High statistics measurement of gluon polarization in low-x region

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4th Japan-Korea PHENIX Collaboration Meeting

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- Accessing Δg via $A_{LL}^{\pi^0}$
- Overview of the measurement
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- A_{LL} analysis
- Results and Discussion

1. Motivation

- Jaffe-Monohar Spin Sum rule.

$$S_z^P = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_z^q + \Delta G + L_z^g$$

- Proton Spin Crisis

  $\Delta\Sigma$ can explain only 30% of proton spin.

  ⇒ "***Can Δ G explain the missed spin part?***"

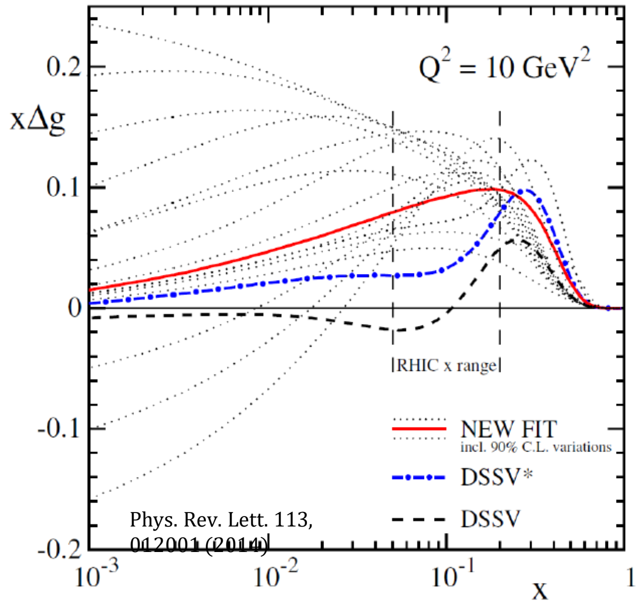
- Many experimental endeavors have been carried out to measure Δg.

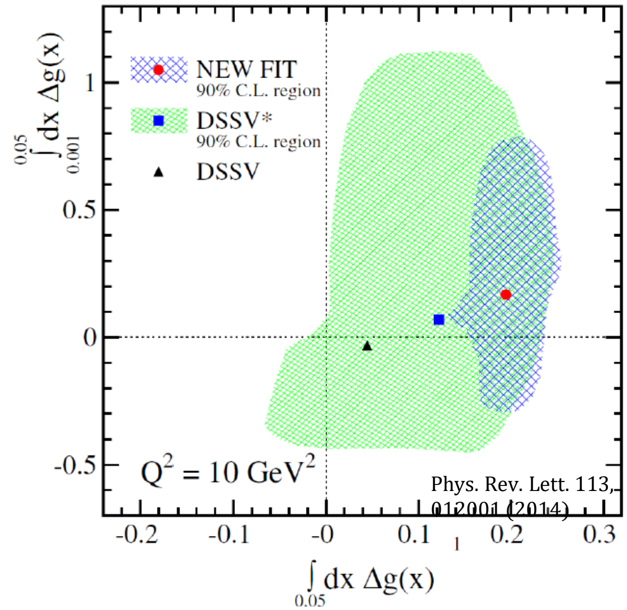
  Polarized $p + p$ is best tool to sense Δg.

  PHENIX $A_{LL}^{\pi^0}$ @ $\sqrt{s} = 62.4, 200$ GeV.

  STAR A_{LL}^{Jet} @ $\sqrt{s} = 200$ GeV

1. Motivation

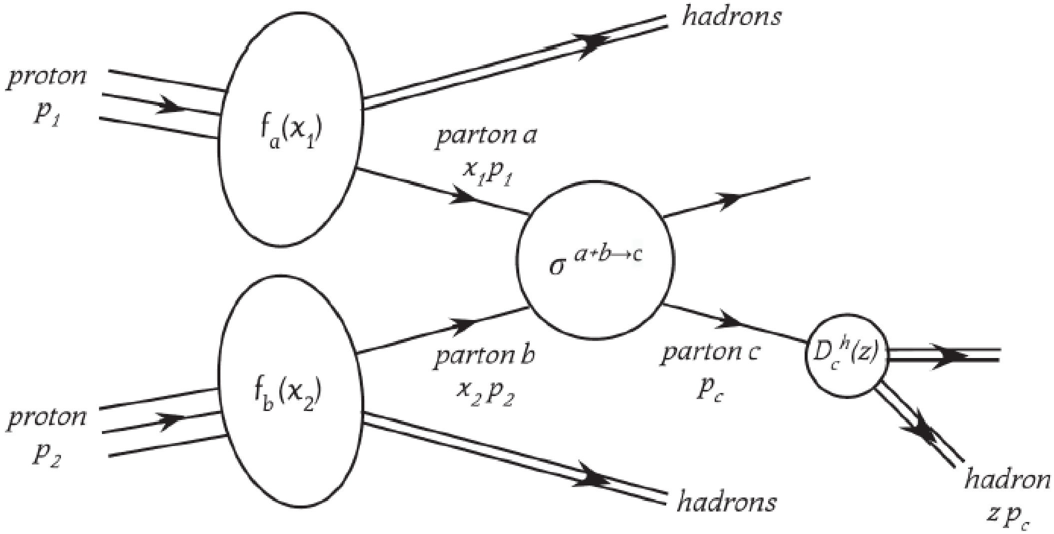


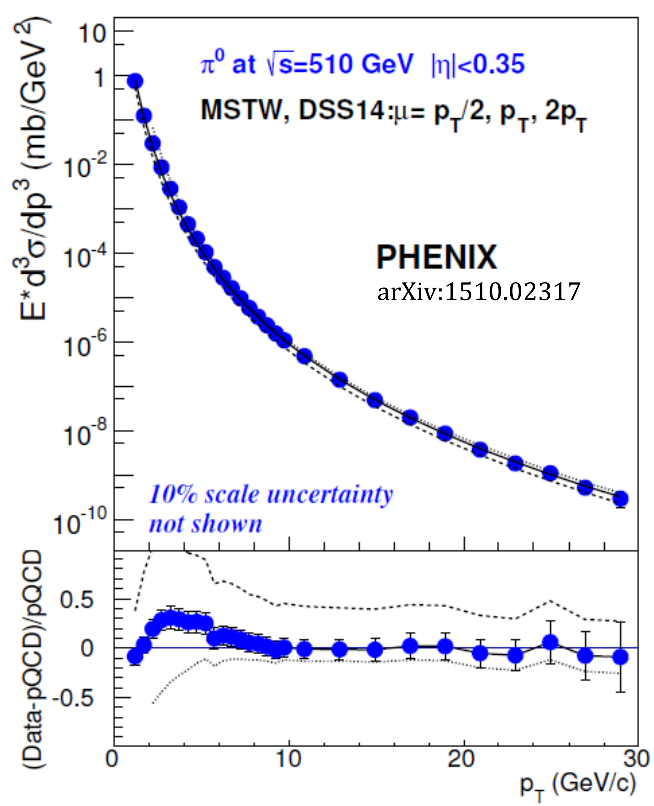


- STAR A_{LL}^{Jet} @ $\sqrt{s} = 200$ GeV constrains Δg, coverage $0.05 \leq x \leq 0.2$.

- **However, large uncertainty still remains.**
  Expanding experimental sensitivity to lower x region is important!
  Measurement at higher $\sqrt{s} = 510$ GeV ($x_T = \frac{2P_T}{\sqrt{s}}$)
  Target x range. $0.01 < x < 0.1$ (P_T coverage: $2 - 20\ \text{GeV}/c$)

2. Accessing Δg via $A_{LL}^{\pi^0}$





- $\sigma^{p+p\to\pi^0+X} = \sum_{f\,a,b=q,\bar{q},g} f_a(x_1) \otimes f_b(x_2) \otimes \hat{\sigma}_{elastic}^{a+b\to c+X} \otimes D_c^{\pi^0}$

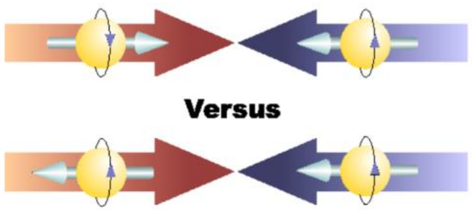
  PDF and FF: by experiments.

  $\hat{\sigma}_{elastic}^{a+b\to c+X}$: by pQCD.

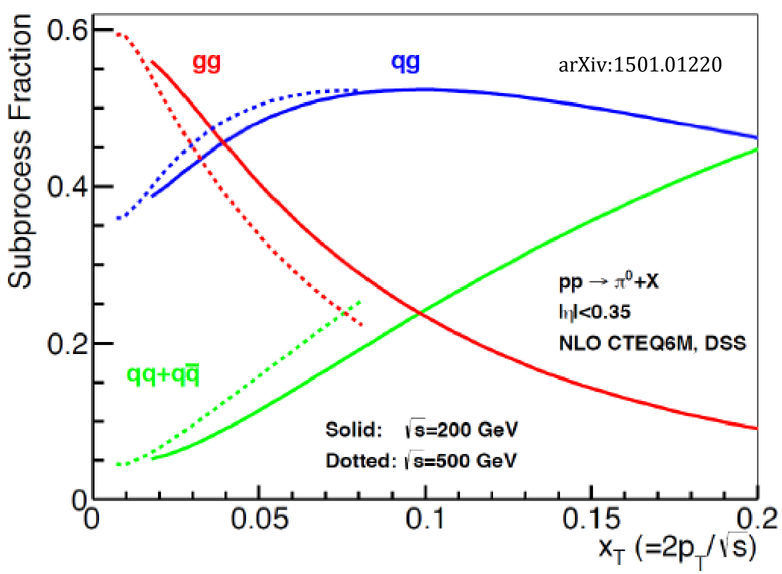
- Nice agreement of unpolarized σ assures that the factorization is valid.

2. Accessing Δg via $A_{LL}^{\pi^0}$

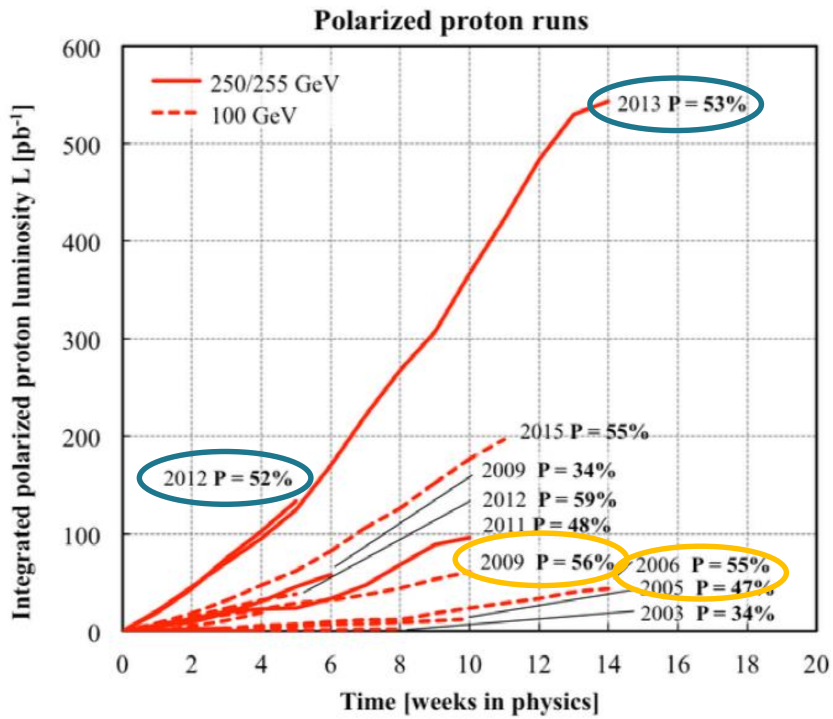
- $$A_{LL}^{h} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_{a,b}=q,\bar{q},g} \Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma}_{elastic}^{a+b\to c+X} \otimes D_c^h}{\sum_{f_{a,b}=q,\bar{q},g} f_a \otimes f_b \otimes \hat{\sigma}_{elastic}^{a+b\to c+X} \otimes D_c^h}$$



- Advantage of $A_{LL}^{\pi^0}$.
  1. Large fraction of π^0 is made by gg or gq scattering.
  2. π^0 cross section is well understood.
  3. Identifiable peak and easy PID.
  4. Large statistics.



3. Overview of the measurement



- 20(2012) and 108 (2013) pb^{-1} of polarized $p+p$ @ $\sqrt{s}=510$ GeV data. 6 times larger luminosity compared to $A_{LL}^{\pi^0}$ @ $\sqrt{s}=200$ GeV.

- The σ and A_{LL} of π^0 @ $\sqrt{s}=510$ GeV result are submitted to PRL. (arXiv:1510.02317)

3. Overview of the measurement

- Measuring A_{LL}

$$A_{LL} = \frac{1}{P_B P_B} \frac{\frac{N_{++}}{L_{++}} - \frac{N_{+-}}{L_{+-}}}{\frac{N_{++}}{L_{++}} + \frac{N_{+-}}{L_{+-}}}$$

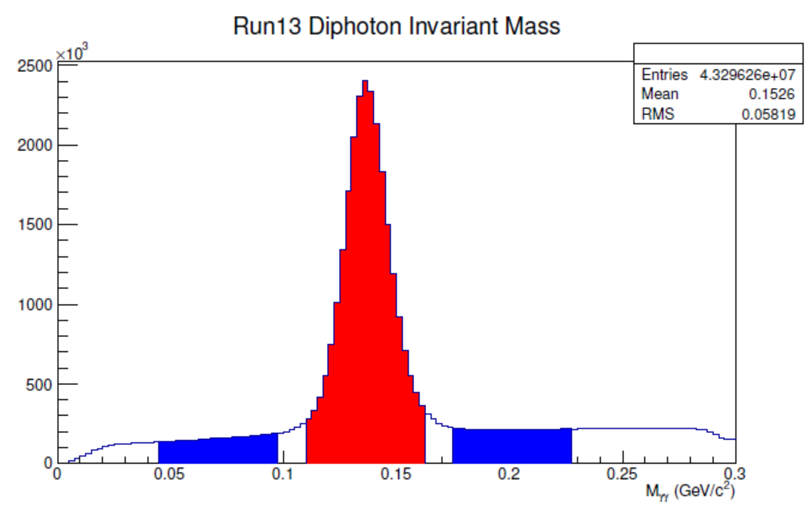
$$= \frac{1}{P_B P_Y} \frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}} \quad \text{where} \quad R = \frac{L_{++}}{L_{+-}}$$

- To correct effect of background, A_{LL}s of two regions are measured.
  Peak region: 112-162 MeV/c^2
  Side region: 47-97 or 117-227 MeV/c^2

$$A_{LL}^{\pi^0} = \frac{A_{LL}^{\pi^0+BG} - rA_{LL}^{BG}}{1-r}, \qquad \sigma_{A_{LL}^{\pi^0}} = \frac{\sqrt{\sigma^2_{A_{LL}^{\pi^0+BG}} + r^2\sigma^2_{A_{LL}^{BG}}}}{1-r}$$

  where r is background fraction under peak region.

- The r is estimated by GPR.

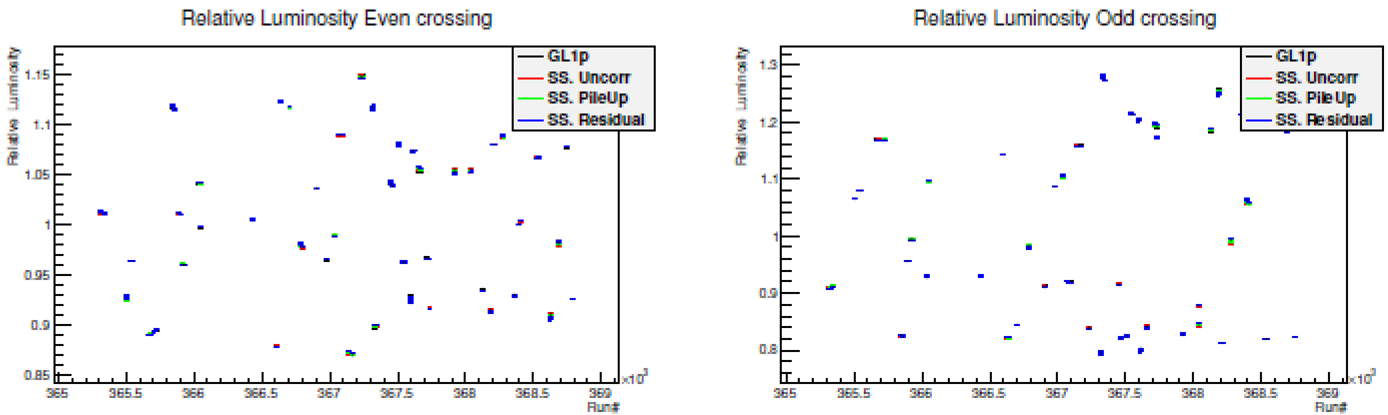


4. Relative Luminosity - Overview

- The Rel. Lumi. is

$$R = \frac{L_{++}}{L_{+-}}$$

Measured with BBC30cm scaler.



(a) Even Crossing (b) Odd Crossing

- Conditions for good luminosity detectors
  1. Low background from noise or beam gas.
  2. High statistics
  3. Same acceptance, i.e. $|Vertex_Z| < 30cm$
  4. No helicity dependence i.e. $A_{LL}^{BBC} = 0$

BBC satisfied the conditions

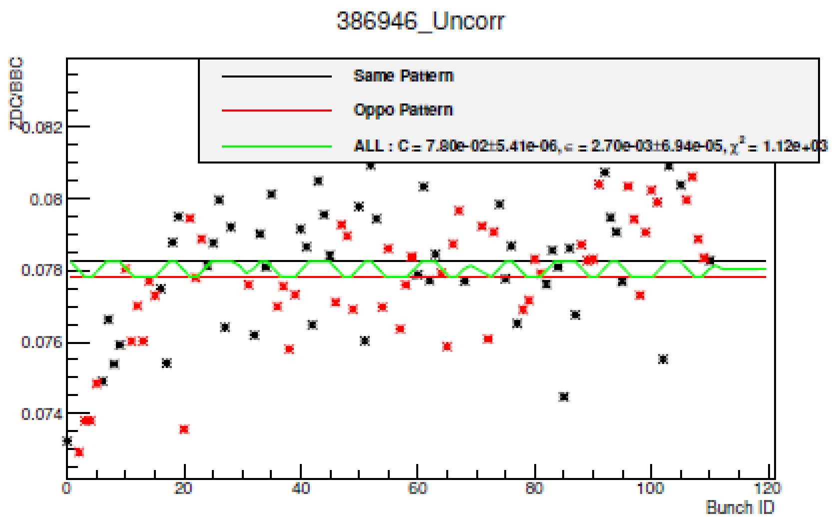
The fourth condition is not that easy.

4. Relative Luminosity - Measuring $A_{LL}^{ZDC/BBC}$

- A_{LL}^{BBC} is estimated by $A_{LL}^{ZDC/BBC}$.

$$A_{LL}^{BBC} = \frac{1}{P_B P_Y} \frac{\frac{N_{BBC}^{++}}{L_{++}} - \frac{N_{BBC}^{+-}}{L_{+-}}}{\frac{N_{BBC}^{++}}{L_{++}} + \frac{N_{BBC}^{+-}}{L_{+-}}} \quad \Rightarrow \quad A_{LL}^{ZDC/BBC} = \frac{1}{P_B P_Y} \frac{\frac{N_{ZDC}^{++}}{N_{BBC}^{++}} - \frac{N_{ZDC}^{+-}}{N_{BBC}^{+-}}}{\frac{N_{ZDC}^{++}}{N_{BBC}^{++}} + \frac{N_{BBC}^{+-}}{N_{BBC}^{+-}}}.$$

- Measuring $A_{LL}^{ZDC/BBC}$ of single run.



called "bunch fitting"

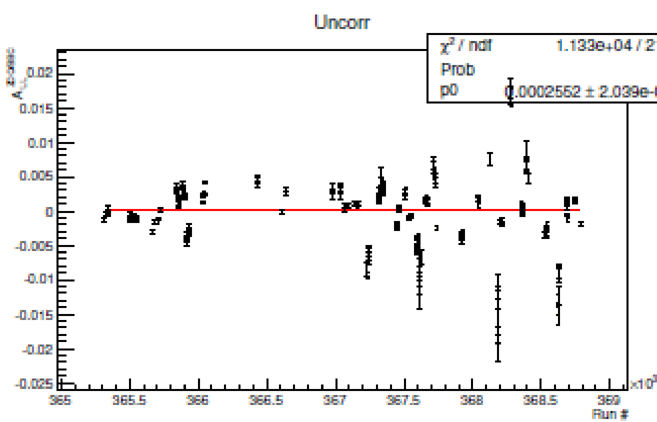
$$r(i) = C \times (1 + \varepsilon_{LL} \times \text{Helicity Index}_{\text{Blue}} \times \text{Helicity Index}_{\text{Yellow}})$$

4. Relative Luminosity - Measuring $A_{LL}^{ZDC/BBC}$

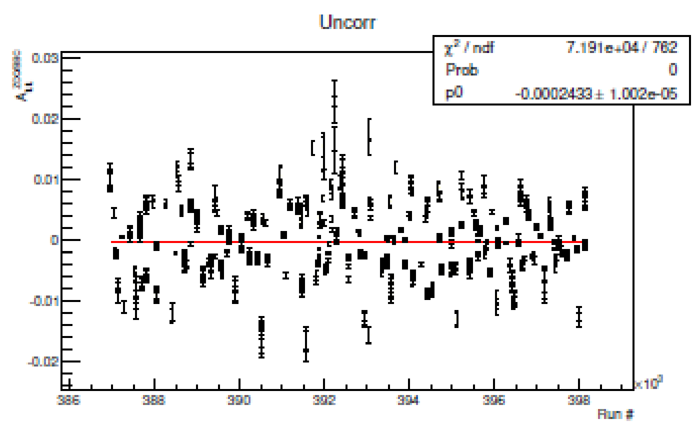
$$A_{LL}^{ZDC/BBC} = \frac{\varepsilon_{LL}}{P_B P_Y}$$

$$\Delta A_{LL}^{ZDC/BBC} = \frac{1}{P_B P_Y}\sqrt{(\Delta\varepsilon_{LL} \times \sqrt{\chi^2_{re}})^2 + \varepsilon^2_{LL}\left((\frac{\Delta P_B}{P_B})^2 + (\frac{\Delta P_Y}{P_Y})^2\right)}$$

- Then, const. fit to obtain whole Run average $A_{LL}^{ZDC/BBC}$.



(a) Run12

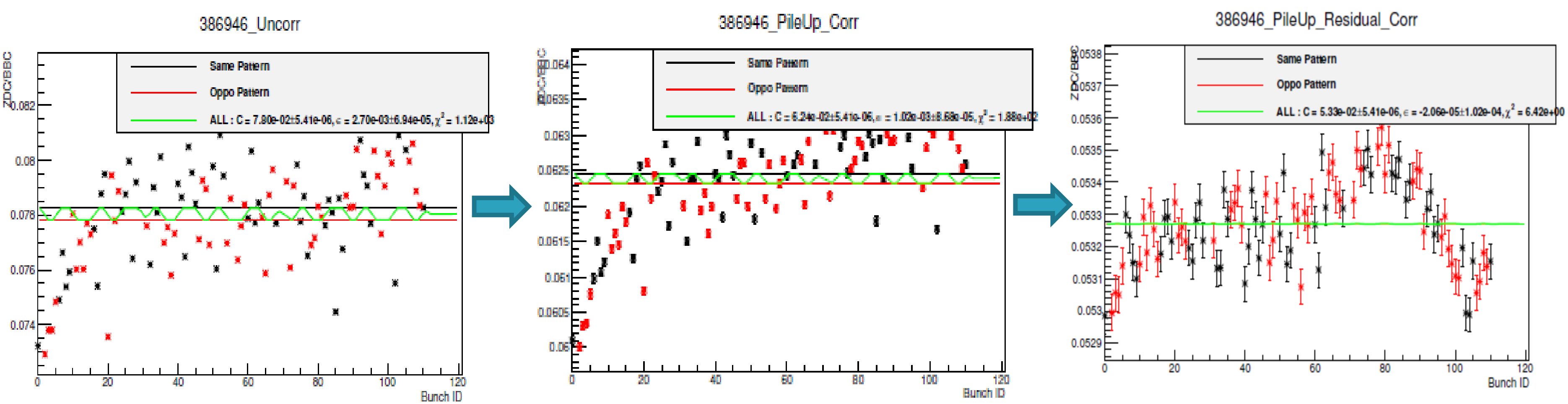


(b) Run13

Called “Run fitting”

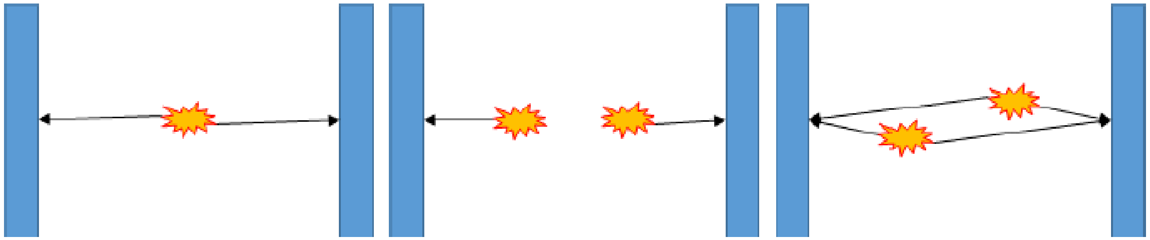
4. Relative Luminosity - Corrections

- To correct scaler miscount by
  1. multiple collisions, single sided collisions: pileup correction(=rate correction)
  2. vertex cut and detector resolution: residual rate correction.



4. Relative Luminosity - Pileup Correction

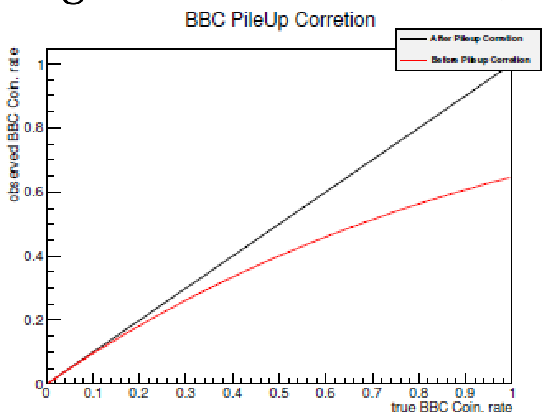
- Pileup correction: to correct piled or single side event.



