The G0 Experiment

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Jlab Users Group Meeting, June 17th 2008

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Carnegie Mellon

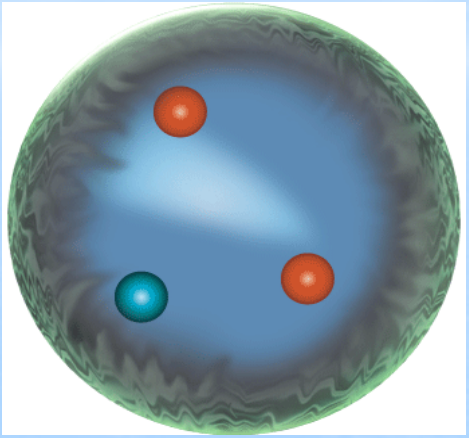
Outline

- Strange quark contribution to the nucleon properties (special interest on the electromagnetic properties).
- G0 experiment: Forward and Backward angle.
- Status of the G0Backward angle experiment analysis.
- Expected results (Soon!!! ☺)

Nucleon constituents

$$p = uud + u\bar{u} + d\bar{d} + s\bar{s} + g + ...$$

valence « sea= virtual pairs »



- The sea contains all flavors, but
  - the u and d sea can't be distinguished from the valence
  - the heavier quarks (c,b,t) are too heavy to contribute much
  - Strange quark is the natural candidate to study the sea.

With how much do virtual strange pairs contribute to the structure of the nucleon ?

Strange Quark Contribution to the Nucleon Properties

- **Mass:** Hyp -> π-N -> $\sigma_s = \langle N|\bar{s}s|N\rangle$ → 0 to 30 % with big theoretical uncertainties.
- **Longitudinal Momentum:** DI ν_μ-Nucleon scattering (NuTeV)

. For x <0.1 $\int_0^1 x(s(x)+\bar{s}(x))dx \sim 2-4\%$

- **Spin:** $\langle N \mid \bar{s}\gamma^\mu\gamma^5 s \mid N \rangle$

  - ν-p elastic scattering (E734 BNL)
  - Polarized Semi-Inclusive DIS (HERMES)
  - PQCD predicts -0.1

$\Delta s = -0.15 \pm 0.09$

$\Delta s \sim 0$ and positive

Strangeness Contribution to the Nucleon Electromagnetic Properties

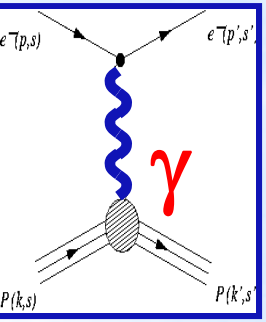
Goal: Determine the contributions of the strange quark sea ($s\ \bar{s}$) to the charge and current distributions in the nucleon :

"strange form factors" G^s_E and G^s_M

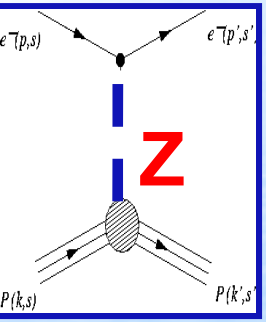
$$\langle N | \bar{s} \gamma^\mu s | N \rangle ?? \longrightarrow G_E^s, G_M^s$$

How do we measure them?

Strange Form Factors



$$G_{E,M}^{\gamma} = \frac{2}{3}G_{E,M}^{u} - \frac{1}{3}G_{E,M}^{d} - \frac{1}{3}G_{E,M}^{s}$$



$$G_{E,M}^{Z,p} = \left(1 - \frac{8}{3}\sin^2\theta_W\right)G_{E,M}^{u} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right)G_{E,M}^{d} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right)G_{E,M}^{s}$$

$\sin^2\theta_W = 0.2312 \quad 0.00015$

Charge symmetry ->

$$G^{u,p} = G^{d,n}; G^{d,p} = G^{u,n}; G^{s,p} = G^{s,n}$$

$$G_{E,M}^{s} = \left(1 - 4\sin^2\theta_W\right)G_{E,M}^{\gamma,p} - G_{E,M}^{\gamma,n} - G_{E,M}^{Z,p} \; ?$$

measured

Parity Violation Asymmetry

- Scatter polarized electrons off unpolarized target,
- Asymmetries of the order of ppm

$$,\frac{M_\gamma}{M_Z} \approx 10^5$$

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

Electric Magnetic Axial

- Proton target

$$A_{PV} = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E + A_M + A_A}{\sigma_p}$$

$$A_E = \varepsilon(\theta) G_E^Z G_E^\gamma \quad --> G_E^s$$

$$A_M = \tau G_M^Z G_M^\gamma \quad --> G_M^s$$

$$A_A = -(1-4\sin^2\theta_W)\varepsilon' G_A^e G_M^\gamma \quad --> G_A^e$$

- Helium target

$$A_{PV} = \frac{G_F Q^2}{\pi\alpha\sqrt{2}}\left[\sin^2\theta_W + \frac{G_E^s}{2(G_E^p + G_E^n)}\right] \rightarrow G_E^s$$

- Deuteron target (static case)

$$A_d = \frac{\sigma_p A_p + \sigma_n A_n}{\sigma_p + \sigma_n}$$

-Complete calculation by Schiavilla et al., is available.

- Enhanced sensitivity to Axial form factor.

PV. Experiments

Forward

Backward

$$A_E = \varepsilon(\theta) G_E^Z G_E^\gamma \quad --> G_E^s$$

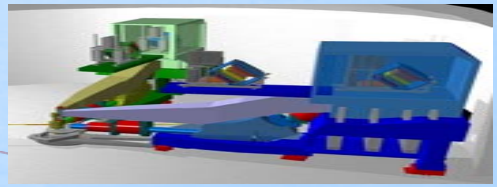
$$A_M = \tau G_M^Z G_M^\gamma \quad --> G_M^s$$

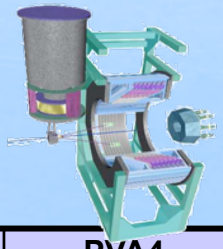
$$A_A = -(1-4\sin^2\theta_W)\varepsilon' G_A^e G_M^\gamma \quad --> G_A^e$$

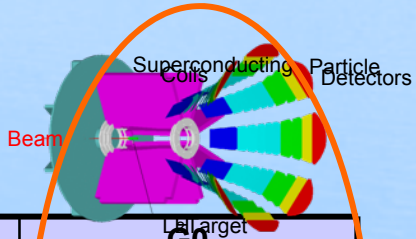
$$\tau = \frac{Q^2}{4M^2}$$

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta}{2}\right)\right]^{-1}$$

$$\varepsilon' = \sqrt{(1-\varepsilon^2)\tau(1+\tau)}$$







	SAMPLE (MIT-Bates) *1998-2002*	HAPPEX I (Jlab) *1998-2002*	HAPPEX II (JLab) *2004-2005*	PVA4 (MAMI) *2002-2008*	G0 (JLab) *2003-2007*
Q^2 (GeV/c)^2	0.04, 0.1	0.48	0.1	0.1, 0.23 (0.48)	**0.12 - 1.0** **(0.23, 062)**
Angle	B	F	F	F/B	F/B
Target	H,D	H	H, ^{4}He	H	H, D
Separation	G_M^s, $G_A^{(p+n)}$	G_E^s + 0.4 G_M^s	G_E^s , G_M^s	G_E^s, G_M^s	G_e^s, G_M^s , $G_A^{(p+n)}$

- HAPPEX-III 2009 at 0.6 GeV^2

G0 Program in Hall C of Jefferson Lab

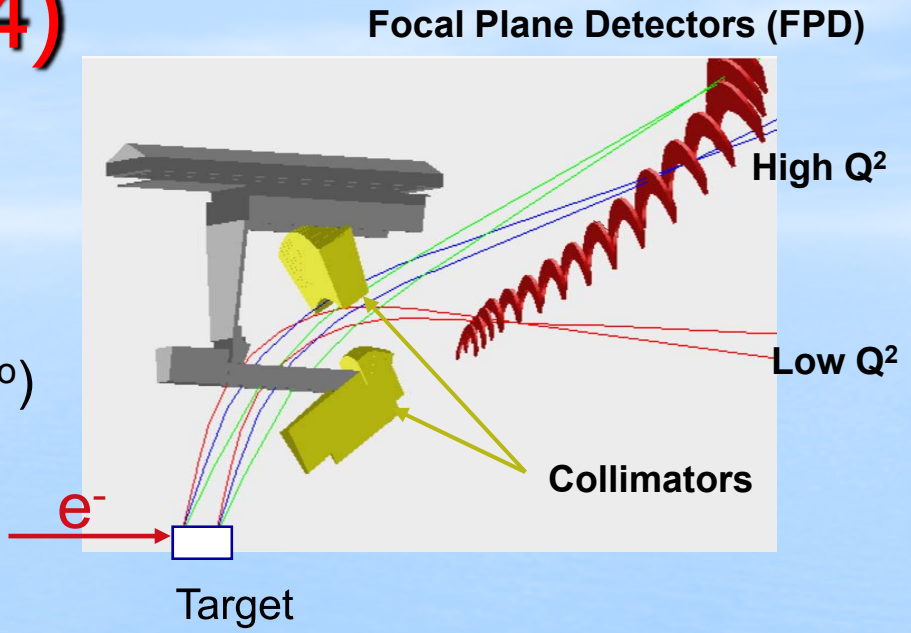
- Forward angle $\vec{e}$ + p …04
- Backward angle $\vec{e}$ + p ...06-07
- Backward angle $\vec{e}$ + d …06-07

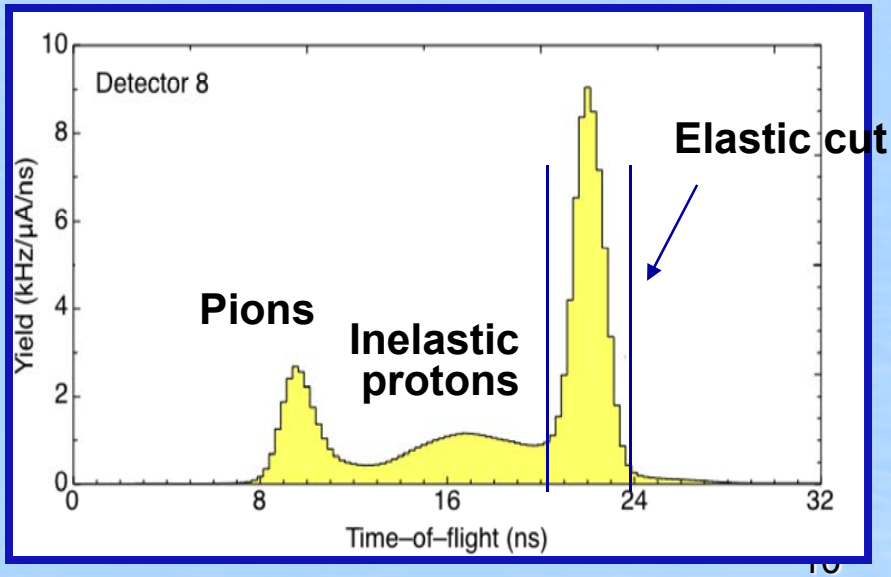
$$\left\{ G_E^s \quad G_M^s \quad G_A^e \right.$$

