Leading neutrons in polarized pp collision at RHIC-PHENIX

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for the PHENIX collaboration

RIKEN BNL Research Center

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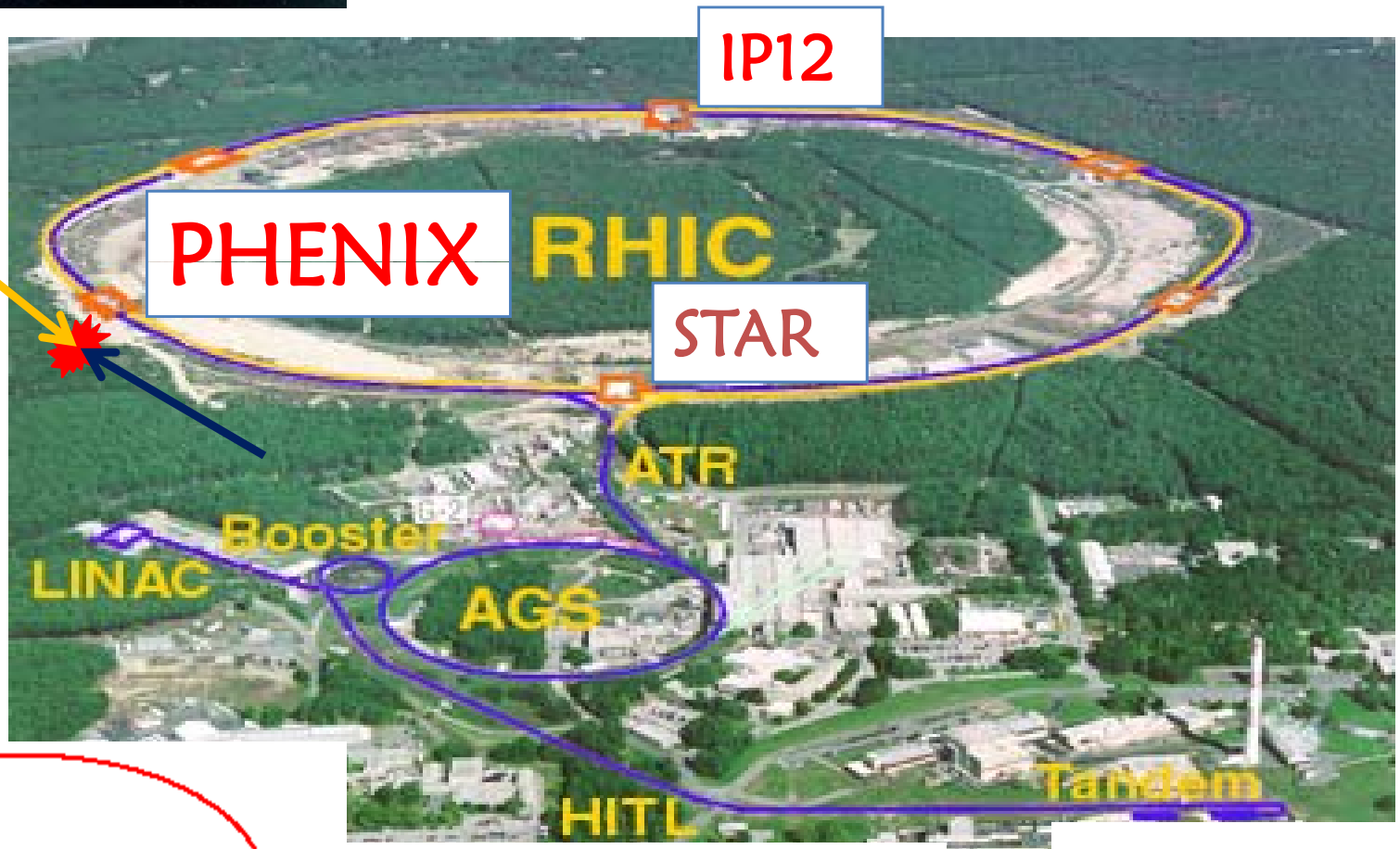
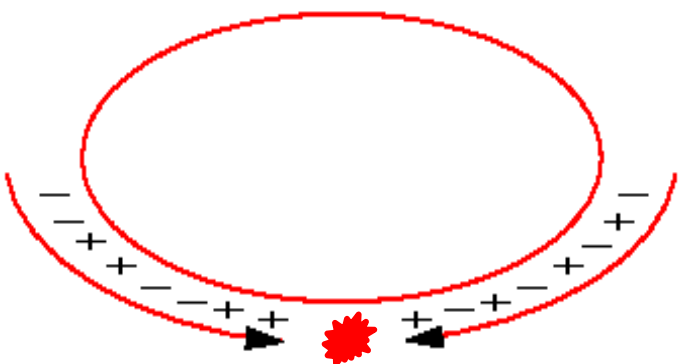
Outline

- Physics motivation
  - Discovery of the finite single transverse spin asymmetry (A_N) for the leading neutron production
- Leading neutron measurements at RHIC-PHENIX
  - A_N
  - Cross section (with other experimental results)
- Theoretical calculation
- Future measurements
- Summary

RHIC

- Relativistic Heavy Ion Collider
- World's first polarized pp collision machine





Spin patterns are

blue beam : ↑↑↓↓…

Yellow beam : ↑↓↑↓…

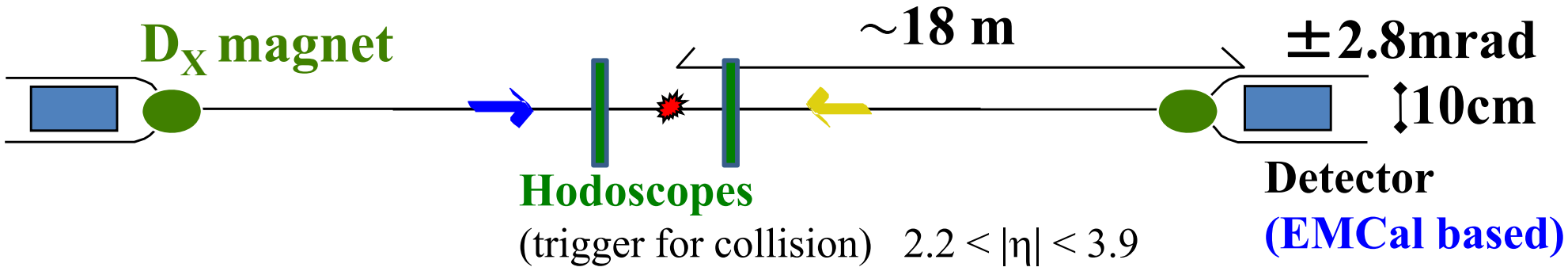
Polarizations :

RUN 2005 : 47%

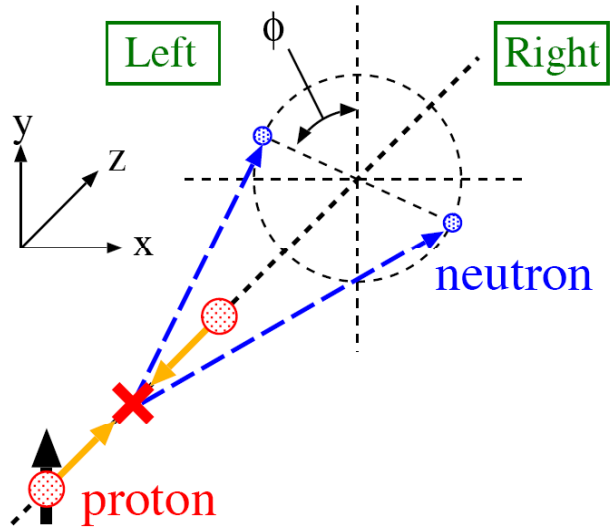
RUN 2006 : 50%

Motivation : Discovery of leading neutron asymmetry (A_N)

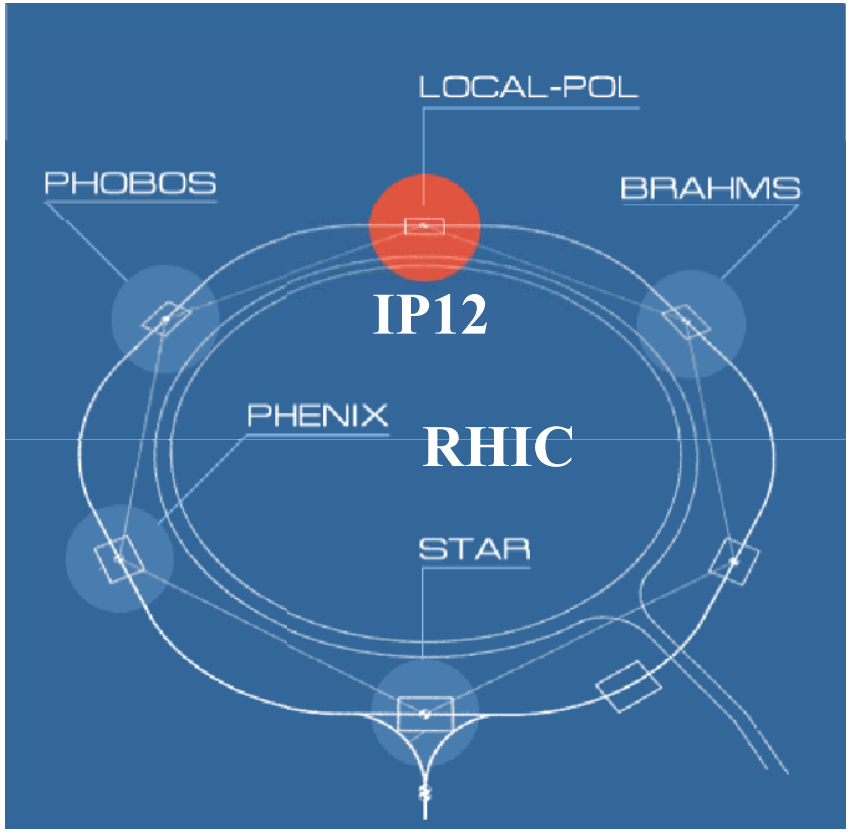
***Polarized pp* collision at $\sqrt{s}$ = 200 GeV (RUN2001-2002)**



A_N : single transverse spin asymmetry



$$A_N \equiv \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}}$$



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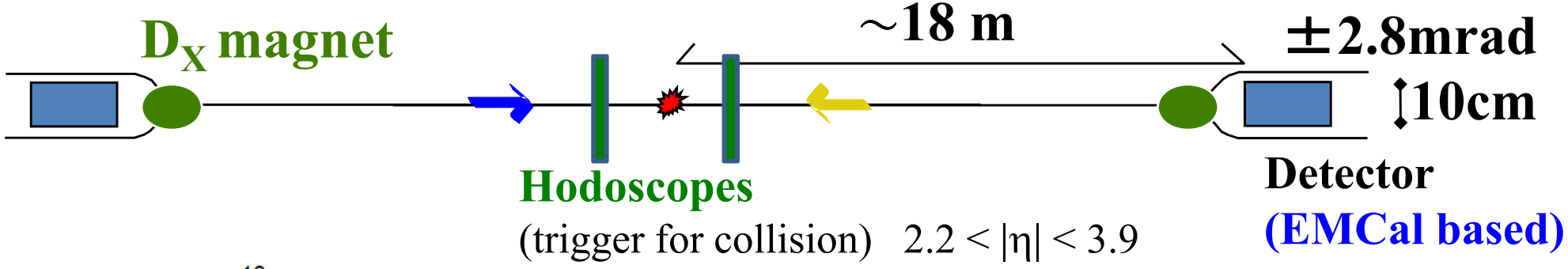
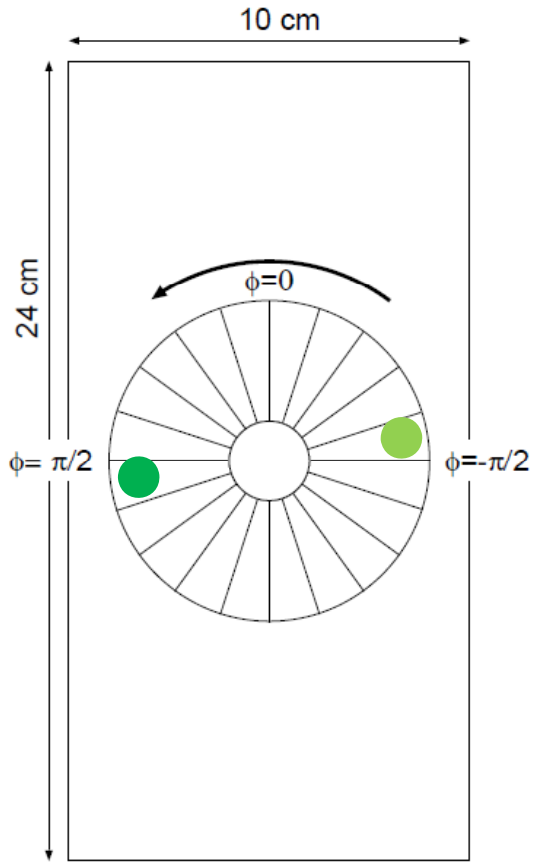
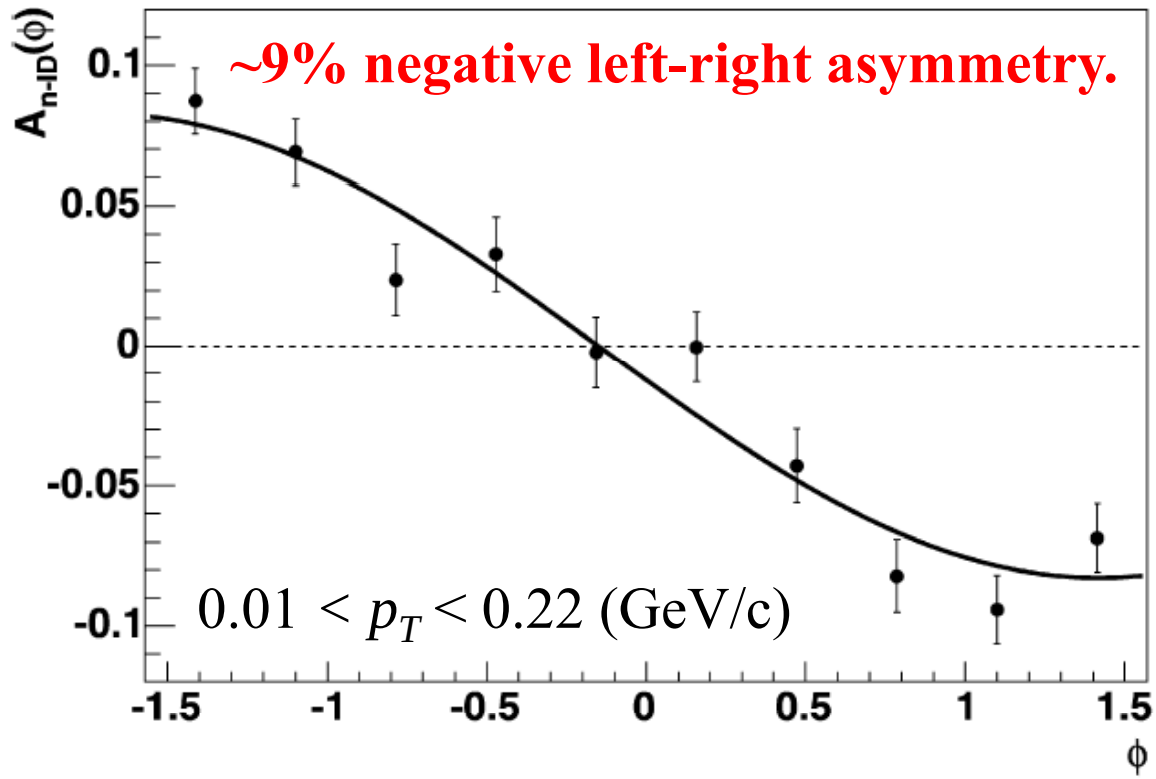




Detector geometry

Physics Letters B 650 (2007) 325–330

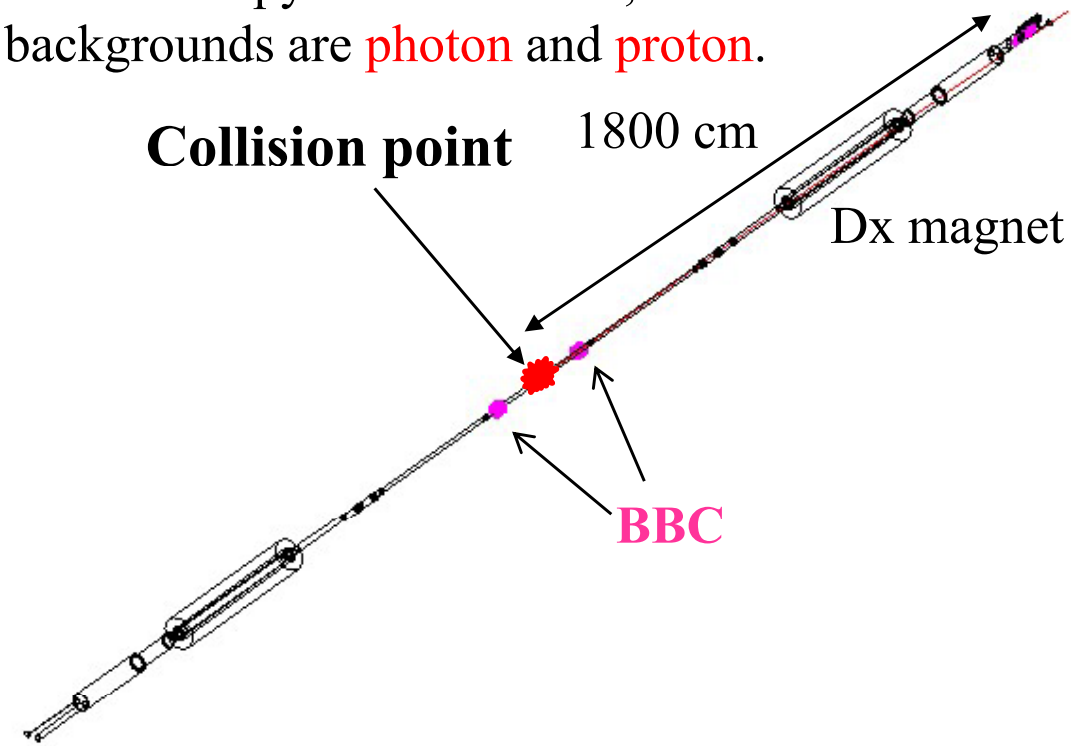


→ Continue to investigate at PHENIX

PHENIX setup

Schematic view from simulation.

- GEANT3 (Geisha)
- From the pythia simulation, Main backgrounds are photon and proton.



