u-Channel Omega Meson Production from the Fpi-2 Experiment

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Fpi2 Collaboration

NSERC CRSNG

UNIVERSITY OF REGINA

Jefferson Lab

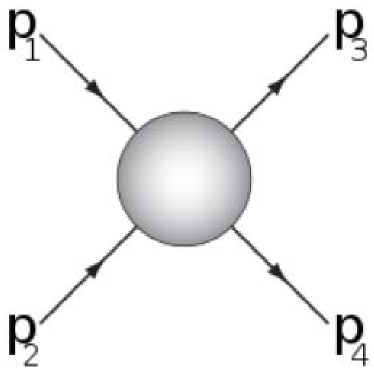
***t*-channel physics**
Forward

***u*-channel physics**
Backward

Outline

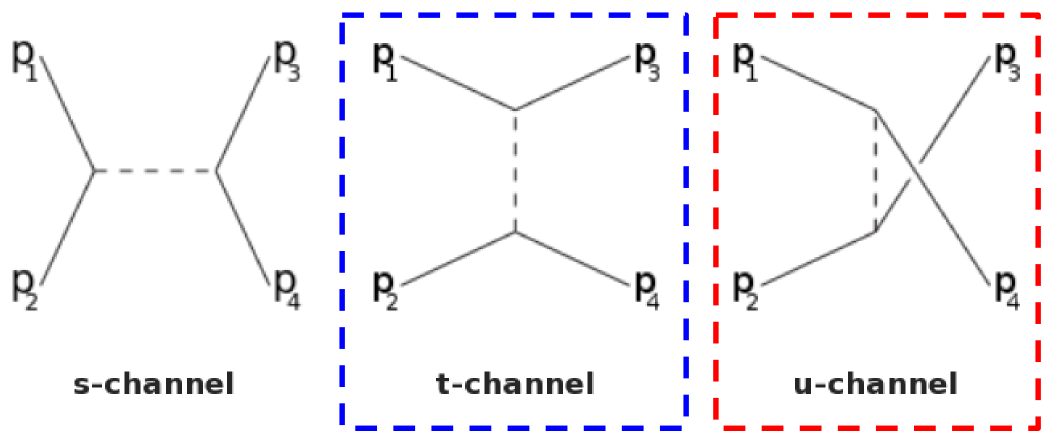
- Motivation
- Where the experimental data came from?
- Underlying Physics regarding u-channel
- Experimental technique and analysis details
- Results and Outlook

Mandelstam variables (*s*,*t*,*u*-Channels)



$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

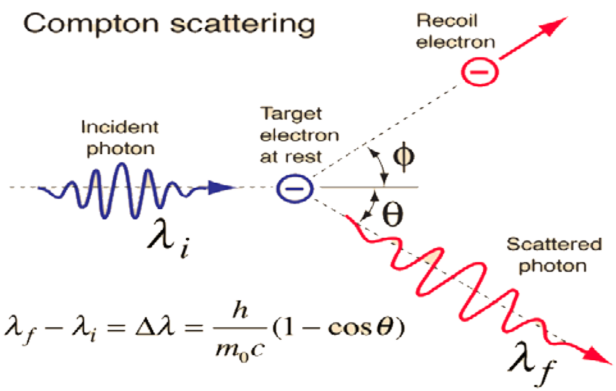
$$\gamma^*(q) + N(p_1) \longrightarrow \pi(p_\pi) + N(p_2)$$
$$s = (p_1 + q)^2; \quad u = (p_\pi - p_1)^2; \quad t = (p_2 - p_1)^2.$$

