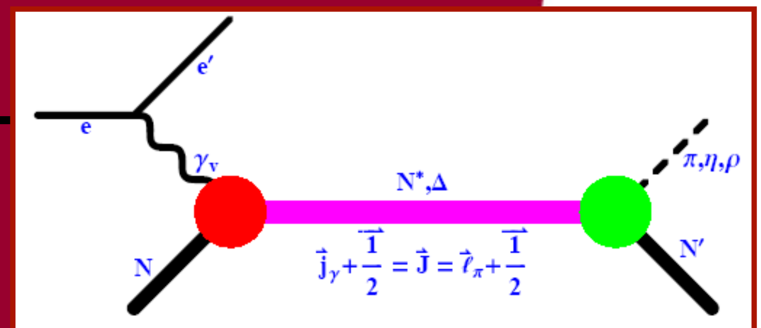
Measurement of the Coulomb quadrupole amplitude in the $\gamma^* p \rightarrow \Delta(1232)$ reaction in the low momentum transfer region (E08-010)



Adam J. Sarty

(co-spokesperson; Saint Mary's University

Other Spokespeople

<u>Nikos Sparveris</u>(Temple U; <u>contact</u> person)

Doug Higinbotham (Jefferson Lab)

Shalev Gilad (MIT)

Postdocs + Students

Michael Paolone (Temple, postdoc)

David Anez(SMU & Dalhousie U., PhD student)

Adam Blomberg (Temple U; PhD student)

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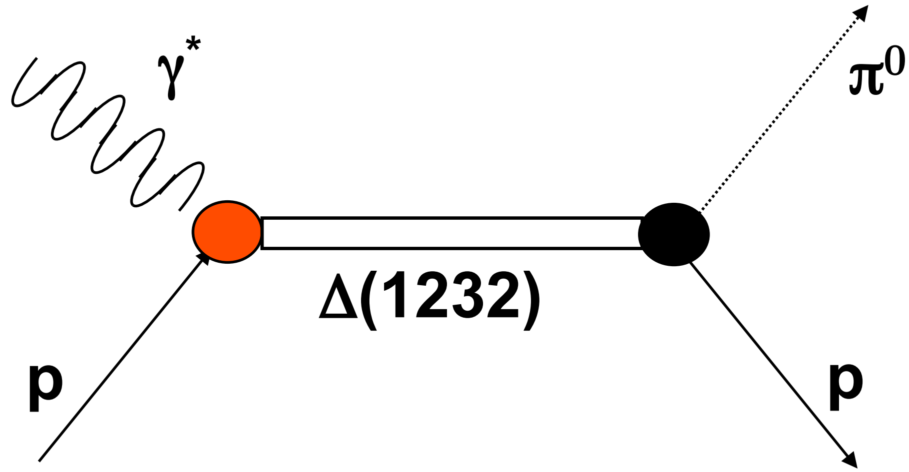
Where/How the Physics comes in:



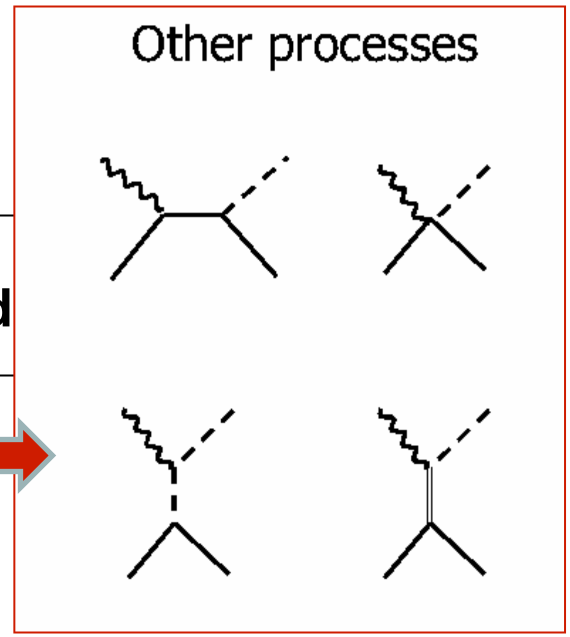
γ^* : **EM Multipolarity of transition**
(Electric, Magnetic, Scalar)
(Dipole, Quadrupole, etc.)

Vertex #1 : **Nucleon Structure model enters here: $\gamma^* + p \rightarrow \Delta$**
(CQM or "pion cloud" Bag Model, etc.)

Vertex #2 : **$\Delta(1232)$ Model for decay**
PLUS $\pi^0 p$ reaction Dynamics

$L_{\pi p}$ value for nomenclature of transition amplitude determined

NOTE: any full model for the reaction has to deal with separating the desired Resonant excitation from "Other Processes")



Goal of these kind of "N → Δ" Experiments:
Quantify "non-spherical" Components of Nucleon wf

Talking with a CQM view of a nucleon wave-function:

- Dominant M_{1+} is a "spin-flip" transition;
  N and **Δ** both "spherical"…L=0 between 3 quarks
- BUT, the Quadrupole transitions (E_{1+}, S_{1+}) "sample" the "not L=0" parts of the wavefunctions.
- Consider writing wavefunctions like so:

$$|N(939)\rangle = a_S\left|\left(S=\tfrac{1}{2}, L=0\right)J^\pi = \tfrac{1}{2}^+\right\rangle + a_D\left|\left(S=\tfrac{3}{2}, L=2\right)J^\pi = \tfrac{1}{2}^+\right\rangle$$
$$|\Delta(1232)\rangle = b_S\left|\left(S=\tfrac{3}{2}, L=0\right)J^\pi = \tfrac{3}{2}^+\right\rangle + b_D\left|\left(S=\tfrac{1}{2}, L=2\right)J^\pi = \tfrac{3}{2}^+\right\rangle$$

then,
we can view the quadrupole tx as…

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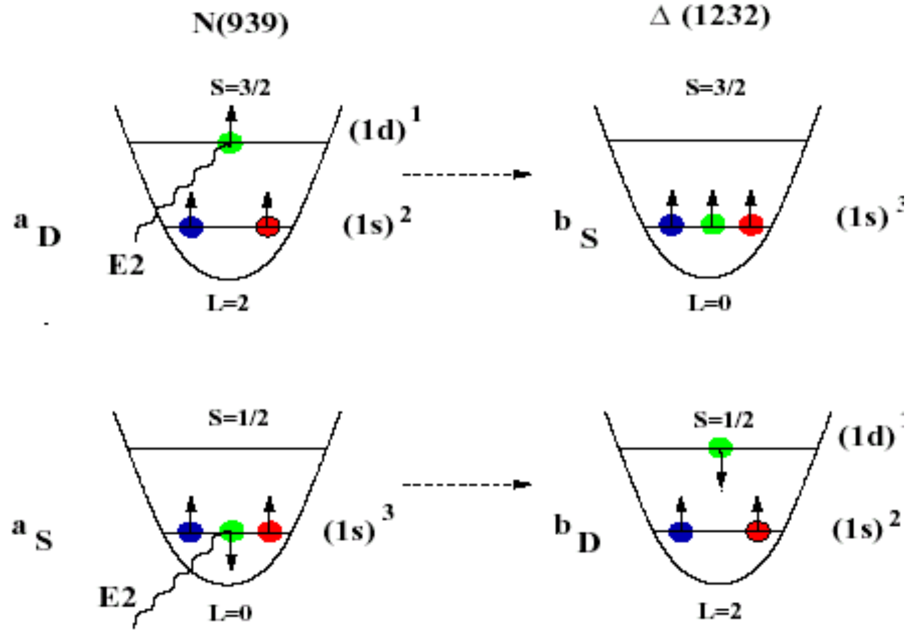
Goal of these kind of "N → Δ" Experiments:
Quantify "non-spherical" Components of Nucleon wf

- These Quadrupole transitions thus give insight into small L=2 part of wf.



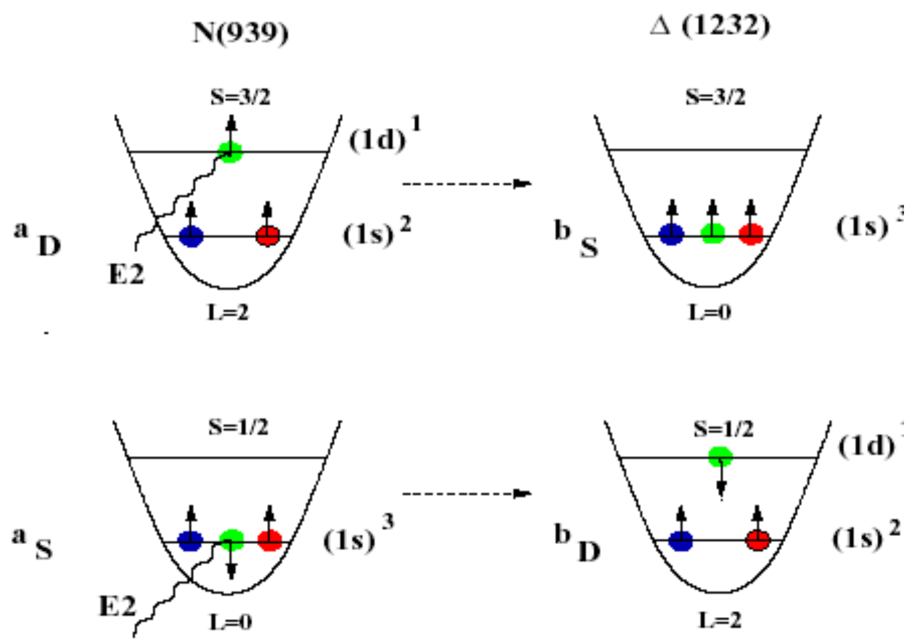
Phys. Rev. **C63**, 63 (2000)

Goal of these kind of "N → Δ" Experiments:
Quantify "non-spherical" Components of Nucleon wf

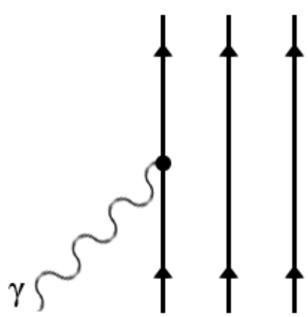
- These Quadrupole transitions thus give insight into small L=2 part of wf.
- Such L=2 parts arise from "colour hyperfine interactions" between quarks