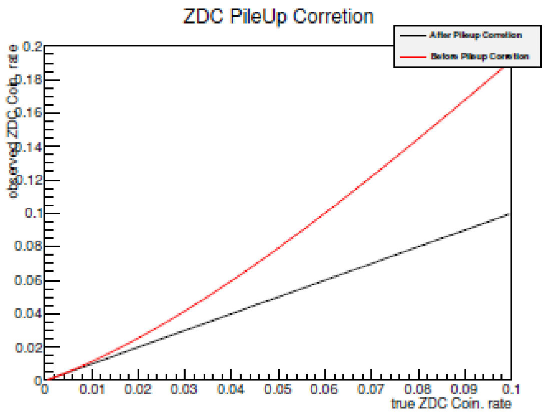
- $$\text{Coin. Rate}^{ob.} = 1 - e^{-\text{Coin. Rate}^{true}(1+k_N)} - e^{-\text{Coin. Rate}^{true}(1+k_S)} + e^{-\text{Coin. Rate}^{true}(1+k_N+k_S)}$$

Note) No vertex cut is considered.

$k_{N(s)}$: single to double hit ratio, measurable with STAR scaler data.



(c) Run13 BBC



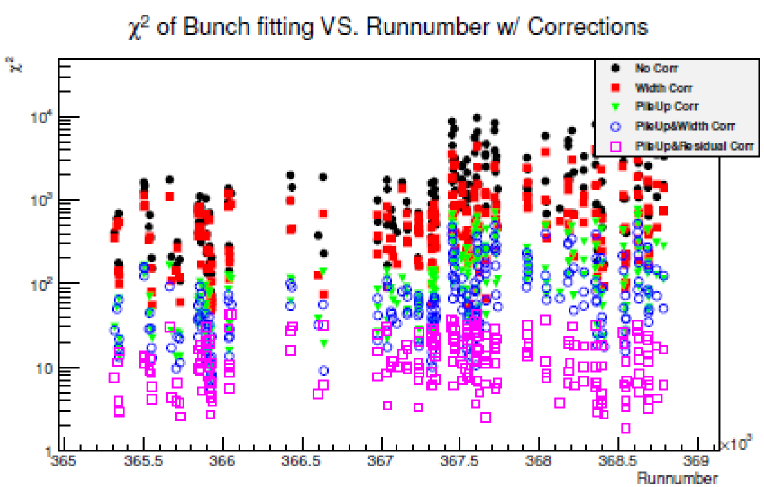
(d) Run13 ZDC

4. Relative Luminosity - Residual Rate Correction

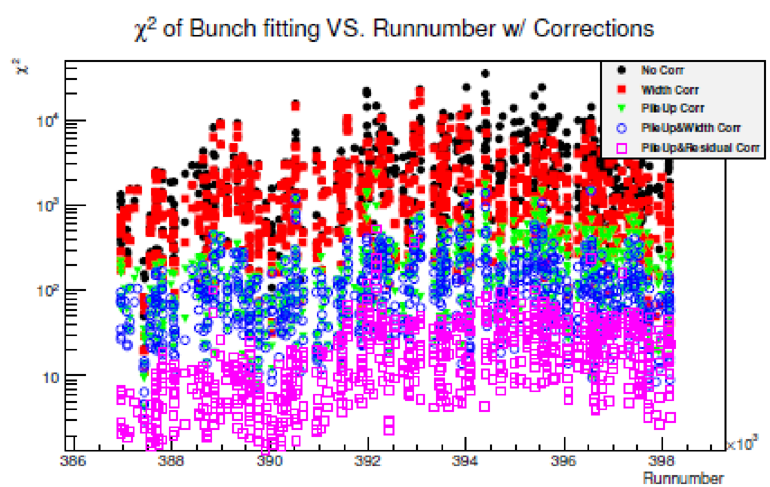
- Residual rate correction: to correct the effect of vertex cut.

$$f = \frac{\text{Observed 30cm vertex}_z \text{ scaler count}}{\text{Observed no vertex}_z \text{ scaler count}}$$

$$\begin{aligned} \text{Rate}_{obs} &\to f\text{Rate}_{obs} \\ \text{Rate}_{obs} &= F(\text{Rate}_{true}) \\ \to f\text{Rate}_{obs} &\approx F(\text{Rate}_{true,vtx}) \end{aligned} \quad \Rightarrow \quad \begin{aligned} \text{Rate}_{true} &= F^{-1}(\text{Rate}_{obs}) \\ \text{Rate}_{true,vtx} &\approx F^{-1}(f\text{Rate}_{obs}) \end{aligned}$$



(a) Run12



(b) Run13

4. Relative Luminosity - Result

- $$\text{Run12: } \Delta A_{LL}(Rel.Lumi) = 2.003 \times 10^{-4}$$
  $$\text{Run13: } \Delta A_{LL}(Rel.Lumi) = 3.853 \times 10^{-4}$$

Cf) $\Delta A_{LL}(Rel.Lumi) = 7.340 \times 10^{-4}$ with width correction, classical way of correcting the effect of vertex cut.

5. Events and γ Selections

- Run QA.
  DAQ live time > 0.5, Spin DB, Polarization>0.1, GL1p and Star scaler agreement
  ⇒ 227 runs (Run12) and 760 runs (Run13) has passed the QA.
  19.93 pb^{-1} (Run12) and 108.1 pb^{-1}.
  Note) QA on EMCal is covered by EMCal run-by-run energy calibration.

- Event Selection.
  ERT_4x4A||ERT_4x4B||ERT_4x4C, $|Vertex_Z| < 30cm$

- Photon ID.
  1. Min energy cut: 0.3 GeV to reject noise hits.
  2. Warnmap cut: To reject abnormal towers.
  3. Shower profile cut: To reject hadron hits
  4. Charge veto cut: To reject charge tracks
  5. ToF cut: To reject ghost clusters

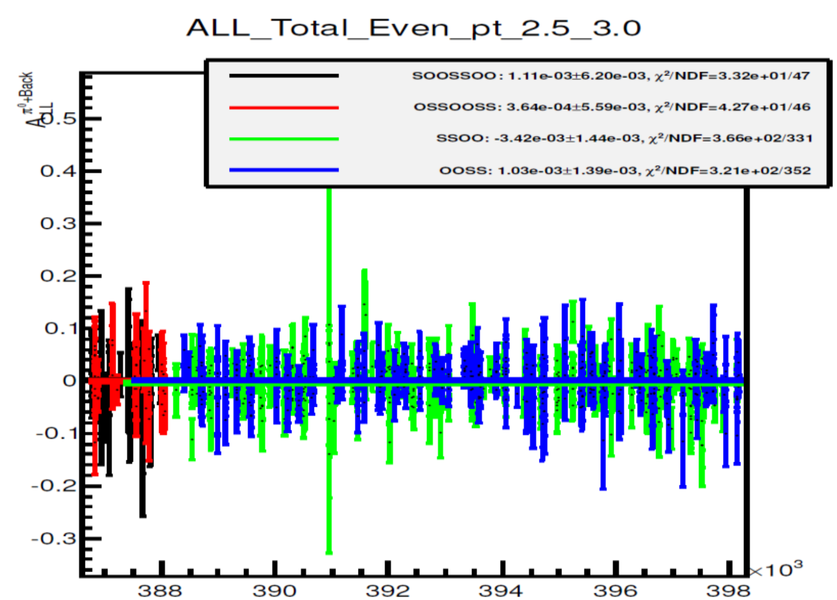
6. A_{LL} Analysis

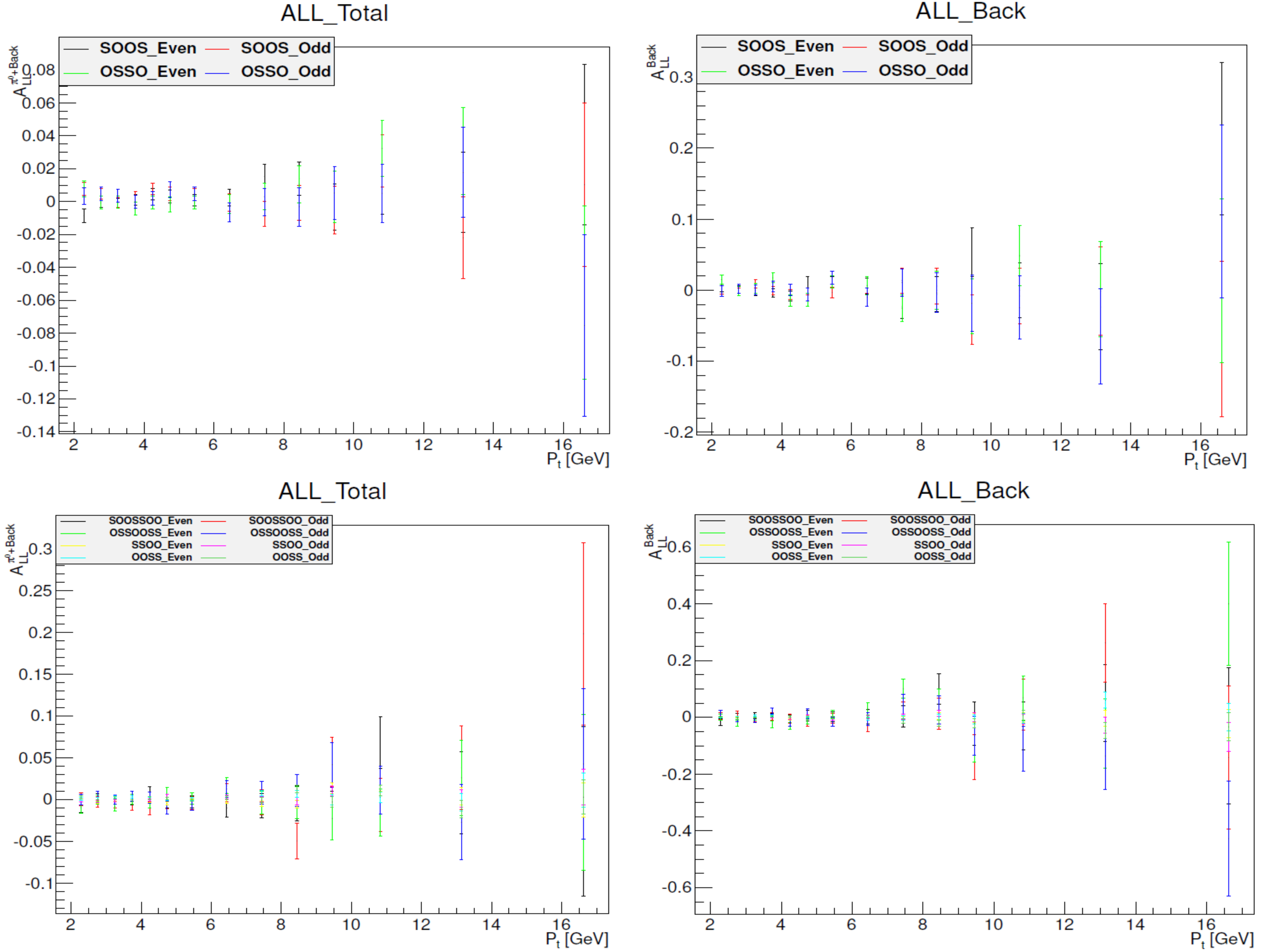
- Run-by-run A_{LL} calculation.
  ∵ Run-by-run prescale make run-dependent effective efficiency.

- Statistical uncertainty of A_{LL}

$$(\Delta A_{LL})^2 = \left(\frac{1}{P_B P_Y}\frac{2RN_{++}N_{+-}}{(N_{++}+RN_{+-})^2}\right)^2\left(\left(\frac{\Delta N_{++}}{N_{++}}\right)^2+\left(\frac{\Delta N_{+-}}{N_{+-}}\right)^2+\left(\frac{\Delta R}{R}\right)\right)^2 + \left(\left(\frac{\Delta P_B}{P_B}\right)^2+\left(\frac{\Delta P_Y}{P_Y}\right)^2\right)A_{LL}^2$$

- Constant fit to get average A_{LL}.
  : To avoid fake asymmetry from ghost cluster,
  Spin pattern separated fitting done.




ALL_Total
SOOS_Even
SOOS_Odd
OSSO_Even
OSSO_Odd
$A_{LL}^{\pi^0+Back}$
P_t [GeV]
ALL_Back
SOOS_Even
SOOS_Odd
OSSO_Even
OSSO_Odd
A_{LL}^{Back}
P_t [GeV]
ALL_Total
SOOSSOO_Even
SOOSSOO_Odd
OSSOOSS_Even
OSSOOSS_Odd
SSOO_Even
SSOO_Odd
OOSS_Even
OOSS_Odd
$A_{LL}^{\pi^0+Back}$
P_t [GeV]
ALL_Back
SOOSSOO_Even
SOOSSOO_Odd
OSSOOSS_Even
OSSOOSS_Odd
SSOO_Even
SSOO_Odd
OOSS_Even
OOSS_Odd
A_{LL}^{Back}
P_t [GeV]

6. A_{LL} Analysis - Background Subtraction

- Background fraction estimation.

$$r = \frac{\int_{m_1}^{m_2} \text{distribution describing background spectrum}}{\int_{m_1}^{m_2} \text{di-photon invariant mass spectrum}}$$

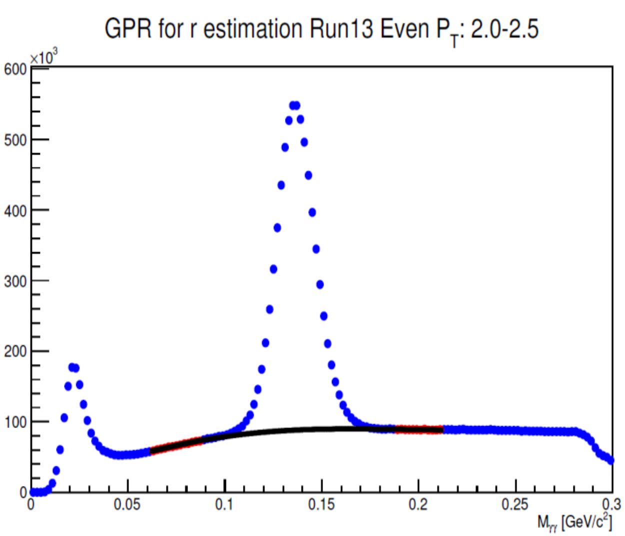
GPR: No functional form is assumed. Uncertainty band is given.

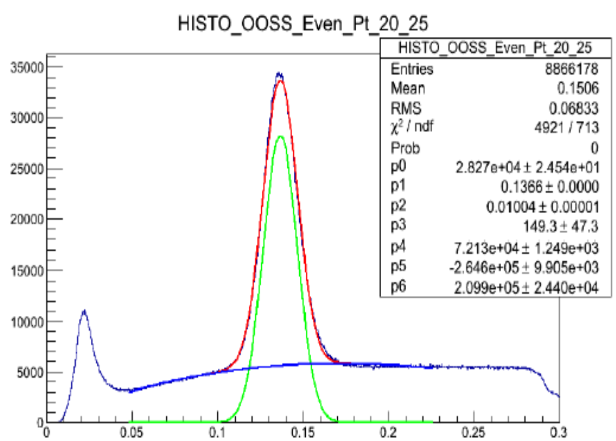
$\Rightarrow$ Best estimator. r obtained by GPR is used for the analysis.

Fitting method: Functional form should be assumed. (Gaus+Pol3 or Voigt+Pol3)

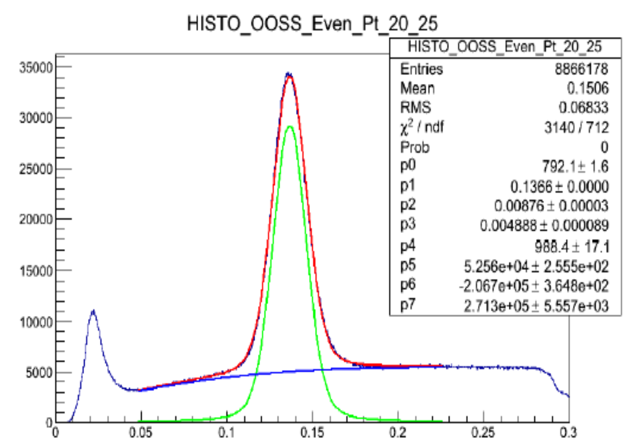
Hard to estimate uncertainty.

$\Rightarrow$ Discrepancy of r is assigned as syst.



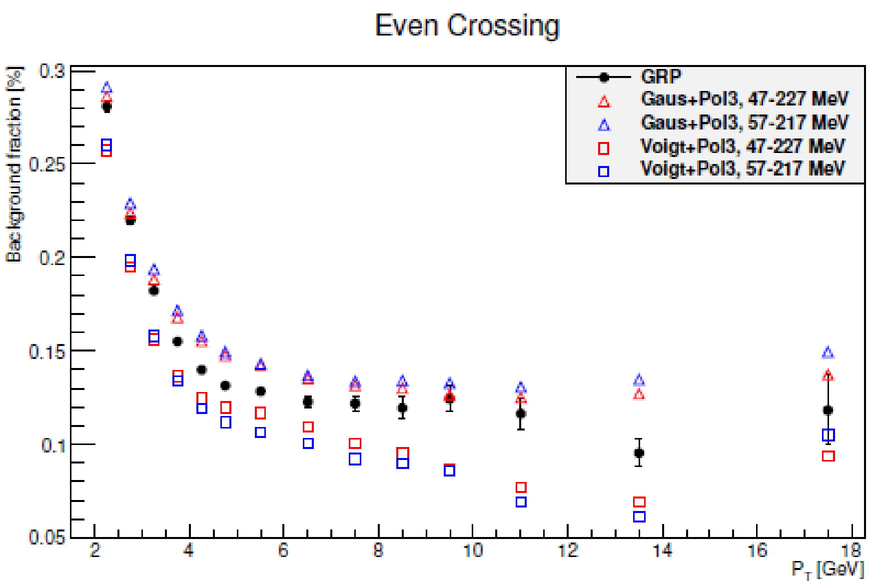


(a) Gaus+Pol3

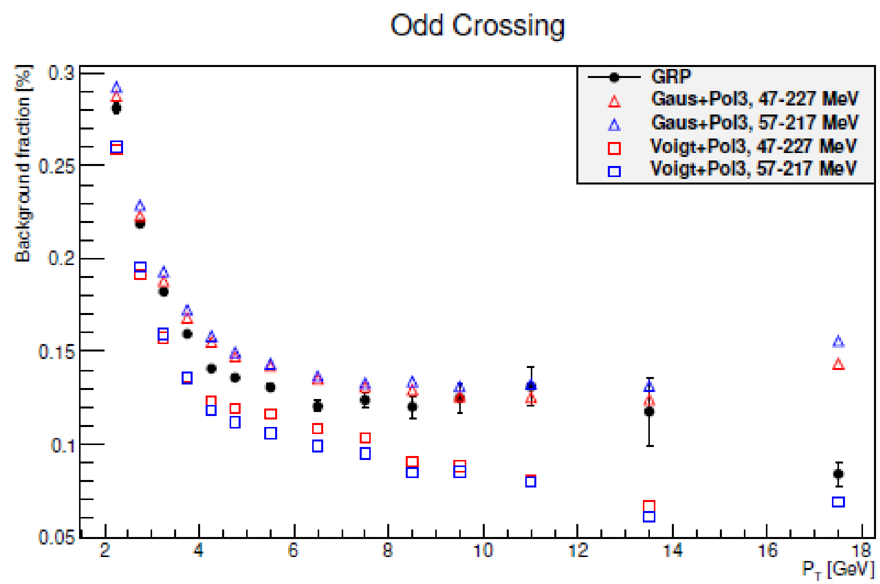


(b) Voigt+Pol3

6. A_{LL} Analysis - Background Subtraction



(a) Even

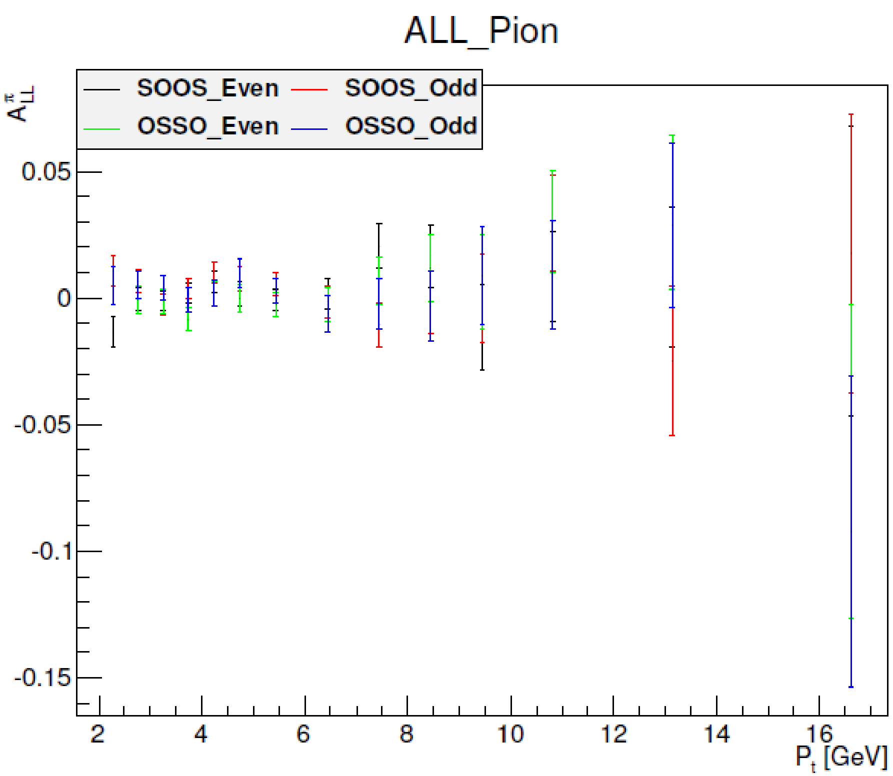


(b) Odd

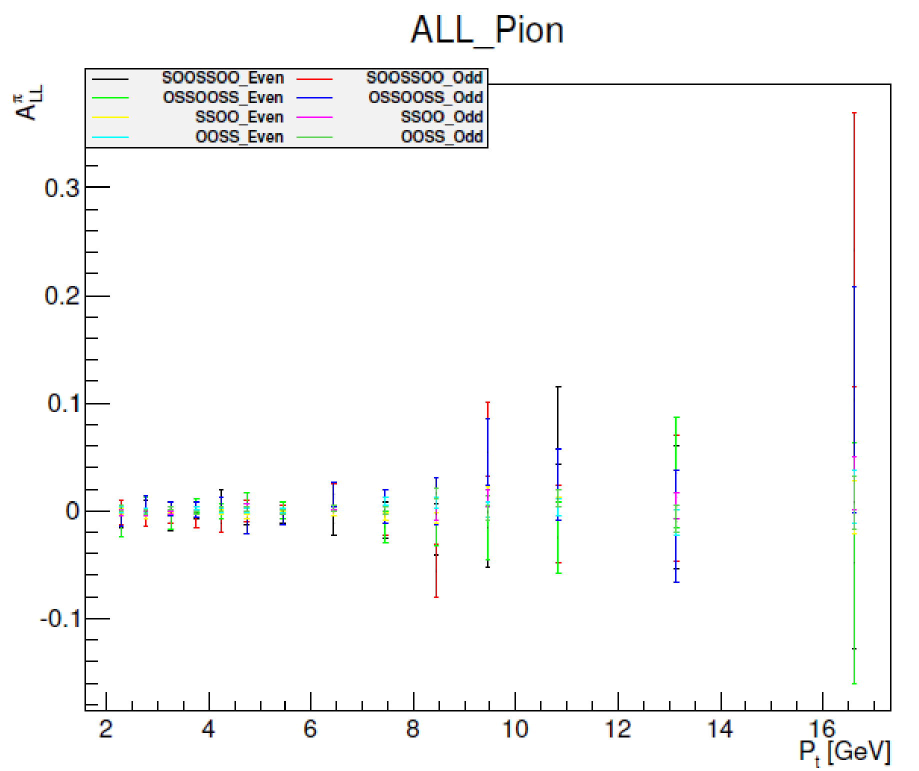
- Background Subtraction.

$$A_{LL}^{\pi^0} = \frac{A_{LL}^{\pi^0+BG} - rA_{LL}^{BG}}{1-r}, \qquad \sigma_{A_{LL}^{\pi^0}} = \frac{\sqrt{\sigma^2_{A_{LL}^{\pi^0+BG}} + r^2\sigma^2_{A_{LL}^{BG}}}}{1-r}$$

6. A_{LL} Analysis - Results

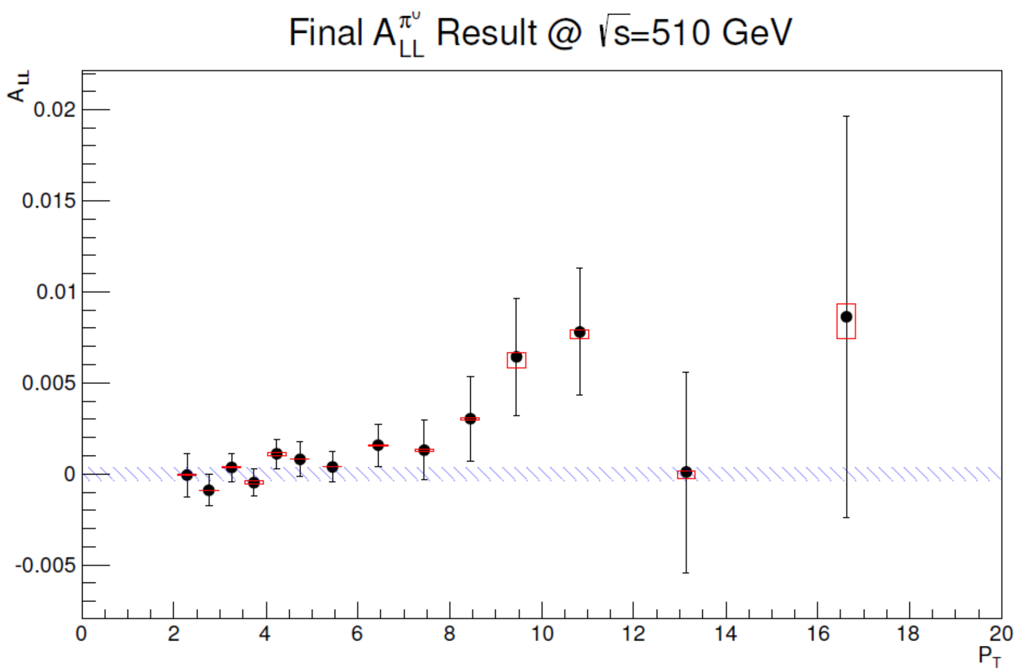


↑. Run12



↑. Run13

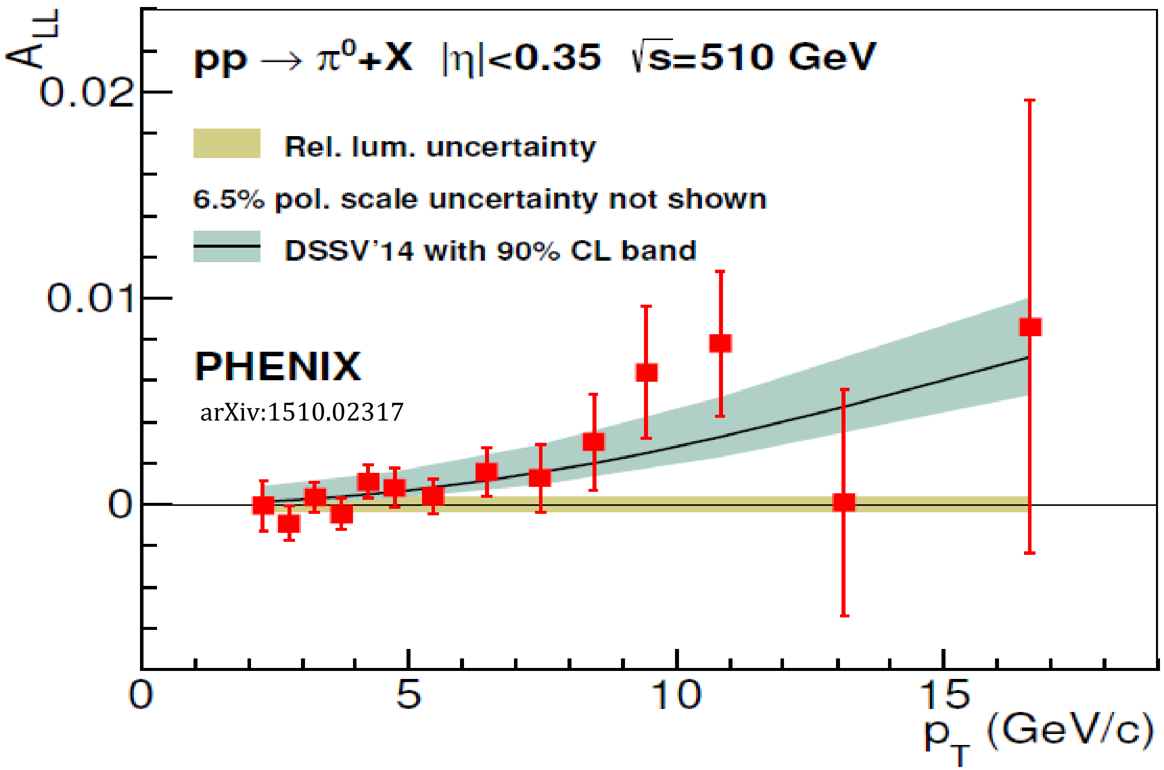
7. Results and Discussion



- Blue band: Syst. from relative luminosity.
  Red box: background fraction estimation.