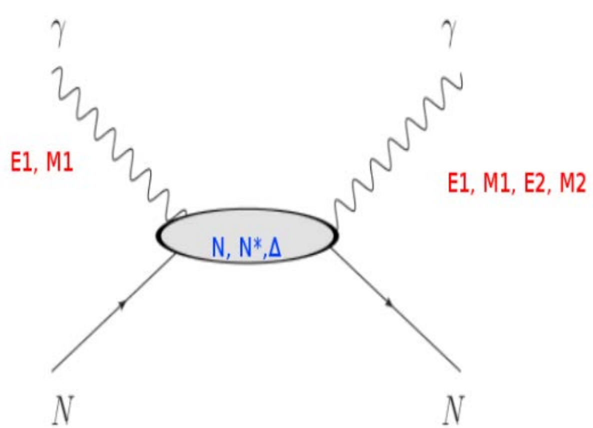


- ***s***: invariant mass of the system
- ***t***: Four-momentum-transfer squared between **target before and after interaction.**
- ***u***: Four-momentum-transfer squared between **virtual photon before interaction and target after interaction**
- ***t*-channel*: -t ~ 0*, after interaction**
  - **Target: stationary,**
  - **Meson: forward**
  - **Measure of how forward could the meson go.**
- ***u*-channel: *-u~0,* after interaction**
  - **Target: forward**
  - **Meson: stationary**
  - **Measure of how backward could the meson go**
- **High *–t* scenario, *t* channel process becomes *u* channel process**

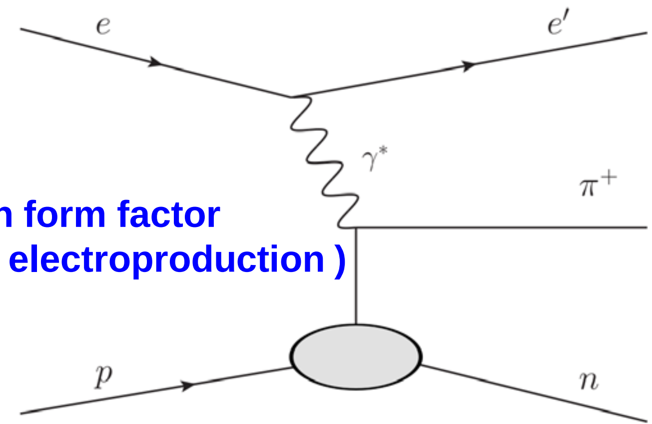
Standard Physics at Hall C (Jefferson Lab)

■ *s*-Channel Physics

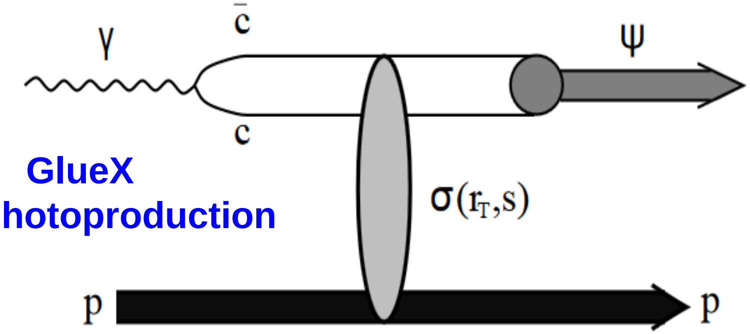




■ *t*-Channel Physics



Pion form factor
(charged π electroproduction)

