

Recent Spin Physics Highlights

(Fresh Powder Faceshots from the Spin Piste)



- **Gluon polarization**
- **Sea quark polarization**
- **Transversity**

W.W. Jacobs, for the STAR Collaboration



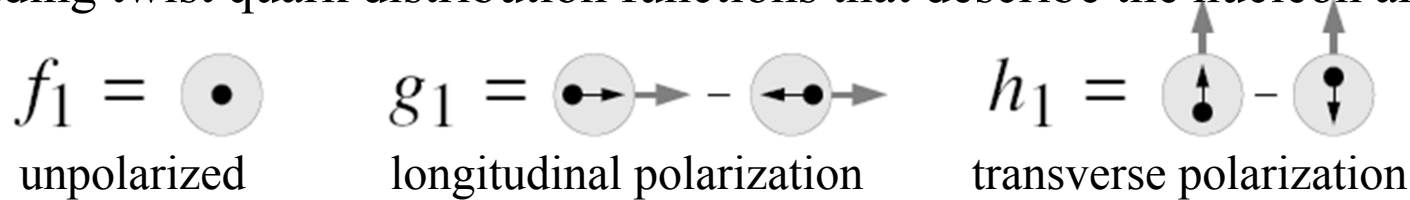
INDIANA UNIVERSITY



LLWI, Chateau Lake Louise, 17-23 February, 2013, Alberta, CA

Probing our Understanding of Nucleon Substructure w/ Spin

The leading twist quark distribution functions that describe the nucleon are:



and historically much of our information comes from DIS (and more recently SIDIS). **Polarized proton hard partonic scattering data at the RHIC collider now impact!**

Longitudinal Spin:

DIS ~ 0.3 poorly constrained

$$\text{Proton spin } \langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$

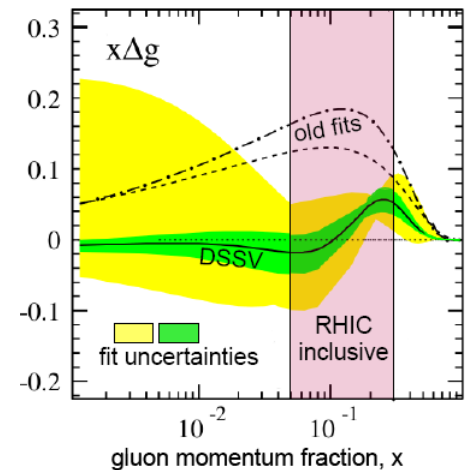
measure at RHIC!

- DIS data consistent with quark helicity contribution only $\sim 30\%$, and limited gluon spin constraint \Rightarrow **“spin crisis”!**
- RHIC polarized proton data is directly sensitive to gluons & provides improved/direct flavor-spin separation vs. SIDIS.

Transverse Spin:

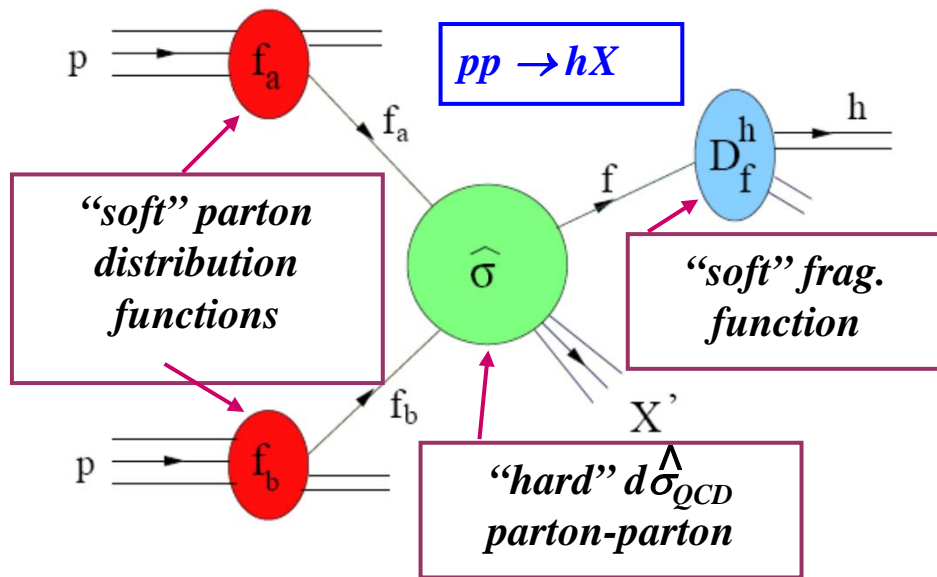
- Data sparse: h_1 can be extracted from pp di-hadron data to high x ... connects to the tensor charge (calculable on the lattice). measure at RHIC!
- Transverse momentum distr. effects in pp relate to orbital angular momentum.

w/ 2006 RHIC results

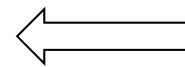


Longitudinally Polarized pp Collisions at RHIC

Hard collisions provide pQCD probes of spin-dependent partonic structure!

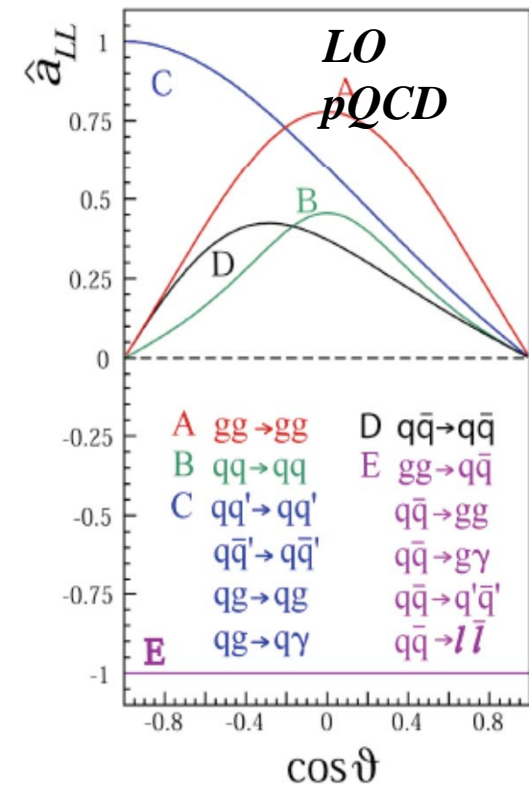
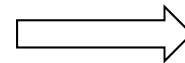


Assumes factorization works



+

large spin correlations at partonic level



Longitudinal double Spin Asymmetry:

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

Δf : polarized parton distribution functions

Use (high x) polarized quarks as a probe (e.g., of gluon polarization!)

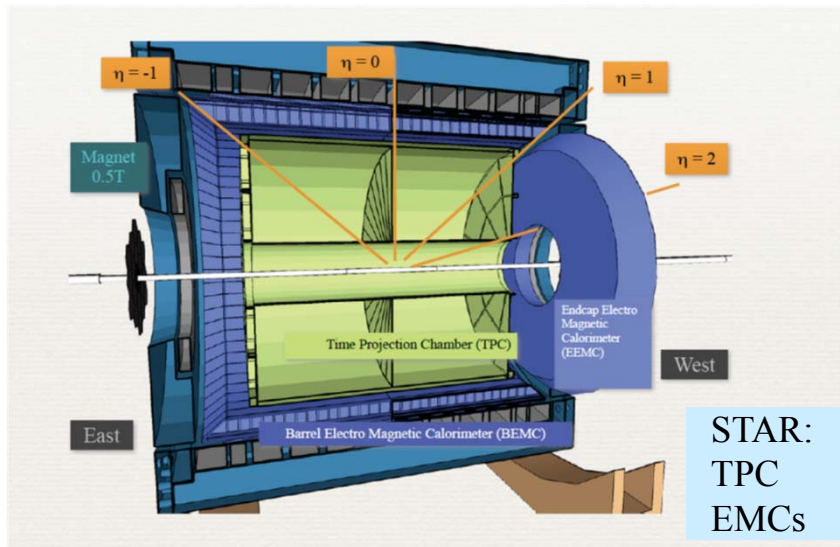


STAR Detector, Jet Reconstruction and Gluons

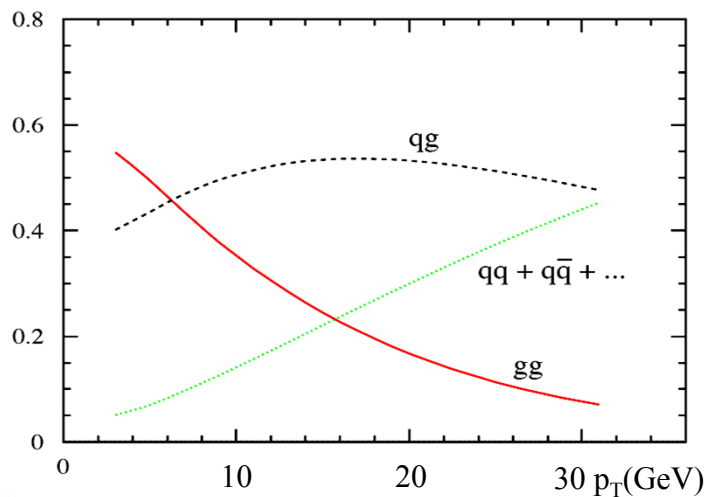
Midpoint cone algorithm (hep-ex/0005012)

- Seed energy $E_T^{\text{seed}} = 0.5 \text{ GeV}$
- Cone radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$
- Split/merge fraction $f = 0.5$

PYTHIA + GEANT to quantify det. response



RHIC kinematics: **gg** and **qg** dominate, jets/hadrons A_{LL} sensitive to **gluon polarization**.

