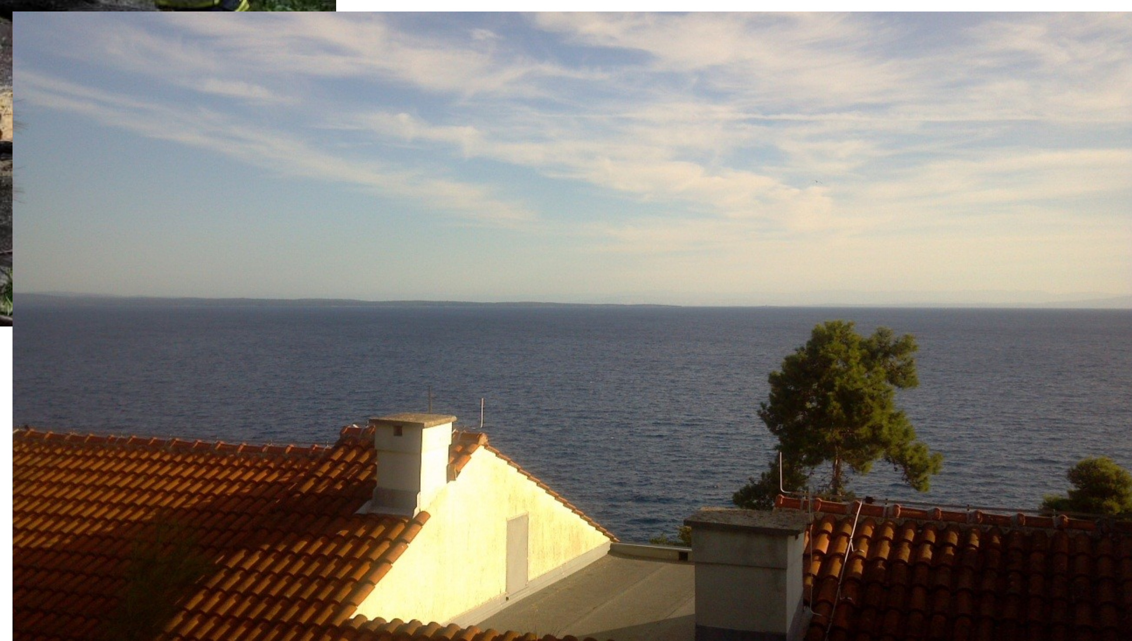
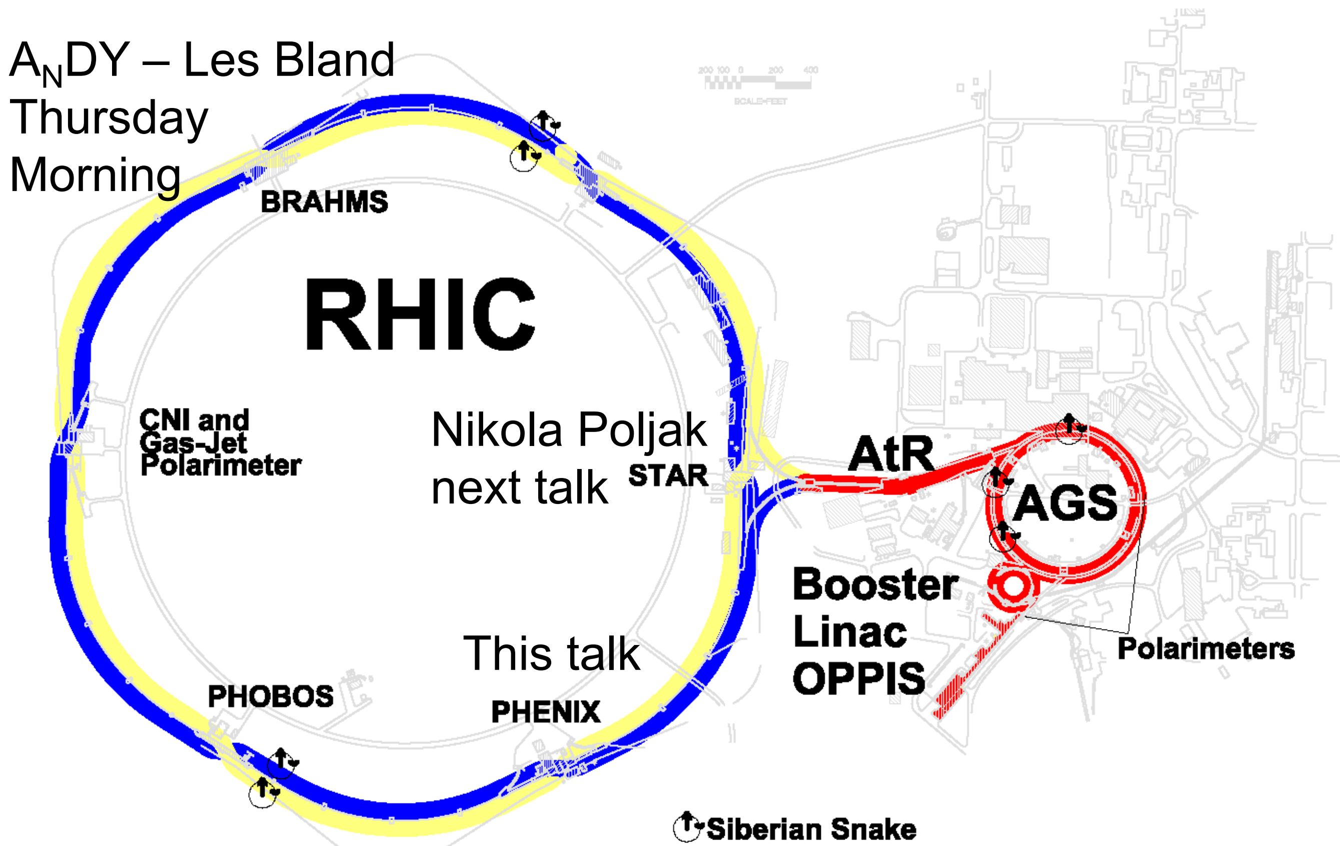
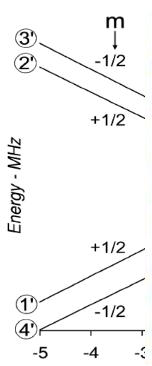
PHENIX results and perspectives on transverse spin asymmetries

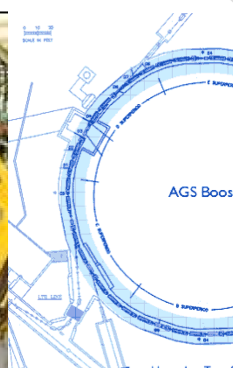


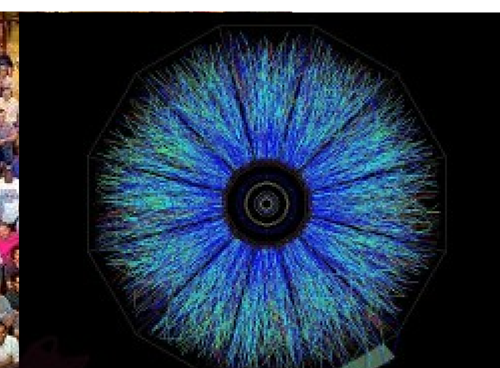
John Koster
for the PHENIX collaboration
RIKEN BNL Research Center
Transversity 2011
2011/08/31

Relativistic Heavy Ion Collider (RHIC)

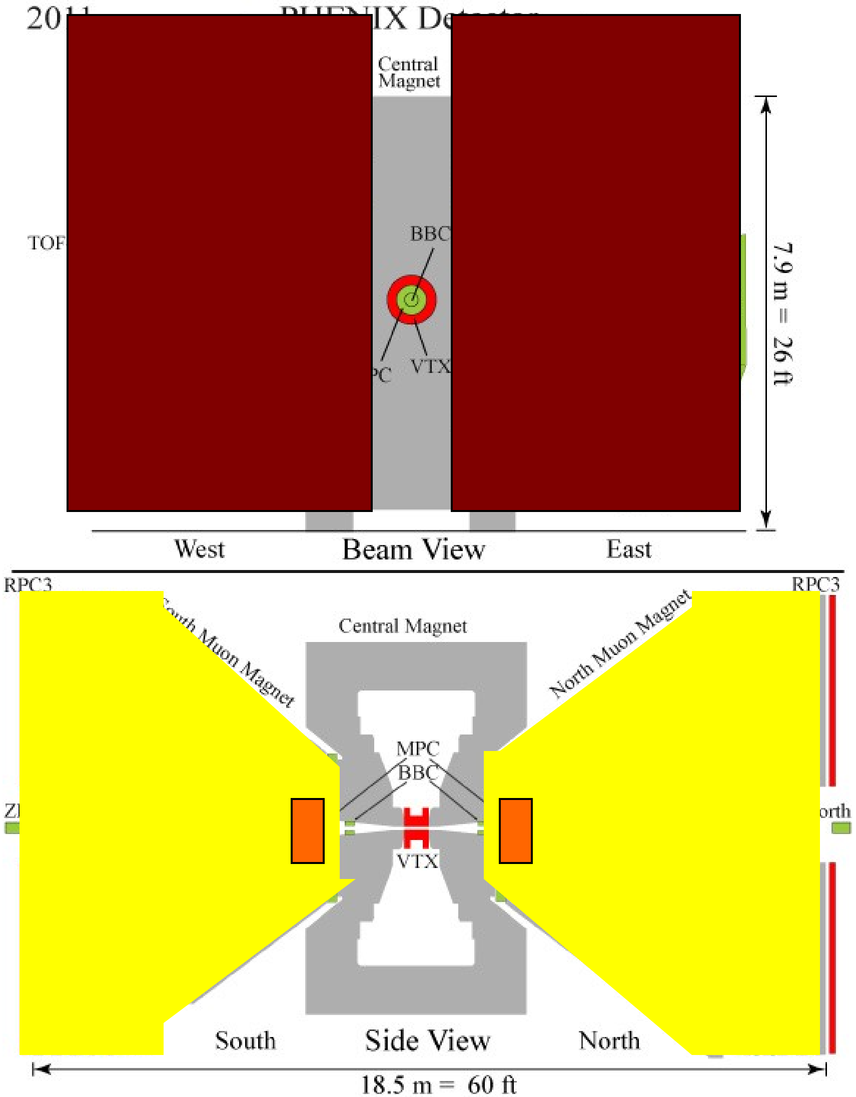








PHENIX Detector at RHIC



Central Arms $|\eta| < 0.35$
- Identified charged hadrons
- π^0, η
- Direct Photon
- J/Ψ
- Heavy Flavor

Muon Arms $1.2 < |\eta| < 2.4$
- J/Ψ
- Unidentified charged hadrons
- Heavy Flavor

MPC $3.1 < |\eta| < 3.9$
- π^0, η

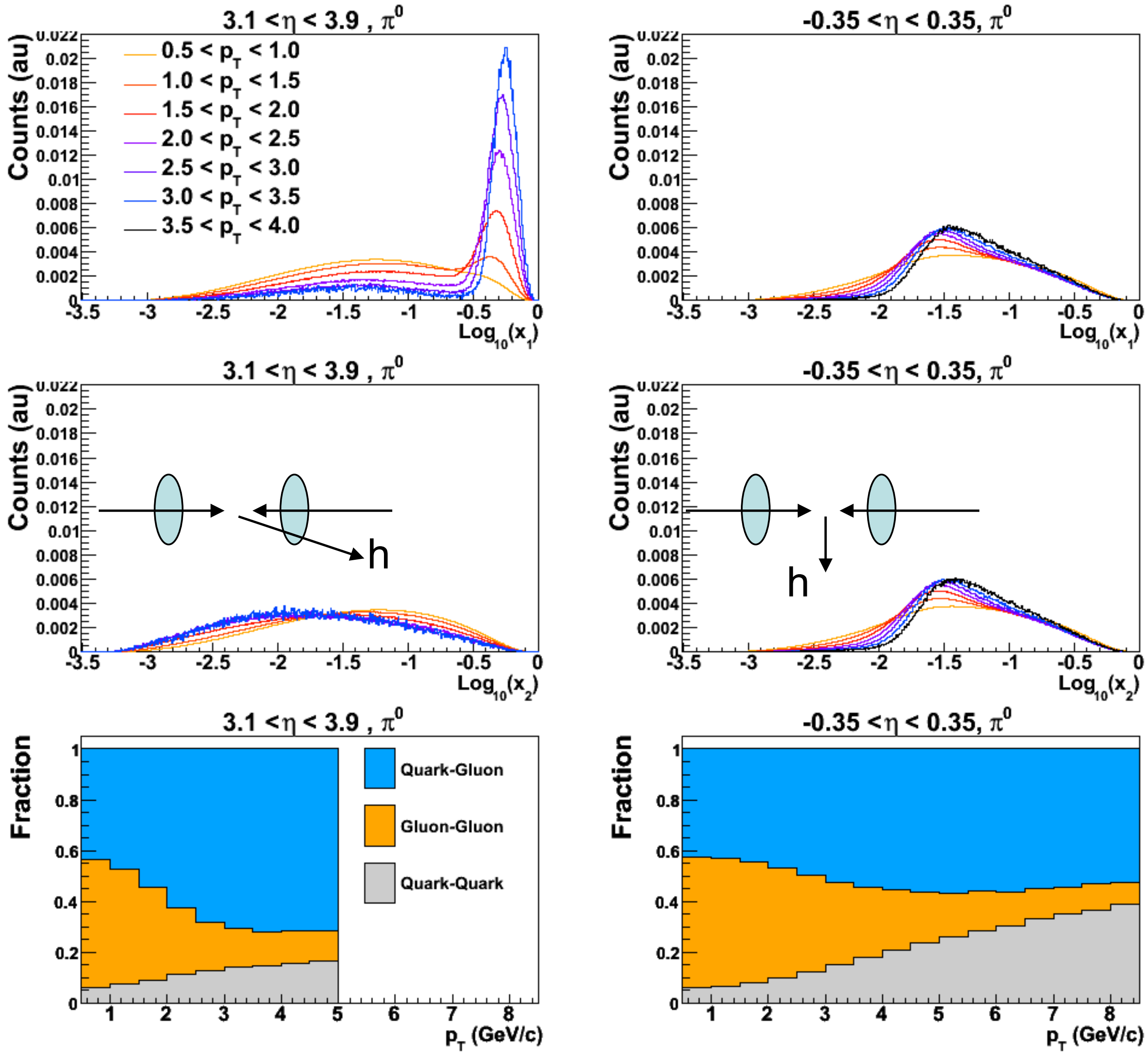
Underlying Event Kinematics of p-p Scattering at $\sqrt{s}$=200 GeV

- Estimated with Pythia simulation package
- Mid-rapidity:

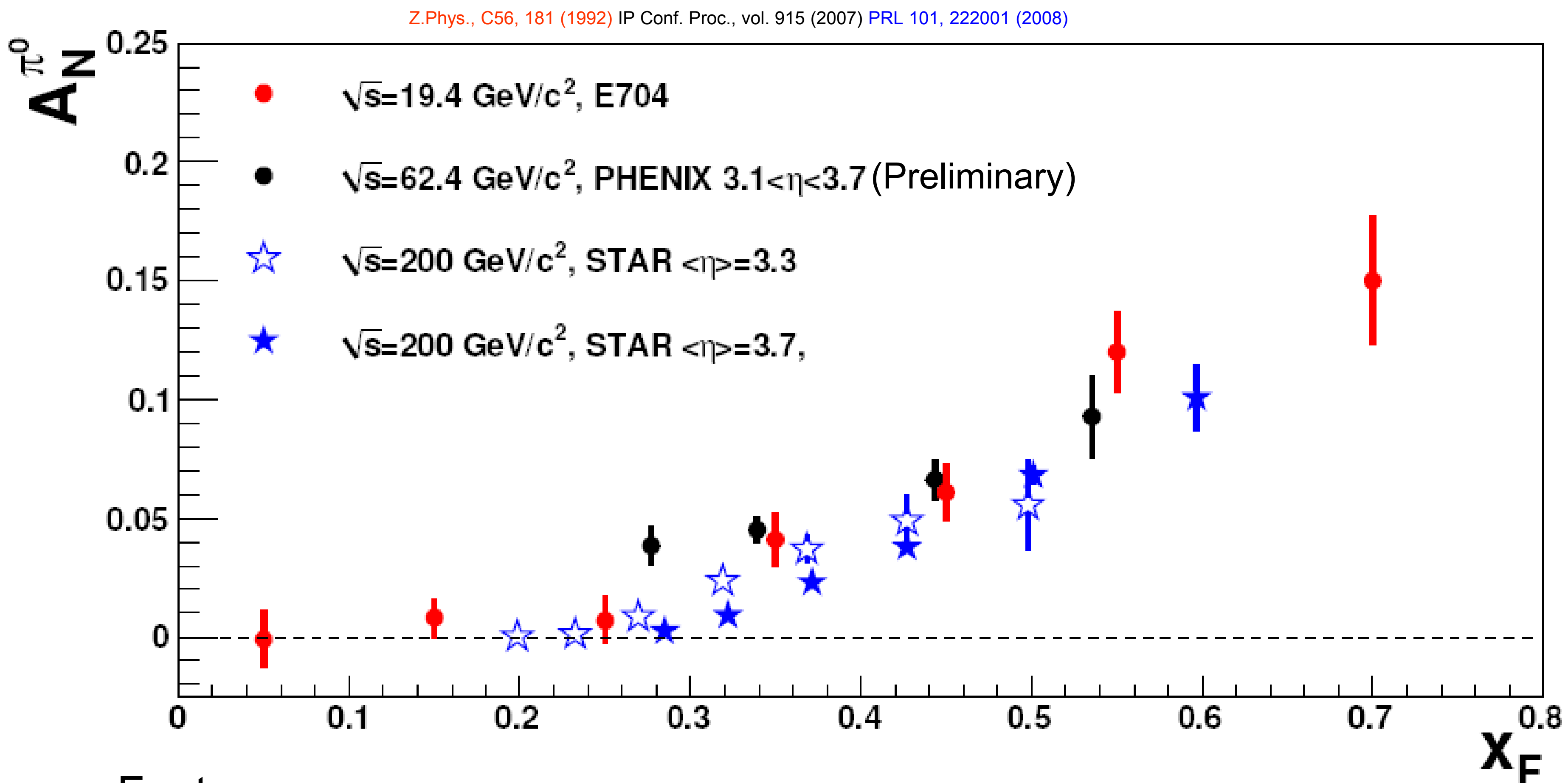
Low p_T dominated by gluon gluon scattering

- Forward-rapidity

High-x + Low-x scattering



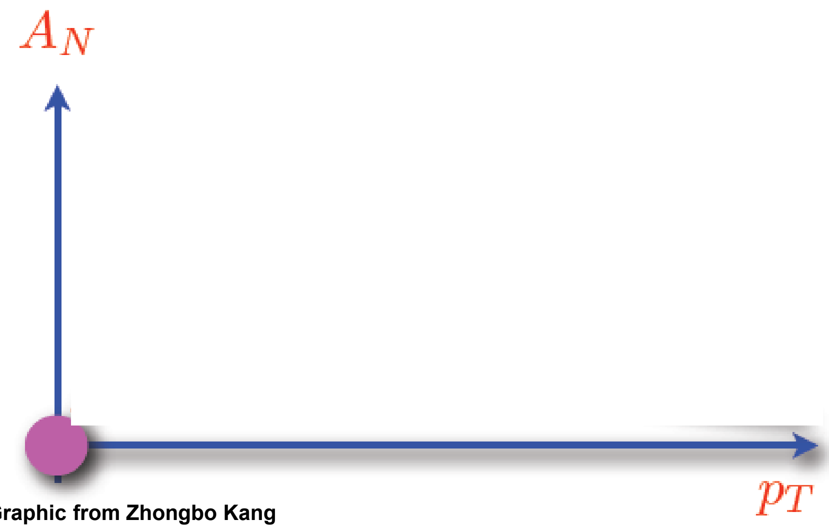
Single Transverse Spin Asymmetries in pp Collisions



Features:

- Forward non-zero asymmetries.
- Asymmetries consistent over an order of magnitude in √s.
- Several theoretical frameworks to explain the results.

Transverse Spin Effects in p↑p Collisions



Graphic from Zhongbo Kang

(III) Higher-twist effects

Twist-3 quark-gluon/gluon-gluon correlators

Expectation: at large p_T, $A_N \sim 1/p_T$

So far, fall-off with p_T has not been observed!

(I) Transversity quark distributions and Collins fragmentation function

Correlation between proton & quark spin + spin dependant fragmentation function

$$\propto \underbrace{\delta q(x)}_{\text{Quark transverse spin distribution}} \cdot \underbrace{H_1^{\perp}(z_2, \bar{k}_{\perp}^2)}_{\text{Collins FF}}$$

J. C. Collins, Nucl. Phys. **B396**, 161 (1993)

(II) Sivers quark-distribution

Correlation between proton-spin and transverse quark momentum

$$\propto \underbrace{\bar{f}_{1T}^{\perp q}(x, k_{\perp}^2)}_{\text{Sivers distribution}} \cdot D_q^h(z)$$

D. Sivers, Phys. Rev. D **41**, 83 (1990)

Neutral Pion Cross-Sections Experiment vs pQCD

PHENIX

New PHENIX Result with Forward π^0's at $\sqrt{s}$=200 GeV

Close agreement with charged pions from BRAHMS.

