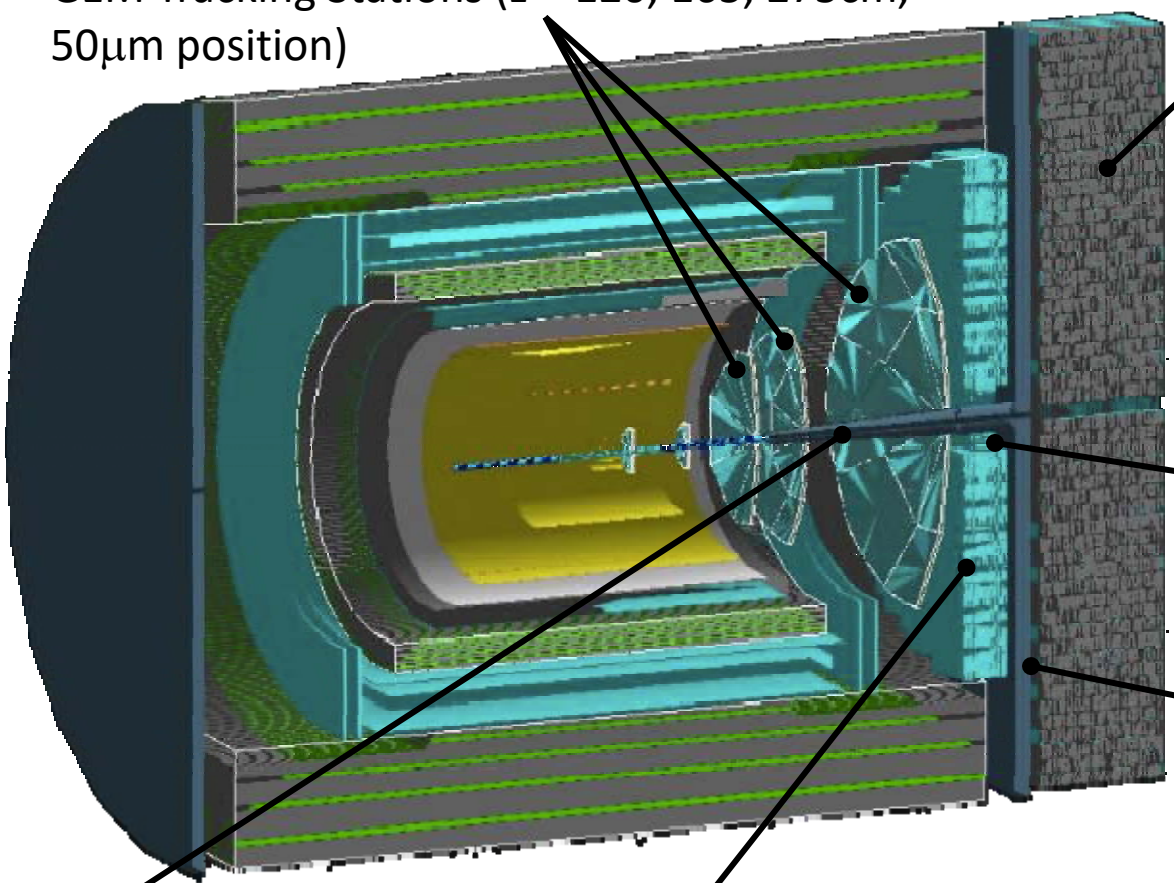
Simulation Studies

J. Lajoie

Iowa State University

Outline

- Brief overview of fsPHENIX
- Performance of forward tracking
- Forward calorimetry performance
- Simulated performance for Drell-Yan
- A few other comments:
  - Forward upsilons
  - Z^0/W statistics
  - Prior forward jet simulations
- Conclusions



GEM Tracking Stations (z = 120, 165, 275cm, 50μm position)

Pb/Sc sandwich hadronic calorimeter (NEW)
10 x 10 x 100 cm^3 towers
($1.2 < \eta < 4.0$)

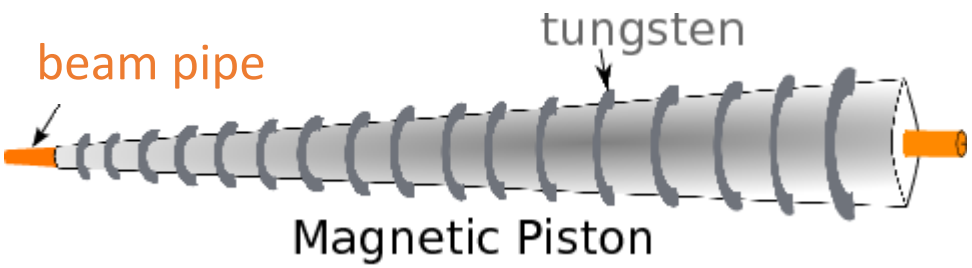
20x20 array of
2.2 x 2.2 x 18 cm^3
PbW (PHENIX MPC)
crystals with 10x10
square hole
(300 crystals total)
$3.0\text{-}3.3 < \eta < 4.0$

Flux return door
between FEMC and
FHCAL (10.2 cm)

Field shaper piston

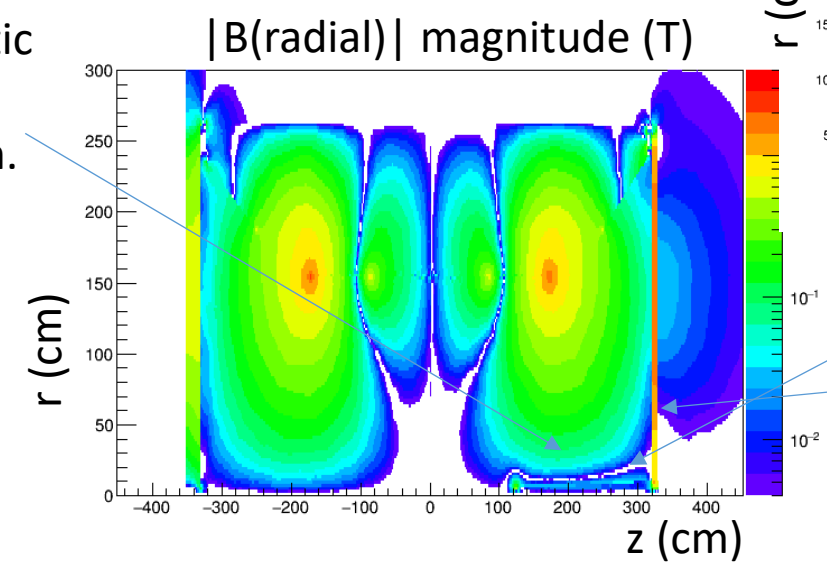
PHENIX PbSc modules (5.5 x 5.5 x 33 cm^3) organized in groups of four modules (3152 modules or 788 groups of 4) ($1.4 < \eta < 3.0\text{-}3.3$), energy resolution $8\%/\sqrt{E}$

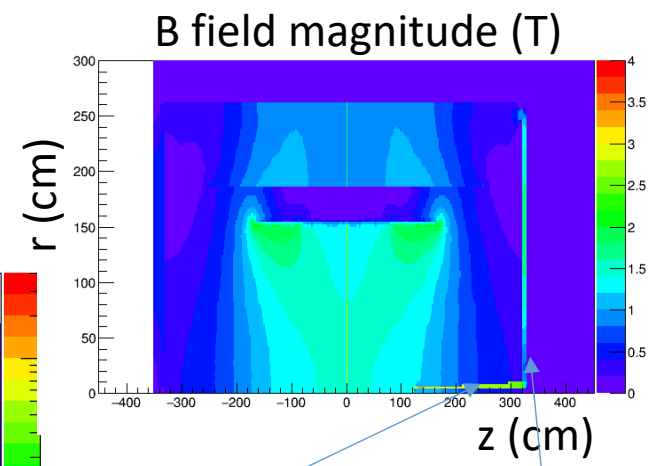
Forward Magnetic Field



HIPERCO-50 high permeability piston around beam pipe, tungsten ribs reduce backgrounds around calorimeter hole.

Piston enhances transverse component of magnetic field, improving momentum resolution.





