Double Helicity Asymmetries of Forward Neutral Pions from $\sqrt{s} = 510$ GeV pp Collisions at STAR

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for the STAR Collaboration

PENNSTATE

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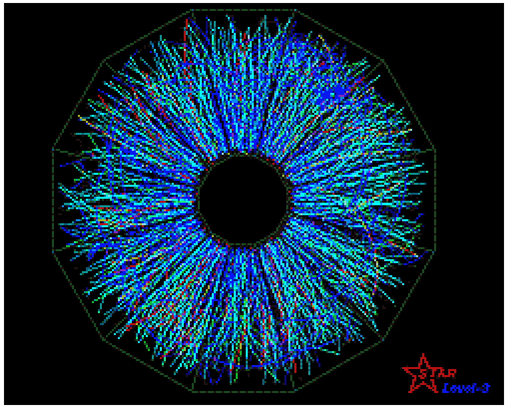
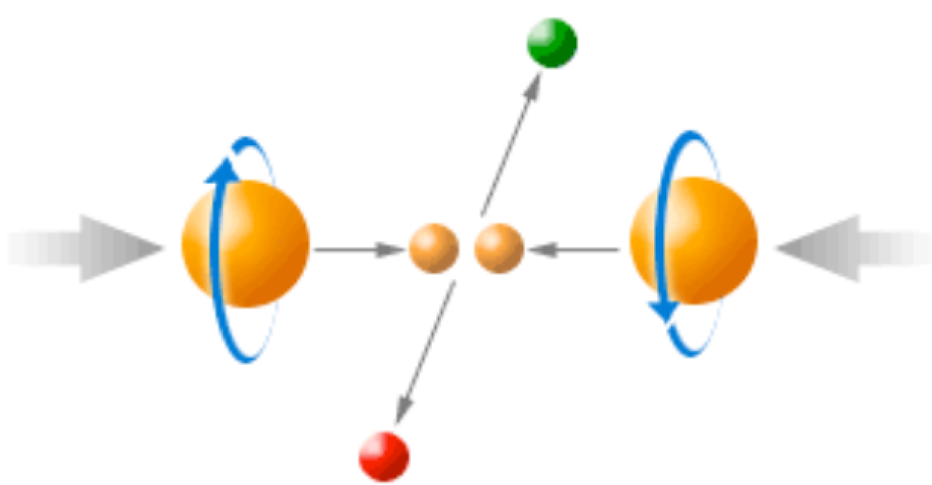
Spin2014
The 21st International Symposium on Spin Physics
Oct. 20-24, 2014
Peking University,
Beijing, China



Outline

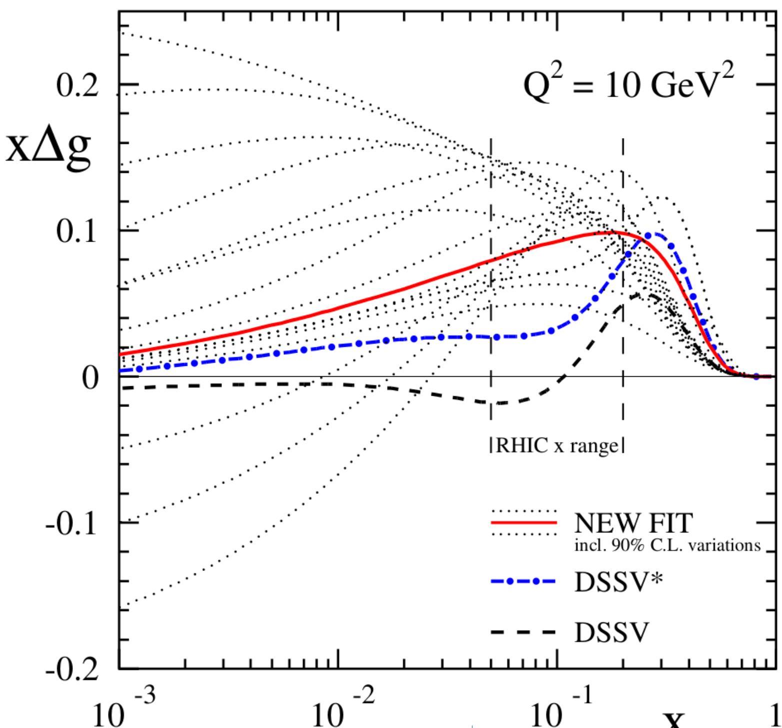
- Current Status of Gluon Polarization
- Double Helicity Asymmetry – A_{LL}
- Forward EM Calorimetry at STAR
- Luminosity Detectors at STAR
- Relative Luminosity and A_{LL} Systematics
- π^0 Event Selection
- Measurement of Forward π^0 A_{LL}



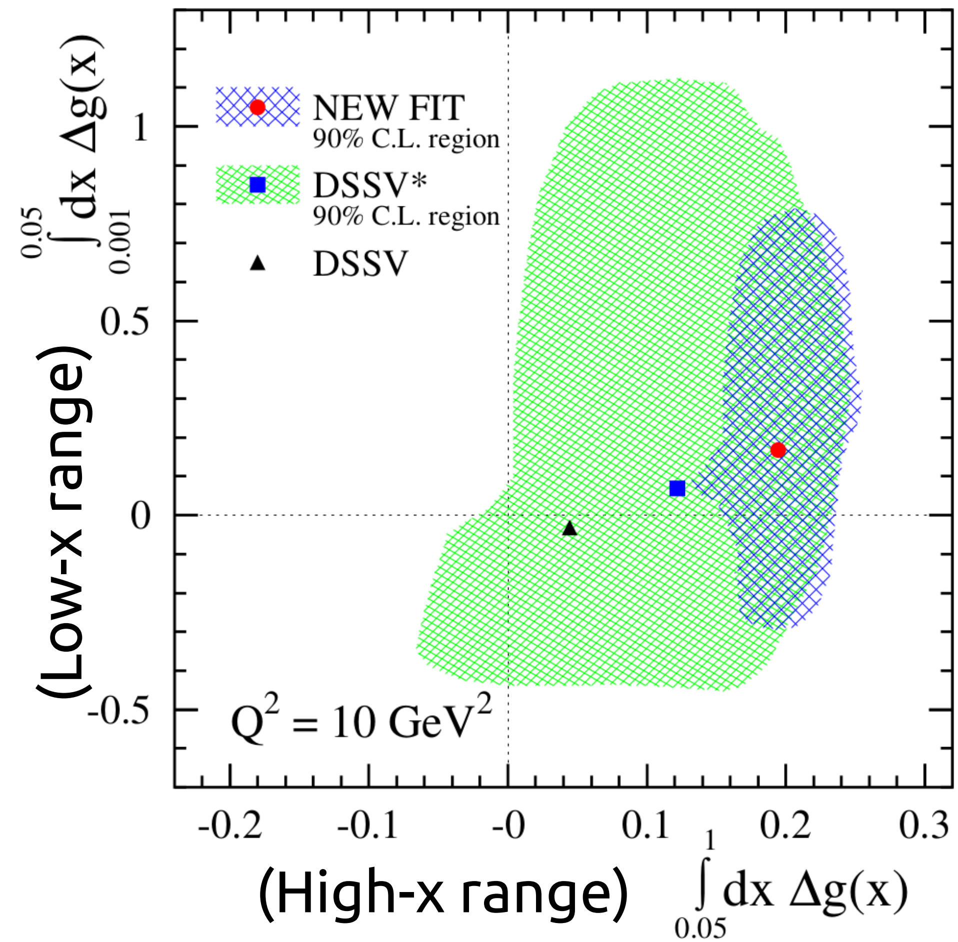
Gluon Polarization $\Delta g(x)$

Proton Spin Sum: $S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$

- $\Delta\Sigma \sim 0.3$
- $L_q, L_g \sim\ ?$
- $\Delta G\ -\ \text{status shown}$



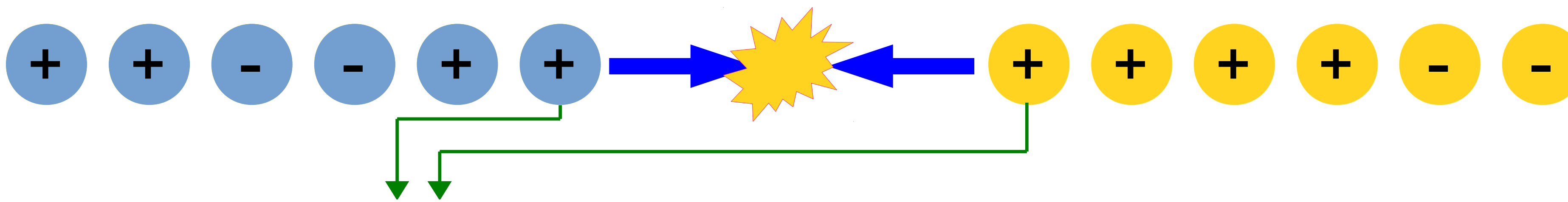
low-x poorly constrained;
accessible via ***forward*** observables



de Florian, Sassot, Stratmann, Vogelsang
Phys. Rev. Lett. 113, 012001 (2014)

Accessing Δg by Measuring A_{LL}

Colliding proton helicities known for each bunch crossing (9.4 MHz at STAR)



$$A_{LL} = \frac{1}{P_a P_b} \frac{(\sigma^{++} + \sigma^{--}) - (\sigma^{+-} + \sigma^{-+})}{(\sigma^{++} + \sigma^{--}) + (\sigma^{+-} + \sigma^{-+})} \propto \frac{\Delta f_1 \Delta f_2}{f_1 f_2}$$

Beam Polarizations
(Measured by RHIC polarimetry group)

