Longitudinal Spin at PHENIX 2015-2016

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Proton Spin Structure
"Spin Puzzle"

Manohar-Jaffe sum rule:

Know very little

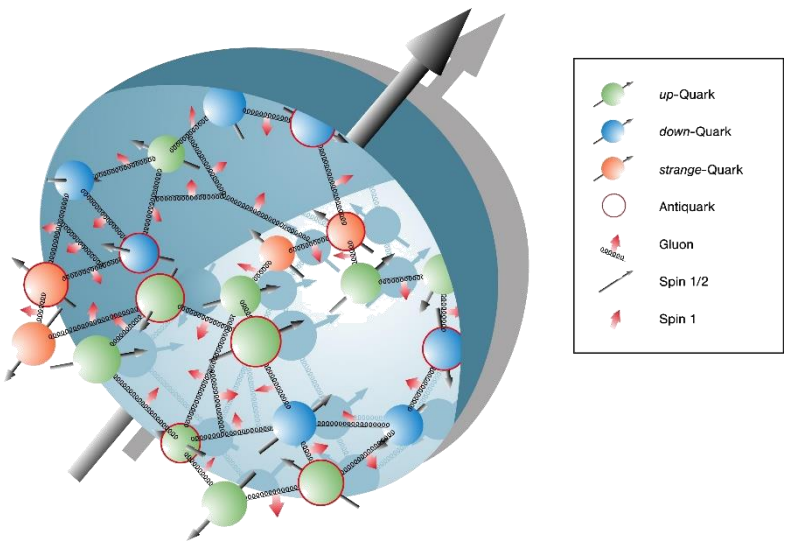
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L_q + \Delta L_g$$

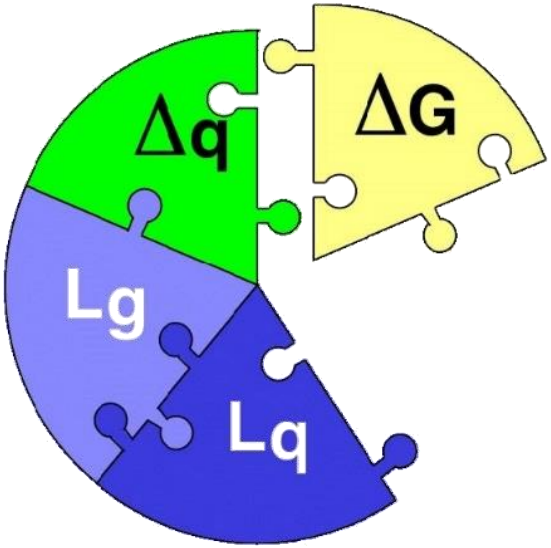
~0.33 (small)

Poorly constrained

$$\Delta\Sigma = \Delta u + \Delta d + \Delta\bar{u} + \Delta\bar{d} + \ldots$$

Poorly constrained





Nucleon Spin Structure History

Major Experimental Innovations

	Quark Spin	Gluon Spin
SLAC -> 2000	E80 – E155	
CERN ongoing	EMC, SMC, COMPASS	
DESY ->2007	HERMES	
JLab ongoing	Hall A,B,C	
RHIC ongoing	(BRAHMS), PHENIX, STAR	

Semi-inclusive + Inclusive DIS processes

Polarized p+p collisions

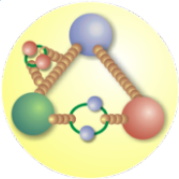
Probes to Nucleon Structure

Electromagnetic Interactions

Photon
Sensitive to electric charge
→ flavor
pp: DY
ep: DIS, SIDIS

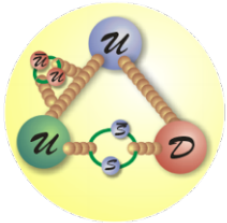
Strong Interactions

Gluon
Sensitive to color charge
→ gluon
jets, single hadrons, direct photon
jets, charm



Weak Interactions

Weak Bosons W & Z
Sensitive to weak charge
→ flavor and helicity
W and Z prod'n
high Q^2 DIS



arXiv:1602.03922

- Various probes in polarized p+p ⟶ Access gluon polarization at LO
- Weak boson ⟶ Flavor separated sea quark polarization.

PHENIX Longitudinal Spin Progress

Gluon Polarization:

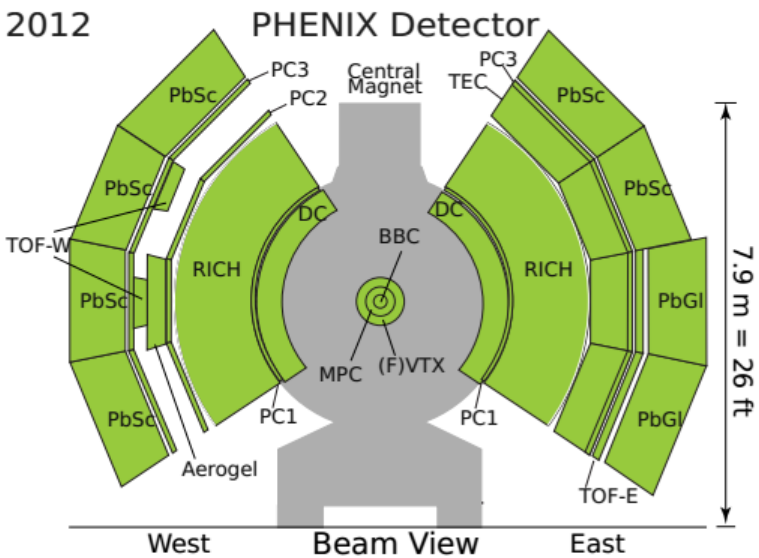
- Run13 510GeV π^0 A_{LL} at central rapidity (Published)
- Run13 510GeV J/ψ A_{LL} at forward rapidity (Submitted)
- Run11,13 500,510GeV π^0 A_{LL} at forward rapidity (Ongoing)
- Run13 charged pion A_{LL} (Ongoing)
- Run13 direct photon A_{LL} (Ongoing)
- Run9, 11 di-π^0 A_{LL}(Ongoing)

Light Sea Quark Polarization

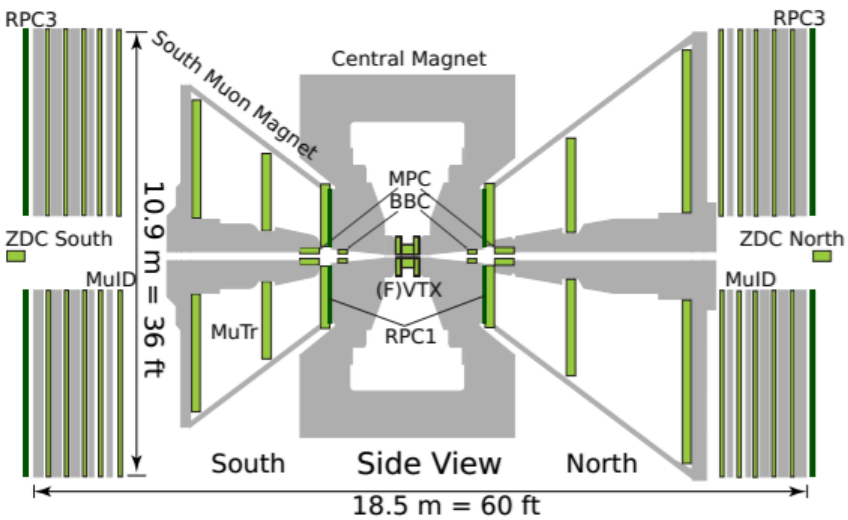
- Run11,12,13 500,510GeV W A_L at central rapidity (Published)
- Run11,12,13 510GeV W A_L at forward rapidity (Preliminary)

PHENIX

PHENIX Central Arm



Forward Muon Spectrometer

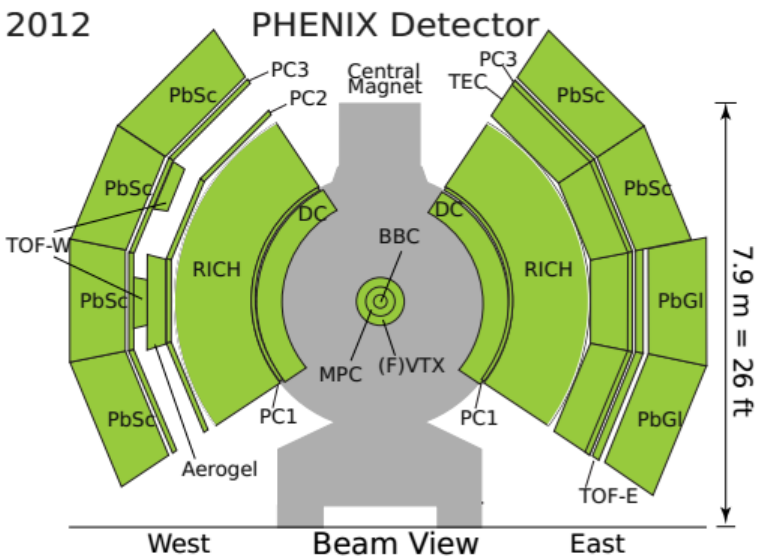


- Energy measured in EM Calorimeter (PbSc + PbGl)
- Momentum/Tracking in Drift Chamber (DC) + Silicon Barrel (VTX)
- PID with Ring Imaging Cherenkov Counter (RICH)
- $|\eta| < 0.35$, $\Delta\phi = 2 \times \frac{\pi}{2}$

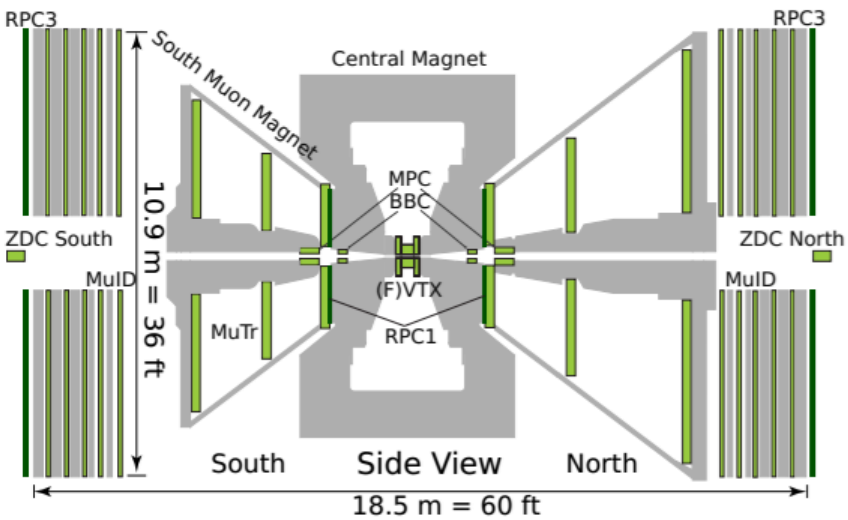
- Silicon strip tracking and vertexing (FVTX)
- Momentum measured in cathode strip tracking chambers (MuTr)
- $\mu^{\pm}$ ID from Iarocci tubes interleaved with steel absorbers (MuID)
- $1.2 < |\eta| < 2.2$, $\Delta\phi = 2\pi$
- Muon Piston Calorimeter (MPC) $3.1 < |\eta| < 3.9$

PHENIX

PHENIX Central Arm



Forward Muon Spectrometer



- $\pi^0 \rightarrow$ di-photon
- $W^{\pm} \rightarrow e^{\pm}$
- Charged pion
- Direct photon
- etc.

- $J/\psi \rightarrow$ di-μ
- $W^{\pm} \rightarrow \mu^{\pm}$
- MPC clusters (π^0)
- etc.

Recent PHENIX Longitudinal Runs

PHENIX Recent Longitudinal Runs:

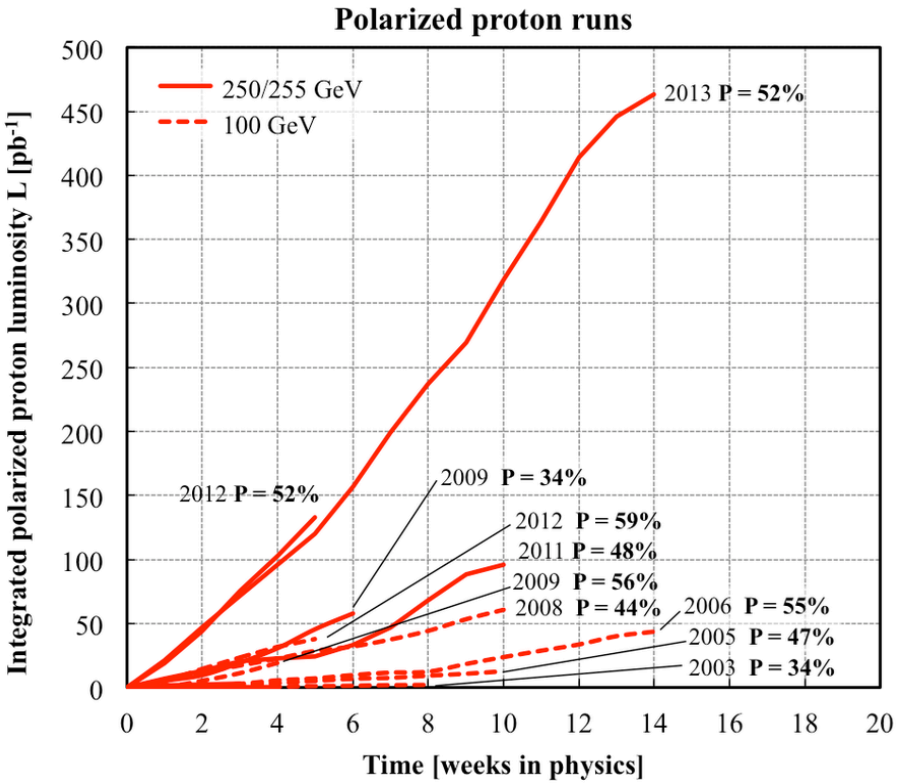
Year	$\sqrt{s}$(GeV)	L(Pb^{-1})	P(%)	FoM(P^4L)
2003	200	0.35	27	0.0019
2004	200	0.12	40	0.0031
2005	200	3.4	49	0.2
2006	200	7.5	57	0.79
2006	62.4	0.08	48	0.0042
2009	500	10	40	0.26
2009	200	14	57	1.4
2011	500	16.7	48	0.88
2012	510	30.03	52	2.2
2013	510	150	55	14

Figure of Merit:

High polarization is essential for effective asymmetry measurement:

Single Spin Asymmetry: $L < P >^2$

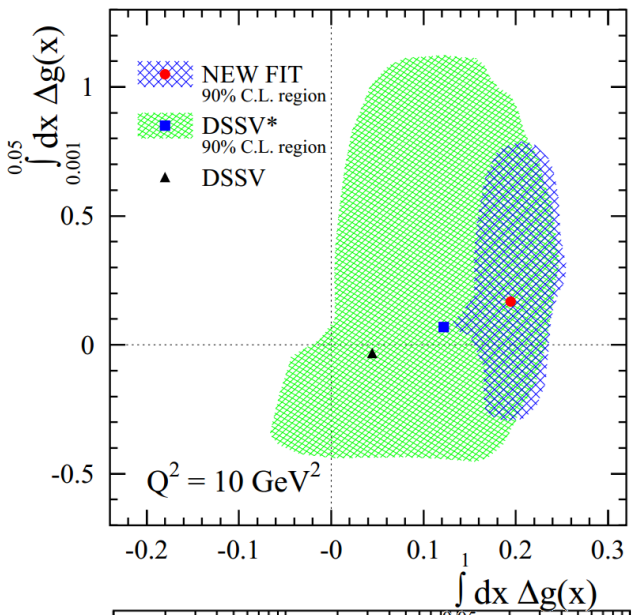
Double Spin Asymmetry: $L < P >^4$

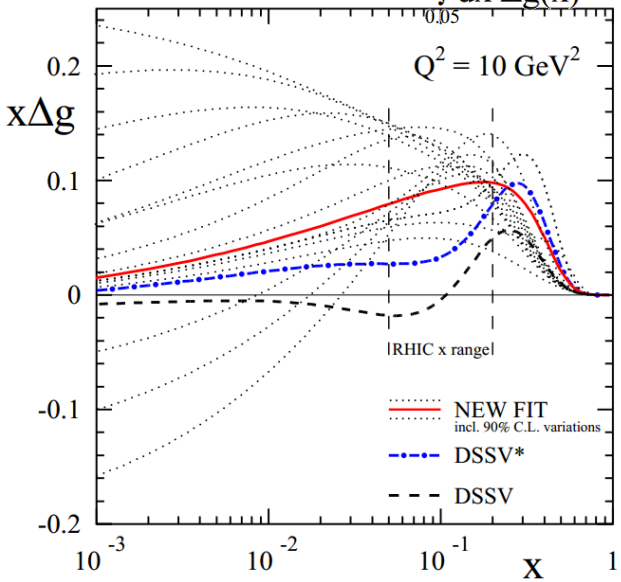


Gluon Polarization (Δg)

2014 DSSV Global Fit

- Including 2009 200GeV RHIC data sets, the 2014 DSSV global fit suggests non zero polarization of gluons in the proton at intermediate x range (0.05~0.2).
- Yet at low x range, the errors of DSSV are still poorly constrained
- Measurements from forward rapidity and higher collision energies needed.