  <u>IF</u>

  the assumption is a "one-body interaction":



Phys. Rev. **C63**, 63 (2000)



$$\hat{Q}_{[1]} = \sqrt{\frac{16\pi}{5}} \sum_{i=1}^{3} e_i r_i^2 Y_0^2(\vec{r}_i) = \sum_i e_i \left(3z_i^2 - r_i^2\right)$$

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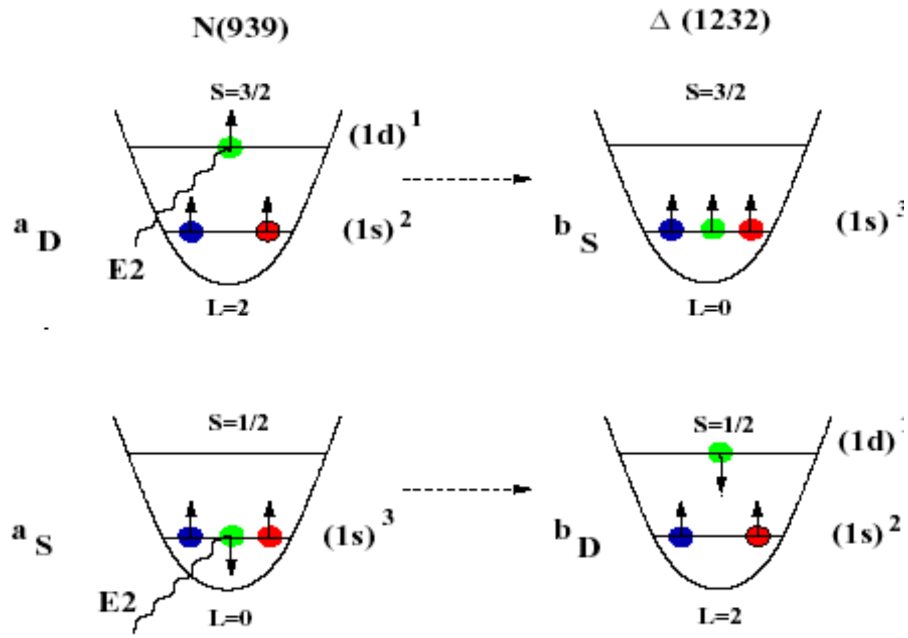
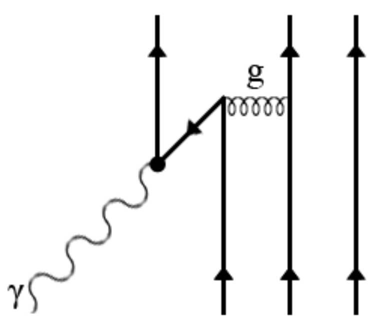
Goal of these kind of "N → Δ" Experiments:
Quantify "non-spherical" Components of Nucleon wf

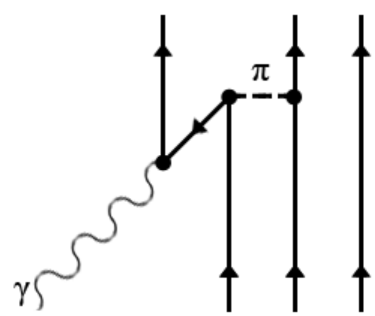
- These Quadrupole transitions thus give insight into small L=2 part of wf.
- **BUT** L=2 transitions can also arise via interactions with virtual exchanged pions (the "pion cloud"):

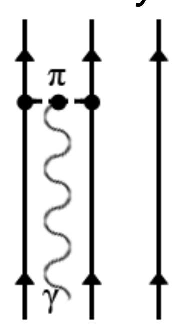
$$\hat{Q}_{[2]} = B \sum_{i \neq j = 1}^{3} e_i \left(3\sigma_{iz}\sigma_{jz} - \vec{\sigma}_i \cdot \vec{\sigma}_j \right)$$



Phys. Rev. **C63**, 63 (2000)







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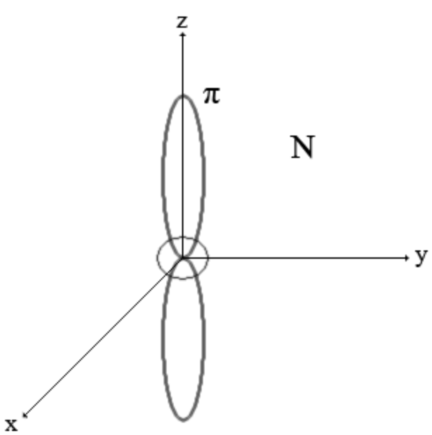
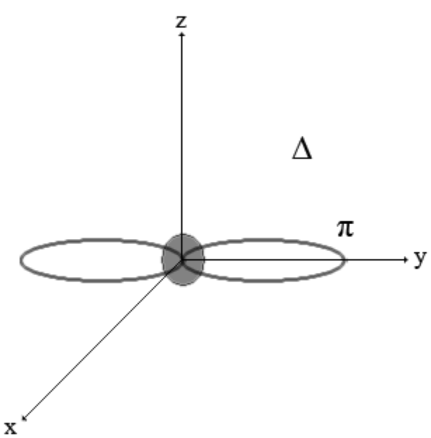
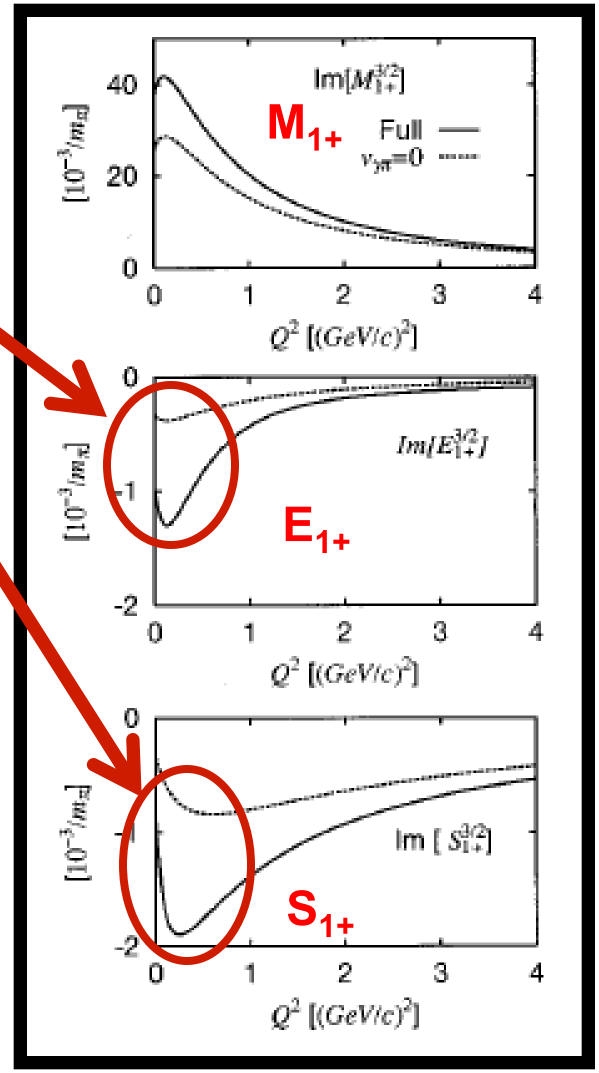
Goal of THIS "N → Δ" Experiment:
FOCUS ON LOW Q^2 WHERE PION CLOUD DOMINATES

- At low momentum transfer: the Pion Cloud dominates the "structure" of wavefunctions
- These pion dynamics dictate the long-range non-spherical structure of the nucleon … and that is where we focus.



