G0 Backward Angle: Jeopardy Review

D. Beck, UIUC
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Main points

- G0 goal is to measure G_E^s, G_M^s and G_A^e over range of momentum transfers with best possible precision
- Requires backward angle H_2 and D_2 measurements
- Modify original plan to run with 499 MHz beam structure
- Improve precision significantly with higher beam current

Quark Currents in the Nucleon

- Measure $G^{\gamma,p}, G^{Z,p}, G^{\gamma,n}$ $\quad G \sim \langle N | \sum e_q \, \bar{q} \Gamma_\mu q | N \rangle$

  - e.g. $G^{\gamma,p} = \frac{2}{3} G^{u,p} - \frac{1}{3}\left(G^{d,p} + G^{s,p}\right)$

  - note: $\left.\begin{aligned} G^{u,p} &= G^{d,n} \\ G^{d,p} &= G^{u,n} \\ G^{s,p} &= G^{s,n} \end{aligned}\right\}$ charge symmetry

    (see G. A. Miller PRC **57** (98) 1492.)

  then

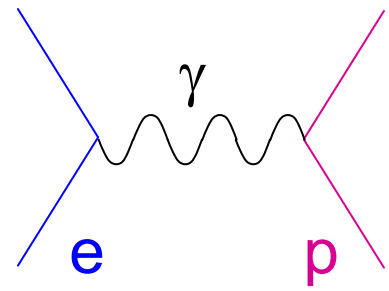
$$\boxed{\begin{aligned} G_{E,M}^{u,p} &= \left(3 - 4\sin^2\theta_W\right) G_{E,M}^{p,\gamma} - G_{E,M}^{p,Z} \\ G_{E,M}^{d,p} &= \left(2 - 4\sin^2\theta_W\right) G_{E,M}^{p,\gamma} + G_{E,M}^{n,\gamma} - G_{E,M}^{p,Z} \\ G_{E,M}^{s,p} &= \left(1 - 4\sin^2\theta_W\right) G_{E,M}^{p,\gamma} - G_{E,M}^{n,\gamma} - G_{E,M}^{p,Z} \end{aligned}}$$

Parity-Violating Electron Scattering

- $G^{Z,p}$ contributes to electron scattering

$$\sigma \propto \left| M^{\gamma} + M^{Z} \right|^{2}$$

- interference term: **large** M^{γ} x small M^{Z}



- interference term violates parity: use $(\vec{e},e')$

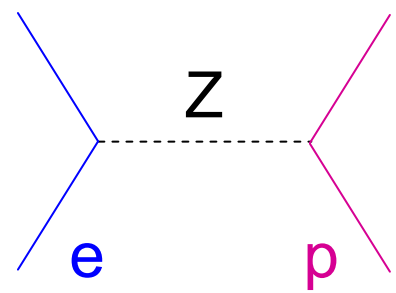
$$A^{PV} \equiv \frac{\sigma_{+} - \sigma_{-}}{\sigma_{+} + \sigma_{-}}$$

$$\propto \frac{A_E + A_M + A_A}{2\sigma_{unp}}$$

where

$$A_E = \varepsilon(\theta) G_E^{\gamma} G_E^{Z}, A_M = \tau G_M^{\gamma} G_M^{Z}$$

$$A_A = -\left(1 - 4\sin^2\theta_W\right)\varepsilon'(\theta) G_M^{\gamma} G_A^{e}$$



G0 Backward: Program

- Match forward angle range with measurements at 3 momentum transfers

Q^2 (GeV^2)	Beam Energy (GeV)	Target	Rate (MHz)	Asymmetry (ppm)
0.3	0.424	H_2	2.03	-18
		D_2	2.80	-25
0.5	0.576	H_2	0.718	-32
		D_2	1.10	-43
0.8	0.799	H_2	0.190	-54
		D_2	0.274	-72

- Measure both H and D targets to separate back angle contributions from G_M^s and G_A^e
  - 30 d running time equalizes statistical, other uncertainties
  - for all energies, uncertainties ~ minimized for equal running times

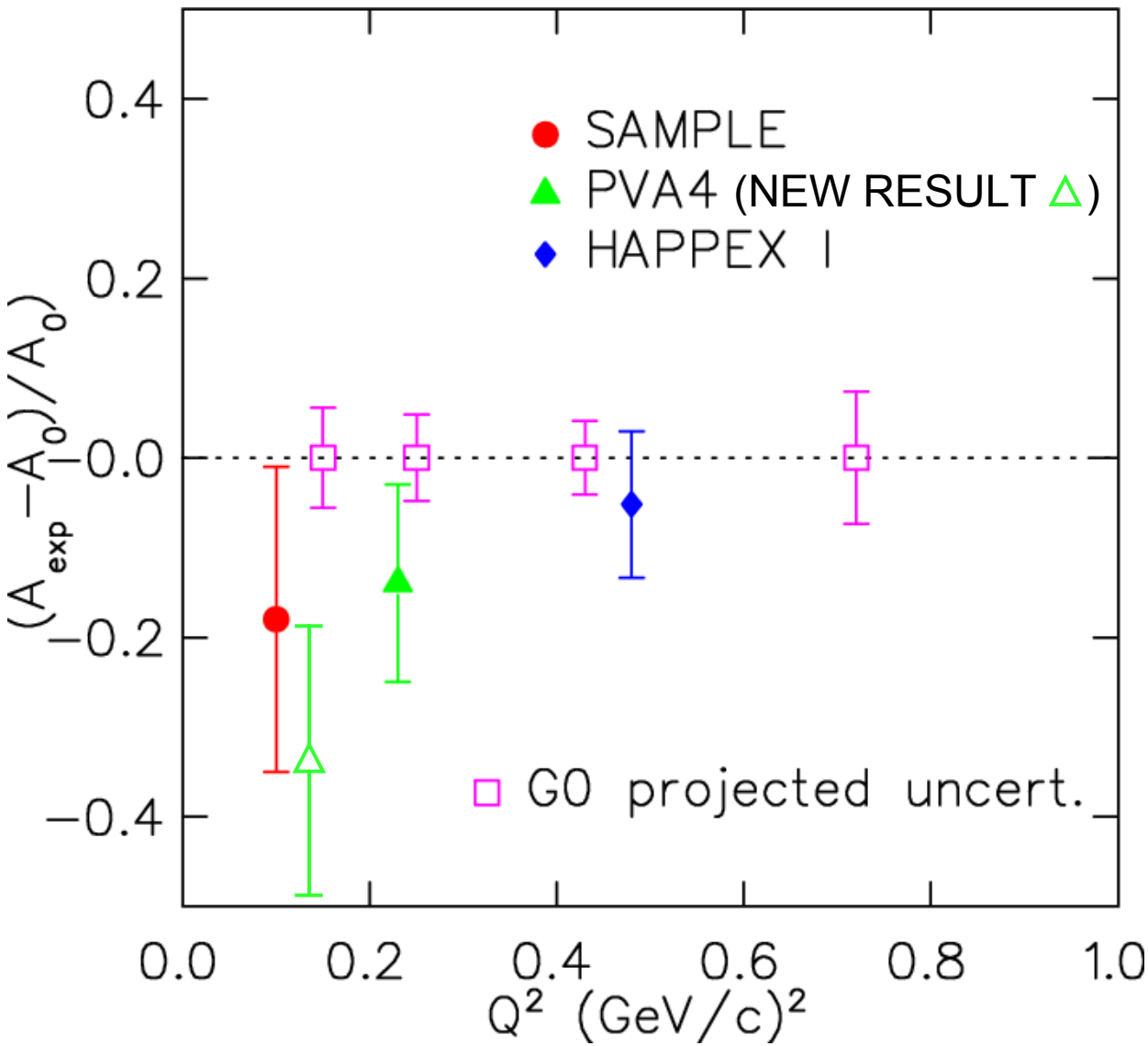
Summary of PV eN Experiments

Lab/Expt	Target	Q^2 (GeV^2)	$\|A_{phys}\|$ (ppm)	Sensitivity	Status
MIT-Bates					
- SAMPLE	H_2	0.10	7	$\mu_s + 0.5\ G_A^e$	published
- SAMPLE-II	D_2	0.10	8	$\mu_s + 2.3\ G_A^e$	published
- SAMPLE-III	D_2	0.04	3	$\mu_s + 2.8\ G_A^e$	published
JLab Hall A					
- HAPPEX		0.47	15	$G_E^s + 0.39\ G_M^s$	published
- HAPPEX II	H_2	0.11	1.5	$\rho_s + \mu_p\mu_s$	running
- HAPPEX He	^4He	0.11	10	ρ_s	running
- Lead	^{208}Pb	0.01	0.5	neutron skin	2005?
Mainz					
- PVA4	H_2	0.23	6	$G_E^s + 0.23\ G_M^s$	accepted
- PVA4 II	H_2	0.11	2	$G_E^s + 0.11\ G_M^s$	analysis
- PVA4 IIA (?)	D_2	0.11, 0.23	3, 8	$G_E^s + \varepsilon\ G_M^s$	2005
- PVA4 III (?)	H_2, D_2	0.23, 0.47	30, 60	G_M^s, G_A^e	2005-6
JLab Hall C					
- G0 forward	H_2	0.1 – 1.0	3 - 40	G_E^s, G_M^s, G_E^e	analysis
- G0 backward	H_2 , D_2	0.3, 0.5 0.8	18 - 70	G_E^s, G_M^s, G_E^e	2005
- Q Weak	H_2	0.03	0.3	Q_W	2006?

