First measurements of parity-violating excitation of the Δ and pion photoproduction

New results from G^0

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The College of WILLIAM & MARY

Jefferson Lab

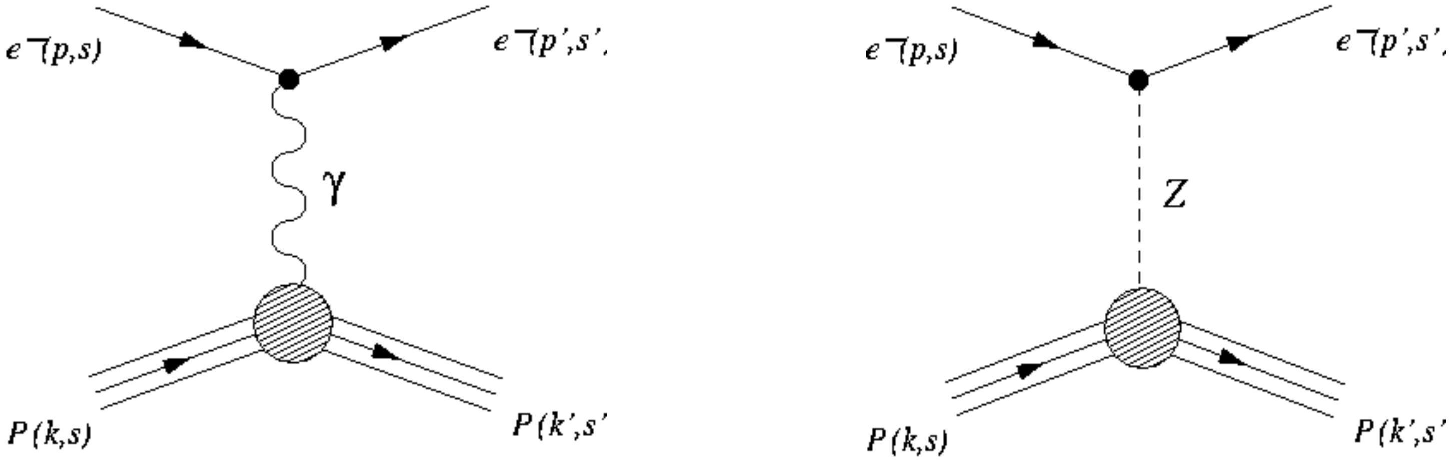
Outline

- *G^0* experiment
- Inelastic processes in parity-violating electron scattering
- Results from $\mathrm{N} \rightarrow \Delta$
- Results from (γ, π^-) on deuteron
- Interpretation

Inelastic analysis: Carissa Capuano (W&M)
Pion analysis: Alex Coppens (U.Manitoba)

Thanks to Carissa, Alex, Jeff Martin (U. Winnipeg) for figures…

Parity-Violating Electron Scattering
⇨ Weak NC Amplitudes



scatter electrons of opposite helicities from unpolarized target

Interference: $\sigma \sim |M^{EM}|^2 + |M^{NC}|^2 + 2Re(M^{EM*})M^{NC}$

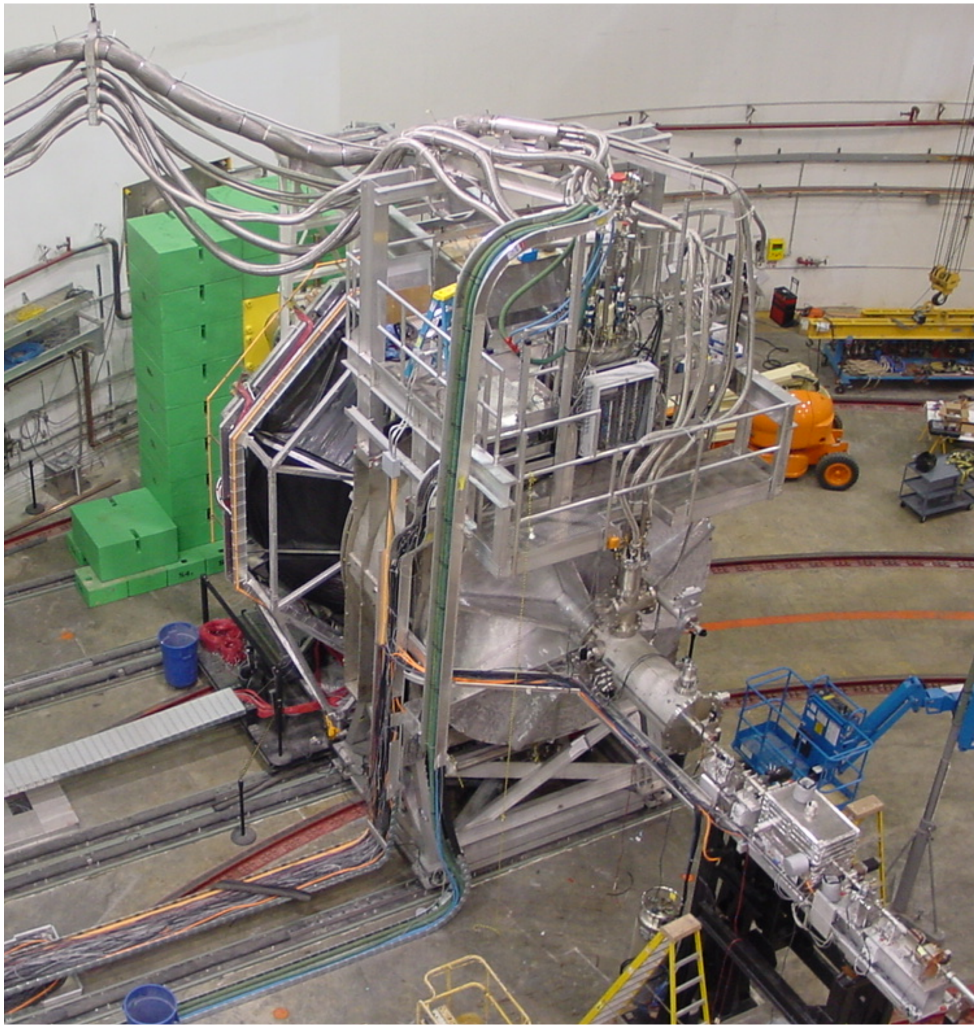
Interference with EM amplitude makes Neutral Current (NC) amplitude accessible ⇨

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{\left|M_{PV}^{NC}\right|}{\left|M^{EM}\right|} \sim \frac{Q^2}{(M_Z)^2}$$

Small ($\sim 10^{-6}$) cross section asymmetry isolates weak interaction

G^0 overview

Superconducting toroidal magnetic spectrometer – counting expt.



Forward angle mode:

LH_2: E = 3.0 GeV

Recoil proton detection

↳ $0.12 \leq Q^2 \leq 1.0$ $(GeV/c)^2$

Backward angle mode:

E = 362, 687 MeV

LH_2, LD_2 electron, pion detection

(quasi)elastic at ~108°

$Q^2 = 0.22$ GeV^2, 0.63 GeV^2

Main Goal: Strange Form Factors of Nucleon

PRL 95 (2005) 092001
PRL 104 (2010) 012001

NIM A 646 (2011) 59

G^0: Ancillary measurements

- In the backward angle mode:

  Also measured *(in parallel with elastic data)* asymmetry for inelastically scattered electrons in the Δ(1232) region (from hydrogen and deuterium targets)

  as well as π^- produced from deuterium target.

- Backgrounds for main (elastic) measurement, but have physics interest in their own right…

- Experiment was not optimized for these processes!

G^0 *N-Δ:* *Introduction*

- **First look at $G^A_{N\Delta}$ in neutral current process**
    - *$Q^2 = 0.34$ GeV/c^2.*
- **What does $G^A_{N\Delta}$ describe?**
    - $G^A(Q^2)$ → Axial elastic form factor for N
        - How is the spin distributed?
    - $G^A_{N\Delta}(Q^2)$ → Axial transition form factor for $N \rightarrow \Delta$
        - How is the spin redistributed during transition?
- **Measure Parity-violating asymmetry A_{inel}**
    - Allows a direct measure of the axial response during $N \rightarrow \Delta$
- **Accessing $G^A_{N\Delta}$:**
    - Previous Measurements: Charged current process
        - Both quark flavor change and spin flip
    - *G^0 N-Δ* Measurement: Neutral current process
        - Quark spin flip only

PV $\mathrm{N} \rightarrow \Delta$ first considered by Cahn & Gilman PRD 17(1978) 1313
…proposed as a Standard Model test!

G^0 N-Δ: Theory

$$A_{inel} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[\Delta^{\pi}_{(1)} + \Delta^{\pi}_{(2)} + \Delta^{\pi}_{(3)}\right]$$

Zhu et al. PRD 65 (2002) 033001

$$\Delta^{\pi}_{(1)} = 2(1\text{-}2\sin^2\theta_W) \approx 1$$

$$\Delta^{\pi}_{(2)} = \text{non-resonant contribution}$$

$$\Delta^{\pi}_{(3)} = 2(1\text{-}4\sin^2\theta_W)\ F(Q^2,s)$$

(resonant term)

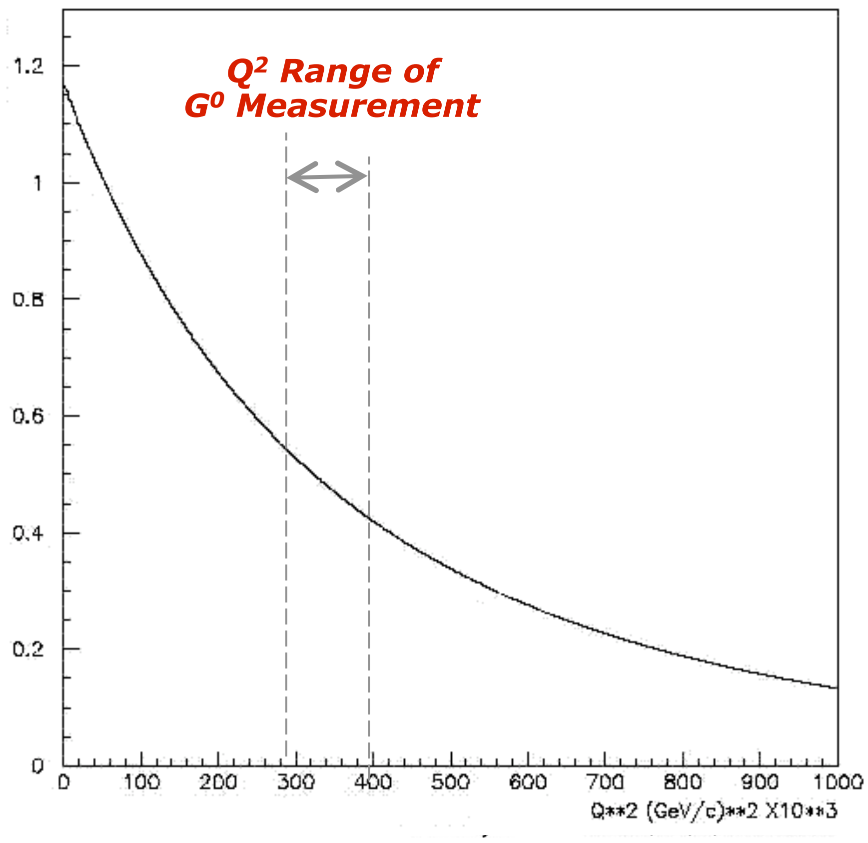
At tree-level:

