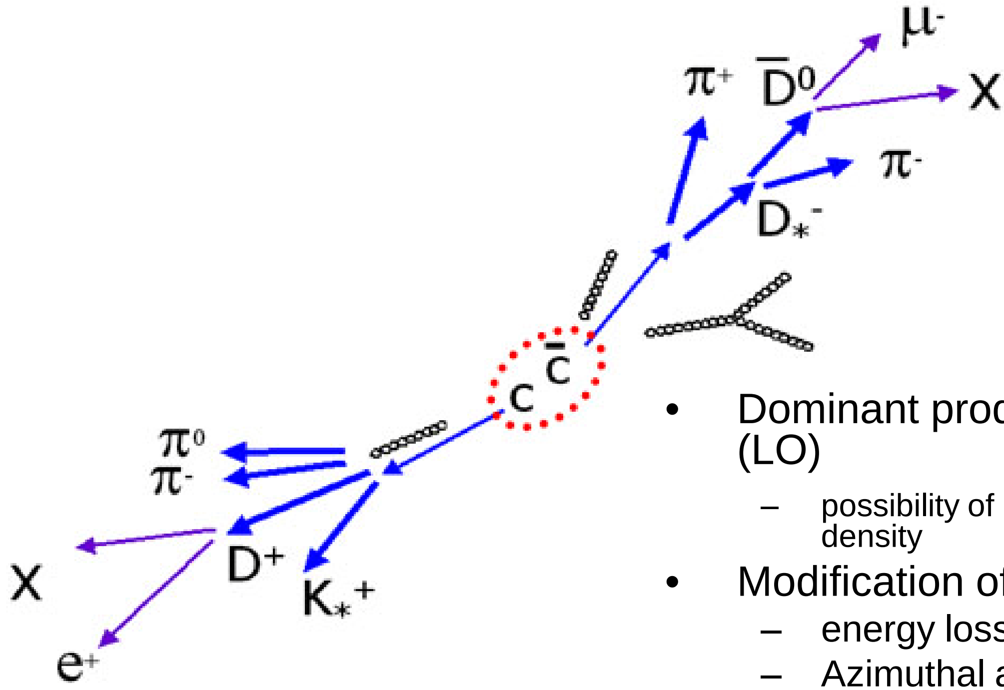
Measuring high pT single electrons from open heavy flavor in pp collisions at sqrt(s) = 200GeV using the PHENIX detector

Why do we study heavy quarks?

- RHIC was built to produce and study the Quark Gluon Plasma
  - Medium is small 1000fm^3
  - Short lived 100 fm/c
  - Must be probed with particles produced in collision
- Hard Probe
  - Charm and especially Bottom, will only be created at beginning
  - Will propagate through and be modified by the medium

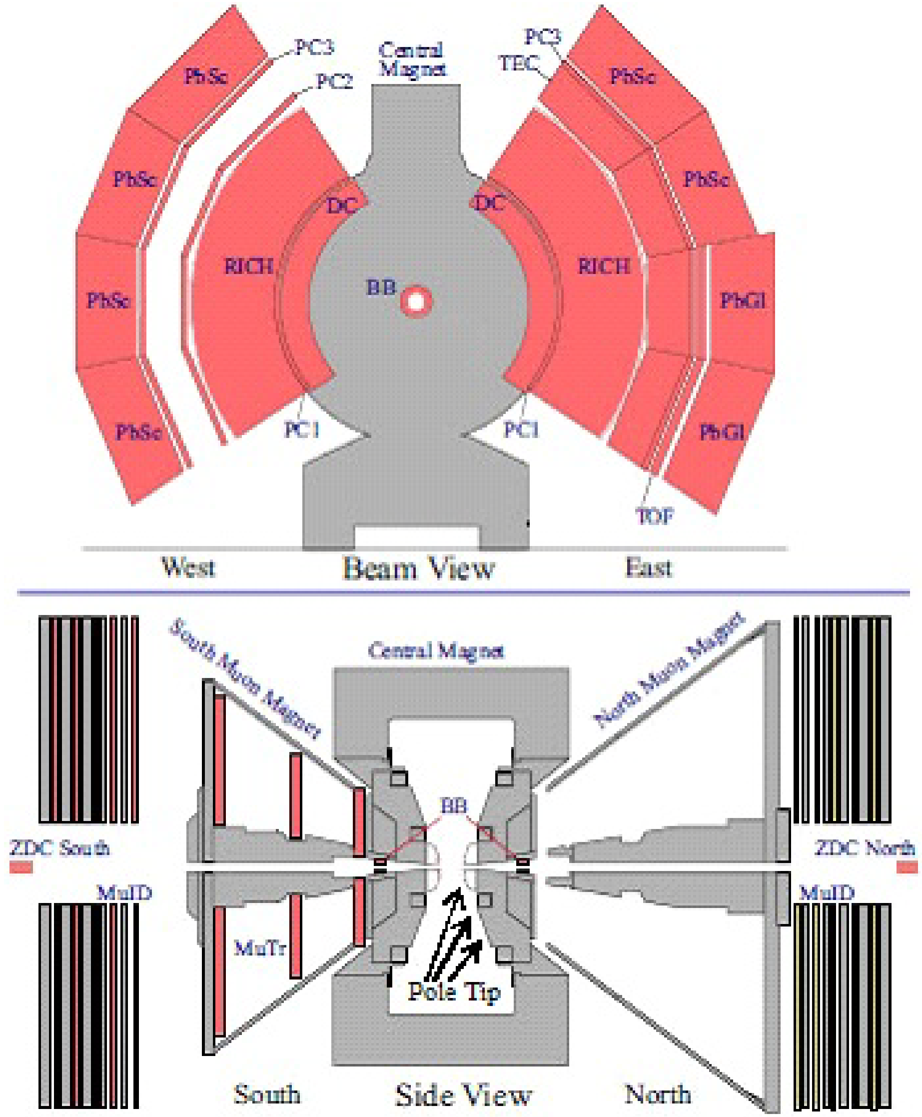
Open Charm (Bottom)



- Dominant production mechanism is gluon fusion (LO)
  - possibility of studying gluon density as a function of system density
- Modification of transverse momentum spectra
  - energy loss ->look for suppression
  - Azimuthal anisotropy or flow
  - di leptons
- Cold and Hot nuclear matter
- J/ψ regeneration
- To make the best measurement of these things you need a pp reference in the same detector

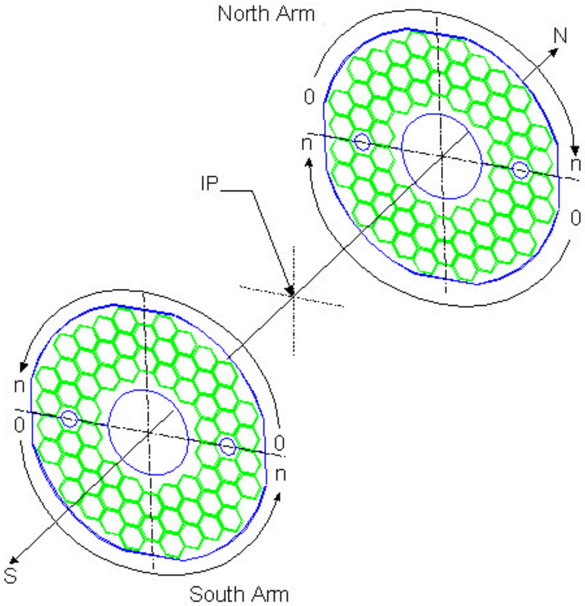
PHENIX Detector

- High Rate, High Multiplicity Spectrometer
- Central arms
  - cover π in azimuth
  - $|\eta|<0.35$
  - central solenoidal field
  - carefully managed material budget
- Writing events at 6+ kHz



Beam Beam Counter

- Provide minimum bias trigger
- Determine z of collision vertex
- Set t_0 for all of PHENIX



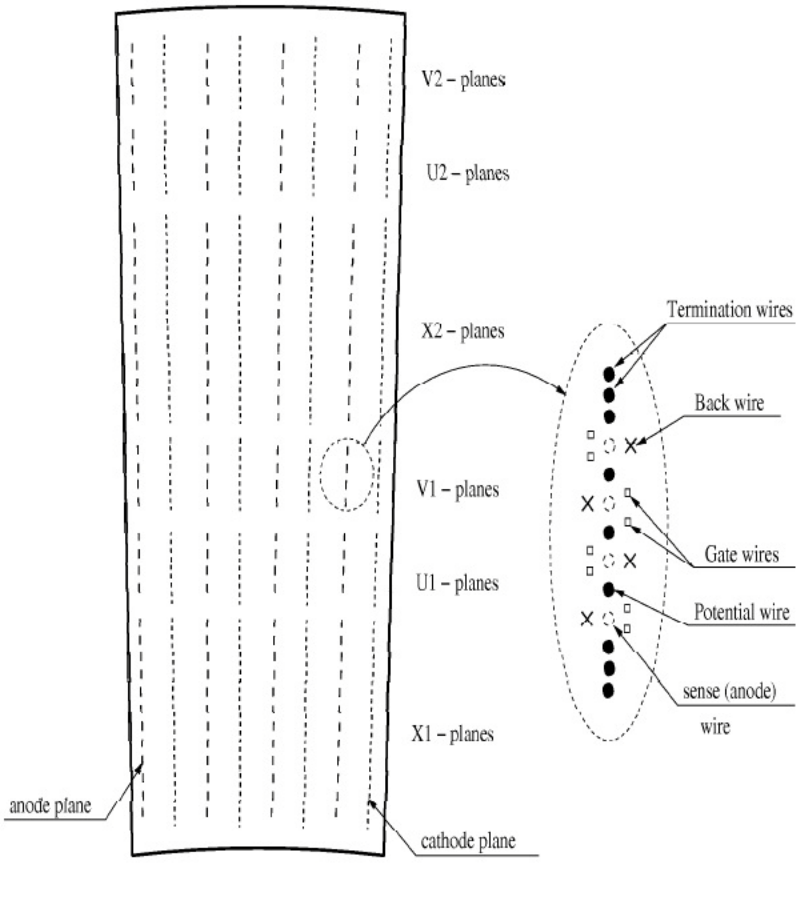
- Two arrays of hexagonal Cerenkov radiators
- Phototubes have intrinsic resolution of 50ps
- 1.44m from center, 3.1<η<4.0

$$t_0^{BBC} = \frac{(t_N^{BBC} + t_S^{BBC})}{2}$$

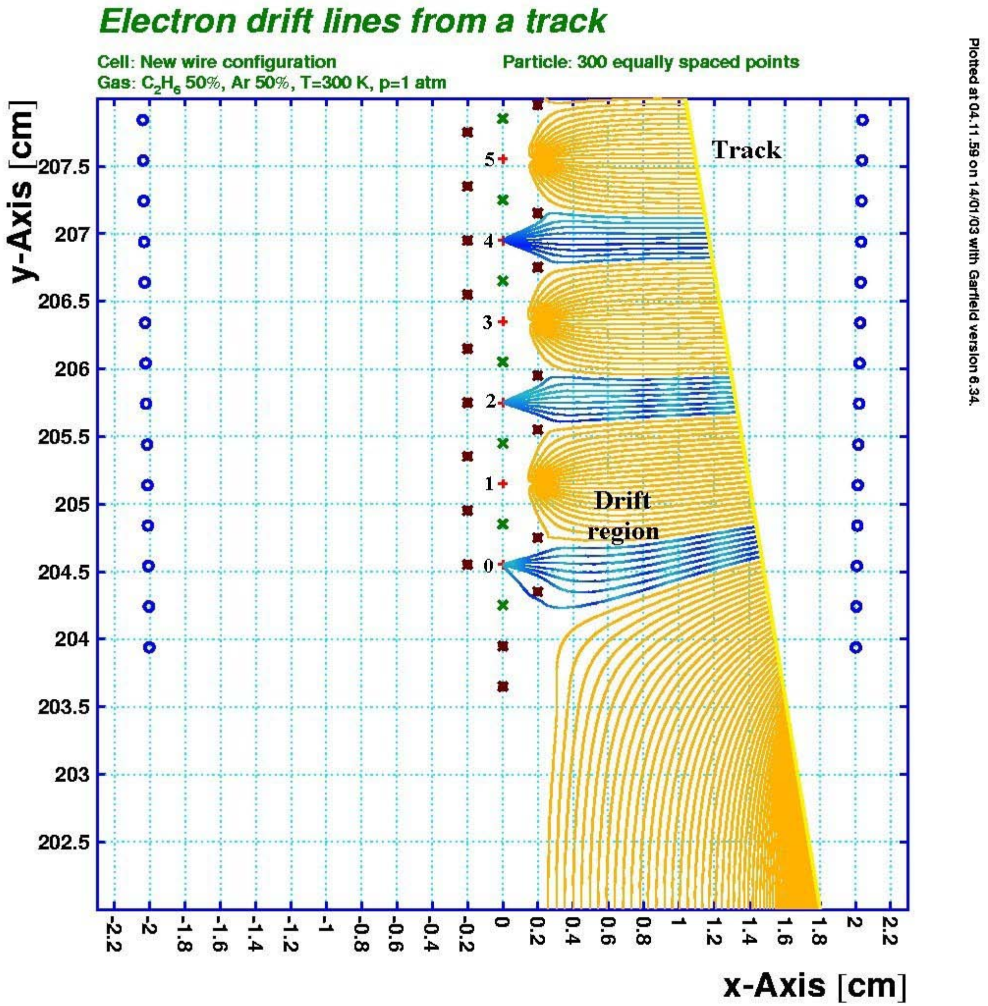
$$z_{vtx}^{BBC} = \frac{(t_N^{BBC} - t_S^{BBC})}{2c}$$

$$\sigma_z^{pp} \approx 1.2cm$$

Drift Chamber

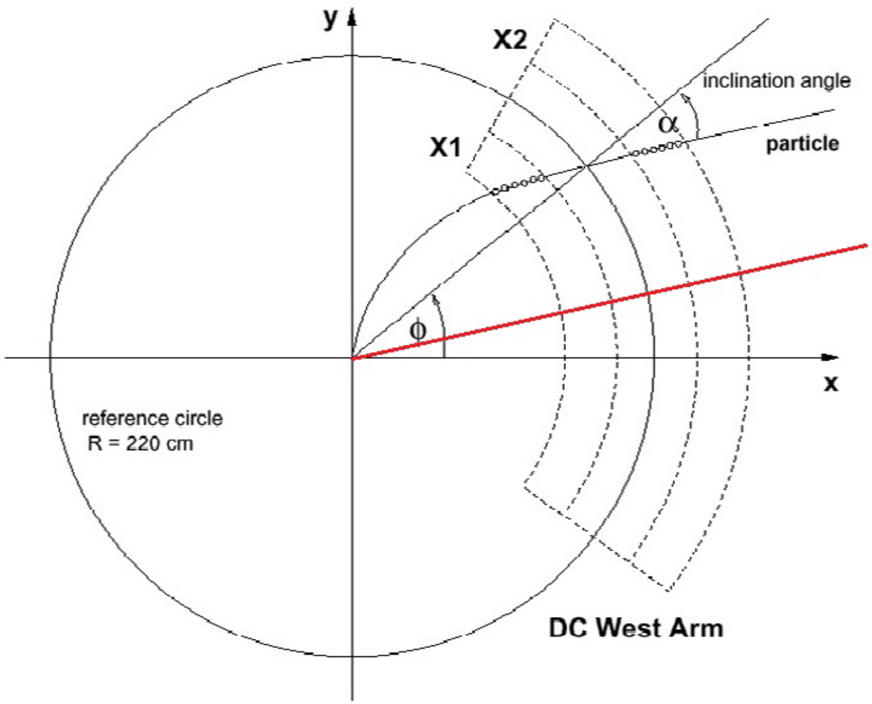


Sector, side view



Drift Chamber

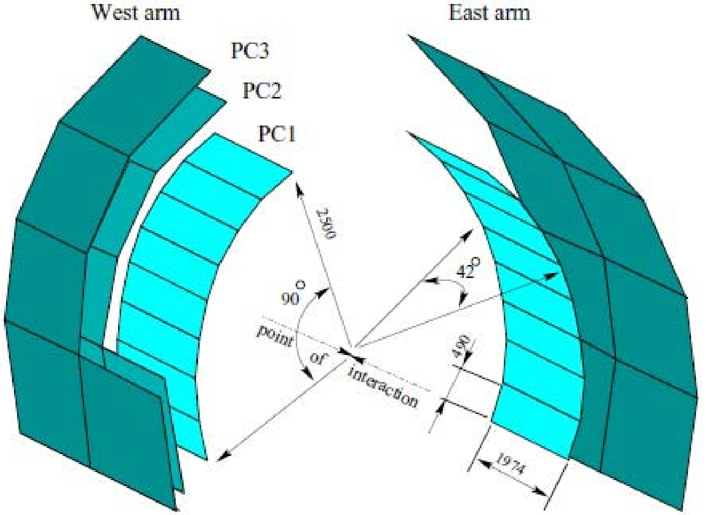
- Accurate determination of charged track transverse momentum p_T .
- Measure, in concert together with PC1 and BBC, z at the DC and, consequently, the angle of a particle track w.r.t. beam axis, .
- Determine the tracks of charged particles though PHENIX.

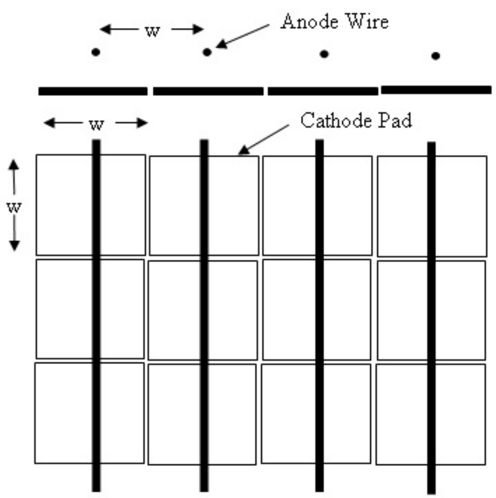


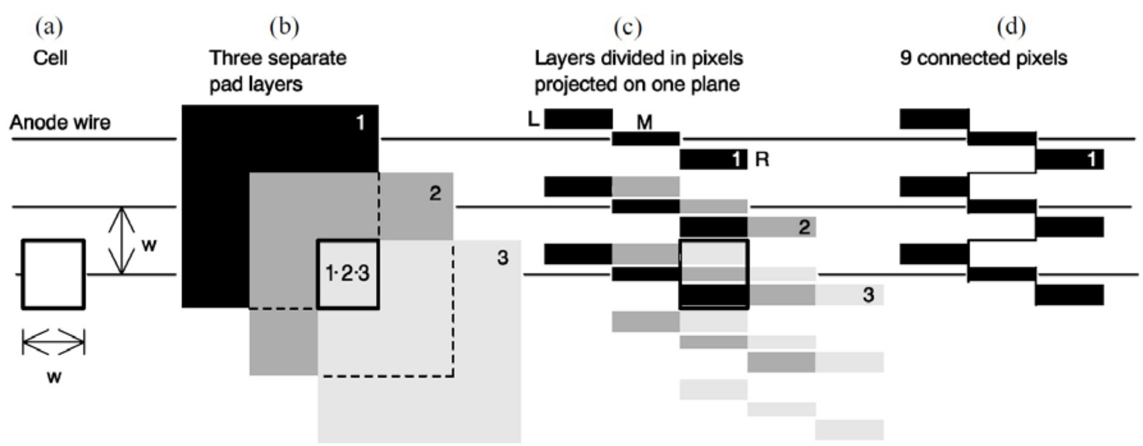
FYI $p_T = 92/\alpha$

Pad Chambers

- Reinforce the tracking of charged particles in r-θ plane
- In particular, PC1 provides z coordinate at the DC
- σ_z =1.7mm (PC1)

