Cross Sections and Spin Observables for Forward Jet Production

A talk primarily about…

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Cross sections and transverse single-spin asymmetries in forward jet production from proton collisions at $\sqrt{s} = 500$ GeV

A_NDY Collaboration[⋆]

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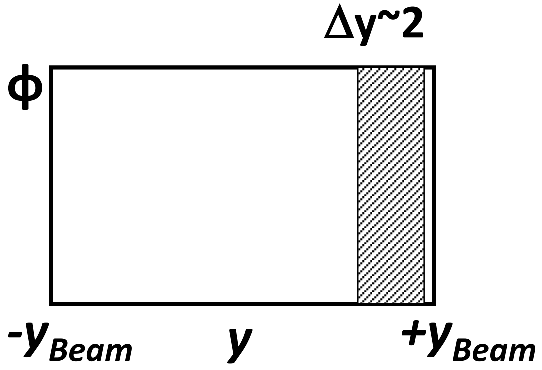
Forward Particle Production

- In this talk, forward means when the observed particle Feynman-x ($x_F=2p_z/\sqrt{s}$) scaling variable is larger than 0.1
- In general, sufficient p_T is required so that pQCD is applicable. Consequently, forward is further defined to require sufficient p_T [which looks to be ~2 GeV/c for inclusive π^0 production]
- RHIC interaction regions have uniquely large length for a collider, when scaled by $\sqrt{s}$. This interaction length does permit space for forward instrumentation



	Free Space (m)	√s (GeV)	Ratio (L/√s)
Tevatron	13	1600	0.0081
LHC	38	13000	0.0029
RHIC	16	500	0.032
	16	200	0.080

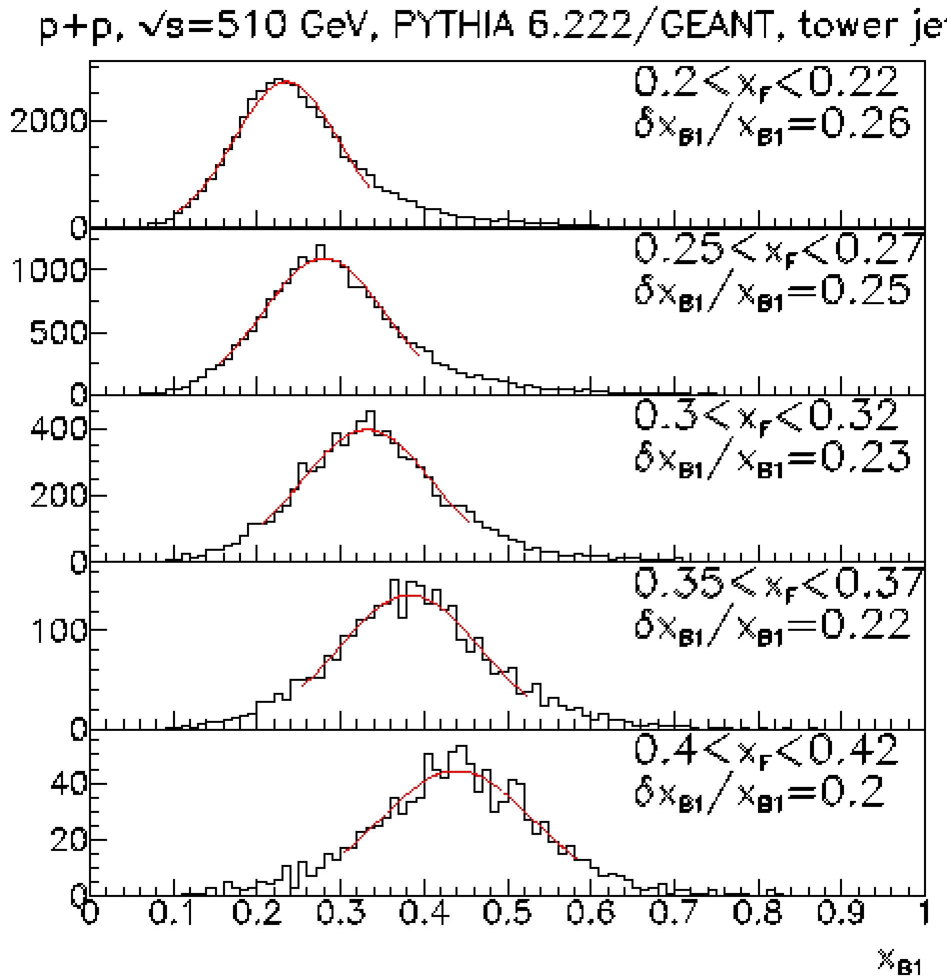
Consider the separation in x-y plane ($d_{\gamma\gamma}$) of a pair of photons from the decay $M\rightarrow\gamma\gamma$, when the plane is L from where M (mass m_M) is produced:

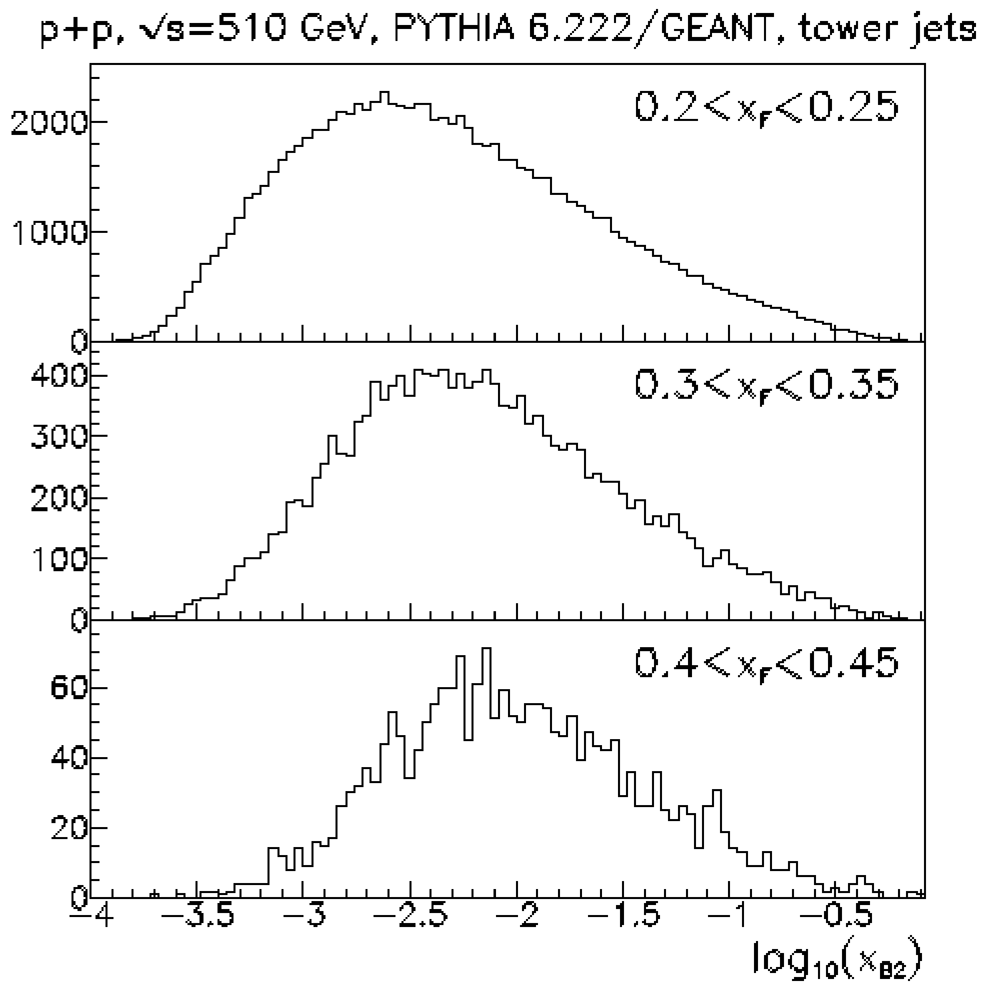
$$d_{\gamma\gamma}^{min} = \frac{L}{\sqrt{s}}\frac{4m_M}{x_F}$$

$\Rightarrow$ Large $L/\sqrt{s}$ enables reconstruction of light mesons to large x_F at large $\sqrt{s}$

Why is large x_F useful? - I

For hard scattering (2→2 processes), $x_F \sim x_1 - x_2$, where x_1 is the Bjorken x of the parton from the hadron heading towards the apparatus and x_2 is the Bjorken x of the parton from the other colliding hadron. In general, forward particle production probes these x values at "low scale" (as set by p_T). Distributions are for inclusive forward jets.



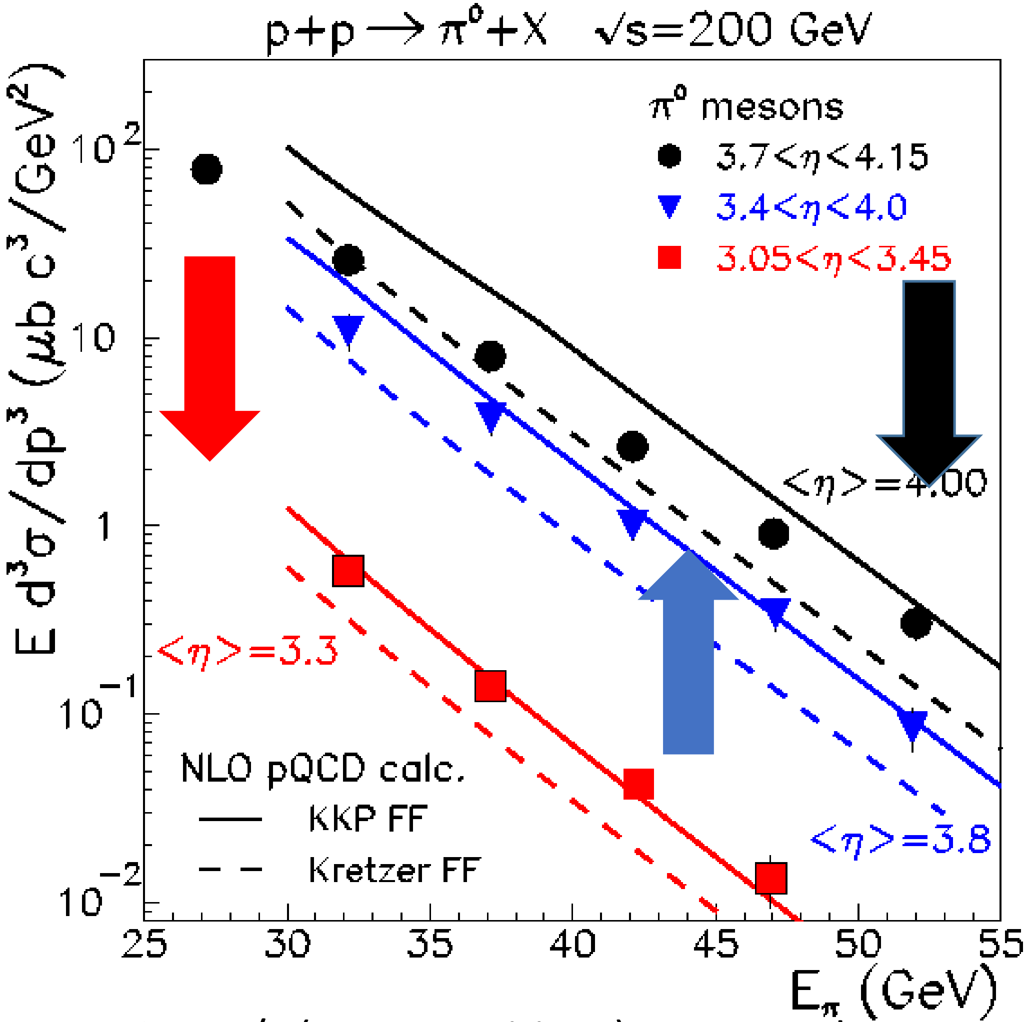


Valence-like quarks for $x_F>0.1$

x_2 is broad, but extends to very low x (~few $\times 10^{-4}$). Forward dijets can select low x (see below)

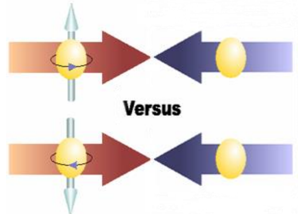
Why is large x_F useful? - II

PRL 97 (2006) 192302

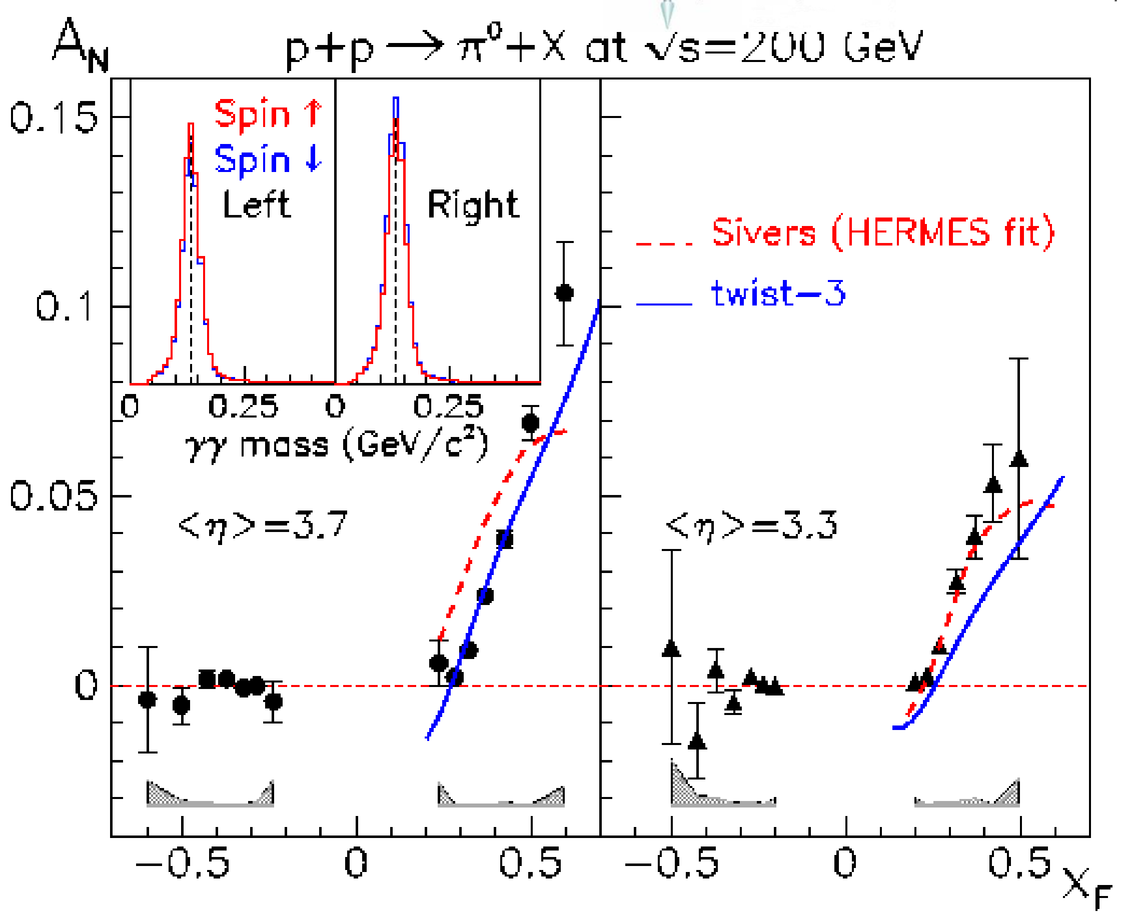


For p_T>2 GeV/c (arrow positions), measured cross sections are in good agreement with NLO pQCD, albeit with large scale dependence which is smaller for jets (see below)

PRL 101 (2008) 222001



$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

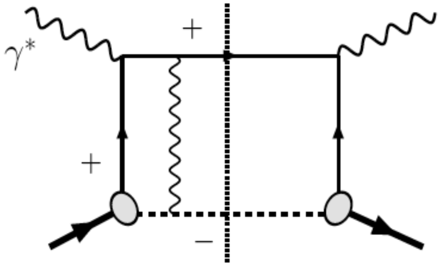


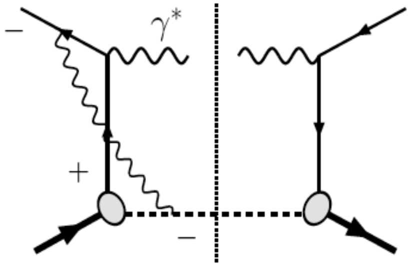
Although cross sections can be described by NLO pQCD, there are still large transverse single-spin asymmetries (SSA), that are expected to be zero in naïve pQCD but can arise from spin-correlated k_T

Attractive vs Repulsive Sivers Effects

Unique Prediction of Gauge Theory !

Simple QED example:

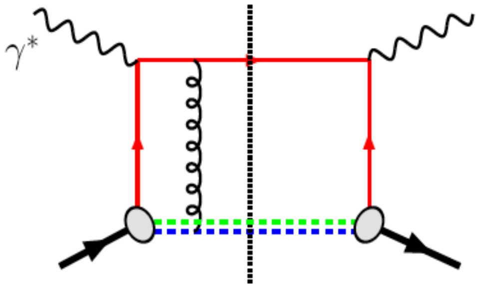


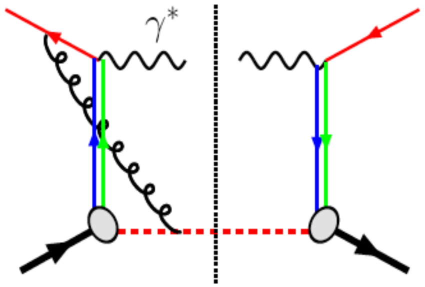


DIS: attractive

Drell-Yan: repulsive

Same in QCD:





As a result:

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

Transverse Spin Drell-Yan Physics at RHIC (2007)

