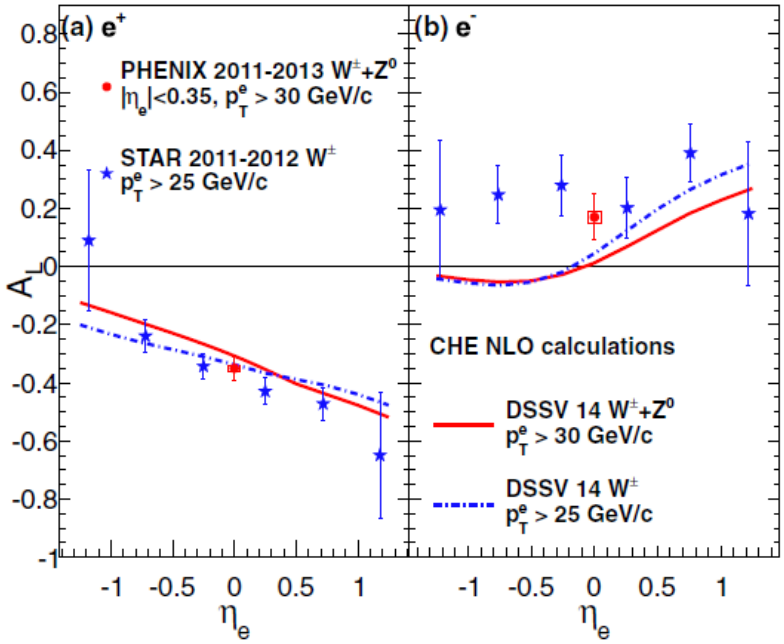
    by extrapolating backgrounds in 10 < p_T < 22 (GeV) by using GPR (Gaussian Process Regression)

    → Resulting dilution factors: 97 % (e^+) and 94 % (e^-) for RUN13 at 30 < p_T < 50 (GeV)
  - Contribution by Z^0 : 7 % (e^+) and 25 % (e^-)

$W^{\pm} \rightarrow e^{\pm}$ Results

PRD93, 051103 (2016)



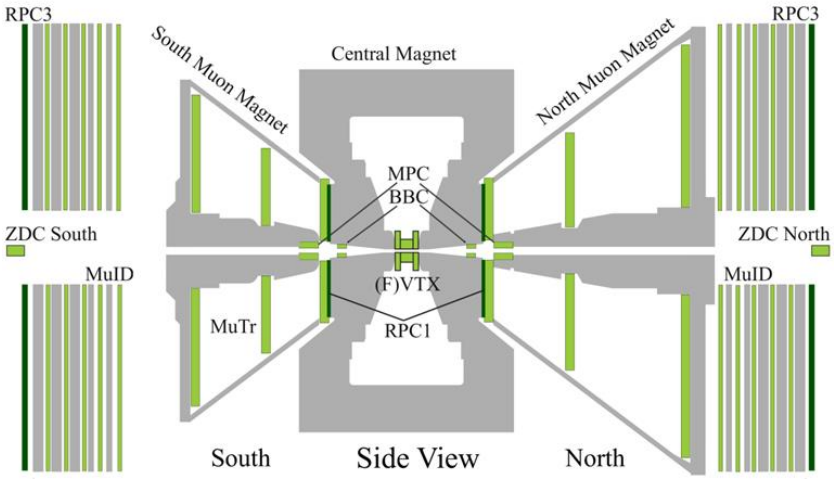


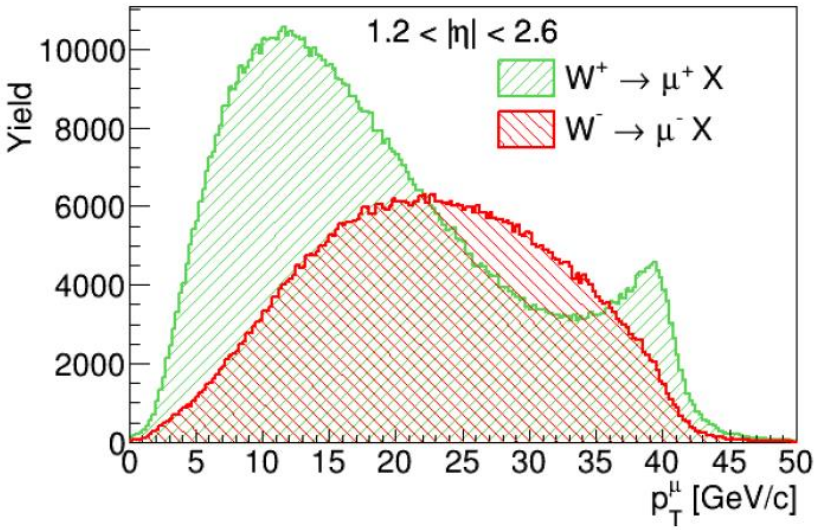
- **$W^{\pm}/Z^0 \rightarrow e^{\pm}$, A_L with integrated RUN11-13 data**
  - $\sqrt{s}$ = 500 (11) / 510 (12, 13) GeV, total Int. L = 240 pb^{-1}
  - Probed Bjorken x of ~ **0.16** (M_W / $\sqrt{s}$)
  - Larger asymmetry than DSSV14 in W^-

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

@ Muon Arms ($1.2 < |\eta| < 2.2/2.4$)

$W^{\pm} \rightarrow \mu^{\pm}$ PHENIX Forward Rapidity



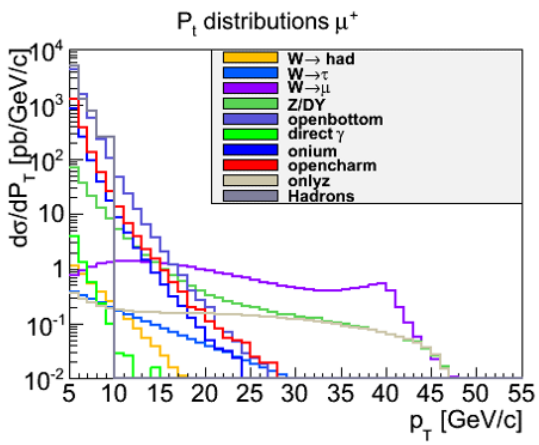


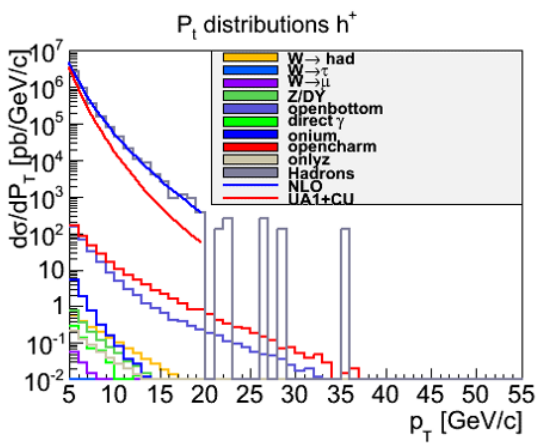
- **Muon Arms**
  - 1.2 < |η| < 2.2 (S) or 2.4 (N), Δϕ = 2π
  - FVTX (Si strip, from 2012)
  - Tracking: MuTr (CS chambers)
  - pID: MuID (steel interleaved Iarocci tubes), RPCs

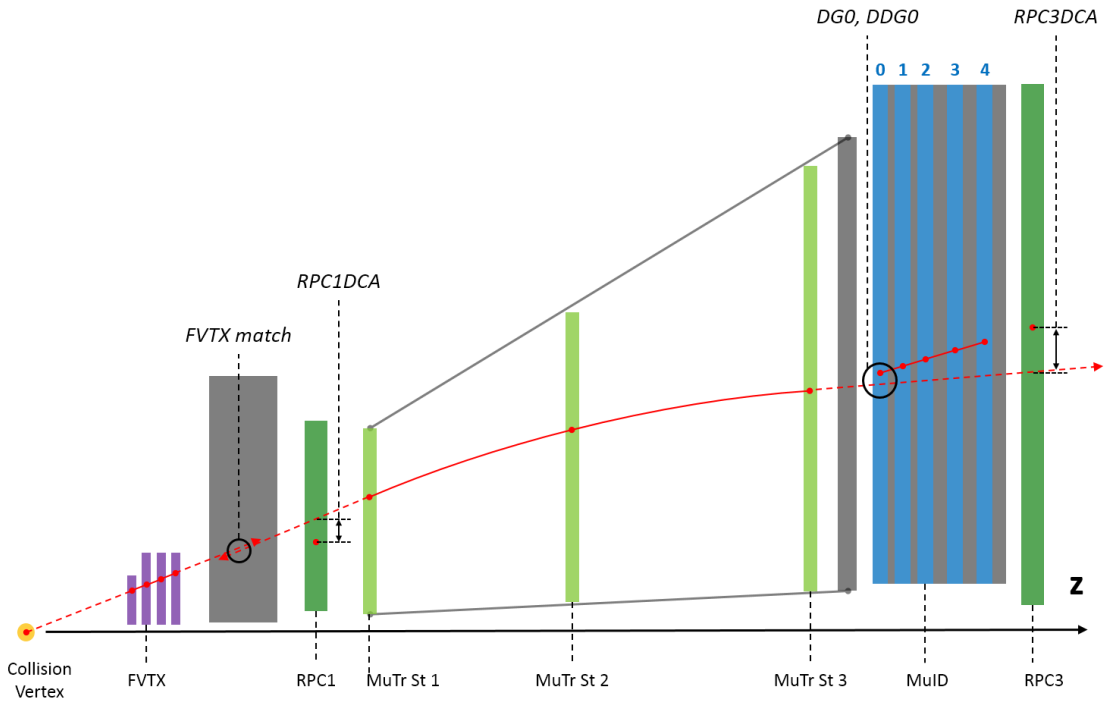
- **$W^{\pm} \rightarrow \mu^{\pm}$ at 1.2 < |η| < 2.2 / 2.4**
  - Suppressed/No Jacobian peak
  - Triggered by momentum
  - Momentum measurement by tracking in B-field
  - Charge determination by tracking in B-field

