SIDIS DIHADRON BEAM SPIN ASYMMETRIES WITH CLAS12

July 2020 CLAS Collaboration Meeting

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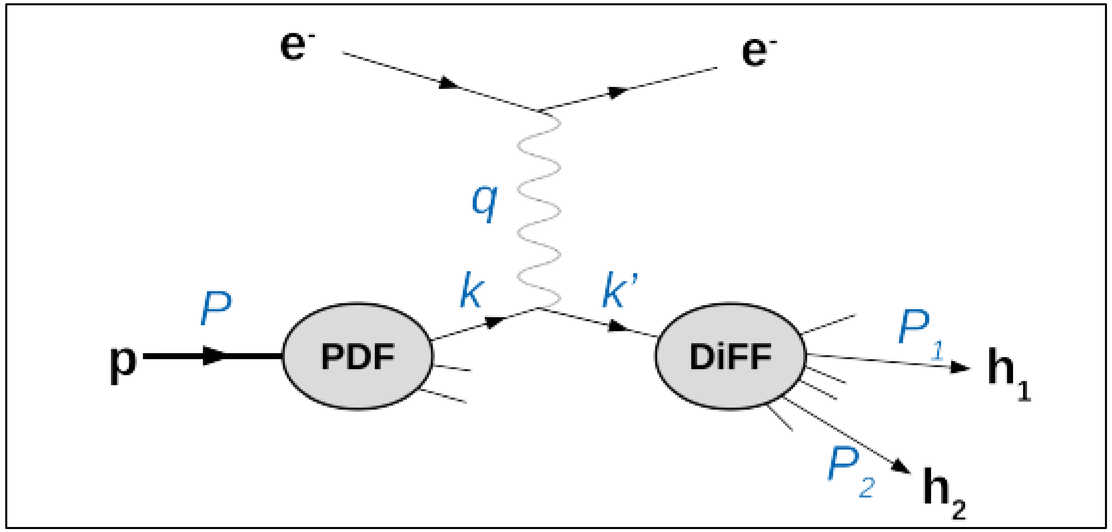
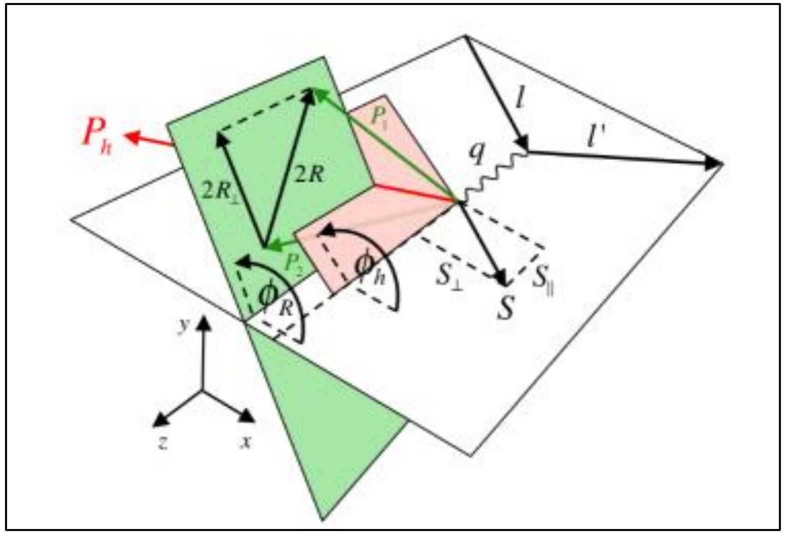
PAPER PLANS

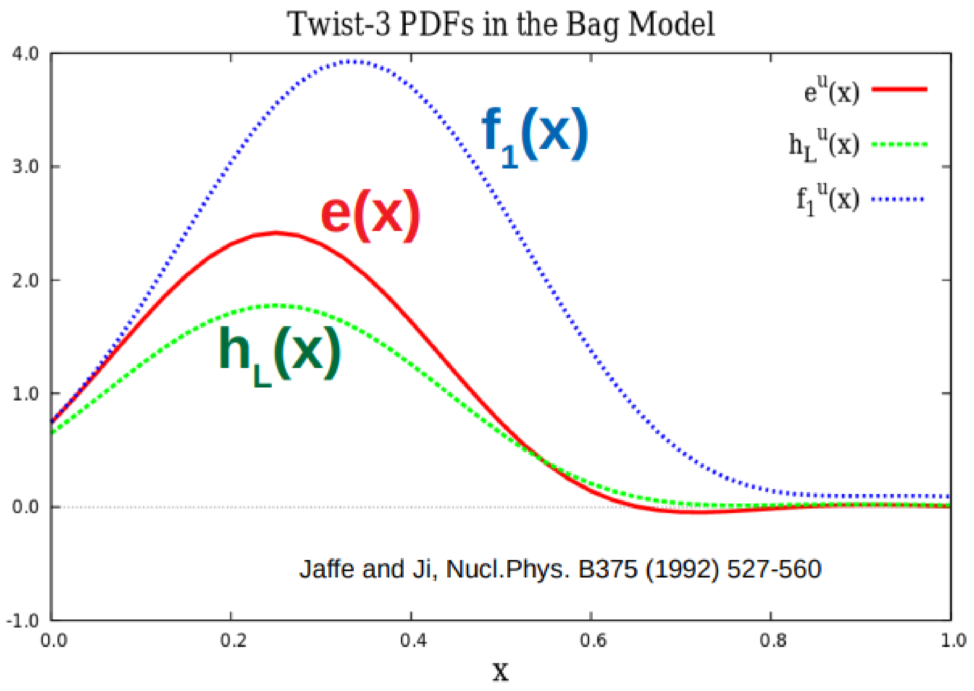
- Aim to publish a PRL paper with CLAS12 dihadron beam spin asymmetries.
- Fall 2018 RG-A, 10.6 GeV, inbending data.
- Measurements:
  - **sin(ϕ_R)** modulation A_{LU}, which significantly improves constraints on twist-3 PDF **e(x).**
  - **sin(ϕ_H-ϕ_R)** modulation A_{LU}, sensitive to the not-yet-constrained helicity DiFF $\mathbf{G_1^{\perp}}$



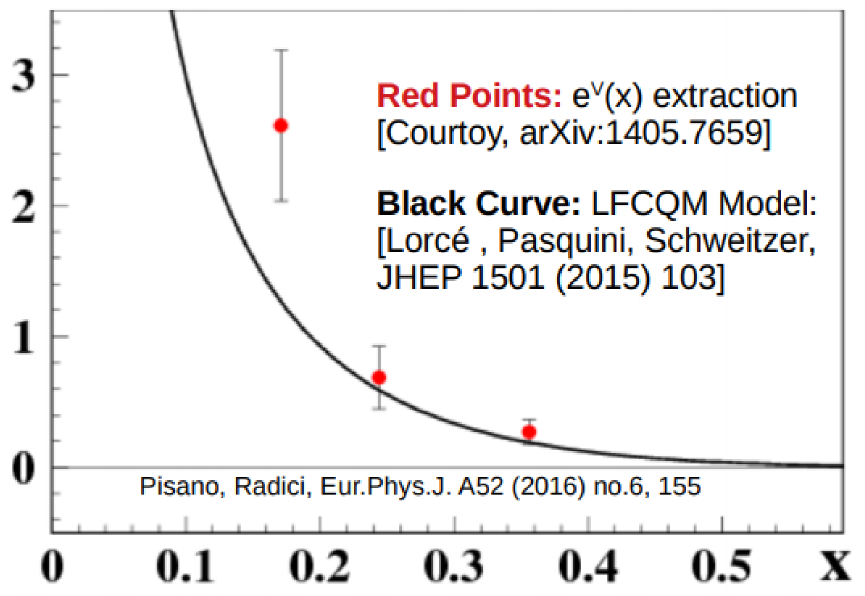


Twist-3 Collinear PDF e(x)

