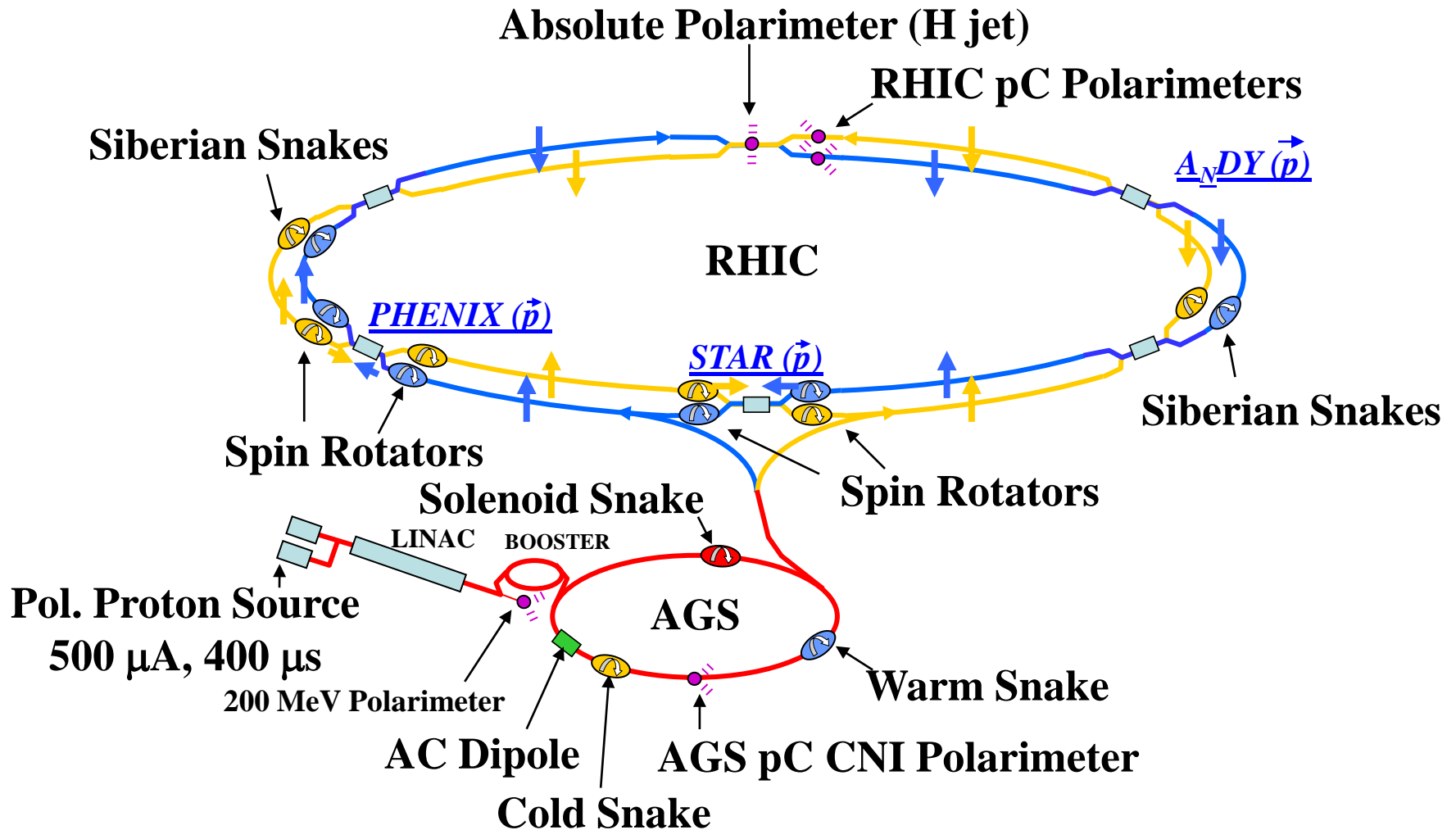


*“I think that I shall never see
A collision as lovely as \vec{e} on \vec{p} ”*

The pp Spin Program at RHIC

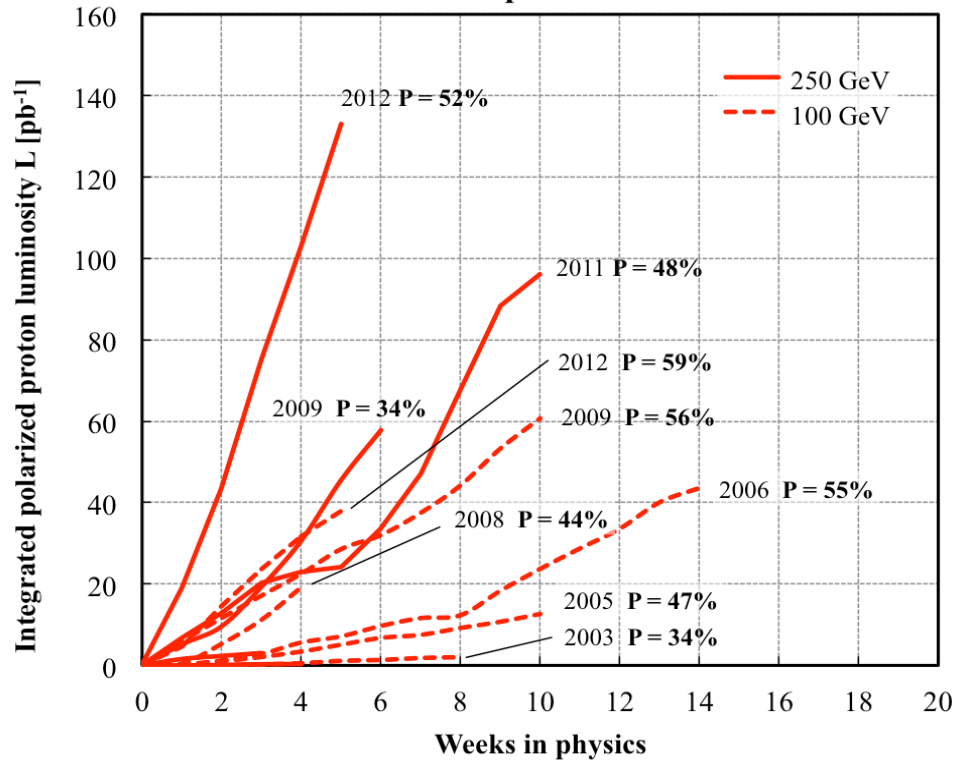
- Status of ΔG measurements
- W/Z^* production and A_L
- Transversity at mid-rapidity

The RHIC rings: A Decade of Developing a Resource

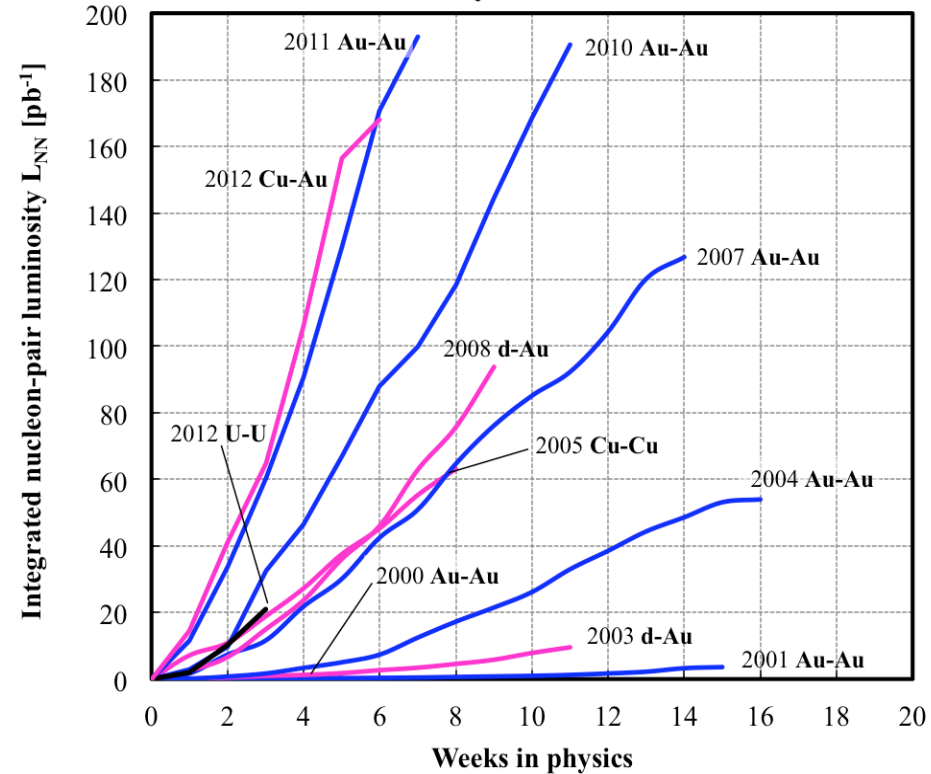


RHIC Performance in Run 12 ...

Polarized proton runs

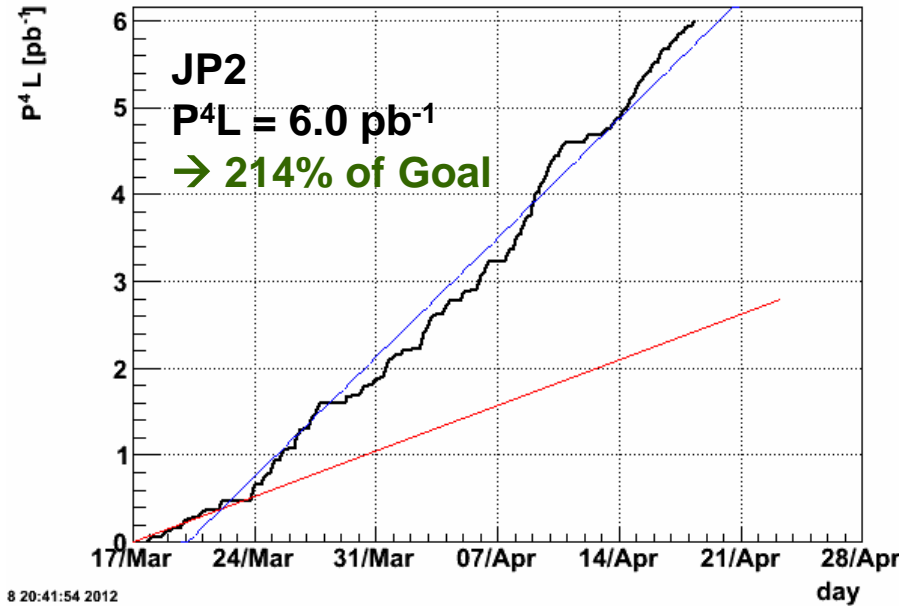
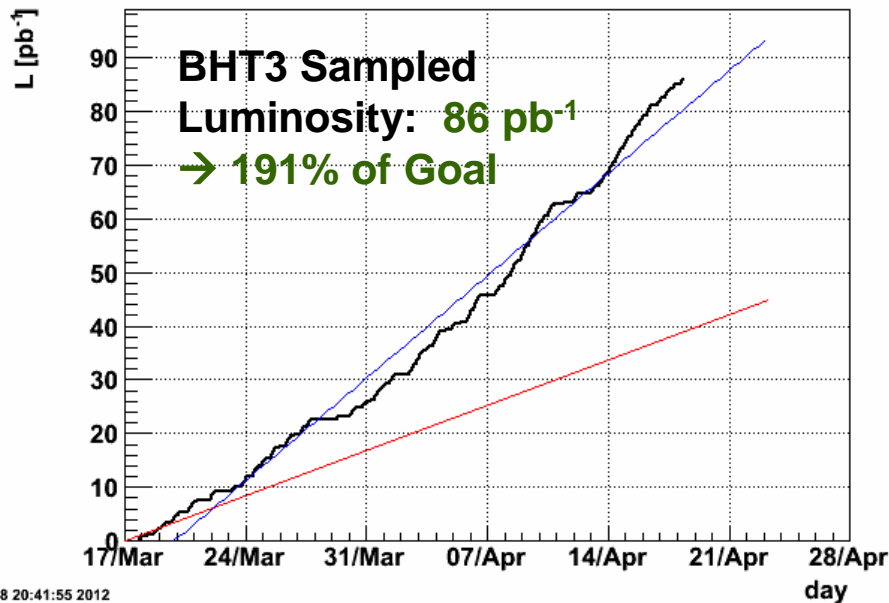


Heavy ion runs



- ✓ ~5 weeks each of pp200 and pp500
- ✓ 2 new heavy-ion species (U+U and Cu+Au)

... and the collaborations are grateful!



Bottom line: For all four species / beam energies, all established run goals were exceeded, often by factors greater than two. Stochastic cooling works!

