Longitudinal Spin Transfer to Λ^0 Hyperons in CLAS12

21/Oct./21, Matthew McEneaney, Duke University

matthew.mceneaney@duke.edu

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Spin Transfer

- Previous experiments have observed small spin transfer coefficients $D_{LL'}$ to Λ
- Λ Spin transfer described by:

$$\frac{dN}{d\Omega_{\mathrm{p}}} \propto 1 + \alpha P_b D(y) D^{\Lambda}_{LL'} \cos\theta_{pL'}$$

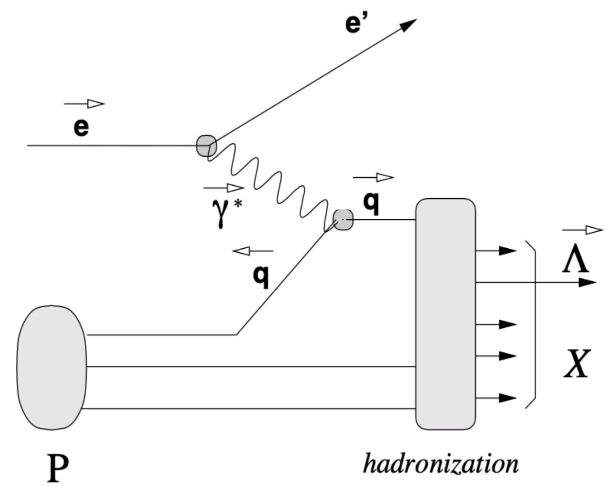
where $D(y) \simeq \frac{1-(1-y)^2}{1+(1-y)^2}$ is the depolarization factor

- Partial spin transfer from struck quark to Λ:

$$D^{\Lambda}_{LL',f}(z) = \frac{G^{\Lambda}_{1,f}(z)}{D^{\Lambda}_{1,f}(z)} = \frac{D^{\Lambda+}_{1,f+}(z) - D^{\Lambda-}_{1,f+}(z)}{D^{\Lambda+}_{1,f+}(z) + D^{\Lambda-}_{1,f+}(z)} \simeq \frac{\Delta q^{\Lambda}_f}{q^{\Lambda}_f}$$

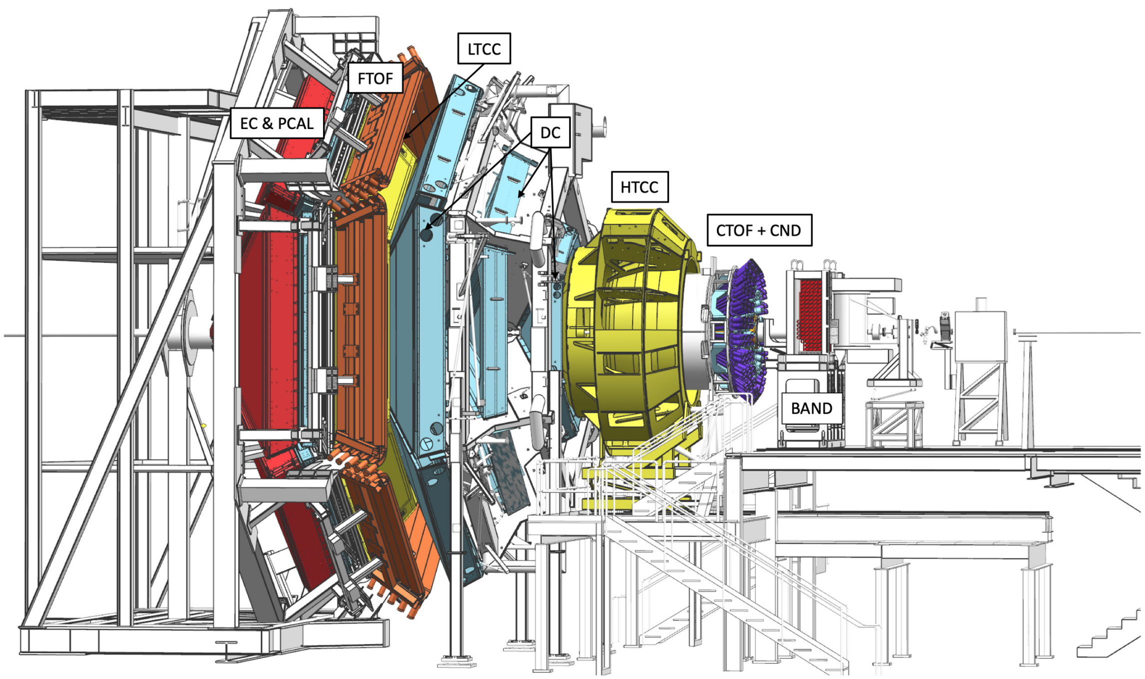
- Since there is a strong u-quark dominance in e^- DIS

