# New Theory Curves and $\eta$ Asymmetry with New $\mathbf{p}_T$ Bins

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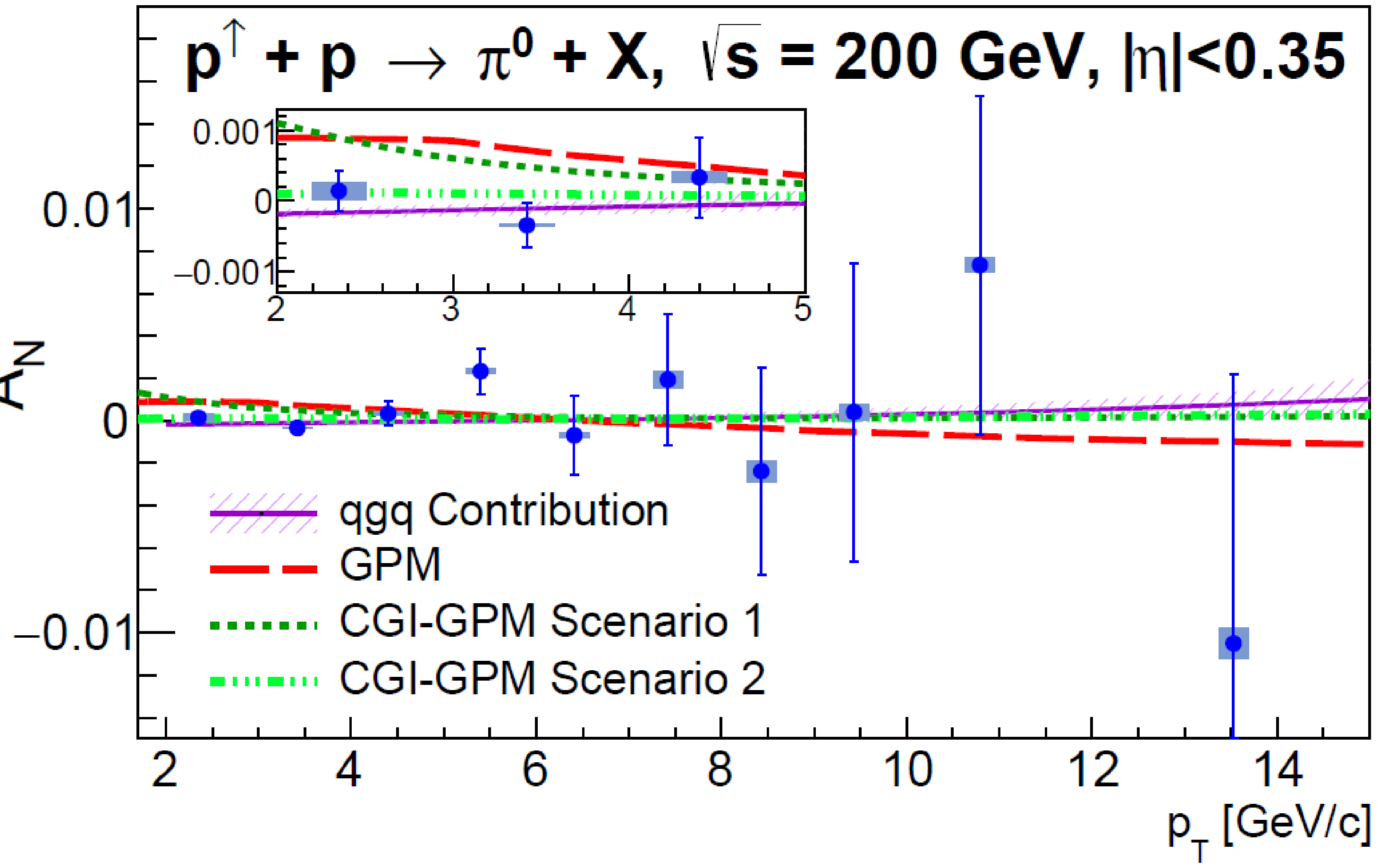
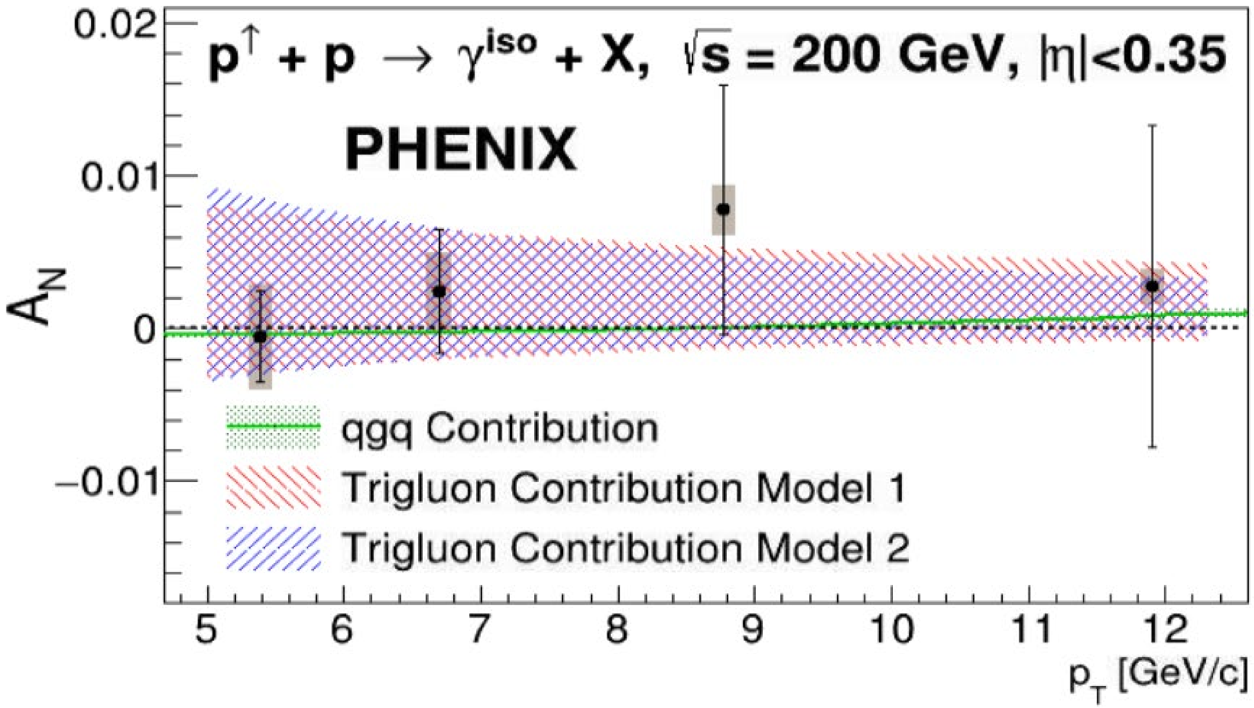
# Theory Curves for $A_N^{\pi^0}$

- GPM (Generalized Parton Model) evaluation for the Sivers function (quark + gluon) https://arxiv.org/pdf/1811.02970.pdf
- Collinear twist-3 qgq contribution from the polarized proton and hadronization https://arxiv.org/pdf/2002.08384.pdf
- Does not include contribution from collinear twist-3 trigluon correlation function https://arxiv.org/pdf/1312.6862.pdf
  - Requested from Shinsuke Yohsida and Yuji Koike, unfortunately code to perform calculations was lost when former postdoc left physics

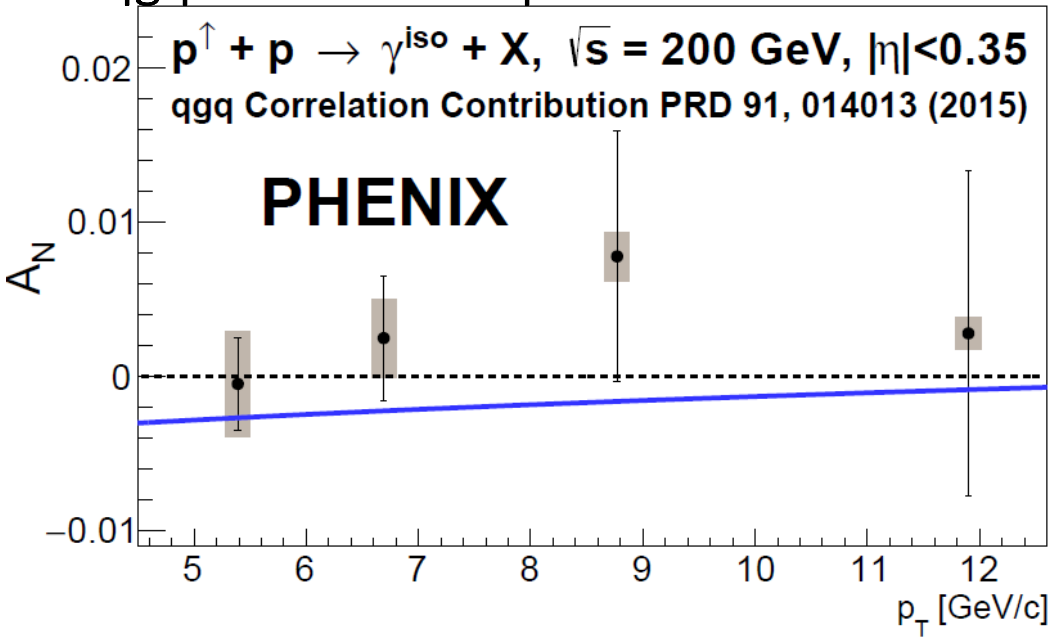


# New Calculation for qgq Contribution for $A_N^{\gamma}$

New Curve:




qgq Contribution prediction from before:



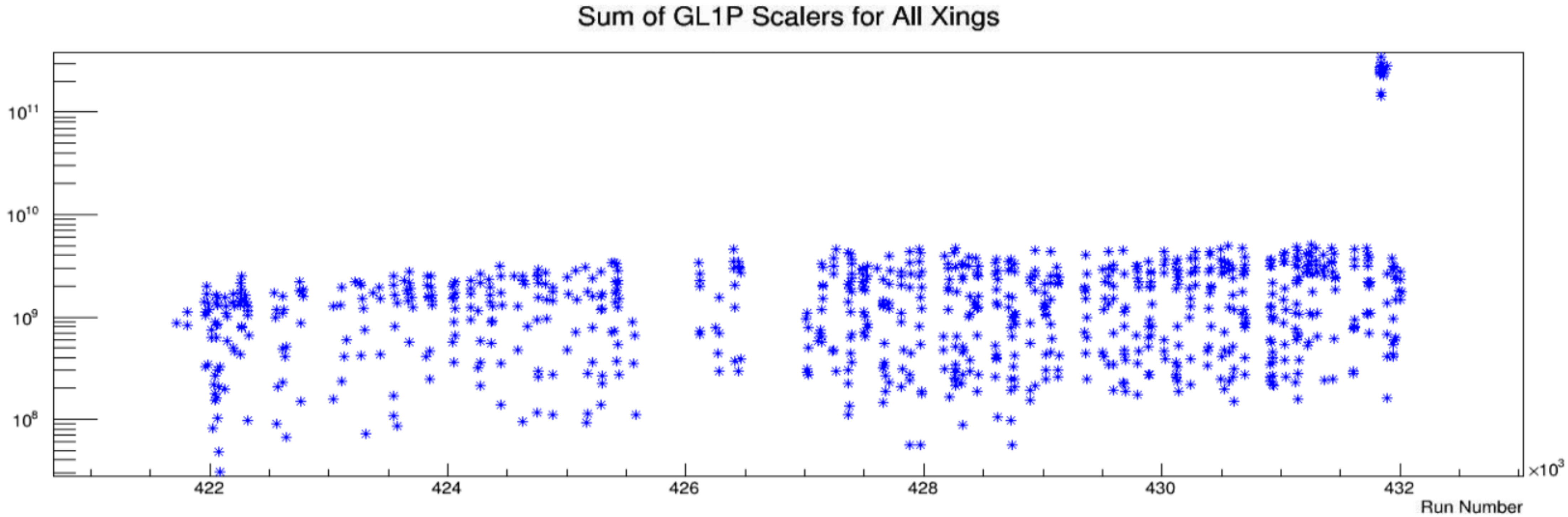

- Updated from Daniel Pitonyak, things that changed:
  - Used a more up-to-date extraction of the Sivers function from https://arxiv.org/pdf/2002.08384.pdf
  - Added the soft fermion pole (SFP) term from the polarized proton
- The new qgq contribution calculation shows that the midrapidity direct photon $A_N$ is more cleanly sensitive to the trigluon correlation function than previously thought

# $A_N^{\eta}$: New $p_T$ bins

| PPG135 $p_T$ Bins [GeV] | $p_T$ Bins From Preliminary [GeV] | New $p_T$ Bins [GeV] |
|---|---|---|
| 2 – 3 | 2 – 3 | 2 – 3 |
| 3 – 4 | 3 – 4 | 3 – 4 |
| 4 – 5 | 4 – 5 | 4 – 5 |
| 5 – 6 | 5 – 6 | 5 – 6 |
| 6 – 7 | 6 – 8 | 6 – 7 |
| 7 – 8 | 8 – 15 | 7 – 8 |
| 8 – ?? | | 8 – 10 |
| | | 10 – 20 |

- After reviewing this result, I realized I was using wider $p_T$ bins than PPG 135
- Able to use finer $p_T$ by combining data from two fills together to calculate the asymmetry rather than calculating the asymmetry fill by fill
    - Same method used for $\pi^0$ and direct photon asymmetries

# Also Eliminated Fills with Problematic GL1P Scalers




Runs with GL1P Scalers that are ~2 orders of magnitude larger than the rest:

431831, 431833, 431834, 431835, 431836, 431837, 431839, 431840, 431844, 431845, 431846, 431859, 431860, 431886, 431888

Correspond to three fills, which are eliminated from the $\pi^0$, $\eta$ and direct photon analyses

# Data Cuts

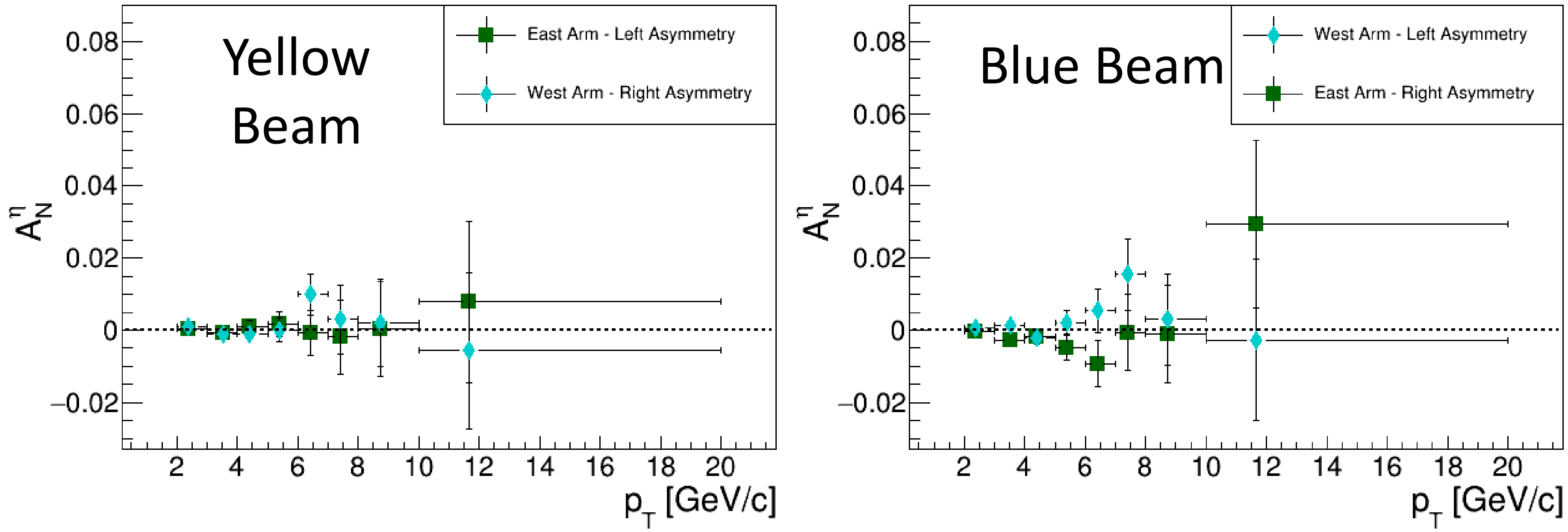
- Using ERT data
- $|z_{vtx}| < 30$ cm
- Cuts for all photon clusters:
  - $0.5 \leq$ Energy $\leq 20$ GeV
  - prob_photon > 0.02
  - $\chi^2$ cut
  - Eliminate dead and warn map clusters
  - Edge tower cut
  - Hot tower cut (fixed bug)
  - | TOF | $\leq$ 5 ns
  - Charged Track Veto Cut
- Photon pair cuts
  - same arm
  - cluster distance greater than 8 cm
  - Energy asymmetry $\alpha = \frac{|E_1 - E_2|}{E_1 + E_2} < 0.8$
  - Used the same invariant mass ranges as PPG135:
    Signal: $480 < M_{\gamma\gamma} < 620$ MeV
    Background: $300 < M_{\gamma\gamma} < 400$ MeV or $700 < M_{\gamma\gamma} < 800$ MeV
- Cuts for the higher energy trigger photon
  - ERT check
  - Highest energy photon in the event to avoid random benefit (not used for preliminary)
  - $p_T \geq 1.5$ GeV (previously $p_T \geq 1.0$ GeV)

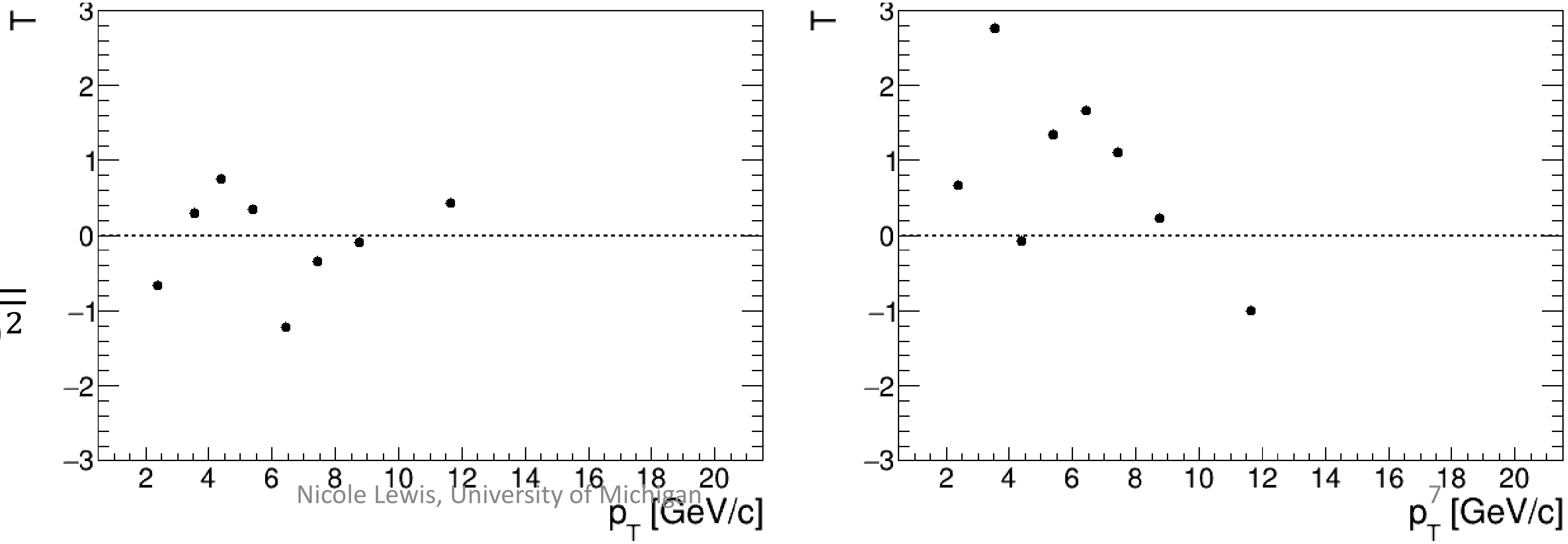
# $\eta$ Asymmetry Before the Background Correction

Relative Luminosity Formula

Signal invariant mass region:
$480 < M_{\gamma\gamma} < 620$ MeV

$$T(p_T) = \frac{A_N^{left} - A_N^{right}}{\sqrt{(\sigma^{left})^2 + (\sigma^{right})^2}}$$