The Spin Puzzle: Understanding nucleon substructure

The RHIC spin program:

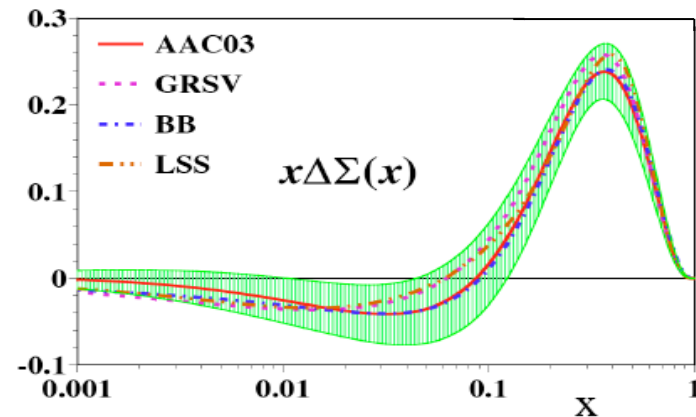
Study **hard partonic scattering** processes in polarized pp collisions, using polarization of one parton to probe helicity preferences of the other

→ Provides a “snapshot” of spin distributions:

$$\langle S_z^p \rangle = \frac{1}{2} = \underbrace{\frac{1}{2} \Delta\Sigma}_{\text{quark helicity}} + \underbrace{\Delta G}_{\text{gluon helicity}} + \langle L_z^{\text{quarks}} \rangle + \langle L_z^{\text{gluons}} \rangle$$

→ pDIS studies consistently show quark helicity contributions ~30%!

1. **Can gluonic spin and partonic orbital angular momentum account for the remaining 70%?**
2. **Can we unravel the individual terms that contribute to $\Delta\Sigma$?**

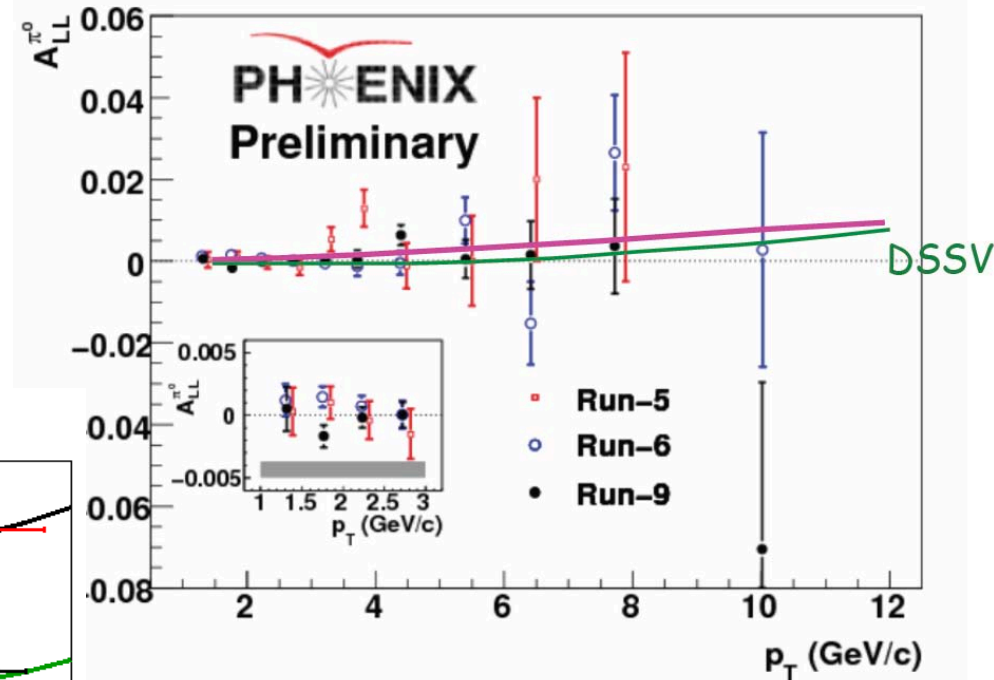
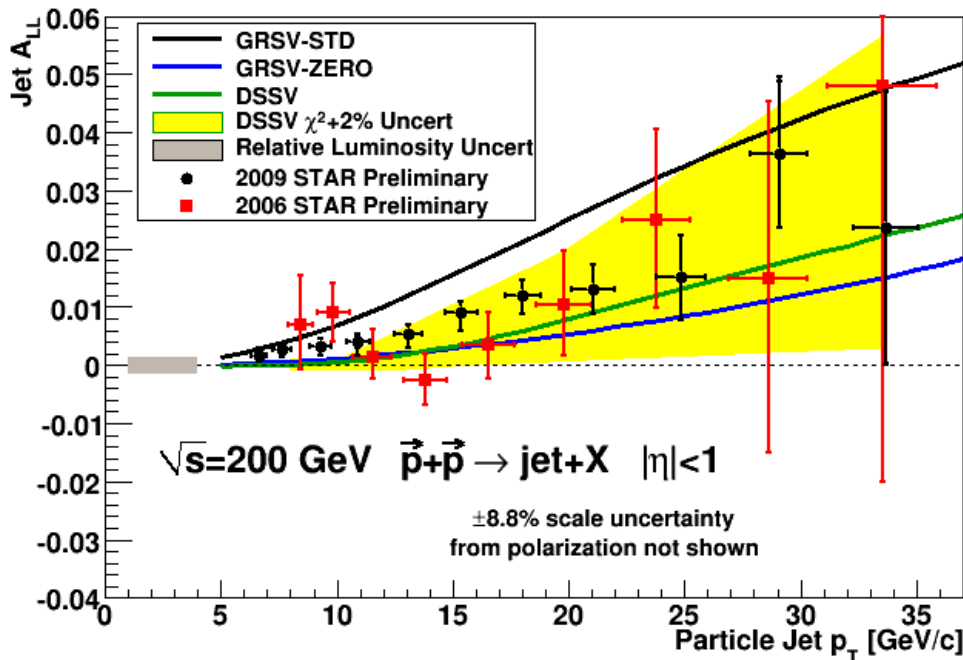


Hirai, Kumano, Saito

Results from 2009: gluon polarization may be non-zero

For inclusive π^0 (PHENIX) and jet (STAR) asymmetries

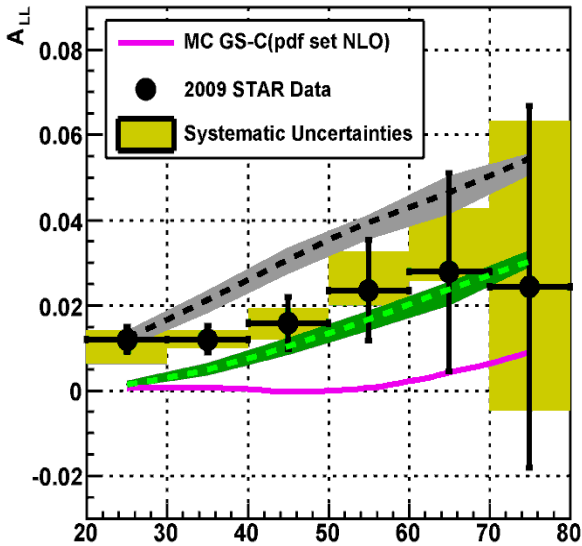
- ❖ Statistical errors ~ 2-3 times smaller than in 2006
- ❖ Data significantly higher than DSSV global fits



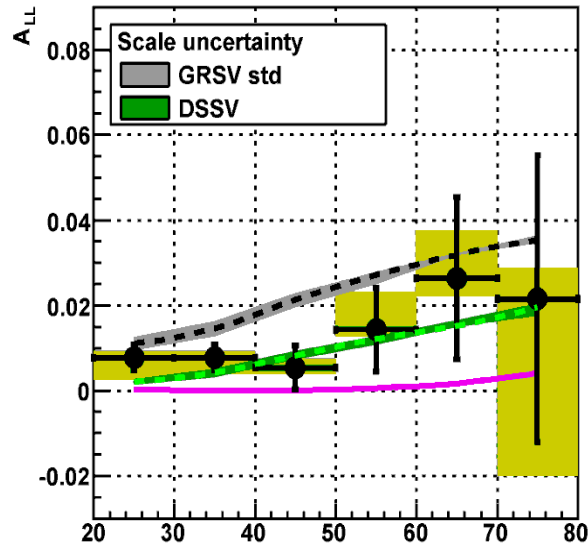
$$\text{STAR Jet } A_{LL} : \int_{0.05}^{0.2} dx \Delta g \sim 0.1$$

Correlation studies: more evidence from di-jets

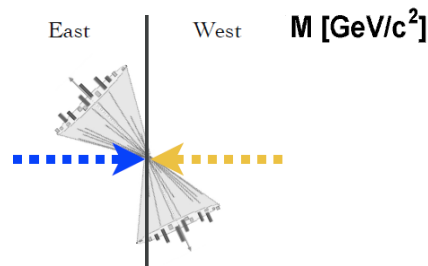
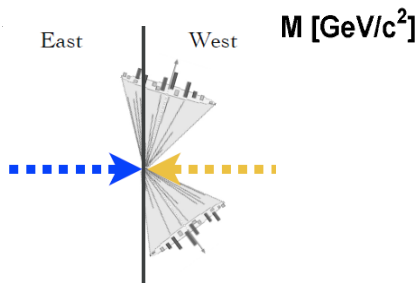
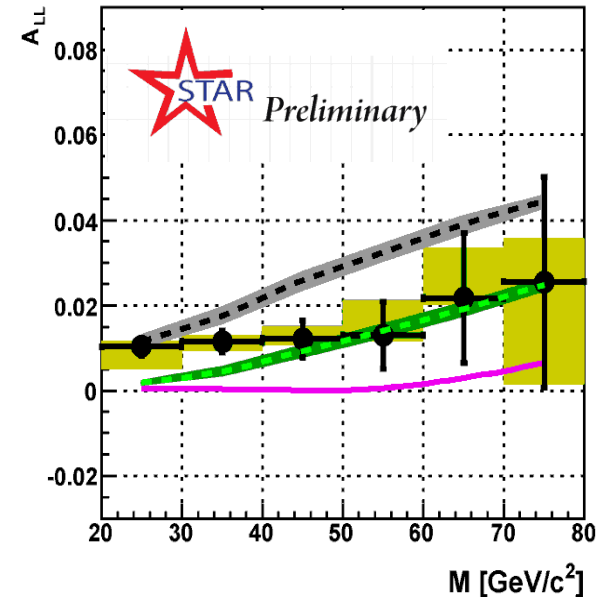
East - East and West - West Barrel



East Barrel - West Barrel

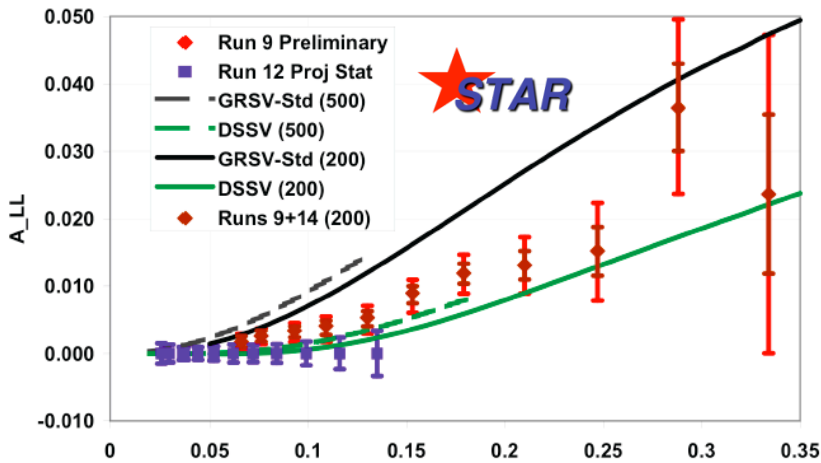


Full Acceptance

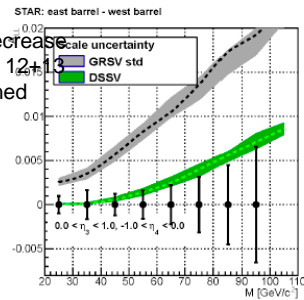
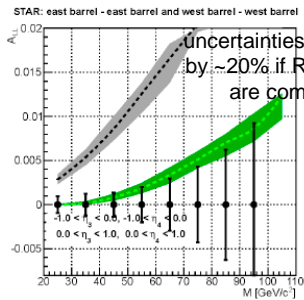
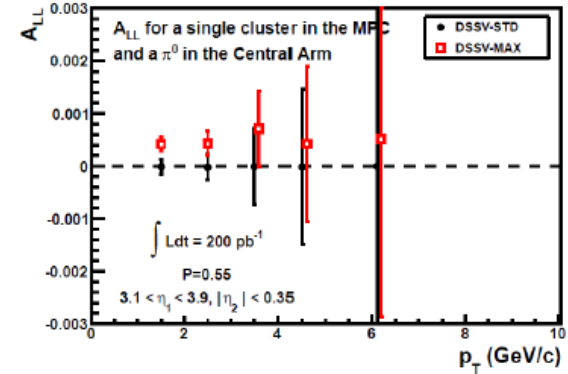
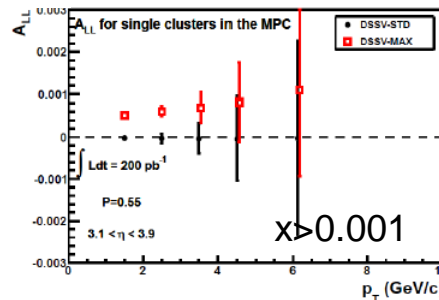
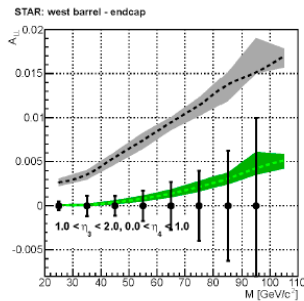
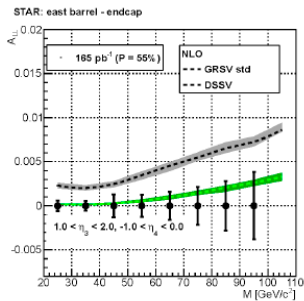
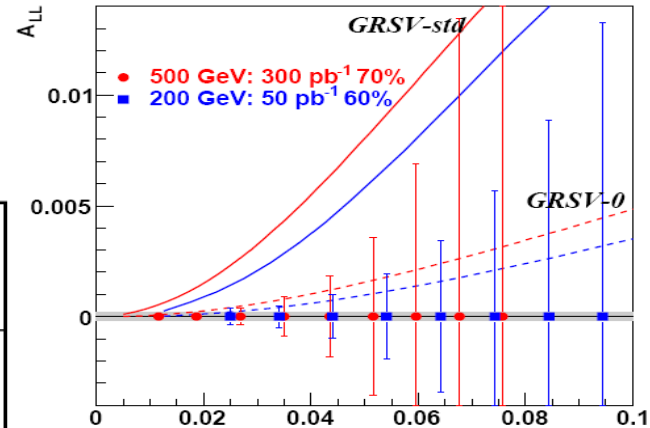


From crude interpolation: 2009 pp200 jet data suggest that perhaps **~ 25% of the proton's spin** may be carried by gluons!