- World first non-zero asymmetry in hadron production is observed! (3.3σ)

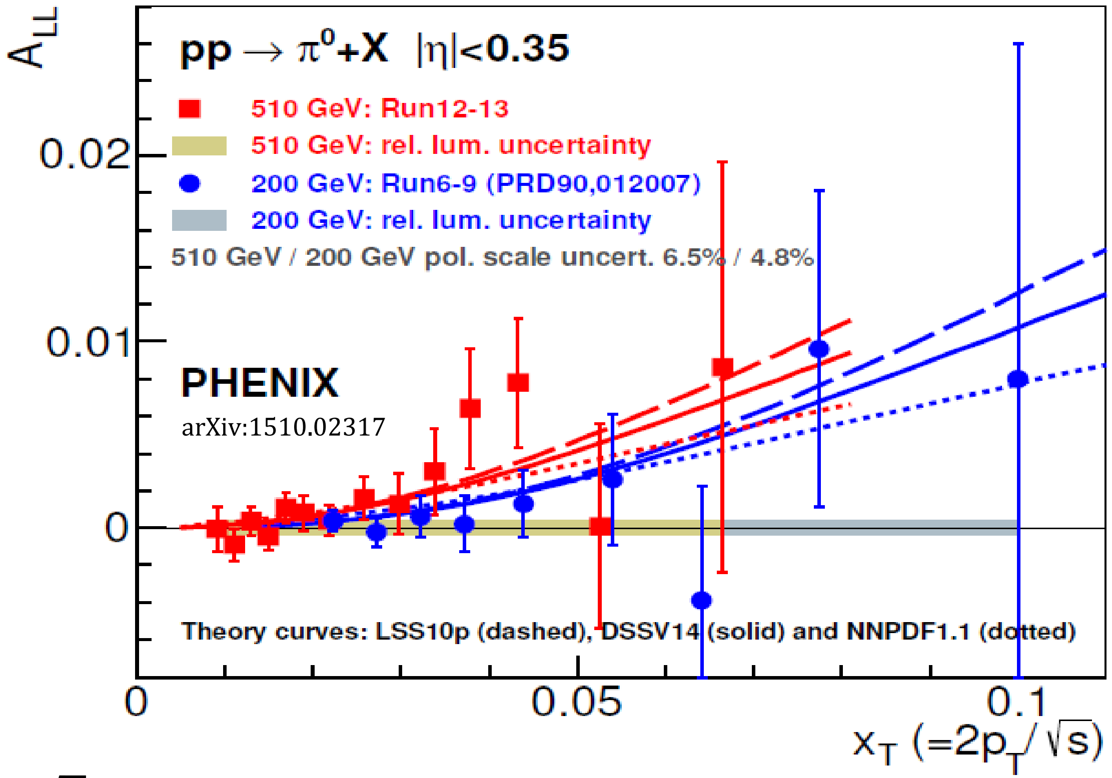
7. Results and Discussion



- Positive ΔG is reconfirmed with higher Q^2 and different channel.

  (Cf. STAR A_{LL}^{Jet} @ $\sqrt{s} = 200$ GeV)

7. Results and Discussion



- The new $A_{LL}^{\pi^0}$ @ $\sqrt{s} = 510$ GeV covers lower x region, $0.01 < x$.

  Cf) $A_{LL}^{\pi^0}$ @ $\sqrt{s} = 200$ GeV: $0.02 < x$

  A_{LL}^{Jet} @ $\sqrt{s} = 200$ GeV: $0.05 < x$

  ⇒ Significant contribution to constrain Δg at lower x is expected.

Summary

- σ and A_{LL} of π^0@ $\sqrt{s} = 510$ GeV are measured and the results are submitted to PRL (arXiv:1510.02317)

- Nice agreement of theoretical to measured π^0 cross section.
  $\Rightarrow$ Our understanding of pQCD and parton-to-hadron fragmentation are mature.

- $A_{LL}^{\pi^0}$ @ $\sqrt{s} = 510$ GeV.
  1. Positive asymmetry is observed.
     $\Rightarrow$ Positive ΔG is reconfirmed with higher Q^2 and different channel.
  2. Lower x range is accessed. $0.01 < x$.
     $\Rightarrow$ Significant contribution to constrain Δg at lower x is expected. (ongoing)

Back Up

1. Motivation

- Proton: the basic QCD object.

  Understanding proton structure

  ⇒Able to explain proton properties by its properties of constituents.

- Spin Sum rule.

  Ellis-Jaffe Spin Sum rule with naïve quark model.

$$S_z^P = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_z^q$$

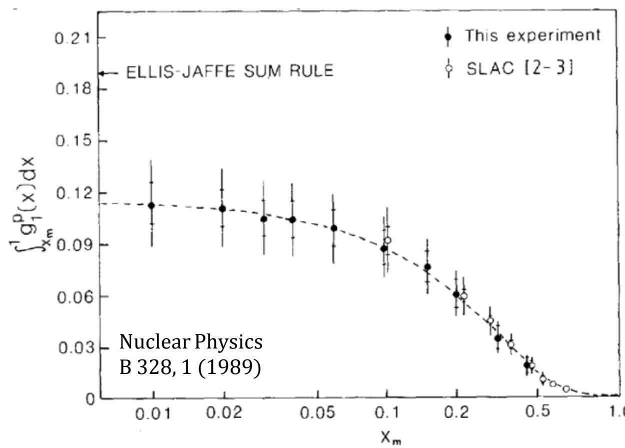
  Ellis-Jaffe sum rule predicted $\int_0^1 dx g_1^P(x, Q^2) = 0.189 \pm 0.005$

- The EMC result: polarized DIS with polarized μ to measure g_1^p.

$$A_1^P = \frac{\sigma_{+-} - \sigma_{++}}{\sigma_{+-} + \sigma_{++}}$$

$$A_1^P = \frac{g_1^P(x, Q^2)}{F_1^P(x, Q^2)}$$

1. Motivation



$$\Rightarrow \int_0^1 g_1^p dx = 0.123 \pm 0.013 \pm 0.019$$

1. Ellis-Jaffe sum rule is violated clearly.
2. $\Delta\Sigma = 0.120 \pm 0.094 \pm 0.138$

- Jaffe-Monohar Spin Sum rule.

$$S_z^P = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_z^q + \Delta G + L_z^g$$

ΔG becomes key of understanding spin structure of proton.

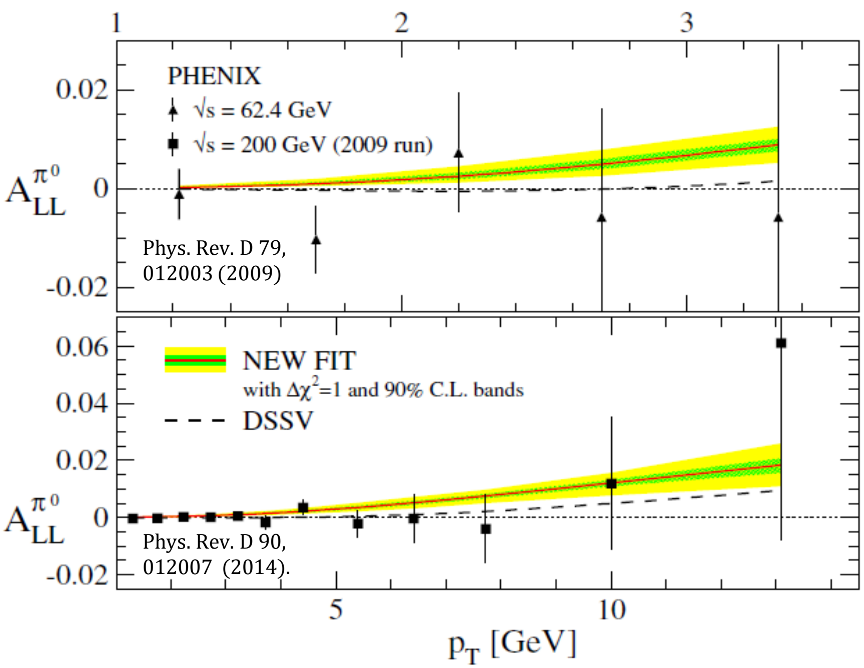
1. Motivation

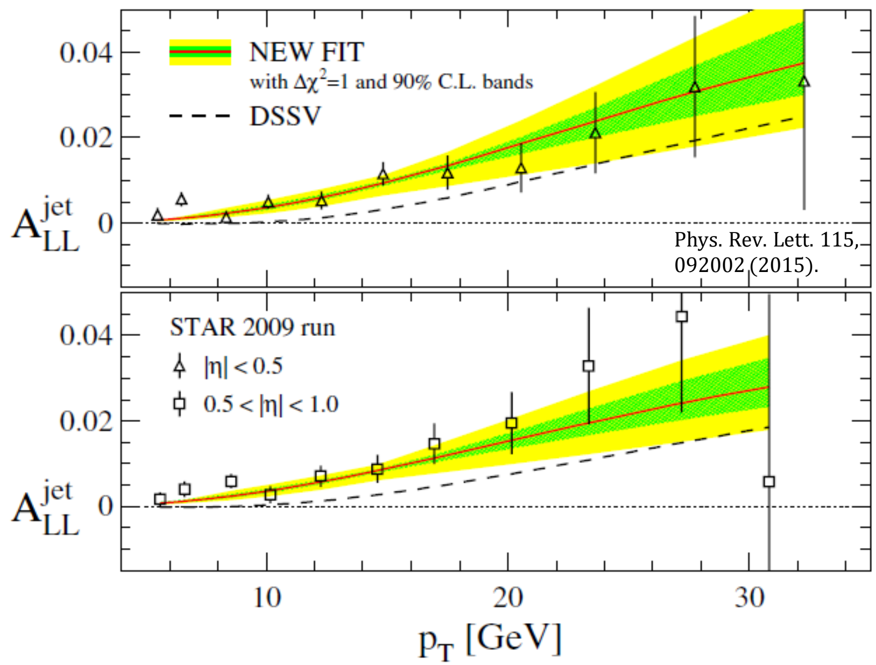
- Current Knowledge of Δg.

  Mostly obtained by $p + p$ collisions.

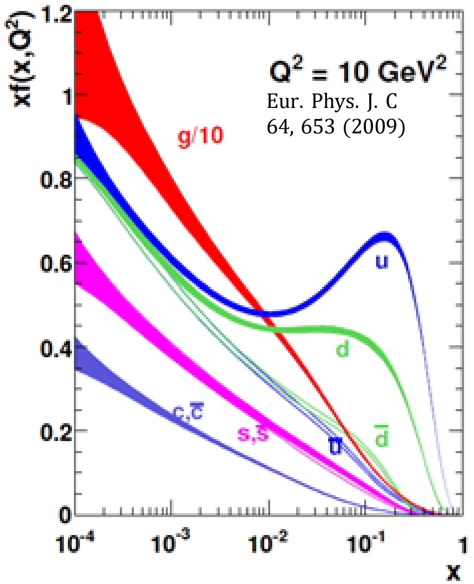
  A_{LL} of π^0 at 62.4 GeV, 200 GeV (PHENIX)

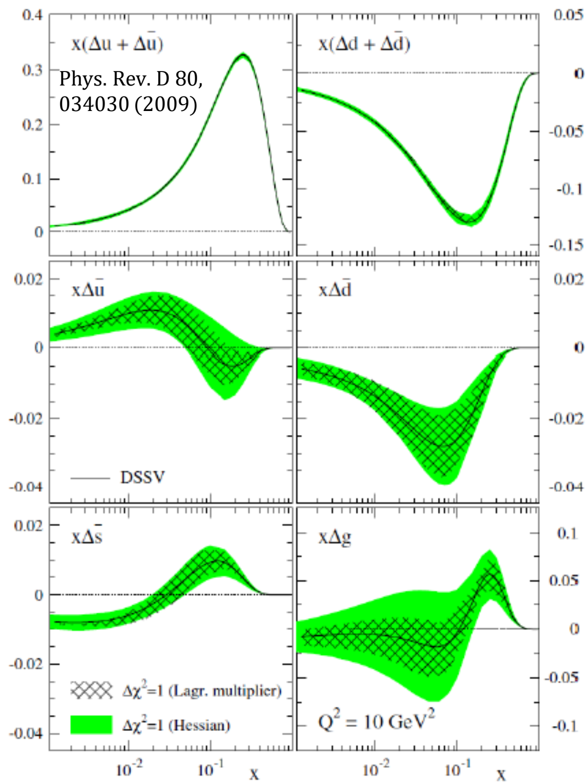
  A_{LL} of jet at 200 GeV (STAR)

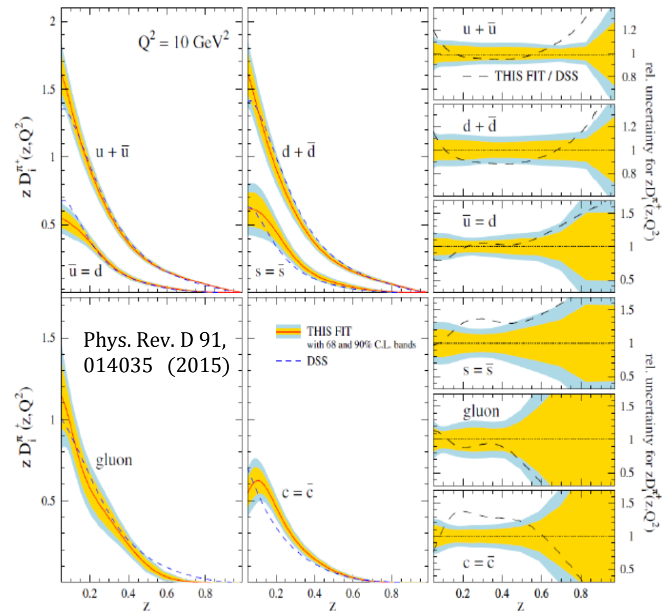




2. Accessing Δg via A_{LL}







3. RHIC Spin Runs

- Spin pattern: check and reduce possible syst. from bunch filling.
- The analysis has been done spin pattern separately to reject false asymmetry. (Discussed later)

P1 B	+	-	+	-	-	+	-	+
Y	+	+	-	-	+	+	-	-
P2 B	-	+	-	+	+	-	+	-
Y	+	+	-	-	+	+	-	-
P3 B	+	-	+	-	-	+	-	+
Y	-	-	+	+	-	-	+	+
P4 B	-	+	-	+	+	-	+	-
Y	-	-	+	+	-	-	+	+
P5 B	+	+	-	-	+	+	-	-
Y	+	-	+	-	-	+	-	+
P6 B	+	+	-	-	+	+	-	-
Y	-	+	-	+	+	-	+	-
P7 B	-	-	+	+	-	-	+	+
Y	+	-	+	-	-	+	-	+
P8 B	-	-	+	+	-	-	+	+
Y	-	+	-	+	+	-	+	-

$\Rightarrow$

SOOS	P1	P4	P5	P8
OSSO	P2	P3	P6	P7

$\because$ physics should invariant under beam change and parity operation.

↑. Run12 spin patterns

3. RHIC Spin Runs

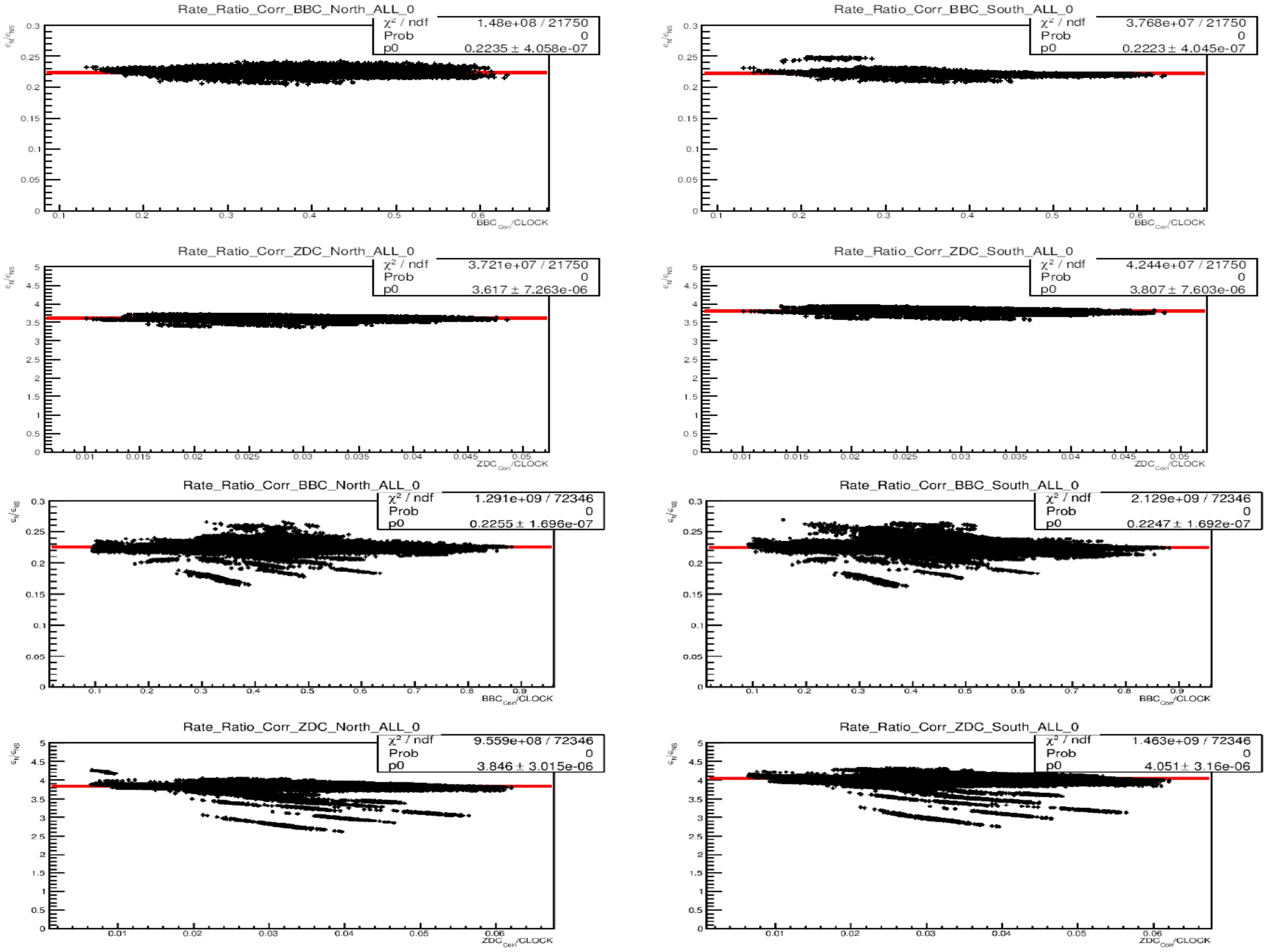
P1 B	+	+	-	-	+	+	-	-	+	+	-	-		
Y	+	+	+	+	-	-	-	-	+	+	+	+	-	-
P2 B	-	-	+	+	-	-	+	+	-	-	+	+		
Y	+	+	+	+	-	-	-	-	+	+	+	+	-	-
P3 B	+	+	-	-	+	+	-	-	+	+	-	-		
Y	-	-	-	-	+	+	+	+	-	-	-	-	+	+
P4 B	-	-	+	+	-	-	+	+	-	-	+	+		
Y	-	-	-	-	+	+	+	+	-	-	-	-	+	+
P5 B	+	+	+	+	-	-	-	-	+	+	+	+	-	-
Y	+	+	-	-	+	+	-	-	+	+	-	-		
P6 B	+	+	+	+	-	-	-	-	+	+	+	+	-	-
Y	-	-	+	+	-	-	+	+	-	-	+	+		
P7 B	-	-	-	-	+	+	+	+	-	-	-	-	+	+
Y	+	+	-	-	+	+	-	-	+	+	-	-		
P8 B	-	-	-	-	+	+	+	+	-	-	-	-	+	+
Y	-	-	+	+	-	-	+	+	-	-	+	+		

P21 B	+	+	-	-	+	+	-	-
Y	+	+	+	+	-	-	-	-
P22 B	-	-	+	+	-	-	+	+
Y	+	+	+	+	-	-	-	-
P23 B	+	+	-	-	+	+	-	-
Y	-	-	-	-	+	+	+	+
P24 B	-	-	+	+	-	-	+	+
Y	-	-	-	-	+	+	+	+
P25 B	+	+	+	+	-	-	-	-
Y	+	+	-	-	+	+	-	-
P26 B	+	+	+	+	-	-	-	-
Y	-	-	+	+	-	-	+	+
P27 B	-	-	-	-	+	+	+	+
Y	+	+	-	-	+	+	-	-
P28 B	-	-	-	-	+	+	+	+
Y	-	-	+	+	-	-	+	+

⇓

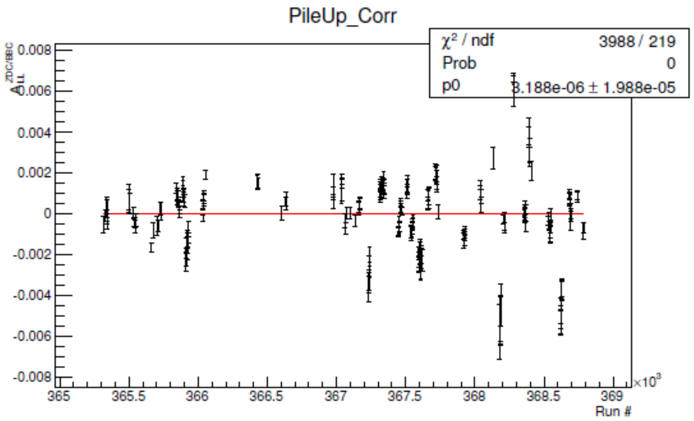
SOOSSOO	P1	P4	P5	P8
OSSOOSS	P2	P3	P6	P7
SSOO	P21	P24	P25	P28
OOSS	P22	P23	P26	P27