$$D^{\Lambda}_{LL'}(z) \approx D^{\Lambda}_{LL',u}(z)$$



A. Airapetian, et al. Physical Review D, 74(7), Oct 2006.

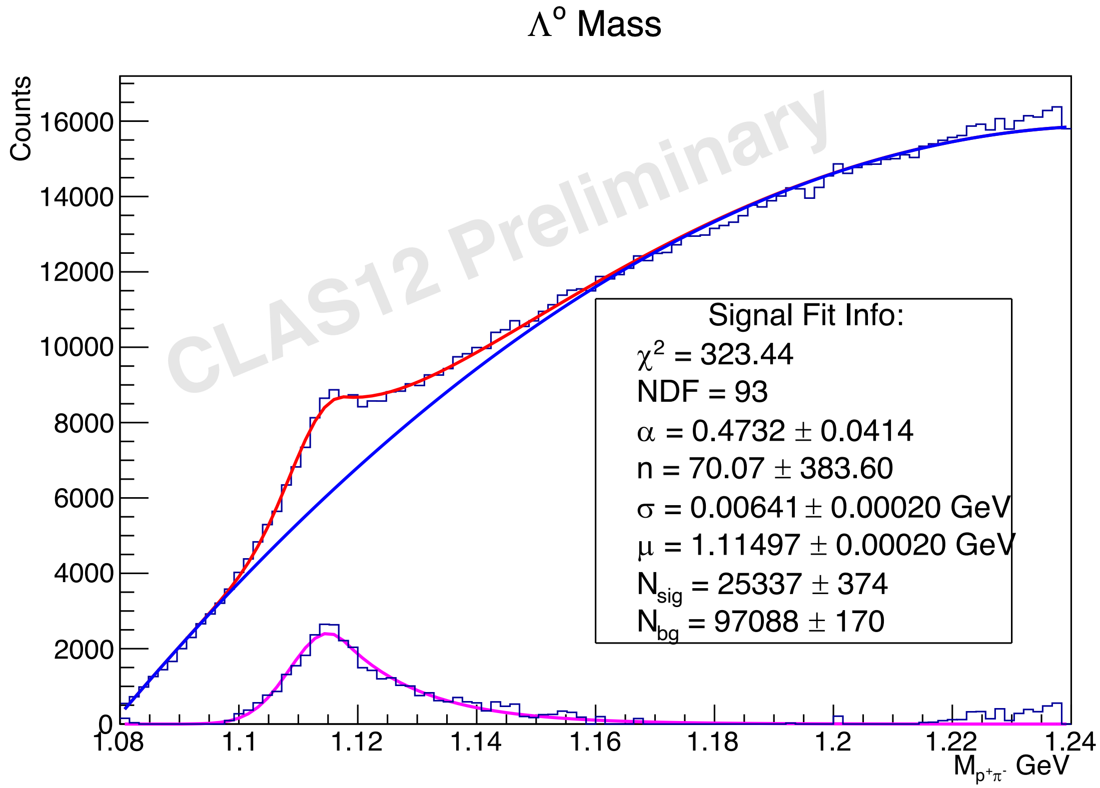
The CLAS12 Experiment



V. Burkert et al., The CLAS12 Spectrometer at Jefferson Laboratory, NIM A, January 2020

- Central Detector
  - Solenoid
  - Silicon Vertex Tracker
  - Central TOF Detector
  - Central Neutron Detector
- Forward Detector:
  - Torus Magnet
  - Drift Chambers
  - Forward TOF Detector
  - Calorimeters (ECAL and PCAL)
  - Cherenkov Counters
- Data Set:
  - Fall 2018 RGA Run Period
  - Unpolarized LH2 Target
  - 10.6GeV beam with 86% polarization
  - Outbending torus

Invariant Mass Signal

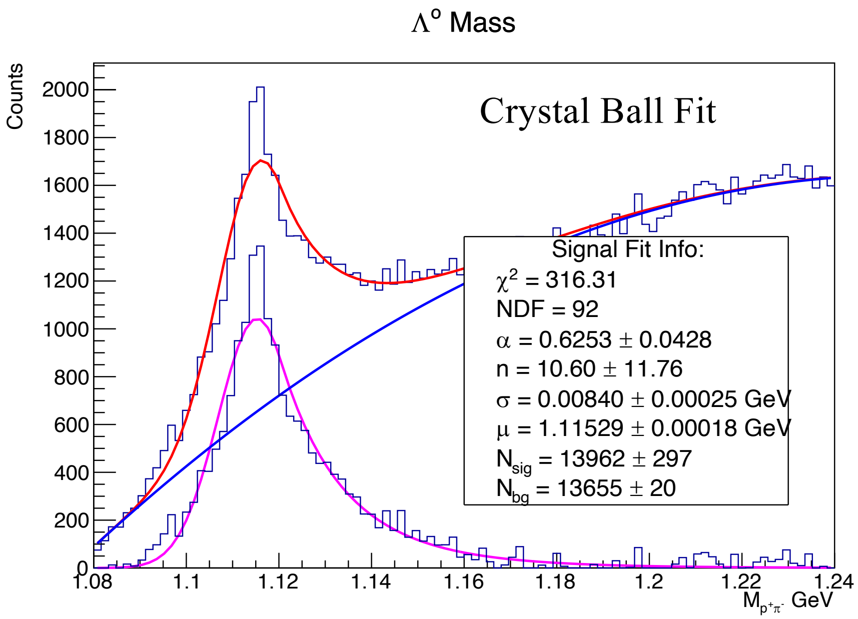


Standard SIDIS cuts:
$Q^2 > 1$ & $W > 2$ & $y < 0.8$ & $x_F > 0$ & $z < 1$
Also require identified $p^+\pi^-$ and scattered e^-

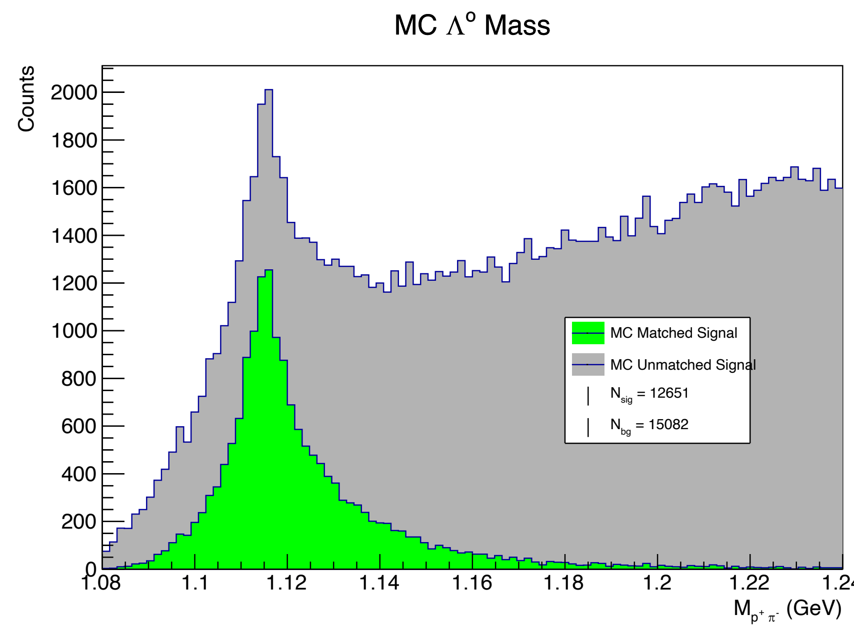
Crystal Ball Fit Function:

$$CB(M;\alpha,n,\mu,\sigma) = N \cdot \exp\left(-\frac{(m-\mu)^2}{2\sigma^2}\right), \quad \frac{m-\mu}{\sigma} > -\alpha$$
$$= N \cdot A\left(B - \frac{m-\mu}{\sigma}\right)^{-n}, \quad \frac{m-\mu}{\sigma} < -\alpha$$

