Measurements of the E asymmetry for $p\pi^-$, $K^0\Lambda/\Sigma^0$, and $d\pi^{\pm}$ channels using G14 data

by

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Outline:

- Short Overview of G14 Experiment/Data
- Brief Intro. of **B**oosted **D**ecision **T**rees (BDT)
- ***E*** Asymmetry for Reaction $\gamma n(p_S) \rightarrow p\pi^-(p_S)$
- ***E*** Asymmetry for Reaction $\gamma d \rightarrow (d\pi_d)\,\pi$
- ***E*** Asymmetry for Reaction $\gamma n(p_S) \rightarrow K^0\Lambda/\Sigma^0(p_S)$

Short Overview of G14

- Longitudinal polarized deuteron (*quasi-free* neutron) target
- Circularly/linearly polarized photon beam
- Target contains solid HD, aluminum cooling wires and KelF cell walls (C_2ClF_3):

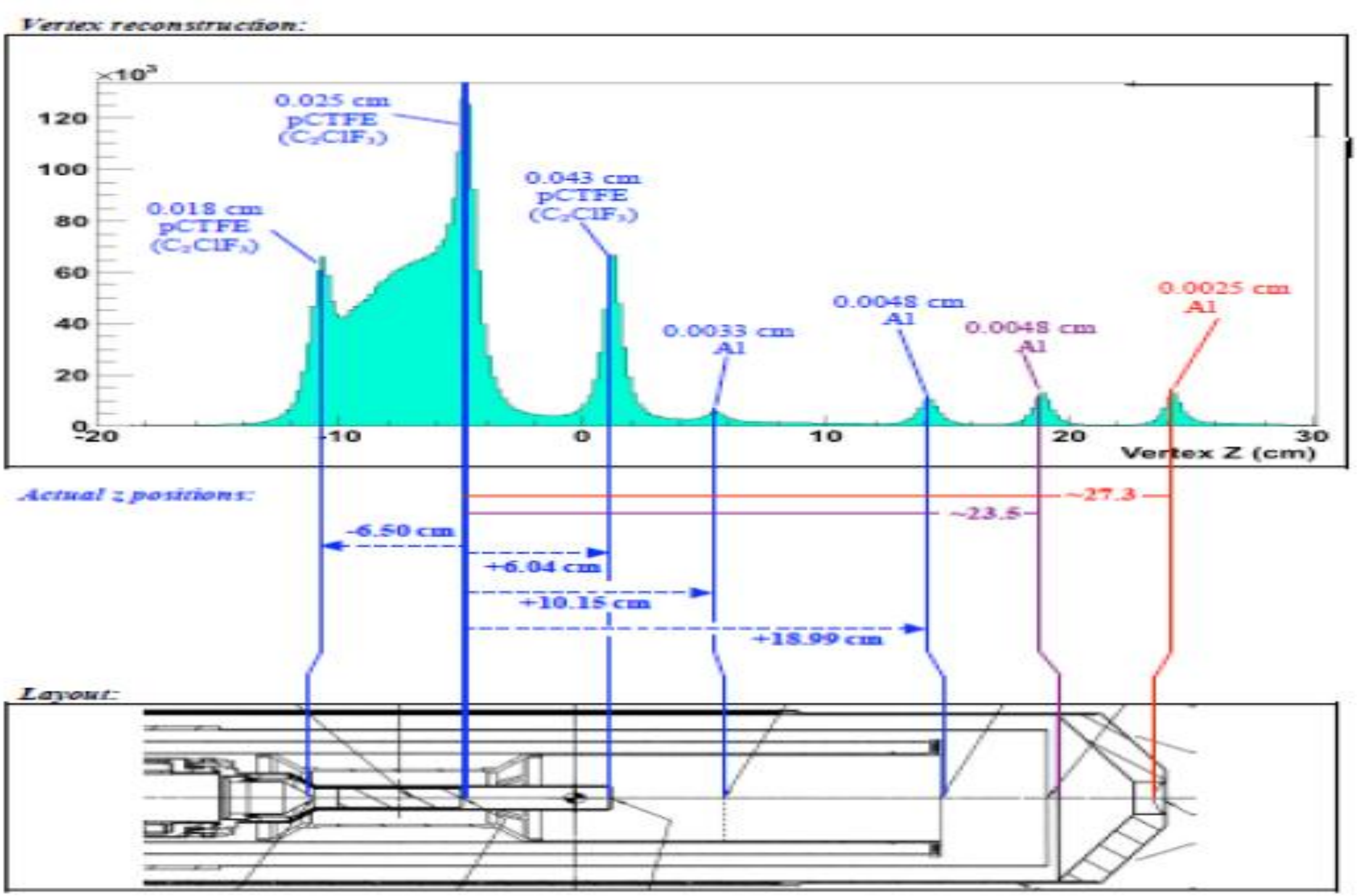
→*Every G14 analysis needs to reject/account for the unpolarized background events from Al wires, and KelF cell walls*

Empty target run period to study the target-material background (Al wires and KelF walls)

$$E = \frac{1}{P_\gamma P_d} \frac{N_{+-} - N_{++}}{N_{+-} + N_{++}}$$

❖++ (target and beam are parallel)
❖+- (target and beam are anti-parallel)

Short Overview of G14



Brief Intro. of BDT

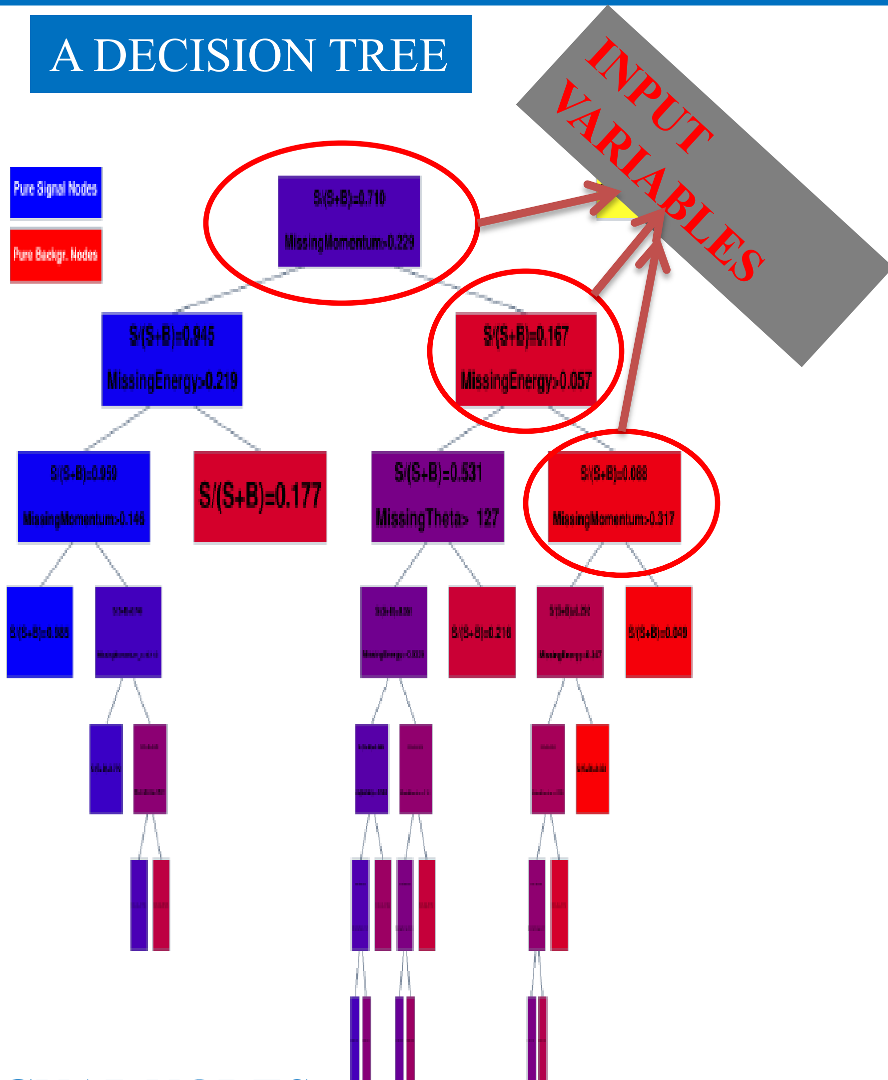
•Motivation: to separate signal and background events with better efficiency than the usual cut-based method
For example: Selecting quasi-free neutron events from target-material background events → need a set of kinematic input variables (e.g., missing mass, missing momentum, missing energy, invariance mass, etc)

•Multivariate BDT method "views" data in high dimension and applies cuts simultaneously on all input variables

•Cut-based method: Apply cuts *sequentially* → not efficient because viewing data in "projected" low dimensional space (very likely lose useful information as a result of projecting

Brief Intro. of BDT

A DECISION TREE



SIGNAL NODES
BACKGROUND NODES

•BDT= A forest of *distinctly-constructed* decision trees
•Tree construction requires **TRAINING data** for both **BG and Signal** event types
→Different analysis task results in different BDT algorithm
→Automate algorithm: “learning” from the training data only, no need for human instructions

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HUMAN TASKS:
•Provide training data with a **good set of input variables** (training data are usually MC data where identity (bg or signal) of each event is known)
•Check for **overtraining**: is the BDT performance good only for the training data, or general for similar data?
•What is the **BDT efficiencies** in separating signal and bg events?

Measuring the *E* Asymmetry for $p\pi^-$ Channel

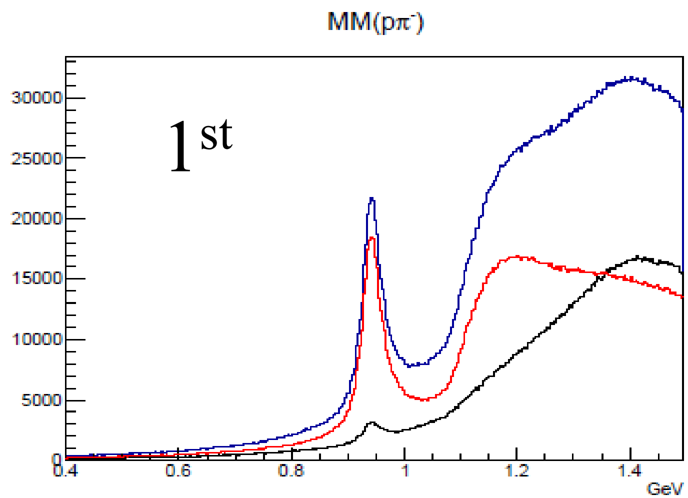
Introduction

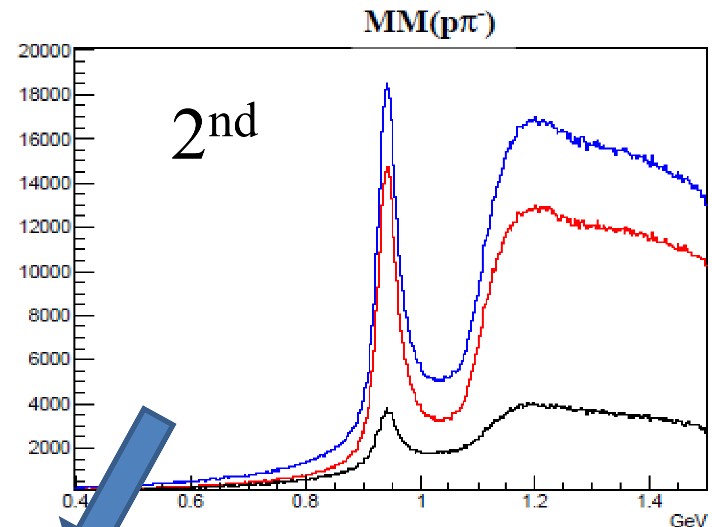
- Three analyses: Target-Material Background Subtraction, Boosted Decision Trees (BDT), and Kinematic Fitting Methods (future talk(s))
- Comparison between BDT and Background Subtraction (this talk)

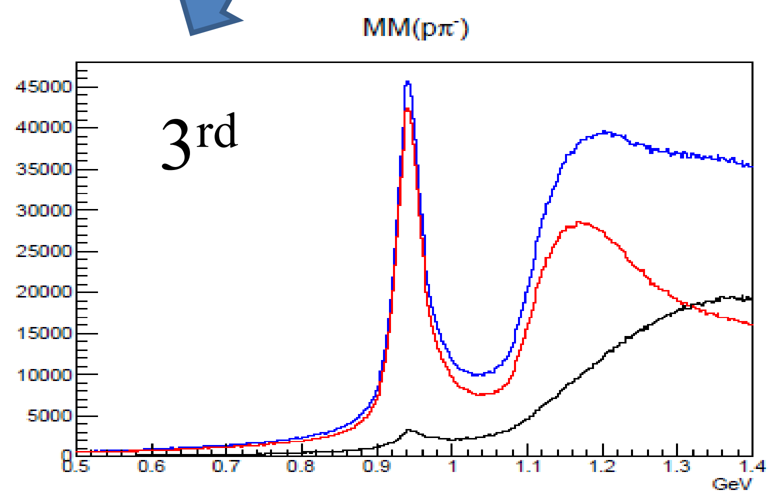
- **$p\pi^-$ Event Selection**
- **Quasi-free Neutron Event Selection**
- **Short Intro. of Background Subtraction**
- **Comparison between BDT and Background Sub.**
- **Plotting E vs. $\cos(\theta^{CM}_{\pi-})$ and compare to the theories**
- **Systematic Study for BDT**

$p\pi^-$ Event Selection*

- 1st :ΔTOF cuts: $|\Delta TOF_{\pi-}| < 1$ ns, no cuts on proton
- 2nd :Fiducial cuts
- 3rd :p and π^- momentum cuts







•Before applying the ith cut(s)

•Rejected by the cut

•Survived the cut

*Details in Back-up Slides

Event Selection: Al Wires and KelF Cell Wall Removal Using BDT method

TRAINING the BDT algorithm:

- Empty-target data utilized as **background training data**
- Quasi-free neutron simulation data (Hulthen wave function built-in) utilized as **signal training data***
- Input variables presented below:

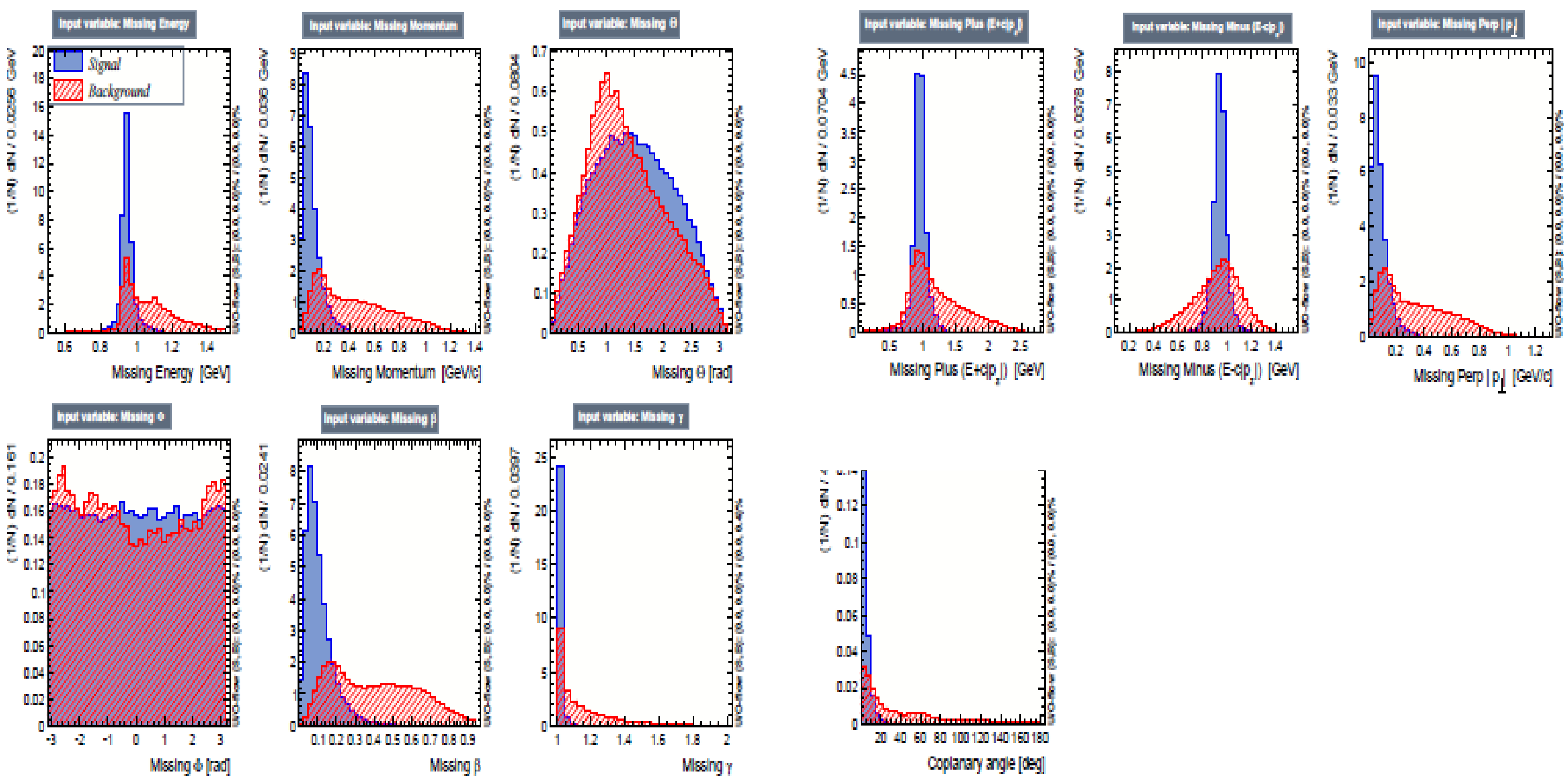
Variable Name	Description
$CoplanaryAngle$	$(p_p \times p_\gamma) \cdot (p_{\pi^-} \times p_\gamma)$
$MissingMomentum$	Total missing momentum
$MissingEnergy$	Total missing energy
$MissingTheta$	Θ of missing momentum
$MissingPhi$	Φ of missing momentum
$MissingBeta$	β
$MissingGamma$	γ
$MissingPlus$	$E^{missing} - c\lvert p_z^{missing}\rvert$
$MissingMinus$	$E^{missing} + c\lvert p_z^{missing}\rvert$
$MissingPerp$	$\lvert p_{transverse}^{missing}\rvert$

*Comparison between MC and real data: back-up slides

Event Selection: Al Wires and KelF Cell Wall Removal Using BDT method

TRAINING the BDT algorithm:

- **Background training data:** Empty-target data
- **Signal training data:** Quasi-free neutron simulation data (Hulthen wave function built-in)

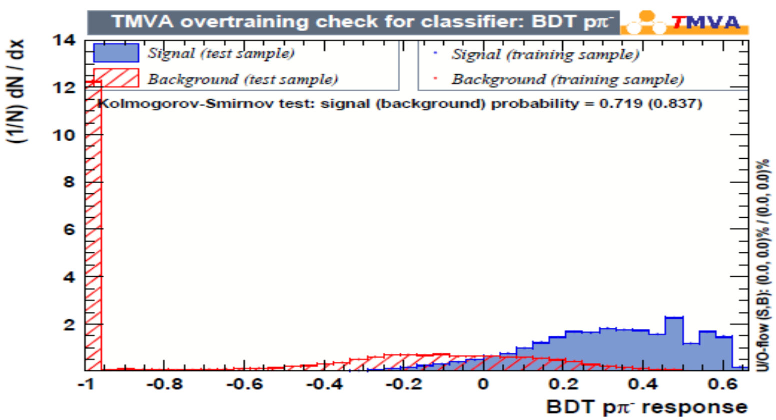


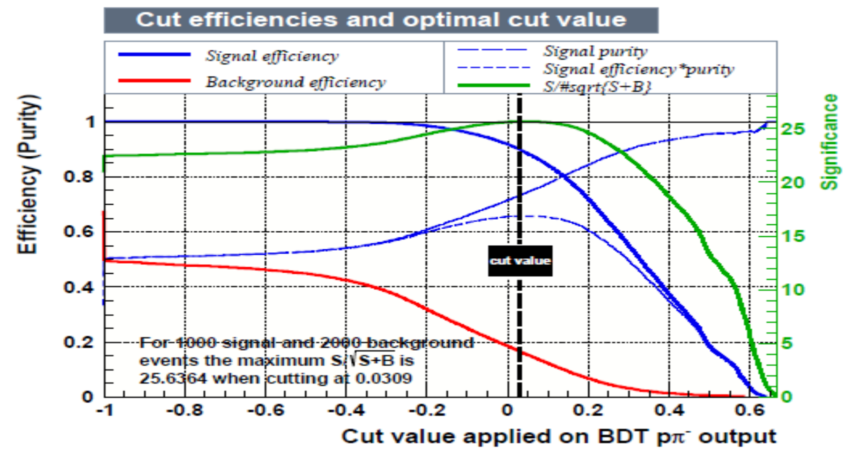
Event Selection: Al Wires and KelF Cell Wall Removal Using BDT method

BDT output: a quantitative assessment of how likely an event is signal or background (i.e., closer to -1, more likely a BG event, closer to +1, more likely a signal event)

Performances of the BDT on training and testing data are consistent.

Placing a cut on BDT output at **0.03** to optimally separate the signal and BG events



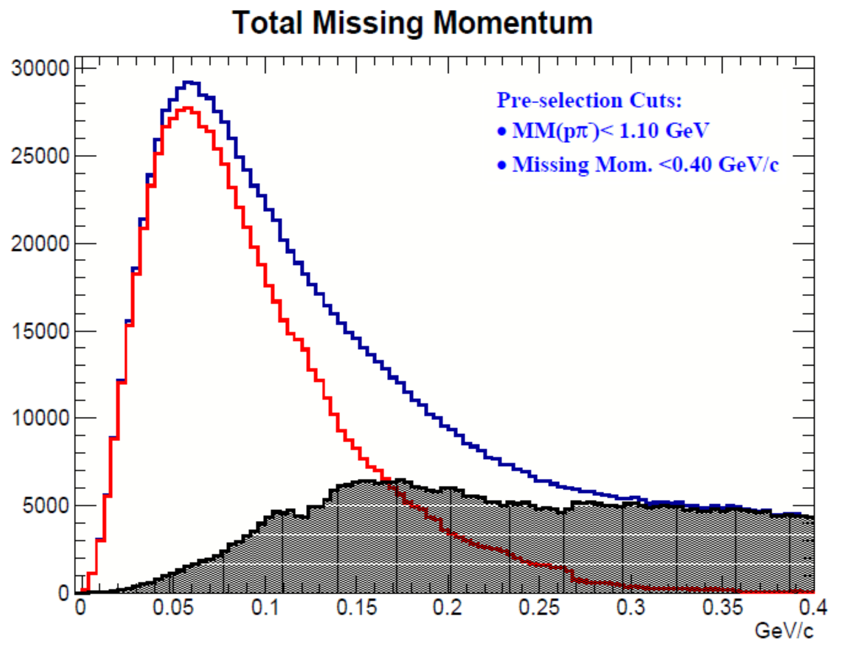


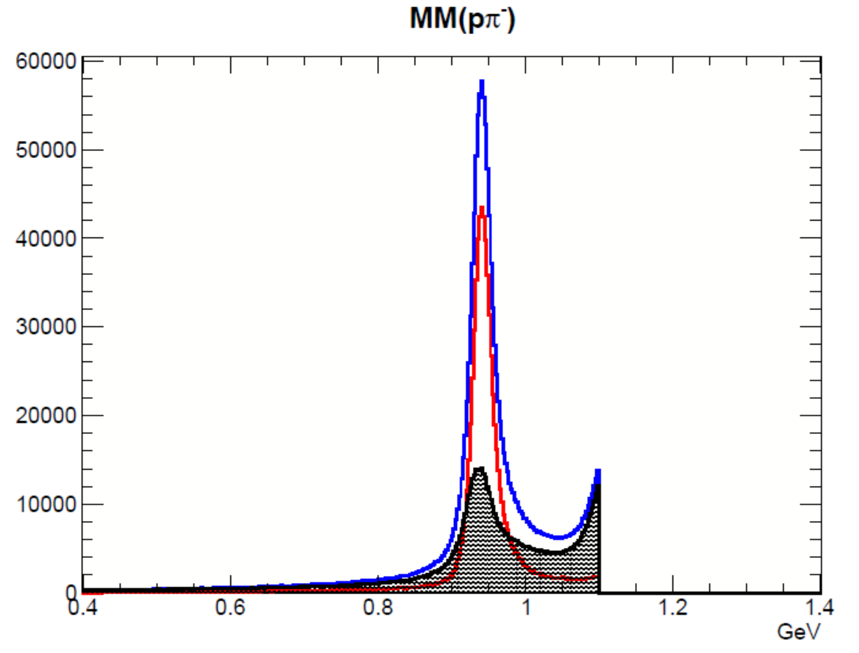
Example tree

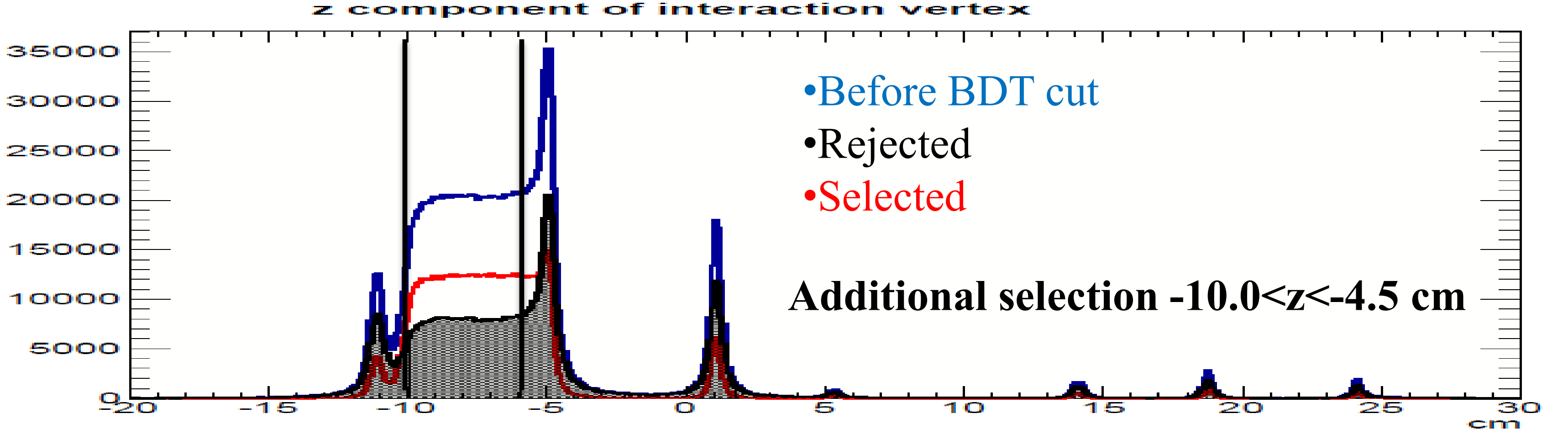
Variable Name	Relative Ranking
MissingMomentum	1.00
CoplanaryAngle	0.37
MissingMinus	0.25
MissingEnergy	0.23
MissingPerp	0.07
MissingTheta	0.06
MissingPlus	0.05
MissingGamma	0.05
MissingBeta	0.04
MissingPhi	0.02

How often each variable was utilized in constructing the decision trees

Event Selection: Al Wires and KelF Cell Wall Removal Using BDT method

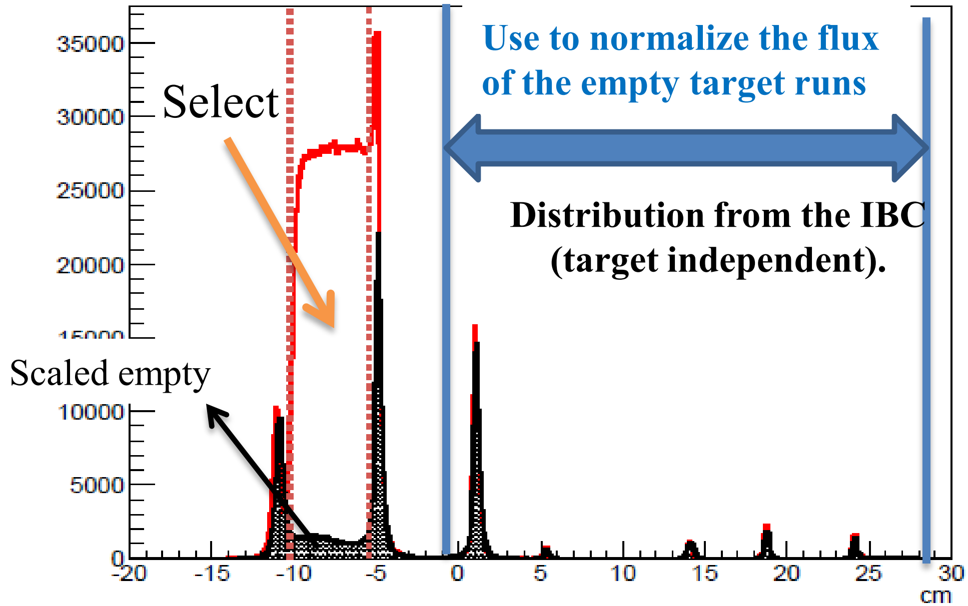






Background subtraction

z-component of interaction vertex



Background (BG) comes mainly from **Al wires inside the target and KelF target cell.**

- Empty target runs to obtain BG distribution.

