Measurement of Forward Jet A_N at RHIC

Some details behind arXiv:1304.1454

Cross Sections and Transverse Single-Spin Asymmetries in Forward Jet Production from Proton Collisions at $\sqrt{s} = 500\,\mathrm{GeV}$

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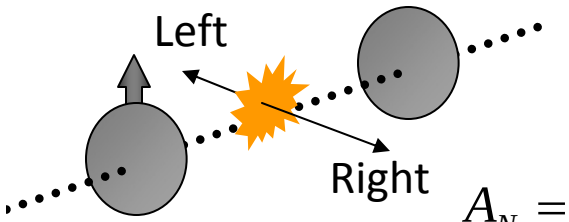
7 May 2013

Transverse Single Spin Asymmetries in $p^{\uparrow} + p \rightarrow \pi + X$



$$A_N = \frac{1}{P}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

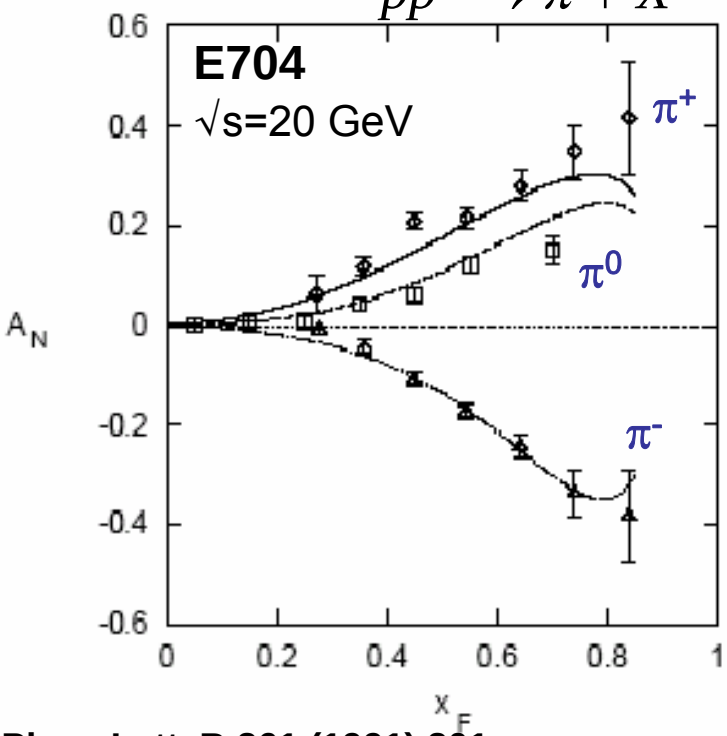
Theory expectation: small A_N for collinear pQCD at leading twist [Kane, Pumplin, Repko, **PRL 41 (1978) 1689**]

$$A_N \propto \frac{m_q}{p_T}$$

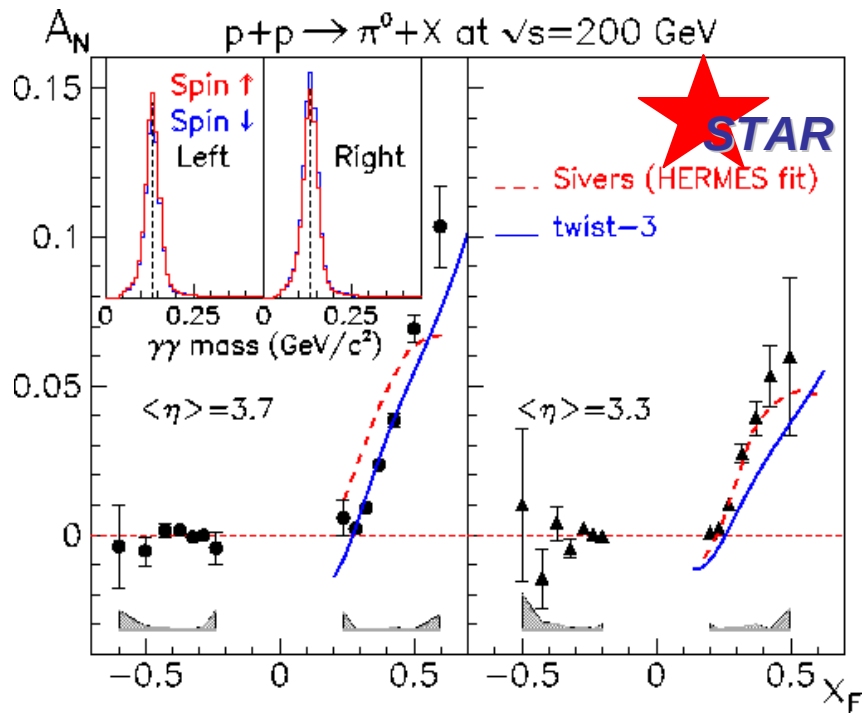
A_N O(10^{-4}) Theory

Experiment:

$$pp^{\uparrow} \rightarrow \pi + X$$



Phys. Lett. B 261 (1991) 201
Phys. Lett. B 264 (1991) 462



PRL 101 (2008) 222001

A_N O(10^{-1}) Measured

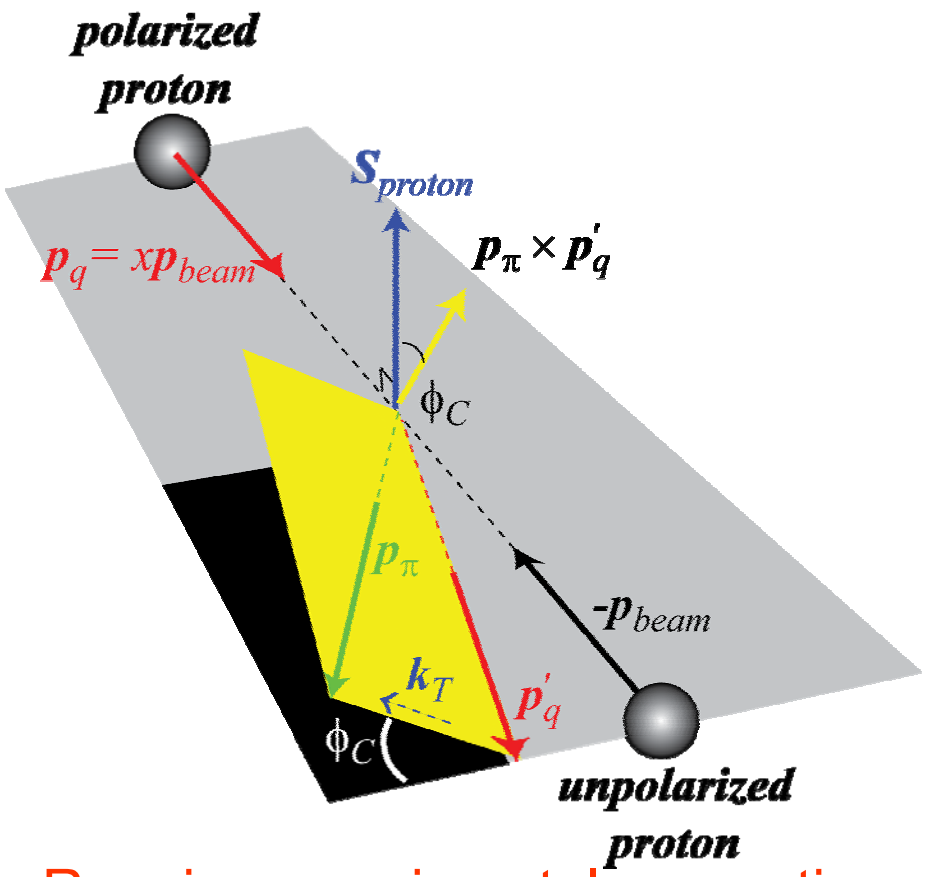
Jets integrate over π^+, π^- and π^0

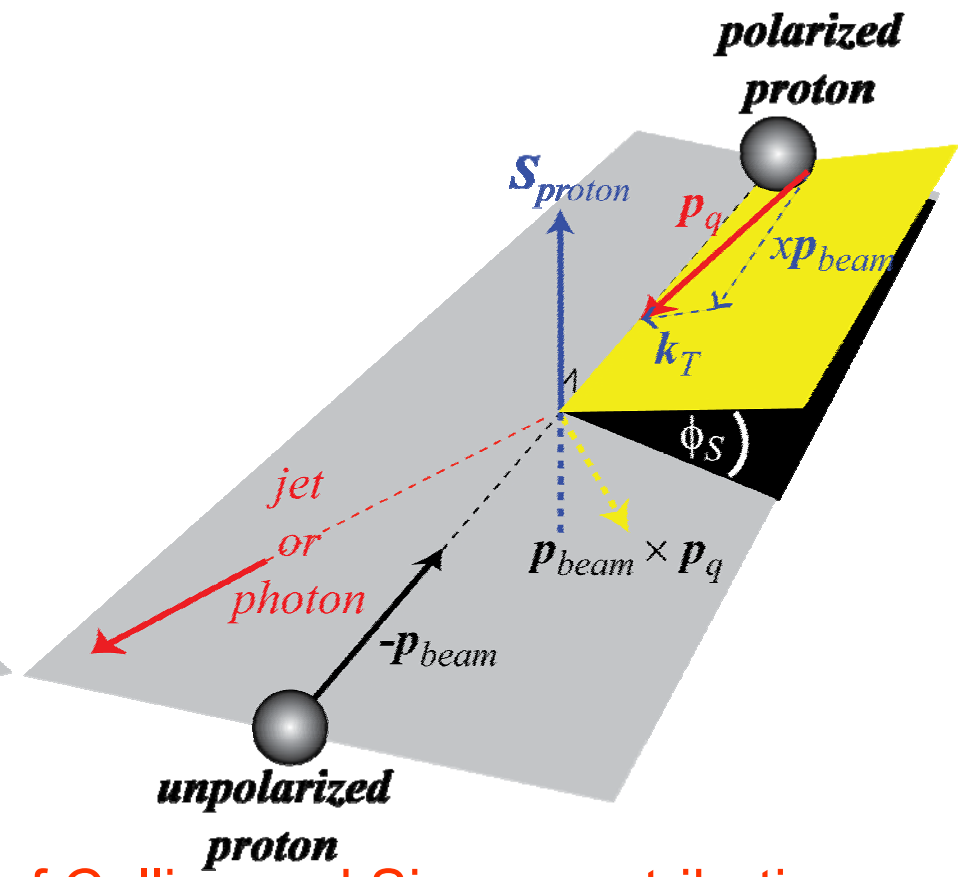
$A_N(\pi^+) \approx -A_N(\pi^-) \Rightarrow$ expect cancellations for jet A_N

Two of the Explanations for Large Transverse SSA

Collins mechanism requires *transverse quark polarization* and *spin-dependent fragmentation*

Sivers mechanism requires *spin-correlated transverse momentum* in the proton (orbital motion). SSA is present for jet, γ or γ^* (DY)





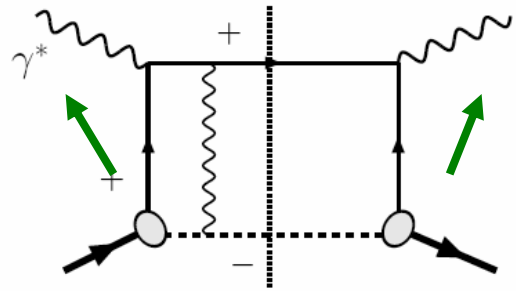
Require experimental separation of Collins and Sivers contributions

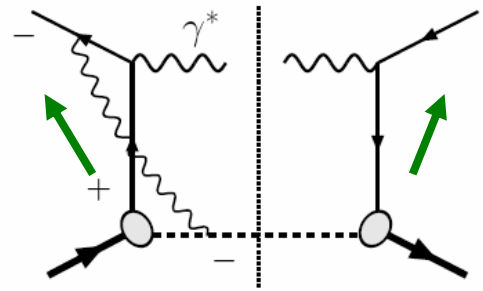
Jets have no Collins contributions

Attractive vs Repulsive Sivers Effects

Unique Prediction of Gauge Theory !