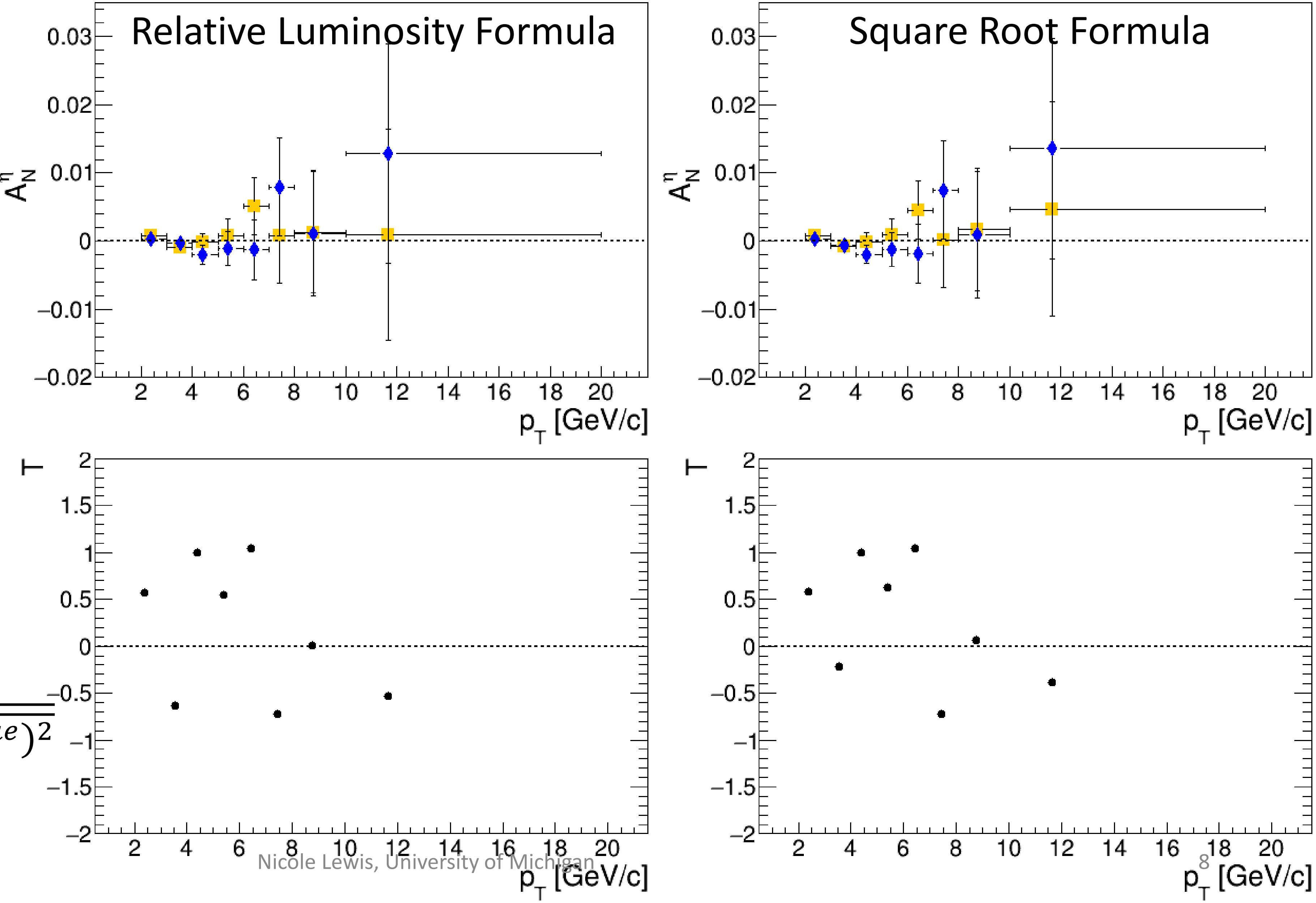


# $\eta$ Asymmetry Before the Background Correction

Signal invariant mass region:
$480 < M_{\gamma\gamma} < 620$ MeV

$$T(p_T) = \frac{A_N^{Yellow} - A_N^{Blue}}{\sqrt{(\sigma^{Yellow})^2 + (\sigma^{Blue})^2}}$$



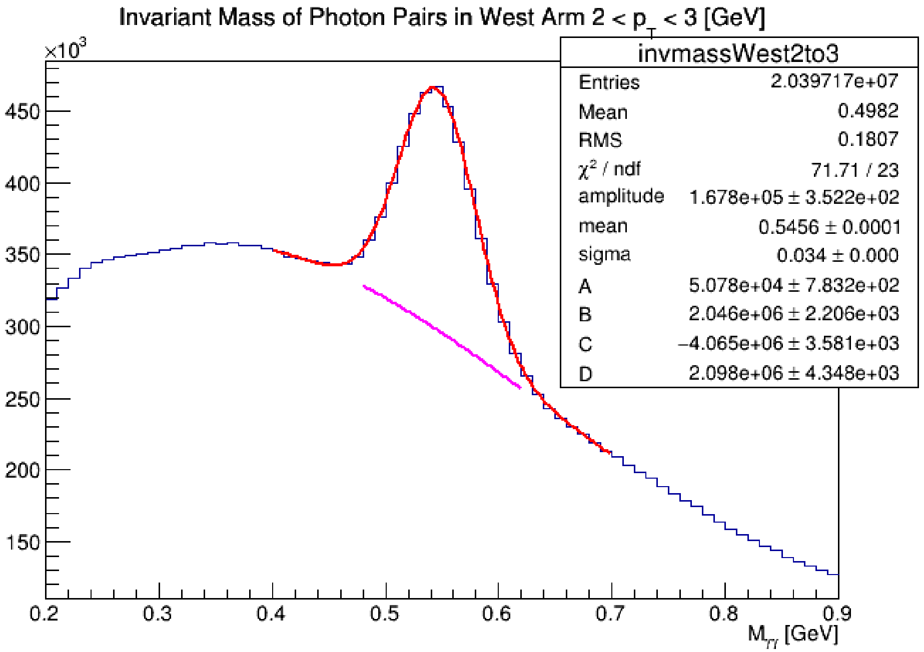
# Background Fraction Fits

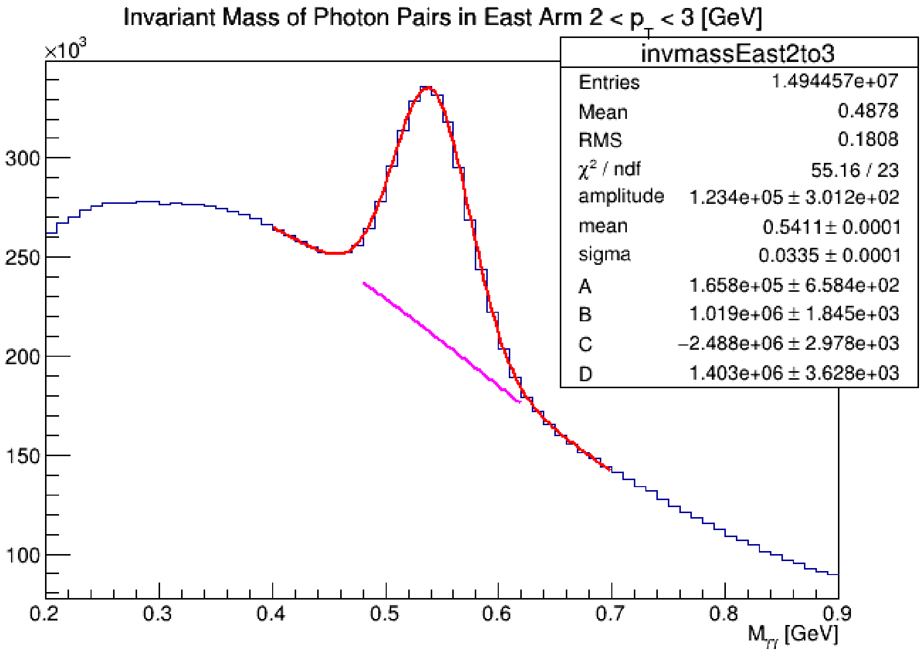
Examples of the invariant mass plots. Rest of the fits are included in the back up

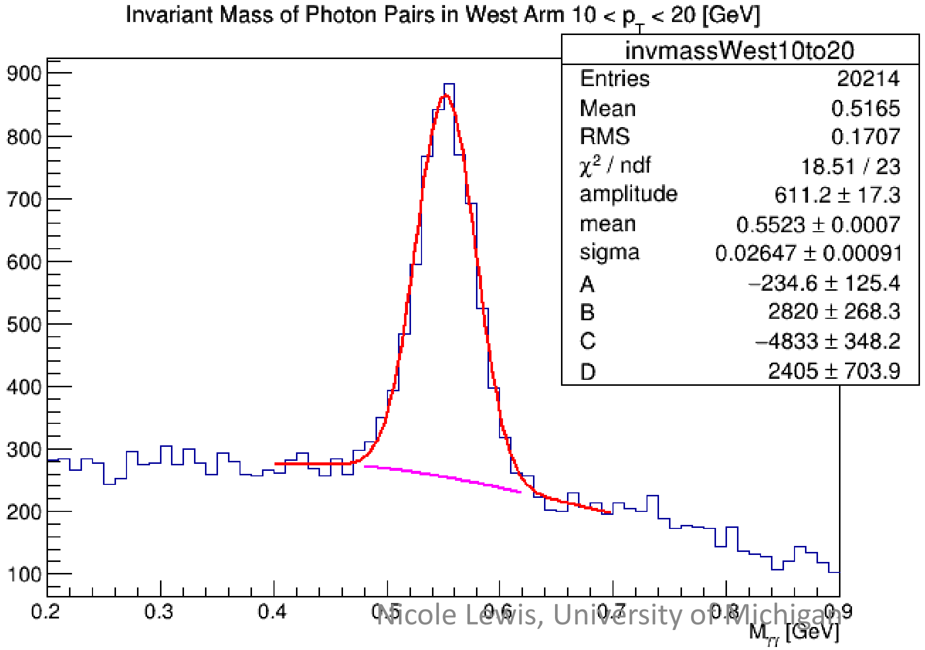
Fit a “Gaus+pol3” function to $0.4 < M_{\gamma\gamma} < 0.7$ GeV

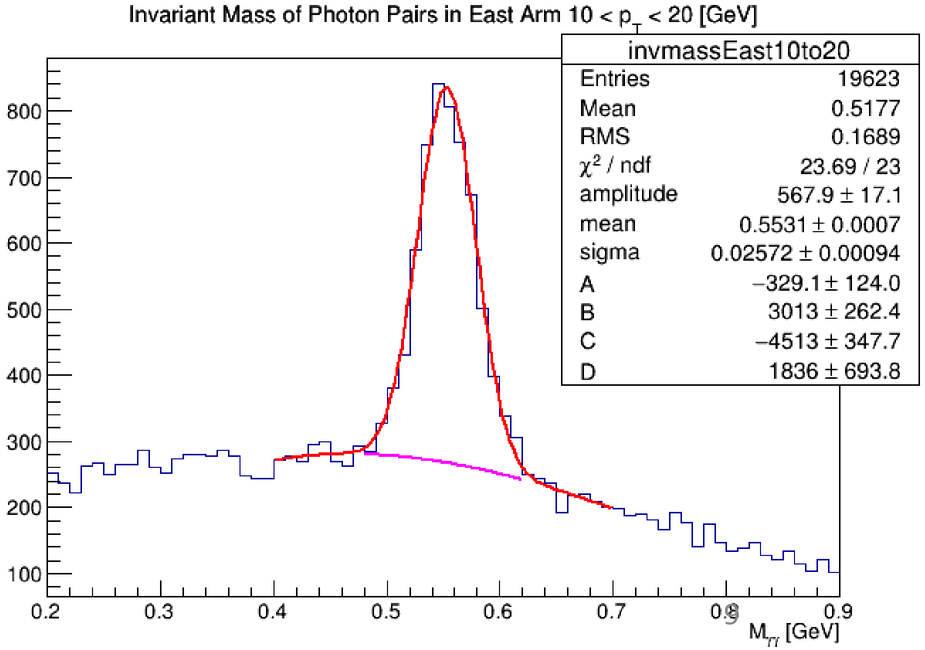
Pink curve represents the “pol3" which describes the combinatorial background

Gaussian part of the fit is not used in the background fraction calculation directly



# Background Fraction

Fit a "Gaus+pol3" function to $0.4 < M_{\gamma\gamma} < 0.7$ GeV

$r = \frac{B}{S+B}$ calculated using the signal region:

$0.480 < M_{\gamma\gamma} < 0.620$ GeV

- $B$ is calculated by integrating the "pol3" part of the fit
- $S+B$ is calculated by summing histogram counts

Same method as $\pi^0$ analysis

| $p_T$[GeV] | West Arm | East Arm | Both Arms |
|---|---|---|---|
| 2 - 3 | 0.715 | 0.712 | 0.714 |
| 3 - 4 | 0.606 | 0.601 | 0.604 |
| 4 - 5 | 0.554 | 0.552 | 0.553 |
| 5 - 6 | 0.52 | 0.519 | 0.519 |
| 6 - 7 | 0.501 | 0.497 | 0.499 |
| 7 - 8 | 0.483 | 0.502 | 0.492 |
| 8 - 10 | 0.466 | 0.482 | 0.474 |
| 10 - 20 | 0.452 | 0.487 | 0.469 |

# Background Asymmetry

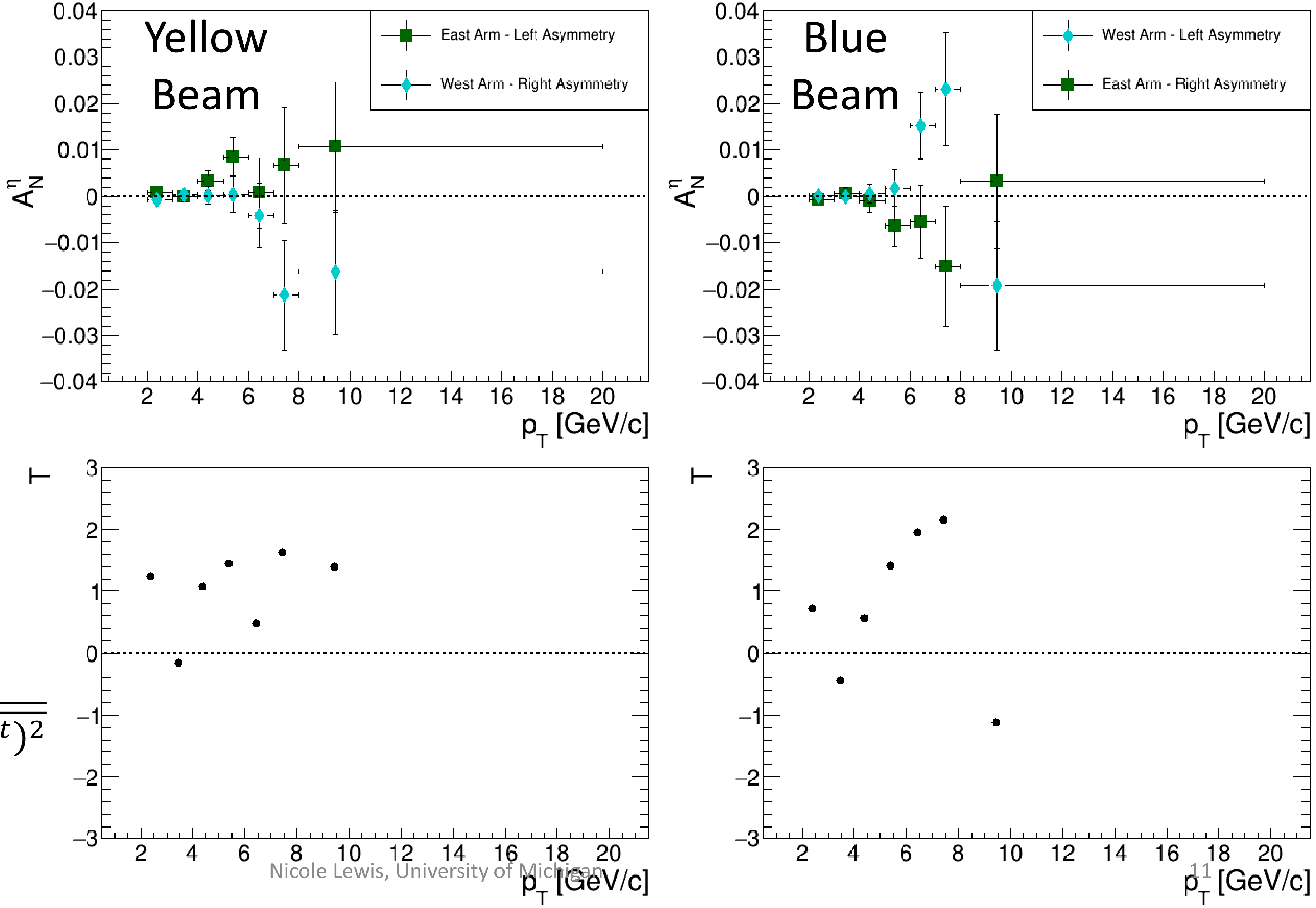
Relative Luminosity Formula

Background invariant mass regions:

$300 < M_{\gamma\gamma} < 400$ MeV

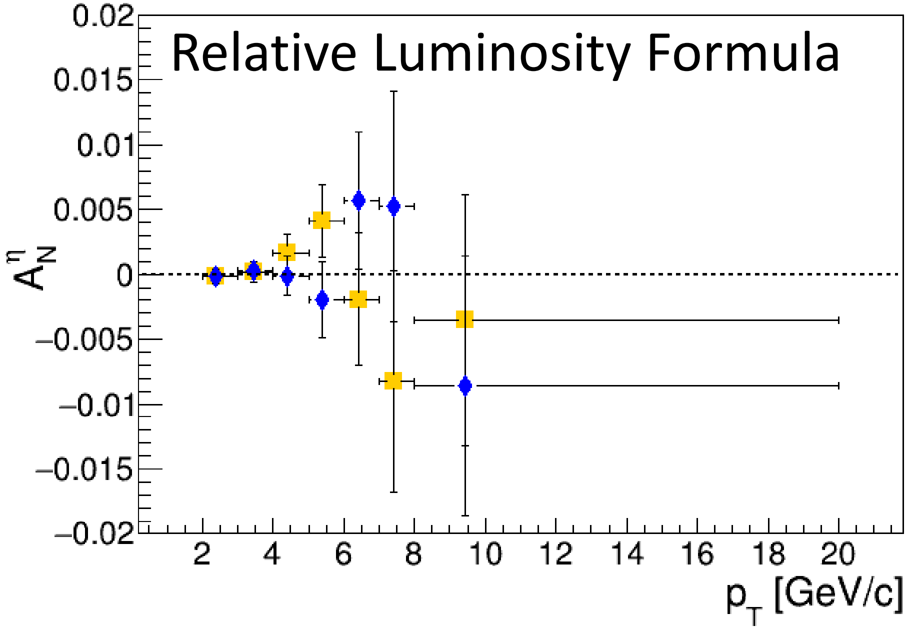
$700 < M_{\gamma\gamma} < 800$ MeV

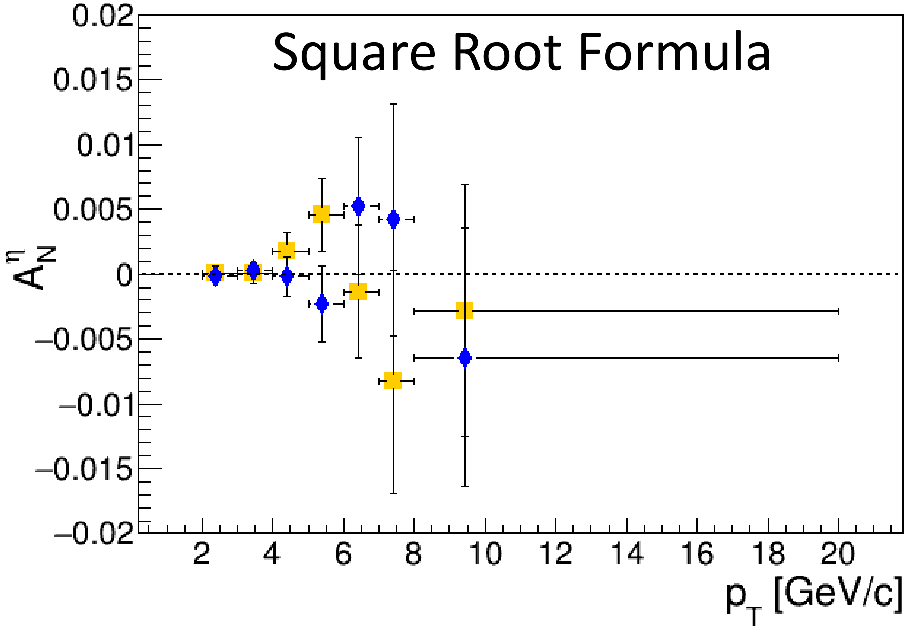
$$T(p_T) = \frac{A_N^{left} - A_N^{right}}{\sqrt{(\sigma^{left})^2 + (\sigma^{right})^2}}$$

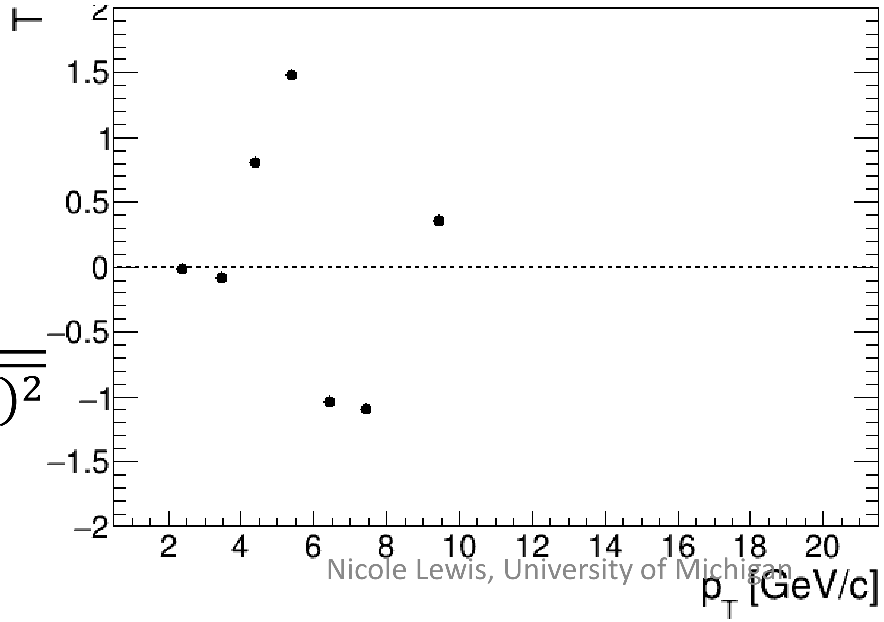


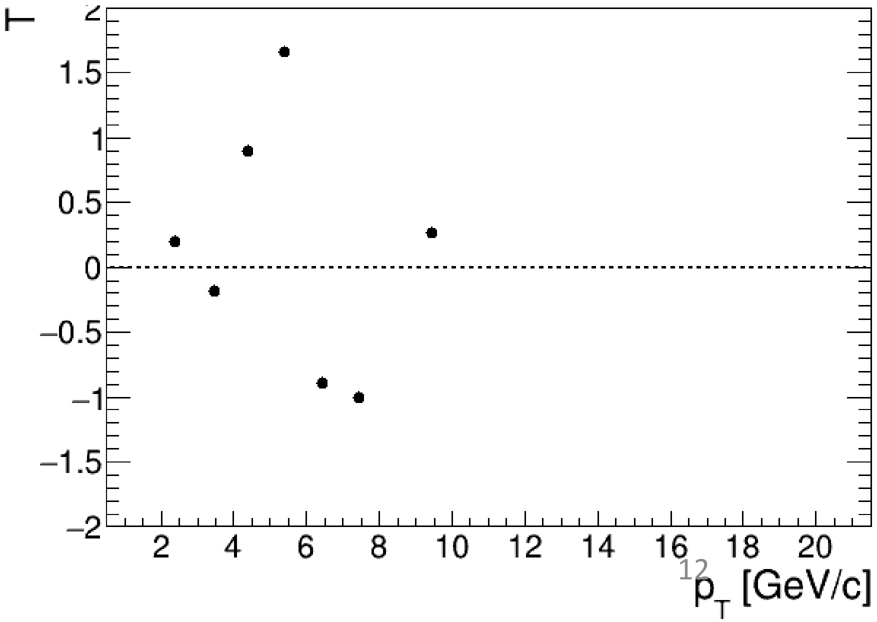
# Background Asymmetry

Background invariant mass regions:
$300 < M_{\gamma\gamma} < 400$ MeV
$700 < M_{\gamma\gamma} < 800$ MeV