Steps:

1. Apply cuts to clean up real data.

→Missing mass, missing momentum, coplanary angle, and target dimension cuts.

1. Run the same analysis on empty target data.

2. Normalize the IBC flux with full target data and obtain the scaling factor.

3. Subtract scaled BG (from empty runs) to align yield ($Y^{3/2}$) and anti align yield ($Y^{1/2}$) of full target runs.

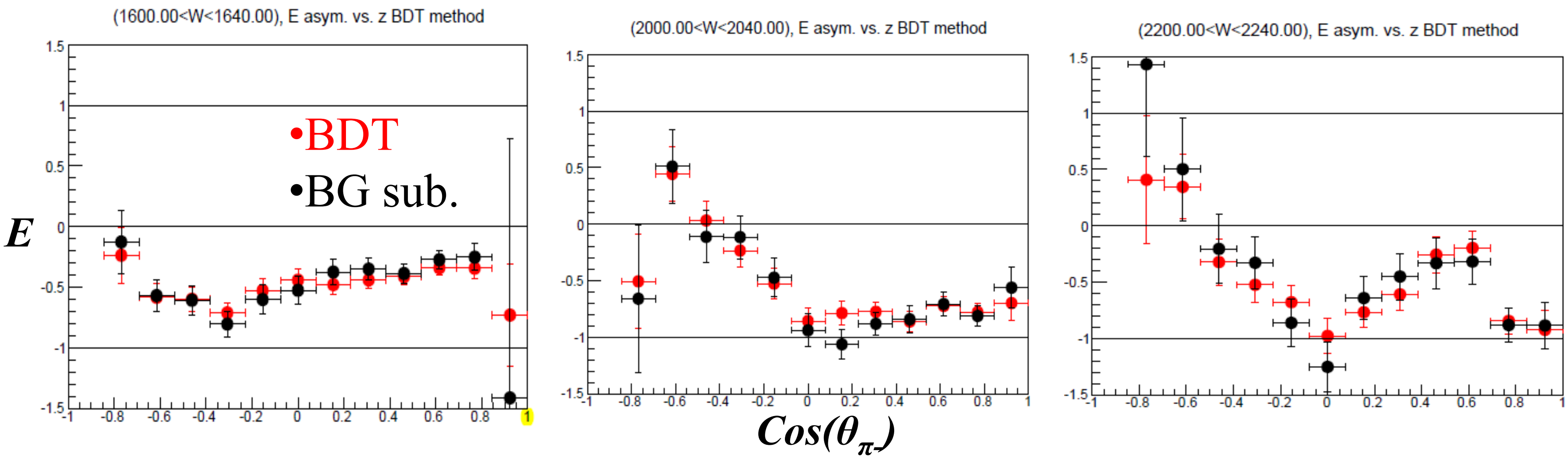
Verified for empty run $Y_{empty}^{1/2} \approx Y_{empty}^{3/2}$

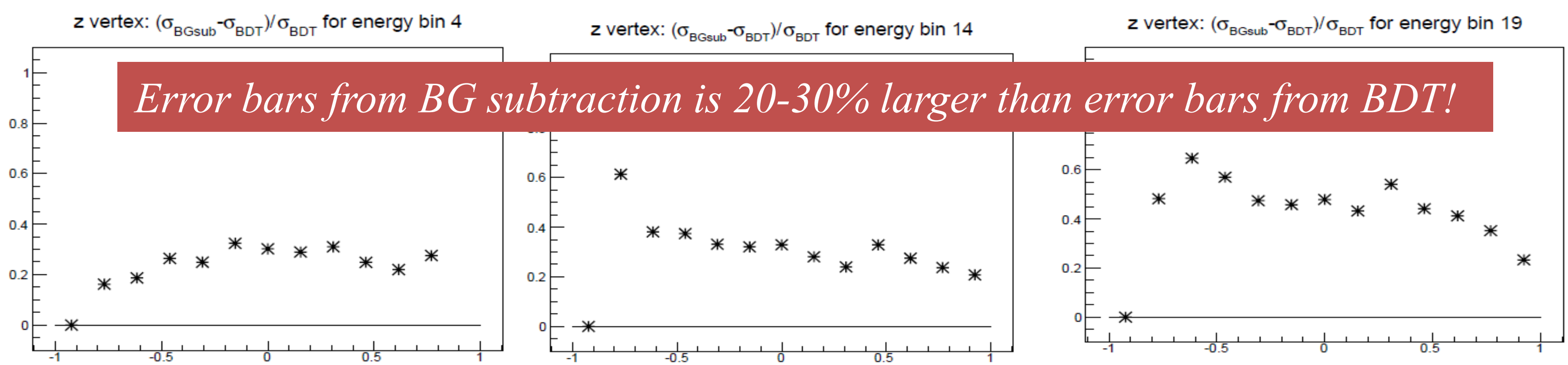
$Y_{BG}=1/2*(Y_{empty}^{1/2}+Y_{empty}^{3/2})*$ scaling factor ***show empty***

$Y_{HD}^{1/2} = Y_{full}^{1/2} - Y_{BG}$ **$Y_{HD}^{3/2} = Y_{full}^{3/2} - Y_{BG}$**

$$E = (P_\gamma \times P_{target})^{-1} \times (Y_{HD}^{1/2} - Y_{HD}^{3/2})/(Y_{HD}^{1/2} + Y_{HD}^{3/2})$$

Comparison between BDT* and Background Subtraction



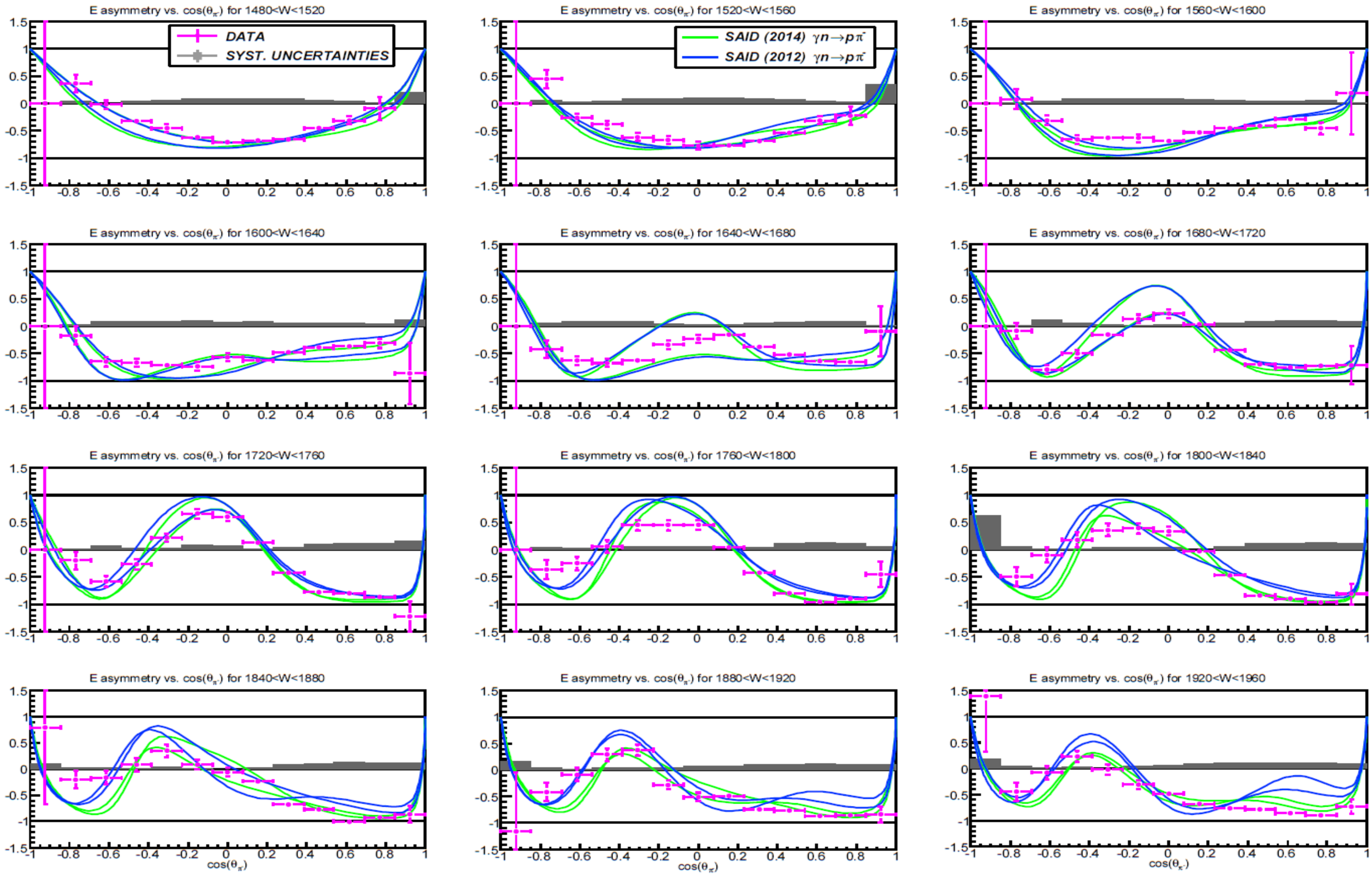


Error bars from BG subtraction is 20-30% larger than error bars from BDT!

Conclusion: two methods are statistically consistent!

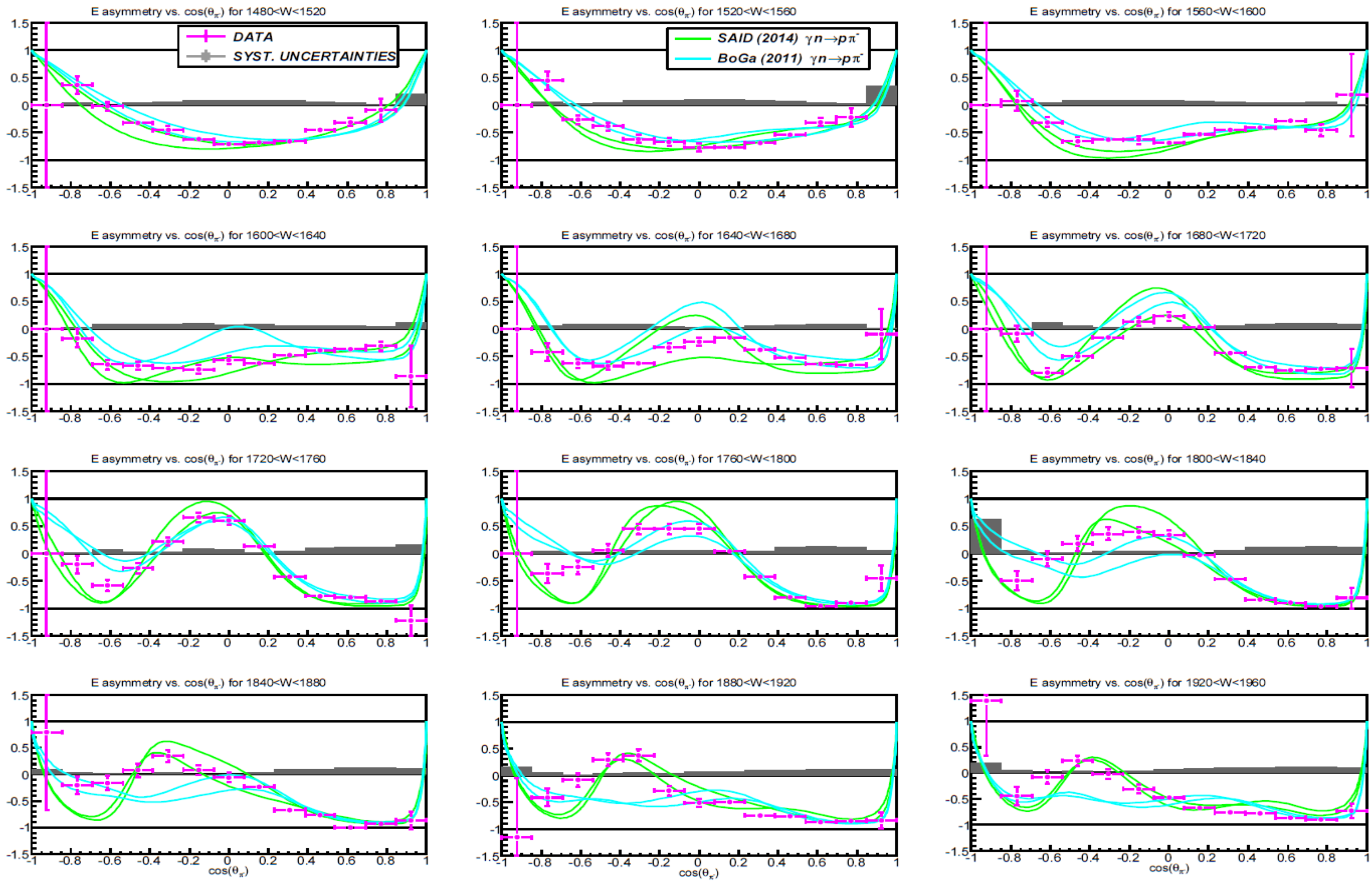
*Correction for remaining background after the BDT selection: back-up slide

Plotting E_{BDT} vs. $\cos(\theta^{CM}_{\pi-})$



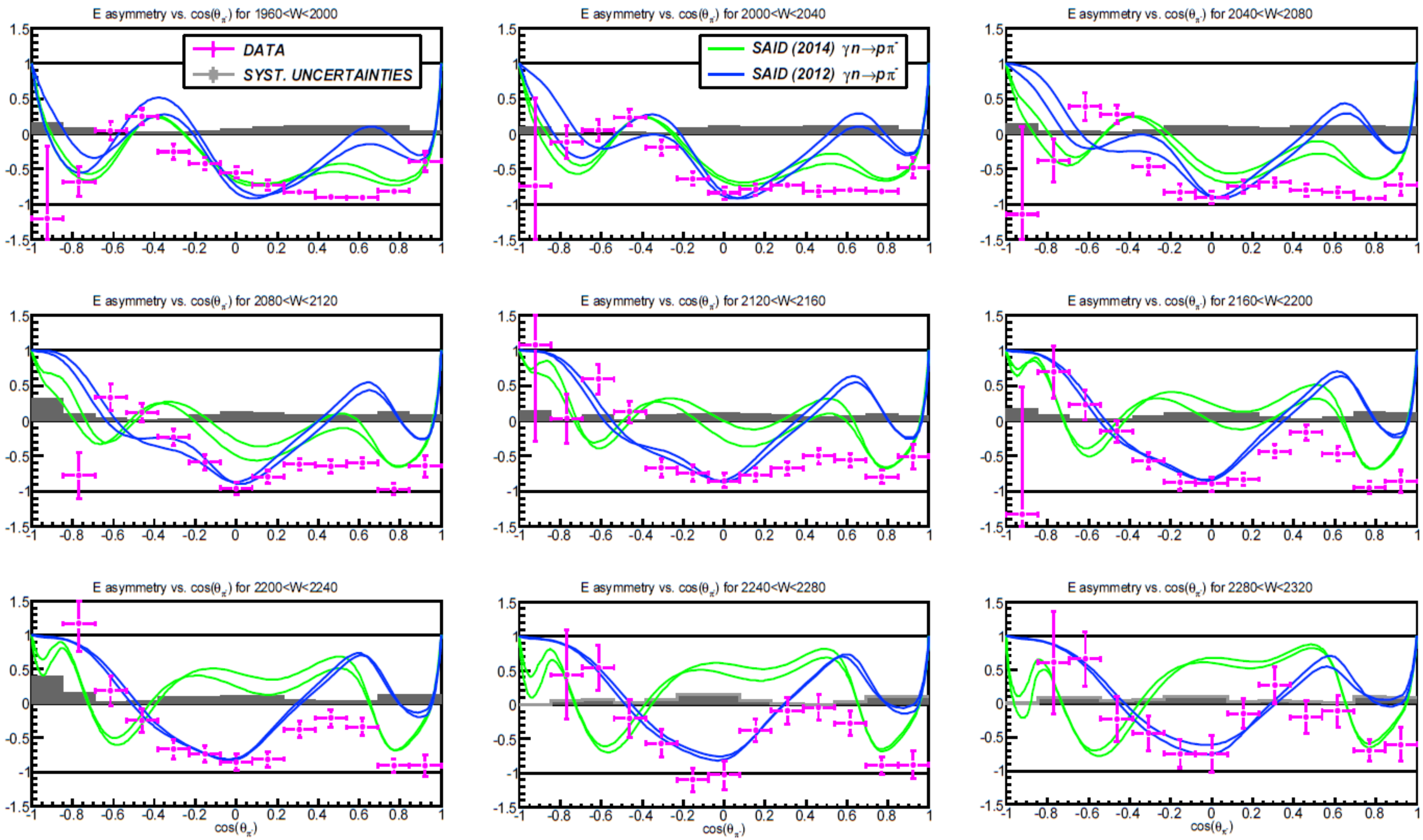
12 W bins: 1480 MeV<W<1960 MeV

Plotting E_{BDT} vs. $\cos(\theta^{CM}_{\pi-})$



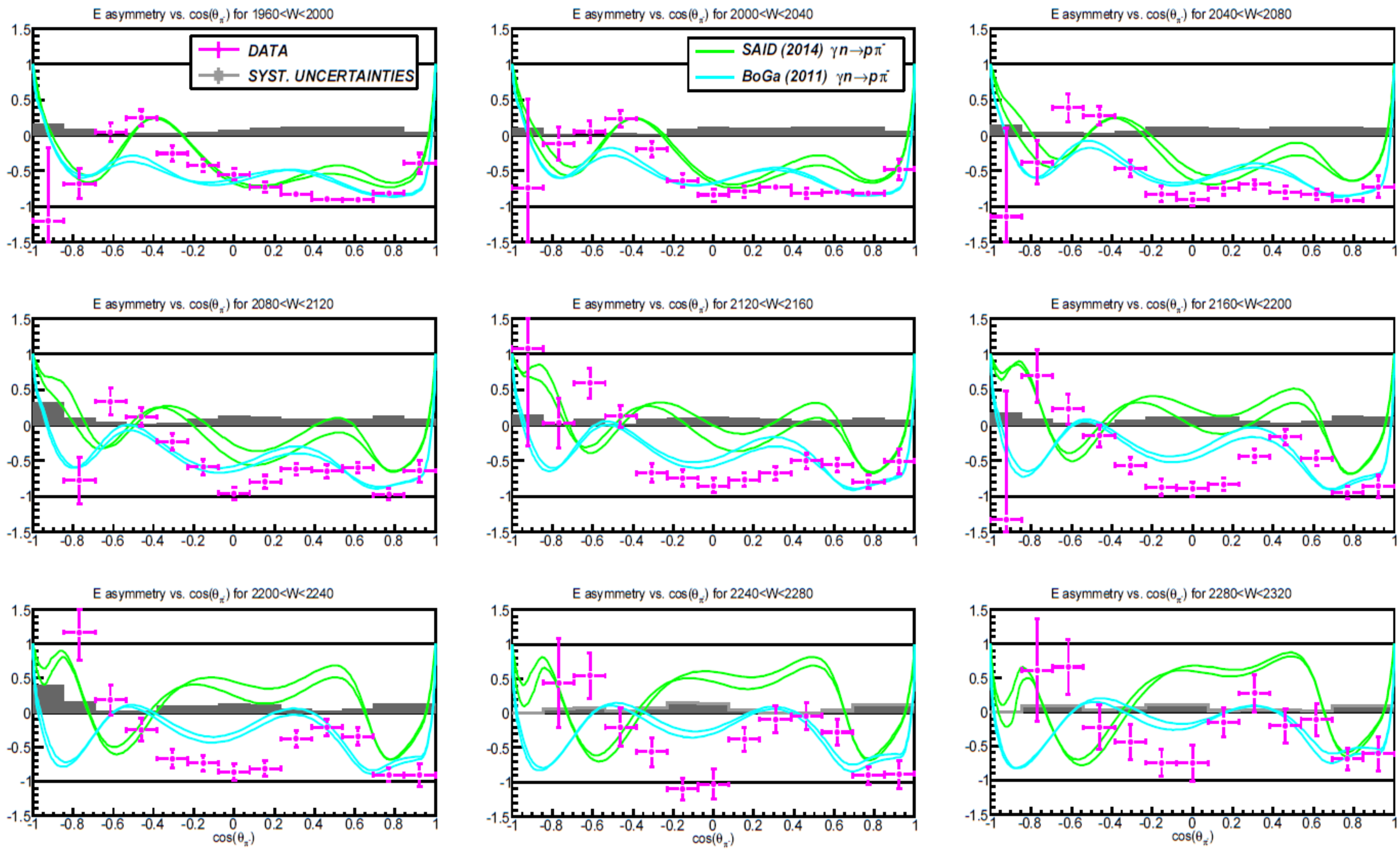
12 W bins: 1480 MeV<W<1960 MeV

Plotting E_{BDT} vs. $\cos(\theta^{\mathrm{CM}}_{\pi-})$



9 W bins: 1960 MeV $<W<$ 2320 MeV

Plotting E_{BDT} vs. $\cos(\theta^{\mathrm{CM}}_{\pi-})$



9 W bins: 1960 MeV<W<2320 MeV

Systematic Studies

•Tightening the z-vetex cut

•Varying the BDT output cut value (three tests)

•Using an artificially “improved” MC data (higher drift chamber resolution)

•Tightening the missing momentum cut (to the same value as the cut value in background sub. method)

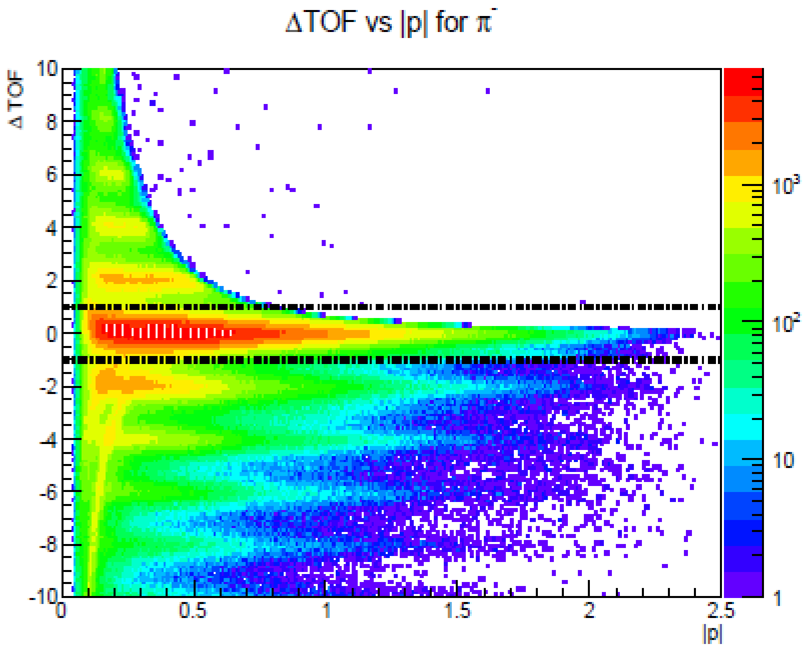
•Using BG sub. as another test on systematic uncertainties

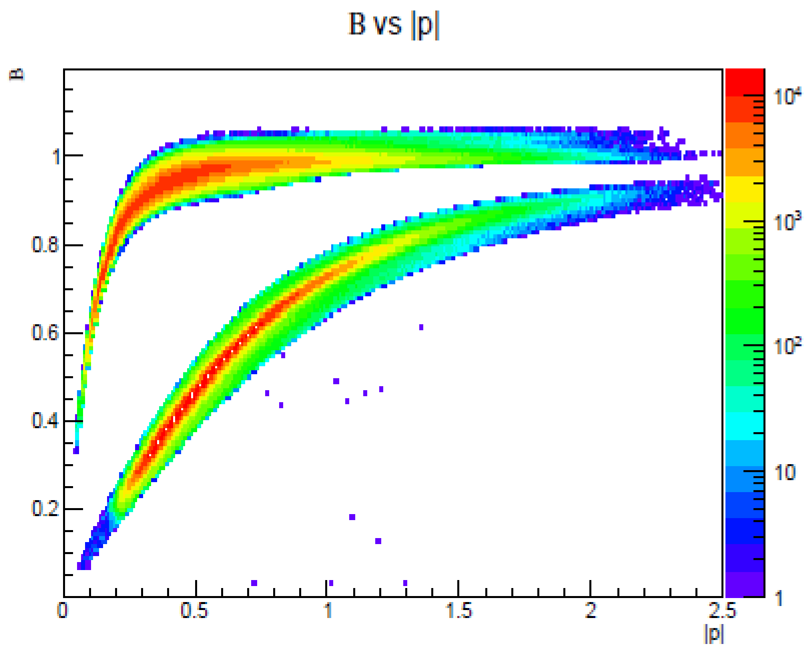
→→→Systematic Uncertainty=13.7% (a multiplicative factor)

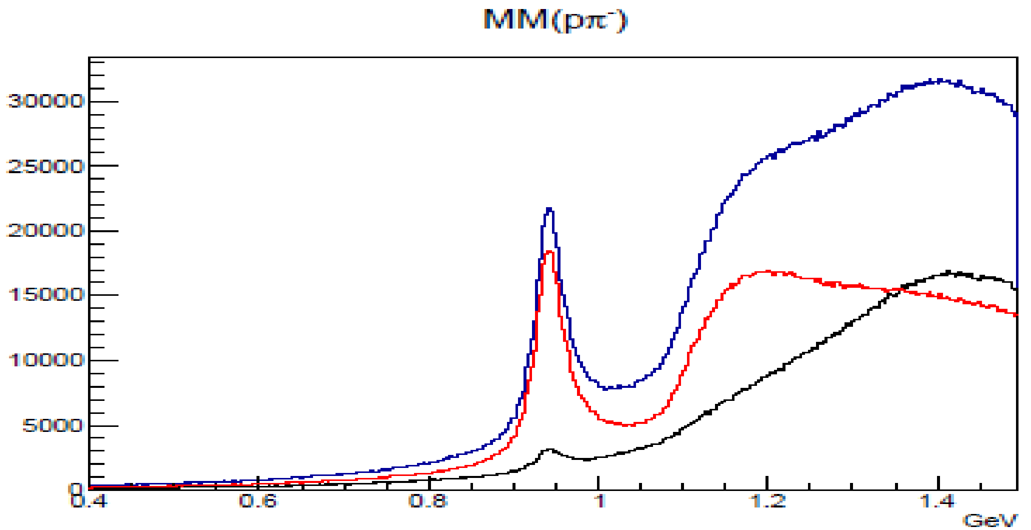
Conclusions:

