The G_2^p Experiment

A Measurement of Proton g_2 Structure Function
And the Longitudinal-Transverse Spin Polarizability

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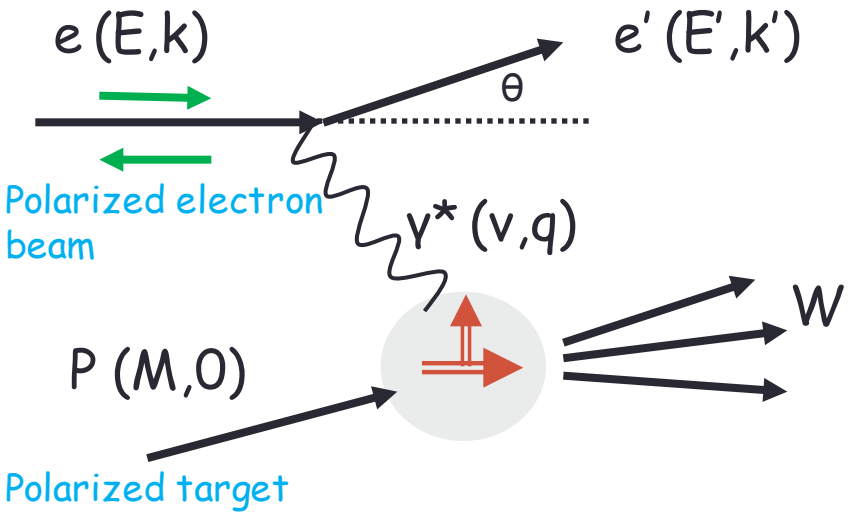
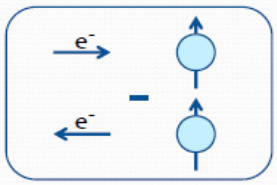
On behalf of the g_2^p collaboration

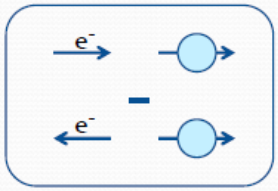
Jefferson Lab

Inclusive Electron Scattering



- Invariant Mass
  $W^2 = M^2 + 2M\nu - Q^2$
- Four momentum transfer squared
  $Q^2 = -q^2$
- Bjorken variable
  $x = Q^2/2M\nu$ for fixed target

$\Delta\sigma_\perp =$  $= \frac{4\alpha^2 E'}{M\nu Q^2 E}\left[\sin\theta\left(g_1 + \frac{2E}{\nu}g_2\right)\right]$ *g_2^p experiment measure*

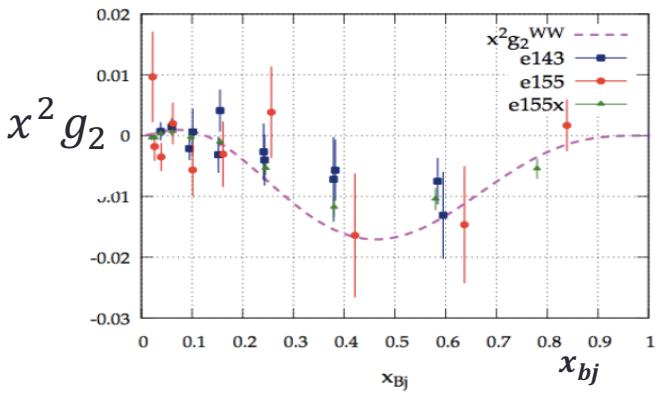
$\Delta\sigma_\parallel =$  $= \frac{4\alpha^2 E'^2}{M\nu Q^2 E}\left[(E + E'\cos\theta)g_1 - 2Mxg_2\right]$

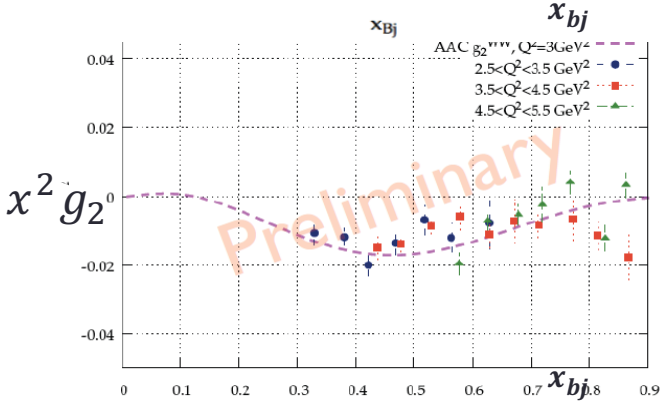
Hall B EG4 measure g_1^p, g_2^p experiment one measurement to cross check

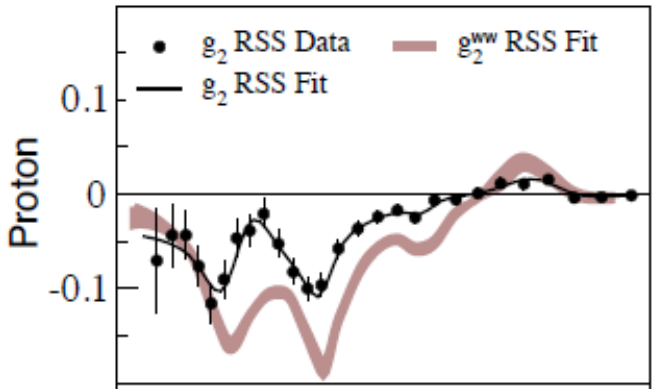
Motivation

- Measure the proton spin structure function g_2 in the low Q^2 region ($0.02 < Q^2 < 0.2\ GeV^2$) for the first time
- Benchmark test of χPT with extraction of δ_{LT}
- Examine the Burkhardt-Cottingham sum rule at low Q^2
- Important inputs for hydrogen hyperfine splitting and proton charge radius measurements