$W^{\pm} \rightarrow \mu^{\pm}$ Approach

MC

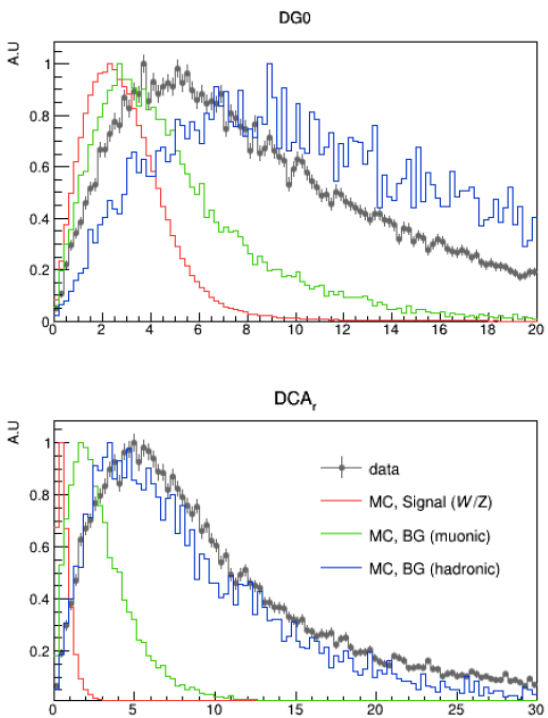


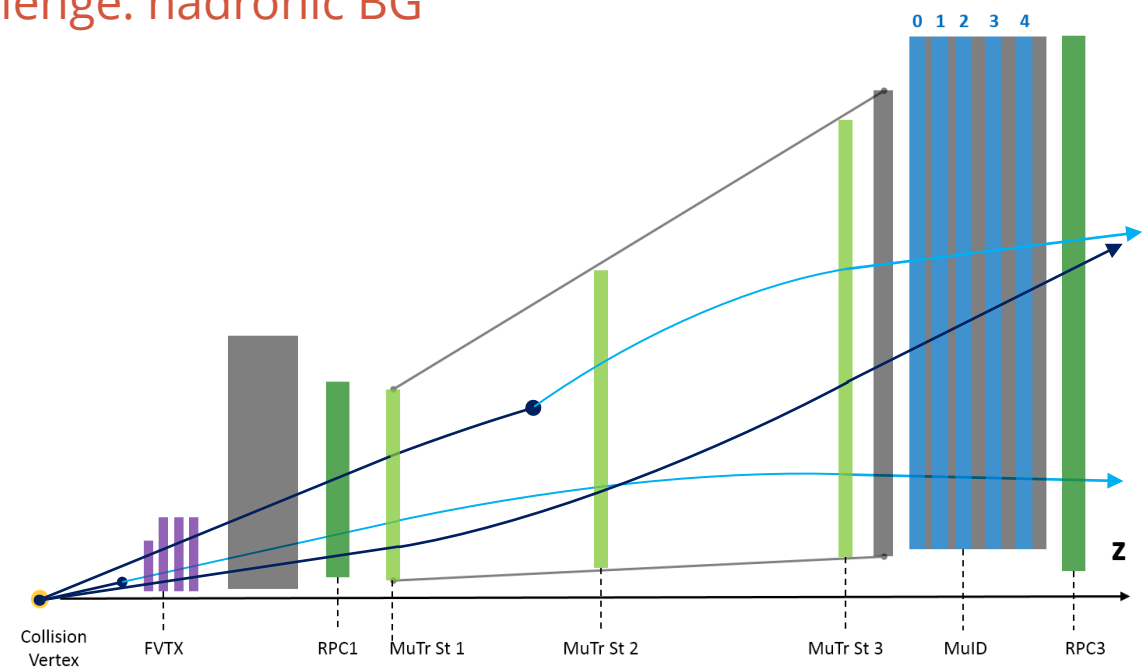




- **Challenges and Approach**
  - In addition to strongly suppressed Jacobian peak,
    - a. Limited detector acceptance
    - b. Abundant backgrounds (both muonic and hadronic)
    - c. Smearing in p_T reconstruction
  - No single variable can discriminate *W* signal from BG clearly, but each variable has advantage over certain type of BG

$W^{\pm} \rightarrow \mu^{\pm}$ Major challenge: hadronic BG



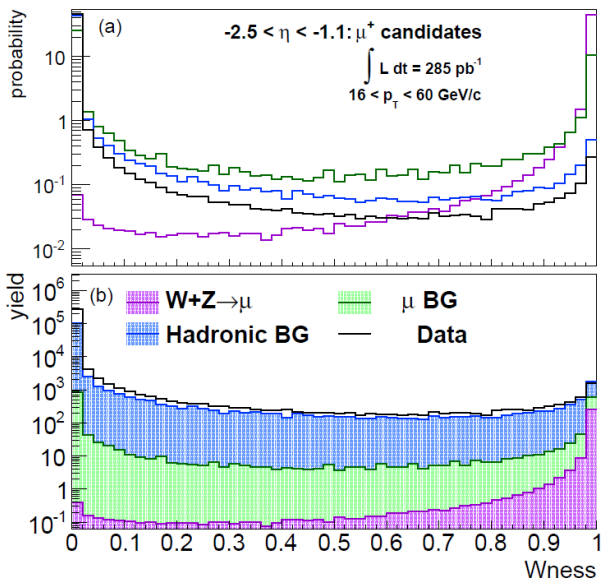


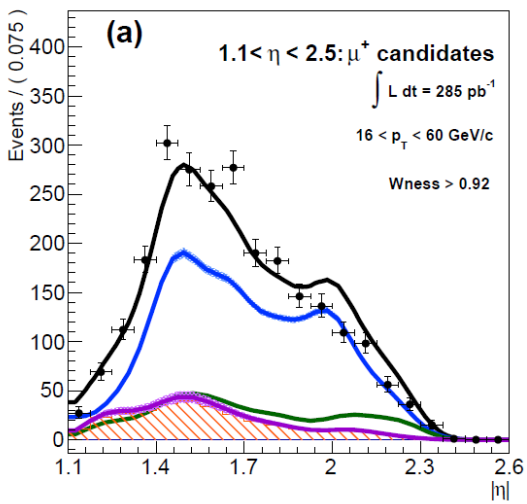
Punch - through	Penetrate through all absorbers and leave trail on detectors
Early muonic decay	Decay to muon before reaching MuTr (DCAr, DCAz)
Late muonic decay	Decay to muon inside MuTr

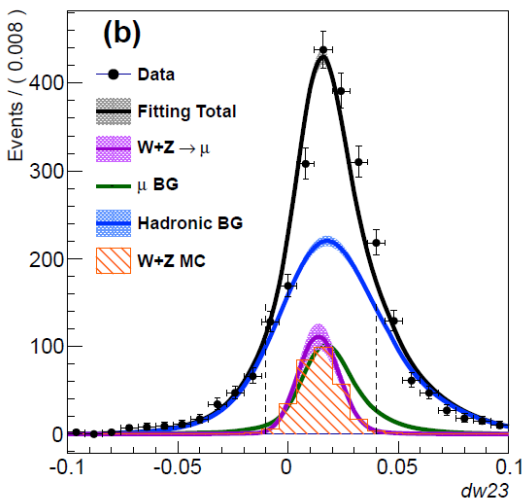
- **Hadronic BG in Muon Arms**
  - Relatively low momentum charged hadrons (mainly $\pi^{\pm}$ and $K^{\pm}$, $p_T < 20$ (GeV))
  - Only small fraction of them penetrate through upstream absorber and reach MuTr, but enormous total cross section creates large backgrounds