Much more precise data – most at 500 GeV – to come



From runs 12, 13, 14 → substantial gains at all kinematics, especially to lower regions of x (down to ~ 0.01)



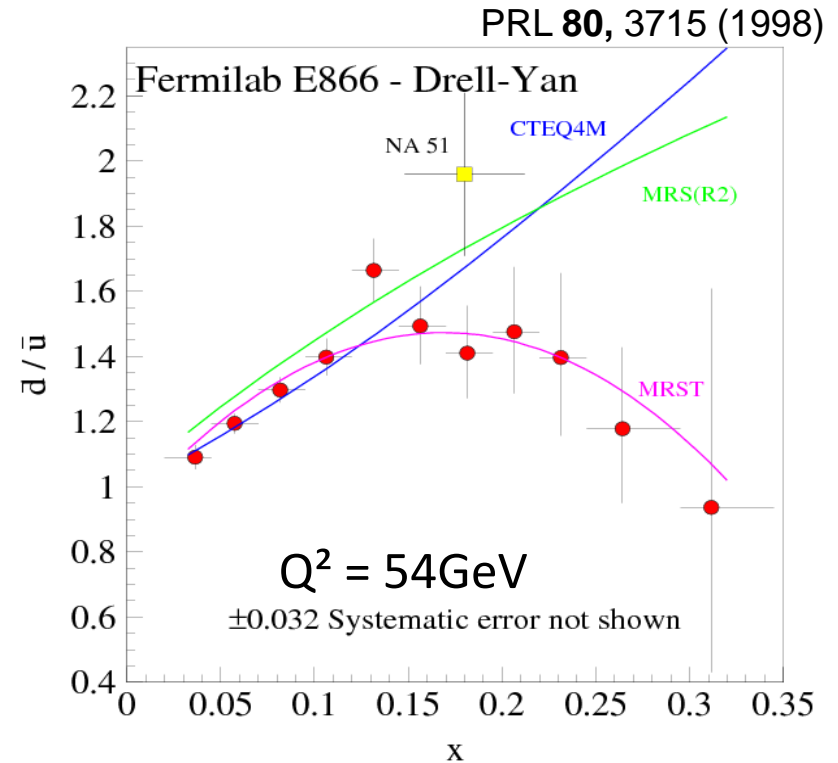
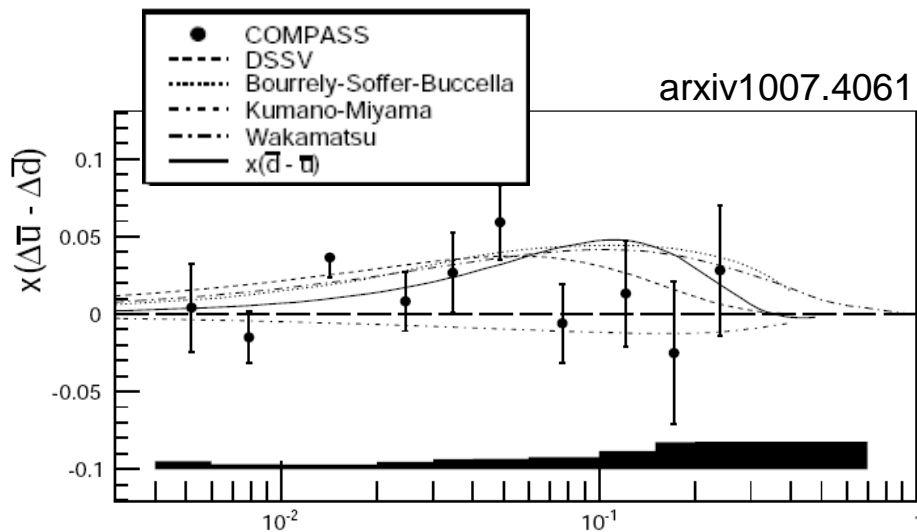
uncertainties decrease by $\sim 20\%$ if Run 12+13 are combined

scale uncertainty

Flavor Asymmetry of the Sea: the RHIC W program

Unpolarized Flavor asymmetry

- Naïve expectation: a “free” gluon splits to u and d pairs equally often
- Quantitative calculation of Pauli blocking does *not* explain \bar{d}/\bar{u} ratio
- E866 results are qualitatively consistent with pion cloud models, chiral quark soliton models, instanton models, etc.

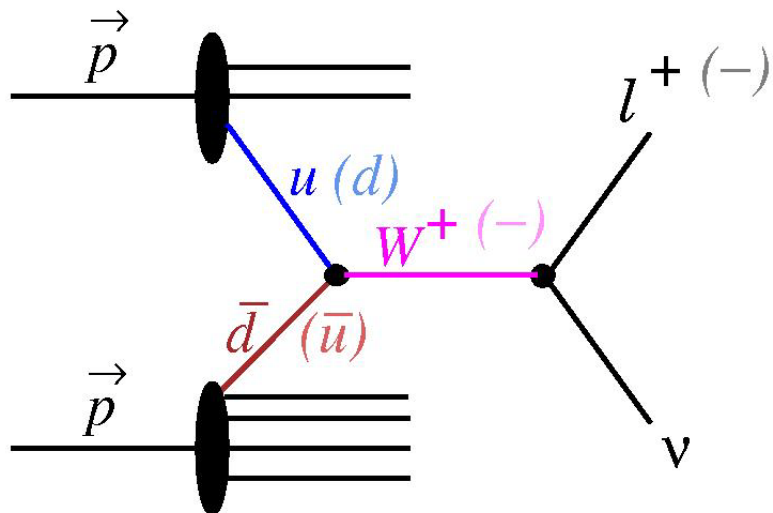


Polarized flavor asymmetry

- “Hints” from recent COMPASS data
- Extracting polarized flavor asymmetry could help differentiate among models

$$x(\Delta\bar{u} - \Delta\bar{d})$$

Probing the Sea Through W Production at RHIC



$$\begin{aligned}
 u + \bar{d} &\rightarrow W^+ \rightarrow e^+ + \nu \\
 \bar{u} + d &\rightarrow W^- \rightarrow e^- + \bar{\nu}
 \end{aligned}$$

$$\sqrt{x_1 x_2} = 0.16$$

- V-A coupling \rightarrow left-handed W's couple l.h. q with r.h. $q \rightarrow$ **perfect spin separation**
- Detect W's through **e^+/e^-** decay channels
- Typically find $x_q > x_q \rightarrow$ **W highly boosted**
- In $W^{+(-)}$ rest frame, lepton is preferentially emitted **along (against) W spin direction**

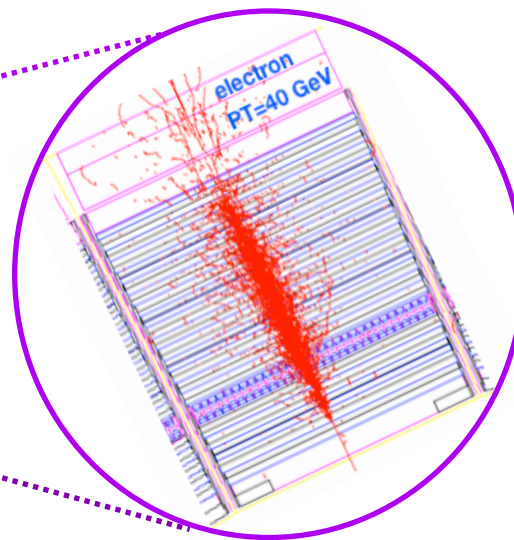
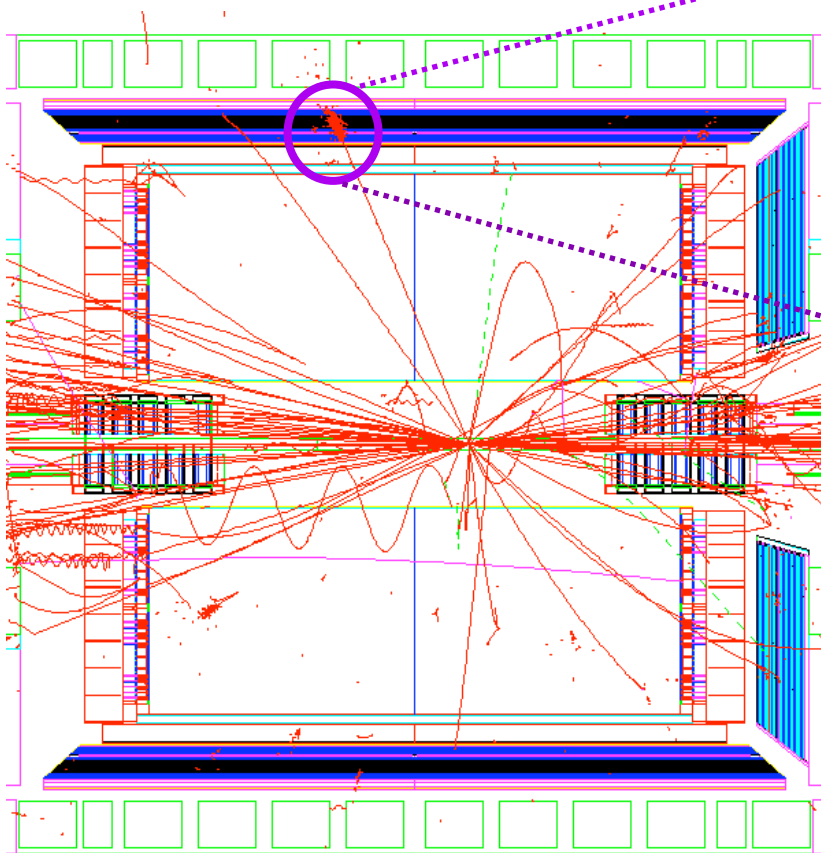
Measure parity-violating single-spin asymmetry: $A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$
 (Helicity flip in one beam while averaging over the other)

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

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

Finding W's at RHIC: a very clean signature!

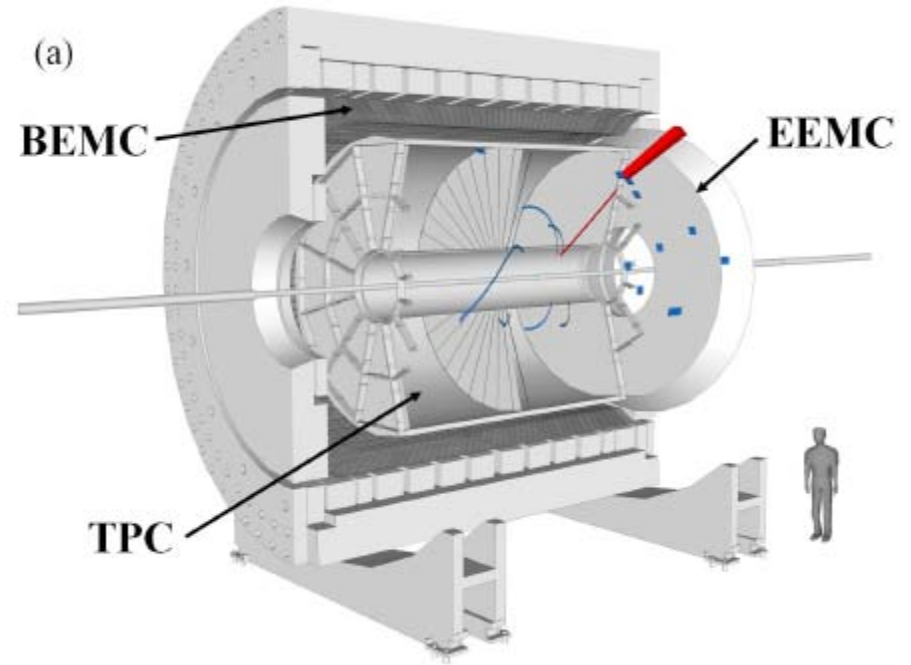
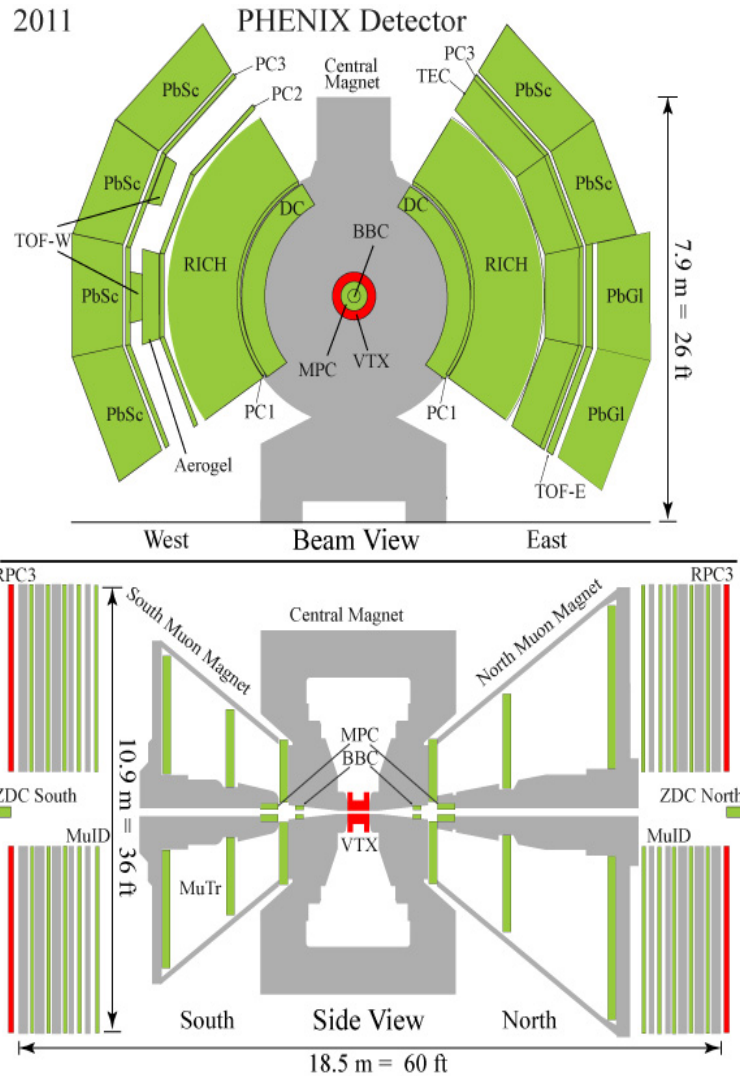
Pythia+Geant
 $p+p \rightarrow W \rightarrow e+\nu$ event
@ 500 GeV