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

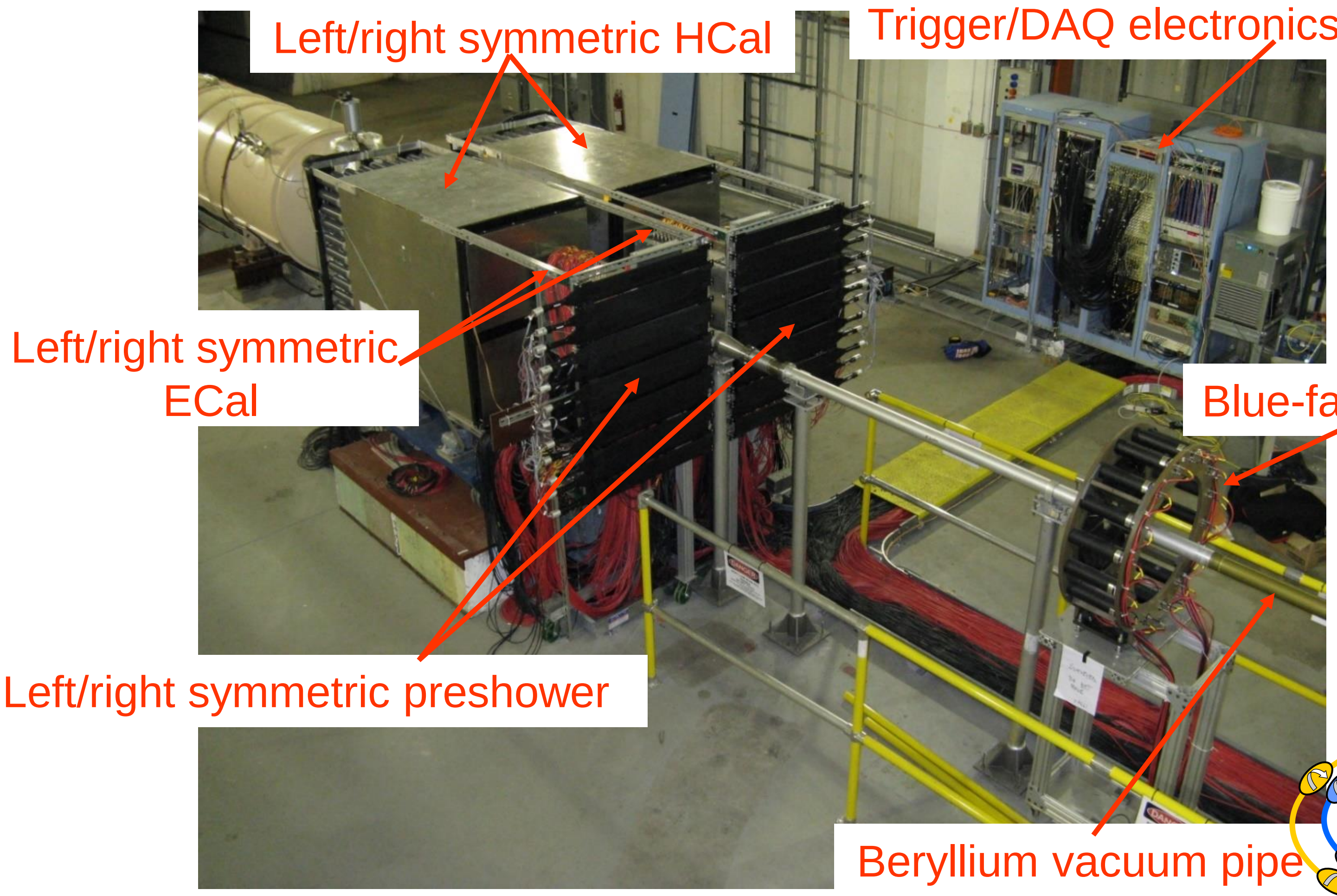
A_NDY Goal

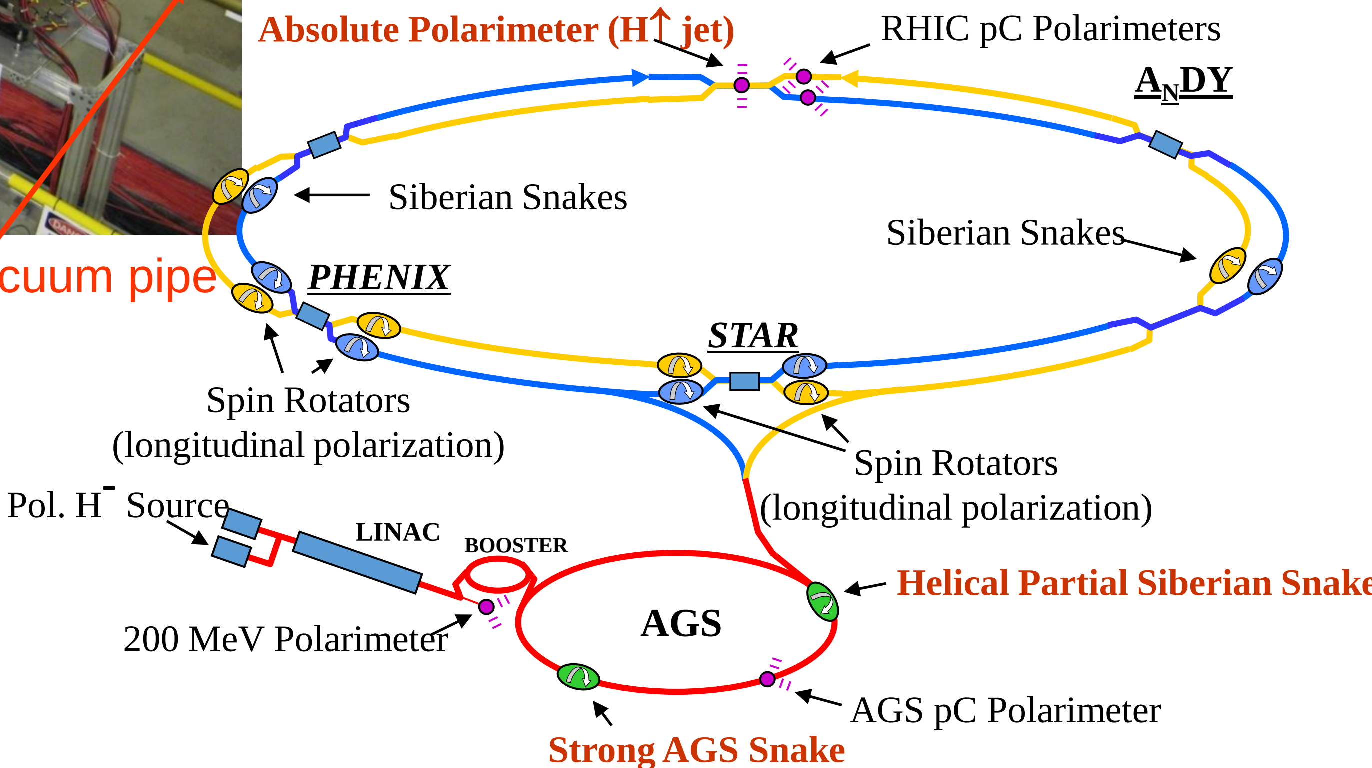
Measure the transverse single spin asymmetry for forward low-mass dileptons produced via the Drell-Yan process to test theoretical predictions of a sign change for the initial-state spin-correlated k_T-dependent distribution function (Sivers function).

The objective was to match as closely as experimentally possible kinematics between DY [dilepton mass and x_1~x_F] and semi-inclusive deep inelastic scattering (Q^2 and Bjorken x].

A_NDY Setup at IP2 for 2011 RHIC Run

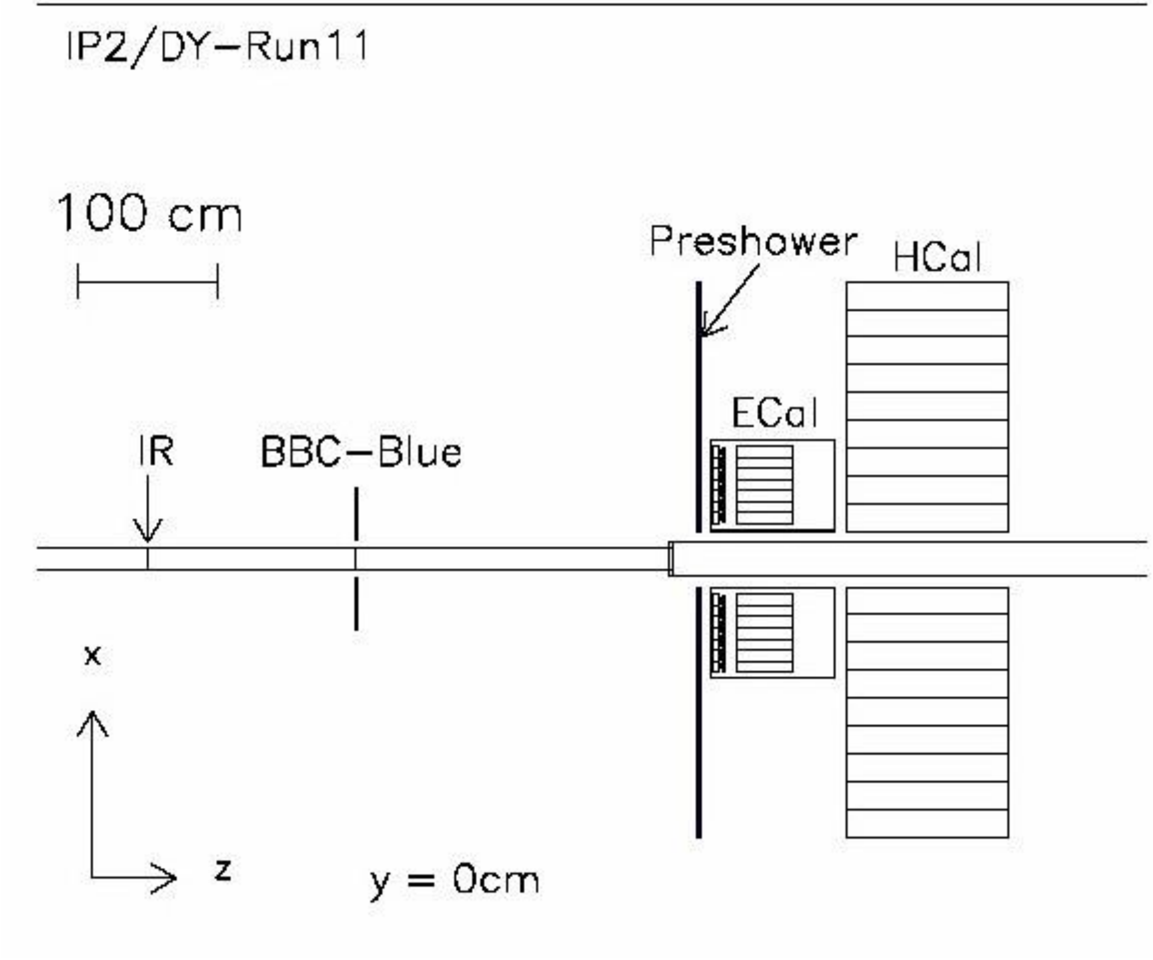
- This was a stage-1 test that could not have worked for forward DY
- The stage-1 test did measure forward jets
- There were not further stages





A_NDY Setup at IP2 for 2011 RHIC Run

PLB 750 (2015) 660



- 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
- In 2012, modular calorimeters were replaced by an annular calorimeter

Calibrations-I

Electromagnetic Response

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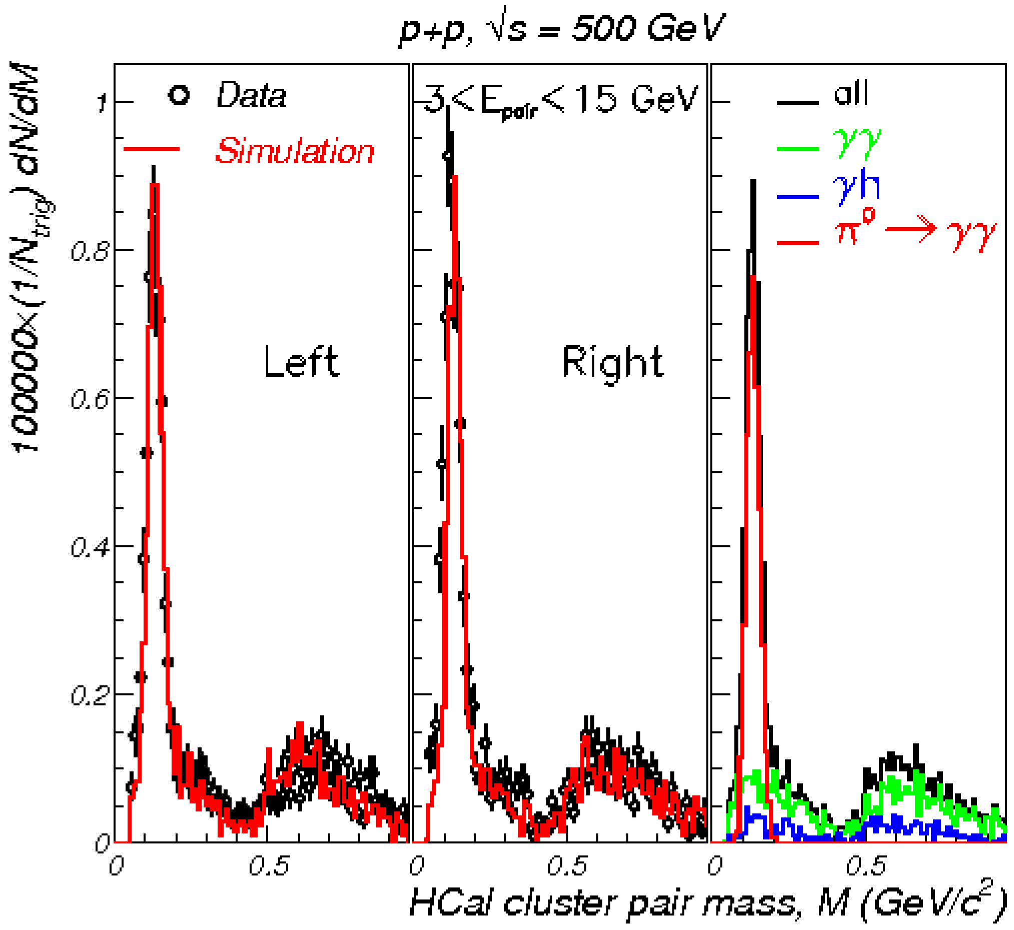
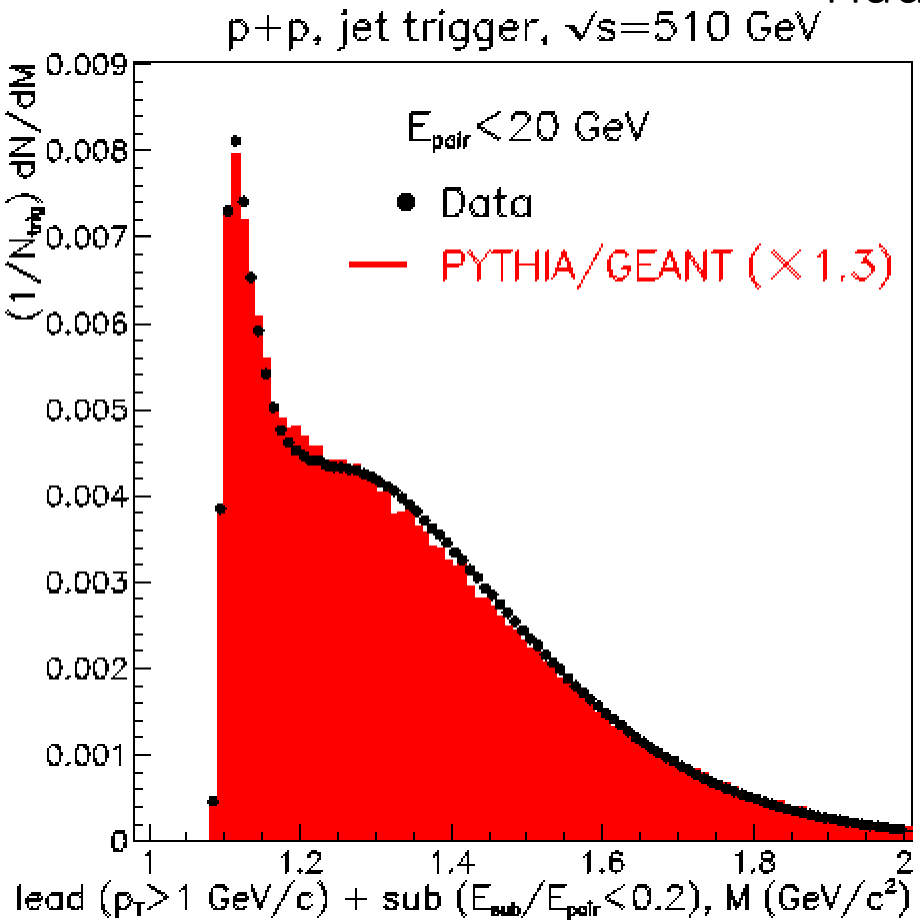


- Cosmic-ray muons were used to adjust relative gains in advance of collisions
- The primary determination of the energy scale was from reconstruction of $\pi^0 \rightarrow \gamma\gamma$ from single-tower cluster pairs. The maximum energy for this calibration was limited by photon merging into the coarse $(10\ cm)^2$ towers. [See below for pixelization results from this same calorimeter]
- Full PYTHIA/GEANT simulation agrees with data, for both the pair-mass resolution of the calorimeter, as well as the neutral pion reconstruction efficiency.
- Subsequent test-beam studies at FNAL [T1064] are consistent with an excellent response of this calorimeter to incident photons and electrons.

Calibrations-II

Hadronic Reponse

arXiv:1308.4705



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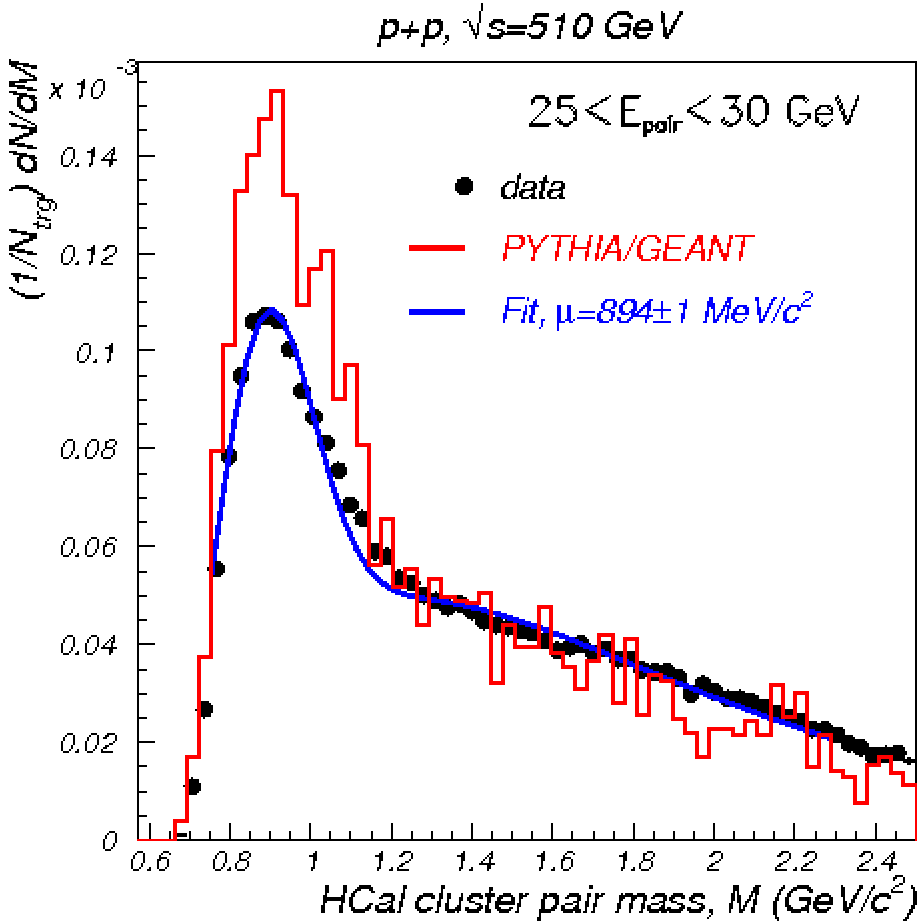
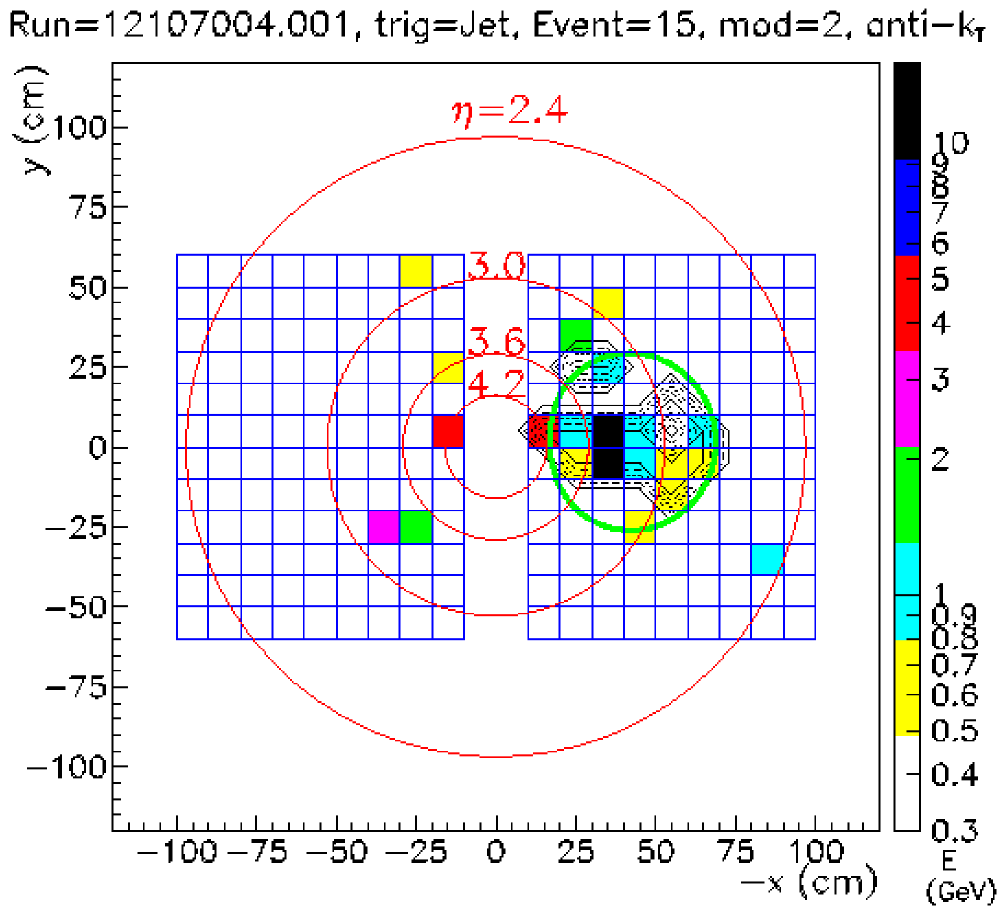


- Use BBC detector to tag HCal clusters made by incident charged hadrons. Mass assignments are then made.
- Tagged cluster-pair mass distributions are consistent with $\Lambda \rightarrow \pi^- p$ (left) and K*(892) $\rightarrow \pi^+ K^-$ (right) and charge conjugates
- Use E=1.12E' – 0.1 GeV for jet finding from an event list of tower energies that use the photon calibration (E')