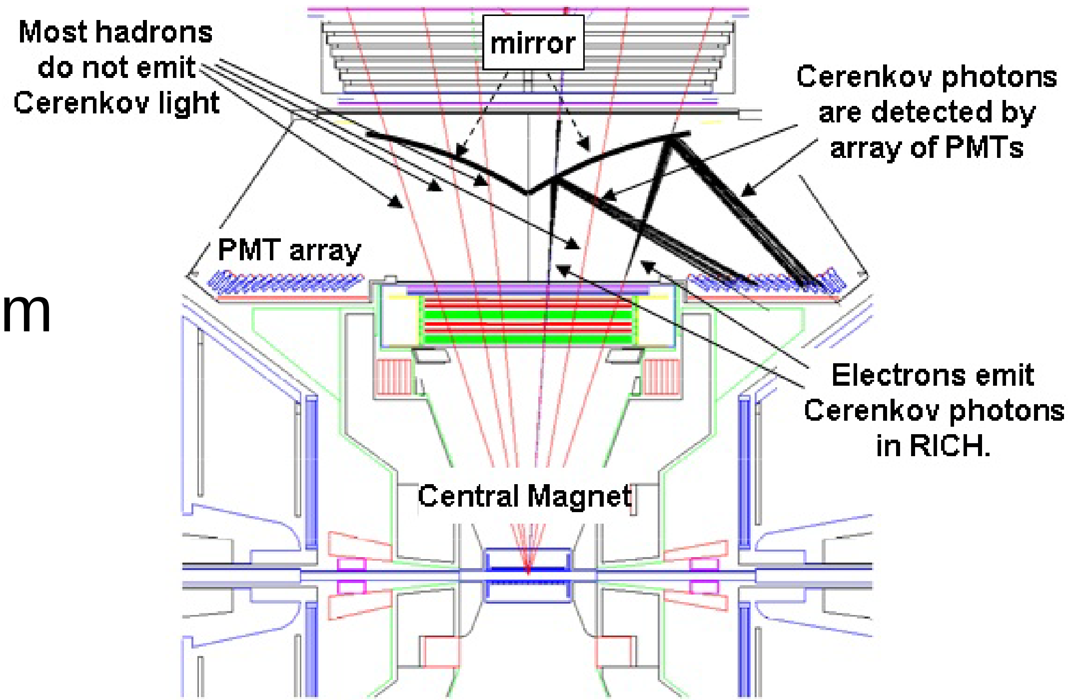






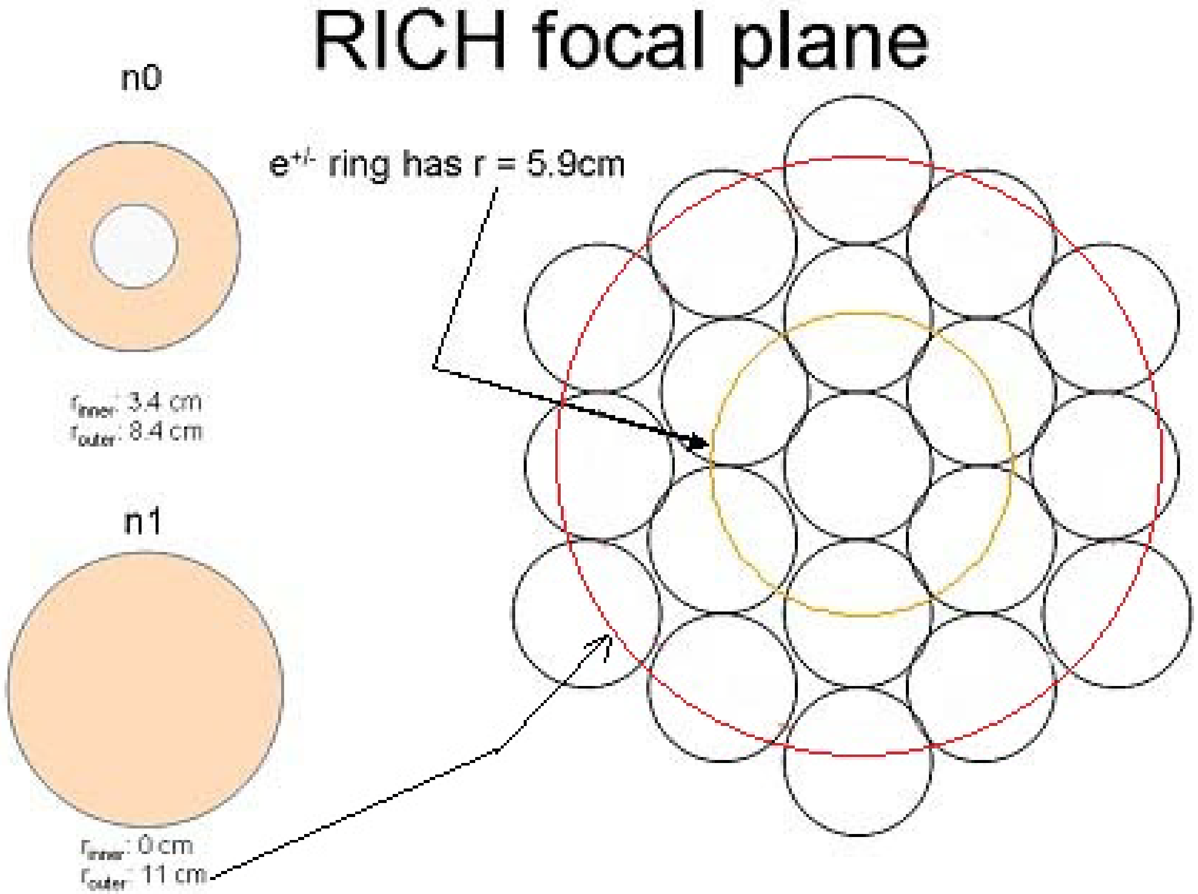
Ring Imaging CHerenkov

- Primary electron identification subsystem
- Threshold Cherenkov
- π's begin to emit Cherenkov light at 4.2 GeV

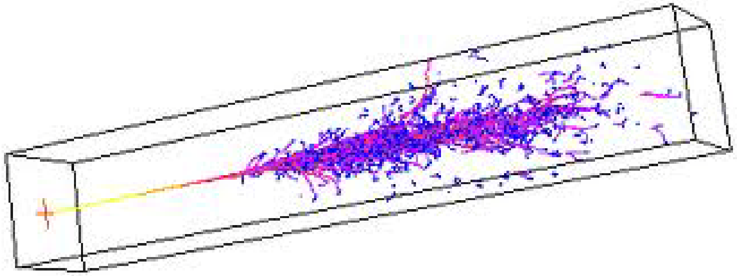


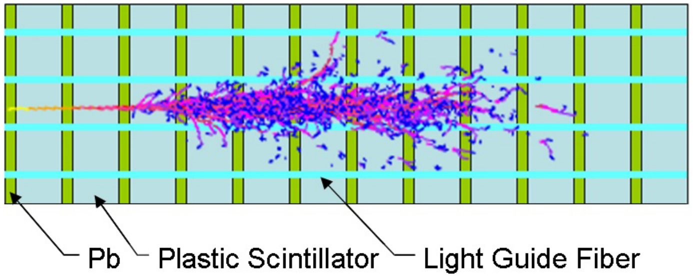
RICH Variables

- n_0 & n_1 are both number of phototubes fired
- There are variables that use pulse height
- n_1 was chosen
  - alignment issue
  - easier to simulate



ElectroMagnetic Calorimeter





- PbGl
  - Better Energy Resolution
  - Better Granularity
  - Proven system (WA98)
- PbSc
  - Better Timing Resolution
  - Better Linearity
  - response to hadrons better understood (in principle)

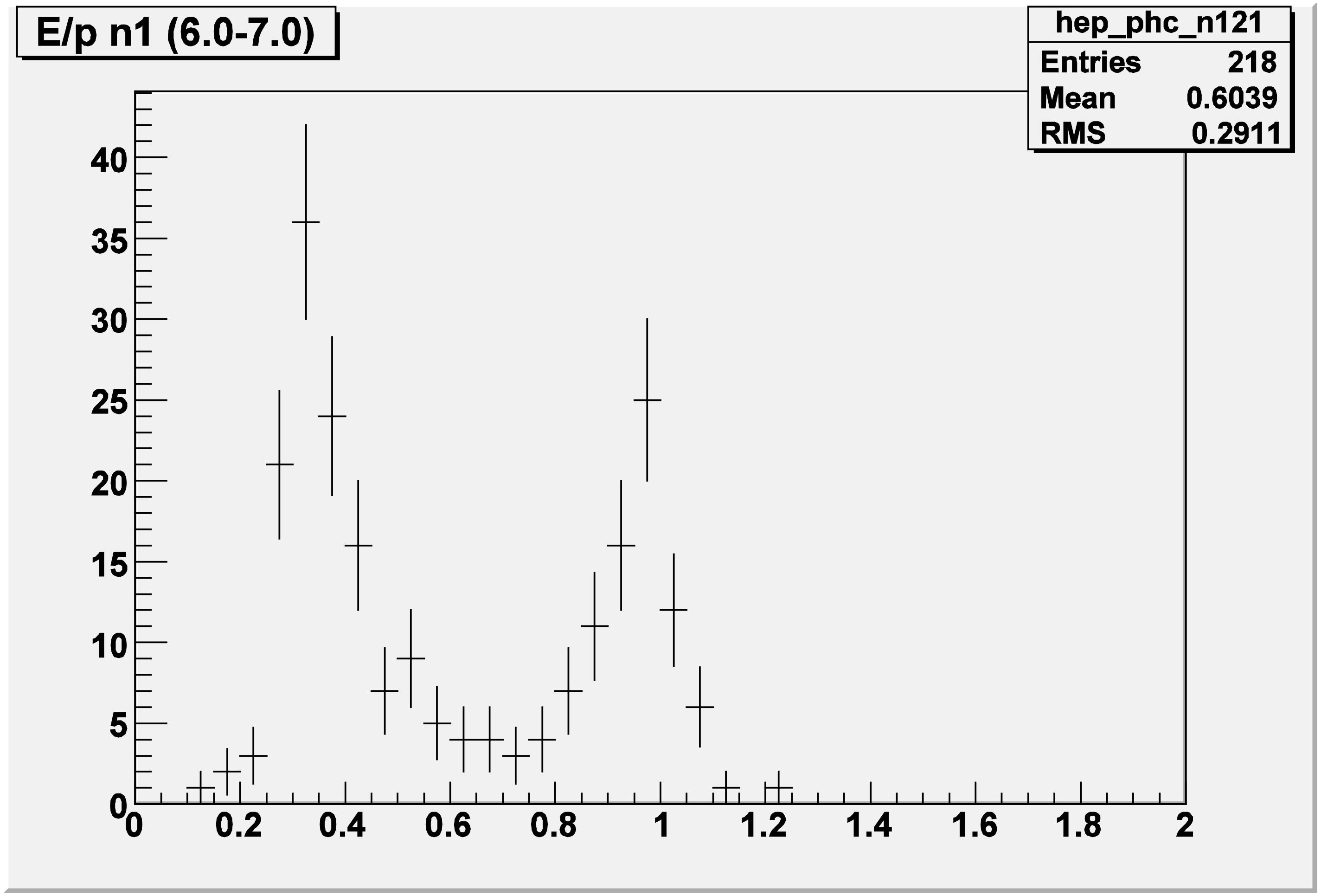
Data Analysis

- Selection Cuts
- Run QA
- Trigger efficiency
- Acceptance Efficiency Correction
- Final Inclusive Spectrum
- Cocktail
- Background subtraction

Selection Cuts

- z vertex, |z|<20cm
- Quality X1/X2 unambiguous
  - 31 PC1 found/ambiguous, UV found
  - 51 PC1 found/unique, UV not found
  - 63 PC1 found/unique, UV found/unique
- EMC
  - matching -> Track to energy cluster
  - shower shape -> EM showers narrower than Hadronic
- RICH, $n_1 \geq 5$
- E/p
  - Centered about one, fixed window
  - Basis of new technique
- Fiducial Cuts -> fine tune matching of simulation to real detector

E/p

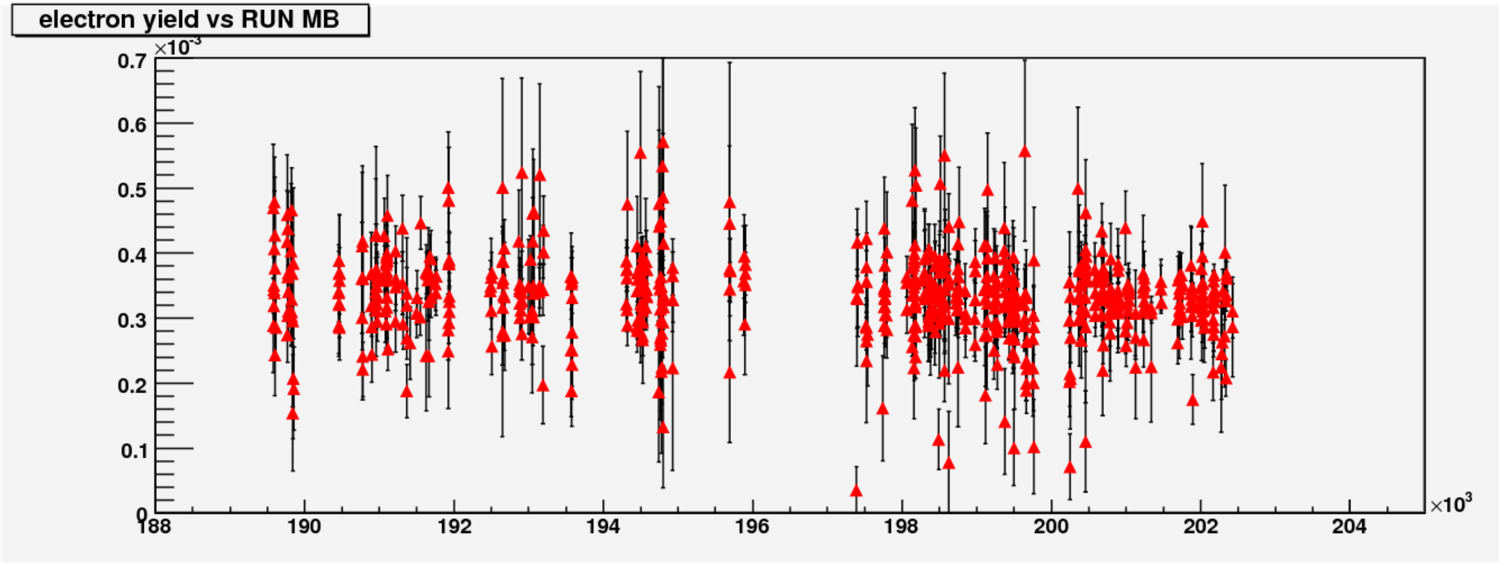


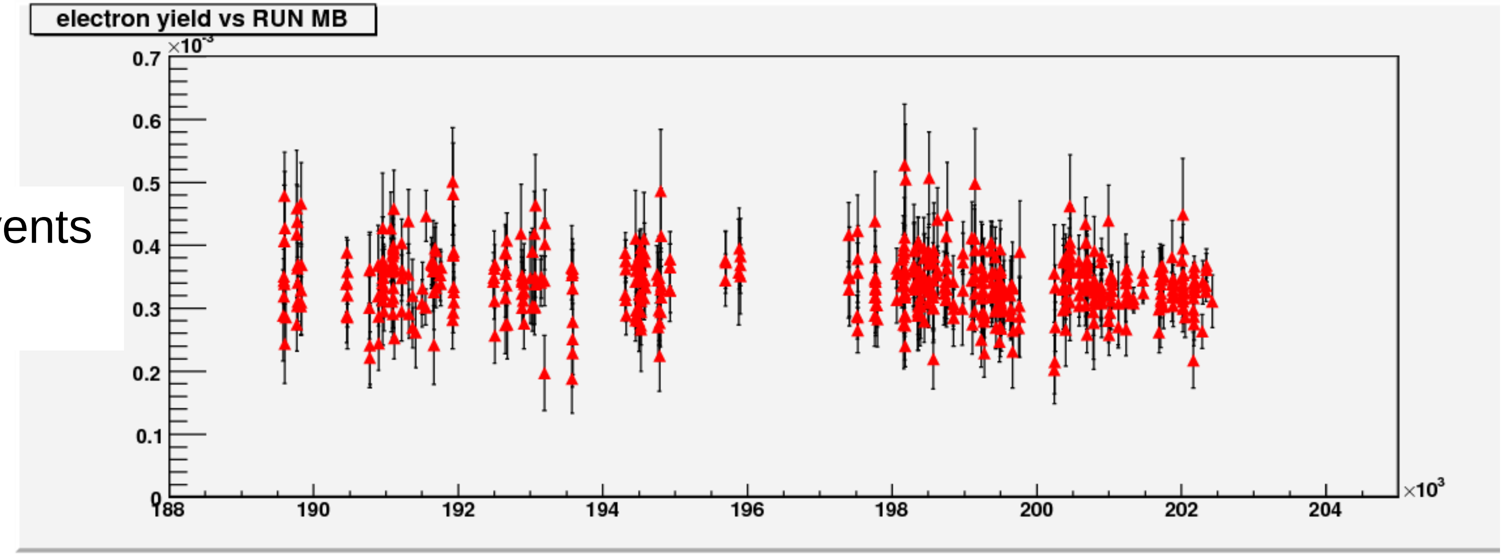
E/p n1 (6.0-7.0)
hep_phc_n121
Entries 218
Mean 0.6039
RMS 0.2911
0
5
10
15
20
25
30
35
40
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

RunQA

- Data consists of two sets,
  - Min Bias
  - Triggered E > 1.4GeV
- For MB data
  - plot electron candidate yield per event vs run number
  - remove outliers
  - look for variations indicating changes in detector performance
- Make list of matching ERT runs
- Merge sets