Beam Beam Counter (BBC)

- 2 identical parts
  - BBC-north and –south
- 64 segments each.
- Quartz Cherenkov counter
  - Count charged particles.
- $3.0 < |\eta| < 3.9$

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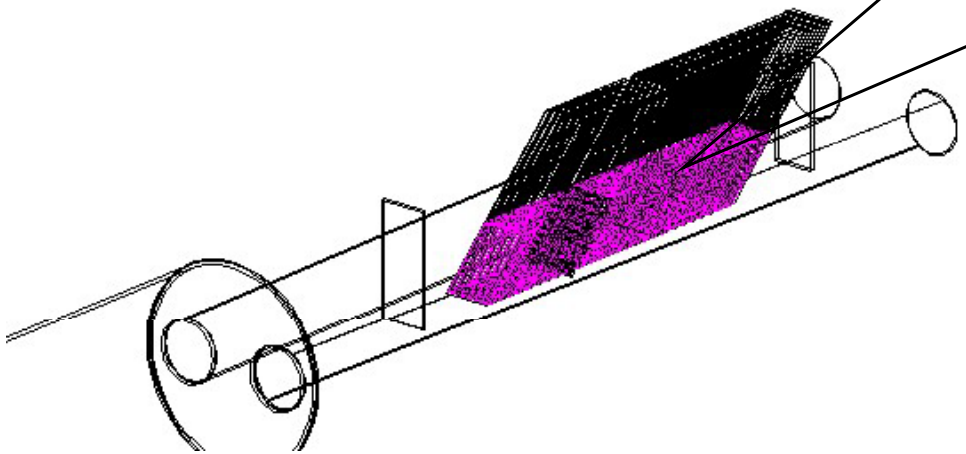

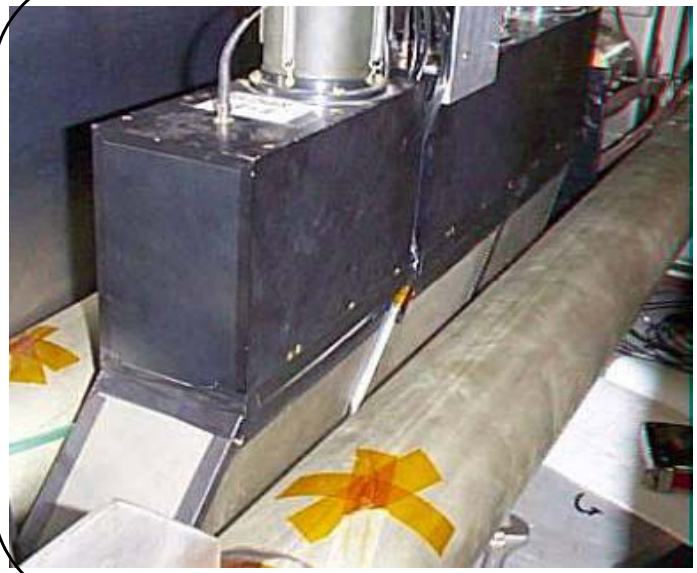

ZDC
(**Z**ero **D**egree **C**alorimeter)

10*10cm
→ ±2.8 mrad

3 modules
$150X_0$ $5.1\lambda_I$

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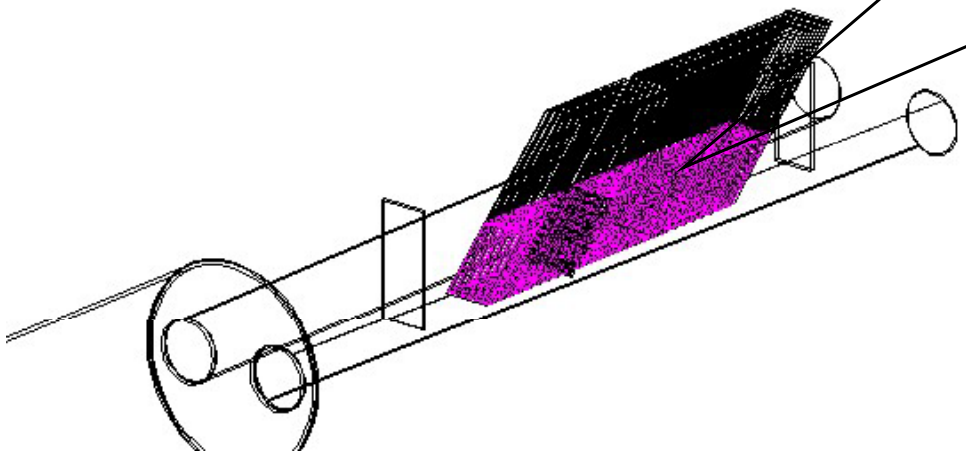

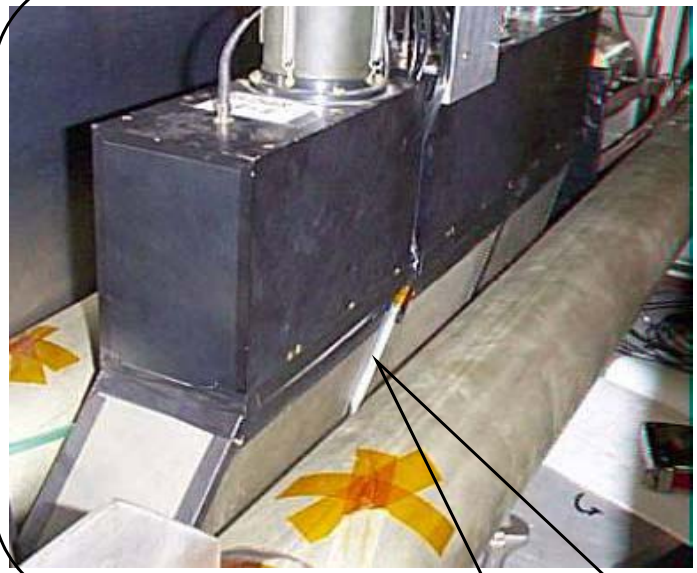

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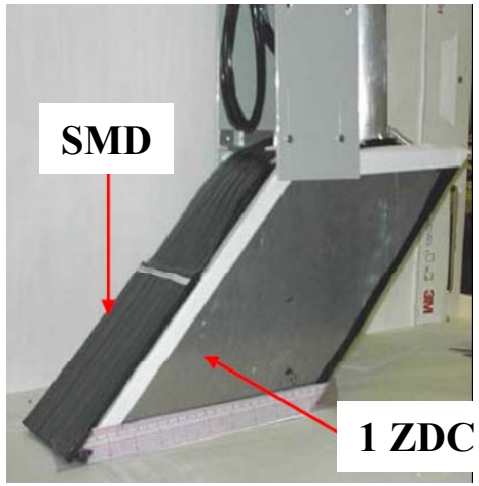

Neutron position can be decided by centroid method.

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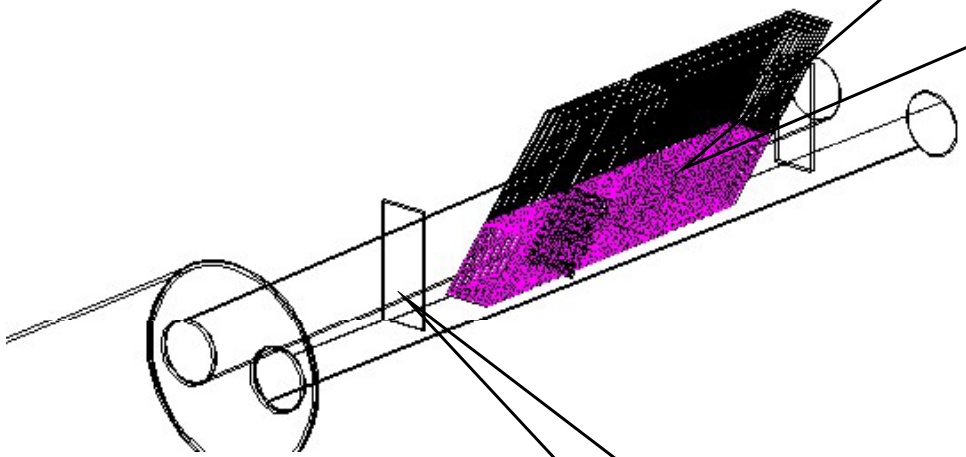

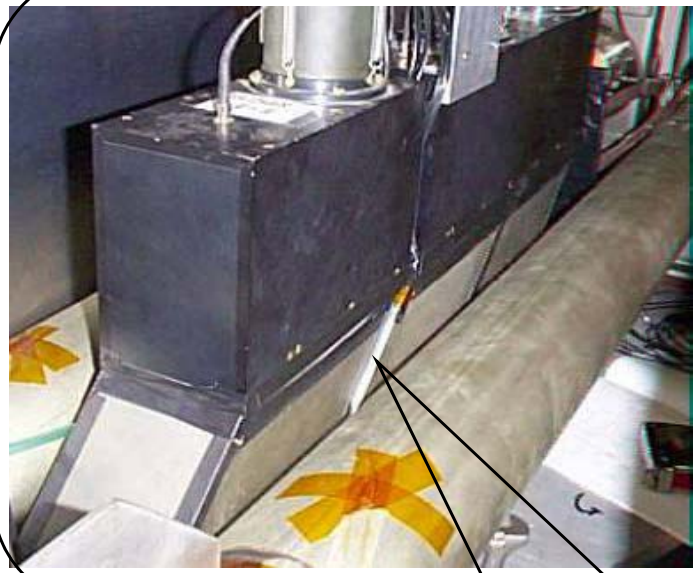

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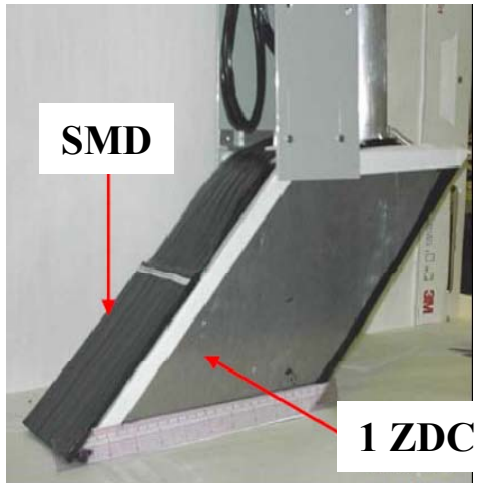
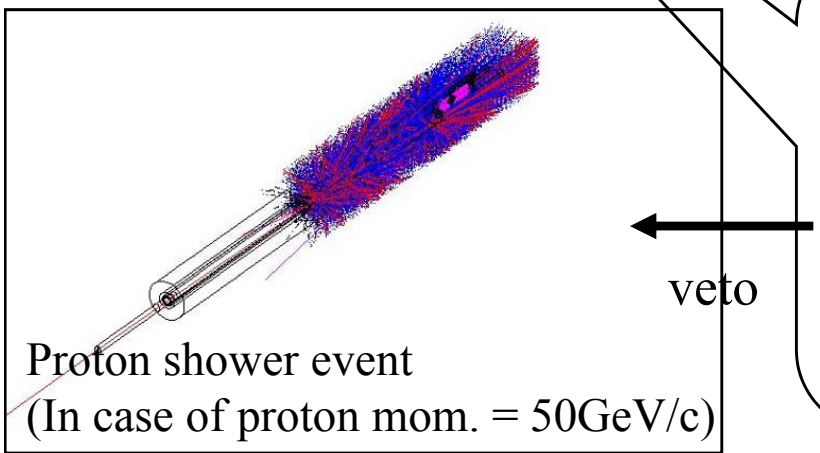


Neutron position can be decided by centroid method.

Charge veto counter

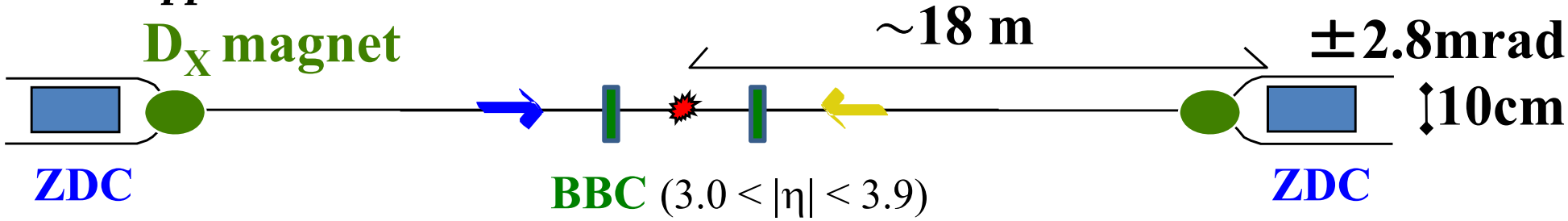


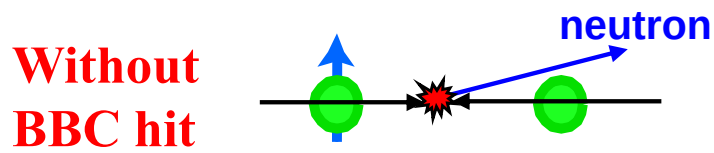
veto

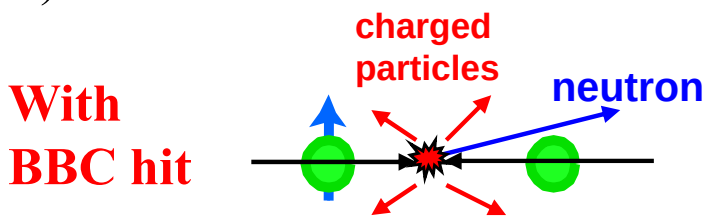
Proton shower event
(In case of proton mom. = 50GeV/c)

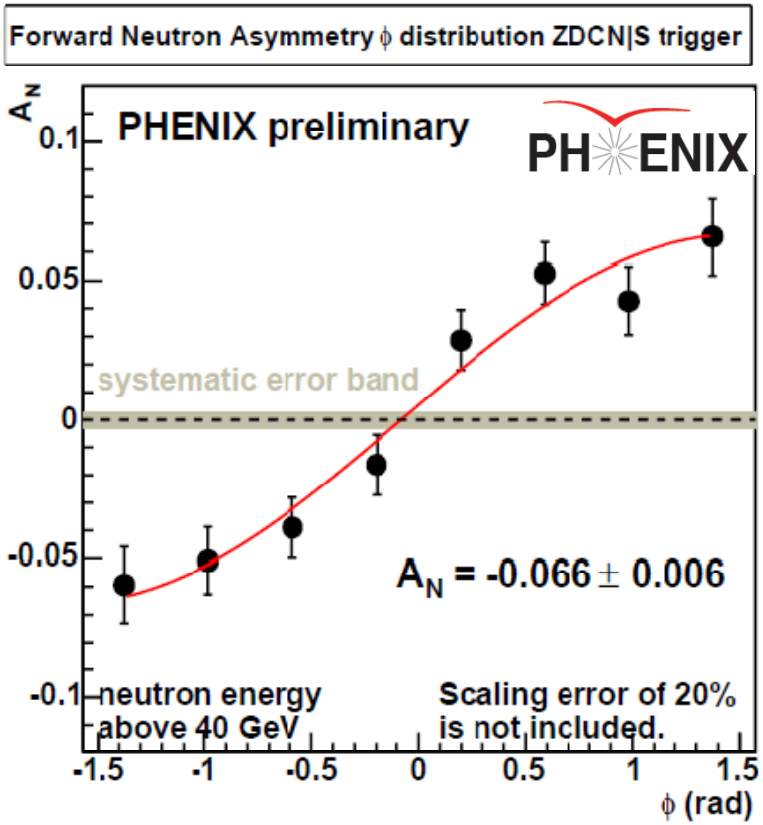
Leading neutron A_N at PHENIX

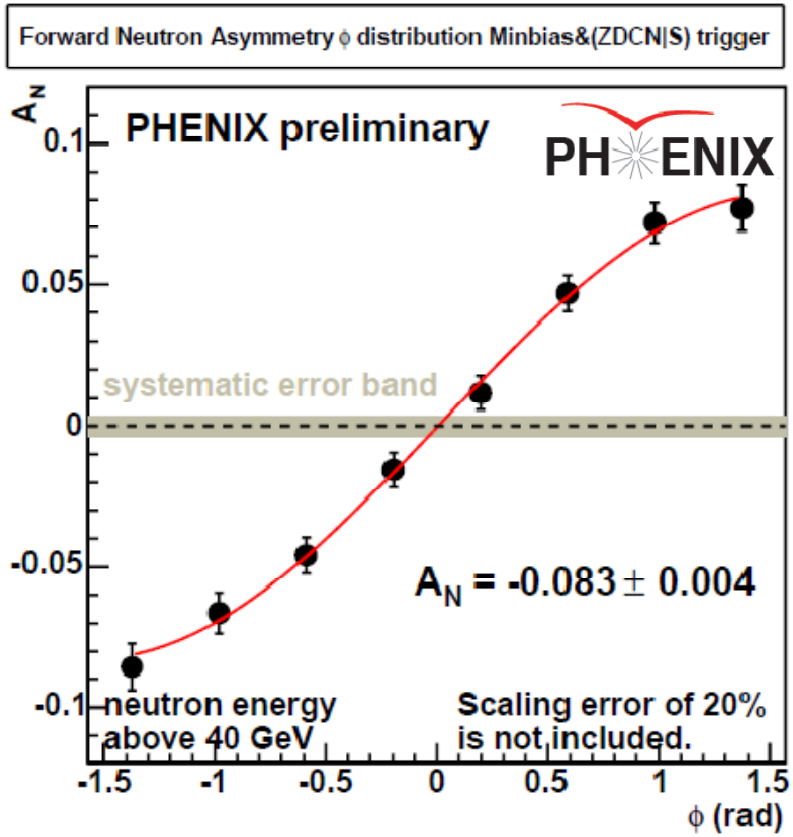
***Polarized pp* collision at $\sqrt{s}$ = 200GeV**