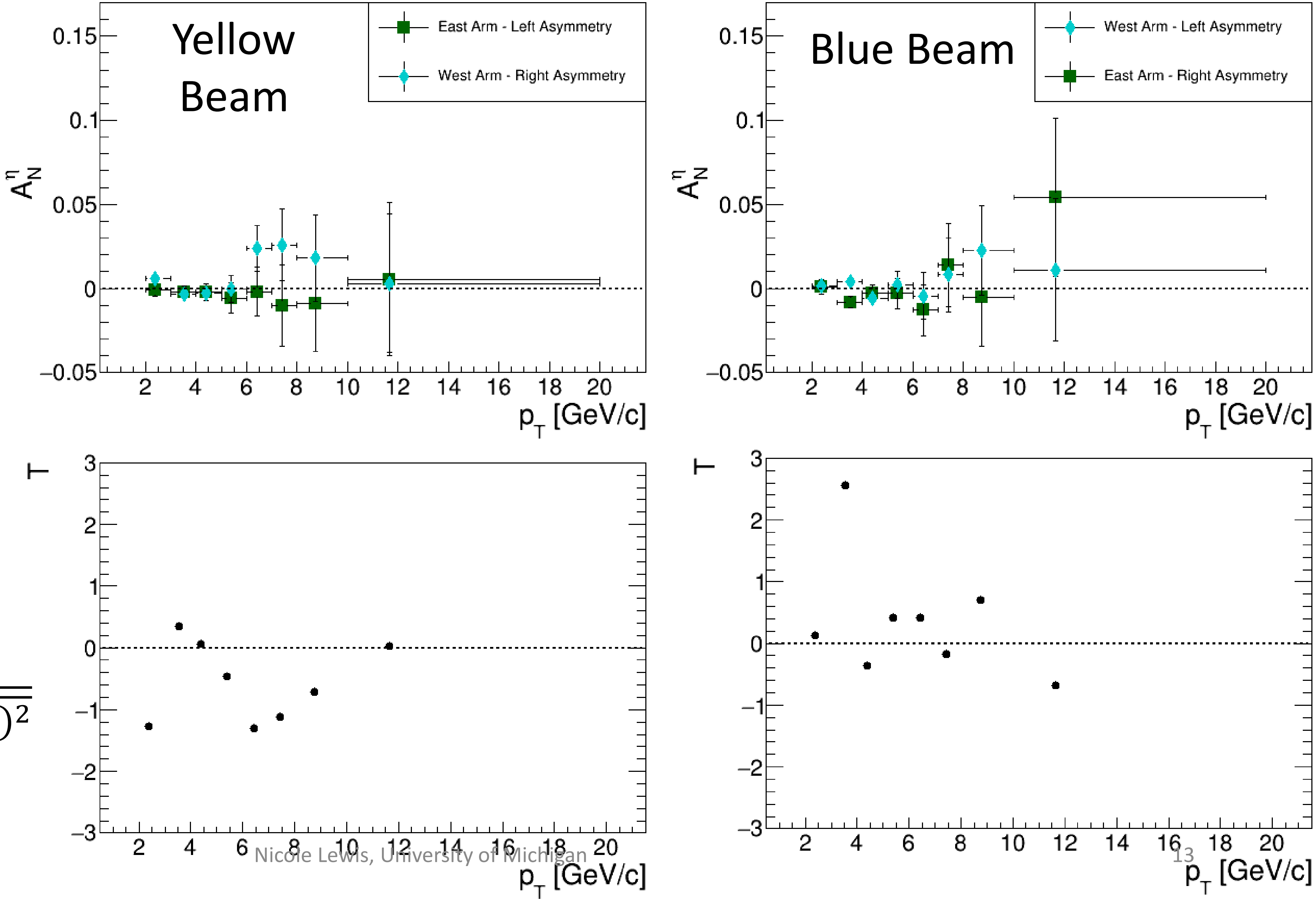




$$T(p_T) = \frac{A_N^{Yellow} - A_N^{Blue}}{\sqrt{(\sigma^{Yellow})^2 + (\sigma^{Blue})^2}}$$

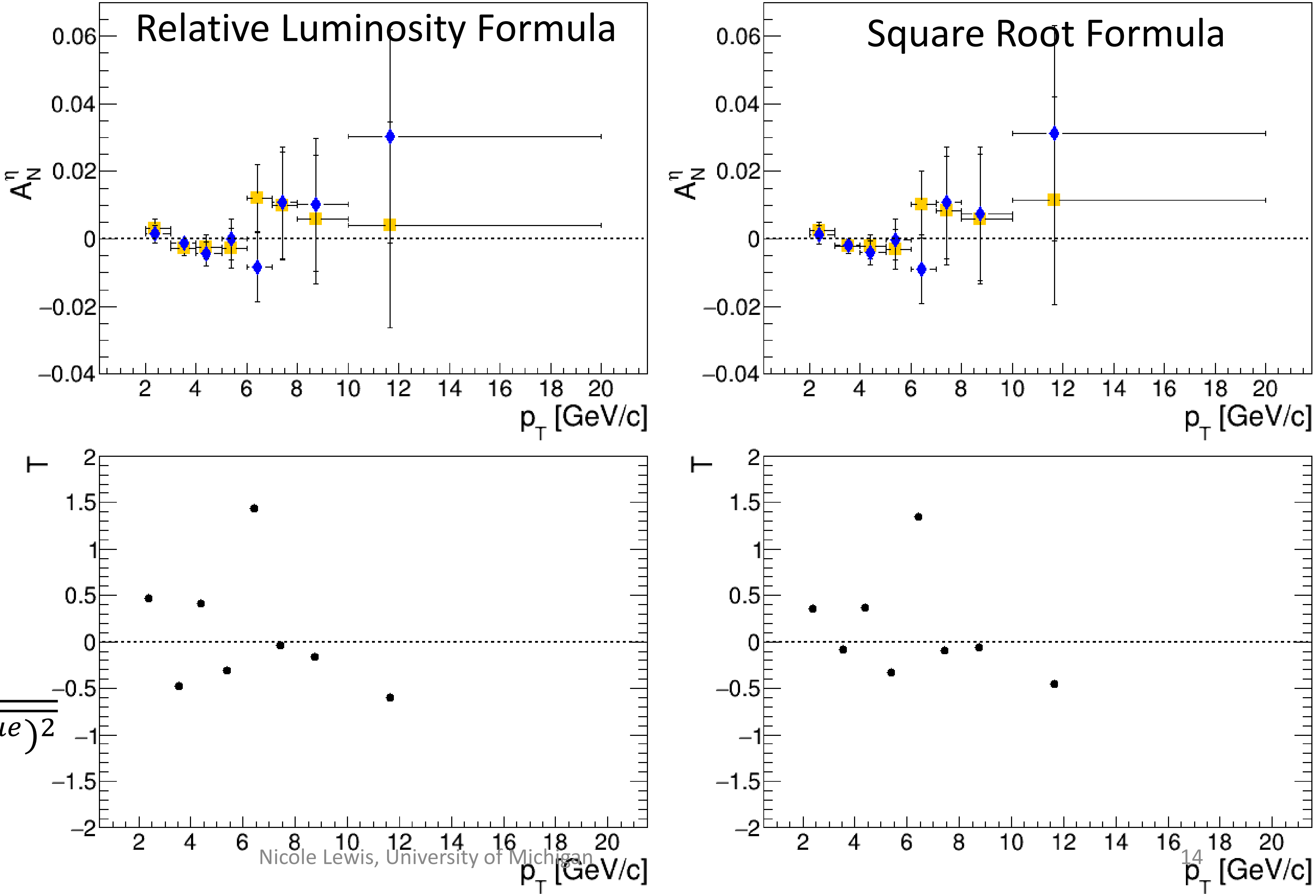
# Background Corrected $\eta$ Asymmetry

Relative Luminosity Formula

$$T(p_T) = \frac{A_N^{left} - A_N^{right}}{\sqrt{(\sigma^{left})^2 + (\sigma^{right})^2}}$$

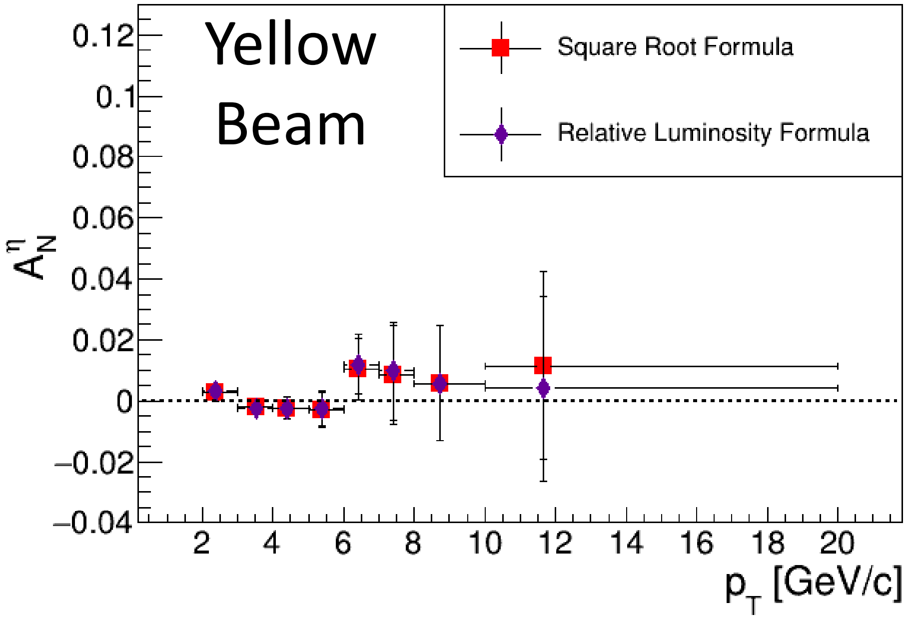


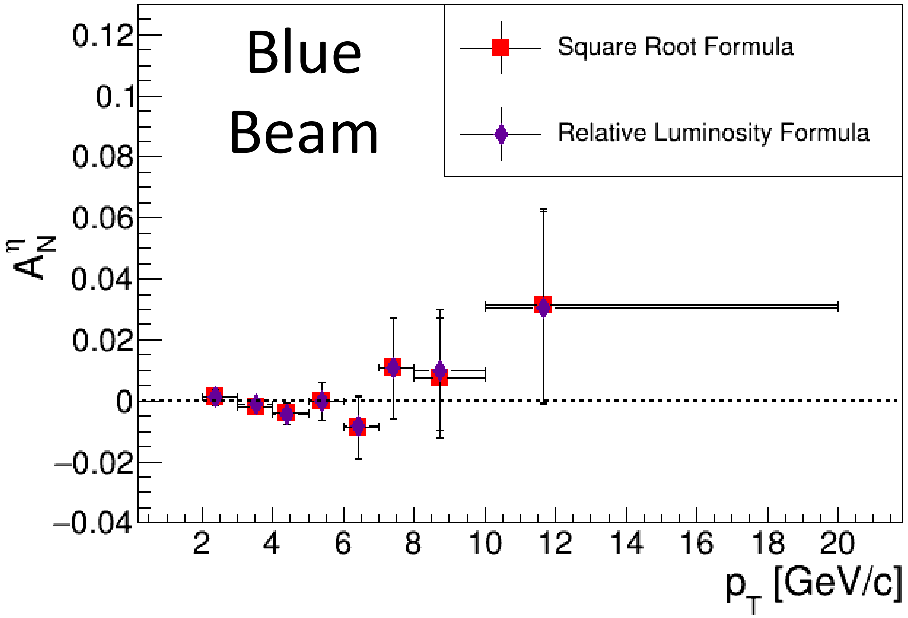
# Background Corrected $\eta$ Asymmetry



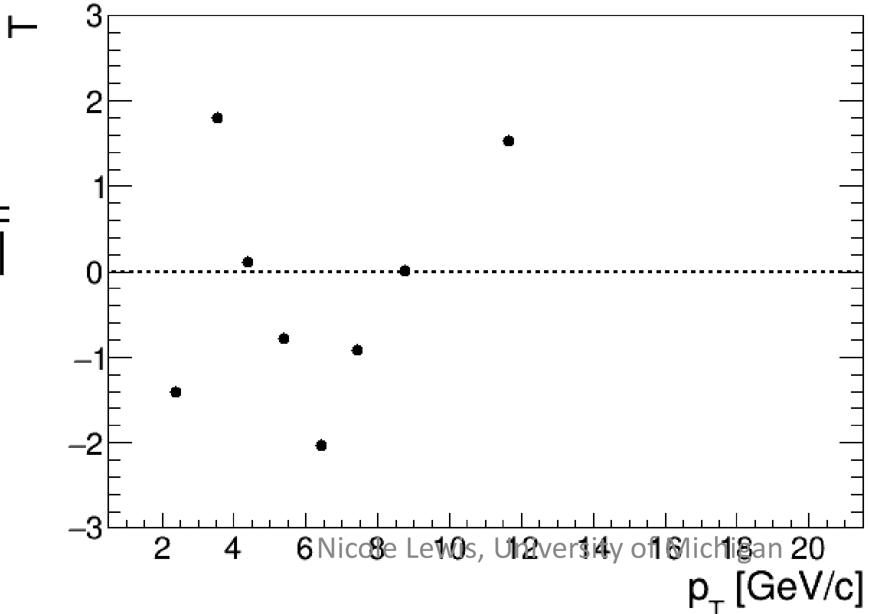

$$T(p_T) = \frac{A_N^{Yellow} - A_N^{Blue}}{\sqrt{(\sigma^{Yellow})^2 + (\sigma^{Blue})^2}}$$

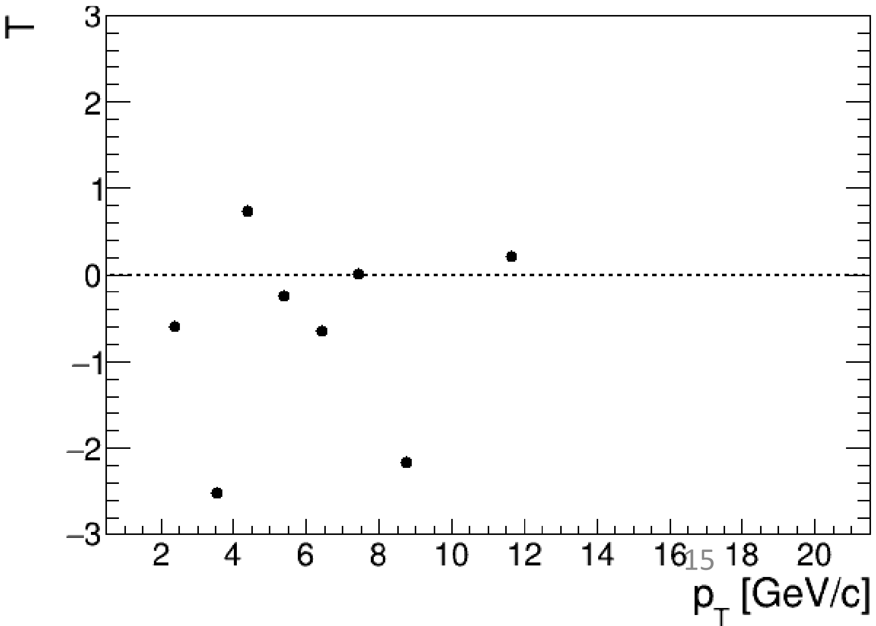
# Background Corrected $\eta$ Asymmetry



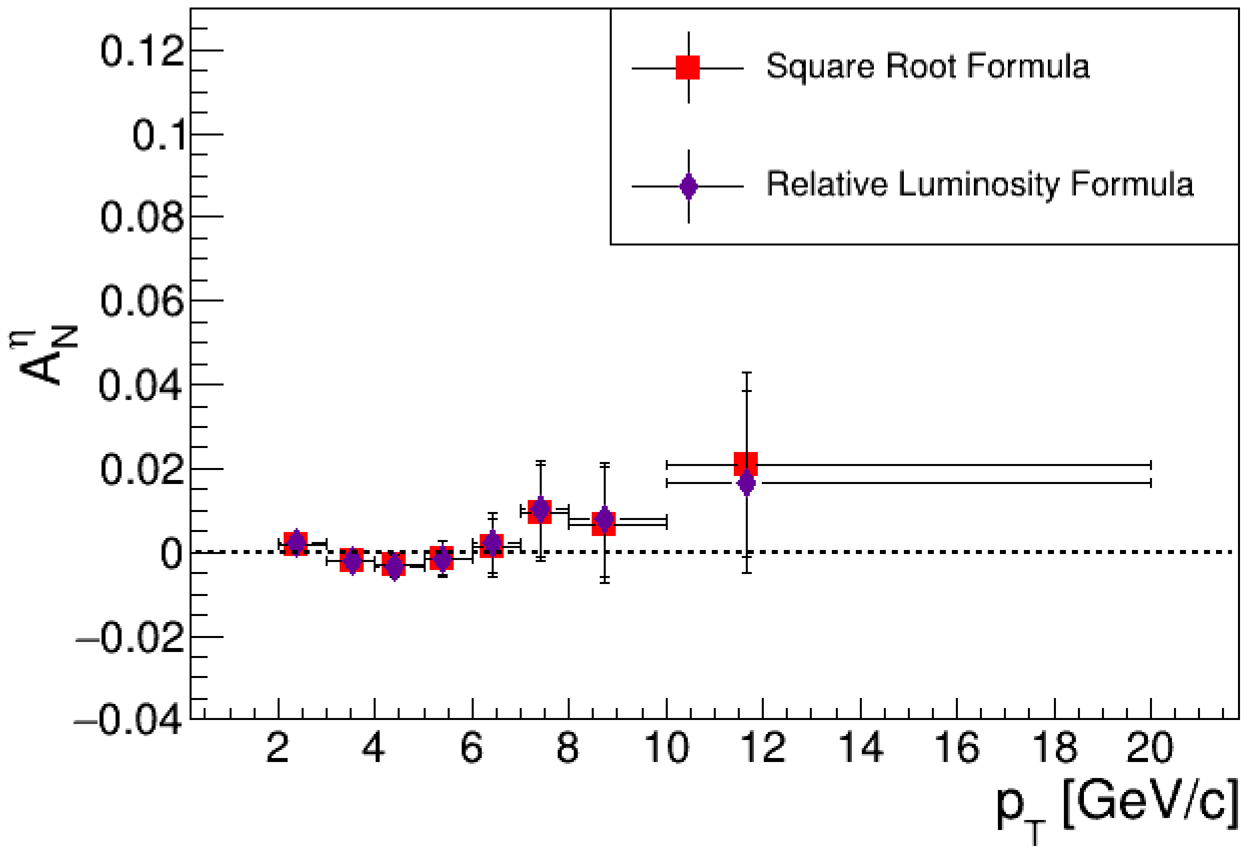

$$T(p_T) = \frac{A_N^{Sqrt} - A_N^{Lumi}}{\sqrt{|(\sigma^{Sqrt})^2 - (\sigma^{Lumi})^2|}}$$

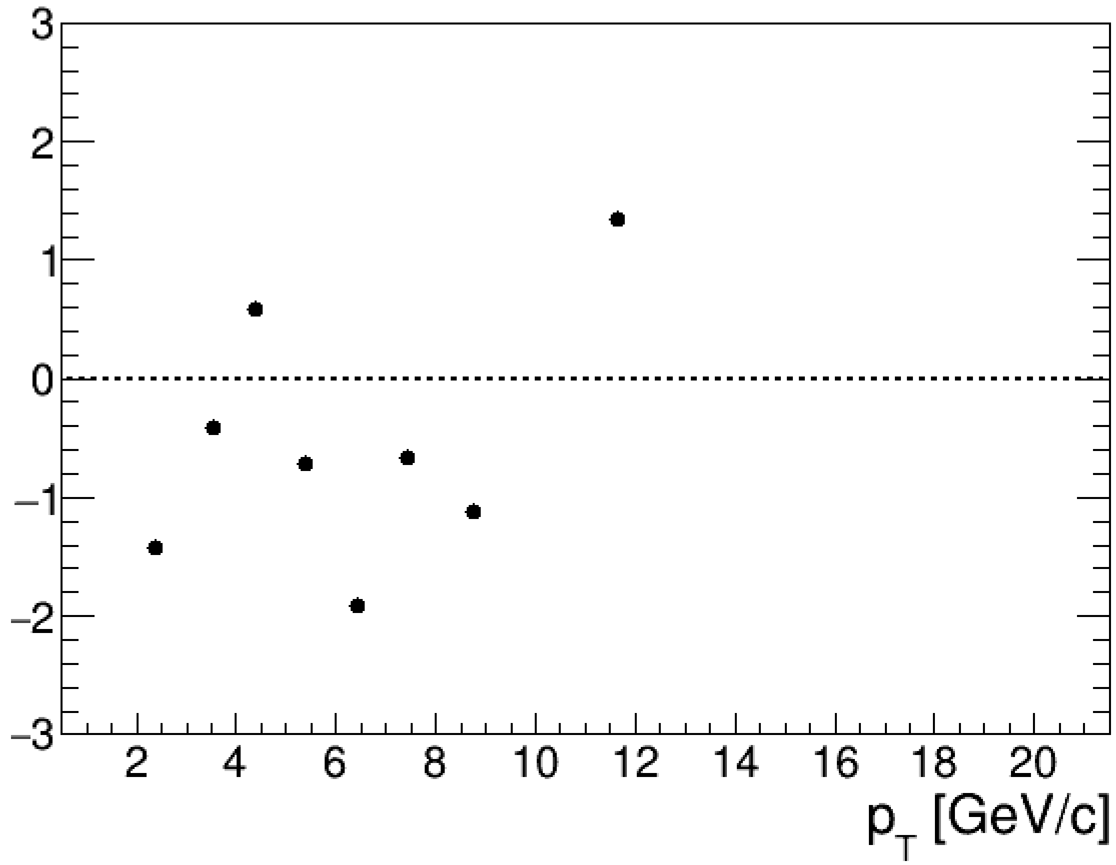


# Background Corrected Beam Averaged Asymmetry

$$T(p_T) = \frac{A_N^{Sqrt} - A_N^{Lumi}}{\sqrt{|(\sigma^{Sqrt})^2 - (\sigma^{Lumi})^2|}}$$



