The Electric Form Factor of the Neutron with Polarized Targets

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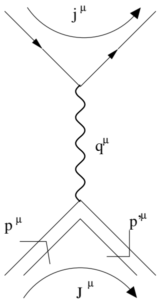
Outline

- Review of G_E^n-I, E02-013
- G_E^n to $Q^2 = 10\ \mathrm{GeV}^2$: E12-09-016
  - Requirements and Setup
  - Background
  - Time of Flight Issues

Nucleon Currents

Scattering matrix element, $M \sim \frac{j_\mu J^\mu}{Q^2}$
Generalizing to spin 1/2 with arbitrary structure, one-photon exchange, using parity conservation, current conservation the current parameterized by two form factors

$$J^\mu = e\bar{u}(p')\left[F_1(q^2)\gamma^\nu + i\frac{\kappa}{2M}q_\nu\sigma^{\mu\nu}F_2(q^2)\right]u(p)$$



Form Factors

- Dirac - F_1, chirality non-flip
- Pauli - F_2, chirality flip

Replace with Sachs Form Factors

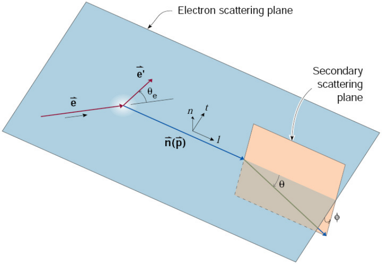
$$\begin{aligned} G_E &= F_1 - \kappa\tau F_2 \\ G_M &= F_1 + \kappa F_2 \end{aligned}$$

G_E/G_M at high Q^2 - Spin Observables, Pol. Transfer

- Akhiezer and Rekalo (1968) - Polarization experiments offer a better way to obtain G_E than Rosenbluth separation
- Polarization observable measurements generally have fewer systematic contributions from nuclear structure and radiative effects

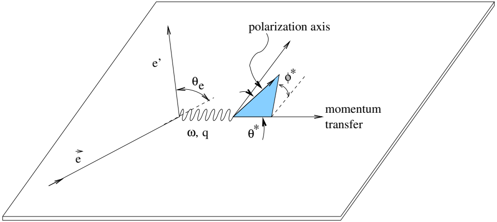
Polarization Transfer

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})\tan\theta_e/2}{2M}$$



G_E/G_M at high Q^2 - Spin Observables, Pol. Target

Long. polarized beam/polarized target transverse to $\vec{q}$ in scattering plane



Helicity-dependent asymmetry roughly proportional to G_E/G_M

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx A_\perp = -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2) G_E/G_M}{(G_E/G_M)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))}$$

Polarized Target Measurements - Nulling asymmetry

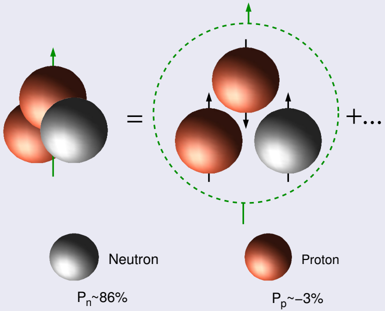
Long. polarized beam/polarized transverse to $\vec{q}$ in scattering plane

$$
\begin{aligned}
\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} &= A_\perp \sin\theta^* \cos\phi^* + A_\parallel \cos\theta^* \\
&= -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)\, G_E/G_M \sin\theta^* \cos\phi^*}{(G_E/G_M)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))} \\
&\quad -\frac{2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2(\theta/2)}\tan(\theta/2)\cos\theta^*}{(G_E/G_M)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))}
\end{aligned}
$$

- $A_\parallel$ provides "reference asymmetry" that is mostly dependent just on kinematic variables
- Setting $A_\parallel$ and $A_\perp$ to cancel by rotating target pol. angle reduces uncertainties contributed by scaling effects in asymmetry such as target and beam polarization
- Need to know G_E^n a priori to do it correctly, only for low Q^2

Polarized ^{3}He Target

- ^{3}He is spin 1/2, 3 body calculations describe polarization as



Polarization is carried mostly in *n*, protons are mostly unpolarized

- 86% only for inclusive case
- D-wave state contributes $\sim$ 10% to w.f. - sensitive to missing momentum range

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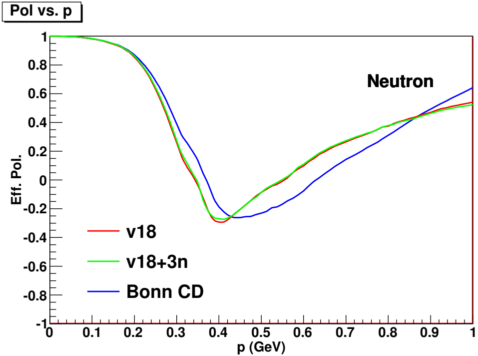

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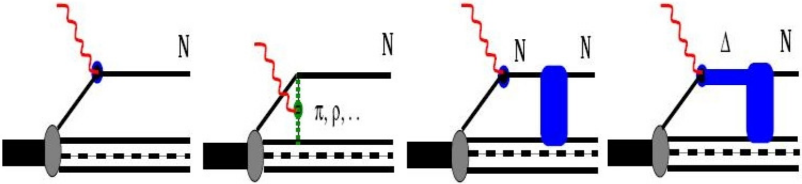
Nuclear Corrections

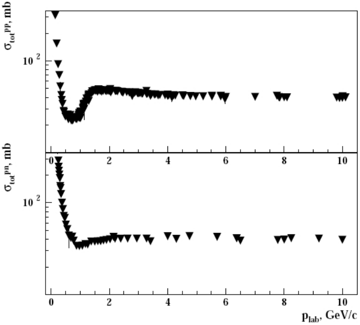
- Nuclear effects evaluated by M. Sargsian in Generalized Eikonal Approximation
  - Determine effective neutron/proton polarization
  - Evaluate rescattering effects on asymmetry
- Considers four main diagrams

