Spin Transfer to Λ Hyperons at CLAS12

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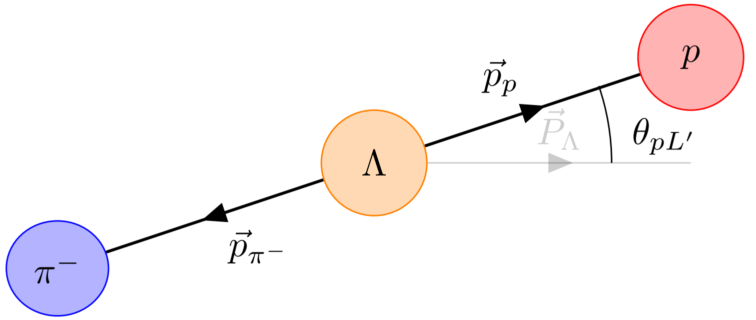
Research supported by:

Longitudinal Spin Transfer

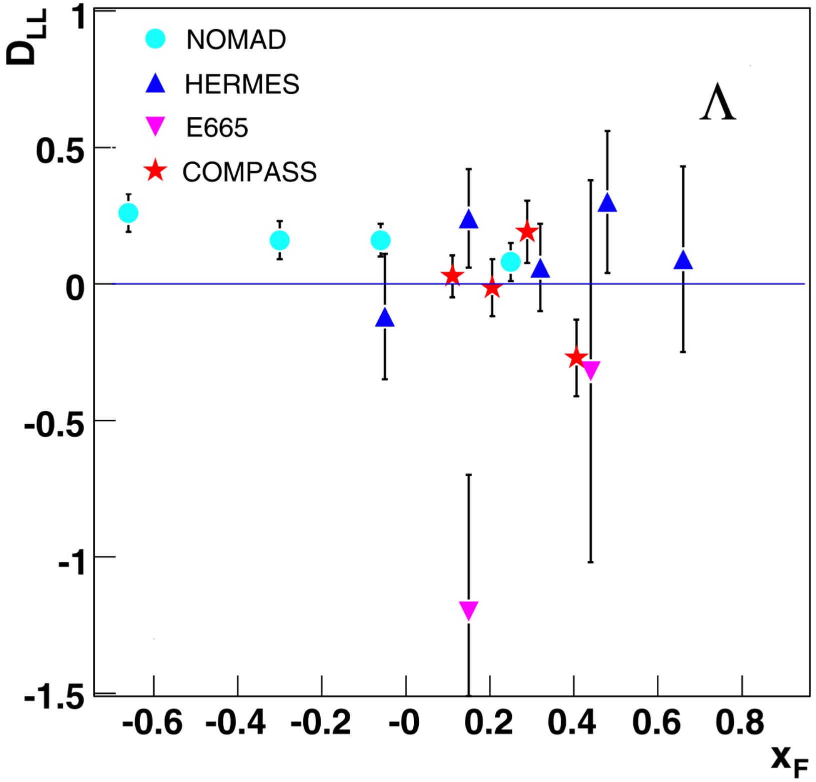


- Λ polarization is easily accessible from the $\Lambda \to p\pi^-$ channel:

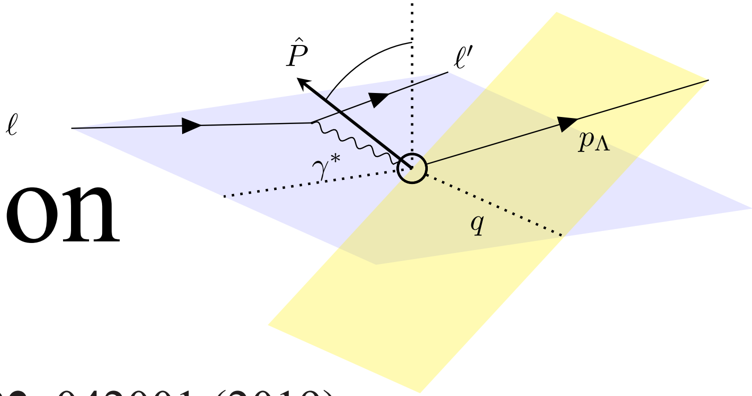
$$\frac{dN}{d\Omega_p} \propto 1 + \alpha P_b D(y) D^{\Lambda}_{LL'} \cos\theta_{pL'}$$

- $D^{\Lambda}_{LL'}$ describes probability for a quark to transfer its polarization to the Λ
- Related to helicity FF G_1^{Λ}

Eur. Phys. J. C (2009) **64**: 171–179



Spontaneous Transverse Polarization



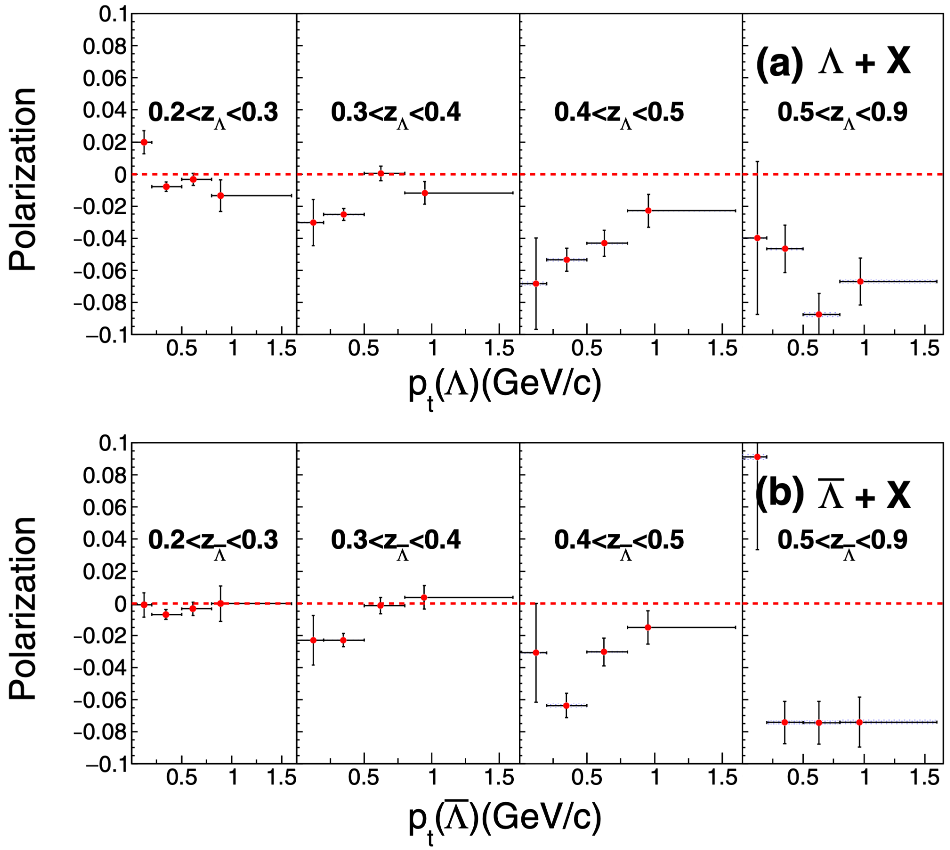
- Large transverse polarization of Λ observed in unpolarized proton collisions

$$\frac{dN}{d\Omega_p} \propto 1 + \alpha P_T^{\Lambda} \cos\theta_{pL'}$$

- Transverse polarization is related to FF $D_{1T}^{\perp\Lambda}$, see Isabella Garzia's talk
- Process-dependent sign is an important test of QCD gauge structure

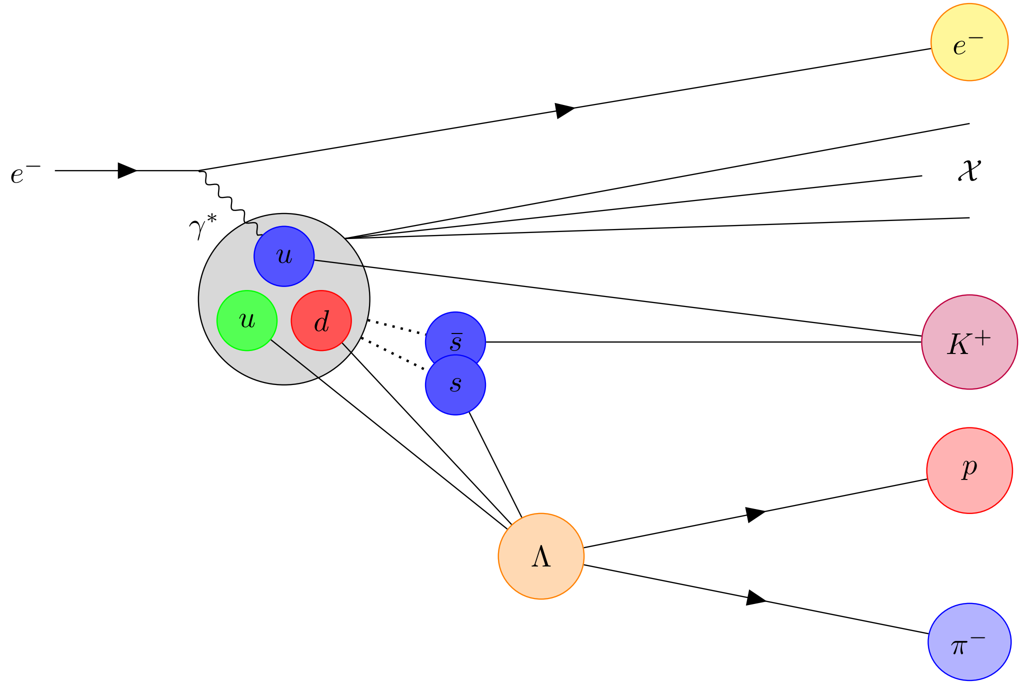
$$D_{1T}^{\perp}{}_{SIDIS} = D_{1T}^{\perp}{}_{e^+e^-} = -D_{1T}^{\perp}{}_{DY}$$

PRL **122**, 042001 (2019)

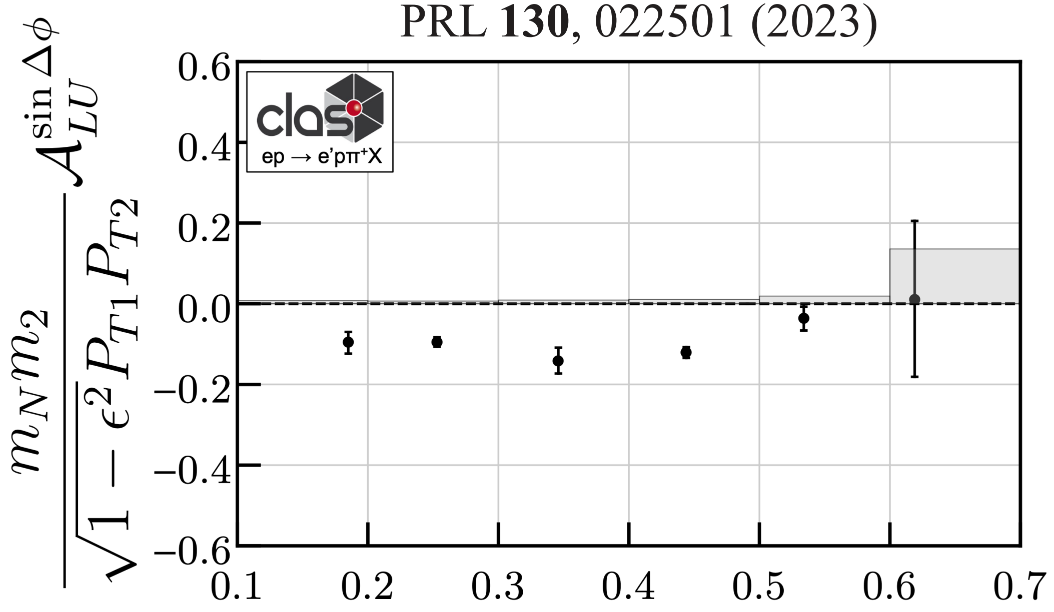


Target Fragmentation Region (TFR) Λs

- Correlations arise due to momentum, spin conservation between a produced $q\bar{q}$ pair
- Provide a means to study the hadronization process in the TFR

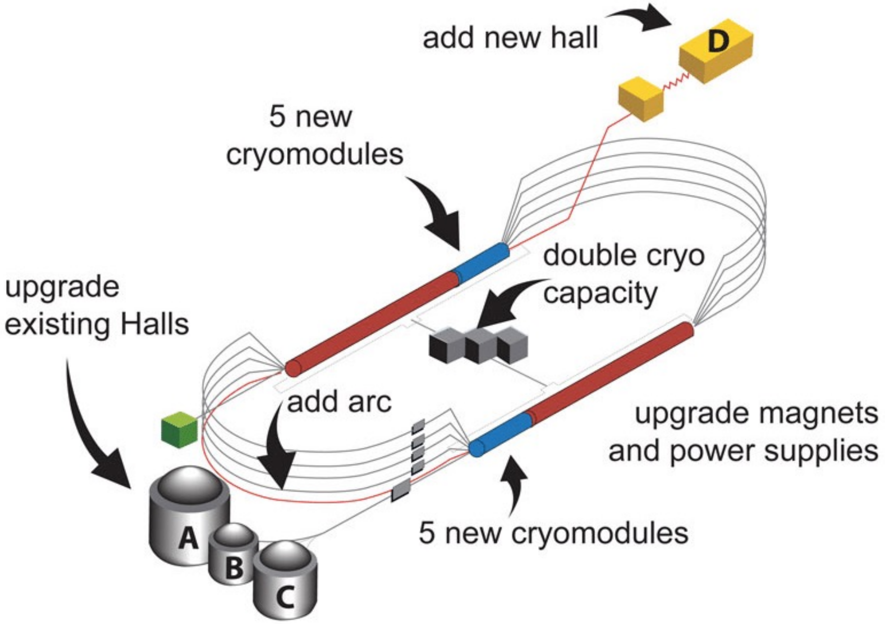


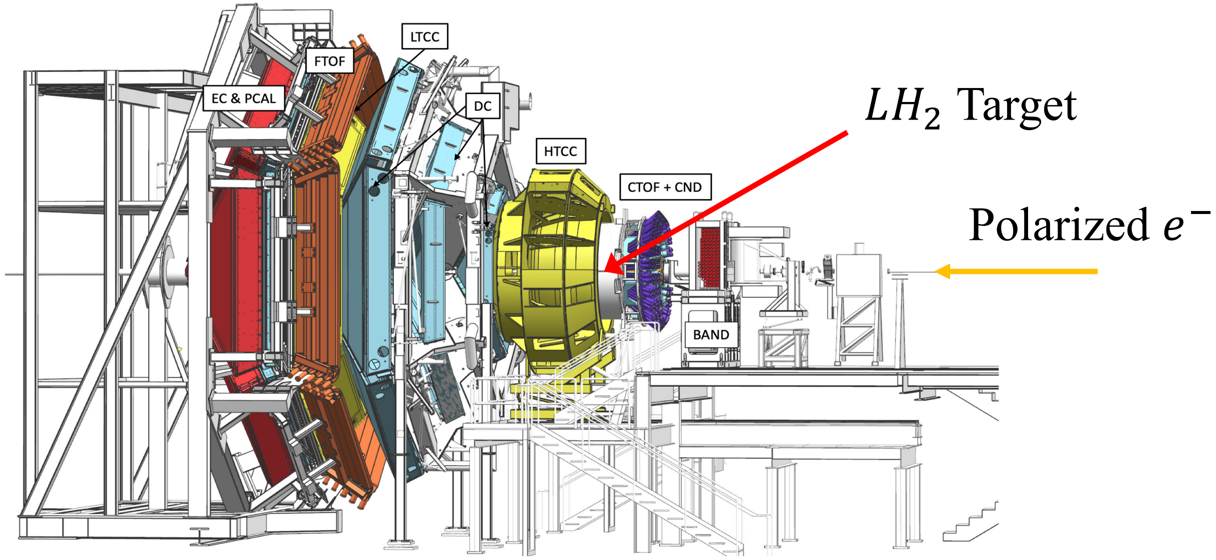
PRL **130**, 022501 (2023)