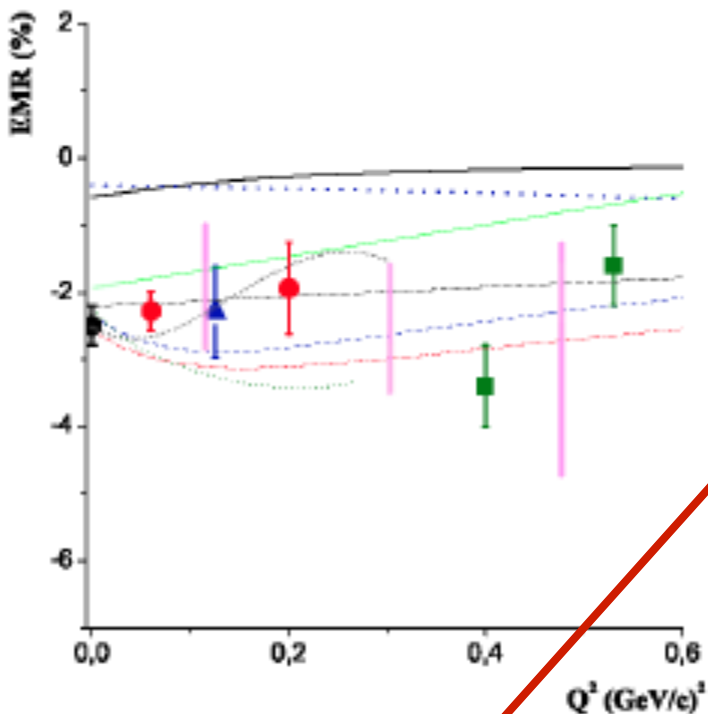


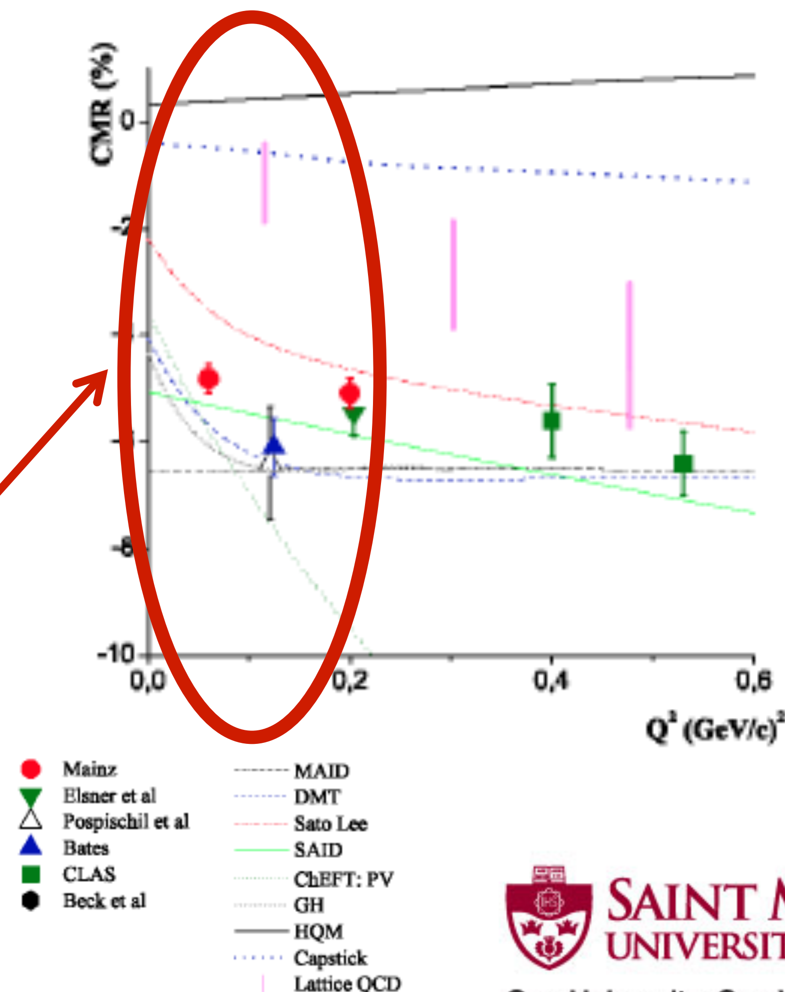


Status of World Data at Low Q^2

(from proposal)

EMR ~ E2/M1 ratio **CMR ~ C2/M1 ratio**





We focus on getting CMR values in this region

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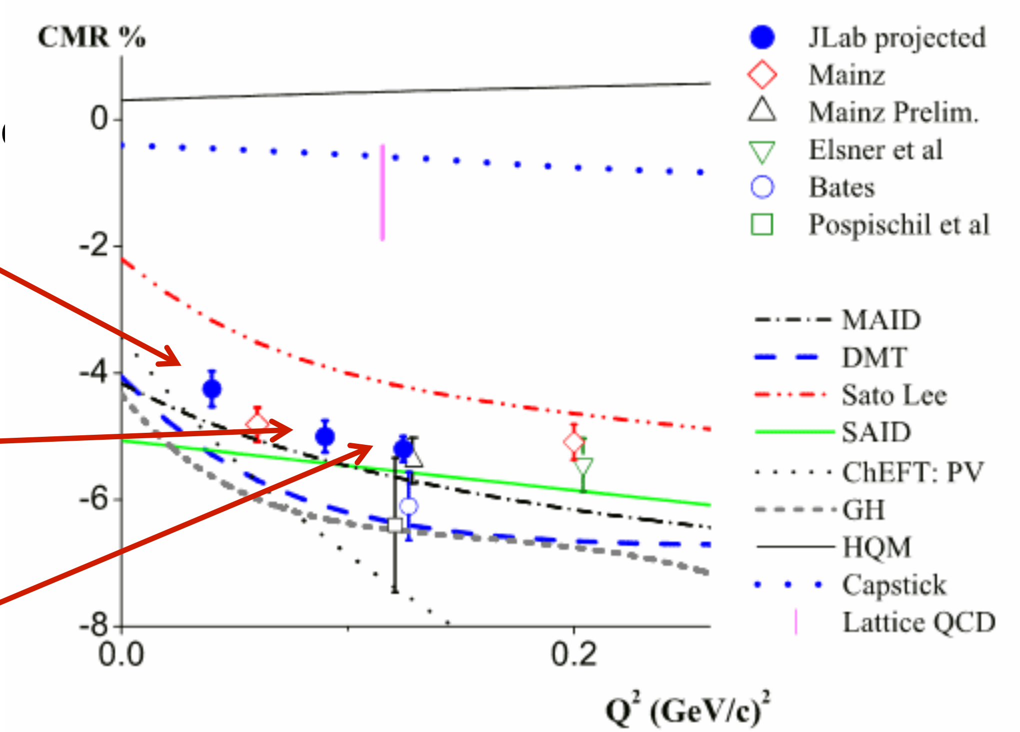
Where our Planned Results Fit

(from proposal)

focus on: CMR ~ C2/M1 ratio at lowest Q^2

- $Q^2 = 0.040\ (\mathrm{GeV}/c)^2$
  - New lowest CMR valu
  - $\theta_e = 12.5°$
- $Q^2 = 0.125\ (\mathrm{GeV}/c)^2$
  - Validate previous measurements
- $Q^2 = 0.090\ (\mathrm{GeV}/c)^2$
  - Bridge previous measurements



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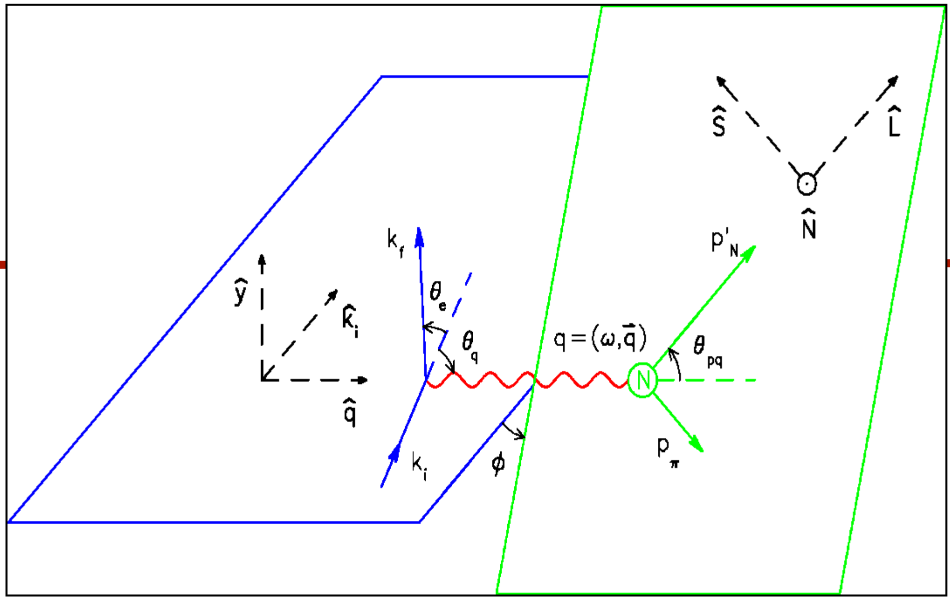
$p(\vec{e}, e' \vec{p})\pi^0$ Responses

18 Response Functions:
Each with their own Unique/Independent combination of contributing Multipole transition amplitudes



$$\frac{d^5\sigma}{d\varepsilon_f d\Omega_e d\Omega_{cm}} = \frac{p_{cm}}{k_{\gamma cm}}\Gamma_\gamma\, \bar{\sigma}_0 \left[1 + hA + \boldsymbol{S}\cdot(\boldsymbol{P} + h\boldsymbol{P}')\right]$$

$$\bar{\sigma}_0 = \nu_L R_L + \nu_T R_T + \nu_{LT} R_{LT}\cos\phi + \nu_{TT} R_{TT}\cos 2\phi$$

$$A\bar{\sigma}_0 = \nu'_{LT} R'_{LT}\sin\phi$$

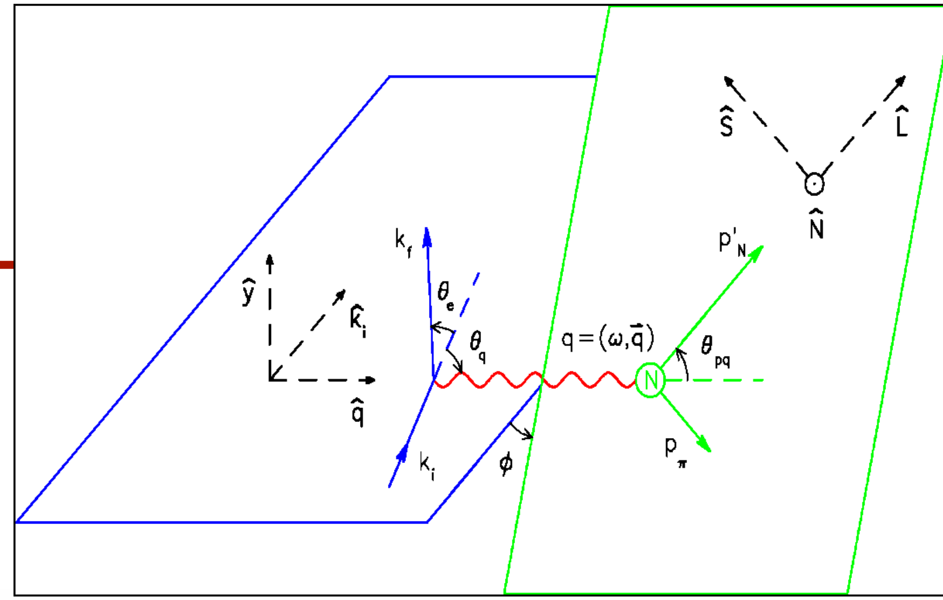
$$P_N\bar{\sigma}_0 = \left[\nu_L R_L^N + \nu_T R_T^N + \nu_{LT} R_{LT}^N\cos\phi + \nu_{TT} R_{TT}^N\cos 2\phi\right]$$

$$P_m\bar{\sigma}_0 = \left[\nu_{LT} R_{LT}^m\sin\phi + \nu_{TT} R_{TT}^m\sin 2\phi\right] \quad (m \in \{L, S\})$$

$$P'_N\bar{\sigma}_0 = \nu'_{LT} R'^N_{LT}\sin\phi$$

$$P'_m\bar{\sigma}_0 = \left[\nu'_{LT} R'^m_{LT}\cos\phi + \nu'_{TT} R'^m_{TT}\right] \quad (m \in \{L, S\})$$