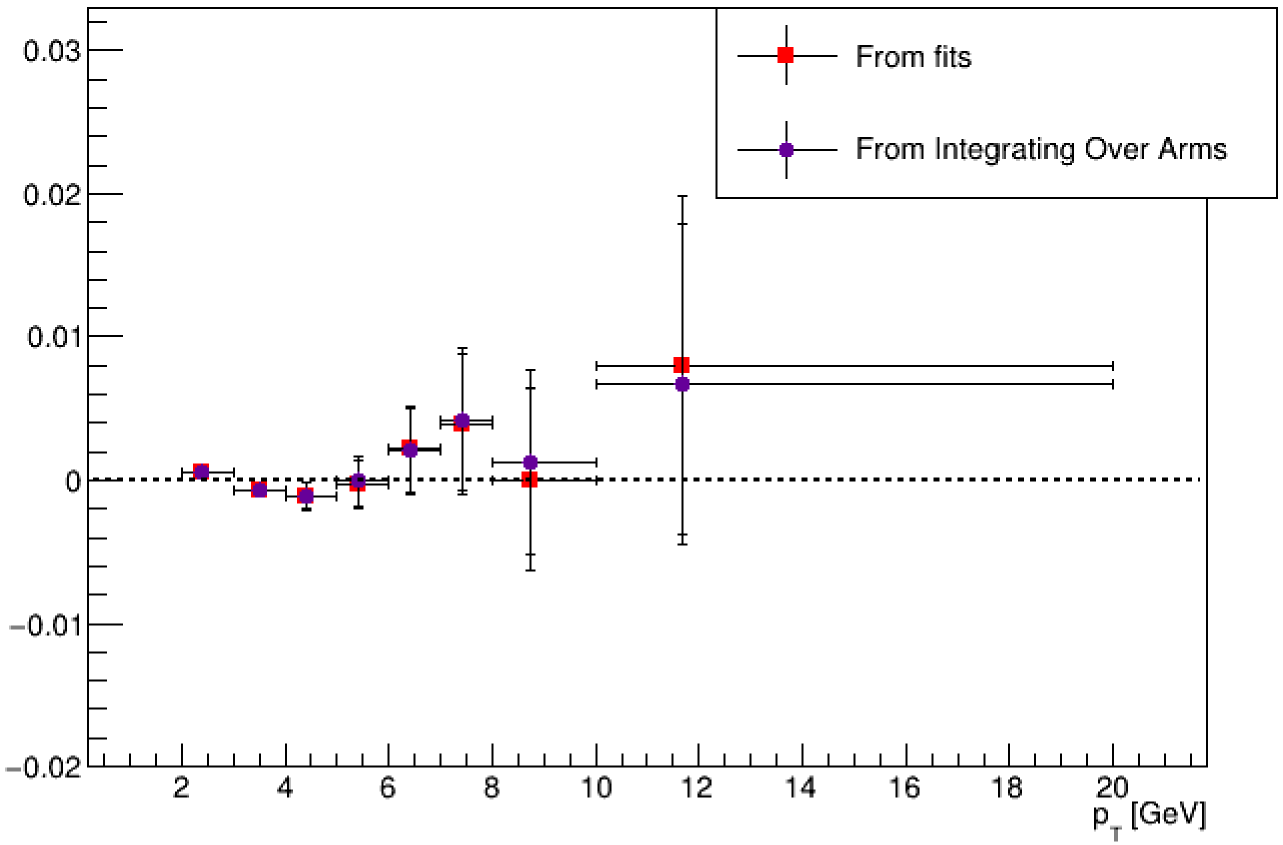
# $\sin \phi$ Modulation

$\phi_s$ is the angle from the spin up direction ($y = 0$ in PHENIX coordinates) and increases to the left of the polarized beam going direction

$$\frac{1}{P}\epsilon_N(\phi_s) = \frac{1}{P}\frac{N^{\uparrow}(\phi_s) - RN^{\downarrow}(\phi_s)}{N^{\uparrow}(\phi_s) + RN^{\downarrow}(\phi_s)} = A_N \sin \phi_s$$

$A_N \sin \phi_s$ fit plots in Back Up

$A_N^{\eta}$, not corrected for background

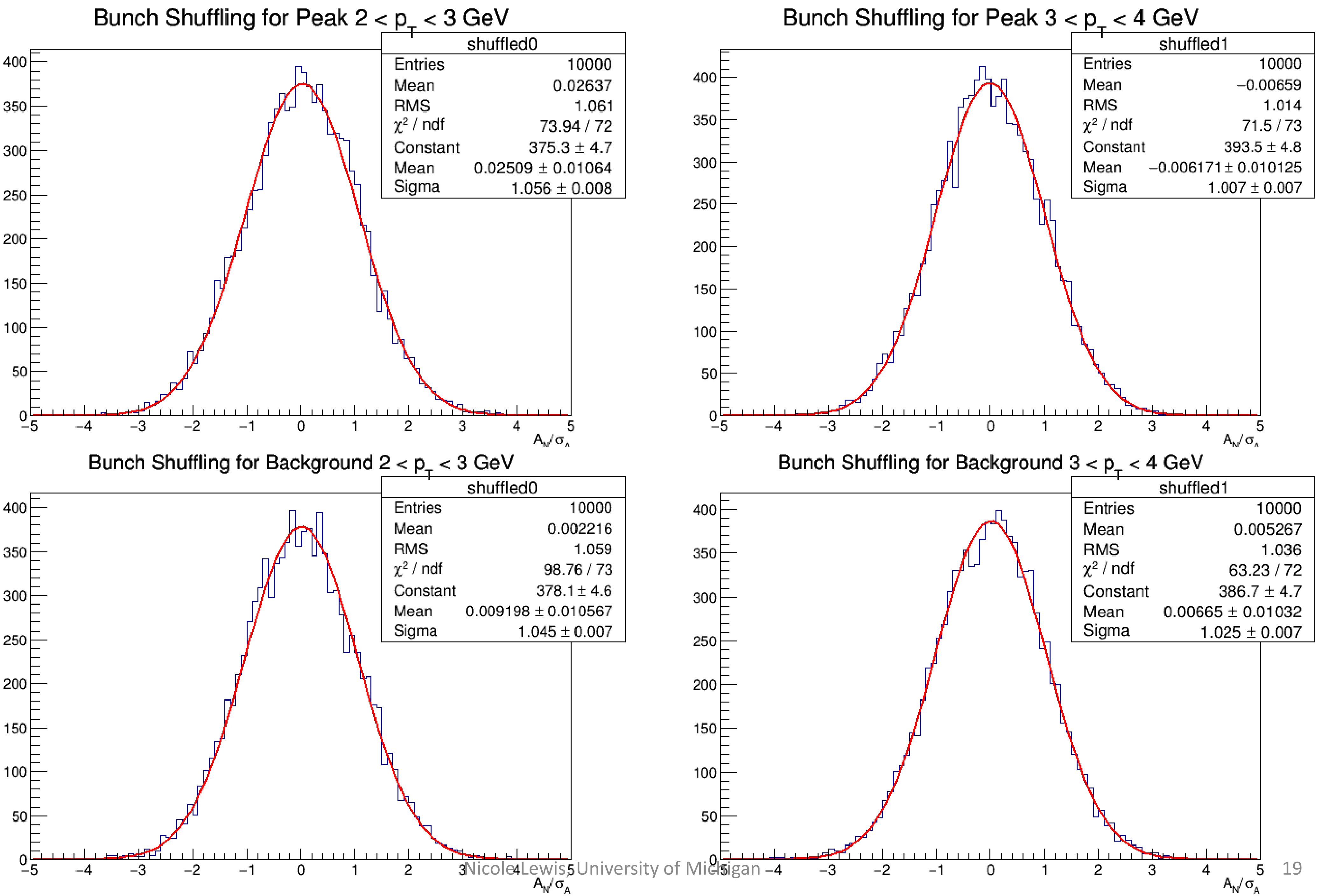


# Bunch Shuffling

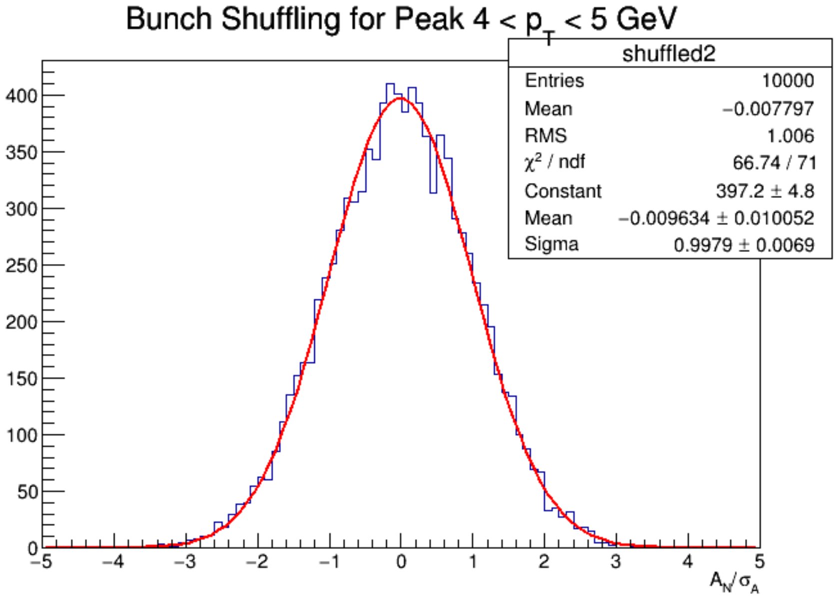
- Randomized each bunch spin combo for every fill 10,000 times

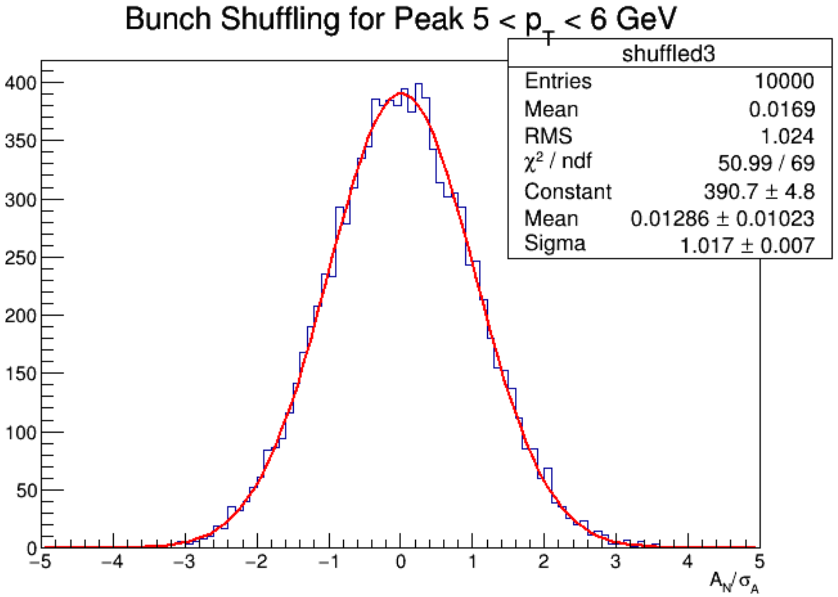
| Spin Combo | Blue Beam | Yellow Beam |
|---|---|---|
| 0 | ↓ | ↓ |
| 1 | ↓ | ↑ |
| 2 | ↑ | ↓ |
| 3 | ↑ | ↑ |

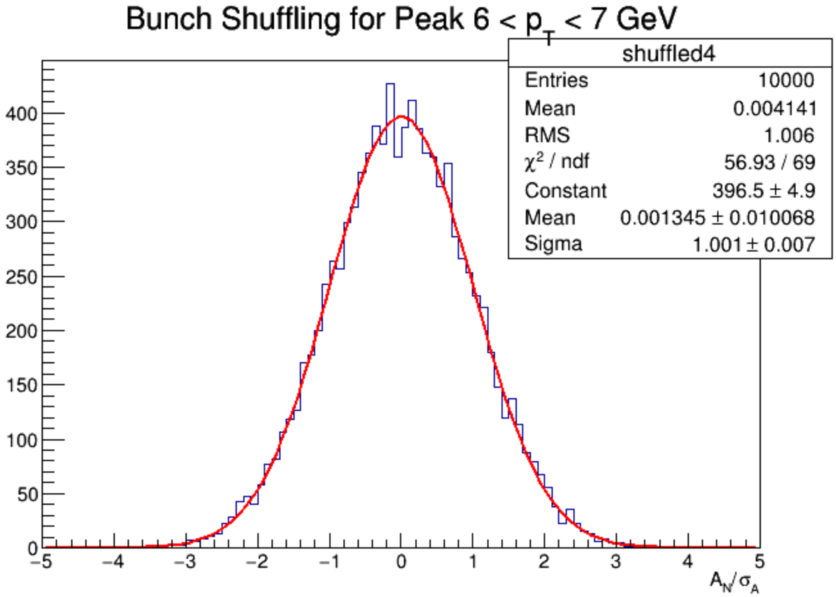
- Used the square root formula to avoid having to recalculate the relative luminosity
  - Shuffled asymmetries are calculated exactly the same way as the central asymmetry value
  - Divided this number by the statistical error of the square root formula for that $p_T$ bin

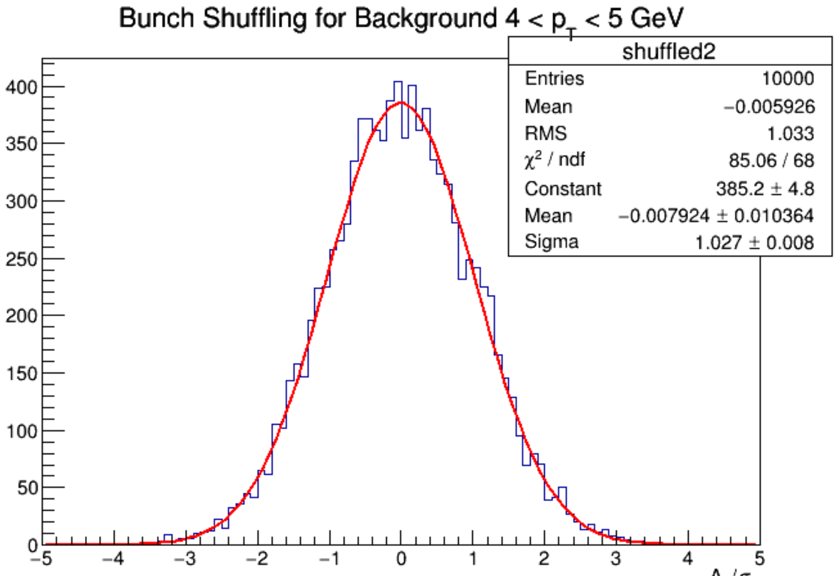


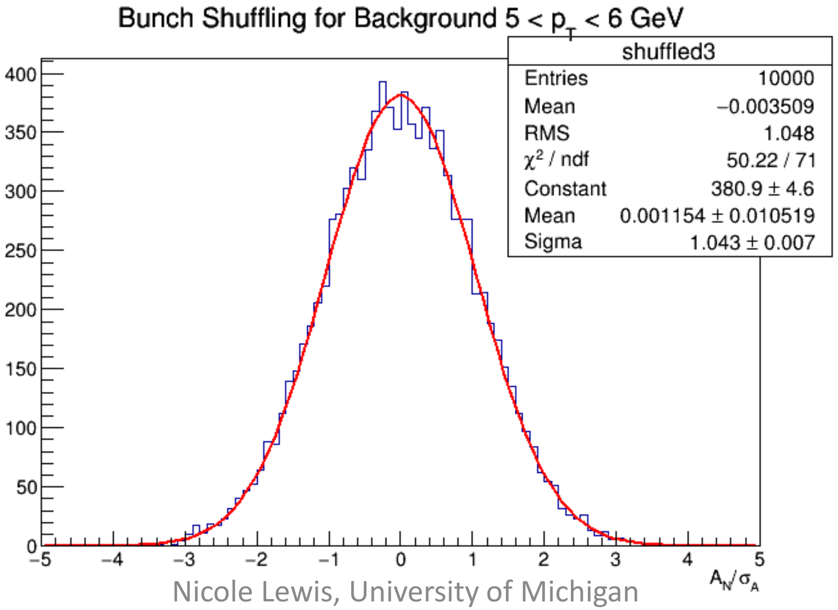
Bunch Shuffling for Peak 2 < $p_T$ < 3 GeV
shuffled0
Entries 10000
Mean 0.02637
RMS 1.061
$\chi^2$ / ndf 73.94 / 72
Constant 375.3 ± 4.7
Mean 0.02509 ± 0.01064
Sigma 1.056 ± 0.008
$A_N/\sigma_A$
Bunch Shuffling for Peak 3 < $p_T$ < 4 GeV
shuffled1
Entries 10000
Mean −0.00659
RMS 1.014
$\chi^2$ / ndf 71.5 / 73
Constant 393.5 ± 4.8
Mean −0.006171 ± 0.010125
Sigma 1.007 ± 0.007
$A_N/\sigma_A$
Bunch Shuffling for Background 2 < $p_T$ < 3 GeV
shuffled0
Entries 10000
Mean 0.002216
RMS 1.059
$\chi^2$ / ndf 98.76 / 73
Constant 378.1 ± 4.6
Mean 0.009198 ± 0.010567
Sigma 1.045 ± 0.007
$A_N/\sigma_A$
Bunch Shuffling for Background 3 < $p_T$ < 4 GeV
shuffled1
Entries 10000
Mean 0.005267
RMS 1.036
$\chi^2$ / ndf 63.23 / 72
Constant 386.7 ± 4.7
Mean 0.00665 ± 0.01032
Sigma 1.025 ± 0.007
$A_N/\sigma_A$

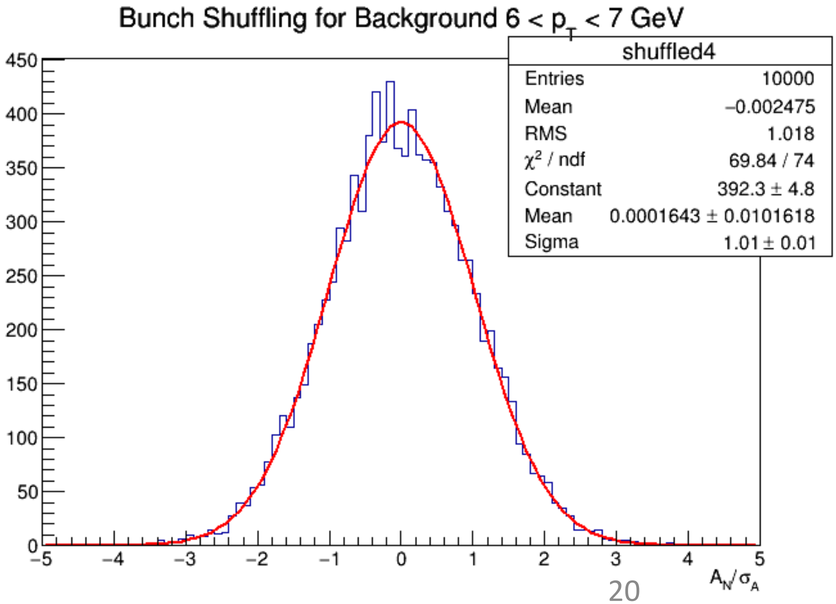

Bunch Shuffling for Peak $4 < p_T < 5$ GeV
shuffled2
Entries 10000
Mean −0.007797
RMS 1.006
$\chi^2$ / ndf 66.74 / 71
Constant 397.2 ± 4.8
Mean −0.009634 ± 0.010052
Sigma 0.9979 ± 0.0069
$A_N/\sigma_A$

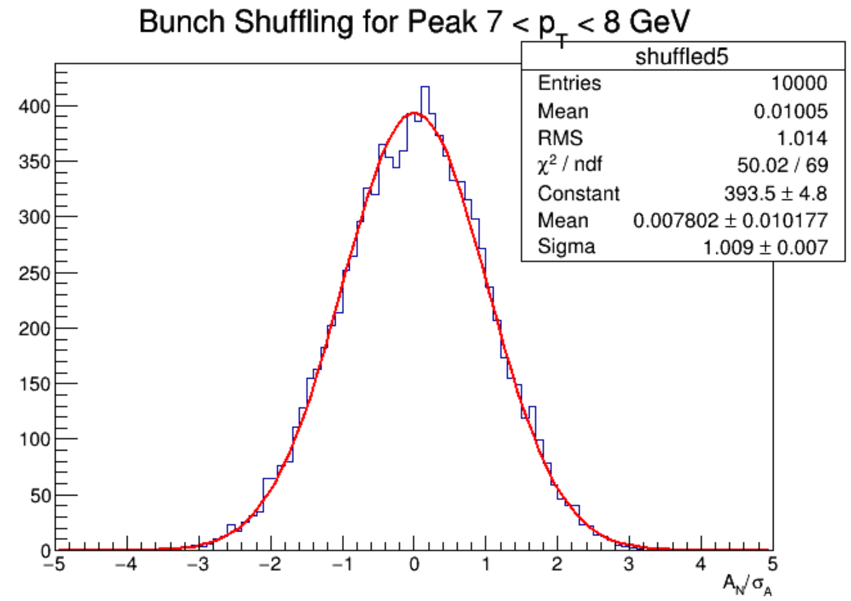

Bunch Shuffling for Peak $5 < p_T < 6$ GeV
shuffled3
Entries 10000
Mean 0.0169
RMS 1.024
$\chi^2$ / ndf 50.99 / 69
Constant 390.7 ± 4.8
Mean 0.01286 ± 0.01023
Sigma 1.017 ± 0.007
$A_N/\sigma_A$