$W^{\pm} \rightarrow \mu^{\pm}$ Analysis

arXiv:1804.04181





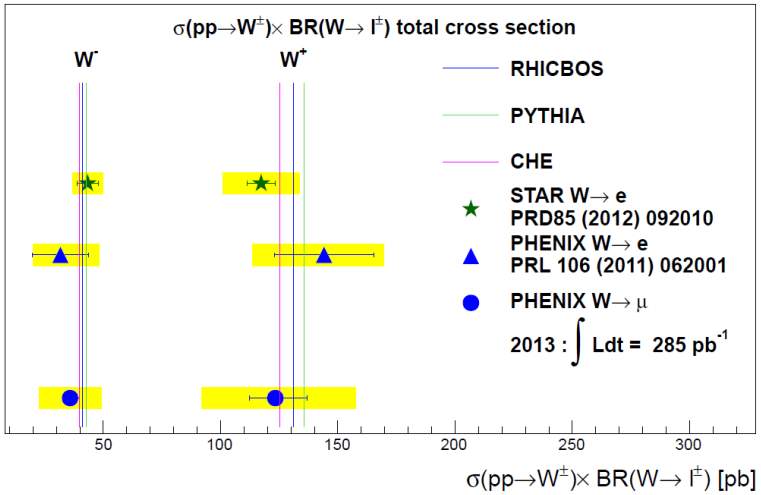


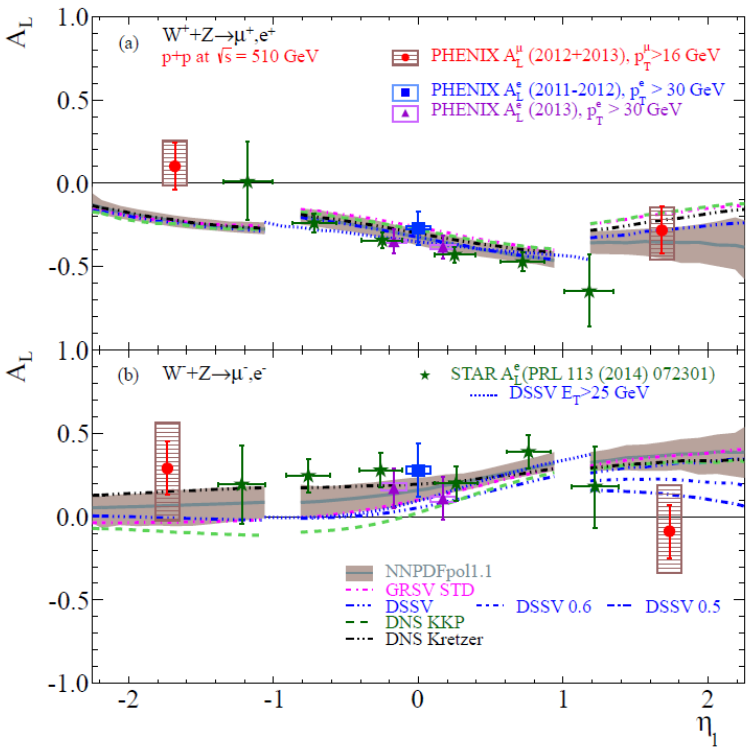
- **Multivariate analysis: *W* likelihood (Wness)**
  - Wness = $\frac{\lambda_{sig}}{\lambda_{sig} + \lambda_{BG}}$, where $\lambda_{sig} = (\lambda_{DG0,\,w} \cdot \lambda_{DDG0,\,w} \cdot \lambda_{DCA_r,\,w} \ldots)$
  - Improve sample purity by applying high Wness filter on μ candidates
  - Signal estimation by unbinned max. likelihood fit

    → Resulting S/BG ratio: <u>15 % ~ 28 %</u> for signal concentrated dw23 region
  - Contribution by Z^0: 18 % (μ^+) and 22 % (μ^-)

$W^{\pm} \rightarrow \mu^{\pm}$ Results

arXiv:1804.04181





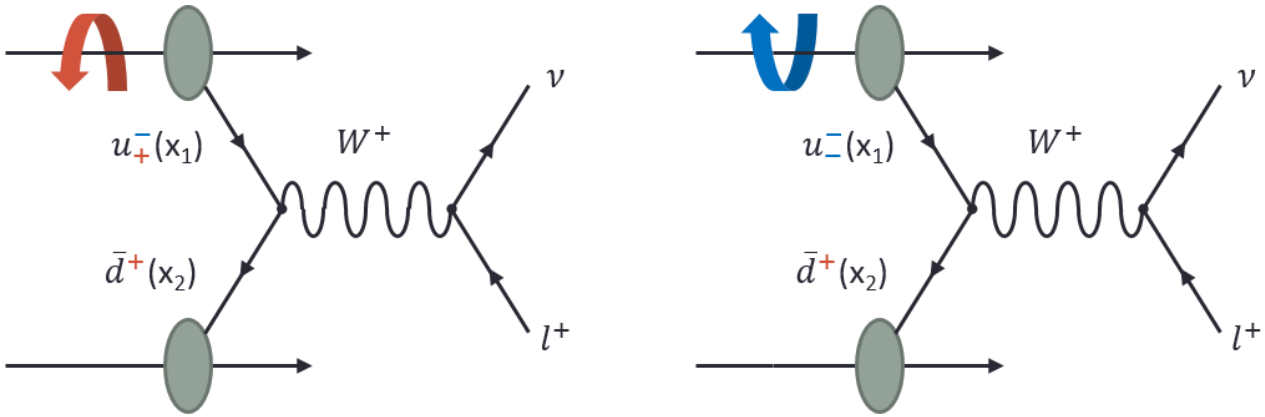
- **$W^{\pm}/Z^0 \rightarrow \mu^{\pm}$, A_L with integrated RUN12-13 data**
  - $\sqrt{s}$ = 510 GeV, Int. L = 53 (2012) + 285 (2013) pb^{-1}
  - **First** $W^{\pm} \rightarrow \mu^{\pm}$ measurement at $|\eta| > 1$, probed Bjorken x of ~ **0.1** (backward) / ~ **0.3** (forward)
  - Consistent cross sections to existing RHIC $W^{\pm} \rightarrow e^{\pm}$ within uncertainties
  - Discrepancy to the theory curves at backward W^{+} and forward W^{-}

Summary

- **$W^{\pm}/Z^0 \rightarrow e^{\pm}$**
  - RUN11 - RUN13, total Int. L = 240 pb^{-1}
  - Signal extraction by Jacobian peak
  - A_L results shows good match to STAR, including larger asymmetry than DSSV14 in W^-

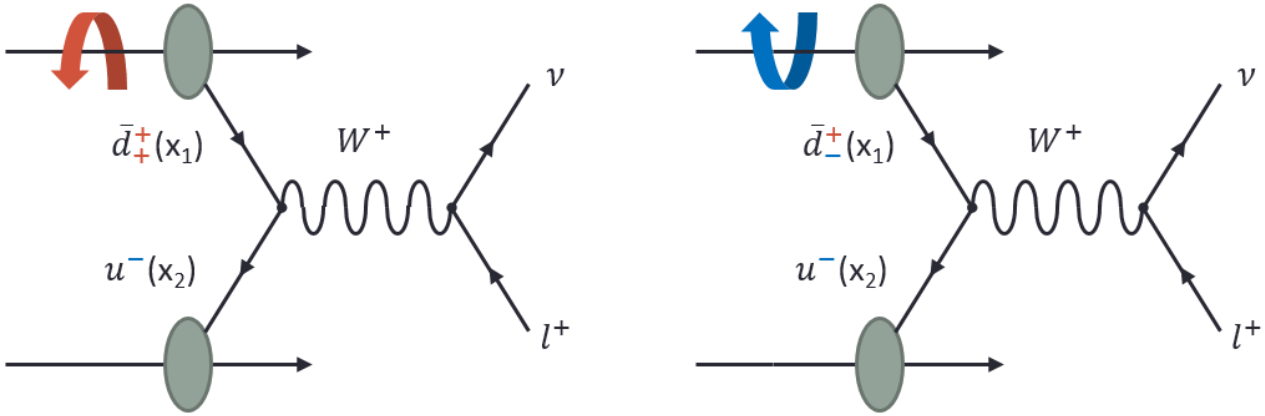
- **$W^{\pm}/Z^0 \rightarrow \mu^{\pm}$**
  - 1st $W^{\pm} \rightarrow \mu^{\pm}$ measurement at $|\eta| > 1$
  - RUN12 - RUN13, total Int. L = 285 pb^{-1}
  - Signal extraction by multivariate analysis and unbinned max. likelihood fit
  - Measured cross sections show reasonable match to the existing results
  - Discrepancy to the theories at backward W^+ and forward W^-