$p(\vec{e}, e'\vec{p})\pi^0$ Responses



18 Response Functions:
Each with their own Unique/Independent combination of contributing Multipole transition amplitudes

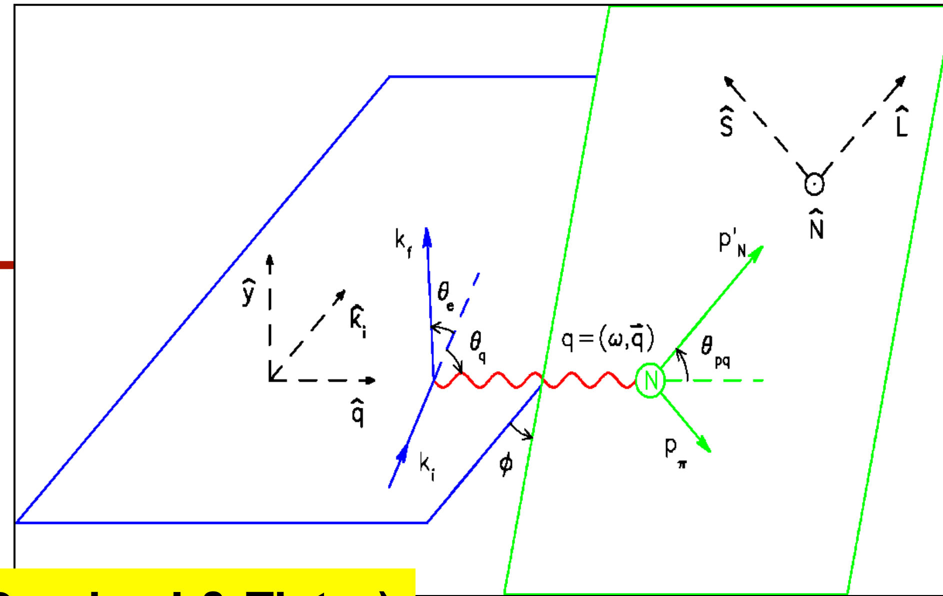
$$\frac{d^5\sigma}{d\varepsilon_f d\Omega_e d\Omega_{cm}} = \frac{p_{cm}}{k_{\gamma cm}}\Gamma_\gamma\, \bar{\sigma}_0\left[1 + hA + \boldsymbol{S}\cdot(\boldsymbol{P} + h\boldsymbol{P}')\right]$$

$$\bar{\sigma}_0 = \nu_L R_L + \nu_T R_T + \nu_{LT} R_{LT} \cos\phi + \nu_{TT} R_{TT} \cos 2\phi$$

- No polarization required for these Responses (R's)
- L and T via cross-sections at fixed (W,Q^2) but different *v*'s ("Rosenbluth")
- **LT** and TT via **cross-sections** at different Out-Of-Plane angles ϕ

- **We will extract just R_{LT} (by left/right measurements) – and σ_0 – since LT term is very sensitive to size of L_{1+} (see next slide…)**

$p(\vec{e}, e'\vec{p})\pi^0$ Responses



18 Response Functions:
Each with their own Unique/Independent combination of contributing Multipole transition amplitudes

For Example: decomp of 5 R's (Drechsel & Tiator)

$$R_L = |L_{0+}|^2 + 4|L_{1+}|^2 + |L_{1-}|^2 - 4\,\mathrm{Re}\{L_{1+}^* L_{1-}\} + 2\cos\theta\,\mathrm{Re}\{L_{0+}^*(4L_{1+} + L_{1-})\} + 12\cos^2\theta\left(|L_{1+}|^2 + \mathrm{Re}\{L_{1+}^* L_{1-}\}\right)$$

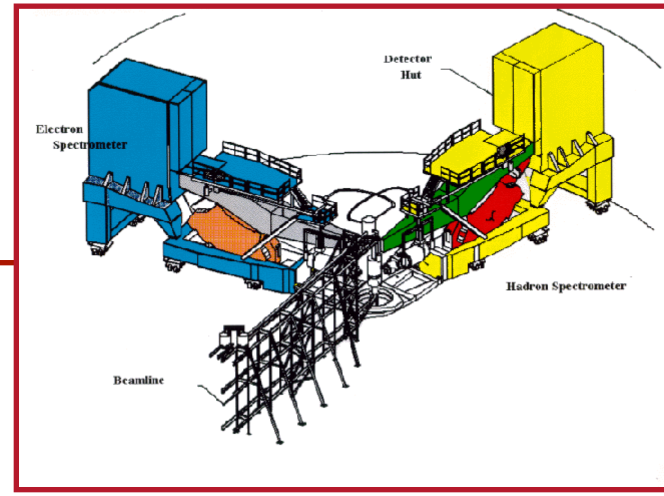
$$R_T = |E_{0+}|^2 + \tfrac{1}{2}|2M_{1+} + M_{1-}|^2 + \tfrac{1}{2}|3E_{1+} - M_{1+} + M_{1-}|^2 + 2\cos\theta\,\mathrm{Re}\{E_{0+}^*(3E_{1+} + M_{1+} - M_{1-})\}$$
$$+ \cos^2\theta\left(|3E_{1+} + M_{1+} - M_{1-}|^2 - \tfrac{1}{2}|2M_{1+} + M_{1-}|^2 - \tfrac{1}{2}|3E_{1+} - M_{1+} - M_{1-}|^2\right)$$

$$R_{TL} = -\sin\theta\,\mathrm{Re}\{L_{0+}^*(3E_{1+} - M_{1+} + M_{1-}) - (2L_{1+}^* - L_{1-}^*)E_{0+} + 6\cos\theta\left(L_{1+}^*(E_{1+} - M_{1+} + M_{1-}) + L_{1-}^* E_{1+}\right)$$

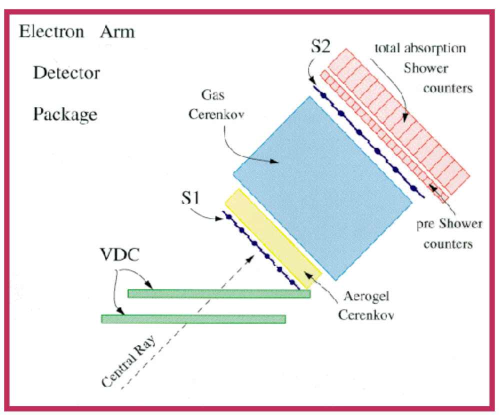
$$R_{TT} = 3\sin^2\theta\left(\tfrac{3}{2}|E_{1+}|^2 - \tfrac{1}{2}|M_{1+}|^2 - \mathrm{Re}\left(E_{1+}^*(M_{1+} - M_{1-}) + M_{1+}^* M_{1-}\right)\right)$$

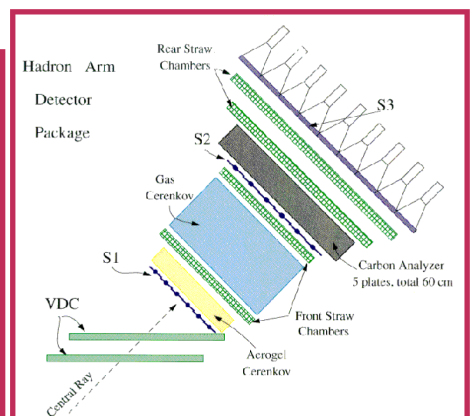
$$R_{TL'} = \sin\theta\,\mathrm{Im}\{L_{0+}^*(3E_{1+} - M_{1+} + M_{1-}) - (2L_{1+}^* - L_{1-}^*)E_{0+} + 6\cos\theta\left(L_{1+}^*(E_{1+} - M_{1+} + M_{1-}) + L_{1-}^* E_{1+}\right)\}$$

Completed Measurements



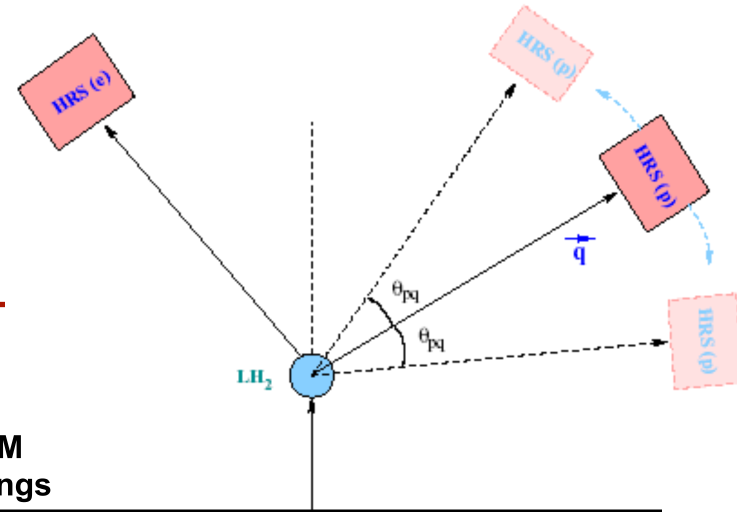
- Jefferson Lab, Hall A
- Feb 27th – Mar 8th, 2011
- 1160 MeV e^{-} beam
- 4 & 15 cm LH_2 target
- Two high resolution spectrometers
  - HRSe and HRSh





- Vertical drift chambers
  - Particle tracking
- Scintillators
  - Timing information
  - Triggering DAQ
- Gas Cerenkov detectors
  - Particle identification
- Lead glass showers
  - Particle identification