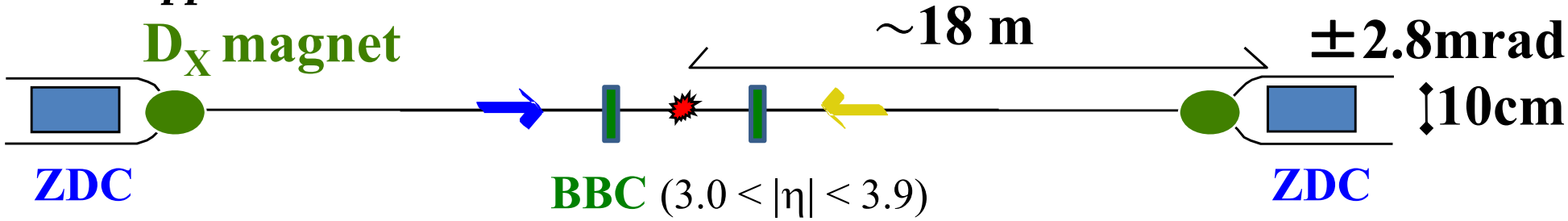


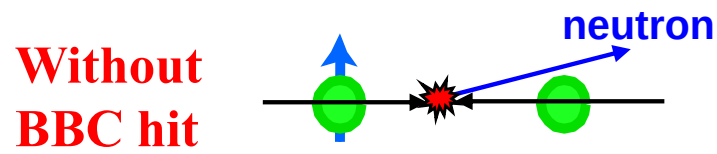


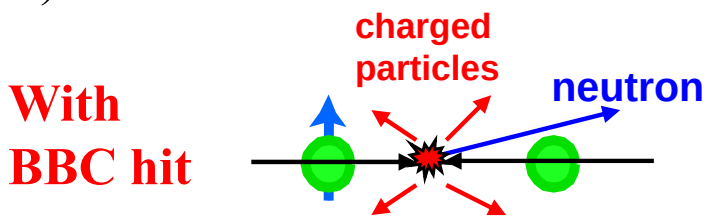


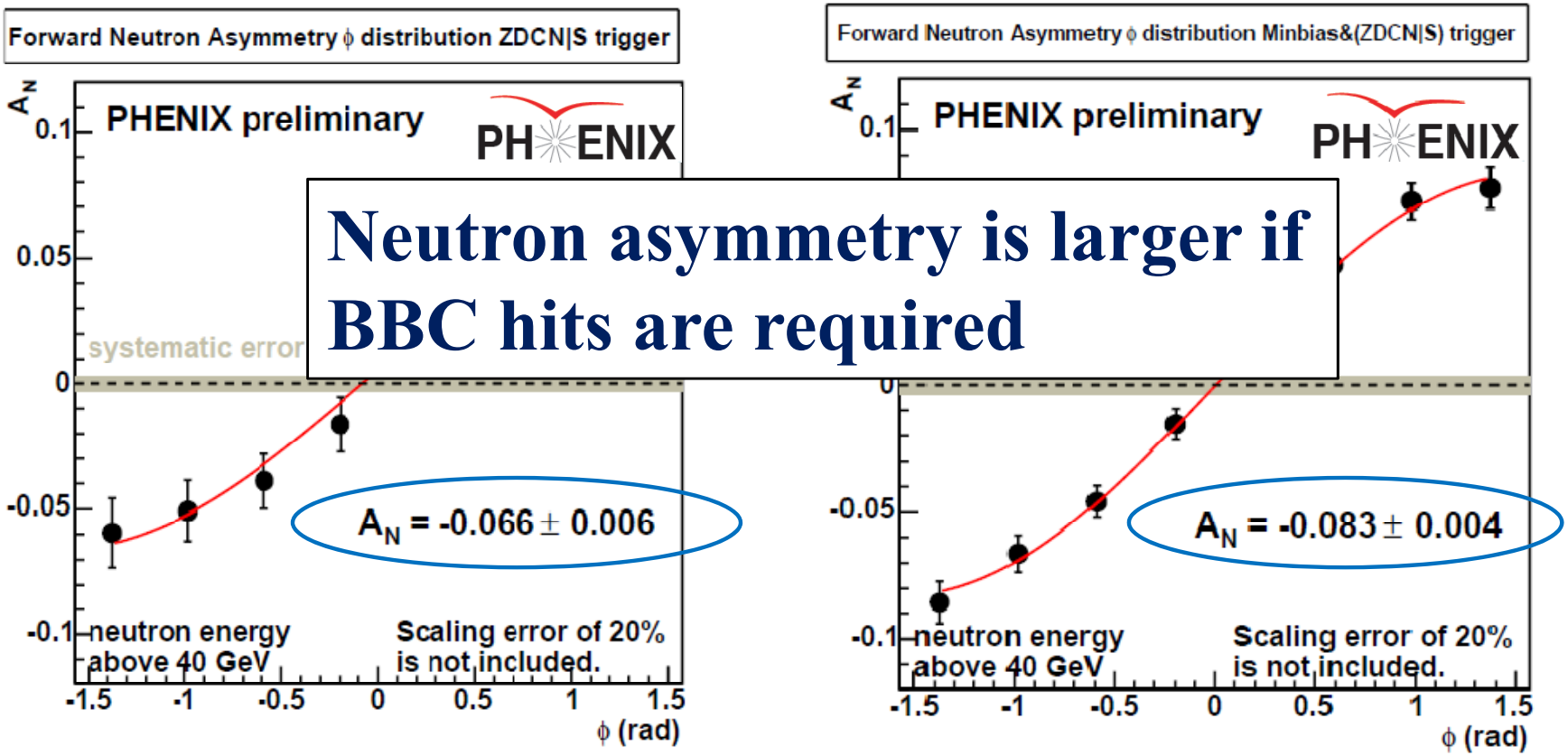
Leading neutron A_N at PHENIX

***Polarized pp* collision at $\sqrt{s}$ = 200GeV**









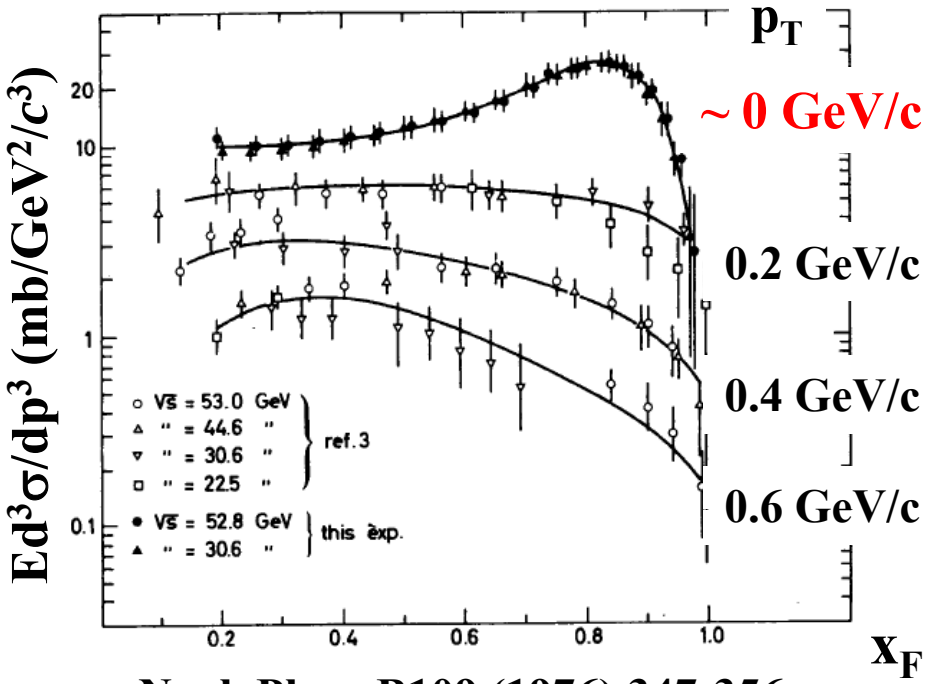
Neutron asymmetry is larger if BBC hits are required

Cross section at ISR and HERA

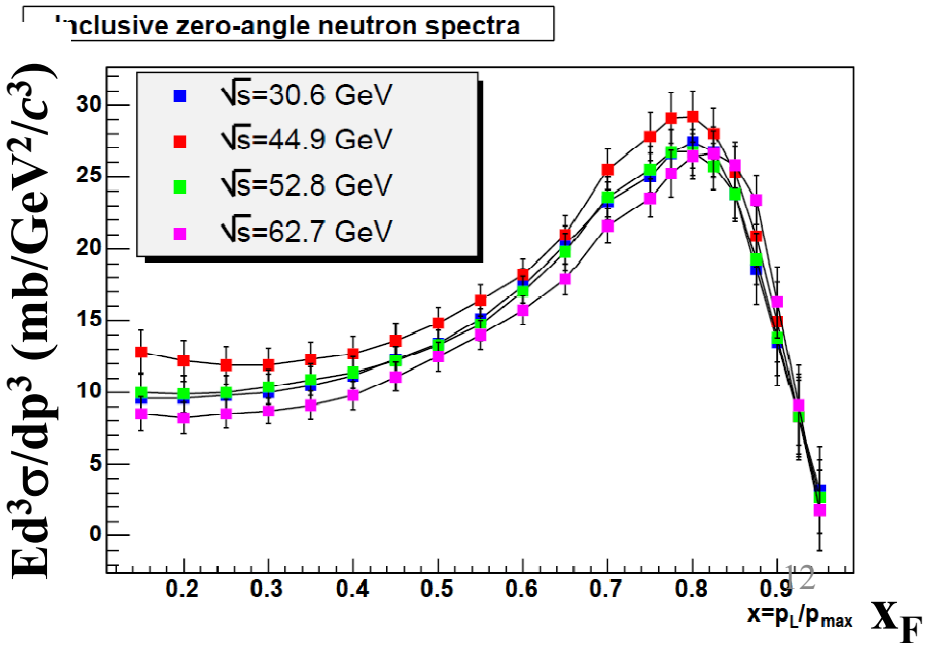
- ISR experiments
  - p+p @ sqrt(s) = 30-63 GeV.
  - Cross section of leading neutron production has peak structure at high x_F (~0.8).
  - Scaling by x_F, not sqrt(s).

- H1 and ZEUS experiments
  - e+p @ sqrt(s) ~ 300 GeV.
  - Also have forward peak

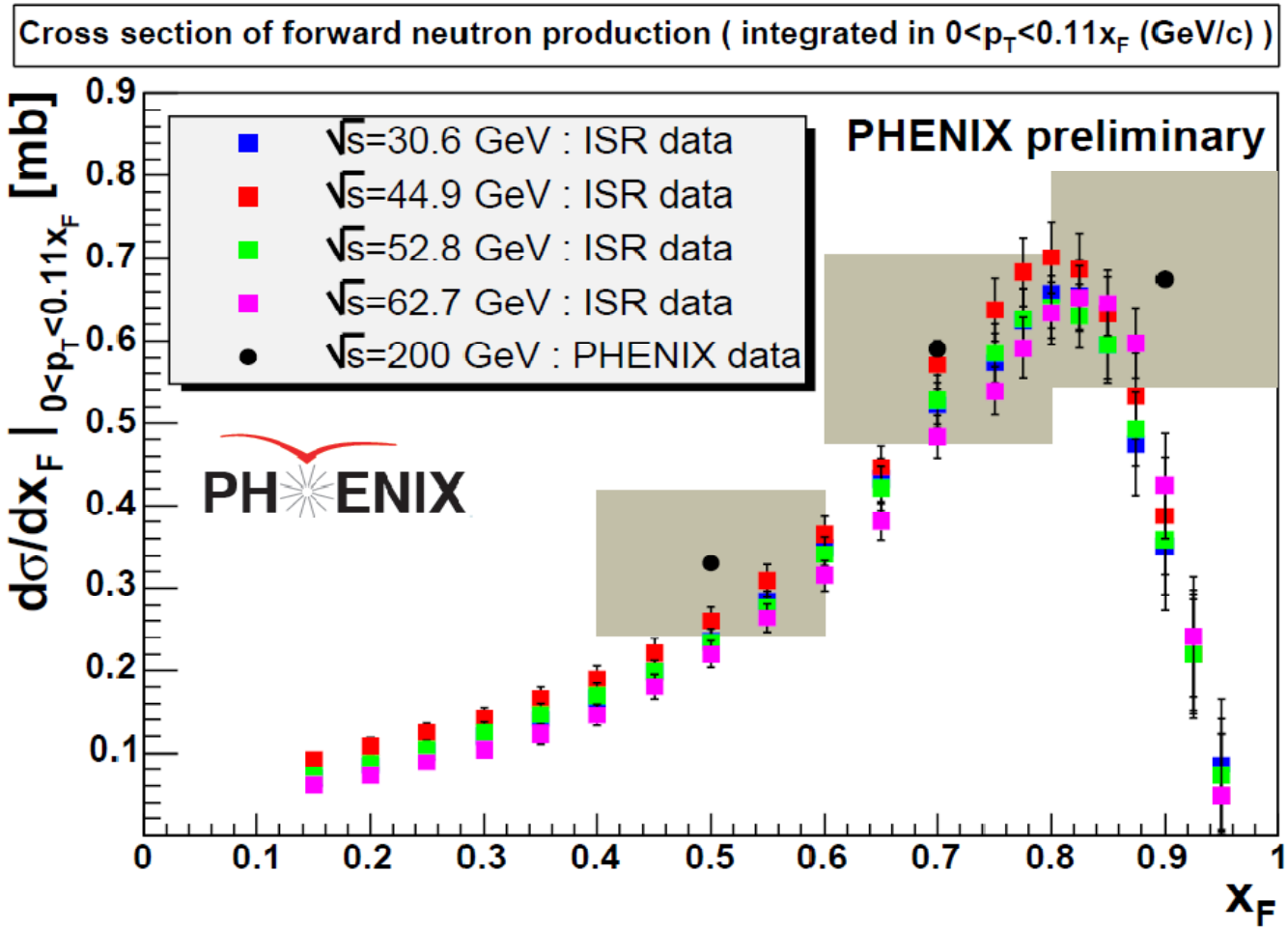
→ Well described by the One Pion Exchange (OPE) model.



Nucl. Phys. B109 (1976) 347-356



Cross section at PHENIX



p_T distribution is assuming ISR result

Integrated p_T area : $0<p_T<0.11x_F$ GeV/c in each x_F point.

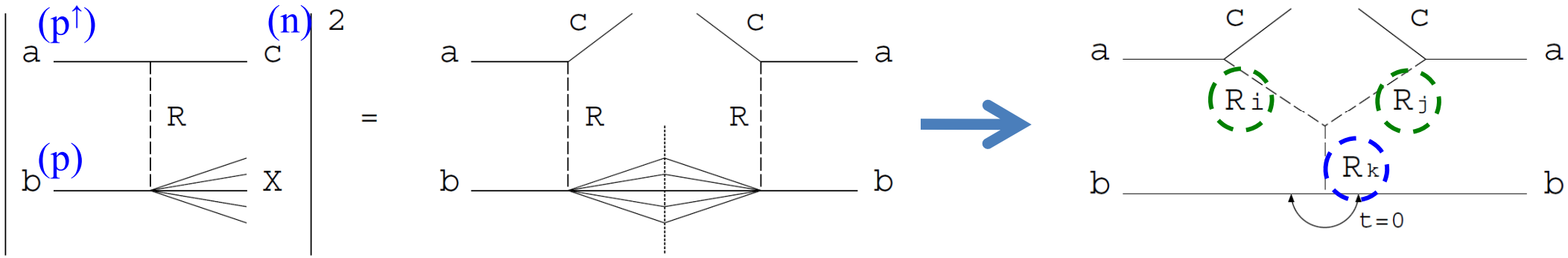
- Cross section is consistent with the ISR data; No evidence for violation of x_F scaling at higher energy.

→ Leading neutron in RHIC energy is also described by the OPE model.

Theoretical model (Regge theory)

Dissociation process

Optical theorem



For $p^{\uparrow}p \rightarrow nX$

- R_k will be Pomeron for high energy scattering.
- R_i and R_j are the isospin-odd reggeon, such as π, ρ, a_2…
- Absorption correction is important.

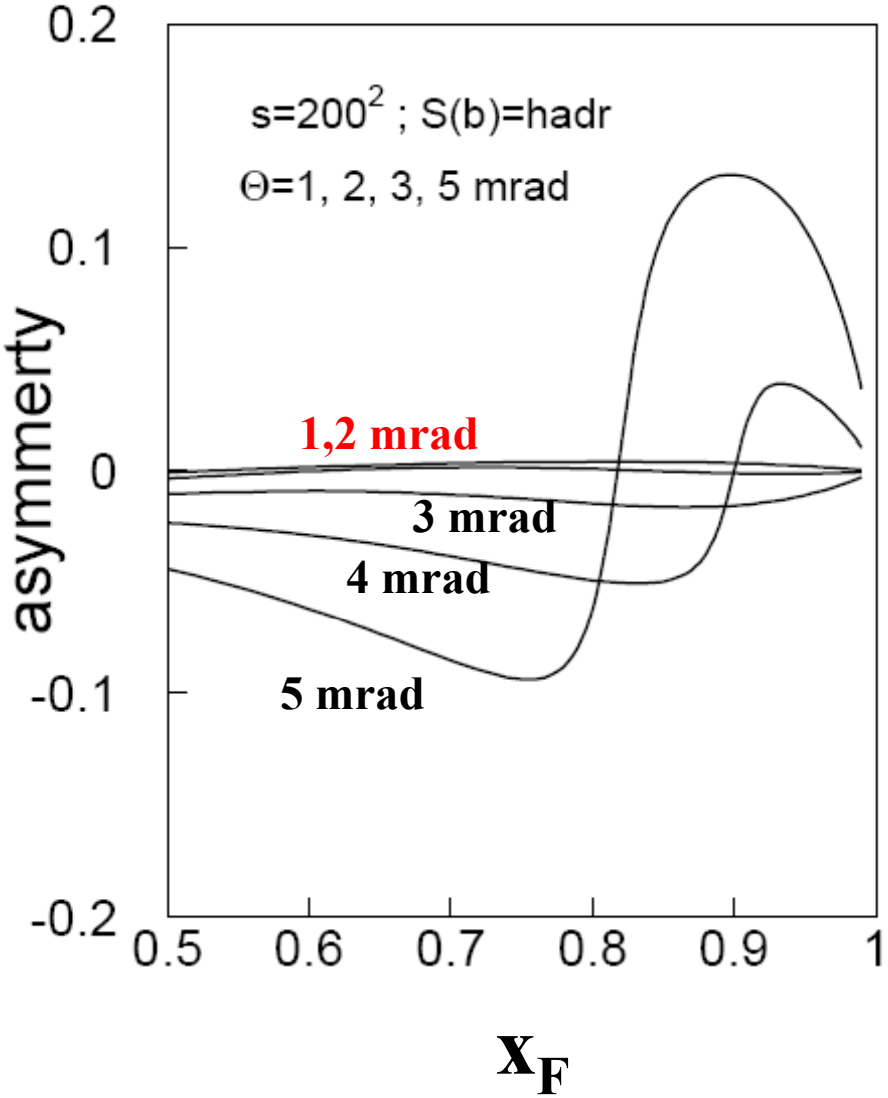
- For cross section : Most of R_i and R_j are π exchange
- For A_N : also expected to be explained by π exchange which has spin flip amplitude
  - In general, finite A_N needs to have interference btw spin flip and non-flip amplitudes.