g_2 Existing Data







- Hard to cleanly measure g_2^p
  No much data before

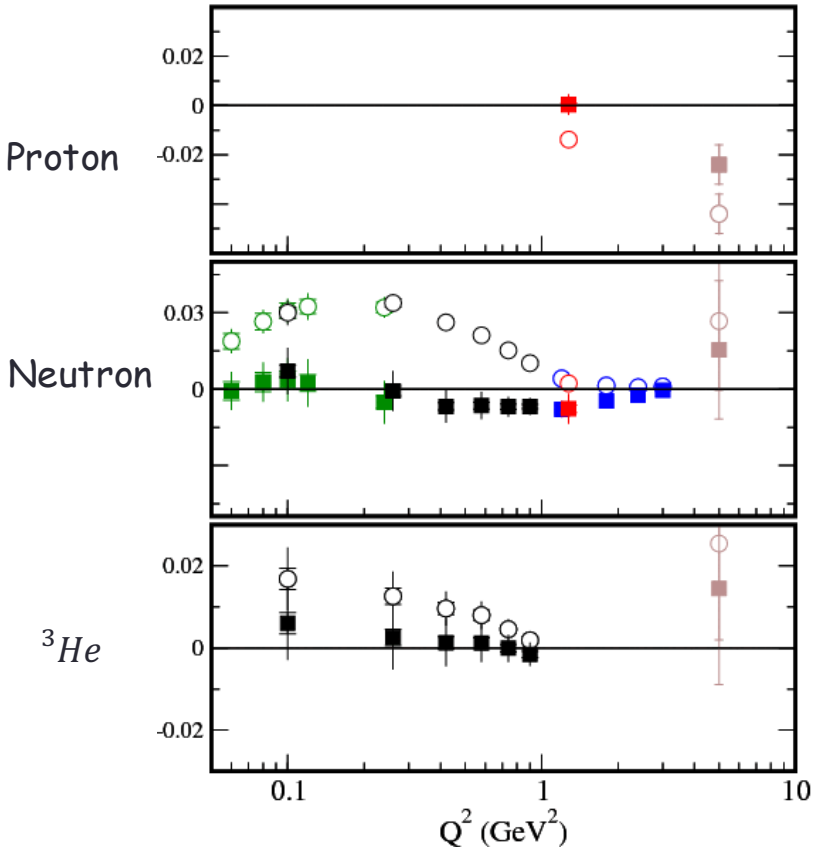
Proton g_2 Data from SLAC
Averaged $Q^2 \approx 5\ GeV^2$

Proton g_2 Data from Jlab SANE
$Q^2 \approx 2.5 \sim 5.5\ GeV^2$

Proton g_2 Data from Jlab RSS
$Q^2 = 1.3\ GeV^2$

K.S., O. Rondon *et al.*
PRL 105, 101601 (2010)

BC Sum Rule



- SLAC E155x
- Hall C RSS
- Hall A E94-010
- Hall A E97-110 (preliminary)
- Hall A E01-012

BC Sum Rule:

$$\int_0^1 g_2(x, Q^2)dx = 0$$

Experiment Test:

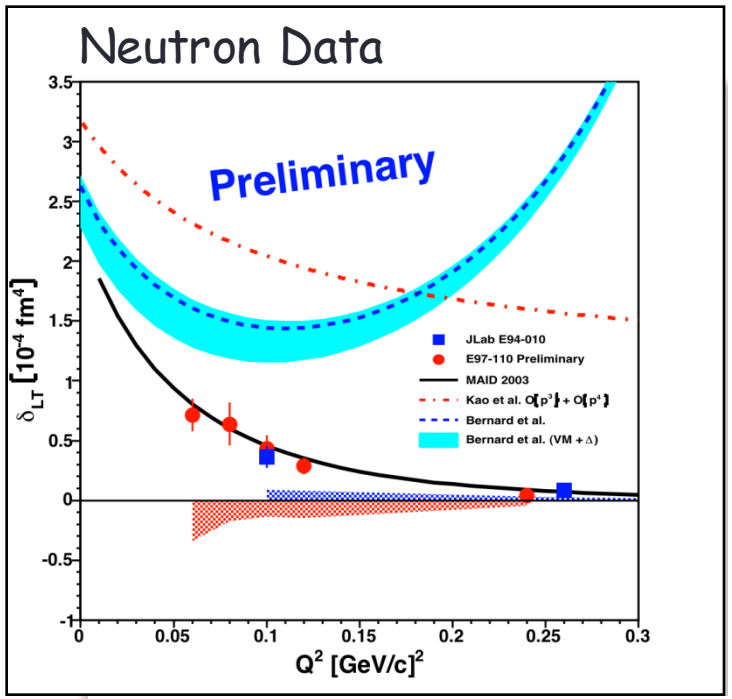
BC = Measured + low_x + Elastic

- Violation suggested for proton at large Q^2
  - Q^2 is not a constant for E155x, varies 0.8 ~ 8.2 GeV^2
- But found satisfied for the neutron & ^{3}He
- Mostly unmeasured for proton

δ_{LT} Puzzle for Neutron

- Generalized Spin Polarizabilities: how nucleons respond to virtual photons

$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} dx x^2 [g_1(x,Q^2) + g_2(x,Q^2)]$$

