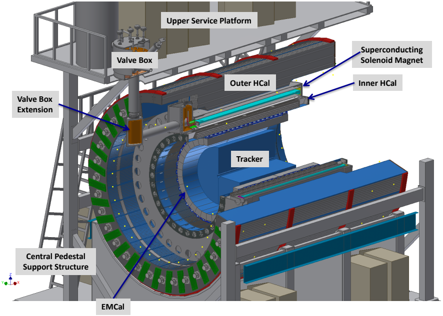
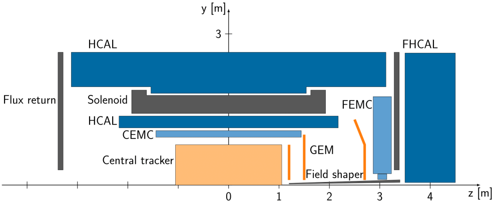
Partonic Structure of Nucleons and Nuclei at sPHENIX

Joe Osborn for the sPHENIX Collaboration

June 20, 2017

sPHENIX Detector



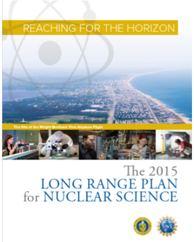


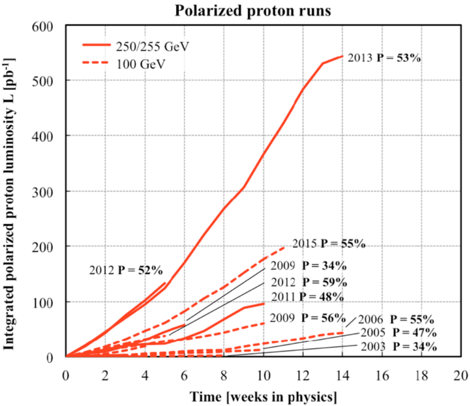
- 2π in azimuth
- $1.3 < \eta < 4$

- 2π in azimuth
- $-1 < \eta < 1$

Why sPHENIX?

"The upgraded **RHIC facility** provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to **explore the spin structure of the proton**."





Dr. T. Hallman at Quark Matter 2017 - U.S. DOE Nuclear Physics "is committed to building sPHENIX"

Complementarity: RHIC and an EIC

- It is necessary to take advantage of RHIC as a hadronic collider before the EIC
- What measurements *require* hadronic collisions?

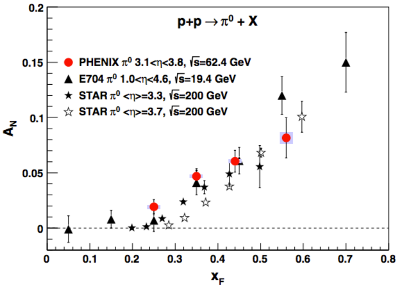
1. Spin-spin and spin-momentum correlation measurements in hadronic collisions
2. Antiquark tagging via Drell-Yan
3. Effects from factorization breaking and color correlations

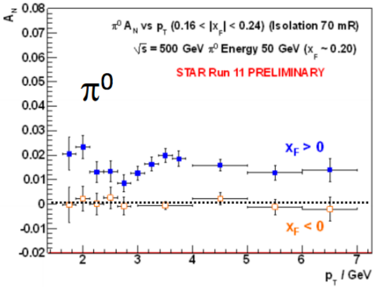
sPHENIX with forward instrumentation will be in an excellent position to measure processes associated with each of these

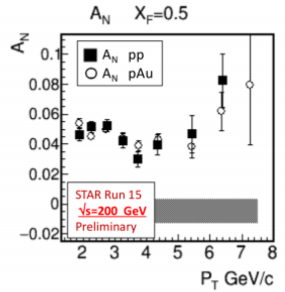
Transverse Single Spin Asymmetries

- Large transverse single spin asymmetries have been measured from $\sqrt{s}$=4.9 GeV up to 500 GeV and 7 GeV/c p_T at $x_F = 0.5$ (!)
- Still an open question as to what physical mechanism(s) is producing the measured asymmetries

Phys. Rev. D 90, 012006 (2014)