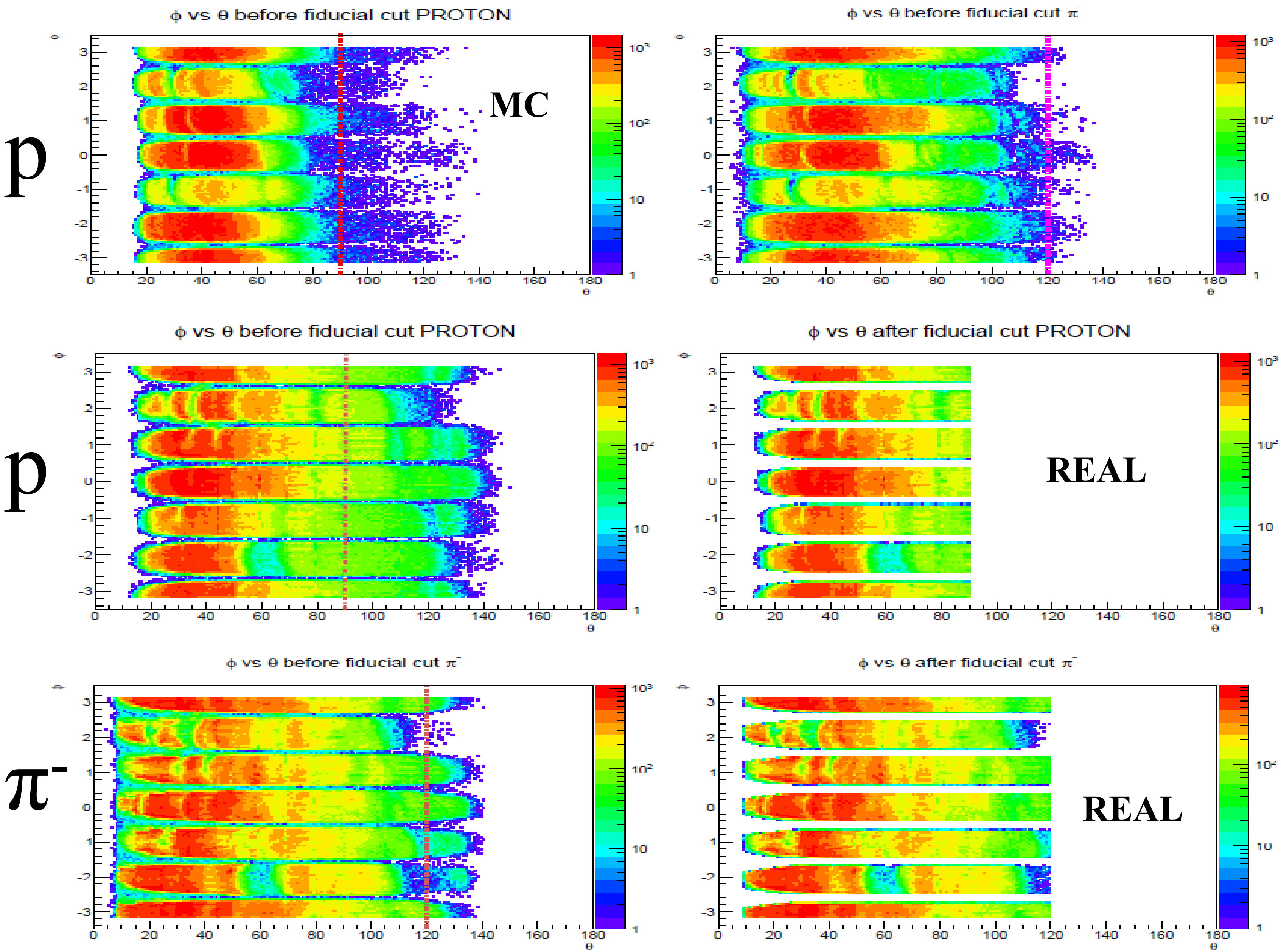
- BDT and BG sub. methods are statistically consistent
- BDT method is more efficient!
- Systematic Uncertainty is around 13.7 % of *E*
- SAID CM12 and ST14, and BoGa 2011 explain well *E* for low energies *W*
- Disagreements between the theoretical models for high energies *W*
- All three models can be improved by the *E* measurements especially the high energies *W*
- *BDT was also employed for the next two analyses*

Back-up


ΔTOF vs |p| for π⁻
Δ TOF
|p|


B vs |p|
B
|p|

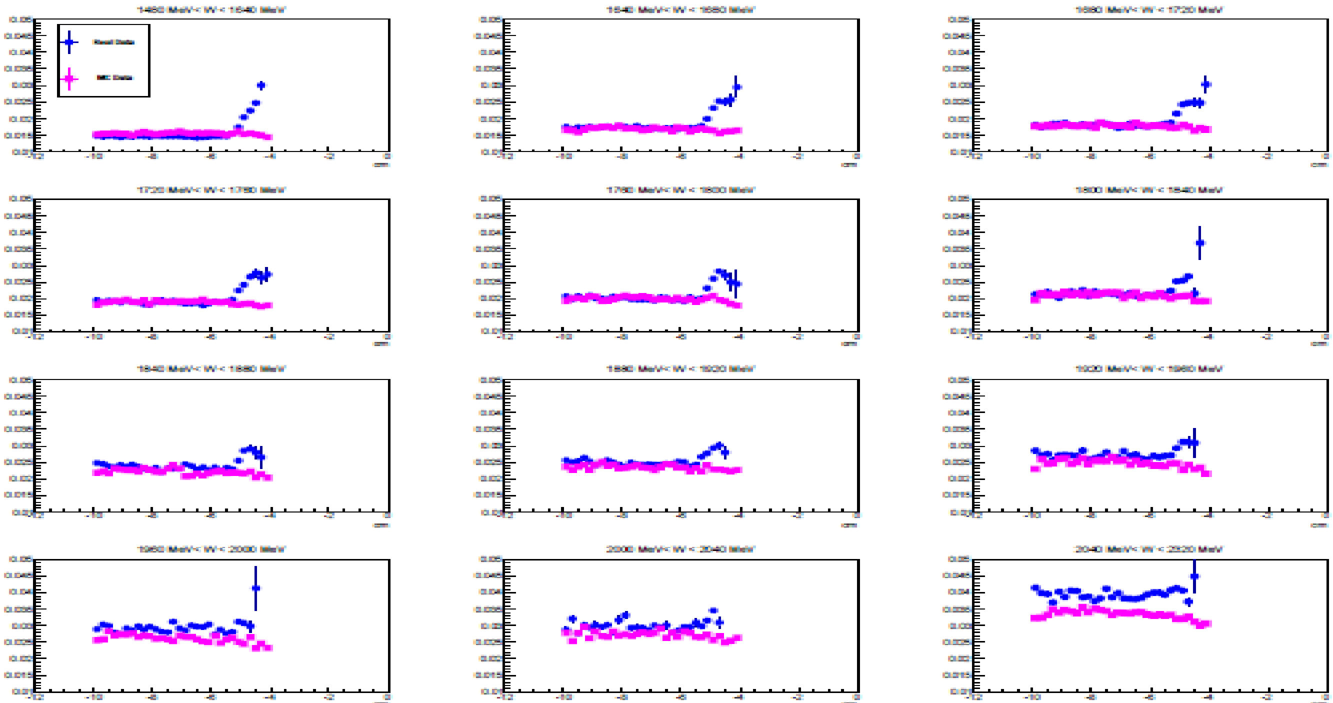

MM(pπ⁻)
GeV

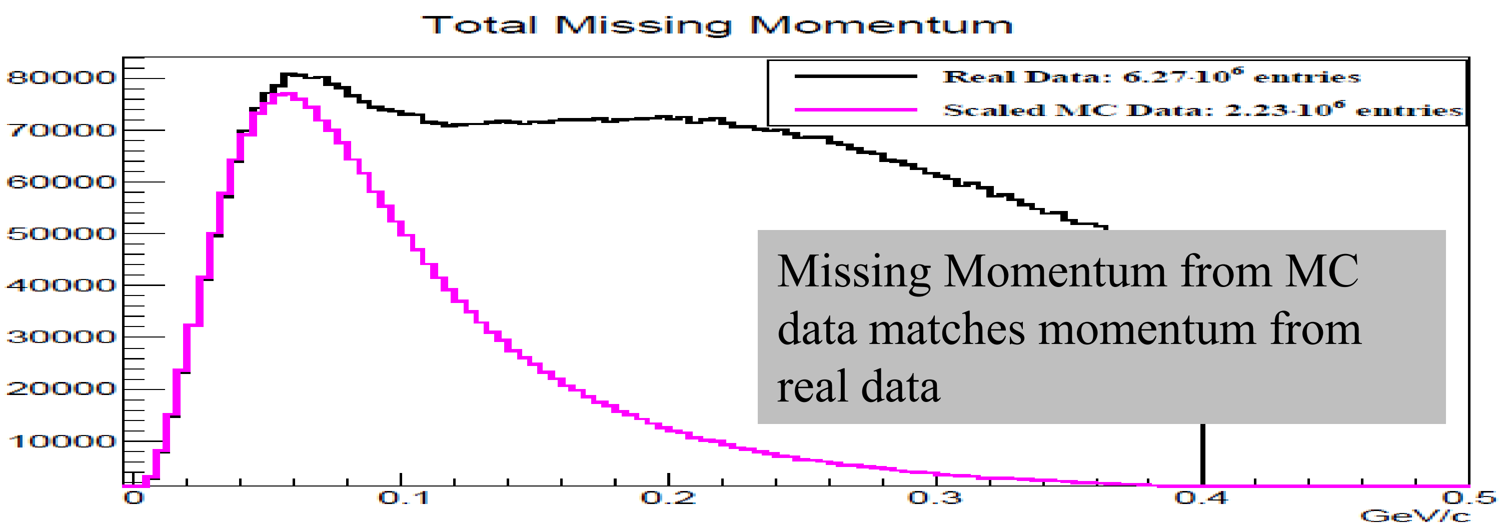


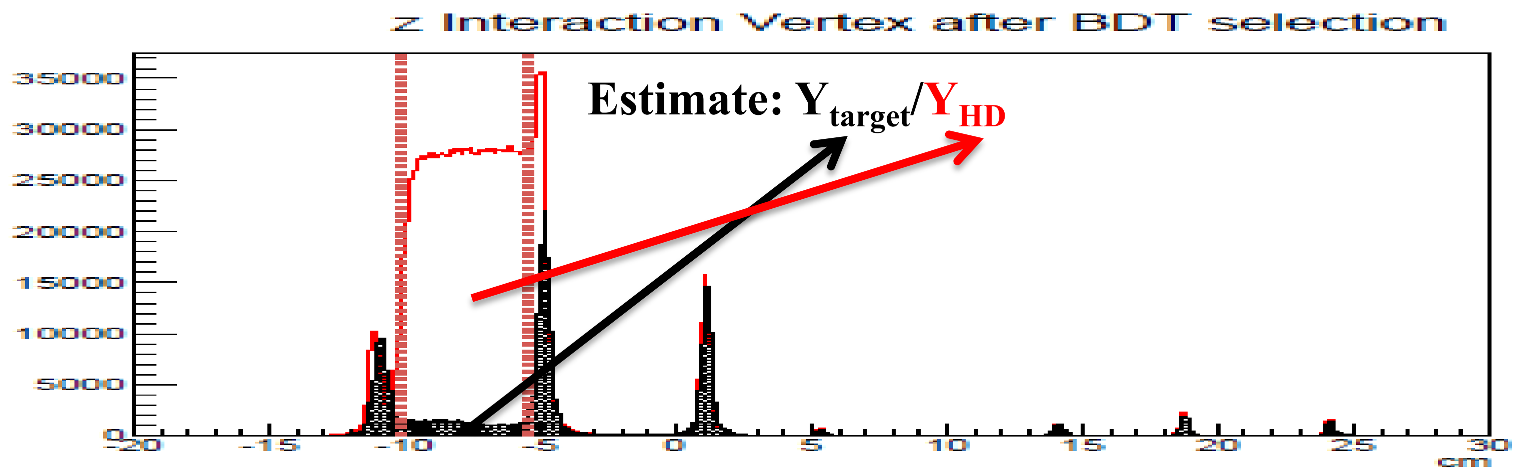
p
p
π⁻
MC
REAL
REAL
ϕ vs θ before fiducial cut PROTON
ϕ vs θ before fiducial cut π⁻
ϕ vs θ before fiducial cut PROTON
ϕ vs θ after fiducial cut PROTON
ϕ vs θ before fiducial cut π⁻
ϕ vs θ after fiducial cut π⁻

Resolution of missing mass from MC matches real data

•MC
•REAL







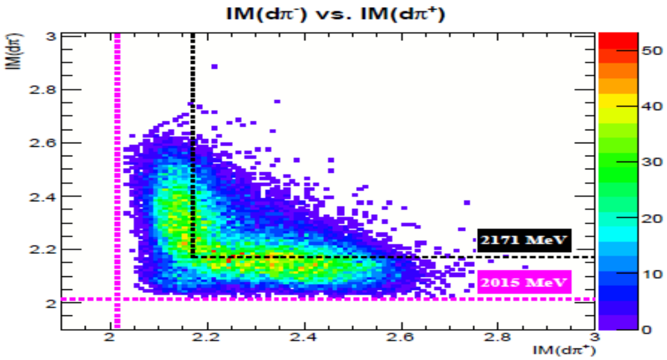
$$E_{full} = \frac{1}{\overline{P_\gamma}} \frac{1}{P_{target}} \frac{\left[Y_{HD}^{\downarrow\uparrow} - Y_{HD}^{\uparrow\uparrow}\right] + \left[Y_{target}^{\downarrow\uparrow} - Y_{target}^{\uparrow\uparrow}\right]}{\left[Y_{HD}^{\downarrow\uparrow} + Y_{HD}^{\uparrow\uparrow}\right] + \left[Y_{target}^{\downarrow\uparrow} + Y_{target}^{\uparrow\uparrow}\right]} = \frac{1}{\overline{P_\gamma}} \frac{1}{P_{target}} \frac{\left[Y_{HD}^{\downarrow\uparrow} - Y_{HD}^{\uparrow\uparrow}\right] + 0}{\left[Y_{HD} + Y_{target}\right]},$$

$$\Leftrightarrow E_{full} = \frac{1}{\overline{P_\gamma}} \frac{1}{P_{target}} \frac{1}{\left[1 + \frac{Y_{target}}{Y_{HD}}\right]} \frac{\left[Y_{HD}^{\downarrow\uparrow} - Y_{HD}^{\uparrow\uparrow}\right]}{\left[Y_{HD}\right]} = \frac{1}{\left[1 + \frac{Y_{target}}{Y_{HD}}\right]} E_{HD},$$

$$\Longrightarrow E_{HD} = \left[1 + \frac{Y_{target}}{Y_{HD}}\right] E_{full},$$

Study a *possible* (NΔ)→dπ decay using g14 data

Outline:



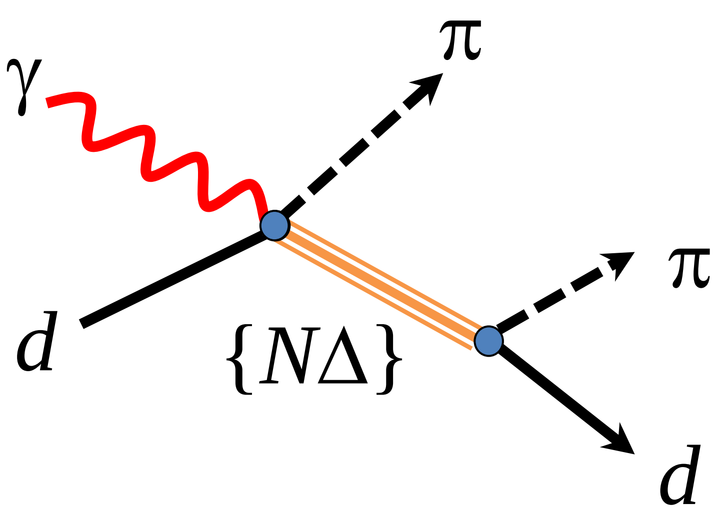
- Introduction
- Event Selection

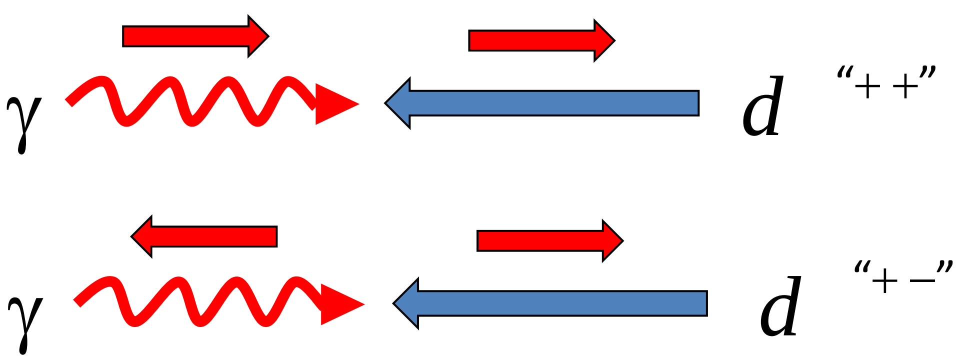
➢ $d\pi^+\pi^-$ Event Selection

➢ Removing target-material Background

- Subtracting ρ Resonance Contribution
- Beam-Target Helicity Asymmetry plots & Model Consideration
- Systematic Studies
- Conclusions

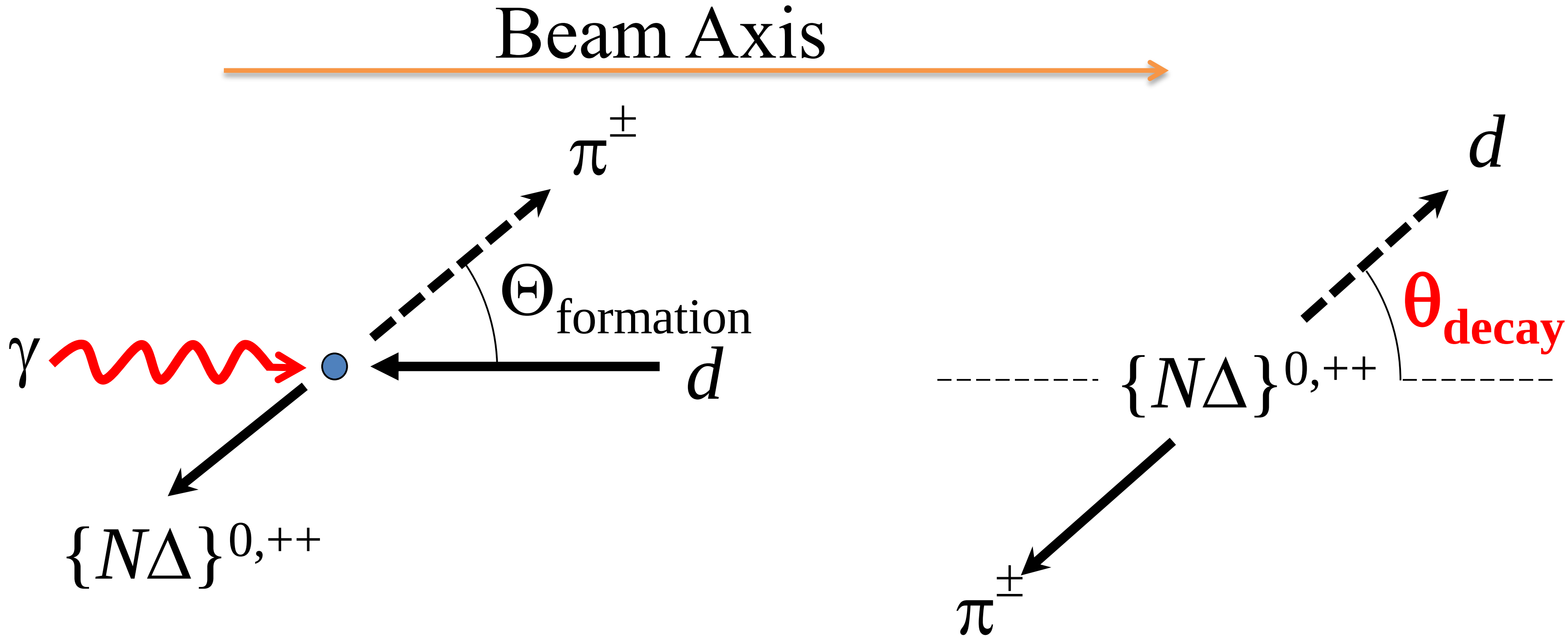
Introduction:





- Assume {*NΔ*} exists as a quasi-bound "**dibaryon**"
- Assume internal $L_{N\Delta}$= 0 of the {*N Δ*}, *positive* parity
- {*NΔ*} then has J_z = +2 or 0 in the Adair frame
- Look for dπ angular distribution in the{*NΔ*} rest frame.

Introduction: Frame & Angle Definitions



Overall c.m. frame

NΔ rest frame

Introduction:

<u>1st Hypothesis:</u>

- ❖ Dibaryon ($N\Delta$) system decays into $d\pi$ final state ($\mathbf{J}_{N\Delta}=\mathbf{J}_d+\mathbf{L}_{d\pi}$)
- ❖ Dibaryon ($N\Delta$) system has $|\mathbf{J}=\mathbf{1},J_z>$ with $\mathbf{L}_{d\pi}=\mathbf{1}$

$|\mathbf{1},2>_{\mathbf{N\Delta}}$ → NOT POSSIBLE

$|\mathbf{1},0>_{\mathbf{N\Delta}}$ → $|\mathbf{J}=\mathbf{1},J_z>_{\mathbf{d}}\oplus|\mathbf{L}=\mathbf{1},L_z>_{d\pi}$**:** function of $Y_{1,\pm1}(\theta,\phi)$, $Y_{1,0}(\theta,\phi)$,

where $Y(\theta,\phi)$ is the spherical harmonic wave function of the angular momentum between the deuteron and pion

Define:

$$E(\cos\theta_d)=\frac{I_0-I_2}{I_0+I_2}=\frac{I_0}{I_0}=+1$$

where $I_2 \sim {}_{d\pi}<1,2|1,2>_{N\Delta}$, and $I_0 \sim {}_{d\pi}<1,0|1,0>_{N\Delta}$

Introduction:

2nd Hypothesis:

❖ Dibaryon (NΔ) system has $|\mathbf{J=2}, J_z\rangle$ with $\mathbf{L}_{d\pi}=\{\mathbf{1,3}\}$

$|\mathbf{2},2\rangle_{N\Delta}$: function of $Y_{1,1}(\theta,\phi)$

$|\mathbf{2},0\rangle_{N\Delta}$: function of $Y_{1,1}(\theta,\phi)$, $Y_{1,0}(\theta,\phi)$, $Y_{1,-1}(\theta,\phi)$

OR

$|\mathbf{2},2\rangle_{N\Delta}$: function of $Y_{3,1}(\theta,\phi)$, $Y_{3,2}(\theta,\phi)$, $Y_{3,3}(\theta,\phi)$

$|\mathbf{2},0\rangle_{N\Delta}$: function of $Y_{3,-1}(\theta,\phi)$, $Y_{3,0}(\theta,\phi)$, $Y_{3,1}(\theta,\phi)$

Define:

$$E(\cos\theta) = \frac{I_0 - I_2}{I_0 + I_2}$$

where $I_2 \sim {}_{d\pi}\langle 2,2|2,2\rangle_{N\Delta}$, and $I_0 \sim {}_{d\pi}\langle 2,0|2,0\rangle_{N\Delta}$

Introduction:

g14 data: Studying reaction: $\gamma\, d \rightarrow d\, \pi^+ \pi^-$

- ❖ Longitudinal polarized deuteron target
- ❖ Circularly polarized photon beam
- ❖ ++ (target and beam are parallel)
- ❖ +- (target and beam are anti-parallel)

$$E(\cos\theta_d) = \frac{1}{P_\gamma P_d} \frac{N_{+-} - N_{++}}{N_{+-} + N_{++}}$$

where N_{++}, N_{+-} are yields of the $\mathbf{d\pi^{\pm}}$ system with parallel and anti–parallel configurations, respectively.

Event Selections

$d\pi^+\pi^-$ Event Selection*:

- ΔTOF cuts

→To reject **misidentified** protons

→To reject wrong timing (wrong beam buckets) events

- Fiducial cuts

→To reject edges of the detectors

→Reject non-HD events (mostly in the deuteron backward direction)

Target-Material BG Removal:

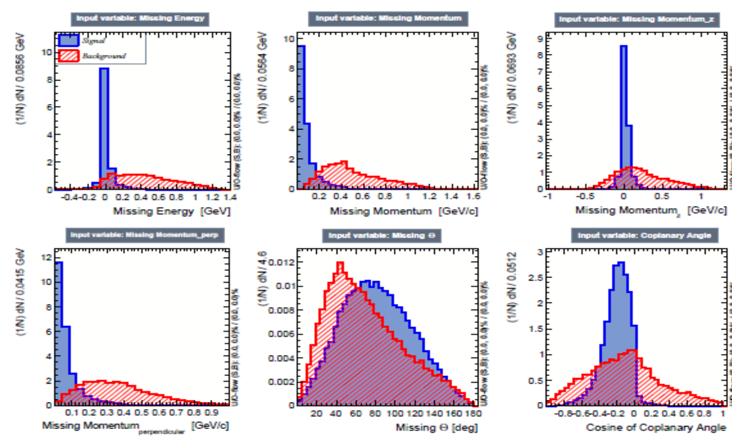
- BDT method

*Details in back-up slides

Event Selection: Al Wires and KelF Cell Wall Removal Using BDT method

TRAINING the BDT algorithm:

- Empty-target data utilized as **background training data**
- Free deuteron simulation data utilized as **signal training data**
- Input variables presented below:



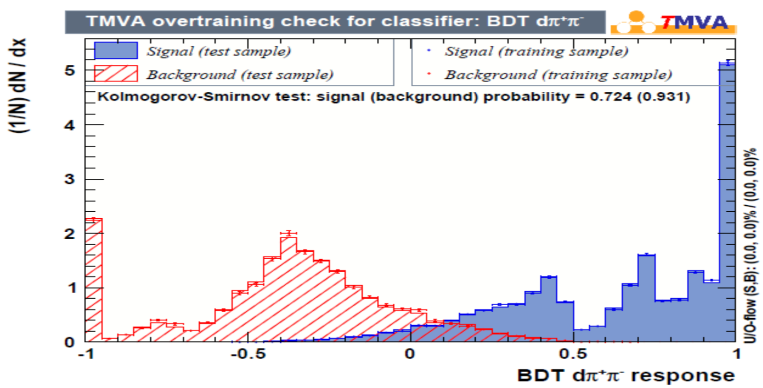
Variable Name	Description
Correlation Angle	$\cos\left((p_{\pi^+} \times p_d) \cdot (p_{\pi^-} \times p_d)\right)$
$MissingMomentum$	Total missing momentum
$MissingEnergy$	Total missing energy
$MissingTheta$	Θ of missing momentum
$MissingMomentum\_z$	$\lvert p_z^{missing} \rvert$
$MissingMomentum\_perp$	$\lvert p_{transverse}^{missing} \rvert$

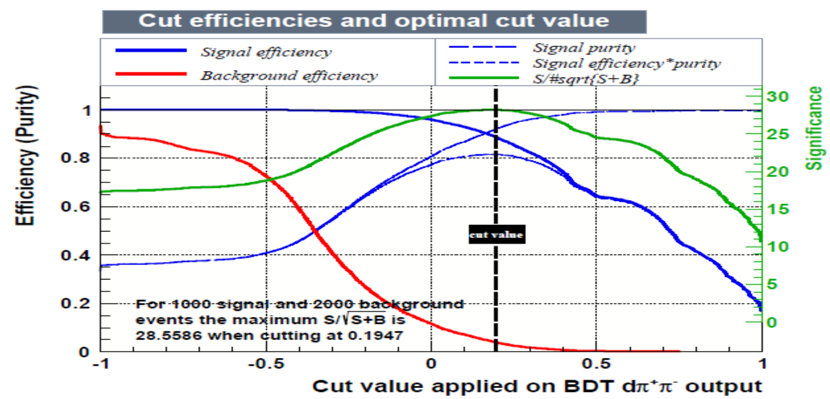
Event Selection: Al Wires and KelF Cell Wall Removal Using BDT method

Performances of the BDT on training and testing data are consistent.

