# Tritium-isospin Experiment Update

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Shujie Li
On behalf of the E12-11-112 Collaboration
Jan 30th, 2019

Jefferson Lab
Exploring the Nature of Matter

University of New Hampshire

Jefferson Lab E12-11-112 (Hall A) :

# Precision Measurement of the Isospin Dependence in the 2N and 3N Short-range Correlation Region

**Tritium Experiment Group:**

2017.12: Comissioning
2018.2-2018.5: E12-11-103 MARATHON
2018.5 E12-14-011 e'p (exclusive SRC)
**2018.5 : E12-11-112 x>1 (inclusive SRC) 2.2 GeV beam**
**2018.9-11 : E12-11-112 x>1 (inclusive SRC) 4.3 GeV beam**
2018.11: E12-17-003 e'K

**E12-14-009 Elastic –not scheduled

# Run Schedule

Fall 2018

**LHRS: Dedicated NN and 3N SRC study (1<xbj<3) with 4.3 GeV beam**

RHRS: QE scan

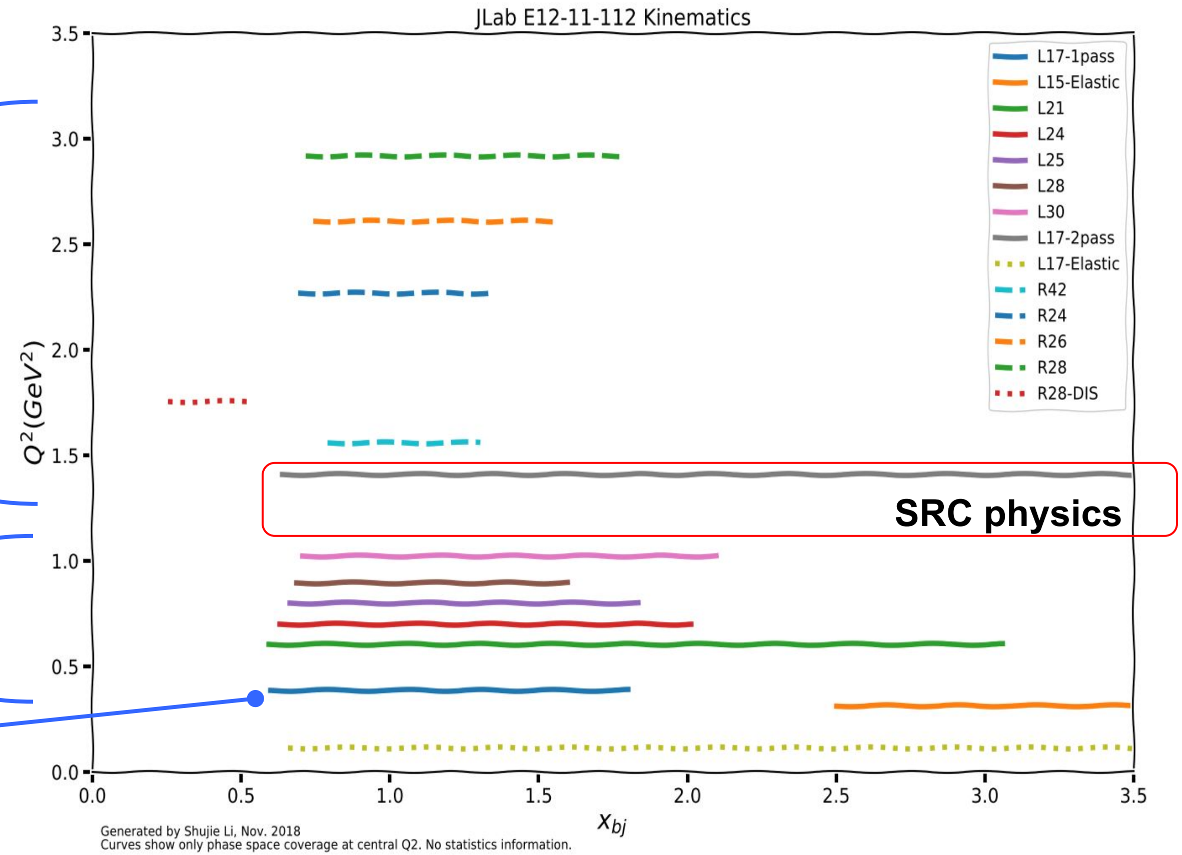
May 2018:

QE scan with 2.2 GeV beam

Dec 2017:

Commissioning

Target “boiling” study ( also QE data at Q2=0.4 GeV2)



Jefferson Lab E12-11-112 (Hall A) :

# Precision Measurement of the Isospin Dependence in the 2N and 3N Short-range Correlation Region

**Spokespersons:**
Patricia Solvignon (UNH), John Arrington (ANL), Donal Day (UVa), Douglas Higinbotham (Jefferson Lab), Zhihong Ye (ANL)
**Students**:
Shujie Li (UNH), Nathaly Santiesteban (UNH), Tyler Kutz (Stony Brook)

**Measurements:**
**1H, 2H, 3H, 3He, (C12, Ti48) inclusive cross sections at 0.6<xbj<3**

**Physics Topics**:

1. Check the 2N SRC isospin dependence at 1<x<2, and also 3N momentum sharing configuration.

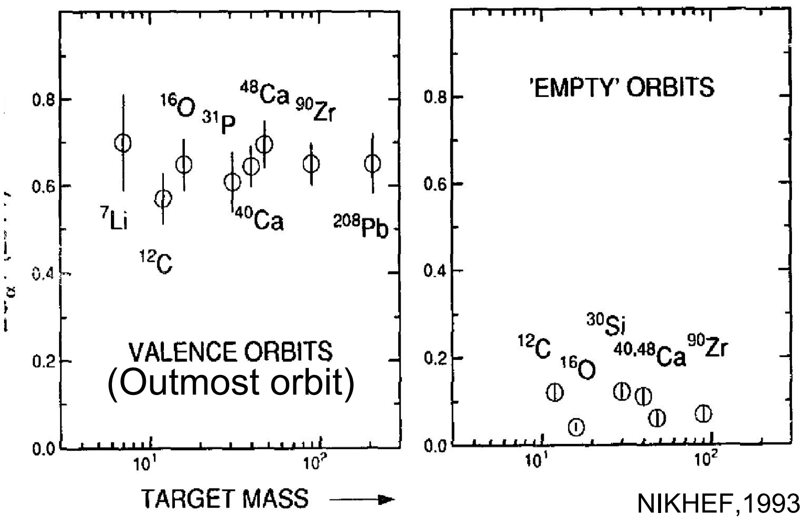
**np pair dominates:** $\frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{\sigma_{np}+\sigma_n}{\sigma_{np}+\sigma_p} \simeq \frac{\sigma_{np}}{\sigma_{np}} = 1$ **no isospin preference:** $\frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{2\sigma_{nn}+\sigma_{pp}}{\sigma_{nn}+2\sigma_{pp}} \xrightarrow{\sigma_p \sim 3\sigma_n} 0.7$

2. Extract GMn from 3He/3H ratios at quasi-elastic peak: $\left(\frac{\sigma_{^3He}}{\sigma_{^3H}}\right)_{QE} \to \left(\frac{\sigma_n}{\sigma_p}\right)_{QE} \to\to G_M^n$

3. **extract Inelastic cross section ratio at low $Q^2$. This could be combined with high $Q^2$ results from world data (e.g. MARATHON) to check the A-dependence of R=L/T

# Nucleons in Nuclei:

## Beyond Shell Model

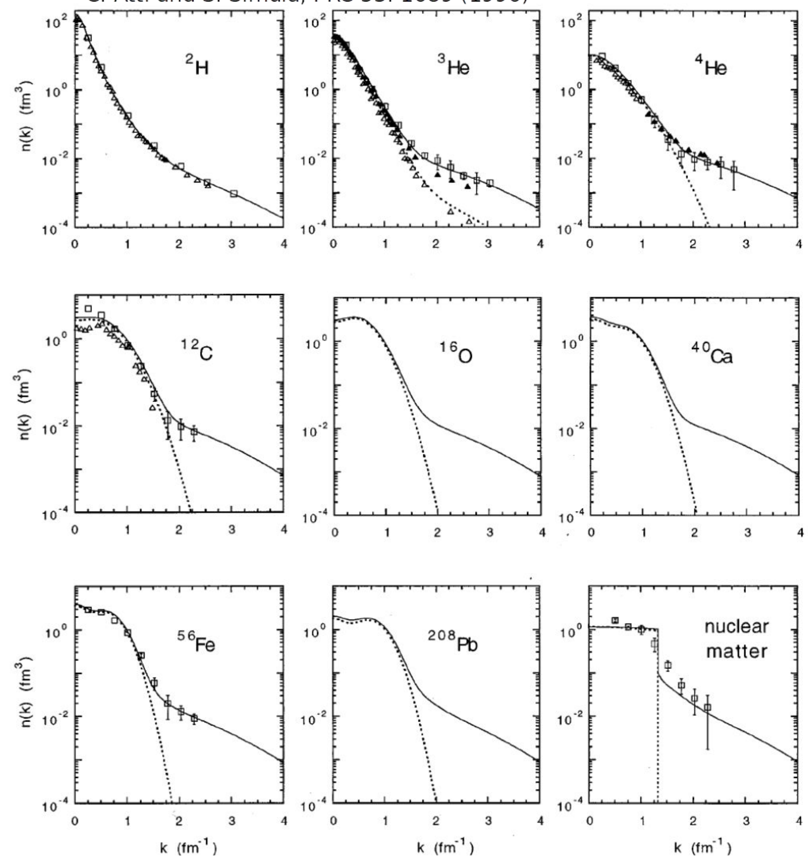



NIKHEF,1993

- The closed orbits are NOT fully occupied.

*"The main effects of NN correlations is to generate high momentum and high removal energy components"*

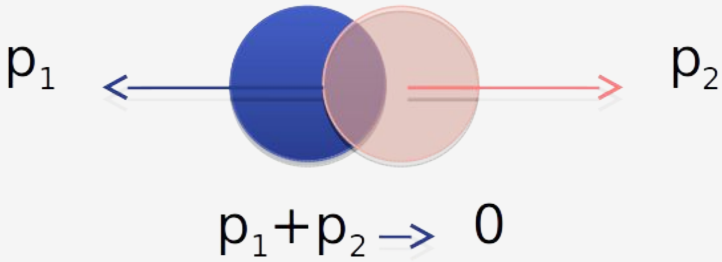
C. Atti and S. Simula, PRC 53. 1689 (1996)



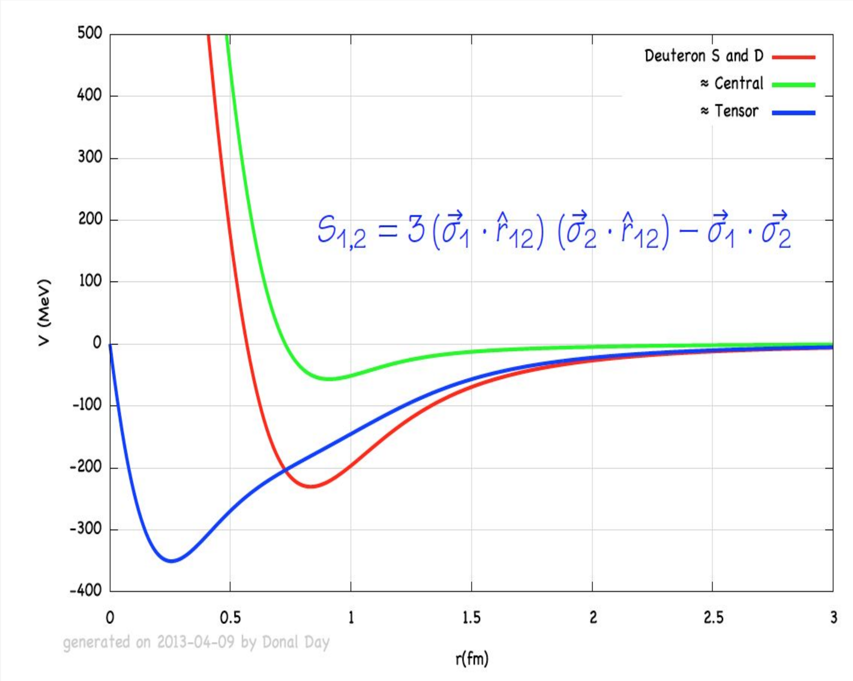

- High momentum nucleons in different nuclei

# Nucleon-Nucleon Short Range Correlation (SRC)

Free nucleon-nucleon potential = **Repulsive core** **+** **attractive tensor force**
T = 1, S = 0 :np, pp, nn pairs. The tensor operator $S_{1,2}$= 0 , no attractive tensor force
T = 0, S = 1: Deuteron-like np pair.

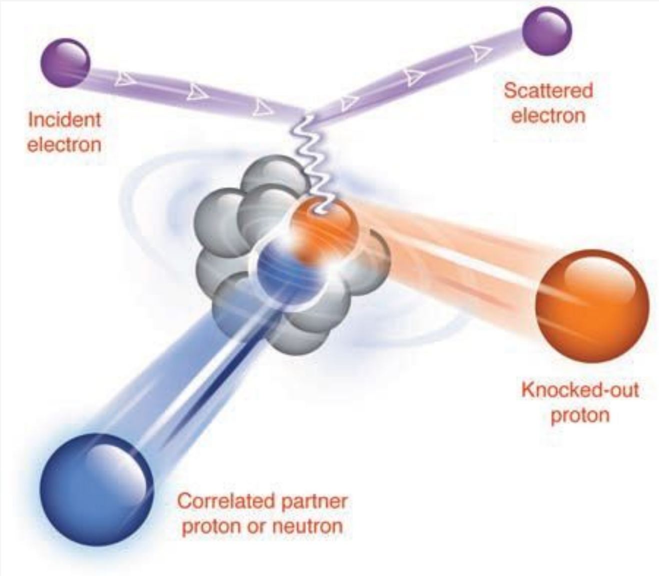



Large back-to-back momentum

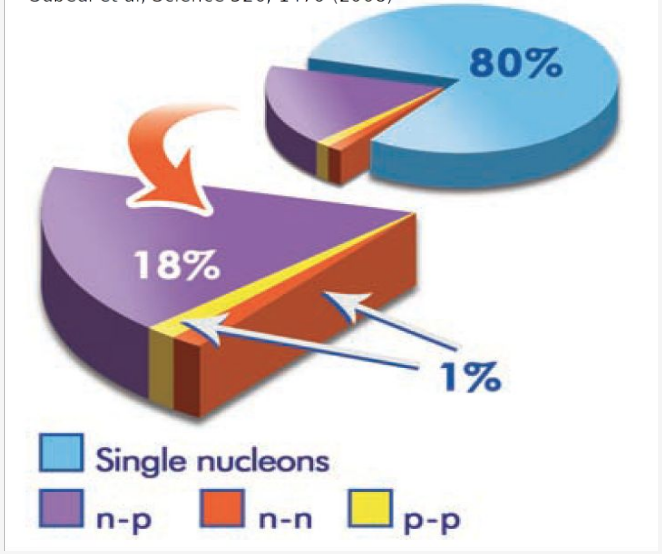


# Nucleon-Nucleon Short Range Correlation (SRC)
## Isospin dependence

Free nucleon-nucleon potential = **Repulsive core** + **attractive tensor force**
T = 1, S = 0 :np, pp, nn pairs. The tensor operator $S_{1,2}$= 0 , no attractive tensor force
T = 0, S = 1: Deuteron-like np pair.