G0 Forward Angle (2004)

- One measurement on LH_2
  - ✓ E_e = 3.045 GeV, 31 MHz beam str.
  - ✓ Recoil proton detection ($52^o < \theta_p < 76^o$)
    - ↳ $0.12 \leq Q^2 \leq 1.0$ GeV^2

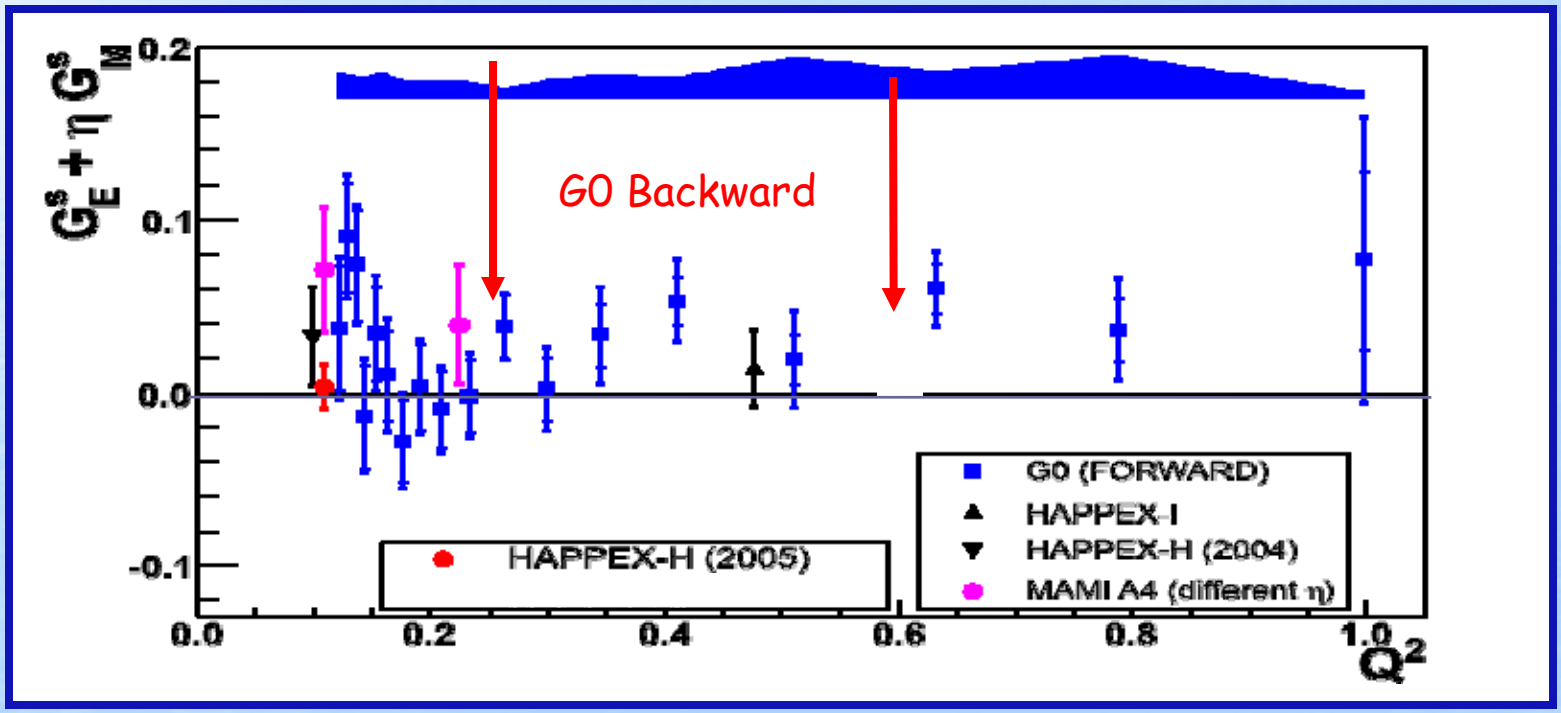
- Counting experiment
  - ✓ Time-of-flight electronics





Results from the Forward angle

$$G_E^s + \eta G_M^s = \frac{4\pi\alpha\sqrt{2}}{G_F Q^2} \frac{\varepsilon G_E^{p\,2} + \tau G_M^{p\,2}}{\varepsilon G_E^p \left(1 + R_V^{(0)}\right)} \left(A_{phys} - A_{NVS}\right)$$



Examining full data set, probability that $G_E^s + \eta G_M^s \neq 0$ is 89%

Compared to ANVS ("No VectorStrange") EM form factors : Kelly PRC 70 (2004) 068202

D.S. Armstrong, *et al.*, PRL 95, 092001 (2005)

Global Analysis at Q^2 ~0.1 GeV^2

- A_{NVS} Contains the term $G_A^{e(T=1)}$

- **R. Young *et al., Phys. Rev. Lett. 99, 122003 (2007)***

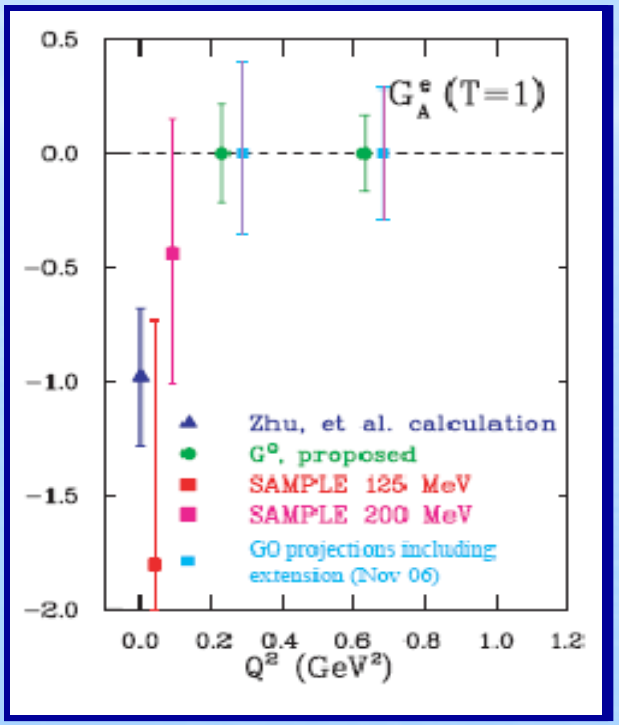
- ***Global fit of all the existing forward angle data***

  - If SAMPLE result is used for the axial form factor G_A^e

G_E^s = 0.002 +- 0.018 & G_M^s = -0.01 +- 0.25

  - **If G_A^e is taken from *Zhu et al., PRD 62 (2000) 033008***

G_E^s = -0.011 +- 0.016 & G_M^s = 0.22 +- 0.2



More measurements of the axial form factor are needed.

G0Backward angle! ☺

G0 Backward Angle Experiment (06-07)

The G0 Backward Collaboration

***G⁰ Spokesperson*: Doug Beck (*UIUC*)**

California Institute of Technology, Carnegie-Mellon University, College of William and Mary, Grinnell College, IPN Orsay, JLab, LPSC Grenoble, Louisiana Tech. Univ., New Mexico State University, Ohio University, TRIUMF, University of Illinois, University of Kentucky, University of Manitoba, University of Maryland, University of Winnipeg, Virginia Tech, Yerevan Physics Institute, University of Zagreb

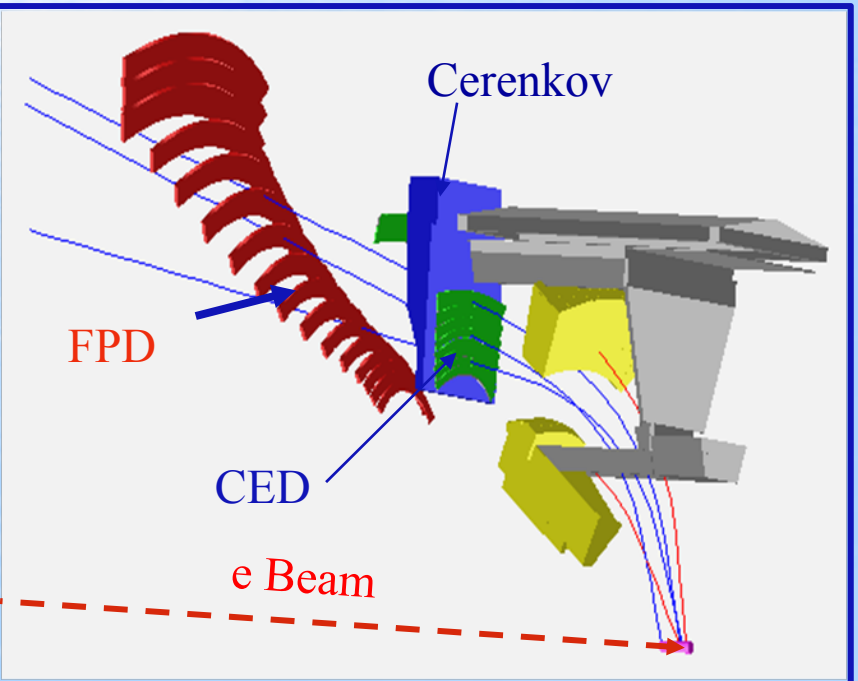
***Analysis Coordinator*: Fatiha Benmokhtar (*CMU*)**