- 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

Helicity Dependent DiFF: $G_1^\perp$

$G_1^\perp =$ 

- 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 $G_1^\perp$

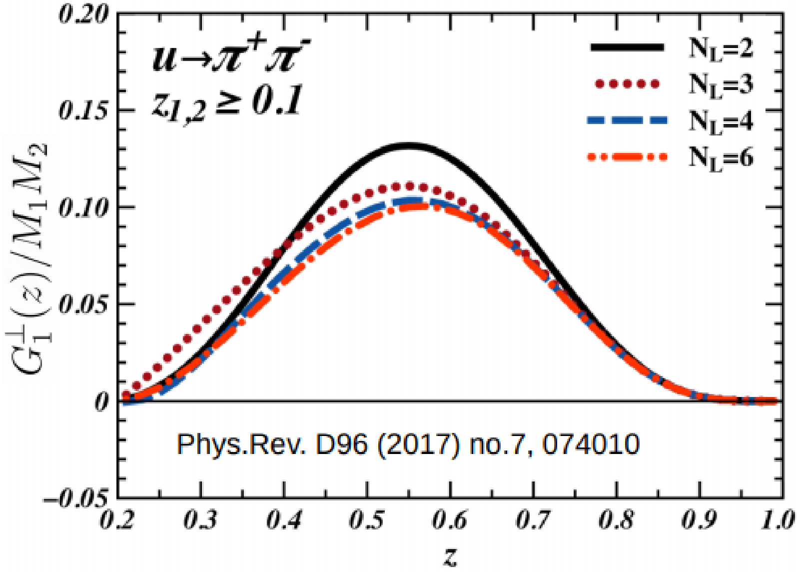
$$A_{LU}(x,y,z,M_h) = \frac{\langle P_h^\perp \sin(\phi_h - \phi_R)/M_h \rangle_{LU}}{\langle 1 \rangle_{UU}}$$
$$= \lambda_l \frac{C'(y)}{A'(y)} \frac{\sum_a e_a^2 \boxed{f_1^a(x)}\, z\, \boxed{G_1^{\perp a}(z, M_h^2)}}{\sum_a e_a^2\, f_1^a(x)\, D_1^a(z, M_h^2)}$$

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

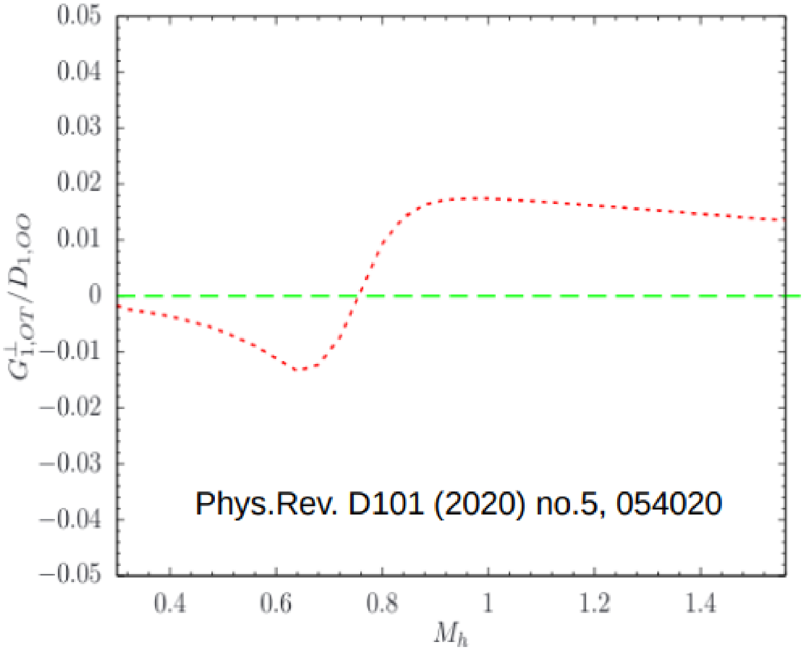
- Recent spectator model calculation predicts sign change at the ρ mass

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

Quark-jet hadronization model prediction



Spectator Model Prediction



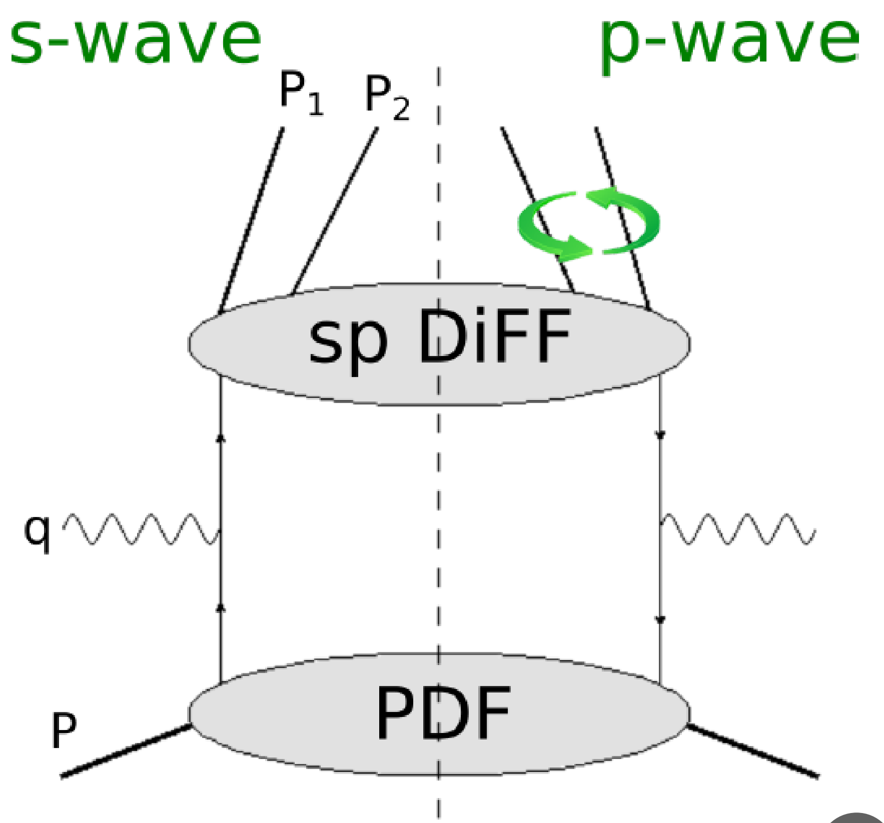
A_{LU} Azimuthal Modulations

A_{LU} contains several modulations of three angles

General Modulation form: $$P_{L,M}(\cos\theta)f(\phi_h, \phi_R, m)$$

L=0: ss
L=1: sp
L=2: pp
M = –L,…,L

- Partial wave expansion → DiFFs for interference of polarized and/or unpolarized dihadrons, organized into angular momentum eigenstates |L,M>
- **θ dependence in *P* is not considered (integrated over) for the 1st publication asymmetry measurement**
- **Consider only Azimuthal dependence in *f*:**
  - **Focus on fitting amplitudes of *f* with M = –1, 0, +1**
    - Sums over values of L, and assumes lowest order partial waves are dominant
    - Going to higher M requires higher L, and for that, θ-dependent fits are more appropriate, an interesting topic of future study



A_{LU} Azimuthal Modulations

F_{LU} Modulations:

Twist 2: $f(\phi_h, \phi_R, m) = \sin(m(\phi_h - \phi_R))$

Twist 3: $f(\phi_h, \phi_R, m) = \sin((1-m)\phi_h + m\phi_R))$

We thus fit for the amplitudes of 4 modulations, sensitive to the following PDF and DiFF convolutions:

m = +1

Twist 2: $\sin(\phi_h - \phi_R)$ → $f_1(x) \otimes \left(G_{1,OT}^{\perp} + G_{1,LT}^{\perp}\right)$

Twist 3: $\sin(\phi_R)$ → $e(x) \otimes \left(H_{1,OT}^{\sphericalangle} + H_{1,LT}^{\sphericalangle}\right)$

m = 0

Twist 2: n/a

Twist 3: $\sin(\phi_h)$ → $e(x) \otimes \left(H_{1,OO}^{\perp} + H_{1,OL}^{\perp} + H_{1,LL}^{\perp}\right)$

m = –1

Twist 2: *cf* m=+1

Twist 3: $\sin(2\phi_h - \phi_R)$ → $e(x) \otimes \left(H_{1,OT}^{\perp} + H_{1,LT}^{\perp}\right)$

