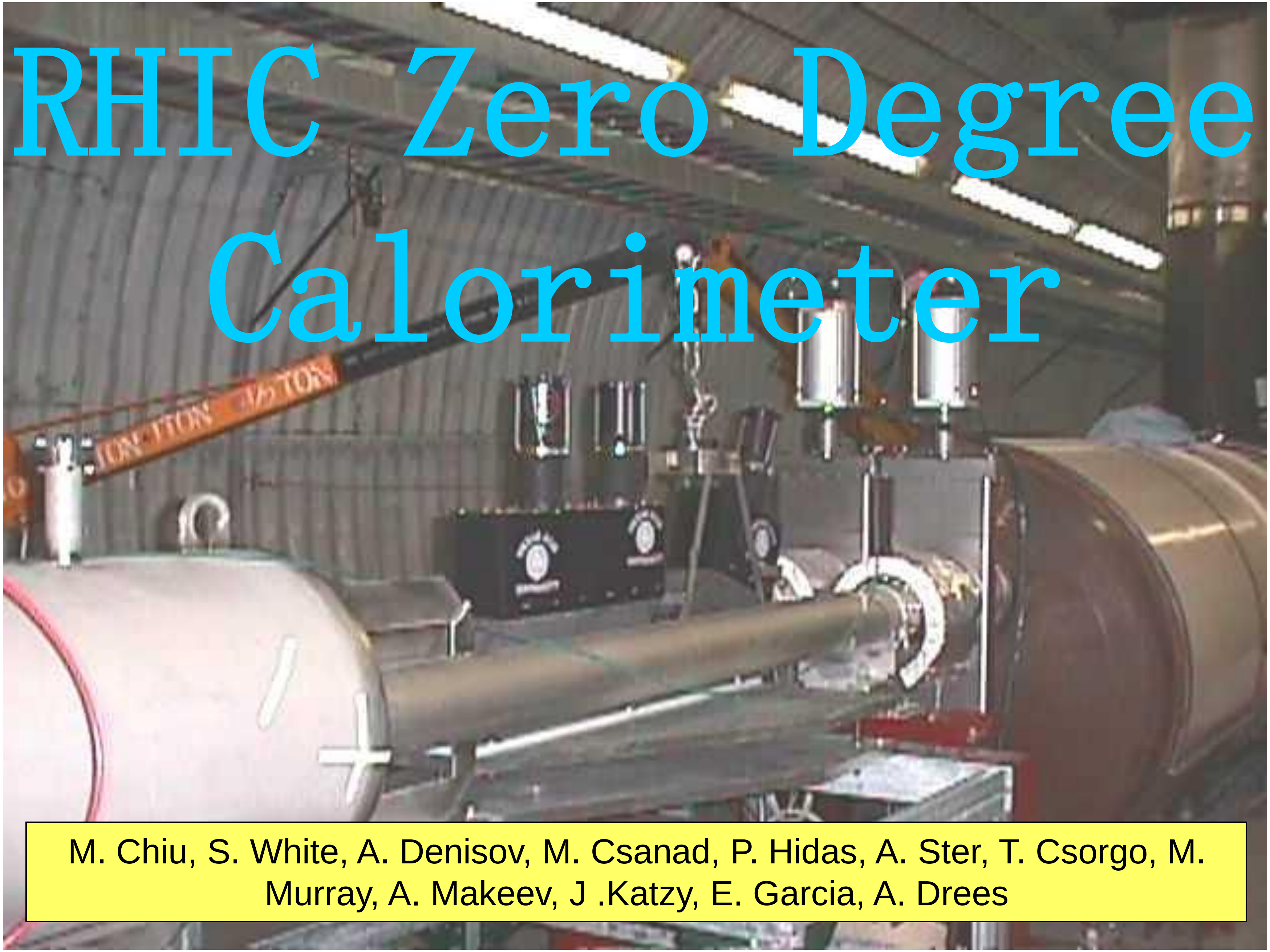
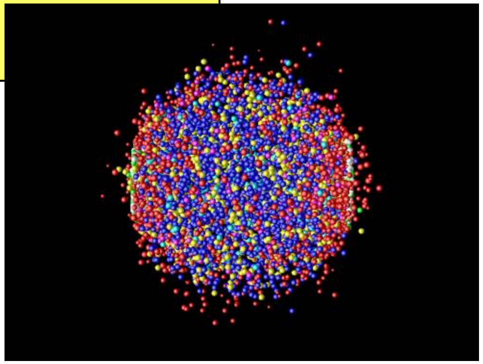
RHIC Zero Degree Calorimeter



M. Chiu, S. White, A. Denisov, M. Csanad, P. Hidas, A. Ster, T. Csorgo, M. Murray, A. Makeev, J .Katzy, E. Garcia, A. Drees

Collider Processes

- You're probably familiar with the "Hadronic Interactions"
- When colliding large nuclei, the Z creates a large photon flux
  - ZDC exploits this for a luminosity measurement
  - Also interesting physics (UCP program, AN063)



Hadronic Interaction

Hadronic Interaction:

Au-Au --> X 6.8 barns

γ-γ:

AuAu --> AuAu + e^+e^- 33 kbarns

AuAu --> AuAu + 2(e^+e^-) 680 barns

AuAu --> AuAu + 3(e^+e^-) 50 barns

γ-N: $L(\gamma\text{-}N) = 10^{29}\ cm^{-2}s^{-1}$ $2 < E\gamma < 300$GeV

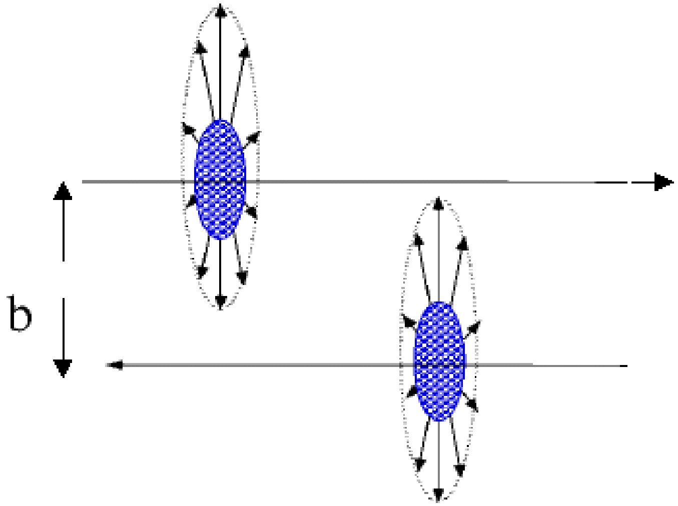
AuAu --> Au+Au* 92 barns

→ X+neutrons

AuAu --> Au*+Au* 3.67±0.26 barns

→ X+neutrons

→ Y+neutrons

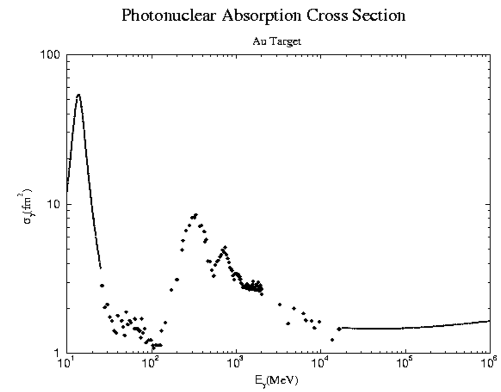


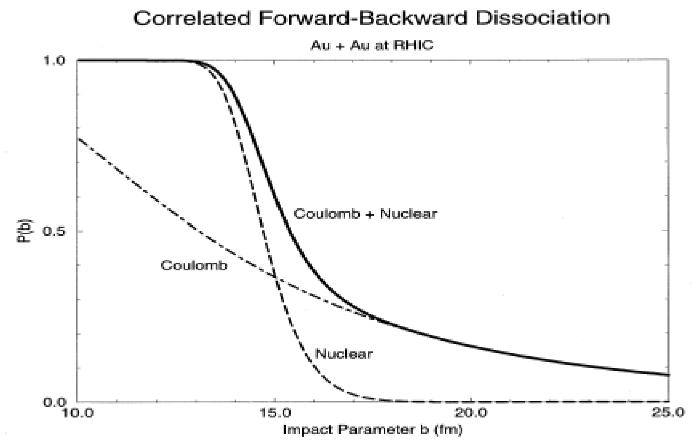
Peripheral Interaction

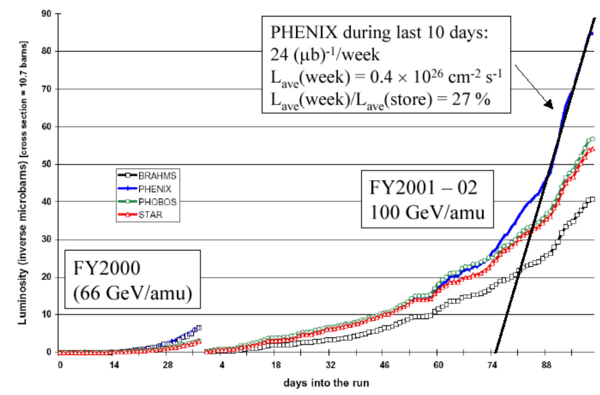
Total Cross-Section

NIM A 417:1-8,1998, nucl-ex/9801002

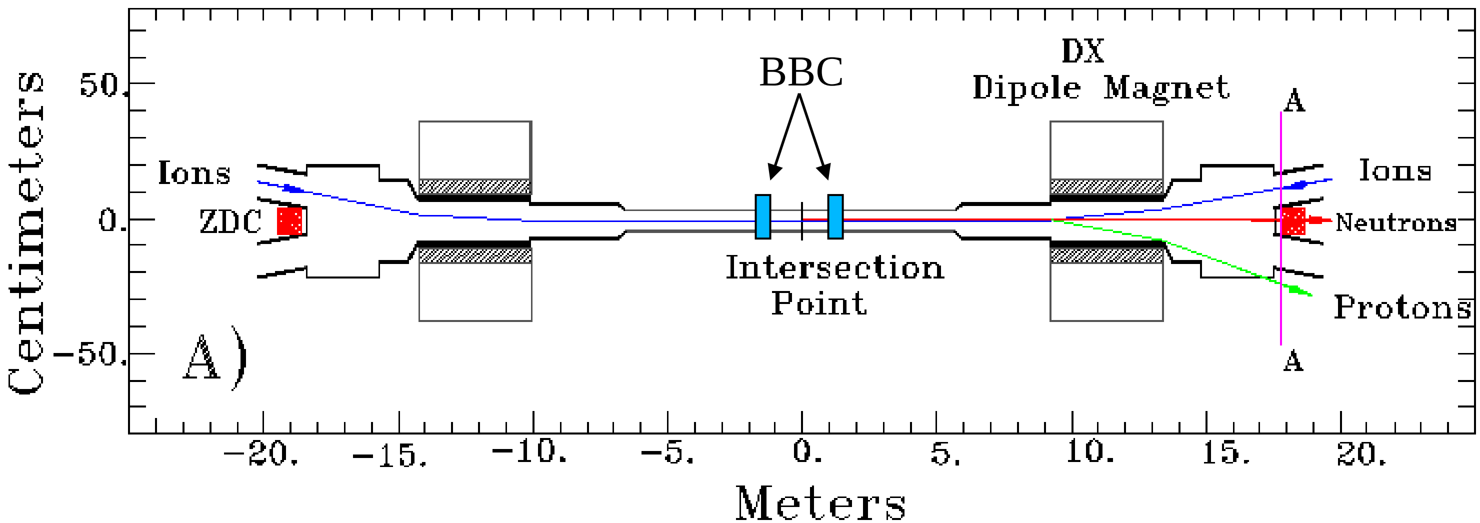
- Use Weiszacker-Williams to calculate equivalent photon flux
  - ie, Fourier Transform EM field to get photons
  - idea first put forth by Fermi
- Take measured photon dissociation data
- Key Point: Integrate through the nuclear radius to reduce uncertainty in lower cutoff for peripheral collisions
- Calculated Cross-Section good to 5%
  - 10.7 barns at root-s = 130 GeV
  - 11.0 barns at root-s = 200 GeV
  - But measurement is pristine



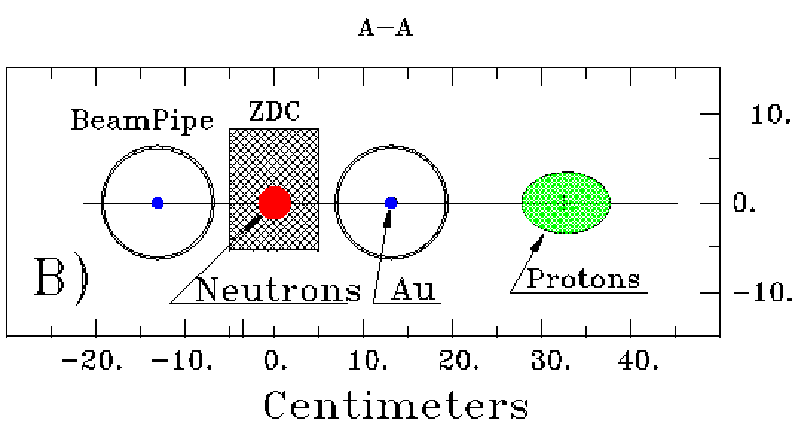




Location, Location, Location



- There is a lot of physics at forward rapidities
- In a collider, you need to have a DX magnet to steer bunches so they collide
    - Spatial Distribution of Charged Particles shown below
- Large Separation = Easy Timing = Very Clean Trigger against Beam Gas and Beam Scrape



The ZDC is a Good Place to Be..