CLAS12 Experiment at JLab

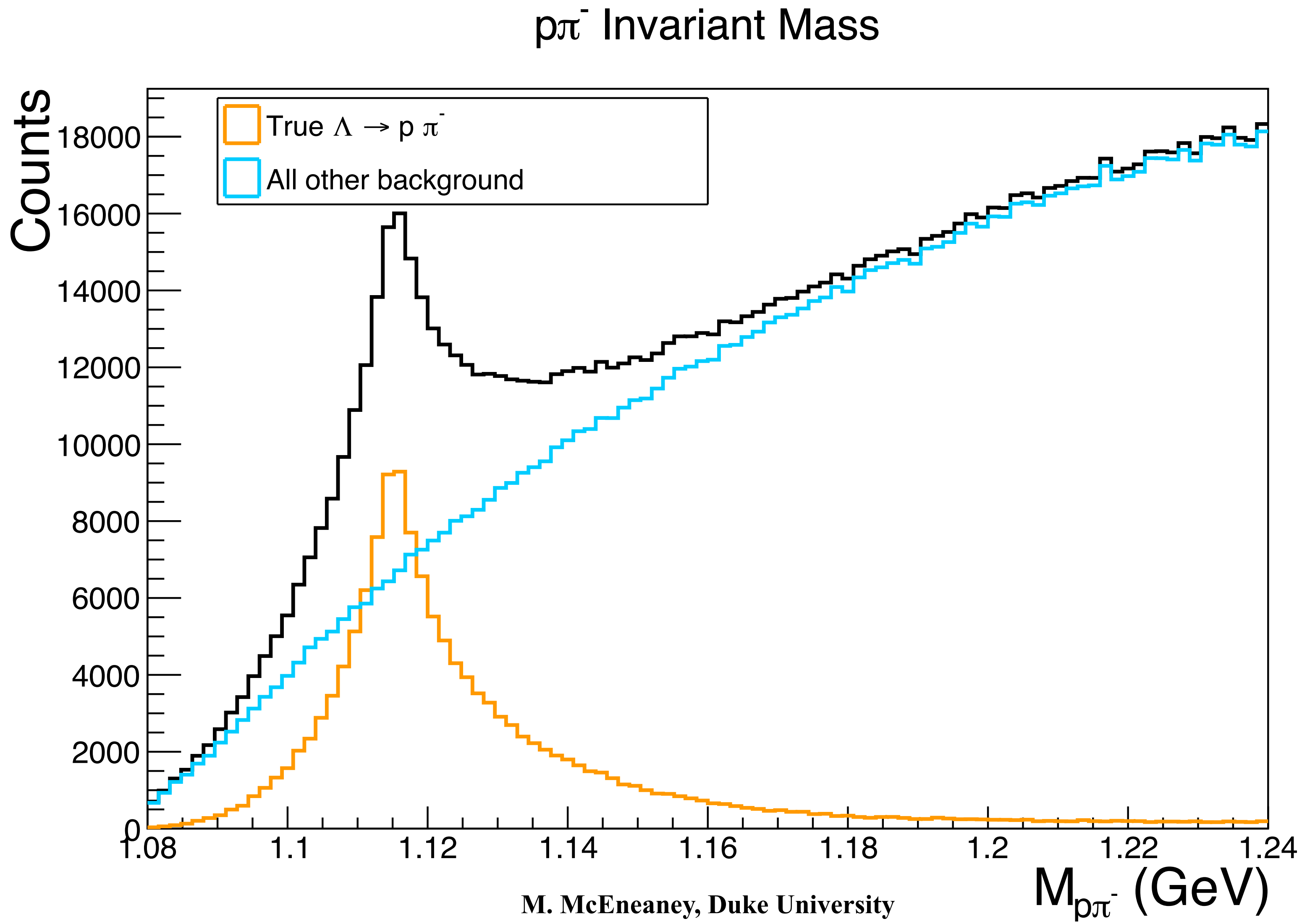
- CEBAF provides highly polarized e^- beam at 10.6GeV
- CLAS12 has excellent momentum resolution and PID with full azimuthal coverage





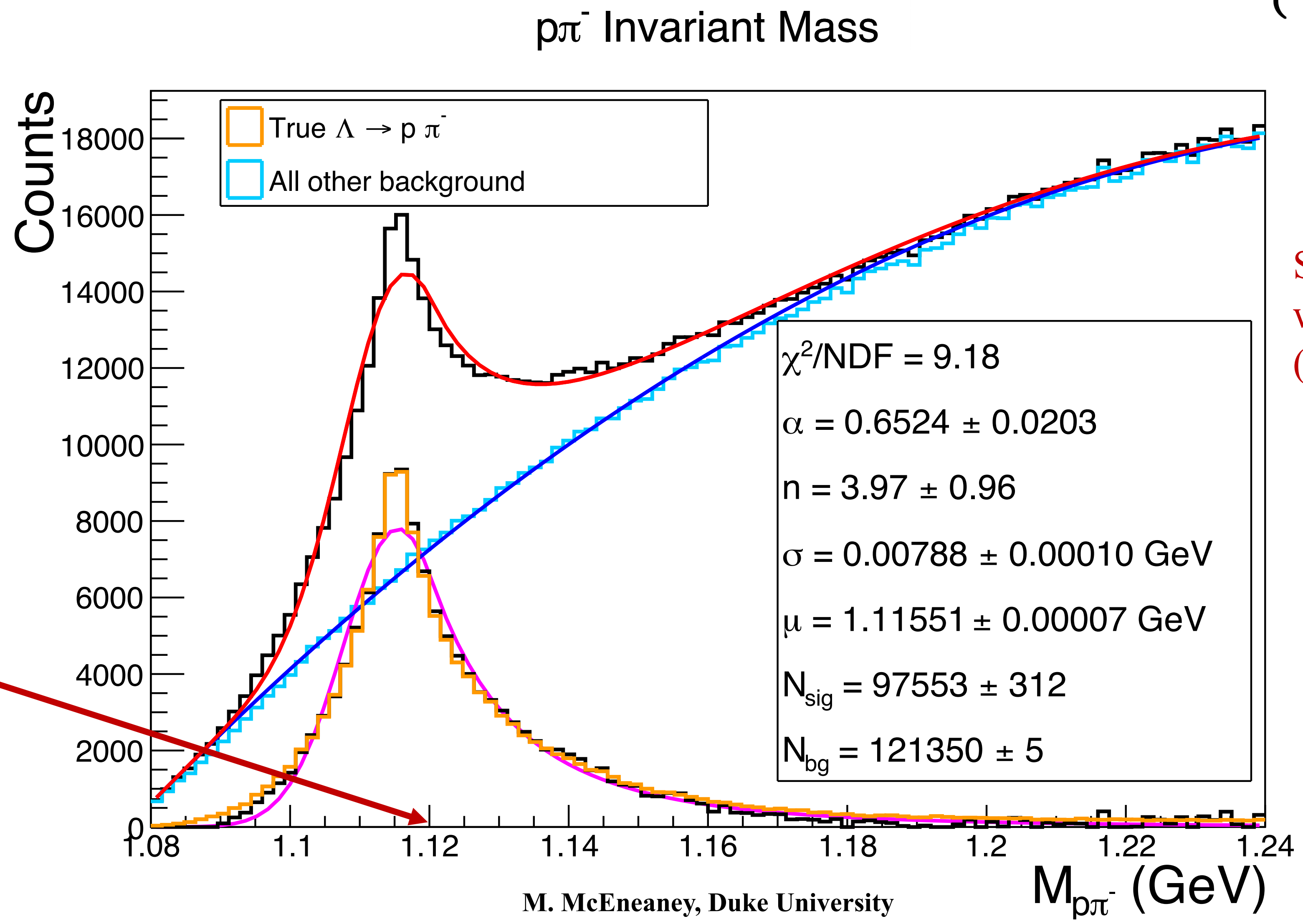
V. Burkert, et al. NIM 2020.

Signal Decomposition MC



Signal Decomposition MC

$$f(x;\alpha,n,\mu,\sigma) = N \begin{cases} \exp -\frac{(x-\mu)^2}{2\sigma^2}, & \frac{x-\mu}{\sigma} > \alpha \\ A(B - \frac{x-\mu}{\sigma})^{-n}, & \frac{x-\mu}{\sigma} \leq \alpha \end{cases}$$

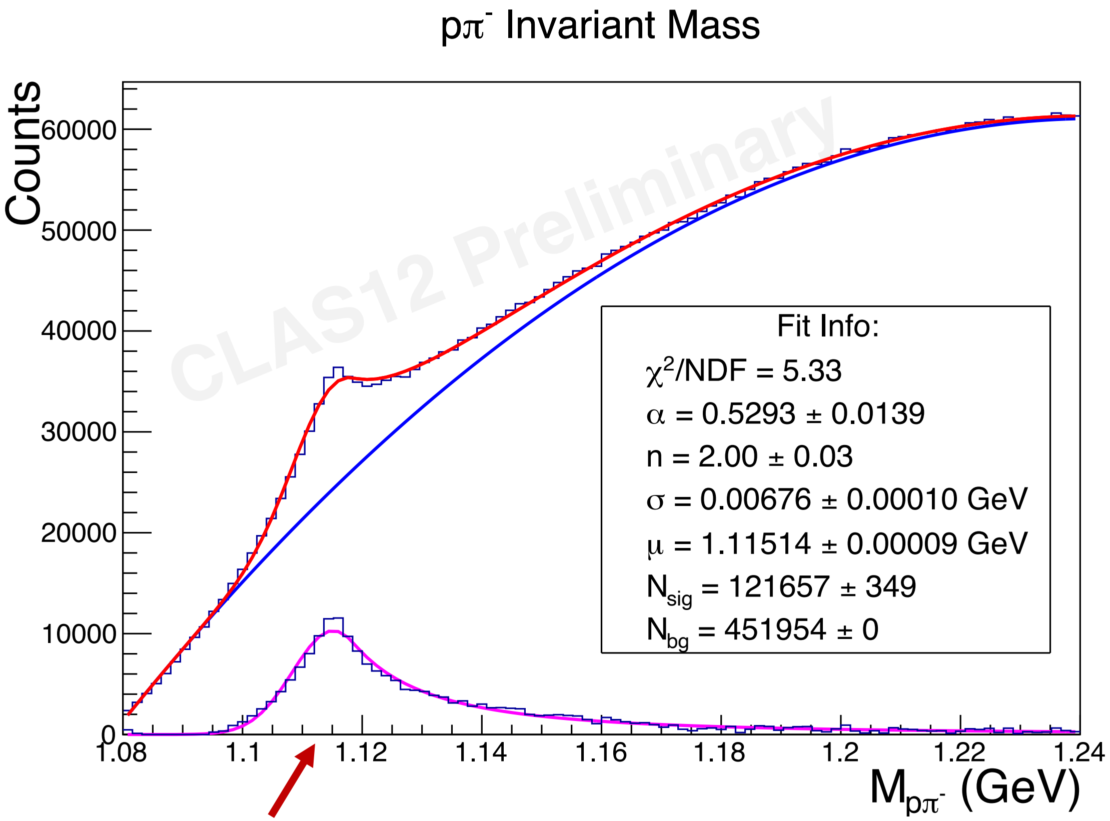


Signal Fit: Gaussian Peak with power law tail (Crystal Ball)