Simple QED example:

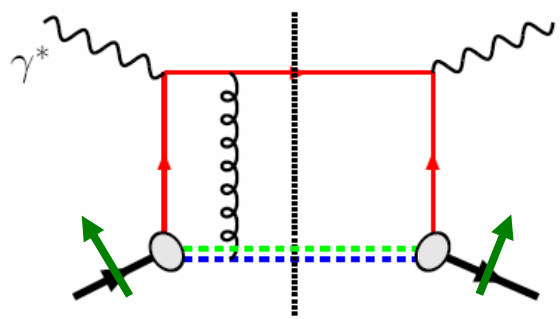


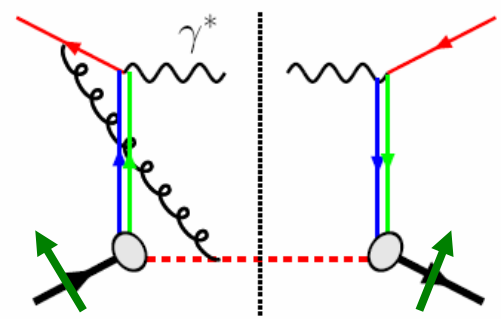


DIS: attractive

Drell-Yan: repulsive

Same in QCD:





As a result:

$$\mathrm{Sivers}|_{\mathrm{DIS}} = -\mathrm{Sivers}|_{\mathrm{DY}}$$

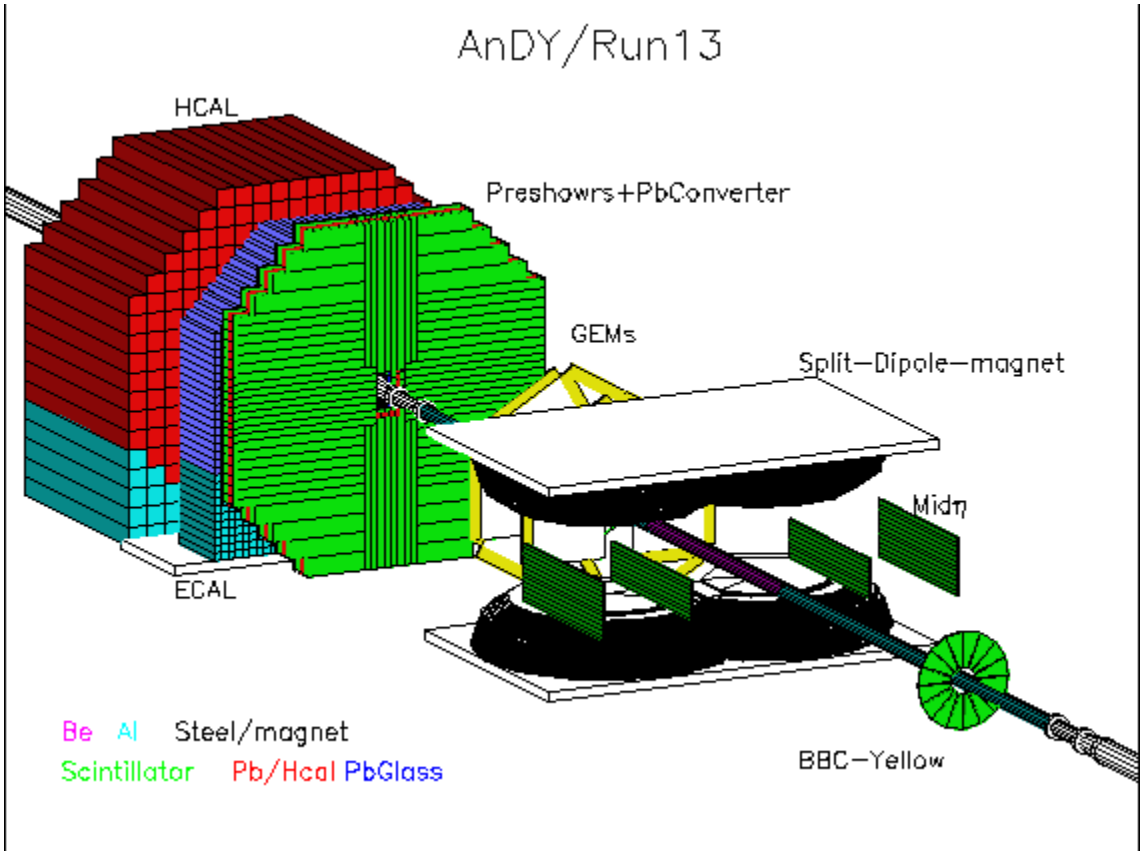
DOE performance milestone HP13

Transverse Spin Drell-Yan Physics at RHIC (2007)

http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf

Goal of A_NDY Project

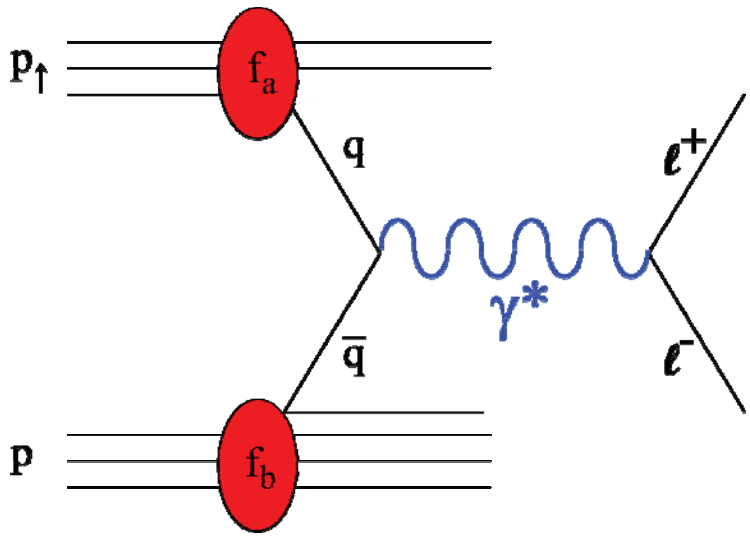
Measure the analyzing power for forward Drell-Yan production to test the predicted change in sign from semi-inclusive deep inelastic scattering to DY associated with the Sivers function



GEANT model of proposed A_NDY apparatus (run-13)

Status of the A_NDY Project

See http://hena.lbl.gov/IP2/Business/review/0-proposal_120229.pdf



A new effort at RHIC to make the first measurement of the analyzing power (A_N) for Drell Yan (DY) production at $\sqrt{s}$=500 GeV

- 2010 – Letter of Intent reviewed by program advisory committee (PAC)
- 2011 – model apparatus operated in RHIC run 11 / full proposal endorsed by PAC
- 2012 – ~2.5 pb^{-1} in RHIC run 12 / time constraint and manpower issues from Brookhaven review

Jets

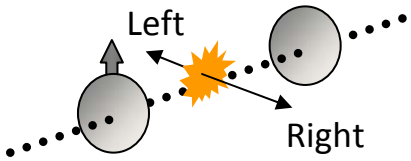
From A_NDY Model Apparatus Operated in 2011 and 2012 RHIC runs

- Measuring A_N for DY at RHIC is challenging, but looks like it can be done.
- Matching kinematics to those used for semi-inclusive DIS requires forward detection at RHIC (not well instrumented)
- Jets must have analyzing power if DY has analyzing power

Do jets produced with moderate x_F have an analyzing power?

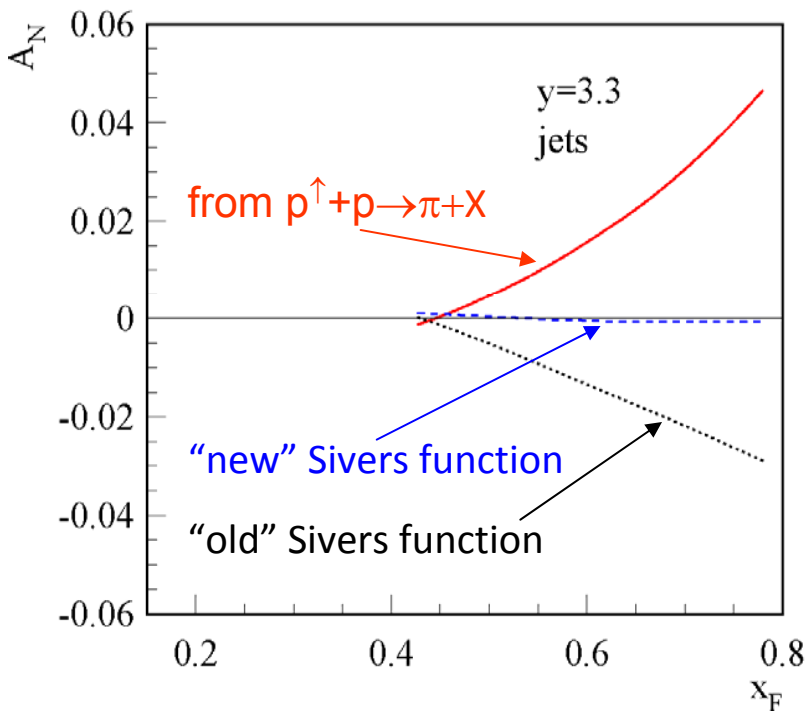
Expectations for Jet A_N

(Prior to Measurements)



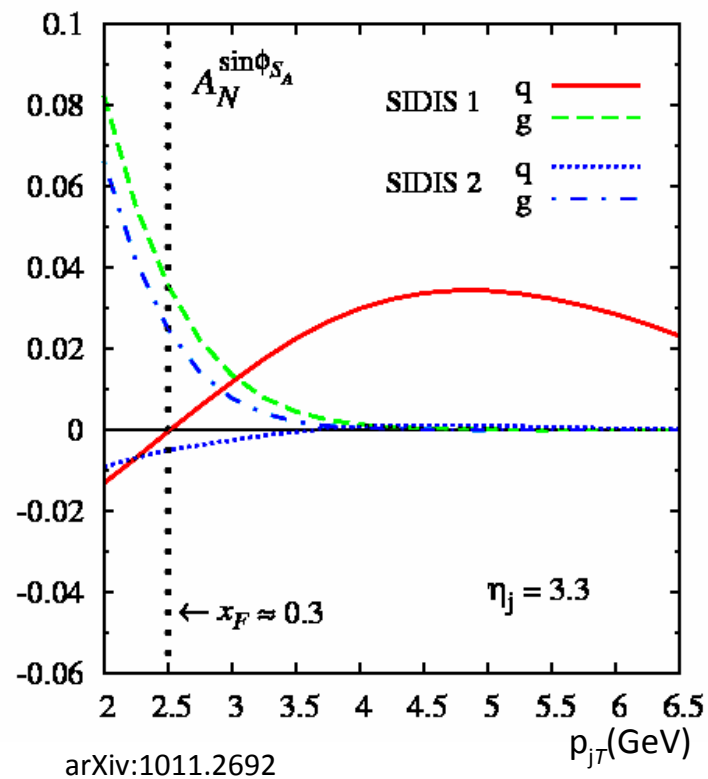
$$A_N = \frac{1}{P}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

√s=200 GeV



arXiv:1103.1591

√s=200 GeV



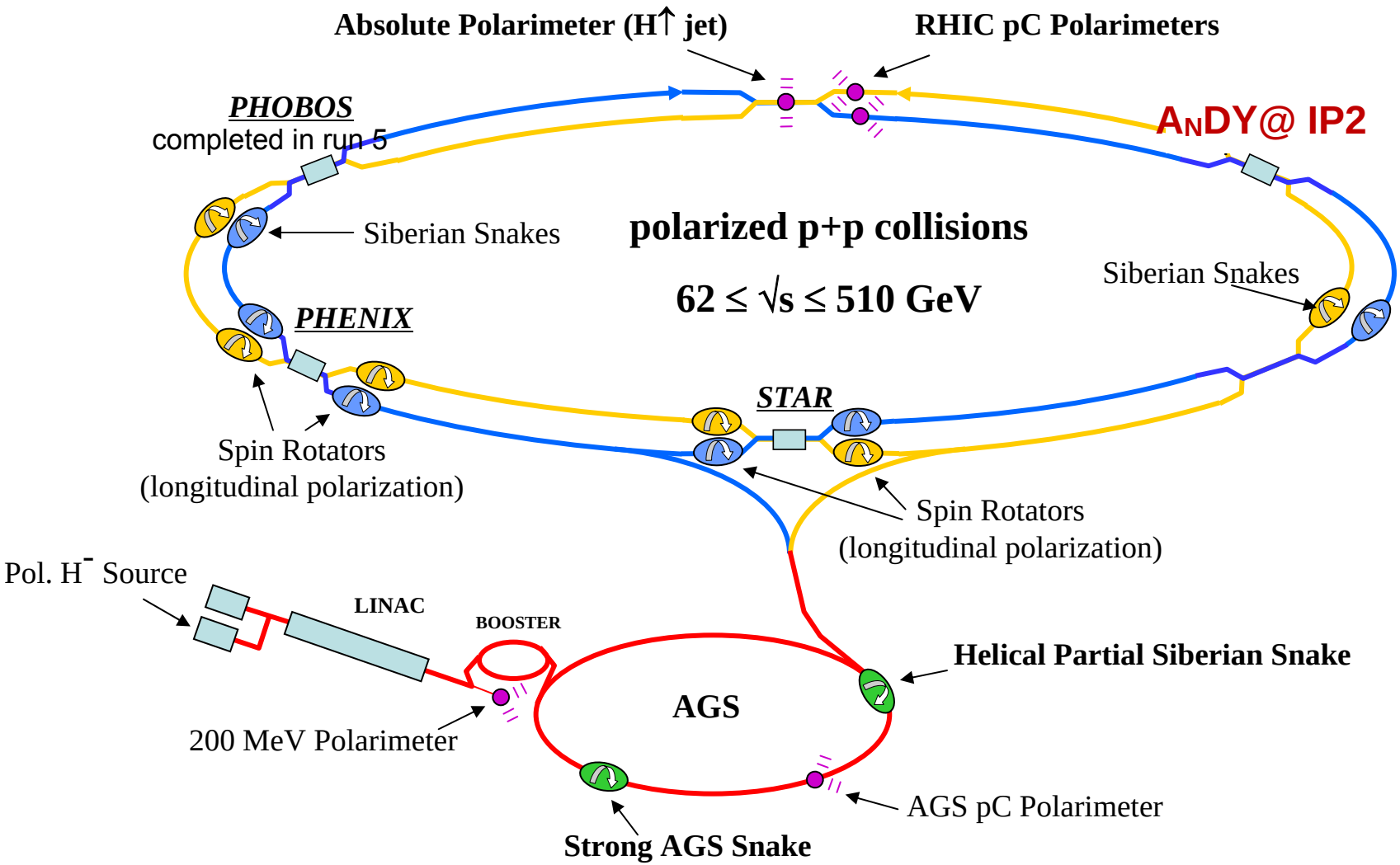
arXiv:1011.2692

√s = 500 GeV jets have 2.5x larger p_T at the same x_F relative to these predictions.