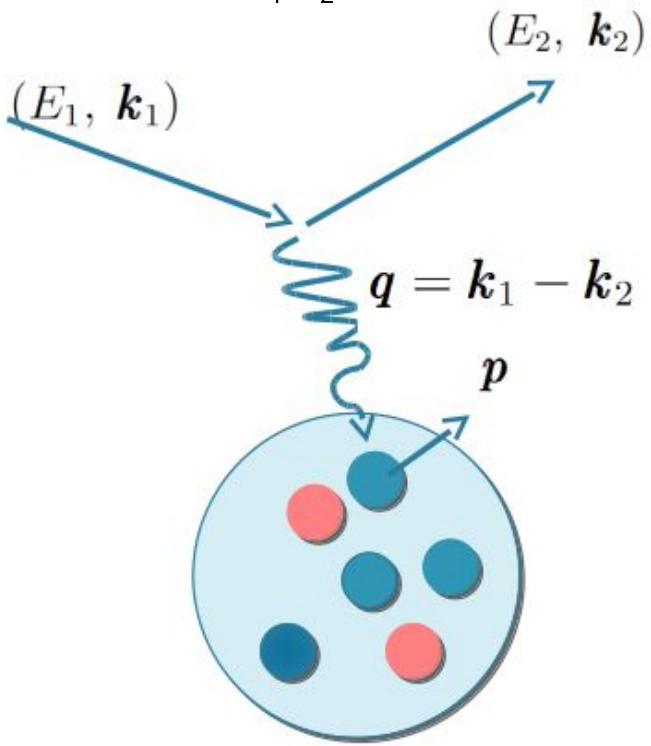

Subedi et al, Science 320, 1476 (2008)

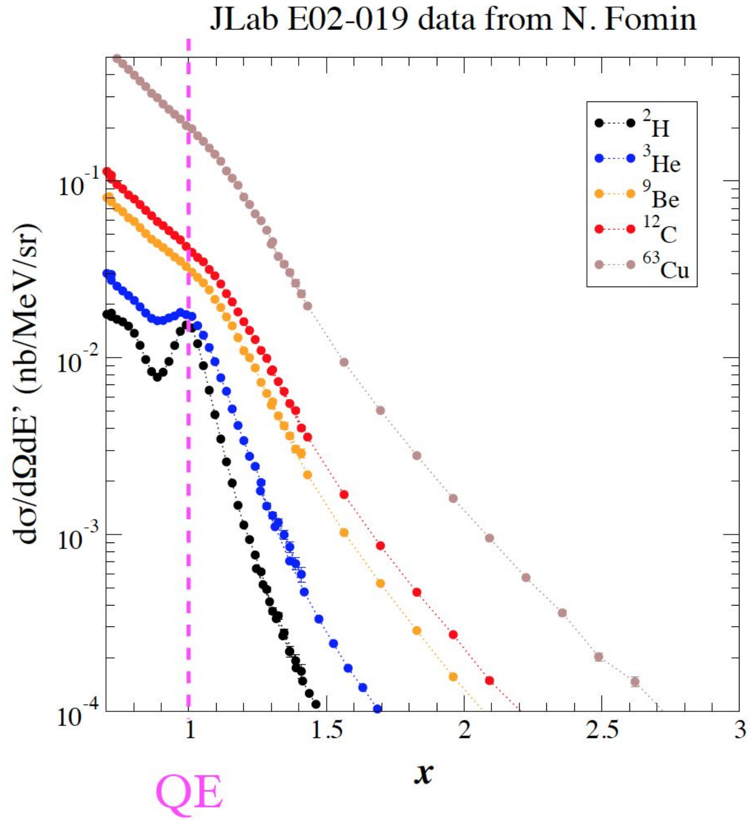



*~20% of nucleons in C12 are short-range correlated pairs. 90% of the pairs are n-p pairs ⇒ isospin 0 pairs dominate*

# Inclusive Quasi-elastic Scattering

4-momentum tranfer $Q^2$=-$q^2$
Bjorken x = $Q^2/2m(E_1$-$E_2)$

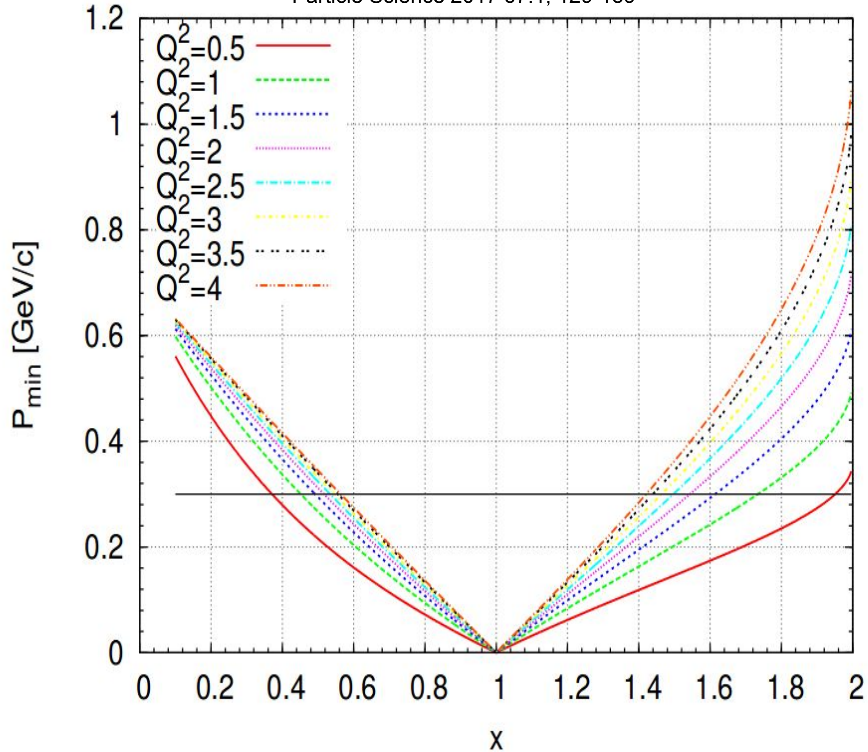


# Probing 2N SRC at x>1

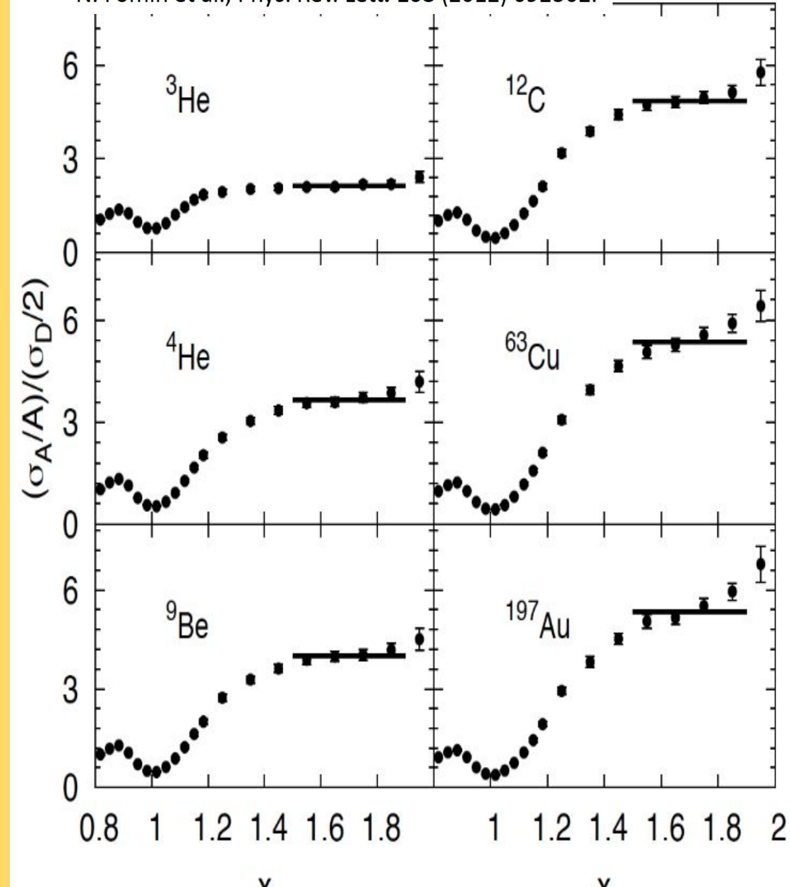
*In inclusive (e,e') quasi-elastic scattering, high momentum nucleons dominate the $x = Q2/2m\nu > 1$ kinematics*

N. Fomin et al, Annual Review of Nuclear and Particle Science 2017 67:1, 129-159

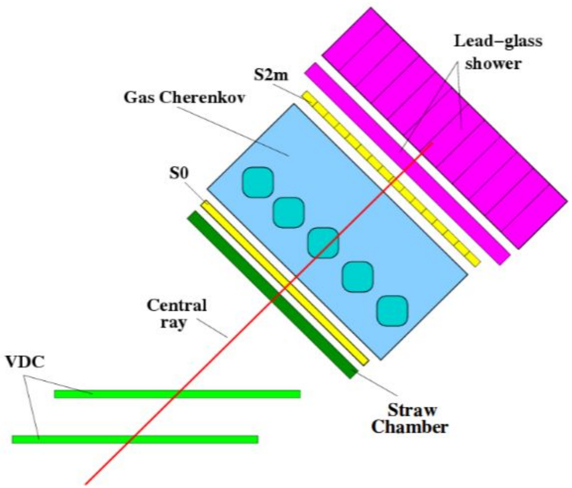



*The x>1 plateau of A/D cross section ratios give the percentage of high momentum pairs in each nucleus*

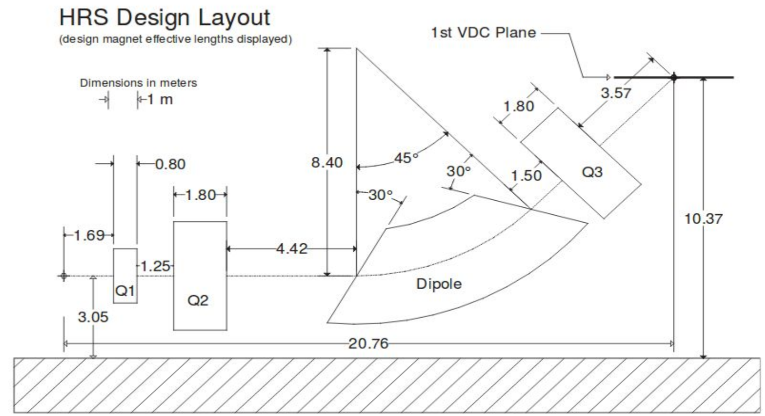
N. Fomin et al., Phys. Rev. Lett. **108** (2012) 092502.

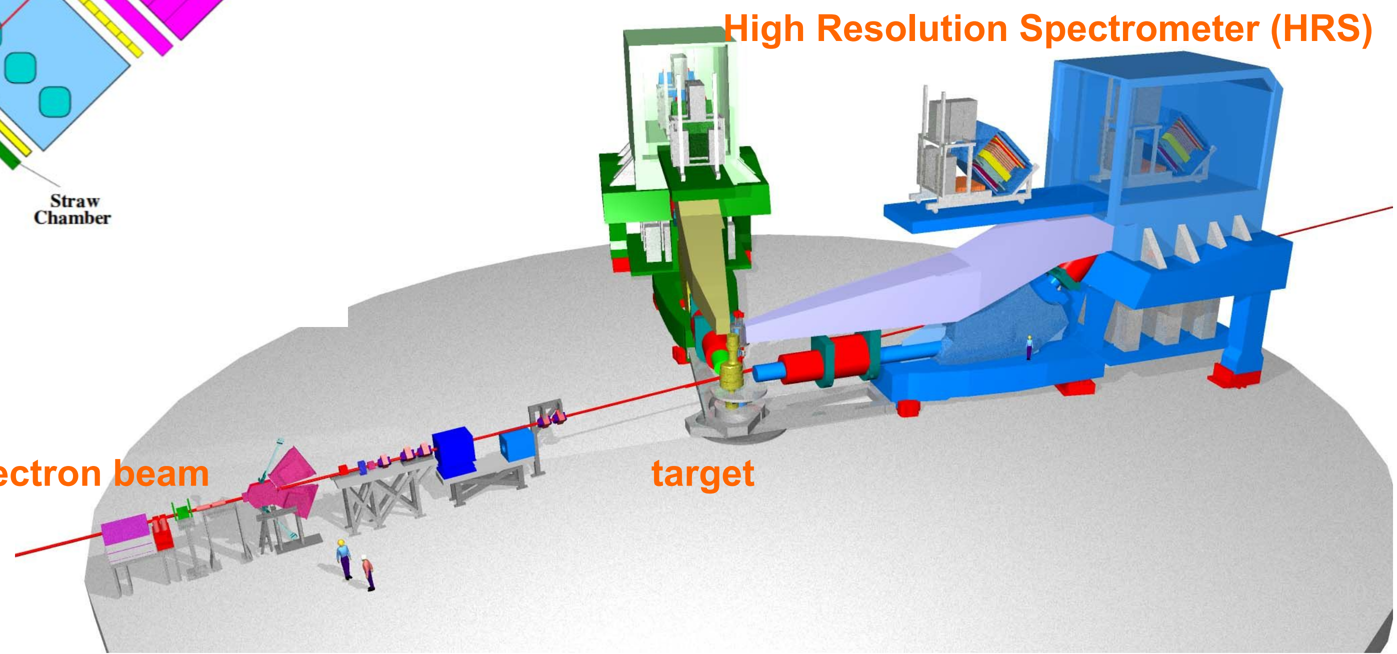


# Experiment Configuration

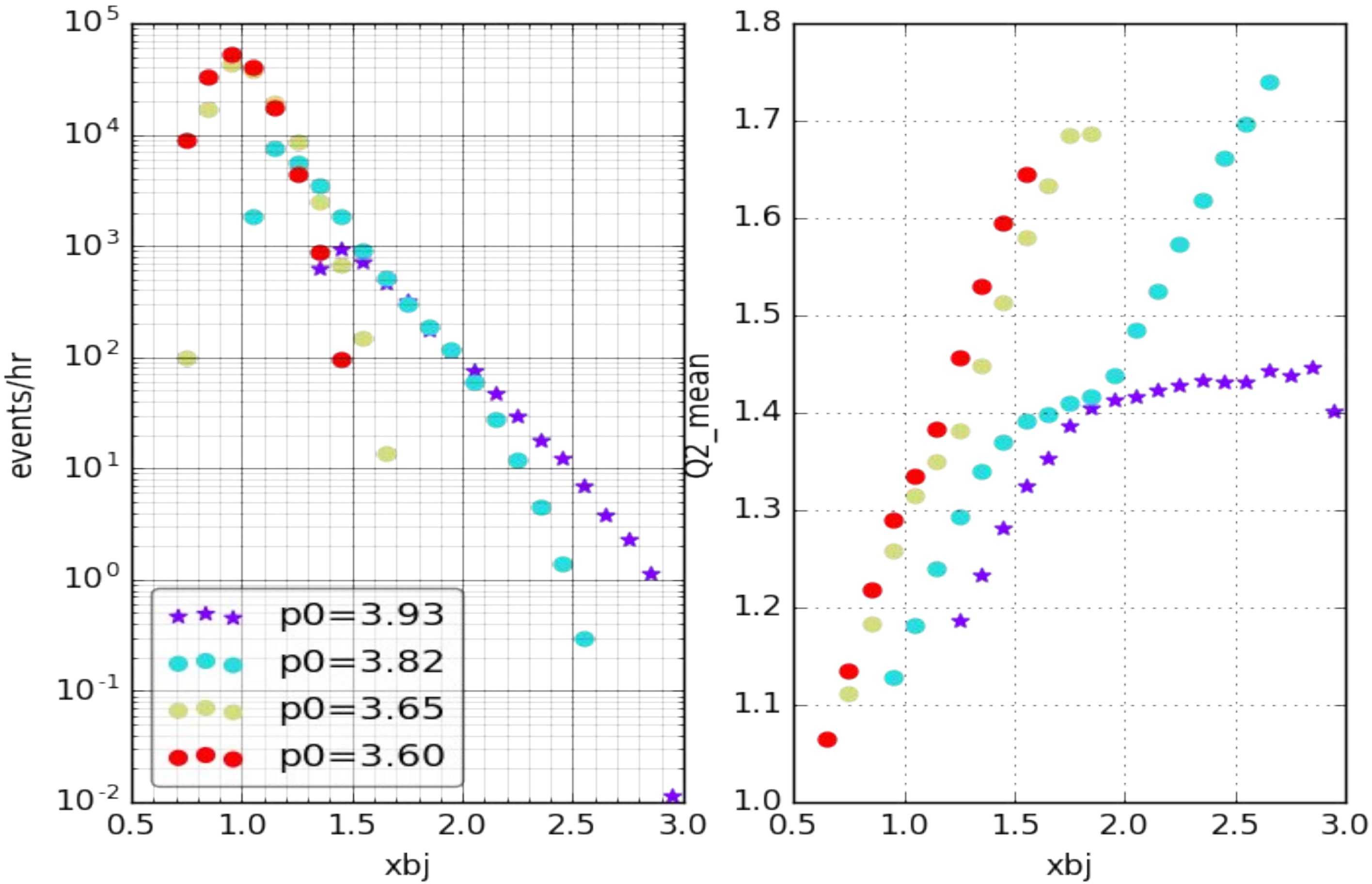



J. Alcorn et al. / Nuclear Instruments and Methods in Physics Research A 522 (2004) 294–346



# Runplan for LHRS at 17 degree with Simulation



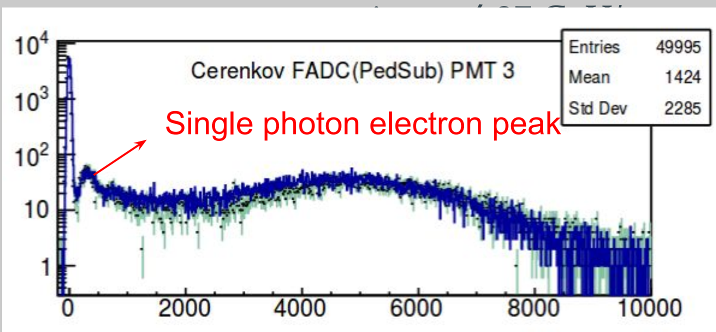
# Electron Detection: Cherenkov + Calorimeters

- **CO2 Cherenkov:**
  - Threshold of Cherenkov radiation:

$$\beta c \geq \frac{c}{n}$$

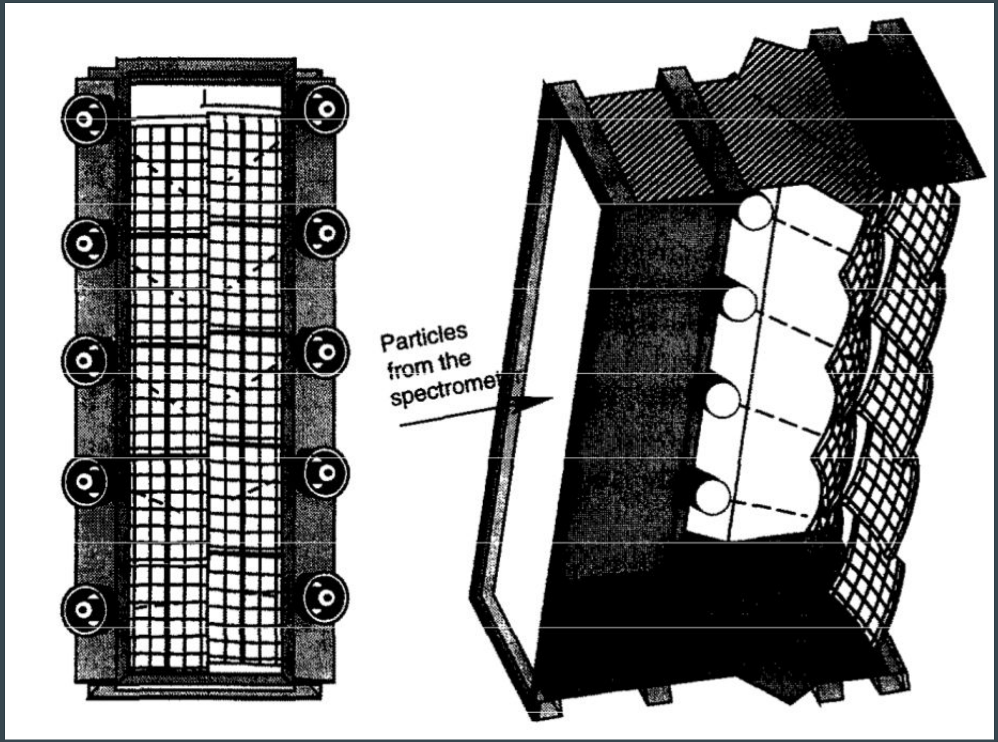
  - HRS Cherenkov Chambers use 1 atm $CO_2$ to reject pions from electrons::