$$A_N \approx \frac{2\,\mathrm{Im}\left(fg^*\right)}{|f|^2 + |g|^2}$$

f : spin non-flip amplitude
g : spin flip amplitude

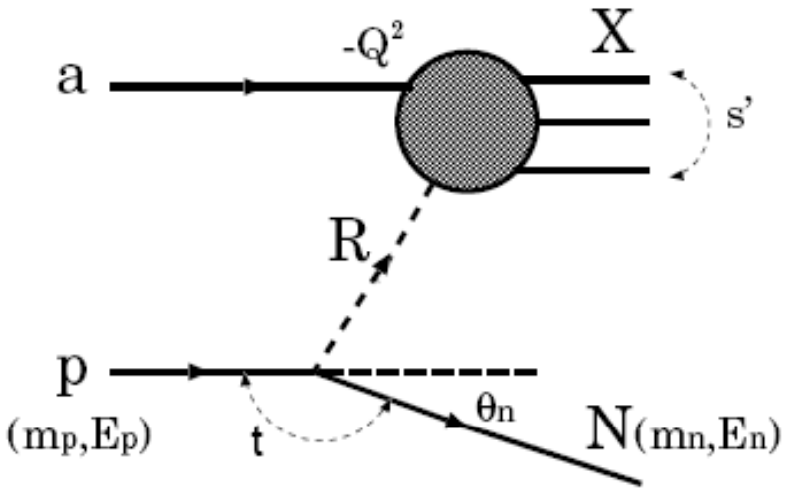
First calculation

B.Z. Kopeliovich, I.K. Potashnikov, I. Schmidt and J.Soffer
arXiv:0807.1449



- Asymmetry is calculated by considering pion exchange in various detection angles.
  - Asymmetry is demonstrated by the OPE model.
- However it is very small so far.
  - PHENIX kinematic region : x_F=0.6-0.8, and $\theta < 2$ mrad.
  - Need to consider other reggeon components. (*e.g.* a_1 exchange)

Future measurement :
A_N measurements at various √ s

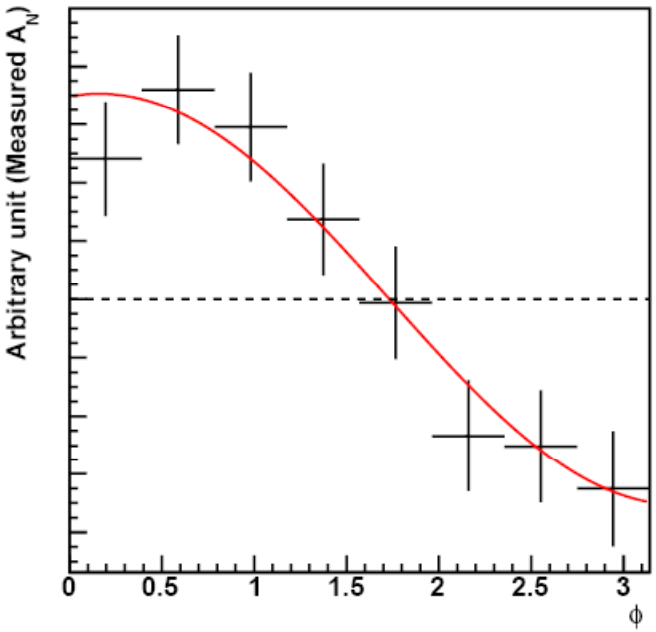


$$x_F = p_L/p_{L(max)} = E_n \cos\theta_n / E_p \sim E_n/E_p$$

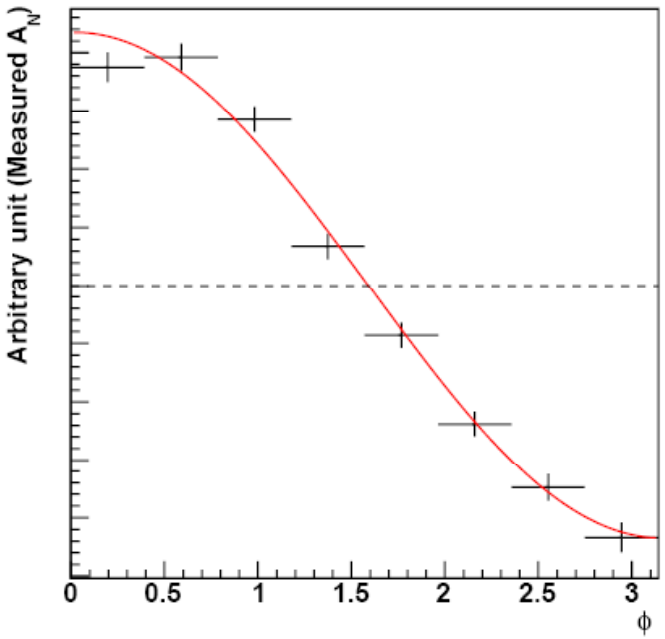
$$p_T = E_n \sin\theta_n \sim x_F E_p \theta_n$$

- p_T is approximately proportional to the incident proton energy. → p_T-dependent A_N
- We have measured finite asymmetries at √ s=62, 410 and 500 GeV
- We already measured significant A_N in all.

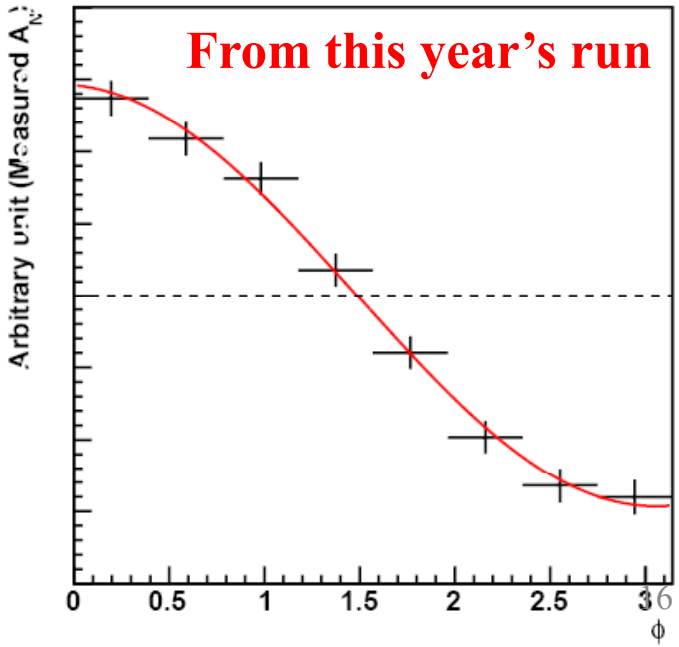
√ s = 62 GeV



√ s = 410 GeV

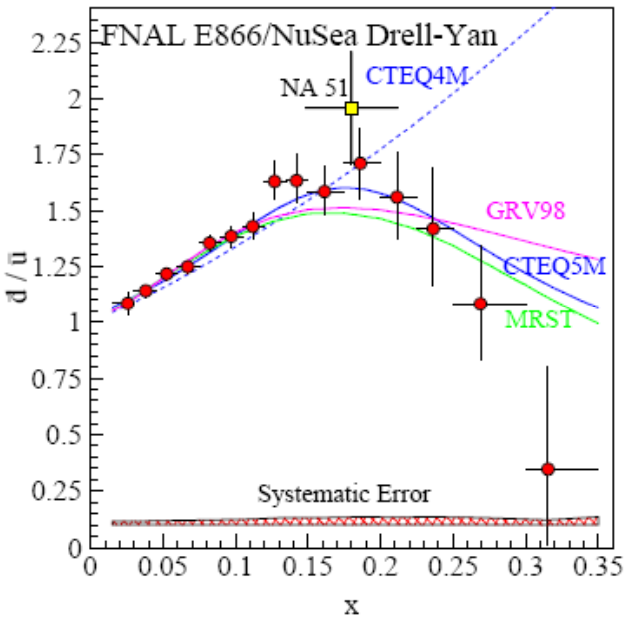


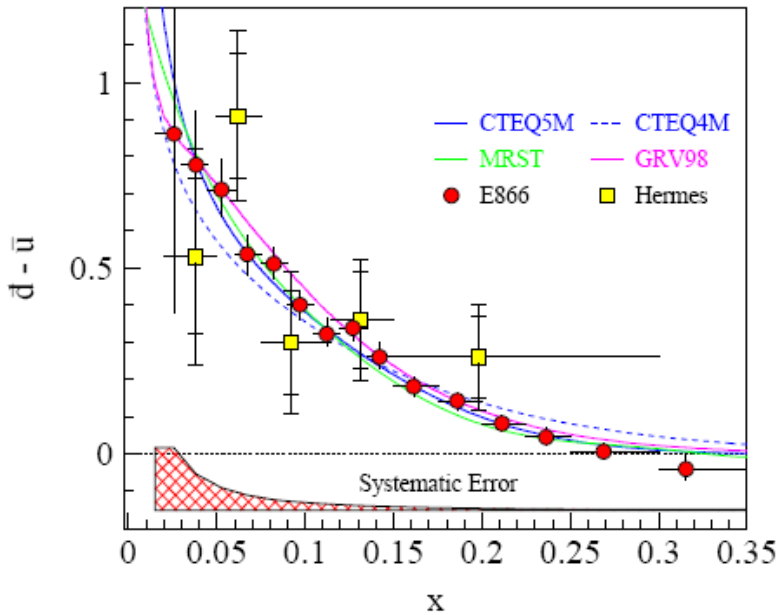
√ s = 500 GeV

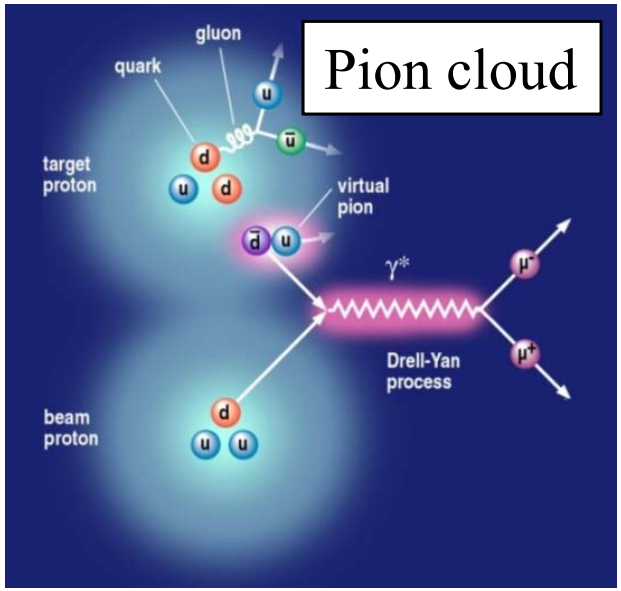


Other pion exchange phenomena in high energy pp interaction

- E866 Drell-Yan measured $\bar{u} < \bar{d}$ in the proton.
  - Pion cloud model explains best for the result







Hadronic structure in the proton ?

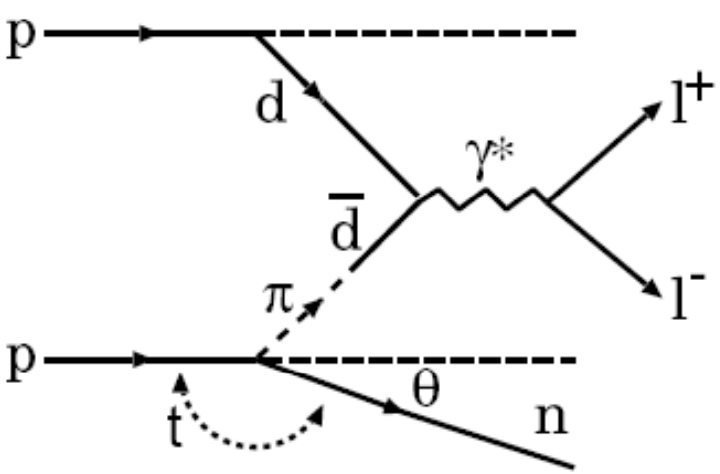
- Meson cloud model
  - Leading neutron cross section is also described by $p \rightarrow n\pi^+$ state. U. D'Alesioa & H.J. Pirner Eur. Phys. J. A 7, 109 (2000)
  - Pion exchange is key for these phenomena.
- Such hadronic structure is very interesting
  - It can explain nuclear force
  - Need to consider in proton spin component?
    - Cross section is not small component in pp scattering

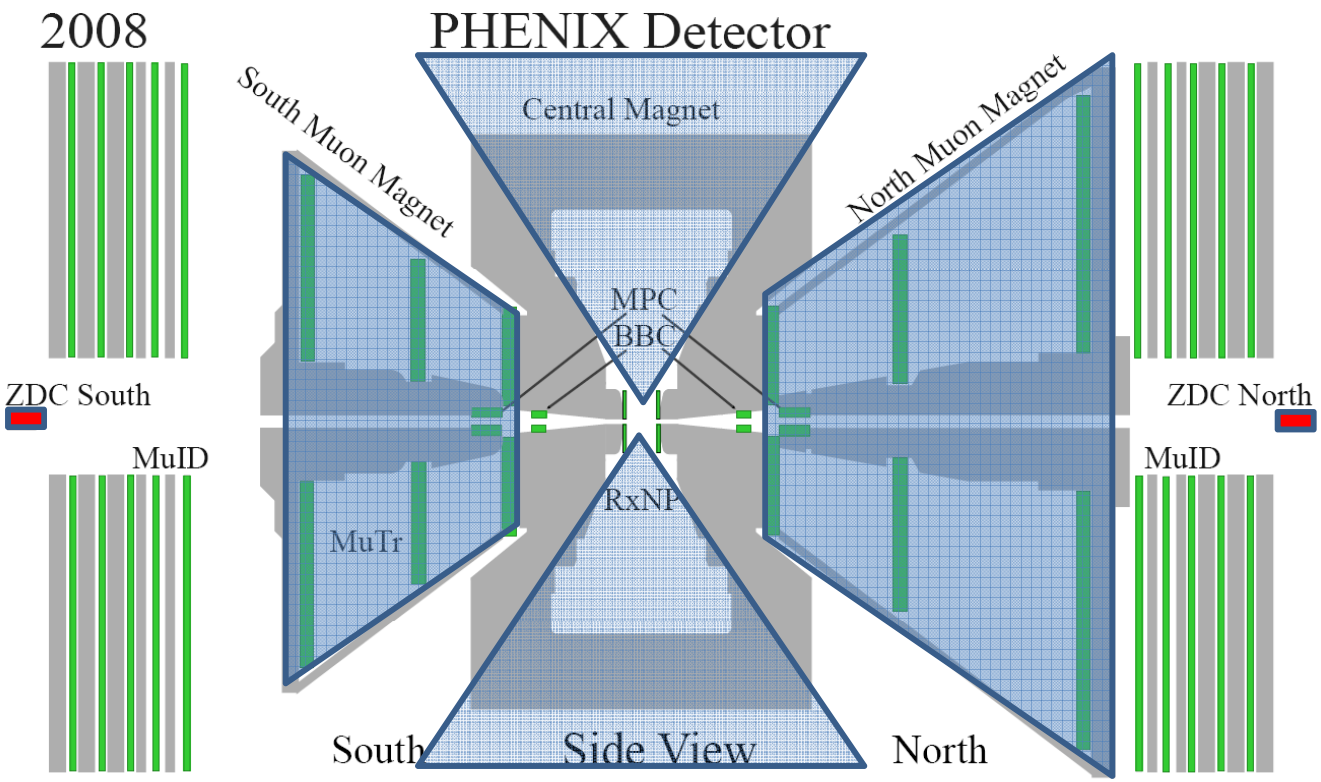
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + \Delta L$$

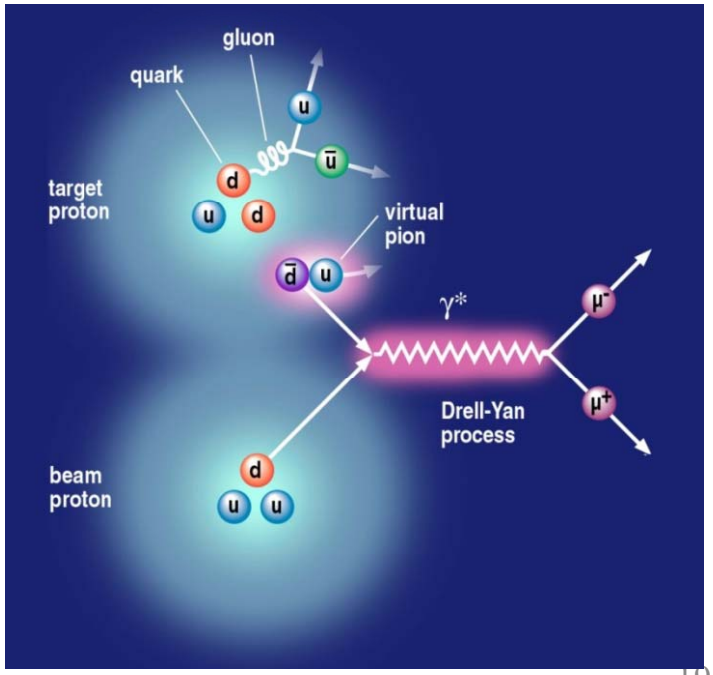
A.W. Schreiber & A.W. Thomas Phys.Lett.B215, 141 (1988)
F. Myhrer & A.W. Thomas hep-ph/0709.4067

Future measurement :
Neutron-tagged Drell-Yan measurement

- Does neutron tagging enhance these productions via quark annihilation?
  - Central arm : $0<|\eta|<0.35$ e-pair
  - Muon arm : $1.2<|\eta|<2.4$ μ-pair





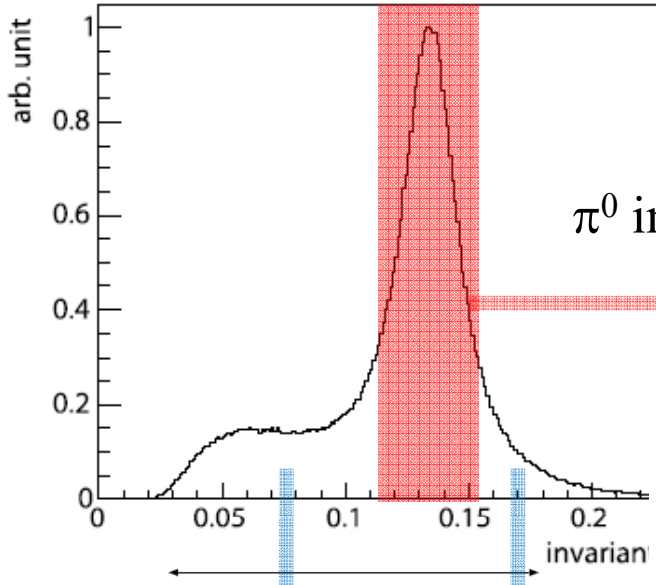


Summary

- We have measured leading neutron production in polarized p+p collisions at RHIC-PHENIX.
  - Cross section is consistent with the ISR result, No evidence for violation of x_F scaling. The OPE model can describe the result.
  - An effort is under way to explain the asymmetry with the same model.
- Future measurements
  - A_N measurements at various $\sqrt{s}$.
    - They will allow us to study of p_T dependence.
    - We also measured significant asymmetry at $\sqrt{s}$=62, 410 GeV and 500 GeV.
  - Semi-inclusive measurement
    - Drell-Yan production associated with leading neutron.