MC: Comparison with Truth-Matched Signal



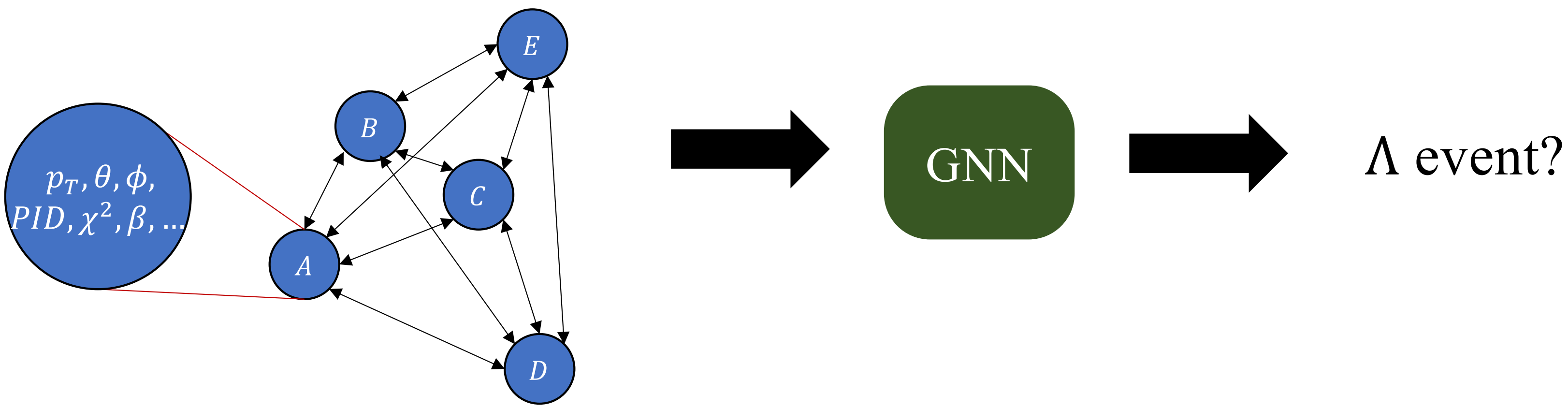
Standard kinematic cuts:
$Q^2 > 1$ & $W > 2$ & $y < 0.8$ & $x_F > 0$ & $z < 1$
and positive $p^+\pi^-$ PID and scattered e^-
(positive PID, $|\chi^2| < 3$, greatest momentum) required.



Truth Matching:
Require a MC truth Λ in event with
$|P_{Rec}^{\Lambda} - P_{MC}^{\Lambda}| < 0.1GeV$

Graph Neural Networks (GNNs)

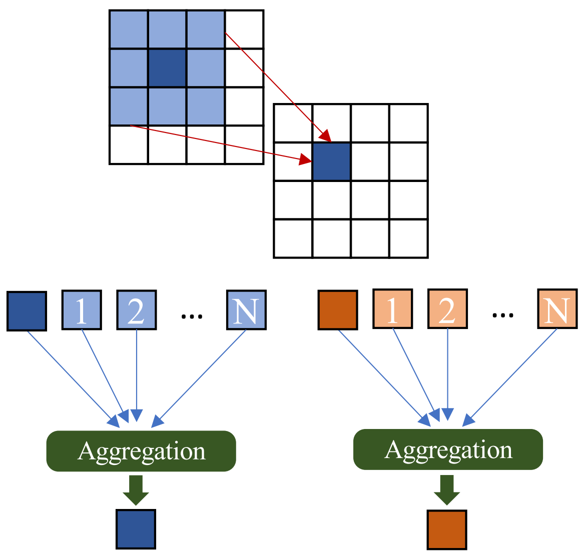
- **Idea**: use GNN to reduce background in invariant mass spectrum on event-by-event basis
- Pass each event as fully-connected, bidirectional graph
- Each particle is a node with its own data: p_T, θ, ϕ, etc.



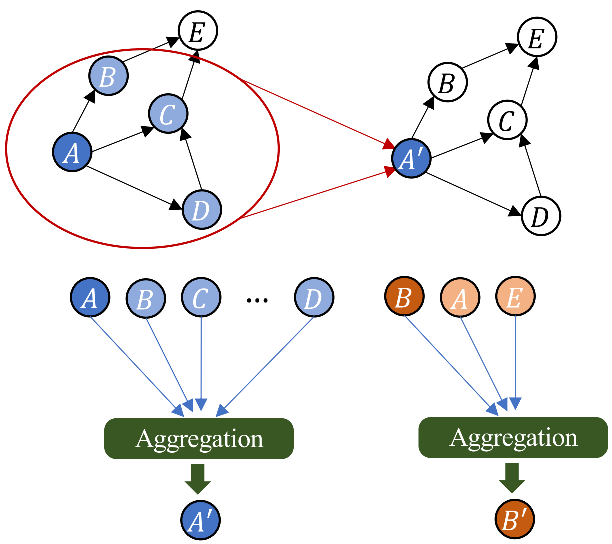
Graph Neural Networks (GNNs)

- At basic level, function as generalized form of CNNs

CNN



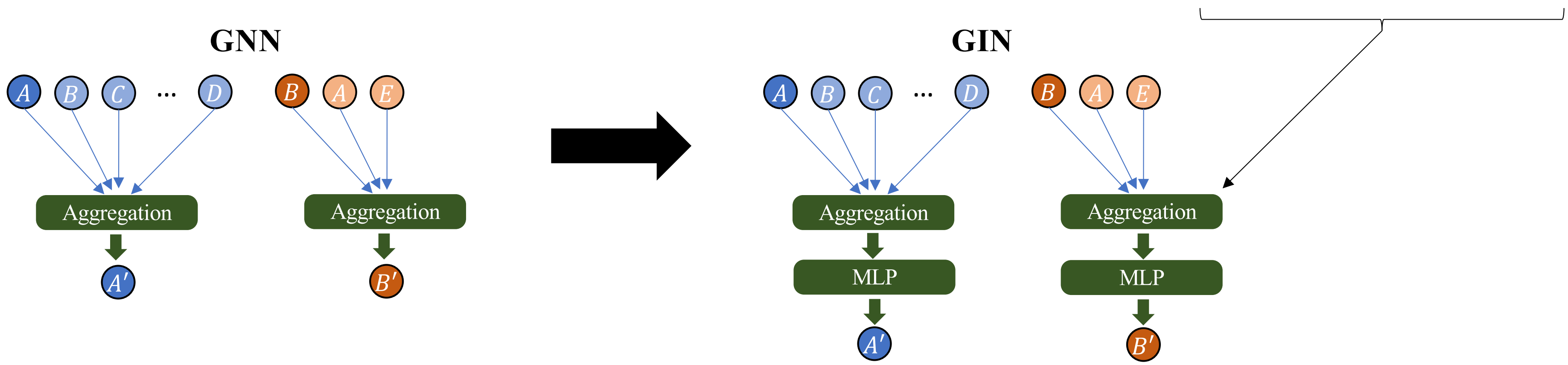
GNN



Graph Isomorphism Network (GIN)