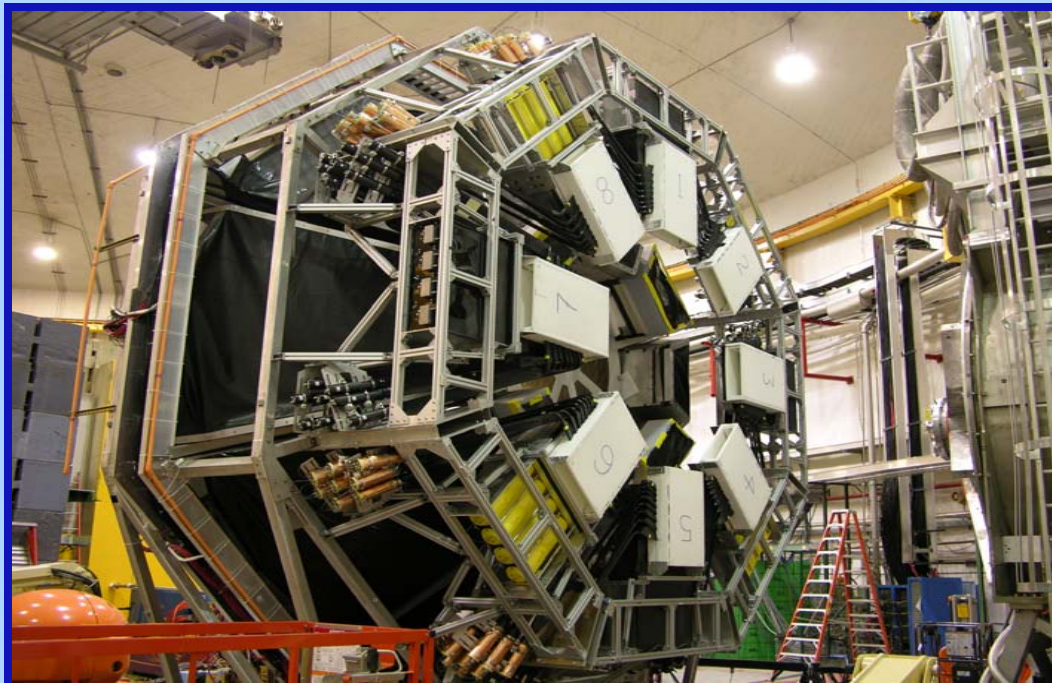
***Students*:**

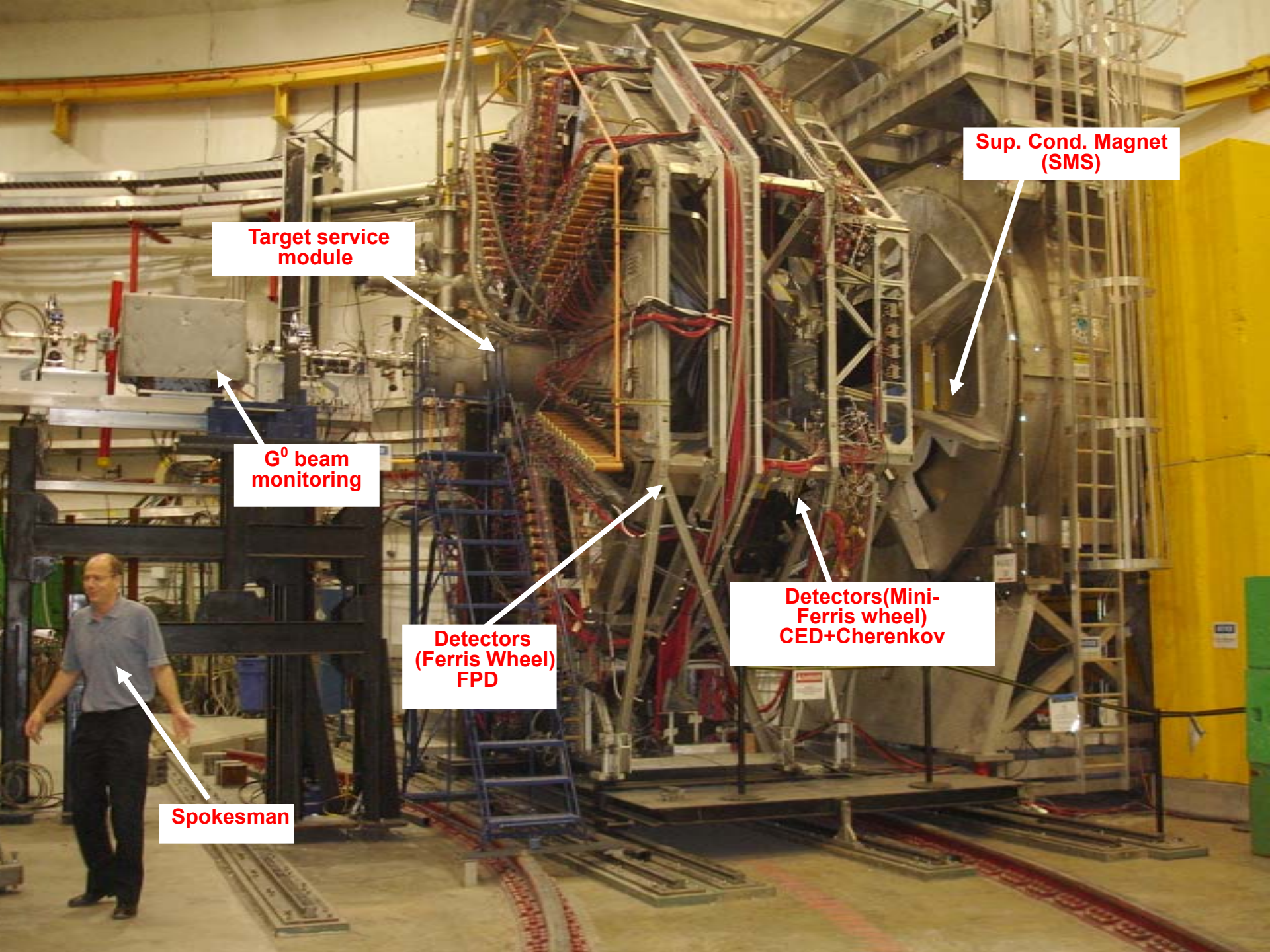
Carissa Capuano (*W&M*), Alexandre Coppens (*Manitoba*), Colleen Ellis (*Maryland*) , Juliette Mammei (*VaTech*), Mathew Muether (*UIUC*), John Schaub (*NMSU*), Maud Versteegen (*LPSC*), Stephanie Bailey (*Ph.D. W&M, Jan '07*)

G0 Backward Angle

- Electron Beam: 362 and 687 MeV -> Q^2: 0.23 and 0.62 GeV^2
- Turn-around of the magnet, change polarity
- Electron off LH_2 or LD_2 target, electron detection : $\Theta = 108°$.
- Add Cryostat Exit Detectors (9 CEDs per Octant)-> separate elastic and inelastic electrons in the CED*FPD space.
- Aerogel Cerenkov detector per octant for π/e separation. ($p_\pi < 380$ *MeV/c*)






Sup. Cond. Magnet (SMS)
Target service module
G0 beam monitoring
Detectors (Ferris Wheel) FPD
Detectors(Mini-Ferris wheel) CED+Cherenkov
Spokesman

Beam Specifications

- 2ns beam structure
- 86 % longitudinal polarization
- Helicity changed every 1/30 sec (MPS).
- Form Asym. from a pseudo-random quartet structure in helicity (+--+ or -++-).
- 2 half wave plate states IN/OUT

Beam Parameter	Achieved (IN-OUT)/2	"Specs"
Charge asymmetry	0.09 +/- 0.08	2 ppm
x position difference	-19 +/- 3	40 nm
y position difference	-17 +/- 2	40 nm
x angle difference	-0.8 +/- 0.2	4 nrad
y angle difference	0.0 +/- 0.1	4 nrad
Energy difference	2.5 +/- 0.5	34 eV
Beam halo	< 0.3 x 10^{-6}	10^{-6}

- **Helicity correlated beam properties**

  -> false asymmetry.

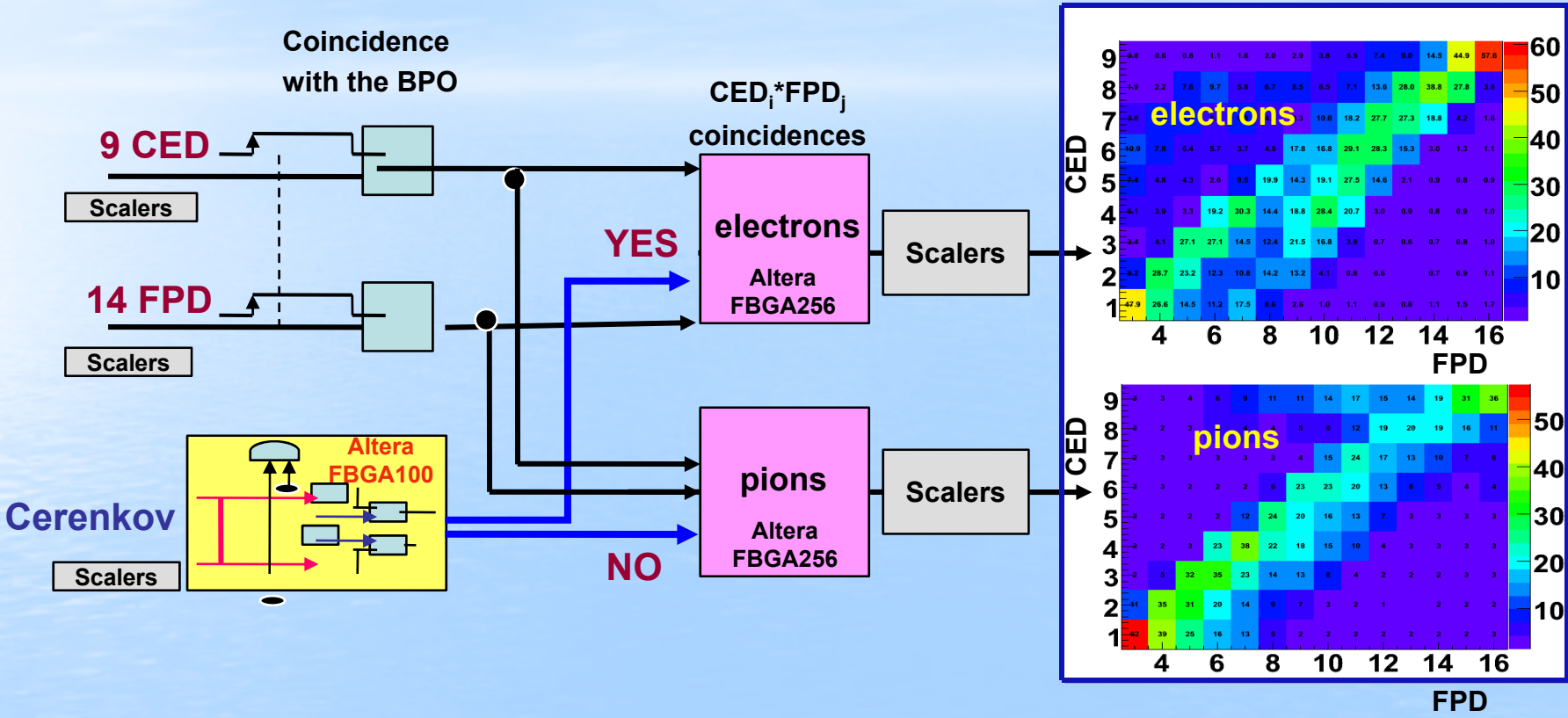
  Correction : linear regression:

$$A_{cor} = A_{meas} - \sum_i \frac{1}{2Y}\frac{\partial Y}{\partial P_i}\Delta P_i$$

⇨ **Very small in our case (ppb)**

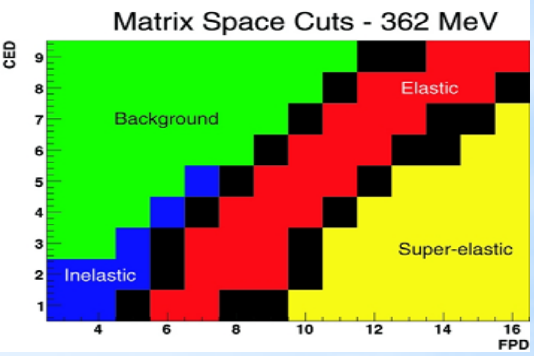
Simplified Electronics Scheme

(for one Octant)