$$f_i = \text{PDF}$$

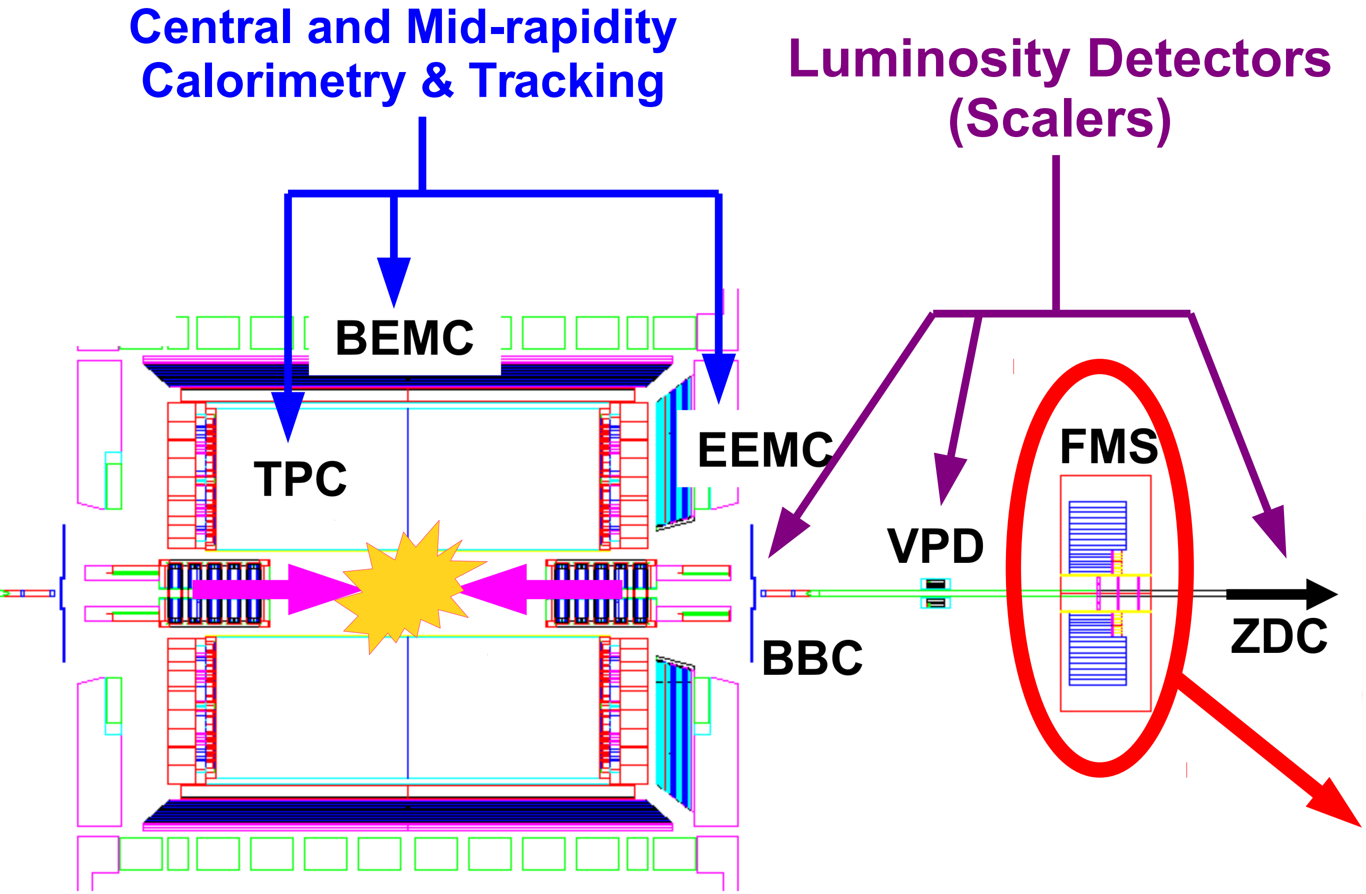
$$\Delta f_i = \text{polarized PDF}$$

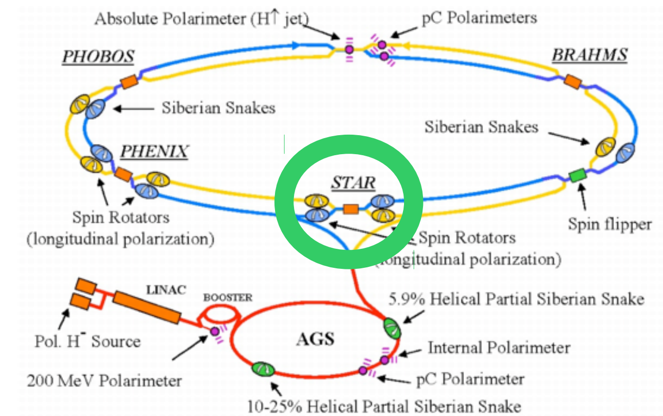
Re-express cross-section: $\sigma^{\pm\pm} = \dfrac{N^{\pm\pm}}{L^{\pm\pm}}$

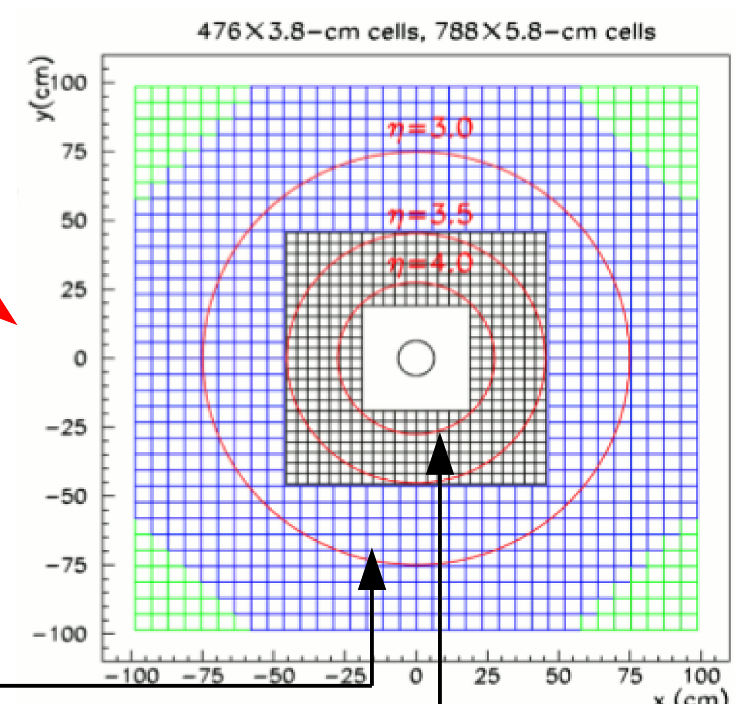
Relative Luminosity: $R_3 = \dfrac{L^{++} + L^{--}}{L^{+-} + L^{-+}}$ → Measured using STAR luminosity detectors

$$A_{LL} = \frac{1}{P_a P_b} \frac{(N^{++} + N^{--}) - R_3 \cdot (N^{+-} + N^{-+})}{(N^{++} + N^{--}) + R_3 \cdot (N^{+-} + N^{-+})}$$

Forward EM Calorimetry at STAR







PRIMARY FOCUS:

FMS – Forward Meson Spectrometer

- Forward pseudorapdity: **$2.5 < \eta < 4$**
- 1,264 **Lead-glass cells** coupled to photomultiplier tubes
  - Large (5.8 x 5.8 cm) outer cells (blue)
  - Small (3.8 x 3.8 cm) inner cells (black)
- Observes $\pi^0 \rightarrow \gamma+\gamma$ as 2 cluster events
- Forward observables → access to **low-x gluons**

Measuring Relative Luminosity at STAR

3 Luminosity Detectors at STAR:
- Beam Beam Counter (**BBC**) – not used in this analysis
- Vertex Position Detector (**VPD**)
- Zero Degree Calorimeter (**ZDC**)

$$R_3 = \frac{L^{++} + L^{--}}{L^{+-} + L^{-+}}$$

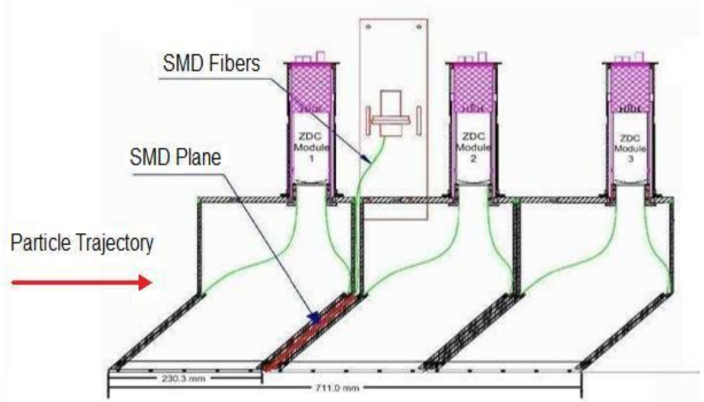
They are “**Scalers**”: for each bunch crossing, they **count** whether or not a “hit” was observed
- Scalers are placed symmetrically on both sides of the interaction point
- A hit on one side is called a “**single count**”
- A hit on both sides within a time window is called a “**coincidence count**”

VPD

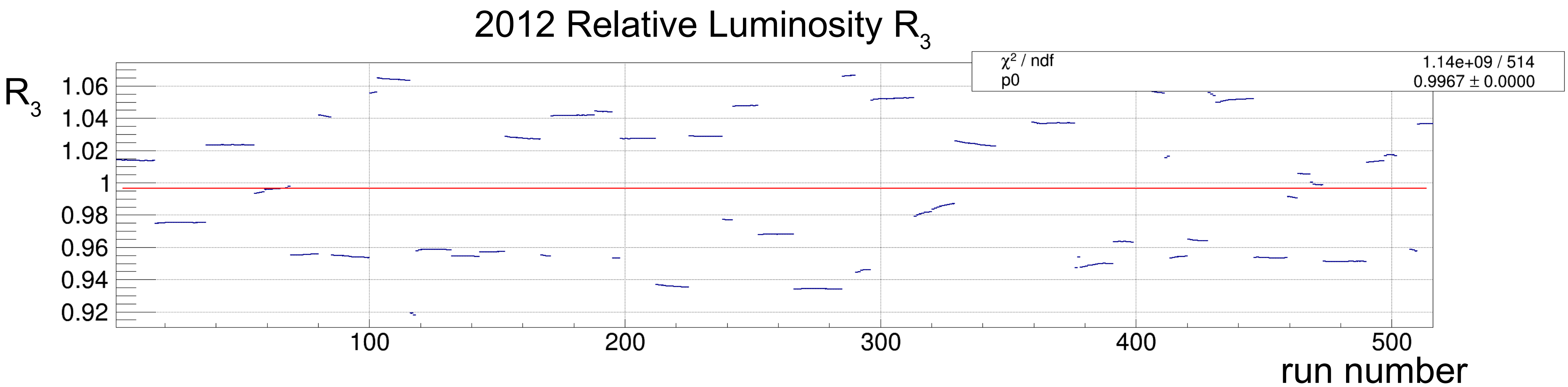
$4.2 < |\eta| < 5.1$
5.7 m from Interaction Point
Hits: mostly charged particles and photons from pion decays

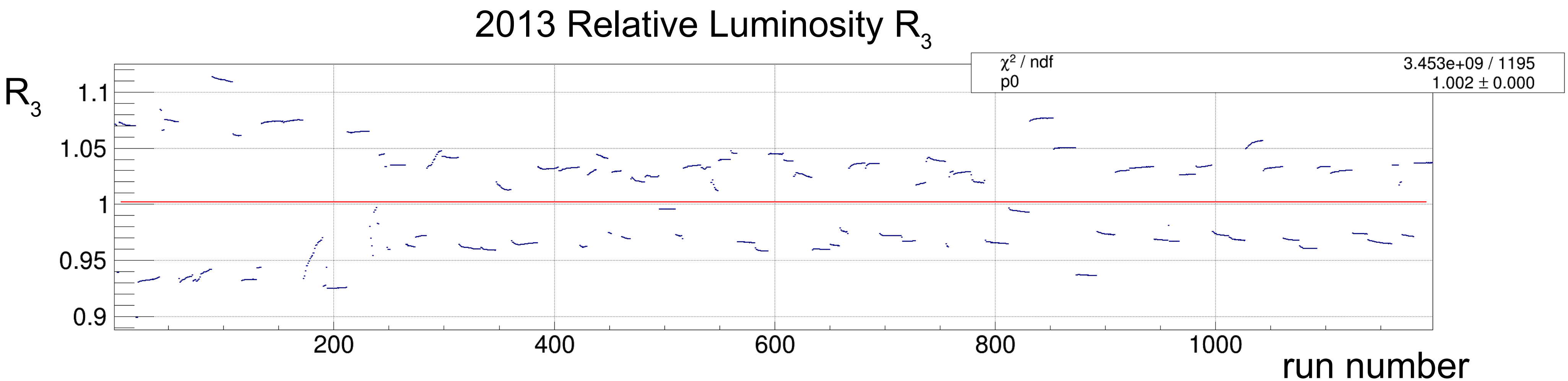
ZDC

$6.5 < |\eta| < 7.5$
18 m from Interaction Point
Hits: mostly neutrons and some neutral kaons; photons only in 1st module
(charged particles are swept away by magnets)