Backup *W* partonic processes



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

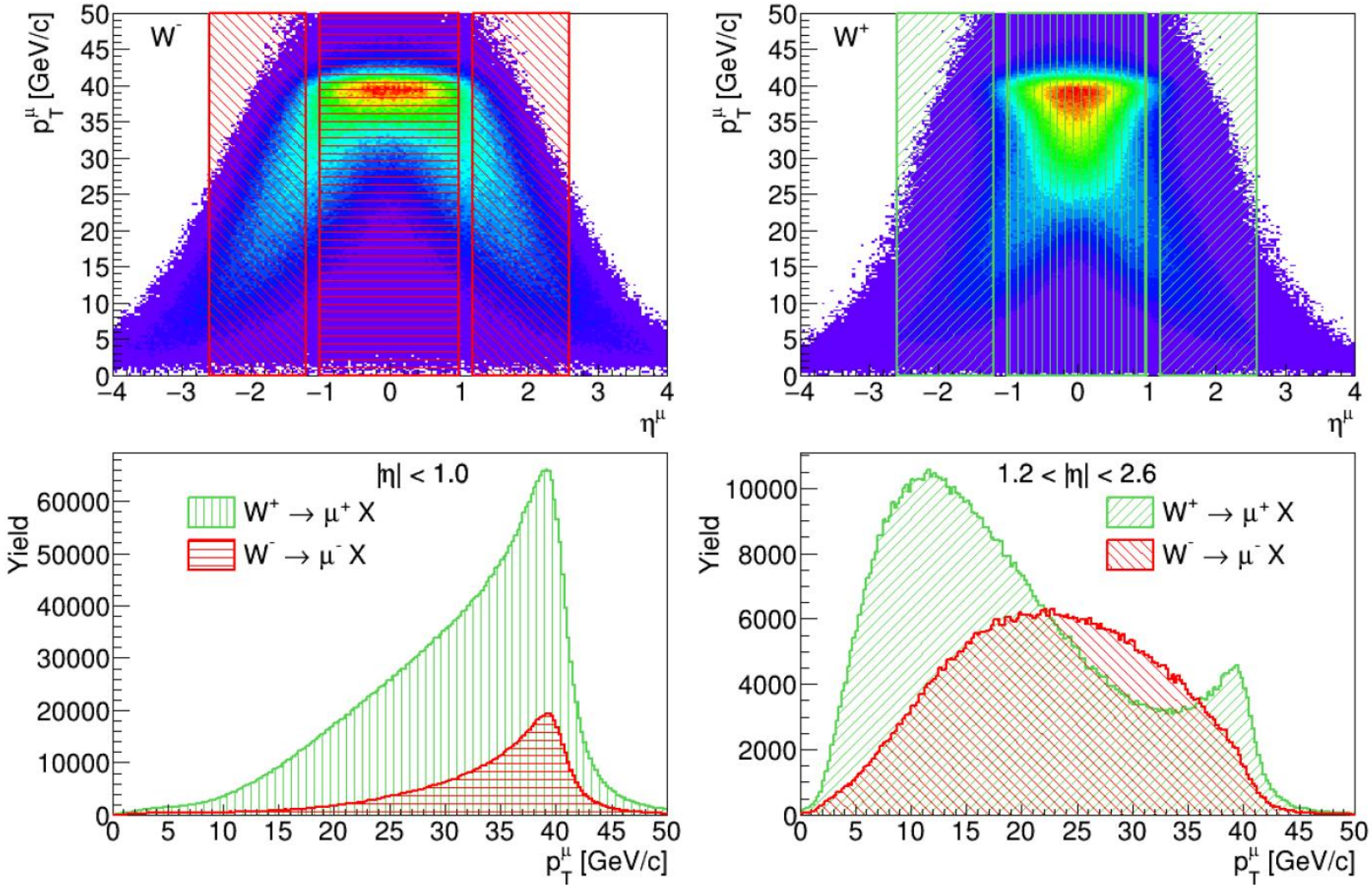
← 1. Δu is being probed



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

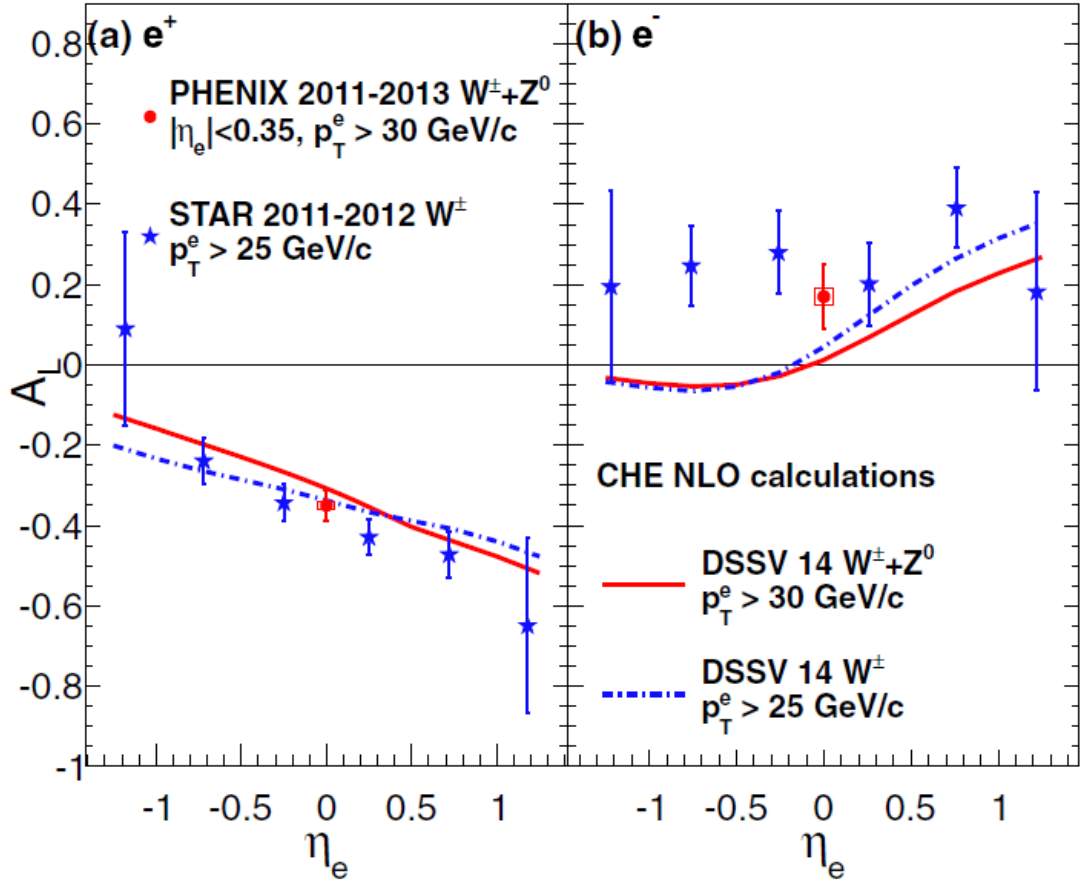
← 2. $\Delta\bar{d}$ is being probed

Backup *W* p_T kinematics in PHENIX acceptance



Backup

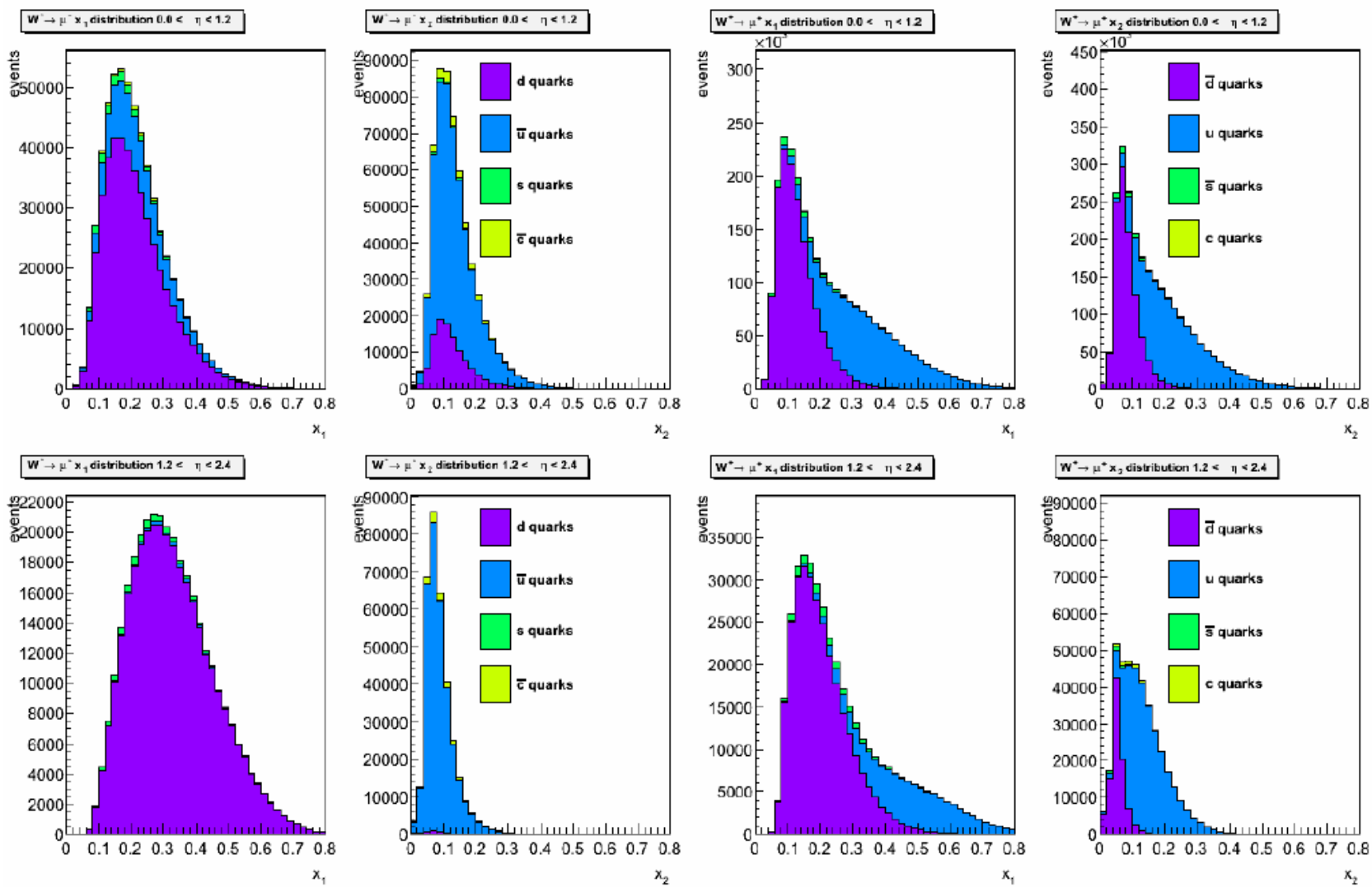
$W^{\pm} \rightarrow e^{\pm}$, with STAR RUN11-12 results