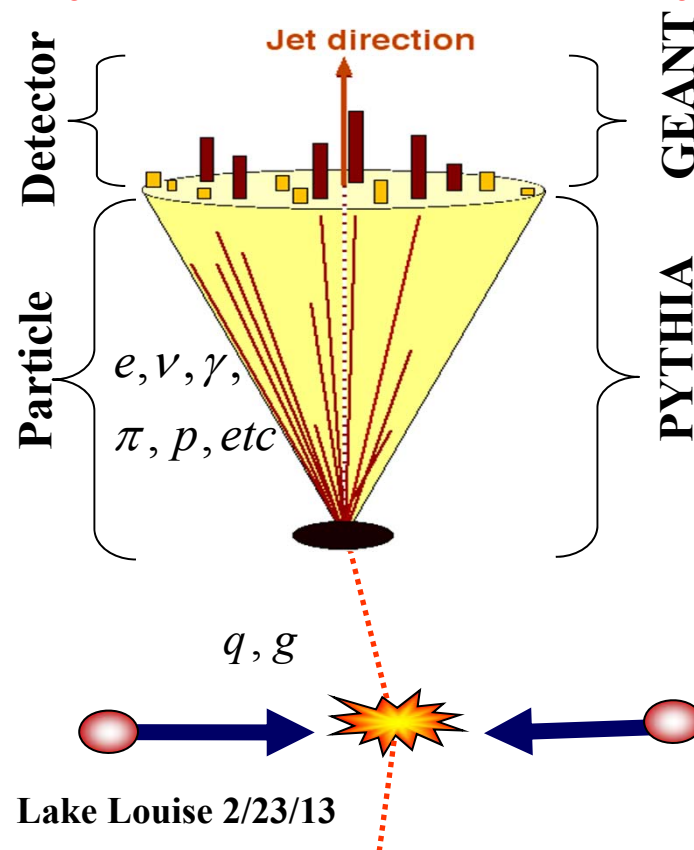


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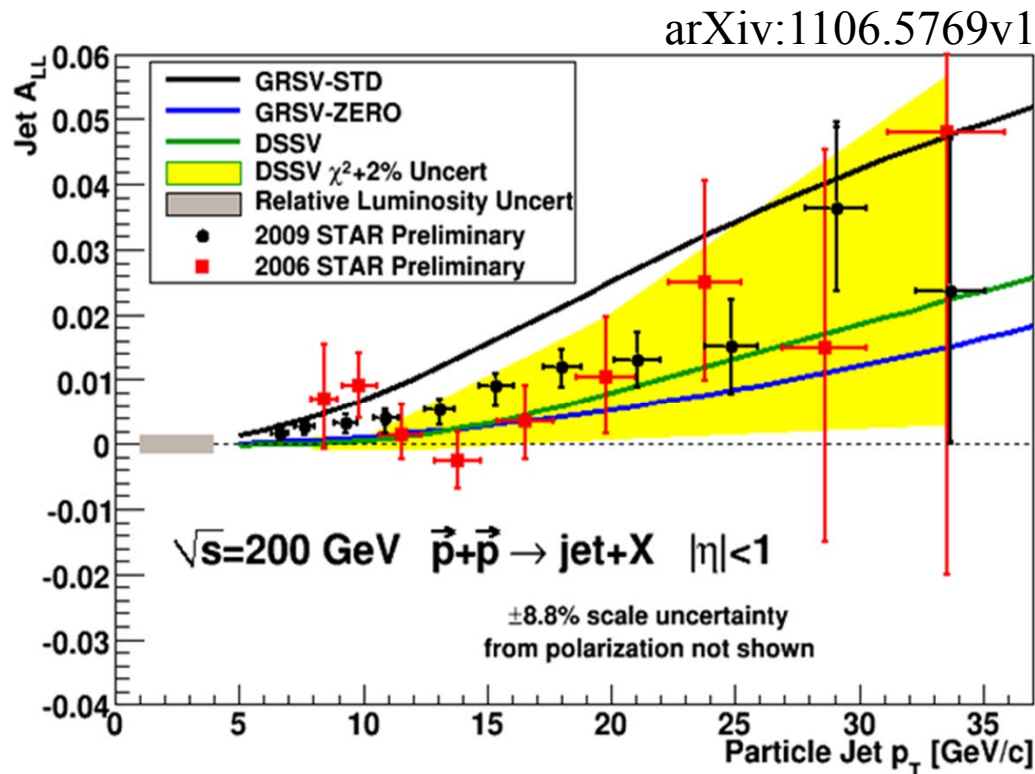
Data jets

MC jets



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2009 STAR Inclusive Jet Results



2009 data are in **black**; 2006 data are in **red**.

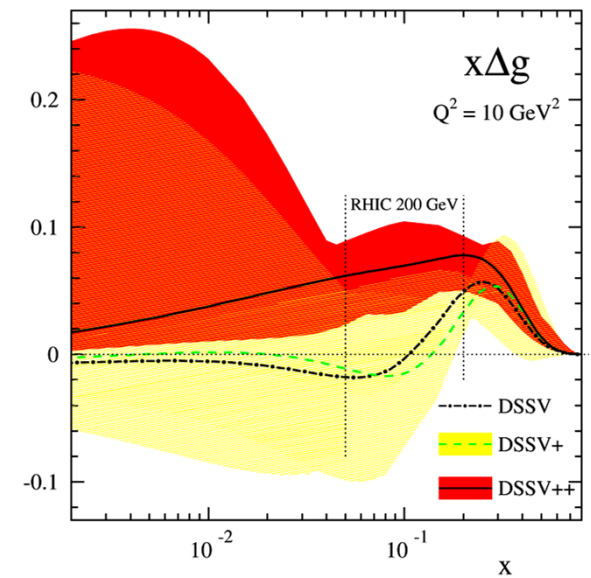
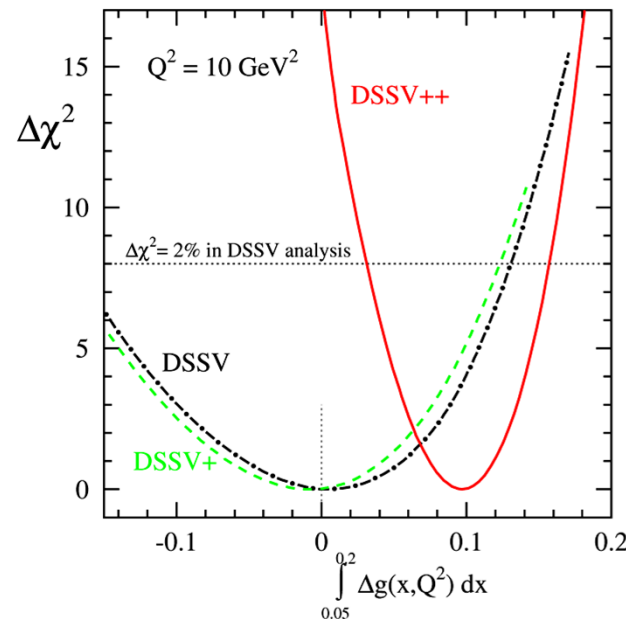
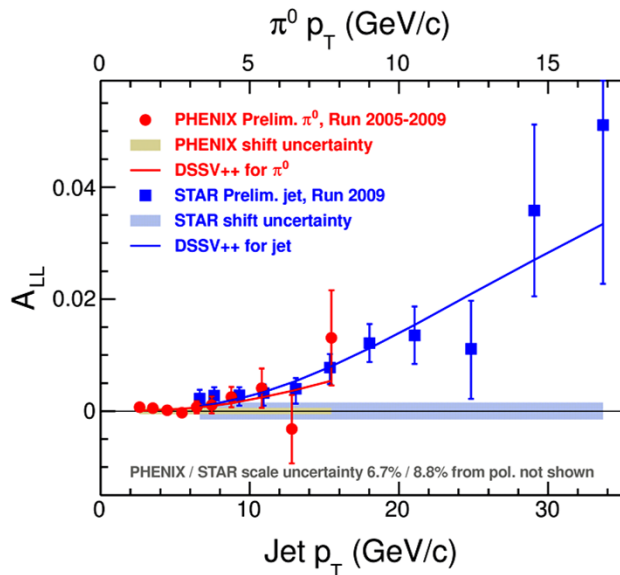
DSSV global fit (green) curve includes the 2006 RHIC data

Note: the yellow band is the $\chi^2+2\%$ DSSV uncertainty

- Exploited in 2009 greatly improved RHIC performance in luminosity, polarization; lowered EMC trigger thresholds + focused on high- p_T region [2009 data are factor of 3 (high- p_T) to > 4 (low- p_T) more precise than 2006].
- 2009 results fall between predictions from DSSV and GRSV-STD indicating gluon contribute in the sensitive kinematic region!**



New global analysis with 2009 RHIC data



- Curve “**DSSV++**” is a new, preliminary global analysis from the DSSV group that includes 2009 A_{LL} measurements from PHENIX π^0 and STAR inclusive jets.
- First evidence of **non-zero gluon polarization** in the RHIC range ($0.05 < x < 0.2$); integral (w/ big error bars) comparable to the quark contribution to the proton spin.
- The **next efforts**: di-jet (and γ -jet) coincidence measurements sensitive to “shape” of $x\Delta g(x)$; e.g., significant **di-jet results** expected from ongoing 2009 analyses and of data at 500 GeV for sampling the lower x region ... more data in bank & to come.