$$F(Q^2, s) \rightarrow G^A_{N\Delta}(Q^2)$$

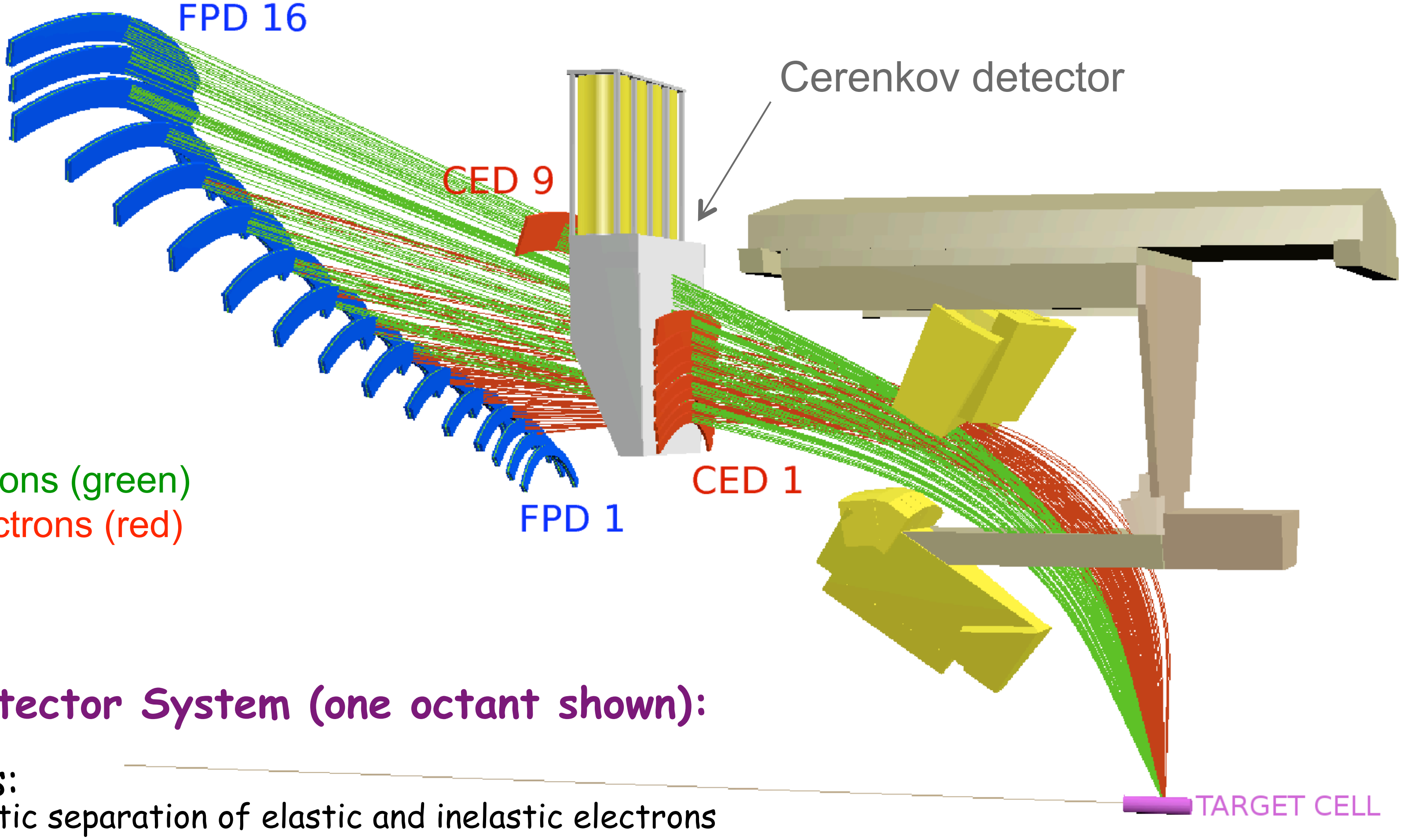
- F contains kinematic information & weak and electromagnetic transition form factors

→Extract $G^A_{N\Delta}$ from F

$G^A_{N\Delta}(Q^2)$ *vs* Q^2



G^0 Backward angle: Detectors



Detector System (one octant shown):

Scintillators:

Kinematic separation of elastic and inelastic electrons

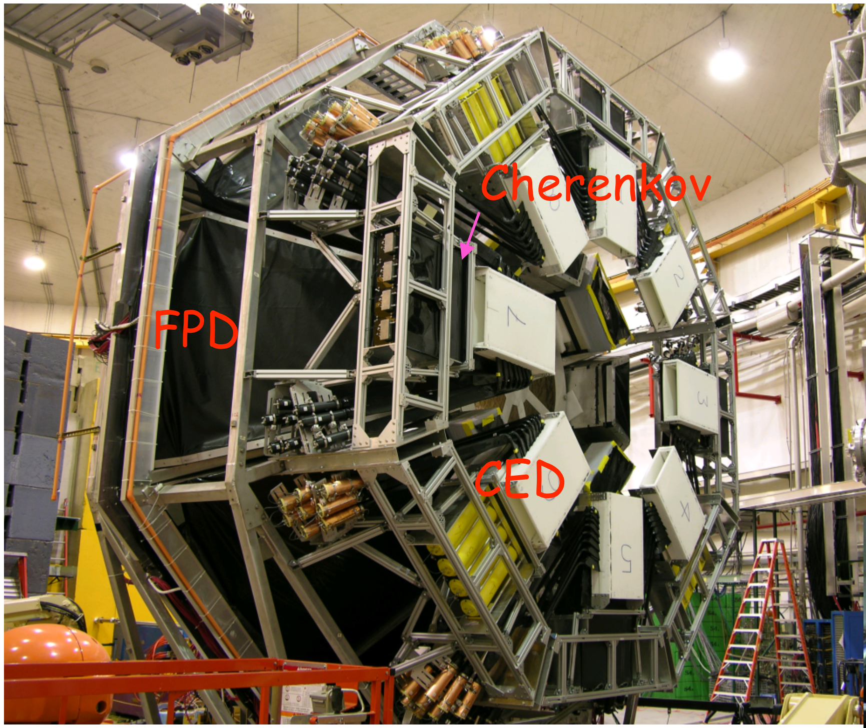
Cryostat Exit Detectors (CED)
Focal Plane Detectors (FPD)

Cerenkov Detectors :

Distinguish pions from electrons; one per octant

Coincidences send to scalers, accumulated during helicity states

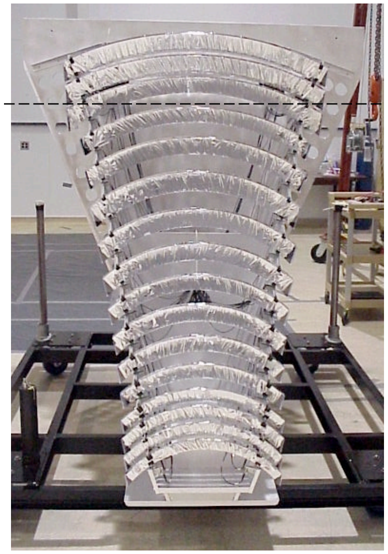
G^0 Backward angle



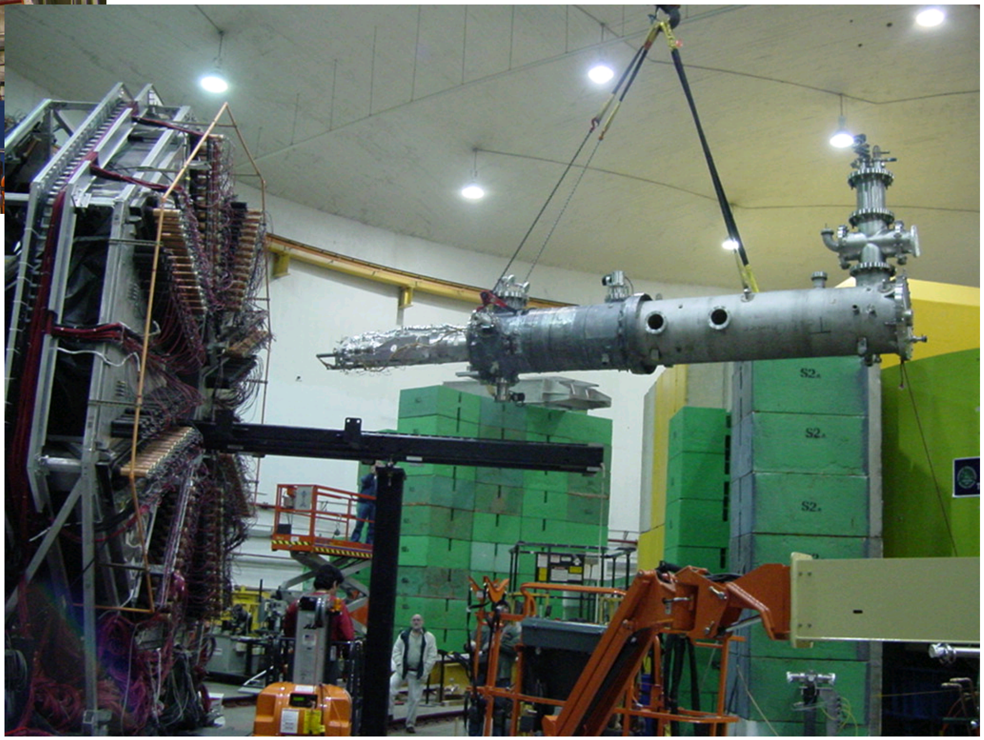
Detector package

Superconducting
Magnet

FPD (1 octant)