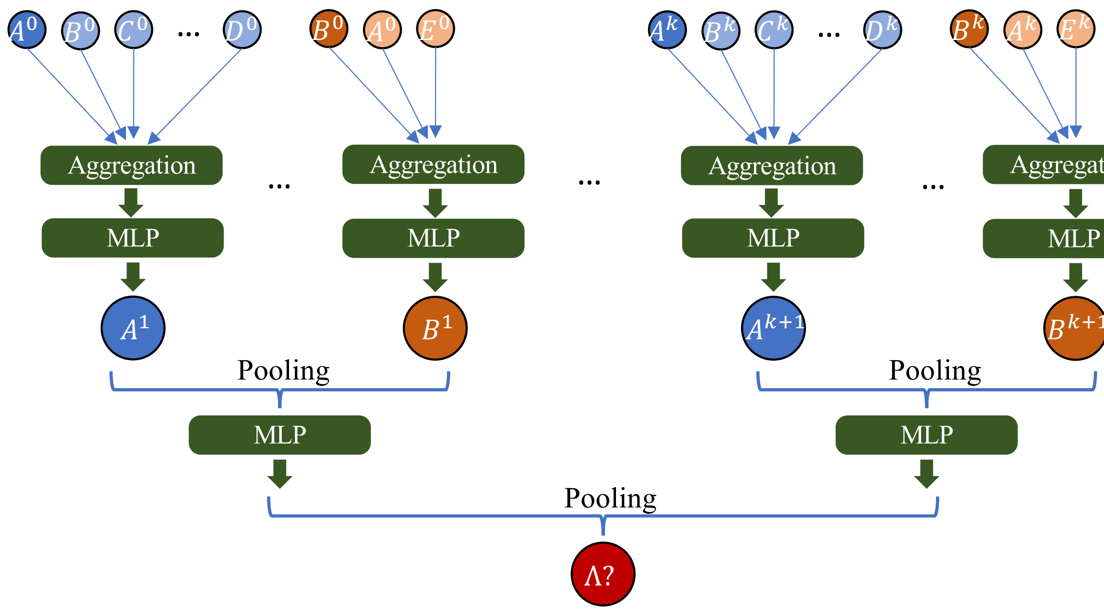
- Based on Weisfeiler-Lehman (WL) Test, essentially ensures aggregation is injective
- Compare with basic GNN convolution:

$$h_v^{(k)} = \text{MLP}^{(k)}\left(\left(1+\epsilon^{(k)}\right)\cdot h_v^{(k-1)} + \sum_{u\in\mathcal{N}(v)} h_u^{(k-1)}\right)$$



Graph Isomorphism Network (GIN)

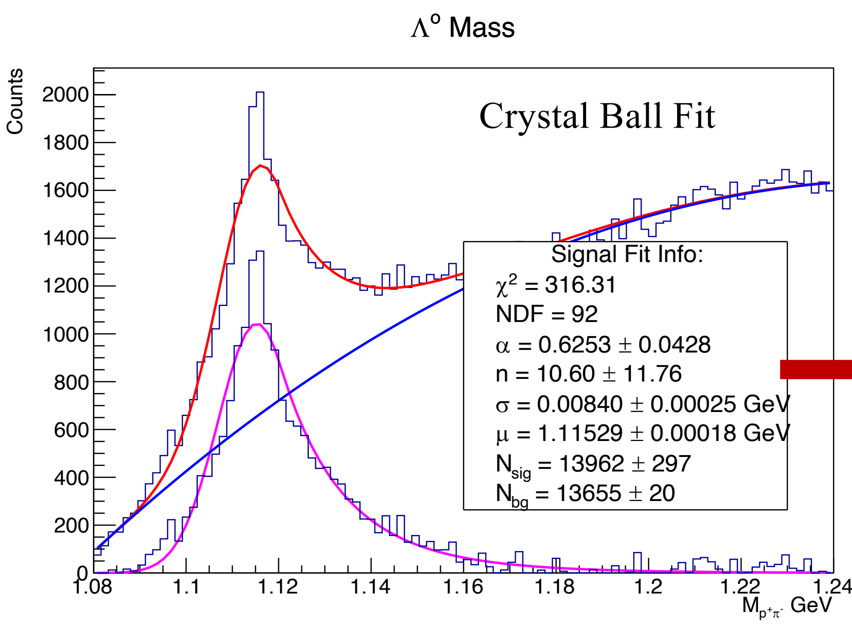
- Aggregation in final layer is across all previous layers/iterations



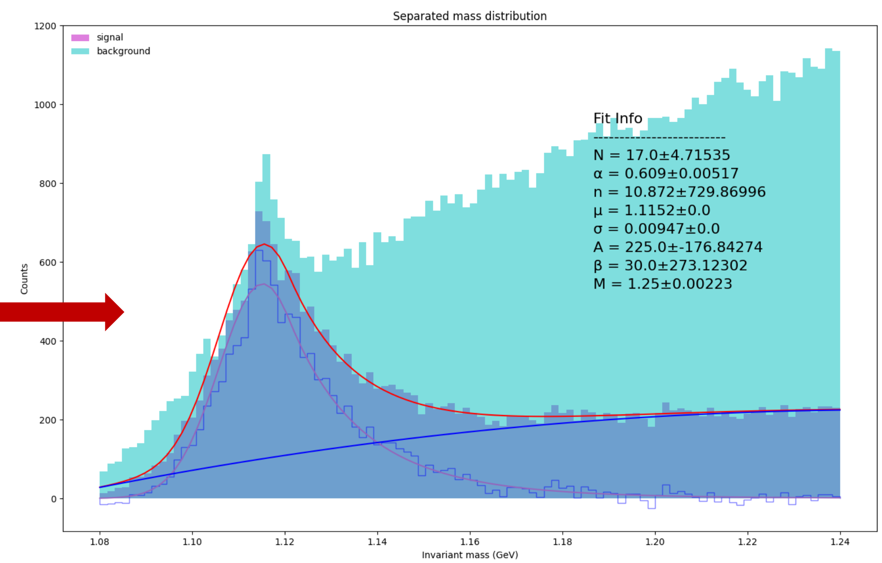
Implementation

- Libraries: Deep Graph Library (DGL), PyTorch, Optuna
- GIN: 5 layers, with 3-layer MLPs, Max pooling
- Dataset: Out-bending MC ~96k events with 50% Λ events, 75/25 training validation split, $p^+\pi^-$ mass $\in (1.10, 1.13)$ GeV
- Particle features: $\Delta\,\widehat{p_T}$, $\Delta\hat{\phi}$, $\Delta\hat{\theta}$, β, χ^2 , PID, status/1000
- Edge features: $\Delta\widehat{p_T}_{ij}$, $\Delta\hat{\phi}_{ij}$, $\Delta\hat{\theta}_{ij}$ (Not used yet)
- Run for ~100 epochs on Duke Compute Cluster GPUs (CUDA 11.4)