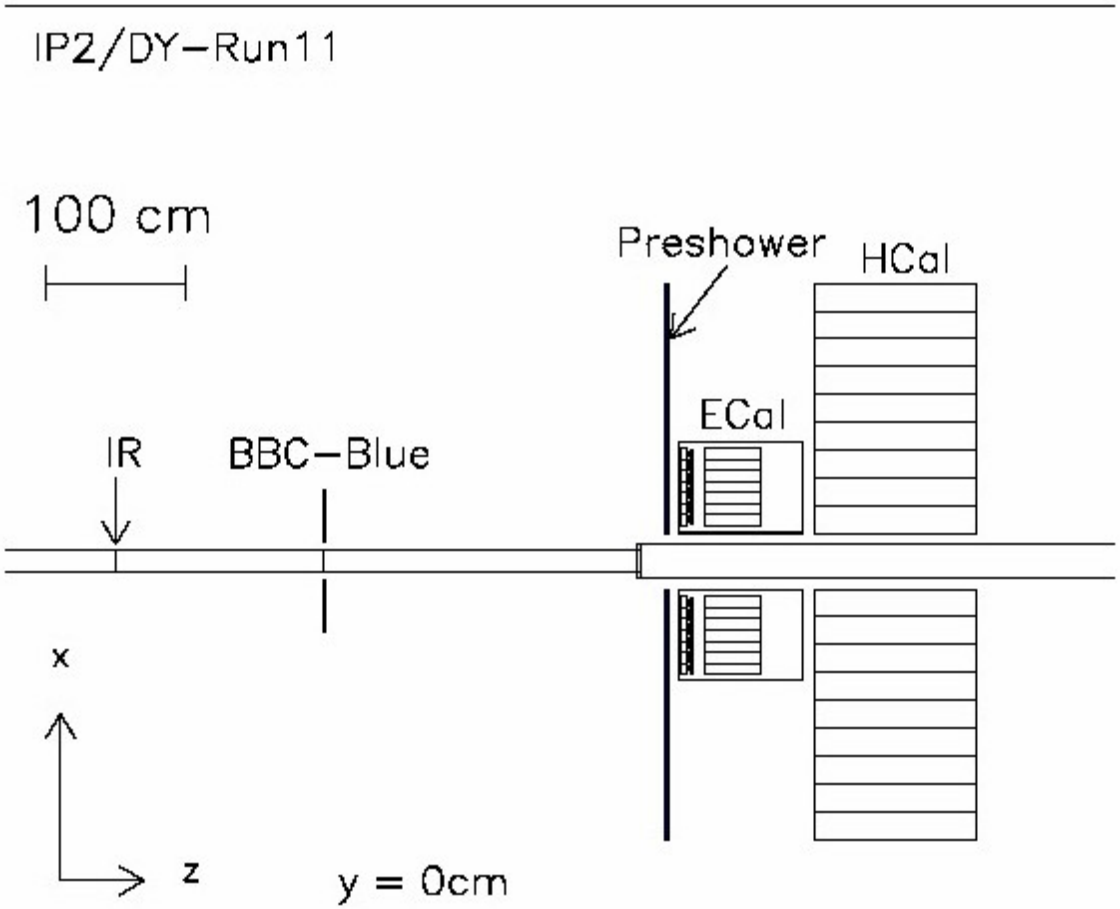
Jets integrate over π^+, π^-, and π^0

"Mirror" A_N for π^+ and π^- should result in cancellations for jet A_N

RHIC as a polarized proton collider

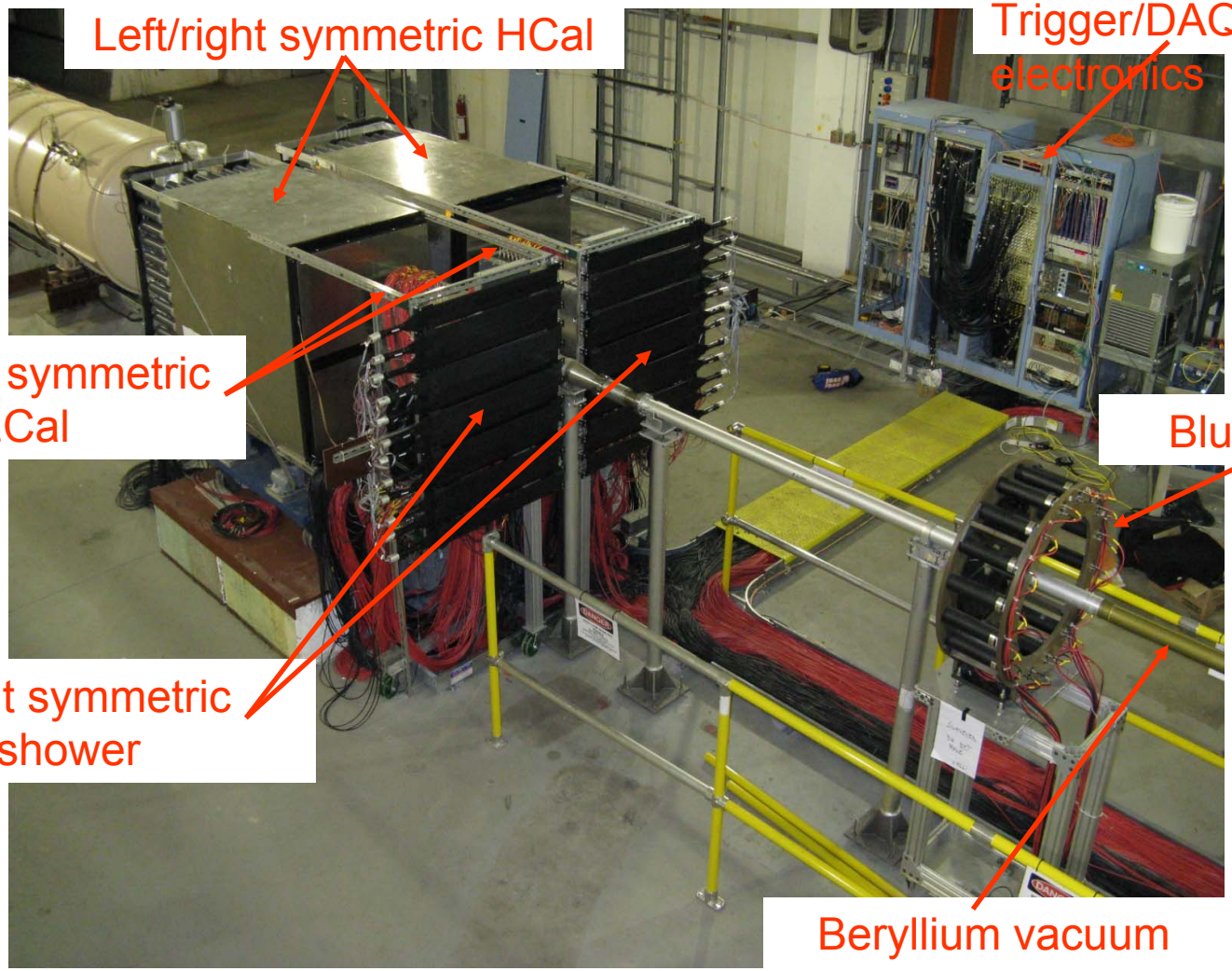


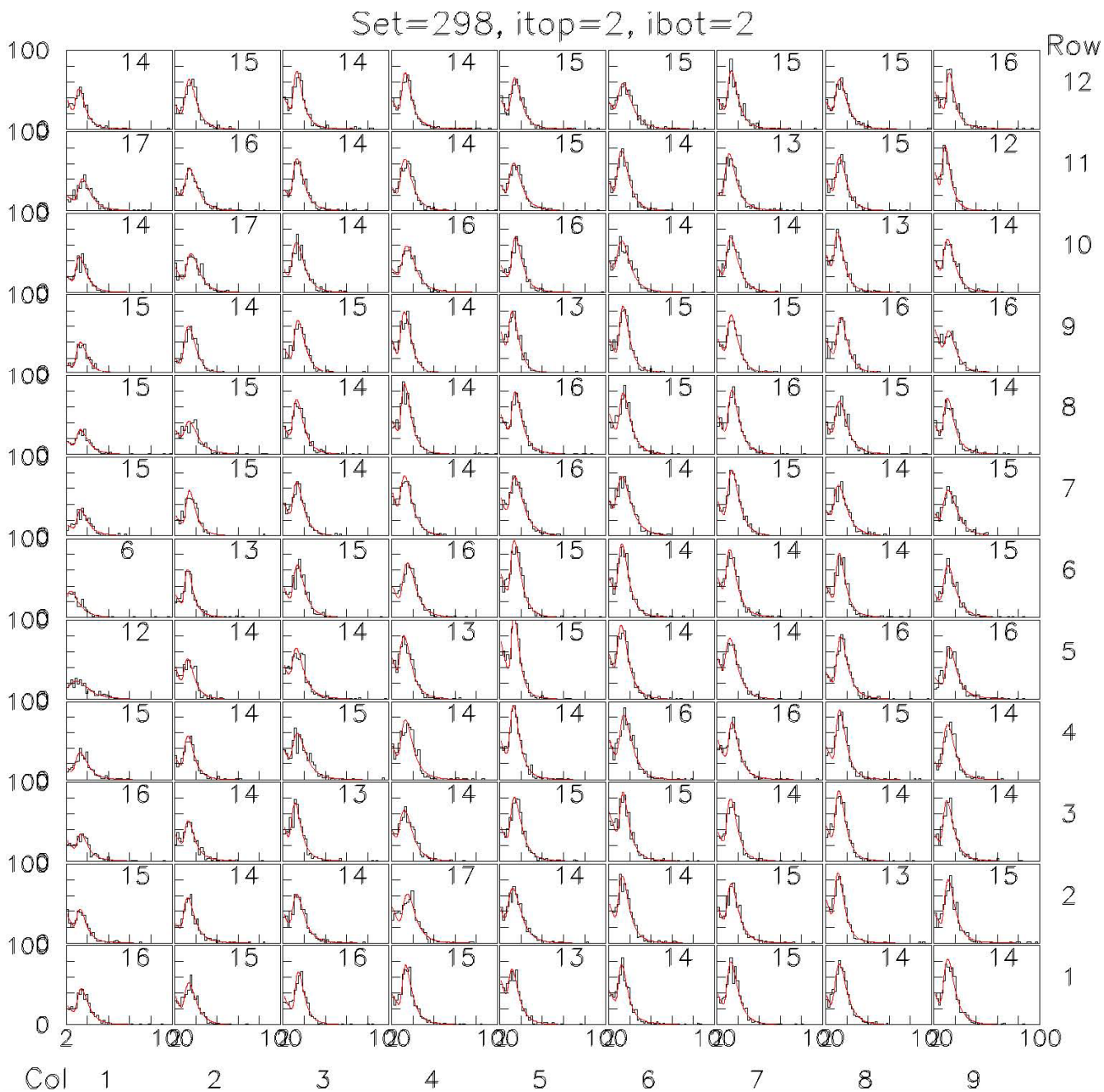
Run-11 setup



- Beam-beam counter (BBC) for minimum-bias trigger and luminosity measurement (from PHOBOS [NIM A474 (2001) 38])
- Zero-degree calorimeter and shower maximum detector for luminosity measurement and local polarimetry (ZDC/ZDC-SMD, not shown)
- Hadron calorimeter (HCal) are L/R symmetric modules of 9x12 lead-scintilating fiber cells, $(10cm)^2$x117cm (from AGS-E864 [NIM406(1998)227])
- Small ECal - 7x7 matrices of lead glass cells, $(4cm)^2$x40cm (loaned from BigCal at JLab)
- Preshower detector - two planes, 2.5 & 10 cm