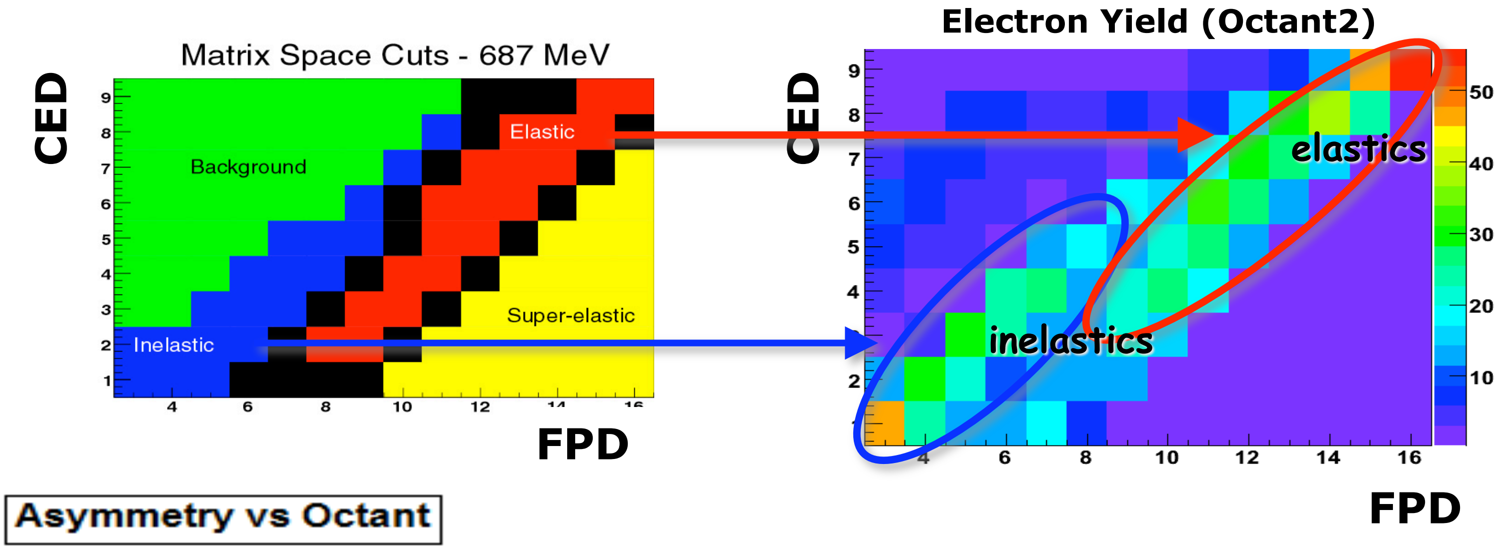


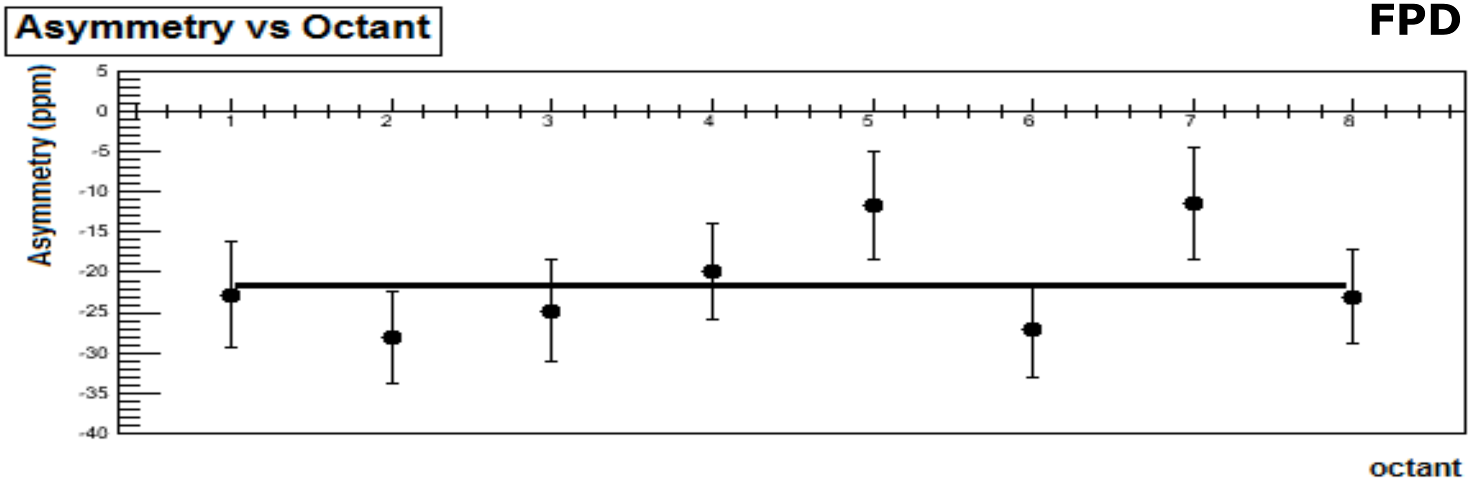
Target system installation



G^0 N-Δ: Data

LH_2

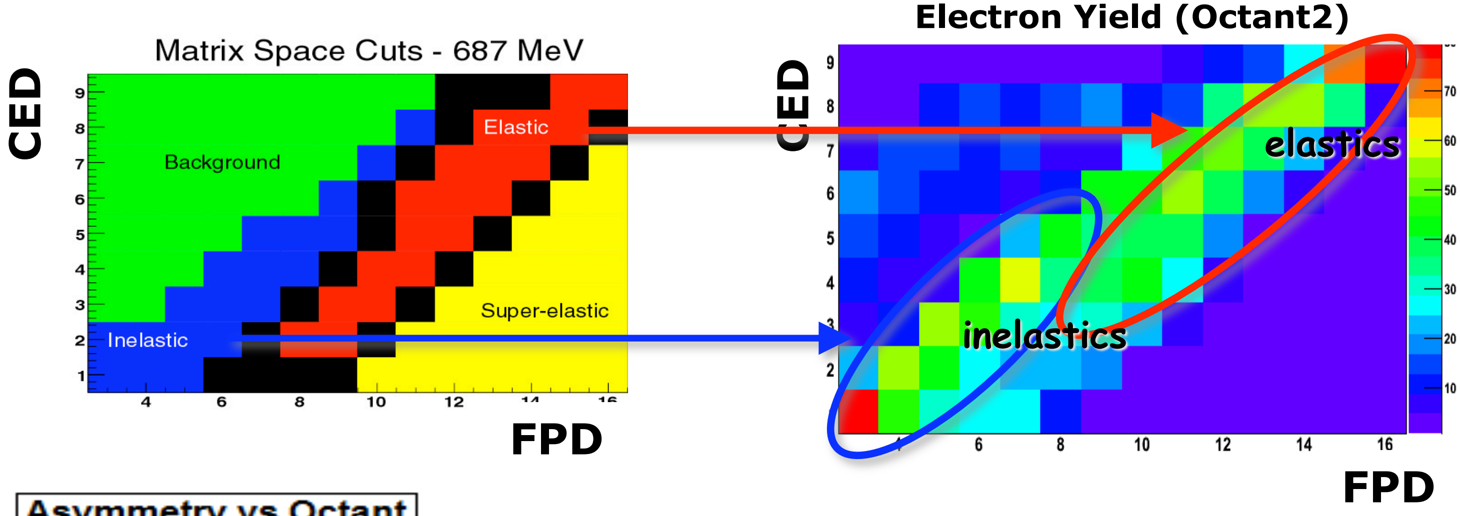




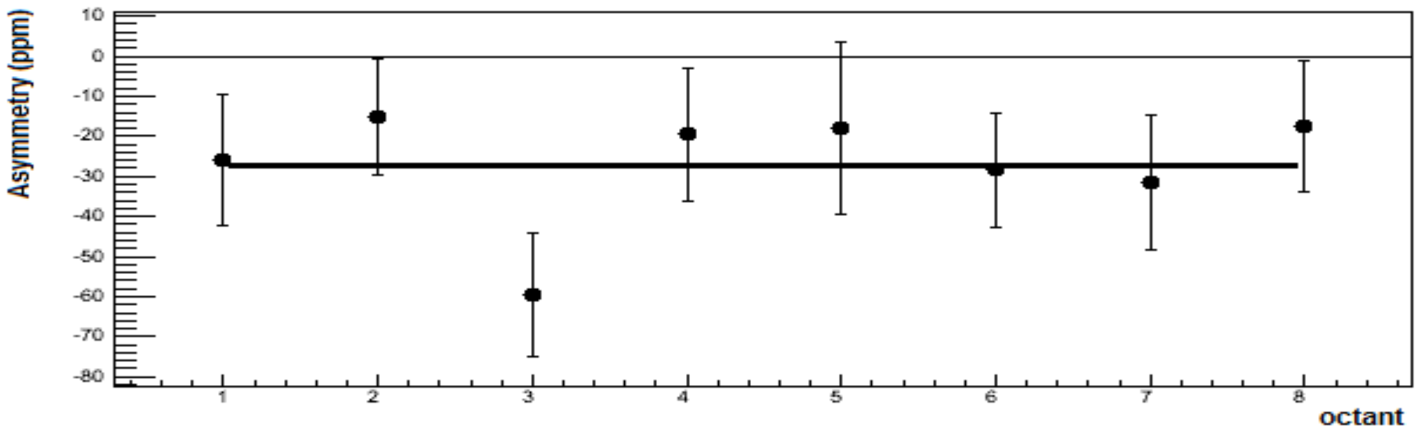
A_{meas} = -22.3 ± 2.2 (stat) ppm (before background correction)

G^0 N-Δ: Data

LD$_2$



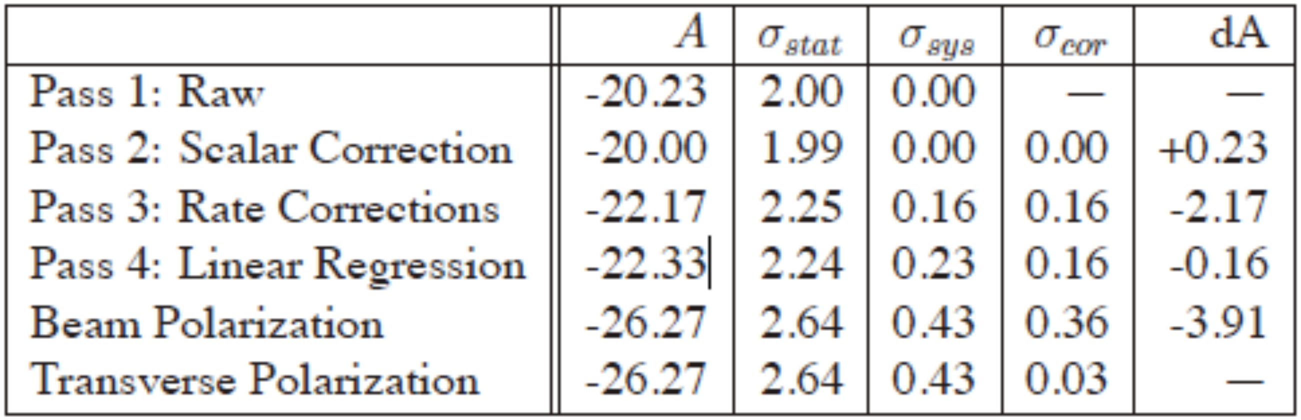
Asymmetry vs Octant



$A_{meas} = -26.4 \pm 5.9$ *(stat) ppm (before background correction)*

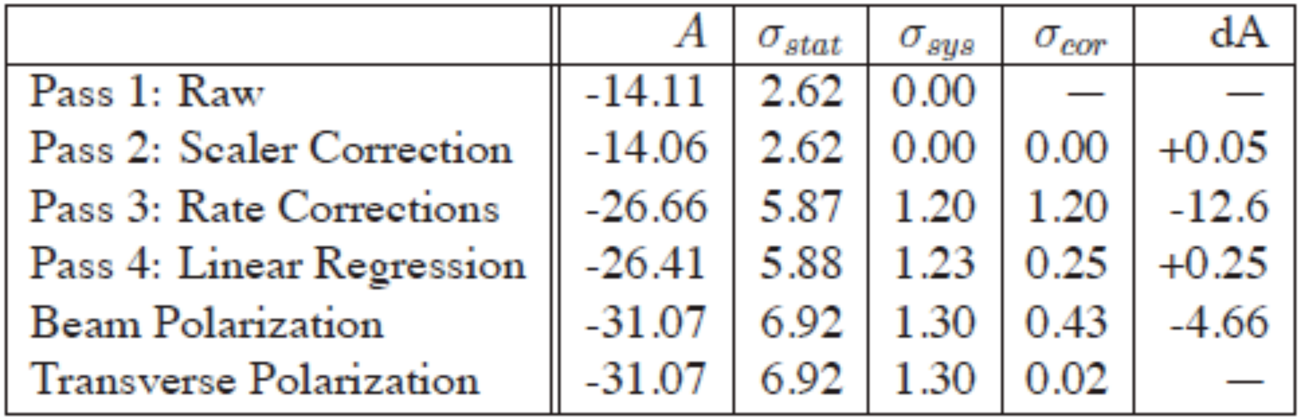
G^0 N-Δ: Corrections (all except backgrounds)

A_{inel} for H 687MeV



	A	σ_{stat}	σ_{sys}	σ_{cor}	dA
Pass 1: Raw	-20.23	2.00	0.00	—	—
Pass 2: Scalar Correction	-20.00	1.99	0.00	0.00	+0.23
Pass 3: Rate Corrections	-22.17	2.25	0.16	0.16	-2.17
Pass 4: Linear Regression	-22.33	2.24	0.23	0.16	-0.16
Beam Polarization	-26.27	2.64	0.43	0.36	-3.91
Transverse Polarization	-26.27	2.64	0.43	0.03	—

A_{inel} for D 687MeV



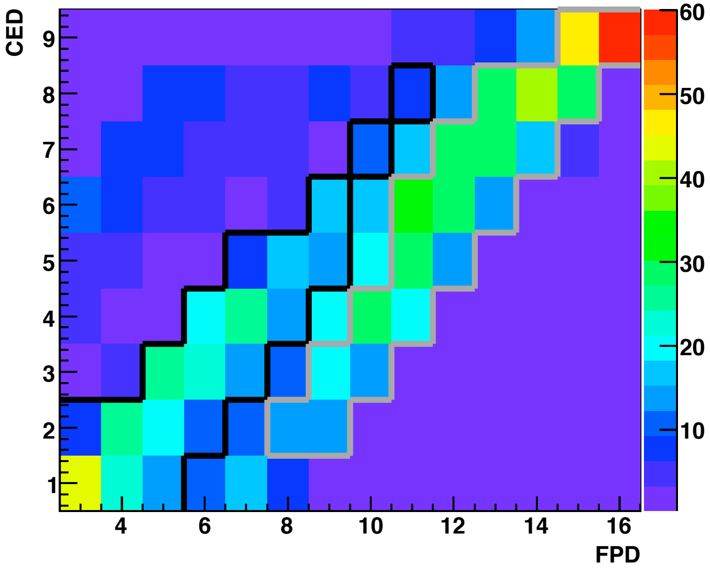
	A	σ_{stat}	σ_{sys}	σ_{cor}	dA
Pass 1: Raw	-14.11	2.62	0.00	—	—
Pass 2: Scaler Correction	-14.06	2.62	0.00	0.00	+0.05
Pass 3: Rate Corrections	-26.66	5.87	1.20	1.20	-12.6
Pass 4: Linear Regression	-26.41	5.88	1.23	0.25	+0.25
Beam Polarization	-31.07	6.92	1.30	0.43	-4.66
Transverse Polarization	-31.07	6.92	1.30	0.02	—

All values in ppm

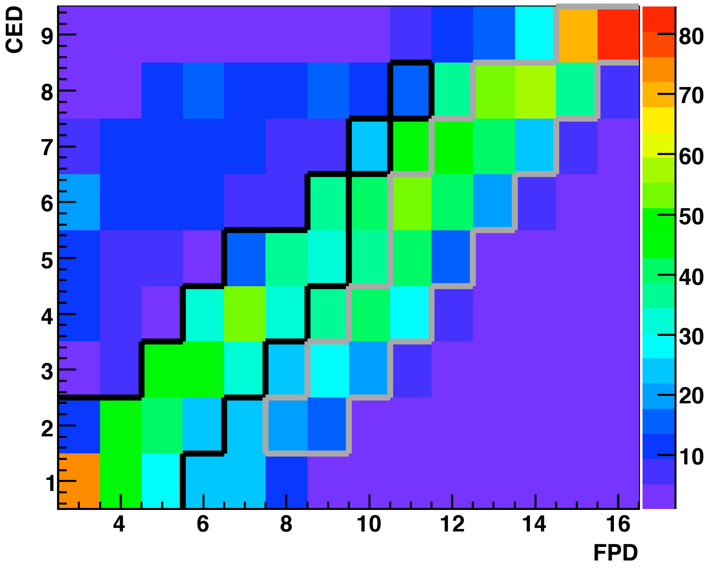
Corrections well understood, statistical error dominates