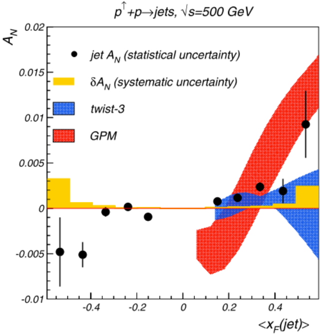




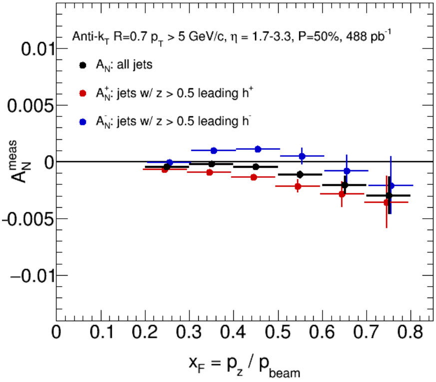


Jet Asymmetry

- AnDY Collaboration measured $\sim$1% jet asymmetries up to $x_F \sim 0.5$ with $\mathcal{L} = 6.5\ \text{pb}^{-1}$
- sPHENIX projects jet measurements up to $x_F \sim 0.75$, with projected $\mathcal{L}$ $\sim$500 pb^{-1} at $\sqrt{s} = 510$ GeV



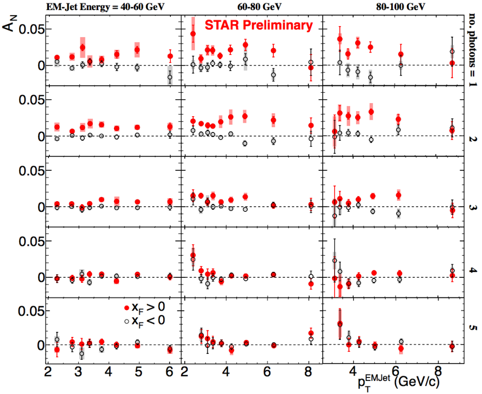
Phys. Lett. B750, 660-685 (2015)



Extending STAR Results

- STAR has many preliminary results correlating the size of the asymmetry with the activity in the vicinity of e.g. the π^0
- Jet reconstruction + tracking will allow for a more global description of events from $-1 < \eta < 3.5$ to better test this interesting observation

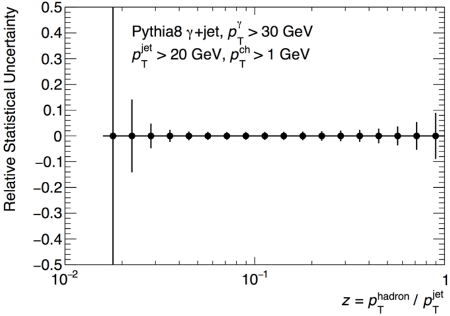
Increasing EM-Jet Energy $\rightarrow$



Increasing number of γ $\downarrow$

Hadronization

- With tracking capabilities covering $-1 < \eta < 3.5$, dedicated studies to hadronization are possible
- Can additionally include spin to probe final-state spin-spin and spin-momentum correlations



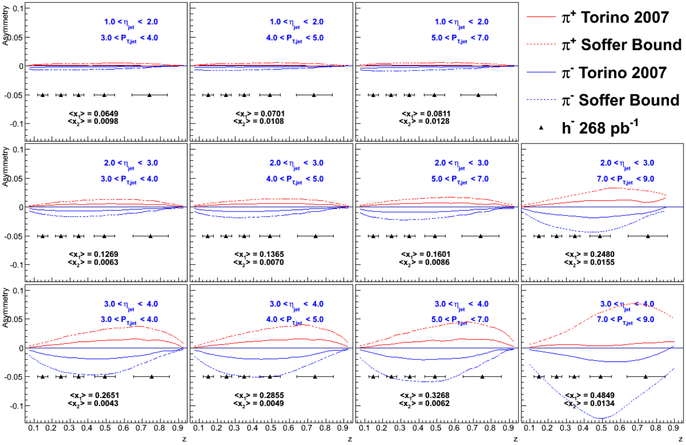
Hadrons within Jets: Transversity

Increasing p_T^{jet} $\rightarrow$

Increasing

η_{jet}

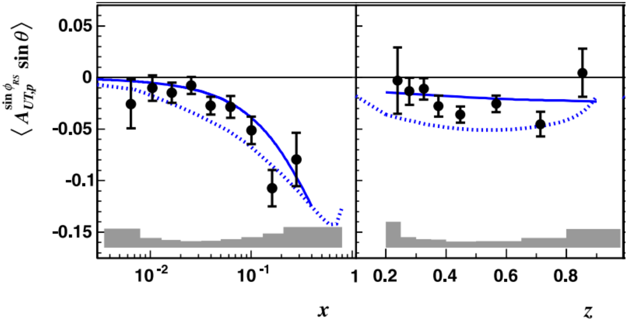
$\downarrow$



- Forward sPHENIX allows jet reconstruction for $x \sim 0.5$ at $\sqrt{s} = 510$ GeV
- Excellent projected statistical precision over large range of x and z