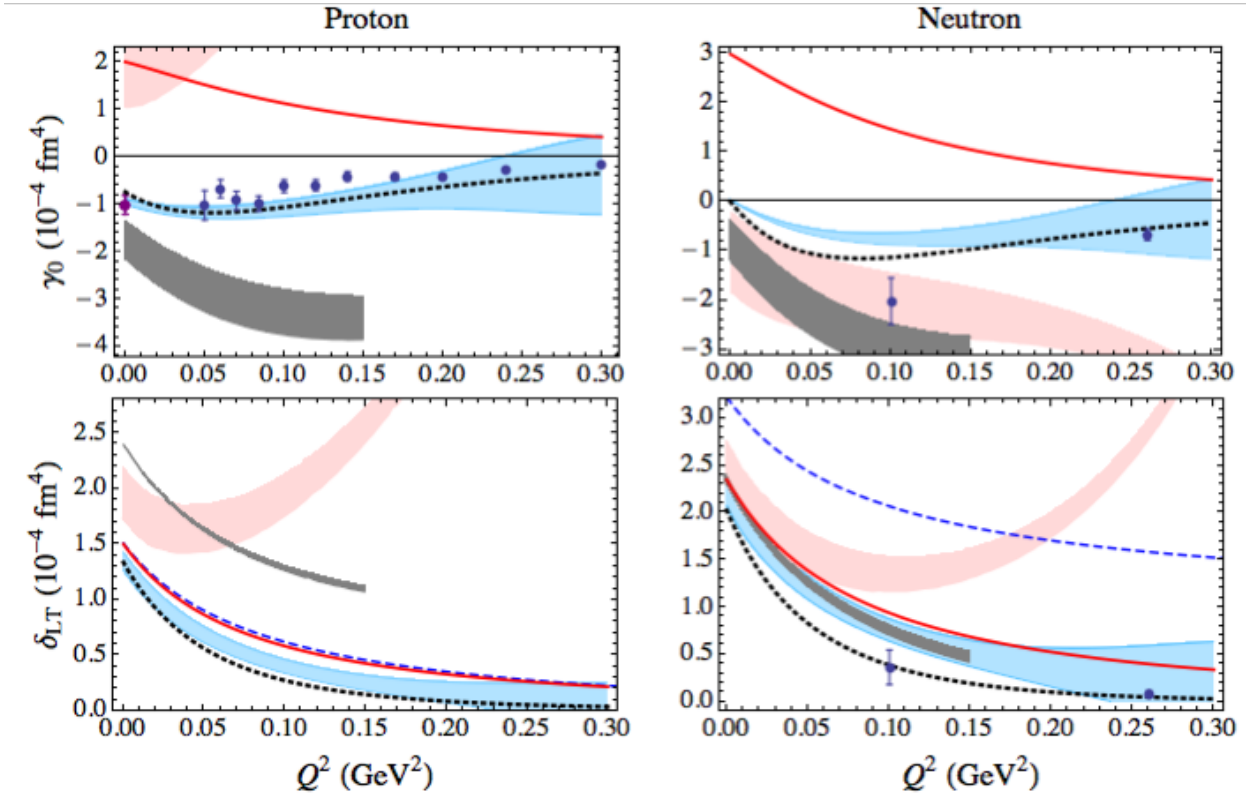


- δ_{LT} not sensitive to Δ, good to test χPT calculations
- Good agreement with MAID model predictions
- χPT fail -- puzzle?
- HBχPT: Kao, Spitzenberg, Vanderhaeghen
- PRD 67:016001(2003)
- RBχPT: Bernard, Hemmert, Meissner
- PRD 67:076008(2003)
- No proton data yet

Plots courtesy of V. Sulkosky : Preliminary E97-110 and Published E94-010

δ_{LT} Puzzle

- Recent Theory Progress about $\delta_{LT}\ (Q^2)$



- Blue Band: χPT
- Lensky, Alarcon & Pascalutsa
- PRC 90 055202 (2014)

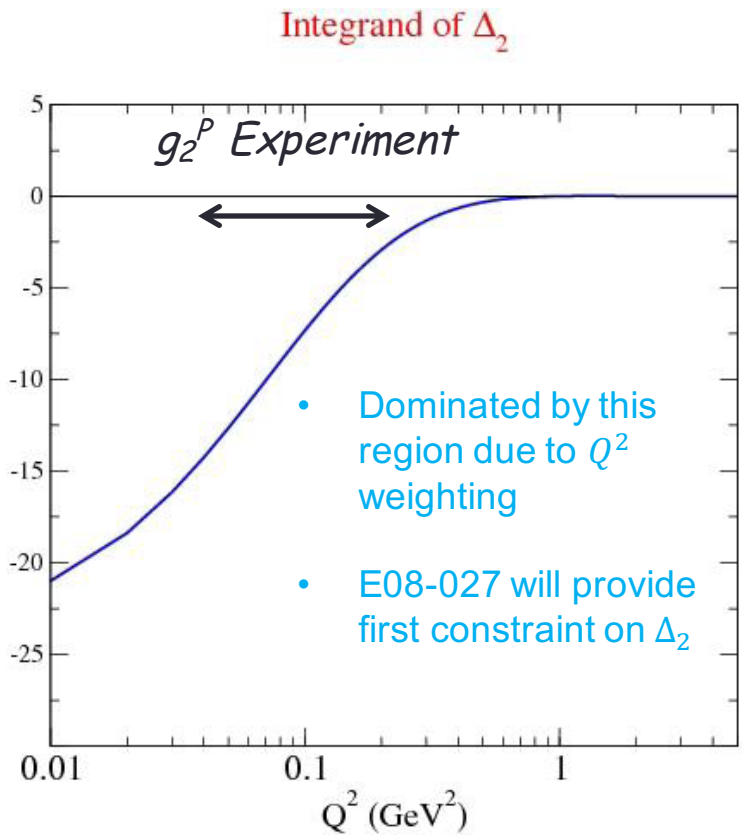
- Grey Band: RBχPT
- Bernard et al., PRD 87 (2013)

- Blacked Dotted: MAID

- Disagreement resolved?
- Need proton data

Hydrogen Hyperfine Splitting

- Hydrogen hyperfine splitting in the ground state has been measured to a relative high accuracy of 10^{-13}.



$$\Delta_E = 1420.405\ 751\ 766\ 7(9)\ MHz$$
$$= (1+\delta)E_F$$

$$\delta = \left(\delta_{QED} + \delta_R + \delta_{small}\right) + \Delta_s$$

Δ_s : proton structure function correction

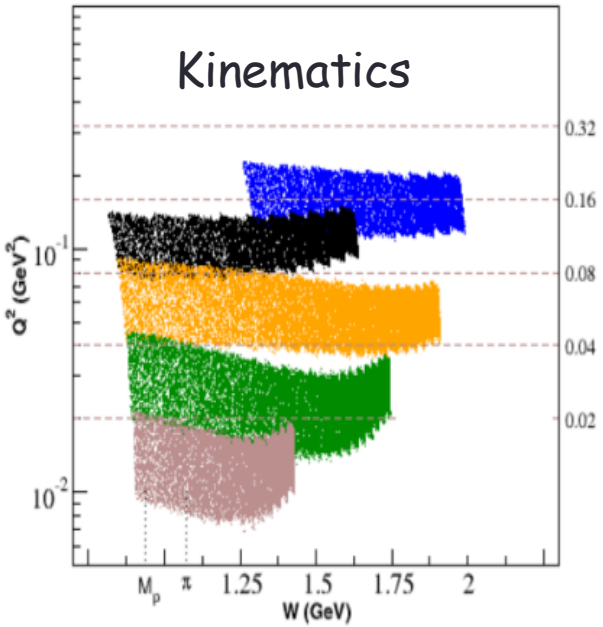
- largest uncertainty
- depends on ground state and excited properties of the proton
  $\Delta_s = \Delta_z + \Delta_{pol}$, $\Delta_{pol} \approx$ 1.3±0.3 ppm