Run-11 setup

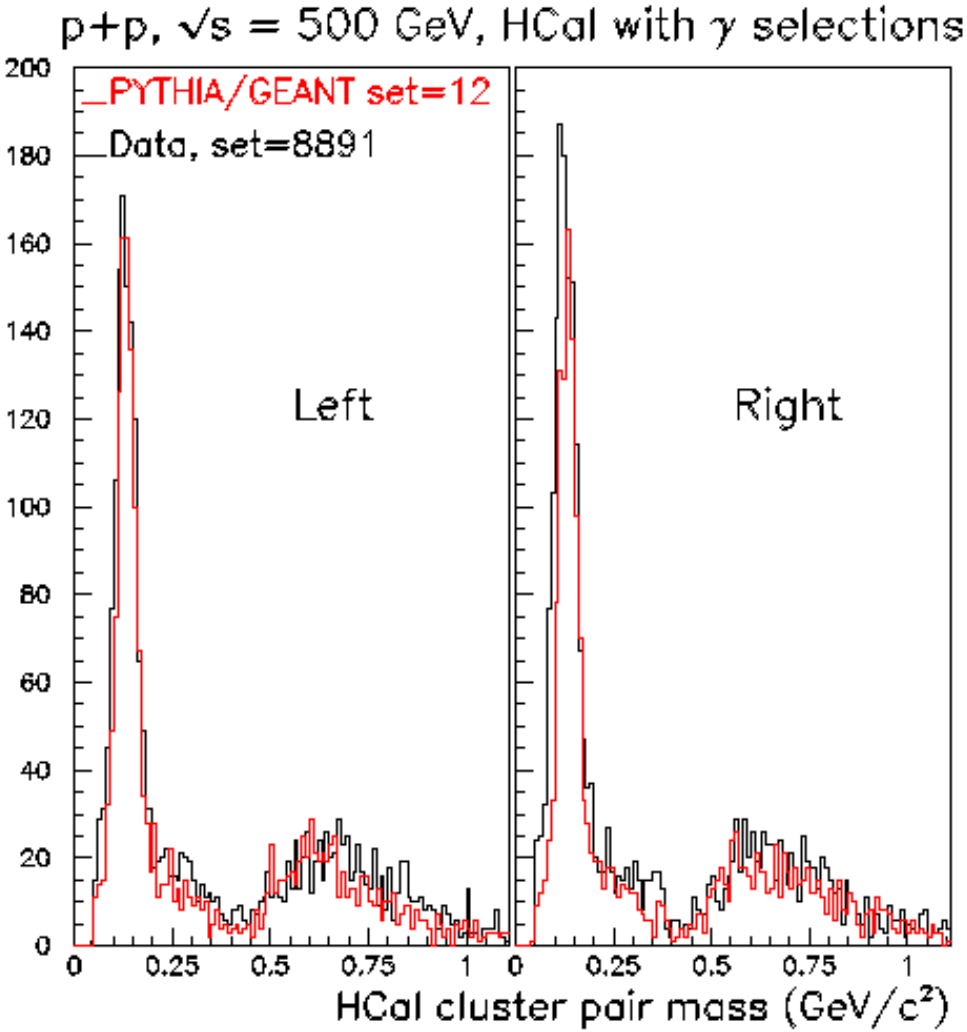

Left/right symmetric HCal
Trigger/DAQ electronics
Left/right symmetric ECal
Blue-facing BBC
Left/right symmetric preshower
Beryllium vacuum pipe



Cosmic Ray Muon Calibrations

- *Prior to run 11 operation, HCal modules had relative PMT gains set by cosmic-ray muon response.*
- *Triggering enabled verification of scintillating fiber attenuation length in each detector*
- *ADC data from beam-left module with fits to Landau distribution (centroid shown) + exponential background*

Calibration - HCal



Cluster pair mass distributions in HCal modules from minimum-bias run-11 data and simulations (absolute normalization) arXiv:1109.0650

- Relative calibration of HCal cells by cosmic ray muons
- Absolute energy scale is set by:

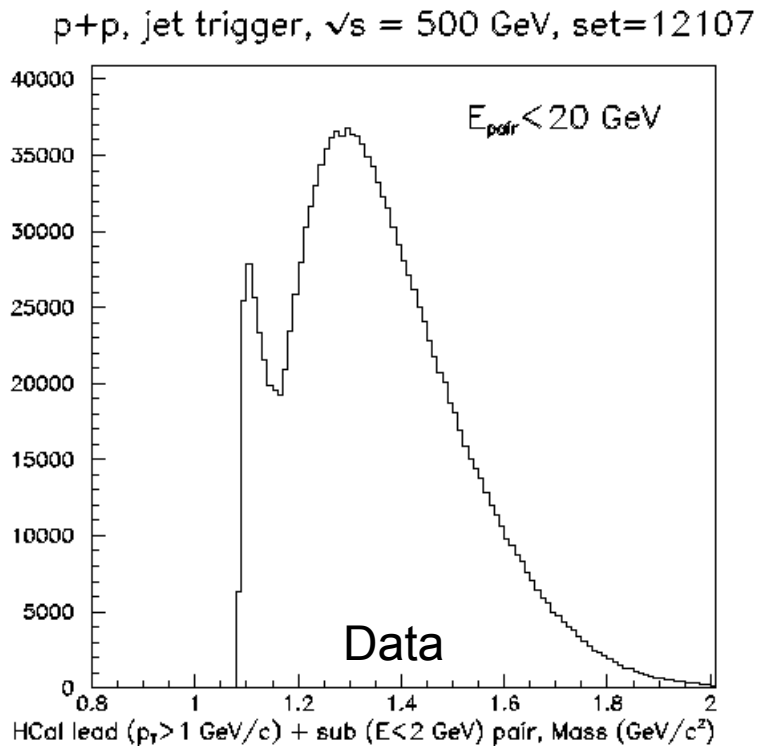
1) slope matching of energy distributions from minimum-bias data and simulation;
2) reconstruction of $\pi^0 \rightarrow \gamma\gamma$ from HCal clusters

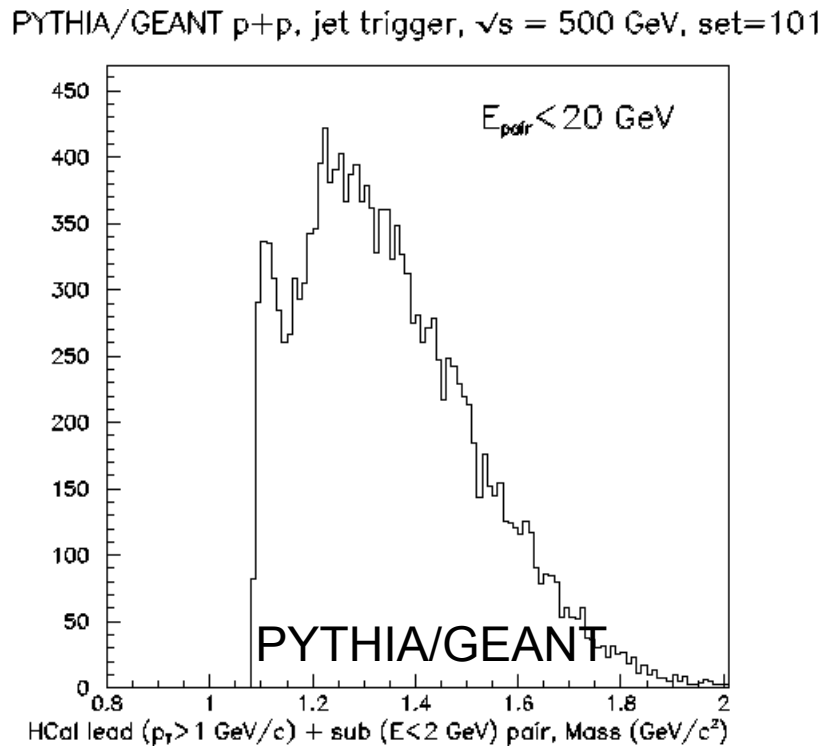
Cuts applied to select "electromagmetic" clusters:

(1) 1-tower clusters; (2) Ecl > 1.8 GeV;
(3) Epair > 5 GeV; (4) zpair < 0.5;
(5) |x|>50 cm to avoid ECal shadow

- Neutral pions set the energy scale for the jets
- Corrections to HCal calibration for hadron showers are expected to be ~15% from simulations

Hadronic Response



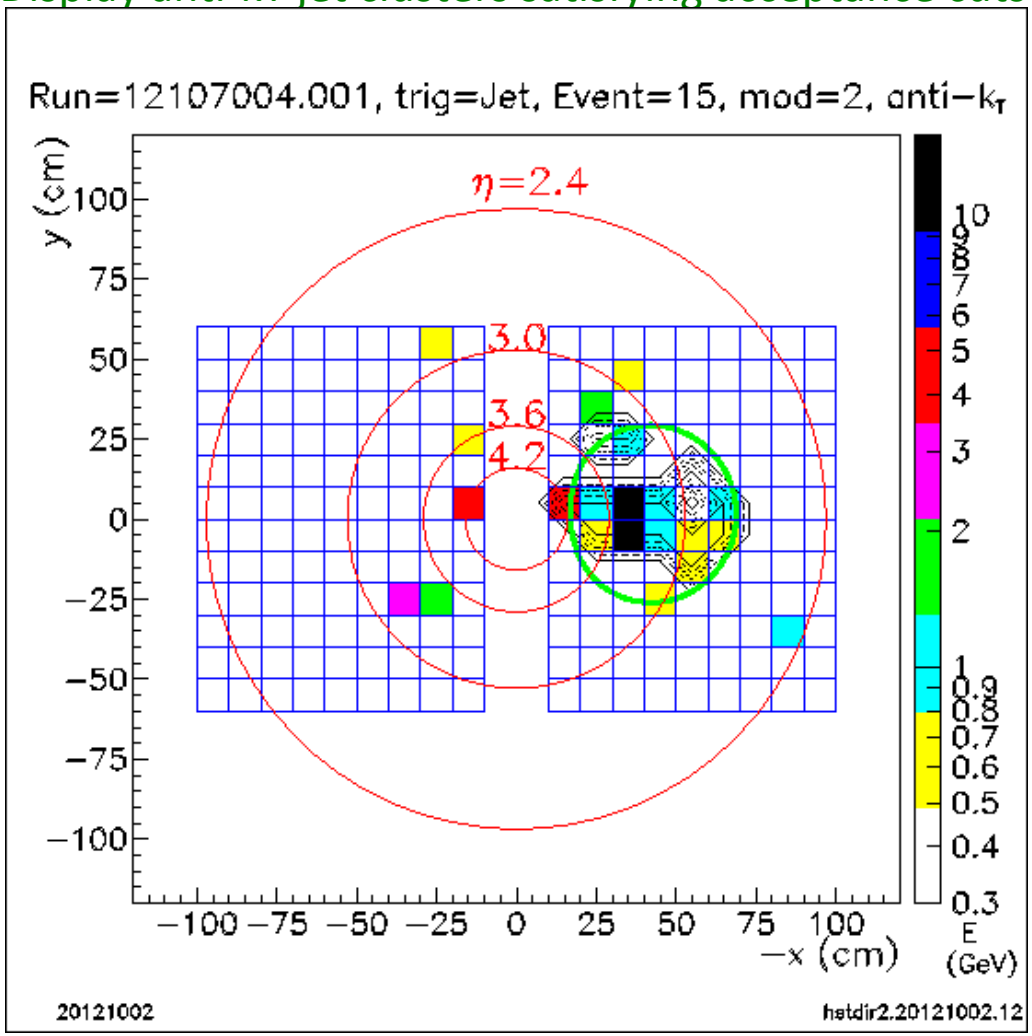


- Best indication of the degree to which electromagnetic and hadronic responses from HCal are similar is from cluster pairs, assigning leading cluster to proton (antiproton) and subleading cluster to π^- (π^+), with rest energies included.
- Attribute peak in invariant mass to Lamba (anti-Lambda)
- Use E=1.12E' – 0.1 GeV for tower energy in jet finder to account for average compensation of hadronic and electromagnetic responses, where E' is tower energy from neutral pion calibration.