Relative Luminosity Measurements





- Measured with VPD, averaging over both singles sides and coincidences
- Cross-checked with other STAR scalers (ZDC, singles, coincidences)

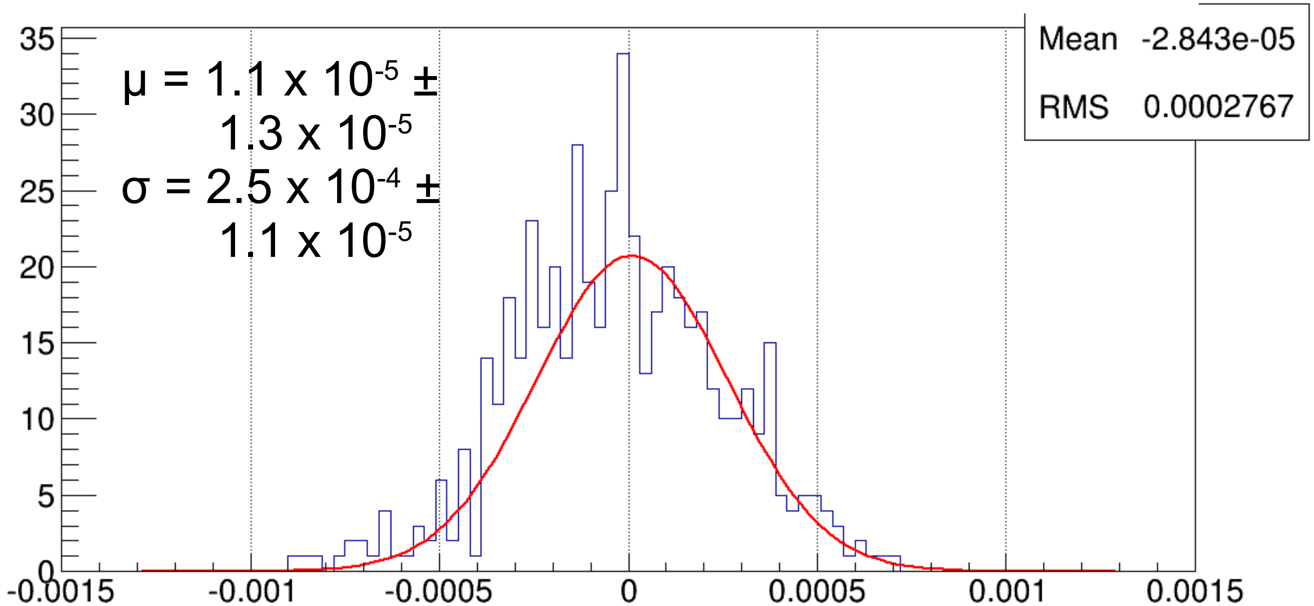
For each run (~30 min.), R ~ 1 ± 0.04

Typical statistical uncertainty ~ 4 x 10^{-5}

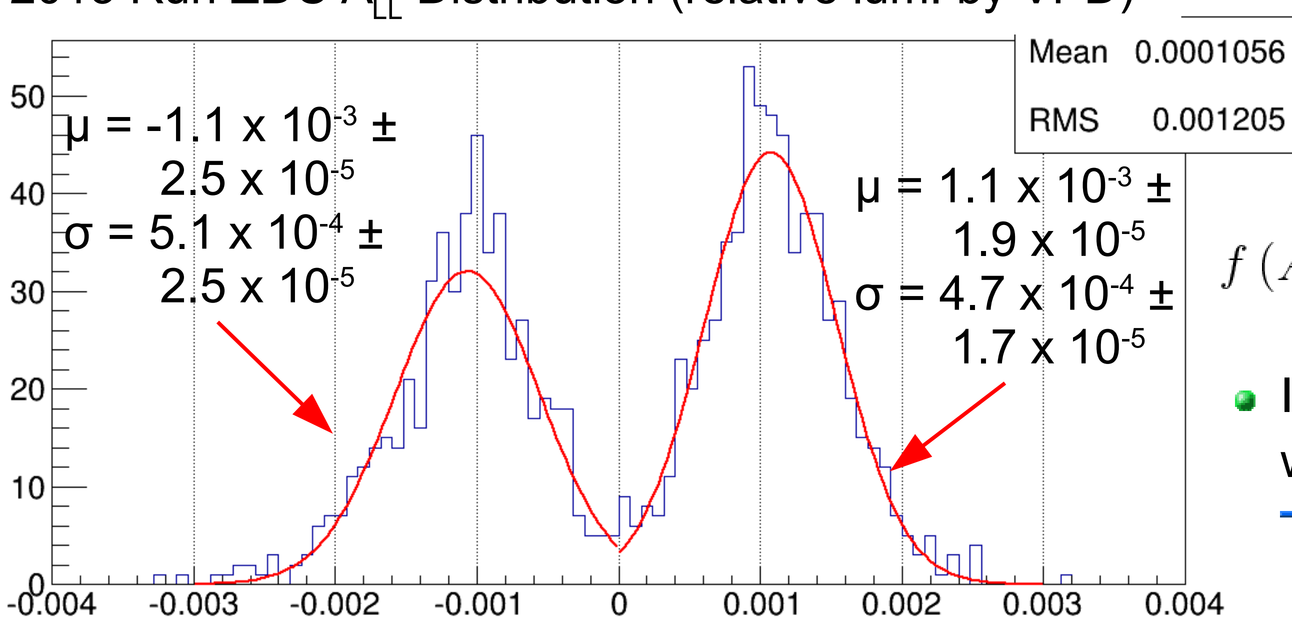
$$R_3 = \frac{L^{++} + L^{--}}{L^{+-} + L^{-+}}$$

Relative Luminosity → π^0 A_{LL} Systematic

2012 Run ZDC A_{LL} Distribution (relative lum. by VPD)



2013 Run ZDC A_{LL} Distribution (relative lum. by VPD)



- Measured A_{LL} in ZDC scaler system using VPD coincidences as a relative luminosity
  - Denoted as "**Scaler A_{LL}**"
- Distribution of this Scaler A_{LL} is shown on the left
  - 1 entry = 1 STAR run (~30 min)
- Red Lines indicate Gaussian fit results, defined with fit parameters c, μ, and σ

Fit Function $f(A_{LL})$:

$$f\left(A_{LL}\right) = c \cdot \exp\left[-\frac{1}{2}\left(\frac{A_{LL}-\mu}{\sigma}\right)^2\right]$$

- In the 2013 Run, this Scaler A_{LL} was correlated with spin pattern
  - The two peaks are fit with two separate Gaussians

Relative Luminosity → π^0 A_{LL} Systematic

- Measurement of Scaler A_{LL} + its uncertainty = **π^0 A_{LL} shift systematic uncertainty**
  - "Shift" denotes a constant bias on A_{LL}
  - Scaler A_{LL} measurement is taken to be the overall mean of the distribution
  - For Scaler A_{LL} uncertainty, we use the fit parameter σ
    → For the 2013 run, the σ of the wider peak is used
  - The overall π^0 A_{LL} systematic is computed as:

π^0 A_{LL} Systematic = Scaler A_{LL} "σ" + | Scaler A_{LL} Mean |

	A_{LL} Shift Systematic Uncertainty
2012 Run	2.8×10^{-4}
2013 Run	6.2×10^{-4}

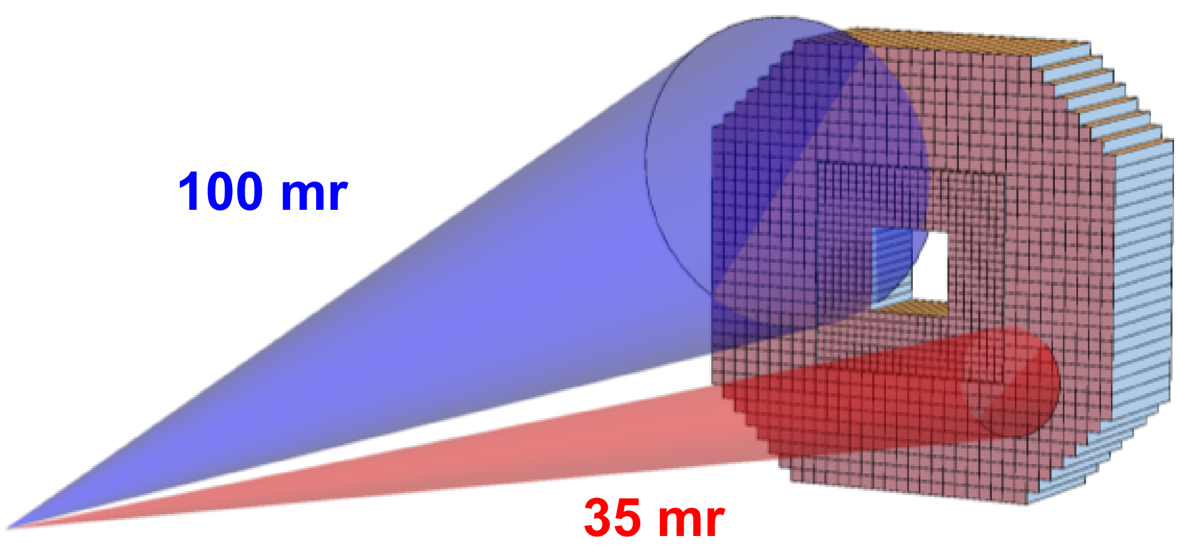
Combining 2012 and 2013 Runs' Systematics:

- For each p_T (or $E_{\gamma\gamma}$) bin: weighted average of 2012 & 2013 systematics based on π^0 statistics

π^0 Event Selection

- Full azimuth: **$-\pi \leq \varphi < \pi$**
- FMS Psuedorapidity: **$2.5 \leq \eta < 4$**
- Transverse Momentum Ranges:
  - 2012 Run: **$2.5 \leq p_T < 10$ GeV/c**
  - 2013 Run: **$2.0 \leq p_T < 10$ GeV/c**

  Different low p_T cutoff to account for trigger threshold adjustment
- Di-photon Energy Range: **$30 \leq E_{\gamma\gamma} < 100$ GeV**
- Energy Sharing: **$Z = |E_1 - E_2| / E_{\gamma\gamma} < 0.8$**
- Mass Cut: Dependent on $E_{\gamma\gamma}$ (see invariant mass slide)
- 2-photon Isolation Cone: **35 mr** and **100 mr** analyzed
  - Isolation cone versus inclusive → See next slide