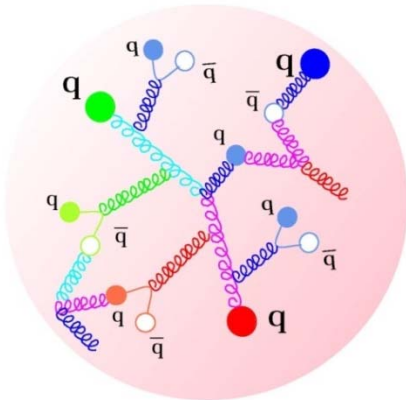


Sea Quarks

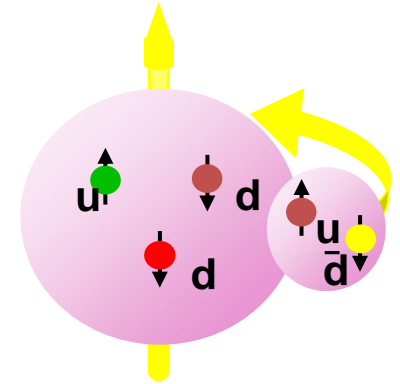
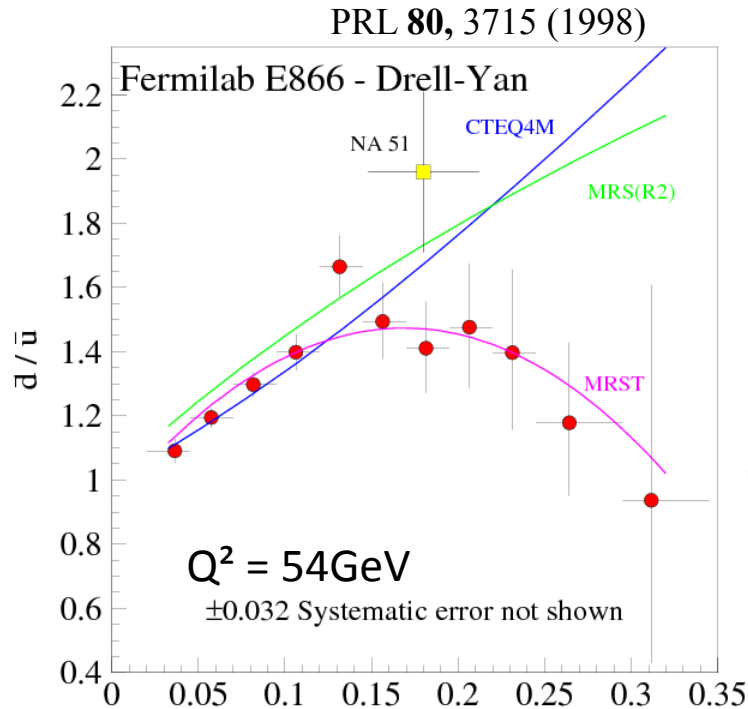


Origin and Symmetry of the Quark Sea

Unpolarized Distributions:



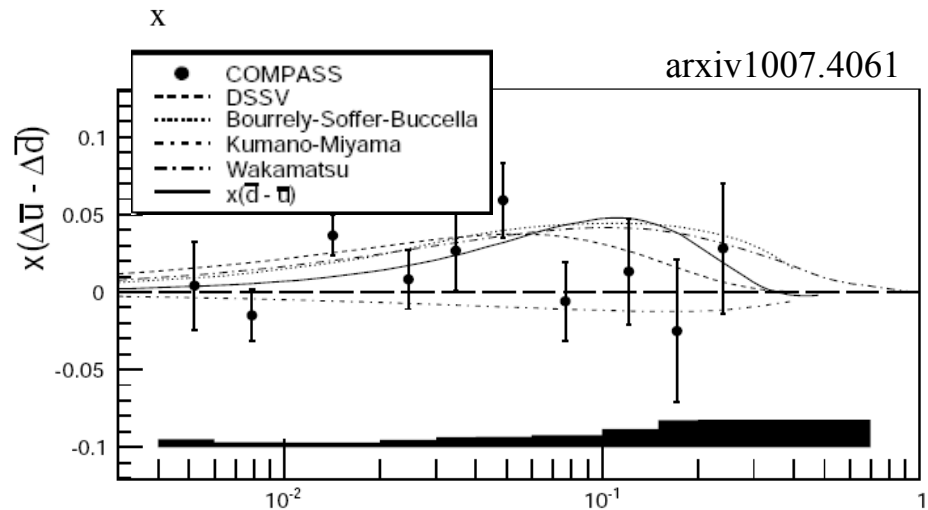
- Perturbative: equal numbers of light anti-quarks.



- E866 data qualitatively consistent w/ pion cloud, instanton and chiral quark models.

Polarized Flavor Asymmetry:

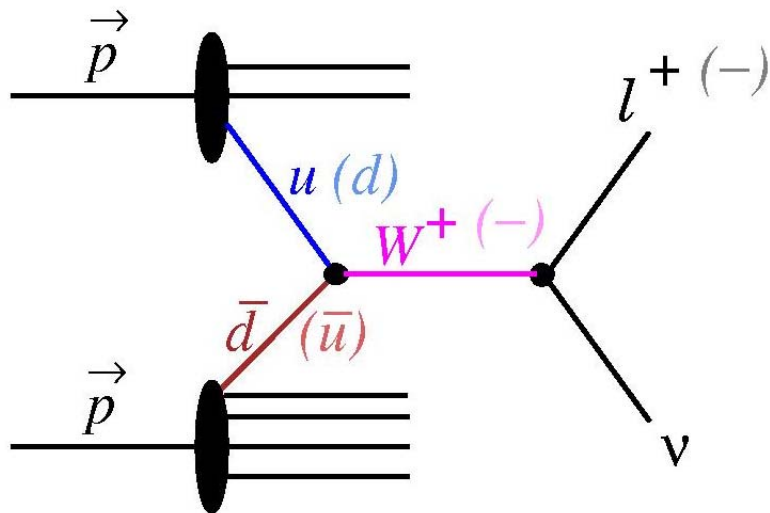
- DSSV global fit suggested a positive difference to a $x(\Delta\bar{u} - \Delta\bar{d})$ sensitivity (arXiv:0904.382).
- Recent semi-inclusive COMPASS data hint at such behavior.



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W Boson Production; Sea Quark Spin Selectivity



$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu$$

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

- Detect W's through **e⁺/e⁻** decay channels.
 - Typically find $x_q > x_{\bar{q}} \rightarrow$ **W highly boosted.**
 - V-A coupling \rightarrow **perfect spin separation.**
 - LH W's = LH quarks + RH anti-quarks.
 - ν helicity gives **preferred direction in decay.**
- W^- preserves initial state kinematics; decay electron emitted along W^- trajectory (and conversely for W^+ where decay positron is anti-parallel to trajectory).

Measure parity-violating single-spin asymmetry:

(Helicity flip in one beam while averaging over the other)

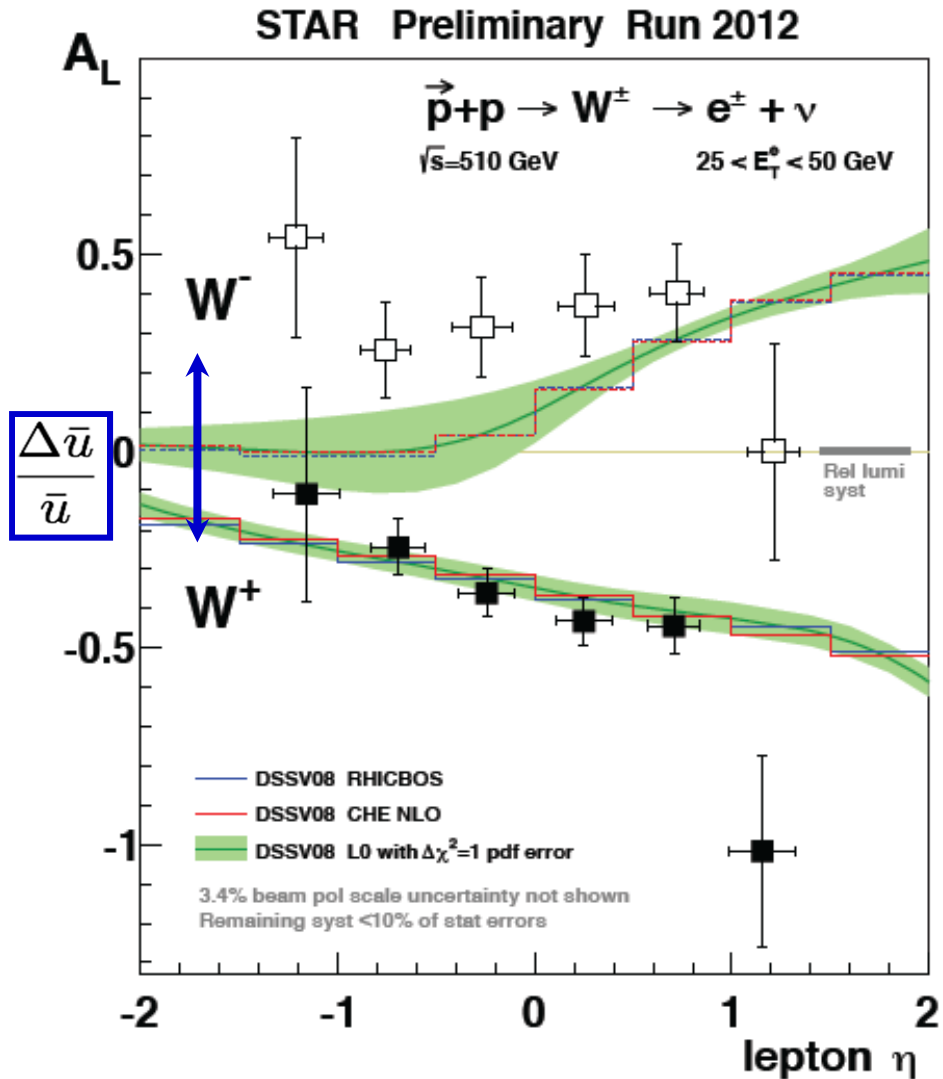
$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

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

Re; quark sum: $\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s} + \dots) dx$