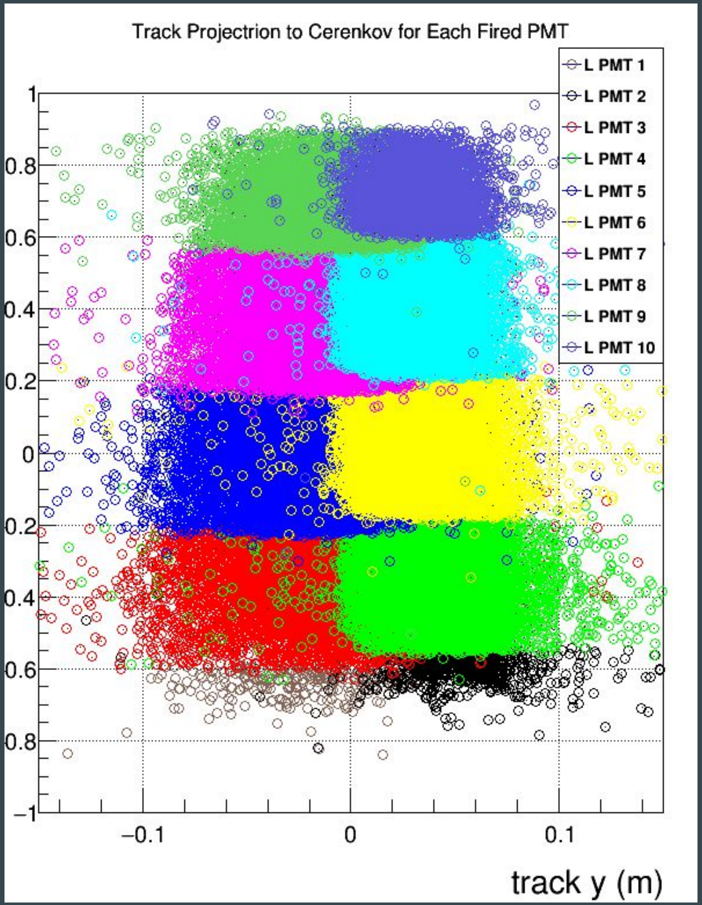
$n = 1.00041 \Rightarrow p_{min,e} = 17.85$ MeV/c



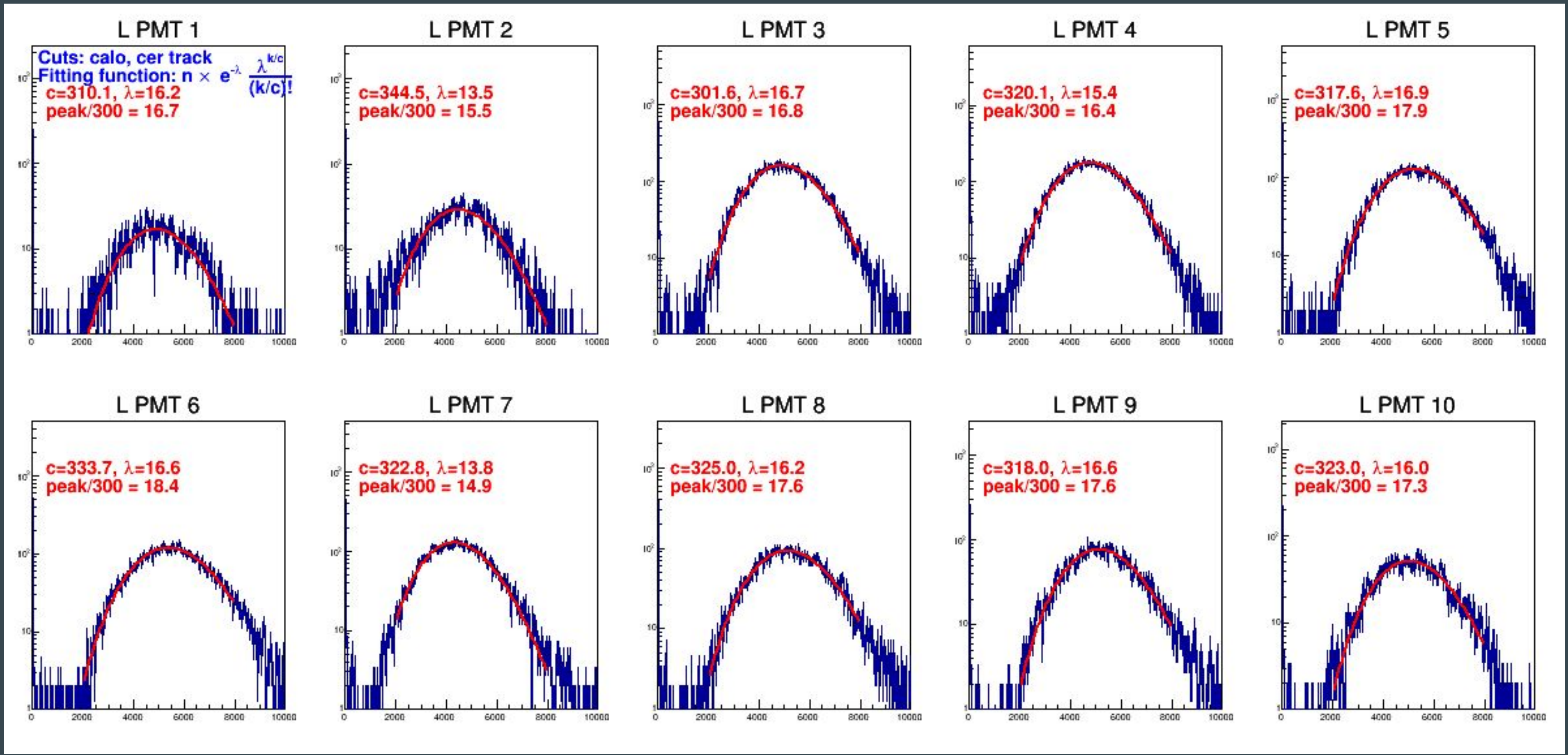

- **Calorimeter(pion rejectors):**
  - Detect ionization energy loss through two layers of lead-glass.

# CO2 Cherenkov Detector



# Cerenkov PMTs Performance:



# PID Cut Efficiency: Cerenkov

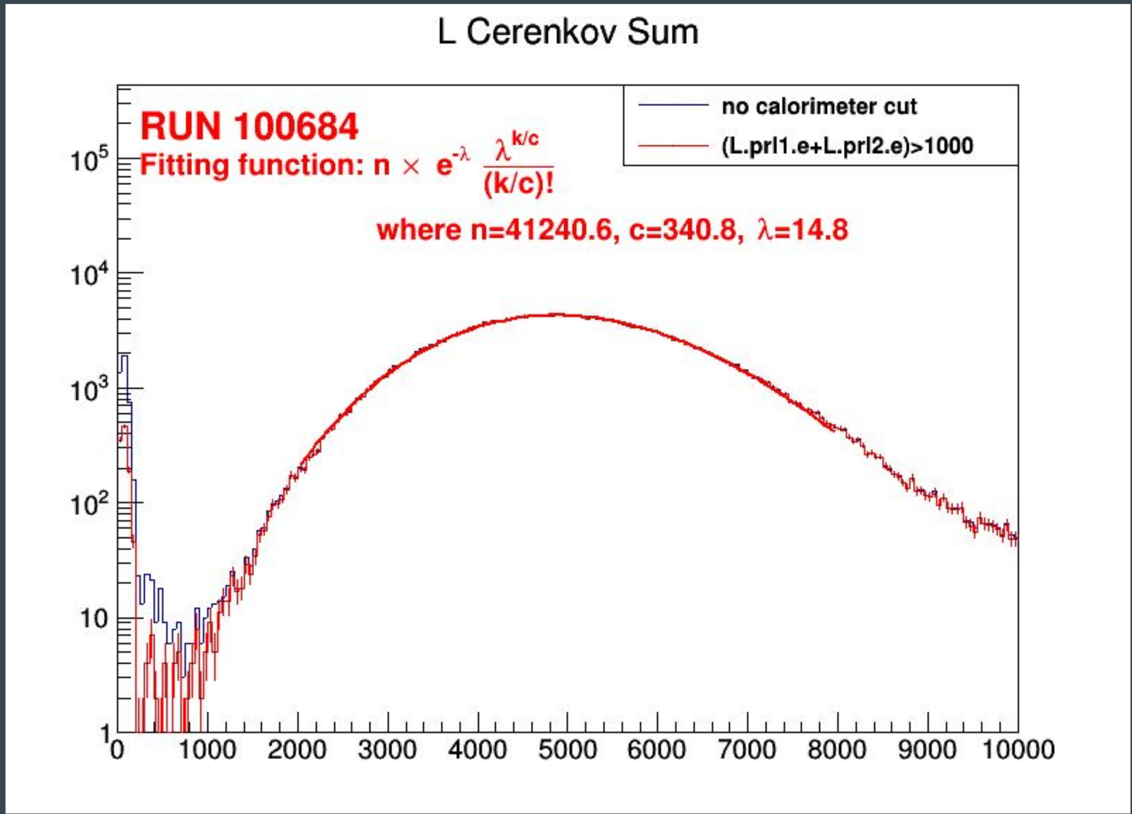
Single photon peak at ADC channel 300 for each PMT

Total number of photons from electron Cerenkov light follows Poisson distribution

ADC Cut on channel 1500:

Prob( L.cer.asum_c<1500|elctron) = 0.01%

Prob( L.cer.asum_c>1500|pion) -> 0



# LHRS PID: electron/pion discrimination

**Kinematics (Run 100684):**

Ebeam = 4.3 GeV

Angle = 17 . 8 degree,

p0 = 3.543 GeV

**Electrons:**

large Cerenkov and calorimeter signals

**Pion contaminations:**

A. $\pi^-$ :

No Cerenkov signal,

small energy deposit in calorimeter

B. $\pi^-$ knock out electron (ionization) before/in Cerenkov:

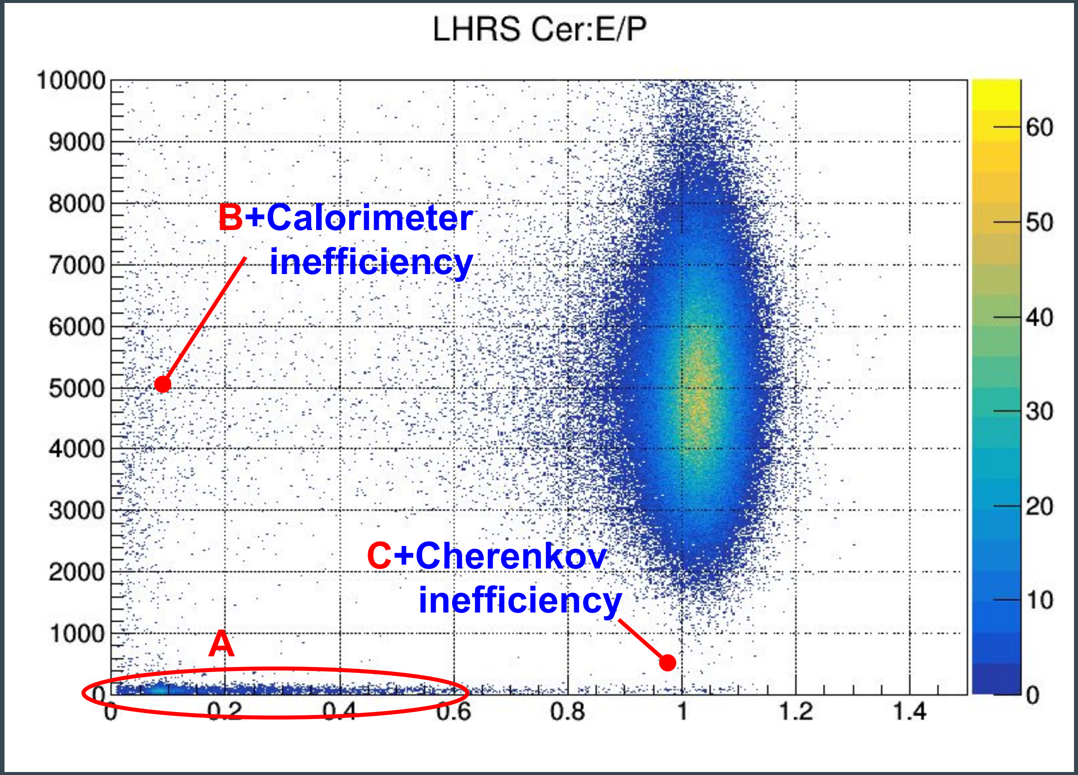
Cerenkov triggered,

small calorimeter signal

C. $\pi^- n \to \pi^0 p \to \gamma\gamma$:

No Cerenkov signal,

large calorimeter signal




- **The combination of B(C) and detector inefficiency is less than 0.1% => detector inefficiency alone << 0.1%**

# Trigger Efficiency

LHRS:

T1: S0 && S2

**Production Trigger!** → T2: (S0 && S2) && Cer

T3: (S0 || S2) && Cer

Cerenkov trigger efficiency

Scintillators (s0, s2) trigger efficiency

Run 100684, events passed PID and one-track cuts

Evtypebits =

2 -> only T1

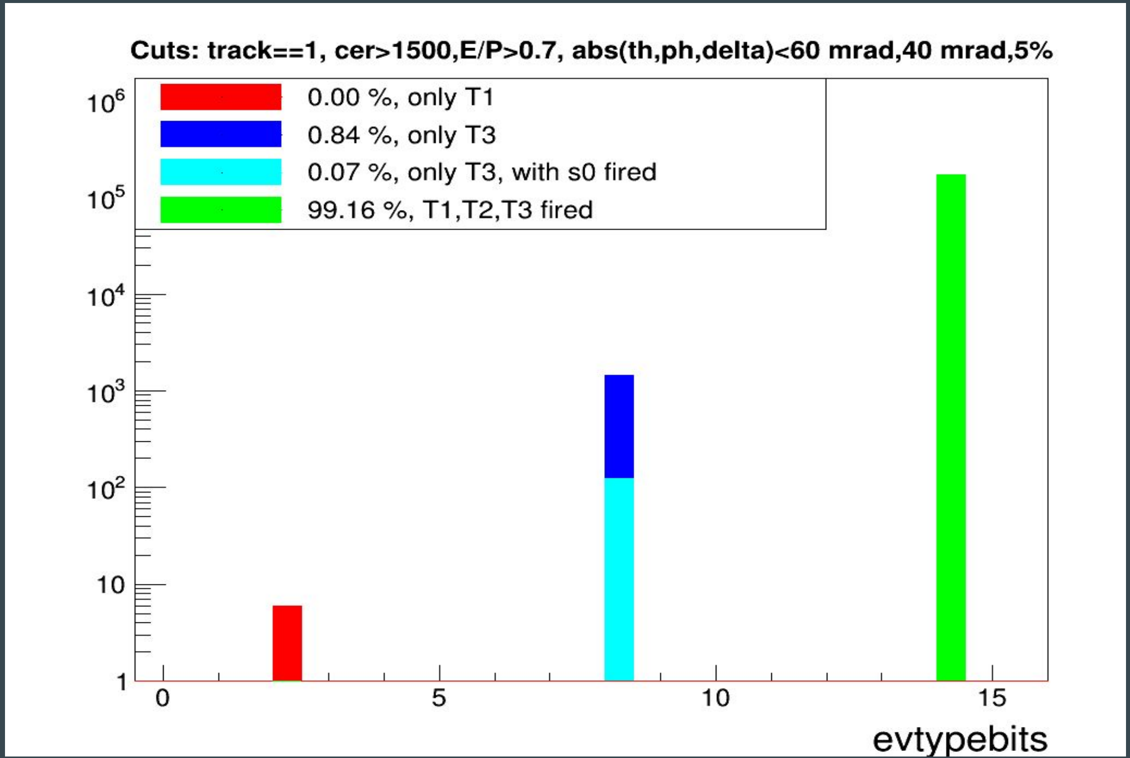
-> Cerenkov trigger inefficient

8 -> only T3

-> S0 or S2 triggers inefficient

14 -> T1 + T2 + T3

-> good



# Optics Calibration:

- Find the one-to-one mapping between focal plane (VDC projected tracking) and  target variables (reaction point)
  - Y_tg (target position as seen by the spectrometer) :
    - fixed by multifoils
  - Phi, theta (in/out-of-plane scattering angle:
    - fixed by sieve pattern
  - Delta (momentum diviation from central ray):
    - fixed by hydrogen elastic scattering

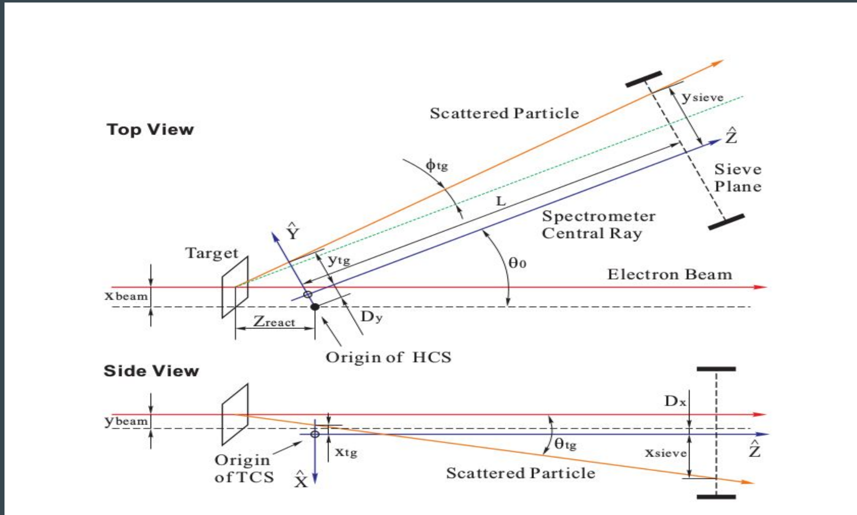
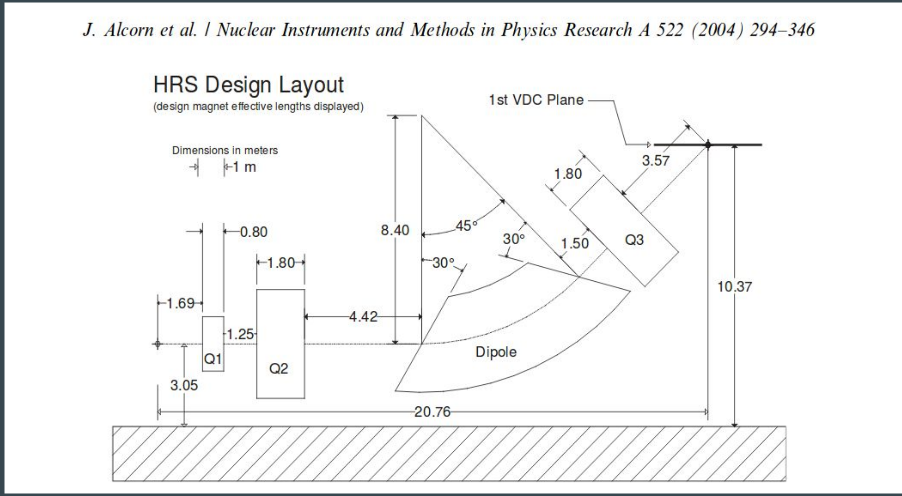


Figure A-2: Target coordinate system (top and side views).