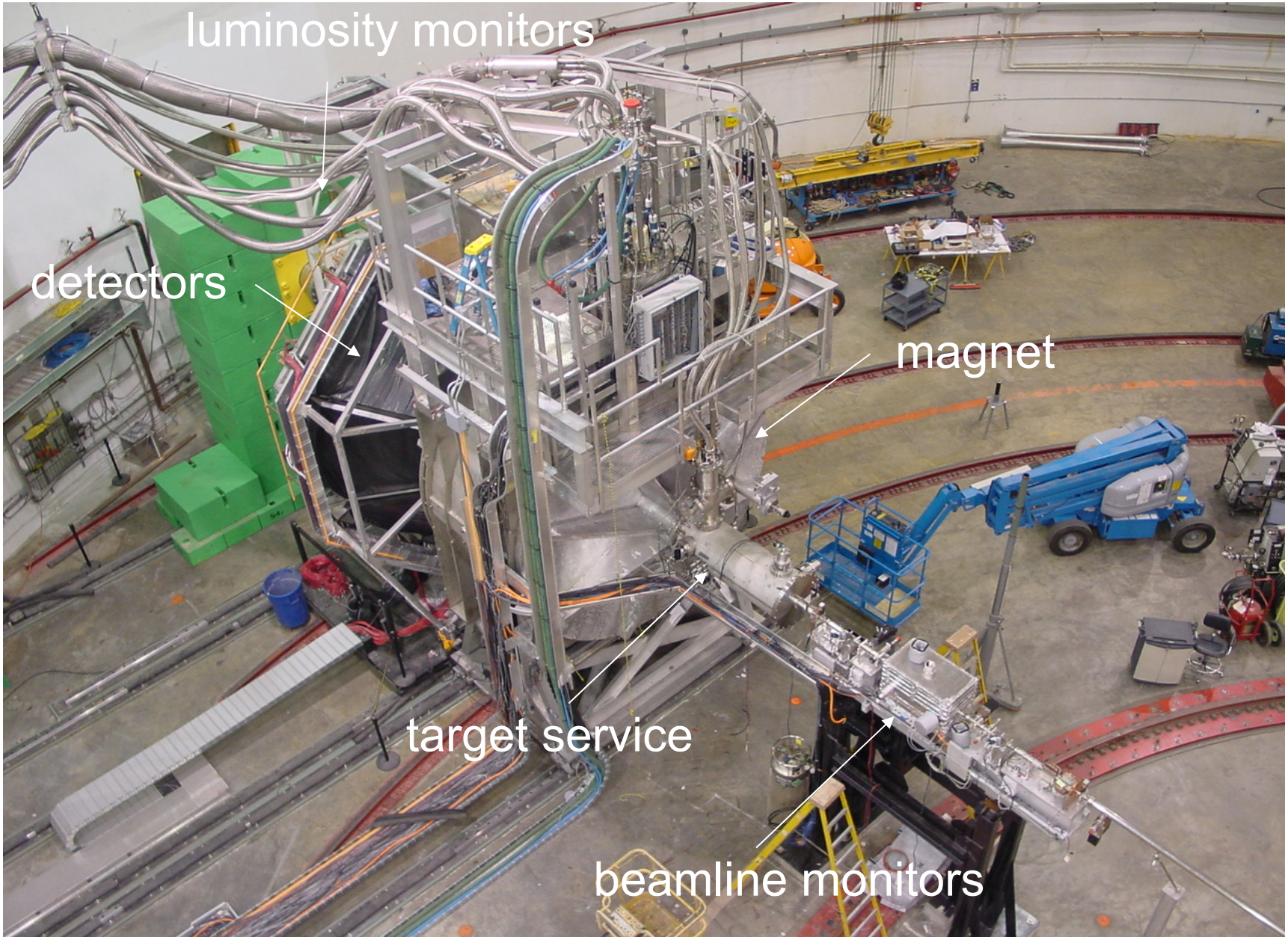
after K. Kumar

PV eN Results To Date

- Sensitivities are different; trend??

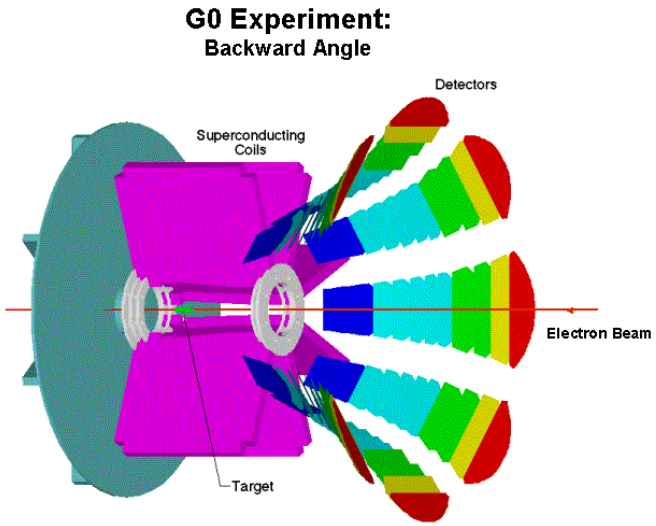


G0 in Hall C: Forward Angle



G0 Backward: Experiment

- Detect electrons at 110°; apparatus turned around
- Separate elastic, inelastic electrons using existing focal plane detectors (FPDs), cryostat exit detectors (CEDs, not shown)
  - provides measurement of momentum and angle



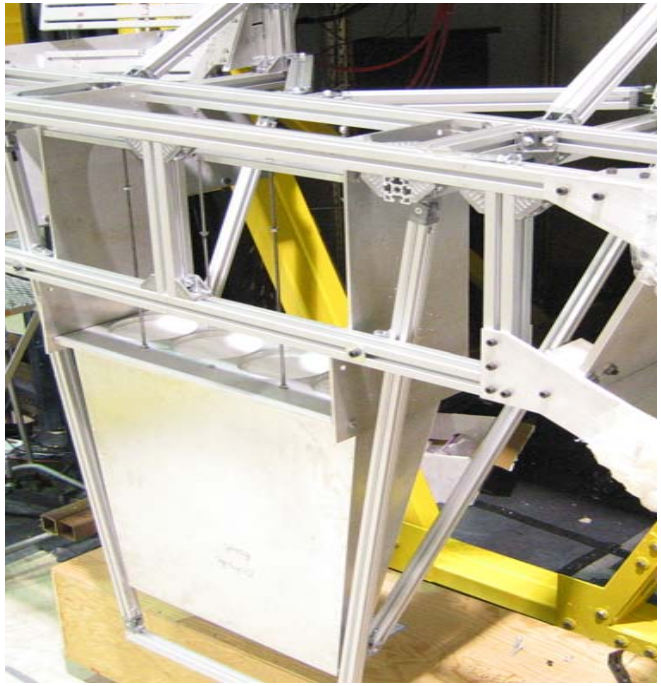
- Pion background in D_2 measurement subtracted using aerogel Cherenkov detector (not shown)
- Target performance will allow us to run at 80 μA (500 W)
  - limited by total power capacity
- Run with 499 MHz (rather than 31 MHz) beam structure
  - eliminates leakage asymmetry problem (forward angle)
  - allows for more straightforward accelerator operation
  - allows for higher beam current (> 40 μA)
- Change from beam trigger to detector trigger

G0 Backward: Added Detectors

- Cryostat exit detectors (CEDs) provide second measurement to determine electron momentum and angle
  - mounting in machined Rohacell box
  - scintillator/light guide fabrication complete
  - first octant being assembled

- Aerogel Cherenkov detector provides particle i.d. for pion rejection
  - prototypes tested in mixed beam at TRIUMF
    - rejection of ~ 100
  - first NA and Fr modules in house; others by end of summer

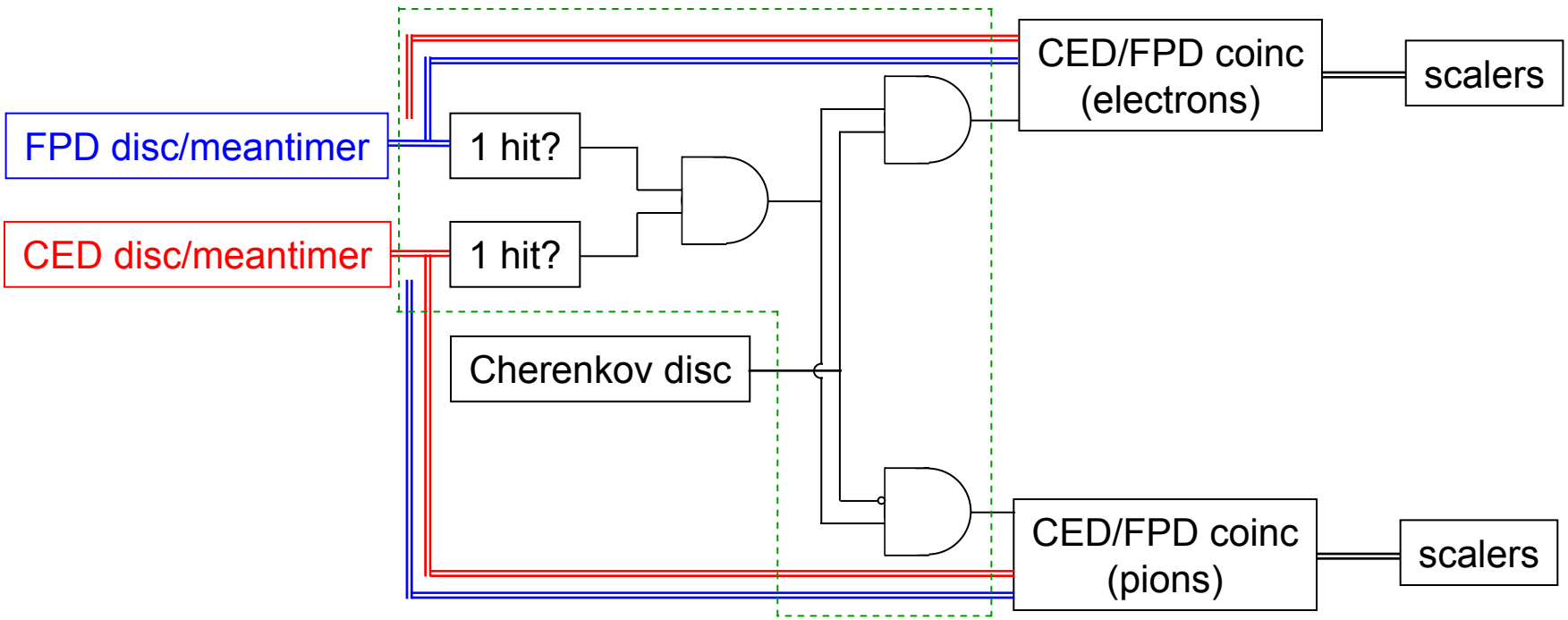
CEDs mounted in Rohacell box



Aerogel Cherenkov detector mounted in final detector frame

G0 Backward: Electronics Schematic

- Trigger on pairs of hits
  - beam pickoff signal (forward angle) replaced by this trigger
- Record both electron and pion yields (asymmetries)



New NIM module
from LPSC

G0 Backward: Background Summary

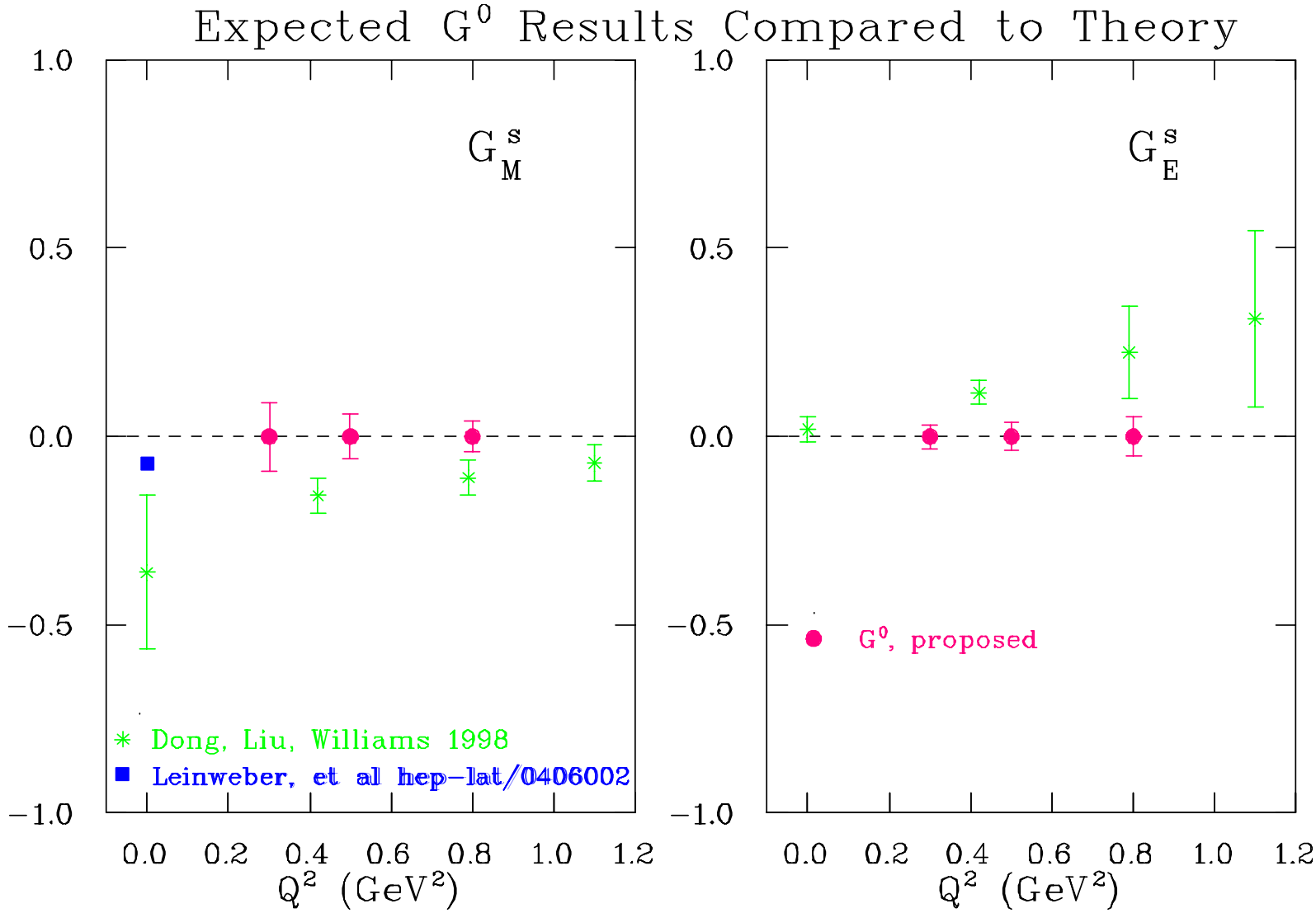
- Backgrounds from inelastic electrons, pions
  - pions measured using Cherenkov, subtracted
  - inelastic electron background subtracted
- Results for deuterium – worst case
  - assume $\Delta f_{inel}/f_{inel}$ = 20%