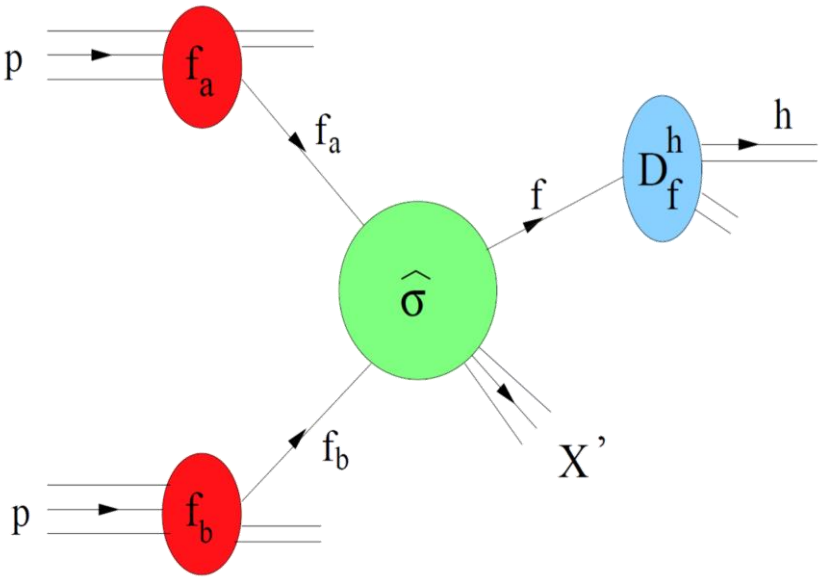


Phys. Rev. Lett. 113, 012001 (2014)

Gluon Polarization and Double Helicity Asymmetries (A_{LL})

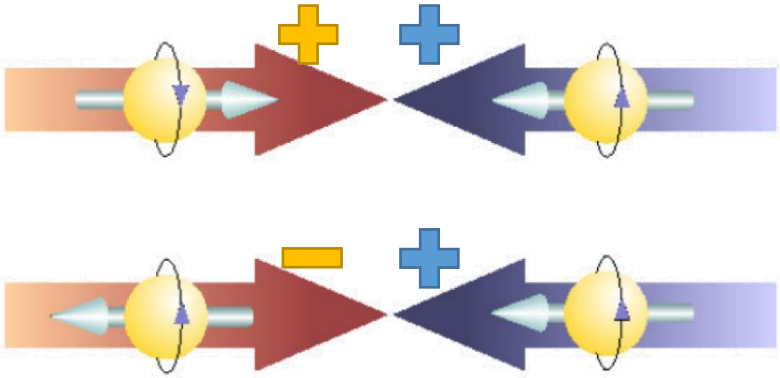
Theoretically:

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c=q,\bar{q},g} \Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma} \otimes D_{h/c}}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes \hat{\sigma} \otimes D_{h/c}}$$



Experimentally:

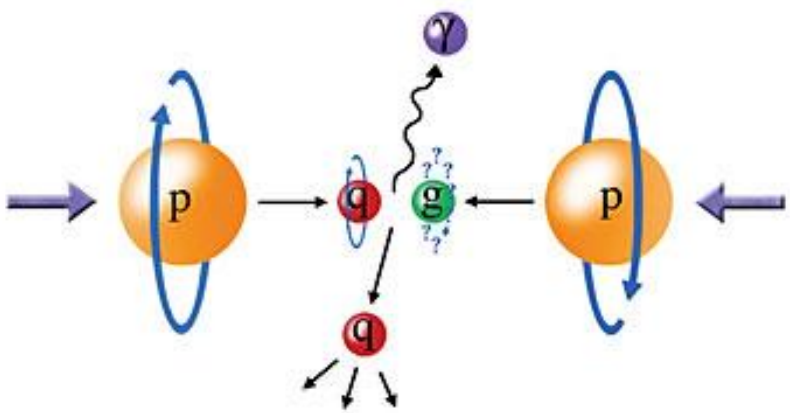
$$A_{LL} = \frac{1}{P_B P_Y} \frac{N^{++} - R\, N^{+-}}{N^{++} + R N^{+-}}$$



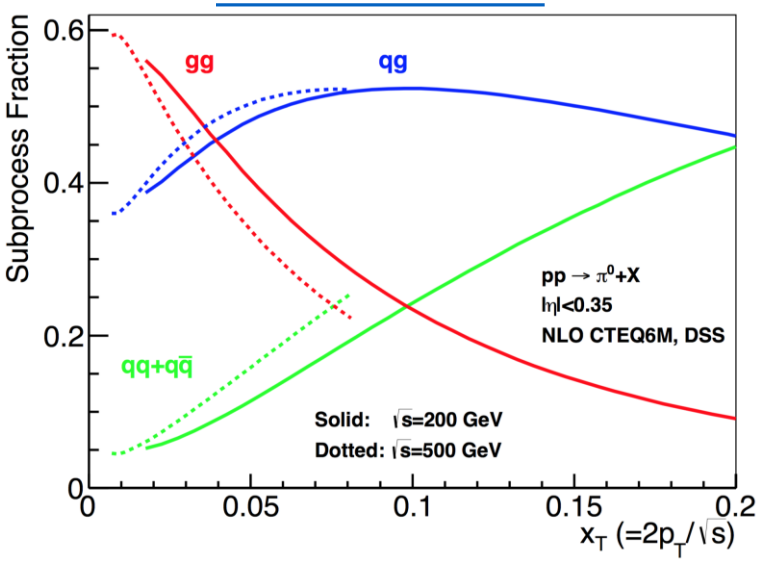
Where $P_{B,Y}$ is the polarization of Blue (Yellow) beam.
And R is the relative luminosity:

$$R = \frac{L^{++}}{L^{+-}}$$

Gluon Polarization and π^0 A_{LL}



arXiv1501.01220



$$\Delta\sigma(pp \to \pi^0 X) \approx \underbrace{\Delta q(x_1)}_{\text{DIS}} \otimes \underbrace{\Delta g(x_2)}_{?} \otimes \underbrace{\Delta\hat{\sigma}^{qg\to qg}(\hat{s})}_{\text{pQCD}} \otimes \underbrace{D_q^{\pi^0}(z)}_{\text{e+e-}} \ldots$$

-- Parton distribution functions

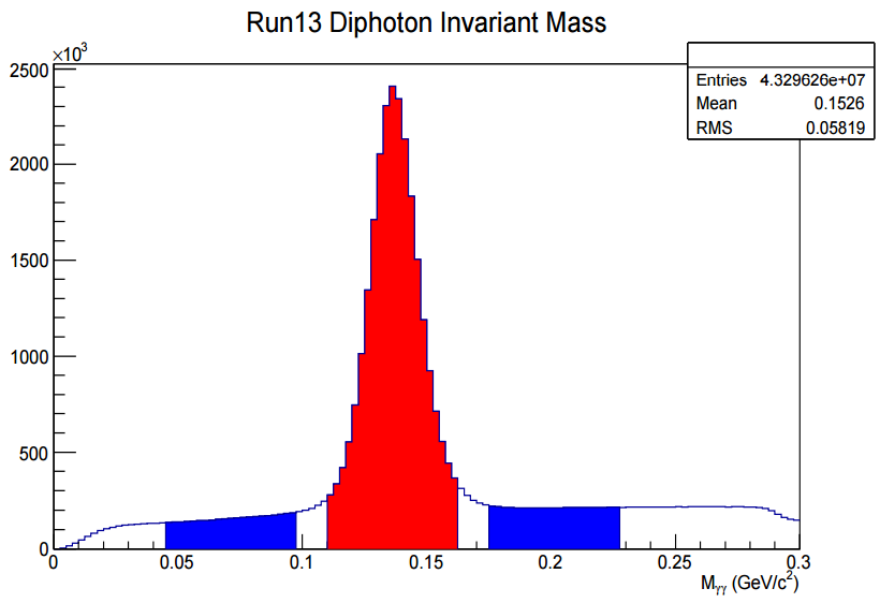
-- Partonic hard scattering rates

-- Fragmentation functions

π^0 A_{LL} measurement at PHENIX

- Reconstruct π^0 peak with γ pair in Electromagnetic Calorimeter at PHENIX (PbSc and PbGl).
- Large cross section + finely segmentation EMCal + high p_T photon trigger.
- Inclusive asymmetry and side band background asymmetry:

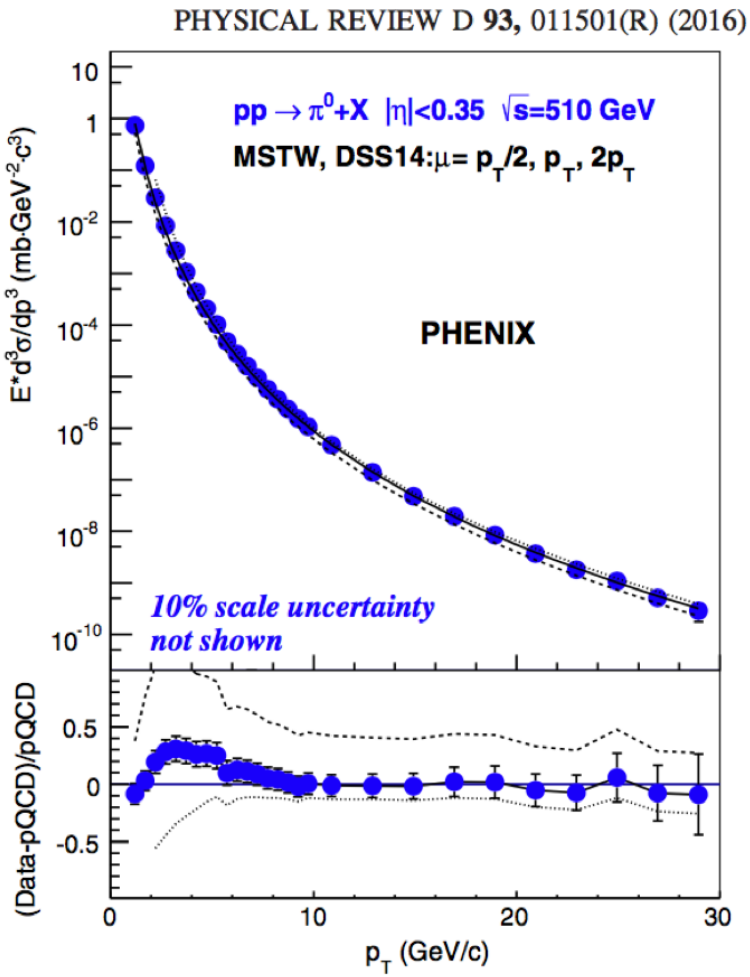
$$A_{LL}^{\pi^0} = \frac{A_{LL}^{(\pi^0+BG)} - rA_{LL}^{BG}}{1-r}$$



$$A_{LL} = \frac{1}{P_B P_Y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

R is the relative luminosity. Uncertainty from R contribute the main source of systematic uncertainty of the asymmetry result.

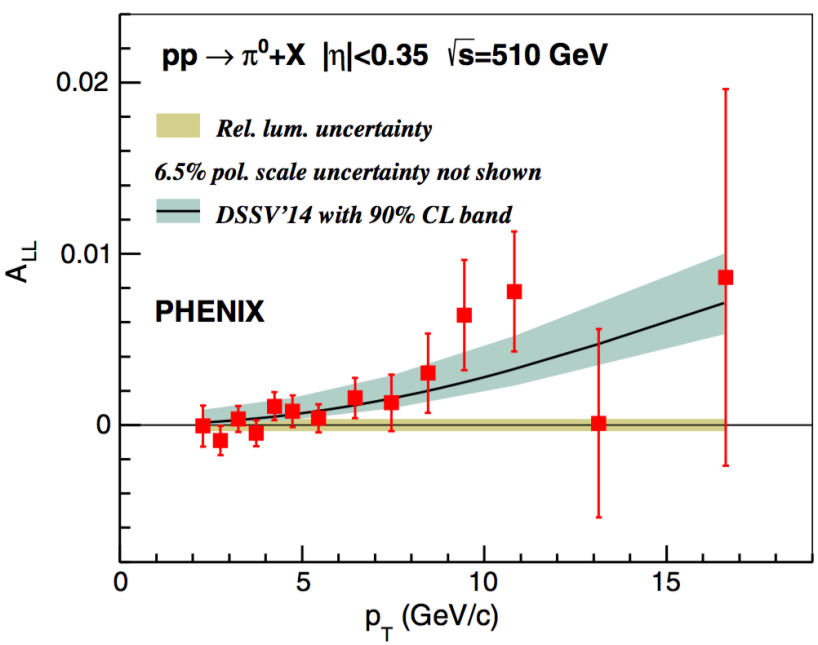
π^0 Cross Section at 510 GeV

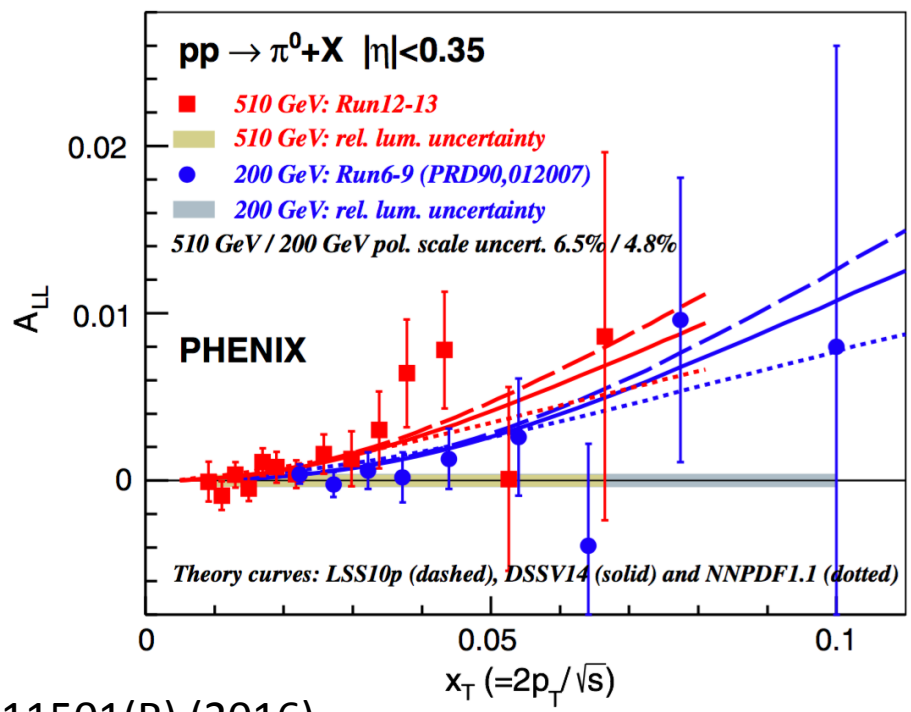


- Cross section results are given for $0.5 < p_T < 30$ GeV/c.
- The cross section is well described by NLO perturbative QCD.

π^0 A_{LL} at central rapidity ($|\eta|$<0.35)

- Recently published Phys. Rev. D 93, 011501(R) (2016).
- The results follows positive trend with p_T and $\sqrt{s}$ as predicted by NLO pQCD.
- Additional constrains on gluon polarization and extended Bjorken x coverage down to ~0.01.