• Placing a cut on BDT output at **0.195** to optimally separate the signal and BG events

BDT output: a quantitative assessment of how likely an event is signal or background (i.e., closer to -1, more likely a BG event, closer to +1, more likely a signal event)



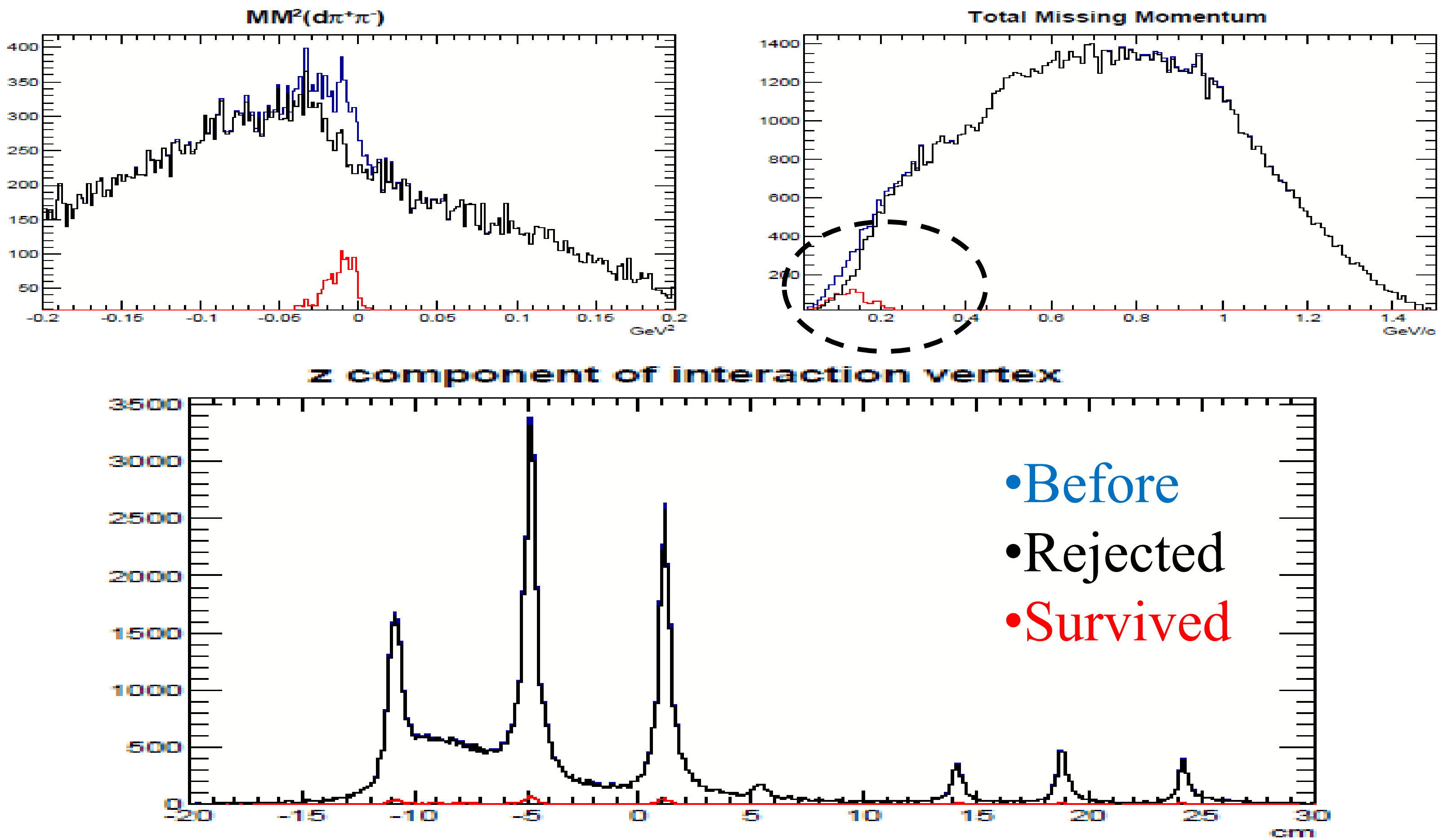


How often each variable was utilized in constructing the decision trees

Variable Name	Relative Ranking
MissingMomentum	1.00
MissingEnergy	0.24
MissingMomentum_perp	0.17
MissingMomentum_z	0.14
Correlation Angle	0.12
MissingTheta	0.10

Event Selection: Al Wires and KelF Cell Wall Removal Using BDT method

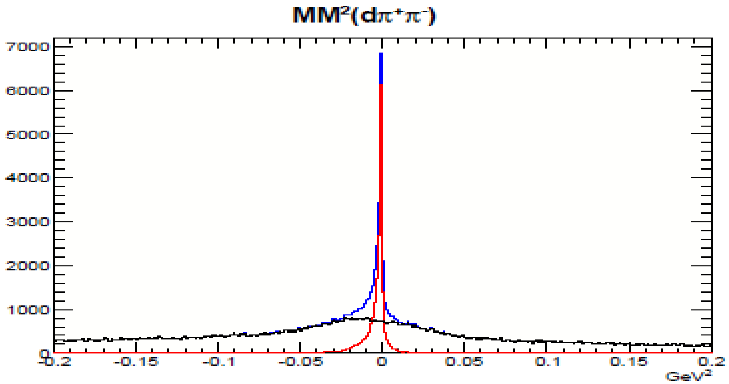
APPLYING the BDT cut to empty-target data

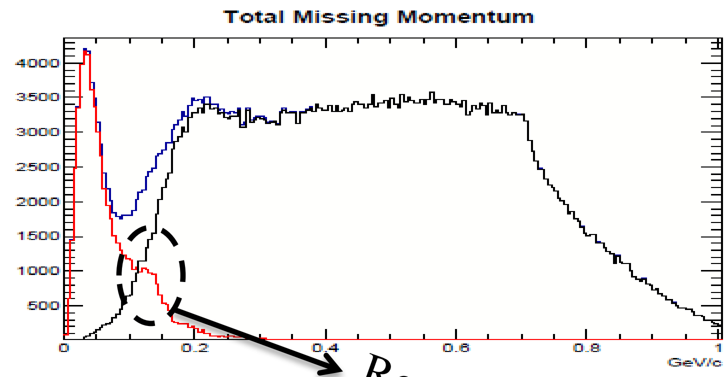


EMPTY-TARGET DATA

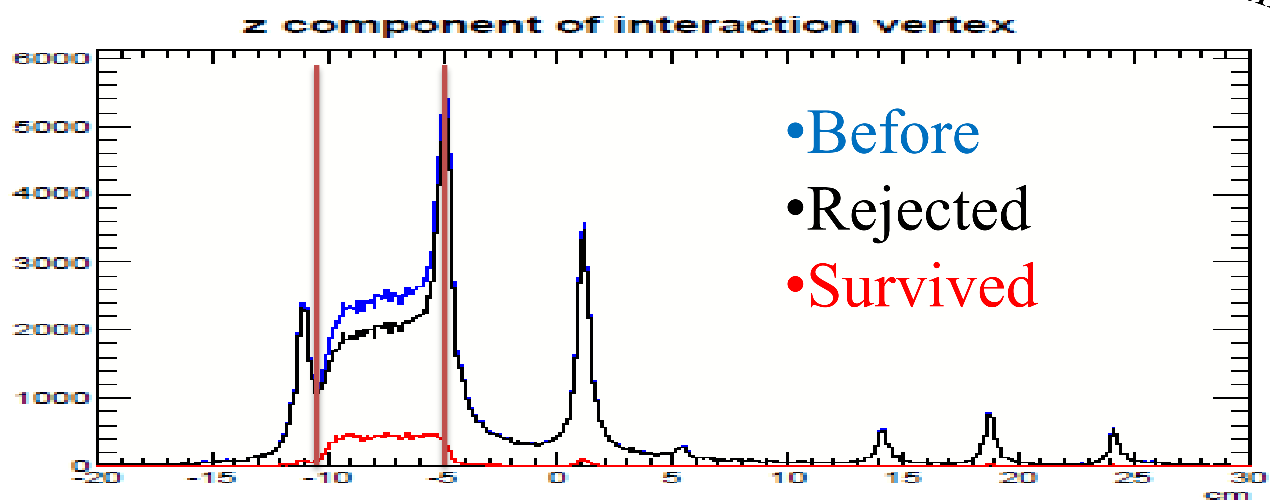
Event Selection: Al Wires and KelF Cell Wall Removal Using BDT method

APPLYING the BDT cut to GOLD2 data

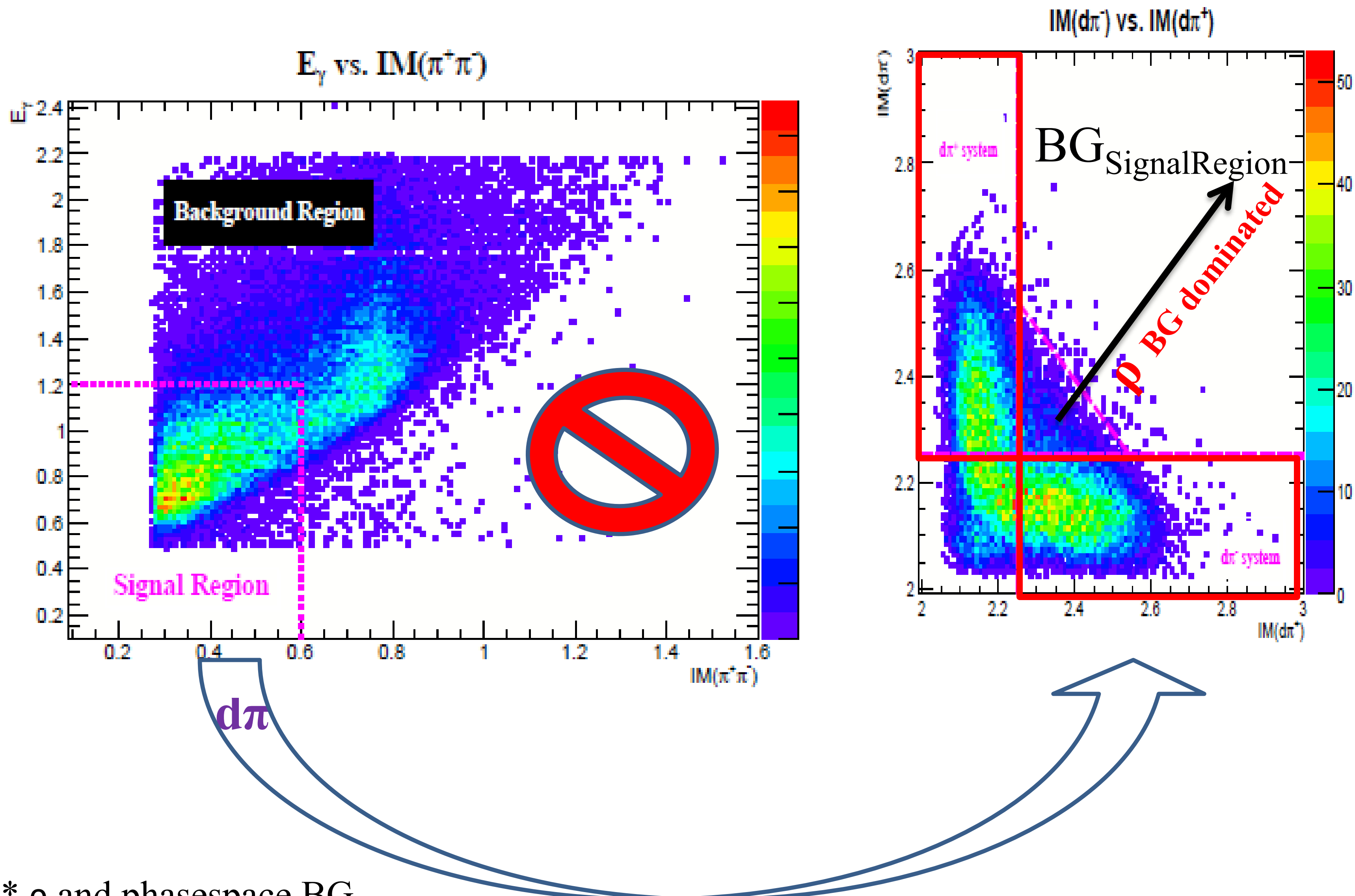




Remaining target-material BG

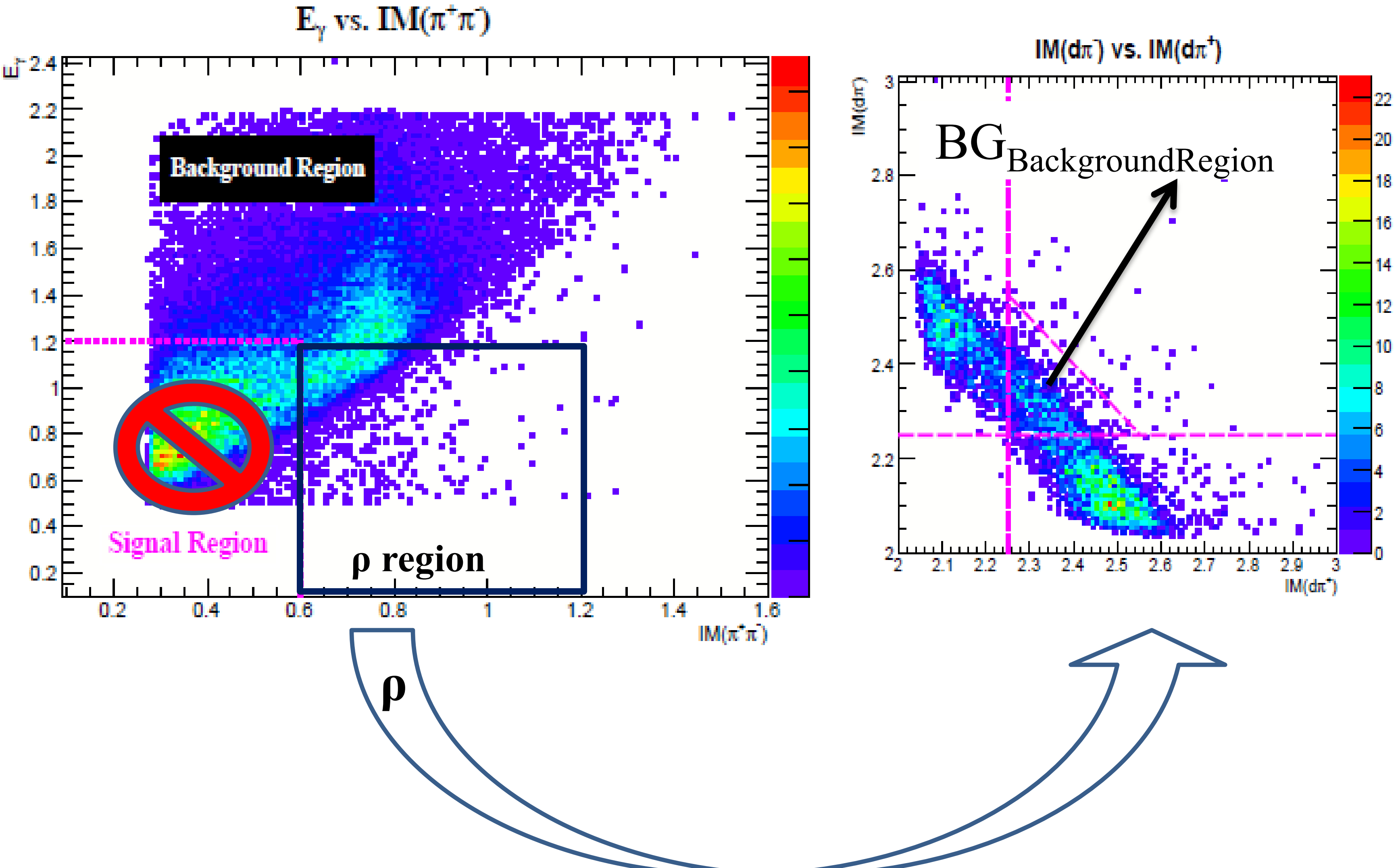


Subtracting Background* Contributions



* ρ and phasespace BG

Subtracting Background Contributions



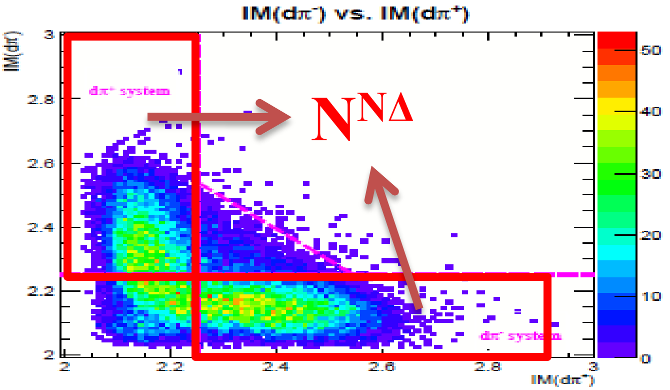
Subtracting ρ Resonance Contribution

Find ε such that: $BG_{SignalRegion} = \varepsilon BG_{BackgroundRegion}$

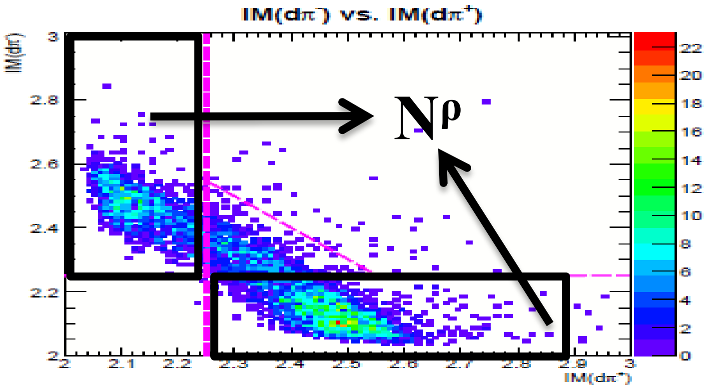
by employing **2D** fitting based on Ξ^2 fitting algorithm (for Poisson distribution)

Apply ρ subtraction (**incoherently**) :

$$E(\cos\theta_d) = \frac{1}{P_\gamma P_d} \frac{(N^{N\Delta}{}_{+-} - \varepsilon N^{\rho}{}_{+-}) - (N^{N\Delta}{}_{++} - \varepsilon N^{\rho}{}_{++})}{(N^{N\Delta}{}_{+-} - \varepsilon N^{\rho}{}_{+-}) + (N^{N\Delta}{}_{++} - \varepsilon N^{\rho}{}_{++})}$$



From Two Previous Slide



From Previous Slide

Model Considerations

$$\vec{J}_{N\Delta} = 2,\ \vec{\mathrm{L}}_{d\pi} = 1$$

$$\left|2,2\right\rangle_{N\Delta} = \chi_d^1 Y_{1,1}$$

$$\left|2,0\right\rangle_{N\Delta} = \alpha_{-1}\chi_d^1 Y_{1,1} + \alpha_0 \chi_d^0 Y_{1,0} + \alpha_{+1}\chi_d^{-1} Y_{1,1}$$

$$I_0 \sim_{d\pi} \left\langle 2,0 \middle| 2,0 \right\rangle_{N\Delta}$$

$$I_2 \sim_{d\pi} \left\langle 2,2 \middle| 2,2 \right\rangle_{N\Delta}$$

$$\vec{J}_{N\Delta} = 1$$

$$I_0 \sim_{d\pi} \left\langle 1,0 \middle| 1,0 \right\rangle_{N\Delta}$$

$$I_2 \sim_{d\pi} \left\langle 1,2 \middle| 1,2 \right\rangle_{N\Delta} = 0$$

$$\Rightarrow \mathrm{E}(\cos\theta_d) = -1$$

$\mathrm{E}(\cos\theta_d)$ has one fitting parameter: $\mathrm{a}_0^2 = |\alpha_0|^2 = 1 - |\alpha_{+1}|^2 - |\alpha_{-1}|^2$

Note that, the Clebsch-Gordan coefficient

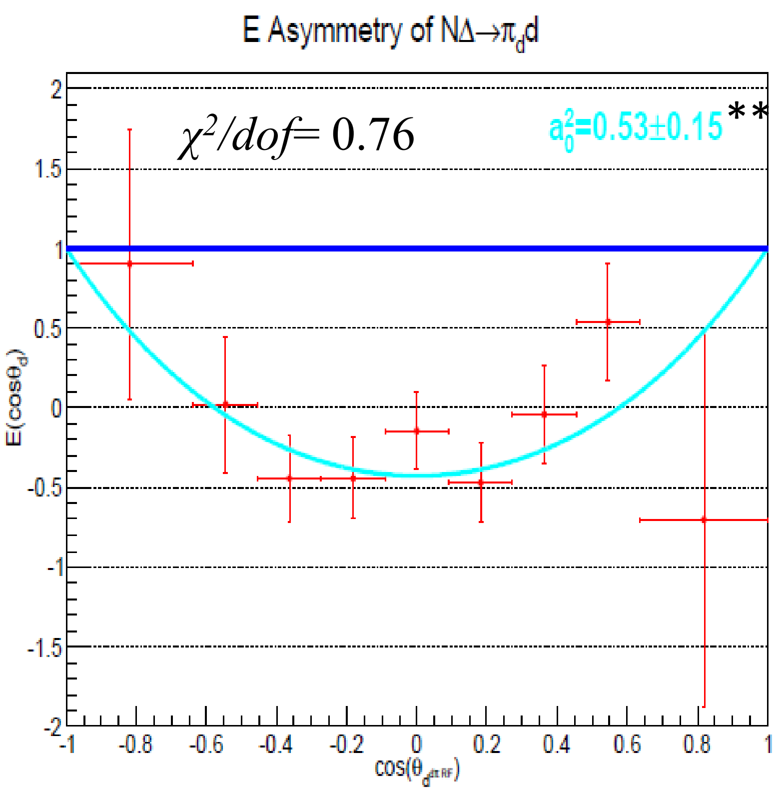
for $\vec{2} = \vec{1} + \vec{1}$: $|\alpha_0|^2 = 2/3$ (this is true for an unpolarized ensemble)

$\vec{J}_{N\Delta} = 2,\ \vec{\mathrm{L}}_{d\pi} = 3$ derived similarly: NEED 3 PARAMETERS

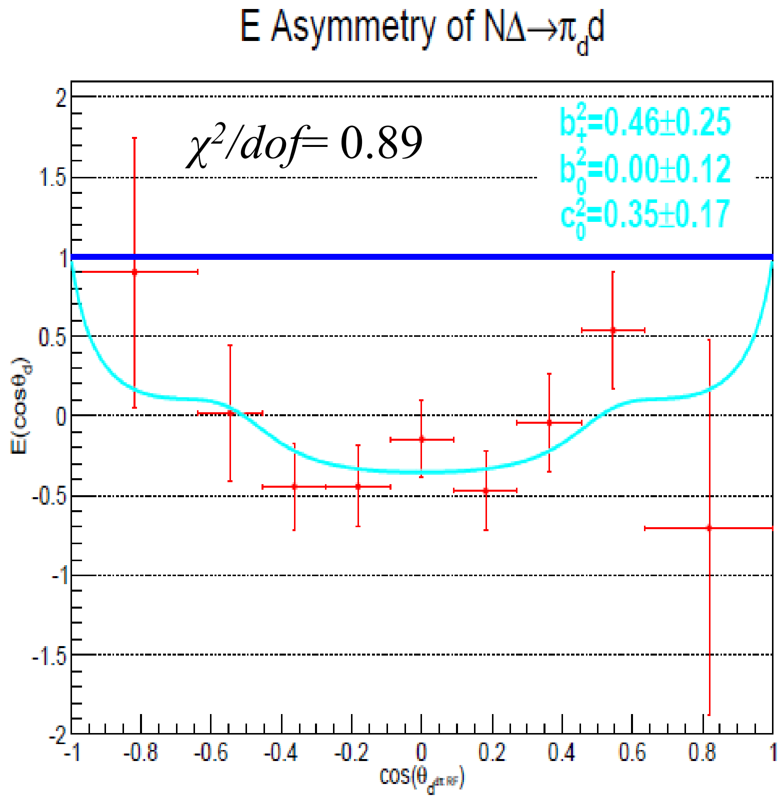
Plotting Helicity Asymmetry

$E(\cos\theta_d) \neq +1 \rightarrow$ ~~Dibaryon (NΔ) system has spin **1**~~

Dibaryon (NΔ) system has spin **2**



$L_{d\pi}$=1

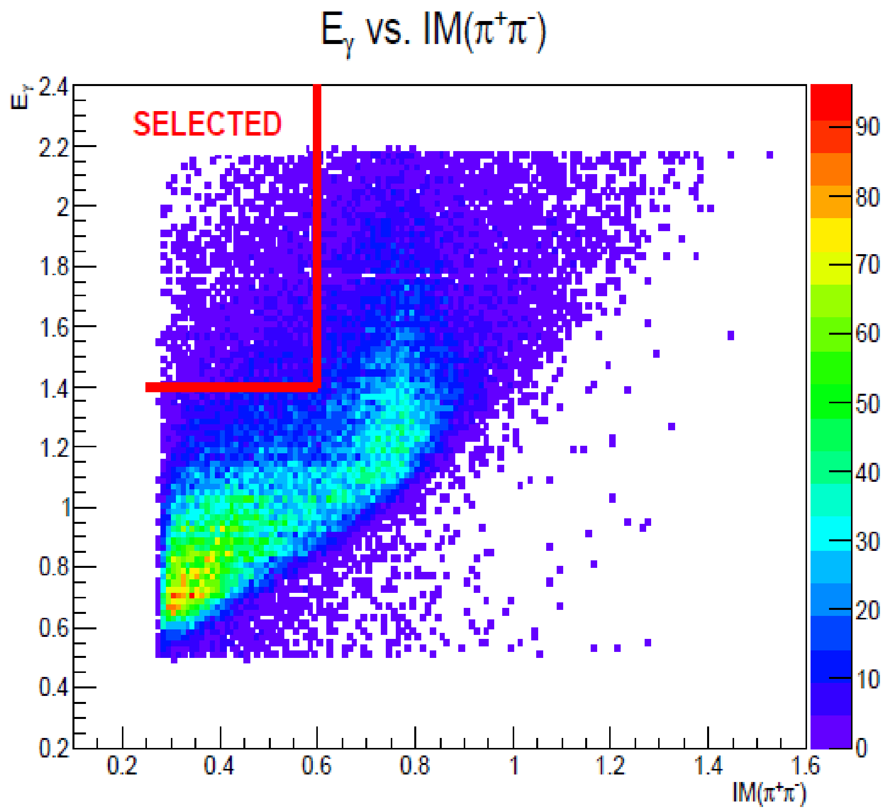


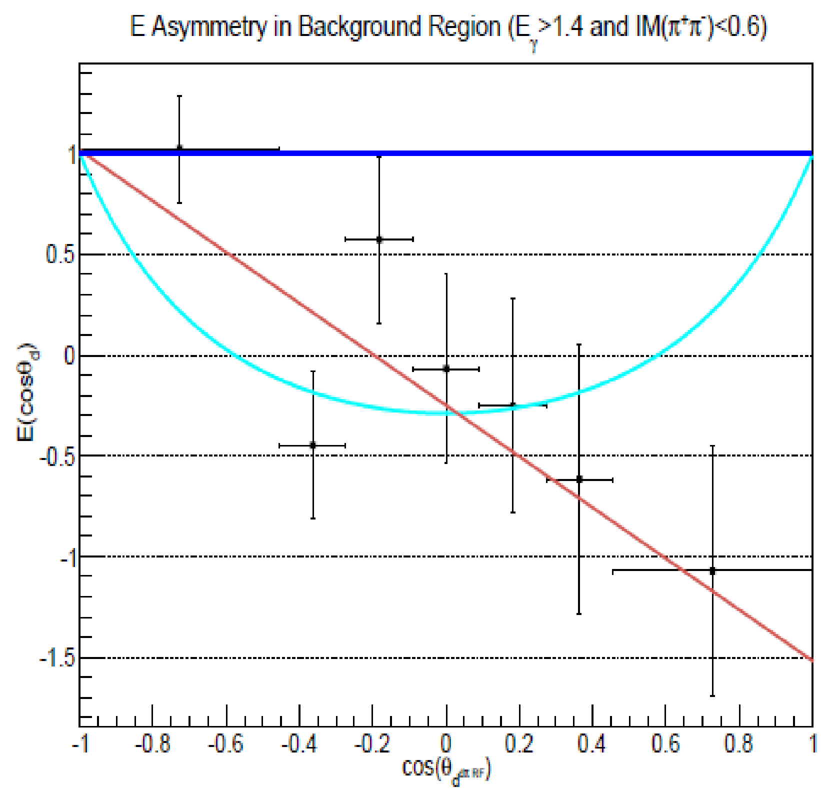
$L_{d\pi}$=3

***: consistent with detected deuteron being unpolarized (newly produced)*

Plotting Helicity Asymmetry

•Selecting region with dominating PHASESPACE background, and computing the E asymmetry
→→→**NO "SMILE" asymmetry**