Dictates key experimental requirements:

- ***Good e.m. calorimetry \rightarrow measure E_e***
- ***Good tracking \rightarrow lepton charge sign***
- ***Large angular coverage \rightarrow isolation cuts on lepton and away-side energy***

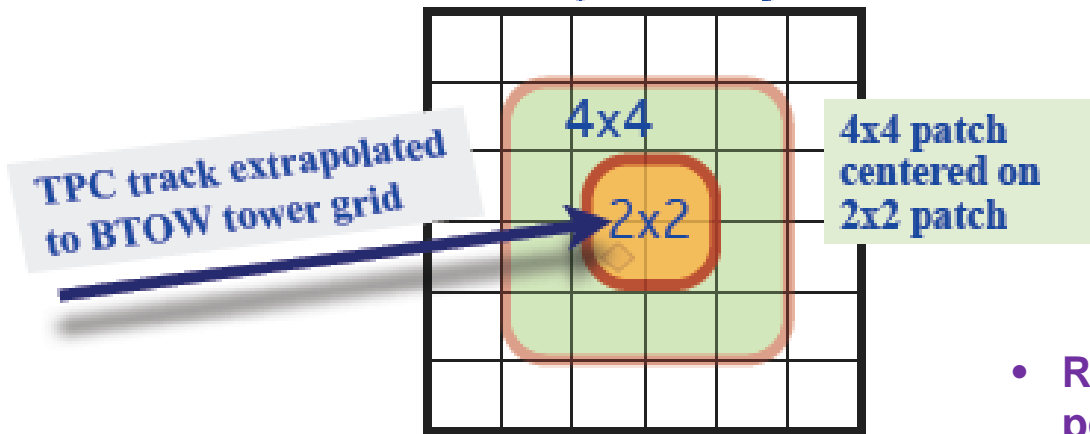
Finding W's at RHIC: Detectors are up to the task!



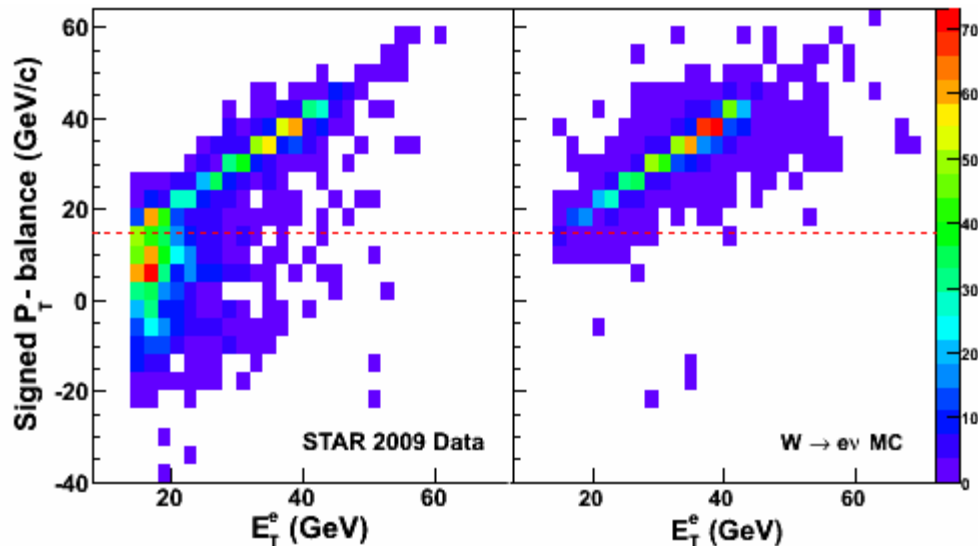
A (possible) real W!

Identify isolated electron candidates

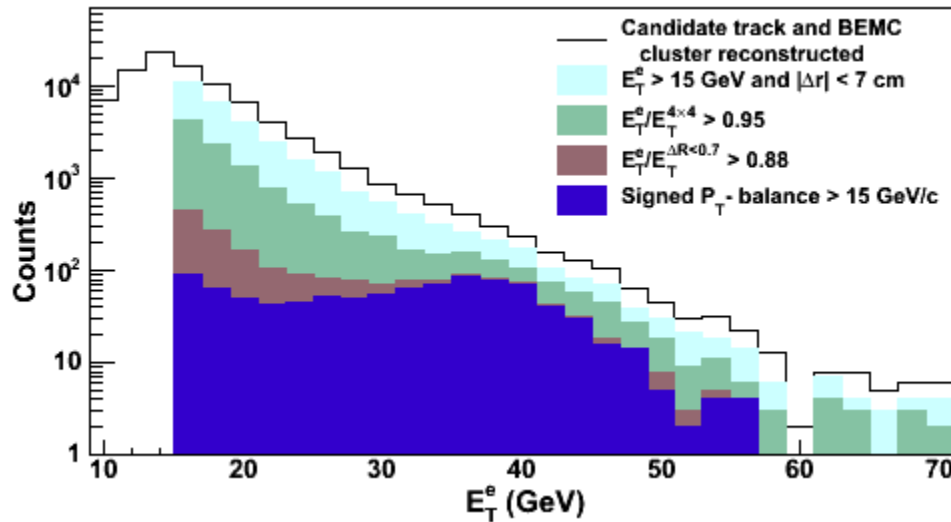
2x2 EM cluster with highest ET sum,
must contain tower pointed by the track



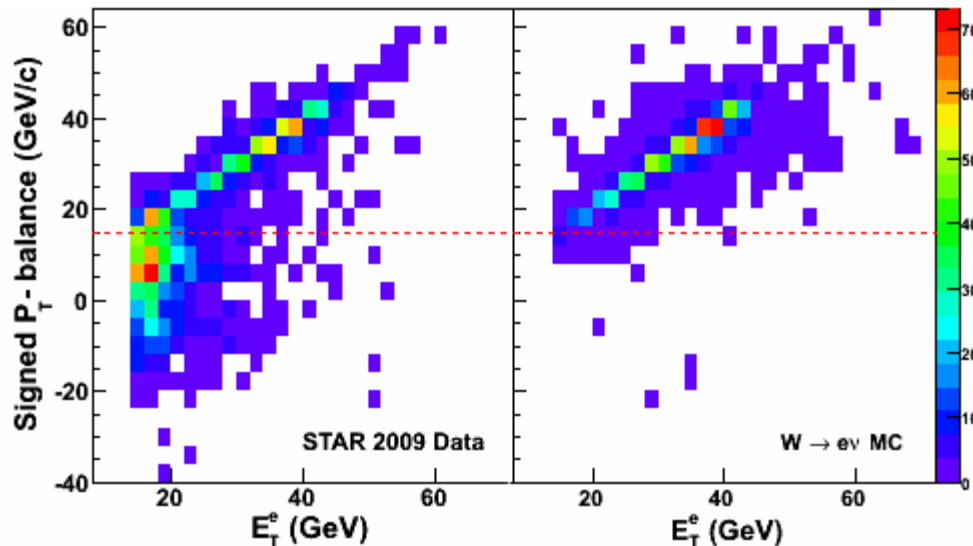
- Require a track with $p_T > 10$ GeV/c to point to a 2 x 2 patch with $E_T > 15$ GeV
- Require $> 95\%$ of energy in 4 x 4 patch to lie inside the central 2 x 2 patch (E_T^e)
- Throw out event if the surrounding cone ($R = 0.7$) has $> 10\%$ of candidate energy E_T
- Throw out event if too much energy is on opposite side (180° away in ϕ) \rightarrow reconstruct jets, check p_T balance



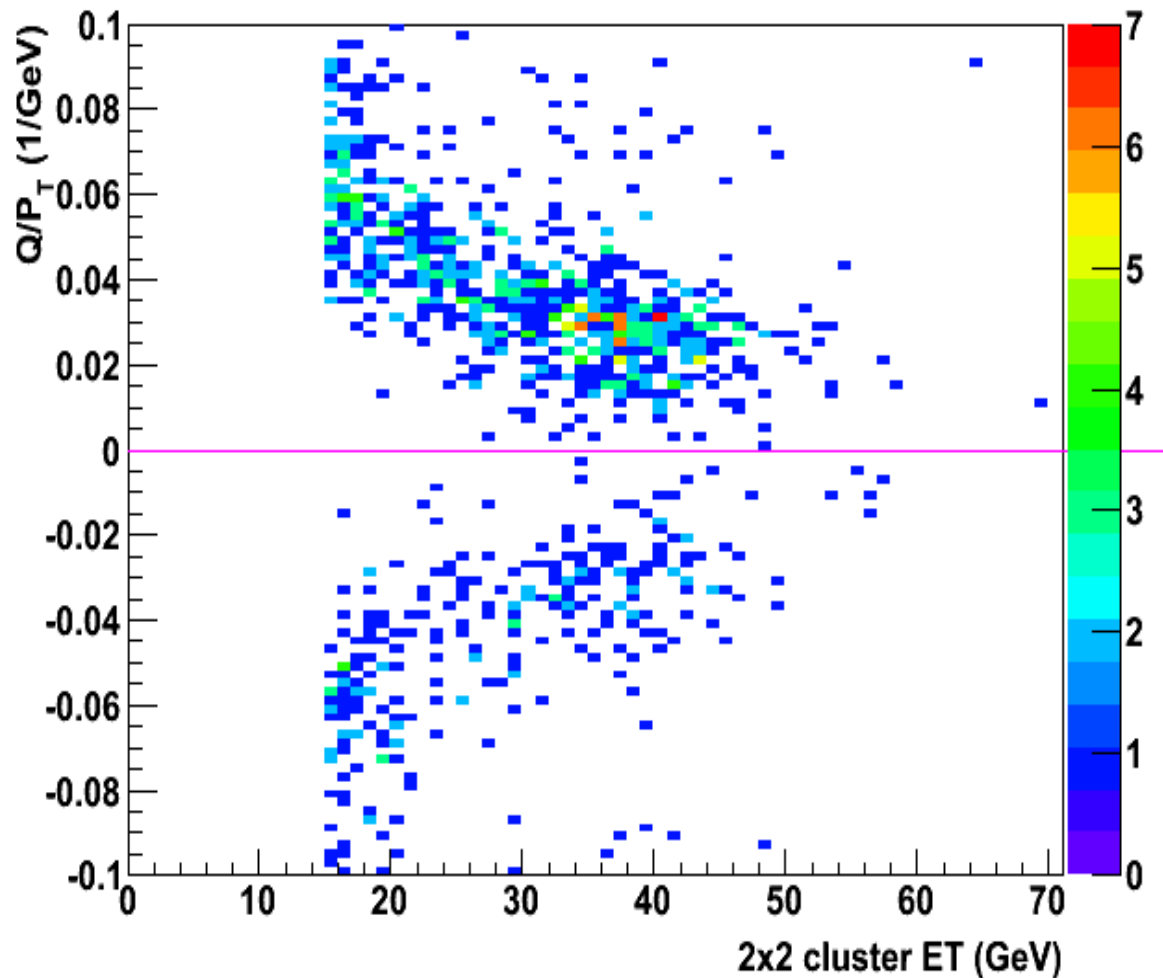
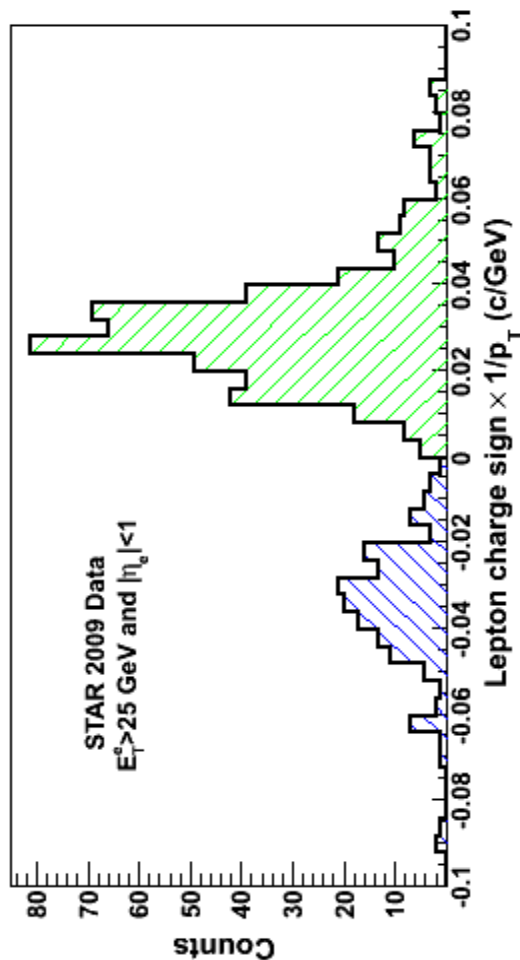
Identify isolated electron candidates