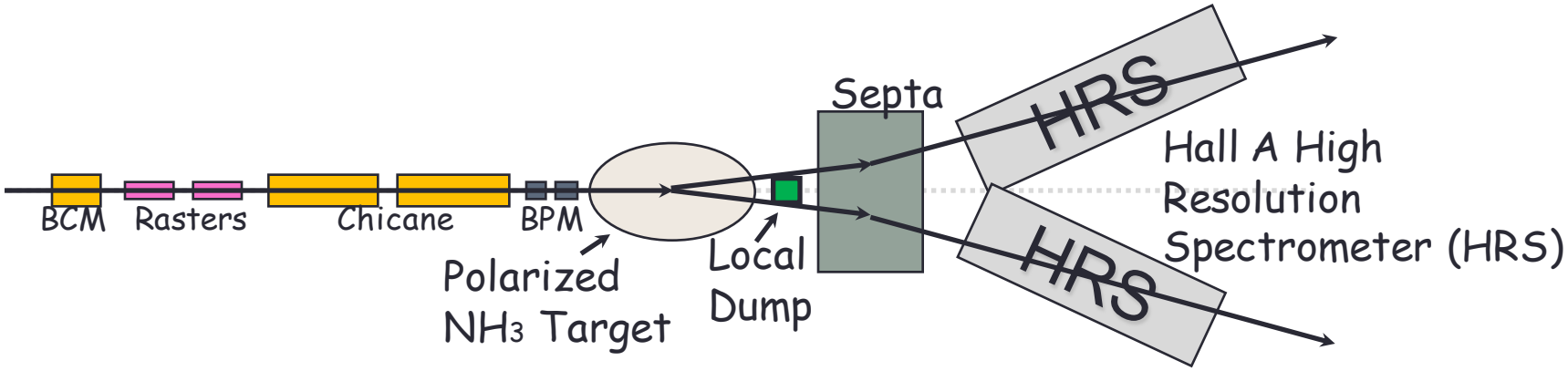
$$\Delta_{pol} = \frac{\alpha m_e}{\pi g_p m_p}(\Delta_1 + \Delta_2)$$

- Improve Δ_2 error from 0.57 to 0.06ppm

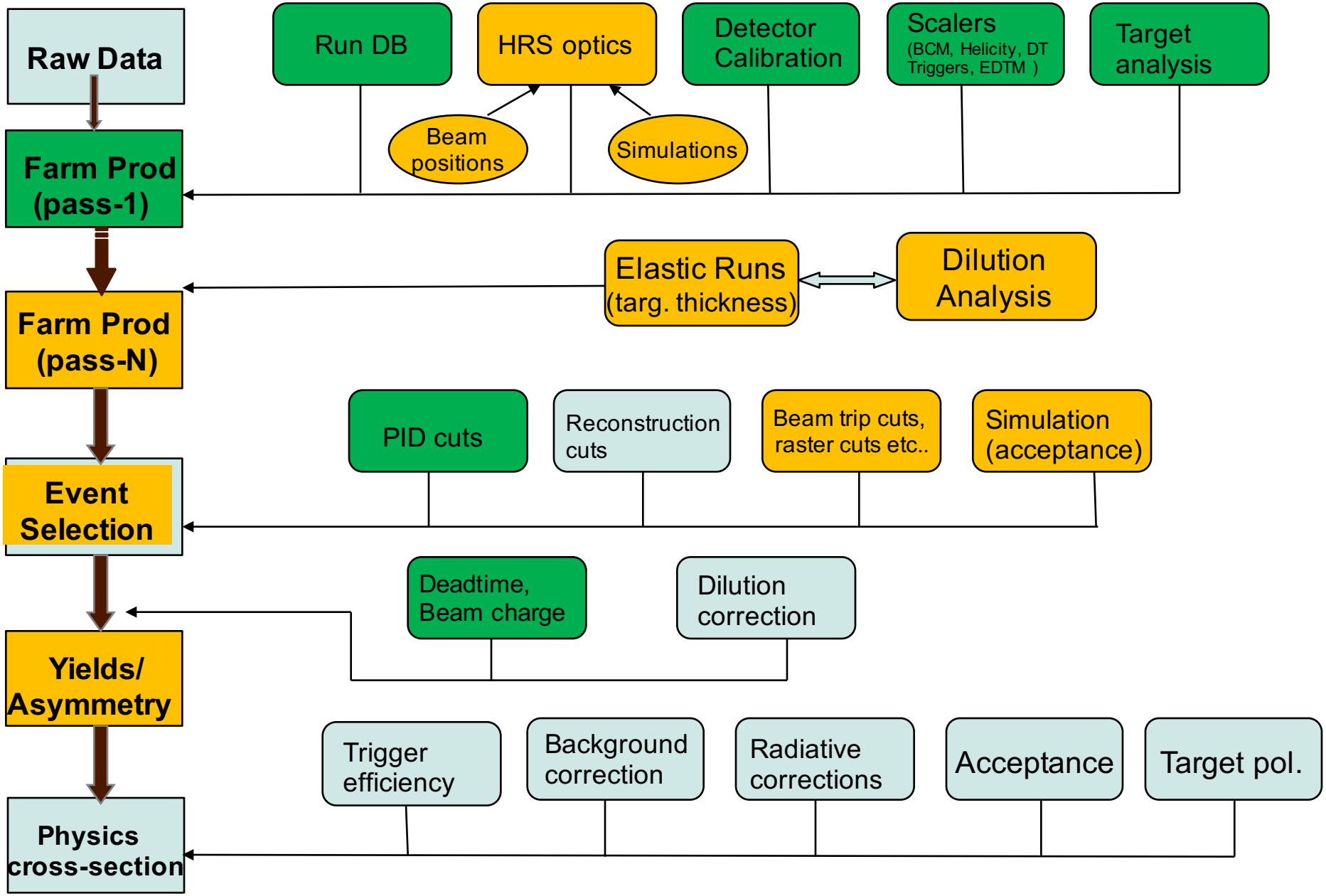
Experiment setup

- Transverse polarized NH_3 target
- Low beam current (< 100nA) diagnostics
- Rasters/Chicane magnets
- Local beam dump
- High DAQ rates 6~7kHz with <30% dead time (Courtesy of Ryan Zielinski)