Jet Reconstruction – Anti-k_T Jet Finder

Trigger on HCal masked ADC Sum in L/R Modules

Display anti-kT jet clusters satisfying acceptance cuts



- Anti-k_T Jet Finder Procedure :
  - Iteratively merge pairs of clusters until clusters cease to satisfy distance criteria
    - No Seed
    - Towers can be outside trigger region
  - Distance Criteria (clusters j,k) :
    - $d_{jk} = \min(k^{-2}_{Tj}, k^{-2}_{Tk})(R^2_{jk}/R^2)$
    - $R^2_{jk} = (\eta_j - \eta_k)^2 + (\Phi_j - \Phi_k)^2$
    - If $d_{jk} < k^{-2}_{Tj}$ then merge clusters j,k
  - Use cone with radius = 0.7 in η-Φ space but cluster towers can fall outside of cone
  - Impose acceptance cuts to accept/reject jet:

    $|\eta_J - 3.25| < 0.25$

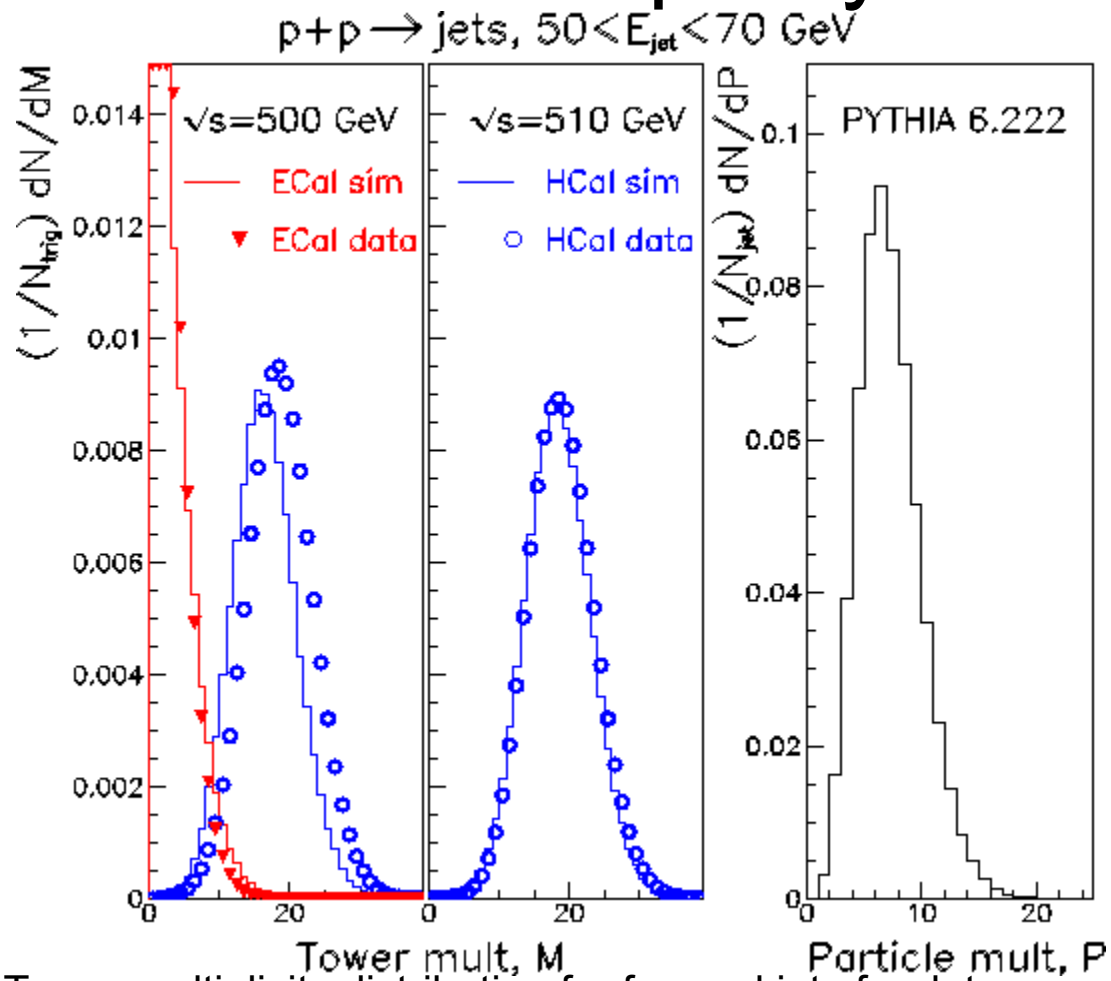
    $|\Phi_J - \Phi^{Off}| < 0.50$

    where $\Phi^{Off} = 0$ for HCL

    $\Phi^{Off} = \pi$ for HCR
  - Energy Cut : $E_{jet} > 30$ GeV
  - Algorithm : arXiv : 0802.1189
    arxiv : 1209.1785

Events look "jetty" / Results with anti-kT algorithm similar to midpoint cone algorithm

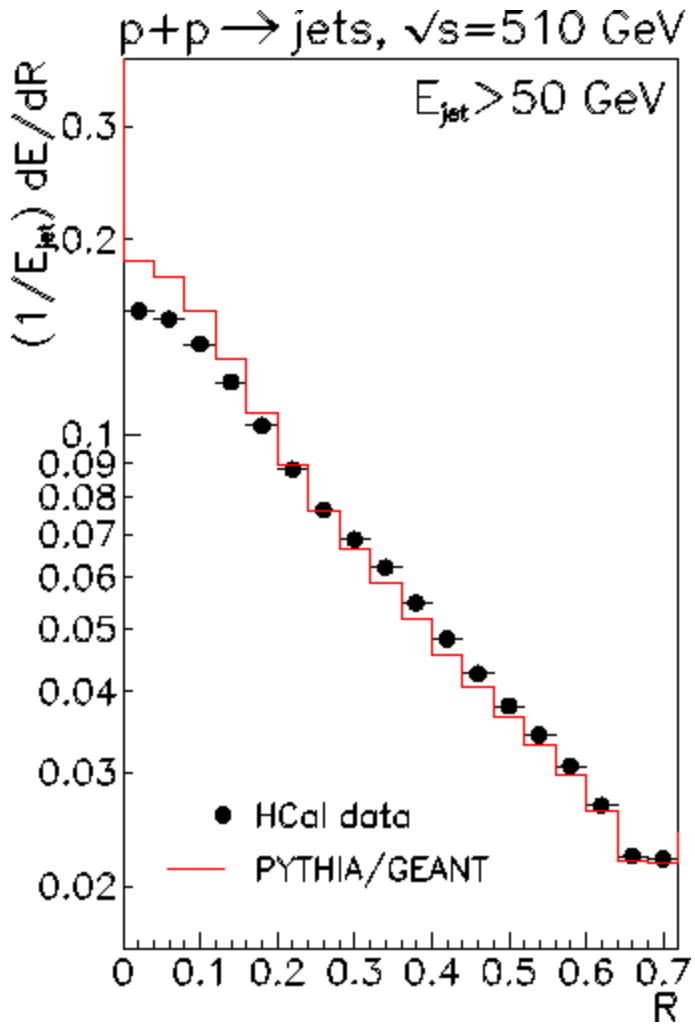
Multiplicity Distributions



Tower multiplicity distribution for forward jets for data compared to PYTHIA/GEANT simulations (left) jets from √s=500 GeV collisions, as used for A_N; and for (middle) jets from √s=510 GeV collisions, as used for jet cross section. (Right) Particle multiplicities deduced from PYTHIA/GEANT simulation

- Jet-triggered data is generally well described by simulation
- Particle multiplicities of forward jets are comparable to what is observed in e^+e^- at √s≈10 GeV. PRD **56** (1997) 17
- Transverse momenta of forward jets at RHIC are similar to those probed in FermiLab fixed target experiments PRL **38** (1977) 1447; PRL **41** (1978) 9; PRL **44** (1980) 514; PRD **31** (1985) 984.

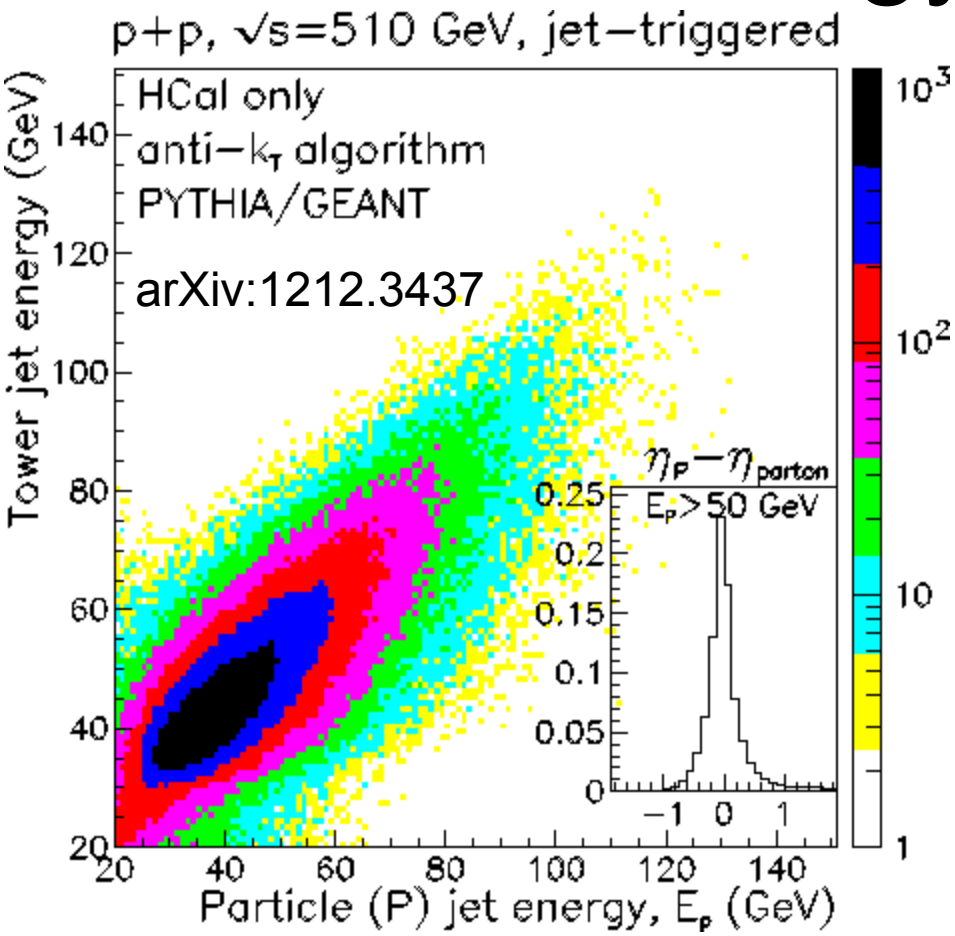
Jet Shape



Event averaged jet shape, corresponding to how the energy depends on the distance a tower is from the thrust axis in (η,φ) space

- Anti-kT algorithm reconstructs clusters that concentrate the energy near the thrust axis of the cluster.
- Some indication that jets in PYTHIA are too narrow, in comparison of full simulation to data.
- Although the anti-kT clusters have on average little energy distant from the thrust axis, studies have shown that the jet energy scales smoothly vary as the cone size used in the jet finder is decreased.