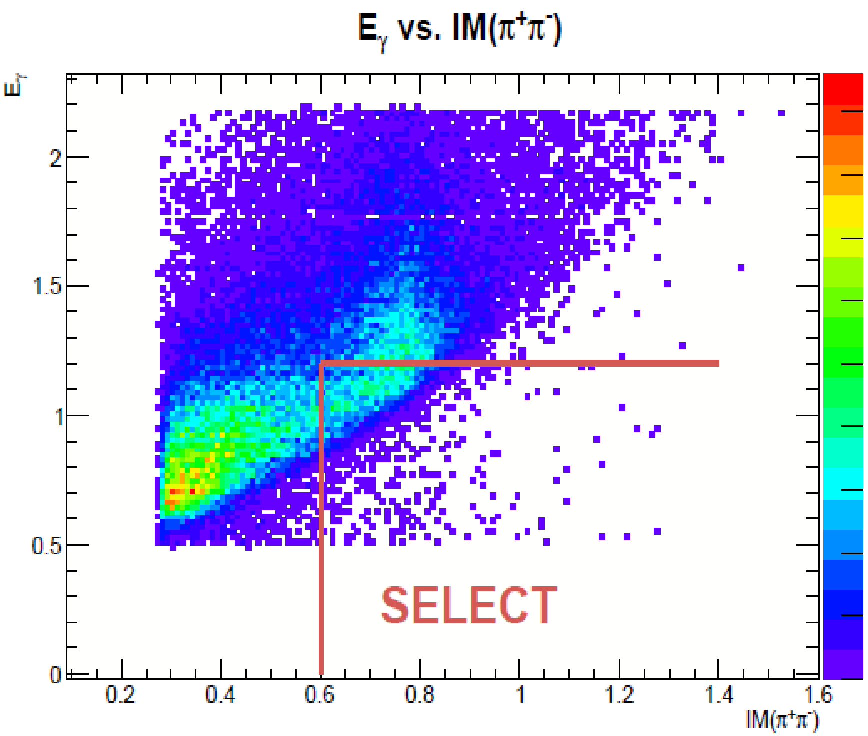


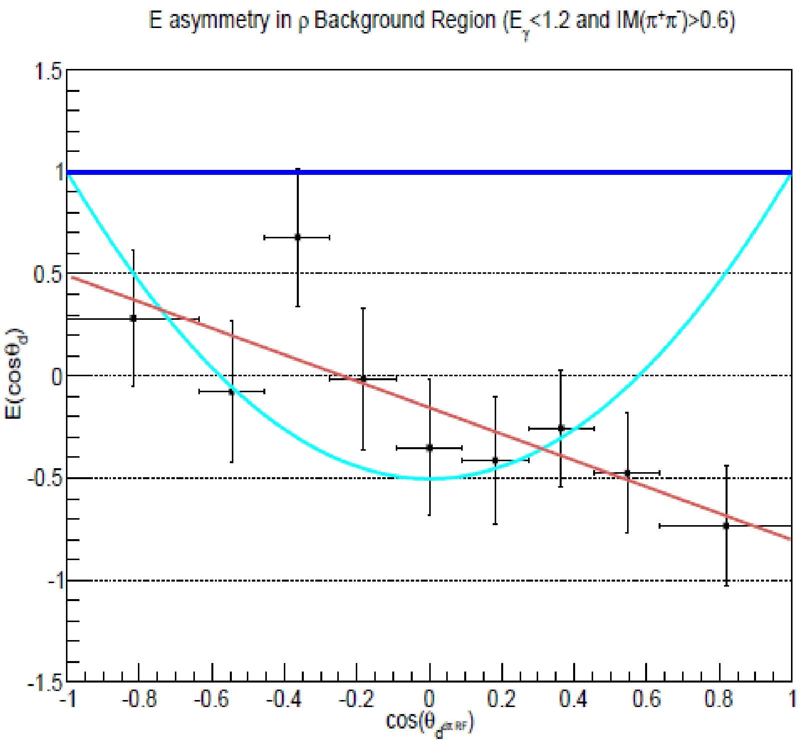
Plotting Helicity Asymmetry

•Selecting region with dominating **ρ** background, and computing the E asymmetry

→→→**NO "SMILE" asymmetry**

Similar looking *E* plots for both BG regions, but different compared to signal region→→→ the PHYSICS are DISTINCT





Systematic Studies

- First test (2 parts): Varying the **ρ** scaling factor (ε) by $\pm 5\sigma_{\varepsilon}$
- Second test: Loosening the E_{γ} cut to 1.6 GeV (from 1.2 GeV)
- Third test: Tightening the $IM(\pi^{+}\pi^{-})$ cut to 0.45 GeV (from 0.6 GeV)
- Forth test: Loosening the BDT output cut to 0.0 (from 0.195)

$J_{N\Delta}=2$, $L_{d\pi}=1$

final-fitting result a_0^2=0.53±0.15			
	a_0^2	$\lvert\sigma_{sys}\rvert$	σ^2_{sys}
1^{st} test (part 1)	0.49	0.04	0.0016
1^{st} test (part 2)	0.56	0.03	0.0009
2^{nd} test	0.49	0.04	0.0016
3^{rd} test	0.50	0.03	0.0009
4^{th} test	0.47	0.06	0.0036
$\sigma^2_{overall}$			0.0086
$\sigma_{overall}$			0.09

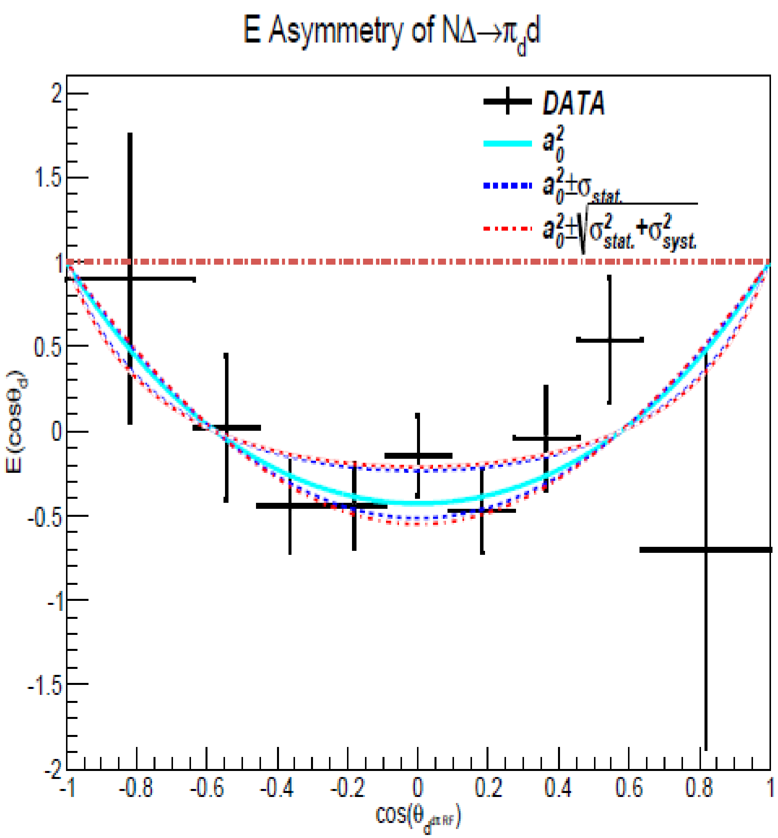
Systematic Studies (Cont.)

$J_{N\Delta}$=2, L $_{d\pi}$=3

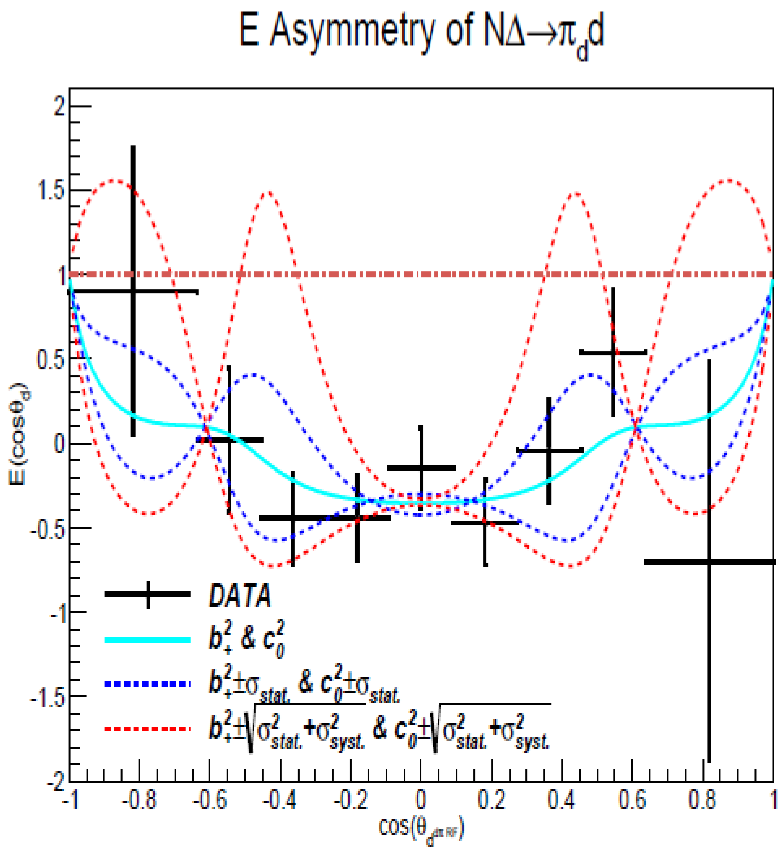
final-fitting result b_+^2=0.46±0.25				final-fitting result c_0^2=0.35±0.17		
	b_+^2	$\lvert\sigma_{sys}\rvert$	σ_{sys}^2	c_0^2	$\lvert\sigma_{sys}\rvert$	σ_{sys}^2
1^{st} test (part 1)	0.52	0.06	0.0036	0.35	0.00	0.0000
1^{st} test (part 2)	0.34	0.12	0.0144	0.35	0.00	0.0000
2^{nd} test	0.55	0.09	0.0081	0.40	0.05	0.0025
3^{rd} test	0.00	0.59	0.3481	0.42	0.07	0.0049
4^{th} test	0.56	0.10	0.0100	0.33	0.02	0.0004
$\sigma_{overall}^2$			0.3842	$\sigma_{overall}^2$		0.0078
$\sigma_{overall}$			0.62	$\sigma_{overall}$		0.09

Systematic Studies (Cont.)

- Adding into fit parameters $\pm\sigma_{stat.}$ and $\pm\ \sigma_{stat.\&\ syst.}$



$J_{N\Delta}$=2, $L_{d\pi}$=1



$J_{N\Delta}$=2, $L_{d\pi}$=3

Conclusions

- Non-zero E asymmetry has been observed in the dπ system
- **$J_{N\Delta}$=1, $L_{d\pi}$=1 can be discarded** since $E \neq +1$
- **$J_{N\Delta}$=2, $L_{d\pi}$=1** fit is best given the data
- **$J_{N\Delta}$=2, $L_{d\pi}$=1** fit parameter suggests the detected neutrons are newly produced (not the target *polarized* neutrons):

$$|\alpha_0|^2 = 0.53 \pm 0.15(stat.) \pm 0.09(syst.) \approx 2/3$$

- **$J_{N\Delta}$=2, $L_{d\pi}$=3** hypothesis overfits the data

BACK UP

"E" Asymmetry in g14 Data

"+ +" $$| J = 2, J_z = +2\rangle_{N\Delta} \rightarrow Y_{1,+1}(\Theta,\phi)\chi^d_{+1}$$

"+ –" $$|2, \quad 0\rangle_{N\Delta} \rightarrow a_{\pm}Y_{1,-1}\chi^d_{+1} + a_0 Y_{1,0}\chi^d_0 + a_{\pm}Y_{1,+1}\chi^d_{-1}$$

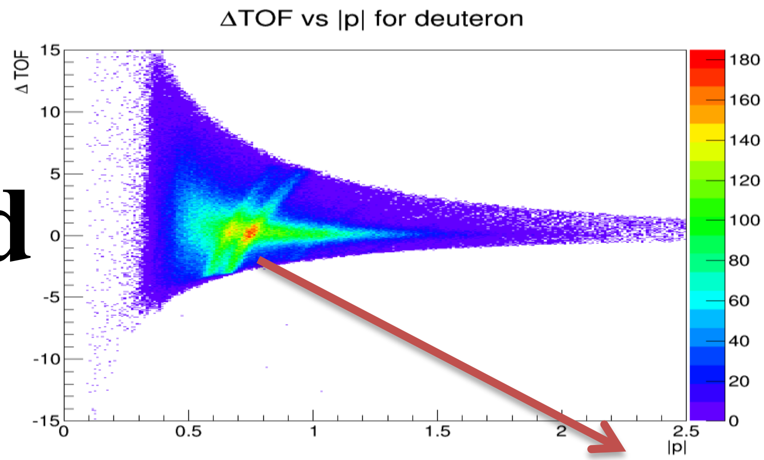
- Compute decay angular distributions
  - Let $a_0^2 = 1 - a_-^2 - a_+^2$ to normalize

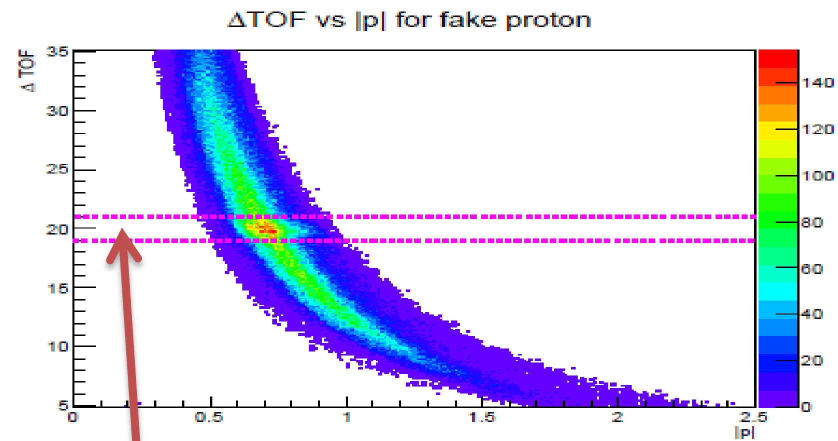
$$I_2 \sim {}_{\pi d}\langle 2,2 | 2,2\rangle_{N\Delta} \qquad\qquad I_0 \sim {}_{\pi d}\langle 2,0 | 2,0\rangle_{N\Delta}$$

$$E = \frac{I_0(\Theta) - I_2(\Theta)}{I_0(\Theta) + I_2(\Theta)}$$

Event Selection: ΔTOF cuts

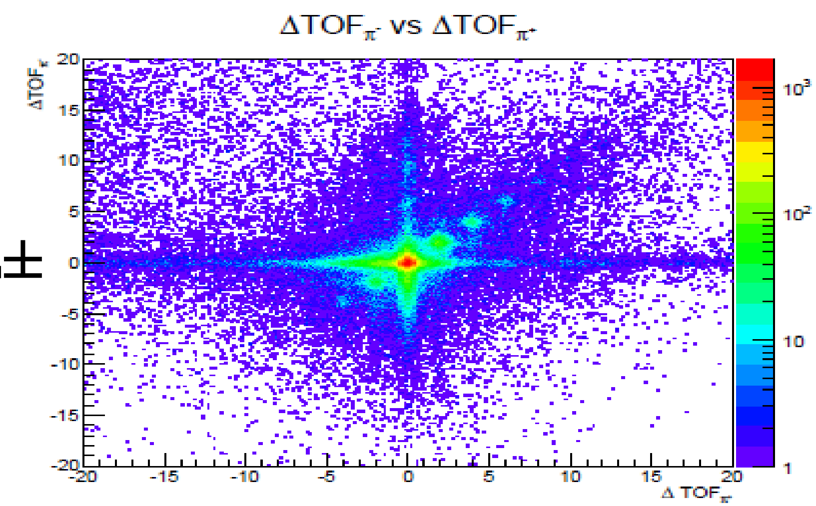
d

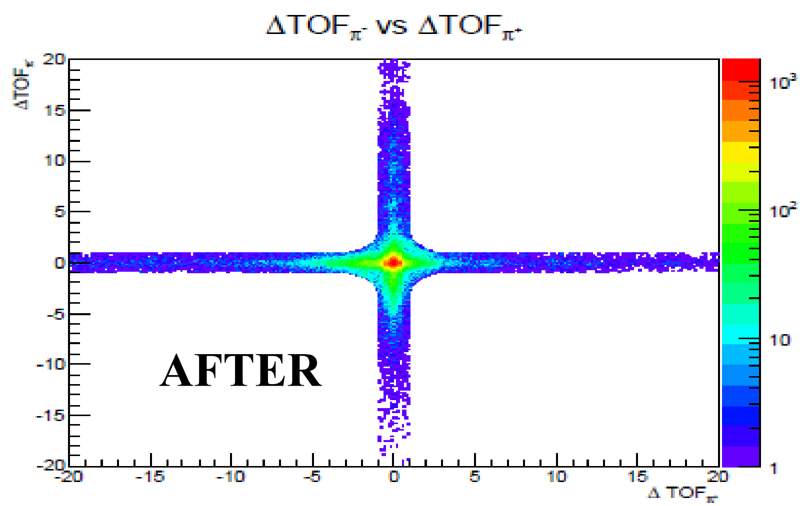




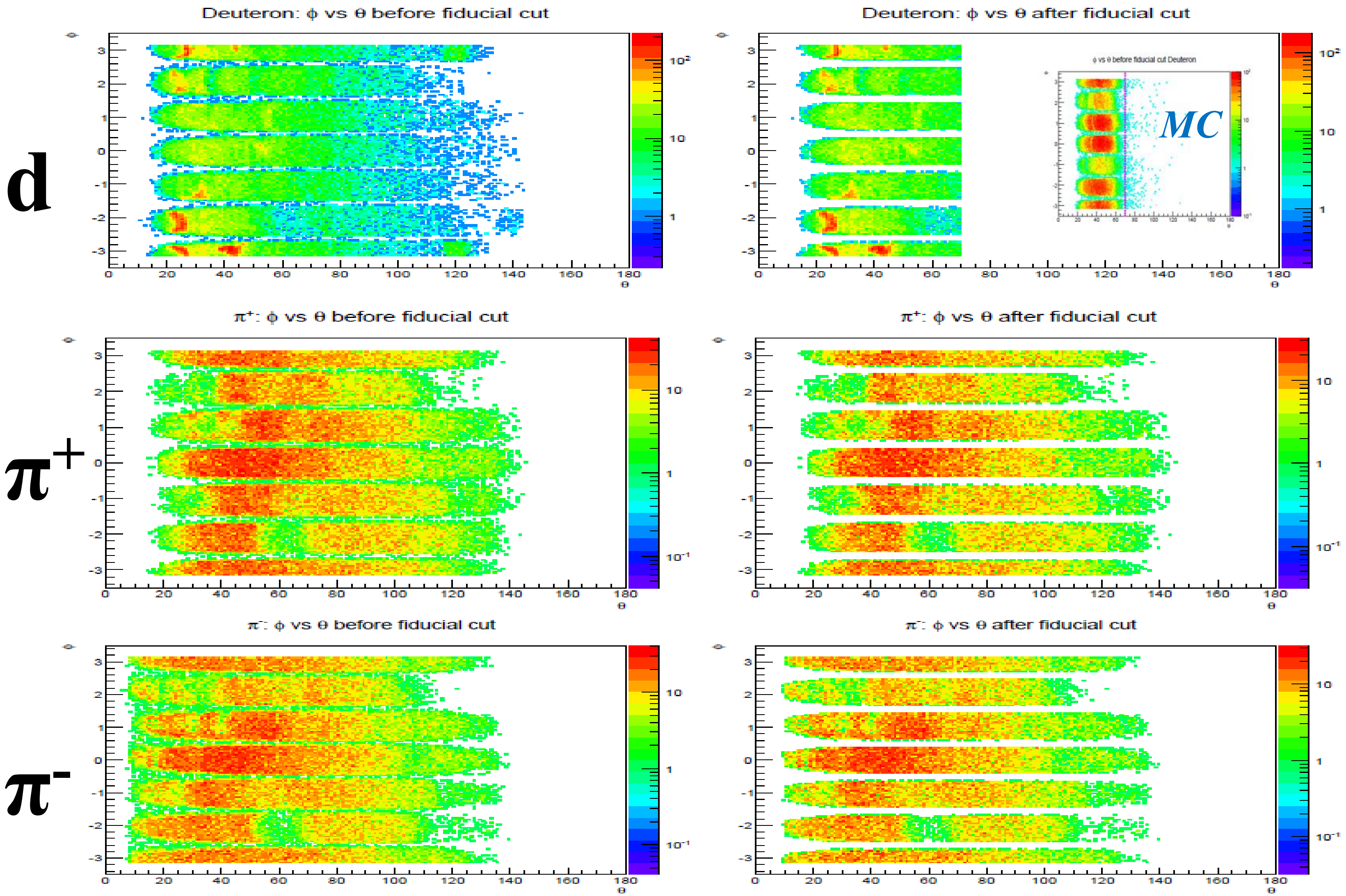
NEED TO REJECT MISIDENTIFIED PROTONS

$\pi^{\pm}$





Event Selection: Fiducial cuts



Results for the E Asymmetry Measurements for $K^0\Lambda$ and $K^0\Sigma^0$

Outline

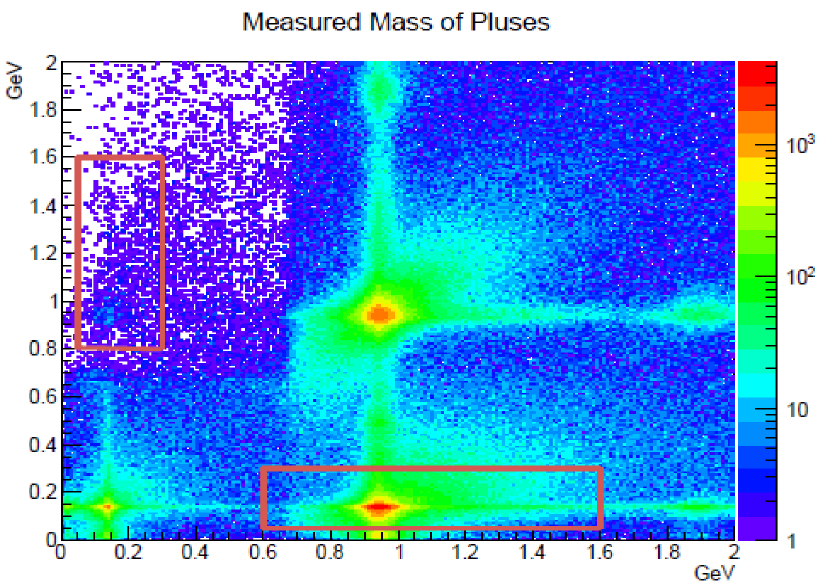
- **$\pi^+\pi^- p\ \pi^-$ Event Selection (Cut-Based Selection)**
  - Particle Identification: Measured Mass Cuts
  - Particle Identification: ΔTOF Cuts
  - Detector Performance: Fiducial Cuts
  - *Quasi-free Neutron* Loose Selection: Squared Missing Mass Cut
  - K^0Y Loose Selection: IM($p\pi_\Lambda^-$) and IM($\pi^+\pi_{K0}^-$) Cuts
- ***Quasi-Free Neutron K^0Y* Event Selection (BDT-Based Selection)**
  - *Quasi-free* Neutron Selection
  - K^0Y Selection, non-strange 4-body phasespace Rejection
  - Separating $K^0\Lambda$ and $K^0\Sigma^0$

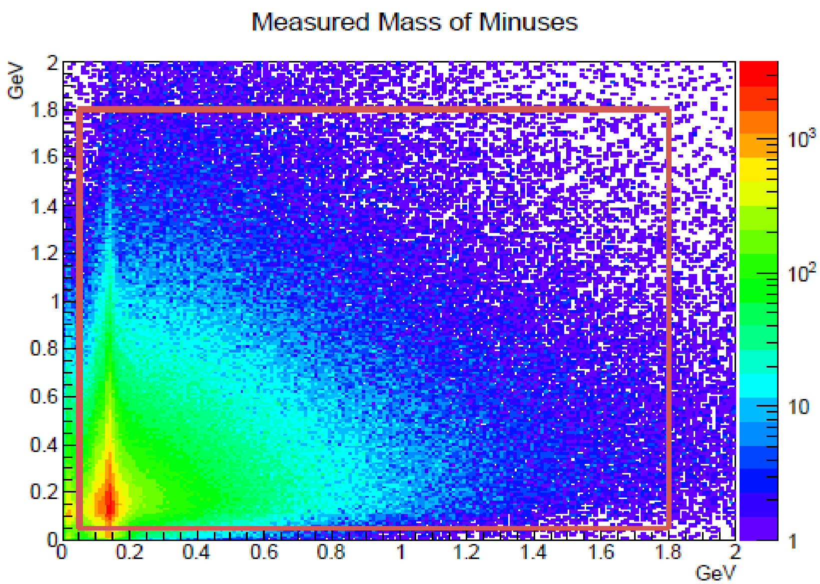
	Quasi-Free Neutrons	Target-Material BG
K^0Y	**SELECT**	***REJECT***
Phasespace BG	***REJECT***	***REJECT***

Outline (Cont.)