↑. Run13 old and new spin patterns

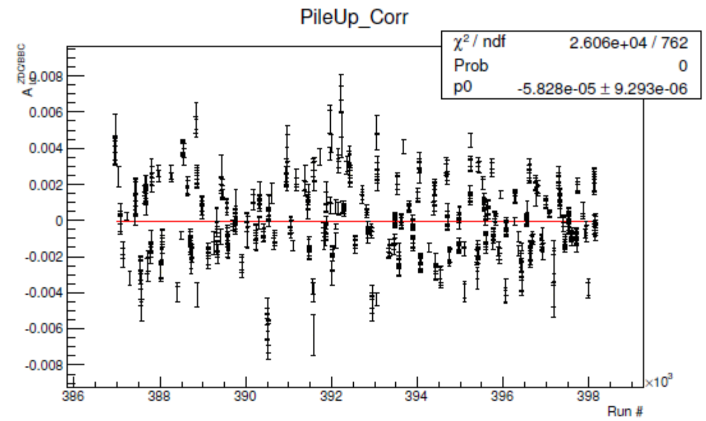


Rate_Ratio_Corr_BBC_North_ALL_0
χ² / ndf 1.48e+08 / 21750
Prob 0
p0 0.2235 ± 4.058e-07
BBC_Coin/CLOCK
Rate_Ratio_Corr_BBC_South_ALL_0
χ² / ndf 3.768e+07 / 21750
Prob 0
p0 0.2223 ± 4.045e-07
BBC_Coin/CLOCK
Rate_Ratio_Corr_ZDC_North_ALL_0
χ² / ndf 3.721e+07 / 21750
Prob 0
p0 3.617 ± 7.263e-06
ZDC_Coin/CLOCK
Rate_Ratio_Corr_ZDC_South_ALL_0
χ² / ndf 4.244e+07 / 21750
Prob 0
p0 3.807 ± 7.603e-06
ZDC_Coin/CLOCK
Rate_Ratio_Corr_BBC_North_ALL_0
χ² / ndf 1.291e+09 / 72346
Prob 0
p0 0.2255 ± 1.696e-07
BBC_Coin/CLOCK
Rate_Ratio_Corr_BBC_South_ALL_0
χ² / ndf 2.129e+09 / 72346
Prob 0
p0 0.2247 ± 1.692e-07
BBC_Coin/CLOCK
Rate_Ratio_Corr_ZDC_North_ALL_0
χ² / ndf 9.559e+08 / 72346
Prob 0
p0 3.846 ± 3.015e-06
ZDC_Coin/CLOCK
Rate_Ratio_Corr_ZDC_South_ALL_0
χ² / ndf 1.463e+09 / 72346
Prob 0
p0 4.051 ± 3.16e-06
ZDC_Coin/CLOCK

4. Relative Luminosity - Pileup Correction



(a) Run12



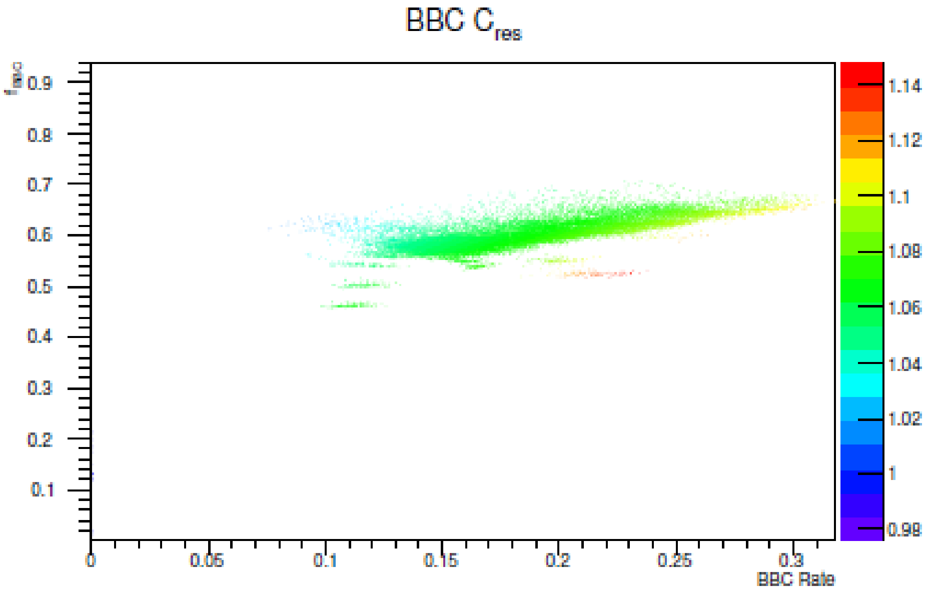
(b) Run13

$$A_{LL}^{ZDC/BBC} = 3.188 \times 10^{-6} \pm 1.988 \times 10^{-5}$$
$$\chi^2_{re}(run fitting) = 3.988 \times 10^{3}/219 = 1.821 \times 10^{1}$$
$$\overline{\chi^2_{re}(bunch fitting)} = 1.531 \times 10^{2}$$

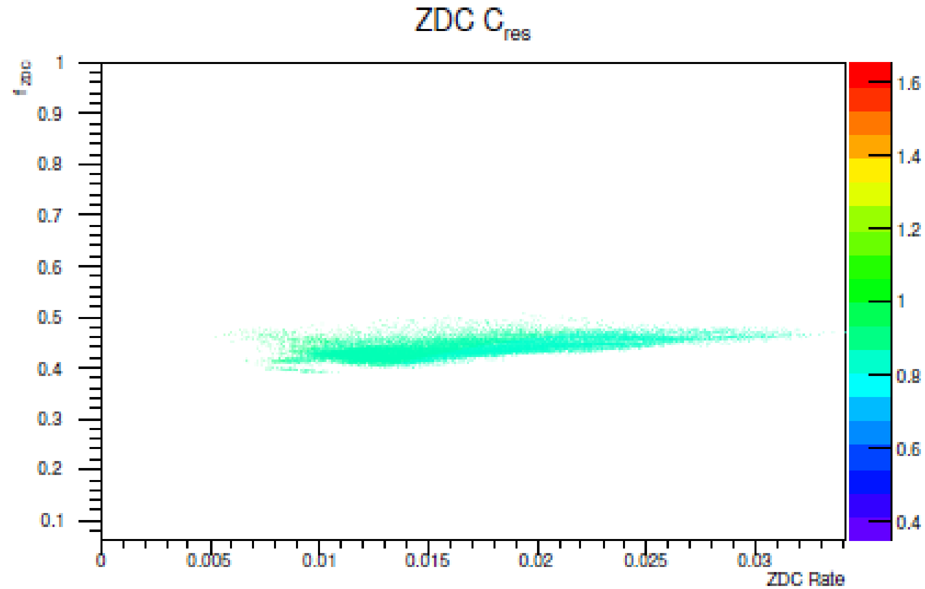
Run12

$$A_{LL}^{ZDC/BBC} = -5.828 \times 10^{-5} \pm 9.293 \times 10^{-6}$$
$$\chi^2_{re}(run fitting) = 2.606 \times 10^{4}/762 = 3.420 \times 10^{1}$$
$$\overline{\chi^2_{re}(bunch fitting)} = 2.047 \times 10^{2}$$

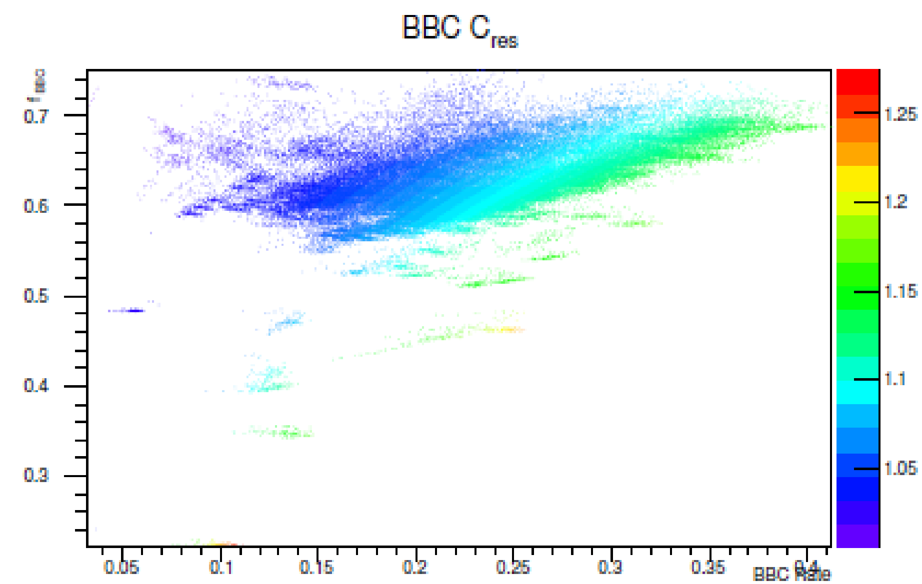
Run13



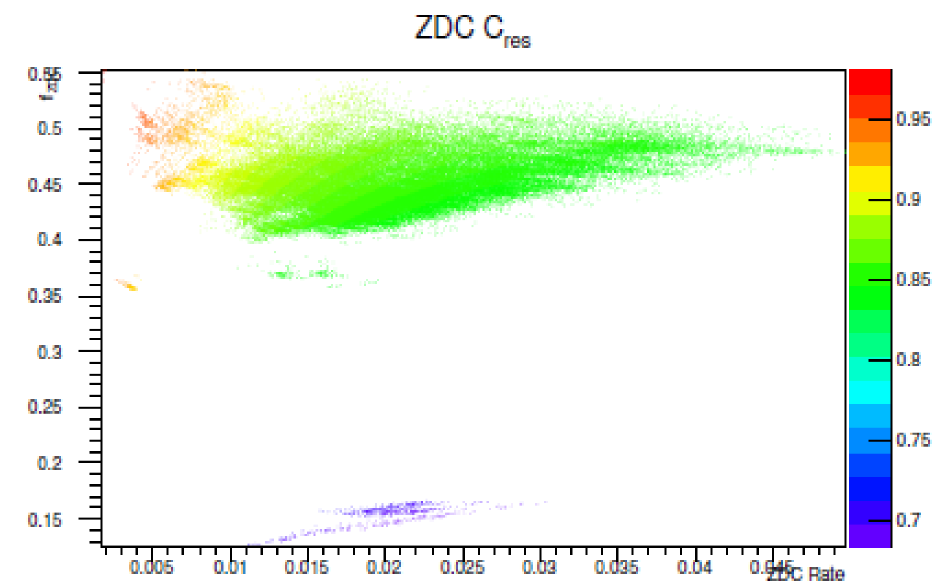
(a) Run12 BBC



(b) Run12 ZDC

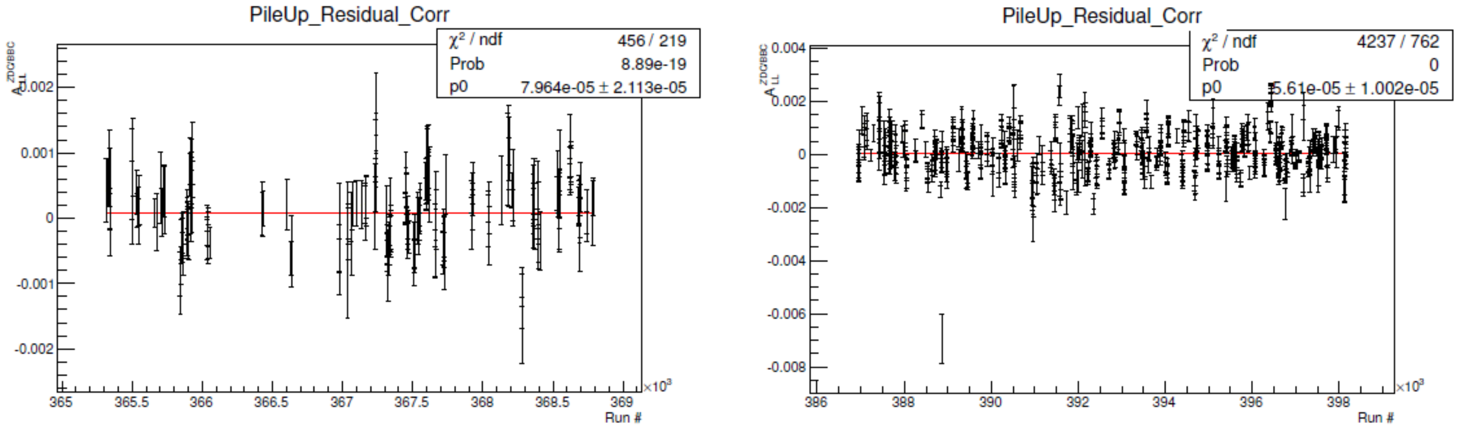


(c) Run13 BBC



(d) Run13 ZDC

4. Relative Luminosity - Residual Rate Correction



(a) Run12 (b) Run13

$$A_{LL}^{ZDC/BBC} = 7.964 \times 10^{-5} \pm 2.113 \times 10^{-5}$$
$$\chi^2_{re}(run\,fitting) = 4.560 \times 10^2/219 = 2.082 \times 10^0$$
$$\overline{\chi^2_{re}(bunch\,fitting)} = 1.454 \times 10^1$$

Run12

$$A_{LL}^{ZDC/BBC} = 5.610 \times 10^{-5} \pm 1.002 \times 10^{-5}$$
$$\chi^2_{re}(run\,fitting) = 4.237 \times 10^3/762 = 5.560 \times 10^0$$
$$\overline{\chi^2_{re}(bunch\,fitting)} = 2.355 \times 10^1$$

Run13

4. Relative Luminosity - Correction

	Uncorr	**Pileup**	**Width**	**Residual**
$A_{LL}^{ZDC/BBC}$	-2.18×10^{-4}	-1.09×10^{-4}	5.47×10^{-4}	1.17×10^{-4}
$\chi^2_{re}(run)$	5.17×10^{1}	1.82×10^{1}	1.65×10^{1}	2.08×10^{0}
$\overline{\chi^2_{re}(bunch)}$	1.68×10^{3}	6.73×10^{2}	9.44×10^{2}	1.45×10^{1}
Syst.Pattern	6.23×10^{-3}	3.44×10^{-4}	9.28×10^{-5}	1.44×10^{-4}

Table 6.1: Run12 summary of corrections on scaler counts.

	Uncorr	**Pileup**	**Width**	**Residual**
$A_{LL}^{ZDC/BBC}$	-2.43×10^{-4}	-5.83×10^{-5}	-1.70×10^{-5}	5.61×10^{-5}
$\chi^2_{re}(run)$	9.44×10^{1}	3.42×10^{1}	2.53×10^{1}	5.56×10^{0}
$\overline{\chi^2_{re}(bunch)}$	3.08×10^{3}	2.05×10^{2}	1.28×10^{2}	2.36×10^{1}
Syst.Pattern	3.00×10^{-3}	1.08×10^{-3}	7.34×10^{-4}	3.69×10^{-4}

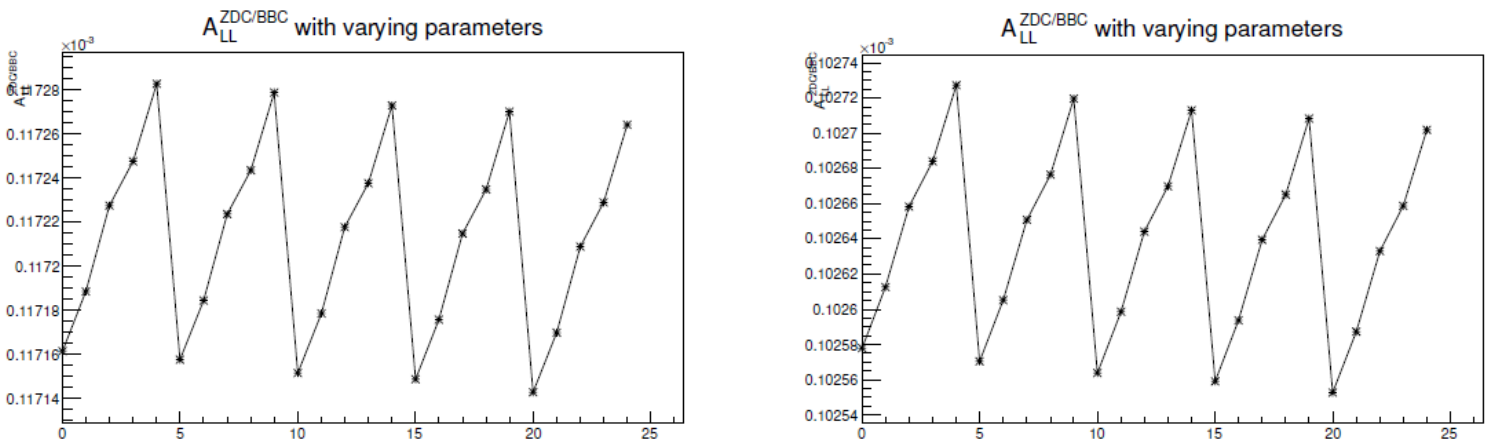
Table 6.2: Run13 summary of corrections on scaler counts.

4. Relative Luminosity - Syst. (Corr.)

- Correction parameters, k_N and k_S are obtained by fitting.

  The k_N and k_S is varied by adding $N \times \sqrt{\chi^2_{Re}} \times \Delta k$ where $N = -2, -1, 0, 1, 2$.

  Then, $A_{LL}^{ZDC/BBC}$ is calculated for each varied k_N and k_S set.



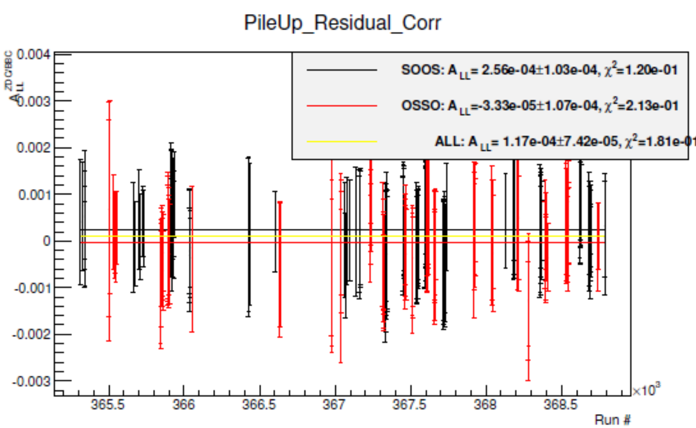
(a) Run12

(b) Run13

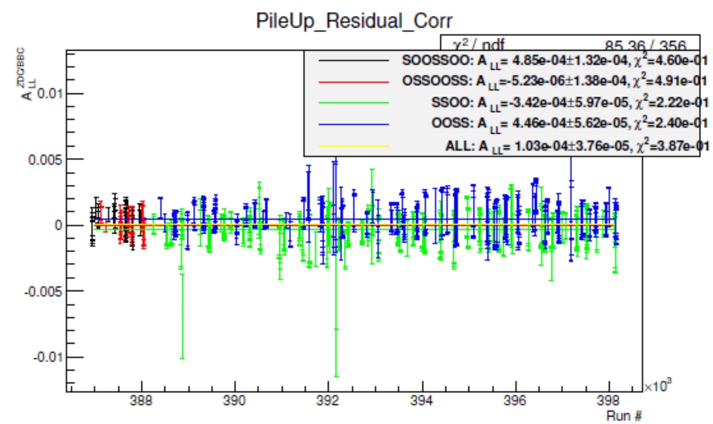
$$\Rightarrow \begin{array}{l} \text{Run13: } \Delta A_{LL}^{ZDC/BBC}(syst.correction) = 7.003 \times 10^{-8} \\ \text{Run13: } \Delta A_{LL}^{ZDC/BBC}(syst.correction) = 8.727 \times 10^{-8} \end{array}$$

4. Relative Luminosity - Syst. (Spin Pattern)

- For each spin pattern, different $A_{LL}^{ZDC/BBC}$ are observed.
  The corrections removed the separation mostly.
  Remaining separation is assigned as syst.

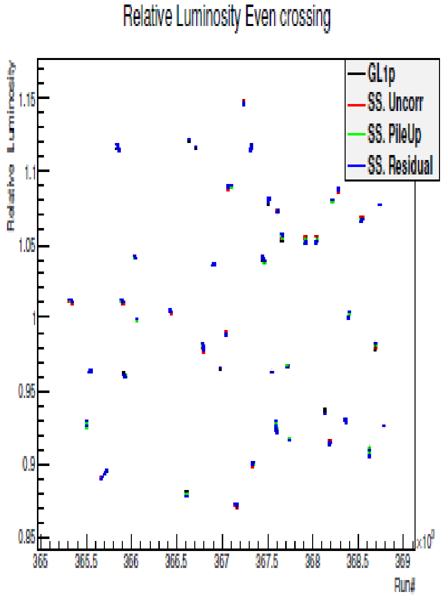


(a) Run12

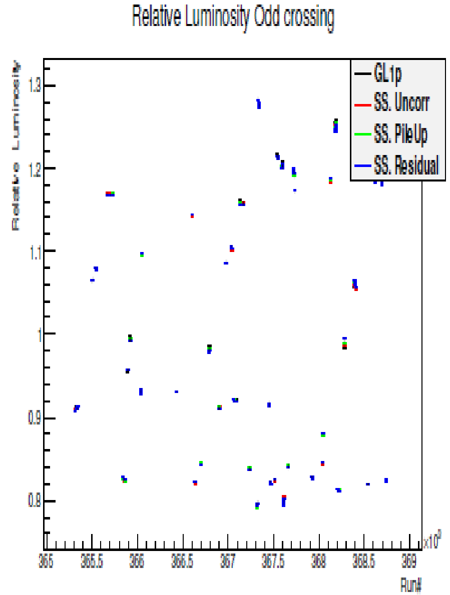


(b) Run13

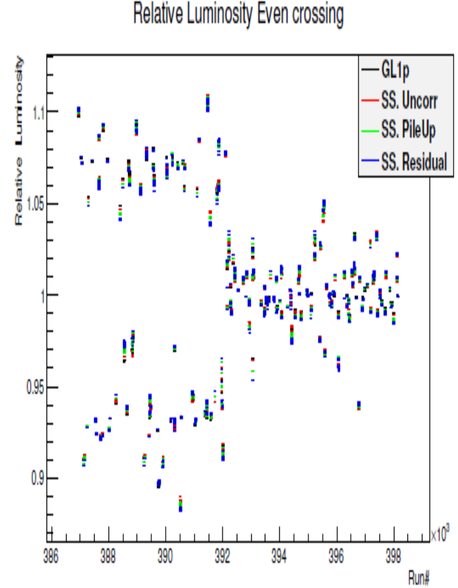
$$\Rightarrow \begin{array}{l} \text{Run12: } \Delta A_{LL}^{ZDC/BBC}(syst, pattern) = 1.445 \times 10^{-4} \\ \text{Run13: } \Delta A_{LL}^{ZDC/BBC}(syst.pattern) = 3.694 \times 10^{-4} \end{array}$$



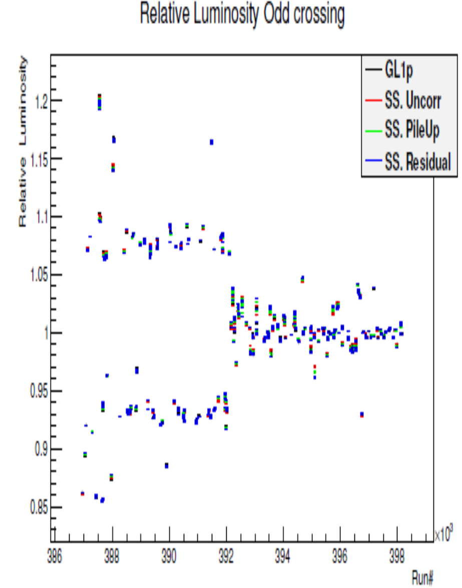
(a) Even Crossing



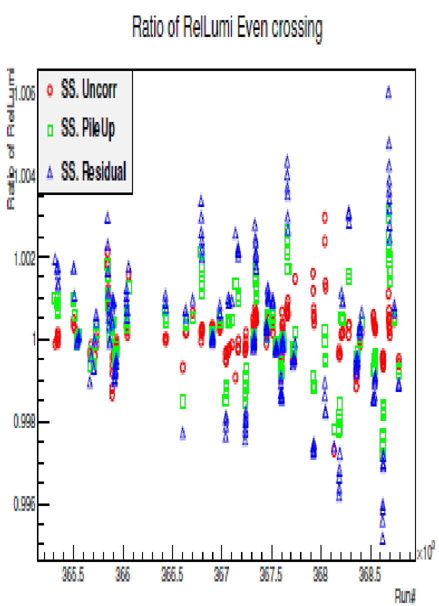
(b) Odd Crossing



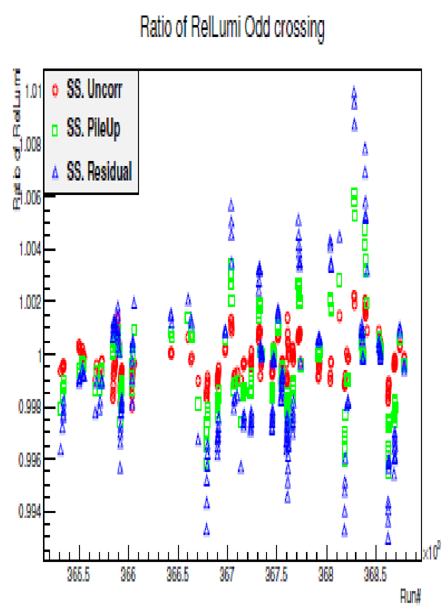
(a) Even Crossing



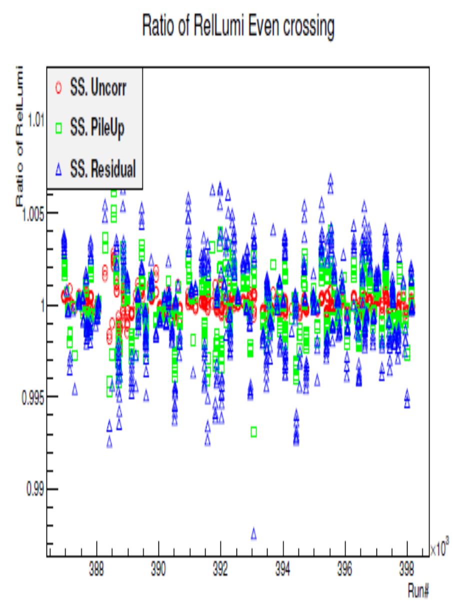
(b) Odd Crossing



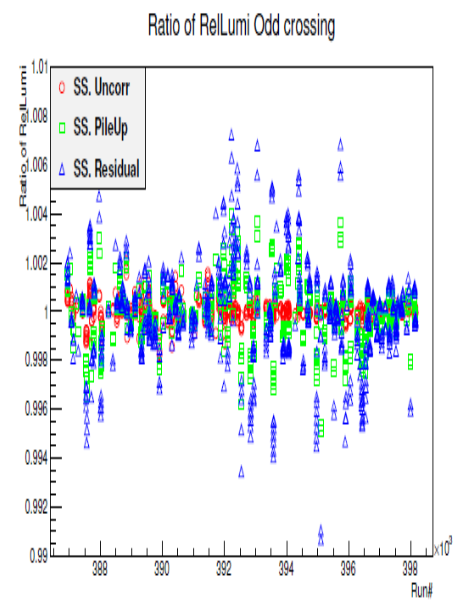
(c) Even Crossing



(d) Odd Crossing



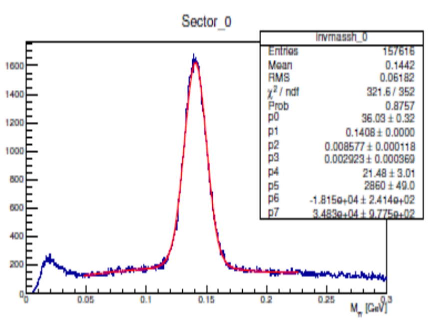
(c) Even Cross



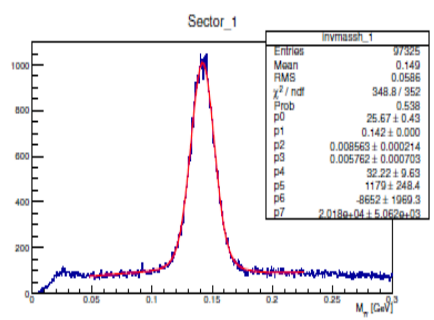
ld Crossing

4. PHENIX and Calibrations

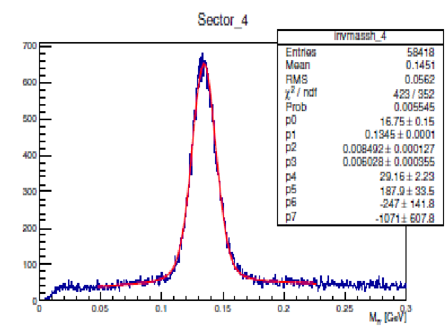
- EMCal energy calibration: calibrated with π^0 peak position.
  Tower-by-tower calibration: with whole run data.
  Run-by-run and sector-by-sector calibration: to reject run-by-run gain shift + QA.