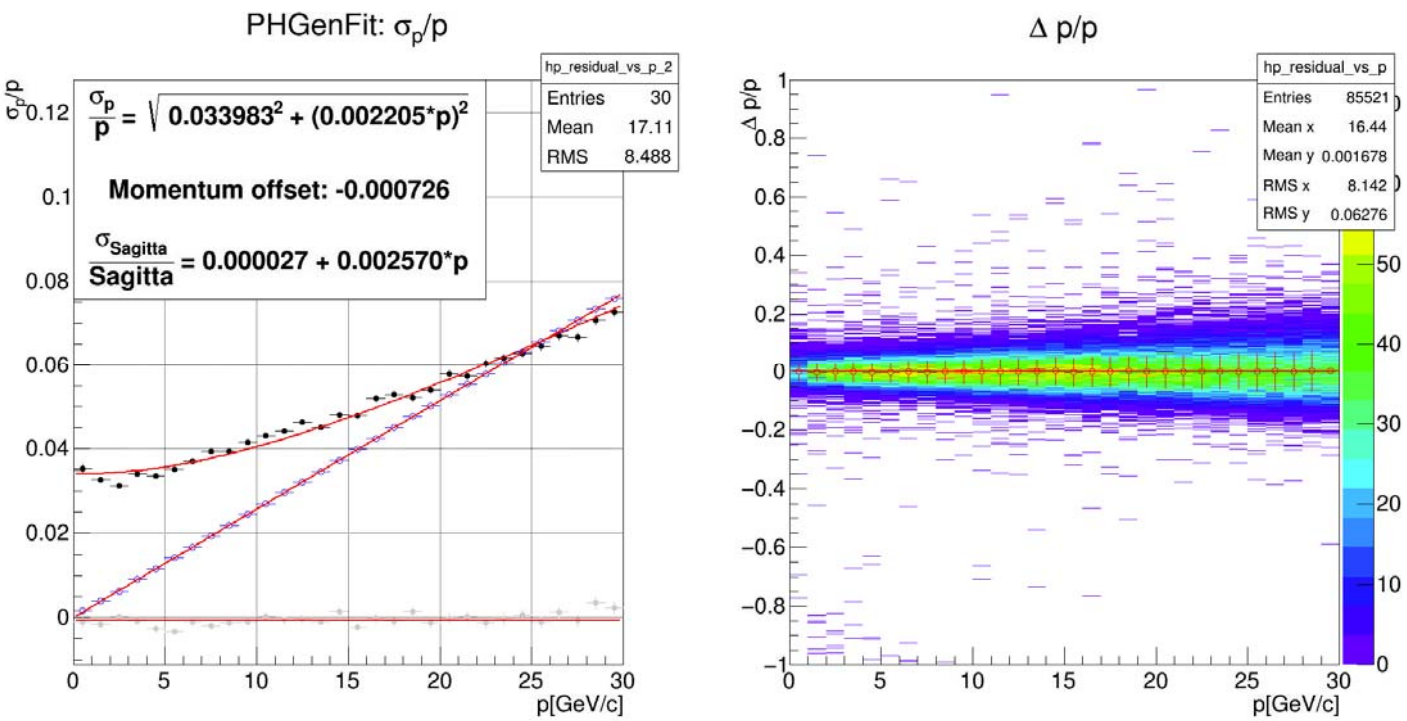
piston

plug door

Forward Tracking

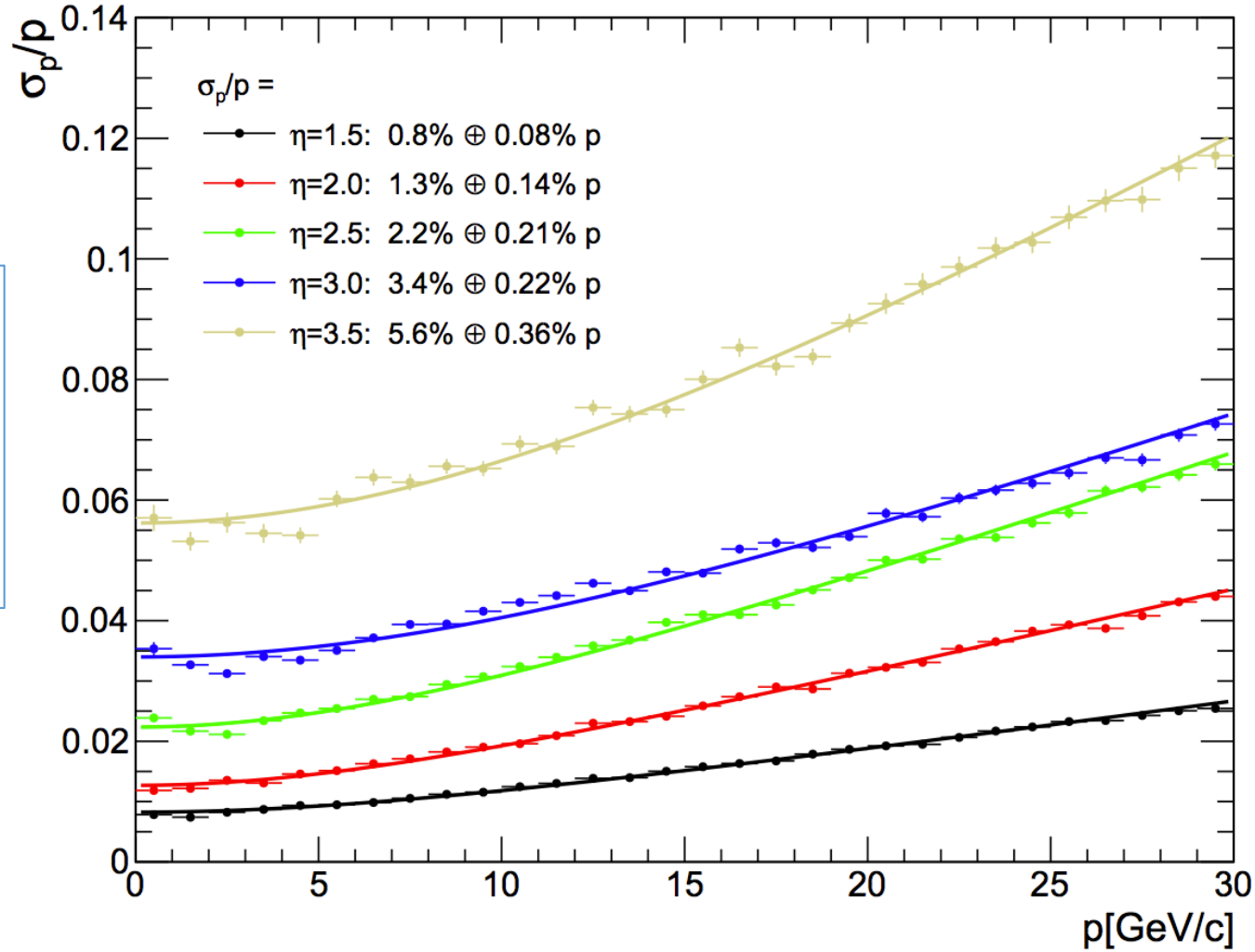
- **G4 Simulation and (PH)GenFit** to extract $(p_{Reco} - p_{True})/p_{True}$ vs p_{True} (right plot)
- For each slice of p_{True}, fit with Gaussian, extract mean as offset (Grey dots), sigma as momentum resolution (σ_p: Black dots), left plot.
- We also calculated $<\sigma_{Sagitta}/Sagitta>$ as a reference (Blue circles): Sagitta is calculated using vertex, station at 120cm and station at 275 cm.

Tracking simulations by Haiwang Yu



Performance vs. Pseudorapidity

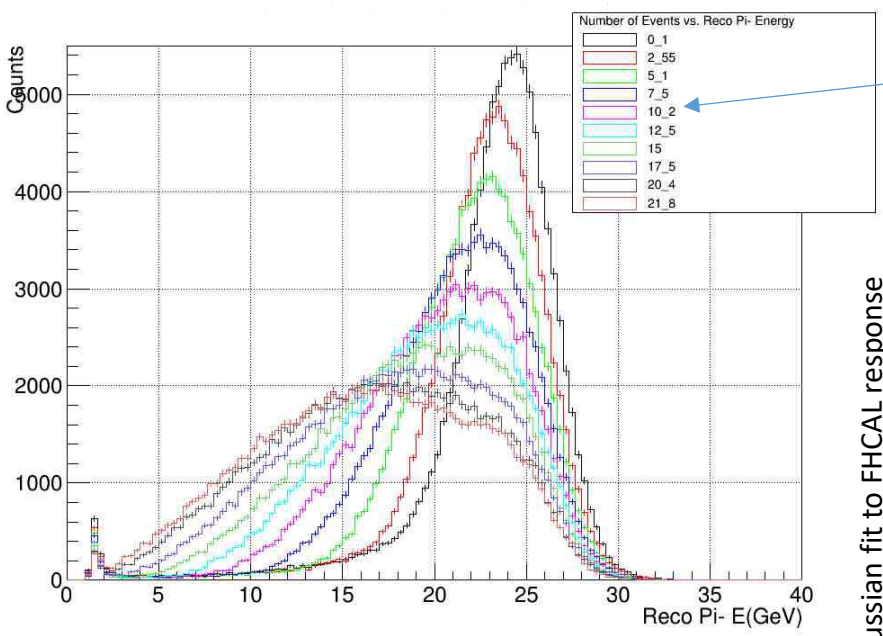
Excellent momentum resolution over the full pseudorapidity range!



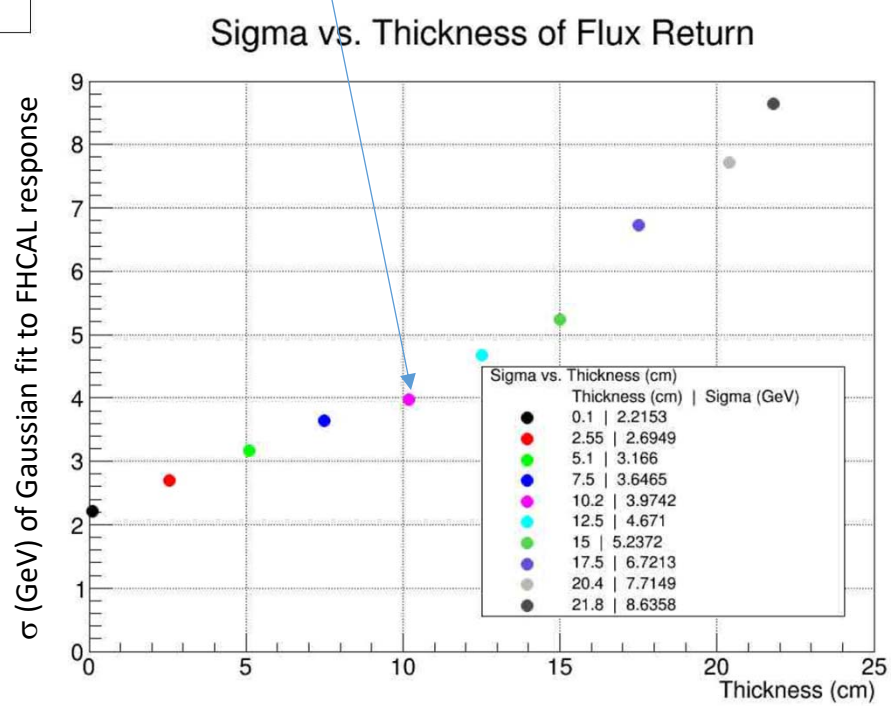
Forward HCAL Simulations

Studies by D. Kapukchyan

Studied the effect of the sPHENIX flux return on the FHCAL energy resolution (examples below are 30GeV pions).
Plug door could be replaced by magnetic FHCAL.

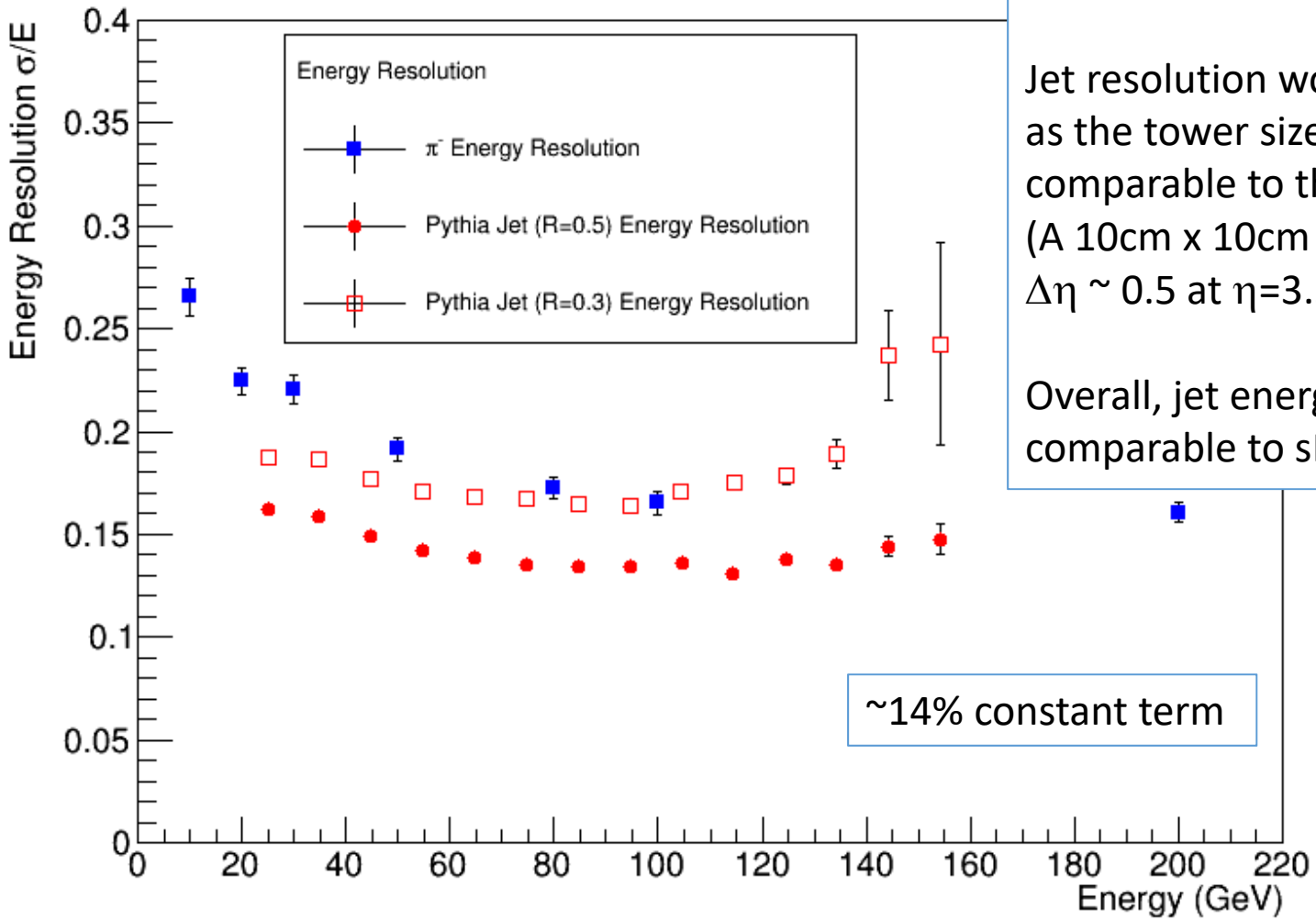


Nominal plug door thickness is 10.2 cm



Plug door decreases response and generates a non-Gaussian tail.

Jet Energy Resolution



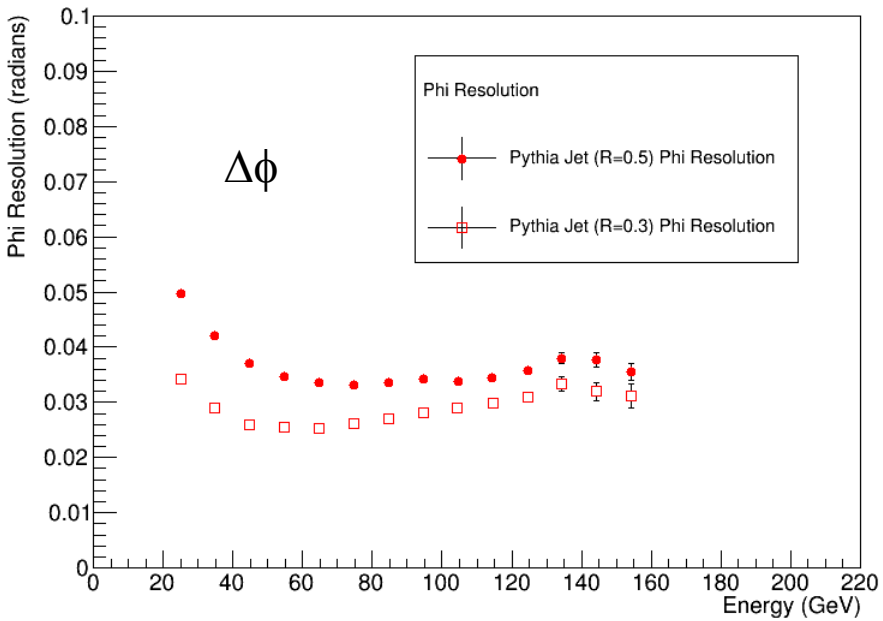
Jets from 510 GeV Pythia8, using jet trigger, jet energy is <u>correlated</u> with pseudorapidity. Required E>20GeV, p_T>5GeV.

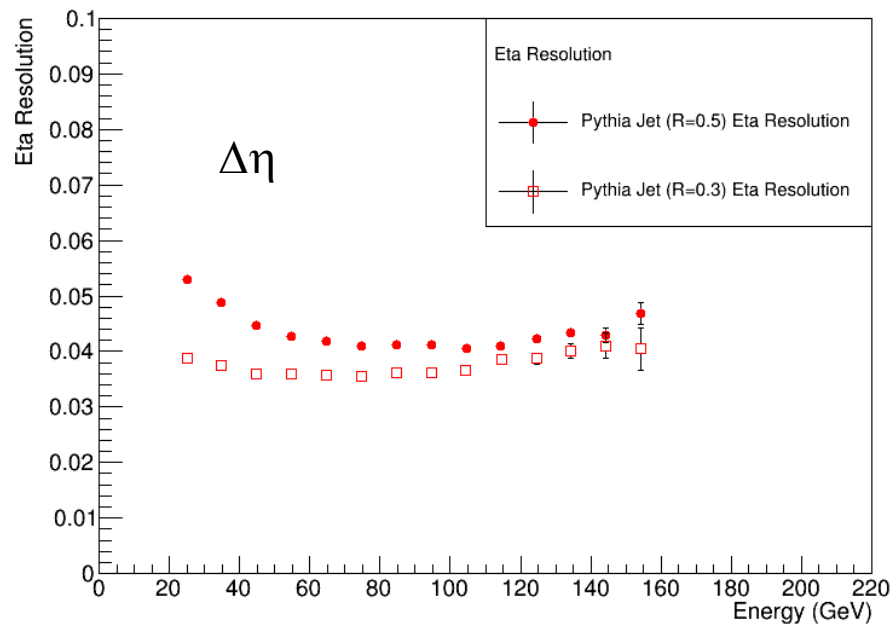
Jet resolution worsens at high η as the tower size gets comparable to the cone size. (A 10cm x 10cm FHCAL tower is Δη ~ 0.5 at η=3.5.)