PHENIX Measurement Strategy

PHENIX

1. A_N Measurements
   - Sensitive to combinations of all three effects
   - At forward and mid rapidity
2. Sivers Measurements (skipped for time)
   - Heavy flavor
   - Back to back hadrons
3. Transversity Measurements
   - Interference Fragmentation Function
   - Collins in Jets
4. sPHENIX – Future rebuilt PHENIX detector with significantly enhanced capabilities.
   - Planned turn-on ~ 2015/2016
   - New exciting physics will become available

Will be done with baseline PHENIX detector.

Existing transverse dataset: ~ 8 pb^{-1}

Projected luminosity for 2012+2013: 33 pb^{-1} and improved polarization.
→Projected error bars are interspersed throughout talk.

(i) Muon Piston Calorimeter A_N

PHENIX's forward electromagnetic calorimeter

Enables A_N measurements for π^0 and η mesons.

Photon merging effects prevent two-photon π^0 analysis for E>20 GeV (p_T>2 GeV/c)

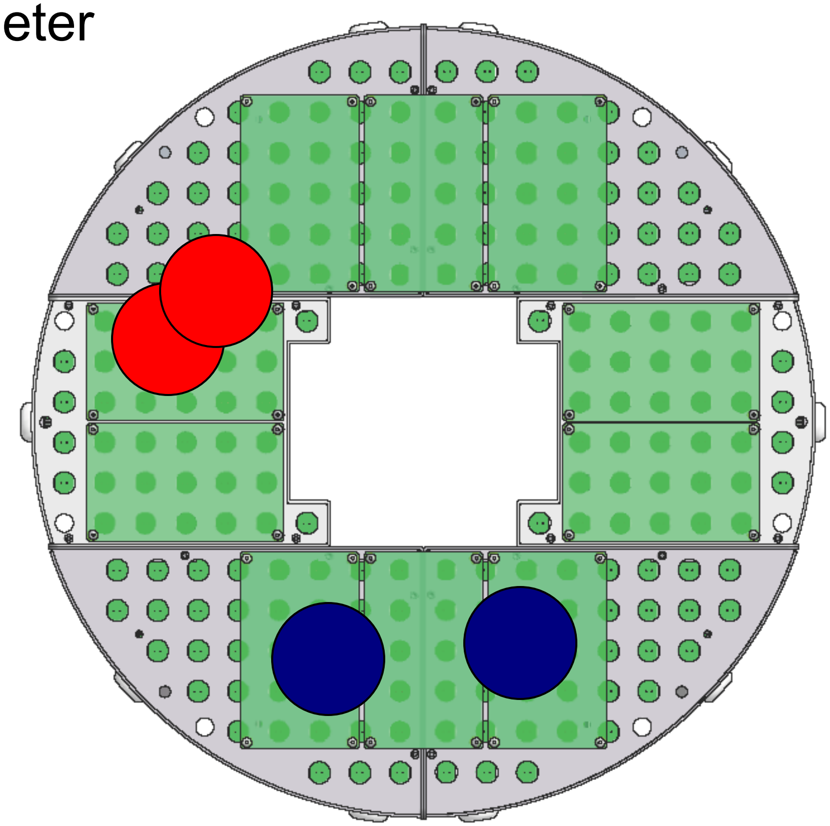
62 GeV

20 GeV → 0.65 x_F:Two-photon π^0 analysis

200 GeV

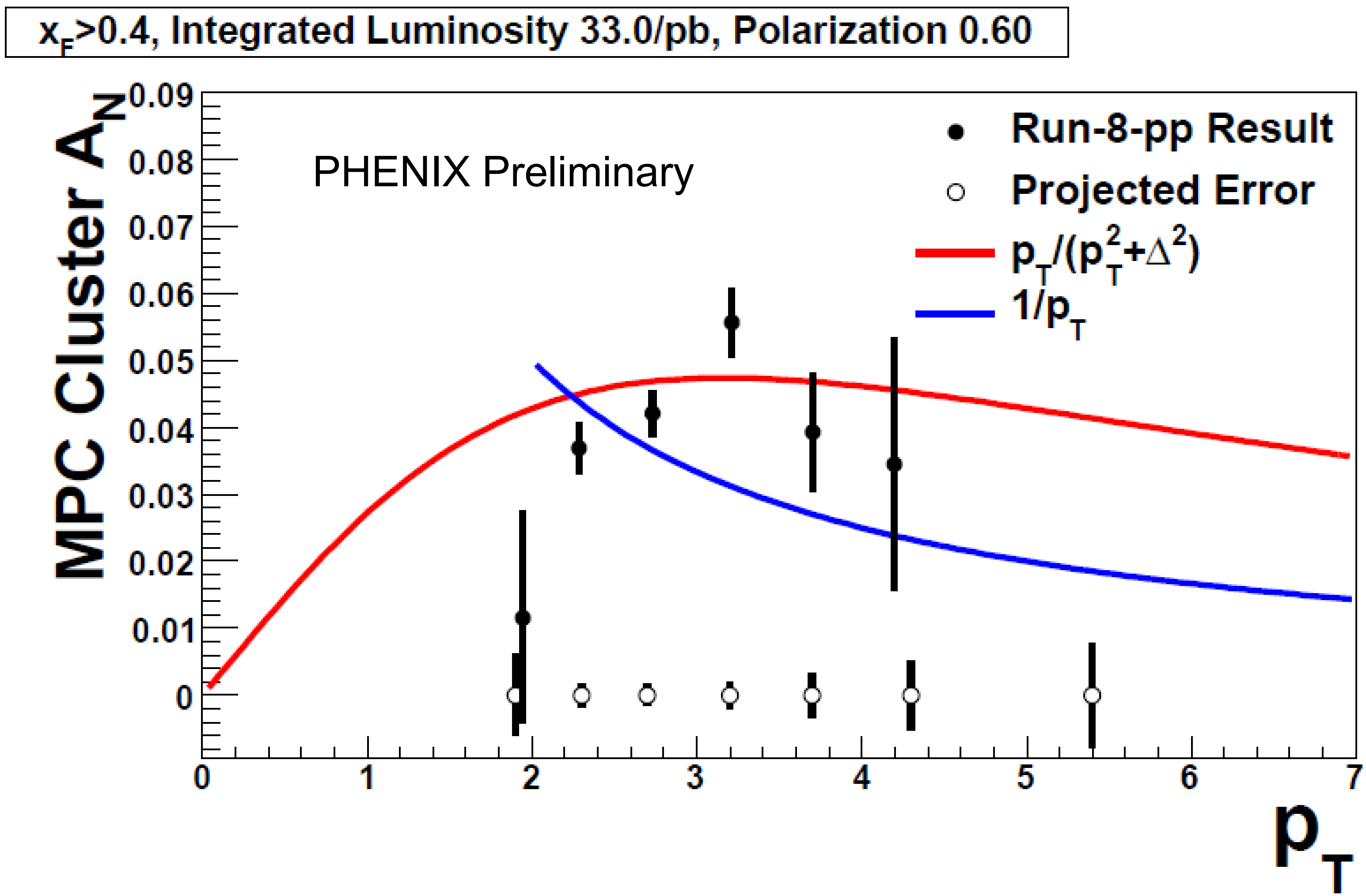
20 GeV → 0.20 x_F : "Single clusters". Yields dominated by π^0's but also get contributions from:

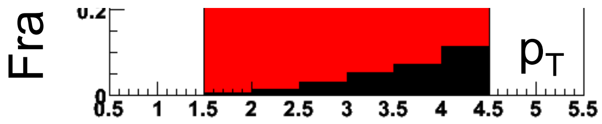
- **Electromagnetic**
  - Direct photons
  - Decay photons (η, etc)
  - Estimated using Pythia (TuneA)
- **Hadronic: ($\pi^{+/-}$, $K^{+/-}$, etc.)**
  - Estimated with Pythia+GEANT. Initial estimate is <10% contamination in lowest energy bin with decreasing fraction as deposited energy increases
  - Qualitatively consistent with expected detector behavior



Decay photon impact positions for low and high energy π^0's

(i) Forward Cluster A_N at $\sqrt{s}$=200 GeV

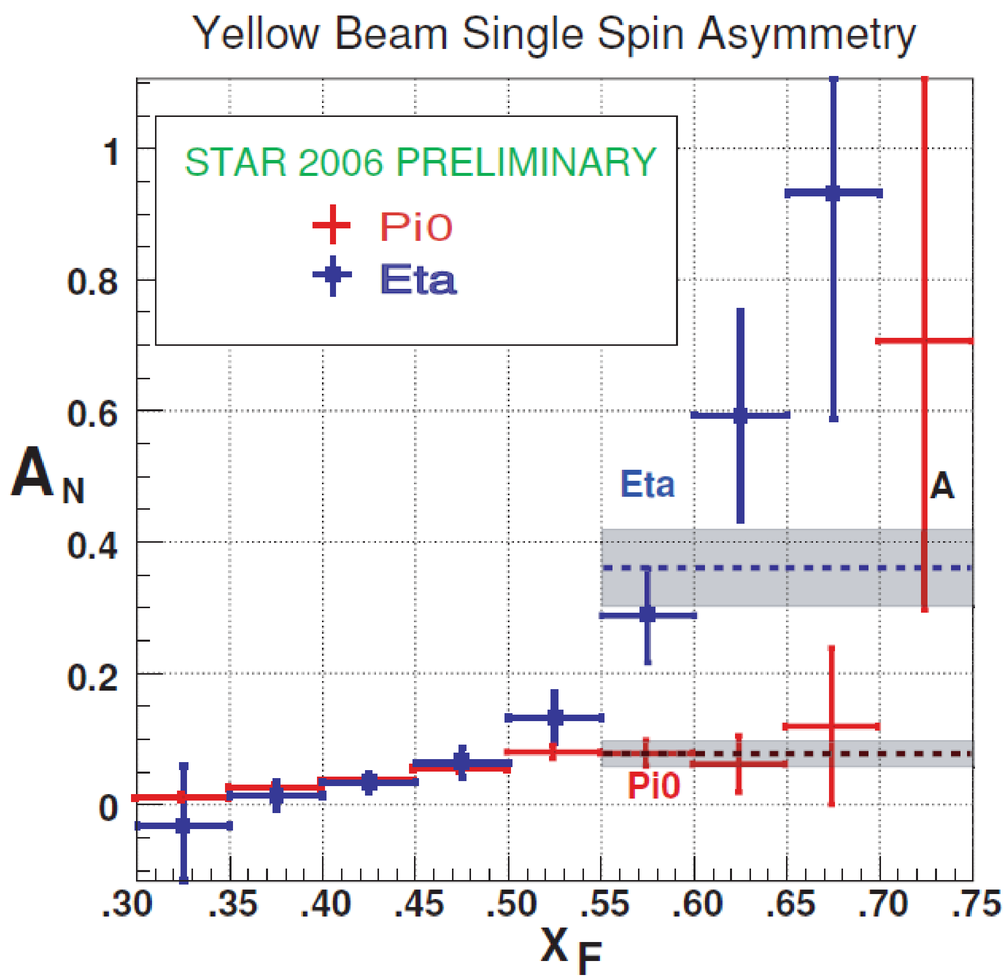




(i) Forward η A_N Measurement at STAR

PHENIX

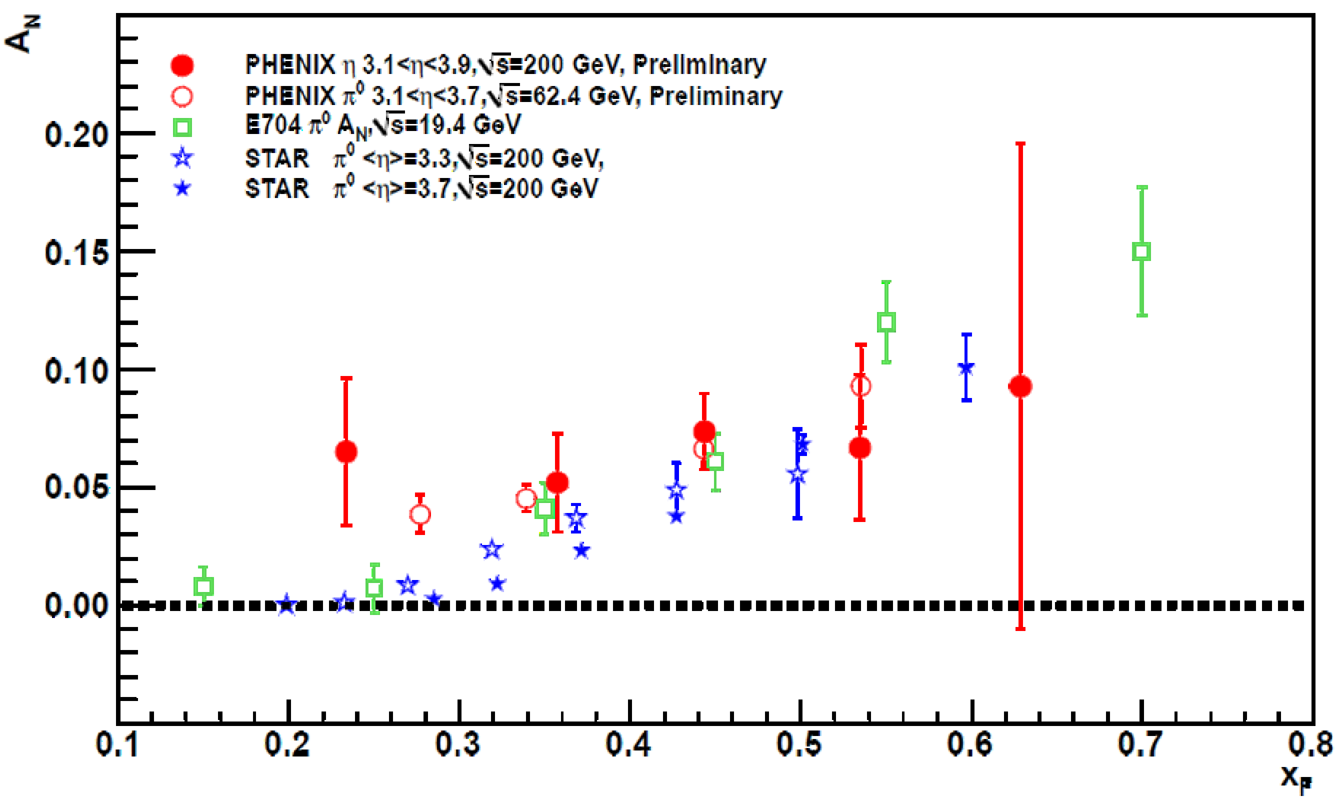
- Interesting eta meson A_N from STAR collaboration
- A_N η > A_N π^0
- Suggesting:
  large transversity x Collins contribution **and**
  Collins η > Collins π^0?
- Strangeness playing a role in asymmetries?



S. Heppelman DIS09 Proceedings arXiv:0905.2840

(i) Forward η A_N Measurement at PHENIX

- Smaller observed η A_n in PHENIX
- Consistent with previous π^0 measurements at various CoM energies.



(i) Forward η A_N Measurement Comparison

PHENIX

Preliminary Results

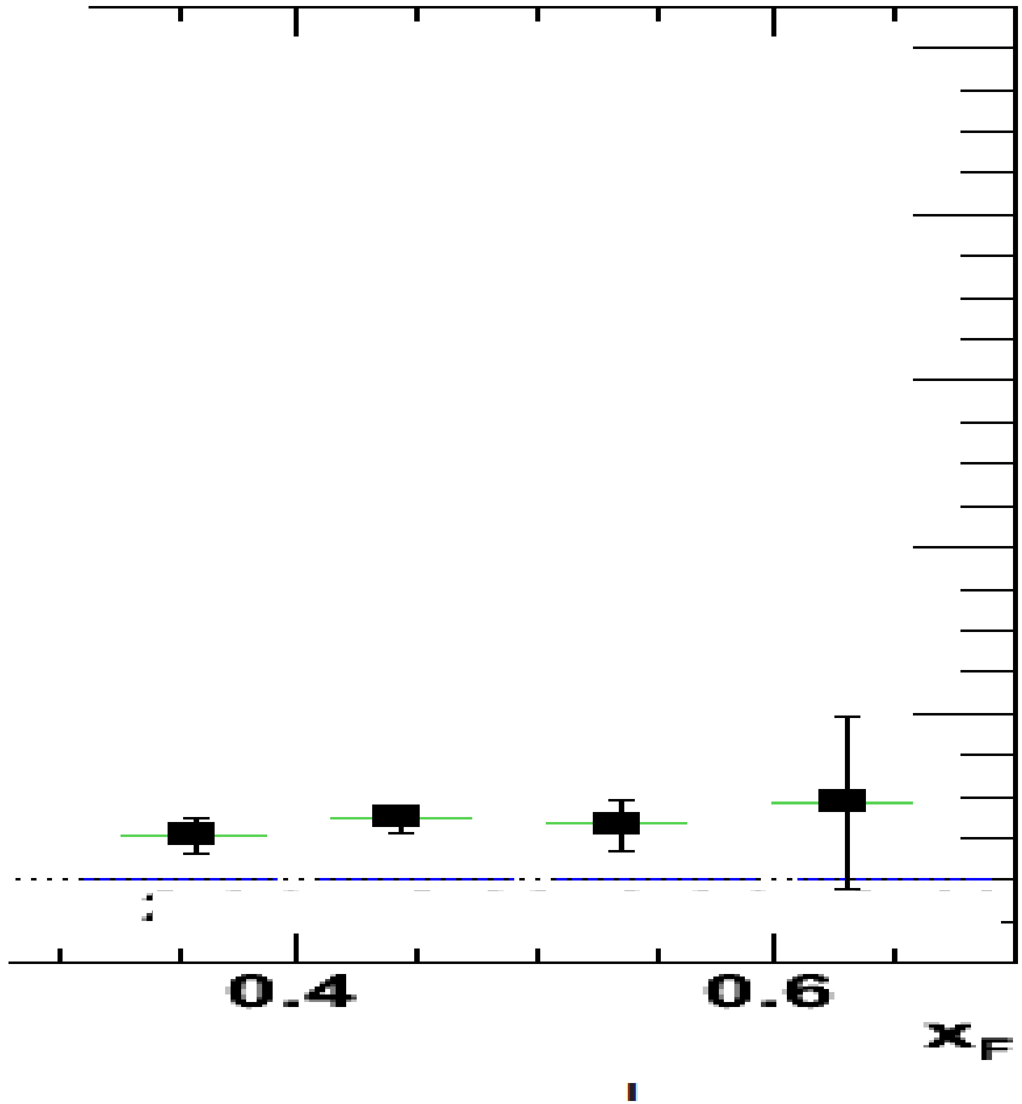
STAR π^0

STAR η

PHENIX η

Some tension between the datasets, especially at interesting high x_F region.
Possible resolutions:

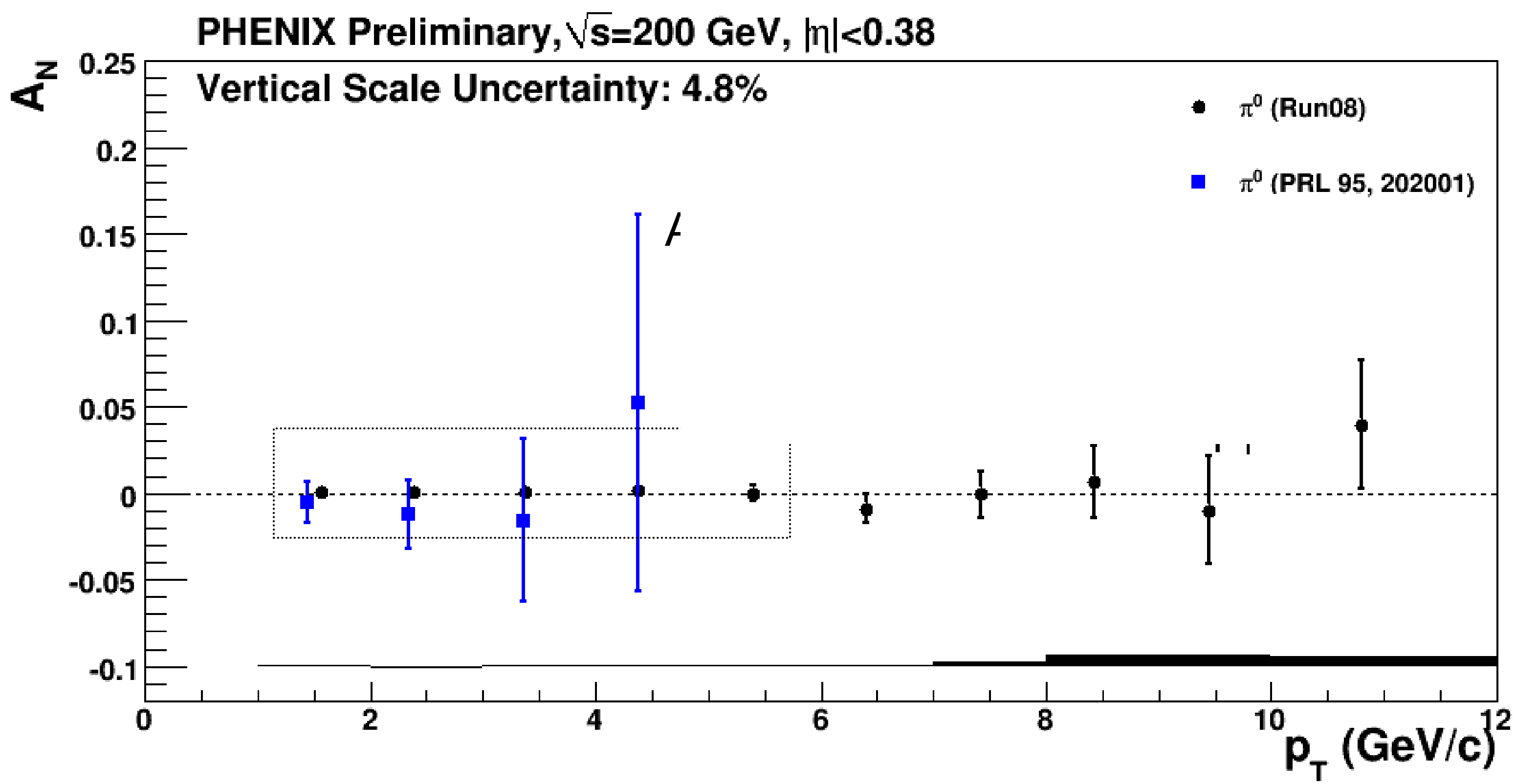
- Both results preliminary.
- STAR <p_T> not provided. Could be different <η> between measurements.
- Datasets have independent polarization errors.
- STAR result did not background subtract (as far as I know).