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 towers until towers 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 $R_{jet} = 0.7$ in η-Φ space but cluster towers can fall outside of cone
  - Impose acceptance cuts to accept/reject jet:

    $|\eta_J - 3.25| < 0.25$

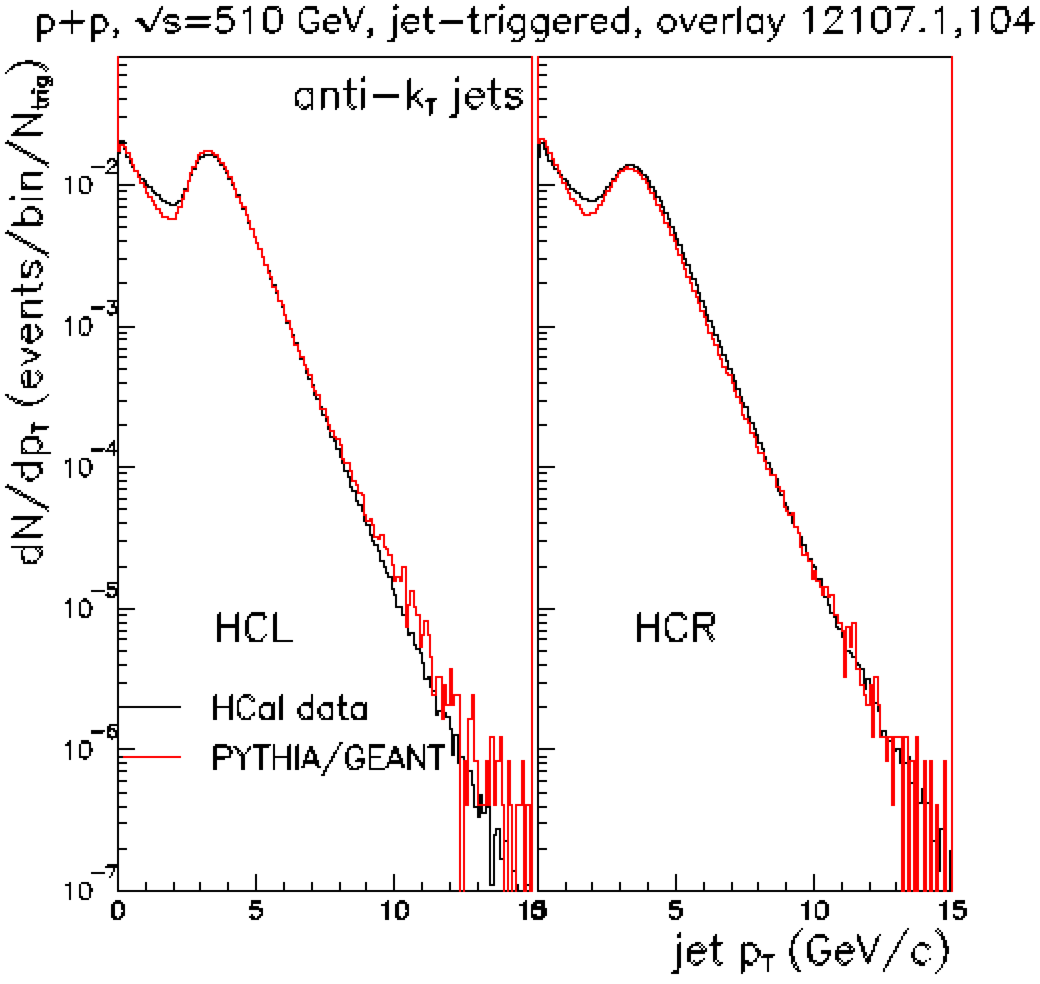
    $|\Phi_J - \Phi^{Off}| < 0.50$

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

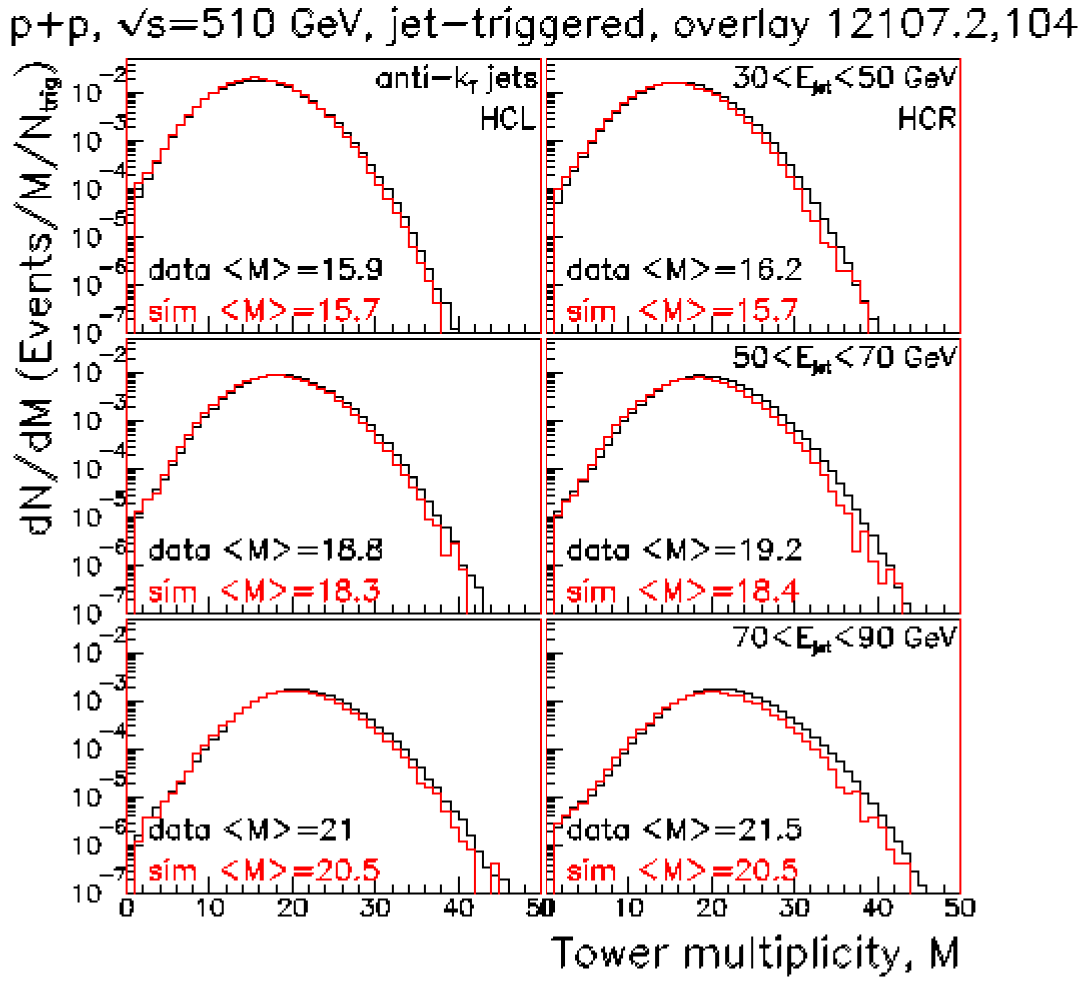
    $\Phi^{Off} = \pi$ for HCR
  - Energy Cut : $E_{jet} > 30$ GeV
  - Algorithm : arXiv : 0802.1189
    arxiv : 1209.1785

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

Comparison of Data to PYTHIA 6.222/GEANT Simulation



Uncorrected p_T distribution of anti-kT clusters



Uncorrected multiplicity of towers in anti-kT cluster

Good description of data by simulation → use simulation for efficiency correction

What is a forward jet?

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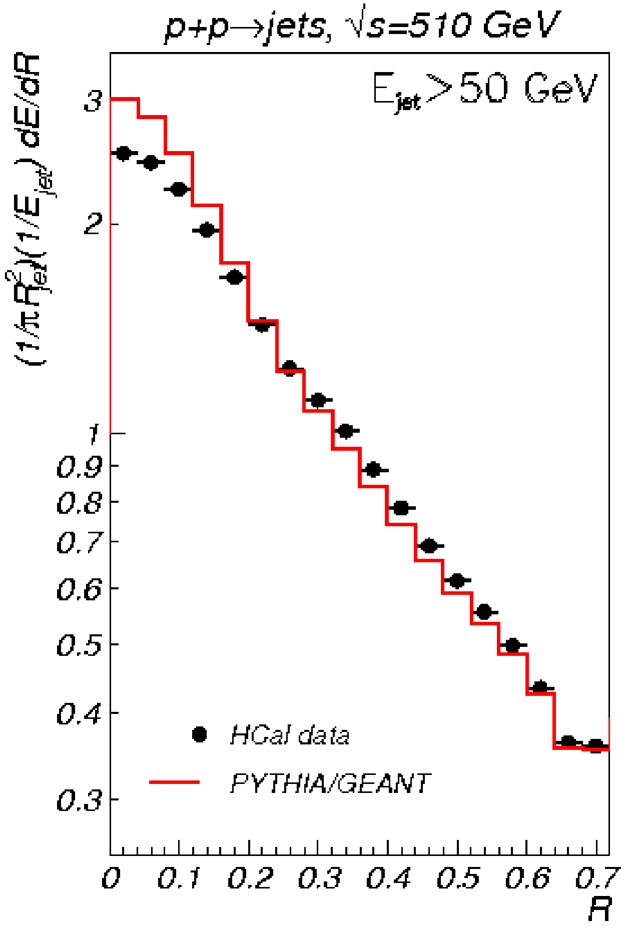
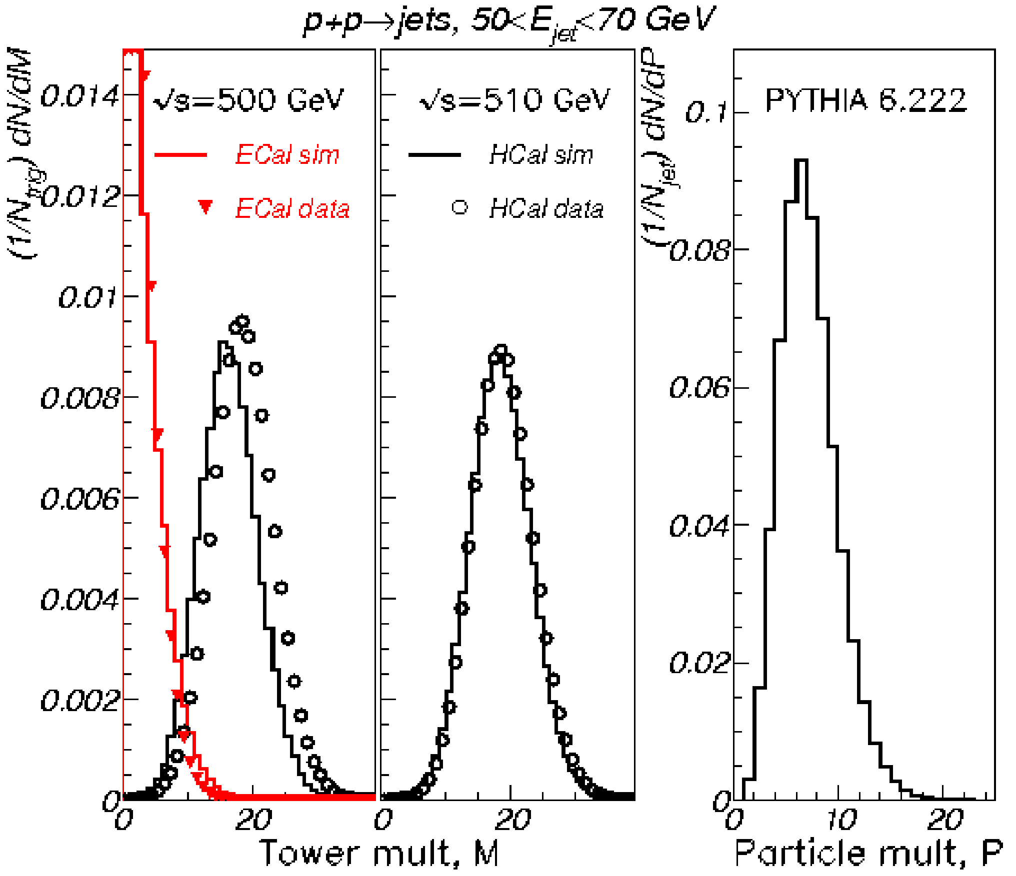


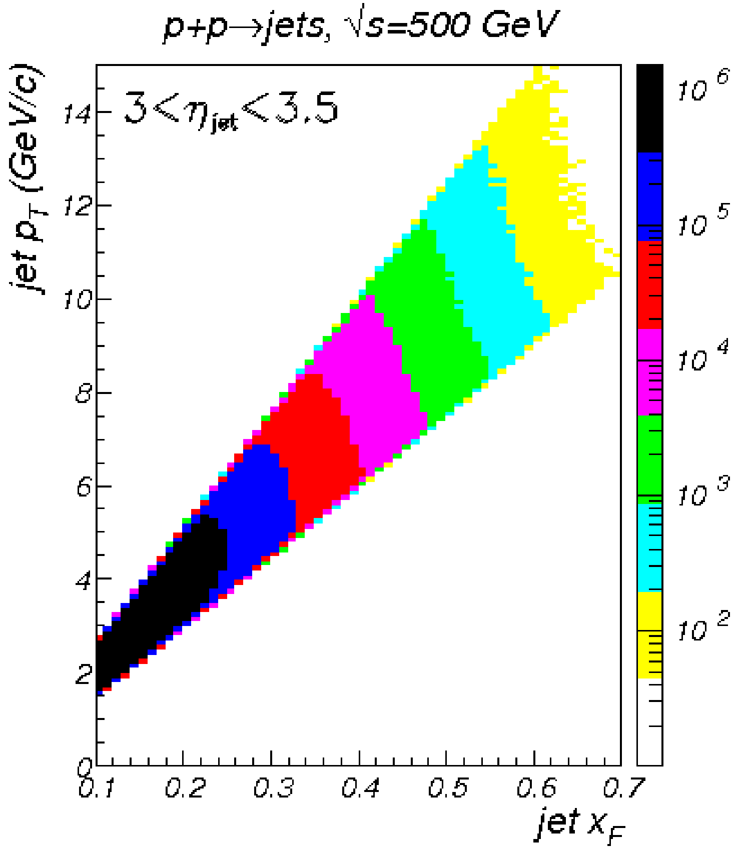
Event averaged jet shape: how the energy is distributed a distance R in η,φ from the thrust axis

⇒ the anti-kT clusters have shapes similar to midrapidity jets



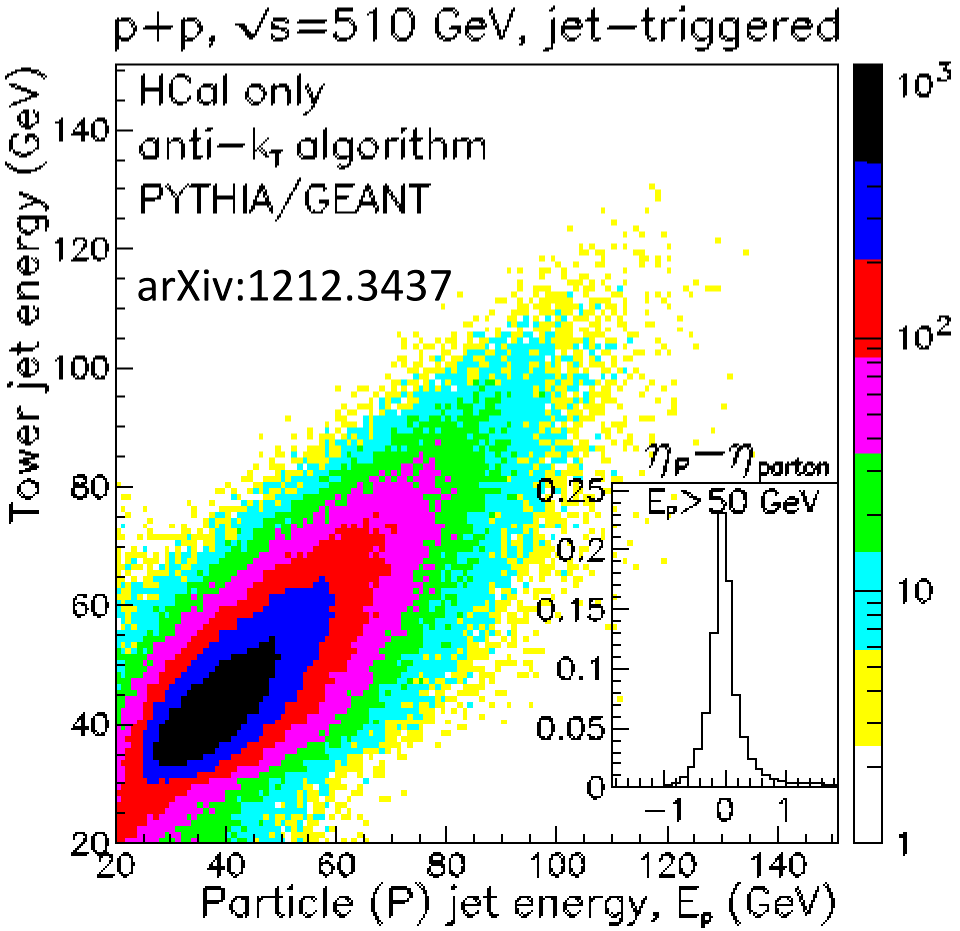
(left) tower multiplicities, as used for A_N;
(middle) tower multiplicities, as used for σ;
(right) incident particle multiplicity from simulation

⇒ multiplicity similar to jets of comparable scale



Acceptance of contained jets from particles with 2.4<η<4.2 correlates x_F and p_T for the jet cluster

Jet Energy Scale - I

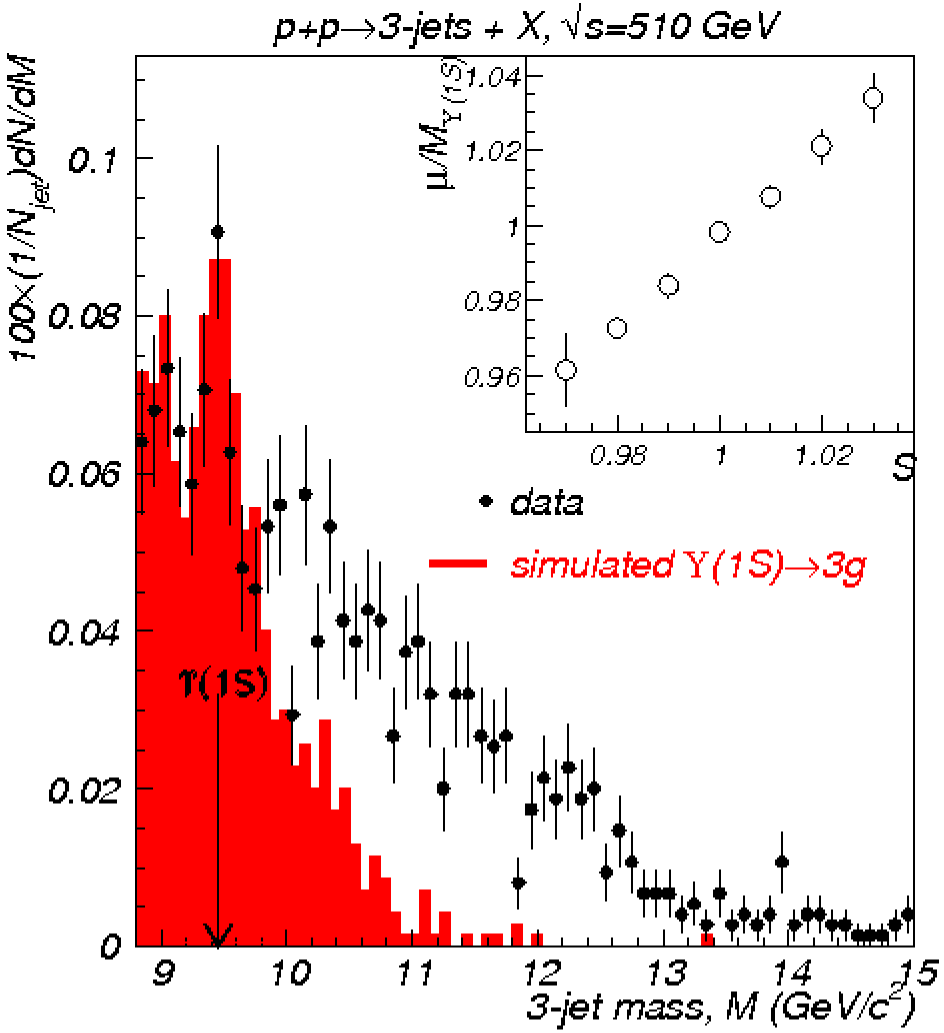


- Simulations confirm energy scale of jets, by comparison of "tower" jets [with full detector response] to "particle" jets [excluding detector response].
- Reconstructed jets are directionally matched to hard-scattered partons as generated by PYTHIA