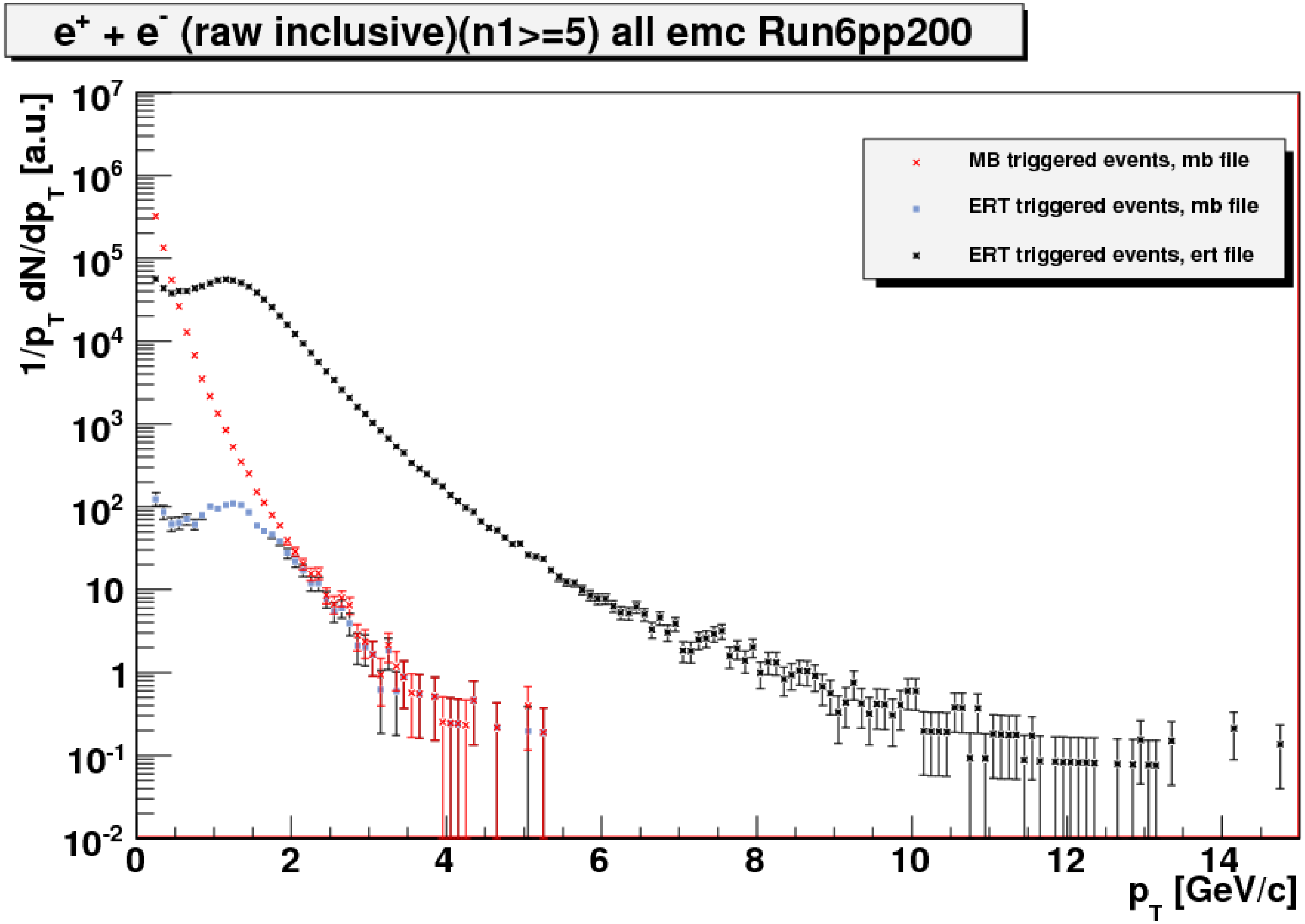
Run QA



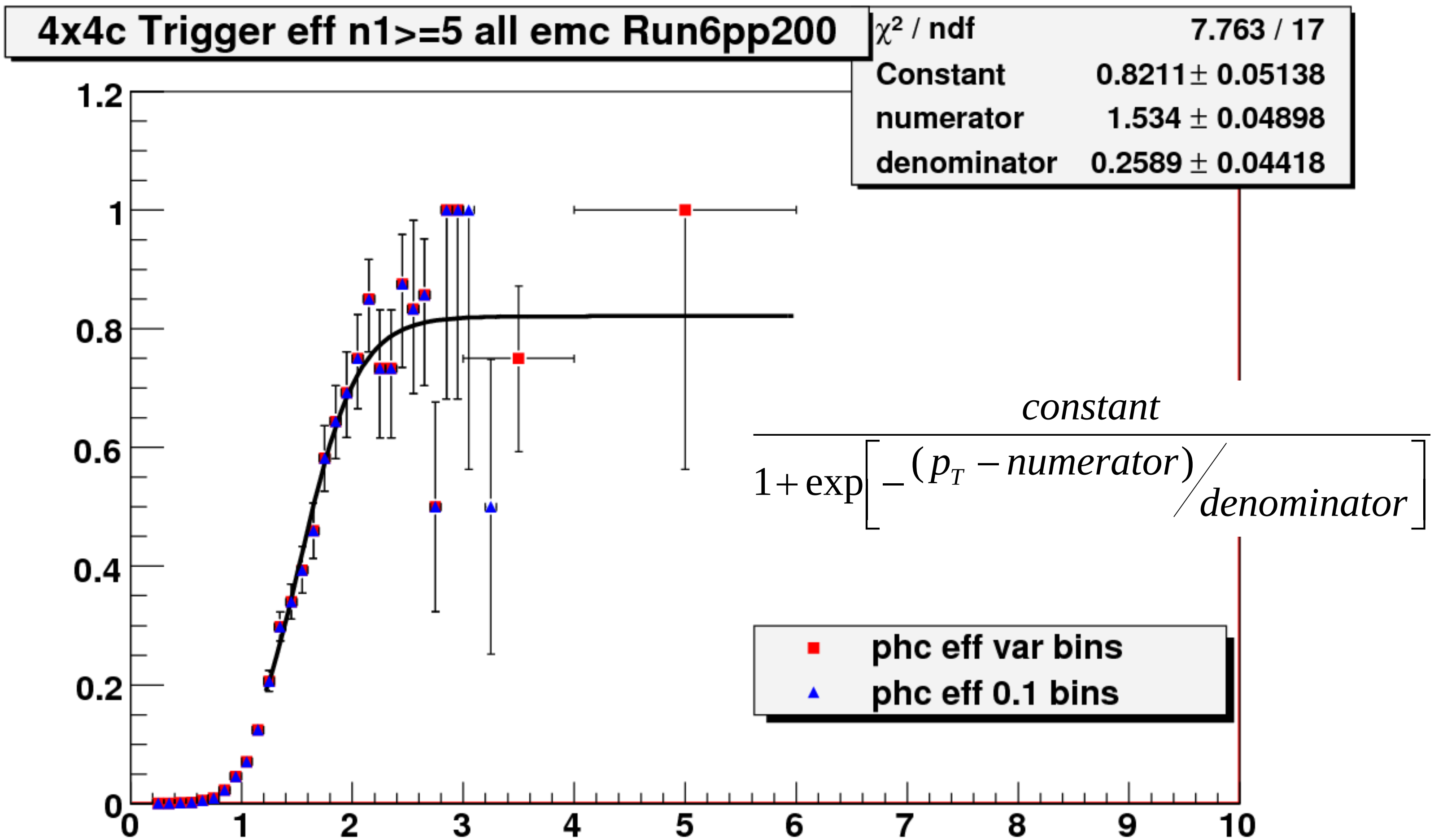


- 50,000 events
- 3σ

Trigger Efficiency

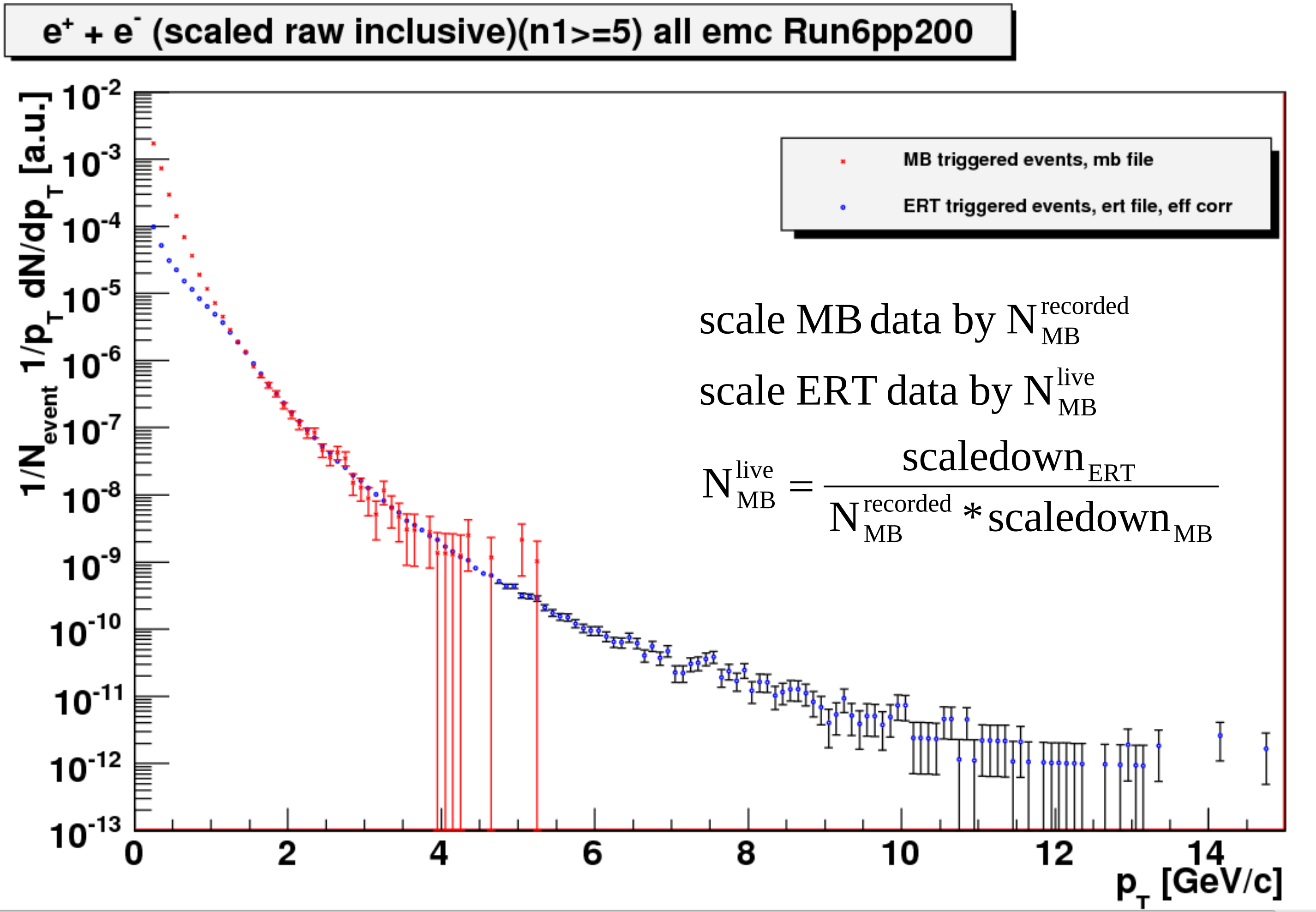


Trigger Efficiency

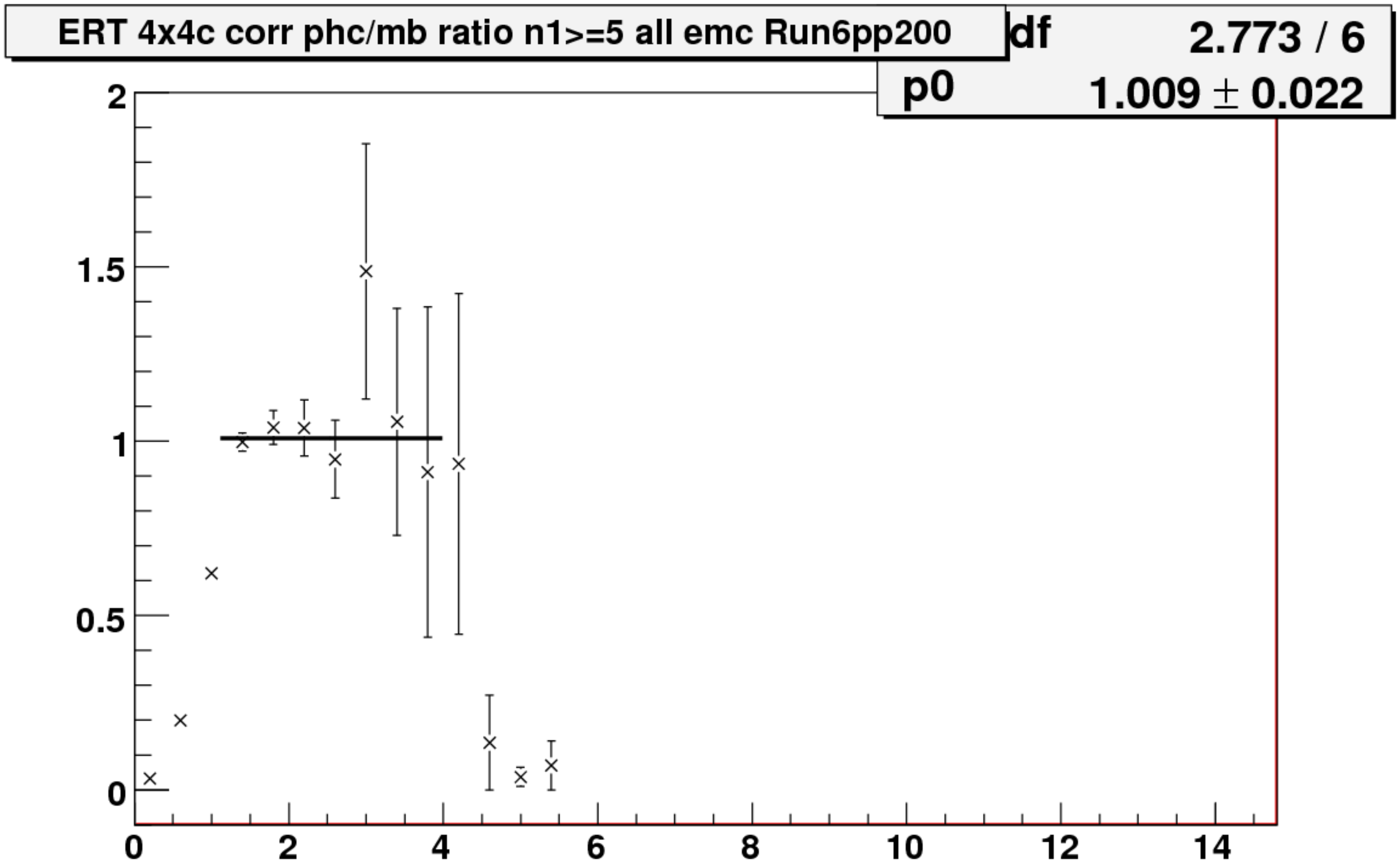


$$\frac{constant}{1+\exp\left[-\left(p_T - numerator\right)\big/ denominator\right]}$$

Trigger Efficiency



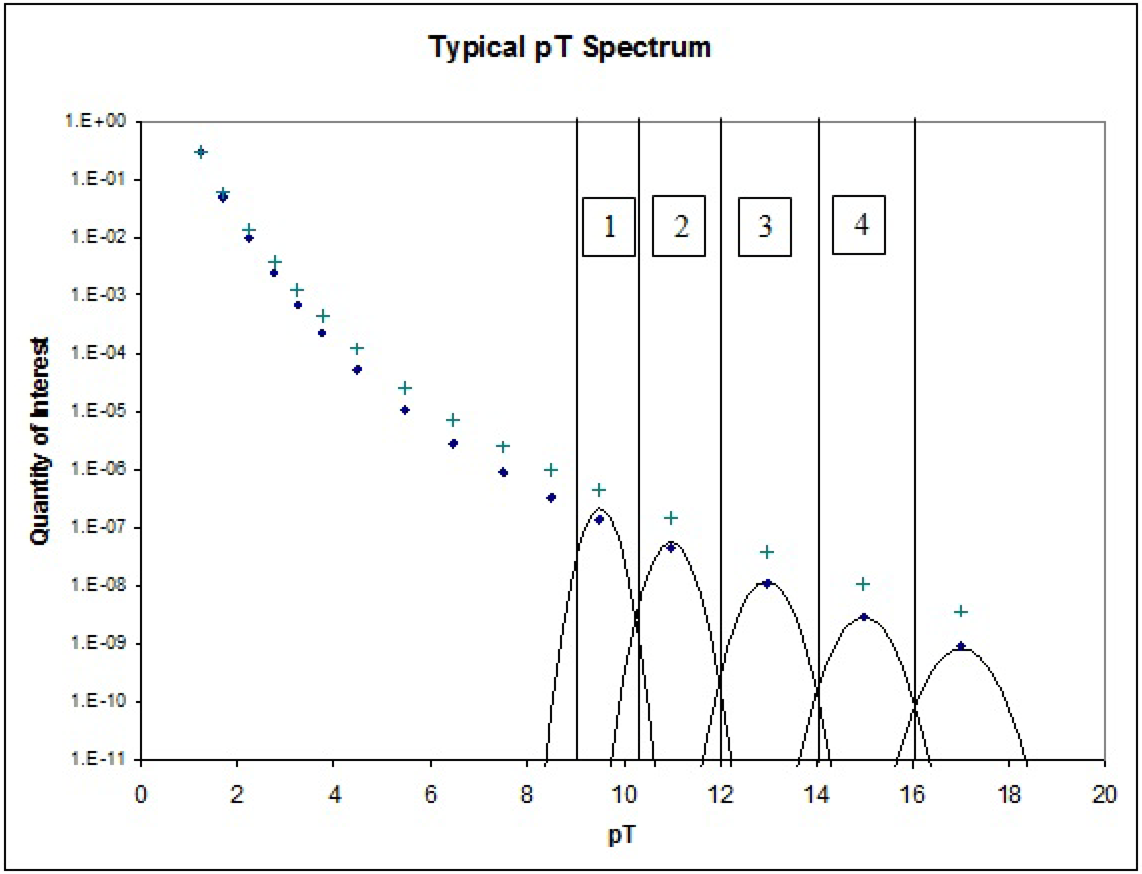
Trigger Efficiency



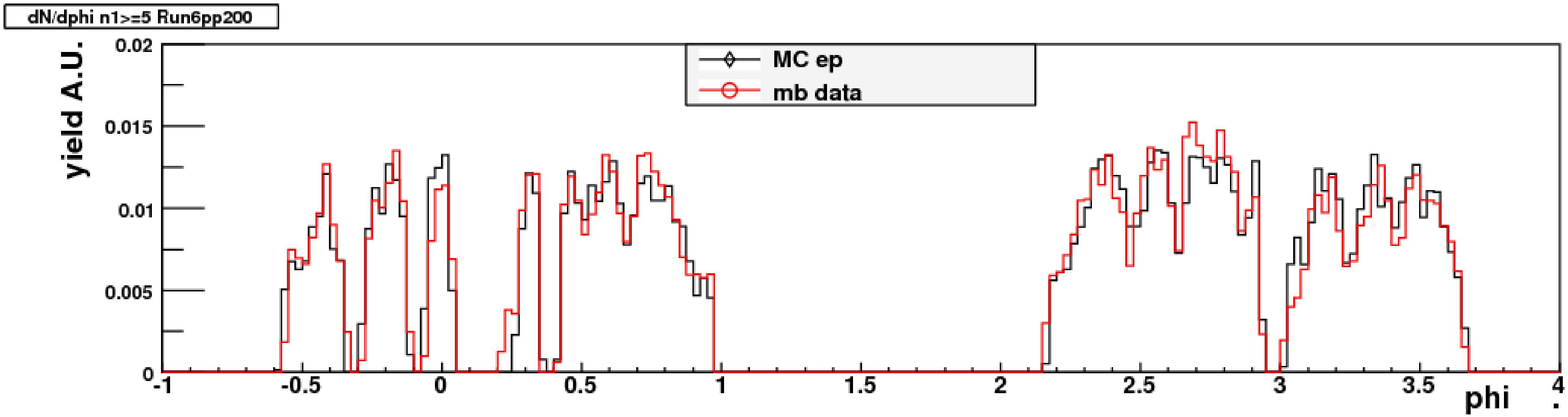
Acceptance Efficiency Correction

- Correct for
  - cut efficiencies
  - acceptance limitations
  - resolution effects -> Steeply falling spectra
- PHENIX Integrated Simulation Application (PISA)
- Generate simulated electrons and propagate through PHENIX with all cuts
- Divide what you get out by what you put in

Steeply Falling Spectrum

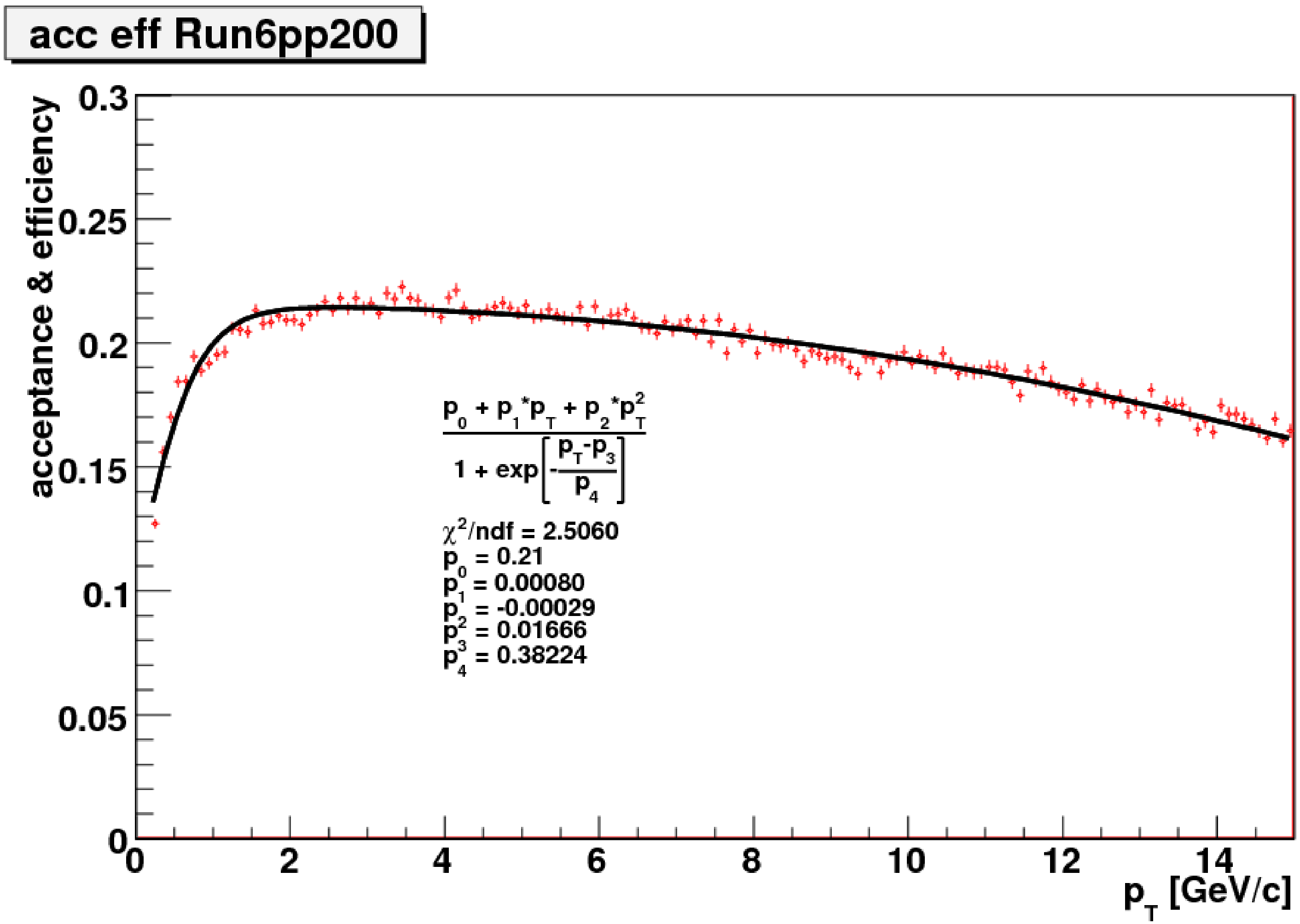


Acceptance Efficiency Correction



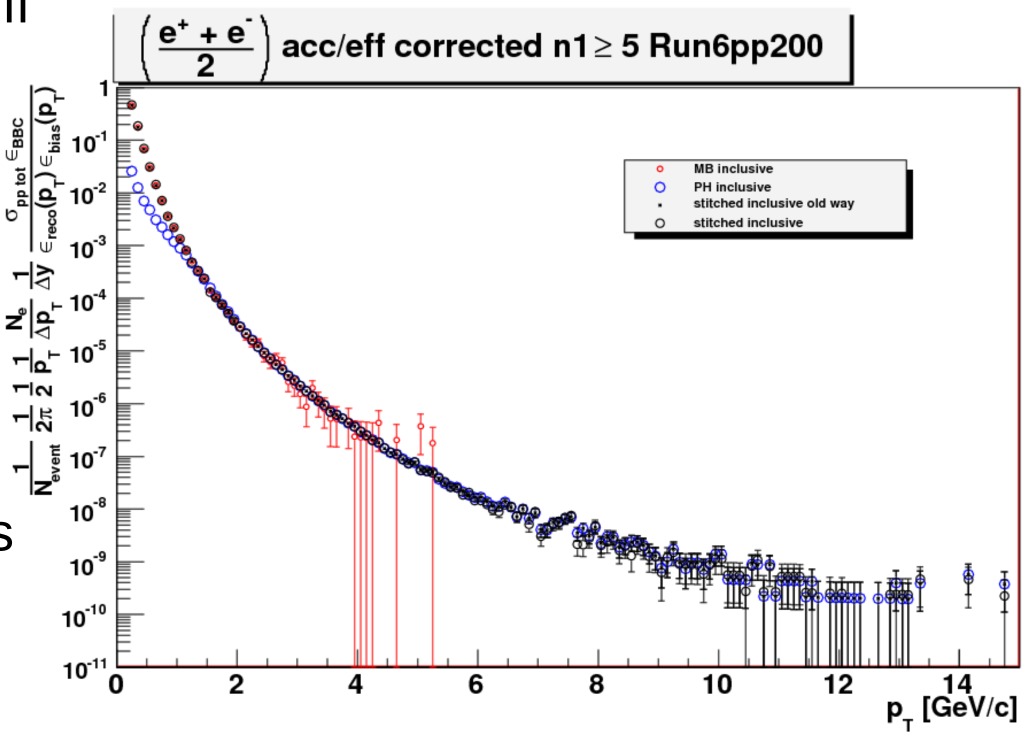
- dN/dphi plot
  - all eID cuts
  - $0.6<p_T<4.0$GeV straight tracks below pion threshold
- check to make sure PISA version of PHENIX is the same as the real version

Acceptance Efficiency Correction



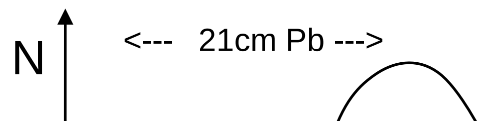
Final Inclusive Spectrum

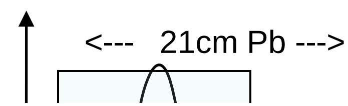
- Divide raw inclusive by acc/eff curve
- Scale 0.5 ((e^+ + e)/2)
- Scale 1/2π
- Scale 1/0.1 (bin width)
- Scale 0.516/0.75 MB trig eff/trig bias
- Scale 42.2 (pp inelastic cross section)



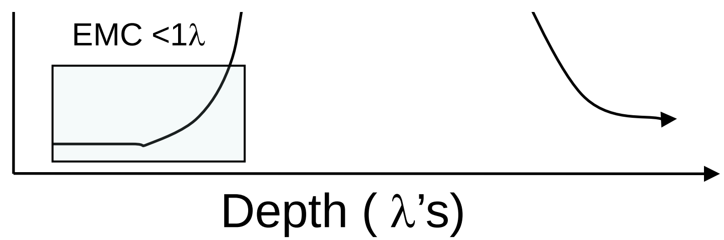
Pions in the EMC

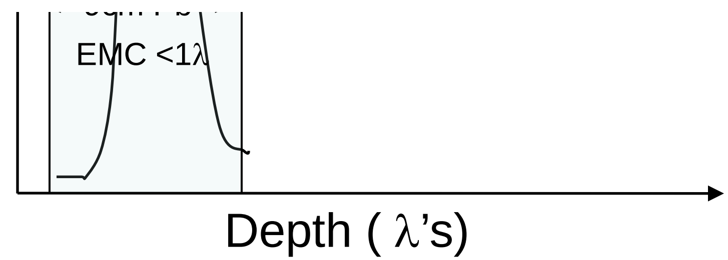
- Most are MIPs, some shower
- Hadronic shower
  - smaller cross sections
  - much larger fluctuation of energy deposit in active medium
  - EMC $<1\lambda$ => never get to shower max
  - 30% of any shower are π^0's