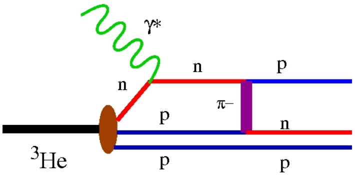


- PWIA, MEC, FSI, IC

FSI Contributions

- MEC and IC become suppressed at higher Q^2
- At high p, total cross sections for σ_{pp}, σ_{pn} becomes roughly constant
- Selection on small missing momenta suppress contributions from FSI
- Charge exchange can modify final asymmetry (unpol. p get into n sample)

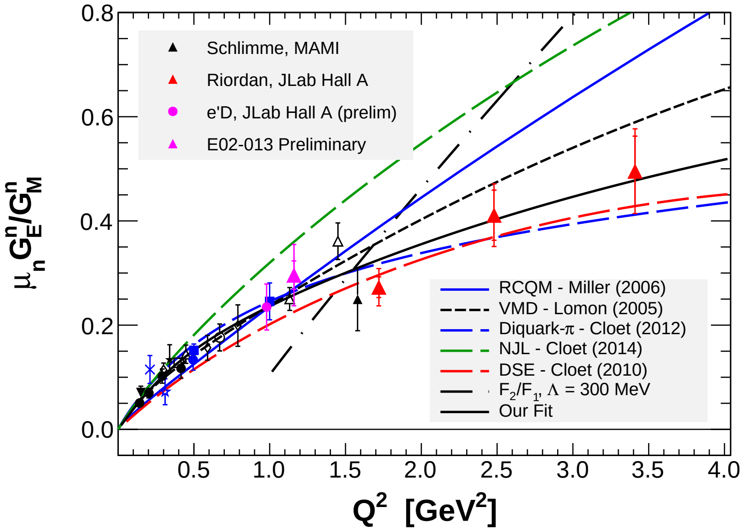




G_E^n Measurements at JLab

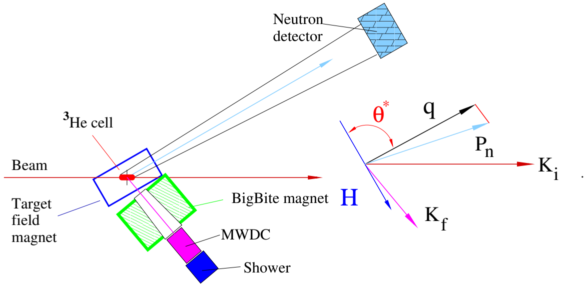
- G_E^n least well measured range of Q^2
- More difficult to measure relative to other FFs since
  - G_E^n is intrinsically small compared to G_M^n
  - Neutron is not stable outside nucleus, use targets $^2\mathrm{H}$ and $^3\mathrm{He}$
- Four experiments done at JLab:
  - Hall C - E93-026 - Zhu *et al.*, Warren *et al.* - $\vec{d}(\vec{e}, e'n)p$, $Q^2 = 0.5, 1.0\ \mathrm{GeV}^2$
  - Hall C - E93-038 - Madey *et al.* - $d(\vec{e}, e'\vec{n})p$, $Q^2 = 0.4 - 1.5\ \mathrm{GeV}^2$
  - Hall A - E02-013 - $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)pp$, $Q^2 = 1.2 - 3.4\ \mathrm{GeV}^2$
  - Hall A - E05-102 - $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)pp$, $Q^2 = 0.4 - 1.0\ \mathrm{GeV}^2$

Neutron Form Factors



E02-013 Experimental Setup

- Polarized $^3\mathrm{He}$ target acts as effective free neutron source
- Two arms to measure coincidence e' and n, allow for cuts on $p_{\mathrm{miss},\perp}$ to suppress FSI



- BigBite - large acceptance spectrometer, reconstructs $\vec{e}'$
- Neutron arm - matches BB acceptance, measures neutron momentum through ToF, performs nucleon charge ID

Polarized $^3\mathrm{He}$ Target

- Target polarized through hybrid spin exchange optical pumping technique
- $\gamma \to \mathrm{Rb} \to \mathrm{K} \to {}^3\mathrm{He}$
- Record high polarization (at the time) with this technique

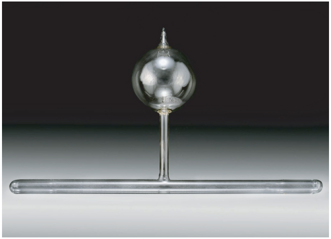


Photo Credit: A. Gavalya

- Measure polarization through NMR/EPR
- Polarization stable and about 30-45% in beam

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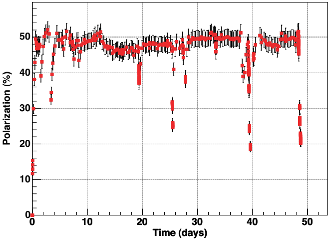

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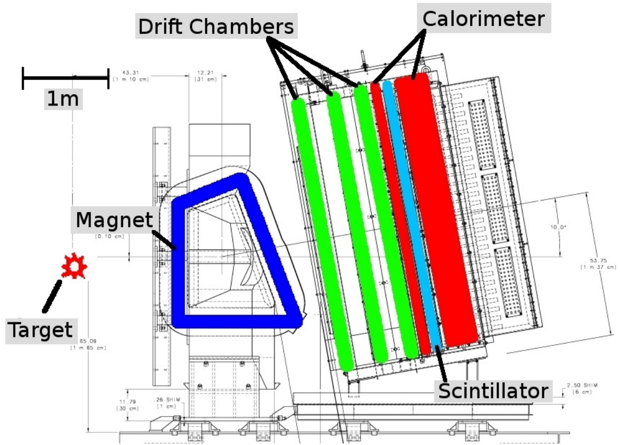
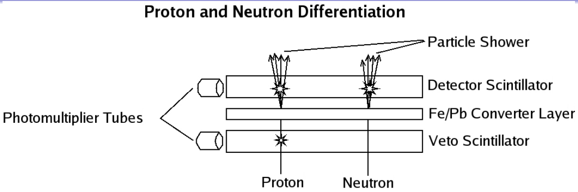
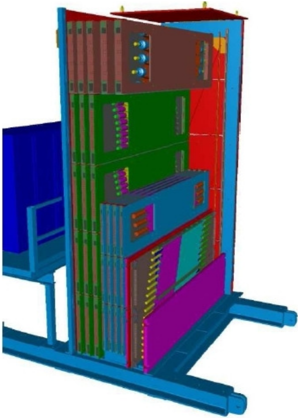
BigBite Detector Set