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

Jet Energy Scale - II

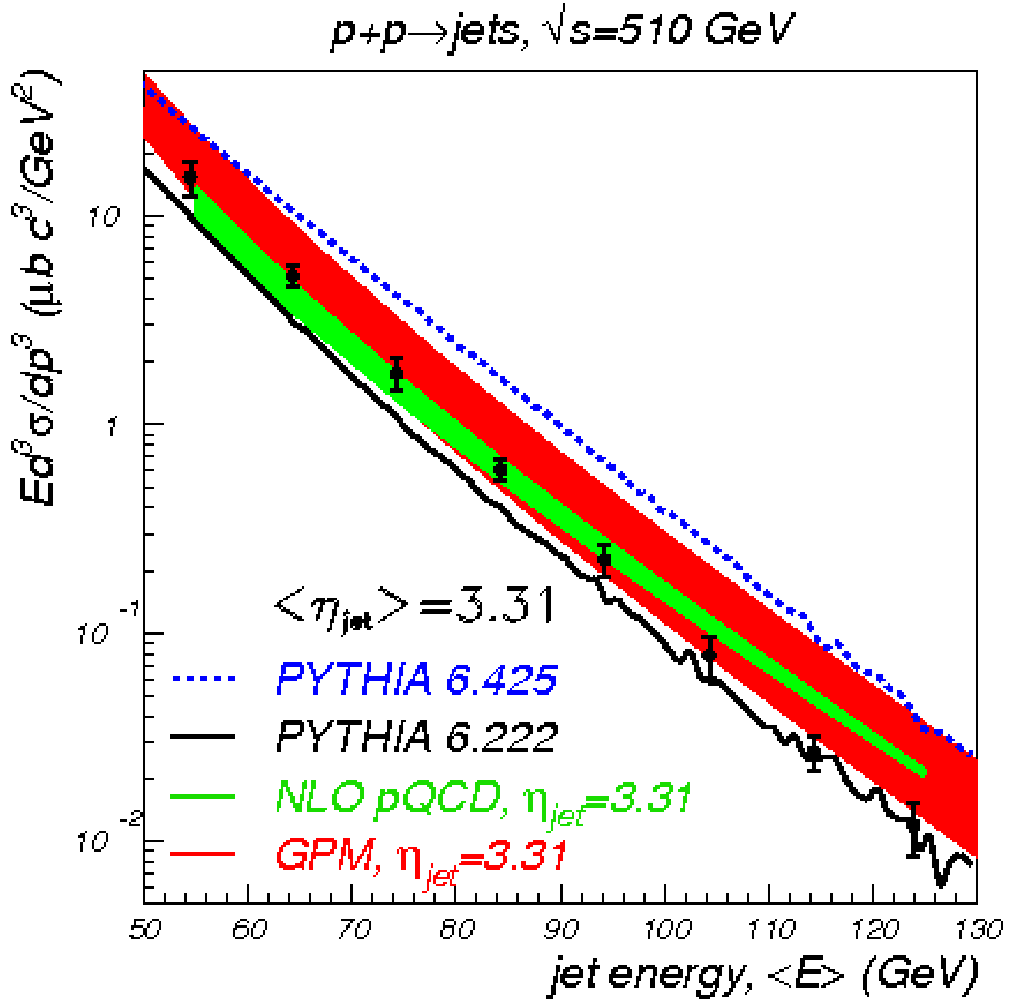
PLB 750 (2015) 660



- Test jet energy scale by reconstruction of invariant mass for multi-jet events
- Observe 3.5σ statistical significance peak, attributed to $\Upsilon(1S)\to 3g$. The red overlay is a simulation of the signal from the PYONIA generator of $\Upsilon(1S)\to 3g$, run through GEANT, and then reconstructed as done for the data
- For the inset, S rescales the energy calibrations, so tests the jet-energy scale.
- Peaks are also observed in 2-jet mass attributed to $\chi_{2b}\to 2$ gluons

Forward Jet Cross Sections

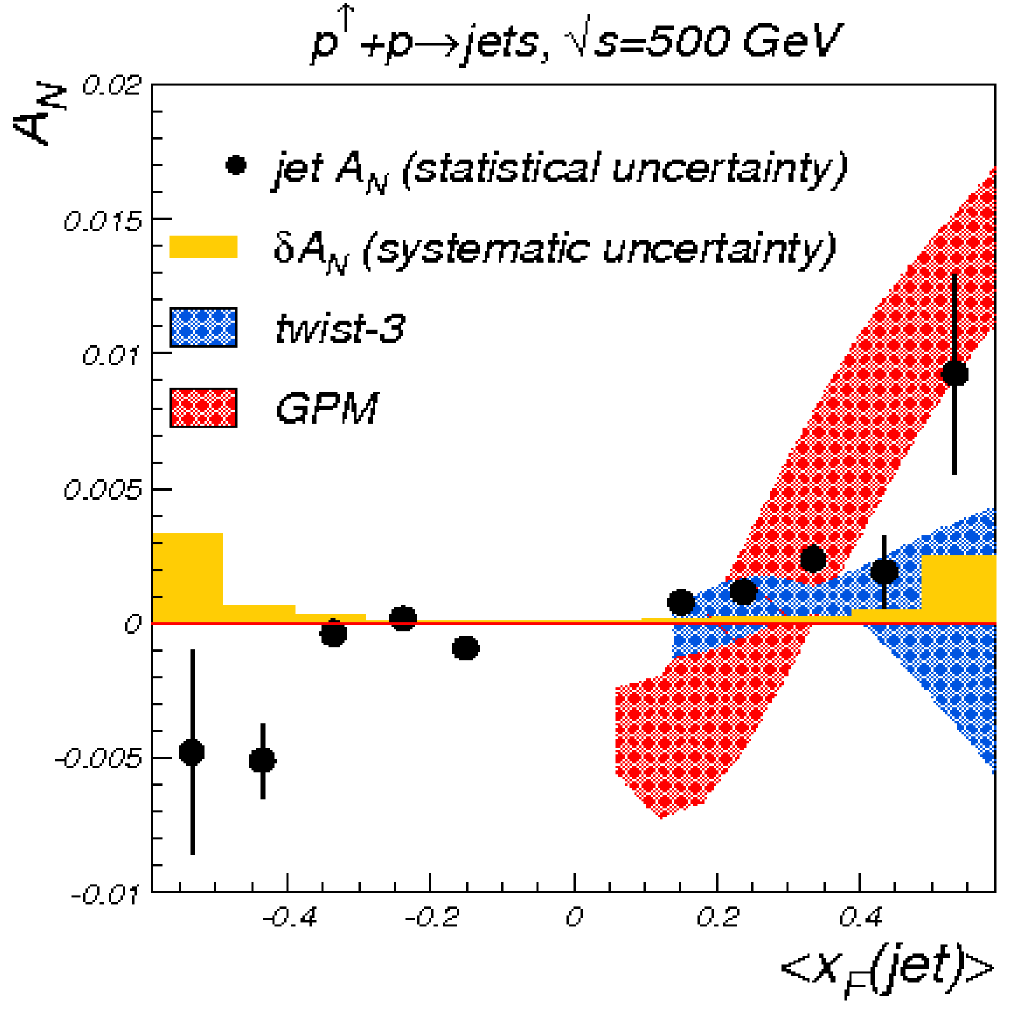
PLB 750 (2015) 660



- Uncertainties include both statistical and systematic estimates [as described in backup]
- Strong dependence on both x_F and p_T requires data/theory comparisons at $<\eta_{jet}>$
- NLO pQCD [PRD 86 (2012) 094009] calculation provides a good description of the data using CTEQ6.6M PDF. Note the small scale dependence [band represents range of scale from $\mu=2p_T$ to $\mu=p_T/2$]
- Leading-order pQCD model calculation assuming factorization in the use of k_T dependent distribution functions [generalized parton model (GPM), PRD 88 (2013) 054023] also describes the data. The larger scale dependence is likely a consequence of a leading-order calculation
- Particle jet reconstructions [no detector effects beyond acceptance] with the anti-kT algorithm with R_{jet}=0.7 are used to compare default PYTHIA 6.222 [prior to tunings for the LHC] and PYTHIA 6.425 ["Field tune A"] to data. PYTHIA 6.222 was previously found to describe forward π^0 production at $\sqrt{s}$=200 GeV [arXiv:hep-ex/040312].

Forward Jet Analyzing Power

PLB 750 (2015) 660

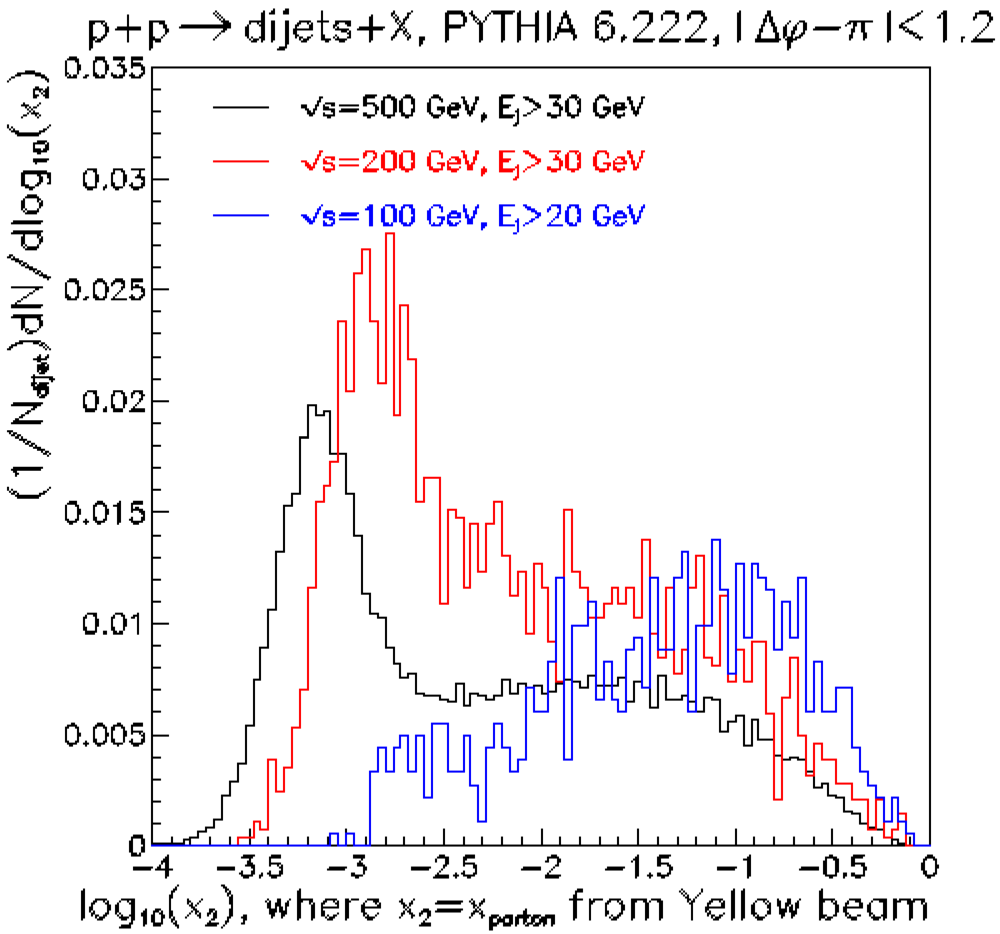


- Analyzing power is computed via the cross-ratio method that exploits the mirror symmetry of the apparatus

$$P_{beam} A_N = \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_R^{\uparrow} N_L^{\downarrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_R^{\uparrow} N_L^{\downarrow}}}$$

  - P_{beam} – beam polarization [0.526±0.027 for x_F>0]
  - $N_{L(R)}^{\uparrow(\downarrow)}$ – number of jets in left or right module for beam-spin up or down in each bin of <x_F(jet)>
- Systematic uncertainties [as described in backup] are quoted separately from statistical uncertainties, and are available in tabulated form in the published paper
- Both theory curves for x_F>0 fit the Sivers function in semi-inclusive deep inelastic scattering. "twist-3" is a collinear approach [PRL 110 (2013) 232301] with color gauge link effects. "GPM" is a generalized-parton model calculation [PRD 88 (2013) 054023]
- Jets with x_F<0 would be described by low-x spin effects: e.g., PRD 89 (2014) 074050 and PRD 89 (2014) 034029

Forward Dijets



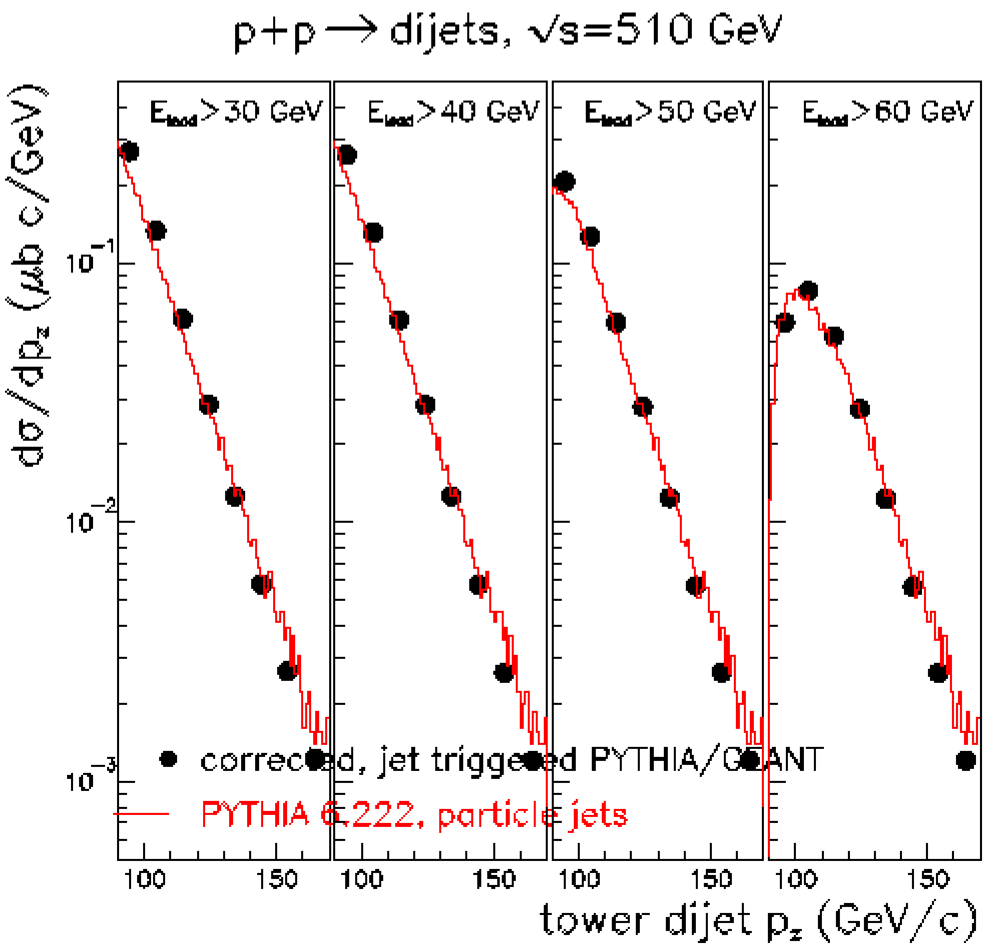
Reconstruction of >1 jet in the forward direction can emphasize hard-scattering contributions from lox-x gluons

Examples of why this is important are

- Extending probes of gluon polarization to low-x by measurement of longitudinal double-spin asymmetries
- QCD processes are the reducible background to forward Drell-Yan production of low-mass virtual photons

Test of Dijet Corrections

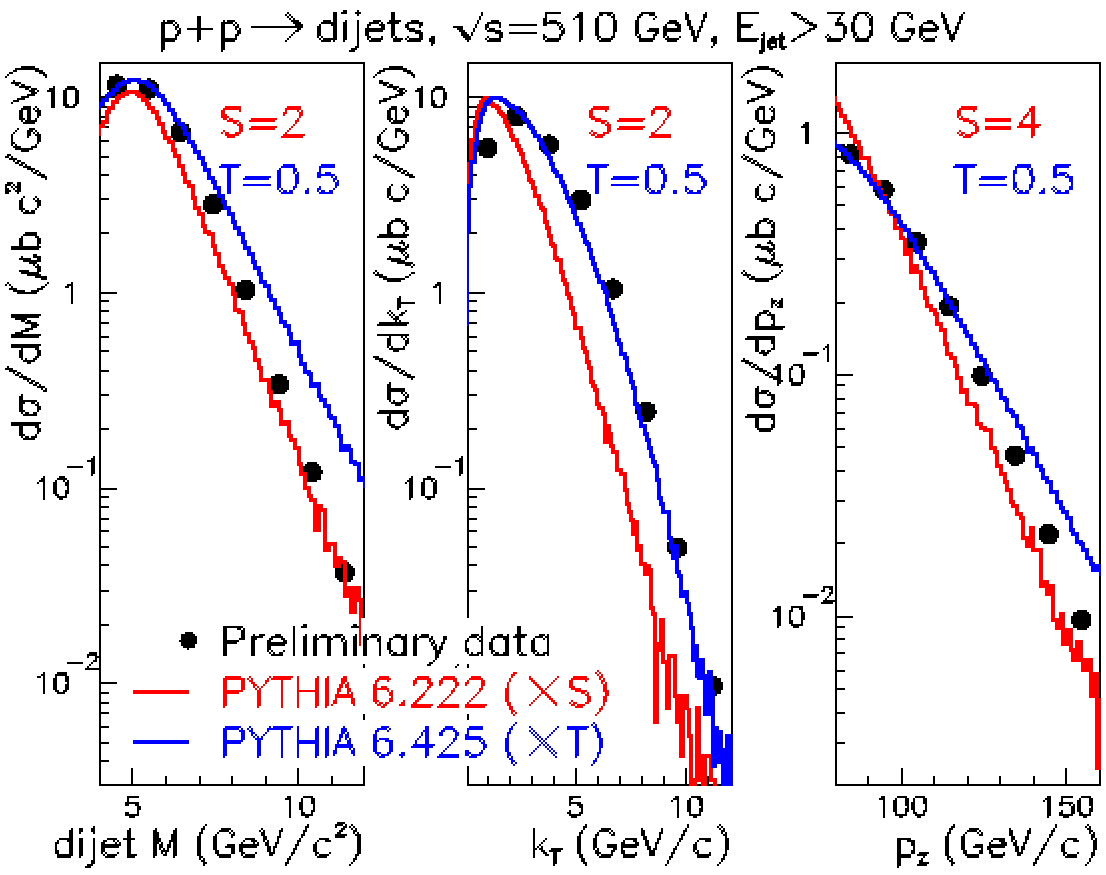
Comparison of corrected PYTHIA/GEANT tower dijets to PTYHIA particle dijets



- It is found that the dijet $\varepsilon_{trig}(V)$ [for $V=M,k_T,p_z$] is the only correction required; i.e., $\varepsilon_{det}(V)=1$
- The dijet correction procedure when applied to PYTHIA/GEANT tower dijets reproduces the input PYTHIA particle dijets (animate for $V=k_T$ and p_z distributions)
- Require $M>4$ GeV/c^2 when reporting $d\sigma/dk_T$ and $d\sigma/dp_z$.

Dijet Results

arXiv:1308.4705



- Use "DY-like" variables, where M is dijet mass assuming massless partons; k_T is the net transverse momentum of the dijet; and p_z is the longitudinal momentum of the dijet
- Preliminary results are efficiency corrected, but at present do not reflect the acceptance imposed on the jet pair [each jet of pair requires $3.0<\eta_{jet}<3.5$, where jets are reconstructed from a nearly annular calorimeter spanning ~$2.4< \eta<4.2$]
- Results are compared to particle dijet results, using default settings for PYTHIA 6.222 and PYTHIA 6.425. Neither version explains the data.