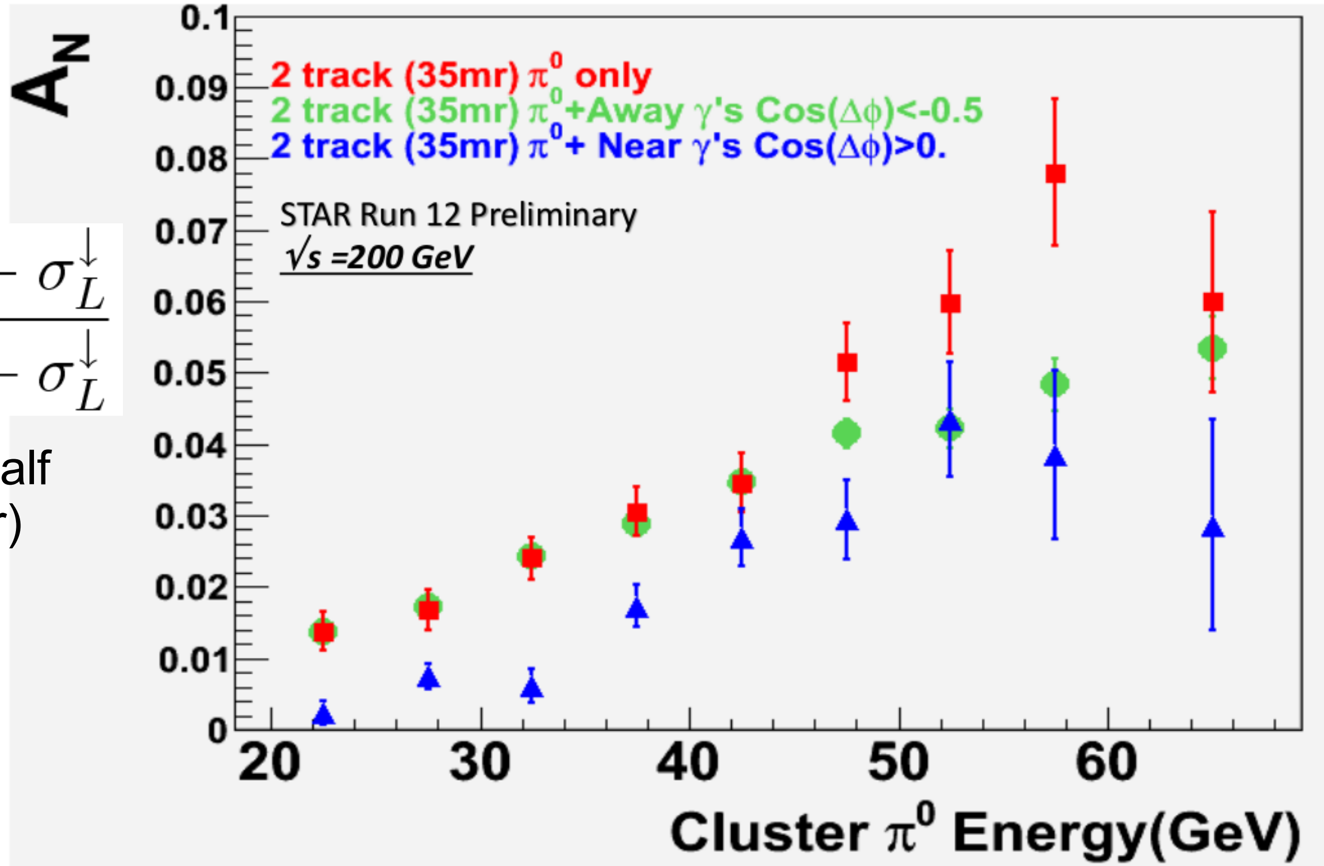
Motivating π^0 Isolation Cones

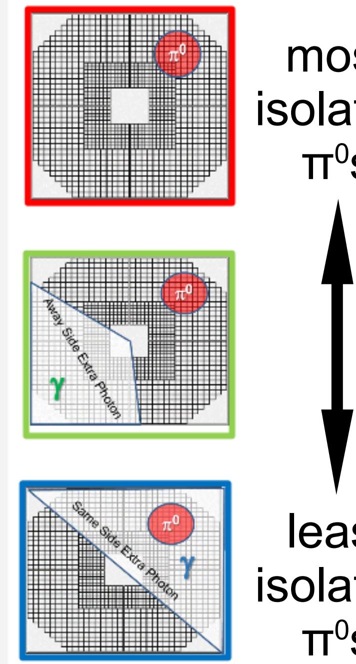
A_N vs. Energy, averaged over pseudo-rapidity.

Compare 3 selection criterion based on photon energy outside the cone (all with 35mR cone and no soft E cut)

$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_L^{\downarrow}}{\sigma_L^{\uparrow} + \sigma_L^{\downarrow}}$$

(“L” = left half of detector)





most isolated π^0s

least isolated π^0s

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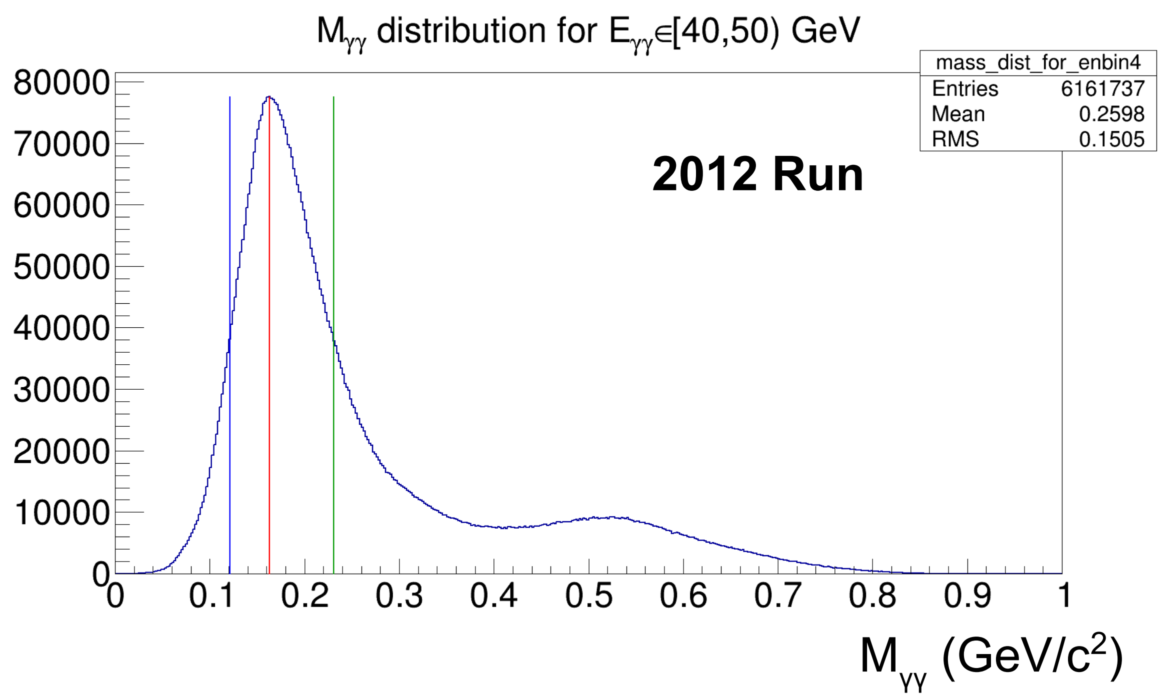
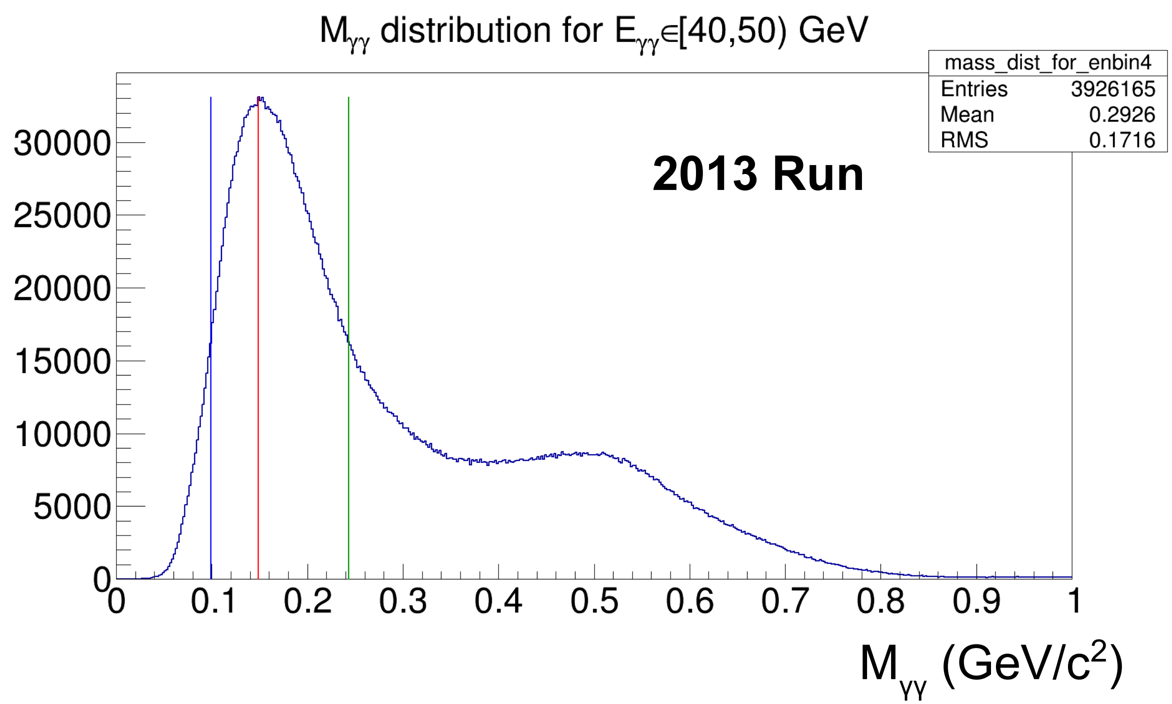
- More *isolated* π^0s have *higher* transverse single spin asymmetry A_N
- We applied similar isolation cuts for π^0 A_{LL}, motivated by the dependence of A_N on π^0 isolation
  - Goal: verify A_{LL} is *NOT* dependent on π^0 isolation; inclusive π^0 to be explored after Spin2014
  - See Yuxi Pan's Spin2014 presentation for more on “isolated” vs. “inclusive” A_N

Figures from Heppelmann, DIS 2013 [Proceedings: PoS (DIS 2013) 240]