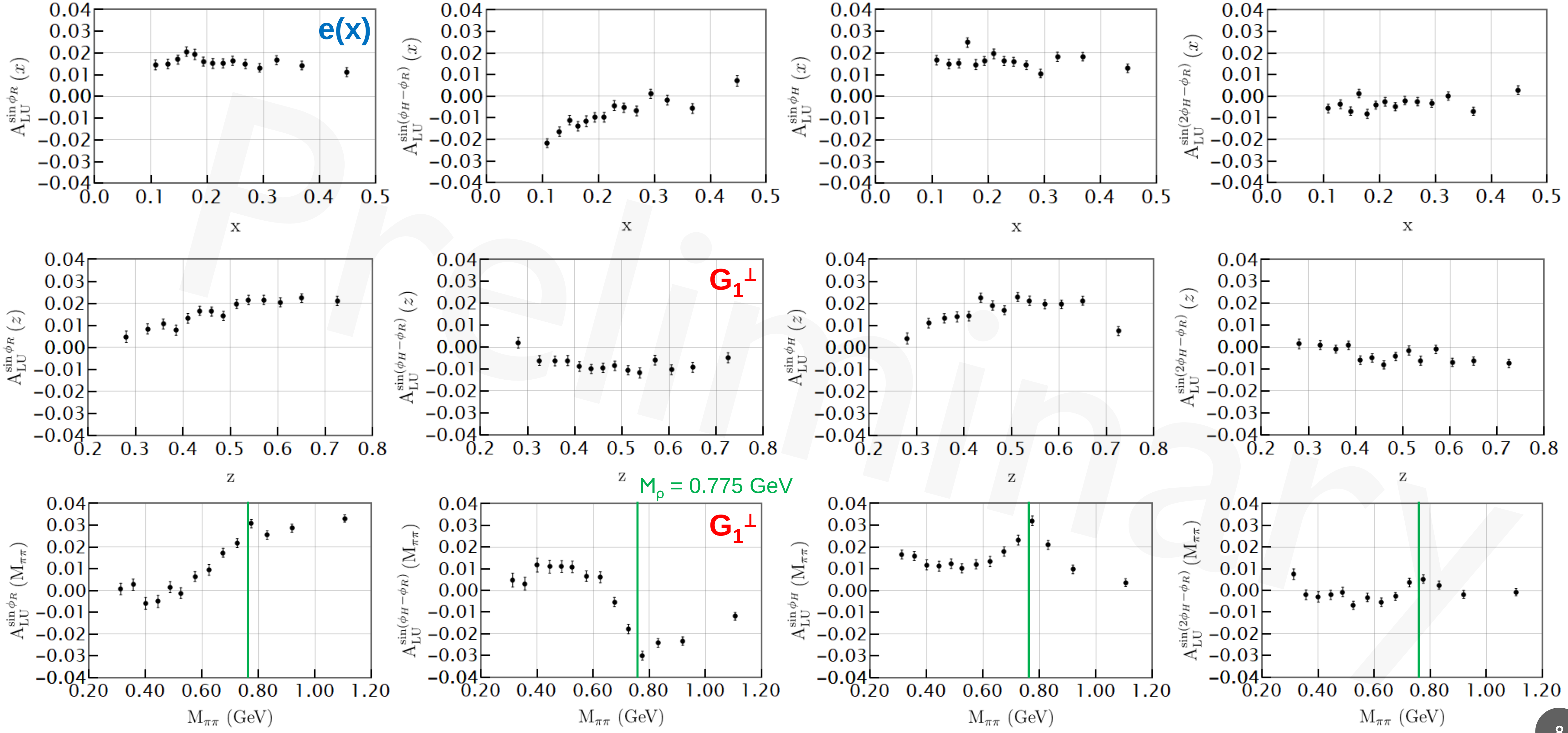
PARTICLE ID

- EventBuilder used as base.
- Fiducial cuts for PCAL and DC.
- Additional refinements (sampling fraction, PCAL energy deposition, vertex, chi2PID).
  - See Stefan Diehl's slides.
- Full agreement between SIDIS single and dihadron publications.
- Heavily vetted and discussed in the RG-A common analysis note.

EVENT SELECTION

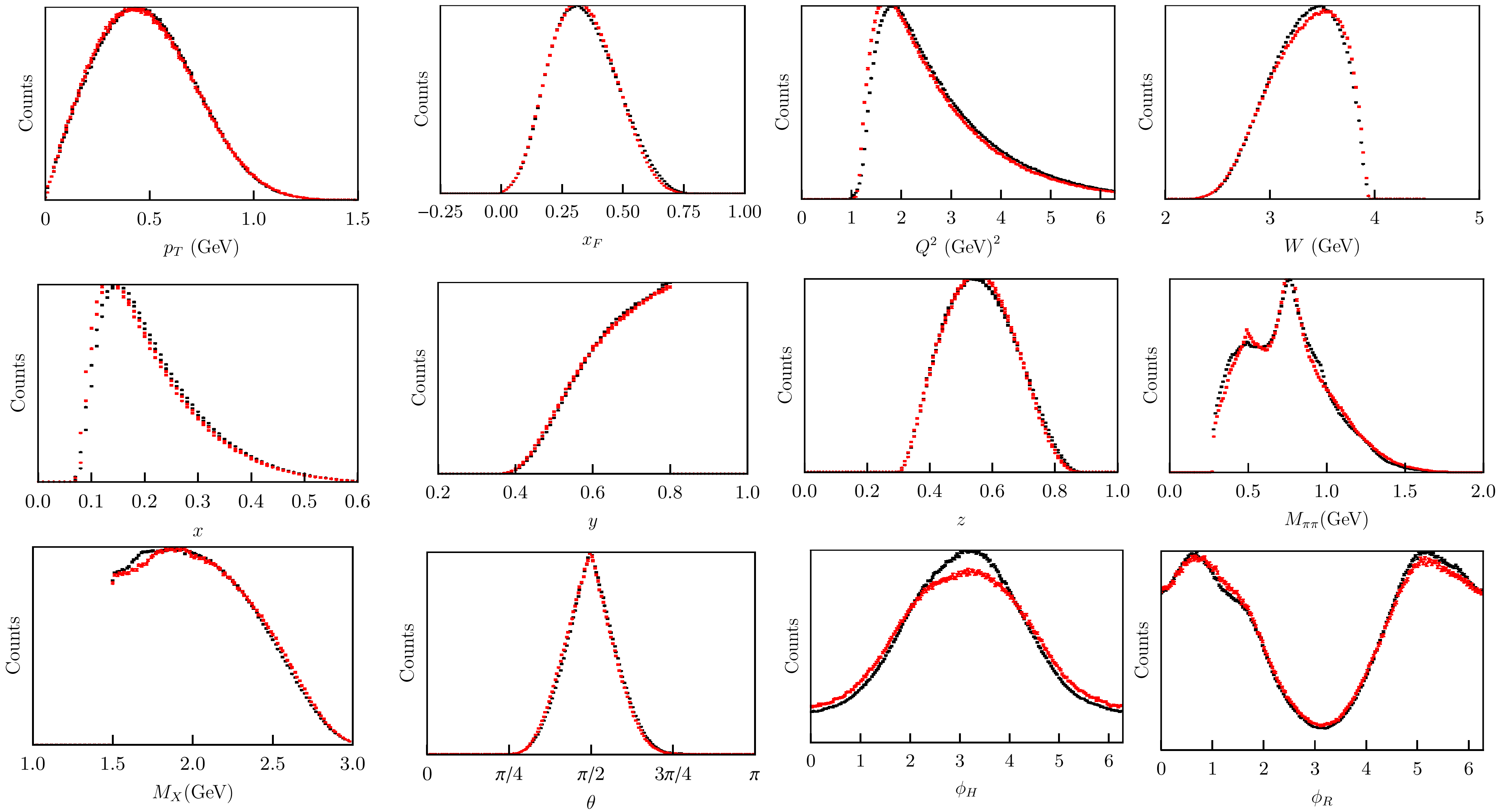
- QA cuts: QADB OkForAsymmetry cuts
- SIDIS cuts: $Q^2 > 1.0$ GeV^2, $W > 2.0$ GeV
- Current fragmentation region: $x_F > 0.00$*
- Exclusivity and radiative effects: $M_X > 1.5$ GeV, $z < 0.95$, $y > 0.8$*, $p_{\pi i} > 1.25$ GeV*
  - *under debate

ALL MODULATIONS



SIDIS MONTE CARLO

- Equal inbending Monte Carlo statistics already produced.
- clasdis generator.