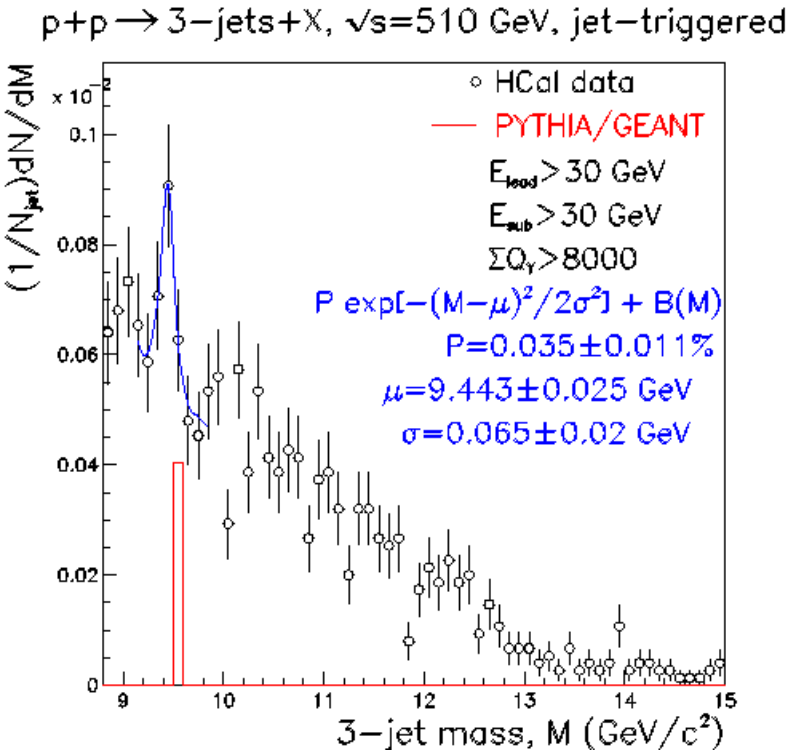
Jet Energy Scale - I

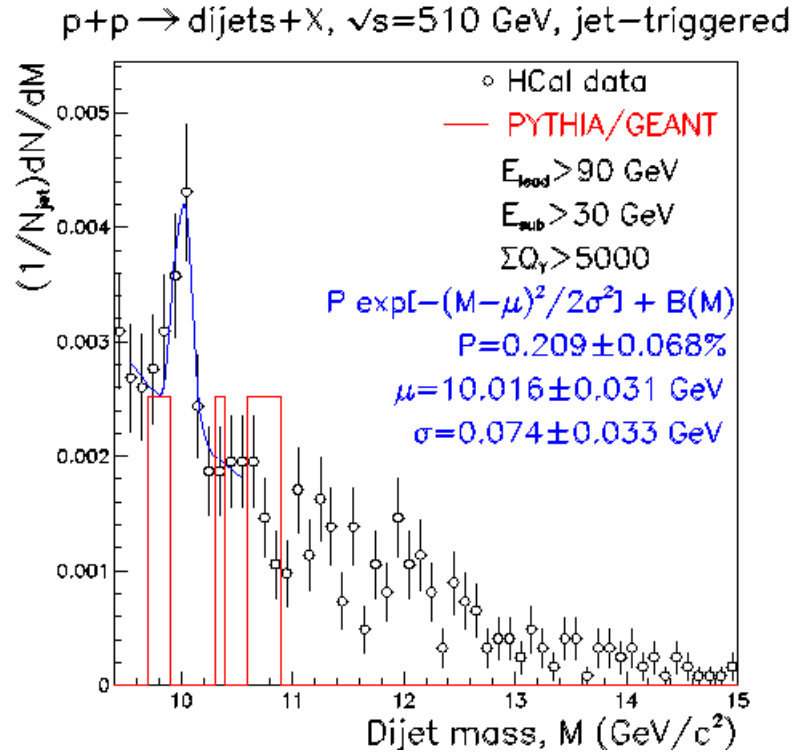


- Simulations confirm energy scale of jets, by comparison of “tower” jets [with full detector response] to “particle” jets [excluding detector response].
- Reconstructed jets are directionally matched to hard-scattered partons as generated by PYTHIA

Correlation between tower jet [from PYTHIA/GEANT] to particle jet [from PYTHIA]. The inset shows the η component of the directional match ($\Delta\eta$) between particle jets and a hard-scattered parton, whose direction is defined by ηparton,φparton. There is a 82% match requiring $|\Delta\eta|,|\Delta\varphi|<0.8$

Jet Energy Scale - II



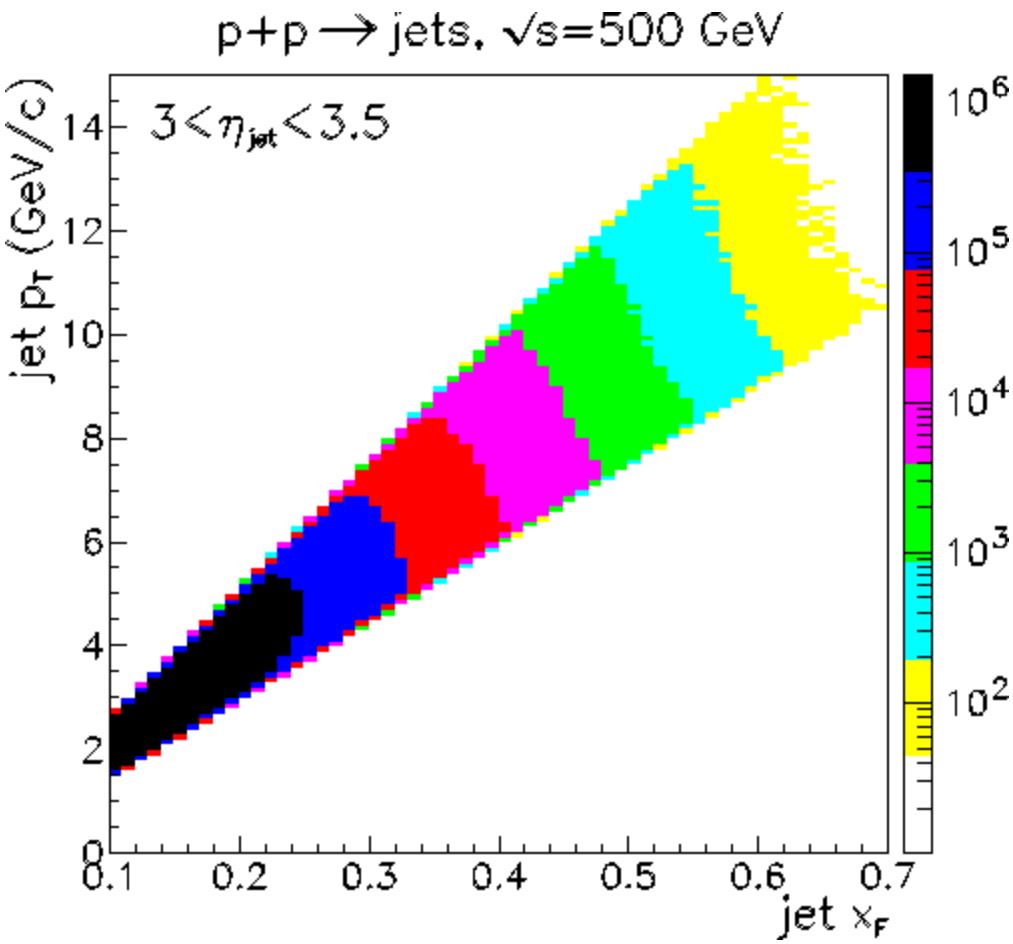


3-jet mass bump attributed to $\Upsilon(1S) \rightarrow 3$ gluons

2-jet mass bump attributed to $\chi_{2b} \rightarrow 2$ gluons

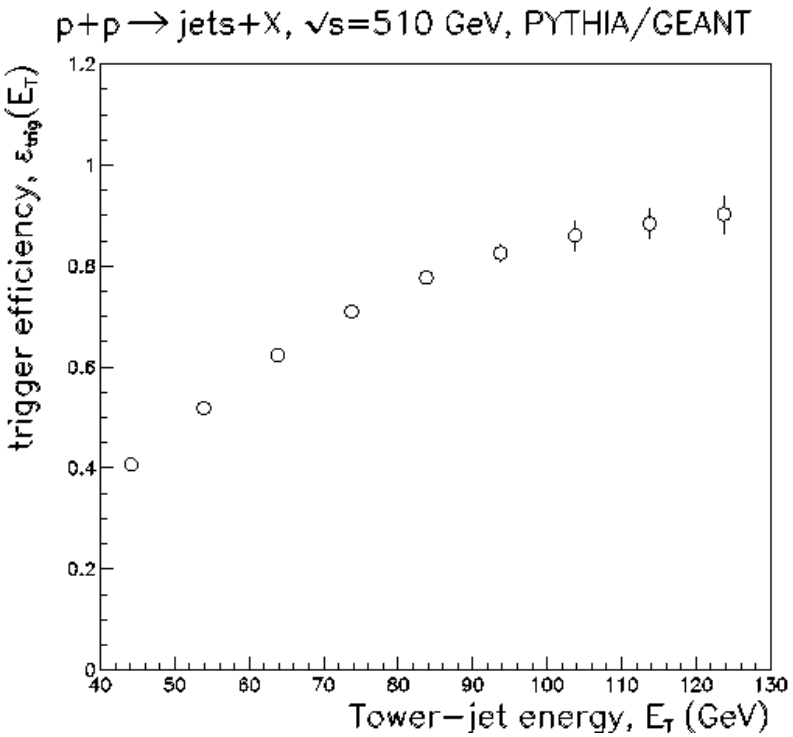
- Jet energy scale also determined from mass peaks in multi-jet events
- Hadronic decays of bottomonium well characterized in e^+e^- PRD **56** (1997) 17
- χ_{Jb} production observed through $\mu+\mu-\gamma$ by ATLAS at LHC PRL **108** (2012) 152001

Reconstructed Jet Kinematics



- Reconstructed jets from data satisfy fiducial volume requirements: $3<\eta_{jet}<3.5$ and $|\varphi_{jet}-\varphi_{off}|<0.5$, where $\varphi_{off}=0$ for left and π for right.
- The fiducial volume requirements impose a strong correlation between jet x_F and p_T, as shown.

Jet Cross Section-I



This shows an evaluation of the trigger efficiency from PYTHIA/GEANT. Inefficiency results from variation of η for each tower for the extended source for the colliding beams. ε_{trig} is checked by extracting cross section from minimum-bias triggers

Definition

The jet invariant cross section is:

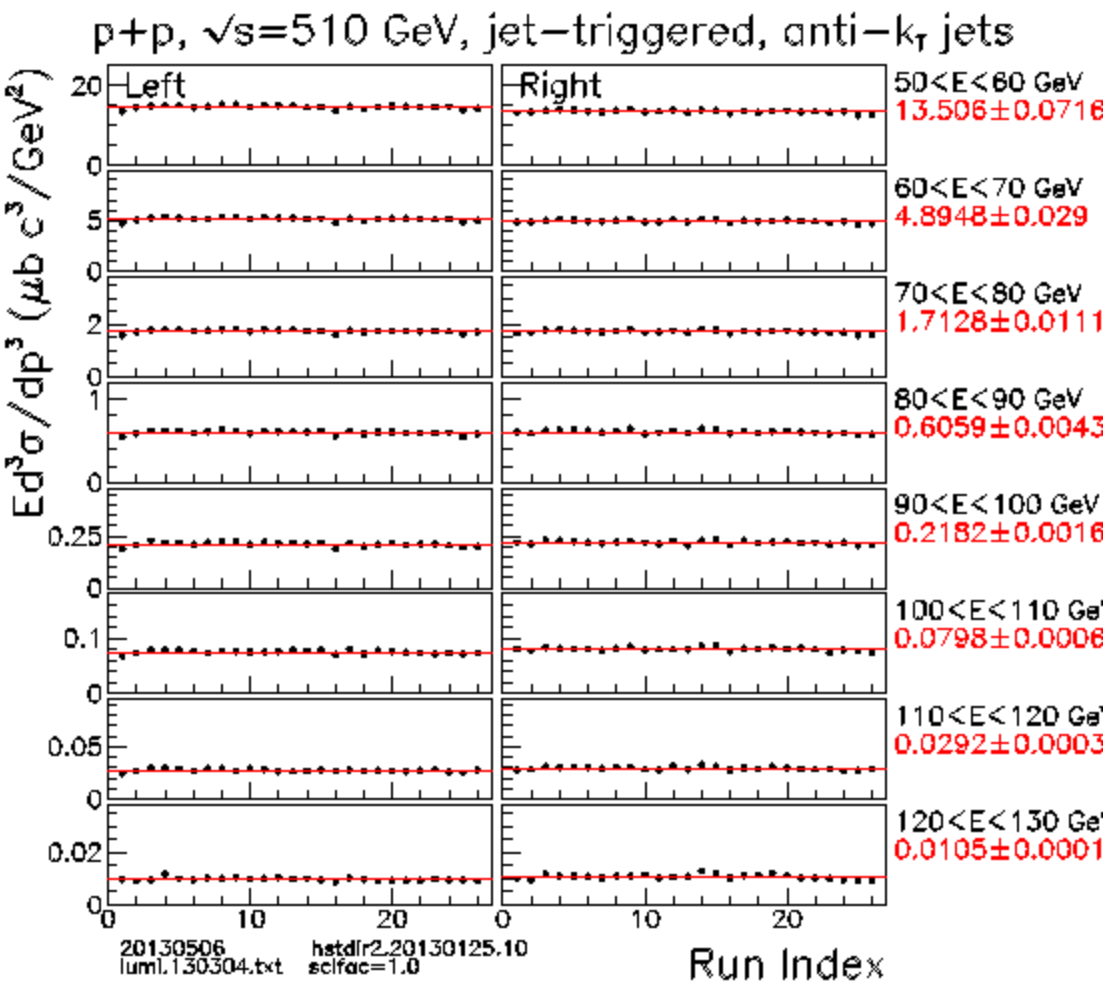
$$E\frac{d^3\sigma}{dp^3} = \frac{N\langle \cosh\eta \rangle}{\varepsilon_{trig}\varepsilon_{\det}L_{samp}\langle p_T \rangle \Delta\eta\Delta\phi\Delta E}$$

where

- N – number of particles detected
- ε_{trig} – trigger efficiency
- ε_{det} – detection efficiency
- L_{samp} – sampled luminosity (time integrated), calibrated by vernier scan
- $\langle\cosh(\eta)\rangle$ - average value of $\cosh(\eta)$ over the acceptance, $\Delta\eta \approx \Delta y$
- $\langle p_T \rangle$ - average value of transverse momentum in acceptance
- $\Delta\eta$, $\Delta\varphi$ - specifies the geometry of the acceptance
- ΔE – width in energy of bin considered

