SIDIS Dihadron Beam Spin Asymmetries

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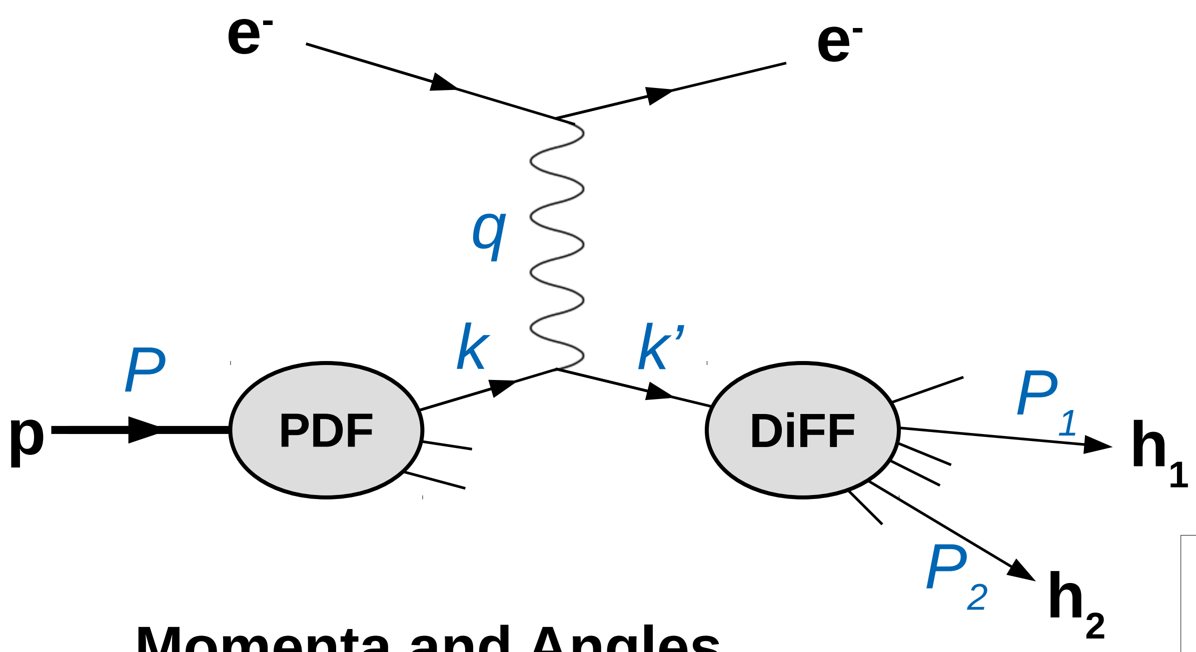
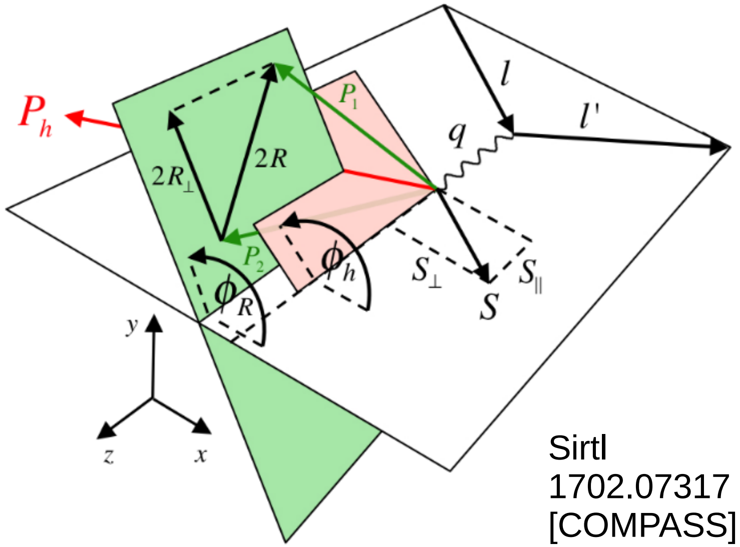
CLAS Collaboration Meeting

25 March 2020

SIDIS Dihadron Production: $e^- p \rightarrow e^- h_1 h_2 X$





Sirtl
1702.07317
[COMPASS]

Momenta and Angles

$$P_h = P_1 + P_2 \quad \rightarrow \quad \phi_h$$

$$R = \frac{1}{2}(P_1 - P_2) \quad \rightarrow \quad \phi_R$$

Kinematic Variables:

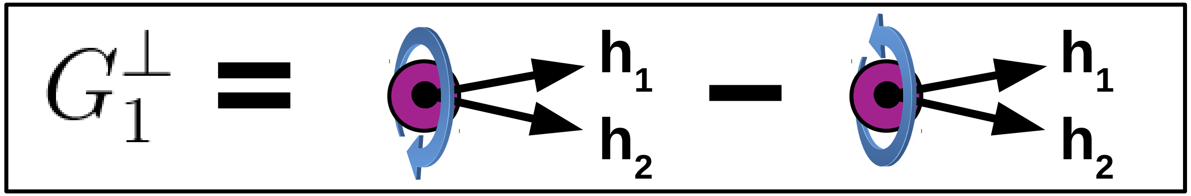
- DIS: Q^2, x, W, y
- Momenta, e.g. P_1, P_2, $P_h^{\perp}$
- Invariant Mass: M_h
- Fragmentation fraction: z
- Missing Mass: M_X
- Dihadron CoM Decay Angle: θ

Structure Functions → PDFs and DiFFs

Structure Function	Twist	$m=0$ Modulation	$m=1$ Modulation	PDF $\otimes$ DiFF
$F_{LU,T}^{P_{\ell,m}\sin(m\phi_h - m\phi_R)}$	2	0	$\sin(\phi_\mathbf{h} - \phi_\mathbf{R})$	$f_1 \otimes \mathbf{G}_\mathbf{1}^{\perp\mid\ell,\mathbf{m}\rangle}$
$F_{LU}^{P_{\ell,m}\sin[(1-m)\phi_h + m\phi_R]}$	3	$\sin\phi_h$	$\sin\phi_\mathbf{R}$	$\mathbf{e}(\mathbf{x}) \otimes H_1^{\perp\mid\ell,m\rangle} + g^\perp \otimes D_1^{\mid\ell,m\rangle}$