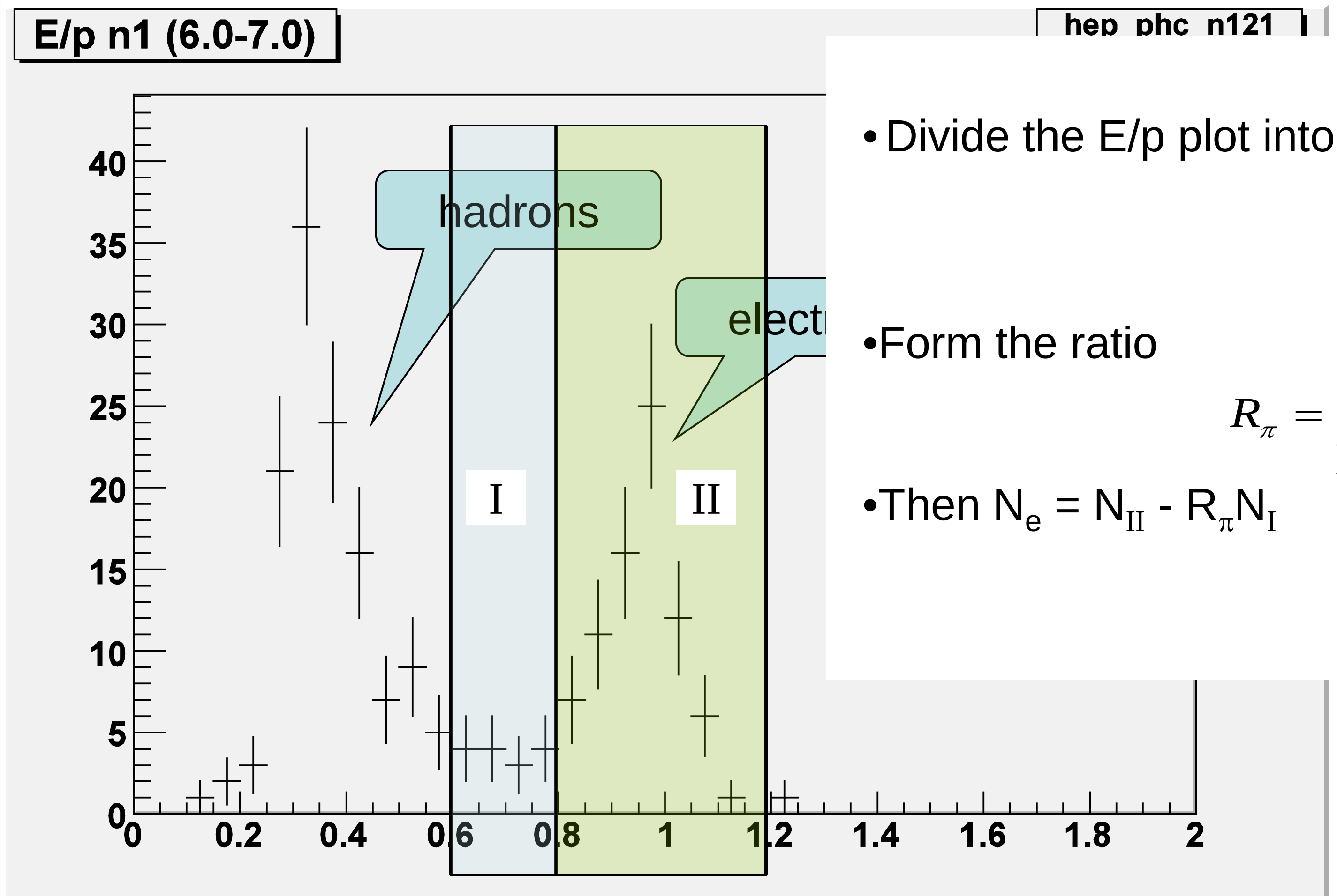
Assert that the energy distribution, scaled by the momentum, is the same for any p_T bin





Cartoon of the longitudinal development of a shower

The Principle



- Divide the E/p plot into two regions
- Form the ratio

$$R_\pi = \int_{II} E/p \Big/ \int_{I} E/p$$

- Then $N_e = N_{II} - R_\pi N_I$

IEEE paper

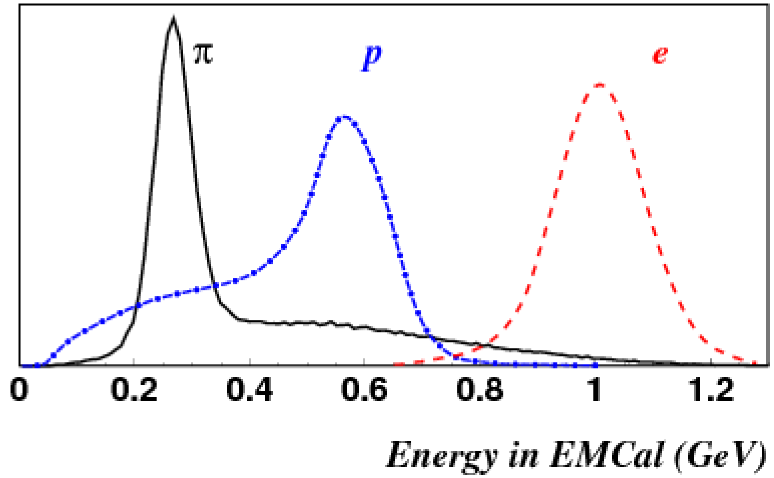


Fig. 7 Top: EMCal response to 1 GeV/c π's, p's and electrons.

The PHENIX Lead-Scintillator Electromagnetic Calorimeter: Test Beam and Construction Experience [1]

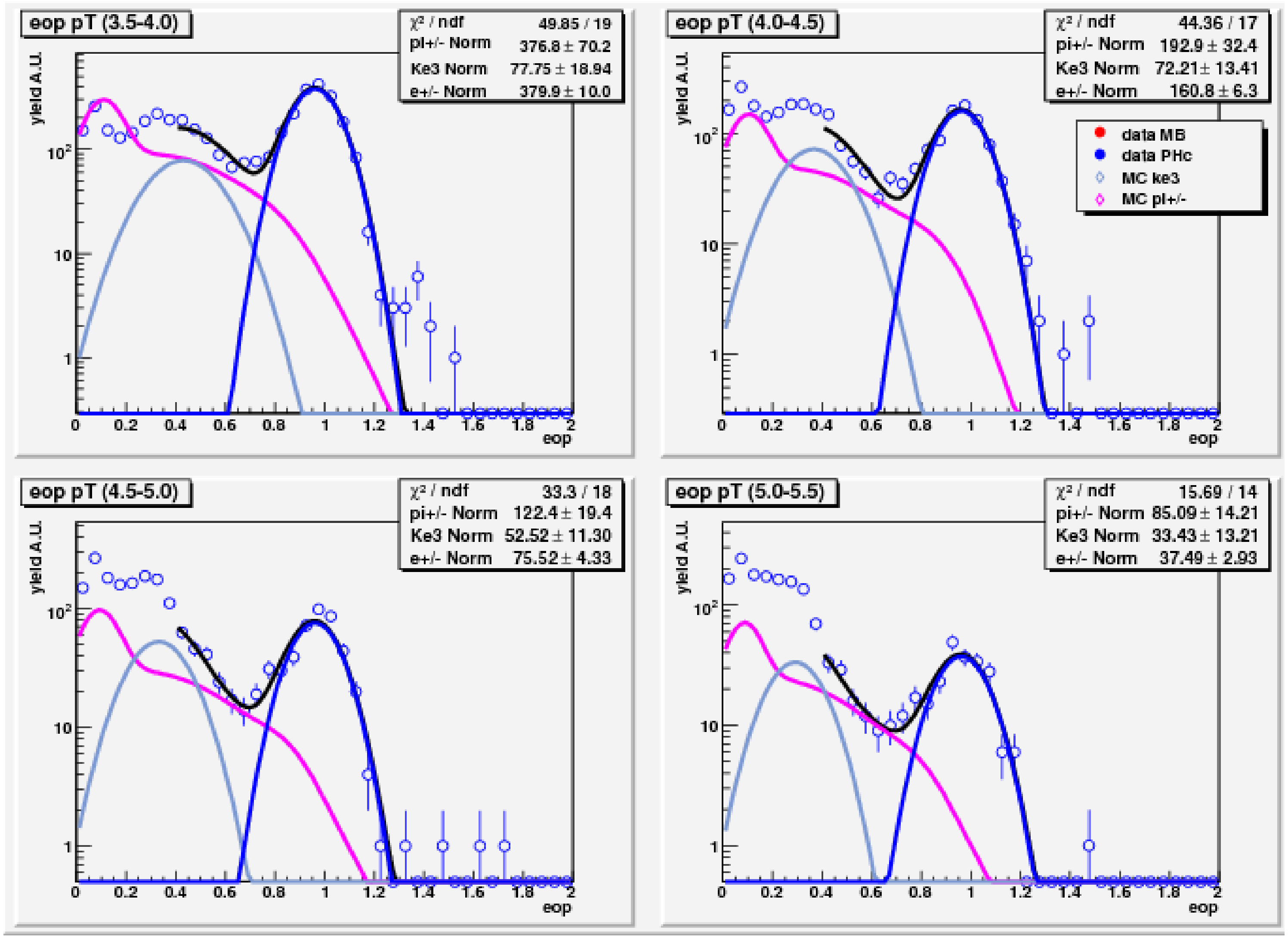
G.David, Y.Goto[2], E.Kistenev, S.Stoll, S.White, C.Woody
Brookhaven National Laboratory, Upton, New York

A.Bazilevsky, S.Belikov, S.Chernichenkov, A.Denisov, V.Kochetkov, Y.Melnikov, V.Onuchin, V.Semenov, V.Shelikhov, A.Soldatov, A.Usachev Institute for High Energy Physics, Protvino, Russia

Background Function

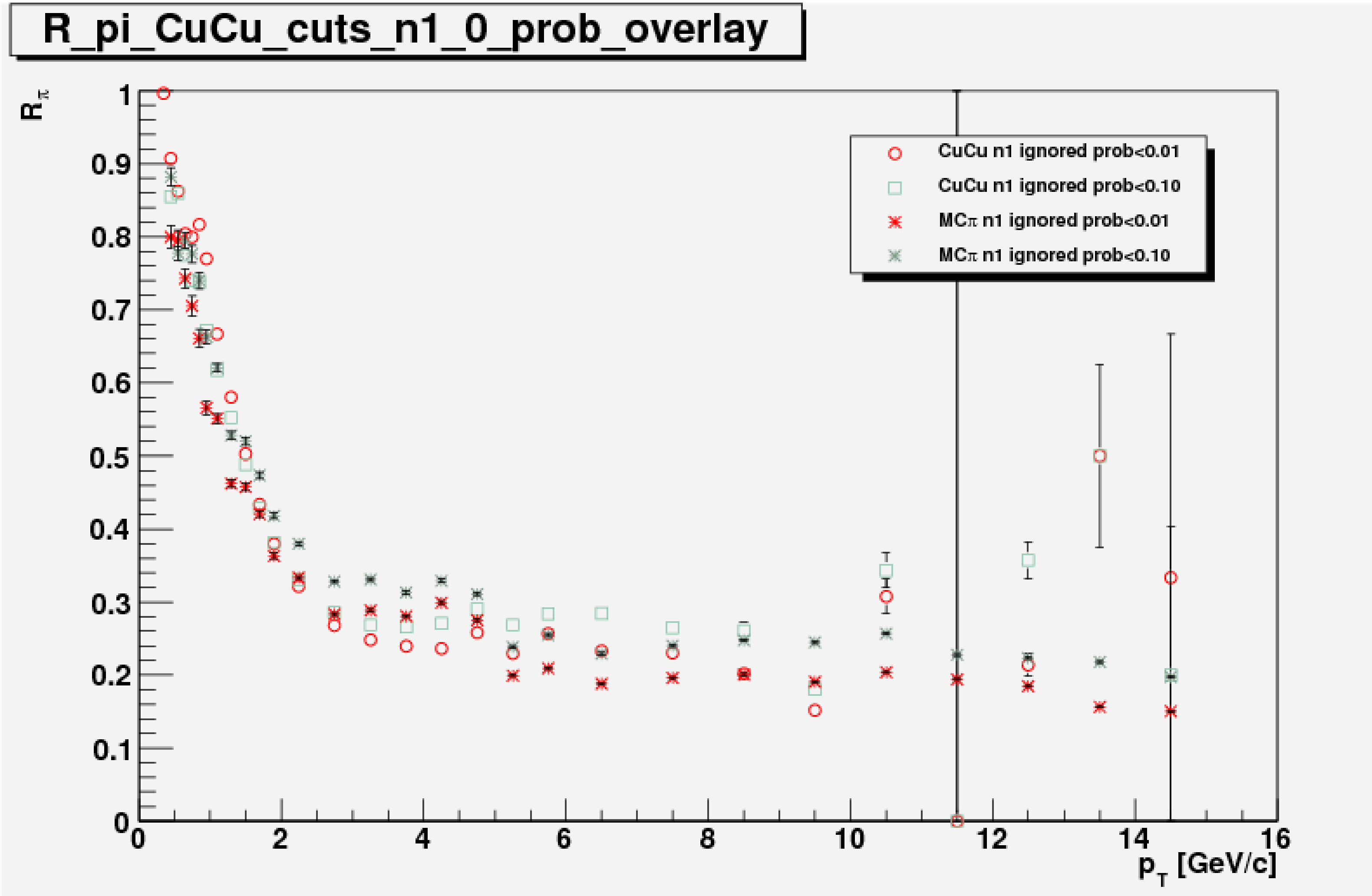
- Ke3, Pions & Electrons
  - Generate Ke3 OSCAR files with modified EXODUS
  - propagate through PISA
  - Plot E/p p_T bin by p_T bin, fit with a function
- The resulting function is a sum of all three, the fit to data will have all parameters fixed except the three normalization constants.
- Use the resulting fits to;
  - Show π's are the only background
  - Demonstrate that MC accurately models π's
- As part of this process
  - wrote a "FastMC" to model π's in the RICH
  - wrote a recalibrator for energy and momentum for PISA
- Final
  - incorporate FastMC result and recalibrator into PISA
  - weight all species in PISA with fits to real data
  - extract R_π from PISA

Final Fit

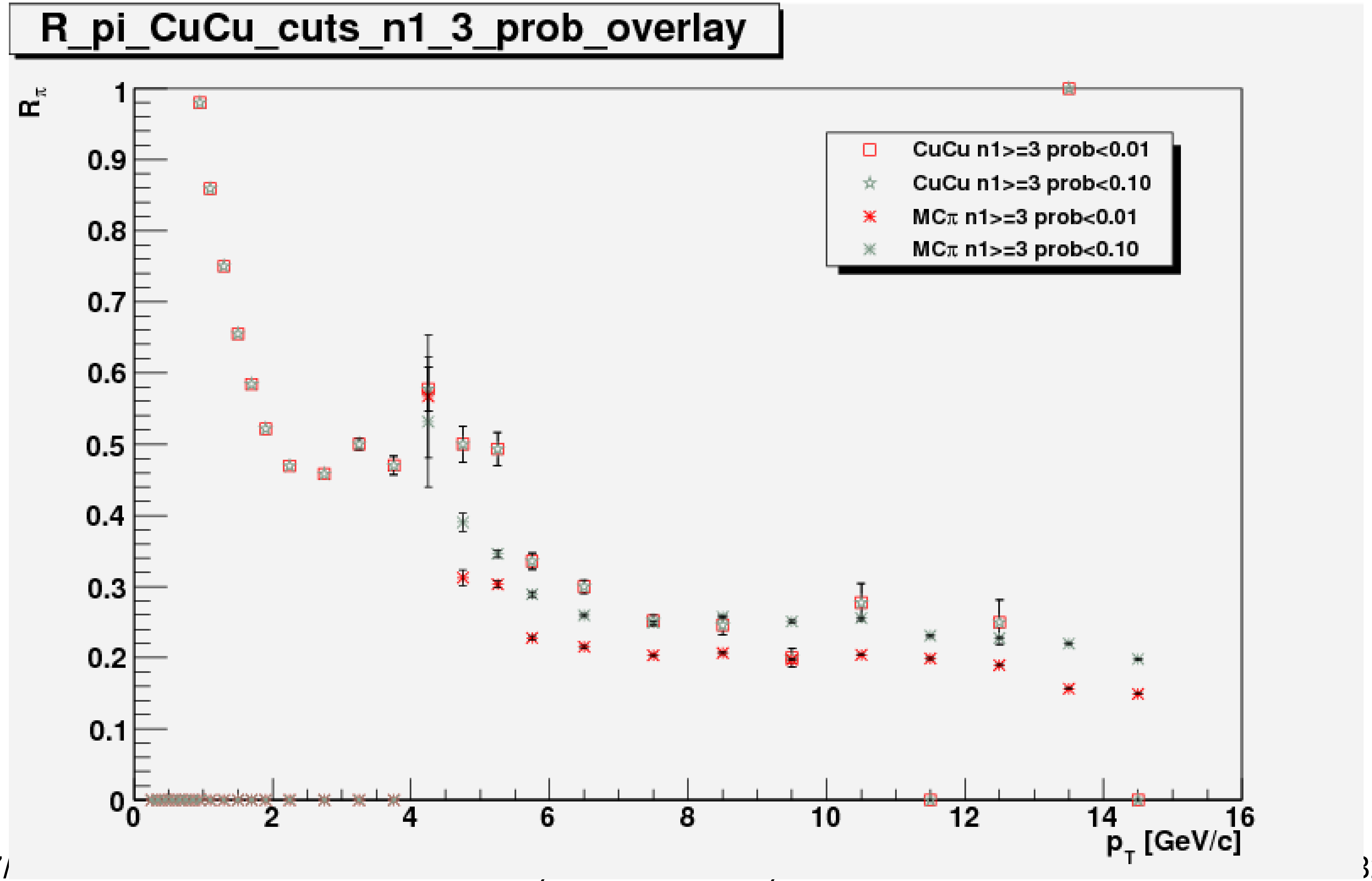


eop pT (3.5-4.0)
χ² / ndf 49.85 / 19
pi+/- Norm 376.8 ± 70.2
Ke3 Norm 77.75 ± 18.94
e+/- Norm 379.9 ± 10.0
eop pT (4.0-4.5)
χ² / ndf 44.36 / 17
pi+/- Norm 192.9 ± 32.4
Ke3 Norm 72.21 ± 13.41
e+/- Norm 160.8 ± 6.3
data MB
data PHc
MC ke3
MC pi+/-
eop pT (4.5-5.0)
χ² / ndf 33.3 / 18
pi+/- Norm 122.4 ± 19.4
Ke3 Norm 52.52 ± 11.30
e+/- Norm 75.52 ± 4.33
eop pT (5.0-5.5)
χ² / ndf 15.69 / 14
pi+/- Norm 85.09 ± 14.21
Ke3 Norm 33.43 ± 13.21
e+/- Norm 37.49 ± 2.93
yield A.U.
eop

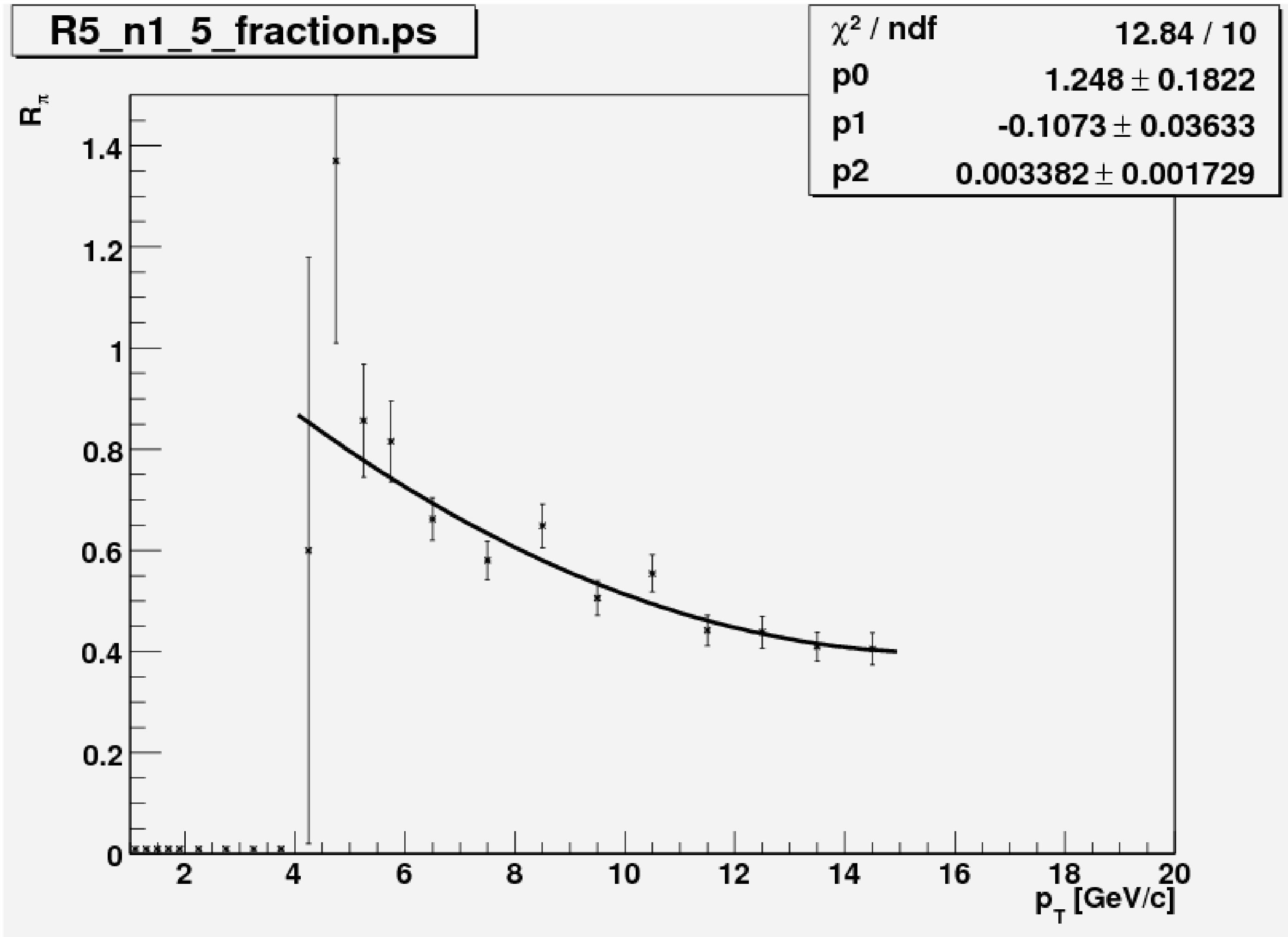
Does PISA produce R_π Accurately?



