Measurement of the cross section and the single transverse spin asymmetry in very forward neutron production from polarized *pp* collisions at RHIC

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for the PHENIX collaboration.

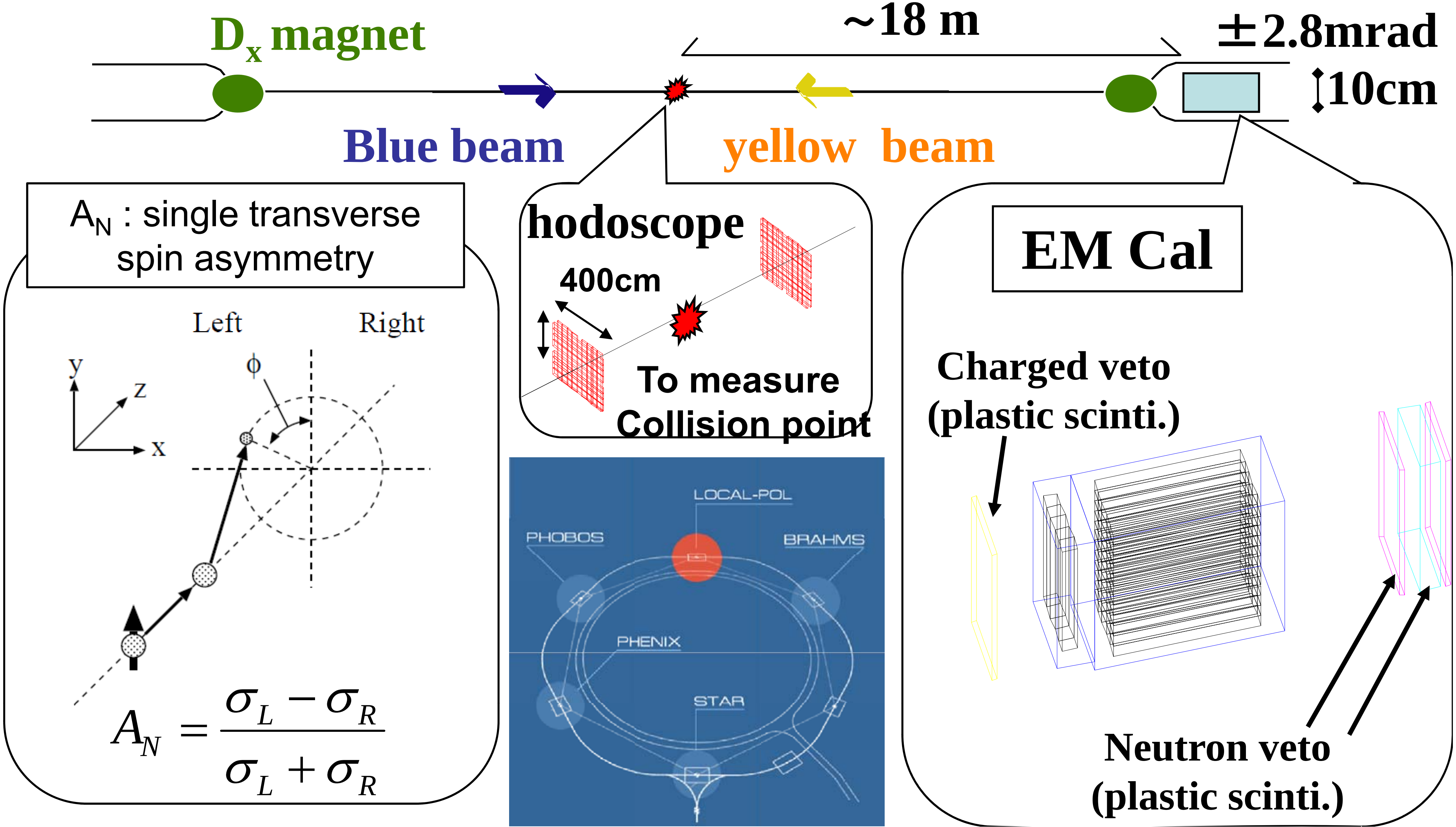
RIKEN Nishina Center / RBRC
Special Postdoctoral Researcher

Outline

- Physics motivation
- Measurement of forward neutron at PHENIX
  - Experimental setup
  - Analysis procedure
- Result of the cross section
  - Very forward case
- Results of the single transverse spin asymmetry
  - ϕ and x_F-dependence
  - Comparing tagged w/ or w/o charged particles
- Charged particles tagged with forward neutron
- Summary

Motivation 1 : Discovery of large A_N in forward neutron production at RHIC.

Polarized pp **collision in sqrt(s) = 200GeV : IP12 Collision Point**



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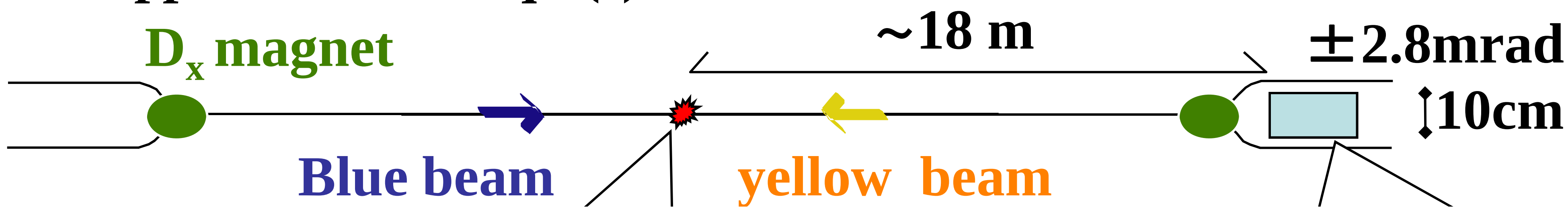
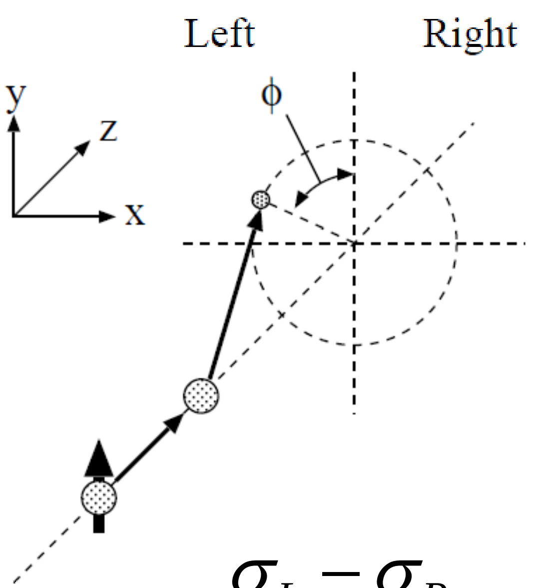
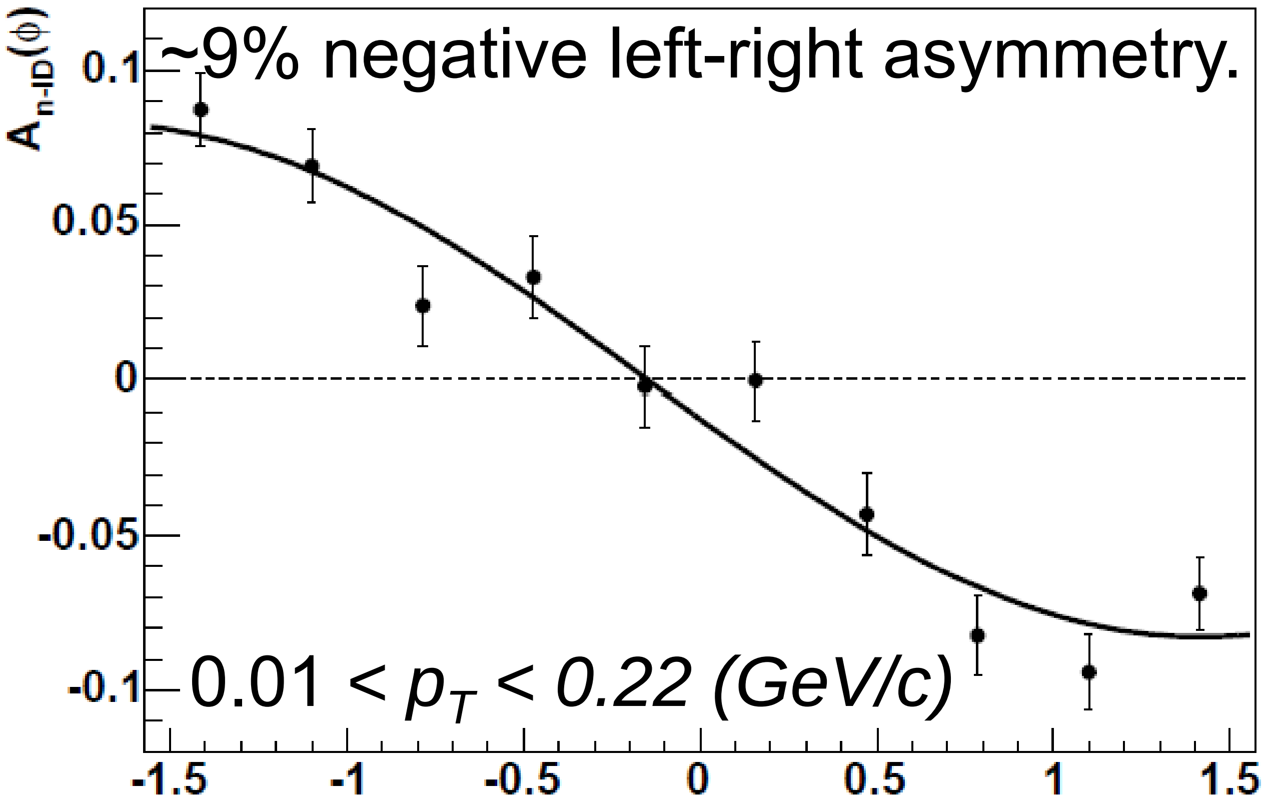


A_N : single transverse spin asymmetry



$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$



Submitted to PLB : hep-ex/0610030

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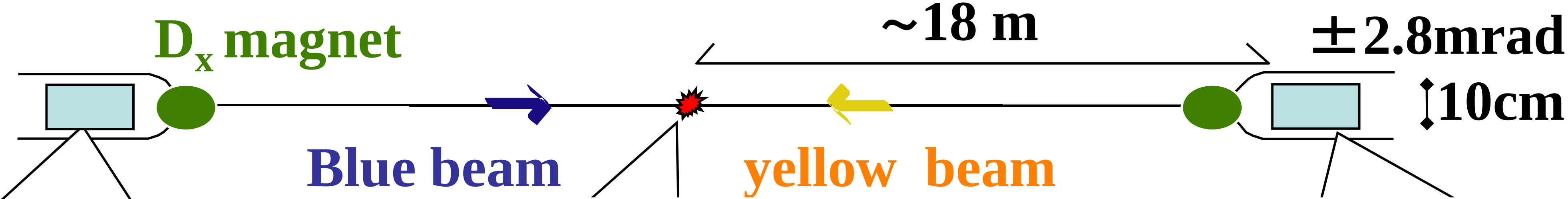

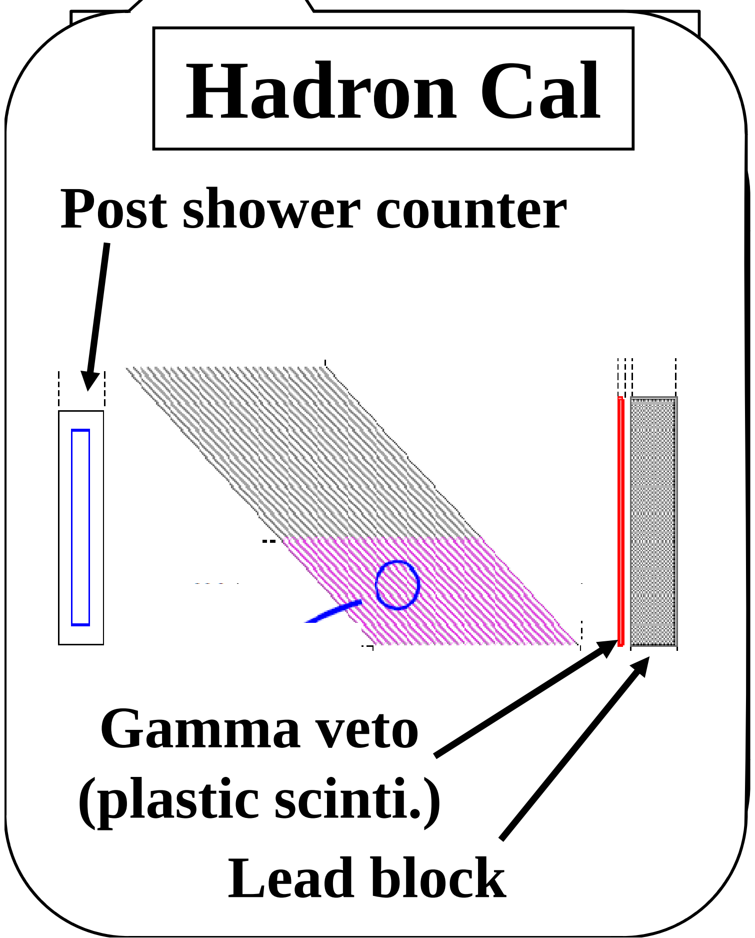

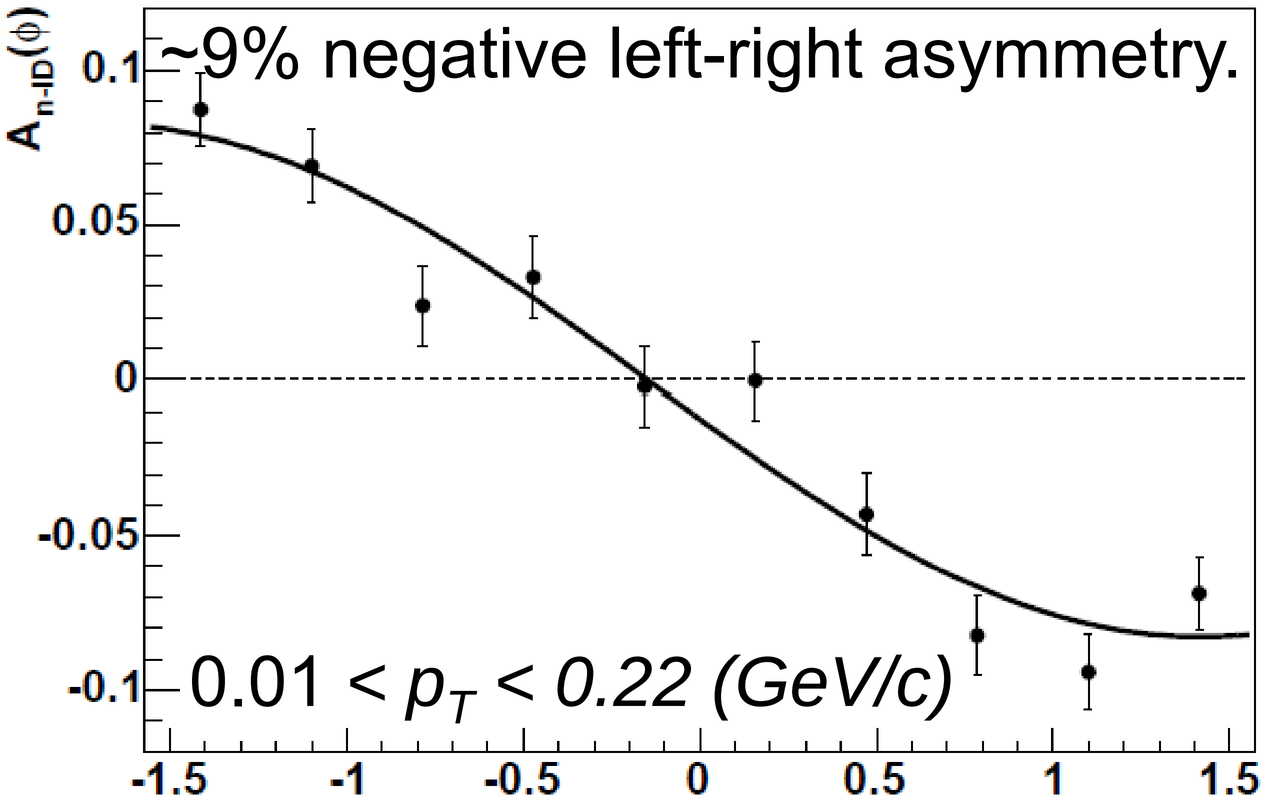

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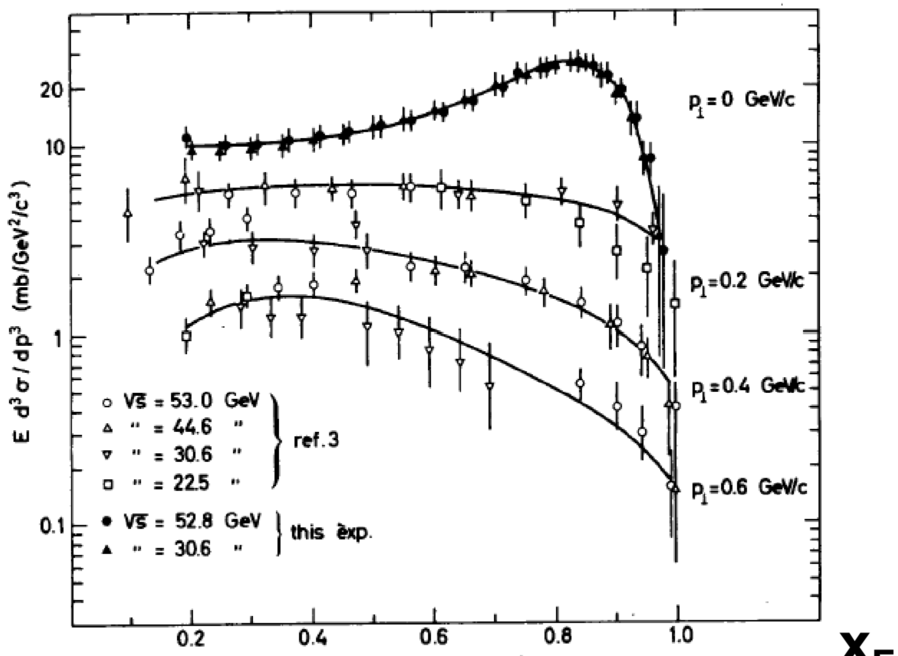
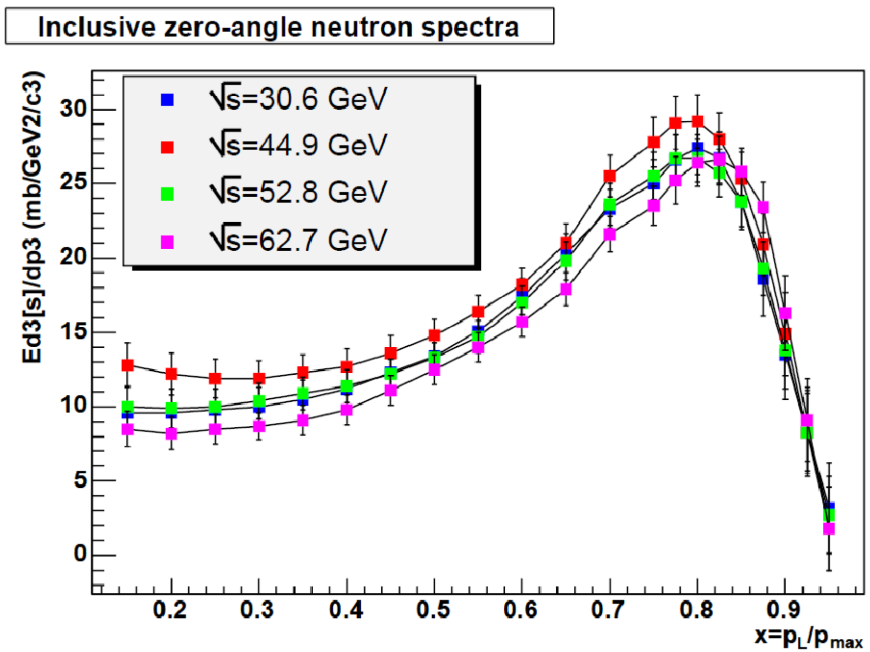
Motivation 2 : Cross section measurements.

- ISR experiment
  - pp sqrt(s)=30~63GeV.
  - cross section of forward neutron production has peak at high x_F.
  - Scaling by x_F, not sqrt(s).

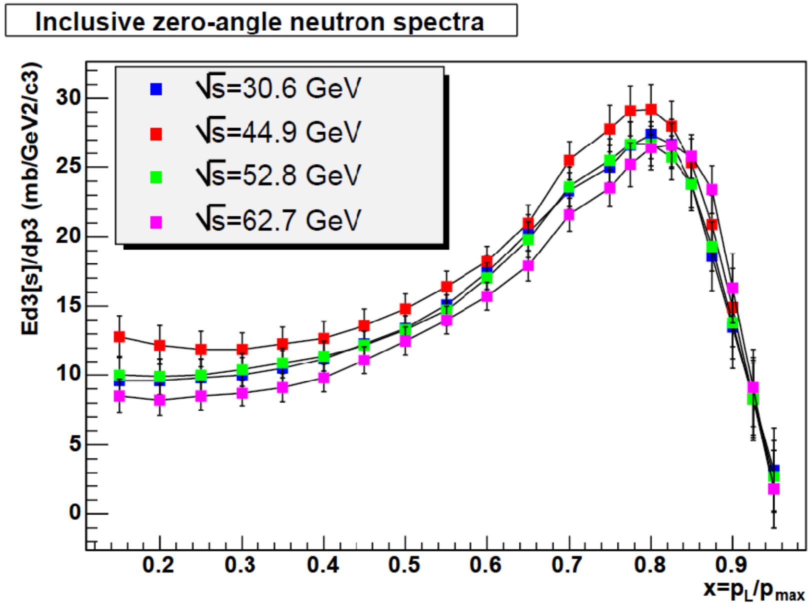


Nucl. Phys. B109 (1976) 347-356

- H1 and ZEUS experiments
  - ep sqrt(s)=300 GeV.
  - Also have forward peak
  - Pion structure fluctuation in proton.



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



- **Does Feynman scaling hold when going to RHIC energy?**
  - From the ISR result, C.S. are described well by x_F scaling at 30<sqrt(s)<63 GeV.
  - Forward neutron C.S. has peak structure and it is well described by **pion exchange model.**
- **What is the mechanism of neutron asymmetry ?**
  - **pion exchange model**
    - Asymmetry can appear due to the interference of spin flip.
  - **Twist-3 model, Siverse effect, Collins effect …**

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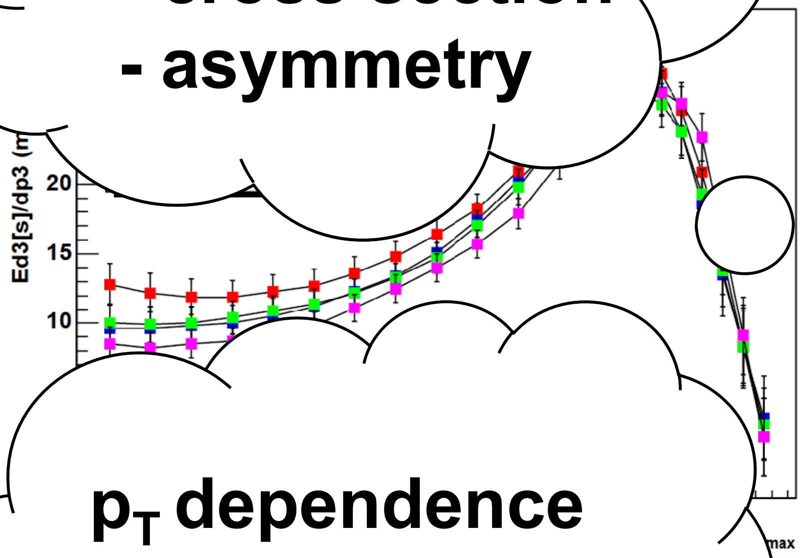
x_F dependence
sqrt(s) = 200 GeV
- cross section
- asymmetry



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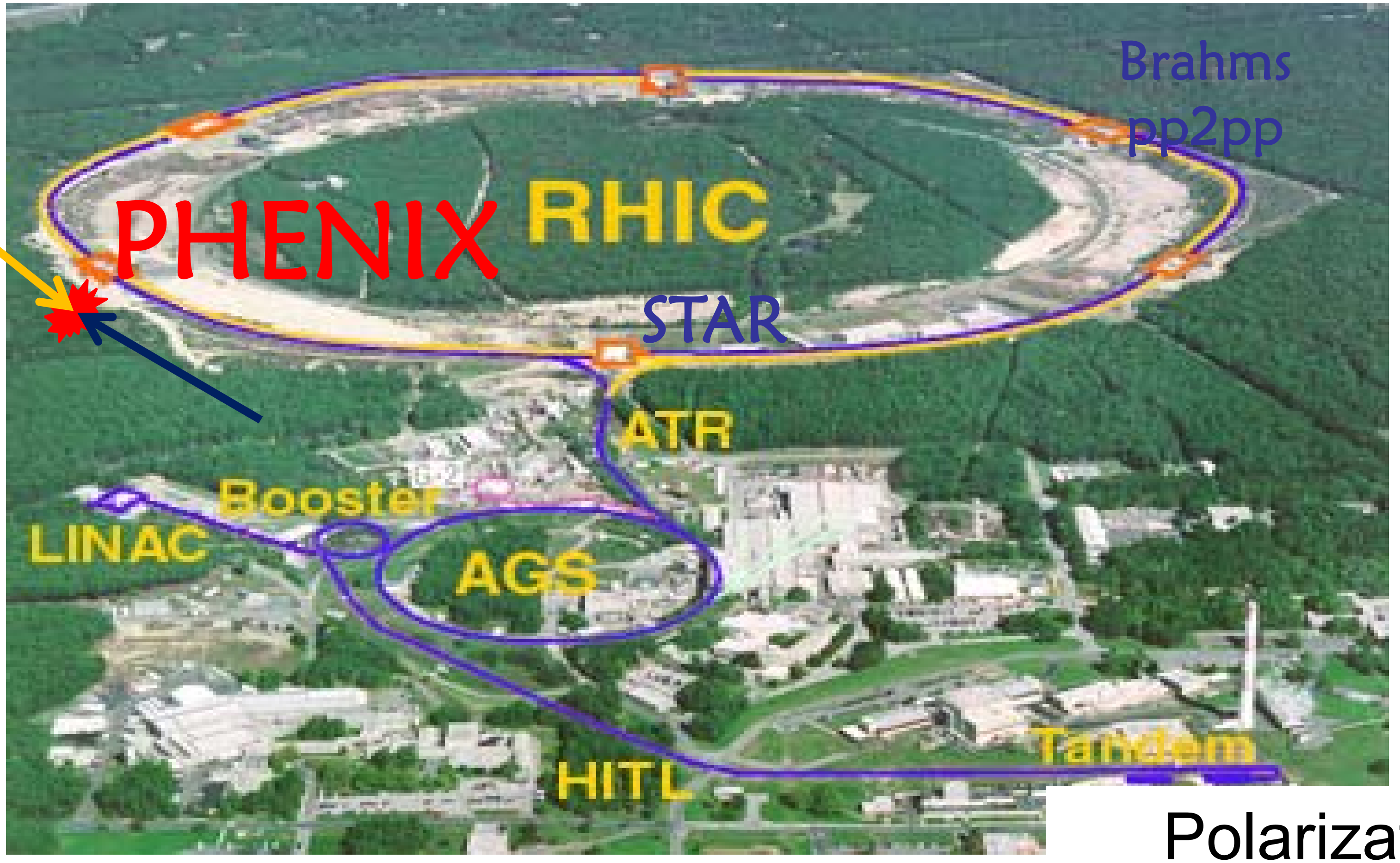
p_T dependence
sqrt(s) = 200 GeV
- asymmetry

→ PHENIX measurement

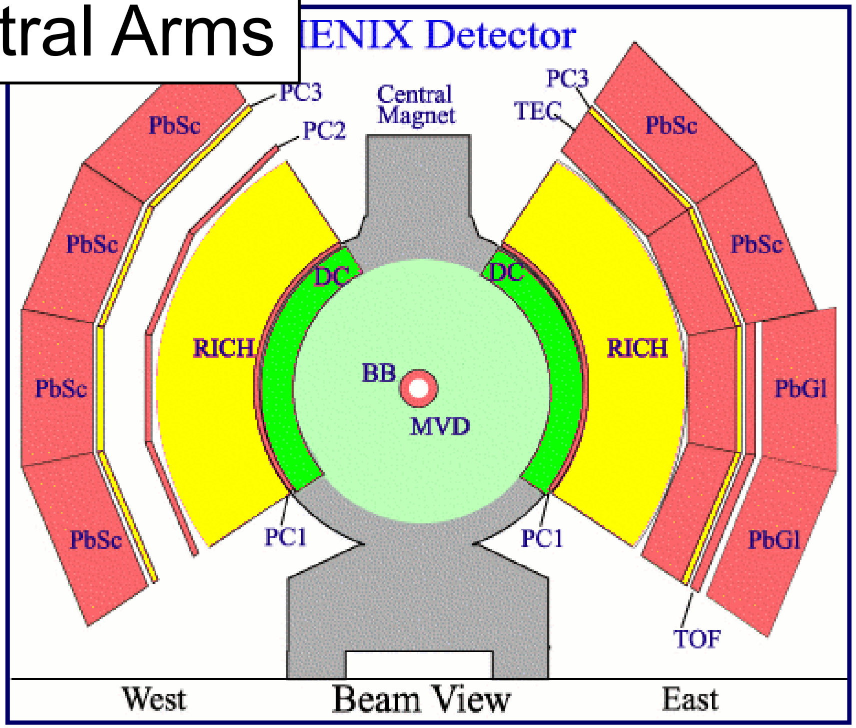
Forward neutron measurement @ RHIC-PHENIX



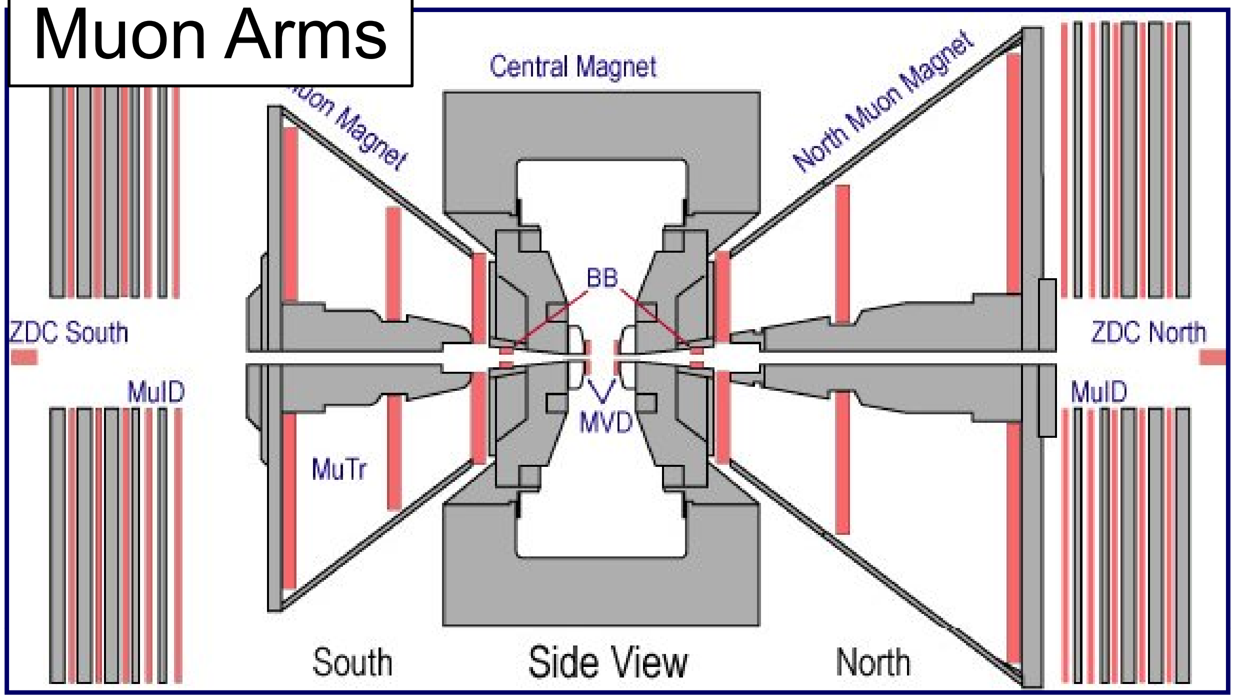
Polarization :
RUN5 : 46%
RUN6 : 62%

Pol. direction beam 1 : ↑ ↓ ↑ ↓ ....
Pol. direction beam 2 : ↑ ↑ ↓ ↓ ....