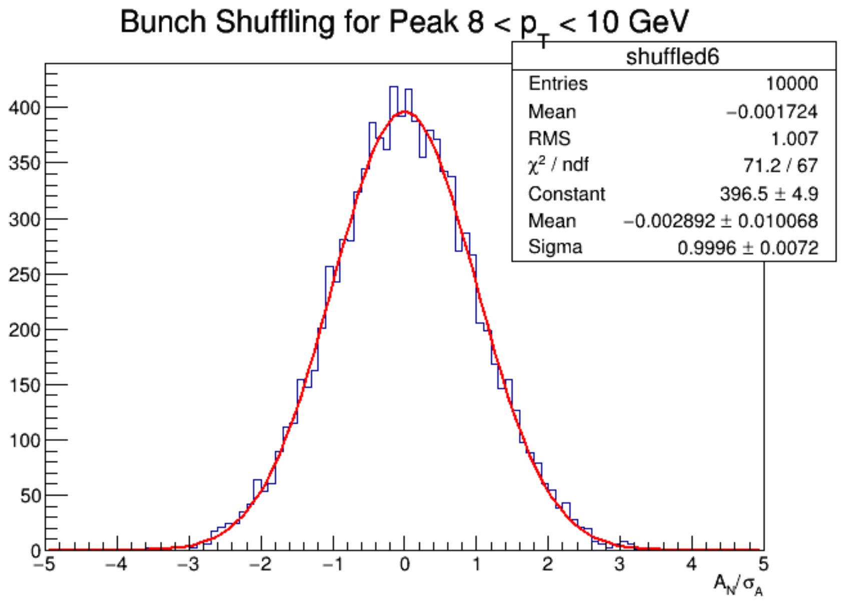

Bunch Shuffling for Peak $6 < p_T < 7$ GeV
shuffled4
Entries 10000
Mean 0.004141
RMS 1.006
$\chi^2$ / ndf 56.93 / 69
Constant 396.5 ± 4.9
Mean 0.001345 ± 0.010068
Sigma 1.001 ± 0.007
$A_N/\sigma_A$

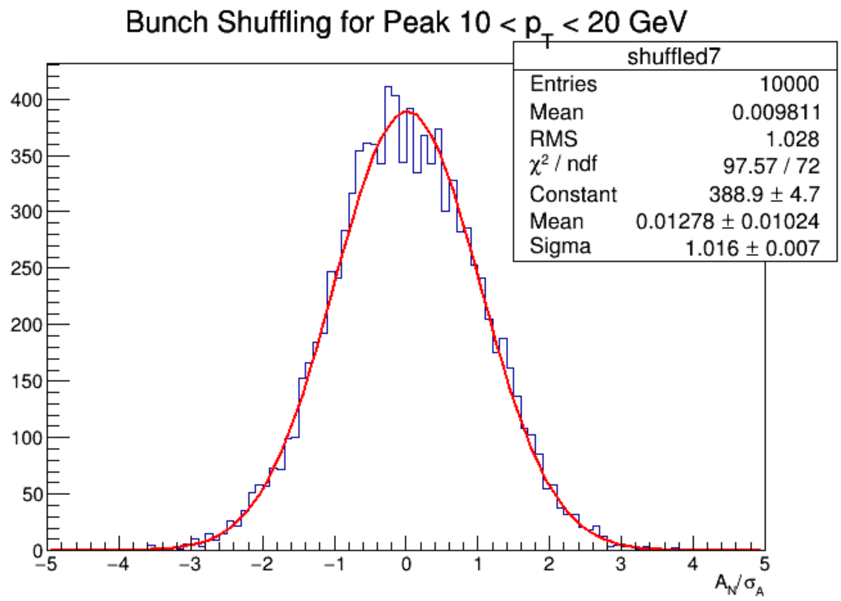

Bunch Shuffling for Background $4 < p_T < 5$ GeV
shuffled2
Entries 10000
Mean −0.005926
RMS 1.033
$\chi^2$ / ndf 85.06 / 68
Constant 385.2 ± 4.8
Mean −0.007924 ± 0.010364
Sigma 1.027 ± 0.008
$A_N/\sigma_A$

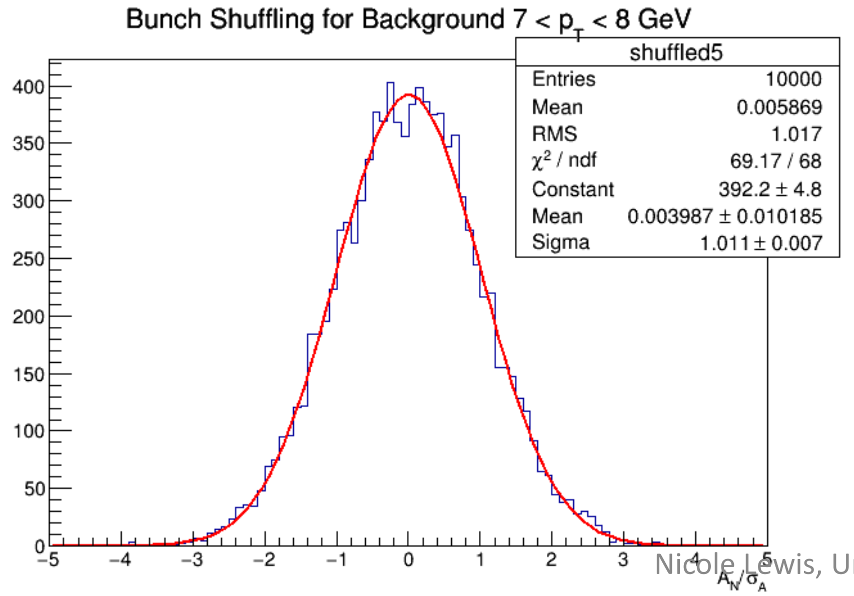

Bunch Shuffling for Background $5 < p_T < 6$ GeV
shuffled3
Entries 10000
Mean −0.003509
RMS 1.048
$\chi^2$ / ndf 50.22 / 71
Constant 380.9 ± 4.6
Mean 0.001154 ± 0.010519
Sigma 1.043 ± 0.007
$A_N/\sigma_A$

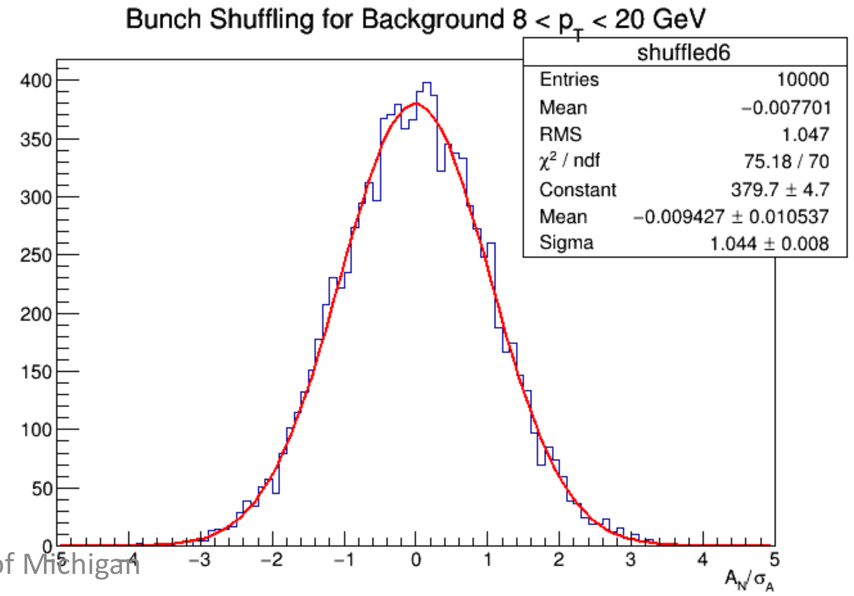

Bunch Shuffling for Background $6 < p_T < 7$ GeV
shuffled4
Entries 10000
Mean −0.002475
RMS 1.018
$\chi^2$ / ndf 69.84 / 74
Constant 392.3 ± 4.8
Mean 0.0001643 ± 0.0101618
Sigma 1.01 ± 0.01
$A_N/\sigma_A$


Bunch Shuffling for Peak 7 < p_T < 8 GeV
shuffled5
Entries 10000
Mean 0.01005
RMS 1.014
χ² / ndf 50.02 / 69
Constant 393.5 ± 4.8
Mean 0.007802 ± 0.010177
Sigma 1.009 ± 0.007
A_N/σ_A


Bunch Shuffling for Peak 8 < p_T < 10 GeV
shuffled6
Entries 10000
Mean −0.001724
RMS 1.007
χ² / ndf 71.2 / 67
Constant 396.5 ± 4.9
Mean −0.002892 ± 0.010068
Sigma 0.9996 ± 0.0072
A_N/σ_A


Bunch Shuffling for Peak 10 < p_T < 20 GeV
shuffled7
Entries 10000
Mean 0.009811
RMS 1.028
χ² / ndf 97.57 / 72
Constant 388.9 ± 4.7
Mean 0.01278 ± 0.01024
Sigma 1.016 ± 0.007
A_N/σ_A


Bunch Shuffling for Background 7 < p_T < 8 GeV
shuffled5
Entries 10000
Mean 0.005869
RMS 1.017
χ² / ndf 69.17 / 68
Constant 392.2 ± 4.8
Mean 0.003987 ± 0.010185
Sigma 1.011 ± 0.007
A_N/σ_A


Bunch Shuffling for Background 8 < p_T < 20 GeV
shuffled6
Entries 10000
Mean −0.007701
RMS 1.047
χ² / ndf 75.18 / 70
Constant 379.7 ± 4.7
Mean −0.009427 ± 0.010537
Sigma 1.044 ± 0.008
A_N/σ_A

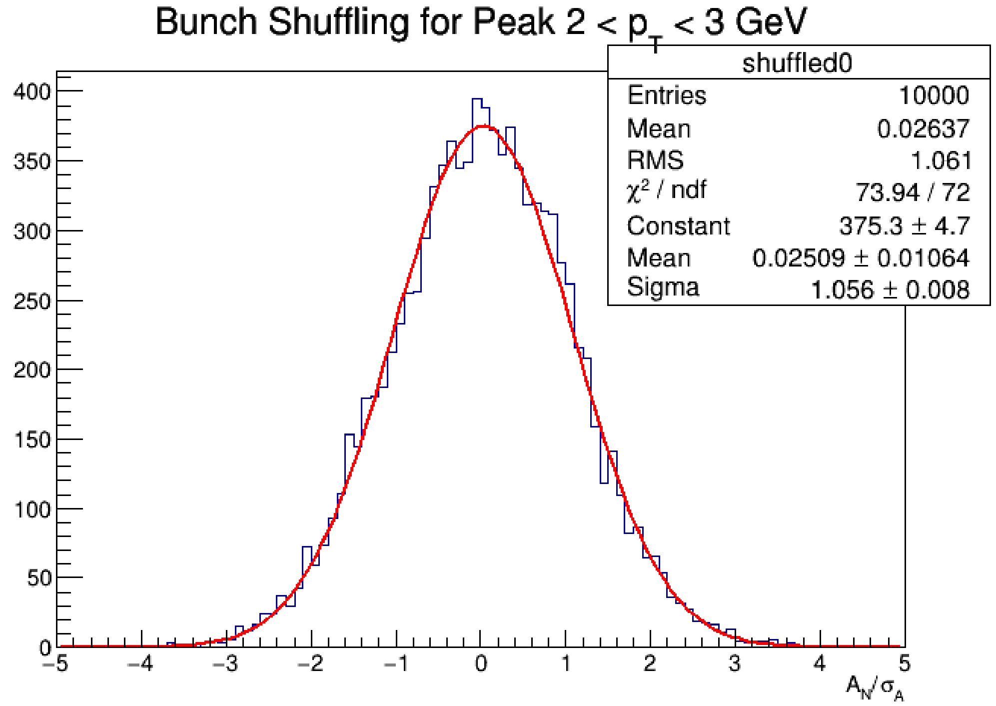
# Bunch Shuffling Summary

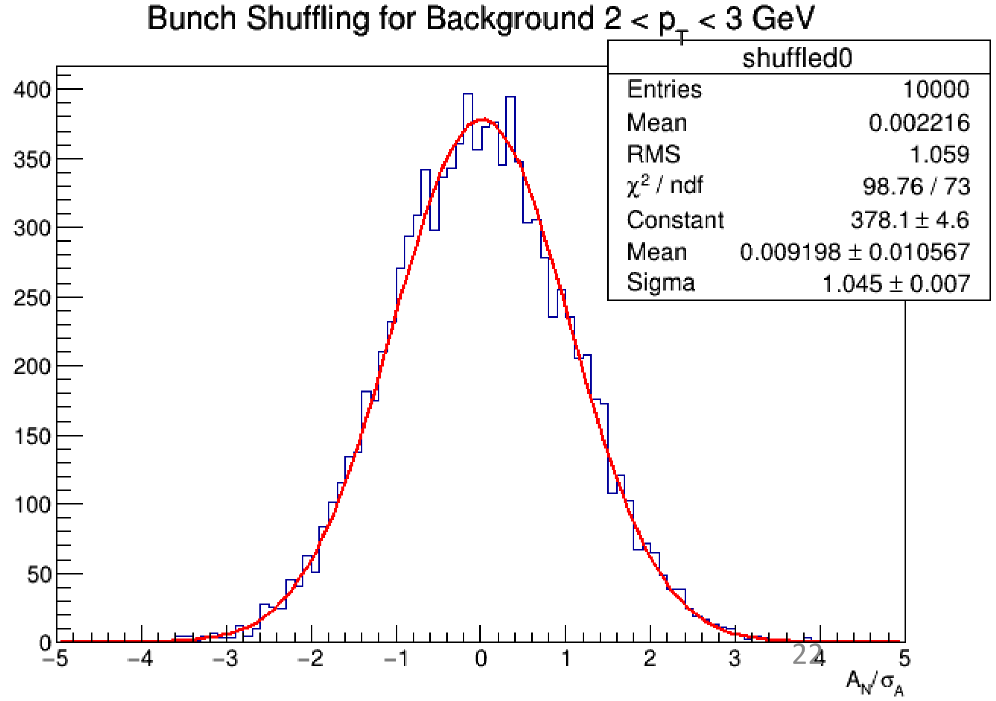
- The widths of the Gaussian fits are consistent with 1, except for the lowest $p_T$ bin
- Extra systematic error from for that bin

$$1.056 \cdot \sigma_{stat} = \sqrt{\left(\sigma_{syst}\right)^2 + (\sigma_{stat})^2}$$

$$\sigma_{syst} = \sqrt{(1.056)^2 - 1} \cdot \sigma_{stat}$$
$$\sigma_{syst} = 0.000620$$

Same formula as $\pi^0$ asymmetry



# Uncertainty on the Background Fraction

Tried fitting ranges

$0.3 < M_{\gamma\gamma} < 0.7$ GeV and
$0.4 < M_{\gamma\gamma} < 0.8$ GeV

To see how much $r$ changed when compared to the central fit range:

$0.4 < M_{\gamma\gamma} < 0.7$ GeV

Propagated $r_{range}$ through the background subtraction formula to assign a systematic error on the $\eta$ asymmetry

| $p_T$[GeV] | $r$ range |
|---|---|
| 2 - 3 | 0.0050 |
| 3 - 4 | 0.0058 |
| 4 - 5 | 0.0049 |
| 5 - 6 | 0.0066 |
| 6 - 7 | 0.0075 |
| 7 - 8 | 0.0066 |
| 8 - 10 | 0.0068 |
| 10 - 20 | 0.0086 |

| $p_T$ (GeV/c) | $\eta$ Asymmetry | Statistical uncertainty | Sys. unc. (rel lumi vs. sqrt) | Sys. unc. (from bg fraction) | Sys. unc. (from bunch shuffling) | Sys unc. (total) |
|---|---|---|---|---|---|---|
| 2.39 | 0.00244 | 0.00183 | 0.000518 | 4.58e-05 | 0.000620 | 0.000809 |
| 3.53 | -0.00199 | 0.00159 | 8.36e-05 | 3.31e-05 | 0 | 8.99e-05 |
| 4.39 | -0.00331 | 0.00248 | 0.000144 | 4.55e-05 | 0 | 0.000151 |
| 5.40 | -0.00139 | 0.00421 | 0.000241 | 3.59e-05 | 0 | 0.000244 |
| 6.41 | 0.00222 | 0.00709 | 0.00112 | 6.35e-06 | 0 | 0.00112 |
| 7.42 | 0.0103 | 0.0115 | 0.000703 | 0.000160 | 0 | 0.000720 |
| 8.75 | 0.00790 | 0.0137 | 0.00124 | 0.000188 | 0 | 0.00125 |
| 11.76 | 0.0168 | 0.0219 | 0.00425 | 0.000370 | 0 | 0.00426 |

Reminder - extra systematic error from bunch shuffling:
(because of a greater than one bunch shuffling width)

$$1.056 \cdot \sigma_{stat} = \sqrt{\left(\sigma_{syst}\right)^2 + (\sigma_{stat})^2}$$

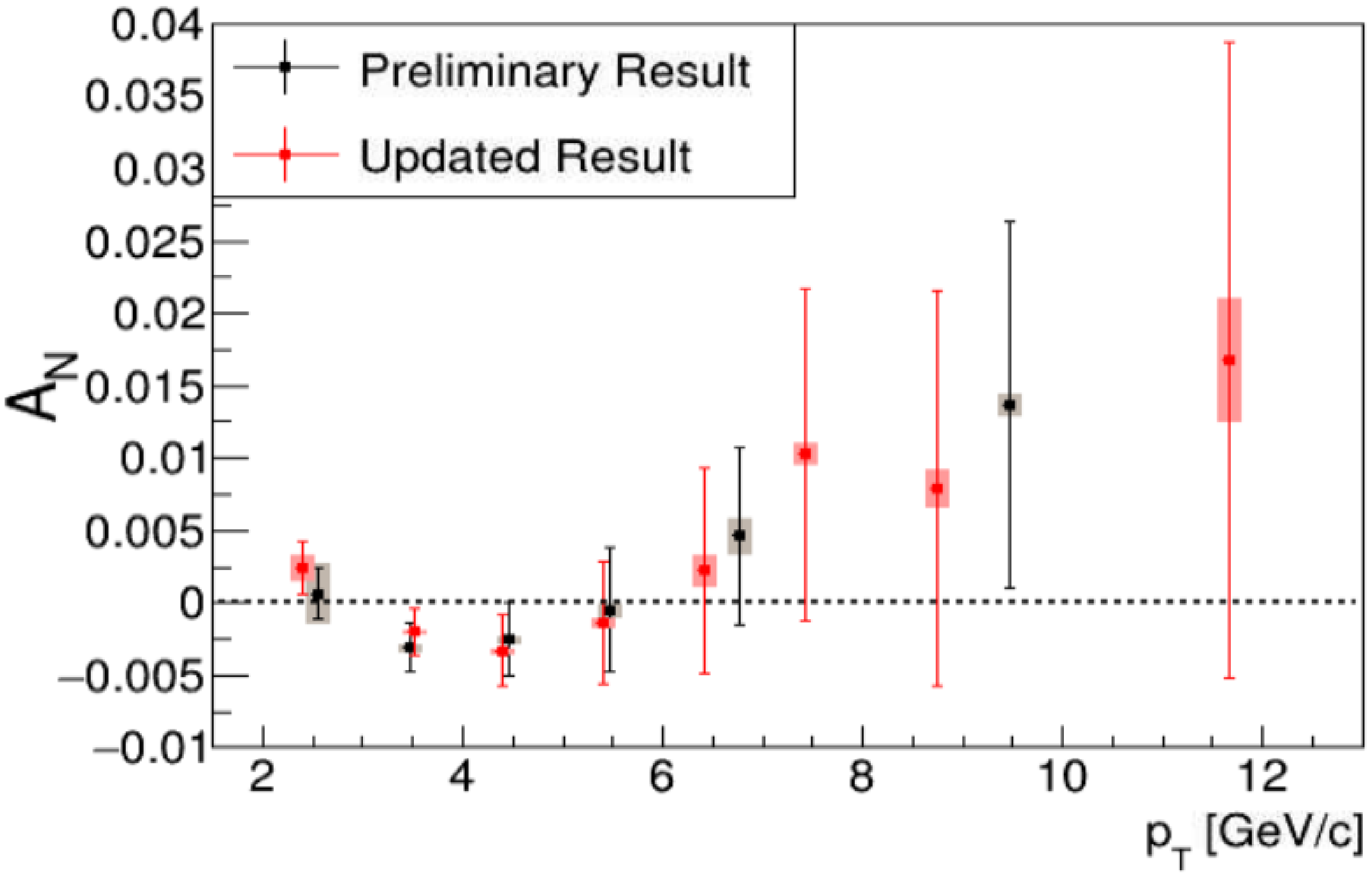
$$\sigma_{syst} = \sqrt{(1.056)^2 - 1} \cdot \sigma_{stat}$$

