Recent Results for Sea Quark Polarization Measurement at RHIC

第2回 高エネルギーQCD・核子構造勉強会 @ Tokyo Institute of Technology
May 31, 2014

Sanghwa Park
Seoul National Univ. / RIKEN

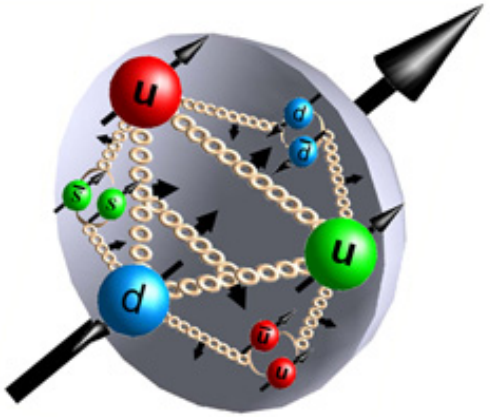
Outline

- Introduction of Spin Physics
  - Nucleon spin structure
  - Proton spin crisis
  - PDFs, DIS, SIDIS measurement
  - W measurement
- Overview of RHIC and Detectors (STAR, PHENIX)
  - Overview of RHIC
  - PHENIX W Measurement
  - STAR W Measurement
- Discussion of the recent results and Summary

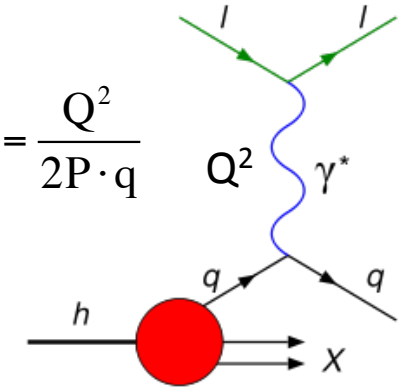
Spin Physics

Nucleon Structure

- Internal structure of nucleon
  - Parton Model (valence quarks, sea quarks, gluons)
  - Structure function $F(x,Q^2)$ ← Parton distribution functions (PDF) $f(x,Q^2)$



Proton



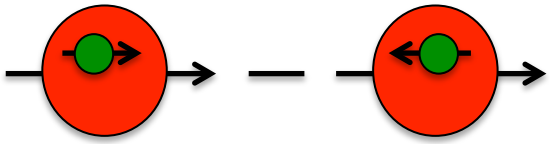
$$x = \frac{Q^2}{2P\cdot q}$$

$$d\sigma = \sum_f \int_0^1 dx\ \Delta f(x,Q^2) \otimes \hat{\sigma}_h \otimes D_f^h$$

  - Spin Structure inside nucleon:

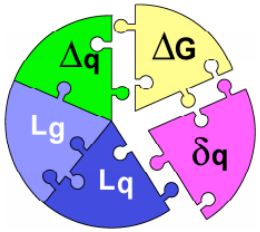
spin-dependent parton distributions functions

$$A(x,Q^2) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\sum_f \left(q_f^+ - q_f^-\right)}{\sum_f \left(q_f^+ + q_f^-\right)} = \frac{\sum_f \Delta q_f(x,Q^2)}{\sum_f q_f(x,Q^2)}$$



$\Delta f(x) = f(x)^+ - f(x)^-$

Proton Spin Structure

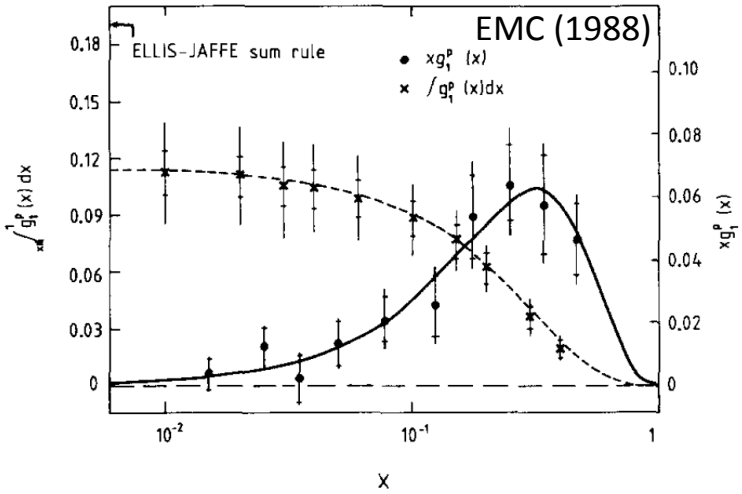


➢ Polarized Deep Inelastic Scattering (DIS)

- EMC (European Muon Collaboration, 1988): First measurement of quark contributions to the proton spin.
- Gives you only (quark + antiquark) contributions

$$\int_0^1 g_1^p(x)dx = 0.114 \pm 0.012(\text{stat}) \pm 0.026(\text{syst})$$

(g_1: spin-dependent structure function of the proton)



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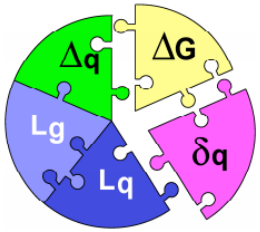

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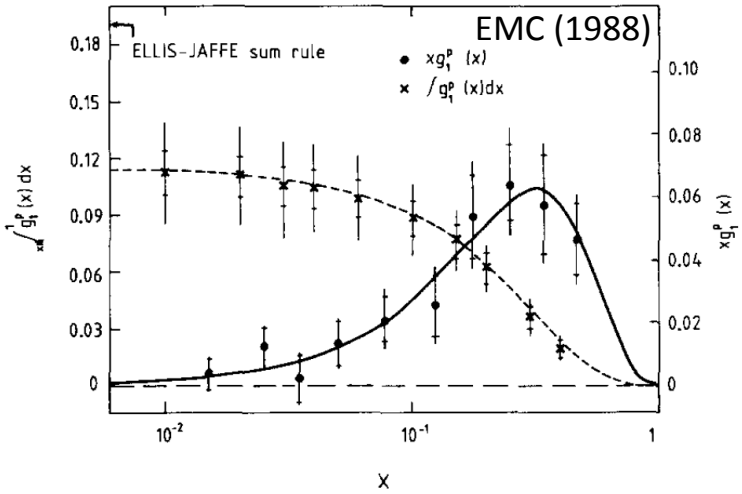
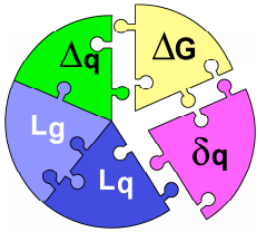


➢ Spin crisis

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

- ΔΣ: sum of quark contributions. As recent result, total quarks' contribution ~25%. (DIS, SIDIS, PP)
- ΔG: gluon contributions.
- L: orbital angular momentum.

Proton Spin Structure



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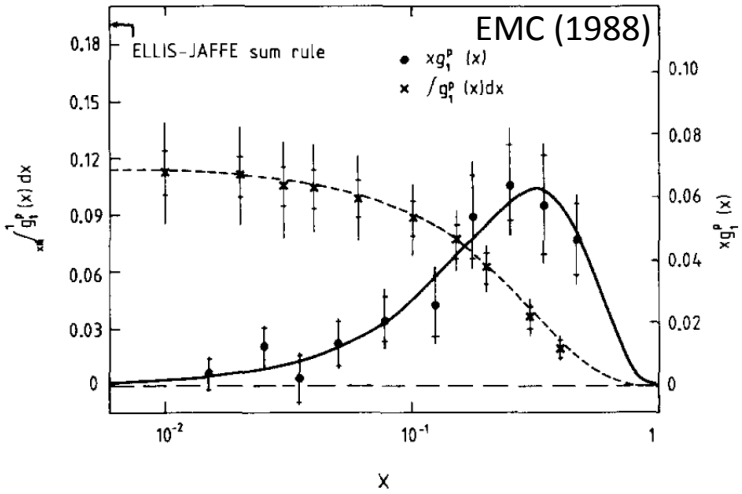

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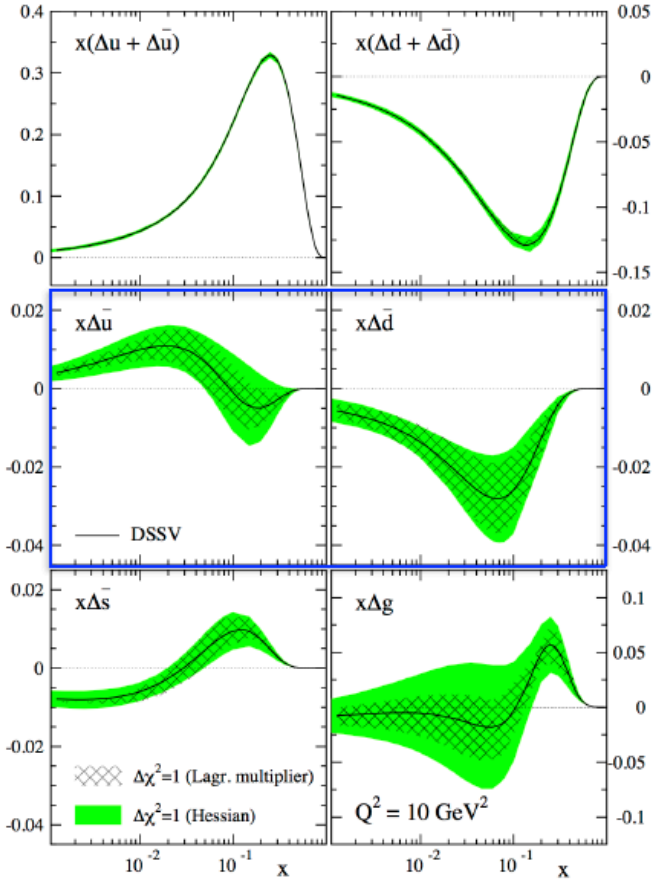
Proton Spin Structure

- Global analysis
  - PDFs are universal
  - All world data to be analyzed
  - Well known quark PDFs.
  - Still large uncertainty of antiquark and gluon PDFs.
  - Further constraints from pp data

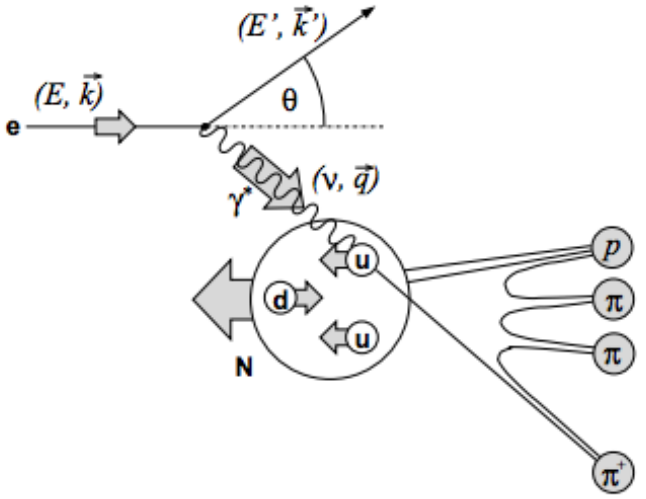


D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, Phys. Rev. D 80, 034030 (2009)

How do we measure antiquark PDFs?

- Semi-Inclusive Deep Inelastic Scattering (SIDIS)
  - The method is almost same as DIS + Measure hadrons in the final state.

    → probability that particular parton produces a particular hadron (Fragmentation Functions). Large uncertainty of FFs.



$\bar{u}d \to \pi^+$
$\bar{u}d \to \pi^-$
$\bar{u}s \to K^+$
$\bar{u}s \to K^-$

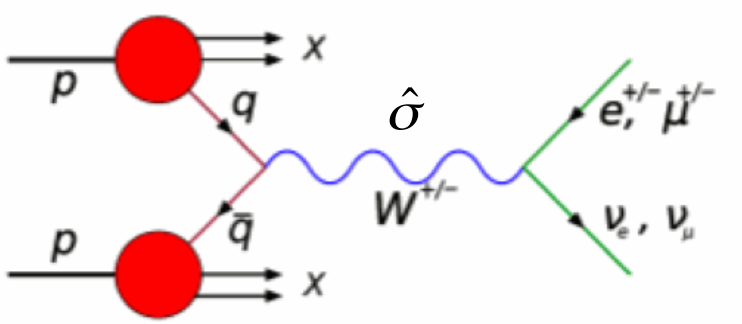
- QCD factorization
- Measure the asymmetry of polarized cross section for access to the spin structure

$$A_1^h(x,Q^2,z) = \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_{q'} e_{q'}^2 q'(x,Q^2) D_{q'}^h(z,Q^2)}.$$

FFs

How do we measure antiquark PDFs?

- W Boson Measurement in longitudinally polarized P+P scattering



- Maximum parity violation of weak interaction. Fixed helicity of incoming quark and antiquark.
  → Left-handed quark + Right-handed antiquark

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

- Free from the fragmentation functions
- Measure W through their lepton decays
- Ideal tool to study the spin structure of the proton ($\Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d}$)

How do we measure antiquark PDFs?

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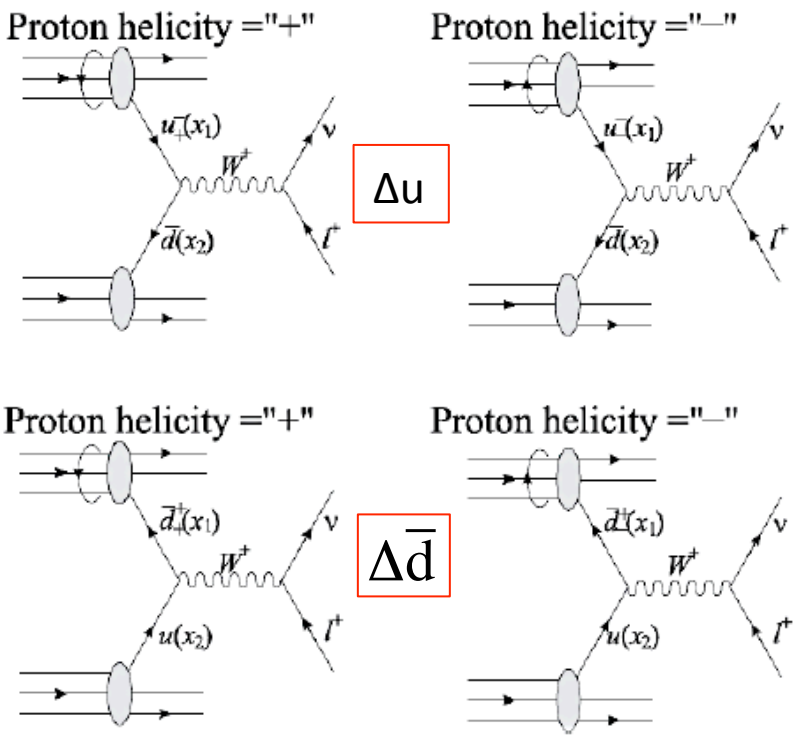
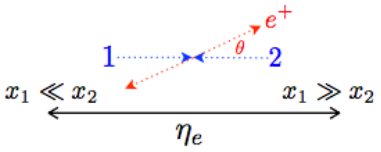
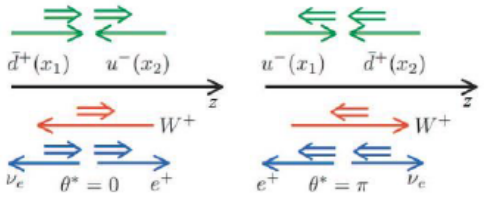


$$A_L = \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-}$$



$$A_L^{W+} \approx \frac{\int dx_1\, dx_2 [\Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2]}{\int dx_1\, dx_2 [\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 + u(x_1)\bar{d}(x_2)(1-\cos\theta)^2]}$$



$$A_L^{W-} \approx \frac{\int dx_1\, dx_2 [\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}{\int dx_1\, dx_2 [\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}$$