Overall, jet energy resolution comparable to sPHENIX barrel.

~14% constant term

Jet Eta,Phi Resolution





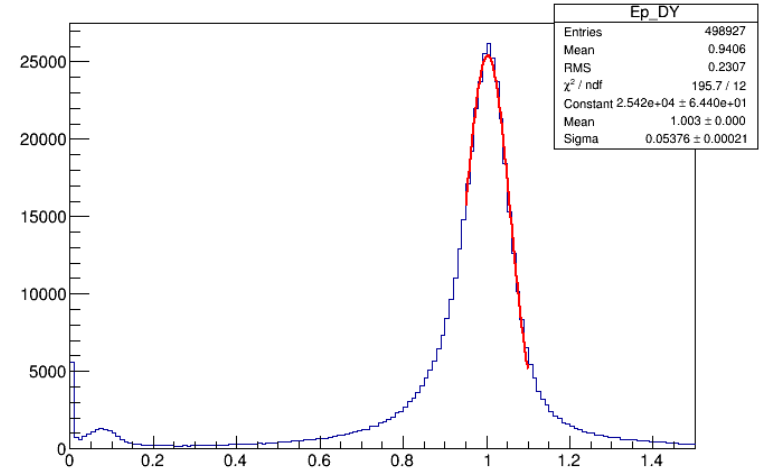
Jet eta, phi resolution approximately 0.04 x 0.03 for R=0.3
Prior studies in p+A show similar performance in p-going direction.

Drell-Yan Signal/BG Simulations

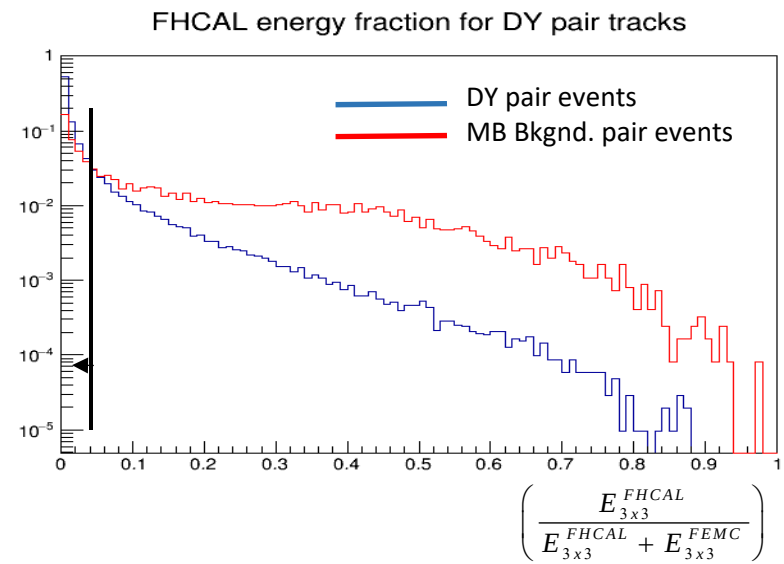
- Full G4 simulation of both signal and backgrounds
- Pythia events are generated using electron trigger
  - Requires at least one e^+/e^- in $1.4<\eta<4.0$ with $p_T>0.5$ GeV
    - Consistent with a scaled EMCal energy trigger
  - This is an energy of 1.1 GeV @ $\eta=1.4$ and 13.7 GeV @ $\eta=4.0$
  - DY events generated using COMPASS tuning
  - MinBias, J/Psi and Upsilon generated and scaled using Pythia tuned to PHENIX data
- Tracks fit using (PH)GenFit
  - "Perfect" tracking algorithm with FGEM efficiencies 0.95
  - Tracks projected into FEMC, FHCAL

DY Cuts and Analysis

- A candidate DY pair requires:
  - Track Cuts:
    - $1.4 < \eta < 4.0$
    - One of the two tracks consistent with firing the electron trigger
    - >= 4 FGEM hits
    - abs(E/p – 1.0) < 3σ
    - FHCAL energy fraction < 0.04
  - Pair Cuts:
    - Tracks have opposite charge sign
    - Mass > 1.0 GeV
    - Only one pair in an event
  - Event Cuts:
    - Pair forward energy fraction >0.44
    - sPHENIX barrel energy < 5 GeV
  - 97% of pairs in DY events are true DY pairs (3% contamination)

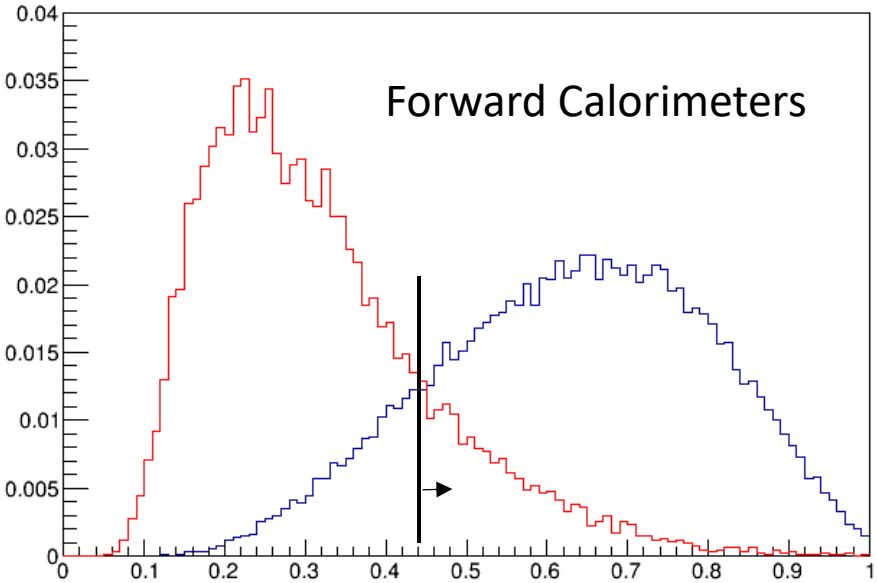


FEMC E33/p



$$\left(\frac{E_{3x3}^{FHCAL}}{E_{3x3}^{FHCAL} + E_{3x3}^{FEMC}} \right)$$

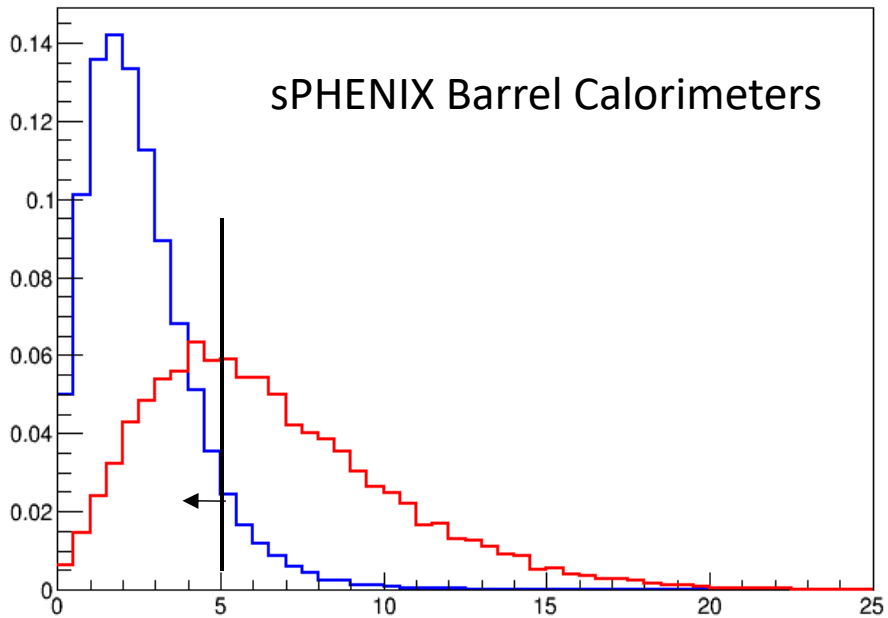
Event Charcterization Cuts



Sum Pair FEMC E33/(FEMC+FHCAL) > 0.44

DY pair events

MB Bkgnd. pair events

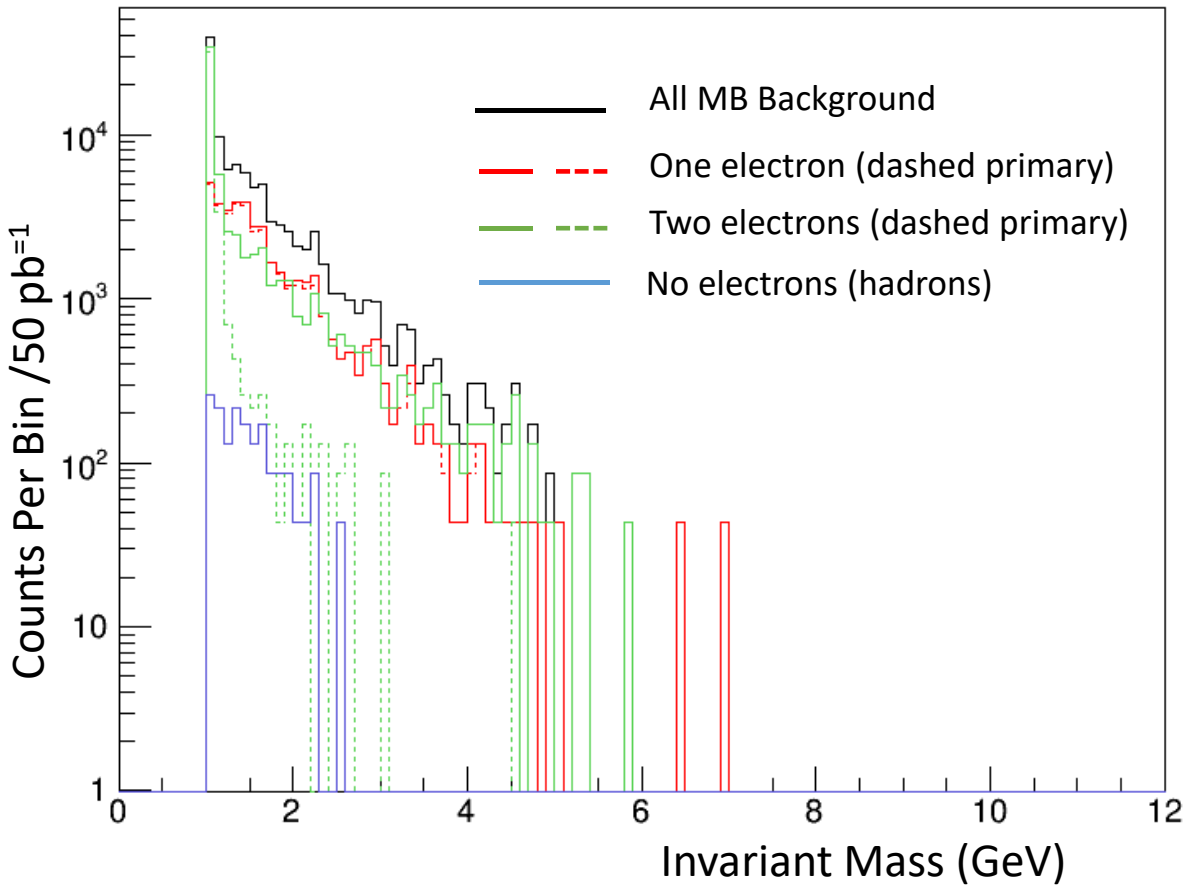


CEMC + IHCAL + OHCAL Energy (GeV)

Event topology cuts are effective in eliminating background processes that generate false DY pairs.