Run 12 (2012) $W^{+/-}$ Results from STAR



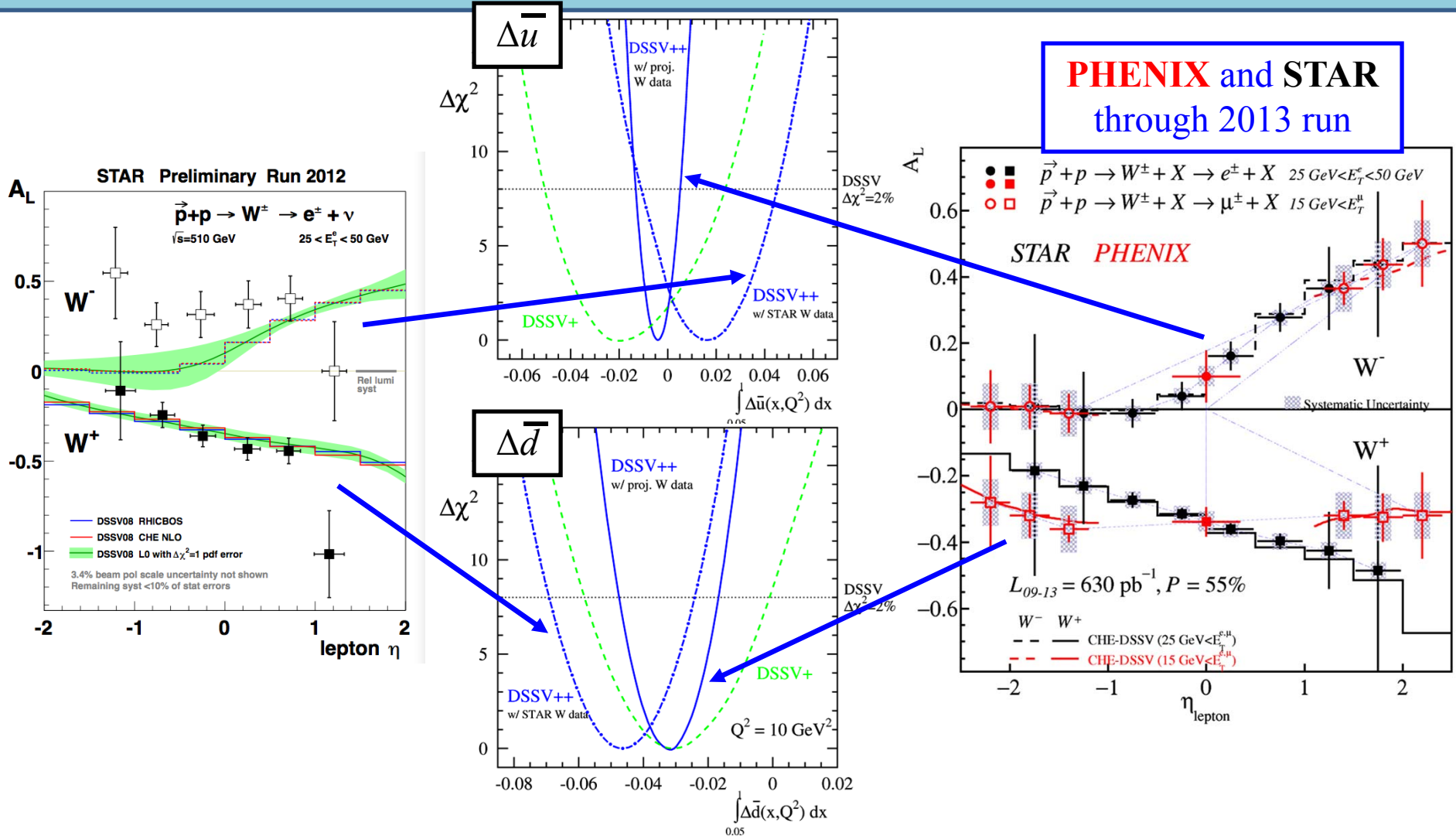
- $A_L(W^-)$ is systematically larger than the DSSV predictions
- The enhancement at $\eta_e < 0$, in particular, is sensitive to the $\Delta\bar{u}$ polarized antiquark distribution

- $A_L(W^+)$ is consistent with theoretical predictions using the DSSV polarized PDFs

- The systematic uncertainties for A_L are well under control for $|\eta_e| < 1.4$



Global Analysis: Run 12 and Future Data



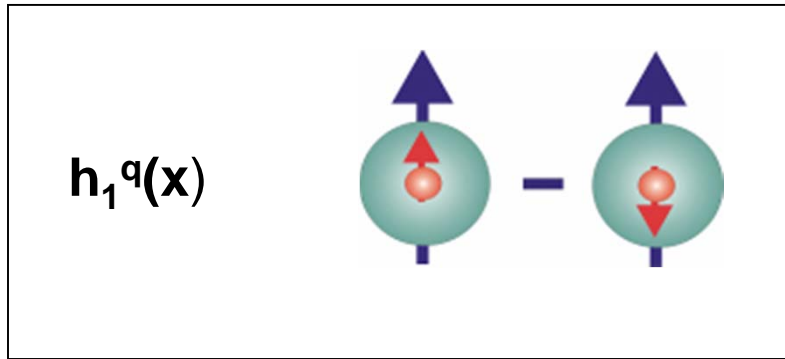
- First preliminary results from 2012 already provide substantial sensitivity.
- Future results will provide a **dramatic reduction in the uncertainties.**



Transversity



Transverse Spin

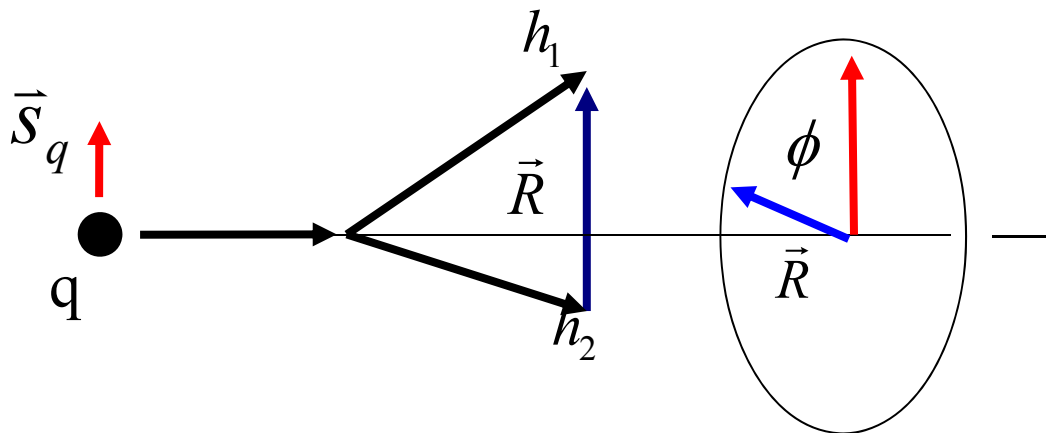


Transversity PDF

quark with spin parallel to the nucleon spin in a transversely polarized nucleon.

Chiral odd, poorly known ... cannot be measured inclusively. Needs a chiral odd partner \rightarrow Fragmentation Function (Collins function, IFF, etc.)

Interference Fragmentation Function (IFF):



Fragmentation of a transversely polarized quark q into two spinless hadron h_1, h_2 carries an azimuthal dependence (e.g., cons. of angular momentum).

$$\propto (\vec{k} \times \vec{R}_T) \cdot \vec{s}_q$$

$$\propto \sin \phi$$

The azimuthal hadron dependence can be used as a transversity signal.

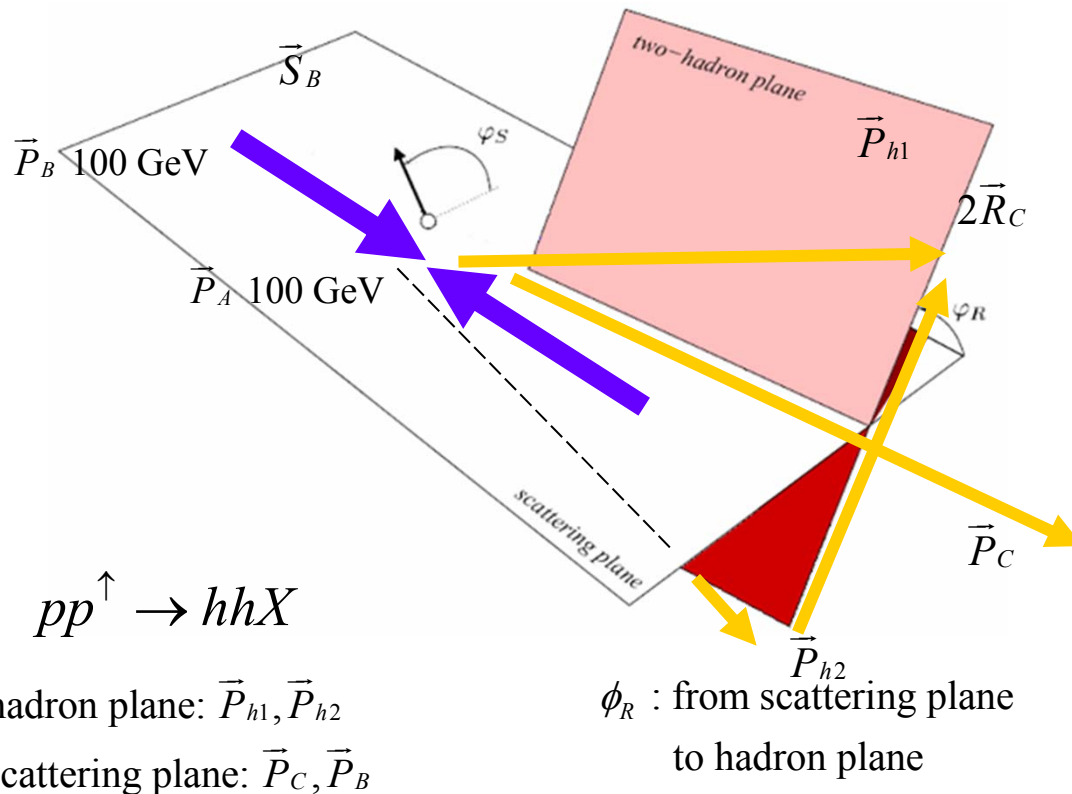


Using Hadron Pairs + IFF in pp Collisions

Measure the hadron pair asymmetry with transversely polarized protons:

$$\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} (\phi_S - \phi_R) = A_{UT} \sin(\phi_S - \phi_R), \text{ where } A_{UT} \propto h_1 \otimes H_1^{\leftarrow}$$