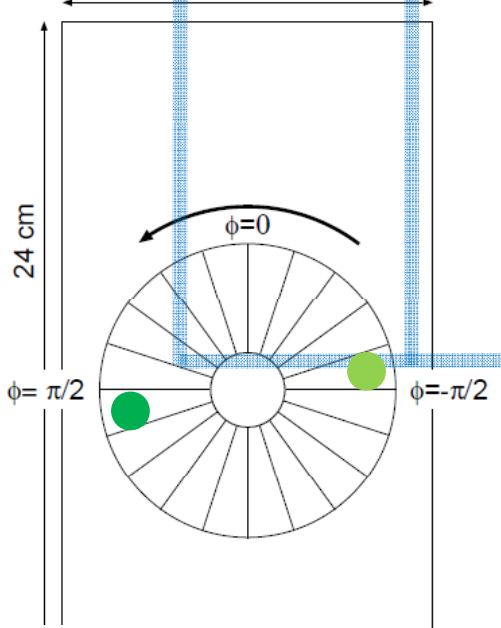
backup

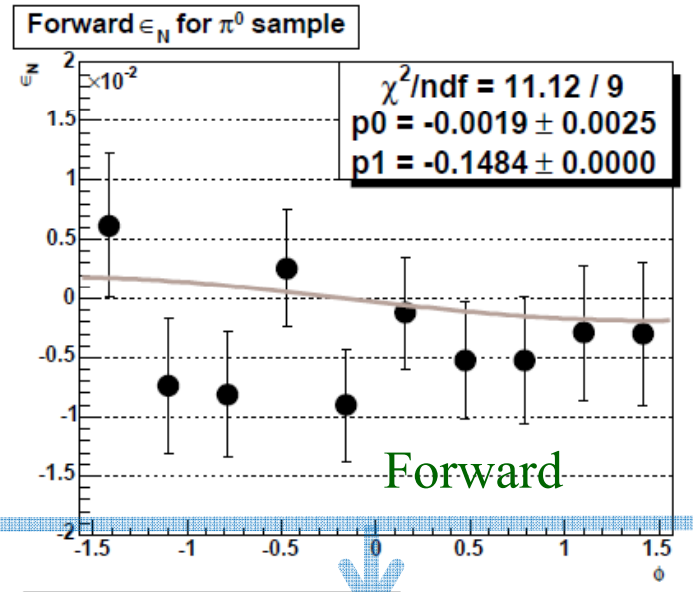
A_N for π^0 sample

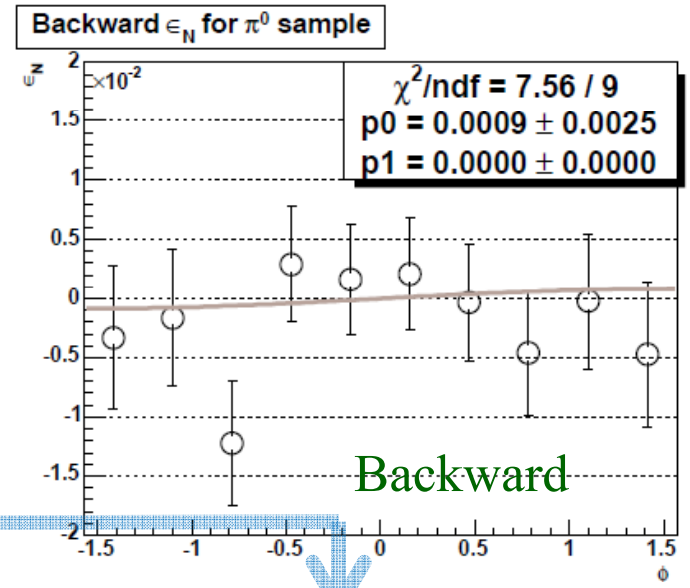


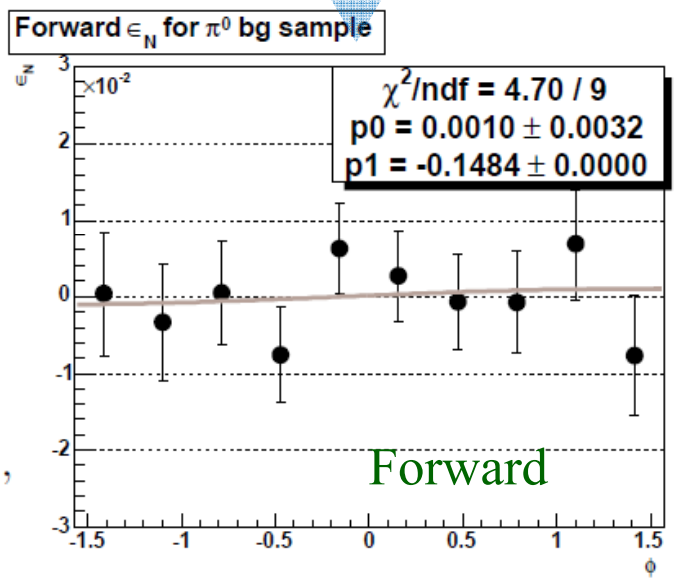
π^0 invariant mass

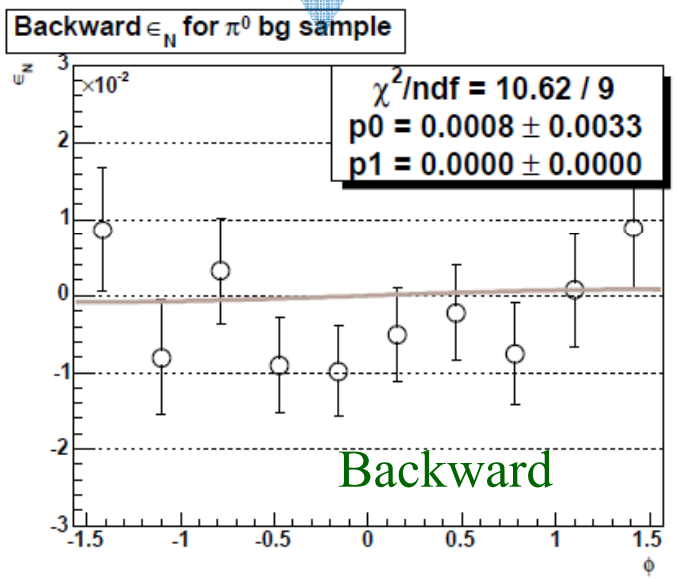
$r = N/(S+N) = 21 \pm 3\%$











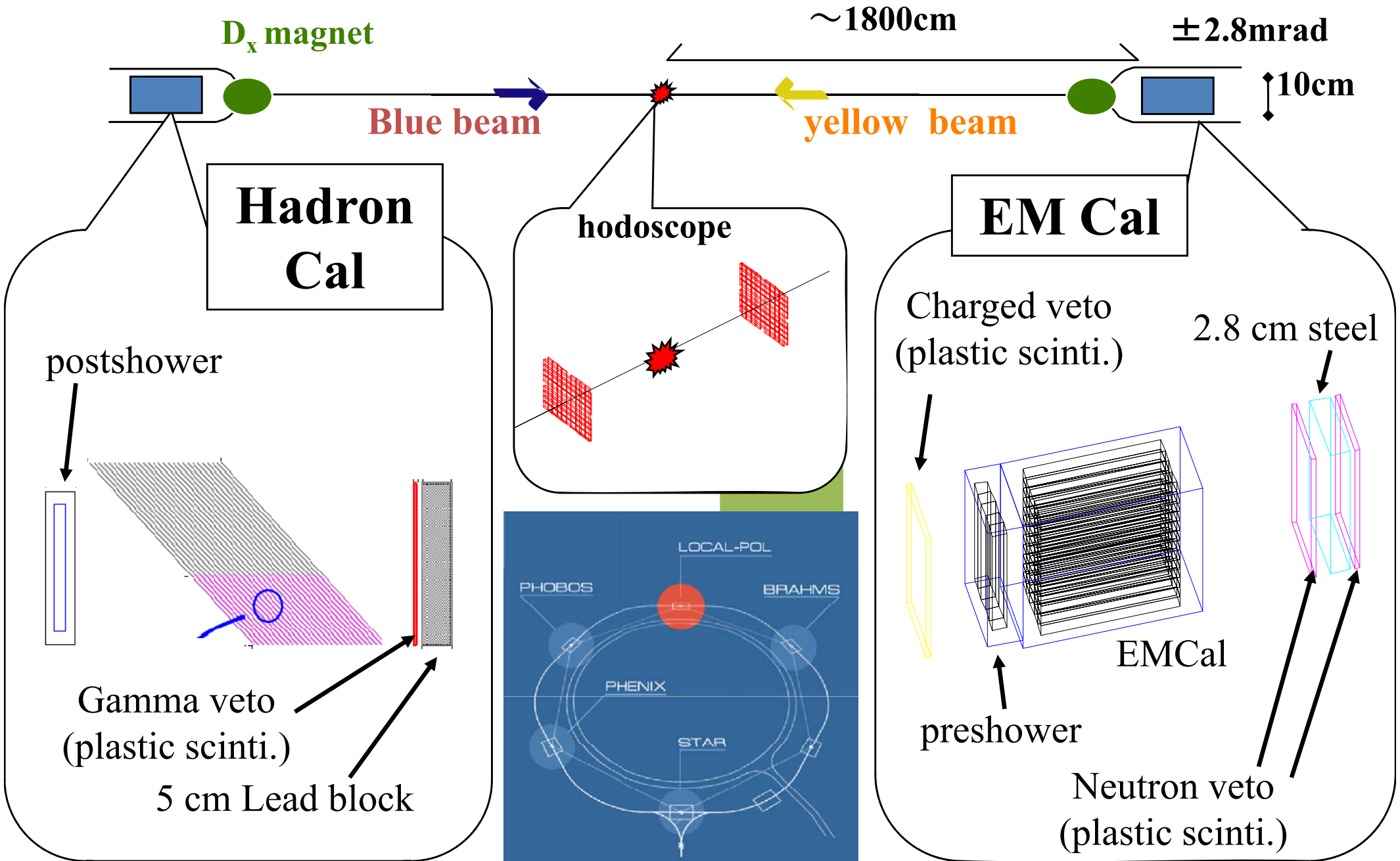
$$A_N^{\pi^0} = \frac{A_N^{\pi^0+bg} - rA_N^{bg}}{1-r},$$

$$\delta A_N^{\pi^0} = \frac{\sqrt{(\delta A_N^{\pi^0+bg})^2 + r^2(\delta A_N^{bg})^2}}{1-r},$$

Blue

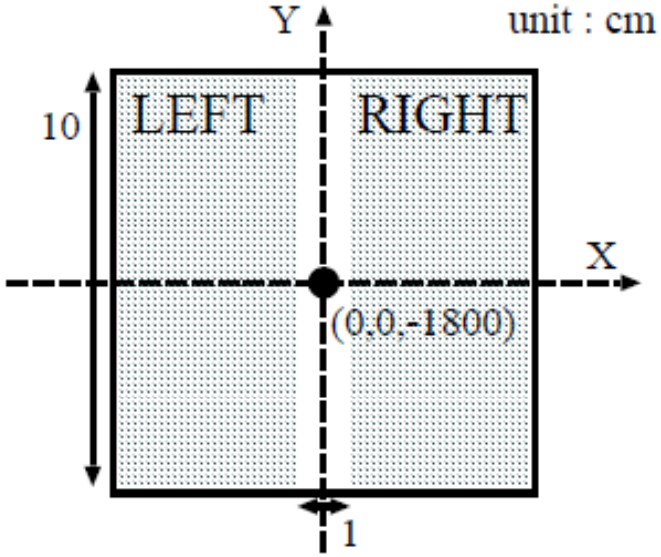
IP12 experiment (Hadron Cal)

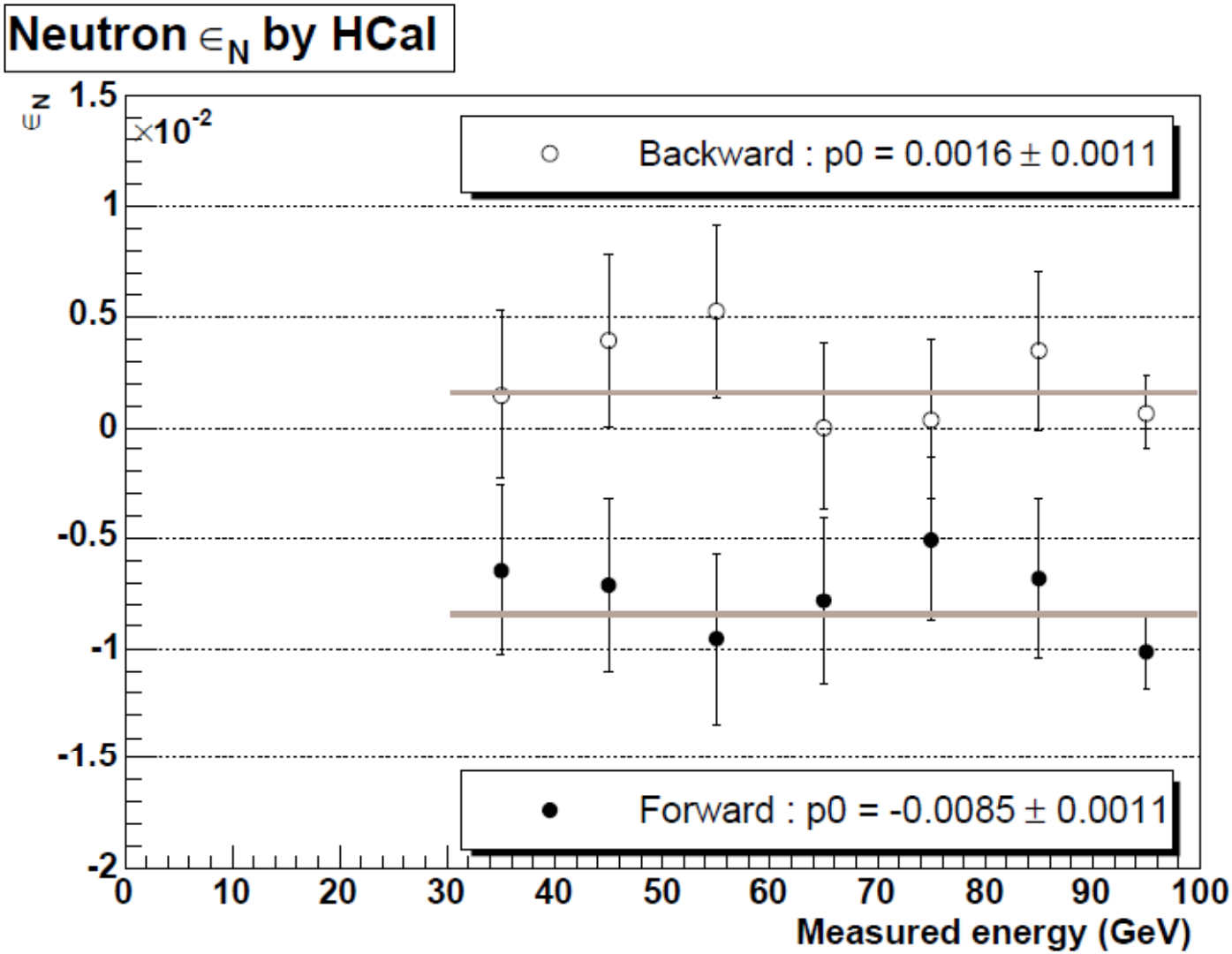
Polarized pp collision at √s=200 GeV



Hadron Cal-based result

Left-Right definition

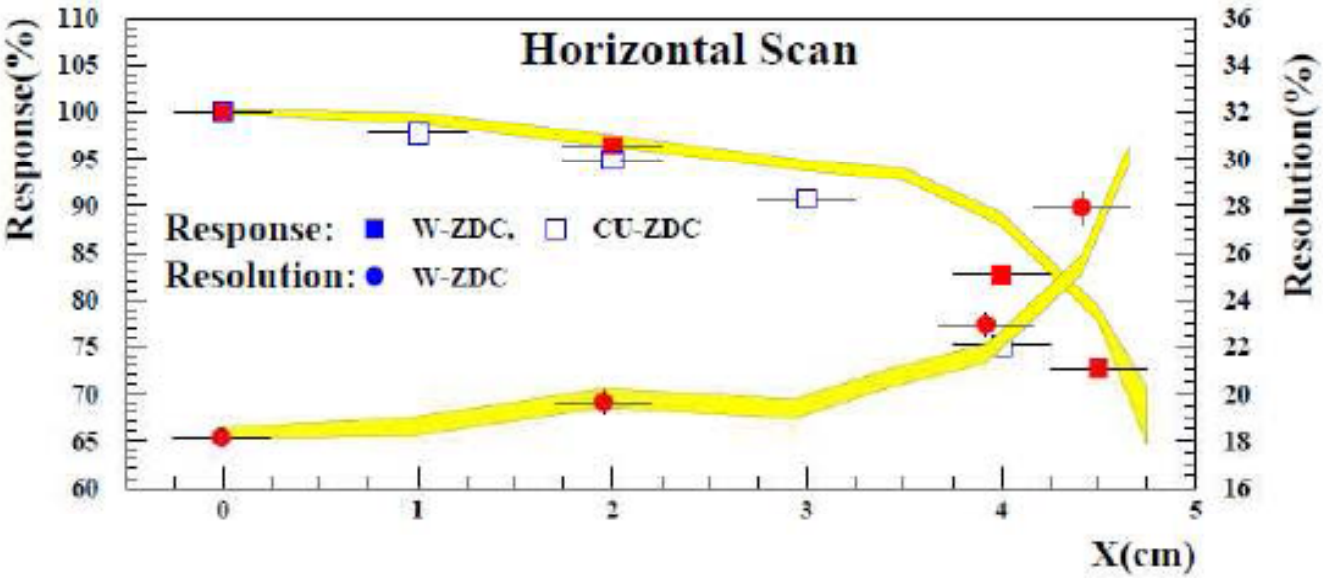


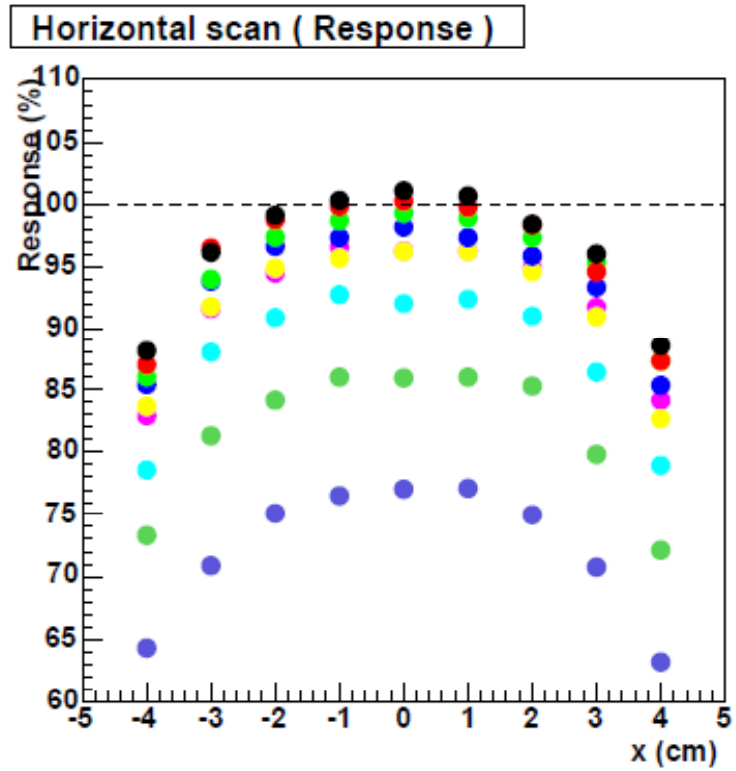


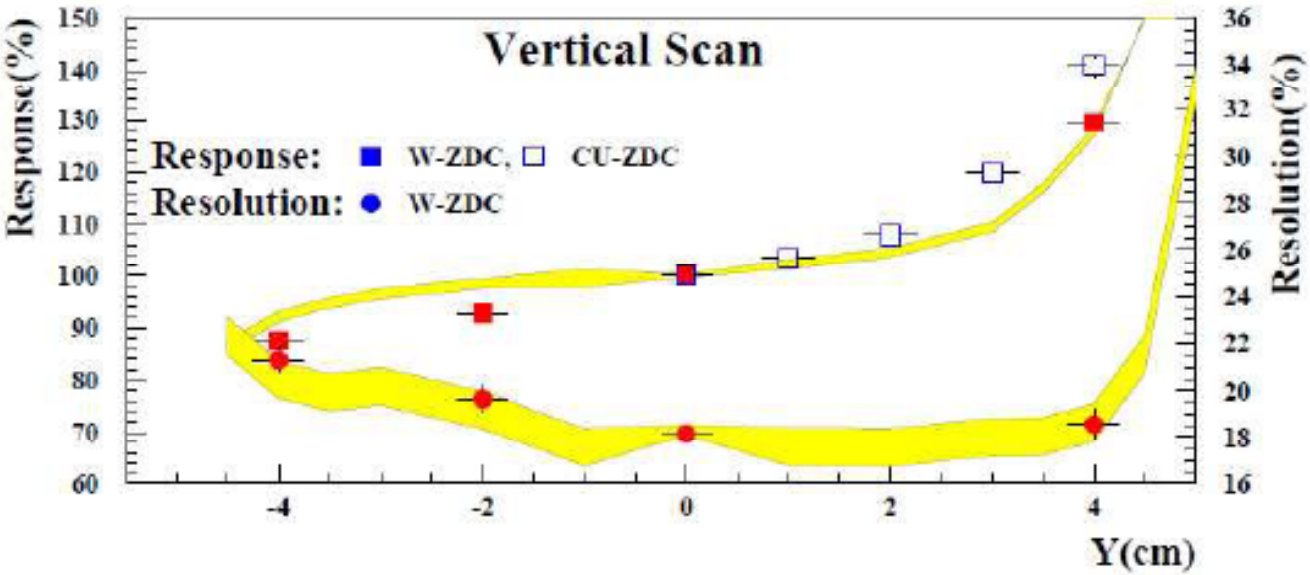
Same results.