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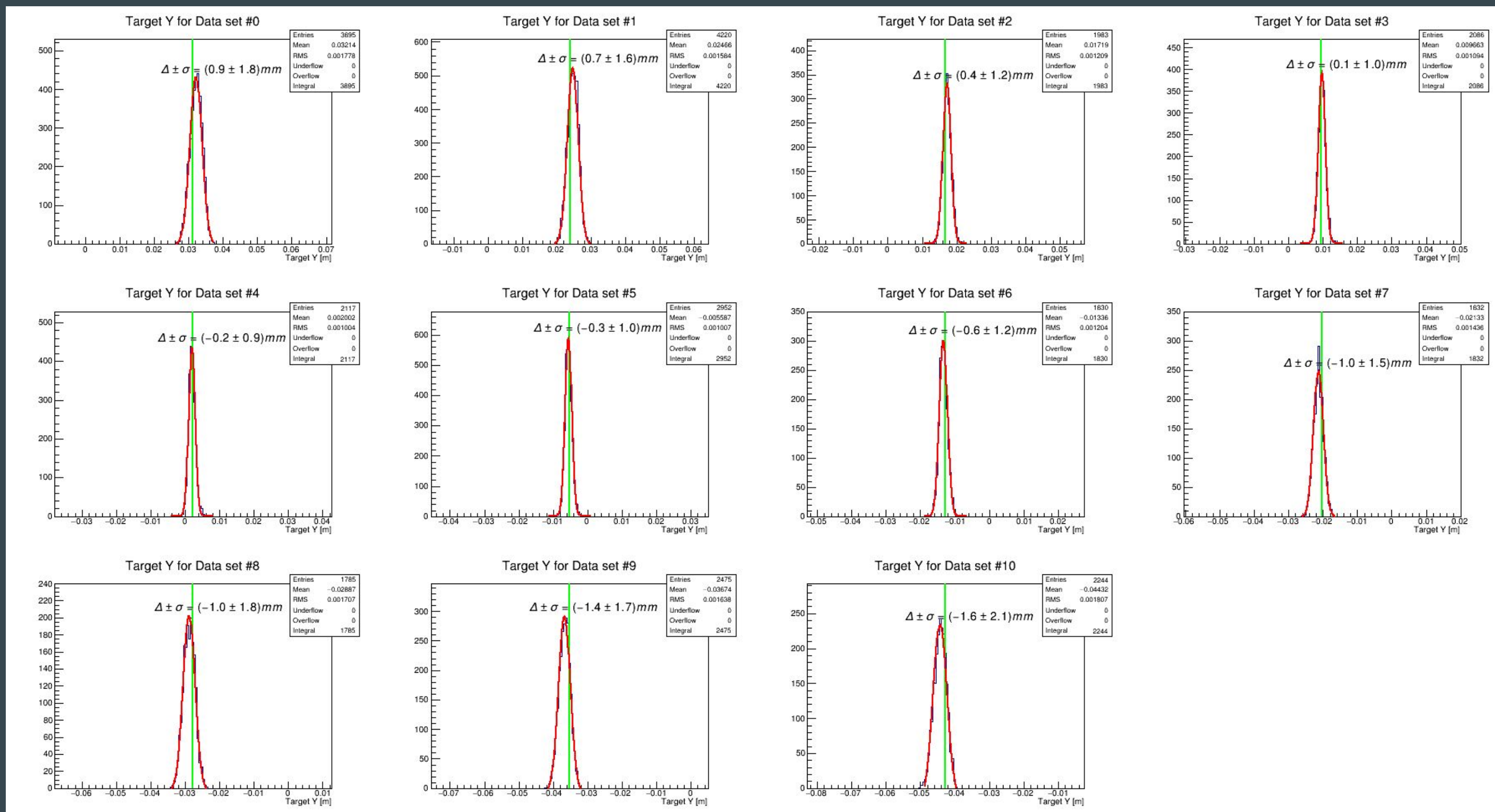
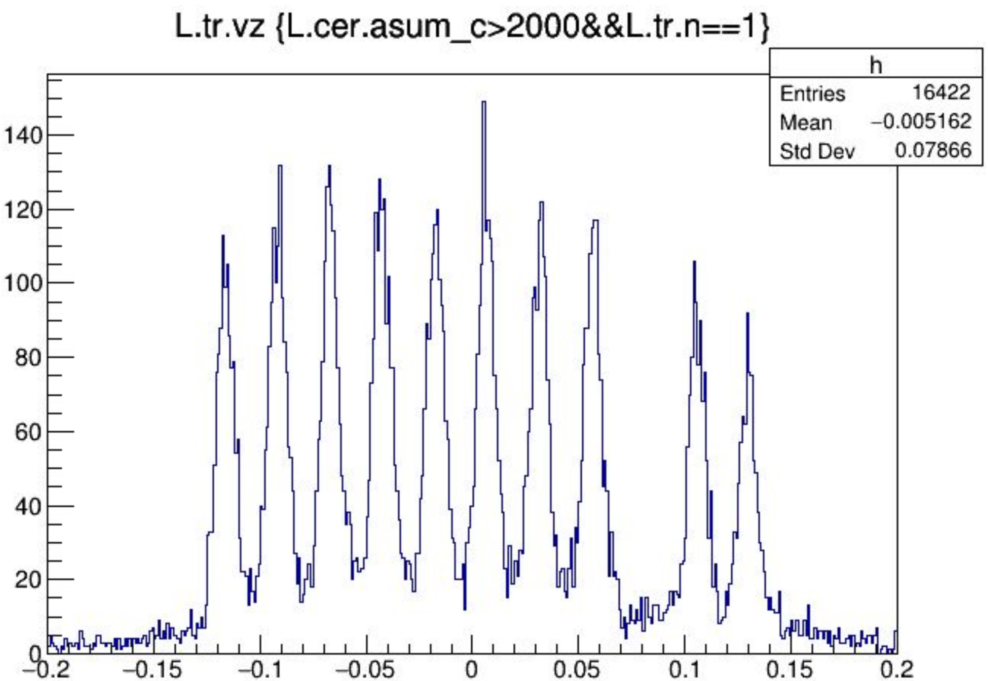
$$\underbrace{\begin{bmatrix}\delta\\ \theta\\ y\\ \phi\end{bmatrix}_{tg}}_{\text{Want}} = \begin{bmatrix} \langle\delta|x\rangle & \langle\delta|\theta\rangle & 0 & 0\\ \langle\theta|x\rangle & \langle\theta|\theta\rangle & 0 & 0\\ 0 & 0 & \langle y|y\rangle & \langle y|\phi\rangle\\ 0 & 0 & \langle\phi|y\rangle & \langle\phi|\phi\rangle \end{bmatrix} \underbrace{\begin{bmatrix}x\\ \theta\\ y\\ \phi\end{bmatrix}_{fp.}}_{\text{Detected}}$$

# Optics Calibration:  target position

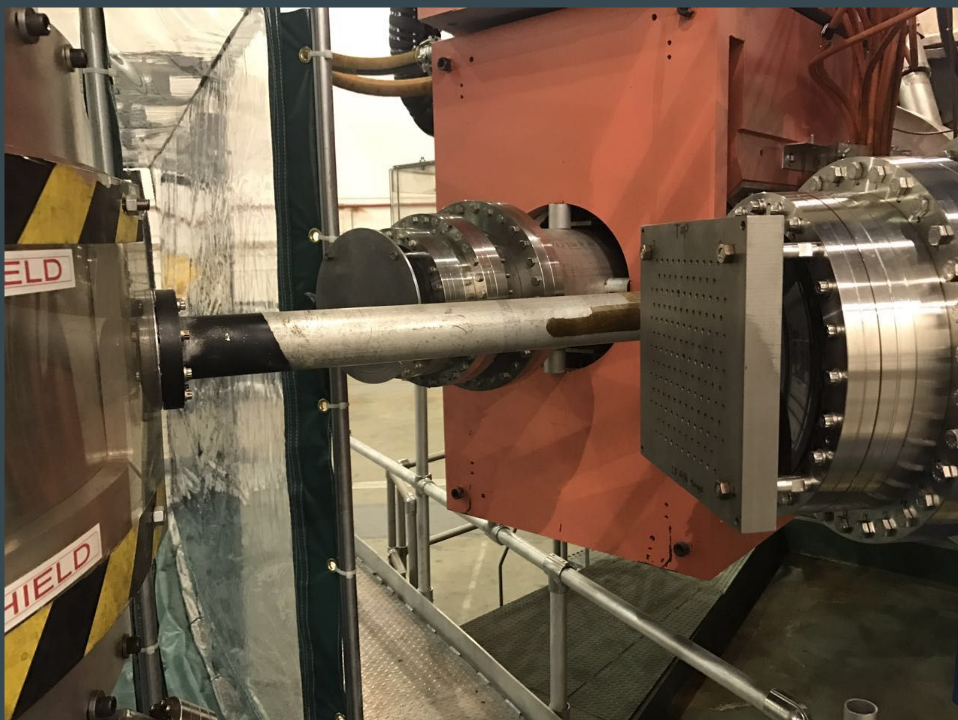


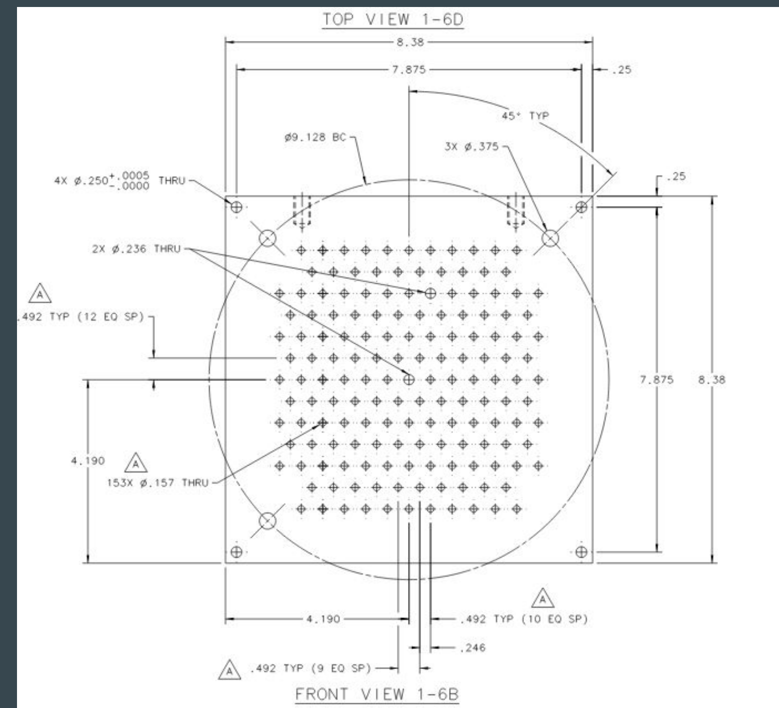
Optics run summary:
https://wiki.jlab.org/tegwiki/index.php/Fall_2018_Optics_Runs



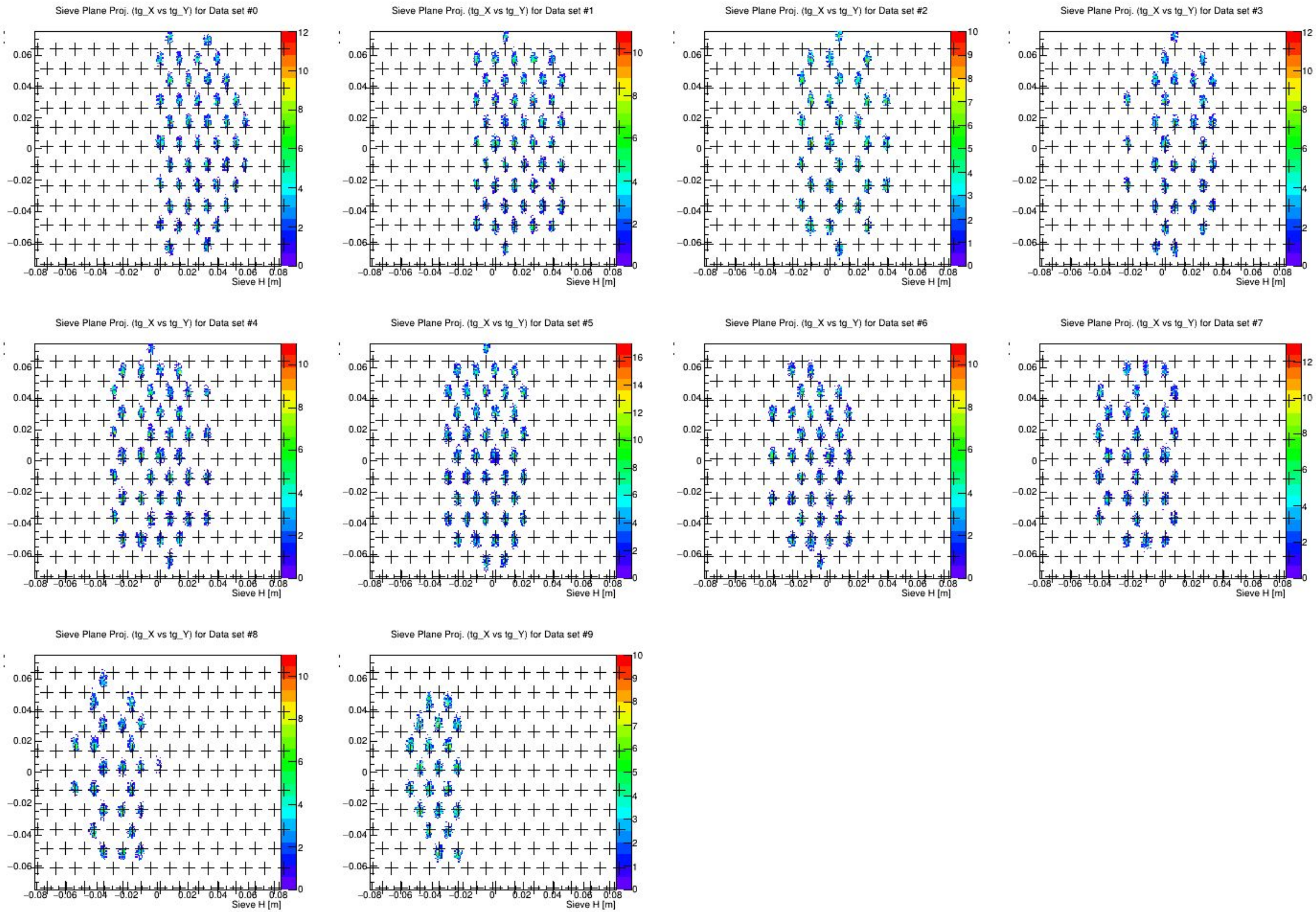

In the Fall run period we only have 10 foils ( the foil at z=7.5cm) is missing

# Sieve:



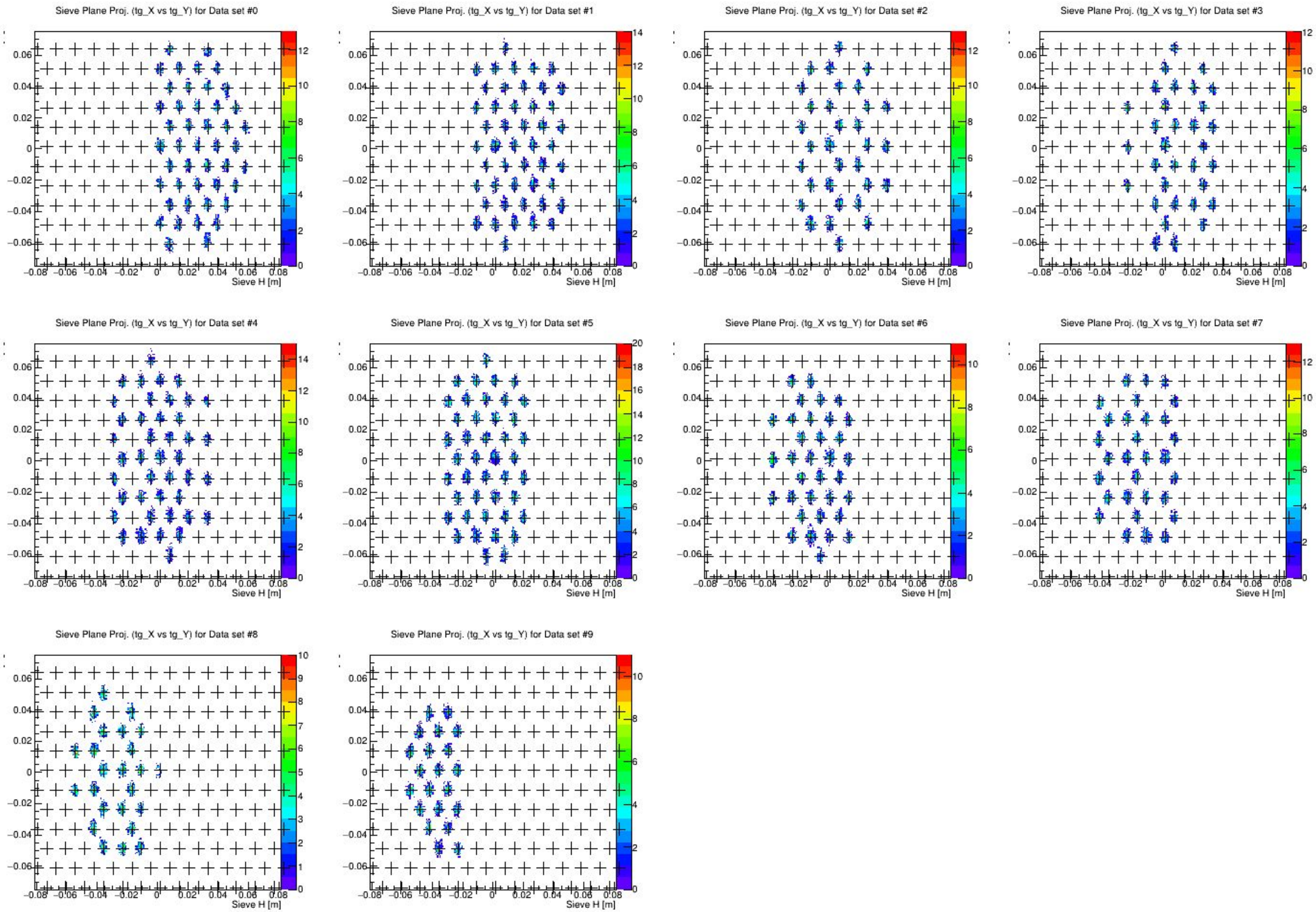

TOP VIEW 1-6D
8.38
7.875
.25
45° TYP
Ø9.128 BC
3X Ø.375
4X Ø.250 +.0005 -.0000 THRU
.25
2X Ø.236 THRU
.492 TYP (12 EQ SP)
7.875
8.38
4.190
153X Ø.157 THRU
4.190
.492 TYP (10 EQ SP)
.246
.492 TYP (9 EQ SP)
FRONT VIEW 1-6B