Central Arms



Muon Arms



PHENIX

Determination of the polarized gluon distribution function is main motivation of spin physics

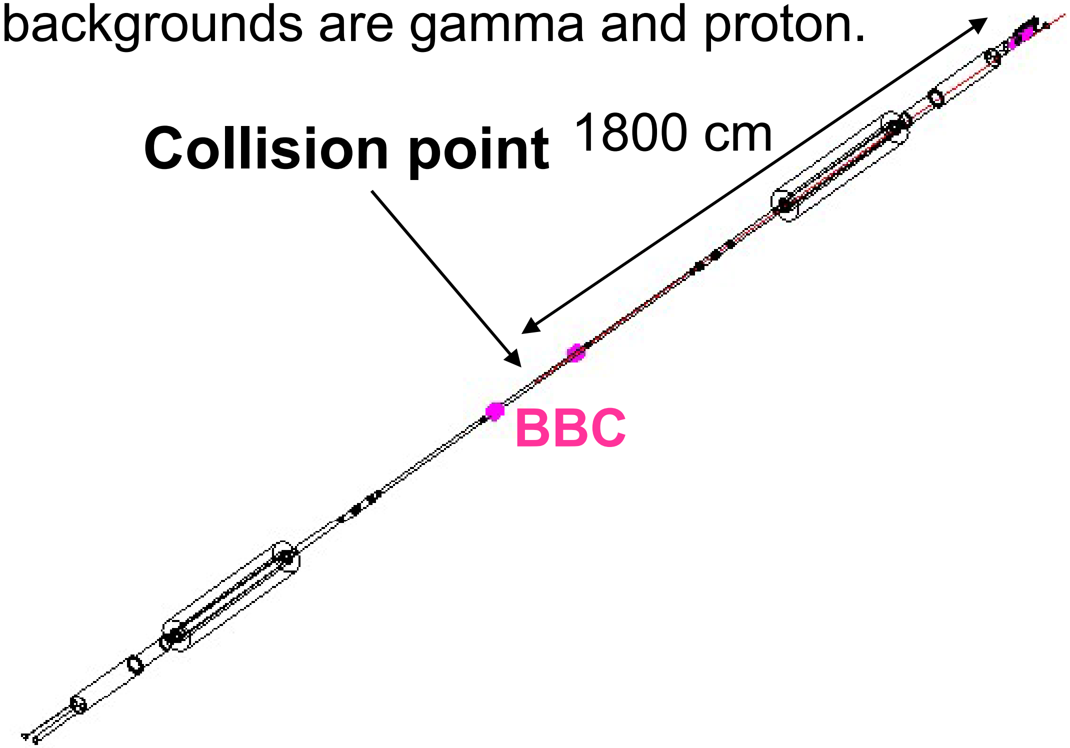
- Central Arms
  - $|\eta| < 0.35$, $\Delta\phi \sim \pi$
  - γ, π^0, e, π^{+-} - identified
- Muon Arms
  - $1.2 < |\eta| < 2.4$
  - μ – identified
- BBC, ZDC
  - Luminosity monitor
  - Minbias trigger (BBC)

Interesting physics in forward area !

Setup

Schematic view from simulation.

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



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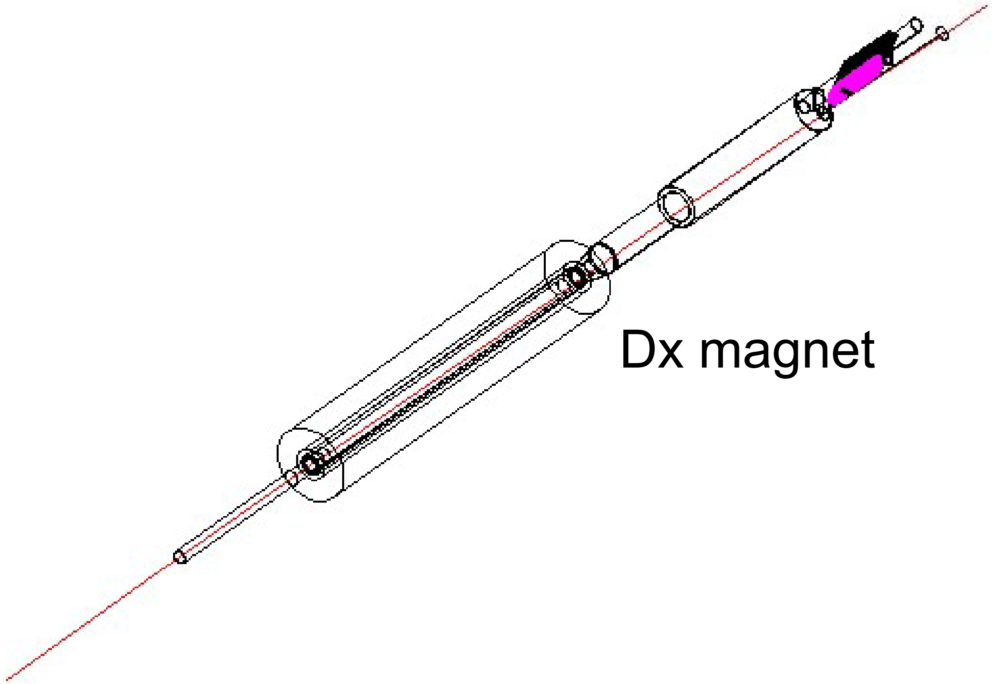

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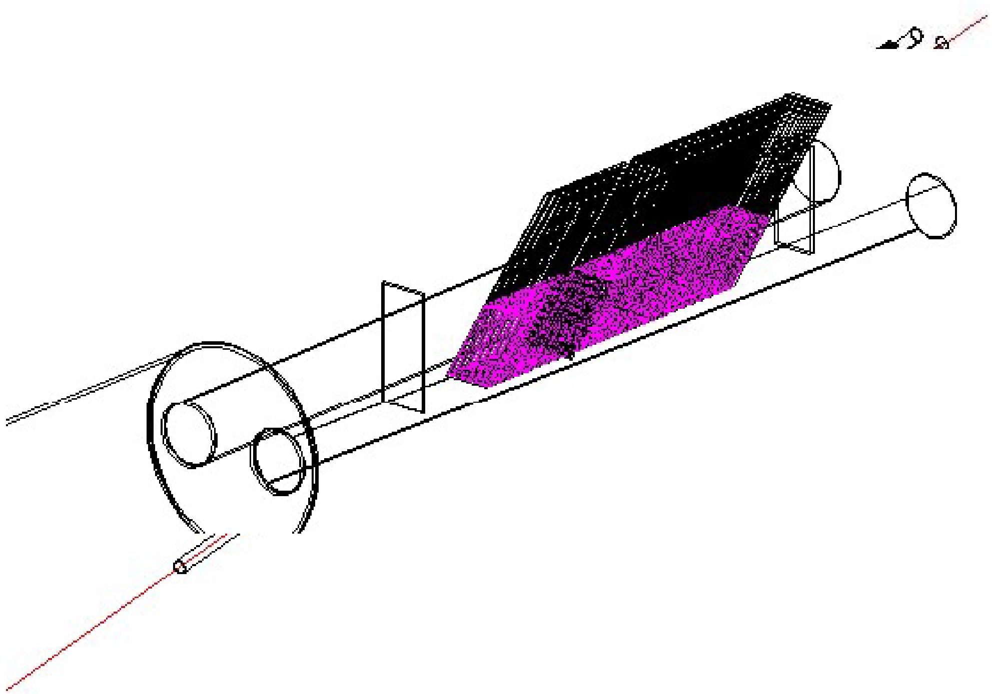

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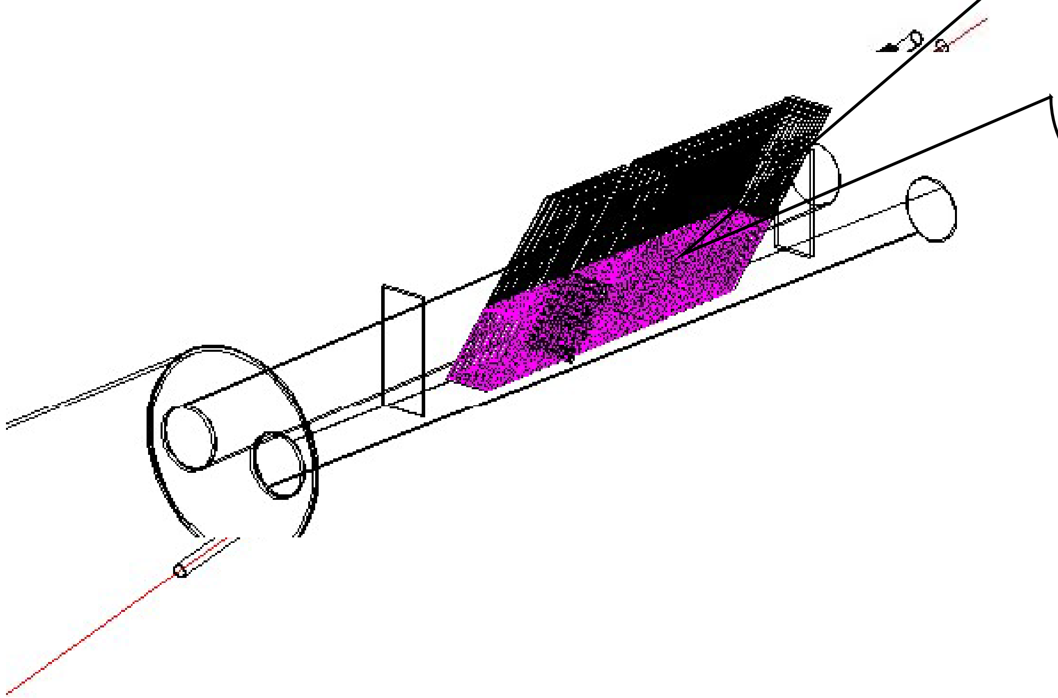

ZDC
(**Z**ero **D**egree **C**alorimeter)

10*10cm
→ 2.8 mrad

3 module
$150X_0$ $5.1\lambda_I$

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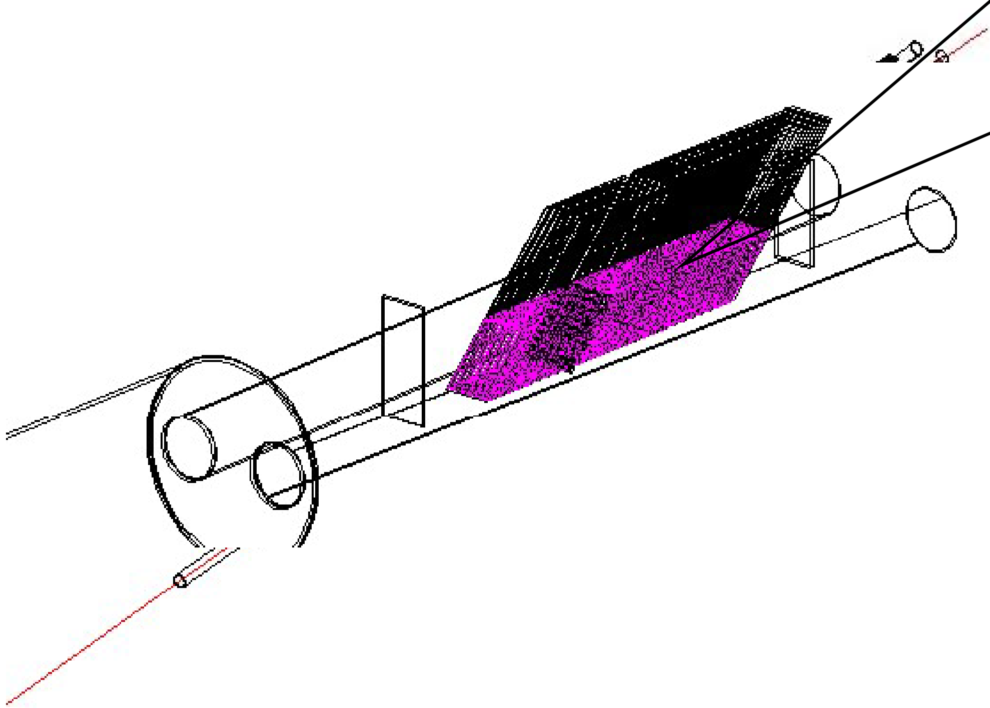

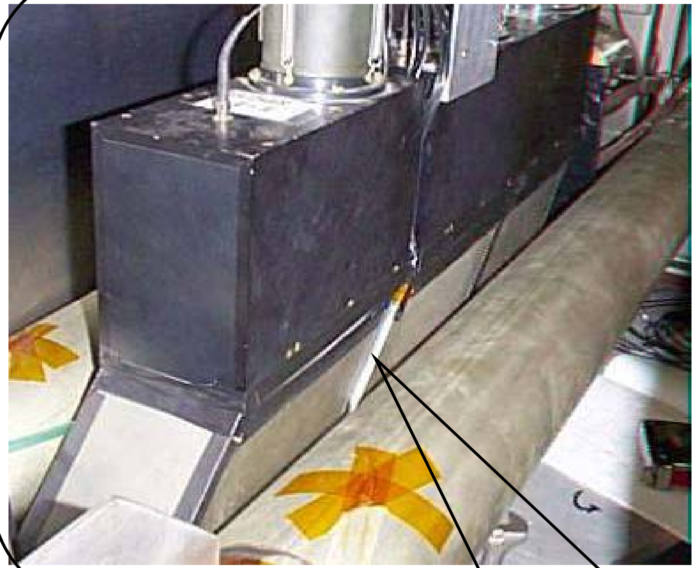

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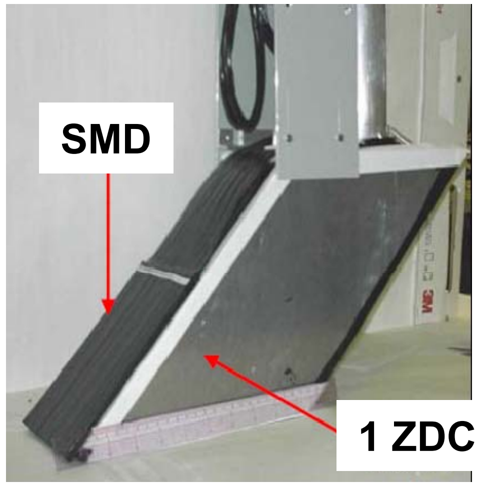

Neutron position can be decided by centroid method.

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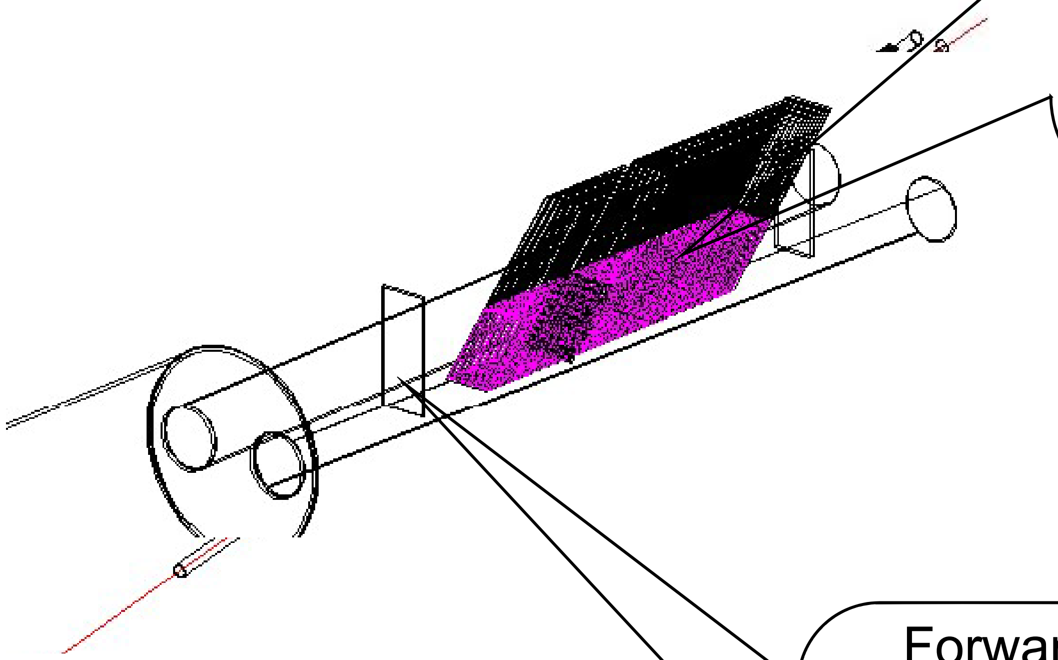

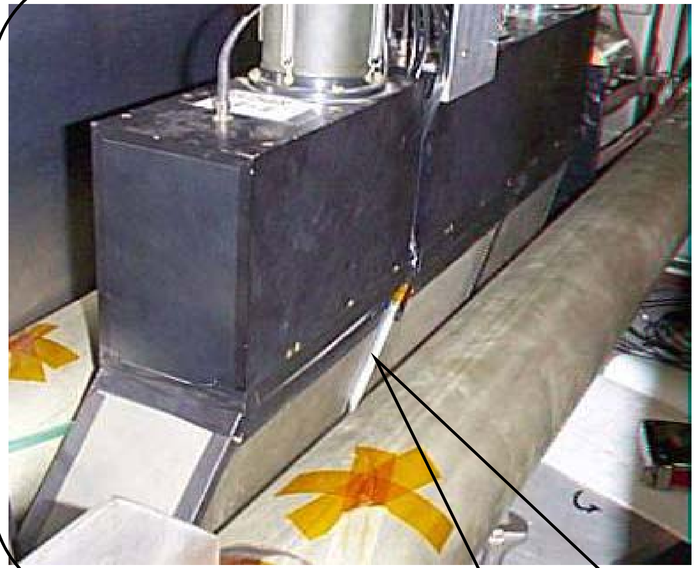

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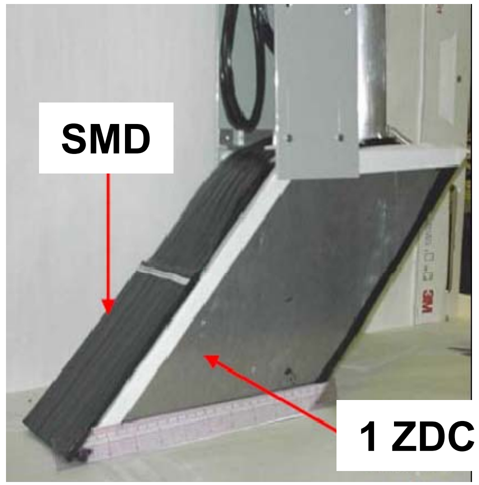
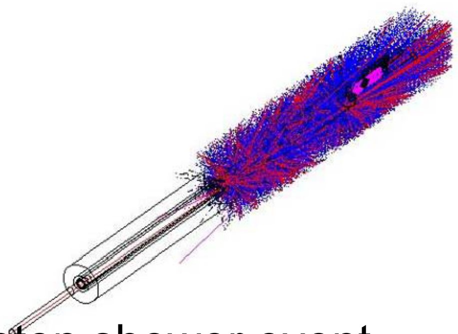


Neutron position can be decided by centroid method.

Forward counter

veto



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

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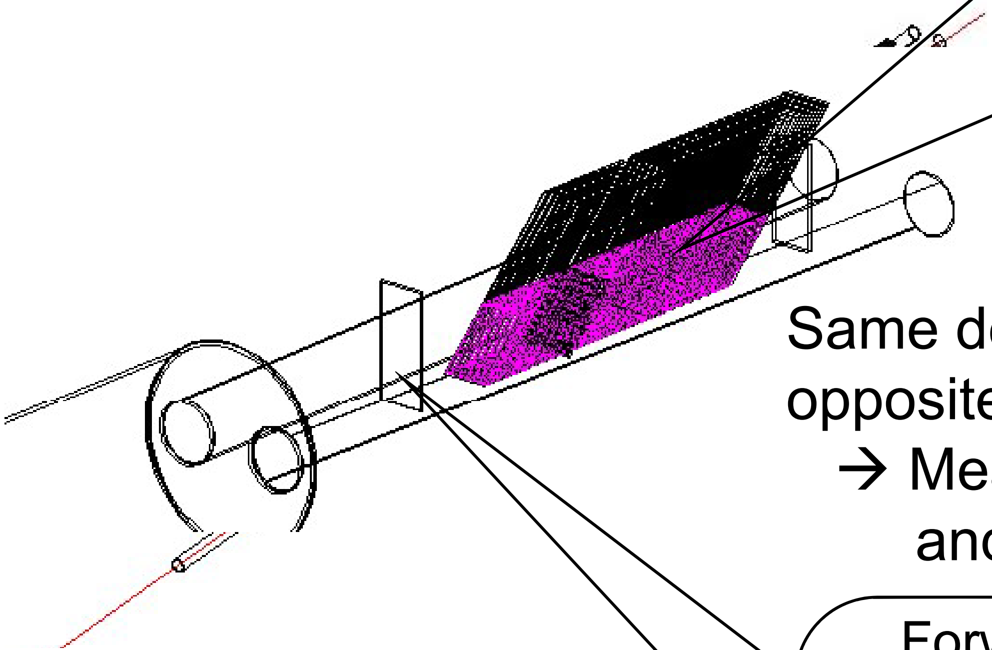

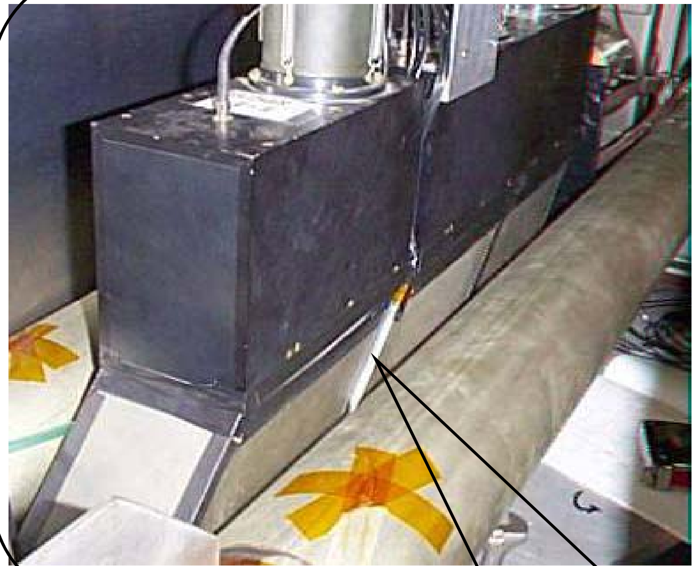

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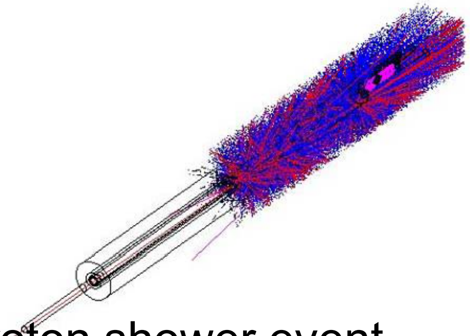
Same detector is in opposite side.
→ Measure **forward** and **backward**.



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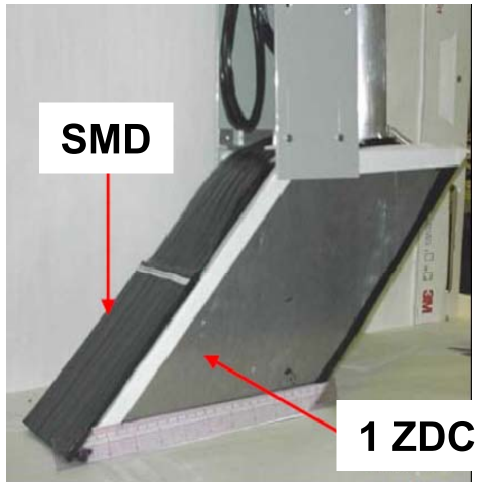

Neutron position can be decided by centroid method.

Analysis outline

- Data set
  - In this analysis, sqrt(s)=200 GeV data from 2005 is used. The data is collected by single neutron trigger w/ or w/o Min. Bias. trigger.
    - Min. Bias. is defined as detecting charged particles in both BBC's (Beam-Beam-Counter : $3.0<|\eta|<3.9$)

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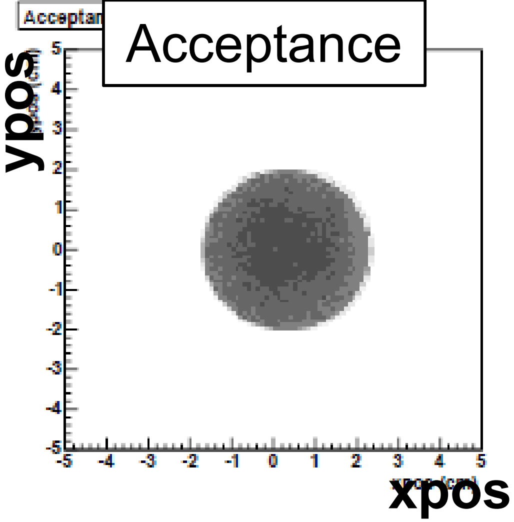
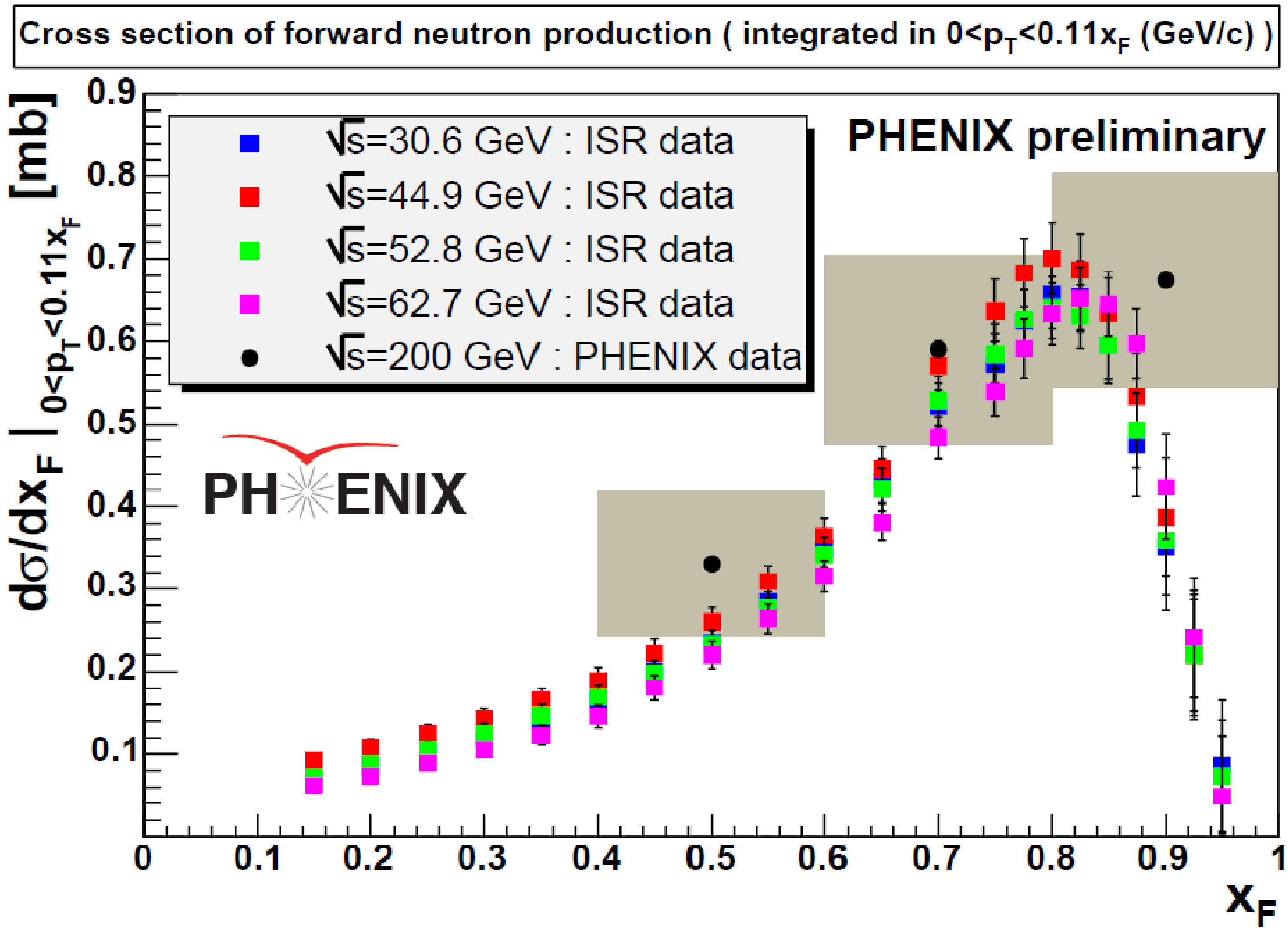
- Simulation (GEANT3 with pythia v.6220 or single particle generator)
  - Background and efficiency after neutron ID cut.
  - Unfold the neutron energy.
  - Smearing effect of asymmetry caused by position cut and resolution.