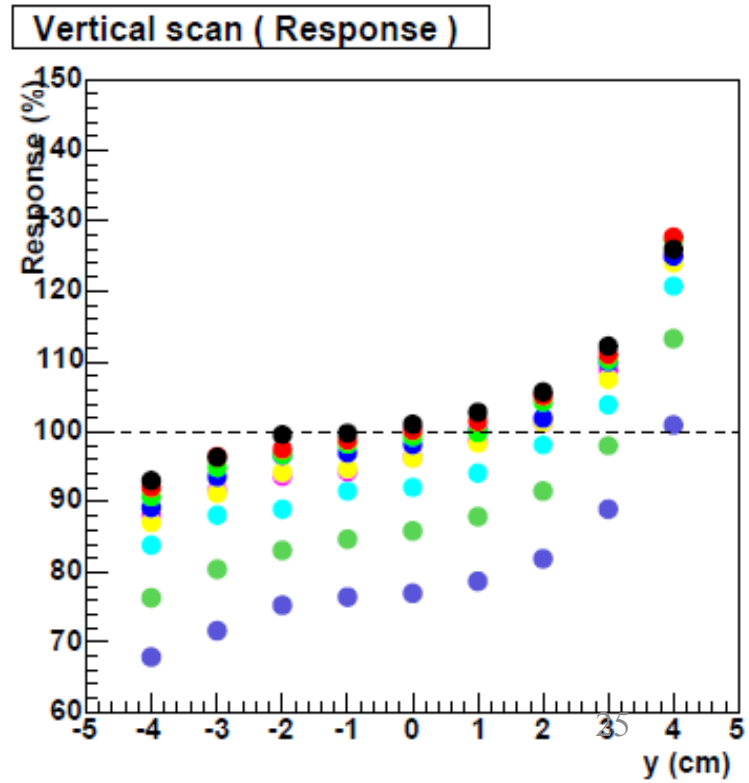
Finite asymmetry can be seen in forward

Edge effect


Horizontal Scan
Response(%)
Resolution(%)
Response: W-ZDC, CU-ZDC
Resolution: W-ZDC
X(cm)


Horizontal scan (Response)
Response (%)
x (cm)

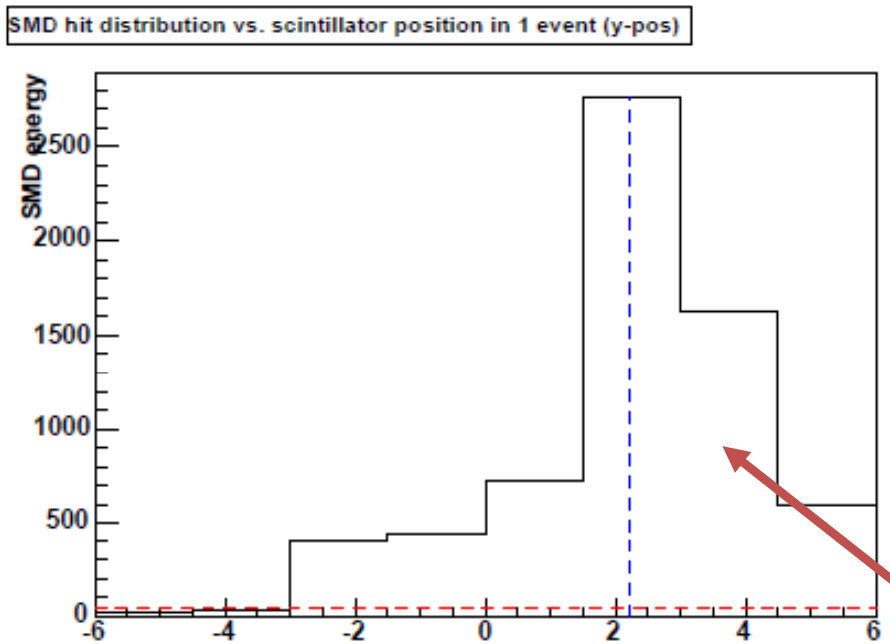

Vertical Scan
Response(%)
Resolution(%)
Response: W-ZDC, CU-ZDC
Resolution: W-ZDC
Y(cm)


Vertical scan (Response)
Response (%)
y (cm)

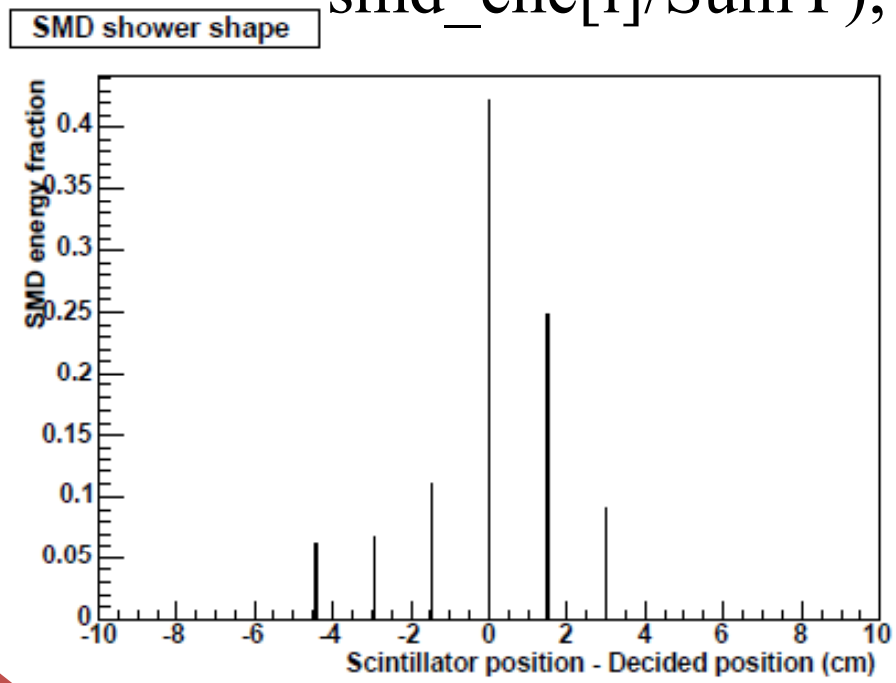
Shower Shape study

- Shower shape

Fill(scinti.pos[i] – ypos, smd_ene[i]/SumY);



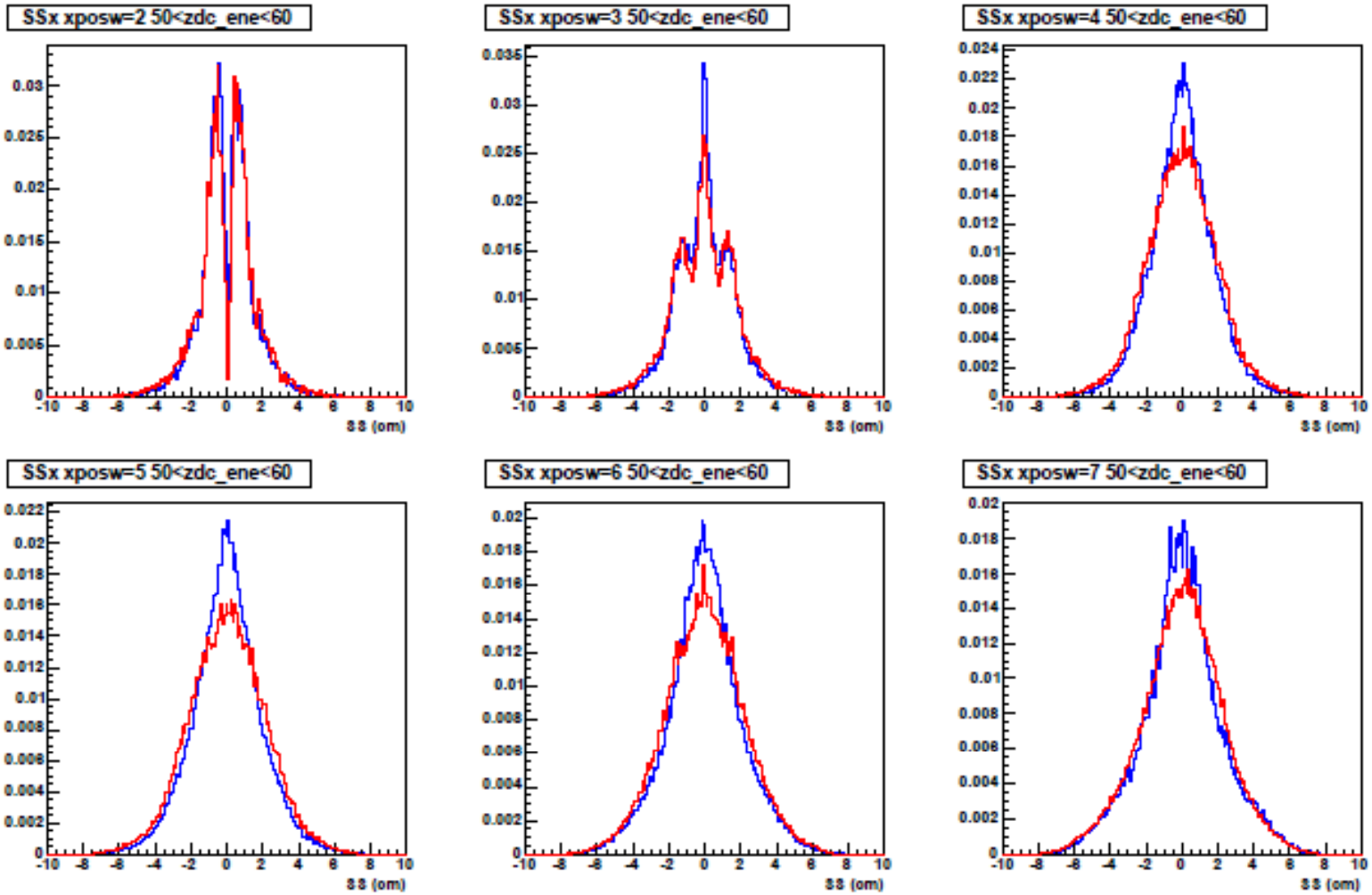
Sincitllator position



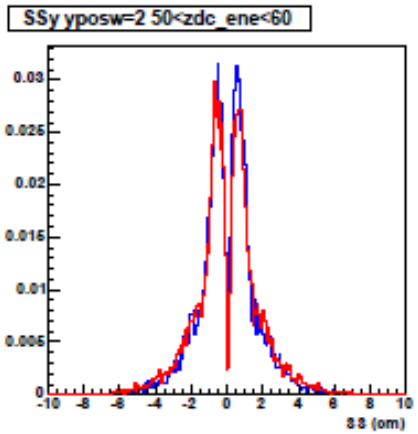
Position decided by centroid method

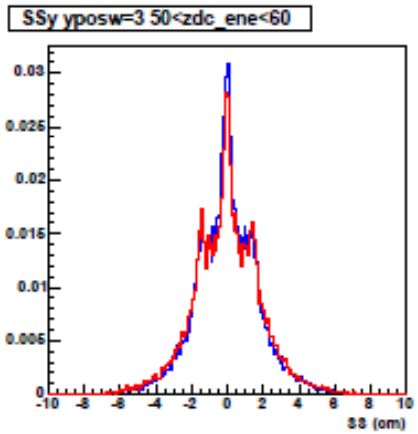
  - Looking by each energy and N of scintillator hits.
- PF (peak fraction)
  - Defined as smd_ene[peak] /Sumy

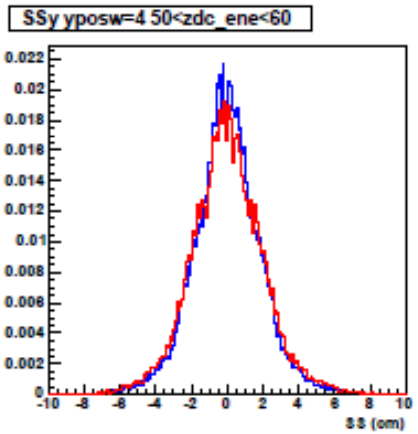
Shower Shape for x

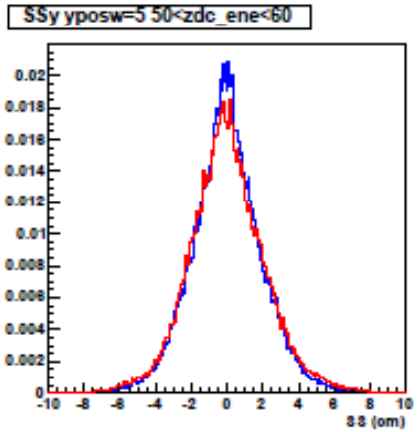


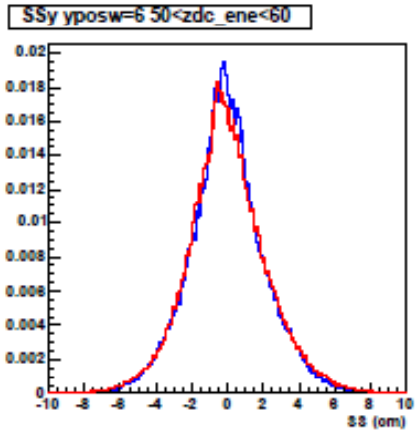
Shower Shape for y

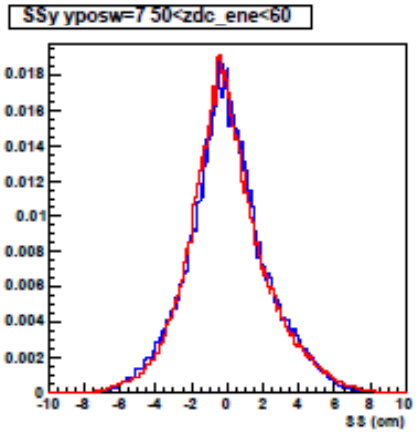


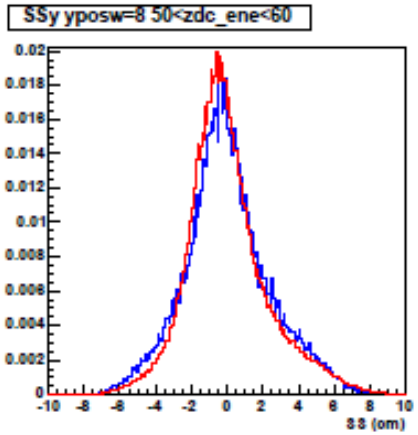








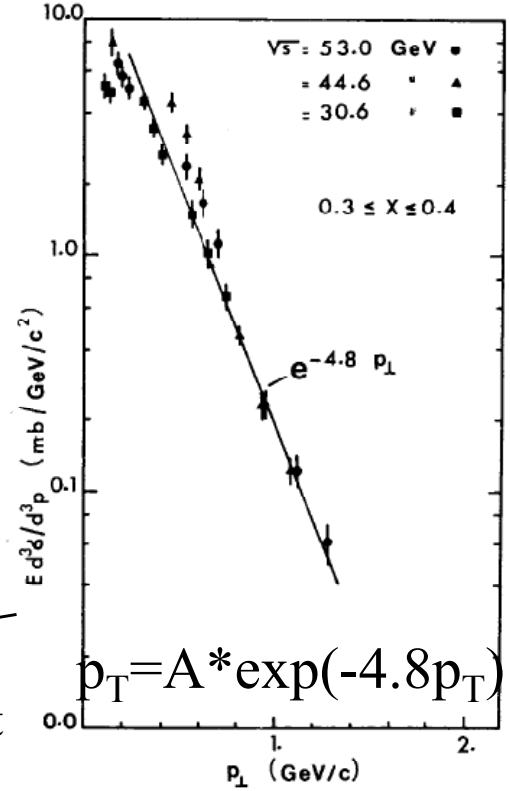




Cross section calculation

- The total cross section with PHENIX neutron cut. is estimated.
  - p_T is not evaluated from our data. As simulation input, ISR result is assumed.
  - In this analysis, radius<2cm from the collision point (1800cm) is calculated.
    1.1 mrad : $0<p_T<0.11x_F$ GeV/c。

Input p_T shape



p_T=A*exp(-4.8p_T)

Assumed

Simulation input

PHENIX data.