$$\Delta^2 A_{qe} = (1 + f_{inel})^2 \Delta^2 A_{meas} + (A_{meas} - A_{inel})^2 \Delta^2 f_{inel} + f_{inel}^2 \Delta^2 A_{inel}$$

Energy (MeV)	Rate (MHz)	Inel. fraction	A_{qe} (ppm)	A_{inel} (ppm)	ΔA_{qe} (%)	Increase (%)
424	2.80	3%	-25	-13	1.8	19
576	1.10	3%	-43	-21	1.8	21
799	0.274	10%	-72	-34	2.1*	28

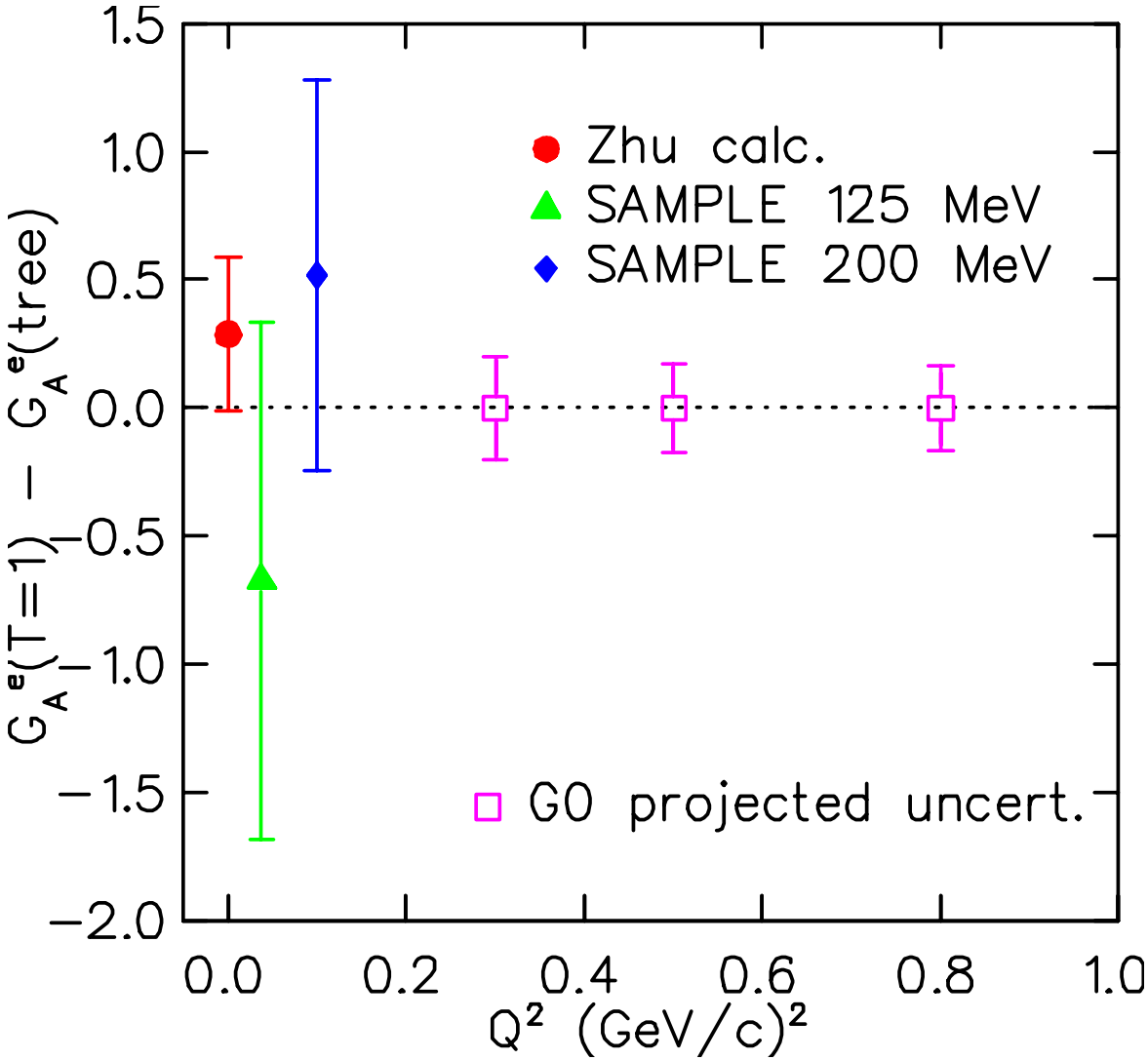
* Note: includes small contribution from pion background

G0 Backward: G_E^s and G_M^s



- includes all uncertainties (I_e=80 μA, P_e=75%)

G0 Backward: G_A^e



- includes all uncertainties (I_e=80 μA, P_e=75%)

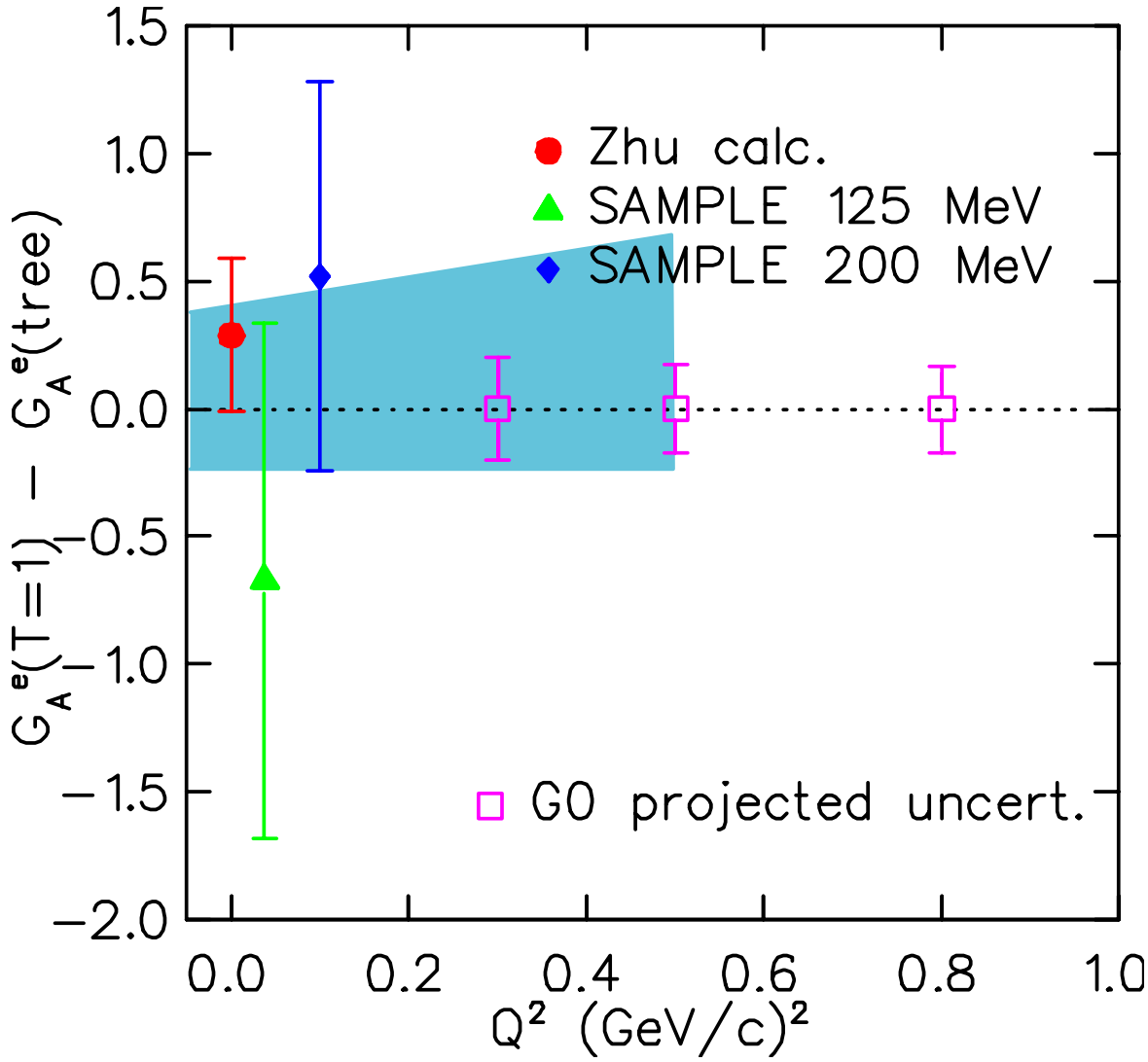
G0 Backward: Beam Time Request

- **Request re-approval of 60 d beam time for first backward measurement**
  - 30 d for each target
  - 80 μA reduces uncertainties in G_M^s and G_A^e by ~ 30%
- Q^2 for first measurement to be determined by physics outcome of forward measurement
  - in consultation with lab
- **Request approval of 10 d of commissioning time for checkout of new setup**
  - CEDs, Cherenkov detectors, electronics, target, background
    - roughly 6 shifts each distributed in 10 d period
    - based on successful forward angle commissioning plan (45 d)

- *Plan to return to the PAC in January to request time for remaining measurements to allow maximum scheduling flexibility*
  - possibility of 2 running periods rather than 3
  - saves 1 installation/removal cycle (~3 mo)