Cross section

p_T distribution is assuming ISR result





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

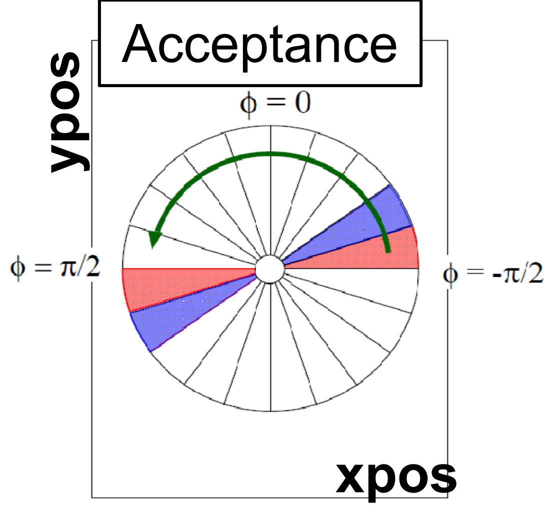
Cross section result is consistent with ISR data. No evidence for violation of x_F scaling at higher energy.

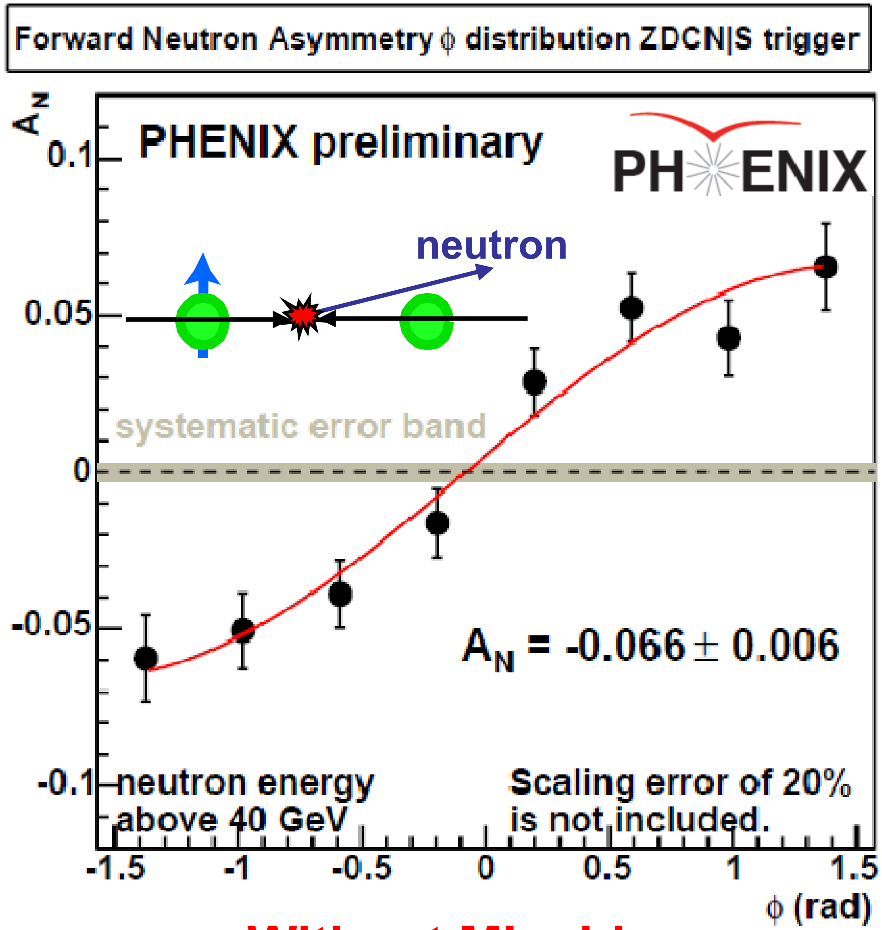
ϕ-dependence of A_N

- Smearing effect is evaluated by simulation.
- For asymmetry calculation, square root formula is used.

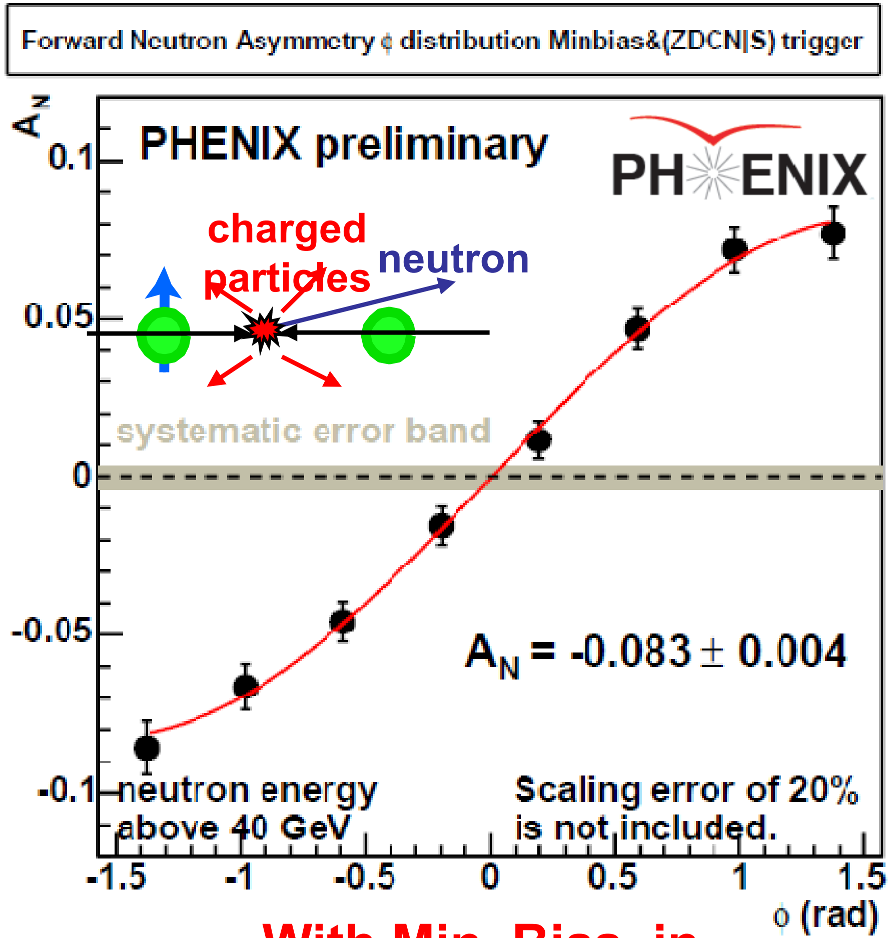
$$A_N \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \approx \frac{1}{Pol.} \frac{\sqrt{N_L^\uparrow N_R^\downarrow} - \sqrt{N_L^\downarrow N_R^\uparrow}}{\sqrt{N_L^\uparrow N_R^\downarrow} + \sqrt{N_L^\downarrow N_R^\uparrow}}$$

Pol.~48%





Without Min. bias.
(Hits in BBC NOT required)



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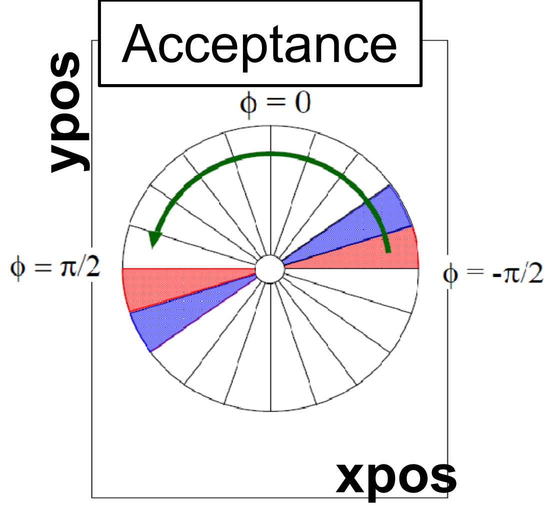

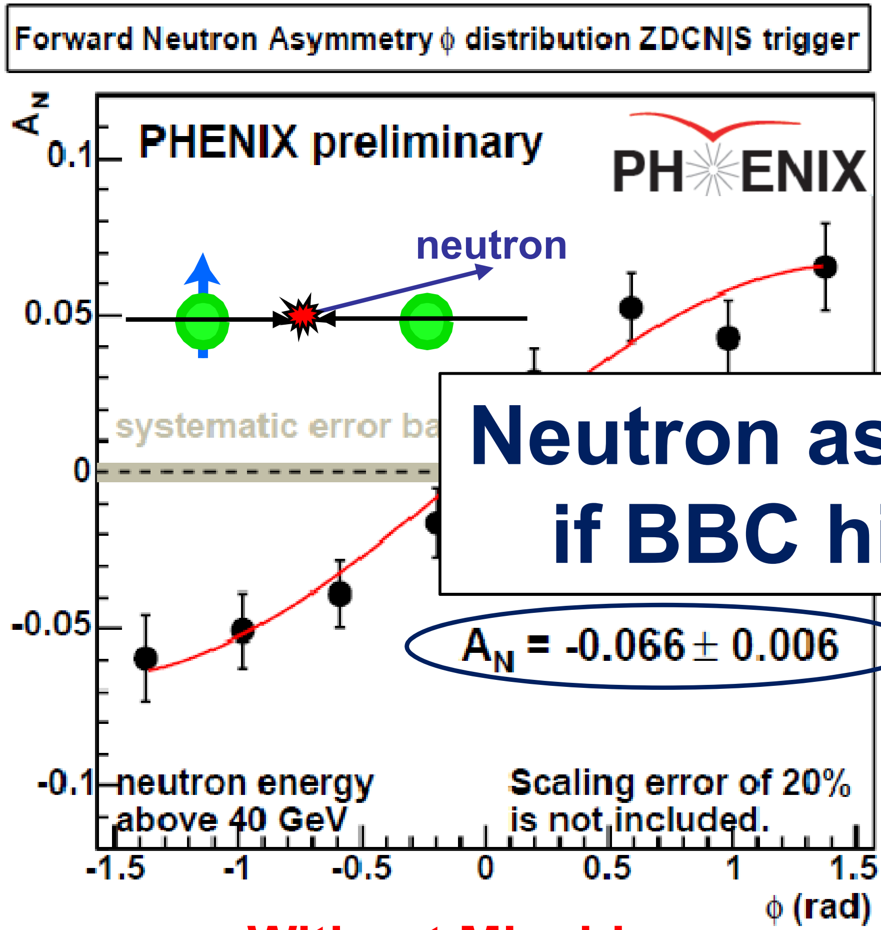

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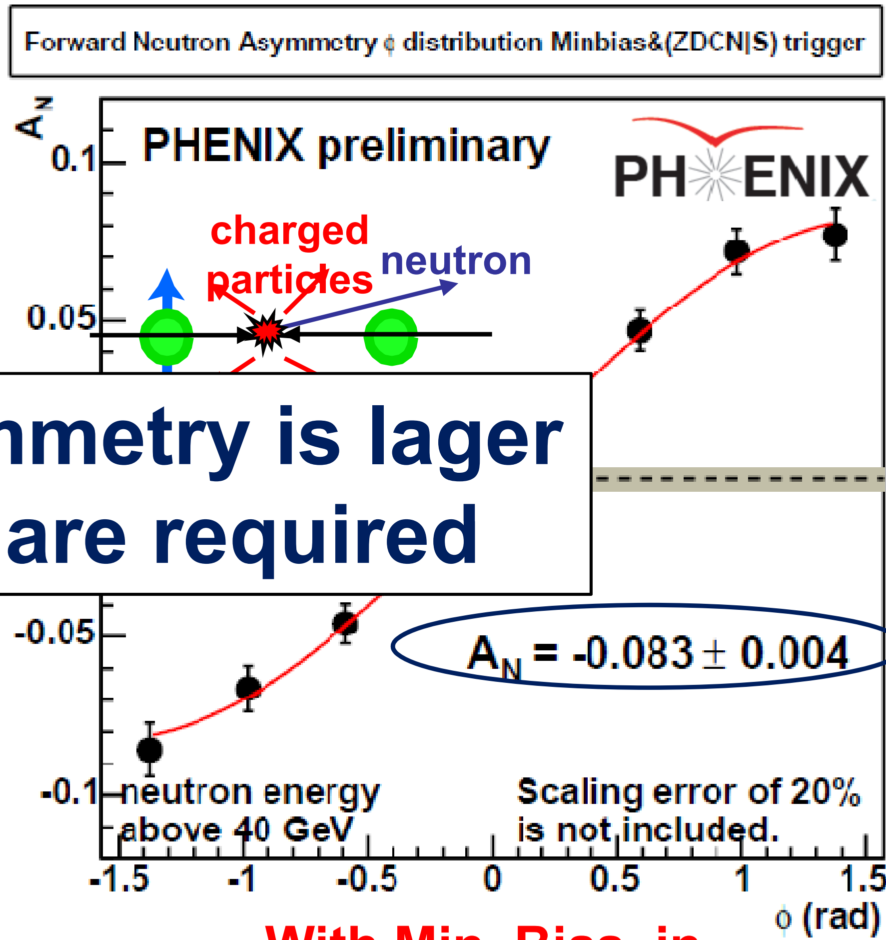

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Neutron asymmetry is lager if BBC hits are required

x_F-dependence of A_N

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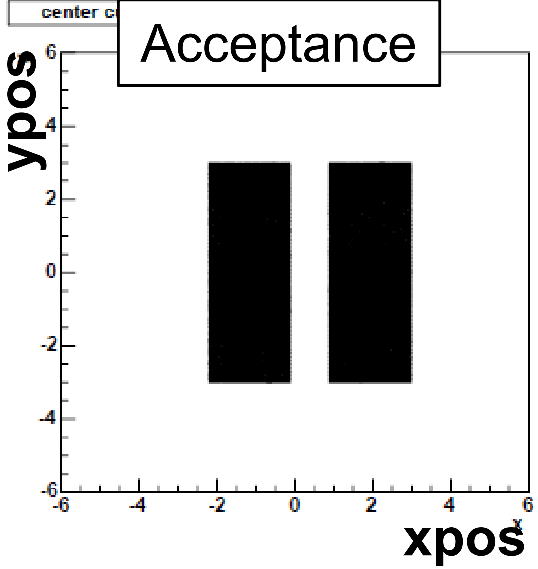
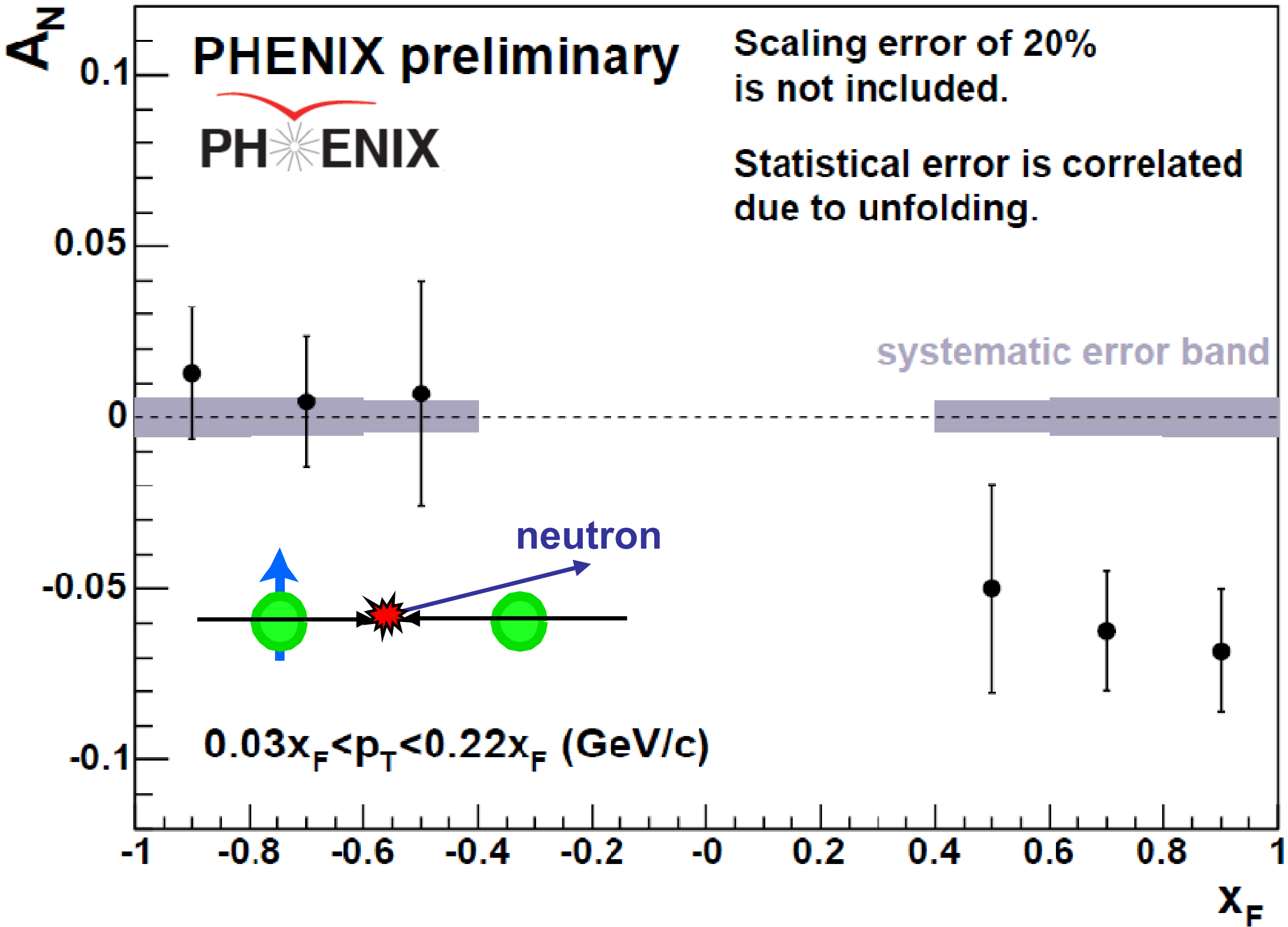


Neutron asymmetry x_F distribution with single neutron trigger



Estimated mean p_T are calculated by simulation assuming ISR p_T distribution.

x_F	Estimated mean p_T (GeV/c)
0.4~0.6	0.088
0.6~0.8	0.118
0.8~1.0	0.144

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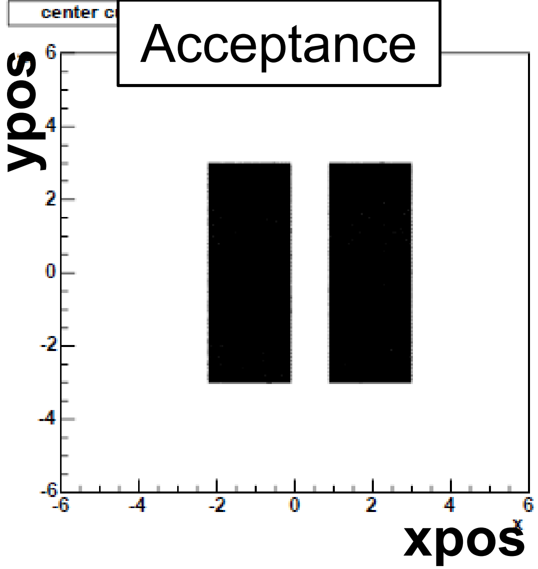
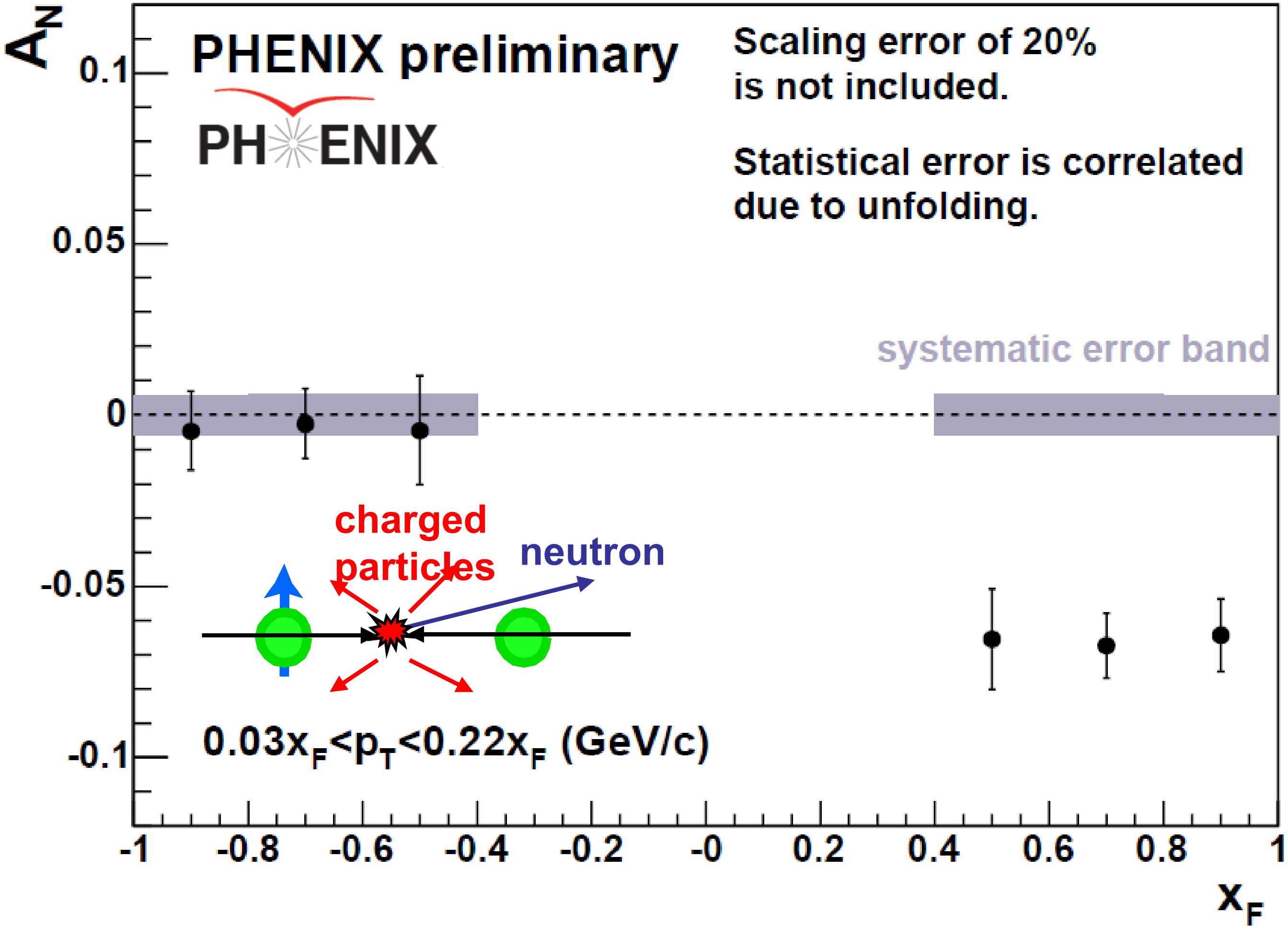


Neutron asymmetry x_F distribution with neutron trigger & MinBias



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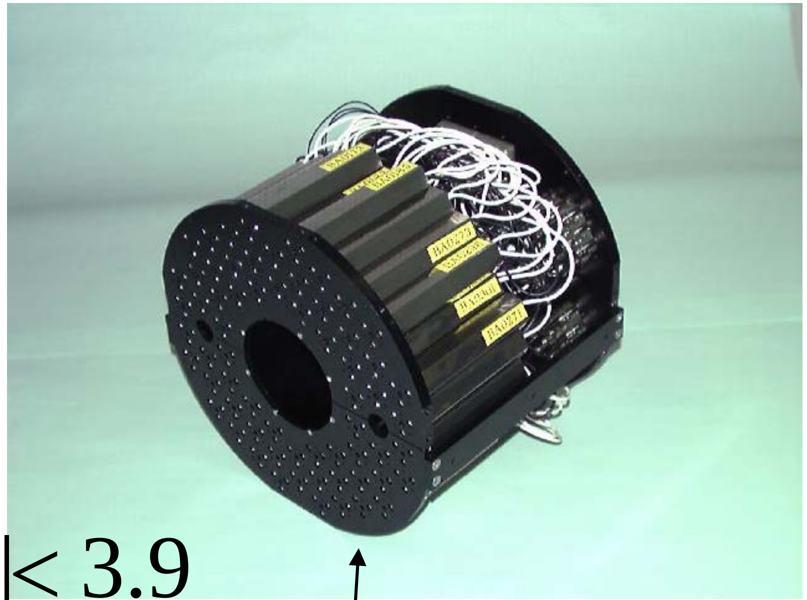
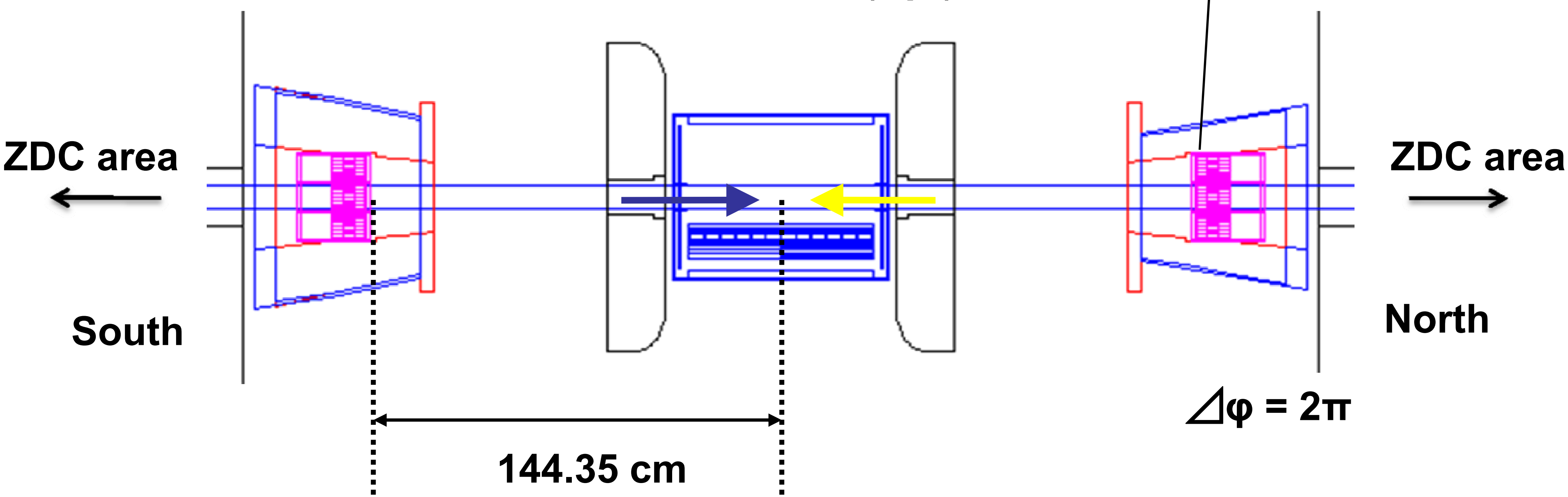
How about charged particles in BBC ?

- 2 identical parts
  - BBC-north and -south
- Quartz Cherenkov counter
  - Count charged particles.
- 64 segments each.



$3.0 < |\eta| < 3.9$

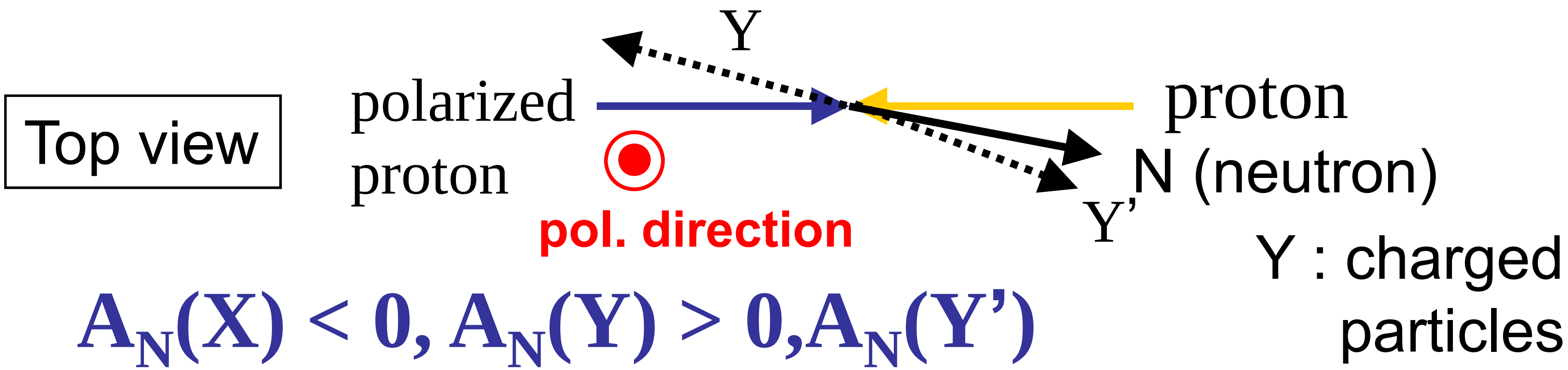


A_N of charged particles.