MinBias Backgrounds

- **59.035M Pythia events saved (32.08B events sampled)**
- **Corresponds to 1.16pb^{-1} integrated lumi**



Observations:

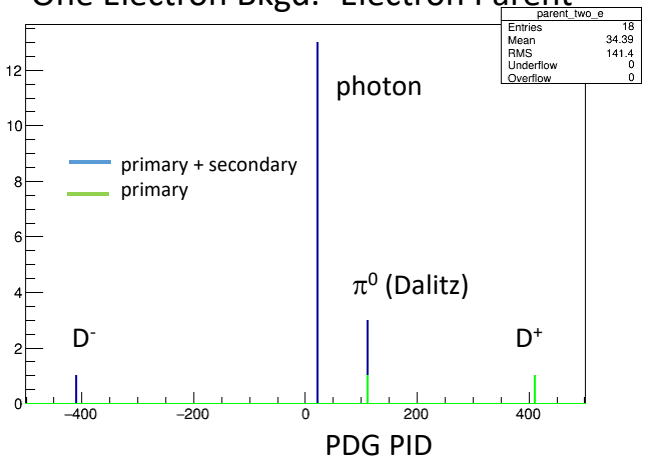
- One-electron background is dominated by primary electrons
- One electron and two-electron backgrounds comparable
- Two-electron background dominated by secondary electrons
- Hadron-Hadron background is negligible

Results shown scaled to 50 pb^{-1}

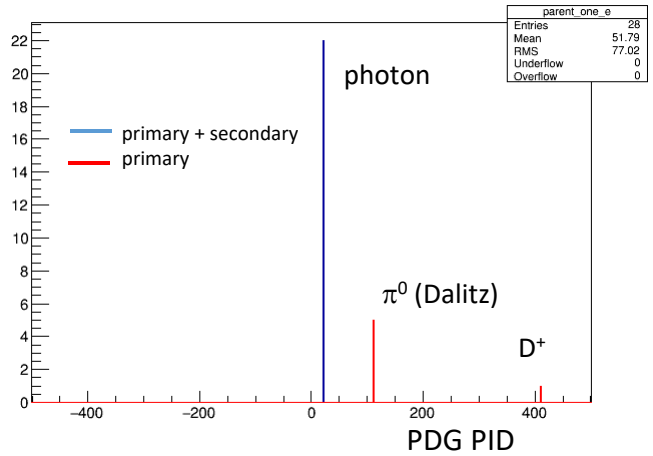
MB Background Sources

- Original MB run did not have parent ID for primaries. Ran a short MB run ($0.05pb^{-1}$) with this information included.
  - Also removed event level cuts to get more statistics

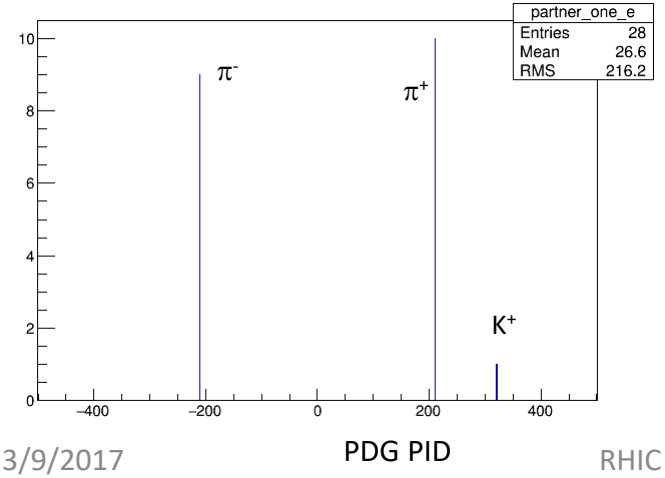
One Electron Bkgd.- Electron Parent



Two Electron Bkgd. – Electron Parents



One Electron Bkgd.- Electron Partner



- One electron background dominated by conversions, π^0 Dalitz, and open charm.
- One electron partners are mostly charged pions.
- Two electron has the same sources.

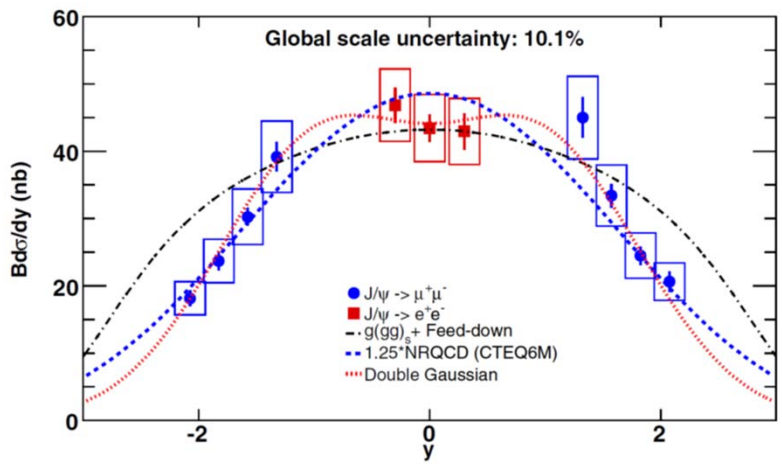
- Event cuts preferentially suppress conversions, π^0 Dalitz becomes relatively more important

Scaling the Quarkonia Contributions

- In principle, the onia contributions should account for directly produced onia + feed down – scale the pythia results to match the PHENIX measurements:

J/Ψ:

PRL **98,** 232002 (2007)



Scale results by:
$\sigma_{PHENIX}/\sigma_{PYTHIA}$ (1.2<y<2.2) = 3.31

Upsilon:

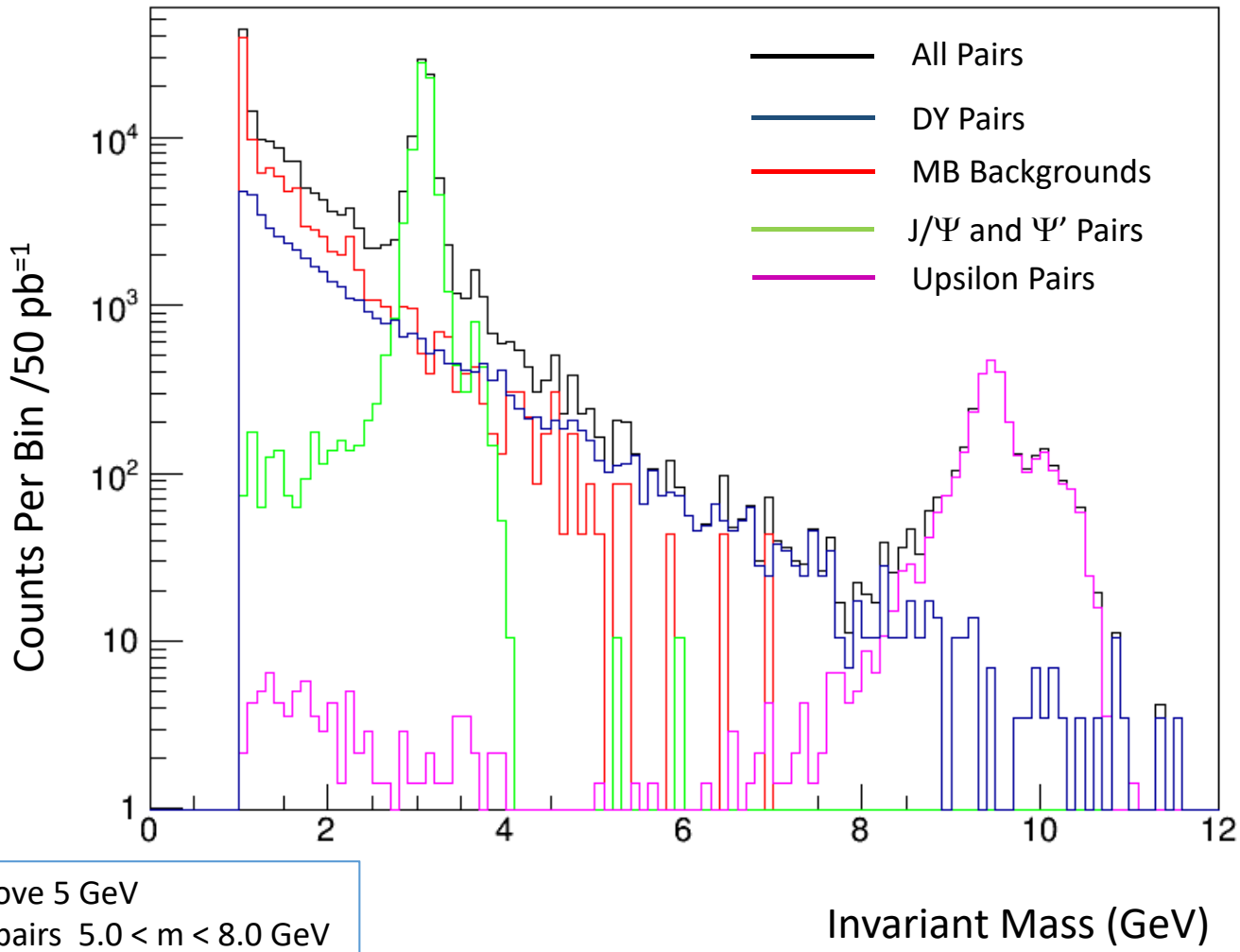
PHYSICAL REVIEW C **87**, 044909 (2013)

TABLE V. Υ invariant yields and cross sections of $p+p$ and $d+$Au data sets are shown. The first uncertainty shown is the statistical uncertainty, and the second is the systematic uncertainty.

Data set	N_{MB}^{BBC} ($\times 10^{11}$)	$B_{\mu^+\mu^-} dN_\Upsilon/dy$ ($\times 10^{-10}$)	$B_{\mu^+\mu^-} d\sigma_\Upsilon/dy$
$p+p$ south	5.1	$3.8 \pm 1.1 \pm 0.5$	$16.0 \pm 4.6 \pm 2.2$ pb
$p+p$ north	5.2	$3.6 \pm 1.0 \pm 0.4$	$15.4 \pm 4.3 \pm 1.8$ pb
$d+$Au south	1.3	$17.8 \pm 5.5 \pm 2.9$	$4.0 \pm 1.2 \pm 0.6$ nb
$d+$Au north	1.3	$25.2 \pm 5.6 \pm 3.3$	$5.7 \pm 1.3 \pm 0.7$ nb

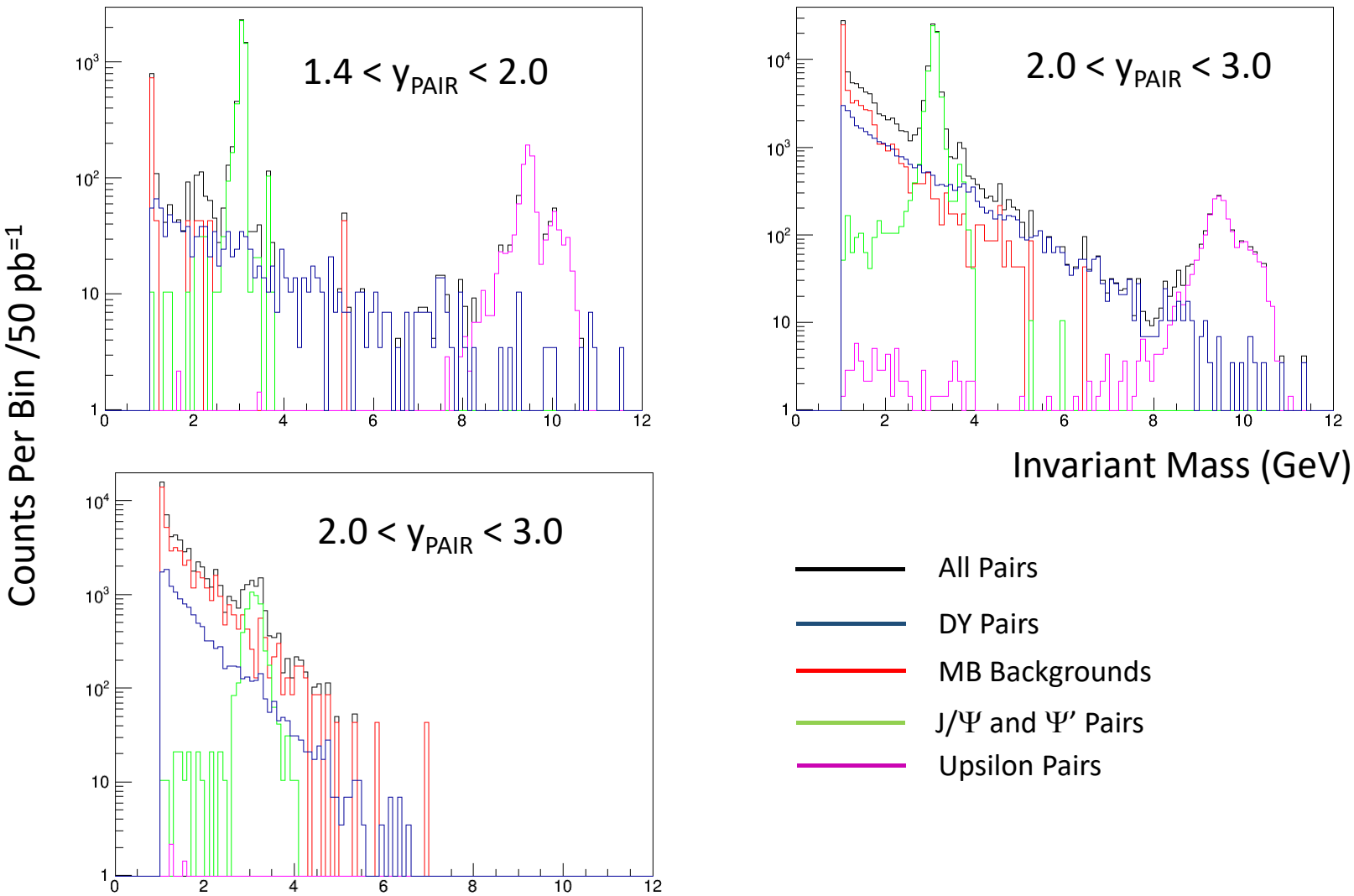
Scale results by:
$\sigma_{PHENIX}/\sigma_{PYTHIA}$ (1.2<y<2.2) = 1.46