PRD93, 051103 (2016)

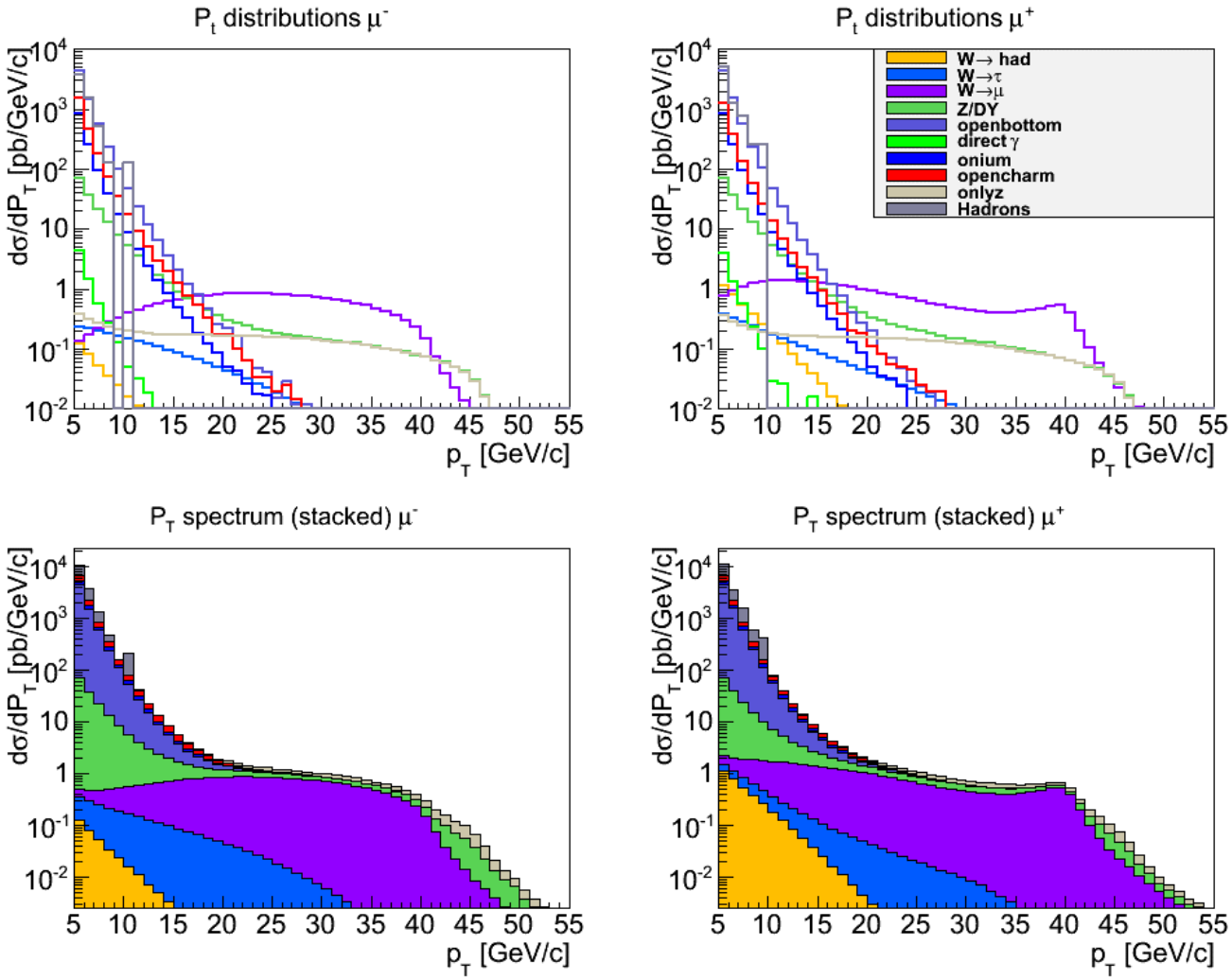
Backup

Bjorken x distributions of $W^{\pm}$



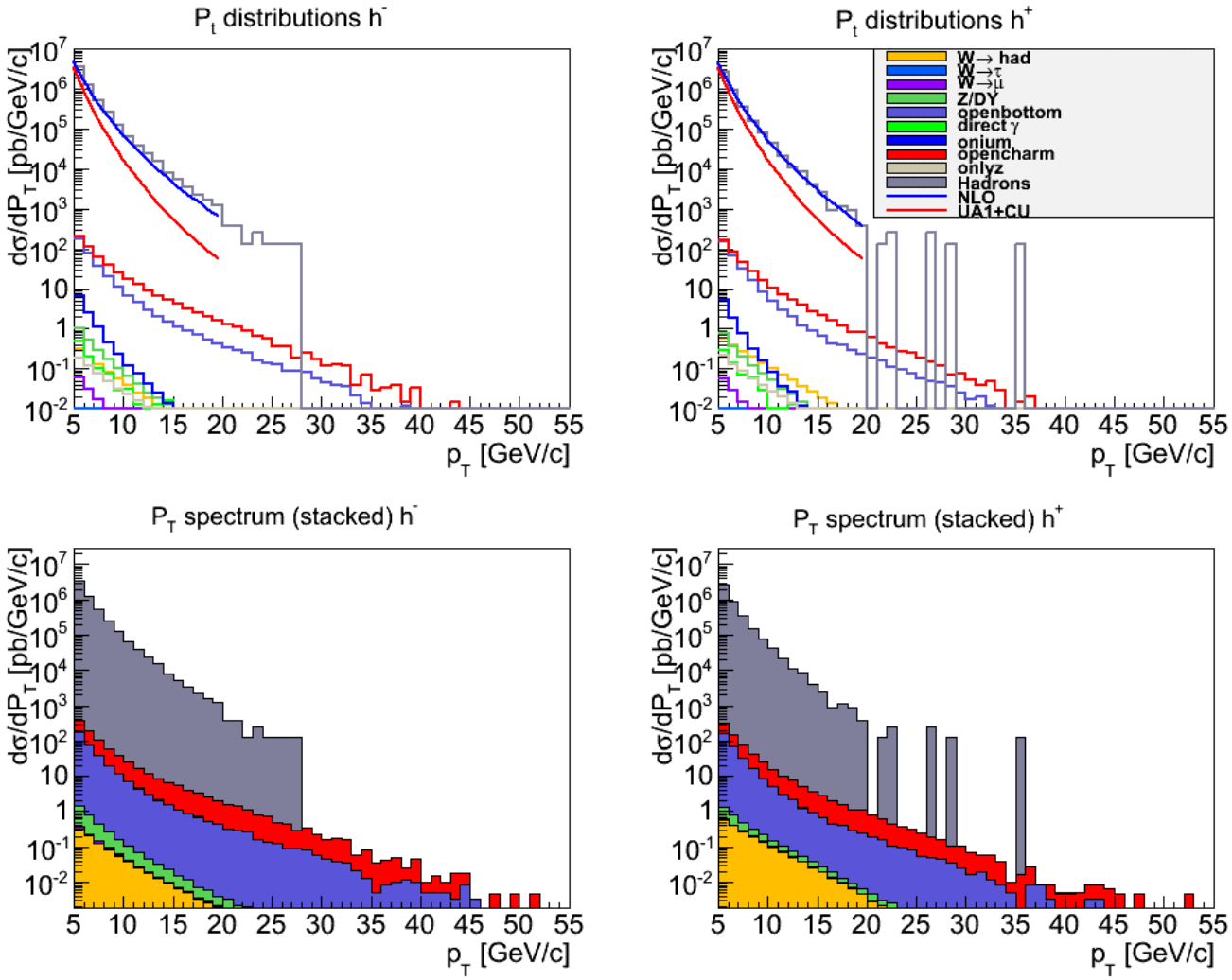
Backup

Muonic decay processes

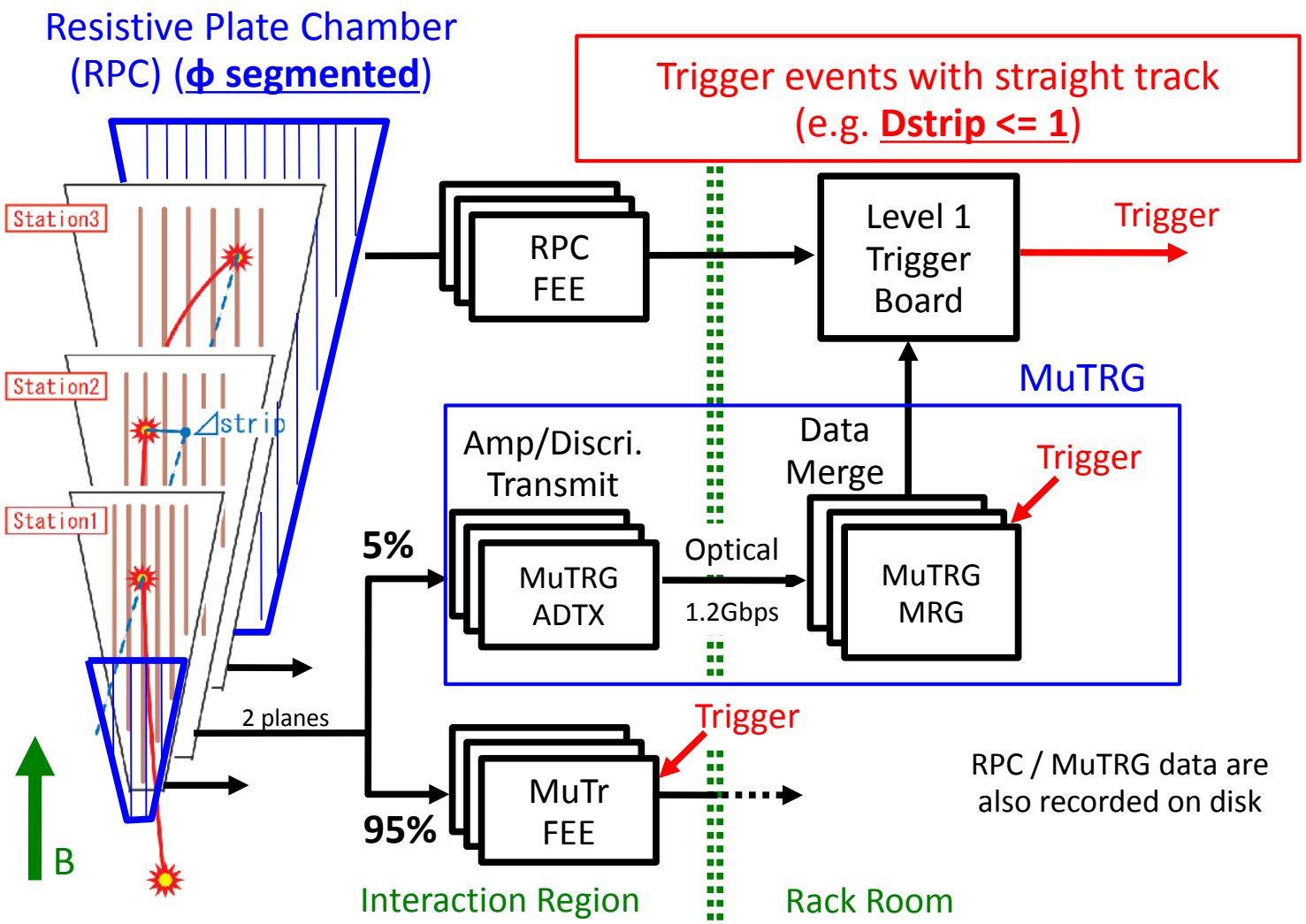


Backup

Hadronic decay processes



Backup μ trigger



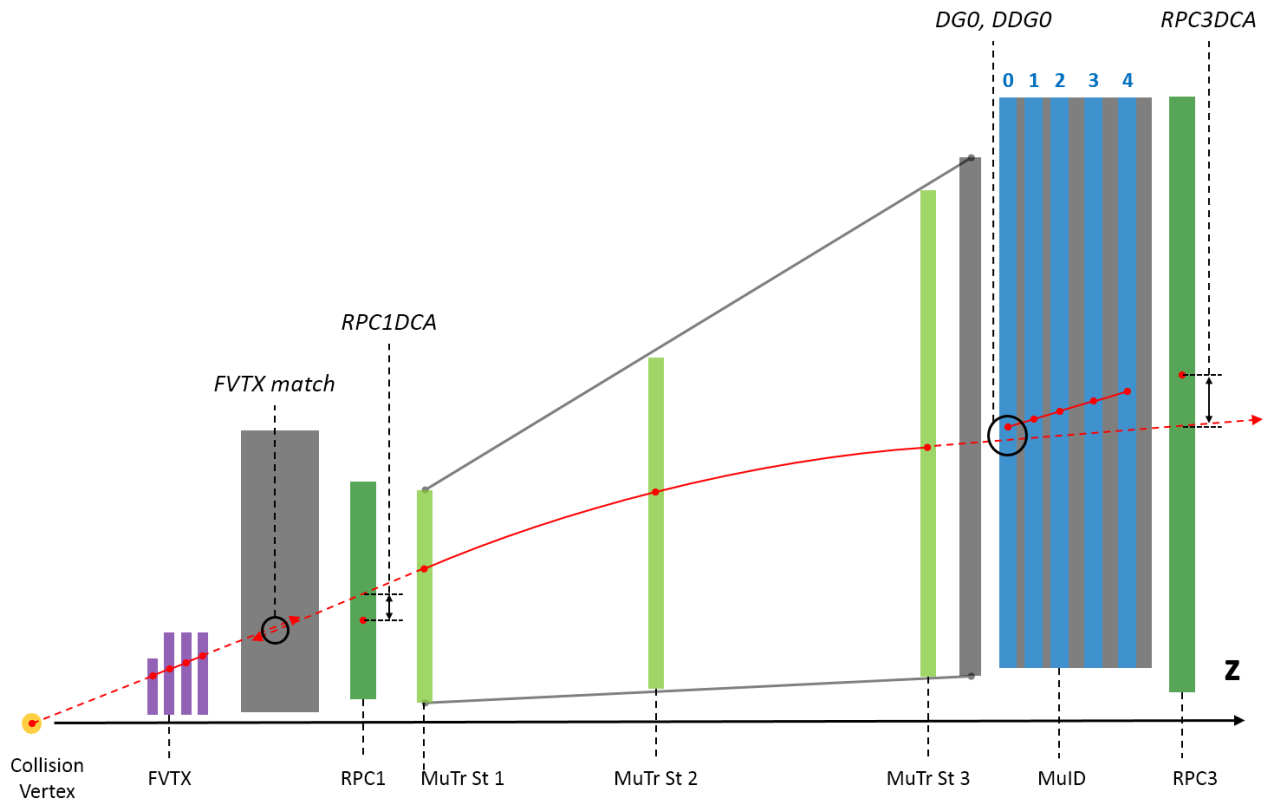
Backup $W^{\pm} \rightarrow e^{\pm}$ results table

PRD93, 051103 (2016)

TABLE I. Number of events recorded for e^+ and e^- for $30 < p_T < 50$ GeV/c and the background contributions, dilution factors, and two-beam polarizations for each analyzed data set.

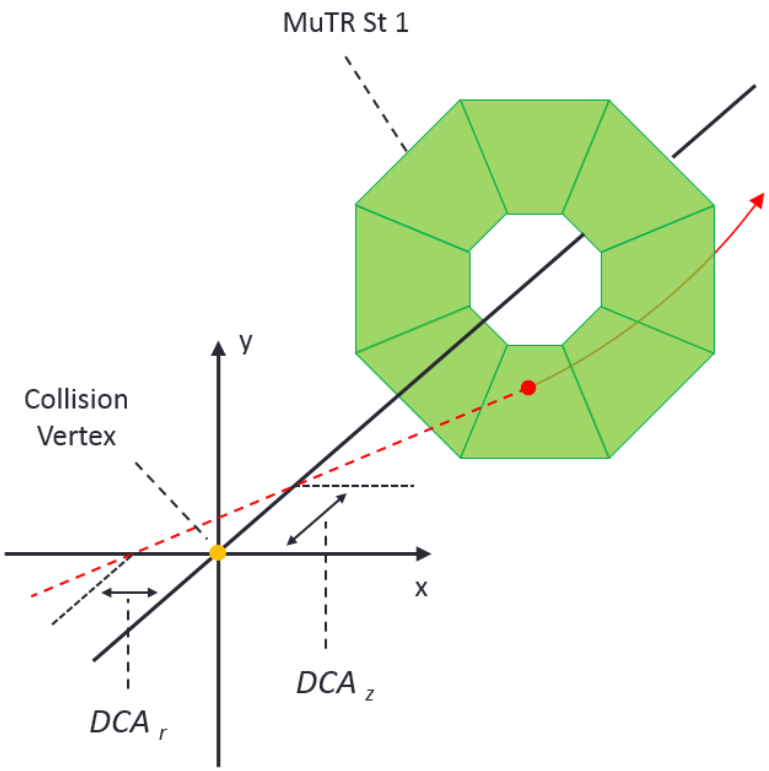
Lepton	Year	Counts	Background contribution	Dilution factor	Polarization B	Polarization Y