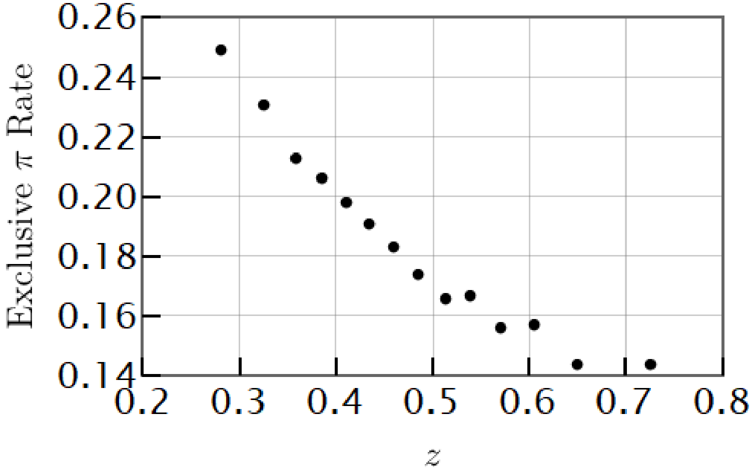


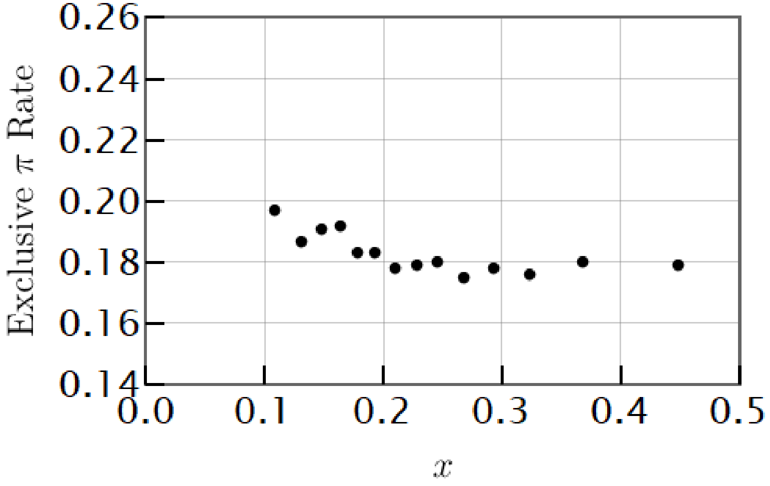
BARYONIC CONTRIBUTIONS

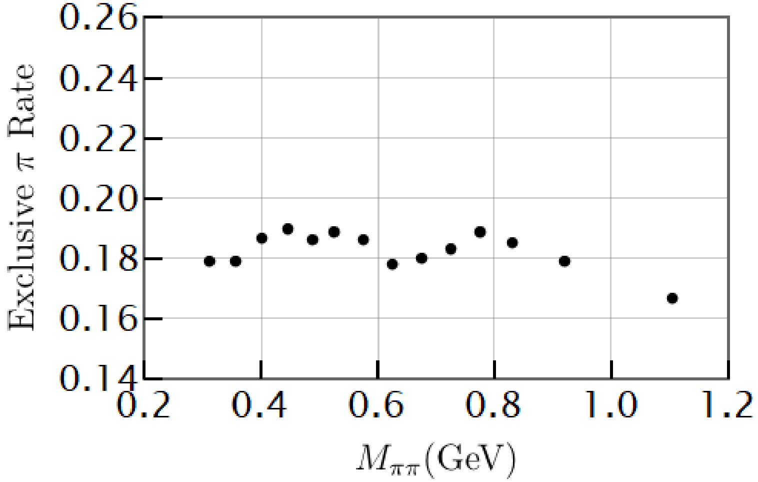
- Use MC to determine baryonic contribution to signal.
- Find all events were one or both pions is from baryonic decay.
- $A_M = (1\text{-}f)A_{true} + f\,A_{baryonic\ background}$
- Scale systematic calculated

1. $\Delta^{++} \to \pi^+ p$
2. $\Delta^{+} \to \pi^+ n$
3. $\Sigma^{+} \to \pi^+ n$
4. $\Delta^{0} \to \pi^- p$
5. $\Delta^{-} \to \pi^- n$
6. $\Sigma^{-} \to \pi^- n$
7. $\Lambda^{0} \to \pi^- p.$

$$\boxed{\frac{\Delta A}{A} \approx \frac{f}{1-f}}$$

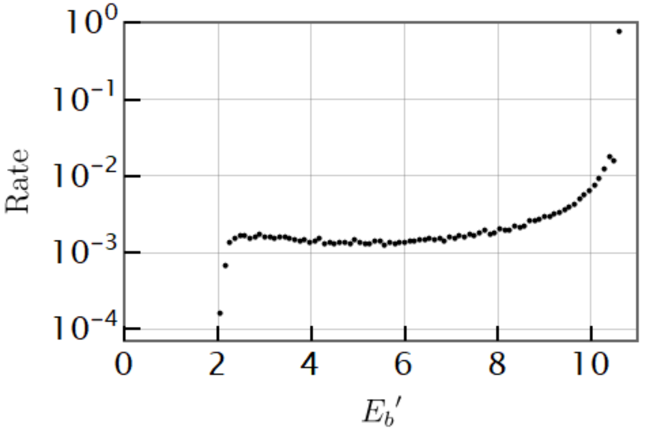


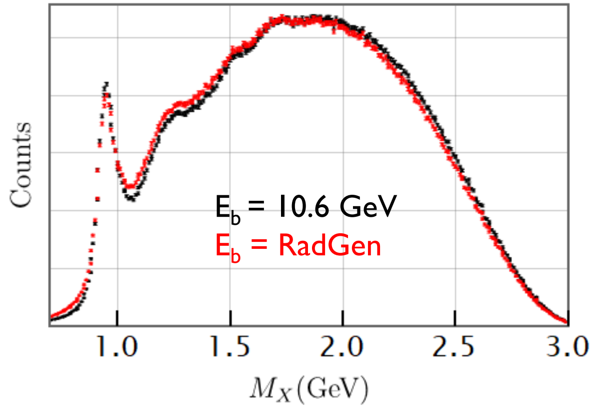


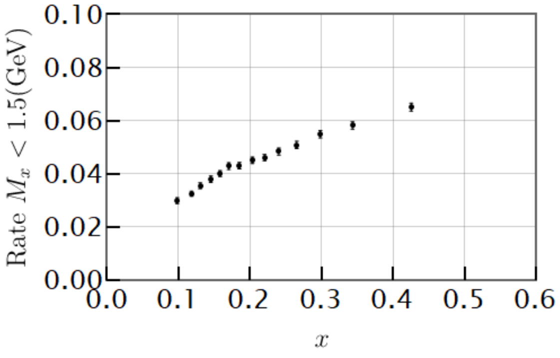


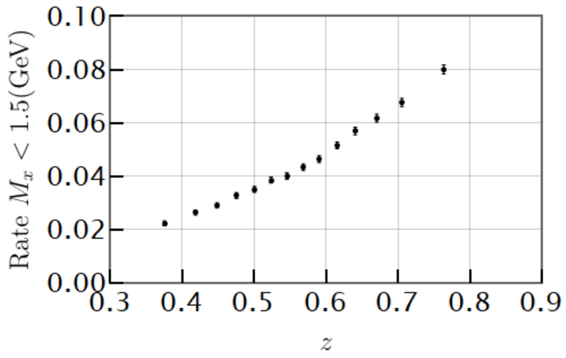
RADIATIVE EFFECTS

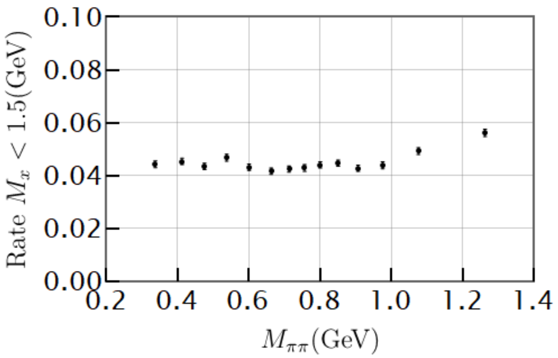
- Use RadGen to generate a distribution of true beam energies.
- Proceed through analysis as normal but use E_b' instead of E_b = 10.6 GeV.