Analysis Flow Chart

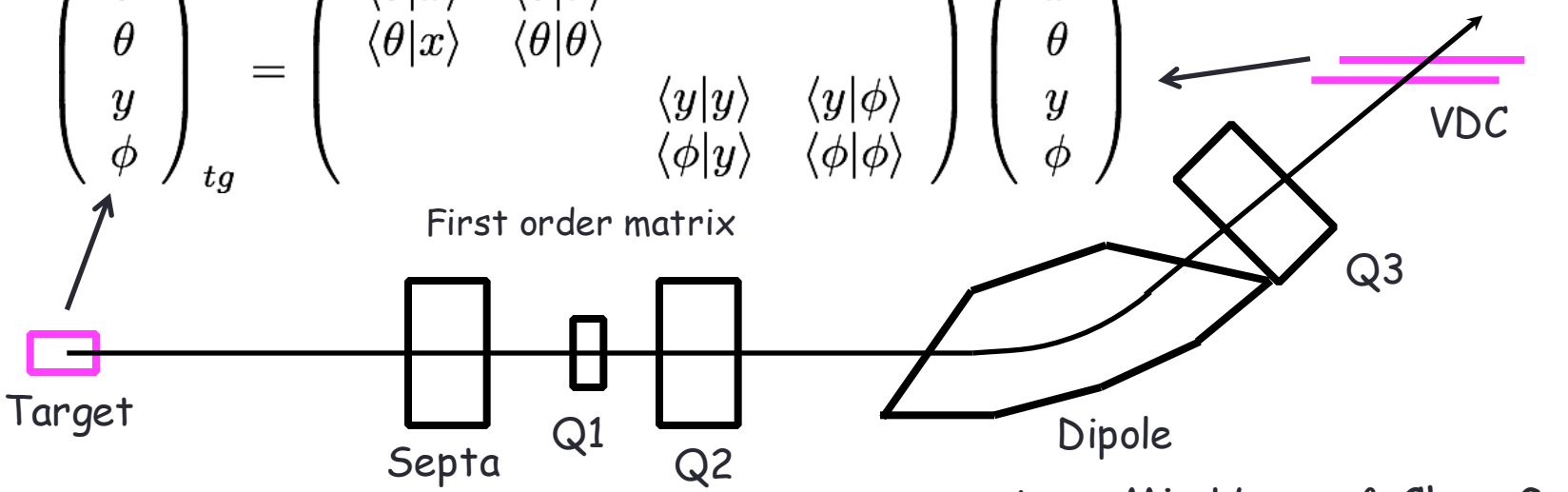


Optics

- Goal: 5% systematic uncertainty when measuring cross section
- 1.0% systematic uncertainty of scattering angle, which will contribute around 4.0% to the uncertainty of cross section
- Reconstruct the kinematics variables of the scattered electrons with the tracking information by a matrix

$$\begin{pmatrix} \delta \\ \theta \\ y \\ \phi \end{pmatrix}_{tg} = \begin{pmatrix} \langle\delta|x\rangle & \langle\delta|\theta\rangle & & \\ \langle\theta|x\rangle & \langle\theta|\theta\rangle & & \\ & & \langle y|y\rangle & \langle y|\phi\rangle \\ & & \langle\phi|y\rangle & \langle\phi|\phi\rangle \end{pmatrix} \begin{pmatrix} x \\ \theta \\ y \\ \phi \end{pmatrix}$$

First order matrix



courtesy Min Huang & Chao Gu

Optics

- Optics without Target Field

  -- Beam energy 2.254 GeV, carbon foil

	LHRS	RHRS	Ref
δ [dp]	1.5×10^{-4}	2.4×10^{-4}	1.1×10^{-4}
θ [out-of-plane angle]	1.59 mrad	1.57 mrad	2.5 mrad
y	3.3 mm	2.9 mm	1.7 mm
φ [in-plane angle]	0.99 mrad	0.82 mrad	0.9 mrad