G^0 N-Δ: Inelastic locus

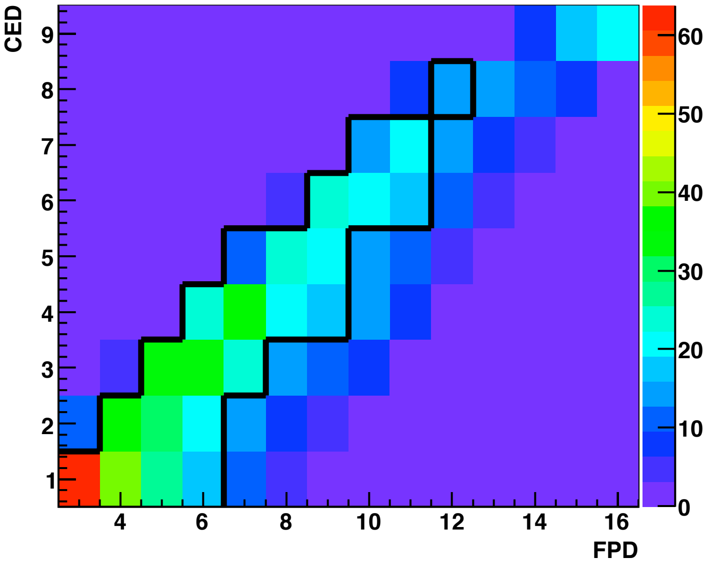
H 687 Oct Avg Electron Yield (Hz/μA)

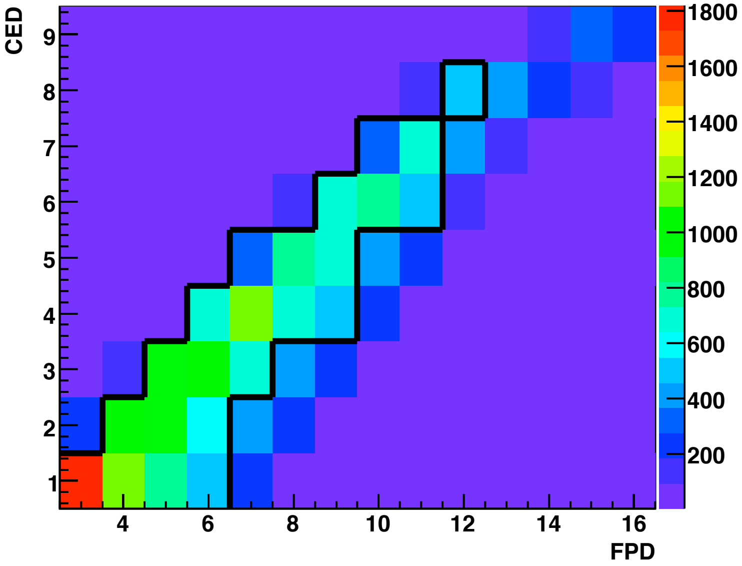


D 687 Oct Avg Electron Yield (Hz/μA)



G^0 N-Δ: Pion locus


H 687 Oct Avg Pion Yield (Hz/μA)


D 687 Oct Avg Pion Yield (Hz/μA)

Misidentified pions a significant background

G^0 N-Δ: Background Correction

- **Correcting the Asymmetry:**
  - Extract A_{inel} from A_{meas} by subtracting backgrounds:

$$A_{inel} = \frac{A_{meas} - \sum f_i^{bg} A_i^{bg}}{1 - \sum f_i^{bg}}$$

- **Backgrounds:**
  - Electrons scattered elastically from target
  - Electrons scattered from Al target walls
  - Electrons from π^0 decay
  - Misidentified π^-

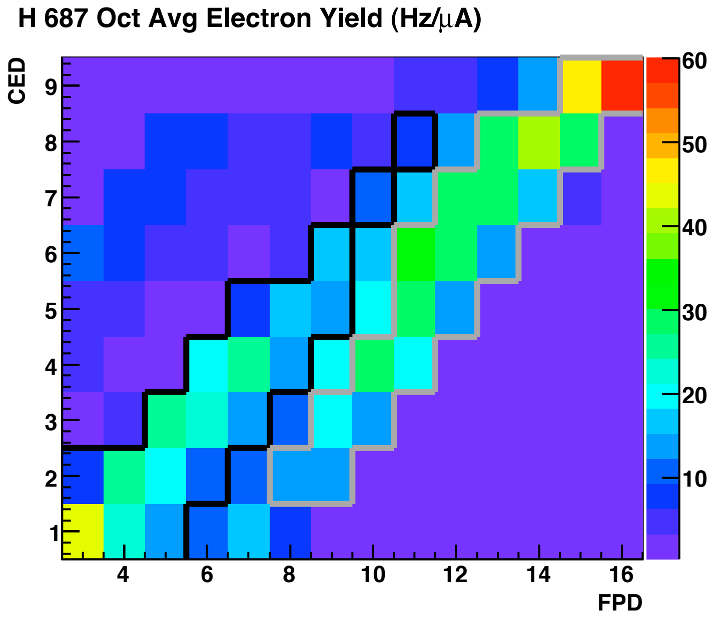
- **Background Asymmetries:**
  - Background from Al target walls: *Dominated by inelastics*
    - Inelastic Al asymmetry unmeasured -> use D asymmetry
  - Pion contamination:
    - Negligible in H target, but significant for D; use direct pion measurement
  - Elastic contribution:
    - Mostly comes from radiative tail: use elastic data & simulation to extrapolate

G^0 N-Δ: Background Dilutions

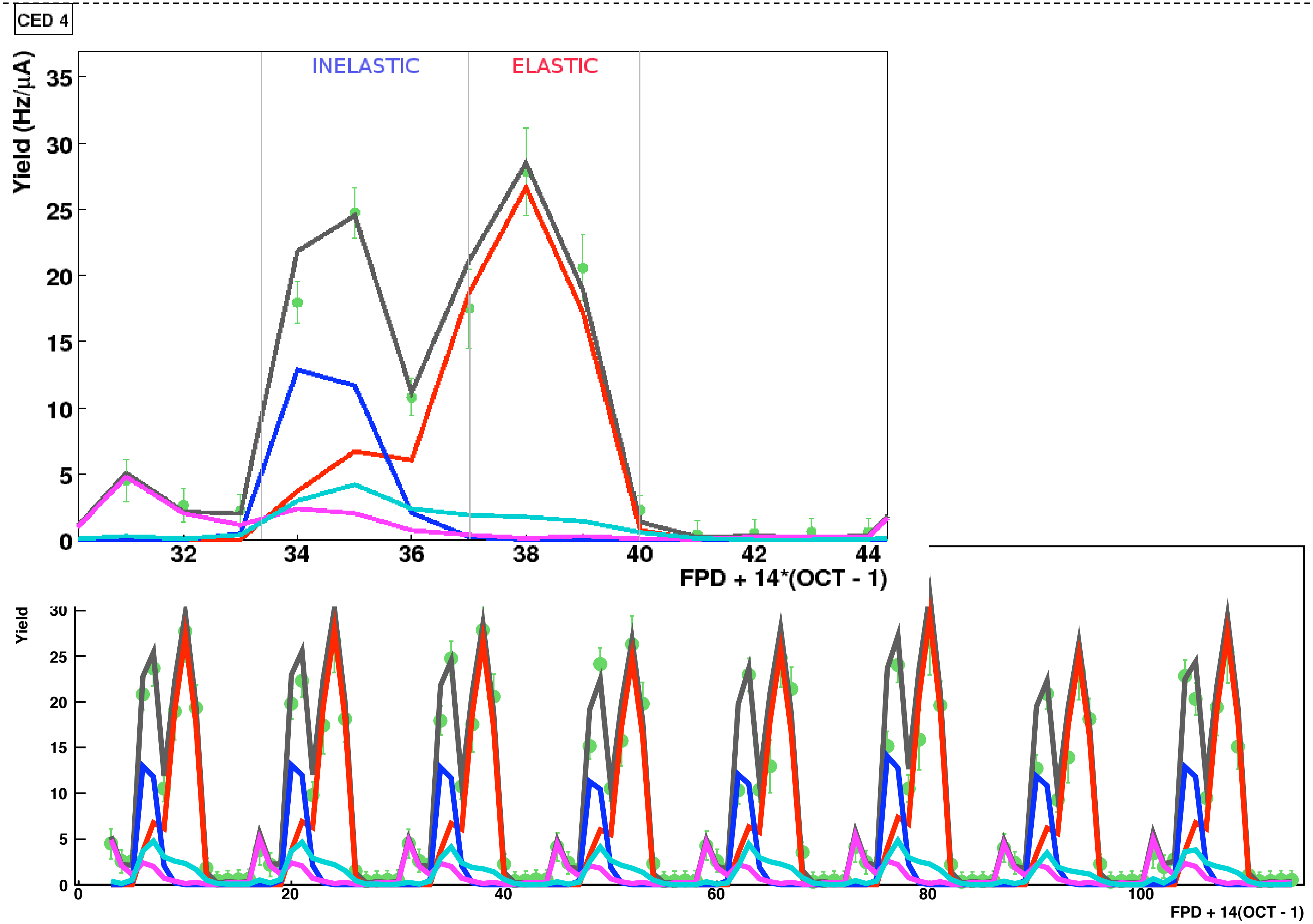
- **Scale Yield vs. FPD for each CED**
  - Before fitting, subtract π^- contamination and Al target-wall yield

    Target wall yield: use separate low-density Gas target measurement;
    scale to remove gas contribution & account for kinematic differences
    between liquid and gas target

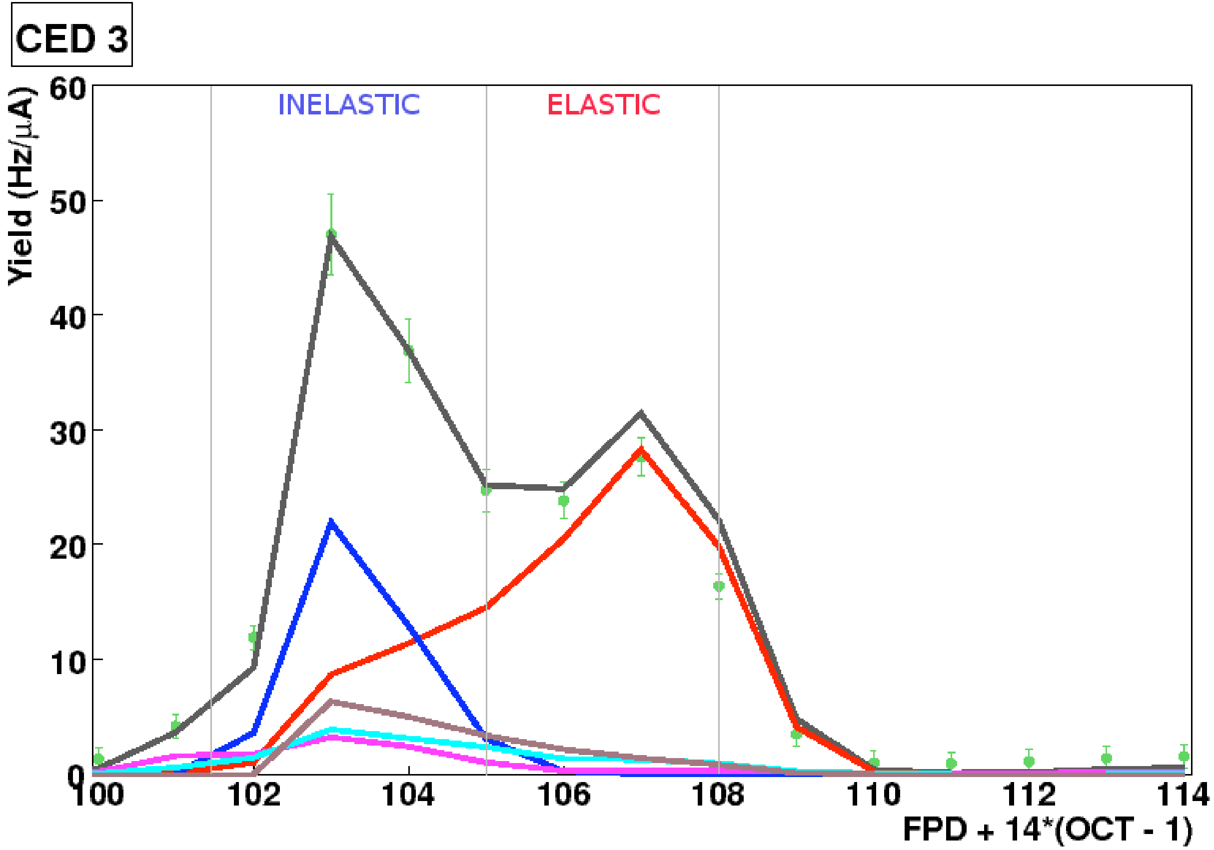
  - Scale the remaining contributions independently to fit the data
  - Require scale factors to vary smoothly across CEDs
  - Constrain scale factors same for all octants