- Luminosity/Cross-Sections
  - $R = L\sigma$
- Event Characterization
  - Centrality (Au+Au, d+Au)
  - Event Vertex and Start-Time
  - Hadronic/Non-Hadronic (Au+Au, d+Au, p+p)
- Clean Triggering
- Ultra-Peripheral Coherent Interactions
- Transverse Spin Asymmetries
  - Local Polarimeter
- Relative Luminosity
  - Crucial for A_{LL}

ZDC Design Goals

- Provide a common luminosity measurement for ALL RHIC experiments
- Provide a common centrality determination
    - Never really got enough cooperation
- Provide a minimum bias trigger free of beam gas background

How to do this?

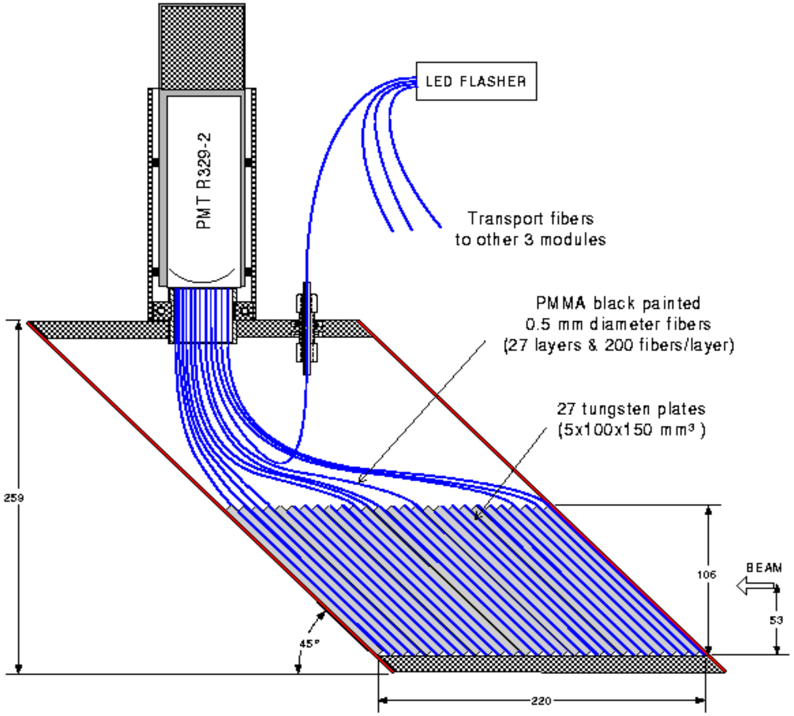
- Measure forward energy (low pt processes)
- At collider, DX magnet sweeps away all charged particles
    - Can only measure neutral particles
- Want to cleanly see single neutron peak
    - Natural spread of emitted neutrons ~ 10%
    - Want detector resolution on that order
- Needs to fit in the crotch behind DX magnet
- Want to be rad hard (expected dose ~ 10^5 rad over 10 years)

Principles of Hadronic Calorimeters

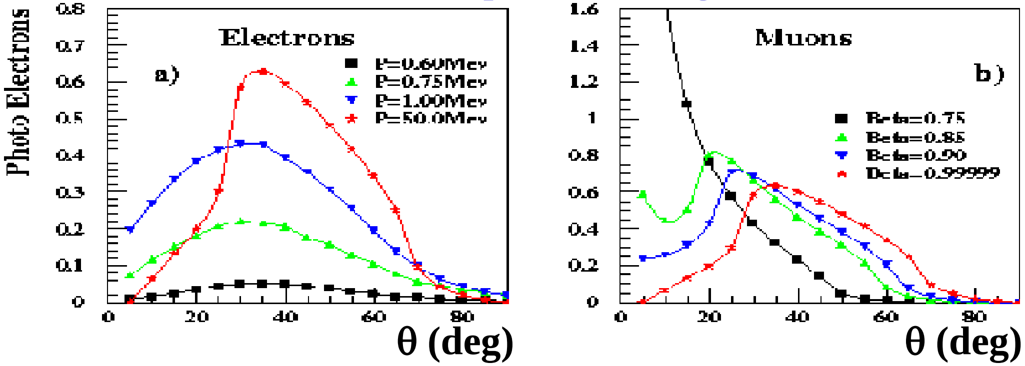
- Types of Calorimeters (all measure deposited energy)
    - Homogeneous (PbGl)
    - Sampling (PbSc, ZDC)
- Calorimeters are based on average measurements
    - energy deposited stochastically (via showers)
    - fluctuations determine energy resolution
- Radiation Length Xo[g cm^{-2}] ~ 180 A/Z^2 for high Z
- Nuclear Interaction Length (17 cm Fe, 18.5 cm Pb, 70 cm Sc)
- Electromagnetic or Hadronic
    - ZDC (6 λ, 150 Xo)
- Compensating or Non-compensating
    - Response to photons and electrons can be very different from hadrons
    - ZDC is non-compensating, ie, it gives a greater signal for photons than neutrons

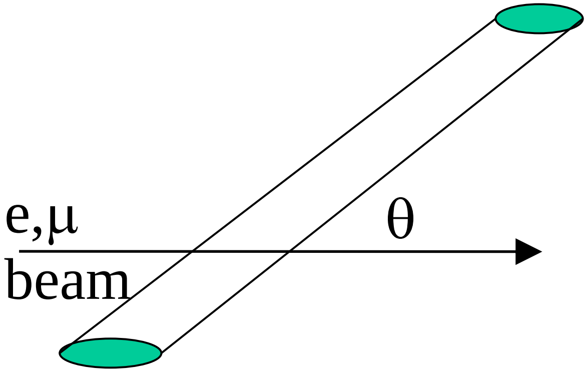
ZDC Design

NIM A 470:488-499,2001, nucl-ex/0008005



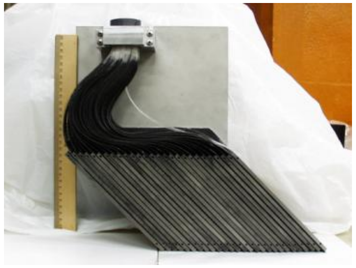
Fiber response vs. angle

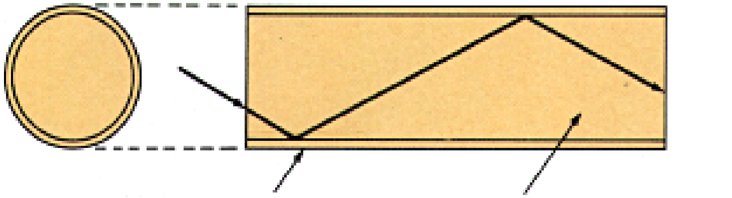




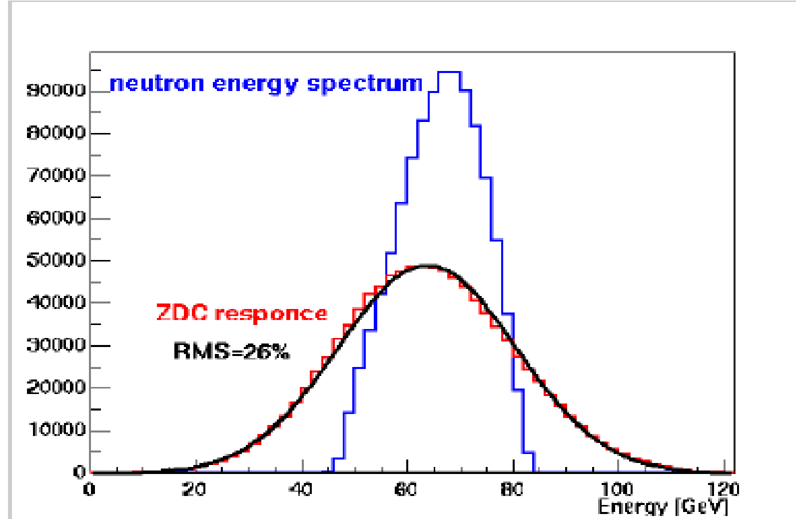
ZDC Calorimeter construction:

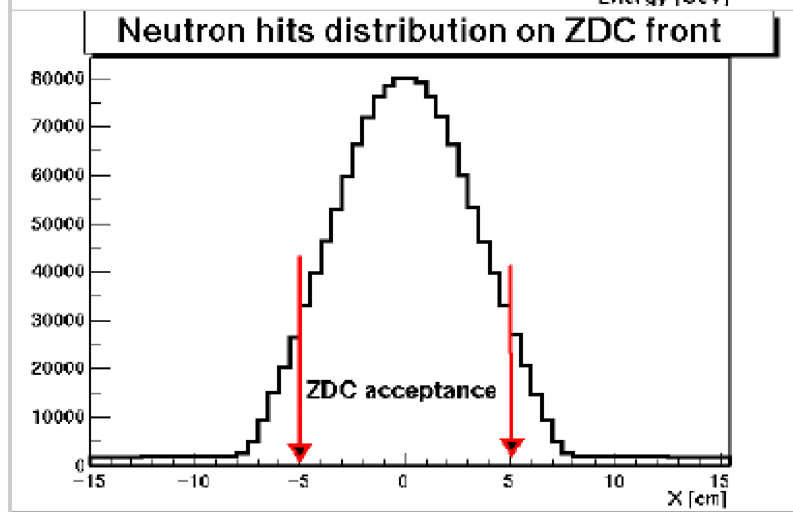
- Tungsten absorber/ fiber (C)sampling
- 2 Lint/module, 3 modules total
- C sampling filters shower secondaries
- Uniform response vs. impact point