- Optics with target field

  Standard HRS + target field + septum

  But septum magnets broken…

Optics

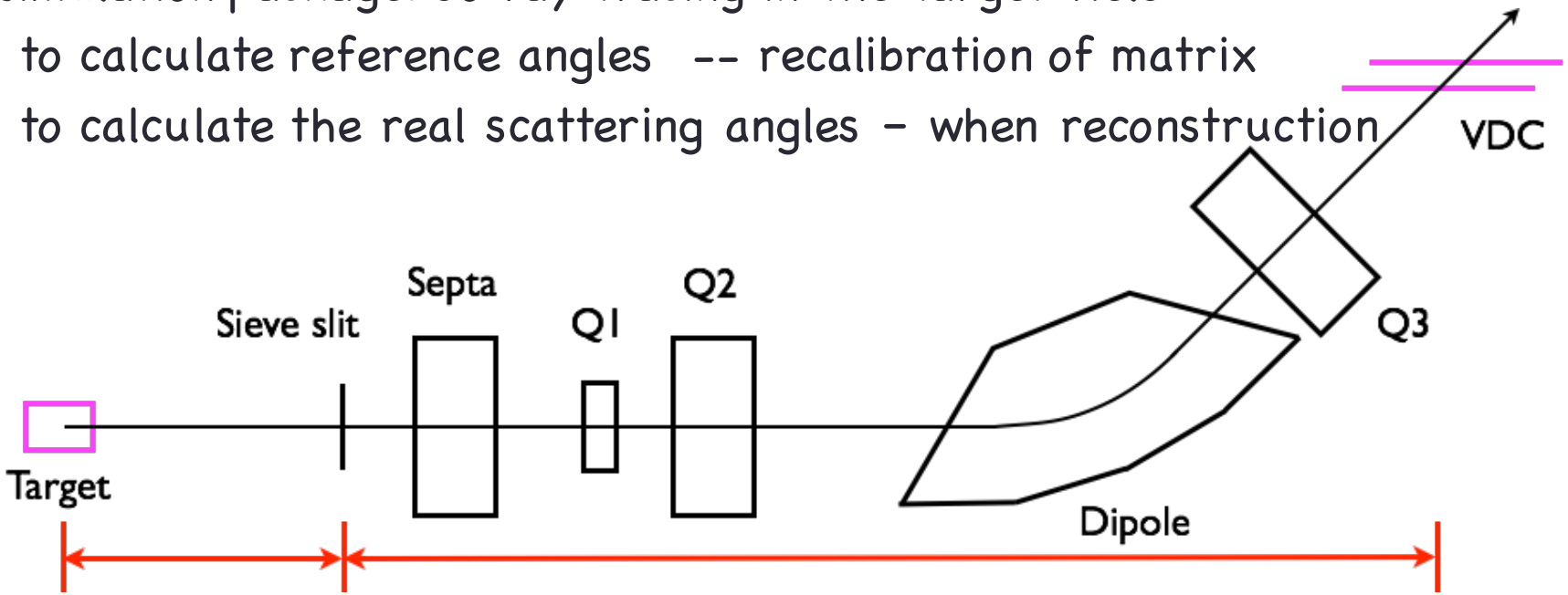
- Optics with Target Field

  Standard HRS + target field + septum

✓use the data taken with the broken septum to recalibrate angle matrix

✓A simulation package: do ray tracing in the target field

- to calculate reference angles -- recalibration of matrix
- to calculate the real scattering angles – when reconstruction



Acceptance

- Unpolarized cross section
- $\frac{d\sigma^{raw}}{d\Omega dE'} = \frac{N \cdot ps \cdot RC}{Q/q \cdot N_{tg} LT \cdot \epsilon_{det}} \frac{Acc}{\Delta\Omega \Delta E'}$
- Use Monte-Carlo simulation to study Acceptance
- $\frac{Acc}{\Delta\Omega \Delta E'} = \frac{1}{\Delta\Omega^{MC} \Delta E'^{MC}} \frac{N_{simu}^{MC}}{N_{acc}^{MC}}$

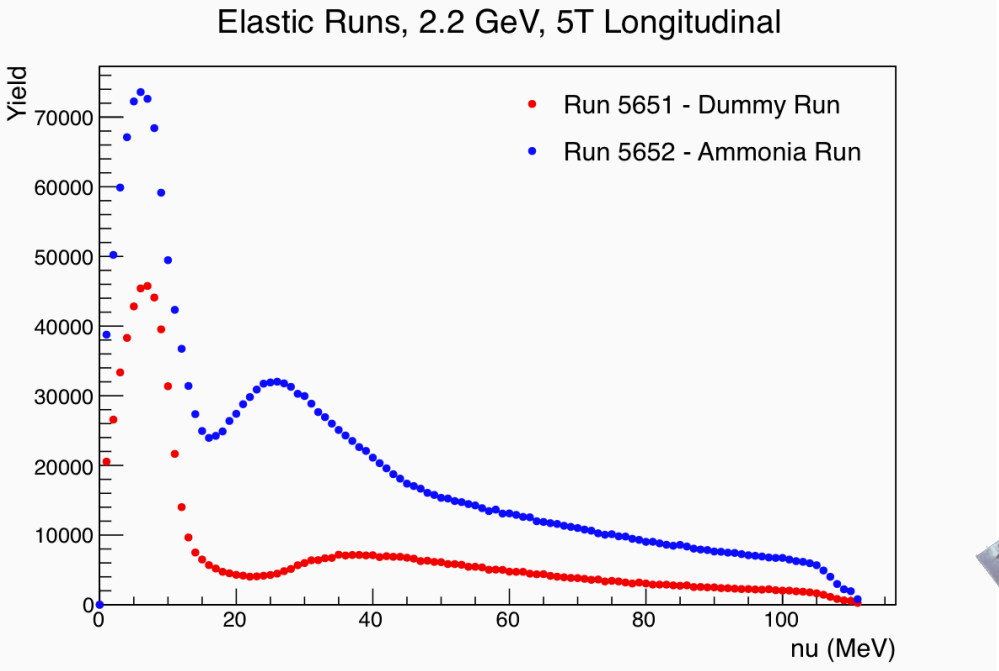
Method:

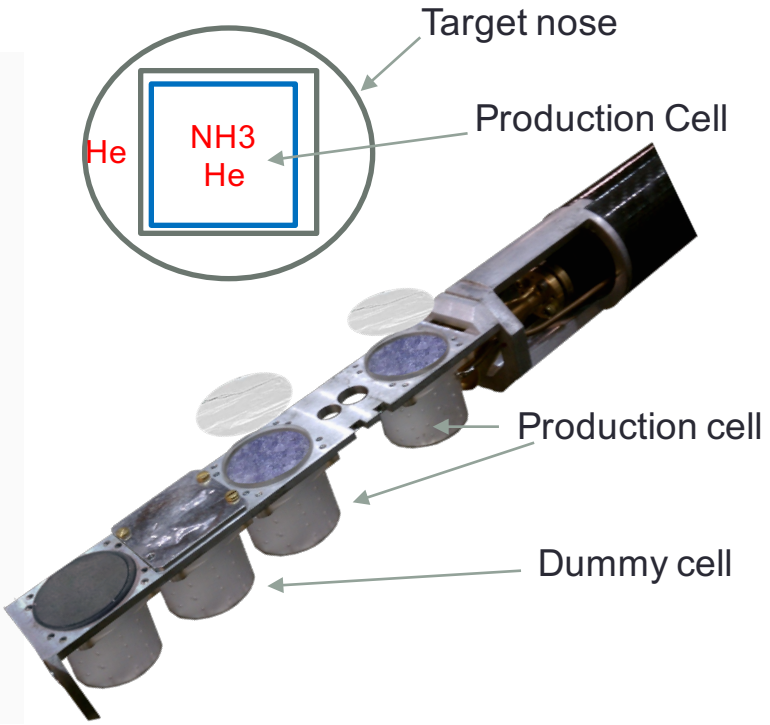
- Generate transport functions to describe trajectories (Snake)
  - Forward/backward between target and focal plane
  - Forward to multiple end-planes along the trajectories to define apertures
- Transport functions compiled into simulation package (g2psim)
- Work still continue …

courtesy of Min Huang

Target Cell Packing Fraction

- Packing Fraction (p_f) -- Ratio of NH_3 volume to the whole cell
- Method: $Y_{prod} = Y_{He}^{out} + (1 - p_f)Y_{He}^{full} + p_f Y_{NH_3}^{full}$
  - ✓ Compare the experiment elastic yields
  - ✓ Extract N/He volume ratio with input from simulation