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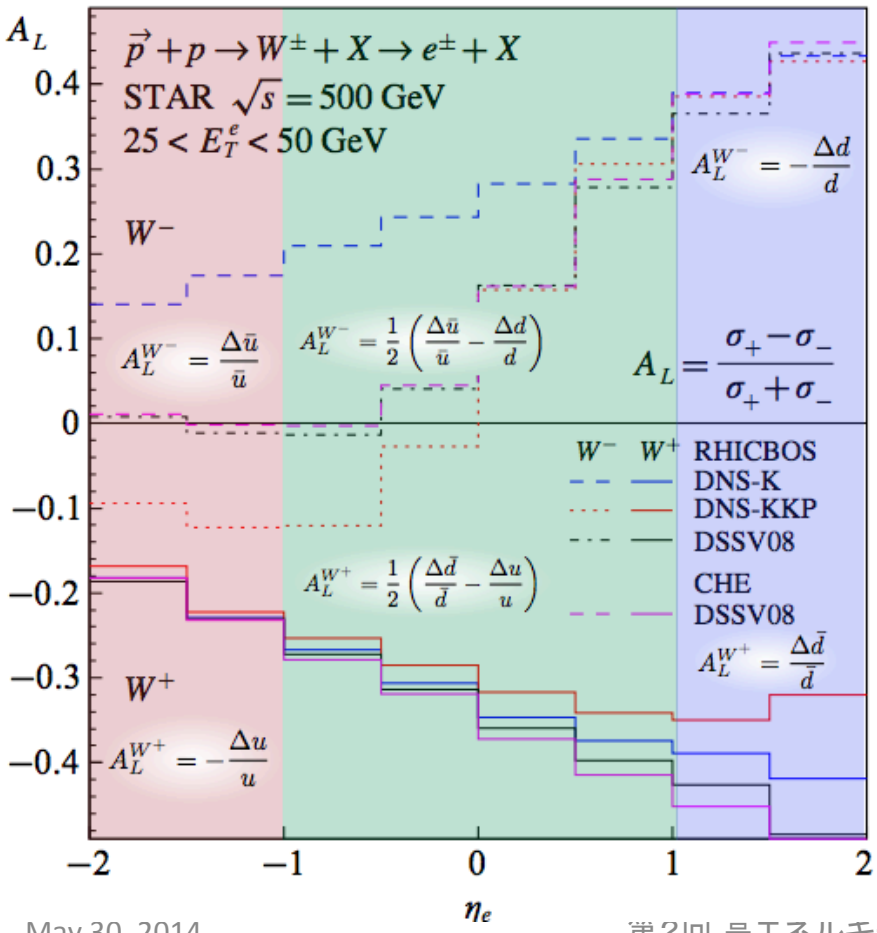

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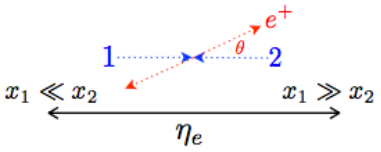

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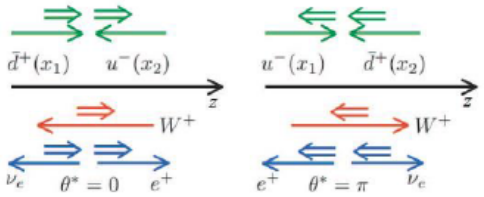

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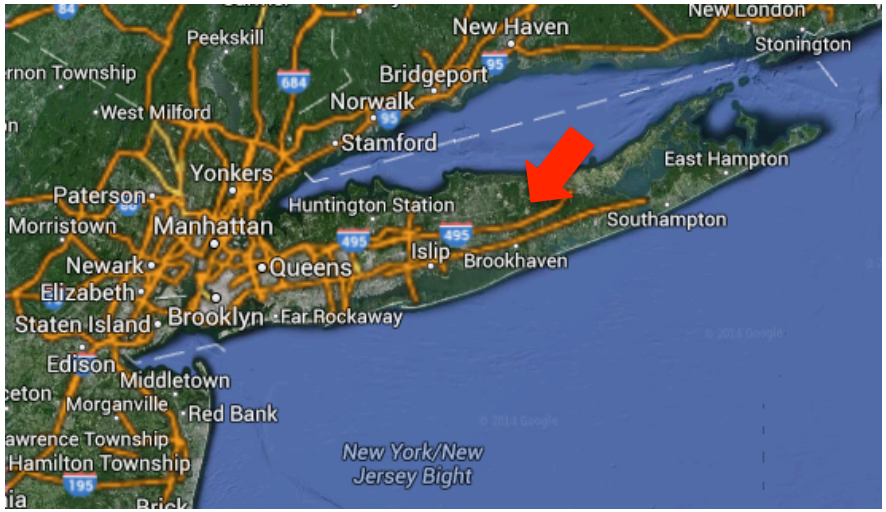
W Measurement @ RHIC

RHIC

- Relativistic Heavy Ion Collider (RHIC).
- The world unique polarized hadron collider



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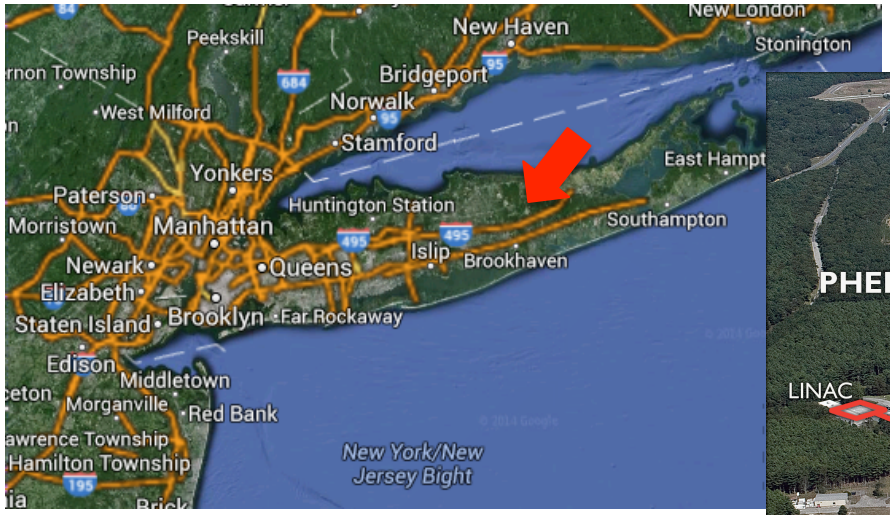

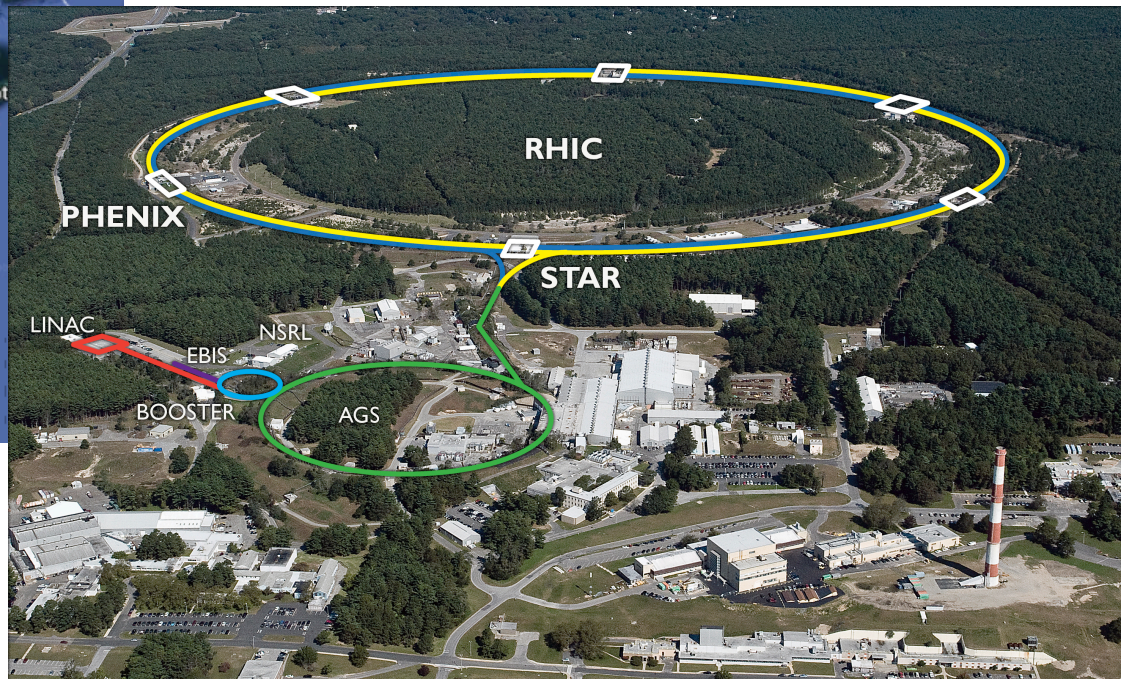

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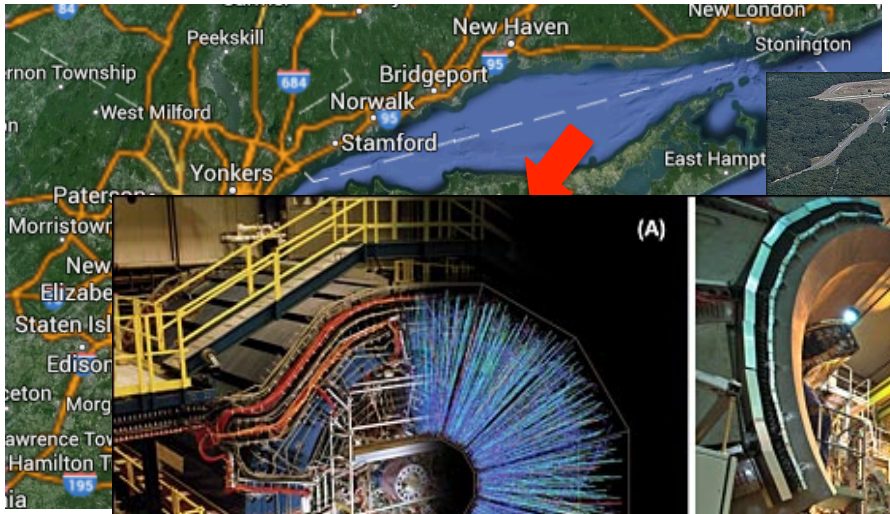
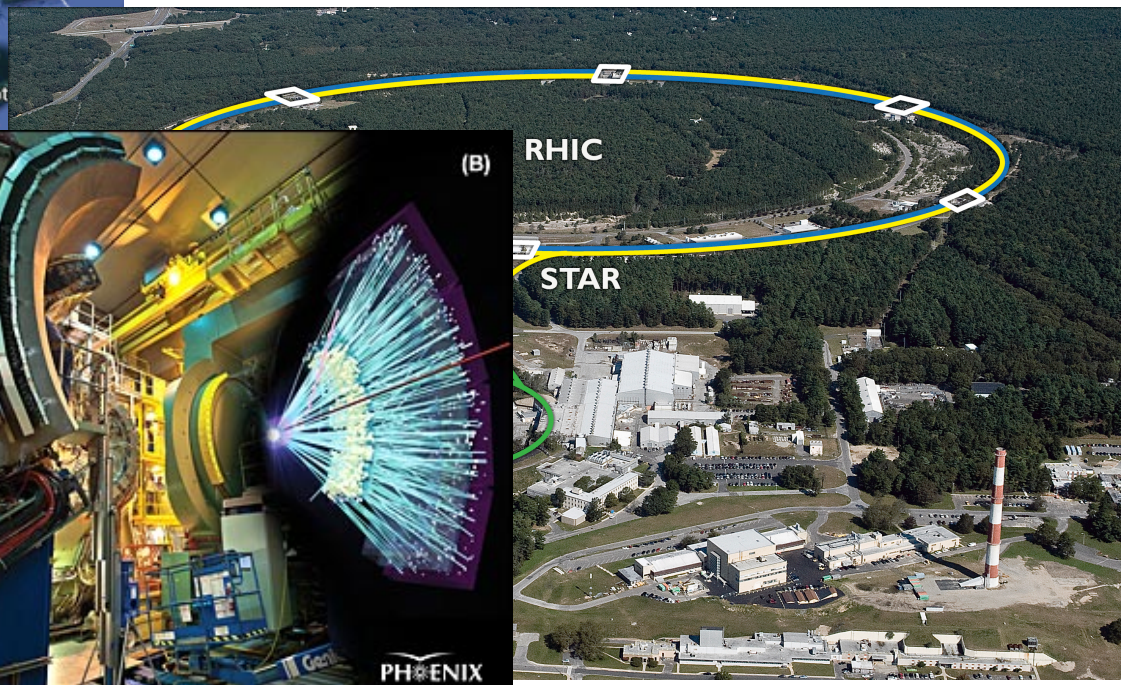
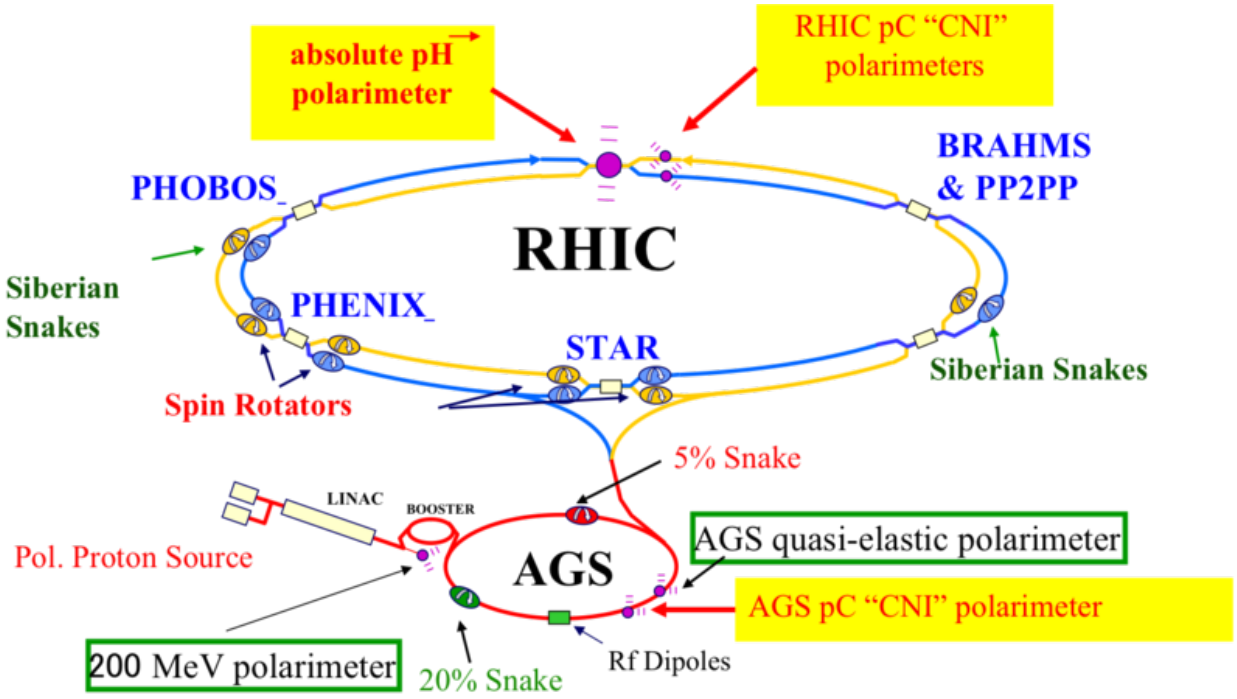




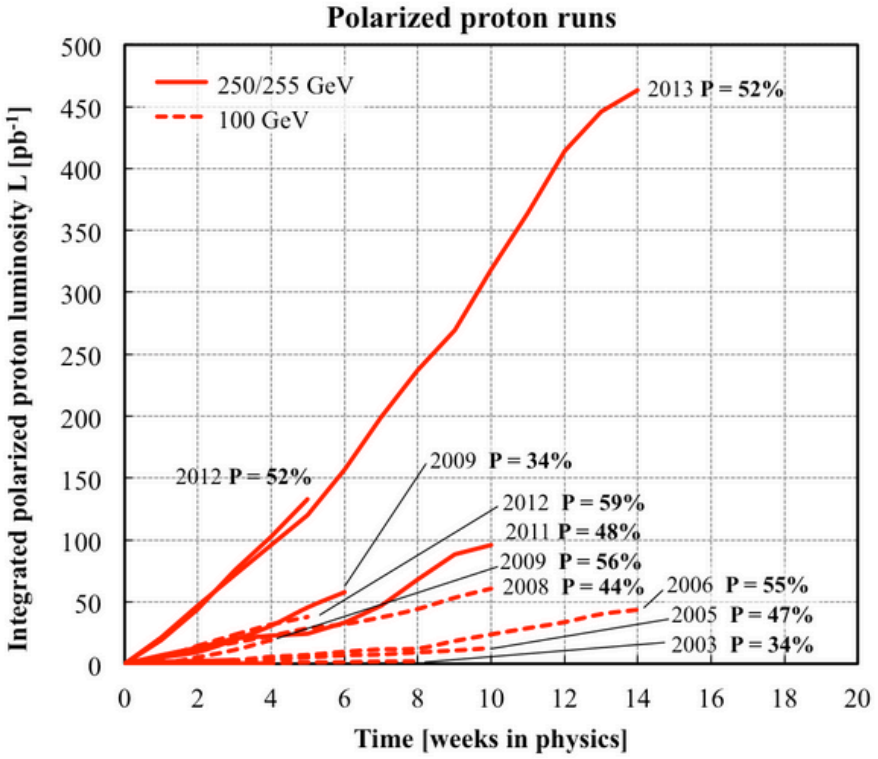
P+P Collisions at RHIC



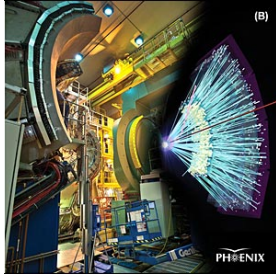
- Polarized proton + proton collisions up to √s = 510 GeV
- Change the polarization at each IR through Spin Rotators
- Different spin patterns