ZDC performance @ ÷S = 130GeV



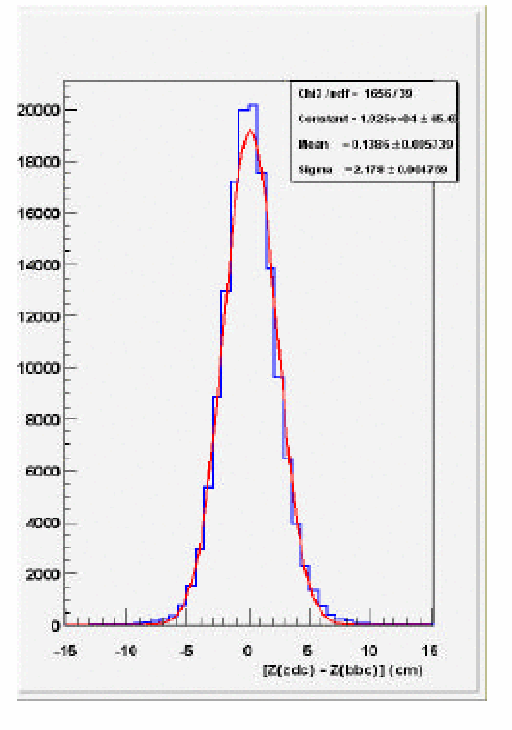


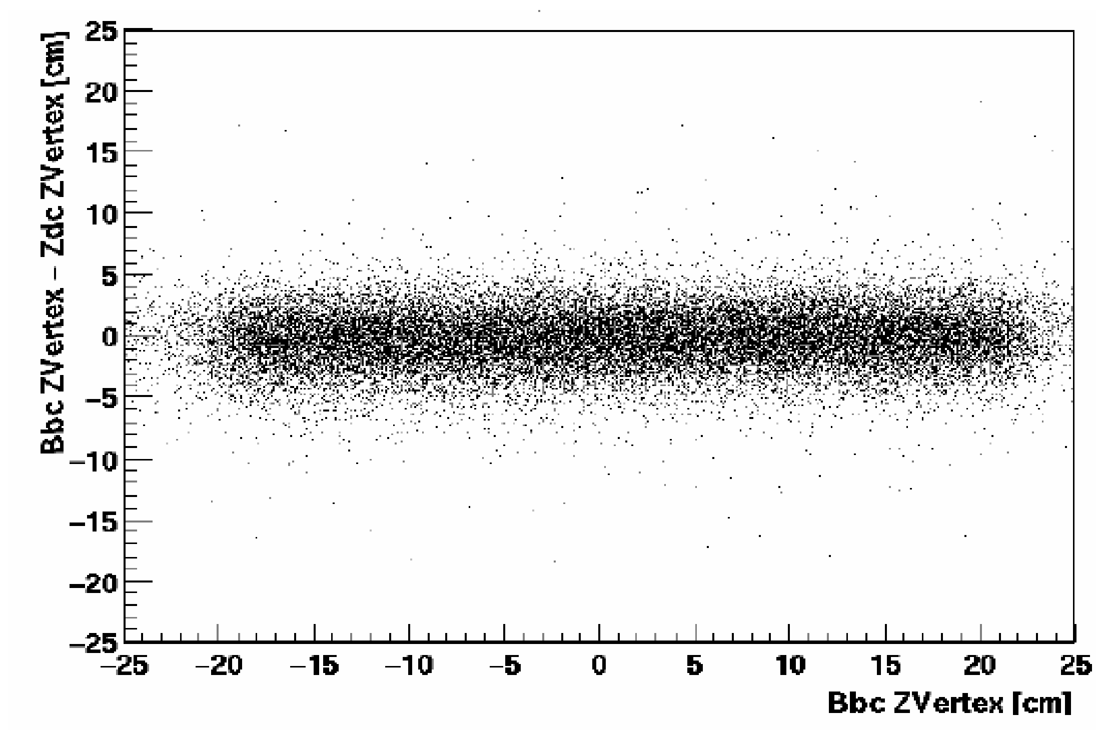
- Energy resolution for 1n is 26% (simulation), 25%(exp.)

- 24% of neutrons out of ZDC acceptance for nuclear events

- ~100% of neutrons from Coulomb Dissociation events in ZDC acceptance

Timing Ability





Single Arm Time Resolution ~ 150 ps

ZDC Z-Vertex Resolution σ_Z ~ 2.5 cm

$z = c^*(t_S - t_N)/2$

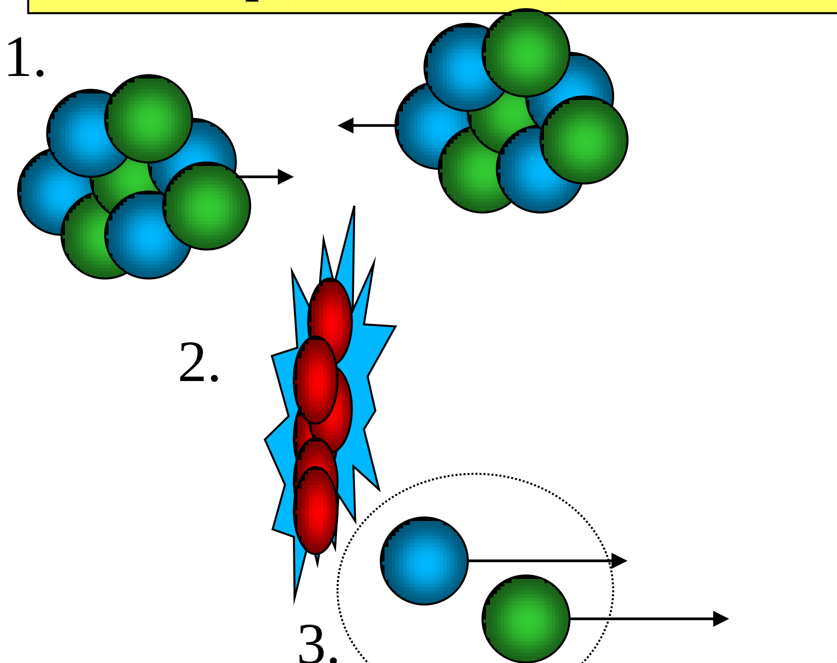
$t0 = (t_N + t_S)/2$

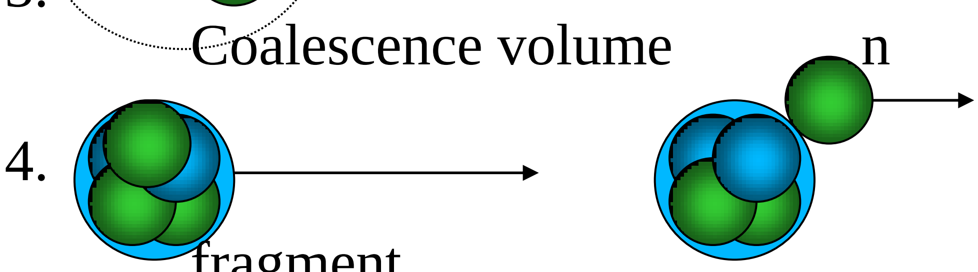
$\sigma_Z = (c/2)^*sqrt(\sigma_T^2 + \sigma_T^2)$

ZDC Physics: Hadronic Interactions

•Since the ZDC sees only neutral, forward going particles, they are affected by any processes which produce or remove free neutrons

- •Coalescence of spectator nucleons into light nuclei (d, triton, alphas)
- •Evaporation of free neutrons from unstable fragments

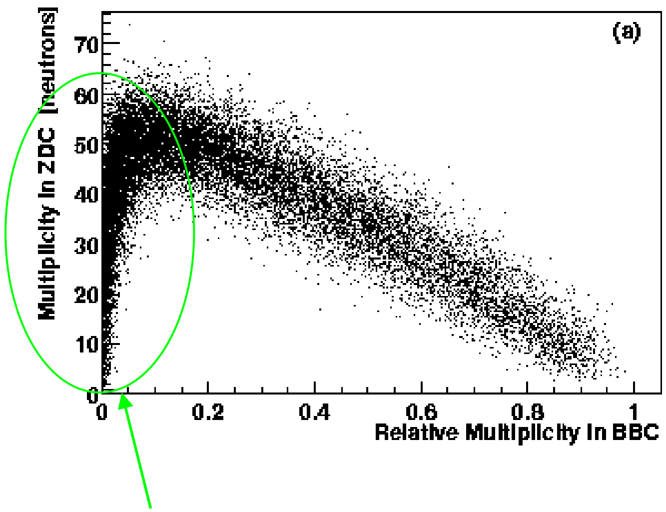




1. Incoming Heavy Ions
2. After collision, spectators are free neutrons, protons, and fragments
3. Free neutrons and protons can coalesce, removing neutron deposition in ZDC
4. Fragments can boil off neutrons, increasing neutron deposition in ZDC

ZDC Centrality Determination

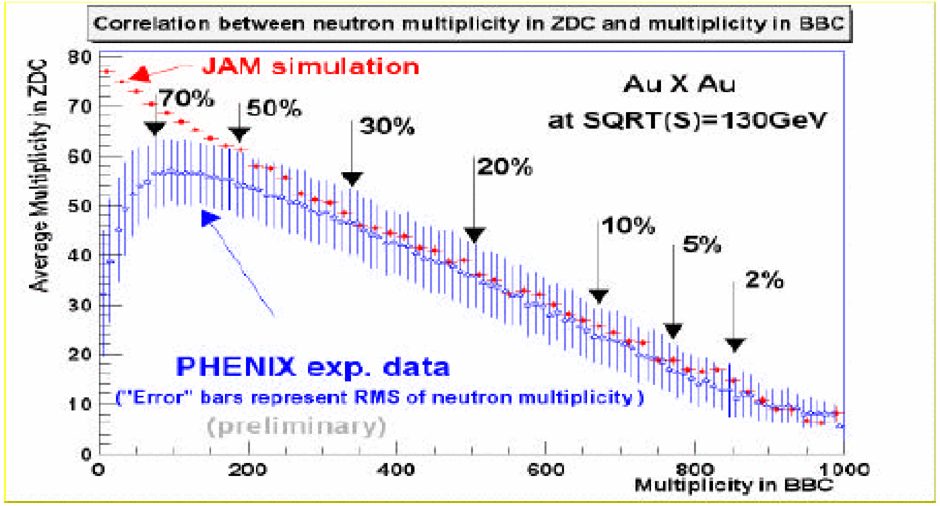
•In more central collisions, we have had good success describing energy spectrum using glauber models followed by coalescence.



•In more peripheral collisions, evaporation dominates.

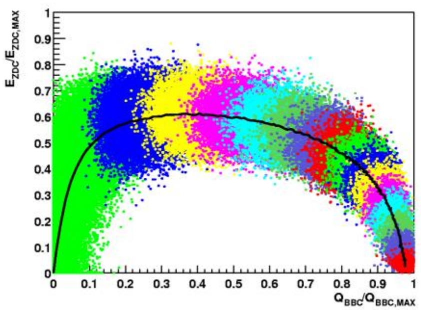
•Process is not well understood theoretically, so it is very hard to model.

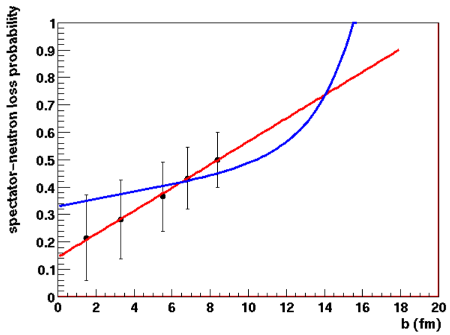
1. Jam plus coalescence



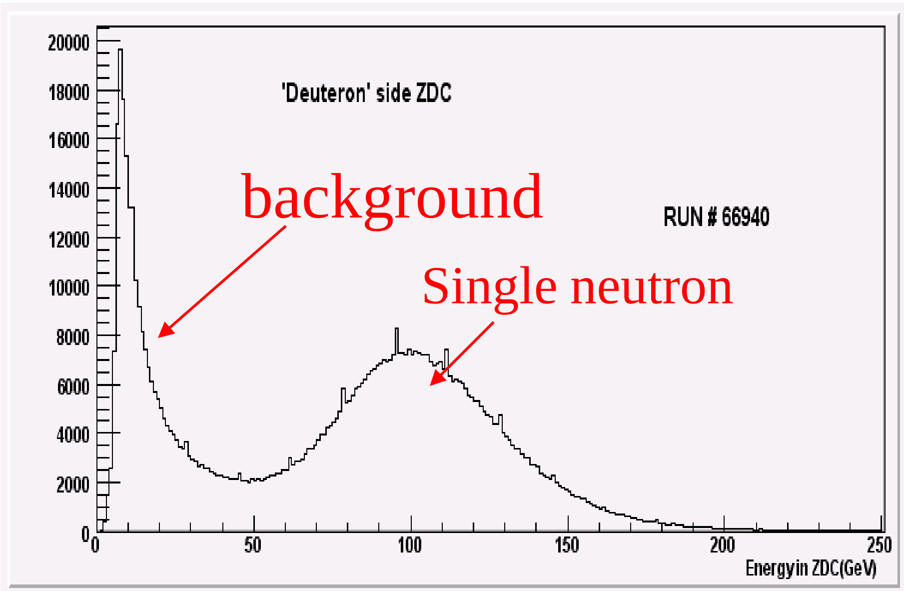
2. Hijing plus coalescence in PISA (Ster)