# 3.93 GeV, before theta phi calibration **Q1 saturated at p0>3GeV**



# 3.93 GeV, after theta,phi calibration

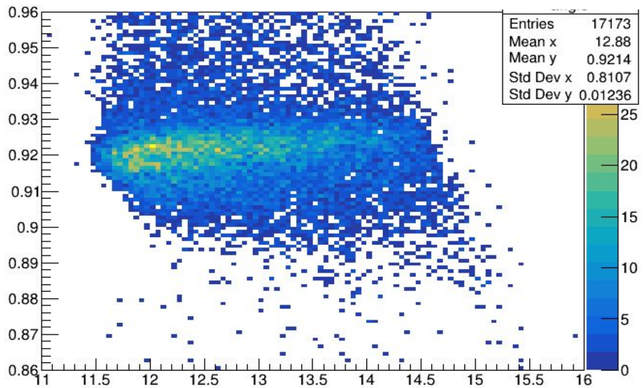
**Q1 saturated at p0>3GeV**



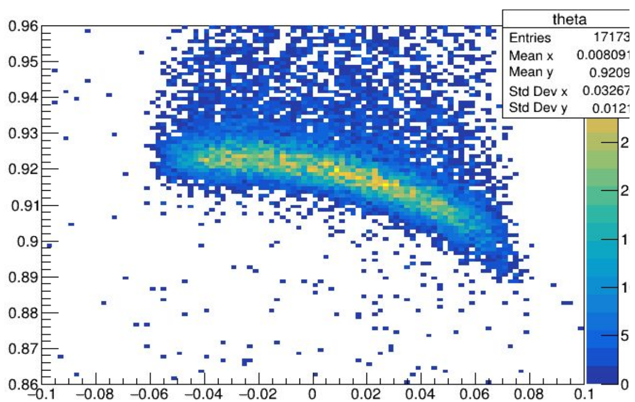
# Manually Delta Calibration with Hydrogen elastic data

**3.93 GeV with new YTP terms but old D term (run 111702)**

## Invariant mass v.s. Angle

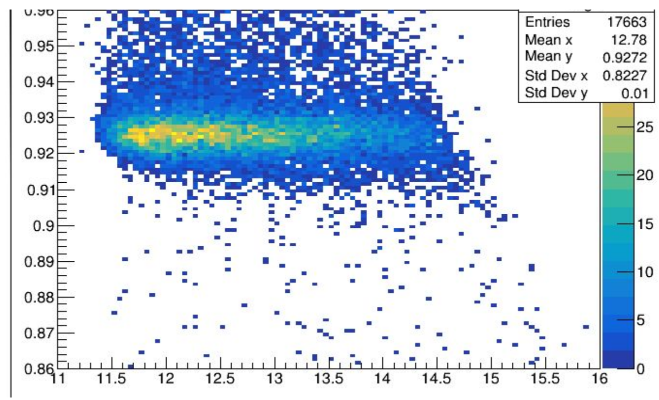



## Invariant mass v.s. targ_theta

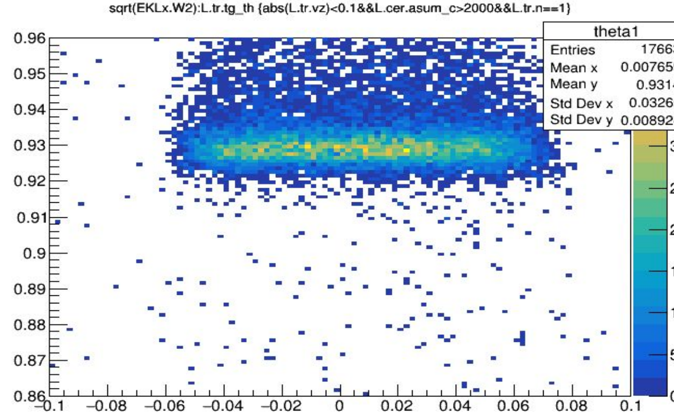



**3.93 GeV, after tweek D100, D200 term (run 111702)**

## Invariant mass v.s. Angle

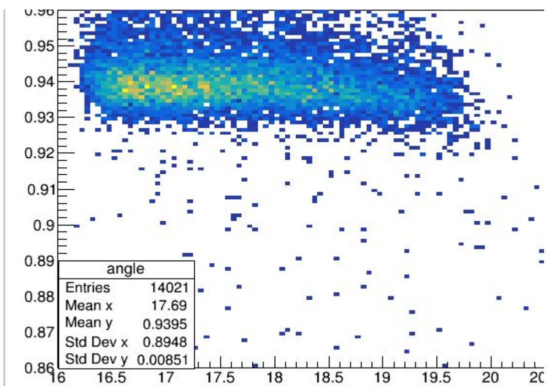



## Invariant mass v.s. targ_theta

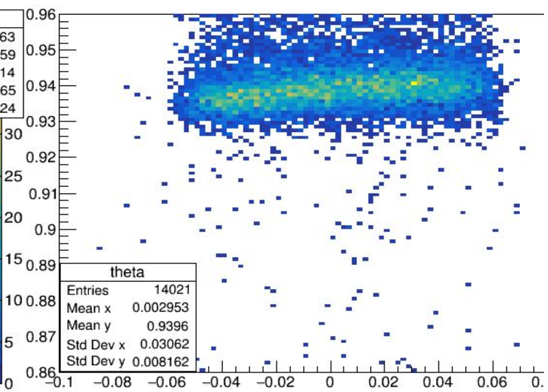



**3.54 GeV from Ep**

## Invariant mass v.s. Angle

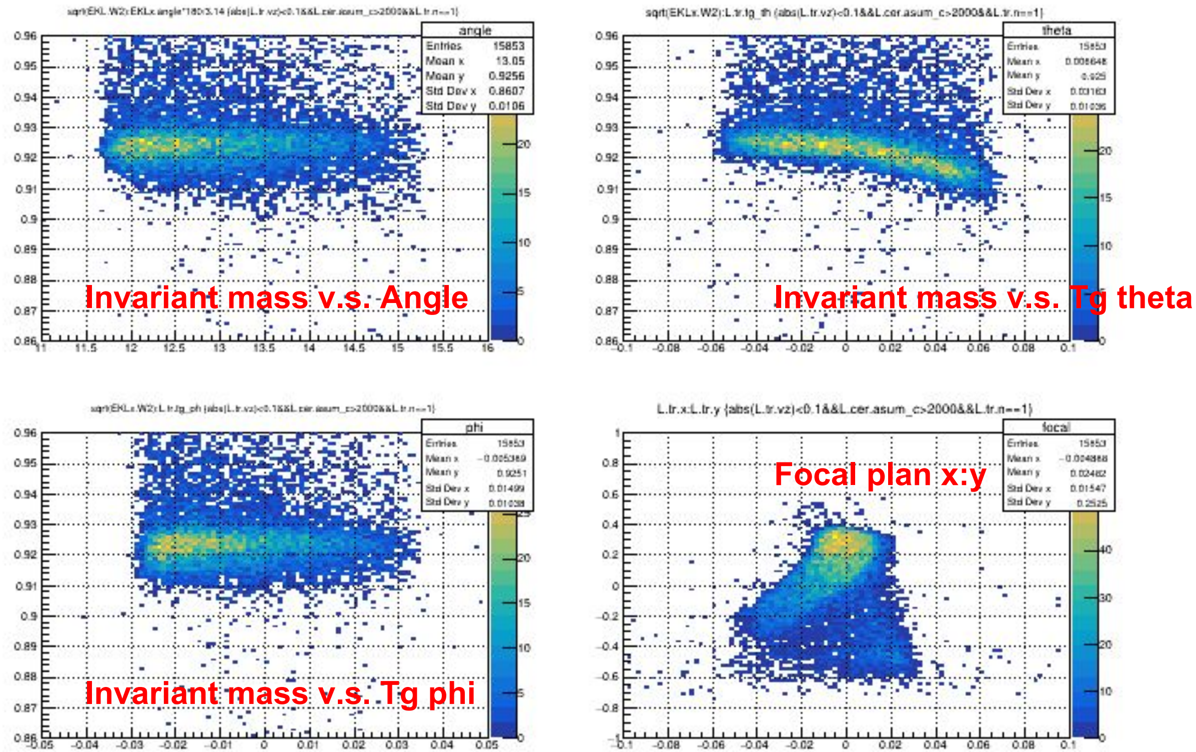



## Invariant mass v.s. targ_theta



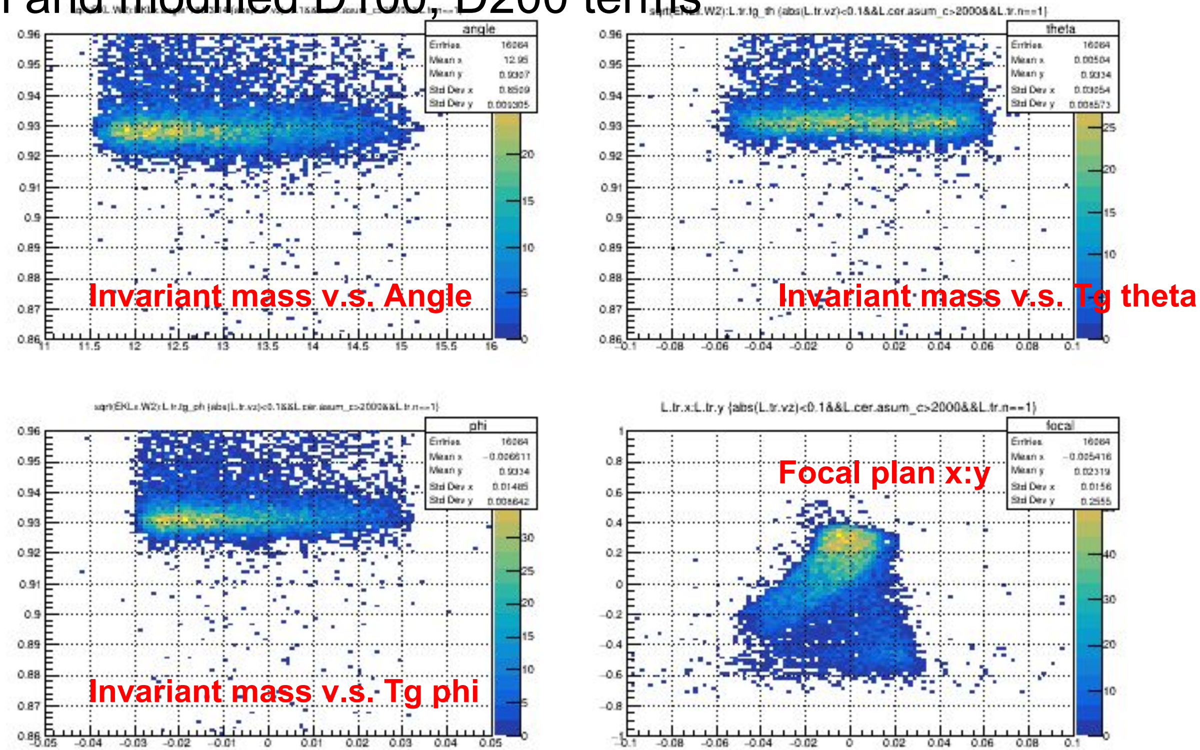
# Manually Delta Calibration with Hydrogen elastic data

## 3.82 GeV at 13 degree (run 111842), with new theta, phi, y calibration



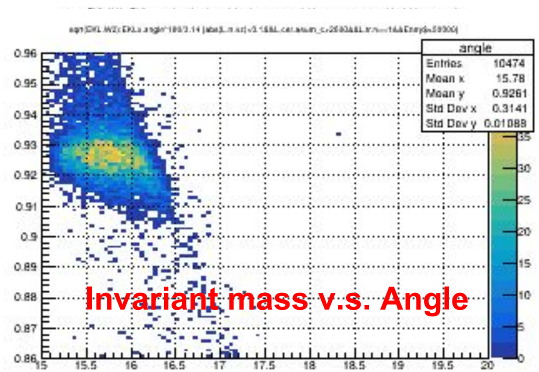
## Manually Delta Calibration with Hydrogen elastic data

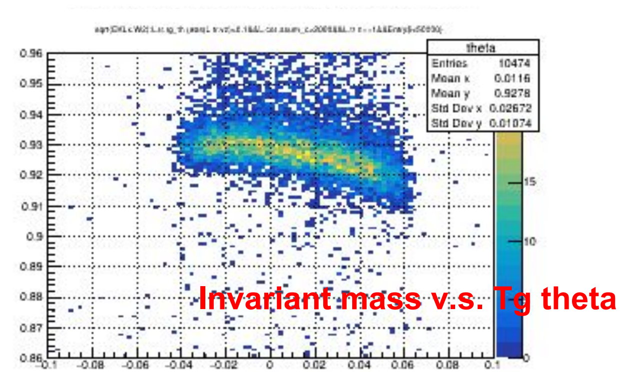
3.82 GeV at 13 degree (run 111842), with new theta, phi, y calibration, energy loss correction and modified D100, D200 terms

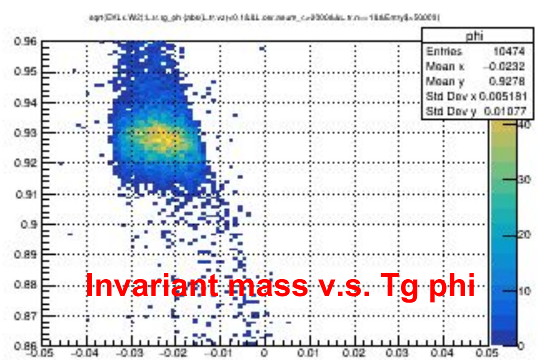


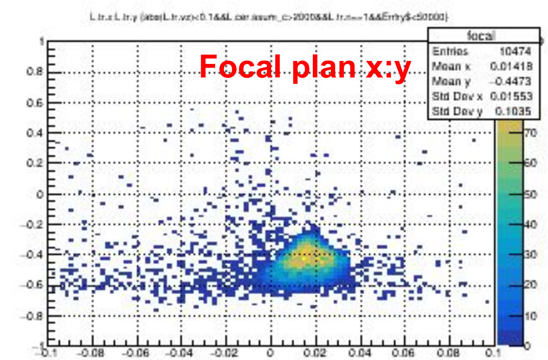
**Manually Delta Calibration with Hydrogen elastic data**