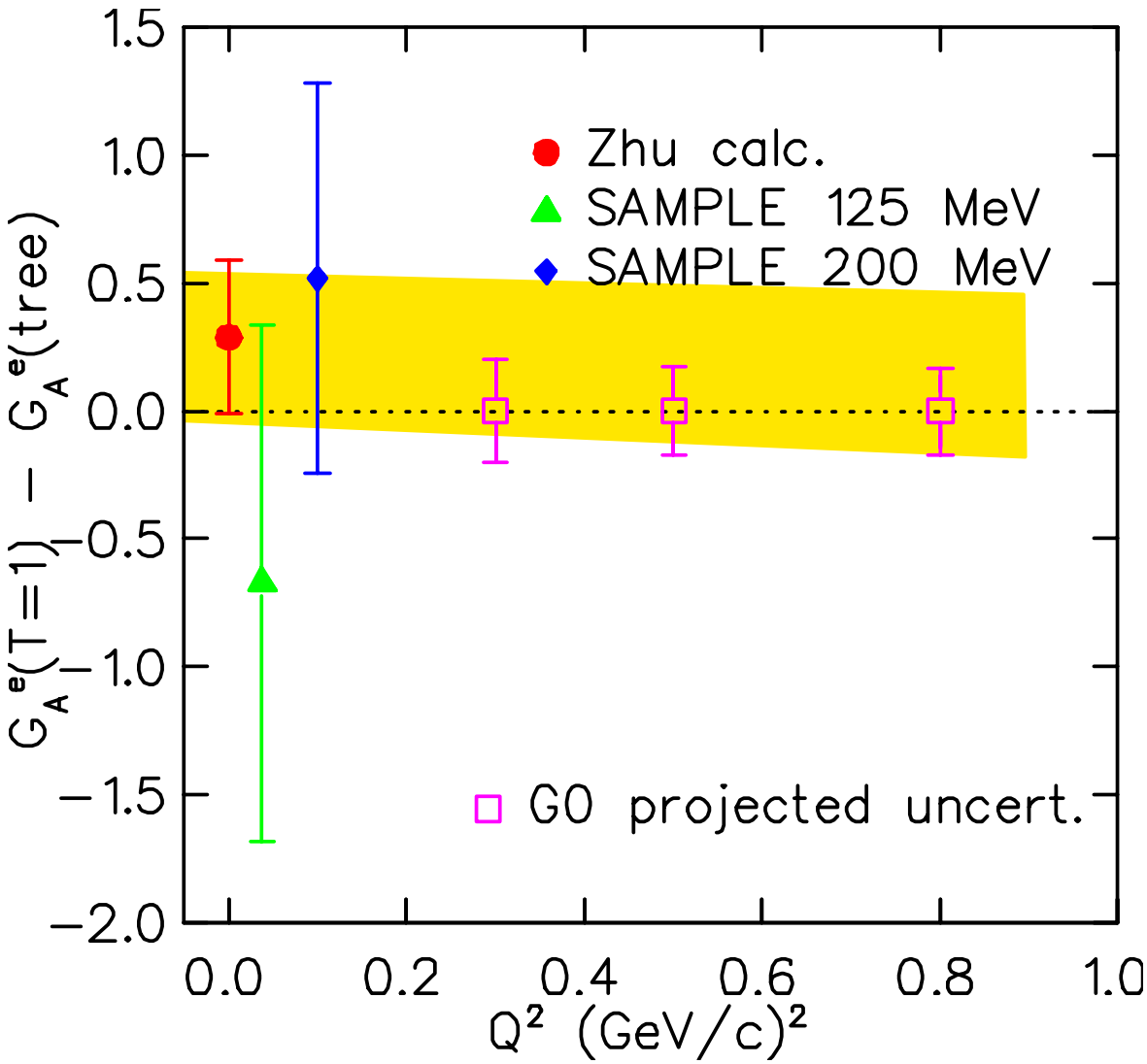
Extra Slides

G0 Backward: G_A^e



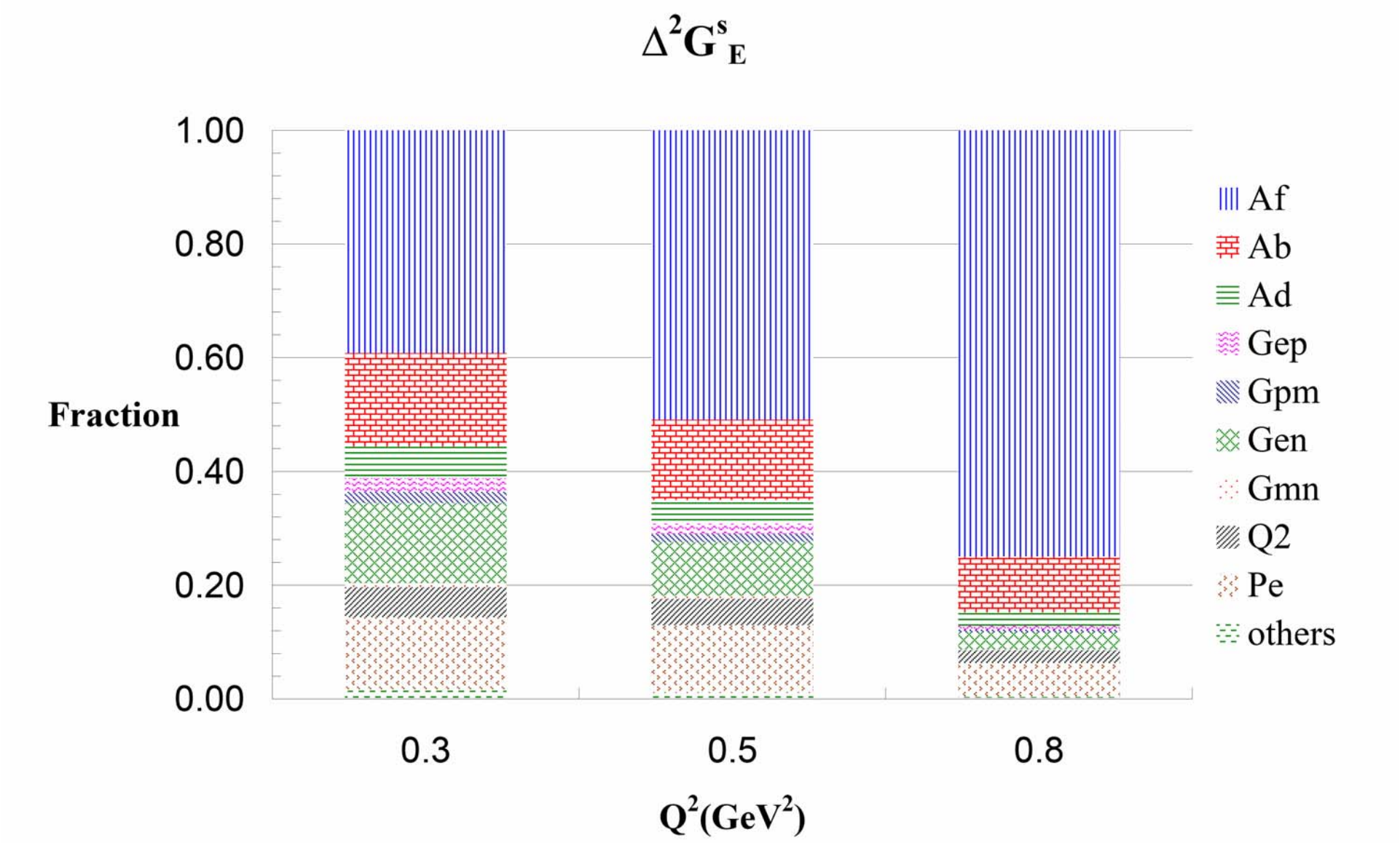
- Theory: Maekawa & van Kolck (chiral perturbation theory) PL **B488** (2000) 167

G0 Backward: G_A^e

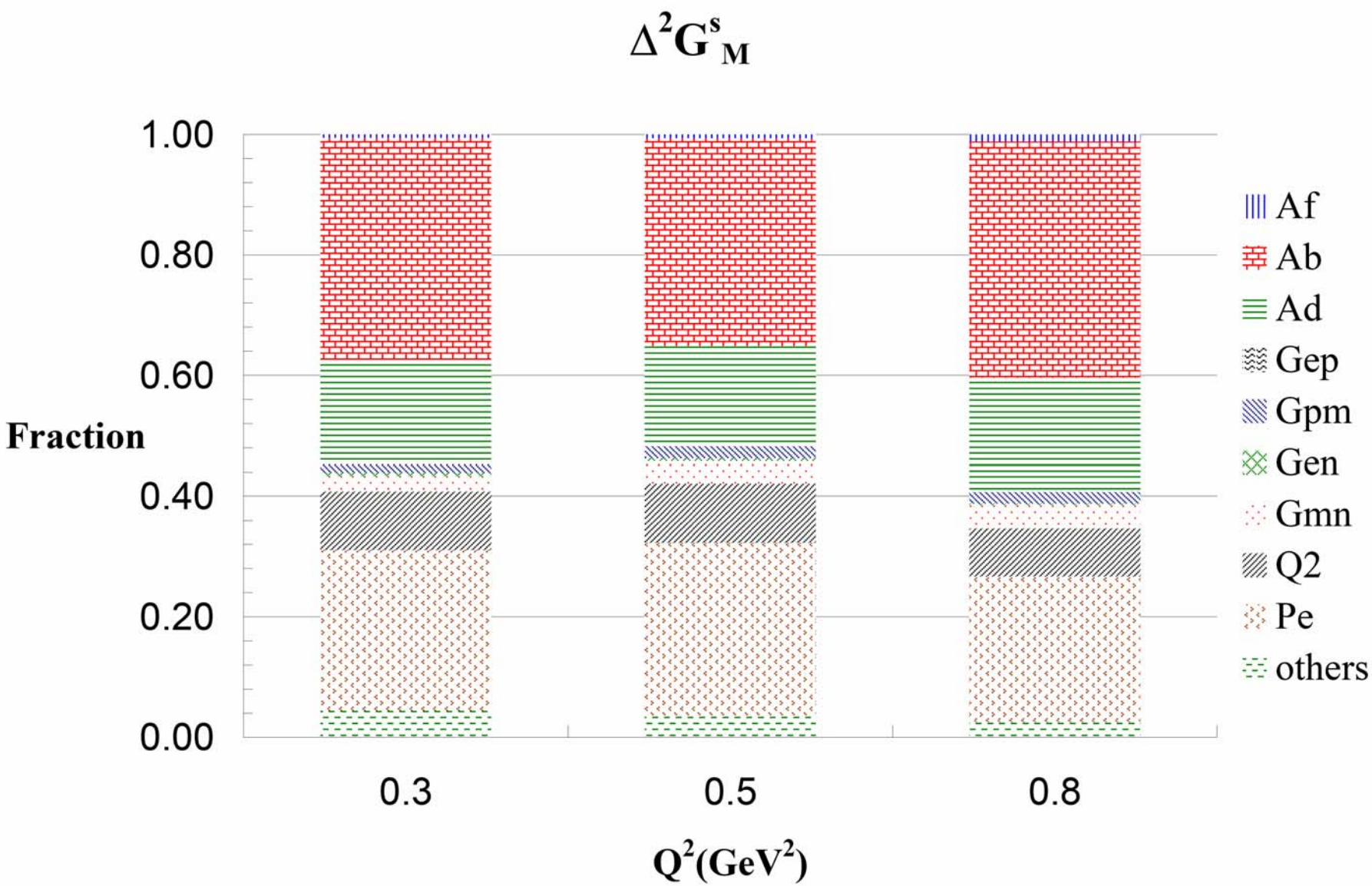


- Theory: Riska (chiral quark model) NP **A678** (2000) 79.