3. Parametrize Forward Neutrons from NA49 data (Reygers)

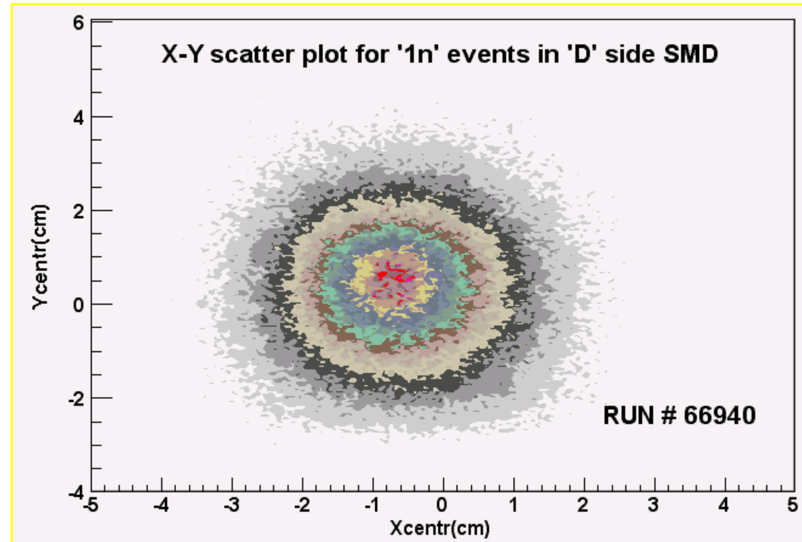


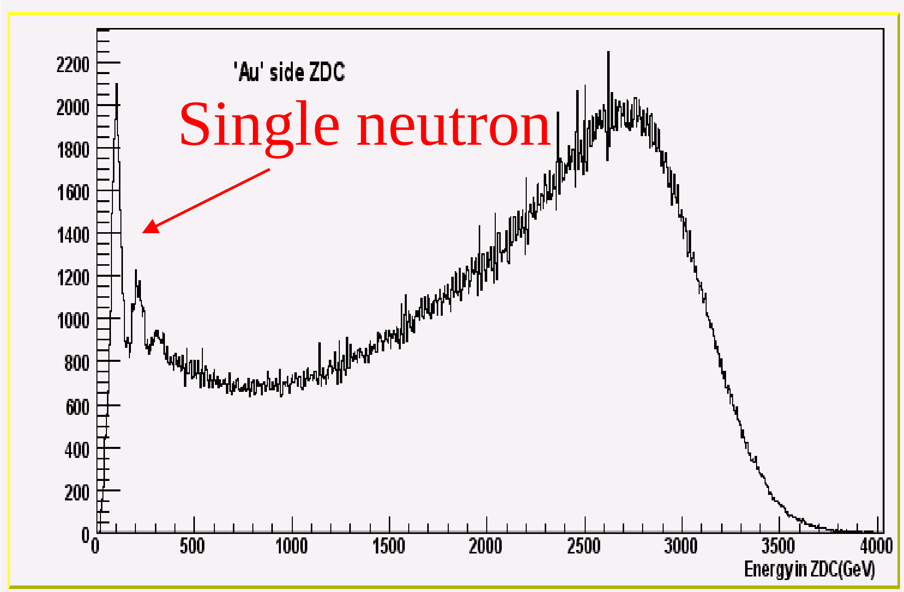


Energy and Spatial distribution in ZDC for d+Au @ 100Gev

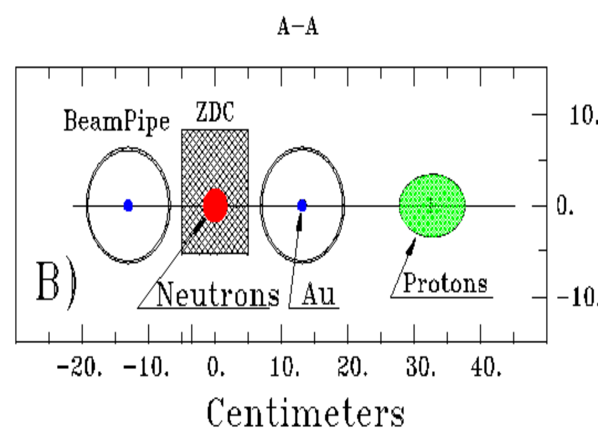


New in Run03

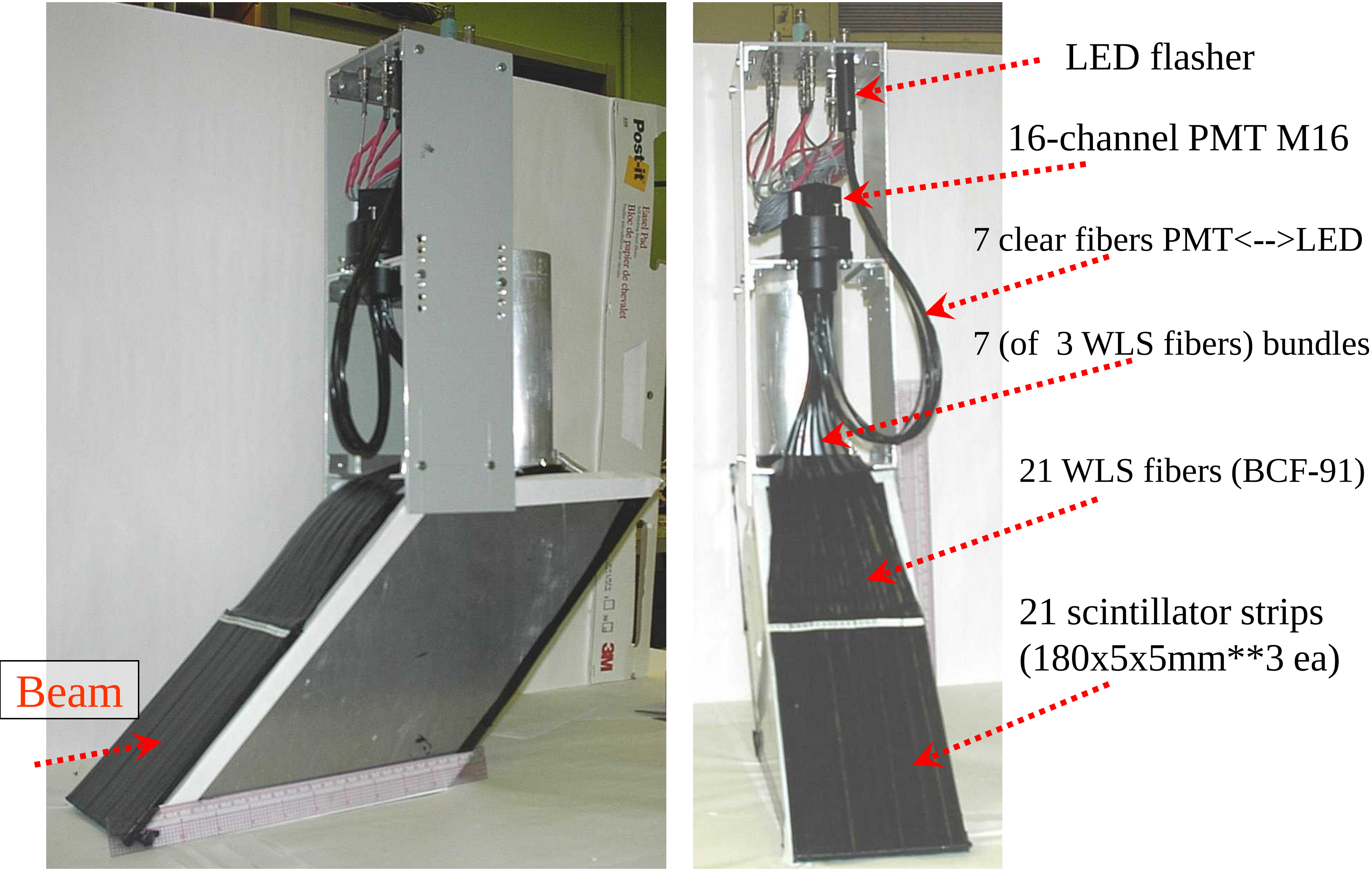




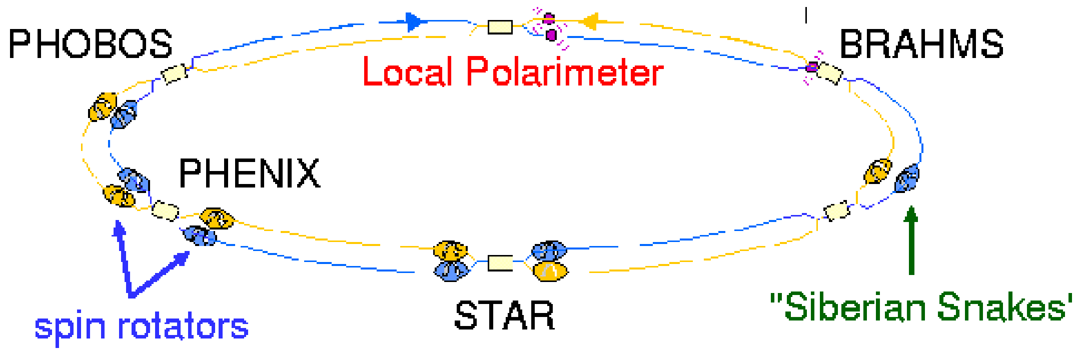
X-Y scatter plot for single neutron events in North SMD



SMD assembled with a preproduction ZDC module

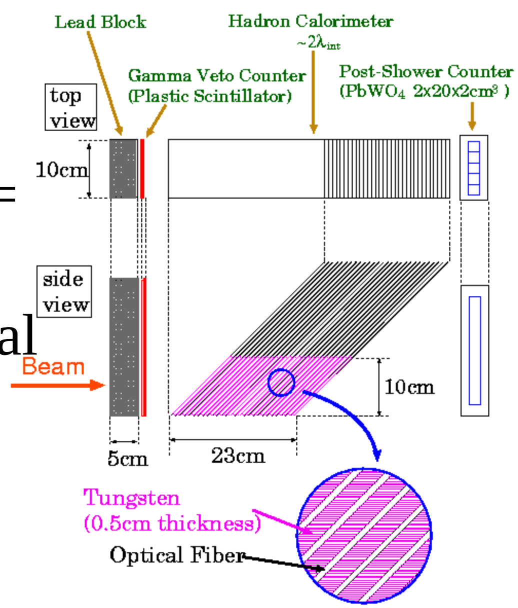


Measurement of +p

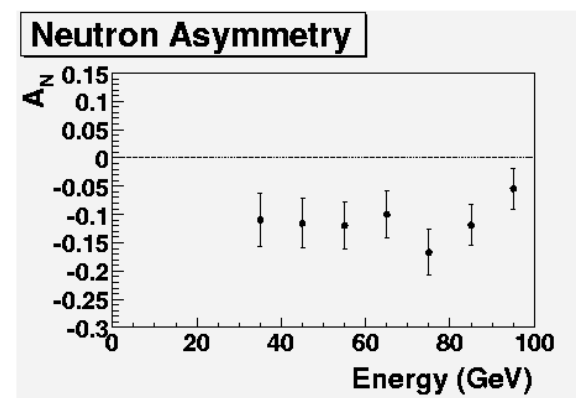


$0<\theta_{Lab}<3$mrad $0<p_T<0.3$ GeV/c $0<x_F<1$

- RHIC Polarimeter measures magnitude of Transverse Polarization
- Spin Rotators Rotate from Transverse to Longitudinal Polarization into PHENIX
- Can monitor this rotation using ZDCs
- Measure Asymmetry $A_N = (N\uparrow - N\downarrow)/(N\uparrow + N\downarrow)$
- Should = 0 for longitudinal polarization