3.82 GeV at 17 degree (run 3605), before calibration



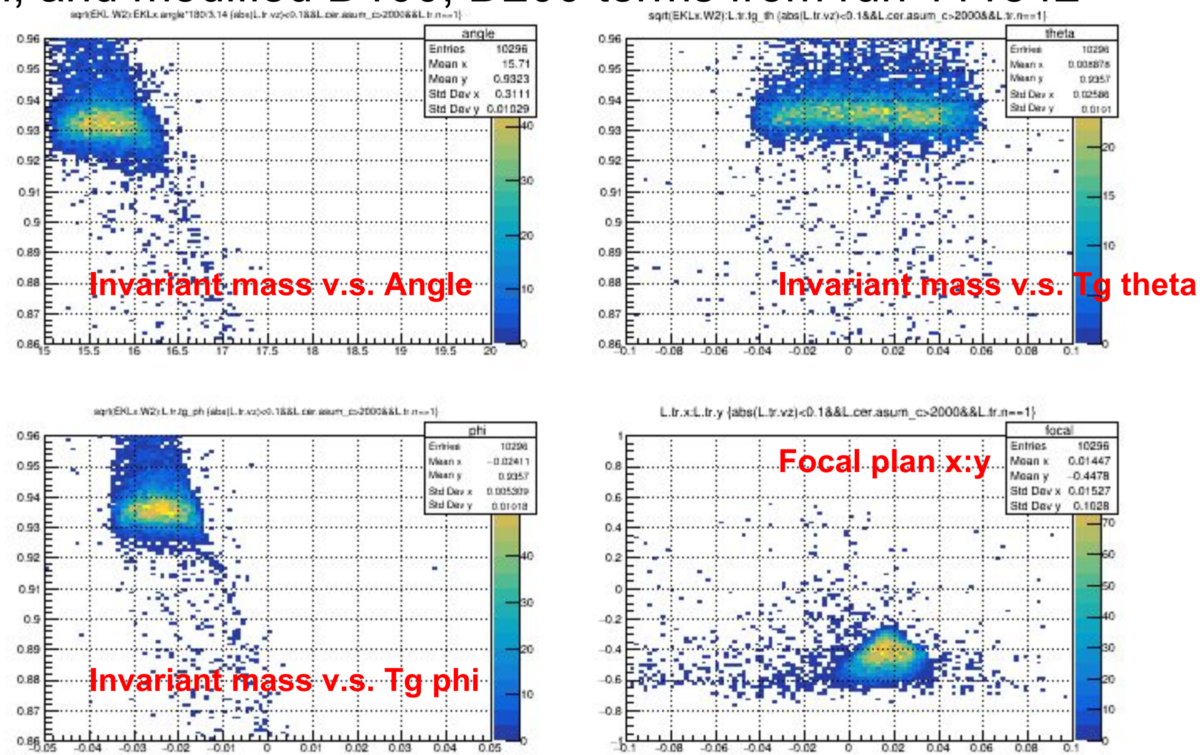



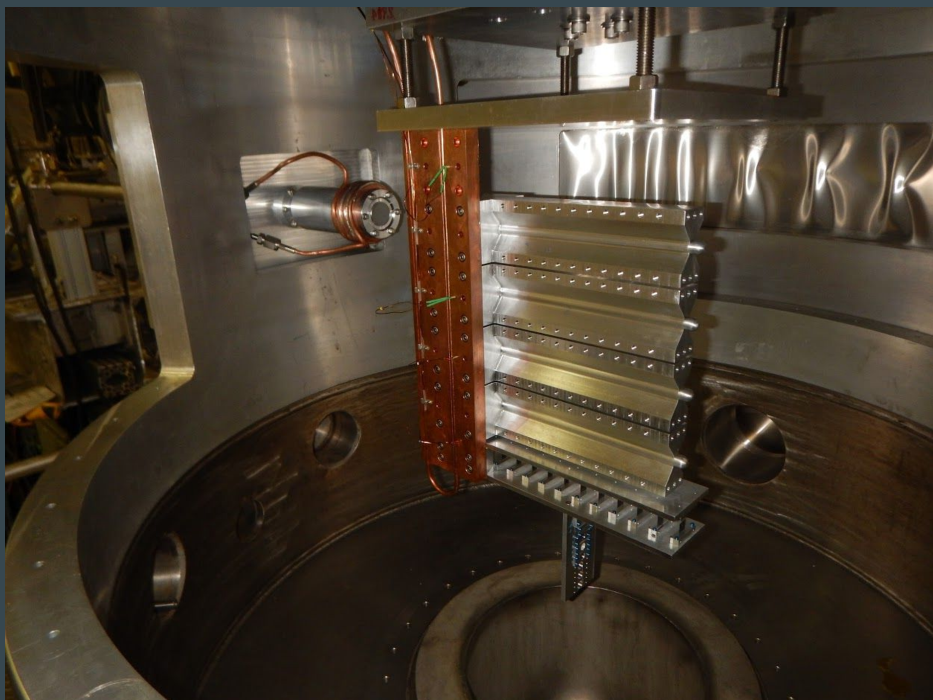
## Manually Delta Calibration with Hydrogen elastic data

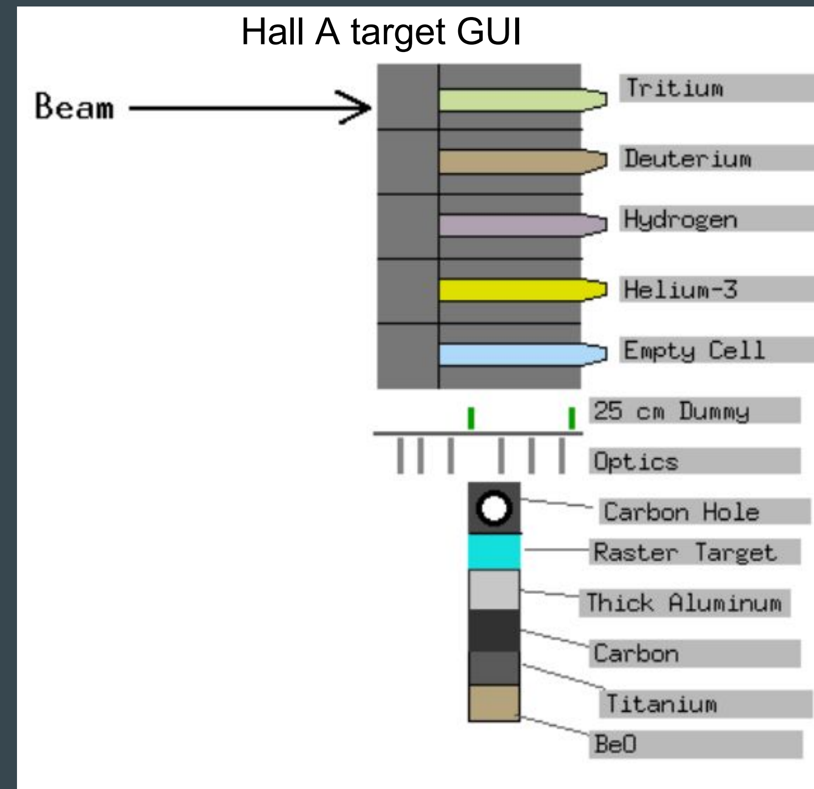
3.82 GeV at 17 degree (run 3605), with new theta, phi, y calibration, energy loss correction, and modified D100, D200 terms from run 111842




**The manually delta adjustments provided by run 111842 also significantly improved the reconstructed quantities in run 3605, which has the same Q1 setting but different focal plane coverage.**

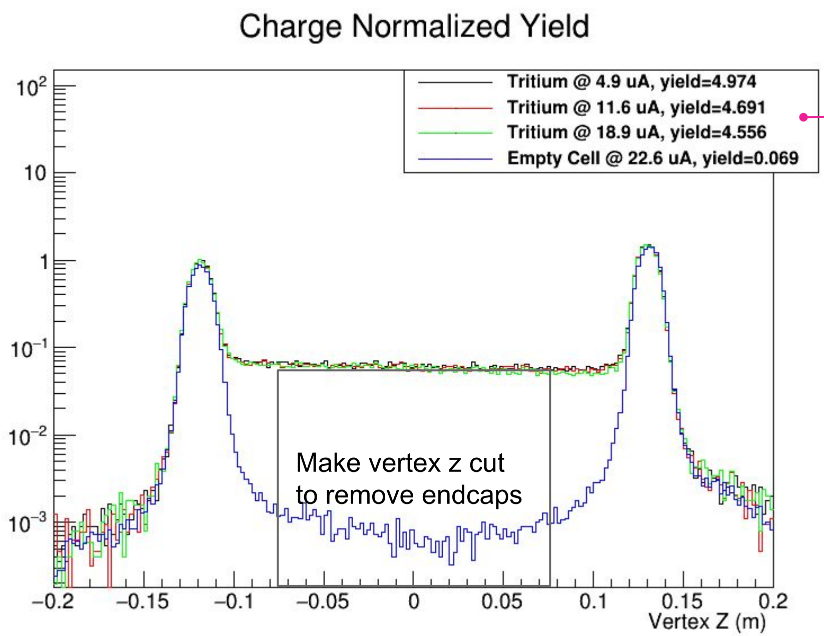
# The Gas Target System:





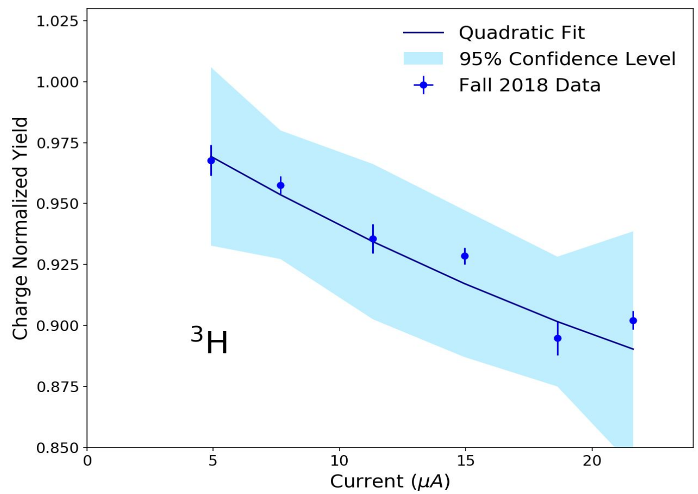
# The Gas Target System: special handling

- ❖ Maximum current = 22.5 uA on gas cells to minimize the risk of gas leak.
- ❖ Endcap(75mg/cm2 Aluminum) being mis-reconstructed into thin gas body ( 77mg/cm2 Tritium)
- ❖ "Boiling": gas density change along beam path (after reached equilibrium which takes less than 1 second)




*The Tritium density reduced by ~ 10 percent at 22.5 uA*

S. Santiesteban et al. , arXiv:1811.12167



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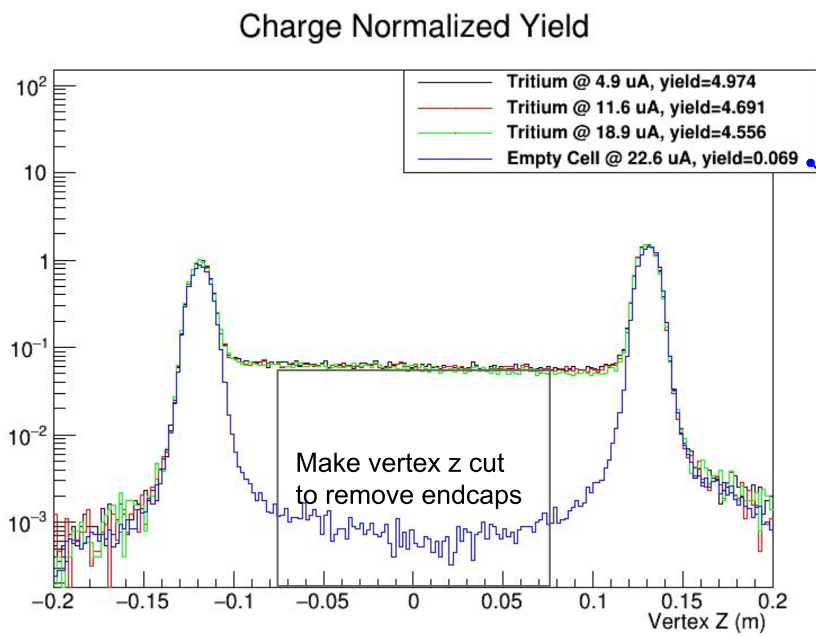
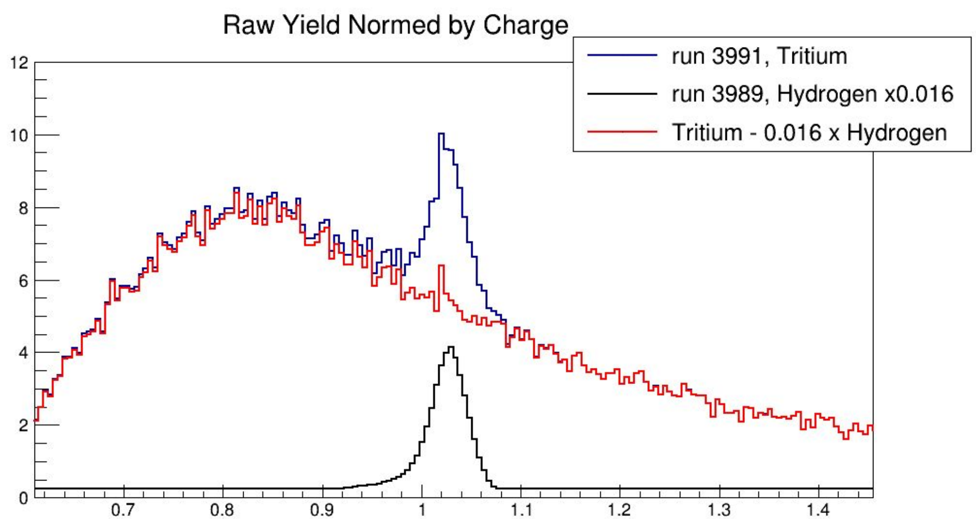
- "Boiling": gas density change along beam path




*The endcap contamination (after vertex cut) varies from less than 0.1% to 10% depends on spectrometer angle and kinematics.*

# The Gas Target System: surprise (>﹏<)

## Hydrogen in the 2nd Tritium cell ( used in the fall 2018)




*gas*

$$H_2O + T_2 \rightarrow HTO + HT$$

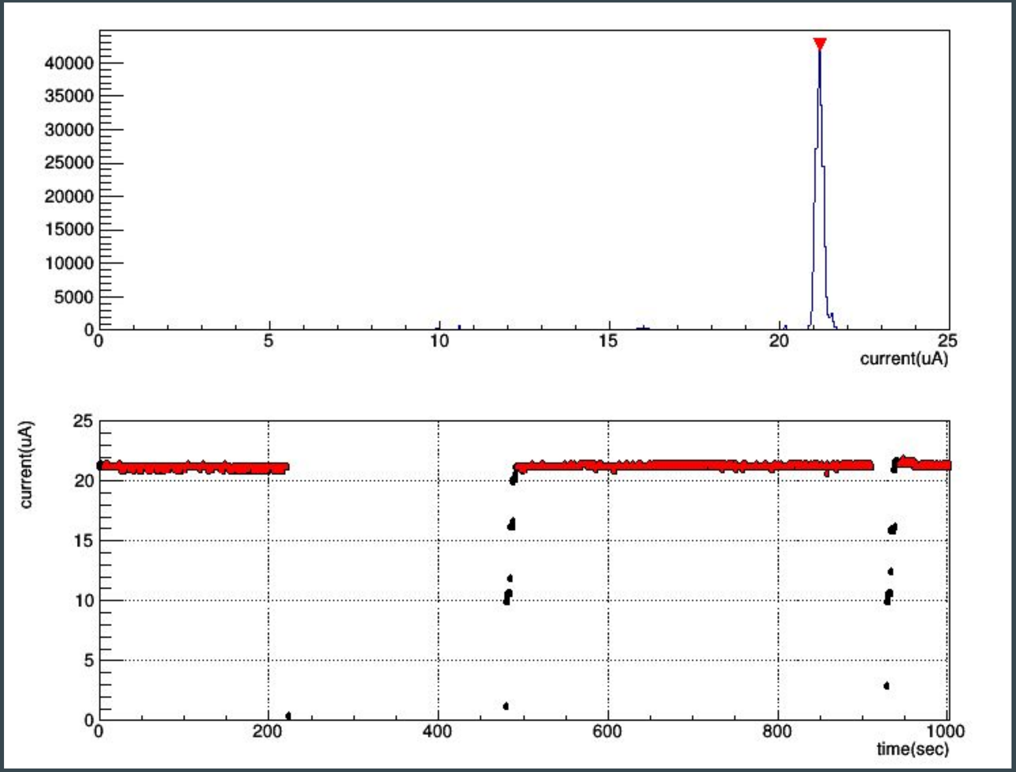
*Liquid, stick to the wall at low temperature*

Tritium replaced by hydrogen:
1.6% * 0.0708 g/cm2 * 3 ( H2O->HTO) / 0.0851g/cm2 = 4.0 %

**Remained tritium density:**
**0. 0851 g/cm2 * (1-4%) ⇒ 0.0817 g/cm2 ??**

# Beam Current and Charge, Livetime:

1. Find beam on currents, loop over fast scaler readout (evLeft/evRight) to find current associated with every TTree event.
2. For each stable beam current, find corresponding events ( **+- 1.5 uA**), also discard events within the first **5 seconds** of stable beam, then accumulate charge and raw trigger signals from scaler, and triggered events (DL.bit2) counts
3. Save event list of events passed beamtrip cuts, record corresponding mean current, charge,, and livetime.



# Extract Yield from Data

For a given good production run $i$, periods of data with stable currents are first identified. Then for events from each good current (allow $1.5uA$ fluctuation) we calculated the following quantities:

- $C_i$ : raw good electron counts per $x_{bj}$ bin,
- $PS_i$ : the prescale factor for the production trigger,
- $LT_i$ : the computer livetime in fraction for the production trigger,
- $eff_i$ : the product of all efficiencies including trigger, tracking, cut efficiencies,
- $Q_i$ : charge with stable beam current,
- $\rho_l$ : effective area density of the target ($g/cm^2$). For a gas cell it should represent the amount of gas after vertex z cut (target length cut),
- $Boiling_i$ : the ratio of the effective gas target density at given beam current comparing to no beam. See the boiling study for details.

The yield for this run

$$\boxed{Y_i = \frac{\#\ of\ observed\ events}{Effective\ Luminosity} = \frac{C_i}{Q_i \cdot \rho_l \cdot Boiling_i \cdot eff_i \cdot LT_i/PS_i}}$$

with $\frac{1}{\sqrt{C_i}}$ as the fractional statistical uncertainty.

The overall yield of a given kinematics is the weighted arithmetic mean of all good production runs under this kinematics:

$$Y_{overall} = \frac{\sum_i C_i}{\sum_i Q_i \cdot \rho_l \cdot Boiling_i \cdot eff_i \cdot LT_i/PS_i}$$

with a fractional statistical uncertainty of $\frac{1}{\sqrt{\sum_i C_i}}$.