Combined 1.4< y_{PAIR} < 4.0



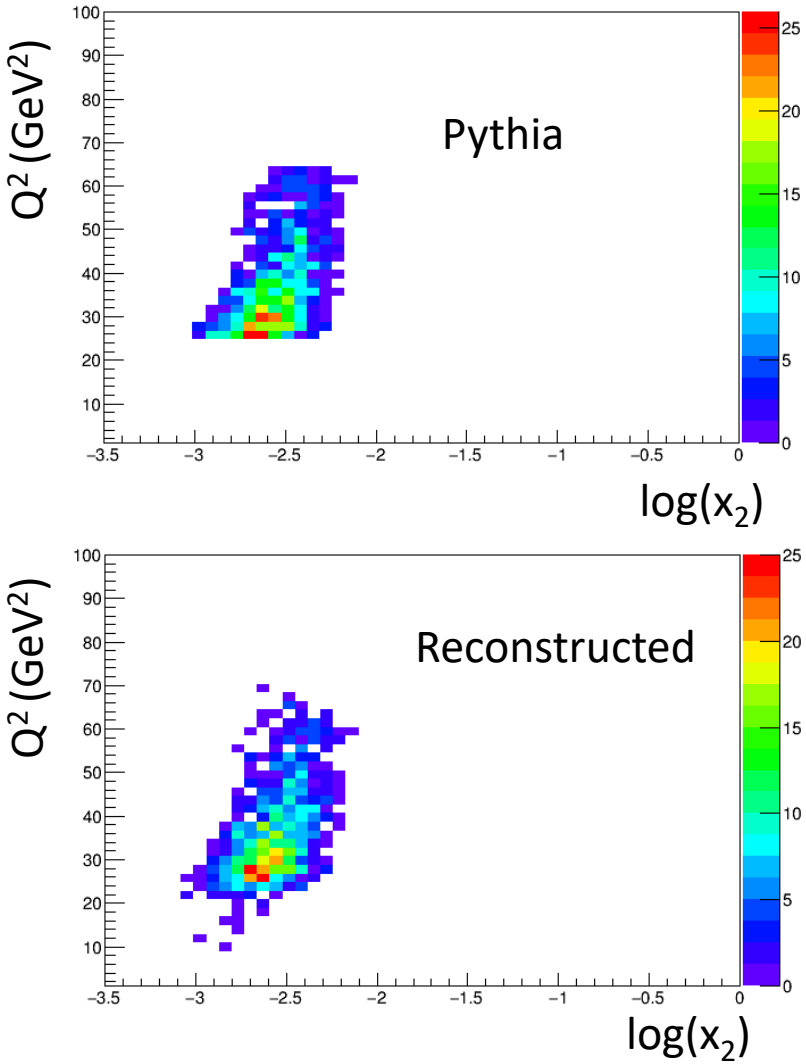
S/B ~ 1 above 5 GeV
~1900 DY pairs 5.0 < m < 8.0 GeV

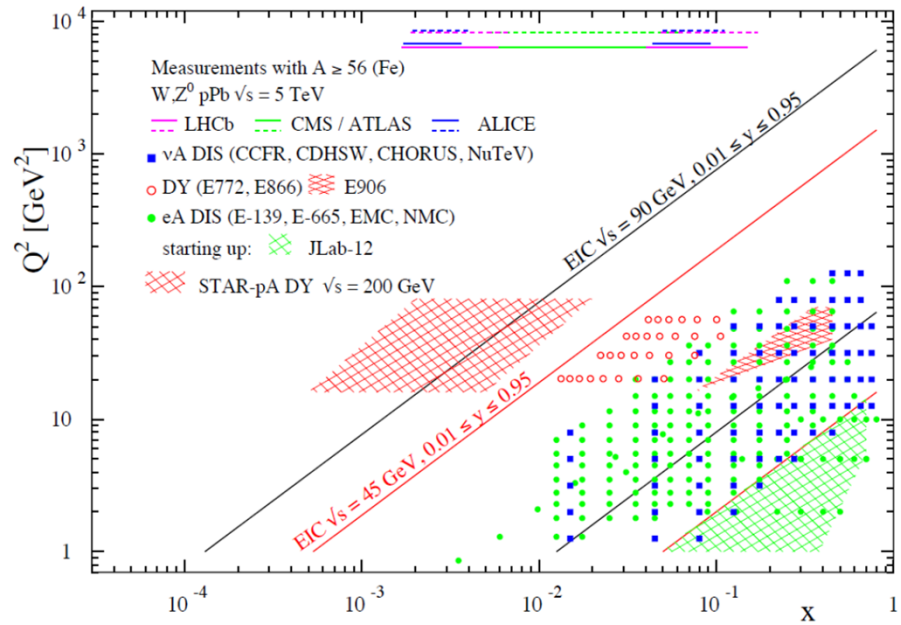
In Different Rapidity Slices



DY Kinematic Acceptance/Resolution I

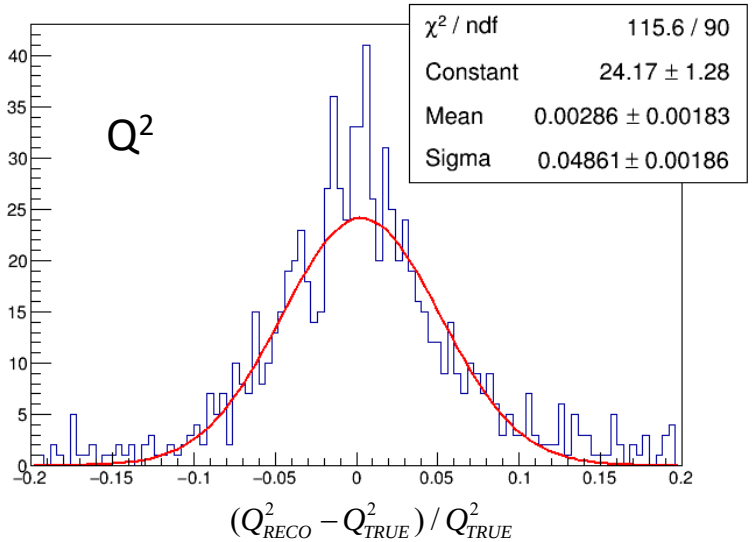
DY pairs with 5.0 < m < 8.0 GeV

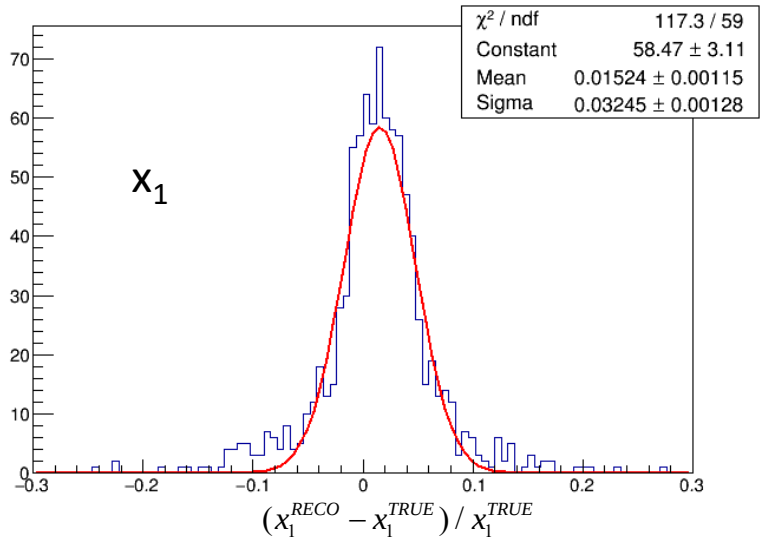


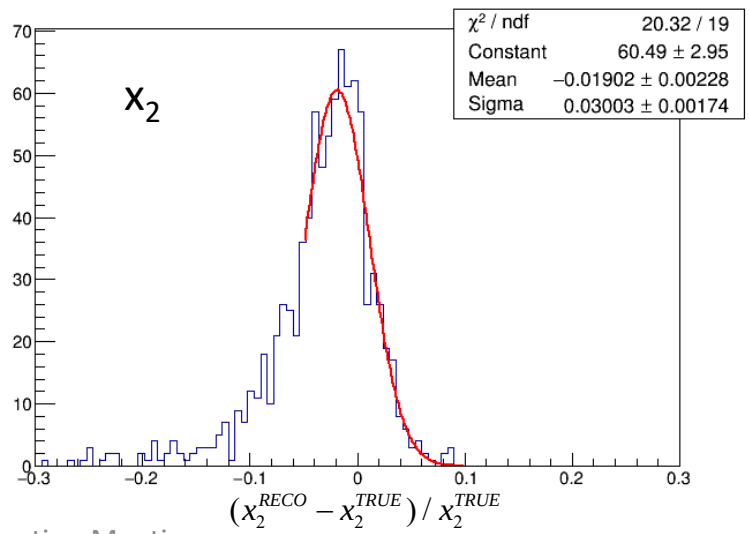


DY Kinematic Acceptance/Resolution I

DY pairs with 5.0 < m < 8.0 GeV

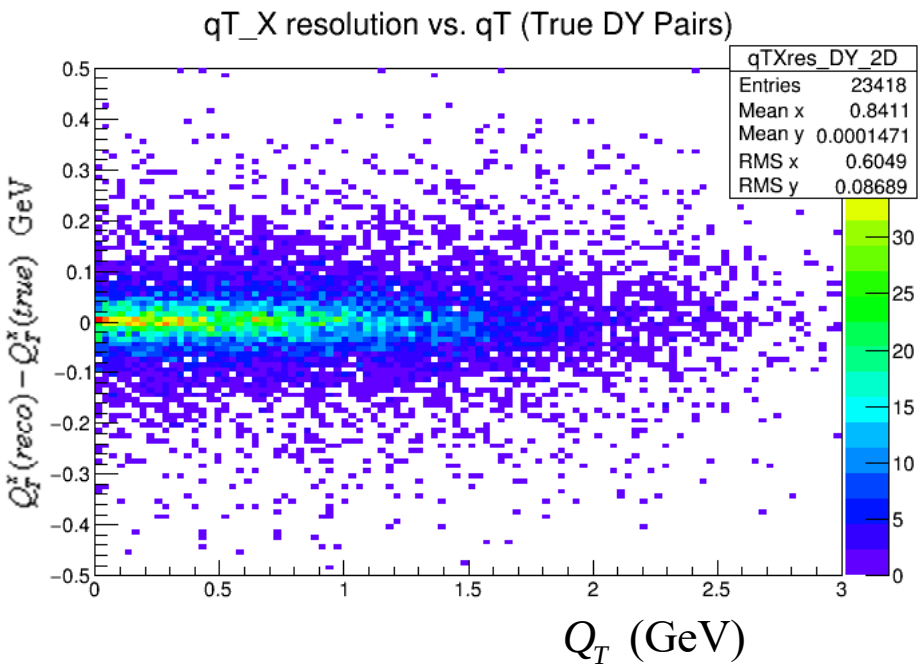






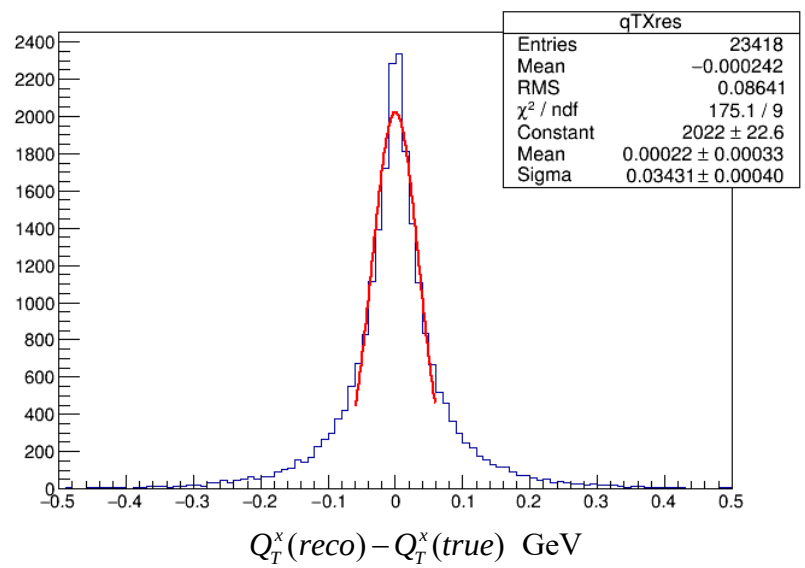
Fractional error in Q^2 about 5%.
Fractional error in x1, x2 about 3%.
x_1 shows a ~1.5% systematic shift up.
x_2 shows a ~2% systematic shift down, with asymmetric tail.