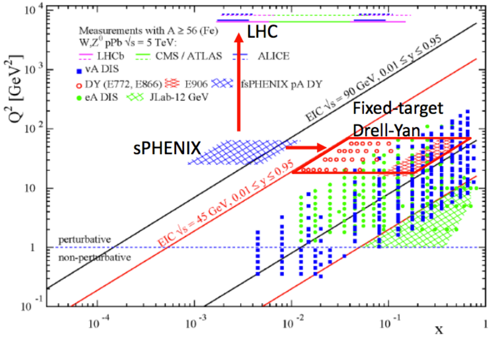
Hadrons within Jets

- Full jet reconstruction will, for the first time, allow *direct* comparisons to SIDIS and e^+e^- asymmetries!
- At LO can determine z and Q^2 for asymmetry measurements which will allow this
- For example, one could imagine analogous plots to COMPASS for transversity $\otimes$ Collins FF in hadronic collisions



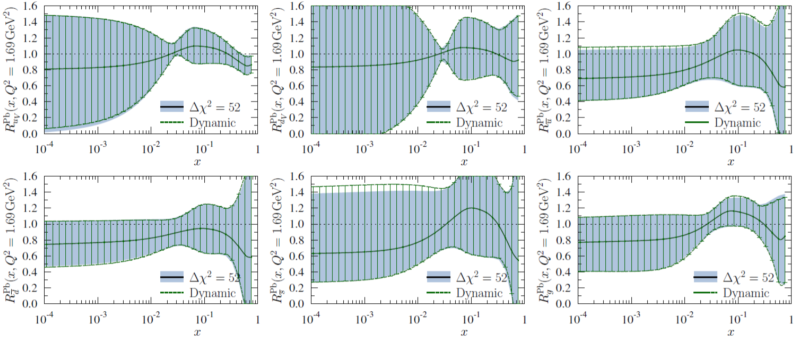
Phys. Lett. B713, 10-16 (2012)

Drell-Yan in p+Au



- Forward sPHENIX occupies unique phase space for Drell-Yan production
- Similar x with LHC experiments, similar Q^2 with FNAL fixed target
- Allows for a true controlled test of x and Q^2 evolution
- Also reaches lower x than the EIC in this particular Q^2 range!

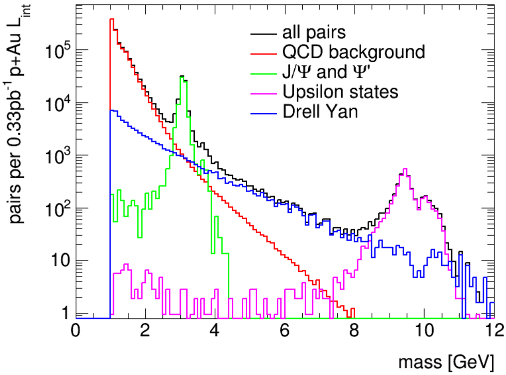
Drell-Yan in p+Au



Eur. Phys. J., C77(3): 163 (2017)

- Necessary before EIC - explicit tagging of antiquarks!
- Nuclear PDFs of antiquarks unconstrained
- Will allow cleaner studies of how the nucleus modifies hadronization at the EIC

Drell-Yan Performance



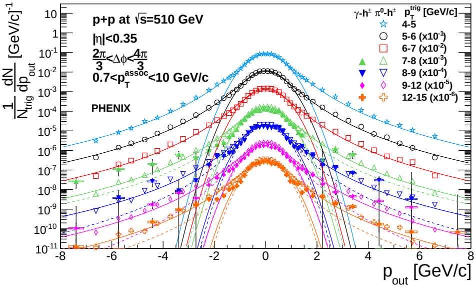
- Drell-Yan performance simulated with PYTHIA6 and full implementation of sPHENIX detector in GEANT4
- Given 0.33 pb^{-1} of integrated p+Au luminosity, expect $\sim$2900 Drell-Yan pairs (and more in $p+p$ with $\sim$ 200 pb^{-1}!)
- Excellent signal-to-background in 5-8 GeV/c^2 region after implementation of cuts