- **Gold 2 Quasi-free Neutron $K^0\Lambda$ and $K^0\Sigma^0$ Event Selection**
- **Corrections for final E measurements**
  - Remaining Target-Material BG Correction
  - Remaining Phasespace BG Correction
  - *"Purify"* the BDT $K^0\Lambda$ /$K^0\Sigma^0$ Selection Samples
- **Plotting the E for both $K^0\Lambda$ and $K^0\Sigma^0$**
- **Systematic Studies**

Particle Identification: Measured Mass Cuts

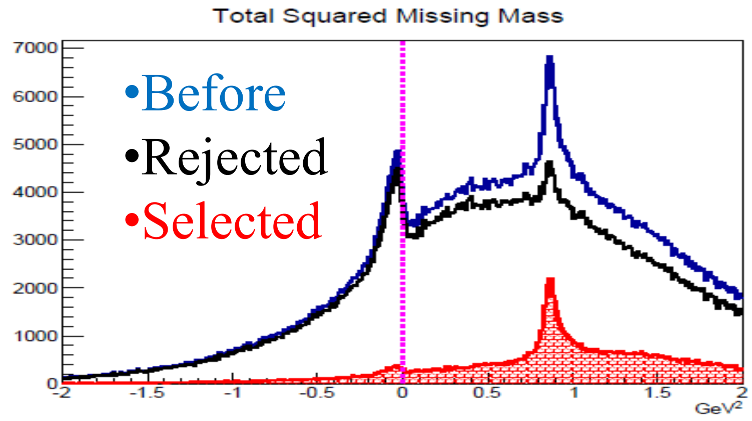




•Selecting events with **2 positive and 2 negative tracks**

•Placing the measured mass cuts (red rectangles) to select $\pi^+\pi^- p\,\pi^-$ events

→Measured masses computed from measured TOF, pathlength, and momentum



ΔTOF and Fiducial Cuts*

- ΔTOF cuts

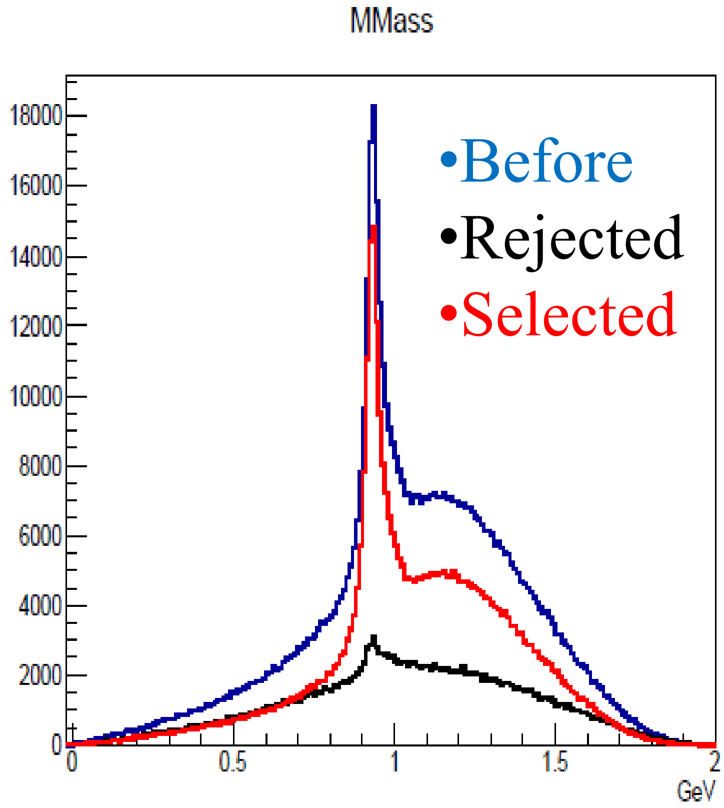
→To reject **misidentified** protons

→To reject wrong timing (wrong beam buckets) events

- Fiducial cuts

→To reject edges of the detectors

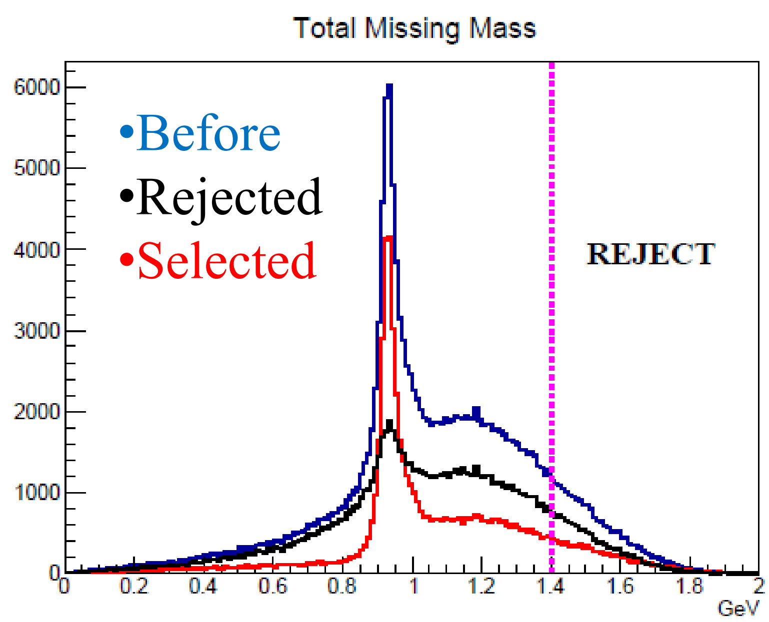
→Reject non-HD events (mostly in the deuteron backward direction)

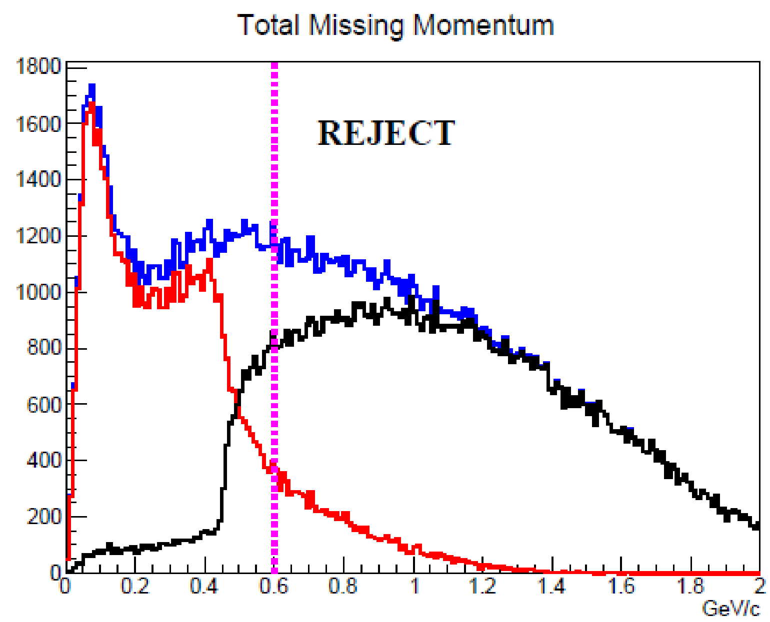


Quasi-free Neutron Loose Selection: Squared Missing Mass Cut

- Assigning the target with the ***neutron*** mass* →→→ Reject events $MM^2 < -0.2\ GeV^2$
- **Effect from the cut is shown below (distributions computed with deuteron mass)**

- *Extra cuts on Missing Mass (at 1.4 GeV), and Missing Momentum (at 0.6 GeV/c)→ remove unambiguous BG events*





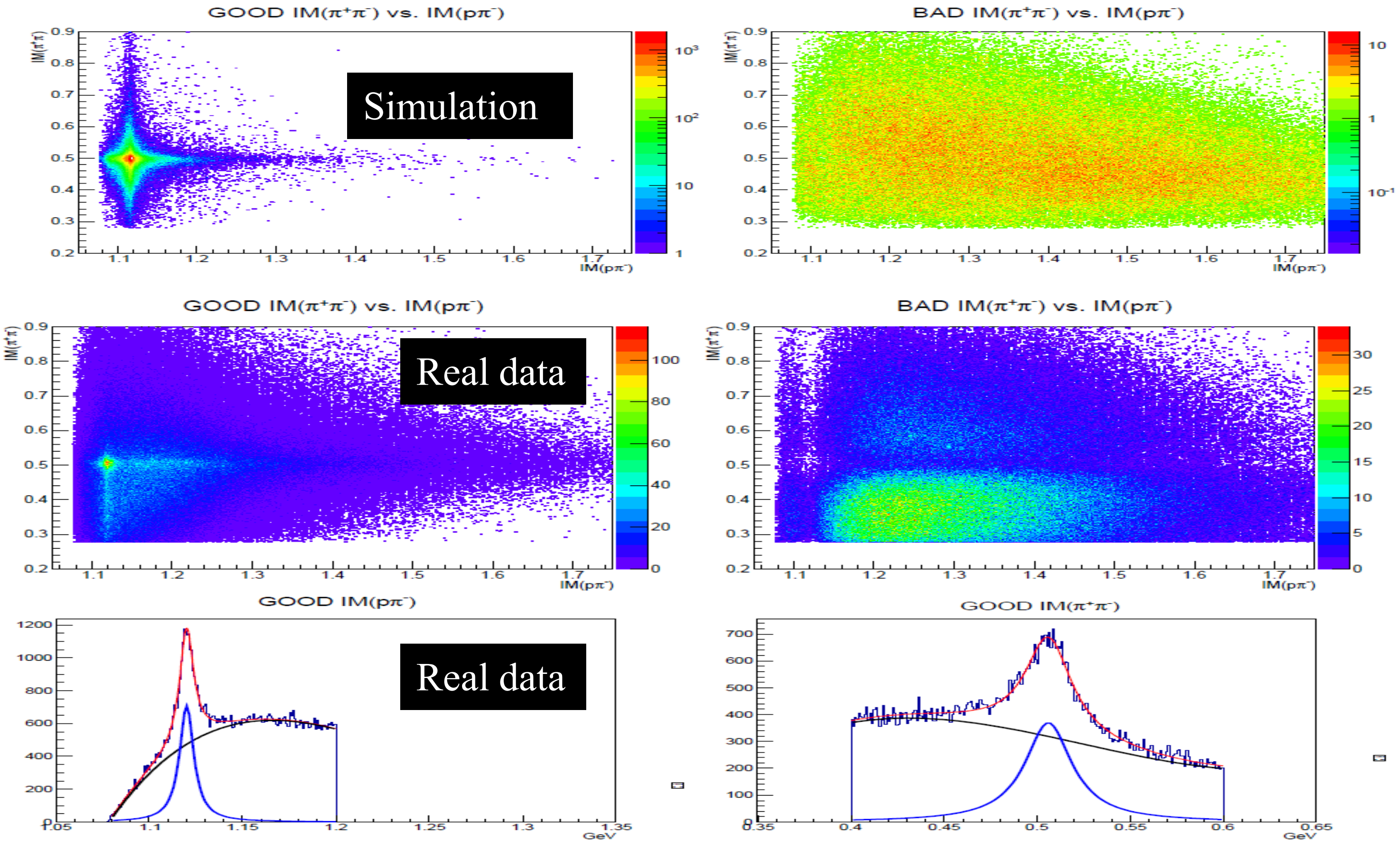
Note that for $K^0\Sigma^0$ events missing mass can be up to 1.4 GeV, and missing momentum can be up to 0.6 GeV/c.

* More details in back-up slides

K^0Y Loose Selection: IM($p\pi_\Lambda^-$) and IM($\pi^+\pi_{K0}^-$) Cuts

Question: ***Which π^- should be paired with the proton, π^+***

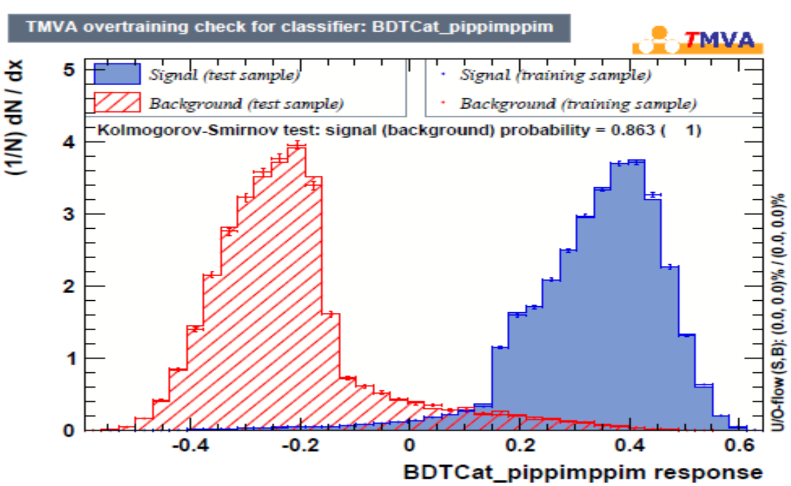
→Procedure implemented used four IM combinations to decide! (back-up slides)

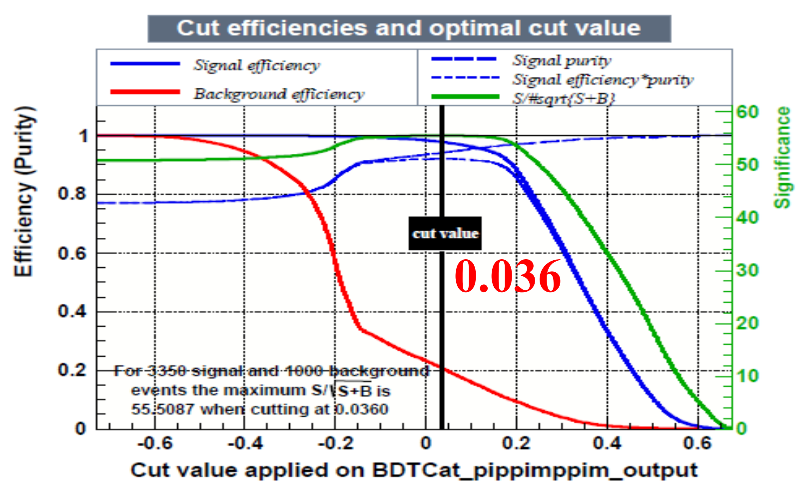


BDT-Based Selection: *Quasi-free* Neutron Selection

TRAINING the 1st BDT algorithm:

Variable Name	Description
$MissingEnergy$	Total missing energy
$MissingMomentum$	Total missing momentum
$MissingTheta$	Θ of missing momentum
$MissingBeta$	β
$MissingGamma$	γ
$CoplanaryAngle$	$\left(p_{(p\pi^-_{\Lambda})} \times p_{\gamma}\right) \cdot \left(p_{(\pi^+\pi^-_{K0})} \times p_{\gamma}\right)$
$MissingPlus$	$E^{missing} + c\lvert p_z^{missing}\rvert$
$MissingMinus$	$E^{missing} - c\lvert p_z^{missing}\rvert$
$MissingPerp$	$\lvert p_{transverse}^{missing}\rvert$



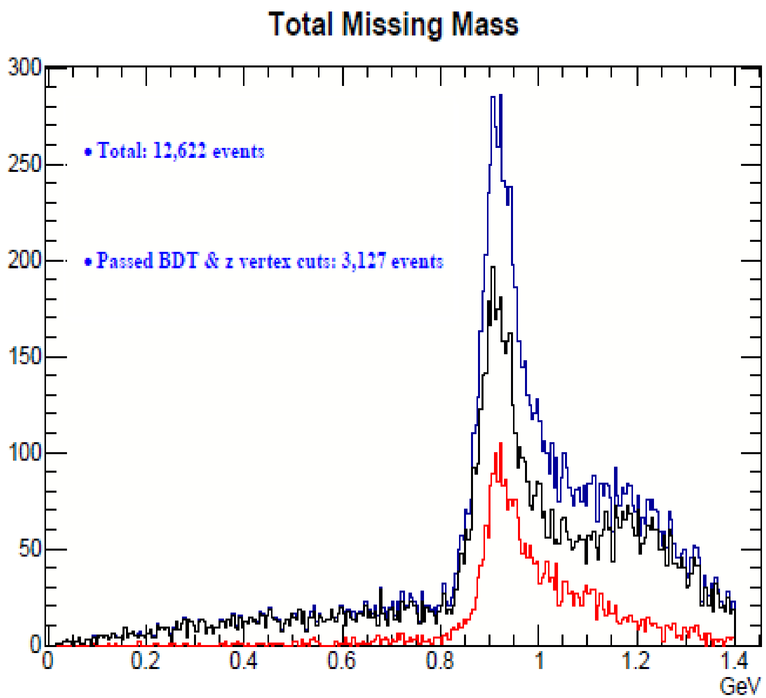


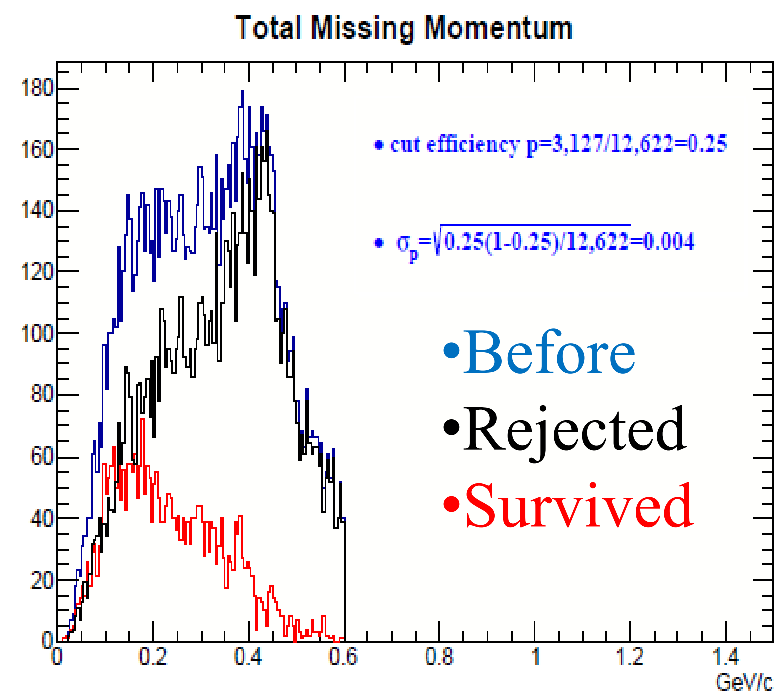
BDT-Based Selection: *Quasi-free* Neutron Selection

APPLYING the 1st BDT cut to empty-target data:

• Estimating **25%** of target-material BG events surviving the 1st BDT cut

•If we have an estimation of initial number of target-material BG events for the real data (for example, the Gold 2 data), then we can estimate the number of remaining BG events.





EMPTY-TARGET DATA

BDT-Based Selection: K^0Y Selection

TRAINING the 2nd BDT algorithm:

- 4-body phasespace simulation data utilized as background training data
- K^0Y signal simulation data as signal training data
- Input variables presented below*:

$$lnlikelihood \equiv \ln\left[f_{BW}(IM(p\pi^-_{\Lambda}), m_{\Lambda}, \Gamma_{\Lambda}) \times f_{BW}(IM(\pi^+\pi^-_{K^0}), m_{K^0}, \Gamma_{K^0})\right]$$

Variable Name	Ranking	Variable Name	Ranking
ln(likelihood)	1.0	$\cos\theta_{K^0}$	0.14
$\cos\theta_{\pi^+\&\pi^-_{K0}}$	0.27	$\lvert P\rvert_{K^0}$	0.13
$(p\pi^-_{K^0})$ decay distance	0.25	p and $\pi^-_{K^0}$ DOCA	0.13
$\cos\theta_{K^0\&\Lambda}$	0.20	$(\pi^+\pi^-_{\Lambda})$ decay distance	0.13
$\beta_{\pi^-_{\Lambda}}$	0.20	$(\pi^+\pi^-_{K^0})$ decay distance	0.12
$\cos\theta_{\Lambda}$	0.19	$\beta_{(\pi^+\pi^-_{K^0})}$	0.12
π^+ and π^-_{Λ} DOCA	0.17	Energy of K^0	0.12
$(p\pi^-_{\Lambda})$ decay distance	0.17	$\beta_{(p\pi^-_{\Lambda})}$	0.11
$\cos\theta_{p\&\pi^-_{\Lambda}}$	0.16	β_{π^+}	0.11
β_p	0.16	$\lvert P\rvert_{\Lambda}$	0.11
K^0 and Λ DOCA	0.15	Energy of Λ	0.10
$\beta_{\pi^-_{K^0}}$	0.14		

*Ranking is known only *after* the training

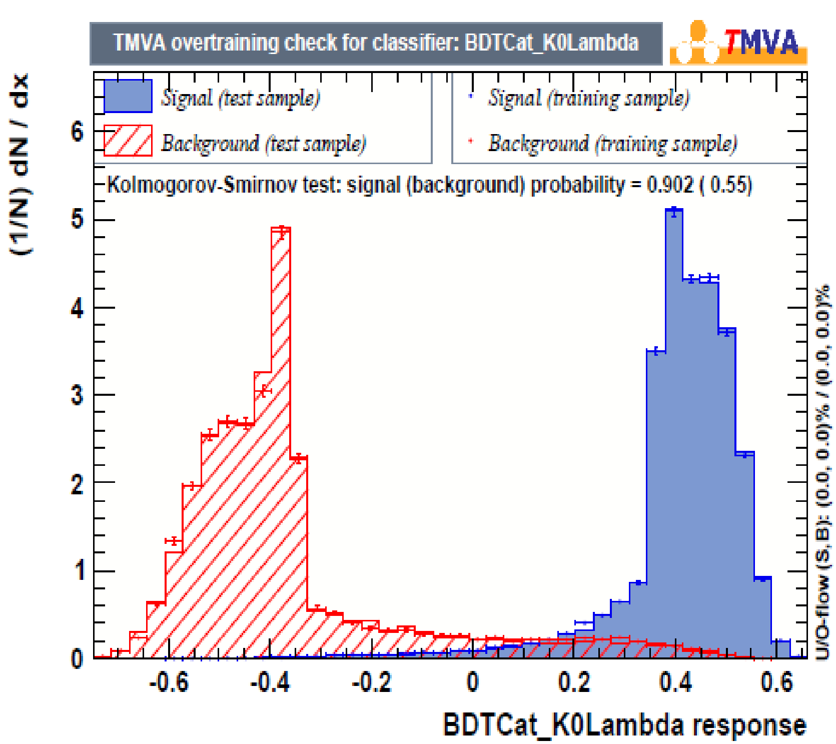
BDT-Based Selection: K^0Y Selection

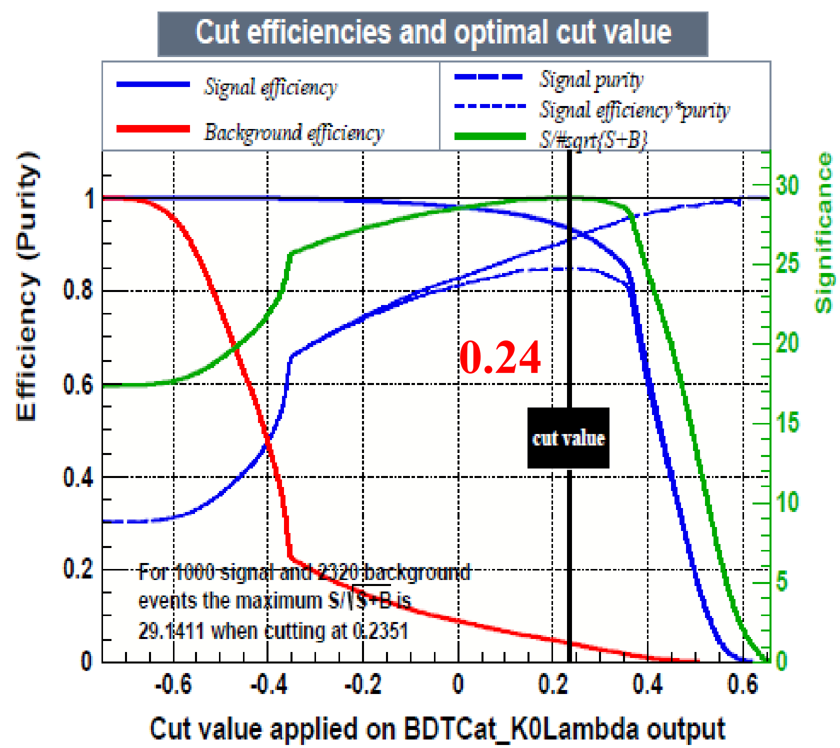
RESULT OF TRAINING the 2nd BDT algorithm:

• Performances of the BDT on training and testing data are consistent.

• Placing a cut on BDT output at 0.24 to optimally separate the signal and BG events

BDT output: a quantitative assessment of how likely an event is signal or background (i.e., closer to -1, more likely a BG event, closer to +1, more likely a signal event)





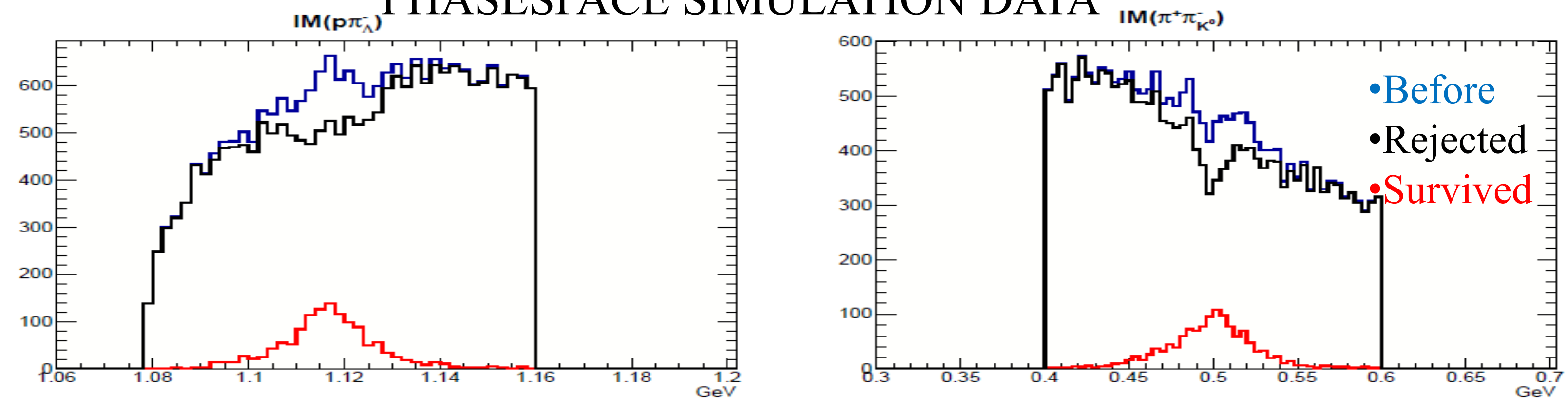
BDT-Based Selection: K^0Y Selection

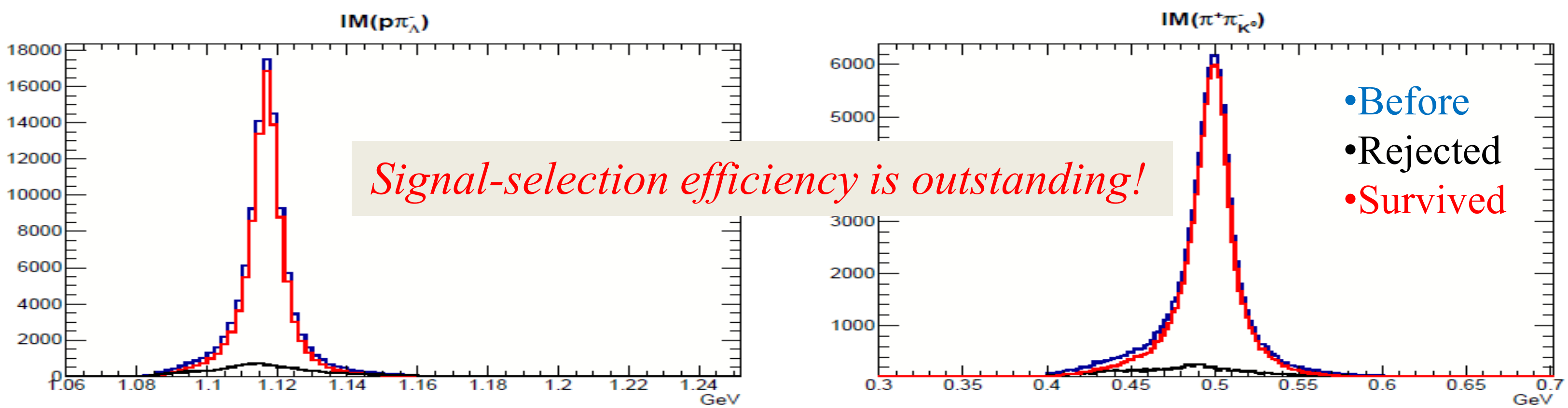
APPLYING the 2nd BDT cut to phasespace BG data:

- Estimating **5.7%** of phasespace BG events surviving the 2nd BDT cut

•If we have an estimation of initial number of phasespace BG events for the real data (for example, the Gold 2 data), then we can estimate the number of remaining BG events.

PHASESPACE SIMULATION DATA





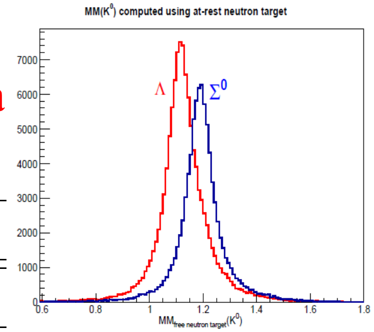
Signal-selection efficiency is outstanding!