Q_T^x Resolution

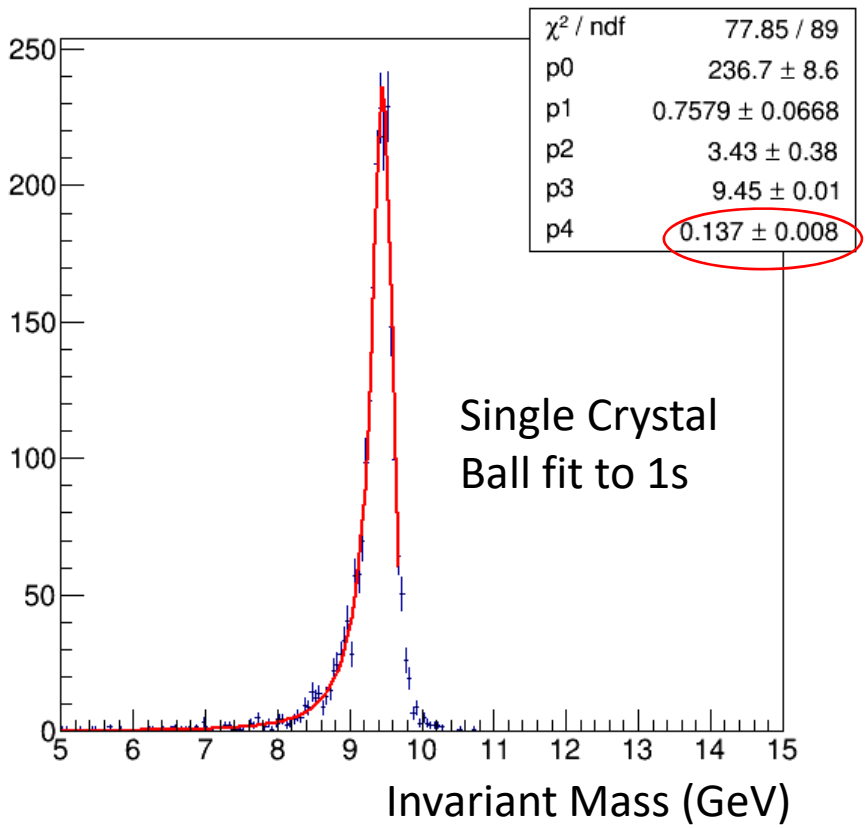


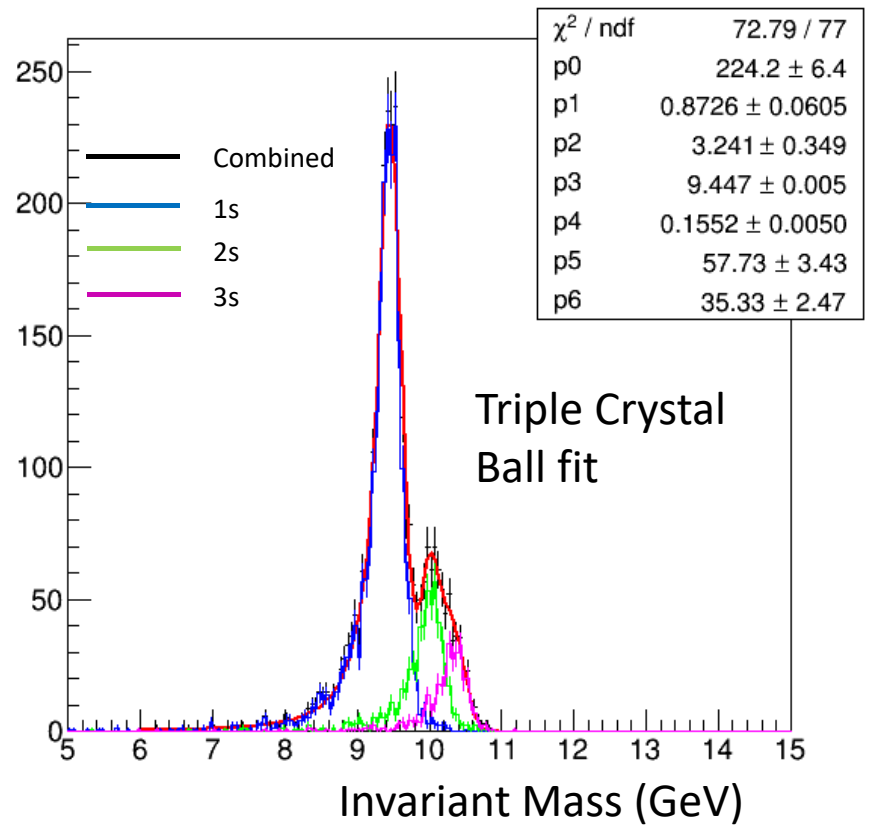
The resolution on the x component of the virtual photon momentum is critical for DY AN – this sets a limit on your ability to define "left" and "right".

The resolution has a Gaussian core with σ ~ 34 MeV, and non-Gaussian tails, as expected from multiple scattering.



What about the Upsilon?

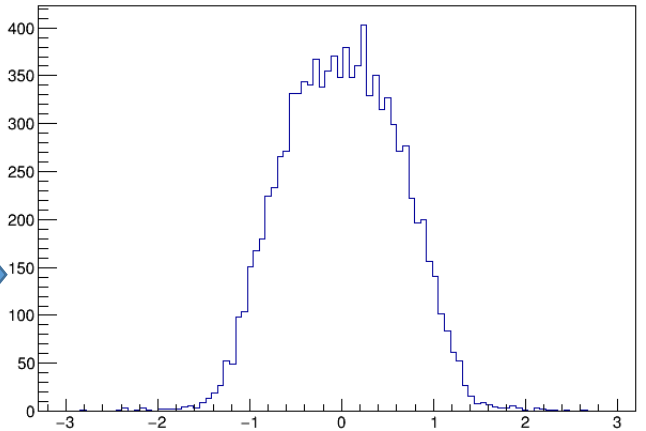




2s/1s ratio = 0.261 from 3CB fit (truth 0.260)
3s/1s ratio = 0.160 from 3CB fit (truth 0.145)

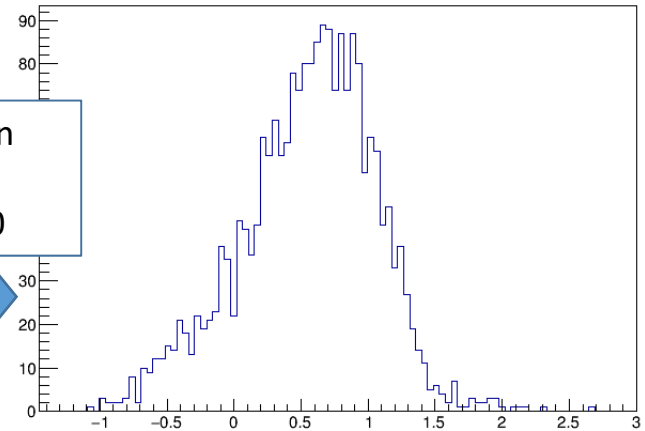
What about the Z^0 (510 GeV)?

y of produced Z^0 :



y of Z^0

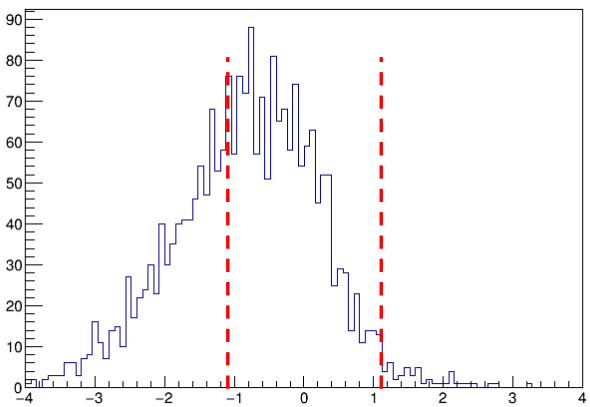
One electron
p_T>5.0 GeV
$1.4 < \eta < 4.0$



y of Z^0

One electron
p_T>5.0 GeV
$1.4 < \eta < 4.0$

Where does the second electron go?



η of second e^-

f+sPHENIX acceptance well-positioned for Z^0 A_N measurement that samples large x in the proton.

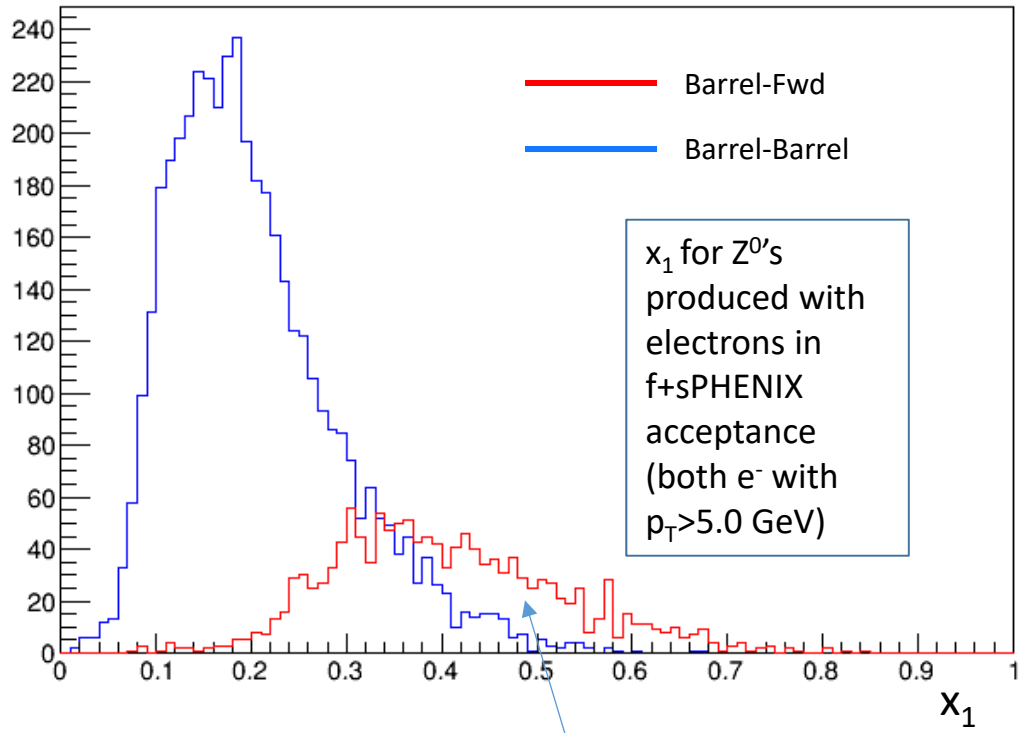
Z^0 Yield and x_1 Coverage

- Cold QCD Plan suggests a possible 510 GeV run could deliver as much 1.1 fb^{-1}
- Assume integrated lumi. is 600 pb^{-1} , this yields:

- 1300 Z^0 with one electron in the forward acceptance ($1.4<\eta<4.0$) and one in the barrel ($-1.1<\eta<1.1$), both with $p_T>5$GeV.

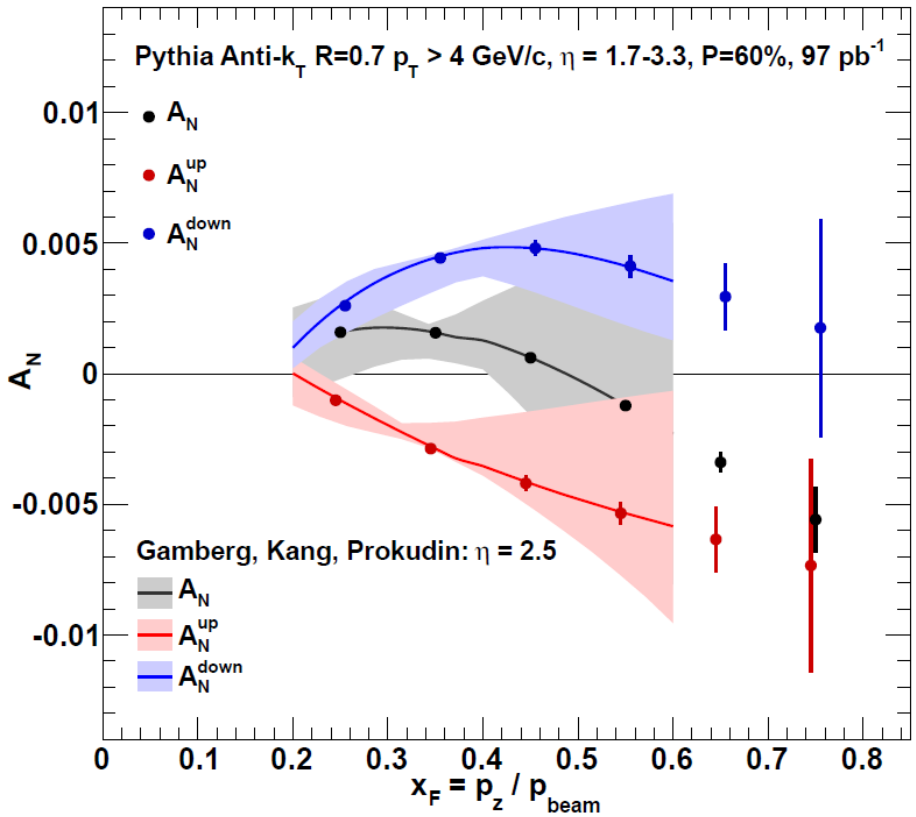
- 4100 Z^0 with both electrons in the sPHENIX barrel ($1.1<\eta<1.1$), both with $p_T>5$GeV.