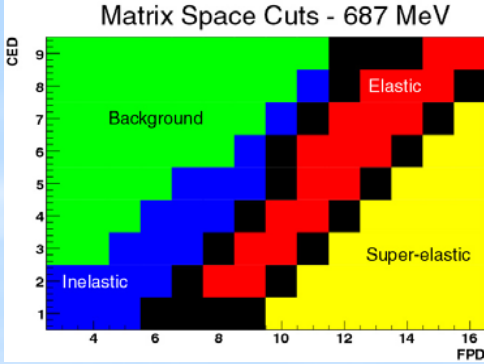
- **Read Scalers for each CED*FPD combination -> Build the coincidence matrix.**

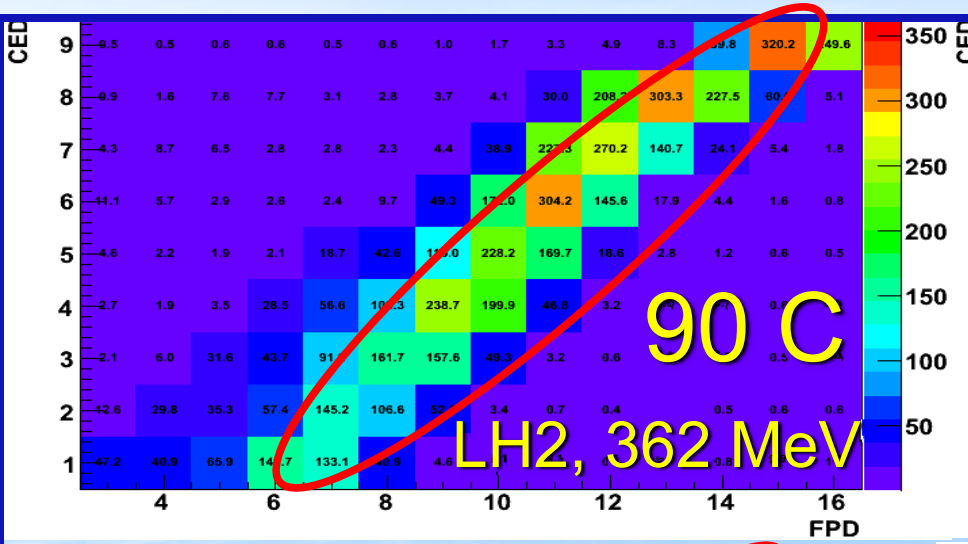
- G0 backward uses 2 kinds of Trigger:
  - Electron trigger: CED*FPD*Cerenkov
  - Pion trigger: CED*FPD no Cerenkov

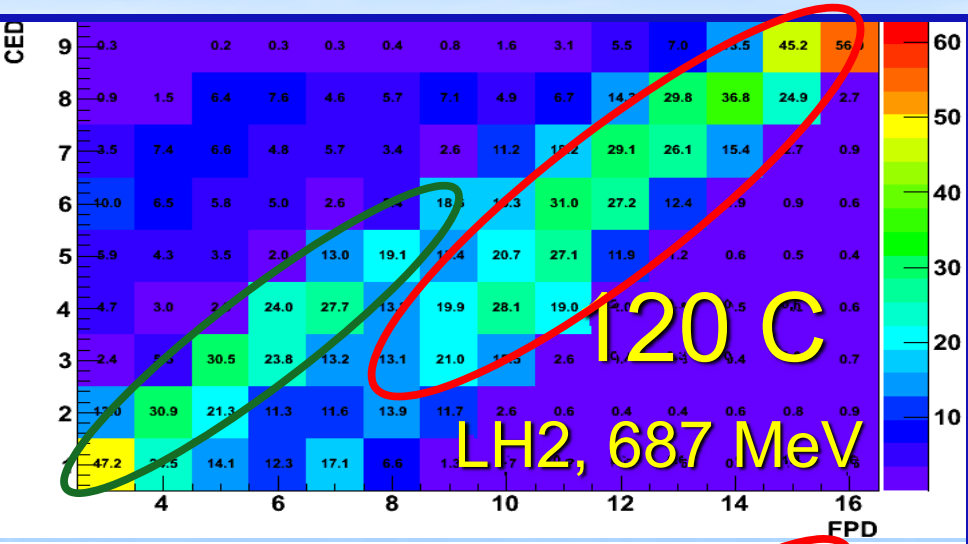


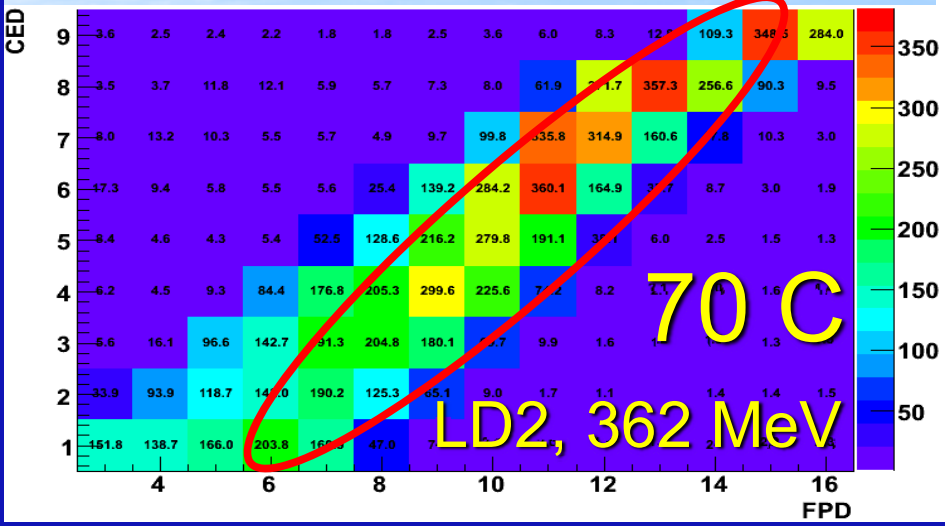
Electron Yield

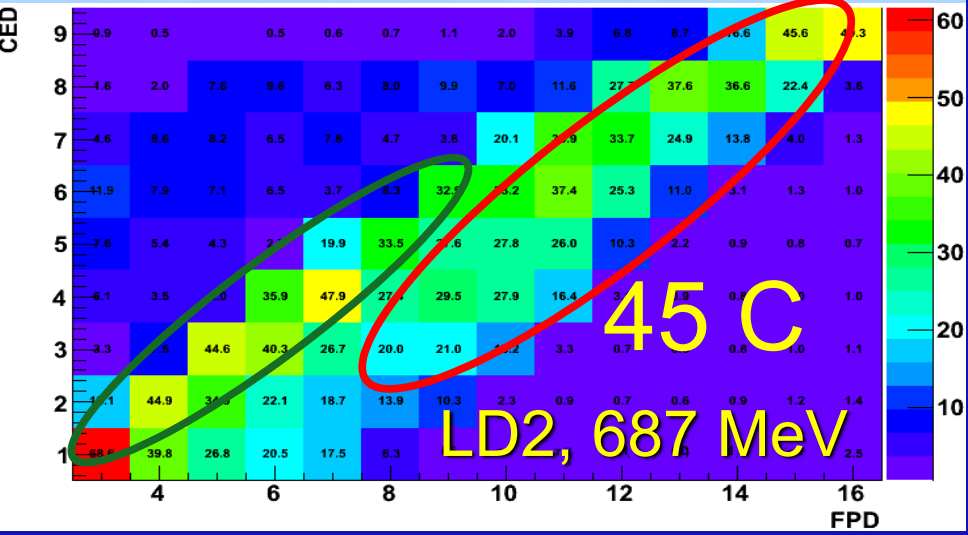
(Hz/μA/Oct)