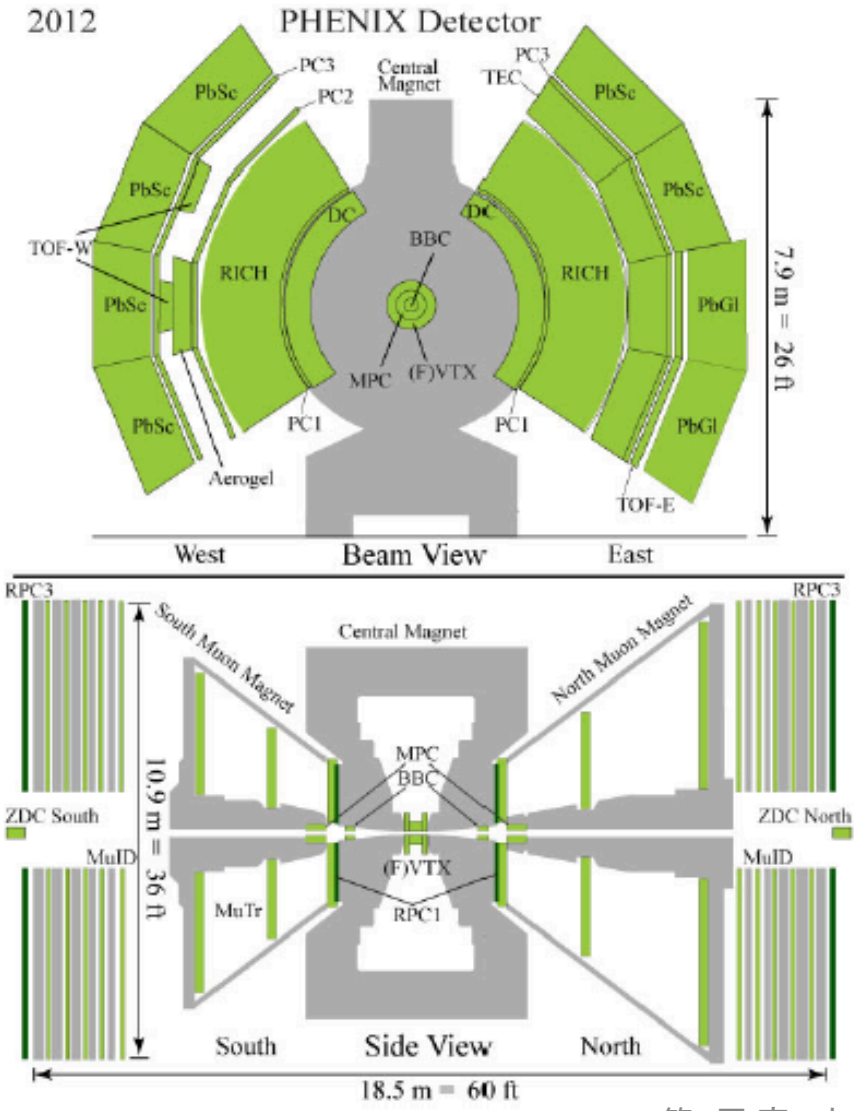
Polarized p+p data @ RHIC

- Longitudinally polarized proton runs 2009 - 2013 at √s = 510 (500) GeV.
- Large statistics in 2013.



PHENIX

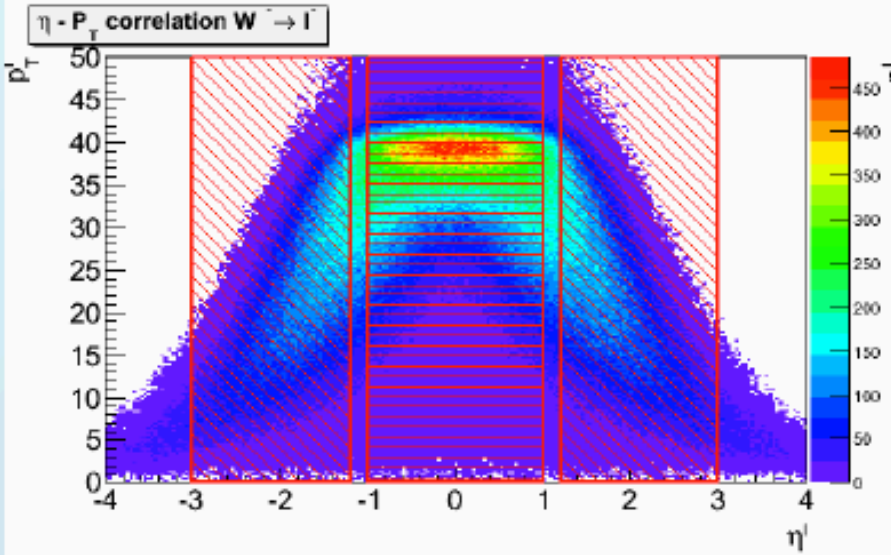


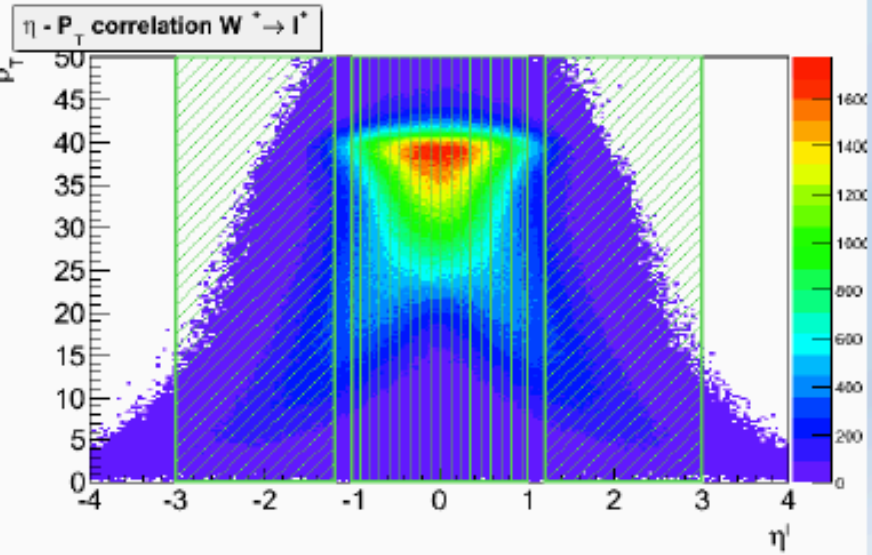


- Central Arm
  - Measure W → e
  - $|\eta| < 0.35$
  - $\Delta\phi = \pi$
  - DC and PC tracking, EMCal triggering
- Forward Arm
  - Measure W → μ
  - $1.2 < |\eta| < 2.2$
  - $\Delta\phi = 2\pi$
  - MuTr, MuID, RPC, FVTX

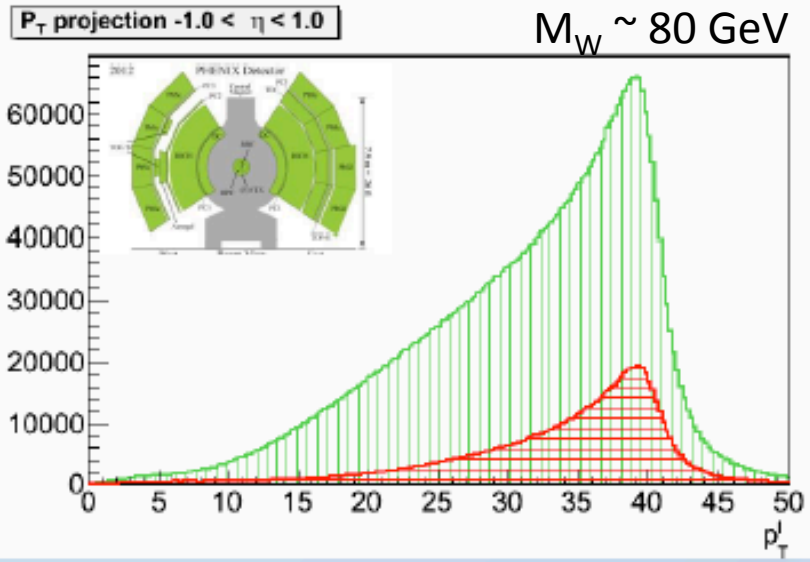
Slide by R. Seidl @ DIS2014

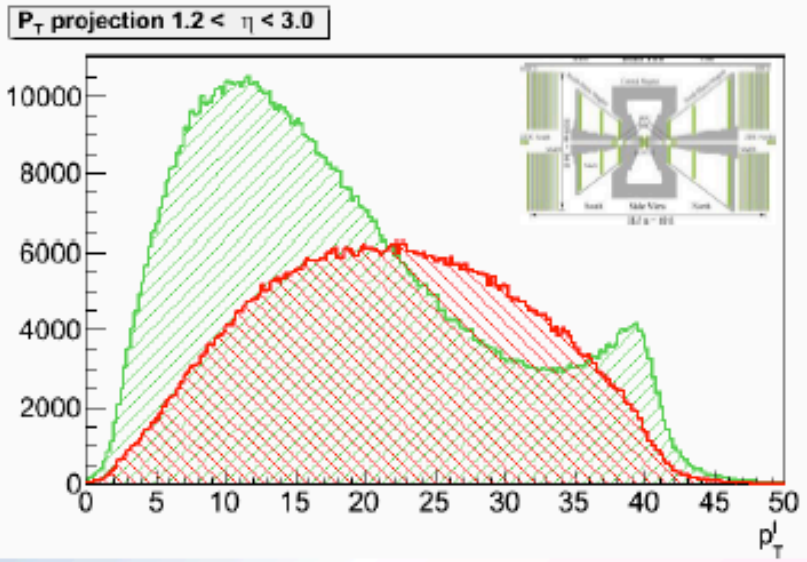
W kinematics





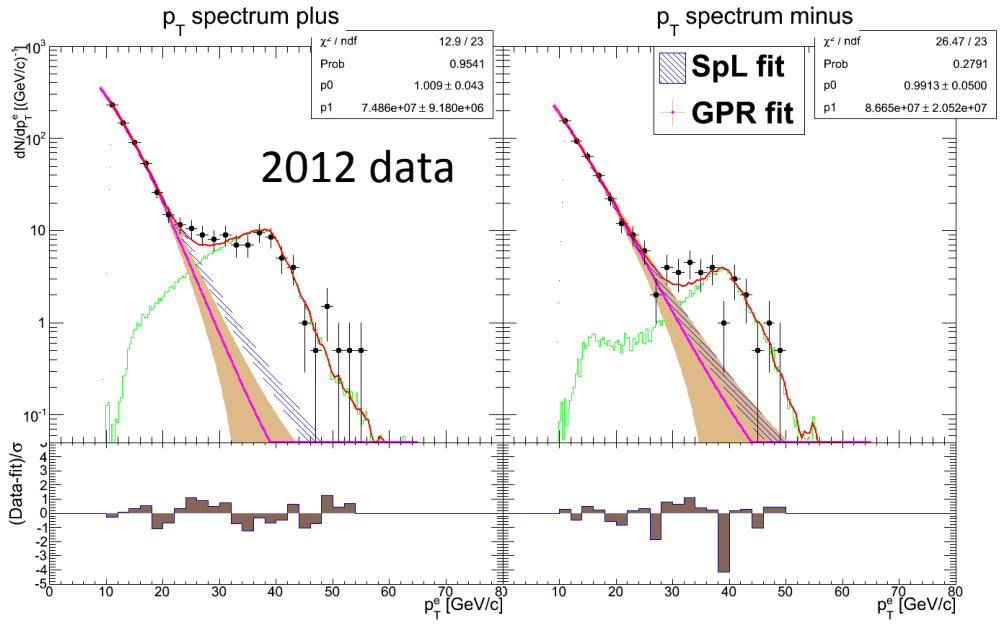
$M_W \sim 80$ GeV



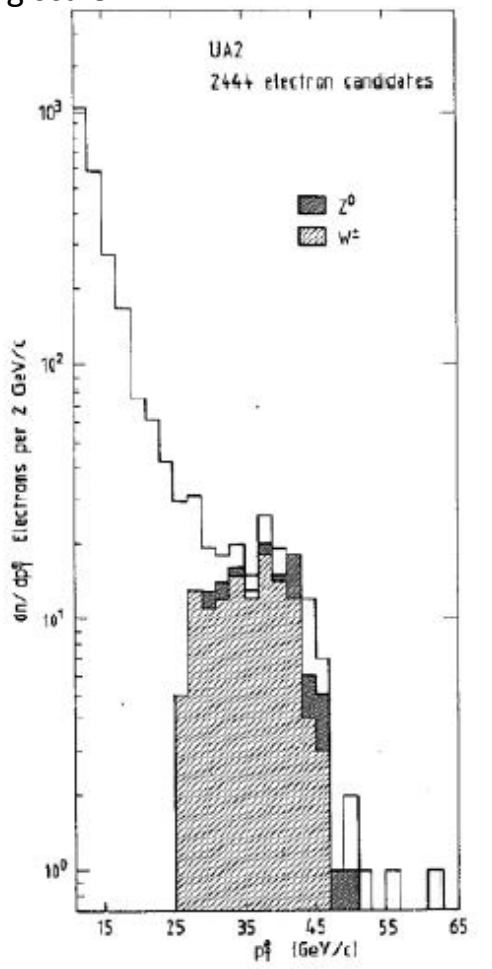


PHENIX W→e Measurement

- Identify W signals by Jacobian peak.
- Reduced BG and estimate its remaining contributions at 30 < pT <50

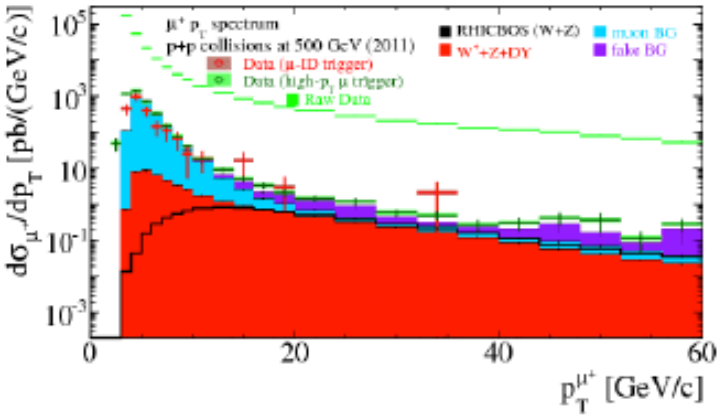


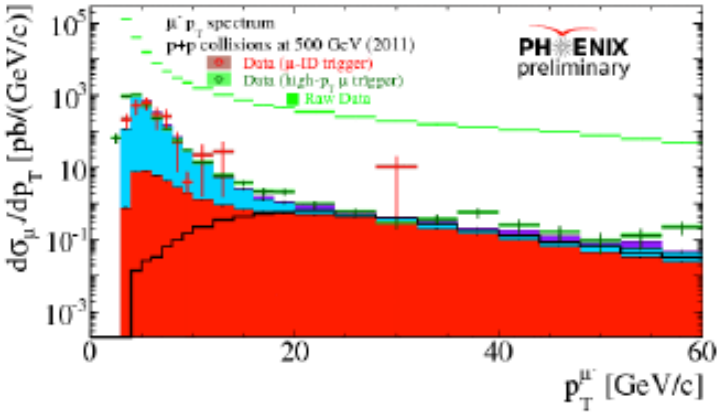
log scale



PHENIX W→μ Measurement

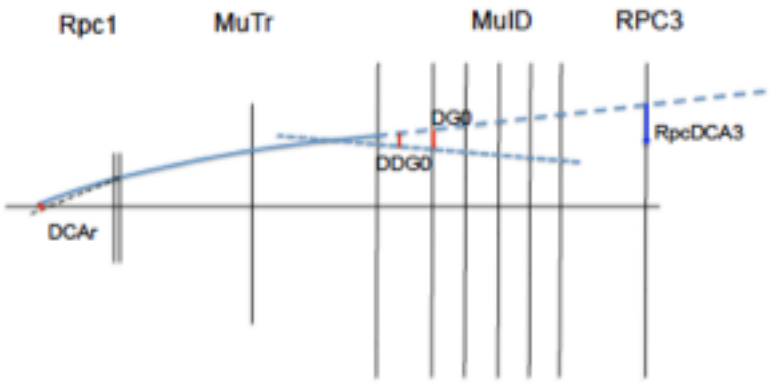
- Different kinematics at forward region.
- Muon BGs get smeared to high pT region
- Large Hadron BG contamination
- Careful signal identification required.