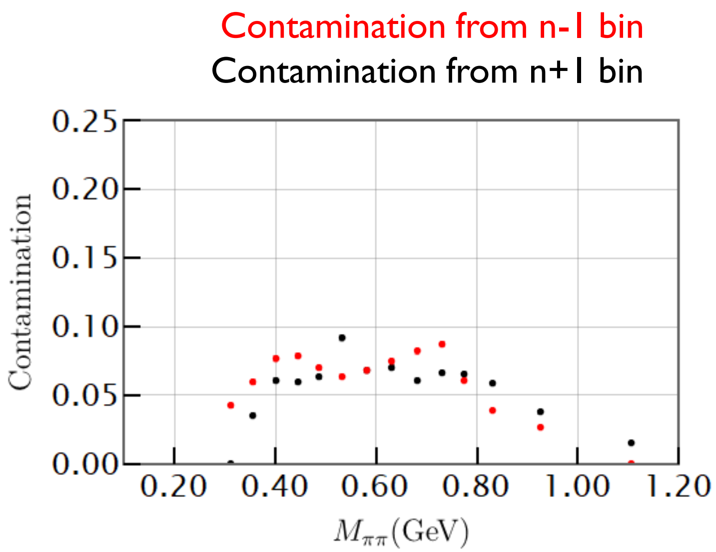
- Calculate the events per bin that actually fall below M_x < 1.5 GeV but are misattributed to our signal due to radiative effects.
- $A_M = (1\text{-}f)A_{true} + f\,A_\gamma$
- Estimate A_γ from BSA(M_X < 1.5 GeV)

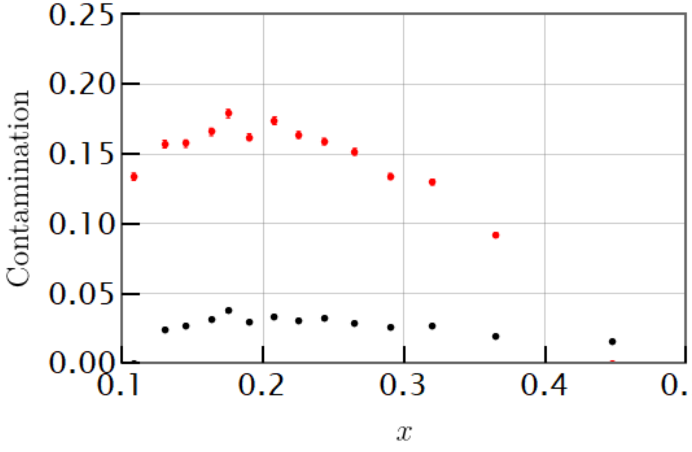
$$\boxed{\frac{\Delta A}{A} \approx \frac{A_\gamma}{A_M}\frac{f}{1-f}}$$

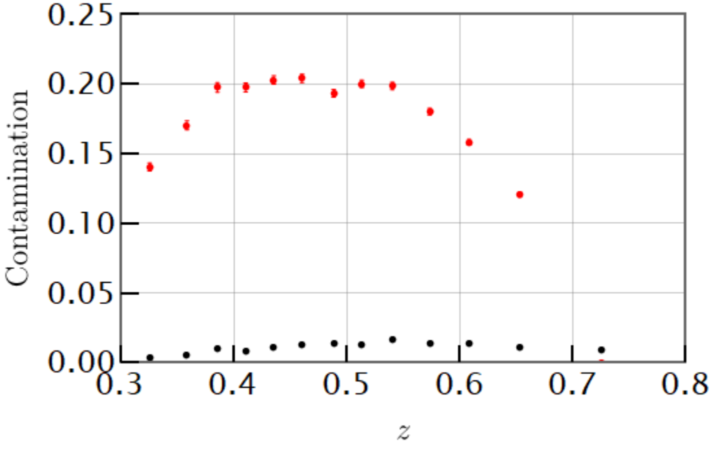
BIN MIGRATION

- Use MC to estimate the rate of counts in each bin coming from a separate bin.
- Separate contamination rates from bins before and after the bin of interest (mean of resolution is not zero).
- Assign an asymmetry based on measured values of adjacent bins.
- We're fortunate: x and z change slowly and mass resolutions are good.
- $A_M = f_{i-1} A_{i-1} + f_{i+1} A_{i+1} + (1 - f_{i-1} - f_{i+1}) A_{true}$

$$\frac{\Delta A}{A} \approx \frac{|(f_{i+1} + f_{i-1})A_M - f_{i-1}A_{i-1} - f_{i+1}A_{i+1}|}{(1 - f_{i-1} - f_{i+1})A_M}$$

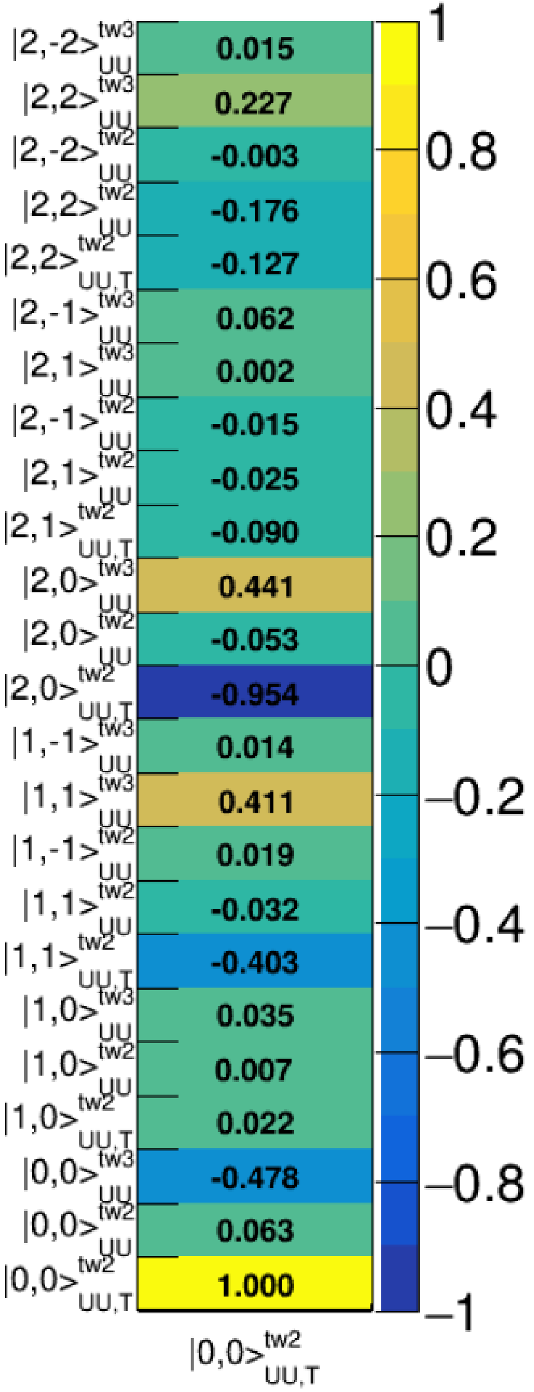






Systematic: F_{UU} Partial Waves

- Non-orthogonality of modulations necessitates simultaneous fits for asymmetry amplitudes
- The asymmetry denominator, proportional to F_{UU}, also includes several modulations
  - Integral nominally gives the total cross section; it is the "amplitude" of the "constant modulation", denoted |1>
  - |1> seems to be also non-orthogonal to other F_{UU} modulation amplitudes $|L,M>_{UU}$
- Figure on right shows $< 1 \mid L,M >_{UU}$
  - $<1|2,0>_{UU}$ is especially large, as expected (technical math reason)
  - Large inner products with 4 other modulations
  - **Significant corresponding amplitudes can scale A_{LU}**