Completed Measurements



#	Q^2 (GeV/c)^2	W (MeV)	θ_{pq}	LEFT ARM Electron Settings θ_e	(MeV/c)	RIGHT ARM Proton Settings θ_p	(MeV/c)	I (μA)	L (cm)	Q (mC)	Time (hrs)
1	0.045	1221	0	12.5	805	25.5	552	15	4	636	19
2	0.045	1221	33	12.5	805	12.5	528	15	4	849	18
3	0.045	1221	33	12.5	805	38.5	528	20	4	1416	17
~~4~~	~~0.045~~	~~1260~~	~~0~~	~~13~~	~~755~~	~~22~~	~~618~~	~~30~~	~~4~~	~~0~~	~~0~~
5	0.090	1230	0	18	770	30	626	80	4	642	3
6	0.090	1230	45	18	770	13.5	576	40	4	1296	10
7	0.090	1230	45	18	770	46	576	80	4	1861	8
8	0.125	1232	0	22	750	31.5	670	80/40	4/15	914	5
9	0.125	1232	30	22	750	21	646	30	15	652	6
10	0.125	1232	30	22	750	41.5	646	50	15	758	5
11	0.125	1232	50	22	750	14.5	606	55	4	1436	8
12	0.125	1232	50	22	750	48	606	80	4	1365	6
13	0.125	1170	0	20.5	826	37.5	574	35	15	285	3
14	0.125	1200	0	21	789	34.5	621	35	15	220	2

Status of Analysis

To access goal of “CMR” requires:

- Extraction **of absolute differential cross sections** for all 13 kinematic settings used
- Will then allow comparison of both cross section (σ_0) and the left-right Responses (R_{LT}) and Asymmetries (A_{LT}) to available theories – plus model-dependent CMR extraction

Method:

- **Two PhD students (Anez, Blomberg) have been working on independent analyses**
- Both have worked through long list of calibrations and checks so far (will quickly show on next slides)
- Trying now to firm up H-elastic normalization

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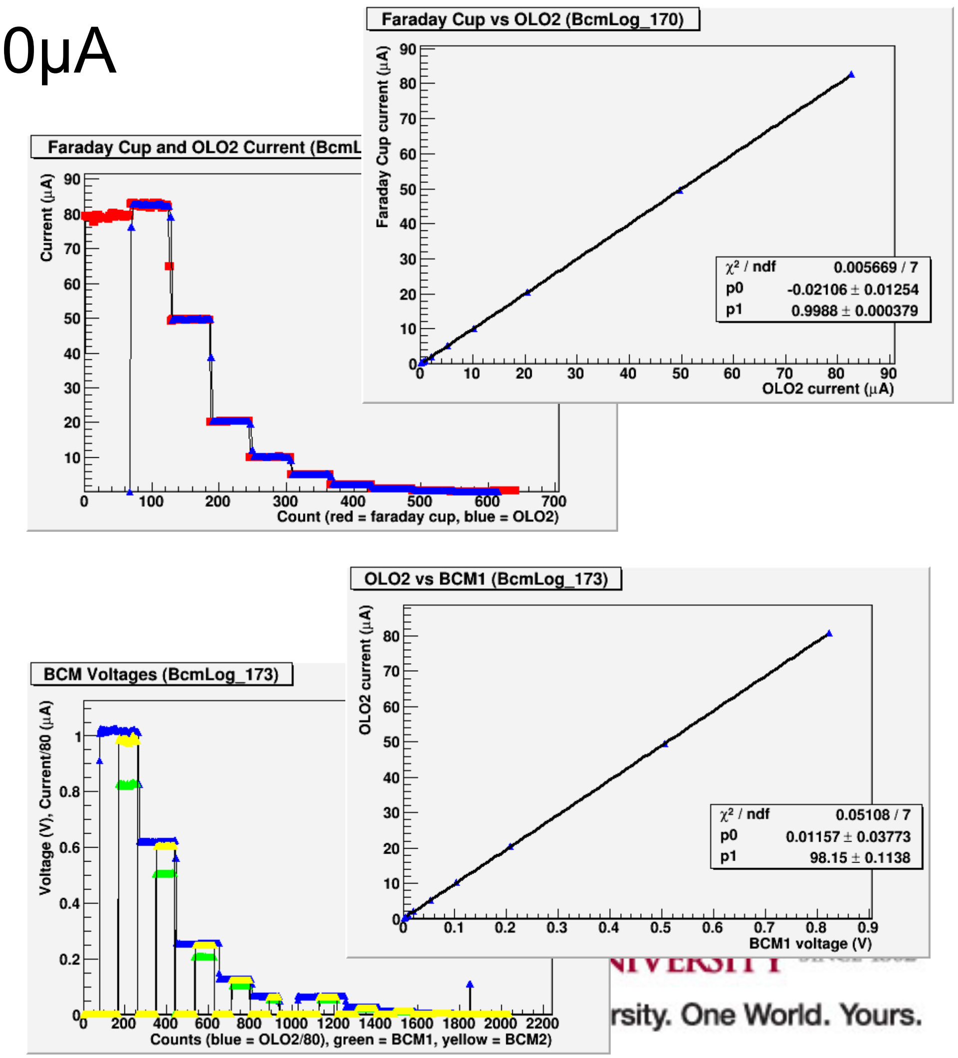
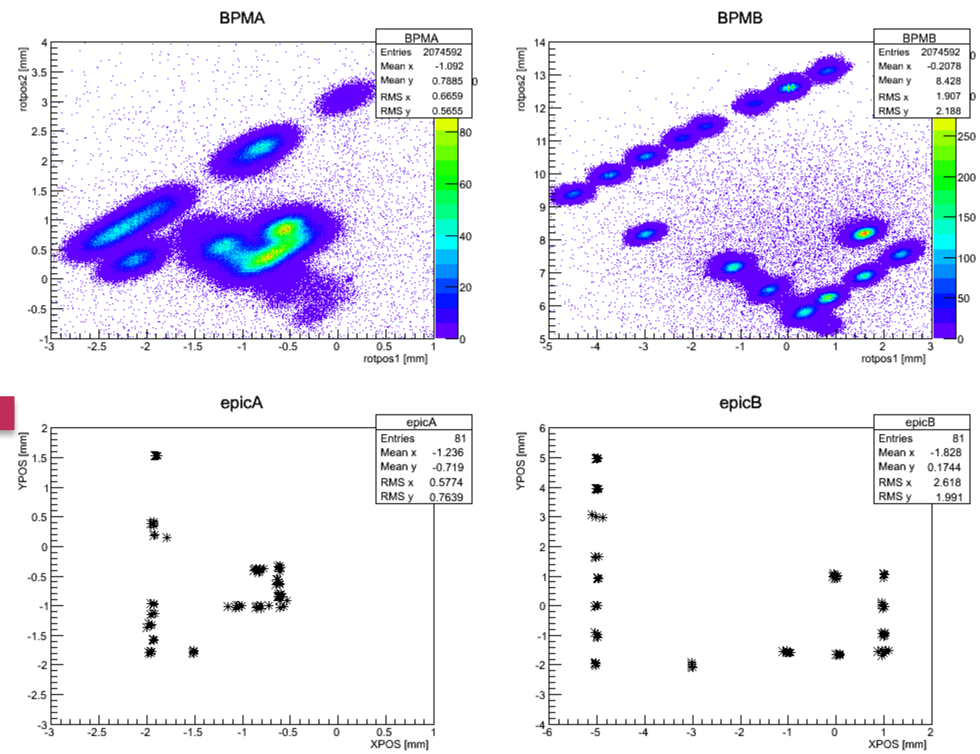
Quick Review of Completed Calibrations/Checks
(shown by Anez/Blomberg at last 2 Collab meetings)

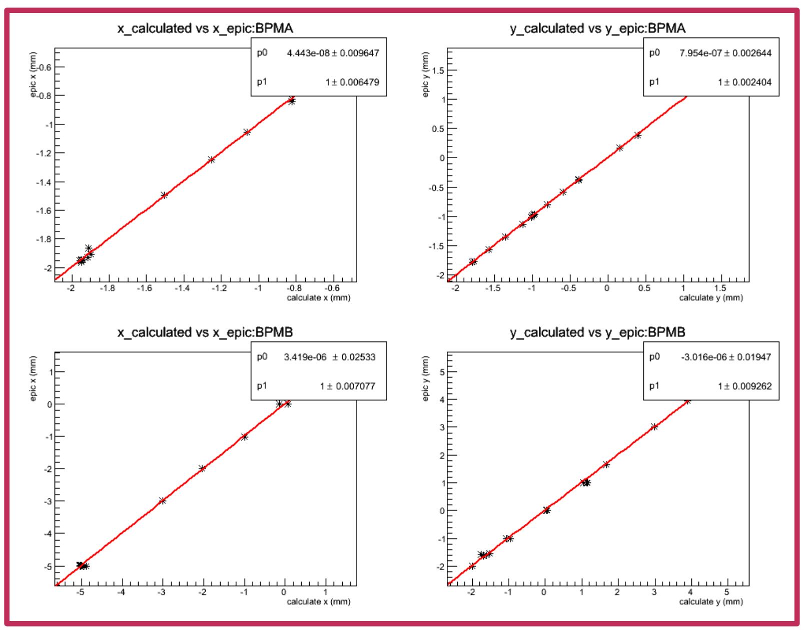
- BCM (beam current): 0.2 - 80μA



Quick Review of Completed Calibrations/Checks
(shown by Anez/Blomberg at last 2 Collab meetings)

- BCM
- BPM, Raster (beam position)





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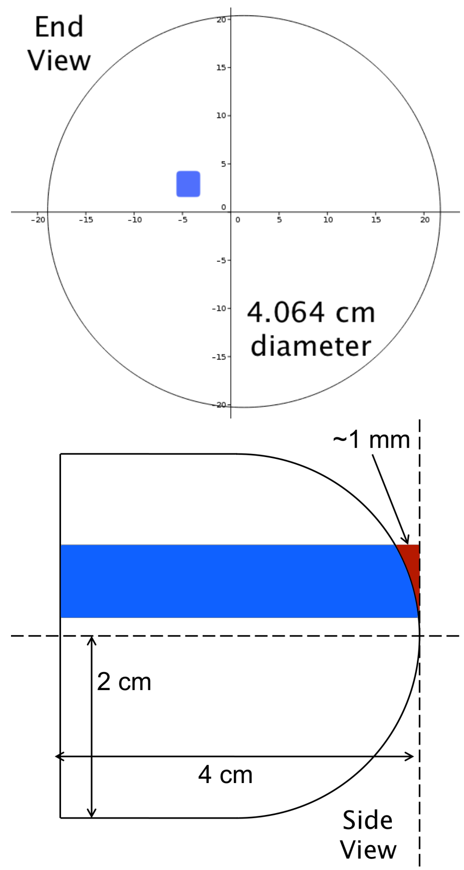
Quick Review of Completed Calibrations/Checks
(shown by Anez/Blomberg at last 2 Collab meetings)