e^+	2011	70	$2.3 \pm 2.3(\text{stat}) \pm 0.6(\text{syst})$	$0.97 \pm 0.03(\text{stat}) \pm 0.01(\text{syst})$	0.51 ± 0.02	0.50 ± 0.02
	2012	105	$2.5 \pm 2.5(\text{stat})^{+4.7}_{-2.5}(\text{syst})$	$0.98 \pm 0.02(\text{stat})^{+0.02}_{-0.04}(\text{syst})$	0.55 ± 0.02	0.57 ± 0.02
	2013	669	$18.6 \pm 7.3(\text{stat}) \pm 14.9(\text{syst})$	$0.97 \pm 0.01(\text{stat}) \pm 0.02(\text{syst})$	0.55 ± 0.02	0.55 ± 0.02
e^-	2011	27	$1.7 \pm 1.6(\text{stat}) \pm 0.7(\text{syst})$	$0.94 \pm 0.06(\text{stat}) \pm 0.02(\text{syst})$	0.51 ± 0.02	0.50 ± 0.02
	2012	47	$5.5 \pm 4.7(\text{stat}) \pm 2.2(\text{syst})$	$0.88 \pm 0.10(\text{stat}) \pm 0.05(\text{syst})$	0.55 ± 0.02	0.57 ± 0.02
	2013	233	$13.9 \pm 5.6(\text{stat})^{+20.0}_{-13.9}(\text{syst})$	$0.94 \pm 0.02(\text{stat})^{+0.06}_{-0.09}(\text{syst})$	0.55 ± 0.02	0.55 ± 0.02