Invariant Mass for 2-photon Events



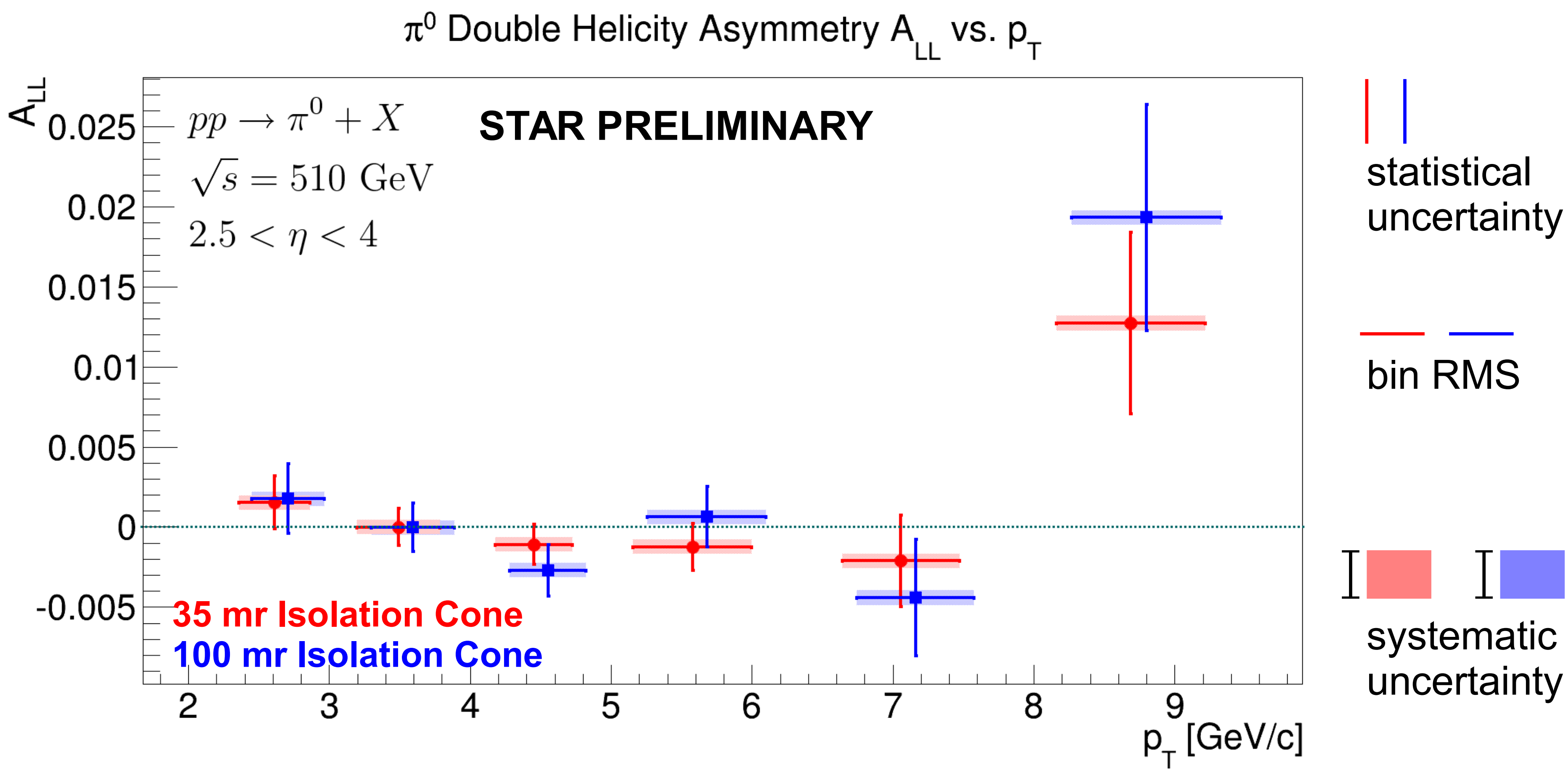


- Trigger thresholds adjusted in 2013 run to increase sensitivity to π^0s in $2 < p_T < 3$ GeV/c region
- π^0 mass peak resolution decreases as Energy ($E_{\gamma\gamma}$) increases
- Mass peak smears toward higher mass as $E_{\gamma\gamma}$ increases
  - $E_{\gamma\gamma}$-dependent mass cut for π^0 candidates (FWHM of peak)

Red Line – mass peak
Blue & Green lines set at FWHM

$$m_{\pi^0} \approx 135\ \mathrm{MeV/c^2}$$

Forward π^0 A_{LL} Measurement – p_T-Dependence



35 mr Constant Fit Result: A_{LL} = $-2.5\times10^{-4} \pm 6.5\times10^{-4}$

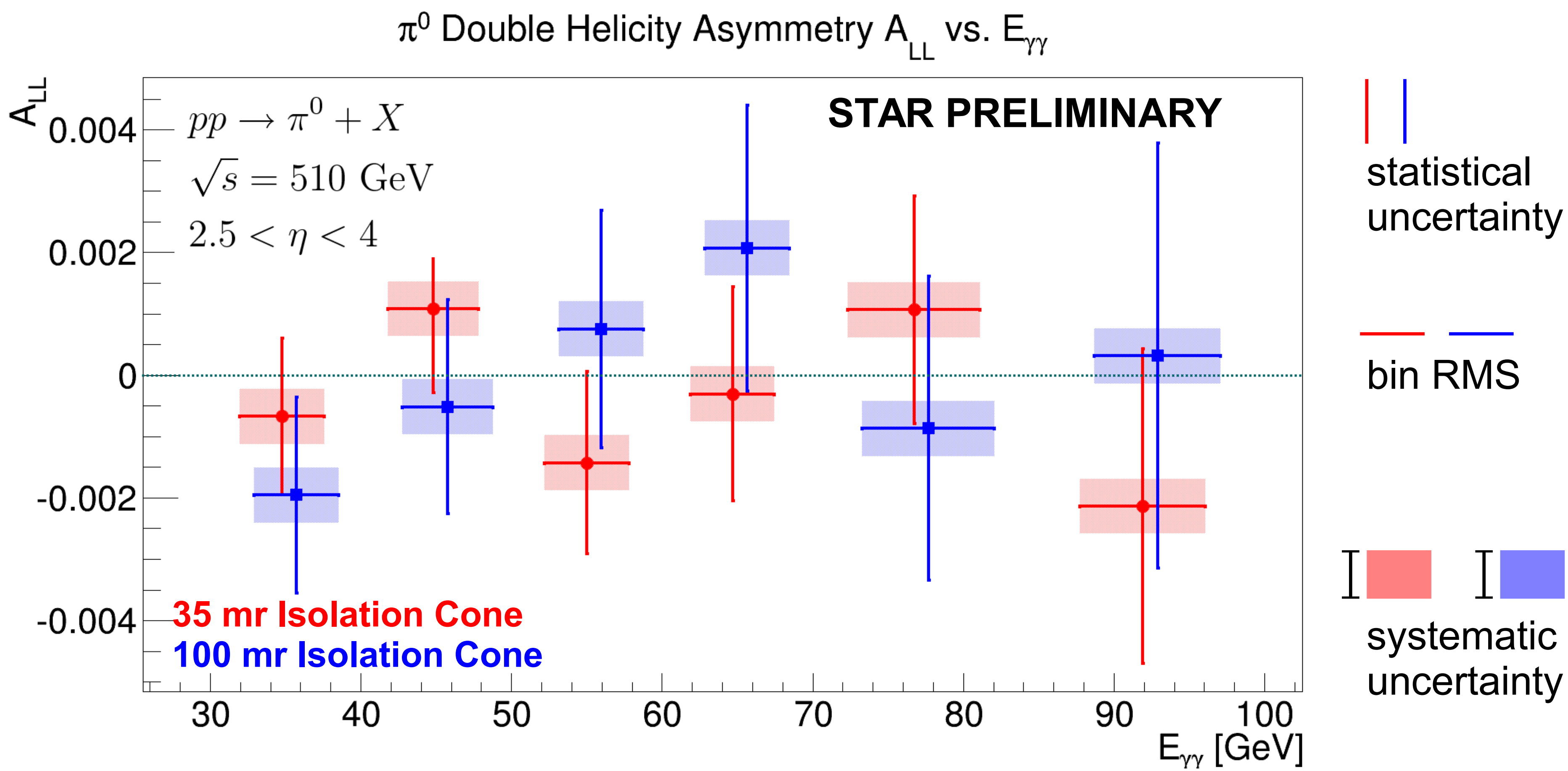
χ^2 / NDF = 7.8 / 5

100 mr Constant Fit Result: A_{LL} = $-3.3\times10^{-4} \pm 8.4\times10^{-4}$

χ^2 / NDF = 12.5 / 5

* 100 mr points are offset by p_T + 0.1 GeV/c for visibility

Forward π^0 A_{LL} Measurement – $E_{\gamma\gamma}$-Dependence



35 mr Constant Fit Result: A_{LL} = -2.5x10^{-4} ± 6.5x10^{-4}

χ^2 / NDF = 2.7 / 5

100 mr Constant Fit Result: A_{LL} = -3.3x10^{-4} ± 8.4x10^{-4}

χ^2 / NDF = 2.5 / 5

* 100 mr points are offset by $E_{\gamma\gamma}$ + 1 GeV for visibility

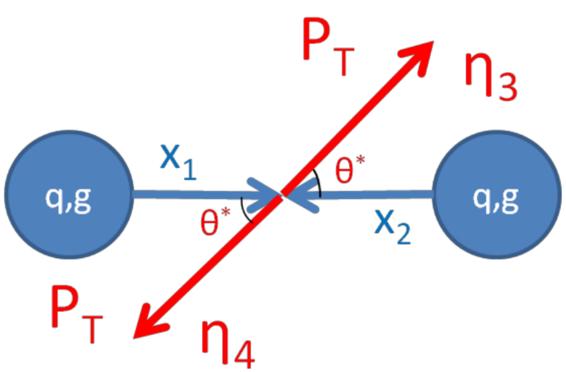
Conclusion

- Forward ($2.5 \le \eta < 4$) π^0 A_{LL} measurement consistent with zero
  - Independence of A_{LL} on π^0 isolation verified
    (cf. large dependence of A_N on π^0 isolation)
- Other systematic uncertainties are still under consideration
  - Trigger Bias – likely sub-dominant
  - Transverse spin component – likely negligible for A_{LL}
- Inclusive analysis coming soon!

backup

Outlook: Accessing low-x Δg(x) via Di-jets

- Forward hadrons from hard *q*, soft *g* processes
- Dijet Kinematics → access to gluon $x \leq 10^{-3}$
- Lowest-x processes accessible in future FCS (Forward Calorimetry System; $2.8 < \eta < 3.7$)