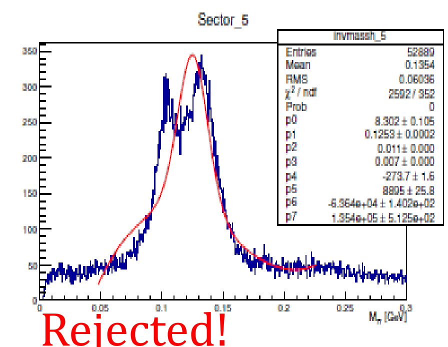
(a) Sector 0



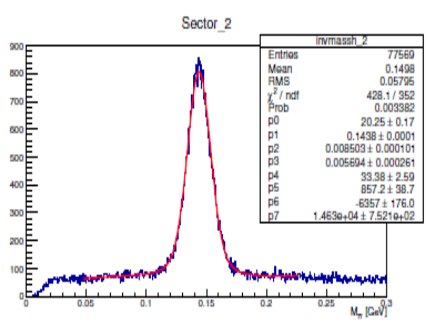
(b) Sector 1



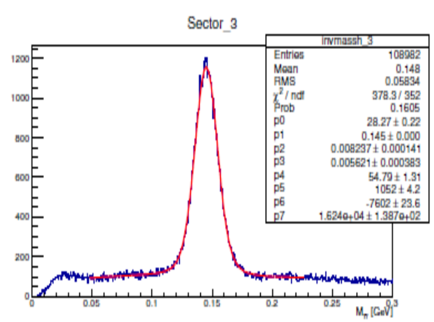
(e) Sector 4



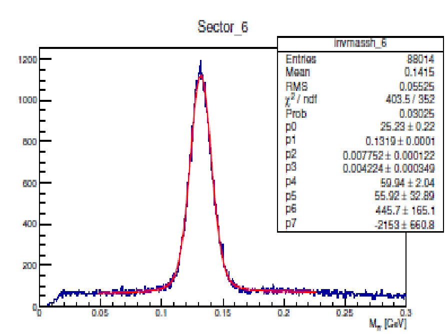
(f) Sector 5



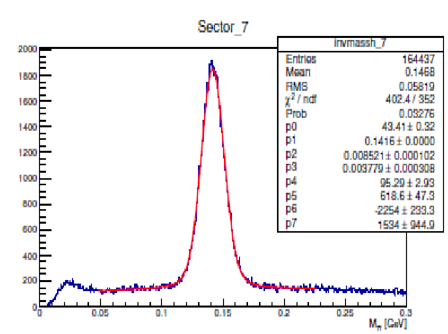
(c) Sector 2



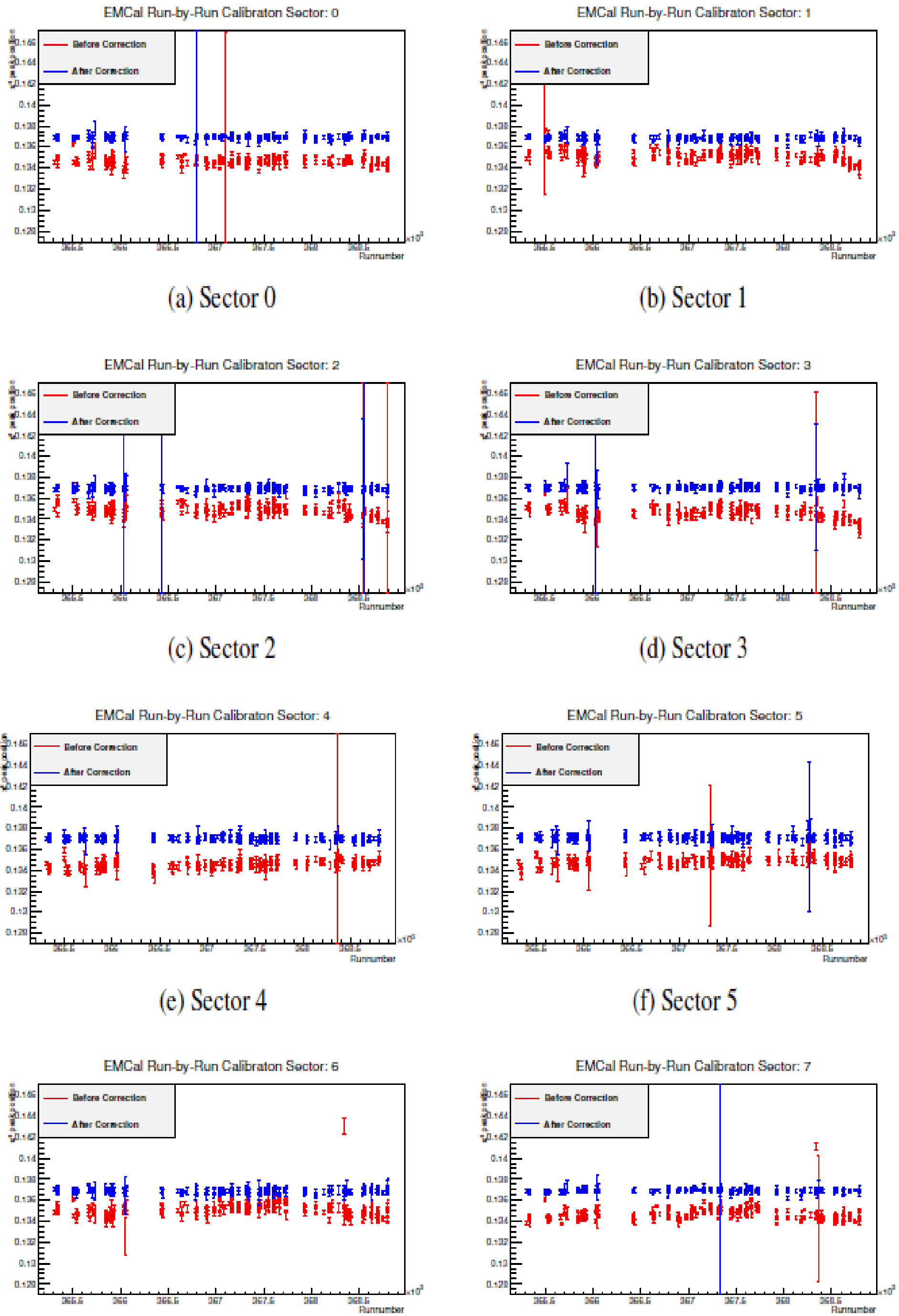
(d) Sector 3



(g) Sector 6



(h) Sector 7

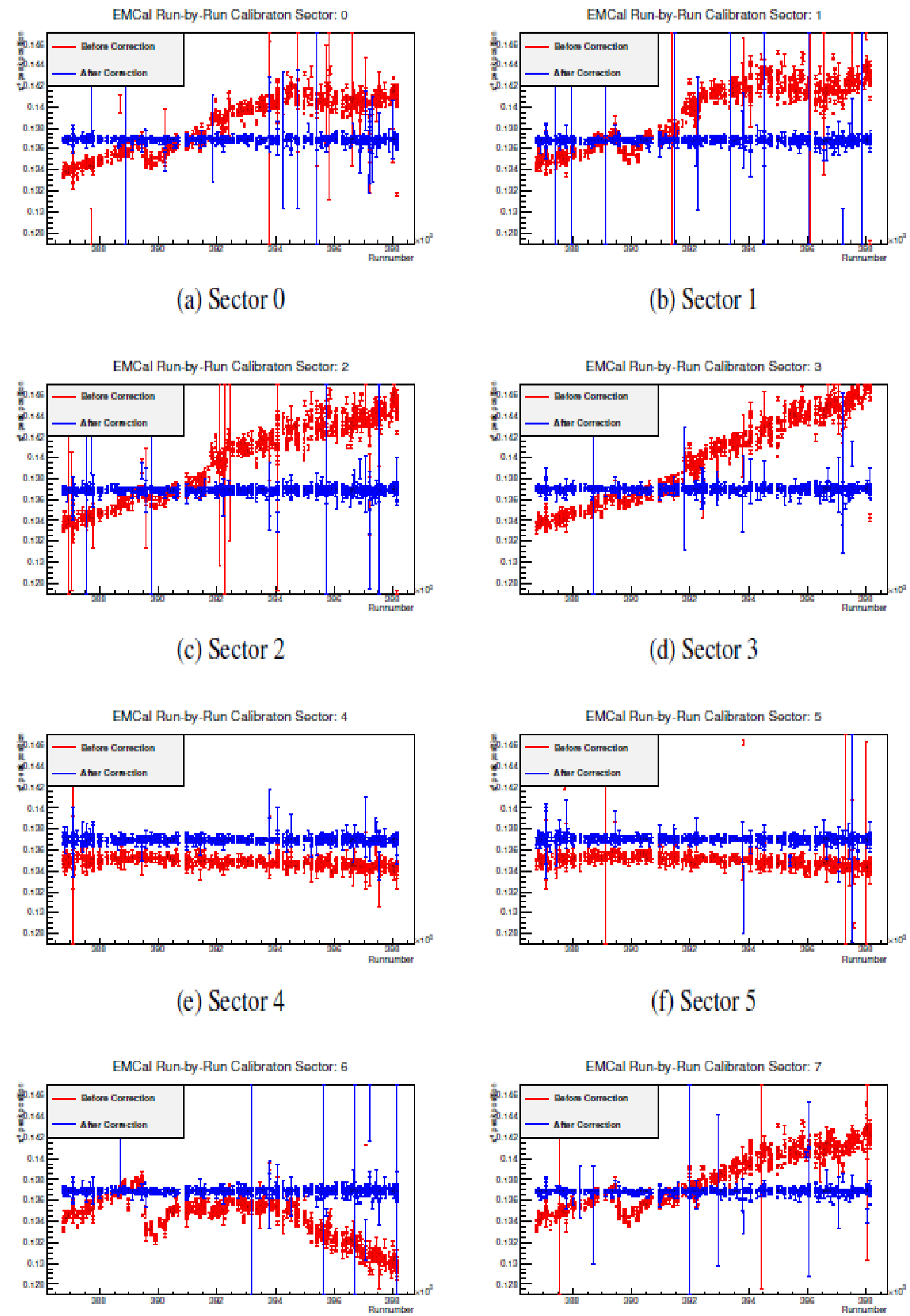


(a) Sector 0 (b) Sector 1

(c) Sector 2 (d) Sector 3

(e) Sector 4 (f) Sector 5

(g) Sector 6 (h) Sector 7



(a) Sector 0 (b) Sector 1

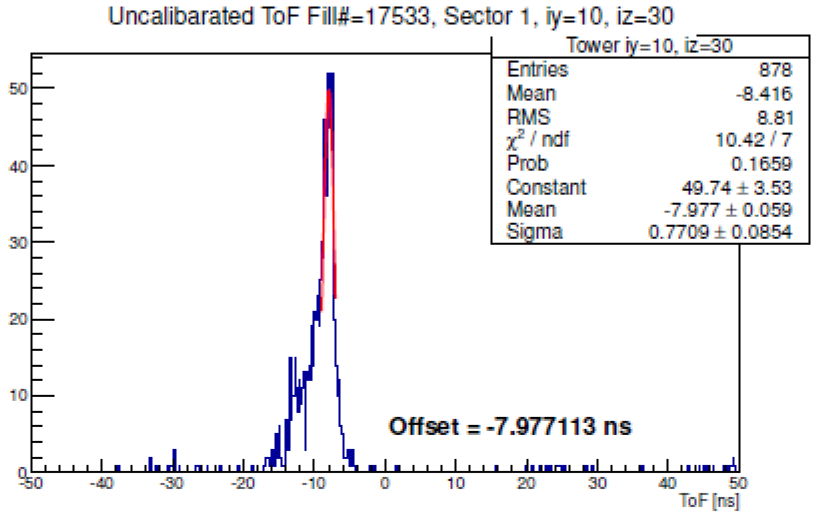
(c) Sector 2 (d) Sector 3

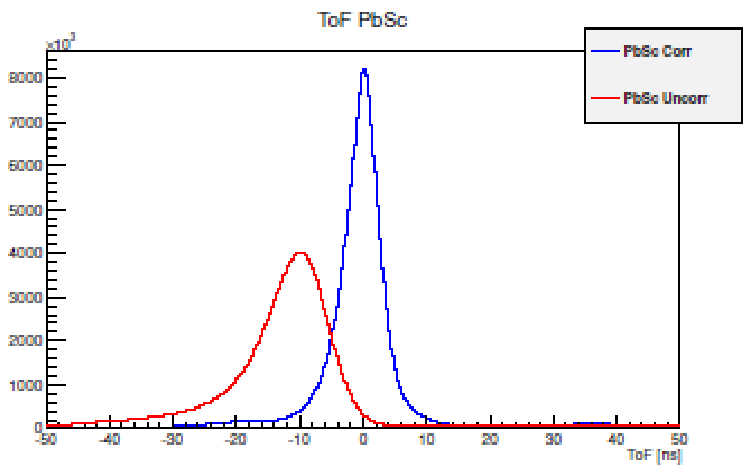
(e) Sector 4 (f) Sector 5

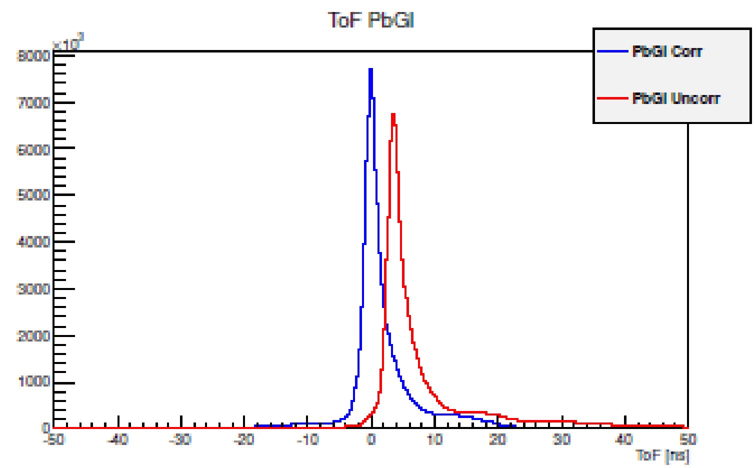
(g) Sector 6 (h) Sector 7

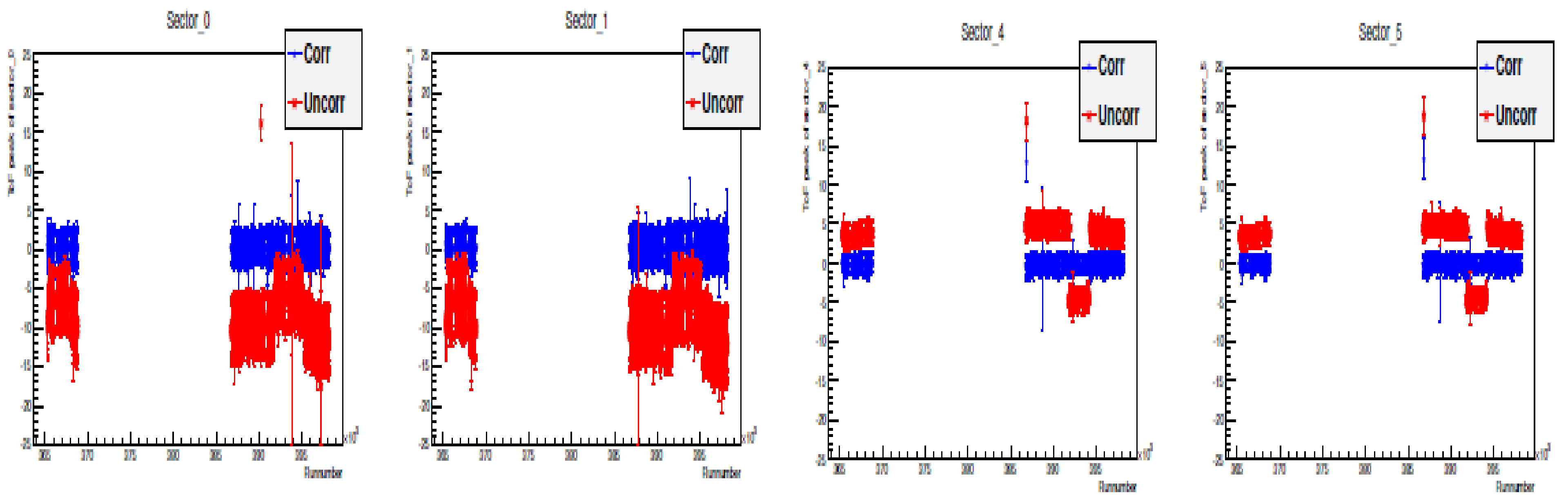
4. PHENIX and Calibrations

- EMCal ToF tower-by-tower calibration: calibrated with γ peak position.



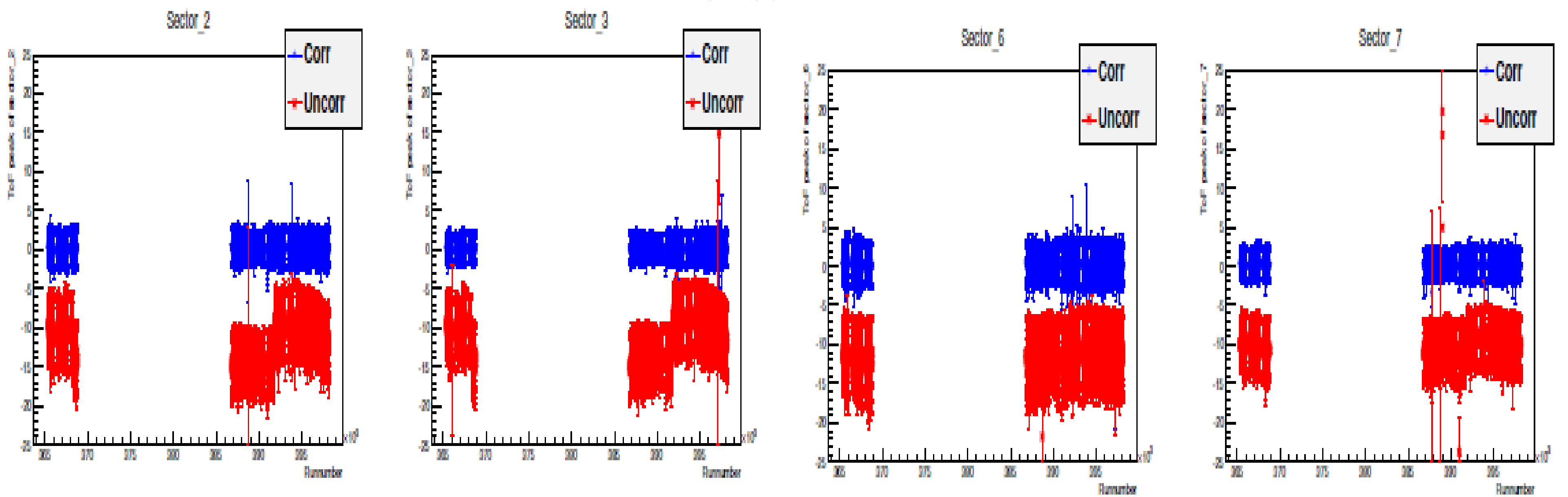






(a) Sector 0 (b) Sector 1 (e) Sector 4 (f) Sector 5

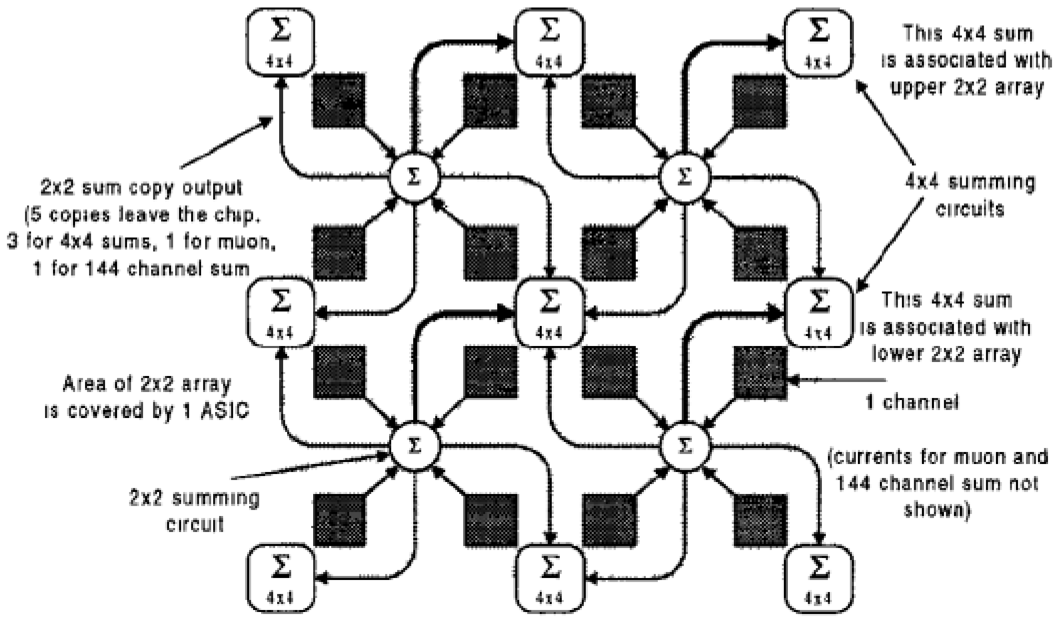
Error bar=FWHM



(c) Sector 2 (d) Sector 3 (g) Sector 6 (h) Sector 7

3. RHIC and PHENIX

- EMCal-RICH Trigger.



Energy sum of 4x4 tower is bigger than predefined threshold.

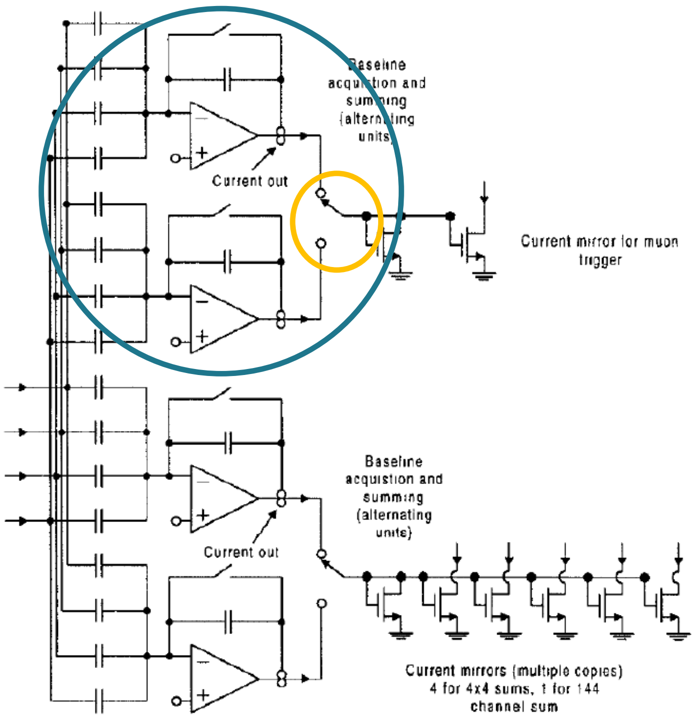
ERT_4x4A: 4.7 GeV

ERT_4x4B: 5.6 GeV

ERT_4x4C: 3.7 GeV

3. RHIC and PHENIX

- Crossing dependence of EMCal-RICH Trigger.
  Summing amp. need 140ns. Cf) 1 BCLK=106ns
  ⇒ two identical circuits to support full bunchs.
  ⇒ Slightly different trigger effi.
  ⇒ The analysis has been done crossing separately.



3. RHIC and PHENIX

- PHENIX DAQ and prescale

If trigger rate is faster then DAQ bandwidth, the trigger need to be prescaled.