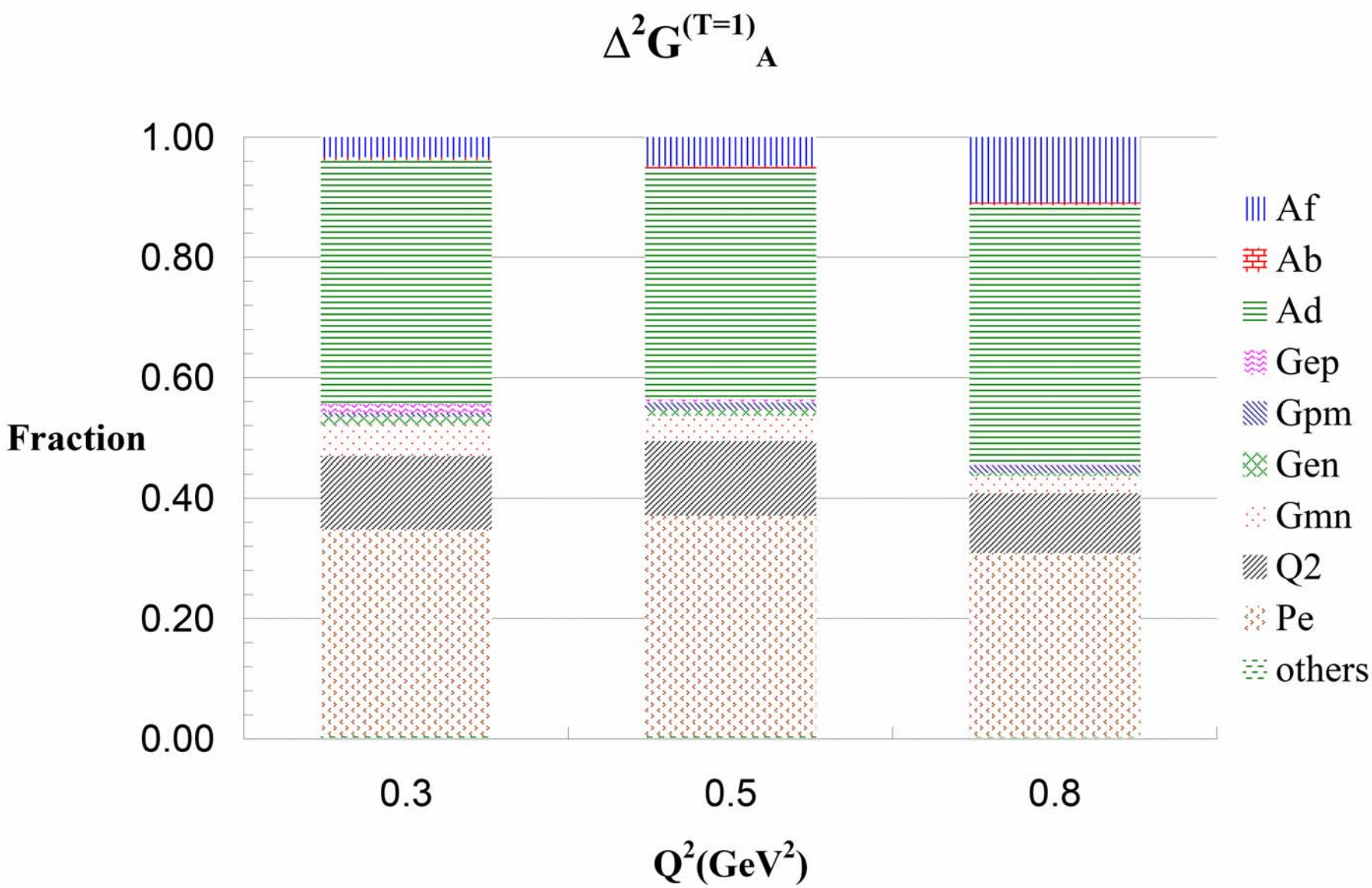
G0 Backward: Uncertainty Contributions G_E^s



G0 Backward: Uncertainty Contributions G_M^s



G0 Backward: Uncertainty Contributions G_A^E



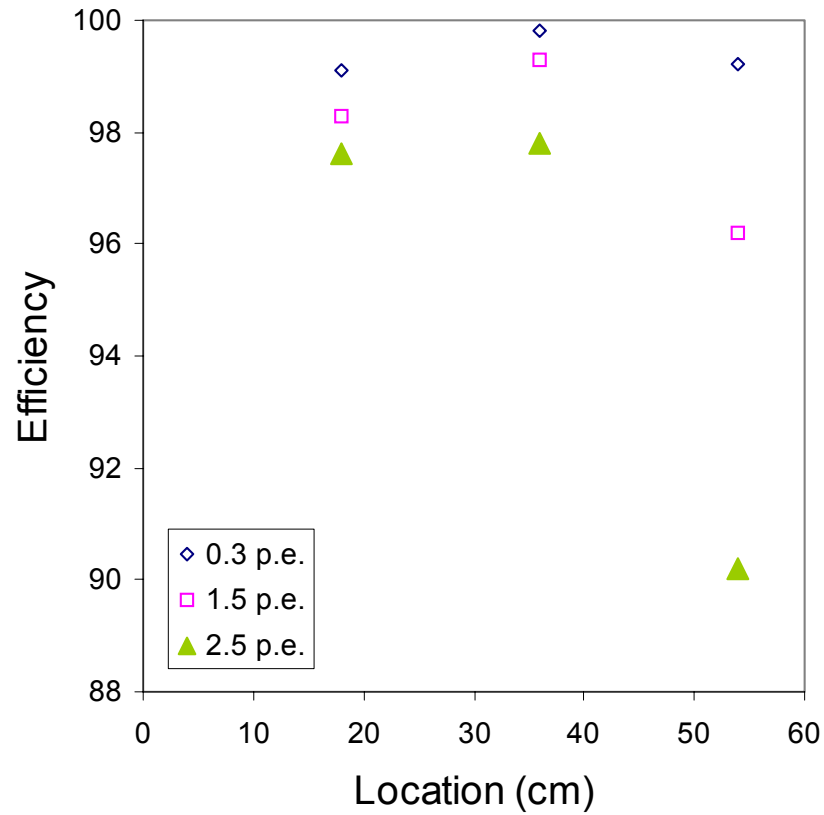
G0 Backward: Detector Thresholds

- Detector thresholds must be reduced relative to forward angle experiment
- Focal plane detector (FPD) thresholds must be reduced from those values used for proton detection
  - actual threshold will remain at 50 mV; tube gain will be increased
  - effective threshold at ~ 1/2 x minimum ionizing signal
    - m.i.p. ~ 200 (100) p.e.
  - downstream beamline shielding *was* necessary to shield FPDs from low energy γs
    - subthreshold, but large anode current contribution
  - NOTE: FPDs 14-16 largest volume detectors
- Cryostat exit detectors designed for electron detection
  - m.i.p. ~ 100 p.e.
  - thresholds also at 50 mV

FPD	ΔGain
1	6.1
2	5.8
3	5.5
4	5.3
5	5.1
6	4.8
7	4.4
8	4.1
9	3.8
10	3.5
11	3.1
12	2.8
13	2.6
14	1.6
15	1.6
16	1.6

G0 Backward: Cherenkov Efficiency

- Efficiency measured with prototype detector with mixed test beam at TRIUMF
  - ~ 6 p.e. peak



- Gradient actually very low

$$\frac{d\varepsilon}{dx} \sim 0.04\,\%/\text{mm at Cherenkov}$$

- c.f.

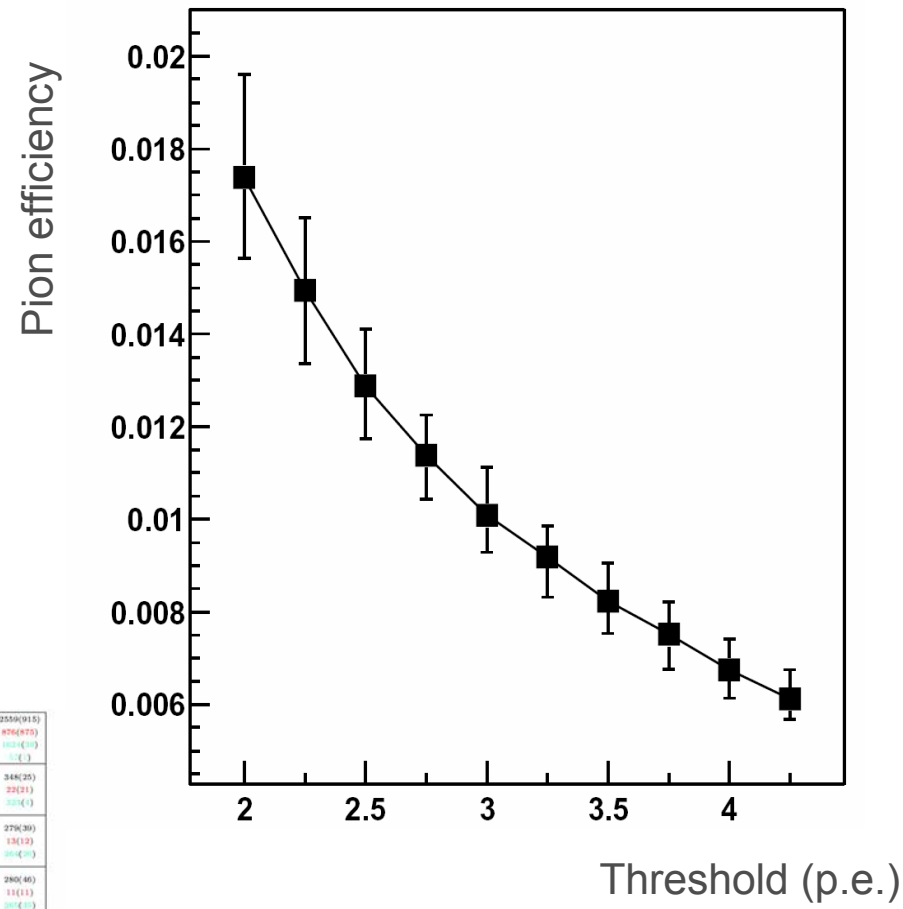
$$\frac{dY}{dx_{beam}} \sim 1\,\%/\text{mm}$$

due to solid angle effect

  - these slopes contribute to false asymmetry of ~ 10^{-9} in forward measurement

G0 Backward: Cherenkov Rejection

- Pion efficiency measured with prototype detector with mixed test beam at TRIUMF
  - rejection factor of ~100



Measure rejection factor on-line using region of spectrum where pions dominate

- function of position (CED no.)