$$\frac{d\sigma}{dx_F} = \left(\frac{N_{neutron}}{Lumi}\right)\left(\frac{1}{dx_F}\right)$$

comparing

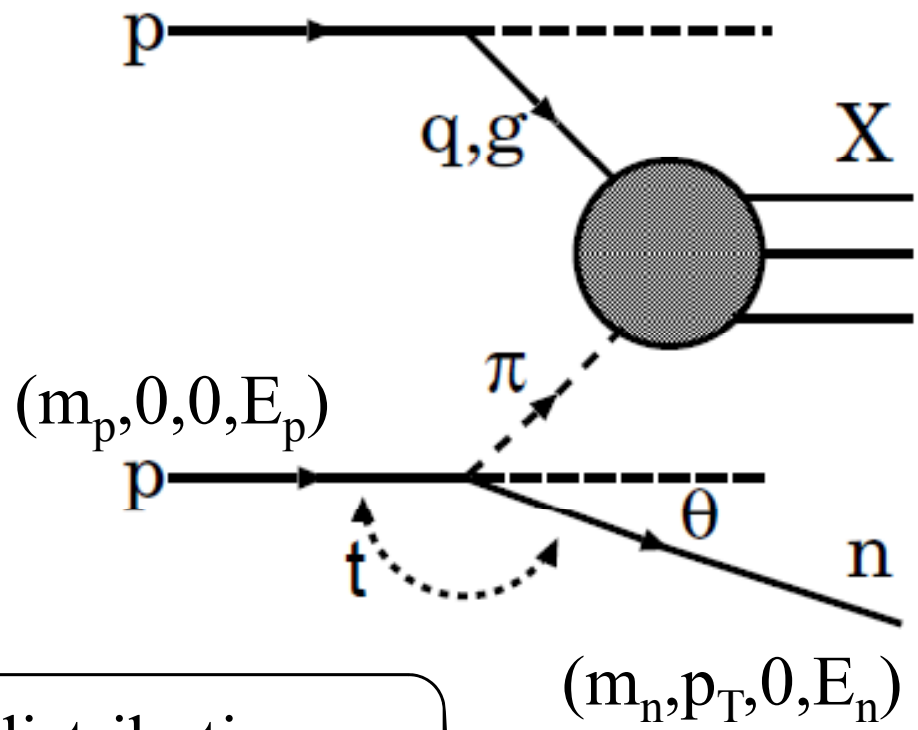
ISR data is converted to current cut. ($0<p_T<0.11x_F$ GeV/c)

$$E\frac{d^3\sigma}{d^3p} = d\sigma\left(\frac{1}{2\pi}\right)\left(\frac{x_F}{dx_F}\right)\left(\frac{1}{p_T}\right)\left(\frac{1}{dp_T}\right) \rightarrow \frac{d\sigma}{dx_F} = (2\pi)\left(\frac{1}{x_F}\right)\int_{Acc.} E\frac{d^3\sigma}{d^3p}p_T dp_T$$

t-range

$$x_F = \frac{E_n}{E_p}$$

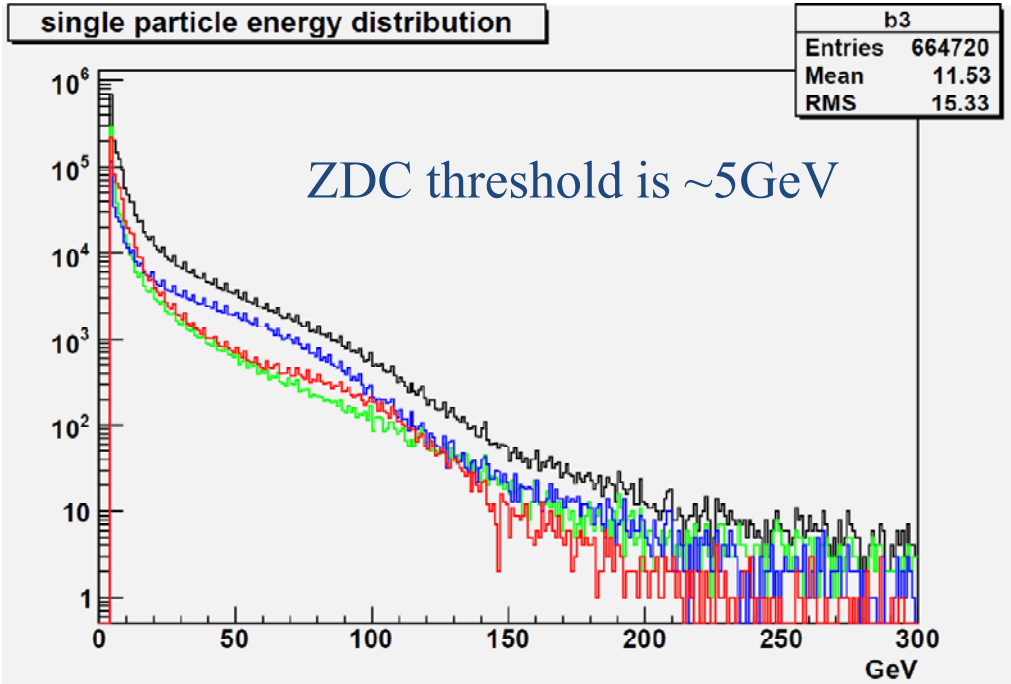
$$t \sim -\frac{p_T^2}{x_F} - \frac{1-x_F}{x_F}\left(m_n^2 - x_F m_p^2\right)$$

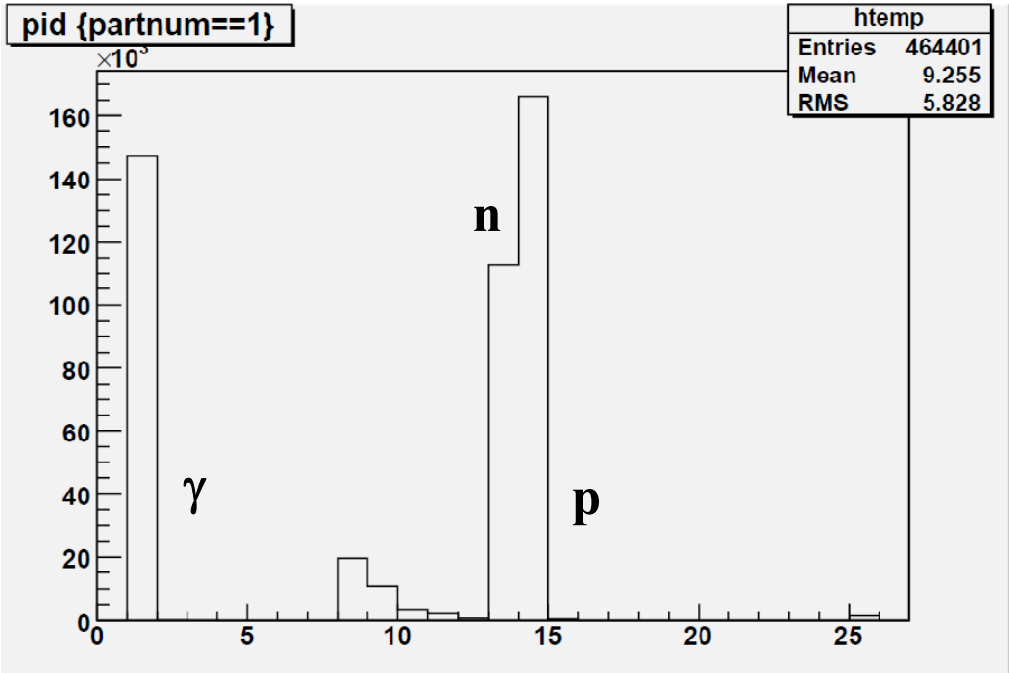


ISR p_T distribution is assuming.

x_F	$\langle p_T \rangle$ (GeV/c)	t (GeV^2)
0.4~0.6	0.088	-0.458
0.6~0.8	0.118	-0.134
0.8~1.0	0.144	-0.033

nID study using pythia input.





Black : sum
Green : gamma
Blue : neutron
Red : proton

pid		pid	
1	Gamma	10	K0 long
2	Positron	11	K+
3	Electron	12	K-
5	Mu+	13	Neutron
6	Mu-	14	Proton
8	Pi+	15	Antiproton
9	Pi-	25	Antineutron

Correction of BG (estimation)

- With SMD cut and center cut (r<0.5), BG are mainly K0 and proton
  - From ISR paper,

The K^0 background, which was subtracted, was assumed to be the average of $K^{\pm}$ production [10]. This background amounts to about 10% at $x = 0.2$ and less than 4% for $x > 0.4$.

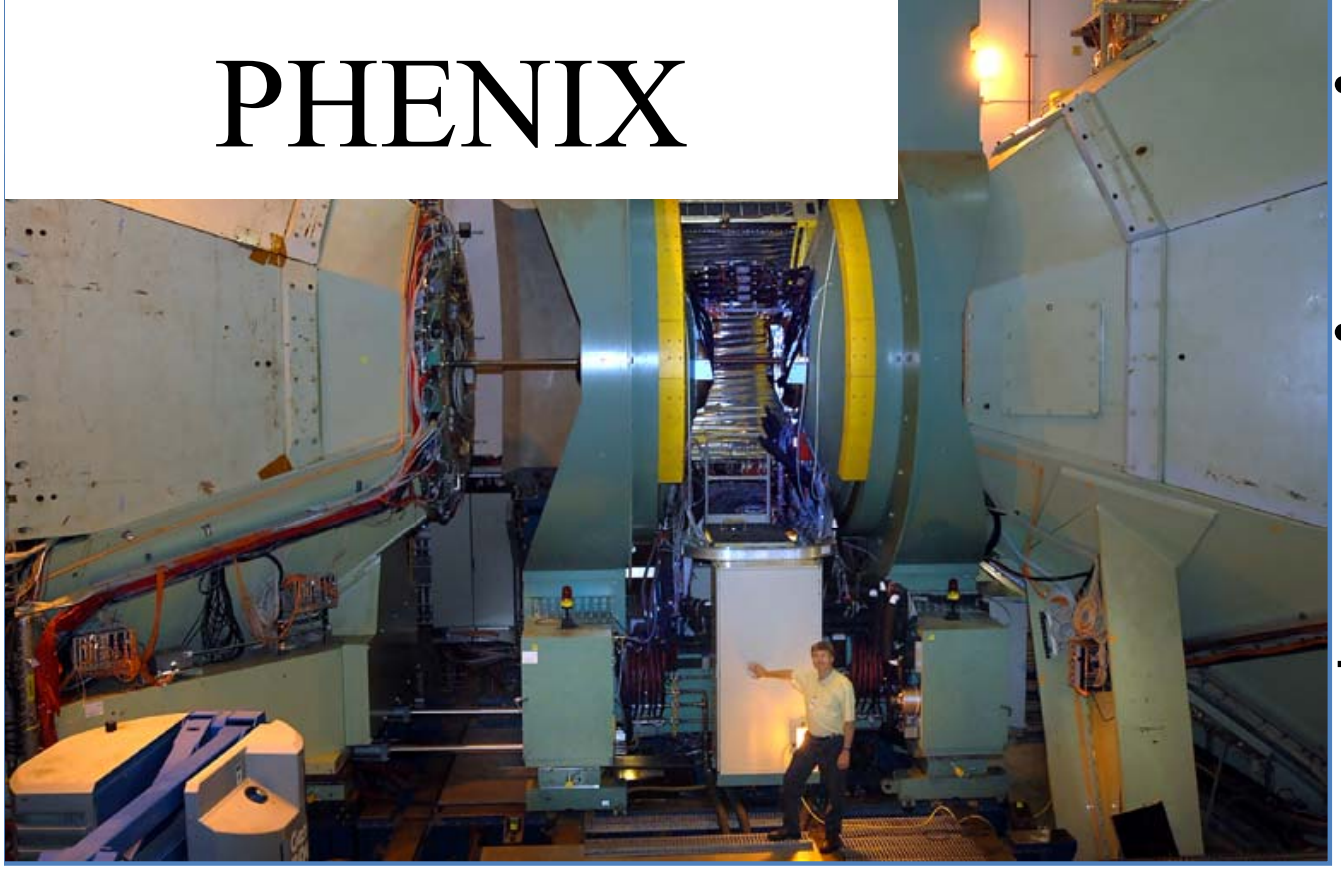
Pythia out.

E (GeV)	K0 (%)	Proton (%)
10-20	16.67	11.11
20-30	5.97	2.99
30-40	4.69	2.34
40-50	1.75	3.59
50-60	1.78	4.14
60-70	1.50	5.00
70-80	1.18	1.76
80-90	0	2.14
90-100	0	9.71

Pythia out is agree K0 ration with ISR data. I used BG distribution after cut from the pythia.

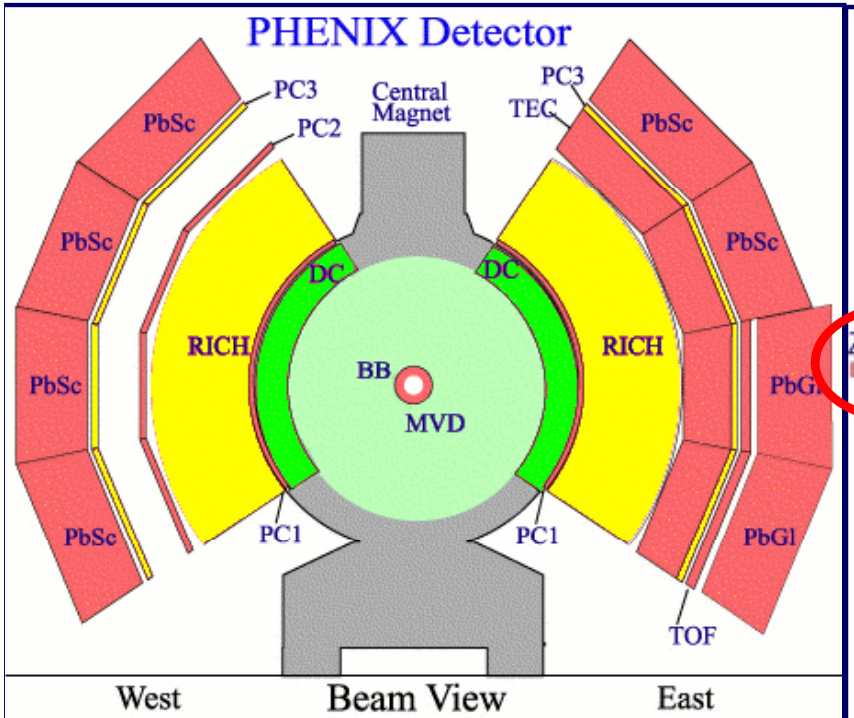
Error will be added 100% of this value

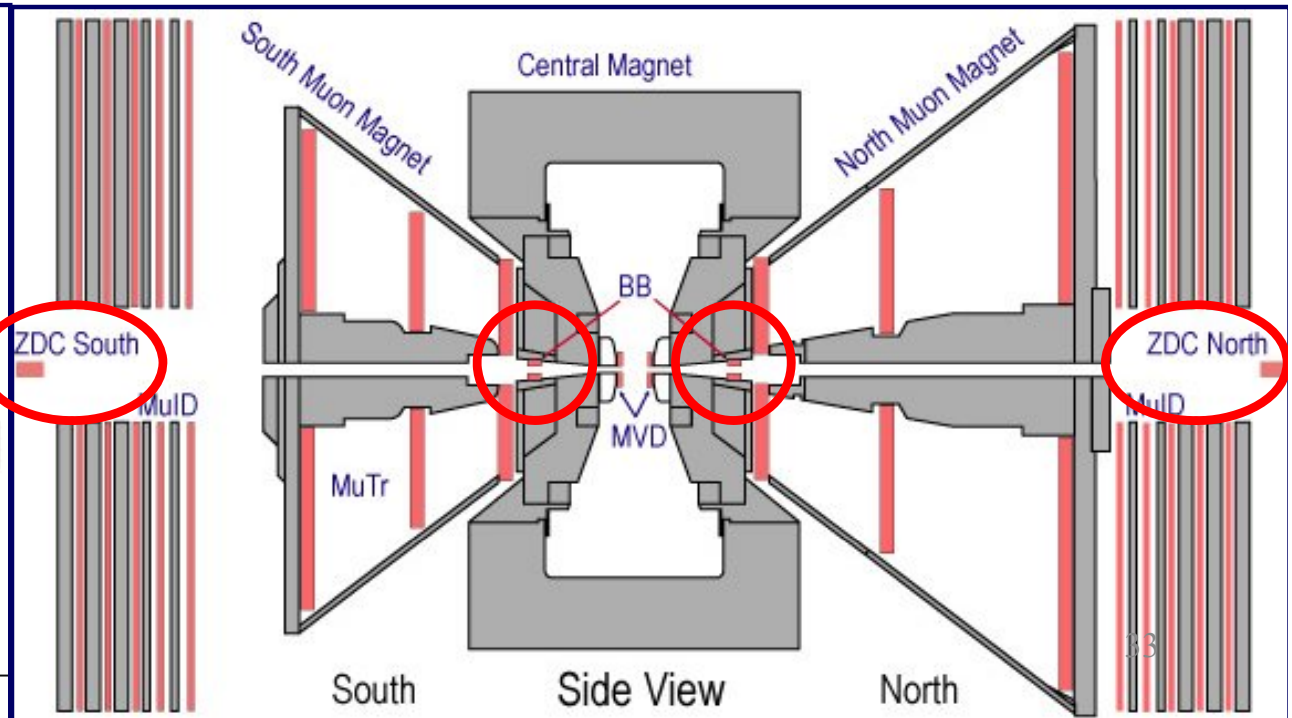
PHENIX



- Central Arms
  - $|\eta| < 0.35$, $\Delta\phi \sim \pi$
  - γ, π^0, e, π^{+-} - identified
- Muon Arms
  - $1.2 < |\eta| < 2.4$
  - μ – identified

→ Polarized gluon structure function is studied for spin physics.