- Differential cross sections are expanded in terms of modulations of ϕ_h, ϕ_R, and θ, with structure function coefficients
  - θ-dependent factors are for partial wave expansion of DiFFs → beyond the scope of this paper
  - ϕ_h, ϕ_R dependent functions are Fourier series functions → *focus on m=1 (and 0)*
- Structure functions contain convolutions of PDFs and Dihadron Fragmentation Functions (DiFFs)
  - m=1 azimuthal modulations are the *primary* dihadron A_{LU} modulations of interest, for accessing
    - $\mathbf{G_1^\perp}$: the helicity-dependent DiFF
    - **e(x)**: the twist-3 collinear PDF
  - m=0 modulations can be identified with the single-hadron structure function modulations, and included as a *correction* in the multi-amplitude fit

Helicity Dependent DiFF: $G_1^{\perp}$



- Accessible in the $\sin(\Phi_h - \Phi_R)$ modulation of dihadron longitudinal beam spin asymmetries, weighted by $P_h^{\perp} / M_h$
- Sensitive to spin-orbit correlations in hadronization
- Not yet constrained by data; quark-jet hadronization model predicts sizable $G_1^{\perp}$

$$A_{LU}(x, y, z, M_h) = \frac{\langle P_h^{\perp} \sin(\phi_h - \phi_R) / M_h \rangle_{LU}}{\langle 1 \rangle_{UU}}$$

$$= \lambda_l \frac{C'(y)}{A'(y)} \frac{\sum_a e_a^2 \boxed{f_1^a(x)} \, z \boxed{G_1^{\perp a}(z, M_h^2)}}{\sum_a e_a^2 \; f_1^a(x) \; D_1^a(z, M_h^2)}$$

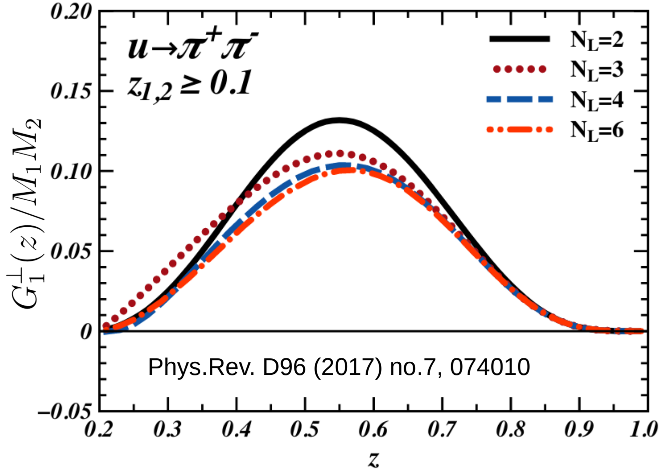
Matevosyan, et al.

- Phys.Rev. D96 (2017) no.7, 074010
- PoS DIS2018 (2018) 150

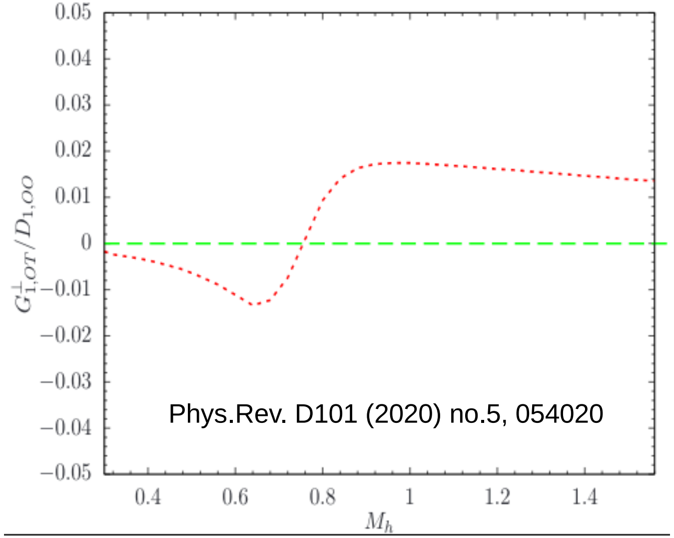
- Recent spectator model calculation predicts sign change at the ρ mass