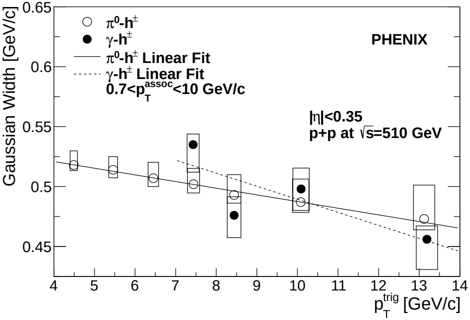
Color in Hadronic interactions

- Effects due to color in initial and final states are now being probed experimentally
- Unique to hadronic interactions! Necessary to study before the EIC!
- Experimental observables now probing *global* QCD event structure (not just $2 \rightarrow 2$ hard scattering!)
- sPHENIX will be the ideal facility at RHIC to study:
  - Factorization breaking in $p+p$ and $p+$A collisions
  - High multiplicity $p+p$ and $p+$A events
  - Color coherence similar to the LHC and Tevatron

Factorization Breaking at PHENIX

- Measure p_{out} nonperturbative momentum widths as a function of p_T^{trig}
- Perturbative transverse-momentum-dependent (TMD) evolution, which comes directly from the TMD QCD factorization theorem, predicts increasing momentum widths with hard scale of interaction
- PHENIX measures decreasing nonperturbative transverse momentum widths



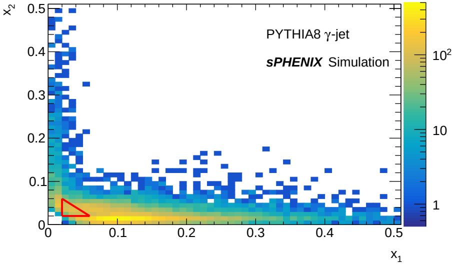


Phys. Rev. D 95, 072002 (2017)

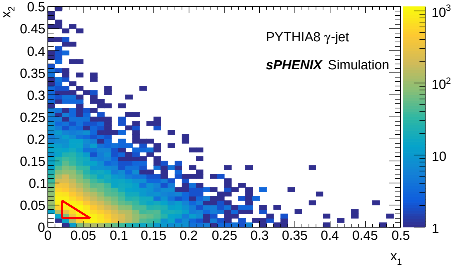
Factorization Breaking

- Specific nonAbelian effect - probing QCD interactions
- γ−jet is the ideal channel to measure effects - limits color flow possibilities with sensitivity to only k_T
- Central-forward (top) and central-central (bottom) γ-jet x_1,x_2 reach at $\sqrt{s} =$ 510 GeV. Red triangle indicates x_1-x_2 reach of PHENIX work

Central-Forward γ-jet

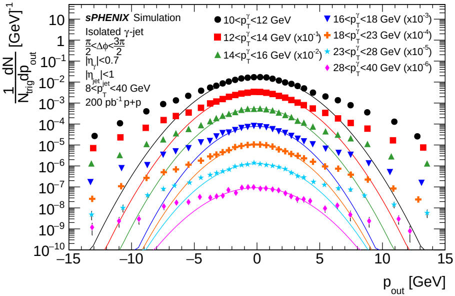


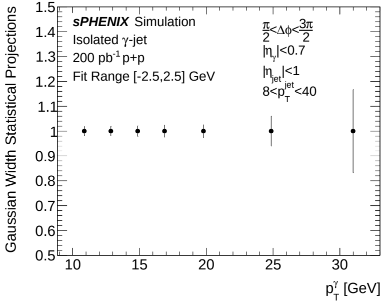
Central-Central γ-jet



Estimated γ-jet Statistical Precision

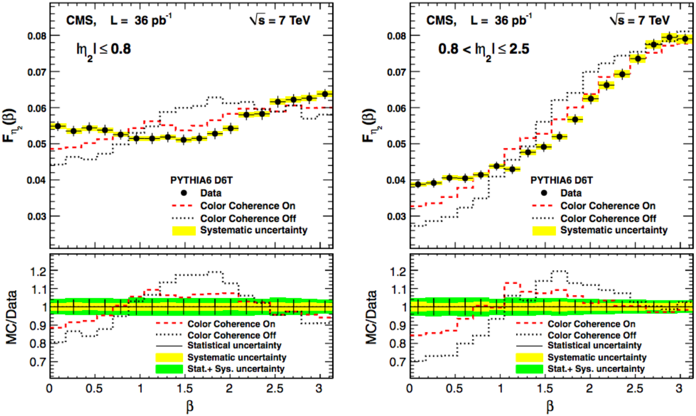
- Dedicated study for statistical estimates given luminosity, efficiency of sPHENIX
- sPHENIX will have incredible statistical precision for γ-jet at RHIC *for the first time*
- Will extend PHENIX factorization breaking work PRD 95, 072002 (2017) to study x dependence as well as role of fragmentation with tracking capabilities