Jet Cross Section-II

Run Dependence



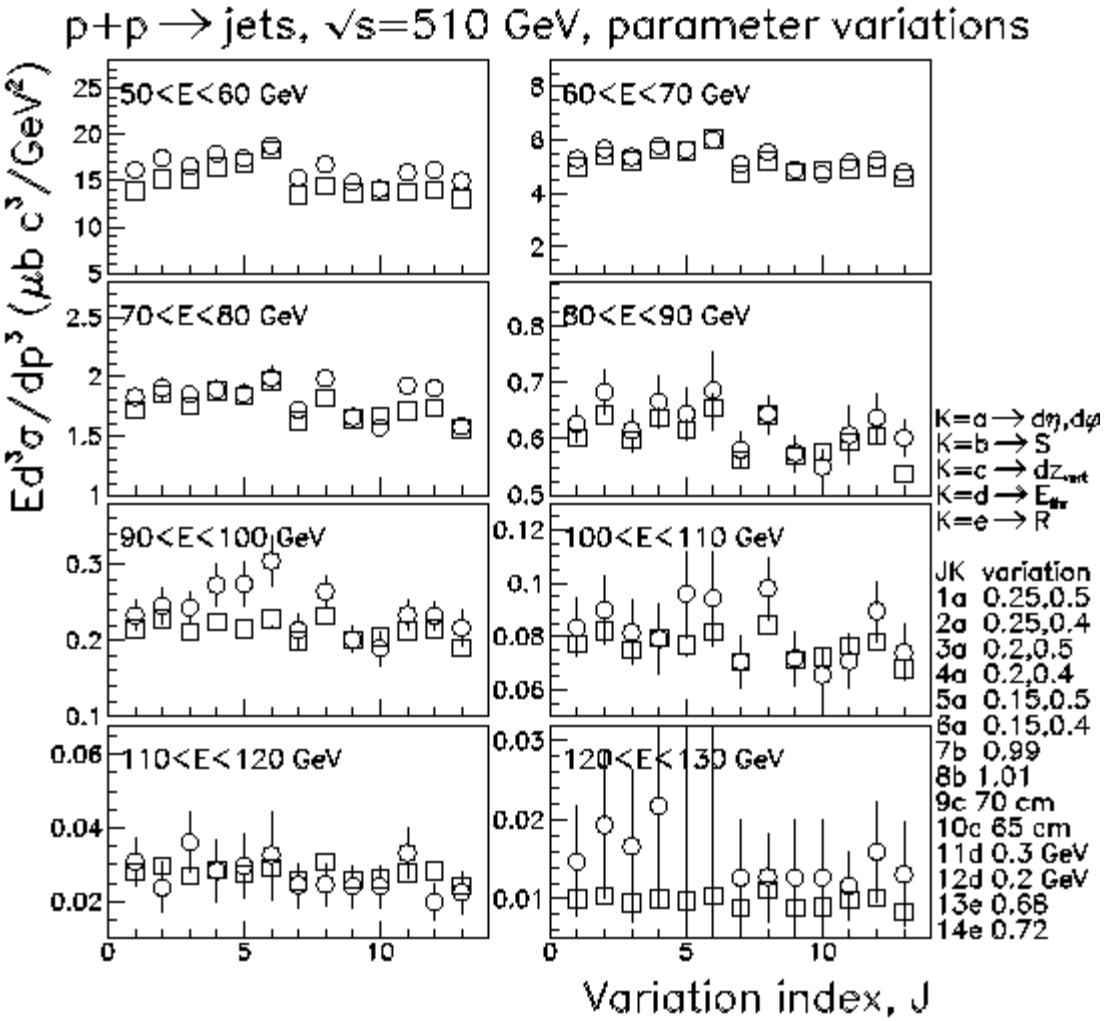
Multiple systematic checks were made for the cross section. This plot shows two:

- Comparison of cross sections from left and right modules
- Stability of cross section with time.

In addition, results were obtained from jet-triggered and minimum-bias triggered samples, to check consistency.

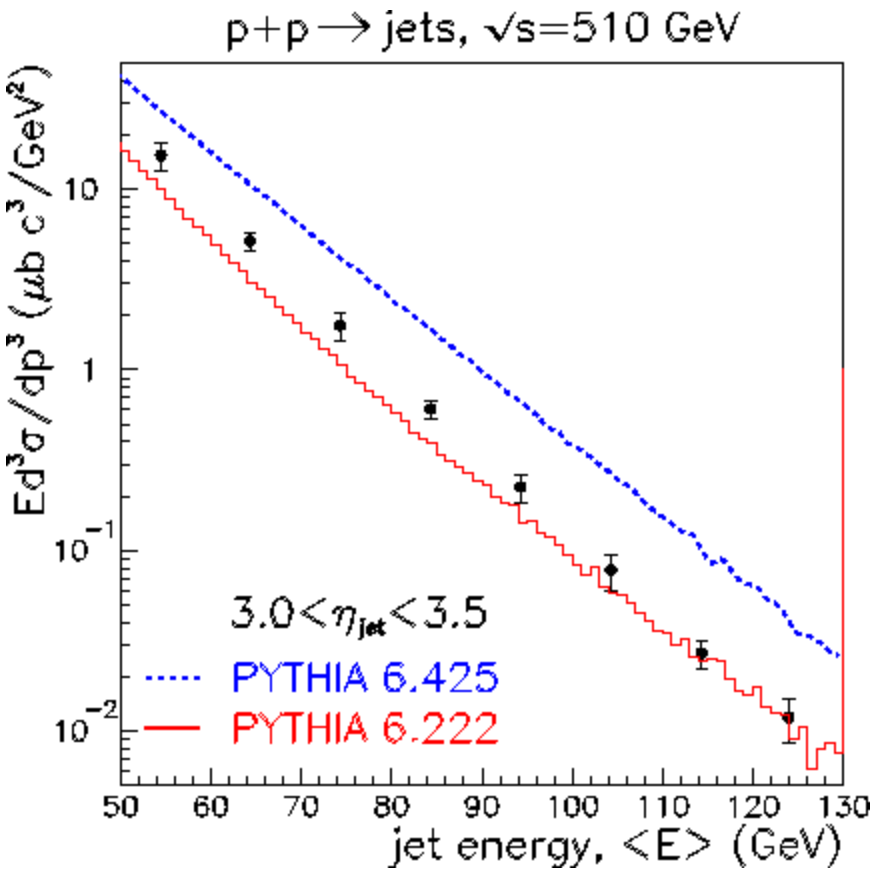
Jet Cross Section-III

Systematic Errors



- The stability of the jet cross section was examined as jet-finder (R,Ethr); jet acceptance (dη,dφ); jet energy scale (S) and vertex selection (dz_{vert}) parameters were varied.
- Results with jet triggered (open squares) and minimum-bias triggered (open circles) events are shown.
- Projections of the resulting cross section on the variation index J result in distributions for each energy bin used to estimate the systematic error for that bin.

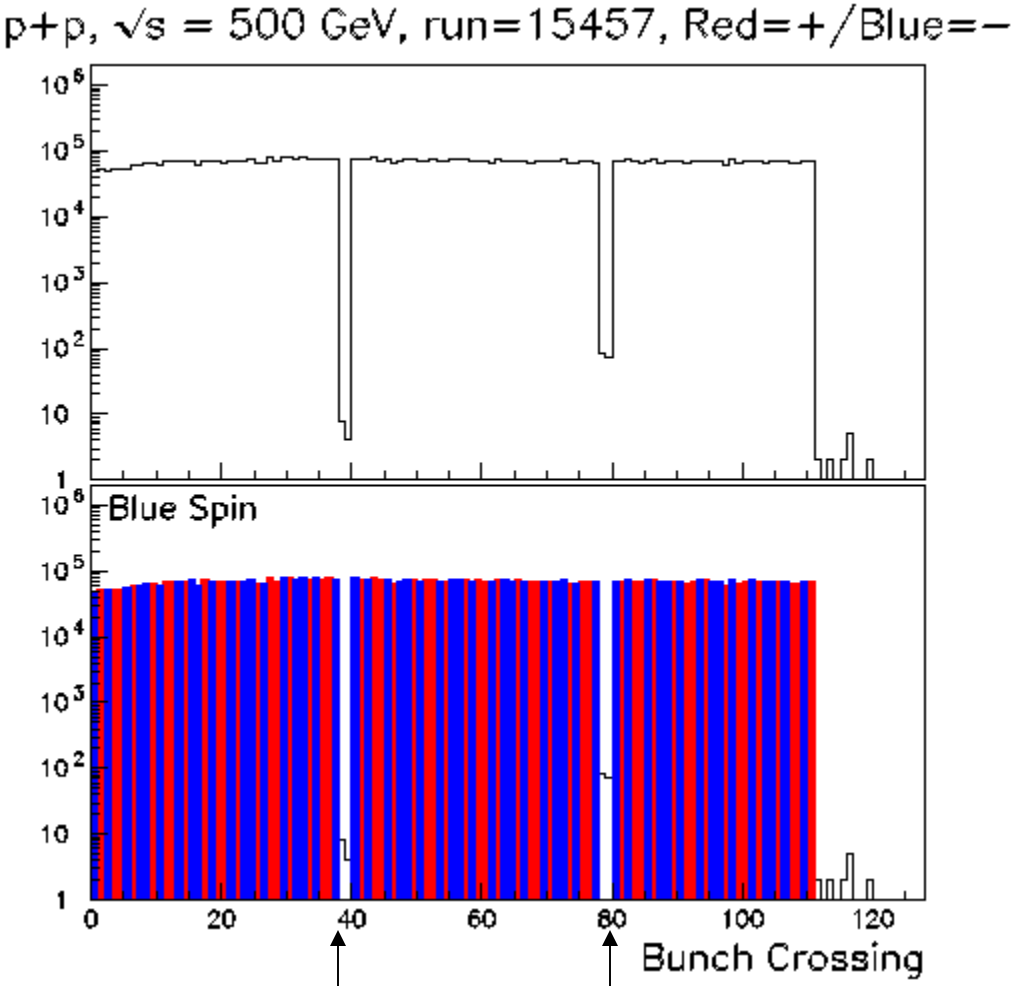
Jet Cross Section



Invariant forward jet cross section measured at $3<\eta<3.5$. Jets are reconstructed via the anti-kT algorithm using R=0.7. The measurements include point-to-point systematic error estimates. The measurements are compared to particle jet results from two versions of PYTHIA

- Measured forward jet cross sections include point-to-point systematic errors as shown.
- PYTHIA 6.222 [Comp. Phys. Commun. 135 (2001) 238] predate tunings of PYTHIA for LHC.
- PYTHIA 6.425 [JHEP **05** (2006) 026] includes tunings of PYTHIA to Tevatron data for use at the LHC.
- Cross sections are best described by PYTHIA 6.222, that also describes forward neutral pion production at RHIC energies [hep-ex/0403012].
- Cross sections are described in leading-order generalized parton model [arXiv:1307.7691]

