Forward Particle Production at Colliders

How an uninstrumented part of phase space became the focus of >25% of RHIC operation

A QCD story in 3 parts…

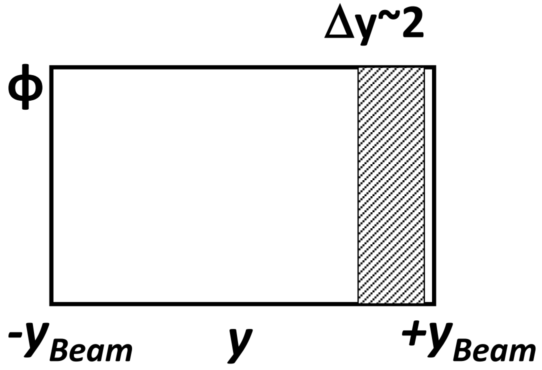
- Part 1 - Spin physics and forward particle production
- Part 2 - Low-x physics and forward particle production
- Part 3 - Towards forward, low-mass Drell-Yan production

… about experimental studies of transverse momentum dependence (TMD)

L.C.Bland
Brookhaven National Laboratory
University of Maryland Seminar
College Park, 4 May 2016

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

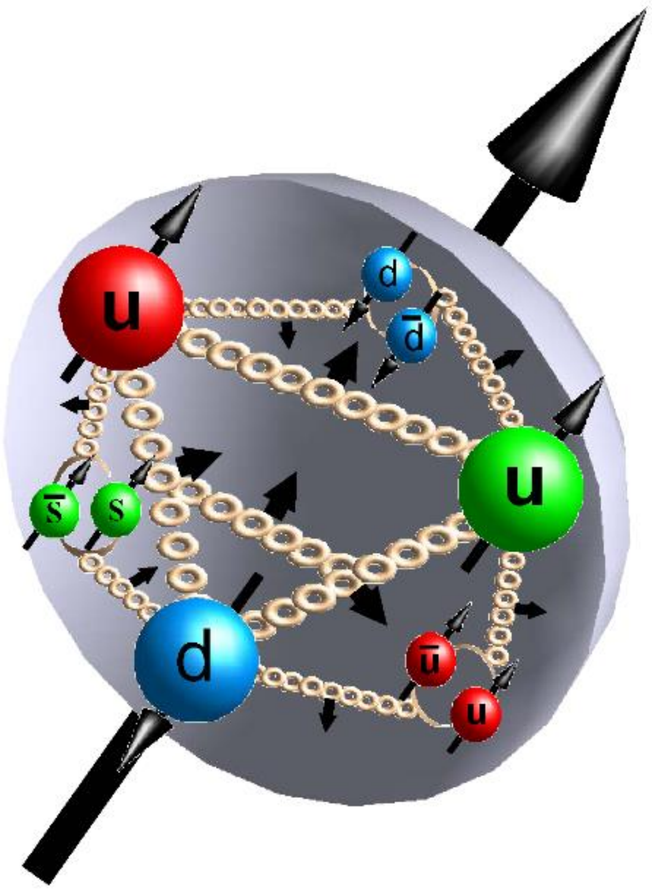
Consider the separation in x-y plane ($d_{\gamma\gamma}$) of a pair of photons from the decay $M\rightarrow\gamma\gamma$, when the plane is L from where M (mass m_M) is produced:

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

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

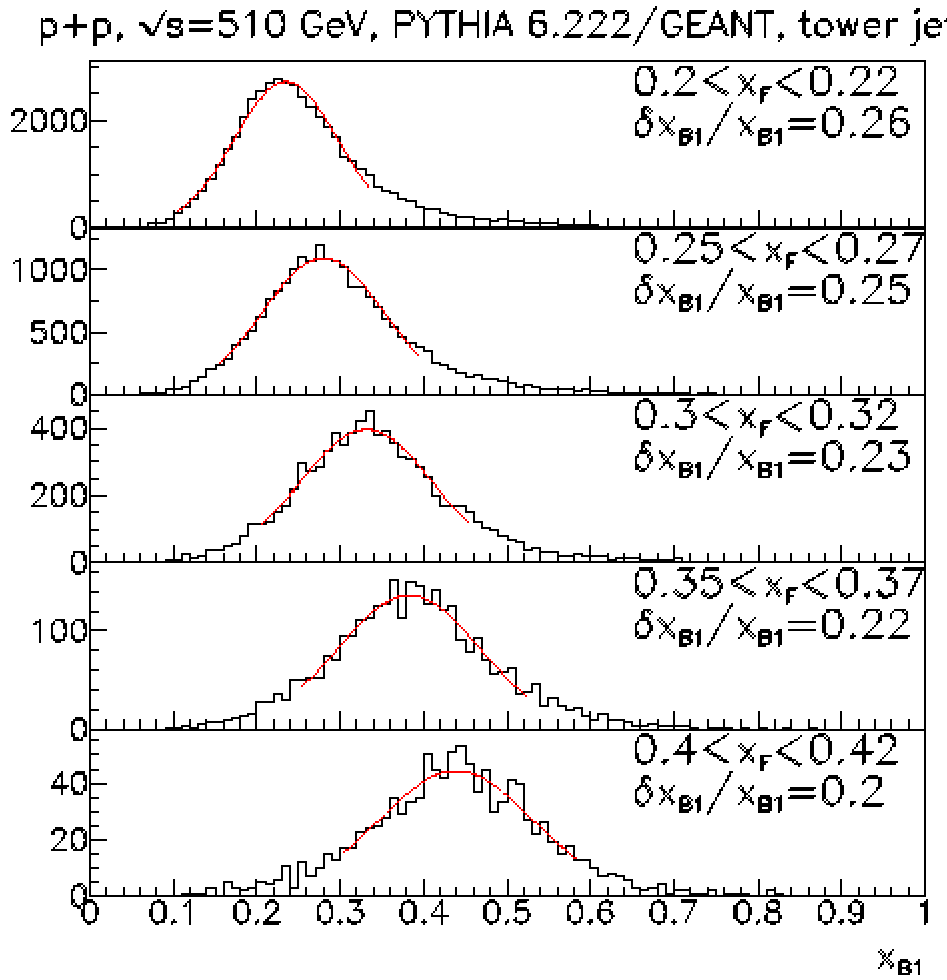
Where is the spin of the proton?

- The proton is characterized by basic properties of mass, spin, size, …
- Global fits to Parton Distribution Functions find that ~50% of the momentum of the proton is carried by gluons
- Polarized deep inelastic scattering finds that quarks account for only ~1/3 of the proton spin: $\Delta\Sigma$=0.33 $\pm$0.03 (stat)$\pm$0.05 (syst)   d'Hose (INT, 2012)
- RHIC spin addresses this question

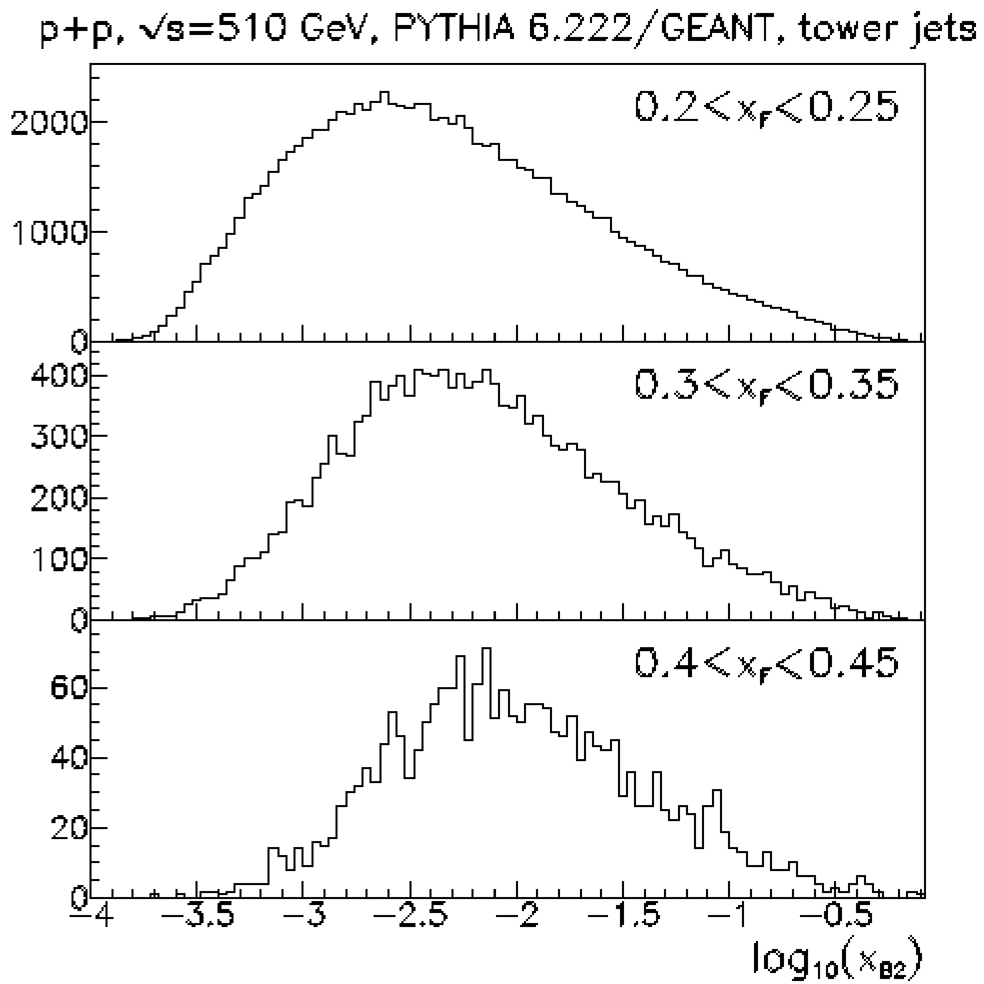


Why is large x_F useful? - I

For hard scattering (2→2 processes), $x_F \approx x_1 - x_2$, 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.

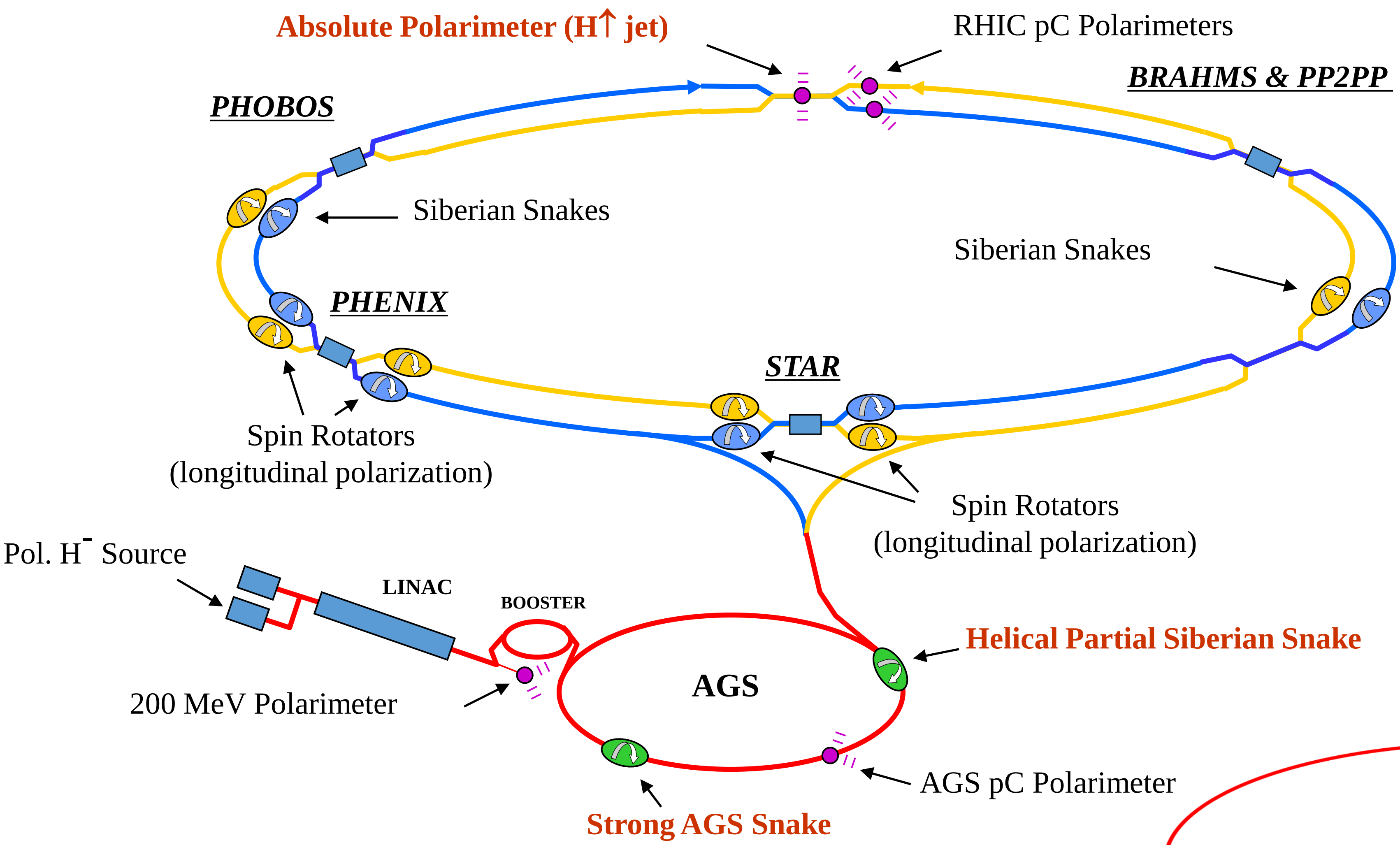


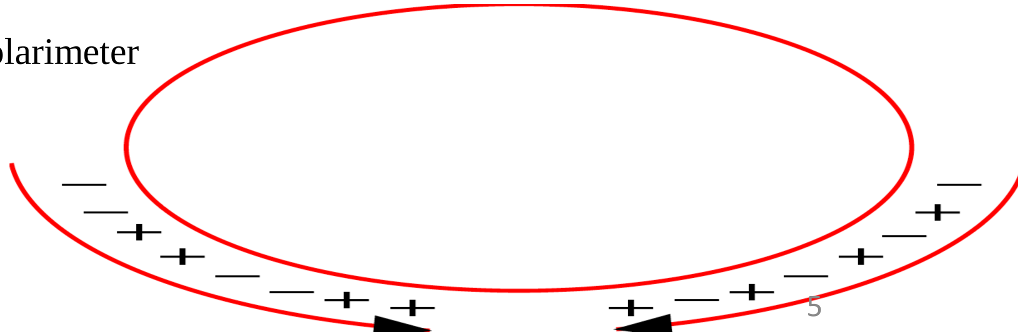
Valence-like quarks for $x_F>0.1$



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

RHIC for Spin





BROOKHAVEN
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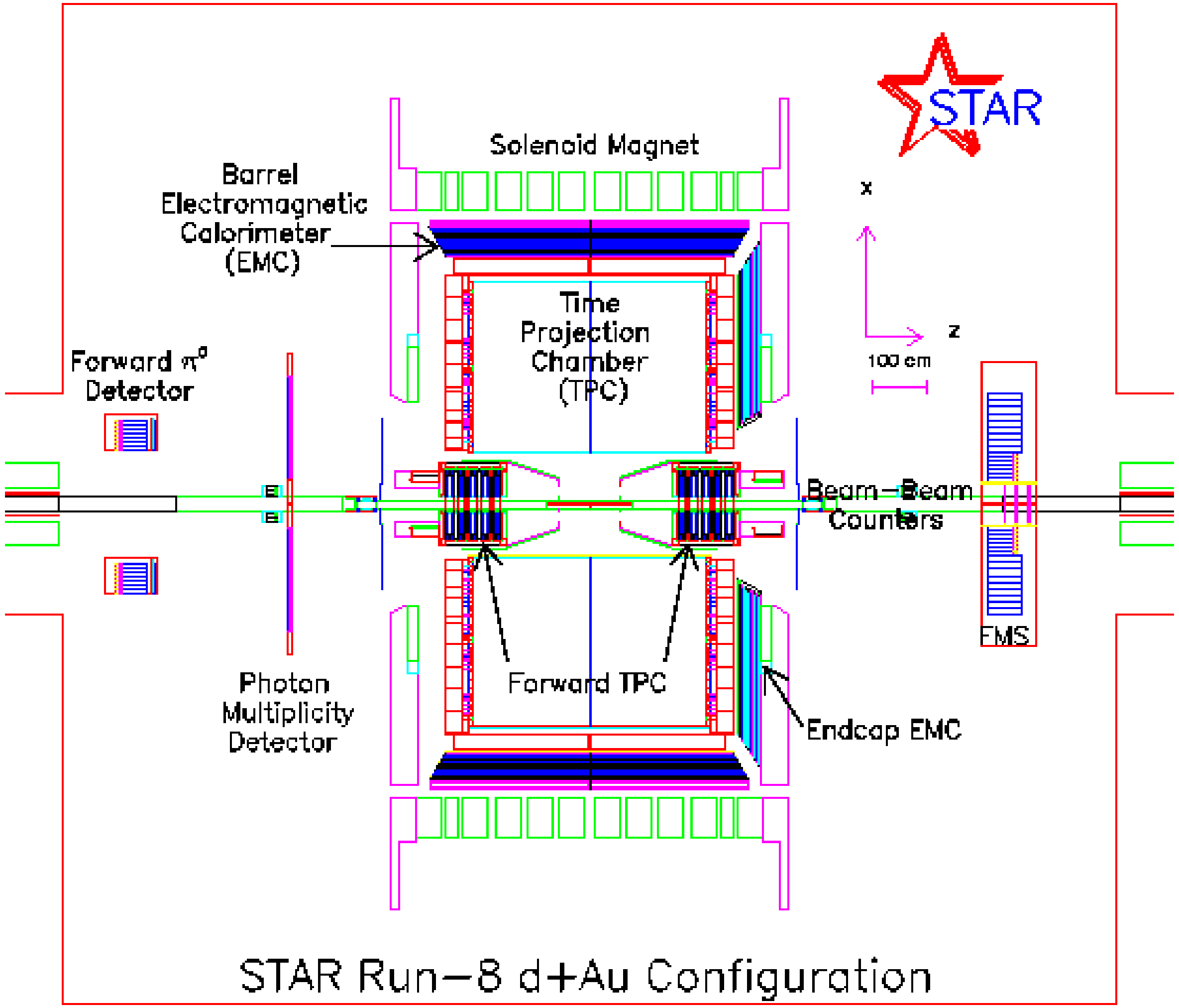
STAR Detector



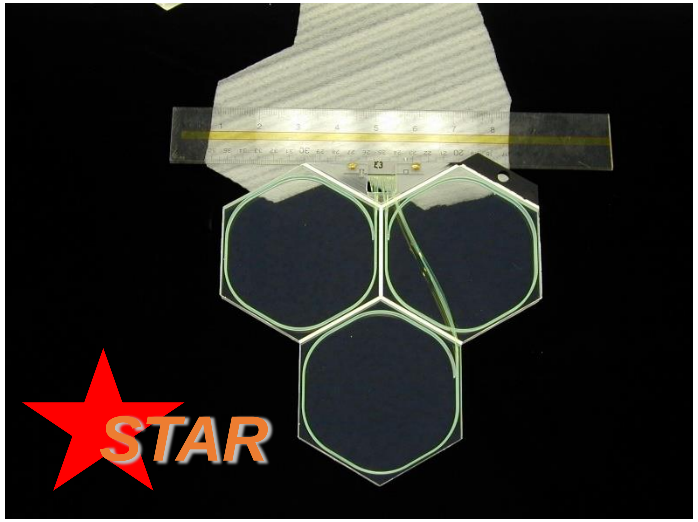
Important features…

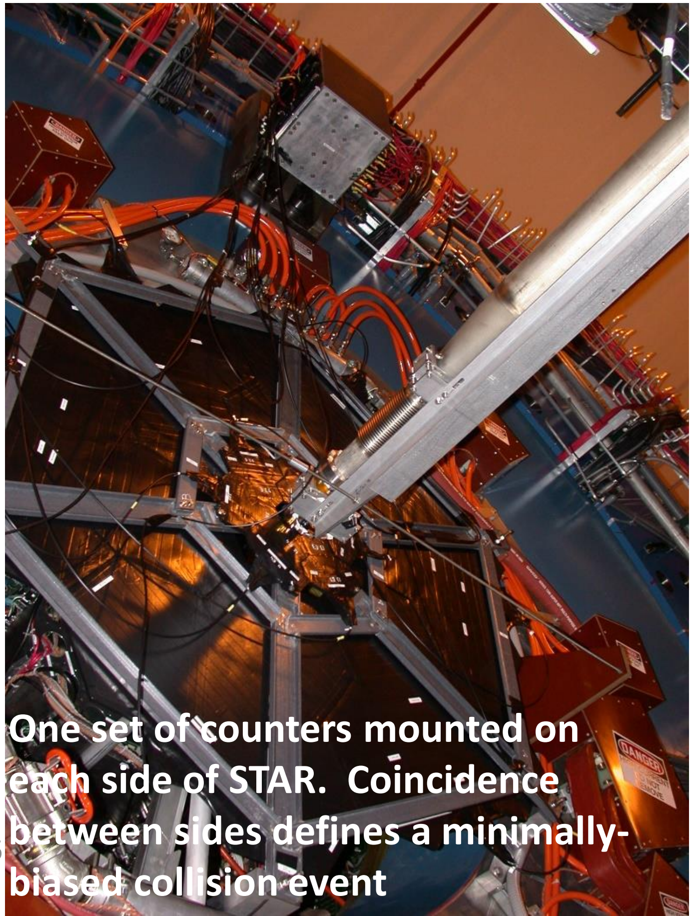
- STAR was designed to study heavy-ion collisions, and then adapted for spin physics
- STAR has ~2-m diameter holes in the poletips of its 0.5 T solenoid $\Rightarrow$ a window to forward physics
- Large rapidity coverage for electromagnetic calorimetry ($-1<\eta<+4$) spanning the full azimuth $\Rightarrow$ azimuthal correlations
- Run-8 was the first run for the Forward Meson Spectrometer (FMS), a 1264-cell lead-glass wall.
- Subsequent upgrades have included silicon near the beam pipe for displaced-vertex measurements [heavy-flavor tracker] and a muon-trigger array at larger radius than the magnet yoke

Beam-Beam Counter

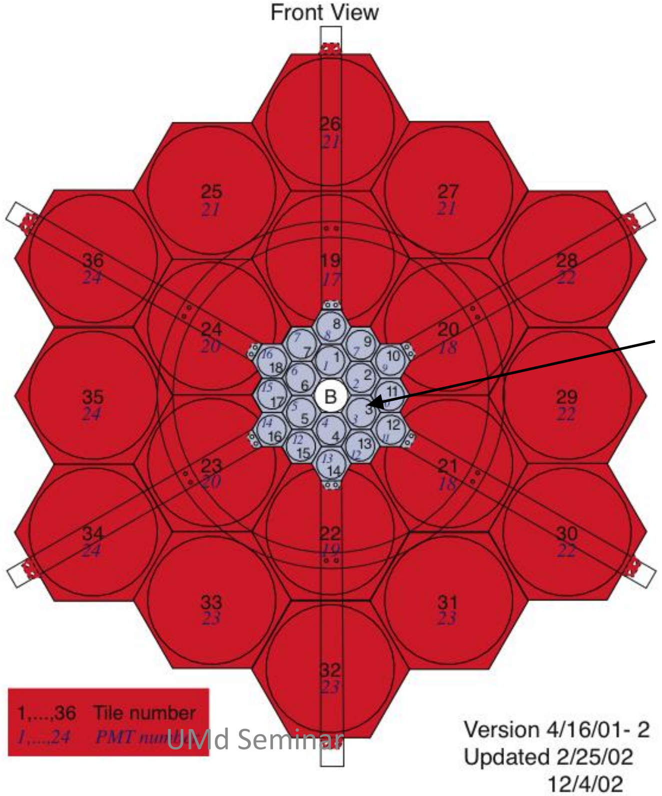
Scintillator annuli tiled by 1cm thick hexagonal tiles with fiber-optic light collection ($2.5<|\eta|<5$)

- Feed back to RHIC for p+p collision tuning at STAR
- Measure spin-dependent relative luminosity ~10^{-3} level
- Measure absolute luminosity ~ 15% level
- Minimum bias trigger (covers ~50% of total σ)
- Measure multiplicity at forward rapidity ⇒ centrality in HI
- Spin effects for forward charged particles ⇒ local polarimeter





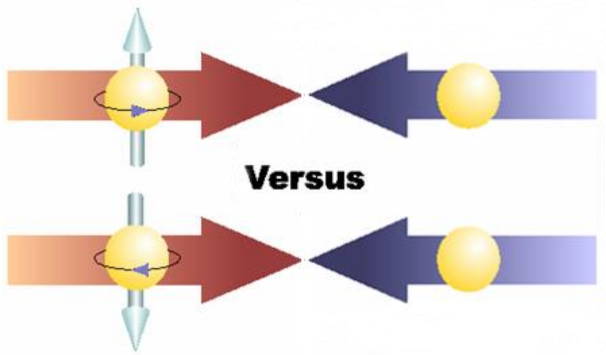
One set of counters mounted on each side of STAR. Coincidence between sides defines a minimally-biased collision event



Azimuthal distribution of hits in the inner tiles ($3.5<|\eta|<5$) found to have spin effects, used for collision polarimeter

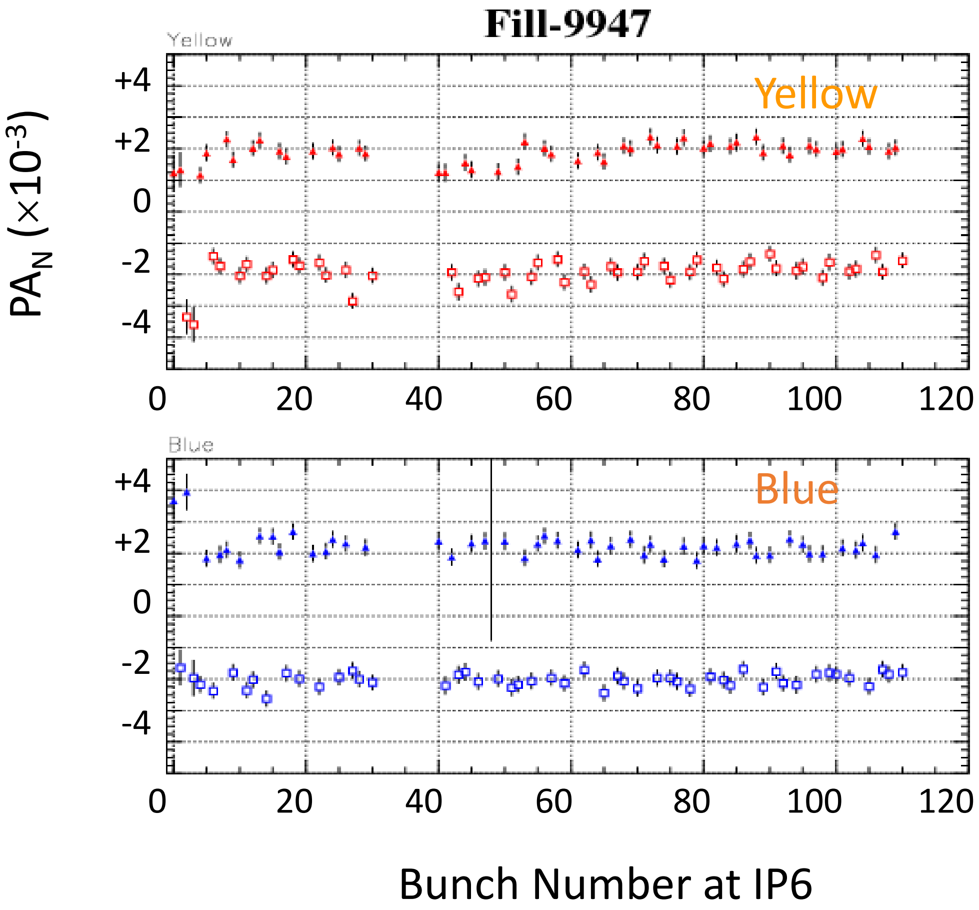
Why Study Transverse Single Spin Asymmetries?