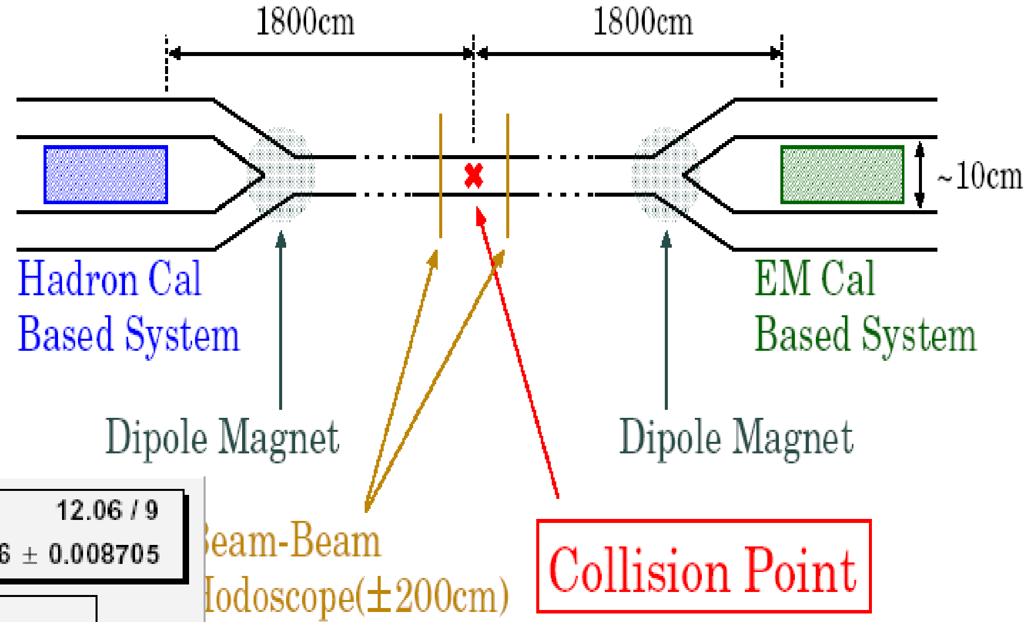
Hadron Cal

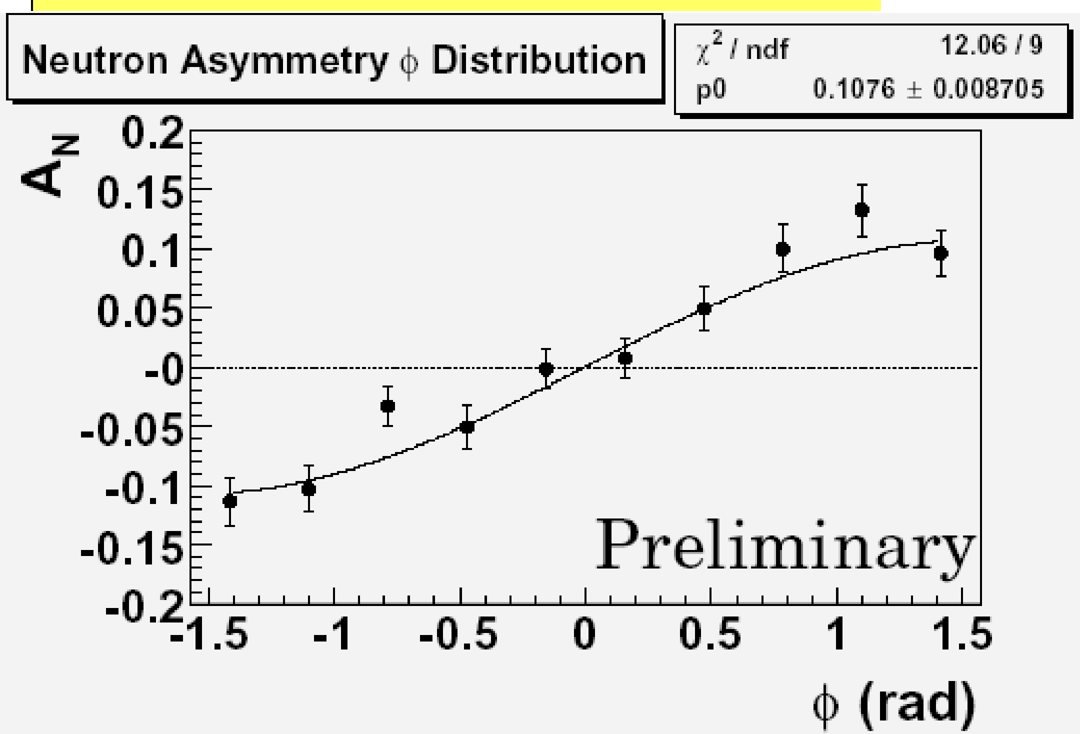


$\langle A_N \rangle = -0.110 \pm 0.015$
additional scale error

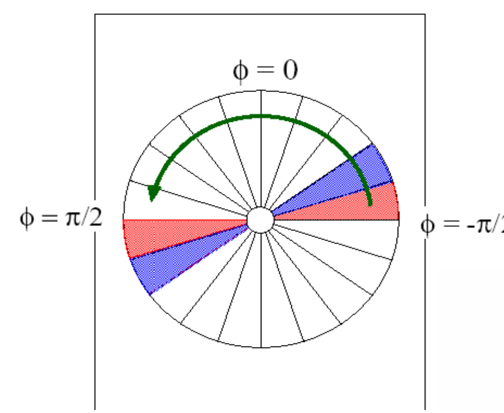
Transverse Spin Asymmetries

- Run02 IP12 experiment to look for π^0, γ asymmetries
  - Not found but they did measure a neutron asymmetry
  - Perhaps understood (?), but look for upcoming paper
- Large asymmetry gives good local (PHENIX) polarimetry.





"Left-Right" asymmetry measured for different slices in phi:



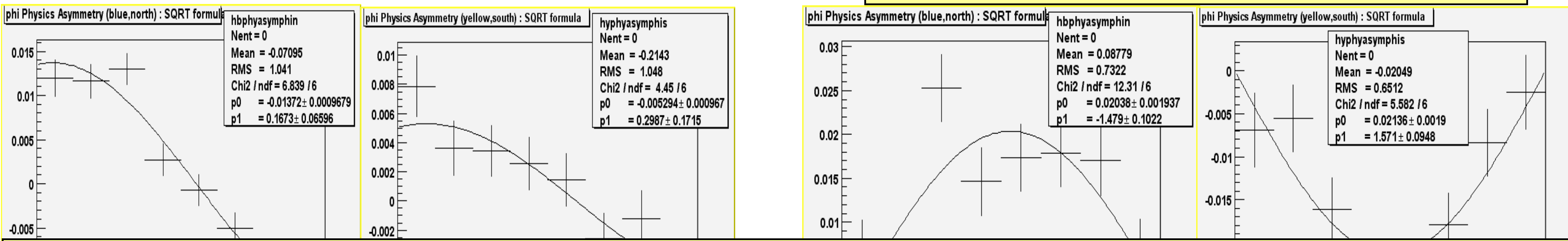
$$A_N = \frac{1}{P_B}\frac{\sqrt{N_{\uparrow L}N_{\downarrow R}} - \sqrt{N_{\uparrow R}N_{\downarrow L}}}{\sqrt{N_{\uparrow L}N_{\downarrow R}} + \sqrt{N_{\uparrow R}N_{\downarrow L}}}$$

Rotator Commissioning at PHENIX

Spin Rotators OFF

Run-03

Spin Rotators ON, Current Reversed



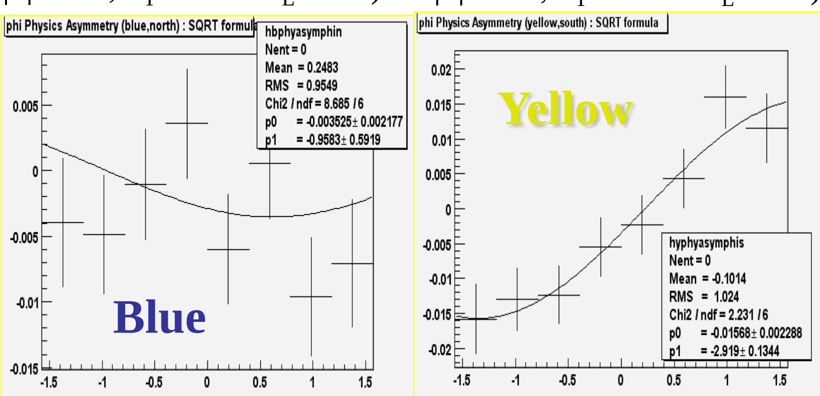
We are extremely glad that we have this local polarimeter at hand to do these checks…Without all this, our gluon polarization measurements would have been completely blind and meaningless! – Abhay Deshpande

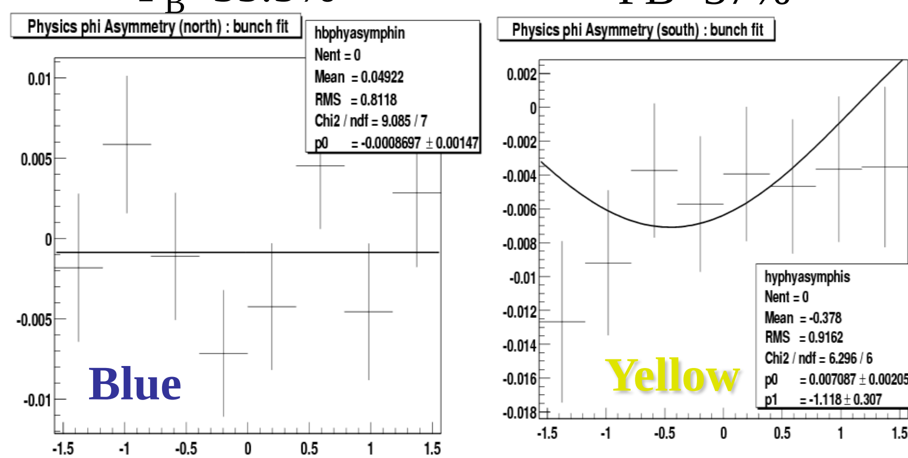
Spin Rotators ON, Almost…

Spin Rotators ON, Correct!

P_B=35.5% PB=37%

|P|=30%, P_T=0% → P_L=30%) |P|=37%, P_T=24% → P_L=28%)





Longitudinal Double Spin Asymmetries

- To determine ΔG, look at A_{LL}:

$$A_{LL} = \frac{\sigma_{\rightarrow\rightarrow} - \sigma_{\rightarrow\leftarrow}}{\sigma_{\rightarrow\rightarrow} + \sigma_{\rightarrow\leftarrow}} = \frac{1}{P_Y P_B} \frac{N_{\rightarrow\rightarrow} - RN_{\rightarrow\leftarrow}}{N_{\rightarrow\rightarrow} + RN_{\rightarrow\leftarrow}},$$

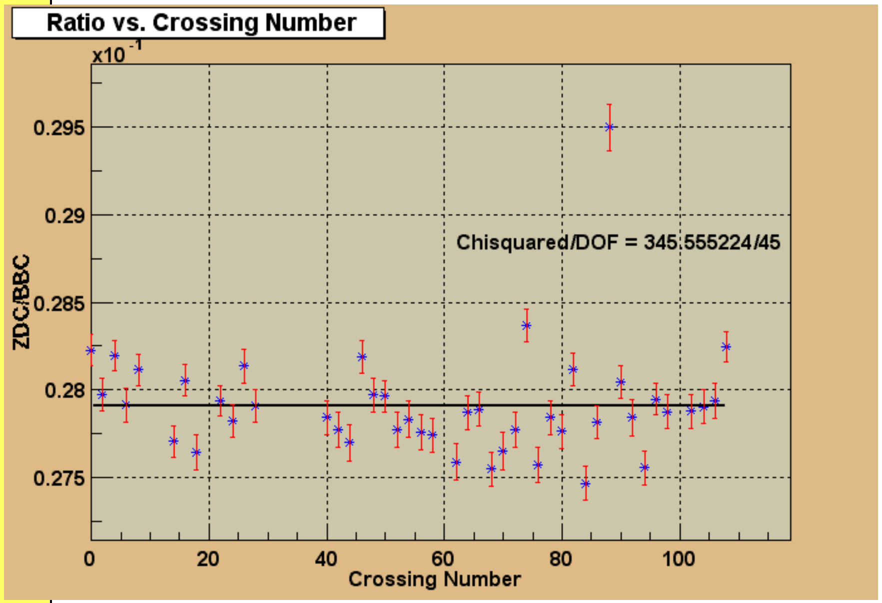
$$R = \frac{L_{\rightarrow\rightarrow}}{L_{\rightarrow\leftarrow}}$$