Luo, et al., Phys.Rev. D101 (2020) no.5, 054020

Quark-jet hadronization model prediction

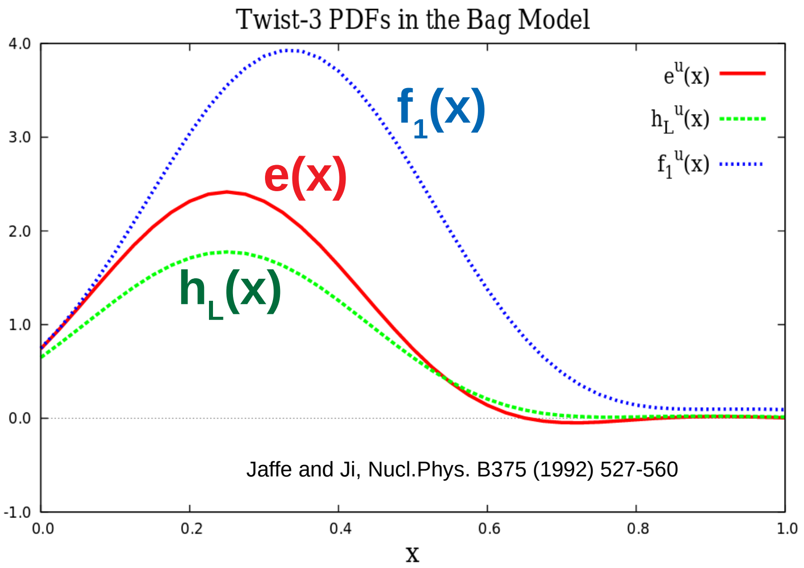


Spectator Model Prediction

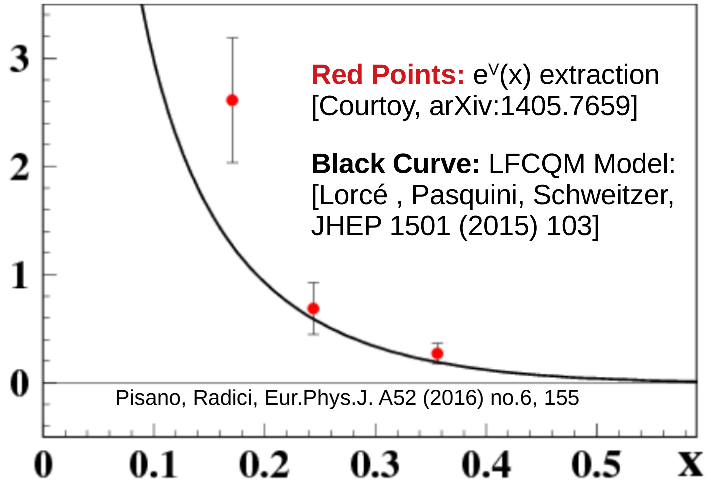


Twist-3 Collinear PDF e(x)

- e(x) decomposition: $e^q(x) = e^q_{\text{sing}}(x) + e^q_{\text{tw3}}(x) + e^q_{\text{mass}}(x)$
  - $e_{sing}(x)$ – proportional to δ(x), which could broaden at low Q^2 (LaMET model, XiangdongJi:arXiv:2003.04478)
  - $e_{tw3}(x)$ – pure twist-3 part → interference between scattering from |q> vs. |qg>
  - $e_{mass}(x)$ – proportional to current quark mass and moments of $f_1(x)$ [twist-2]
- Physical interpretation from moments of e(x):
  - Force exerted by gluon field on q↑ after scattering
  - Pion-nucleon σ term, representing the contribution to the nucleon mass from the finite quark masses



Extraction of $e^V(x)$ from CLAS6 preliminary A_{LU} and A_{UL}



Additional References:

Bacchetta and Radici, Phys.Rev. D69 (2004) 074026

Efremov and Schweitzer, JHEP 0308 (2003) 006

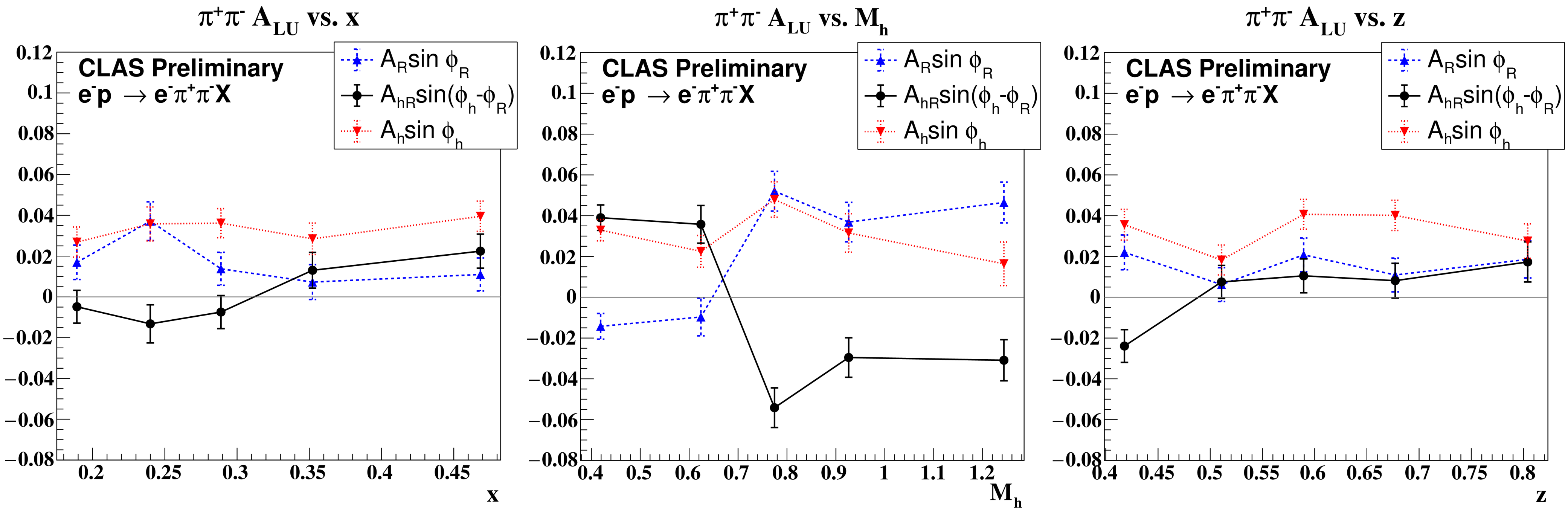
Burkardt, Phys.Rev. D88 (2013) 114502

Pereira, PoS (DIS2014) 231

Mulders, Tangerman, Nucl.Phys. B461 (1996) 197-237

Sirtl, PhD Thesis

DNP2019 Preliminary Results



- Simultaneous fit to m=0,1 modulations
- There appears to be a sign change near M_ρ
- A_R has opposite M_h dependence to A_{hR}
- A_h is a constant 3-4%
- ±3.8% polarization scale uncertainty

$$\boxed{A_{hR}\sin(\phi_h-\phi_R) \quad + \quad A_R\sin\phi_R \quad + \quad A_h\sin\phi_h}$$