Does PISA produce Rπ Accurately?



R_π



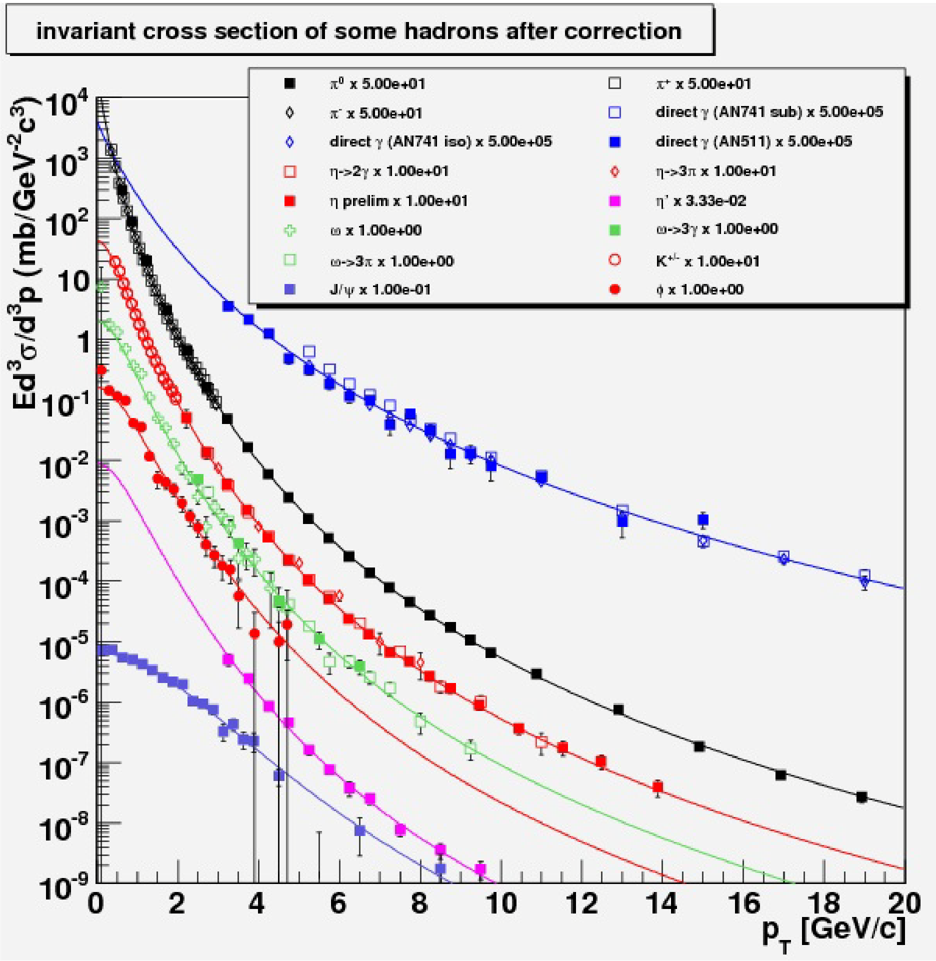
R5_n1_5_fraction.ps
χ^2 / ndf 12.84 / 10
p0 1.248 ± 0.1822
p1 -0.1073 ± 0.03633
p2 0.003382 ± 0.001729
R_π
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2
4
6
8
10
12
14
16
18
20
p_T [GeV/c]

Cocktail of Electrons

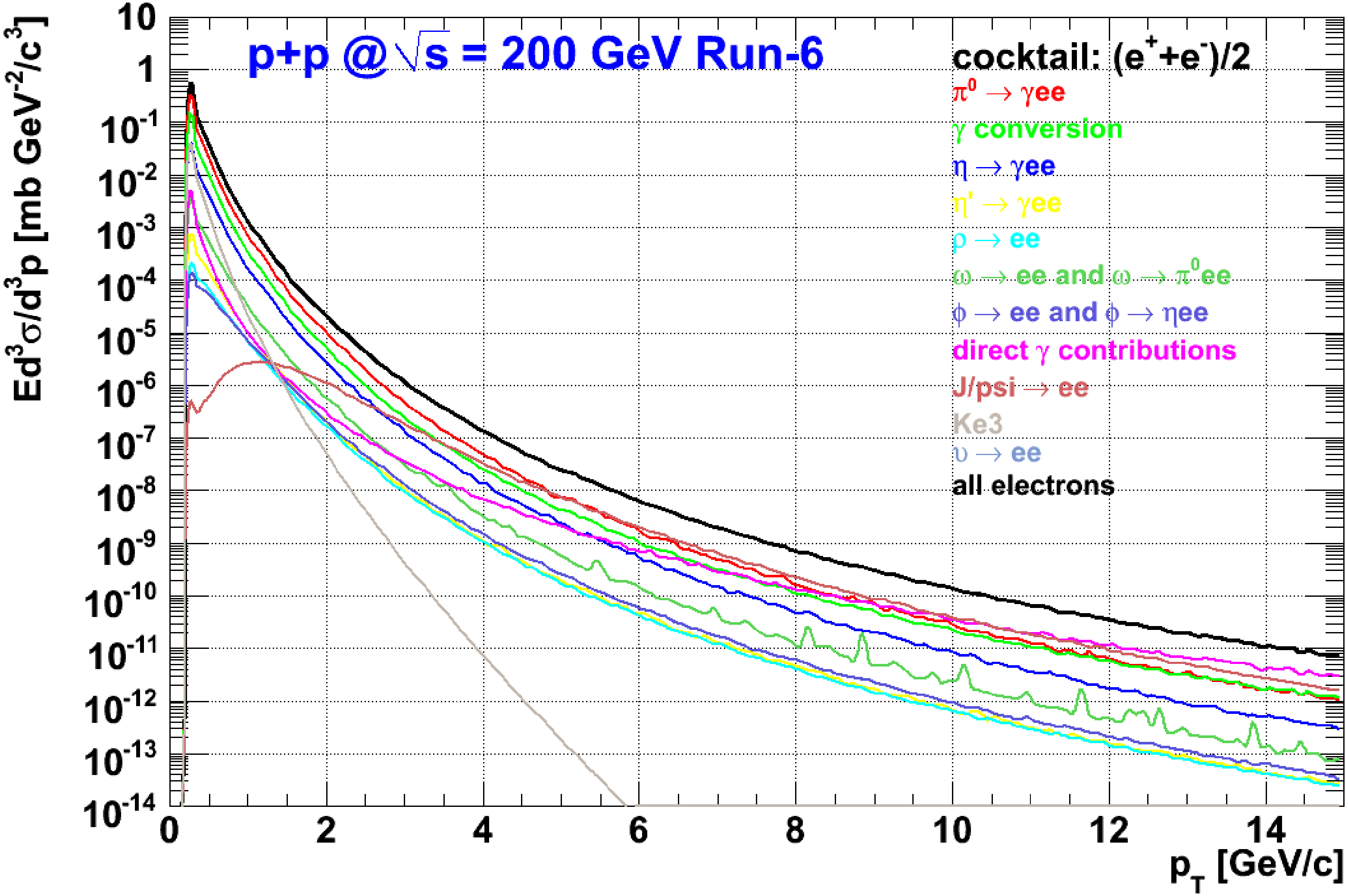
- Primary ingredient is π data

$$E\frac{d^3\sigma}{dp^3} = f\_c\left(e^{-(f\_a p_T + f\_b p_T^2)} + p_T / p_0\right)^{-f\_n}$$

$$\sqrt{(p_T/c)^2 - m_{\pi^0}^2 + m_h^2},$$

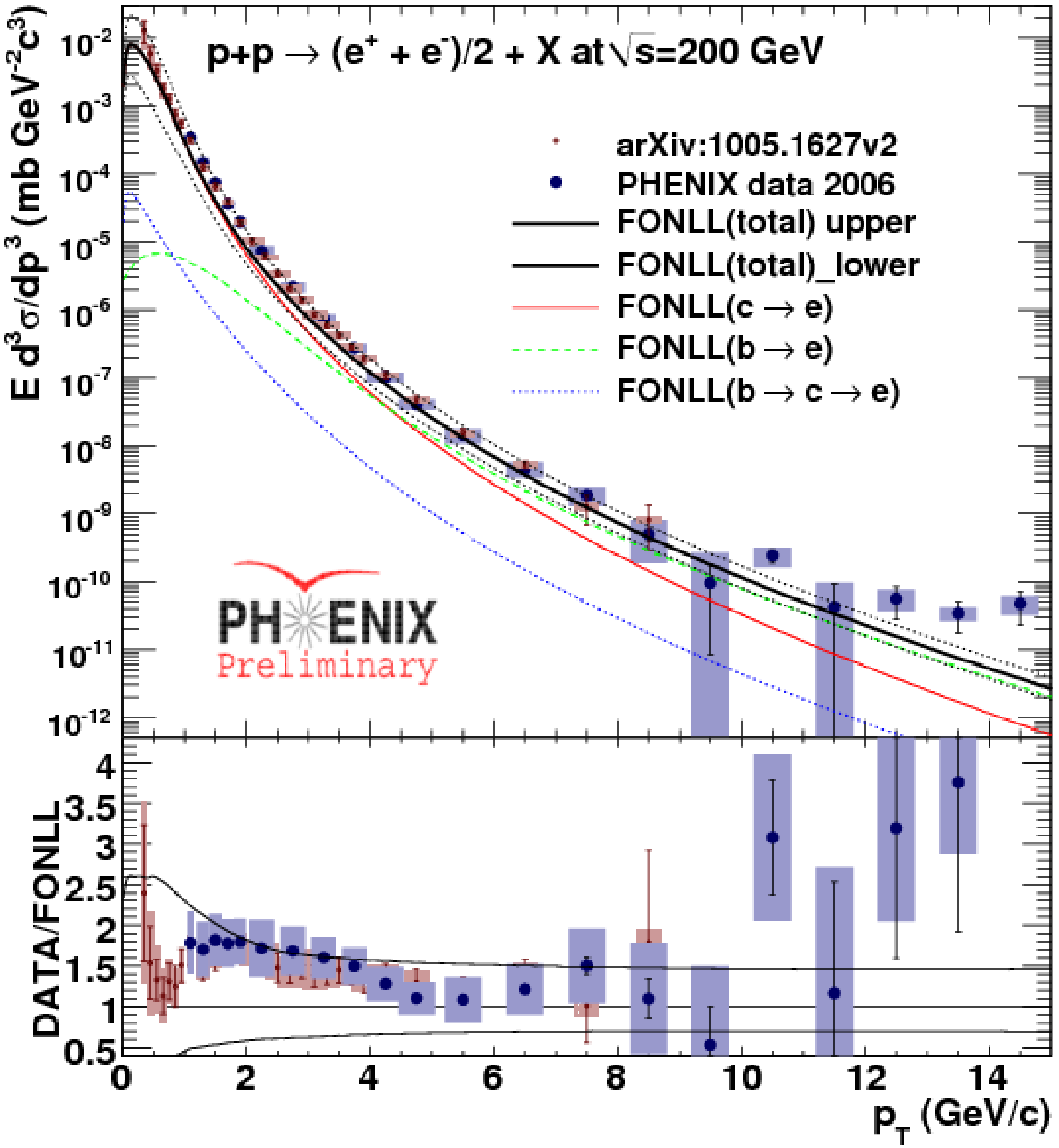


Cocktail of Electrons

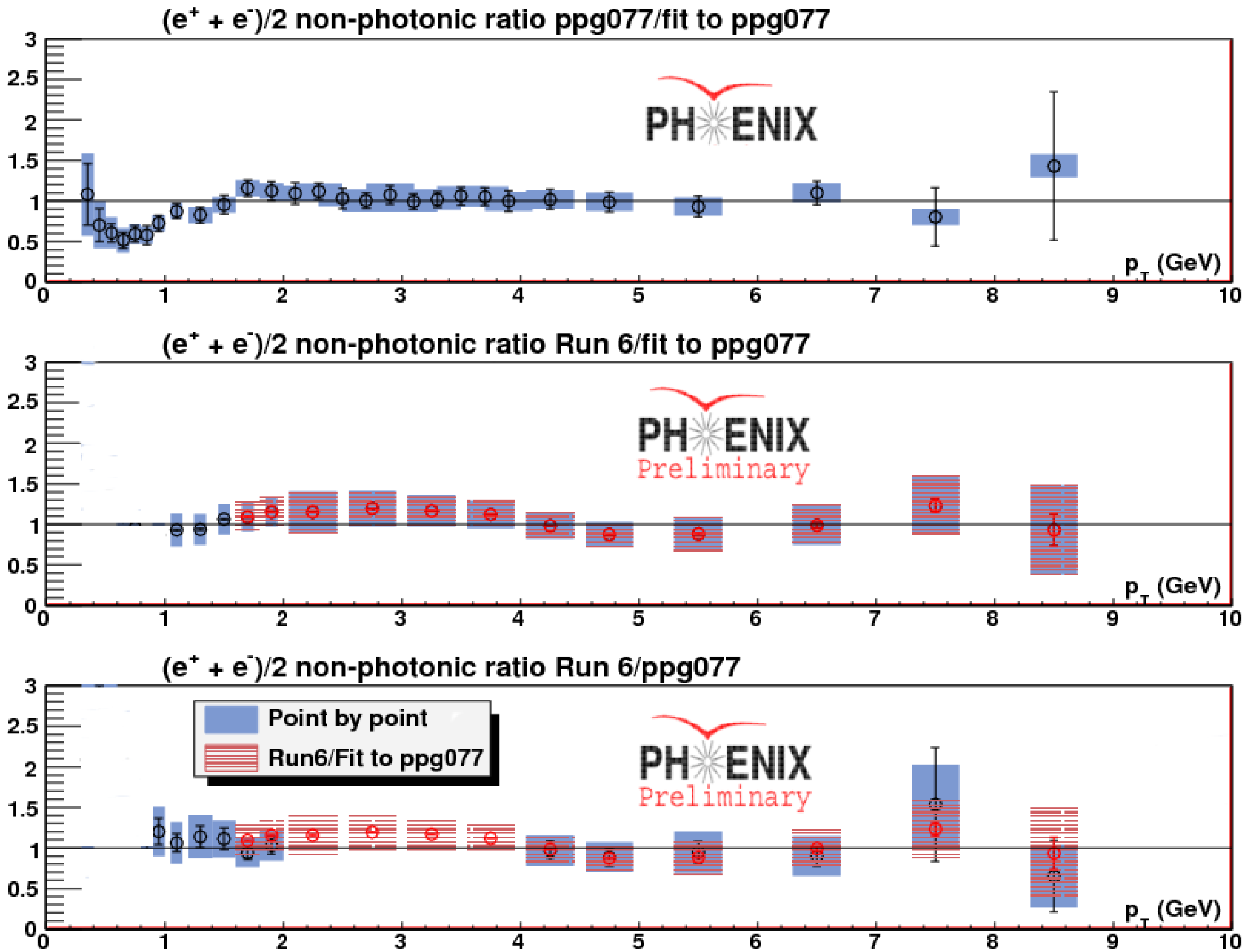


Final Spectrum

- Re bin & Bin shift correct
  - inclusive
  - cocktail
  - R_π
- Subtract Cocktail & Background
- Calculate Systematic Errors



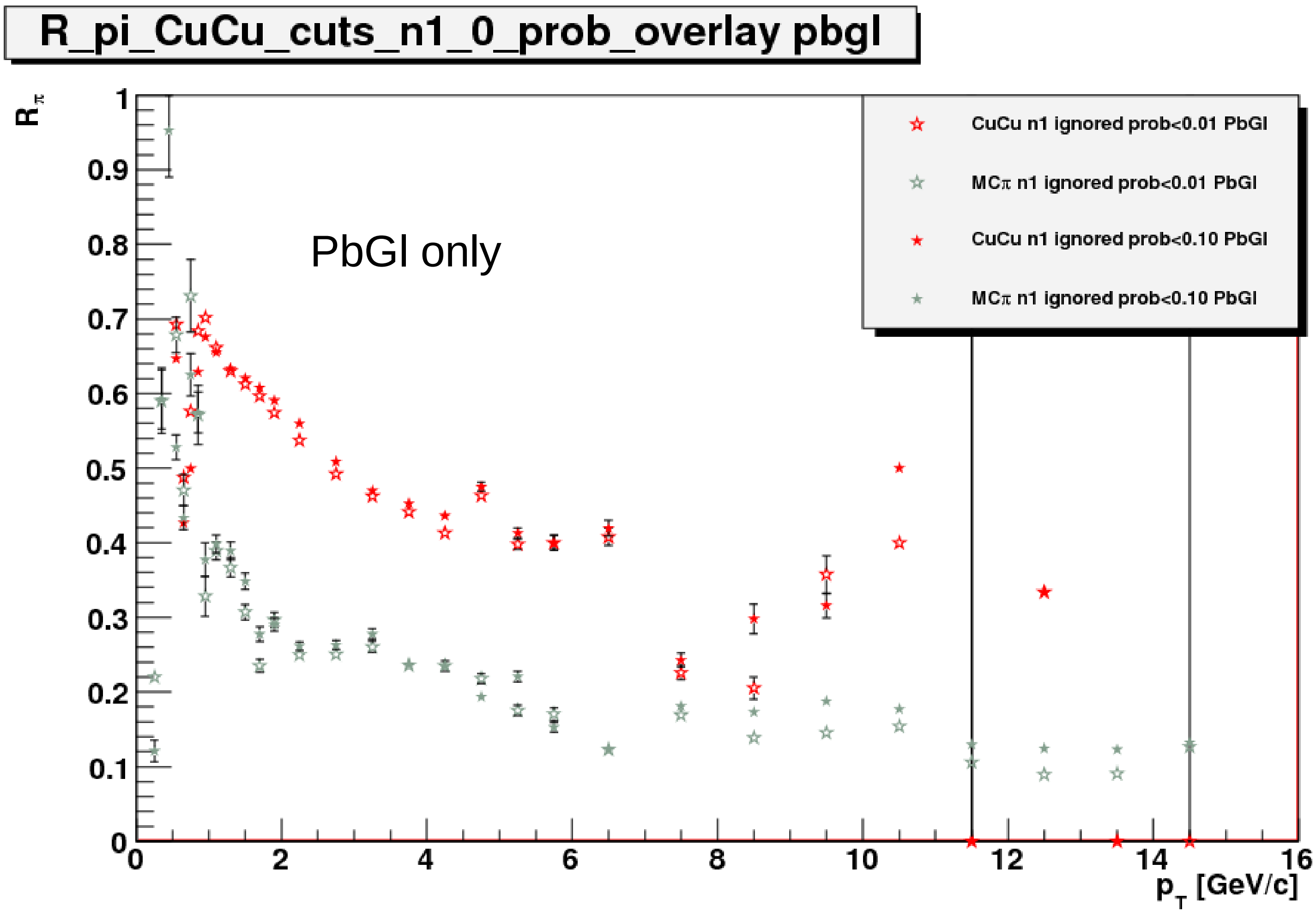
Comparison to Published PHENIX Data



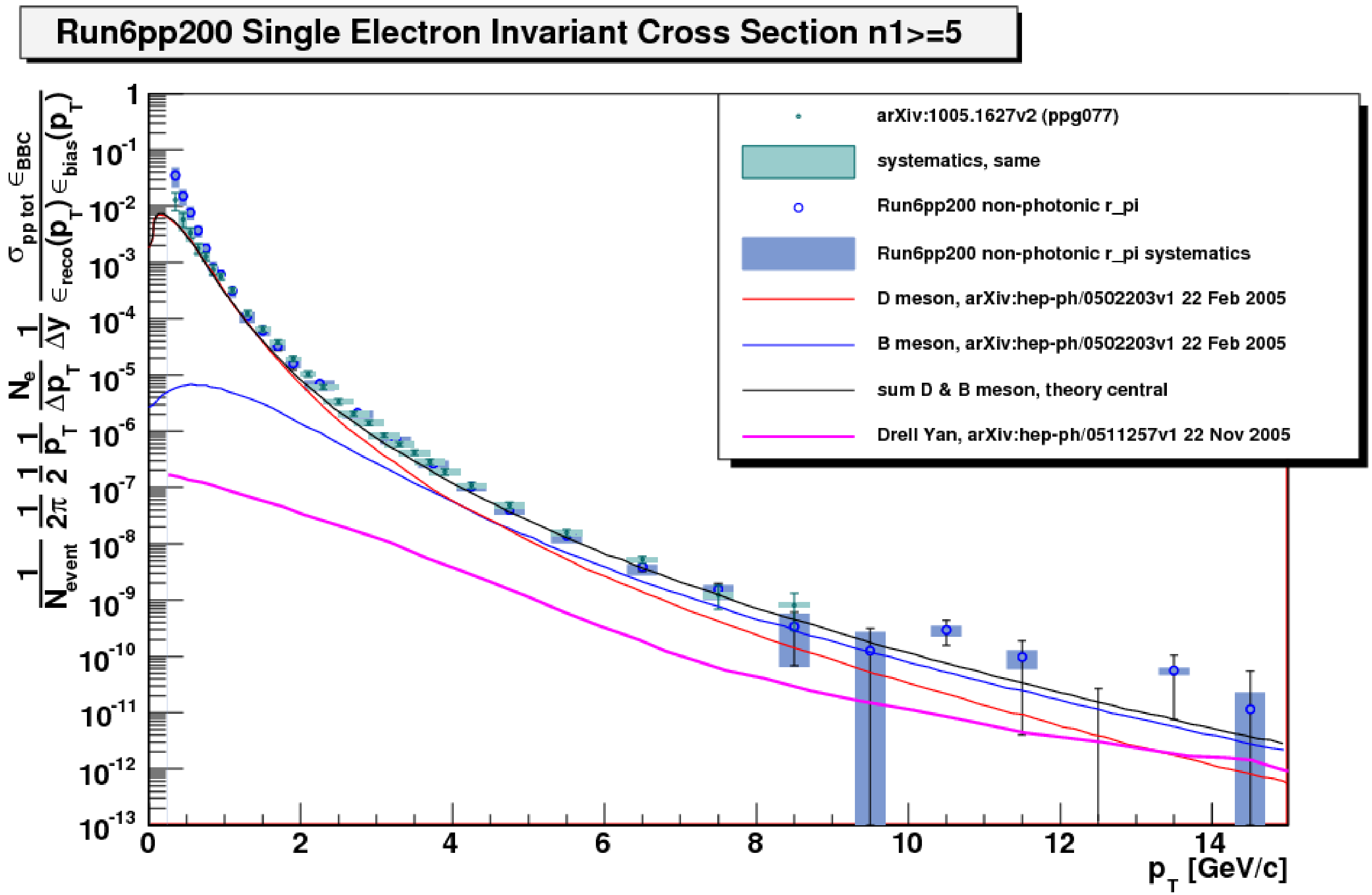
Conclusion

- Successfully demonstrated a new technique for subtraction of hadron contamination
- Significantly extended the PHENIX pp reference for single electrons from open heavy flavor
- Hope to add Run5 and Run8 statistics
- SVTX and displaced vertex -> check my work