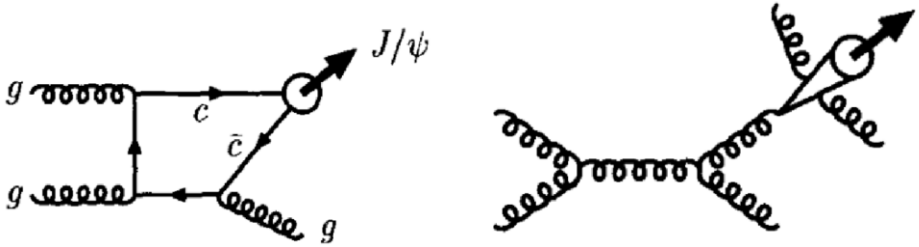
PRD 93, 011501(R) (2016)

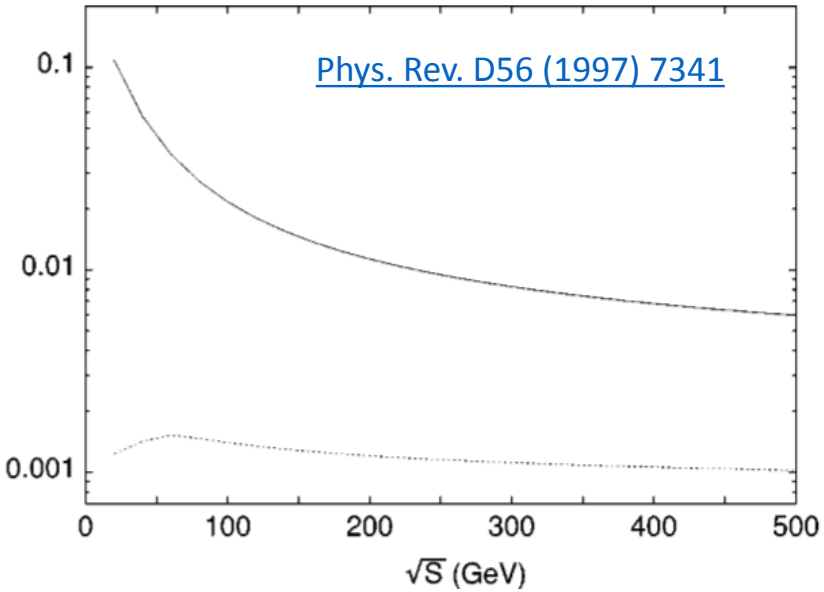
J/ψ production at RHIC

At RHIC energies J/ψ production is dominated by gluon-gluon fusion.

The A_{LL} for J/ψ can be written (LO):

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \hat{a}^{gg\to J/\psi} \frac{\Delta g(x1)}{g(x1)} \frac{\Delta g(x2)}{g(x2)}$$



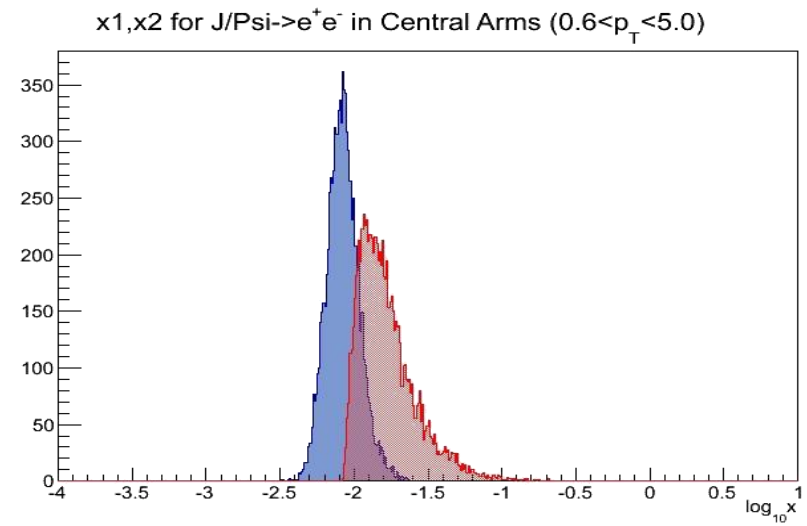


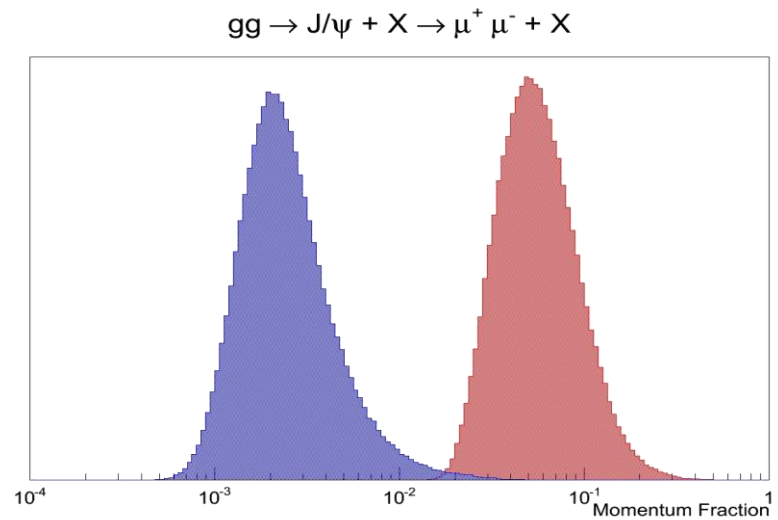
$q\bar{q}$ to gg ratios of unpolarized (solid) and polarized (dashed) processes

Bjorken x range for J/ψ production at Forward Rapidity

Benefits of Forward Rapidity

- At forward rapidity the x distributions of the two gluons are at very different region.
- Instead of probing $\sim(\Delta g/g)^2$ we are probing $\frac{\Delta g(x1)}{g(x1)}\frac{\Delta g(x2)}{g(x2)}$
- High-x gluon sits in the x-range where RHIC Run9 data already has constraints on the Δg
- Therefore, this forward $J/\psi \to \mu^+\mu^-$ A_{LL} gives sensitivity to possible sign change in Δg and cleanly accesses down to $x \sim 2 \times 10^{-3}$





from Pythia simulation

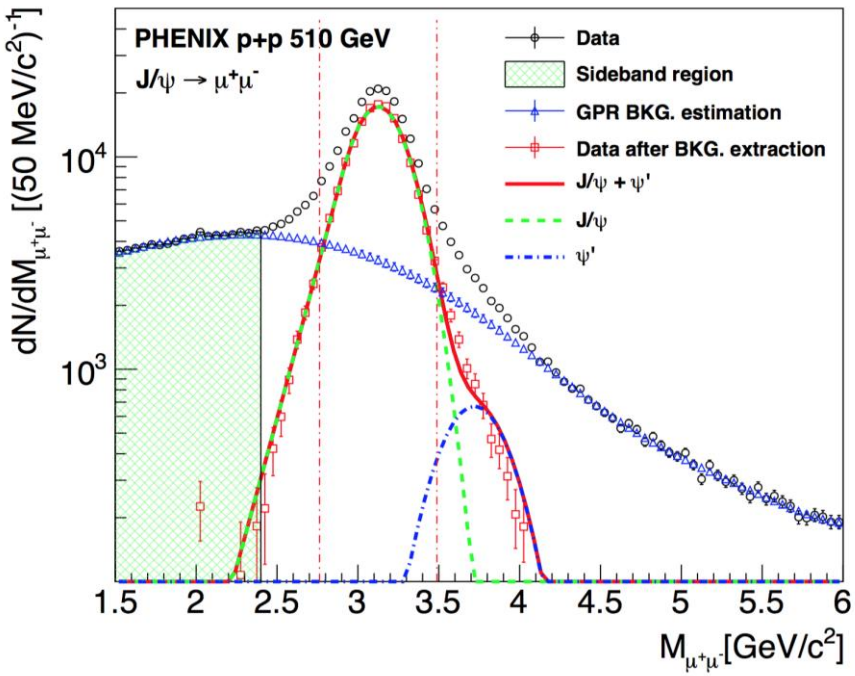
J/ψ A_{LL} Measurement Procedure

Outline

- Analyze south and north arm separately, and divide data from each arm into 3 p_T bins. So 6 subsets total.
- Fit each subsets for 2σ J/ψ mass window and background fraction "r".
  - CB shape for J/ψ, Gaussian for ψ'
  - Gaussian Process Regression (GPR) for background shape
- Sideband region is defined as $M_{\mu\mu} \in [1.5GeV, 2.5GeV]$
- Calculate $A_{LL}^{incl.}$ in the 2σ J/ψ mass window
- Estimate the background asymmetry from a sideband

$$A_{LL}^{J/\psi} = \frac{A_{LL}^{incl.} - r * A_{LL}^{BKG.}}{1 - r}$$

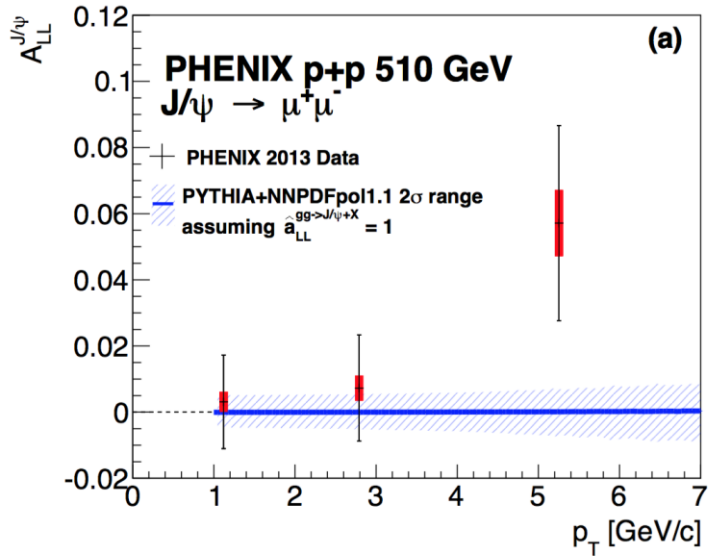
$$\Delta A_{LL}^{J/\psi} = \frac{\sqrt{(\Delta A_{LL}^{incl.})^2 + r^2 * (\Delta A_{LL}^{BKG.})^2}}{1 - r}$$

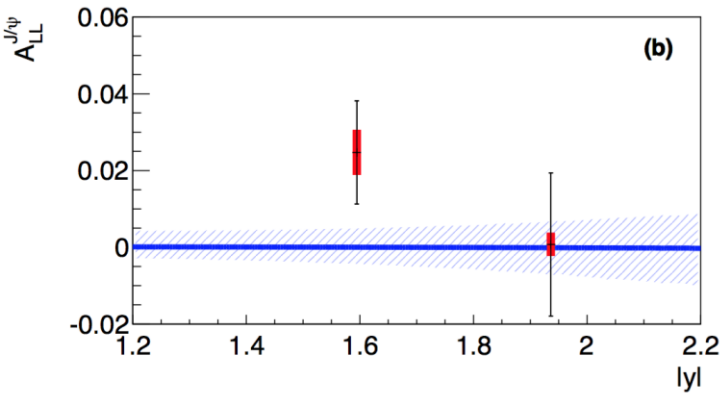


Gaussian Process Regression (GPR) background fraction extraction

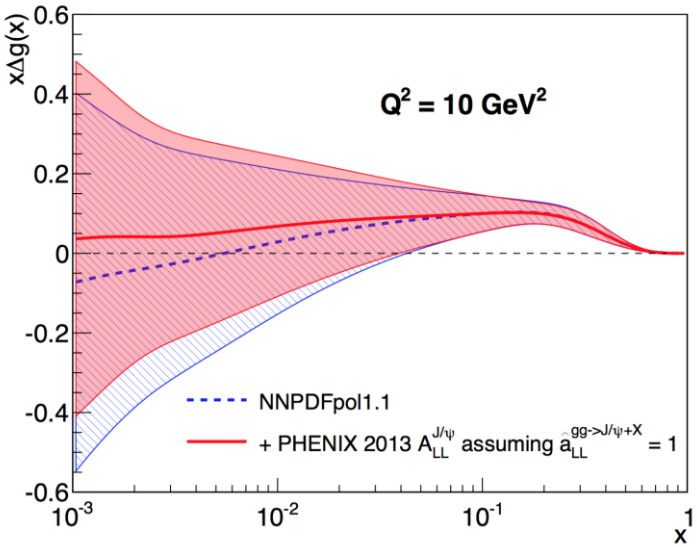
J/ψ A_{LL} at Forward Rapidity Results

Submitted to PRD. arXiv:1606.01815





NNPDFpol 1.1: Nucl. 616 Phys. B 887, 276 (2014).
Re-weighting method: Nucl. Phys. B 849, 112 (2011)



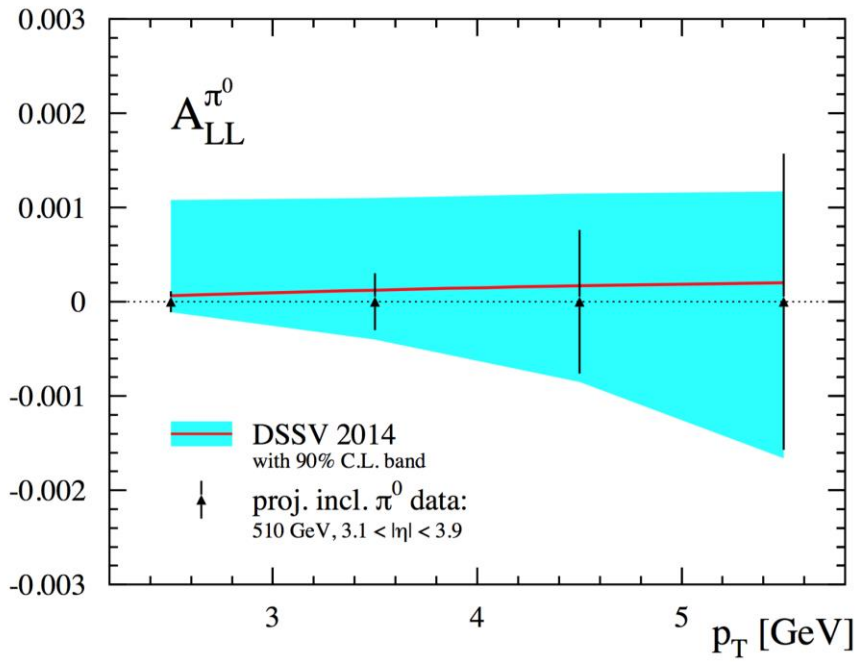
- Currently the constraining power on gluon polarization limited by large production mechanism uncertainty.
- Favors positive gluon polarization under assumption that $\hat{a}^{gg\to J/\psi} = 1$.
- Universality test of the helicity-dependent gluon densities and QCD factorizations.

Other ongoing Analyses on Δg

- PHENIX PPG formed on Run11 MPC cluster A_{LL} measurement. Run13 data undergoing. Could extend the constraints on Δg down to x ~ 10^{-3}.

- Run13 charged pion A_{LL}
- Run13 direct photon A_{LL}
- Run9, 11 di-π^0 A_{LL}

arXiv1501.01220



Impact on Gluon Polarization of the RHIC Data

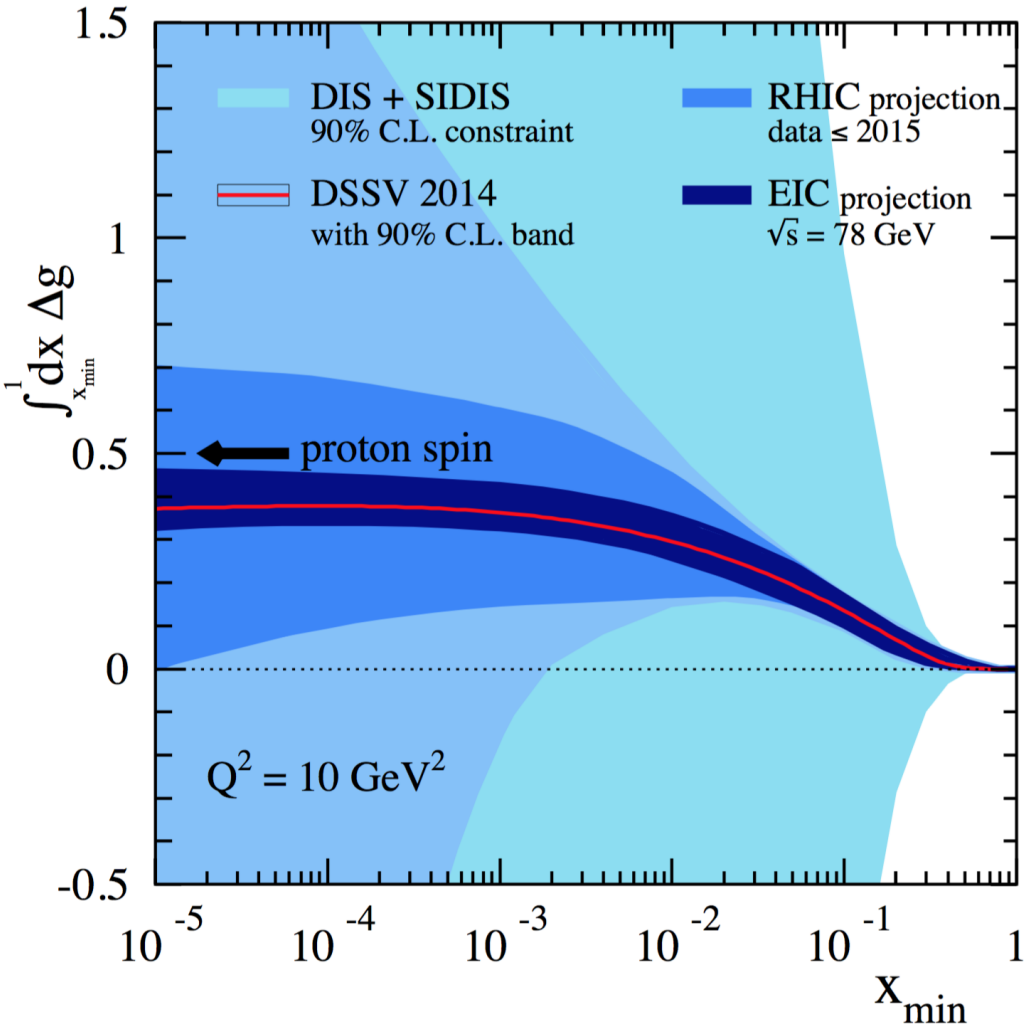
Projection with and without pseudo-data for current and future RHIC measurements up to Run-2015.