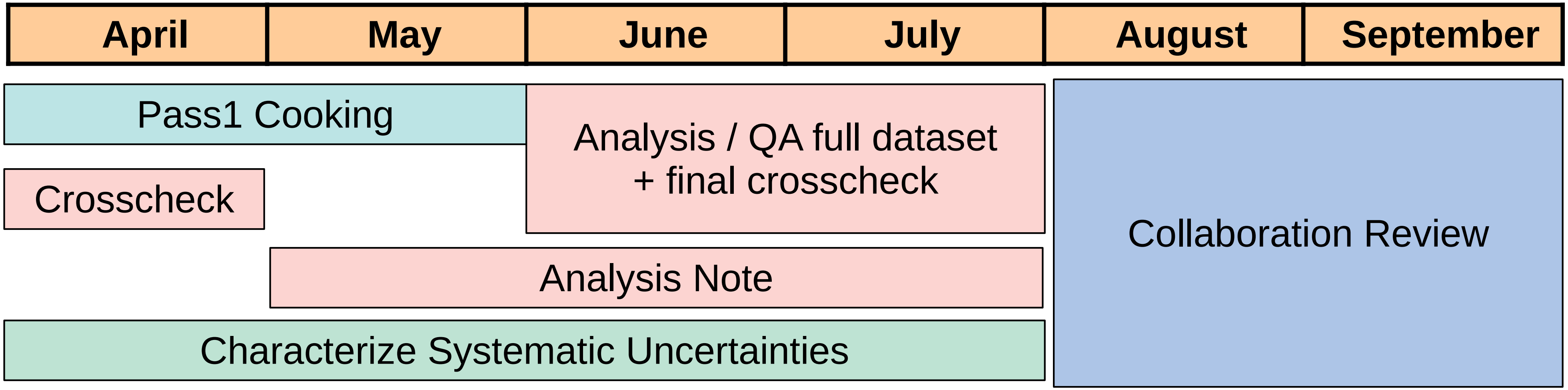
Simultaneous fit performed, because these modulations are **not orthogonal** within the acceptance limitations

https://www.jlab.org/indico/event/343/session/7/contribution/76

Paper Plans

- Aim to publish a PRL paper with CLAS12 dihadron beam spin asymmetries
- The main focus is on the $\sin(\phi_R)$ modulation, which will allow theorists to better constrain the twist-3 PDF $e(x)$
- Acceptance limitations necessitate the simultaneous measurement of additional azimuthal modulations, such as $\sin(\phi_h - \phi_R)$, sensitive to the not-yet-constrained helicity DiFF $G_1^{\perp}$
  - While we see a signal for the $G_1^{\perp}$ modulation and can show it as part of the multi-amplitude fit, more work needs to be done for its interpretation, e.g., this modulation needs to be weighted by the dihadron transverse momentum
  - Partial waves of the dihadron fragmentation can also be measured
  - These considerations are better left for a longer, subsequent paper; however, we should show all modulations that we include in the simultaneous fit regardless

Estimated Timeline



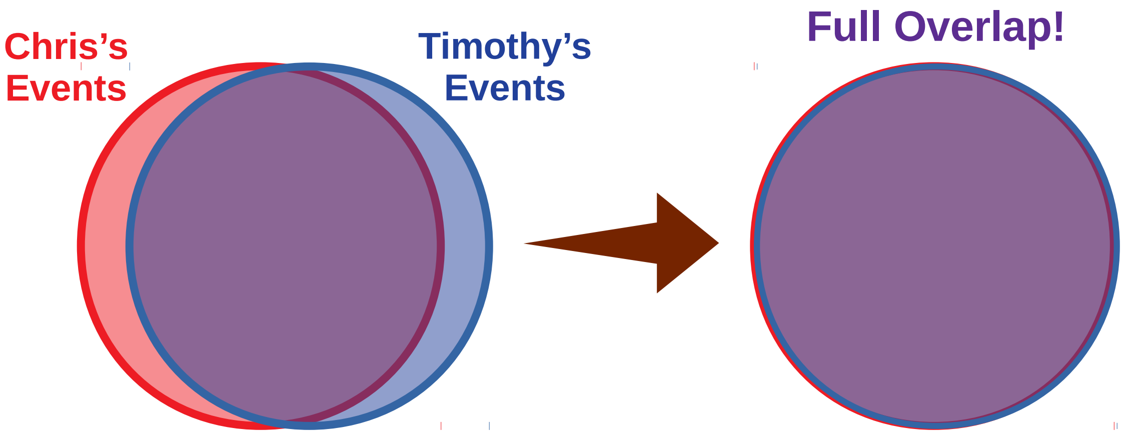
Crosscheck with Timothy Hayward

Event-by-event Crosschecking:
All variables match up to 6 sig-figs!

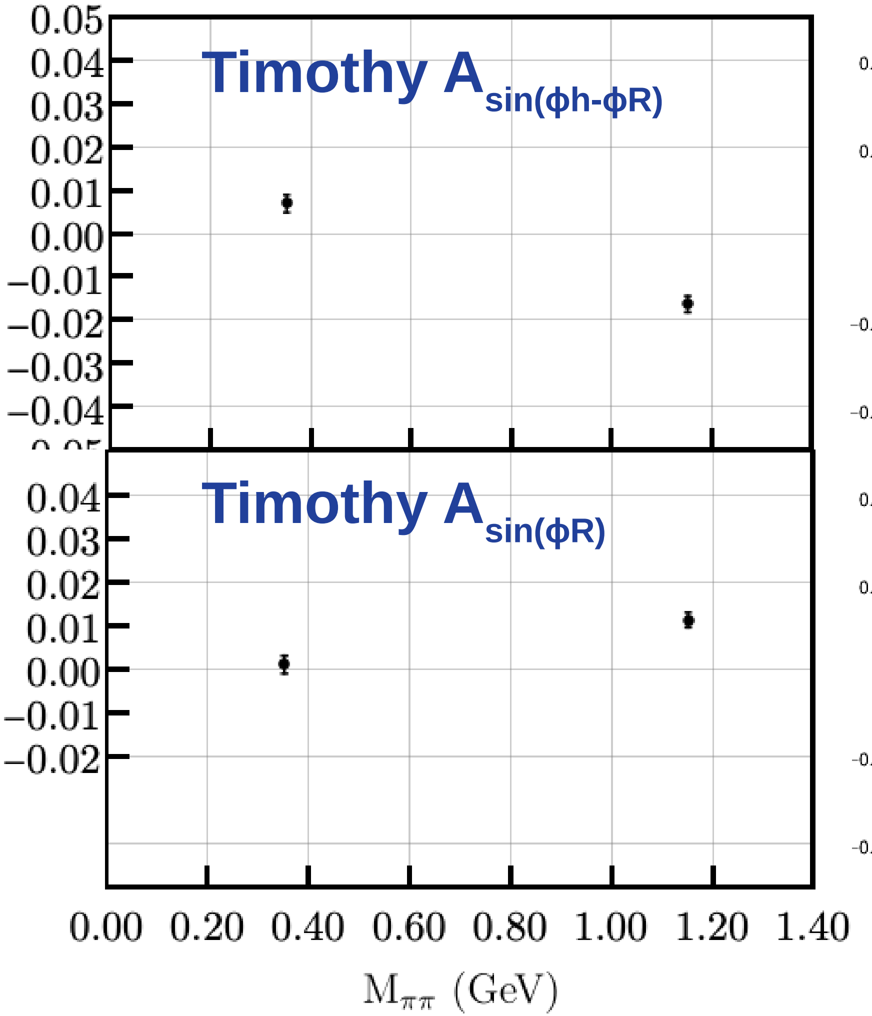
```
EVENT 25820 found (hash=2582039491000)
       var         chris       timothy          diff
 ---------     ---------     ---------     ---------
      pipP       2.44338       2.44338       0.00000
      pimP       1.50590       1.50590       0.00000
      eleP       5.54208       5.54208       0.00000
        Q2       3.16892       3.16892       0.00000
         W       2.68524       2.68524       0.00000
         x       0.33360       0.33360       0.00000
         y       0.47736       0.47736      -0.00000
        Mh       1.00462       1.00461       0.00000
        xF       0.40326       0.40326      -0.00000
     Zpair       0.78224       0.78224       0.00000
     Mmiss       1.14164       1.14164      -0.00000
    PhPerp       0.59682       0.59682       0.00000
     theta       1.31385       1.31385       0.00000
      PhiH      -2.48972      -2.48972       0.00000
      PhiR      -0.36612      -0.36612       0.00000
```