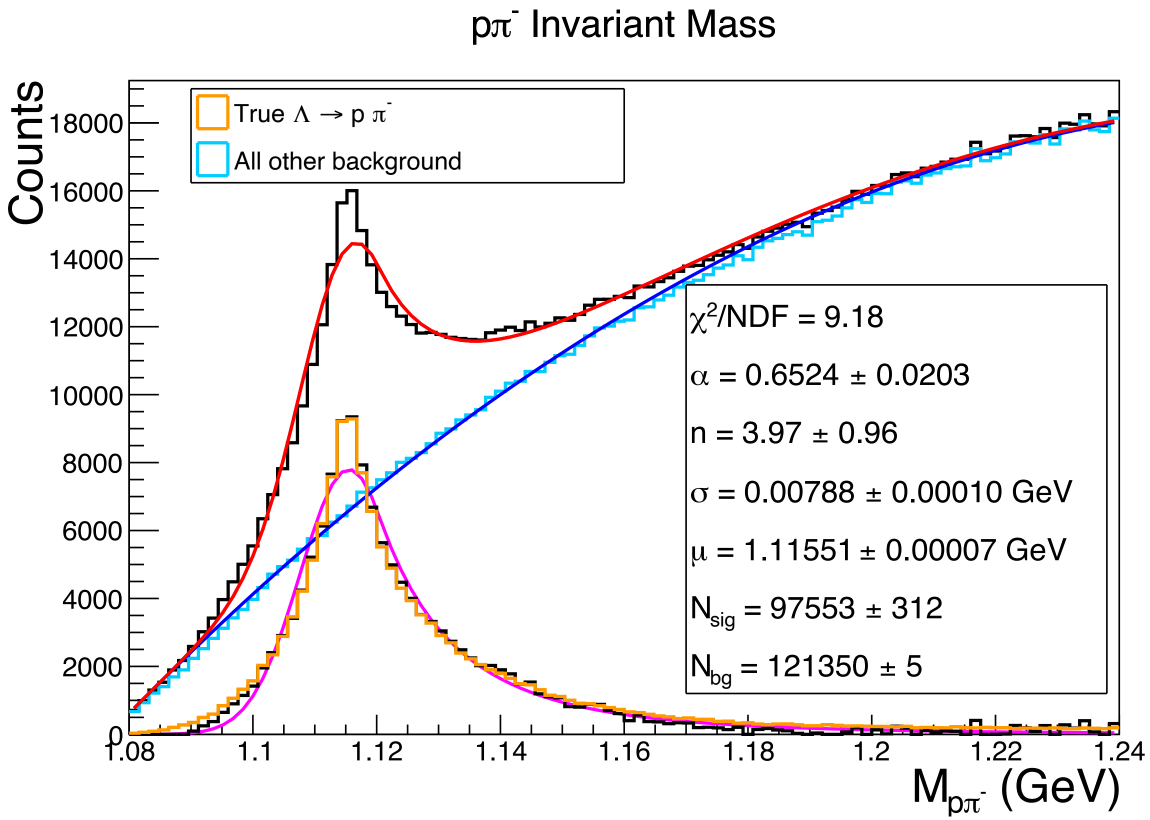
Integrate from 1.10 – 1.13 GeV

Signal Fit on Data

Data



MC



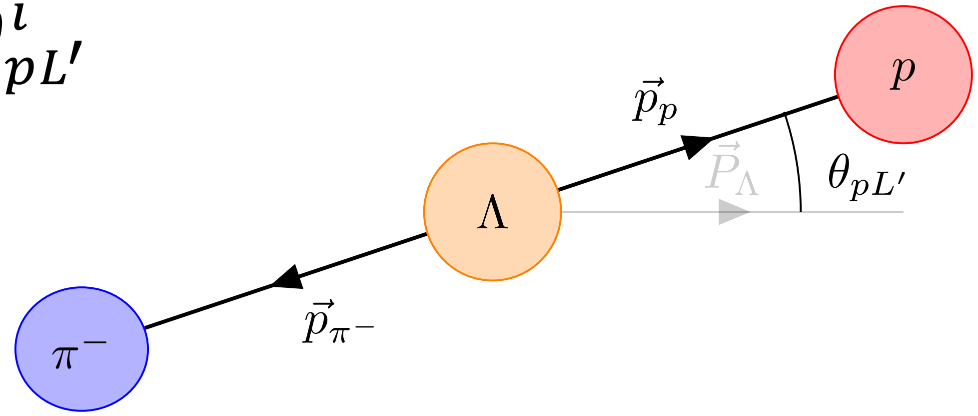
Integrate from $1.10 - 1.13\ GeV$

$D_{LL'}$ Extraction

- Linear fit to cross-section requires acceptance correction
- Maximum Likelihood (ML) method requires **equal** amounts of positive and negative helicity events

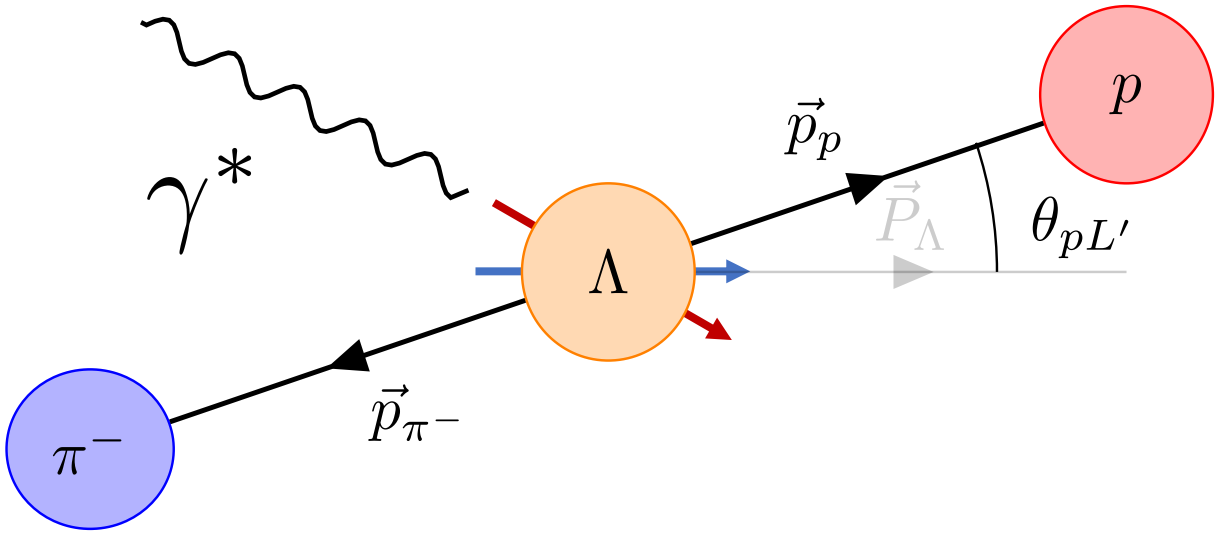
$$D^{\Lambda}_{LL'} = \frac{1}{\alpha \overline{P_b^2}} \cdot \frac{\Sigma_{i=1}^{N_\Lambda} P_{b,i} D(y_i) \cos\theta^i_{pL'}}{\Sigma_{i=1}^{N_\Lambda} D^2(y_i) \cos^2\theta^i_{pL'}}$$

- No acceptance correction needed for ML



Choice of Λ Polarization Axis

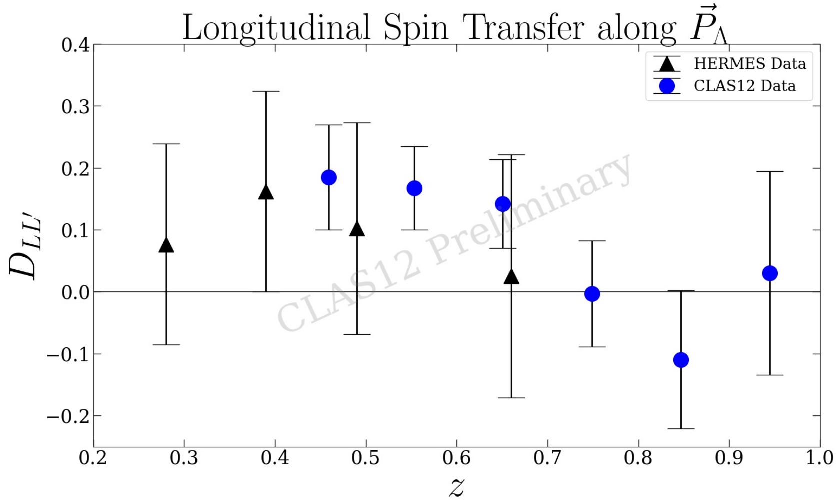
- $\cos\theta_{pL'}$ is the angle between the proton momentum and the Λ polarization axis L'
- Two choices used for L'
  - Along P_Λ
  - Along P_{γ^*}

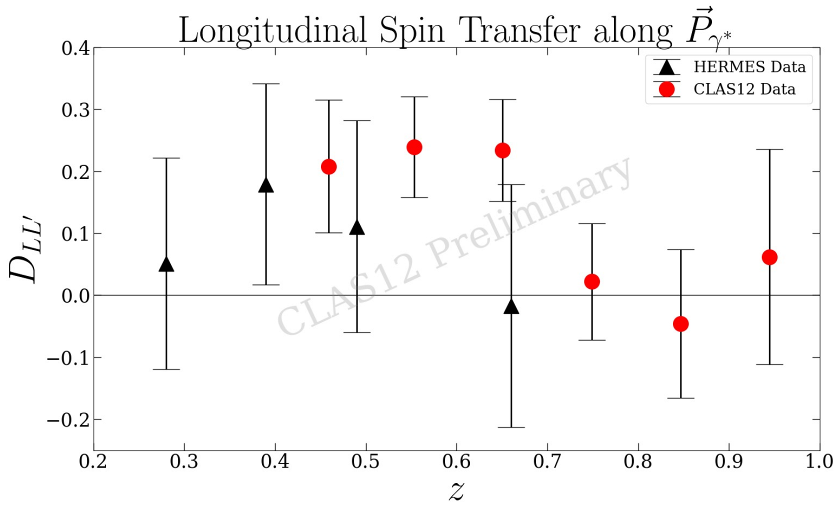


Maximum Likelihood (ML) Results

$$D_{LL'}^{\Lambda} = \frac{D_{LL'_{sig}} - \epsilon D_{LL'\,bg}}{1 - \epsilon}$$

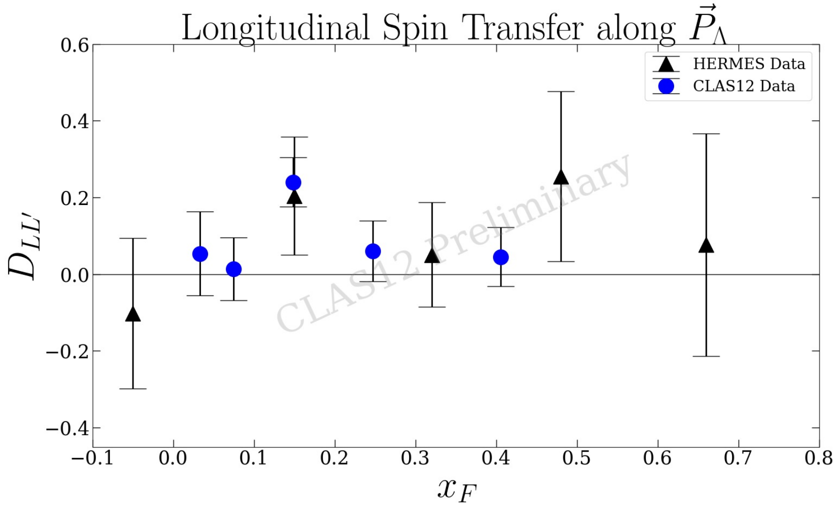
vs. z

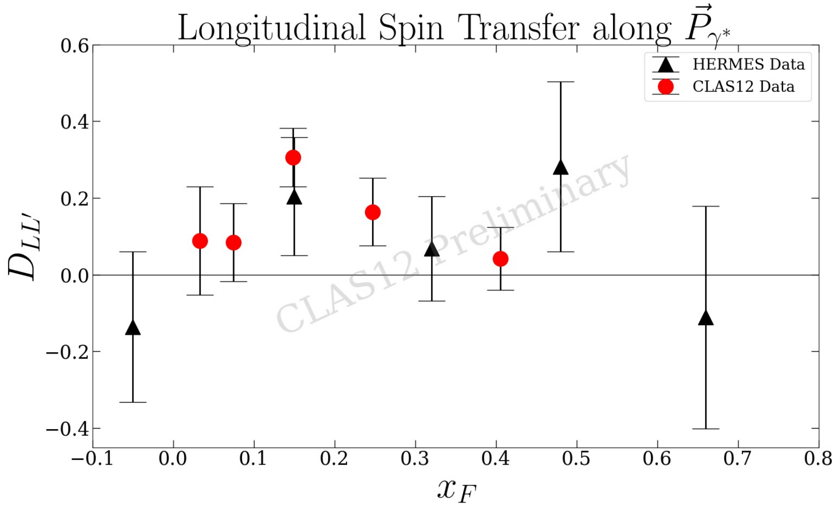




Note: errors are solely statistical

vs. x_F

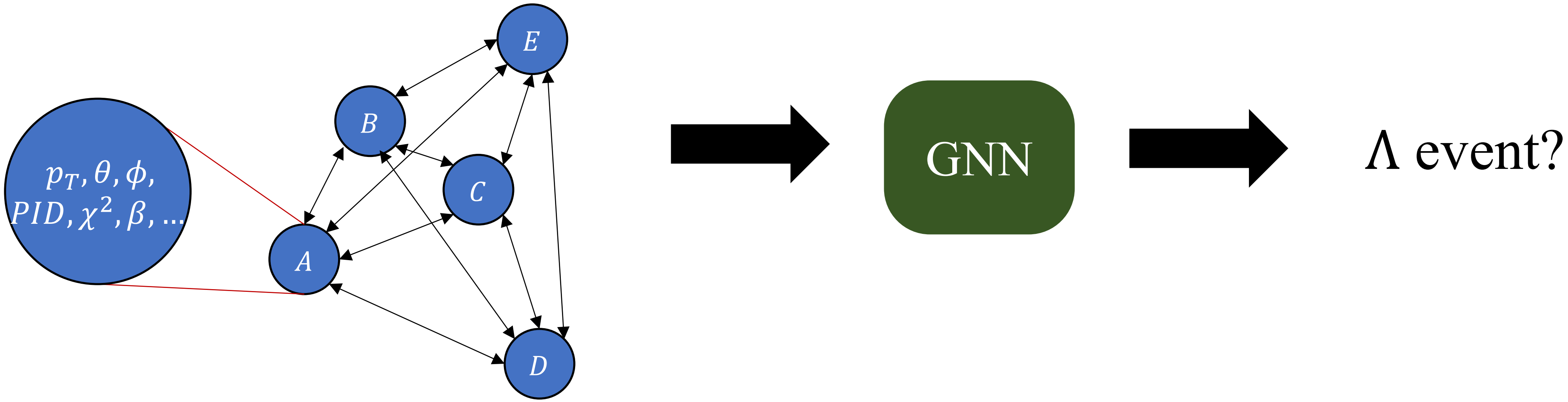




HERMES results from PRD, **74**(7), Oct 2006

Graph Neural Networks (GNNs)

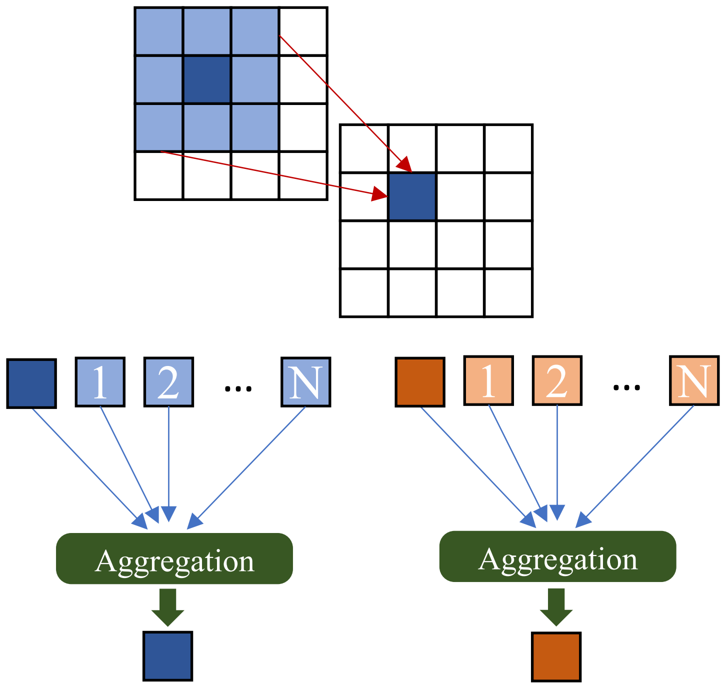
- **Idea**: use GNN to reduce background in invariant mass spectrum on event-by-event basis
- Pass each event as fully-connected, bidirectional graph
- Each particle is a node with its own data: p_T, θ, ϕ, etc.