2015 - 2016:

- Published/Submitted:
  - Run9 200GeV Central π^0 A_{LL}
  - Run13 510GeV Central π^0 A_{LL}
  - Run13 510GeV Forward J/ψ A_{LL}

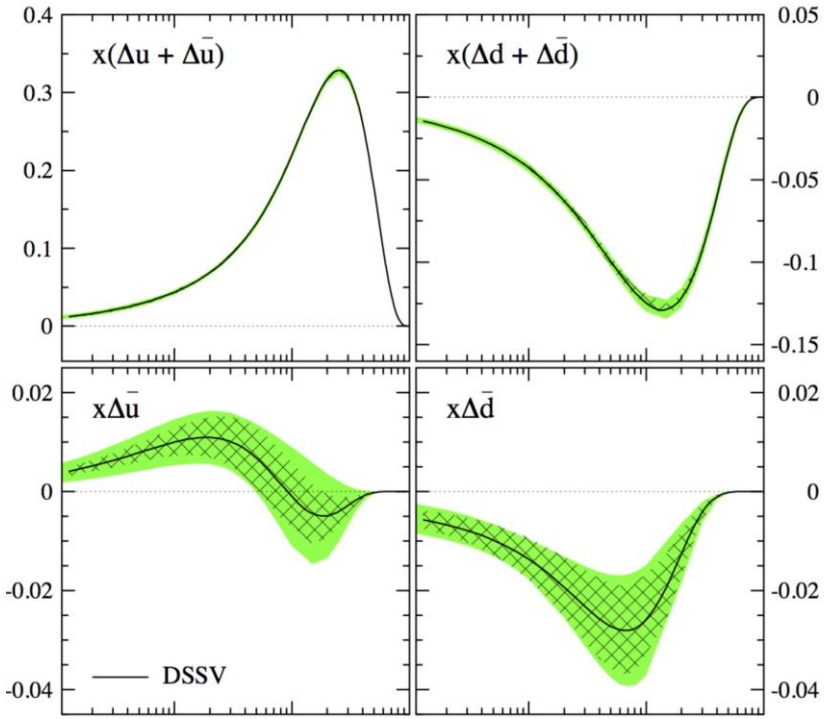
- Ongoing
  - Run11 500GeV Forward π^0 A_{LL}
  - Run13 510GeV Forward π^0 A_{LL}
  - Run13 510GeV Central $\pi^{\pm}$
  - Run13 510GeV Central direct photon
  - Run9, 11 di-π^0 A_{LL}

arXiv:1602.03922



Flavor Separated Light Sea Quark Polarization, $\Delta\bar{u}\ (x)$, $\Delta\bar{d}(x)$

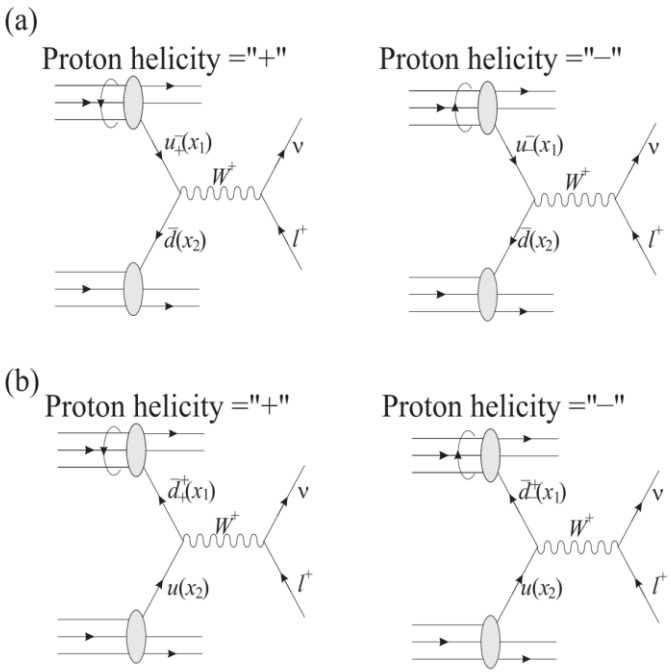
DSSV 2008 PRL **101** (2008), 072001



- Polarized SIDIS measurements (SMC, HERMES, COMPASS) sensitive to flavor separated quark anti-quark spin contributions. Limited by large uncertainties of fragmentation functions.
- Light Sea Quark Polarization relatively poorly constrained.

$W^{\pm}$ boson Single Helicity Asymmetry (A_L)

arXiv:hep-ph/0007218



- At RHIC, (anti)quark polarizations measured using maximal parity violation in W production.
- W couples to only left-handed quarks and right-handed anti-quarks.
- no fragmentation involved
- higher scale Q^2 set by W mass
- extract $\Delta\bar{u}, \Delta\bar{d}$

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

Flipping the spin orientation of one of the colliding protons and averaging over the other:

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

where,

- N is electron yield normalized by luminosity
- P is luminosity weighted polarization

$W^{\pm} \to l^{\pm}$ Flavor Sensitivity

$W^{\pm} \to \mu^{\pm}$
(forward rapidity)

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

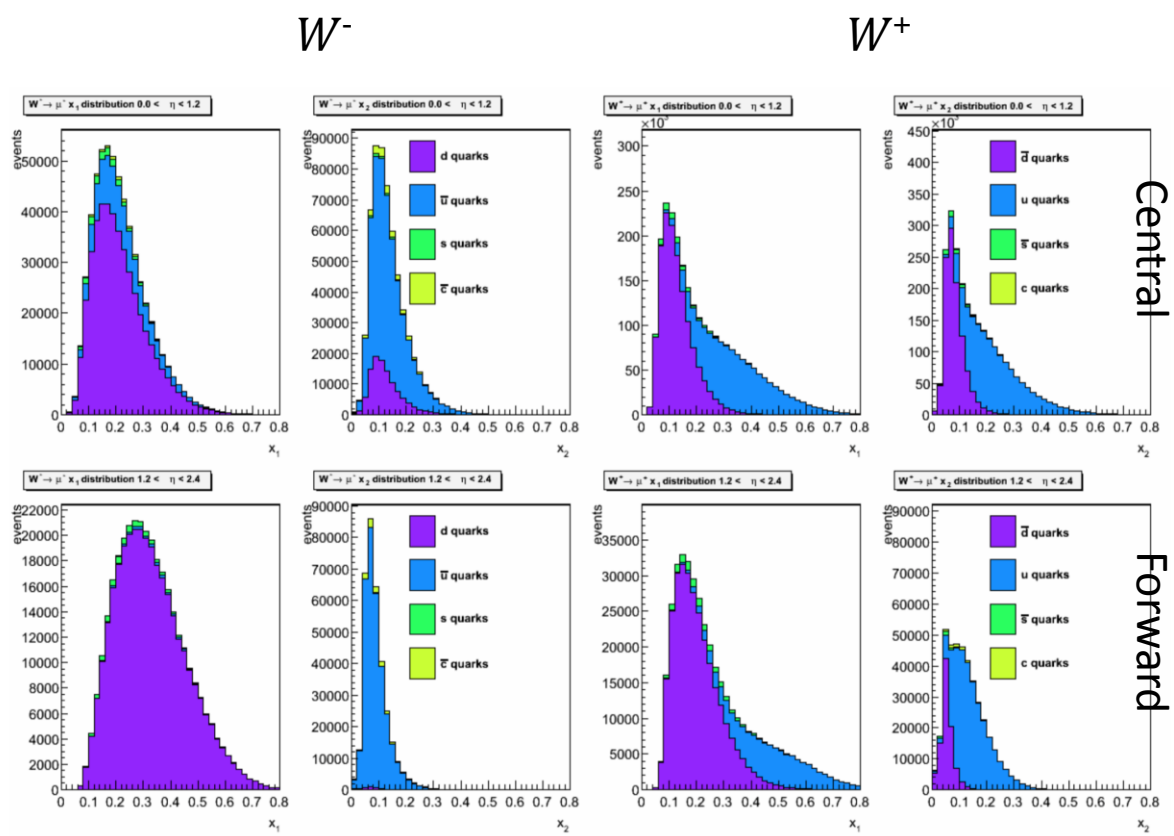
$$A_L^{W^-} \approx \frac{\Delta d}{d}$$ (forward rapidity)

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

$$A_L^{W^-} \approx \frac{\Delta\bar{u}}{\bar{u}}$$ (backward rapidity)

$W^{\pm} \to e^{\pm}$
(mid-rapidity)
measuring the mixture of quark flavor contribution:

- For W^+, combination of Δu and $\Delta\bar{d}$
- For W^-, combination of $\Delta\bar{u}$ and Δd



Measurements in Different Rapidity

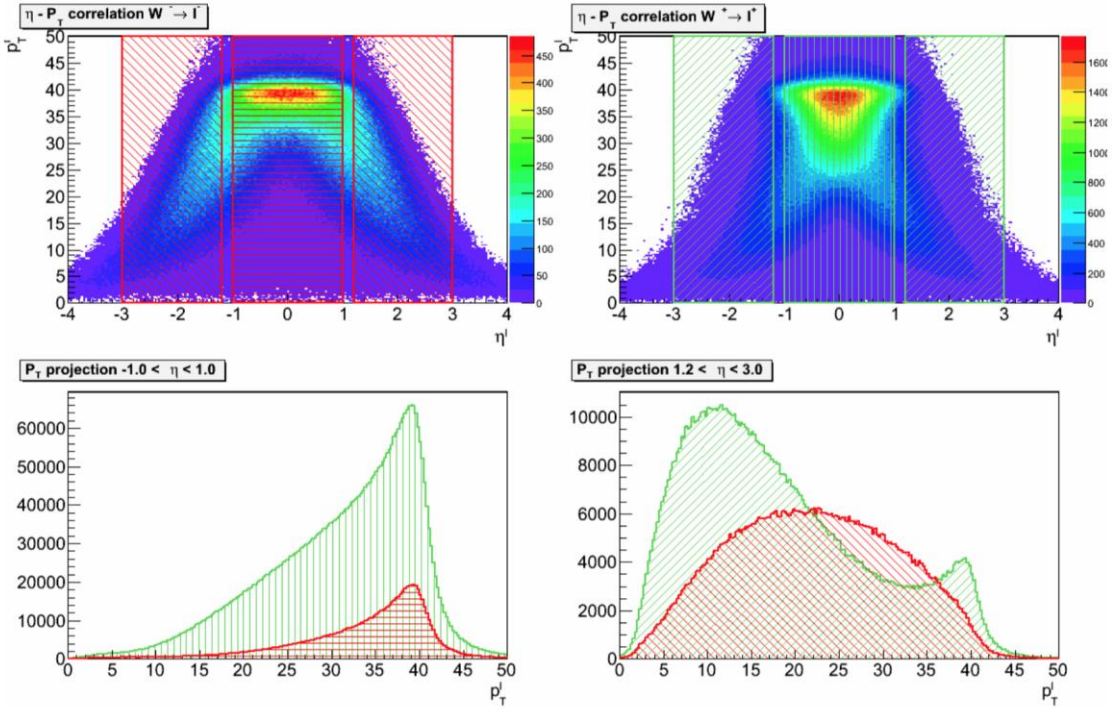
Detector is non-hermetic, Cannot identify W's on event by event basis.

Central rapidity:

- Clear Jacobian peak at ~40 GeV corresponding to the signal.
- Select high p_T (30~50GeV) region from the $e^{\pm}$ pT spectra.

Forward rapidity:

- No clean peak.
- Multivariate likelihood method combining some sensitive variables.
- Unbinned likelihood fit to extract background fraction.



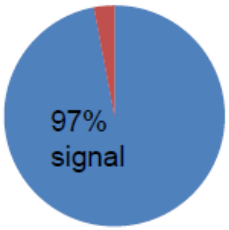
Run 13 $W^{\pm} \rightarrow e^{\pm}$ Electron p_T Spectra

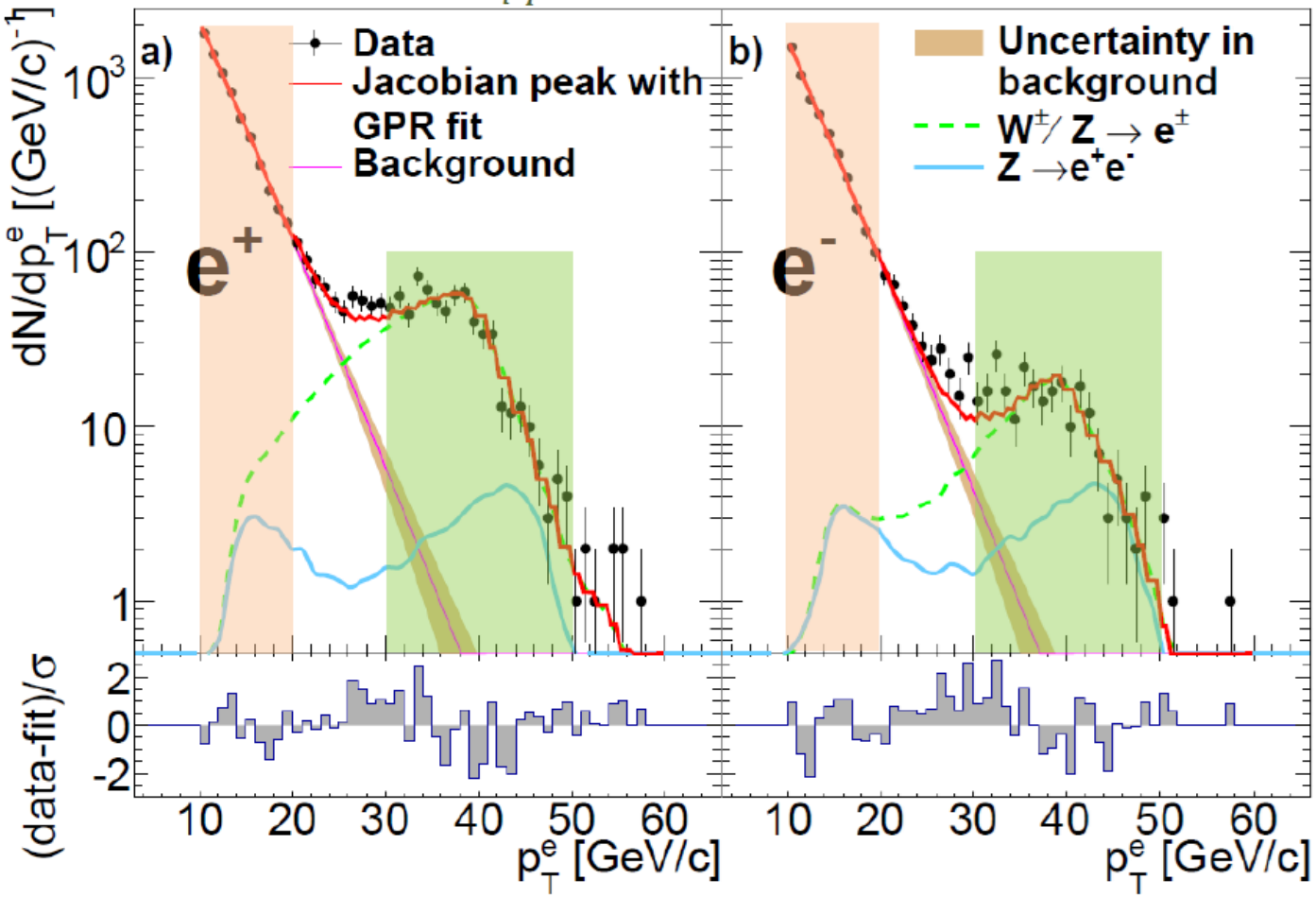
Signal region: $30 < p_T < 50$ GeV Background region: $10 < p_T < 20$ GeV