Systematic: F_{UU} Partial Waves

name	$\|\psi\rangle$	$\psi(\phi_h, \phi_R, \theta)$	overlap $\langle 1 \psi \rangle$	PDF⊗FF
d_0	$\|0,0\rangle^{tw3}_{UU}$	$\cos(\phi_h)$	-0.5	$hH^{\perp}_{1,OO}$ and $f^{\perp}D_{1,OO}$
d_1	$\|1,1\rangle^{tw2}_{UU,T}$	$\sin(\theta)\cos(\phi_h - \phi_R)$	-0.4	$\frac{1}{2}f_1 D_{1,OT}$
d_2	$\|1,1\rangle^{tw3}_{UU}$	$\sin(\theta)\cos(\phi_R)$	0.4	$\frac{R}{p_T}hH^{\sphericalangle}_{1,OT}$ and $\frac{1}{2}f^{\perp}D_{1,OT}$
d_3	$\|2,0\rangle^{tw2}_{UU,T}$	$\frac{1}{2}\left(3\cos^2\theta - 1\right)$	-0.95	$\frac{1}{2}f_1 D_{1,LL}$
d_4	$\|2,0\rangle^{tw3}_{UU}$	$\frac{1}{2}\left(3\cos^2\theta - 1\right)\cos(\phi_h)$	0.4	$\frac{1}{2}hH^{\perp}_{1,LL}$ and $\frac{1}{2}f^{\perp}D_{1,LL}$

- Most significant modulations shown above
- We don't know enough about the PDFs and FFs, relative to $D_{1,OO}$
- **Plan: provide a table of <1|L,M> (for each kinematic bin) as supplementary material**
  - Also a good idea for the F_{LU} modulations as well
  - This is in lieu of a systematic uncertainty
  - Maximize the information we convey, and minimize the assumptions we make

Relative Luminosity

$$R = n_+/n_-$$

$n_\pm$ is the number of events in DST file with REC::Particle, REC::event, RUN::config banks, for helicity ±1

This ratio depends on HWP position; <u>not</u> symmetric about 1

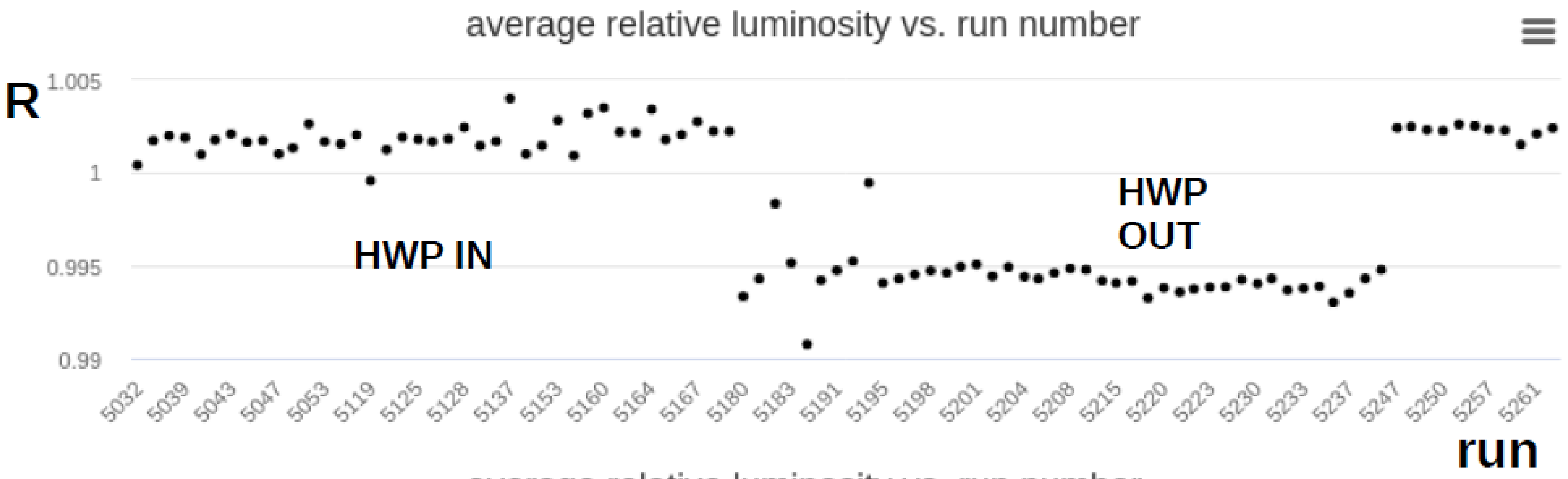
Effect on asymmetry:

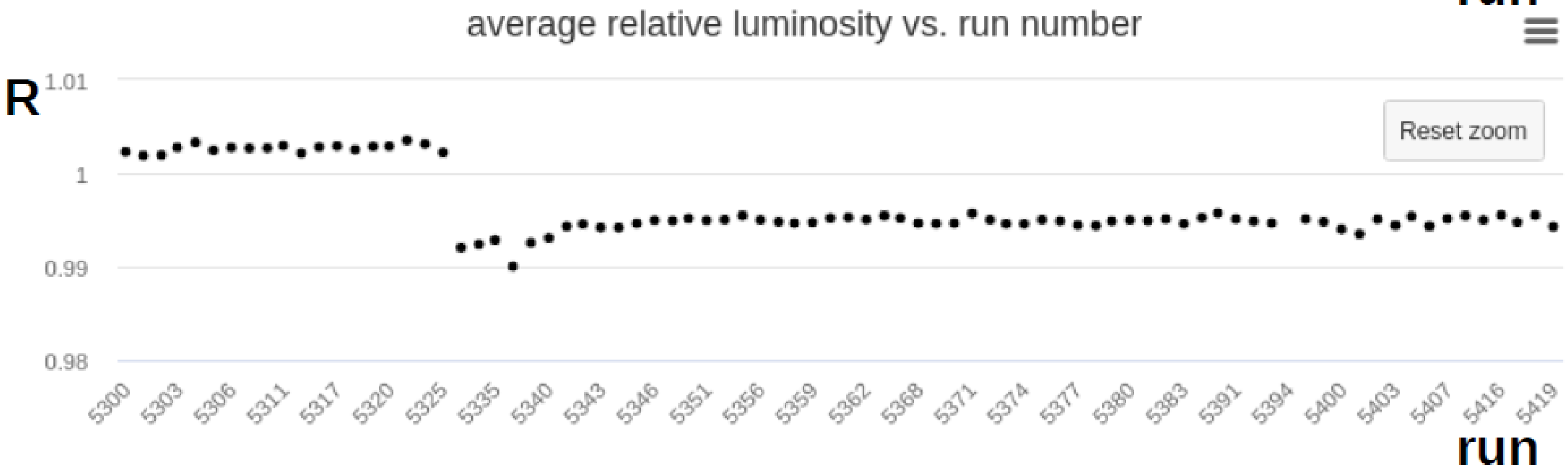
Average offset from 1: $\Delta R=0.0025$

$\Delta A \approx \Delta R/2PR = 0.0015$ shift

~7% of a typical 2% asym.

Caveat: this is biased by the trigger and acceptance, and likely includes "garbage"; prefer to use an observable with minimum bias





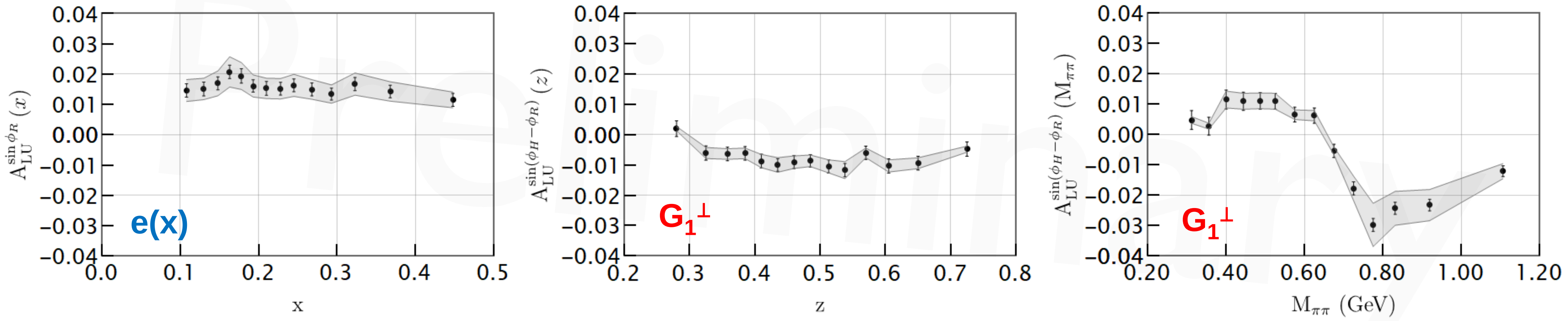
SUMMARY OF SYSTEMATICS

- Assuming the A_{UU} waves are treated separately we are dominated by the baryonic contributions… but please don't quote us on these until the analysis note.