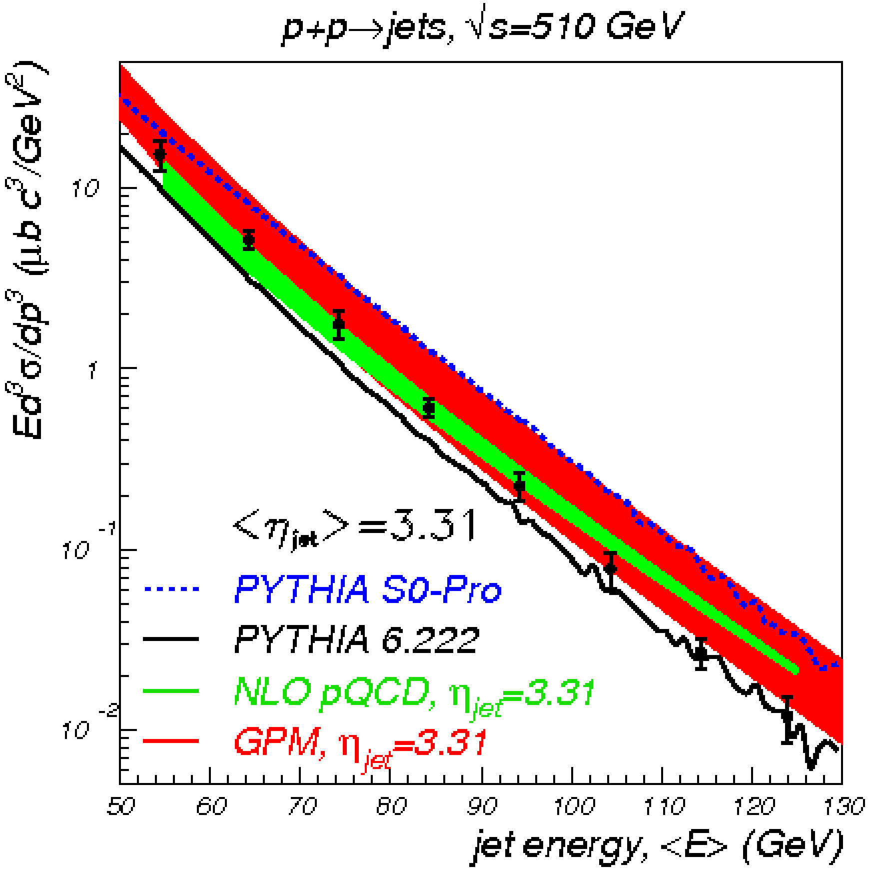
PYTHIA Tunings

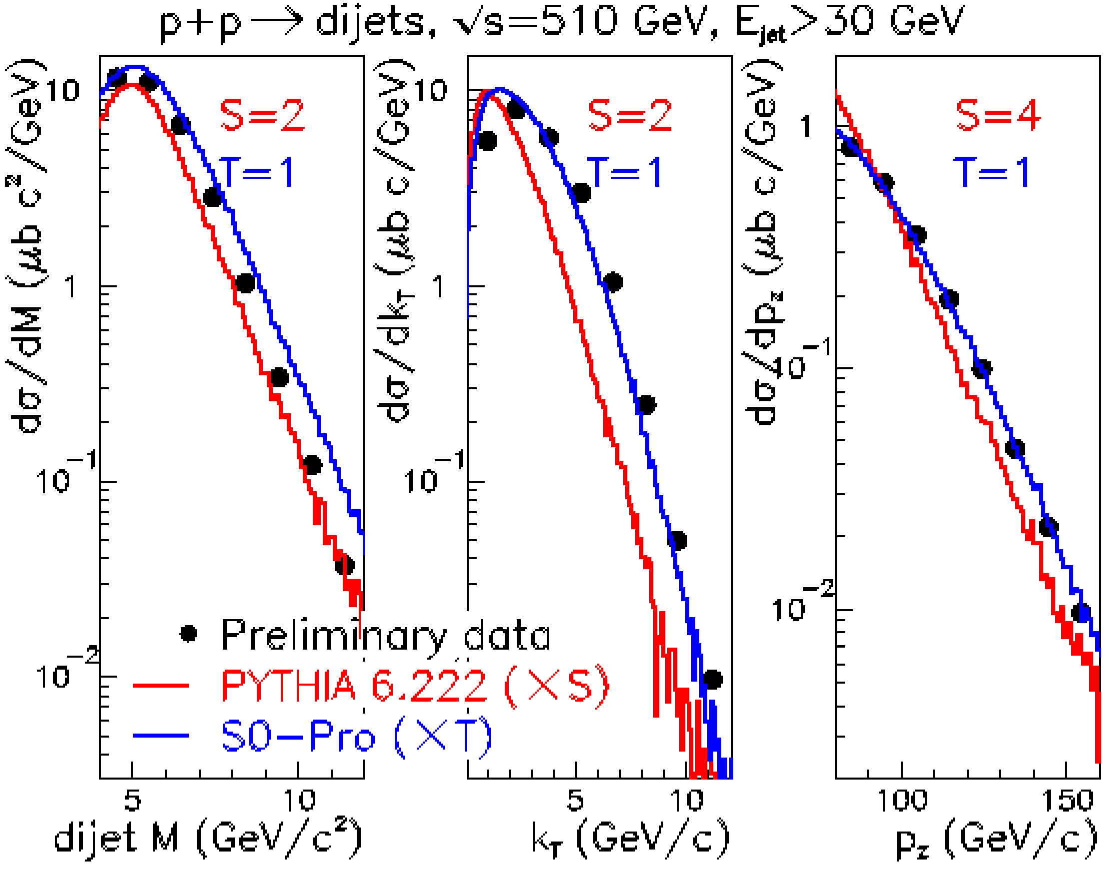
- The LHC high-energy program has prompted many retunings of PYTHIA, so that backgrounds in e.g. dijet mass are well modeled to allow new particle searches. See P.Z. Skands, PRD 82 (2010) 074018 [arXiv:1005.3457]

- PYTHIA tunings most commonly adjust initial-state and final-state showering parameters; multi-parton interaction model parameters; etc. As will be shown, inclusive forward jets and forward dijets from RHIC are sensitive to these tunings [as should be expected, since the rapidities involved for forward dijets at RHIC rival those from midrapidity at the LHC]

- In general, any serious low-x physics study of forward particle production will need to deal with the physics of parton showers and multi-parton interactions. It is not good to attempt to “correct” measurements for these effects. Experimental results should report what’s observed, rather than subtracting model-dependent quantities from what is measured [in my opinion…]

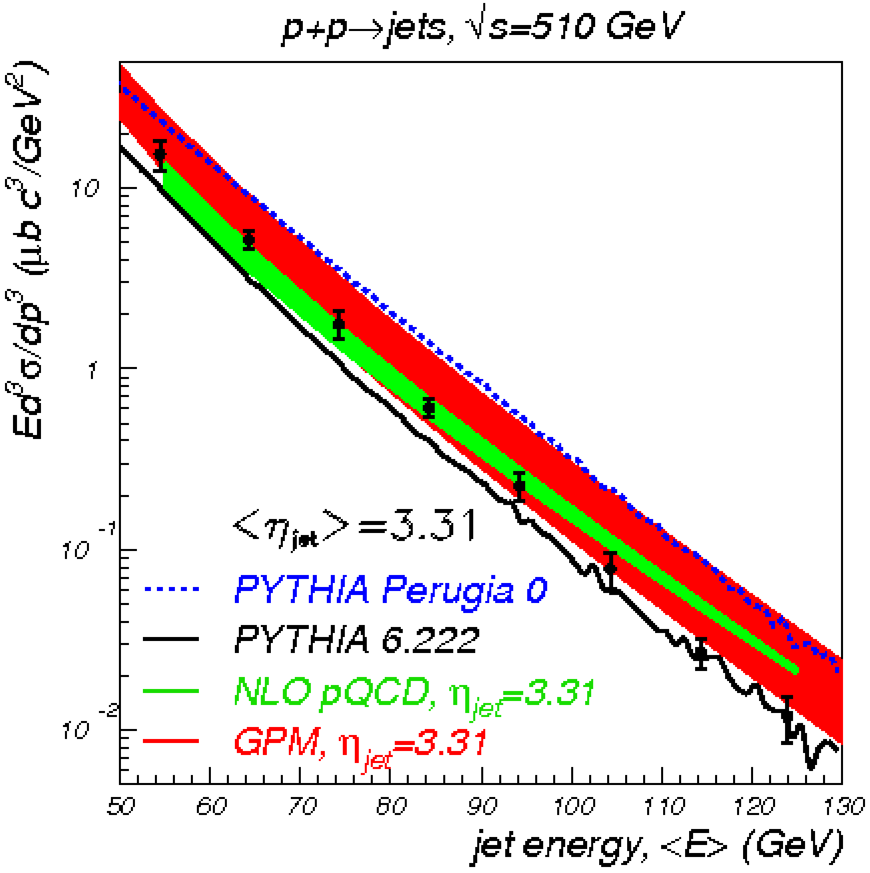
Data versus S0-Pro Tune

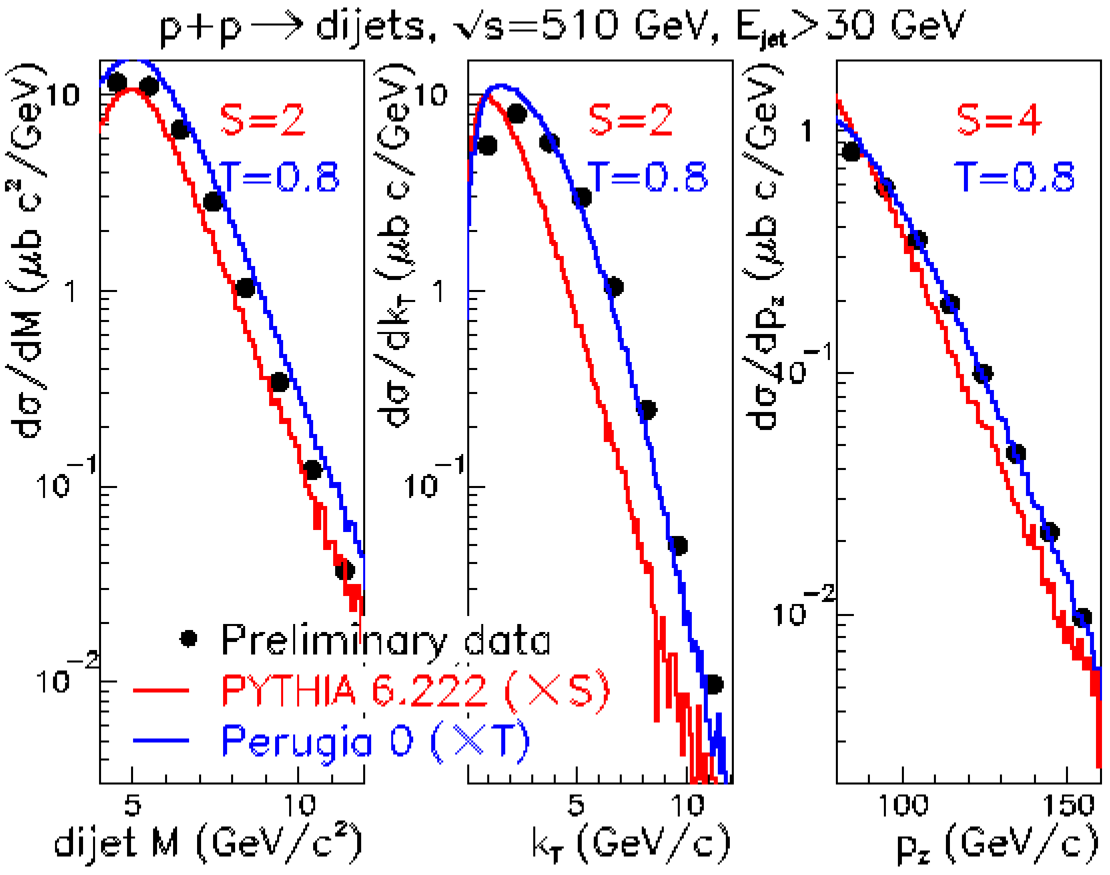




- Good fit to dijets in distribution shape and normalization
- Overpredicts the inclusive jet cross section

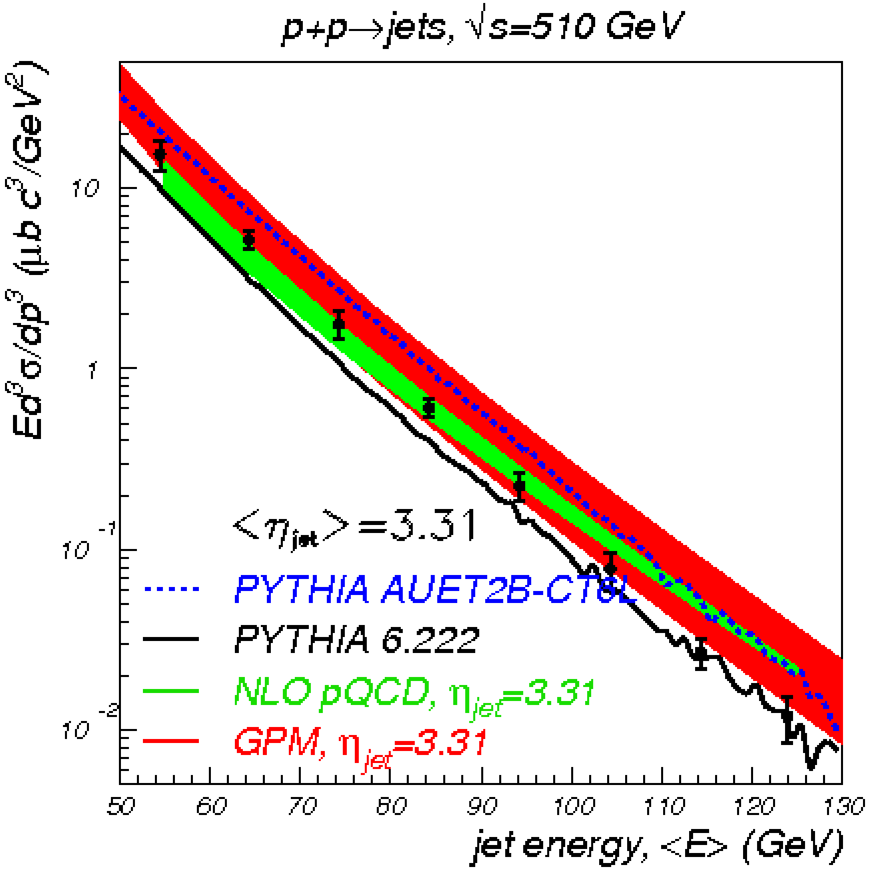
Data versus Perugia 0 Tune

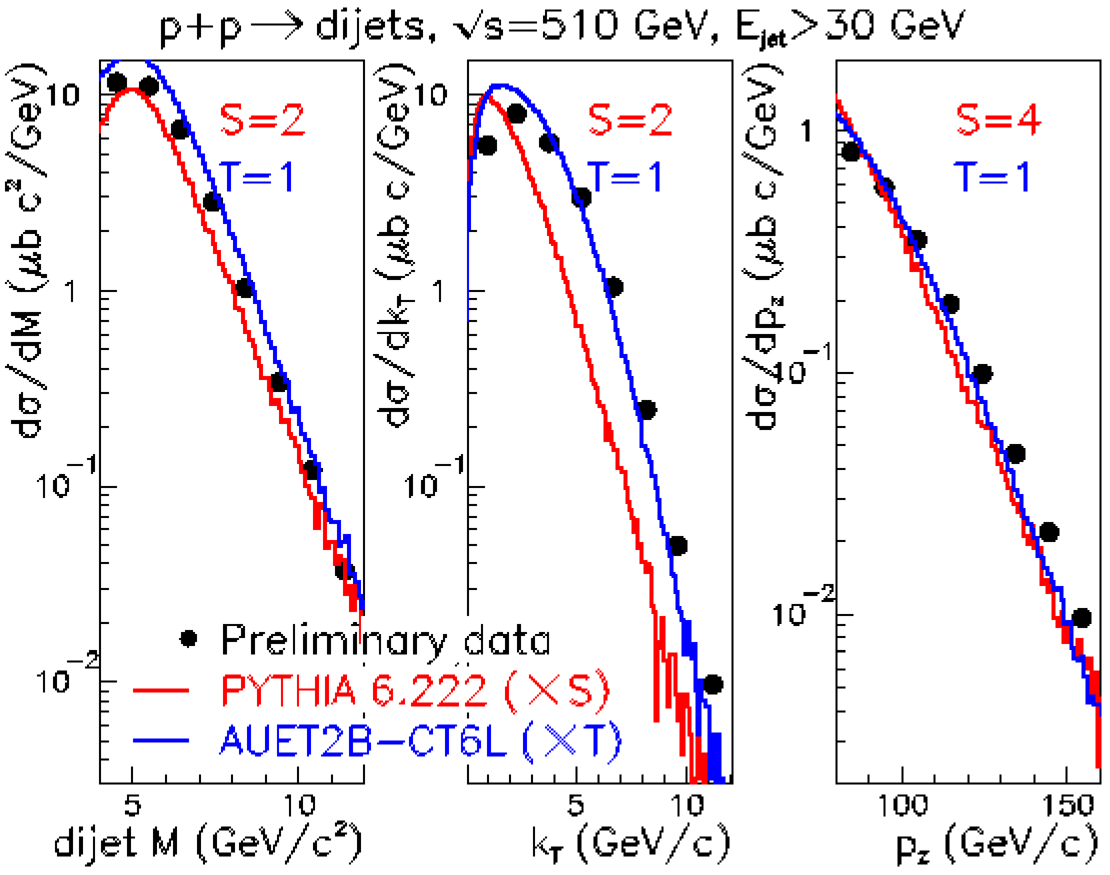




- Perugia 0 is commonly used for RHIC midrapidity data
- Overpredicts dijet cross sections by ~20%
- Overpredicts inclusive jet cross section

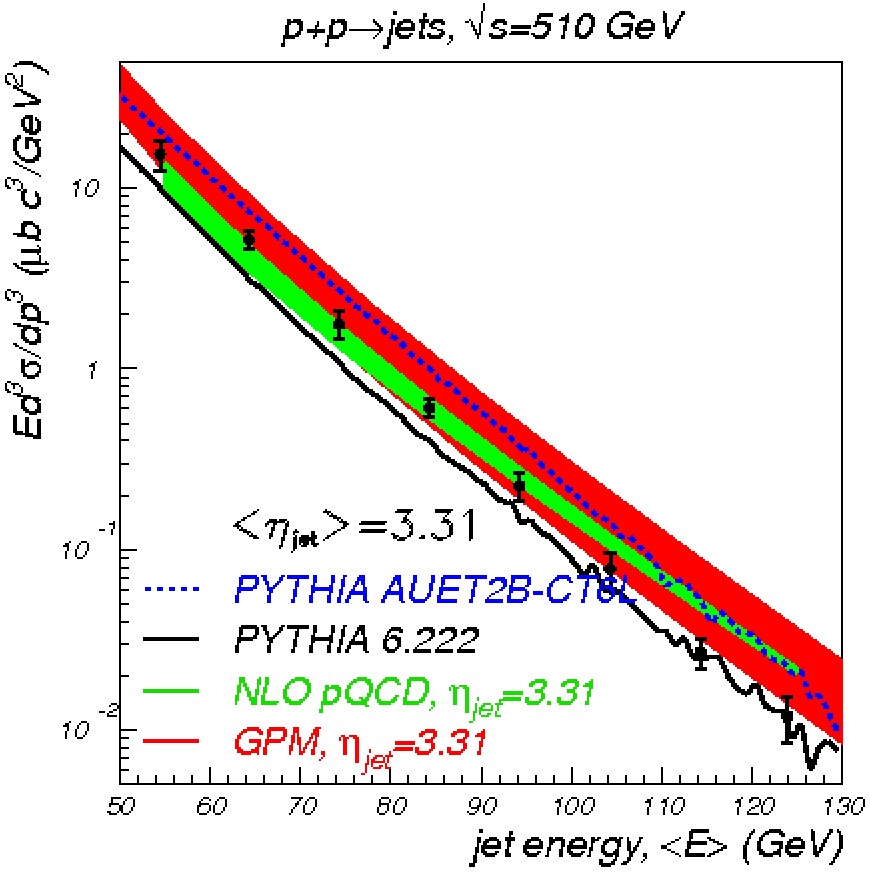
Data versus Atlas [AUET2B-CT6L] Tune

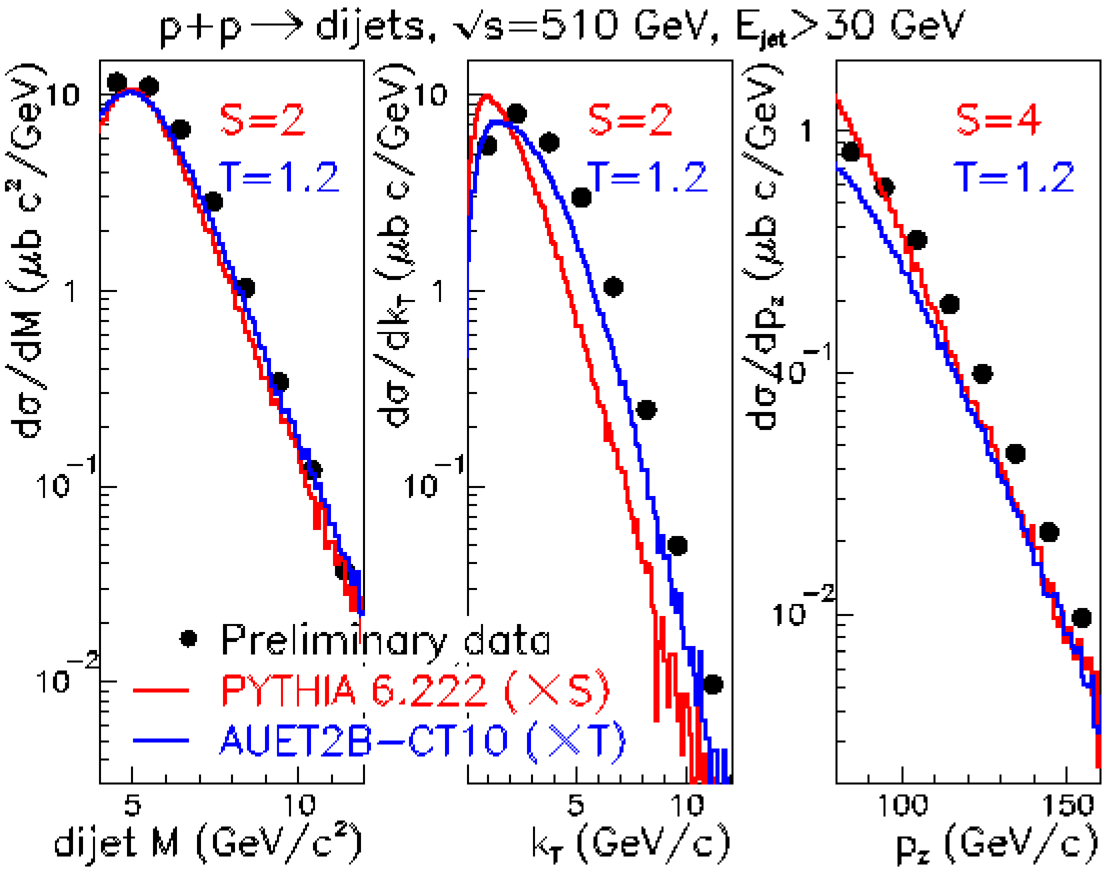




- PYTHIA tune developed by Atlas [arXiv:1512.001917], including LHC 7 TeV data
- Reasonable representation of dijet distributions and normalization
- Better description of inclusive jet result than other tune