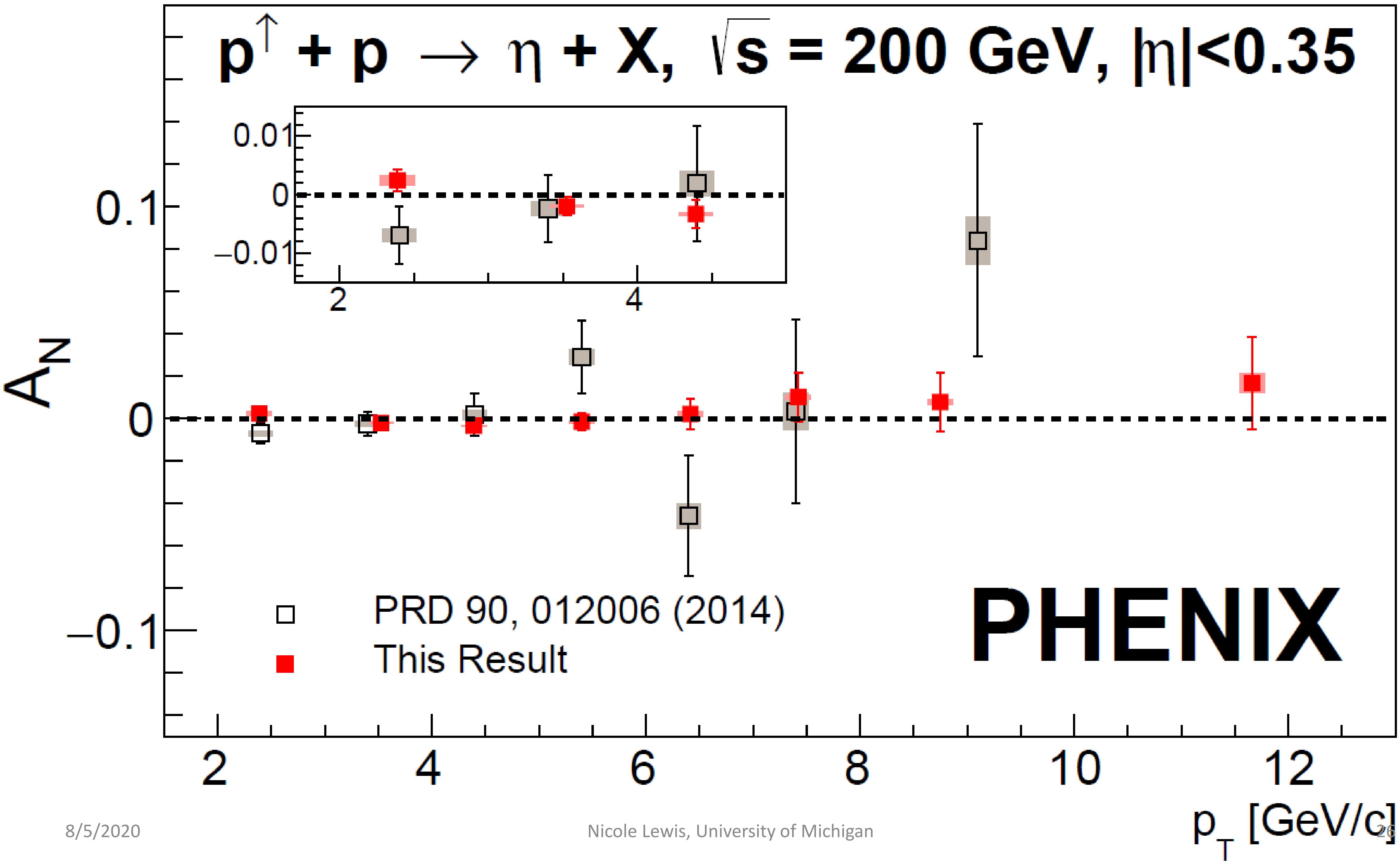
# Consistent with preliminary values

Things that changed since preliminary:

- Fixed bug in hot tower cut
- Higher energy photon $p_T > 1.5$ GeV (1.0 GeV used for preliminary)
- Require higher energy photon to be the highest energy photon in the event
- Removed 3 fills
- Changed method of calculating the background fraction
- Different formula for assigning the systematic error from bunch shuffling

All consistent with $\pi^0$ analysis





p↑ + p → η + X, √s = 200 GeV, |η|<0.35
A_N
0.1
0
−0.1
0.01
0
−0.01
2
4
2
4
6
8
10
12
p_T [GeV/c]
PRD 90, 012006 (2014)
This Result
PHENIX

# Back Up

# Photon Pair Counts

U - spin up, D - spin down, L - left, R - right, Y - yellow beam asymmetry, B - blue beam asymmetry

Signal
$480 < M_{\gamma\gamma} < 620$ MeV

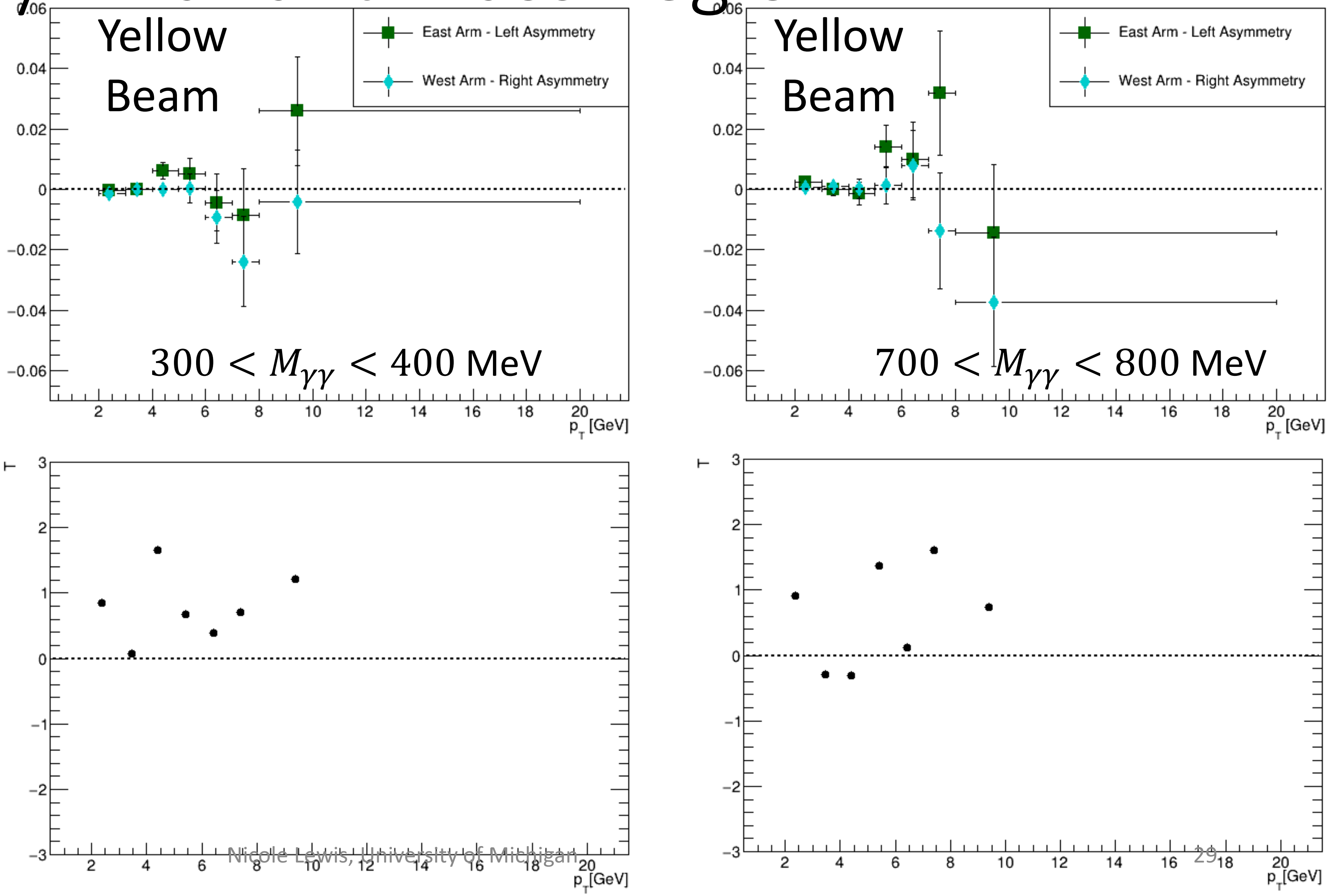
| $p_T$[GeV] | ULY | DLY | URY | DRY | ULB | DLB | URB | DRB |
|---|---|---|---|---|---|---|---|---|
| 2 - 3 | 1944849 | 1945879 | 2741977 | 2748194 | 2743831 | 2746340 | 1943899 | 1946829 |
| 3 - 4 | 1400540 | 1402581 | 1764747 | 1764456 | 1764524 | 1764679 | 1402402 | 1400719 |
| 4 - 5 | 471452 | 471371 | 566300 | 566053 | 565022 | 567331 | 471426 | 471397 |
| 5 - 6 | 142937 | 142838 | 165844 | 165955 | 165869 | 165930 | 143112 | 142663 |
| 6 - 7 | 46754 | 46805 | 53151 | 53767 | 53562 | 53356 | 46935 | 46624 |
| 7 - 8 | 17674 | 17723 | 19617 | 19699 | 19811 | 19505 | 17686 | 17711 |
| 8 - 10 | 10736 | 10743 | 11924 | 11957 | 11949 | 11932 | 10733 | 10746 |
| 10 - 20 | 3697 | 3683 | 3802 | 3787 | 3793 | 3796 | 3631 | 3749 |

Background:
$300 < M_{\gamma\gamma} < 400$ MeV
$700 < M_{\gamma\gamma} < 800$ MeV

| $p_T$[GeV] | ULY | DLY | URY | DRY | ULB | DLB | URB | DRB |
|---|---|---|---|---|---|---|---|---|
| 2 - 3 | 2001232 | 2001647 | 2710144 | 2710917 | 2708566 | 2712495 | 2000623 | 2002256 |
| 3 - 4 | 1225706 | 1226586 | 1529674 | 1531373 | 1529071 | 1531976 | 1224677 | 1227615 |
| 4 - 5 | 369856 | 368856 | 444255 | 444633 | 444180 | 444708 | 369206 | 369506 |
| 5 - 6 | 104169 | 103361 | 120831 | 121044 | 120993 | 120882 | 104026 | 103504 |
| 6 - 7 | 32475 | 32458 | 36914 | 36757 | 37091 | 36580 | 32531 | 32402 |
| 7 - 8 | 11757 | 11682 | 13055 | 12777 | 13053 | 12779 | 11797 | 11642 |
| 8 - 10 | 7136 | 6938 | 7638 | 7596 | 7553 | 7681 | 7031 | 7043 |
| 10 - 20 | 2160 | 2260 | 2386 | 2267 | 2283 | 2370 | 2191 | 2229 |

# Cross Check - Splitting the Background Asymmetry By Invariant Mass Region

Relative Luminosity Formula Yellow Beam Cross Check



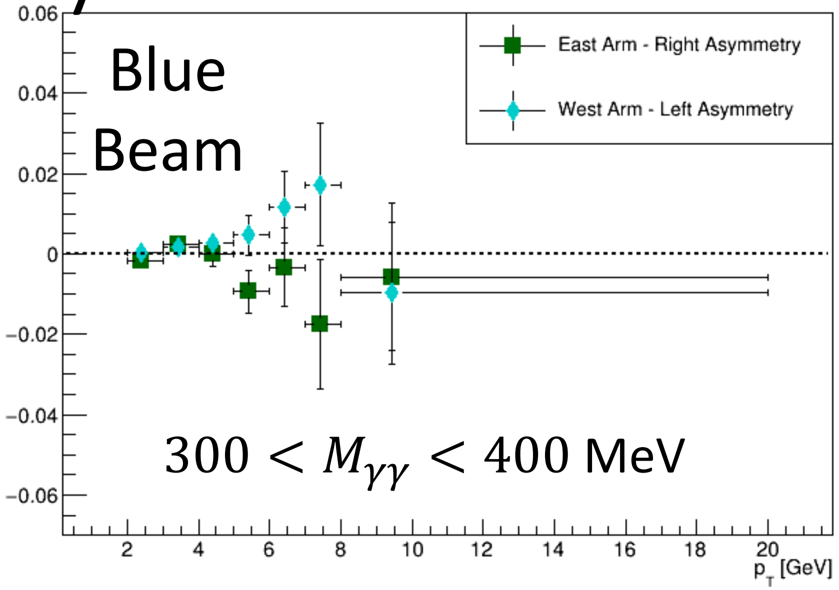

$$T(p_T) = \frac{A_N^{left} - A_N^{right}}{\sqrt{(\sigma^{left})^2 + (\sigma^{right})^2}}$$

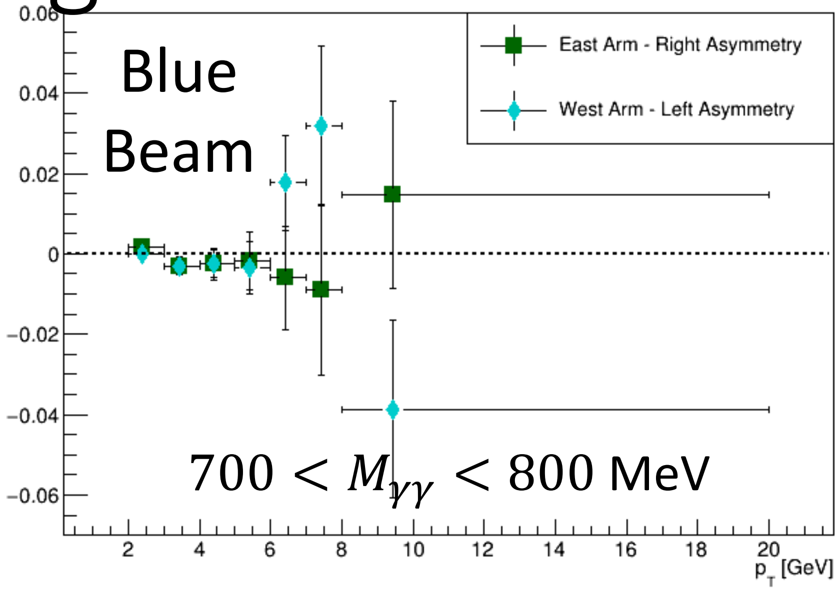
# Cross Check - Splitting the Background Asymmetry By Invariant Mass Region

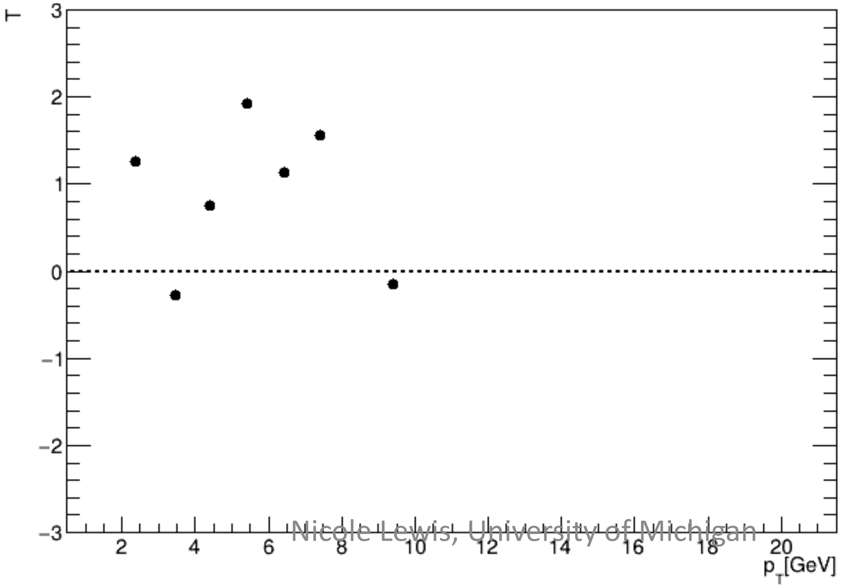
Relative Luminosity Formula

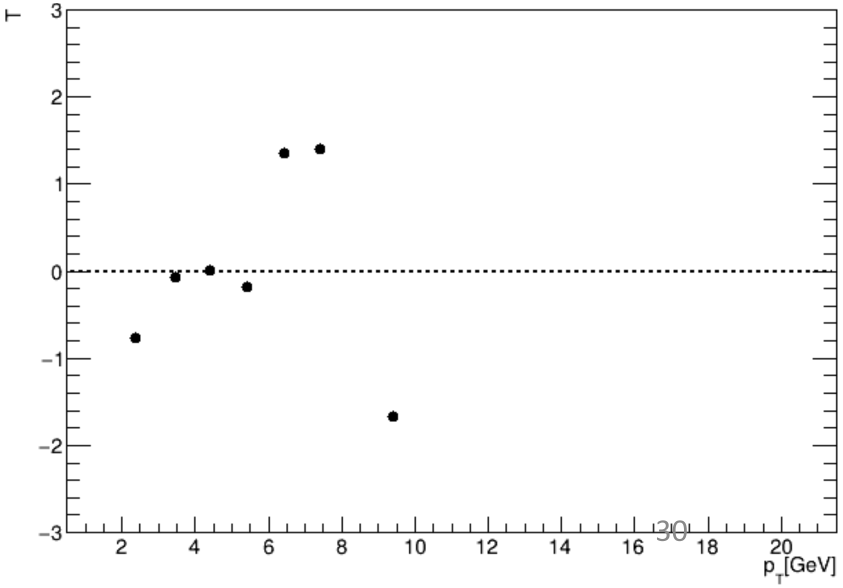
Blue Beam Cross Check

$$T(p_T) = \frac{A_N^{left} - A_N^{right}}{\sqrt{(\sigma^{left})^2 + (\sigma^{right})^2}}$$



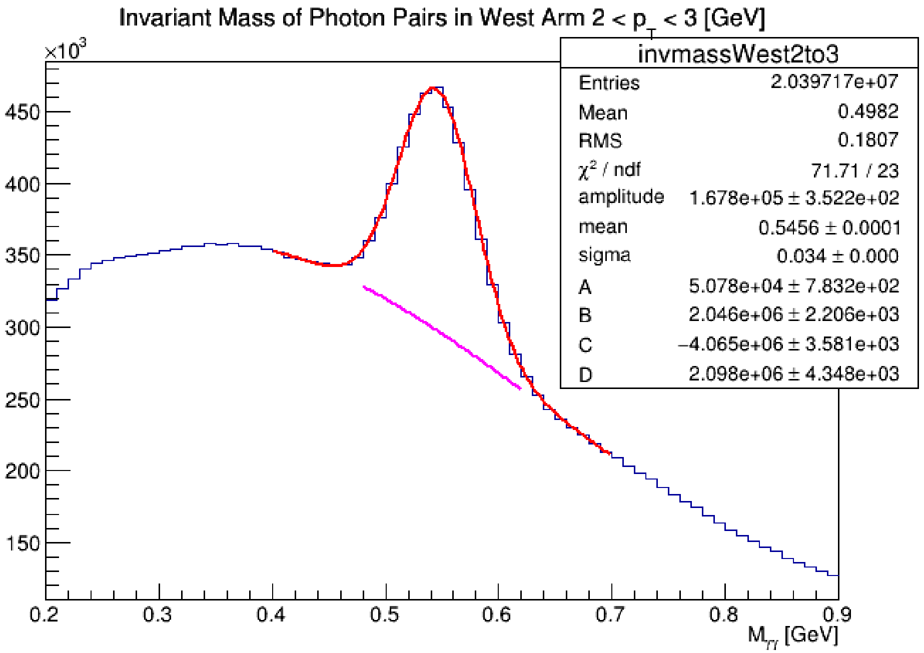



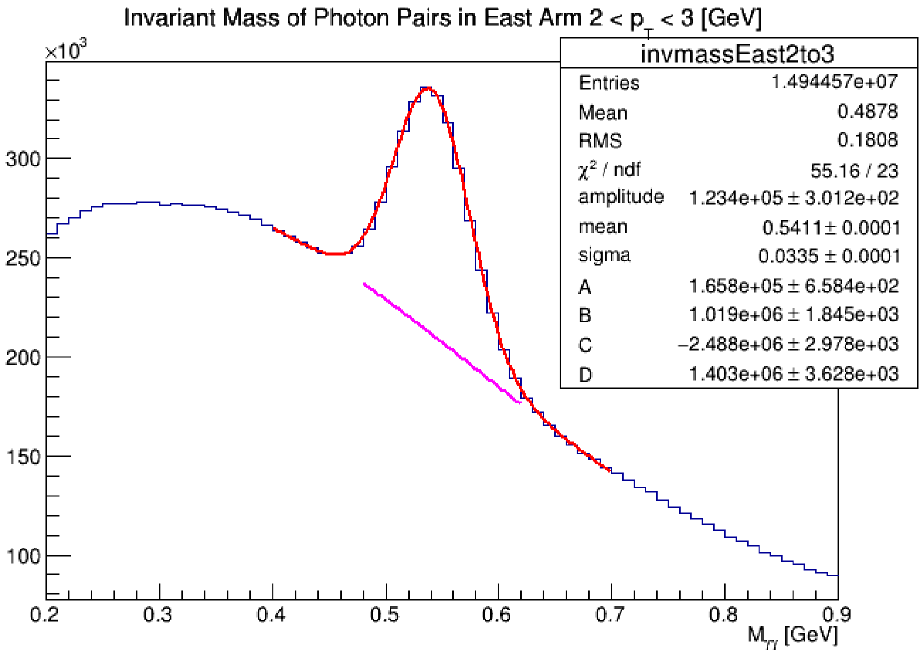
# Background Fraction Fits

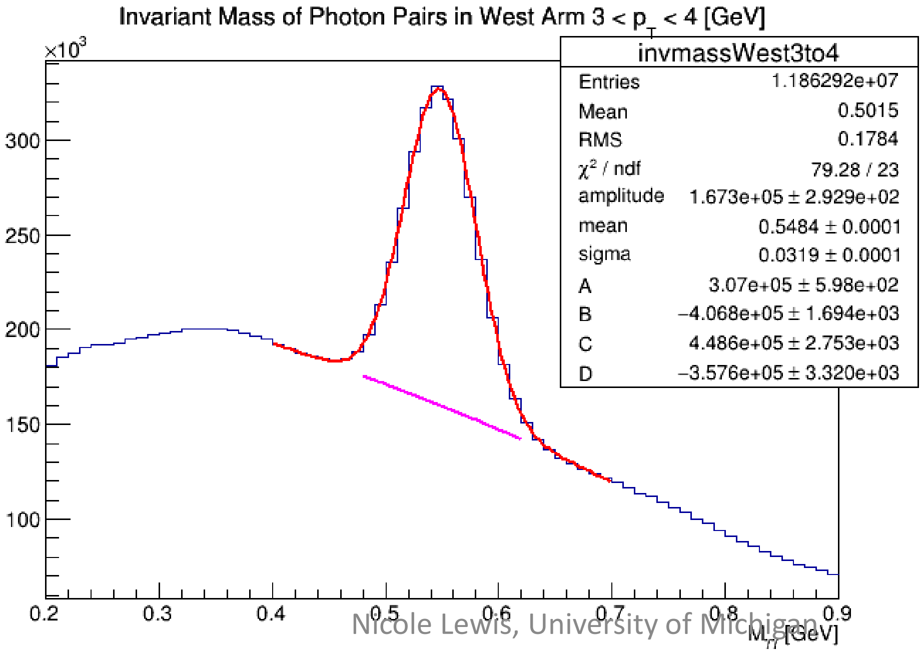
Fit a “Gaus+pol3” function to $0.4 < M_{\gamma\gamma} < 0.7$ GeV