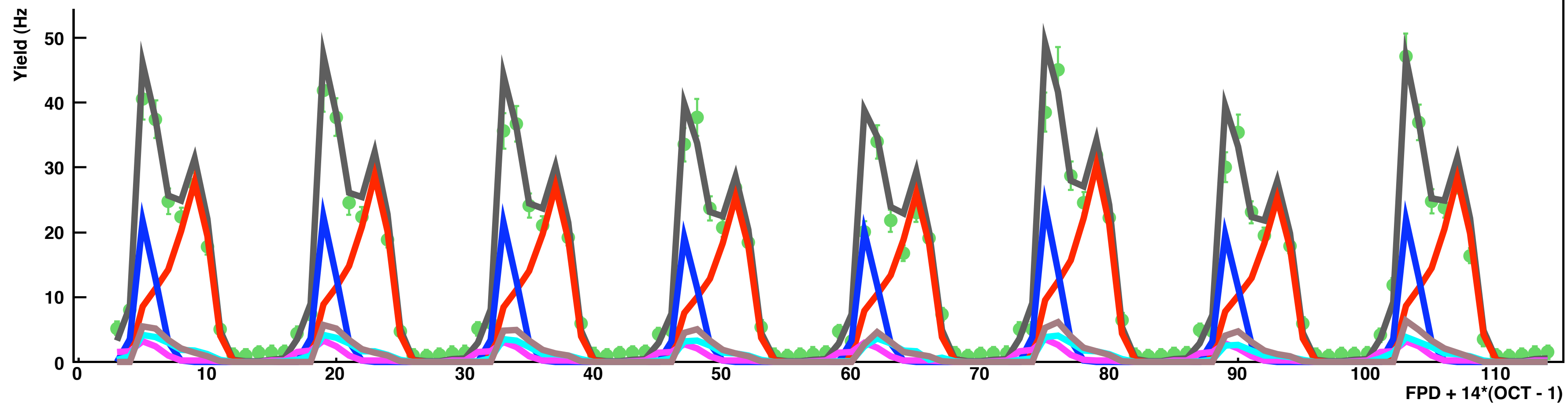


G^0 N-Δ: **Background Dilutions LH2**

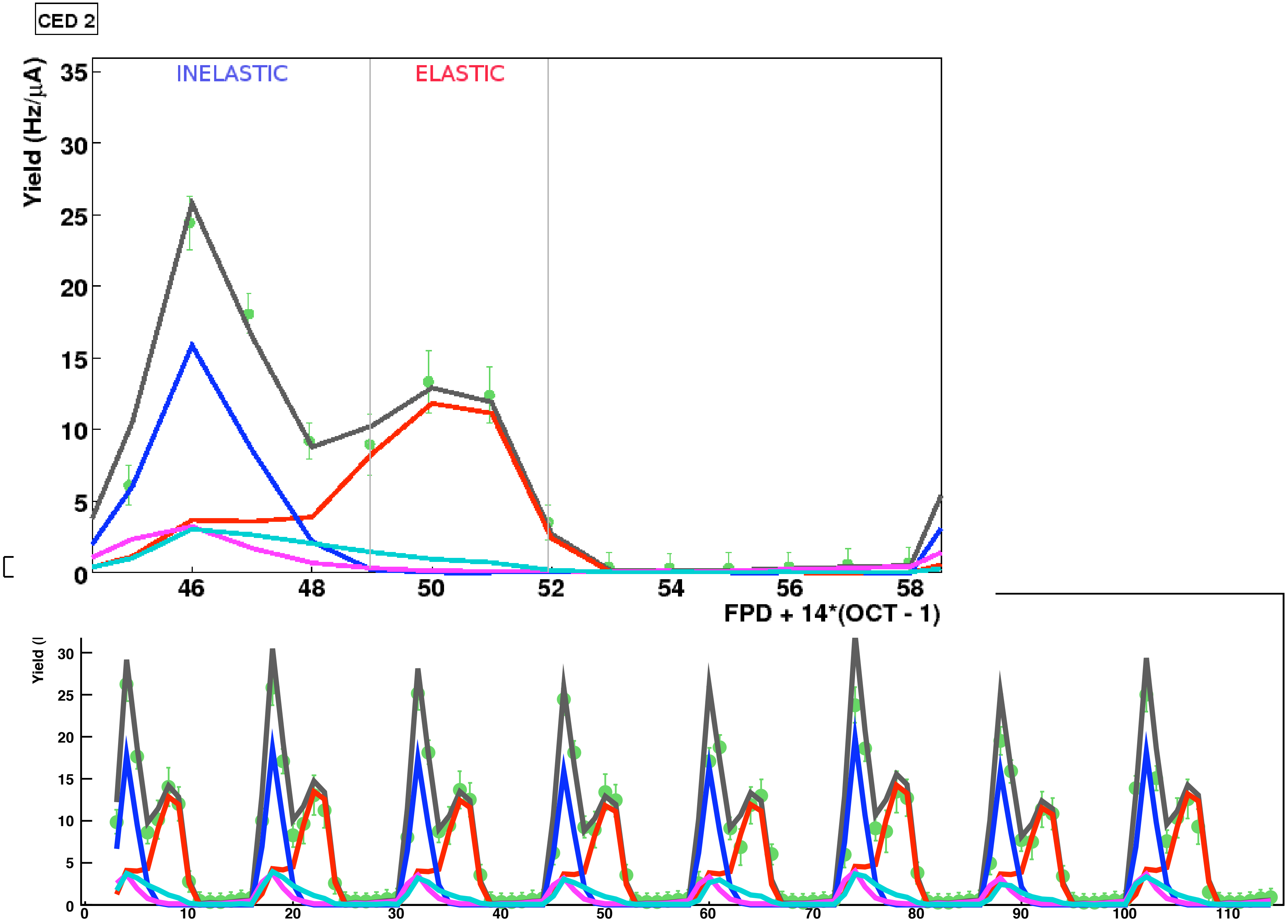


G^0 N-Δ: Background Dilutions LH2

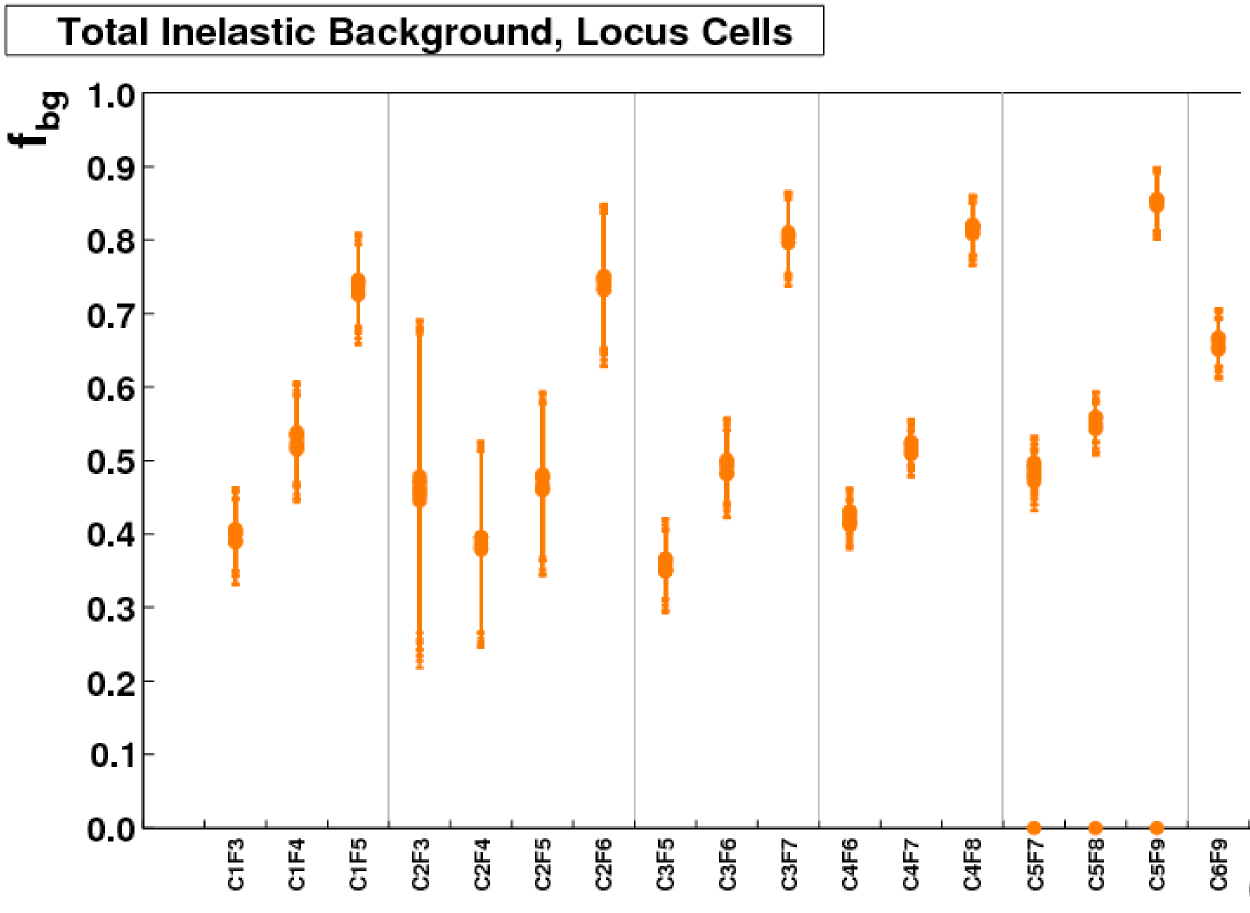


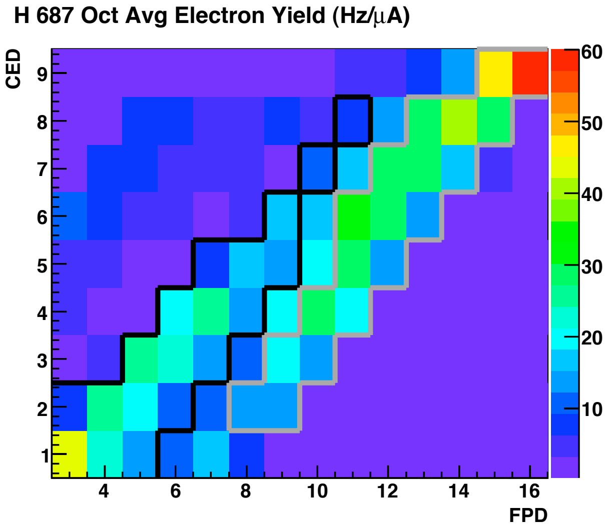


G^0 N-Δ: Background Dilutions LD2



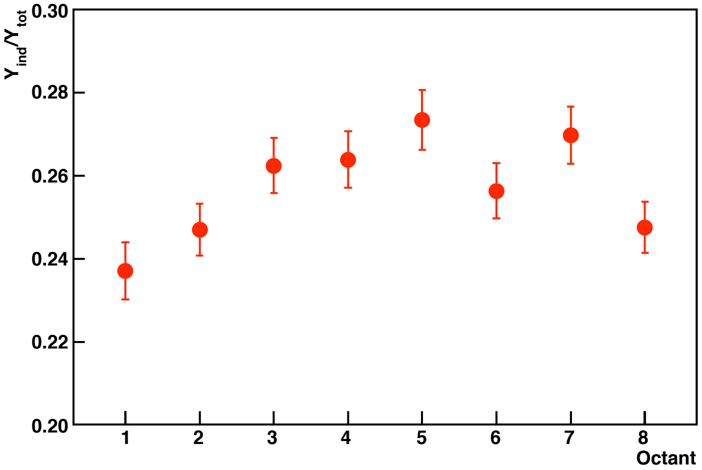
G^0 *N-Δ:* **Background Dilutions** *(by cell)*