# Yield (rate) Calculation from Monte-Carlo Simulation

Good events in simulation and XEMC

20 uA

$$rate_{MC} = I \cdot \rho_l / A \sum_{N_{tot}} \boxed{\frac{d\sigma}{d\Omega}} \varepsilon(\Omega) \frac{\Omega_{tot}}{N_{tot}} \cdot efficiency$$

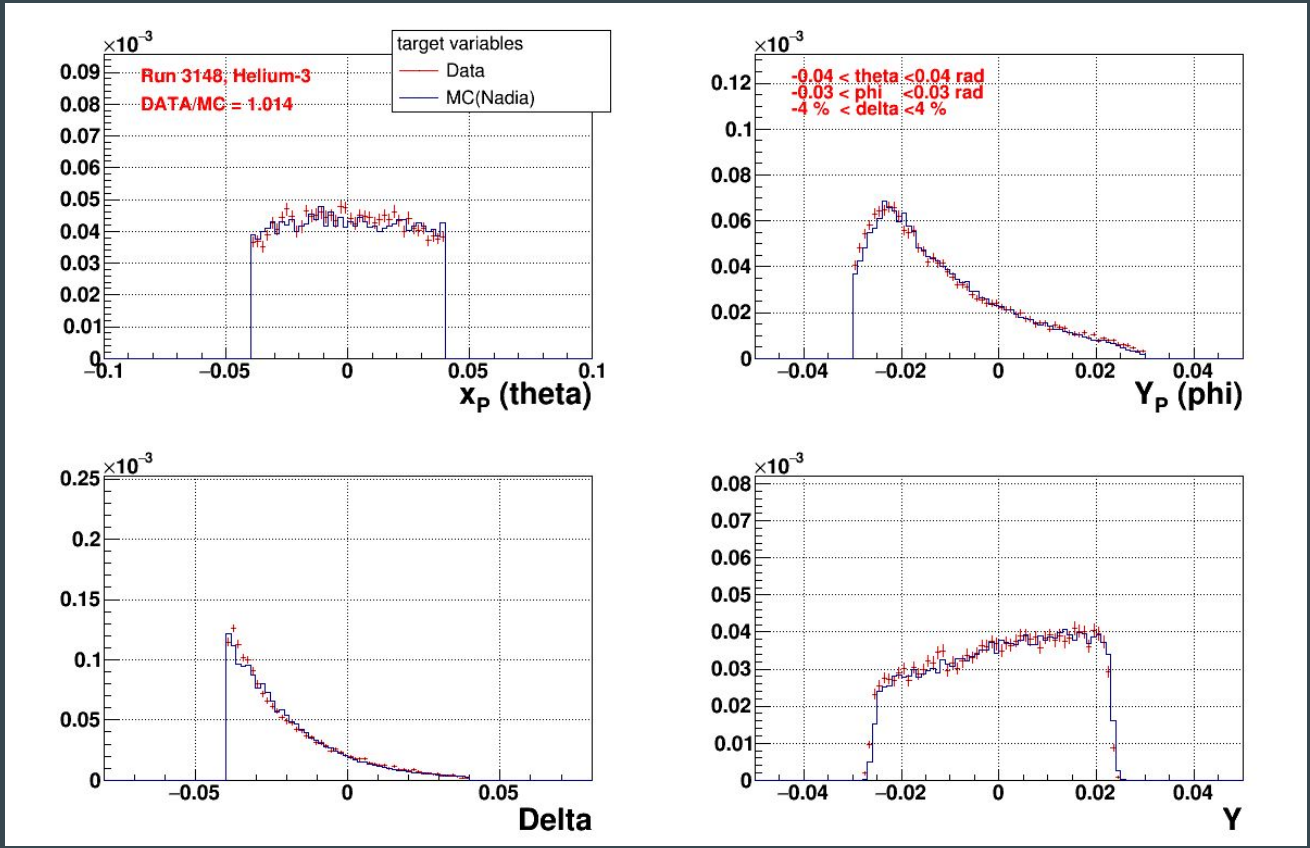
# of **trials** in simulation

(!! The single arm simulation will only record good events)

Cross section tables generated from XEMC model:

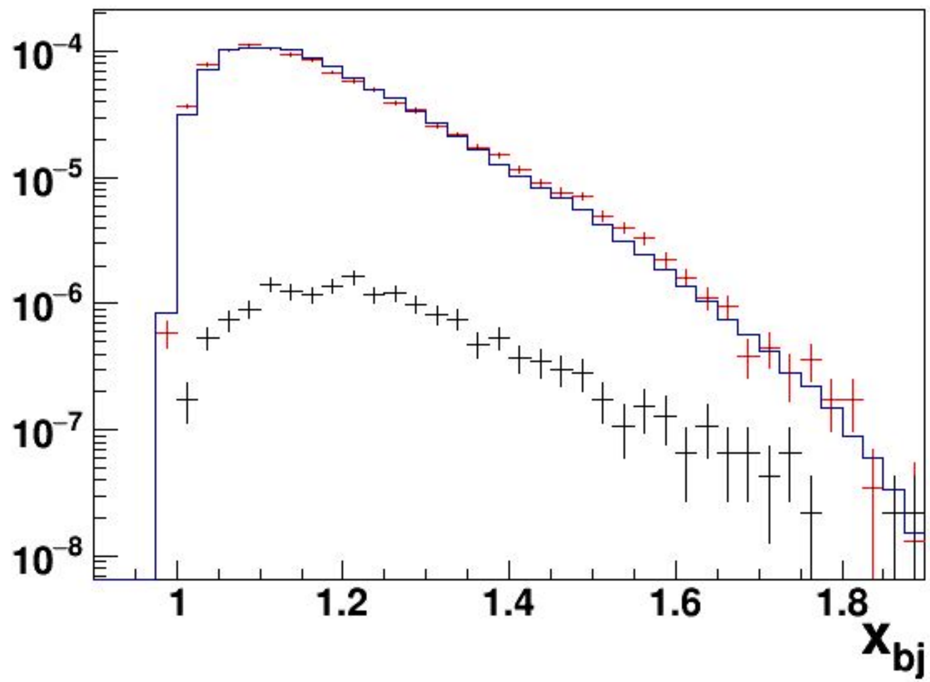
- from Zhihong
- Included bremsstrahlung radiation
- y-scaling. Use He3 fitting parameter for H3

# Compare Data vs MC Simulation



# Compare Data vs MC Simulation

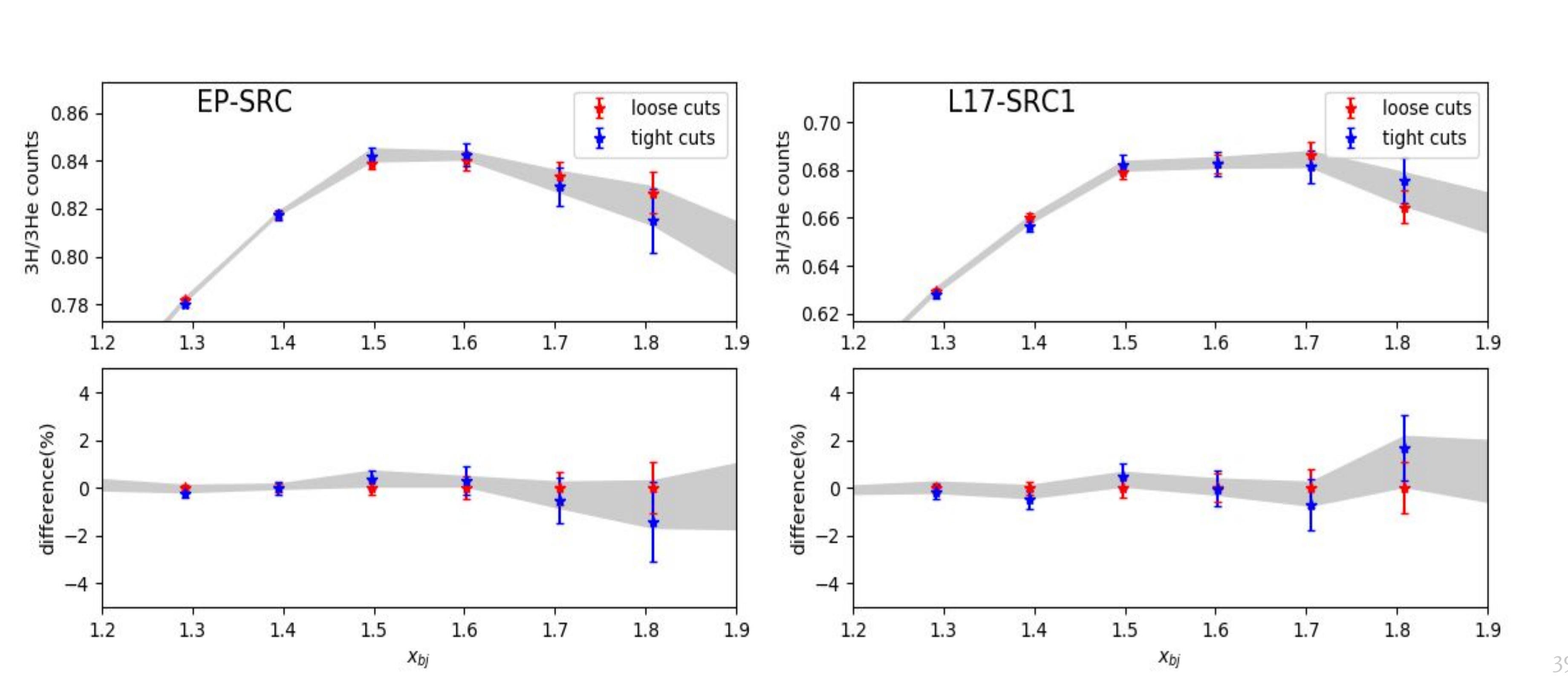
Red: data, blue: simulation, black: endcap contamination from empty cell



# Acceptance Cuts Sensitivity:

Blue: theta, phi, delta = 0.035rad, 0.025rad, 3.5%

**Red: theta, phi, delta = 0.060rad, 0.035rad, 4.5% (picked)**



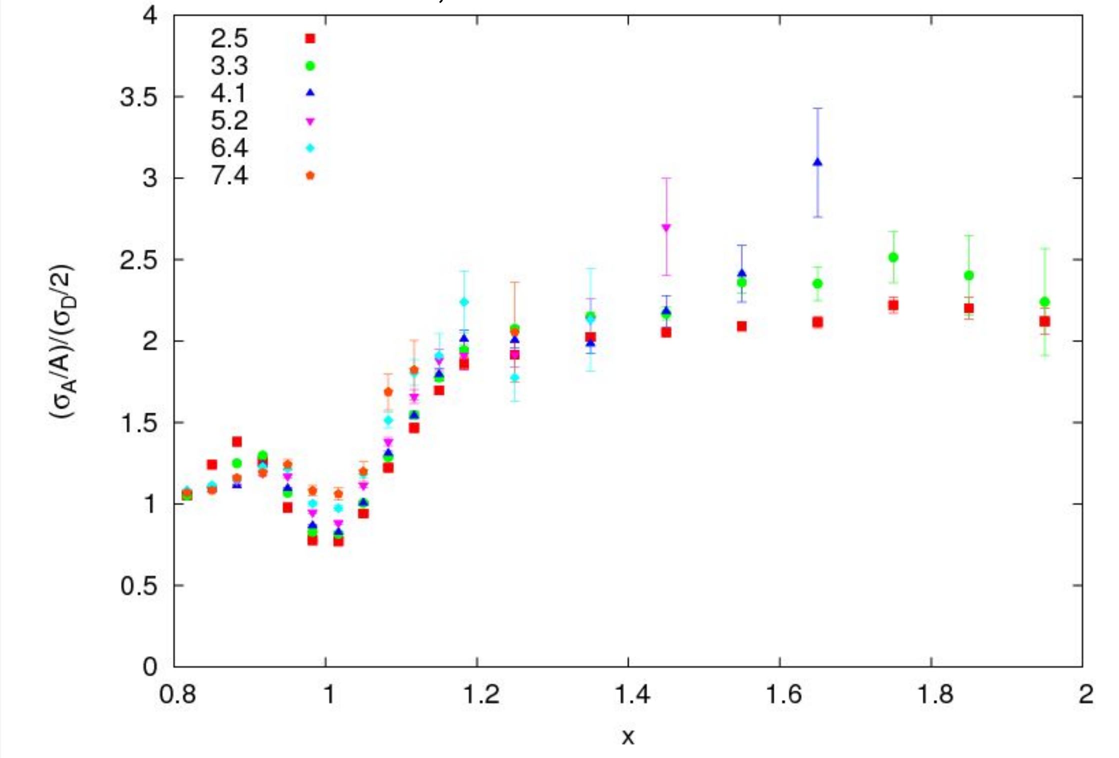
# SRC Analysis Status:

Combined analysis of data from 2 experiments:

- 1.4 GeV2 data from this experiment (red)
- 1.8 GeV2 data from the exclusive SRC (blue)

## Calibration result: 3He/2H ratio

N. Fomin, arxiv: 1206.6343



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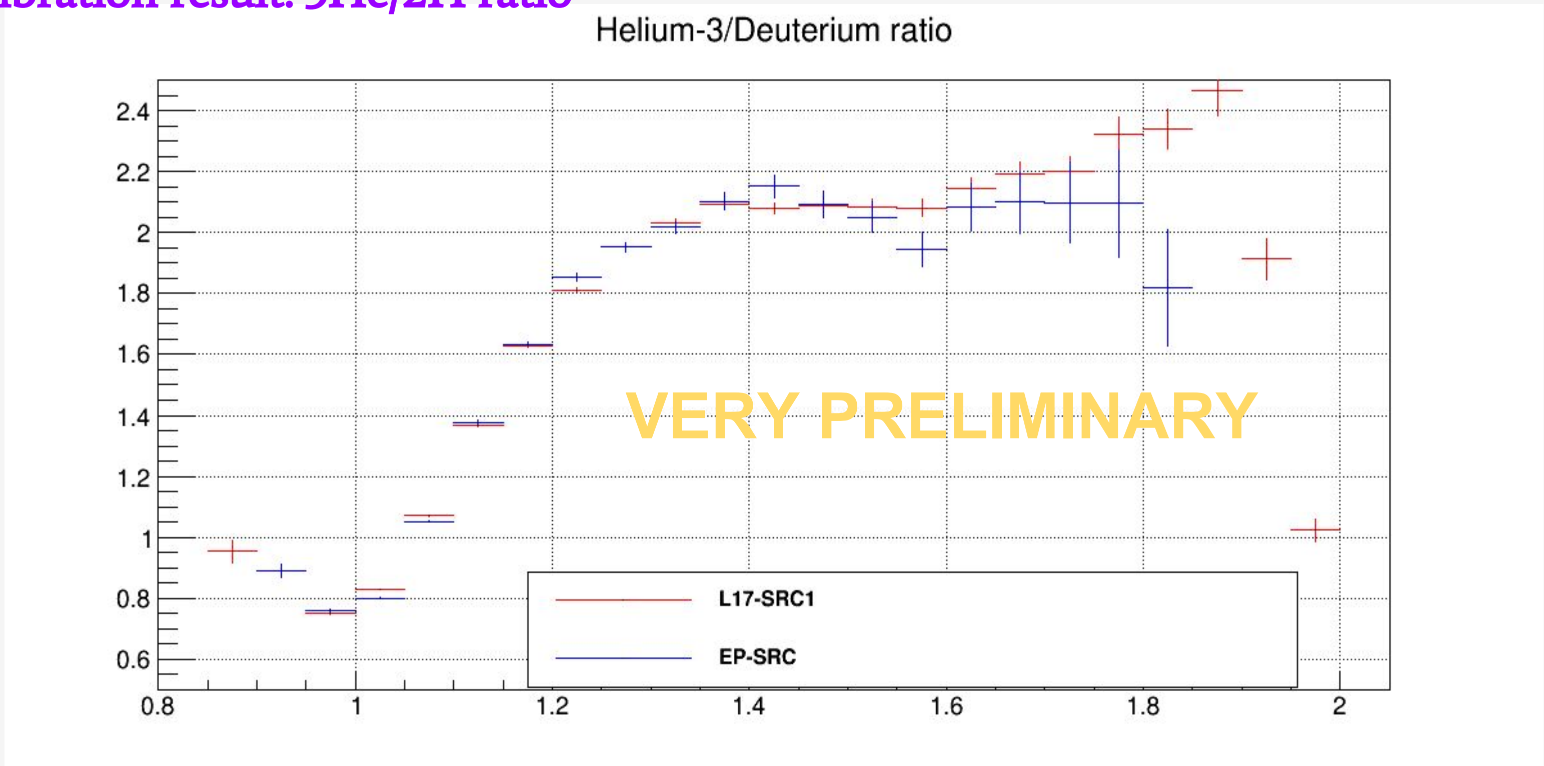
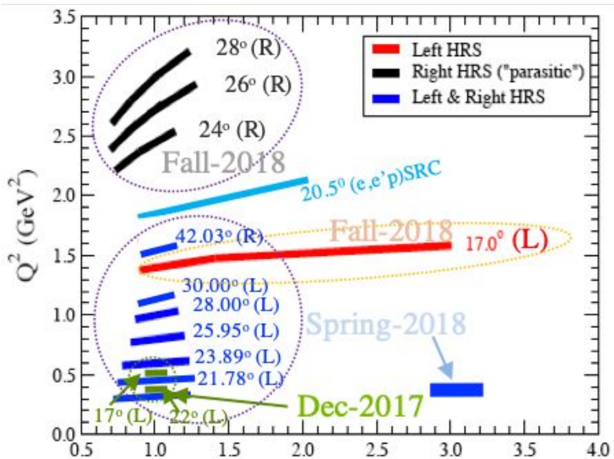
**Calibration result: 3He/2H ratio**



# ➢Status of GMn (inclusive-SRC) Analysis: by Nathaly Santiesteban (UNH) and Zhihong Ye



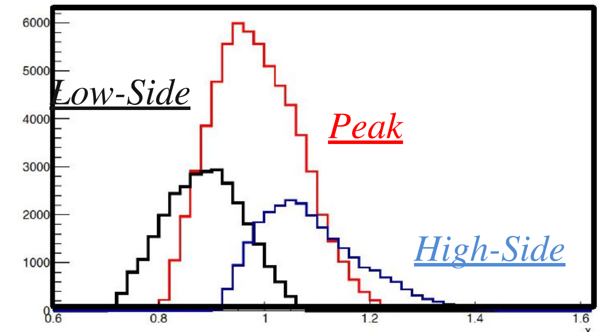

- 12 QE kinematics ranged from 0.3GeV$^2$ to 3GeV$^2$
- Data analysis is in parallel with the SRC analysis
- Different physics interpolation at x=1 peaks