(i) Mid-rapidity π^0 A_N Measurement

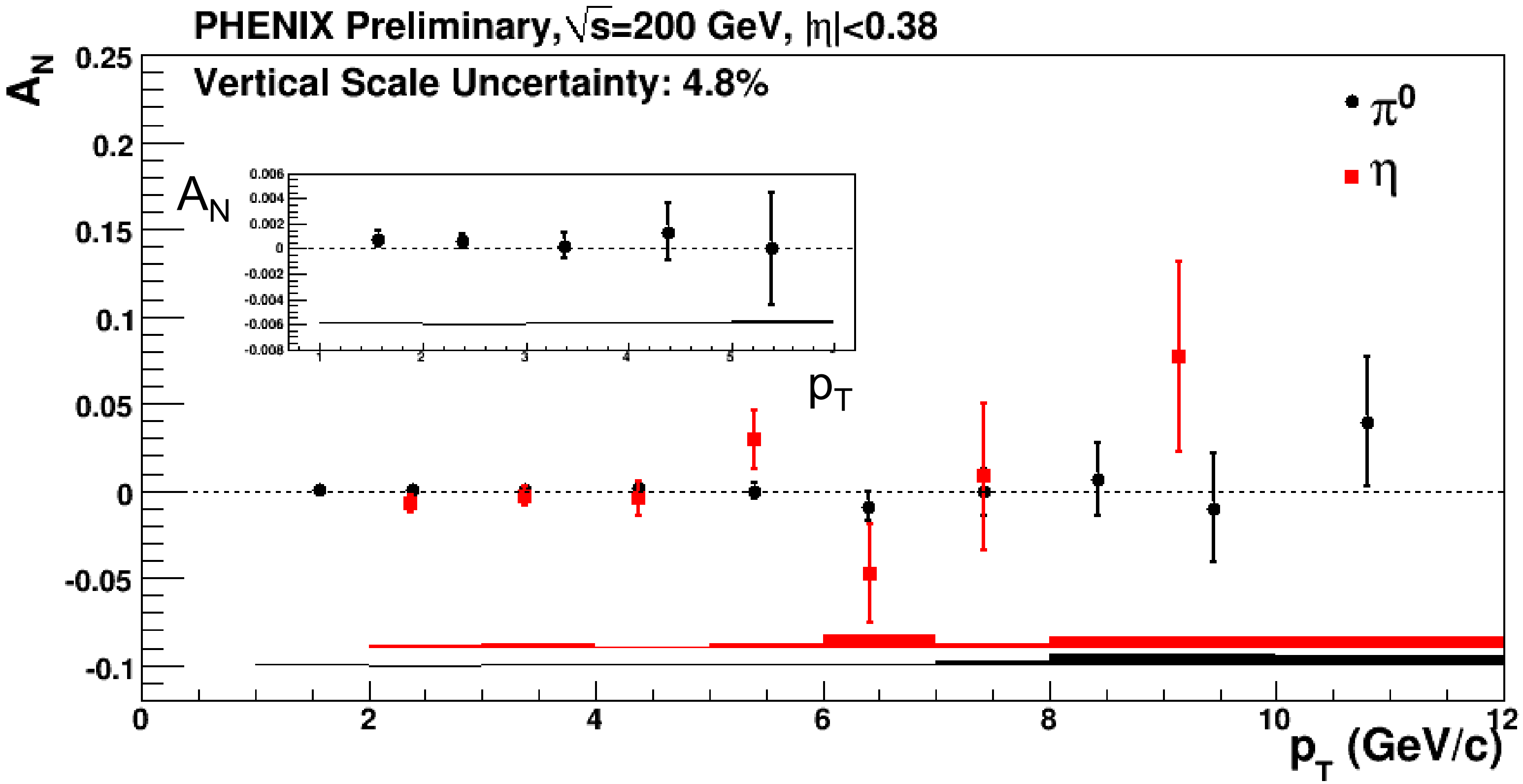
2002 Published Result

2008 Preliminary Result



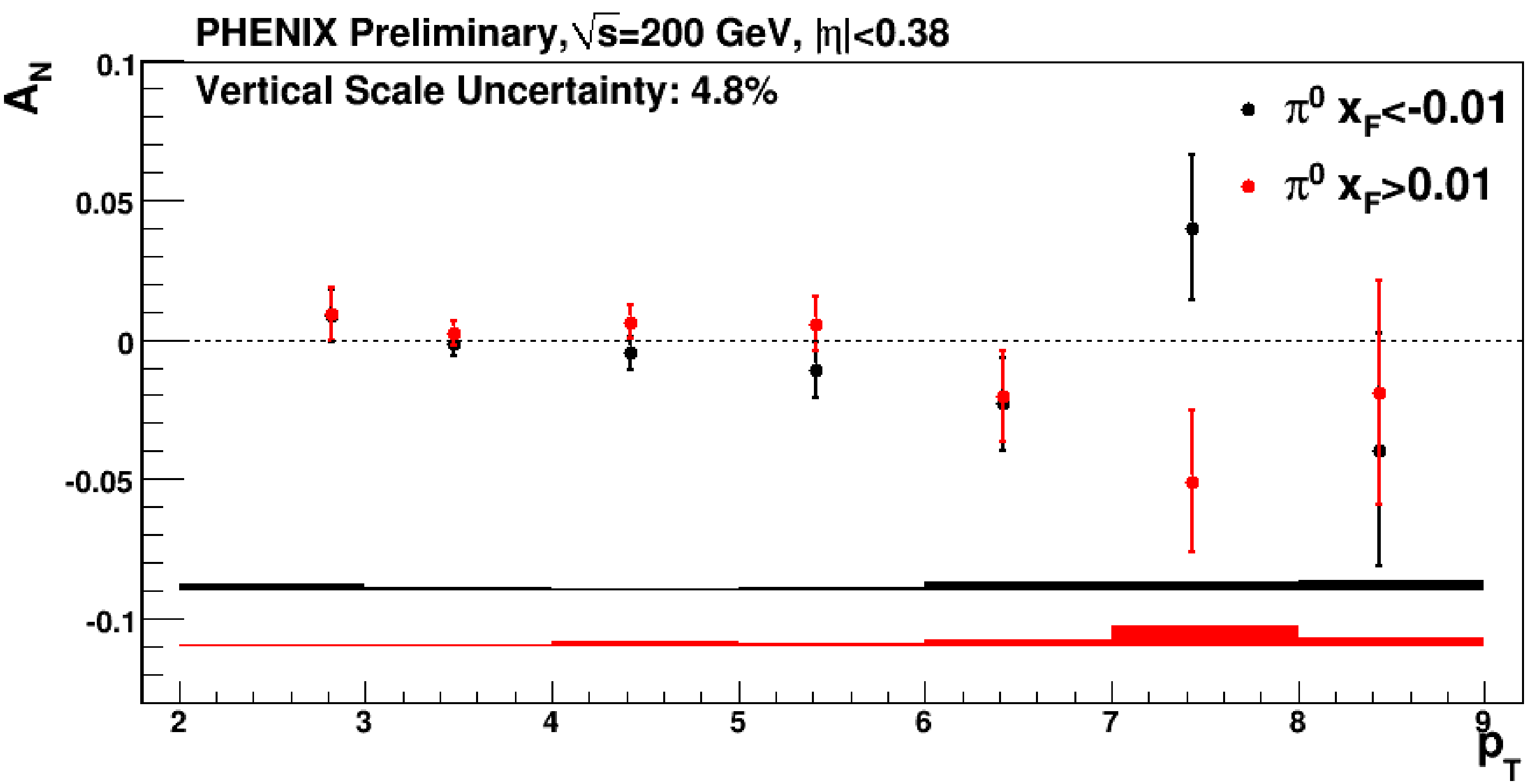
- Previous result shown to be sensitive to gluon Sivers function.
- New result will be published with 20x smaller error bars.

(i) Mid-rapidity π^0 and η A_N



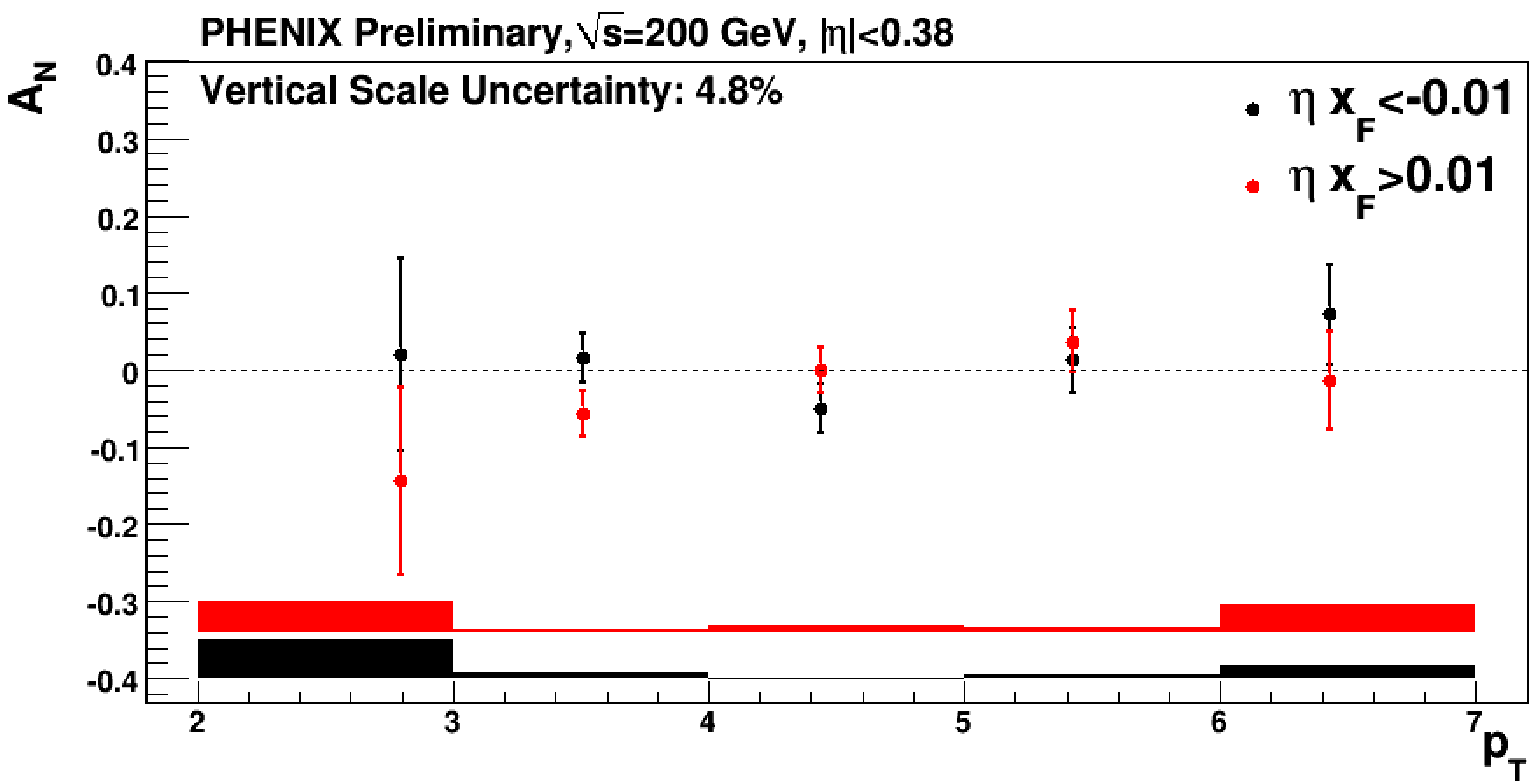
- A_N consistent with zero

(i) Mid-rapidity π^0 A_N $|x_F|>0.01$



- A_N consistent with zero

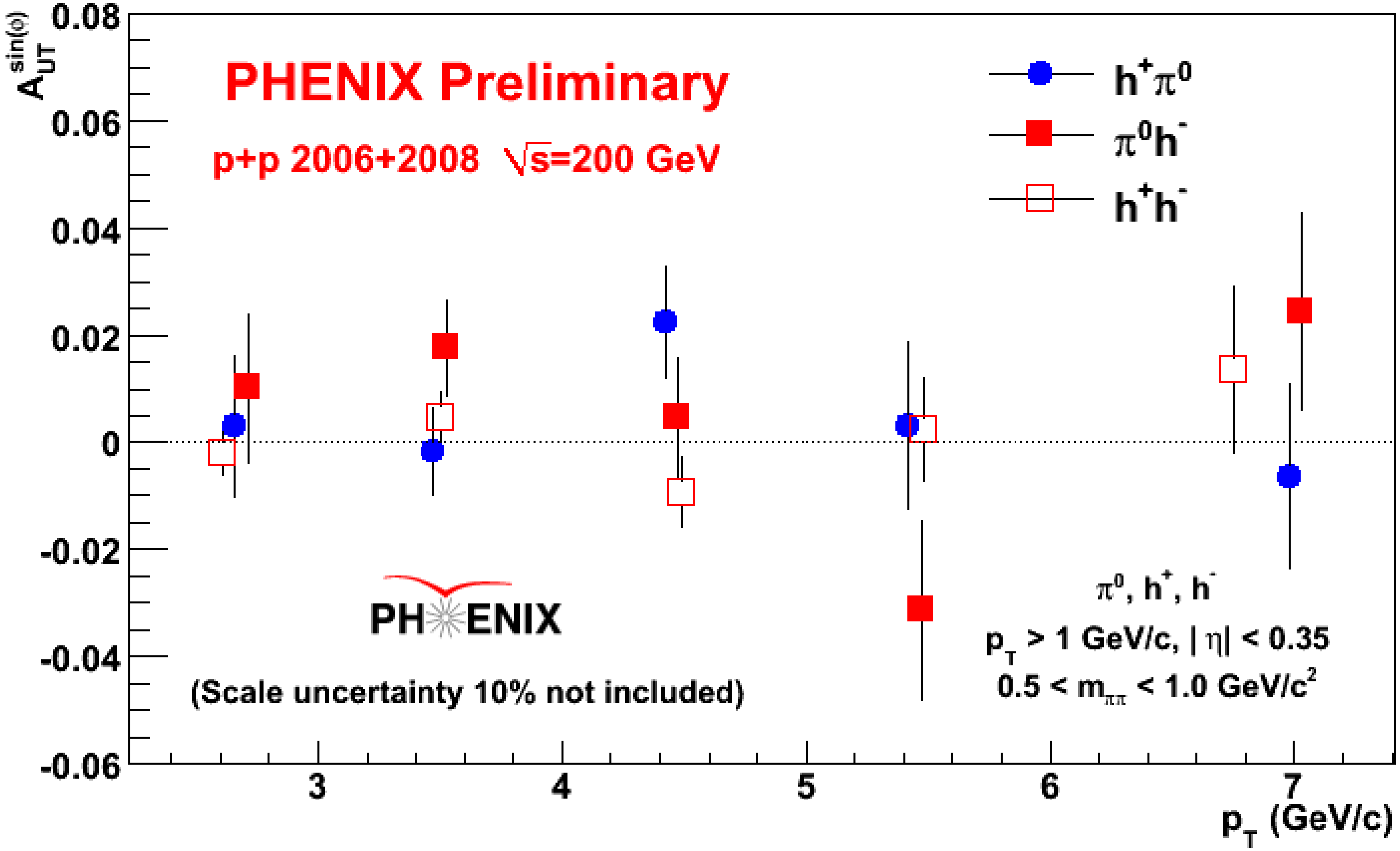
(i) Mid-rapidity η A_N $|x_F|>0.01$



- A_N consistent with zero

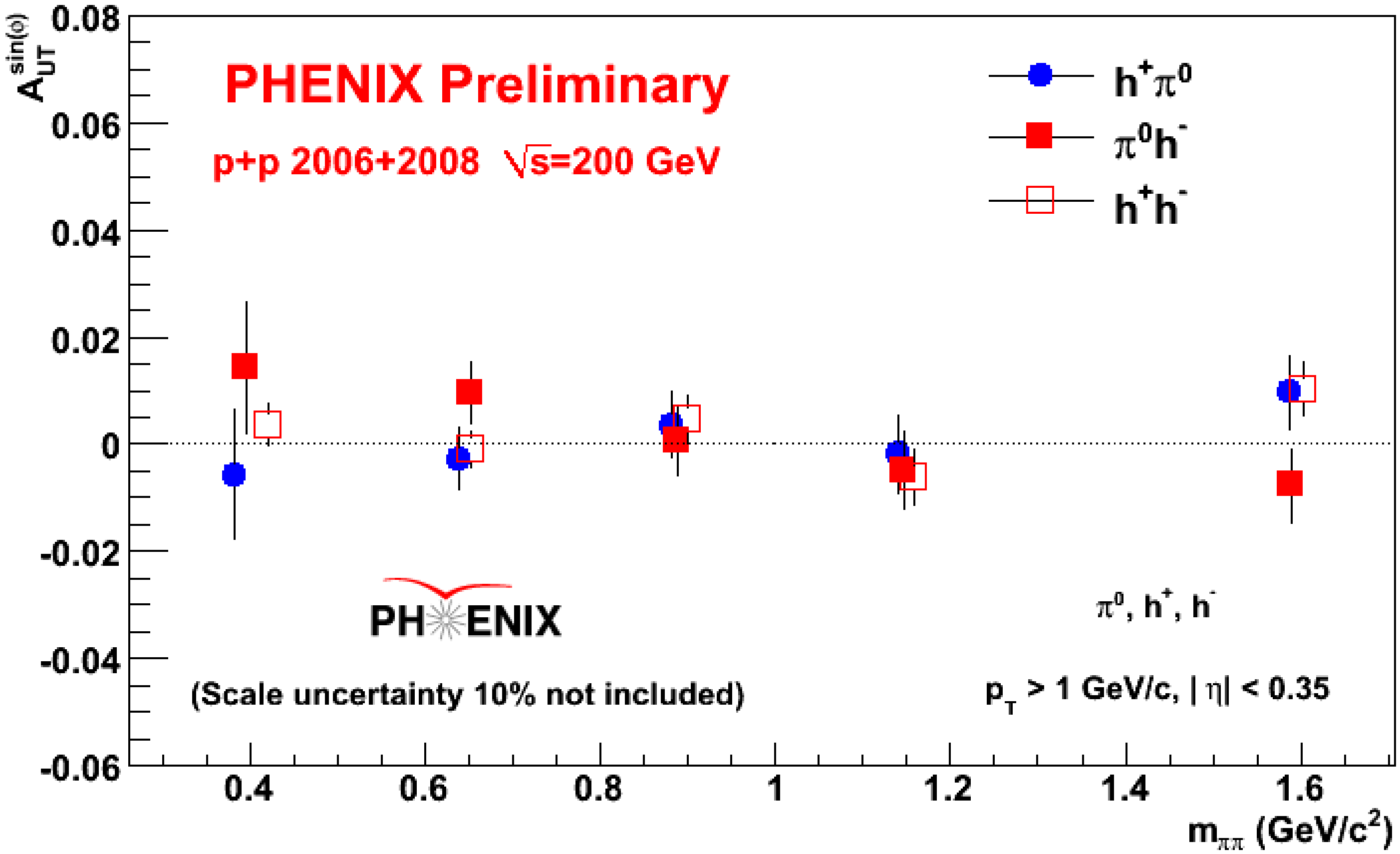
3. Transversity Measurements
   - Interference Fragmentation Function
   - Collins in Jets