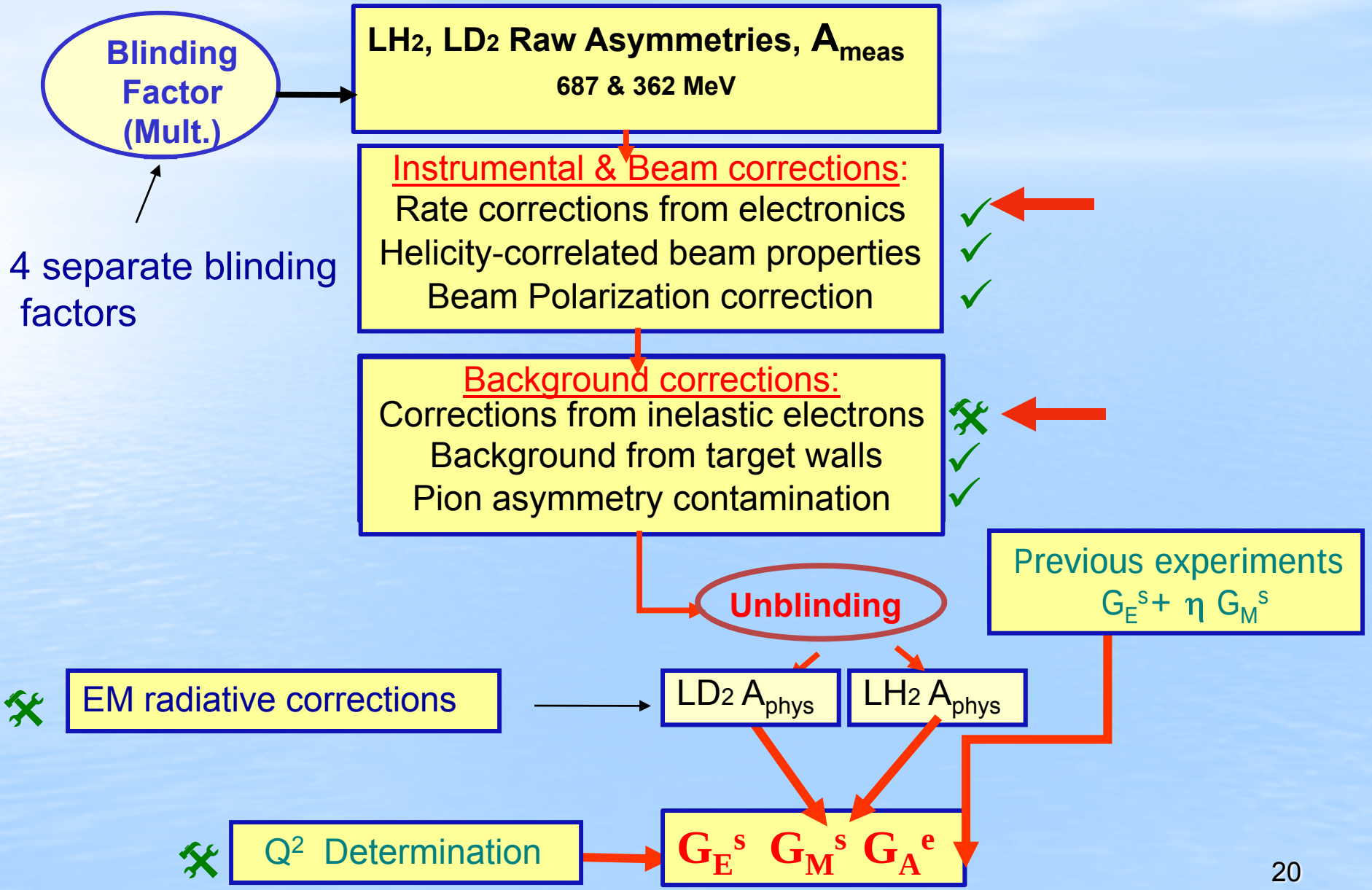








G0Back Analysis Strategy



G0 Analysis

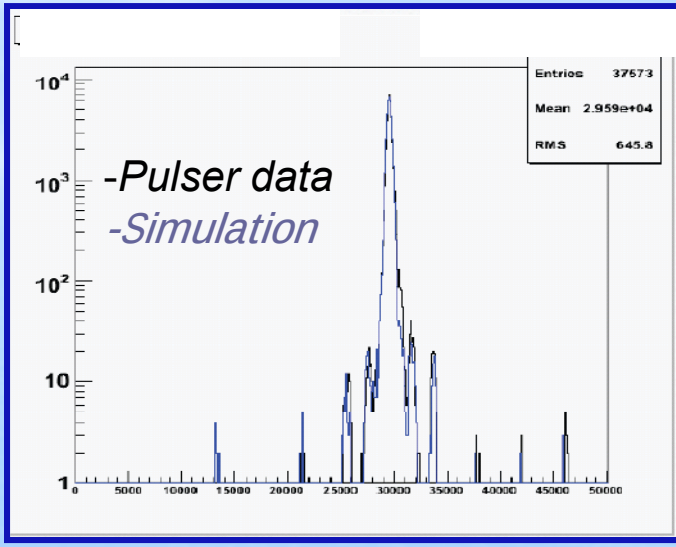
Four Passes per Analysis Replay

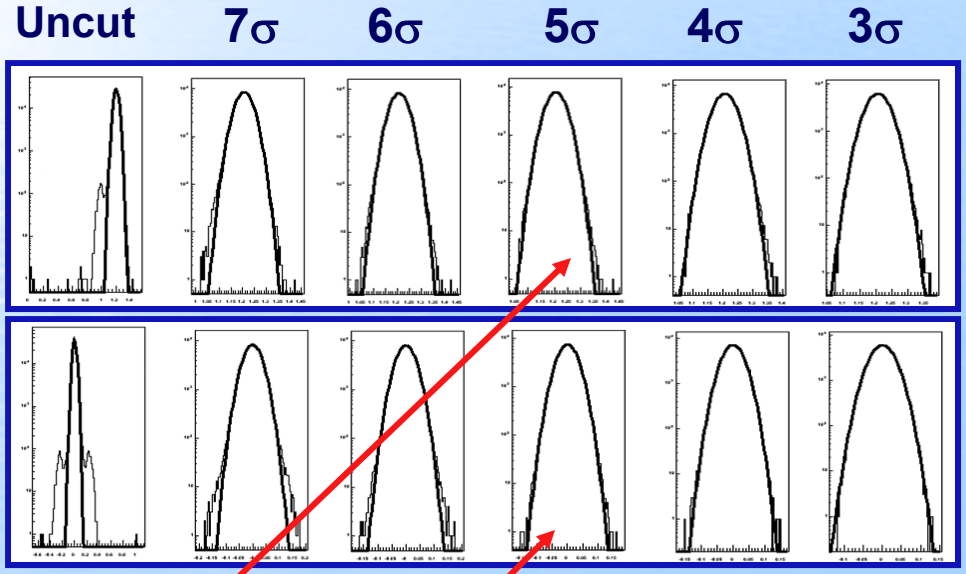
Analyzer Database

- **Pass 1:**
  - **Uncorrected yields & blinded asymmetries**
- **Pass 2:**
  - **Scaler counting correction (the famous ‘problem’! ☺)**
- **Pass 3:**
  - **Electronic correction (deadtime, randoms, contamination)**
- **Pass 4:**
  - **Linear regression correction**

NA Scaler Counting 'Problem'

- **An occasional bit drop in a North American scaler was traced down to trigger electronics. Was noticed at high rates: LD2 target at 362 MeV. This was fixed during the run (Jan07)**
- **Problem blind to helicity.**





Cut on yield

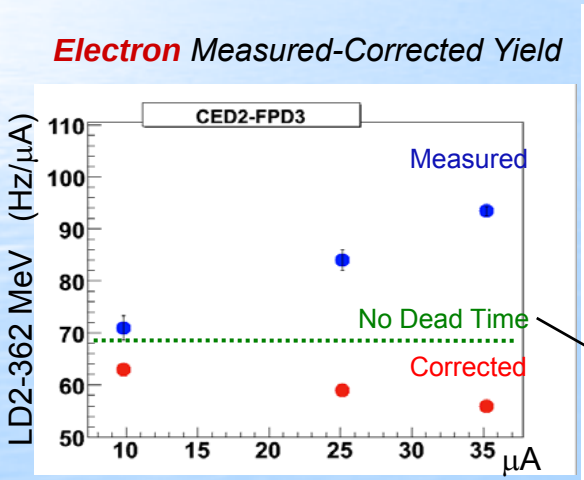
Effect on Asymmetry

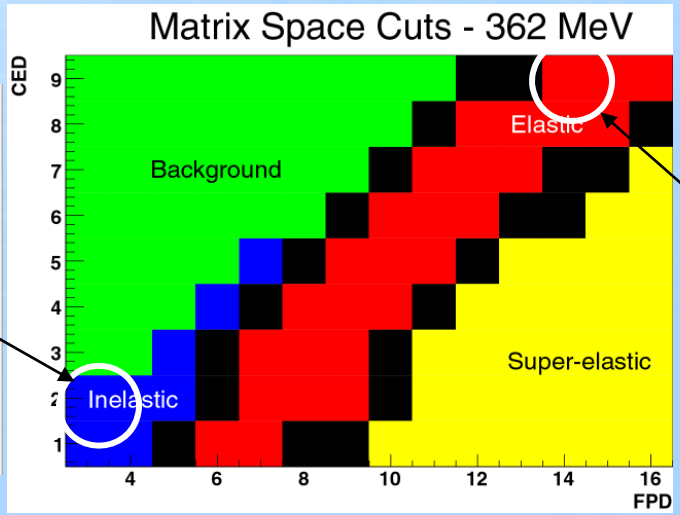
- Test by cutting data; compare with French octants.
- Confirmed by unchanged asymmetry after fix

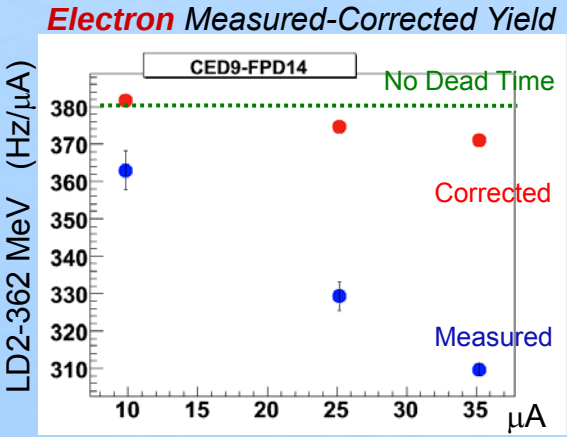
5σ cut removes ~1% of our data for 362MeV LD2,which is the worst case! ☺

Rate Correction for Electronic Related Effects

- **Dead Time and Randoms in CEDxFPD coincidences and cerenkov electronics.**
- **All the electronics chain was simulated.**
- **Current scan runs**



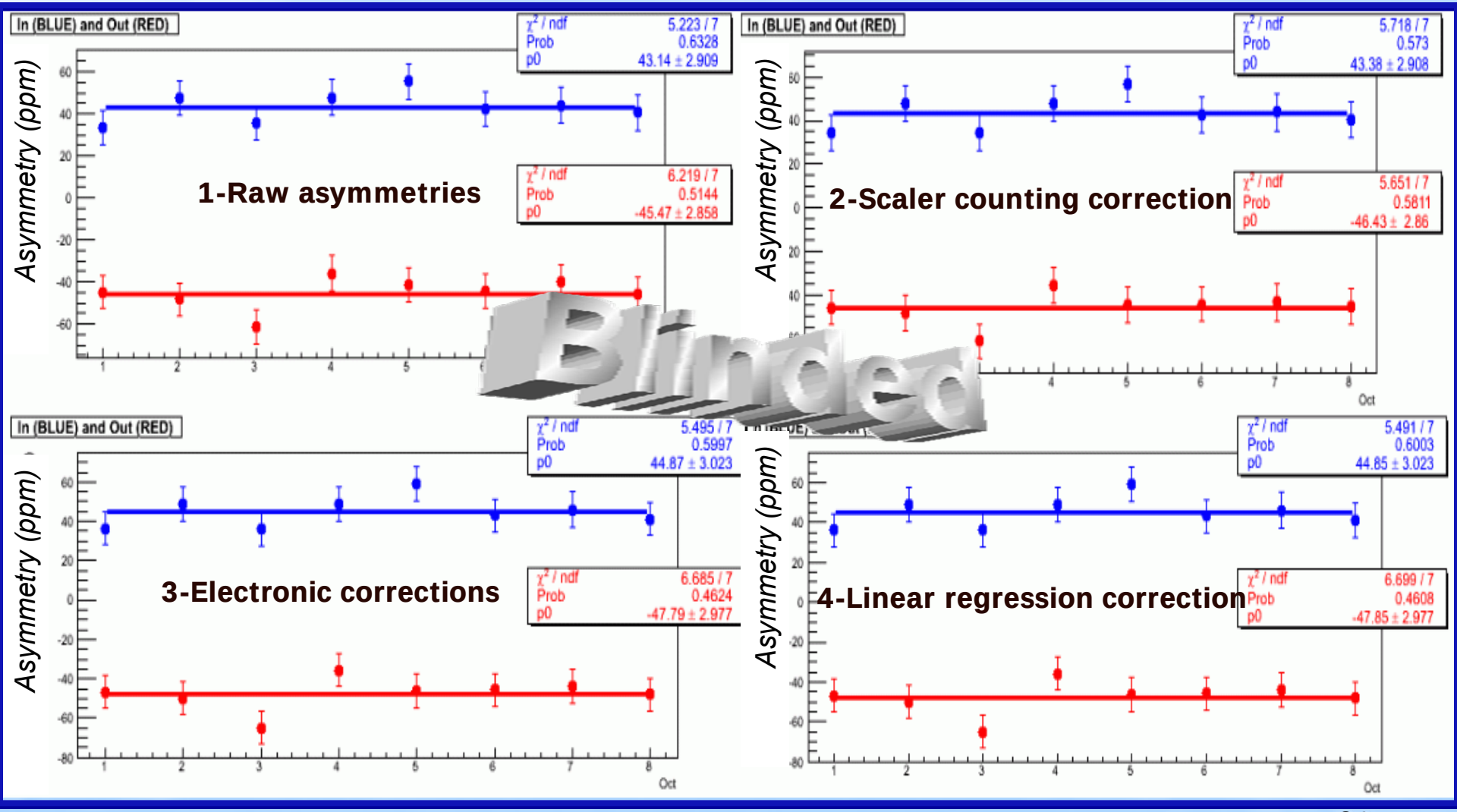




Global correction: ~ 2-4% to the asymmetry in the elastic locus.