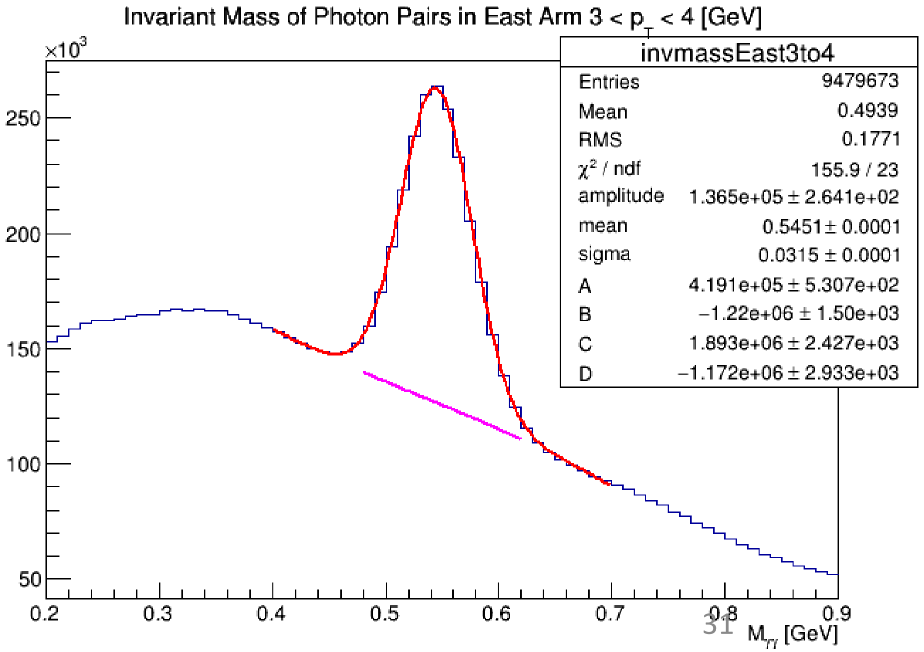
Pink curve represents the “pol3" which describes the combinatorial background

Fit function is only used to estimate the background contribution, Gaussian part of the fit is not used directly



# Background Fraction Fits

Fit a "Gaus+pol3" function to $0.4 < M_{\gamma\gamma} < 0.7$ GeV

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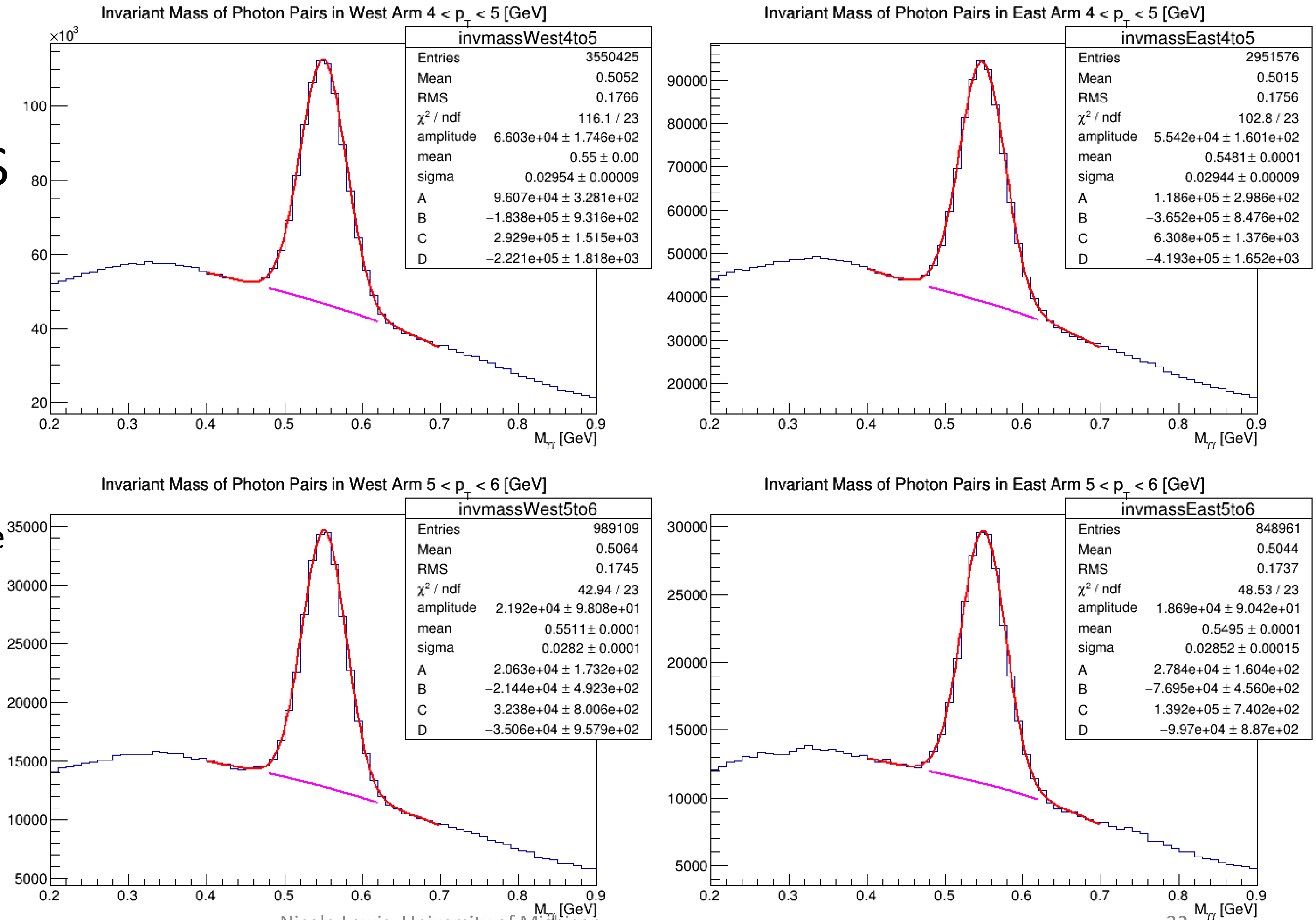

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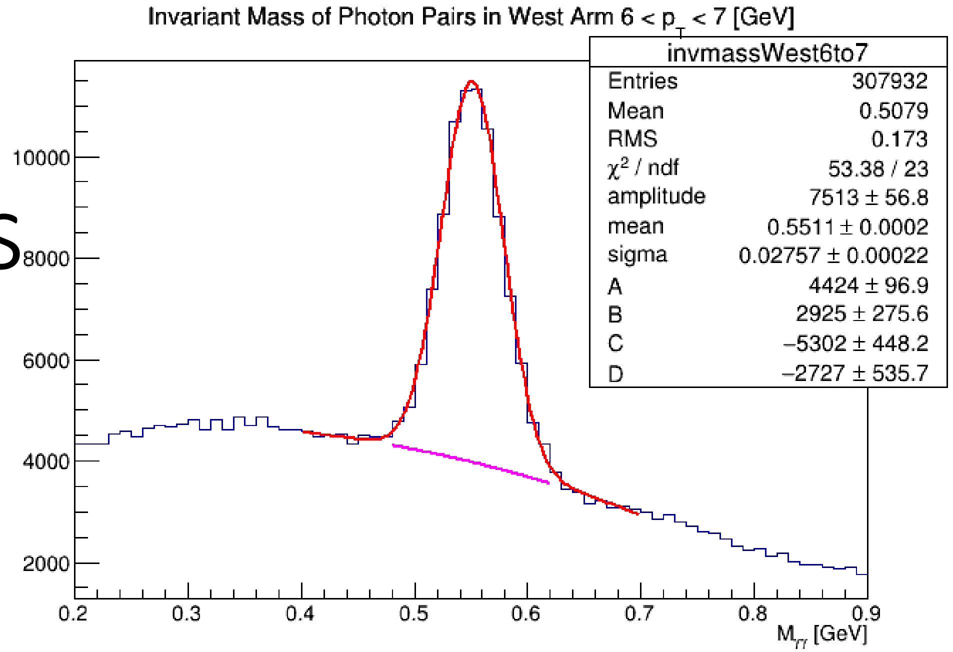
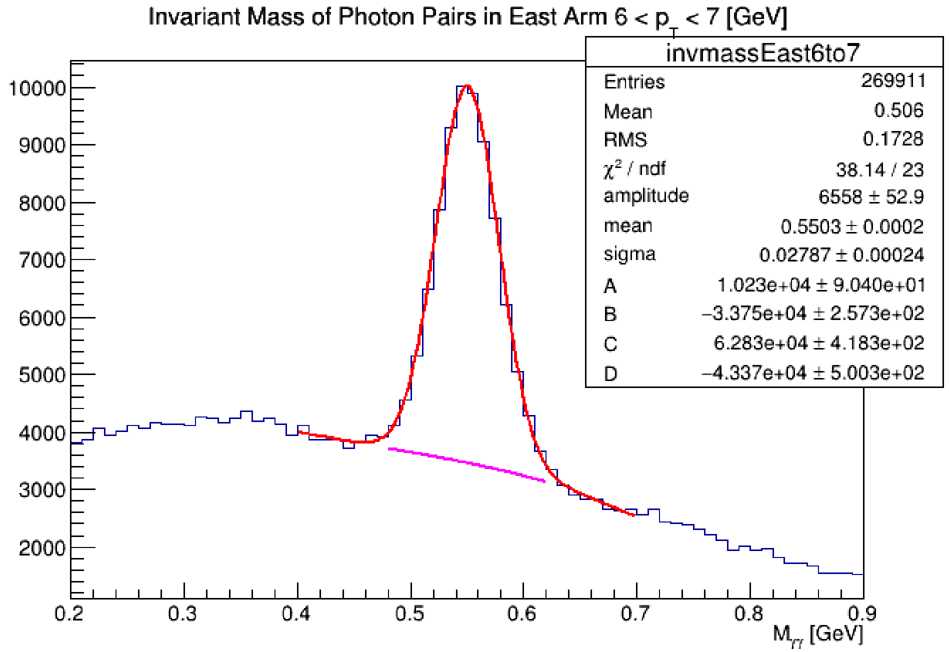
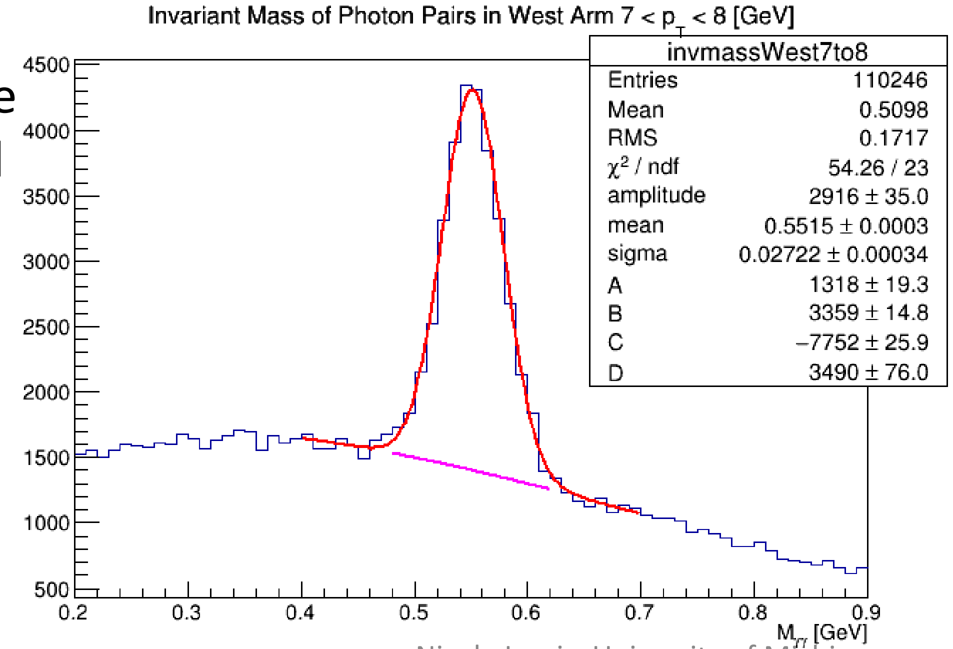
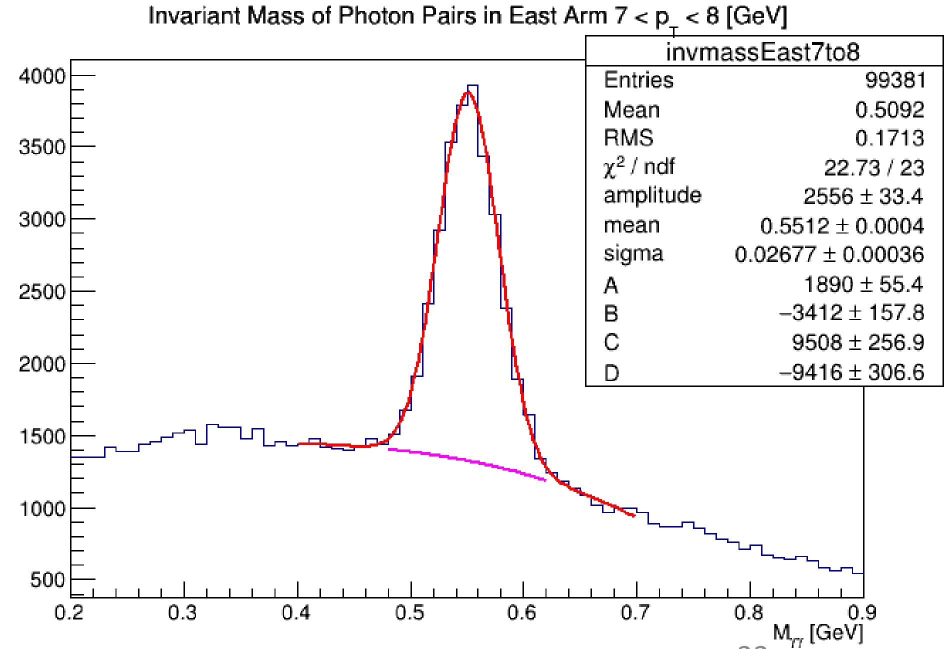


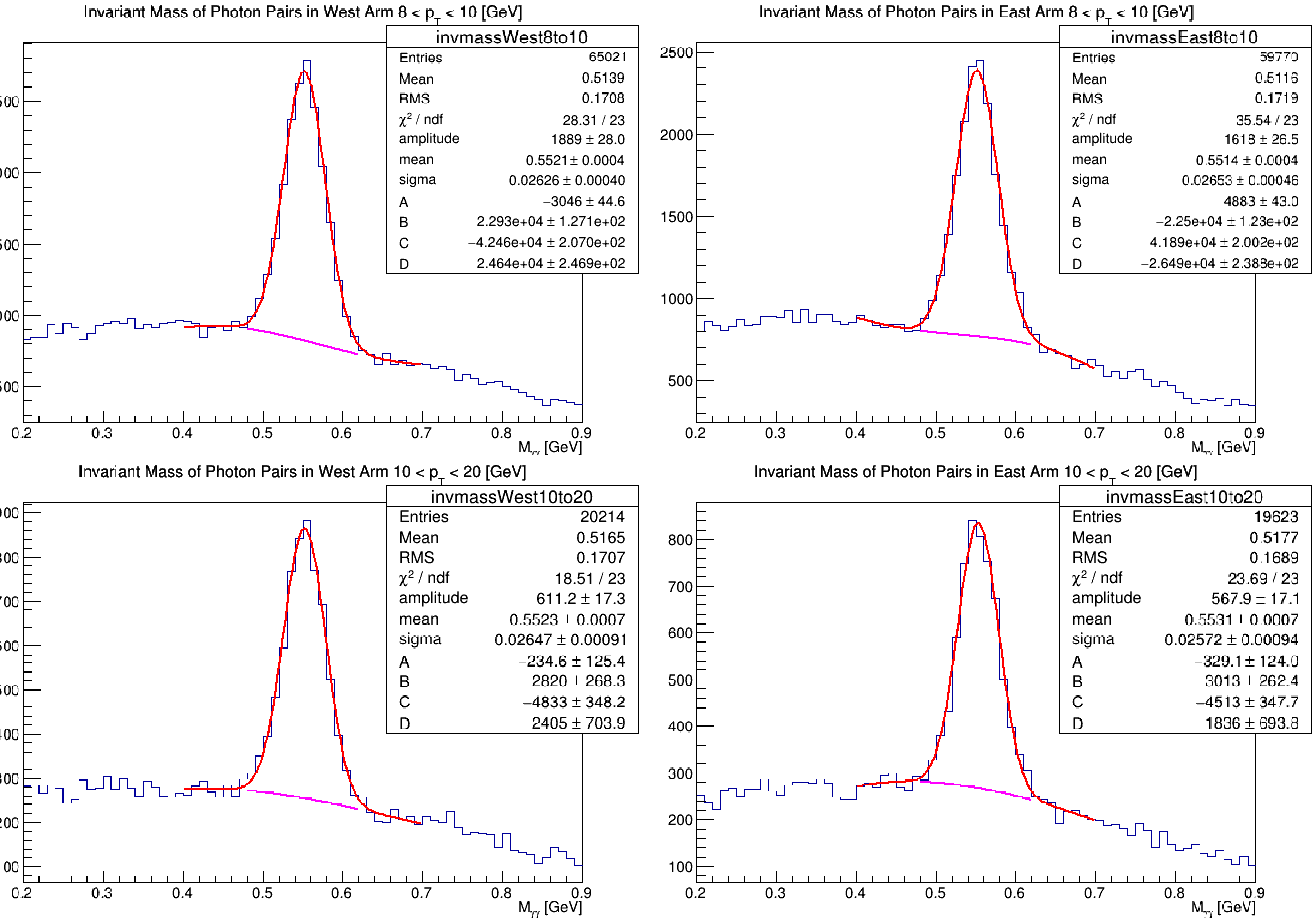



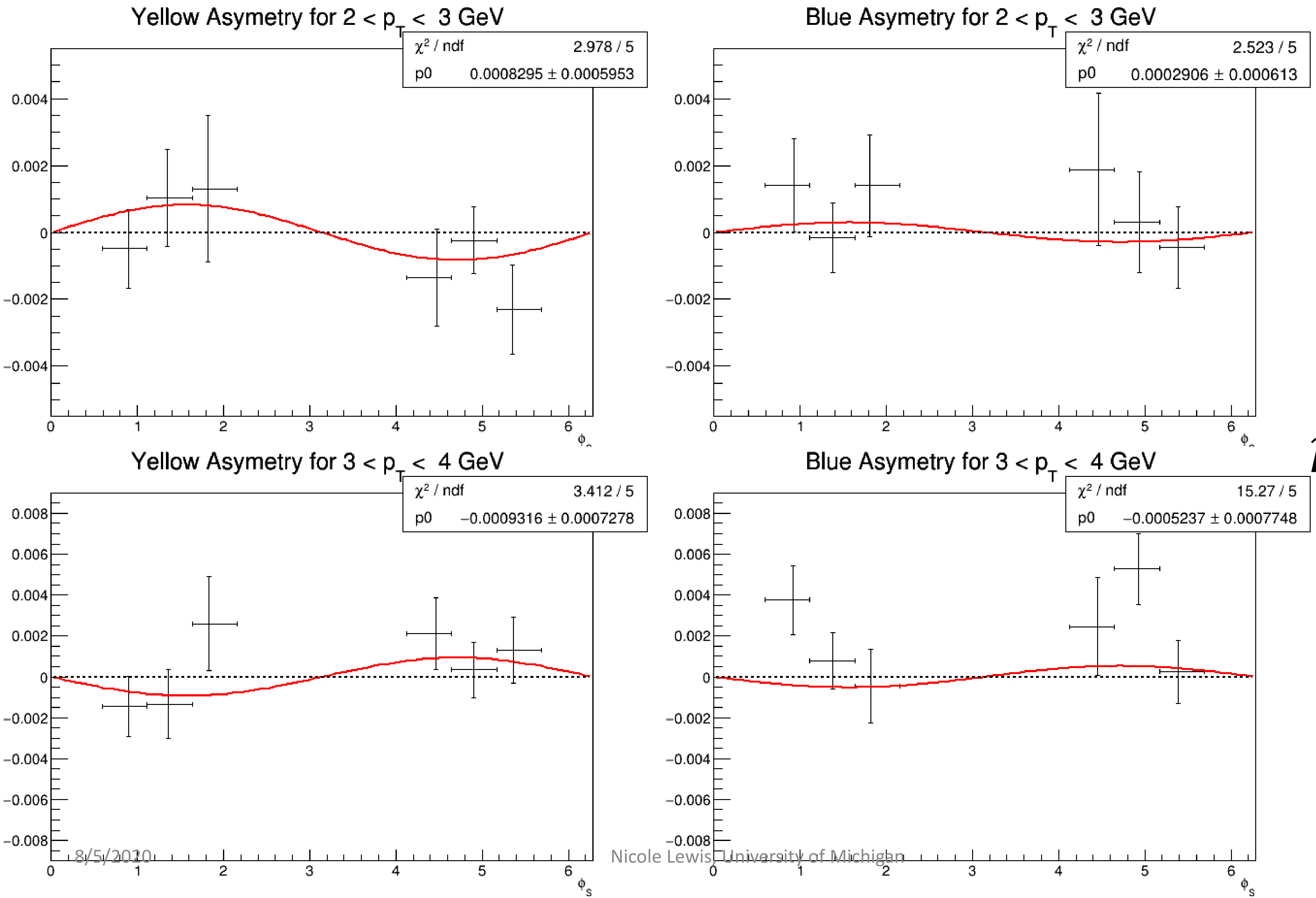
# Background Fraction Fits

Fit a “Gaus+pol3” function to $0.4 < M_{\gamma\gamma} < 0.7$ GeV

Pink curve represents the “pol3" which describes the combinatorial background

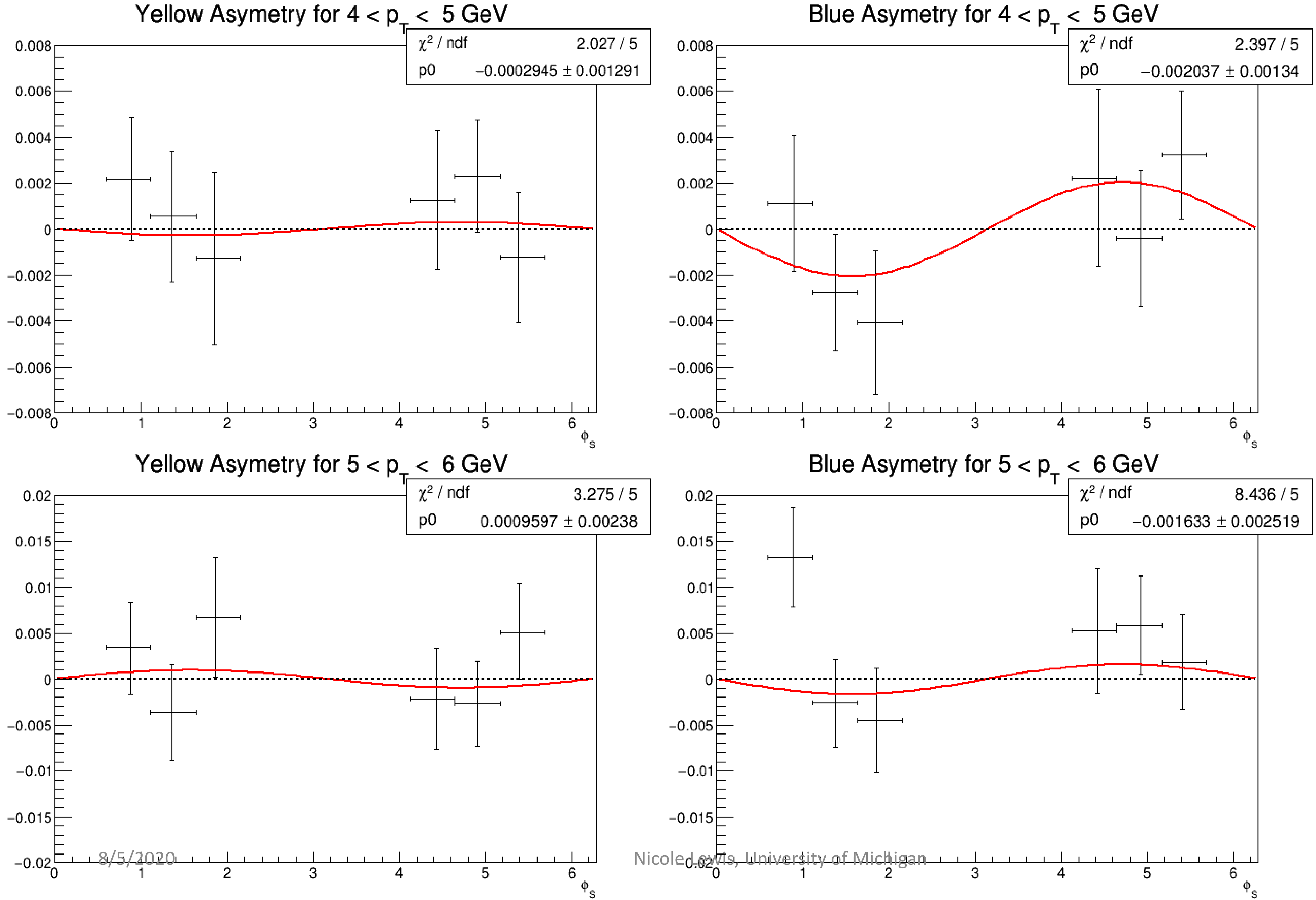
Fit function is only used to estimate the background contribution, Gaussian part of the fit is not used directly





