A Measurement of Proton g_2 Spin Structure Function at low Q^2

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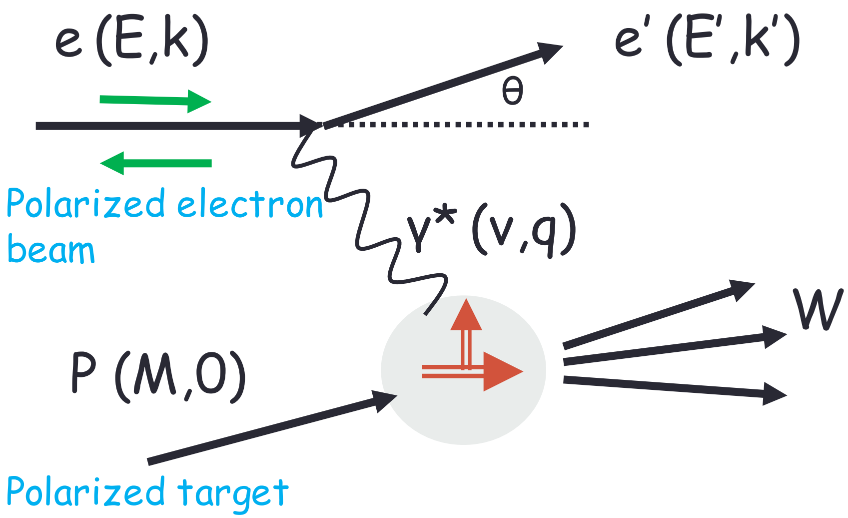
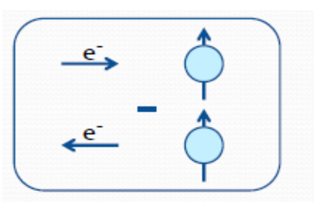
On behalf of the g_2^p collaboration

Inclusive Electron Scattering

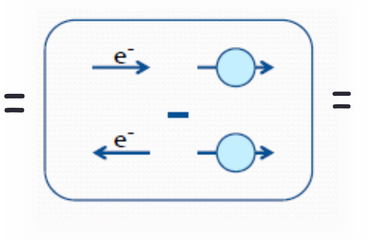


- Invariant Mass
  $W^2 = M^2 + 2M\nu - Q^2$
- Four momentum transfer squared
  $Q^2 = -q^2$
- Bjorken variable
  $x = Q^2/2M\nu$ for fixed target

$\Delta\sigma_\perp =$ 

$= \frac{4\alpha^2 E'}{M\nu Q^2 E}\left[\sin\theta\left(g_1 + \frac{2E}{\nu} g_2\right)\right]$

g_2^P experiment measure

$\Delta\sigma_\parallel =$ 

$= \frac{4\alpha^2 E'^2}{M\nu Q^2 E}\left[(E + E'\cos\theta) g_1 - 2Mx g_2\right]$

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

Proton g_2 Existing Data

- little data previously, hard to measure g_2^p

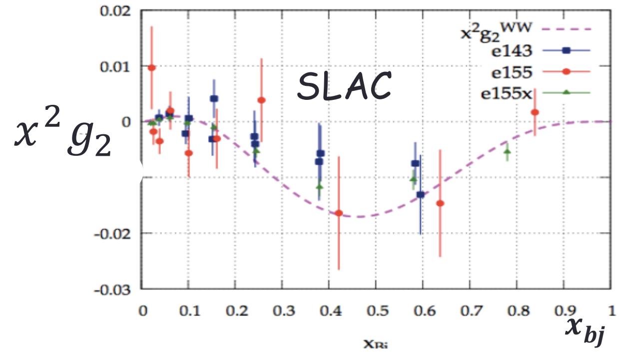
- First precise measurement of Proton g_2 from SLAC, averaged $Q^2 \approx 5\ GeV^2$

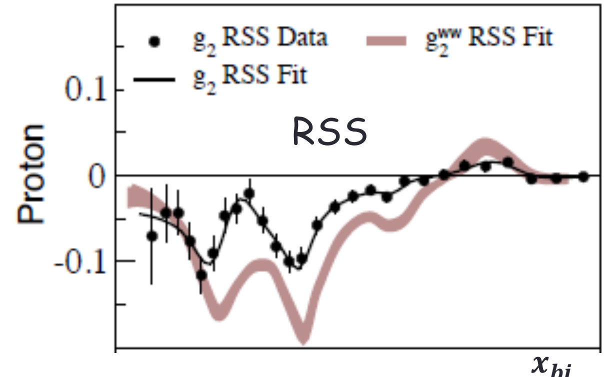
- Measurements from Jefferson Lab

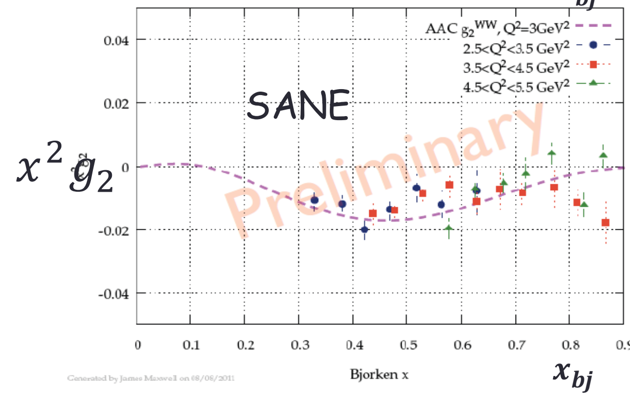
- Jlab RSS -- medium Q^2
  $1 < Q^2 < 2\ GeV^2$ -- Published
  K.Slifer, O. Rondon *et al.* PRL 105, 101601 (2010)