Data versus Atlas [AUET2B with CTEQ10] Tune

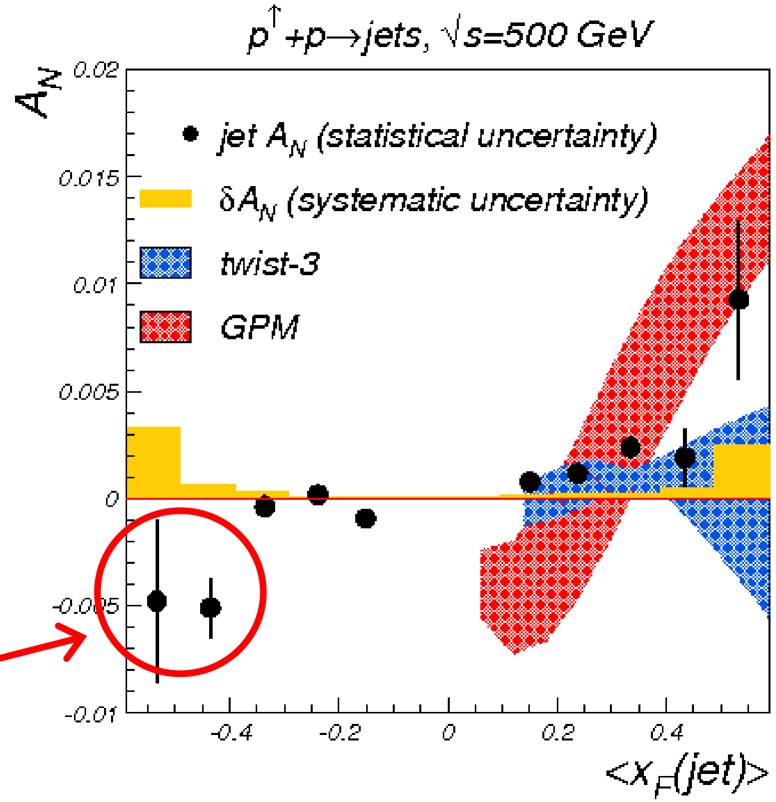




- This is AUET2B-CT6L, replacing the PDF by CTEQ10 [which differs from CTEQ6 for low-x gluons]
- Reasonable description of inclusive jet data
- ~20% overprediction of dijet data

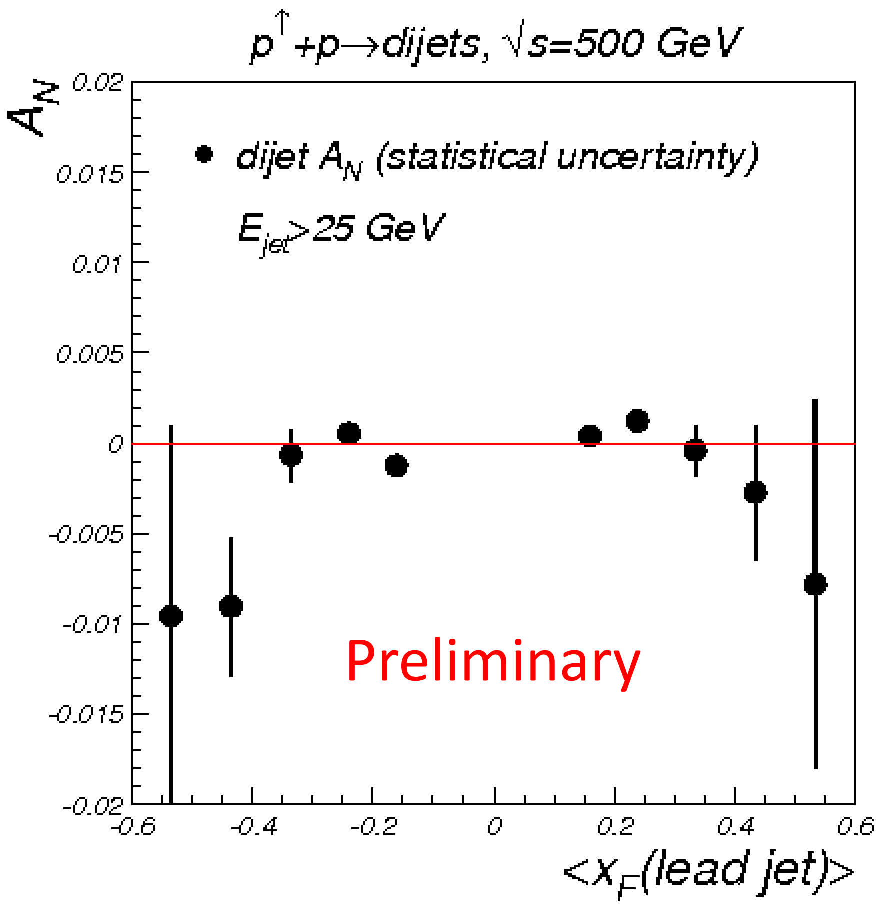
Are there transverse SSA for dijets?

- Relevant because dijets are the dominant background for forward DY production of dileptons
- Important for low-x physics [e.g. PRD 89 (2014) 074050 and PRD 89 (2014) 034029], in that forward dijets emphasize low-x whereas inclusive jets involve a broad distribution of Bjorken x



Are these hints of non-zero A_N from low-x physics?

First Look at Dijet Analyzing Power

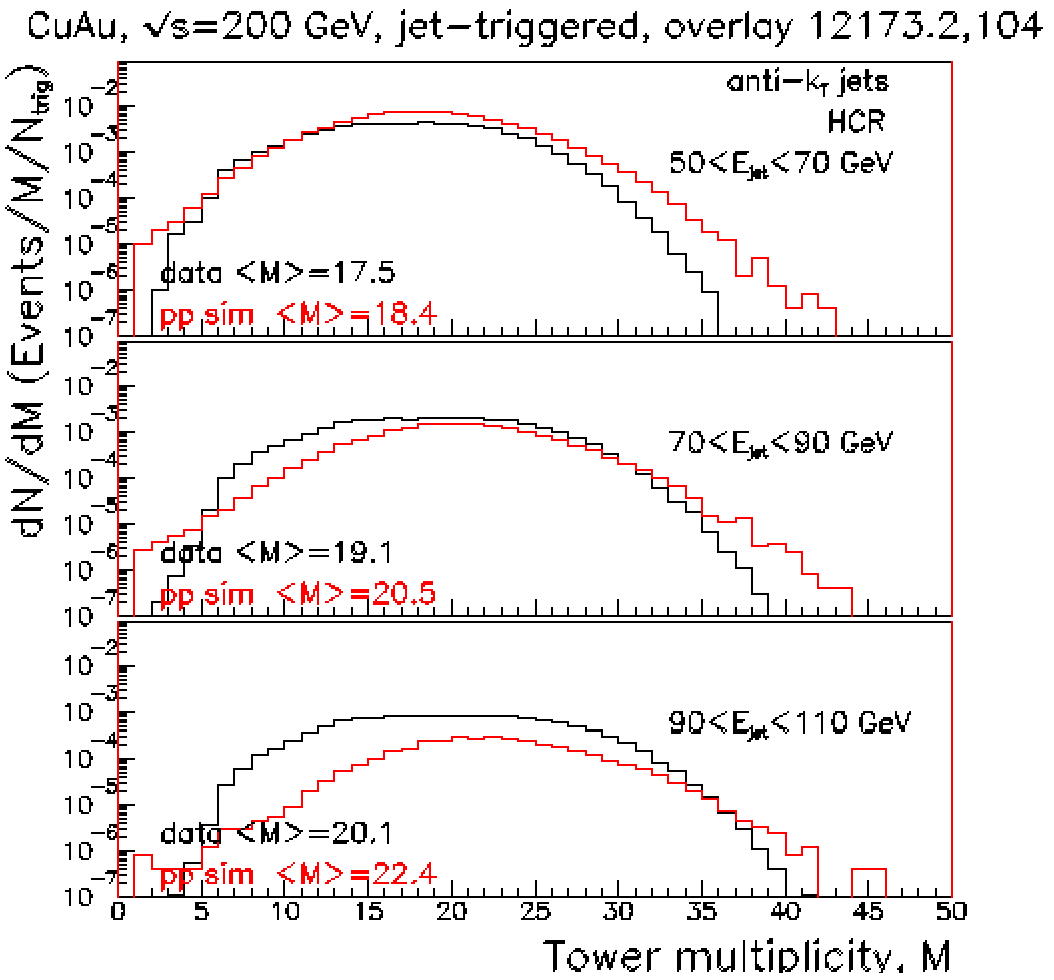


- Identify jet-like clusters with the anti-kT algorithm with Rjet=0.7 [identical to the inclusive jet analysis]. Select events with >1 valid jet. Each valid jet is with η_{jet},φ_{jet} acceptance selections imposed and has E_{jet}>25 GeV.
- The azimuthal angle of the jet pair is used for spin sorting [replacing the azimuthal angle of a single jet, for the inclusive analysis]
- A_N for dijets is computed via the cross-ratio method, so systematic uncertainties are expected to be similar in size to inclusive jet systematic uncertainties
- The results are a function of the lead-jet <x_F>, to facilitate comparison to the inclusive-jet results
- A_N(dijet) is consistent with zero for x_F>0
- 2.4σ statistical significance non-zero A_N(dijet) for x_F<0

Conclusions

- Forward jets [x_F>0.1] are consistent with next-to-leading order pQCD for pp collisions at $\sqrt{s}$=500 GeV
- Forward jets have a non-zero transverse single spin asymmetry consistent with spin-correlated k_T [Sivers]
- Forward jet pairs are sensitive to low-x gluons at low scale, with the caveat that multi-parton interactions and partonic showers can be a significant background.
- Forward inclusive jet and dijet cross sections from RHIC can be described by the same PYTTHIA tunes as used at the LHC

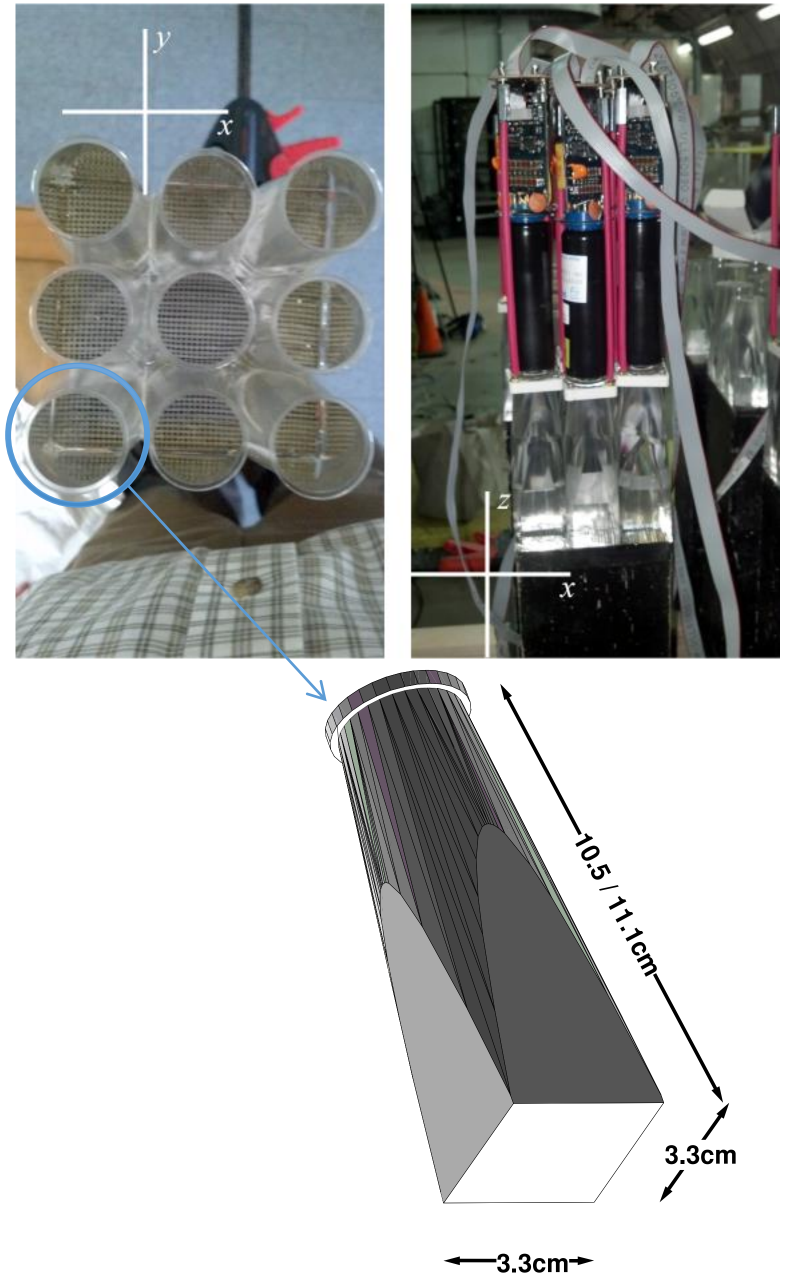
Outlook – I: Forward Jets in HI Collisions?



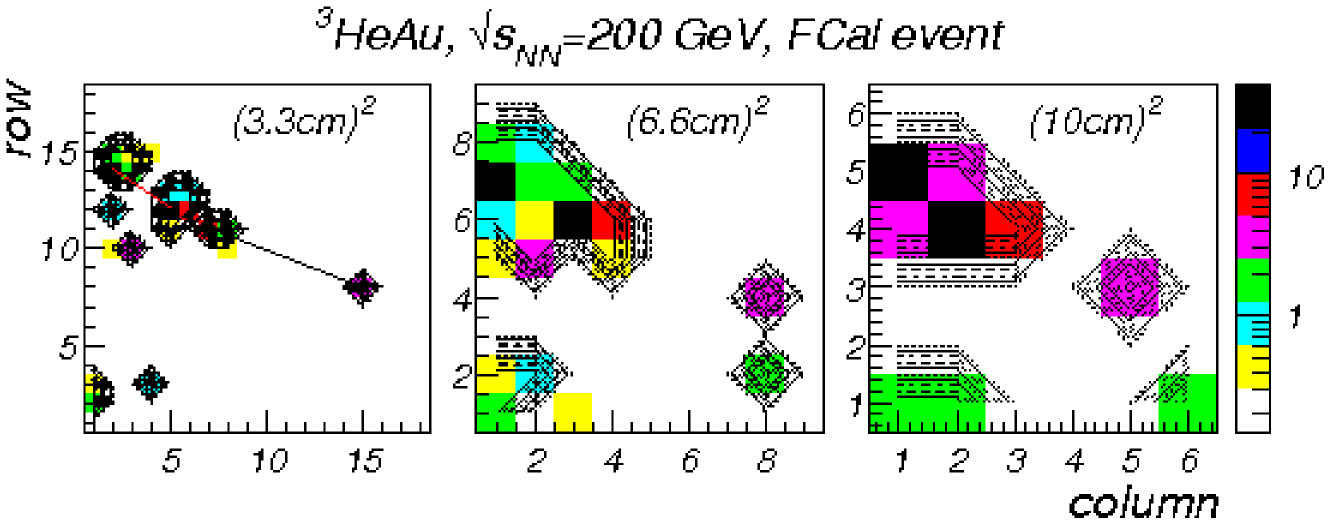
"pp sim" is in reference to PYTHIA 6.222/GEANT for p+p at √s=510 GeV, with jets reconstructed with R_{jet}=0.7 The comparison of the normalizations to CuAu are irrelevant. The tower multiplicities of the jets in CuAu are comparable to those from pp.

- The anti-kT jet finder developed for $p^{\uparrow}$+p collisions at √s=500 GeV [arXiv:1304.1454] produces reasonable jets for centrality-averaged CuAu, when compensated R_{jet}=0.5 jets [arXiv:1308.4705] are reconstructed.
- A first look was made for the modular HCal, in comparison to p+p PYTHIA/GEANT simulations at √s=510 GeV.
- A modular HCal at STAR could enable rapidity correlation studies in AuAu for at least some of the centrality values.