CED 9 40480 Hz (4360 Hz)	179(10) 173(0)	329(26) 320(0)	323(25) 315(0)	181(9) 172(0)	146(14) 137(0)	208(19) 189(0)	320(31) 19(18) 297(0)	292(84) 21(20) 267(0)	268(97) 27(26) 235(0)	261(55) 38(37) 217(0)	776(118) 47(47) 720(0)	1546(141) 57(56) 1463(0) 32(0)	2780(155) 86(85) 2638(0) 35(0)	6746(1043) 918(917) 5845(0) 16(0)	5736(1431) 1325(1323) 4255(0) 15(0)	2559(915) 876(875) 1624(0) 53(0)
CED 8 39105 Hz (3674 Hz)	3(0)	92(1) 90(0)	112(2) 109(0)	173(9) 160(0)	805(16) 800(0)	2472(25) 2369(0)	2865(16) 2831(0)	1139(35) 1120(0)	1087(77) 14(13) 1054(0) 12(0)	2095(80) 20(20) 2012(0) 63(0)	8050(509) 361(361) 7340(0) 169(0)	9678(1335) 1091(1090) 8405(0) 183(0)	3121(927) 885(885) 2161(0) 75(0)	902(324) 292(292) 609(0)	478(67) 60(60) 418(0)	348(25) 22(21) 326(0)
CED 7 48767 Hz (4062 Hz)	56(0) 56(0)	82(38) 75(0)	229(17) 229(0)	874(19) 869(0)	1542(6) 1536(0)	1084(1) 1079(0)	1236(24) 13(13) 1217(0)	759(33) 13(13) 717(0) 29(0)	3467(123) 37(37) 3354(0) 76(0)	15704(954) 479(479) 15060(0) 156(0)	11450(1753) 1280(1280) 9981(0) 189(0)	1965(727) 653(653) 1279(0) 33(0)	554(157) 133(133) 416(0)	271(69) 32(31) 236(0)	180(30) 15(15) 161(0)	279(39) 13(12) 264(0)
CED 6 69783 Hz (4525 Hz)	98(3) 97(0)	301(13) 296(0)	945(24) 935(0)	1294(22) 1284(0)	576(19) 556(0)	766(11) 755(0)	1631(108) 14(14) 1556(0) 50(0)	10511(403) 82(82) 10279(0) 150(0)	24462(1279) 550(550) 23604(0) 308(0)	12320(1463) 1127(1127) 11000(0) 193(0)	2825(865) 783(783) 1987(0) 55(0)	576(141) 120(119) 449(0)	352(54) 23(23) 329(0)	295(31) 14(14) 277(0)	282(23) 11(11) 268(0)	280(46) 11(11) 265(0)
CED 5 83279 Hz (3785 Hz)	155(1) 154(0)	1032(10) 1027(0)	1147(45) 1120(0)	570(65) 501(0)	620(29) 603(0)	2299(84) 2214(0) 77(0)	22242(635) 95(95) 21633(0) 507(0)	20880(877) 391(391) 20370(0) 91(0)	11447(1190) 932(932) 10350(0) 164(0)	2787(740) 672(672) 2061(0) 54(0)	980(206) 161(161) 819(0)	388(73) 23(23) 359(0)	374(42) 10(10) 359(0)	435(33) 421(0)	259(17) 247(0)	305(5) 294(0)
CED 4 116845 Hz (4603 Hz)	862(35) 859(0)	1142(55) 1120(0)	939(48) 923(0)	910(54) 857(0)	8164(135) 19(19) 7974(0) 171(0)	29534(615) 99(99) 29029(0) 406(0)	36472(1469) 538(538) 35593(0) 341(0)	12630(1301) 943(943) 11590(0) 96(0)	4094(884) 786(785) 3219(0) 89(0)	1745(225) 215(215) 1510(0) 19(0)	1163(109) 41(41) 1105(0) 16(0)	1288(38) 13(13) 1261(0) 14(0)	1214(93) 10(10) 1189(0) 14(0)	1333(63) 1303(0) 30(0)	706(72) 688(63) 18(0)	778(55) 753(0) 18(0)
CED 3 108733 Hz (4254 Hz)	349(1) 348(0)	820(35) 809(0)	1559(102) 13(13) 1520(0) 26(0)	13817(251) 26(26) 13544(0) 248(0)	29509(790) 90(90) 28941(0) 478(0)	24779(982) 400(400) 24118(0) 259(0)	18350(1444) 1001(1001) 17550(0) 799(0)	3426(745) 622(622) 2759(0) 45(0)	1891(340) 208(208) 1664(0) 19(0)	1300(160) 47(47) 1228(0) 24(0)	1263(63) 20(20) 1224(0) 19(0)	1003(50) 14(14) 974(0) 14(0)	925(77) 13(13) 896(0) 16(0)	1100(78) 13(12) 1057(0) 15(0)	932(33) 11(11) 910(0) 10(0)	823(48) 805(0) 18(0)
CED 2 98309 Hz (3464 Hz)	405(33) 396(0)	1823(99) 12(12) 1776(0) 35(0)	19086(317) 36(35) 18760(0) 290(0)	26648(548) 81(81) 26227(0) 339(0)	21671(749) 313(313) 21118(0) 239(0)	11292(1076) 750(750) 10377(0) 166(0)	6463(965) 733(733) 5626(0) 104(0)	1480(295) 191(191) 1274(0) 14(0)	1196(83) 54(54) 1124(0) 18(0)	1020(37) 28(28) 976(0) 15(0)	1151(70) 26(26) 1107(0) 17(0)	699(54) 23(23) 669(0) 16(0)	518(27) 15(15) 494(0)	710(28) 19(19) 664(0)	332(25) 12(12) 311(0)	475(24) 15(15) 458(0)
CED 1 134057 Hz (4567 Hz)	5234(115) 5201(100) 33(0)	31964(685) 49(49) 31466(0) 449(0)	47963(920) 152(151) 47156(0) 655(0)	30992(1183) 499(490) 30174(0) 319(0)	15049(1299) 970(970) 13967(0) 112(0)	4399(826) 753(753) 3555(0) 90(0)	4481(490) 364(364) 4053(0) 64(0)	1985(110) 64(64) 1860(0) 61(0)	2364(60) 39(39) 2299(0) 26(0)	2081(100) 29(29) 2013(0) 39(0)	1617(66) 31(31) 1555(0) 30(0)	1264(118) 22(22) 1220(0) 19(0)	844(54) 17(17) 811(0) 16(0)	867(74) 21(21) 831(0) 15(0)	551(36) 17(17) 526(0) 13(0)	771(51) 19(18) 720(0) 33(0)
single rates	FPD 1 82434 Hz (1432 Hz)	FPD 2 134854 Hz (3244 Hz)	FPD 3 134419 Hz (3966 Hz)	FPD 4 97704 Hz (3678 Hz)	FPD 5 90822 Hz (3954 Hz)	FPD 6 85750 Hz (3984 Hz)	FPD 7 111967 Hz (5787 Hz)	FPD 8 66534 Hz (4139 Hz)	FPD 9 62684 Hz (4368 Hz)	FPD 10 49753 Hz (4162 Hz)	FPD 11 38924 Hz (3962 Hz)	FPD 12 24742 Hz (2804 Hz)	FPD 13 18465 Hz (2139 Hz)	FPD 14 16710 Hz (2044 Hz)	FPD 15 12687 Hz (1874 Hz)	FPD 16 10696 Hz (1635 Hz)

G0 Backward: Beam Background

- Two types: beam halo, hall background

- Beam halo
  - measurements during forward angle experiment
  - rates in small scintillators near beam pipe ~ 20 kHz

- To do: Hall background calculations (radiation protection group)
- Experience in forward measurement
  - useful in determining source of low energy background
  - *recall*: detectors close to downstream shower from 2.3% radiation length target
  - sub-threshold
    - did not affect recorded spectra
    - did generate large anode current – worry about tube lifetime
  - note that singles rates in the detectors varied from 90 kHz (FPD 1) to 270 kHz (FPD 13)

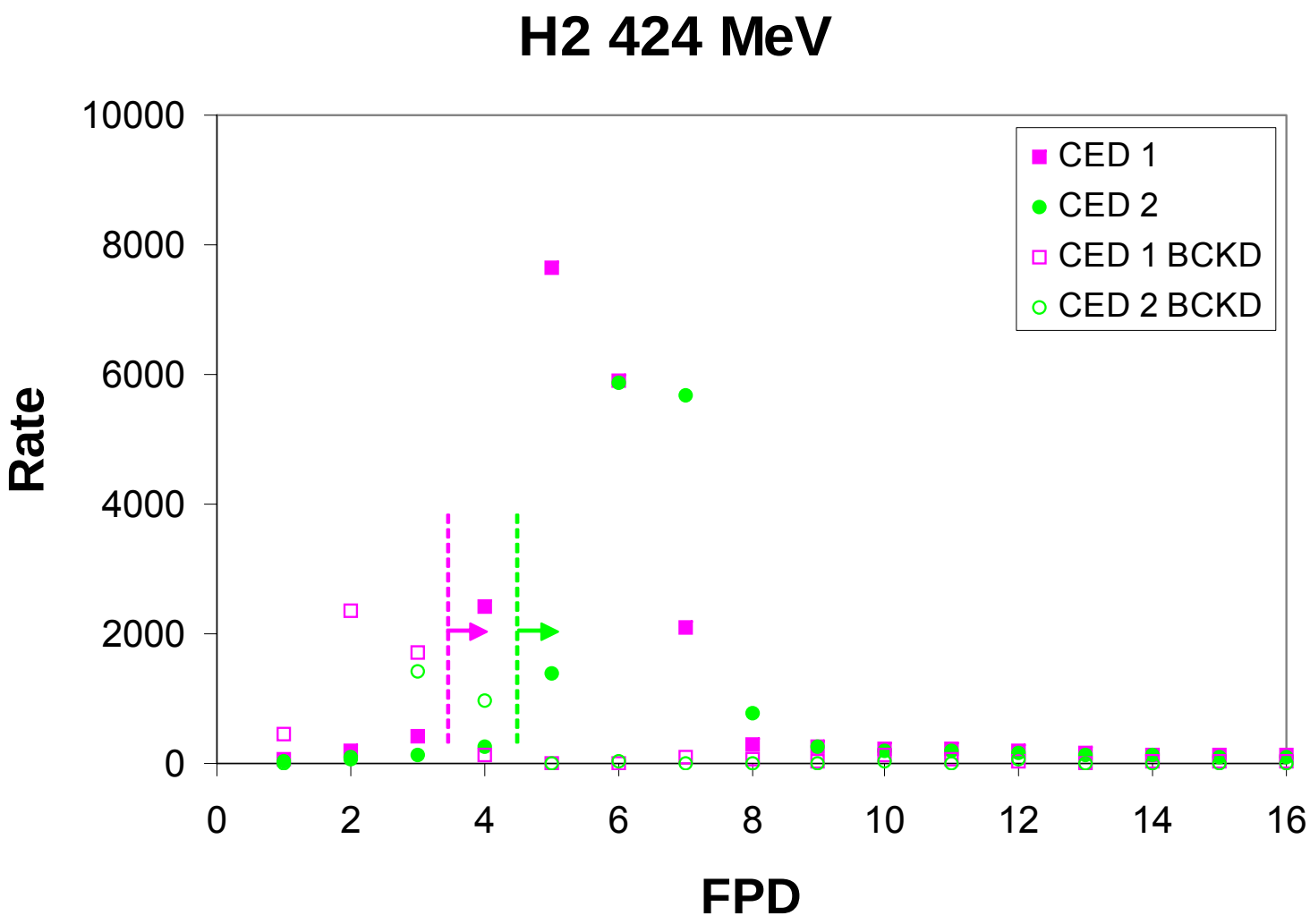
G0 Backward: Beam Specifications (1)

- Set stringent requirements for forward angle run – MET!
  - Helicity-correlated specs particularly important
- Same requirements for backward run are appropriate
  - easier with 499 MHz beam structure

Beam Parameter	**Achieved**	**"Specs"**
charge asymmetry	-0.14 ± 0.32 ppm	1 ppm
x position differences	3 ± 4 nm	20 nm
y position differences	4 ± 4 nm	20 nm
x angle differences	1 ± 1 nrad	2 nrad
y angle differences	1.5 ± 1 nrad	2 nrad
energy differences	29 ± 4 eV	75 eV