K^0Y SIGNAL SIMULATION DATA

BDT-Based Selection: $K^0\Lambda$/ $K^0\Sigma^0$ Separation

TRAINING the 3rd BDT algorithm:

- **$K^0\Sigma^0$ as "background" training data, $K^0\Lambda$ as "signal" training data**
- Input variables presented below:



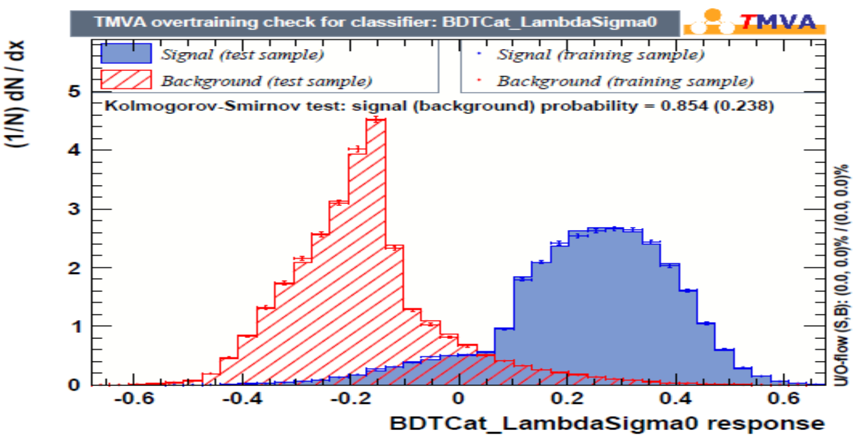
Variable Name	Description
Missing Mass	Total missing mass (deuteron target)
Missing Energy	Total missing energy (deuteron target)
Missing Momentum	Total missing momentum (deuteron target)
Missing Theta	Θ of the missing momentum in lab coordinate (deuteron target)
Missing Beta	$\beta_{missing}$ (deuteron target)
Missing Gamma	$\gamma_{missing}$ (deuteron target)
Missing Plus	$E^{missing} - c\lvert p_z^{missing}\rvert$ (deuteron target)
Missing Minus	$E^{missing} + c\lvert p_z^{missing}\rvert$ (deuteron target)
Missing Perp	$\lvert p_{transverse}^{missing}\rvert$ (deuteron target)
Coplanary Angle	$\left(p_{(p\pi^-_\Lambda)} \times p_\gamma\right) \cdot \left(p_{(\pi^+\pi^-_{K0})} \times p_\gamma\right)$ (deuteron target)
Missing Mass off K^0	$MM(\pi^+\pi^-_{K0})$ (*at-rest* neutron target)
$\theta_{K^0\&\Lambda}$	angle between $(\pi^+\pi^-_{K0})$ and $(p\pi^-_\Lambda)$ in $(\gamma n_{\text{at-rest}})$ rest frame

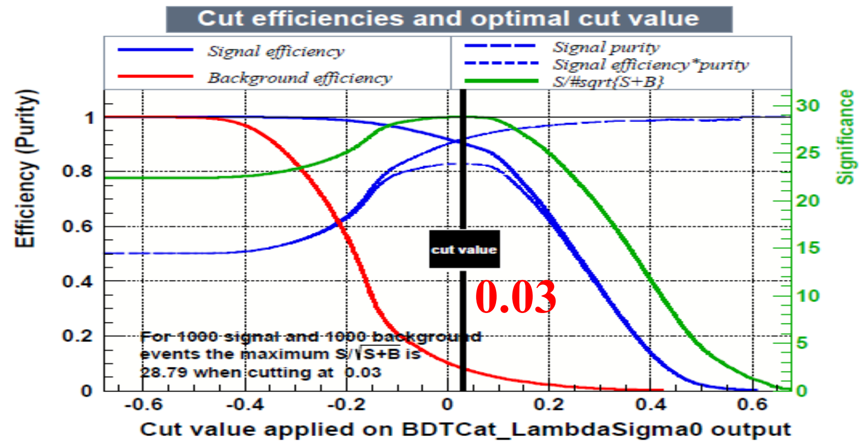
BDT-Based Selection: $K^0\Lambda / K^0\Sigma^0$ Separation

RESULT OF TRAINING the 3rd BDT algorithm:

- Performances of the BDT on training and testing data are consistent.
- Placing a cut on BDT output at **0.03** to optimally separate the "signal" and "BG" events

BDT output: a quantitative assessment of how likely an event is signal or background (i.e., closer to -1, more likely a BG event, closer to +1, more likely a signal event)



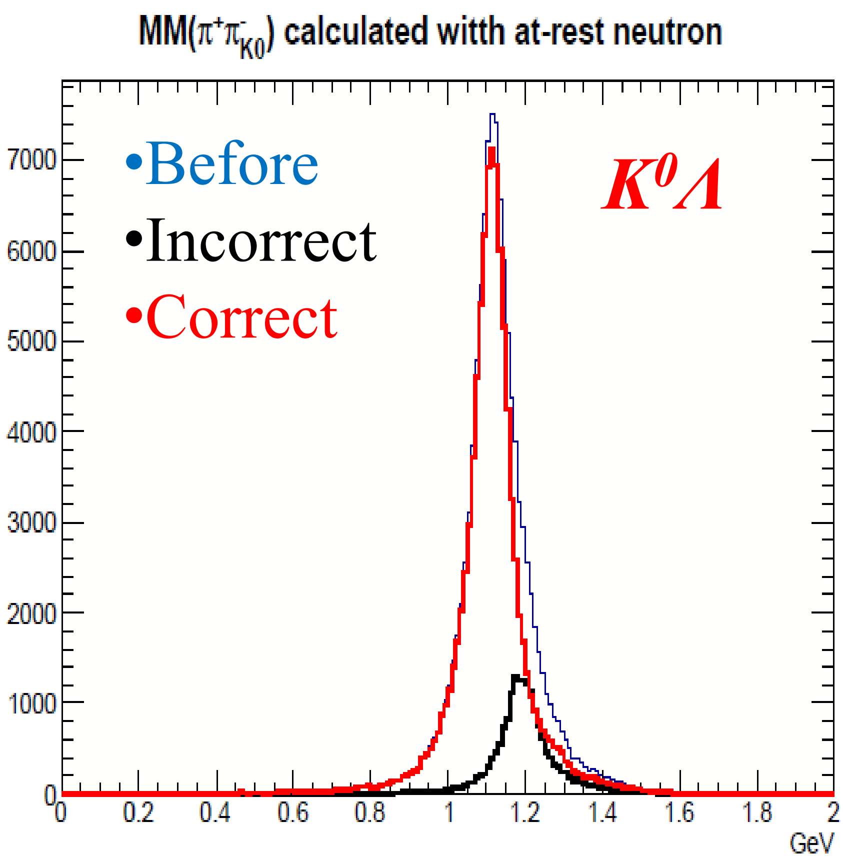


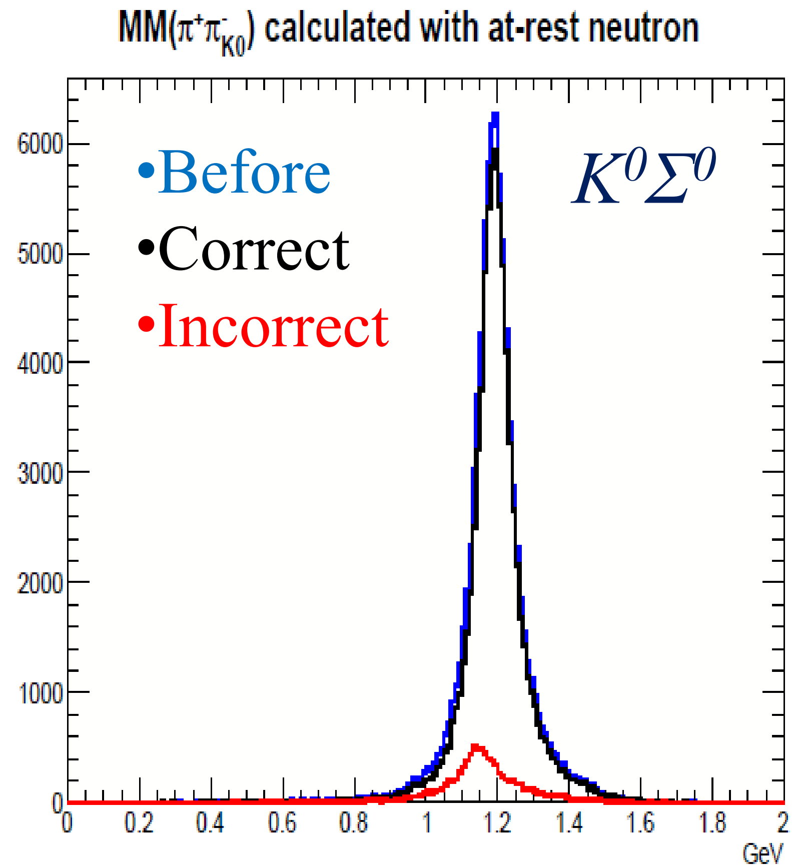
Variable Name	Ranking	Variable Name	Ranking
Missing Energy	1.00	Missing Theta	0.22
Missing Mass	0.72	Missing Gamma	0.19
Missing Mass off K^0	0.70	$\theta_{K^0\&\Lambda}$	0.19
Missing Momentum	0.56	Missing Beta	0.15
Missing Minus	0.28	Missing Plus	0.08
Missing Perp	0.26	Coplanary Angle	0.05

BDT-Based Selection: $K^0\Lambda / K^0\Sigma^0$ Separation

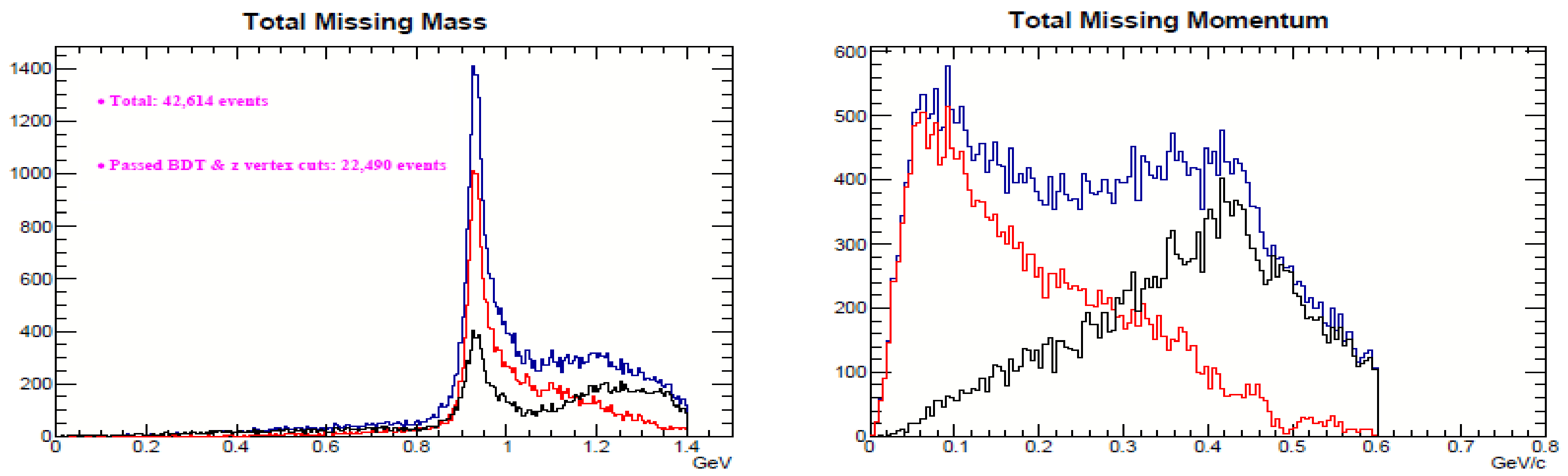
APPLYING the 3rd BDT cut to K^0Y signal data:

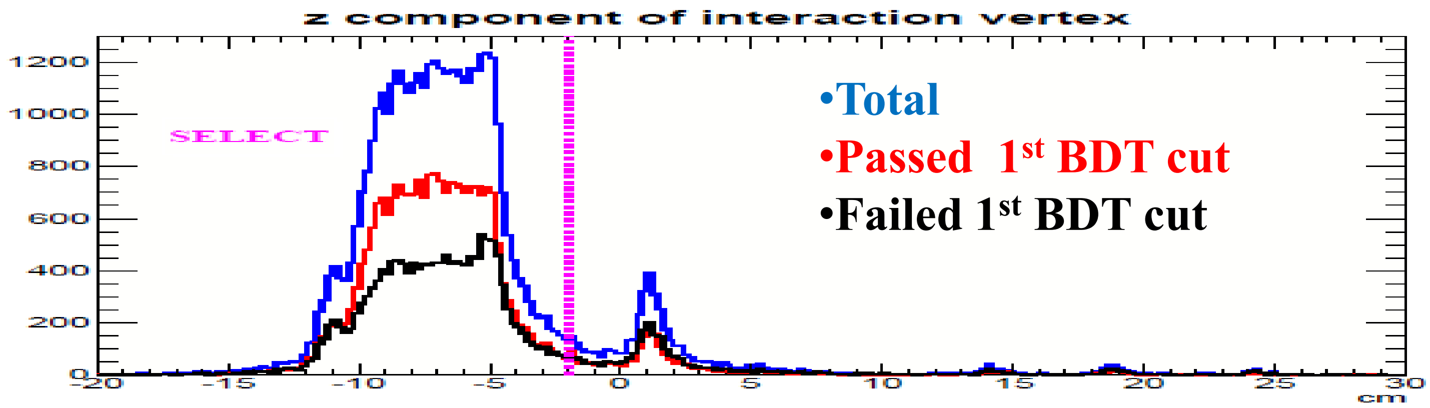
- $K^0\Lambda$ "signal" data: 87.1% events correctly identified as $K^0\Lambda$
- $K^0\Sigma^0$ "BG" data: 91.1% events correctly identified as $K^0\Sigma^0$



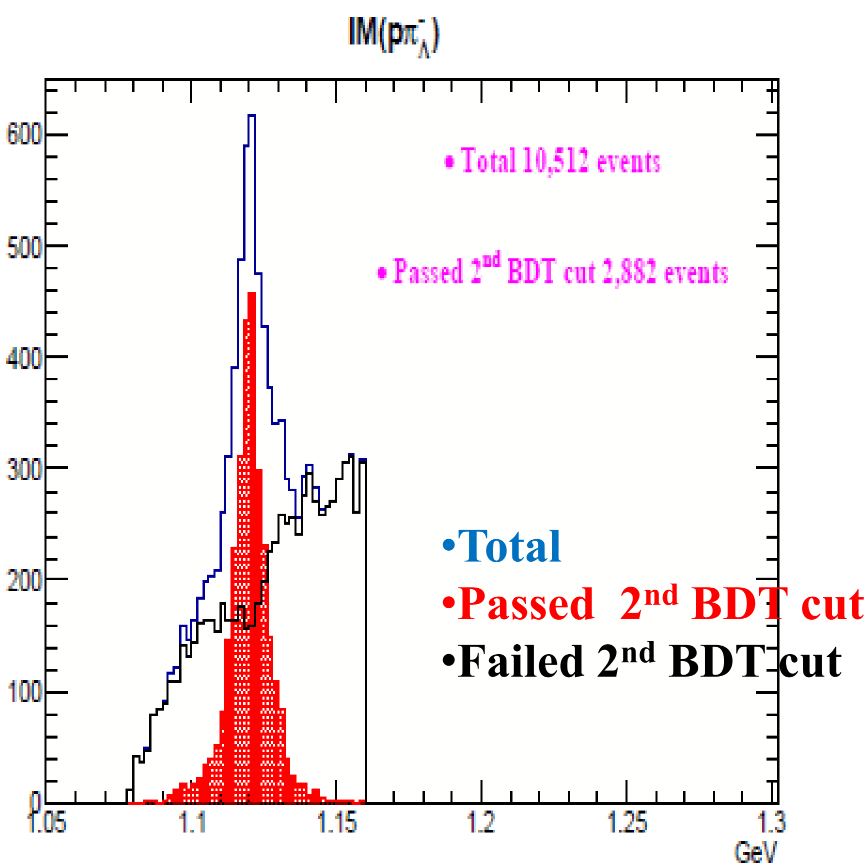


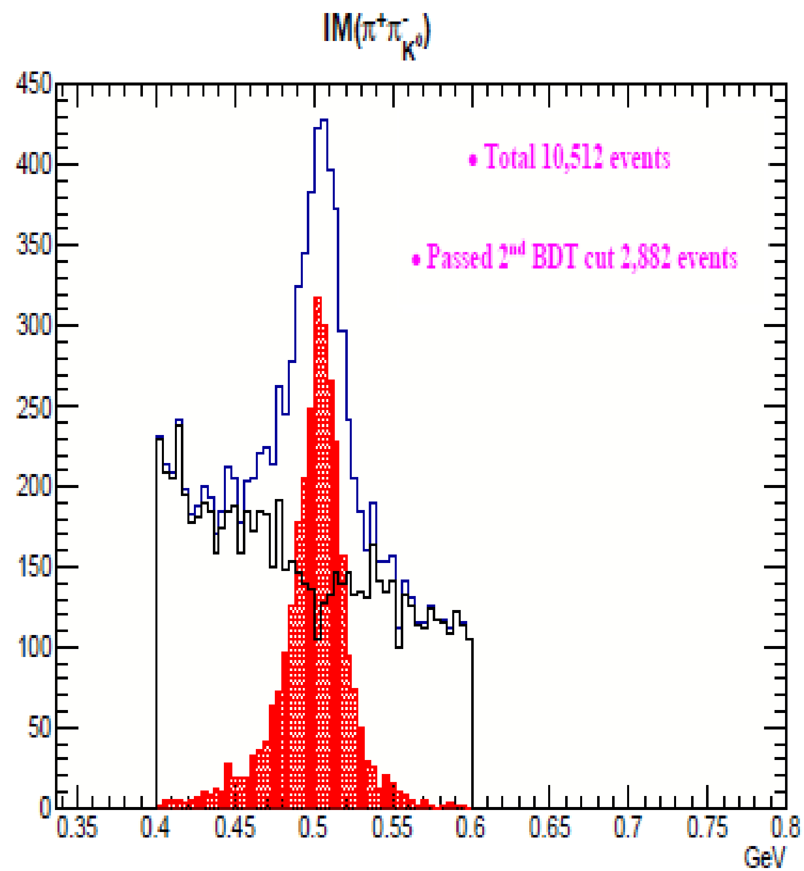
Gold 2 Quasi-free Neutron Event Selection



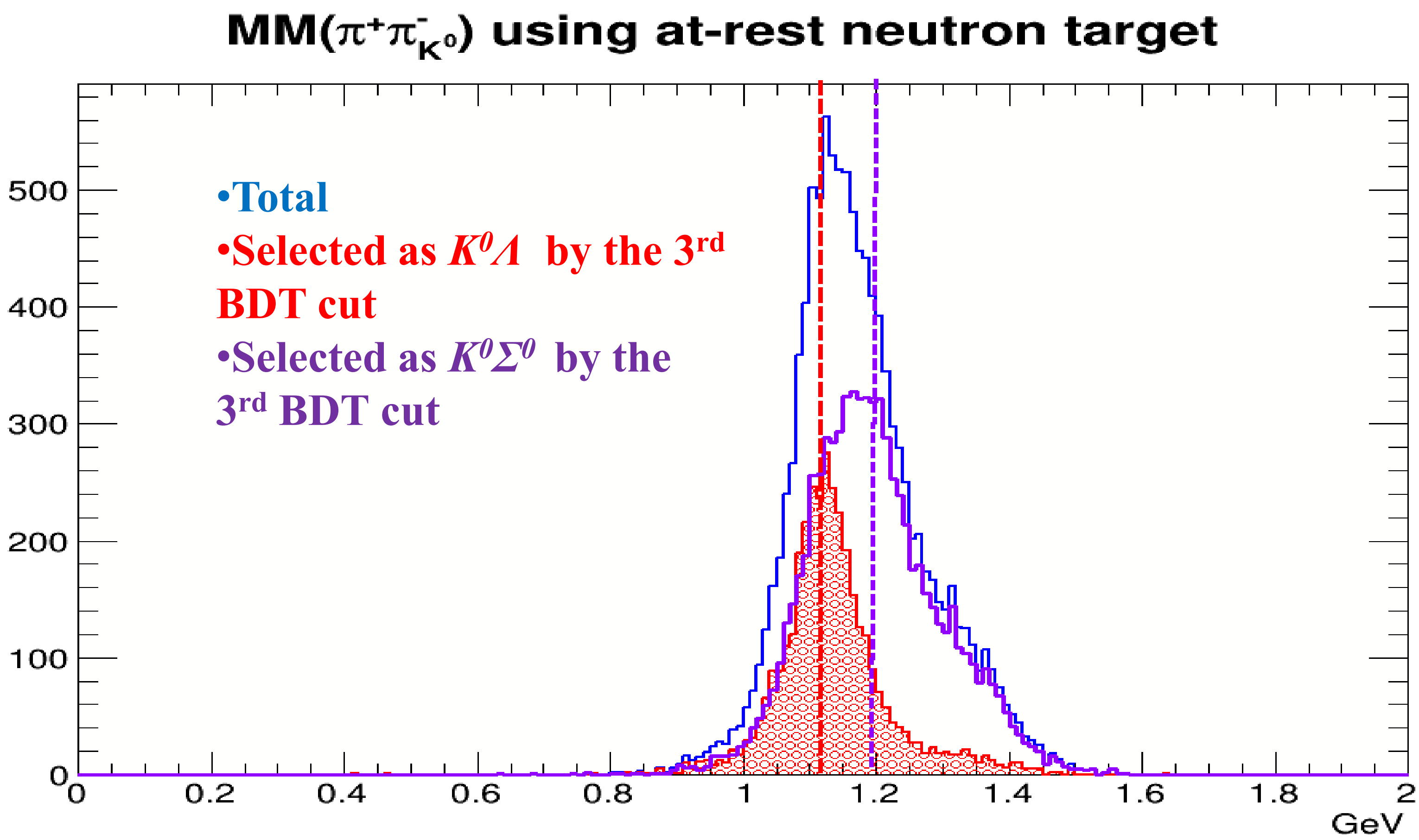


Gold 2 Quasi-free Neutron K^0Y Event Selection





Gold 2 Quasi-free Neutron $K^0\Lambda$ and $K^0\Sigma^0$ Event Selection



Corrections for Remaining Backgrounds

- **ESTIMATING THE *INITIAL* NUMBER OF TARGET-MATERIAL BG EVENTS (back-up slide)**
- After the 1st BDT there would be 25% of target-material background remaining
- **Estimate remaining background: 0.25x initial background: $Y_{targetBG}$**

- **Obtain the number of events that passed the 1st BDT cut: Y_{BDT_1}**

- **Estimate the number of quasi-free neutron events:**

$$Y_{quasi\text{-}free} = Y_{BDT\_1} - Y_{targetBG}$$

- **Compute the ratio : $R^{targetBG} = Y_{targetBG} / Y_{quasi\text{-}free}$**

Corrections for Remaining Backgrounds

•**ESTIMATING THE *INITIAL* NUMBER OF PHASESPACE BG EVENTS (back-up slide)**

•After the 2nd BDT there would be 5.7% of phasespace background remaining

•**Estimate remaining background: 0.057x initial BG: $N_{phasespaceBG}$**

•**Obtain the number of events that passed the 2nd BDT cut: N_{BDT_2}**

•**Estimate the number of quasi-free neutron K^0Y events:**

$$N_{K0Y} = N_{BDT\_2} - N_{phasespaceBG}$$

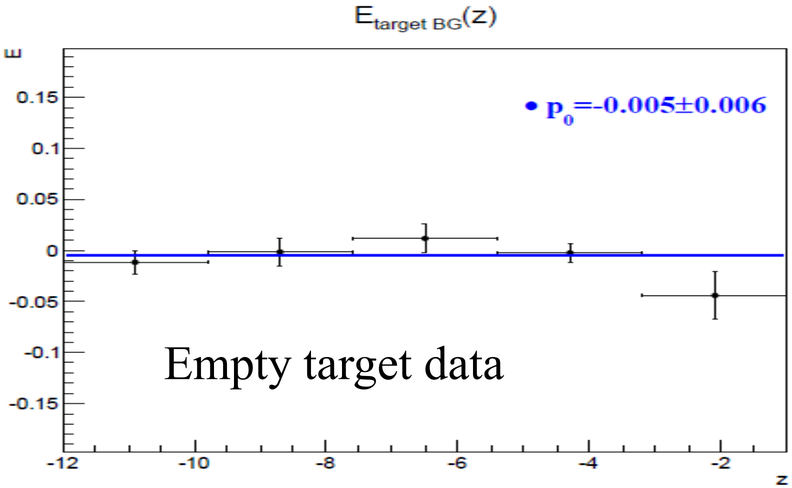
•**Compute the ratio : $R^{phasespaceBG} = N_{targetBG} / N_{K0Y}$**

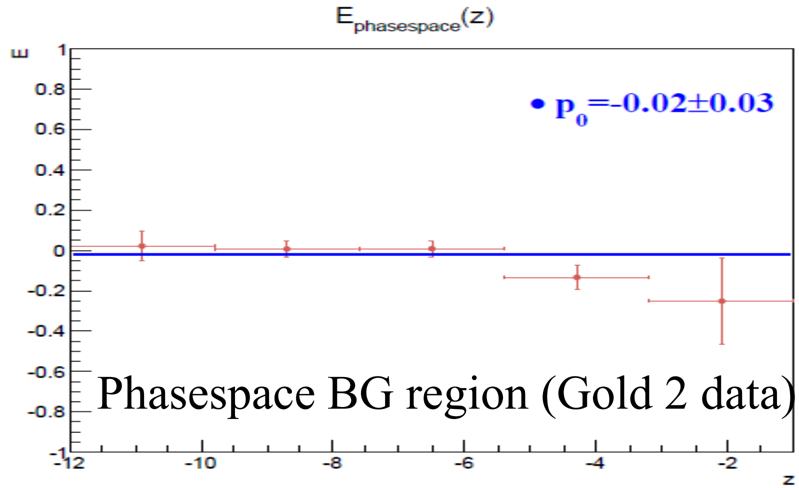
Corrections for Remaining Backgrounds

$$Y_{BDT} = Y^{K^0Y} + Y^{remaining} = \left(1 + R^{phasespaceBG}\right) Y^{K^0Y}$$

- Y^{BDT}: # passed the first two BDT cuts
- Y^{K0Y}: # K^0Y events
- $Y^{remaining}$: # remaining phasespace bg
- RphasespaceBG= $Y^{remaining}/Y^{K0Y}$

$$Y_{BDT} = \left(1 + R^{phasespaceBG}\right)\left[Y_{HD}^{K^0Y} + Y_{targetBG}^{K^0Y}\right] \quad Y_{BDT} = \left(1 + R^{phasespaceBG}\right)\left(1 + R^{targetBG}\right) Y_{HD}^{K^0Y}$$





If both backgrounds have zero E asymmetry, then

$$E_{corrected}^{K^0Y} = \left(1 + R^{phasespaceBG}\right)\left(1 + R^{targetBG}\right) E_{BDT}^{K^0Y}$$