IFF
Transversity



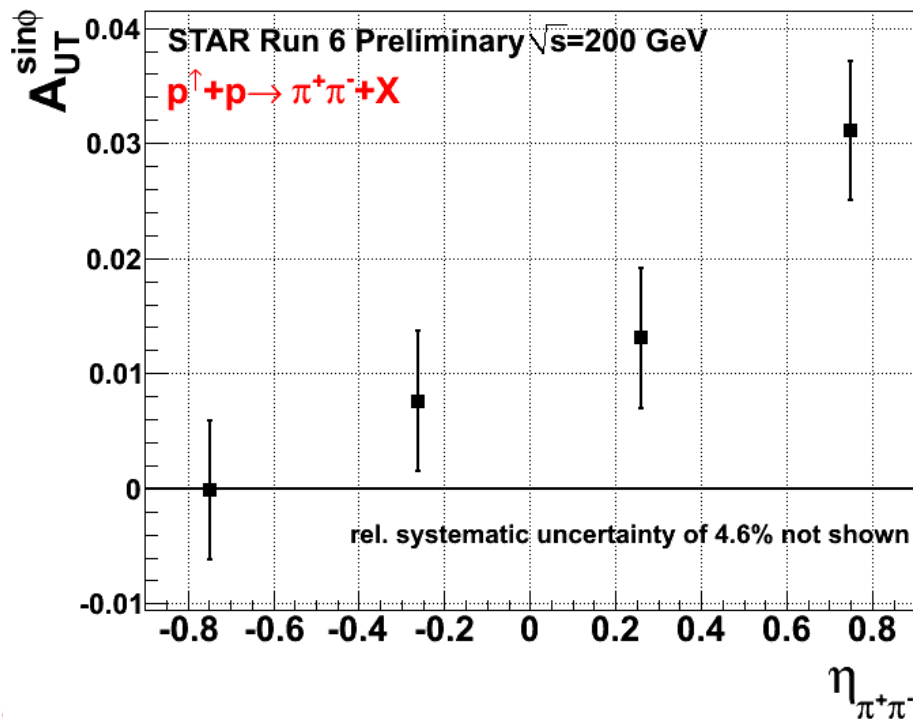
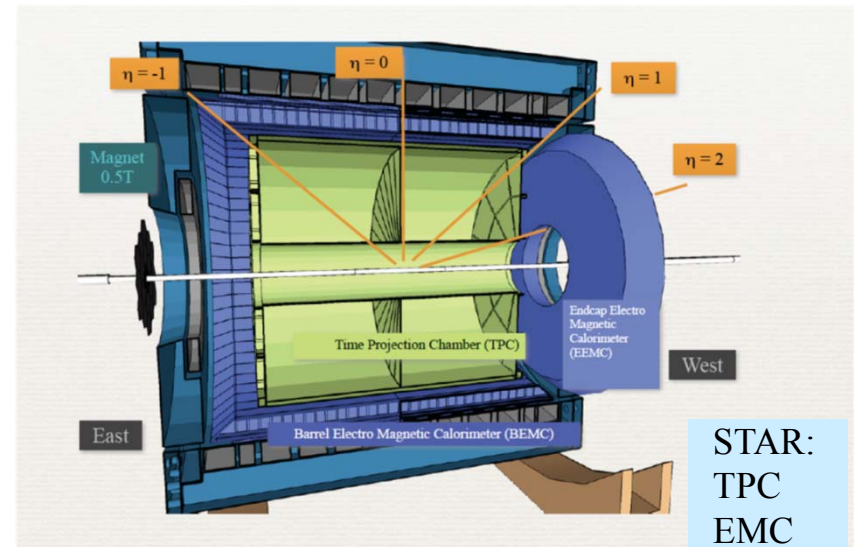
p+p c.m.s. = lab frame
 \vec{P}_A, \vec{P}_B : momenta of protons
 $\vec{P}_{h1}, \vec{P}_{h2}$: momenta of hadrons
 $\vec{P}_C = \vec{P}_{h1} + \vec{P}_{h2}$
 $\vec{R}_C = (\vec{P}_{h1} - \vec{P}_{h2}) / 2$
 \vec{S}_B : proton spin orientation



New STAR Data Shows Transversity Signal

First significant signal of transversity in polarized proton collisions

- Use Charged track pairs in STAR TPC
- PID for charged pions with dE/dx
- Bin yield asymmetries in ϕ_{RS} and fit with $\sin(\phi_{RS})$ amplitude/polarization

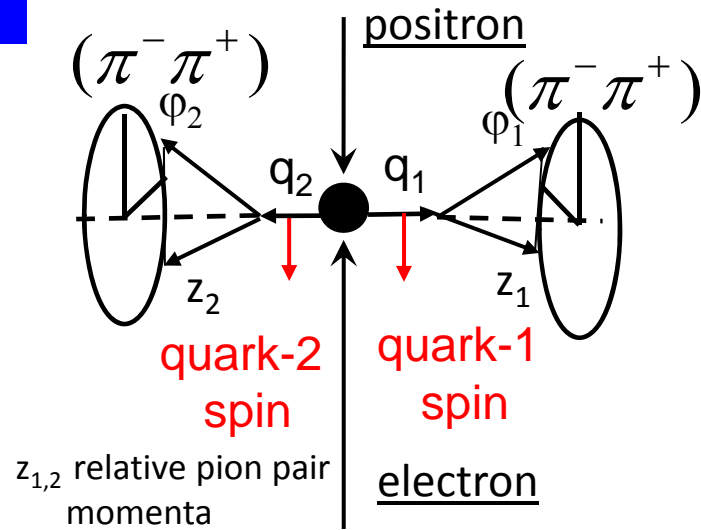


- Strong Rapidity Dependence
- STAR upgrades will cover $\eta < 2$ in the near future
- $\langle x_{Bj} \rangle 0.25$ (current) $\rightarrow 0.45$: **not** probed in SIDIS yet!
- Proposed STAR Forward upgrade: $\eta < 4$

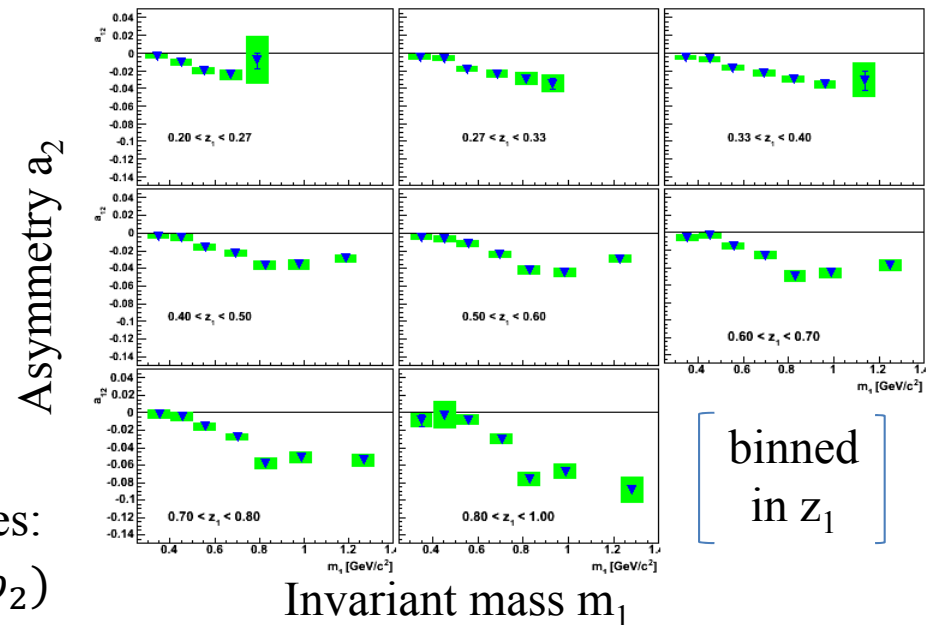
IFF from Belle and Transversity Extraction



Interference Fragmentation Functions measured at Belle detector at $e^+ e^-$ collider

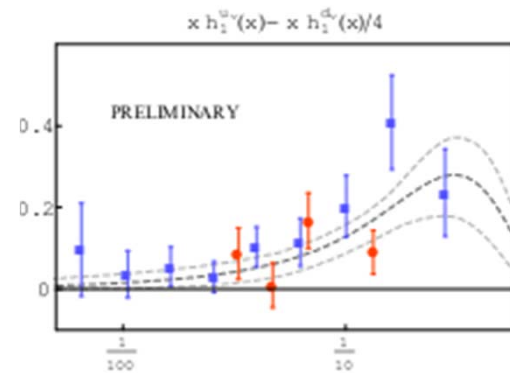


Anselm Vossen et. al, PRL 107, 072004(2011)



Signal requires correlation in two hemispheres:
 $Asym \propto H^<(z_1, m_1)\bar{H}^<(z_2, m_2) \cos(\varphi_1 + \varphi_2)$

Using COMPAS and HERMES data with Belle IFF: initial point-by-point transversity extraction. [M. Radici at FF workshop, RIKEN, 11/2012]



STAR pp data soon to come; and push to higher x



Summary and Conclusions

- Exciting new Spin Physics results from STAR/RHIC
- First strong evidence that gluons contribute to the proton spin ... STAR+PHENIX data in global fit results in ~ 0.1 contribution for the accessible region.
- Spin-flavor separated sea quark polarization w/ W boson production; with an updated (DSSV++) global analysis, suggests a larger \bar{u} polarization compared to initial predictions.
- Transverse spin pp shows first strong di-hadron signal at mid-rapidity; coupled with fragmentation functions from Belle, will lead to an extraction of transversity.