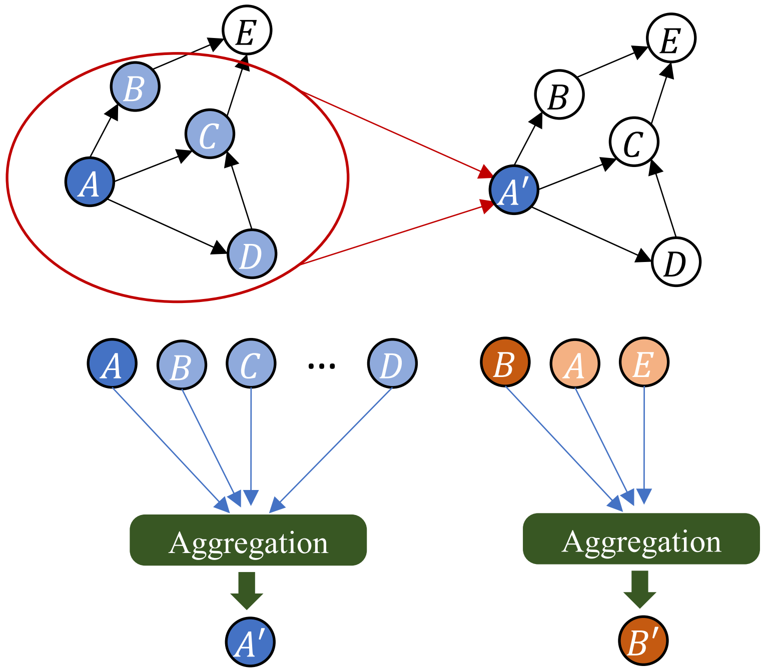
Graph Neural Networks (GNNs)

- At basic level, function as generalized form of CNNs

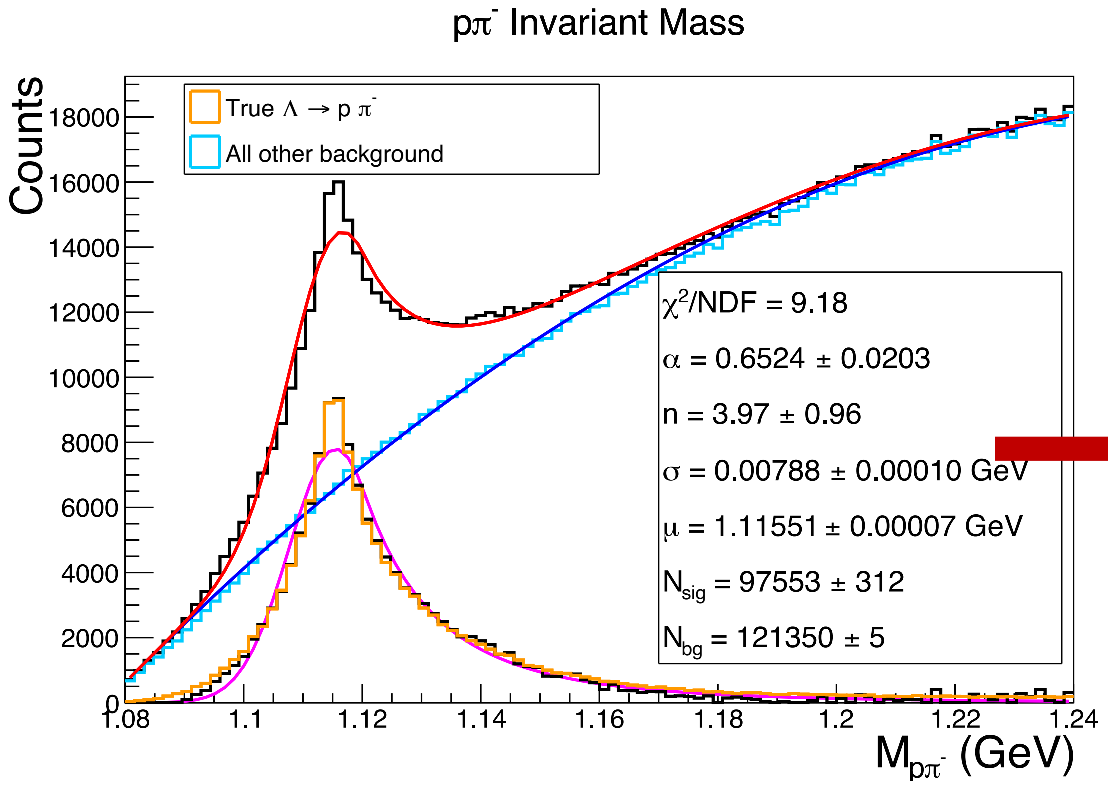
CNN



GNN

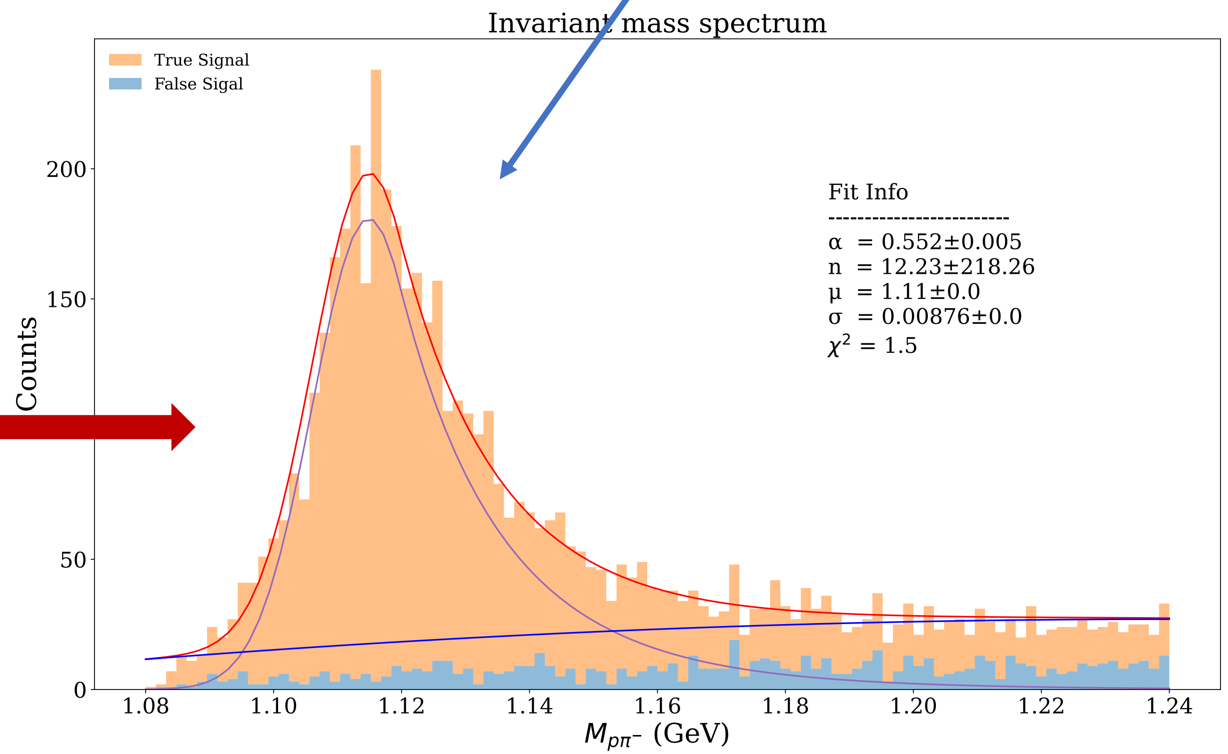


GIN Evaluation on MC



Before NN

Signal shape is preserved

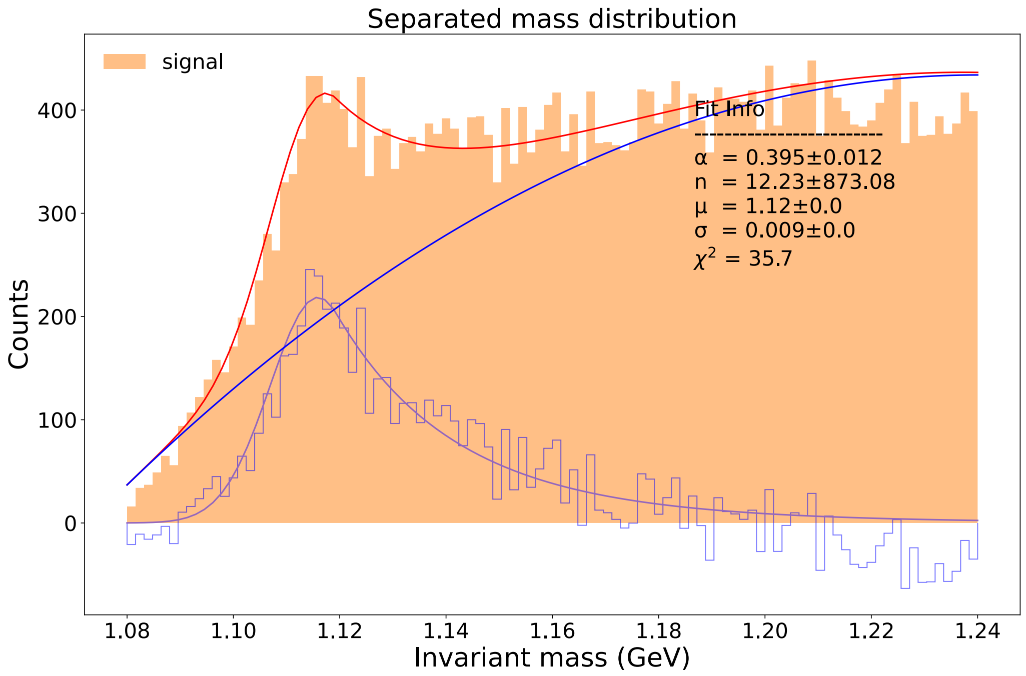


After NN

83.7% Test accuracy and background is significantly reduced!

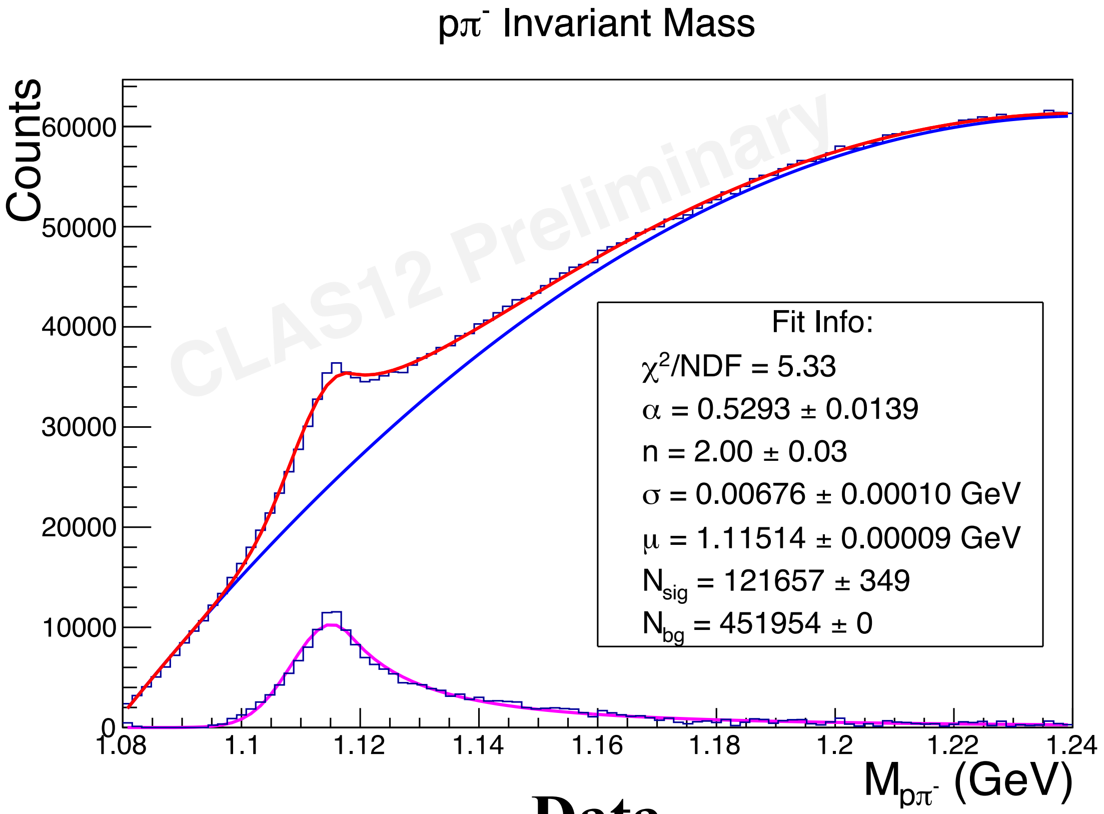
GIN Evaluation on Data

- Evaluate on 24k events
- FOM=$N_{sig}/\sqrt{N_{tot}}$ is 65.74 compared to 34.11 without the GIN