Four Pass Asymmetries

(LH2 687 MeV)



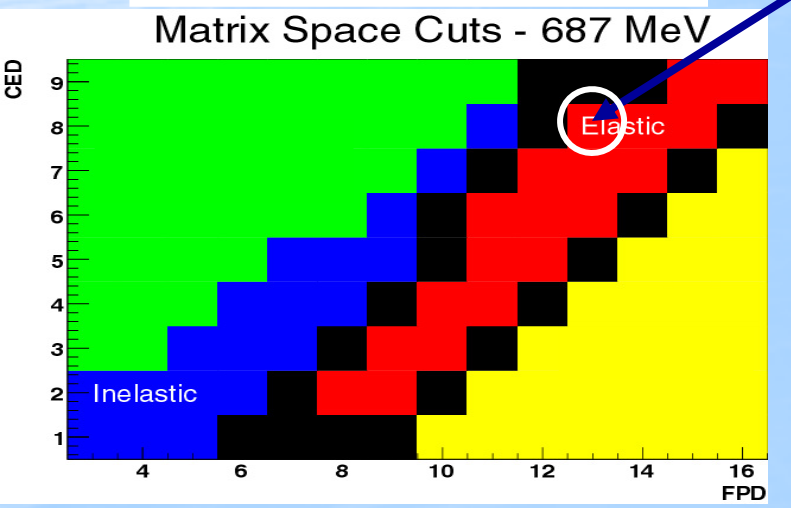
LH2 687 Field Scan

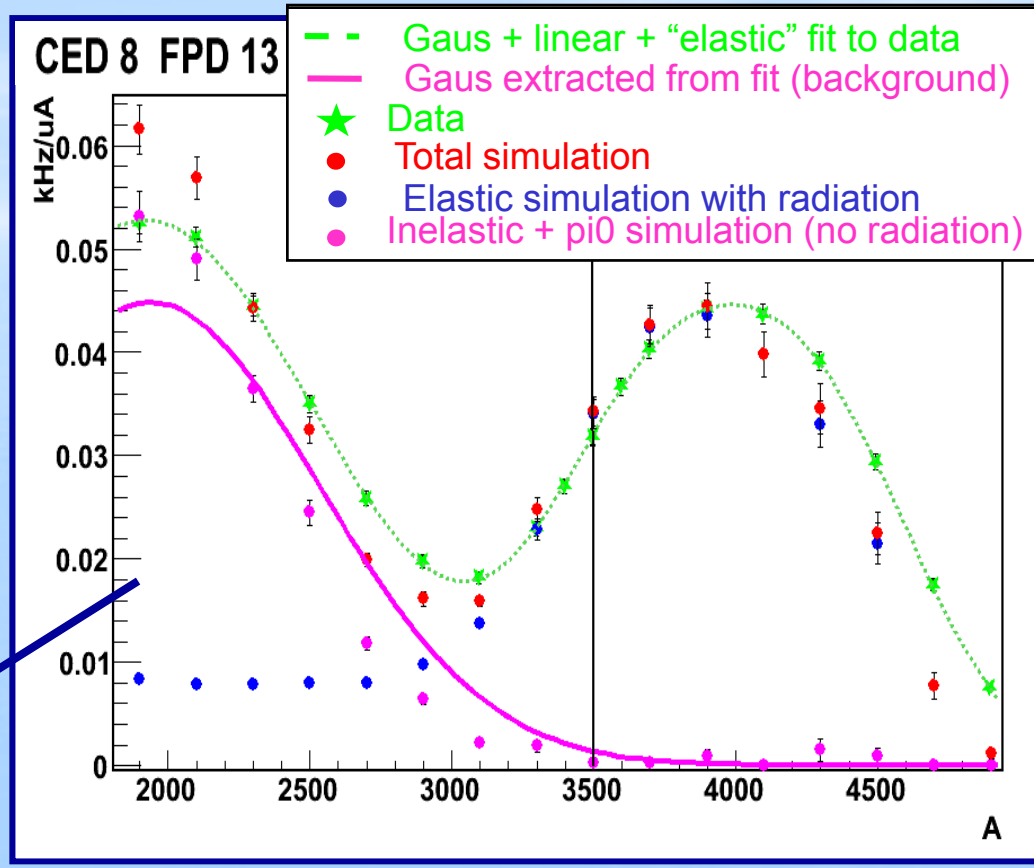
-Nominal field current set at 3500 A.

- Vary the field and study the CED*FPD yield.

$$f = \frac{rate_{nom}^{bck,fit}}{rate_{nom}^{tot,data}}$$

$$A_{el} = \frac{A_{meas} - fA_{back}}{1 - f}$$





$f < 5\ \%$

We do understand the backgrounds and work is in progress.

Other Corrections

- **Helicity-Correlated Beam Properties: Linear Regression:**
  - Sensitivities to helicity-correlated beam motion smaller at backward angles. Elastic Electron False Asymmetries: < 4ppb

- **Electromagnetic Radiative Corrections**
  - Simulation program for radiative corrections is under development:

$$R \sim 4\%$$ (preliminary.)

- **Transverse Beam Asymmetry:** Very small: under study.
- **Many other small checks were done.**

From Asymmetries to Strange Form Factors

- Proton

$$A = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{1}{\varepsilon G_E^{p\,2} + \tau G_M^{p\,2}} \left\{ \left(1 - 4\sin^2\theta_W\right)\left(\varepsilon G_E^{p\,2} + \tau G_M^{p\,2}\right)\left(1 + R_V^p\right) - \right.$$
$$\left(\varepsilon G_E^p G_E^n + \tau G_M^p G_M^n\right)\left(1 + R_V^n\right) - \varepsilon G_E^p \left(G_E^s + \eta G_M^s\right)\left(1 + R_V^{(0)}\right) -$$
$$\left. \varepsilon'\left(1 - 4\sin^2\theta_W\right) G_M^p G_A^e \right\}$$

See: J. Liu PhD. thesis, UMD 2006.

- Deuteron

$$A = -\frac{G_F Q^2}{2\alpha\sqrt{2}} \frac{v_L R_L^V(q,\omega) + v_T R_T^V(q,\omega) - \left(1 - 4\sin^2\theta_W\right) v'_T R_T^A(q,\omega)}{v_L R_L^\gamma + v_T R_T^\gamma}$$

Ref: Diaconescu, Schiavilla & van Kolck, PRC **63** (2001) 044007
(Addition of the 2body currents corrections)

From Asymmetries to Strange Form Factors

$$A(q,\omega,\theta_e) = a_0 + a_1 G_E^s + a_2 G_M^s + a_3 G_A^{e(T=1)} + a_4 G_A^s$$

to be extracted

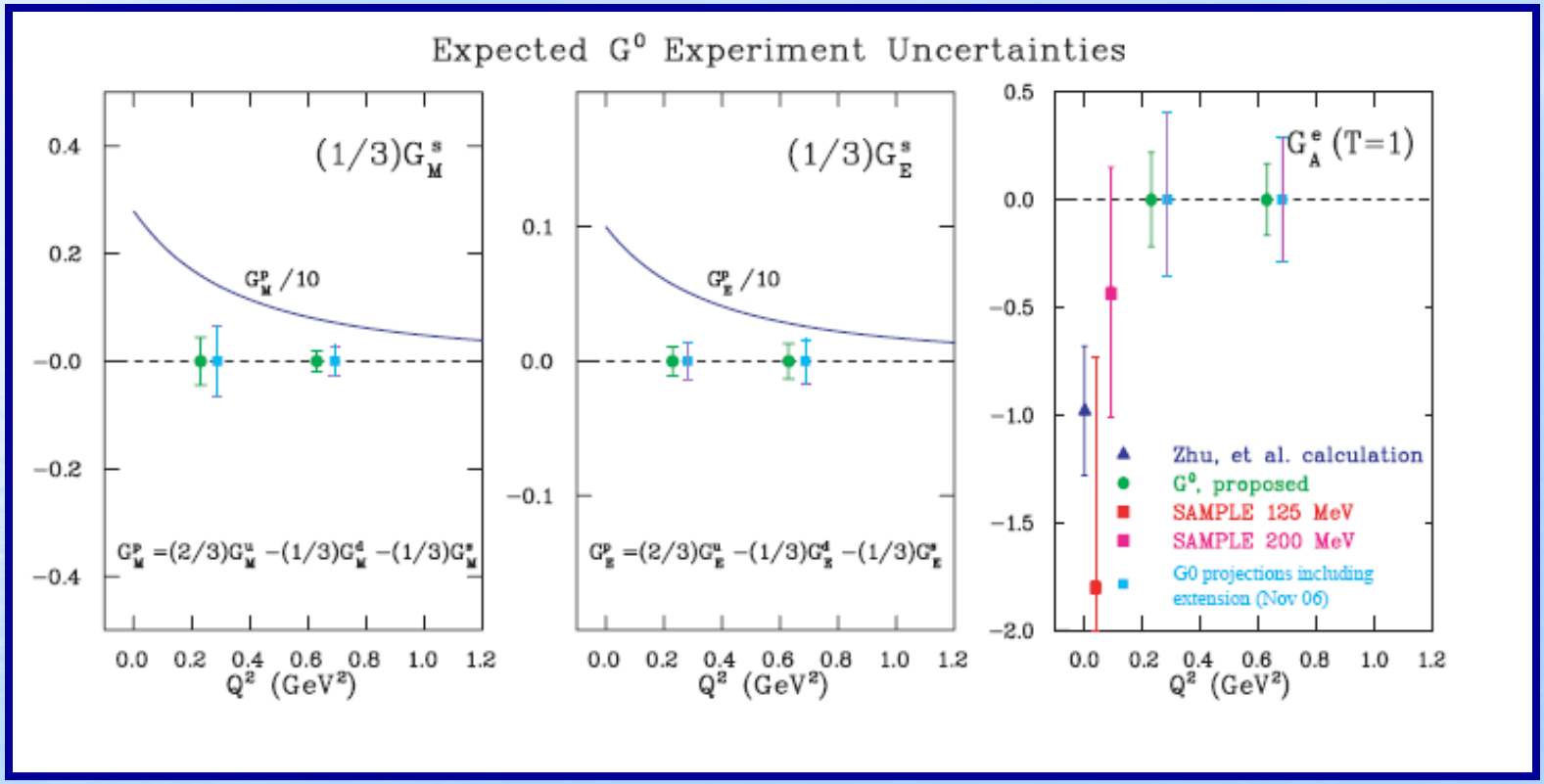
Isoscalar sff

(Estimated)

- **We will use the best and up to date inputs for the quantities going into the a_i *coefficients.***

- **Solve the system for the G0 Forward (proton target) and G0 Backward kinematics (proton and deuteron targets)**

Expected G0 Results



- Error bars dominated by statistics.
- Systematic experimental: backgrounds → Small
- Systematic from the nucleon form factors

G0 Summary

- G0 Forward angle
  - $G_E^s + nG_M^s$ from Q^2=0.12 to 1 GeV^2
  - Strange quark contribution non-zero at 89% confidence level
  - Nicely consistent with emerging picture at Q^2=0.1 GeV^2
  - Gave some clues about where to look next (HAPPEX-III)

- G0 Backward angle
  - Provide clean separation of G_E^s, G_M^s, and G_A at Q2=0.23 and 0.6 GeV^2
  - Data Analysis almost at the end, complete separation coming soon! ☺

Additional Program to the G0 Experiment

- Parity-violation in electro and photo excitation of the Delta resonance: - inelastic electron
  - photopion asymmetries).