Color Coherence Studies

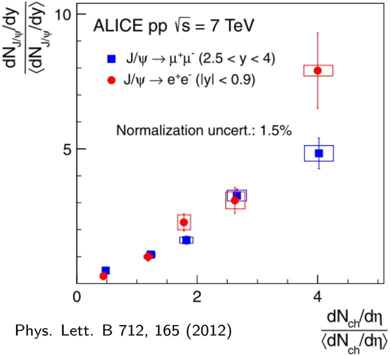
- Color coherence studies performed at the LHC and Tevatron
- RHIC offers potential to study effects from color at lower $\sqrt{s}$
- sPHENIX can study effects in central and forward regions, where effects from color have been measured to be stronger



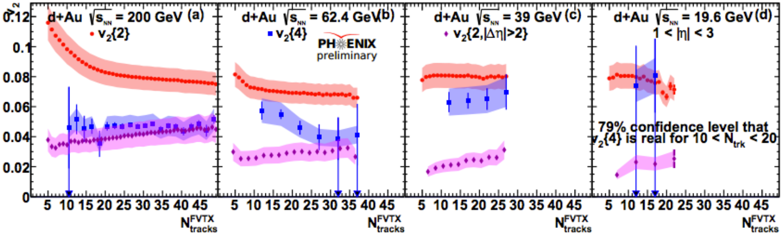
Eur. Phys. J C74:2901 (2014)

High Multiplicity Studies at RHIC

- Surprising results from RHIC and the LHC show novel phenomena in high multiplicity p+p and p+A
- Long range $\Delta\eta$ correlations have been measured in p+p to track multiplicities as low as 40-50!
- sPHENIX will be in a unique position due to its large, continuous acceptance and high-rate trigger



Phys. Lett. B 712, 165 (2012)

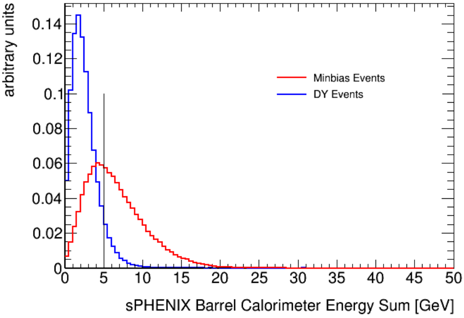


Conclusions

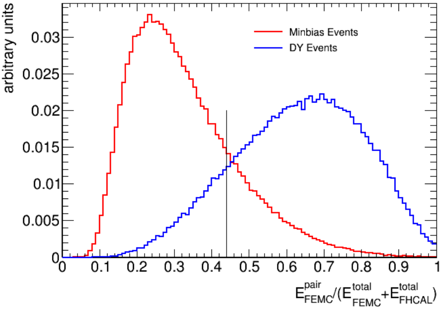
- The sPHENIX detector has been designed as a high-rate jet and tracking detector, providing an optimal ground to study proton structure
- sPHENIX with forward instrumentation physics program is complementary to the EIC - necessary to probe physics specific to hadronic interactions
- In particular sPHENIX with forward instrumentation will be in an excellent position to measure
  - Transverse spin-spin and spin-momentum correlations
  - Drell-Yan in $p+p$ and $p+$Au
  - Effects from color in hadronic interactions
- sPHENIX LOI for forward instrumentation recently submitted to BNL: https://www.sphenix.bnl.gov/web/node/450

Back Up

Drell-Yan Cuts



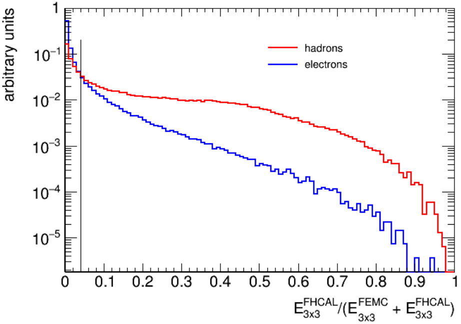
- Barrel energy required to be small



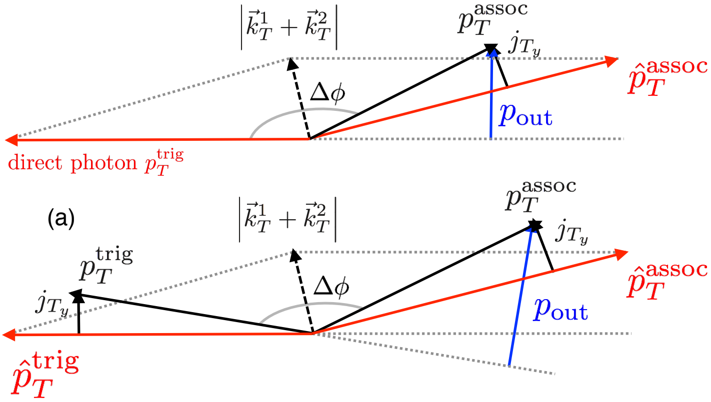
- Energy in forward region required to be mostly from the DY pair