	1	2	3	4	5	6	7	8	9
A(2)	O		O	O			O		
B(0)	O			O					
C(4)	O		O	O	O		O		O
recorded	O(A,B,C)			O(A,B)			O(C)		

Different prescale is selected as luminosity decay.

ERT_4x4A: 0~2

ERT_4x4B: 0

ERT_4x4C: 0~4

- Scaler board: since BBC, ZDC are highly prescaled, independent scaler boards record prescale free trigger counts.

5. Events Selections

- π^0 Reconstruction.

  Direction cosine from $vertex_z$ to EMCal hits. Multiply cluster energy.

  $$P_{\gamma,\mu} = (E, Ecos\theta_x, Ecos\theta_y, Ecos\theta_z)$$

  By momentum conservation,

  $$P_{\pi^0,\mu} = P_{\gamma_1,\mu} + P_{\gamma_2,\mu}$$

  If invariant mass

  $$M_{\gamma\gamma} = \sqrt{P_{\pi^0,\mu} P^{\mu}_{\pi^0}}$$

  $112 MeV/c^2 < M_{\gamma\gamma} < 162 MeV/c^2$, the γ pair is considered π^0 decay γ pair.

- Trigger requirement to assure trigger bias is same for every π^0.

  i.e. want to reject π^0 from $p + p \rightarrow \pi^0 + c + X$

  $\Rightarrow$ require ERT trigger for every π^0.

  Practically ERT trigger is require for higher energy cluster.

  Called triggered cluster, paired cluster.

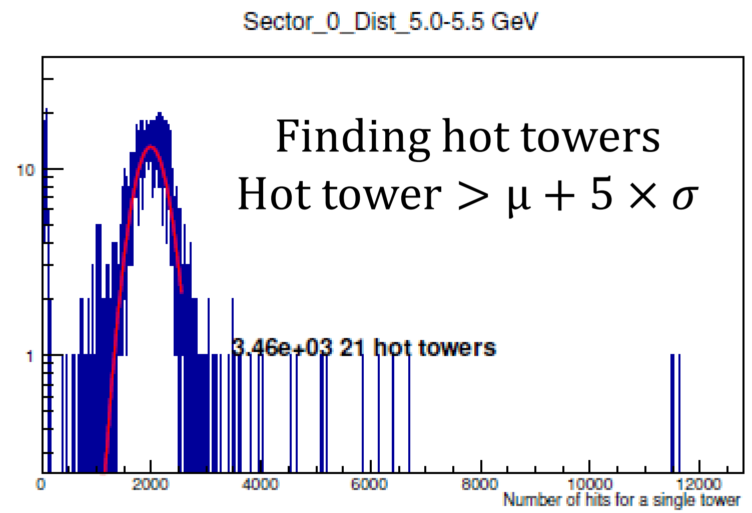
5. Events Selections

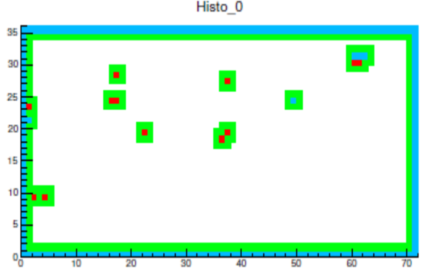
- Photon ID.
  1. Min energy cut: 0.3 GeV to reject noise hits.
  2. Warnmap cut: To reject abnormal towers.
  3. Shower profile cut: To reject hadron hits
  4. Charge veto cut: To reject charge tracks
  5. ToF cut: To reject ghost clusters

- Warnmap cut: To reject noisy, dead, uncalibrated, and the adjacent tower
  - Dead tower ≡ completely no hit
  - Uncalibrated towers in tower-by-tower energy calibration.
  - Adjacent tower to the bad towers

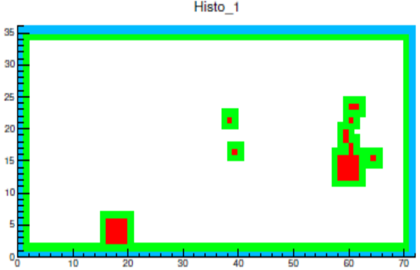
  ∵ Cluster spreads over at least 3x3 towers

  ⇒ 17% towers are rejected.

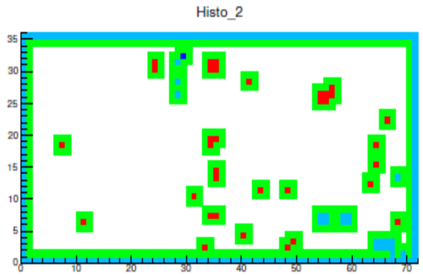




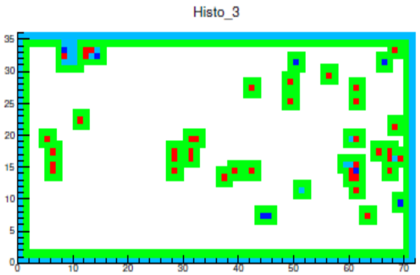
(a) Sector 0



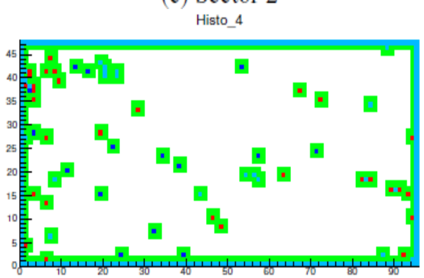
(b) Sector 1



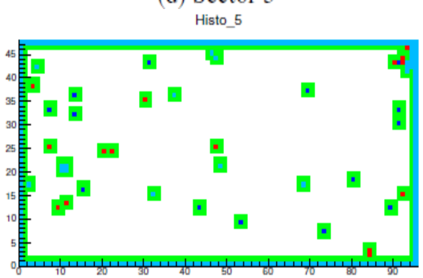
(c) Sector 2



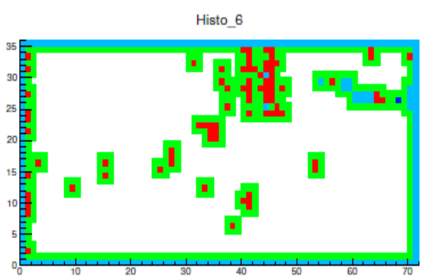
(d) Sector 3



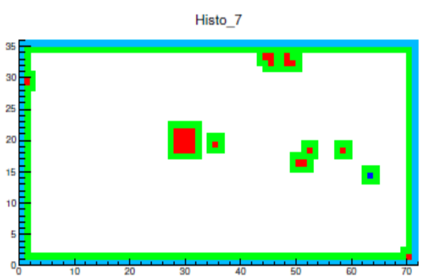
(e) Sector 4



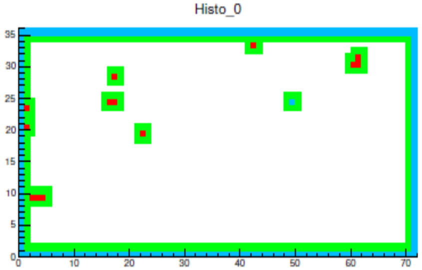
(f) Sector 5



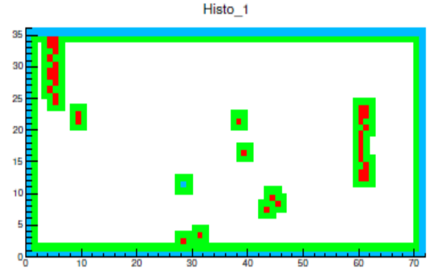
(g) Sector 6



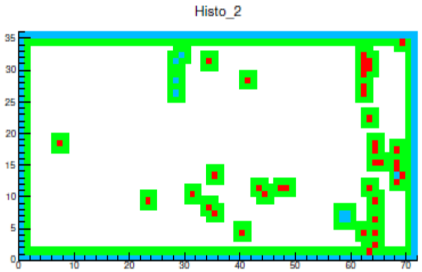
(h) Sector 7



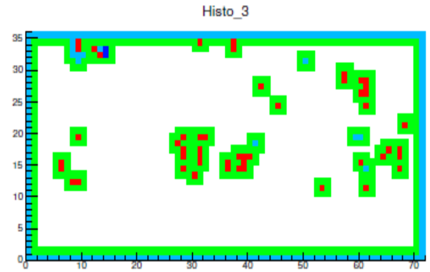
(a) Sector 0



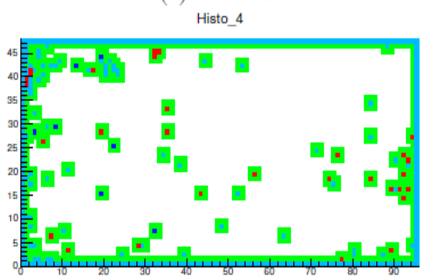
(b) Sector 1



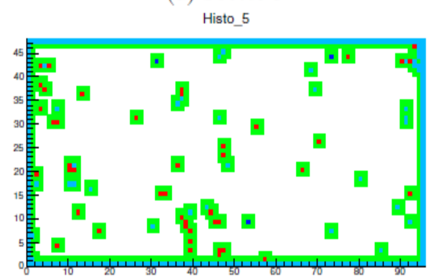
(c) Sector 2



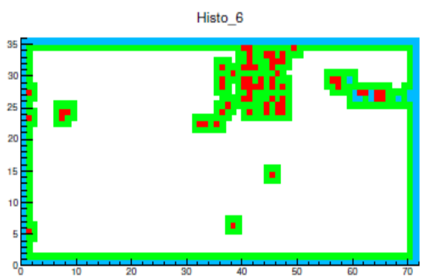
(d) Sector 3



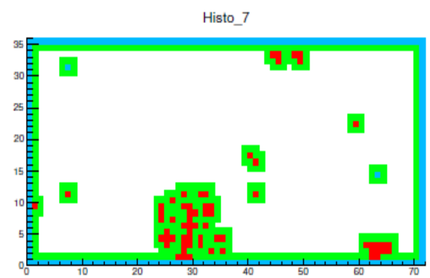
(e) Sector 4



(f) Sector 5



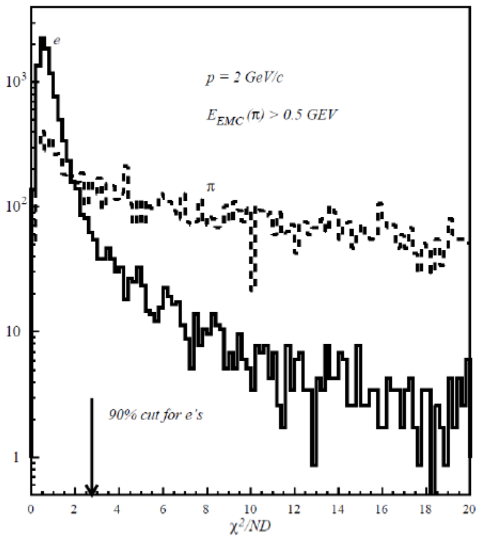
(g) Sector 6

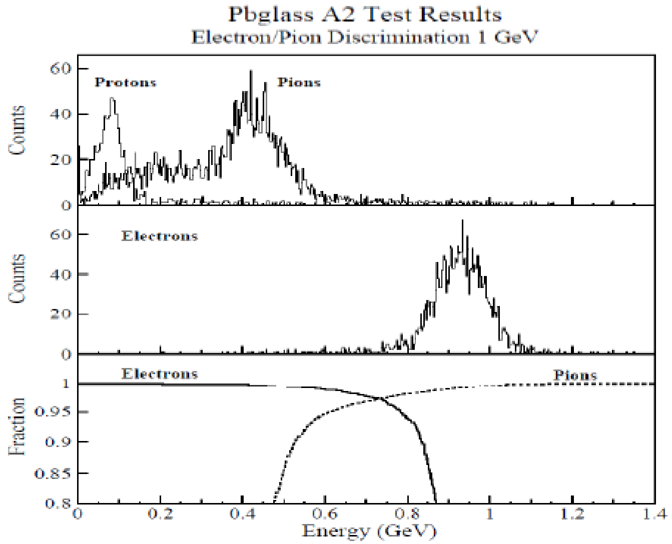


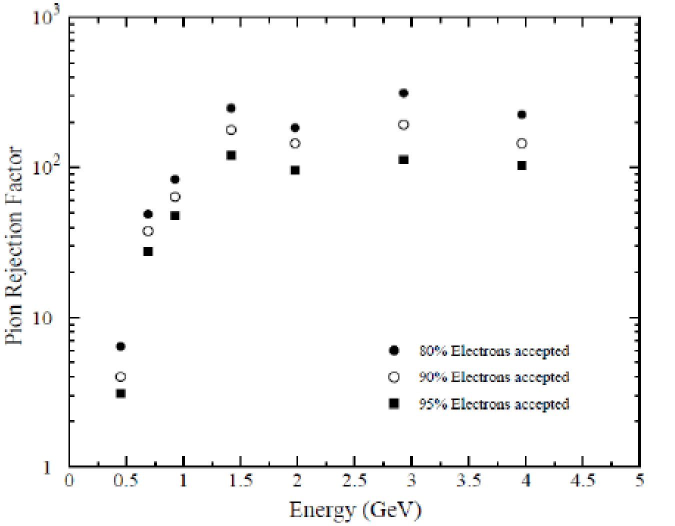
(h) Sector 7

5. Events Selections

- Shower shape cut: to reject hadron
  PHENIX EMCal can distinguish hadron by shower shape and $deposited\ energy/P$.
  Cut level: killing 2% real EM clusters (Convention in PHENIX)

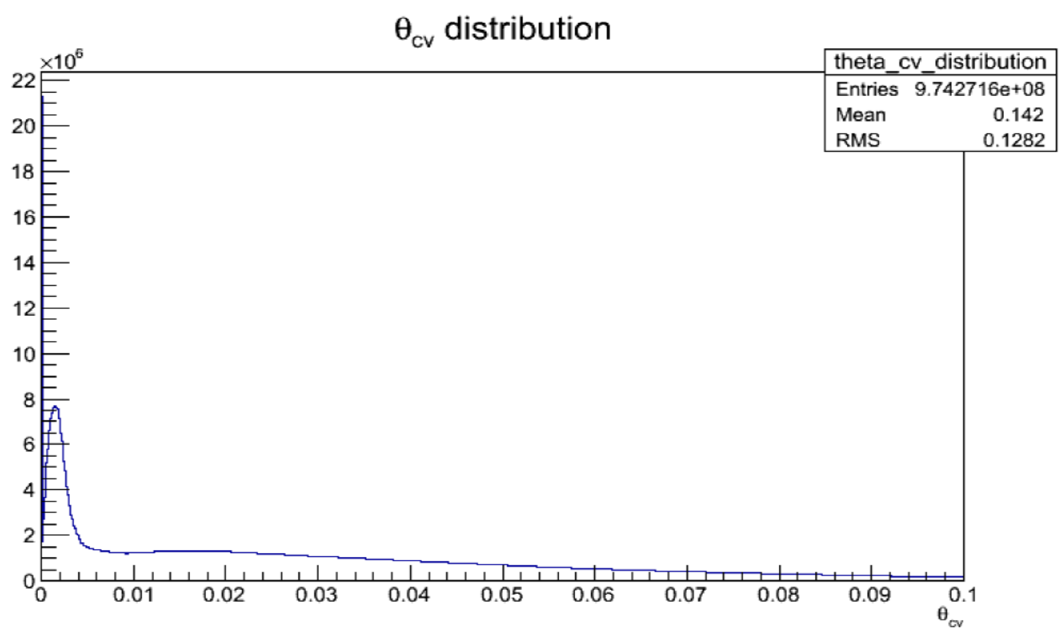




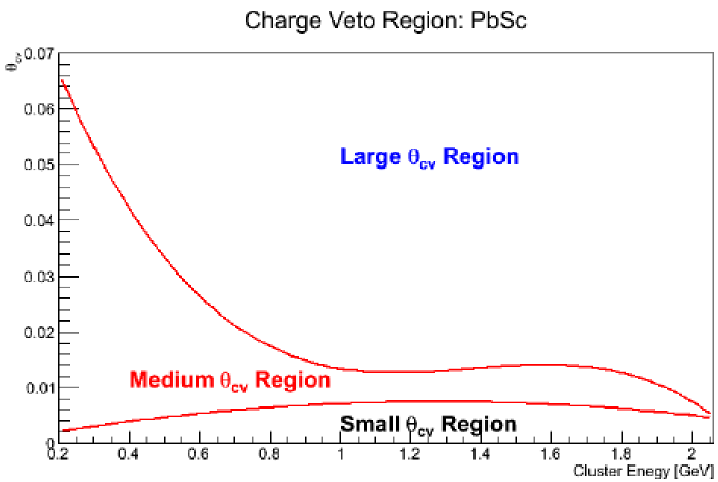


5. Events Selections

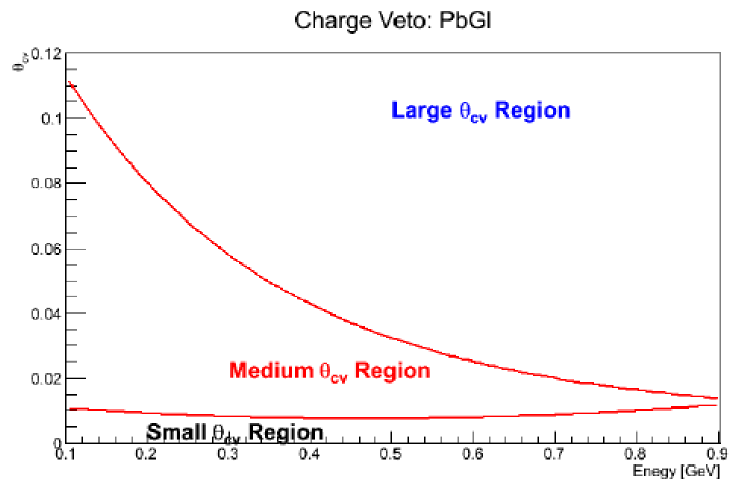
- Charge veto cut: to reject charged tracks.
  θ_{cv}: the opening angle between two vector, one from $vertex_z$ to EMCal hit
  the other from $vertex_z$ to PC3, 20cm(PbSc), 40cm(PbGl) inner.



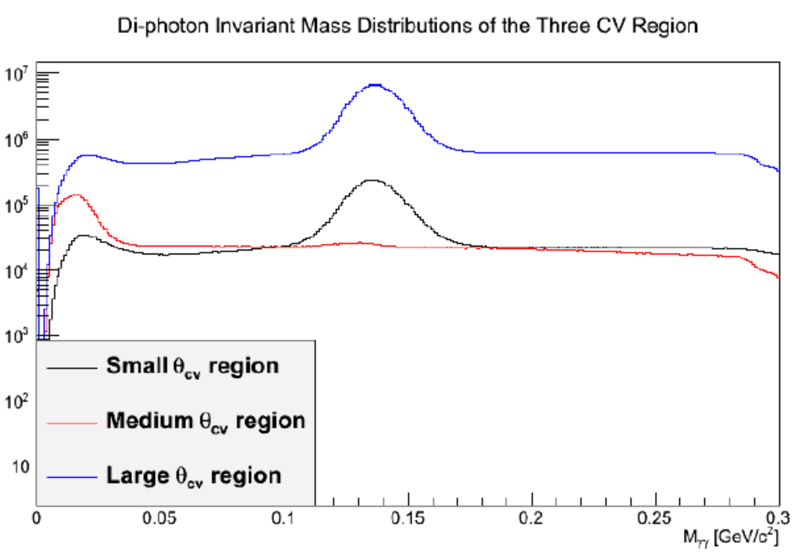
5. Events Selections

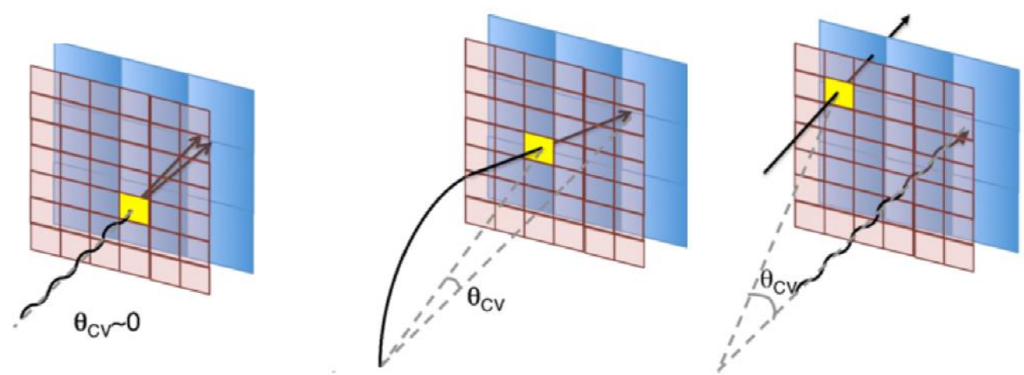


(a) Charge Veto Region: PbSc



(b) Charge Veto Region: PbGl

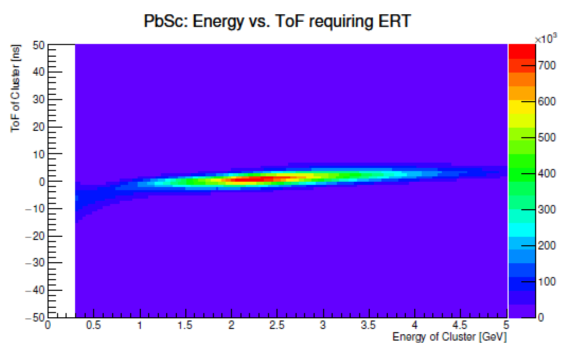




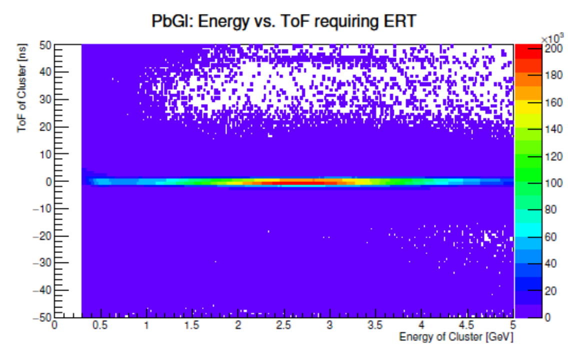
(a) "Small" θ_{CV} (b) "Medium" θ_{CV} (c) "Large" θ_{CV}

5. Events Selections

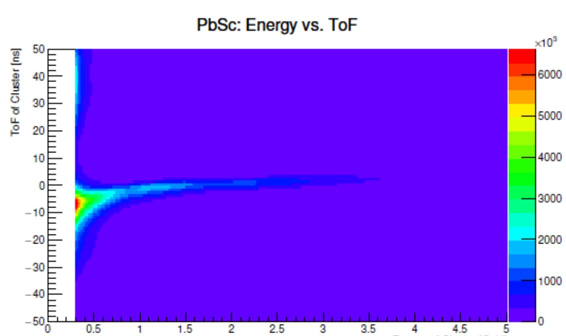
- ToF Cut: to reject ghost cluster.
  Cluster can survive up to three bunch crossings and make low energy background.
  Because they don't associate event t_0, they have wider ToF distribution.
  $|ToF| < 15ns$