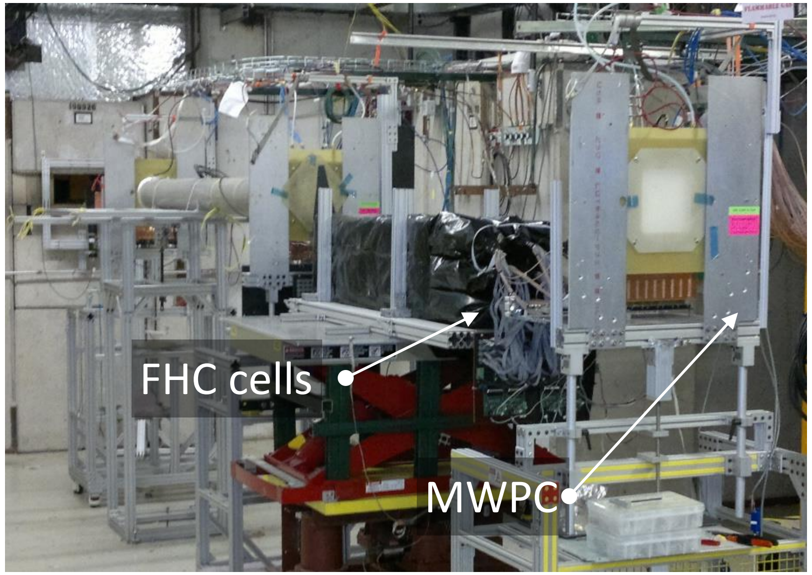
Outlook-II : Pixelizing AGS-E864 cells



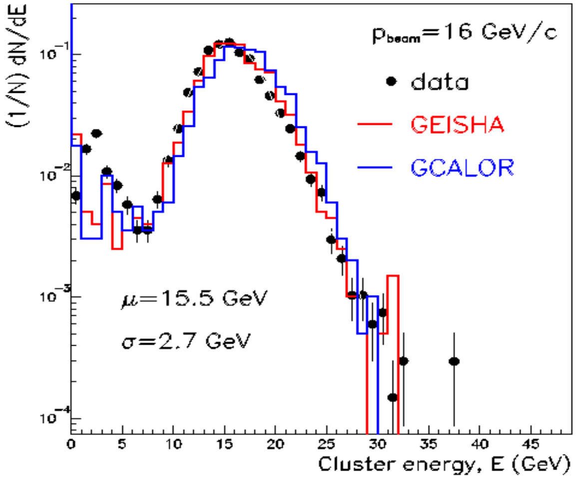
- Transverse resolution is increased by pixelizing
  - (10 cm)^2 cells ➔ 3×3 array of (3.3 cm)^2 cells
  - Stack (6-cell)^2 forward calorimeter at STAR in 2014
  - “looking within” cell shows clear structures



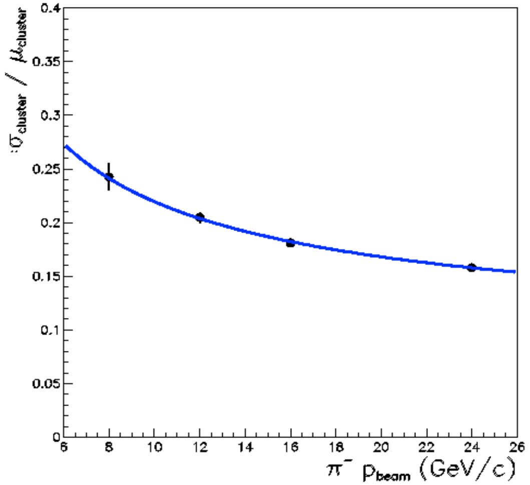
Outlook III - Results from Fermilab Test Beam Facility-T1064



Cluster energy distribution of center pixel for π^- beam

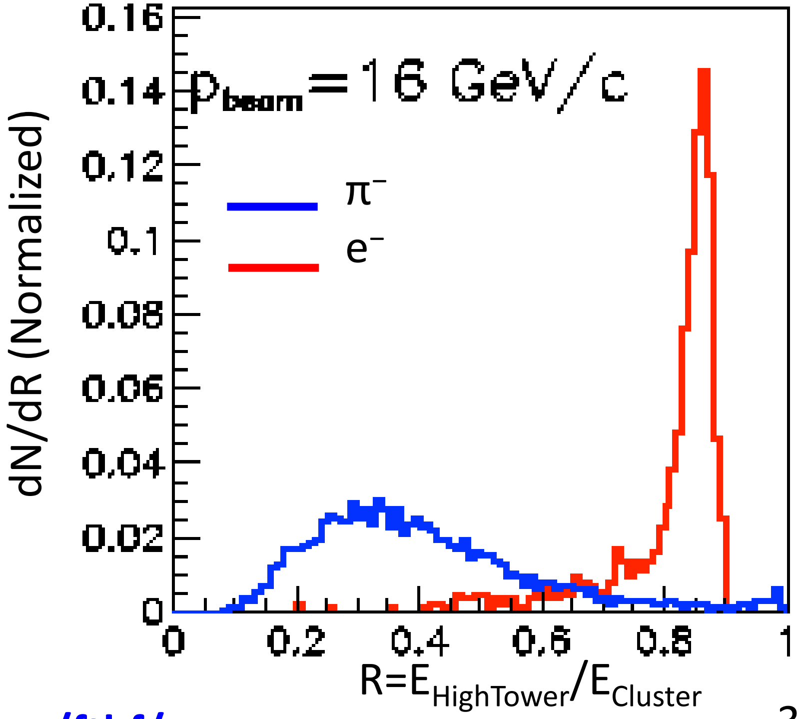


Cluster energy resolution for π^- on central pixel



- 1 GeV (π,*K*,*p*) to 120 GeV *p* (resolution <3%)
- Cerenkov Detector (Particle Identification)
- MWPC Tracking System (Beam profile, trigger)

- 3×3 Cells (9×9 pixel) were used
- Studied shower shapes of e^- & π^- at beam momenta : 8, 12, 16, 24 GeV/c
- Simulations shows **good** agreement with data
- **Shows clean separation between e^- & π^- shower shapes**

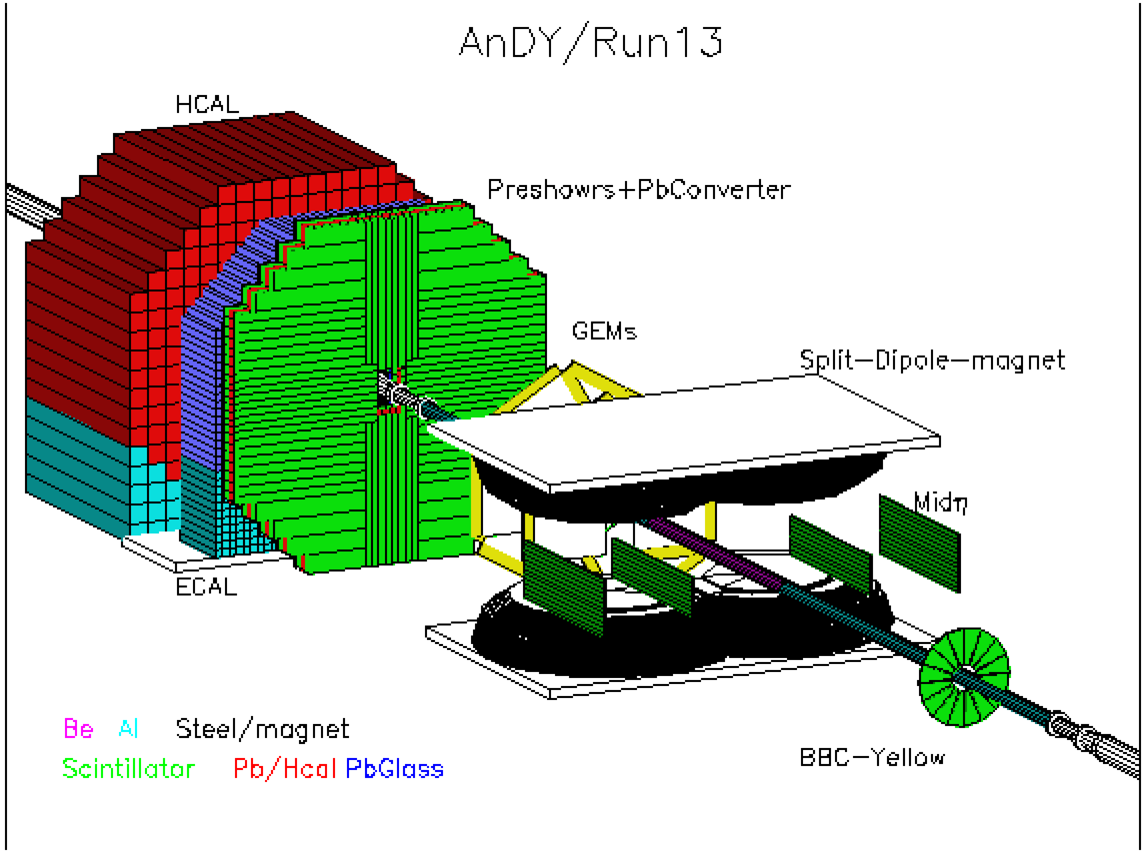


http://ppd.fnal.gov/ftbf/

Backup

Goal of A_NDY Project

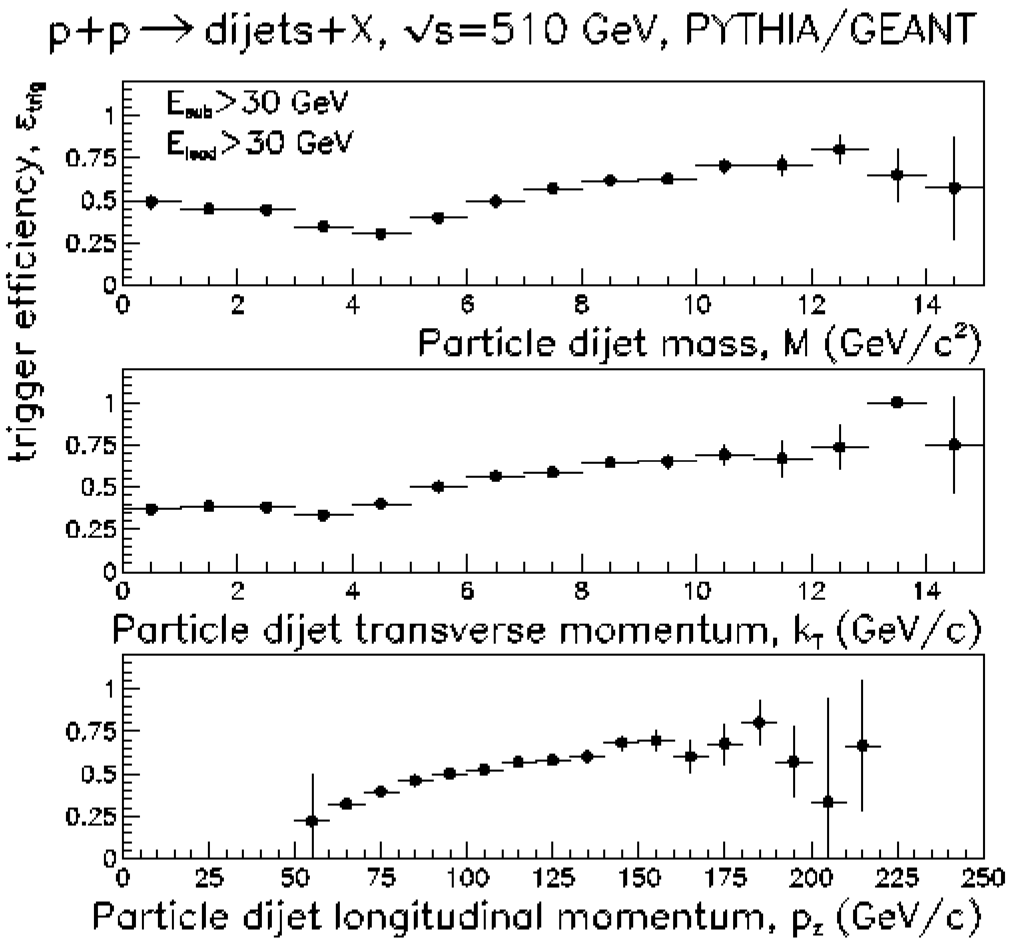
Measure the analyzing power for forward Drell-Yan production to test the predicted change in sign from semi-inclusive deep inelastic scattering to DY associated with the Sivers function



GEANT model of proposed A_NDY apparatus (run-13)

Dijet Trigger Efficiency

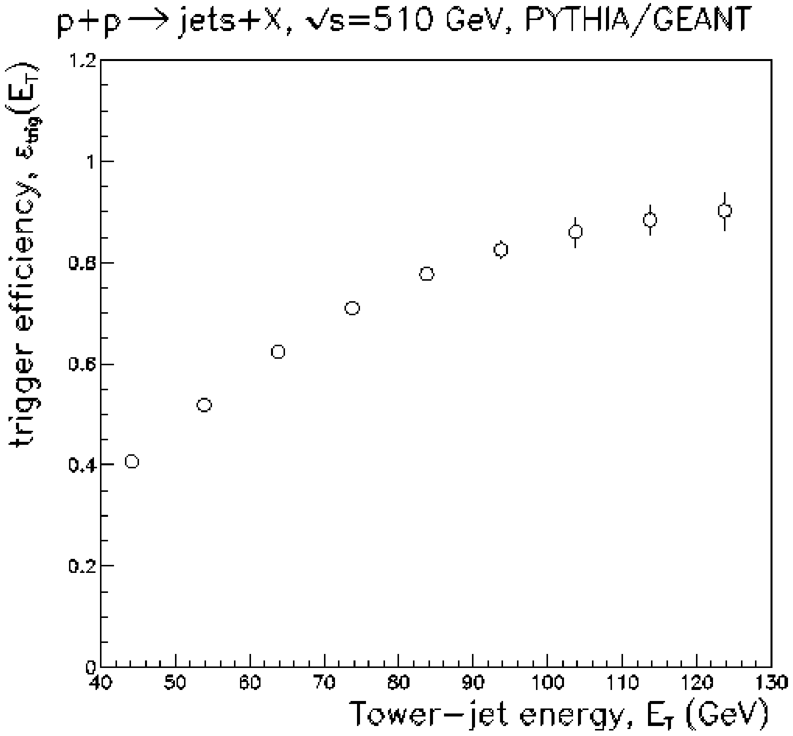
Results prior to convolution integrals



- Analyze the correlation between particle and tower jets from PYTHIA/GEANT simulation to determine dijet finding efficiency
- The dijet efficiencies $\varepsilon_{trig}(V_{part})$ [for V_{part}=M,k_T,p_z] behave as expected, becoming larger at larger energies.
- The dijet variable M is not well measured for M<4 GeV/c^2, since small dijet mass corresponds to small dijet opening angle, and the “leading jet” being large leaves little acceptance for the “subleading jet”.
- Consequently, the focus will be on M>4 GeV/c^2. [Note: the reducible background for DY with M<4 GeV/c^2 is dominated by inclusive jet production]

Jet Cross Section-I

Definition



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

The jet invariant cross section is:

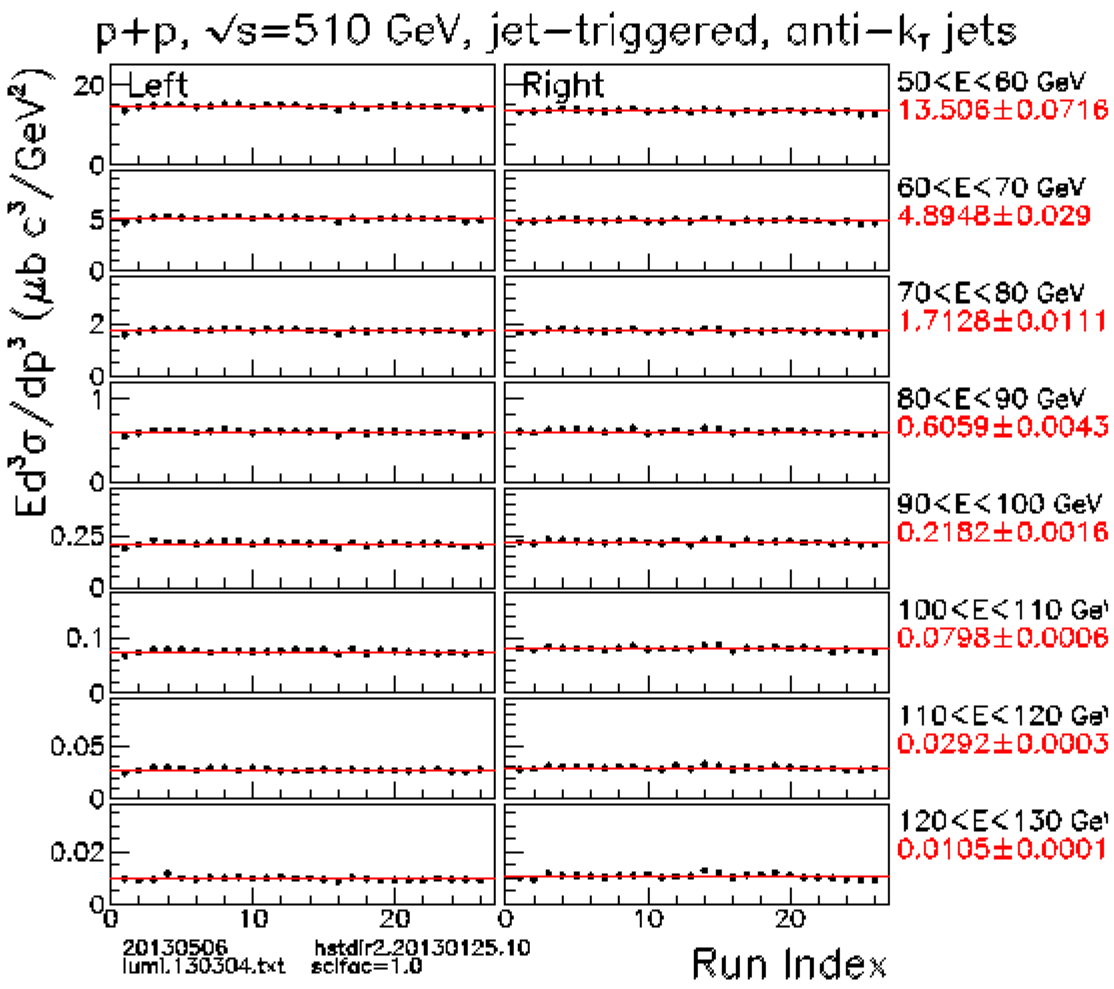
$$E\frac{d^3\sigma}{dp^3} = \frac{N\langle\cosh\eta\rangle}{\varepsilon_{trig}\varepsilon_{\det}L_{samp}\langle p_T\rangle\Delta\eta\Delta\phi\Delta E}$$

where

- N – number of particles detected
- ε_{trig} – trigger efficiency
- ε_{det} – detection efficiency
- L_{samp} – sampled luminosity (time integrated), calibrated by vernier scan
- <cosh(η)> - average value of cosh(η) over the acceptance, $\Delta\eta\approx\Delta y$
- <p_T> - 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



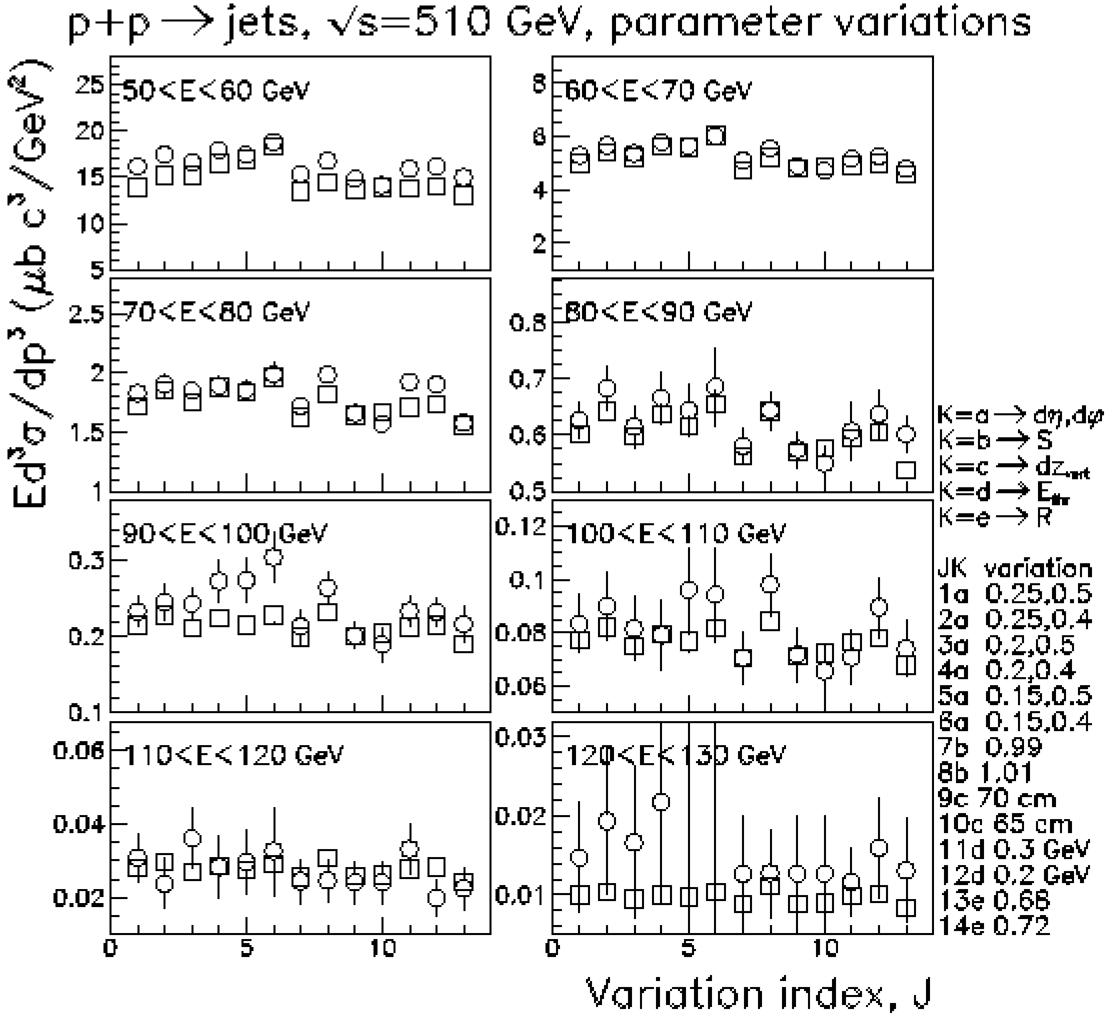
Multiple systematic checks were made for the cross section. This plot shows two:

- 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.