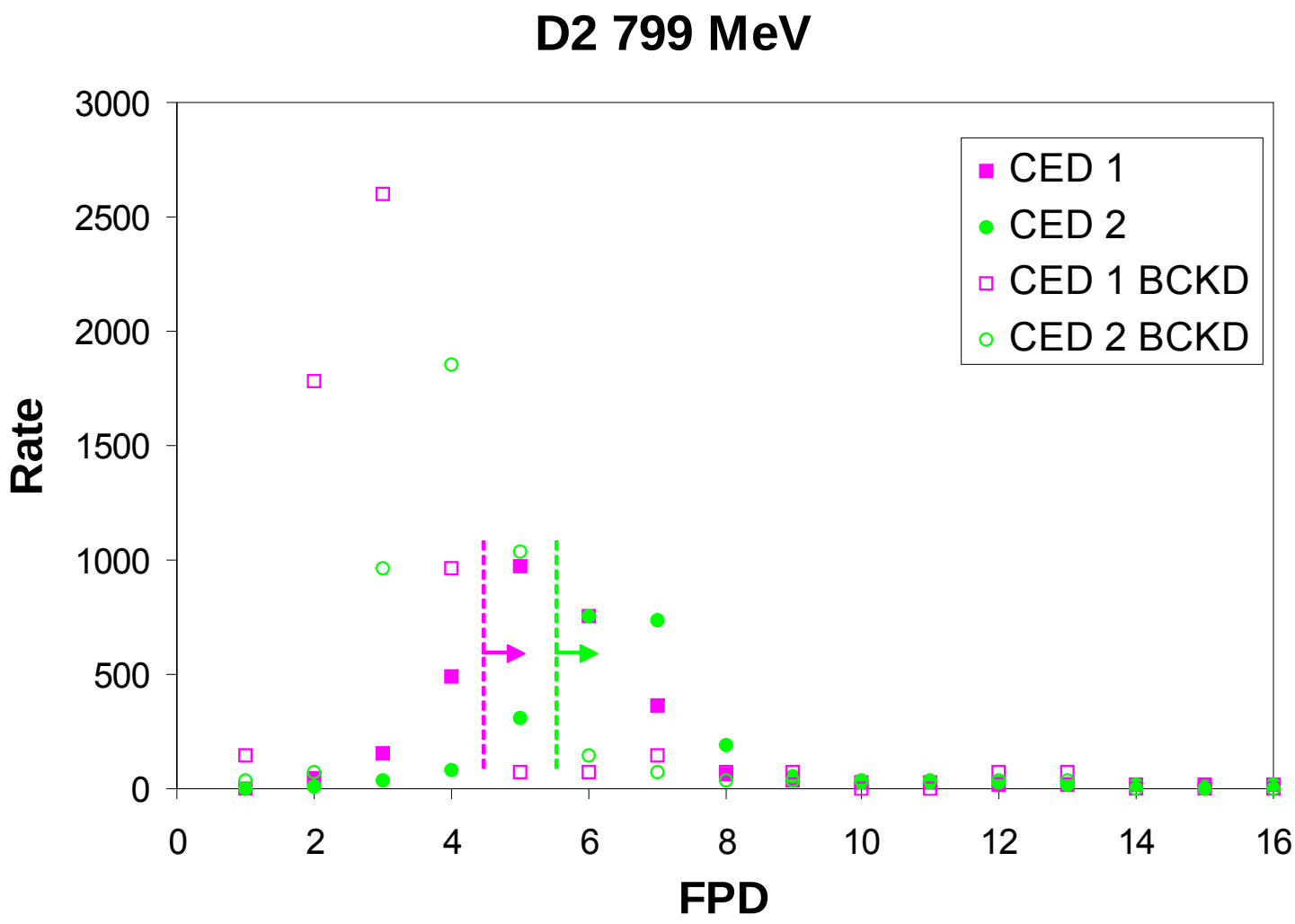
G0 Backward: H_2 Separation

- Best case example
  - Simulation: background in ‘elastic bins’ (CED/FPD pair) few %



G0 Backward: D_2 Separation

- Worst case example
  - Simulation: background in 'elastic bins' (CED/FPD pair) ~10 %



G0 Backward: Elastic Selection

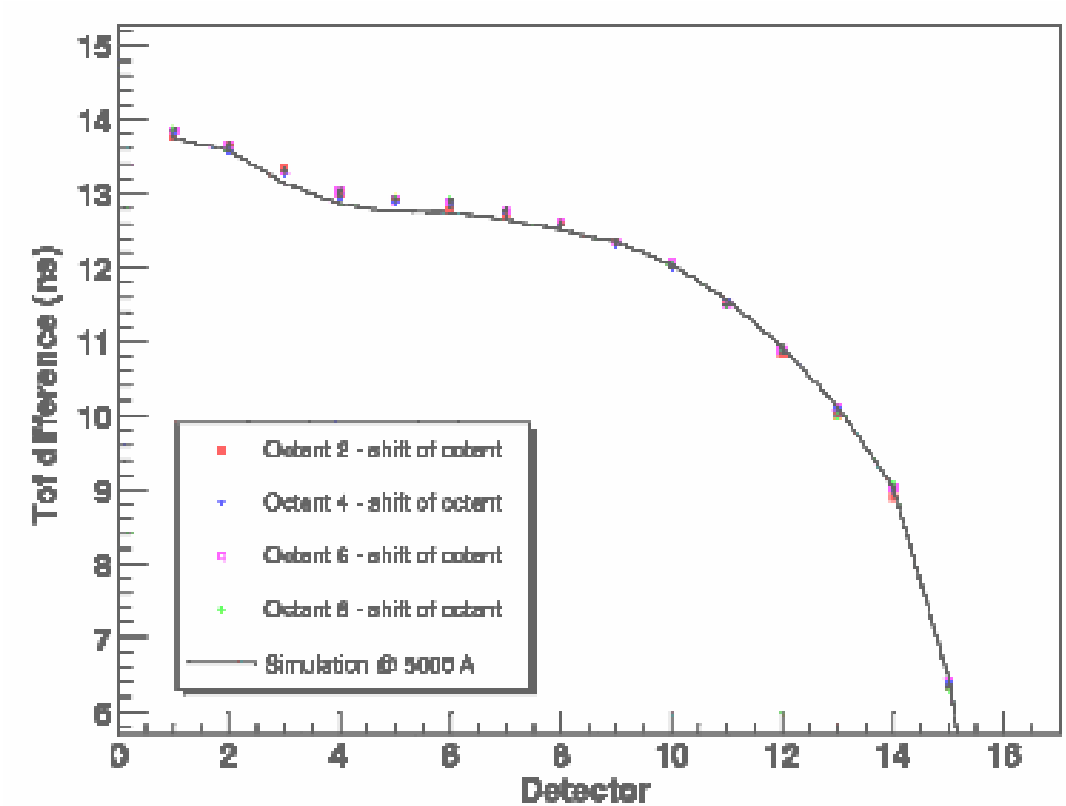
- Worst case example: 799 MeV D2 – *inelastic/elastic*

FPD/CED	1	2	3	4	5	6	7	8	9
1	36.33	6.17							
2	17.09	26.78	2.85						
3	1.97	22.91	39.92						
4	0.08	3.32	14.84	27.26					
5	0.10	0.19	2.60	18.75					
6	0.41	0.10	0.52	2.35	10.93	68.86	11.38		1.95
7	1.16	0.19	0.12	0.24	1.32	8.15	5.69		1.76
8	1.90	0.69	0.36	0.05	0.16	0.07	4.00	5.29	2.74
9		1.32	1.57	0.34	0.06	0.13	1.39	7.40	1.95
10		1.42	3.70	3.61	0.23	0.05	0.06	1.02	1.57
11		1.61	5.29	17.08	1.61	0.31	0.06	0.14	2.60
12		2.47	5.69	3.70	3.70	1.61	0.28	0.08	1.72
13			5.69			2.64	1.16	0.25	0.08
14							2.47	1.23	0.11
15							5.69	3.36	
16									

G0 Forward: Spectrometer Calibration

- Measure timing difference between pions and protons using Fastbus monitoring electronics

- Together with incident energy measurement, determined field integral and calibrated momentum transfer
  - relative timing to 100 ps
  - field integral determination to ~1%

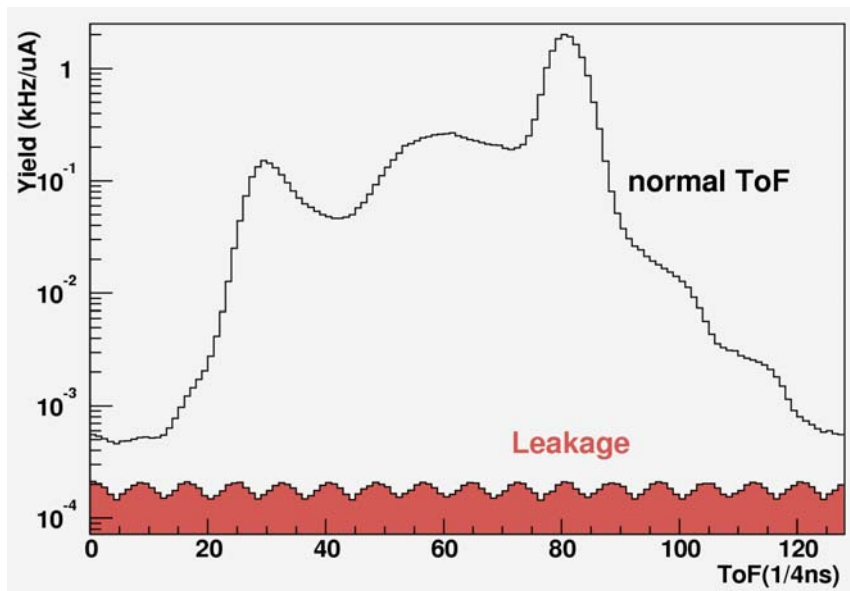


G0 Forward: Leakage Asymmetry (1)

- Laser light in polarized source does not 'turn-off' completely between pulses

- Normal operation
  - some (~10^{-3}) electrons produced by Hall A and B lasers 'leakage' comes into Hall C slit (chopper)

- G0 time structure
  - some (~10^{-3}) electrons produced by Hall A and B laser 'leakage' comes into Hall C main beam pulse (every 32 ns)
  - *some (~10^{-3}) electrons produced by Hall A, B and C laser 'leakage' comes in time between main Hall C beam pulses (every 2 ns)*