- R is the relative luminosity, and can be measured (to some accuracy) at PHENIX.
- Our Goal: $\delta R/R < 0.1\%$ for each fill
  → $\delta A_{LL} < 2 \times 10^{-3}$
  (expected A_{LL} for pions ~ 3×10^{-3} @P_T=3 GeV/c)

Relative Luminosity

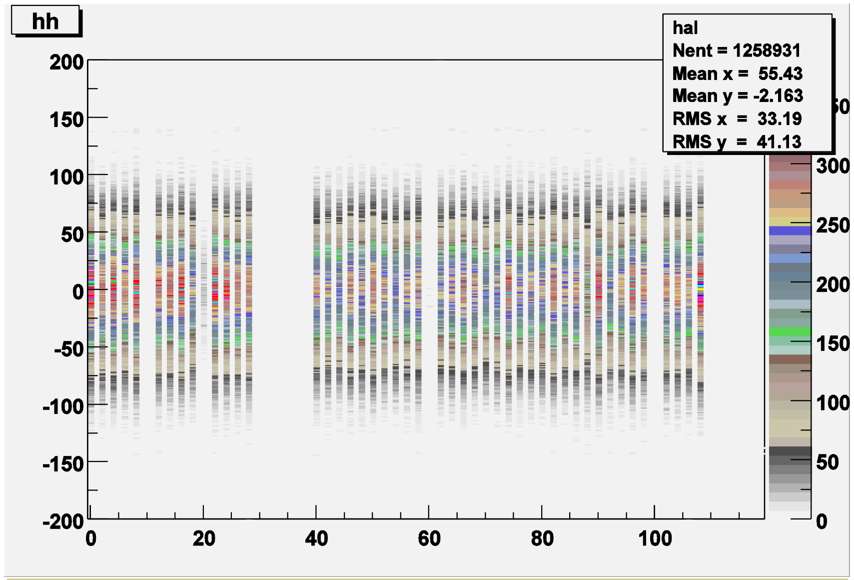
- In order to investigate our ability to measure the relative (++ vs. +-) luminosity:
  - look at ratio of 2 detector scalars crossing-by-crossing:
    - $a(i) = N_A(i)/N_B(i)$
  - Ratio should be the same for all crossings (constant) if:
    - $N_A(i) = \int L\sigma_A\varepsilon_A$ and $N_B(i) = \int L\sigma_B\varepsilon_B$
    - B is always BBCLL1
      A is one of the others (CH2-8).
  - Fit this by the expected pattern:
    - $a(i) = C[1+A_{LL}P_B(i)P_Y(i)]$
    - C, A_{LL} are the fitting parameters.
  - Precision of relative luminosity can be estimated by:
    - $\delta C/C$
  - If χ^2 of the fitting is bad, look for other factors in N(i).

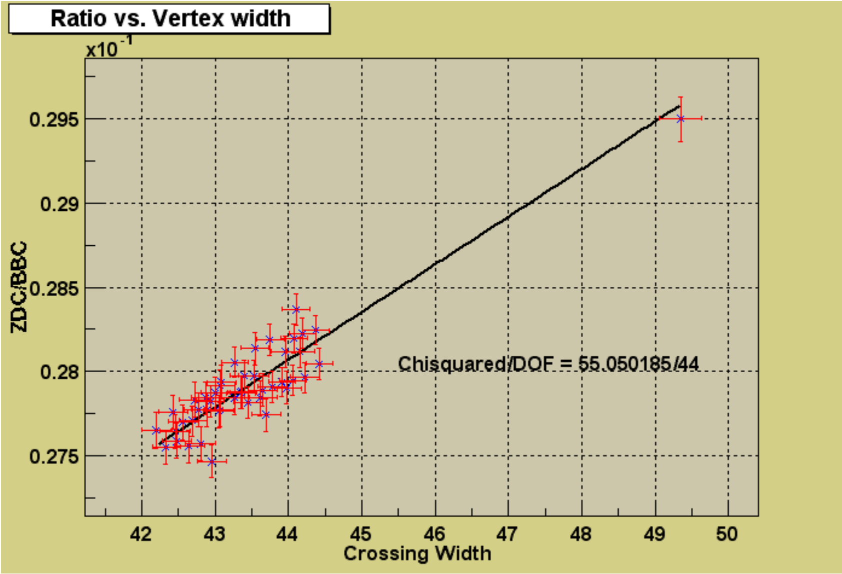
Ratio of Zero-Degree Counter scalars to Beam-Beam Counter scalars, sorted by bunch crossing and fit to a constant.



Correction Factors

- What other factors could play a role in the determination of the scalar rate besides the luminosity?
  - Vertex width
- Vertex width also measured crossing by crossing.
- Look for a correlation of the ZDC/BBC ratio with the vertex width:
  - Good correlation
- Can correct ratio for this factor.



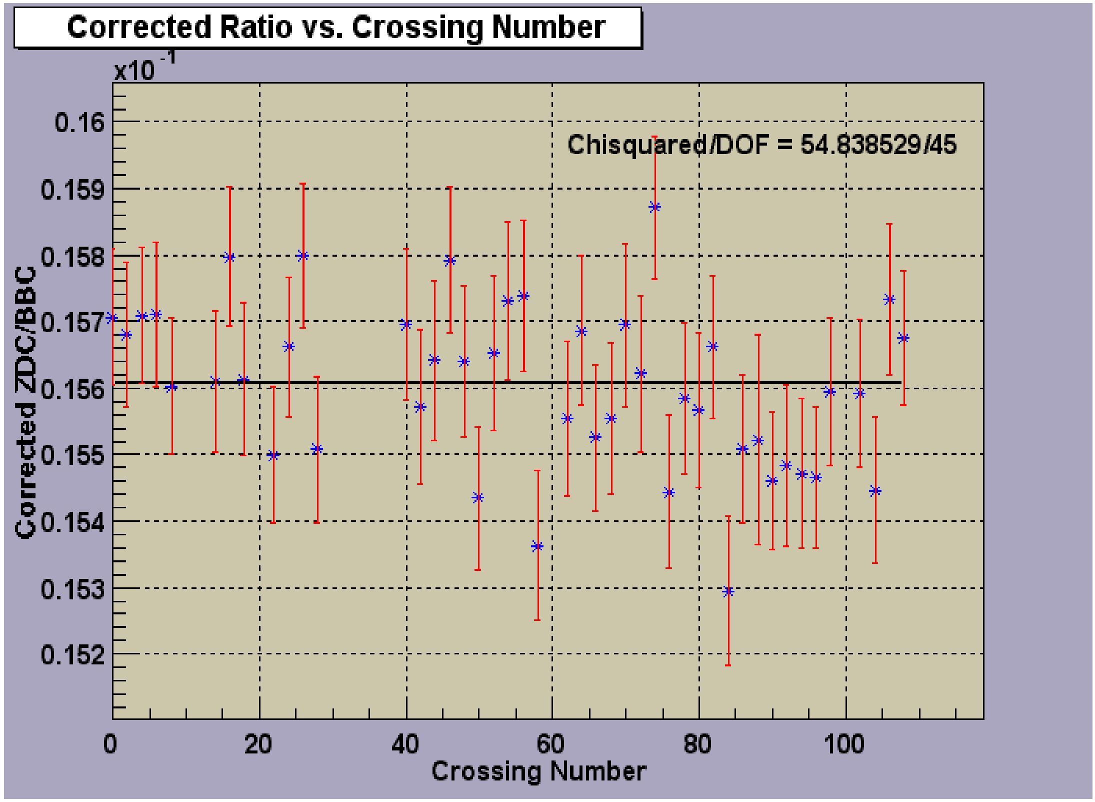


Limit on Relative Luminosity Measurement

- After correction for (measured) vertex width, the ratio of counts in the two detectors is consistent with constant up to our level of statistics
- This means that if we apply correction for this the precision on R goes from:

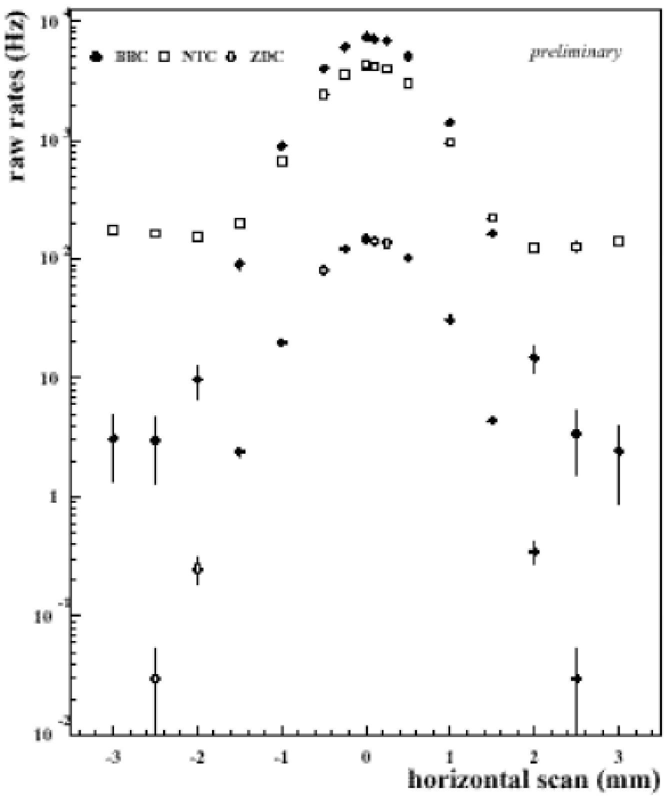
0.11% → 0.06%

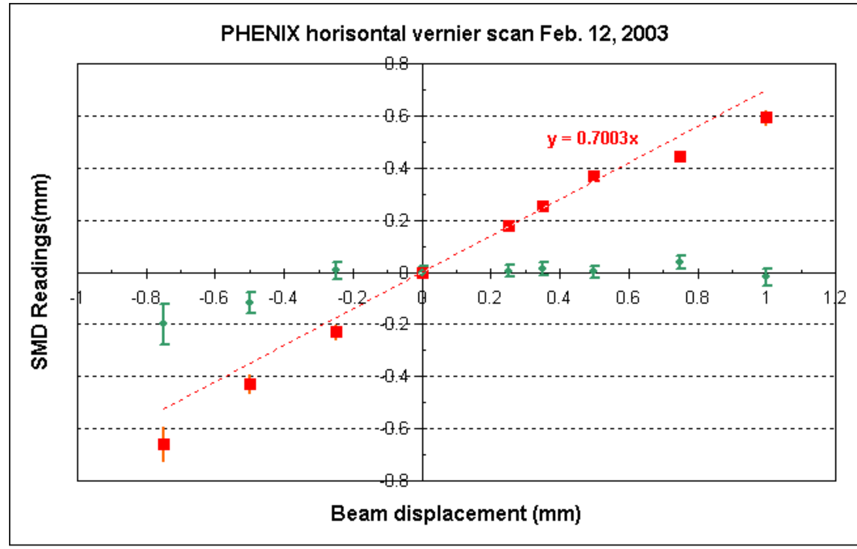
(syst. limited) (stat. limited)