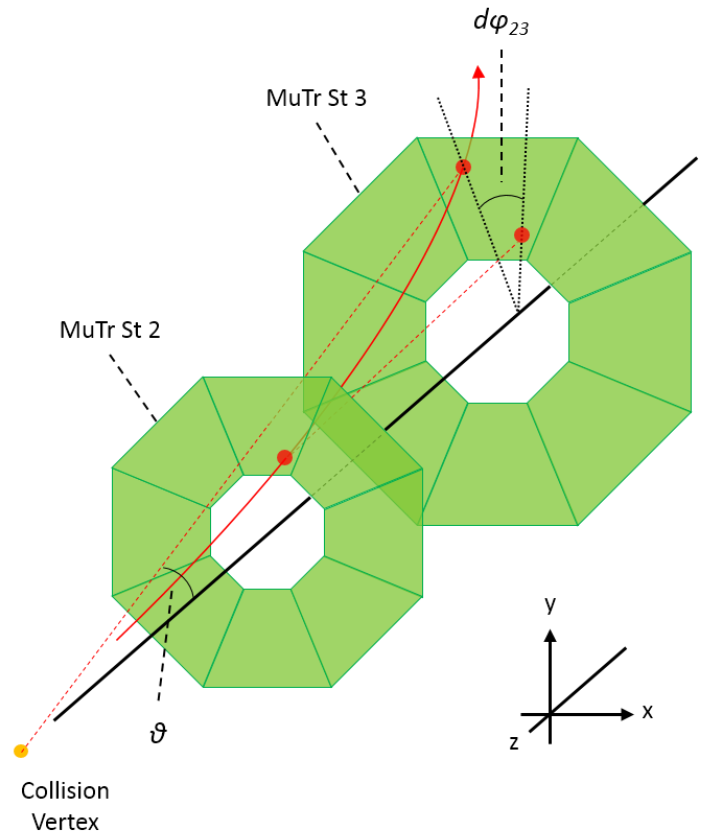
Backup $W \rightarrow \mu$ analysis variables



FVTX match	Match between FVTX track and MuTr residuals in Δr, $\Delta\phi$, and $\Delta\theta$
RPC1(3)DCA	Difference btw RPC1(3) hit cluster and track at RPC1(3) z
DG0	Distance difference btw track – road at 1st MuID plane's z
DDG0	Angular difference btw track – road at 1st MuID plane's z

Backup $W \rightarrow \mu$ analysis variables

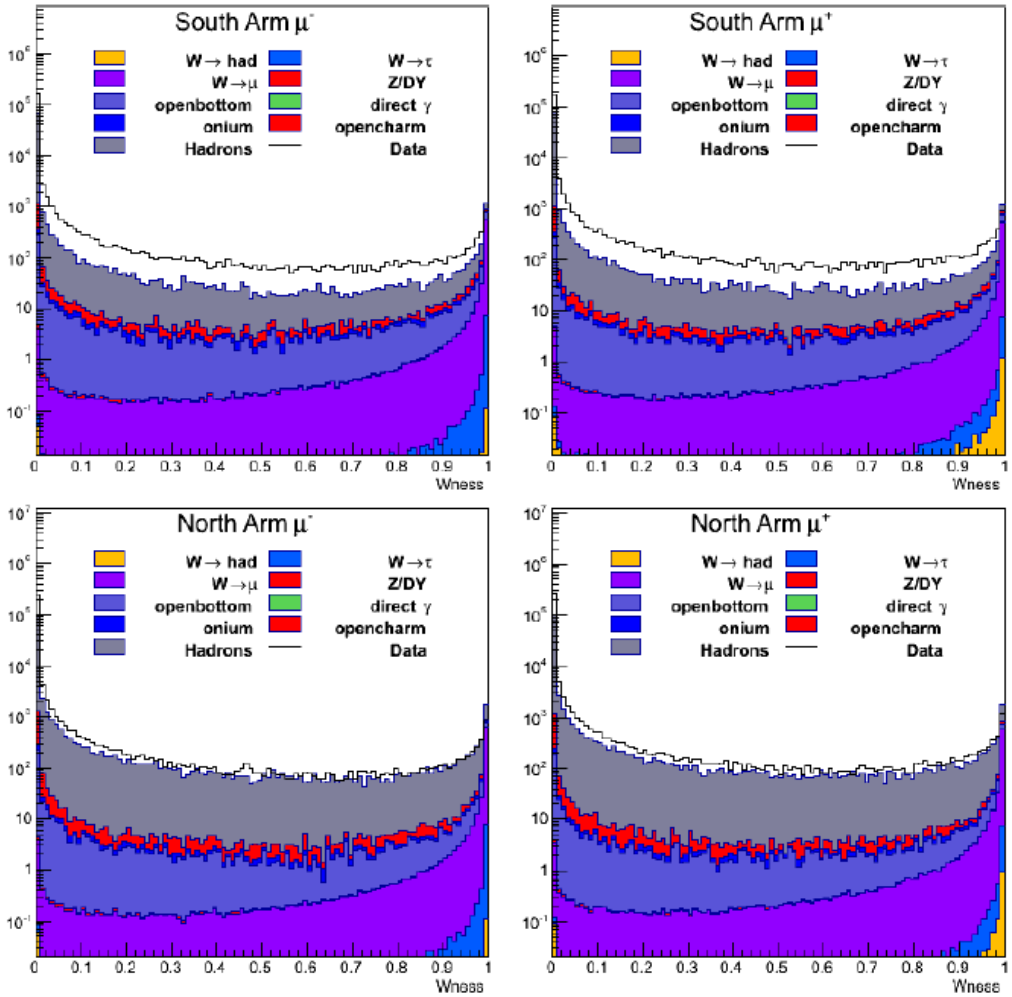




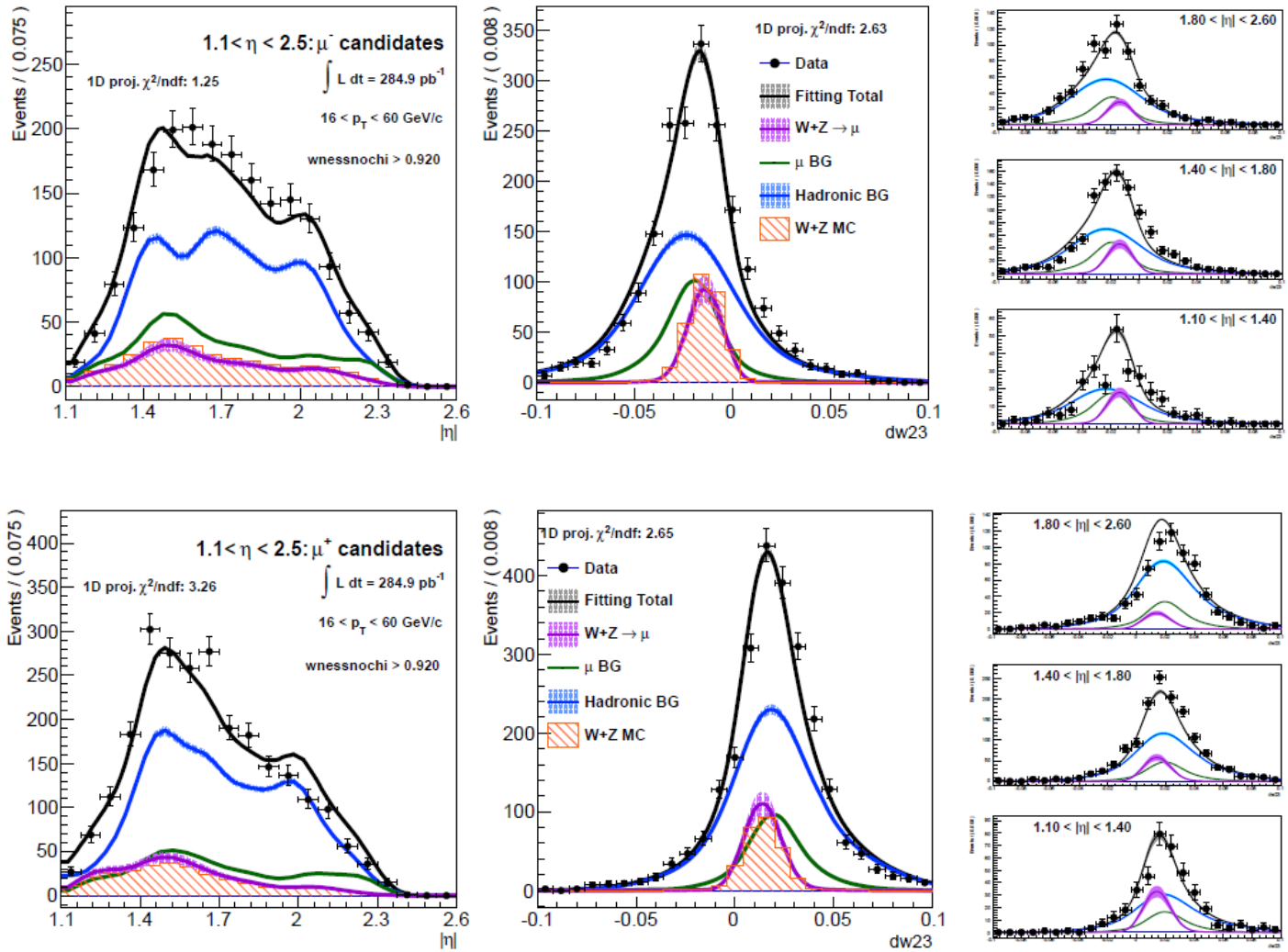
DCA_r	Radial distance of extrapolated track at vertex z
DCA_z	Z distance of extrapolated track at vertex z, **NOT used** due to multiple collision
dw23	Weighted sagitta ($pT \times \sin\theta \times d\phi_{23}$), one of two variables for signal extraction fit