- Asymmetry is 0 if data is selected by BBC only.
- Finite asymmetries are shown tagged with forward neutron. 4σ
  - Opposite direction as neutron $(2.28\pm0.55\pm0.10)*10^{-2}$
  - Same direction as neutron $(-4.50\pm0.50\pm0.22)*10^{-2}$ 9σ

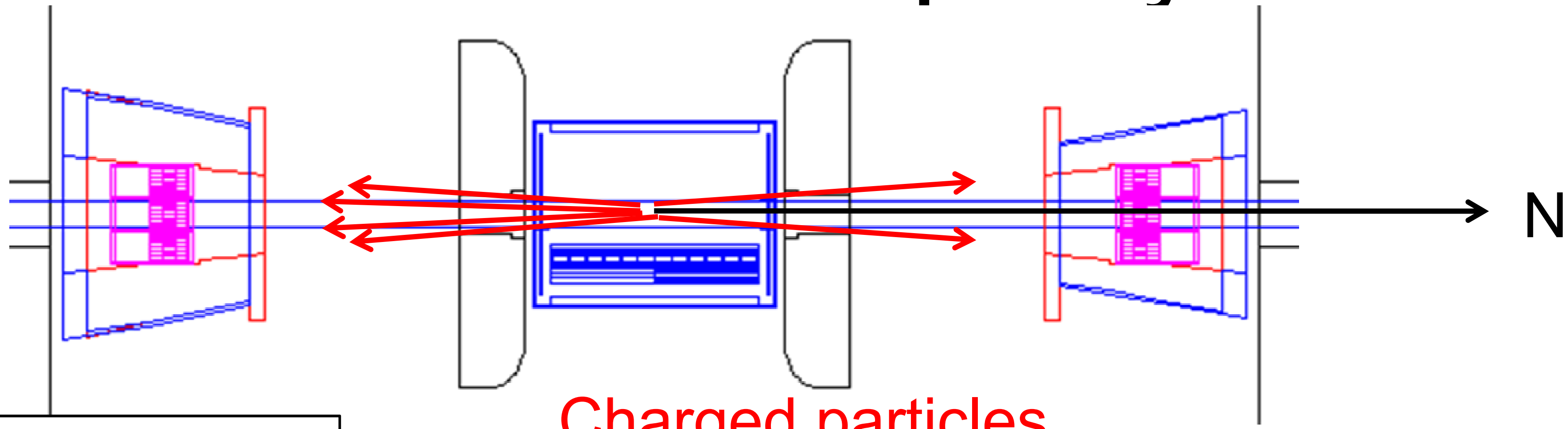
PHENIX preliminary

→ Big correlation between forward charged particles and neutron !



$$A_N(X) < 0,\ A_N(Y) > 0,A_N(Y')$$

BBC multiplicity



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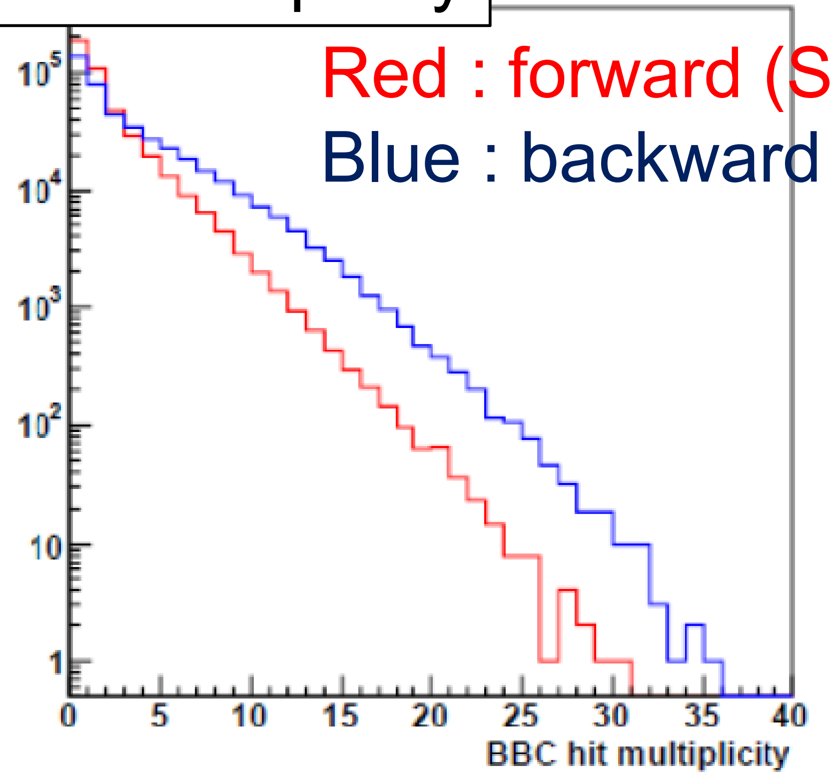
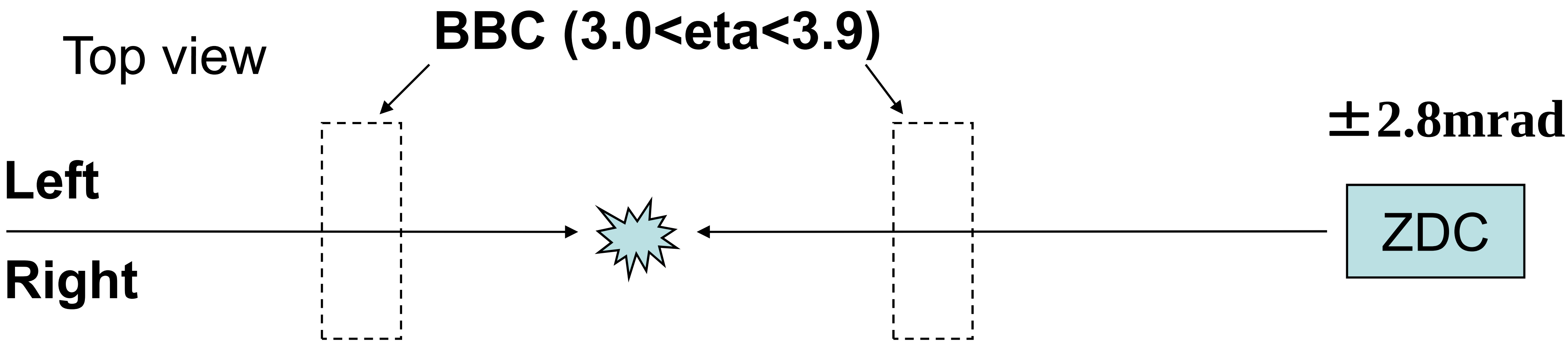


Red : forward (Same direction as N)

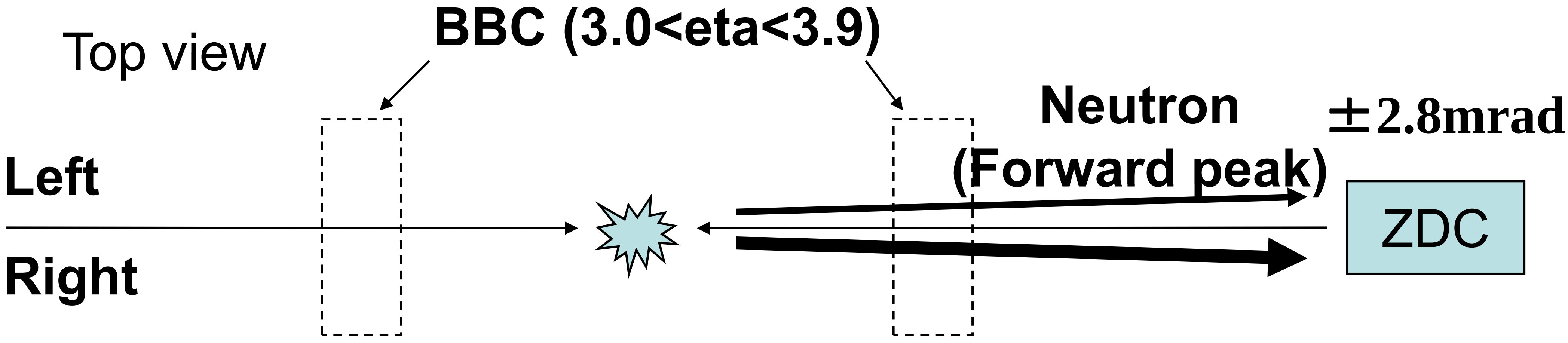
Blue : backward (Opposite direction as N)

- Forward BBC multiplicity is lower if tagged with forward neutron.
- Can be explained by OPE.
  - πp-scattering occurs with lower momentum π.

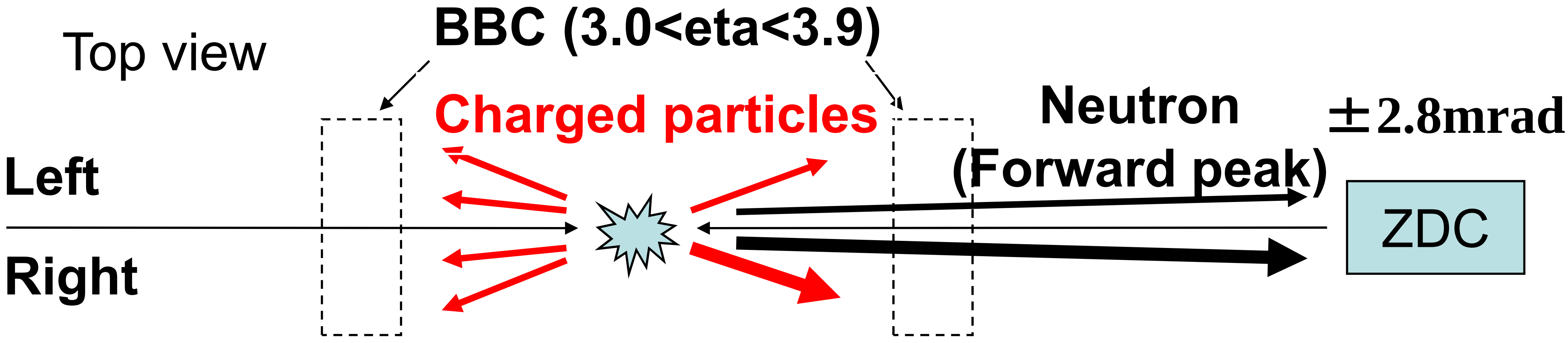
Overall picture for forward measurements at PHENIX



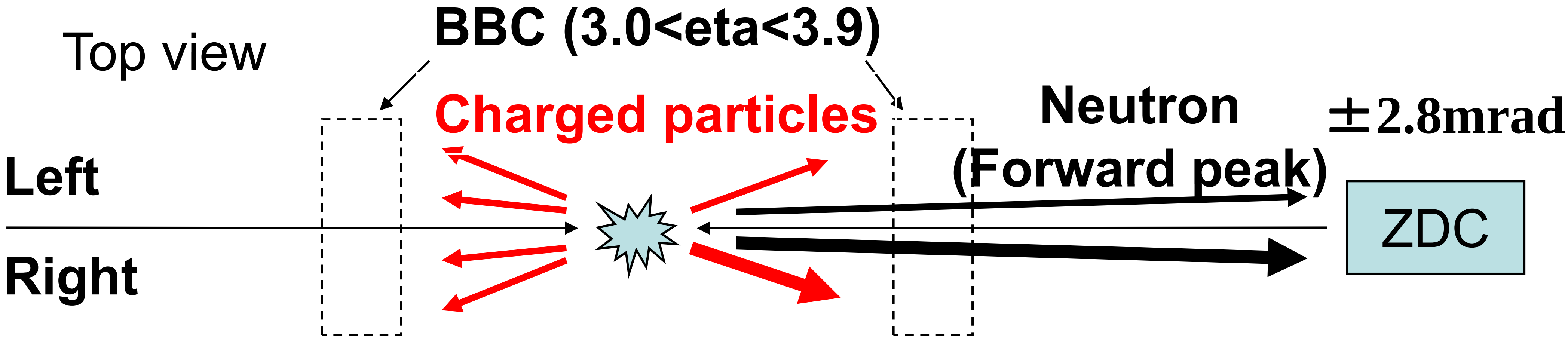
Overall picture for forward measurements at PHENIX



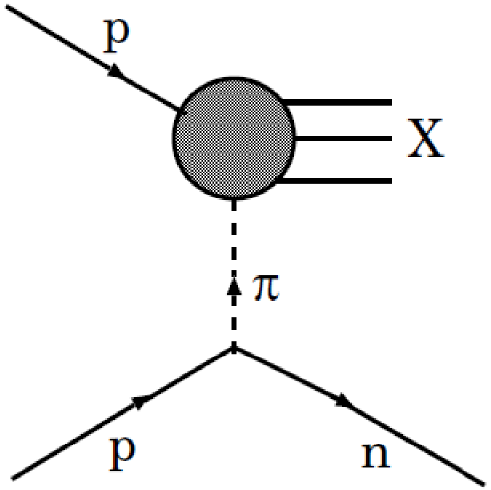
Overall picture for forward measurements at PHENIX



Overall picture for forward measurements at PHENIX

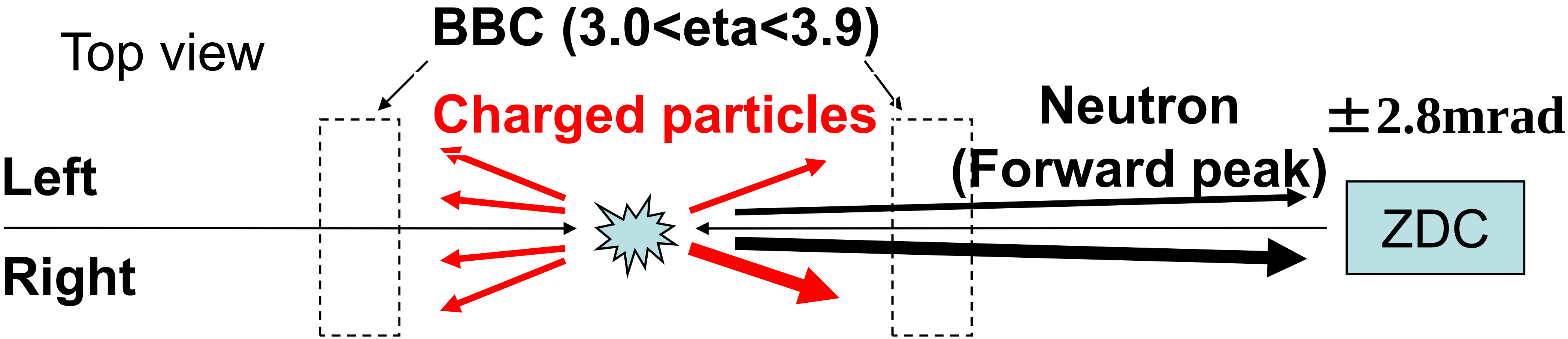


Compare with pion exchange model

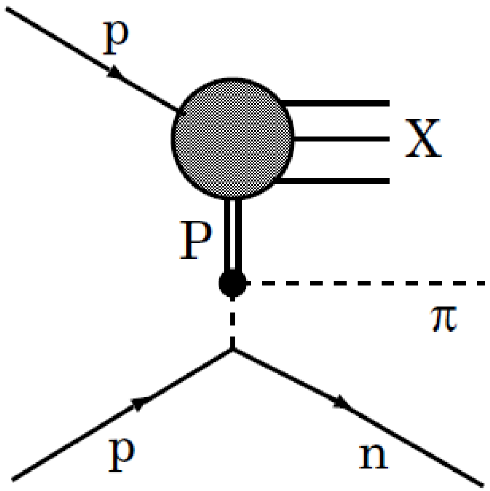


☺ Forward peak
☺ Neutron asymmetry (pion exchange)
☺ N.of charged particles in BBC
Forward < Backward
(Forward energy will be lower)
? Charged particles asymmetry in BBC
(N*(Δ*) → n+X)

Overall picture for forward measurements at PHENIX



Compare with pion exchange model



☺ Forward peak

☺ Neutron asymmetry (pion exchange)

☺ N.of charged particles in BBC

Forward < Backward

(Forward energy will be lower)

? Charged particles asymmetry in BBC

($N^*(\Delta^*) \rightarrow n+X$)

Deck model (Phys.Rev.D15:1903,1977)

Summary

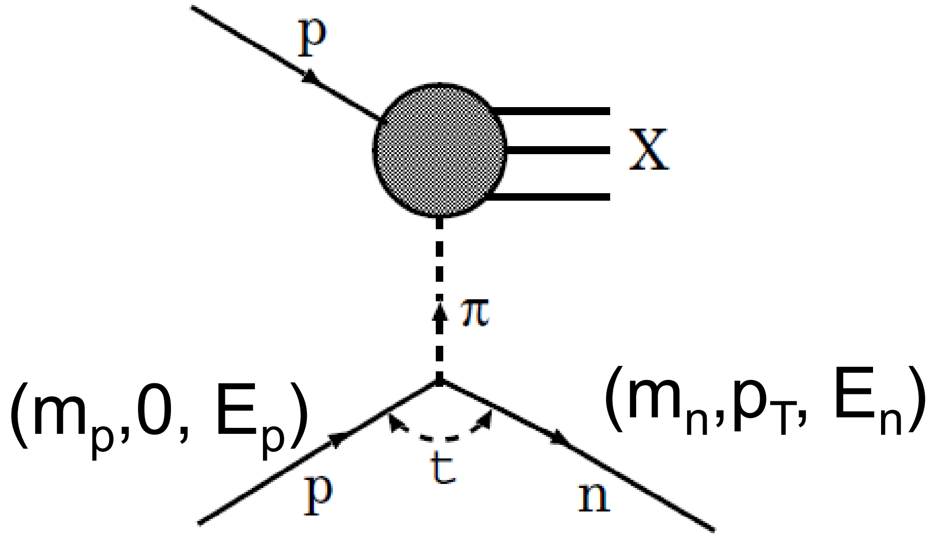
- The cross section and the single transverse spin asymmetries of forward neutron production in sqrt(s)=200 GeV polarized *pp* collision are measured at RHIC-PHENIX.
- Cross section (Very forward, $0<p_T<0.11x_F$ GeV/c)
  - It is consistent with ISR data at $p_T \sim 0$ (GeV/c).
  - No evidence for violation of x_F scaling.
- A_N of forward neutron
  - Analyzing power of forward neutron tagged w/ charged particles is lager than w/o them.
  - Negative asymmetry, flat x_F-dependence.

← Theoretical calculation is very welcome.

- A_N of charged particles
  - Finite value if forward neutron is tagged.
  - Forward BBC multiplicity is lower if forward neutron is tagged.

Future analysis

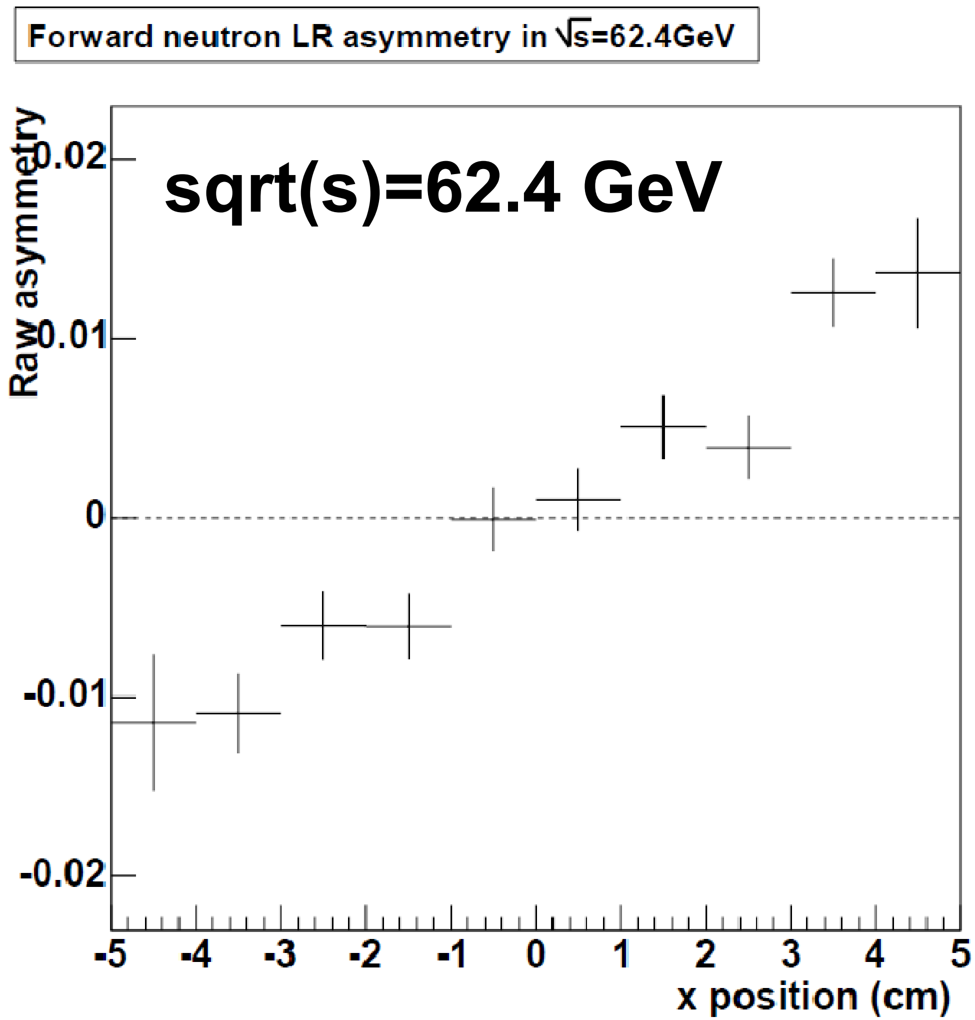
- p_T-dependence
  - Important parameter same as x_F (of course t for the OPE model).
  - It will be studied by r-dependence.

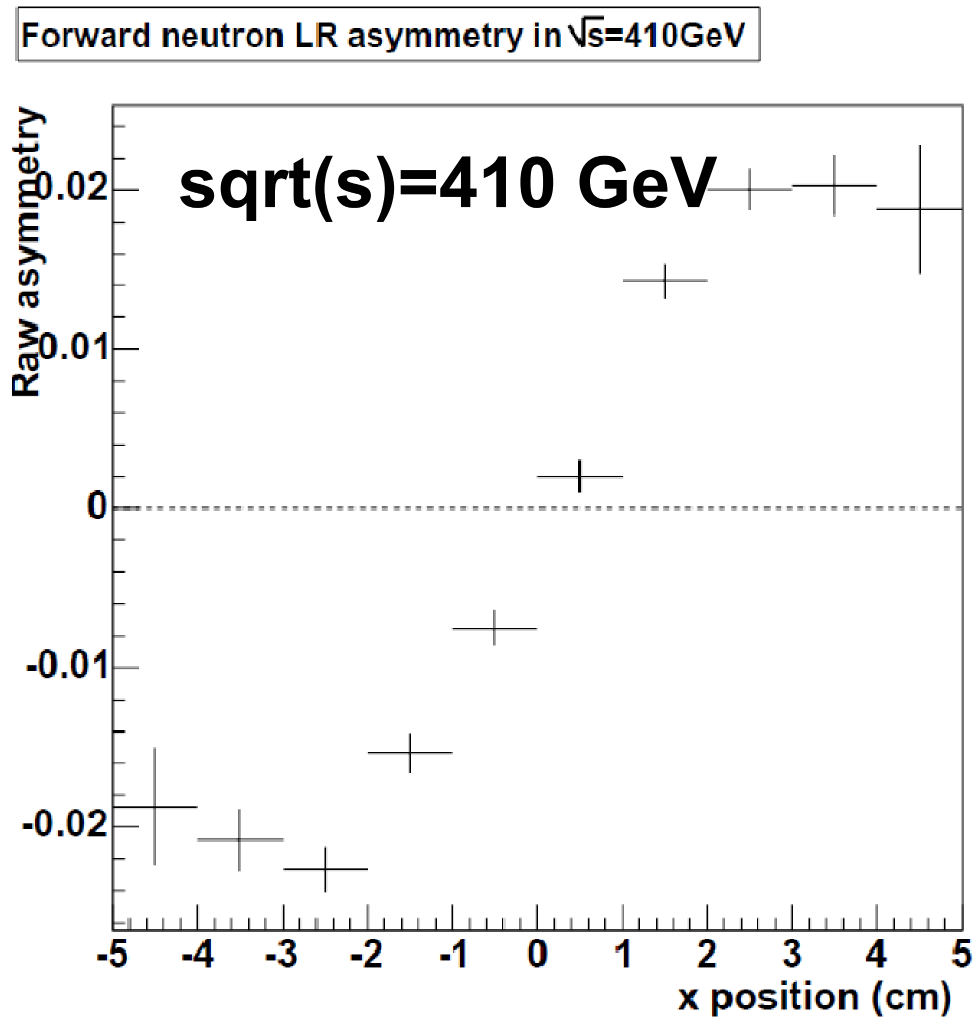


$$x_F \sim \frac{E_n}{E_p} \qquad t \sim -\frac{p_T^2}{x_F} - \frac{1-x_F}{x_F}\left(m_n^2 - x_F m_p^2\right)$$

- Other correlation tagged with forward neutron.
  - A_N of charged particles tagged with forward neutron.

We can see finite asymmetry in other energy RUNs !