- JLab SANE -- high Q^2
  $2 < Q^2 < 6\ GeV^2$ -- Analysis in progress

- JLab g2p -- low Q^2
  $0.02 < Q^2 < 0.2\ GeV^2$ -- Analysis in progress







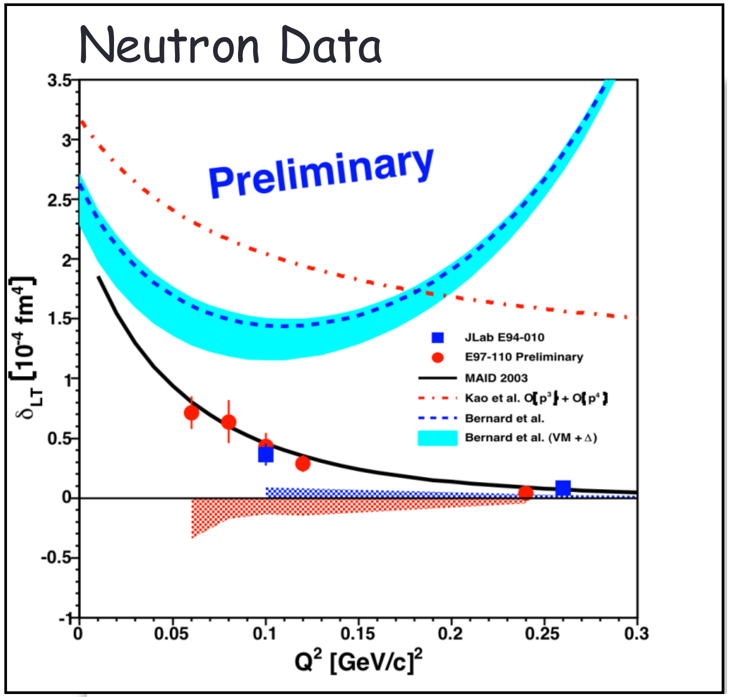
Motivation

- 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 generalized LT polarizability δ_{LT}
  - Examine the Burkhardt-Cottingham sum rule at low Q^2
  - Important inputs for hydrogen hyperfine splitting and proton charge radius measurements

δ_{LT} Puzzle for Neutron

- Generalized Spin Polarizabilities: how nucleons respond to virtual photons

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



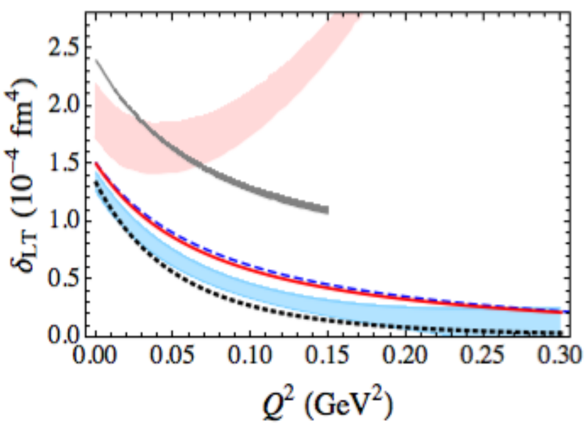
- δ_{LT} less sensitive to Δ, good to test χPT calculations
- Good agreement with MAID model predictions
- χPT fail -- puzzle?
- HBχPT: Kao, Spitzenberg, Vanderhaeghen
- PRD 67:016001(2003)
- RBχPT: Bernard, Hemmert, Meissner
- PRD 67:076008(2003)
- No proton data yet

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

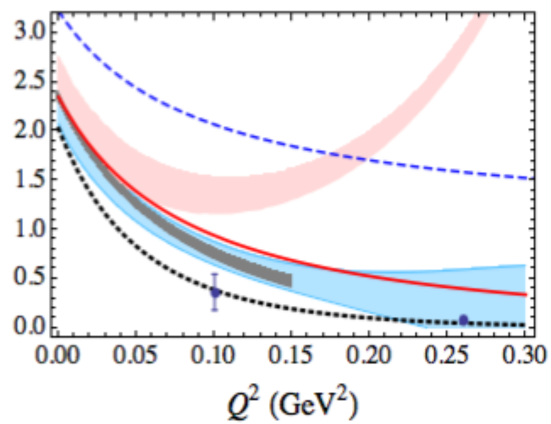
δ_{LT} Puzzle

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

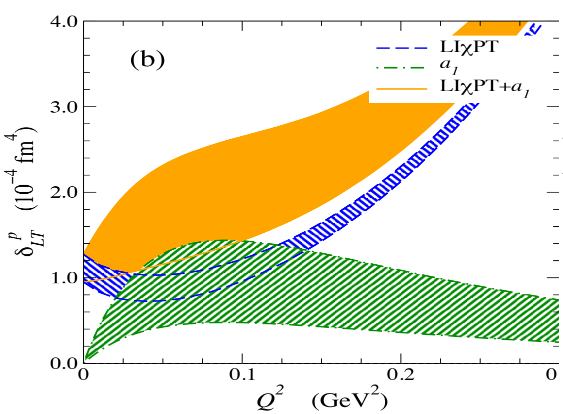
Proton

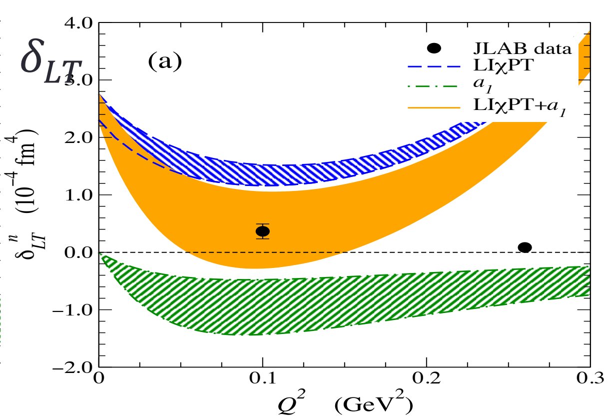


Neutron



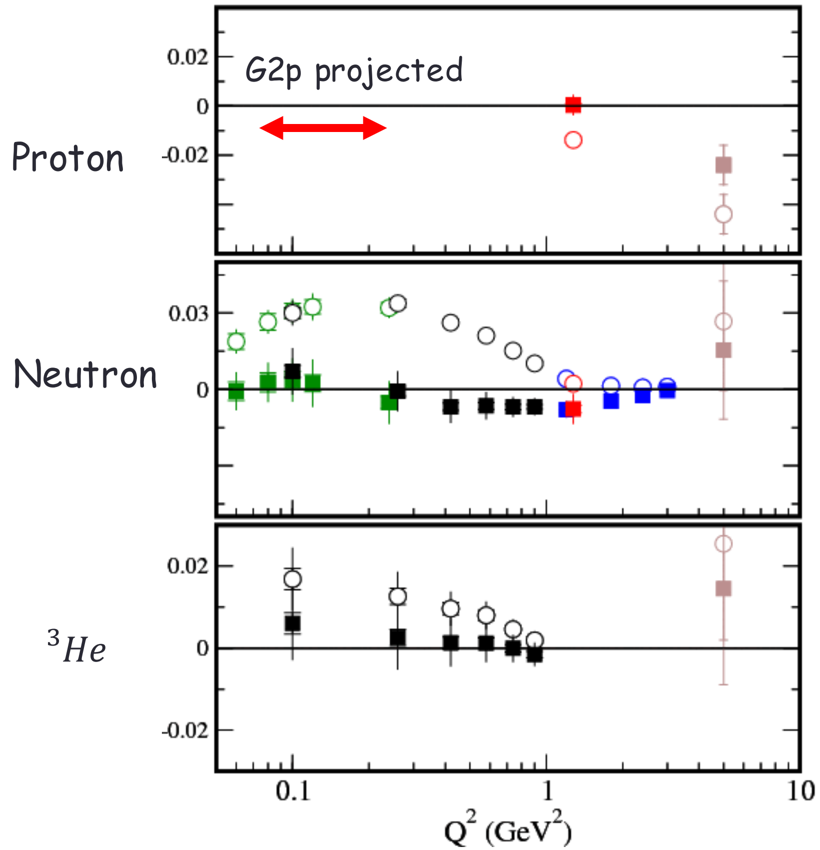
- Blue Band: HBχPT
- Lensky, Alarcon & Pascalutsa PRC 90 055202 (2014)
- Grey Band: RBχPT
- Bernard et al., PRD 87 (2013)
- Blacked Dotted: MAID