Neutron Arm

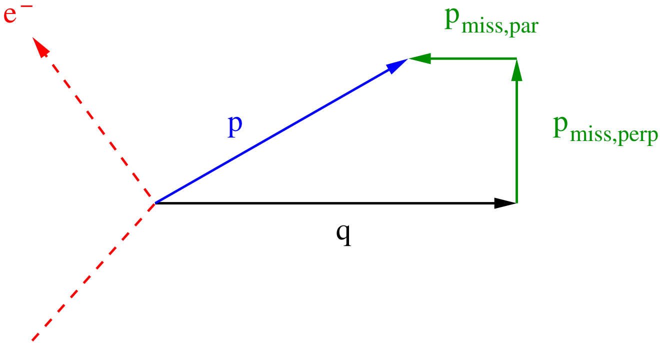


- Neutron arm detects recoiling proton/neutron, $\eta \sim 50\%$
- Measures momentum through ToF, charge through veto layers
- Time resolution $\sigma_t = 300\ \mathrm{ps}$, nucleon momentum resolution $\sigma_p \approx 300\ \mathrm{MeV}$ for $Q^2 = 3.4\ \mathrm{GeV}^2$ point
- Covers 5m $\times$ 1.6m about about 10m away - Matches BigBite acceptance for QE electrons
- Few hundred kHz rate/bar, relatively low threshold



Quasielastic Selection

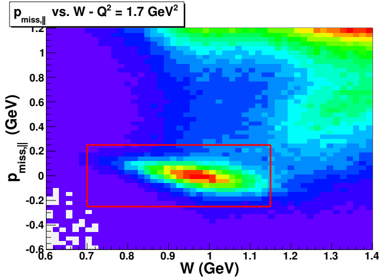
Need to reliably separate neutral QE events



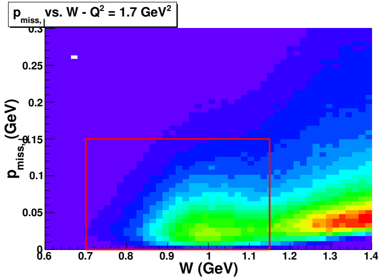
- Invariant mass assuming free stationary nucleon target
- Missing mass of $^3\mathrm{He}(e, e'n)X$

$Q^2 = 1.7\ \mathrm{GeV}^2$ Quasielastic Selection

$p_{\mathrm{miss},\parallel}$ vs W

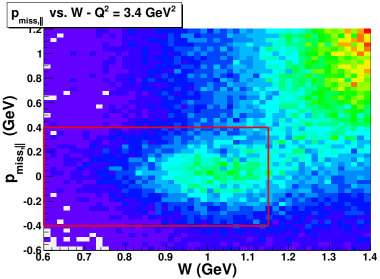


$p_{\mathrm{miss},\perp}$ vs W

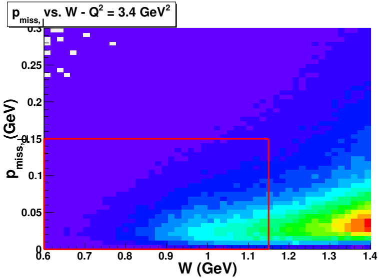


$Q^2 = 3.4\ \mathrm{GeV}^2$ Quasielastic Selection

$p_{\mathrm{miss},\parallel}$ vs W



$p_{\mathrm{miss},\perp}$ vs W



- Momentum resolution degraded due to shorter time-of-flight

Proton Contamination

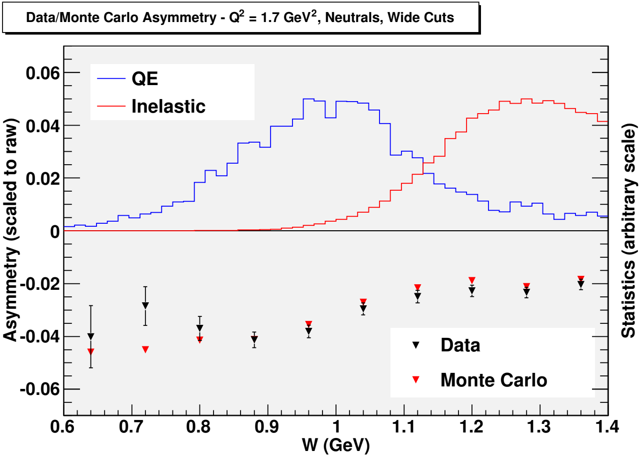
- Veto not 100% efficient, full detector not symmetric in p and n efficiency and varies with energy!
- Evaluated through uncharged/charged ratios of $\mathrm{H_2}$, $^3\mathrm{He}$, $\mathrm{N_2}$
  - e.g. $\frac{\mathrm{N_{p\to n}}}{\mathrm{N_{p\to p}}} = \frac{N_{\mathrm{un}}}{N_{\mathrm{ch}}}\Big|_{\mathrm{H_2}}$

$$D_p = \frac{1}{1 + \frac{\mathrm{N_{p\to n}}}{\mathrm{N_{n\to n}}}}$$

- Monte Carlo simulations generally in agreement
- Evaluated to be 10-25% with systematic error of few percent
- Small proton asymmetry contributions are taken into account