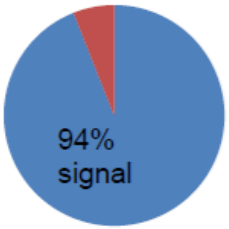
Background estimation using two independent methods:

- Gaussian Processes for Regression (GPR)
- Modified power law $\{f(p_T) = \frac{1}{p_T^{[0]+[1]*\log(p_T)}}\}$

fit simultaneously with simulated jacobian peak shape

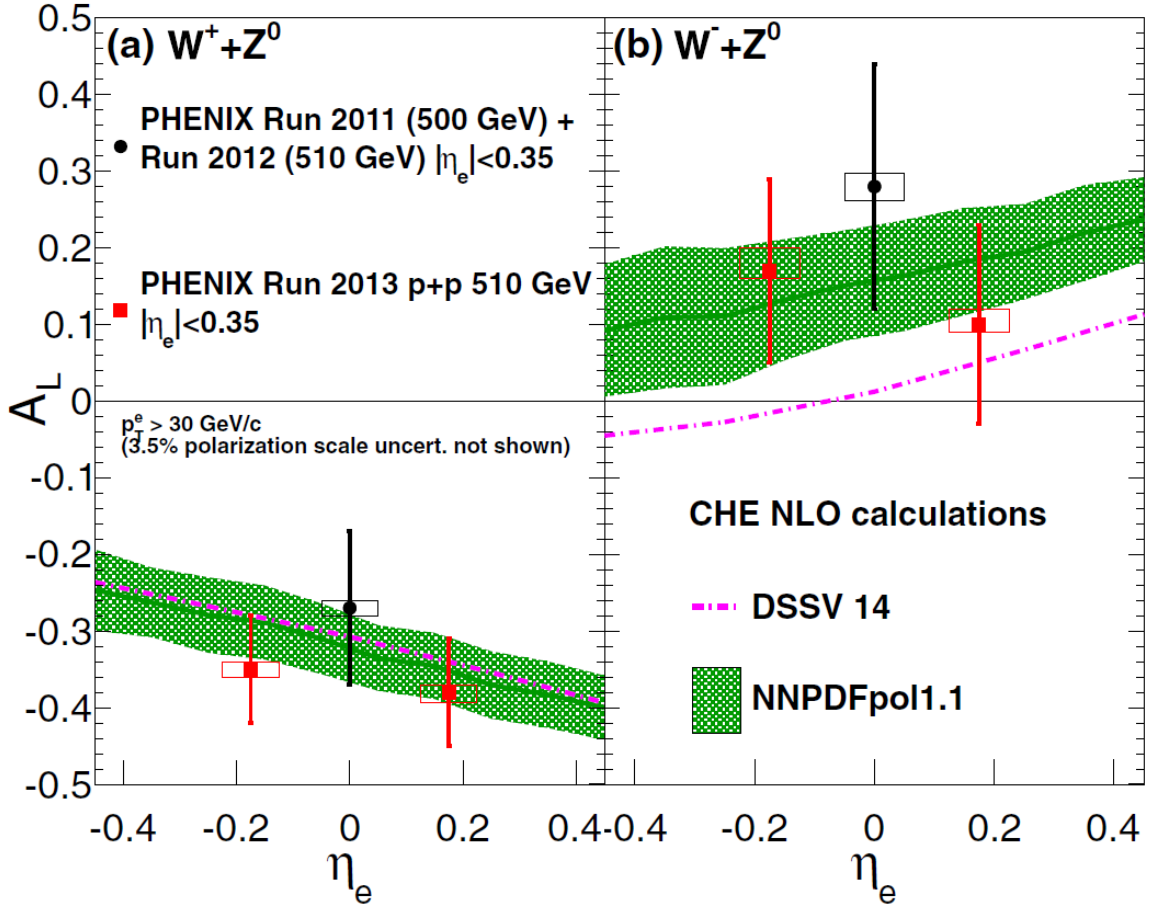






Run 11,12, 13 $W^{\pm} \rightarrow e^{\pm}$ A_L Results

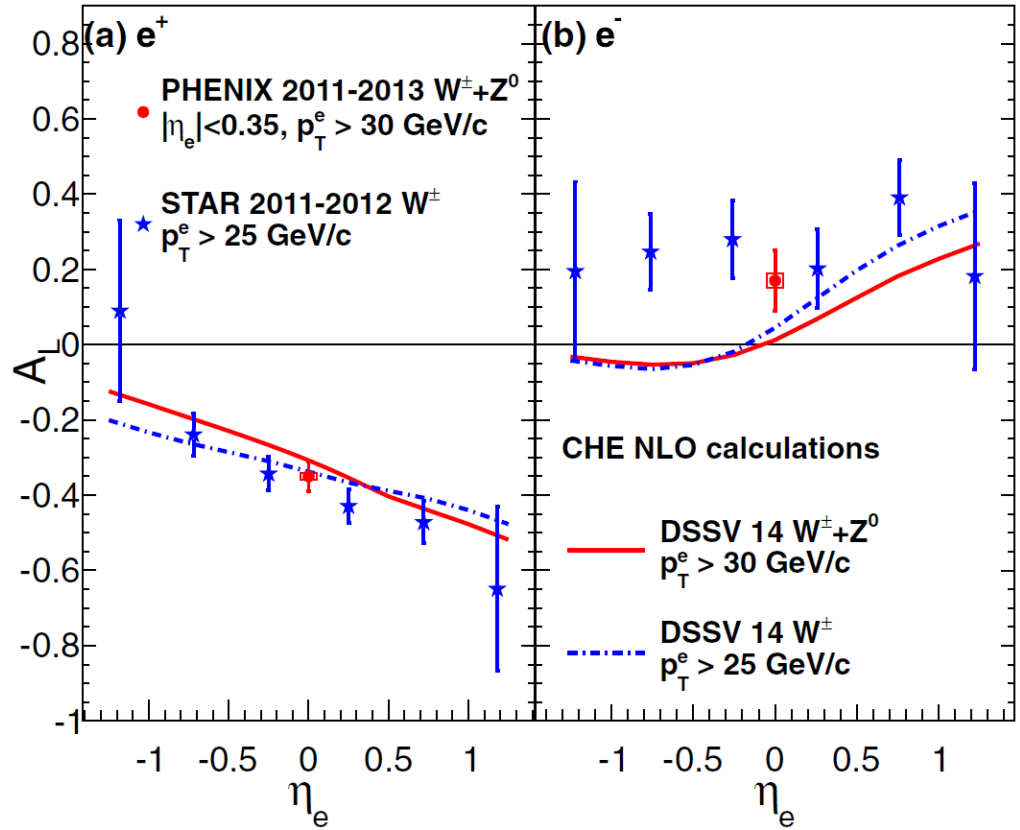
Recently published: PRD 93, 051103(R)(2016)



Comparing with STAR 2011-2012 data

- Comparison with STAR results.
- Both data sets show the same trend with respect to the DSSV central values.
- Show preference to a larger $\Delta\bar{u}$ contribution.

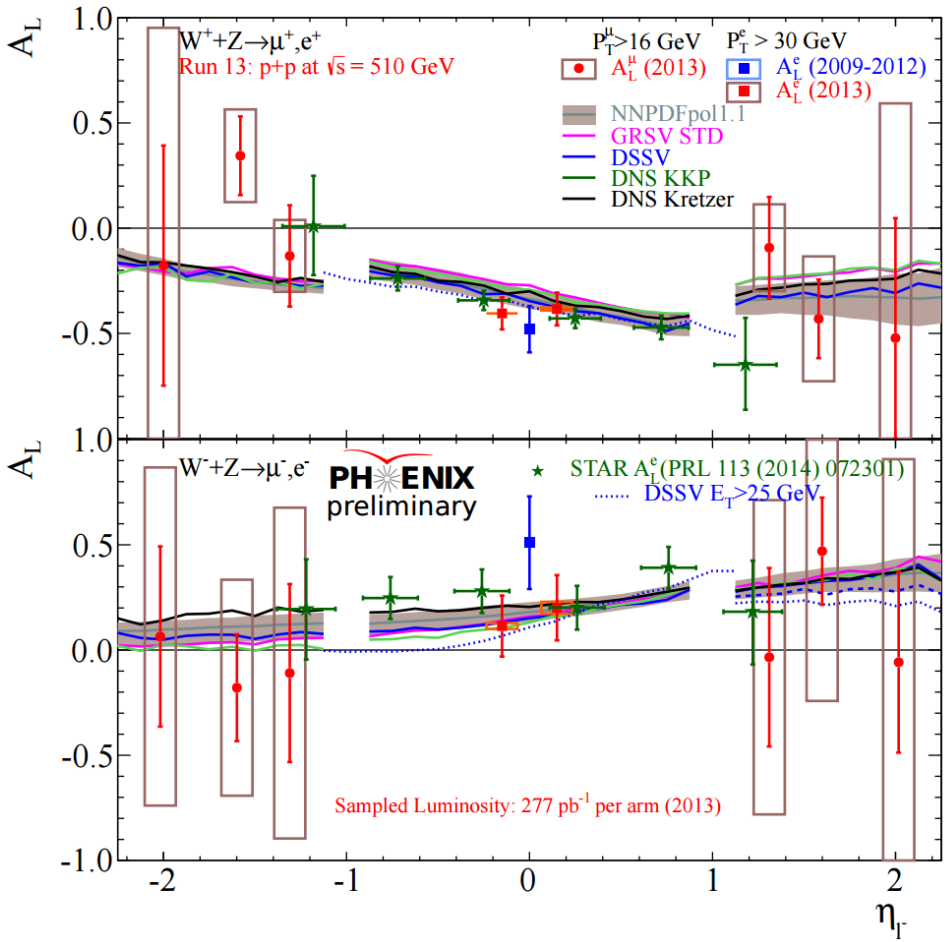
PRD 93, 051103(R)(2016)



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

Run 2013 preliminary $W^{\pm} \rightarrow \mu^{\pm}$ A_L results:

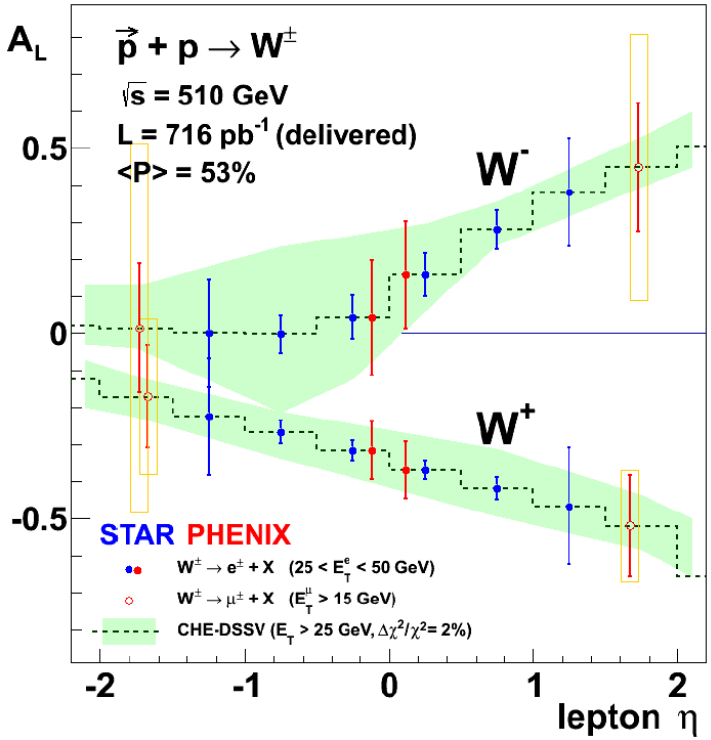
- Results are in agreement with theoretical predictions within uncertainties.
- Currently working to improve the systematic uncertainties.
- Moving towards the final result and publication.

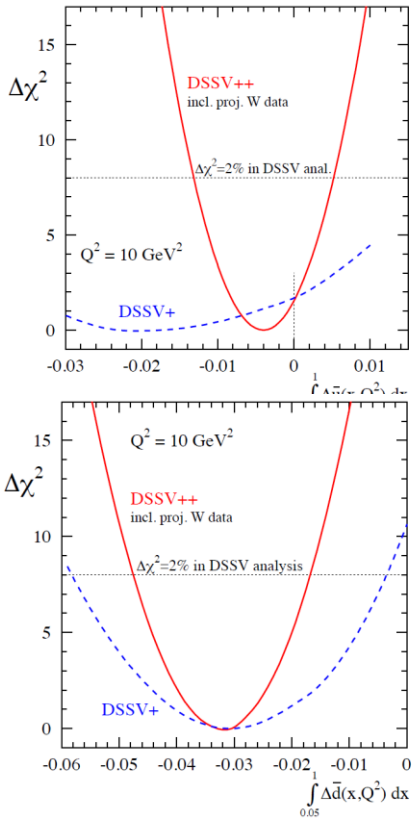


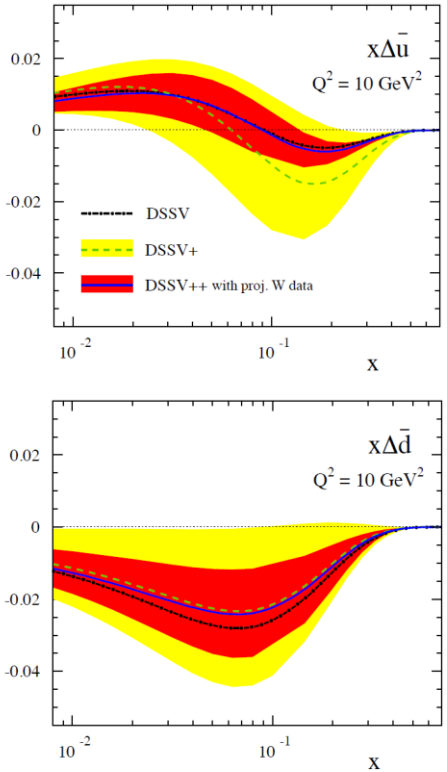
RHIC $W^{\pm} \to l^{\pm}$ data Impact on Light Sea Quark polarizations

Significant improvement on light sea quark polarization.

arXiv: 1501.01220







Summary

Run13 π^0 A_{LL} at central rapidity ($|\eta| < 0.35$) published at PRD Rapid Communications.

- Extend the $\Delta g(x)$ constraints down to $x \sim 10^{-2}$.
- Could reduce the global fit uncertainties on $\Delta g(x)$

Run13 J/ψ A_{LL} at forward rapidity submitted to PRD.

- Sensitive to gluon polarization down to $x \sim 2 \times 10^{-3}$.
- Universality check for the QCD factorization of the gluon helicity dependent P.D.F.
- Could improve the gluon polarization precision at smaller x with further knowledge on the production mechanism.

$W \rightarrow e$ A_L at central rapidity have been published at PRD Rapid Communications

- Consistent with DSSV global analysis.
- Favoring larger $\Delta\bar{u}(x)$ contribution.
- Could improve uncertainties on $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$.

$W \rightarrow \mu$ A_L at forward rapidity preliminary results :

- Consistent with DSSV global analysis.
- Currently working on systematic uncertainties.
- Moving towards publication.

Many ongoing longitudinal analyses. Stay tuned.