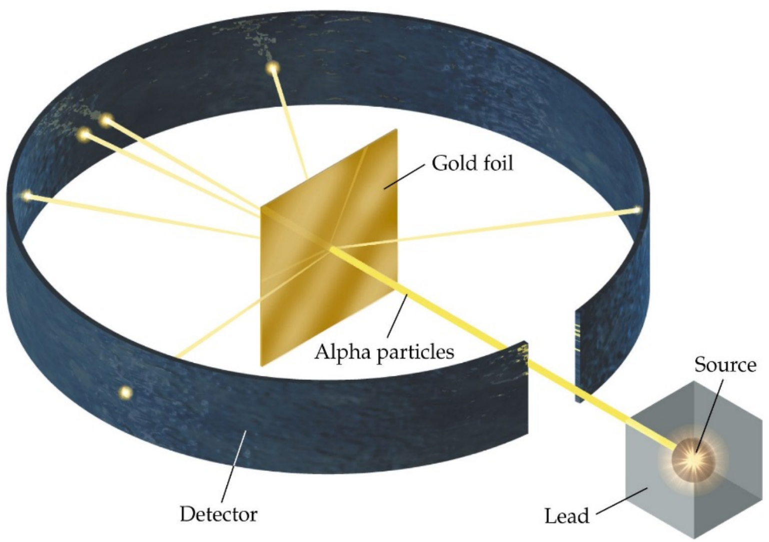


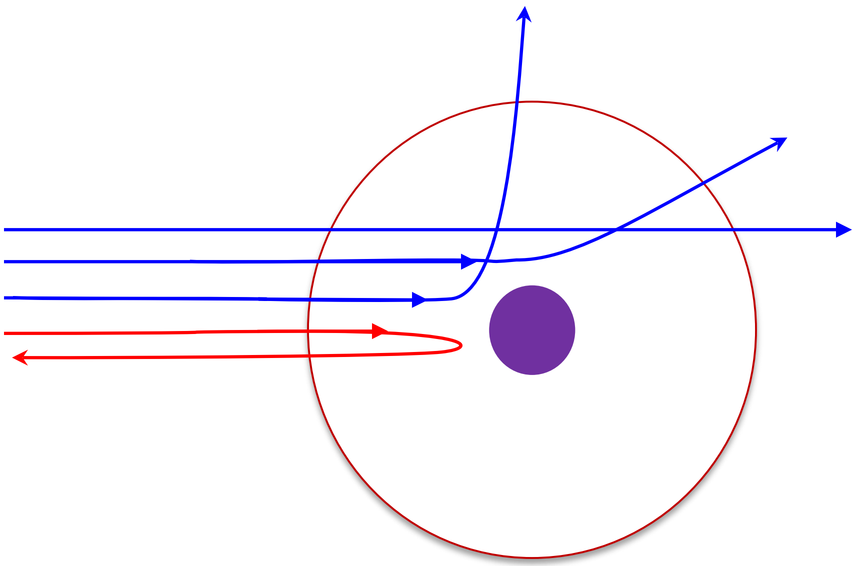
GlueX
J/psi photoproduction

All could be parameterized in four Lorentz invariant Quantities: *x*, *W* ($\sqrt{s}$), Q^2 and *t*

What about *u*? Should we include *u*?