MC Invariant Mass



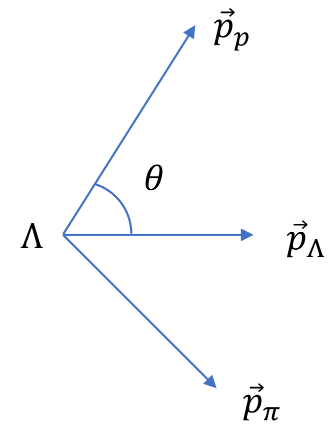
Before NN



After NN

85% Test accuracy and background is significantly reduced!

Experimental Extraction



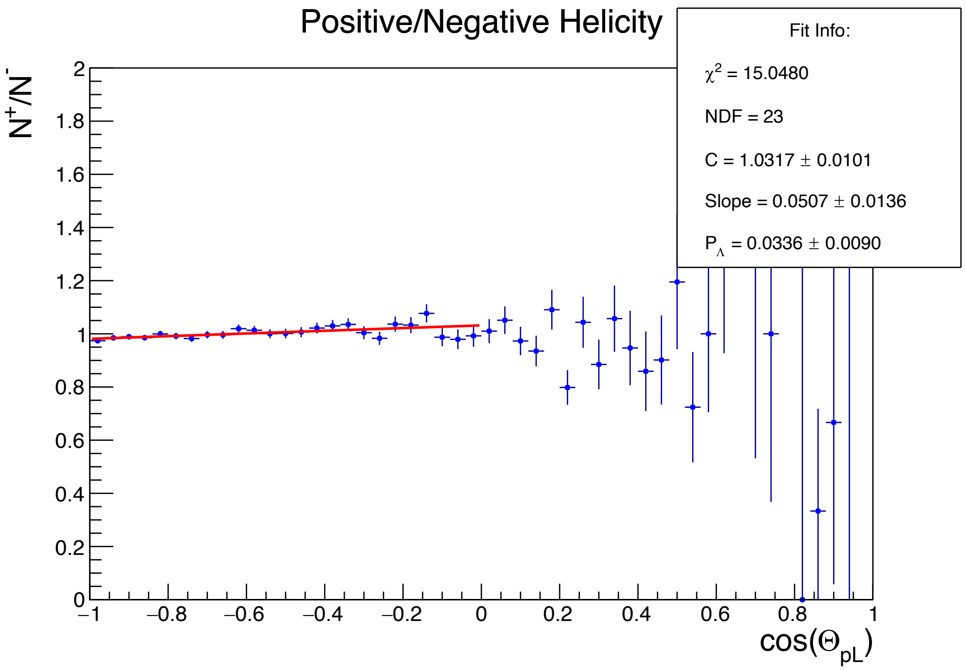
- Choices for Λ spin quantization axis
  - Axis 1: along Λ momentum
  - Axis 2: along the virtual photon momentum in Λ rest frame
- Helicity balance method extracts on event-by-event basis:

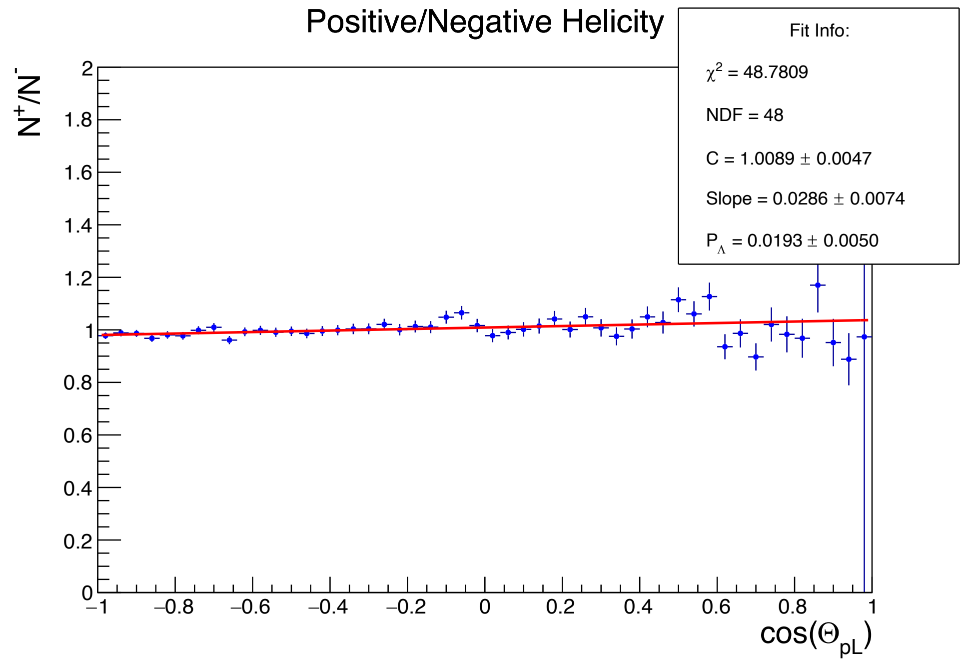
$$D_{LL'}^{\Lambda} = \frac{1}{\alpha \overline{P_b^2}} \cdot \frac{\sum_{i=1}^{N_\Lambda} P_{b,i} D(y_i) \cos \theta_{pL'}^{i}}{\sum_{i=1}^{N_\Lambda} D^2(y_i) \cos^2 \theta_{pL'}^{i}}$$

- No acceptance corrections needed since $\overline{P_b} = 0$ (beam polarization reverses at 30Hz).
- Linear fit method looks at the $\cos\theta$ distributions, however this requires acceptance correction.