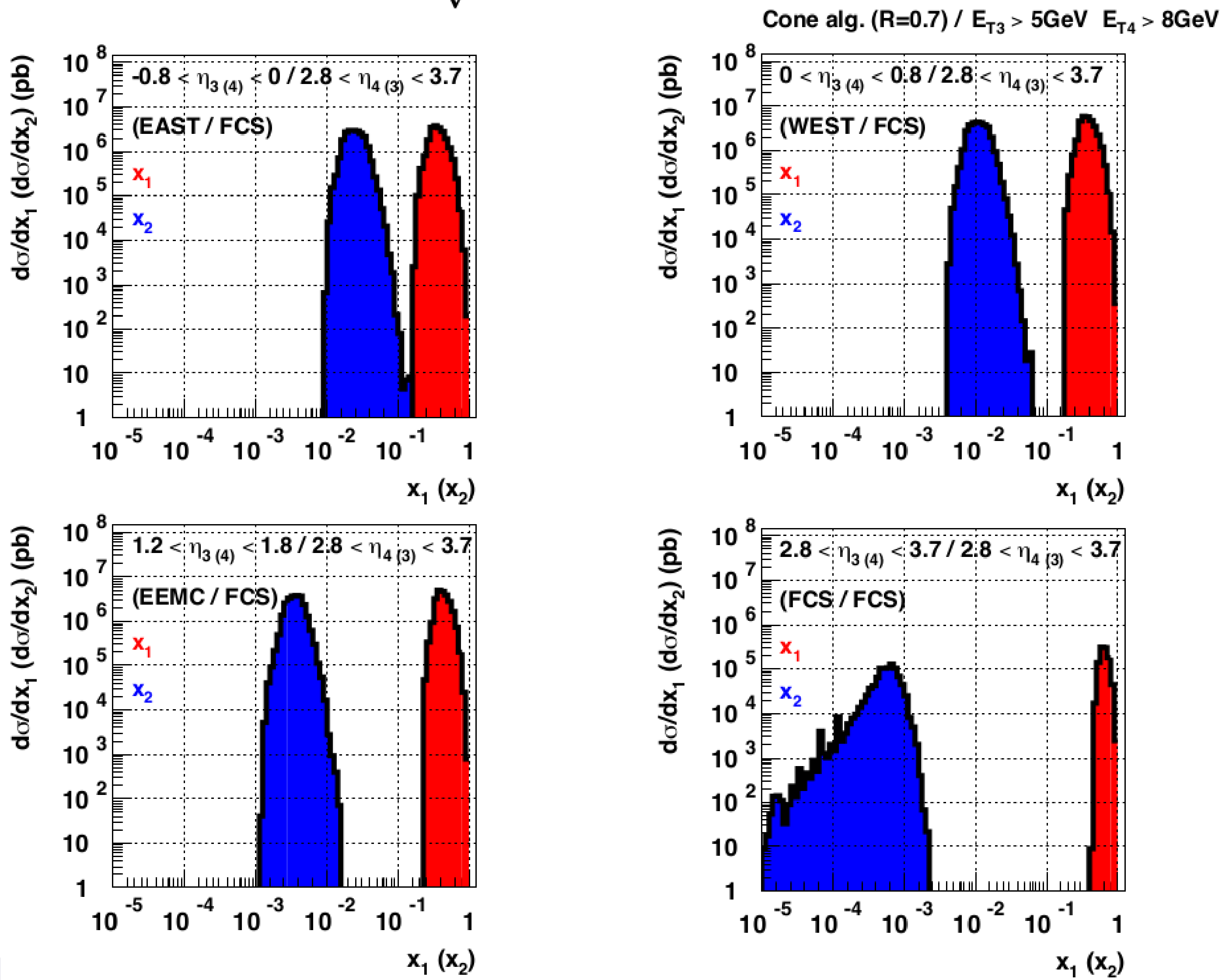


$$x_1 = \frac{p_T}{\sqrt{s}}\left(e^{\eta_3} + e^{\eta_4}\right)$$

$$x_2 = \frac{p_T}{\sqrt{s}}\left(e^{-\eta_3} + e^{-\eta_4}\right)$$

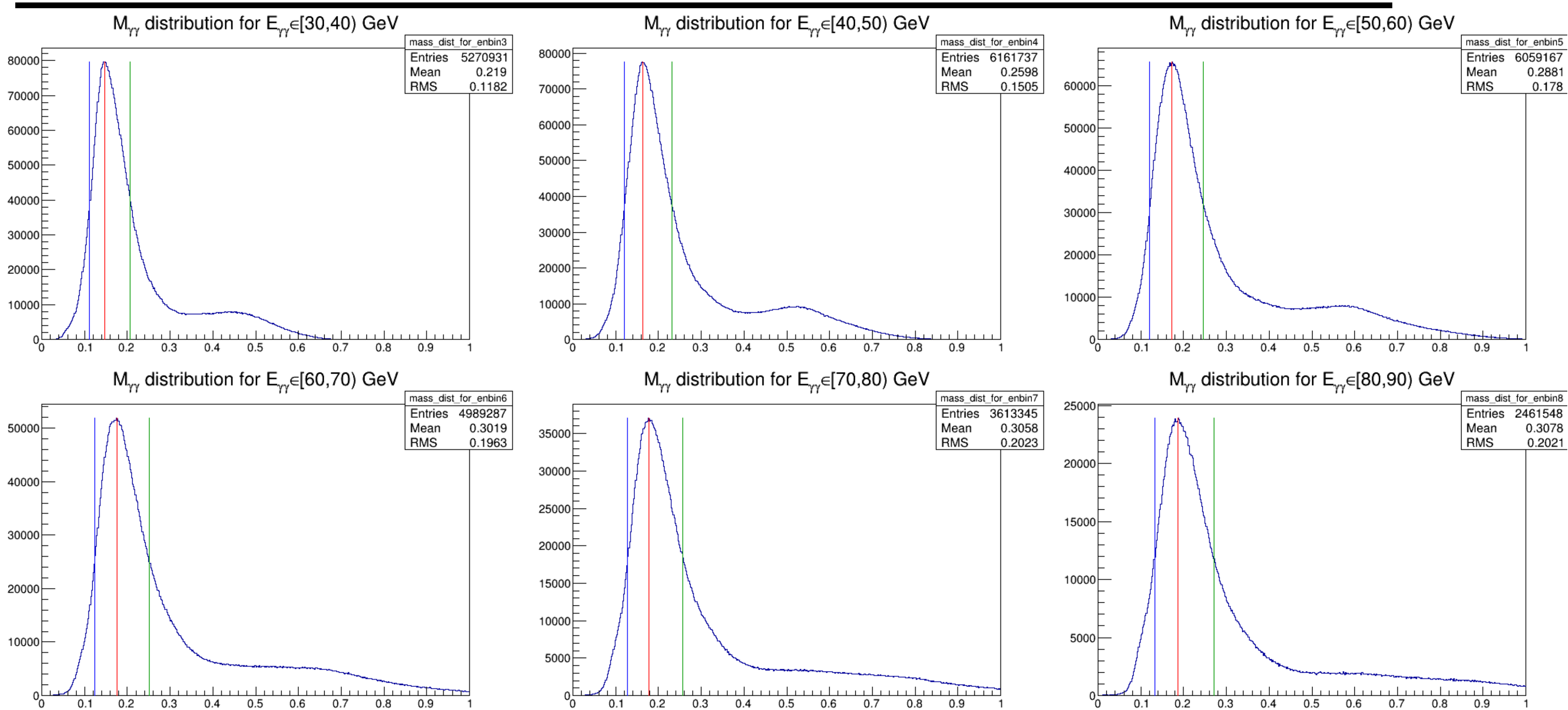
(leading-order x_1 and x_2 equations)

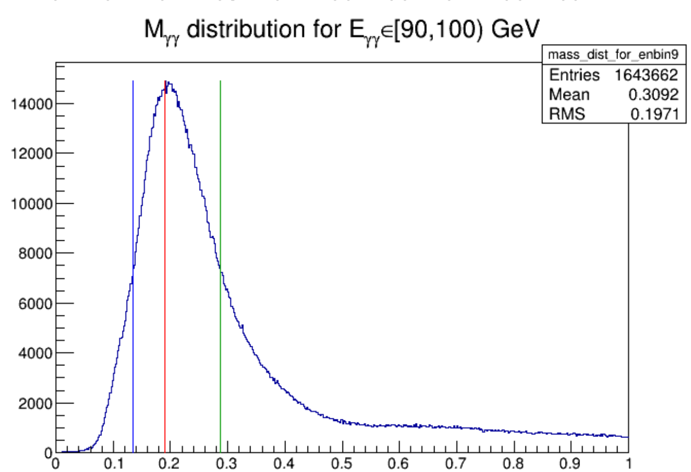
$\sqrt{s} = 500\,\mathrm{GeV}$



Surrow – arXiv: 1407.4176

Energy-Dependent π_0 Mass Cuts – 2012 Run





Vertical Lines Legend

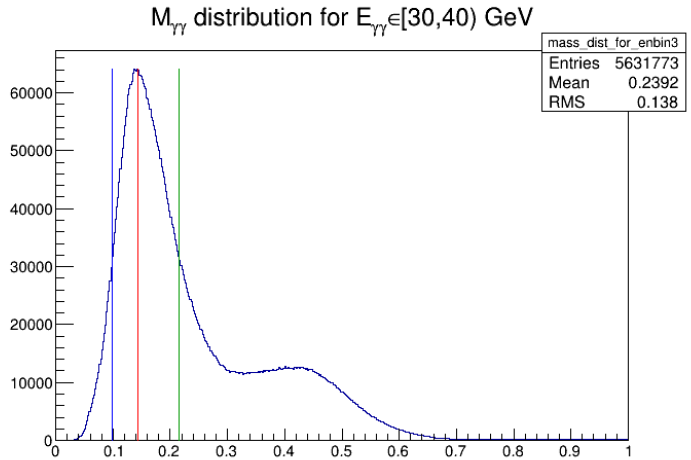
M low bound

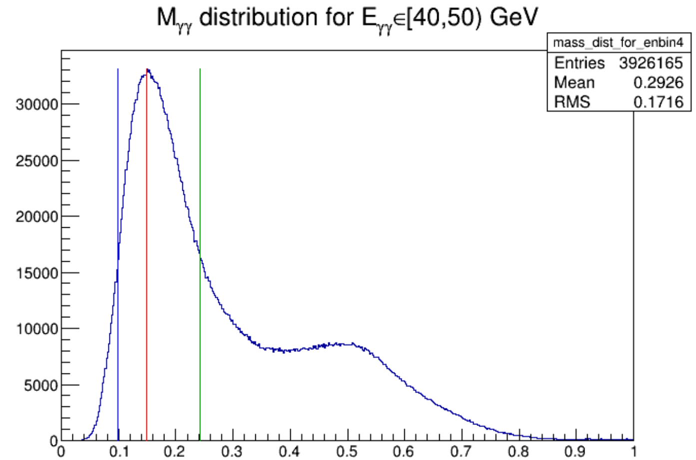
M max bin

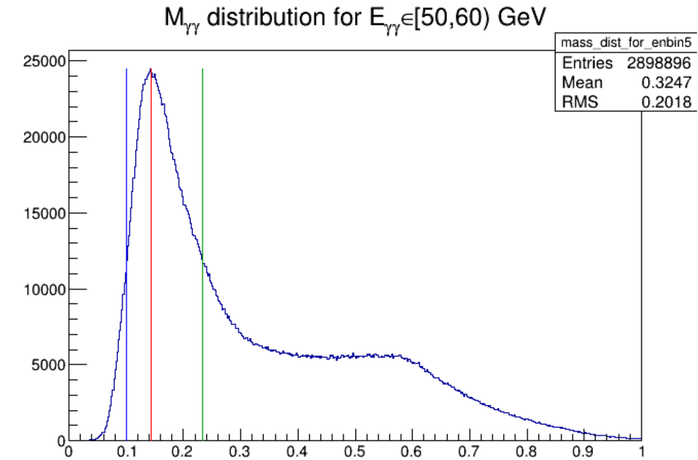
M high bound

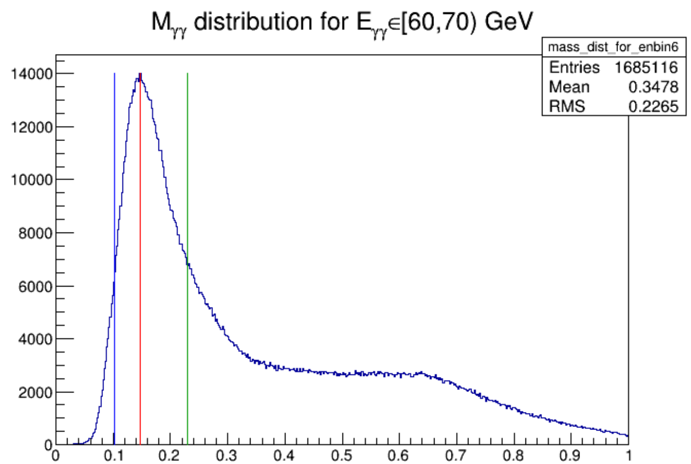
Bounds are set at the full width at half max of the π^0 mass peak for each 10 GeV $E_{\gamma\gamma}$ bin