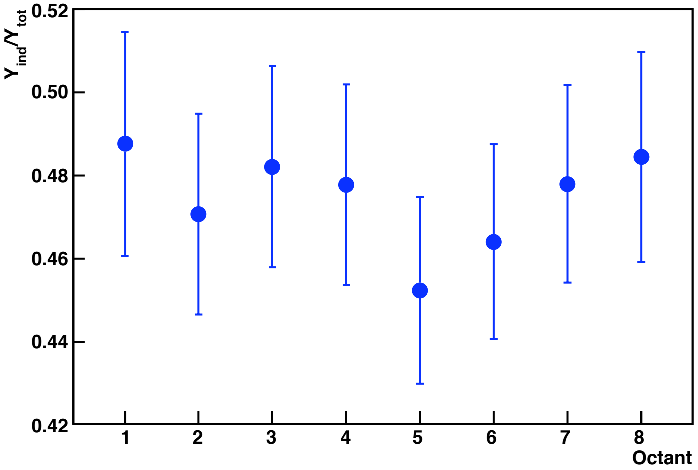


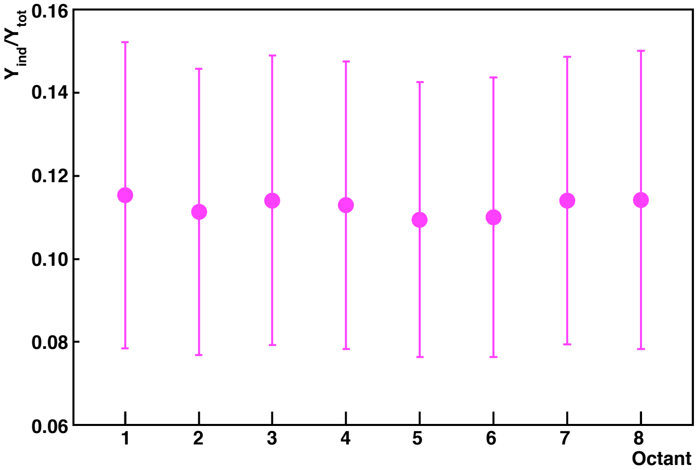


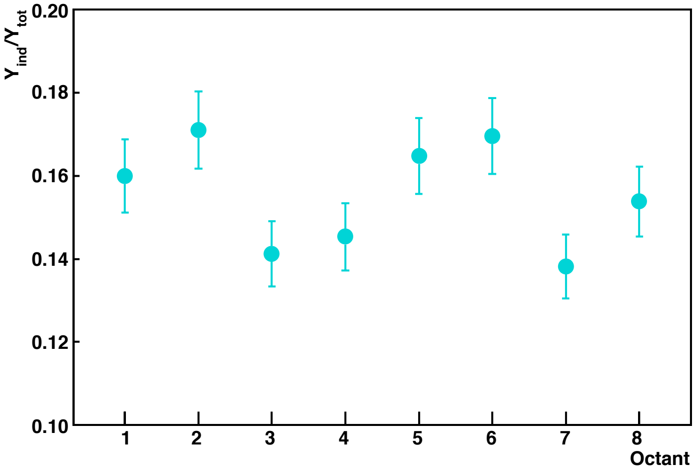
For each cell, all octants separately plotted

G^0 N-Δ: Background Dilutions (by octant)

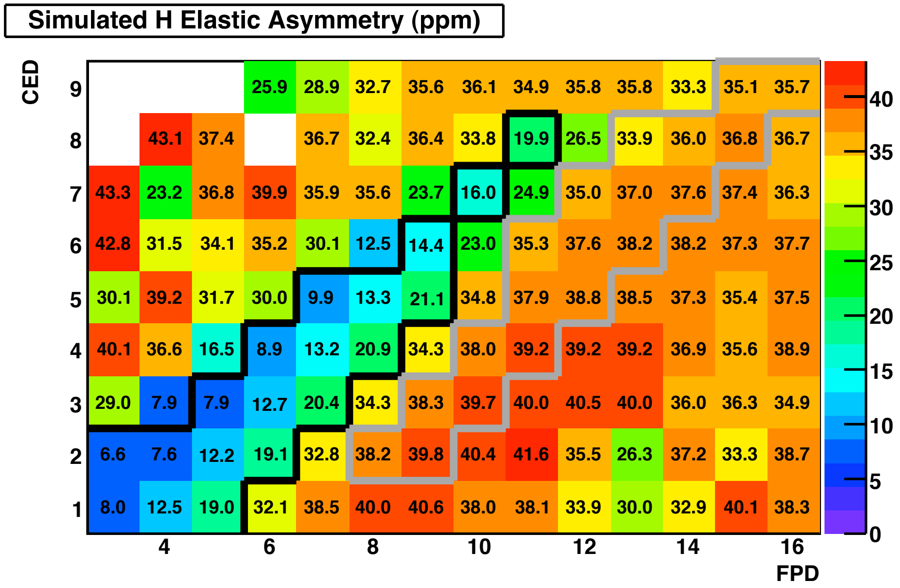

Inelastic Locus: Elastic Contribution


Inelastic Locus: Inelastic Contribution


Inelastic Locus: π^0 decay Contribution

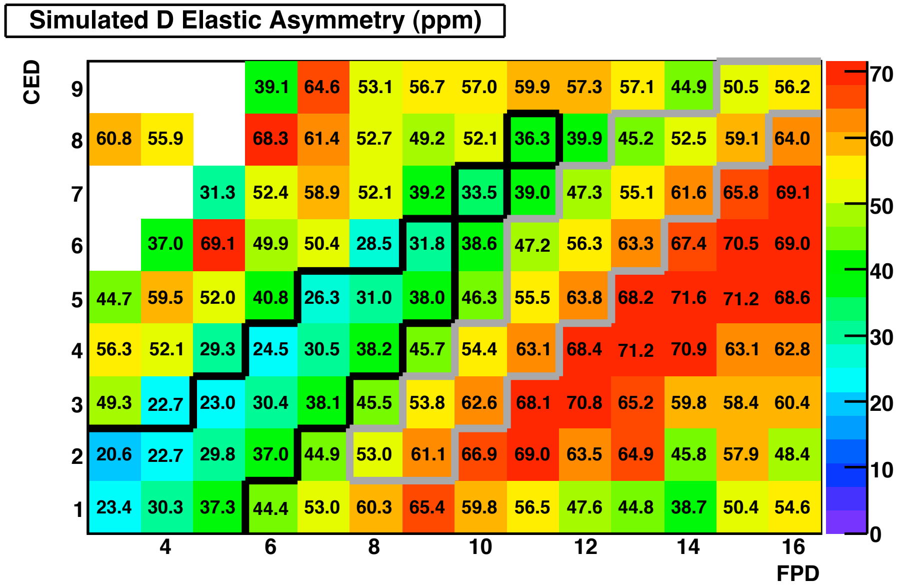

Inelastic Locus: Empty Target Contribution

G^0 N-Δ: Elastic Radiative Tail



Simulated H Elastic Asymmetry (ppm)

CED		4		6		8		10		12		14		16
9				25.9	28.9	32.7	35.6	36.1	34.9	35.8	35.8	33.3	35.1	35.7
8		43.1	37.4		36.7	32.4	36.4	33.8	19.9	26.5	33.9	36.0	36.8	36.7
7	43.3	23.2	36.8	39.9	35.9	35.6	23.7	16.0	24.9	35.0	37.0	37.6	37.4	36.3
6	42.8	31.5	34.1	35.2	30.1	12.5	14.4	23.0	35.3	37.6	38.2	38.2	37.3	37.7
5	30.1	39.2	31.7	30.0	9.9	13.3	21.1	34.8	37.9	38.8	38.5	37.3	35.4	37.5
4	40.1	36.6	16.5	8.9	13.2	20.9	34.3	38.0	39.2	39.2	39.2	36.9	35.6	38.9
3	29.0	7.9	7.9	12.7	20.4	34.3	38.3	39.7	40.0	40.5	40.0	36.0	36.3	34.9
2	6.6	7.6	12.2	19.1	32.8	38.2	39.8	40.4	41.6	35.5	26.3	37.2	33.3	38.7
1	8.0	12.5	19.0	32.1	38.5	40.0	40.6	38.0	38.1	33.9	30.0	32.9	40.1	38.3



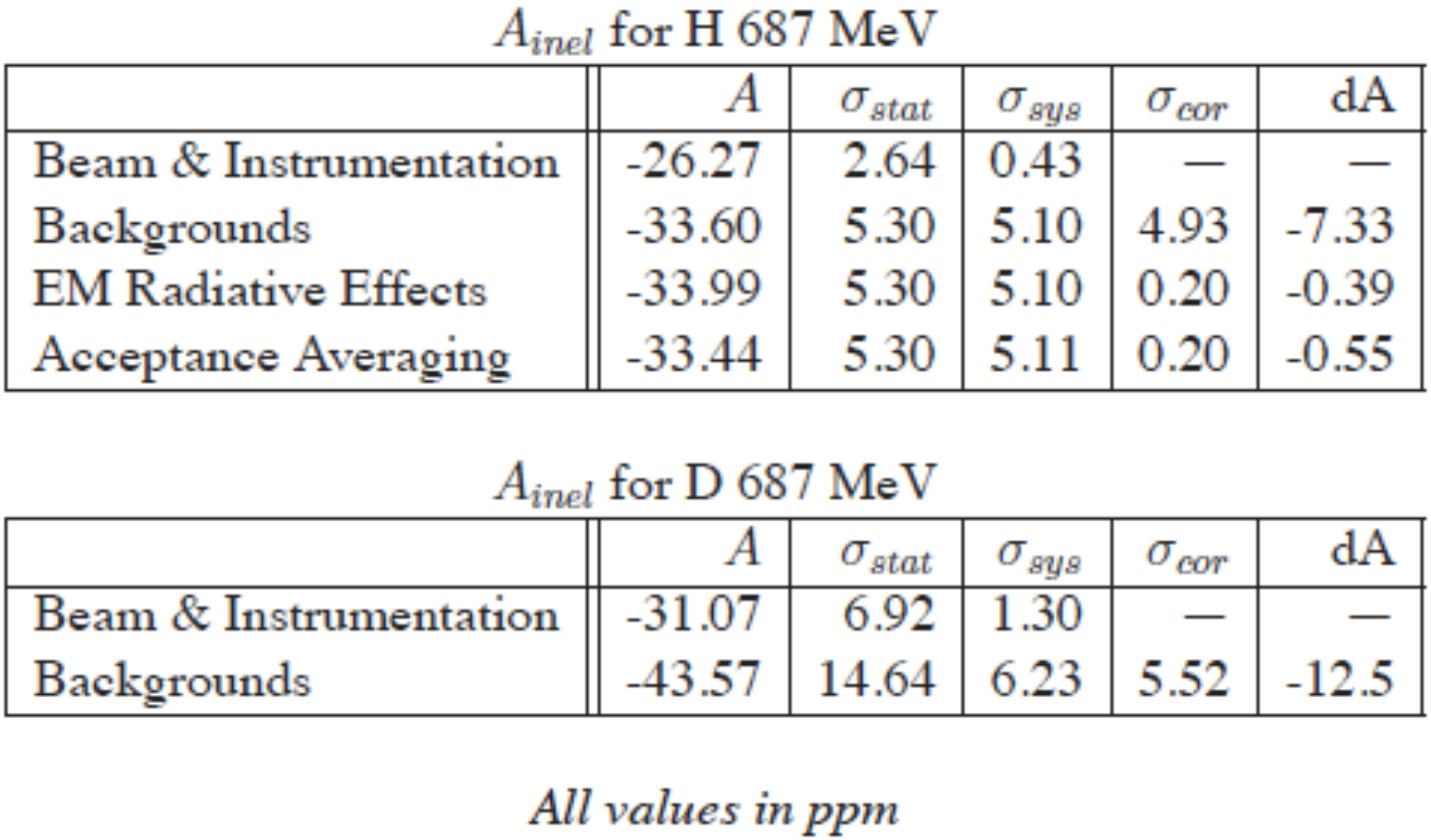
Simulated D Elastic Asymmetry (ppm)

CED		4		6		8		10		12		14		16
9				39.1	64.6	53.1	56.7	57.0	59.9	57.3	57.1	44.9	50.5	56.2
8	60.8	55.9		68.3	61.4	52.7	49.2	52.1	36.3	39.9	45.2	52.5	59.1	64.0
7			31.3	52.4	58.9	52.1	39.2	33.5	39.0	47.3	55.1	61.6	65.8	69.1
6		37.0	69.1	49.9	50.4	28.5	31.8	38.6	47.2	56.3	63.3	67.4	70.5	69.0
5	44.7	59.5	52.0	40.8	26.3	31.0	38.0	46.3	55.5	63.8	68.2	71.6	71.2	68.6
4	56.3	52.1	29.3	24.5	30.5	38.2	45.7	54.4	63.1	68.4	71.2	70.9	63.1	62.8
3	49.3	22.7	23.0	30.4	38.1	45.5	53.8	62.6	68.1	70.8	65.2	59.8	58.4	60.4
2	20.6	22.7	29.8	37.0	44.9	53.0	61.1	66.9	69.0	63.5	64.9	45.8	57.9	48.4
1	23.4	30.3	37.3	44.4	53.0	60.3	65.4	59.8	56.5	47.6	44.8	38.7	50.4	54.6

Asymmetry of elastic radiative tail varies strongly over inelastic region.