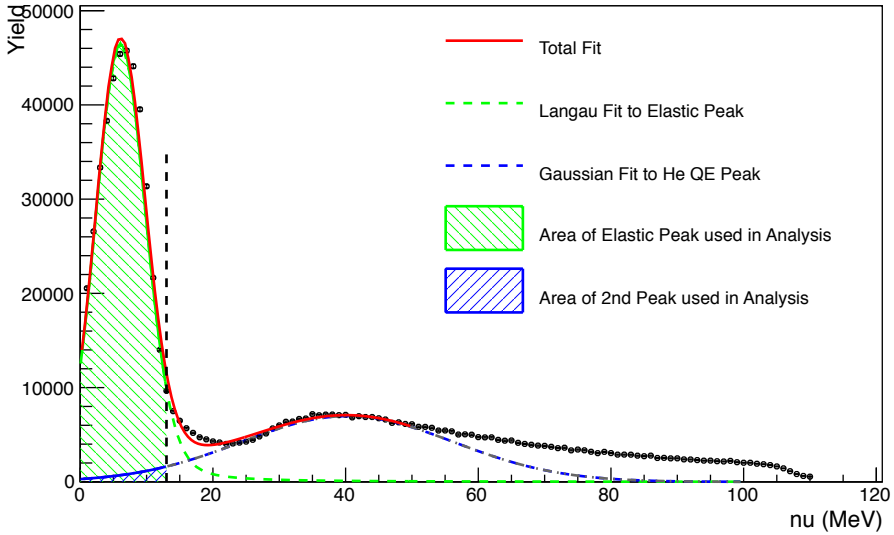




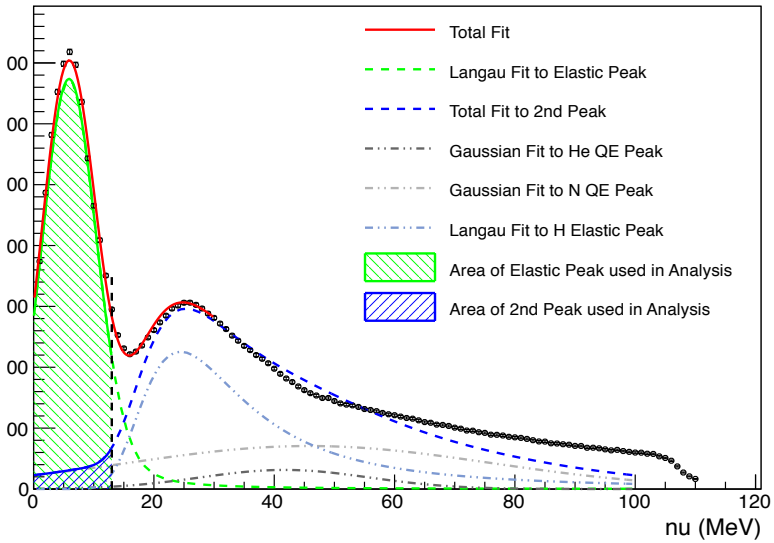
Target Cell Packing Fraction

- Packing Fraction (p_f) -- $Y_{prod} = Y_{He}^{out} + (1 - p_f)Y_{He}^{full} + p_f Y_{NH_3}^{full}$

Fit to Dummy Run



Fit to Production Run



- Only concerned with elastic peak

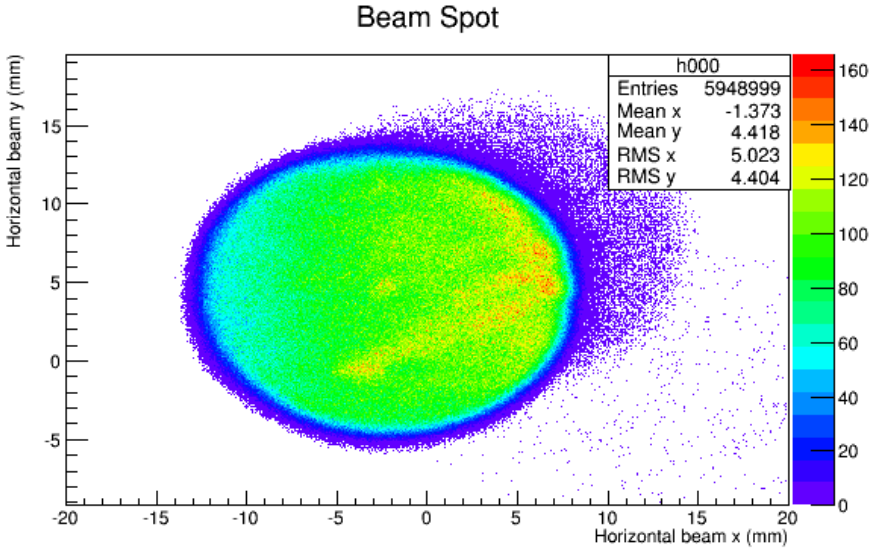
- 2nd peak: contributions from multiple materials -- QFS model to understand relative contributions