(iii) Interference FF Measurement at PHENIX



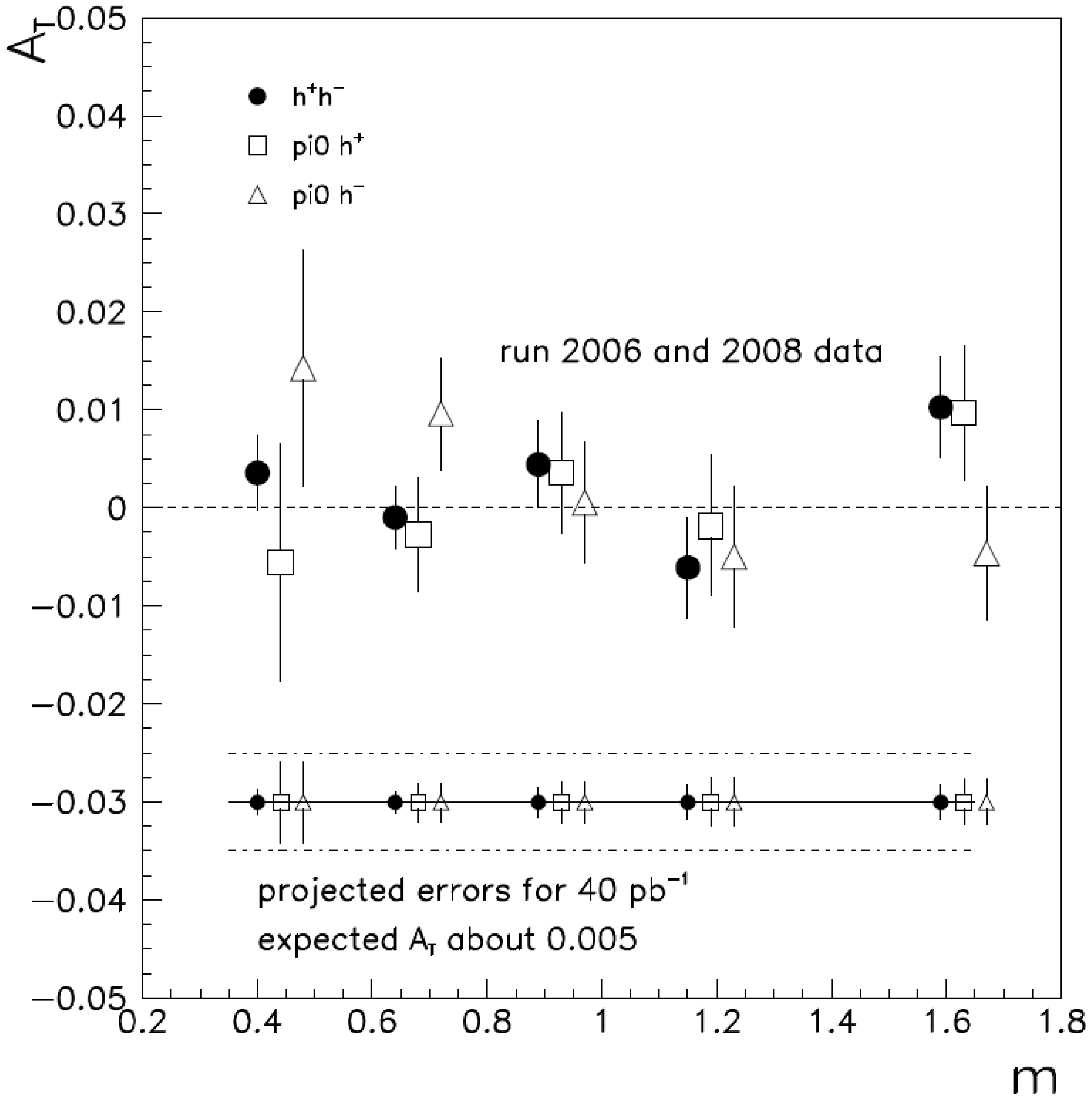
Motivation and theoretical interpretation already introduced in several talks…

No significant asymmetries seen at mid-rapidity.

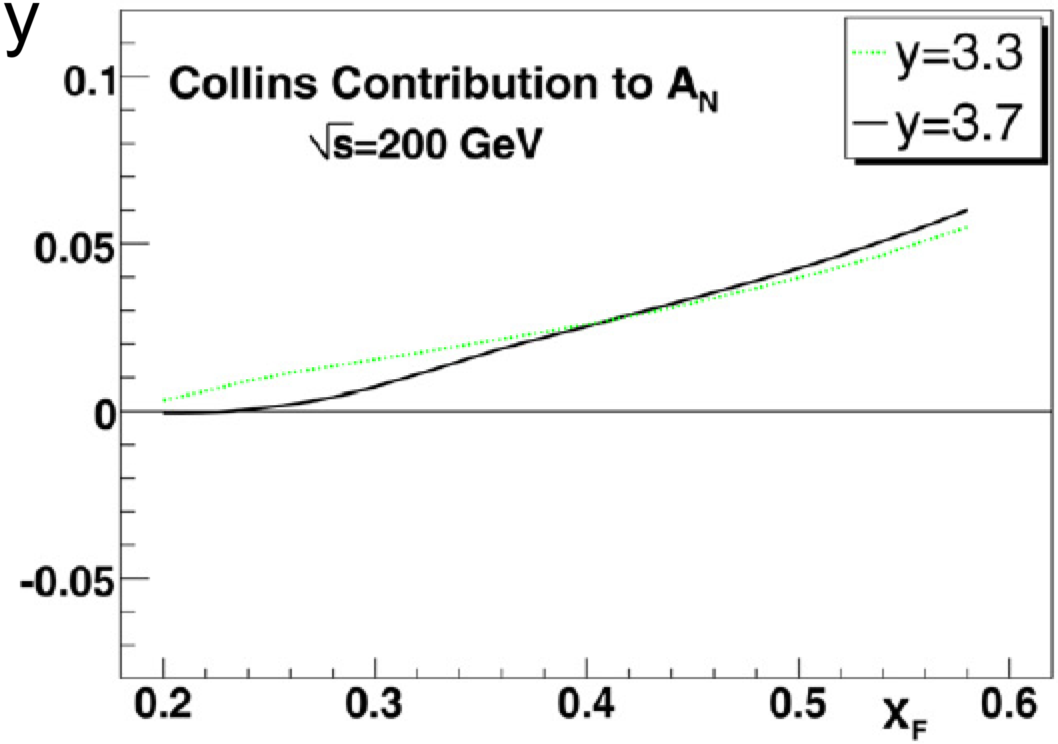


No significant asymmetries seen at mid-rapidity.

(iii) IFF Projected Error Bars



- Measurement originally proposed in:
  F. Yuan, PLB 666 (2008) 44-47
- Measure:
  $p(P_A,S)+p(P_B)\rightarrow jet(P_j)\rightarrow H(P_H)+X$
  Define two angles:
  φ_S proton spin direction
  φ_H hadron angle around jet axis
  Measure: azimuthal modulation of $\sin(\varphi_H - \varphi_S)$



Model dependent calculations show that Collins effect can produce large forward single spin asymmetries.

PHENIX

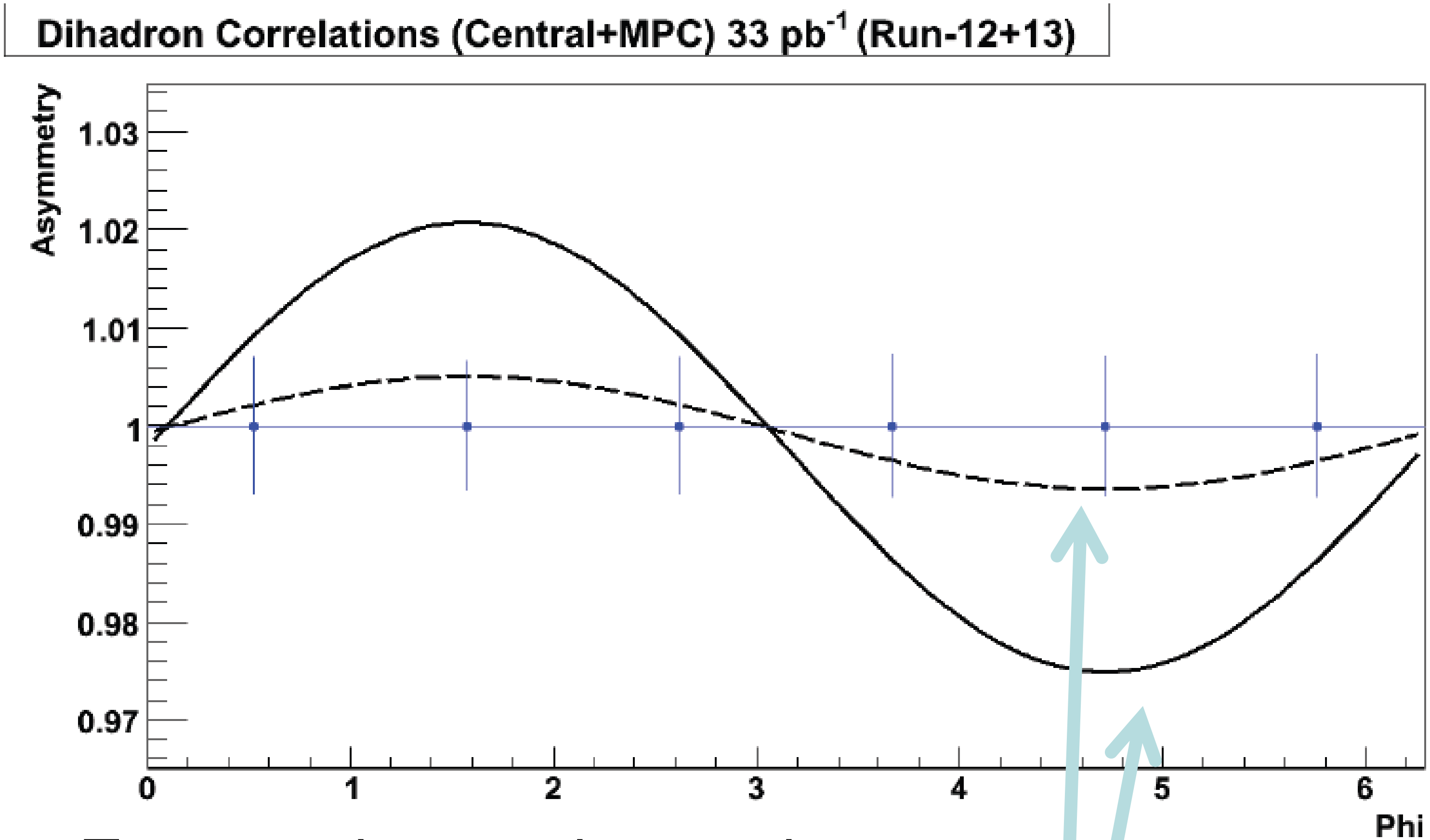
Planned measurement:

- Measure near-side jet axis using PHENIX central arm.
  - Central arm recently upgraded with large acceptance silicon tracker (| η |<1.2)
- Measure away side neutral pion in forward region using MPC.

Projected asymmetries:

- Added transverse spin processes in Pythia to predict the asymmetries for various transversity distributions.
- Collins function taken from analysis of SIDIS+BELLE data.

(iii) Predicted Collins Asymmetries



Transversity tuned to produce:

25% of PHENIX forward A_N

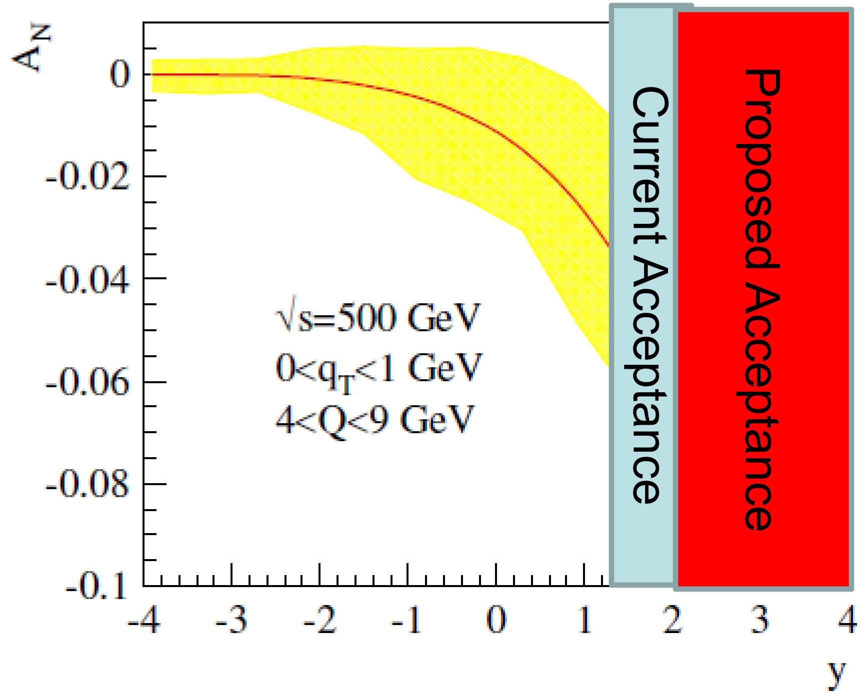
100% of PHENIX forward A_N

4. sPHENIX – Future rebuilt PHENIX detector with significantly enhanced capabilities.
   - Planned turn-on ~ 2015/2016
   - New exciting physics will become available

(iv) Drell-Yan at PHENIX

- Expected sign flip in DY A_N between SIDIS and pp.
- Existing PHENIX muon arms can do a measurement. However:
  - Non-ideal pseudorapidity coverage: $1.4<\eta<2.2$
  - Projected transverse 2012-2016 integrated luminosity: 33 pb^{-1} at $\sqrt{s}$=200 GeV.
    2-sigma measurement at PHENIX.
  - Dedicated RHIC experiment (A_NDY) will collect substantially larger transverse spin dataset through this time period at $\sqrt{s}$=200 and 500 GeV. See L. Bland's talk for details.

Estimated DY A_N

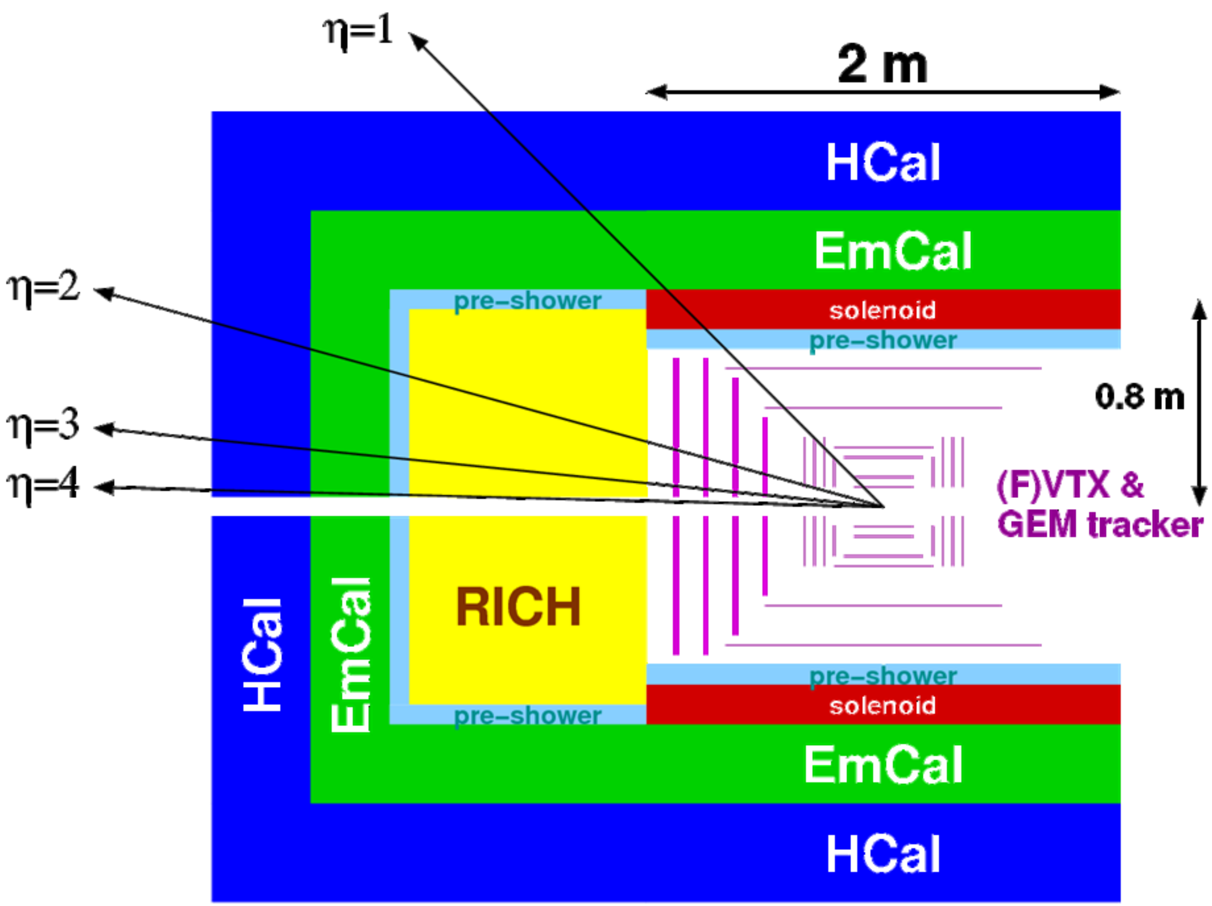


Z. Kang and J. Qiu. Phys. Rev., D81:054020, 2010

Proposed sPHENIX detector:

- Complete redesign of PHENIX detector.
- Forward spectrometer optimized for DY and spin physics. ($2<\eta<4$ coverage)
- 2015/2016 planned first run.
- Detector simulations underway.

(iv) Proposed sPHENIX Design



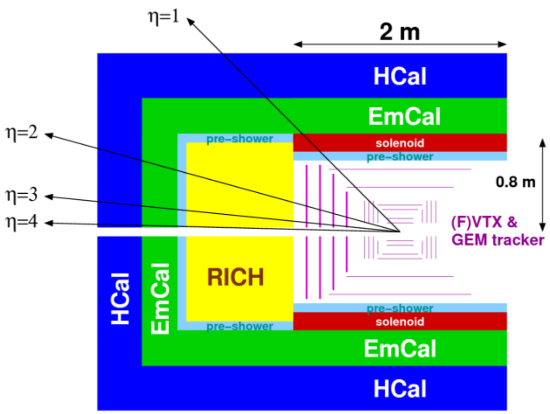
ıents

EmCal: **electromagnetic calorimeter for: π^0, Direct γ, $e^{+/-}$measurements**

RICH: **$e^{+/-}$, charged hadron identification**

GEM-Tracker+FVTX **charged particle momentum/charge-sign measurement**

(iv) Proposed sPHENIX Design



1) HCal
2) EMcal
3) Aerogel+RICH
4) GEM-Tracker+FVTX

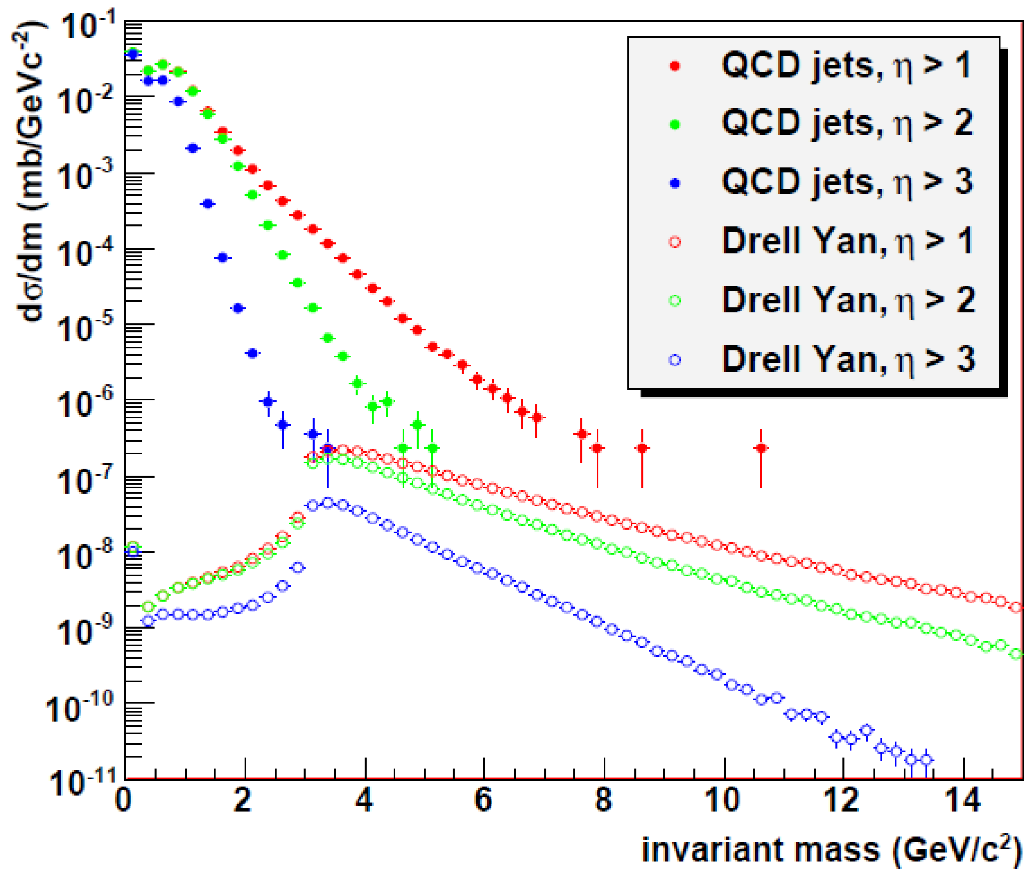
Measurement	Physics	Detector Req.
Drell-Yan	Sivers function Transversity distribution Boer-Mulders function	1, 2, 3, 4
Identified $h^{+/-}$ IFF*	Transversity distribution	1, 3, 4
Hadron in Jet Collins*	Transversity distribution	1, 2, 3, 4
Jet A_N	Sivers function	1, 2
Direct Photon A_N	Sivers function	2, 4
Identified $h^{+/-}$ A_N *	Sivers, Collins, higher-twist mixture	1, 3, 4

* Connection to underlying distribution requires polarized FF measurements/extractions

- Performed a fast detector simulation:
  - Track resolution: $\frac{\Delta p}{p} \approx 2\%$
  - EM energy resolution: $\frac{\Delta E}{E} \approx 5.95\%/\sqrt{E} \oplus 0.76\%$
  - Hadronic energy resolution: $\frac{\Delta E}{E} \approx 50\%/\sqrt{E} \oplus 5\%$
  - $e^{+/-}$ efficiency: 94% (p>10 GeV/c)
- 2 billion Pythia events with QCD and diffractive processes generated to find Drell-Yan backgrounds

PHENIX

- QCD Backgrounds decrease with increasing pseudorapidity
- Forward rapidities: QCD backgrounds are at a small level.
- Drell-Yan for $M<3$ GeV/c^2 not physical (Pythia settings)



With substantial upgrades to PHENIX, why not also consider upgrades to RHIC?