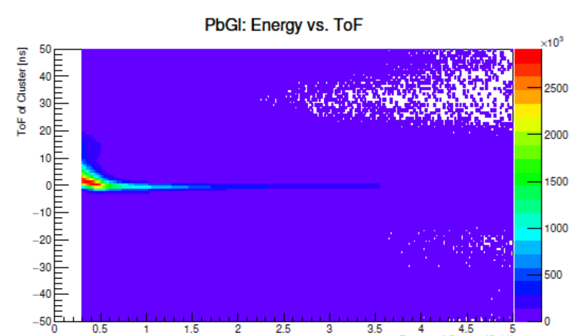
(a) PbSc, ERT on cluster is required



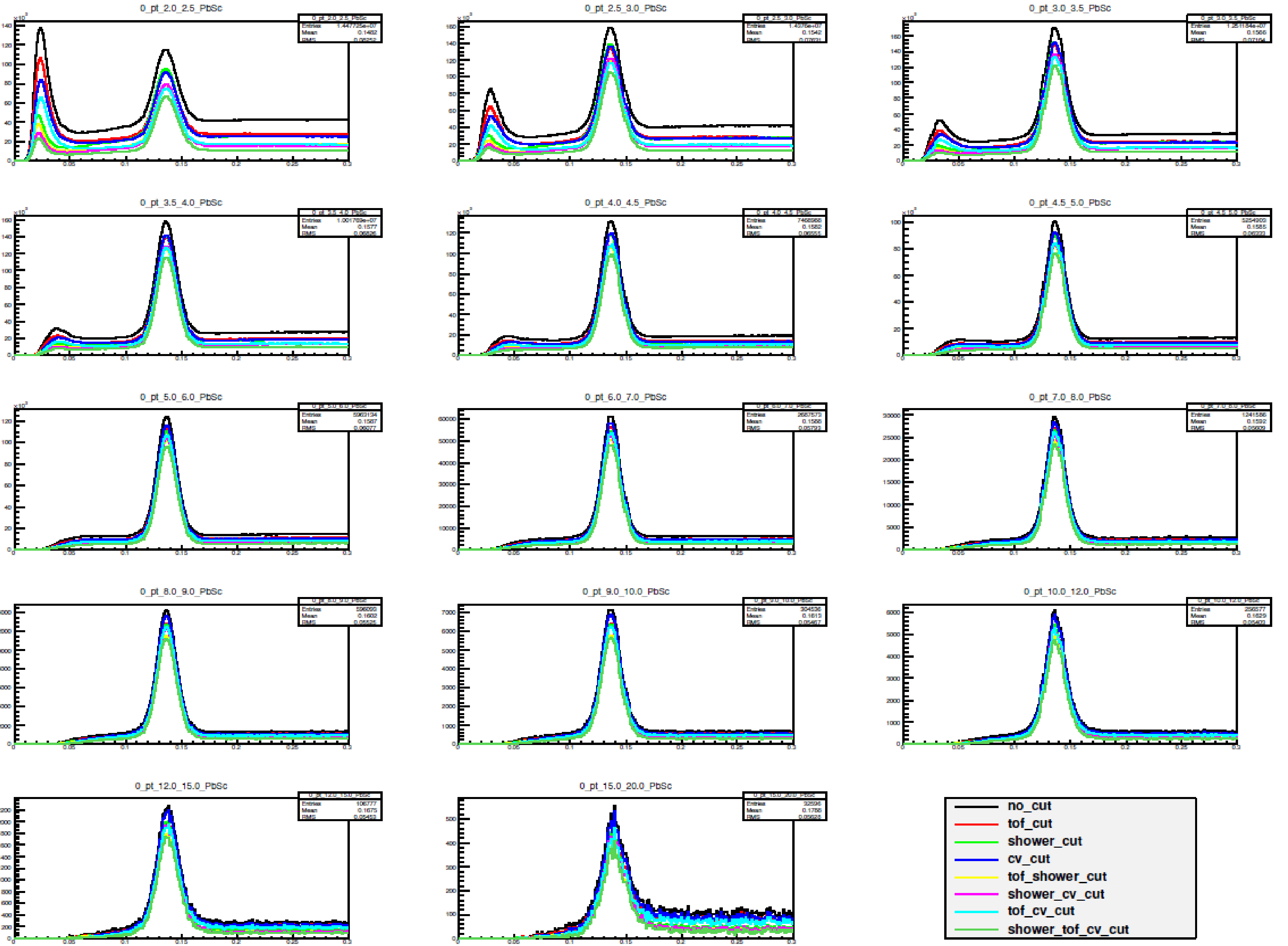
(b) PbGl, ERT on cluster is required



(c) PbSc, ERT on cluster is not required



(d) PbGl, ERT on cluster is not required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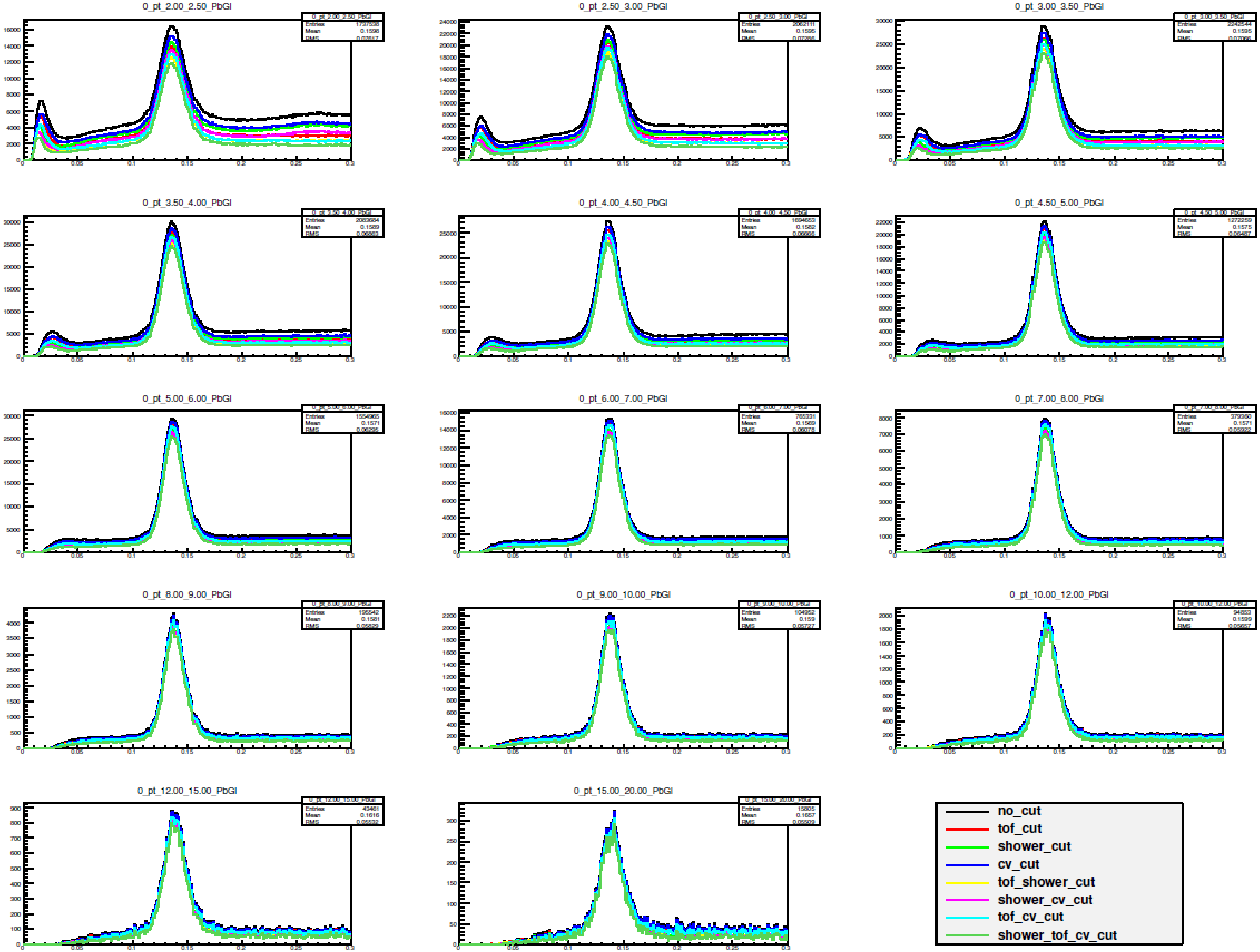
0_pt_2.5_3.0_PbSc
0_pt_3.0_3.5_PbSc
0_pt_3.5_4.0_PbSc
0_pt_4.0_4.5_PbSc
0_pt_4.5_5.0_PbSc
0_pt_5.0_6.0_PbSc
0_pt_6.0_7.0_PbSc
0_pt_7.0_8.0_PbSc
0_pt_8.0_9.0_PbSc
0_pt_9.0_10.0_PbSc
0_pt_10.0_12.0_PbSc
0_pt_12.0_15.0_PbSc
0_pt_15.0_20.0_PbSc
no_cut
tof_cut
shower_cut
cv_cut
tof_shower_cut
shower_cv_cut
tof_cv_cut
shower_tof_cv_cut



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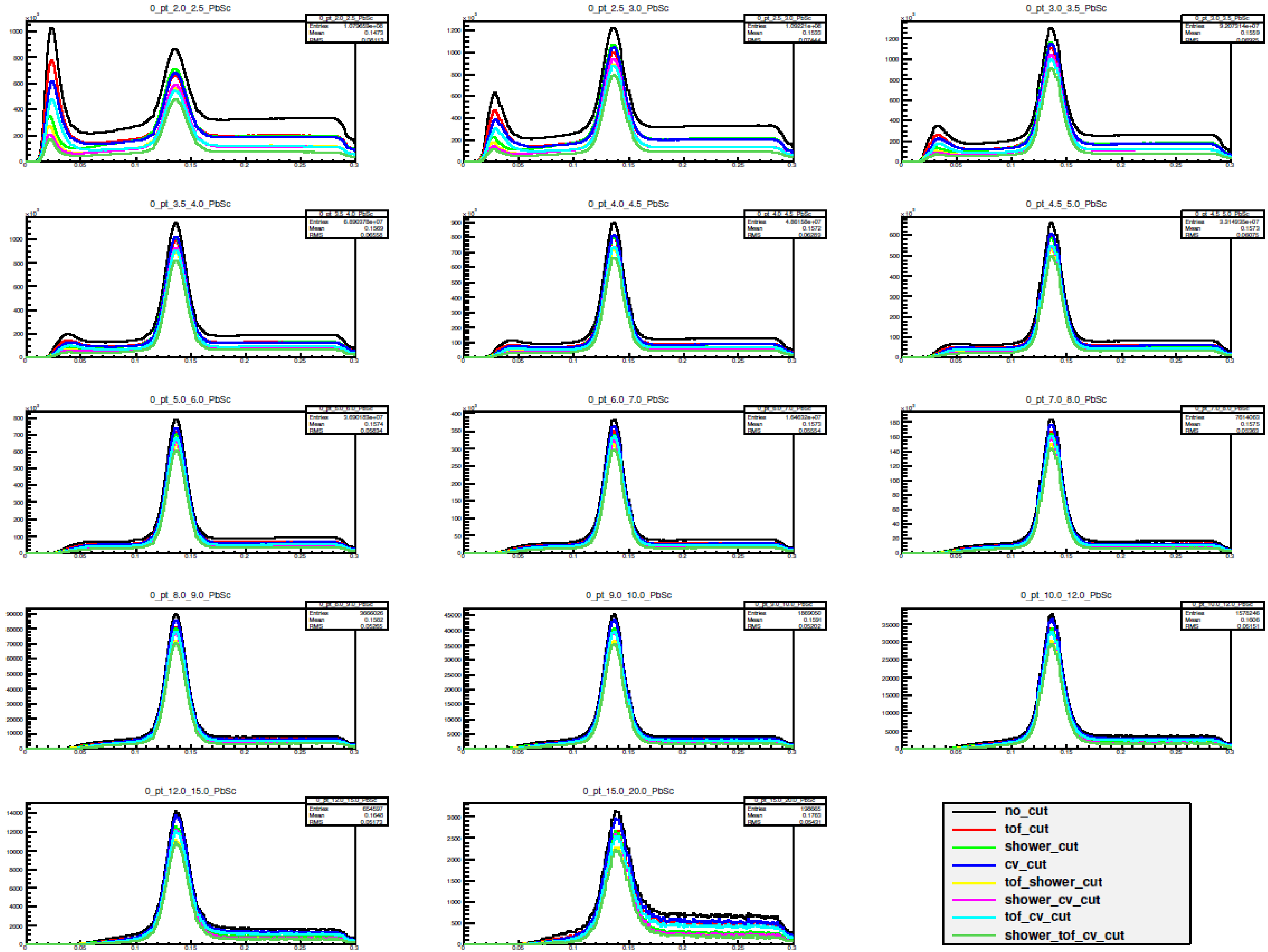
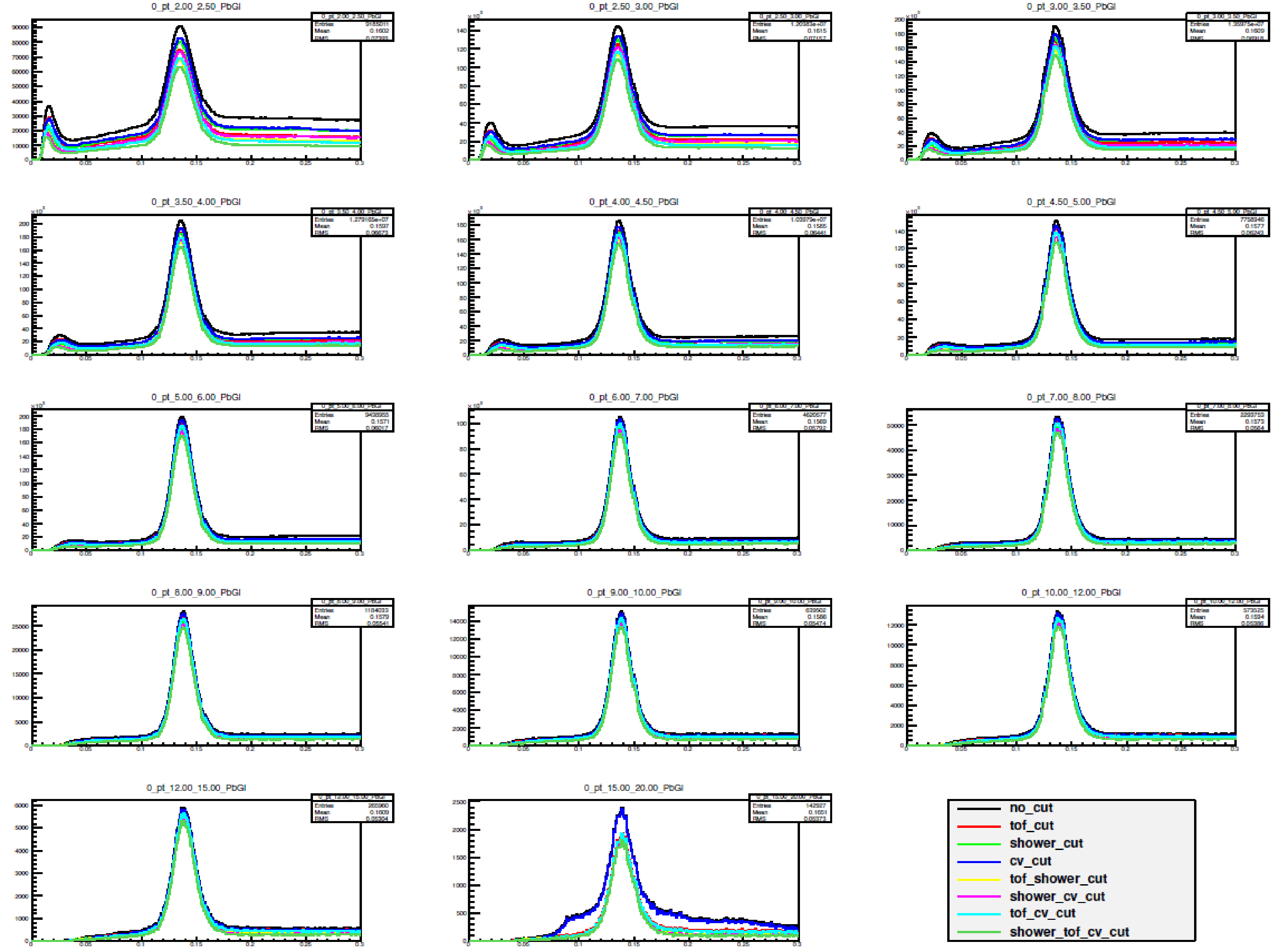
0_pt_2.50_3.00_PbGl
0_pt_3.00_3.50_PbGl
0_pt_3.50_4.00_PbGl
0_pt_4.00_4.50_PbGl
0_pt_4.50_5.00_PbGl
0_pt_5.00_6.00_PbGl
0_pt_6.00_7.00_PbGl
0_pt_7.00_8.00_PbGl
0_pt_8.00_9.00_PbGl
0_pt_9.00_10.00_PbGl
0_pt_10.00_12.00_PbGl
0_pt_12.00_15.00_PbGl
0_pt_15.00_20.00_PbGl
no_cut
tof_cut
shower_cut
cv_cut
tof_shower_cut
shower_cv_cut
tof_cv_cut
shower_tof_cv_cut



0_pt_2.0_2.5_PbSc
0_pt_2.5_3.0_PbSc
0_pt_3.0_3.5_PbSc
0_pt_3.5_4.0_PbSc
0_pt_4.0_4.5_PbSc
0_pt_4.5_5.0_PbSc
0_pt_5.0_6.0_PbSc
0_pt_6.0_7.0_PbSc
0_pt_7.0_8.0_PbSc
0_pt_8.0_9.0_PbSc
0_pt_9.0_10.0_PbSc
0_pt_10.0_12.0_PbSc
0_pt_12.0_15.0_PbSc
0_pt_15.0_20.0_PbSc
no_cut
tof_cut
shower_cut
cv_cut
tof_shower_cut
shower_cv_cut
tof_cv_cut
shower_tof_cv_cut



0_pt_2.00_2.50_PbGl
0_pt_2.50_3.00_PbGl
0_pt_3.00_3.50_PbGl
0_pt_3.50_4.00_PbGl
0_pt_4.00_4.50_PbGl
0_pt_4.50_5.00_PbGl
0_pt_5.00_6.00_PbGl
0_pt_6.00_7.00_PbGl
0_pt_7.00_8.00_PbGl
0_pt_8.00_9.00_PbGl
0_pt_9.00_10.00_PbGl
0_pt_10.00_12.00_PbGl
0_pt_12.00_15.00_PbGl
0_pt_15.00_20.00_PbGl
no_cut
tof_cut
shower_cut
cv_cut
tof_shower_cut
shower_cv_cut
tof_cv_cut
shower_tof_cv_cut

7. A_{LL} Analysis

- Run-by-run A_{LL} calculation.
  ∵ Run-by-run prescale make run-effective efficiency.

- Statistics requirement.
  For signal region: $N_{++} + N_{+-} > 10$
  For side region: $N_{++} > 0$ && $N_{+-} > 0$ to avoid dividing by zero.

- Choice of P_T binning.

$$\langle P_T^{\pi^0} \rangle = \frac{\langle P_T^{\pi^0+BG} \rangle - r \langle P_T^{BG} \rangle}{1-r}$$

P_T bin (GeV/c)	$\langle P_T \rangle$ (Run12)	$\langle P_T \rangle$ (Run13)	$\langle P_T \rangle$ (Comb.)
2.0-2.5	2.2757e+0	2.2801e+0	2.2795e+0
2.5-3.0	2.7618e+0	2.7627e+0	2.7626e+0
3.0-3.5	3.2516e+0	3.2507e+0	3.2508e+0
3.5-4.0	3.7458e+0	3.7440e+0	3.7442e+0
4.0-4.5	4.2415e+0	4.2401e+0	4.2403e+0
4.5-5.0	4.7387e+0	4.7378e+0	4.7379e+0
5.0-6.0	5.4475e+0	5.4460e+0	5.4462e+0
6.0-7.0	6.4458e+0	6.4454e+0	6.4454e+0
7.0-8.0	7.4445e+0	7.4454e+0	7.4452e+0
8.0-9.0	8.4470e+0	8.4471e+0	8.4472e+0
9.0-10.	9.4507e+0	9.4512e+0	9.4511e+0
10.-12.	1.0824e+1	1.0824e+1	1.0824e+1
12.-15.	1.3140e+1	1.3140e+1	1.3140e+1
15.-20.	1.6615e+1	1.6627e+1	1.6624e+1

7. A_{LL} Analysis

- Statistical uncertainty of A_{LL}

$$(\Delta A_{LL})^2 = \left(\frac{1}{P_B P_Y}\frac{2RN_{++}N_{+-}}{N_{++}+RN_{+-})^2}\right)^2\left(\left(\frac{\Delta N_{++}}{N_{++}}\right)^2+\left(\frac{\Delta N_{+-}}{N_{+-}}\right)^2+\left(\frac{\Delta R}{R}\right)\right)^2 + \left(\left(\frac{\Delta P_B}{P_B}\right)^2+\left(\frac{\Delta P_Y}{P_Y}\right)^2\right)A_{LL}^2$$

, where $\sigma_{N_{\gamma\gamma}} = \sqrt{\frac{k^2}{k}N_{\gamma\gamma}}$ due to multiplicity.

- The validity of above uncertainty Eq. and unknown syst. are tested by bunch shuffling.

- The run-by-run A_{LL} is fit with constant. Pattern-by-pattern fitting to avoid false A_{LL} due to the ghost cluster.

P_T (GeV)	k_{en}^2 P, E	k_{en}^2 S, E	k_{en}^2 P, O	k_{en}^2 S, O
2.0-2.5	1.0591	1.1266	1.0592	1.1222
2.5-3.0	1.0438	1.1077	1.0440	1.1066
3.0-3.5	1.0358	1.0975	1.0353	1.0979
3.5-4.0	1.0303	1.0908	1.0303	1.0892
4.0-4.5	1.0265	1.0830	1.0259	1.0845
4.5-5.0	1.0222	1.0775	1.0221	1.0771
5.0-6.0	1.0325	1.1148	1.0325	1.1130
6.0-7.0	1.0247	1.1007	1.0249	1.1013
7.0-8.0	1.0217	1.0925	1.0205	1.0879
8.0-9.0	1.0176	1.0790	1.0172	1.0798
9.0-10.	1.0157	1.0757	1.0162	1.0754
10.-12.	1.0227	1.0965	1.0265	1.1065
12.-15.	1.0297	1.1243	1.0263	1.1014
15.-20.	1.0318	1.1108	1.0301	1.0947

7. A_{LL} Analysis

- Ghost clusters.
  Decay time of clusters in PHENIX EMCal: 3 BCLK.
  ⇒ Source of low energy background cluster.
  ⇒ Source of false A_{LL} at low P_T.

- N_r: average number of real clusters, N_g: average number of ghost clusters.

$$
\begin{aligned}
N_0 &= N_r \\
N_1 &= N_r + N_g \\
N_2 &= N_r + 2N_g \\
N_3 &= N_r + 3N_g \\
N_4 &= N_r + 3N_g \\
N_5 &= N_r + 3N_g \\
N_6 &= N_r + 3N_g \\
N_7 &= N_r + 3N_g \\
&\dots
\end{aligned}
$$

For “SOOS” pattern

For “S” $\binom{N_r}{2} + \binom{N_r+3N_g}{2} + \binom{N_r+3N_g}{2} + \binom{N_r+3N_g}{2} \dots$

For “O” $\binom{N_r+N_g}{2} + \binom{N_r+2N_g}{2} + \binom{N_r+3N_g}{2} + \binom{N_r+3N_g}{2} + \dots$

For “OSSO” pattern, similar but opposite situation occurs.

⇒ That’s how false A_{LL} at low P_T due to the ghost clusters.

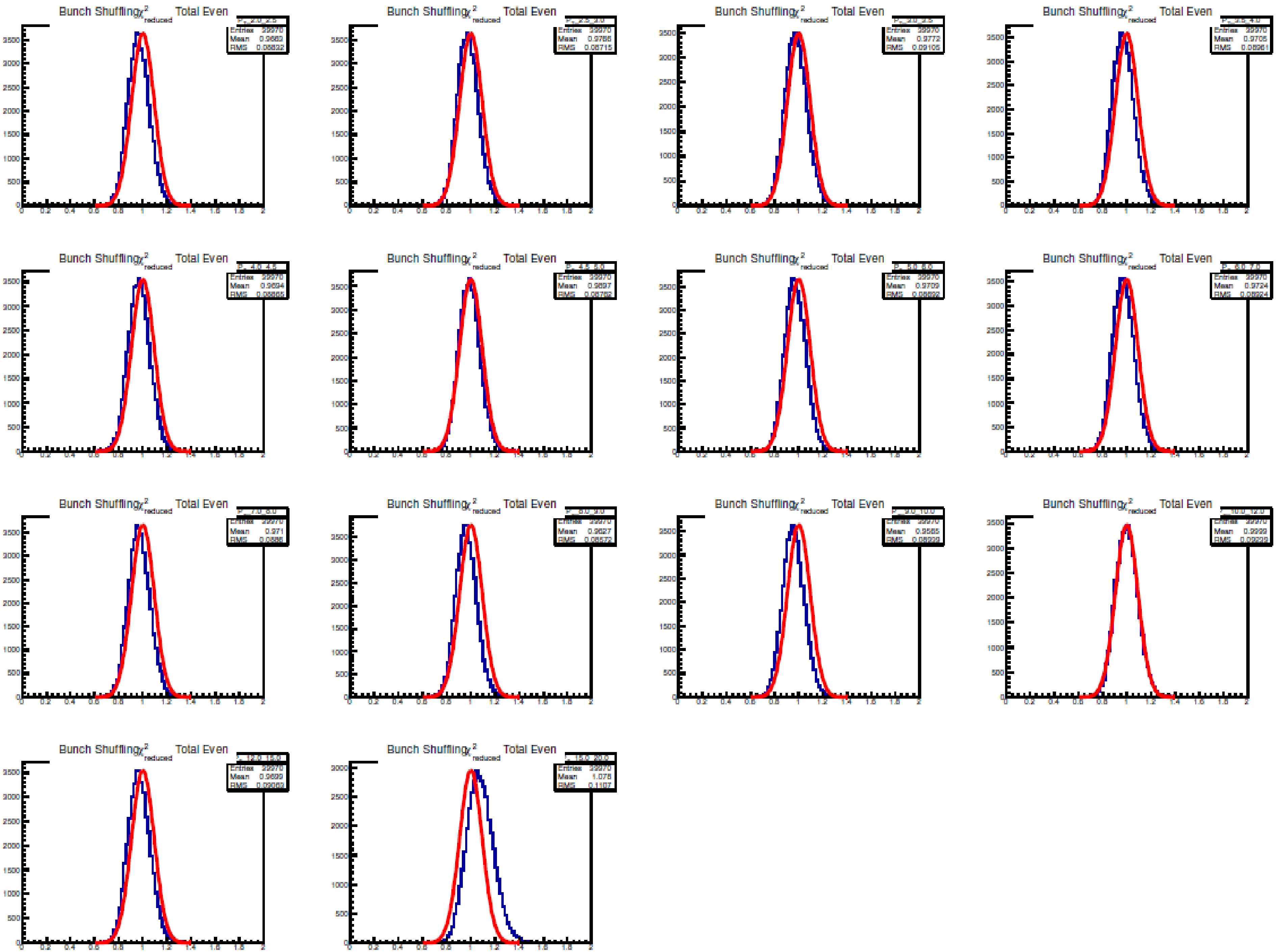
- Cure: ToF cut to reject the ghost clusters.
  pattern-by-pattern background correction.

8. QA: A_{LL} Analysis – Bunch shuffling

- Bunch shuffling is boot-strapping method to extract the statistical uncertainty by model independent way.
  : The valid of the uncertainty Eq. and the existence of unknown syst. can be checked.

- 1. 40,000 random spin patterns are generated.
  2. Run-by-run A_{LL} is calculated.
  3. Const. fit and χ^2_{re} is obtained.
  4. Measured and theoretical χ^2_{re} distributions are compared.

- Good agreement is achieved.
  That means the uncertainty Eq. is valid and no unknown syst.