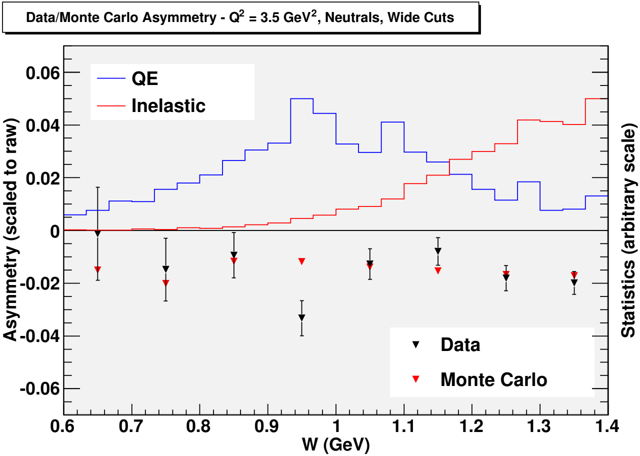
- Accidental Background: 2%
- Nitrogen dilution: 5%
- Misidentified protons: 20%
    - Evaluated through data and Geant4 monte carlo
- Inelastic Events: 0 - 15%
    - Evaluated through Geant4 monte carlo + MAID
- Nuclear effects + FSI: 5%

Inelastic Contribution/Subtraction - $Q^2 = 1.7\ \mathrm{GeV}^2$



- Asymmetry similar to elastic asymmetry overall correction is smaller

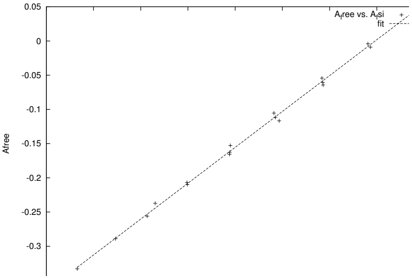
Inelastic Contribution/Subtraction - $Q^2 = 3.4\ \mathrm{GeV}^2$

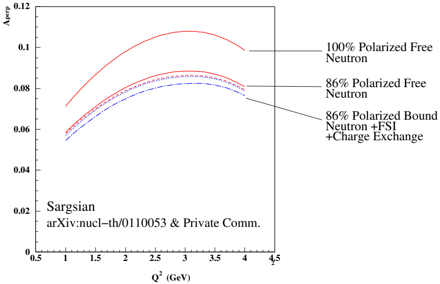


- Asymmetry similar to elastic asymmetry overall correction is smaller

FSI Results

- Effective polarization highly dependent on missing momentum cuts
- Very different from 86% inclusive assumption, $P_n >\sim 95\%$
- Scanning all kinematics for variety of G_E^n values and our cuts:

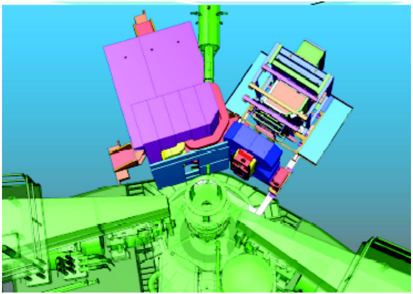


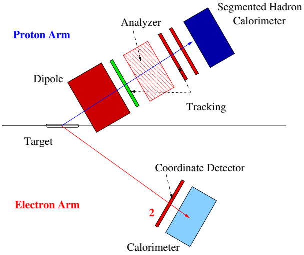


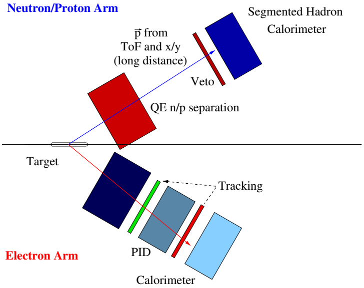
- Correction from A to A_{free} is very linear in A

G_E^n with SBS

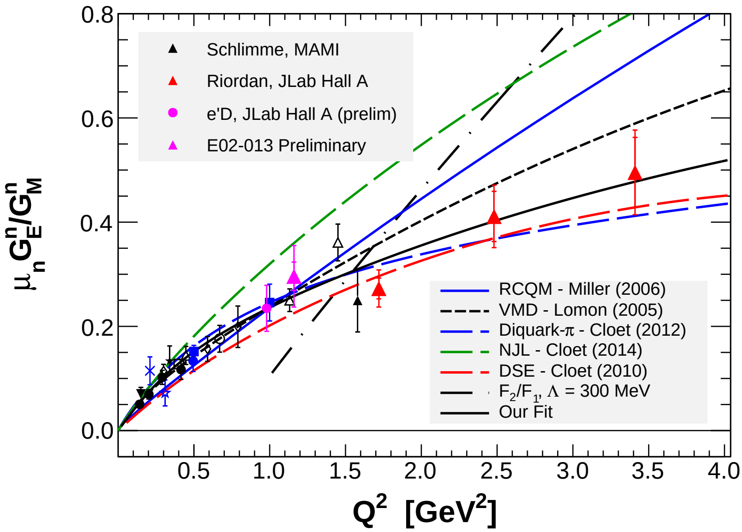
- Super Bigbite builds on large acceptance/moderate resolution experience
- Talk from Gregg Franklin yesterday







Neutron Form Factors



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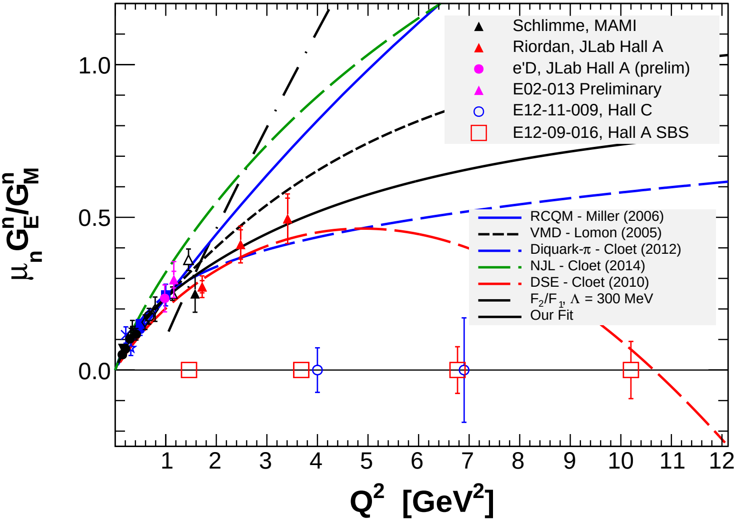