- Yellow Band: Contribution from axial anomaly
- N. Kochelev and Y. Oh, PRD 85, 016012 (2012)
- Disagreement resolved?
- Need proton data

BC Sum Rule



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

BC Sum Rule:

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

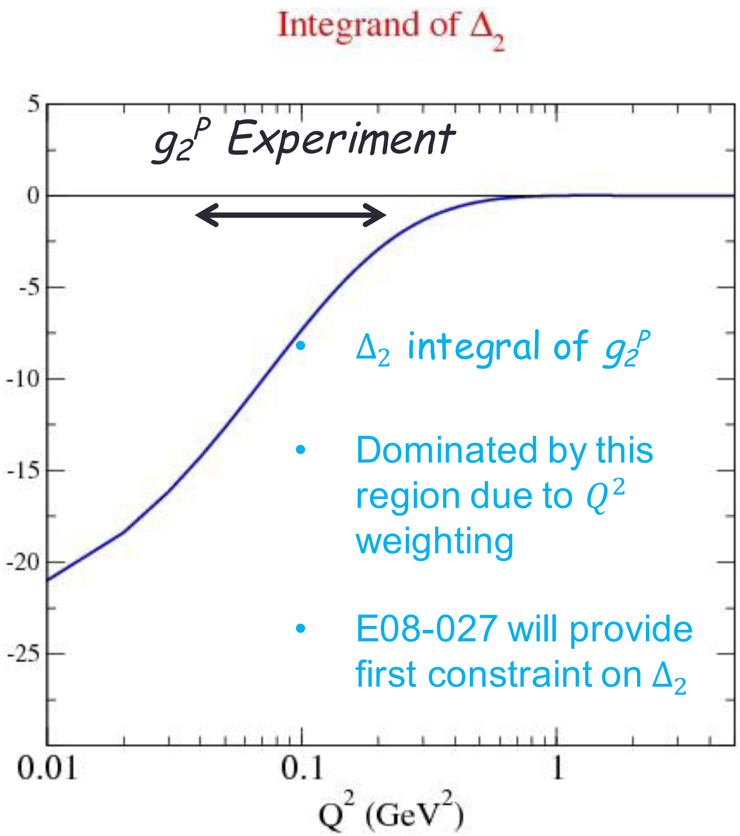
Experiment Test:

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 & ^3He
- Mostly unmeasured for proton

Hydrogen Hyperfine Splitting

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



- Δ_2 integral of g_2^p
- Dominated by this region due to Q^2 weighting
- E08-027 will provide first constraint on Δ_2

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

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

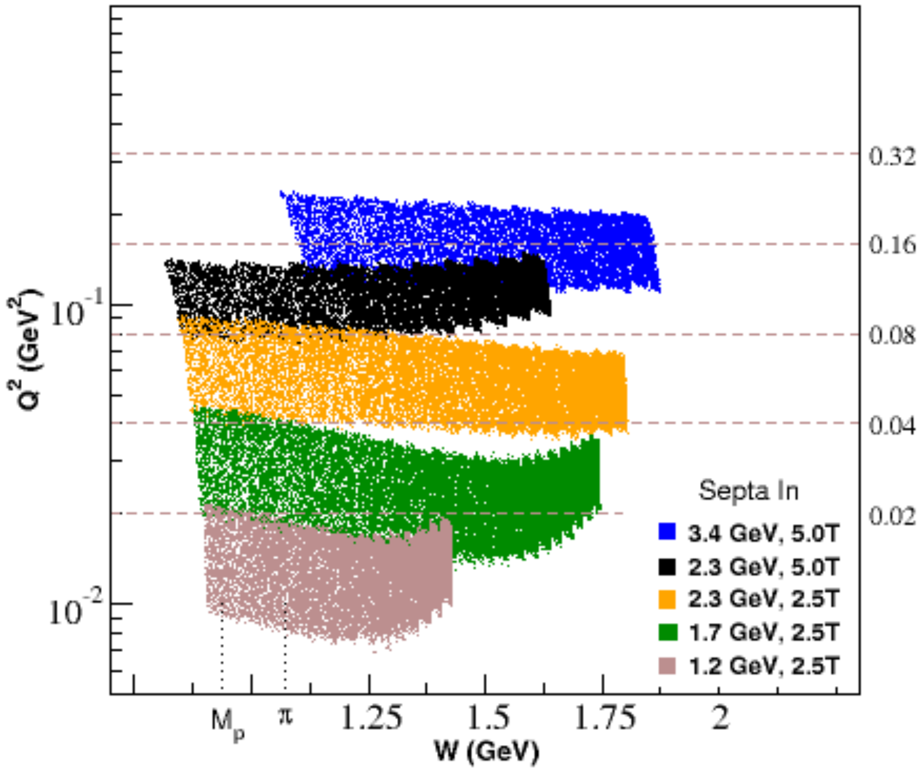
Δ_s : proton structure function correction

- 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

The g_2^p Experiment Kinematic Coverage



M_p < W < 2 GeV
0.02 < Q^2 < 0.2 GeV^2

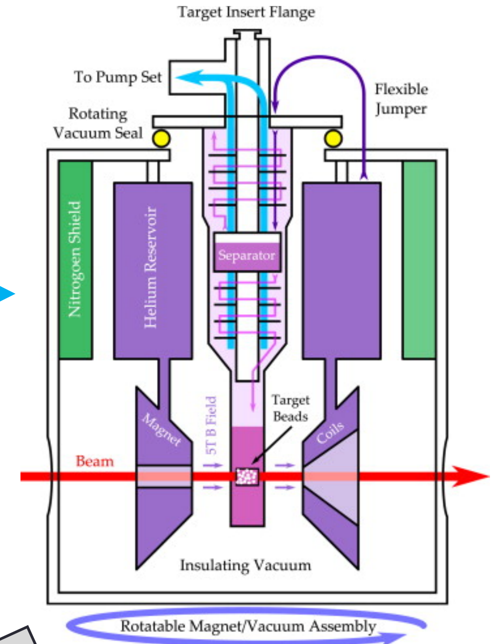
- Data taken in 2012
- Beam ~ 50nA, polarization > 80%
- Polarized NH_3 target 2.82cm
  pol ~ 70% (5T), pol ~ 15%(2.5T)