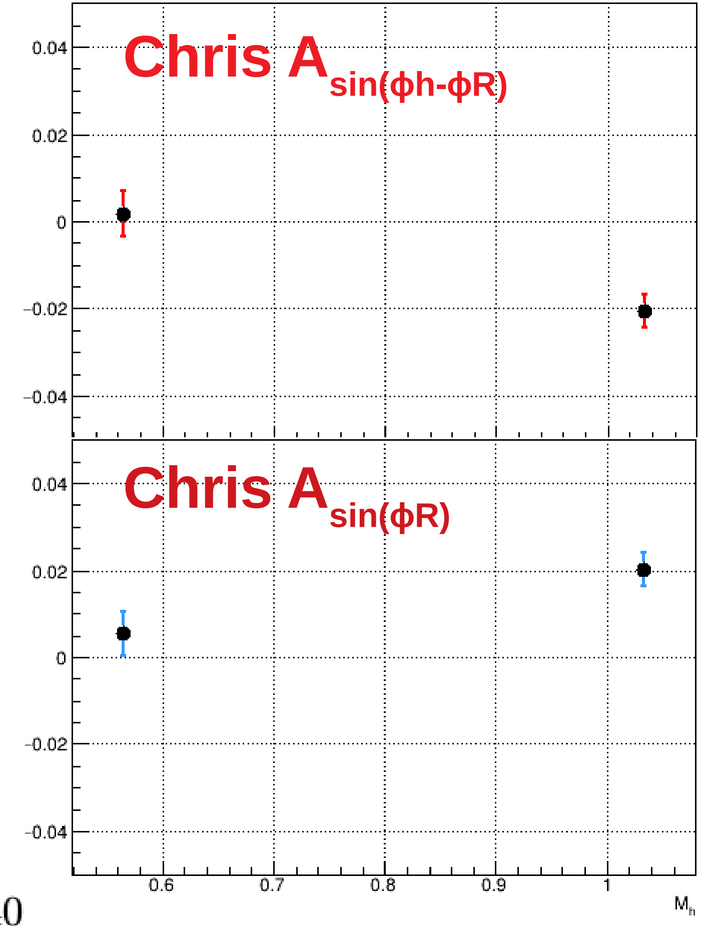
This was the easy part….

- Significantly more effort needed to get our full data samples to match
- At first, we had a 10% difference in our overall yield, and a fraction of our events had some mismatches in several variables
- We made several small corrections, and now our total yield difference is at the 0.0025% level



Crosscheck with Timothy Hayward





Asymmetry comparison

10 runs from DNP cook

- Polarization = 1
- Relative Lumi = 1
- Kinematic Factor = 1
- Disable fiducial volume cuts and vertex cuts
- 2 mass bins, above and below ρ mass

There are still some issues to resolve

Systematic Uncertainties

Uncertainty	Estimate*	Status / Comments
Beam Polarization	1.5–3% on scale	Straightforward: obtain from polarization measurements
Radiative Corrections	3% ?	Need to discuss with Harut
Acceptance	--	Plan to estimate with MC asymmetries
PID / Matching Fraction	--	Needs further study; MC matching fraction is around 75-80%
Baryonic Resonances	~14% on scale	Details below
Additional modulations of the unpolarized x-section	<40% on scale	This is likely very conservative; details below
Cut Boundary Choices		Started exploring; details below
Horizontal Uncertainties / bin migration		Details below

* these are all approximate values

Systematic from Baryonic Contribution (Δ,Σ,etc.)