Backups

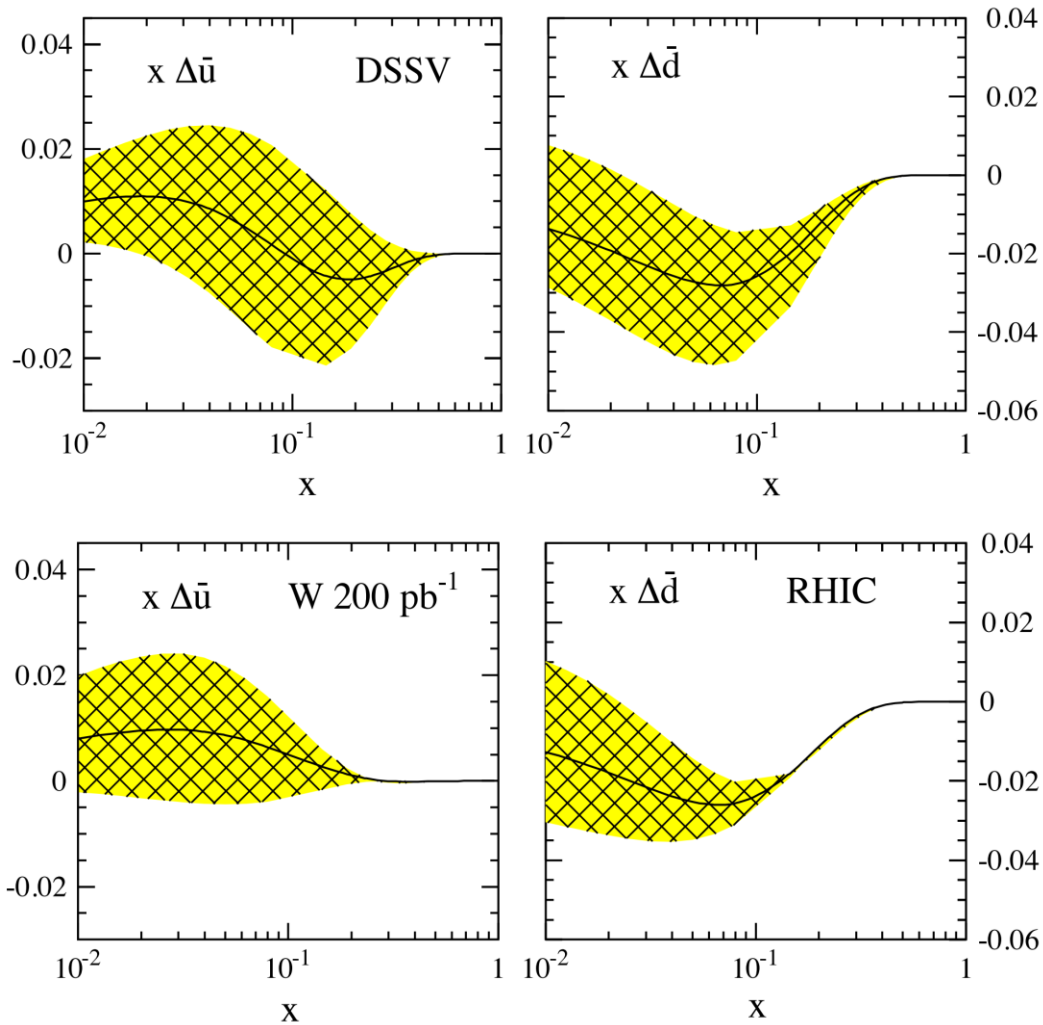
Impact on Sea-quark polarizations

Phys. Rev. D 81, 094020 (2010)

DSSV global analysis

- Phys. Rev. D 80, 034030 (2009)
- Phys. Rev. Lett. 101, 072001 (2008)

DSSV + 200pb^{-1} simulated W A_L pseudo-data

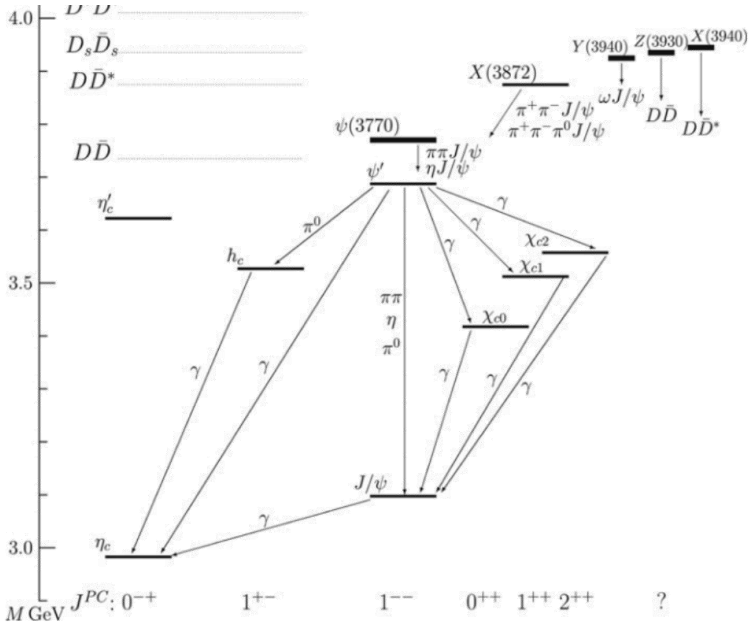


J/ψ A_{LL} @ forward rapidity

Excited states feed-down

Charmonium

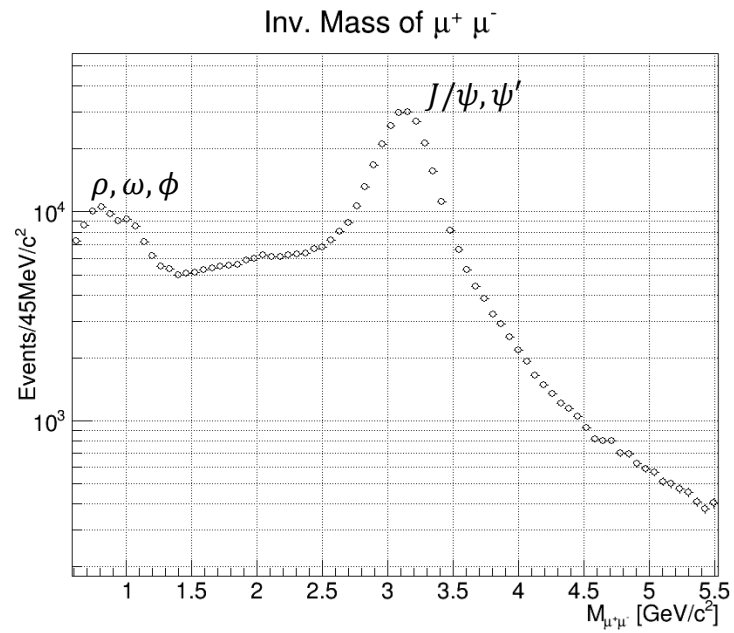
- Except for J/ψ's, excited charmonium states are also generated in RHIC p+p collisions
- χ_c and ψ' feed-down forms a sizable portion
  - Phys. Rev. D 85, 092004 (2012)
- ψ' overlaps with J/ψ
- Different calculating schemes gave different Δg depends for each excited states (Phys. Rev. D 56, 7341 (1997))
  - Good test bed for different aspects of NRQCD factorization and scaling



J/ψ A_{LL} @ forward rapidity

Event and track selection

- Vertex selection: |BBC_Z|<30 cm
- common PHENIX muon tracks quality cuts including:
  - from same arm
  - track matching between muon tracker and identifier
  - penetrating muon candidates cuts
  - etc.
- RPC timing cut are applied to guarantee J/ψ's are from the right bunch crossing



$\mu^+\mu^-$ *inv. mass spectrum* after event and μ track selection

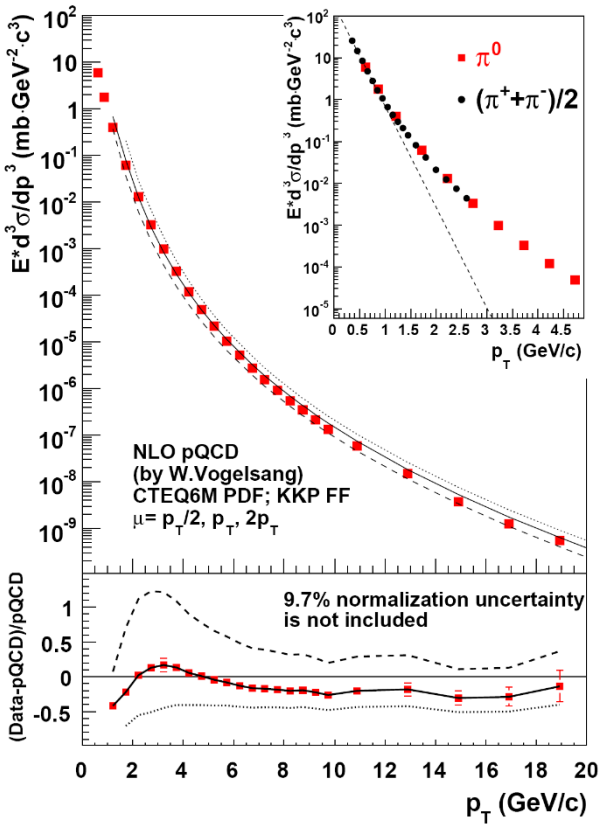
sideband region is used to estimate background asymmetry

Unpolarized Cross Sections at Lower Energies

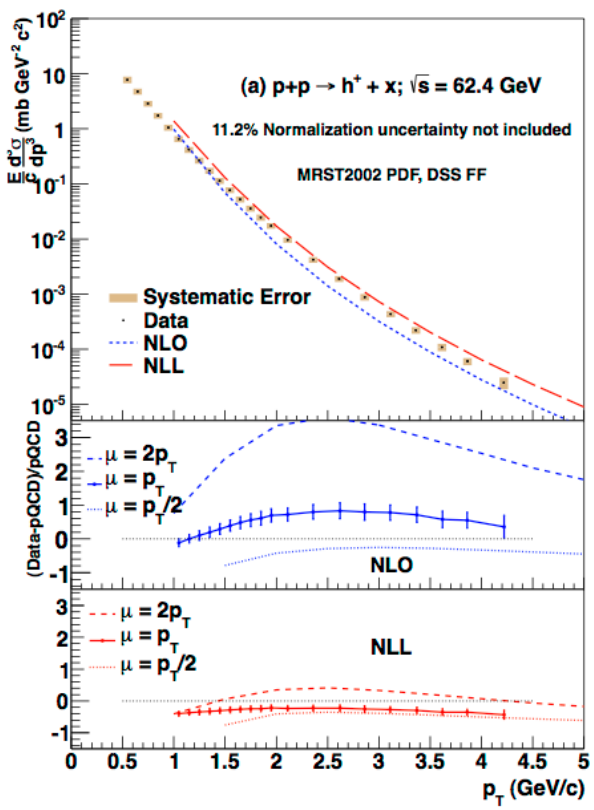
PRD 76, 051106

arXiv:1202.4020

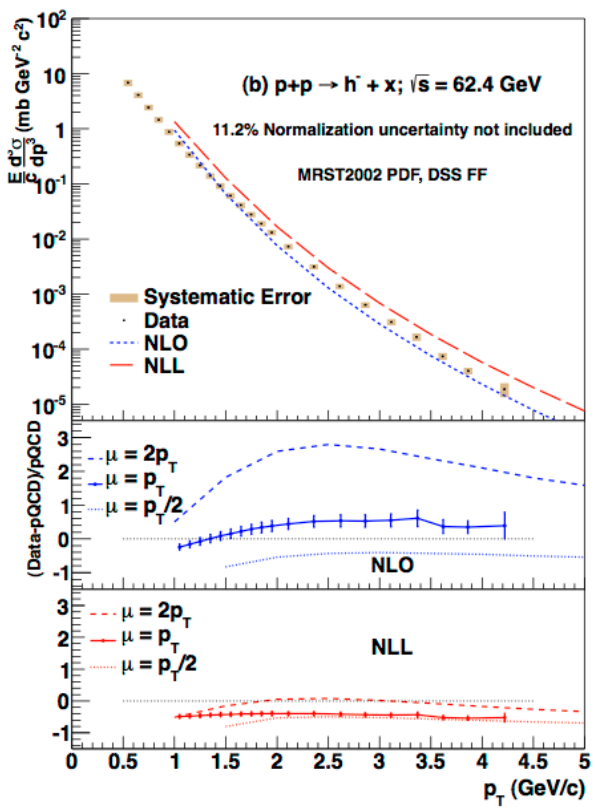
π^0 at 200GeV



h^+ at 62.4GeV



h^- at 62.4GeV

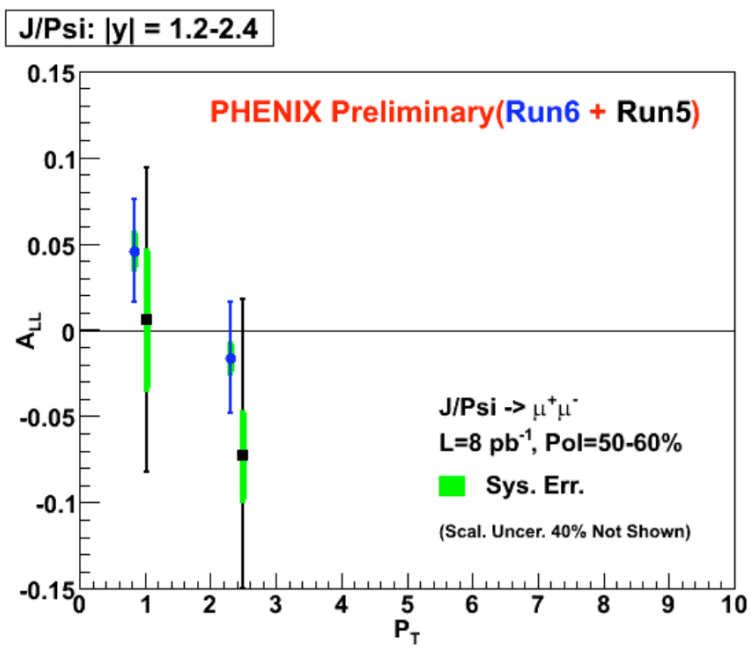


- **NLO QCD Calculation Cross-sections consistent with Data.**
- **pQCD works over a very broad kinematic range at RHIC energies**