Rutherford Experiment

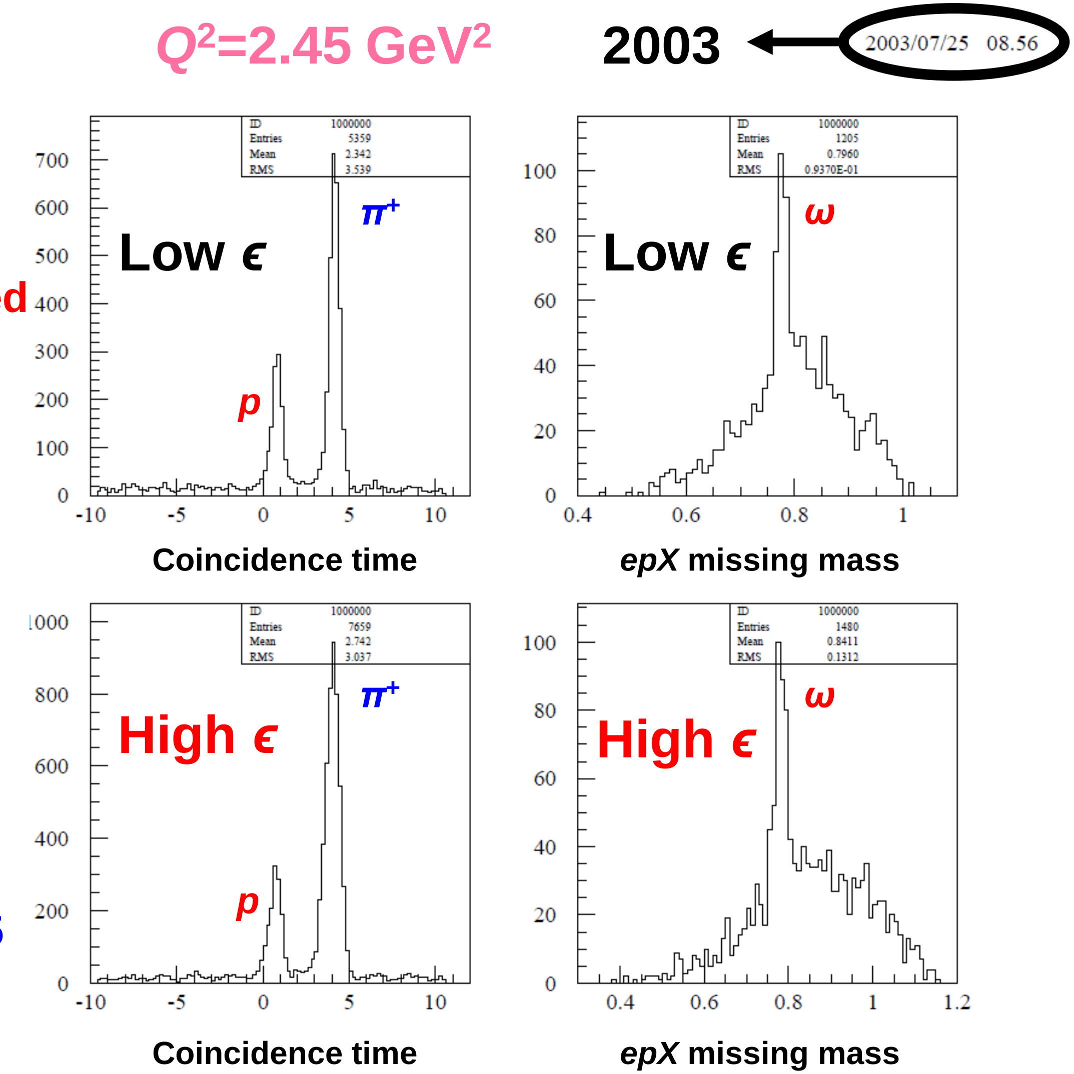




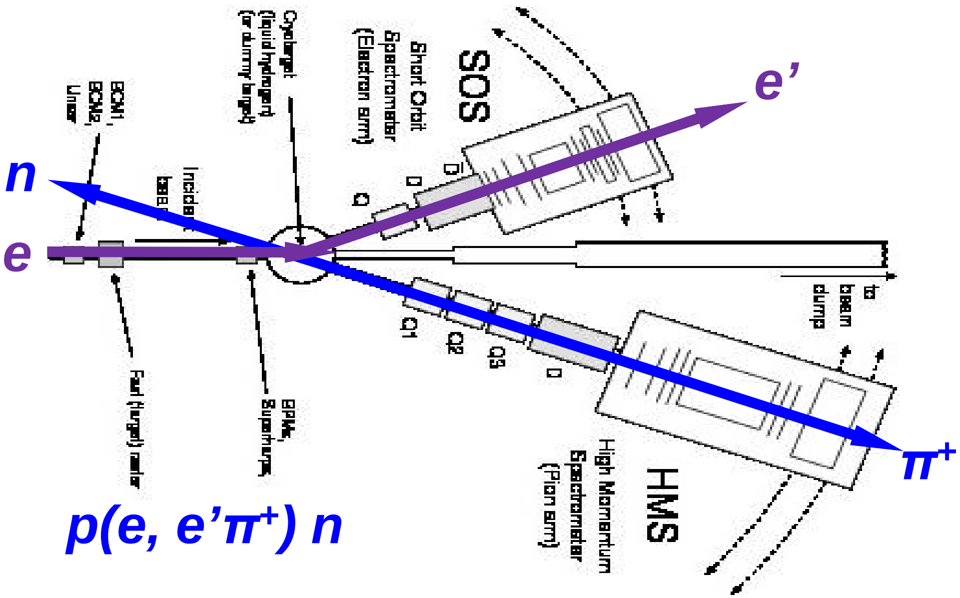
- **Rutherford Experiment:**
  - **Need both forward and backward scattered alpha particles to yield complete atomic structure!**
- **What about nucleons?**
  - Does ***t*-channel** physics contain all the nucleon structure information?
  - ***u*-channel** physics contain **unique information** whose meaning is unclear (B. Pire et. al)
- How do we **access u-channel** physics?