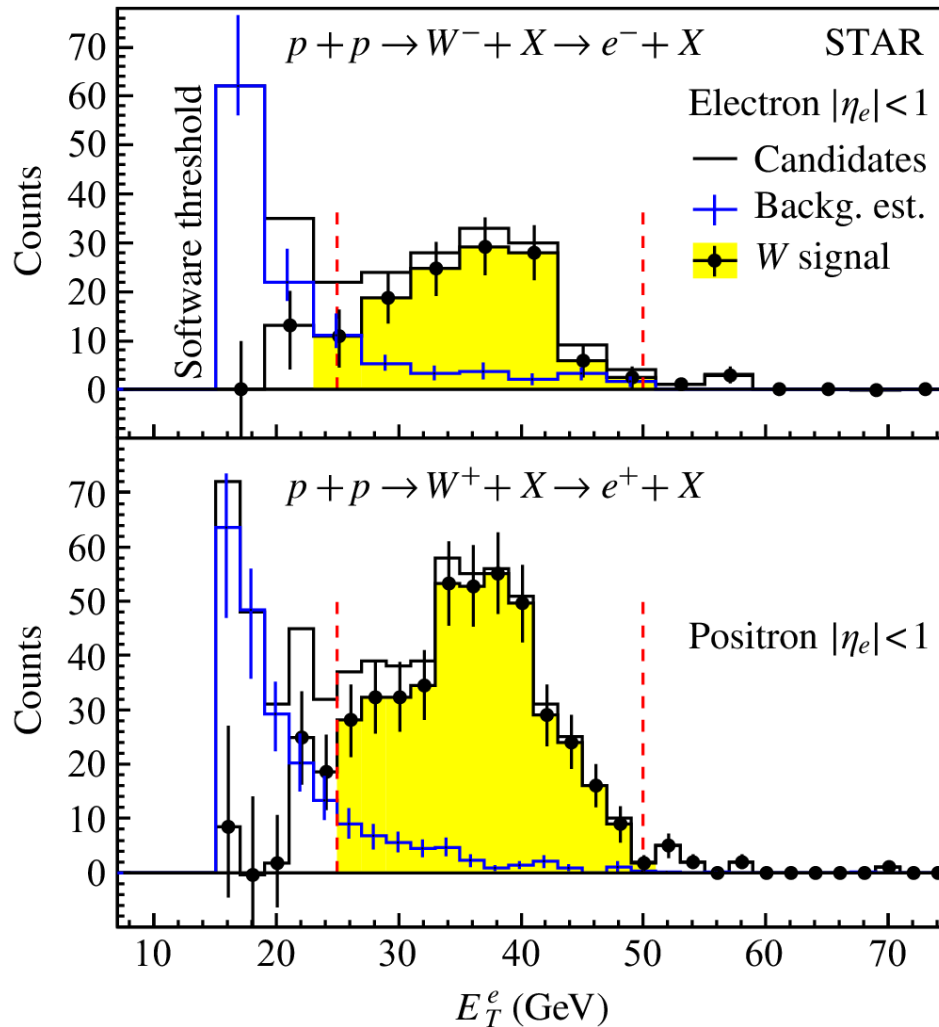
- Require a track with $p_T > 10 \text{ GeV}/c$ to point to a 2×2 patch with $E_T > 15 \text{ GeV}$
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- Throw out event if the surrounding cone ($R = 0.7$) has $> 10\%$ of candidate energy E_T
- Throw out event if too much energy is on opposite side (180° away in ϕ) \rightarrow reconstruct jets, check p_T balance



Ensure that lepton charge separation is robust



STAR W's from Run 9 – corrected yields



W signal displays features expected of characteristic “Jacobian Peak” (e.g., with peak at $\sim 1/2$ of W mass)

Background estimation: expect contributions from

– Electroweak:

- $Z \rightarrow e^+e^-$
- $W \rightarrow \tau \nu$

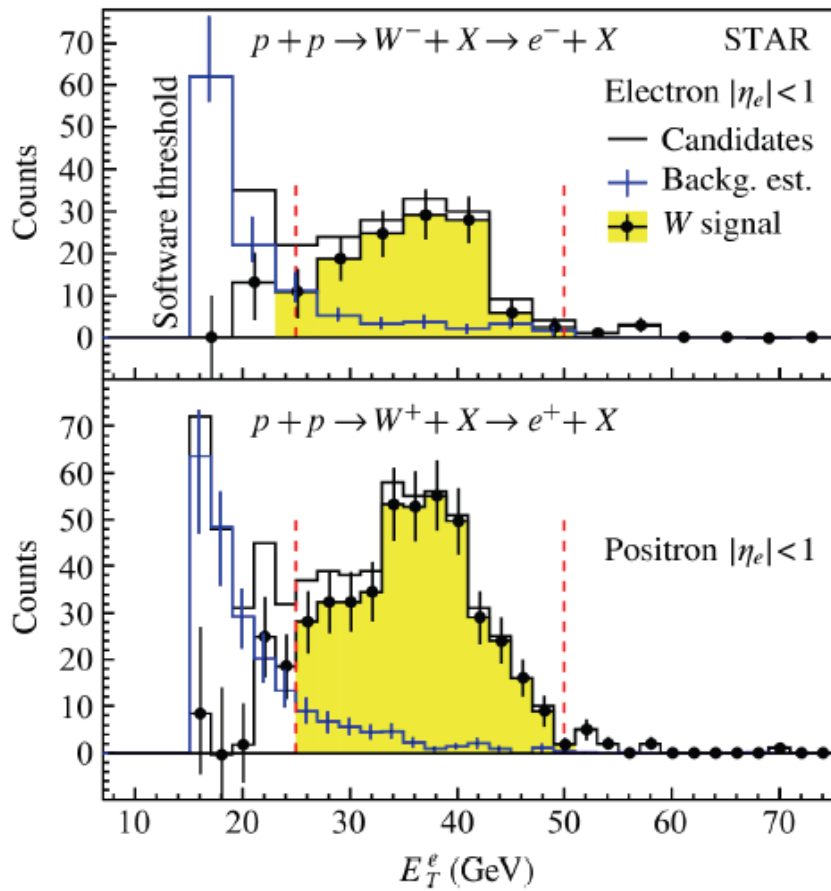
– QCD:

- Data-driven

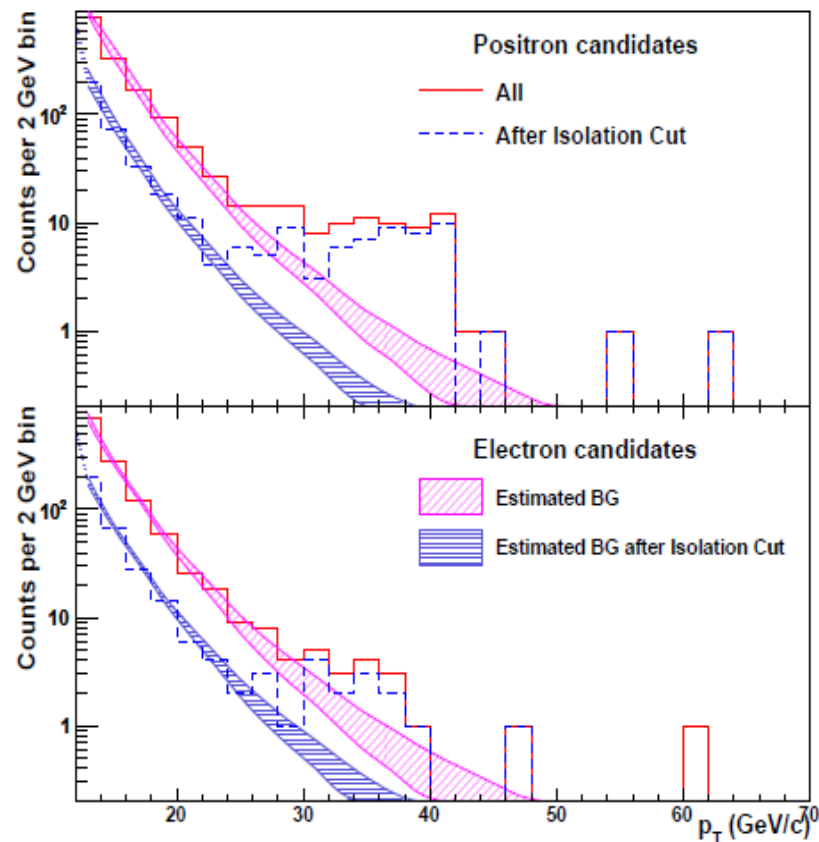
arXiv:1009.0326

Final W yields used for cross sections and A_L

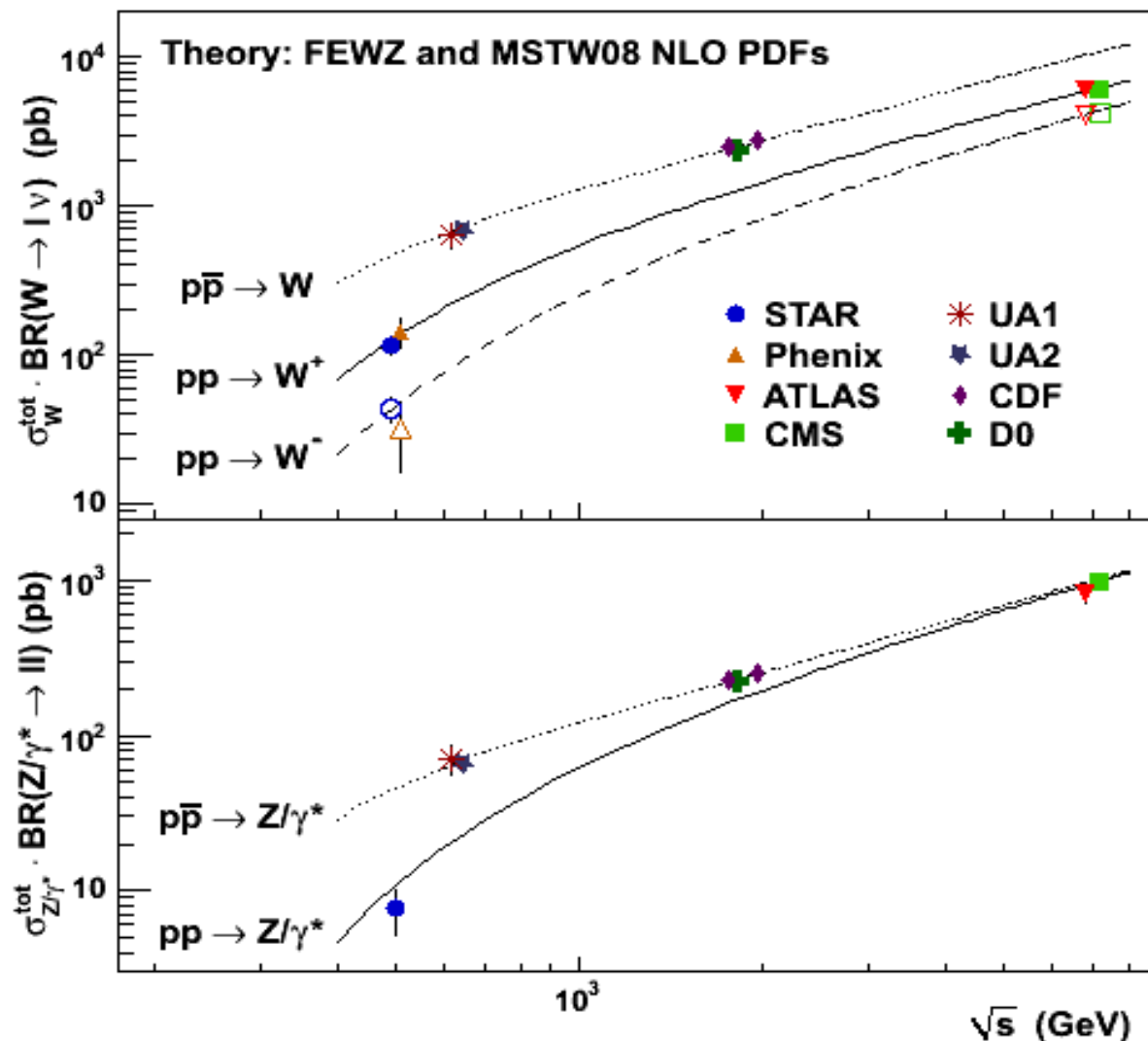
STAR: $|\eta^e| < 1$



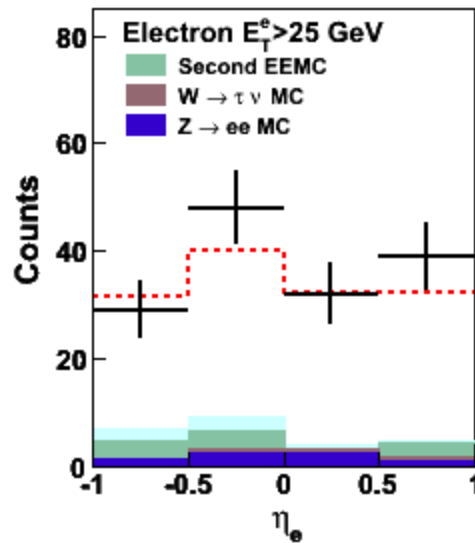
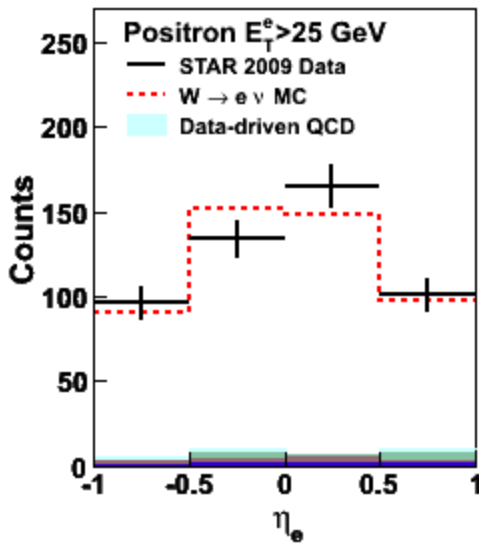
PHENIX: $|\eta^e| < 0.35$