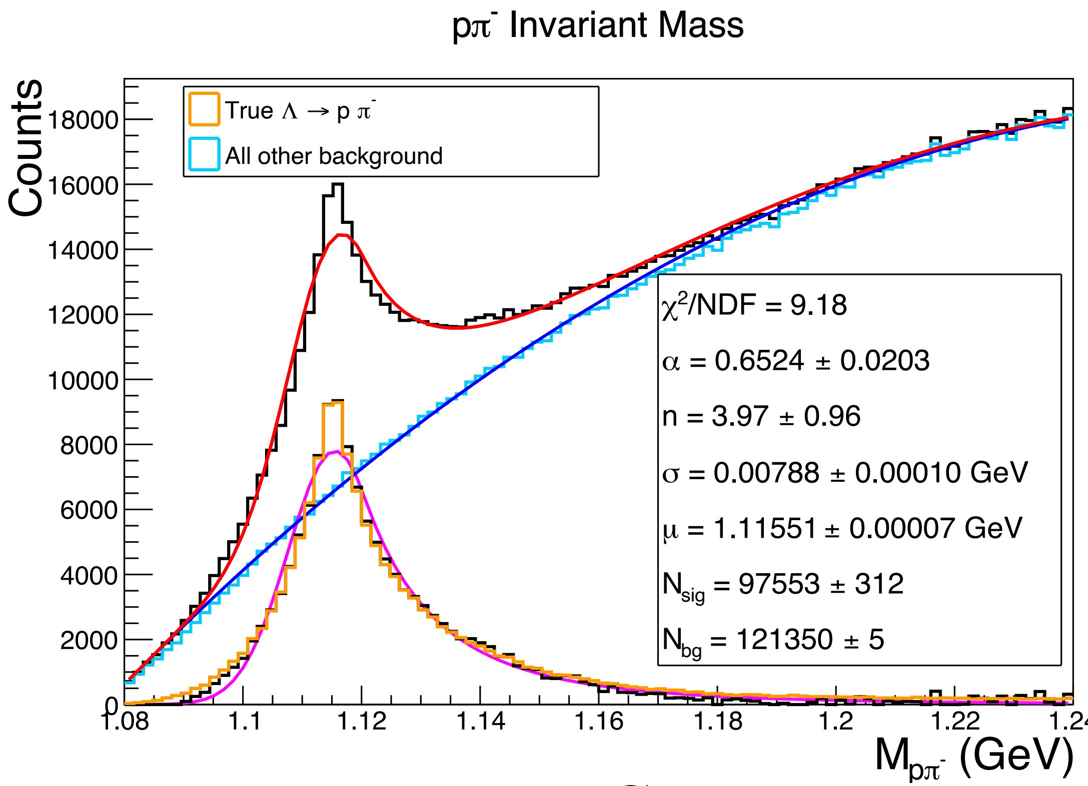


Domain Adaptation

- **Problem**: target domain does not match source domain



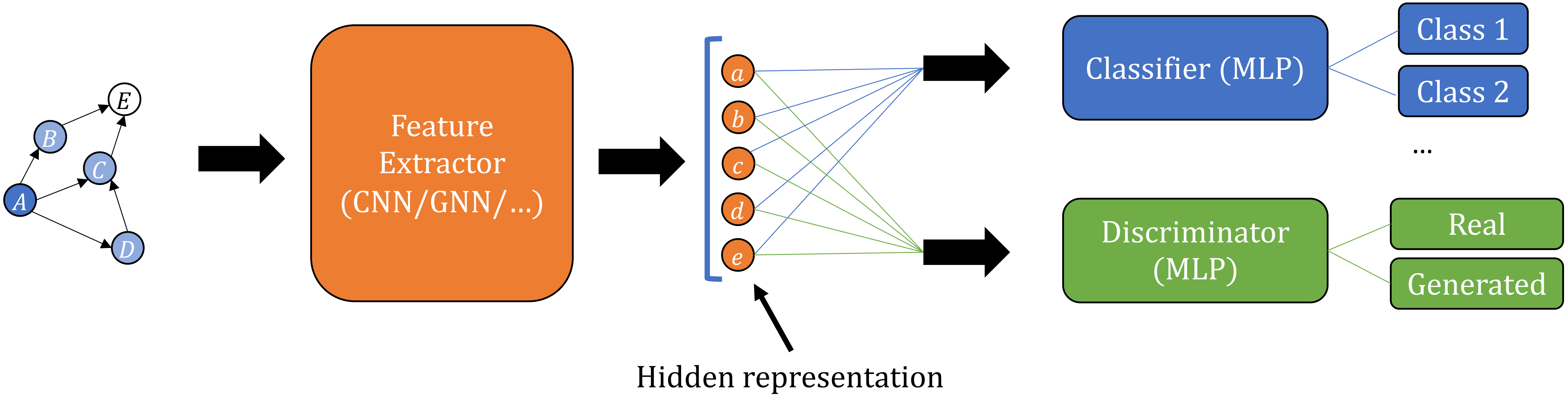
Data



MC

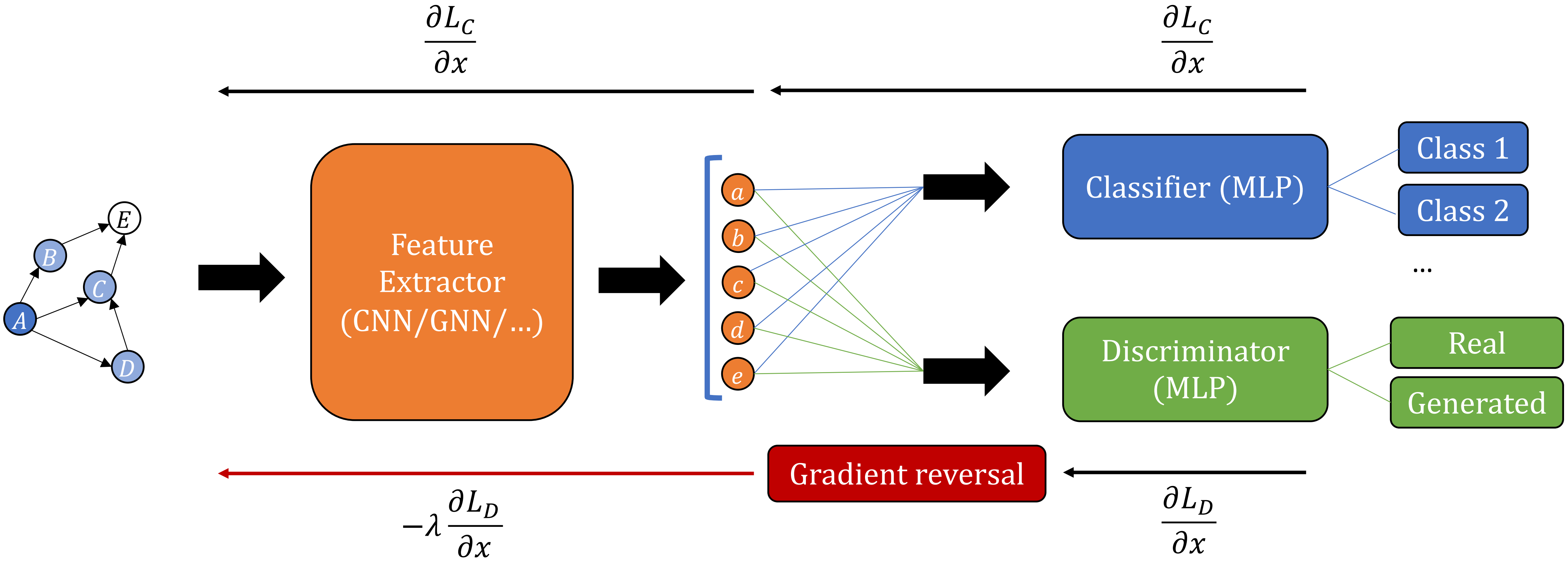
Domain Adversarial NNs

- Minimizes distinction between real and training data
- Two objectives: classification task and domain discrimination



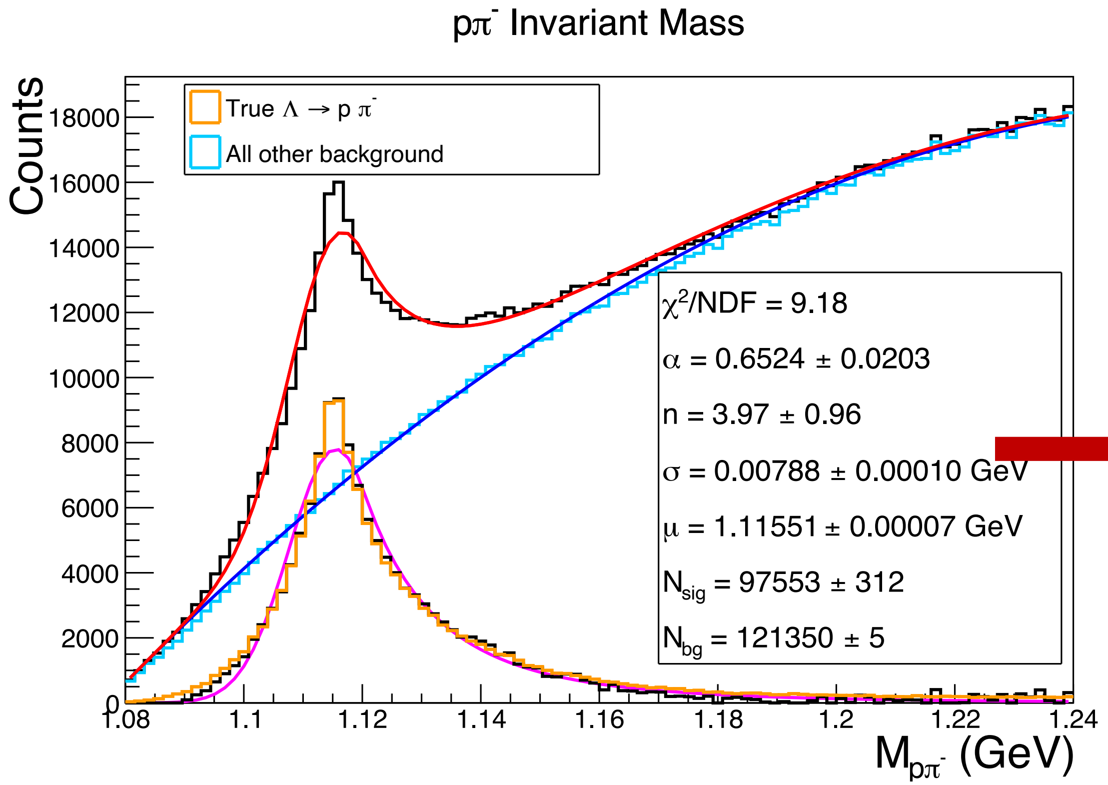
Domain Adversarial NNs

- Reverse gradient from discriminator loss during backpropagation

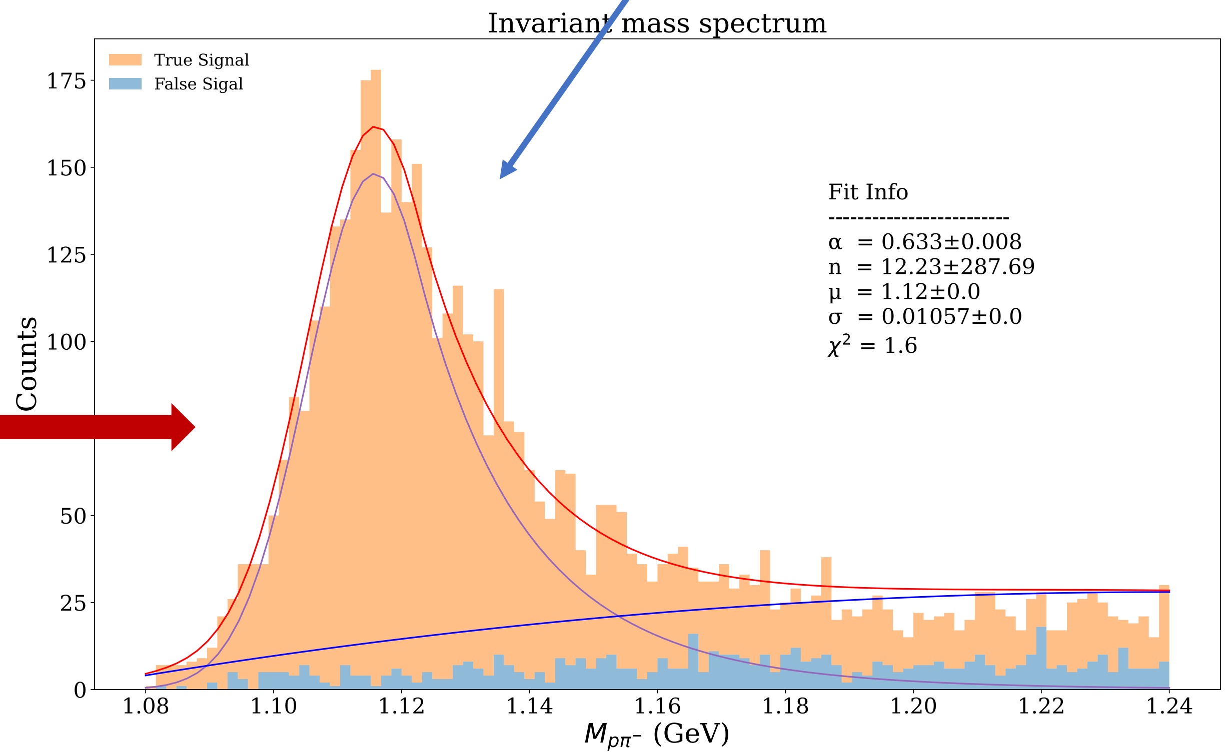


DAGIN Evaluation on MC

Signal shape is preserved



Before NN

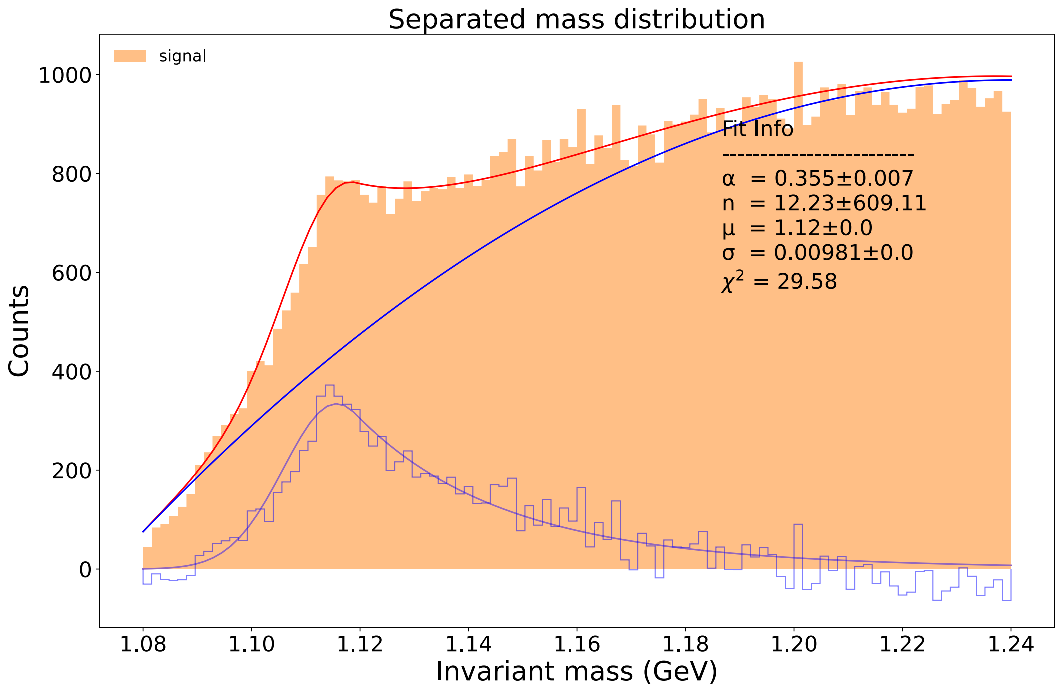


After NN

82.9% Test accuracy and background is significantly reduced!