Backup

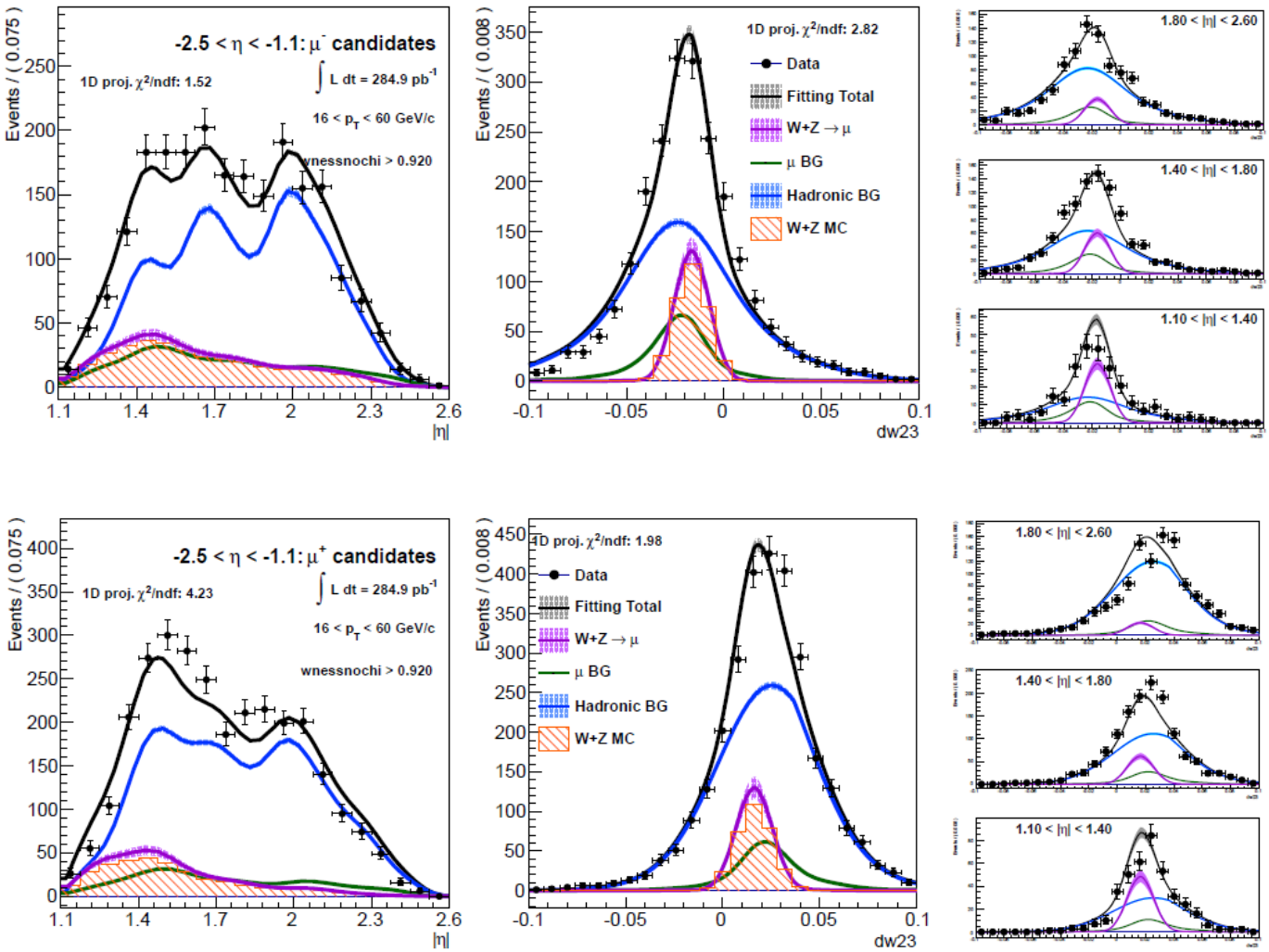
Stacked Wness for each Arm/Charge



Backup $W \rightarrow \mu$ signal extraction by unbinned max. likelihood fit (1)

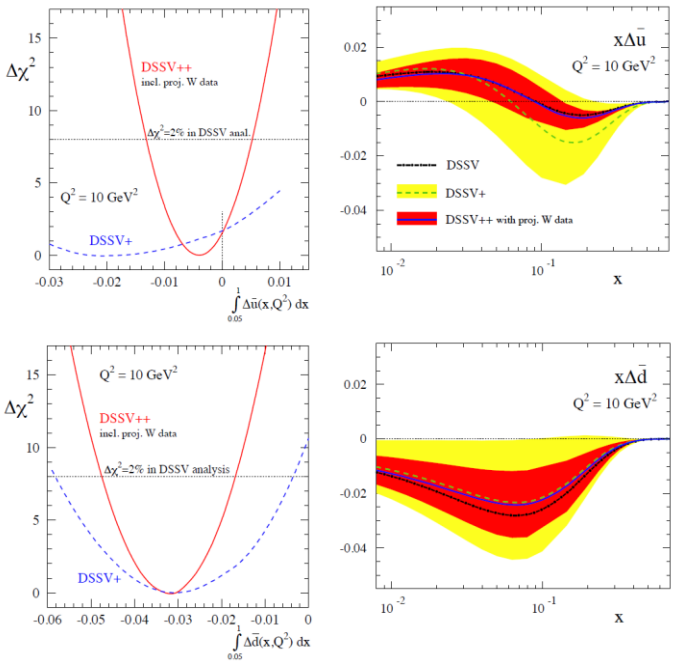


Backup $W \rightarrow \mu$ signal extraction by unbinned max. likelihood fit (2)

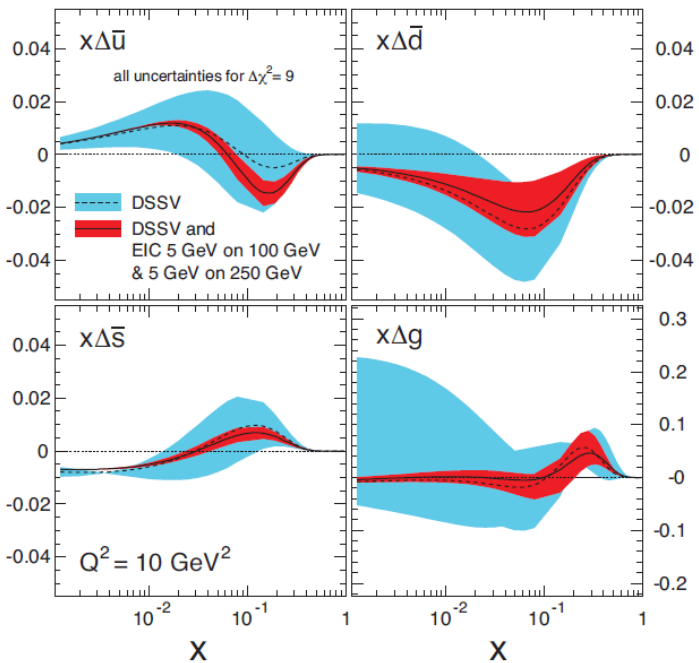


Backup Outlook

arXiv: 1501.01220



arXiv: 1212.1701



- **Improve global analysis with existing RHIC data, Move toward to the EIC**
  - Significant constraint in $\Delta\bar{q}$ is expected once **all** existing RHIC data included in the global analysis
  - Even further constraint can be possible with future EIC data

Backup

Future RHIC data taking perspectives

arXiv: 1602.03922

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3 First look at GPD Eg	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR None None
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η evolution of ETQS fct. properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for γ A_N for diffractive events	Yes Forward instrum. None None
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY):Yes Forward instrum. None Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. None Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity observables as in 2017 run	Yes Forward instrum. None
	202X	$\vec{p}\vec{p}$ @ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Yes Forward instrum.

Table 1-2: Summary of the Cold QCD physics program propsed in the years 2017 and 2023 and if an additional 500 GeV run would become possible.