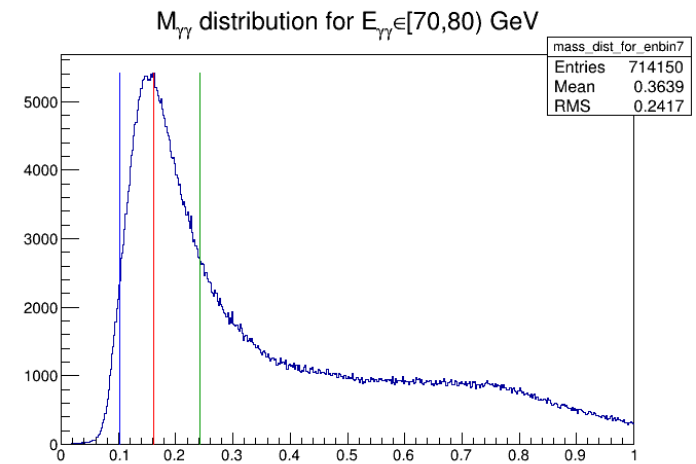
Energy-Dependent π_0 Mass Cuts – 2013 Run

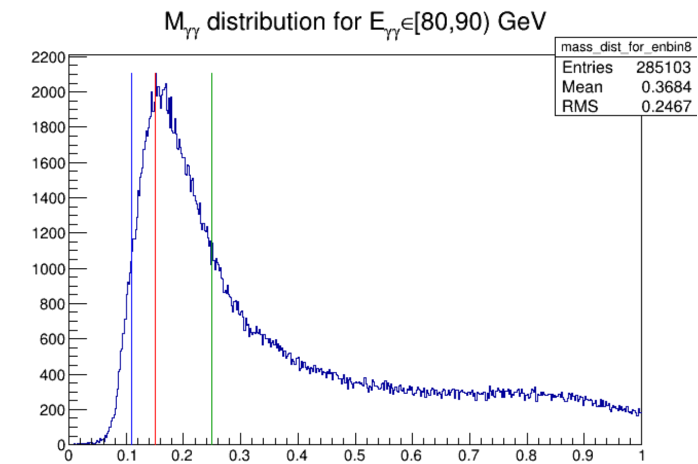


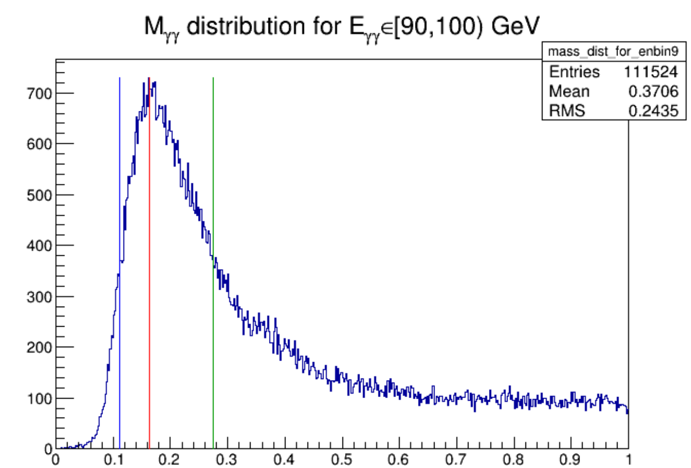












Vertical Lines Legend

M low bound

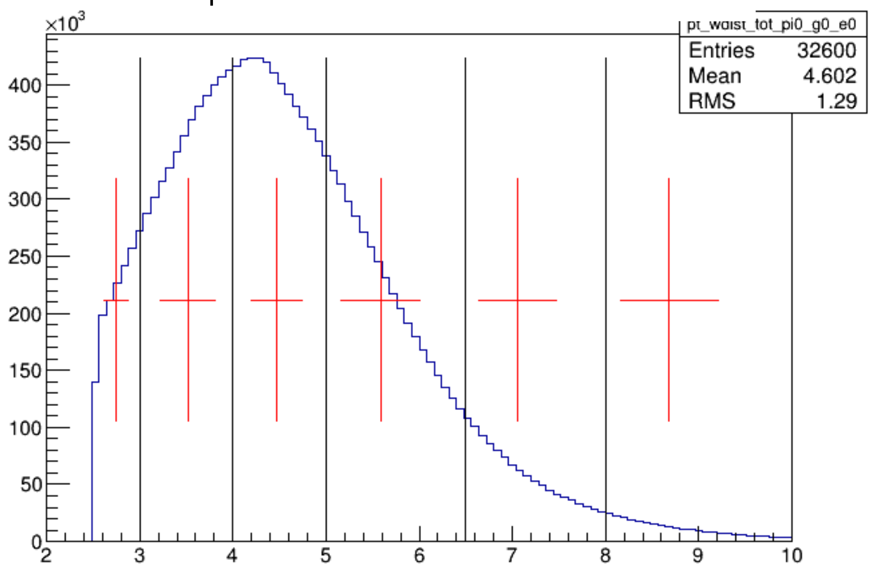
M max bin

M high bound

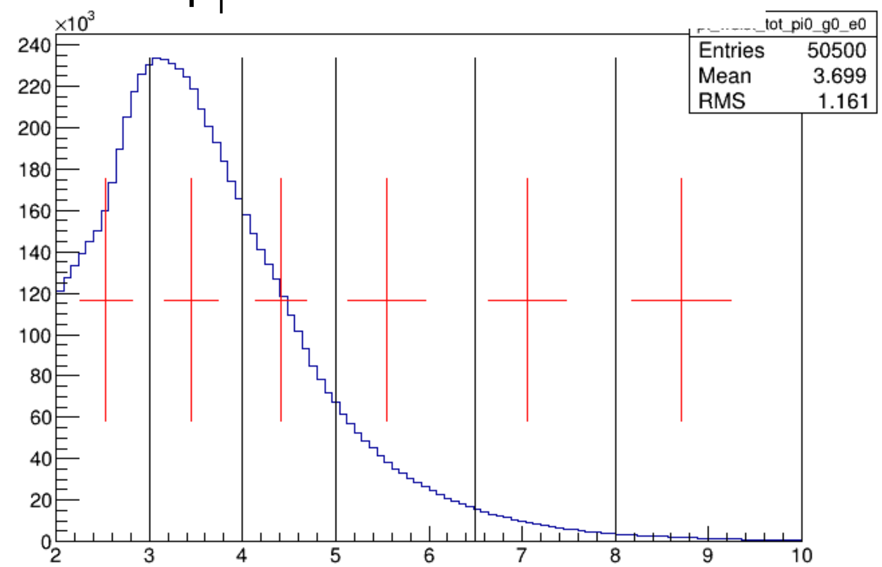
Bounds are set at the full width at half max of the π^0 mass peak for each 10 GeV $E_{\gamma\gamma}$ bin

π^0 p_T Distributions

π^0 p_T distribution for 2012 run



π^0 p_T distribution for 2013 run



For above plots:
Black vertical lines are p_T bin boundaries; red lines indicate p_T bin means & RMSs

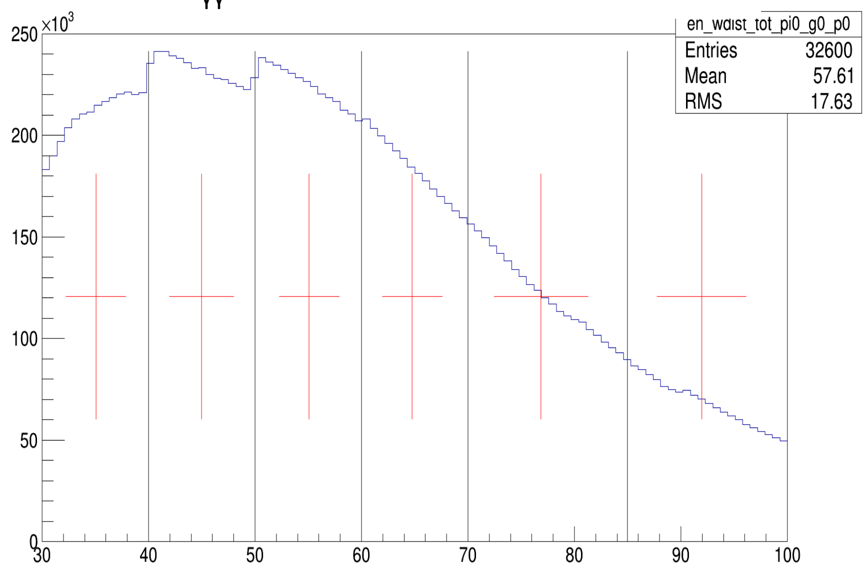
Trigger thresholds adjusted in 2013 to increase sensitivity in $2<p_T<3$ GeV/c region

2012 Run Cut:
$2.5 \leq p_T < 10$ GeV/c

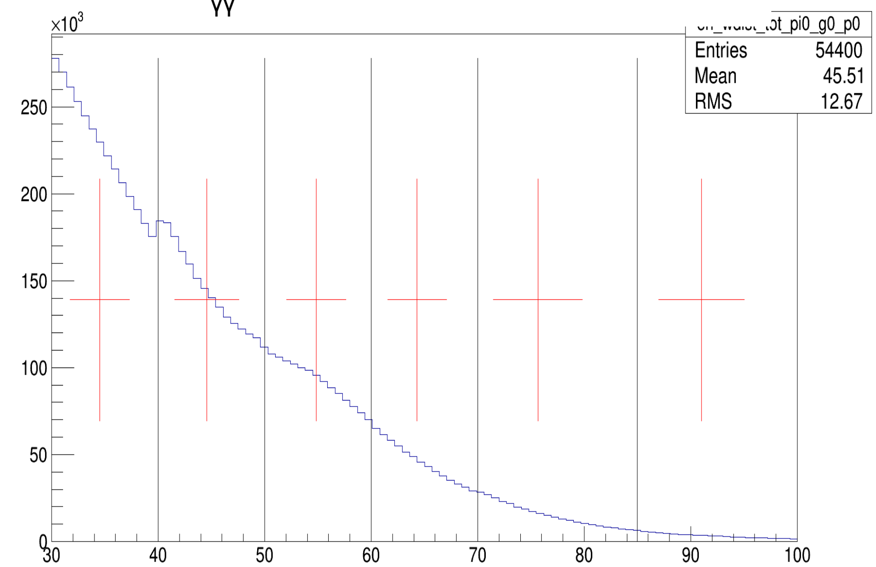
2013 Run Cut:
$2.0 \leq p_T < 10$ GeV/c

π^0 $E_{\gamma\gamma}$ Distributions

π^0 $E_{\gamma\gamma}$ distribution for 2012 run



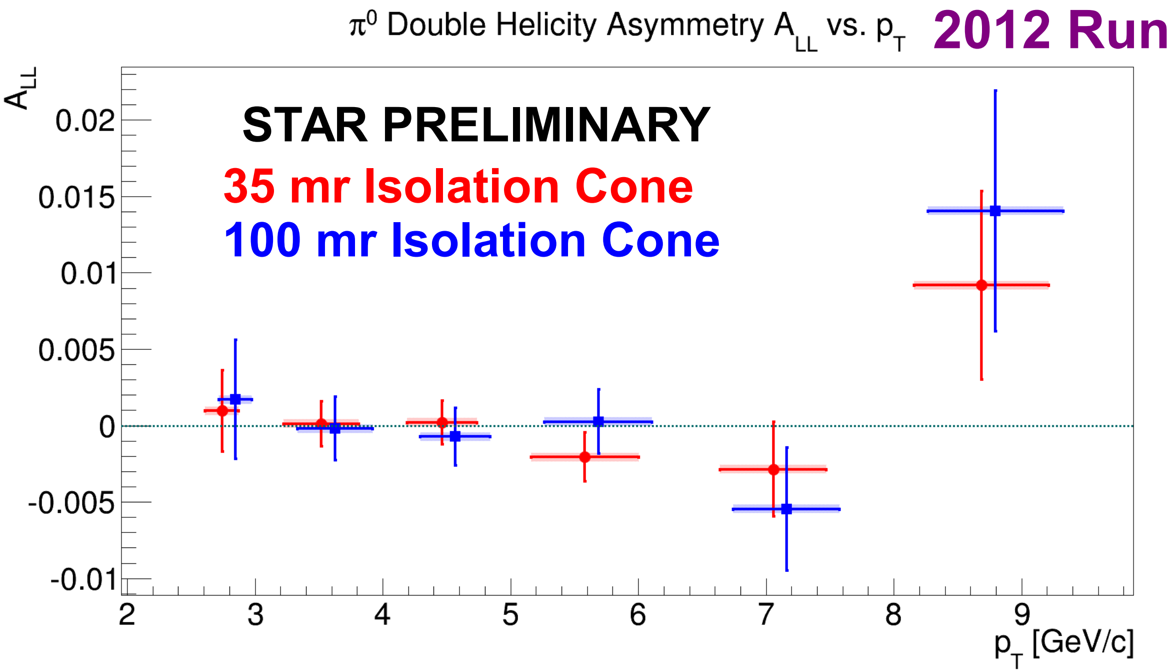
π^0 $E_{\gamma\gamma}$ distribution for 2013 run