- BCM
- BPM, Raster
- Target Corrections:
  - Length Corrections:
    Thermal Contraction
    Window Thickness
    Beam Offset & End-Cap Curvature

    Effect:
    15 cm ➔ 14.8 ± 0.02 cm
    4 cm ➔ 3.86 ± 0.004 cm



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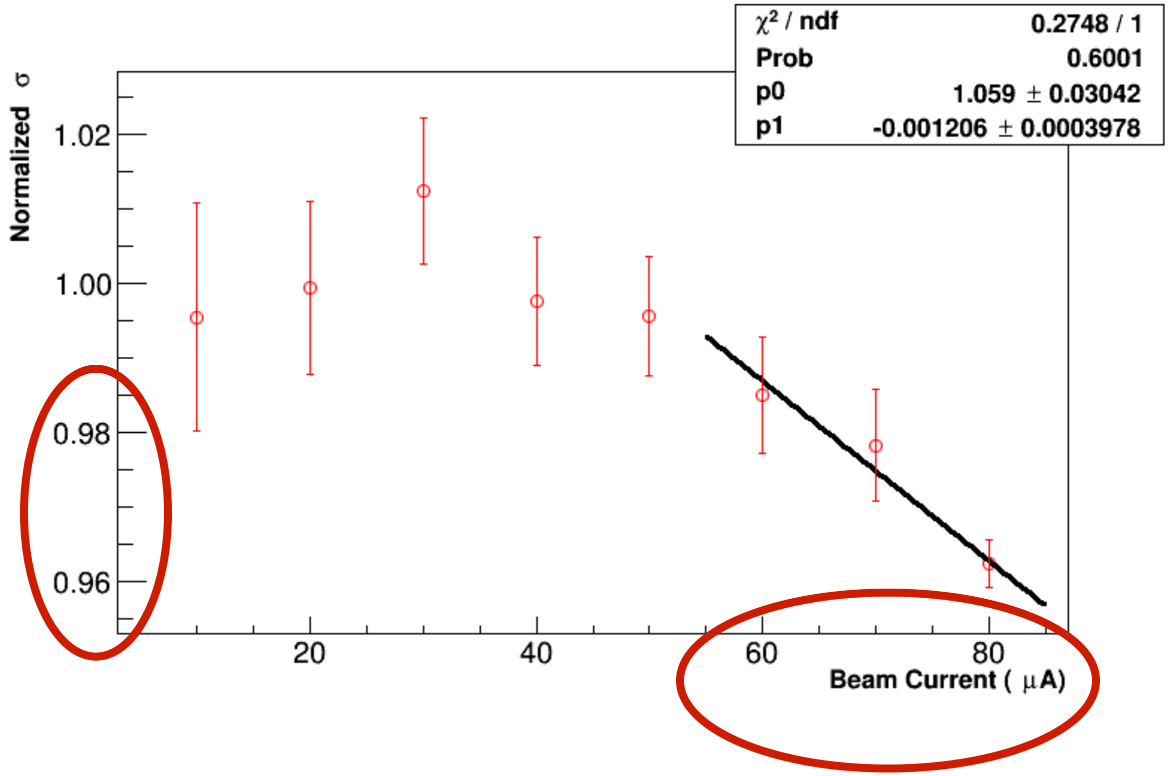
Quick Review of Completed Calibrations/Checks
(shown by Anez/Blomberg at last 2 Collab meetings)

- BCM
- BPM, Raster
- Target Corrections:
  - Length Corrections:
  - Boiling Tests



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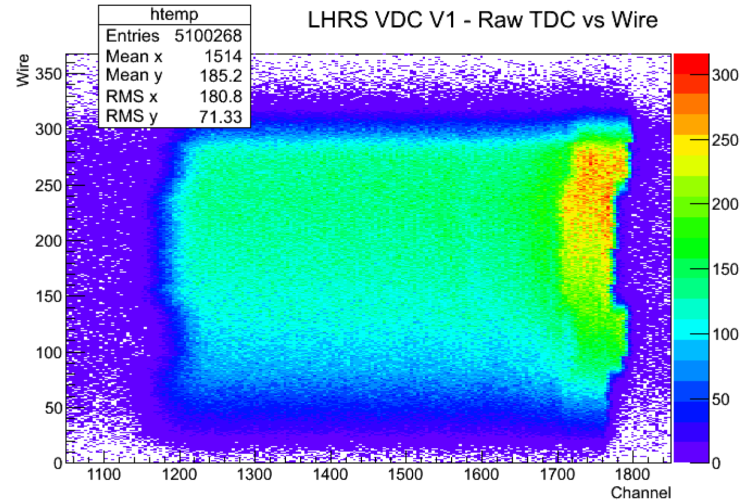
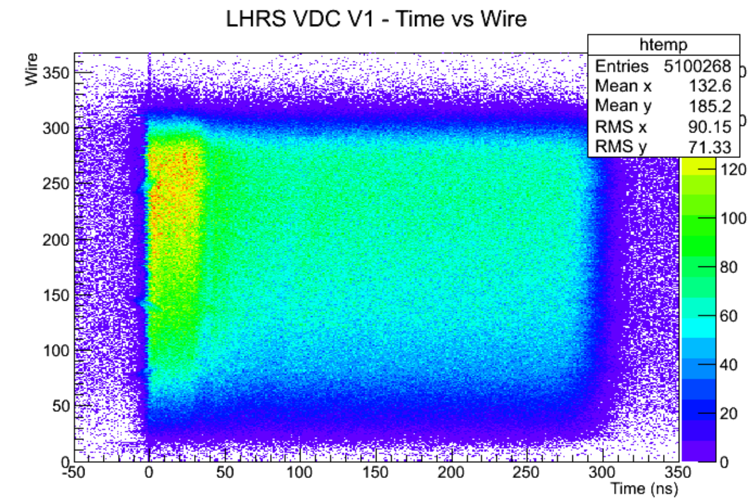
Quick Review of Completed Calibrations/Checks
(shown by Anez/Blomberg at last 2 Collab meetings)

- BCM
- BPM, Raster
- Target Corrections
- VDCs (timing vs wire #)

Before Calibration

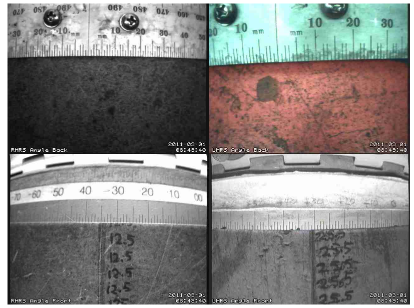


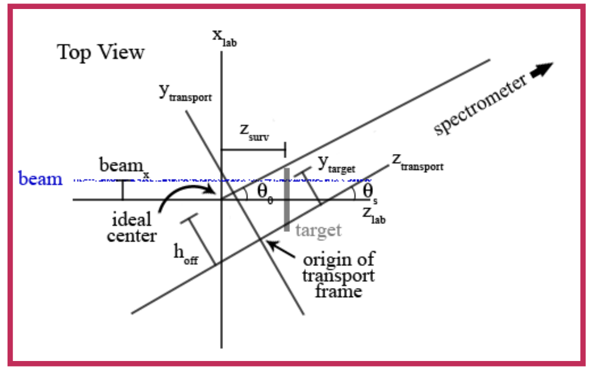
After Calibration

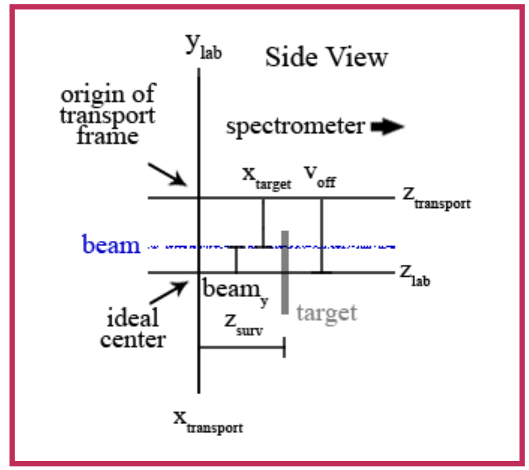


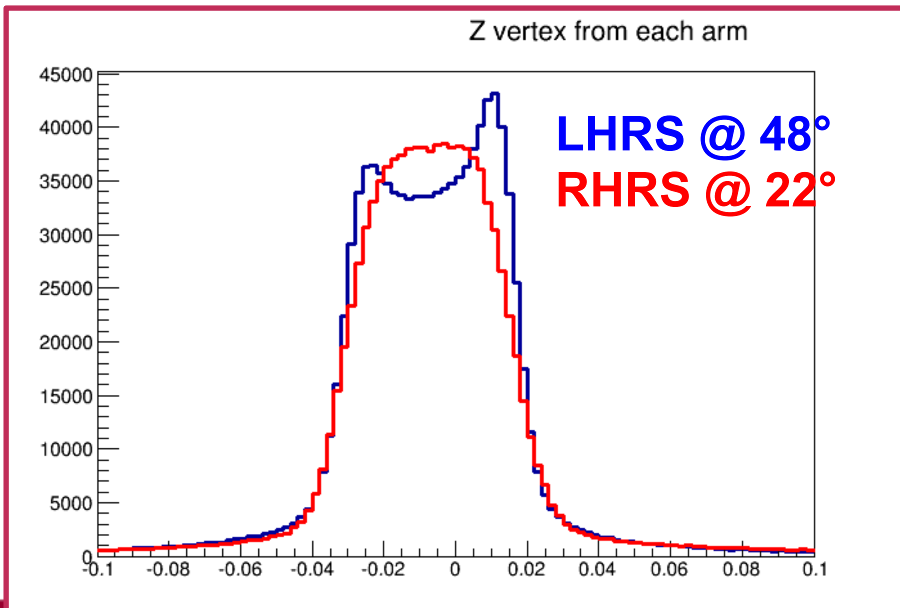
Quick Review of Completed Calibrations/Checks
(shown by Anez/Blomberg at last 2 Collab meetings)