Drell-Yan Background Fraction

- Drell-Yan events are identified using event cuts on previous page as well as tight cuts on the single $e^{\pm}$ and $e^{\pm}$ pair
- QCD background is estimated via a triggered and anti-triggered sample
- Dominant background comes from conversions, Dalitz decays. Heavy flavor is a small contribution



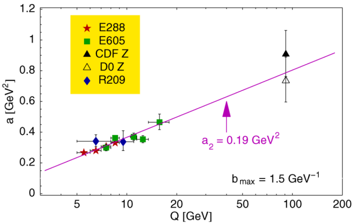
p_{out} and Correlations

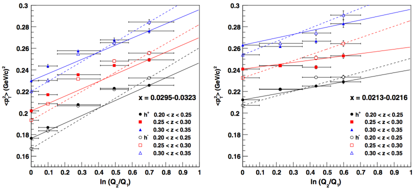


Expectations from Collins-Soper-Sterman (CSS) Evolution

- Expectation from CSS evolution is that any momentum width sensitive to nonperturbative k_T grows with the hard scale
  - Broadening due to increased phase space for hard gluon radiation
- Note that the CSS evolution equation comes directly out of the derivation for TMD factorization
- Phenomenological studies have shown that DY/Z and SIDIS follow this expectation

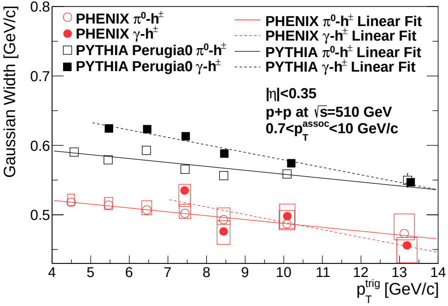
Phys. Lett. B 633, 710 (2006) (DY/Z)





Phys. Rev. D 89, 094002 (2014) (SIDIS)

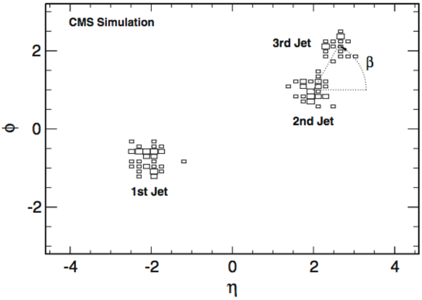
Gaussian Widths with a PYTHIA Simulation



- Gaussian widths of p_{out} distributions also decrease with hard scale p_T^{trig}
- Sensitive to *only* nonperturbative k_T and j_T in the nearly back-to-back region $\Delta\phi \sim \pi$
- PYTHIA replicates slope almost exactly, but shows 15% difference in magnitude of widths

Color Coherence Definition of β

Eur Phys. J C74:2901 (2014)

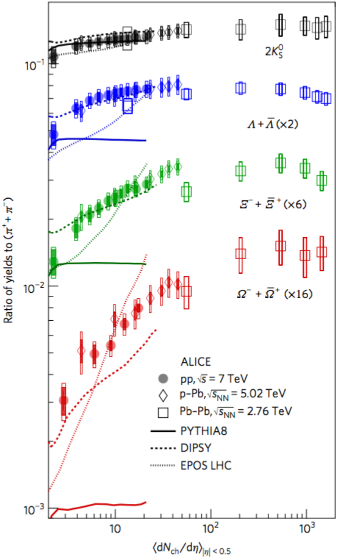


$$\tan\beta = \frac{|\Delta\phi_{23}|}{\Delta\eta_{23}}$$

- β is defined as the angle in η,ϕ space between the second leading jet and third jet
- Third jet is due to hard gluon radiation
- Color coherence effects should be larger at $\beta \sim$0,π
- i.e. studying interactions of hard scattering with beam remnants

- Additional references: Phys. Rev. D 50, 5562 (1994), Phys. Lett. B 414, 419 (1997)

Other High Multiplicity Results

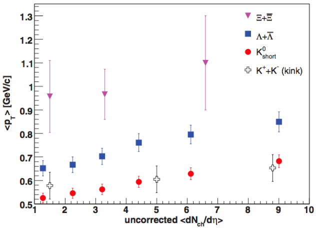


Nature Physics 13, 535-539 (2017)