Answer #1 – Practical Benefit



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

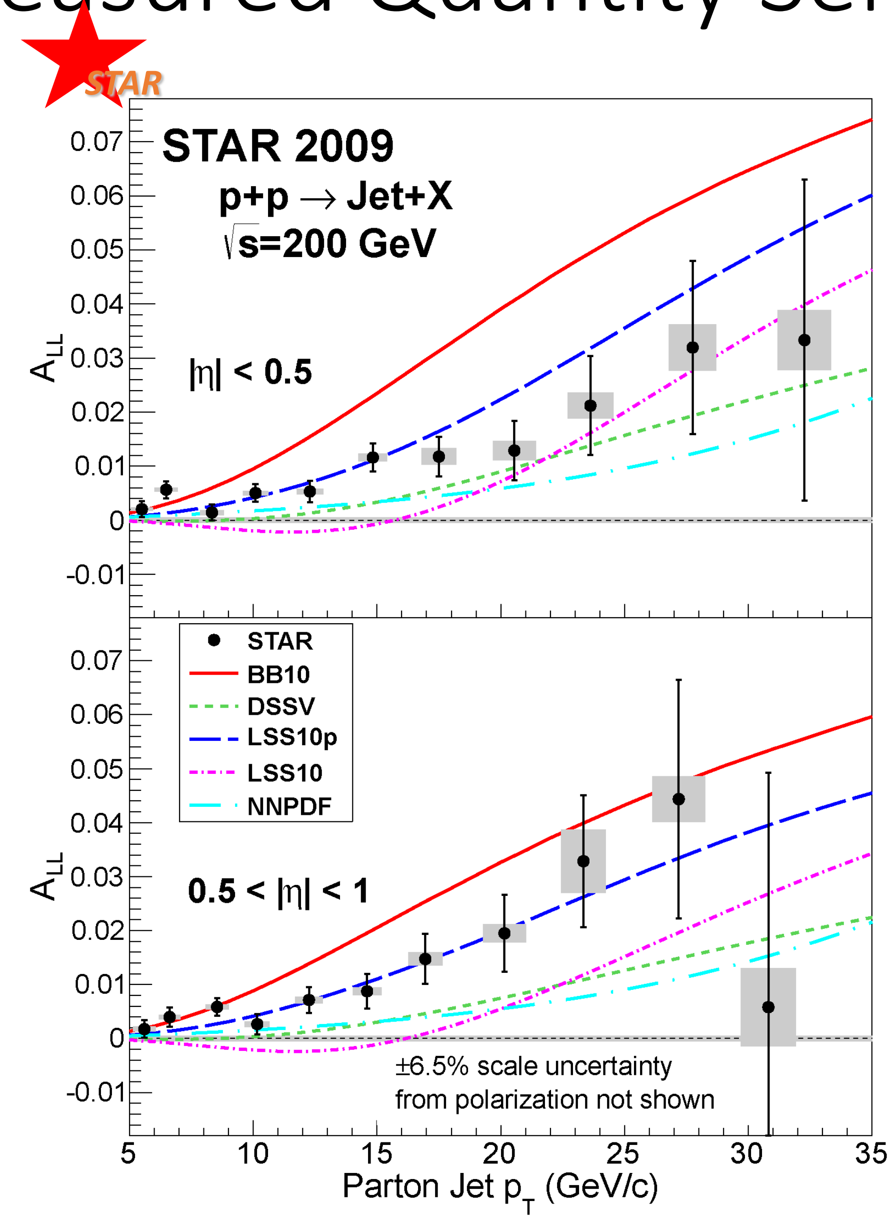
Colliding-beam polarimeter, √s=200 GeV



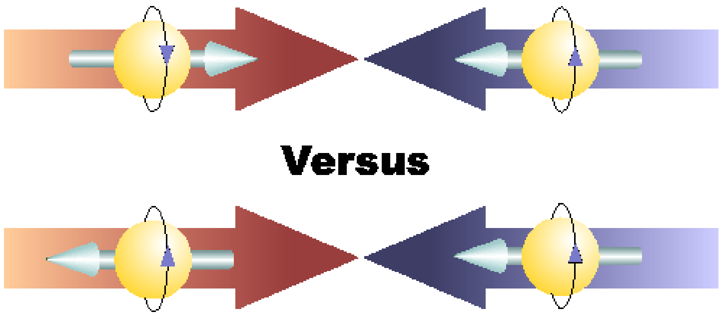
Analyzing power is a tool to measure beam polarization (P) and is one example of transverse single spin asymmetries (SSA) with origins yet to be fully understood.

Used to tune spin rotator magnets to make longitudinal polarization

Measured Quantity Sensitive to Gluon Polarization



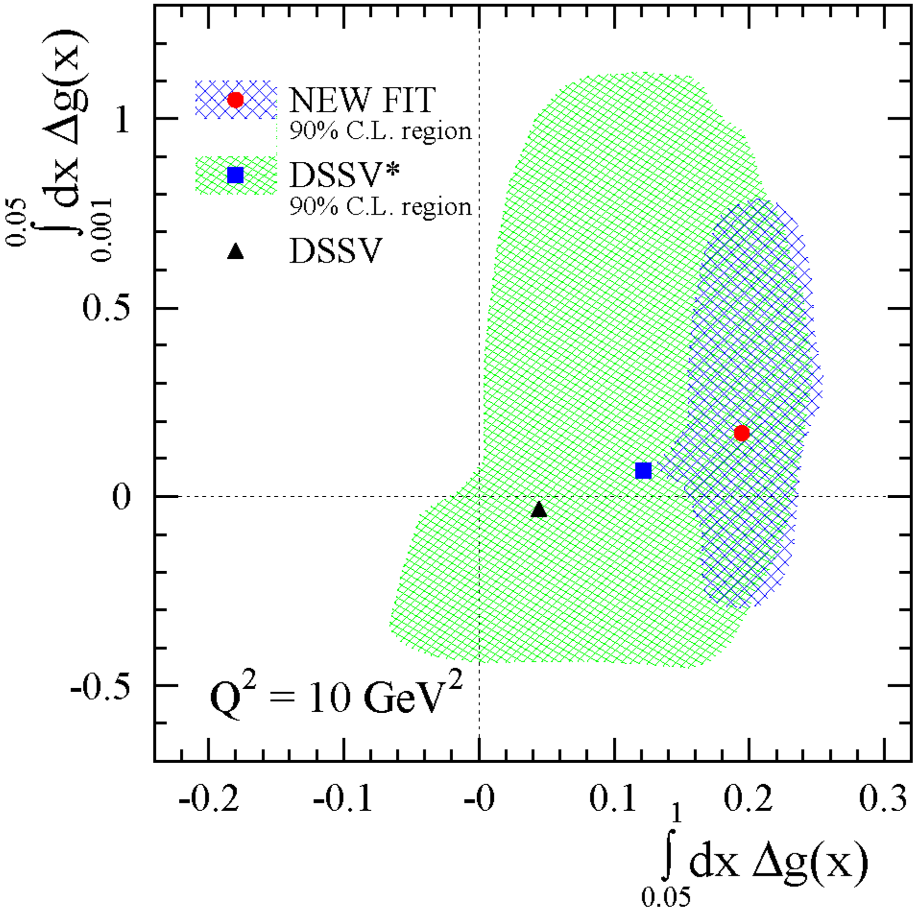
PRL 115 (2015) 092002
[arXiv:1405.5134]



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

- Helicity asymmetry for inclusive jet production is measured as a function of p_T.
- Measurements are sensitive to gluon polarization at $<x>\sim 2p_T/\sqrt{s}$

Implications of Measurement

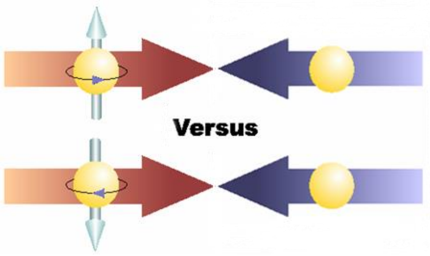


de Florian, Sassot, Stratmann, Vogelsang PRL 113 (2014) 012001 / arXiv:1404.4293

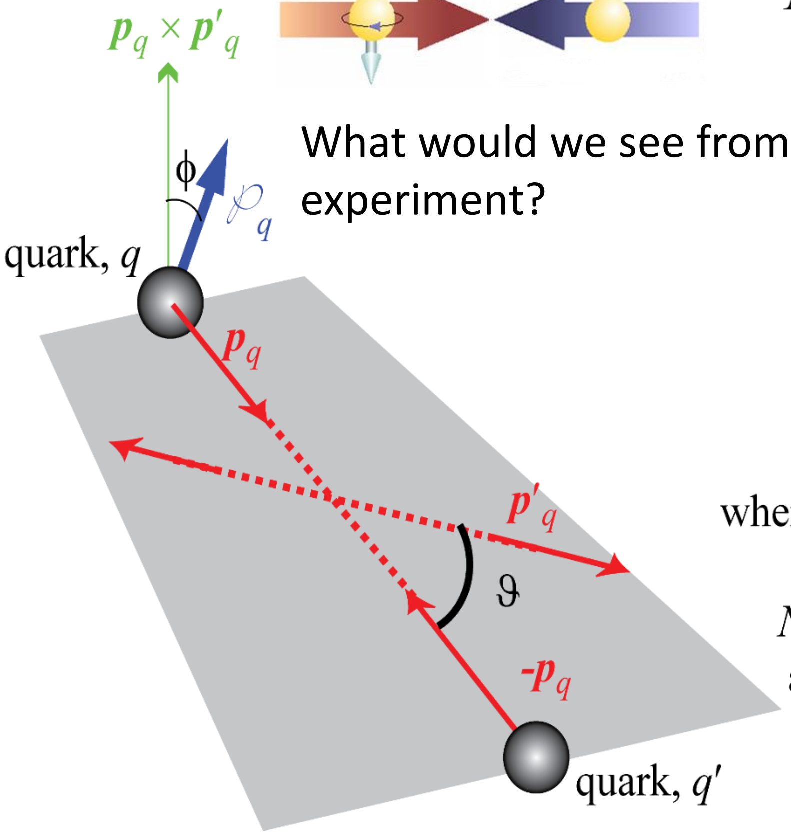
Evidence for polarization of gluons from global NLO fit to inclusive jet data from STAR, neutral pion data from PHENIX and polarized deep inelastic scattering

Low-x gluon polarization requires further measurement

What Measurements Could Be Sensitive to Orbital Angular Momentum?



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



What would we see from this gedanken experiment?

$$N(\vartheta,\phi) = N_0(\vartheta)\,[1 + \wp_q A_N \cos\phi]$$

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

where, $\wp_q$ is quark transverse polarization;
$A_N \propto \mathrm{Im}(NF^*)$;
N is the non-*helicity*-flip amplitude;
and F is the *helicity*-flip amplitude

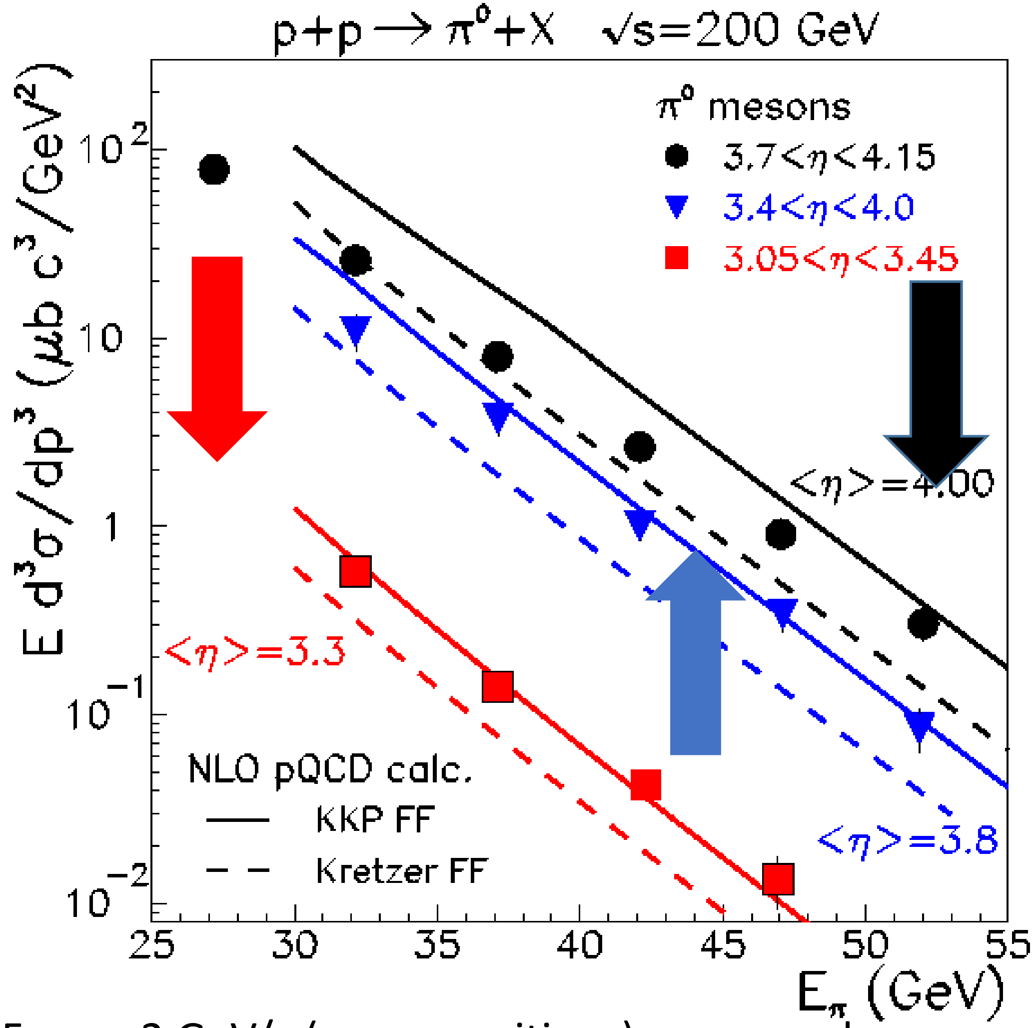
$F \to 0$ as $m_q \to 0$ in vector gauge theories, so $A_N \sim m_q/p_T$

or, $A_N \sim 0.001$ for $p_T \sim 2$ GeV/c

Kane, Pumplin and Repko PRL **41** (1978) 1689

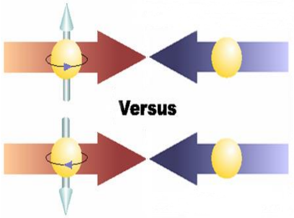
Why is large x_F useful? - II

PRL 97 (2006) 192302

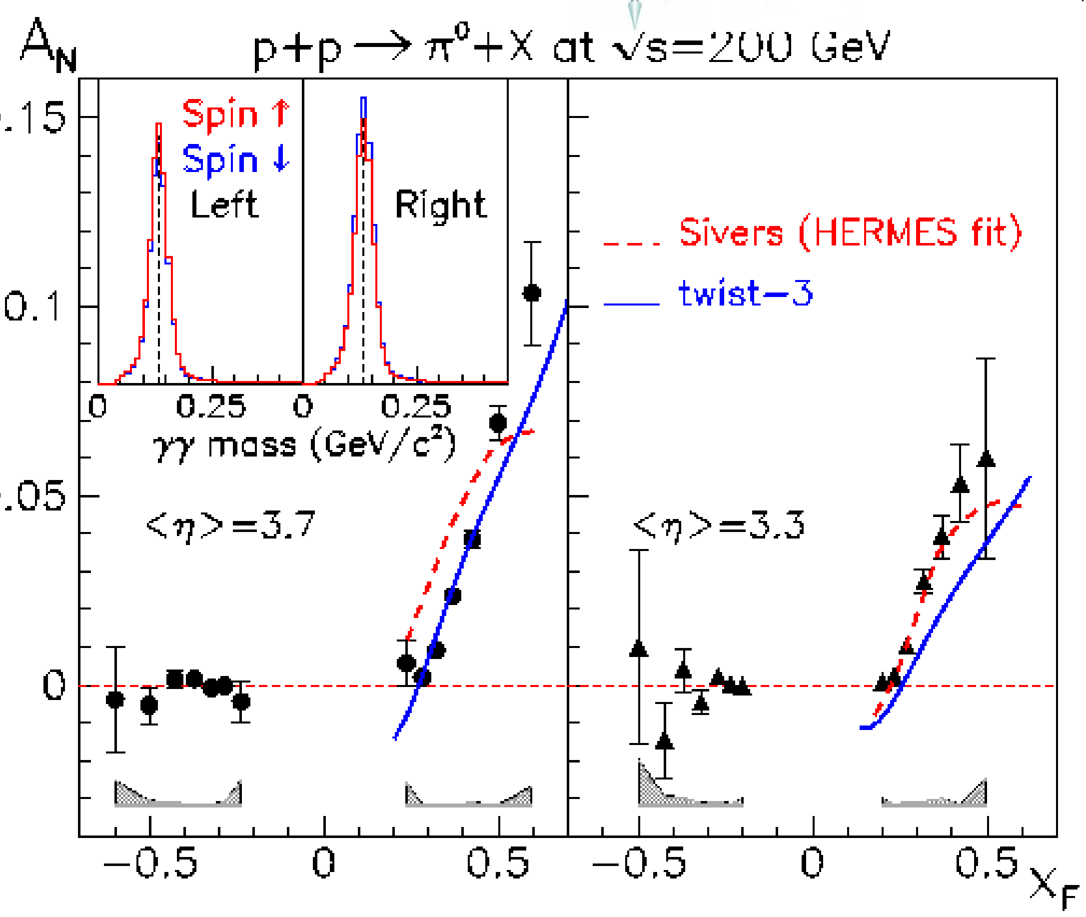


For p_T>2 GeV/c (arrow positions), measured cross sections are in good agreement with NLO pQCD, albeit with large scale dependence which is smaller for jets (see below)

PRL 101 (2008) 222001

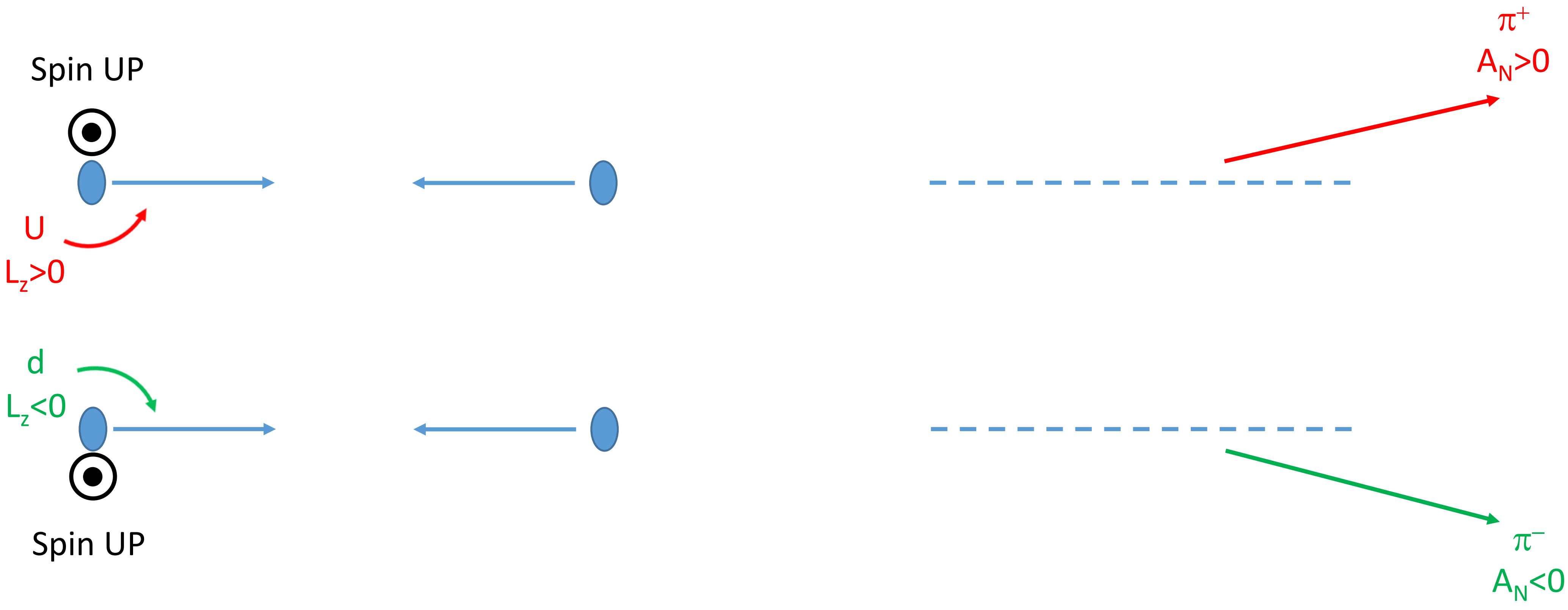


$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$



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

An intuitively appealing picture…



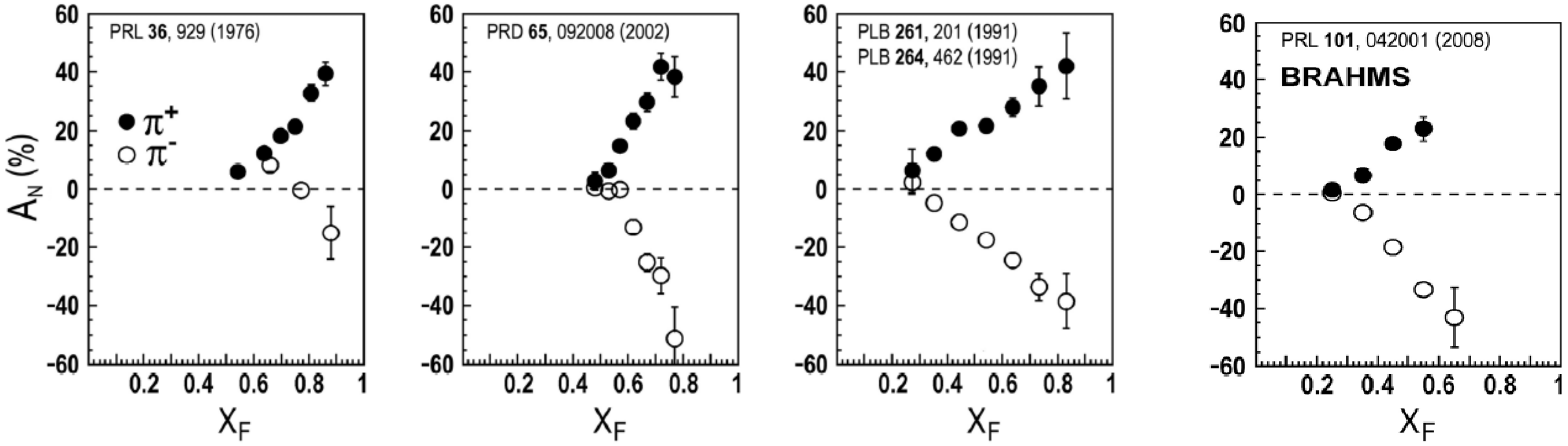
Forward Pion Asymmetries Versus √s

ANL
√s=4.9 GeV

BNL
√s=6.6 GeV

FNAL
√s=19.4 GeV

RHIC
√s=62.4 GeV

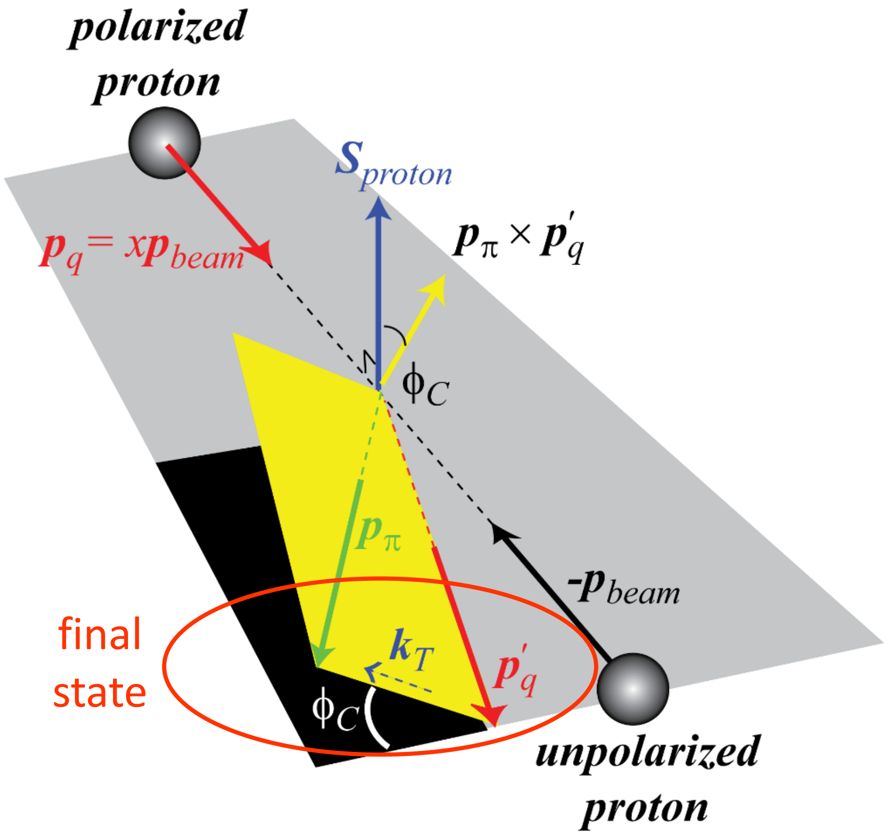


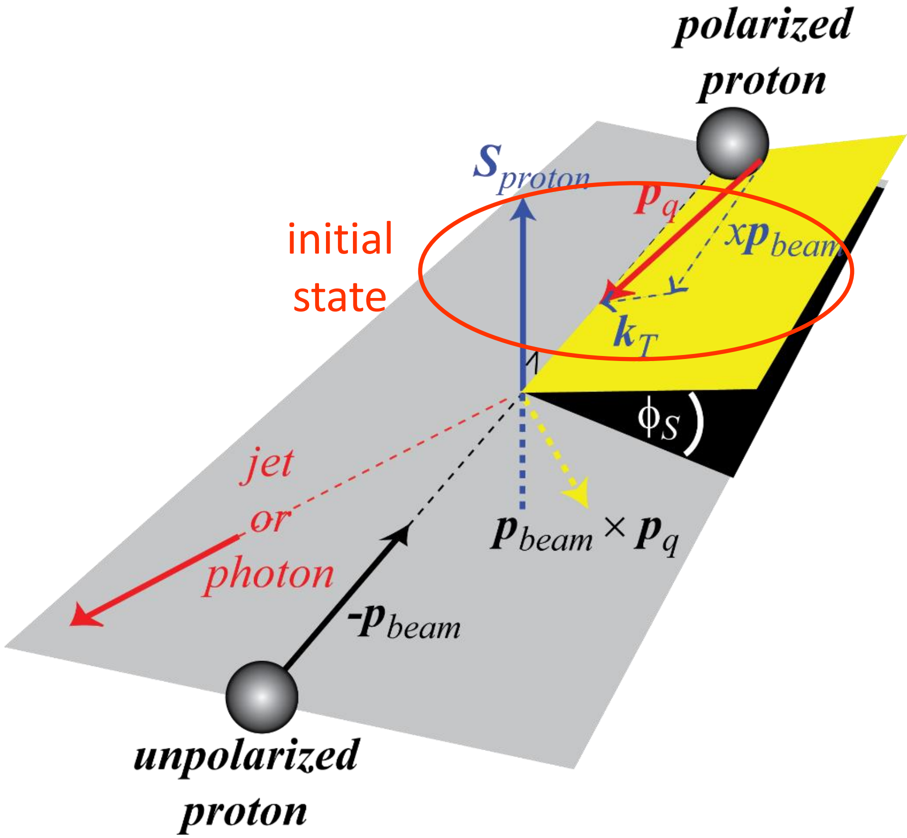
Forward pion analyzing power in p+p collisions exhibits similar x_F dependence over a broad range of √s

Issue 1 – Inclusive π production does not distinguish initial-state versus final-state k_T

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

Sivers mechanism requires *spin-correlated transverse momentum* in the proton (orbital motion, TMD distribution) and color-charge interaction. SSA is present for jet or γ





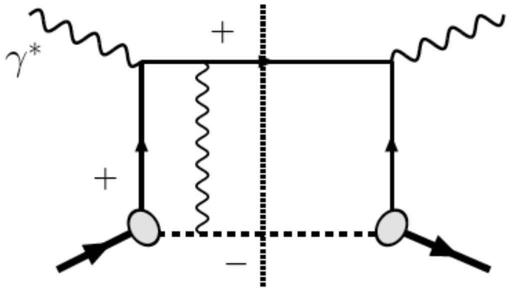
Other mechanisms have been suggested in recent years

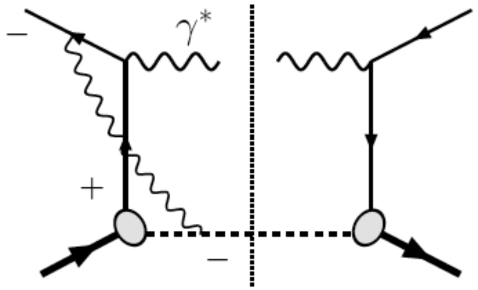
Issue 2 - Factorization

- Factorization is used for inclusive particle production for collinear distribution and fragmentation functions, and in general, works well for RHIC energies
- TMD factorization is not proven for inclusive (or, more complicated) hadro-production, although has been proven for Drell-Yan production.
- Twist-3 collinear calculations are based on factorization. Moments of qg correlators from twist-3 analyses are related to the Sivers function

Issue 3 – Initial-State versus Final-State Interactions

Simple QED example:

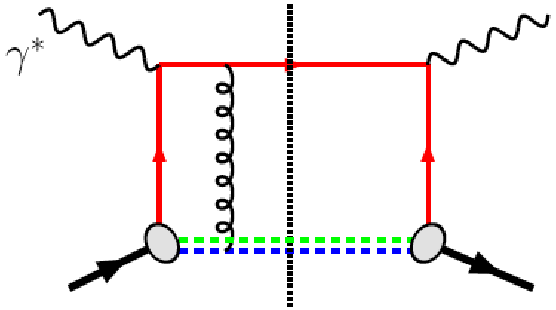


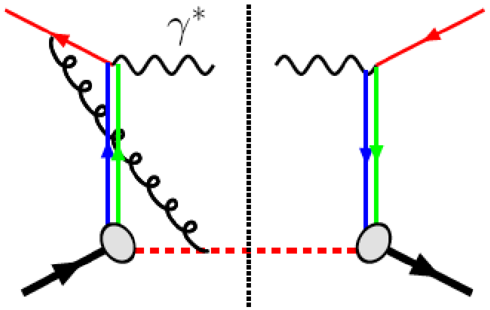


DIS: attractive

Drell-Yan: repulsive

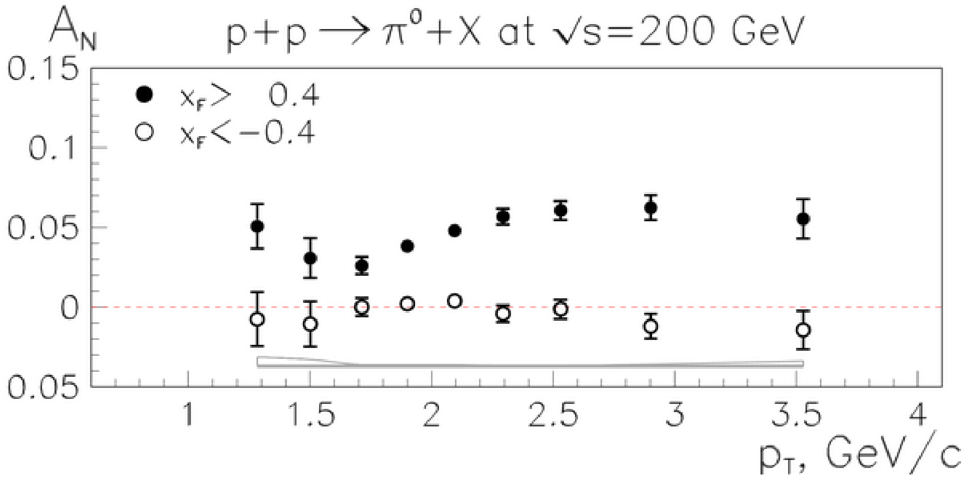
Same in QCD:



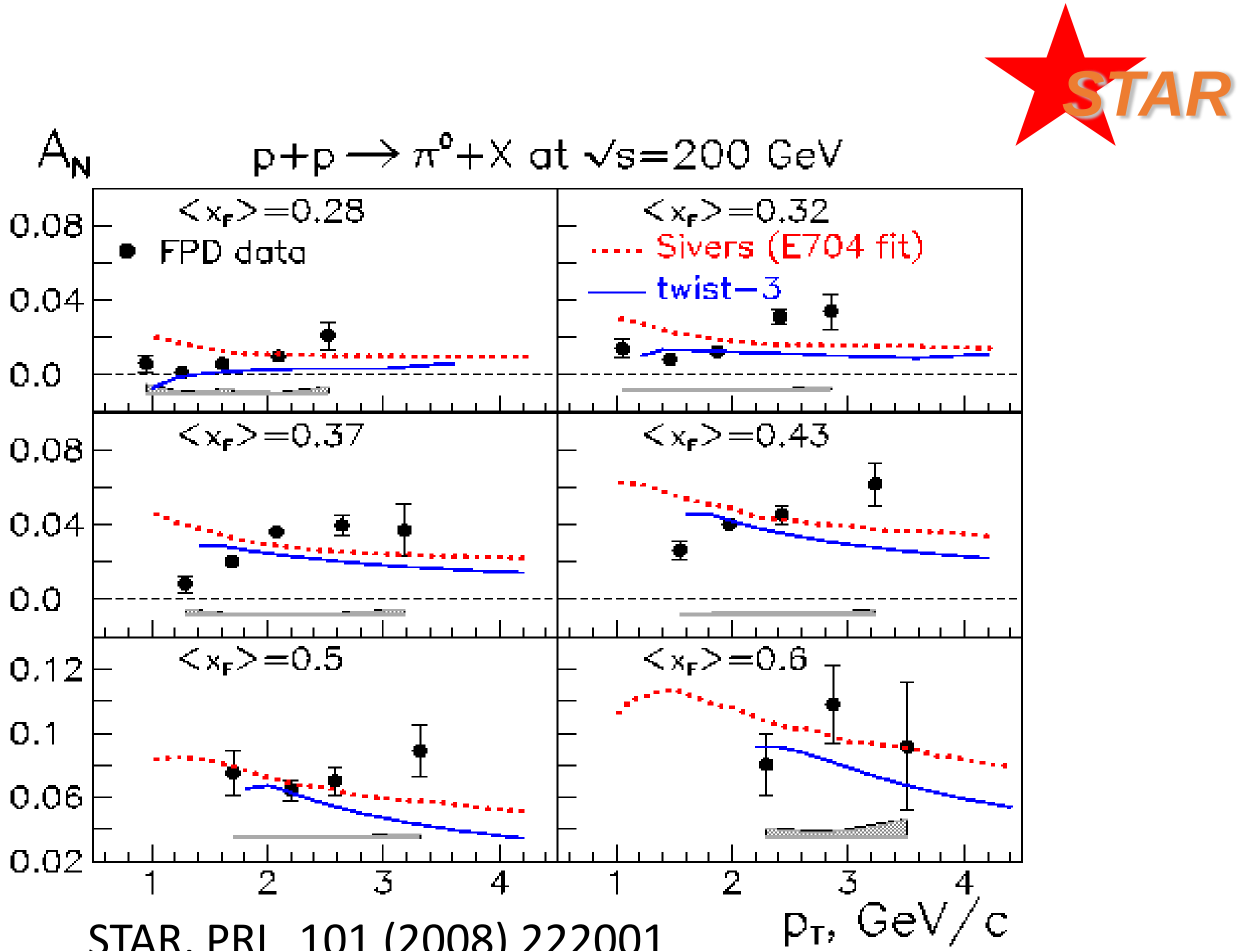


In general, particle production in p+p collisions will mix initial-state (DY-like) and final-state (SIDIS-like) interactions. Present understanding is that $p^{\uparrow}+p\rightarrow\pi X$ is DY-like $\Rightarrow$ "sign-mismatch" between SIDIS and $p^{\uparrow}+p\rightarrow\pi X$ transverse SSA [arXiv:1103.1591]

Issue 4 - p_T Dependence of Inclusive π^0 A_N



B.I. Abelev et al. (STAR) PRL **101** (2008) 222001



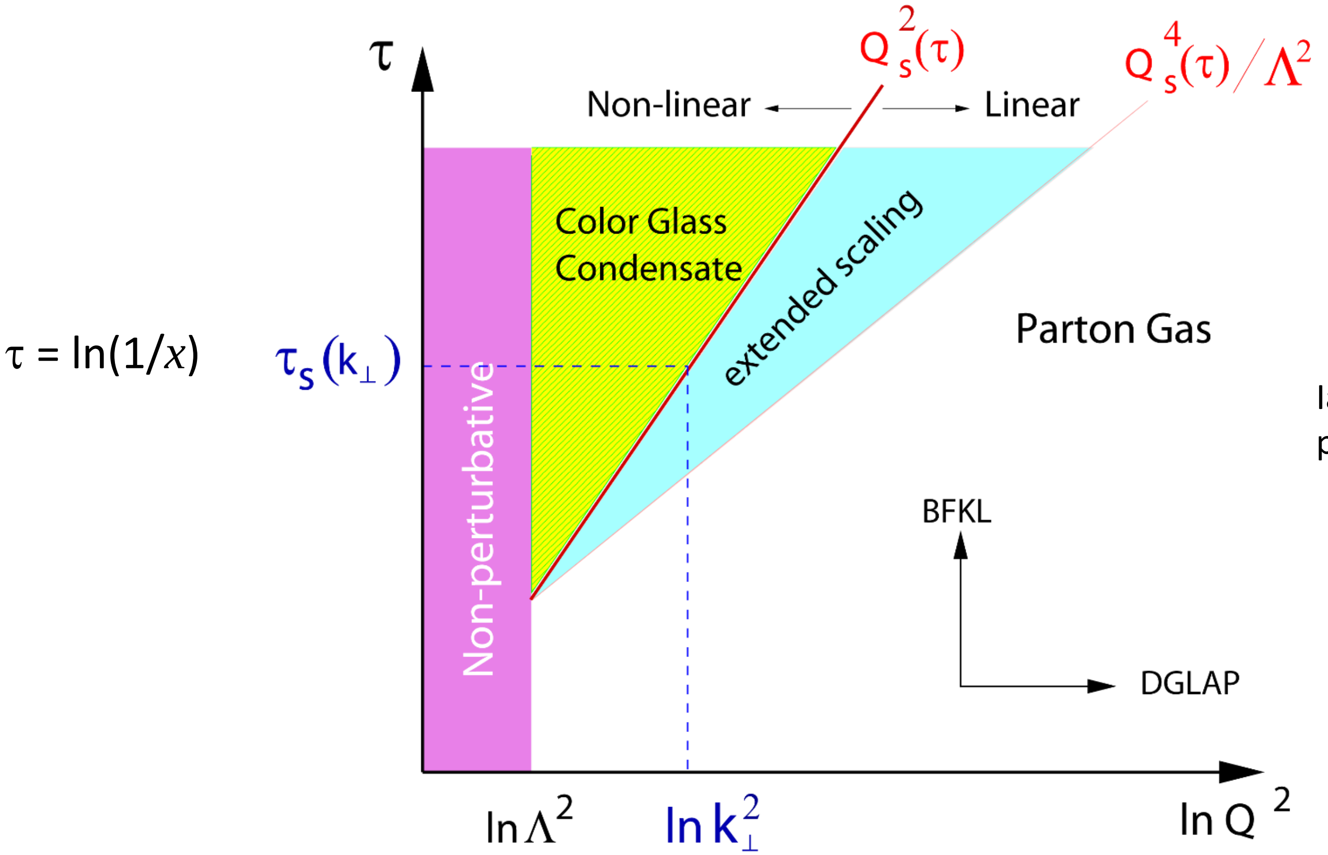
STAR, PRL 101 (2008) 222001

- Rising p_T dependence in data, whereas theory expects A_N to decrease with increasing p_T
- Preliminary results [DIS2013] show that data trends persist to $p_T \approx 8$ GeV/c

Summary of Forward Spin Physics…

- RHIC has determined that gluons contribute to the spin of the proton [although, orbital angular momentum can still be important…]
- RHIC can be exploited to extend measurements sensitive to gluon polarization to low x
- There are large transverse single spin asymmetries for forward pion production
- Parton orbital angular can be pursued at RHIC in a model-dependent fashion via forward, low-mass DY

Gluon Saturation and the Color Glass Condensate

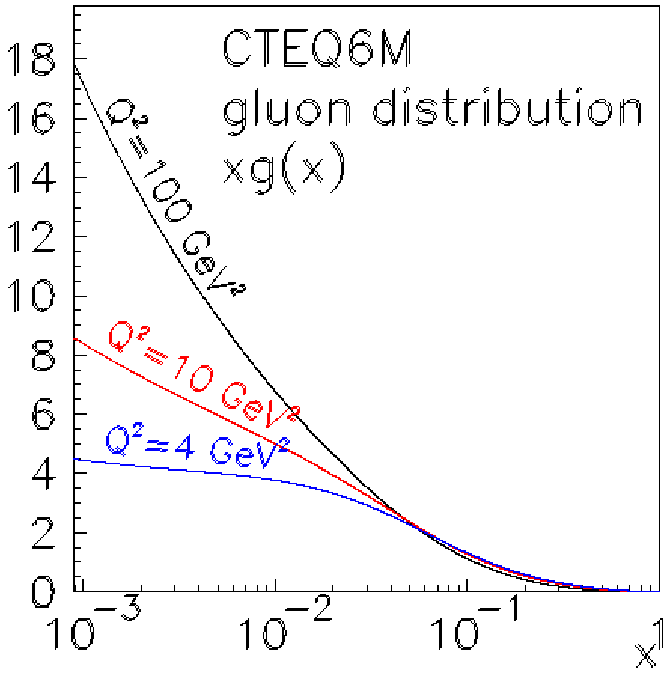


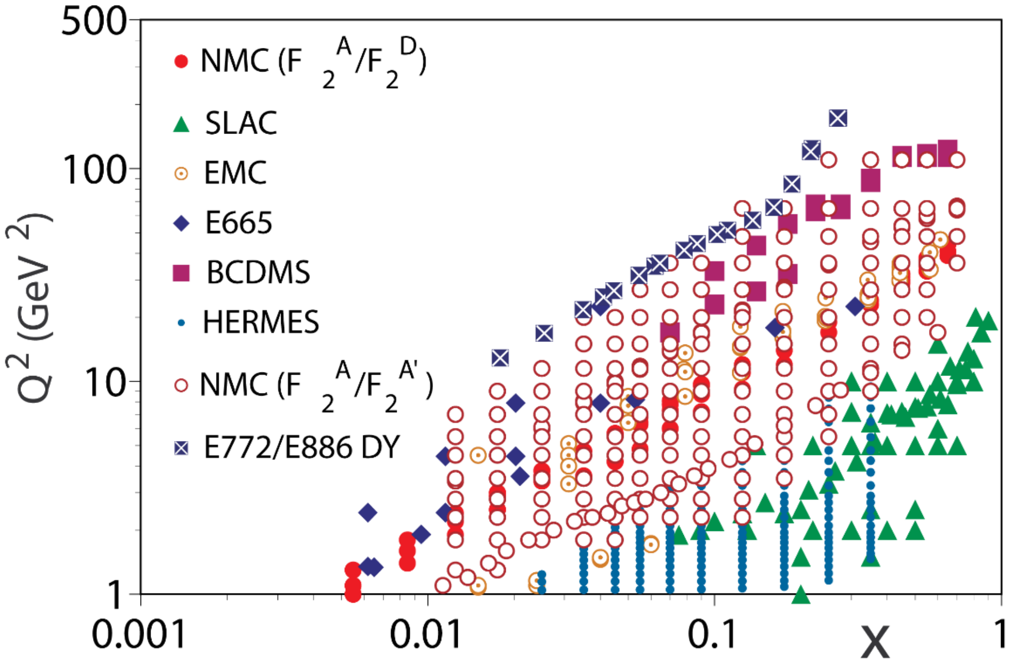
Iancu, Venugopalan hep-ph/0303204

- Does the low-x gluon density saturate, and is this a high-energy phase of matter?
- Would a Color Glass Condensate be universal for both nuclear DIS and hadronic probes of nuclei at high energy?

Deep Inelastic Scattering from Nuclear Targets

Kinematic Coverage Restricted to Fixed Target Experiments (no EIC, yet)



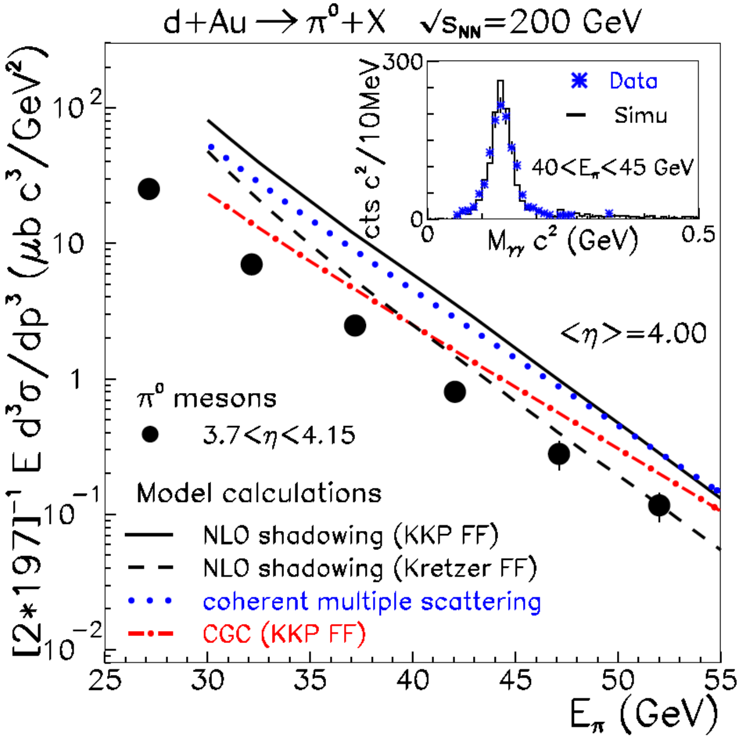


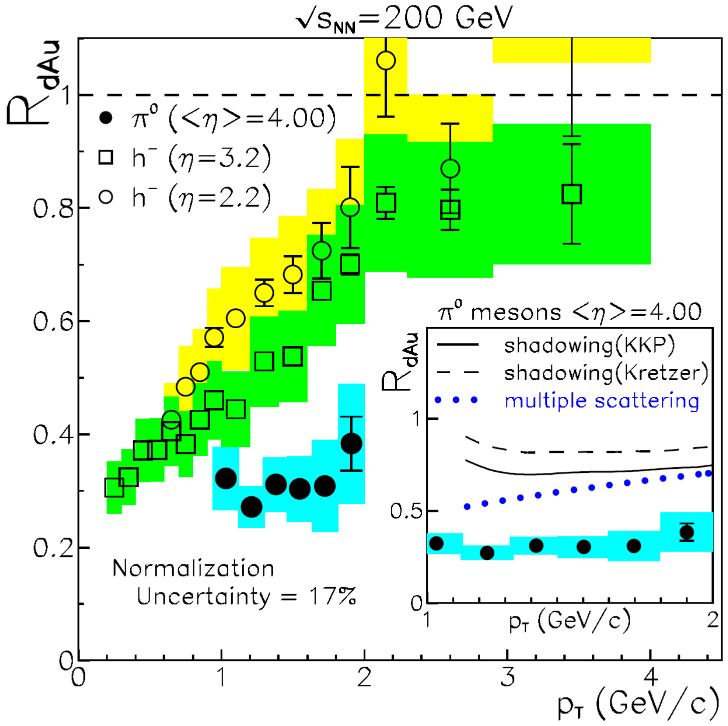
From Hirai, Kumono, Nagai PRC **70** (2004) 044905, and references therein

- Growth of gluon distribution at low-x within the proton cannot continue forever
- Gluon density in nucleus only known to x~0.02 since $g(2x) \sim \partial F_2(x,Q^2)/\partial \ln(Q^2)$

Hints of Gluon Saturation from Large-Rapidity Particle Production in d+Au Collisions at RHIC?

STAR





$$R_{dAu} = \frac{\sigma_{inel}^{pp}}{\langle N_{bin} \rangle \sigma_{hadr}^{dAu}} \frac{\sigma(dAu \to \pi)}{\sigma(pp \to \pi)}$$

d+Au→π^0+X cross sections at $\sqrt{s_{NN}}$ = 200 GeV and <η>=4.0 [STAR, Phys.Rev.Lett. **97** (2006) 152302]

NLO pQCD calculations using gluon shadowing [Guzey, Strikman and Vogelsang PLB **603** (2004) 173]

CGC model calculation [Dumitru, Hayashigaki, Jalilian-Marian, Nucl.Phys. **A770** (2006) 57]

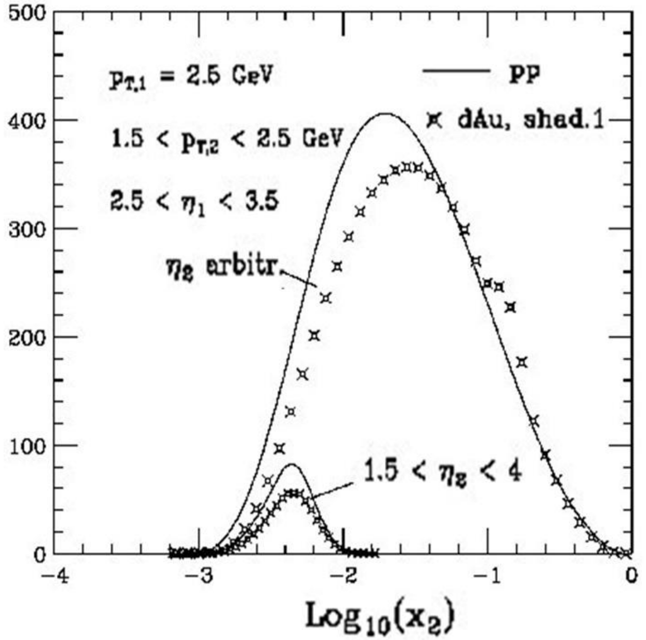
- Large-rapidity d+Au cross sections are suppressed
- Data are best described by CGC model calculation
- Many other possible explanations of suppression

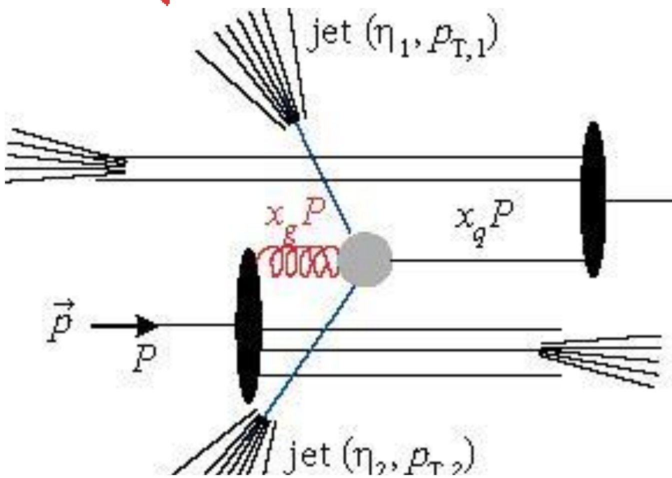
Forward Production

Inclusive and particle correlations

$$x_+ \approx \frac{p_T}{\sqrt{s}}\left(e^{+\eta_1} + e^{+\eta_2}\right) \xrightarrow[\eta_1 >> \eta_2]{} x_F$$

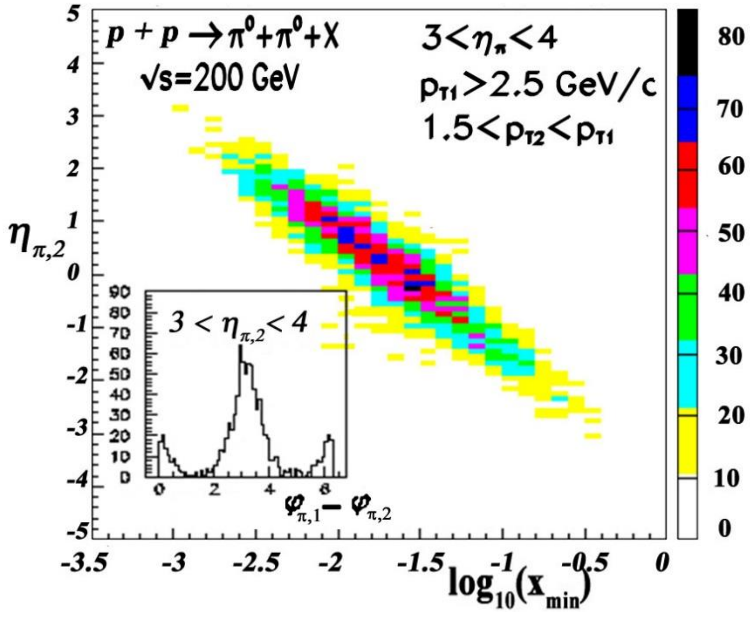
Guzey, Strikman and Vogelsang, PLB603 (2004) 173





$$x_- \approx \frac{p_T}{\sqrt{s}}\left(e^{-\eta_1} + e^{-\eta_2}\right) \xrightarrow[\eta_1 >> \eta_2]{} x_F e^{-(\eta_1+\eta_2)}$$

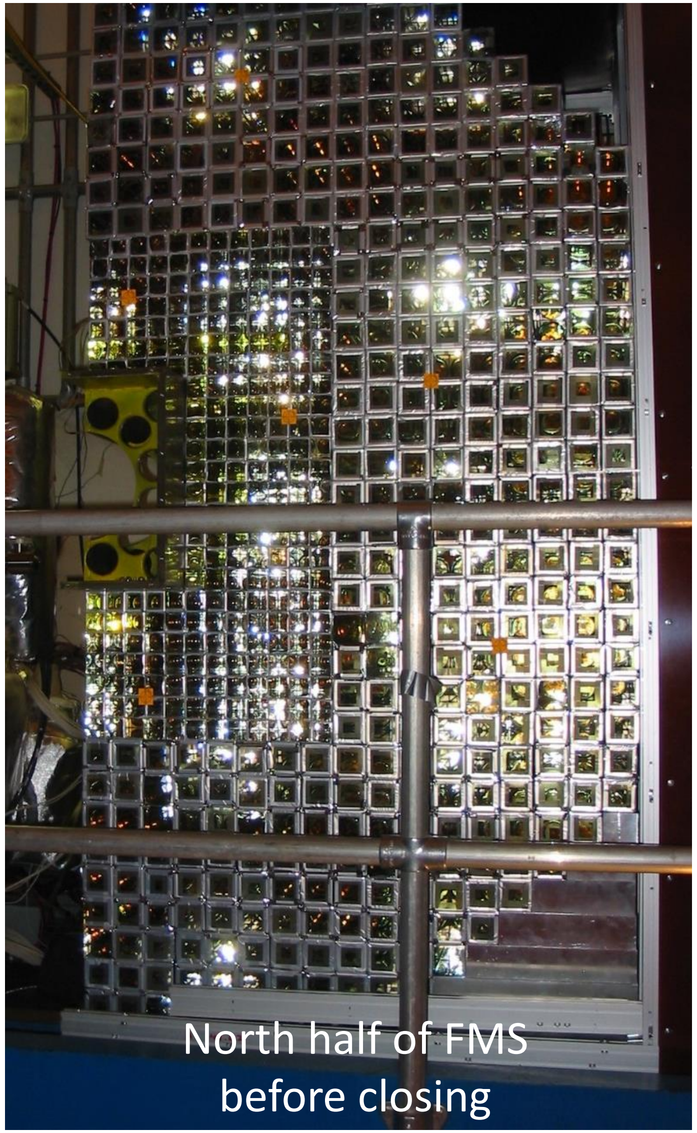
hep-ex/0502040



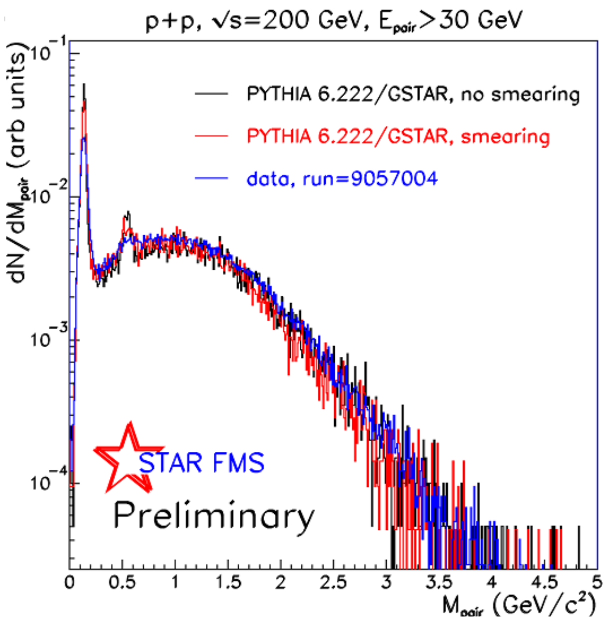
PYTHIA Simulation

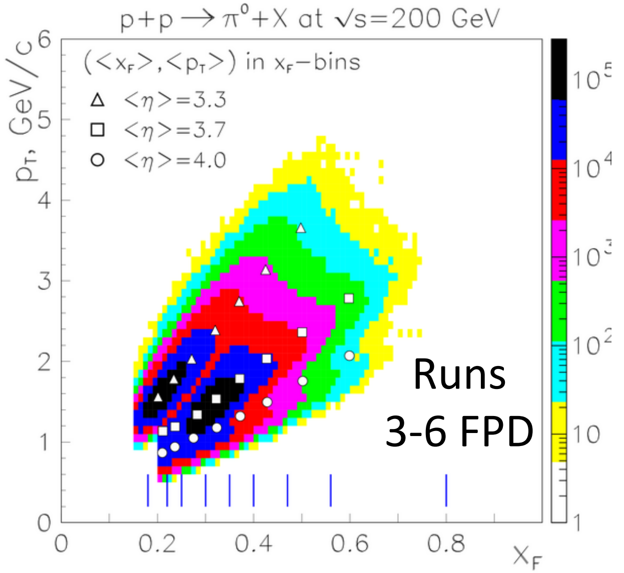
- constrain x_{gluon} probed by high-x quark by detection of second hadron serving as jet surrogate.
- span broad pseudorapidity range (-1<η<+4) for second hadron ⇒ span broad range of x_{gluon}
- provide sensitivity to higher p_T for forward π^0 ⇒ reduce 2→3 (inelastic) parton process contributions thereby reducing uncorrelated background in $\Delta\phi$ correlation.