Spin Sorting

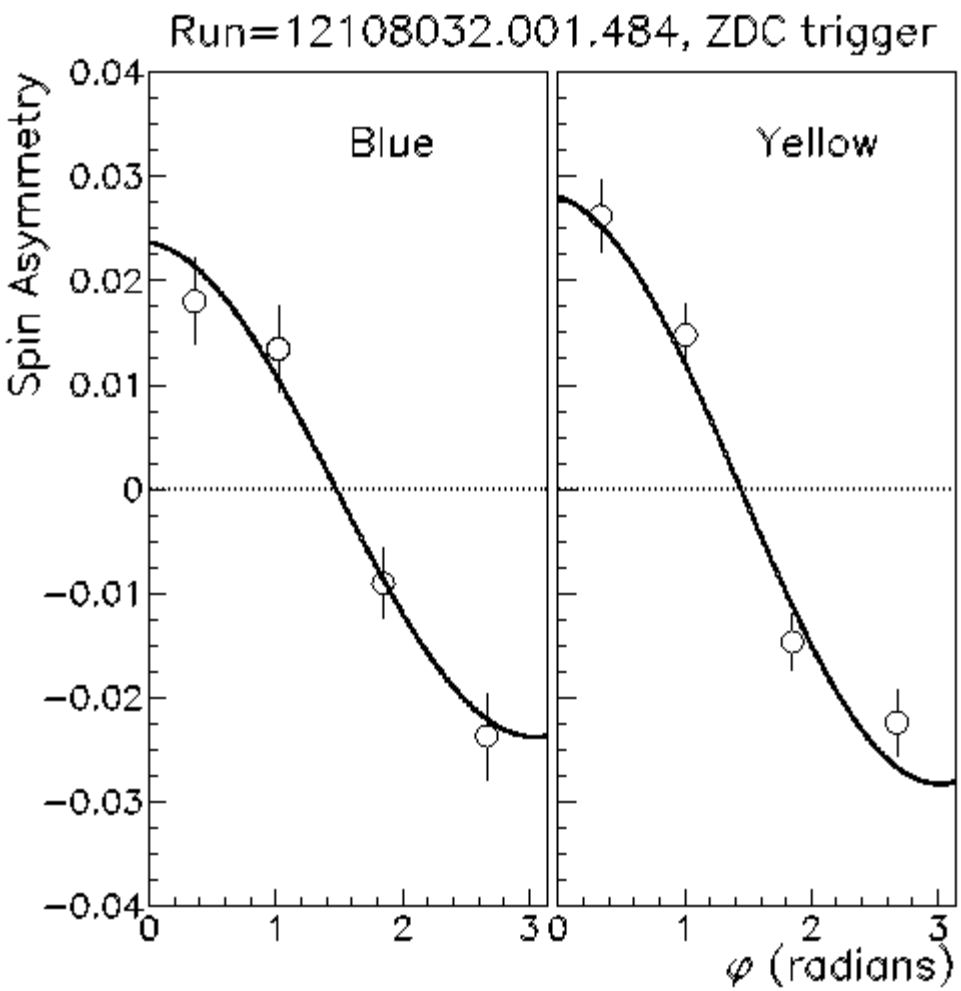


Yellow single beam

Blue single beam

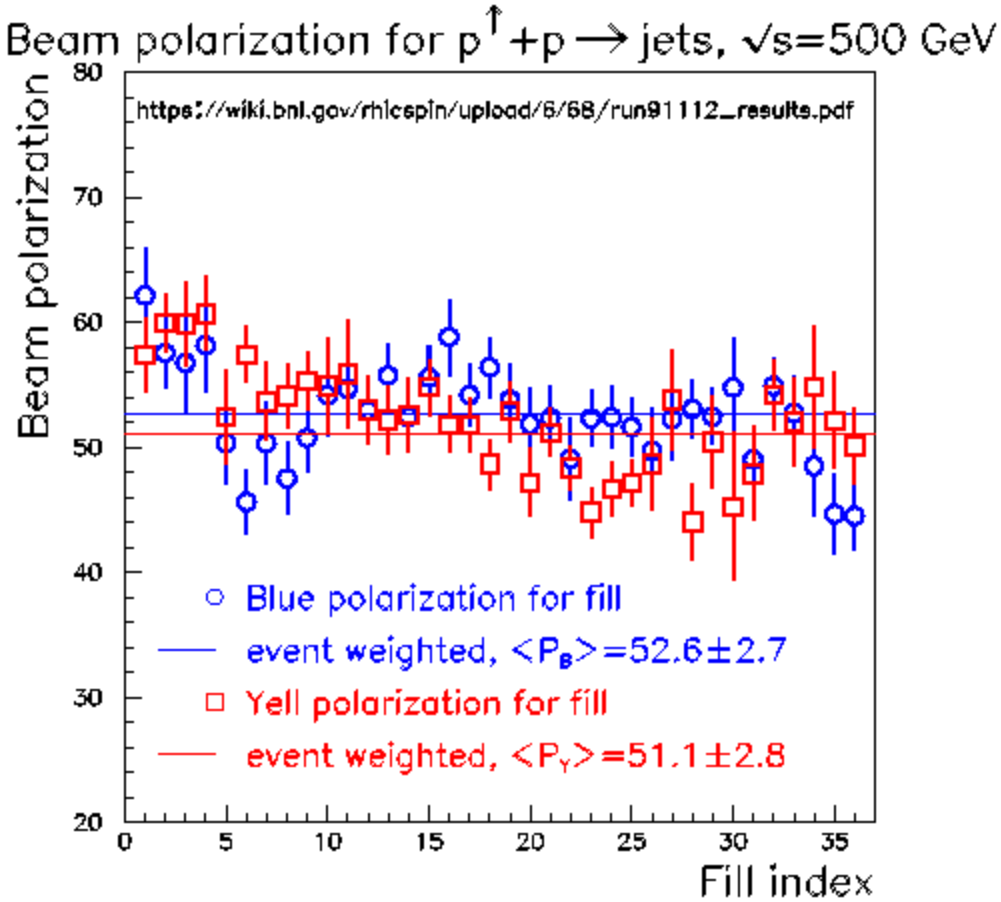
- RHIC has a pattern of polarization directions injected for each fill.
- Polarization for colliding beams is established by counting (C) the 9.38 MHz clock, and identifying specific bunch crossings by B=mod(C,120)
- Polarization pattern for a fill is communicated from the accelerator to the experiments.
- Bunch counter distributions also assess single-beam backgrounds

Spin Direction



- The analyzing power for forward neutron production [$A_N(n)$] has been measured to be positive [PLB **650** (2007) 325]
- $A_N(n)$ is measured with zero-degree calorimeters [NIM A **499** (2003) 433], and provides colliding beam experiments with a local polarimeter.
- Confirm the spin direction used for jet measurements by measuring $A_N(n)$ concurrent with measuring $A_N(jet)$.
- This fixes the sign of $A_N(jet)$.

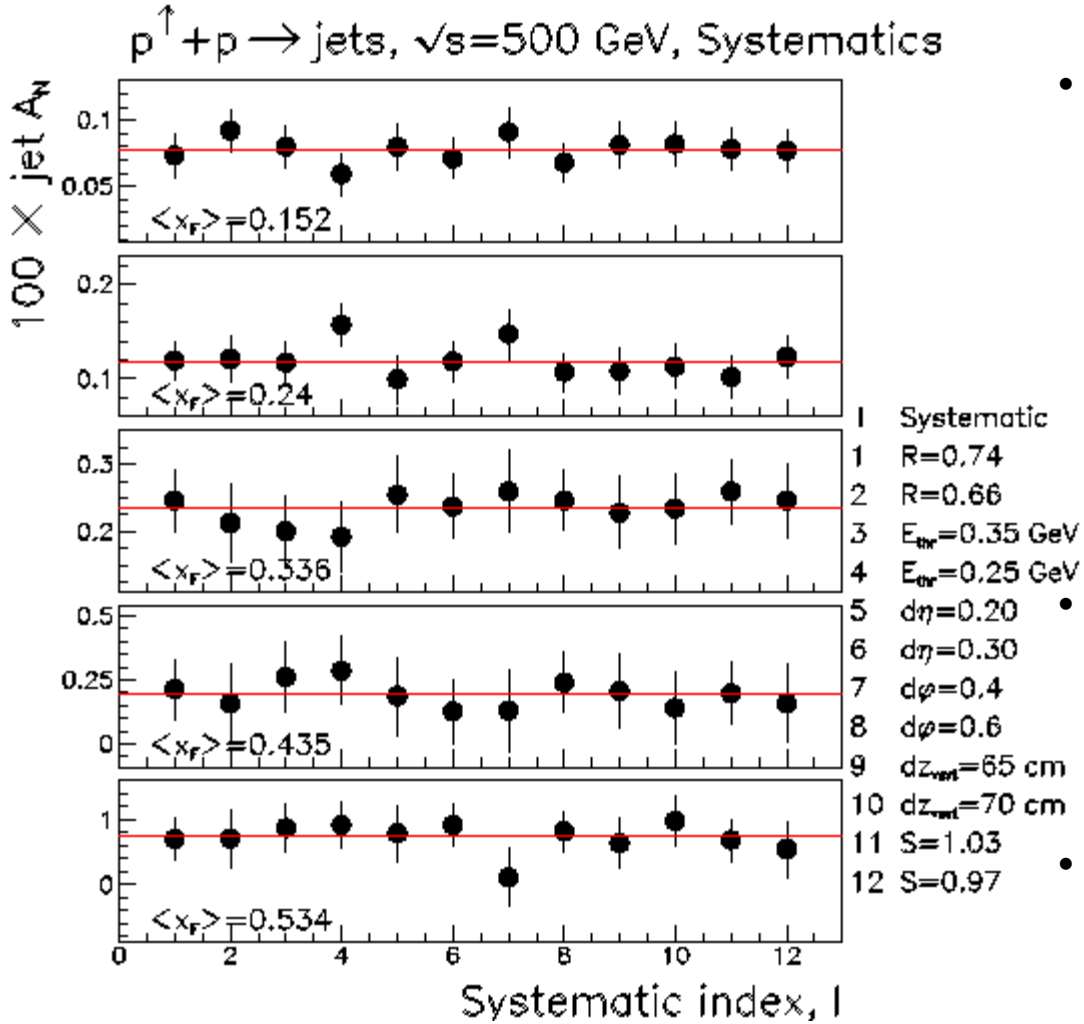
Beam Polarization



- Polarization of colliding beams is measured by the polarimeter group [see reference noted in plot].
- Measurements of p+carbon elastic scattering in the Coulomb-nuclear interference region provide a relative polarimeter
- Measurements of p+p elastic scattering in the Coulomb-nuclear interference region from a polarized gas jet target provides an absolute polarimeter

Jet Analyzing Power

Definition and Systematics



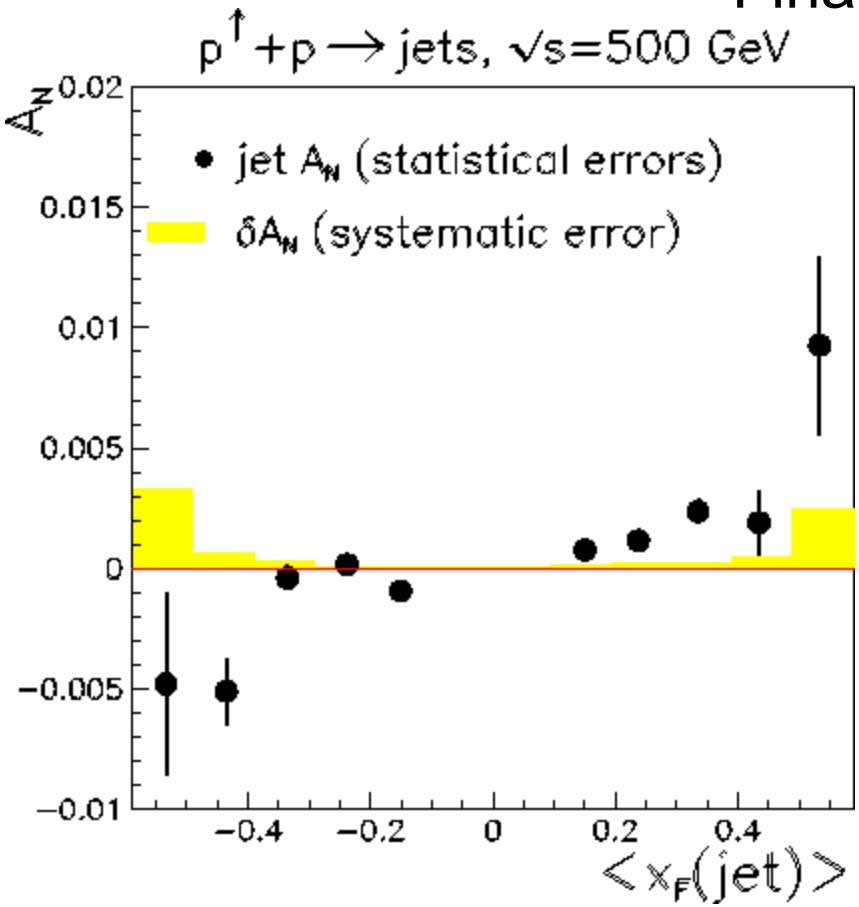
- A_N(jet) exploits mirror (left/right) symmetry of apparatus with spin-↑/spin-↓ of colliding beams, via a cross-ratio…

$$A_N = \frac{1}{P}\frac{\sqrt{N_L^{\uparrow}N_R^{\downarrow}} - \sqrt{N_L^{\downarrow}N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow}N_R^{\downarrow}} + \sqrt{N_L^{\downarrow}N_R^{\uparrow}}}$$

- Systematic errors for A_N(jet) are in part computed by varying parameters analogous to manner done for cross section.
- Bottom line is that A_N(jet) is statistics limited, because of cancellation of systematic errors from symmetry.

Jet Analyzing Power

Final Results



- A_N(jet) is small and positive for $x_{F,jet}>0$, compatible with cancellations from pion production: $A_N(\pi^+)\approx A_N(\pi^-)$
- A_N(jet) is compatible with Sivers functions fit to semi-inclusive DIS [see talk by Gamberg and arXiv:1302.3218]
- Expect the most definitive test of understanding remains measuring the analyzing power for DY production.

Analyzing power for forward jet production. Jets are reconstructed with the anti-kT algorithm using R_{jet}=0.7. Preliminary results [arXiv:1212.3437] reported comparable A_N with the mid-point cone algorithm. Systematic errors do not include scale uncertainty from the beam polarization measurements

Conclusions

- Our measured forward jet cross section is compatible with hard scattering.
- Our measured analyzing power for forward jet production is small and positive
- A_N(jet) constrains knowledge of Sivers functions that arise from orbital angular momentum of quarks and gluons in the proton.
- The most definitive experiment to test present understanding is a measurement of the analyzing power for DY production.