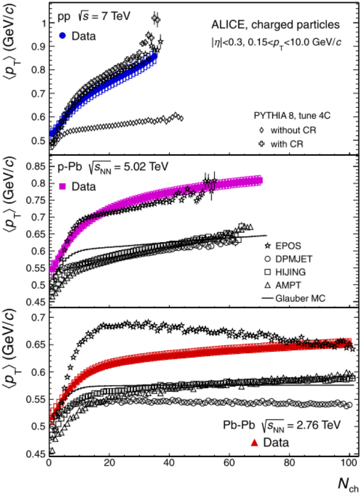
- Strangeness enhancement in high multiplicity $p+p$ and $p+$A!
- Once thought to be a signature of the QGP, now measured in $p+p$...?
- Hydrodynamics? Color connections? Something else?

Other High Multiplicity Results

- $\langle p_T \rangle$ increase per-particle at RHIC and LHC
- Feature can be reproduced in PYTHIA "only if a mechanism of hadronization including color correlations (reconnections) is considered" (PLB 727, 371 (2013))

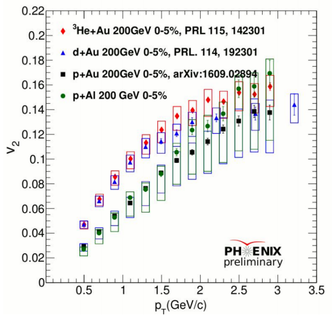


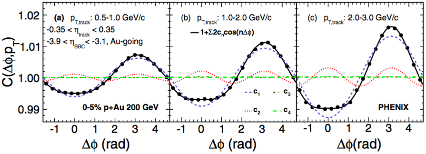
Phys. Rev. C 75,064901 (2007)



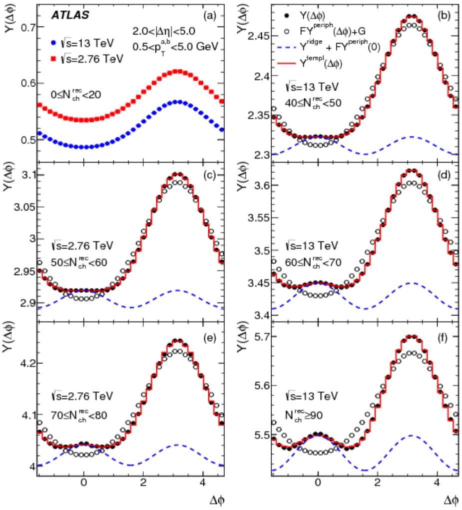
Phys. Lett. B 727, 371 (2013)

Other High Multiplicity Results





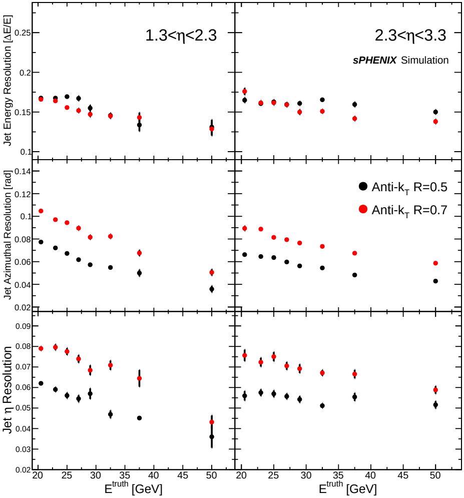
Phys. Rev. C95, 034910 (2017)



Phys. Rev. Lett. 116, 172301 (2016)

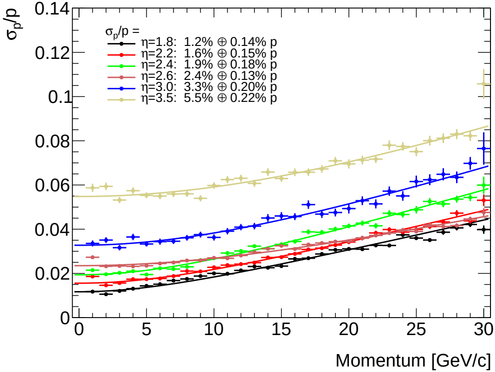
Forward sPHENIX Jet Response

- Jet response determined with PYTHIA8 and full GEANT4 simulation of forward sPHENIX detector
- Response at $\sqrt{s} = 510$ GeV under good control