Fit $cos\theta_1$ (acceptance corrected)

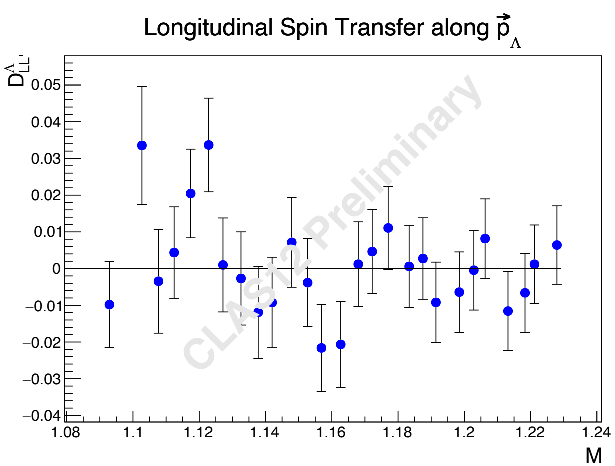
$$P_\Lambda = \frac{1}{\alpha}\frac{Slope}{C}$$

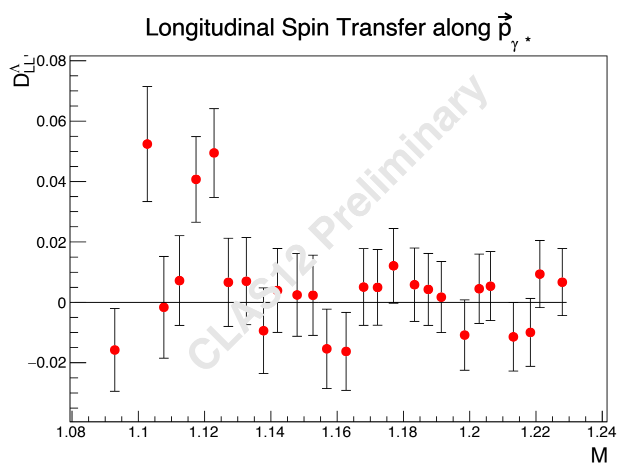




Helicity Balance vs. Invariant Mass

vs. Invariant Mass





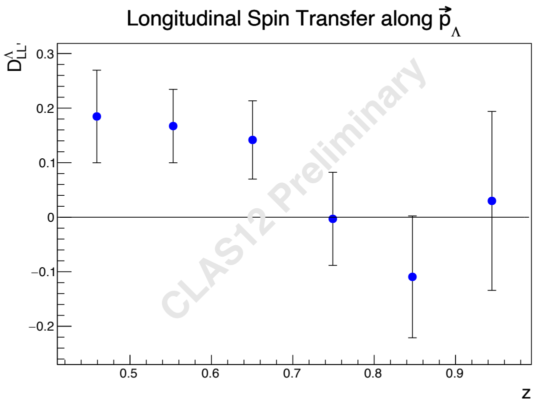
Note: errors are solely statistical

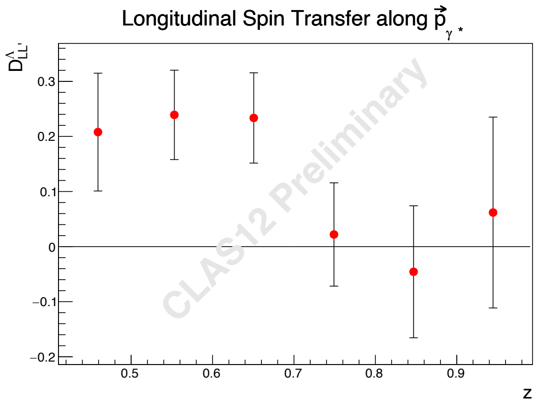
No BG Correction

Helicity Balance (BG corrected)

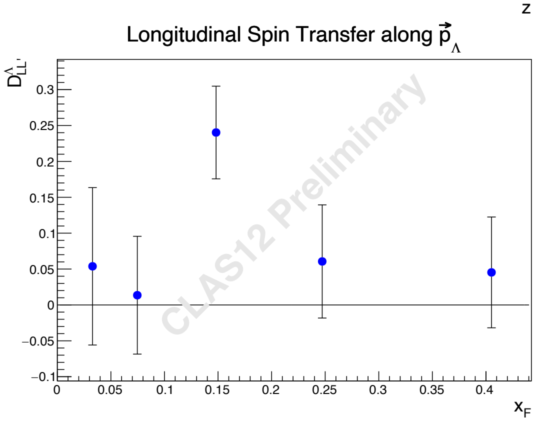
$$D_{LL}^{\Lambda} = \frac{D_{LL_{peak}} - \epsilon D_{LL_{bg}}}{1-\epsilon}$$