"*Purify*" the BDT $K^0\Lambda/\Sigma^0$ Selection Samples

- N_Λ^{true} ($N_{\Sigma^0}^{true}$) is the total number of $K^0\Lambda$ ($K^0\Sigma^0$) events in the real data (such as Gold 2 data),
- N_Λ^{BDT} ($N_{\Sigma^0}^{BDT}$) is the number of events that have the BDT output larger (smaller) than 0.02,
- ω_Λ (ω_{Σ^0}) is the BDT efficiency for the $K^0\Lambda$ ($K^0\Sigma^0$) events (i.e., percentage of number of events that are correctly "identified"),

$$\Rightarrow N_\Lambda^{BDT} = \omega_\Lambda N_\Lambda^{true} + (1 - \omega_{\Sigma^0}) N_{\Sigma^0}^{true},$$

$$\Rightarrow N_{\Sigma^0}^{BDT} = (1 - \omega_\Lambda) N_\Lambda^{true} + \omega_{\Sigma^0} N_{\Sigma^0}^{true},$$

$$N_\Lambda^{true} = \left[\omega_\Lambda - \frac{(1-\omega_{\Sigma^0})}{\omega_{\Sigma^0}}(1-\omega_\Lambda)\right]^{-1} \left[N_\Lambda^{BDT} - \frac{(1-\omega_{\Sigma^0})}{\omega_{\Sigma^0}} N_{\Sigma^0}^{BDT}\right]$$

$$N_{\Sigma^0}^{true} = \left[\omega_{\Sigma^0} - \frac{(1-\omega_\Lambda)}{\omega_\Lambda}(1-\omega_{\Sigma^0})\right]^{-1} \left[N_{\Sigma^0}^{BDT} - \frac{(1-\omega_\Lambda)}{\omega_\Lambda} N_\Lambda^{BDT}\right]$$

Systematic Studies

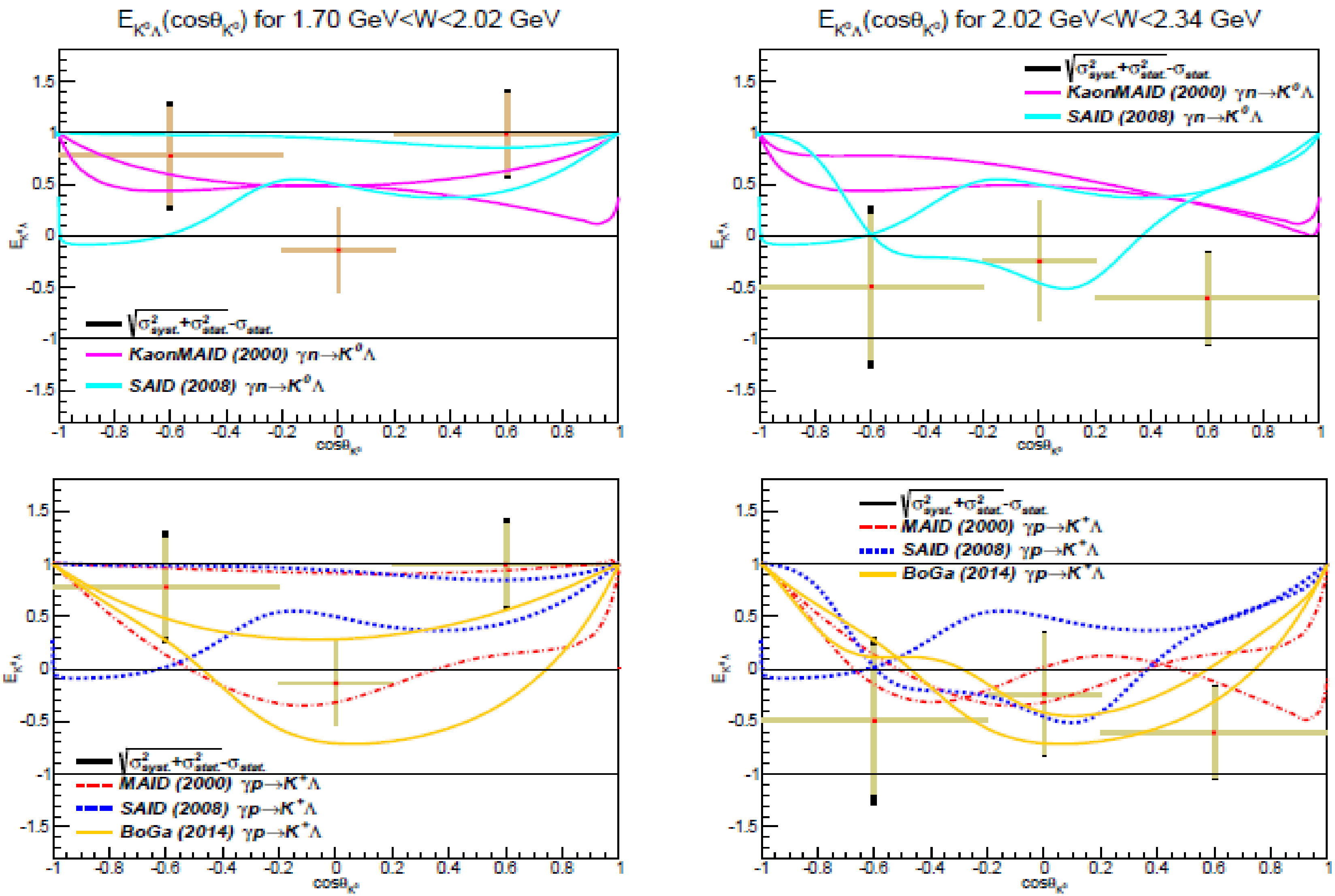
•Reserve the BDT selection sequence (select K^0Y events first, then select quasi-free events)→NO CHANGE IN THE FINAL *E* VALUES

•Loosen the 1st BDT cut to keep more target-material background → check robustness of the background correction

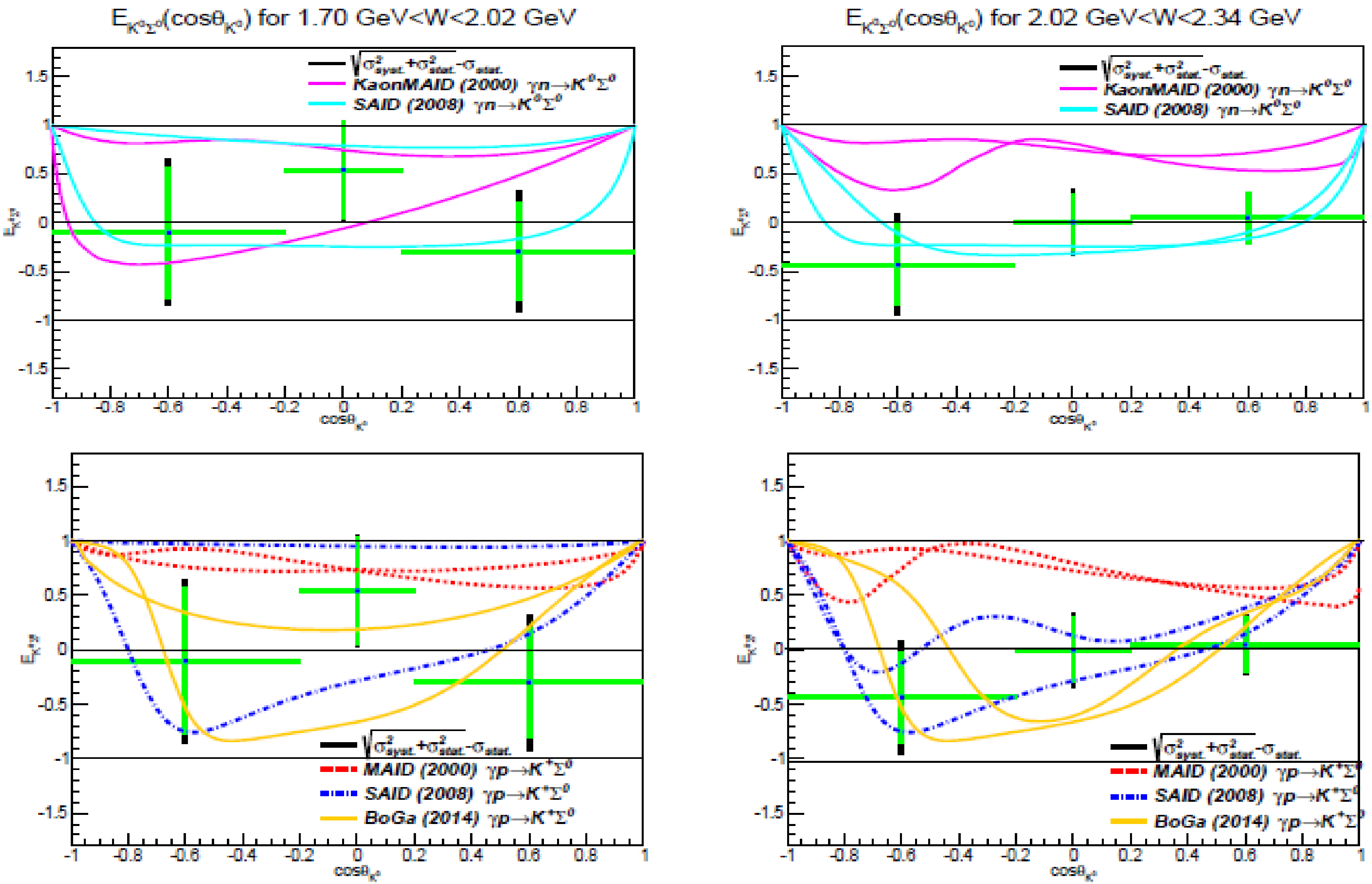
• Loosen the 2nd BDT cut to keep more phasespace background → check robustness of the background correction

•Remove the $\boldsymbol{K^0\Lambda}$ **and** $\boldsymbol{K^0\Sigma^0}$ "purify" procedure → check the sensitivity of the final *E* measurements on the procedure

Plotting the E Asymmetry for $K^0\Lambda$



Plotting the E Asymmetry for $K^0\Sigma^0$



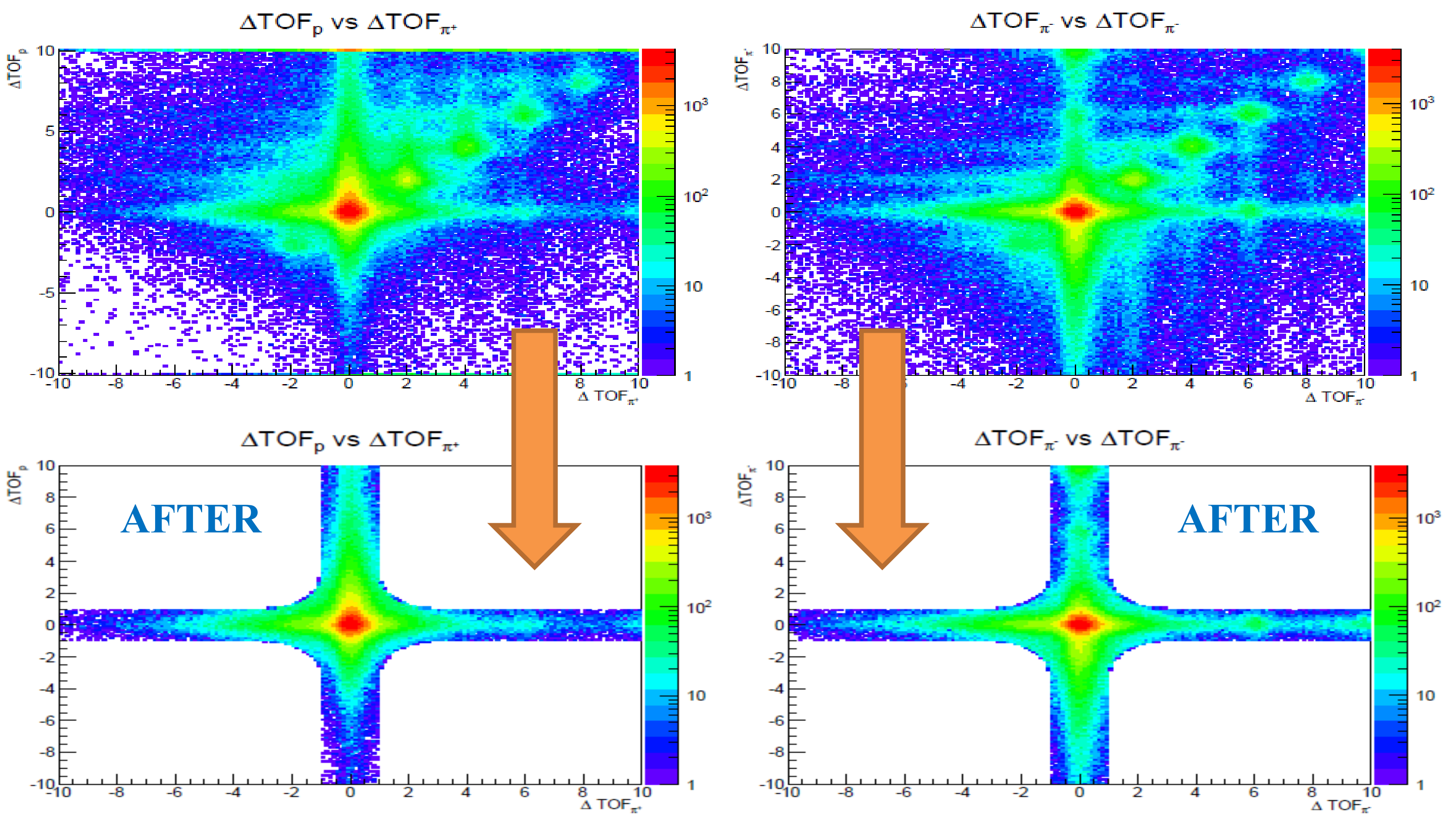
Conclusion

- Presented procedures to select quasi-free K^0Y
- Presented the final E measurements for K^0Y
- Presented systematic uncertainties
- Qualitatively, the proton models explain $E_{K0\Lambda}$ measurements better
- Qualitatively, SAID models follows the $E_{K0\Sigma0}$ measurements better than the MAID models

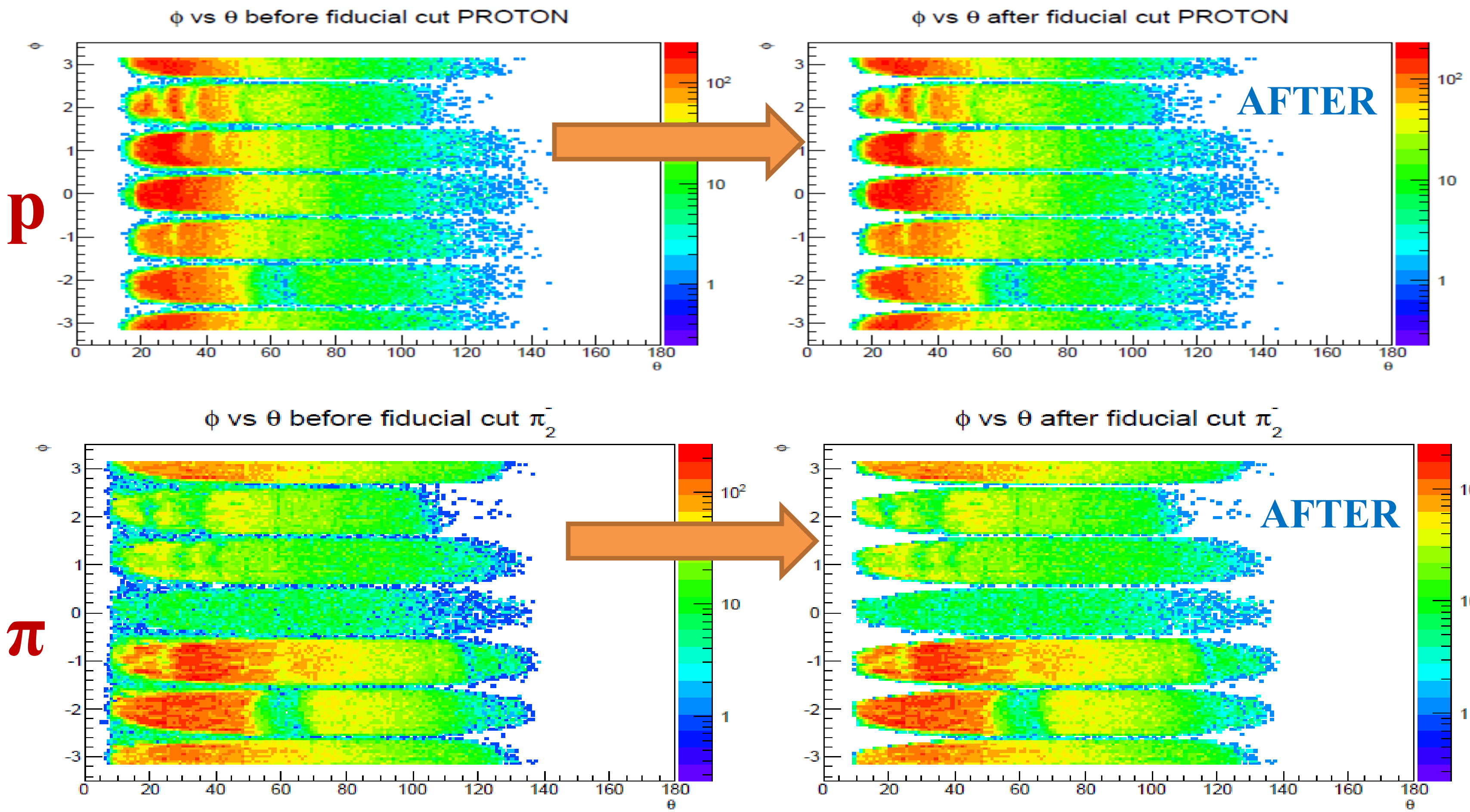
BACK UP

Particle Identification: ΔTOF Cuts

REJECTING WRONG-TIMING EVENTS



Detector Performance: Fiducial Cuts

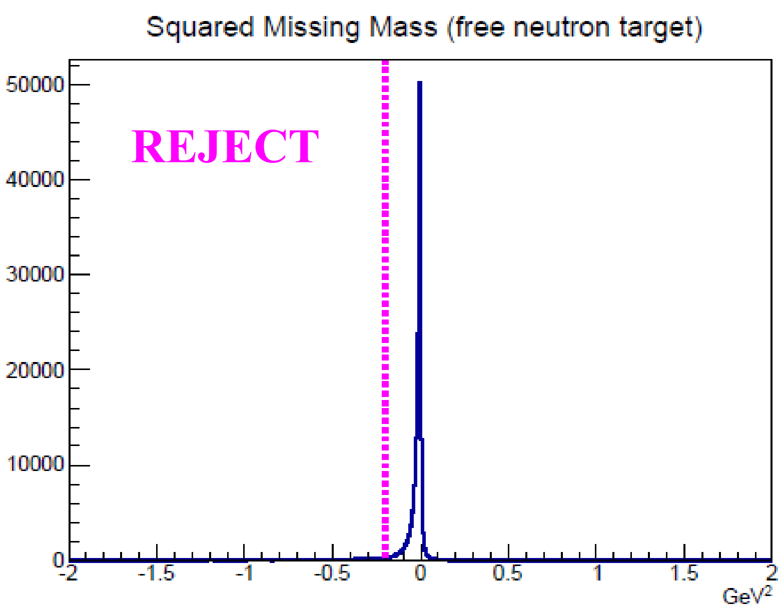


To remove regions that are difficult to simulate

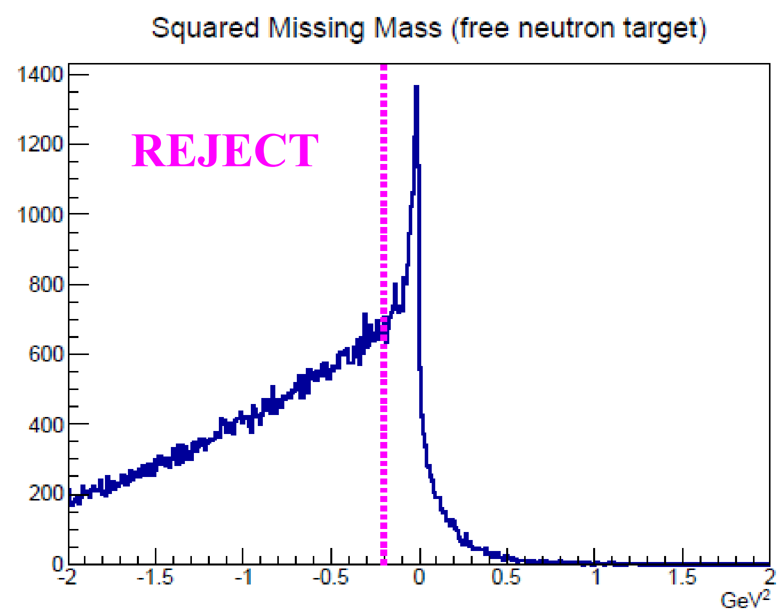
Quasi-free Neutron Loose Selection: Squared Missing Mass Cut

- Assigning the target with the mass of ***at-rest (free)*** neutron
- Computing the squared missing mass
- Study both K^0Y signal simulation and empty-target data

→→→ Place cut at -0.2 GeV^2



K^0Y signal simulation

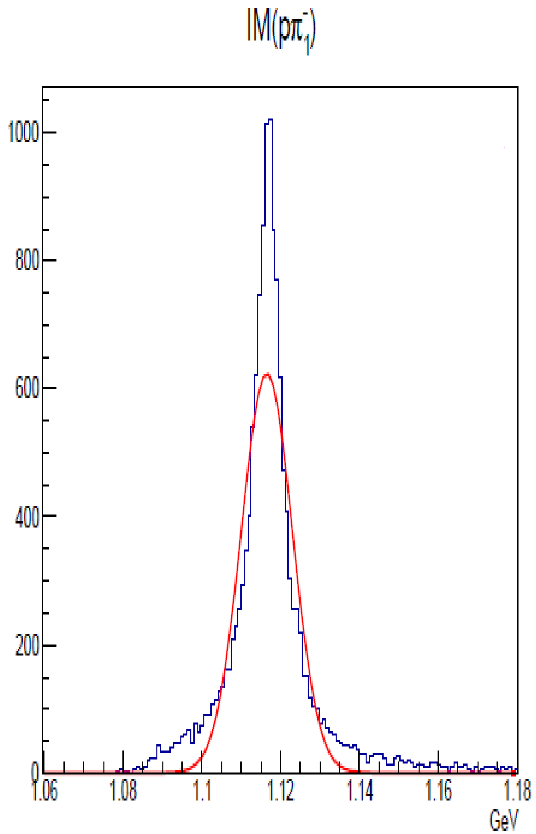


empty-target data

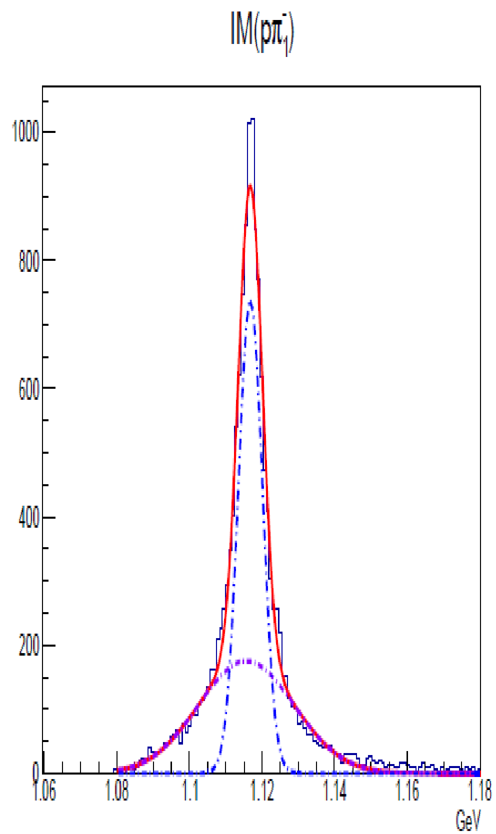
K^0Y Loose Selection: IM($p\pi_\Lambda^-$) and IM($\pi^+\pi_{K0}^-$) Cuts

Question: Would a Gaussian fit well the IM($p\pi_\Lambda^-$) and IM($\pi^+\pi_{K0}^-$) distributions?

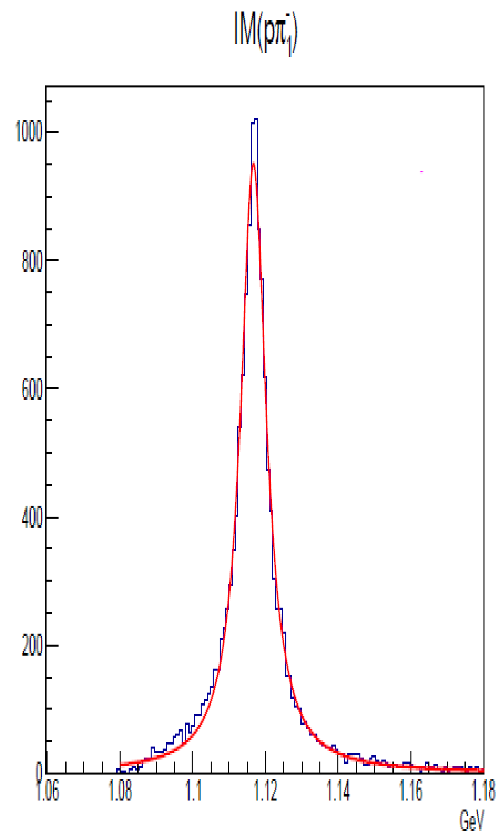
→From K^0Y simulation the answer is no, but double Gaussian or Lorentzian are OK



Single Gaussian



Double Gaussian



Breit-Wigner

K^0Y Loose Selection: IM($p\pi_{\Lambda}^-$) and IM($\pi^+\pi_{K0}^-$) Cuts

Question: ***Which π^- should be paired with the proton (π^+)***

→Implementing the following procedure:

1. Compute $IM(p\pi_1^-)$, $IM(p\pi_2^-)$, $IM(\pi^+\pi_1^-)$, and $IM(\pi^+\pi_2^-)$,
2. Compute the product of $f_{BW}(IM(p\pi_1^-), m_\Lambda, \Gamma_\Lambda) \times f_{BW}(IM(\pi^+\pi_2^-), m_{K^0}, \Gamma_{K^0})$, where $f_{BW}(m, m_0, \Gamma) = \frac{\Gamma}{2\pi[(m-m_0)^2+(\Gamma/2)^2]}$ is the probability distribution function of the Breit-Wigner distribution with parameter m_0 being the centroid of the distribution, and Γ being the full width at half maximum (FWHM); these variables were obtained from fits,
3. Compute the product of $f_{BW}(IM(p\pi_2^-), m_\Lambda, \Gamma_\Lambda) \times f_{BW}(IM(\pi^+\pi_1^-), m_{K^0}, \Gamma_{K^0})$,
4. Compare results of Step 2 and Step 3. If the product in Step 2 is greater, then pairing π_1^- with p, and π_2^- with π^+; otherwise, reversing the assignment.

Corrections for Remaining Backgrounds

ESTIMATING THE *INITIAL* NUMBER OF TARGET-MATERIAL BG EVENTS

1. Plot the histograms of the z-component of the interaction vertex of both full-target (Silver 1&2, for example) data and empty-target data

2. Scale the empty histogram such as the yields $Y_{empty} = Y_{full}$ for $0 < z < 30$ cm (this region is outside the target, thus remains the same during the whole experiment),

3. Scale the yield of empty data Y_{empty} for $-15 < z < -2$ cm using the scaling number obtained in step 2 (note that events with $z > -2$ cm were never utilized to get the estimated survival portion),

4. Get the number of scaled yield from the empty-target data (this is the best estimate of the *initial* number of target-material background events).

Corrections for Remaining Backgrounds

ESTIMATING THE *INITIAL* NUMBER OF PHASESPACE BG EVENTS

1. Plot the $IM(p\pi^-_\Lambda)$, and $IM(\pi^+\pi^-_{K^0})$ distributions for the full-target (Silver 1&2, for example) data, and record the the total initial number of events,
2. Fit each invariant mas distribution with a sum of a Breit-Wigner distribution (signal fit) and a 3^{rd} polynomial function (background fit),
3. Integrate the signal and background fits (for both $IM(p\pi^-_\Lambda)$, and $IM(\pi^+\pi^-_{K^0})$ distributions),
4. For each invariant mas distribution, compute the signal-to-background ratio from the obtained integrations
5. Compute the weighted average of the two signal-to-background ratios
6. Compute the *initial* number of phasespace background events by ultilizing the obtained weighted-average ratio and the total initial number of events.