Systematic	Average Scale Error
Beam Polarization	3%
Baryonic Contributions	22%
Radiative Effects	3%
Bin Migration	3%
Relative Luminosity	7% effect, correctable
PID Assignment (Kaon contamination)	--, probably relatively large
Acceptance Effects	--, likely correctable
Uncertainty in A_{UU}	Supplementary table of inner products

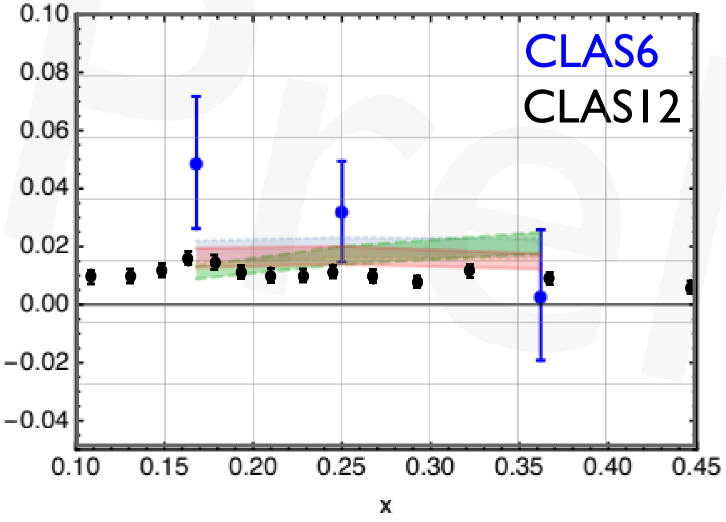
ONE DIMENSIONAL RESULTS

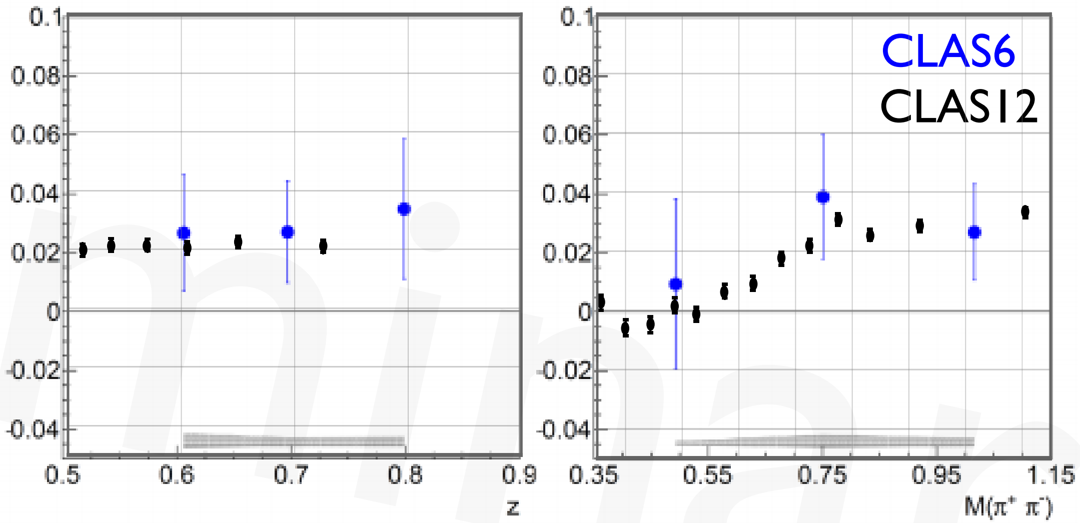
- Significant nonzero asymmetry sensitive to e(x) is measured and will help greatly constrain the PDF.
- First measurements sensitive to $G_1^{\perp}$ are shown and a nonzero signal is present.
- The sign change around the ρ mass was recently predicted in the “spectator model”.



COMPARISON TO CLAS6 / THEORY

- Comparison to preliminary results from e1f CLAS6 data (Mirazita et al.)
- Spectator model (green), bag model (red), LFCQM (grey dotted).
- All plots are $\sin(\varphi_R)$ modulations.
- Good agreement… CLAS12 statistics dwarf CLAS.



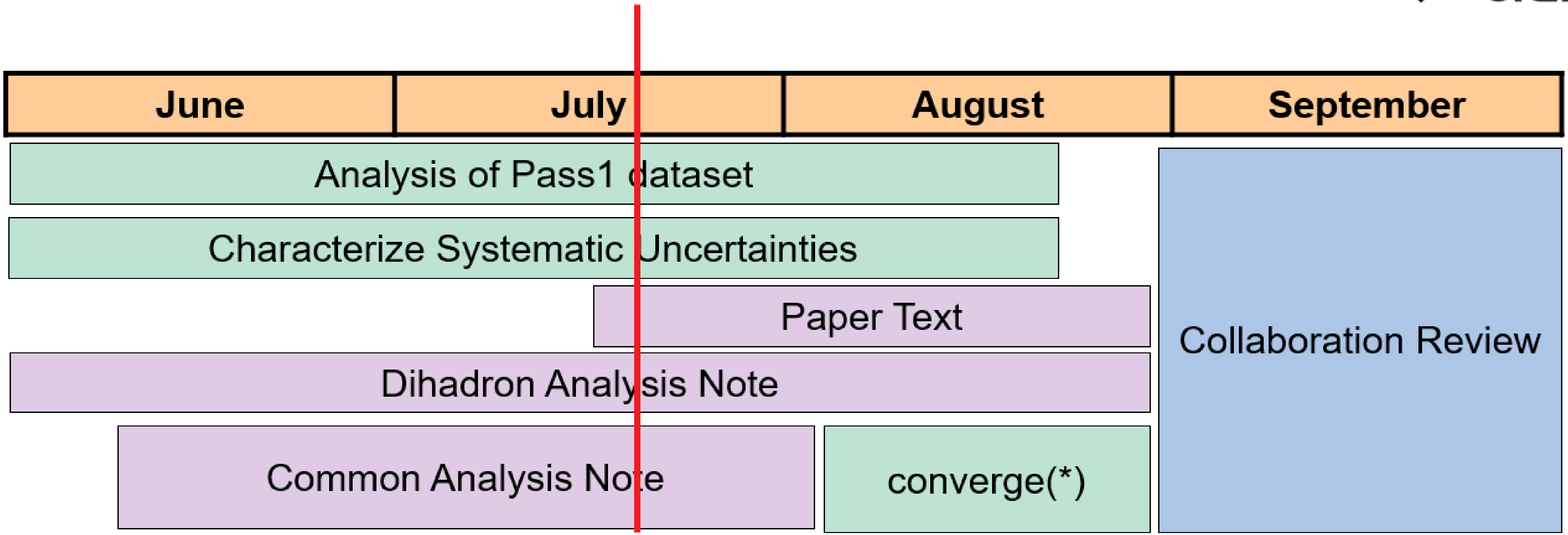


CONCLUSIONS

- Significant measurements sensitive to the PDF e(x) and the DiFF $G_1^{\perp}$ are observed.
- RG-A common analysis in final steps.
- SIDIS dihadron analysis note/paper has significant progress and will hopefully be finalized in the coming weeks


Charged dihadron beam-spin asymmetries from CLAS12

Estimated Timeline



(*) Converge:

- Ensure our cuts match those outlined in the common analysis note, e.g., fiducial cuts, PID cuts, QA
- Final cross check between two independent analyses from Timothy and Chris

BACK UP

BEAM POLARIZATION

- From Stefan Diehl
- Final numbers under discussion among experts.

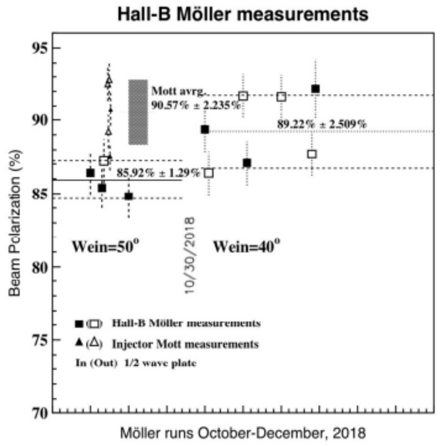
7.0.1 Uncertainty of the beam polarization

The beam polarisation was measured with a Moller polarimeter upstream of CLAS12 several times during the fall 2018 run period. More details of the procedure can be found in the common RG-A analysis note. The result of the measurements are shown in Fig. 7.1.