Problem with PISA



PbSc Only



Run6pp200 Single Electron Invariant Cross Section n1>=5
arXiv:1005.1627v2 (ppg077)
systematics, same
Run6pp200 non-photonic r_pi
Run6pp200 non-photonic r_pi systematics
D meson, arXiv:hep-ph/0502203v1 22 Feb 2005
B meson, arXiv:hep-ph/0502203v1 22 Feb 2005
sum D & B meson, theory central
Drell Yan, arXiv:hep-ph/0511257v1 22 Nov 2005
$\frac{1}{N_{event}} \frac{1}{2\pi} \frac{1}{2} \frac{1}{p_T} \frac{N_e}{\Delta p_T} \frac{1}{\Delta y} \frac{\sigma_{pp\,tot}\,\epsilon_{BBC}}{\epsilon_{reco}(p_T)\,\epsilon_{bias}(p_T)}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
0
2
4
6
8
10
12
14
p_T [GeV/c]

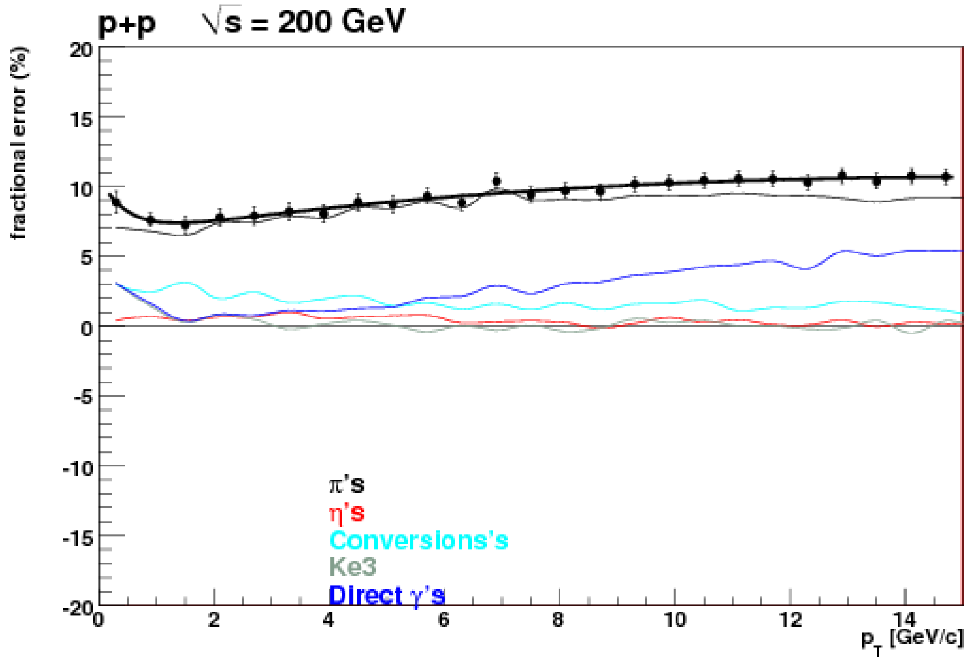
backup

Overall Systematic Error

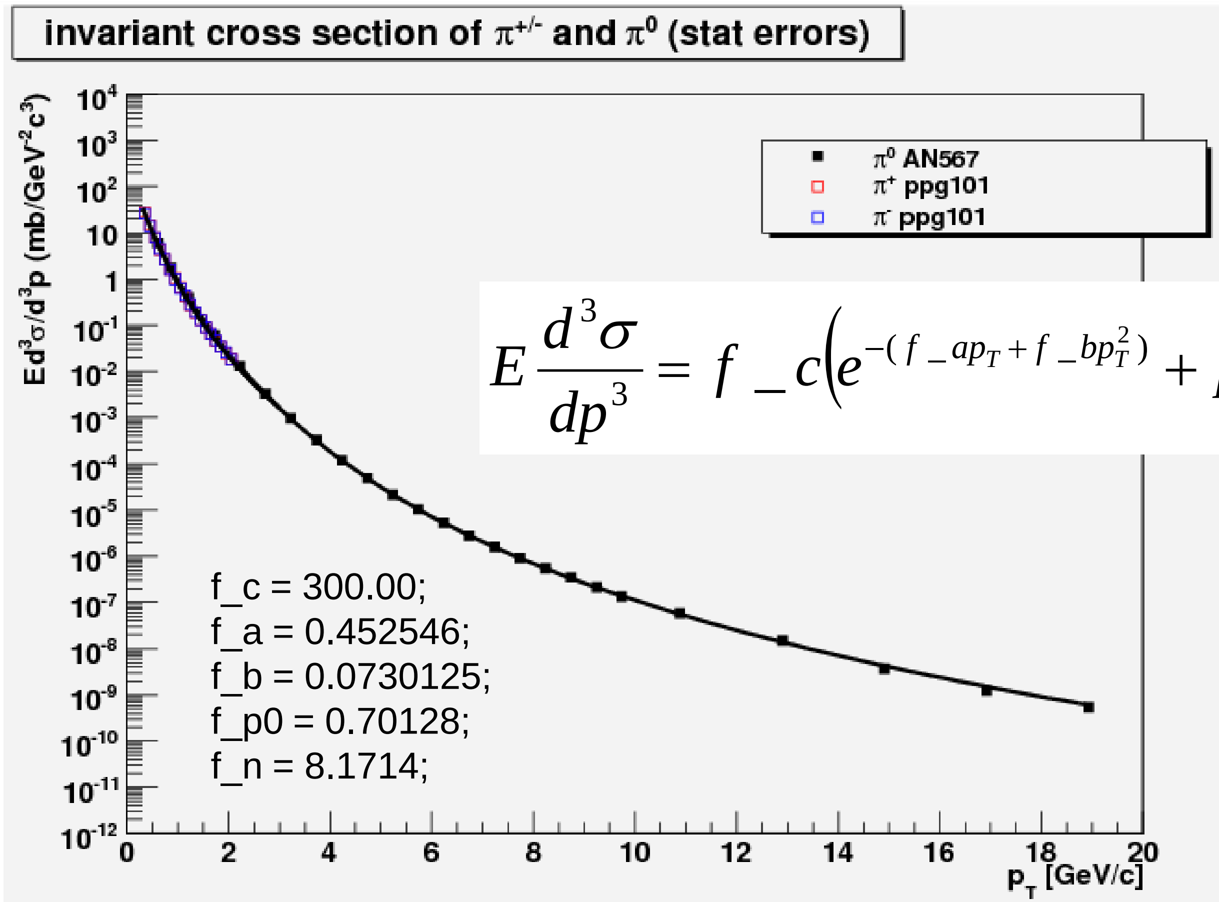
- Cocktail
- R_{π} -> +/- 25%
- Acc/eff -> +/- 10%
- Three separate final spectra are created and added in quadrature to get final error boxes

Systematic Error in Cocktail

- Pions
  - Move pion data points up(down) by their sys errors
  - re fit hagedorn, feed parameters into EXODUS
  - calculate fractional change in total
- Other Elements
  - change weights by their fractional uncertainties
  - put into EXODUS
  - calculate fractional change in total

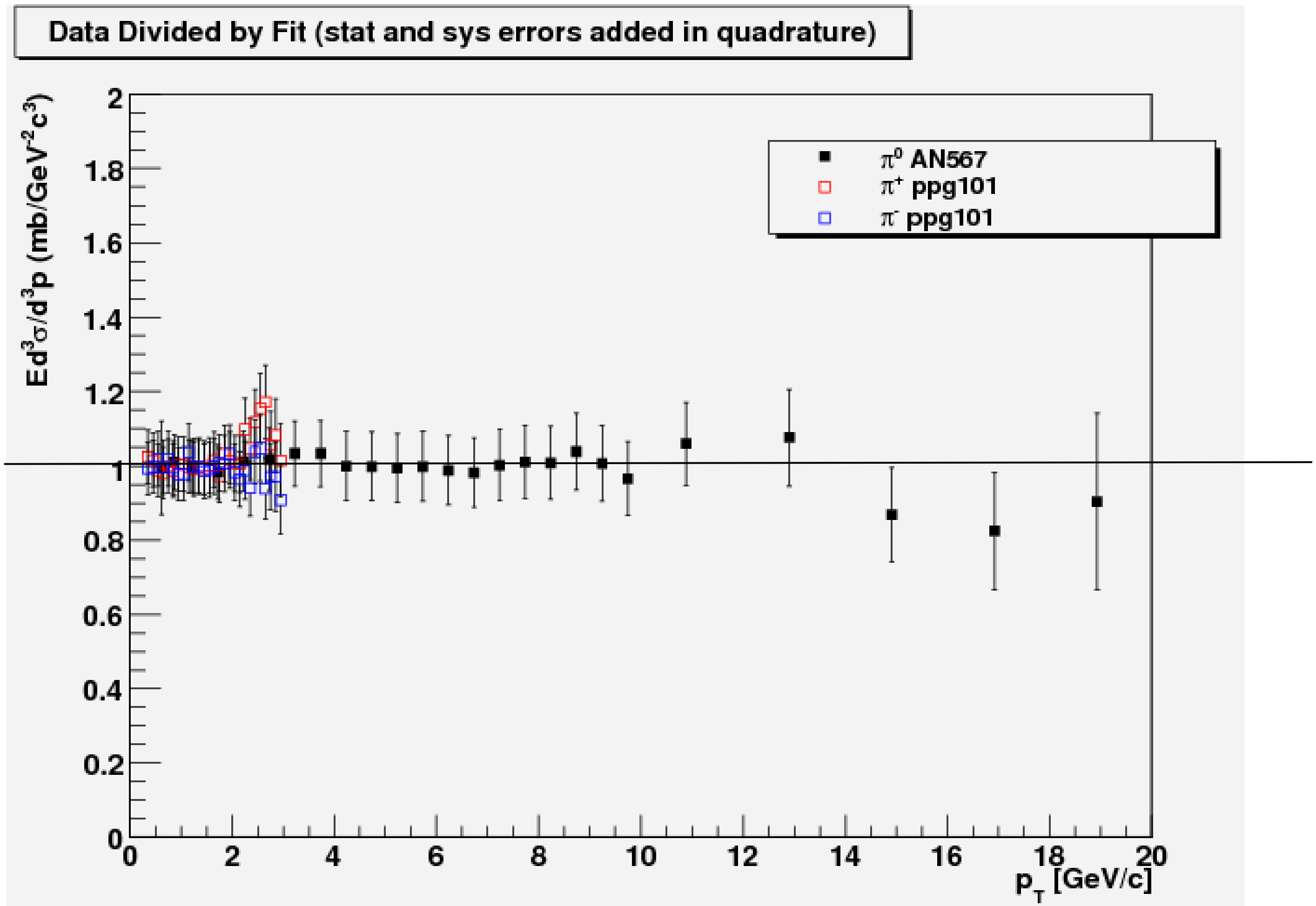


Fit to Latest π Data



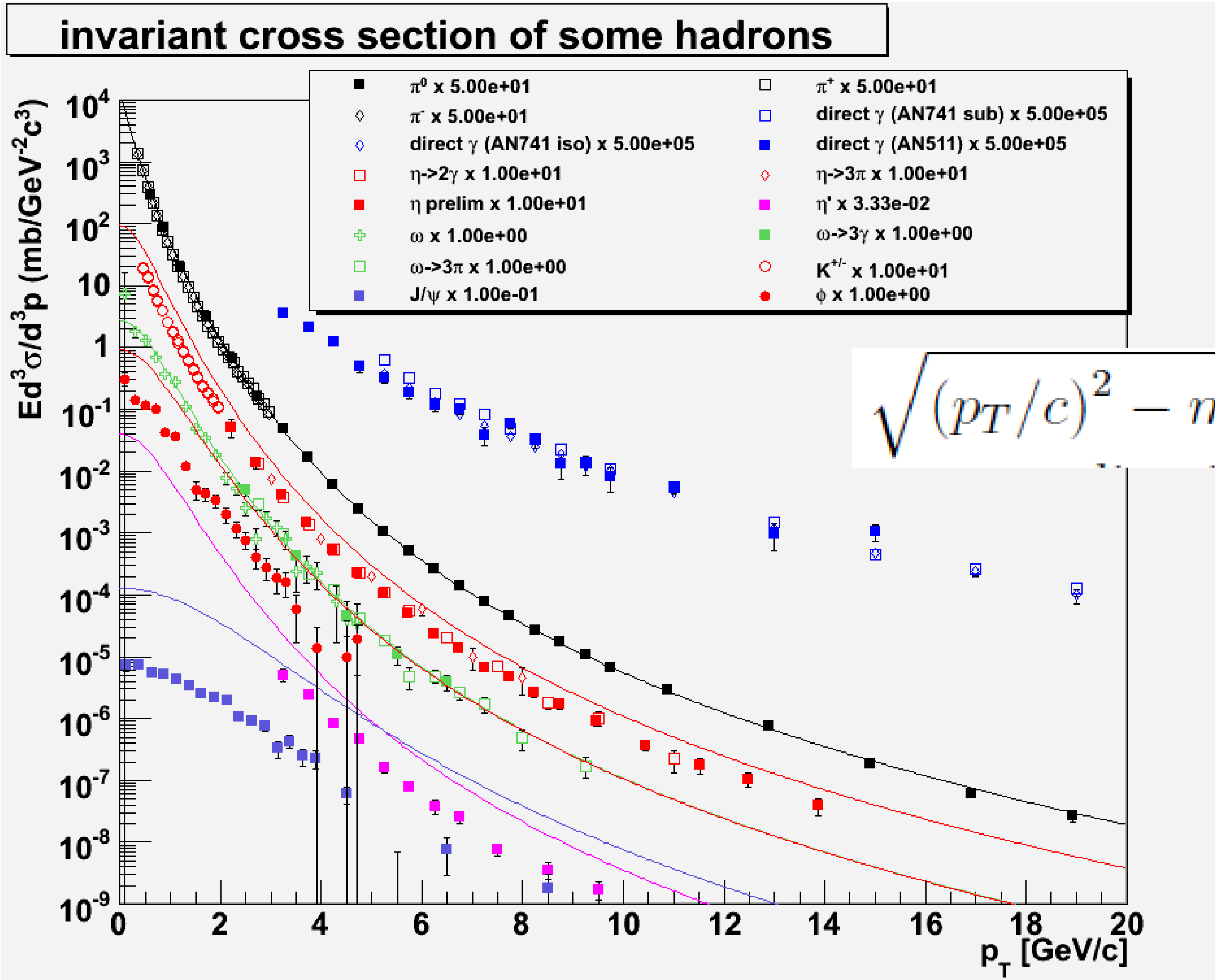
$$E\frac{d^3\sigma}{dp^3} = f\_c\left(e^{-(f\_a p_T + f\_b p_T^2)} + p_T / p_0\right)^{-f\_n}$$

Ratio



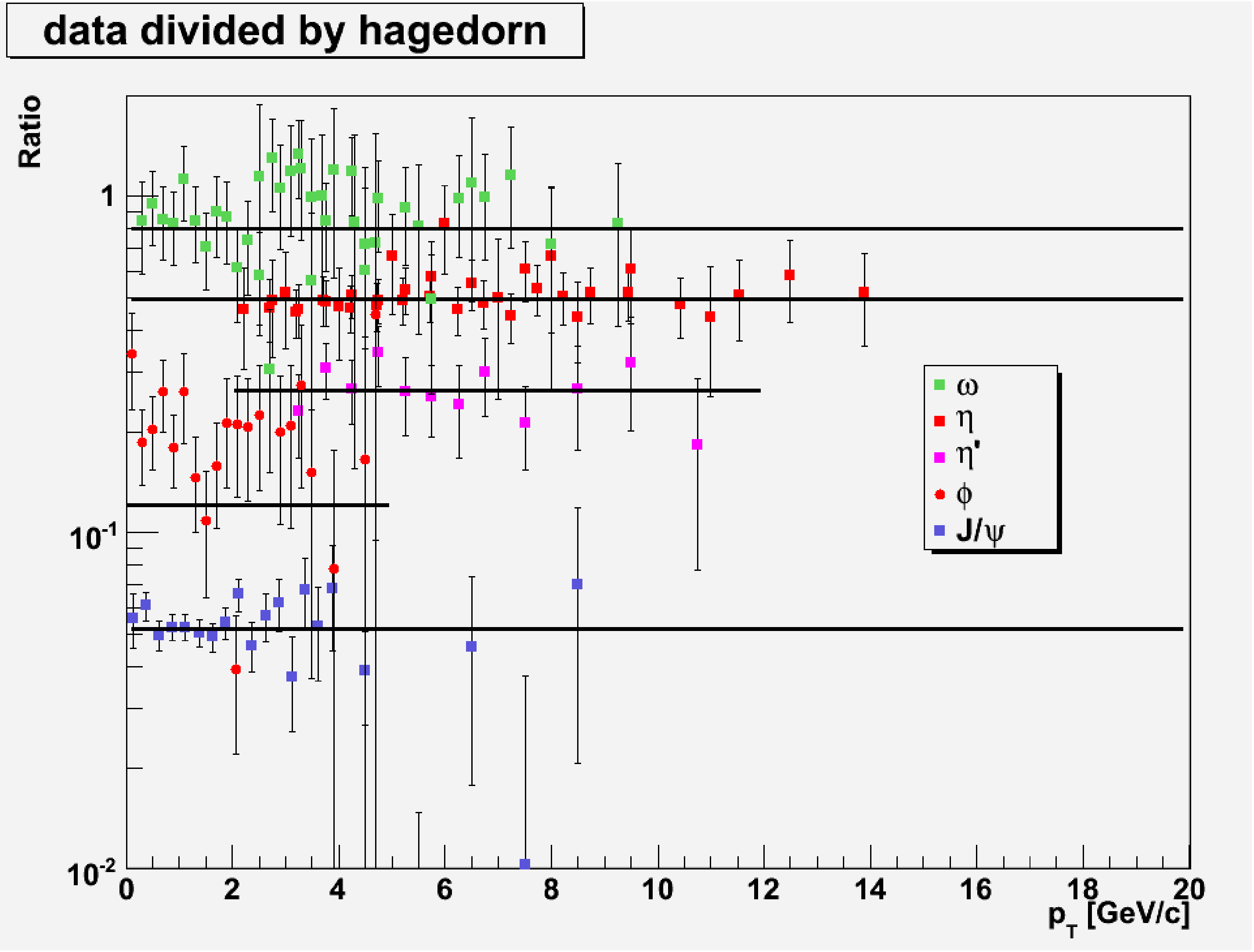
Data Divided by Fit (stat and sys errors added in quadrature)
π^0 AN567
π^+ ppg101
π^- ppg101
$Ed^3\sigma/d^3p$ (mb/GeV^{-2}c^3)
p_T [GeV/c]
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20

m_T Scaling

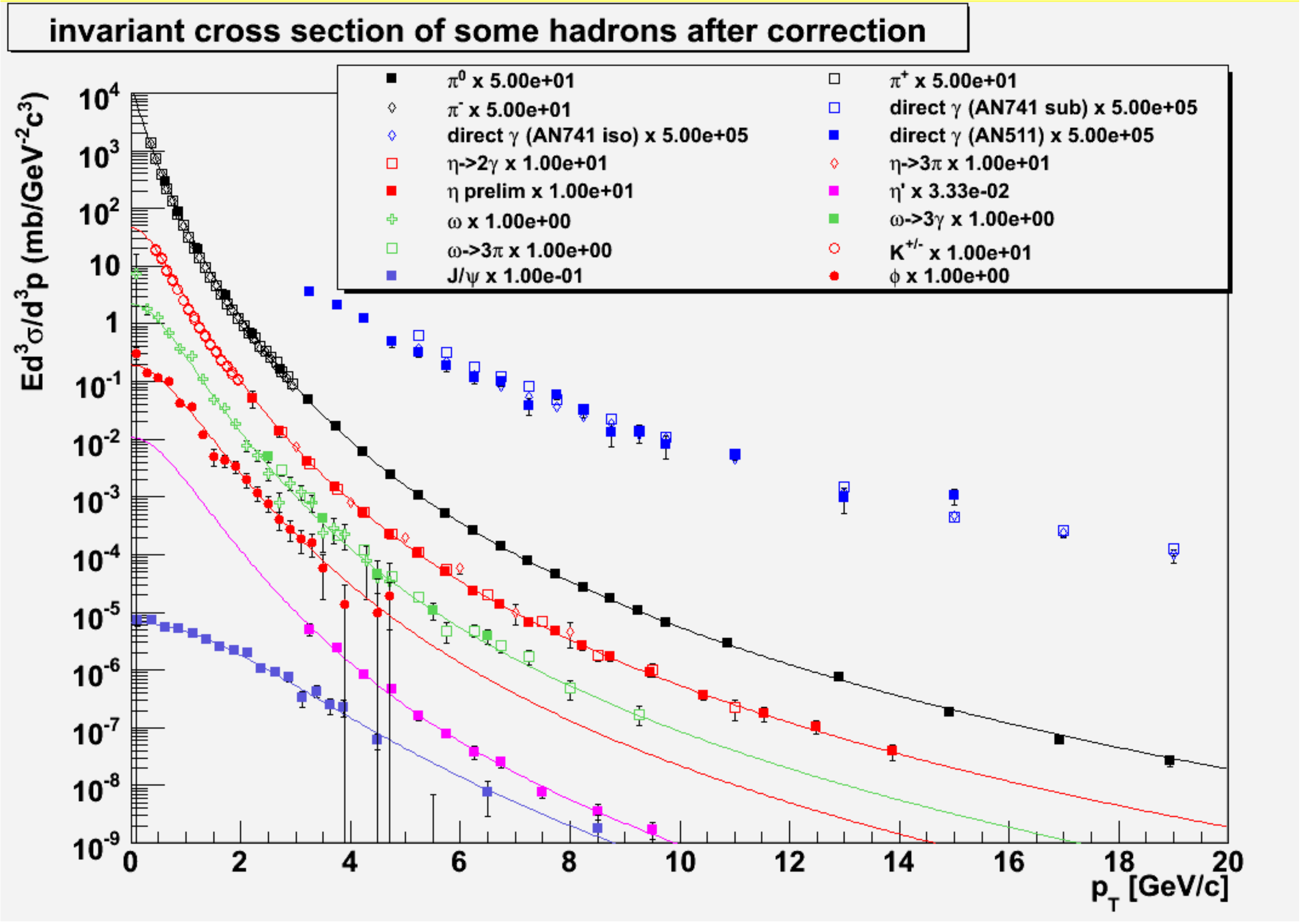


$$\sqrt{(p_T/c)^2 - m_{\pi^0}^2 + m_h^2},$$

Additional Normalization Constant



Final Fit


invariant cross section of some hadrons after correction
π^0 x 5.00e+01
π^+ x 5.00e+01
π^- x 5.00e+01
direct γ (AN741 sub) x 5.00e+05
direct γ (AN741 iso) x 5.00e+05
direct γ (AN511) x 5.00e+05
η->2γ x 1.00e+01
η->3π x 1.00e+01
η prelim x 1.00e+01
η' x 3.33e-02
ω x 1.00e+00
ω->3γ x 1.00e+00
ω->3π x 1.00e+00
$K^{+/-}$ x 1.00e+01
J/ψ x 1.00e-01
ϕ x 1.00e+00
$Ed^3\sigma/d^3p$ (mb/GeV^{-2}c^3)
p_T [GeV/c]