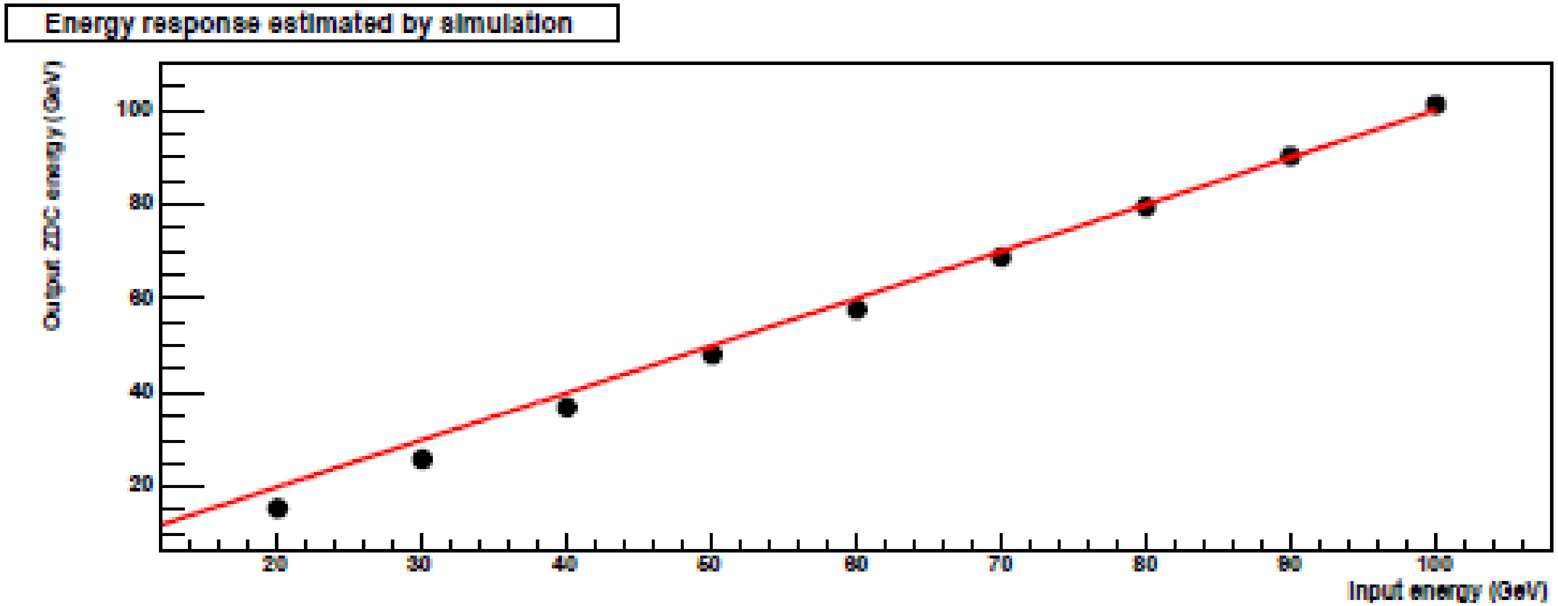


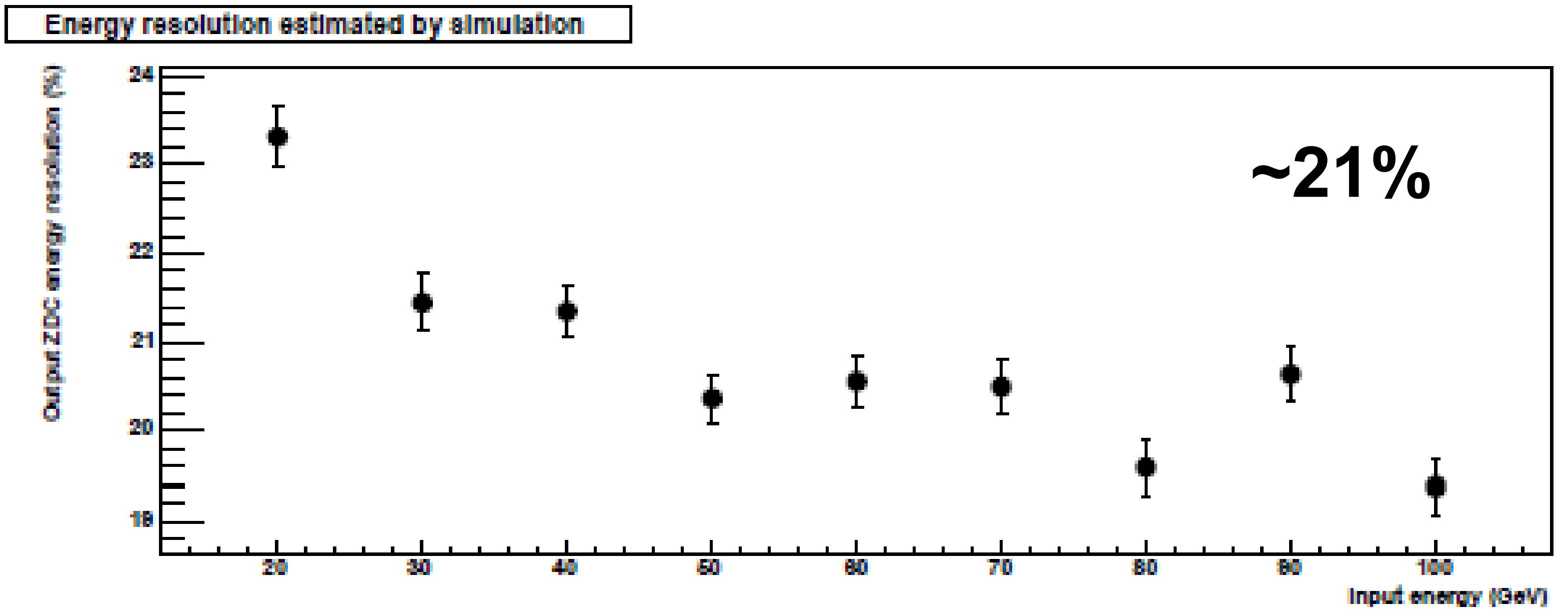


→ go to 500 GeV

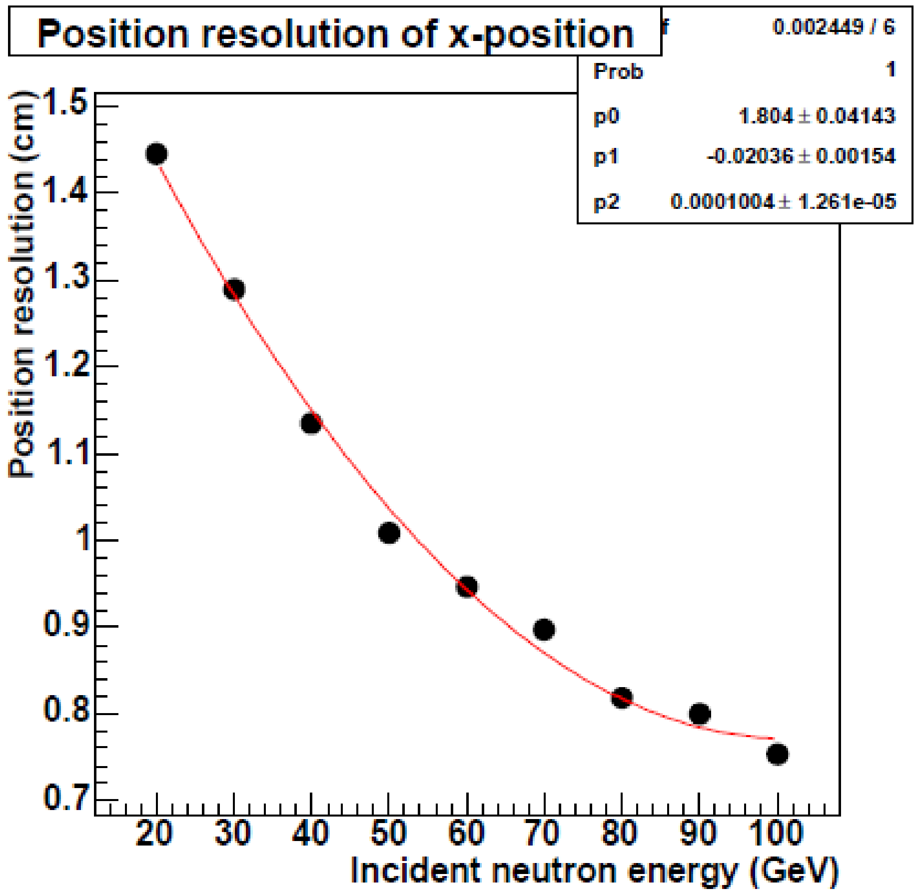
backup

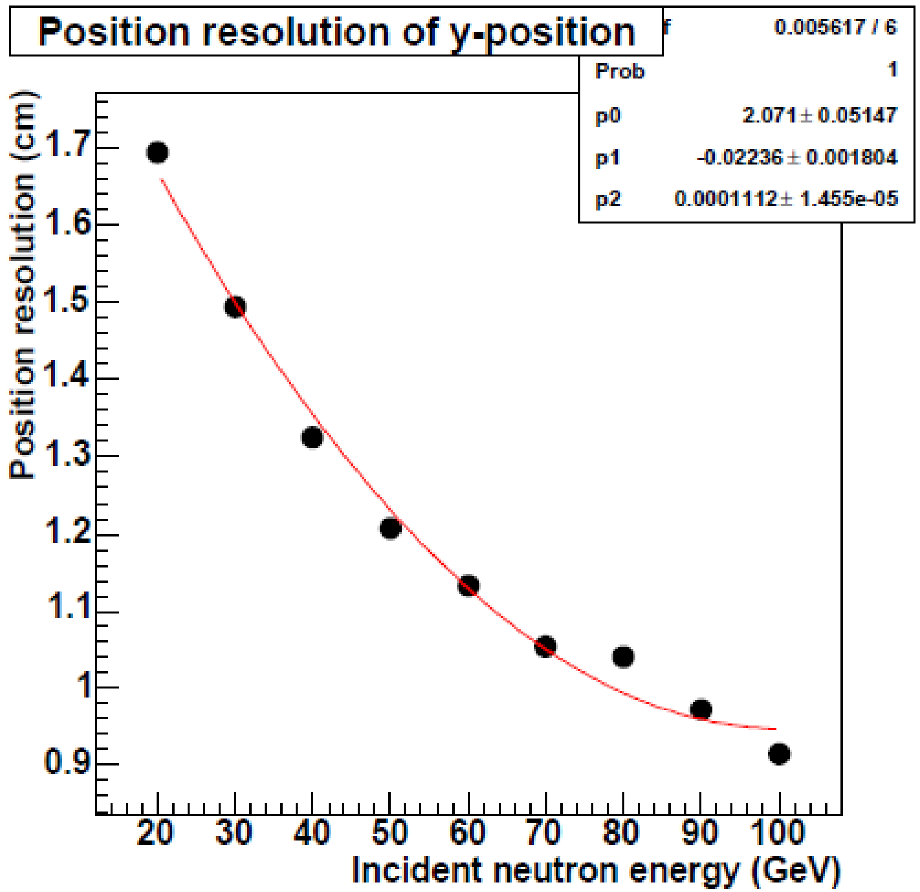
Energy resolution

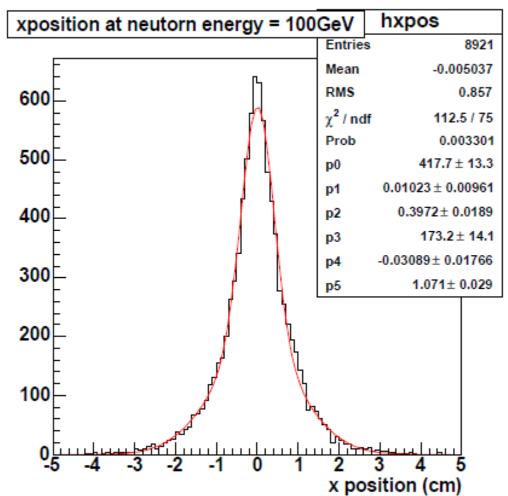




Position resolution

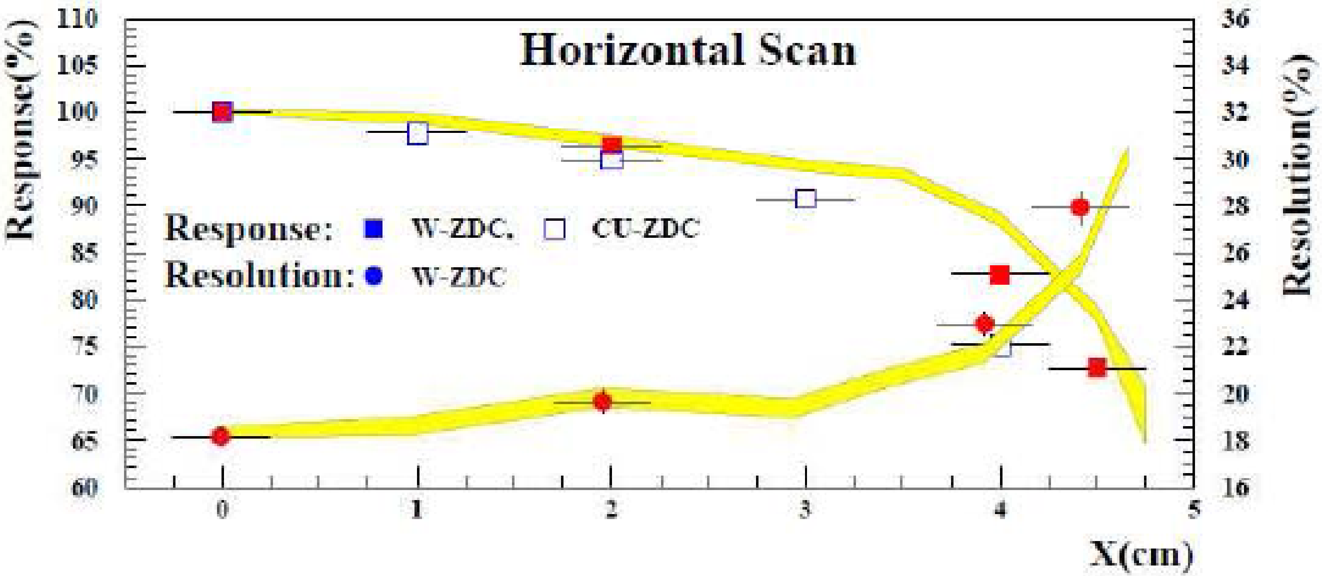




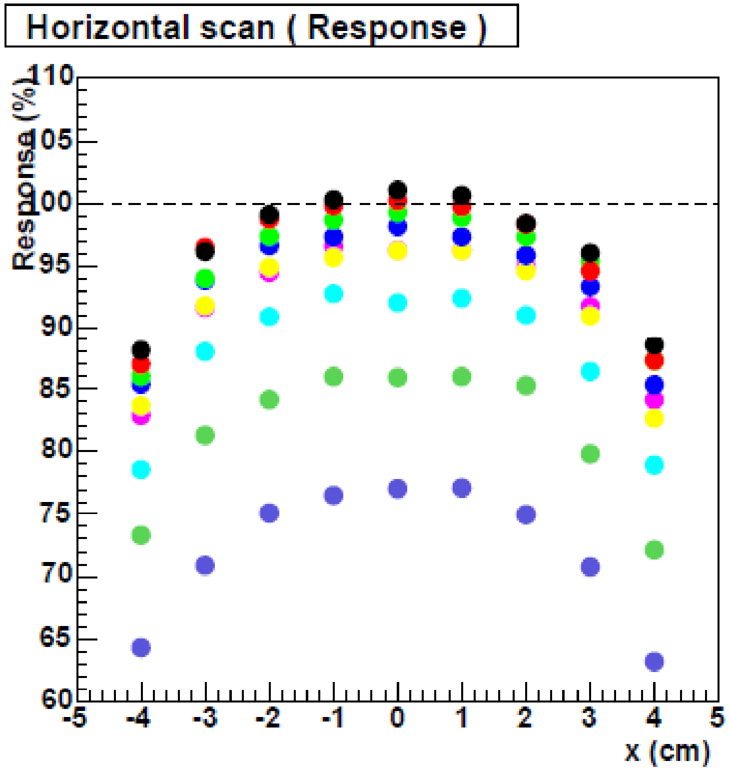


$$\sigma_{total} = \frac{\int g_1(x)dx\sigma_1 + \int g_2(x)dx\sigma_2}{\int g_1(x)dx + \int g_2(x)dx}$$

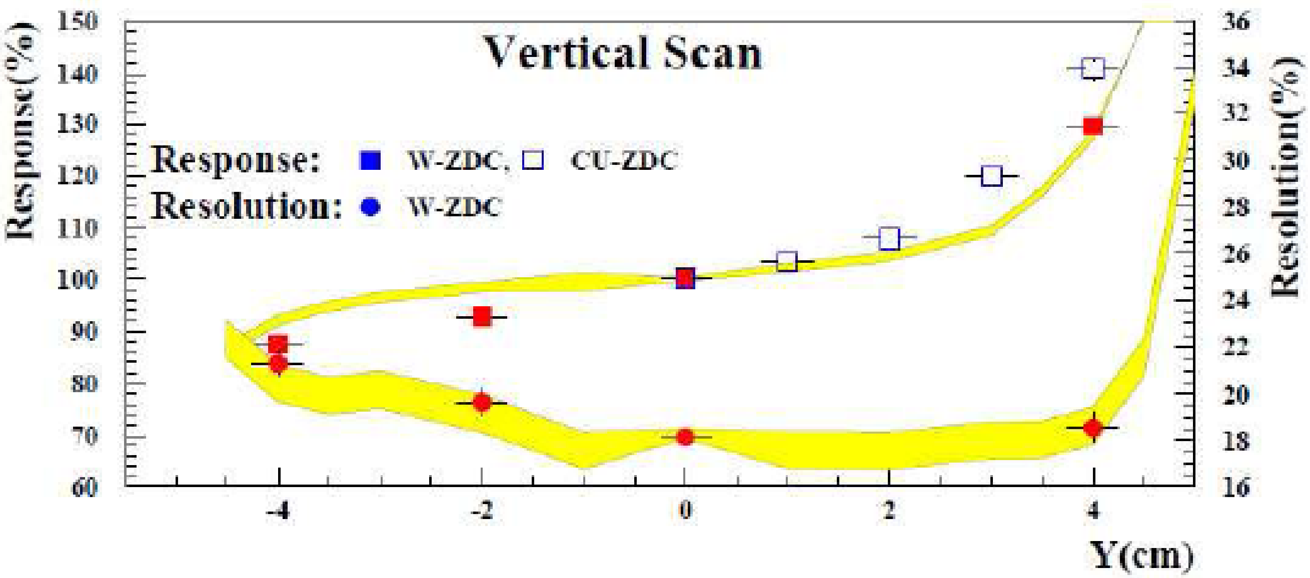
Edge effect



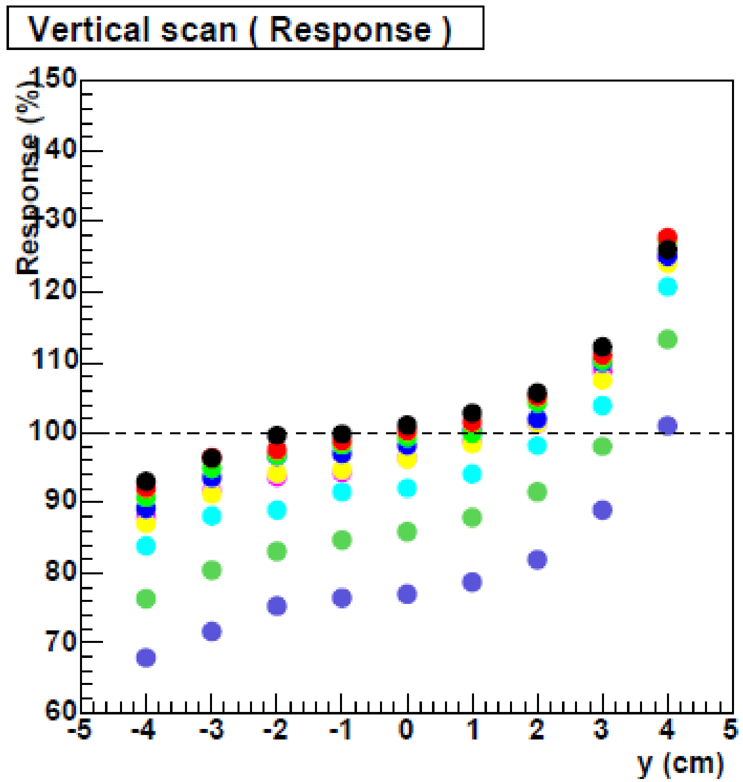
Horizontal Scan
Response(%)
Resolution(%)
Response: W-ZDC, CU-ZDC
Resolution: W-ZDC
X(cm)



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

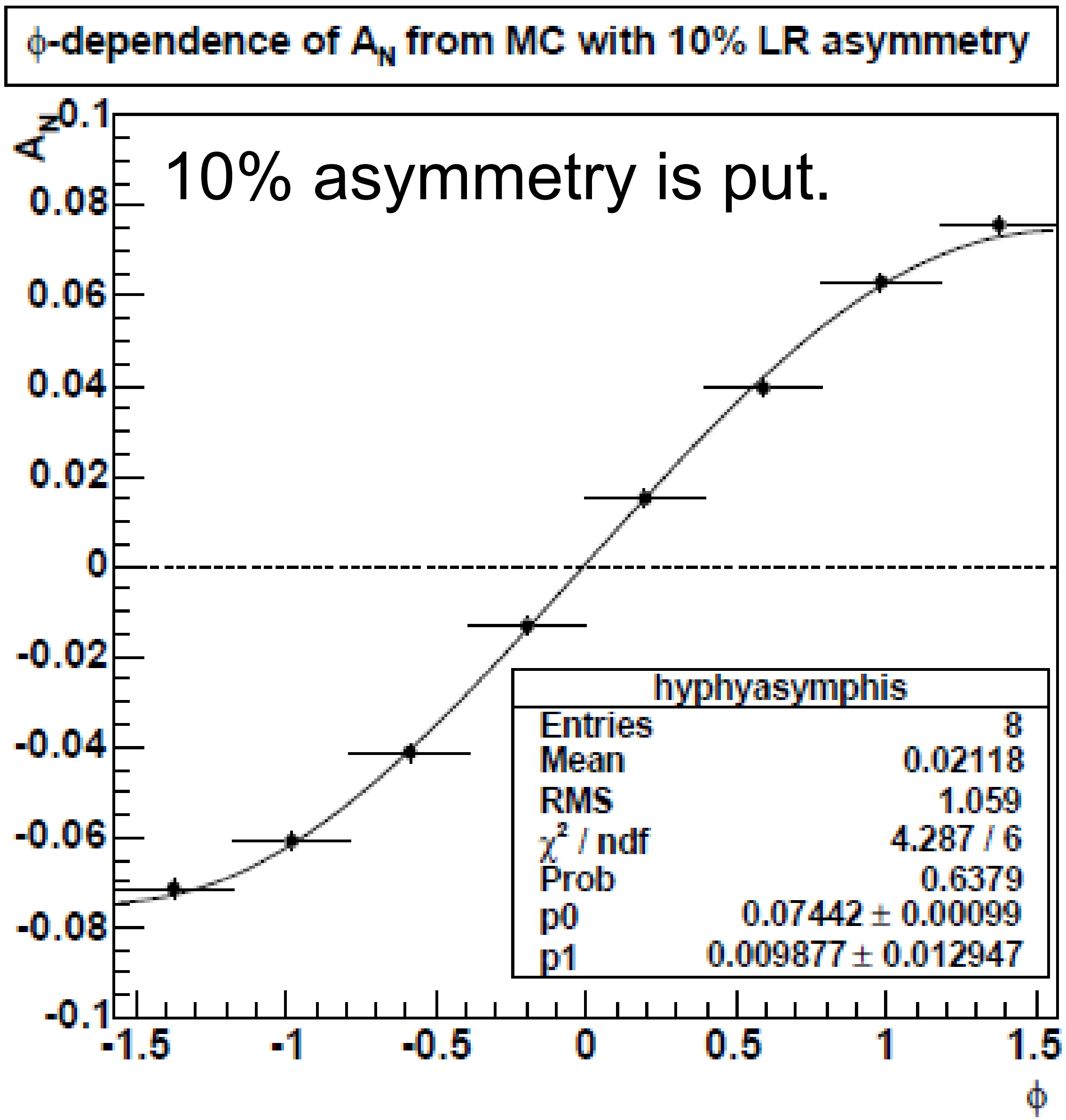


Vertical Scan
Response(%)
Resolution(%)
Response: W-ZDC, CU-ZDC
Resolution: W-ZDC
Y(cm)



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

Smearing effect for ϕ-asymmetry



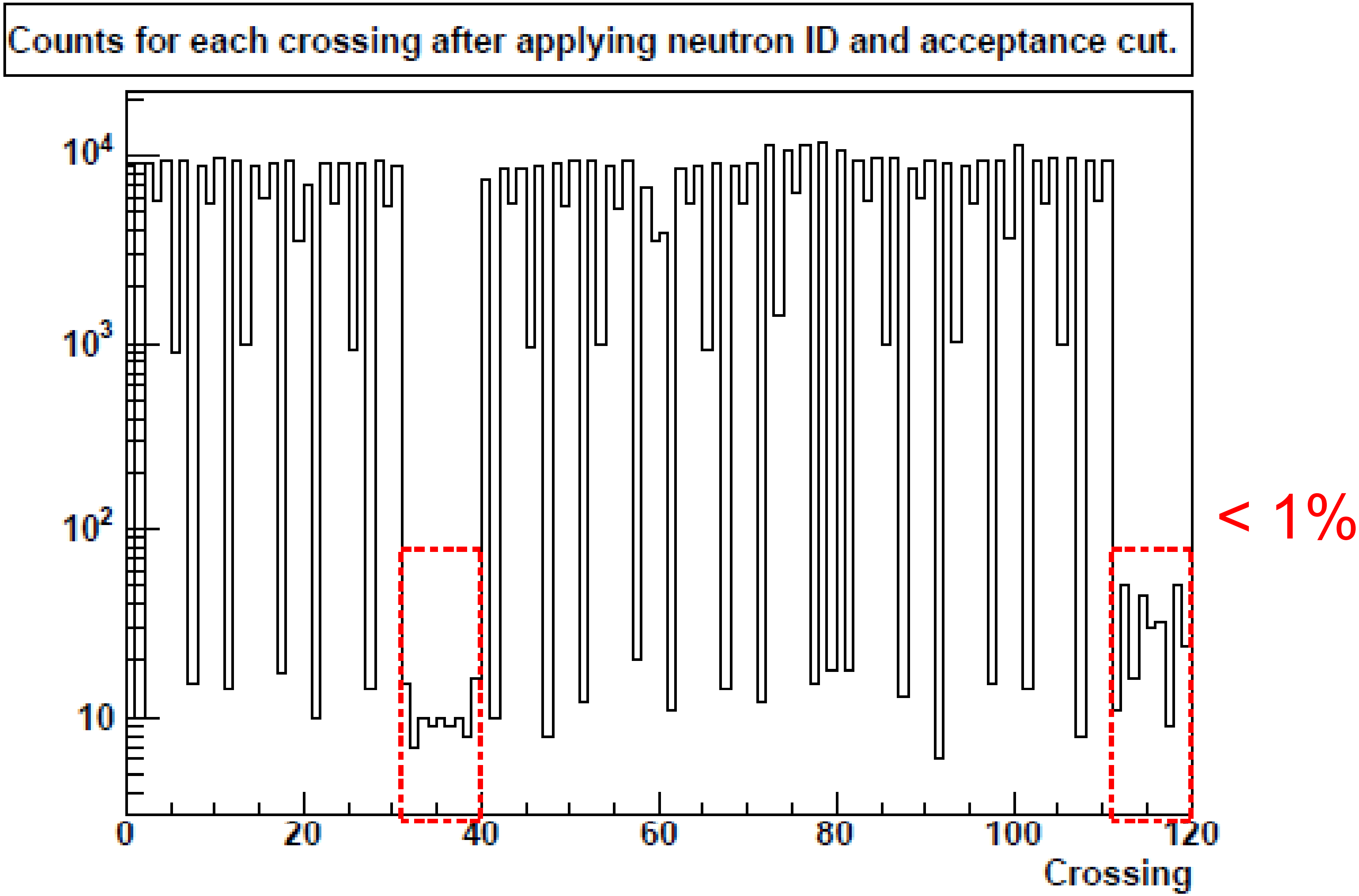
Smeared to 7.4%

Event ratio.

- For Left-Right asymmetry (RUN#178606), after neutron ID,
  - BBC hits & ZDC hit : 3167520
  - ZDC hit : 16576168

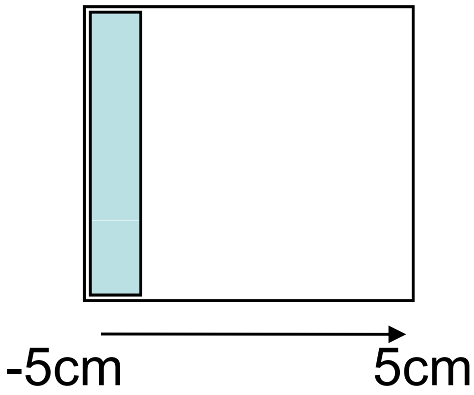
    → ~5 times higher for neutron detection.

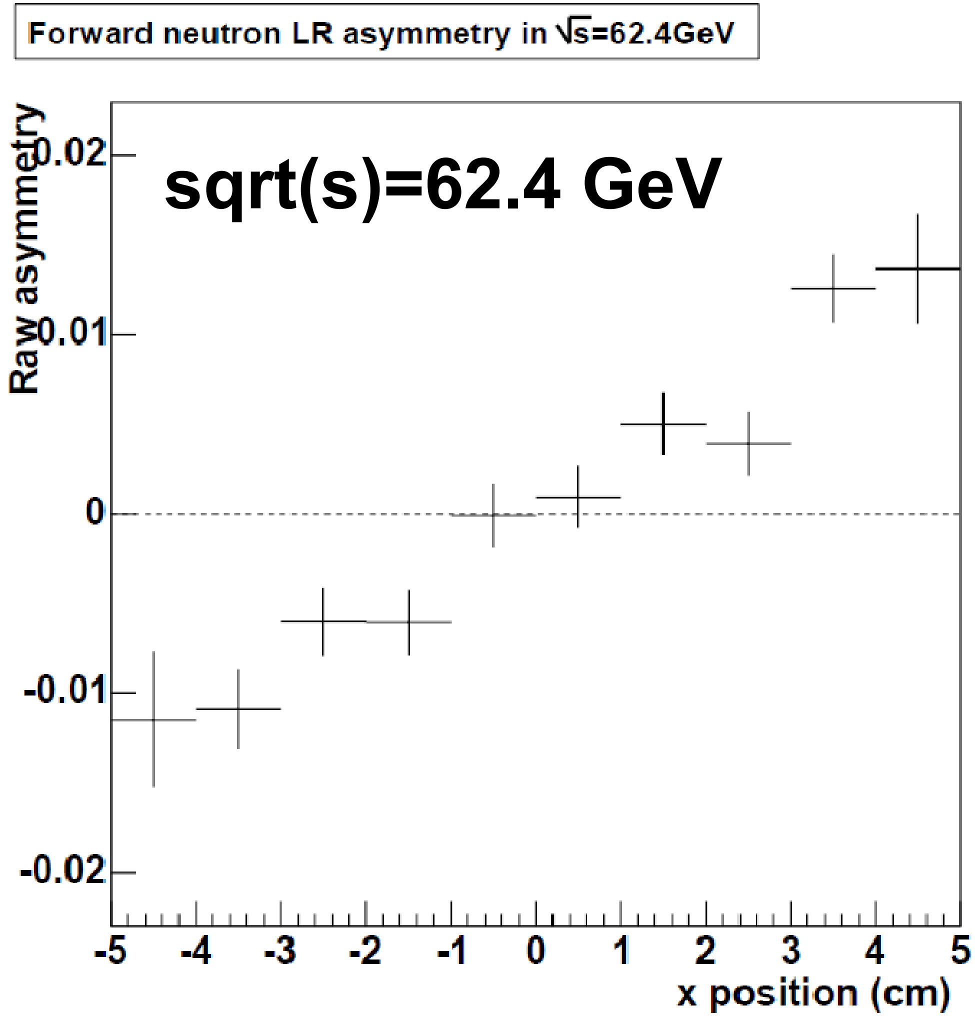
Beam gas study.

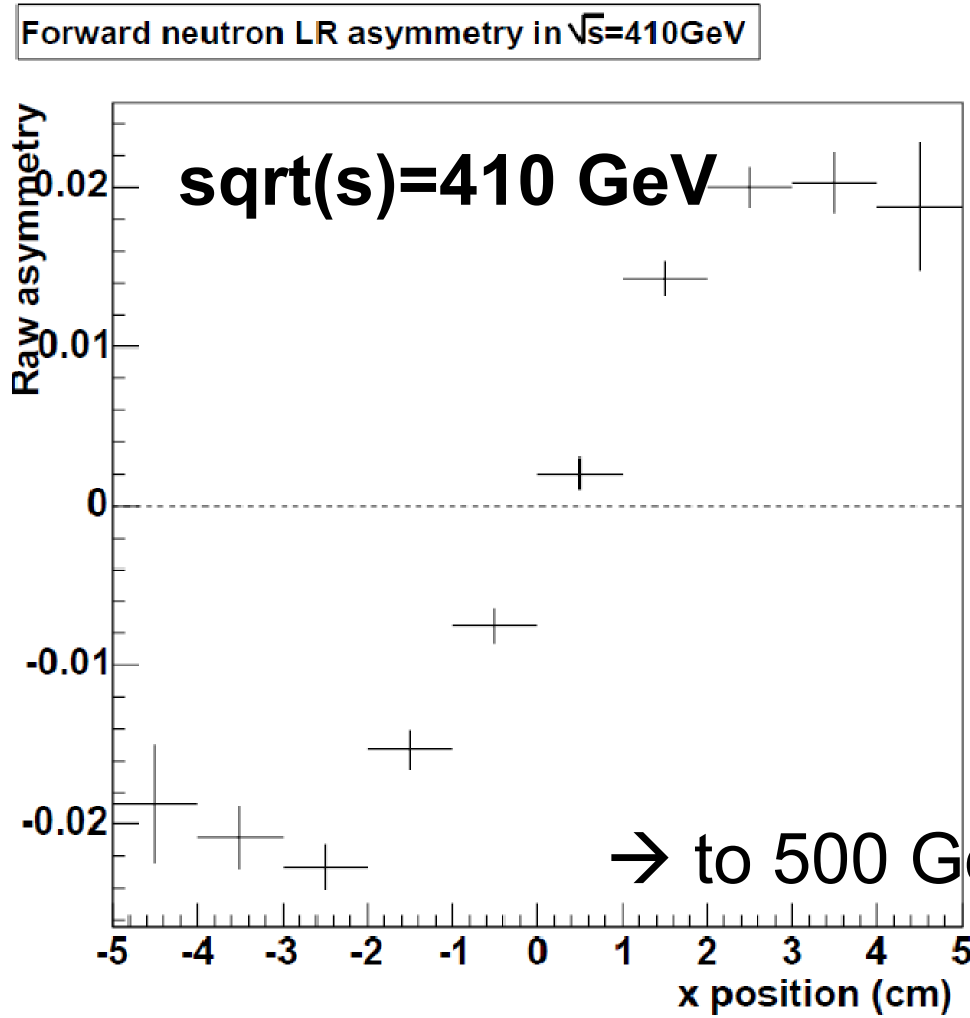


We can see finite asymmetry in other energy RUN !

$$A_N \equiv \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{1}{Pol.} \frac{N^{\uparrow} - RN^{\downarrow}}{N^{\uparrow} + RN^{\downarrow}} \qquad R \equiv \frac{L^{\uparrow}}{L^{\downarrow}}$$