Since the Wein-angle has been changed during the run periods, two different run ranges have to be considered. The average beam polarizations for the two run ranges has been determined to:

- $(85.92 \pm 1.29)\%$ for run ≤ 5328
- $(89.22 \pm 2.51)\%$ for run ≥ 5331

Since the in-bending run period which reaches from run 5032 to run 5407 spreads over both regions, the luminosity weighted average of the polarization has to be determined. For the event which pass all quality cuts, 65.8% are in the first and the remaining 34.2% are in the second run range. For the out-bending run period which reaches from run 5422 to run 5666, all runs are in the second run period.



The systematic uncertainty of the Moller measurement, which results from the calibration uncertainty of the Moller polarimeter has been estimated to 2 %. This leads to the following luminosity weighted beam polarizations for the two torus fields:

- $(87.05 \pm 1.71\ (\text{stat}) \pm 2.0\ (\text{sys}))\%$ for the in-bending run period
- $(89.22 \pm 2.51\ (\text{stat}) \pm 2.0\ (\text{sys}))\%$ for the out-bending run period

The sum of the statistical and systematic uncertainty of the beam polarisation is considered to contribute to the systematic uncertainty of the BSA measurement. For the contribution to the BSA measurement we get from Eq. 4.1:

$$\frac{\delta F_{LU}^{sin\phi}/F_{UU}}{F_{LU}^{sin\phi}/F_{UU}} = \frac{\delta A_{LU}^{sin\phi}}{A_{LU}^{sin\phi}} = \frac{\delta BSA}{BSA} = \frac{\delta P_e}{P_e} \tag{7.1}$$

which leads to the following systematic uncertainties:

- 4.26 % for the in-bending run period
- 5.05 % for the out-bending run period

INJECTED ASYMMETRIES

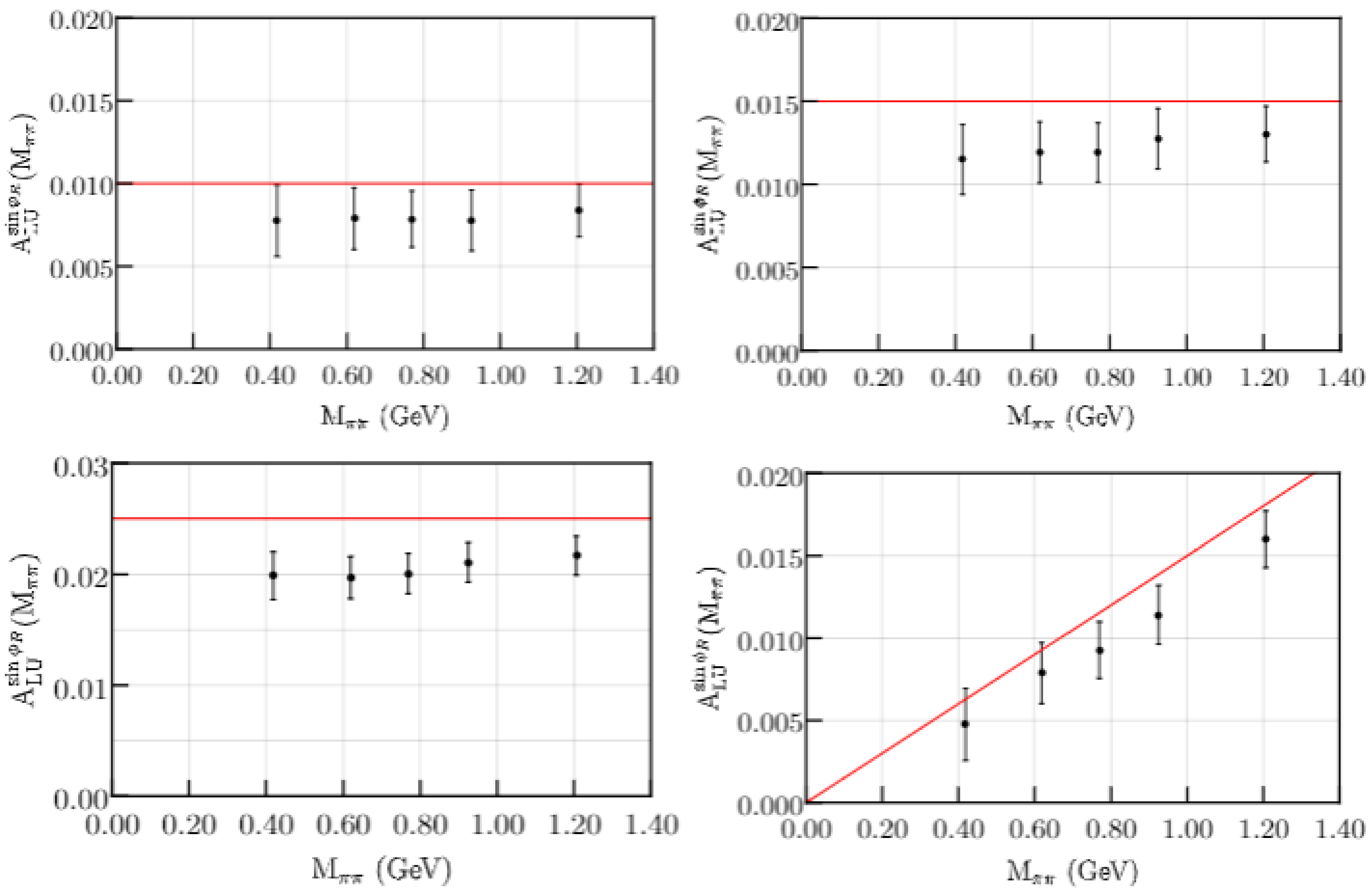


FIG. 10: (Color online). The reconstructed asymmetries (black points) that result from an injected asymmetry of 10%, 15%, 25% and a linearly increasing asymmetry. The reconstructed asymmetry corresponds to around 80% of the injected value.

BSA OF MISSING MASS

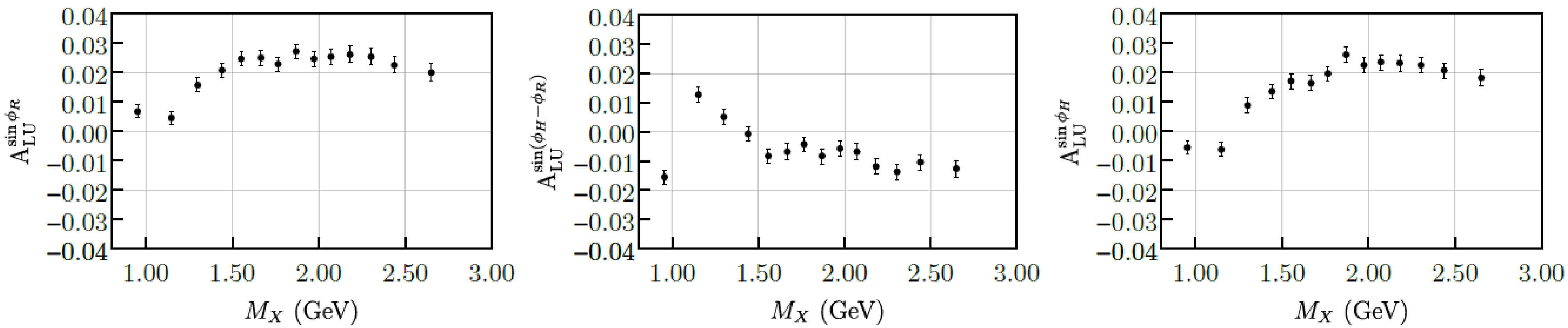


FIG. 6: The beam-spin asymmetries for $\sin\phi_R$, $\sin(\phi_H - \phi_R)$ and $\sin\phi_H$ as a function of the missing mass, M_X. A non-constant dependence is observed below 1.5% indicating contributions from exclusive reactions and radiative effects.

G. Extracting A_{LU}