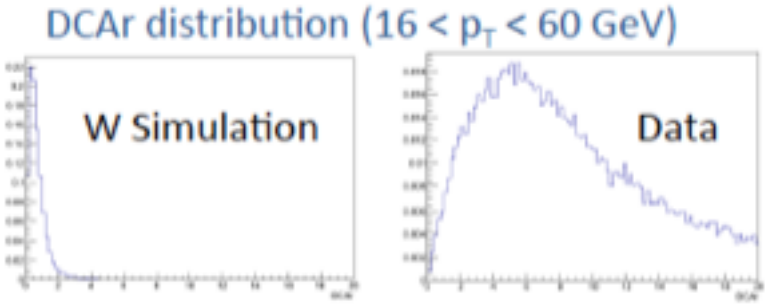




PHENIX W→μ Measurement

- Reduce BG using likelihood-based pre-selection using multivariate cut based on signal MC and data (mostly BG)
- estimate the S/B by performing unbinned maximum likelihood fit. (2D fit with η, dw23)
- S/B ratio for 2012 dataset is about ~ 0.3 (preliminary).





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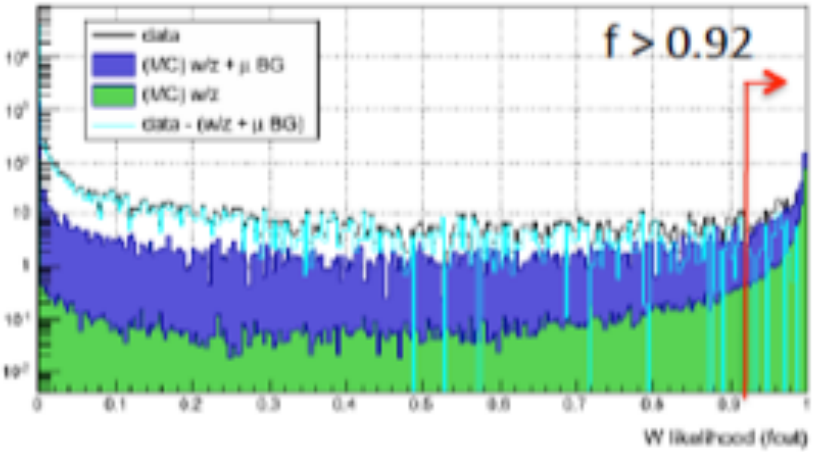
- Multivariate cut for pre-selection

$$f \equiv \frac{\lambda_{sig}}{\lambda_{sig} + \lambda_{BGs}}$$

$$\lambda = \left[p(DG0, DDG0) \cdot p(\chi^2) \cdot p(DCAr) \cdot p(RpcDCA) \right]$$



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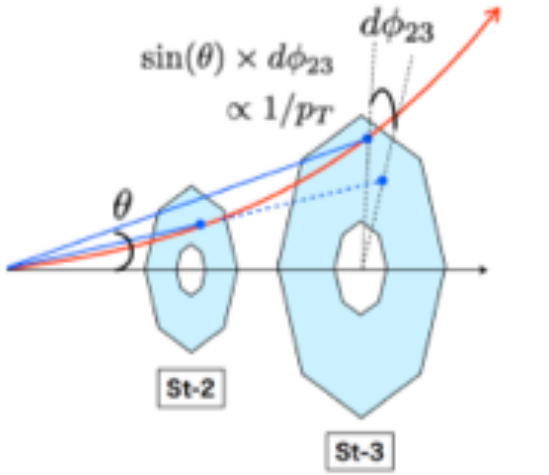

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- estimate the S/B by performing unbinned maximum likelihood fit. (2D fit with η, dw23)
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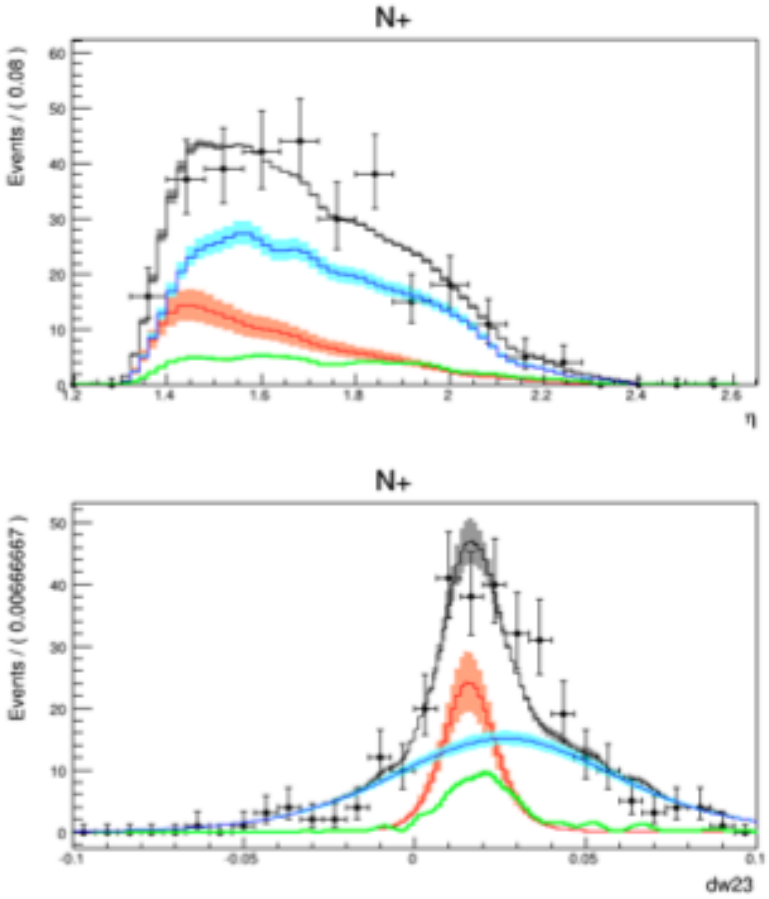
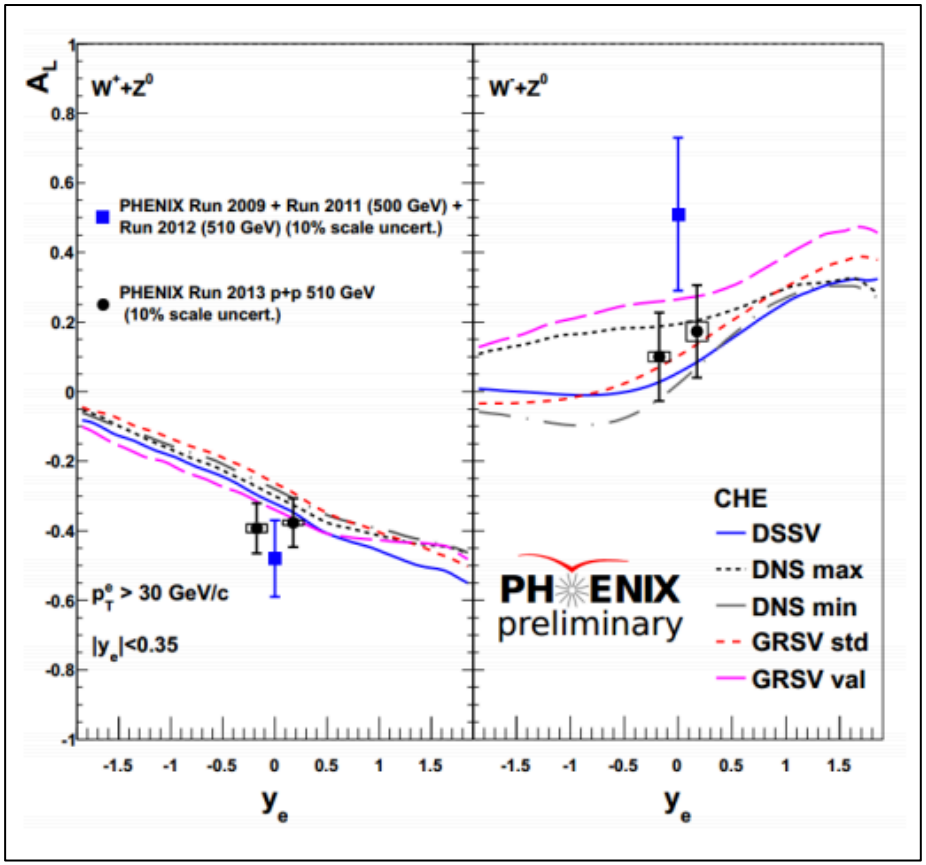
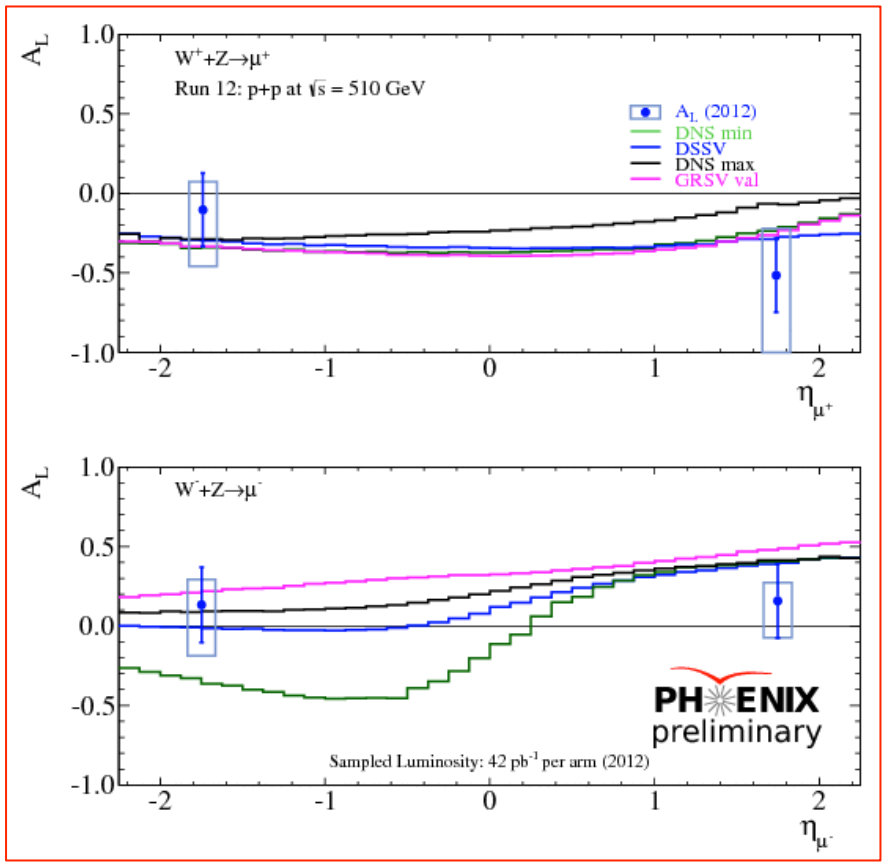
- Inclusion of FVTX will give you improvement of BG estimation.
- Many efforts have been made.



PHENIX A_L Result

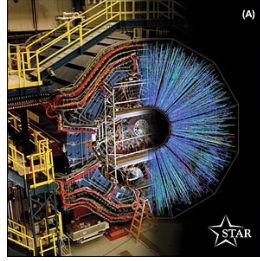


mid-rapidity (central arm)

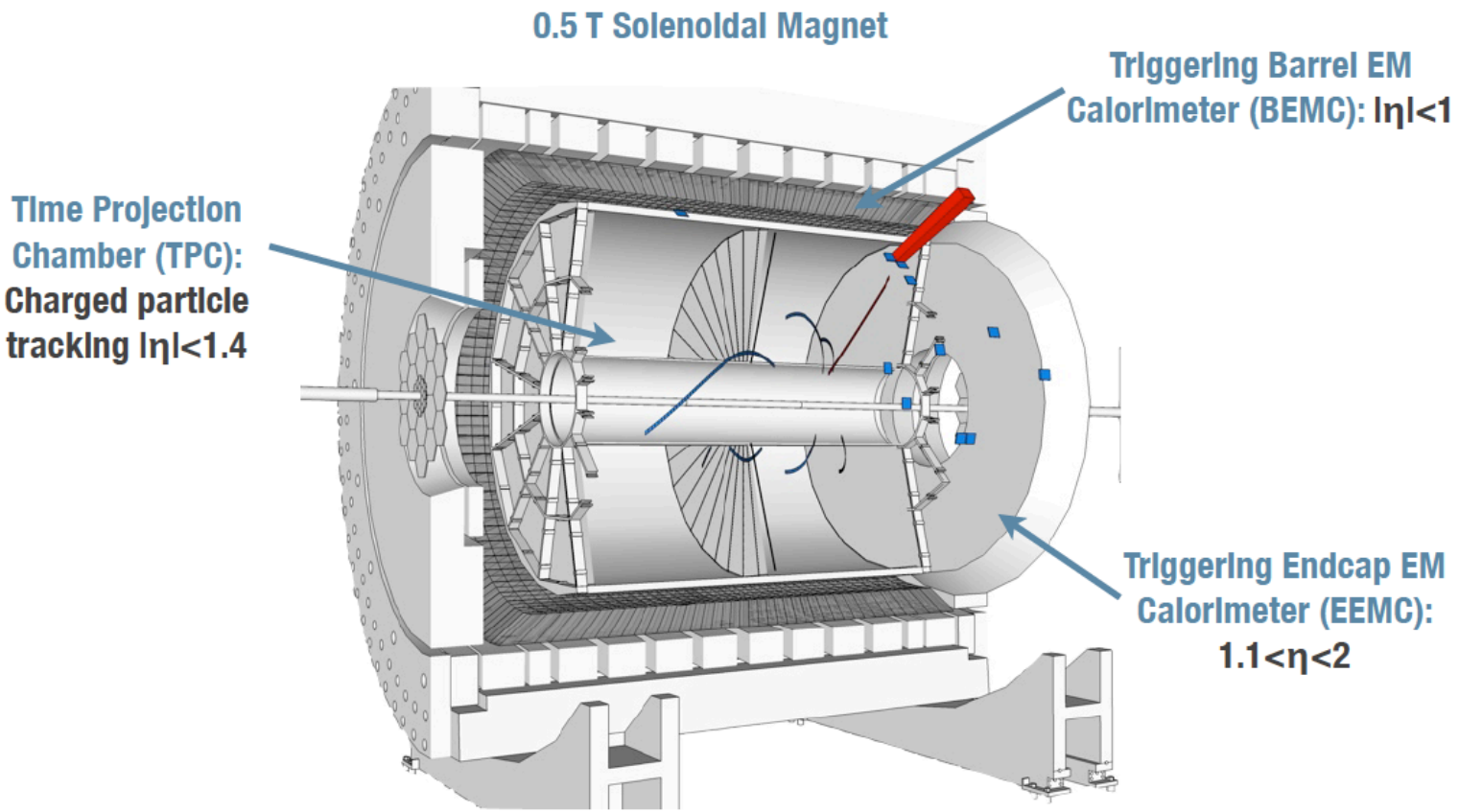


Forward rapidity (muon arm)

STAR

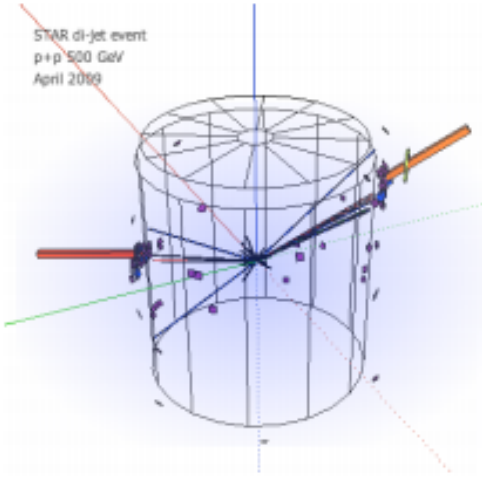


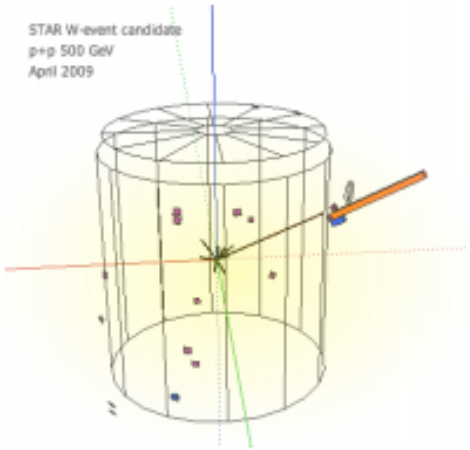
STAR Detector Overview



Slide by J. Stevens @DIS2014

STAR W → e Measurement





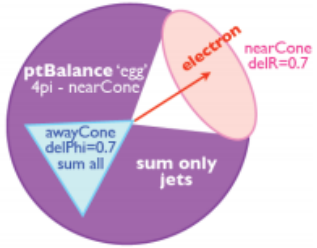
- Isolate electron/position with EeT (~40GeV)
- Large missing energy from undetected neutrinos
- pT-balance cut to suppress Z, QCD BG