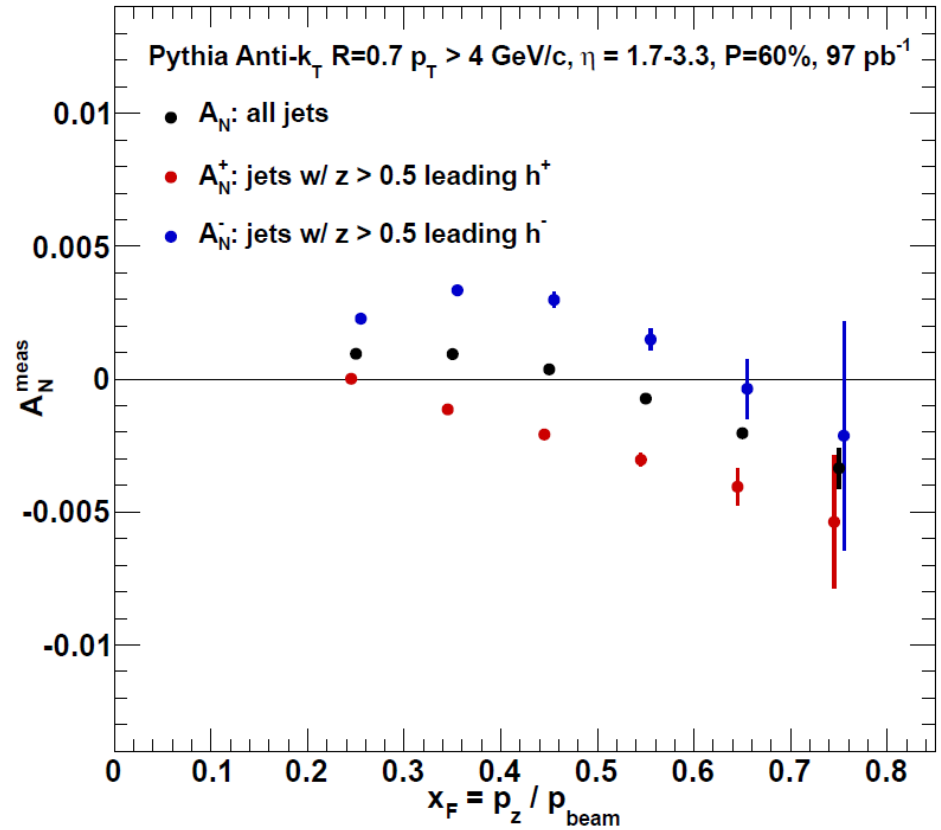
- W similar, but x10 higher cross section.



Barrel-Fwd correlations reach high x in the polarized nucleon!

Prior Forward Jet Studies (200 GeV)





Gamberg, Kang and Prokudin: *Phys Rev. Lett*. 110:232301 (2013)

Projected fsPHENIX data points (97pb^{-1}) compared to theoretical model.
Currently repeating these simulations using new fsPHENIX design at 510 GeV.

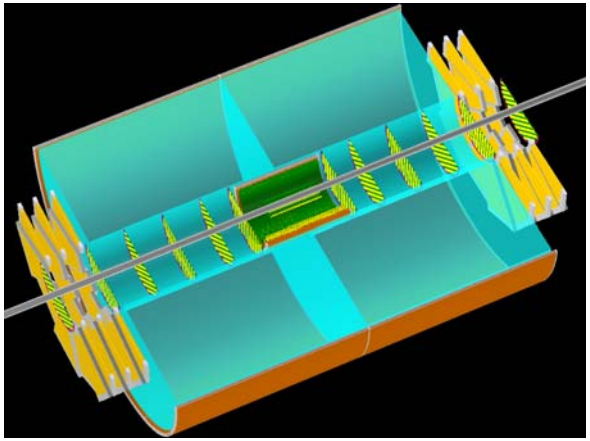
Conclusions

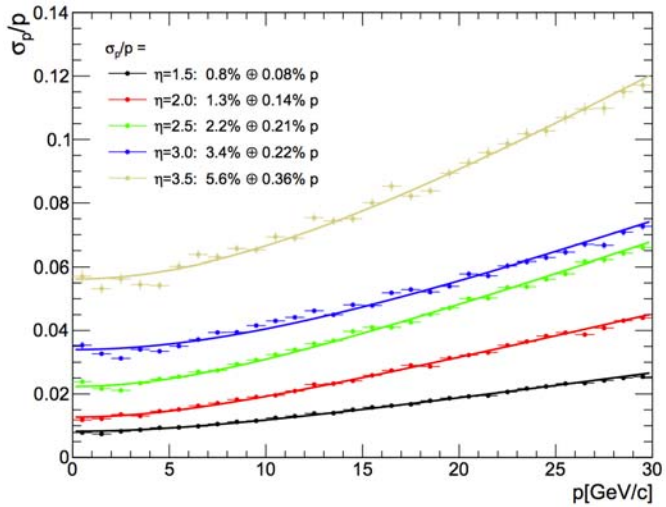
- The fsPHENIX design has excellent momentum resolution and calorimetry
  - Homogeneous acceptance complementary to sPHENIX barrel
  - Possible to improve calorimetry design with magnetic FHCAL replacing plug door.
- Some physics simulation studies available (representative, not exhaustive)
  - A DY measurement between the J/Ψ and the Upsilon looks very possible in 200 GeV p+p/p+A in fsPHENIX
  - Sidelines:
    - Separation of the Upsilon 2s/3s by fitting also seems reasonable at first glance
    - Reasonable Z^0/W yields would be available in a long 510 GeV run
    - Prior forward jet simulations still relevant
  - Detailed jet simulations (200 and 510 GeV) are underway

BACKUP

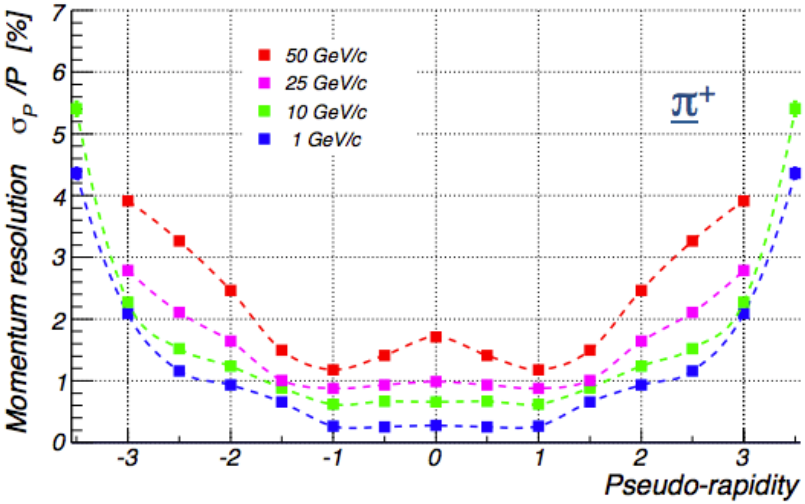
Tracking Comparison

- Resolution is about x2 of BeAST: BeAST has a x2 stronger magnetic field + silicon tracker, fsPHENIX uses a much longer tracking arm.
- High momentum resolution could be improved by switching from GEM to high precision silicon tracker.





sPHENIX FGEM



BeAST

PHPythia6 Simulations

- Using PHPythia6 with Pythia version 6.421 compiled with LHAPDF 5.4.1
- Center of mass energy is 200GeV
  - Consistent with planned sPHENIX reference running for p+p and p+A
- Events are generated using single electron triggers (as configured with PHPy6ForwardElectronTrig)
  - Requires at least one e^+/e^- in $1.4<\eta<4.0$ with $p_T>0.5$ GeV
    - Consistent with a scaled EMCal energy trigger
  - This is an energy of 1.1 GeV @ $\eta=1.4$ and 13.7 GeV @ $\eta=4.0$
    - This trigger is probably a little loose, but I wanted to start with something loose and cut harder (if necessary) later on.

DY Simulations

- Events were generated according to this configuration file:
  - Note no IS/FS parton showers, purely a LO calculation
  - LO PDF set used (CTEQ6m)
  - K-factors are known for LO DY to be ~2-2.5 (I used 2.5 in what follows)
  - Trigger eff 0.348

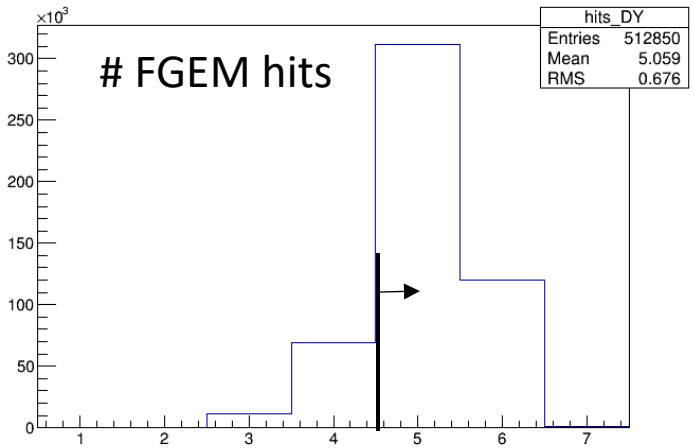
```
roots 200
proj p
targ p
frame cms
msel 0
msub 1 1  // qqbar->gamma*/Z
mdme 174 1 0
mdme 175 1 0
mdme 176 1 0
mdme 177 1 0
mdme 178 1 0
mdme 179 1 0
mdme 180 1 0
mdme 181 1 0
mdme 182 1 1 # Only allow Z0 decays to electrons
mdme 183 1 0
mdme 184 1 0 # Only allow Z0 decays to muons
mdme 185 1 0
mdme 186 1 0
mdme 187 1 0
mdme 188 1 0
mdme 189 1 0
mstp 52 2 // use LHAPDF
mstp 51 10000 // CTEQ6m
mstp 61 0 // initial PS off
mstp 71 0 // final PS off
parp 111 1.0 // min mass of remnant
parp 91 0.9 // width of Gaus k_perp
ckin 1 0.5  // min parton sqrt(s)
```

From a COMPASS talk by C. Quintans

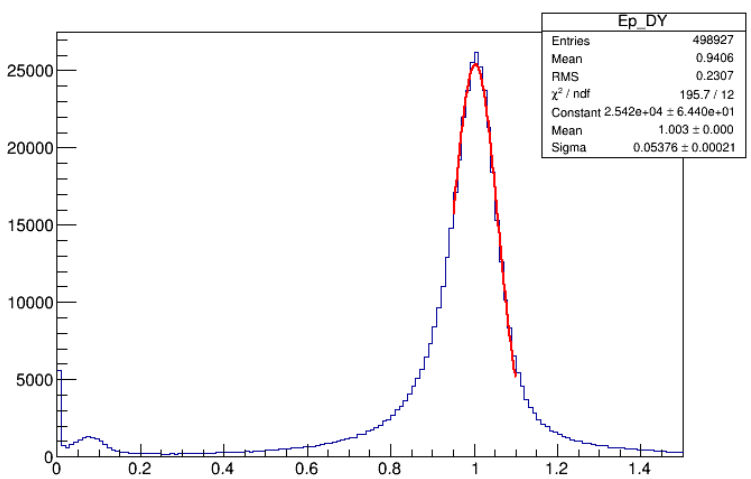
Kenyon, 1982

Group	Beam and target	Momentum/$\sqrt{s}$ (GeV/c)/(GeV)	Measured cross section: Naive Drell–Yan prediction
NA3 (Badier *et al* 1980b)	($\bar{p}$–p): Pt	150	2.3 ± 0.4
NA3 (Badier *et al* 1979b)	p: Pt	200	2.2 ± 0.4
CFS (Ito *et al* 1981)	p: Pt	300/400	$1.7^{+0.73}_{-0.58}$
CHFMNP (Antreasyan *et al* 1981b)	pp	44, 63	1.6 ± 0.2
MNTW (Smith *et al* 1981)	p: W	400	1.6 ± 0.3
NA3 (Lefrançois 1980)	π^-: Pt	200	2.2 ± 0.3
NA3 (Lefrançois 1980)	π^+: Pt	200	2.4 ± 0.4
NA3 (Lefrançois 1980)	(π^-–π^+): Pt	200	2.4 ± 0.4
Omega (Corden *et al* 1980a)	π^-: W	40	2.45 ± 0.42
Omega (Corden *et al* 1980a)	π^+: W	40	2.52 ± 0.49
Omega (Corden *et al* 1980a)	(π^-–π^+): W	40	2.22 ± 0.41

DY Track Cuts (DY e^+/e^-)

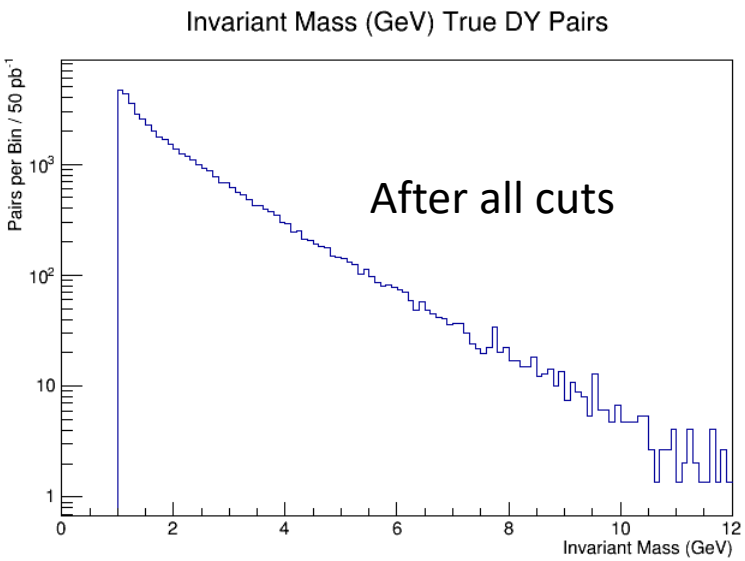


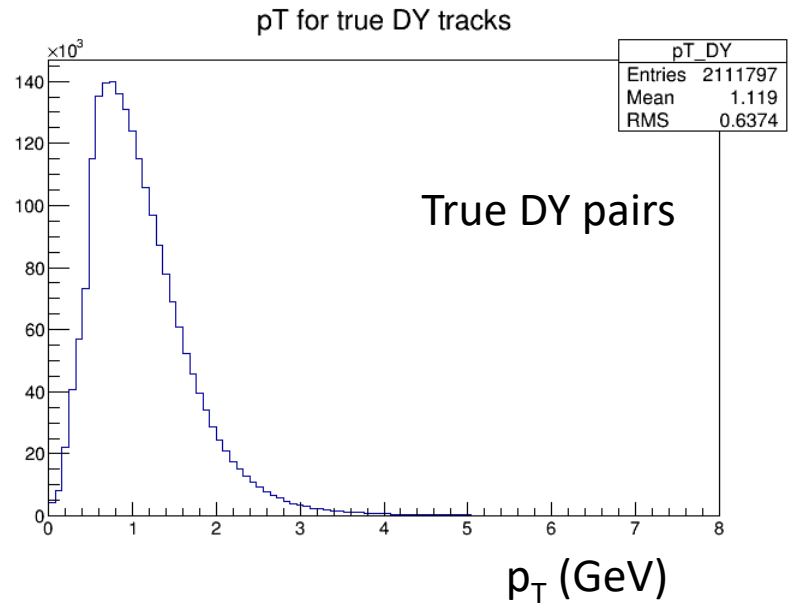
Tracks cuts were selected to be efficient for true electron tracks from DY pairs.