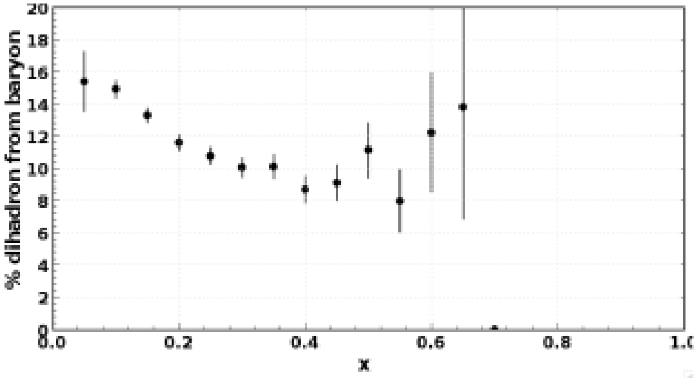
$$A_{\text{measured}} = (1-f)A_{\text{true}} + f A_{\text{baryonBG}}$$

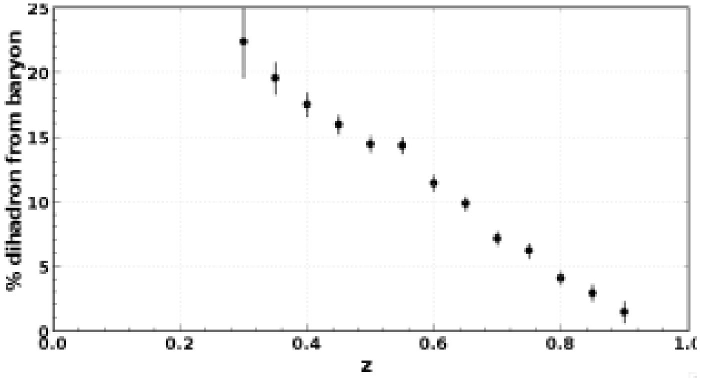
Baryon fraction: Contributions of ~12%. Strong z dependence, as expected.

Assume fA_{BG} is negligible

$$\frac{\Delta A}{A} = \frac{f}{1-f}$$

~14%





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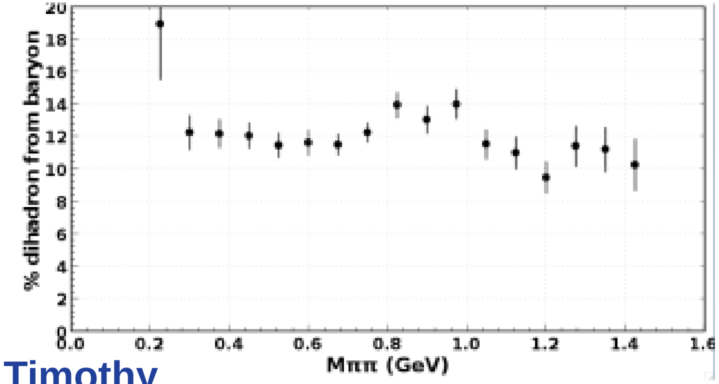
- Any z cut would have the effect of increasing statistical error bars by more than it decreased the systematic.



Slide from Timothy

Systematic from Additional $d\sigma_{UU}$ Modulations

Two considerations:

- Contributions from |0,2> partial wave of D_1 DiFF
  - This term survives integration of $d\sigma_{UU}$ over $\phi h,\phi R,\theta$
  - Following methodology developed by HERMES (see next slide)
    - https://arxiv.org/pdf/0803.2367.pdf
    - https://inis.iaea.org/collection/NCLCollectionStore/_Public/40/003/40003576.pdf

- Contributions from other non-orthogonal modulations
  - CLAS acceptance causes linear dependence with a few other modulations of $d\sigma_{UU}$
  - Subdominant, since they are suppressed by a factor of 0.4, but need to be thought about how to evaluate their effect
  - Could do a fit similar to Stefan’s analysis, to determine the impact of the asymmetries with and without their inclusion

Systematic from Additional dσ$_{UU}$ Modulations

$$A_{LU} = \frac{d\sigma_{LU} \text{ moment}}{\int d\sigma_{UU}}$$

With 4π acceptance, 2 terms survive in the denominator*; they contain the |0,0> and |2,0> partial waves of the DiFF $D_1^{|L,M>}$

* assumes truncation at L=2

Fit form: $A_{LU} = \frac{A(\theta, \phi_h, \phi_R)}{1 + B(3\cos^2\theta - 1)/4}$

A parameter represents asymmetry amplitude(s)

B parameter represents: $\boxed{B = D_{1,LL}/D_{1,OO}}$

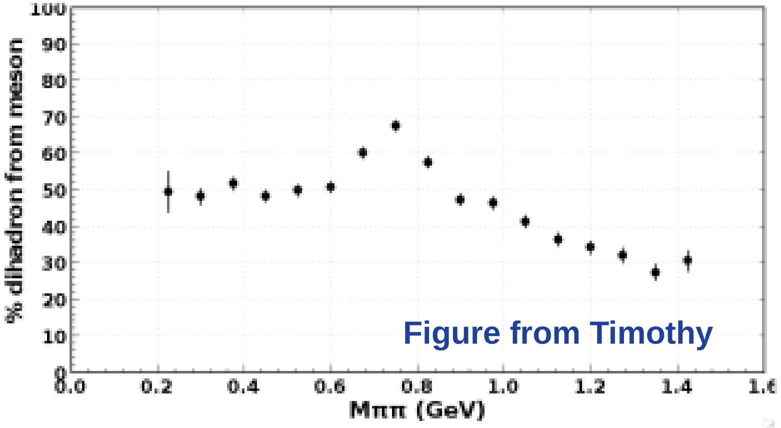
- Vary **B** within limits imposed by **DiFF positivity bounds**, in order to evaluate systematic effect on **A**; this is called the “B-scan”

- $D_{1,OO}$ contains a pure p-wave part, and both are constrained in a positivity bound together with $D_{1,LL}$
- Use MC to evaluate the fraction of $D_{1,OO}$ from the p-wave (vector meson) contribution
- Denote this fraction by f_{VM}