dN/dy

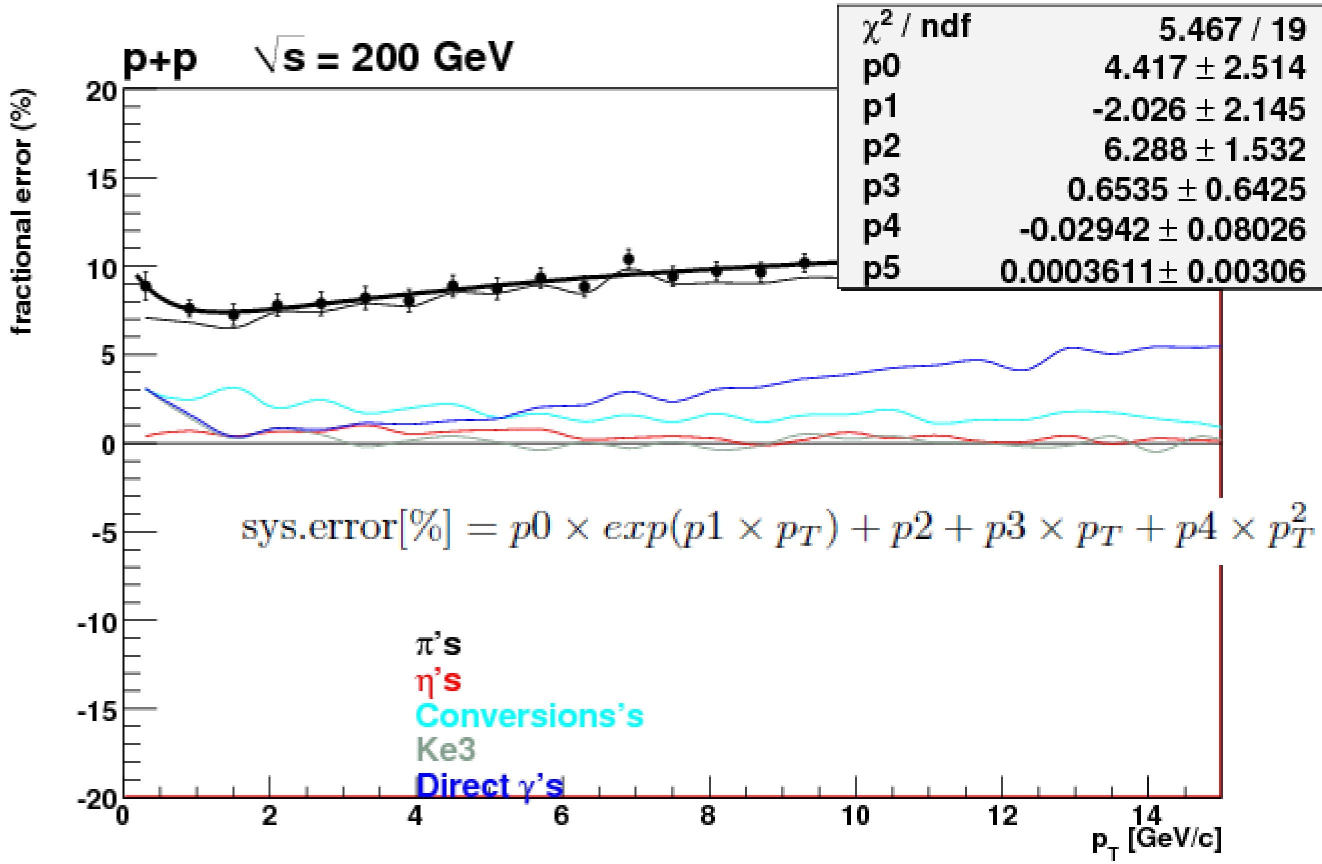
- 1.01653 dN/dy π
- 0.107884 η
- 0.0161826 η'
- 0.08953762 ρ → $\sigma_\rho/\sigma_\omega$ = 1.15
- 0.0778588 ω
- 0.00946404 ϕ
- 0.0000170768 J/ψ
- 0.000000111960 Y → $d\sigma_Y/dy$ / $Bd\sigma_{J/\psi}/dy$ = 0.006556291
- 0.0000025 ψ' →$\sigma_{\psi'}/\sigma_{J/\psi}$ = 0.14
- 0.0262 Direct Photon
- 0.00162 Ke3

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{2\pi}\frac{1}{p_T}\sigma_{inel}\frac{dN}{dy}\frac{dN}{dp_T} = Hagedorn$$

$$\frac{dN}{dy} = \frac{2\pi}{\sigma_{inel}}\int_0^\infty p_T Hagedorn(p_T)$$

assume dN/dy is constant y<|0.5|

Systematic Error in Cocktail

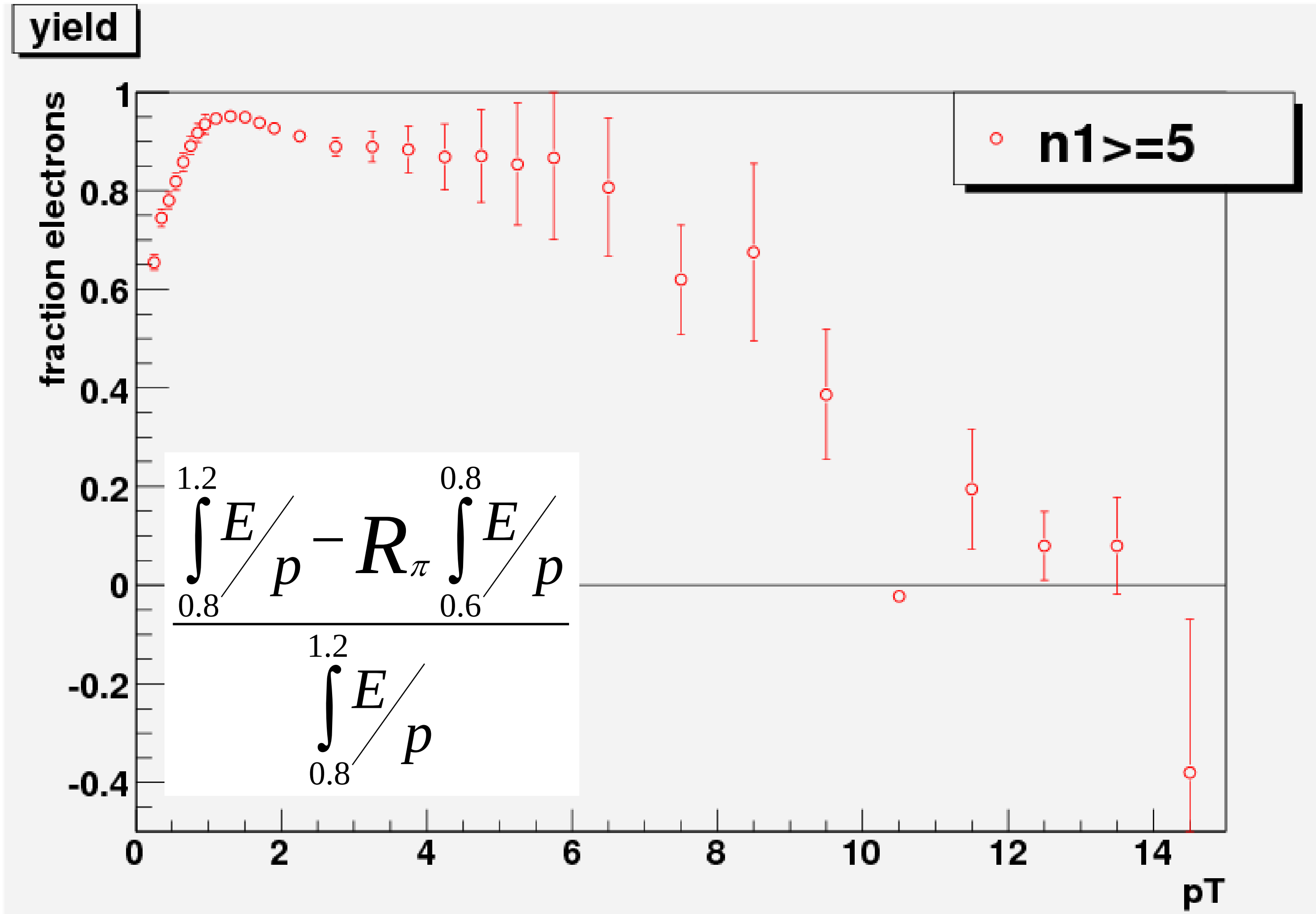


$$\mathrm{sys.error}[\%] = p0 \times exp(p1 \times p_T) + p2 + p3 \times p_T + p4 \times p_T^2 + p5 \times p_T^3$$

Systematic Error in Cocktail

- Pions
  - Move pion data points up(down) by their sys errors
  - re fit hagedorn, feed parameters into EXODUS
  - calculate fractional change in total
- Mesons
  - change meson/pion ratio by fractional uncertainty in normalization factor
  - put into EXODUS
  - calculate fractional change in total
- Conversions
  - change convprob +/- 10%
  - convprob is ratio of pi/pi dalitz
- Direct Photons
  - sys error from AN goes from 20-10% pT dependent
  - for now using 15%

Yield Fraction



Model The Background

- From data

$$\frac{\int_{0.8}^{1.2} E/p - R_\pi \int_{0.6}^{0.8} E/p}{\int_{0.8}^{1.2} E/p}$$

- This can be re written

$$\frac{N_e}{N_e + N_\pi} \longrightarrow \frac{N_e/N_e}{N_e/N_e + N_\pi/N_e}$$

- To Calculate

$$N_\pi/N_e = \frac{\pi}{e} \frac{\int_{0.8}^{1.2} E/p(\pi)}{\int_{0.0}^{2.0} E/p(\pi)} \frac{frac\_\pi\_n_1 >= 5}{frac\_e\_n_1 >= 5}$$

Terms

- π/e
  - Got most recent π^0 data from AN567 K. Boyle, A. Bazilevsky, A. Deshpande, Y. Fukao
  - Fit with Hagedorn function
  - For electrons got FONLL function from ppg065
  - Divided two functions (plots)
- Fraction in E/p window
  - Integrals done on MC π E/p distributions

$$\frac{\int_{0.8}^{1.2} E/p(\pi)}{\int_{0.0}^{2.0} E/p(\pi)}$$

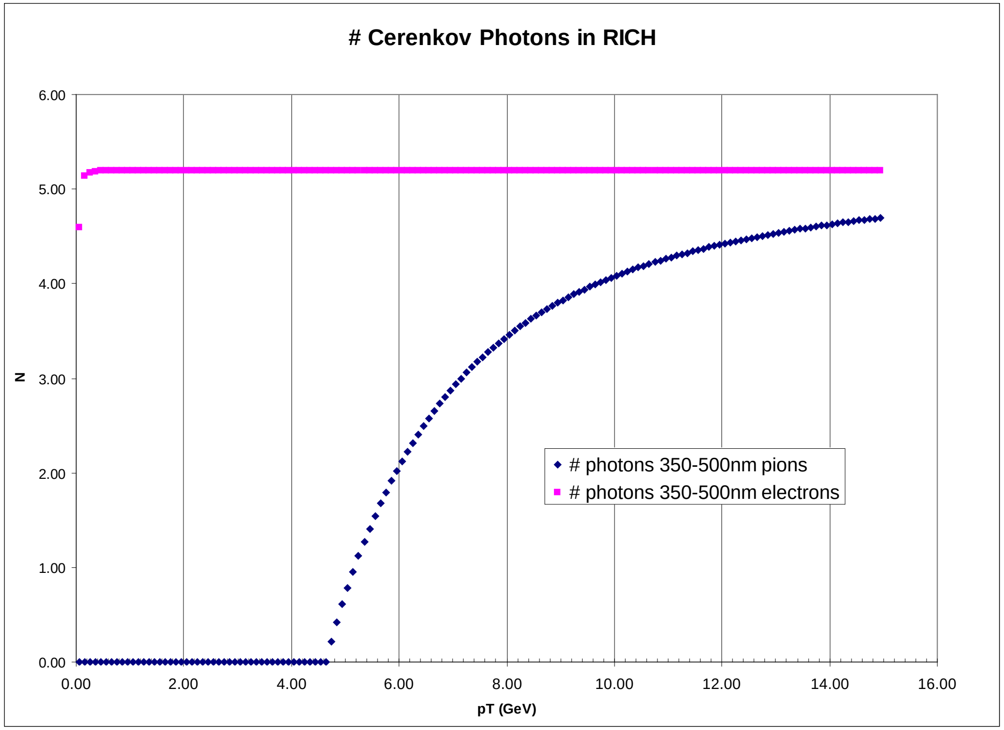
Model The RICH

$$\frac{frac\_\pi\_n_1 >= 5}{frac\_e\_n_1 >= 5}$$

- Cerenkov Turn On -> Frank-Tamm

$$\frac{dE}{dx} = \frac{q^2}{4\pi}\int_{v>c/n(\omega)} \mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right) d\omega$$

$$\#\,photons350-500nm = 390 * \sin^2\theta_c * n_{CO_2} * path\_length$$



n_1 turn on

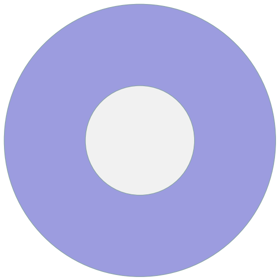
- Normalize Cerenkov curve to asymptotic electron n_1 mean
- Generate a π with random p_T
- Determine n_1 mean for pion from the Cerenkov curve
- Generate pion n_1 from poisson distribution with this mean
- dN/dp_T vs p_T normalized to one is the turn on
- Close but not good enough (plot)
- Then used reconstructed p_T
- Think of a better way to model RICH
  - n1 is number of PMT's not PE's

Toy MC

- Generate track
  - Cerenkov angle
  - # photons from poisson with mean from Cerenkov curve
  - Distribute randomly in 2pi azimuth
- Propagate the resulting ring to an array of phototubes