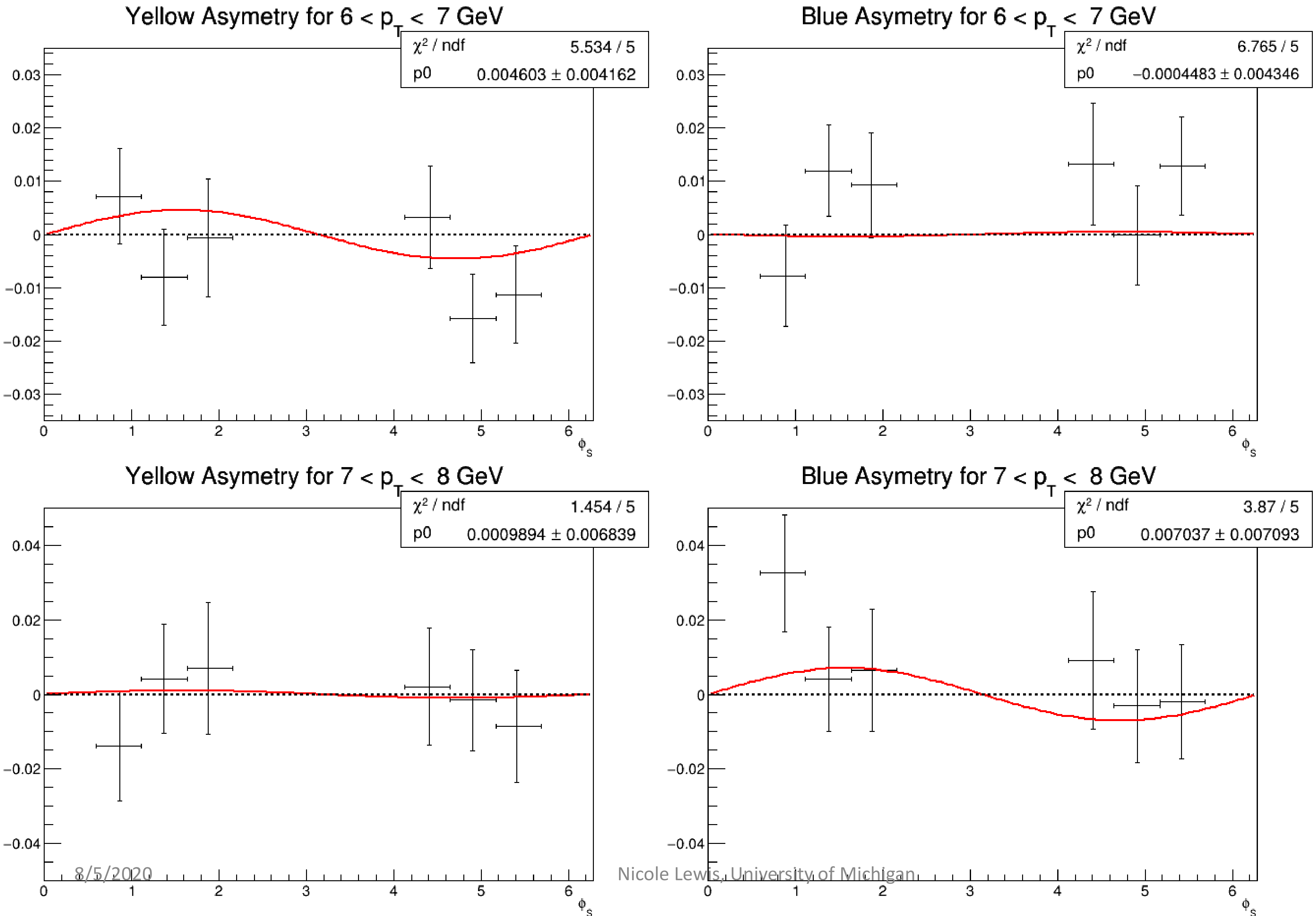

Fitting

$$p0 \sin \phi_S$$

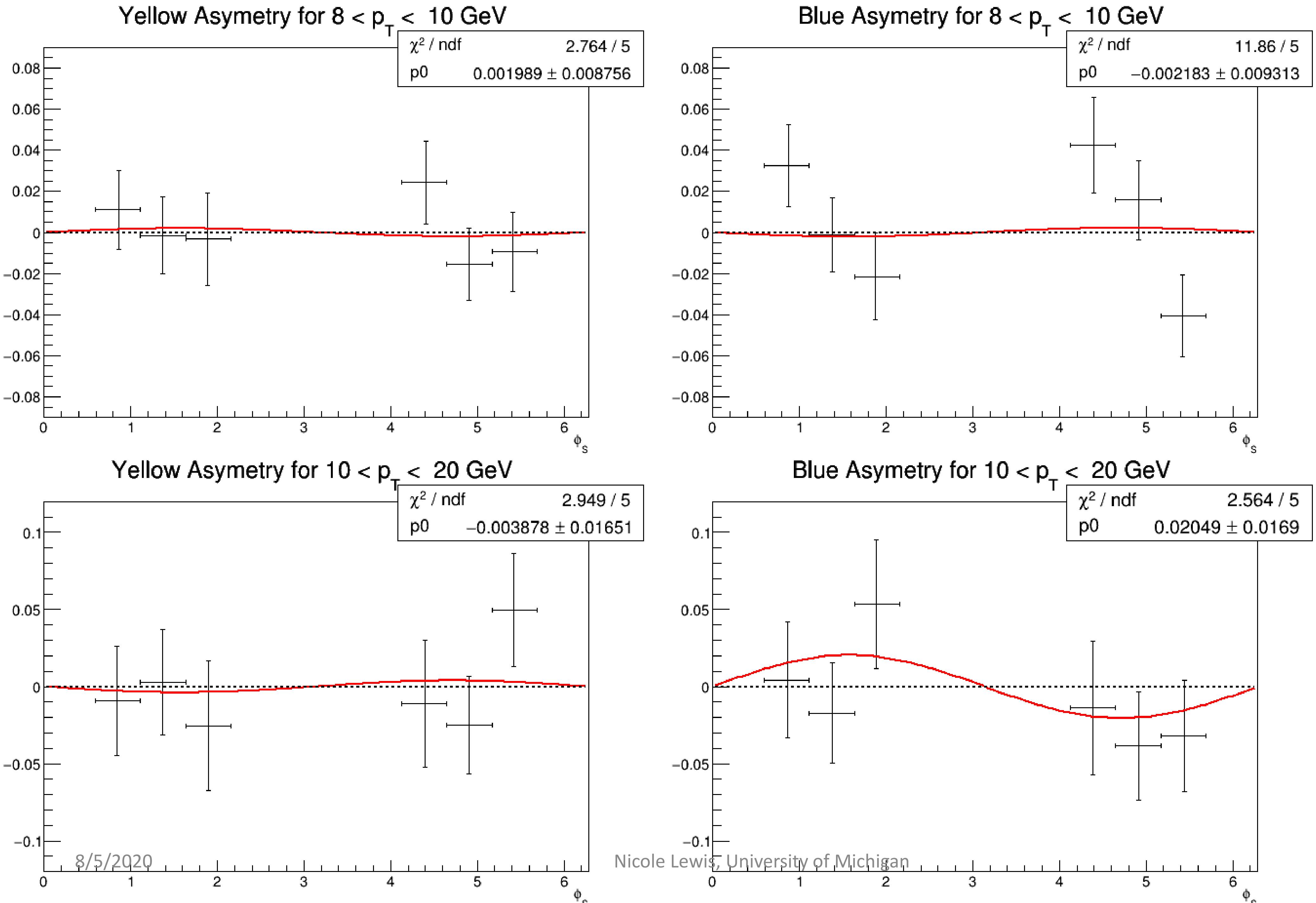



Fitting

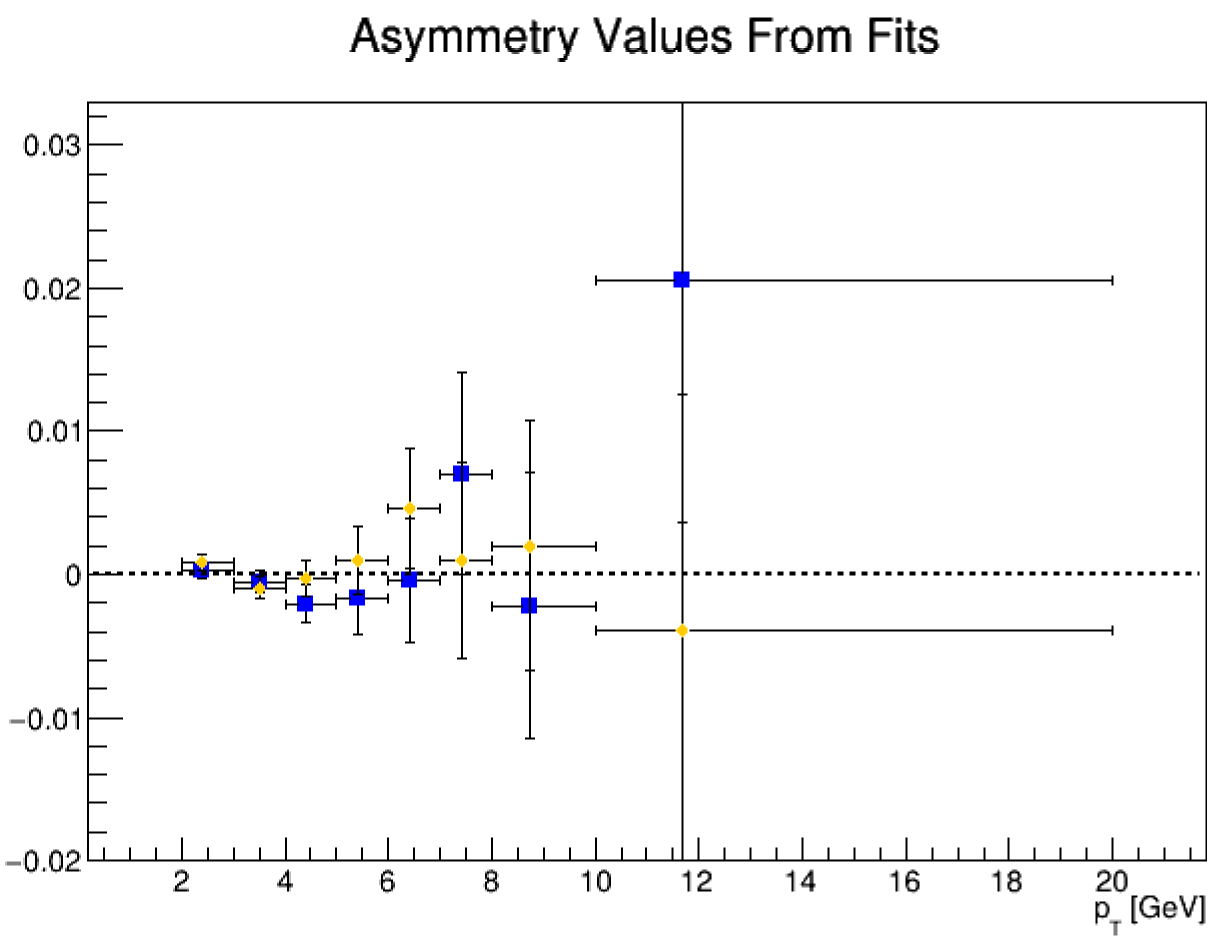
$p0 \sin \phi_S$

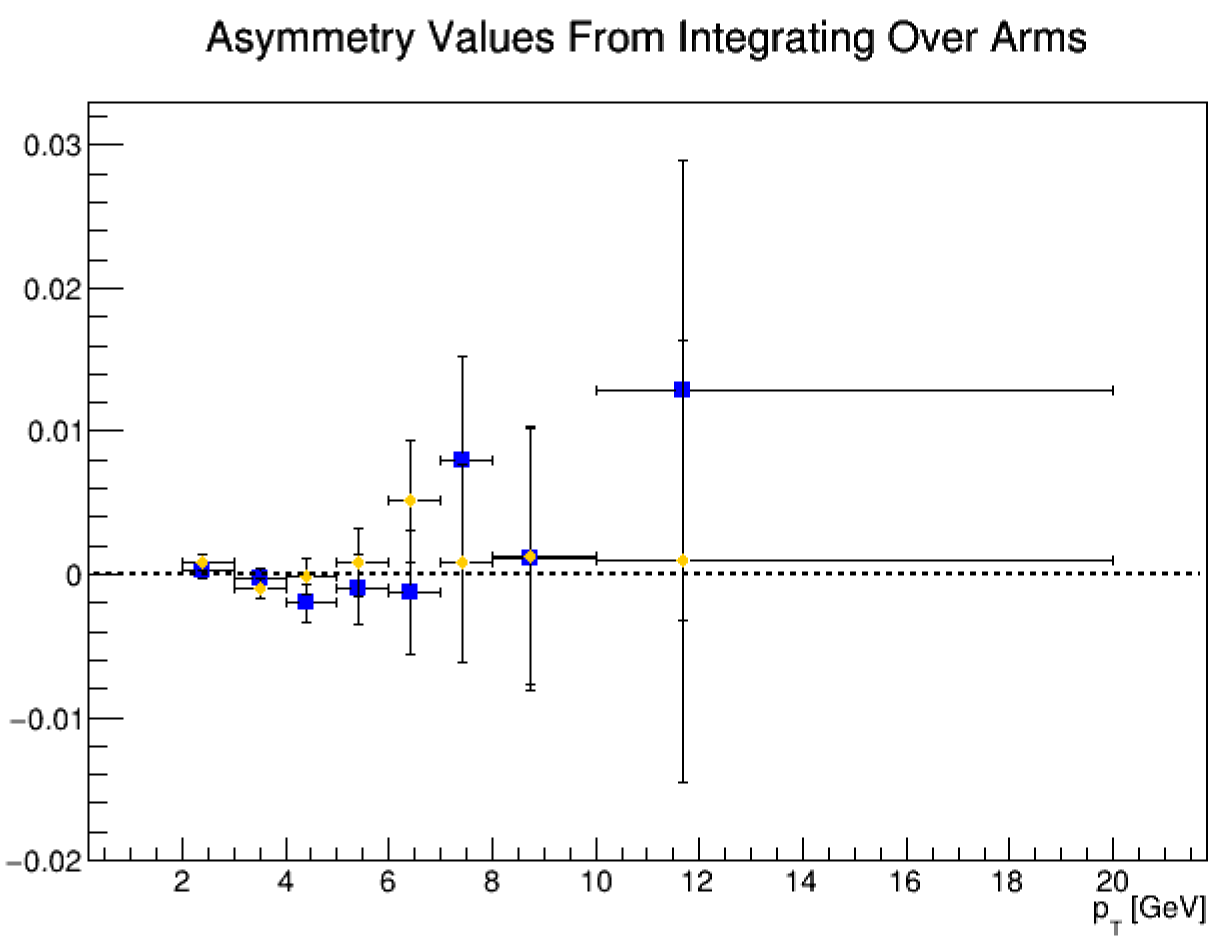


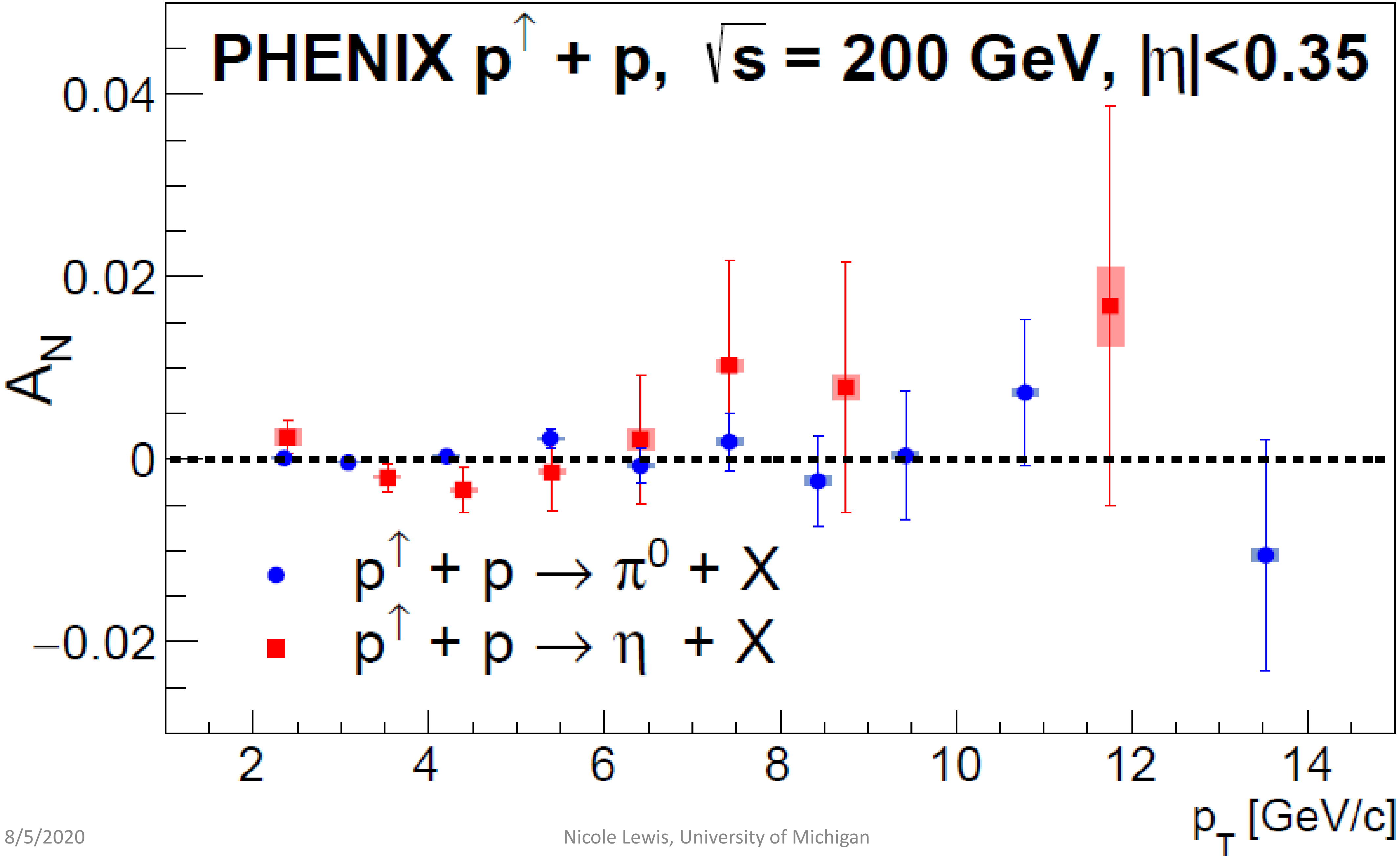

# Fitting $p0 \sin \phi_S$




Fitting
$p0 \sin \phi_S$


Asymmetry Values From Fits
0.03
0.02
0.01
0
−0.01
−0.02
2
4
6
8
10
12
14
16
18
20
$p_T$ [GeV]


Asymmetry Values From Integrating Over Arms
0.03
0.02
0.01
0
−0.01
−0.02
2
4
6
8
10
12
14
16
18
20
$p_T$ [GeV]



PHENIX p↑ + p, √s = 200 GeV, |η|<0.35
0.04
0.02
0
−0.02
$A_N$
p↑ + p → π0 + X
p↑ + p → η + X
2
4
6
8
10
12
14
$p_T$ [GeV/c]