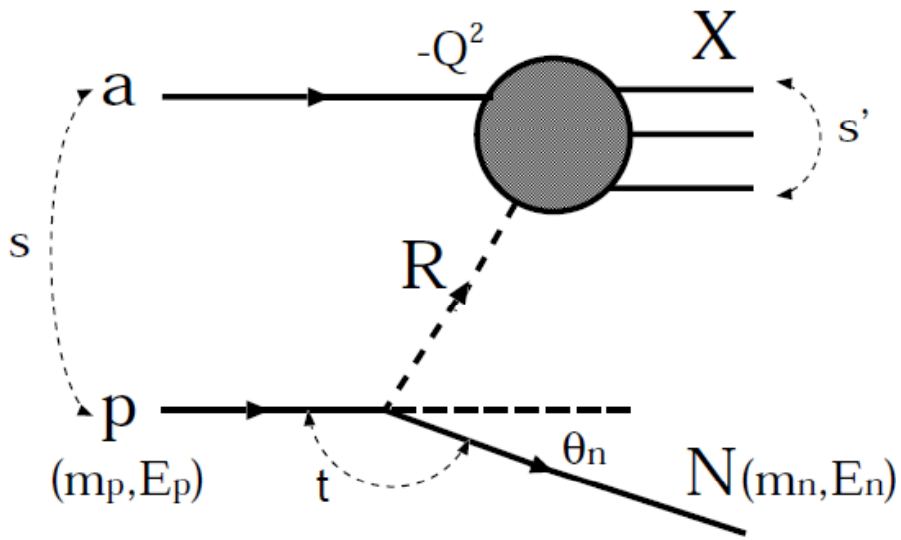
EMCal spec. for π^0 measurment

Central ARM

$$\Delta E = \frac{8.1}{\sqrt{E}} + 2.4(\%)$$

$$\Delta x = \frac{5.9}{\sqrt{E}} + 1.4(mm)$$

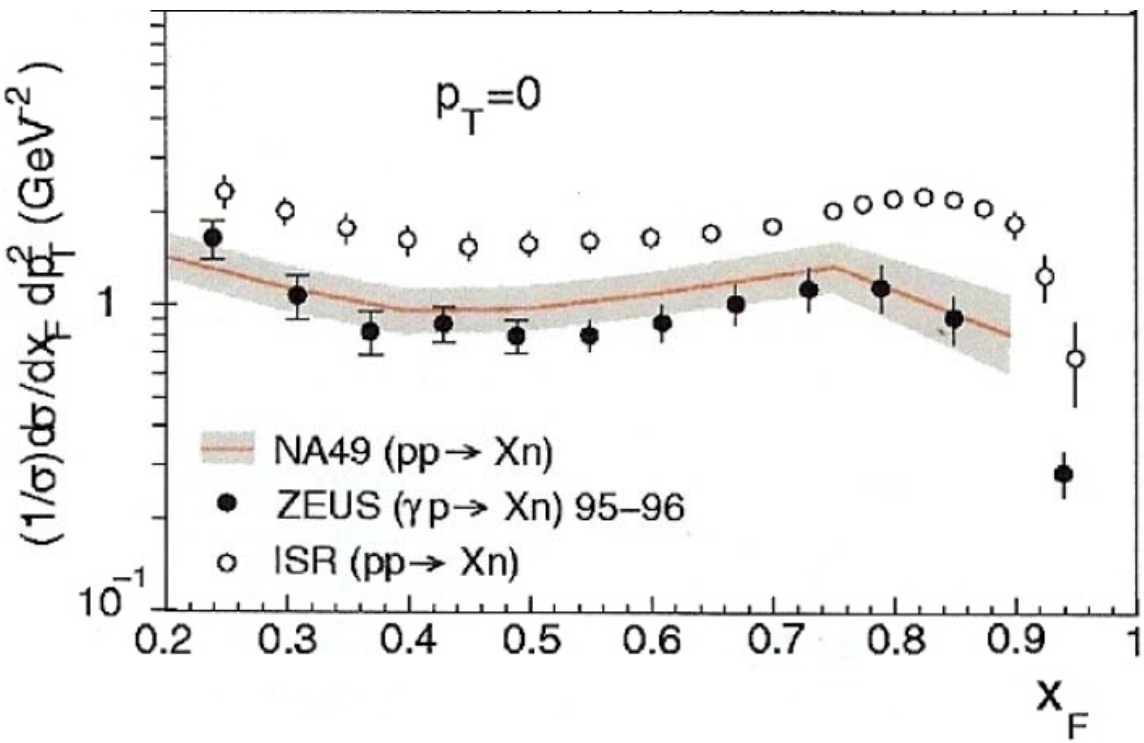
Comparison with HERA??



Regge factorization.

$$\left.\frac{d^3\sigma_{ap}\to nX}{dx_F dp_T^2}\right|_{\pi} = f_{\pi/p}(x_F,t)\cdot\sigma_{total}^{a\pi}(s')$$

$$\frac{1}{\sigma_{tot}^{\gamma p}}\frac{d^2\sigma^{\gamma p\to Xn}(x_L,p_T^2)}{dx_L\,dp_T^2} = \frac{1}{\sigma_{tot}^{pp}}\frac{d^2\sigma^{pp\to Xn}(x_L,p_T^2)}{dx_L\,dp_T^2}.$$

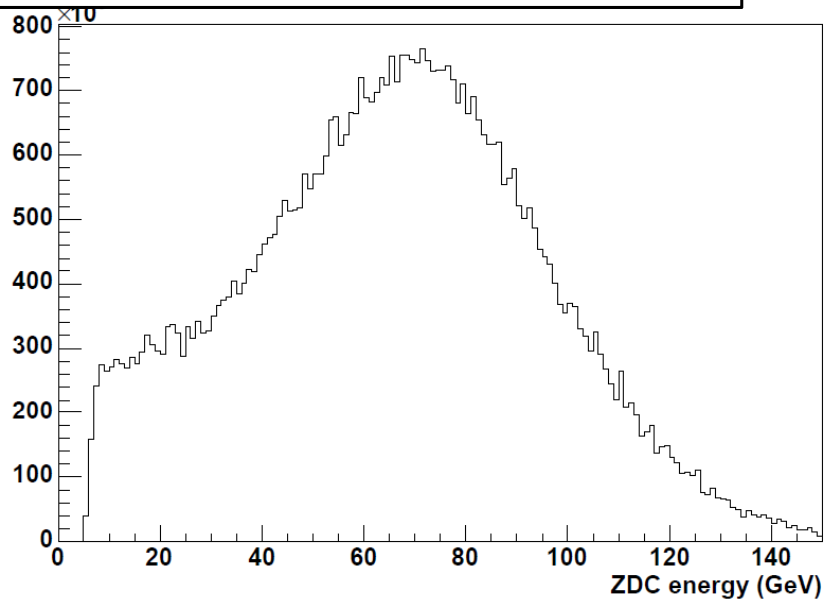


NA49 : pp Ep=158 G e V, √s~18 GeV

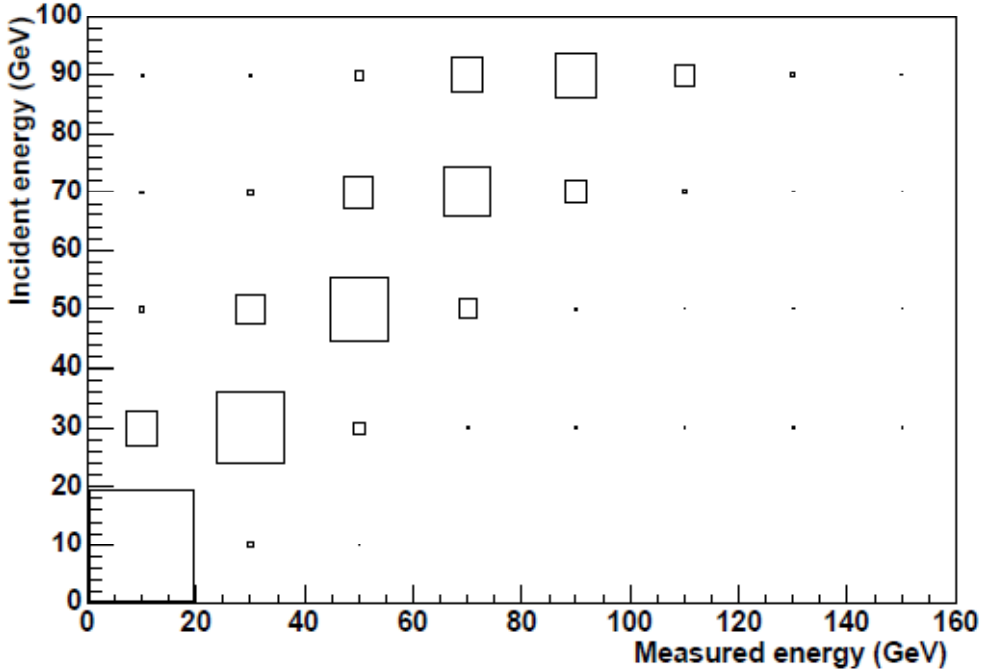
Eur.Phys.J.C33:S515-S517,2004.

Energy unfolding

Measured Energy distribution : y



x vs. y estimated by simulation → $\mathcal{A}$



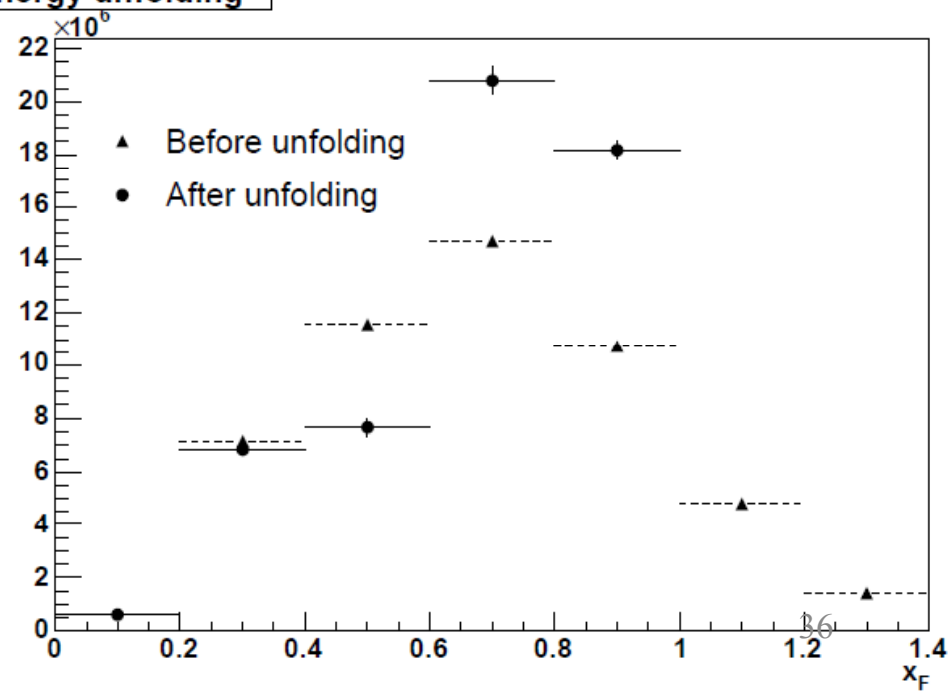
x : Initial energy distribution

y : Measured energy distribution

$$y(E') = A(E', E)x(E).$$

$$\vec{x} = A^{-1}\vec{y}, \qquad V_x = A^{-1}V_y(A^{-1})^T,$$

Energy unfolding



-Eenrgy resolution@100 GeV is 20%

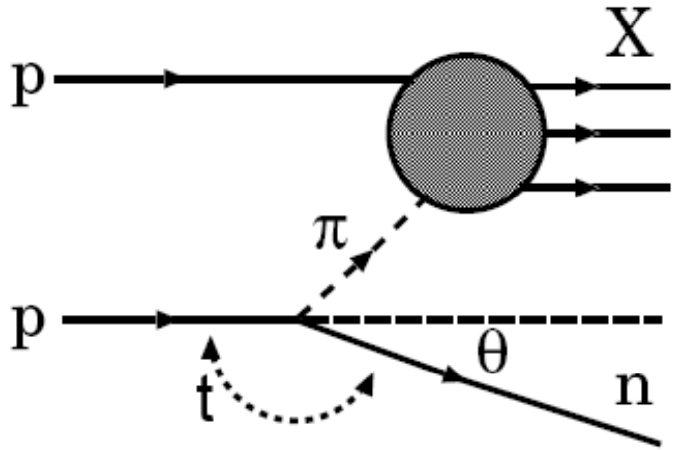
→ Bin width is selected as 20 GeV.

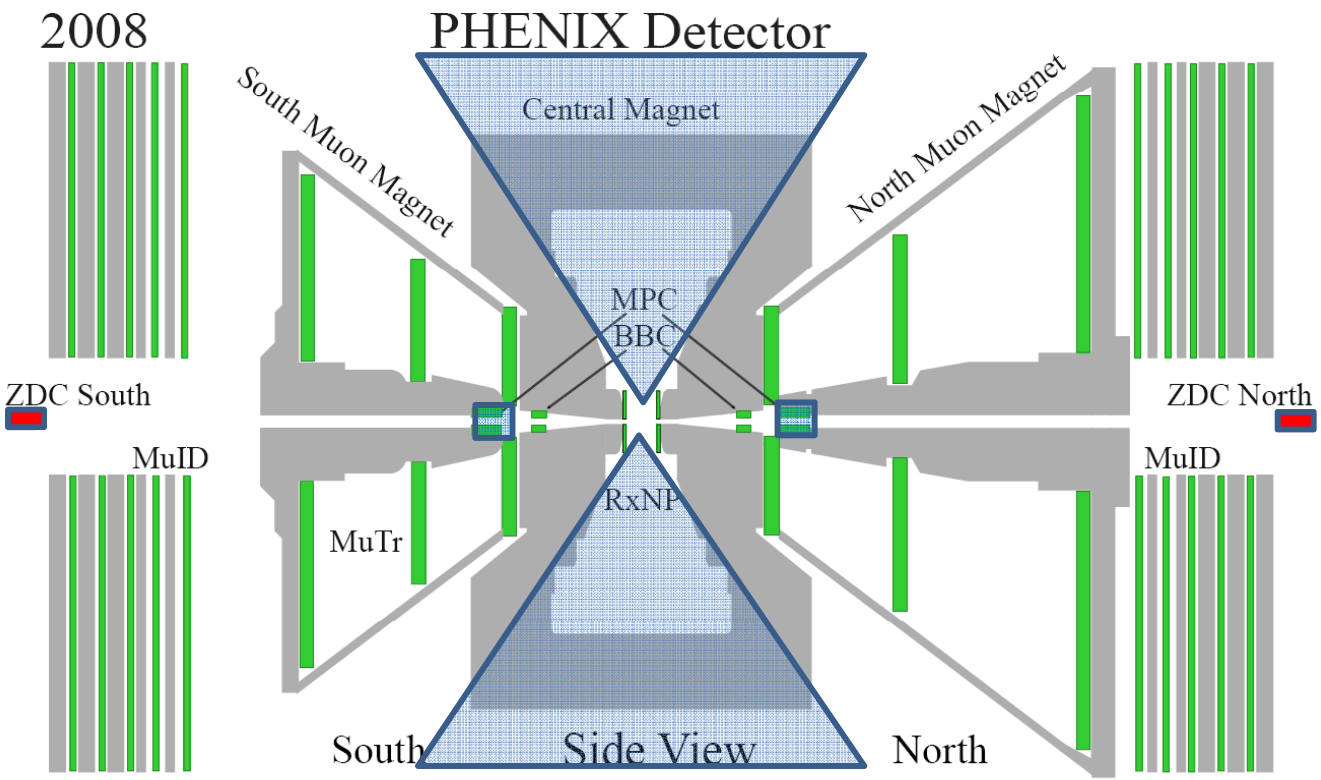
-x_F<0.4 region affects the enegy cut, >20 GeV.

→ Use 3 bins above x_F=0.4.

Future measurement : Neutron-tagged π^0 measurements

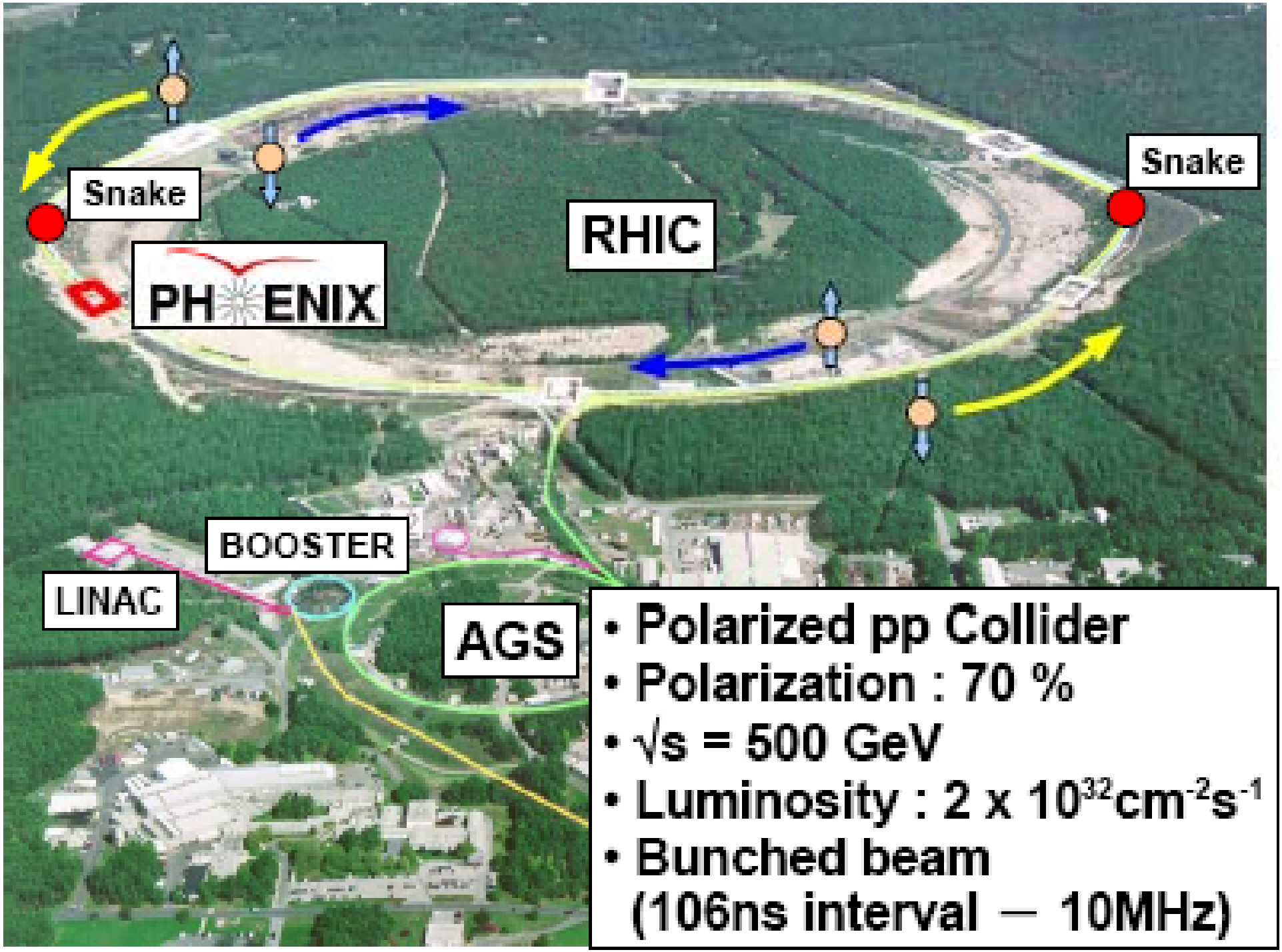
- PHENIX is capable to measure π^0 precisely.
  - Central arm : $0<|\eta|<0.35$
  - Muon Piston Calorimeter (MPC) : $3.1<|\eta|<3.7$
    - Almost same as BBC acceptance.





These data are already corrected.
The results will be available in the near future.

RHIC



- Polarized pp Collider
- Polarization : 70 %
- $\sqrt{s}$ = 500 GeV
- Luminosity : 2 x 10^{32} $cm^{-2}s^{-1}$
- Bunched beam
  (106ns interval – 10MHz)