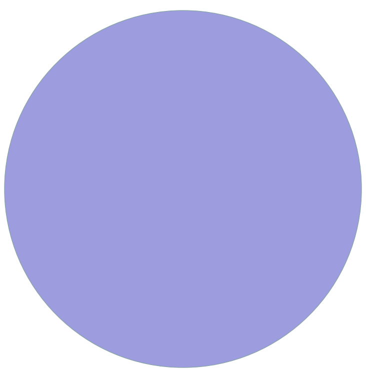
RICH focal plane

n0



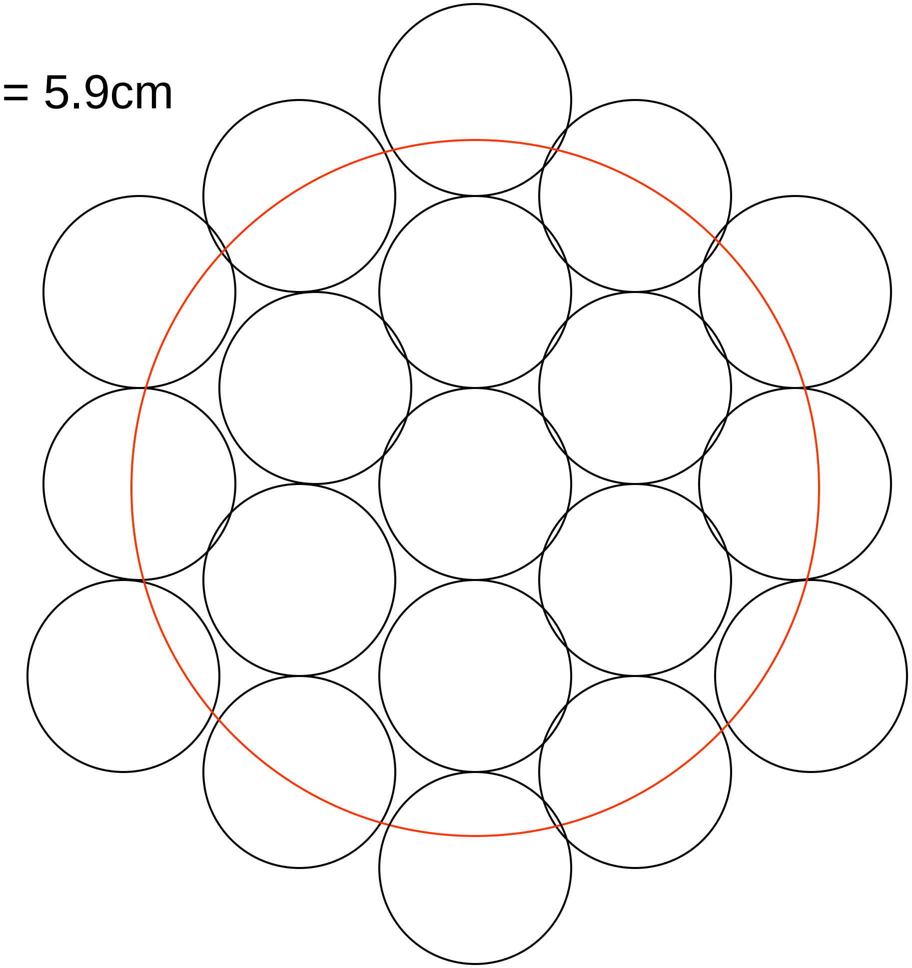
r_{inner}: 3.4 cm
r_{outer}: 8.4 cm

n1



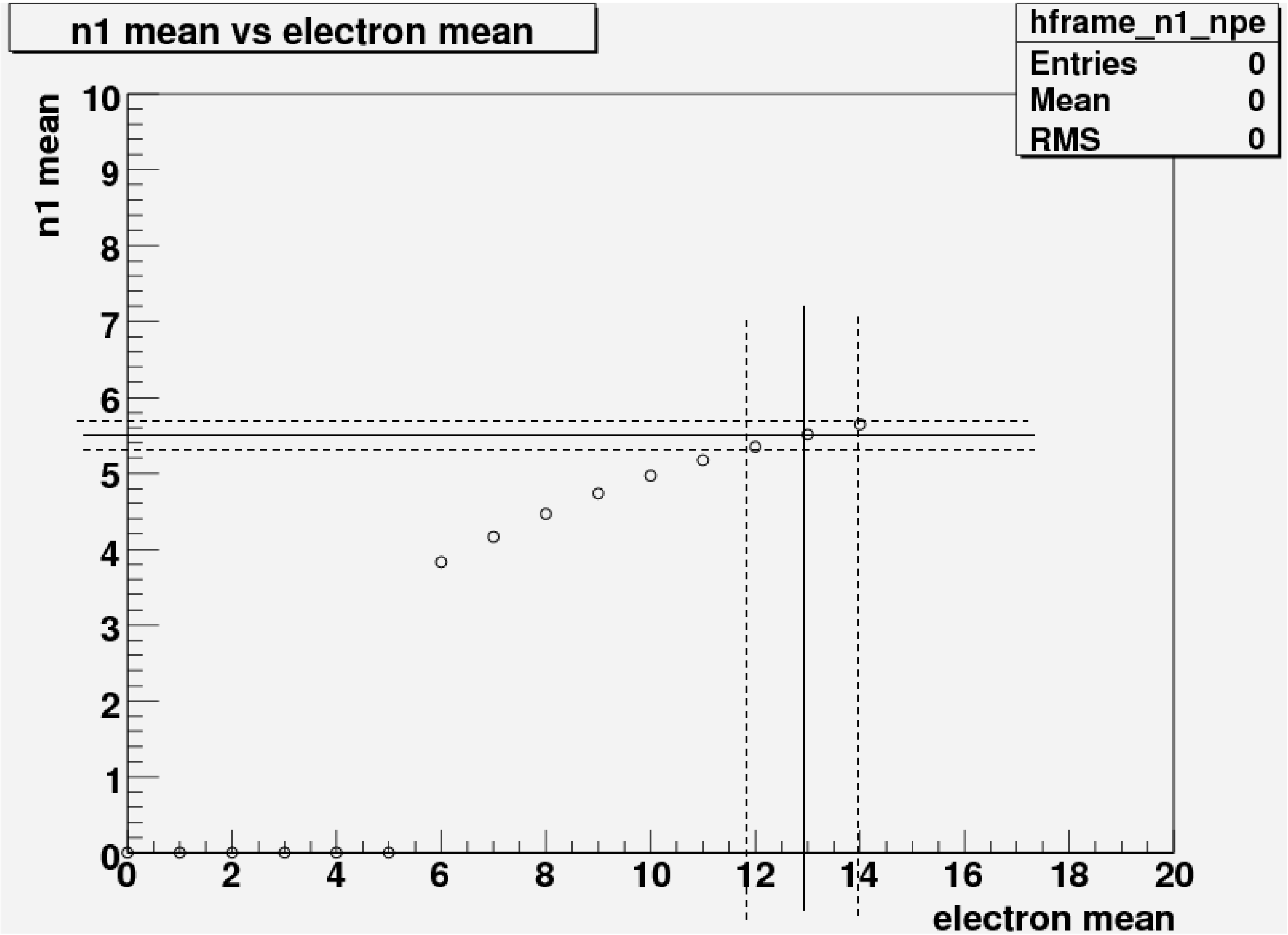
r_{inner}: 0 cm
r_{outer}: 11 cm

$e^{+/-}$ ring has r = 5.9cm

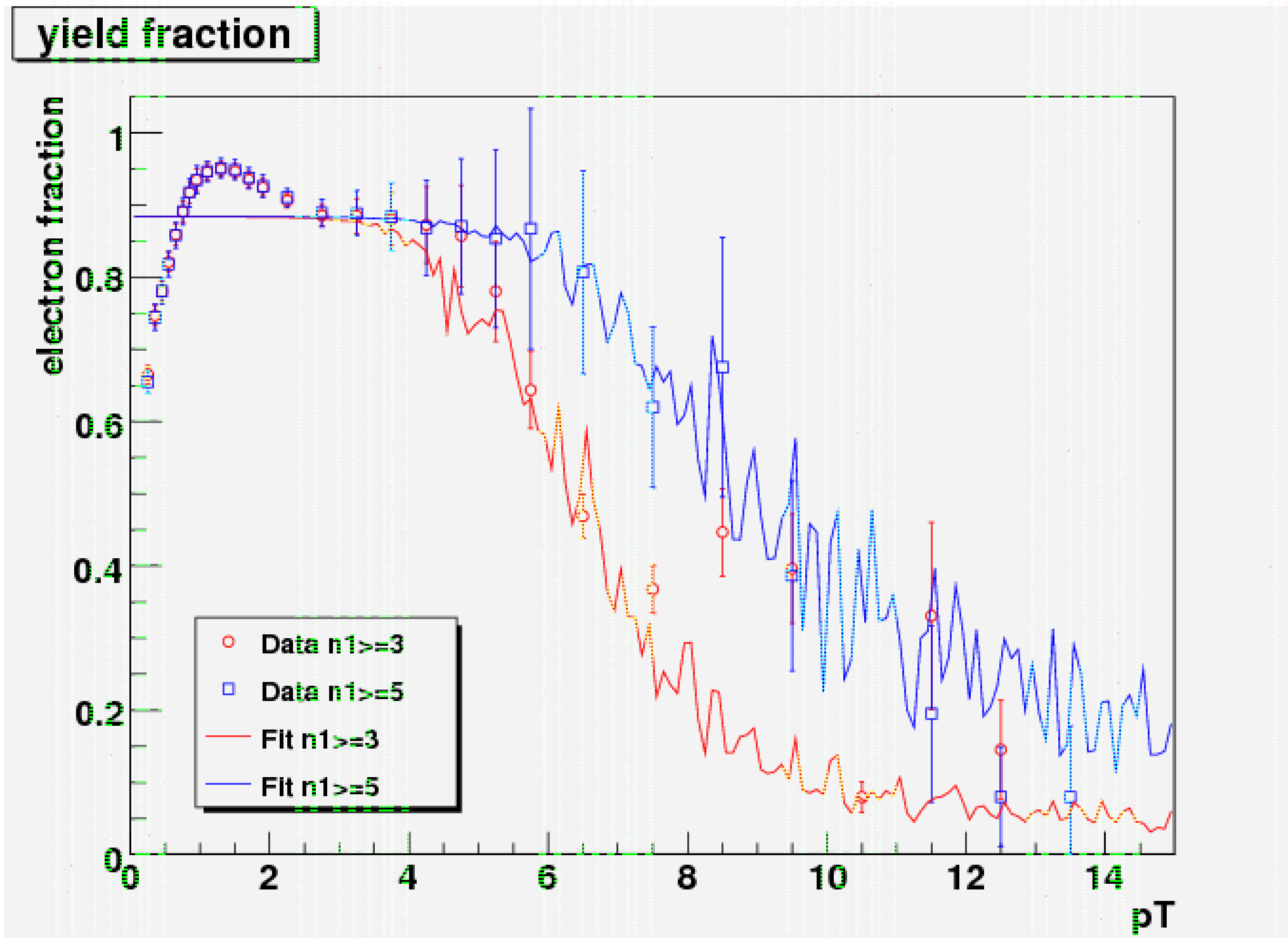


Kept mask centered on tube hit by track projection

Match Toy to Data by Varying the Asymptotic Value of the Number of Cerenkov Photons in Curve for e+/-

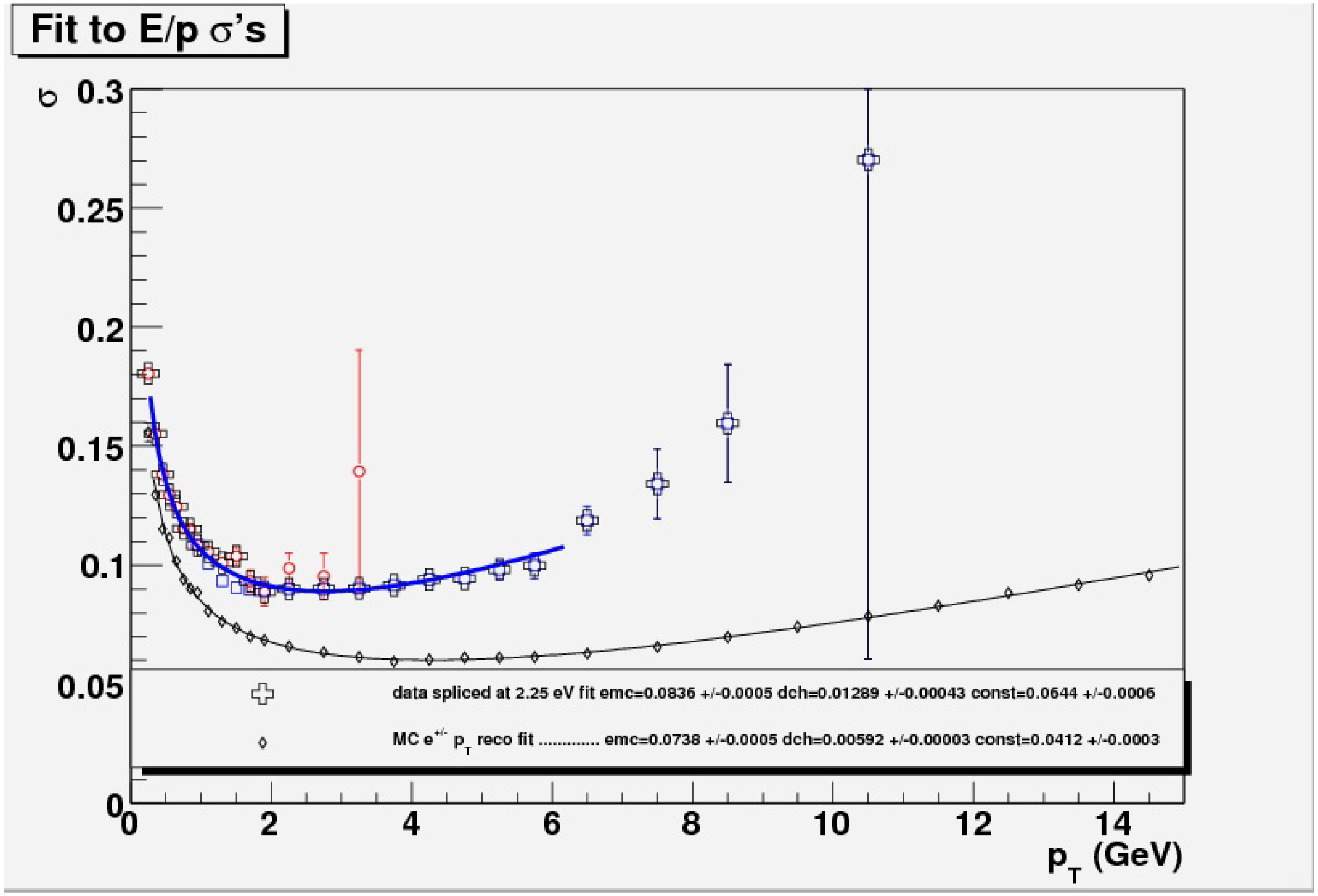


Money Plot



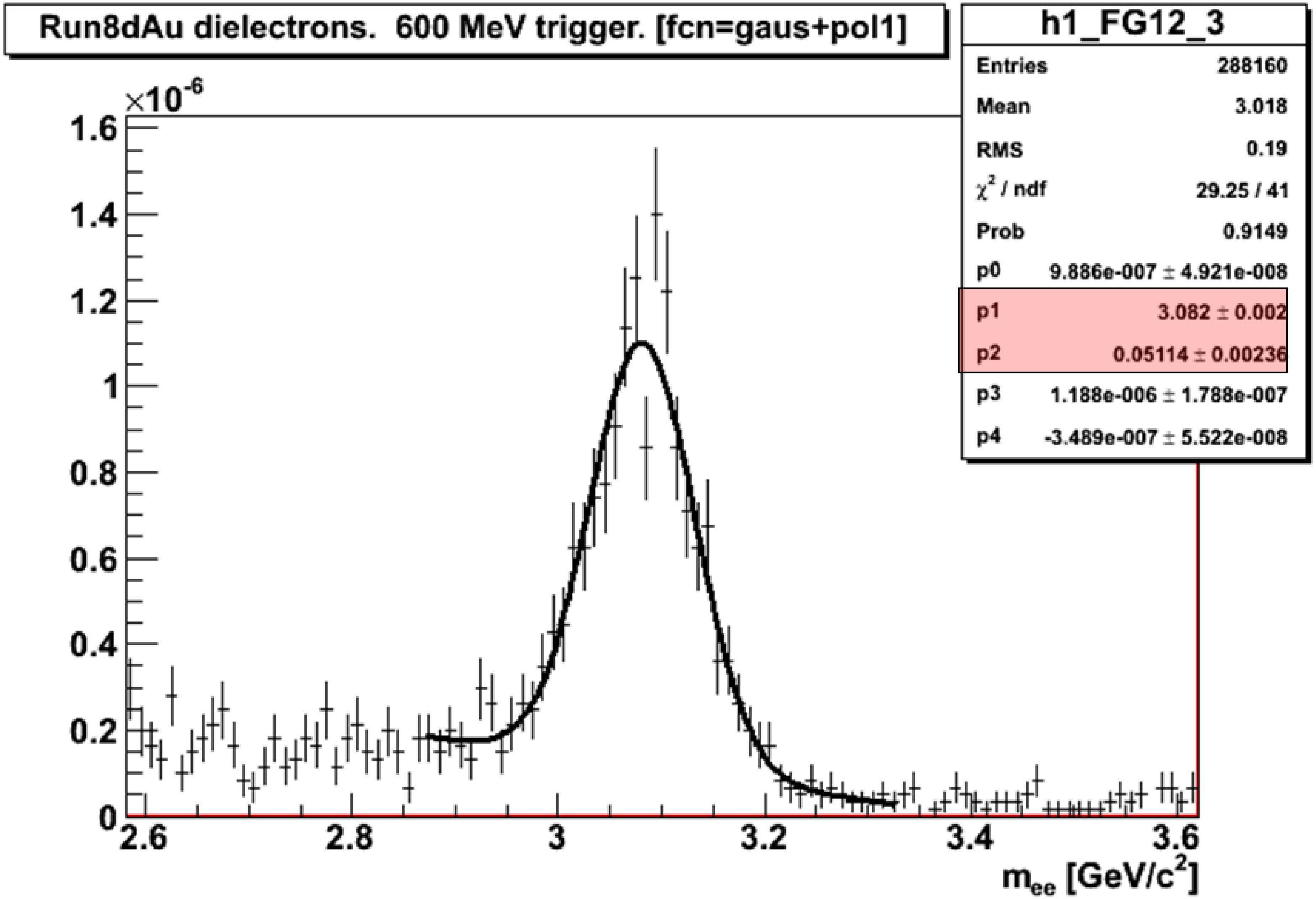
yield fraction
electron fraction
pT
0
0.2
0.4
0.6
0.8
1
0
2
4
6
8
10
12
14
Data n1>=3
Data n1>=5
Fit n1>=3
Fit n1>=5

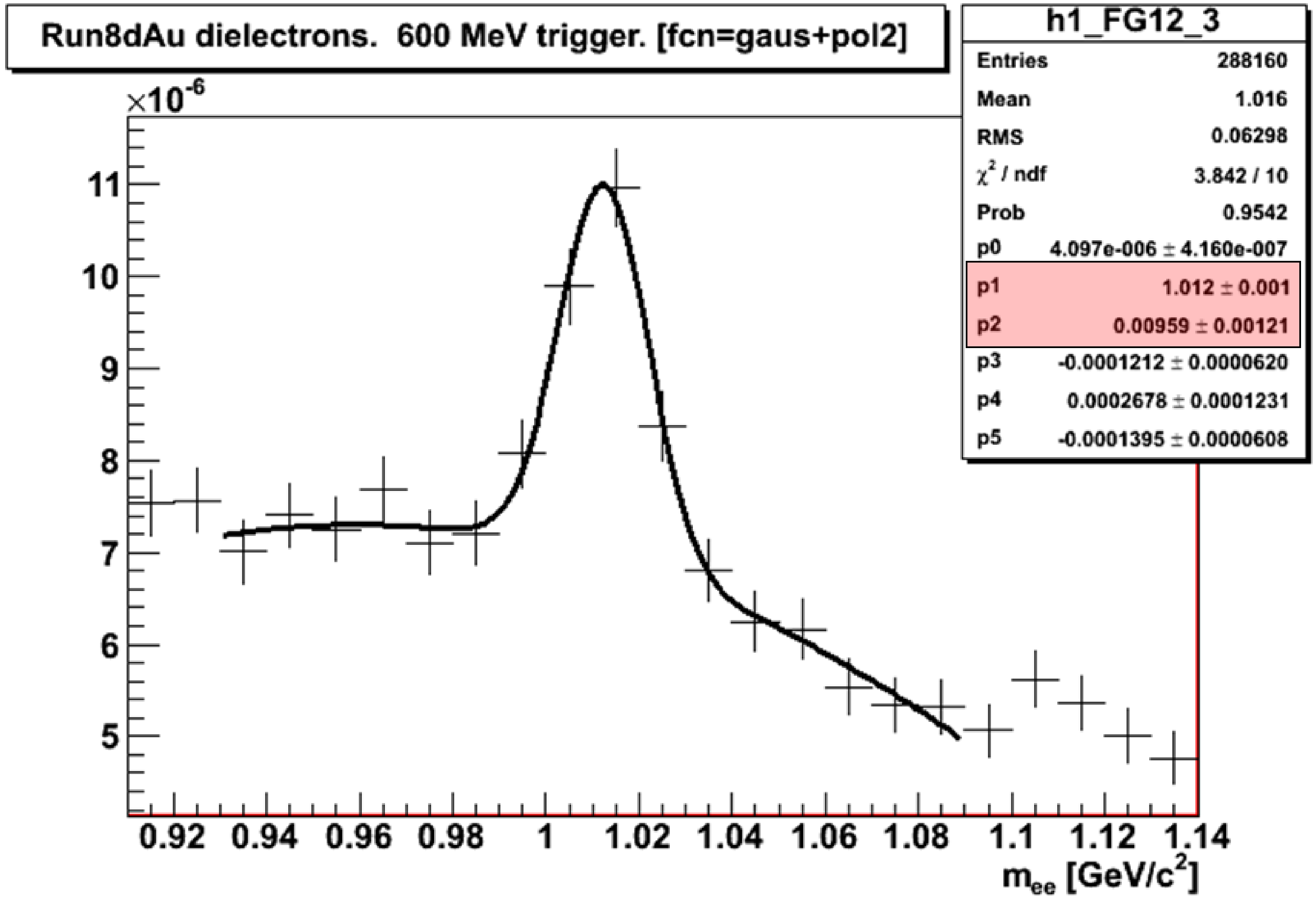
Before



Fit to E/p σ's
σ
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
12
14
p_T (GeV)
data spliced at 2.25 eV fit emc=0.0836 +/-0.0005 dch=0.01289 +/-0.00043 const=0.0644 +/-0.0006
MC e+/- p_T reco fit .... emc=0.0738 +/-0.0005 dch=0.00592 +/-0.00003 const=0.0412 +/-0.0003

Better Way to Smear




Run8dAu dielectrons. 600 MeV trigger. [fcn=gaus+pol2]
h1_FG12_3
Entries 288160
Mean 1.016
RMS 0.06298
χ² / ndf 3.842 / 10
Prob 0.9542
p0 4.097e-006 ± 4.160e-007
p1 1.012 ± 0.001
p2 0.00959 ± 0.00121
p3 -0.0001212 ± 0.0000620
p4 0.0002678 ± 0.0001231
p5 -0.0001395 ± 0.0000608
×10⁻⁶
11
10
9
8
7
6
5
0.92 0.94 0.96 0.98 1 1.02 1.04 1.06 1.08 1.1 1.12 1.14
mee [GeV/c²]

Then The Miracle Occurs

$$\sqrt{2}\,\frac{\delta m}{m} = \frac{\delta p}{p}$$

$$J/\Psi \rightarrow \frac{\delta m}{m} = \frac{51.1}{3082} = 1.66\% \rightarrow \frac{\delta p}{p} = 2.34\%$$

$$\phi \rightarrow \frac{\delta m}{m} = \frac{9.59}{1012} = 0.95\% \rightarrow \frac{\delta p}{p} = 1.34\%$$

$$\left(\frac{\delta p}{p}\right)^2 = C_1^2 + C_2^2 p^2$$

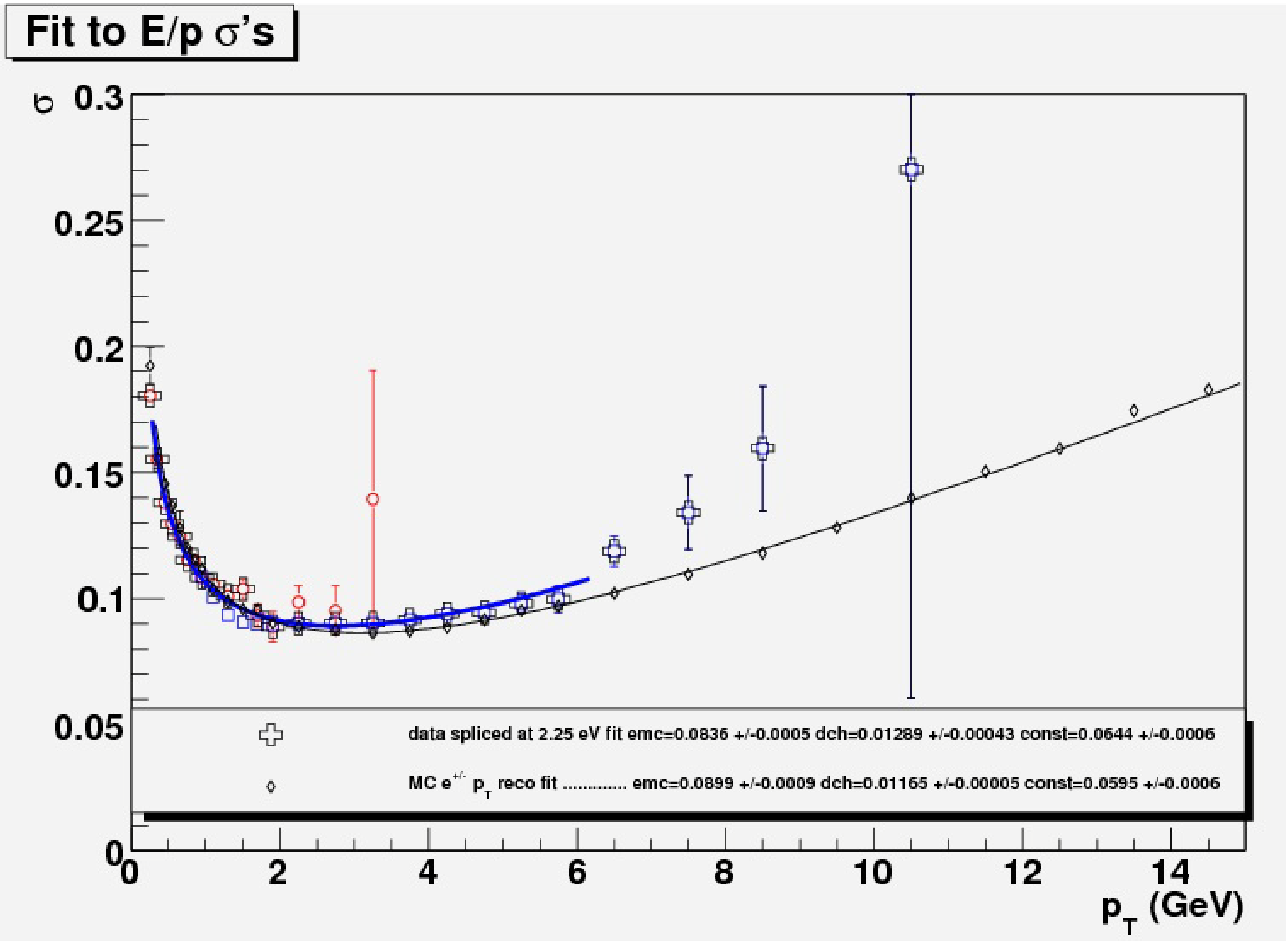
$$J/\Psi \rightarrow 2.34^2 = C_1^2 + C_2^2 (1.774)^2$$

$$\phi \rightarrow 1.34^2 = C_1^2 + C_2^2 (0.650)^2$$

$$C_2^2 = \frac{\left(2.34^2 - 1.34^2\right)}{\left(1.774^2 - 0.650^2\right)}$$

$$C_2 = 1.16\% \text{ and} \Rightarrow C_1 = 1.1\%$$

After


Fit to E/p σ's
σ
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
12
14
pT (GeV)
data spliced at 2.25 eV fit emc=0.0836 +/-0.0005 dch=0.01289 +/-0.00043 const=0.0644 +/-0.0006
MC e+/- pT reco fit .... emc=0.0899 +/-0.0009 dch=0.01165 +/-0.00005 const=0.0595 +/-0.0006