Bunch Shuffling $\chi^2_{reduced}$ Total Even
Bunch Shuffling $\chi^2_{reduced}$ Total Even
Bunch Shuffling $\chi^2_{reduced}$ Total Even
Bunch Shuffling $\chi^2_{reduced}$ Total Even
Bunch Shuffling $\chi^2_{reduced}$ Total Even
Bunch Shuffling $\chi^2_{reduced}$ Total Even
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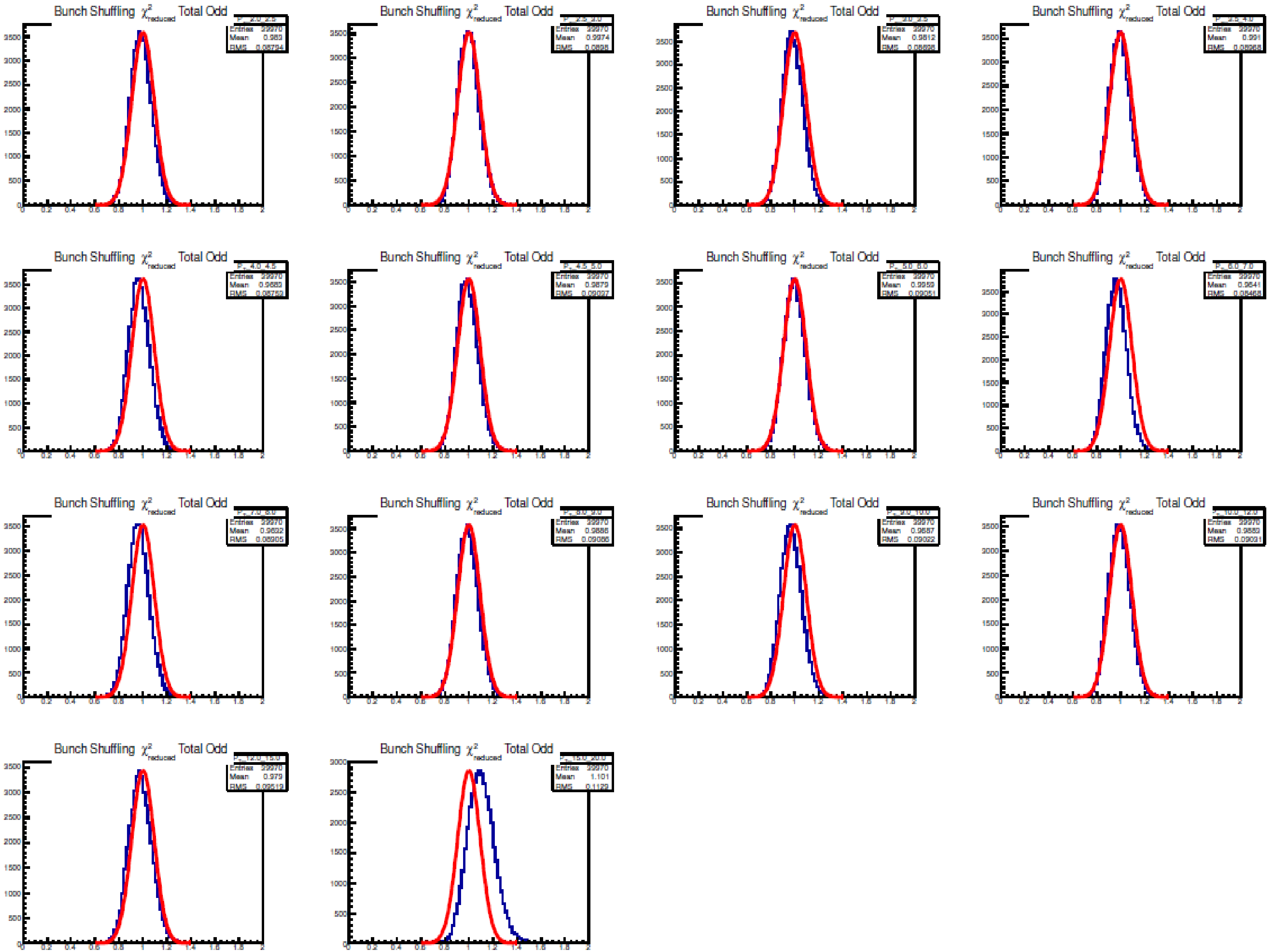

Bunch Shuffling $\chi^2_{reduced}$ Total Odd
Bunch Shuffling $\chi^2_{reduced}$ Total Odd
Bunch Shuffling $\chi^2_{reduced}$ Total Odd
Bunch Shuffling $\chi^2_{reduced}$ Total Odd
Bunch Shuffling $\chi^2_{reduced}$ Total Odd
Bunch Shuffling $\chi^2_{reduced}$ Total Odd
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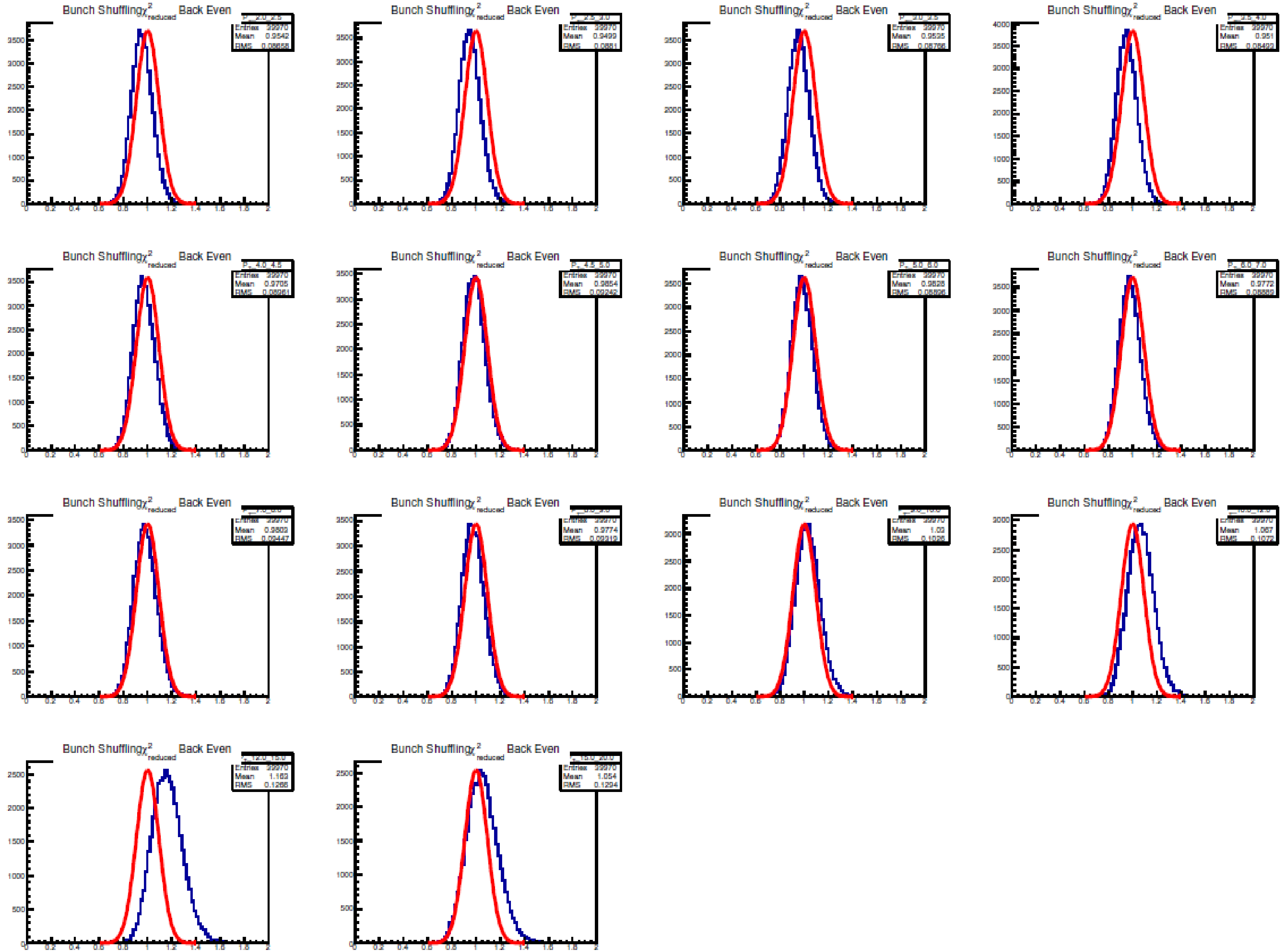
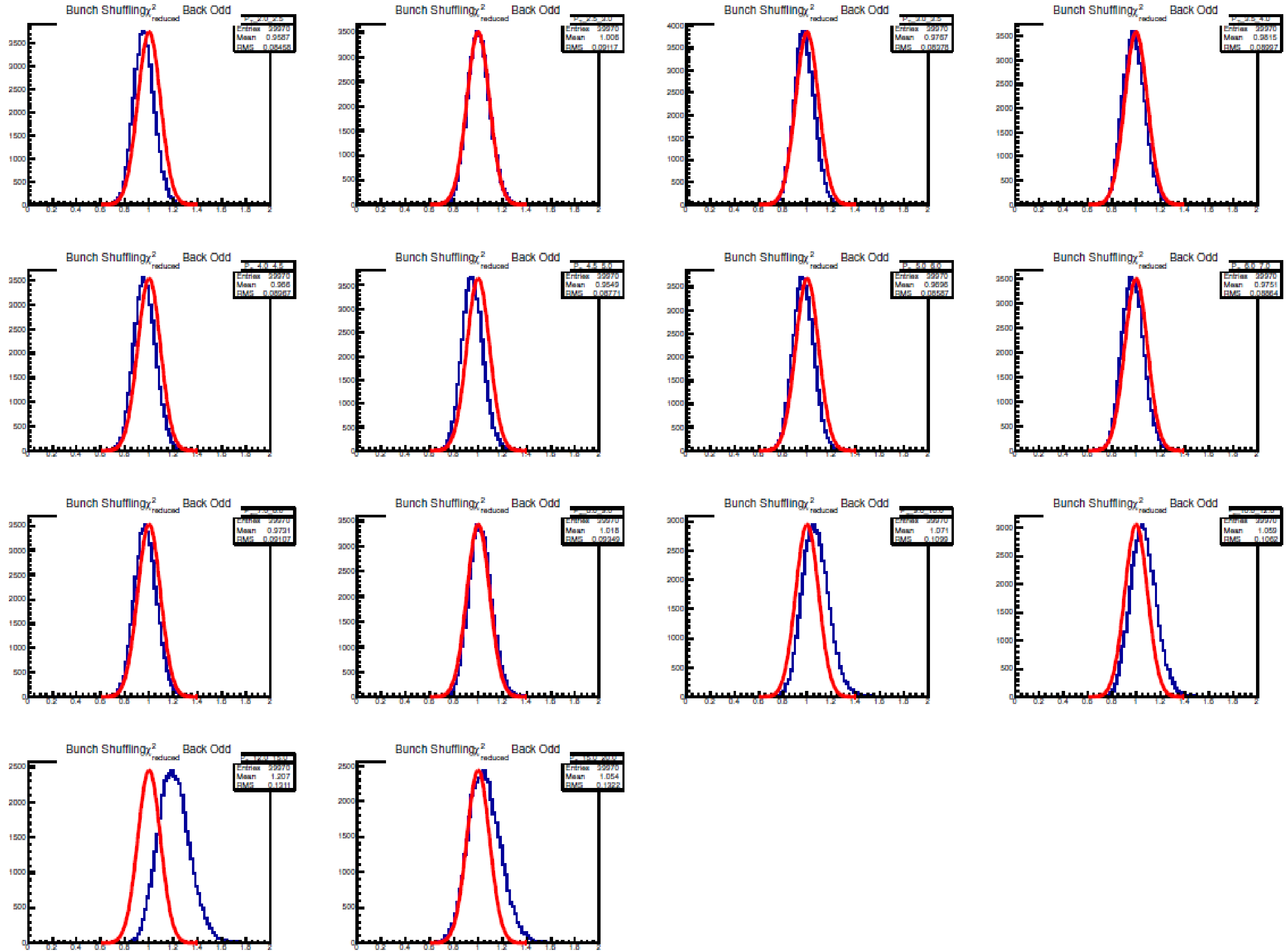
Bunch Shuffling $\chi^2_{reduced}$ Total Odd


Bunch Shuffling$\chi^2_{reduced}$ Back Even
Entries 39970
Mean 0.9542
RMS 0.08658
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Entries 39970
Mean 0.9499
RMS 0.0881
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Entries 39970
Mean 0.9535
RMS 0.08786
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Entries 39970
Mean 0.951
RMS 0.08499
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Entries 39970
Mean 0.9705
RMS 0.08961
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Entries 39970
Mean 0.9854
RMS 0.09242
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Entries 39970
Mean 0.9828
RMS 0.08898
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Entries 39970
Mean 0.9772
RMS 0.08889
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Mean 0.9803
RMS 0.09447
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Mean 0.9774
RMS 0.09319
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Mean 1.03
RMS 0.1026
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Mean 1.067
RMS 0.1073
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Entries 39970
Mean 1.163
RMS 0.1266
Bunch Shuffling$\chi^2_{reduced}$ Back Even
Entries 39970
Mean 1.054
RMS 0.1294


Bunch Shuffling $\chi^2_{reduced}$ Back Odd
Bunch Shuffling $\chi^2_{reduced}$ Back Odd
Bunch Shuffling $\chi^2_{reduced}$ Back Odd
Bunch Shuffling $\chi^2_{reduced}$ Back Odd
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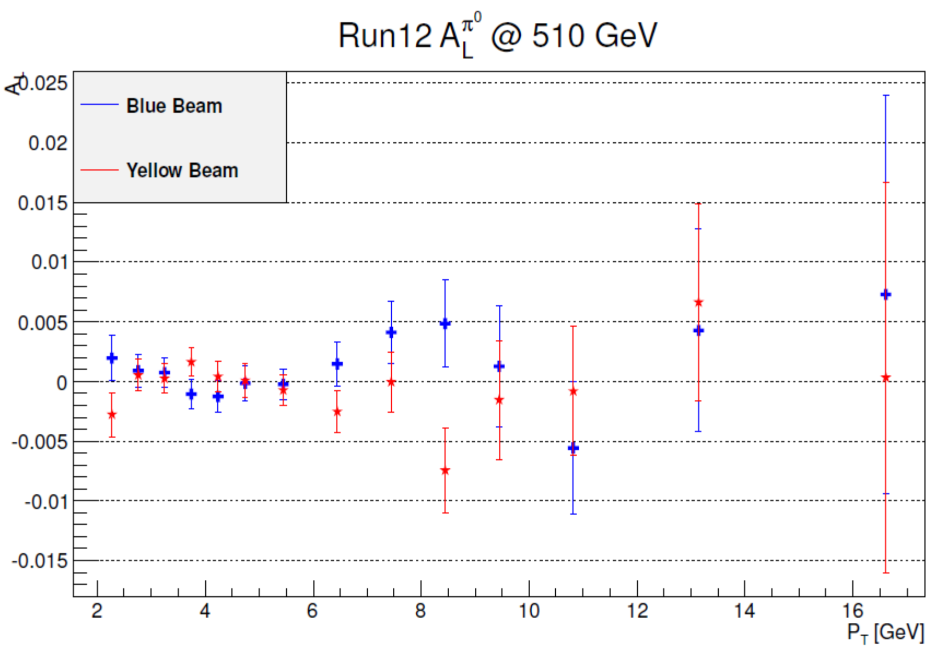
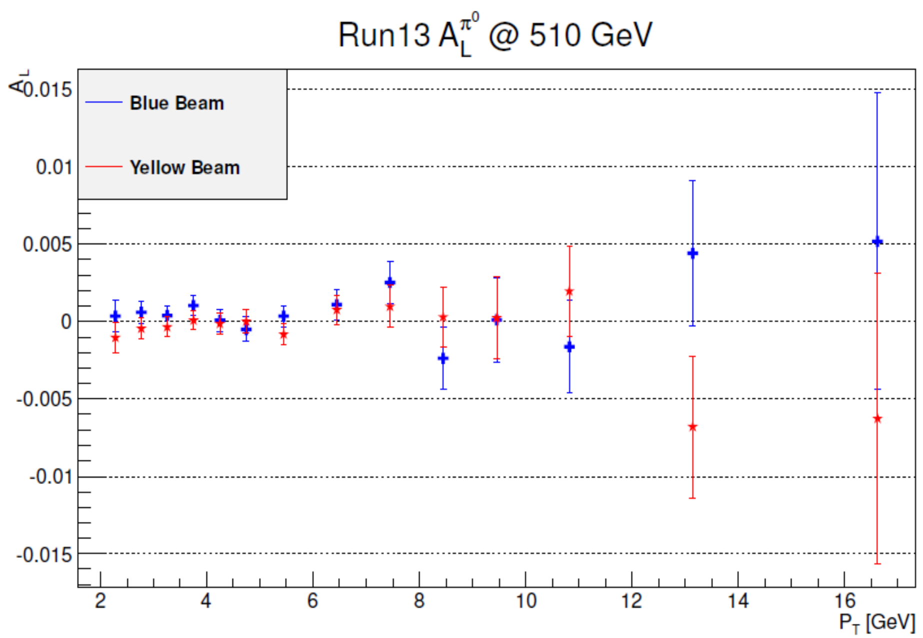
8. QA: A_{LL} Analysis – A_L Measurement

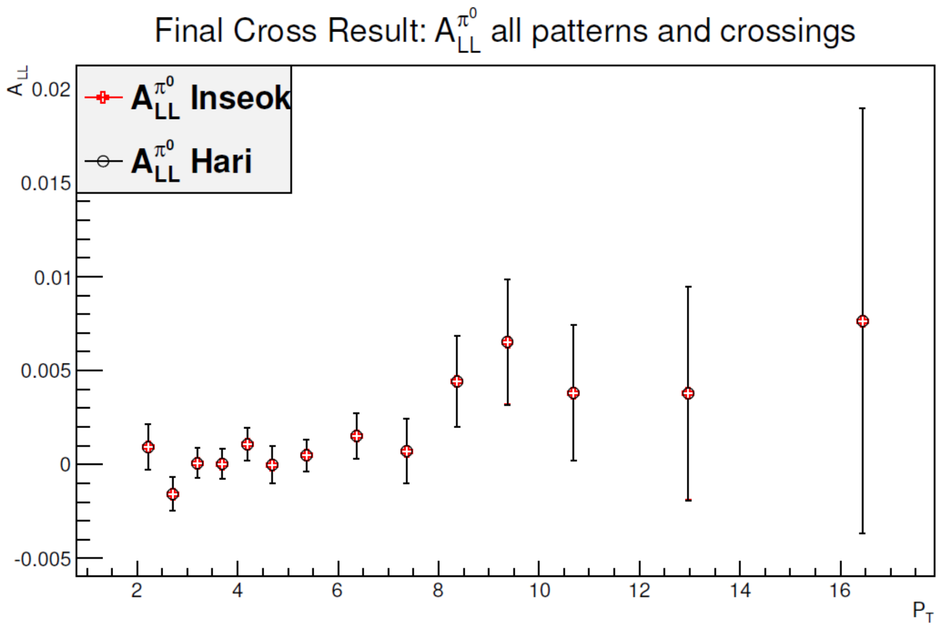
- Because strong interaction is parity invariant, A_L should be zero.
- Measurement procedure is same to A_{LL}.





8. QA: A_{LL} Analysis – Parallel Cross Check

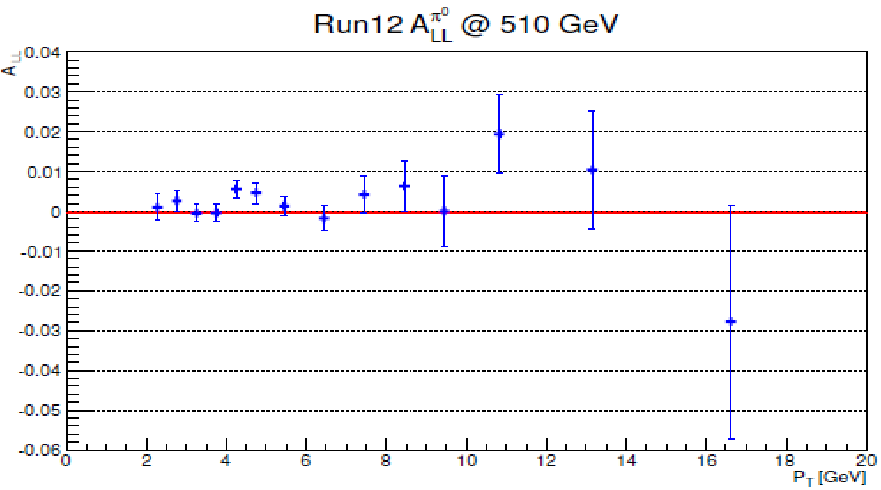
- For Run13, intensive cross check has been done with Geogia University student. Perfect agreements are achieved.



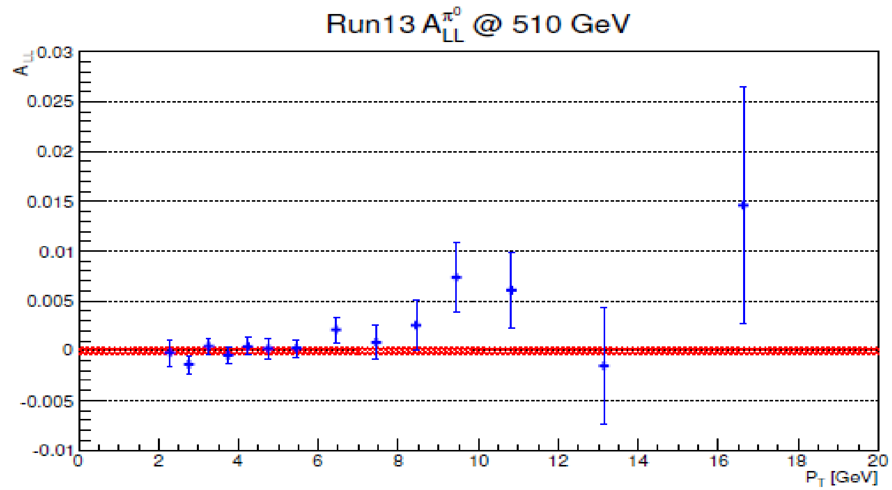
Note) run-by-run energy calibration is not included, here.

P_T	$A_{LL}^{\pi^0}(H)$	$\Delta A_{LL}^{\pi^0}(H)$	$A_{LL}^{\pi^0}(I)$	$\Delta A_{LL}^{\pi^0}(I)$	Comp.
2.0-2.5	9.293e-4	1.206e-3	9.269e-4	1.206e-3	1.943e-3
2.5-3.0	-1.565e-3	8.899e-4	-1.565e-3	8.899e-4	-3.886e-4
3.0-3.5	6.651e-5	7.920e-4	6.788e-5	7.920e-4	-1.719e-3
3.5-4.0	3.860e-5	7.945e-4	3.872e-5	7.945e-4	-1.504e-4
4.0-4.5	1.077e-3	8.619e-4	1.078e-3	8.619e-4	-1.274e-3
4.5-5.0	-2.017e-5	9.794e-4	-2.190e-5	9.794e-4	1.764e-3
5.0-6.0	4.812e-4	8.705e-4	4.815e-4	8.705e-4	-2.362e-4
6.0-7.0	1.524e-3	1.204e-3	1.524e-3	1.204e-3	-1.546e-4
7.0-8.0	7.147e-4	1.708e-3	7.152e-4	1.708e-3	-2.922e-4
8.0-9.0	4.427e-3	2.432e-3	4.425e-3	2.432e-3	6.568e-4
9.0-10	6.532e-3	3.339e-3	6.535e-3	3.339e-3	-7.712e-4
10.-12.	3.813e-3	3.613e-3	3.813e-3	3.613e-3	2.112e-5
12.-15.	3.779e-3	5.672e-3	3.785e-3	5.672e-3	-9.829e-4
15.-20.	7.641e-3	1.132e-2	7.641e-3	1.132e-2	5.637e-6

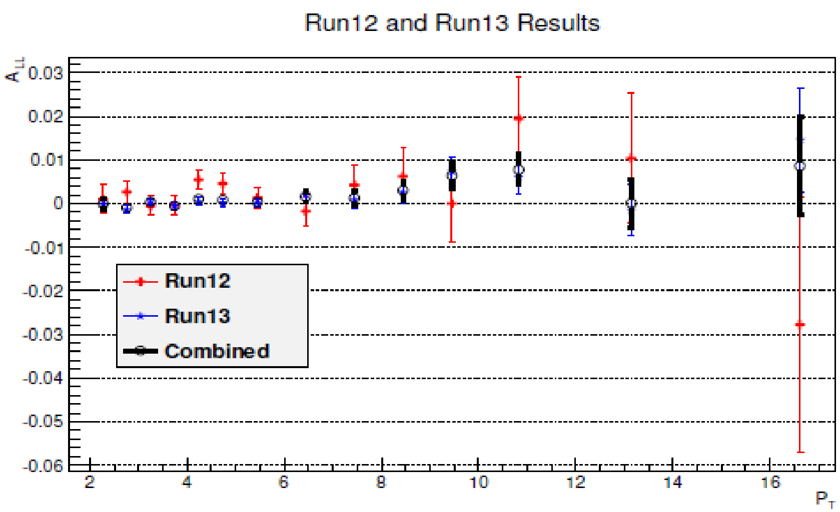
7. Results and Discussion



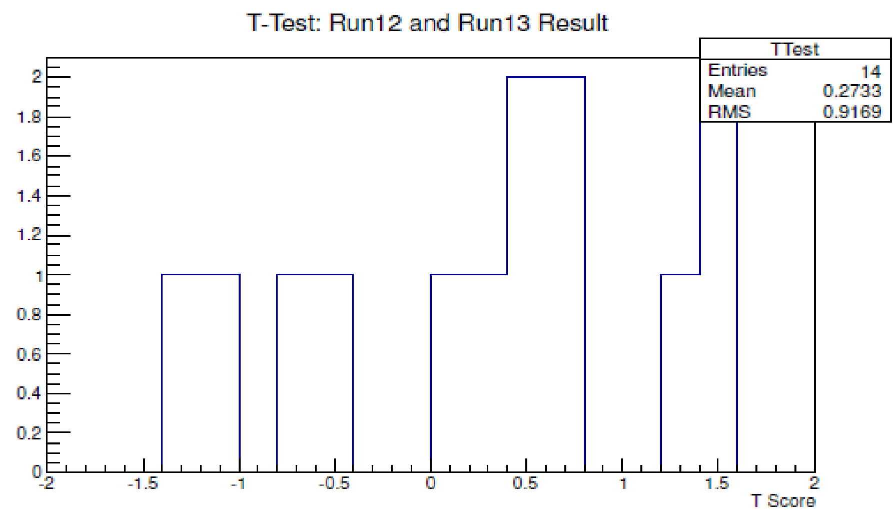
(a) Run12



(b) Run13



(a) Run12 and Run13 $A_{LL}^{\pi^0}$



(b) T-test of Run12 and Run13