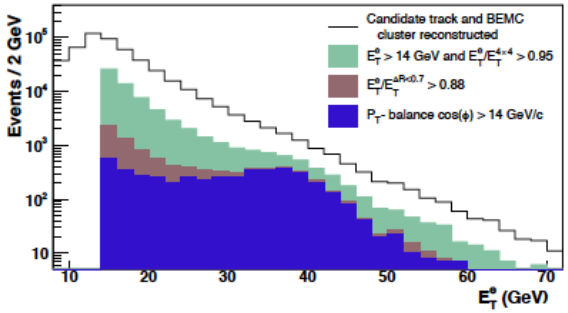
- p_T-balance cut

$$\vec{p_T}^{\,bal} = \vec{p_T}^{\,e} + \sum_{\Delta R>0.7} \vec{p_T}^{\,jets}$$

$$P_T\text{-balance}\cos(\phi) = \frac{\vec{p}_T^{\,e} \cdot \vec{p}_T^{\,bal}}{|\vec{p}_T^{\,e}|}$$

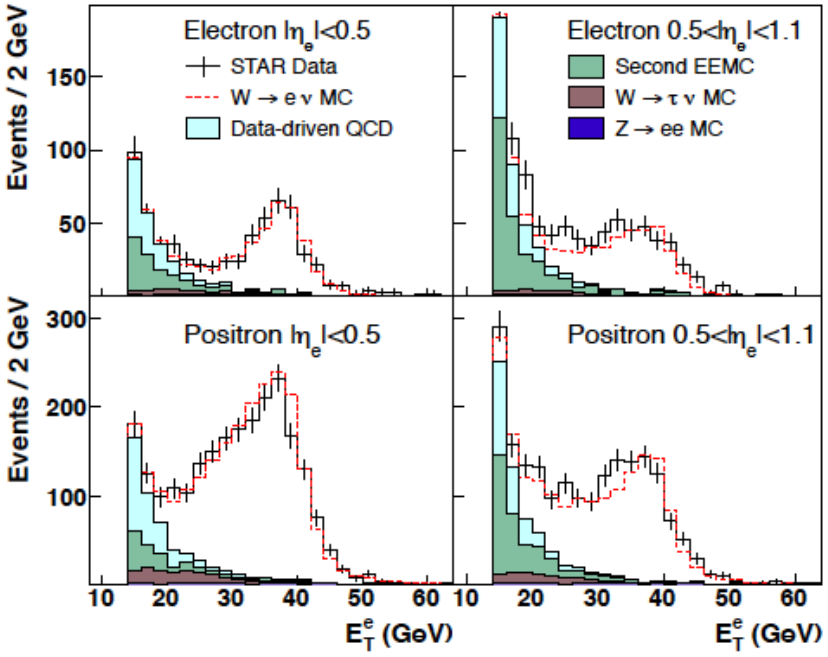
Transverse plane view





STAR W → e Measurement

Mid-rapidity background estimation



NEW arXiv:1404.6880

W Signal

- "Jacobian Peak"

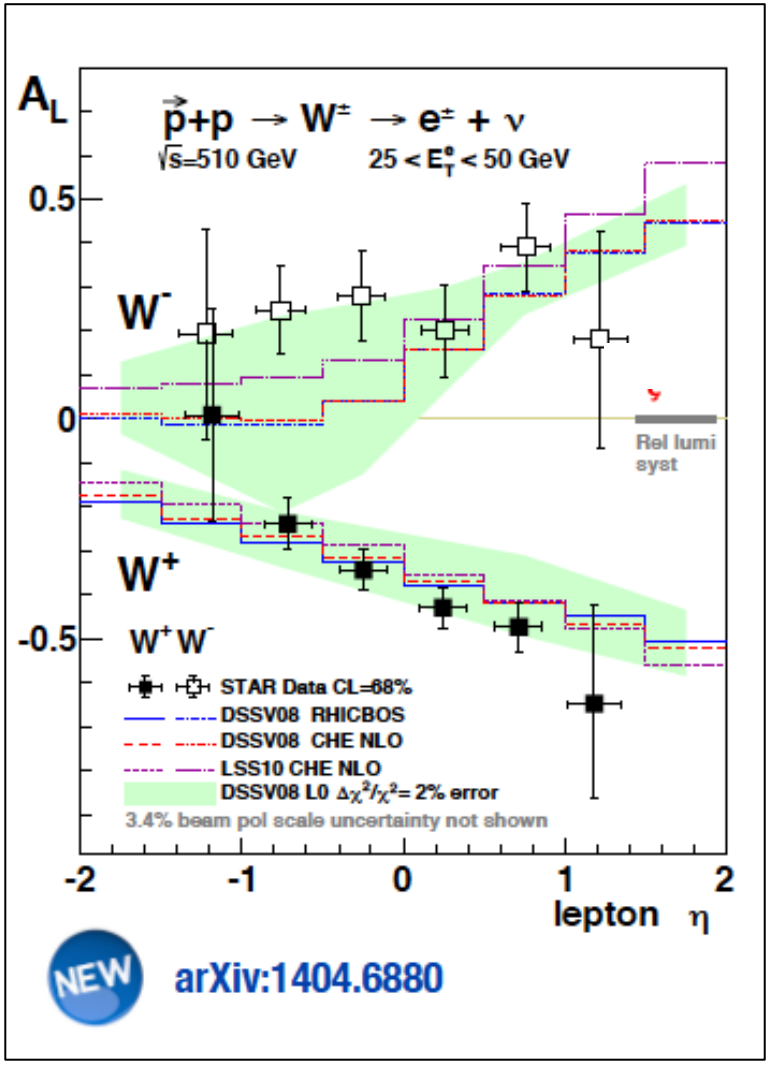
Electroweak

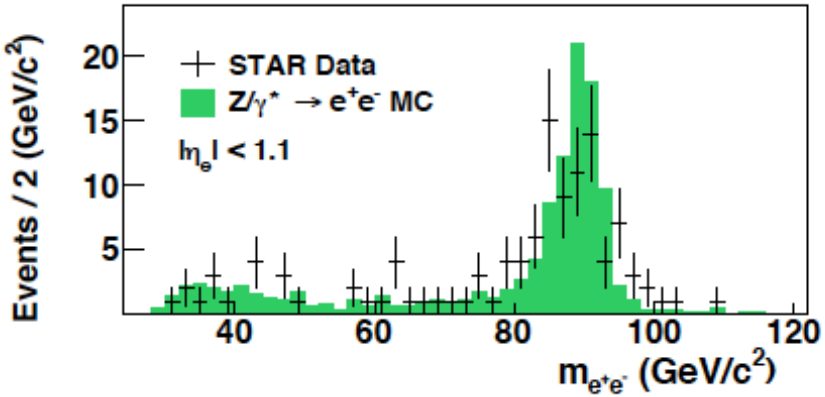
- Z → ee MC
- W → τν MC

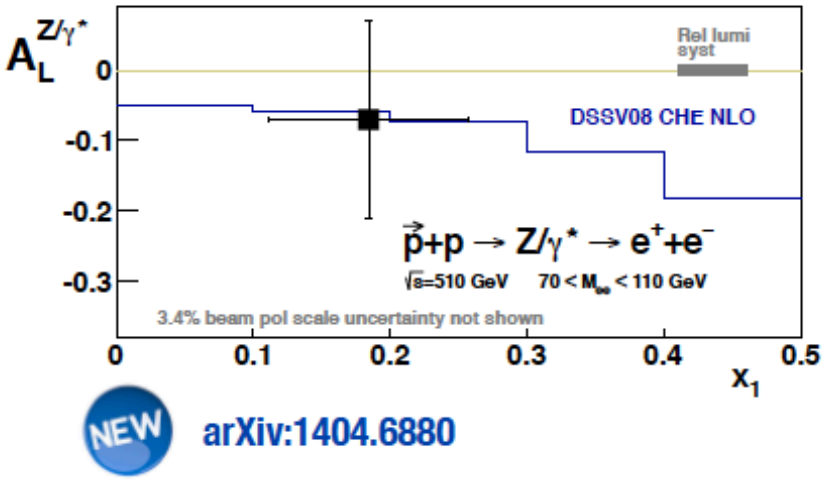
QCD Background

- Second EEMC
- Data-driven QCD

STAR A_L Result



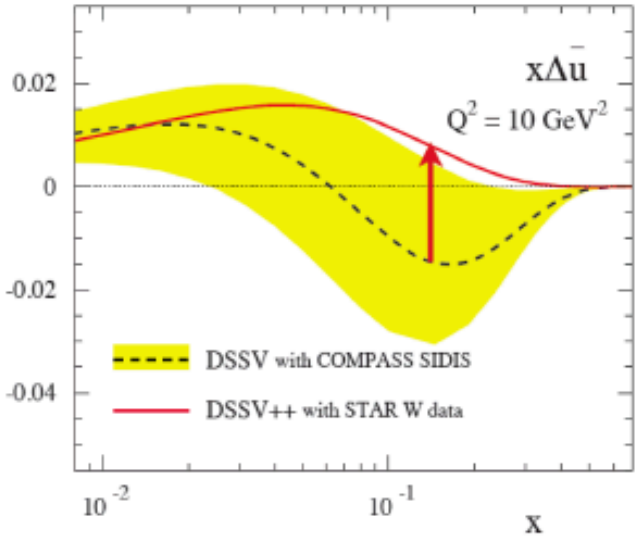




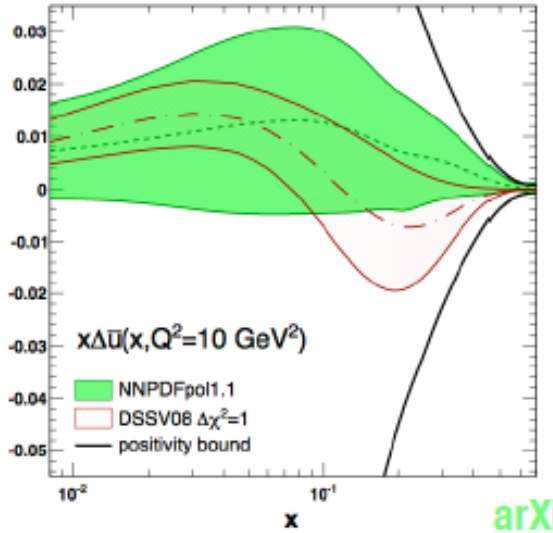
Sea quark polarization

Slide by J. Stevens @DIS2014

DSSV++ (prelim.)

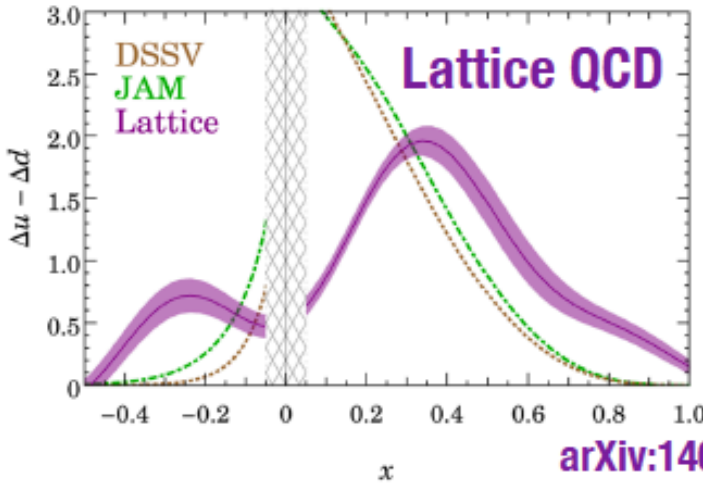


NNPDFpol1.1



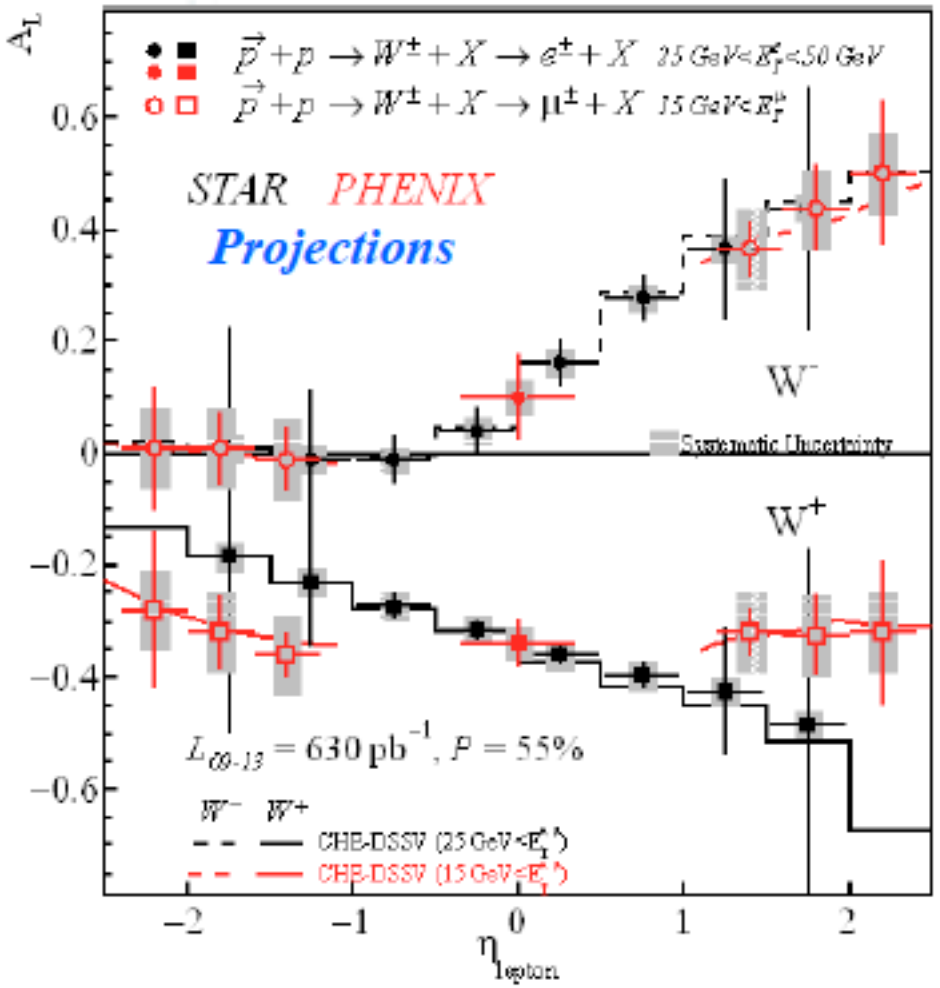
arXiv:1403.0440

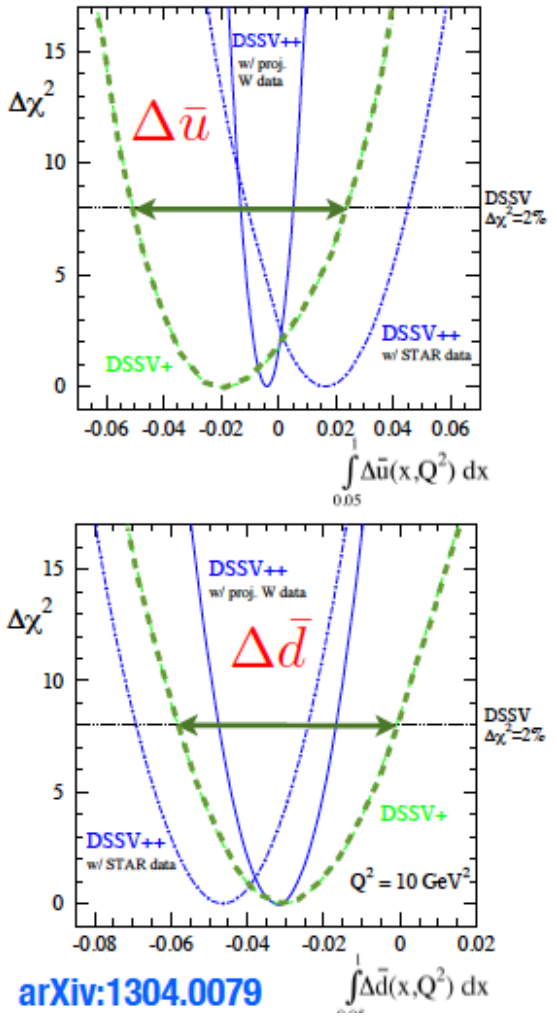
- Lots of recent progress!
- Preliminary STAR data included in fits by **DSSV** and **NNPDF** (talk by E. Nocera)
- Even first attempts to calculate flavor asymmetry in **lattice QCD**