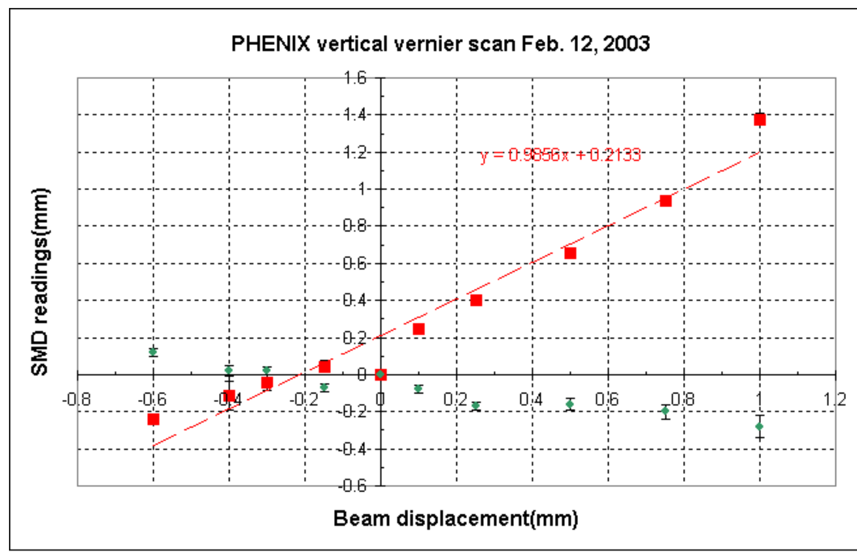


ZDC/SMD (Local Polarimeter) saved the day in two ways for the “Hot Off the Presses” PHENIX Preliminary Results for $\Delta G/G$

Correlation between ZDC/SMD measurements and beam displacement during vernier scan

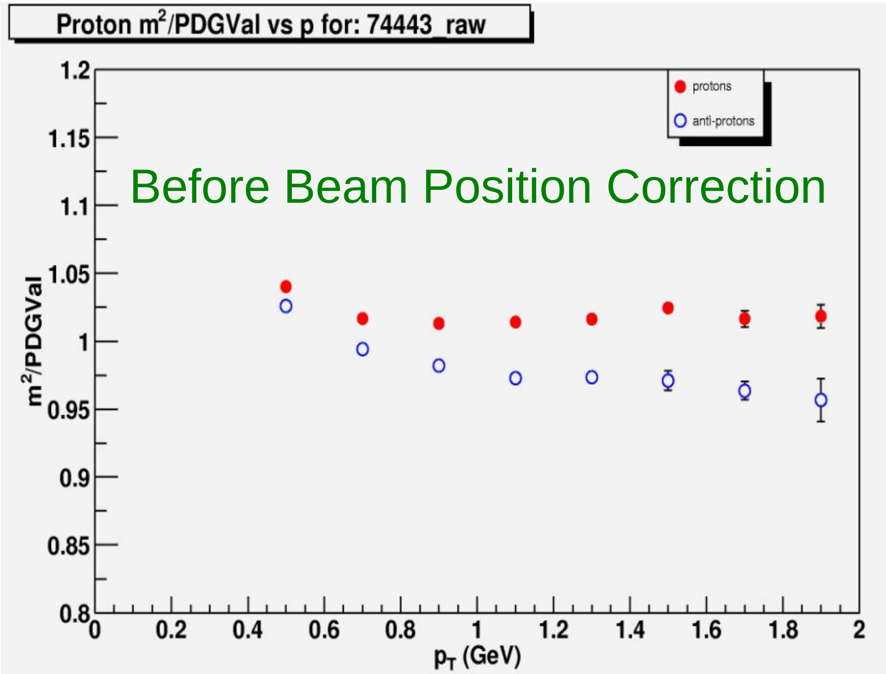


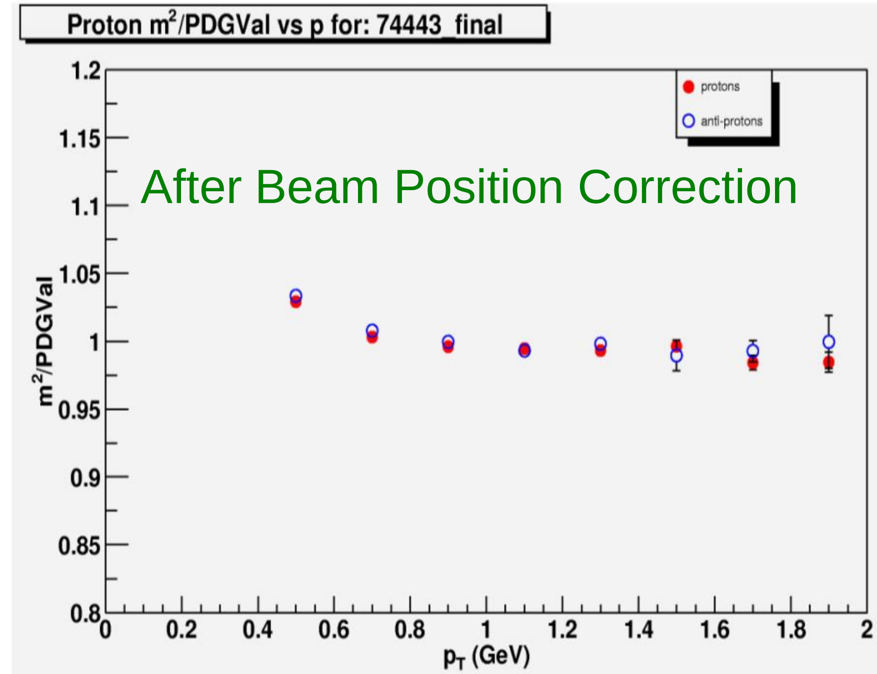




- Count Rate vs Beam Displacement
- SMD Position vs Beam Displacement

Mass Splitting Phenomenon

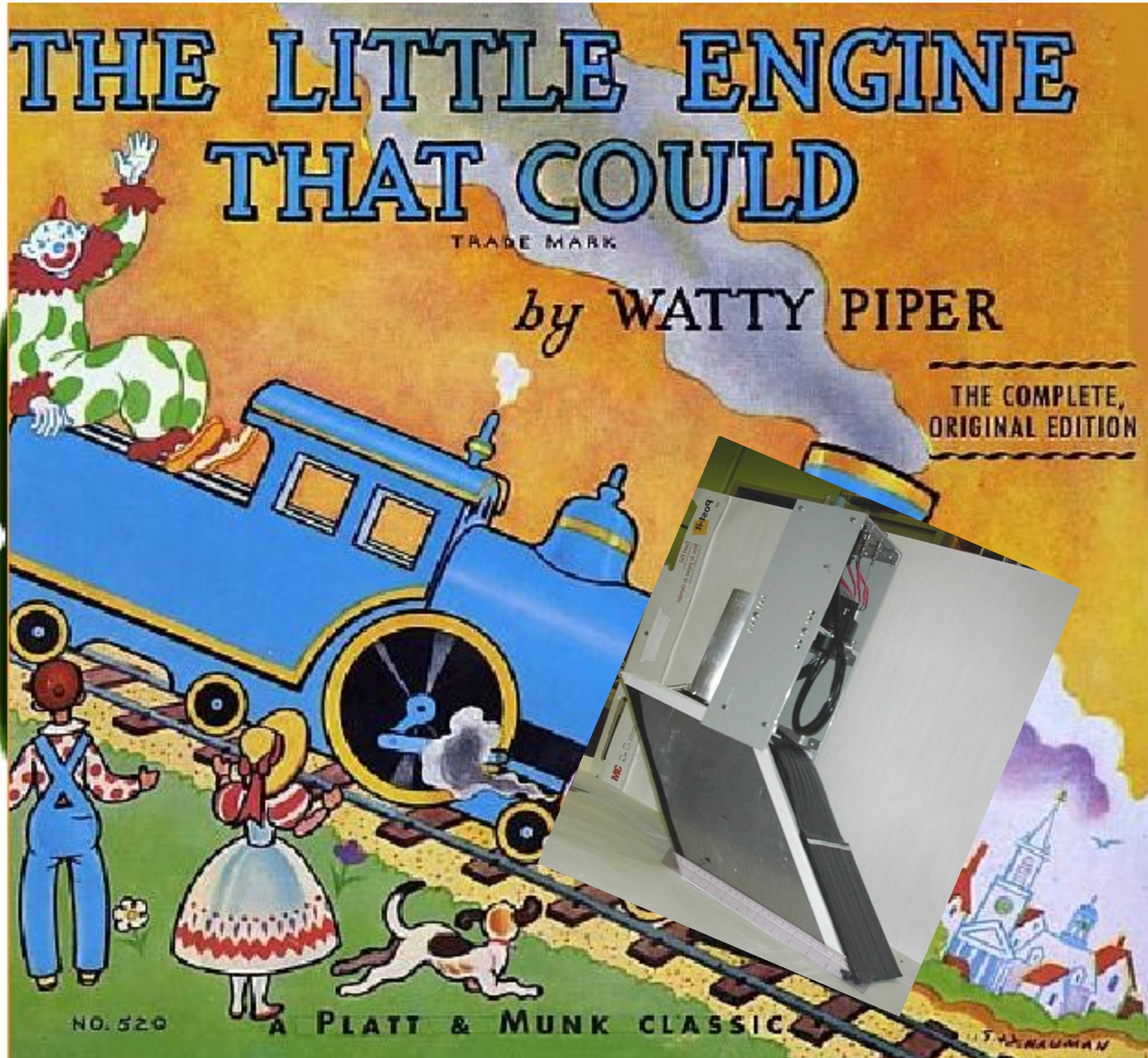




- Identified particles show a split in the mass^2 for positive and negative tracks
- Input to this calculation is only track angle at DC and TOF.
  - TOF is charge independent, so it must be track angle
- Beam motion measured by ZDC-SMD
- Beam x-y position correction applied.
  - Splitting gone.

Summary and Conclusions

- ZD … l)
  - L … ent
  - C
  - E … n
  - T
  - p
  - M
- The … IC
  - C … olliders



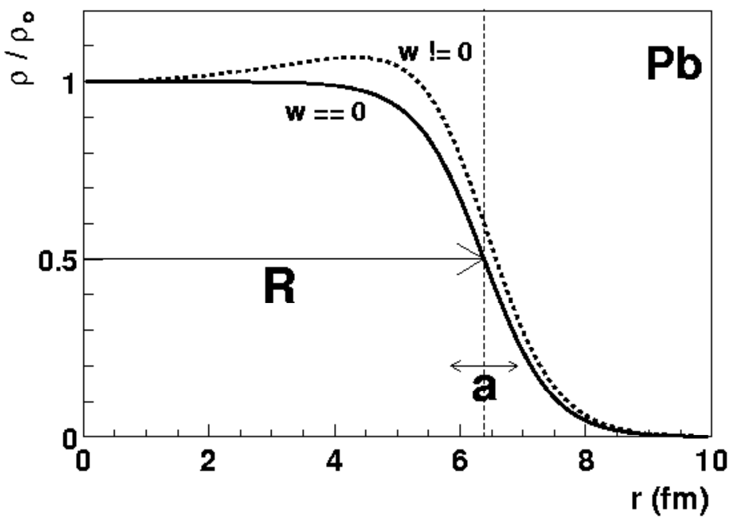
Glauber Model

Glauber R. J., Phys. Rev. 100 242 (1955); in: Lectures in the theoretical physics, ed. W. E. Brittin, L. G. Dunham, Interscience, N. Y., 1959, v. 1, p. 315.