- BCM
- BPM, Raster
- Target Corrections
- VDCs
- HRS Mispointing









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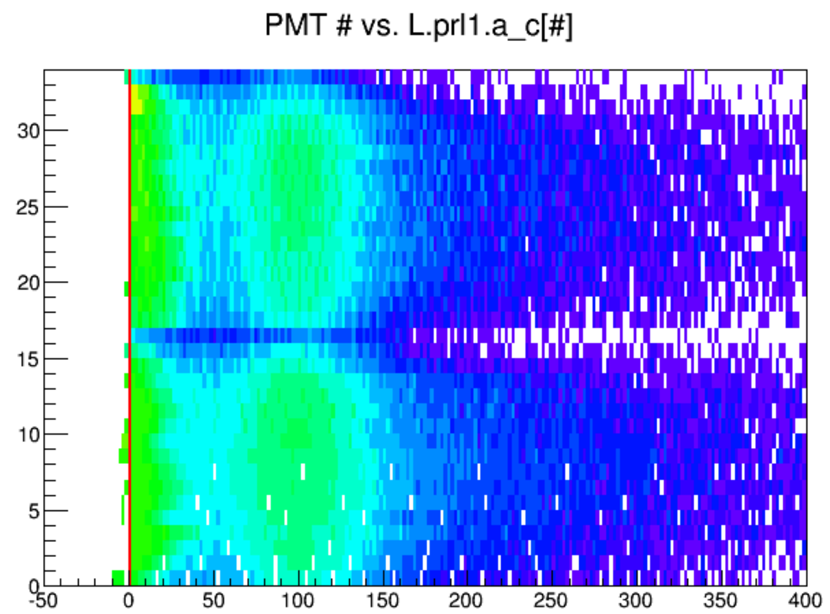
Quick Review of Completed Calibrations/Checks
(shown by Anez/Blomberg at last 2 Collab meetings)

- BCM
- BPM, Raster
- Target Corrections
- VDCs
- HRS Mispointing
- Particle ID – Pion Rejection



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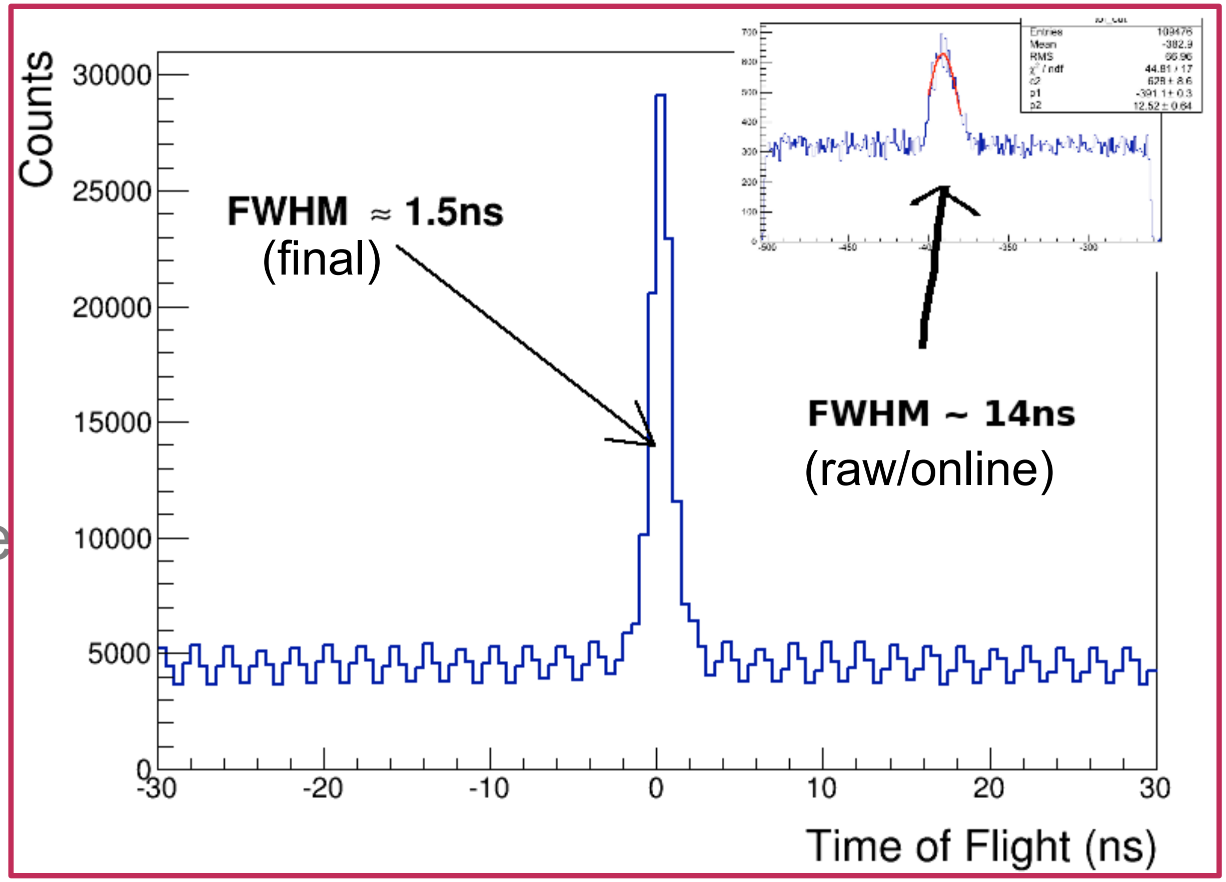
Quick Review of Completed Calibrations/Checks
(shown by Anez/Blomberg at last 2 Collab meetings)

- BCM
- BPM, Raster
- Target Corrections
- VDCs
- HRS Mispointing
- Particle ID – Pion Re
- Coincidence Timing
  - that took a lot of work ….
  - Had an annoying "double peak" problem(s): S1 miswire in LHRS, S2 miswire in RHRS (solution shown last year)
  - Plus standard offset & pathlength corrections



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Quick Review of Completed Calibrations/Checks
(shown by Anez/Blomberg at last 2 Collab meetings)

- BCM
- BPM, Raster
- Target Corrections
- VDCs
- HRS Mispointing
- Particle ID – Pion Rejection
- Coincidence Timing
- Efficiencies:
  - Live time ≈ 90%
  - Handling Multi-Hit Events: Single-track cut ≈ 70-80%
    - Multi-Track Analysis – correlate VDC tracks to S2 hits give Improved Efficiency ≈ **90-95%**

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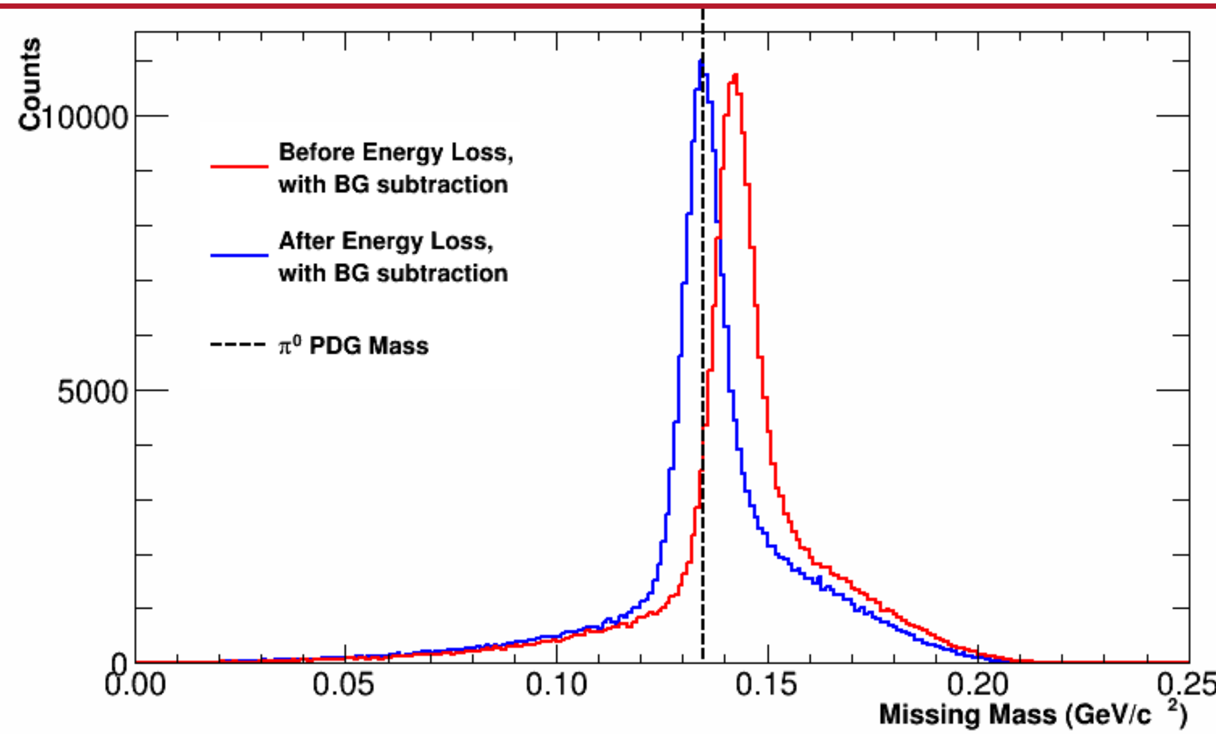
- BCM
- BPM, Raster
- Target Corrections
- VDCs
- HRS Mispointing
- Particle ID – Pion
- Coincidence Timing
- Efficiencies
- Energy-loss corrections



Background-subtracted Missing-Mass Spectrum: shows good π_0 mass obtained w/ eloss corrections