- polarized ^3He
  - Provides access to polarized neutron
- $\sqrt{s}$=630 GeV running
  - Reposition magnets to increase maximum center of mass energy from 500 GeV
  - W cross-section doubles
- Factor of ~100 increase in luminosity also under consideration.

Summary and Outlook

PHENIX has exciting measurements for the near-term and long-term at RHIC

Near Term

Figure of merit (P^2L):
on disk: 2.3 pb^{-1}
projected: 11.9 pb^{-1}

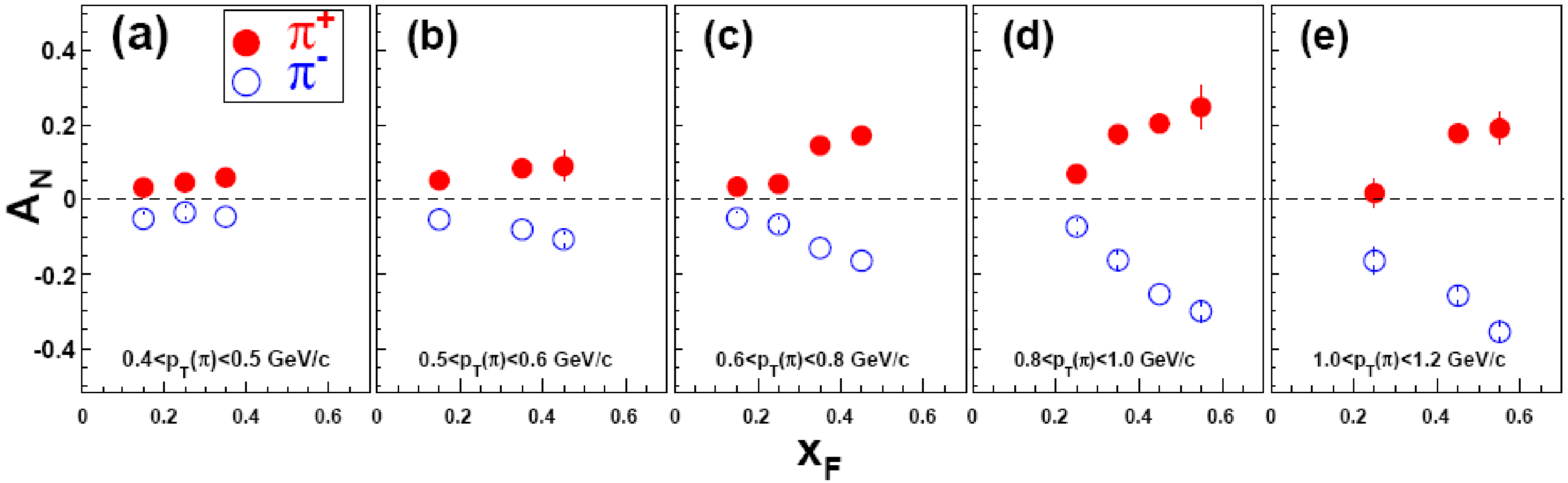
Long Term

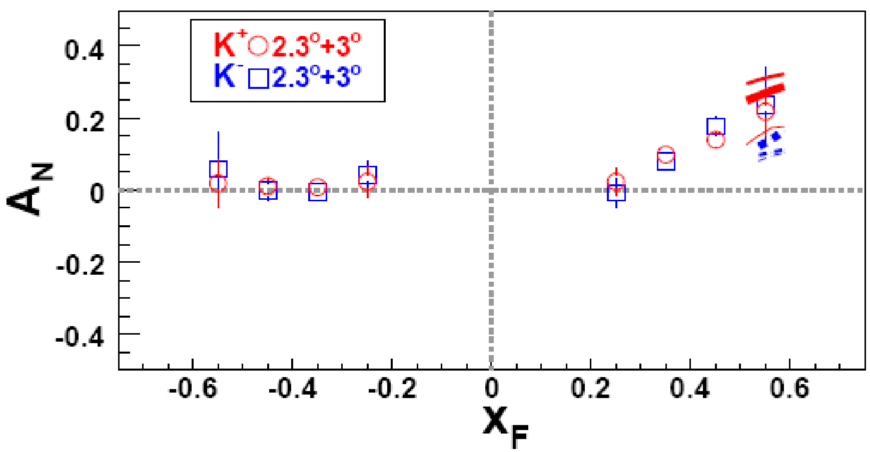
sPHENIX opportunities now being explored through simulation

- Drell-Yan most worked out channel.
- Simulations on other channels starting now to determine detector requirements.
- If our theory colleagues have an important physics channel which I have left out, please let us know!

Backup

Charged Hadron A_N Measurements by the BRAHMS Collaborations





Asymmetries from the BRAHMS collaboration Phys.Rev.Lett.101:042001,2008

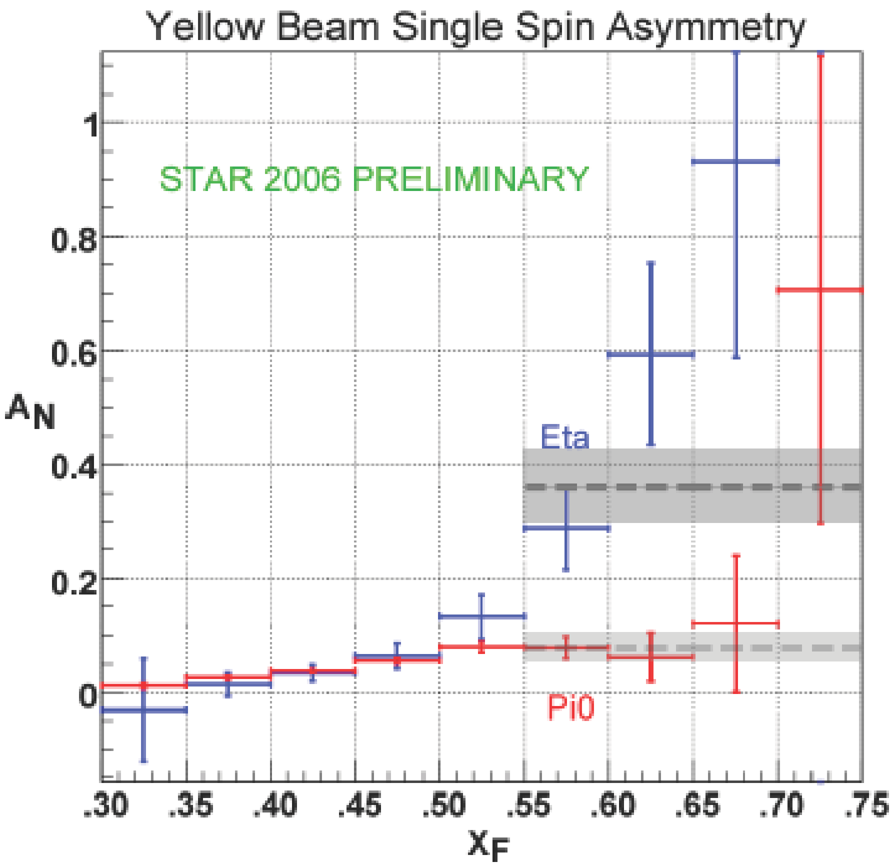
Kaon asymmetries are the same sign
Do not follow pattern of charged pions

Eta and pi0 A_N at Forward rapidity (slide from Steve Heppelmann, DIS09)

http://www.ft.uam.es/DIS2009/

STAR $A_N(x_F)$ in π^0 and Eta Mass Regions

$$p^{\uparrow} + p \rightarrow M + X \quad M \rightarrow \gamma + \gamma \qquad \sqrt{s} = 200\,GeV$$



1. $N_{photon} = 2$
2. Center Cut (η and ϕ)
3. Pi0 or Eta mass cuts
4. Average Yellow Beam Polarization = 56%

$$.55 < X_F < .75$$

$$\langle A_N \rangle_\eta = 0.361 \pm 0.064$$

$$\langle A_N \rangle_\pi = 0.078 \pm 0.018$$

For $.55 < X_F < .75$, the asymmetry in the η mass region is greater than 5 sigma above zero, and about 4 sigma above the asymmetry in the π^0 mass region.

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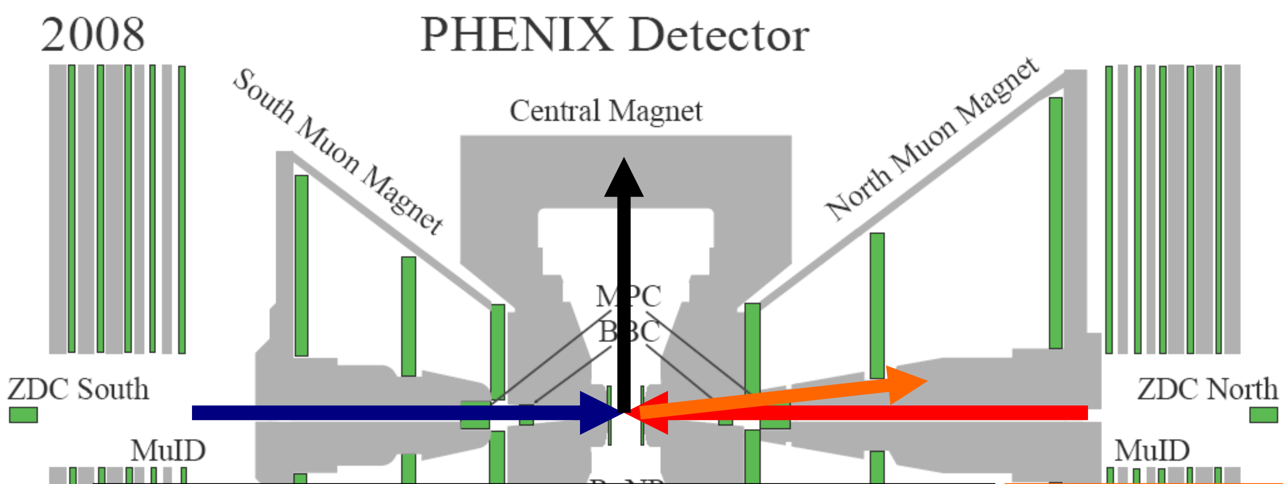
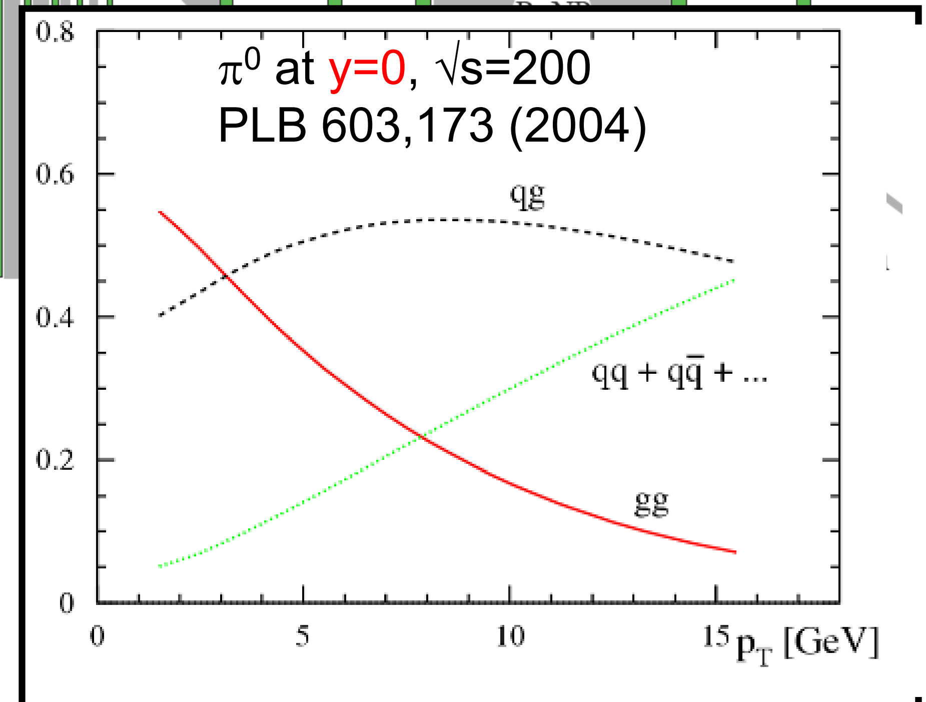
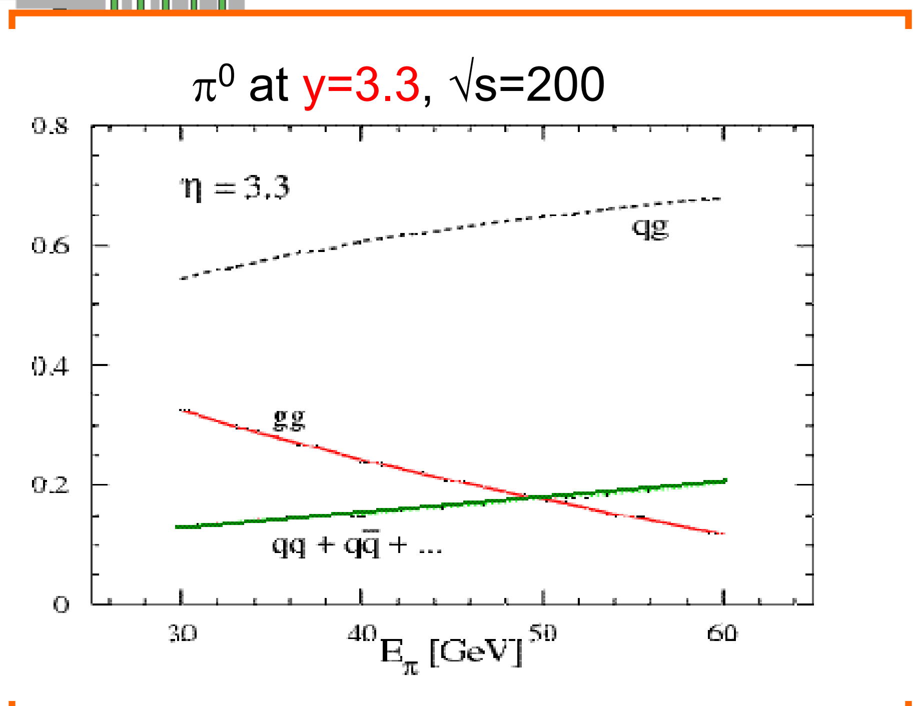
Motivation (continued)



Rapidity of detected particle varies:

- Production mechanism
- Parton x_1 , x_2





RHIC ∫L* and Polarization

PHENIX

Run	Energy	Polarization	Transverse	
	[GeV]	[%]	L [pb^{-1}]	LP^2 [pb^{-1}]
2002	**200**	**15**	**0.15**	**3.4×10^{-3}**
2005	**200**	**49 (47)**	**0.16**	**3.5×10^{-2}**
2006	**62**	**48**	**0.02**	**4.6×10^{-3}**
2006	**200**	**57 (51)**	**2.7**	7.0×10^{-1}
2008	**200**	**46**	**5.2**	1.1×10^{0}

2008 figure of merit was not a large increase over 2006 figure of merit

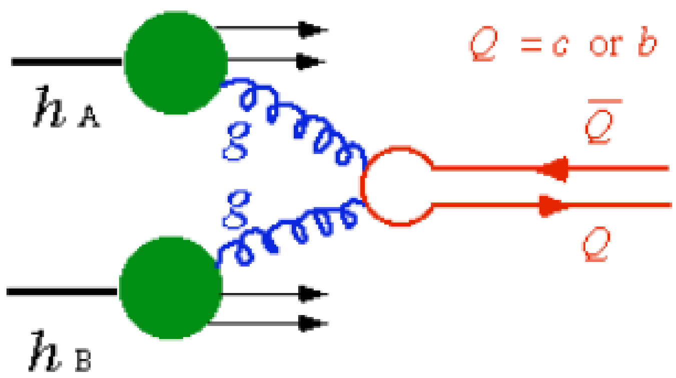
Further study shows PHENIX accumulated a significant and new dataset

PHENIX

1. A_N Measurements
   - Sensitive to combinations of all three effects
   - At forward and mid rapidity
2. Sivers Measurements
   - Heavy flavor
   - Back to back hadrons
3. Transversity Measurements
   - Interference Fragmentation Function
   - Collins in Jets

D meson A_N

- Production dominated by gluon-gluon fusion at RHIC energy

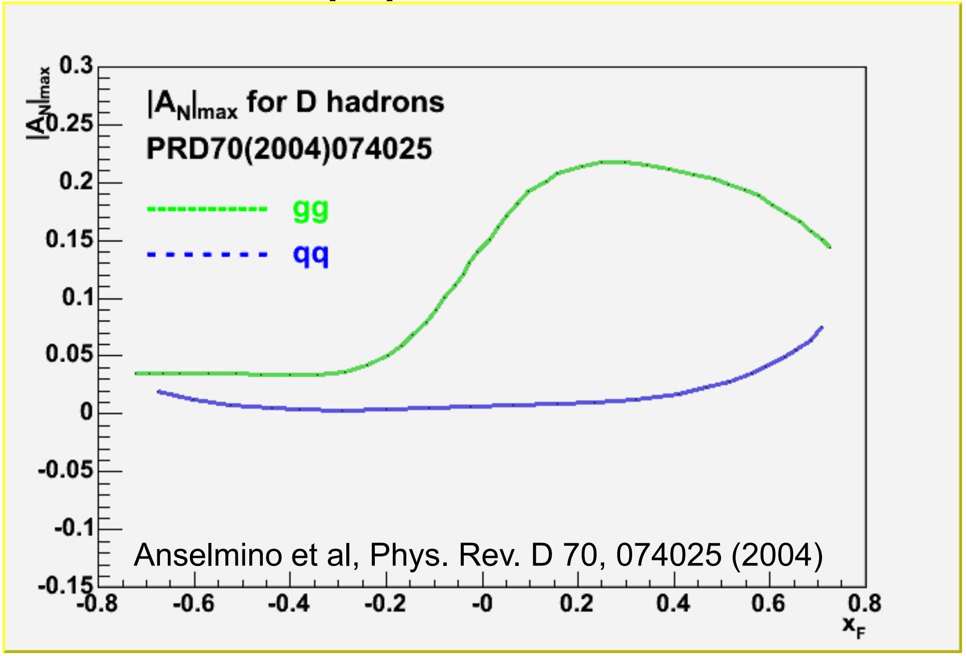


- Gluon transversity zero
→Asymmetry cannot originate from Transversity x Collins

- Sensitive to gluon Sivers effect

Theoretical prediction:

$p^{\uparrow}p \rightarrow DX$

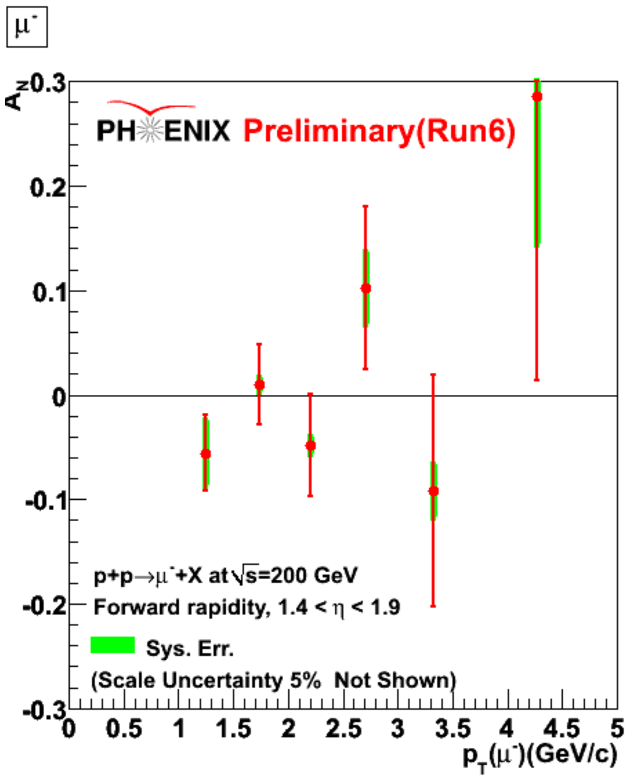


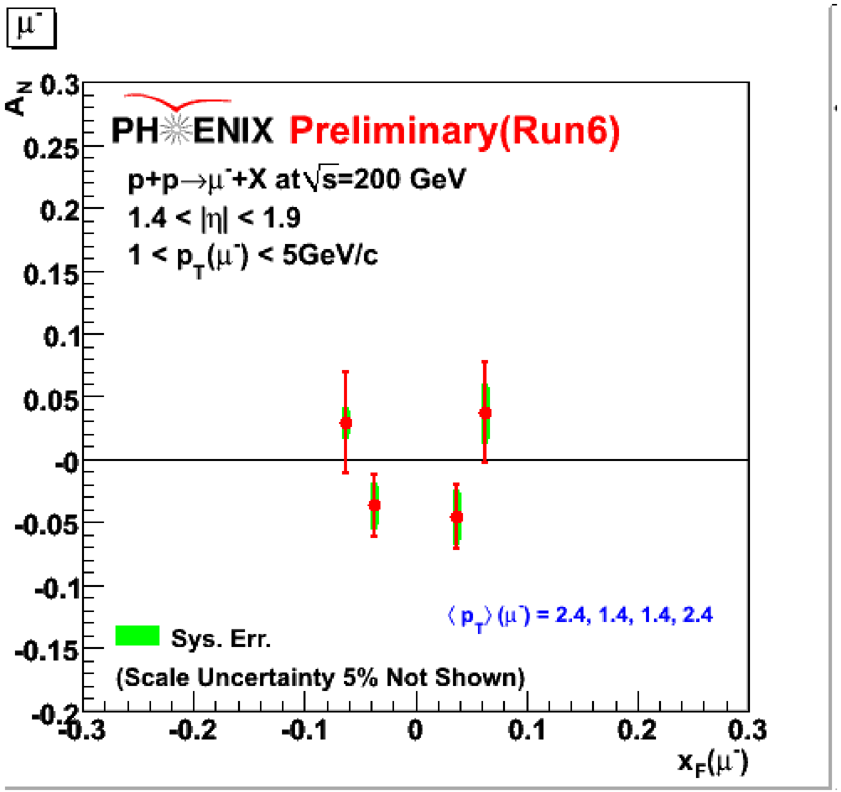
Gluon Sivers=Max
Quark Sivers=0
Gluon Sivers=0
Quark Sivers=Max

(ii) Constraints on Sivers Function: Heavy Flavor

PHENIX: no reconstruction of D meson
Exploratory measurements of A_N for single muons
Dominated by charm production in current kinematic range

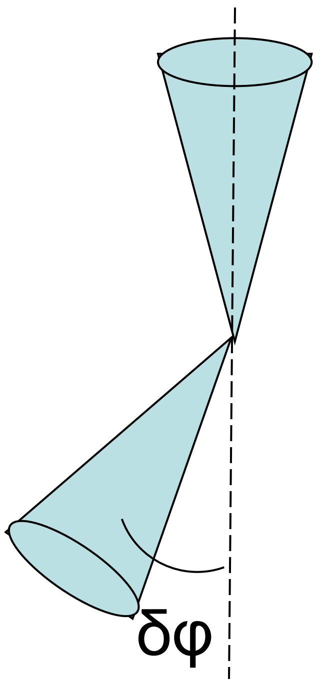
- Predicted asymmetry smeared by decay kinematics
- Measurements will be enhanced significantly by the inclusion of precision tracking: VTX (installed) and FVTX (to be installed for next run).

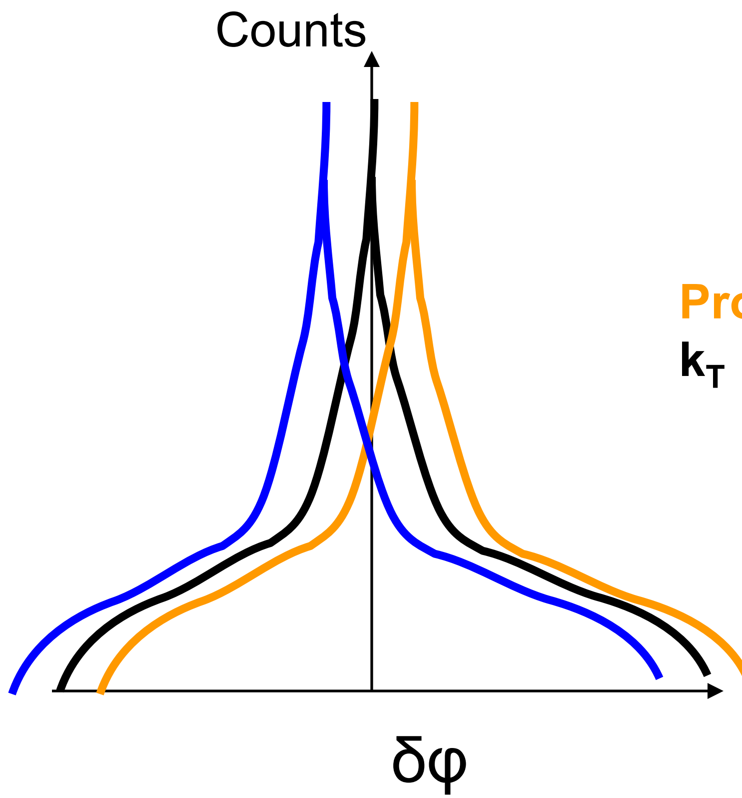


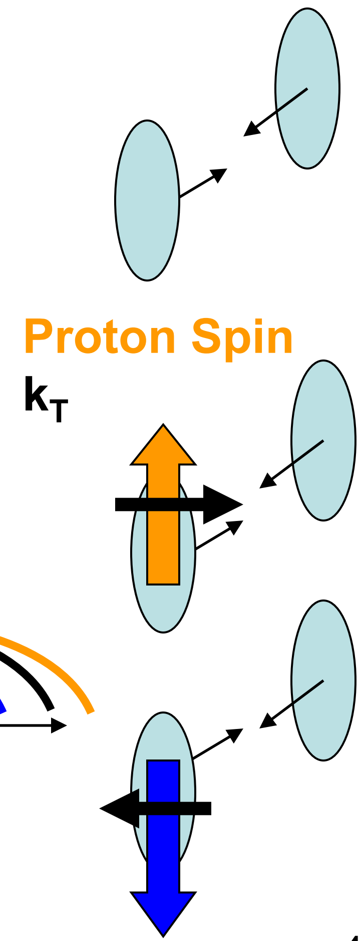


(ii) Constraints on Sivers Function: DiJet Production

Azimuthal distribution of Di-Jet production in pp
Suggested in: Boer, Vogelsang, Phys. Rev. D 69, 094025





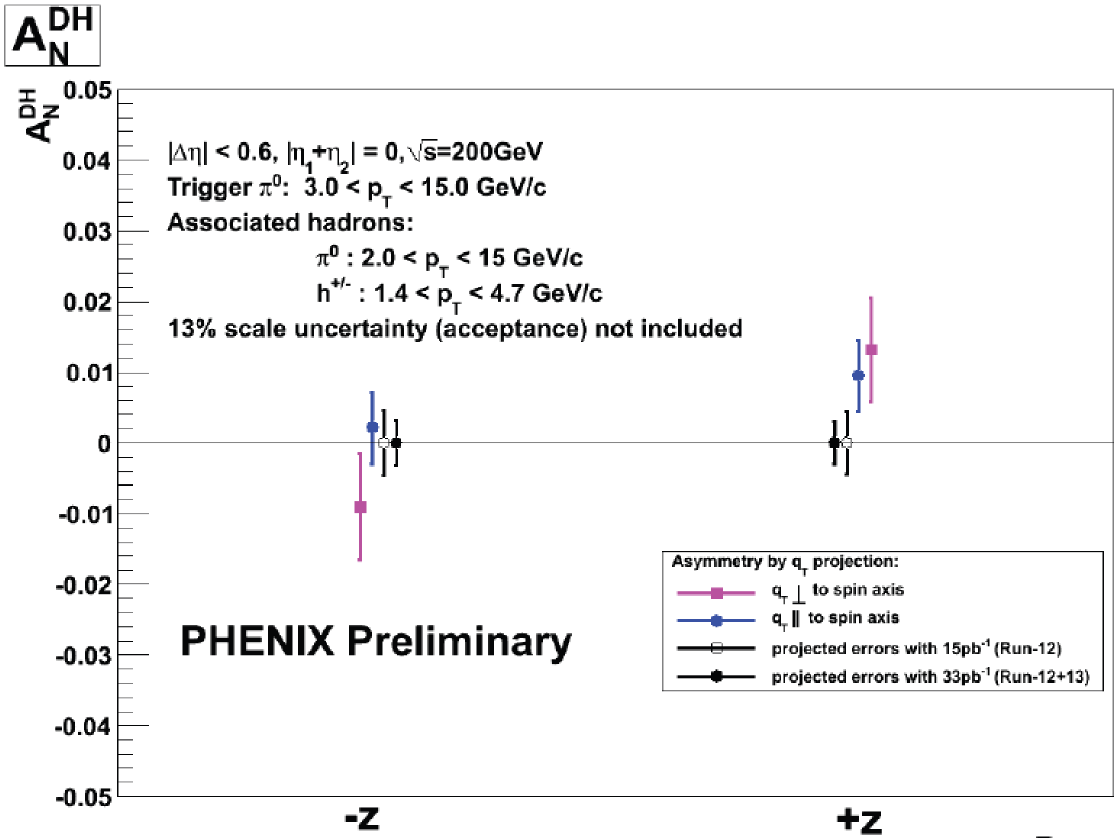


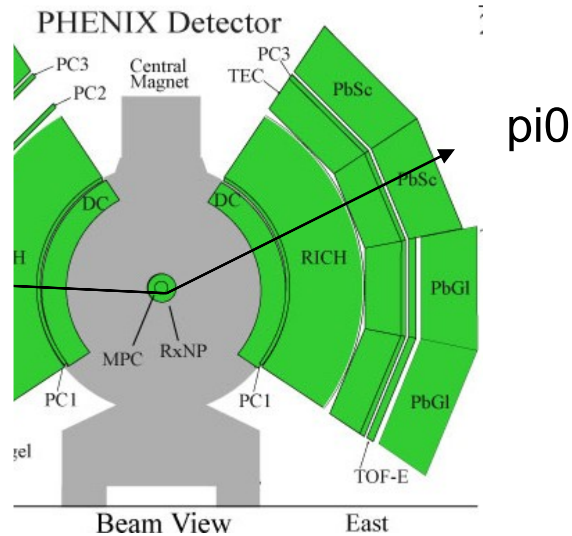
Beam is in and out of page
Look at back-to-back jet
opening angles

Sensitive to Sivers function only!

No Collins-type effects

(ii) Constraints on Sivers Function: DiHadron Production





- Asymmetry consistent with zero

lysis possible in different
ns of rapidity

P_{Beam}

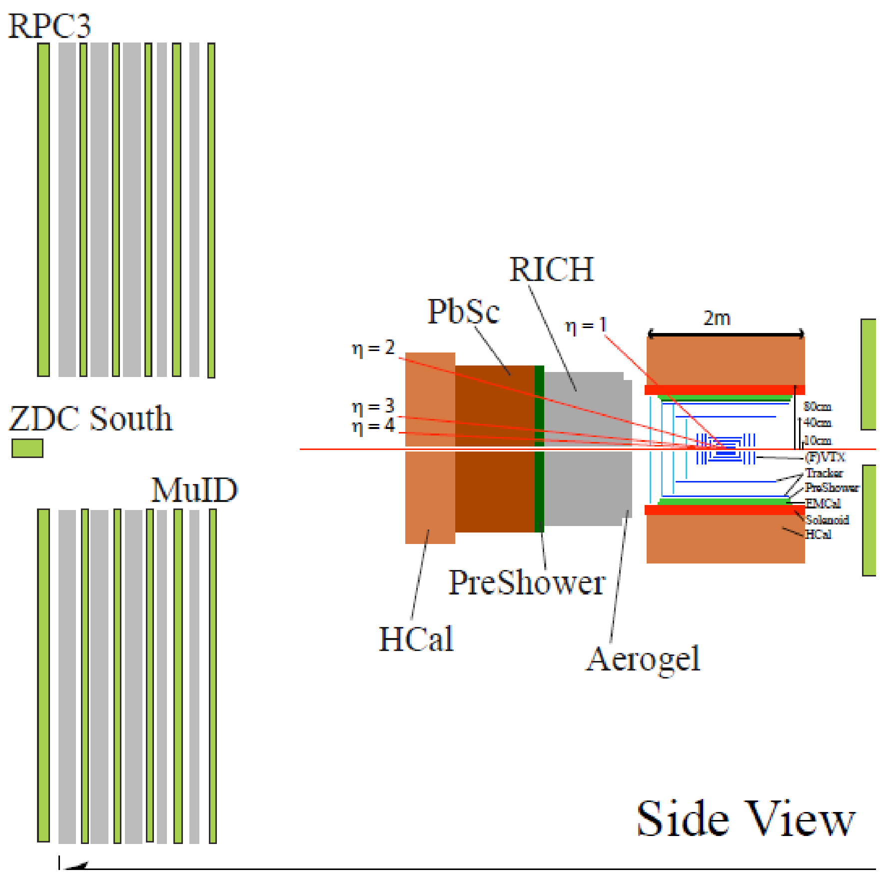
	3.7	-2.0	-0.35	1.4	3.1
η_{max}	-3.1	-1.4	+0.35	2.0	3.9

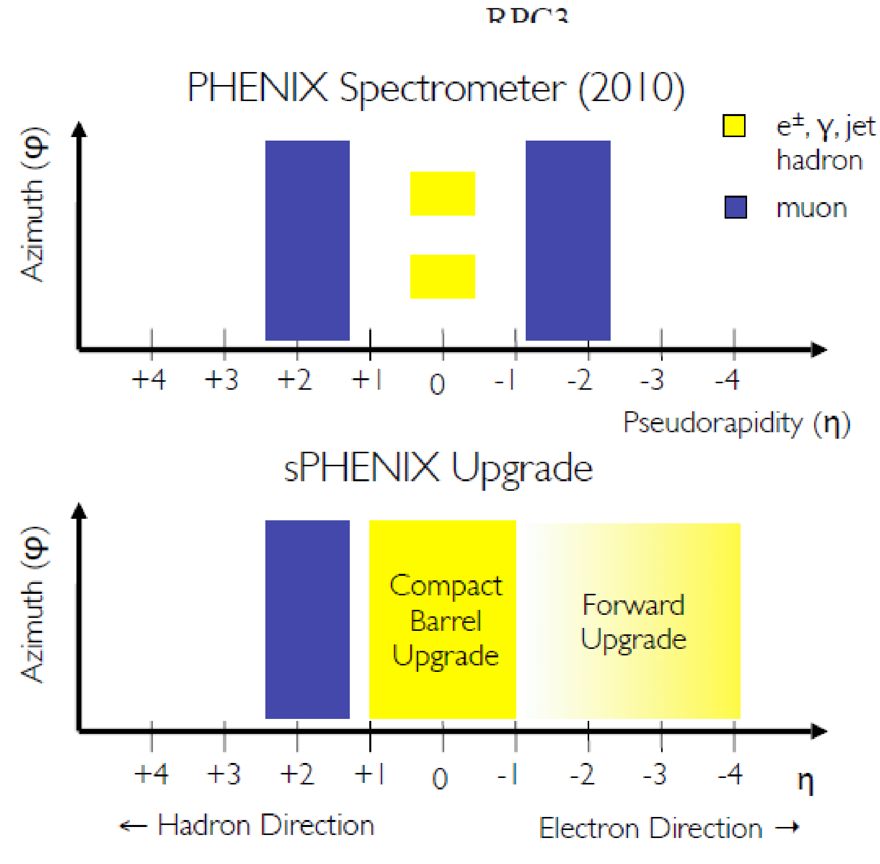
Works in progress…

Drell Yan Simulation Slides

- From OLEG EYSER
  University of California - Riverside

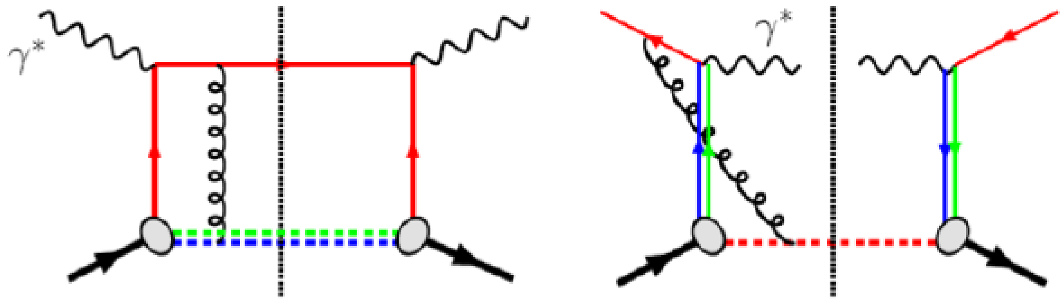
sPHENIX detector acceptance

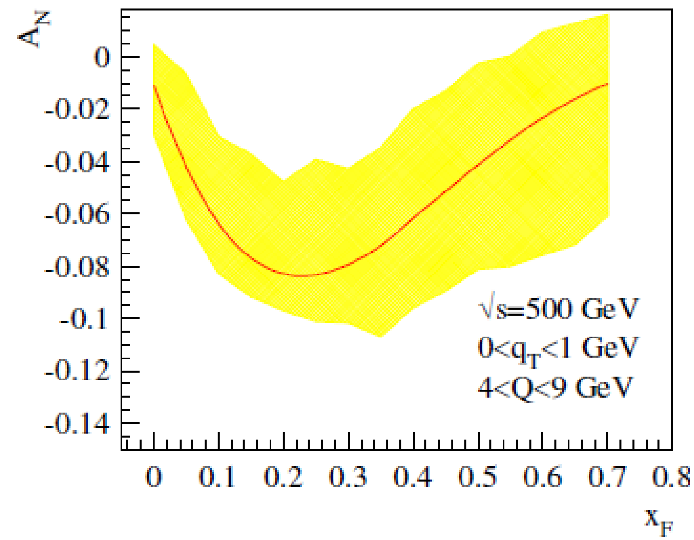




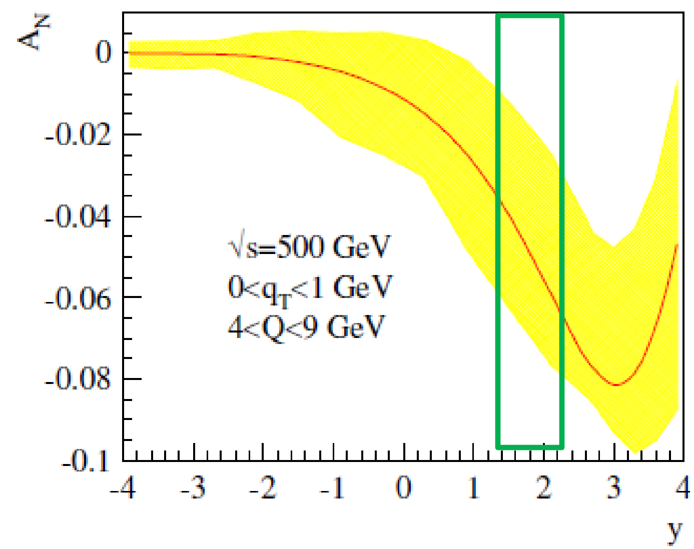
- Data Acquisition System
- Trigger capabilities