Beam Energy /GeV	Target Field /T
2.254	2.5
1.706	2.5
1.158	2.5
2.254	5.0
3.352	5.0

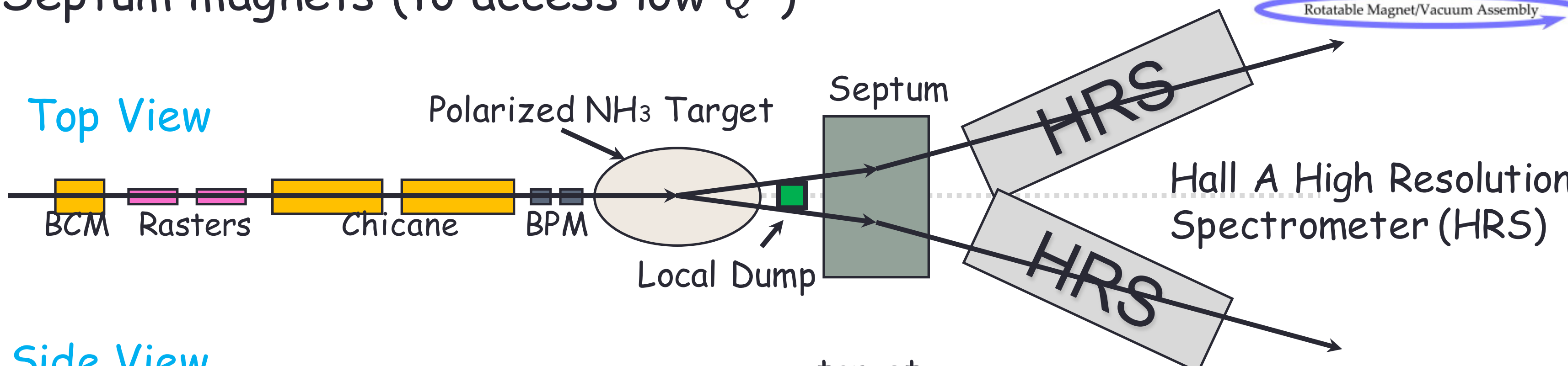
Experiment setup

❑ Unique/Challenging Setup in Hall A

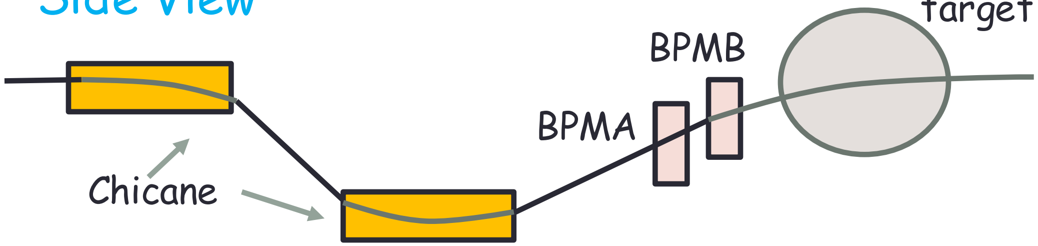
- Transverse polarized NH_3 target (5T/2.5T)
- Low beam current/new BPM receiver
- Slow rasters first time use
- Chicane magnets (to deal with strong target field)
- Septum magnets (to access low Q^2)