World data set for W production in pp and p̄p colliders

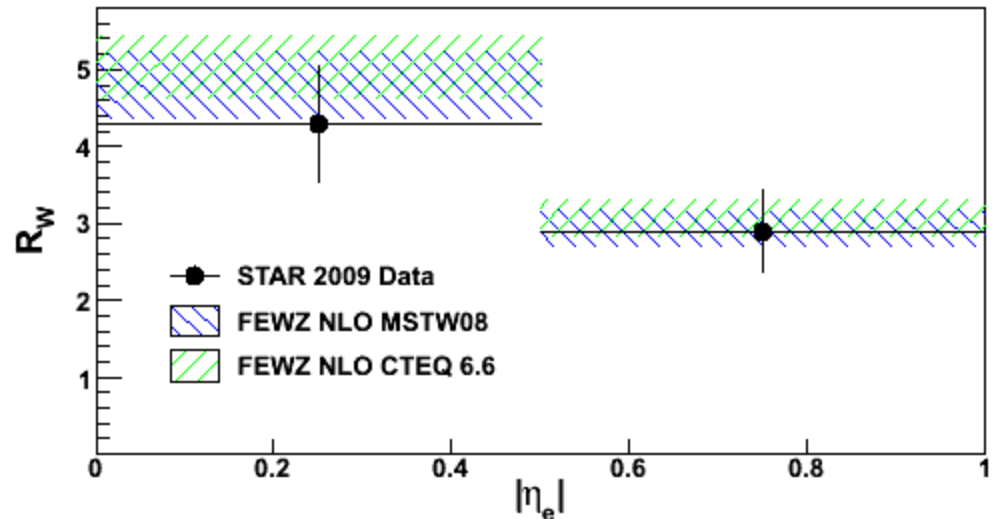


Initial look at some η dependencies

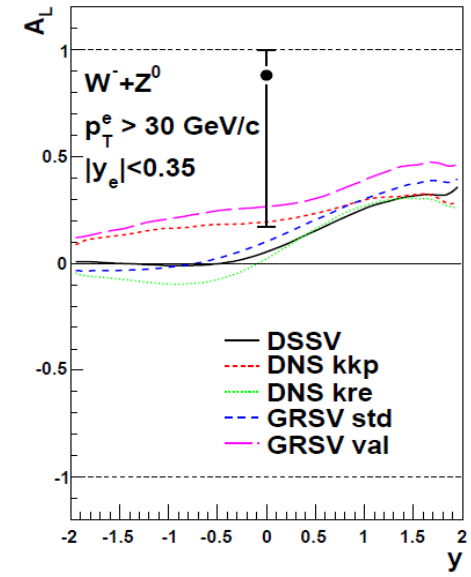
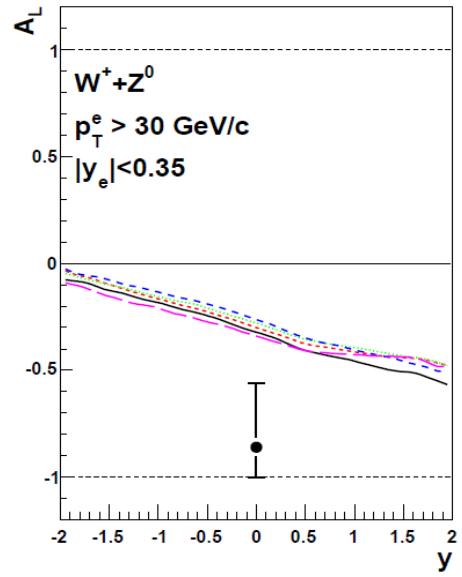
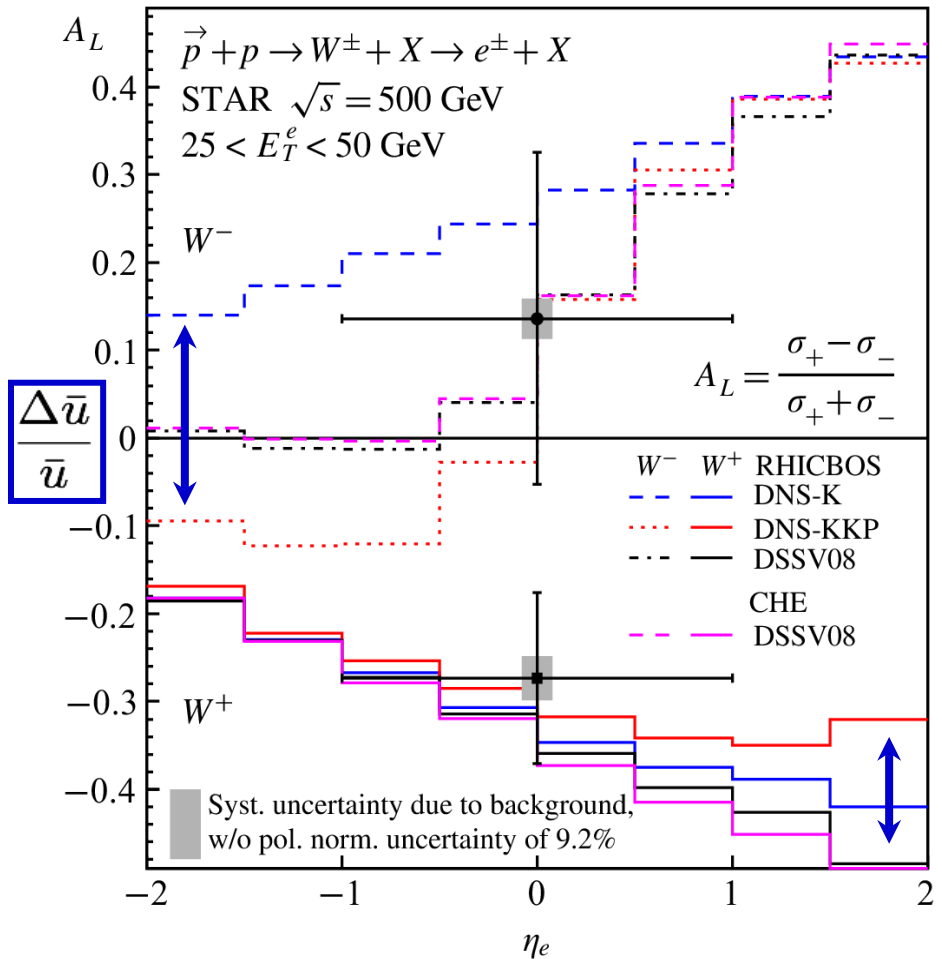


Lepton η distributions in reasonable agreement with MC \rightarrow weaker lepton “boost” for W^+ results in tightly clustering at $\eta = 0$

Ratio of W^+ / W^- eliminates dominant systematic error of absolute luminosity \rightarrow in excellent agreement with NLO calc's w/ different PDF's

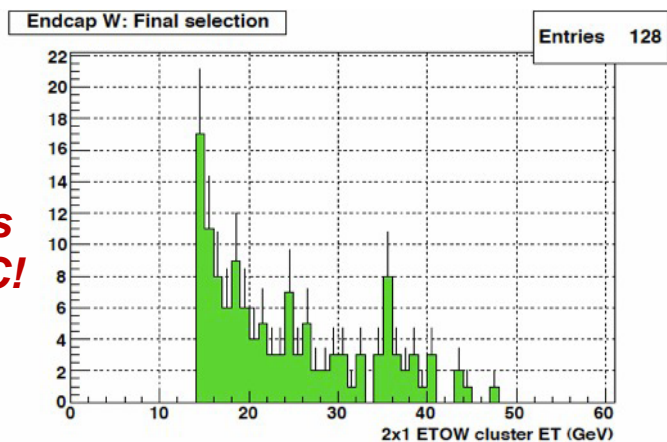
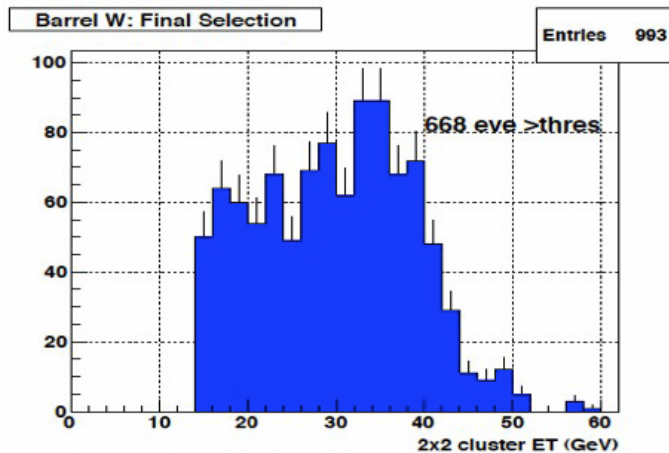
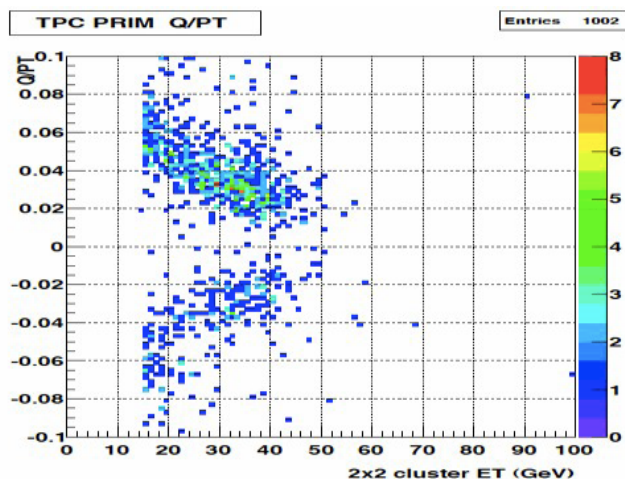


Initial AL results: 2009 (first 500 GeV run!)

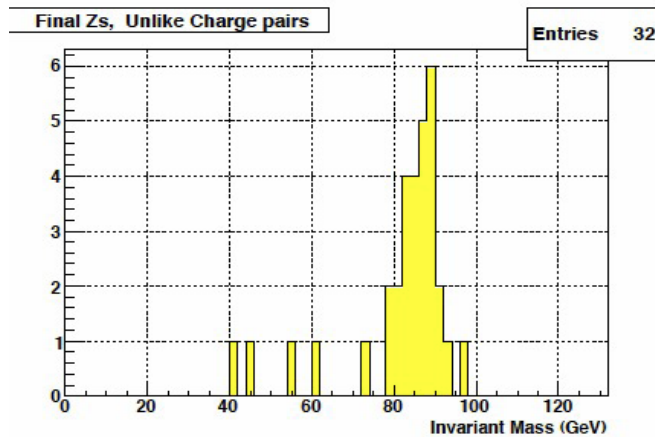


At forward/backward rapidity, increased sensitivity to a single quark flavor
Need to push measurements (and detectors) towards the beam pipe!