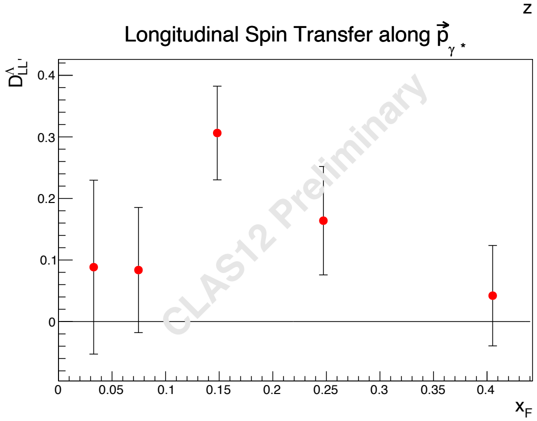
vs. z





vs. x_F

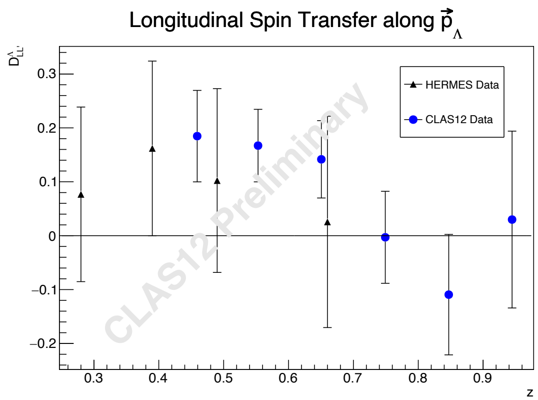


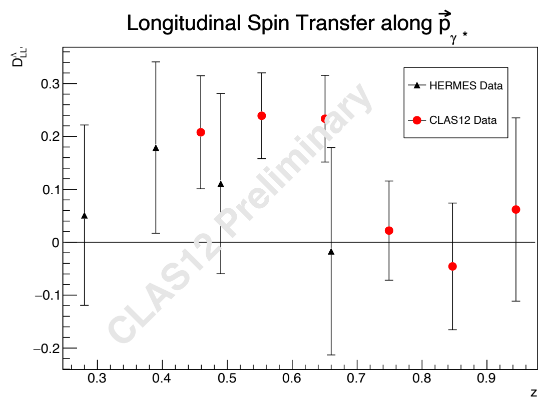


Note: errors are solely statistical

Helicity Balance: Comparison with HERMES

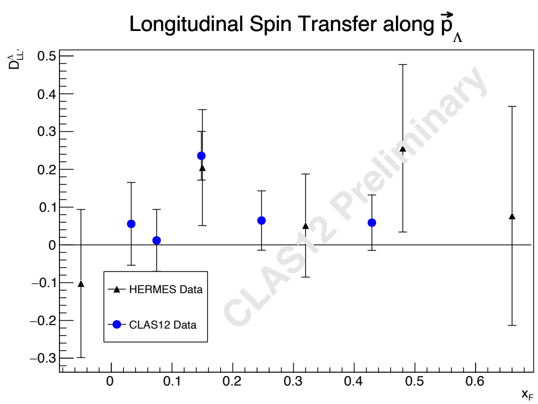
vs. z

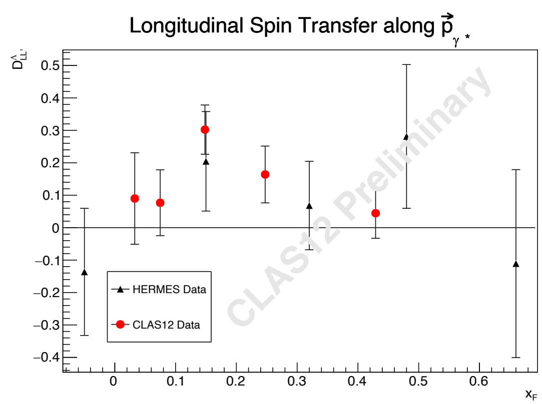




Note: errors are solely statistical

vs. x_F





HERMES Results from:
A. Airapetian, et al. Physical Review D, 74(7), Oct 2006.

Systematic Uncertainties

- Uncertainties from fit errors and incorrect particle PID were minimal (<0.001).
- Spin transfer in sidebands is also fairly small:

Preliminary Helicity Balance

$\cos\theta_{pL'}$ along $\vec{p_\Lambda}$	$\cos\theta_{pL'}$ along $\vec{p_\gamma}$
-0.00141 ± 0.01293	0.00113 ± 0.01387
-0.00185 ± 0.03183	-0.00810 ± 0.03535

- Results from linear fit method are consistent within uncertainties but require better statistics.

Summary

- Preliminary averaged $D_{LL'}$ measurements:

Preliminary Helicity Balance

$\cos\theta_{pL'}$ along $\vec{p_{\Lambda}}$	$\cos\theta_{pL'}$ along $\vec{p_{\gamma}}$
0.0618 ± 0.0963	0.118 ± 0.107

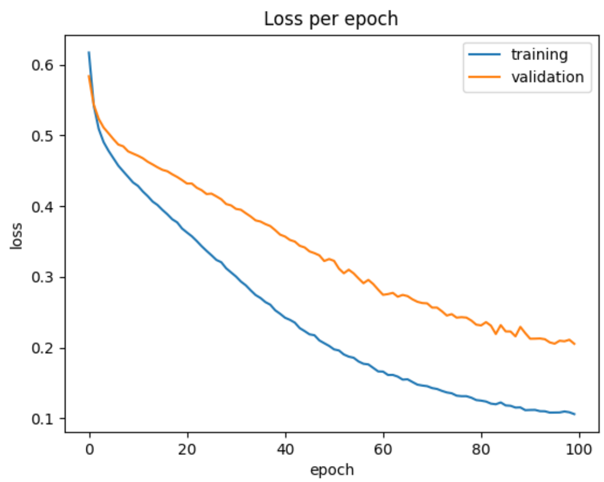
- In general, consistent with HERMES ($D_{LL'} = 0.11 \pm 0.10(stat) \pm 0.03(syst)$ and NOMAD ($-P_{\Lambda}^{\nu} = 0.09 \pm 0.06\ (stat) \pm 0.03\ (syst)$)
- GNNs significantly reduce background in MC with up to ~85% test accuracy
- Next steps: Validate GNNs performance on data samples, then re-extract $D_{LL'}$ with GNN-filtered mass spectrum

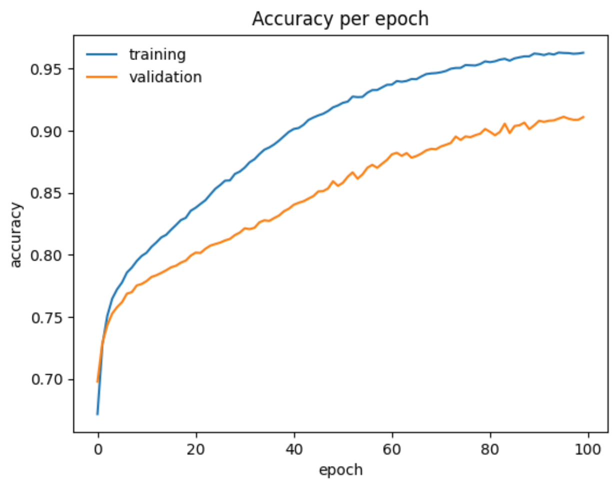
Thank you!

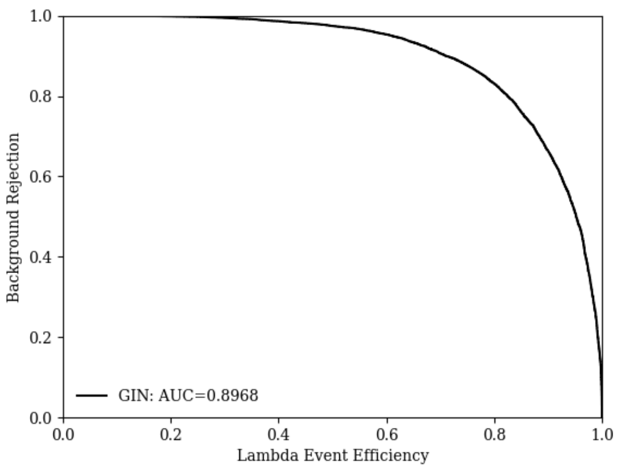
Research supported by:

Training Results: GIN

- Optimize with Adam $lr = 10^{-5}, batch = 1024$
- Test accuracy is ~85% but still need to reduce overtraining