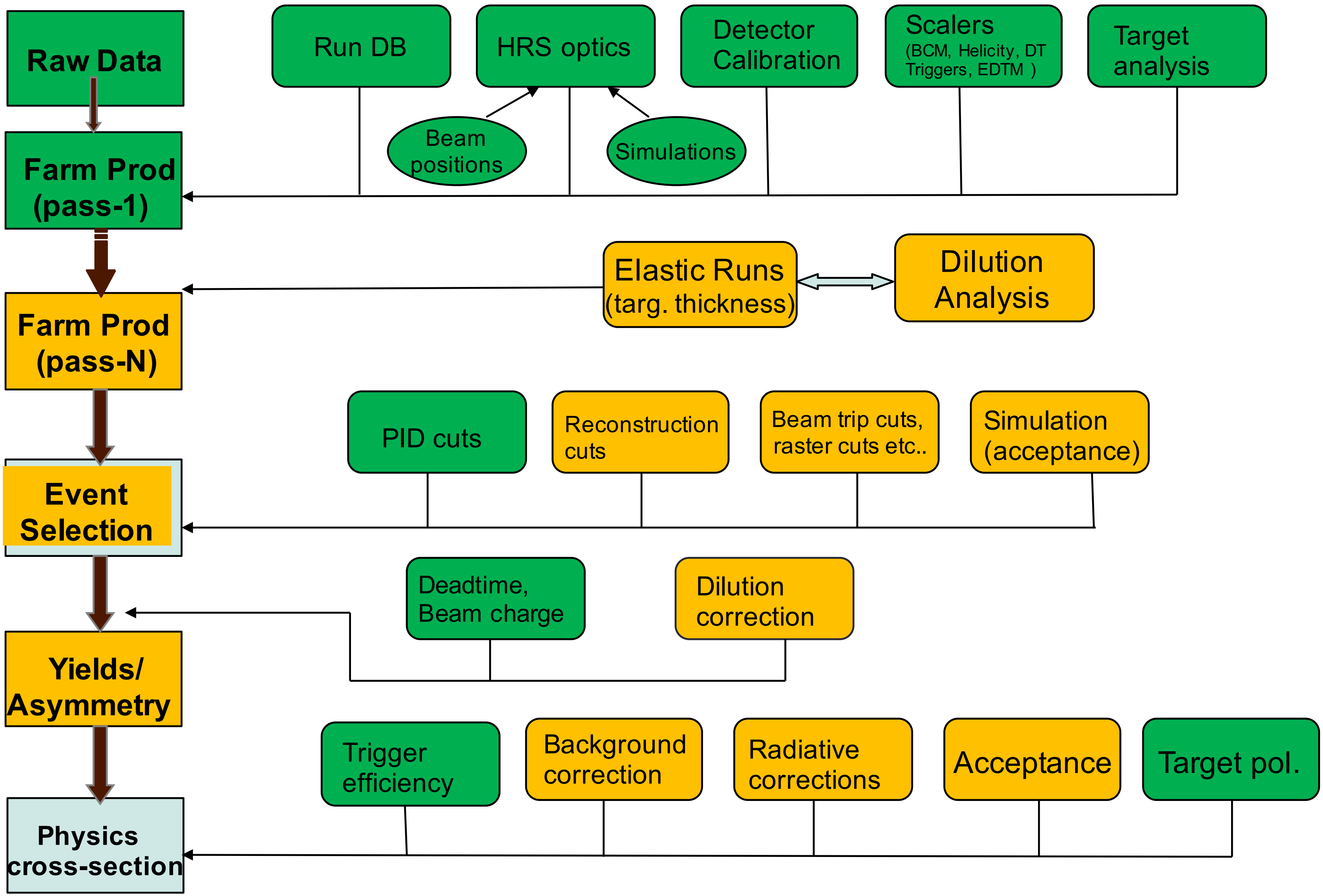
Top View



Side View



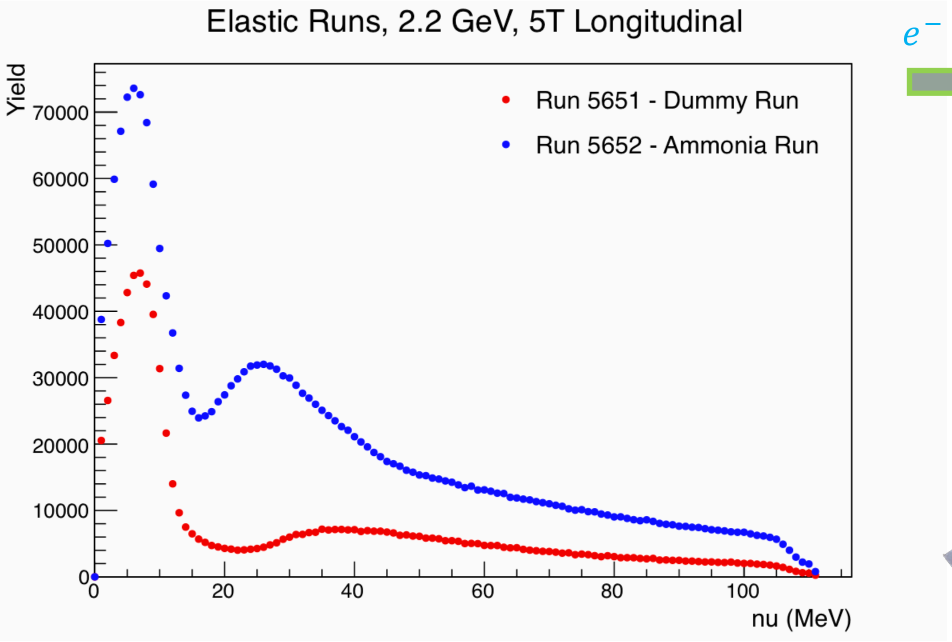
Analysis Flow Chart

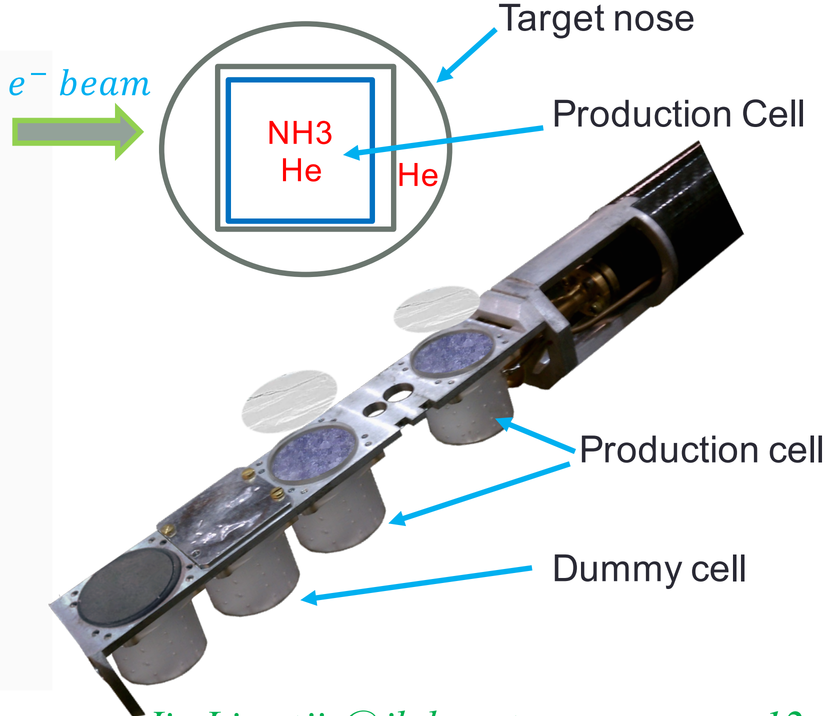


Target Cell Packing Fraction

- ❑ Cross section: need know absolute proton numbers in target
- 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

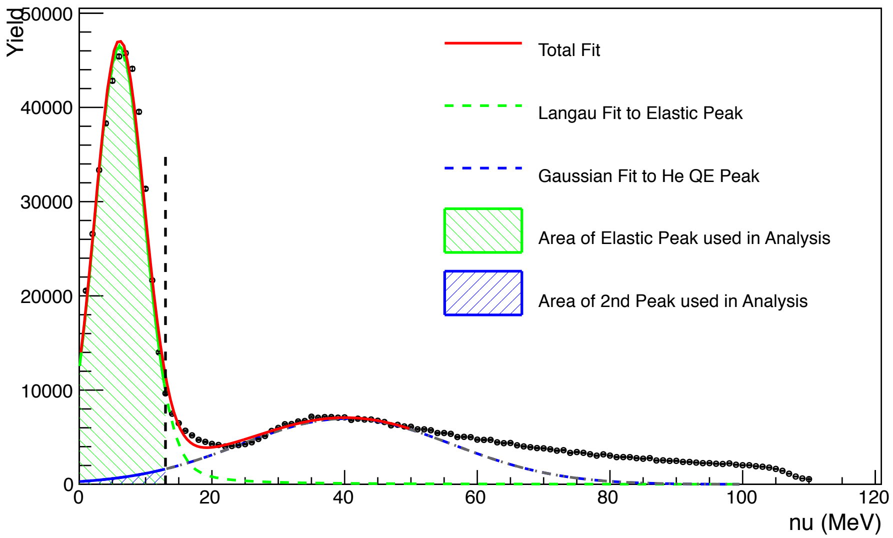




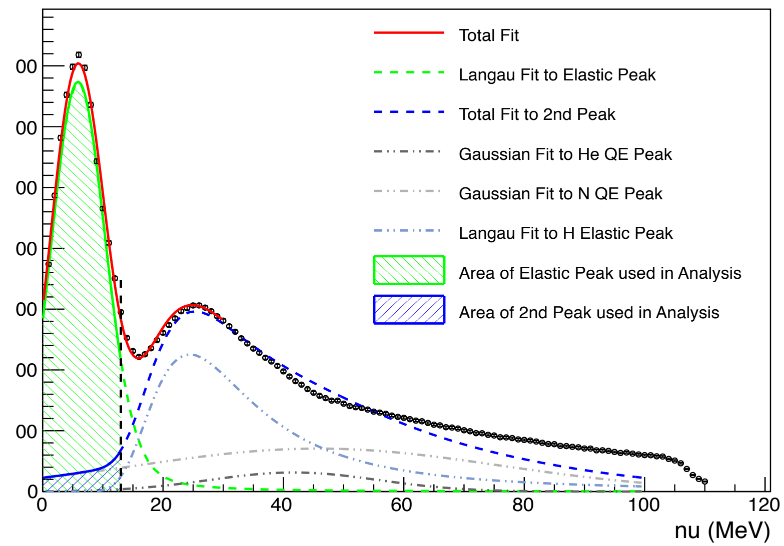
Target Cell Packing Fraction

- 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):
$p_f = 0.579 \pm 0.025$