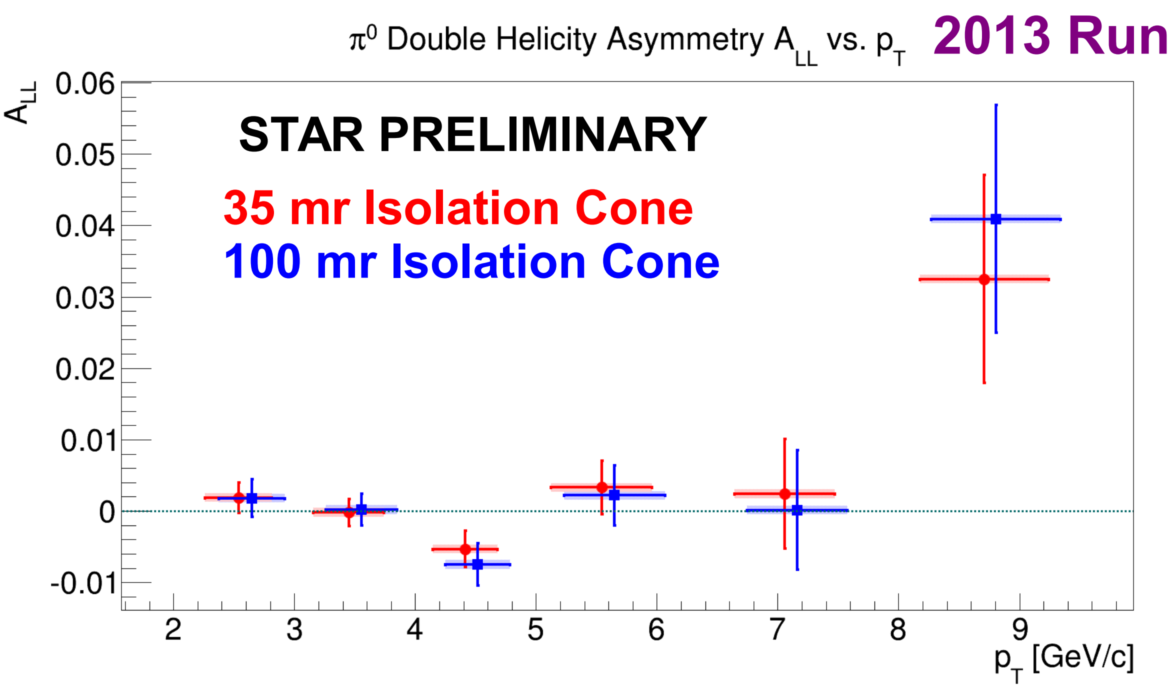


For above plots:
Black vertical lines are $E_{\gamma\gamma}$ bin boundaries; red lines indicate $E_{\gamma\gamma}$ bin means & RMSs

2012 and 2013 Run Cut:
$30 \leq E_{\gamma\gamma} < 100$ GeV

Forward π^0 A_{LL} Measurement for 2012 vs. 2013





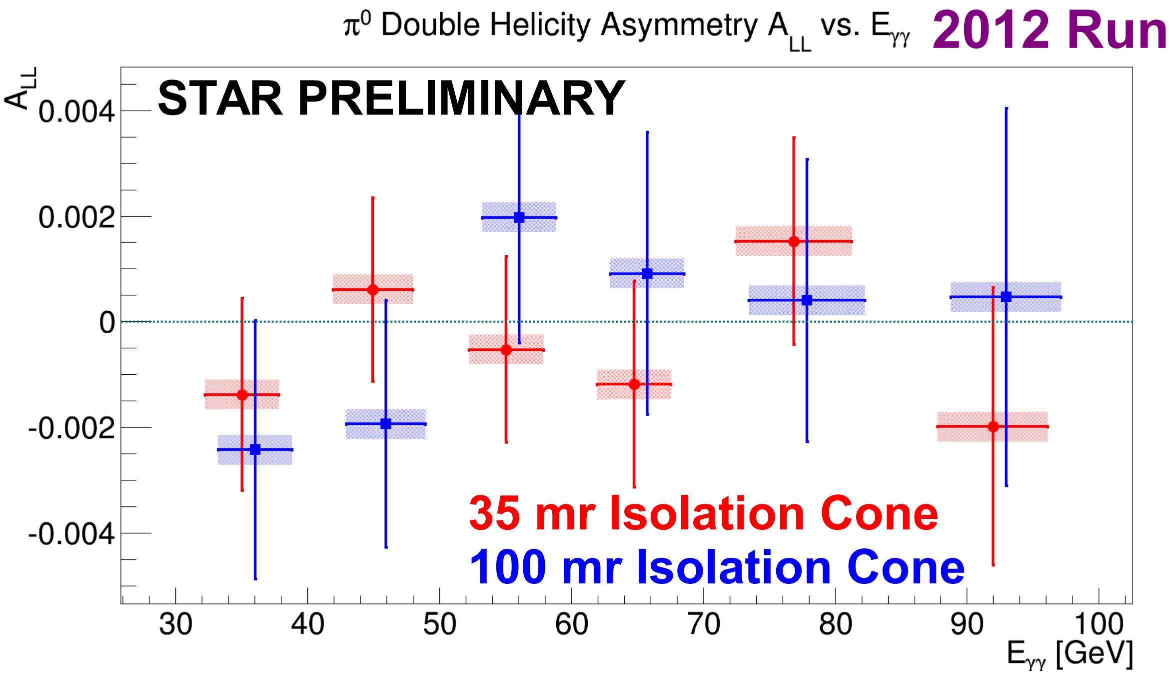
p_T Dependence

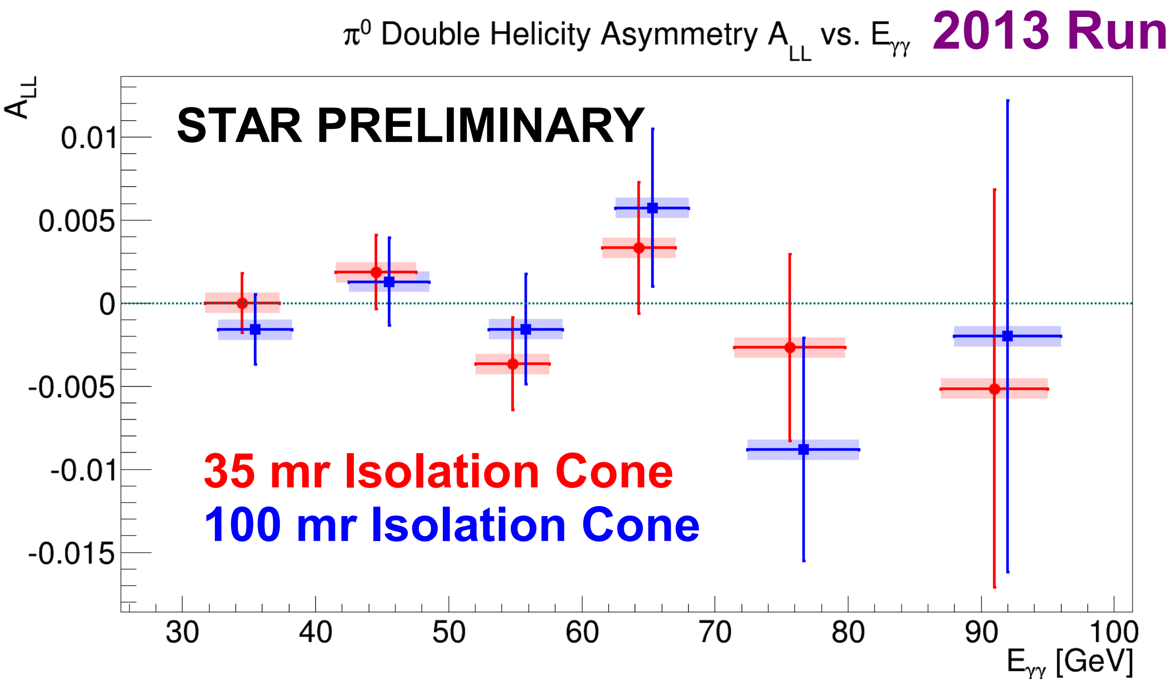
statistical uncertainty

bin RMS

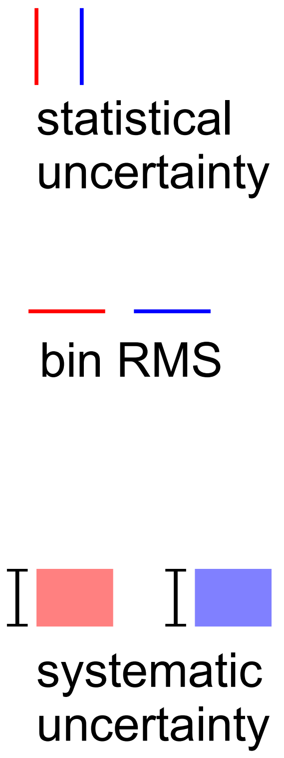
systematic uncertainty

Forward π^0 A_{LL} Measurement for 2012 vs. 2013





$E_{\gamma\gamma}$ Dependence



Combining Data to Measure A_{LL}

- STAR takes data in ~30 minute periods, called runs
  - Combine runs via maximum likelihood method (MLM)

MLM value: $$\bar{A}_{LL} = \frac{\sum_i P_a^{(i)} P_b^{(i)} \left[N_{++}^{(i)} + N_{--}^{(i)} - R_3^{(i)} \left(N_{+-}^{(i)} + N_{-+}^{(i)} \right) \right]}{\sum_i \left(P_a^{(i)} P_b^{(i)} \right)^2 \left[N_{++}^{(i)} + N_{--}^{(i)} + R_3^{(i)} \left(N_{+-}^{(i)} + N_{-+}^{(i)} \right) \right]}$$

(sums over runs)

Statistical Uncertainty: $$\delta_{\bar{A}_{LL}}^{stat} \approx \frac{1}{\langle P_a \rangle \langle P_b \rangle \sqrt{N_{tot}}}$$

Need 3 coincident measurements:
h-dependent yields ← calorimetry (viz. FMS)
Relative Luminosity ← scaler detectors (BBC, ZDC, VPD)
Beam Polarizations ← RHIC polarimetry (~55% +/- 5%)