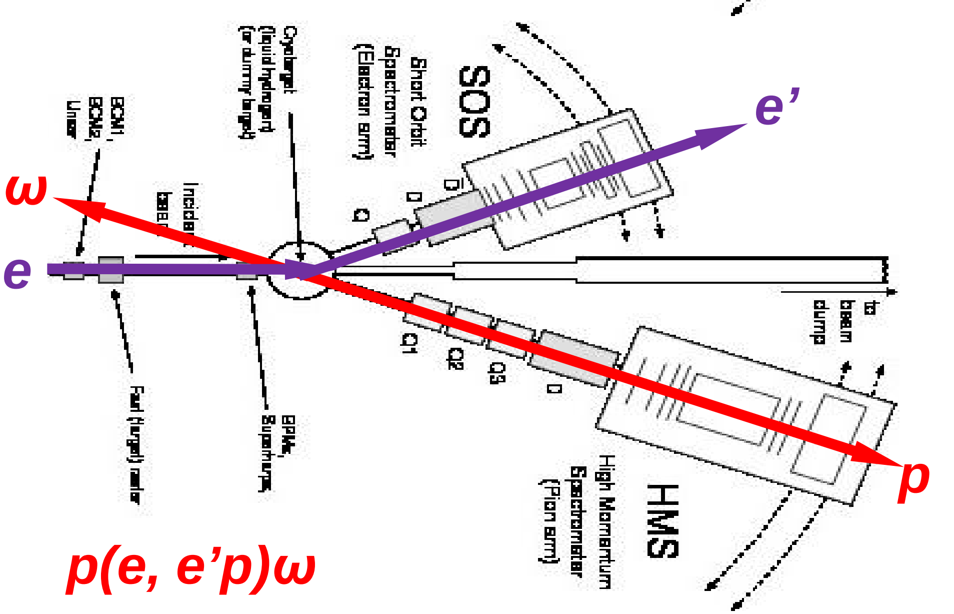
Omega Data Analysis

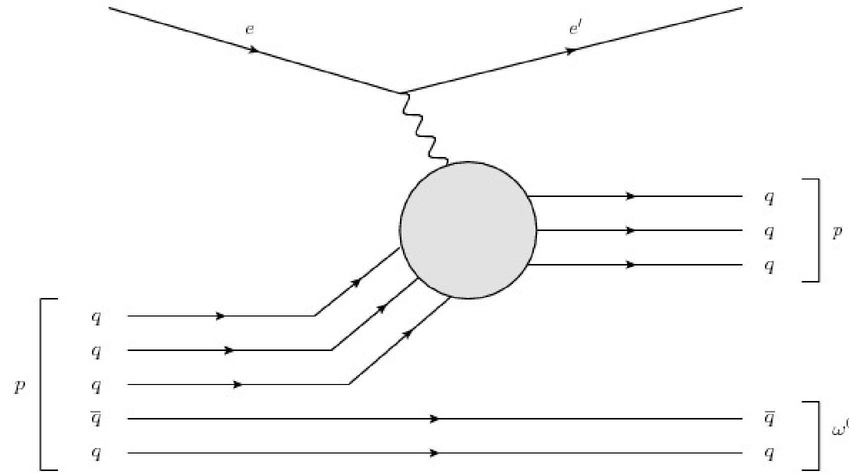
- Fpi-2 (E01-004) 2003
  - Spokesperson: **Garth Huber, Henk Blok**
  - Standard HMS and SOS (e) configuration
  - **Electric form factor of charged** through exclusive π production
- Primary reaction for Fpi-2
  - ***p(e, e' π^+)n***
- In addition, we have for free
  - ***p(e,e' p)ω***
- Kinematics coverage
  - ***W*= 2.21 GeV, *Q*^{2}=1.6 and 2.45 GeV^2**
  - Two ϵ settings for each Q^2



t-Channel π vs *u*-Channel ω^0 Production







Mark Strikman: A proton being knocked out of a proton process

- HMS along the *q*-vector (p_{γ^*})
  - $p_{\pi+}$ is parallel to p_{γ^*} (Forward)
  - p_{ω} is anti-parallel to p_{γ^*} (Backward)