- Models for G_E^n are highly divergent for high Q^2

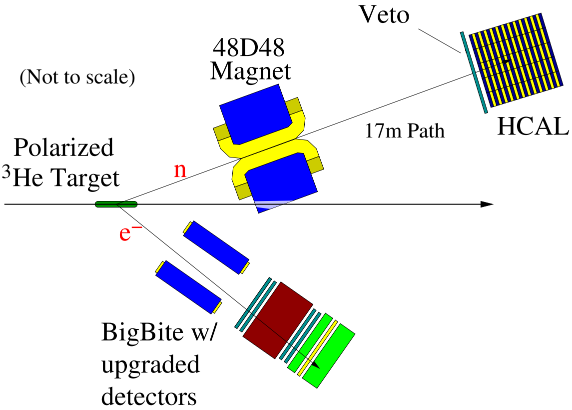
Kinematics

- Four points overlapping at low Q^2 and extending to 10 GeV^2

Q^2 (GeV^2)	Time (days)	E_i (GeV)	θ_e (deg)	p_e $(\mathrm{GeV/c})$	θ_n (deg)	p_n $(\mathrm{GeV/c})$
1.5	1	2.2	40.0	1.42	39.4	1.44
3.7	2	4.4	34.0	2.44	29.9	2.74
6.8	4	6.6	34.0	3.00	22.2	4.44
10.2	31	8.8	34.0	3.38	17.5	6.29

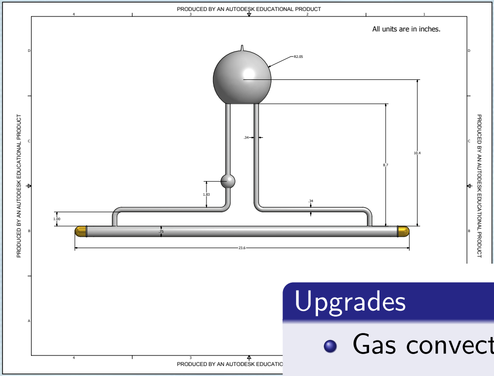
Q^2 (GeV^2)	A_{exp} (Galster)	$\mu_n G_E^n / G_M^n$ (Galster)	$\mu_n G_E^n / G_M^n$ (Our fit)
1.5	-0.0153	0.224	0.296
3.7	-0.0242	0.308	0.497
6.8	-0.0393	0.368	0.650
10.2	-0.0326	0.403	0.742

High Q^2 G_E^n Experimental Layout



- Upgraded Bigbite detector stack for higher rates, better PID
- Hadron calorimeter at 17 m
- Place magnet $B \cdot dl = 1.7\ \mathrm{T} \cdot \mathrm{m}$ at 2.8 m from target to deflect protons

Target cell design for SBS G_E^n experiment



- 60 cm target-chamber length will deliver desir
- Convection-based design, now well tested in Pro
- Contains 6 STP liters of ^{3}He in 750 cm^3 volume
- Will use copper metal end windows with gold el

Wednesday, October 21, 15

Upgrades

- Gas convection
- Metal windows
- $10\ \mu A \rightarrow 60\ \mu A$
- $40\text{ cm} \rightarrow 55\text{ cm}$
- $P = 45\% \rightarrow 60\%$

Stolen from Gordon Cates

Upgraded BigBite Components

- Require 4 planes with coverage: 2 $150 \times 40\ \mathrm{cm}^2$ and 2 $200 \times 50\ \mathrm{cm}^2$
- Estimated rates are $\sim 100\ \mathrm{kHz/cm^2}$ - drift chambers replaced by GEM chambers
- Occupancy about 1% in 30ns for 36k channels, tracking should be relatively easy compared to GEp (factor 5 less rate), tree search applicable
- Momentum resolution of $\sigma_p/p \sim 0.5\%$ for e^- of $3-4\ \mathrm{GeV}$

G_E^p

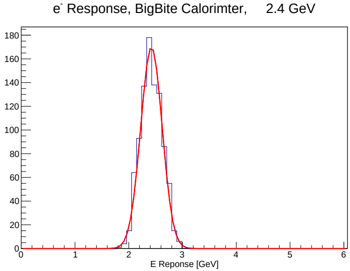
Q^2 (GeV^2)	1st GEM Rate (kHz/mm^2)
5	0.6
8	1.4
12	5.2

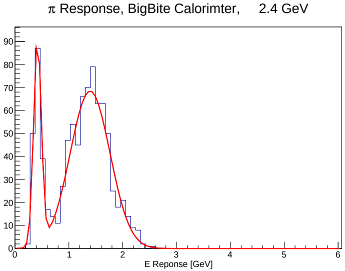
G_E^n

Q^2 (GeV^2)	1st GEM Rate (kHz/mm^2)
1.5	2.4
4	1.2
7	1.0
10	1.3

Upgraded BigBite Components

- π^-/e^- rate about 3:1
- Bigbite shower/preshower form trigger - at least preshower online rejection necessary to keep rates ~ 2 kHz
- BigBite GRINCH+preshower pushes rejection to $\sim 10^4$ combined and pion contributions to signal $< 0.1\%$





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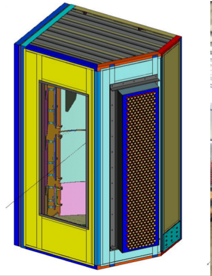
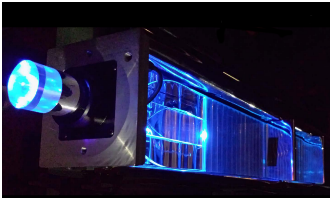


HCAL + 48D48

- HCAL uses 12×24 15 × 15 cm^2 iron/scintillator design for hadron calorimetery
- 48D48 removes background and deflects protons out of QE acceptance - loss of 20% statistics at 2.8 m for extended target



- Spatial resolution of 1.5 $\mathrm{cm} \rightarrow 10\ \mathrm{mrad}$
- ToF resolution critical for QE selection - see later slides
- Detector plane can provide additional PID