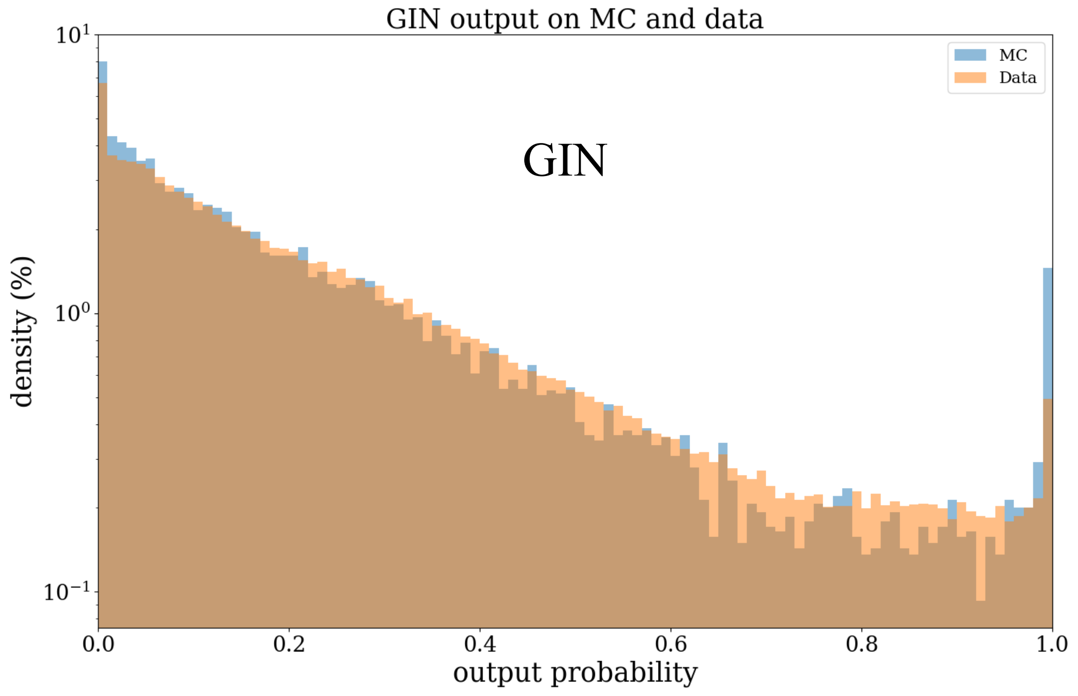
DAGIN Evaluation on Data

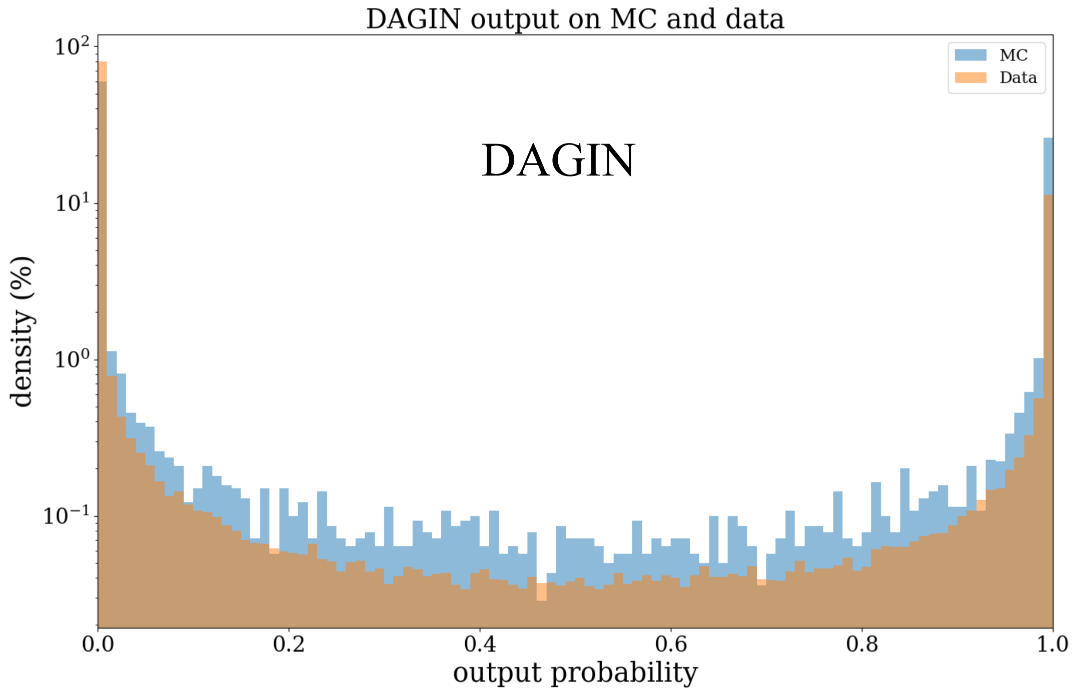
- Evaluate on 24k events
- FOM=$N_{sig}/\sqrt{N_{tot}}$ is 42.09 compared to 34.11 without the GIN



NN Output on Data and MC

- Kolmogorov-Smirnov statistic is 0.035 for GIN and 0.261 for DAGIN





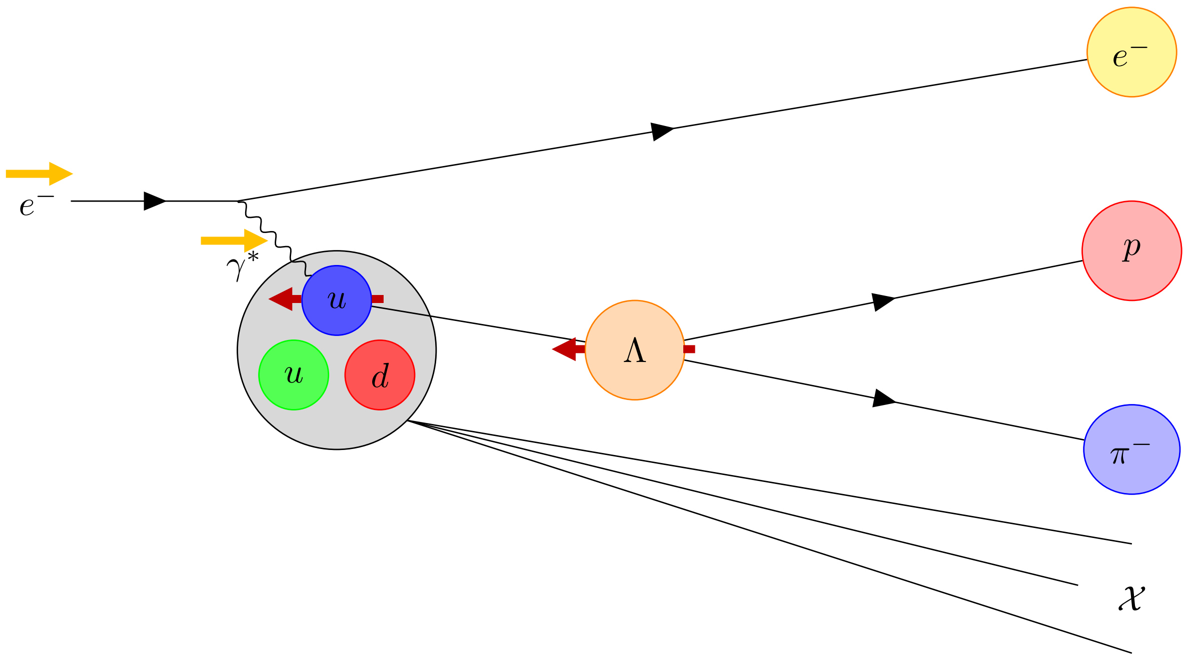
Summary and Next Steps

- Preliminary extraction of $\left\langle D_{LL'}^{\Lambda} \right\rangle = 0.0618 \pm 0.0963(stat)$ is consistent with previous measurements
- Machine learning methods need further validation
- Next steps:
    - Secondary vertex reconstruction method recently implemented
    - Measurement of Λ spontaneous transverse polarization
    - ΛK spin orbit correlations


Thank you!

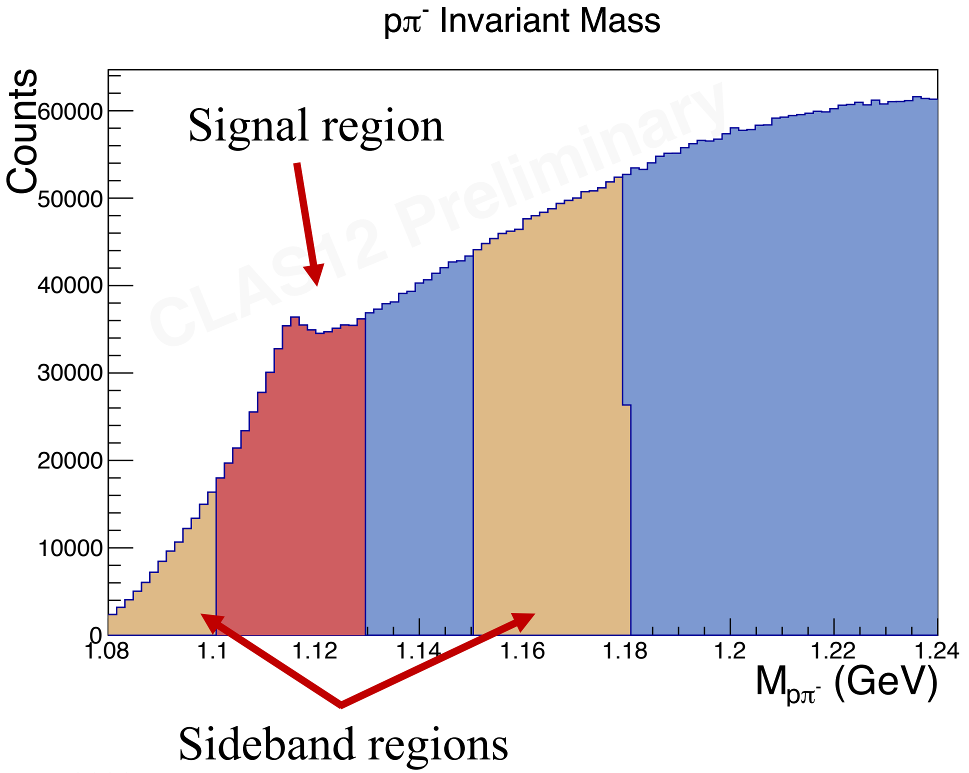
Longitudinal Spin Transfer

- Polarized electron selects a quark with the opposite spin
- Polarization of quark is transferred to hadrons after fragmentation



Sideband Background Correction

- Assume background polarization is independent of $M_{p\pi^-}$
- Subtract polarization computed in sideband regions

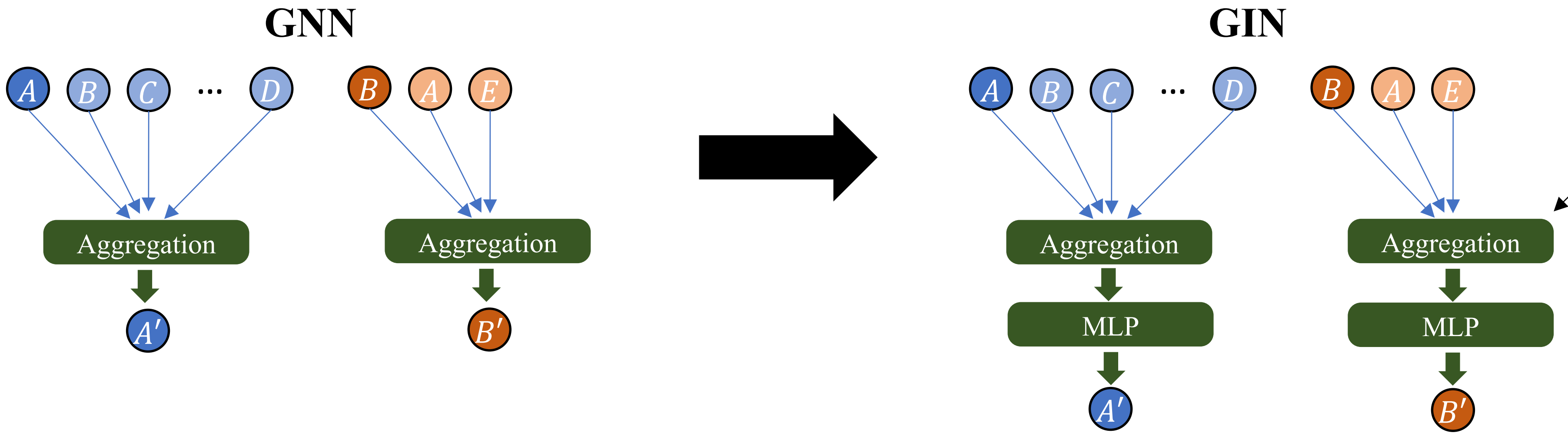


$$D^{\Lambda}_{LL'} = \frac{D_{LL'_{sig}} - \epsilon D_{LL'_{bg}}}{1-\epsilon}$$

Graph Isomorphism Network (GIN)