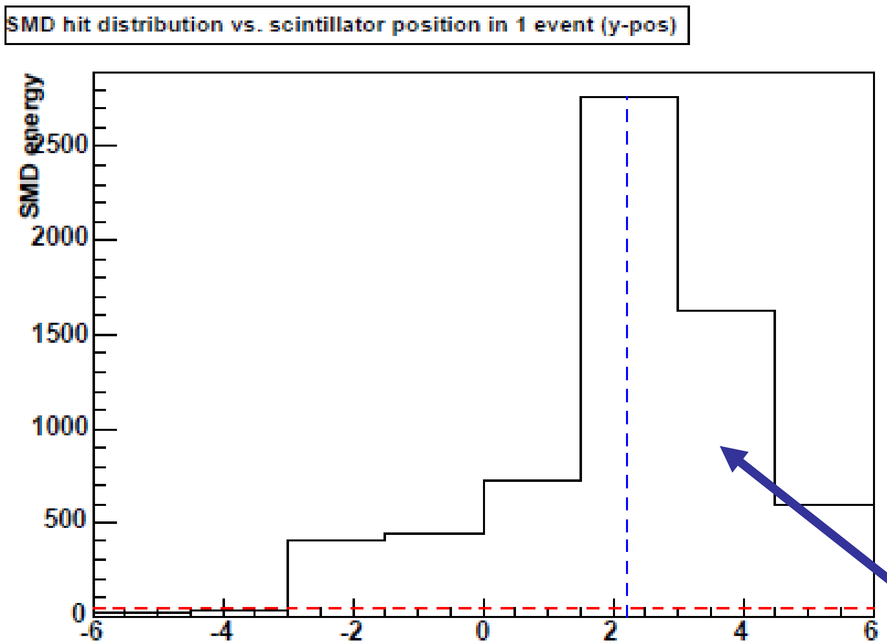


→ to 500 GeV

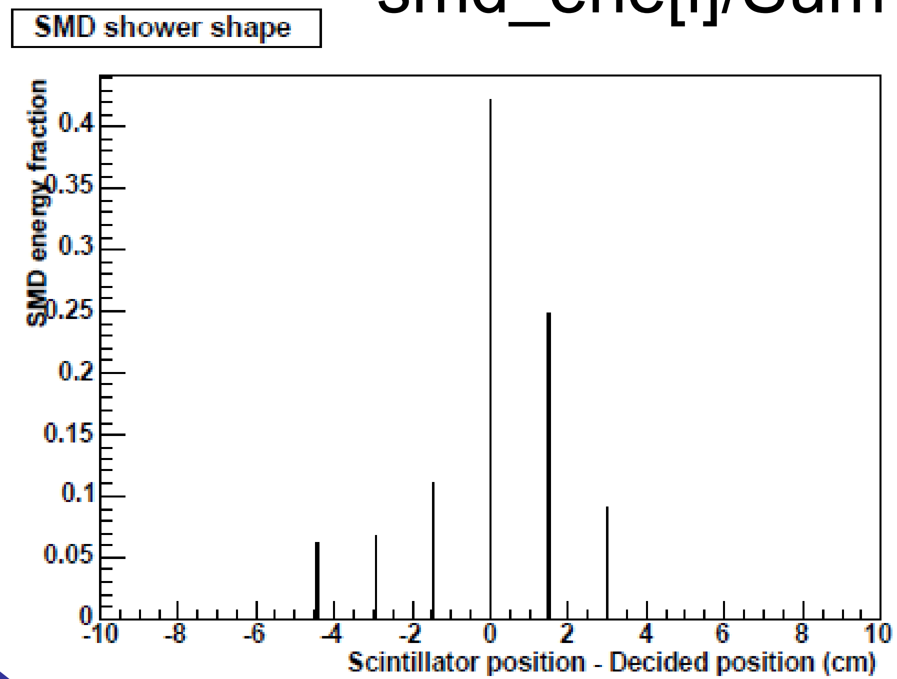
Shower Shape study

- Shower shape

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



Sincitllator position

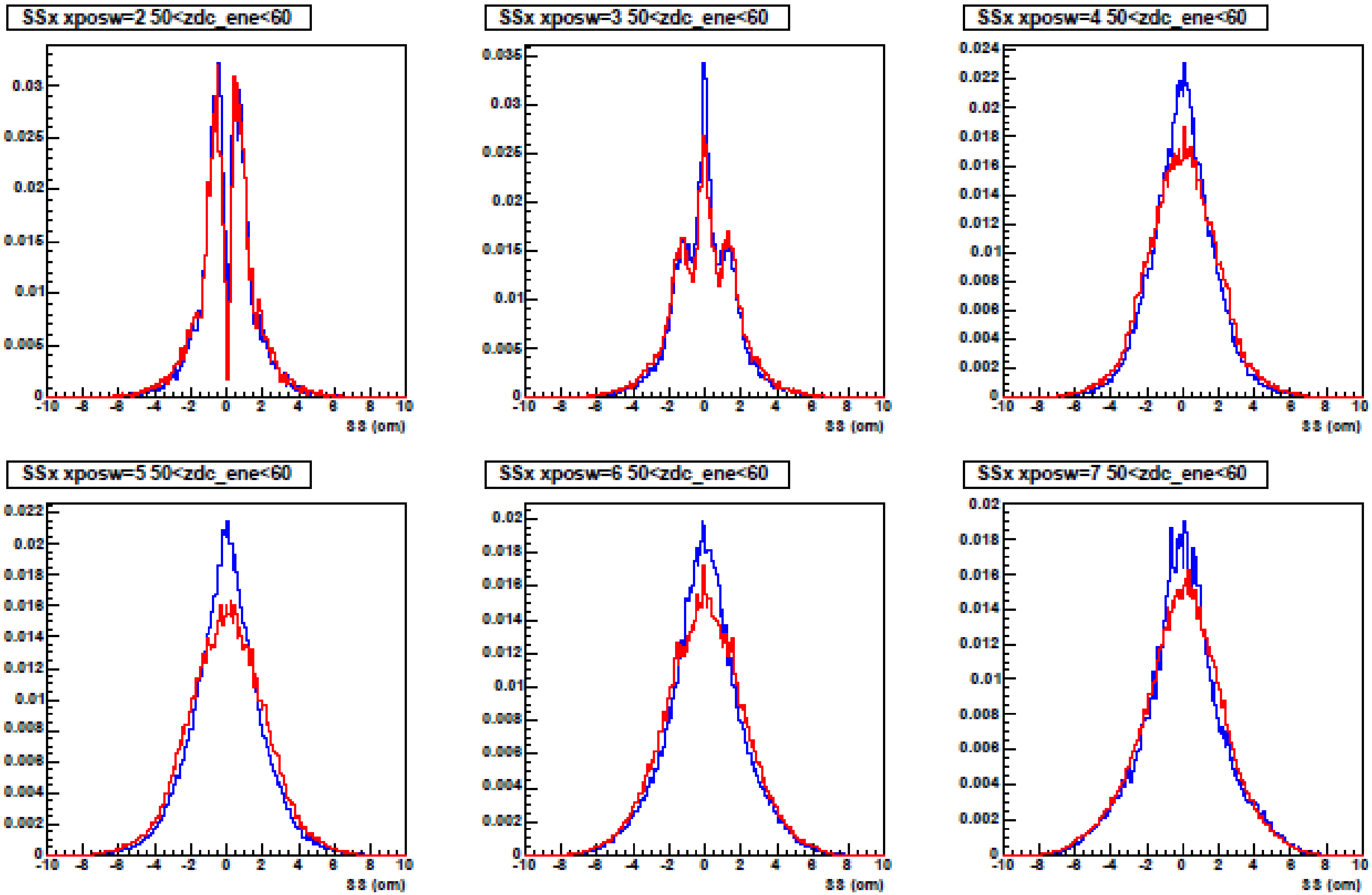


Position decided by centroid method

  - Looking by each energy and N of scintillator hits.

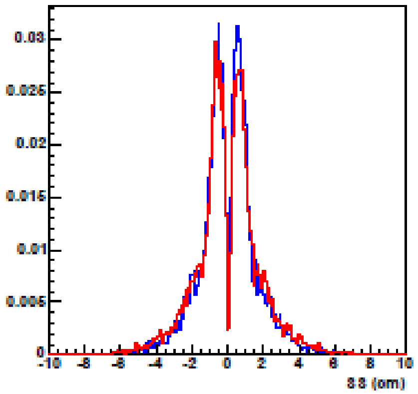
- PF (peak fraction)
  - Defined as smd_ene[peak] /Sumy

Shower Shape for x

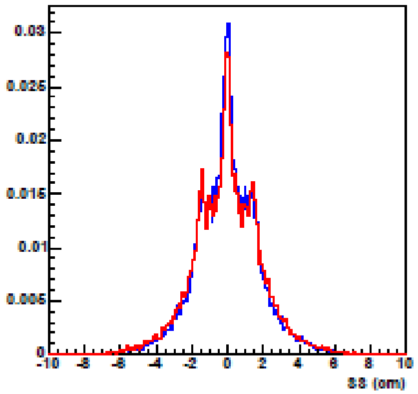


Shower Shape for y

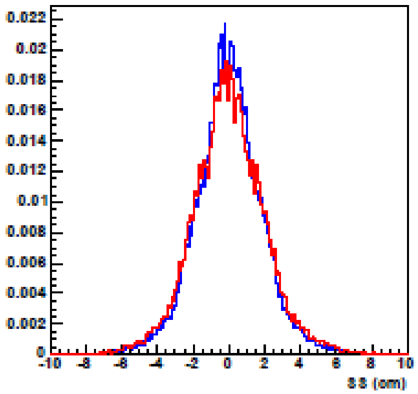
SSy yposw=2 50<zdc_ene<60



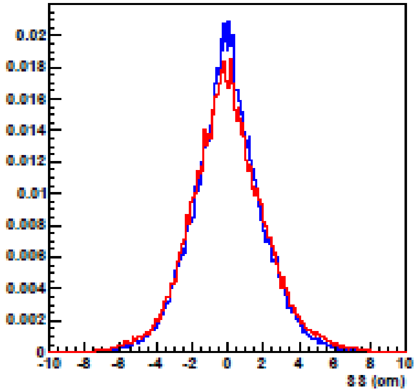
SSy yposw=3 50<zdc_ene<60



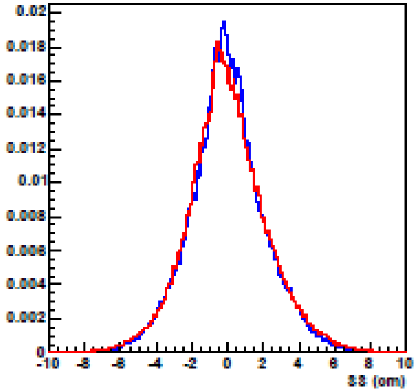
SSy yposw=4 50<zdc_ene<60



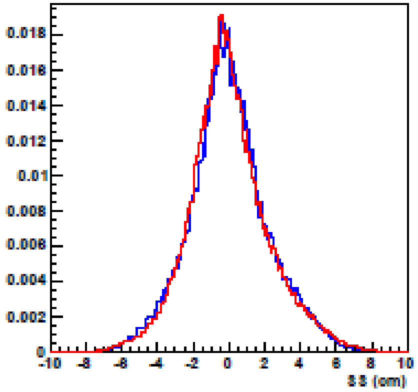
SSy yposw=5 50<zdc_ene<60



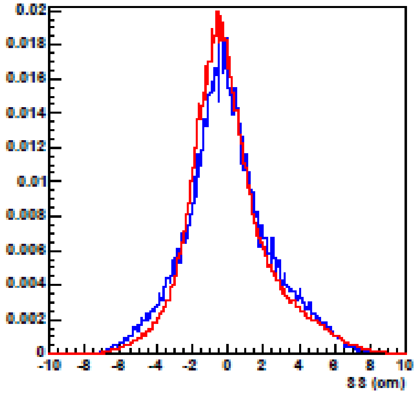
SSy yposw=6 50<zdc_ene<60



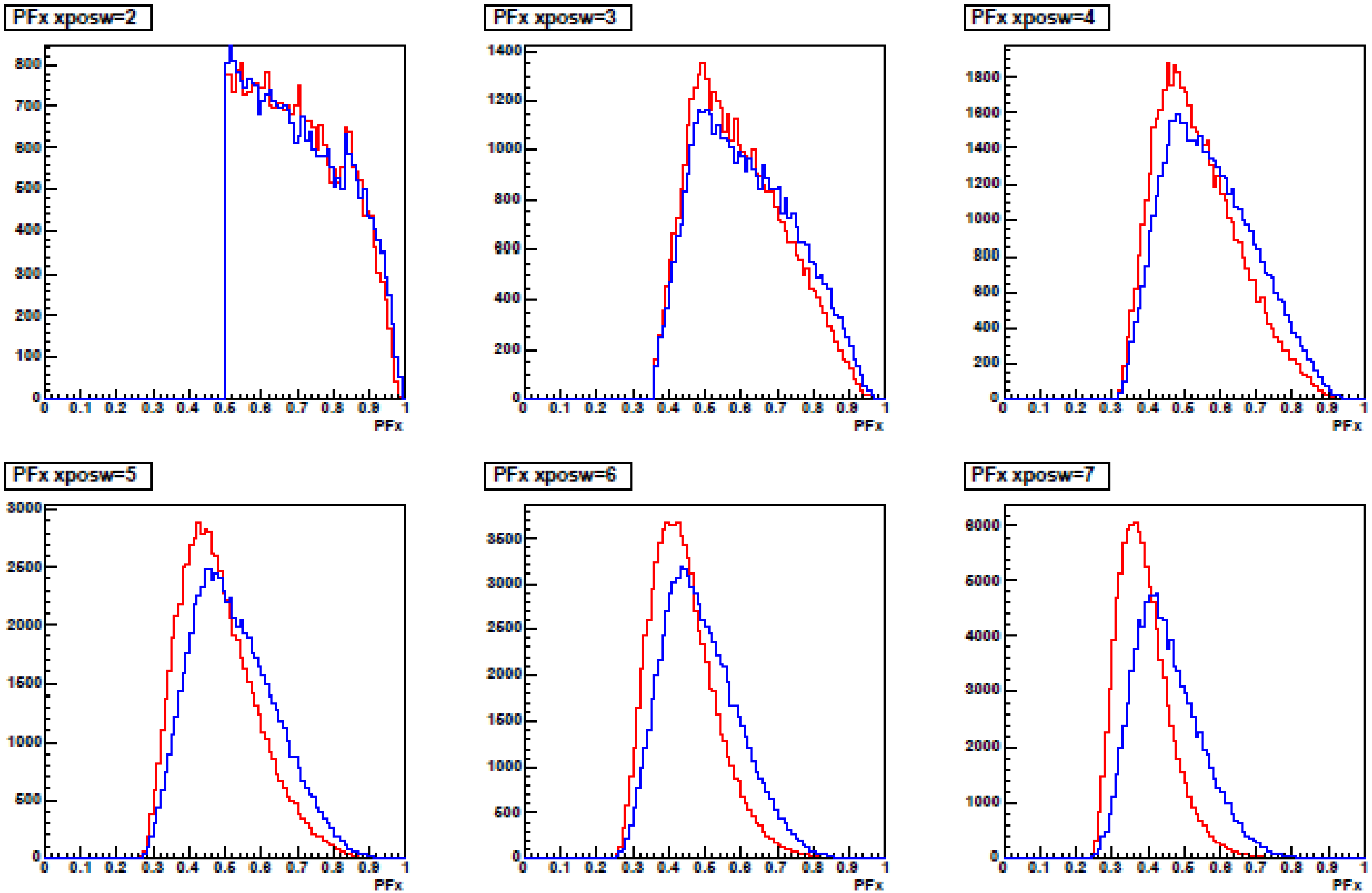
SSy yposw=7 50<zdc_ene<60



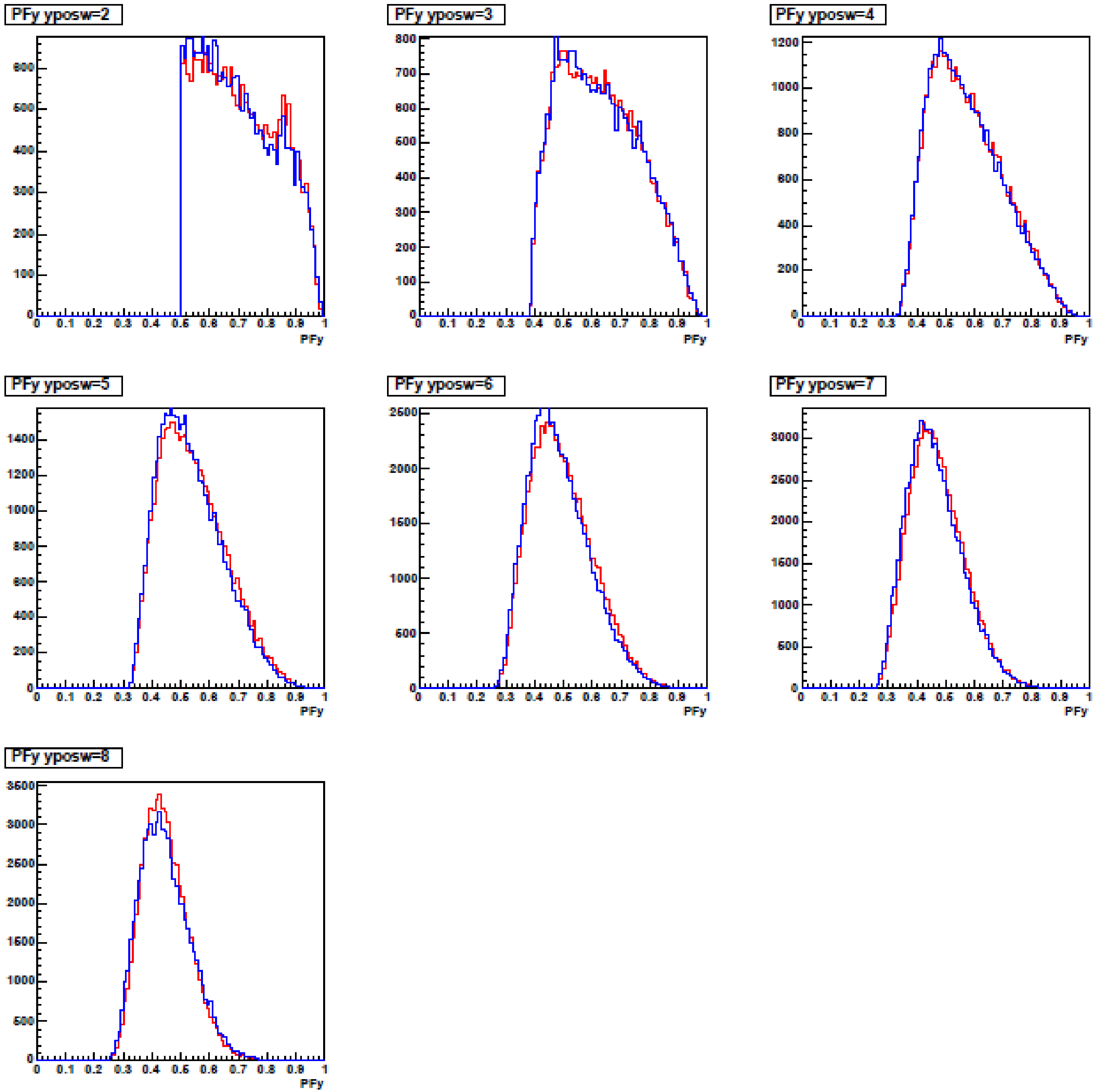
SSy yposw=8 50<zdc_ene<60



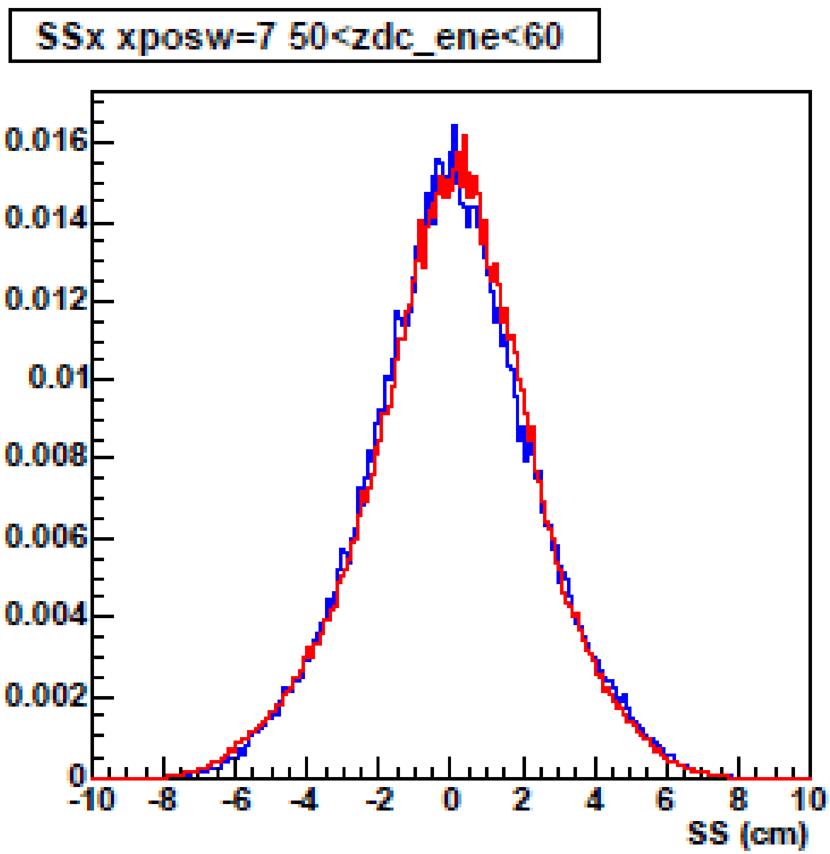
Peak fraction for x

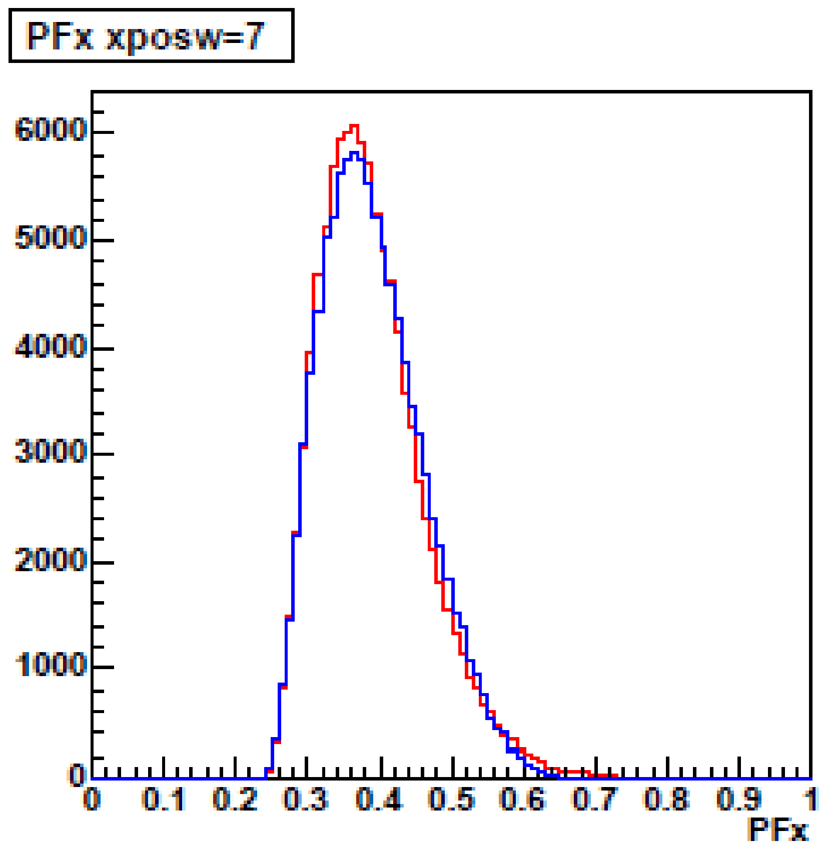


Peak fraction for y



After the smearing.

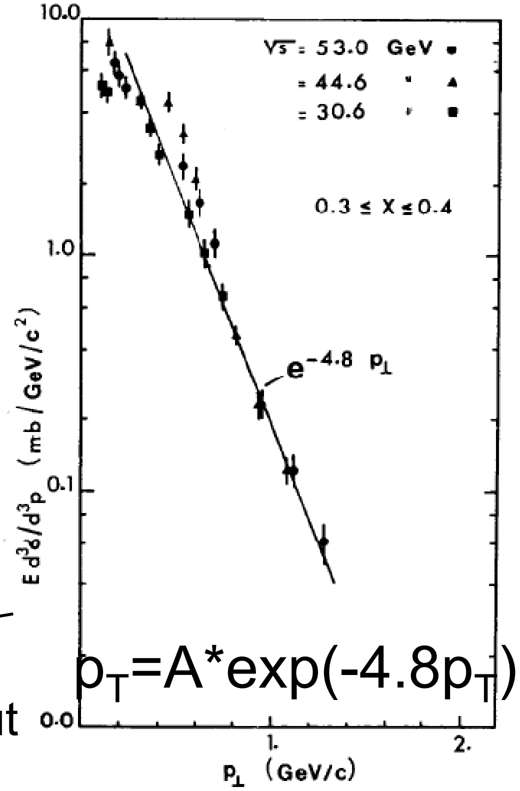




Cross section calculation

- 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

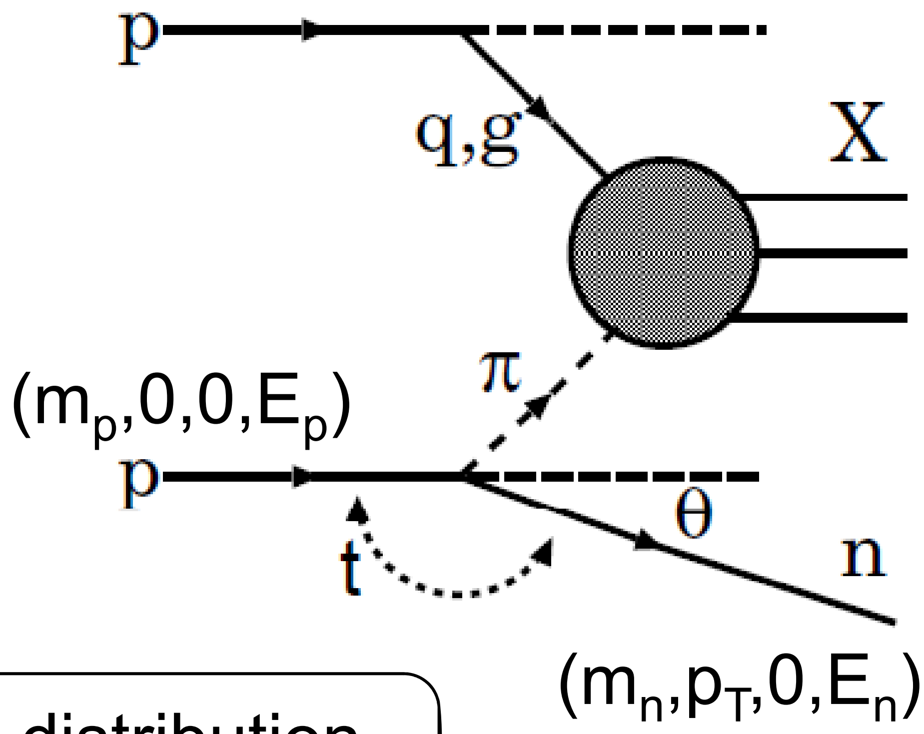
ISR data is converted to current cut. ($0<p_T<0.11x_F$ GeV/c)

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

t-range

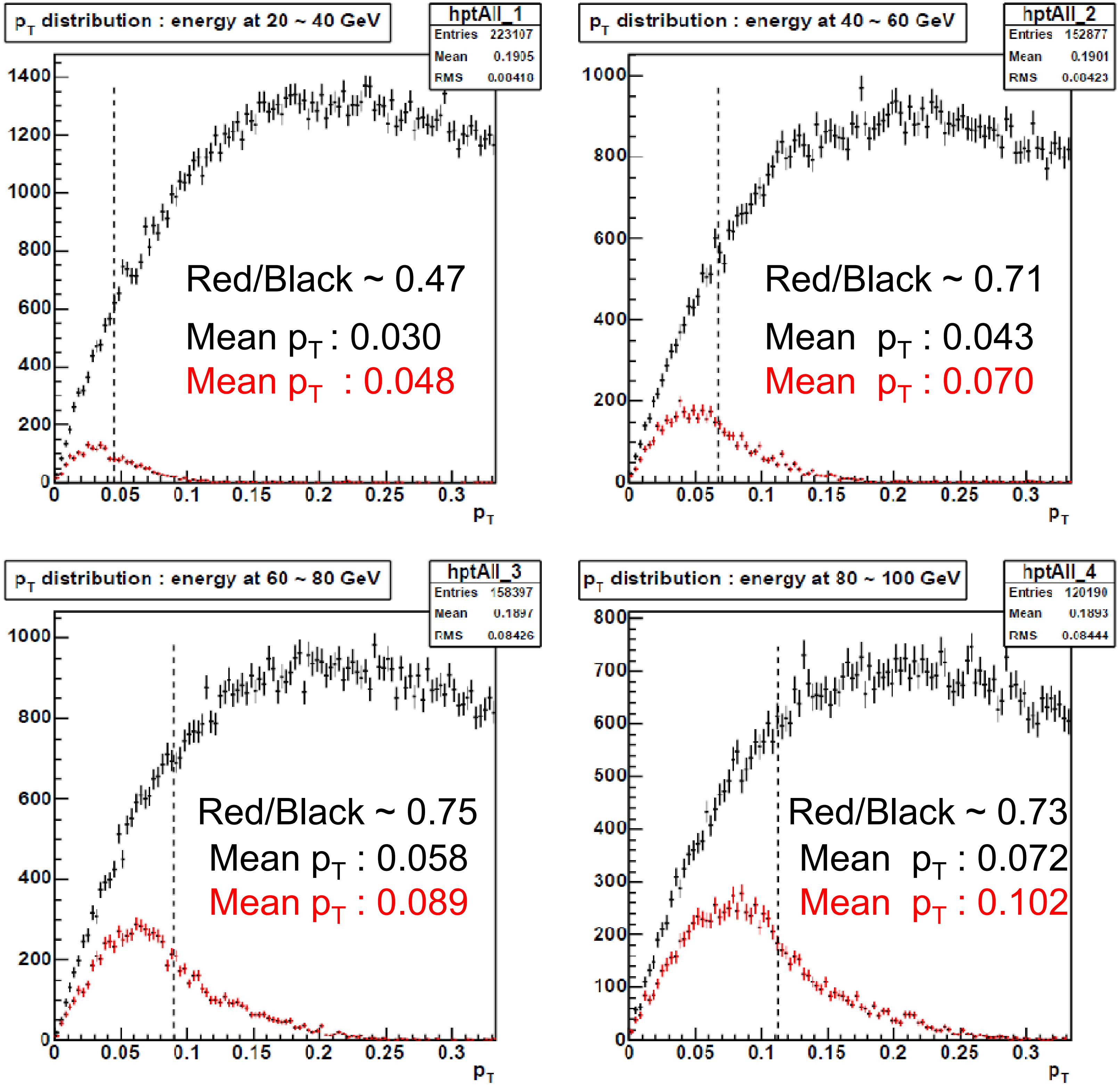
$$x_F = \frac{E_n}{E_p}$$

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



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



p_T distribution : energy at 20 ~ 40 GeV
hptAll_1
Entries 223107
Mean 0.1905
RMS 0.00410
Red/Black ~ 0.47
Mean p_T : 0.030
Mean p_T : 0.048
p_T
p_T distribution : energy at 40 ~ 60 GeV
hptAll_2
Entries 152877
Mean 0.1901
RMS 0.00423
Red/Black ~ 0.71
Mean p_T : 0.043
Mean p_T : 0.070
p_T
p_T distribution : energy at 60 ~ 80 GeV
hptAll_3
Entries 158397
Mean 0.1897
RMS 0.08426
Red/Black ~ 0.75
Mean p_T : 0.058
Mean p_T : 0.089
p_T
p_T distribution : energy at 80 ~ 100 GeV
hptAll_4
Entries 120190
Mean 0.1893
RMS 0.08444
Red/Black ~ 0.73
Mean p_T : 0.072
Mean p_T : 0.102
p_T

Systematic error for C.S.

- Systematic error in calibration
  - Energy calibration ~5%
  - SMD relative calibration (it is including in SMD cut eff)
  - Trigger bias correction. < 10%
- Systematic error in simulation
  - Acceptance few % from pt distribution by SMD pos cut.
  - SMD cut eff. ~3%
  - Neutron ID
    - SMD shape match. ~ 3%
    - Forward counter match. ~5%
  - Background estimation. apply 100% error for BG ratio.
    - Mainly from K0 and proton
    - For cross section 8%
  - 2 particle in 1 event ~ 5%
- Systematic error in luminosity
  - Cross section error 13% (22.9 mb * 0.591) for NoVtxCut
- In total
  - For shape after cut : ~11.6% For scaling of cross section : 17.1%

Systematic error for phi-asym.