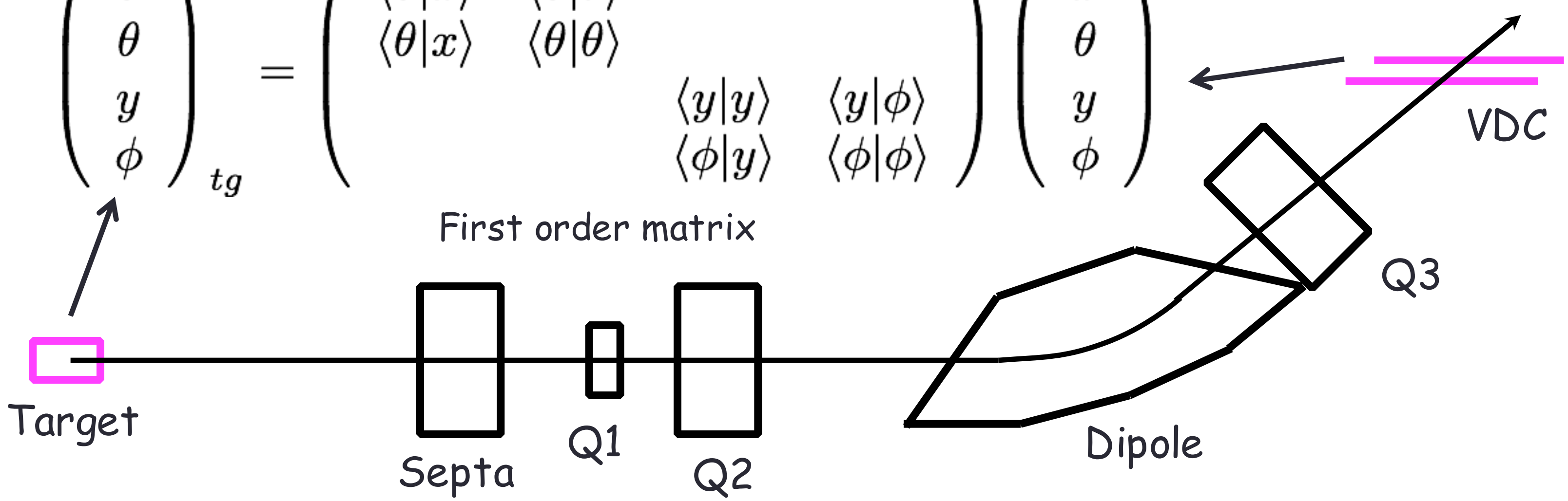
courtesy of Melissa Cummings

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



Optics

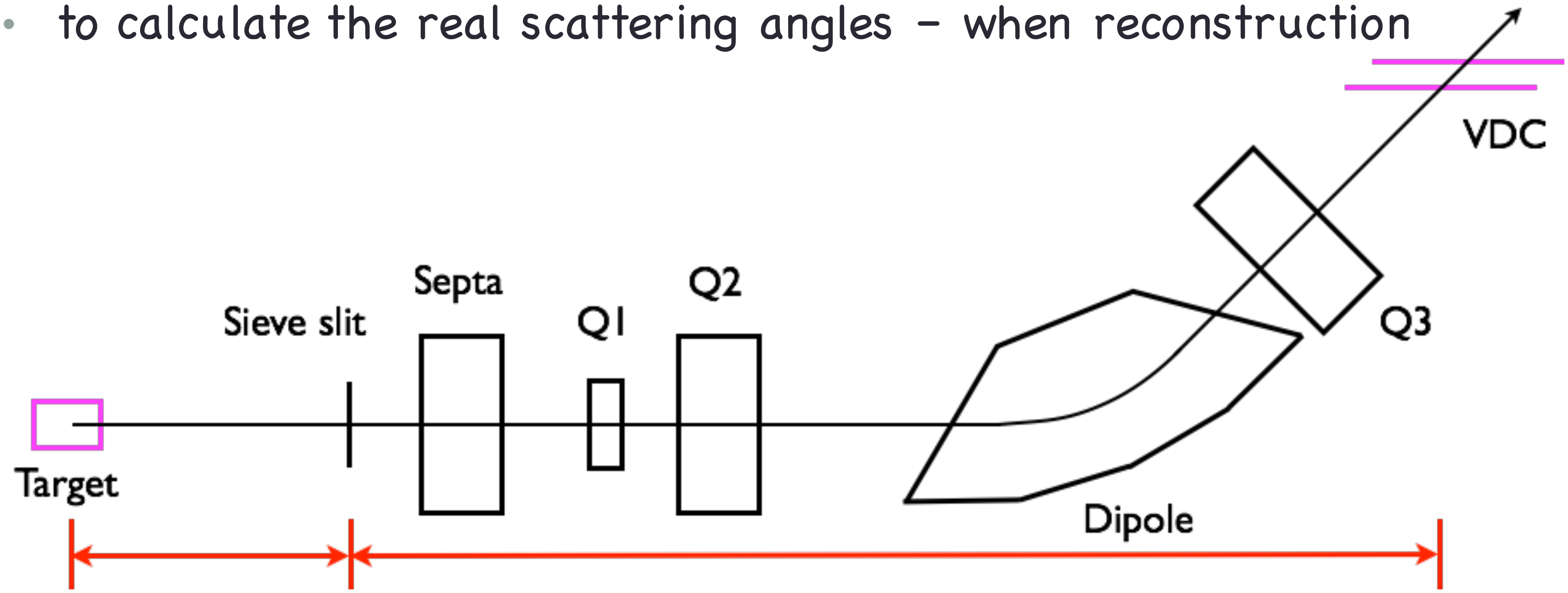
❑ Optics with Target Field

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 sieve slits

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



Optics

- Optics with target field
  Standard HRS + target field + septum (burnt twice)