- Nucleons are distributed according to a density function (e.g. Woods-Saxon)
- Nucleons travel in straight lines and are not deflected as they pass through the other nucleus
- Nucleons interact according to the **inelastic cross section** σ_{NN} measured in pp collisions, even after interacting
  - Participants – counts nucleons which interact
  - Binary collisions – counts collisions

Nucleus Parameters

$$\rho(r) = \frac{\rho_0\left(1 + wr^2 / R^2\right)}{1 + \exp((r - R)/a)}$$



Electron Scattering Measurements

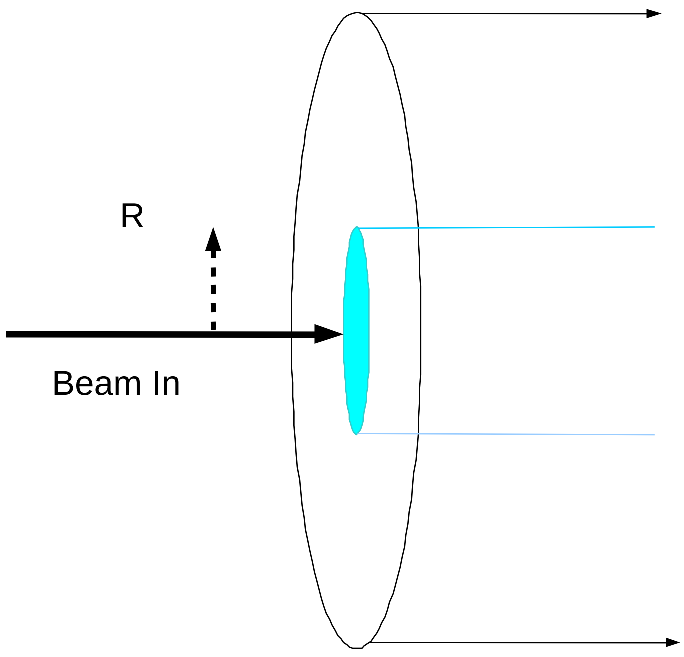
Nucleus	A	R	a	w
C	12	2.47	0	0
O	16	2.608	0.513	-0.051
Al	27	3.07	0.519	0
S	32	3.458	0.61	0
Ca	40	3.76	0.586	-0.161
Ni	58	4.309	0.516	-0.1308
Cu	63	4.2	0.596	0
W	186	6.51	0.535	0
Au	**197**	**6.38**	**0.535**	**0**
Pb	208	6.68	0.546	0
U	238	6.68	0.6	0

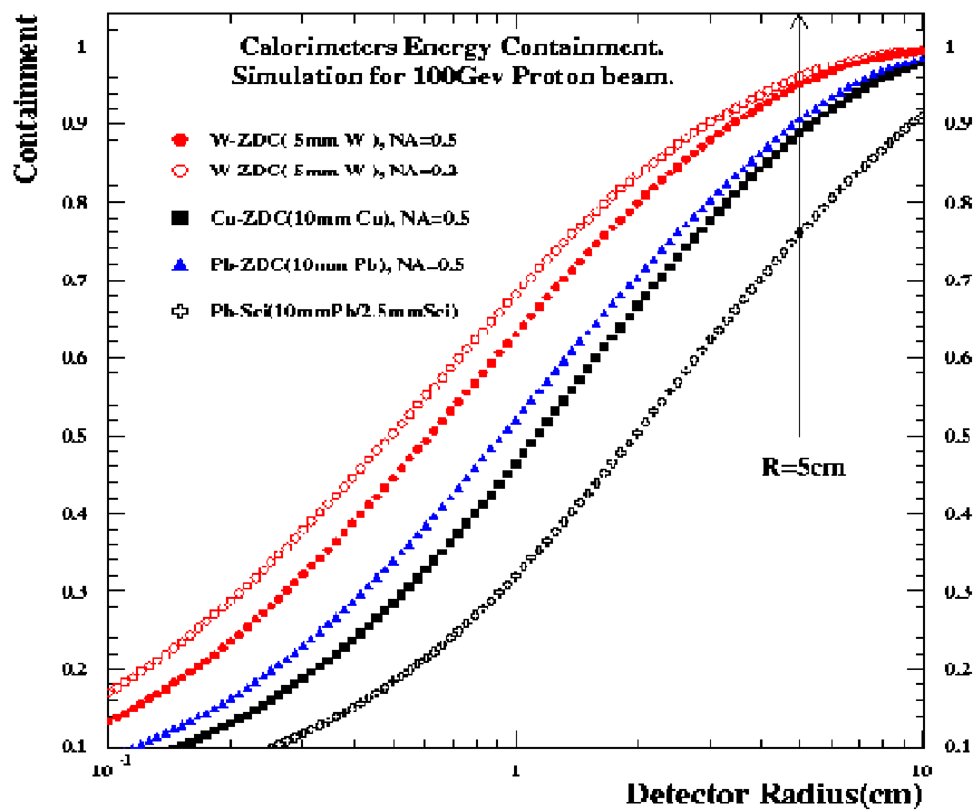
H. DeVries, C.W. De Jager, C. DeVries, 1987

$$T_A(s) = \int_{-\infty}^{+\infty} \rho_A(\vec{s}, z)$$

Shower Size Considerations

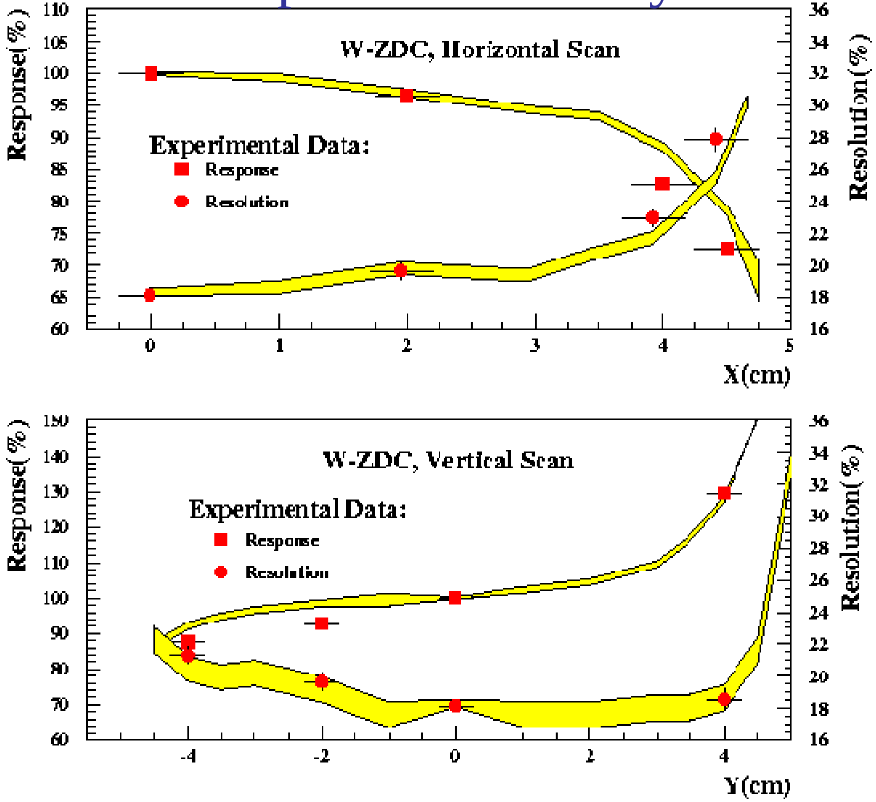
Effective Shower Size Scintillator vs. ZCAL



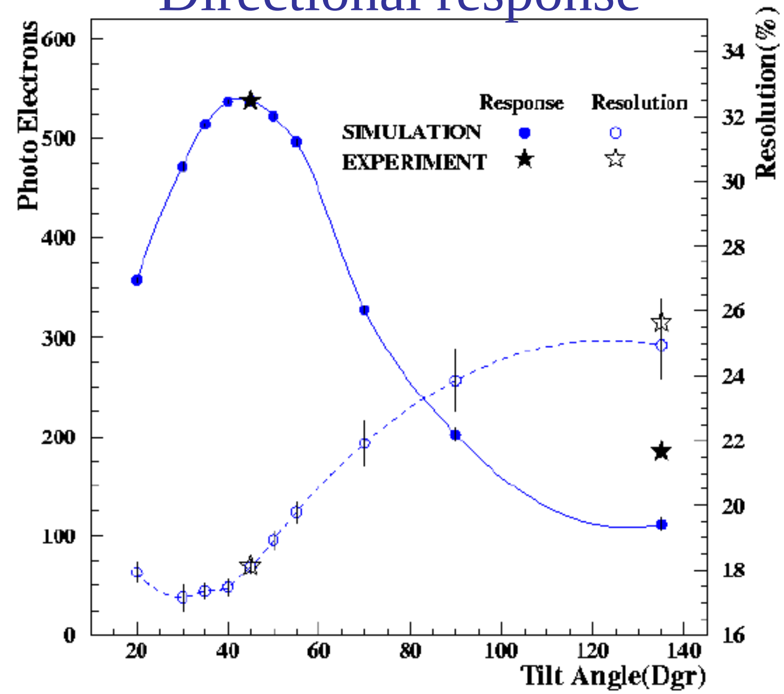


Test Beam Measurements (100 Gev p)

Response uniformity

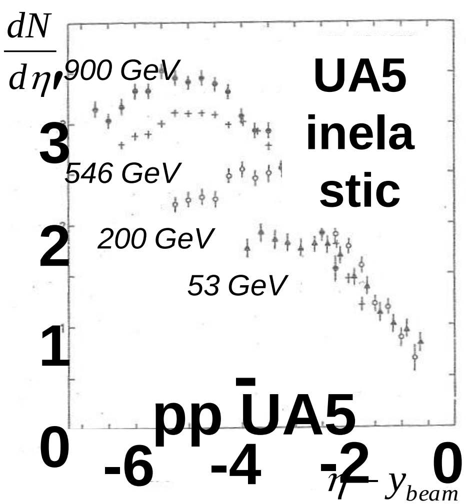


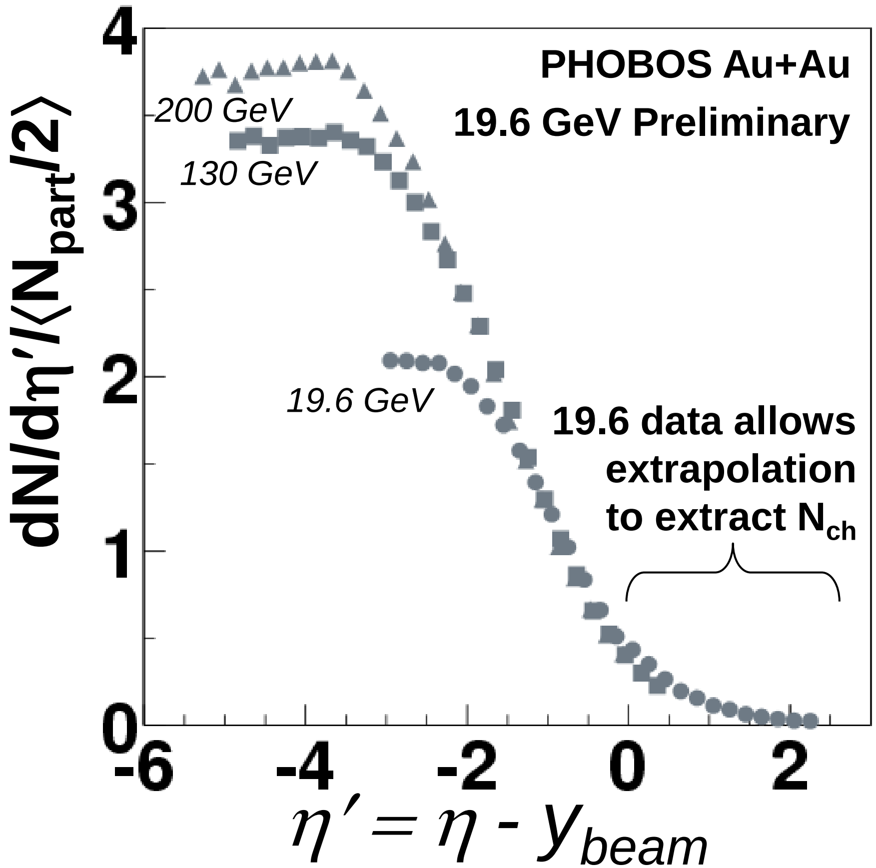
Directional response



Forward (Fragmentation)

Limiting Fragmentation





"At high energies the number of particles produced by the fragmenting target is independent of the target, projectile, and beam energy."

J. Benecke, T.T. Chou, C.N. Yang, and E. Yen, "Hypothesis of Limiting Fragmentation in High Energy Collisions", Physical Review, 188, 2159 (1969)

Bibliography

- S.N.White,``Forward measurements in RHIC and LHC heavy ion collisions,'' Nucl. Instrum. Meth. A409, 618 (1998).
- H.~Appelshauser et al.[NA49 Collaboration],``Spectator nucleons in Pb + Pb collisions at 158-A-GeV,'' Eur. Phys. J. A2, 383 (1998).
- A.J.Baltz, C.Chasman and S.N.White, ``Correlated forward - backward dissociation and neutron spectra as luminosity monitor in heavy ion colliders,'' Nucl. Instrum. Meth. A417, 1 (1998) nucl-ex/9801002.
- M.~Lundin et al., ``On the electromagnetic energy resolution of Cerenkov fiber calorimeters,'' Nucl. Instrum. Meth. A372, 359 (1996).