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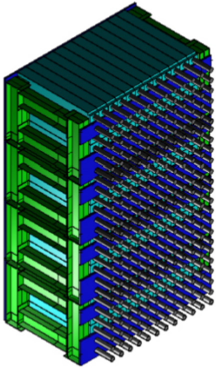

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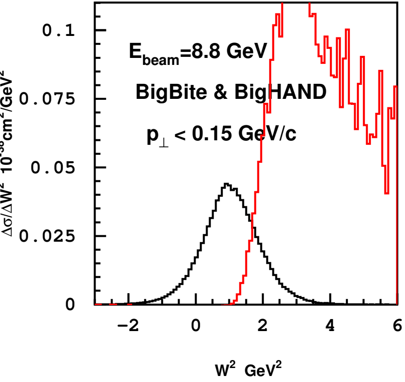
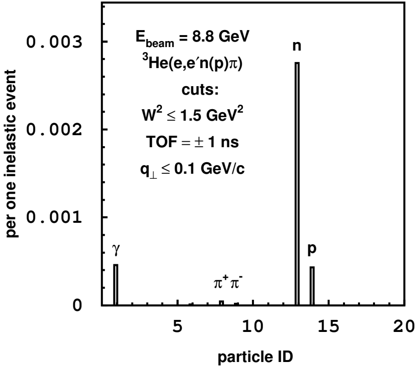
Quasielastic Selection and Backgrounds

- Cuts on missing momenta (θ_{pq} and ToF), invariant mass allow for suppression of inelastic events
- Inelastics can be corrected using Monte Carlo with MAID or sideband subtraction/deconvolution





- Background mostly neutrons, photons probably removable with energy resolution, some inelastic protons

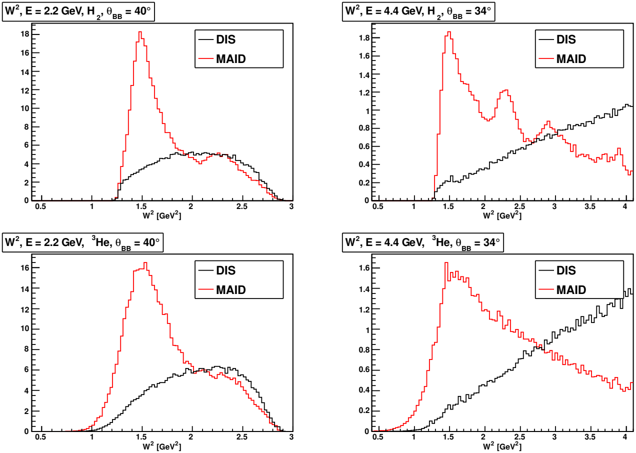
Time of Flight Concerns

- Time-of-flight resolution critical to suppresion of inelastics and systmatics
- Control is dependent on cuts and understanding of background form
- MAID only goes to $Q^2 \sim 4\ \mathrm{GeV}^2$, asymmetry not well contrainted (look at CB, pol. $^3\mathrm{He}$ DIS data?)
- Worse resolution translates into poorer statistics - need to map based on reasonable models

Have developed MC with:

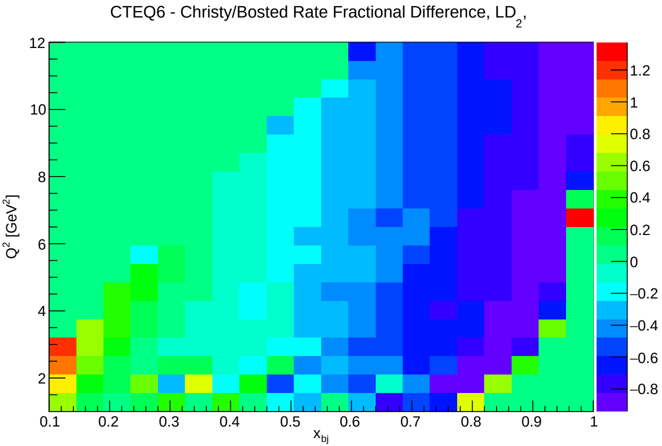
- Full acceptance/magnetic propagation for all detectors
- Elastic and inelastic events
  - Form factors from Kelly
  - π production from MAID
  - π production using DIS cross sections and assuming $N + \pi$ final state
- Radiative effects from equivalent radiator approximation, glass target windows

MAID vs. DIS - Elastics only



- MAID only available for lower two Q^2
- DIS underpredicts (mostly Δ) by factor of ~ 8

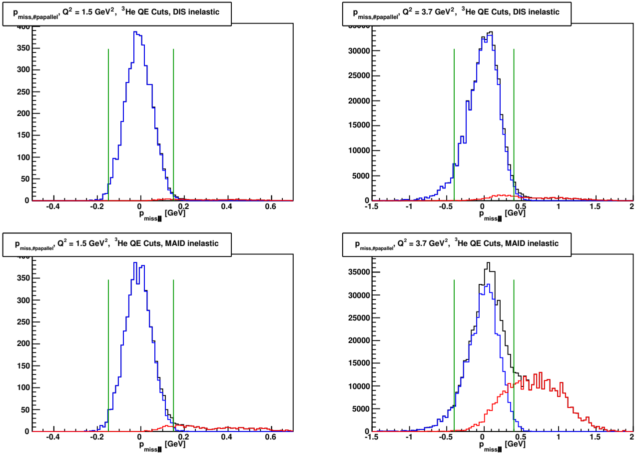
MAID vs. DIS - Elastics only



- MAID only available for lower two Q^2
- DIS underpredicts (mostly Δ) by factor of ~ 8