Polarized Drell Yan





- Valid factorization
- No fragmentation
  - Direct correlation of intrinsic transverse quark momentum to the proton spin
- Fundamental QCD test
  - Sign of asymmetry compared to SIDIS



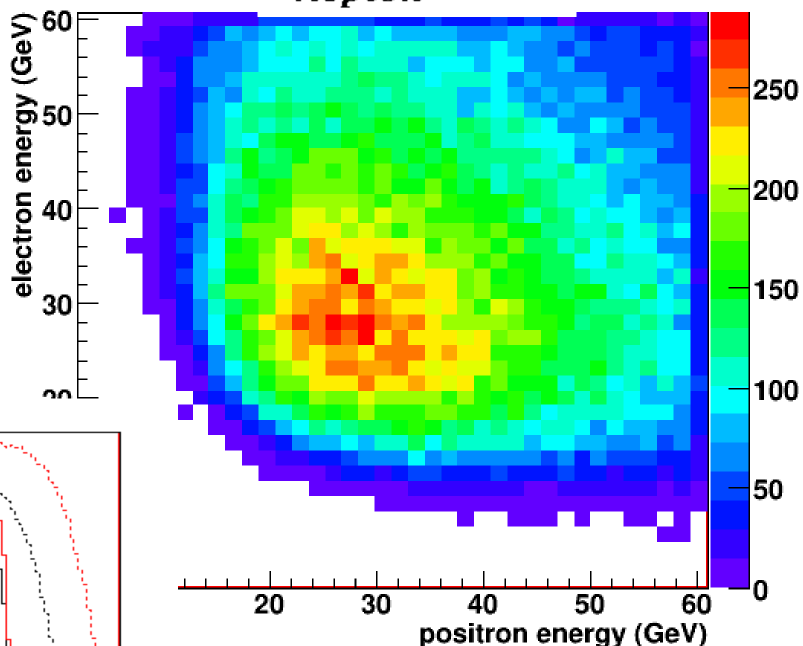
Z. Kang and J. Qiu. Phys. Rev., D81:054020, (2010)

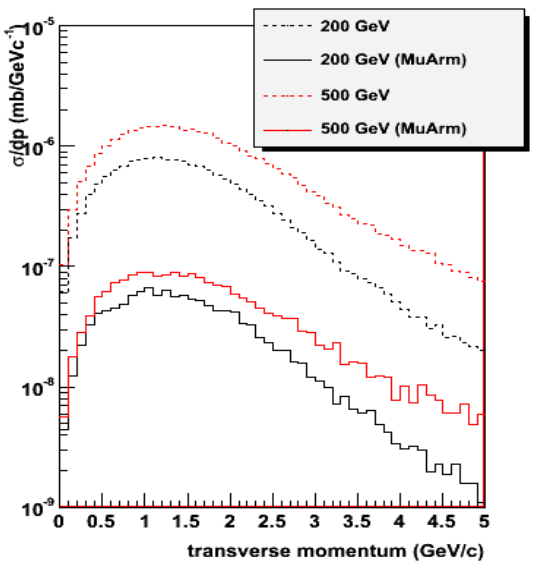
- Leptons have large energies
- Larger cross section with increased collision energy
- Large A_N for y > 2
  - More forward favorable over PHENIX Muon arm detectors ($1.2 < \eta < 2.4$)
- Forward rapidities more susceptible to large x > 0.3

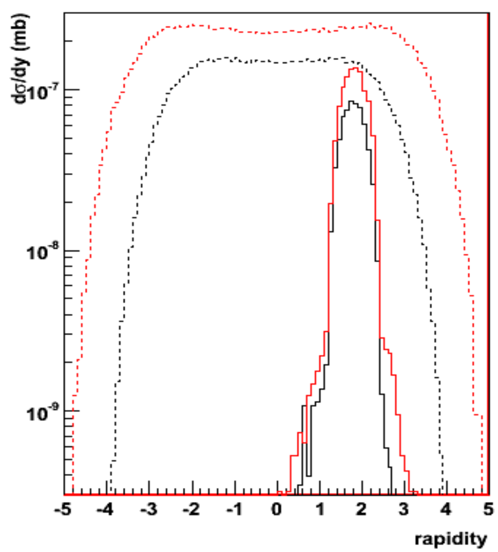
DY: electron-positron pairs

$m_{inv} > 3$ GeV/c^2

$\eta_{lepton} > 3.0$

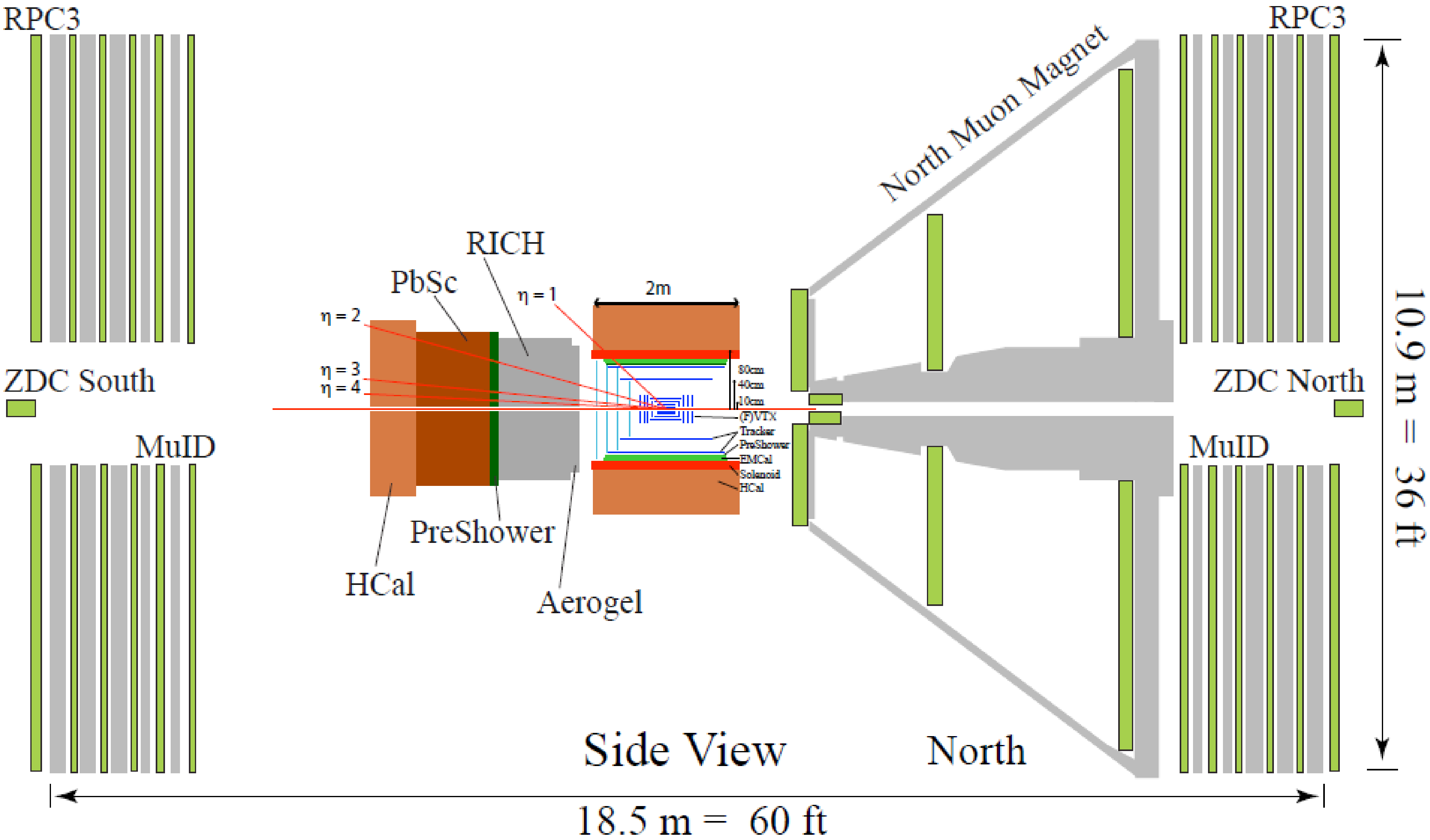






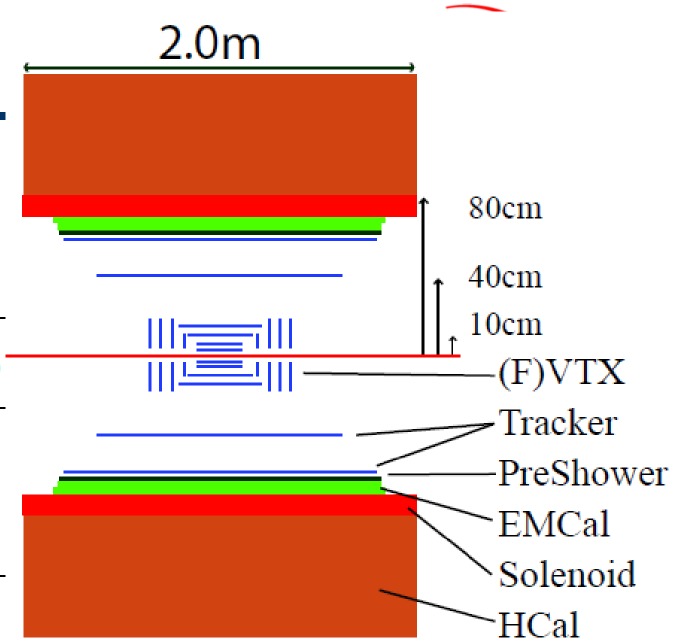
$e^{\pm}$ vs. $\mu^{\pm}$

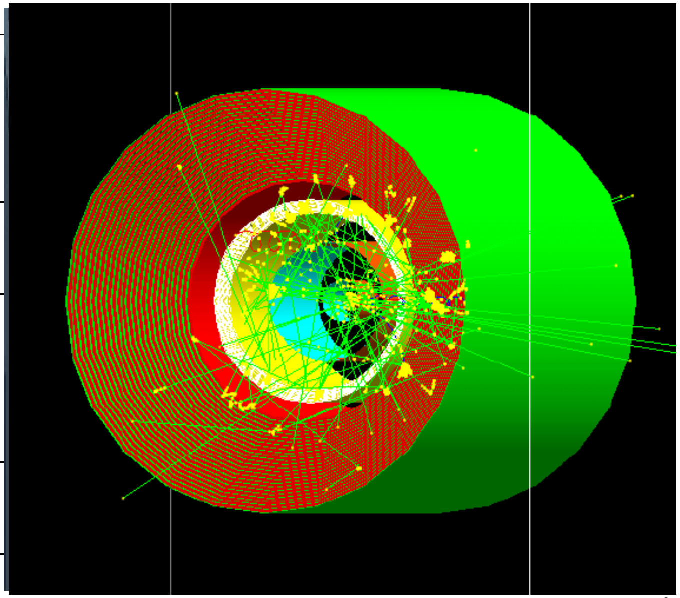
Proposed PHENIX Upgrades



Central Arm Detectors

Detector	Technology	Segmentation	R (cm)	N_{chan} ($\times 10^6$)
Inner Tracking	VTX Pixels	$50\,\mu m \times 425\,\mu m$	2.5 5	1.5 3
Inner Tracking II	VTX Strip Pixels	$80\,\mu m \times 0.1\,cm$	10 14	1.6 2.2
Outer Tracking	New Strips	$80\,\mu m \times 3\,cm$	40 60	1 2.2
Compact EMCal PS	Si-W	$300\,\mu m \times 6\,cm$	61	0.3
Compact EMCal	Si-W E1 Si-W E2	$0.75\,cm \times 0.75\,cm$ $1.50\,cm \times 1.50\,cm$	61–64 64–68	0.110 0.03
Hadronic Cal	Fe-Sc	$0.1\eta \times 0.1\phi$	80–142	0.0012

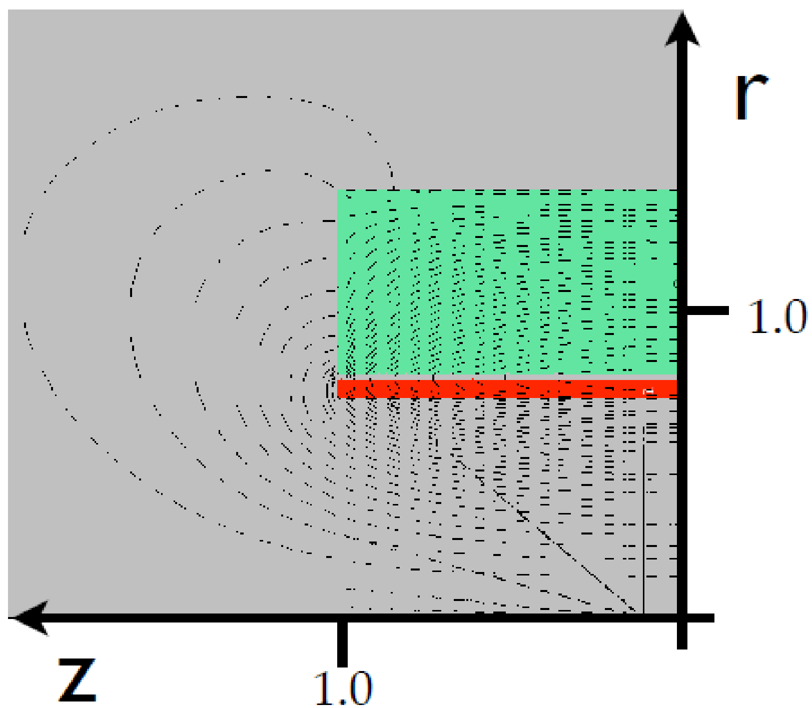




Magnet

- Solenoid similar to D0
  - Magnetic field: B = 2 T
  - Magnet dimensions: d = 1 m, l = 2 m
- Field return with small forward impact

η	θ (degrees)	$\int B\,dl$ (T-m)
0.0	90.0	1.506
1.0	40.4	1.322
2.0	15.4	0.387
3.0	5.7	0.140
4.0	2.1	0.052

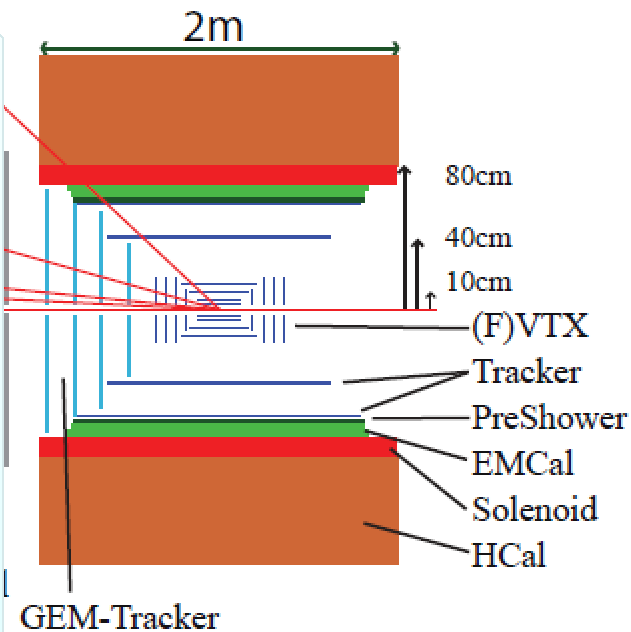


Forward Detectors

IX

- Forward direction: $1.0 < |\eta| < 4.0$
- Momentum / charge identification
- Optimized for electron / photon identification
- Hadron rejection (identification)

❖ **Tracking**
- Good resolution with small radiation length
- Displaced vertex from heavy flavor <100 μm
  - VTX & FTVX in use before 2013
- R&D for CMOS MAPS
  - Severe material constraints for e+p / e+A



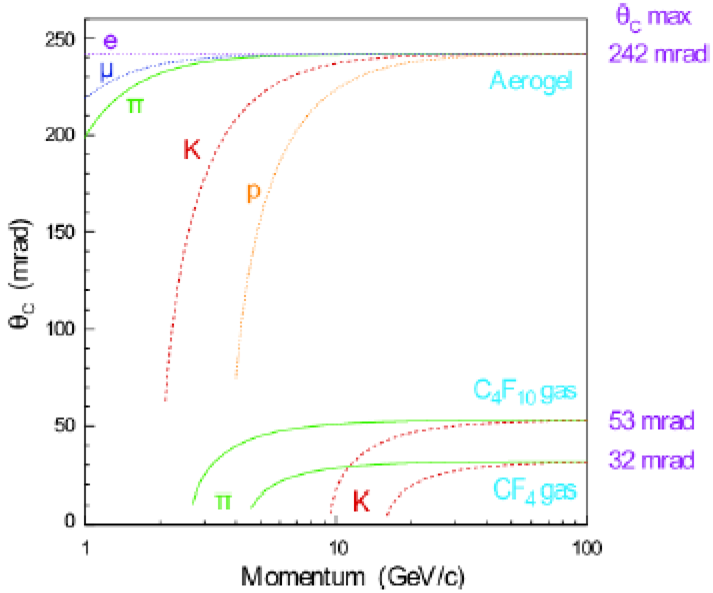
Calorimetry & Particle ID

- Combine electro-magnetic and hadronic calorimetry with a preshower detector
- EMCal: PbGl / PbSc / $PbWO_4$
  - Large longitudinal momenta require small Moliere radius
  - π^0 reconstruction up to 80 GeV desirable for A_N at high x_F
  - Radiation hardness at large pseudo-rapidities
- HaCal: FeSc (same as central HaCal)
  - Typical energy resolution needed
  - If muon ID is beneficial: CALICE concept
- PreShower
  - Based on FOCAL proposal
  - $2 \cdot X_0$ with two layers of Si strips (500 μm pitch)
- Full GEANT4 modeling not done yet

Ring Imaging Cerenkov Detector

- Dual-radiator RICH
  - Combine aerogel and gas radiator
    - $n_{aerogel} > 1.03$
    - $n_{C4F10} = 1.00137$
  - Particle ID up to p = 60 GeV/c
- Light-weight mirrors
  - Glass coated beryllium or carbon fiber
- Photon detectors: $\lambda_{radiator}$
  - PMT, APD, HPD, GEM…
  - R&D needed to determine the best solution for the requirements

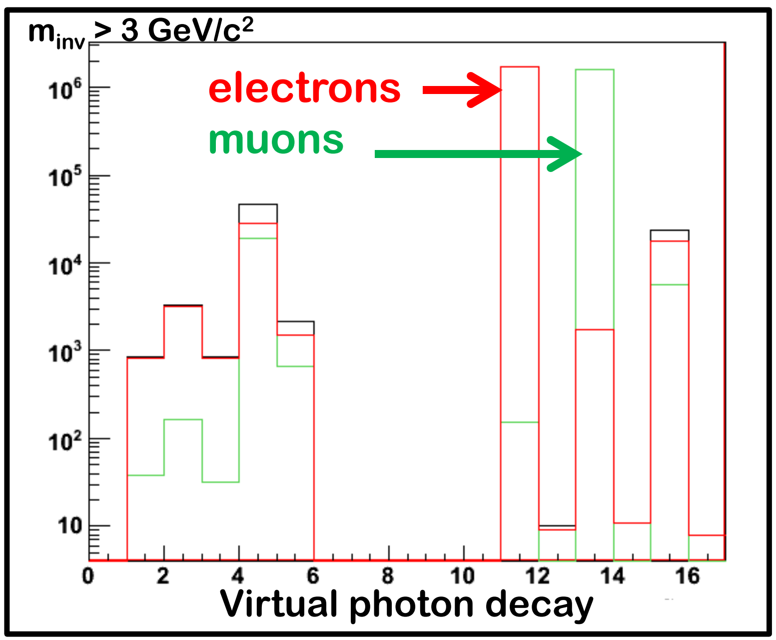
LHCb multi-radiator RICH

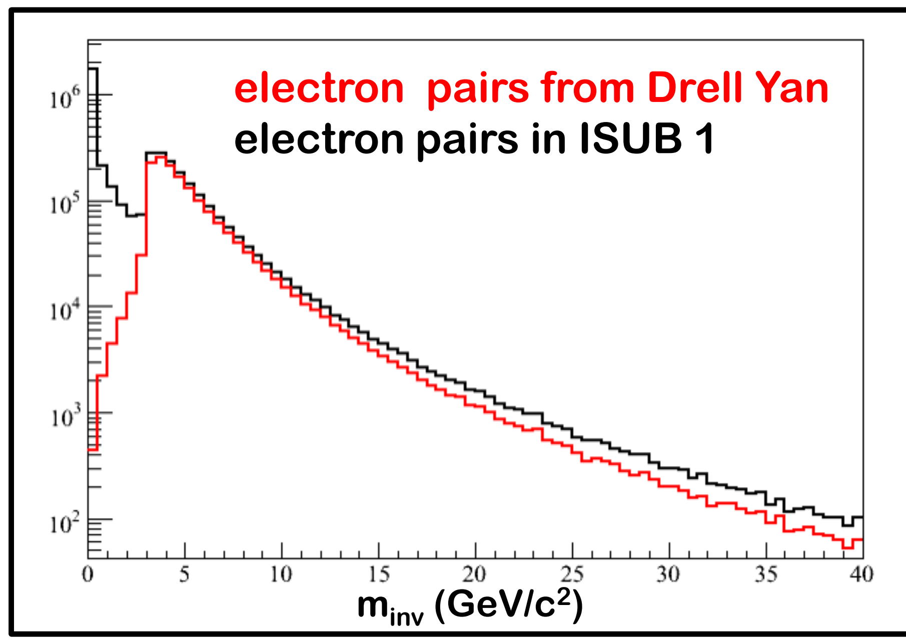


Simulation settings

- PYTHIA 6.4
  - Tune A
  - Drell Yan: ISUB 1
  - QCD jets: ISUBs 11, 12, 13, 28, 53, 68
  - Elastic, diffraction, and low-p_T: ISUBs 91, 92, 93, 94, 95
- ISUB 1: γ^* decay modes