Bounds on variation of B: $\boxed{-2f_{VM} \leq B \leq 4f_{VM}}$

Systematic from Additional $d\sigma_{UU}$ Modulations

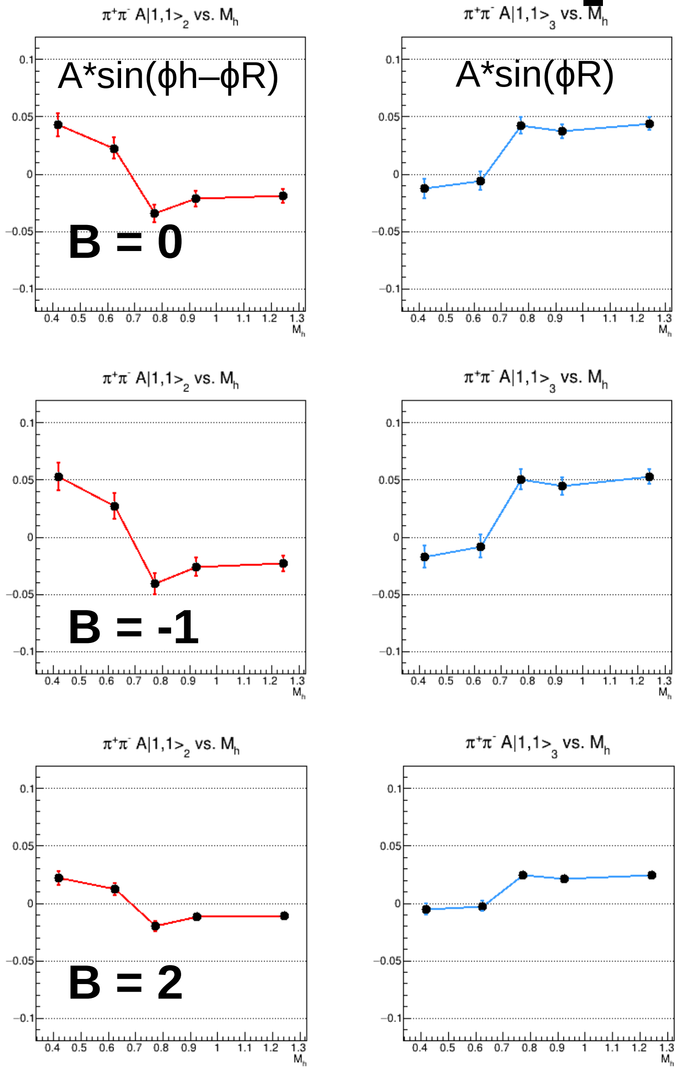
f_{VM}



- The real value of this number is an experimental question.
- Inclusion of the "b-scan" with F_{VM} = 0.5 is a good start.

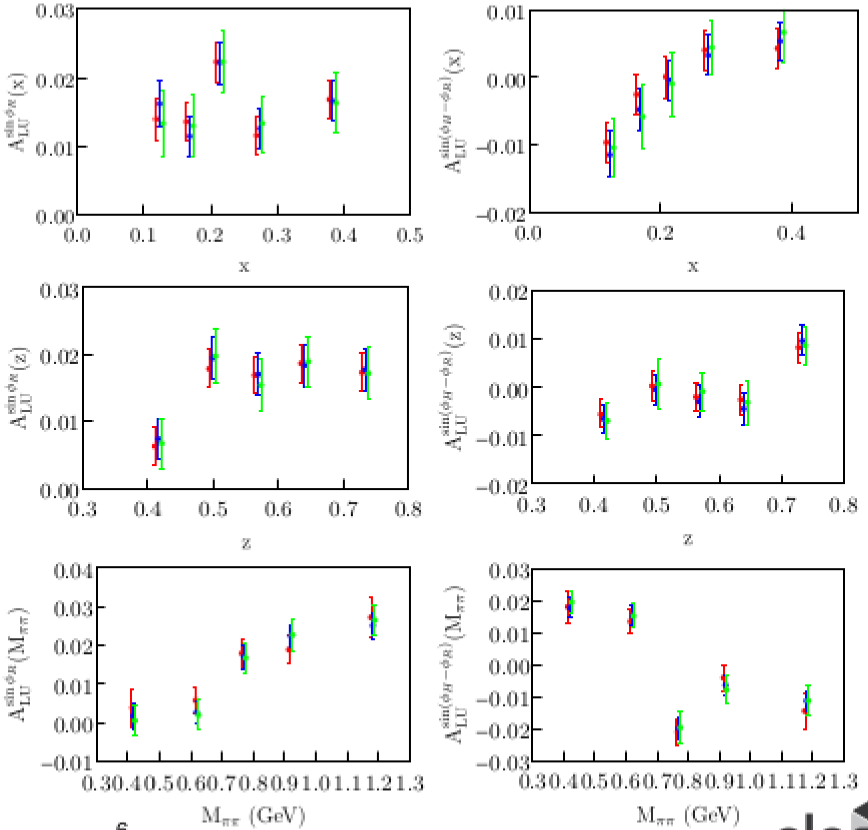
Scale systematic of ΔA/A < 40%

- This may be a bit conservative…
- It may be more accurate to do a fit including the denominator amplitudes



Sensitivity to Fiducial Volume Cut Choices

- Performed simultaneous fit to φ_R, φ_H and φ_H- φ_R modulations using the so called loose, medium and tight cuts from the DPWG DNP fiducial volume cuts.



- No immediate large concerns.
- Values typically change by a few percent.
- Statistical errors always increase by a larger amount.