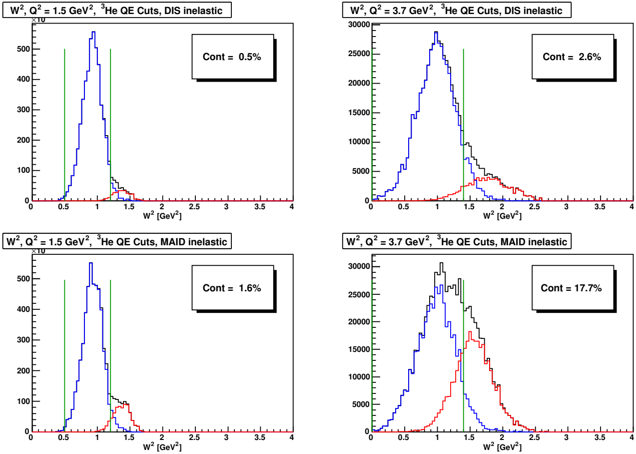
MAID vs. DIS - $p_{m,\parallel}$

$\delta t = 0.5$ ns



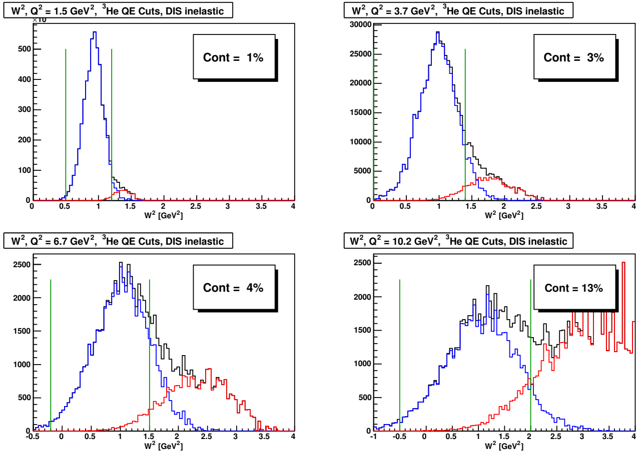
Black - all, blue - QE, red - Inelastic

$\delta t = 0.5$ ns


W², Q² = 1.5 GeV², ³He QE Cuts, DIS inelastic
Cont = 0.5%
W², Q² = 3.7 GeV², ³He QE Cuts, DIS inelastic
Cont = 2.6%
W², Q² = 1.5 GeV², ³He QE Cuts, MAID inelastic
Cont = 1.6%
W², Q² = 3.7 GeV², ³He QE Cuts, MAID inelastic
Cont = 17.7%
W² [GeV²]

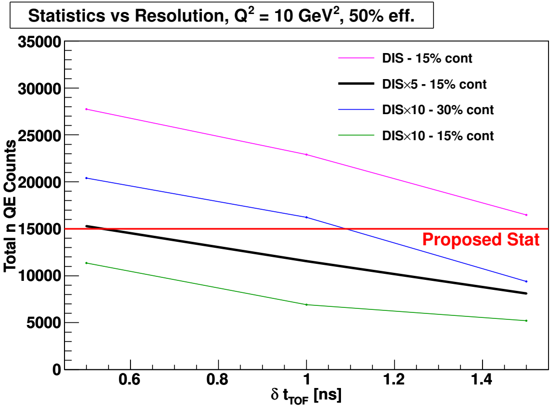
DIS - W^2

$\delta t = 0.5$ ns



- DIS predictions for highest Q^2 become problematic if higher by by large factor
- Proposal rate was based on $\sim$ order of magnitude higher *DIS*

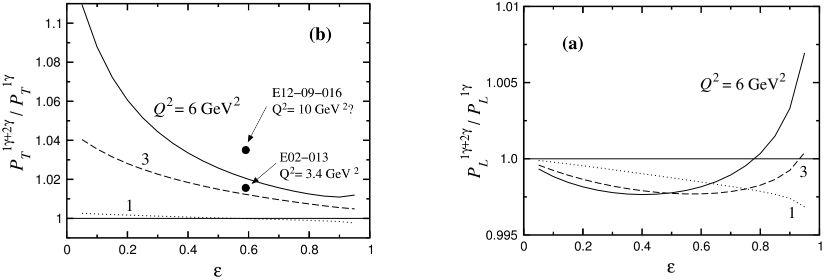
Counts vs. Time of Flight Resolution



- Scaling DIS $\times$ 5, 15% contamination needs about 0.5 ns resolution
- Could probably do OK with 1 ns resolution, loss of 20% statistics

Two Photon Effects

- Two photon effects for polarized target related to effects in polarization transfer
- Only considered proton ground state for box diagrams
- Asumming similar size correction as proton:



Blunden, Melnitchouk, Tjon, Phys. Rev. C 72, 034612 (2005)

Assuming Galster for G_E^n, Kelly for G_M^n:

Q^2 [GeV^2]	time [days]	stat [%]	sys [%]
1.5	1	1.3	2.4
3.7	2	6.0	4.4
6.8	4	19.8	7.3
10.2	31	22.5	6.6

Systematic uncertainties to asymmetries at highest Q^2

Quantity	Expected Value	Rel. Uncertainty
Beam polarization P_e	0.85	2.4%
Target polarization $P_{^3\mathrm{He}}$	0.60	3.3%
Neutron polarization P_n	0.86	2.3%
Nitrogen dilution D_{N_2}	0.94	2.1%
Background dilution D_{back}	0.95	$<1\%$
Final state interactions	0.95	2.1%
Inelastic correction	0.8-1.2	5.0%
Angular error from $A_\parallel$		$<1\%$
Systematic error in G_E^n/G_M^n		6.6%

Requirements for Instrumentation in G_E^n/G_M^n Measurement

To achieve $\sim 10\%$ at $Q^2 = 10\ \mathrm{GeV}^2$ given luminosity $6 \times 10^{36}\mathrm{Hz/cm}^2$ (60 cm target, 60 μA), 60% polarization:

BigBite Requirements	
2 $150 \times 40\ \mathrm{cm}^2$ chambers	
2 $200 \times 50\ \mathrm{cm}^2$ chambers	
e^- acceptance	40 msr
p_e	$1 - 3.0\ \mathrm{GeV}$
δp_e	1%
Angular Range	$35 - 40^\circ$
e^- detector rates	$100\ \mathrm{kHz/cm}^2$
e^- ToF	0.25 ns
δE	$\sim 10\%$
π rejection	100-300:1
$\delta\theta_e$	~ 1 mrad
δv_z	~ 0.5 cm