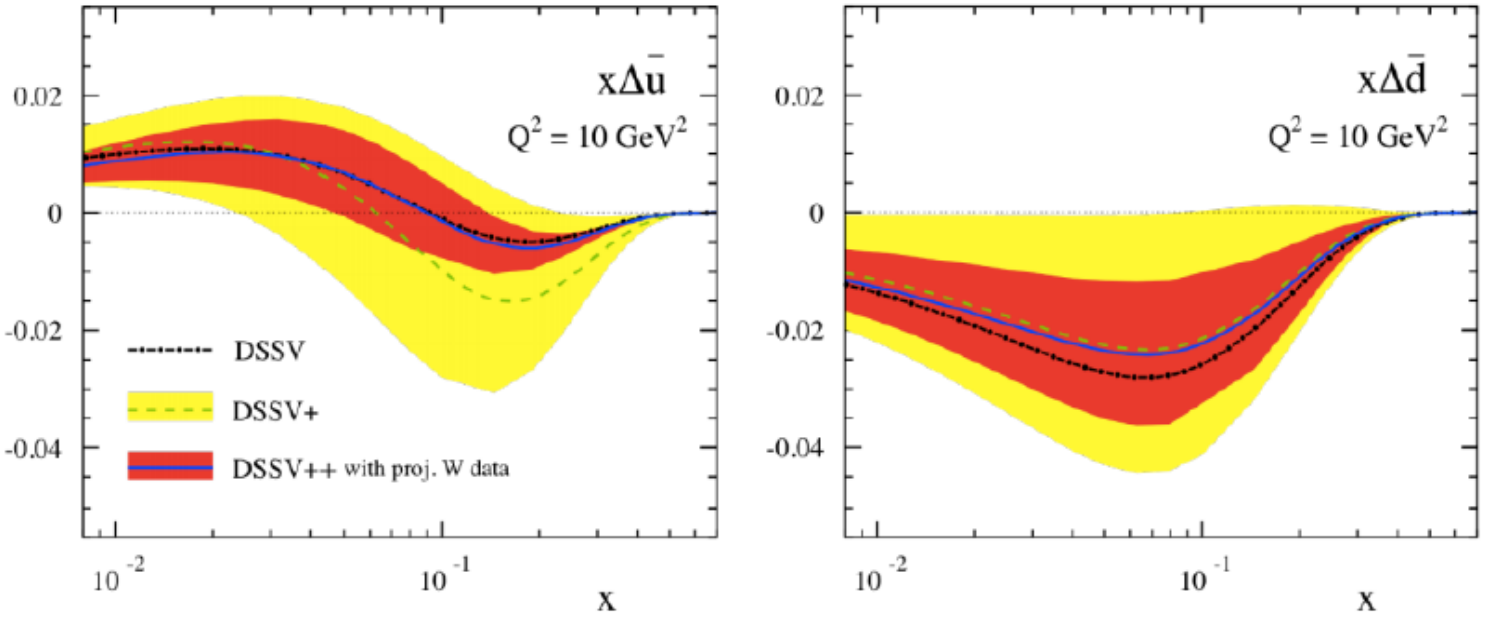
arXiv:1402.1462

Impact of RHIC data





Impact of RHIC data



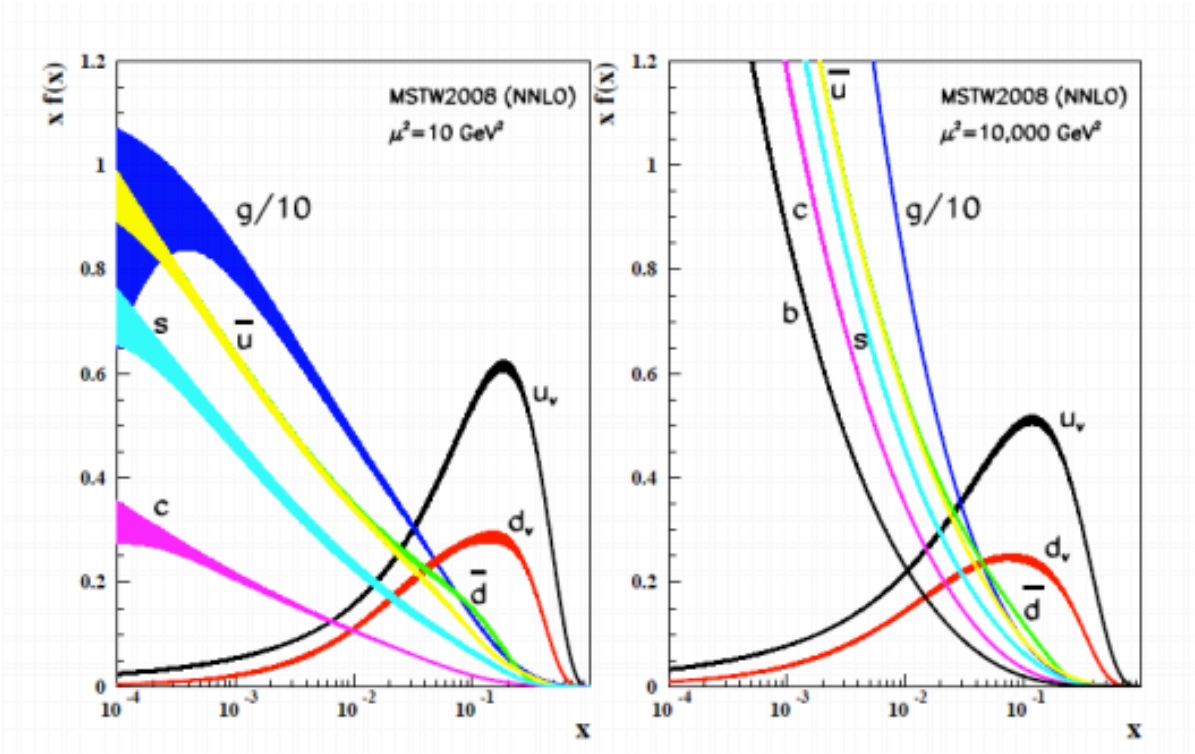
- Expected impact of RHIC pp data.
- Significant impact will be made on the uncertainty of the anti-quark polarized PDFS

Summary

- W measurement provides us clean access to sea quark polarization.
- STAR and PHENIX has measured A_L^W at $\sqrt{s}$ = 510 GeV from 2009 - 2013.
- Recent results from STAR and PHENIX were reported.
- Higher precision data from 2013 is being analyzed → Significantly improve our knowledge of sea quark polarization.

Backup

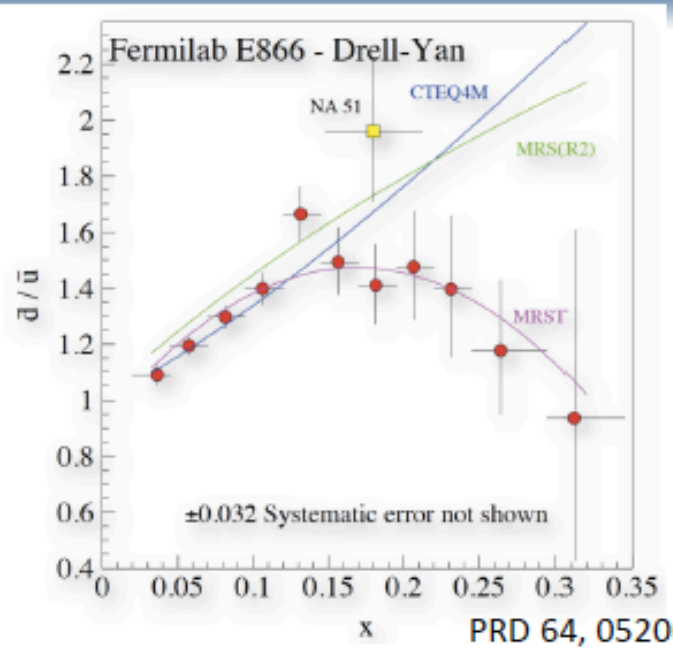
Unpolarized PDFs



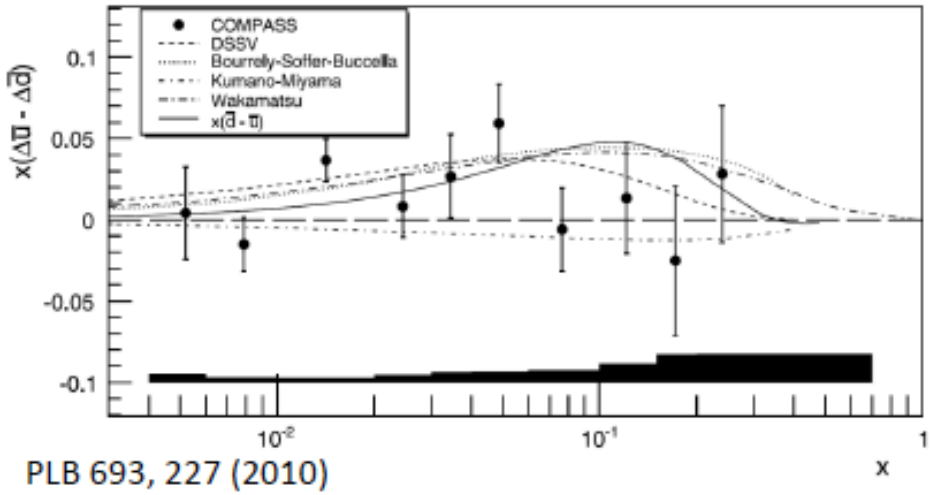
MSTW2008 (arxiv:0901.0002) NNLO PDFs

Flavor asymmetry of the sea

- **Unpolarized flavor asymmetry**
  - Quantitative calculation of Pauli blocking does not explain $\bar{d}/\bar{u}$ ratio

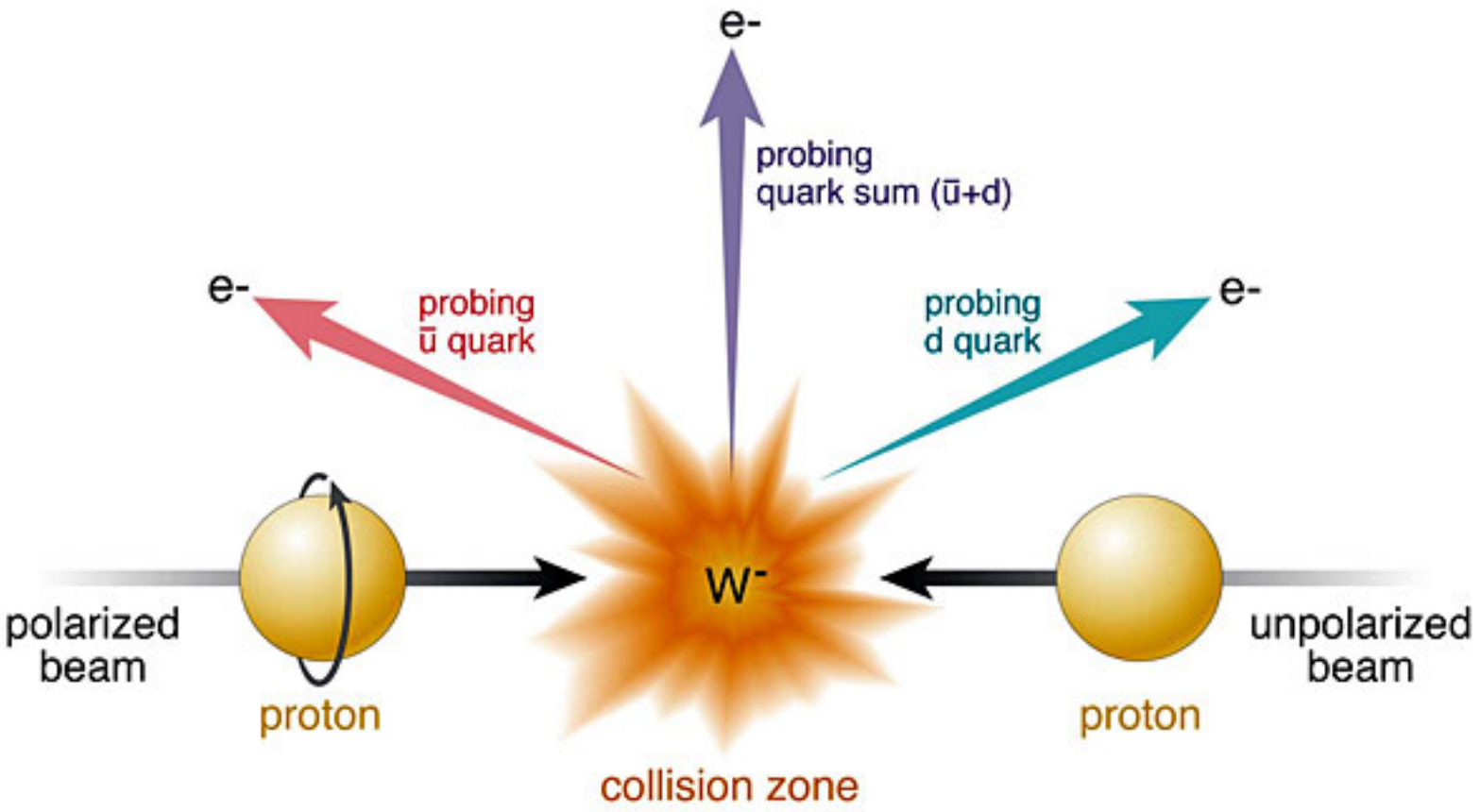


PRD 64, 052002 (2001)

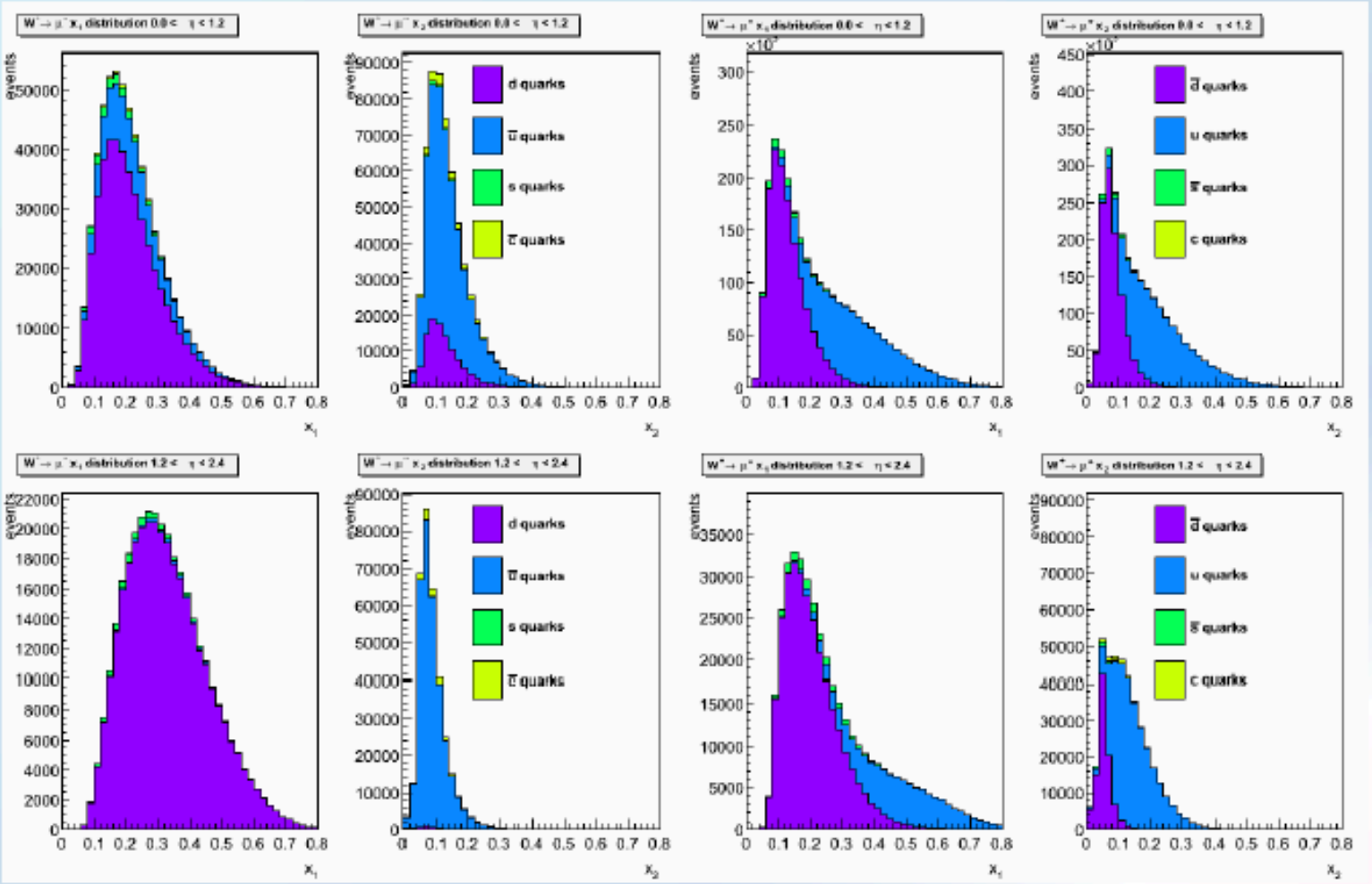


PLB 693, 227 (2010)

- **Polarized flavor asymmetry**
  - Polarized flavor asymmetry $x(\Delta u - \Delta d)$ could help differentiate models


e-
probing
quark sum (ū+d)
e-
probing
ū quark
probing
d quark
e-
W-
polarized
beam
proton
proton
unpolarized
beam
collision zone