Energy/GeV	Field		Septum	RMS δ [dp]	RMS θ /mrad [out-of plane angle]	RMS φ/mrad [in-plane angle]
2.254	0T		484816	1.5e-4	1.6	0.8
2.254	2.5T	Trans	484816	2.0e-4	1.7	1.7
2.254	2.5T	Trans	403216	3.0e-4	3.2	1.9
1.706	2.5T	Trans	400016	2.4e-4	2.4	1.5
1.158	2.5T	Trans	400016	3.2e-4	3.1	1.3
2.254	5.0T	Long	400016	2.2e-4	1.6	1.2

courtesy Min Huang & Chao Gu

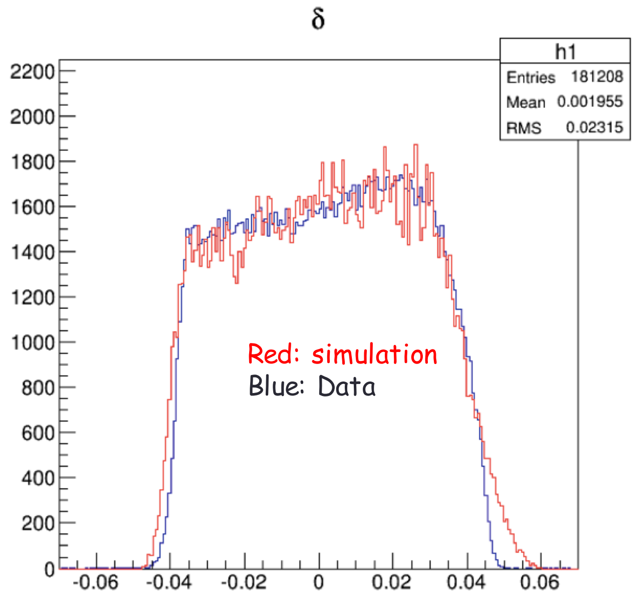
Acceptance

- 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

$$\frac{Acc}{\Delta\Omega\Delta E'} = \frac{1}{\Delta\Omega^{MC}\Delta E'^{MC}} \frac{N_{simu}^{MC}}{N_{acc}^{MC}}$$



E 2.2 GeV, momentum 1.7 GeV, 2.5T Trans

Method:

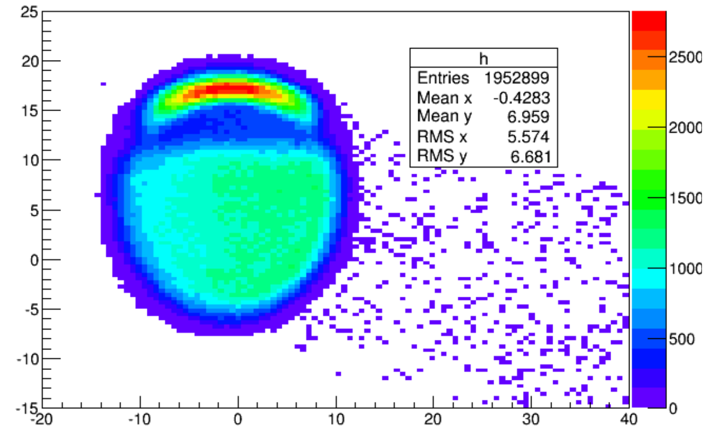
- Generate transport functions to describe trajectories (Snake)
  - Forward/backward between target and focal plane
  - Forward to multiple end-planes along the trajectories to define apertures
- Transport functions compiled into simulation package (g2psim)

courtesy of Min Huang

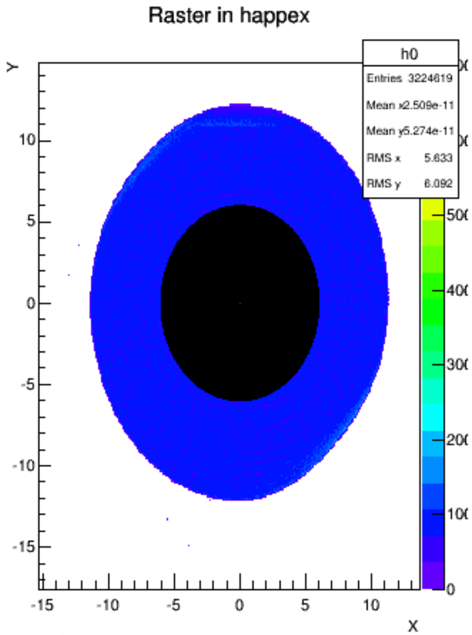
Yields Drift

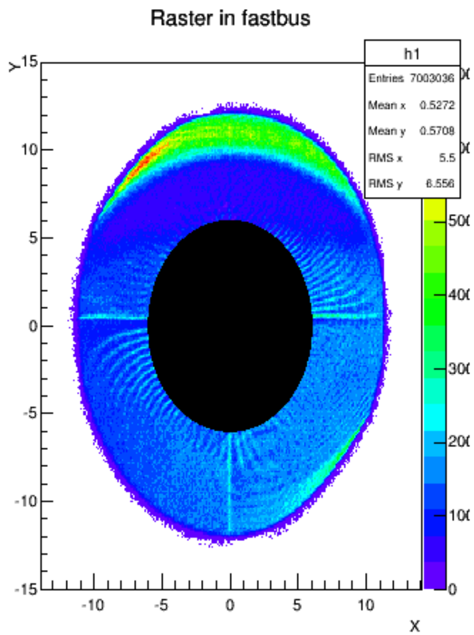
- Around 7% data have yields spread > 3.5% respect to runs in the same setting, some settings even can be 10% - 34%

Beam Spot: y vs x (mm)