Use GEANT 3, scaled to our own *elastic* backward angle results, make cell-by-cell correction.

G^0 N-Δ: Result



A_{inel} for H 687 MeV

	A	σ_{stat}	σ_{sys}	σ_{cor}	dA
Beam & Instrumentation	-26.27	2.64	0.43	—	—
Backgrounds	-33.60	5.30	5.10	4.93	-7.33
EM Radiative Effects	-33.99	5.30	5.10	0.20	-0.39
Acceptance Averaging	-33.44	5.30	5.11	0.20	-0.55

A_{inel} for D 687 MeV

	A	σ_{stat}	σ_{sys}	σ_{cor}	dA
Beam & Instrumentation	-31.07	6.92	1.30	—	—
Backgrounds	-43.57	14.64	6.23	5.52	-12.5

All values in ppm

Acceptance Averaging: $\langle A(Q^2, W)\rangle \rightarrow A(\langle Q^2\rangle, \langle W\rangle)$

G^0: Axial radiative corrections

Axial radiative corrections can be large and uncertain…

S.L. Zhu, C.M. Maekawa, B.R. Holstein & M.J. Ramsey-Musolf PRL **87** (2001)20180,2
S.L. Zhu, *et al.* PRD **65** (2002) 033001

Found in particular: "many-quark" axial r.c. leads to new PV $\gamma N\Delta$ coupling d_Δ^-

$$A_\gamma^- \equiv \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = -\frac{2d_\Delta^-}{C_3^V}\frac{M_N}{\Lambda_\chi}$$

Inelastic asymmetry does not vanish at $Q^2=0$!

"Natural" scale $d_\Delta^\pm \sim g_\pi$

Enhancement mechanism proposed: $|d_\Delta^\pm| = 25g_\pi$ (or larger)
would help solve puzzle of large asymmetries in Hyperon radiative decays

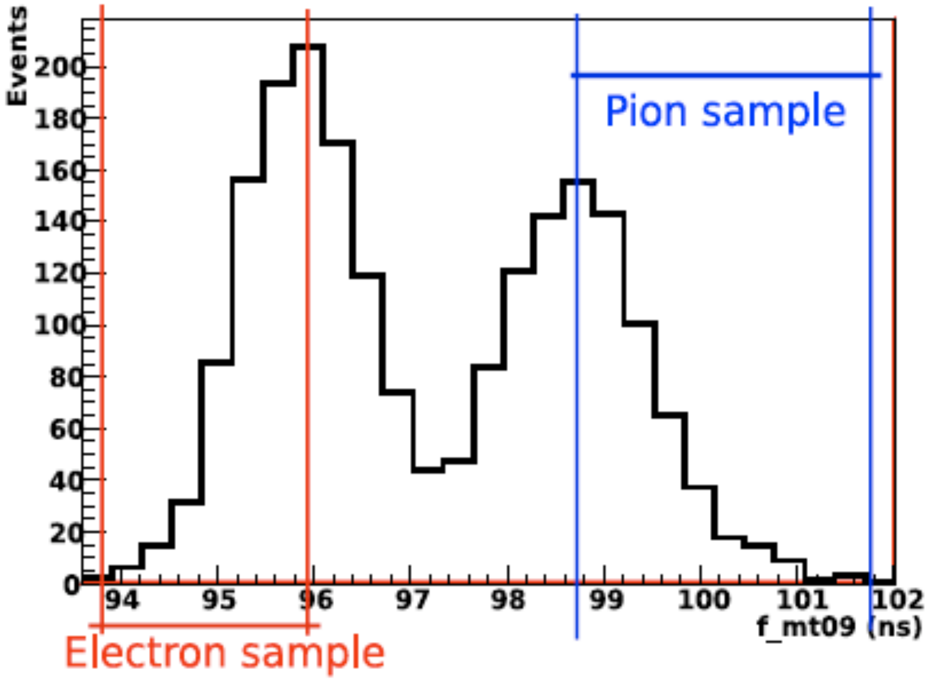
Enhanced values would lead to measurable (few ppm) asymmetries in (γ,π^-)

Would confuse extraction of $G^A_{N\Delta}(Q^2)$ from inelastic data

G^0: *Pion photoproduction*

362 MeV LD2 data

Misidentified electrons a background:
Use TOF spectra from pulsed-beam runs to determine Cerenkov detector inefficiency ➔ 2.6% background.

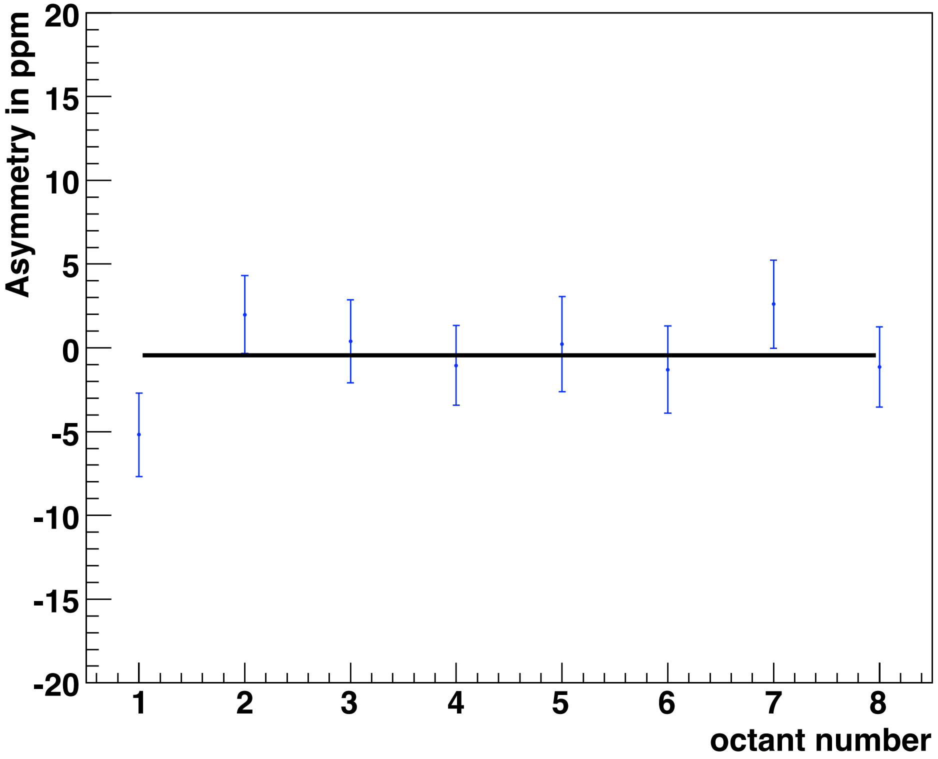


Target wall background: 2%

Corrections for:
- rate-effects
- polarization,
- helicity-correlated beam properties

➔ under good control

G^0: *Pion photoproduction:*



Correct for electroproduction (average $Q^2 = 0.0032\ \mathrm{GeV}^2$) using GEANT 3 simulation

Result: $A^-_\gamma = -(0.36 \pm 1.1 \pm 0.4)$ ppm

Implies: $d_\Delta^- = (8.4 \pm 24 \pm 8.3)\, g_\pi$

Will neglect this contribution in the following…

G^0 N-Δ: Models ($\Delta_{(2)}$ and $\Delta_{(3)}$)

1) "Default" model:

- MAID for $\Delta_{(2)}$
- use dipole form for $G^A_{N\Delta}(Q^2)$ with M_A = 1.03 GeV
- $F(Q^2)$ from Adler parameterization (S.L. Adler PRD **12**(1975)2644)
  parameters from N. Mukhopadhyay et al. (Nucl. Phys. A **633**(1998) 481.)

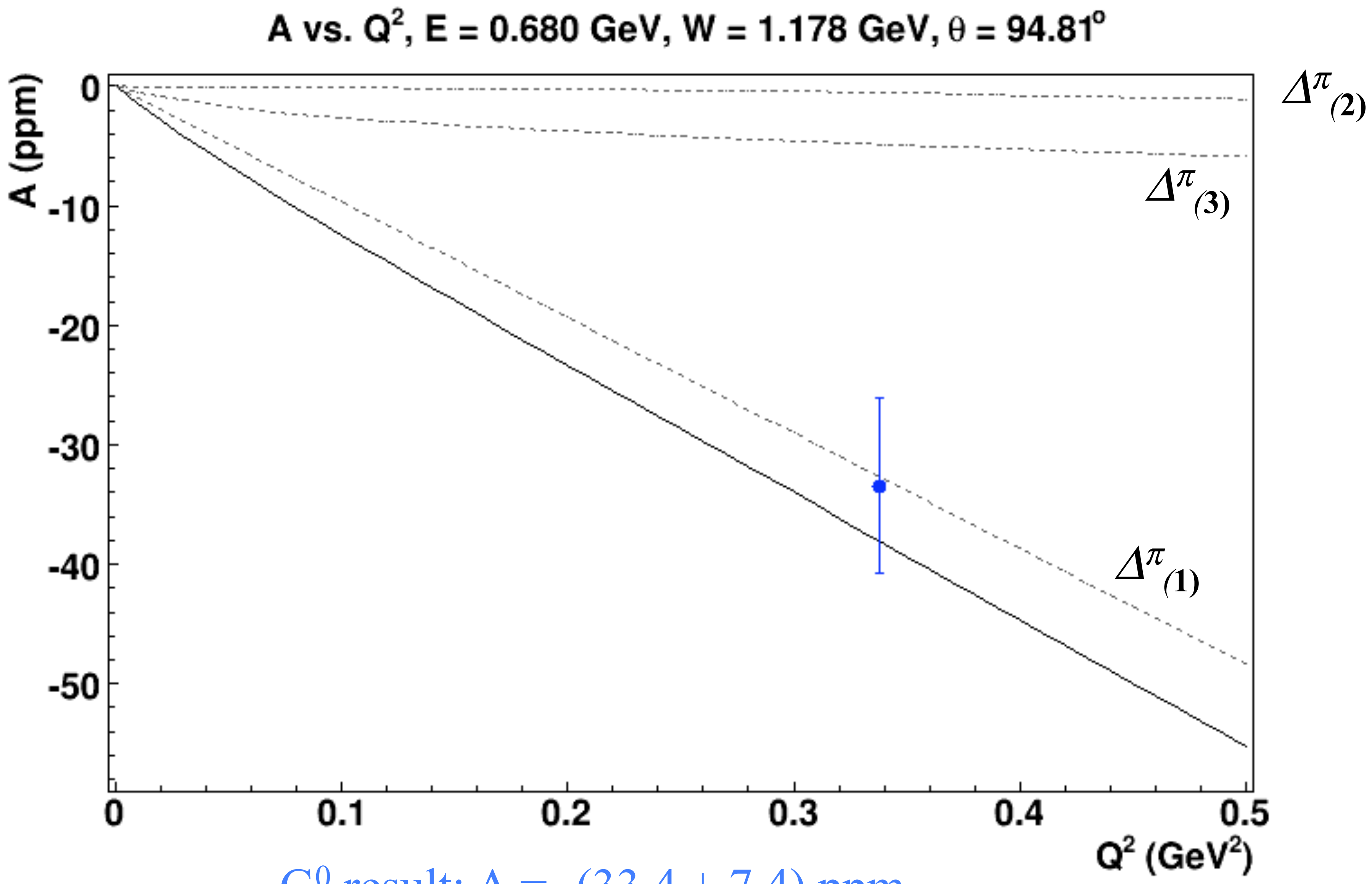
3) Dynamical Model of electroweak pion production:

K. Matsui, T. Sato & T.S.H. Lee, Phys. Rev. C **72,** 025204 (2005).
and T.S.H. Lee (private communication)
- hadronic effective chiral Lagrangian; field operators: N,Δ,π,ω,ρ and
effective Lagrangians for πNN,πNΔ,ωNN…

- $\Delta_{(3)}$ uses alternate form: $G^A_{N,\Delta}(Q^2) = (1 + aQ^2)\exp(-bQ^2)G_A(Q^2)$,