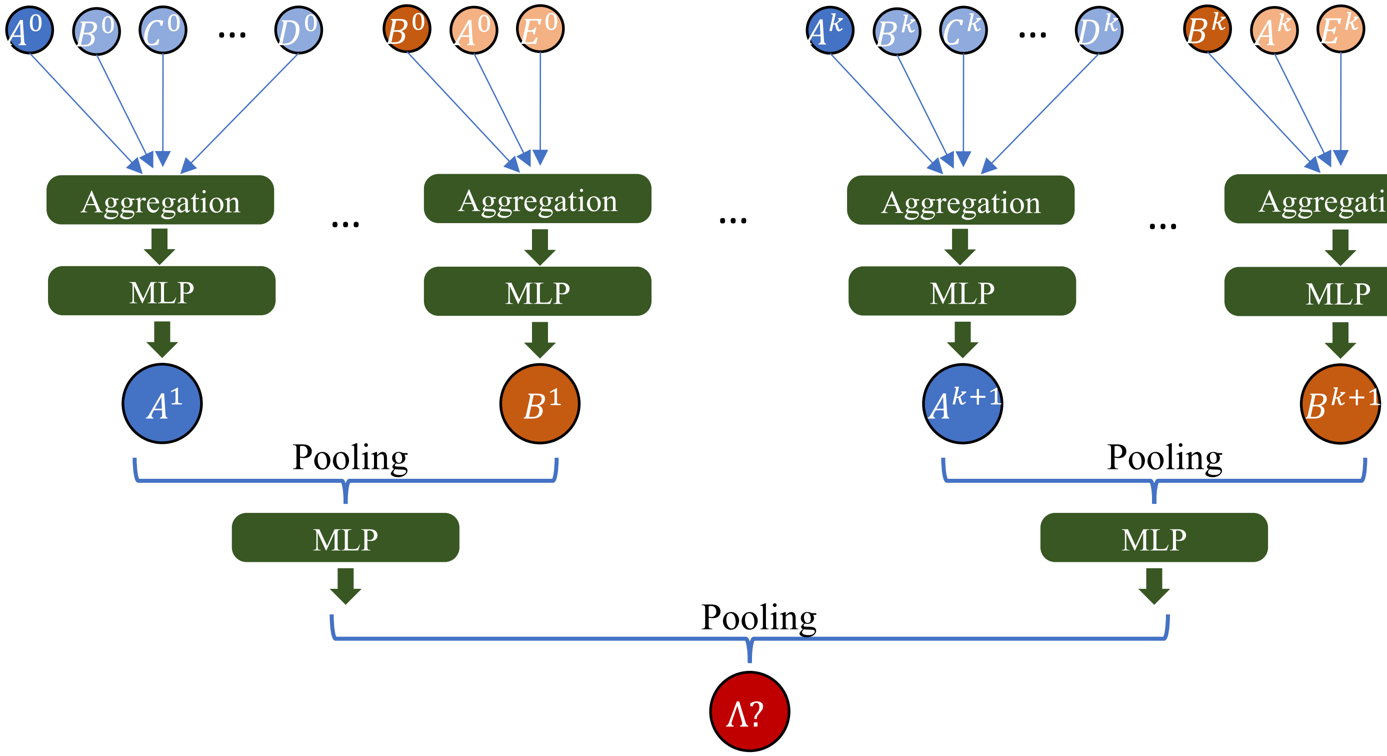
- Similar to Weisfeiler-Lehman (WL) Test, essentially ensures aggregation is injective
- Compare with basic GNN convolution:

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



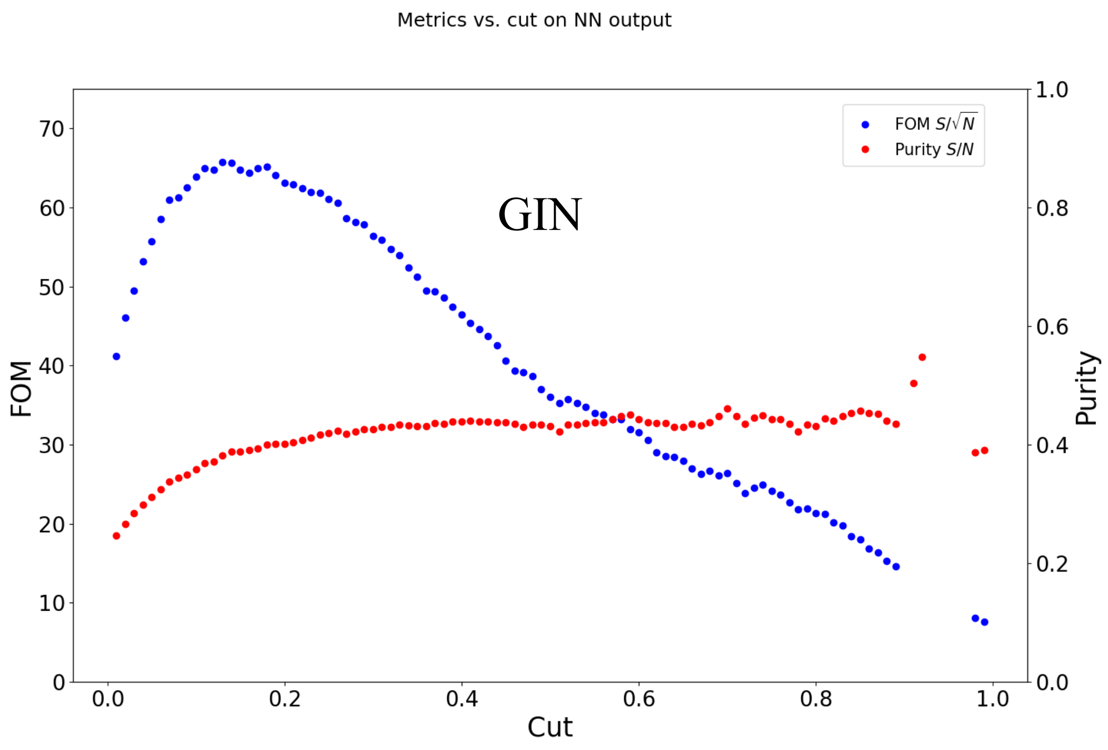
Graph Isomorphism Network (GIN)

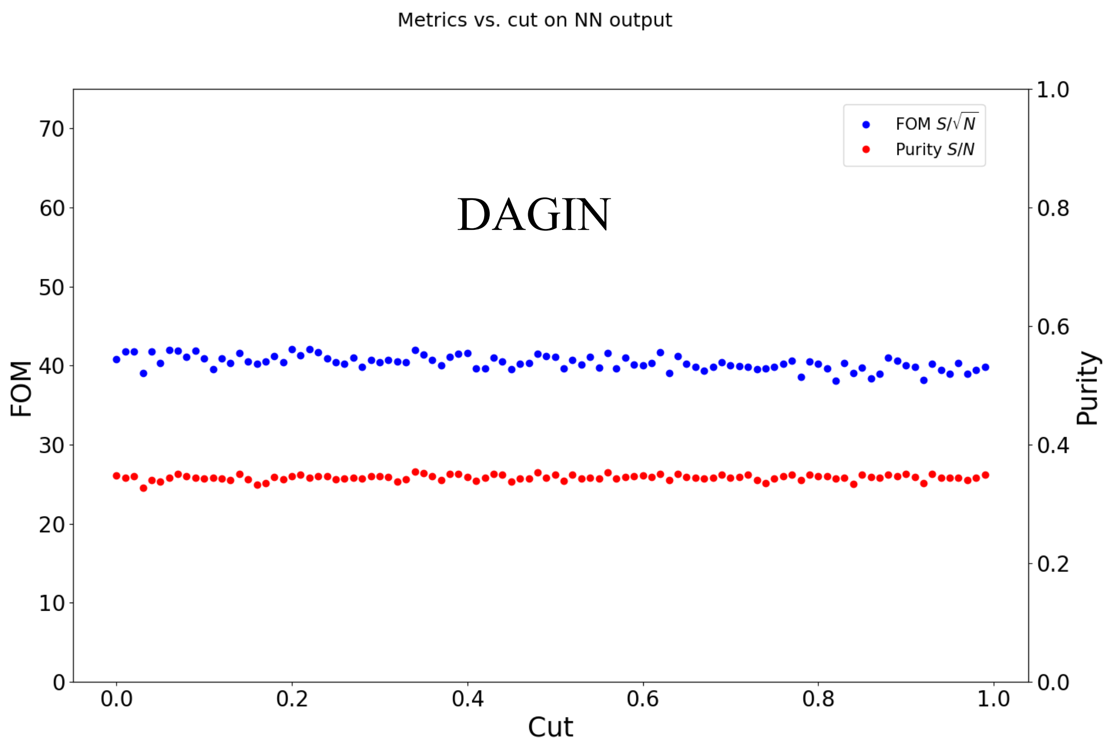
- Aggregation in final layer is across all previous layers/iterations



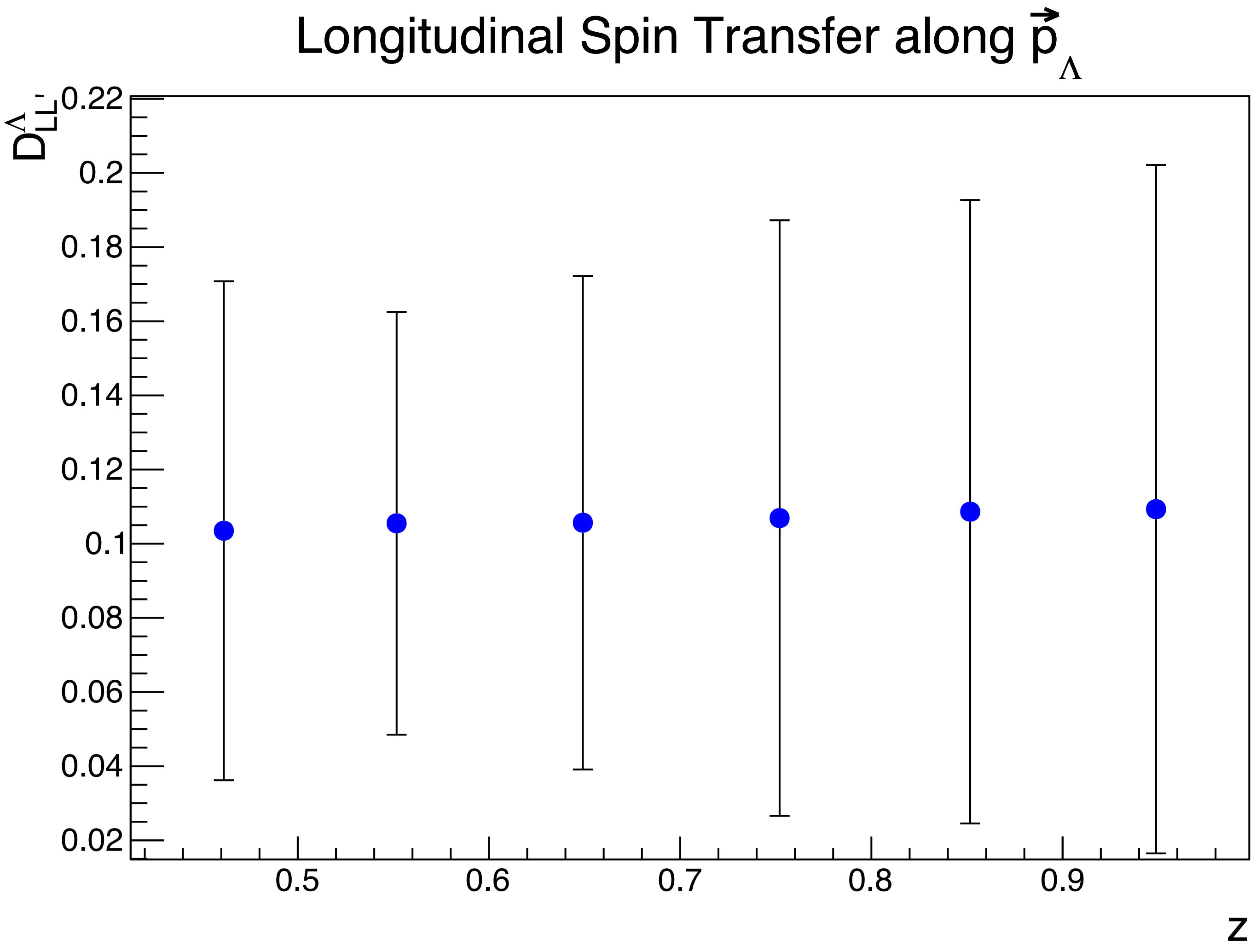
Optimization of NN Cut

- Scan FOM and purity as a function of NN cut





Asymmetry Injection



Weight $cos\theta_{REC}$ by :

$$1 + \alpha D(y) P_b D_{LL',injected} cos\theta_{MC}$$

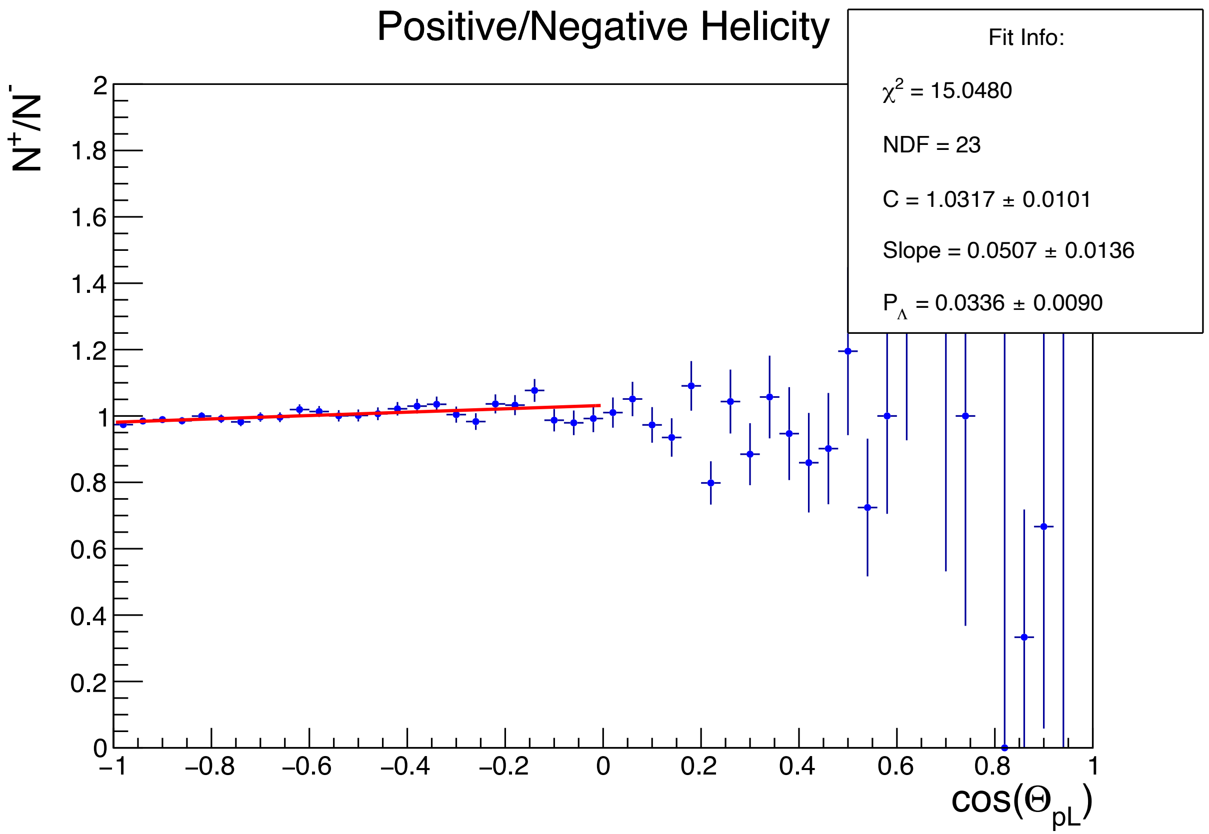
$D_{LL',injected} = 0.1$ for Signal and
$D_{LL',injected} = 0.01$ for Background