  - Analysis in good progress

- Beam normal asymmetries and two-photon exchange. - -
  - Analysis in good progress.

Backup Slides

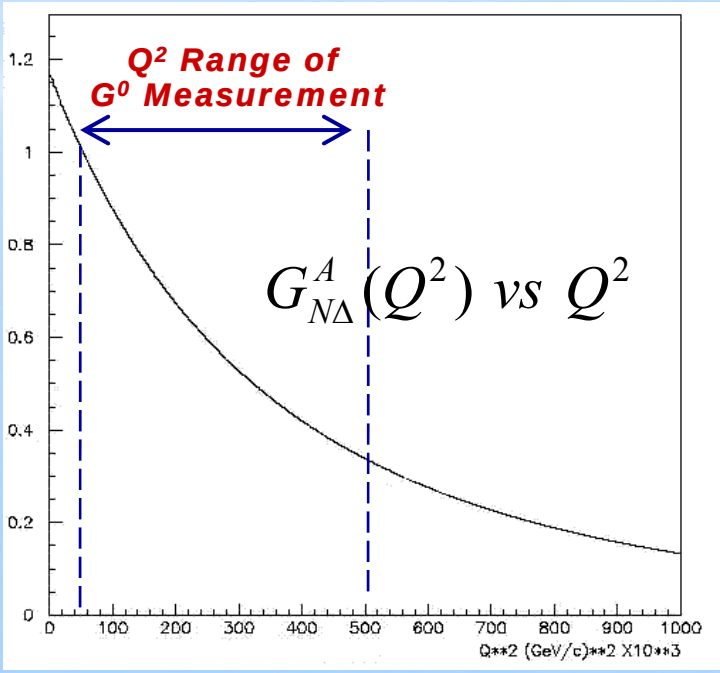
Measurement of the Parity Violating Asymmetry in the $N \rightarrow \Delta$ Transition

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

$\Delta_{(1)} = 2(1-\sin^2\theta_W) = 1$ **(Standard Model)**

$\Delta_{(2)}$ = **non-resonant contrib. (small)**

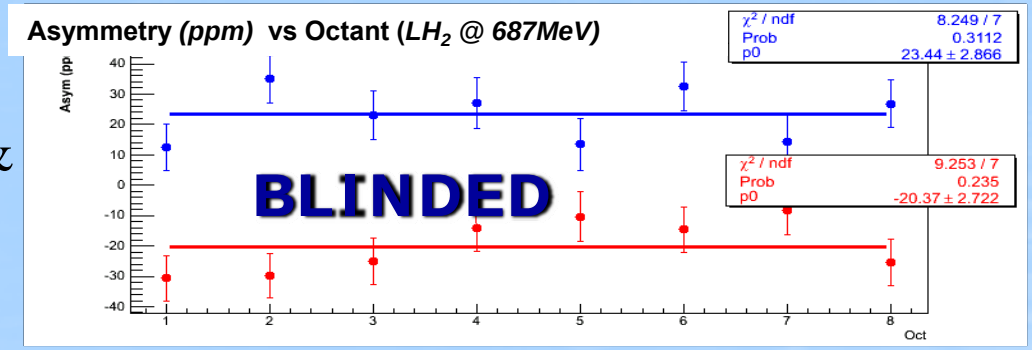
$\Delta_{(3)} = 2(1-4\sin^2\theta_W)\, F(Q^2,s) \rightarrow$ *(N-Δ resonance)*



At tree-level:

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

- F contains kinematic information & weak transition form factors
  → Extract $G^A_{N\Delta}$ from F



Raw Blinded Asymmetry *(averaged over inelastic region)*

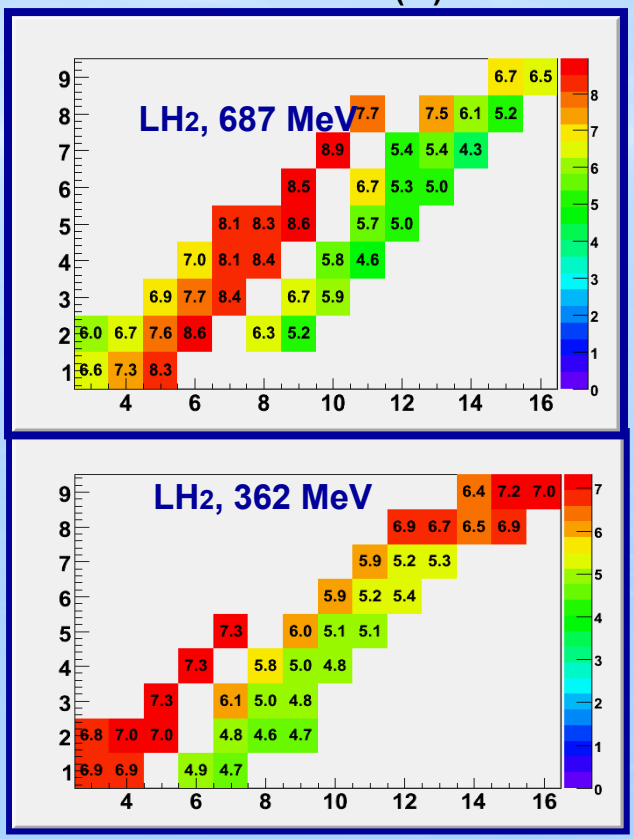
Some examples of corrections

- Deadtime corrections to the yield
  - Simulated the complete electronics chain:

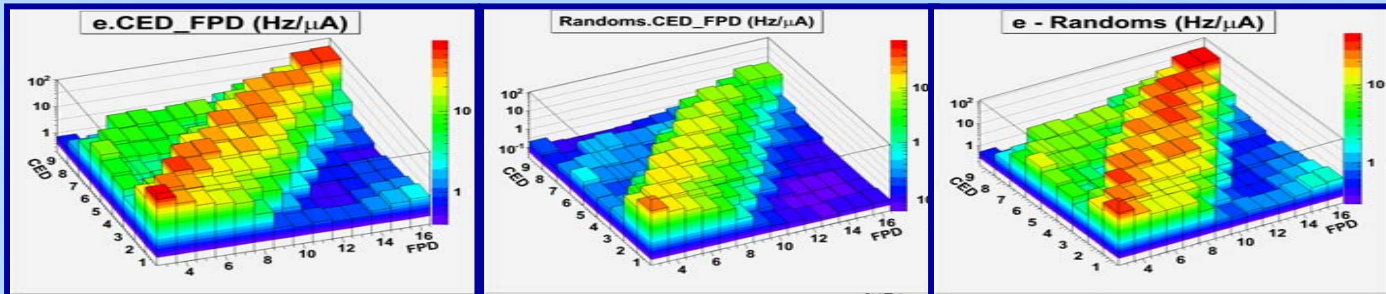
LH_2, 687 MeV, 60 μA	**~ 7%**
LH_2, 362 MeV, 60 μA	**~ 6%**
LD_2, 687 MeV, 20 μA	**~ 9%**
LD_2, 362 MeV, 35 μA	**~13%**

(work in progress)

Deadtimes (%)

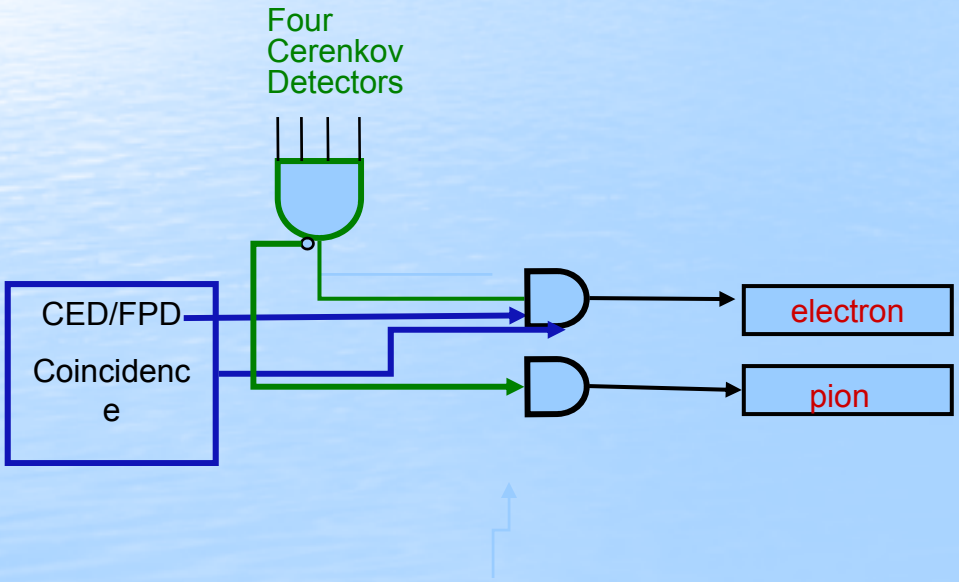


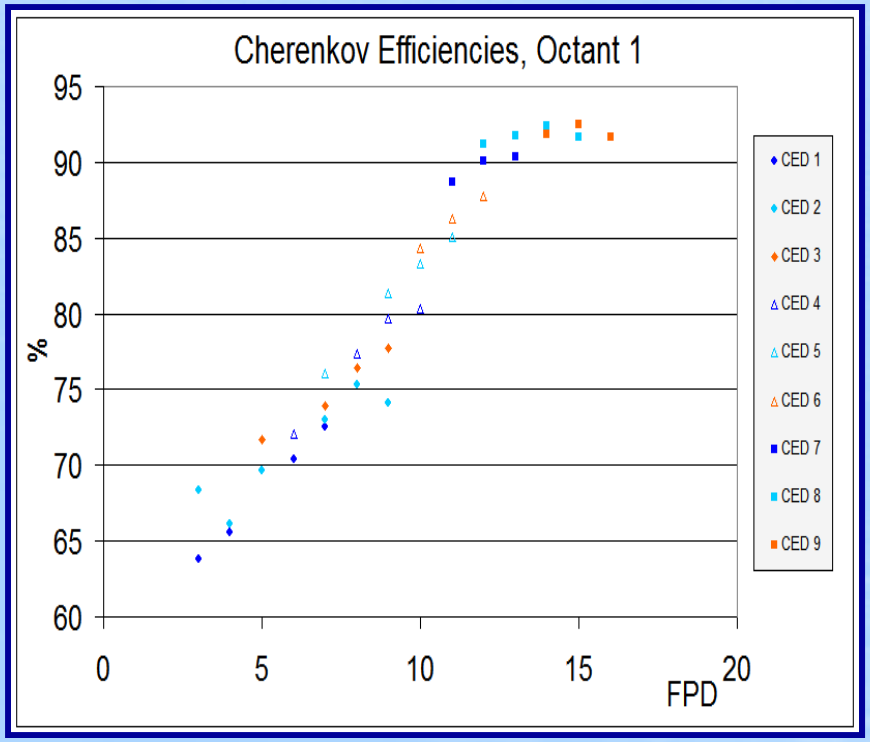
- Randoms corrections
  - LH2 randoms small
  - LD2 randoms significant, esp. inelastic el.
    - measure directly!