FEMC E33/p

DY Pair Mass and P_T





Counts scaled to 50pb^{-1} sampled p+p luminosity (simulated events sampled 74.2 pb^{-1})

MB Simulations

- Events were generated according to this configuration file:
  - Standard Pythia MB
  - CTEQ6LL PDF's
  - Trigger eff: 0.00184
  - **59.035M events saved (32.08B events sampled)**
    - **Corresponds to 1.16pb^{-1} integrated lumi**

```
roots 200
proj p
targ p
frame cms
msel 1
mstp 52 2 // use LHAPDF
mstp 51 10041 // CTEQ6LL
mstp 91 1
parp 91 2.5
pmas 4 1 1.5
pmas 5 1 4.8
```

- Note that compared to the DY signal simulation, this is the Pythia equivalent of an NLO calculation

Quarkonia Simulations

- J/Ψ events were generated according to this configuration file:
  - Trigger eff: 0.263
  - **991k events saved (3.8B events sampled)**
    - **Corresponds to 15.9pb^{-1} integrated lumi (using Pythia cross section)**
- Upsilon(1S) events were generated according to the configuration on the next page
  - Trigger eff: 0.0784
  - **498k events saved (6.4B events sampled)**
    - **Corresponds to 101.3pb^{-1} integrated lumi (using Pythia cross section)**
- The Ψ' and Upsilon (2s), (3s) were included by scaling the yield and mass of the 1s state.

```
roots 200
proj p
targ p
frame cms
msel 0
msub 86 1  // g+g -> J/Psi
mdme 858 1 1 // J/Psi -> ee
mdme 859 1 0 // J/Psi -> mumu
mdme 860 1 0 // J/Psi -> random
mstp 51 7
```

Ψ' Fraction from :
arXiv:1609.06550 (PPG188)

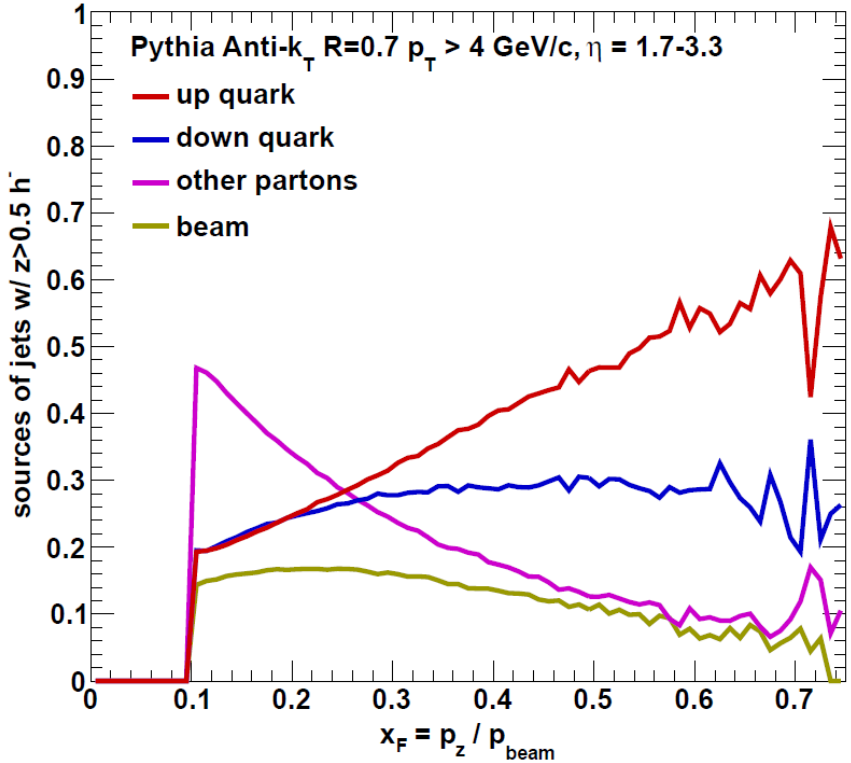
Upsilon fractions from:
D. Acosta et al.,
Upsilon production and polarization in p+p collisions at √s=1.8 TeV.
Phys. Rev. Lett., 88:161802, (2002)

Upsilon (1s) Pythia Configuration

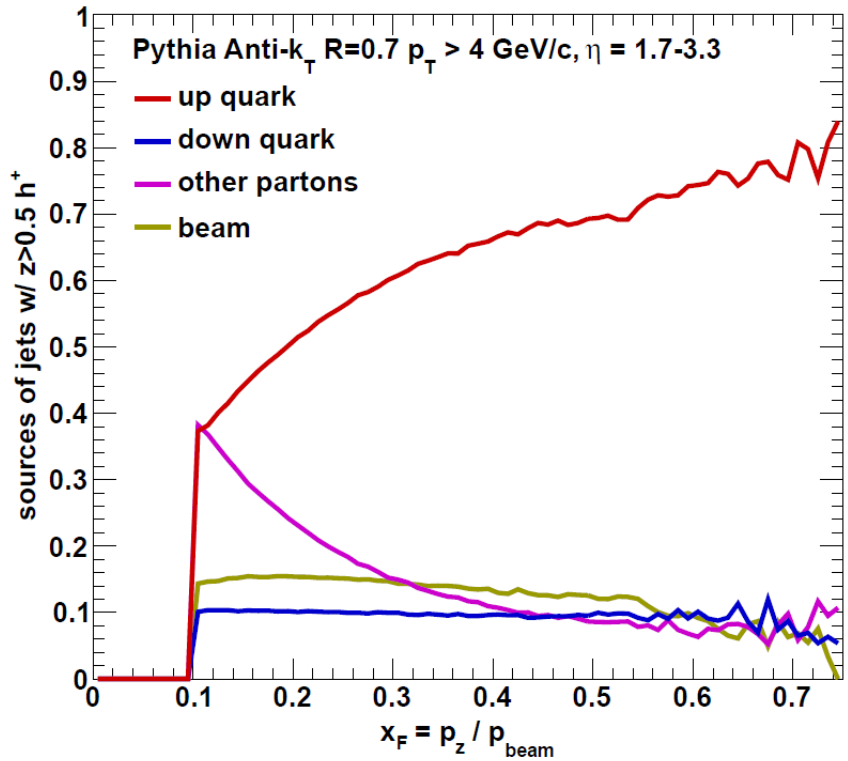
```
roots   200
proj    p
targ    p
frame   cms
msel    0     // turn on all prod. mechanisms manually
msub 461 1          // gg -> QQ[3S(1) 1 ] g
msub 462 1          // gg -> QQ[3S(8) 1 ] g
msub 463 1          // gg -> QQ[1S(8) 0 ] g
msub 464 1          // gg -> QQ[3P(8) J ] g
msub 465 1          // gq -> qQQ[3S(8) 1 ]
msub 466 1          // gq -> qQQ[1S(8) 0 ]
msub 467 1          // gq -> qQQ[3P(8) J ]
msub 468 1          // qq -> gQQ[3S(8) 1 ]
msub 469 1          // qq -> gQQ[1S(8) 0 ]
msub 470 1          // qq -> gQQ[3P(8) J ]
msub 471 1          // gg -> QQ[3P(1) 0 ] g
msub 472 1          // gg -> QQ[3P(1) 1 ] g
msub 473 1          // gg -> QQ[3P(1) 2 ] g
msub 474 1          // gq -> qQQ[3P(1) 0 ]
msub 475 1          // gq -> qQQ[3P(1) 1 ]
msub 476 1          // gq -> qQQ[3P(1) 2 ]
msub 477 1          // qq -> gQQ[3P(1) 0 ]
msub 478 1          // qq -> gQQ[3P(1) 1 ]
msub 479 1          // qq -> gQQ[3P(1) 2 ]
mdme 1034 1 1  // upsilon -> ee turned on
mdme 1035 1 0  // upsilon -> mumu turned off
mdme 1036 1 0  // upsilon -> tautau turned off
mdme 1037 1 0  // upsilon -> dd~ turned off
mdme 1038 1 0  // upsilon -> uu~ turned off
mdme 1039 1 0  // upsilon -> ss~ turned off
mdme 1040 1 0  // upsilon -> cc~ turned off
mdme 1041 1 0  // upsilon -> g g g turned off
mdme 1042 1 0  // upsilon -> gamma g g turned off
mstp    51 4    // structure function for GRV94 L
parp    38 15.73    // GeV^3; from Upsilon(1S) Width, (from babar parameterisation)
parp    39 0.0035  // tuned to fit upsilon production from chi_b in ppbar collisions @ 1.8 TeV
parp    31 2.5  // k factor
ckin    3  2.0  // min parton pt of 2.0
```

Jet Sources

Jets with negative hadron z>0.5



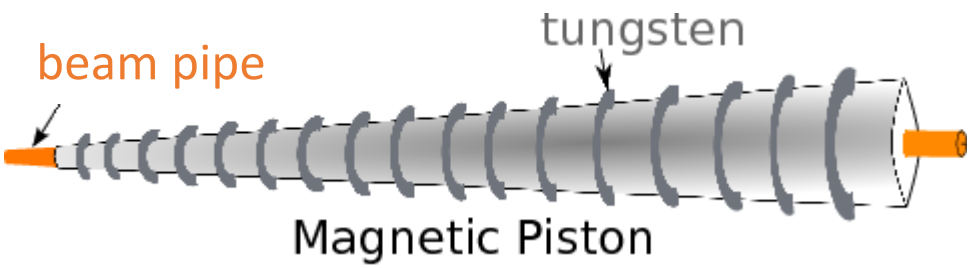
Jets with positive hadron z>0.5



Jets from standard PYTHIA Tune A, beam remnants from Tune A with k_T=0.36.

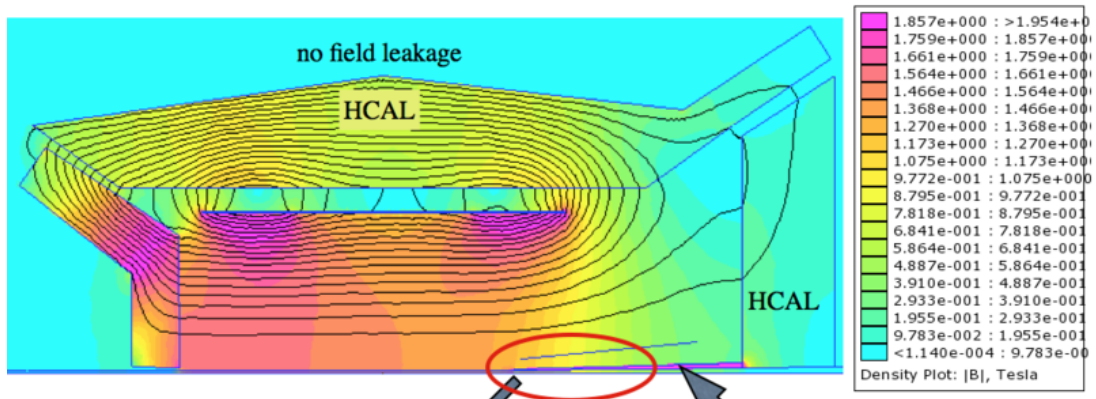
A cut on the charge of the leading hadron changes the composition of the jet sample.

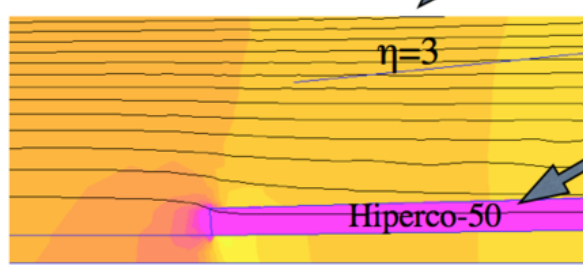
Forward Magnetic Field



HIPERCO-50 high permeability piston around beam pipe, tungsten ribs reduce backgrounds around calorimeter hole.

Piston enhances transverse component of magnetic field for η>3.0, improving momentum resolution.





Passive Piston helping flux return at small angle

Hiperco-50: 49%Co+49%Fe alloy provide high field saturation (<2.25T)