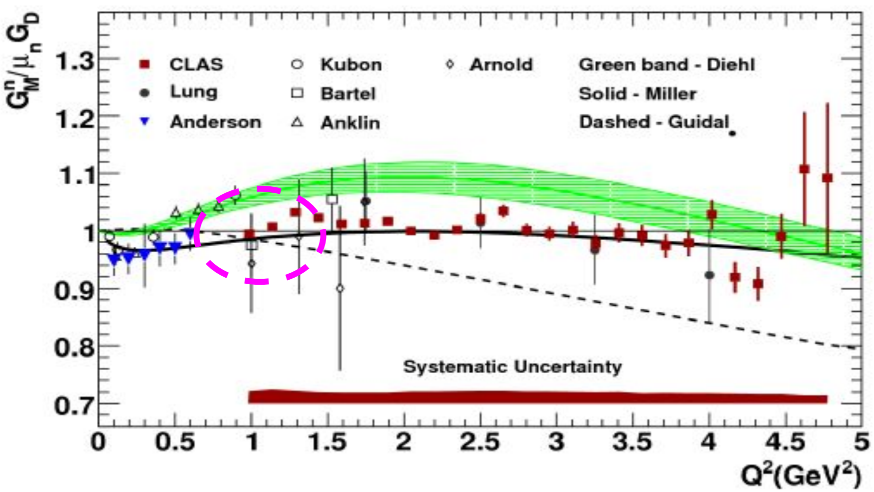
$$R(Q^2) = \frac{[d^2\sigma/dEd\Omega]_{^3H}}{[d^2\sigma/dEd\Omega]_{^3He}} \simeq \frac{2(d\sigma/d\Omega)_n + (d\sigma/d\Omega)_p}{(d\sigma/d\Omega)_n + 2(d\sigma/d\Omega)_p},$$

$$\frac{(d\sigma/d\Omega)_n}{(d\sigma/d\Omega)_p} = \frac{2R-1}{R-2}$$

$$G_M^n = \tau^{-1/2}\sqrt{\frac{(\frac{d\sigma}{d\Omega})_n}{(\frac{\sigma}{d\Omega})_{Mott}}\epsilon(1+\tau) - \epsilon(G_E^n)^2}$$

- To cover the entire QE peak (and long tails), three set of data were taken:




- The new data will address the discrepancy in 0.5<$Q^2$<1 GeV$^2$

## ➢Low $Q^2$ inelastic cross section ratio of 3H, 3He by Tyler Kutz

Spring 2018 data (MARATHON):

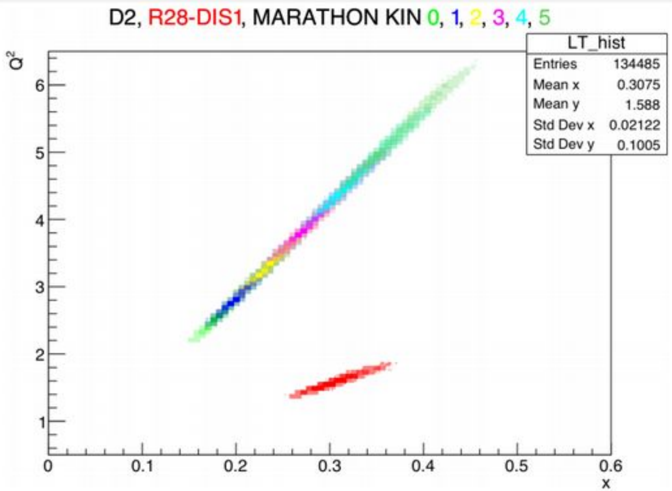
| | $E_0$ (GeV) | $E'$ (GeV) | $\theta$ (°) |
|---|---|---|---|
| KIN 0 | 10.6 | 3.1 | 16.807 |
| KIN 1 | 10.6 | 3.1 | 17.755 |
| KIN 2 | 10.6 | 3.1 | 19.115 |
| KIN 3 | 10.6 | 3.1 | 20.578 |
| KIN 4 | 10.6 | 3.1 | 21.930 |
| KIN 5 | 10.6 | 3.1 | 23.213 |

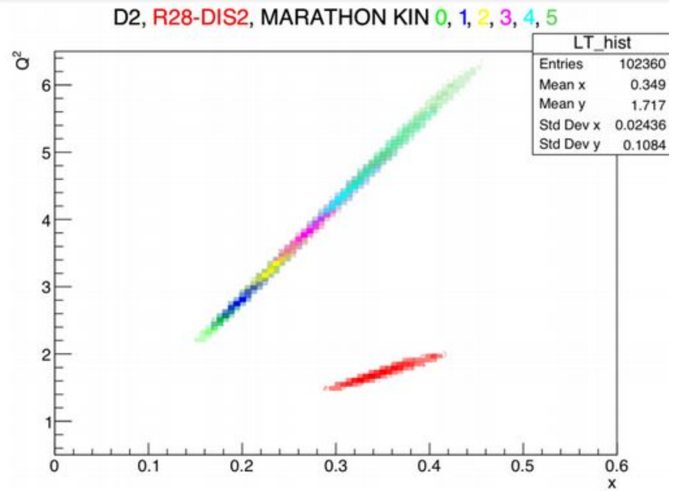
Fall 2018 data:

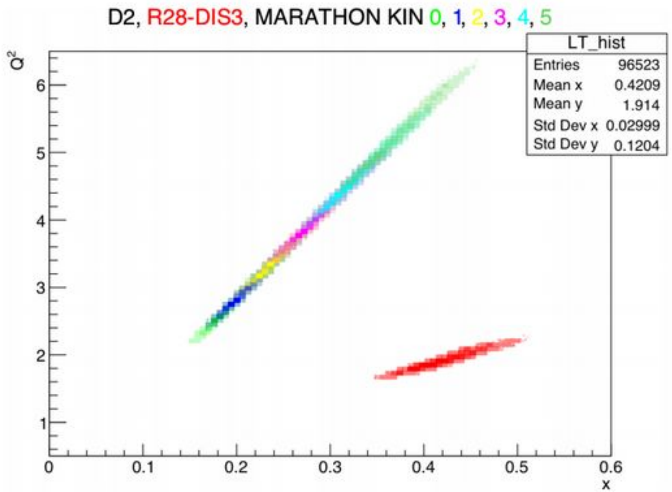
| | $E_0$ (GeV) | $E'$ (GeV) | $\theta$ (°) |
|---|---|---|---|
| R28-DIS1 | 4.3 | 1.58 | 28.004 |
| R28-DIS2 | 4.3 | 1.71 | 28.004 |
| R28-DIS3 | 4.3 | 1.91 | 28.004 |

Targets: 1H, 2H, 3H, 3He, Ti48

# ➢Low $Q^2$ inelastic cross section ratio of 3H, 3He by Tyler Kutz



# Next step:

SRC:

fine-tuning x>1 ratio results

Analyze x>2 data

Extract absolute cross sections (??)

GMn and DIS: continue data analysis

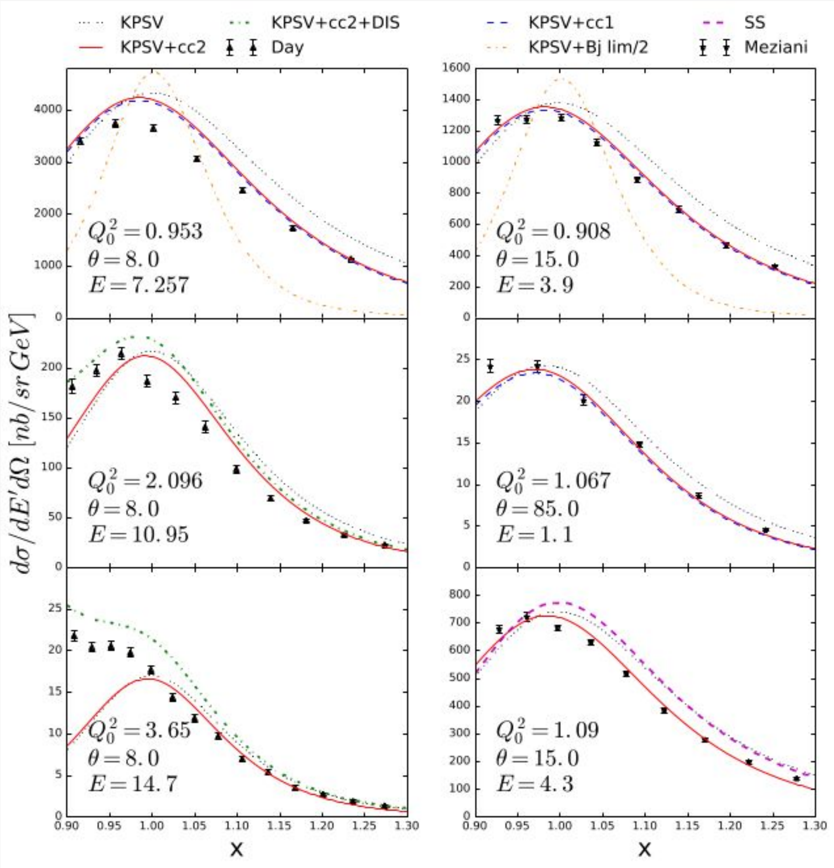
More:

SRC v.s. EMC

3H  and 3He nuclear smearing study with QE data

# Test 3H and 3He nuclear smearing and off-shell correction models

A.J.Tropiano, et. al., arXiv:1811.07668



# Thanks to:

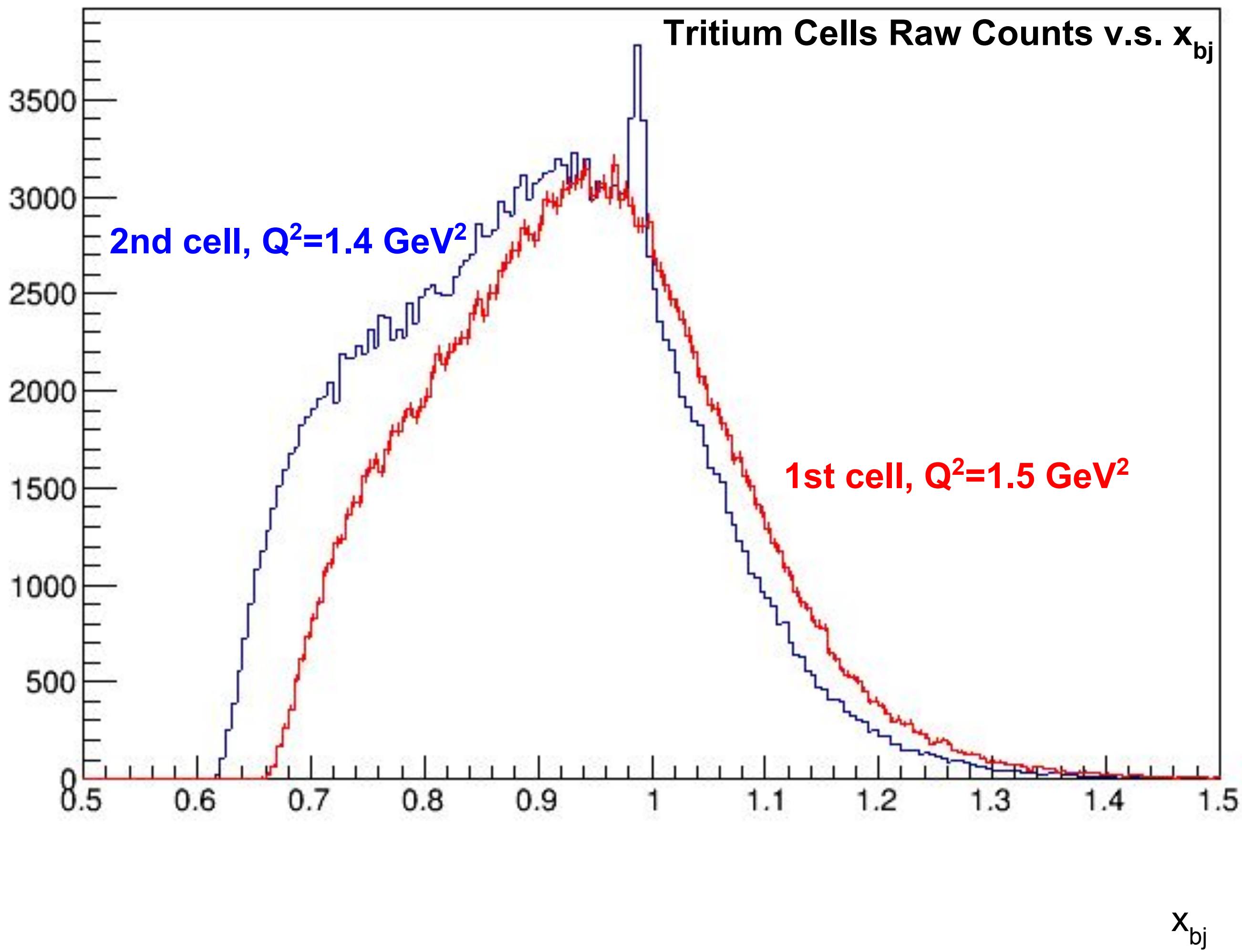
The tritium group students

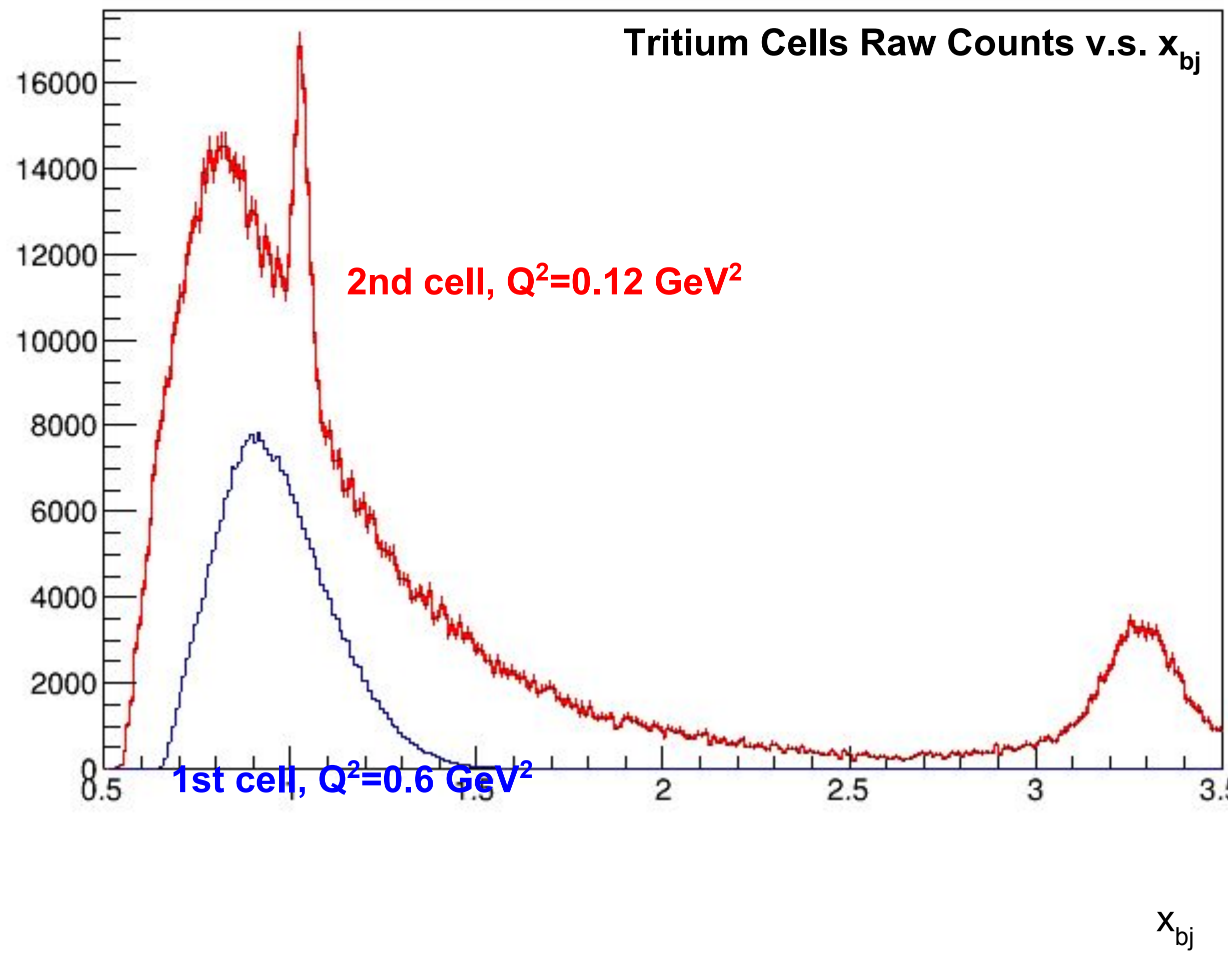
Florian, Evan, Meekins

Shift workers

Hall A engineer/tech group

The GMp collaboration


Tritium Cells Raw Counts v.s. $x_{bj}$
2nd cell, $Q^2$=1.4 GeV$^2$
1st cell, $Q^2$=1.5 GeV$^2$
3500
3000
2500
2000
1500
1000
500
0
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
$x_{bj}$



Tritium Cells Raw Counts v.s. $x_{bj}$
2nd cell, $Q^2$=0.12 GeV$^2$
1st cell, $Q^2$=0.6 GeV$^2$
0
2000
4000
6000
8000
10000
12000
14000
16000
0.5
1
1.5
2
2.5
3
3.5
$x_{bj}$

# Nucleons in Nuclei:

## Independent Particle Shell Model(IPSM)

- Low energy, non-relativistic:

$$[\sum_i -\frac{\hbar^2}{2m_N}\nabla_i^2 + \sum_{i<j} v_2(\boldsymbol{x}_i,\boldsymbol{x}_j) + \sum_{i<j<k} v_3(\boldsymbol{x}_i,\boldsymbol{x}_j,\boldsymbol{x}_k) + ...]\Psi_A = E_A\Psi_A$$

- Nucleons move independently in an averaged potential induced by the rest of the

$$[-\frac{\hbar^2}{2m_N}\nabla_i^2 + U(\boldsymbol{x})]\phi_\alpha(\boldsymbol{x}_i) = \epsilon_\alpha\phi_\alpha(\boldsymbol{x}_i)$$