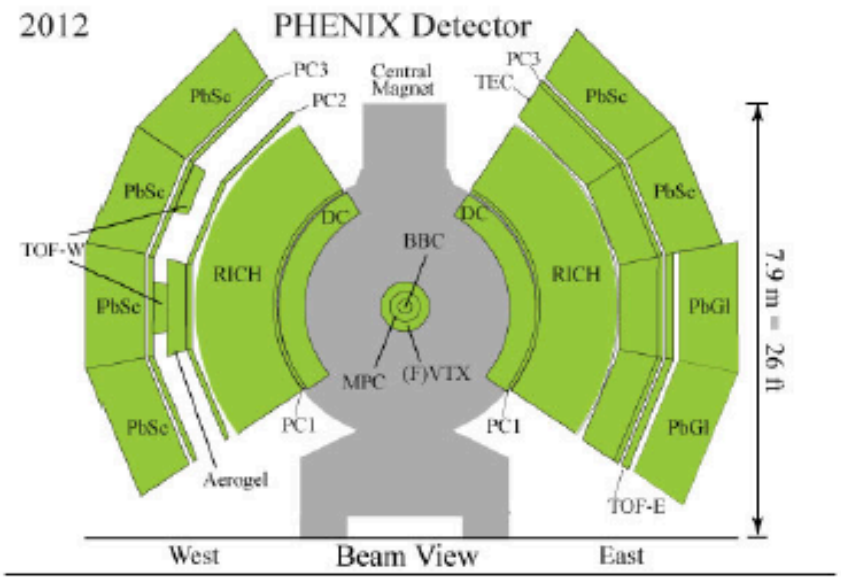
Pythia: quark flavors and x ranges

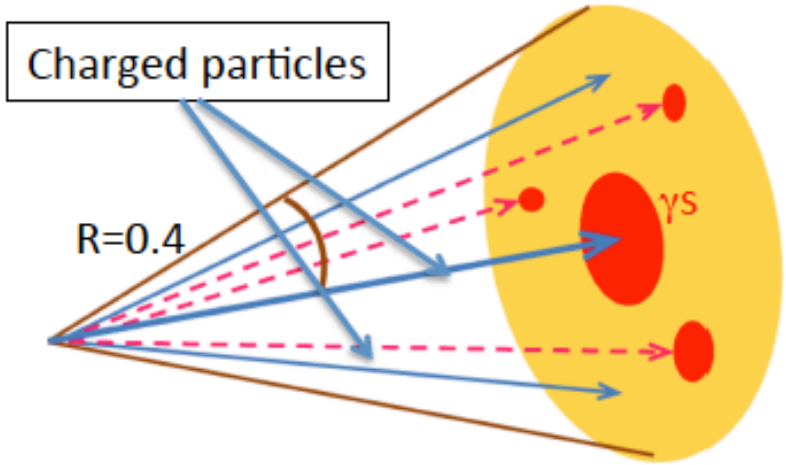


$W^- \rightarrow \mu$ case: almost entirely forward d quarks and backwards $\bar{u}$

$W^+ \rightarrow \mu$ case: predominantly forward $\bar{d}$ quarks and backwards u

Central Arm Measurement





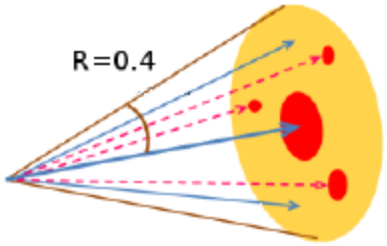
- Observable: electron/positron
  from $W^{-/+} \rightarrow e^{-/+} + \nu_e$
- $(\Delta\bar{d} + \Delta u)$ from W^+, $(\Delta\bar{u} + \Delta d)$ from W^-
- Backgrounds:
  - Reducible:

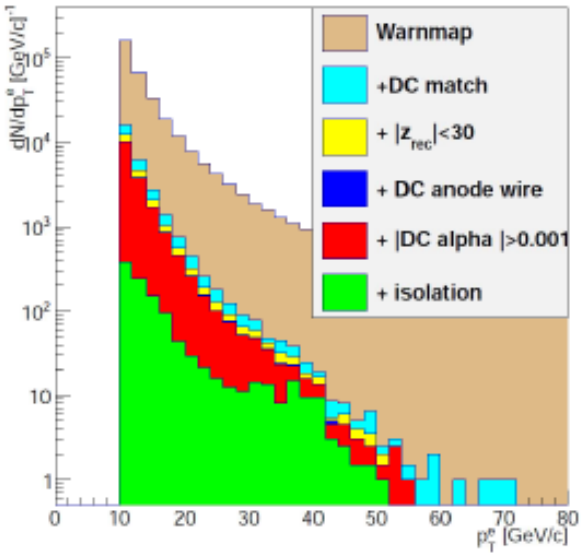
    Cosmic, $\gamma \rightarrow e^+e^-$ conversion from $\pi/\eta \rightarrow \gamma\gamma$, direct photon, Beam related BGs
  - Irreducible:

    $Z \rightarrow e^+ + e^-$, Leptonic decay of charm, bottom to $e^{\pm}$
- W event identification
  - Jacobian peak at $pT=M_W/2$ in pT spectrum
  - Measure high pT electrons using EMCal
  - DC-EMCal matching ($\Delta\varphi < 0.01$ rad)
  - Relative isolation cut < 10%

Relative isolation cut

- Main background discriminator
- Energy in a cone of R=0.4 divided by energy of the candidate
- After basic cuts it reduces background by a factor of 10 while leaving the signal region relatively untouched





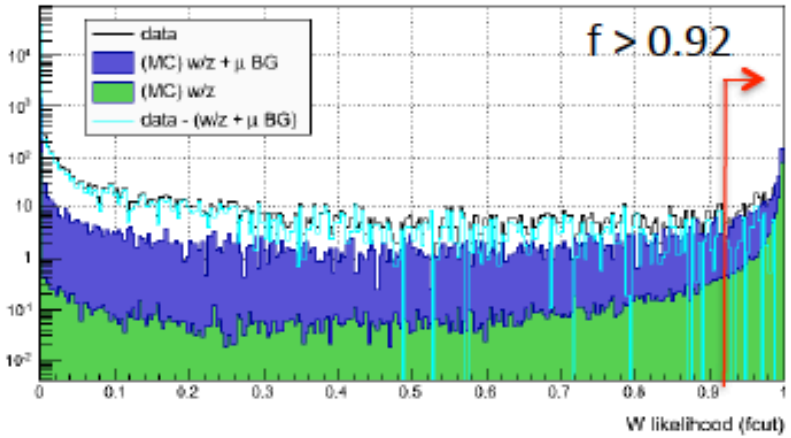
Signal Extraction in Forward Arm Analysis

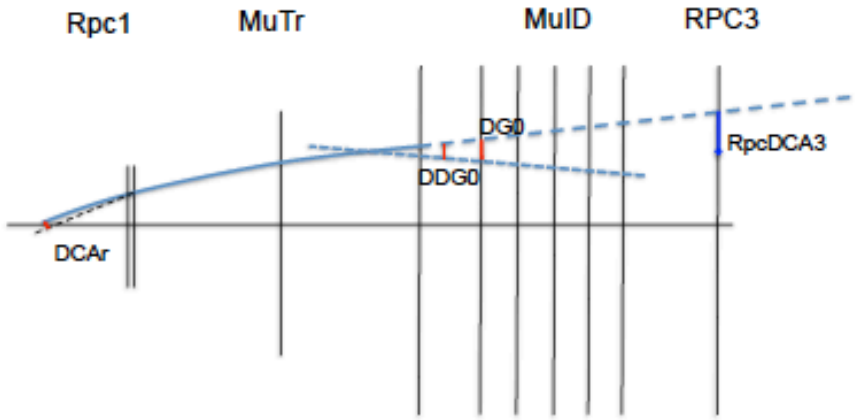
- Likelihood-based signal selection
  - Pre-selection: multivariate cut using likelihood ratio
  - S/B ratio extraction: unbinned maximum likelihood fitting (next page)

- Multivariate cut for pre-selection

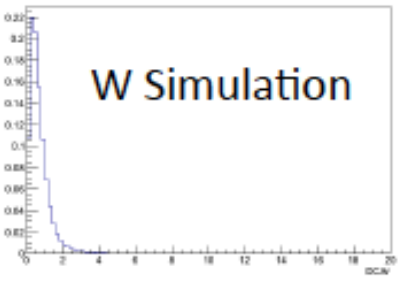
$$f \equiv \frac{\lambda_{sig}}{\lambda_{sig} + \lambda_{BGs}}$$

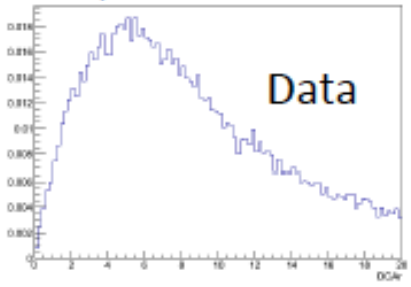
$$\lambda \equiv \left[p(DG0, DDG0) \cdot p(\chi^2) \cdot p(DCAr) \cdot p(RpcDCA) \right]$$





DCAr distribution ($16 < p_T < 60$ GeV)



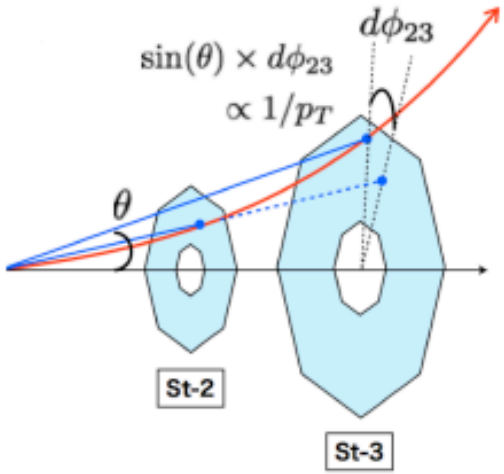


Signal Extraction in Forward Arm Analysis

- Extended unbinned maximum likelihood fitting

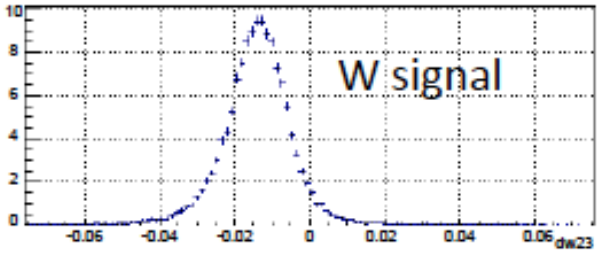
$$\mathcal{L}(\theta|X) \equiv \frac{n^N e^{-n}}{N!} \prod_{x_i \in X}^{N} \left[\sum_c \frac{n_c}{n} p_c(x_i) \right], \quad n = \sum_c n_c$$

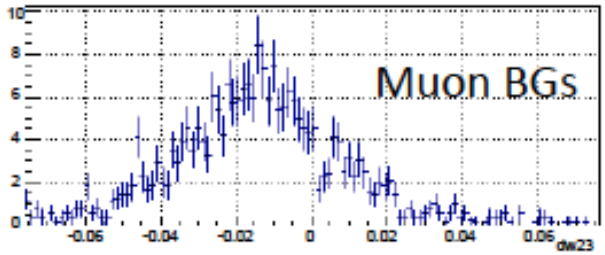
- Probability distribution functions extracted from simulation (W signal, muon BGs) and data (hadron BGs) using eta, dw23 (reduced azimuthal bending).

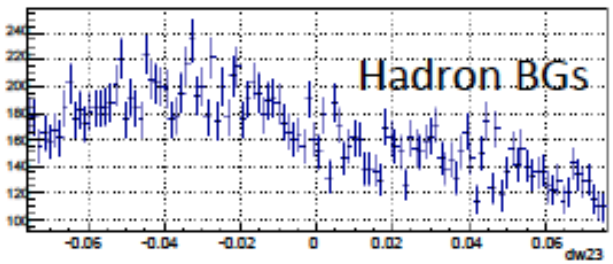


$$\mathrm{dw23} \equiv \mathrm{pT} \times \sin\theta \times \mathrm{d}\phi 23$$

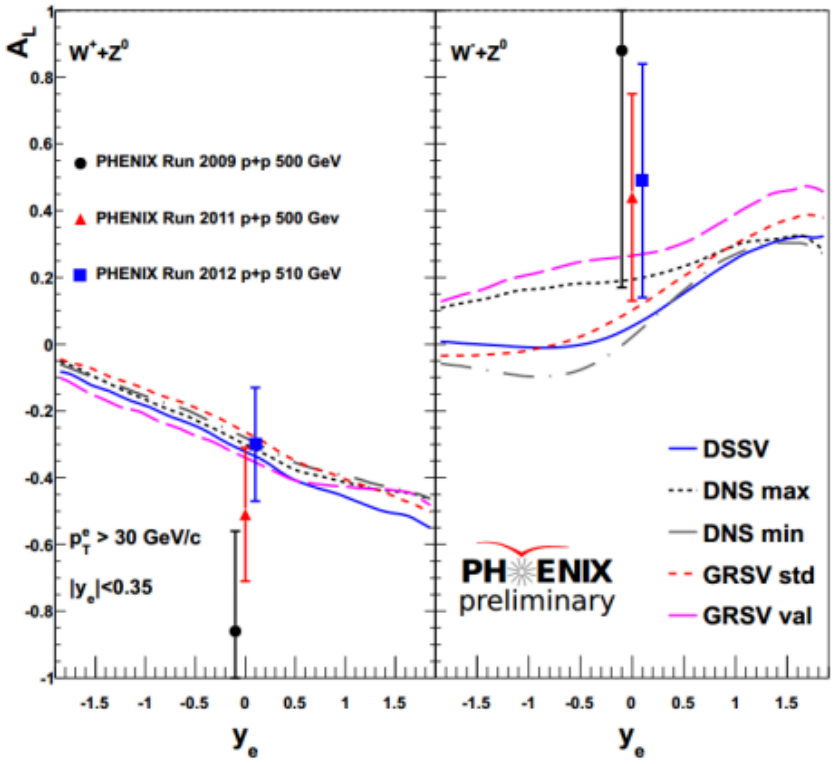
dw23 distributions ($16 < p_T < 60$ GeV)

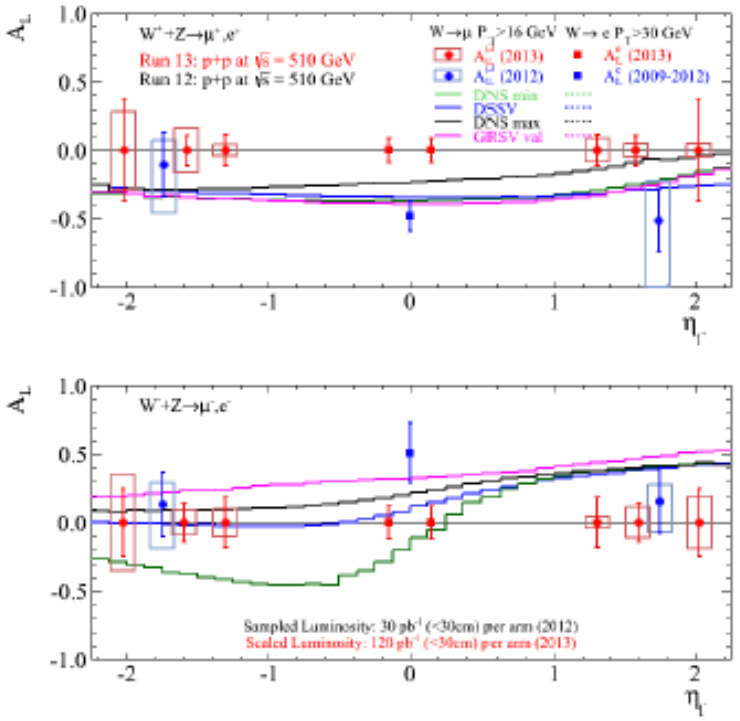






PHENIX Result



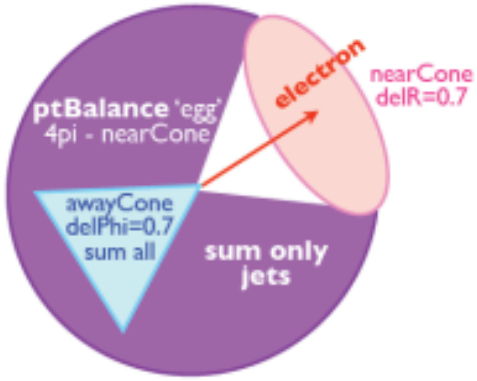


Recent results - W production

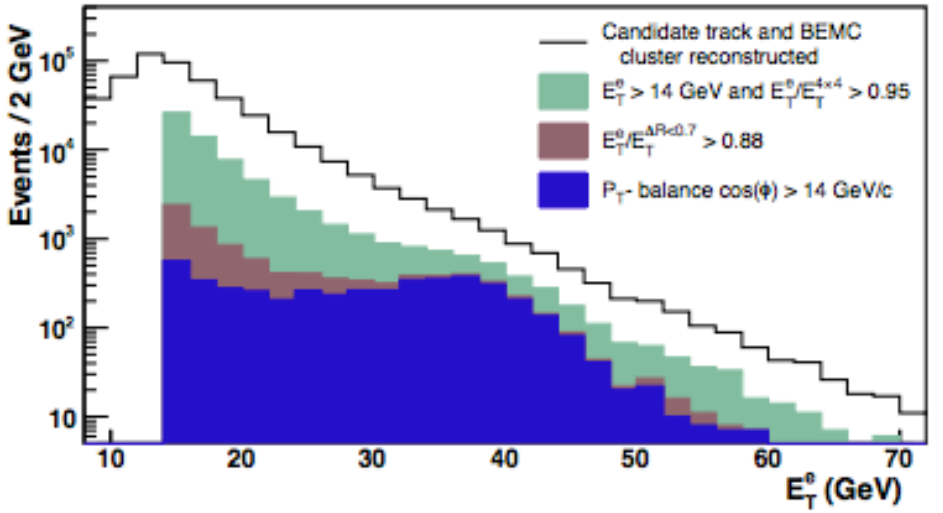
- Mid-rapidity STAR selection criteria
  - Match p_T > 10 GeV track to BEMC cluster
  - Isolation ratios
  - p_T-balance cut