STAR Forward Meson Spectrometer

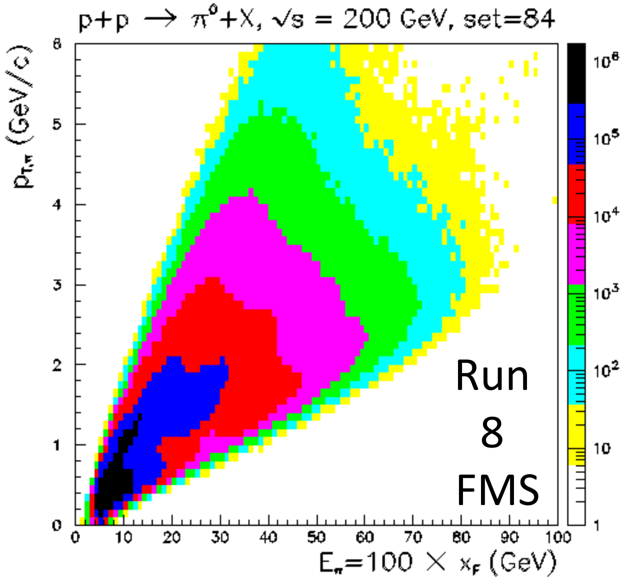


- 20× larger acceptance than the forward pion detector (FPD).
- 2π azimuth for $2.5<\eta<4.0$
- Discriminate single γ from $\pi^0 \rightarrow \gamma\gamma$ up to ~60 GeV

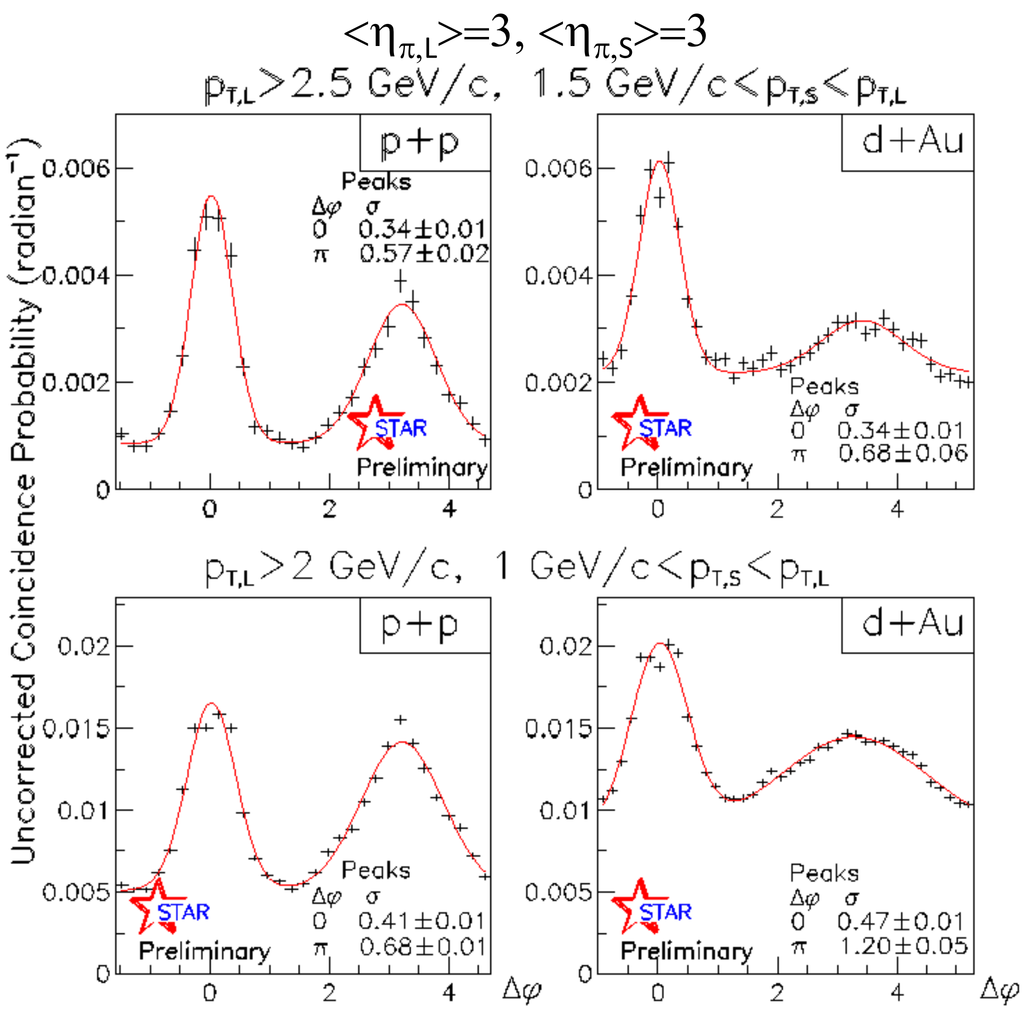




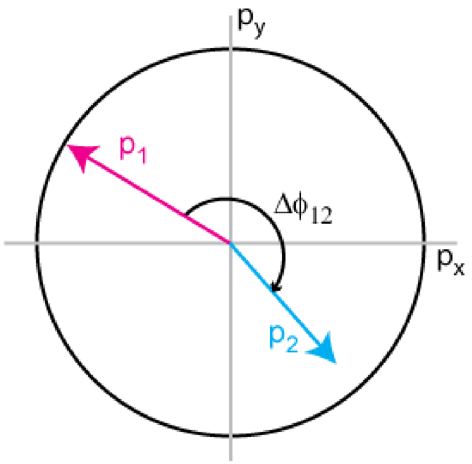
Phys. Rev. Lett. 99:142003 (2007)



Forward di-pion azimuthal correlations

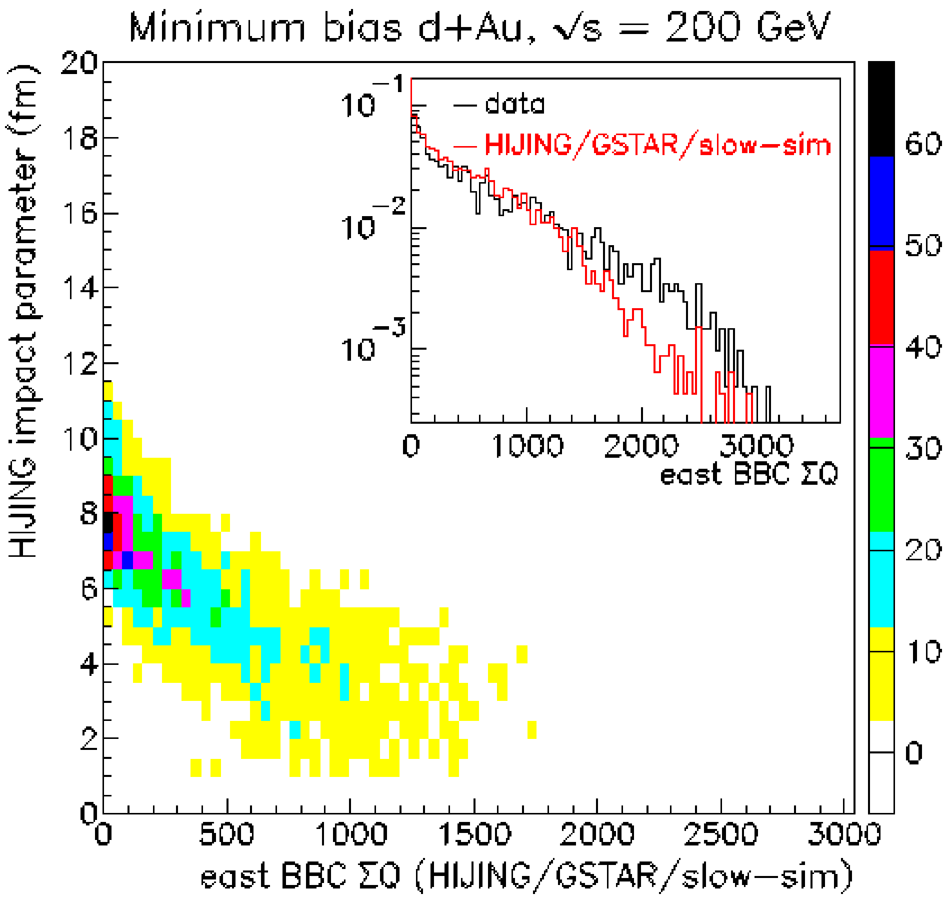


arXiv:1005.2378



- Forward π^0 pairs probe the lowest x. From 2→2 scattering: ~0.001<x<0.005
- Forward π^0 pairs are detected via 4 γ
- Jet-like correlations for p+p consistent with NLO pQCD description of inclusive forward π^0 cross section
- Significant broadening observed in d+Au relative to p+p

Centrality Definition



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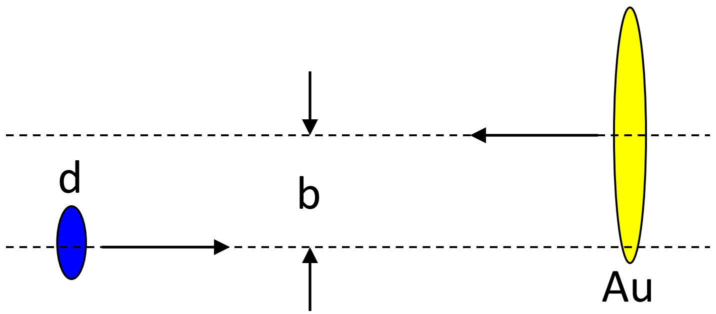
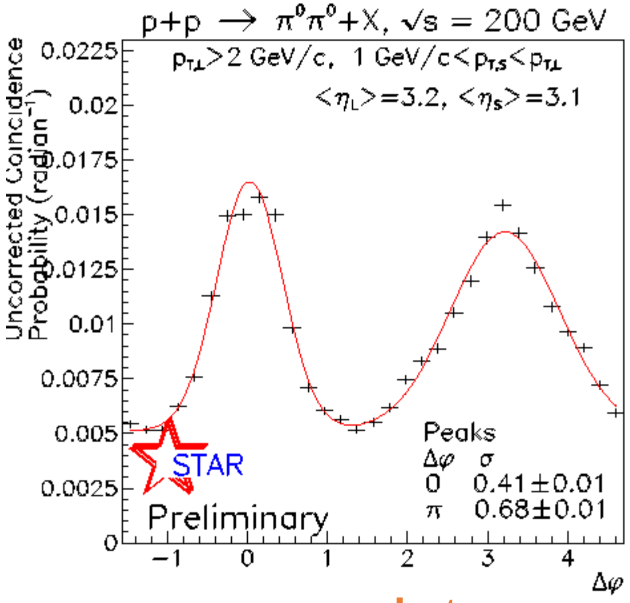


- relate particle production in Au beam direction (5 < -η < 3) to impact parameter for collision through a model (HIJING)
- Observe maximum of ~50 minimum-bias equivalent particles in Au beam direction
- Define…
  - **peripheral**: ΣQ<500 (<b>~7 fm)
  - **central**: 2000< ΣQ<4000 (<b>~2.7 fm)

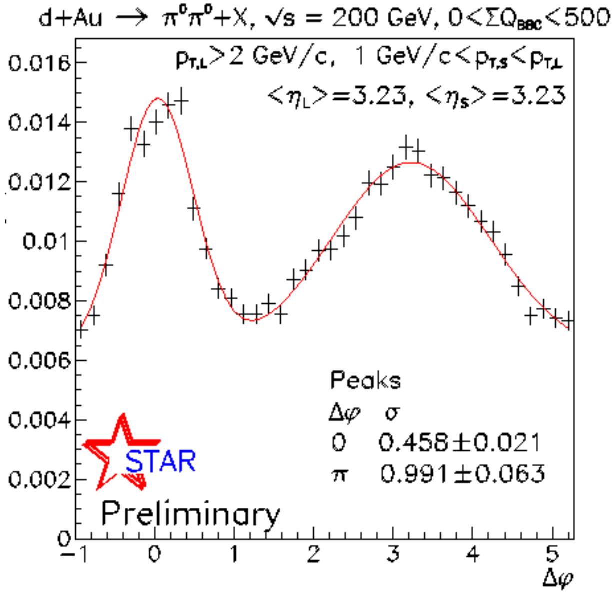
Centrality dependence of forward di-pion correlations

Leading P_T $\pi^0 > 2$ GeV

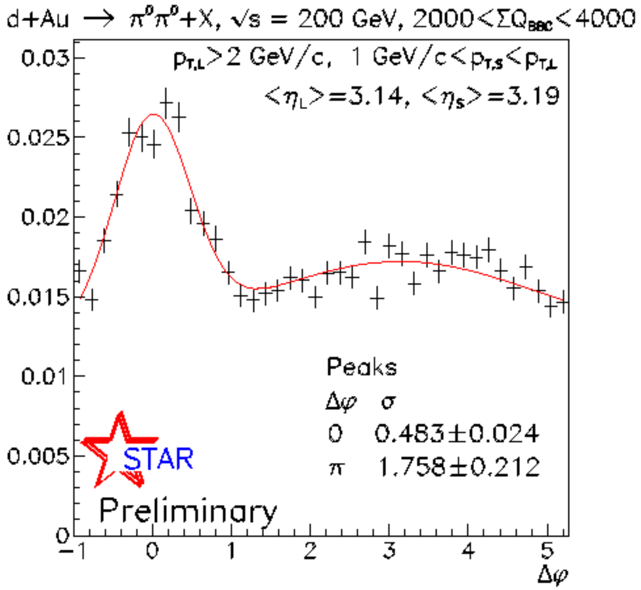
arXiv:1005.2378



pp data



dAu peripheral

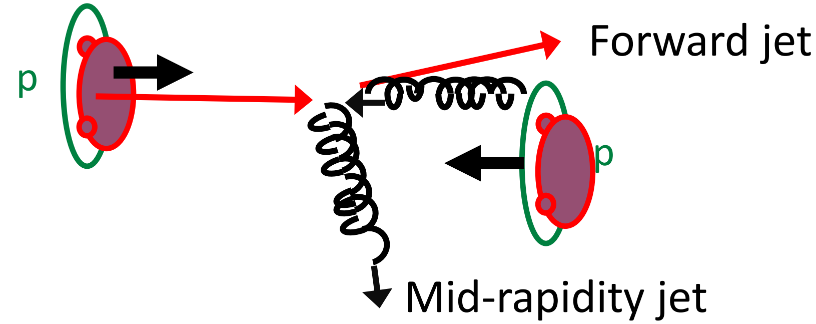


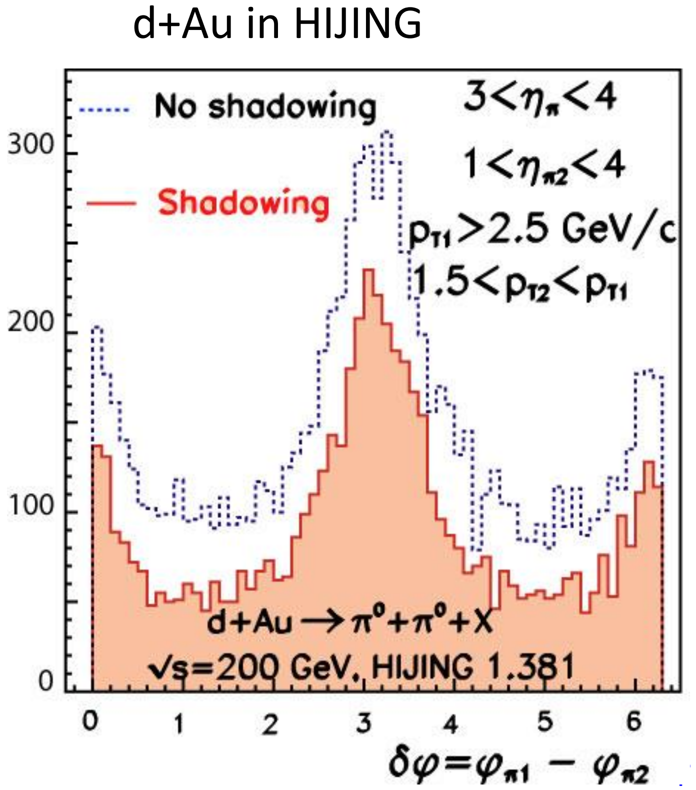
dAu central

- Away-side peaks evident in peripheral dAu and pp.
- Away-side peaks in peripheral dAu are roughly 50% wider than in pp.
- Significant dependence on centrality is evident in azimuthal decorrelation.
- … caution: dAu results are “recovered” from a timing issue with electronics

Back-to-back Angular Correlations

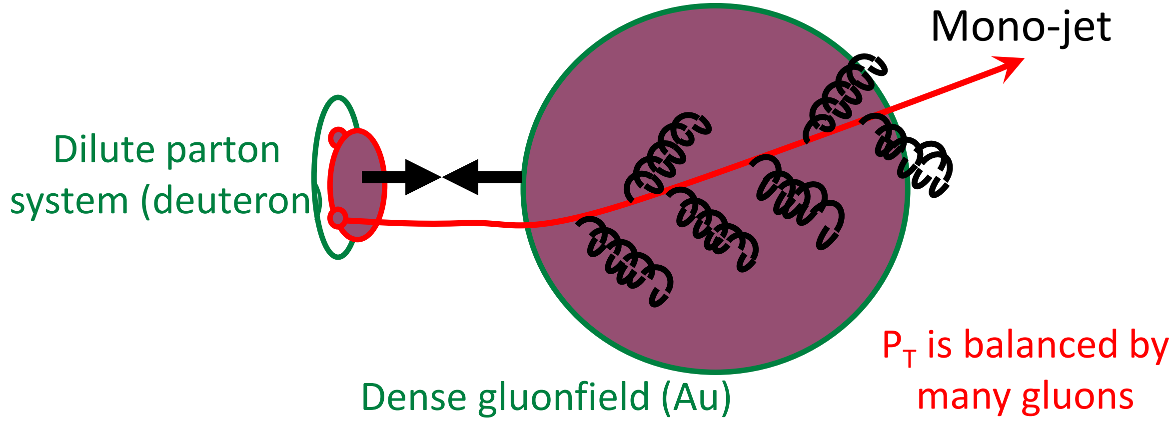
pQCD 2➔2 process =back-to-back di-jet (Works well for p+p)





With high gluon density

2➔1 (or 2➔many) process = Mono-jet ?



CGC predicts suppression of back-to-back correlation

Conventional shadowing changes yield, but not angular correlation

Summary of Saturation Physics…

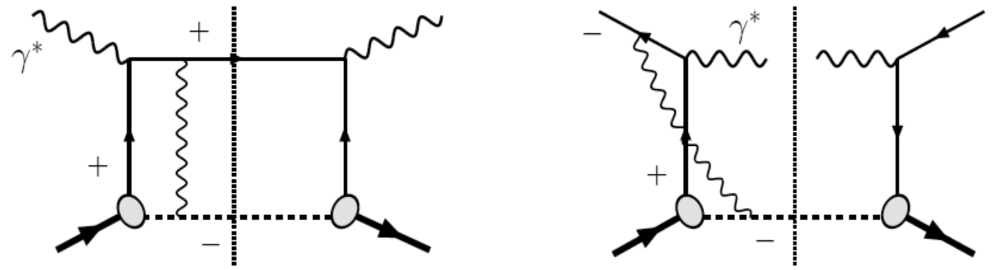
- Inclusive particle production in the forward direction is suppressed in p+A collisions relative to p+p at RHIC energies [unlike at midrapidity, with Cronin peak]

- Although particle correlations were suggestive of gluon saturation, technical issues with new electronics required checks to be made. It took ~7 years from run-8 d+Au collisions to run-15 p+A collisions at RHIC…

Attractive vs Repulsive Sivers Effects

Unique Prediction of Gauge Theory !

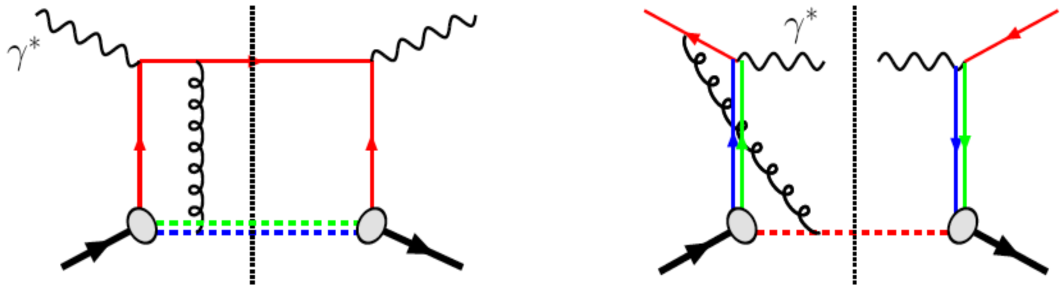
Simple QED example:



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

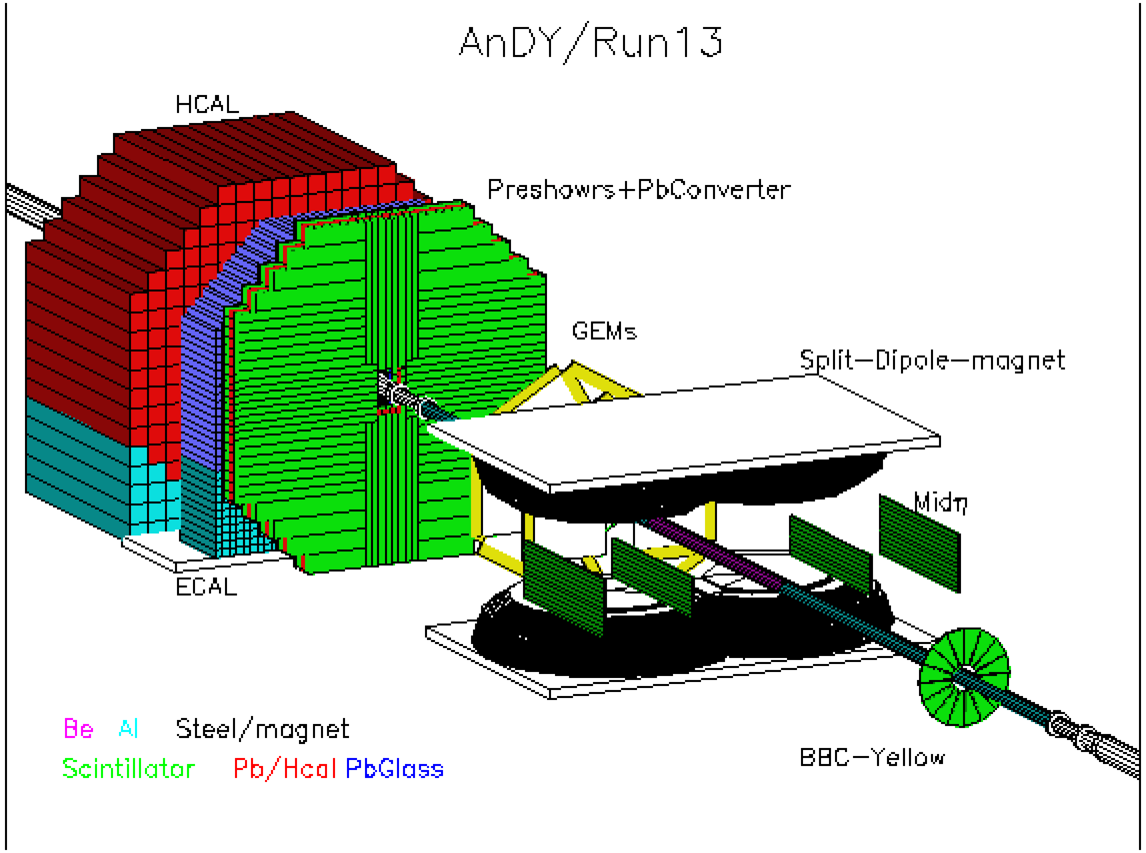
A_NDY Goal

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] ⇒ forward, low-mass DY

Goal of A_NDY Project

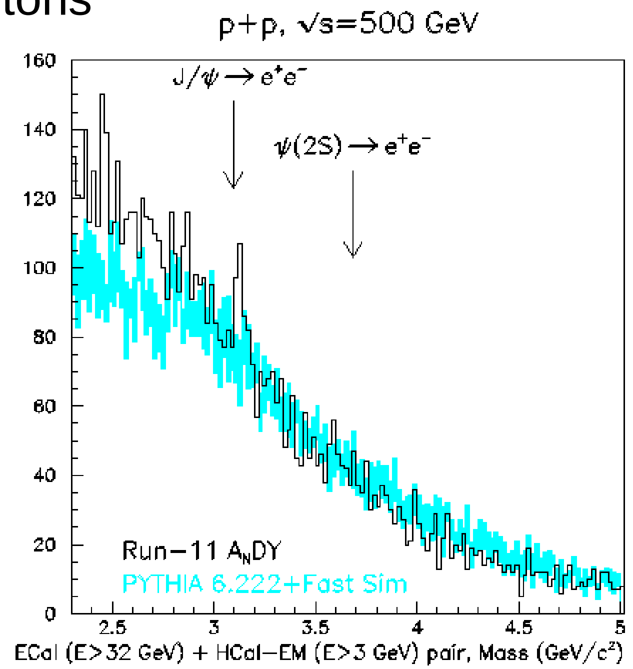
Measure the analyzing power for forward Drell-Yan production to test the predicted change in sign from semi-inclusive deep inelastic scattering to DY associated with the Sivers function



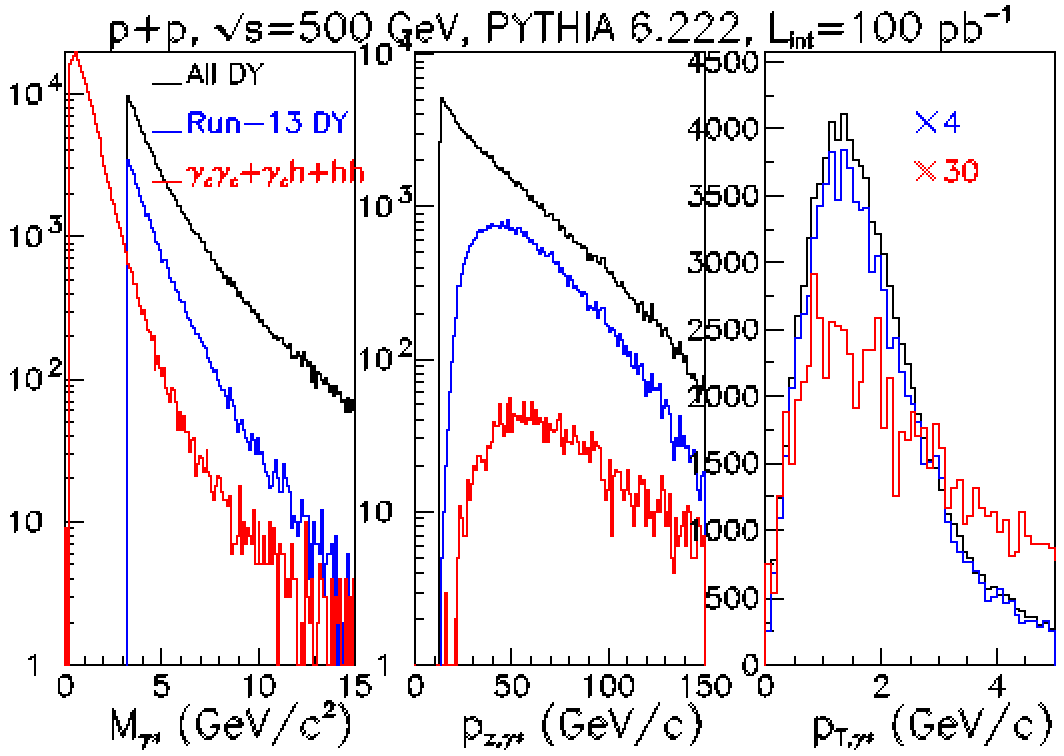
GEANT model of proposed A_NDY apparatus (run-13)

Strategy for Estimates

- Experience with run-11 analysis, shows that full PYTHIA/GEANT required ~2.5 weeks to generate 0.5 pb^{-1} of QCD background simulation.
- We are exploring the possibility of using NSERC for GEANT simulations.
- Until then, use fast simulator, benchmarked to run-11 data
- Reducible backgrounds: QCD hadron + photons
- Irreducible backgrounds: heavy quarks



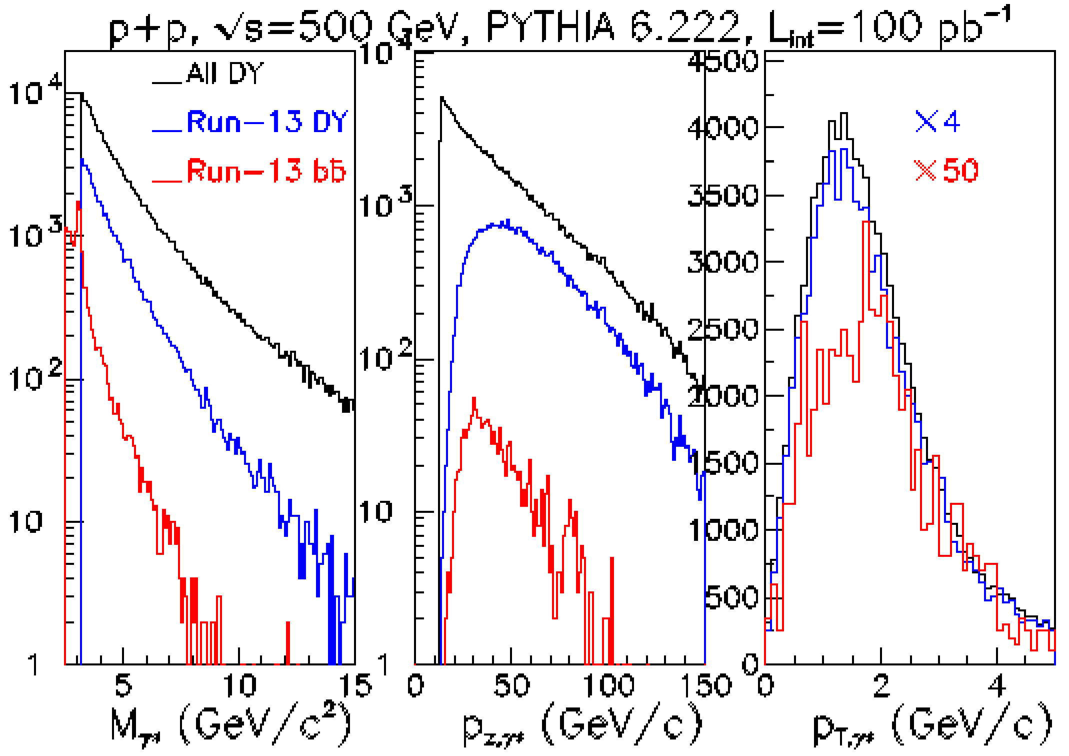
Reducible Backgrounds – from PYTHIA



$p_{z,\gamma*}$ and $p_{T,\gamma*}$ require $M_{\gamma*}$>4 GeV/c^2

Estimate that QCD backgrounds are <10% of the DY signal for $0.05<x_{F,\gamma*}<0.3$ and $p_{T,\gamma*}<2$ GeV/c (to overlap SIDIS).