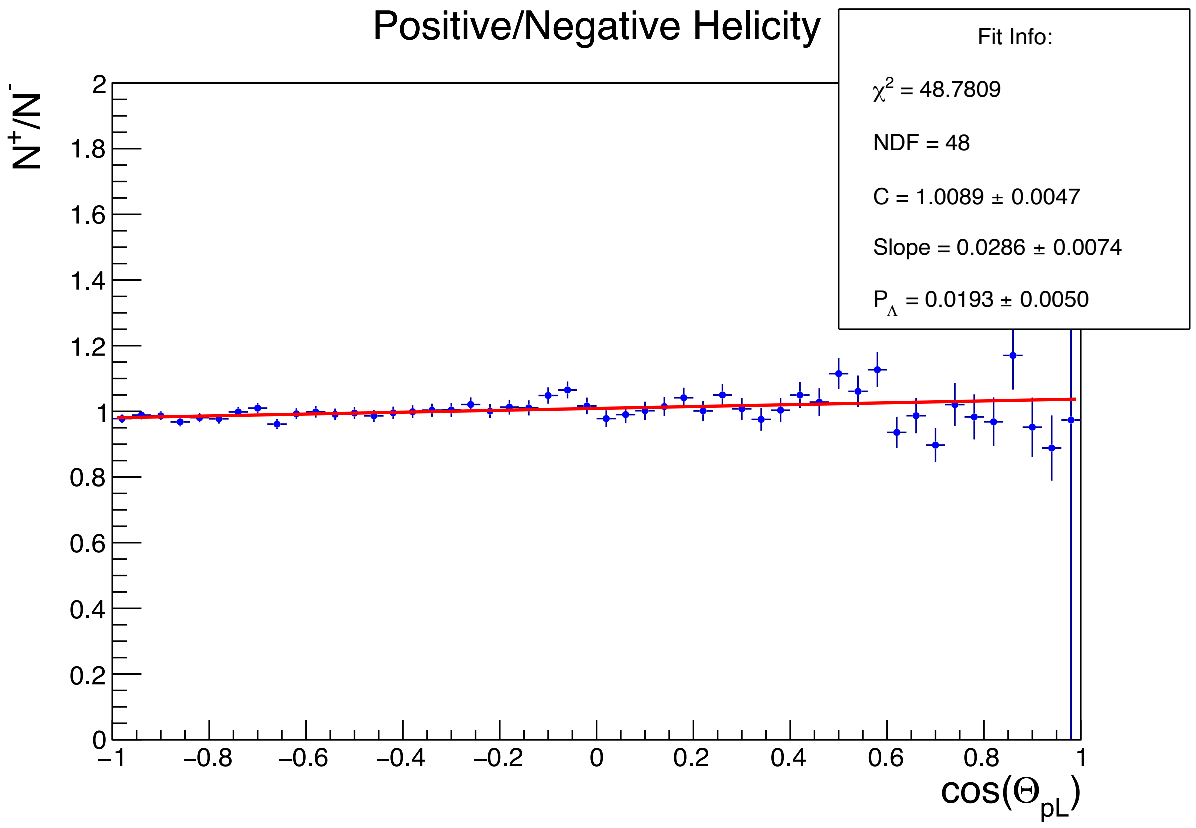
Averaged result is:

$$D_{LL',REC} = 0.107 \pm 0.078$$

Fit $cos\theta$ (acceptance corrected)

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





Note: No GNN applied

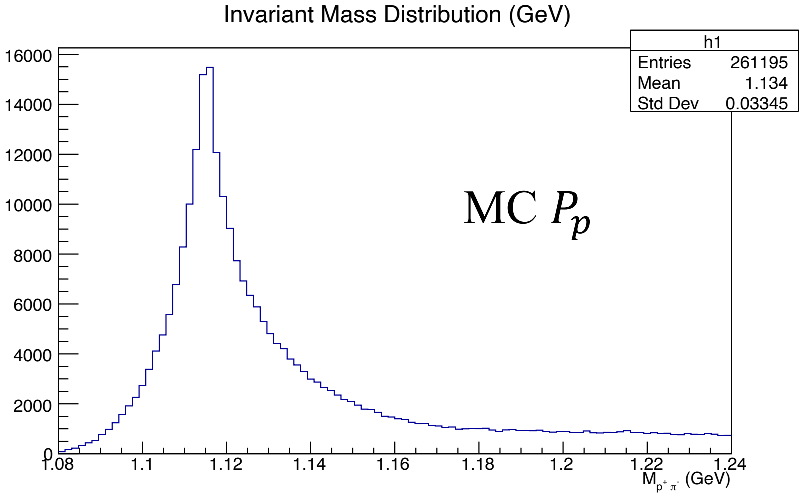
Systematic Uncertainties

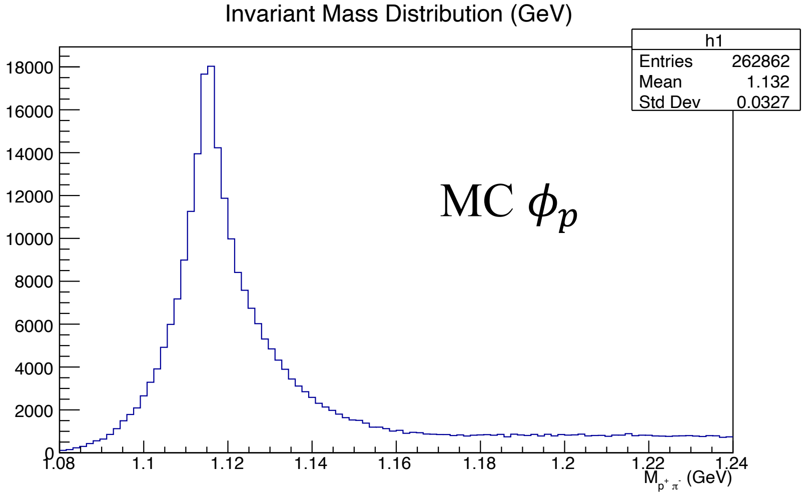
- Uncertainties from fit errors and incorrect particle PID were minimal (<0.001).
- Spin transfer in sidebands is fairly small:

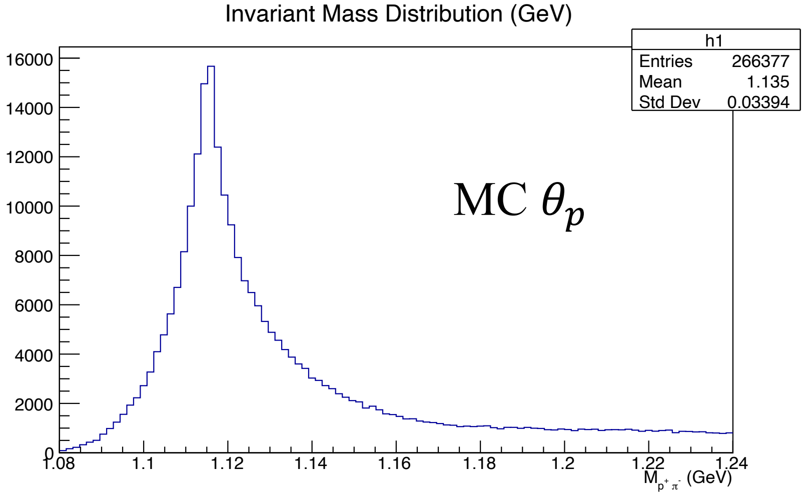
Preliminary Helicity Balance	
$\cos\theta_{pL'}$ along $\vec{p_\Lambda}$	$\cos\theta_{pL'}$ along $\vec{p_\gamma}$
-0.00141 ± 0.01293	0.00113 ± 0.01387

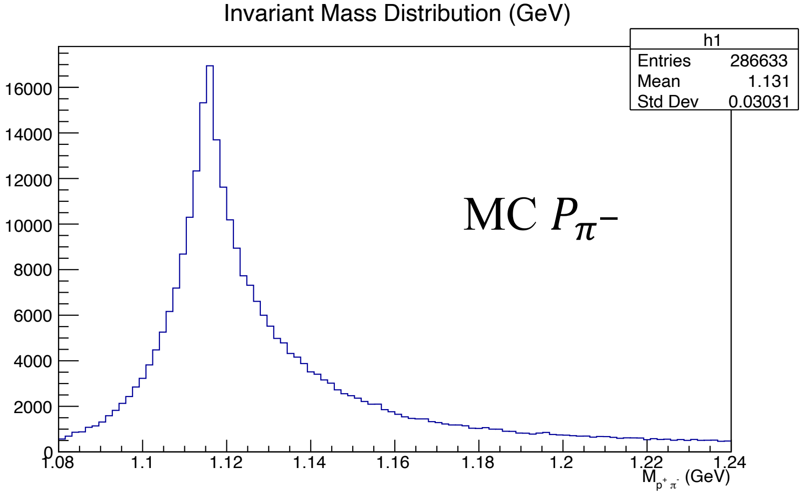
- Results from linear fit method are consistent within uncertainties but require better statistics.

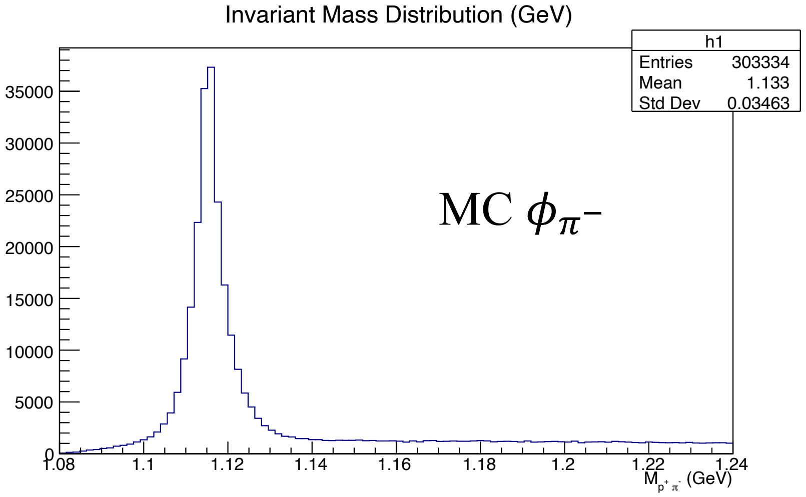
REC/MC Mass Resolutions

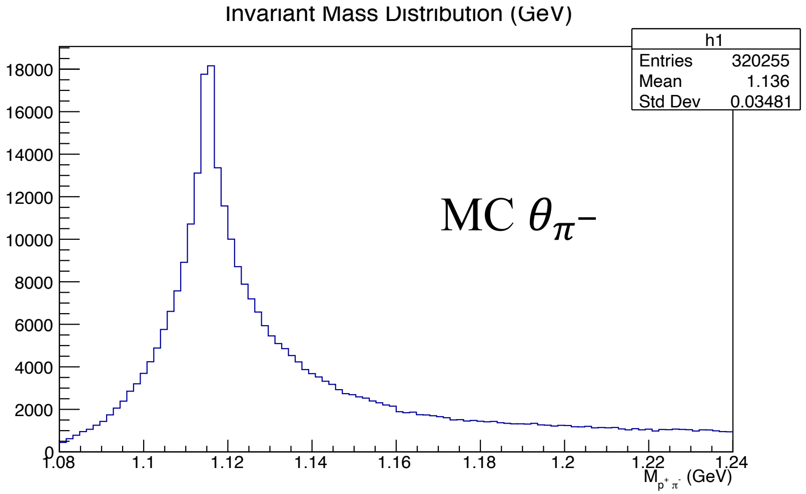






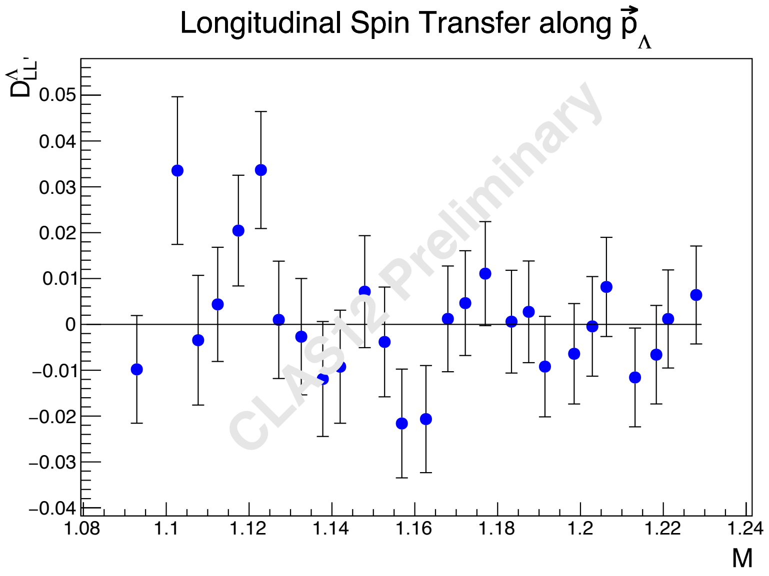


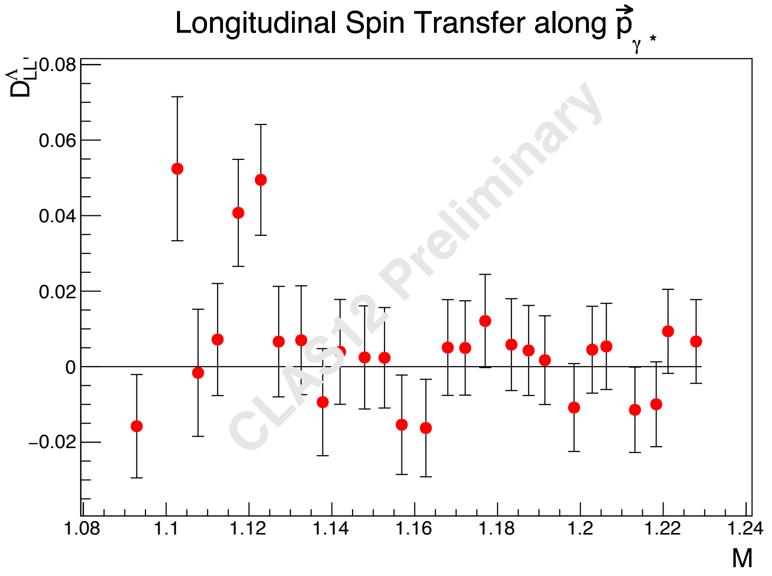




Helicity Balance vs. Invariant Mass

vs. Invariant Mass





Note: No GNN applied, errors are solely statistical