First look at STAR results from Run 12: $P^2L \approx 25 \text{ pb}^{-1}$

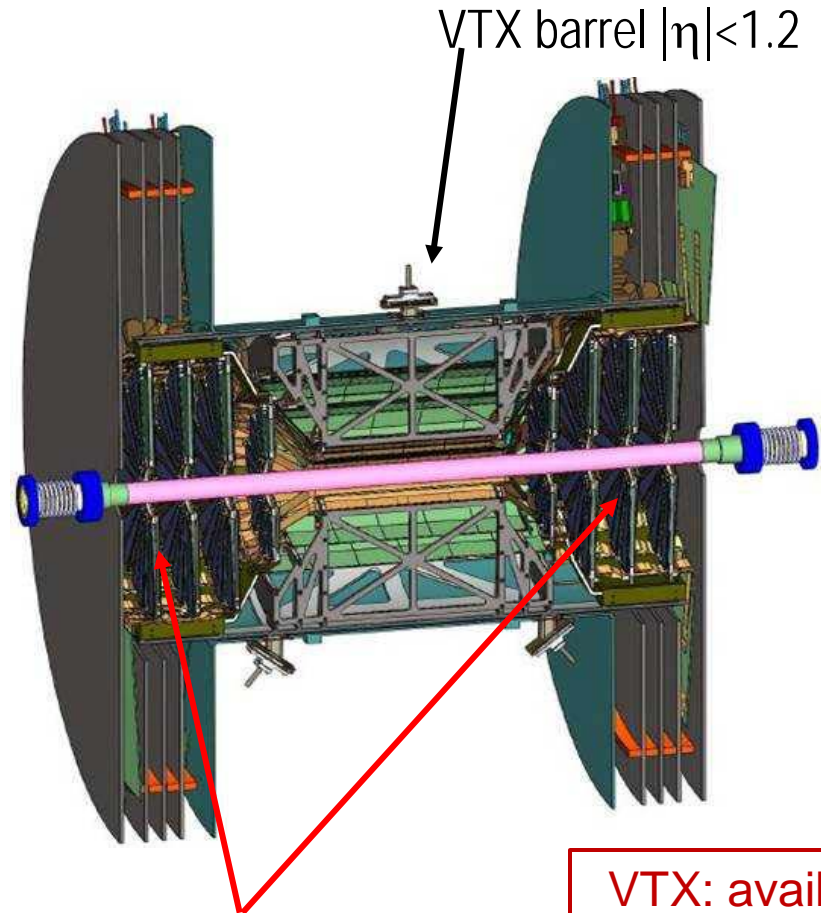
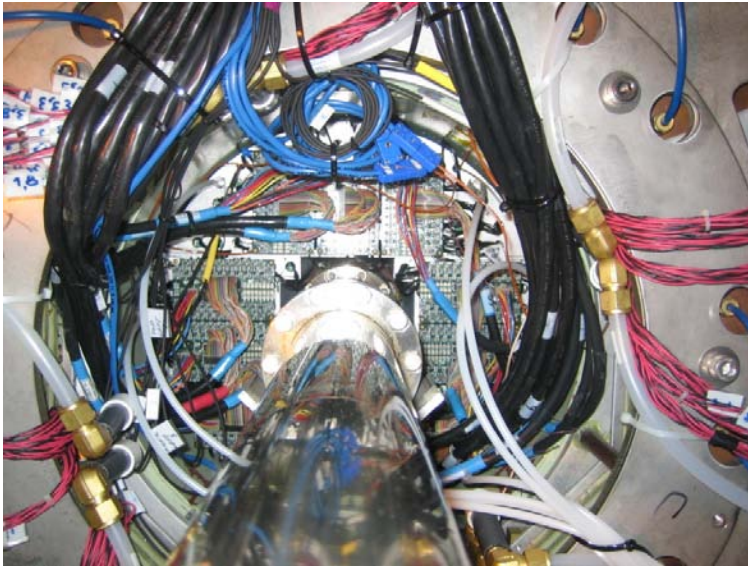


See W's
in EEMC!



... and Z's!

New forward detectors: PHENIX



Muon Piston Calorimeter (MPC):
 PbWO_4

$3.1 < |\eta| < 3.9$ 2π azimuth

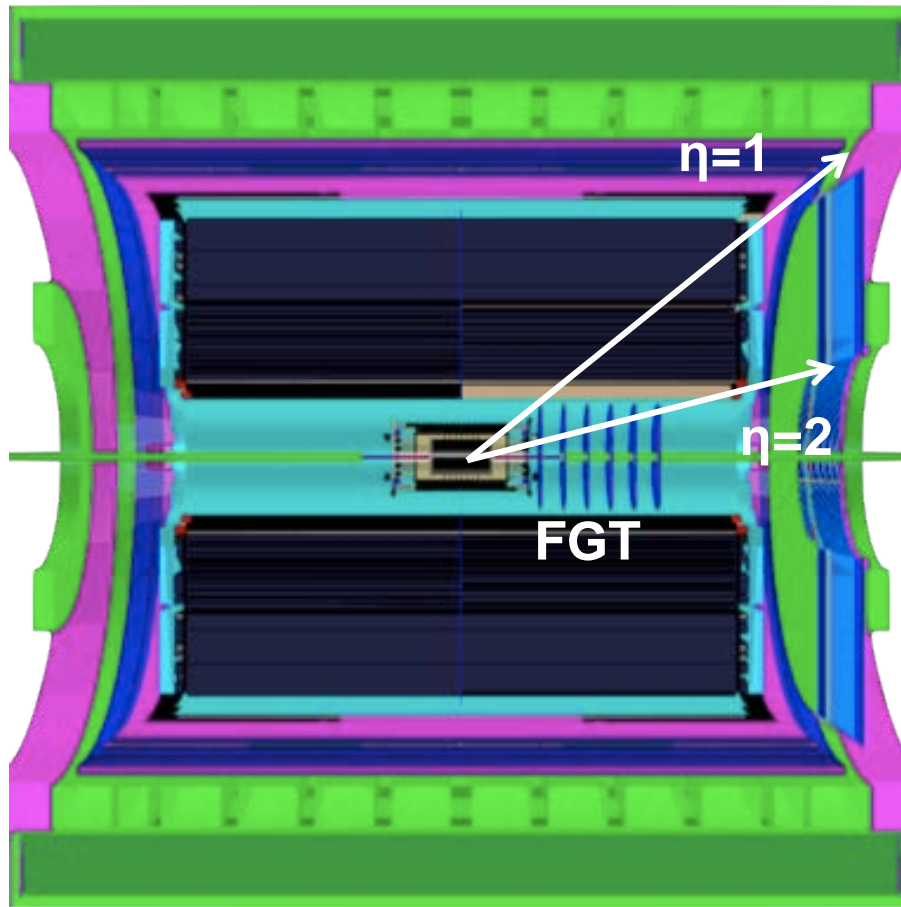
Gives access to lower $x \rightarrow 10^{-3}$

Fully available from 2008

FVTX endcaps
 $1.2 < |\eta| < 2.7$
mini strips

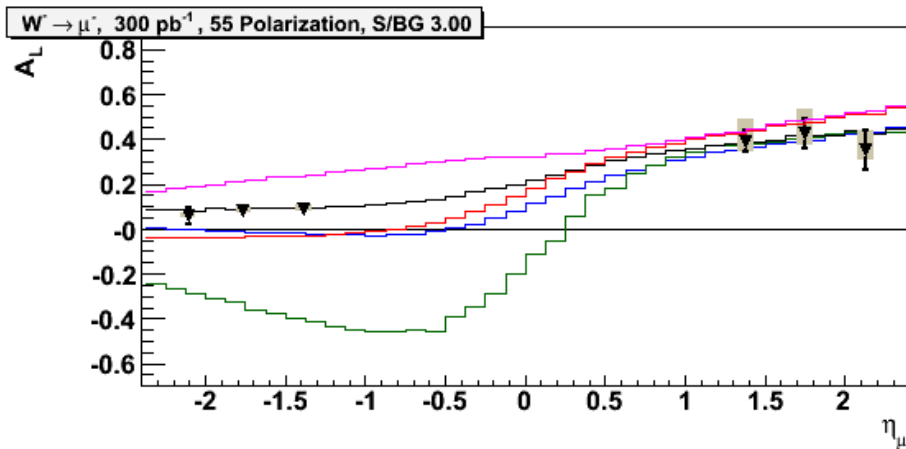
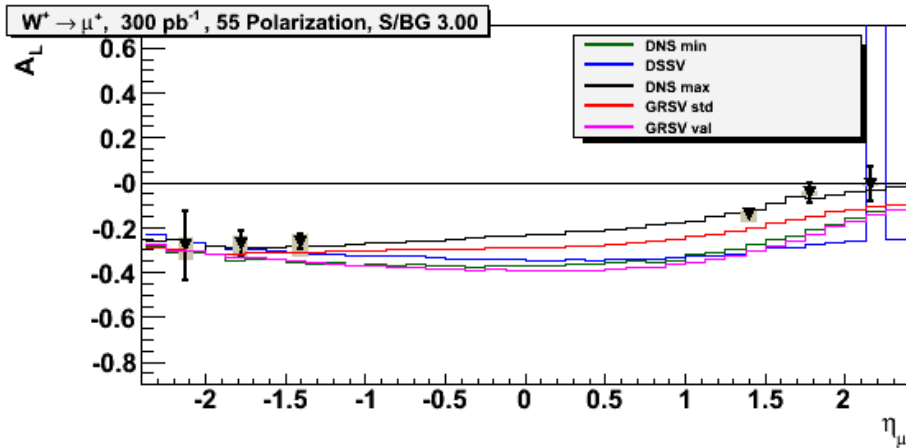
VTX: available
from 2011
FVTX: available
from 2012

Forward Tracking into the Endcap: FGT Upgrade

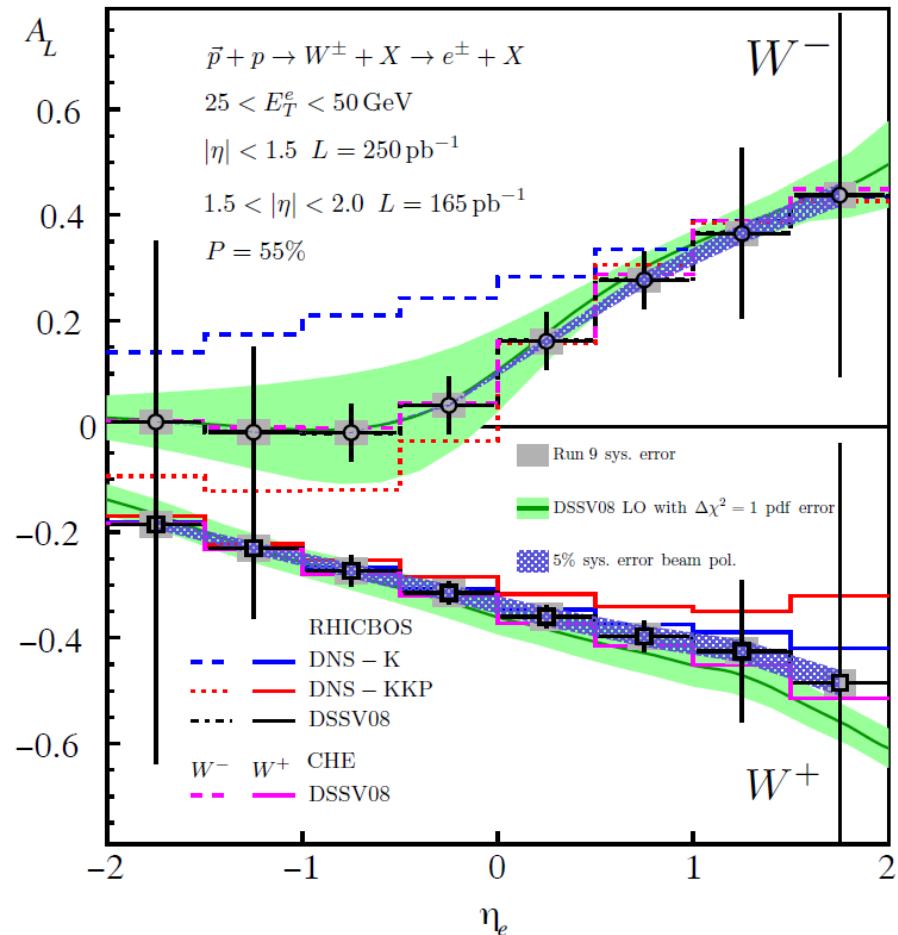


FGT: 6 light-weight triple-GEM disks using industrially produced GEM foils (Tech-Etch Inc.)
14 (out of 24) quadrants installed for Run 12

Expected W asymmetries at PHENIX and STAR

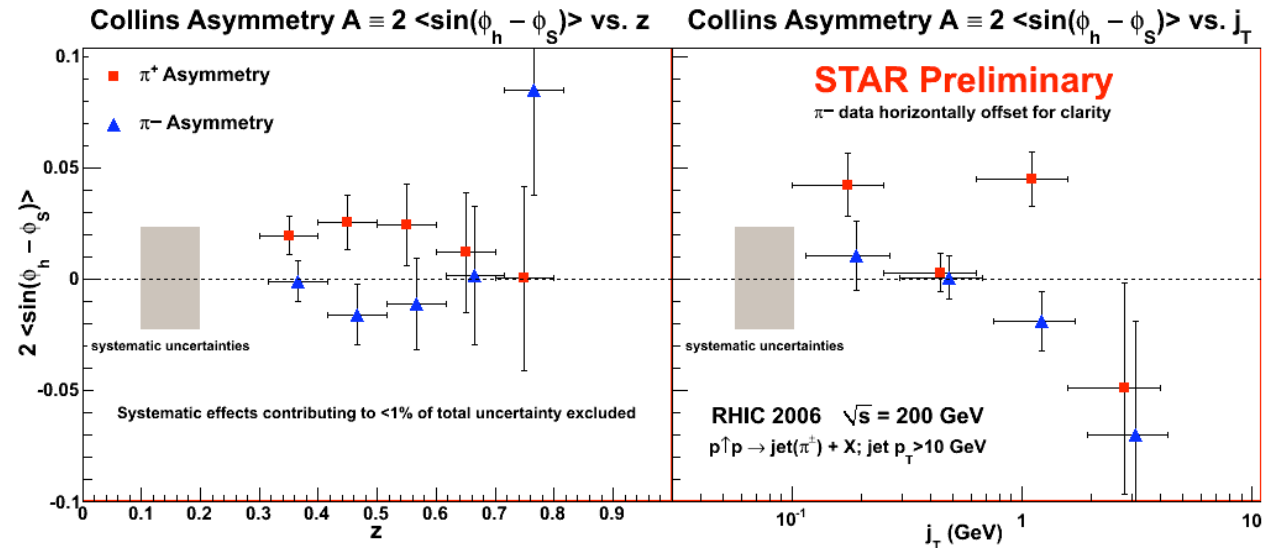
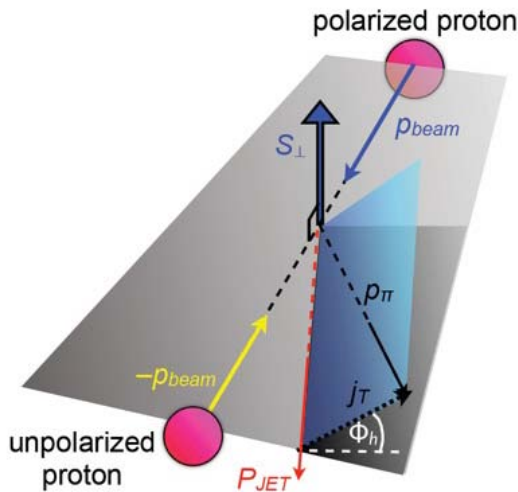