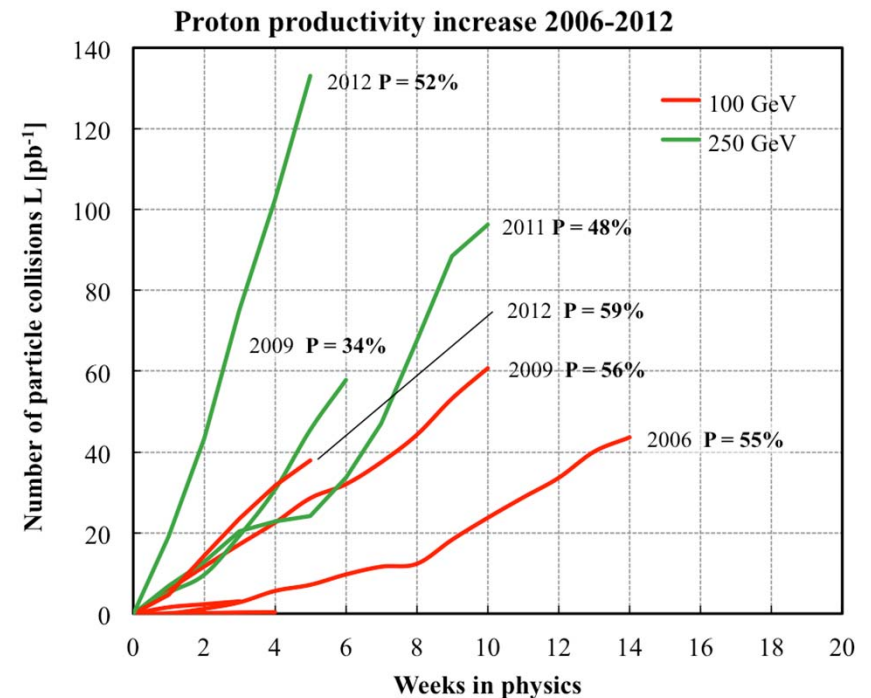
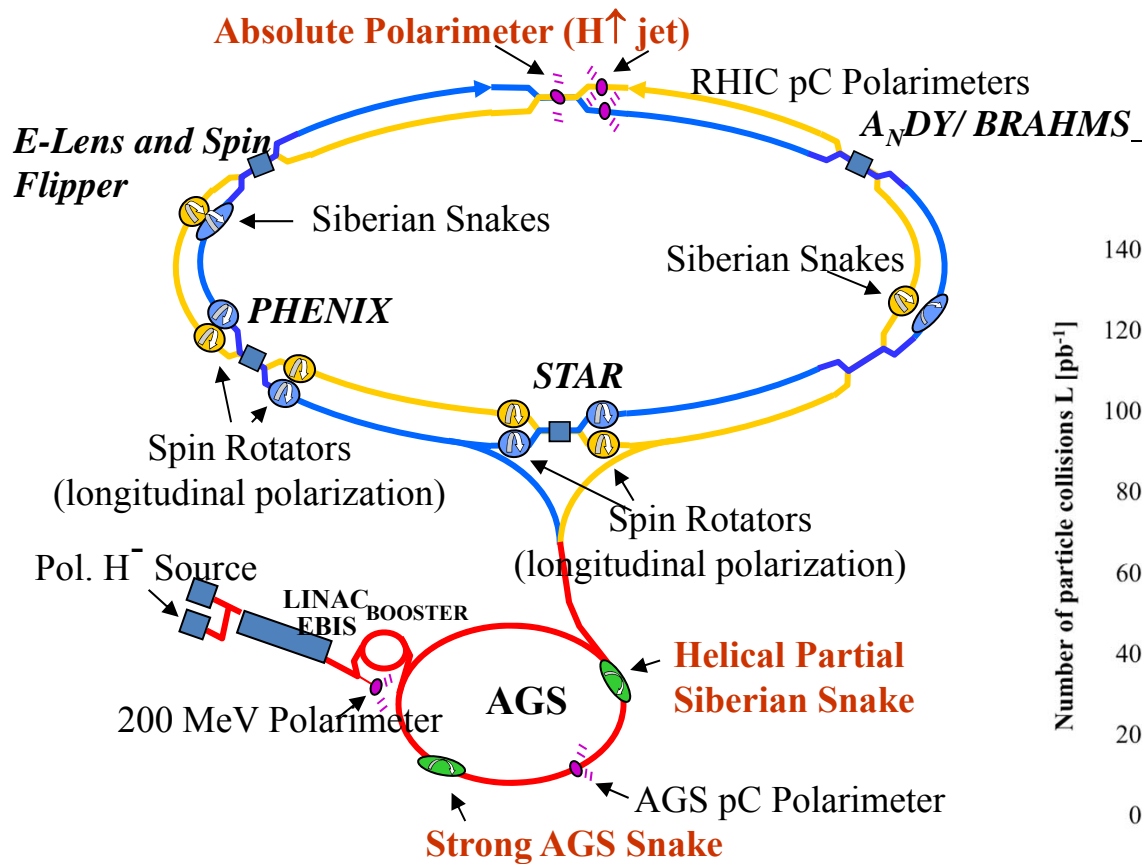
Thank you!



Backup Slides



RHIC: Polarized pp Collider & QCD Machine



Versatility:

- Polarized p+p Sqrt(s) collisions at 62.4 GeV, 200 GeV and 500 GeV

Recent Spin Runs:

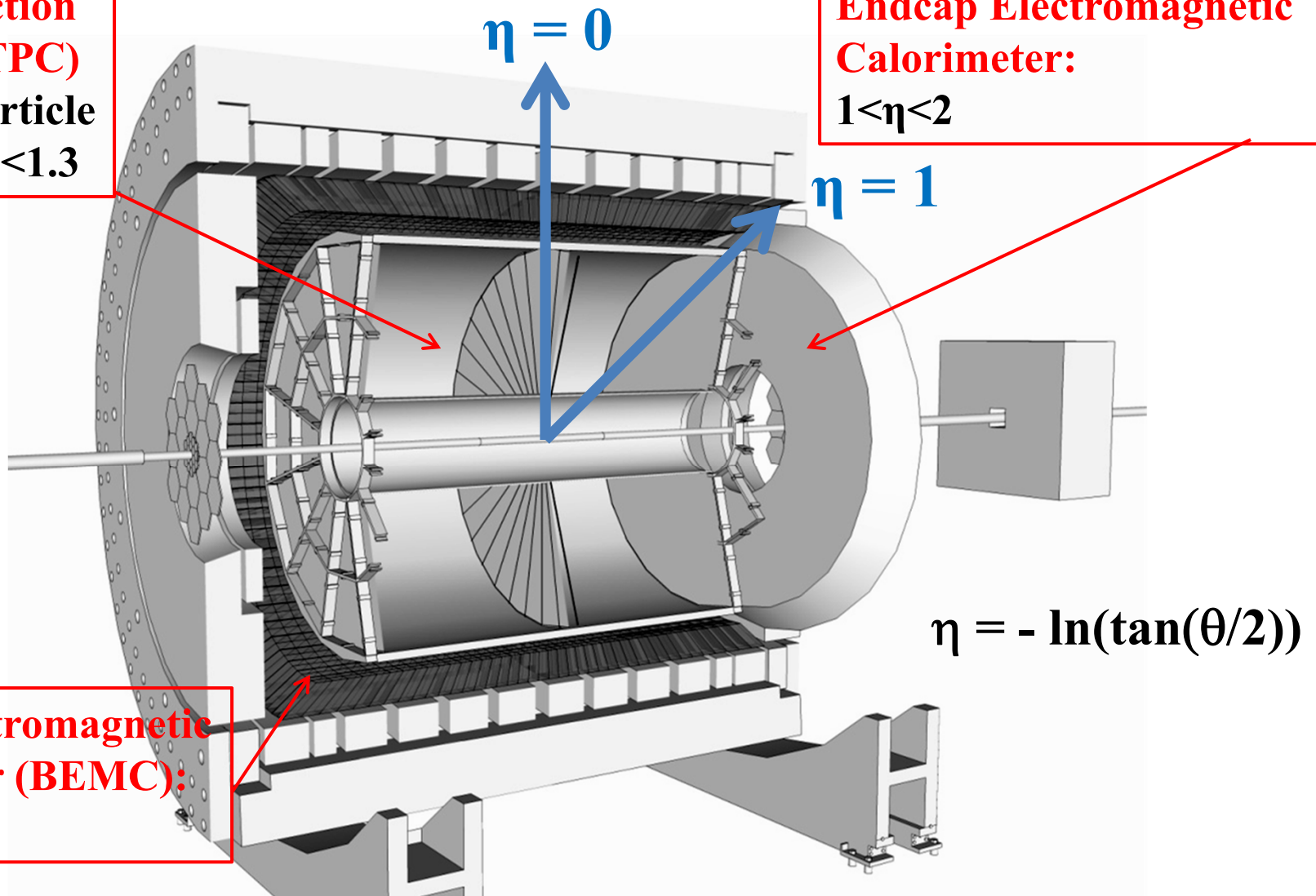
- 2009: first 500 GeV polarized running (longitudinal)
- 2011, 2012: 510 GeV polarized running (longitudinal and transverse).



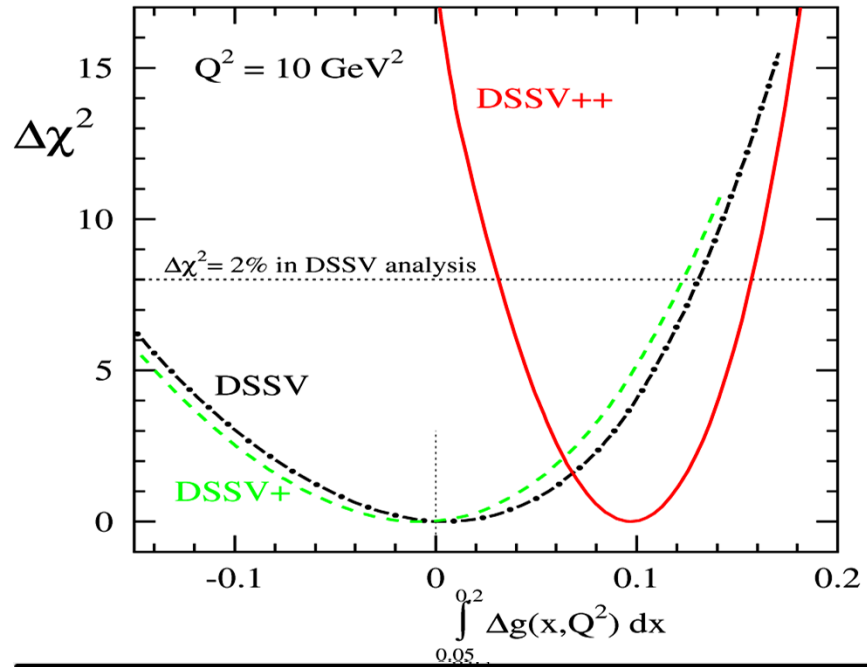
Solenoidal Tracker at RHIC

Time Projection Chamber (TPC)
Charged Particle Tracking $|\eta| < 1.3$

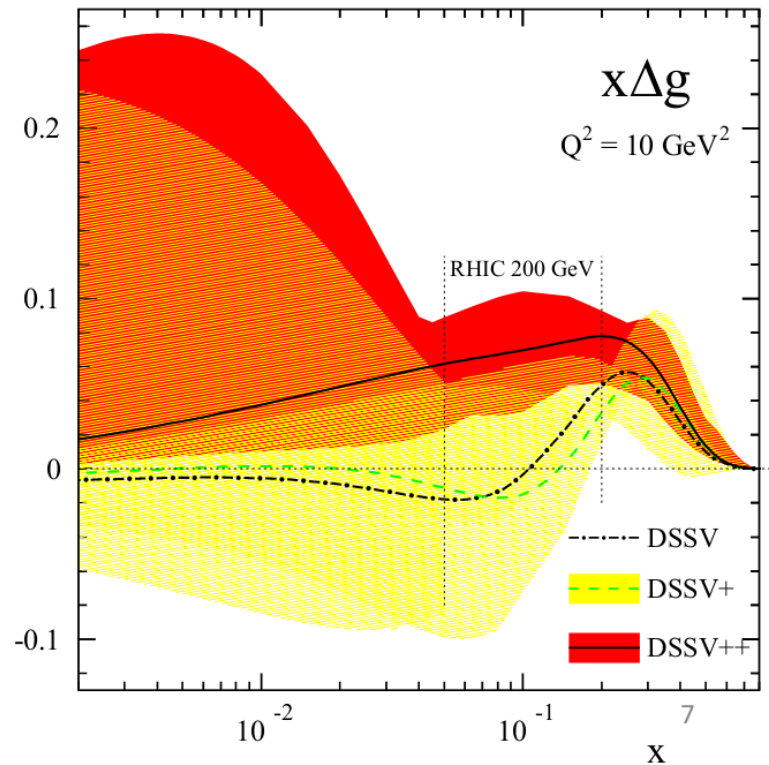
Endcap Electromagnetic Calorimeter:
 $1 < \eta < 2$