- Cut the raster size (corresponding charge) to remove the boundary effects

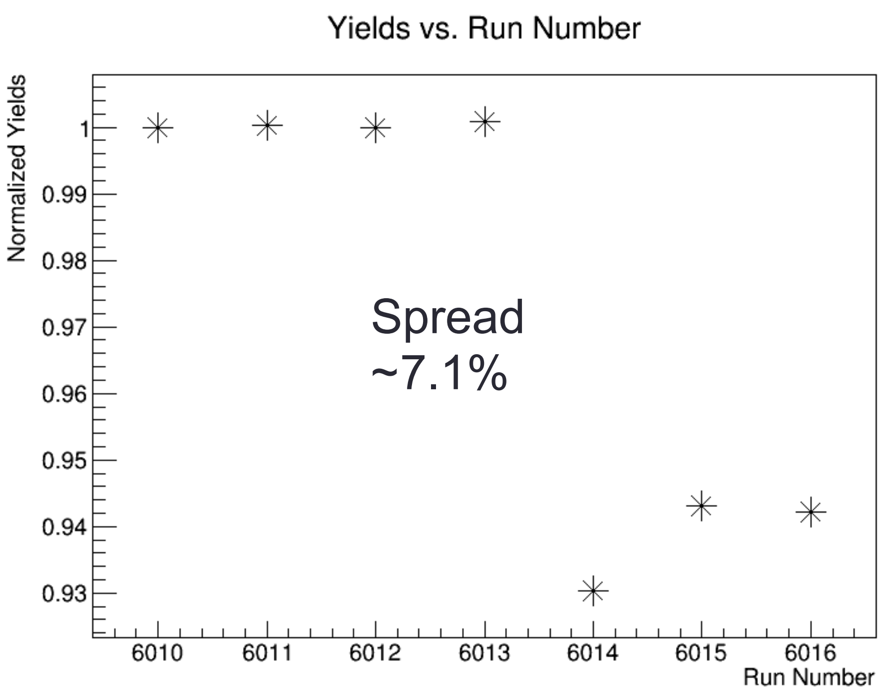


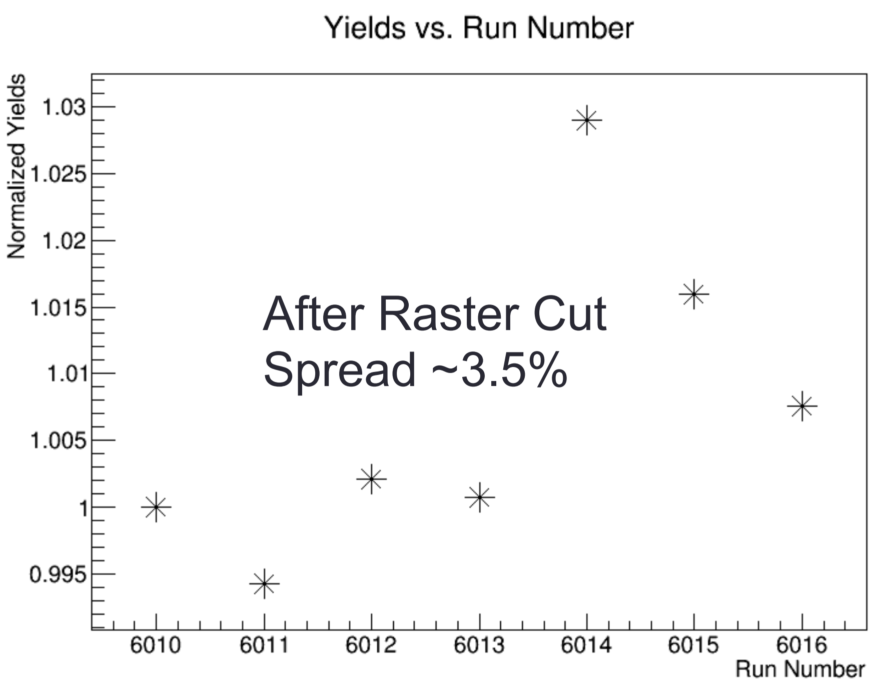


- The black circle is the 6mm (radius) raster cut

Yields Drift

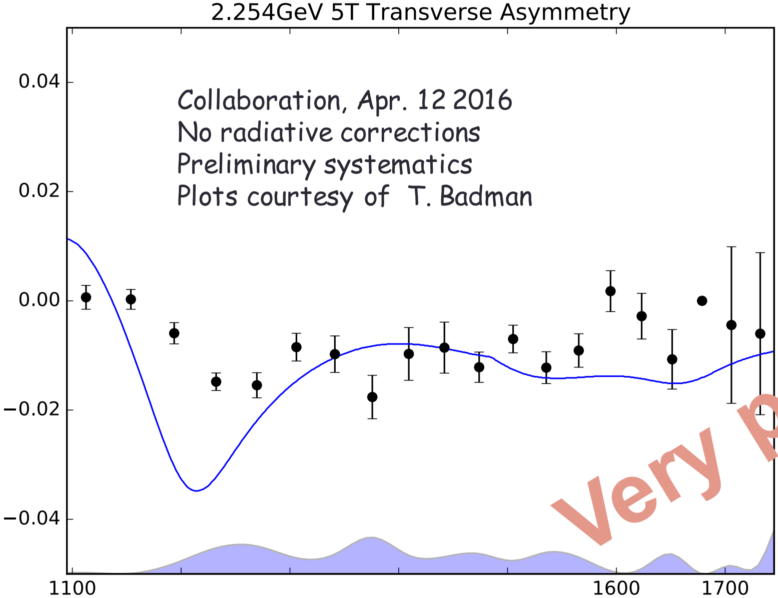
- Yields spread drops after applying raster cut

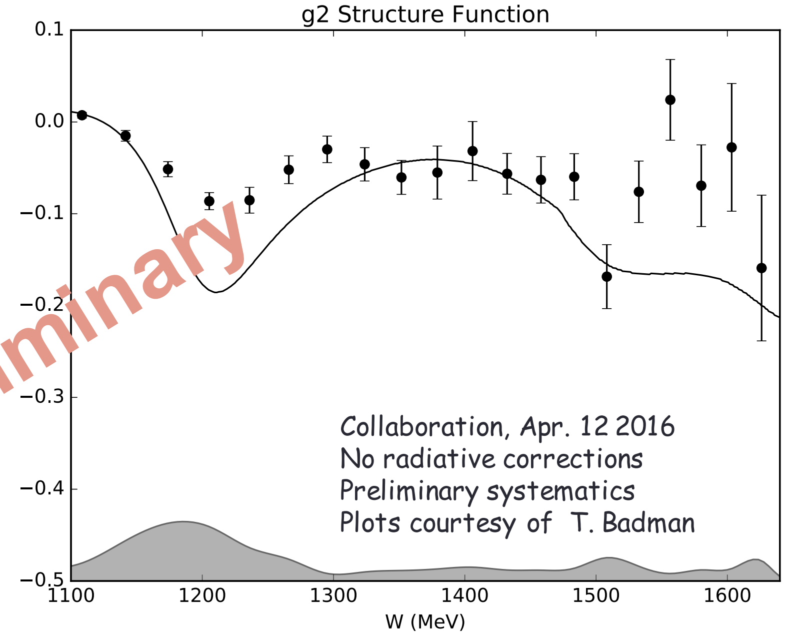




- Yields Drift problem resolved for half of these yields drifting data
- More systematics study are going on

Preliminary Results





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

$$\Delta\sigma_{\perp} = 2A_{\perp}\sigma_0$$

- ✓ Fully radiated (black/blue curve)
- ✓ Cross section models: Peter Bosted's fit (unpolarized) and MAID 2007 (polarized)
- ✓ Models 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
- Results will help to understand several physics puzzles, such as δ_{LT}
- Analysis is in progress…

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
- **Jlab Target Group**
- **Hall A Collaboration**

- **Graduate Student**
  - Toby Badman (UNH)
  - Melissa Cummings (W&M, Graduated)
  - Chao Gu (UVa)
  - Min Huang (Duke, Graduated)
  - Jie Liu (UVa)
  - Pengjia Zhu (USTC, Graduated)
  - Ryan Zielinski (UNH)
- **Advisor: Xiaochao Zheng**

Thanks!