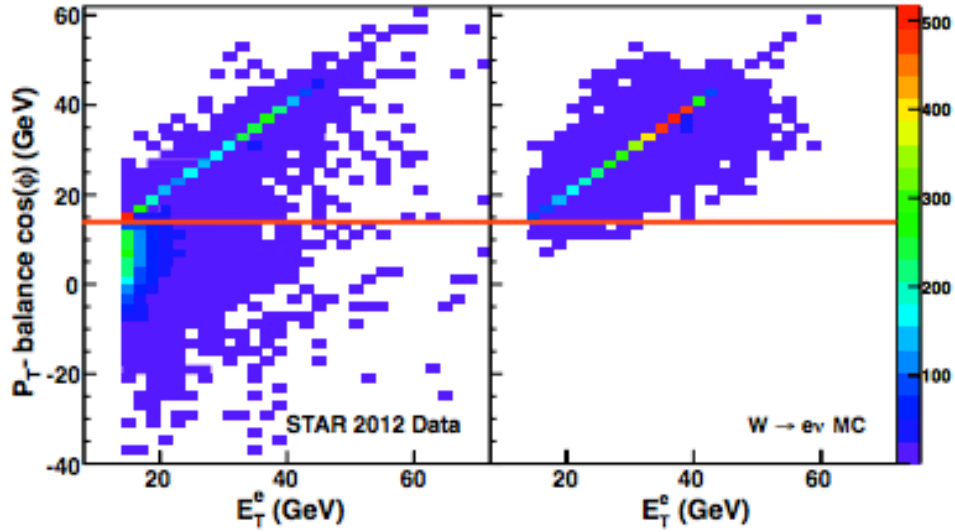
$$\vec{p_T}^{\,bal} = \vec{p_T}^{\,e} + \sum_{\Delta R>0.7} \vec{p_T}^{\,jets}$$

$$P_T\text{-balance}\cos(\phi) = \frac{\vec{p}_T^{\,e} \cdot \vec{p}_T^{\,bal}}{|\vec{p}_T^{\,e}|}$$

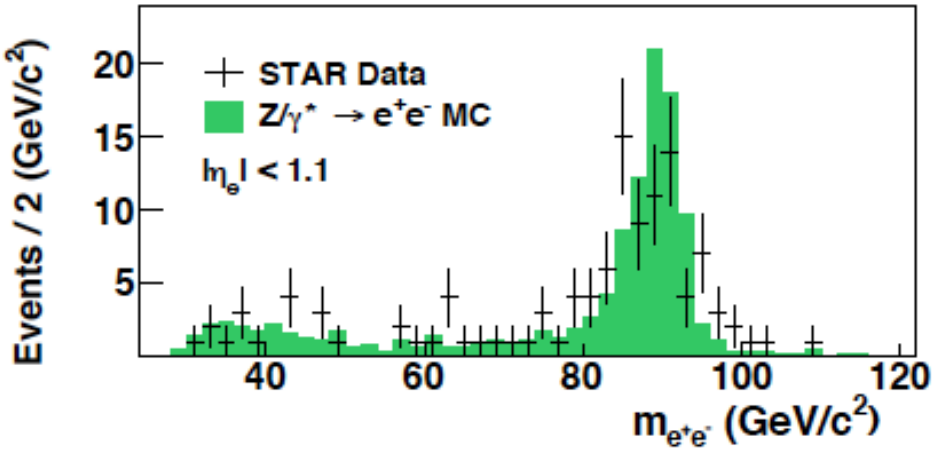


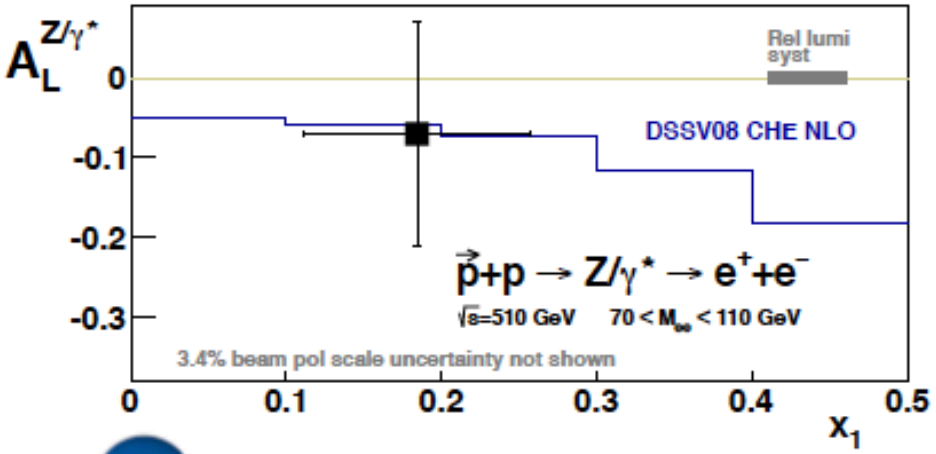
Transverse plane view





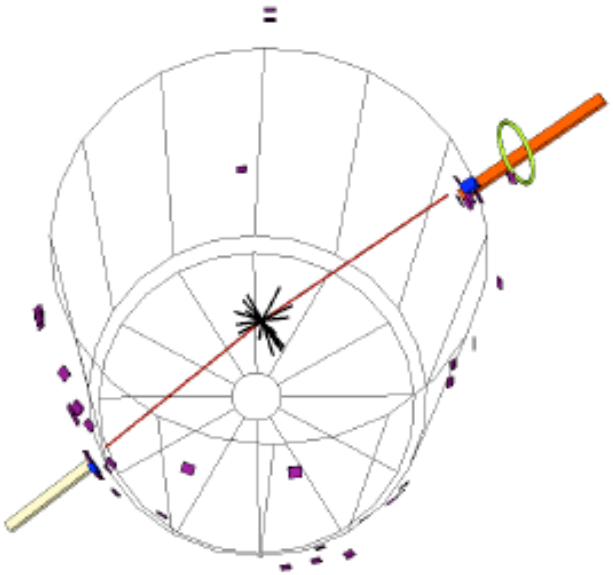
STAR Z A_L





NEW arXiv:1404.6880

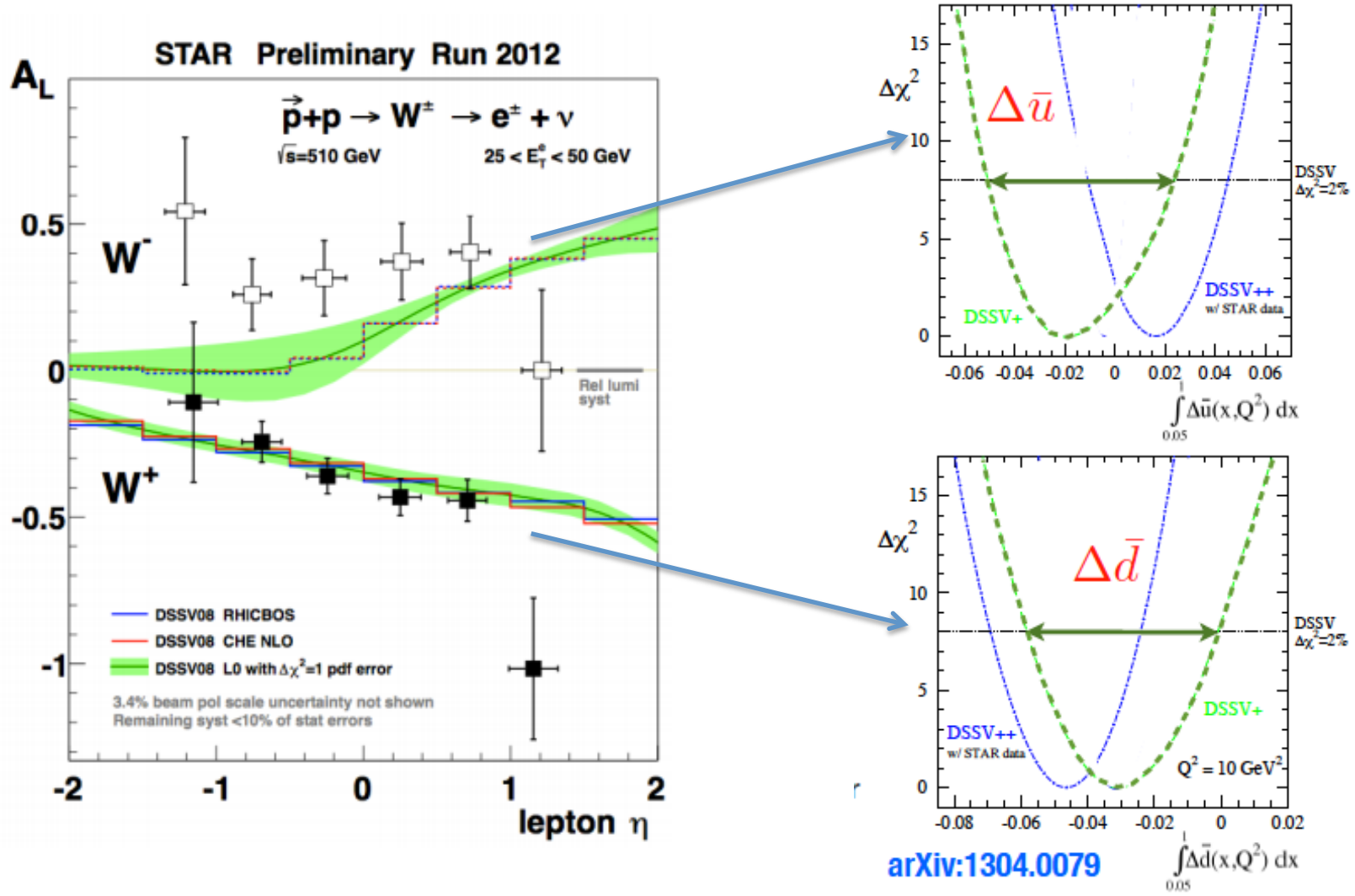
Z → e⁺e⁻ Candidate



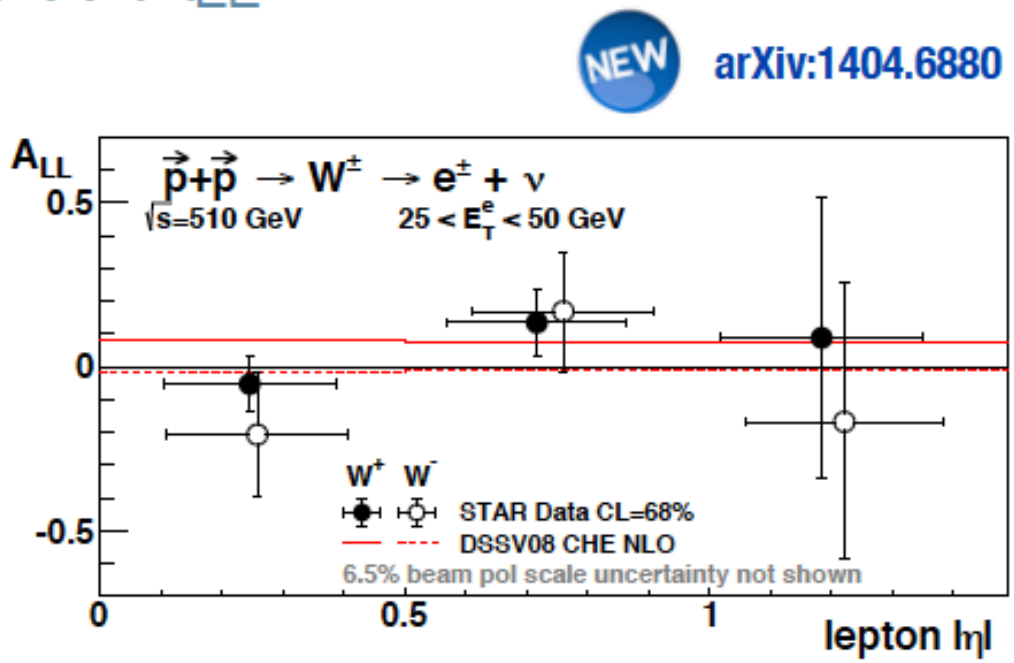
Reconstruct initial state kinematics at leading order:

$$x_{1(2)} = \frac{M_{ee}}{\sqrt{s}} e^{\pm yz}$$

STAR A_L Result



STAR W A_{LL}



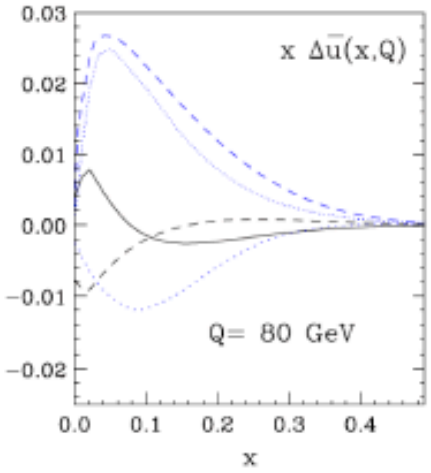
- Probes different combination of quark polarizations

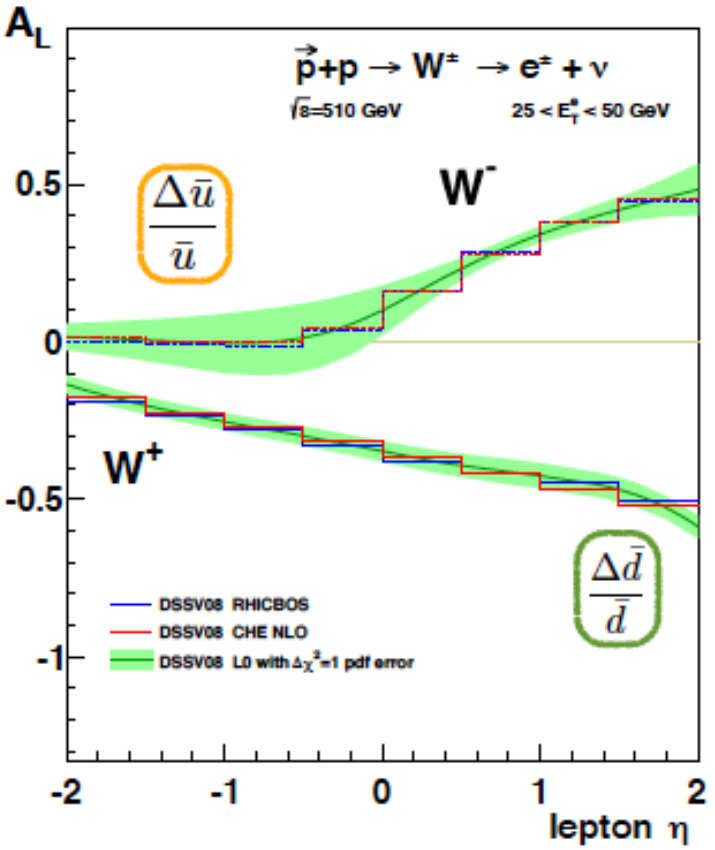
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \qquad A_{LL}^{W+} \sim \frac{\Delta u}{u}\frac{\Delta \bar{d}}{\bar{d}} \qquad A_{LL}^{W-} \sim \frac{\Delta d}{d}\frac{\Delta \bar{u}}{\bar{u}}$$

- Asymmetries expected to be smaller, and first measurement consistent with predictions from DSSV

Expectations for W A_L

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





- Large parity-violating asymmetries expected
- Simplified interpretation at forward and backward rapidity

- DSSV $\Delta\chi^2 = 1$ band underestimates the theoretical uncertainty (and Lagrange multiplier estimates for a $\Delta\chi^2/\chi^2$ = 2% error are in progress)