- Measurement : 1%
  - Bunch shuffling result is ~2% of statistics, RUN5 local pol analysis note. (AN462)
  - Center scan ~ 1%
  - Beam gas BG at ZDCN|S trigger : 0.2%
- Simulation uncertainty 4.1%
  - Simulation stat 2%
  - pT match : few%
  - BG estimation 3%
  - Center cut scan 2%
- Total : 4.2%

- Online polarization 20% → scaling error.

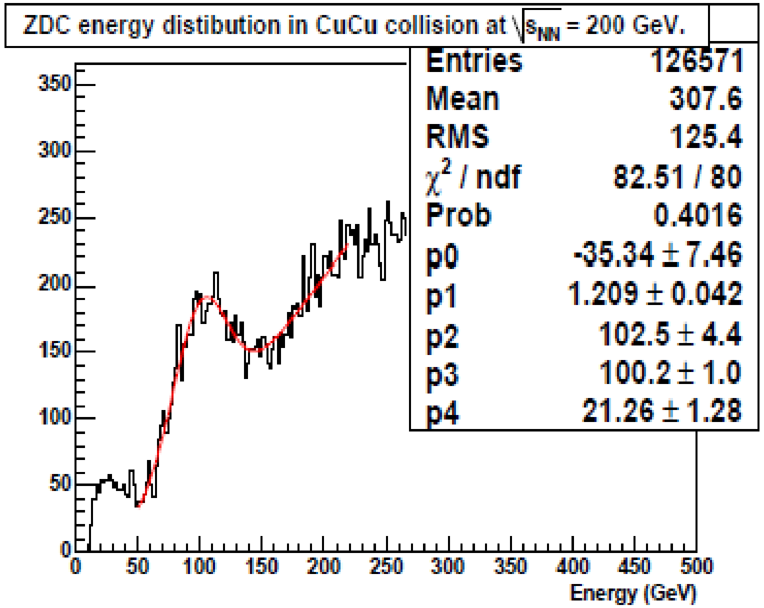
Systematic error for x_F-asym.

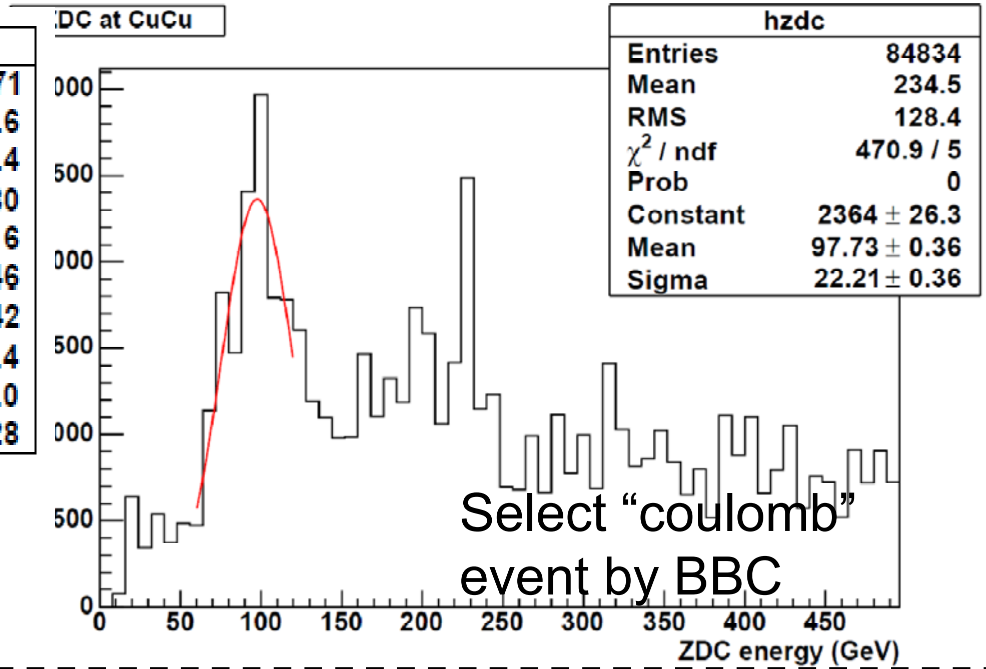
- Estimation from measurement : 2%
  - ~4% of statistics, by bunch shuffling.
  - Center scan ~ 2%
  - Beam gas BG at ZDCN|S trigger : 0.2%
  - Unfolding : calibration (bin by bin → 18p)
    - x_F : 0.4~0.6 : 2.1%   0.6~0.8 : 0.3%   0.8~1.0 : 0.3%
- Simulation uncertainty 7.8%
  - BG estimation 3%
  - Position smearing estimated by center cut scan (Differences between PHENIX and flat x_F inputs) 7.2%
  - Unfolding : linearity (bin by bin → 17p)
    - x_F : 0.4~0.6 : 12.1%   0.6~0.8 : 2.1%   0.8~1.0 : 2.1%
- Total : 8.1% of asymmetry value (not including blue term)

Calibration (ZDC)

- Neutron cainbration is done by 1 neutron peak from heavy ion run.

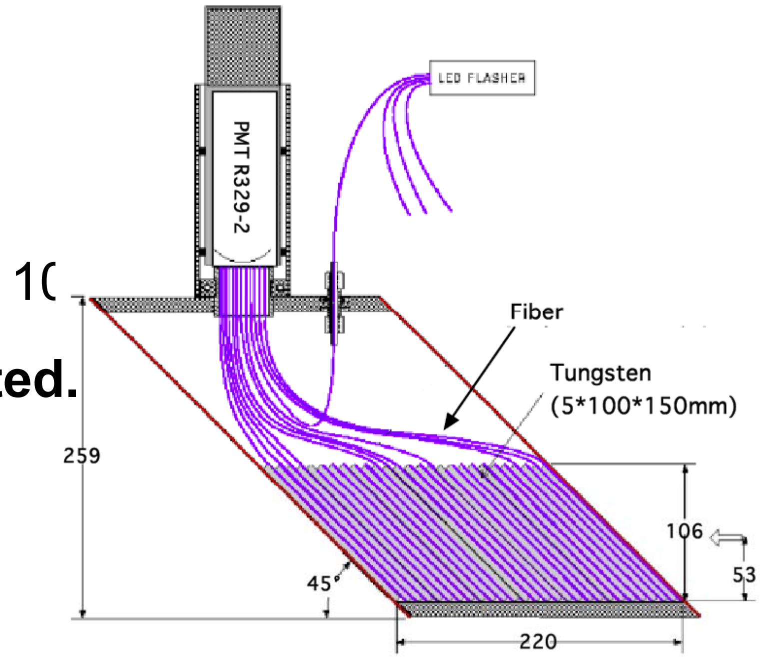
We can see 100 GeV peak in CuCu event

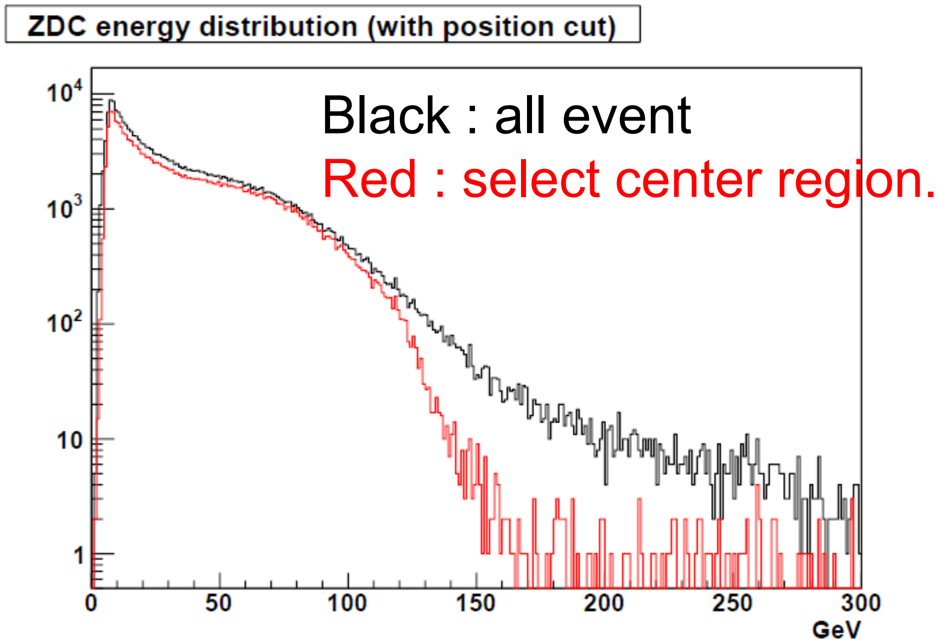




Select "coulomb" event by BBC

pp event after calibrated.



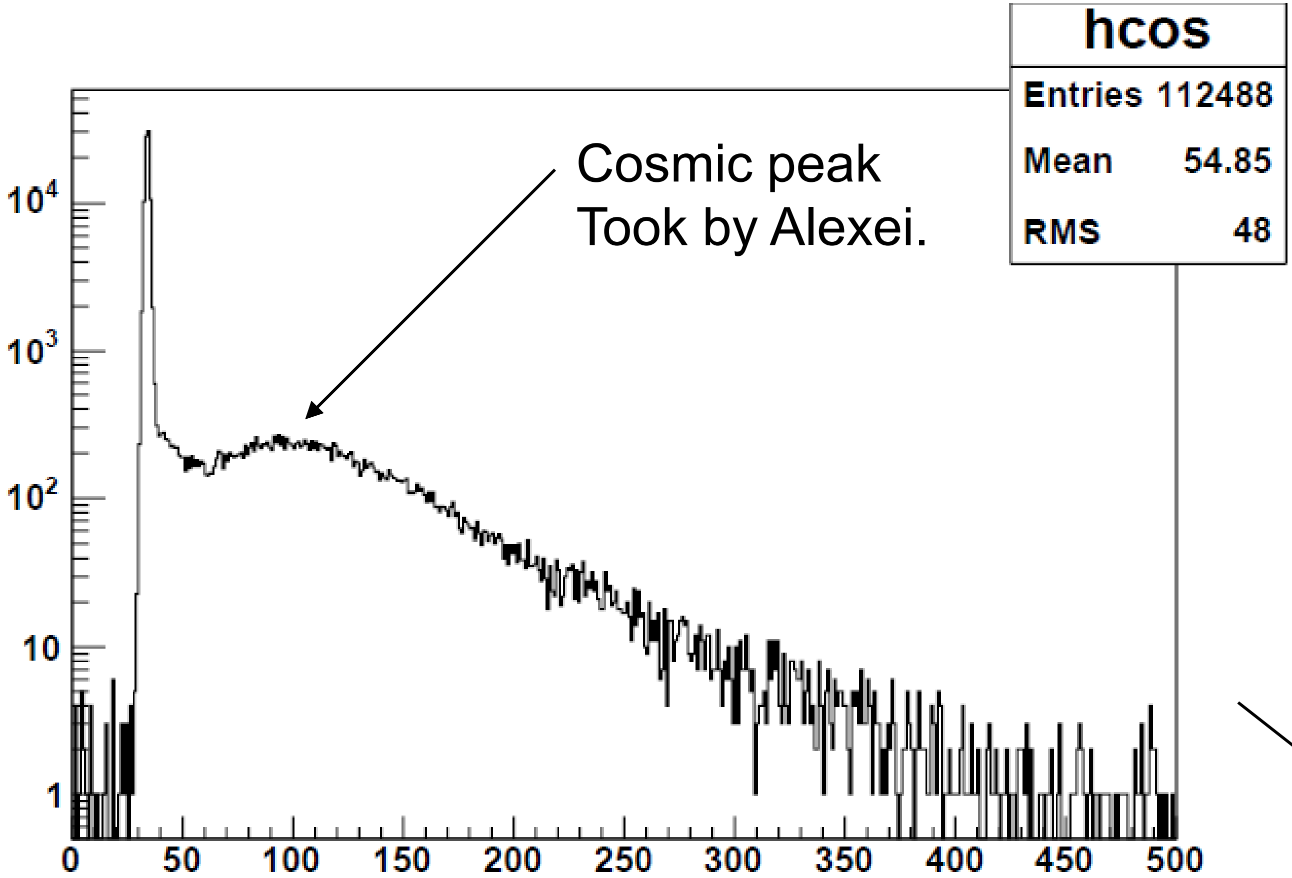


Black : all event

Red : select center region.

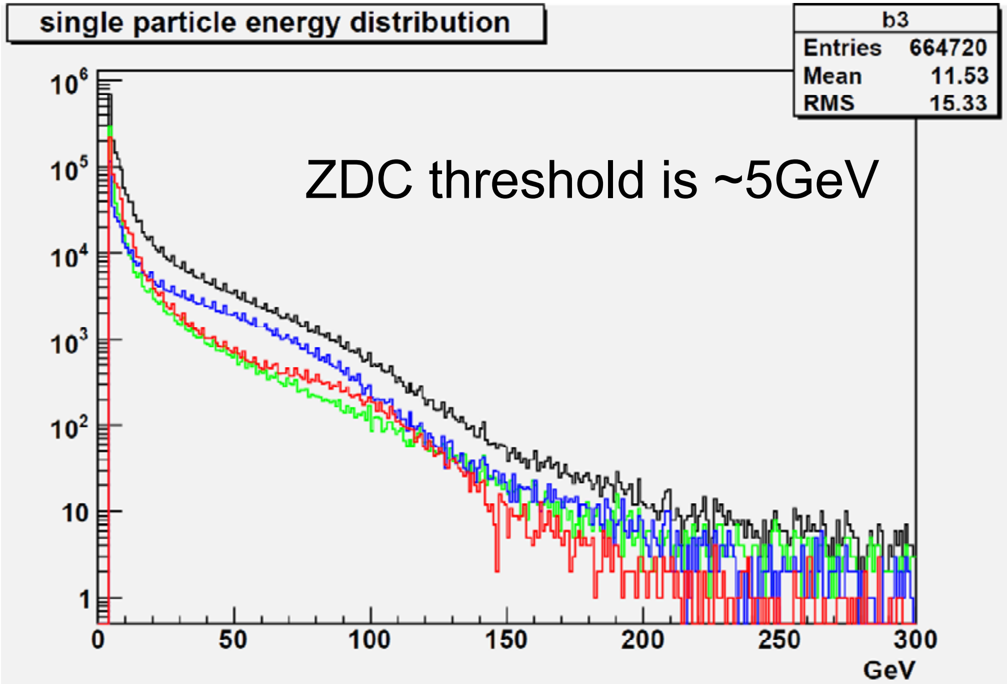
Calibration (SMD)

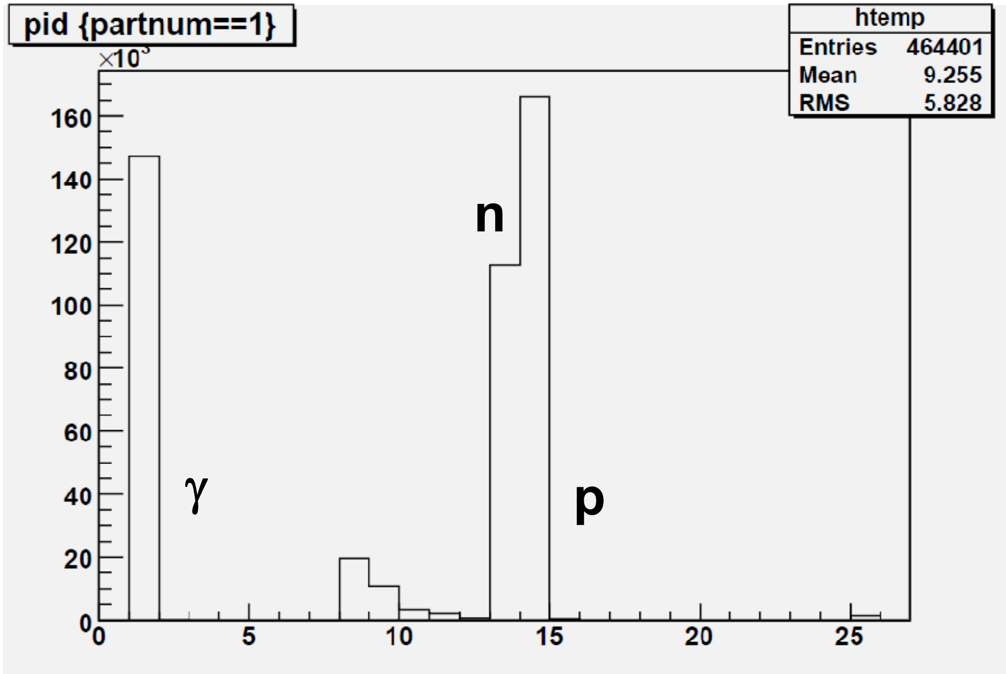
Relative gain of each channels are matched by cosmic ray data.



Compared with simulation data.
See simulation term.

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.

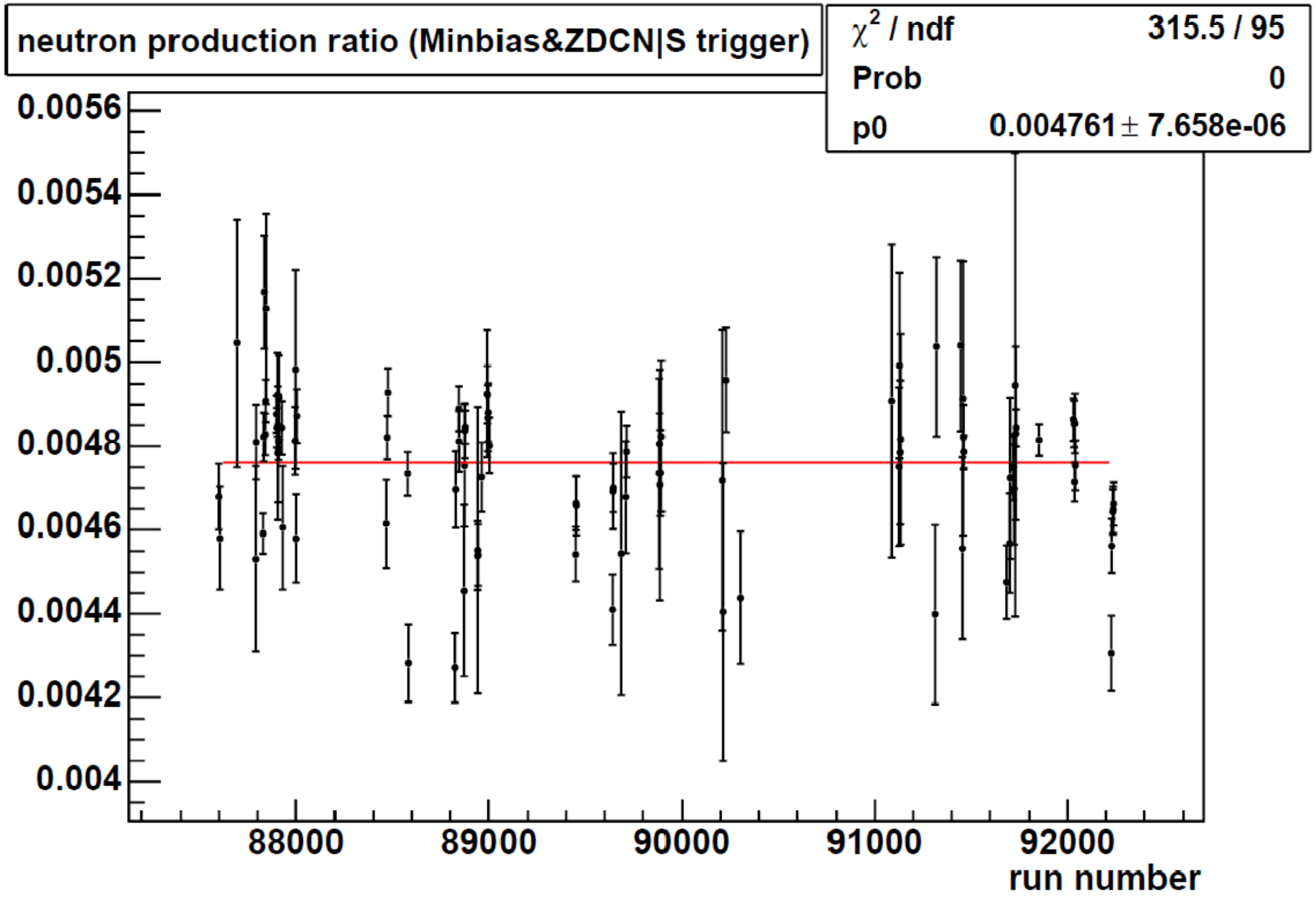
E (GeV)	K0 (%)	Proton (%)
10-20	16.67	11.11
20-30	5.97	2.99
30-40	4.69	2.34
40-50	1.75	3.59
50-60	1.78	4.14
60-70	1.50	5.00
70-80	1.18	1.76
80-90	0	2.14
90-100	0	9.71

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

Neutron measurement stability

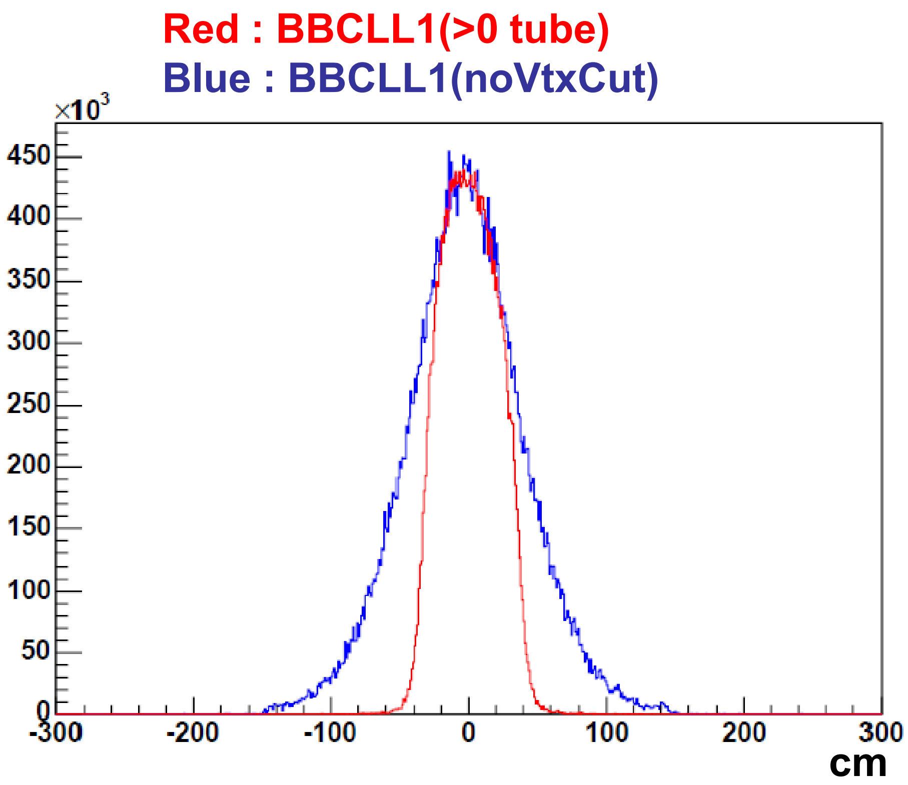
$$\frac{N\ of\ \ neutronID}{N\ of\ \ BBCLL1}$$

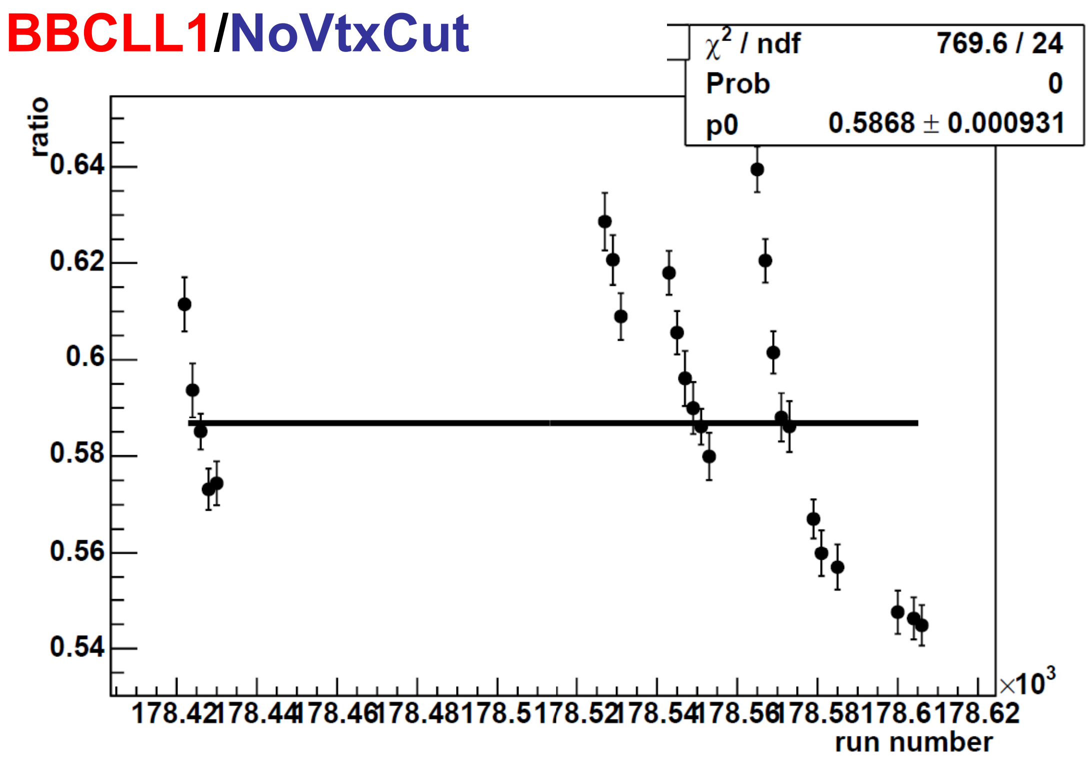


Stability = 7.65762e-06/4.76148e-03*sqrt(315.5/95) = 0.3 %.

BBCLL1 bias study.

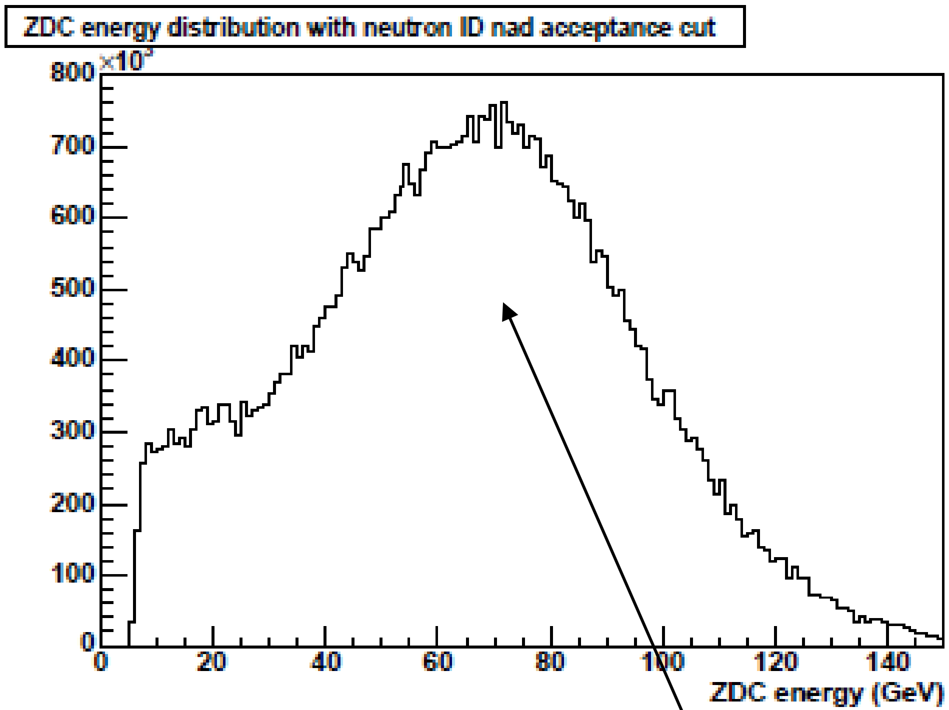
RUN5 pp MB looking 22.9 ± 9.7mb
For neutron C.S. correct BBCLL1 cut efficiency.