10M events for Drell Yan
100M+ event for QCD background

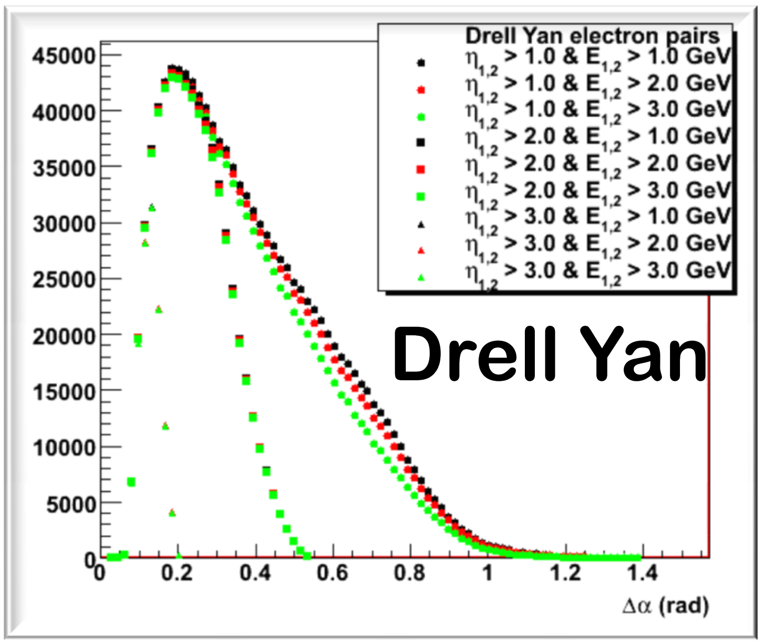




Electron pair kinematics

- Drell Yan leptons have large energies
  - Forward direction has desired asymmetry
- Background from QCD
  - Decreases with lepton energy
  - Decreases with lepton rapidity

Opening angle of electron-positron pairs



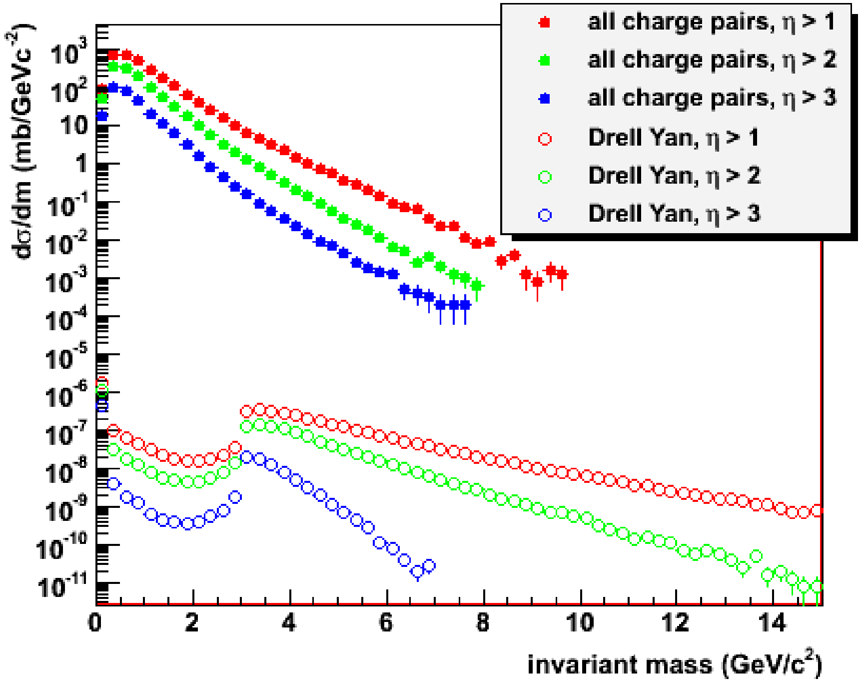
lepton energy cut
E > 1.0 GeV
E > 2.0 GeV
E > 3.0 GeV

lepton pseudo-rapidity cut
○ $\eta > 1.0$
□ $\eta > 2.0$
△ $\eta > 3.0$

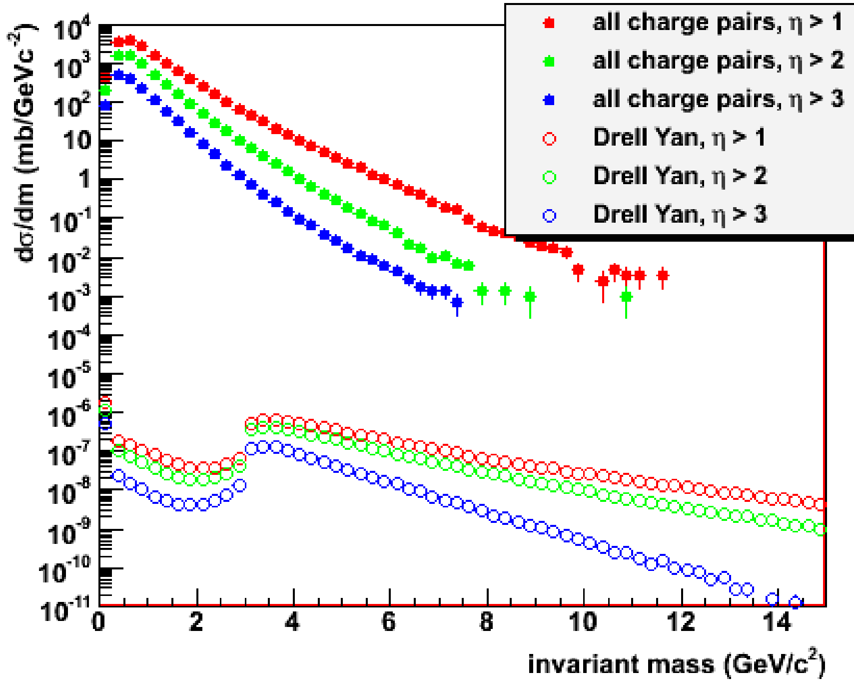
Hadron rejection

- All charged particle pairs between J/Ψ and ϒ
- Hadron suppression 10^3-10^4 needed at 500 GeV
  - Drell Yan signal reduced in 200 GeV forward

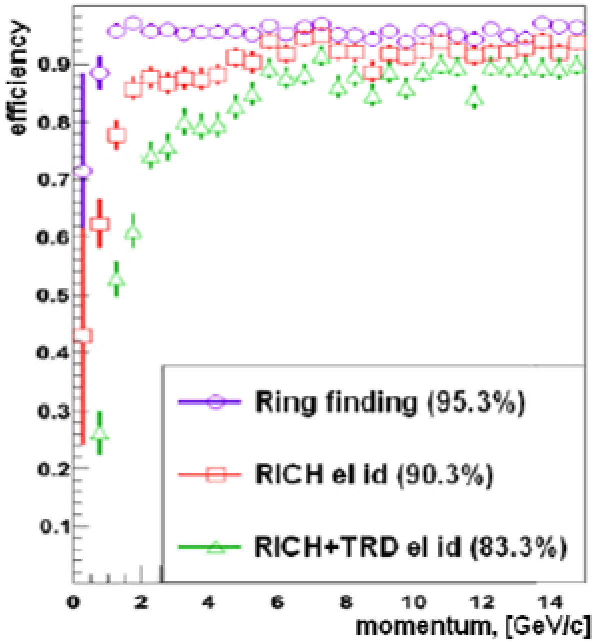
200 GeV

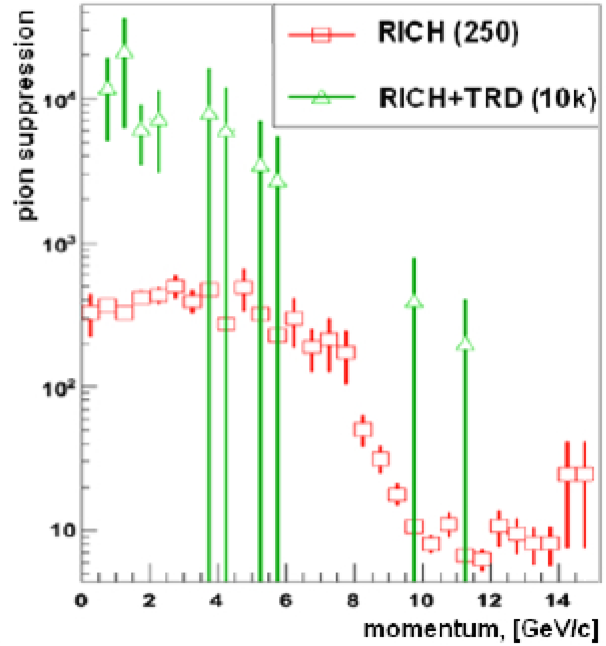


500 GeV



Fast detector modeling: RICH





Lose electrons due to detector efficiency

Mis-identify mesons as electrons

Ring Recognition and Electron Identification in the RICH detector of the CBM experiment at FAIR

Journal of Physics: Conference Series **219** (2010) 032015

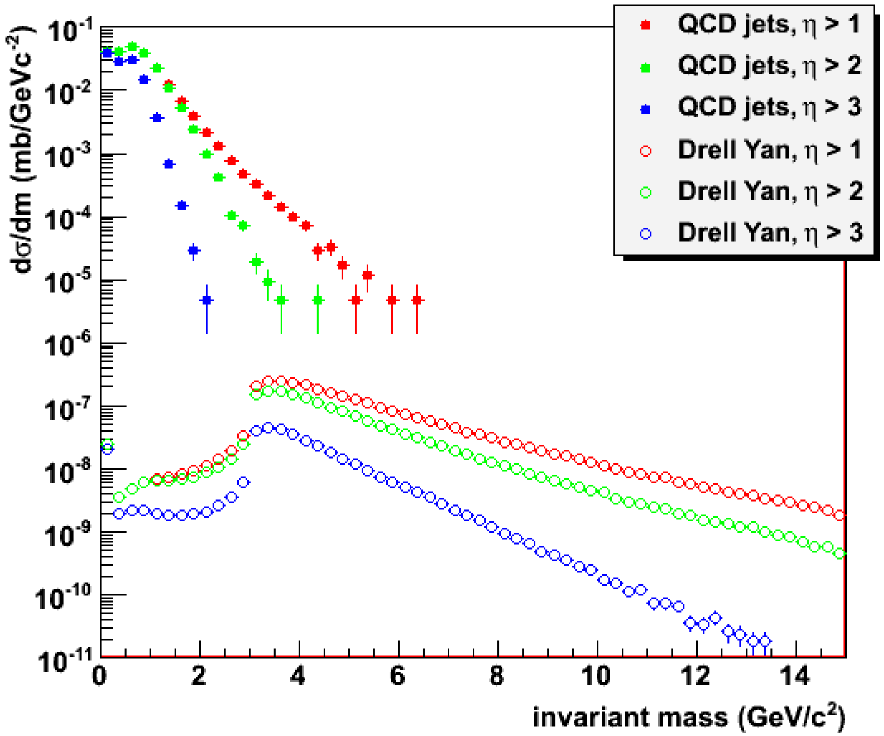
http://iopscience.iop.org/1742-6596/219/3/032015/pdf/1742-6596_219_3_032015.pdf

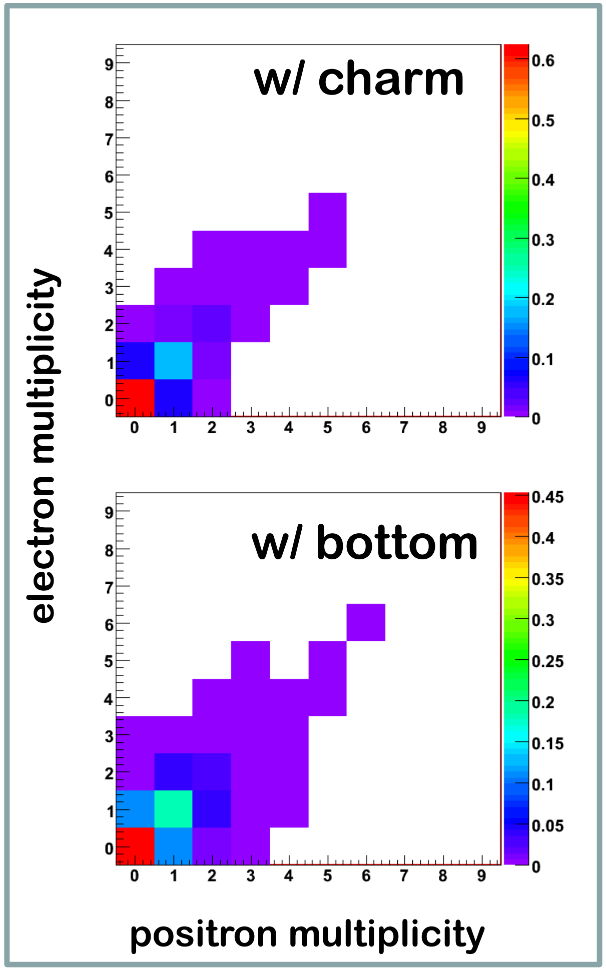
Detector smearing

- Track resolution
  - Momentum smearing $\frac{\Delta p}{p} \approx 2\%$
- Energy resolution
  - Electromagnetic shower $\frac{\Delta E}{E} \approx 5.95\%/\sqrt{E} \oplus 0.76\%$
  - Hadronic interaction in the EMCal
    - $l \approx 1 \cdot \lambda_I$
    - $\frac{E_{dep}}{E} = 35\% \pm 14\%$
  - Hadronic interaction in the HaCal $\frac{\Delta E}{E} \approx 50\%/\sqrt{E} \oplus 5\%$
- Electron efficiency 94% (p>10 GeV/c)
- preShower is not included yet
  - additional hadron rejection ≈10
- All rapidity cuts are on the leptons' pseudo-rapidity (detector acceptance)

Charge identification

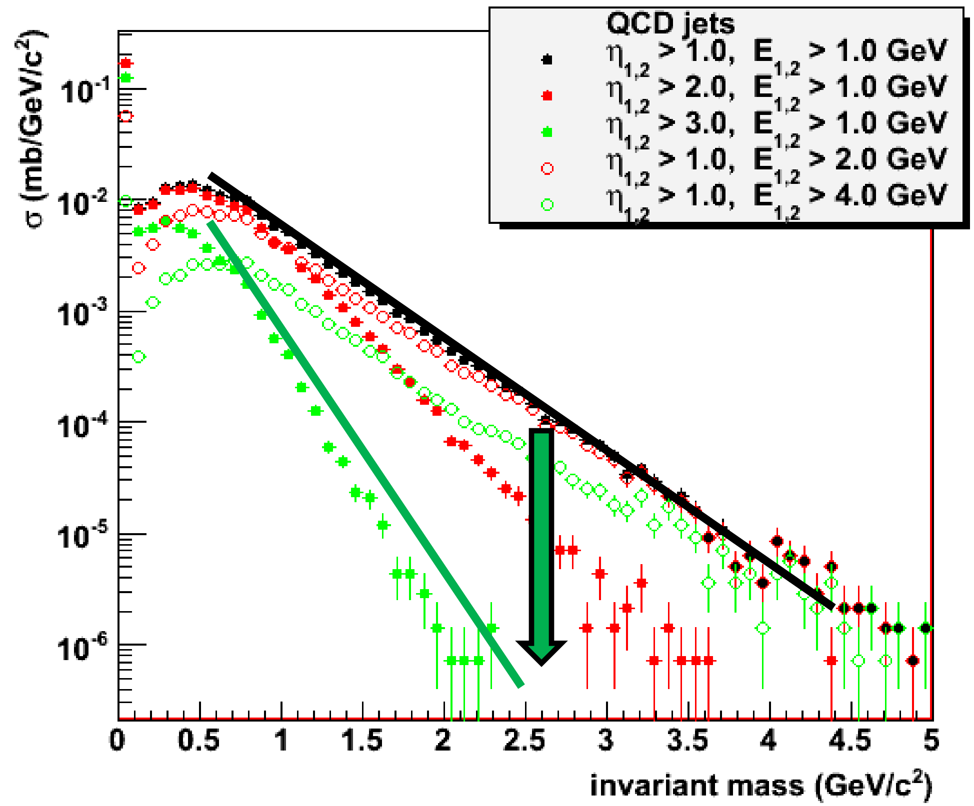
- Lepton multiplicities are small in the detector acceptance
  - ≈50% increase at small m_{inv}
  - Negligible effect for m_{inv} > 2 GeV/c^2





Background kinematics

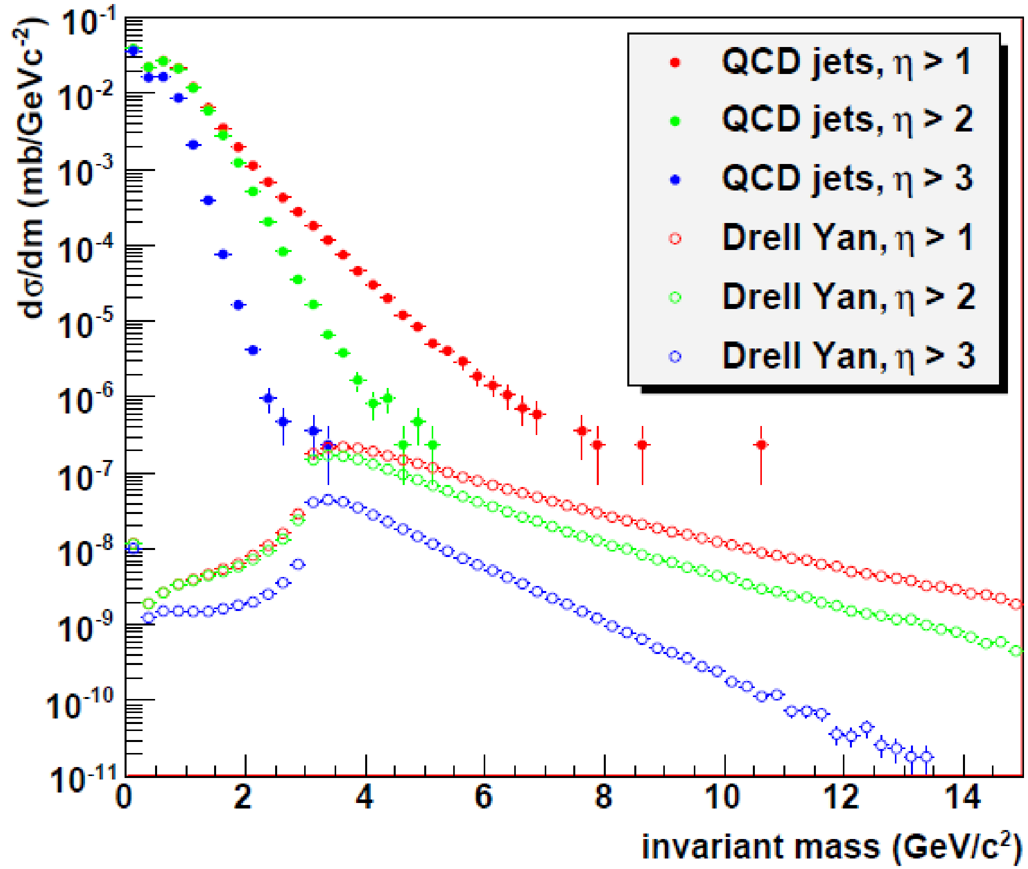
- Electrons and positrons from hard QCD processes are uncorrelated
  - Opening angles are comparable to Drell Yan: detector acceptance
  - Lepton energies of Drell Yan decays are large
  - Energy cut removes QCD background at small m_{inv}
  - Large energies in QCD background favor mid-rapidity
  - Energy asymmetry has not been instrumented yet



QCD jet background

hard QCD and diffractive processes

- Drell Yan signal
  - 3 – 10 GeV/c^2
- Energy cut
  - $E_{1,2}$ < 2 GeV
- Forward rapidities
  - Effectively no background left
  - Statistically limited
  - Drell Yan for m_{inv} < 3 GeV/c^2 not physica



Heavy flavor contributions

- More low mass heavy flavor in forward directions
- Charm & bottom contributions increase with m_{inv}
- Need designated heavy flavor simulation
- Comparison at $m_{inv} < 3$ GeV/c^2 needs more studies
  - See previous slide
  - Smaller energy cut