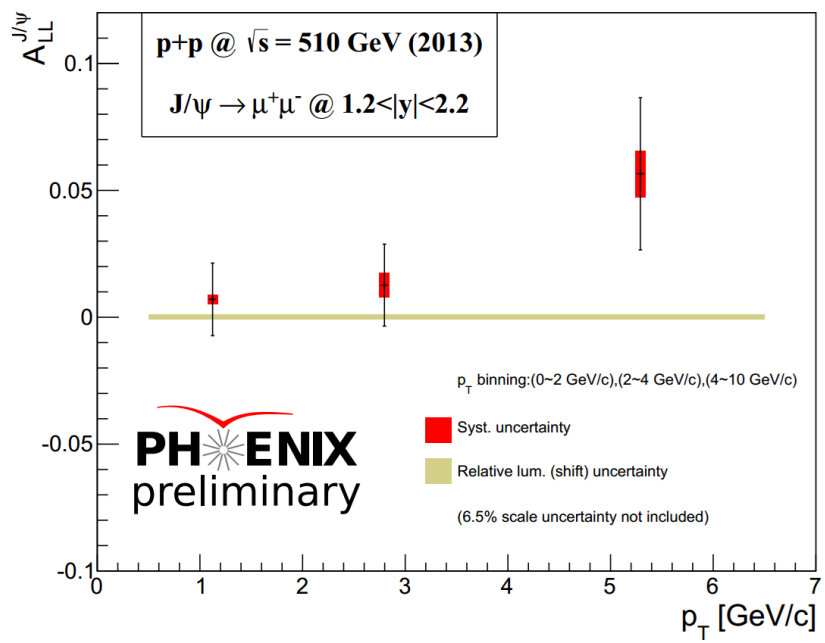
J/ψ A_{LL} @ forward rapidity

recent results

$$pp \to J/\psi + \mathrm{X} \to \mu^+ + \mu^- + X$$
$$@\ \sqrt{s} = 200GeV$$

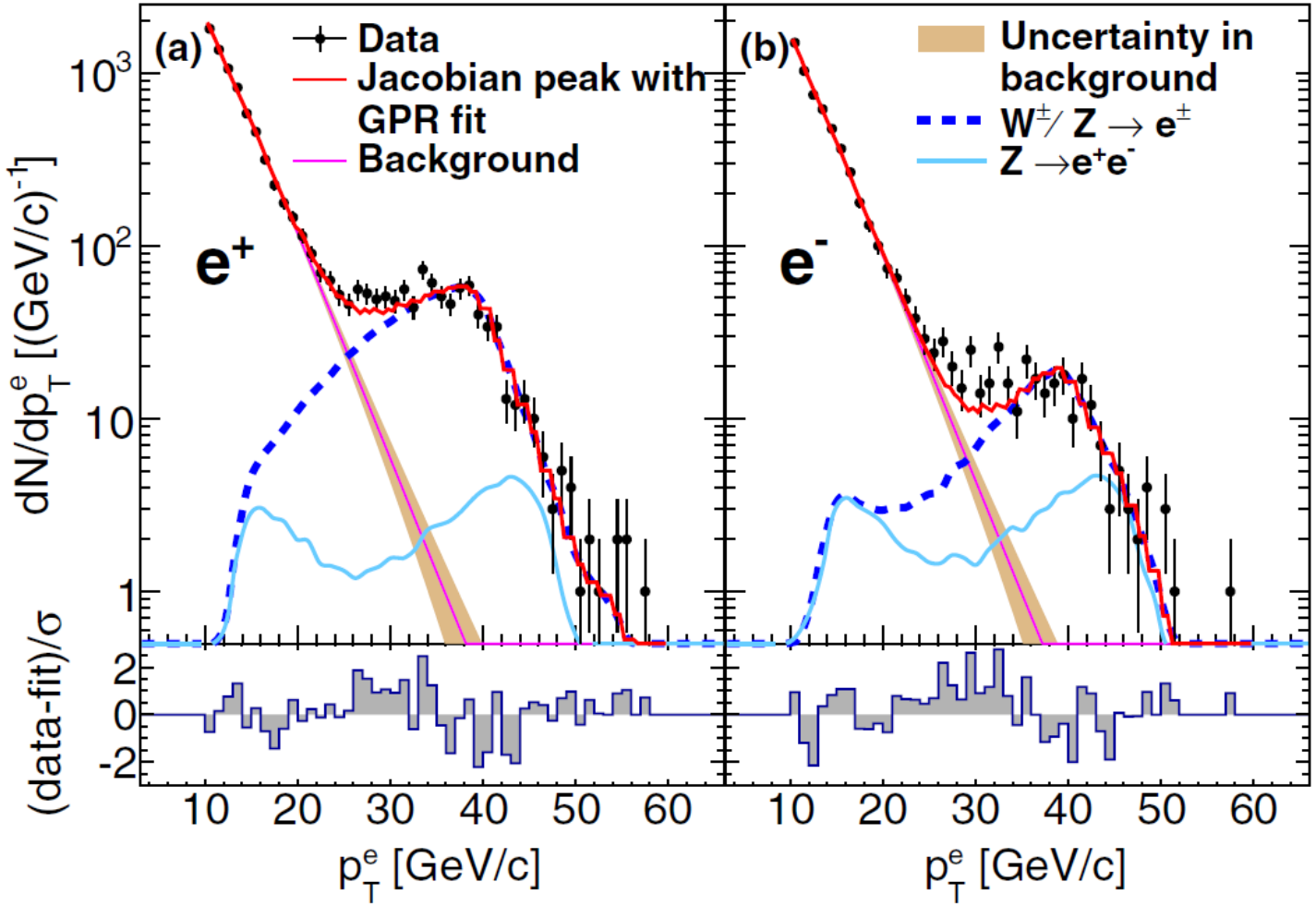


$$pp \to J/\psi + \mathrm{X} \to \mu^+ + \mu^- + X$$
$$@\ \sqrt{s} = 510GeV$$

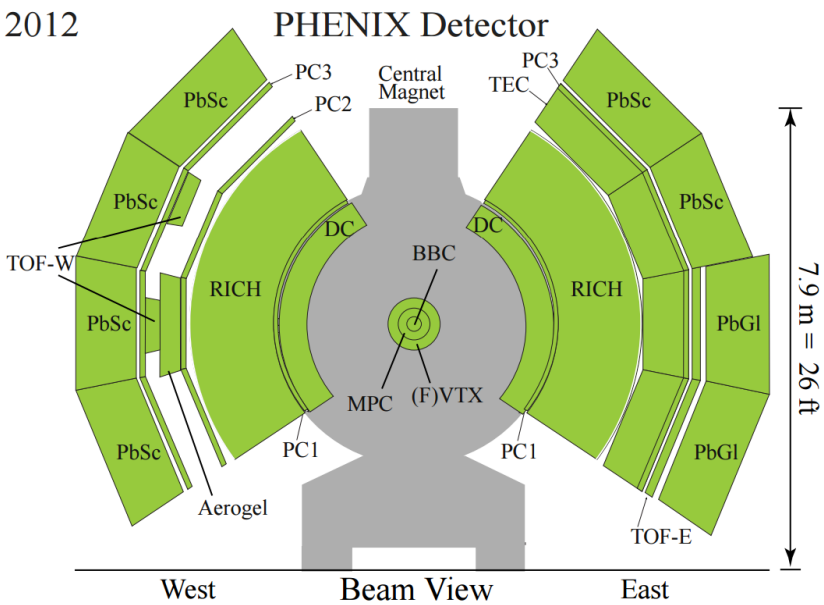


Run 13 $W\pm$ Spectra

PRD 93, 051103(R)(2016)



Mid-rapidity $W^{\pm} \rightarrow e^{\pm}$ Analysis



<u>Strategy</u>

Looking for high energy $e\pm$

- Online trigger based on EMC 4x4 tower sum
  - fully efficient at pT>10 GeV
- High energy EMC clusters matched to DC tracks
  - ($\Delta\phi$ < 0.02 rad)

<u>Basic Cuts:</u>

- Vertex cut: |z| < 30 cm
- Removal of tracks with DC |α|<1 mrad
  - α – bending angle ∝ p_T
- Time of Flight cut
  - reduces cosmic background

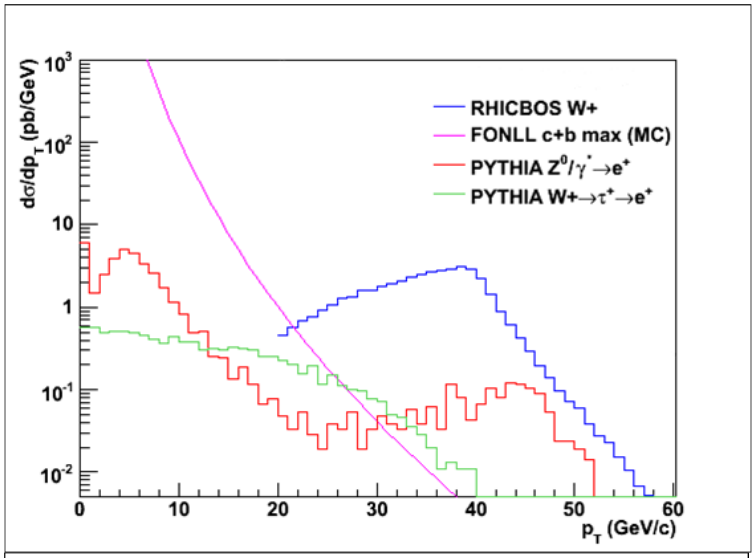
Background Processes

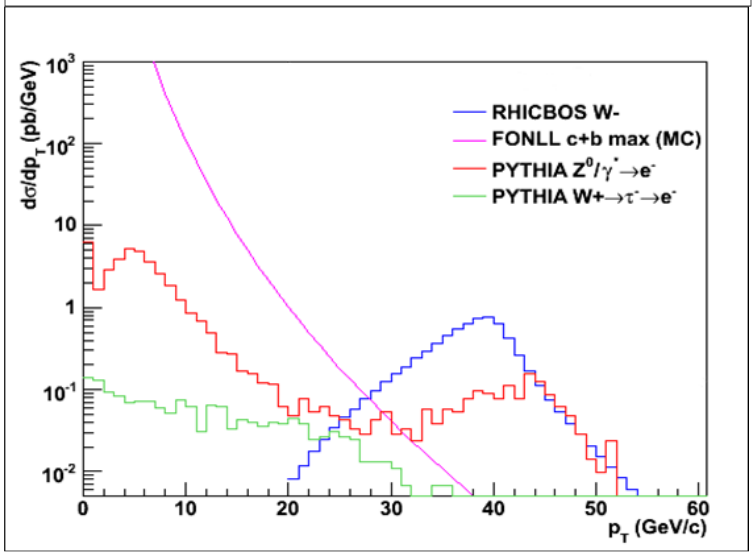
Irreducible background:-

- $Z \rightarrow e^{+} + e^{-}$ (part of signal)
- Heavy quark decay: $c, b \rightarrow e^{\pm} + X$
- $W \rightarrow \tau + \nu_{\tau} \rightarrow e\, \nu_{e}\, \nu_{\tau}\, \overline{\nu_{\tau}}$

Reducible background:-

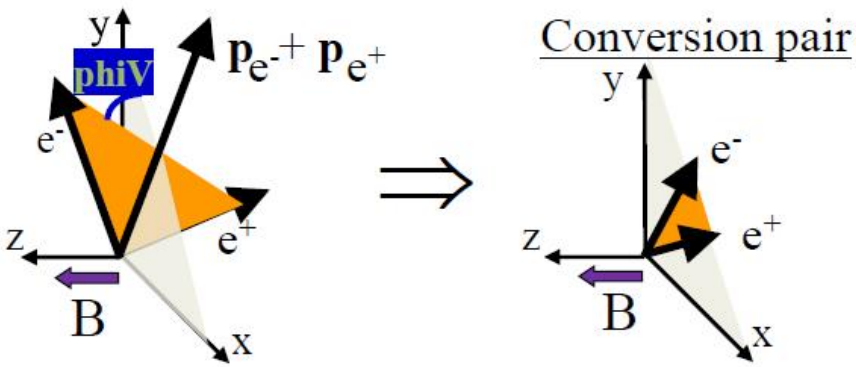
- Charged hadrons
- $\pi^{0} \rightarrow \gamma \rightarrow e^{+}e^{-}$ before DC
  - VTX increases photon conversions (thickness ~14% X_0)
- Cosmic background
- Accidental track match



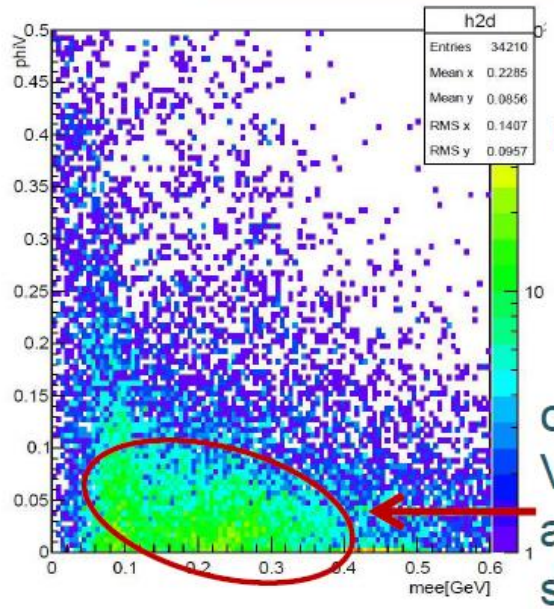


Photon Conversions from VTX

phiV is the angle plane of pair makes with plane normal to beam direction



VTX conversions

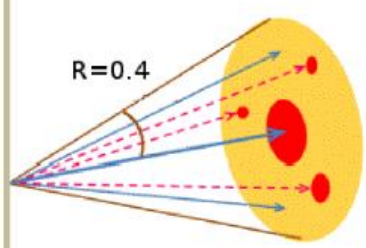


π^0 simulations

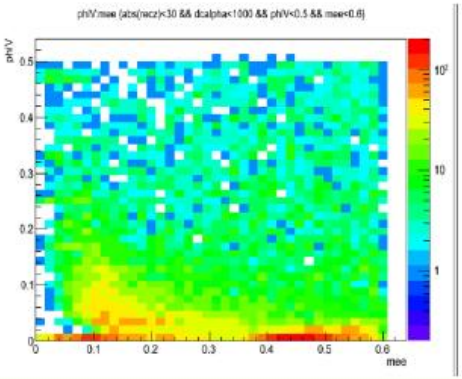
conversions in VTX barrels and electronic support

Isolation cut

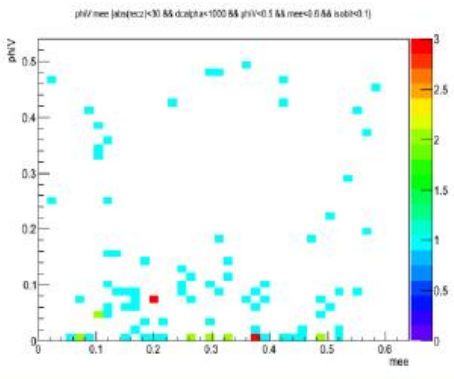
rel. isolation cut = $\frac{(E_{tot} - E_{candidate}) + p_{DC}}{E_{candidate}}$ in a cone of R=0.4 < **10%**