Impact of Run 9 on ΔG



- RHC Run 9 data narrows $\Delta\chi^2$ profile and shifts central value
- DSSV++ fit gives first non-zero ΔG in RHC sensitivity region
- DSSV++ statistically consistent with previous DSSV result



DSSV: PRL 101, 072001 $\int_{0.05}^{0.2} \Delta g(x) dx = 0.005^{+0.129}_{-0.164}$

DSSV+: DSSV & Compass

DSSV++: DSSV+ & RHC Run 9 $\int_{0.05}^{0.2} \Delta g(x) dx = 0.1^{+0.06}_{-0.07}$



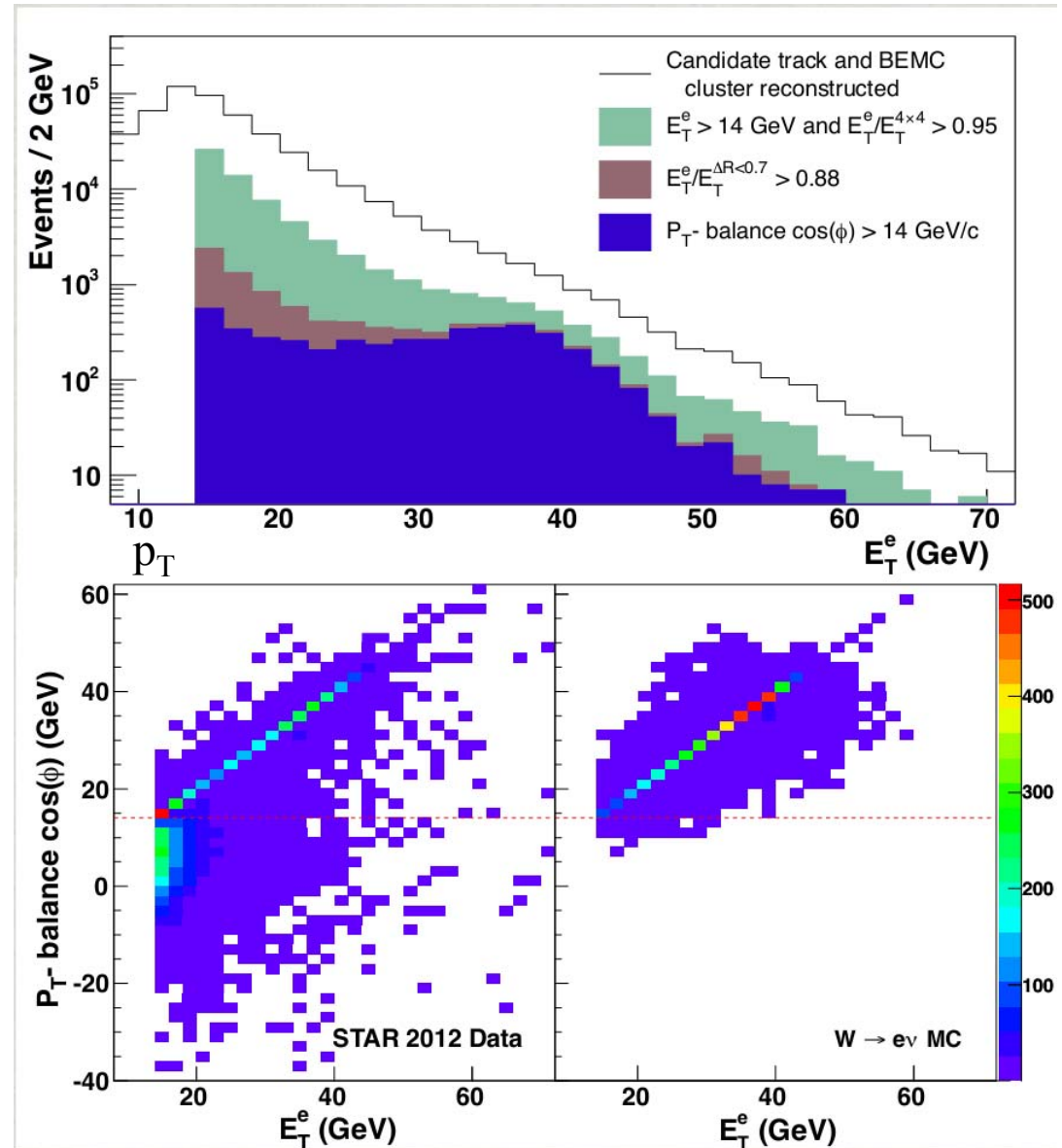
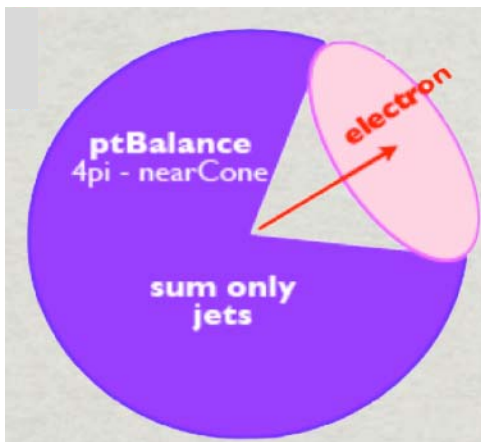
[for DSSV++, etc., see: <http://www.bnl.gov/npp/docs/RHIC-Spin-WriteUp-121105.pdf>]

Finding W's in pp Collisions at STAR

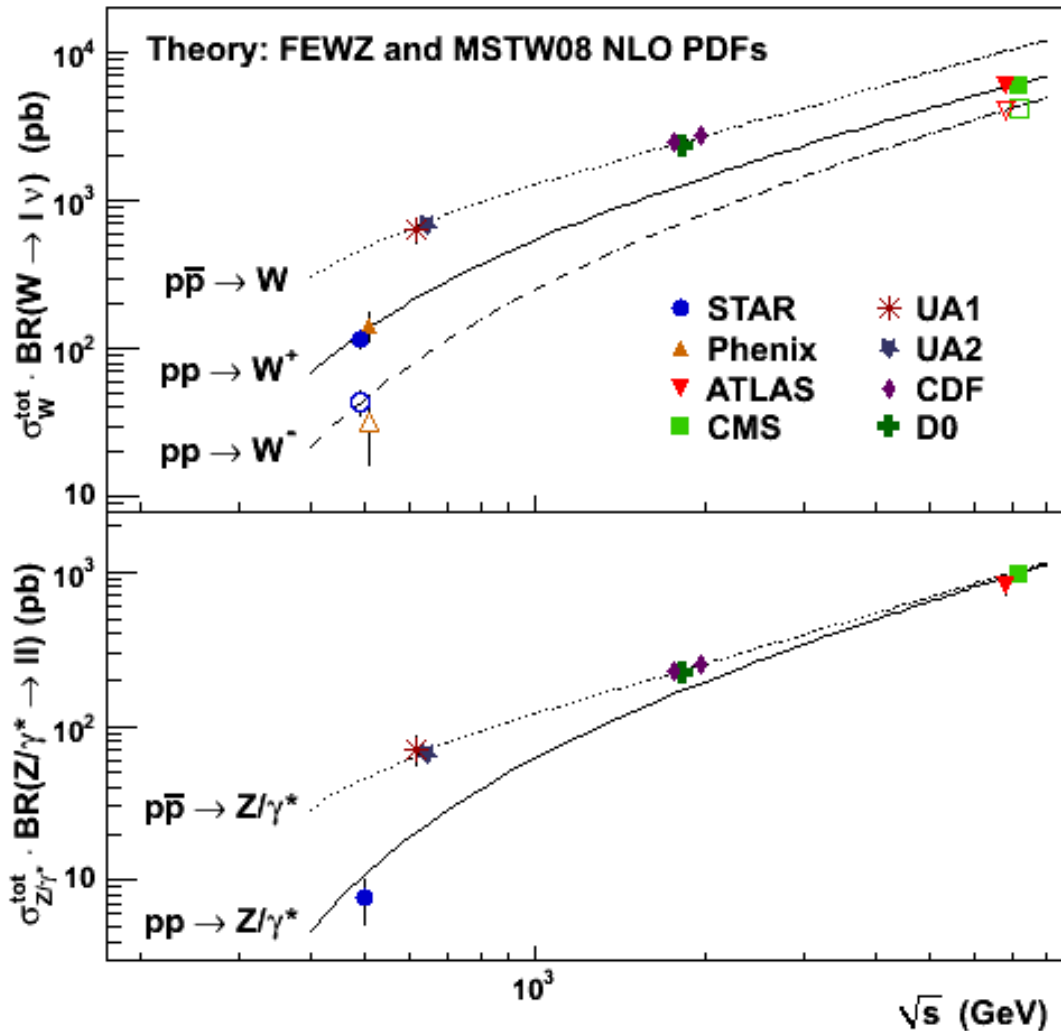
- Match $p_T > 10$ GeV track to EMC cluster
- Isolation Ratios
- P_T -balance