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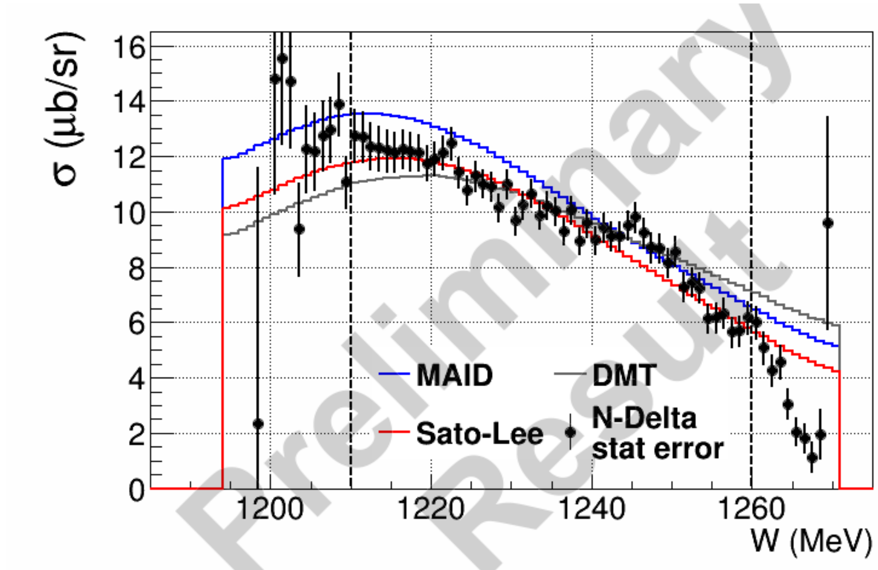
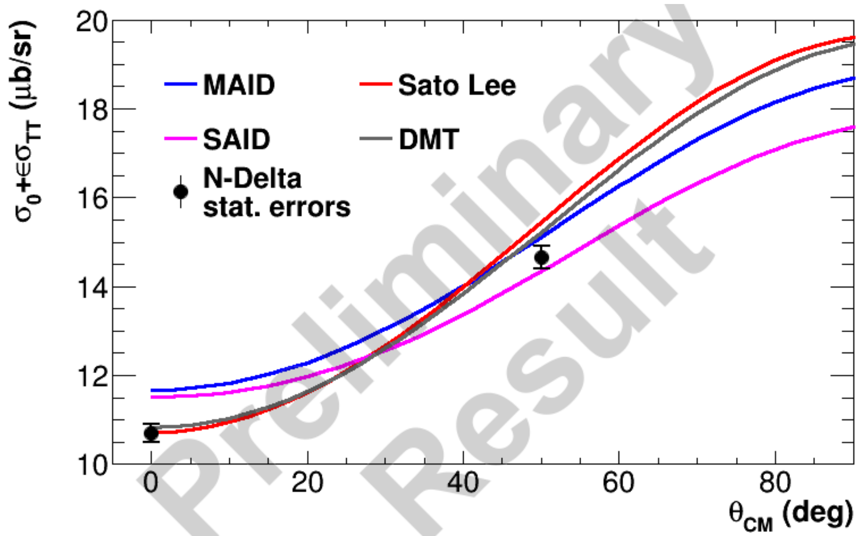
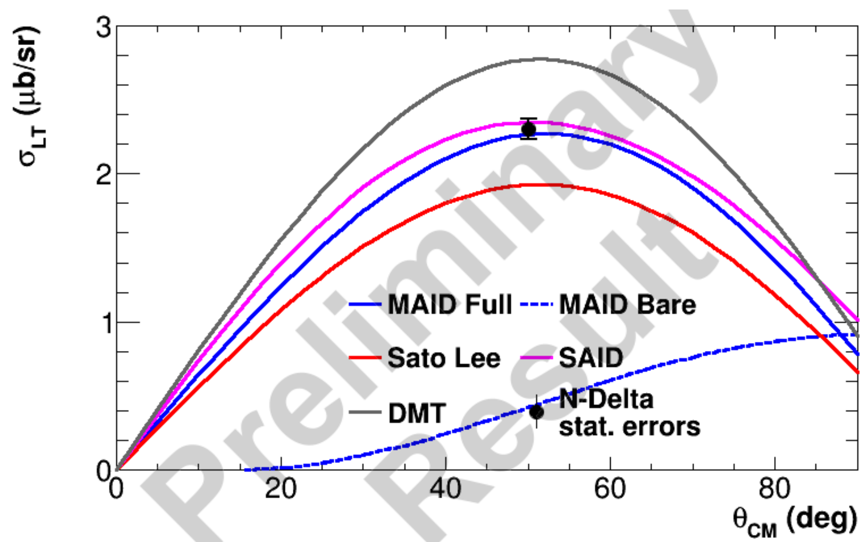
This gave us early Prelim Results
(shown by Blomberg at last June Collab meeting)

“Middle” Q^2: 0.090 $(GeV/c)^2$
(θ_{pq} = 0° and 45°)



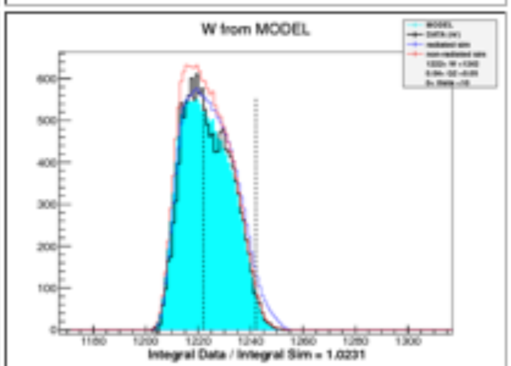
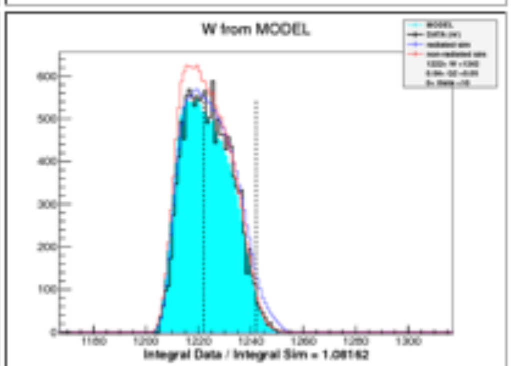




What we've been working on
(and where we are now)

- Making sure handling all Radiative Effects properly for the production data
  - using MCEEP as our simulation tool.
  - we think this is under control; last checks to ensure agreement between the 2 independent analyses when comparing radiatively-corrected distributions.

Sample (we have lots of these distributions!):

	Kinematic 1	Kinematic 1
Length:	4	4
	Run 2083	Run 2292
W		

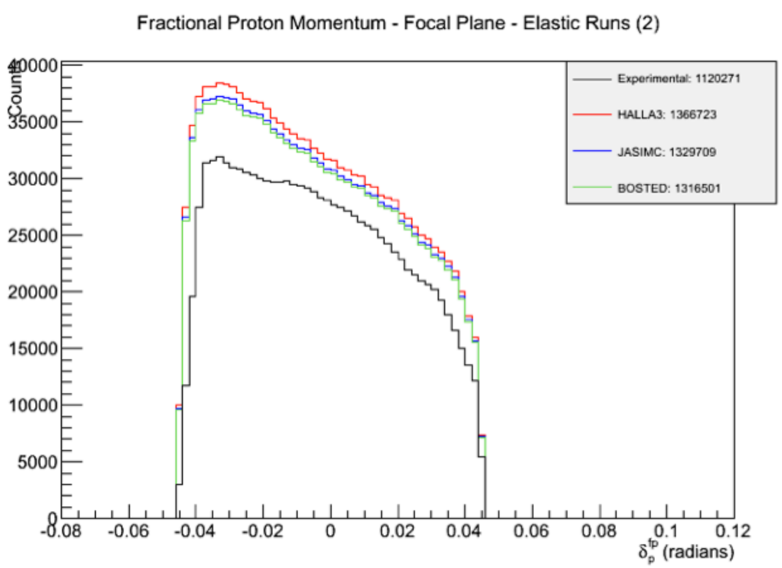
Red = MCEEP no rad
Blue = MCEEP w/ rad

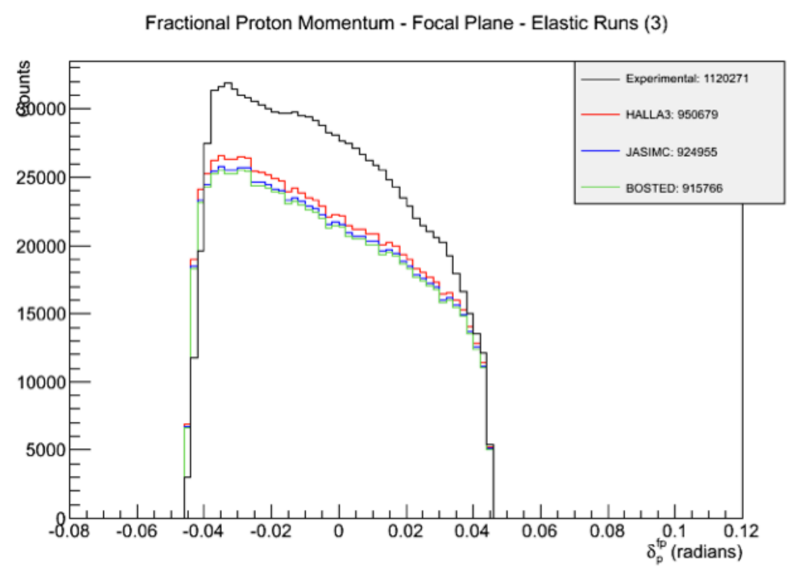
Cyan (shaded) = MCEEPed theory (no rad)

Black = rad-corrected data (data x red/blue)

What we've been working on
(and where we are now)

- CURRENT JOB (maybe the last remaining one!): Understanding our overall Normalization to H elastic data
  - need to understand handling of Radiation for elastics in MCEEP…
  - Two different radiation models available in MCEEP … one equivalent to what is used for production data (w/ multiphoton contributions), one unique to elastic (includes "full angular distribution" of radiation…)
    - We get data BELOW elastic for one rad-model, and ABOVE for the other!
    - IF ANYONE IN COLLAB HAS DONE THIS – CONTACT US ☺





CONCLUSION:

- We are converging!

- We think the elastics Normalization issue is the last remaining hurdle to overcome

- Within next 6 months, our plan:
  - Get confirmed agreement between 2 analyses – "freeze" extracted cross section results
  - Proceed to form R_{LT} response functions and extract CMR for our 3 Q^2s

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