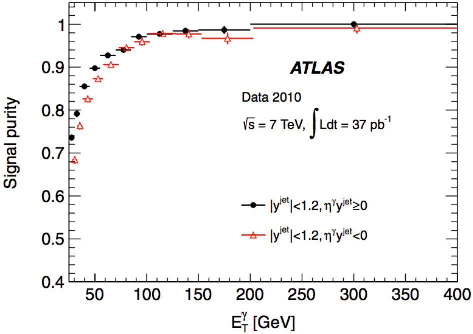
Forward sPHENIX Tracking Resolution

- Tracking resolution determined with the full GEANT4 simulation of forward tracking
- Tracks reconstructed with a GenFit2-based Kalman filter fit (J. Phys. Conf. Ser., 608(1):012042, 2015)



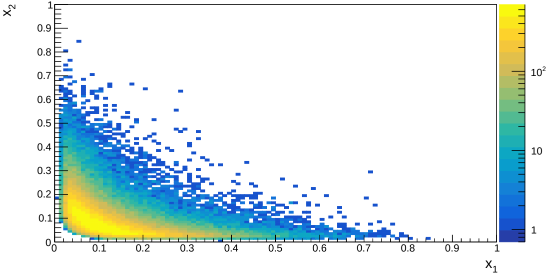
γ-jet Signal Purity

- Using ATLAS Phys. Rev. D 85, 092014 (2012) as an example
- Measure isolated γ+jets
- Reach signal purity of $\sim$ 95% by $x_T = 2E_T/\sqrt{s} = 2 \times 100/7000 \approx 0.03$
- For RHIC energies this x_T corresponds to $E_T \approx 3$ GeV, so at $E_T^{\gamma} >$10 GeV we could expect to have very high signal purity



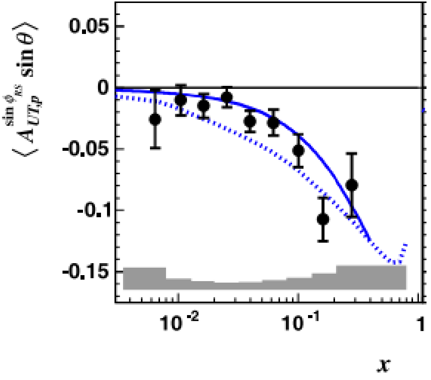
Dijet Correlations

- Dijet correlations provide full $2 \to 2$ event reconstruction at LO
- Can be used to probe a number of different physics effects
- Will have access to huge range of x_1 and x_2 at $\sqrt{s}$ =200 GeV from $-1 < \eta < 3.5$ with central-central and central-forward correlations



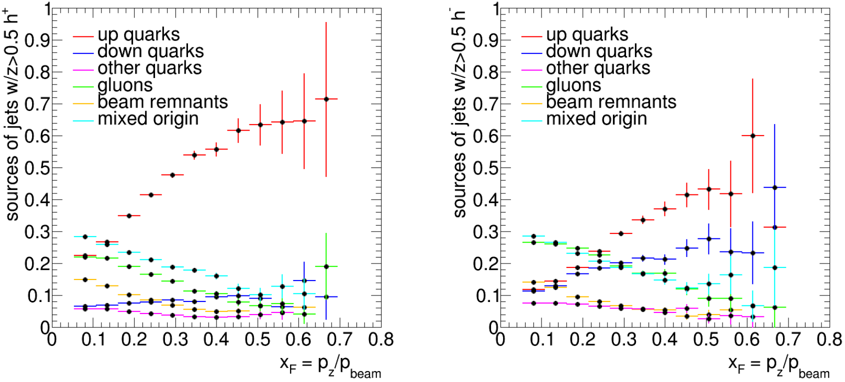
Hadrons within Jets: Transversity

- Current measurements from SIDIS constrain transversity up to $x \sim 0.3$
- Can measure transversity coupled with Collins fragmentation function at RHIC
- Will provide constraints at higher x

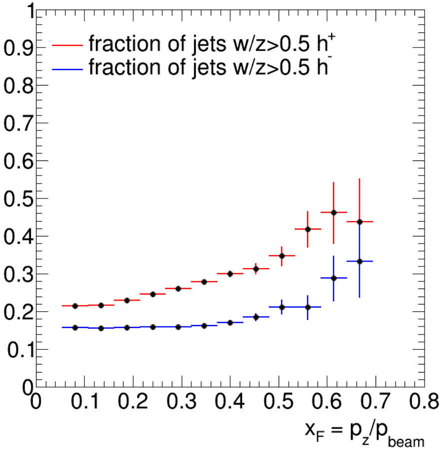


Phys. Lett. B713, 10-16 (2012)

Jet Sources with Leading Hadron Cuts



- Jet sources with leading charge tagged hadron from PYTHIA6



- Fraction of jets which have a large z leading hadron