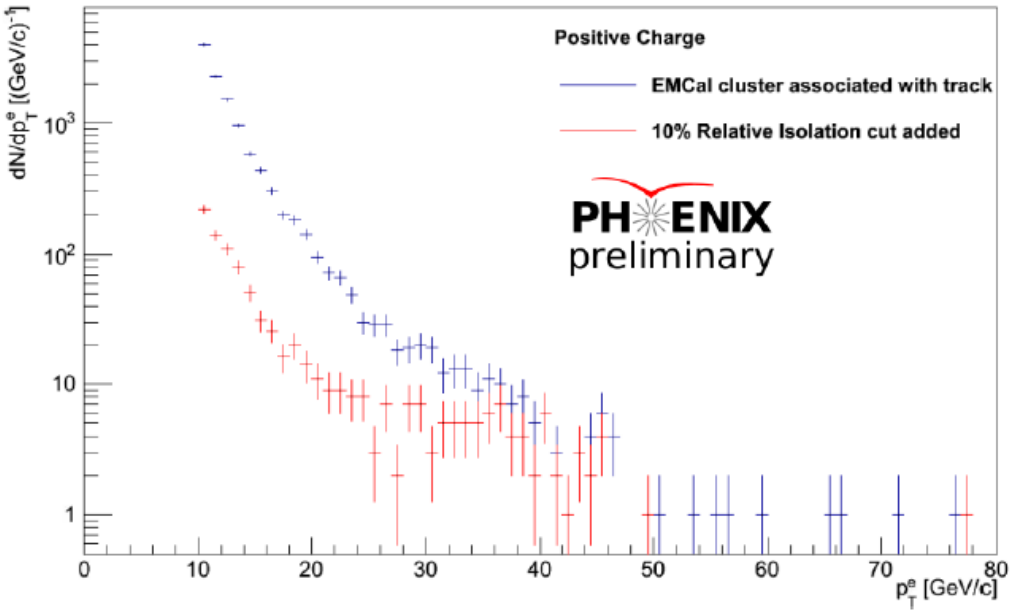
Before isolation cut

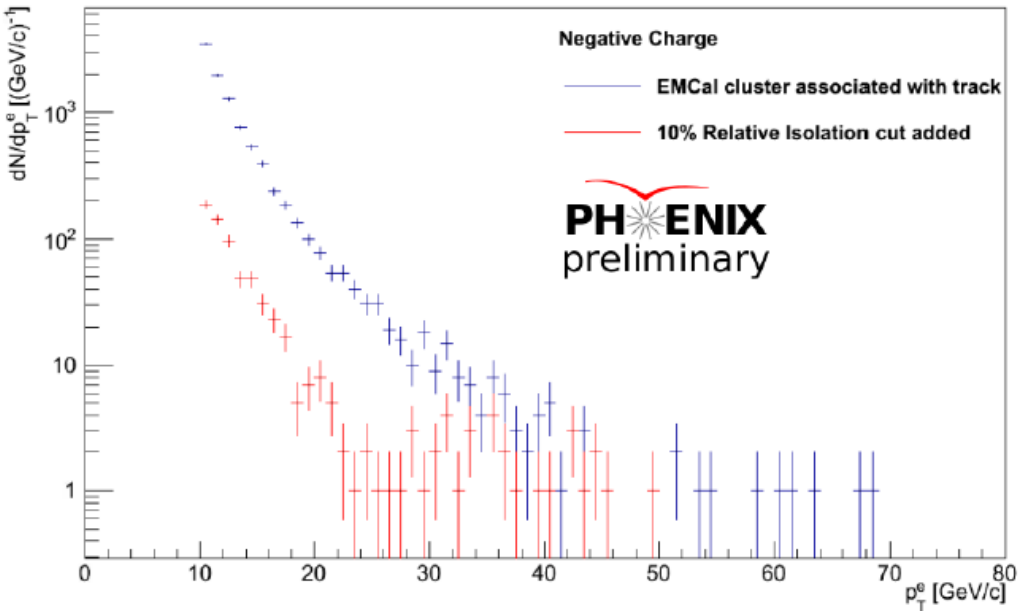


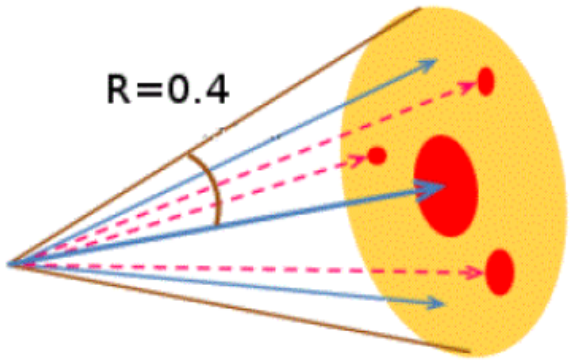
After isolation cut



Isolation Cut

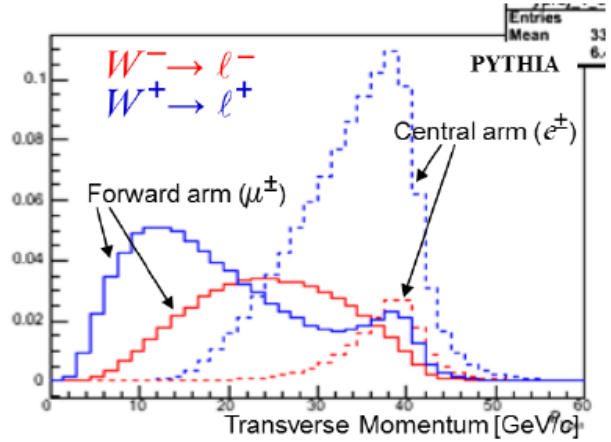




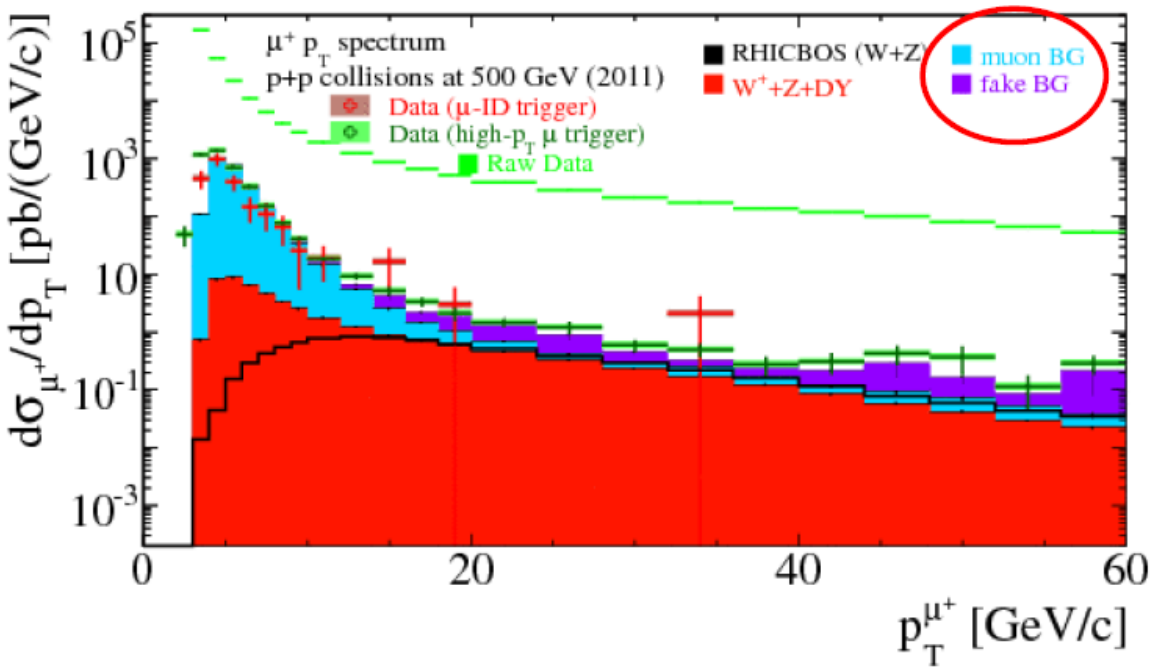


The relative isolation cut removes more than a factor of 10 in the background dominated region (10-20 GeV) while leaving the signal region (30-50 GeV) relatively untouched

Background Processes



No jacobean peak to distinguish signal from background

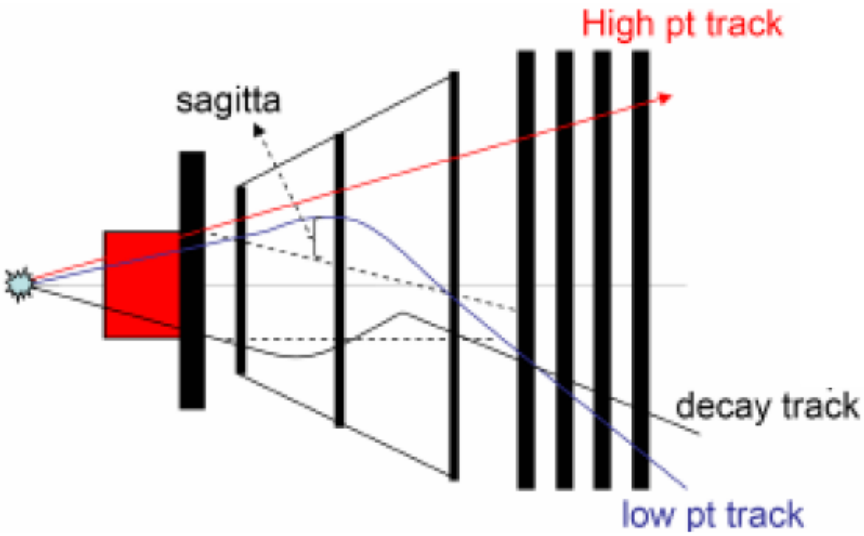


- **Hadronic BG:**

Low energetic hadrons decay within MuTr, misreconstructed as high pT track =>"fake muons"

- **Muon BG:**

From heavy flavor, quarkonia, Drell-Yan; get smeared to high pT



Multivariate cut for pre-selection

Multivariate cut for pre-selection:

- Determine likelihood "λ" of an event to be signal or background

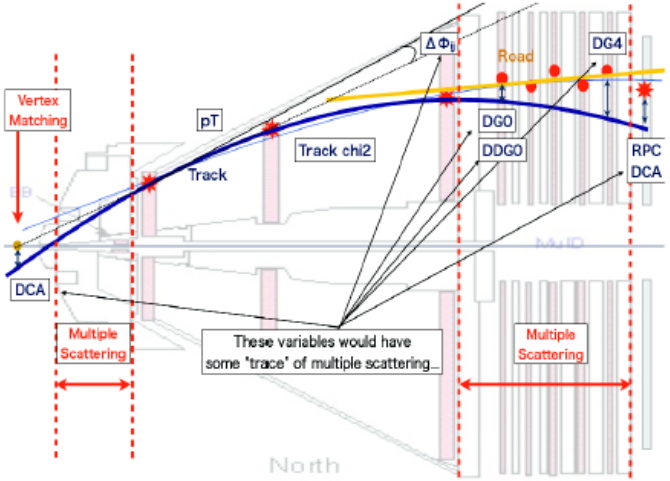
$$\lambda = p(DG0, DDG0)p(chi2)p(DCA_r)p(Rpc1/3dca)p(dr_{fvtx} * d\theta_{fvtx})p(d\phi_{fvtx})$$

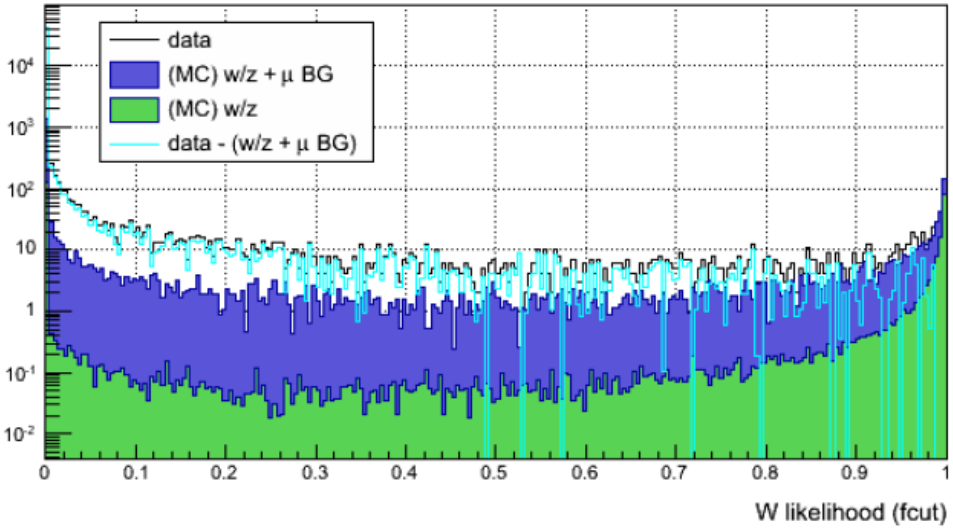
- Calculate "Wness" defined as

$$Wness = \frac{\lambda_{sig}}{\lambda_{sig}+\lambda_{bkg}}$$

λ_{sig} - from Pythia+PISA MC simulation
λ_{bkg} - from data

- Events with Wness > 0.92 are selected





Background fraction extraction - dw23

Unbinned maximum likelihood fit

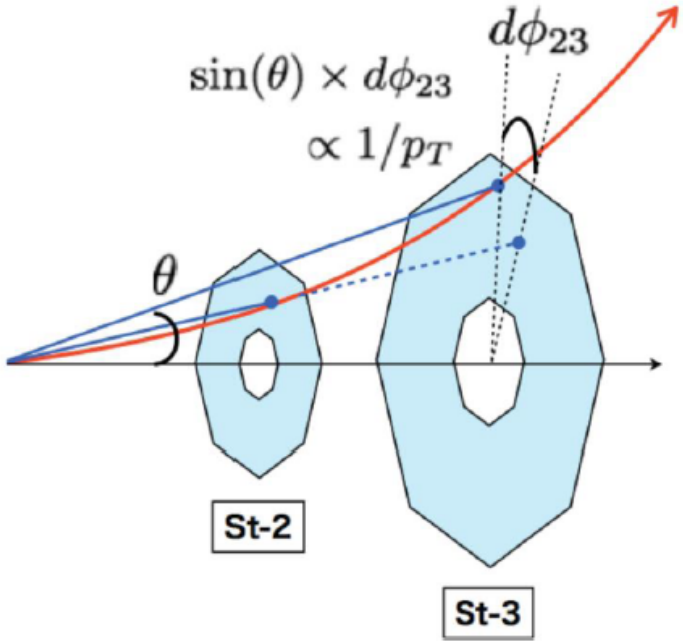
- Signal and background fractions calculated minimizing likelihood function

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

$p_c(x_i)$ – probability distribution functions from simulation (W signal, muon BGs) and data (hadron BGs) using η, dw23

$$x_i = (\eta_i, \mathrm{dw}_{23i}) \qquad \theta = (n_{sig}, n_\mu, n_{had})$$

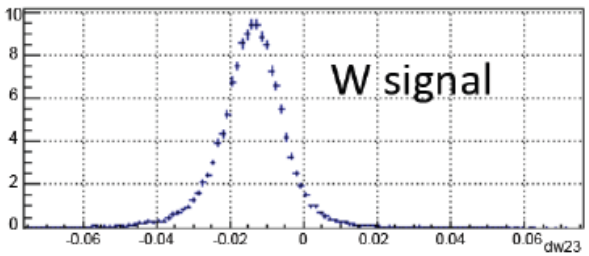
- Hadronic BG dominates at low Wness
  - extrapolate dw23 to Wness > 0.92

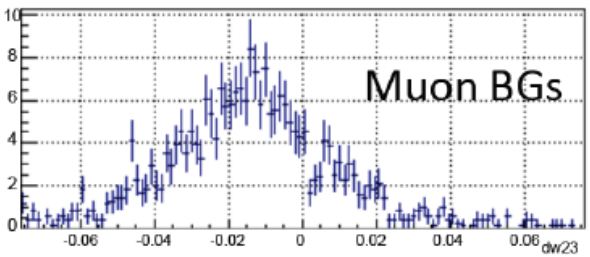


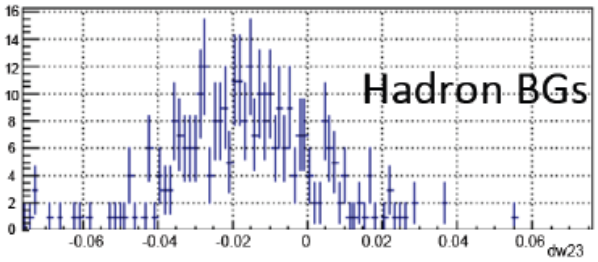
$$\mathrm{dw23} \equiv p_T \times \sin(\theta) \times d\phi_{23}$$

(reduced azimuthal bending)

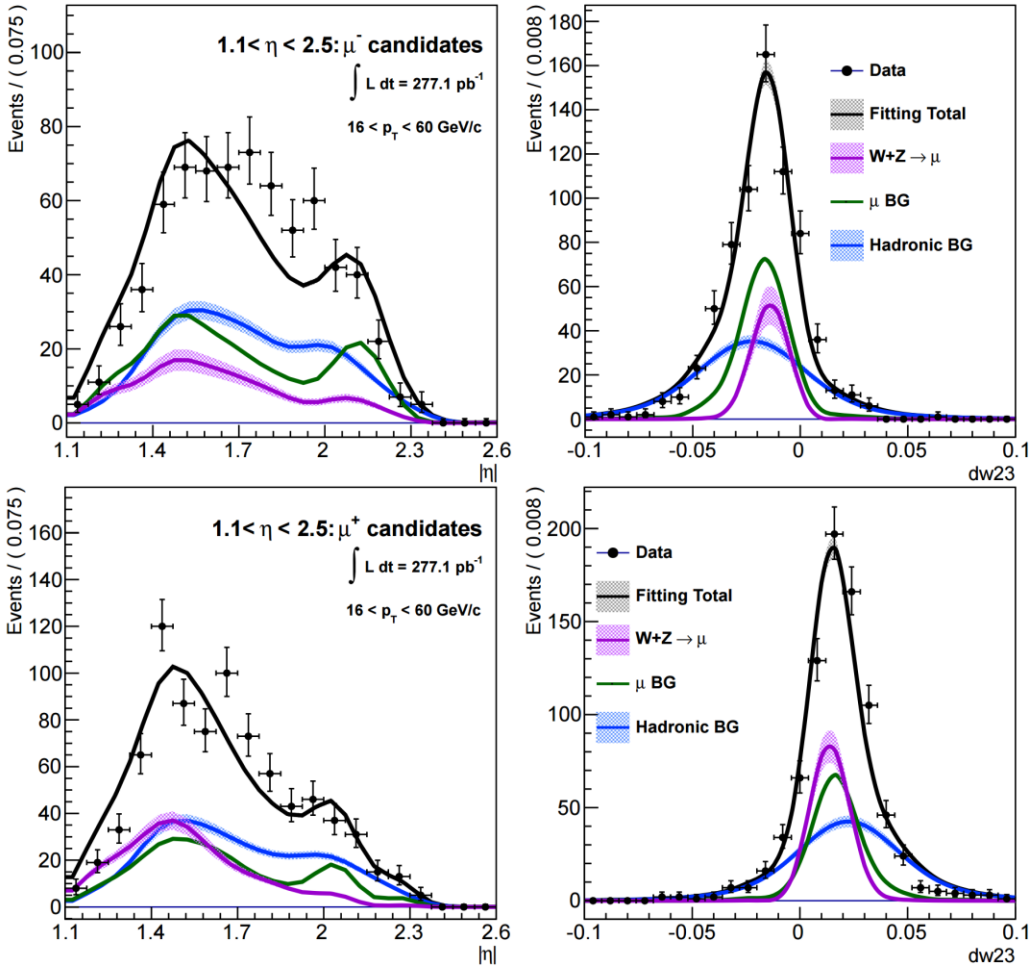
dw23 distributions (16 < p_T < 60 GeV/c, f > 0.02)







Background fraction extraction - Fitting results

- 16 < p_T < 60 GeV/c, f_sig > 0.92
- Use η and dw23 fits to count and calculate S/B
- S/B ratio used as a dilution factor to calculate the corrected asymmetry.

1D projections of 2D unbinned maximum likelihood fit