Nucleon Arm Requirements	
N acceptance	30 msr
p_n	$1 - 10\ \mathrm{GeV}$
Angular Range	$17 - 40^\circ$
$\delta\theta_{p_n}$	10 mrad
δt_{ToF}	0.5 ns
$B \cdot dl$	$1.7\, T \cdot m$
Total rate	20 kHz

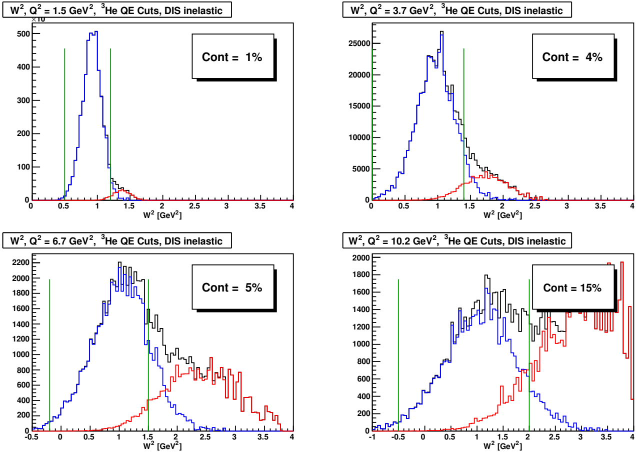
Summary

- G_E^n can be measured to $Q^2 = 10\ \mathrm{GeV}^2$ with SBS to $\sim 10 - 20\%$ accuracy
- HCAL needs ToF resolution on order of $0.5 - 1\ \mathrm{ns}$
- Upgraded target that can handle 60 $\mu\mathrm{A}$ with 60% polarization required
- Other requirements fall within SBS defintions

BACKUP SLIDES

DIS - W^2

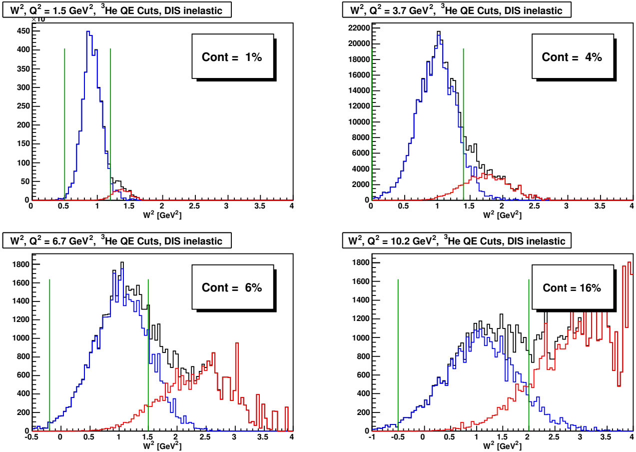
$\delta t = 1.0$ ns



- Adjusting cuts so contamination is about the same, loss of statisics is about 20%

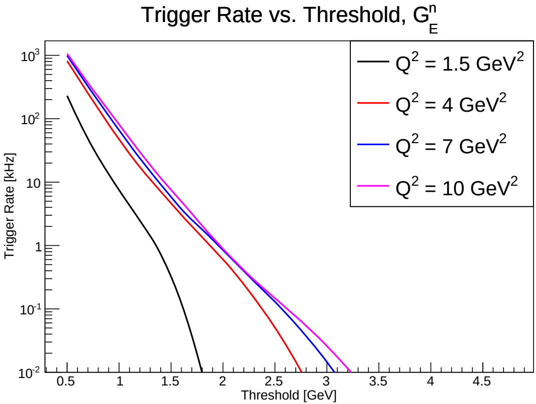
DIS - W^2

$\delta t = 1.5$ ns



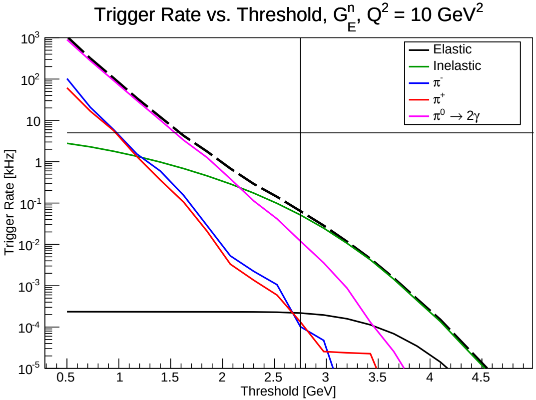
- Adjusting cuts so contamination is about the same, loss of statisics is about 50%

Trigger



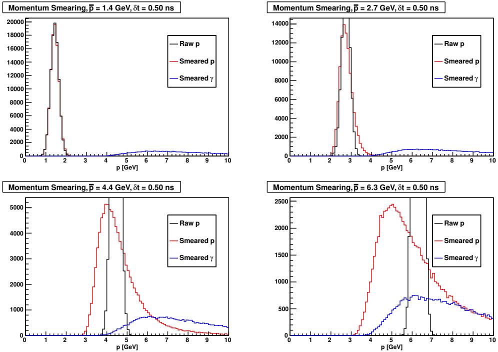
- Rates above include elastic e^-, DIS e^-, and π^{+-0}
- Single arm shower/preshower (with ps cut) keeps will have < 2 kHz trigger rate without affecting QE cuts
- Need to allow some inelastic in trigger - prescale lower threshold

Trigger



- Rates above include elastic e^-, DIS e^-, and π^{+-0}
- Single arm shower/preshower (with ps cut) keeps will have < 2 kHz trigger rate without affecting QE cuts
- Need to allow some inelastic in trigger - prescale lower threshold

Smearing and Photons



- Smearing ToF is asymmetric in p
- For highest momentum transfers $\beta = 1$ particles can get smeared in (from small $p_{m,\parallel}$)
- 48D48 and energy resolution of HCAL should suppress
- π^0 production could contribute - need to study responses, rates