Cerenkov Efficiencies

- Electron detection efficiency
- Determined using three different techniques
- Does not change asymmetry

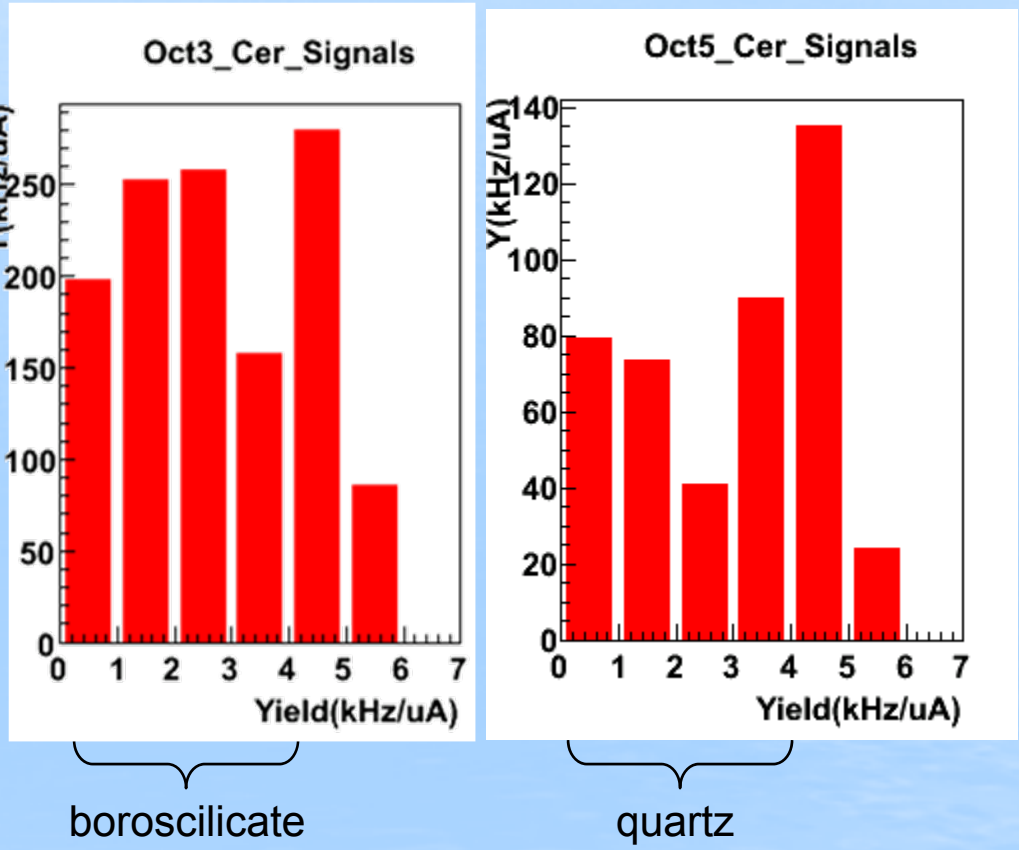




Quartz PMTs

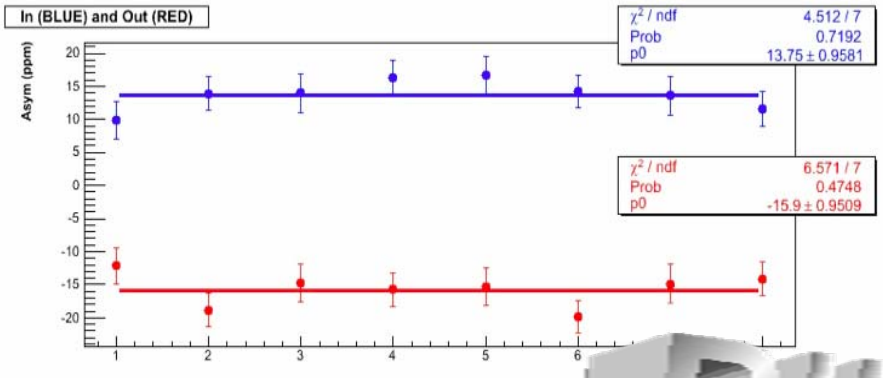
- Aerogel Cerenkov counters for π/e separation (LD2)
  - 4 - 5 in. PMTs each
  - boroscilicate glass very sensitive to neutrons
  - replace with quartz
  - beam current for LD2 limited by
    high real π rates $\oplus$
    (neutron) Ch. accidentals

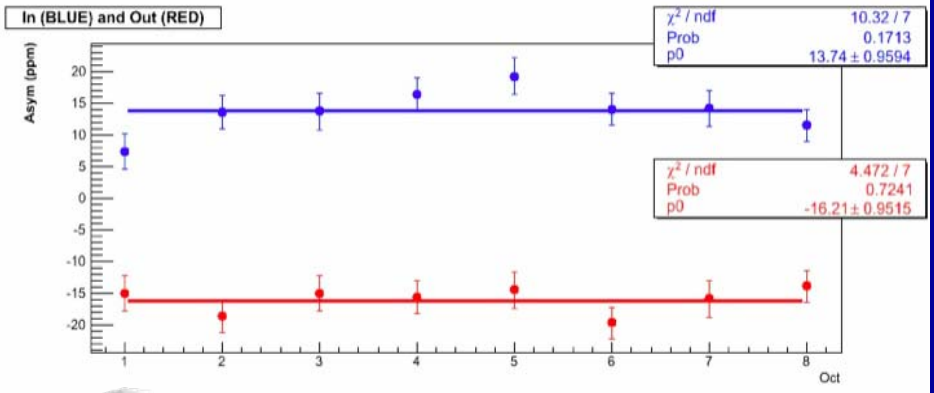
- quartz tubes allow increase in effective electron efficiency by ~x2
  - current limits 20 μA (35 μA) at 687 (362) MeV
- final tubes installed over Xmas break



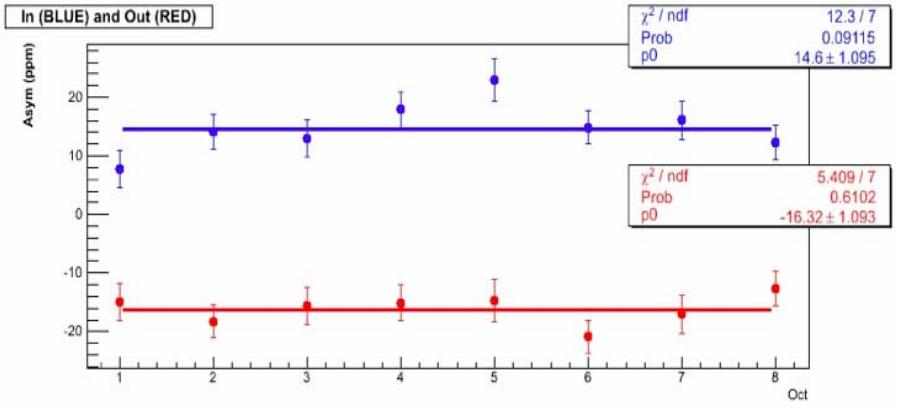
Note difference in vertical scales

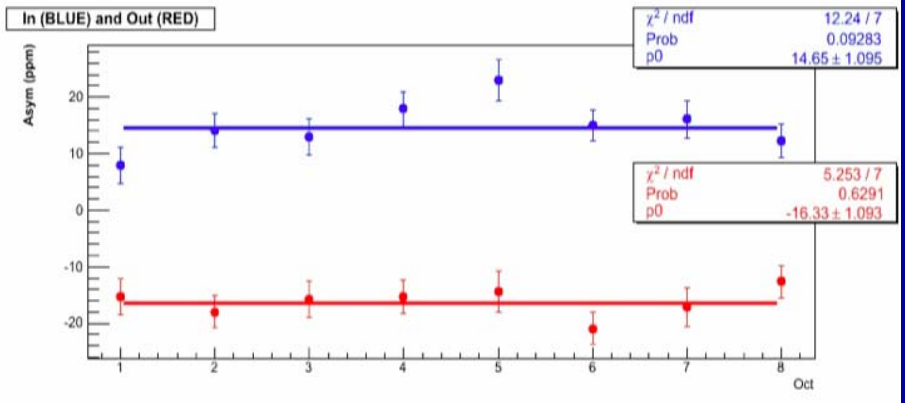
Four Pass Asymmetries (LD2 362 MeV)





Blinded



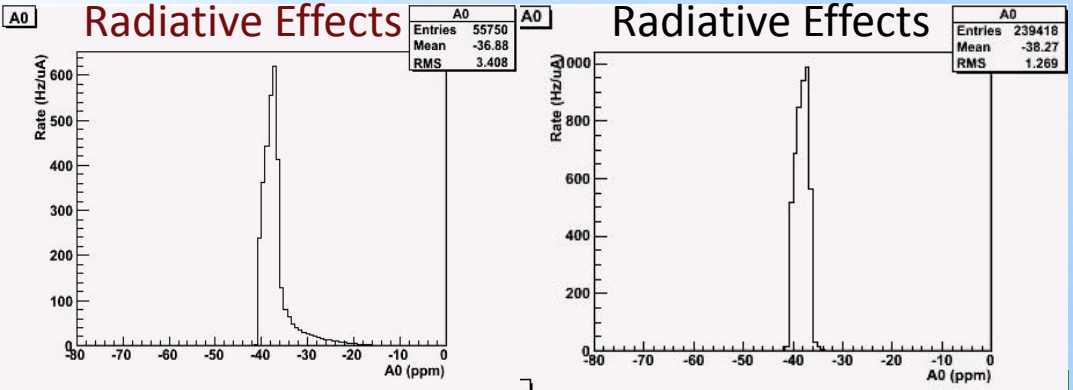


Electromagnetic Radiative Corrections

Target	Energy	$A_{0\ rc}$	$A_{0\ tree}$	$Rc_{correction}$
LD2	687	-46.6	-48.43	3.7%
LD2	362	-13.64	-14.17	3.9%
LH2	687	-36.81	-38.22	3.8%
LH2	362	-10.1	-10.49	3.9%

Preliminary Raw Blinded

LH2 687 With Radiative Effects



LH2 687 Without Radiative Effects

Follow process of Tsai [SLAC=PUB-848] 1971.

Compute asymmetry [A_p^R] based on the kinematics at the reaction vertex after the radiative emission.

This is compared to Born asymmetry calculation [A_p^T] with $G_E^s = G_E^s = 0$

Both A_p^R and A_p^T are calculated including ionization losses in the target prior to scattering.

$$R_C = A_p^T / A_p^R$$

Geant Strategy:

- Generate electron at random point in target
- Assign random scattering direction and energy to the electron
- Calculate cross section and asymmetry for that scattering process