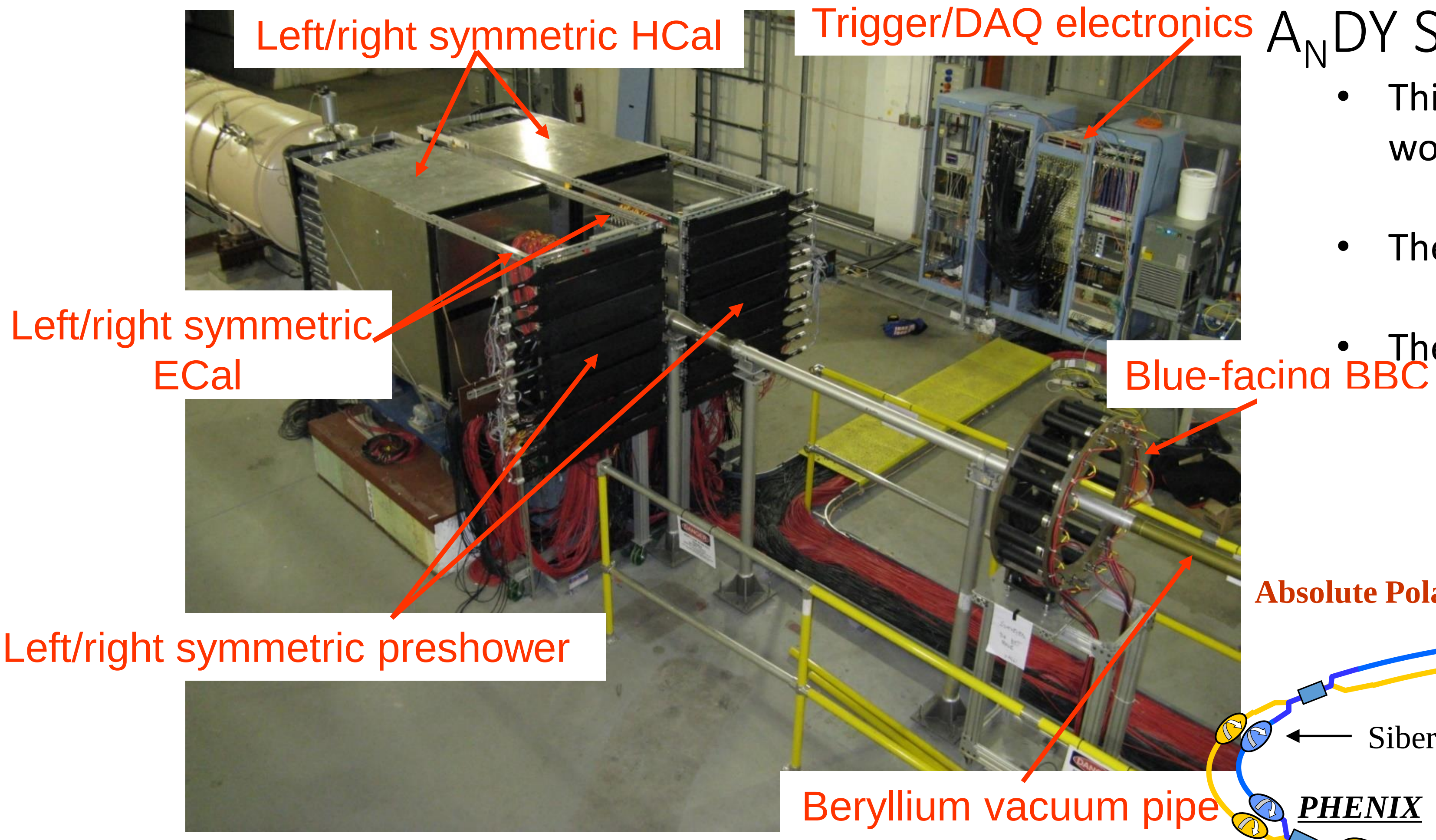
Irreducible Backgrounds – from PYTHIA



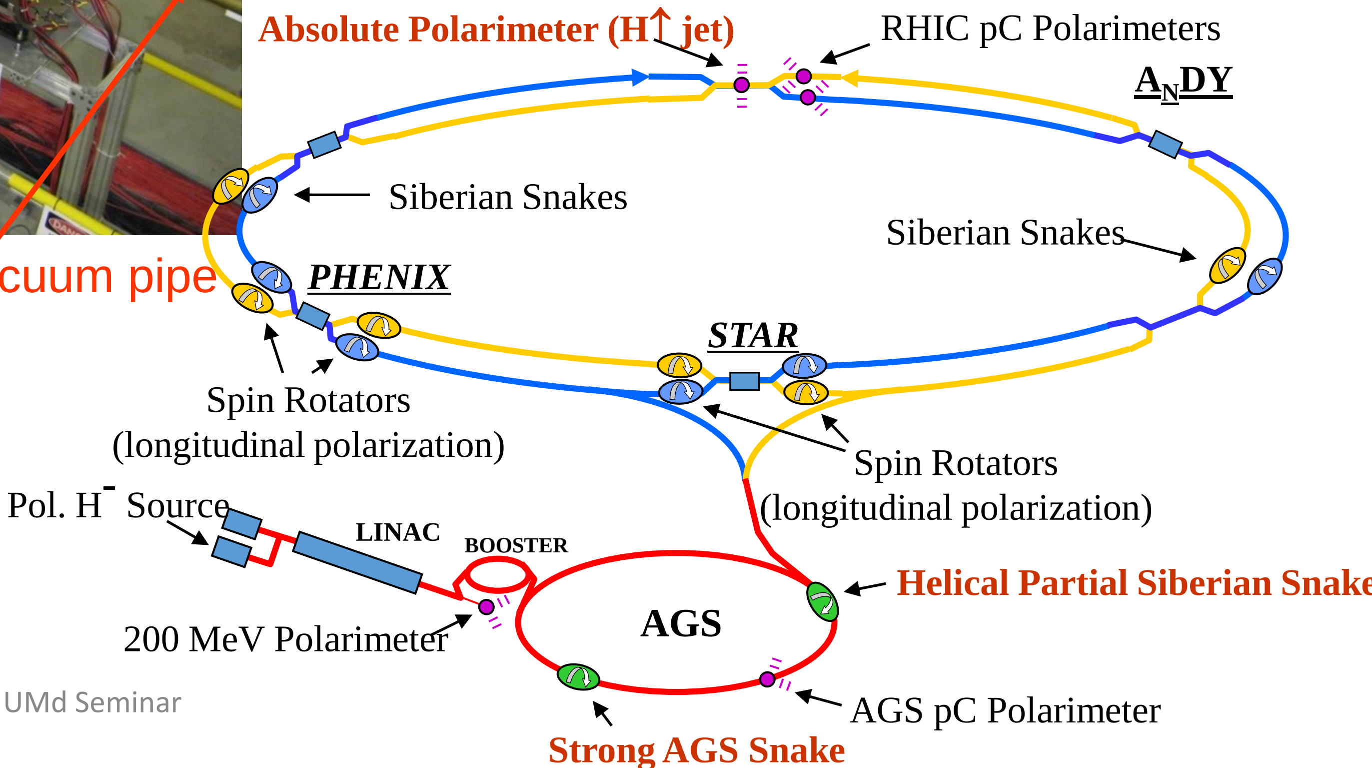
$p_{z,\gamma*}$ and $p_{T,\gamma*}$ require $M_{\gamma*}$>4 GeV/c^2

Estimate that open-bottom backgrounds are ~5% of the DY signal for $0.05<x_{F,\gamma*}<0.3$ and $p_{T,\gamma*}<2$ GeV/c (to overlap SIDIS).

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

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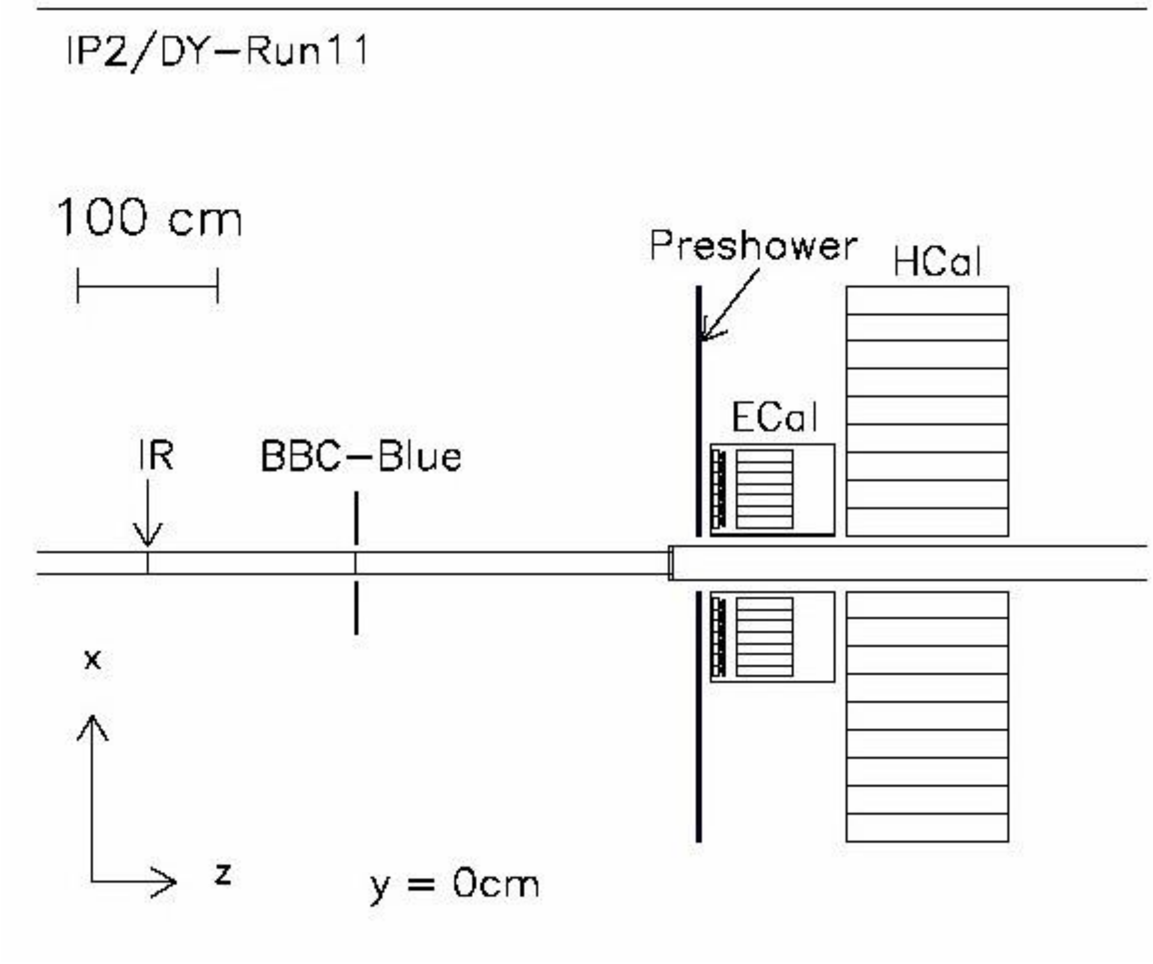

- Beam-beam counter (BBC) for minimum-bias trigger and luminosity measurement (from PHOBOS [NIM A474 (2001) 38])
- Zero-degree calorimeter and shower maximum detector for luminosity measurement and local polarimetry (ZDC/ZDC-SMD, not shown)
- Hadron calorimeter (HCal) are L/R symmetric modules of 9x12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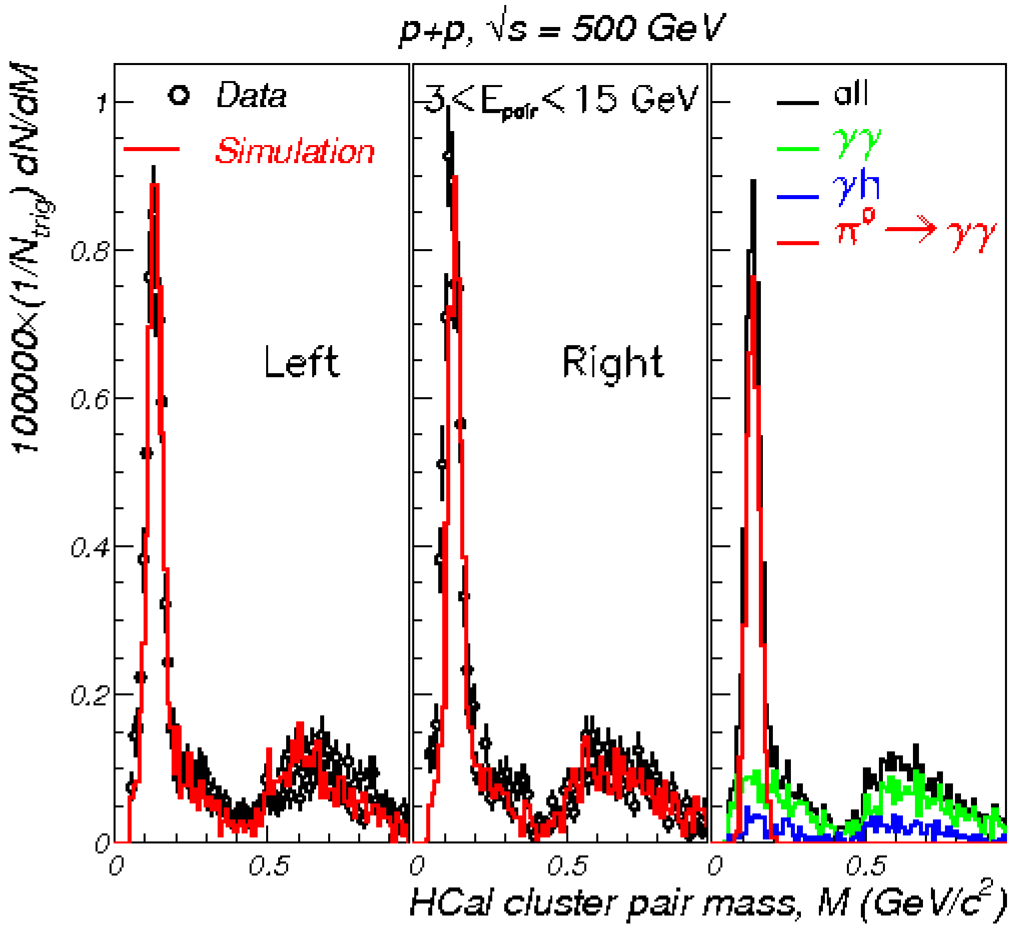
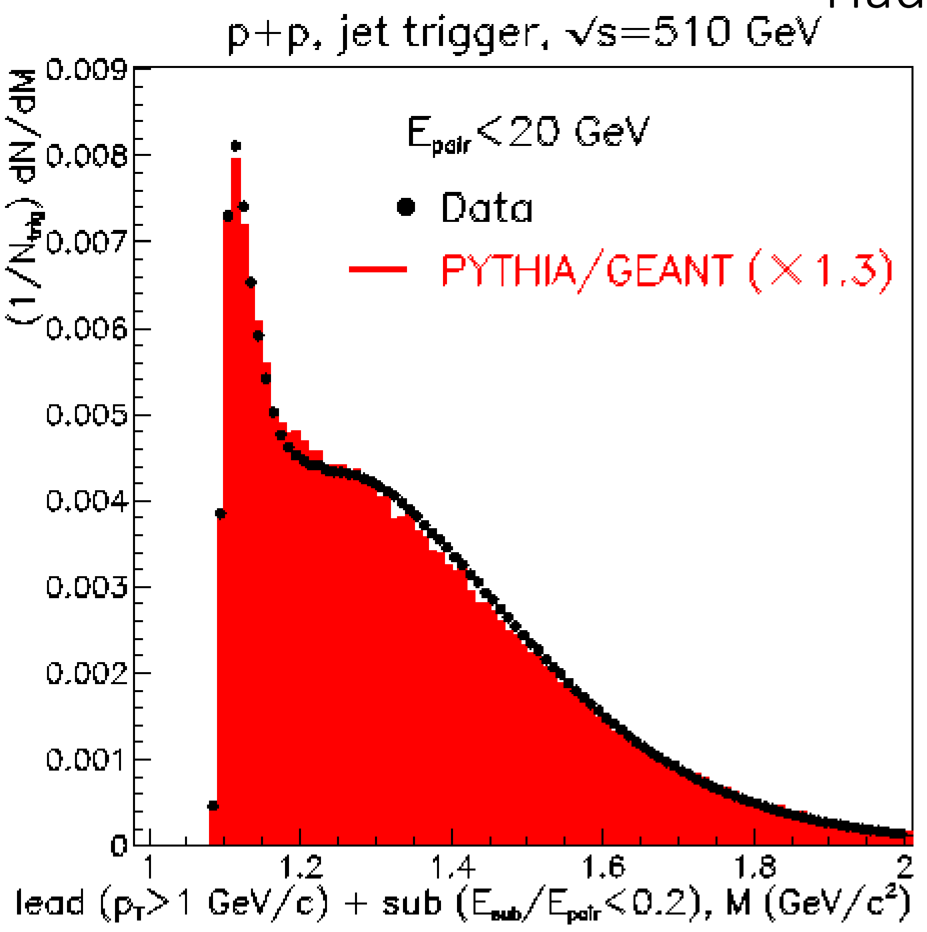


- Cosmic-ray muons were used to adjust relative gains in advance of collisions
- The primary determination of the energy scale was from reconstruction of $\pi^0 \rightarrow \gamma\gamma$ from single-tower cluster pairs. The maximum energy for this calibration was limited by photon merging into the coarse (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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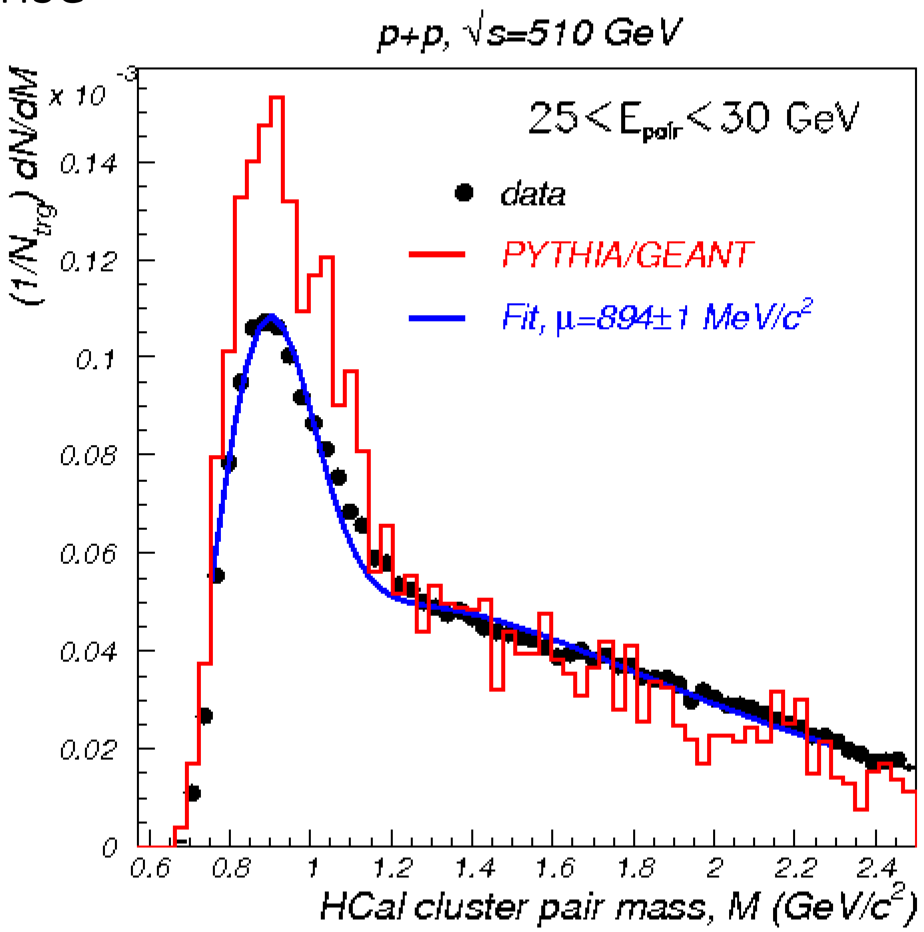
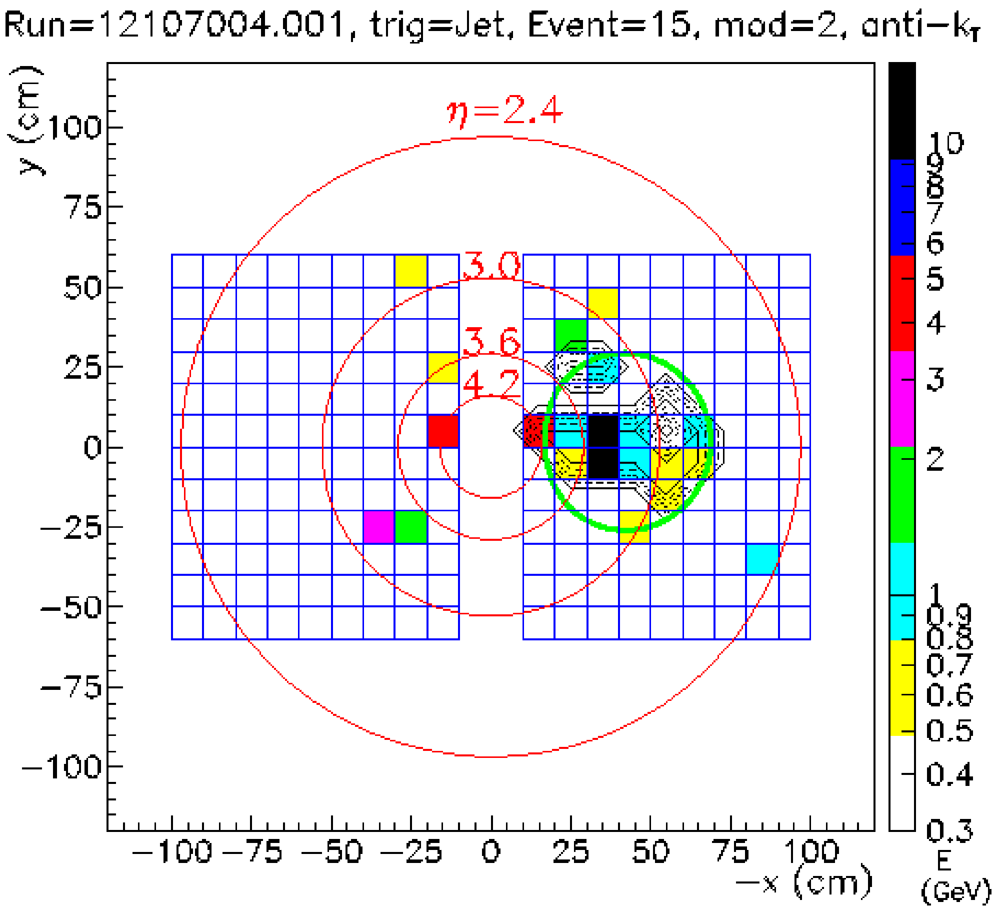


- Use BBC detector to tag HCal clusters made by incident charged hadrons. Mass assignments are then made.
- Tagged cluster-pair mass distributions are consistent with $\Lambda\rightarrow\pi^- p$ (left) and K*(892) $\rightarrow\pi^+K^-$ (right) and charge conjugates
- Use E=1.12E' – 0.1 GeV for jet finding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

    $|\eta_J - 3.25| < 0.25$

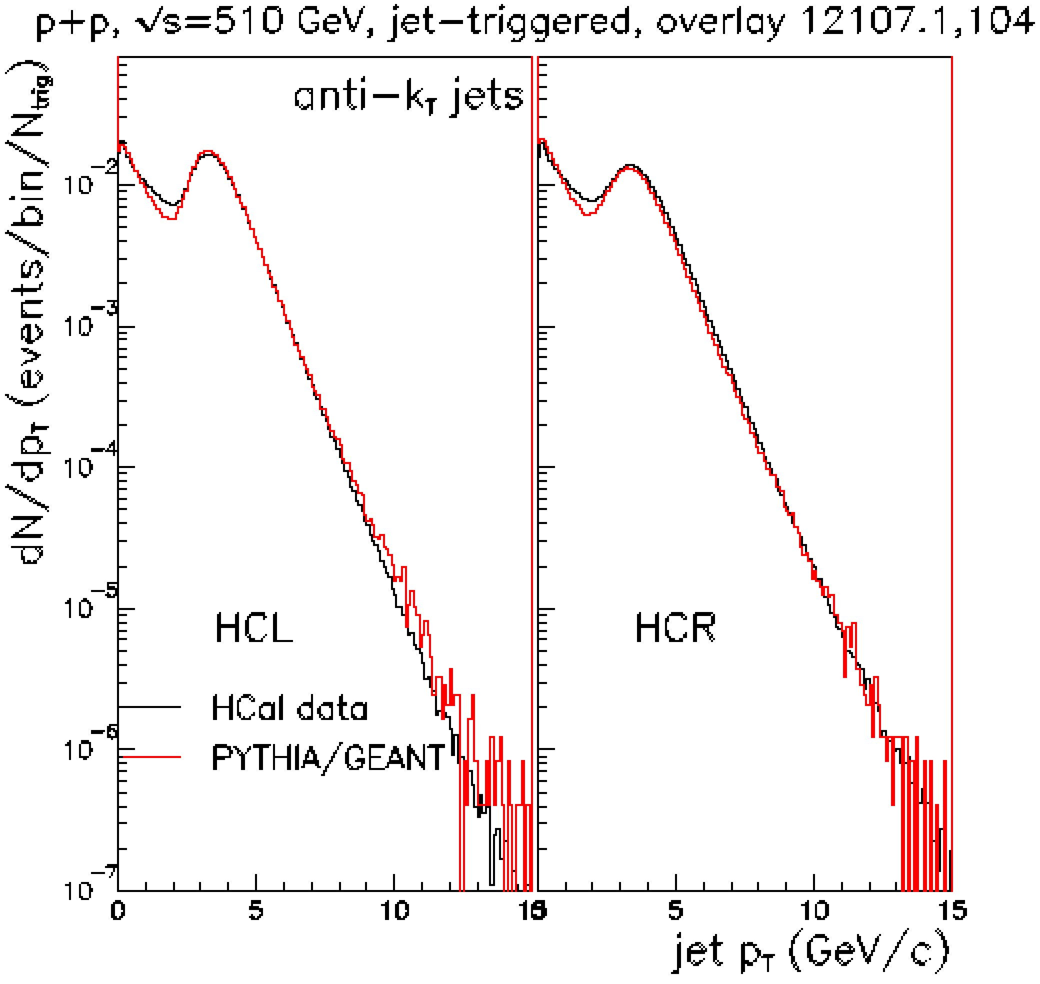
    $|\Phi_J - \Phi^{Off}| < 0.50$

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

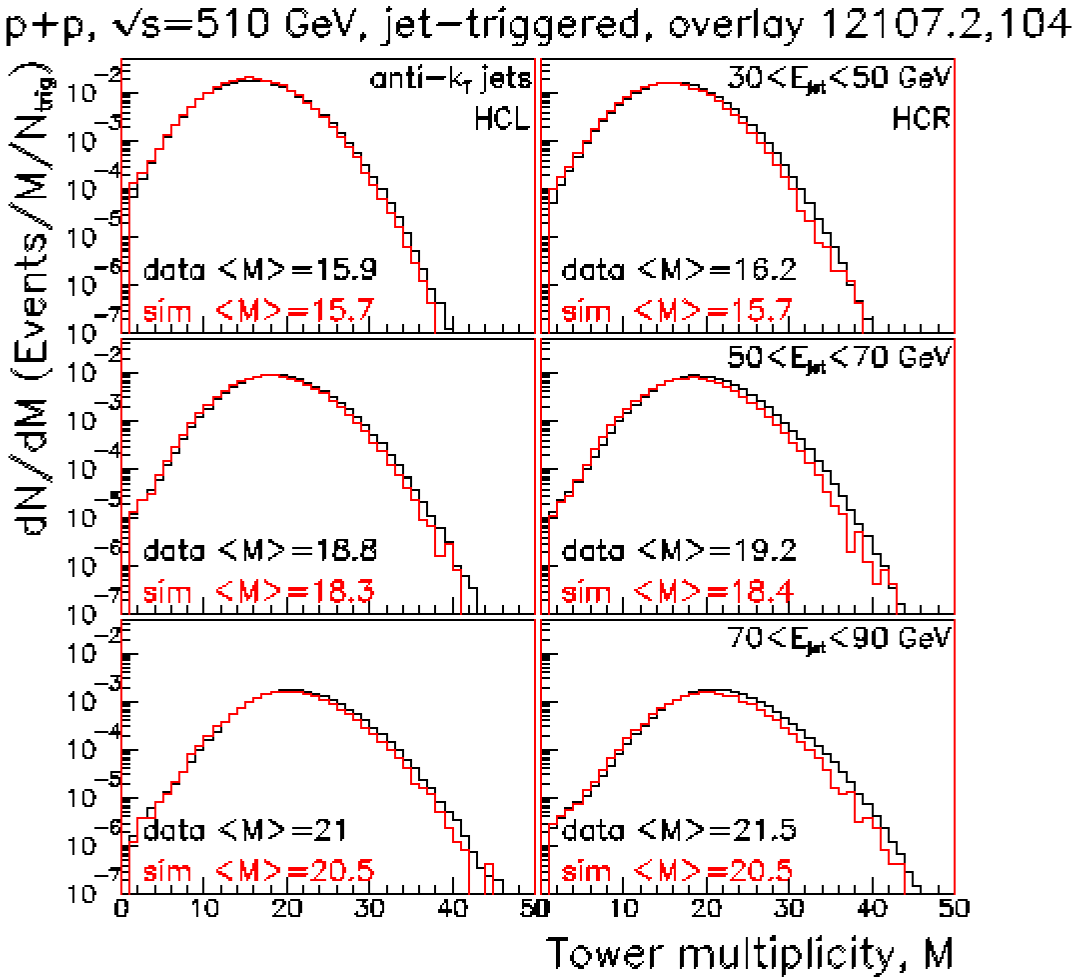
    $\Phi^{Off} = \pi$ for HCR
  - Energy Cut : $E_{jet} > 30$ GeV
  - Algorithm : arXiv : 0802.1189
    arxiv : 1209.1785