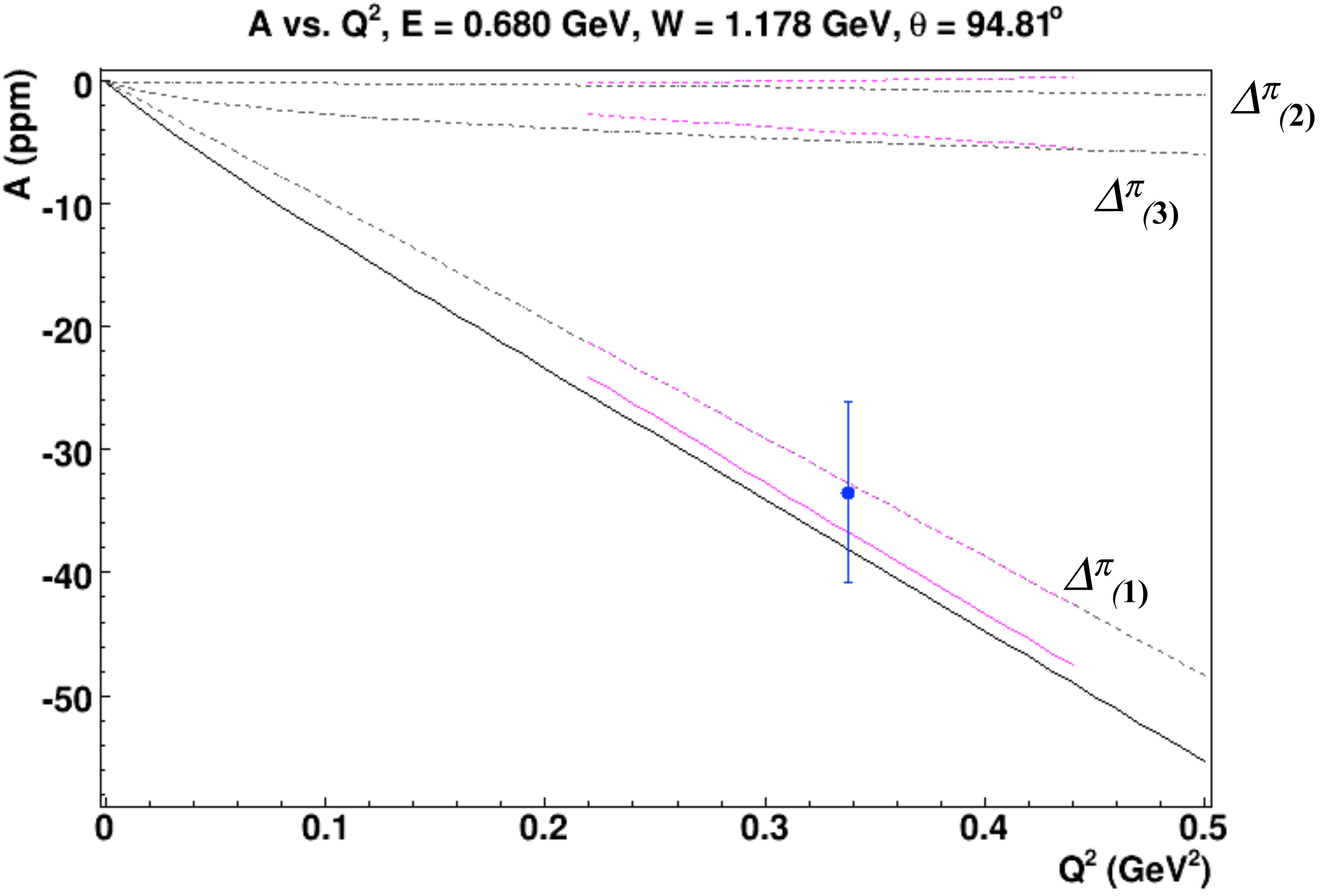
with a = 0.154 GeV^{-2} b = 0.166 GeV^2 and M_A = 1.02 GeV
(from fit to neutrino charged-current pion production data)

G^0 N-Δ: Result (default model)

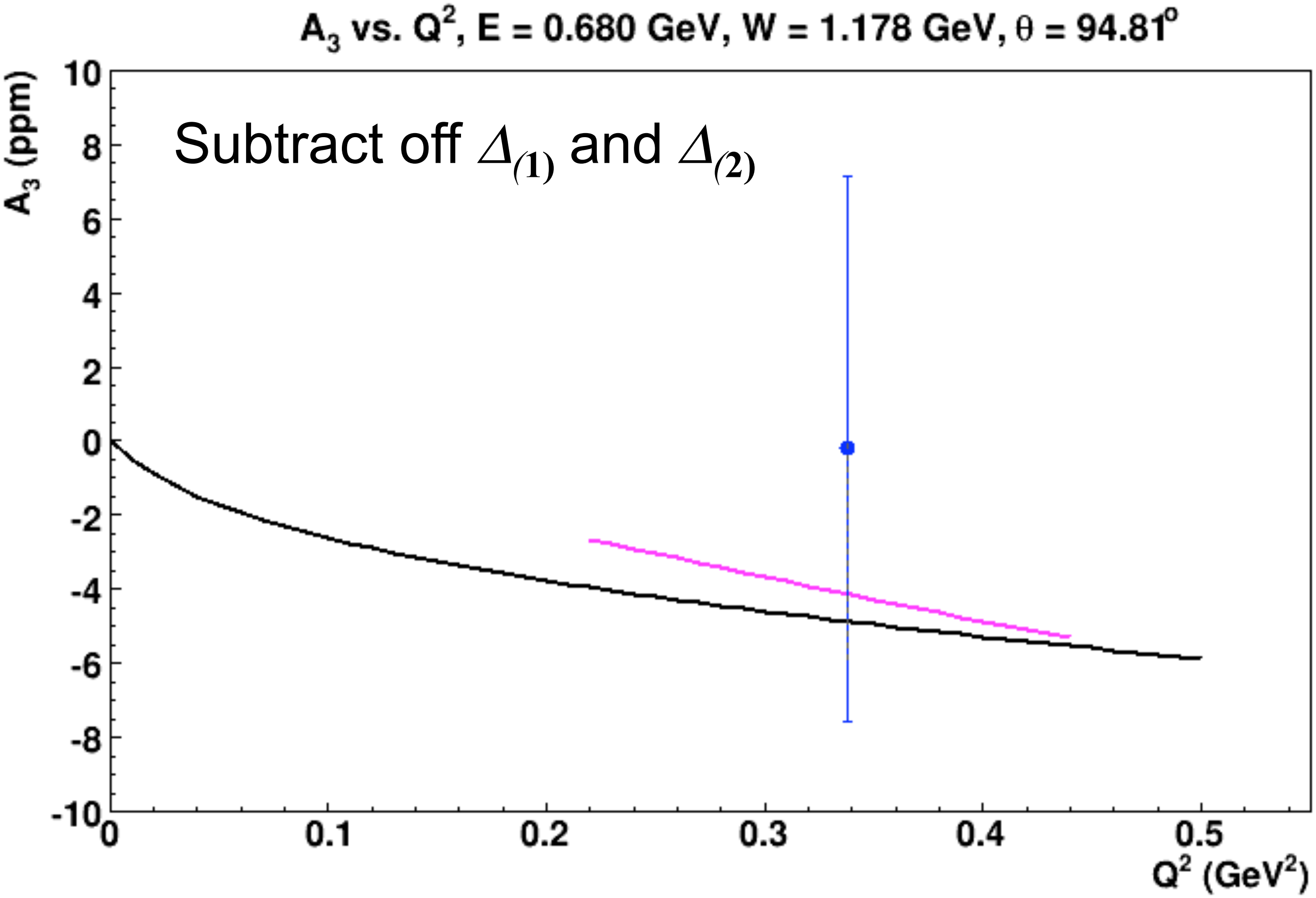


G^0 result: A = -(33.4 ± 7.4) ppm

G^0 N-Δ: Dynamical Model of Matsui, Sato and Lee



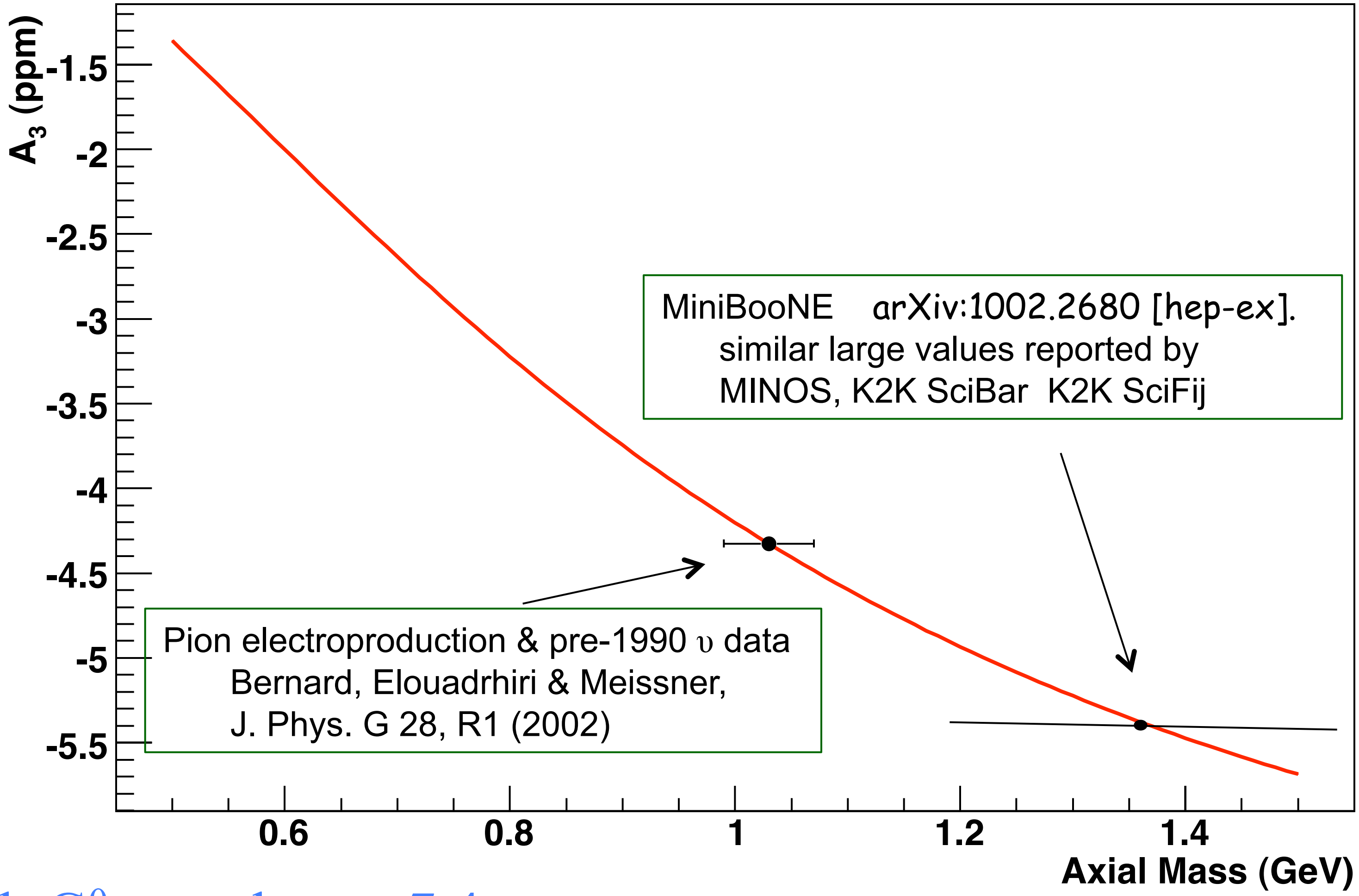
G^0 N-Δ: extracting $\Delta^{\pi}_{(3)}$



$\Delta^{\pi}_{(3)}$ consistent with theory, but data not precise enough to provide $G^{A}_{N\Delta}$

G^0 N-Δ: *Axial Mass ?*

One would need a precision of about ± 0.5 ppm to say anything significant about M_A …



MiniBooNE arXiv:1002.2680 [hep-ex].
similar large values reported by
MINOS, K2K SciBar K2K SciFij

Pion electroproduction & pre-1990 υ data
Bernard, Elouadrhiri & Meissner,
J. Phys. G 28, R1 (2002)

Recall: G^0 error bar: ±7.4 ppm

Summary

- First measurement of PV asymmetry in inelastic scattering to the Δ
- First measurement of PV asymmetry in (γ,π^-)

- $\mathrm{N}\rightarrow\Delta$ consistent with theory, but not precise enough to give useful information on $G^A_{N\Delta}(Q^2)$ or on axial mass M_A

- (γ,π^-) consistent with theory; does not favor *very* enhanced d_Δ^-
  but still room for sizable values

- Qweak has data in-hand on asymmetry at very low Q^2 ;
  analysis underway & more data likely will be taken…
  improve precision on d_Δ^-?