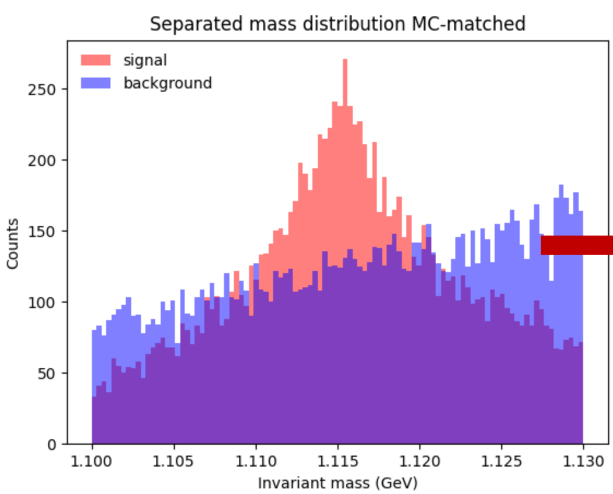


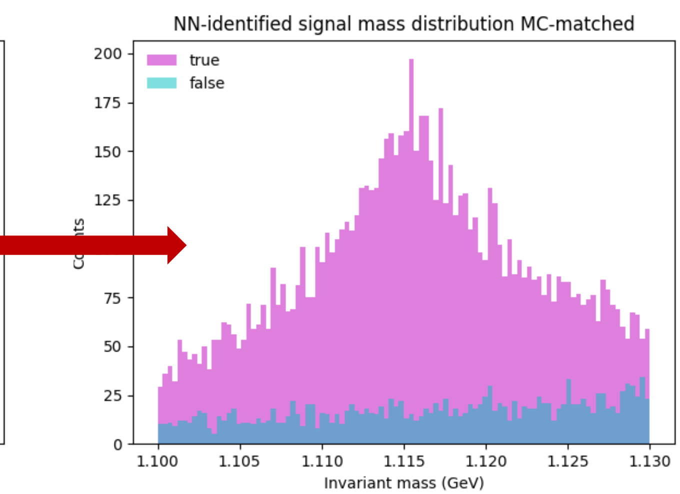


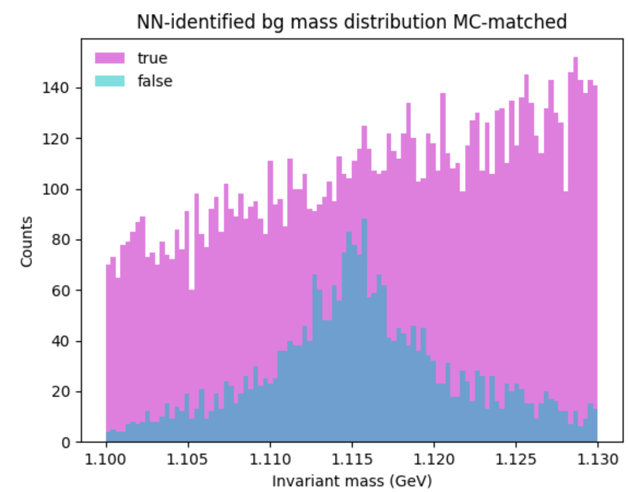


Initial Results: GIN

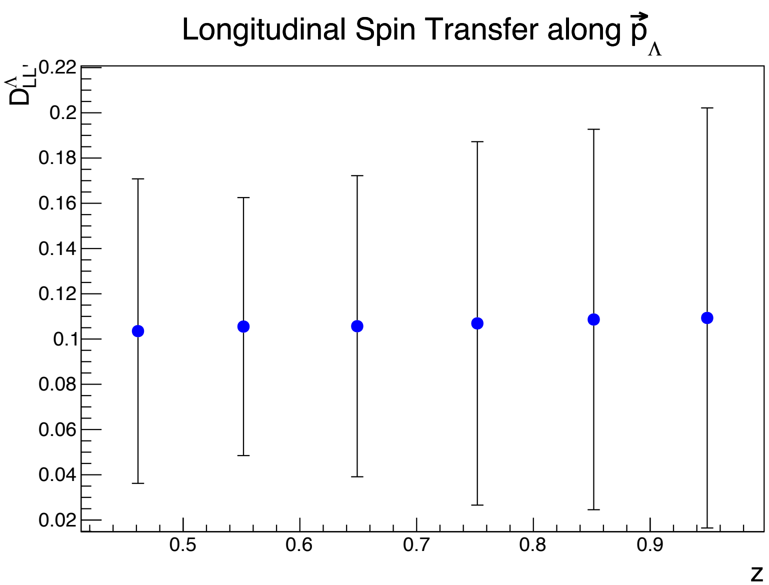
- Background is significantly reduced for NN-identified signal!



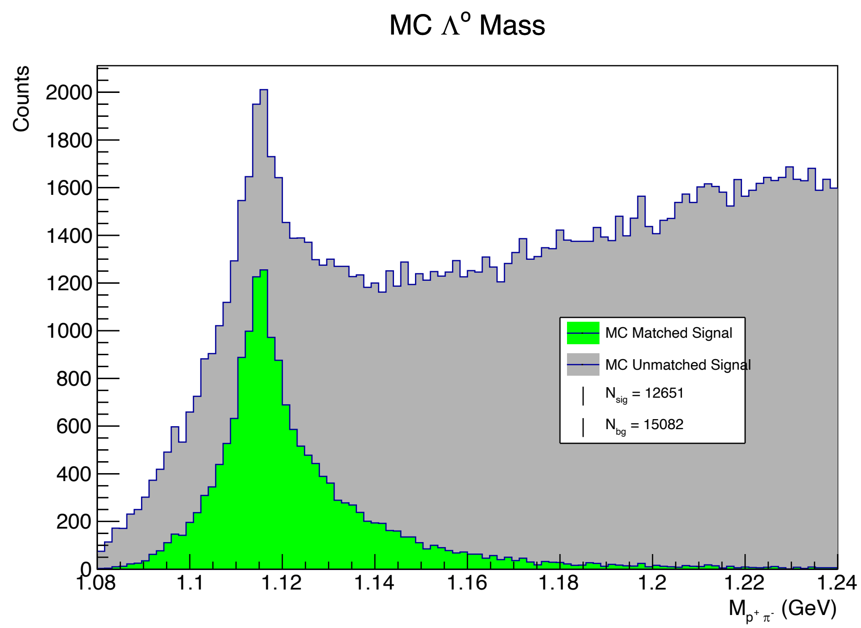




MC: Asymmetry Injection Helicity Balance



Weight $cos\theta_{REC}$ by $1 + \alpha D(y) P_b D_{ll,injected} cos\theta_{MC}$
with $D_{ll,injected} = 0.1$, averaged result is $D_{ll} = 0.107 \pm 0.078$



Truth Matching:
Require a MC truth Λ in event with
$|P^{\Lambda}_{Rec} - P^{\Lambda}_{MC}| < 0.1 GeV$

/work/clas12/rg-a/montecarlo/fall2018/torus+1/clasdis/nobg/

REC/MC Mass Resolutions