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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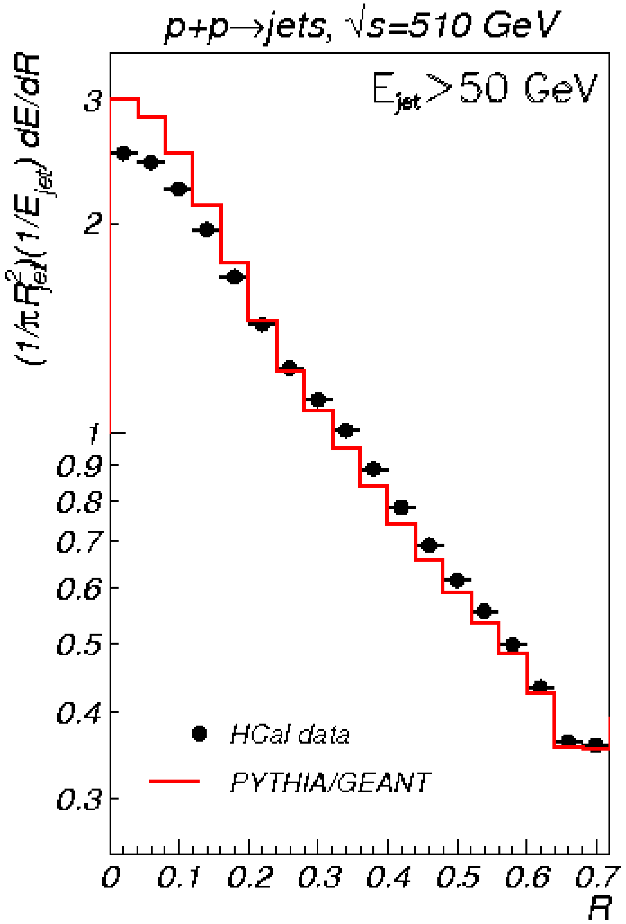
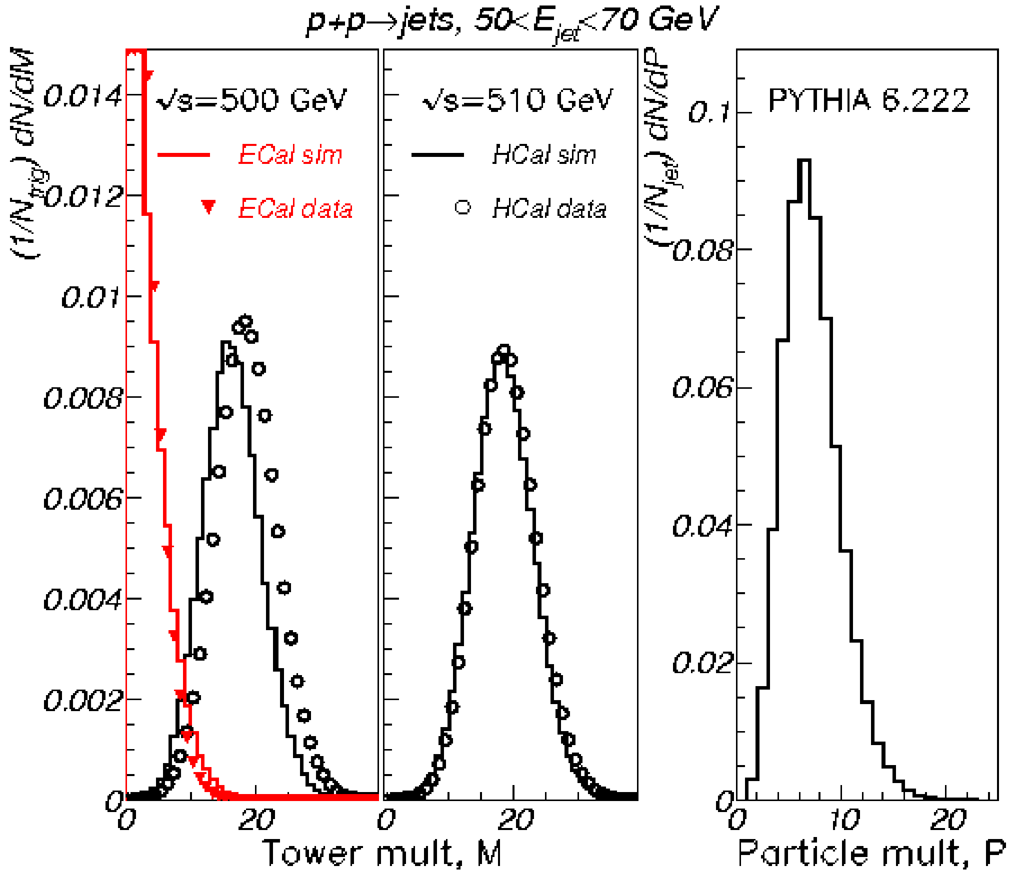
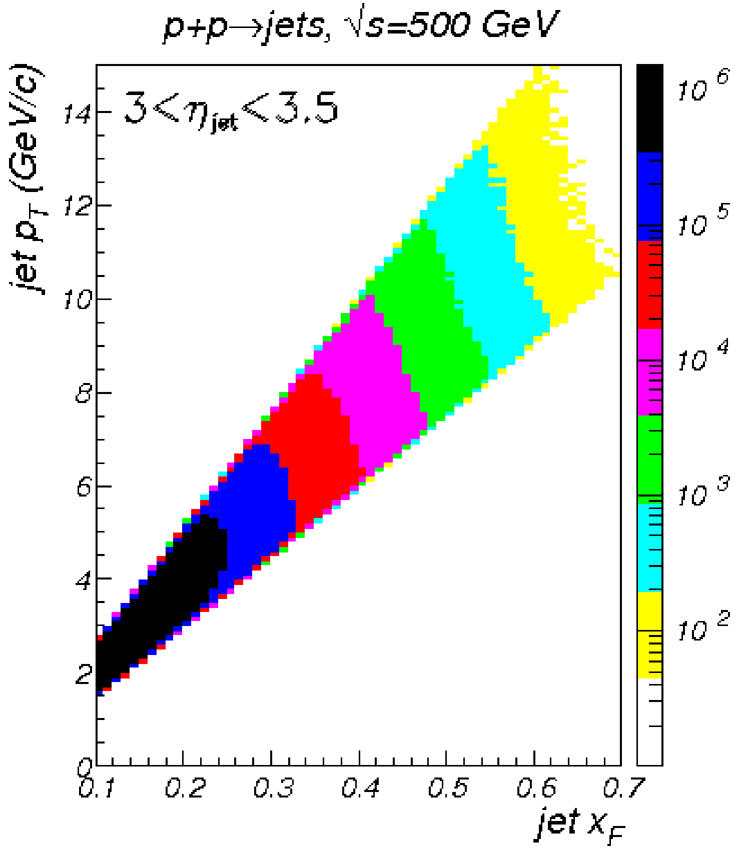






Event averaged jet shape: how the energy is distributed a distance R in η,φ from the thrust axis

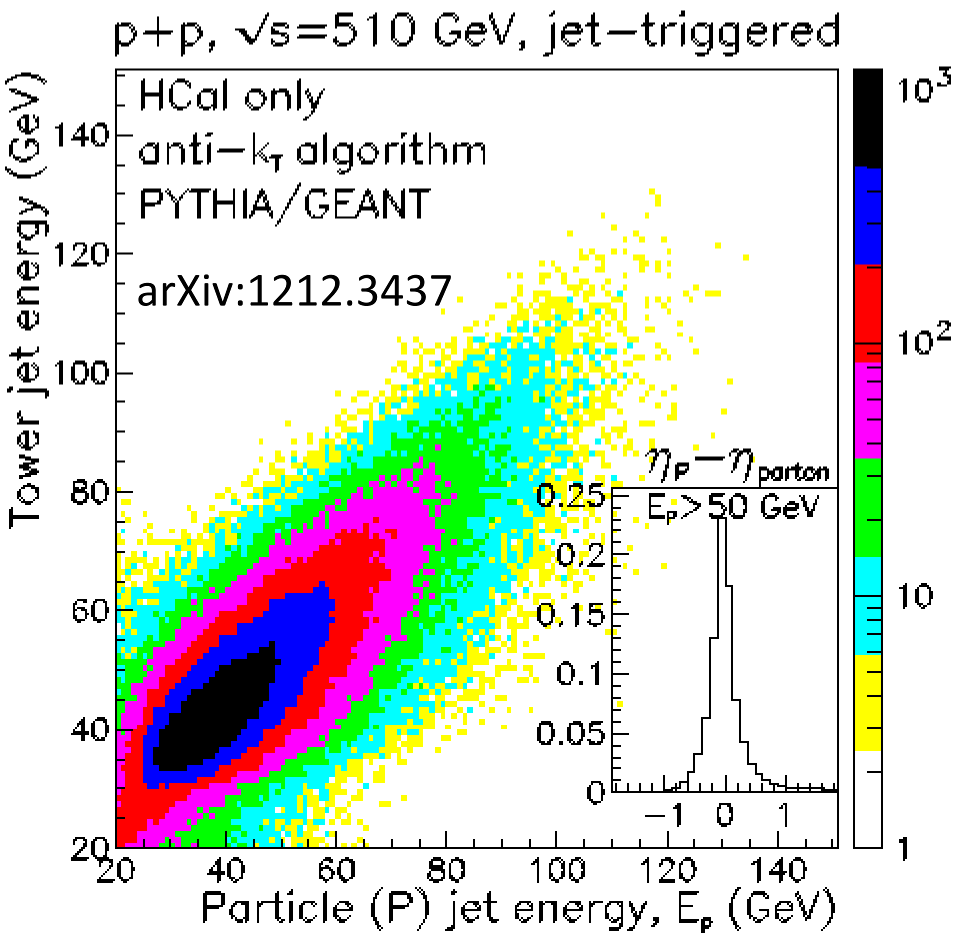
⇒ the anti-kT clusters have shapes similar to midrapidity jets

(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 $2.4<\eta<4.2$ 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

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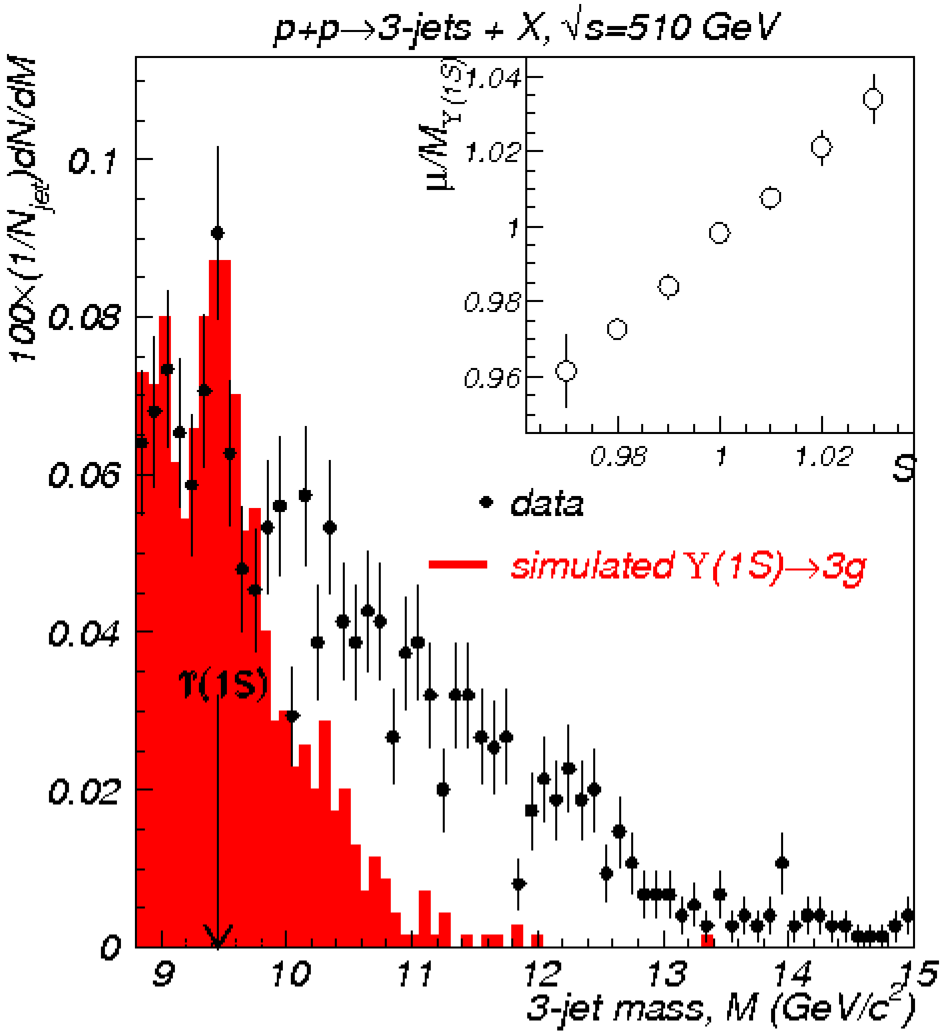

- Test jet energy scale by reconstruction of invariant mass for multi-jet events
- Observe 3.5σ statistical significance peak, attributed to ϒ(1S)→3g. The red overlay is a simulation of the signal from the PYONIA generator of ϒ(1S)→3g, run through GEANT, and then reconstructed as done for the data
-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

Forward Jet Cross Sections

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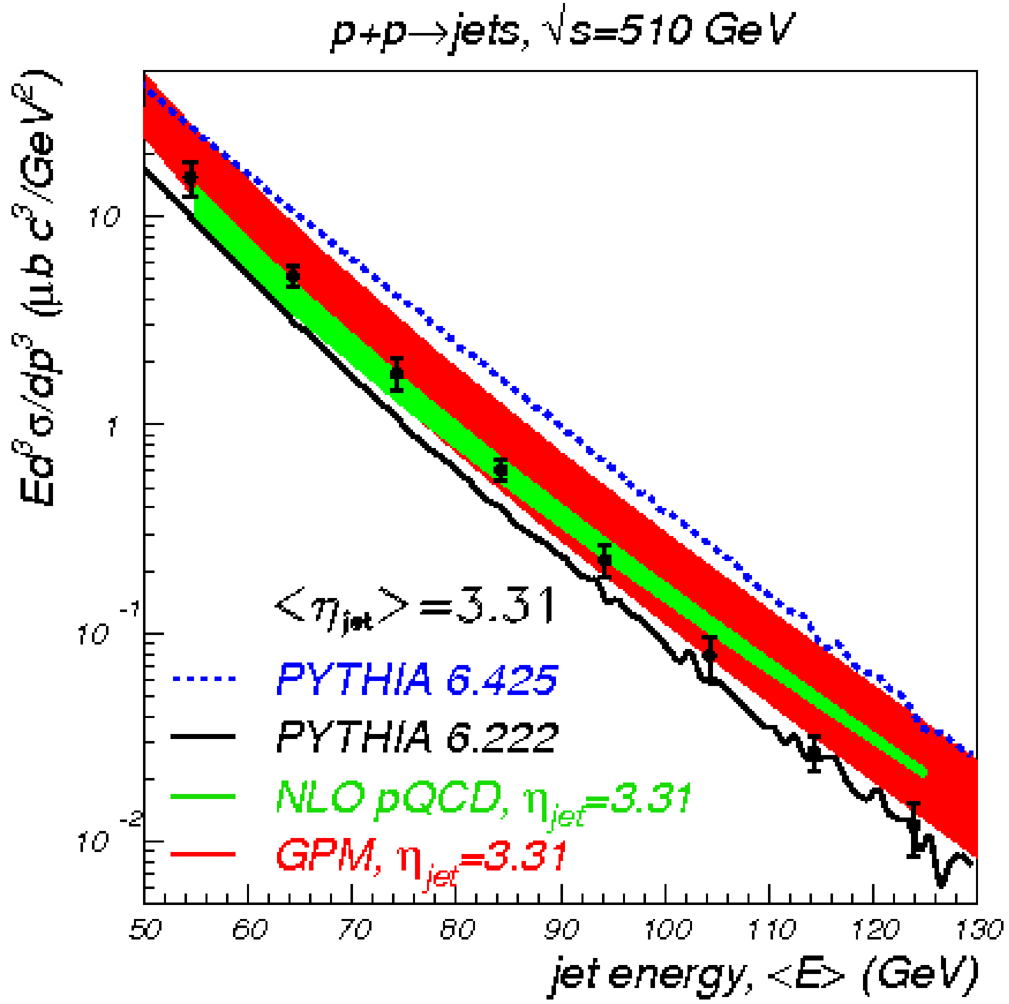

- Uncertainties include both statistical and systematic estimates [as described in backup]
- Strong dependence on both x_F and p_T requires data/theory comparisons at $<\eta_{jet}>$
- NLO pQCD [PRD 86 (2012) 094009] calculation provides a good description of the data using CTEQ6.6M PDF. Note the small 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

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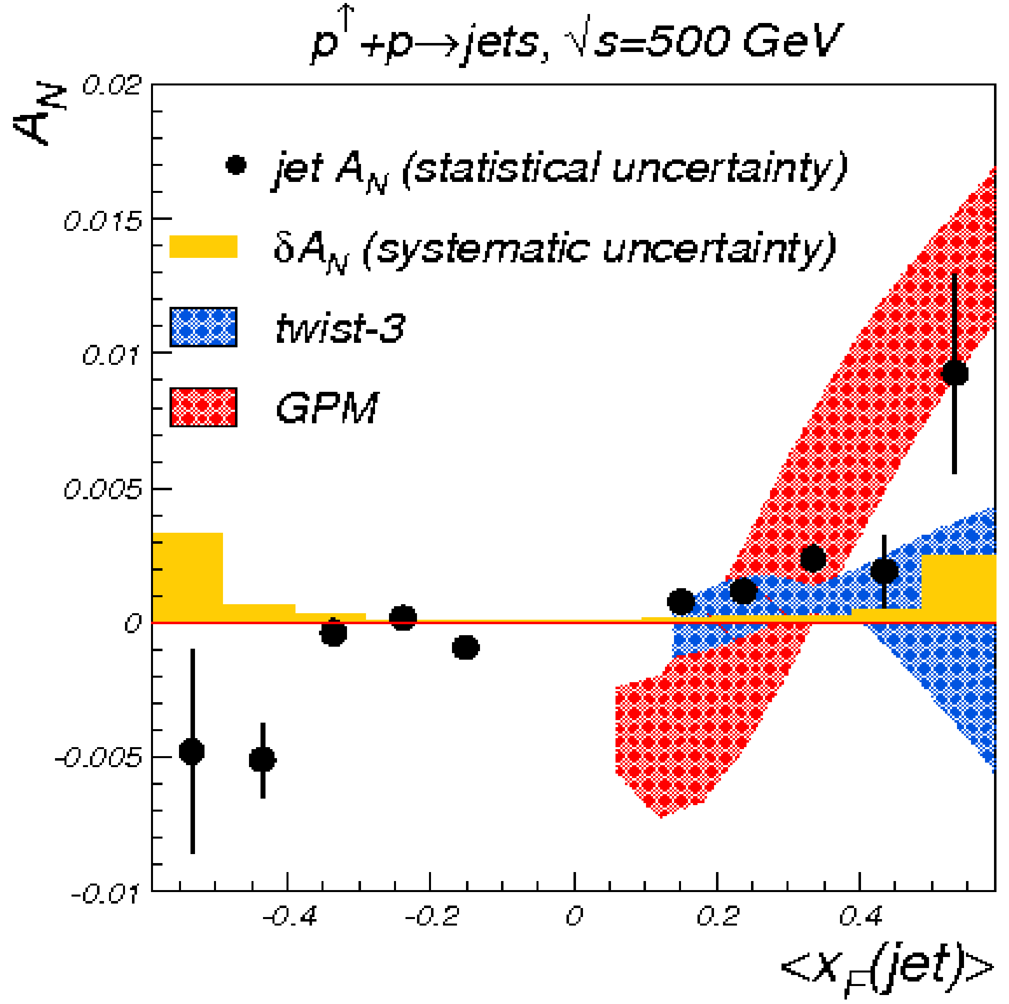
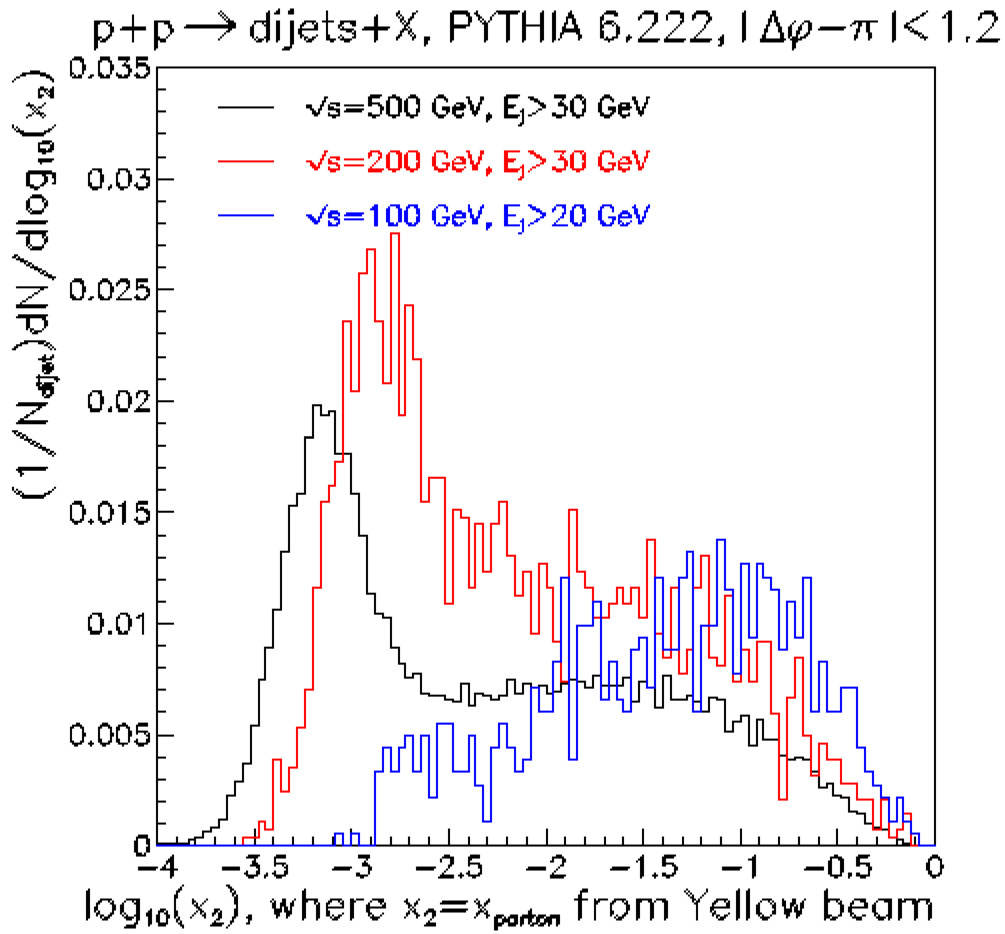


- Analyzing power is computed via the cross-ratio method that exploits the mirror symmetry of the apparatus

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

  - 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



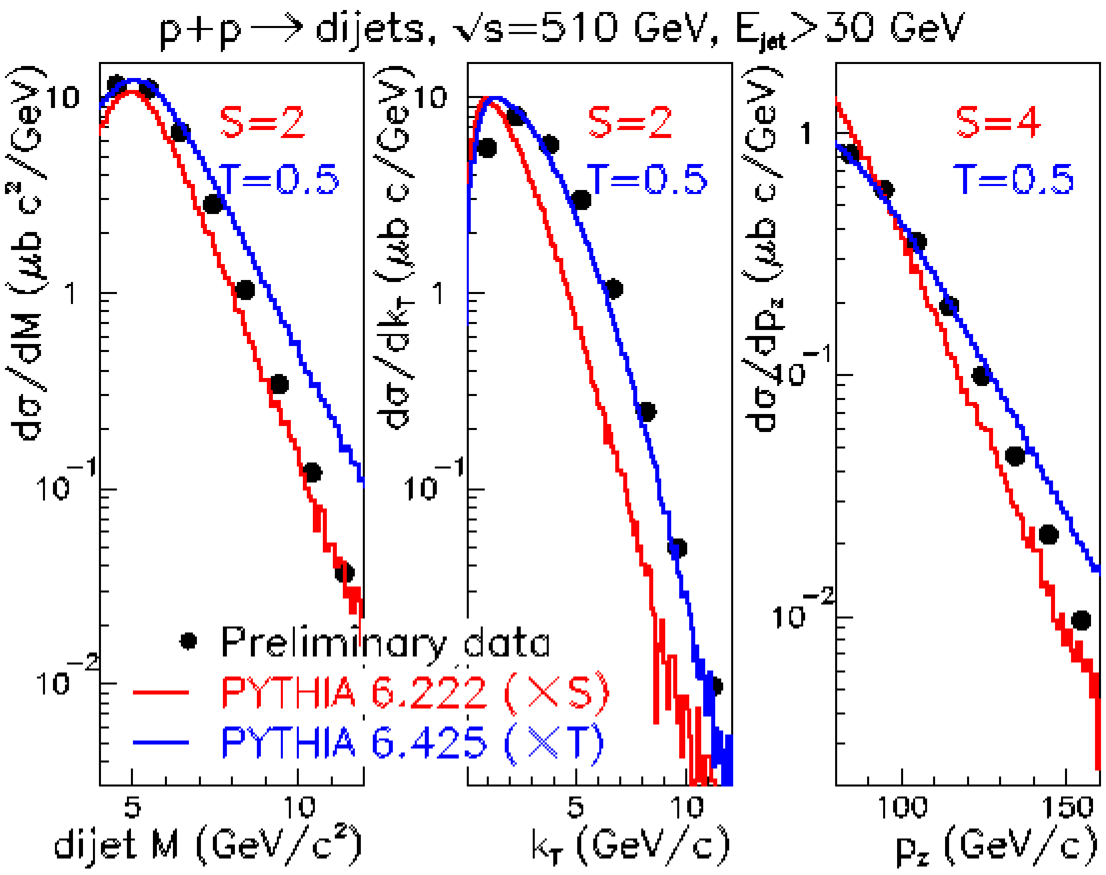
Reconstruction of >1 jet in the forward direction can emphasize hard-scattering contributions from lox-x gluons

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

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.

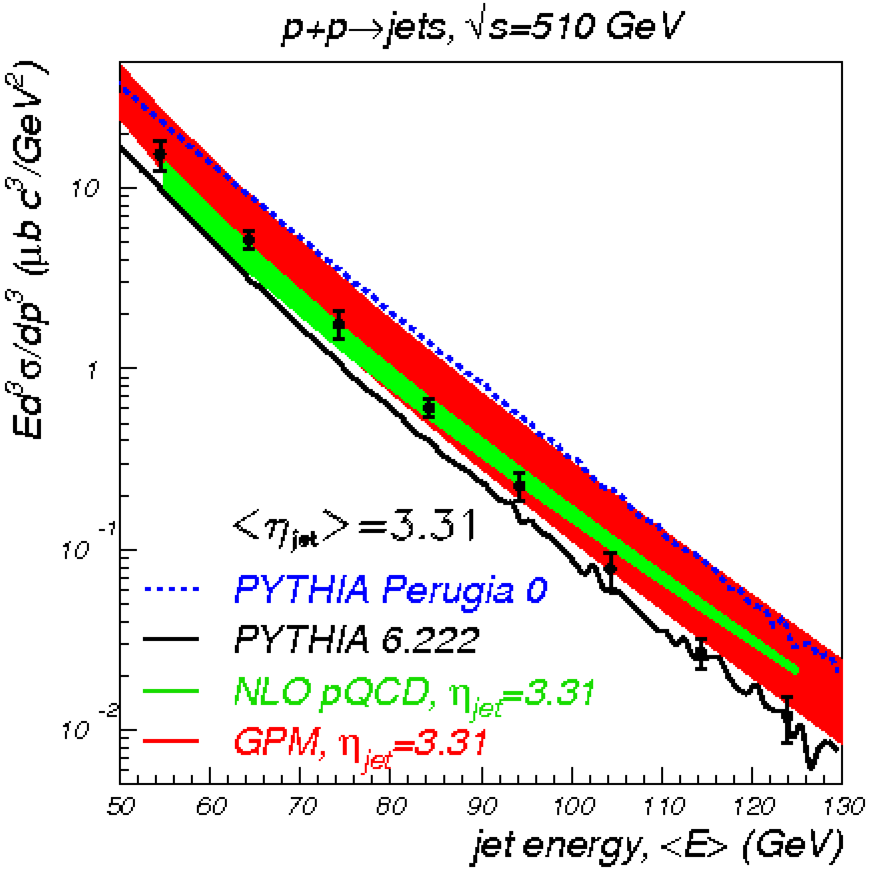
PYTHIA Tunings

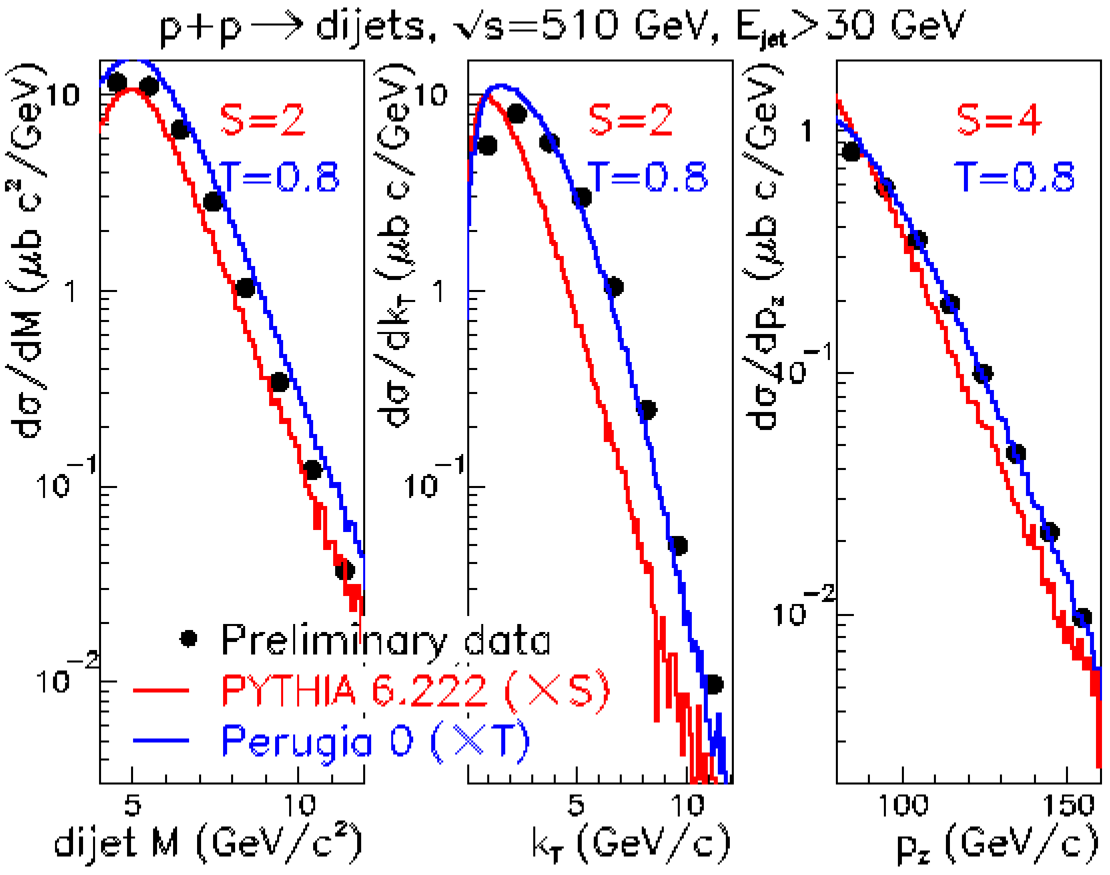
- The LHC high-energy program has prompted many retunings of PYTHIA, so that backgrounds in e.g. dijet mass are well modeled to allow new particle searches. See P.Z. Skands, PRD 82 (2010) 074018 [arXiv:1005.3457]

- 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…]