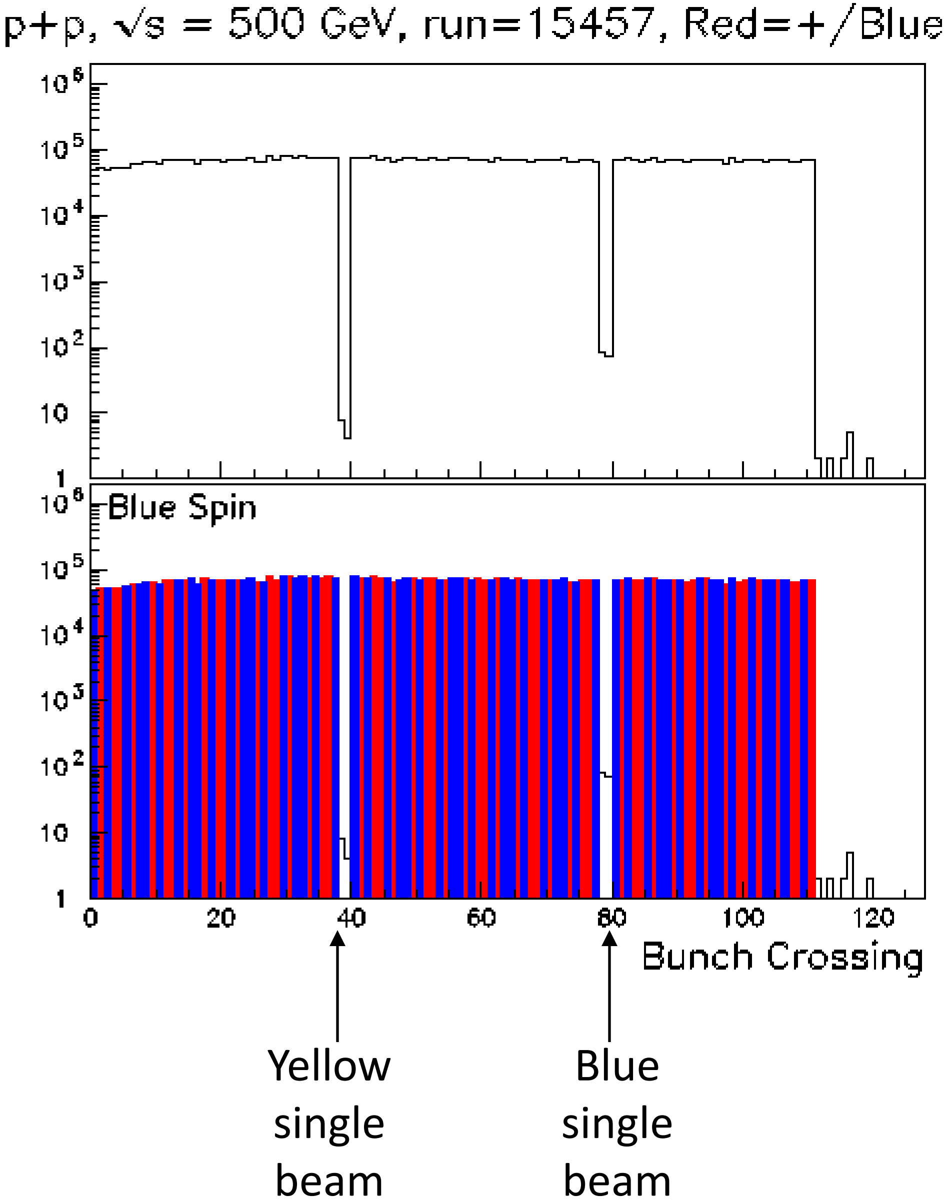
Jet Cross Section-III

Systematic Errors



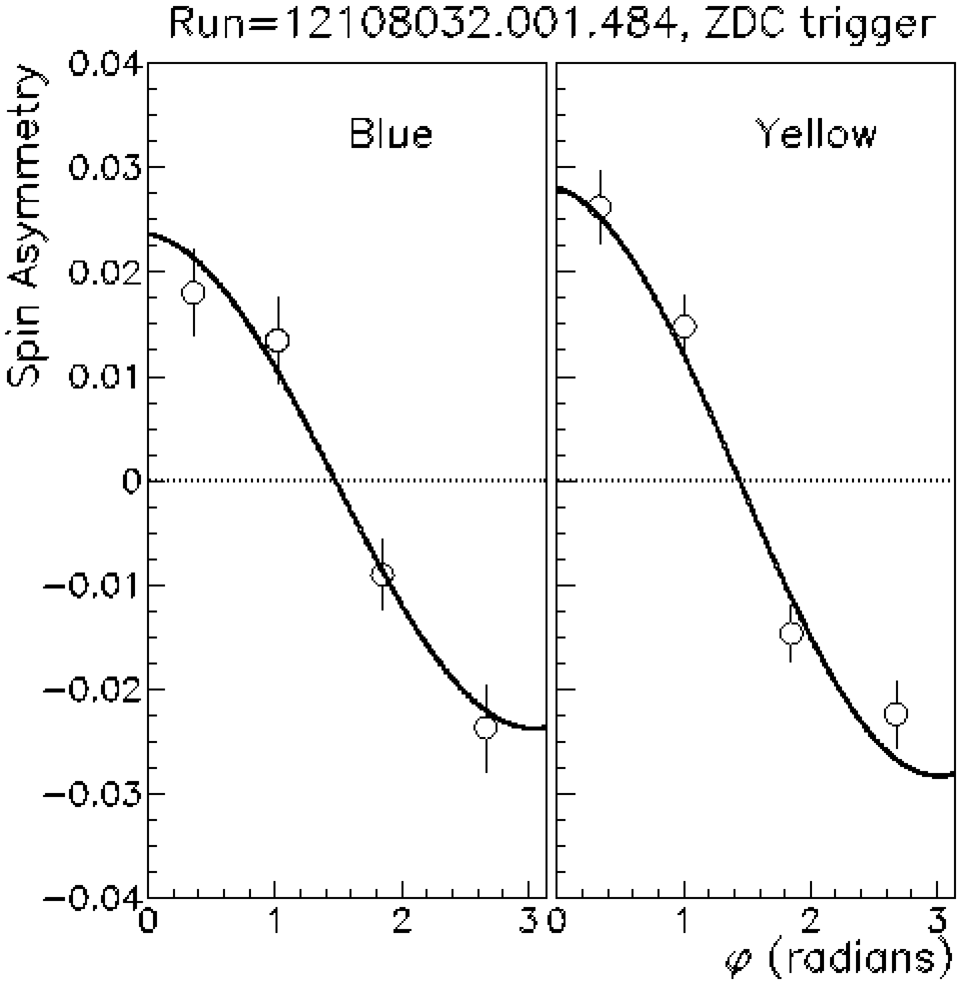
- The stability of the jet cross section was examined as jet-finder (R,Ethr); jet acceptance (dη,dφ); jet energy scale (S) and vertex selection (dz_{vert}) parameters were varied.
- Results with jet triggered (open squares) and minimum-bias triggered (open circles) events are shown.
- Projections of 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.

Spin Sorting



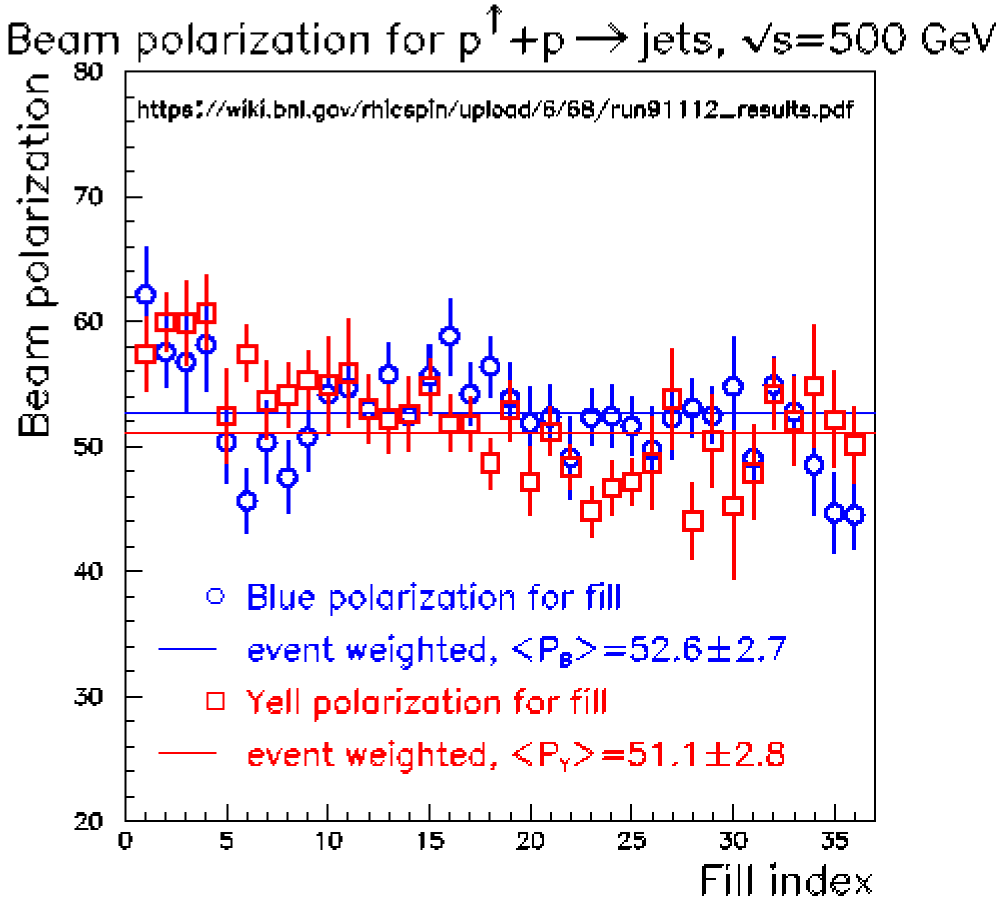
- RHIC has a pattern of polarization directions injected for each fill.
- Polarization for colliding beams is established by counting (C) the 9.38 MHz clock, and identifying specific bunch crossings by B=mod(C,120)
- Polarization pattern for a fill is communicated from the accelerator to the experiments.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

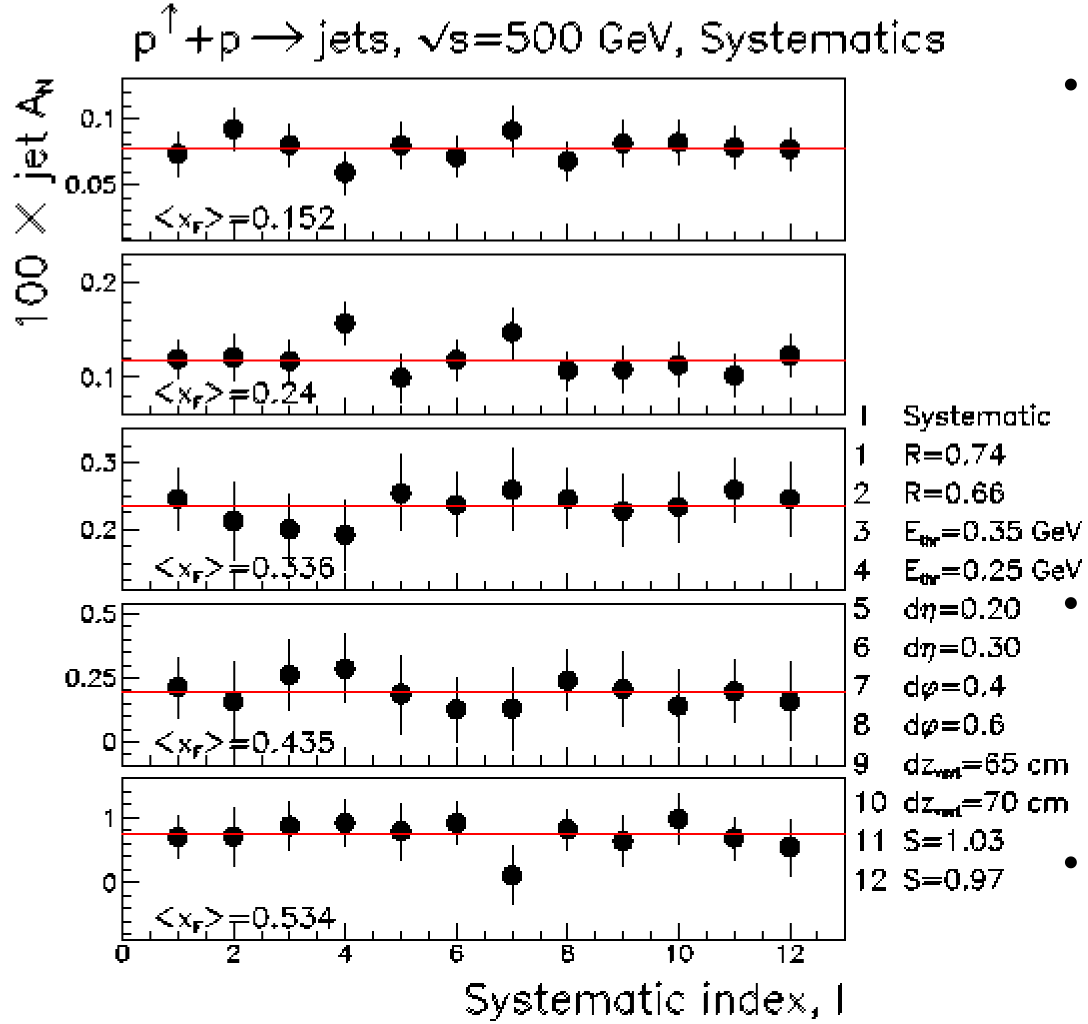
Beam Polarization



- 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

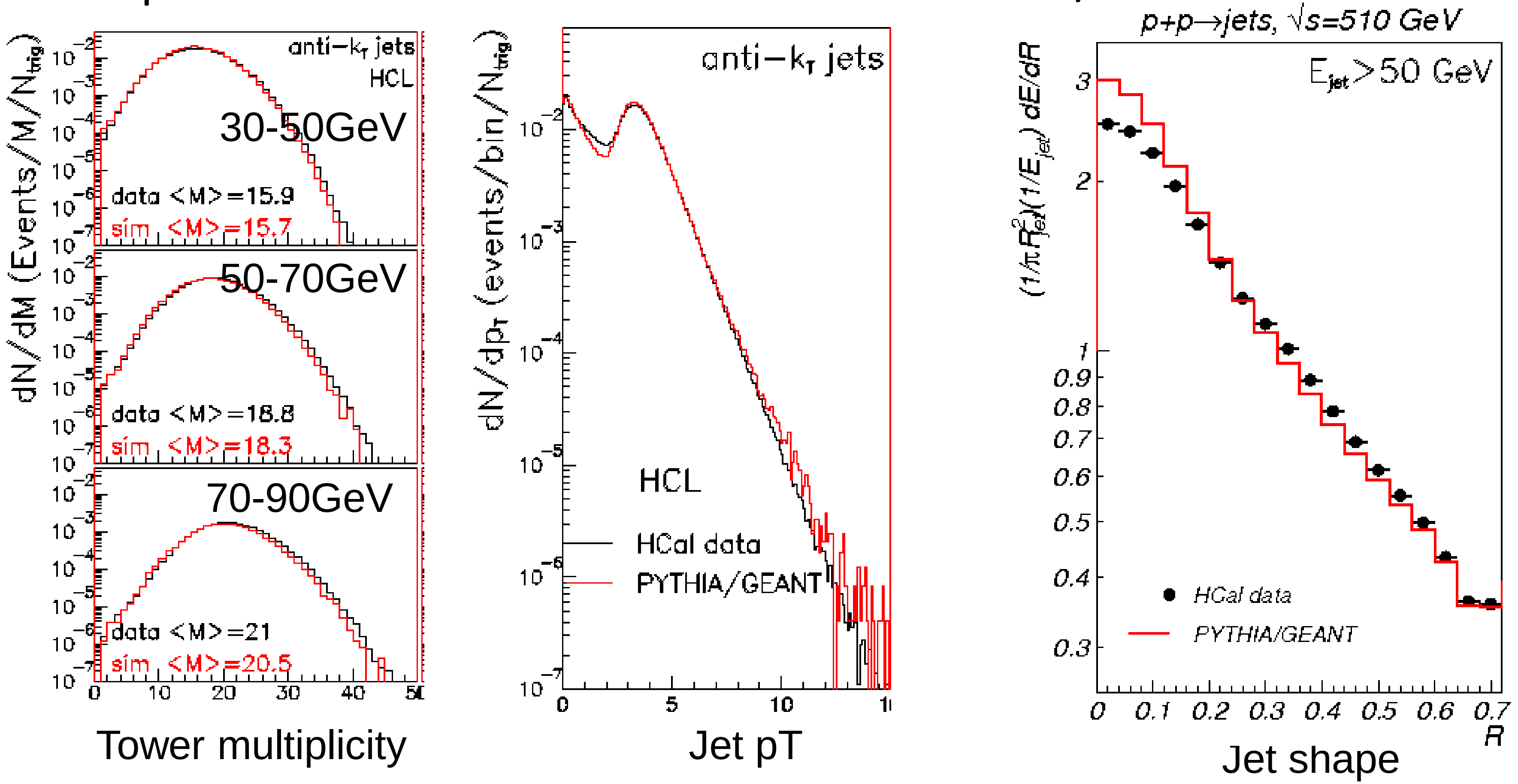


- A_N(jet) exploits mirror (left/right) symmetry of apparatus with spin-↑/spin-↓ of colliding beams, via a cross-ratio…

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

- 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.

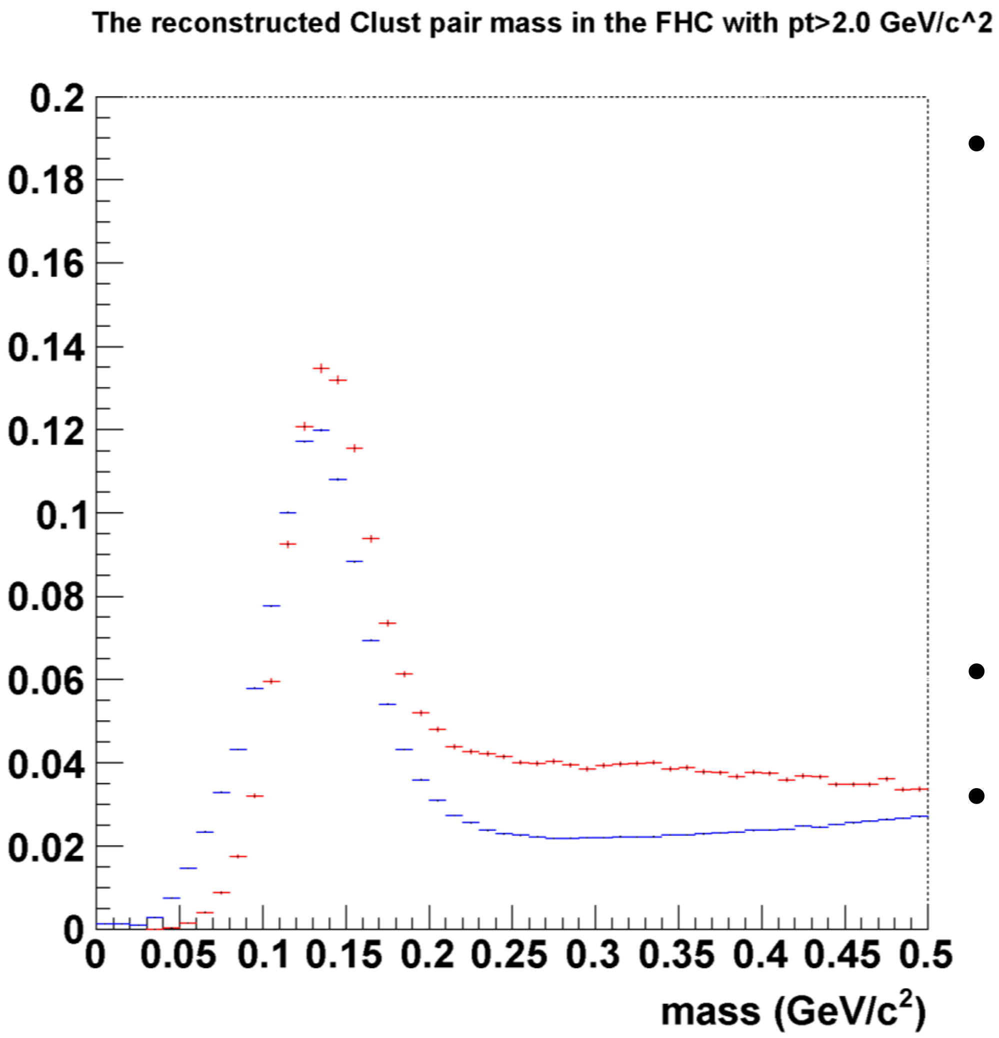
Comparison of Data to PYTHIA 6.222/GEANT Simulation



- Jet p_T and x_F are calculated from anti-kT cluster with R_{jet}=0.7 ignoring mass
- Tower multiplicity agrees with full simulation, meaning particle multiplicity can be deduced
- Given the agreement between data and full simulation, the latter is used for efficiency corrections, e.g. ε_{trig} [trigger efficiency (see backup)]

Jet-triggered data is well described by simulation

Resolution



- Compare forward pair mass from
  - (red) ^3He+Au with FHC
  - (blue) d+Au with FMS

  (Xuan Li - QM12 proceedings)
- Results are comparable
- Spaghetti calorimetry has demonstrated in electron test beam to give good resolution [Leverington, NIM **A596** (2008) 327]