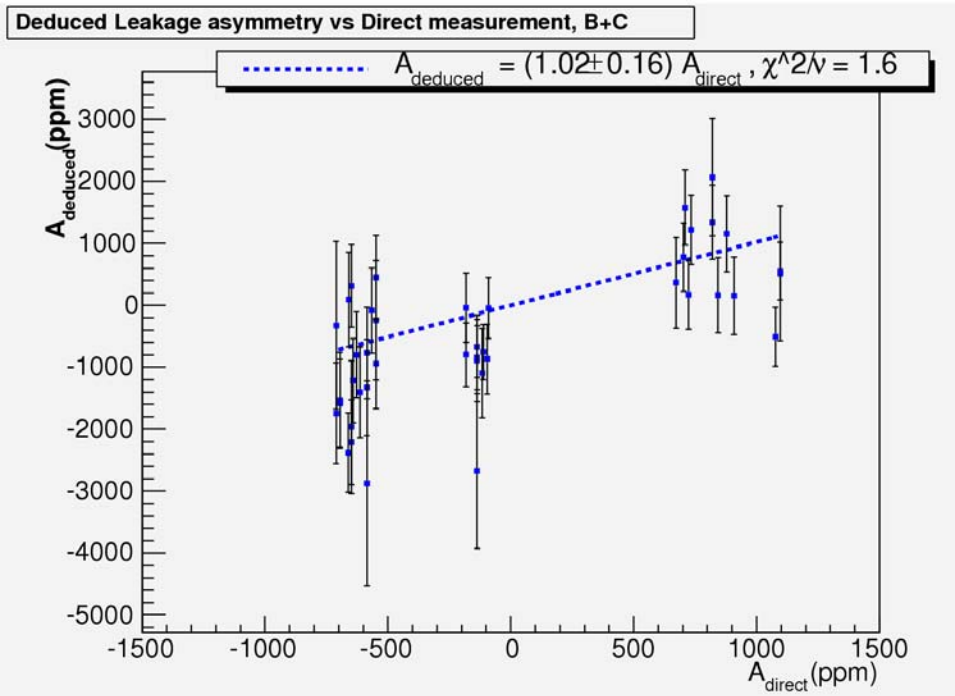


Schematic leakage current in G0 tof spectrum

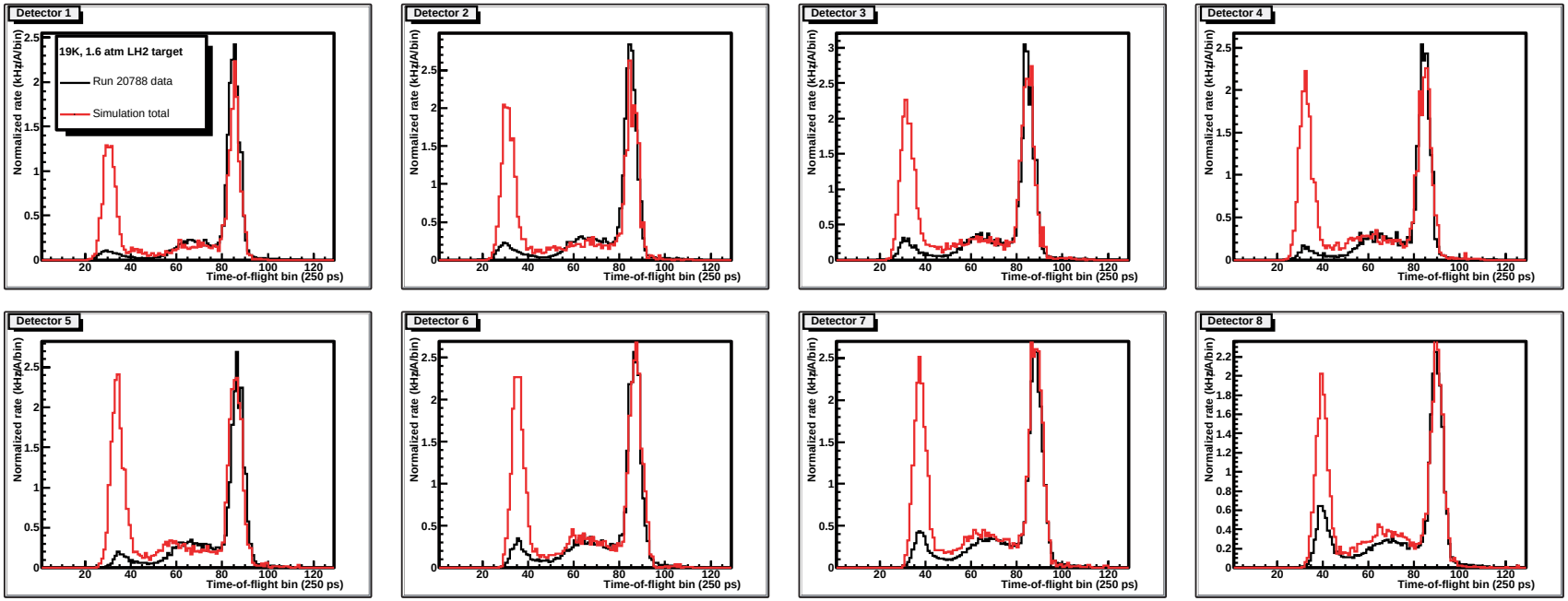
G0 Forward: Leakage Asymmetry (2)

- Key problem: leakage beams have different (large!) asymmetry than main Hall C beam
  - current monitors see all beams
  - feedback system to eliminate helicity-correlated beam current asymmetry *induces* current asymmetry in main Hall C beam
  - false asymmetry ~ 1 ppm for elastics

- Can see leakage asymmetry more or less directly in the time 'between' main pulses
  - after the slowest particles from the previous pulse (deuterons)
  - before the fastest particles from the current pulse (direct γs)
  - in general very sensitive in regions where counting rate is low



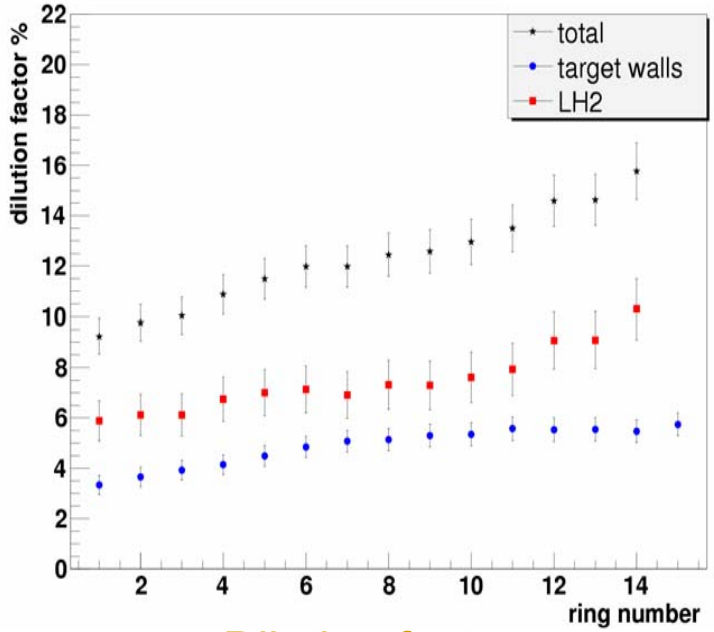
G0 Forward: Background Subtraction



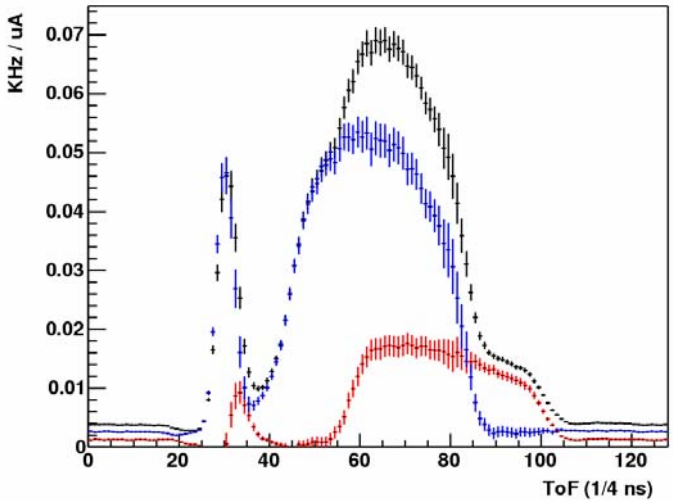
- Background under elastic proton peak – 2 main sources
  - inelastic protons from hydrogen
  - inelastic protons from aluminum and helium in target cell
- Strategy
  - determine correction to elastic asymmetry purely from data
    - yield and asymmetry in time bins around elastic peak
  - understand background yield and asymmetry from simulation/calculation

G0 Forward: Background Subtraction

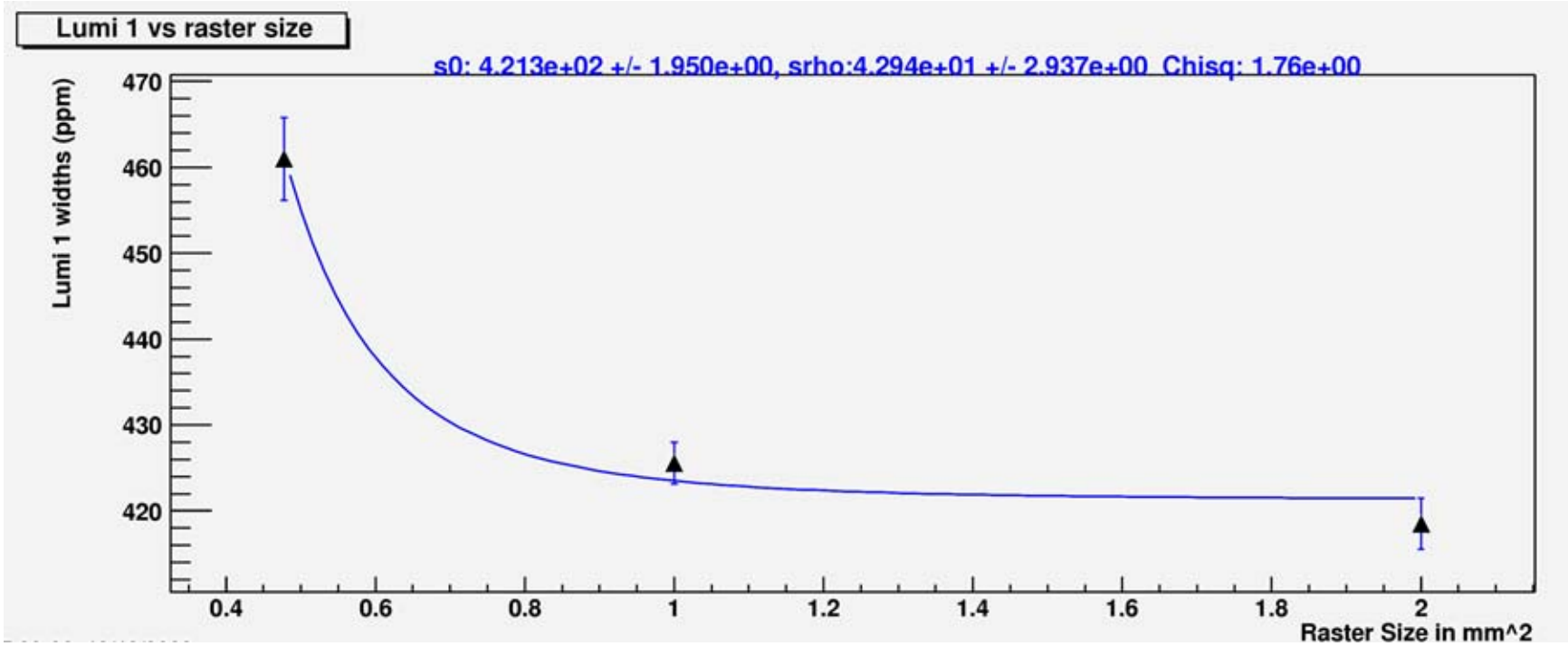
- Dilution factors: 9.5 – 15 ± 1%
  - using simple fits or simulation
- Aluminum/helium yield and asymmetry well understood from special runs
  - “flyswatter” target (1 mm aluminum, downstream end)
    - limited data ← mechanical failure
  - aluminum frame (3 mm, upstream end)
  - “empty” target running (H2 gas at two different densities)
- Investigating inelastic hydrogen asymmetries



Dilution factors



Entrance and exit target windows

G0 Forward: Target Performance

- Target performance exceeded expectations
- Two important issues for PV experiments
  - density fluctuations
    - this “noise” must be smaller than counting statistics
  - overall power
    - must maintain sub-cooling of target
- Target boiling contribution < 200 ppm