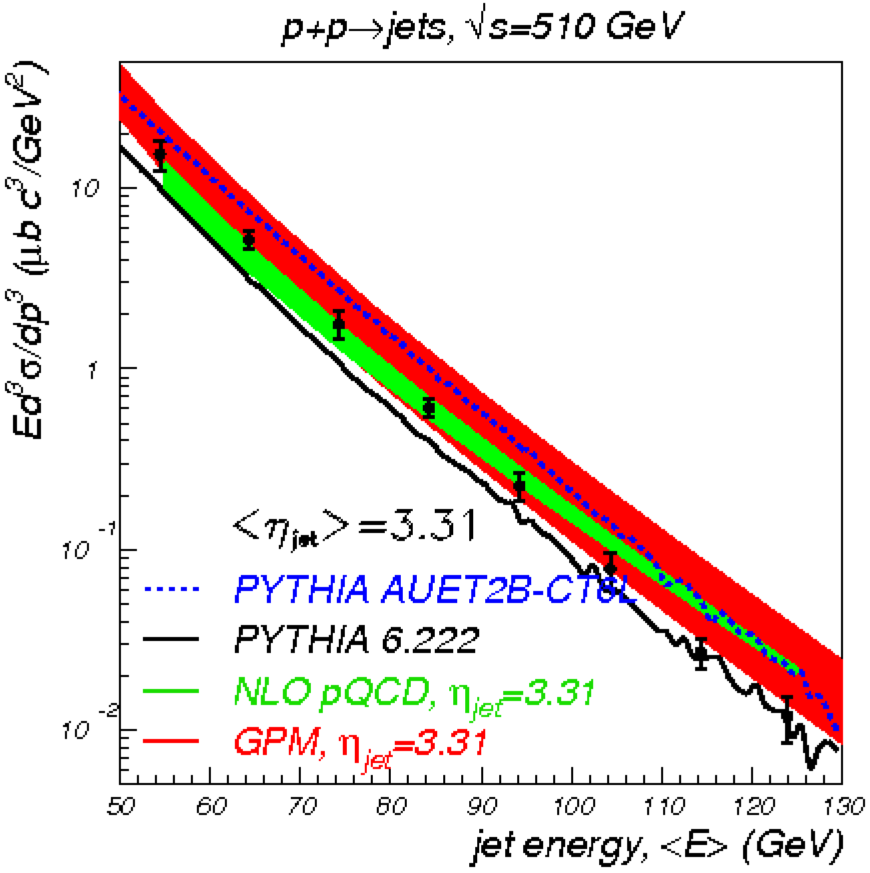
Data versus Perugia 0 Tune

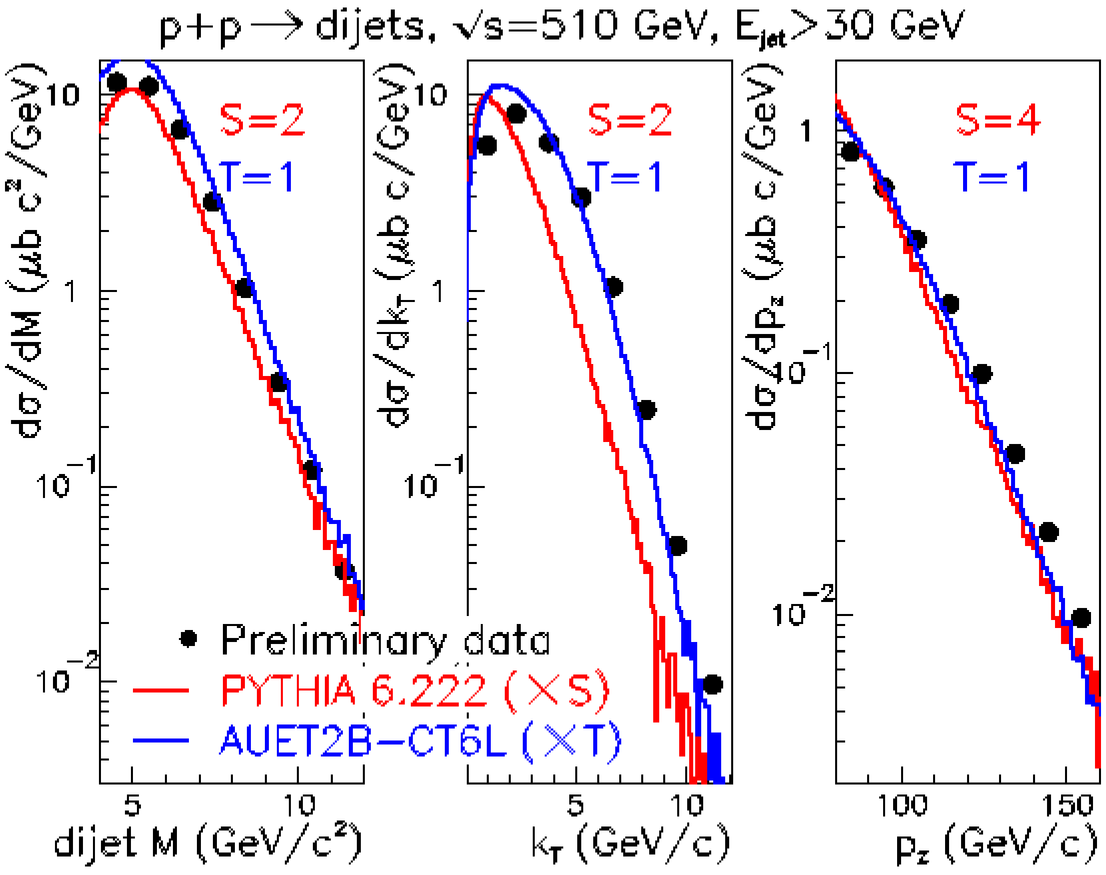




- Perugia 0 is commonly used for RHIC midrapidity data
- Overpredicts dijet cross sections by ~20%
- Overpredicts inclusive jet cross section

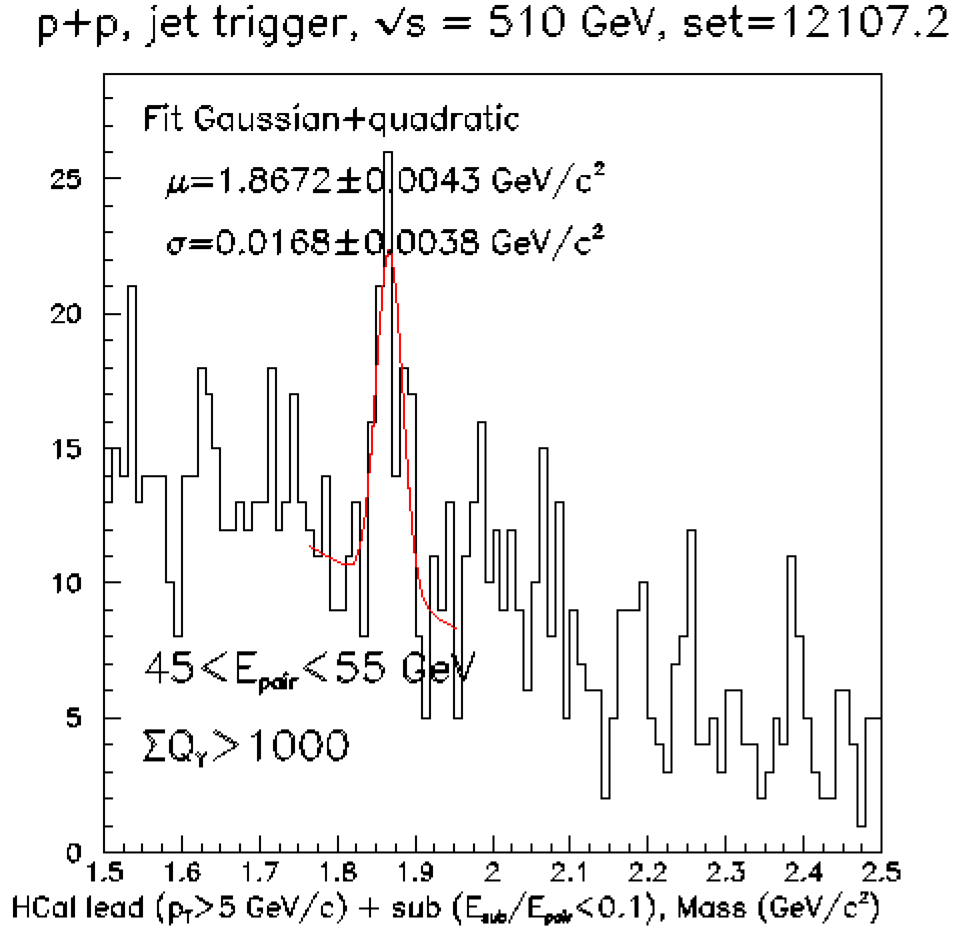
Data versus Atlas [AUET2B-CT6L] Tune

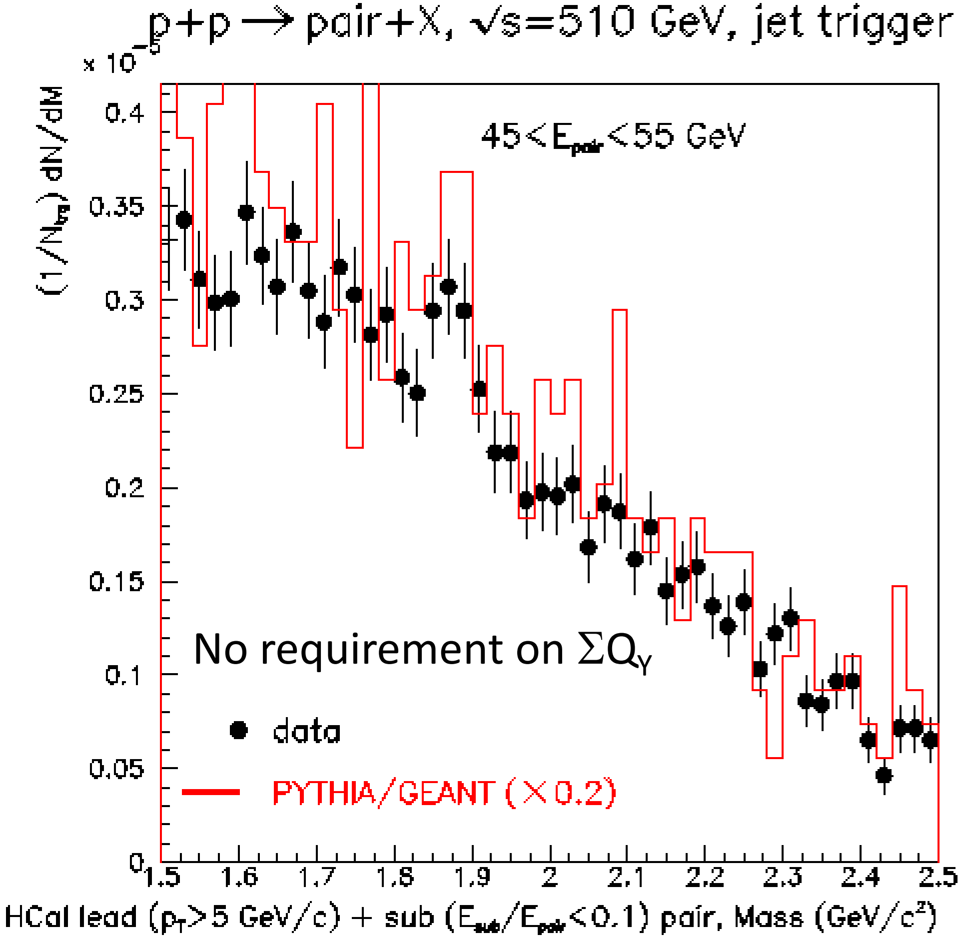




- PYTHIA tune developed by Atlas [arXiv:1512.001917], including LHC 7 TeV data
- Reasonable representation of dijet distributions and normalization
- Better description of inclusive jet result than other tune

What about heavy-flavor irreducible backgrounds?



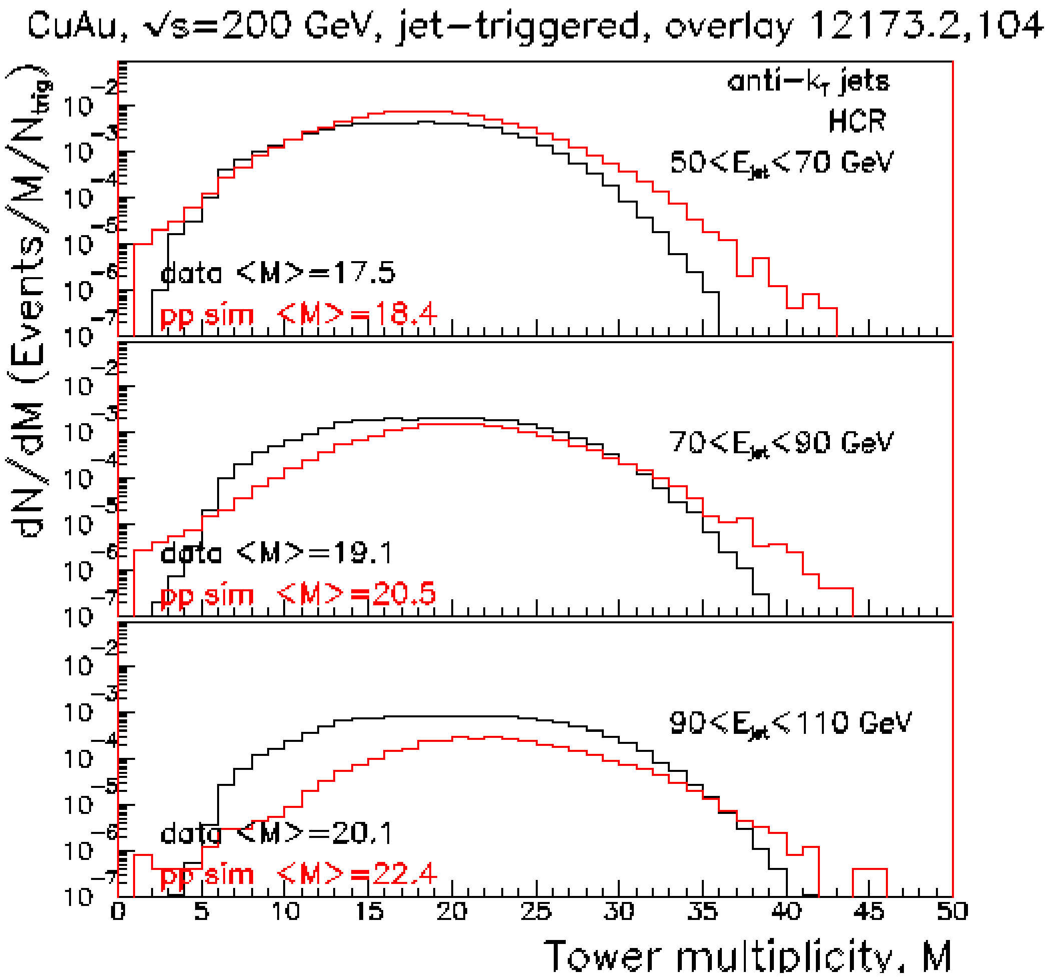


- Direct reconstruction of large x_F D mesons, from two-cluster analysis with mass assignments…
- Yield in data is 3×10^{-6} of all jet-triggered events
- 3.8σ statistical significance in data, with PYTHIA/GEANT consistent with the shape of dN/dM (limited by statistics)
- Narrow mass peak could be due to $D^{\pm}\rightarrow K_S\pi^{\pm} \rightarrow \pi^0\,\pi^0\,\pi^{\pm} \rightarrow 4\gamma\,\pi^{\pm}$, with photons merging into one cluster

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 PYTHIA tunes as used at the LHC
- The story is best completed by a future effort to measure forward, low-mass DY production

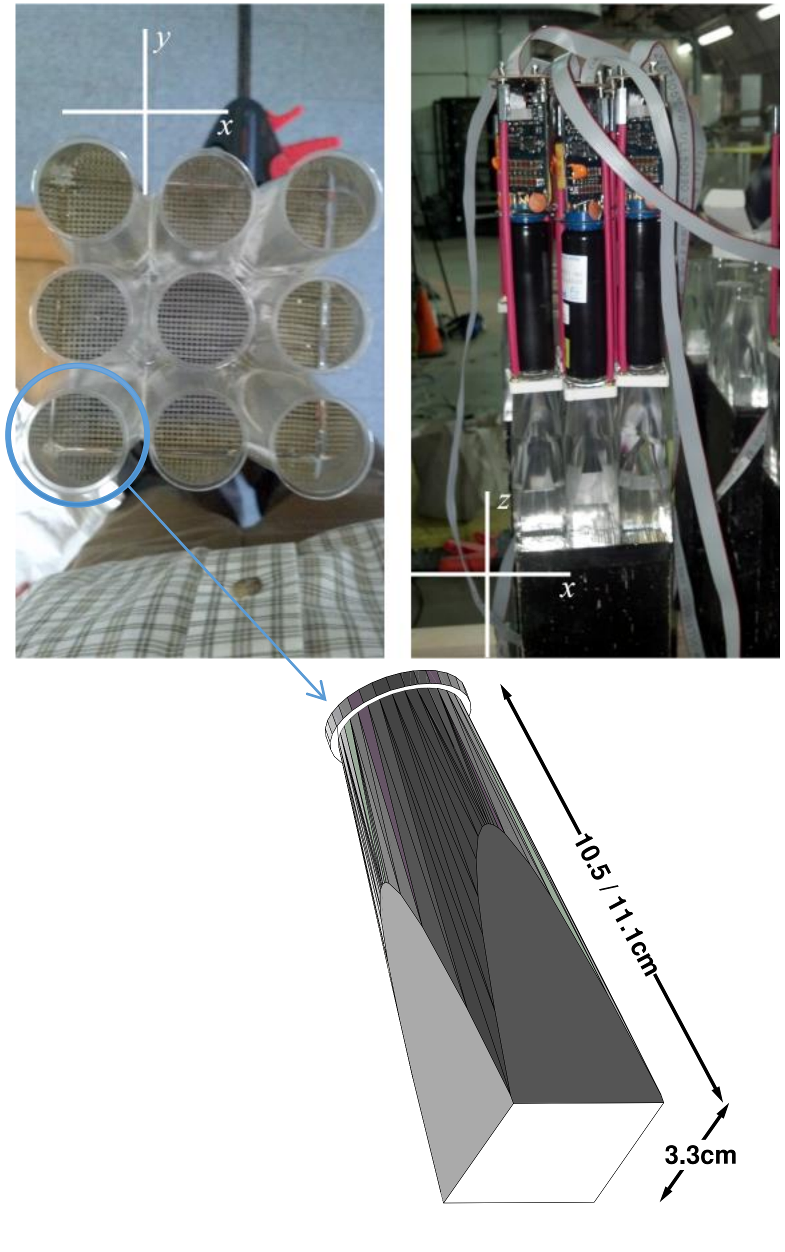
Outlook – I: Forward Jets in HI Collisions?



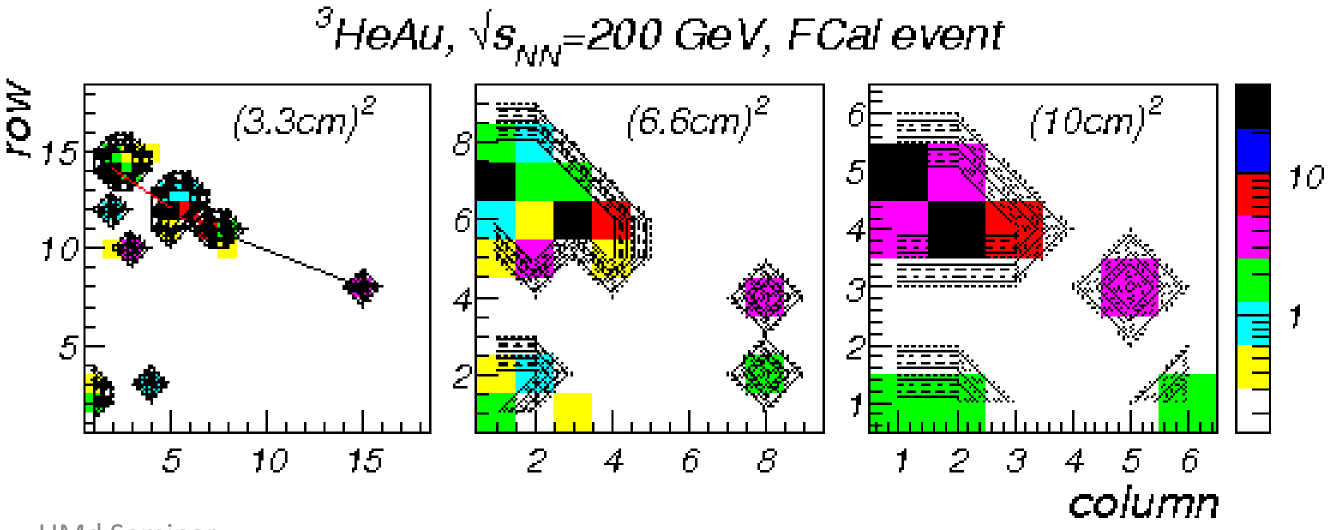
"pp sim" is in reference to PYTHIA 6.222/GEANT for p+p at √s=510 GeV, with jets reconstructed with R_{jet}=0.7 The comparison of the normalizations to CuAu are irrelevant. The tower multiplicities of the jets in CuAu are comparable to those from pp.

- 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.

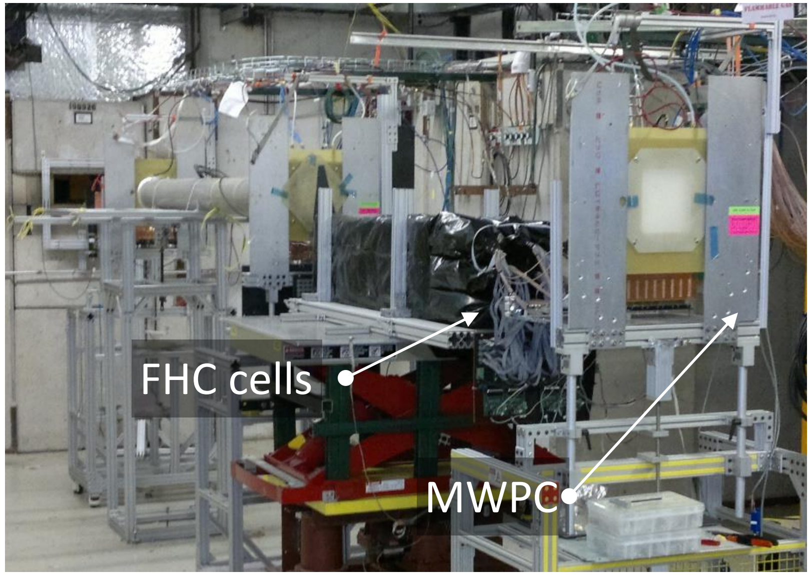
Outlook-II : Pixelizing AGS-E864 cells



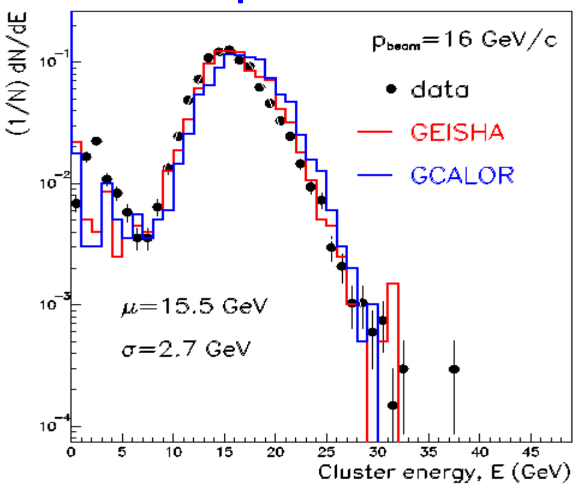
- Transverse resolution is increased by pixelizing
  - (10 cm)^2 cells ➔ 3×3 array of (3.3 cm)^2 cells
  - Stack (6-cell)^2 forward calorimeter at STAR in 2014
  - “looking within” cell shows clear structures



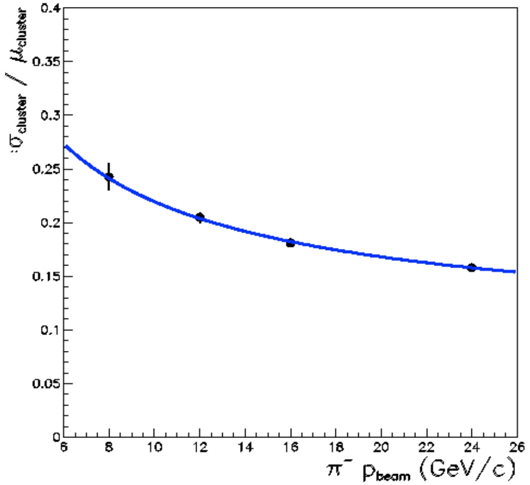
Outlook III - Results from Fermilab Test Beam Facility-T1064



Cluster energy distribution of center pixel for π^- beam

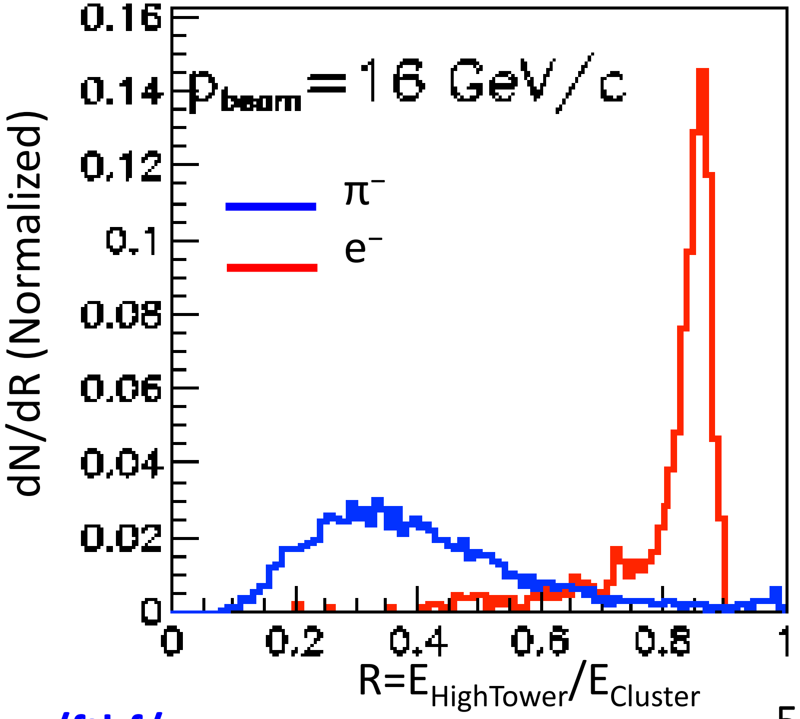


Cluster energy resolution for π^- on central pixel



- 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

Collaborators

Forward jets / A_NDY

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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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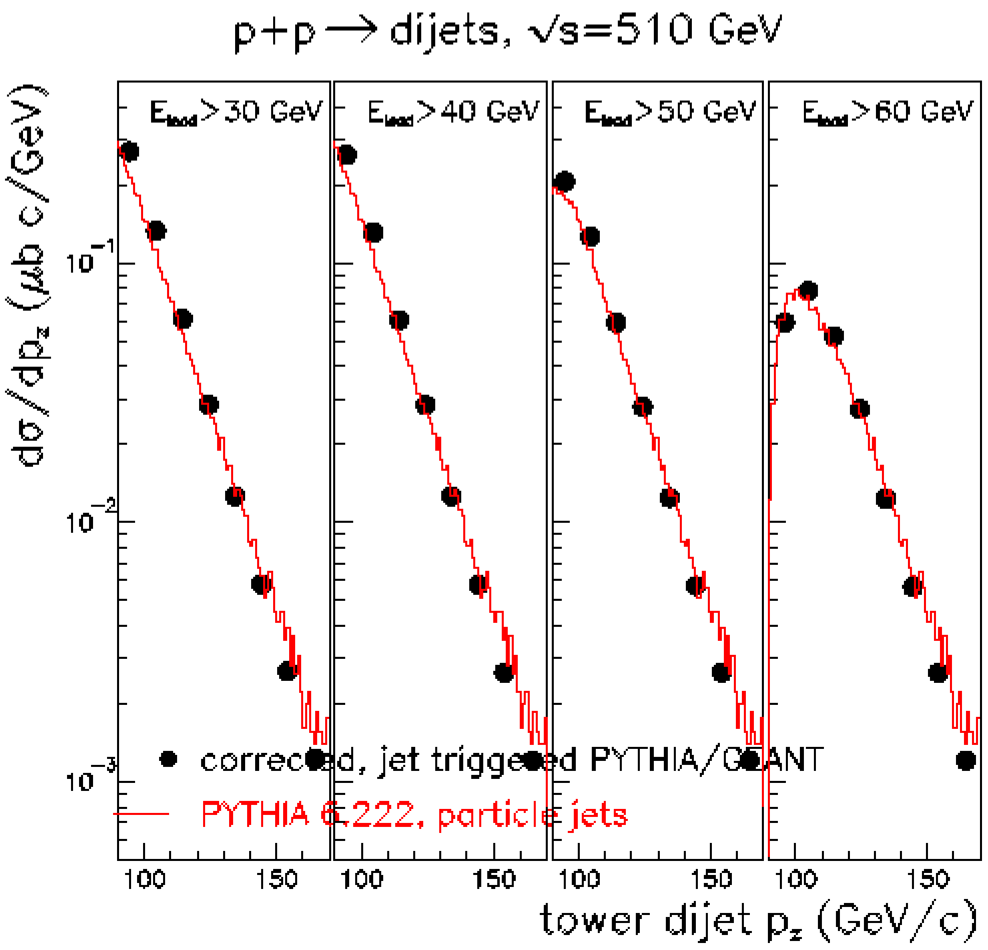
Forward π^0 / STAR

Thanks to STAR. Special thanks to A.Ogawa, A. Gordon; H.J.Crawford, J.Engelage, C.Perkins, E. Judd, L.V.Nogach, G.Rakness, E.Braidot, X.Li, P.Shanmuganathan …