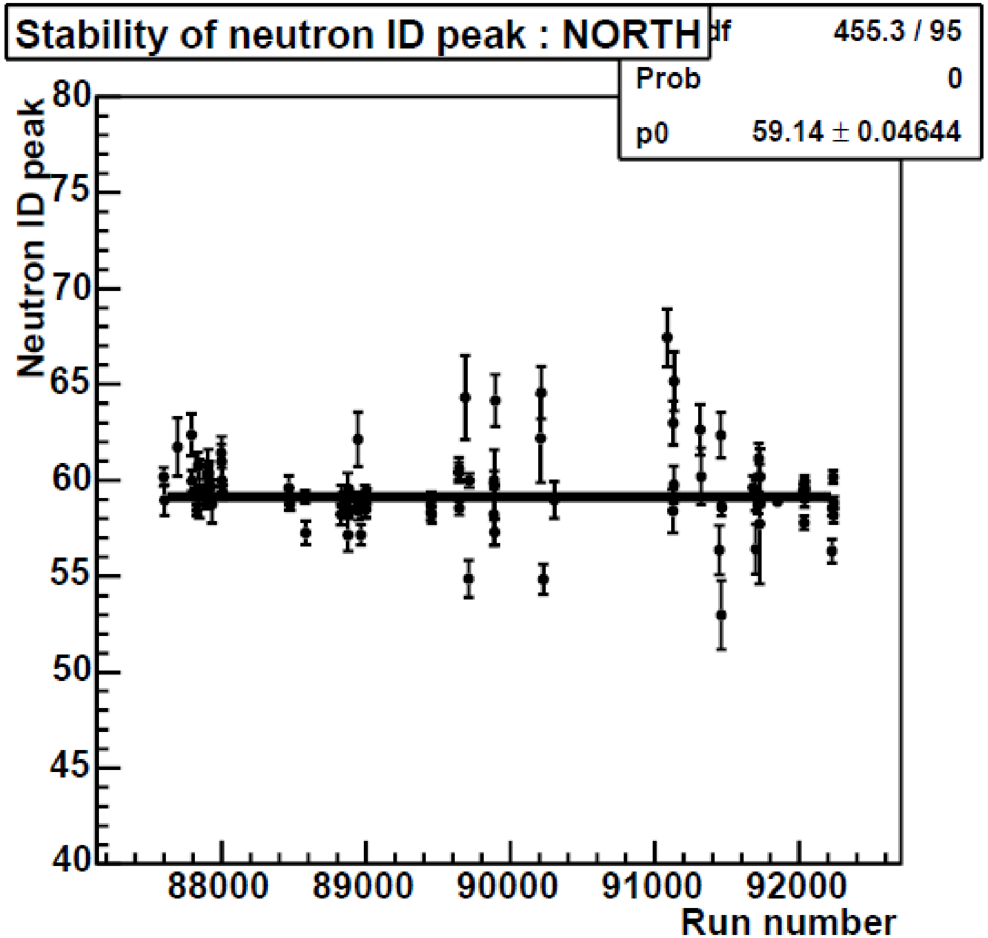




0.591 ± 0.05 (for maximum error)
→ 8.46%

Stability of neutron peak after cut

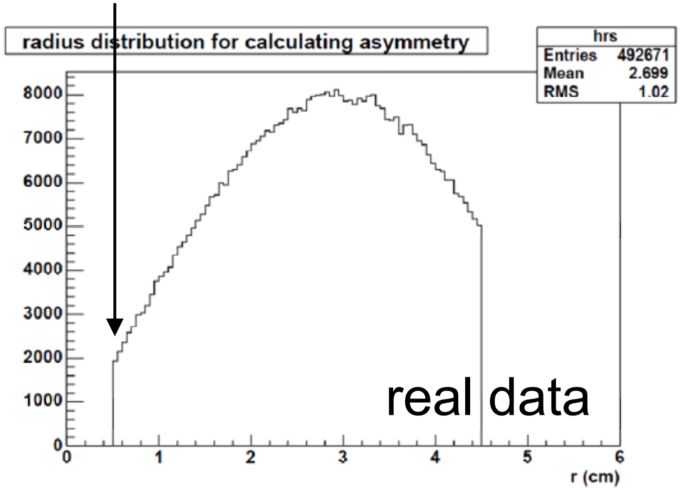


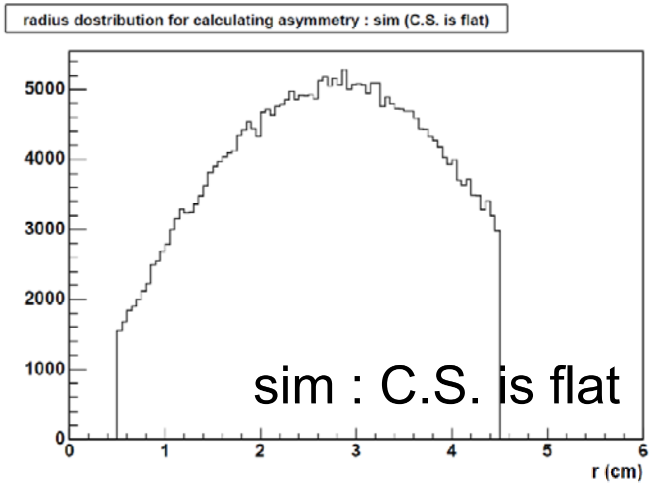


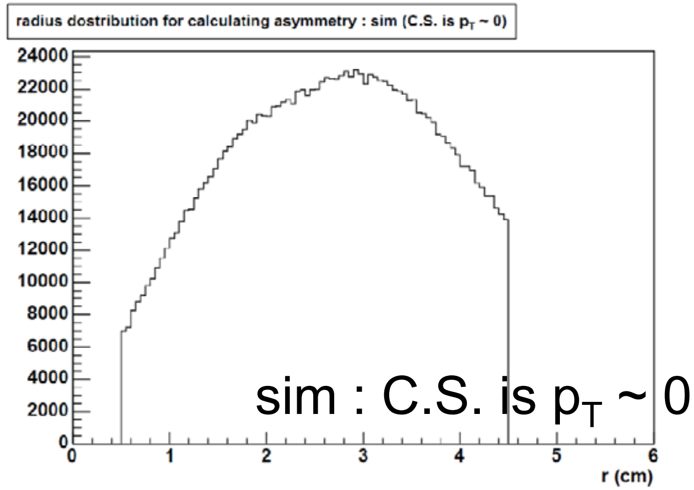
This peak

Radius distribution for calculating asymmetry

Center cut by r>0.5cm







Cut radius	0.5	1.0	2.0
Real data	0.0308	0.0320 (1.039)	0.0341 (1.107)
sim (center)	0.0829	0.0853 (1.029)	0.0922 (1.112)
sim (flat)	0.0814	0.0829 (1.018)	0.0884 (1.086)

* () means ration to cut radius = 0.5.

Differences of ratio will be systematic error : 2%

前方中性子測定

ISR実験

〇sqrt(s)=30~63 GeV

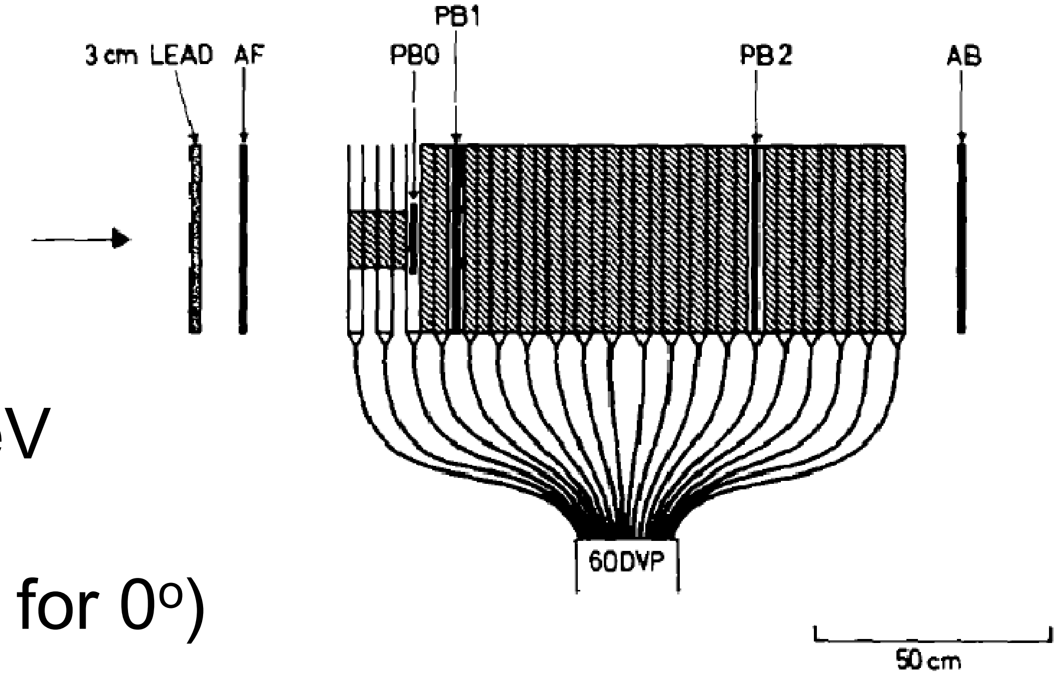
〇STAC

40*40*80 cm^3 (iron) 5.5λ_I

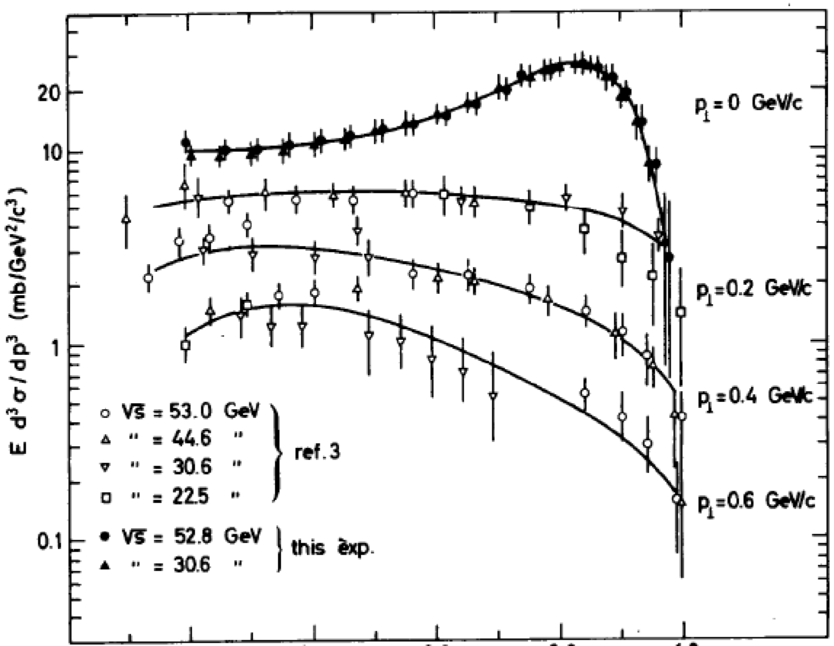
res. 26%@20GeV 19%@30GeV

〇They were placed in

0^o,20^o,66^o,119^o,(±1)mrad (56m for 0^o)



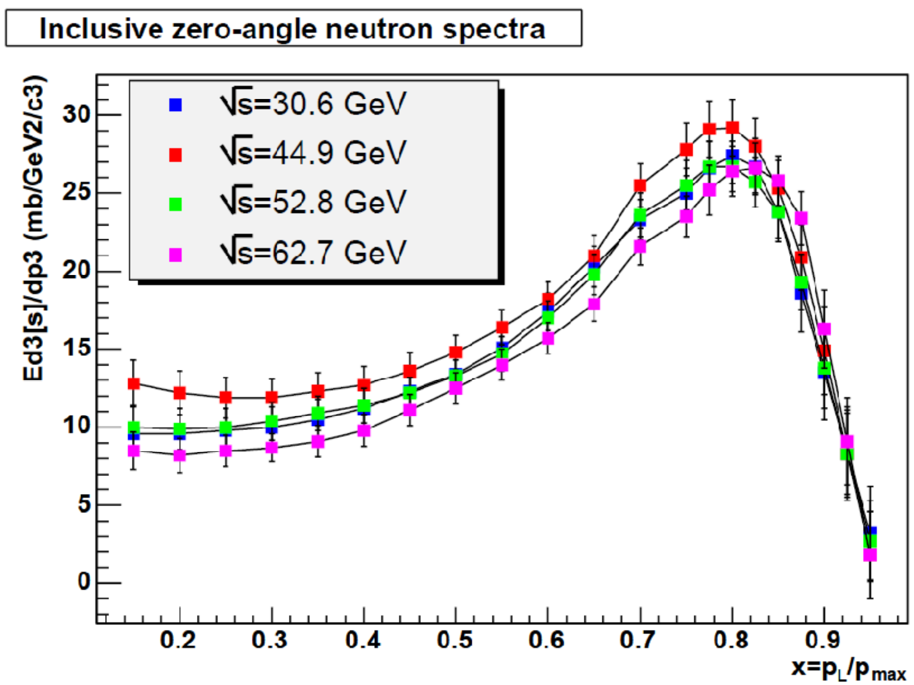
Forward peak



x_F

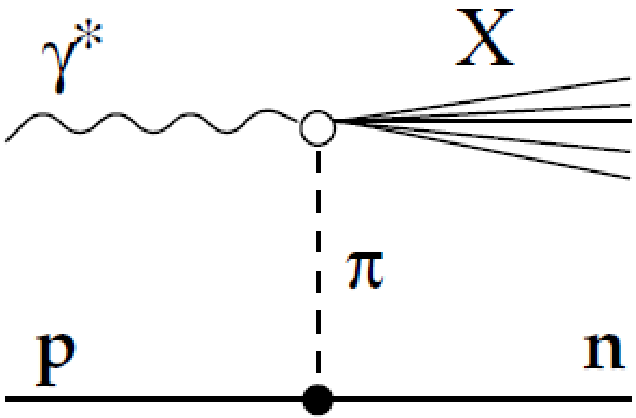
Nucl. Phys. B109 (1976) 347-356

x_F scaling



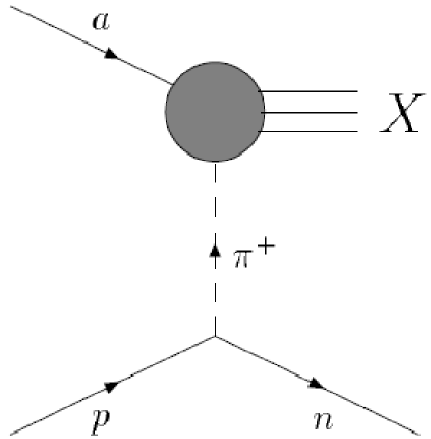
One pion exchange model

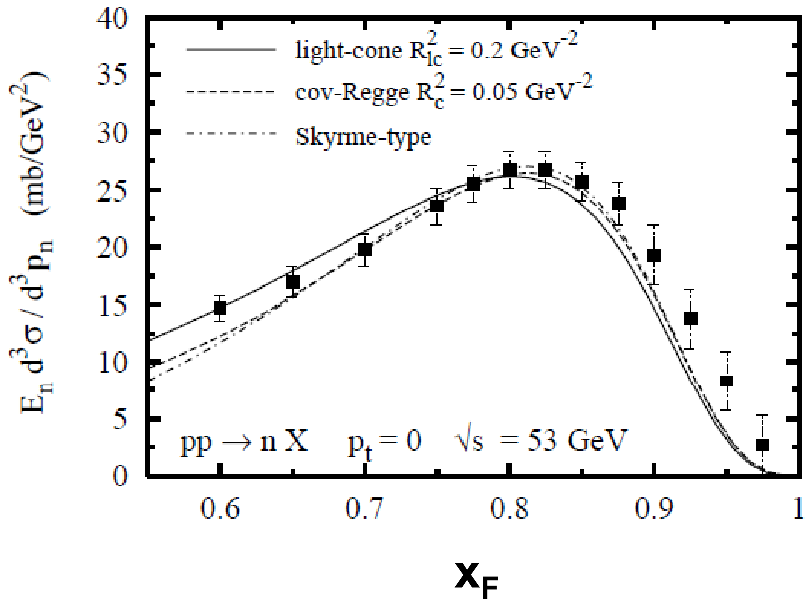
B. Kopeliovich et al. Z.Phys.C73:125-131,1996



π pole

Eur.Phys.J.A7:109-119,2000

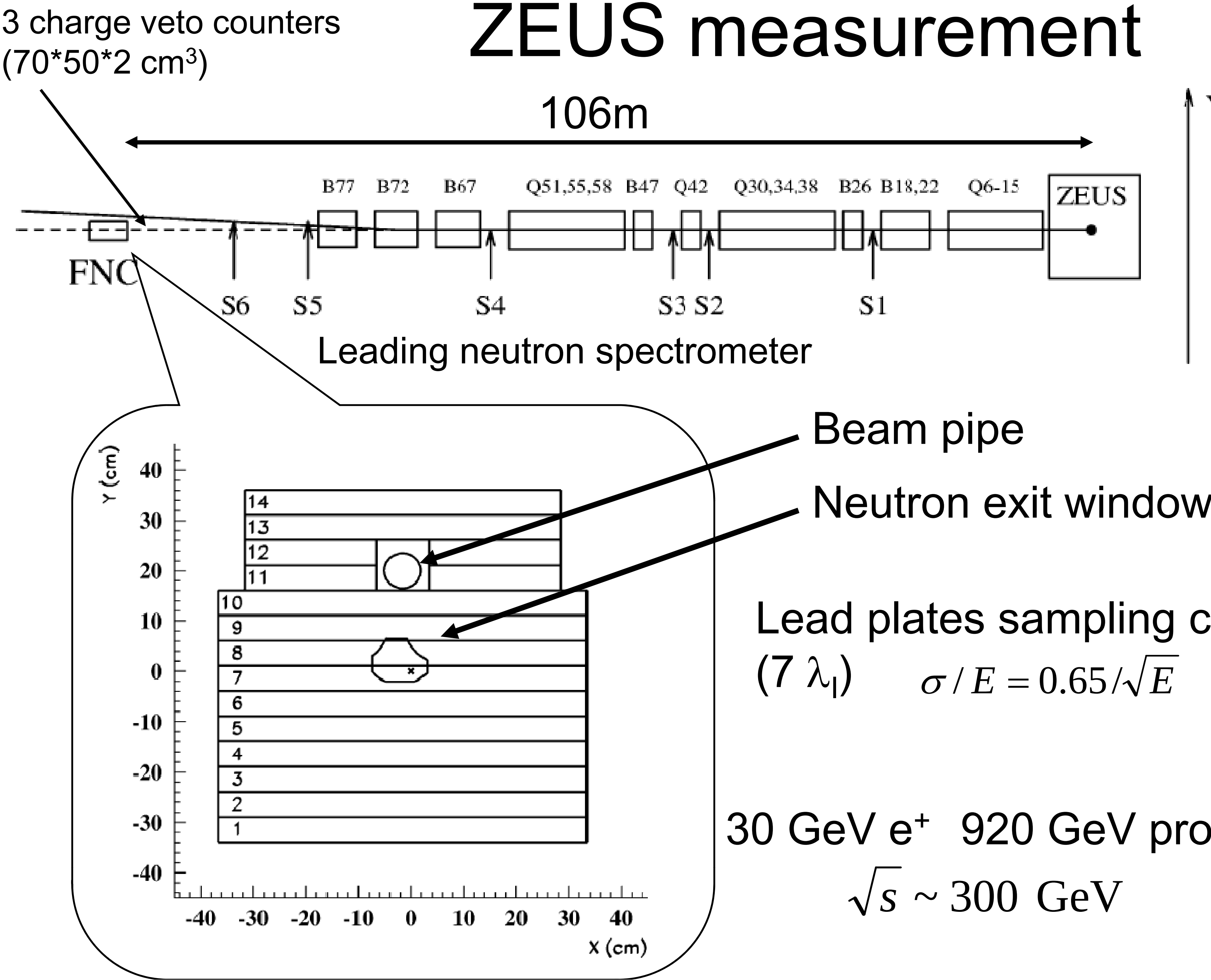




$$\frac{d\sigma_{hp\to Xn}}{dx_L\,dt} = f_{\pi/p}(x_L, t)\sigma_{\rm tot}^{h\pi}(s'),$$

Meson cloud model

ZEUS measurement



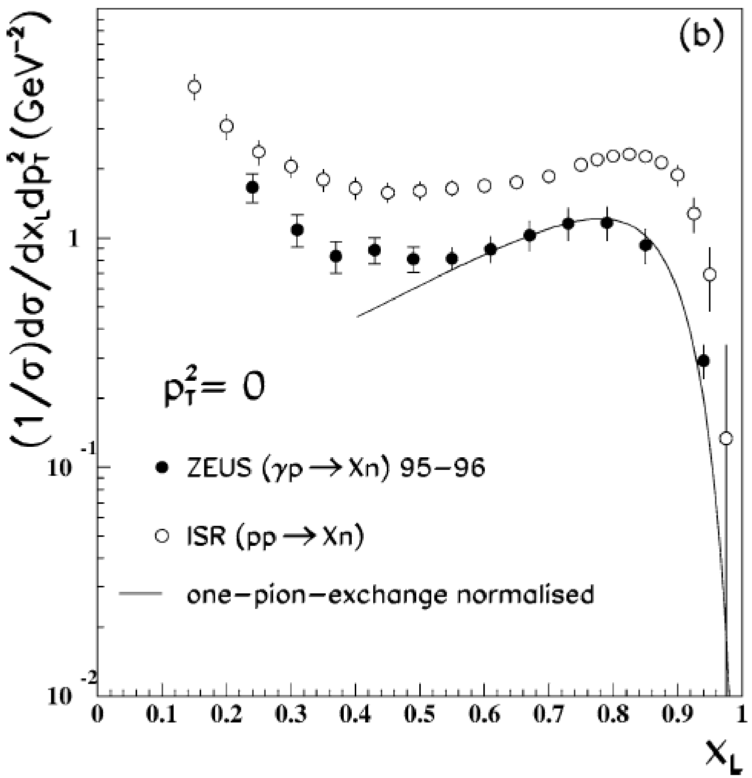
Lead plates sampling cal.
(7 λ_I) $\sigma / E = 0.65/\sqrt{E}$

30 GeV e^+ 920 GeV proton

$\sqrt{s} \sim 300\ \text{GeV}$

ZEUS results

Forward neutron



S. Chekanov et al. nuclear Physics B 637 (2002) 3–56

$$\frac{d\sigma_{ep\rightarrow e'nX}}{dx_L\,dt} = f_{\pi/p}(x_L,t)\sigma^{e\pi}(s'),$$

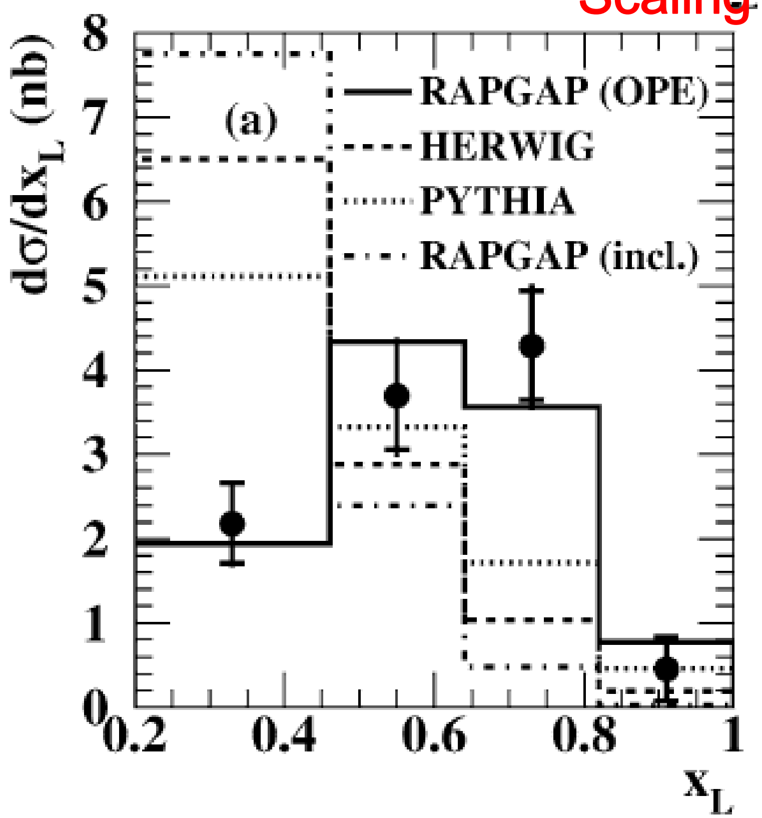
C.S. of neutron-tagged $D^{*\pm}$

epでの重クォーク生成はγg融合

↓

もし交換されたパイオンと仮想光子との反応ならパイオン内部のグルーオン構造関数が見えるはず

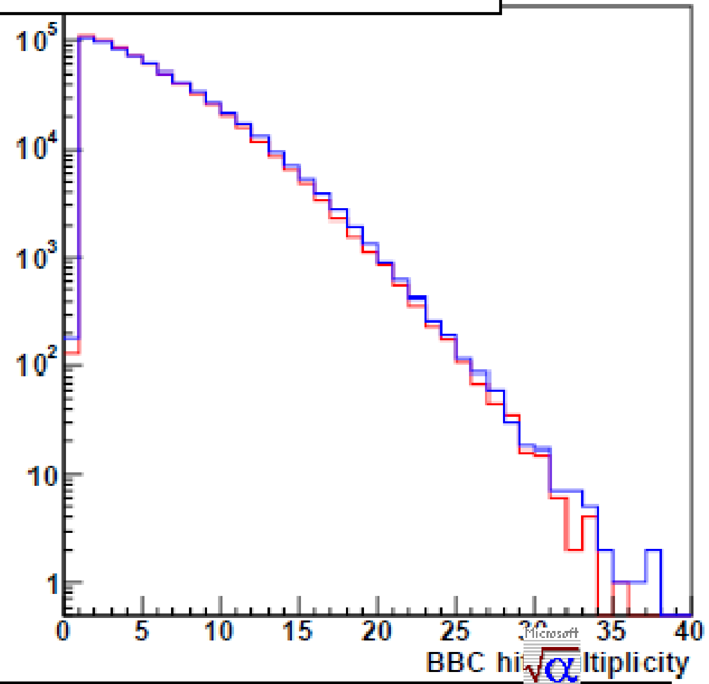
Scaling is unreliable



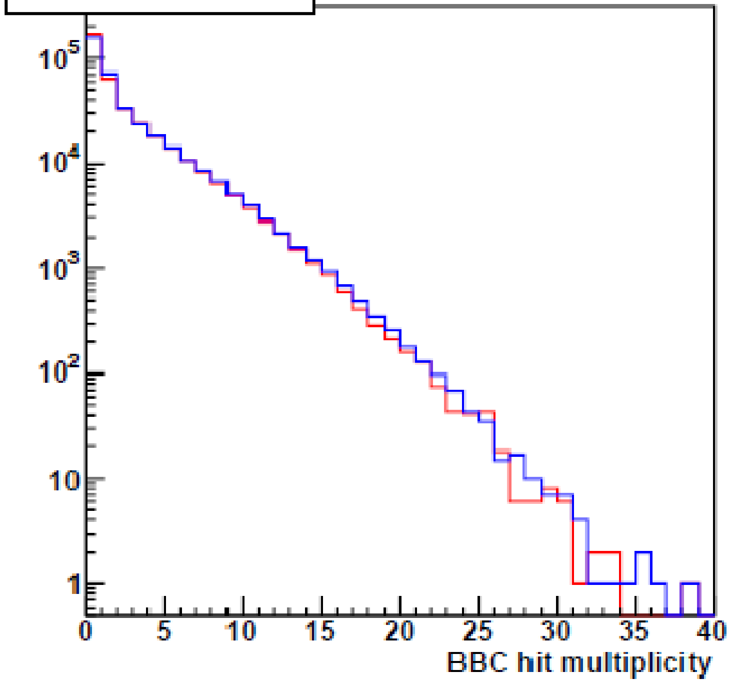
S. Chekanov et al. physics Letters B 590 (2004) 143–160

BBC multiplicity distribution for various triggers

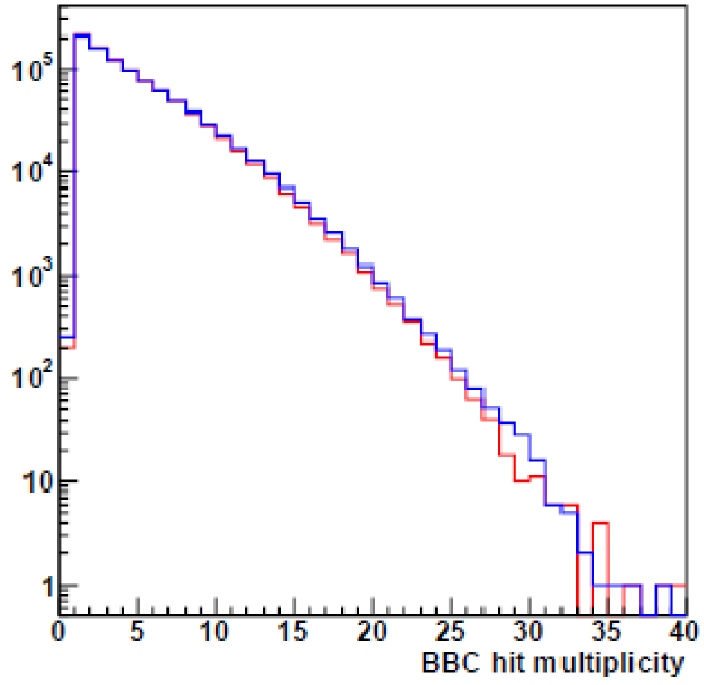
Minimum bias



ZDCN|S



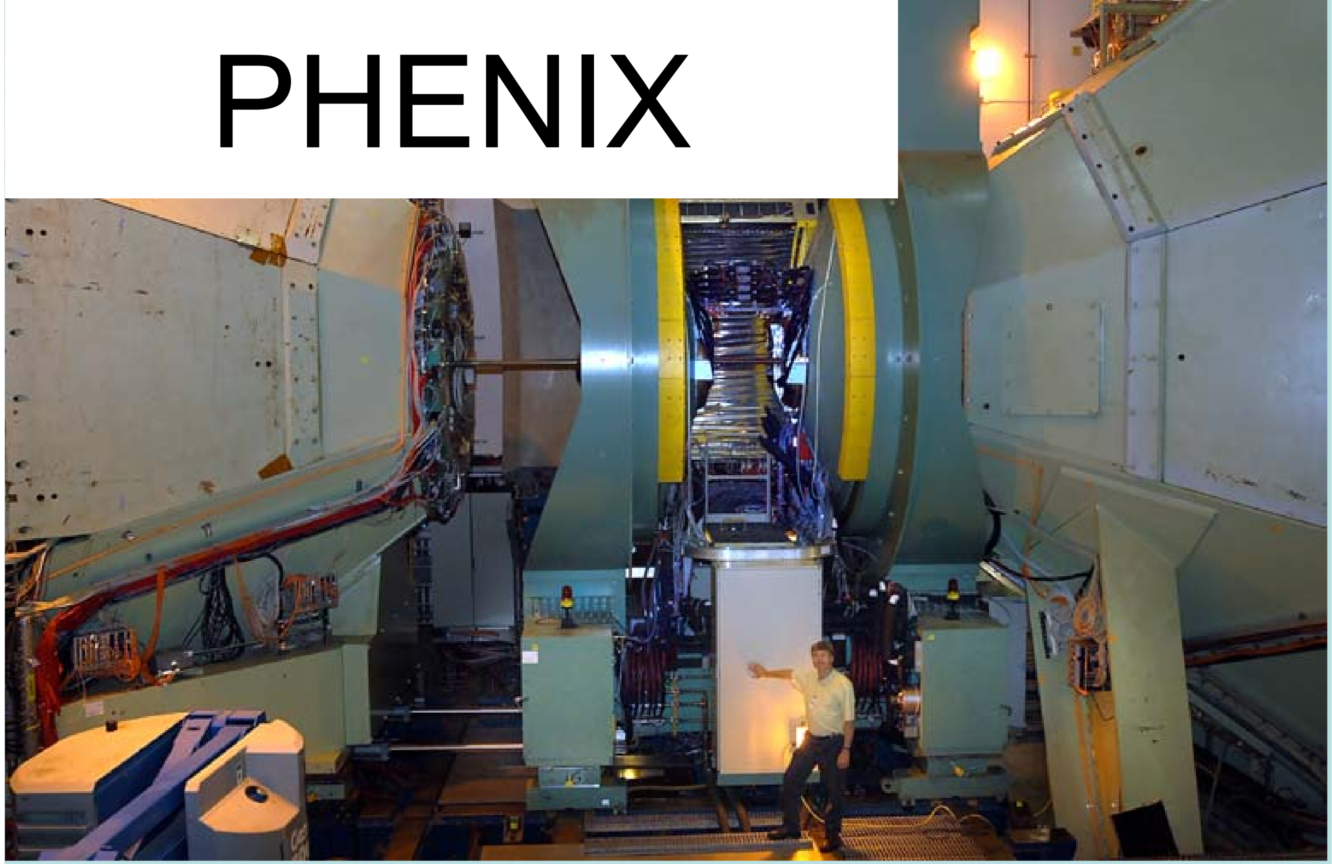
BBCLL1&(ZDCN|S)



Red : SOUTH
Blue : NORTH

No cut required. Just biased by trigger.

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.