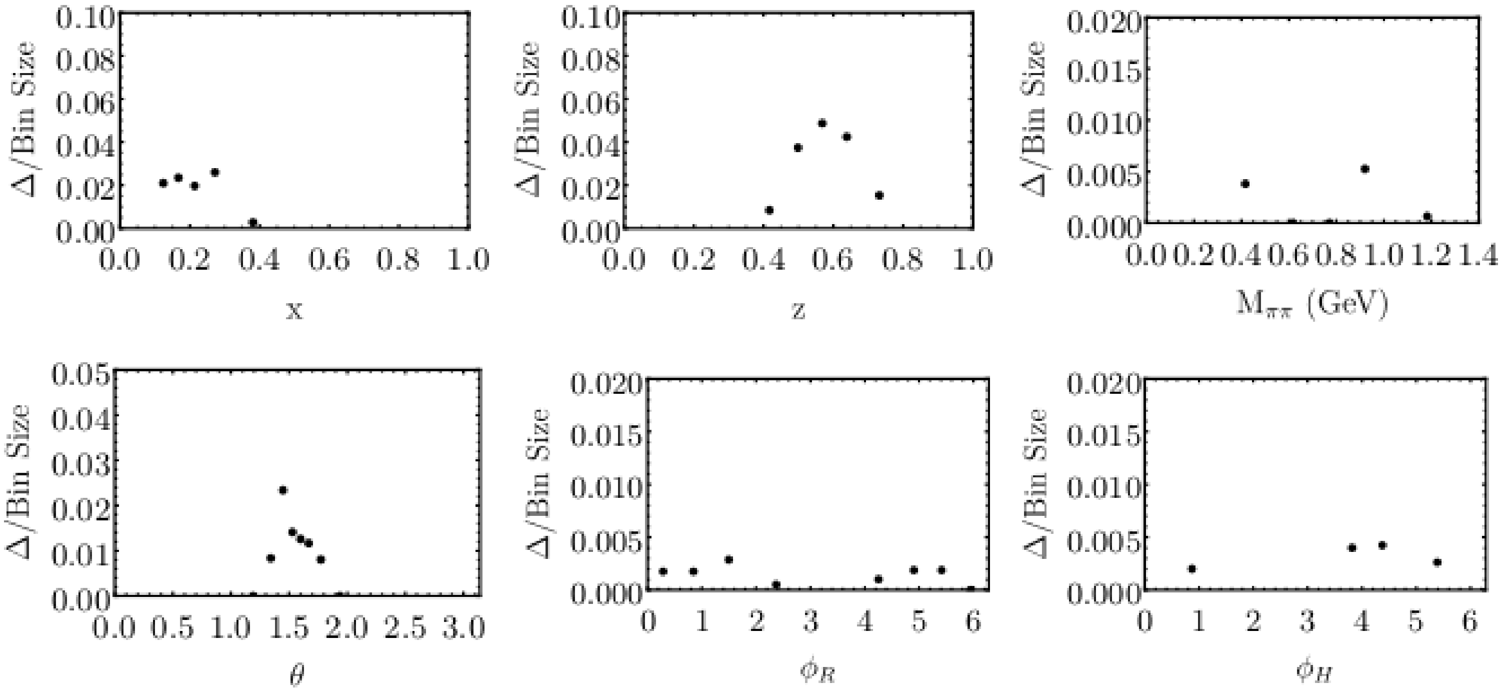
6

Slide from Timothy

Horizontal (M_h,x,z) Uncertainties

- Used MC in:
  - /work/clas12/gangel/Simu_DNP19/T-1.00_S-1.0/F18/MC_DIS_LUND_*.hipo
- Calculated the difference between reconstructed and generated variables. Largest effect in x and z bins.

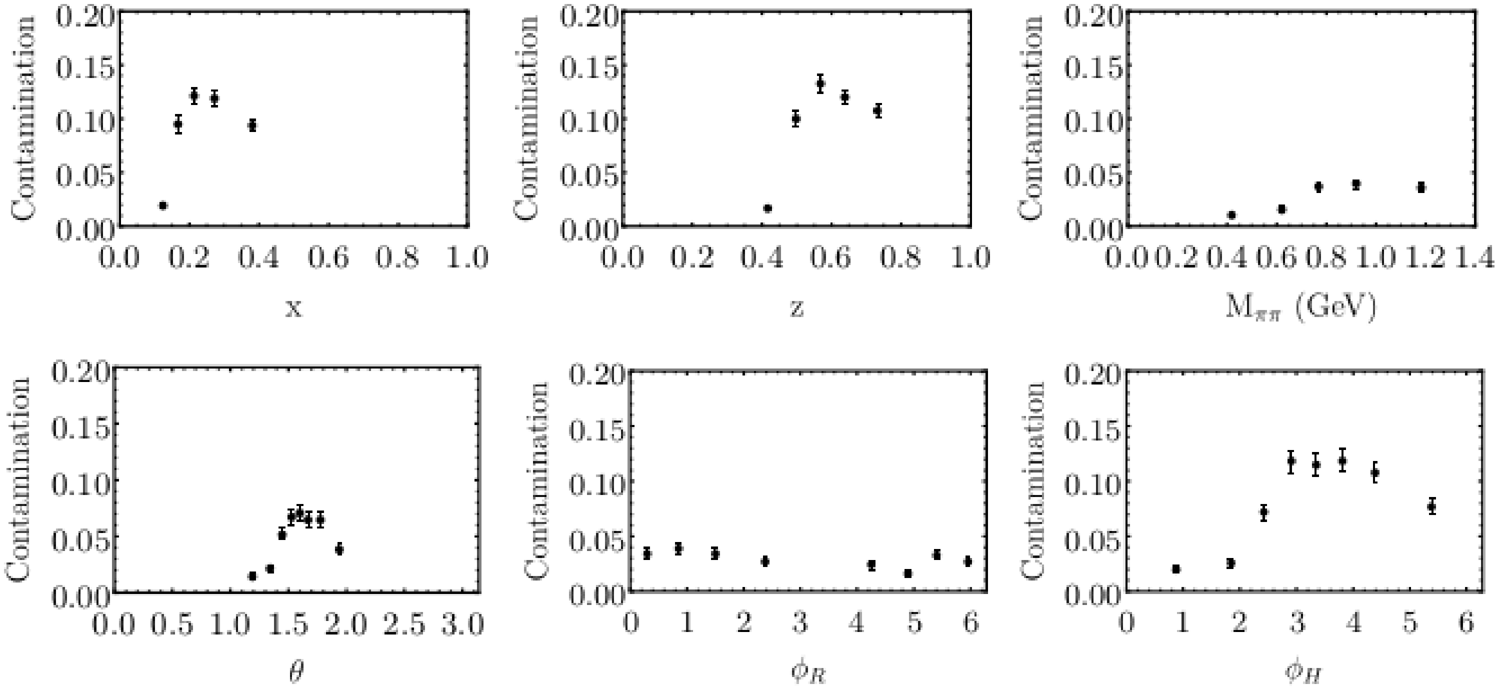
Scales don't match!



Slide from Timothy

Bin Contamination

- Tracked the number of times a reconstructed value was assigned a different bin than the generated value.
- Depending on bin effects on the order of 0-13% of events (could optimize?).



Slide from Timothy

Summary and Outlook

- This analysis is making steady progress
- Current focus is resolving some last issues in the cross check and on estimating systematic uncertainties
- Analysis note is in progress, will focus on it more after the cross check
- Our analysis codes will likely be fully ready for the output of Pass-1 as soon as it is available
- We hope to have the analysis and paper ready by the end of the summer