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

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



World data set: W production in pp and pp colliders



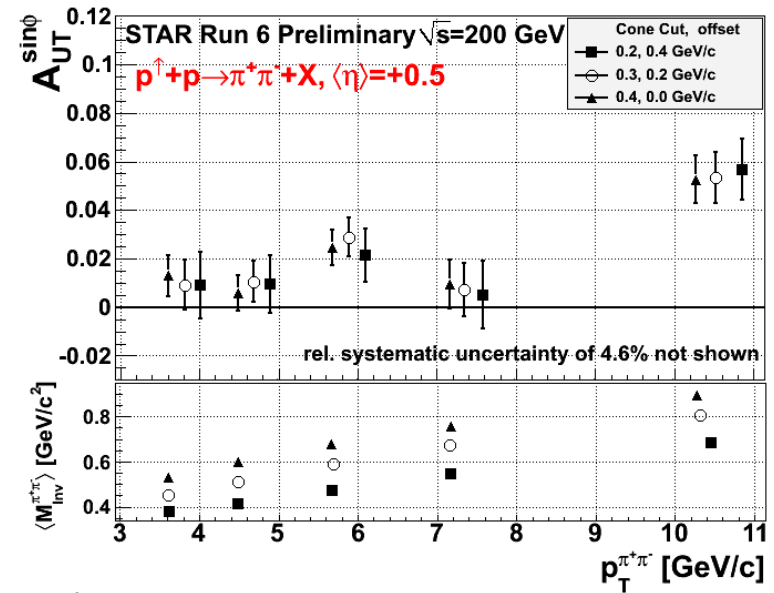
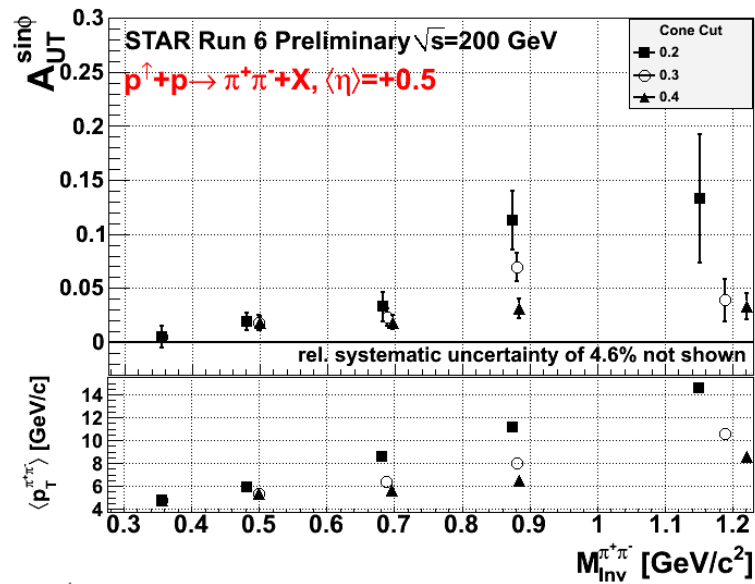
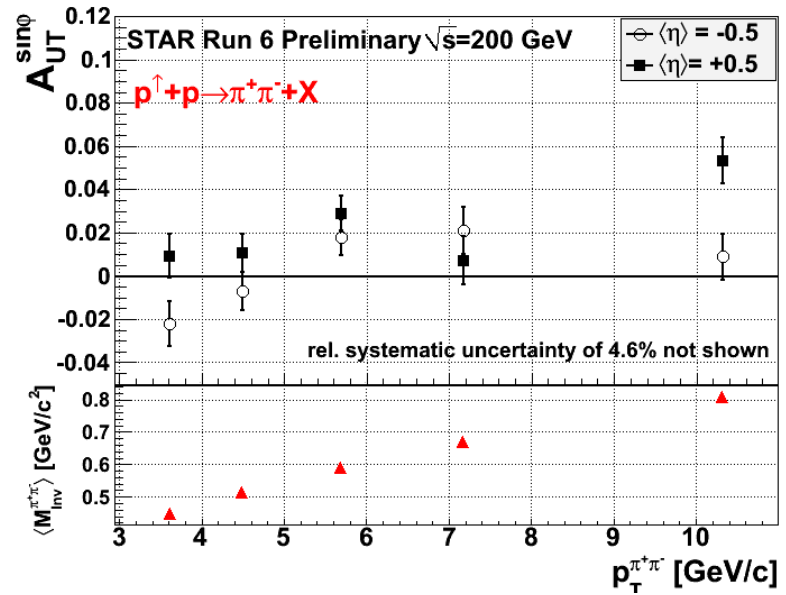
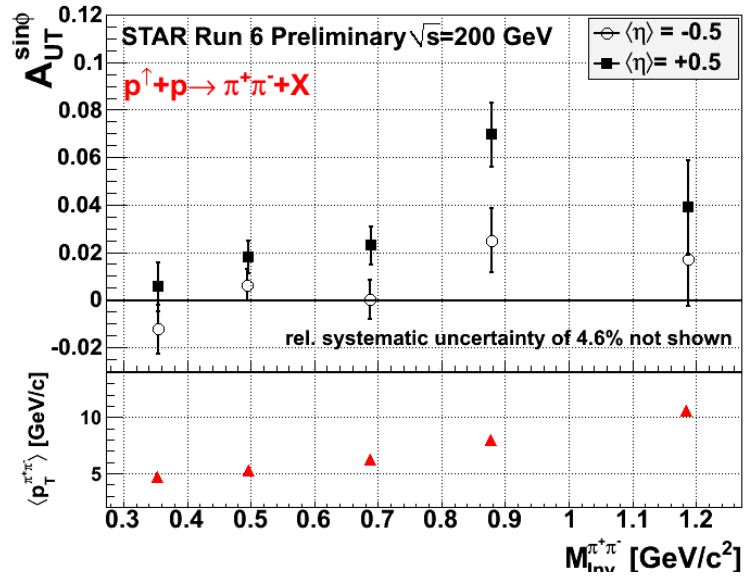
First cross sections for W and Z production at pp colliders (RHIC and LHC) measured at the same time.

Data from J. Stevens thesis (IU, 2012).

Excellent agreement between the measured and expected cross sections.

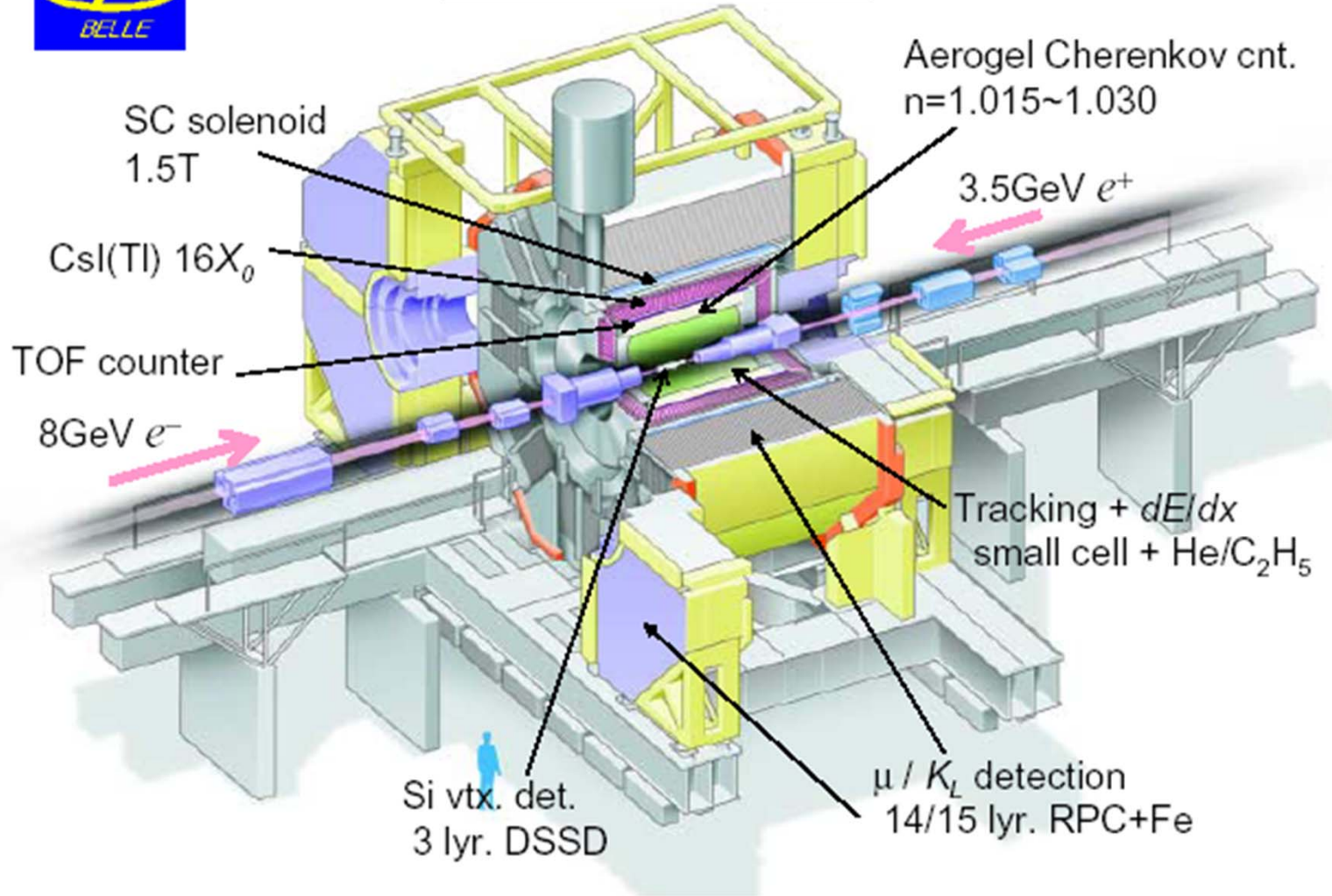


STAR Transverse Spin di-Hadron Correlation





Belle Detector



- KEKB: $L > 2.11 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
- Asymmetric collider: 8GeV e⁻ + 3.5 GeV e⁺
- $\Upsilon(4S)$: 702.6 pb⁻¹ on/ 89.5 pb⁻¹ off
- Center-of-mass Energy 10.58/1.52 (on/off)