Test of Dijet Corrections

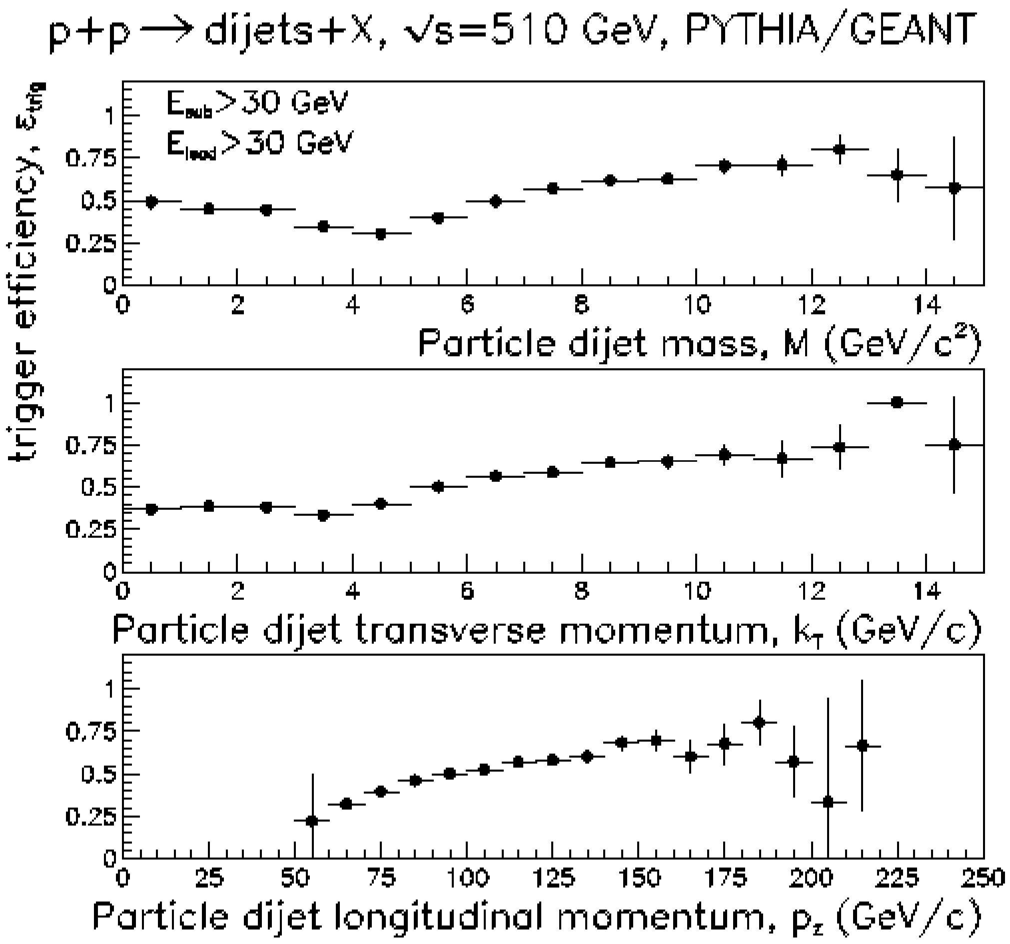
Comparison of corrected PYTHIA/GEANT tower dijets to PTYHIA particle dijets



- 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 Trigger Efficiency

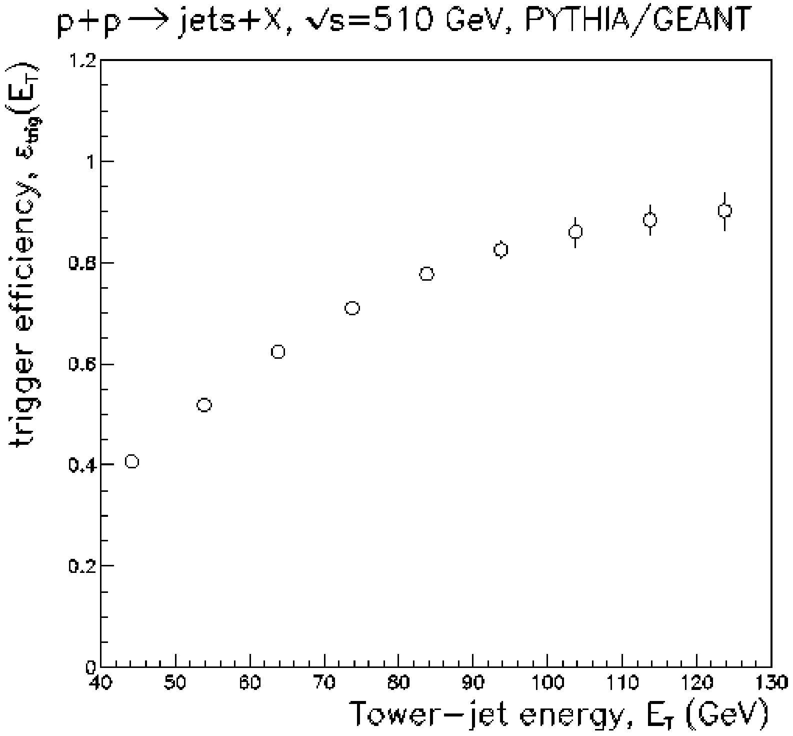
Results prior to convolution integrals



- 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:

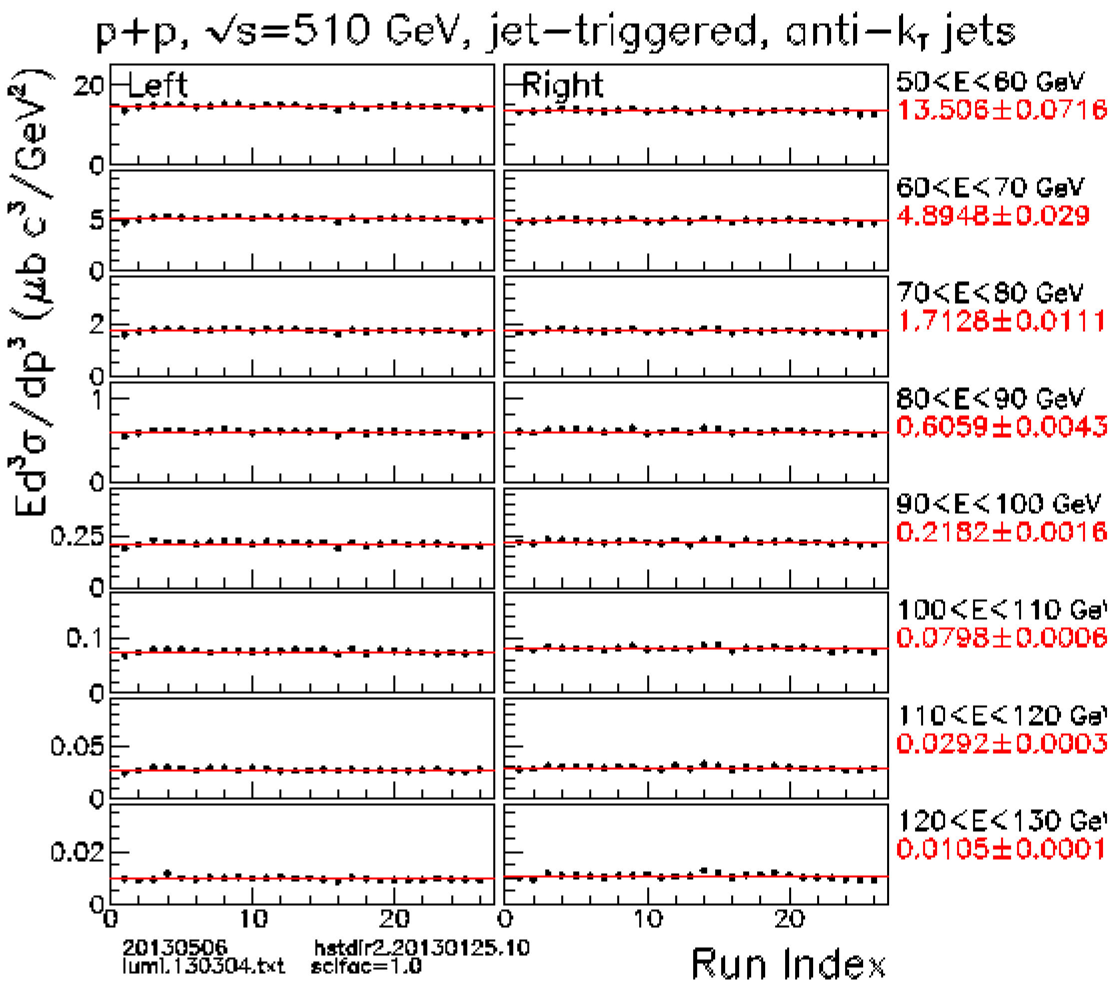
$$E\frac{d^3\sigma}{dp^3} = \frac{N\langle \cosh\eta \rangle}{\varepsilon_{trig}\varepsilon_{\det}L_{samp}\langle p_T \rangle \Delta\eta\Delta\phi\Delta E}$$

where

- N – number of particles detected
- ε_{trig} – trigger efficiency
- ε_{det} – detection efficiency
- L_{samp} – sampled luminosity (time integrated), calibrated by vernier scan
- $\langle\cosh(\eta)\rangle$ - average value of cosh(η) 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



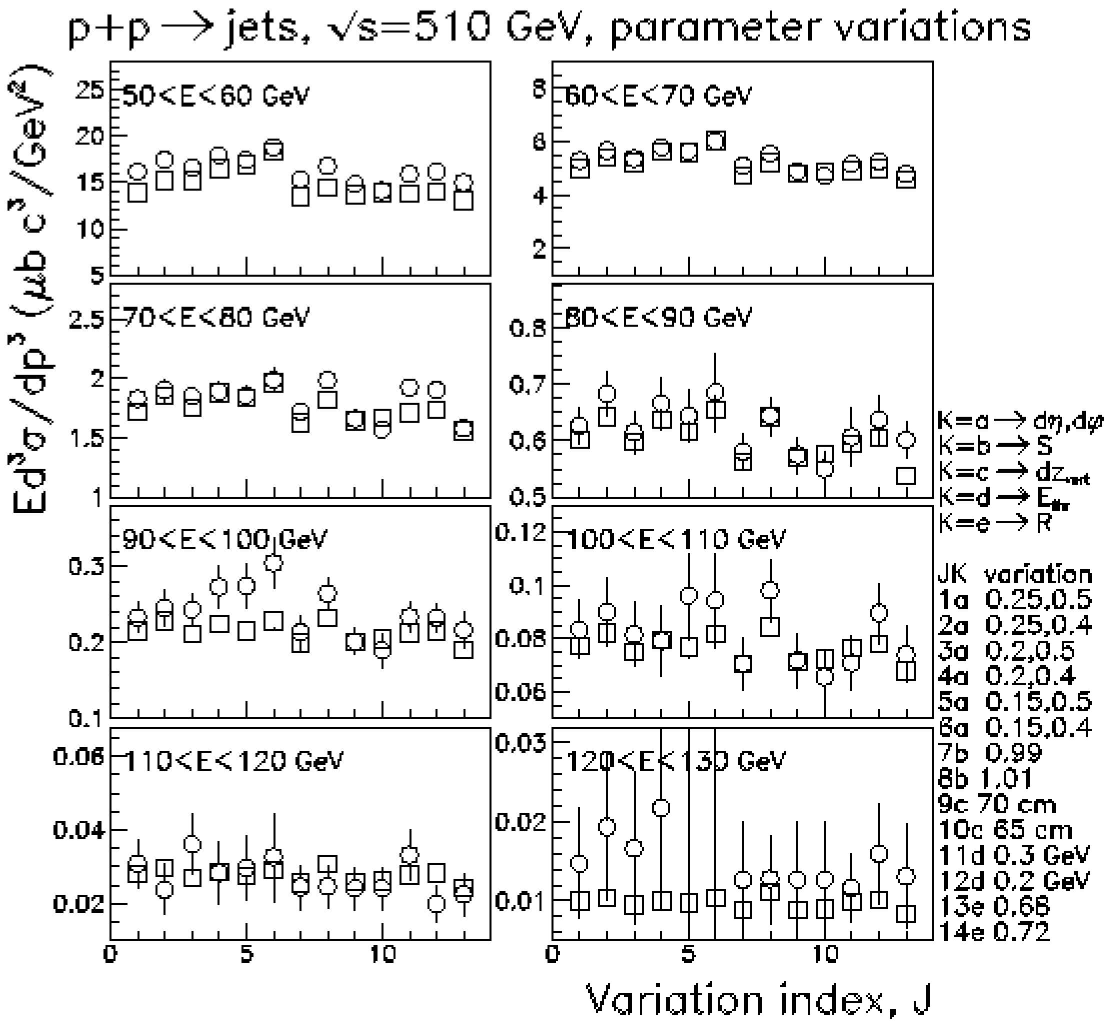
Multiple systematic checks were made for the cross section. This plot shows two:

- 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.

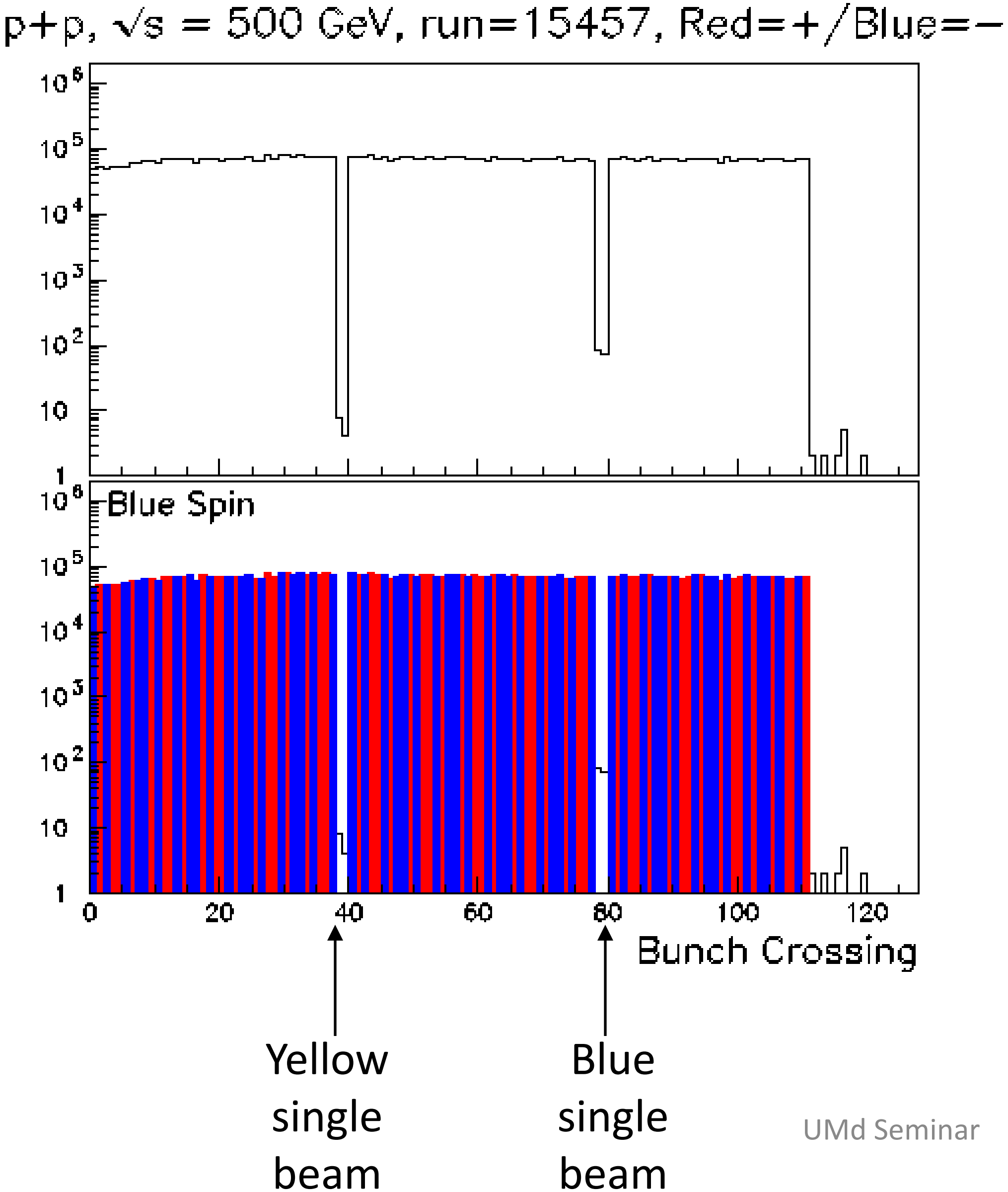
Jet Cross Section-III

Systematic Errors



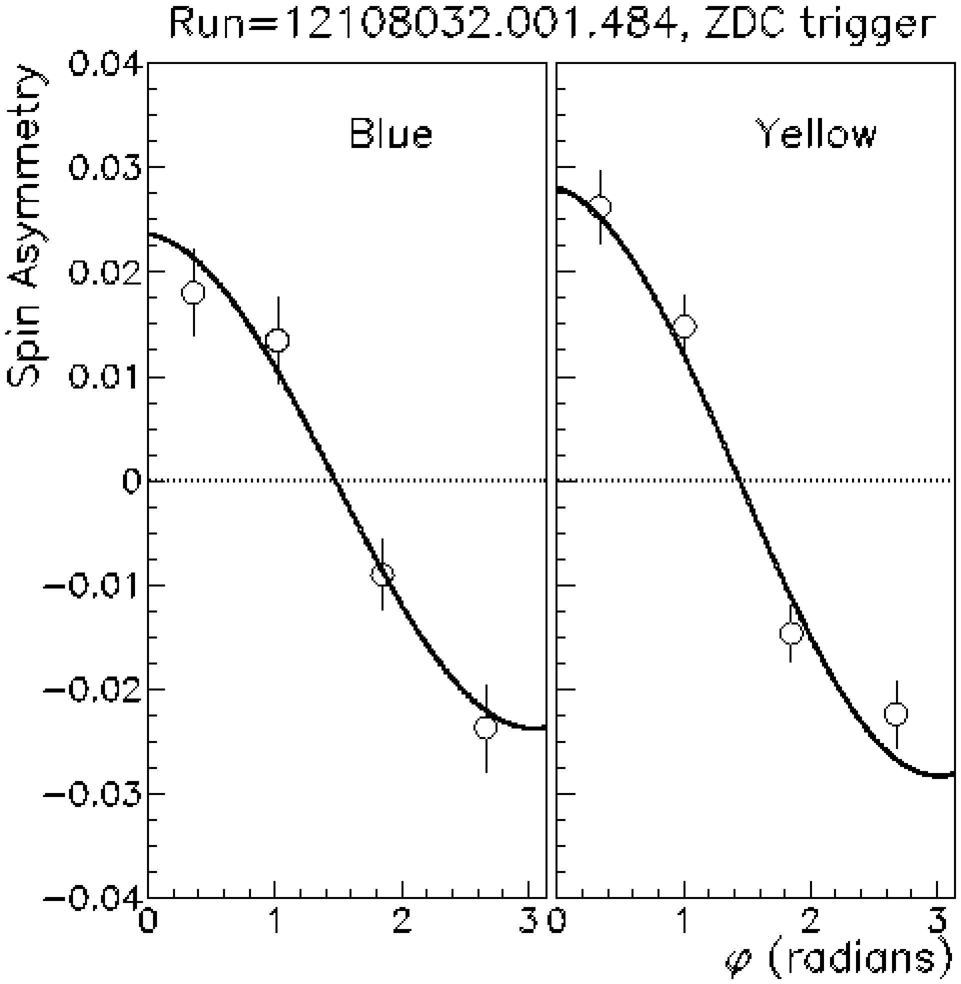
- The stability of the jet cross section was examined as jet-finder (R,Ethr); jet acceptance (dη,dφ); jet energy scale (S) and vertex selection (dz_{vert}) parameters were varied.
- Results with jet triggered (open squares) and minimum-bias triggered (open circles) events are shown.
- Projections of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

Spin Sorting



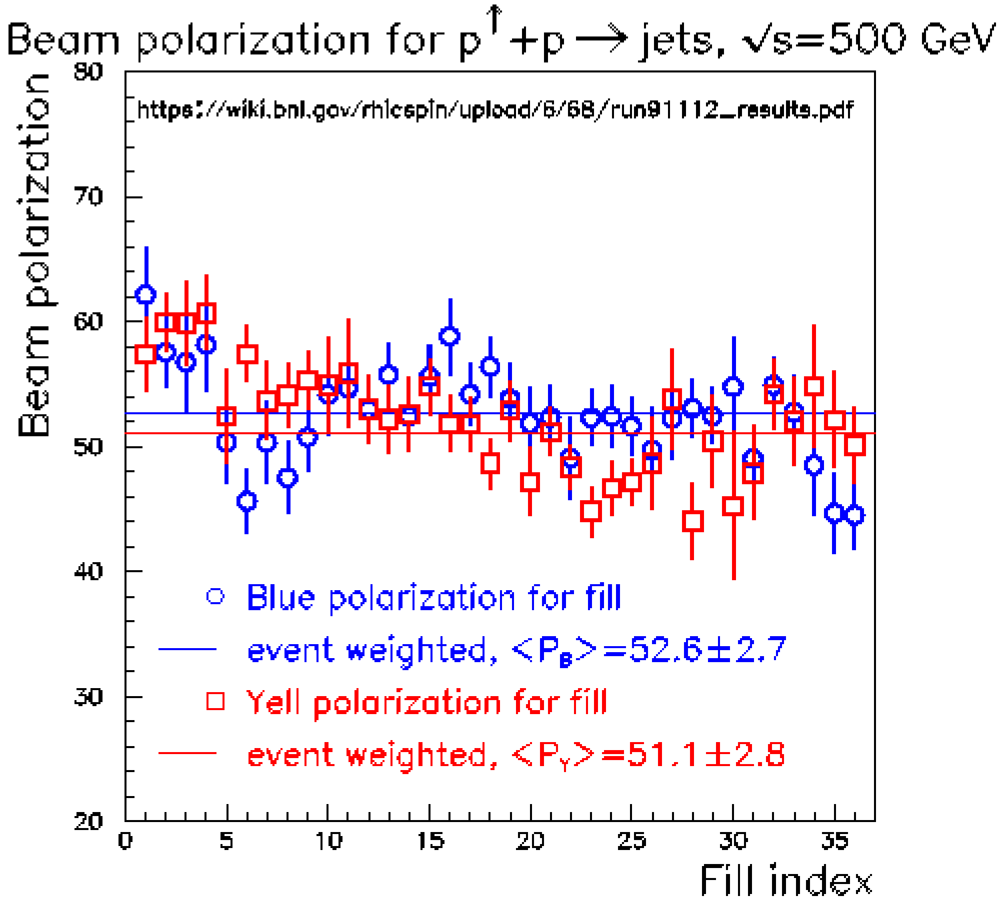
- RHIC has a pattern of polarization directions injected for each fill.
- Polarization for colliding beams is established by counting (C) the 9.38 MHz clock, and identifying specific bunch crossings by B=mod(C,120)
- Polarization pattern for a fill is communicated from the accelerator to the experiments.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

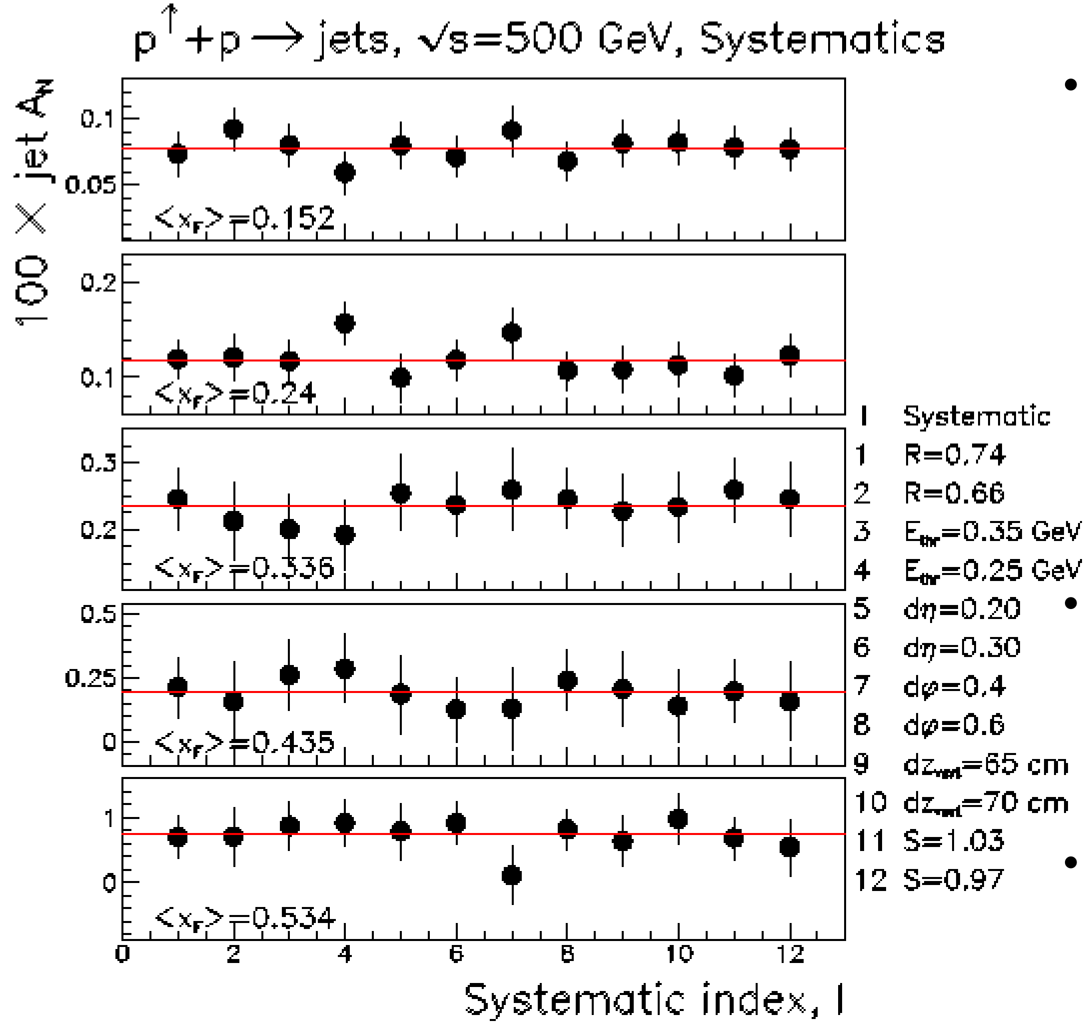
Beam Polarization



- 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

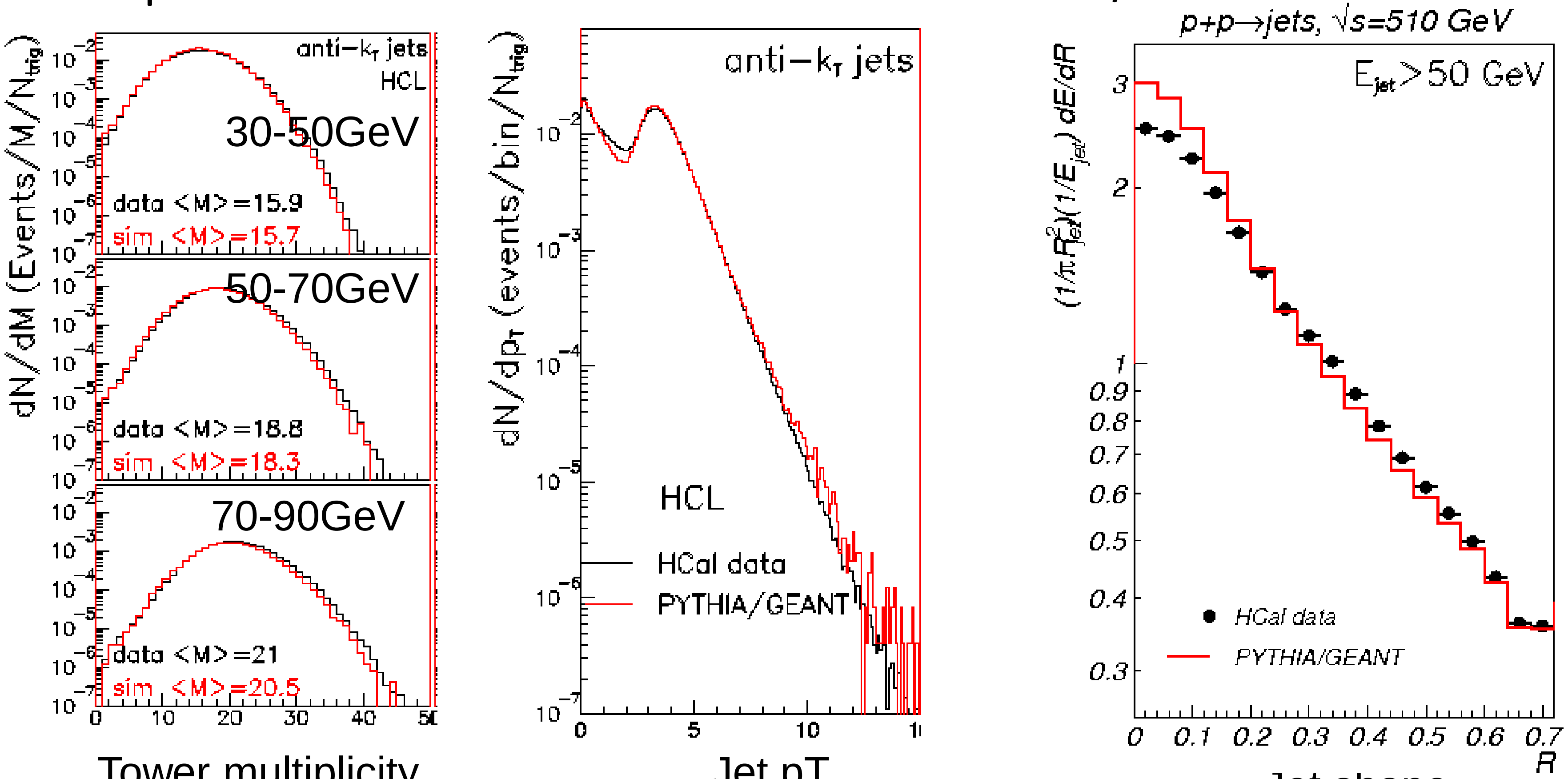


- A_N(jet) exploits mirror (left/right) symmetry of apparatus with spin-↑/spin-↓ of colliding beams, via a cross-ratio…

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

- 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



Tower multiplicity | Jet pT | Jet shape

- 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