STAR Run 12 + Run 13 Projections $\sqrt{s} = 500 \text{ GeV}$



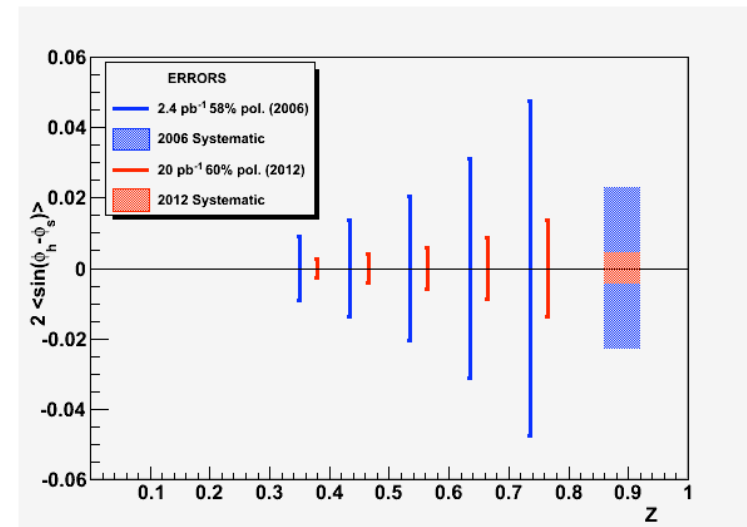
- Confirm (or not) quark polarizations in valence region, $x = 0.1-0.3$
- Provide new constraints on antiquark helicities (no FF, high Q^2)

Moving towards transversity: Mid-rapidity Collins effect

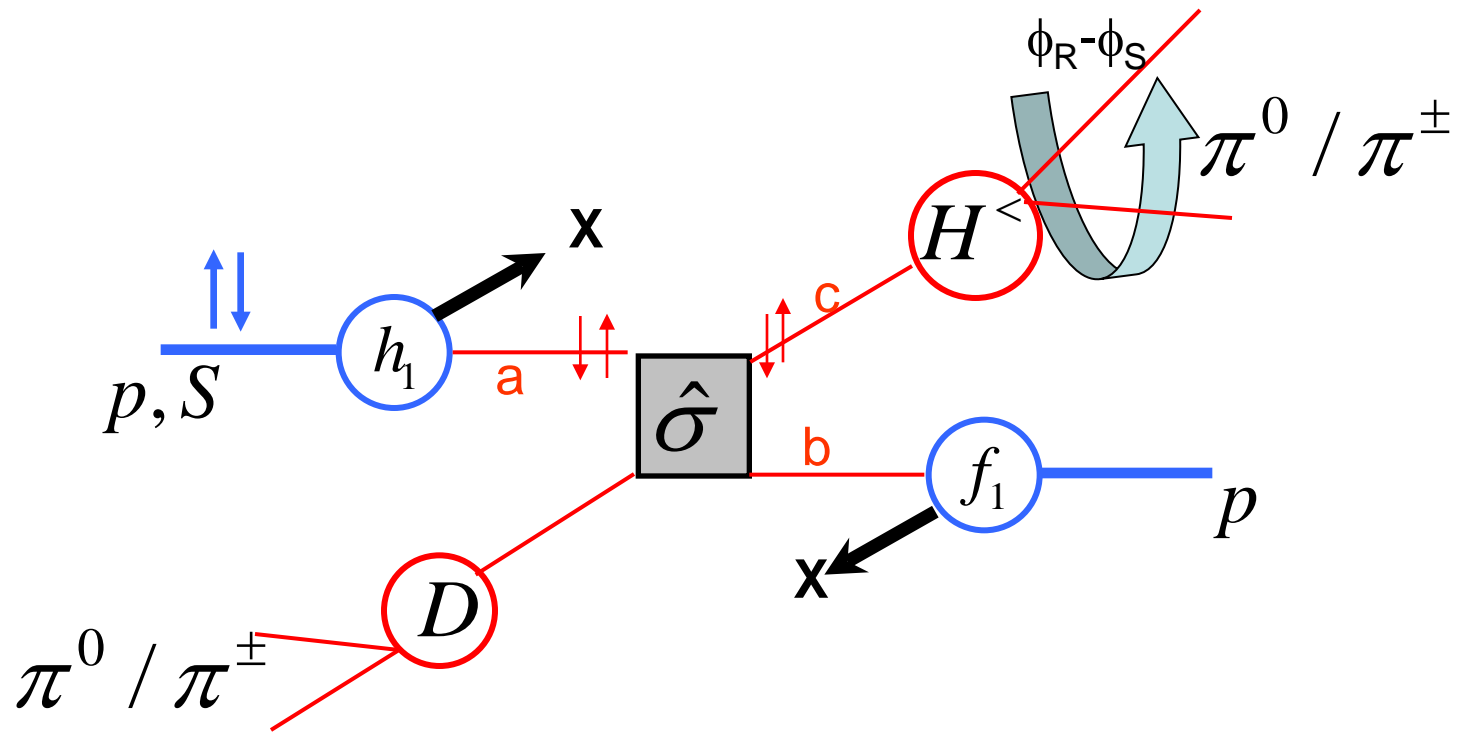


$$d\sigma \approx d\sigma^{UU} (1 + A_N \sin(\phi_h - \phi_s))$$

- Measure spin-dependent azimuthal distributions of charged pions in fully reconstructed jets
- **Sensitive to convolution of transversity and Collins fragmentation function**
- Expect improved uncertainties with new runs and larger simulations to reduce syst.



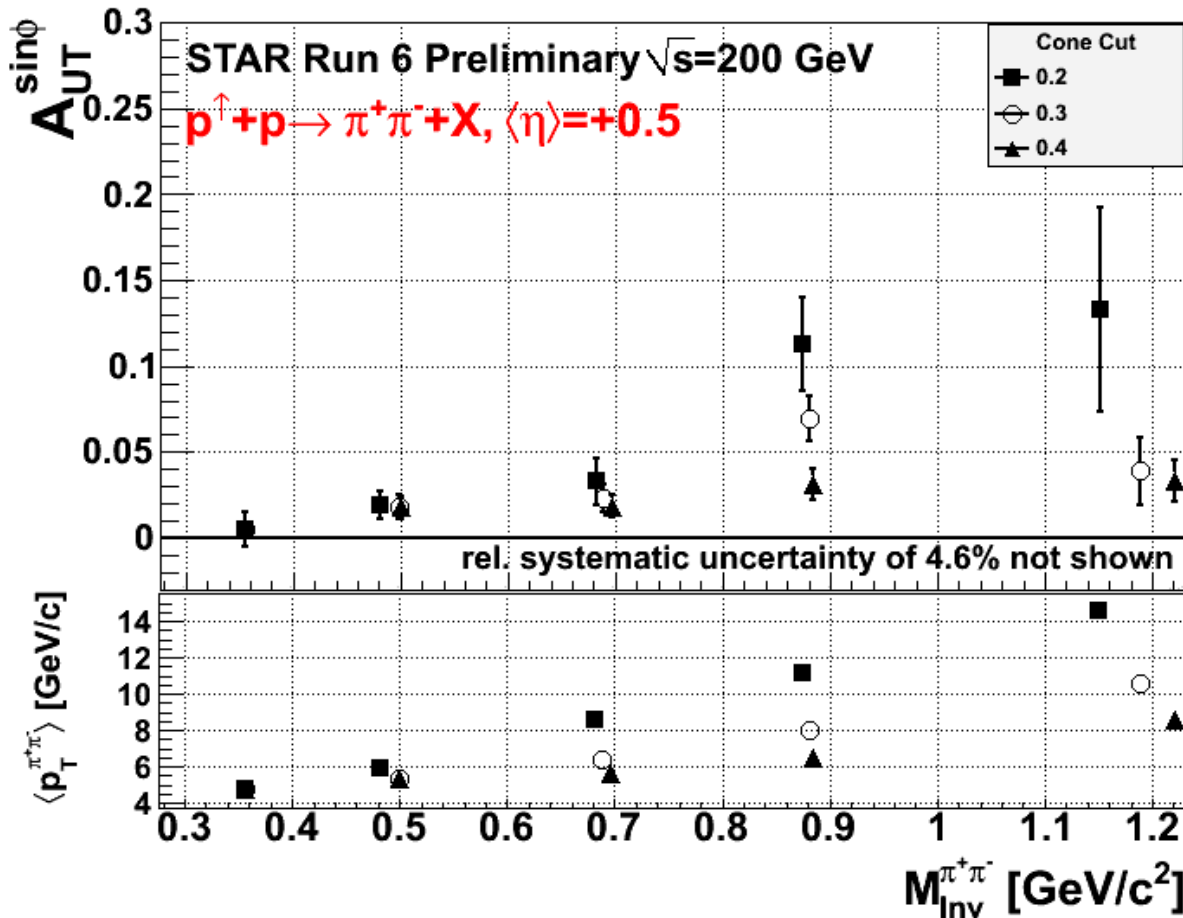
New tool: Interference Fragmentation Function



$$\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}(\phi_S - \phi_R) = A_{UT} \sin(\phi_S - \phi_R) \quad A_{UT} \propto h_1 \cdot H_1^<$$

ϕ_S : Angle between polarization vector and event plane

IFF at STAR: First results

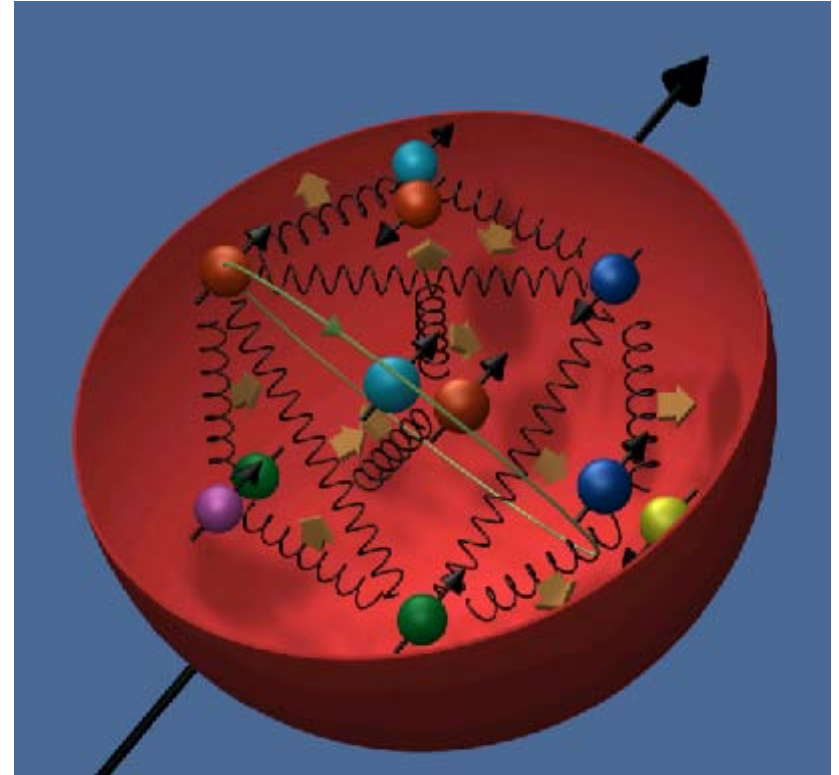


Combining these data with the IFF measurements carried out at Belle, one can extract – for the first time – quark transversity, point by point.

Greatly increased statistics already exists on tape!

Outlook: the Spin Physics Program at RHIC

- ★ First tantalizing hints of non-zero gluonic contributions to the spin of the proton – perhaps as large as the contributions from quarks
- ★ Initial studies of W/Z^* production very encouraging, limited statistics → quantities studied to date are consistent with NLO calculations
- ★ Over next 2-3 years: should achieve high precision on ΔG , begin to map out x dependence; study PV single-spin asymmetries A_L over broad η
- ★ Very exciting glimpse of transversity!



→ *Must view these studies as key components of broader program to understand all aspects of parton spin behavior in the nucleon!*