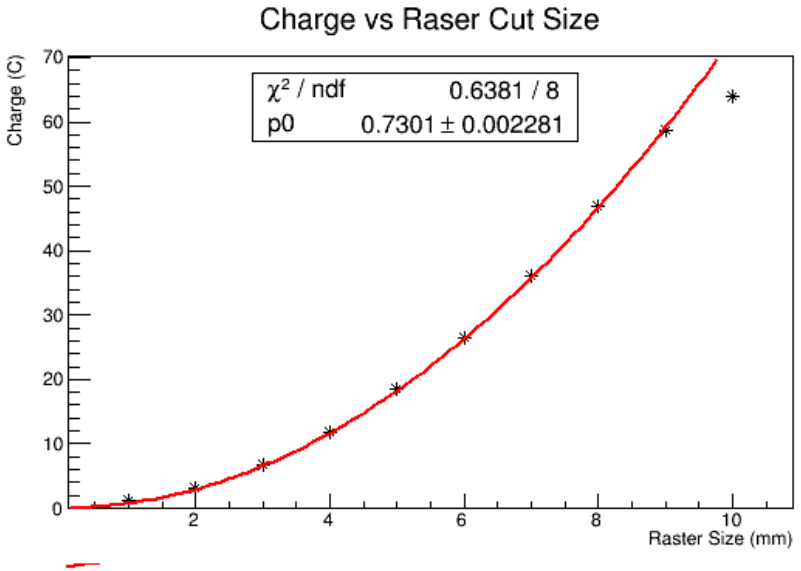
Preliminary Result (material 17):
$p_f = 0.579 \pm 0.025$

courtesy of Melissa Cummings

Yields Drift

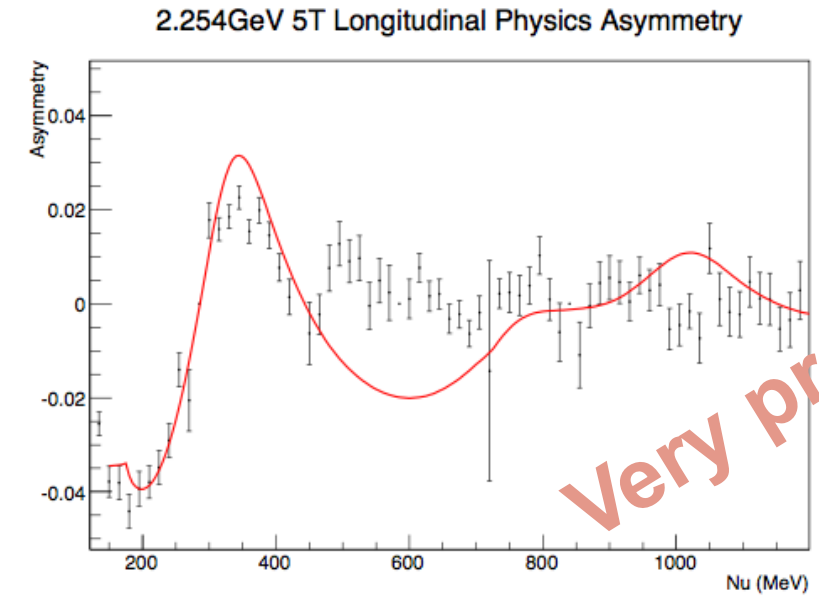
- Around 7% data have yields spread > 3.5% respect to runs in the same setting
- Method: Cut the raster size (corresponding charge) to remove the boundary effects

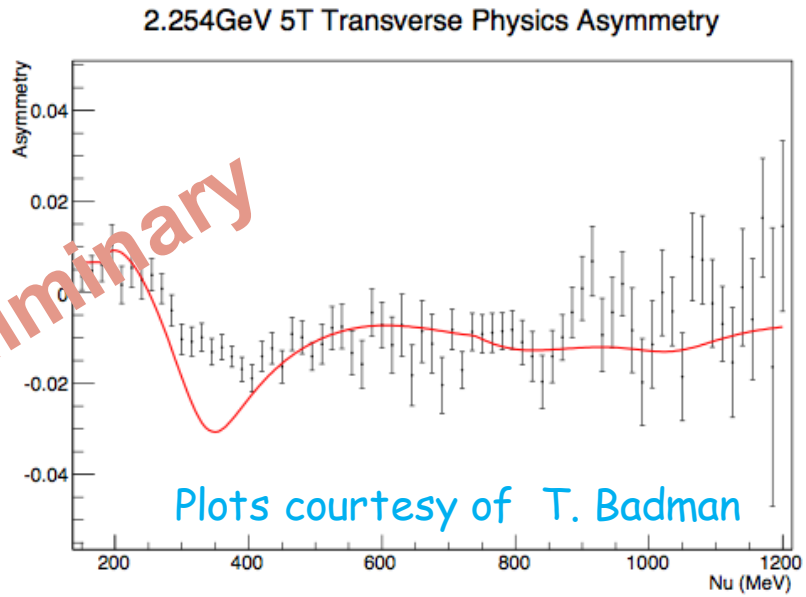




- Yields Drift problem resolved for half of these yields drifting data

Preliminary Results





Very preliminary

Plots courtesy of T. Badman

$$\Delta\sigma_{\perp} = A_{\perp} \times \sigma_0$$

$$A_{\perp} = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\downarrow\Rightarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\downarrow\Rightarrow}}$$

$$A_{\parallel} = \frac{\sigma^{\uparrow\Uparrow} - \sigma^{\downarrow\Uparrow}}{\sigma^{\uparrow\Uparrow} + \sigma^{\downarrow\Uparrow}}$$

- ✓ Fully radiated asymmetries (red curve)
- ✓ Cross section models: Peter Bosted's fit (unpolarized) and MAID 2007 (polarized)
- ✓ Include Unpolarized and polarized elastic tail
- ✓ Radiating methods: Mo/Tsai (unpolarized) and Akushevich/Ilyichev/Shumeiko (polarized)

Summary

- The g2p experiment took data covering $M_p < W < 2$ GeV, $0.02 < Q^2 < 0.2$ GeV^2
- Will provide a precision measurement of g_2^p in the low Q^2 region for the first time
- Results will help to understand several physics puzzles, such as δ_{LT}
- Analysis is in progress
  - Target polarizations: Nucl. Instrum. Meth. A738(2014)54
  - BPM reconstruction: Nucl.Instrum.Meth. A808 (2016) 1-10 …

G_2^P Collaboration

- **Spokepeople**
  - Alexandre Camsonne (Jlab)
  - Jian-Ping Chen (JLab)
  - Don Crabb (UVA)
  - Karl Slifer (UNH)
- **Post Docs**
  - Kalyan Allada
  - Elena Long
  - James Maxwell
  - Vince Sulkosky
  - Jixie Zhang
- **Graduate Student**
  - Toby Badman
  - Melissa Cummings
  - Chao Gu
  - Min Huang
  - Jie Liu
  - Pengjia Zhu
  - Ryan Zielinski

Thanks!