Nucleon Fragmentation Process

Before interaction

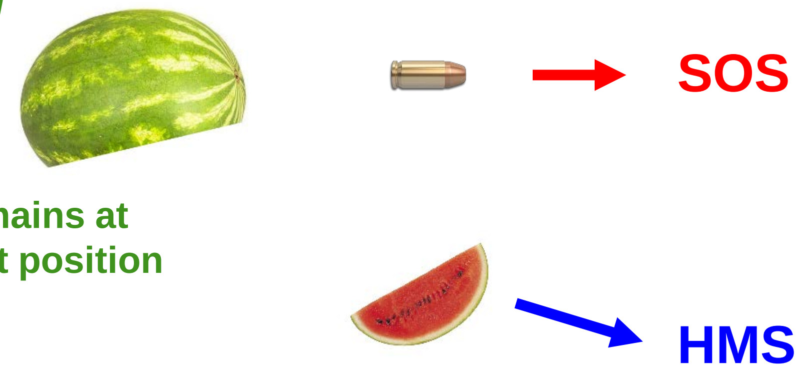
e + *H*

Standard nucleon Fragmentation gives a weird picture

After interaction

***t*-channel**

n

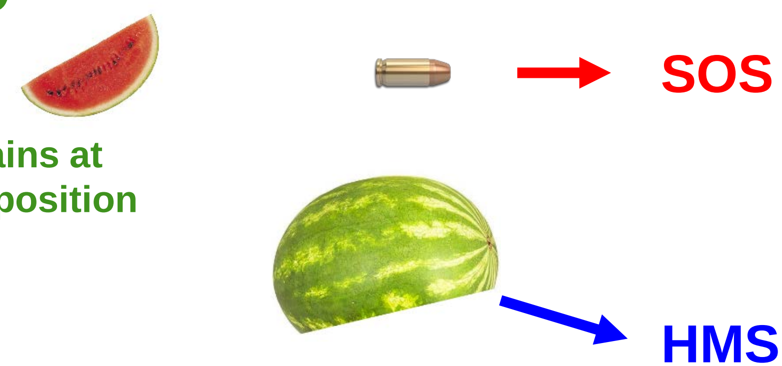


Remains at target position

- ***H*(*e*, *e'* π^+)*n***

***u*-channel**

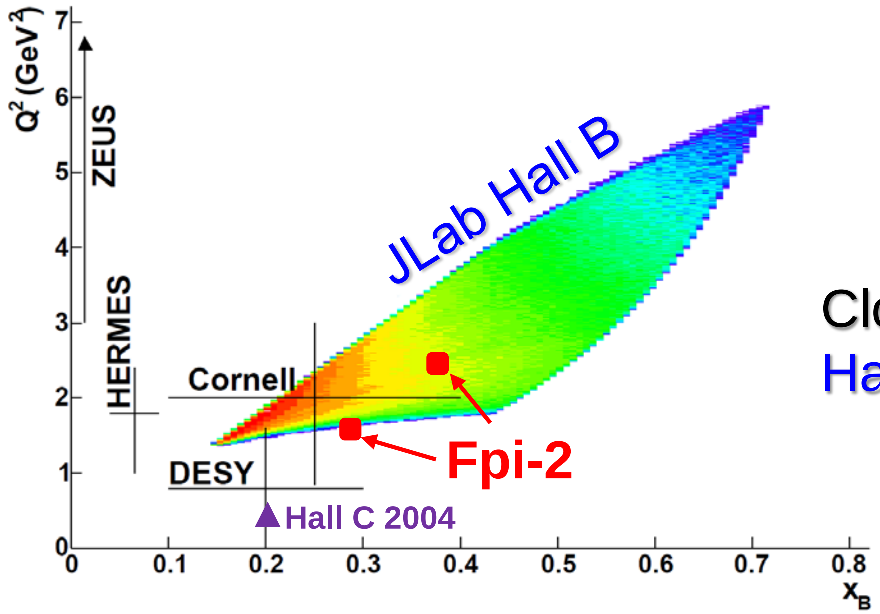
ω



Remains at target position

- ***H*(*e*,*e'* *p*)*ω***
- **Exclusive Chanel: *ω* is not tagged**

Exclusive ω Electro-Production Data

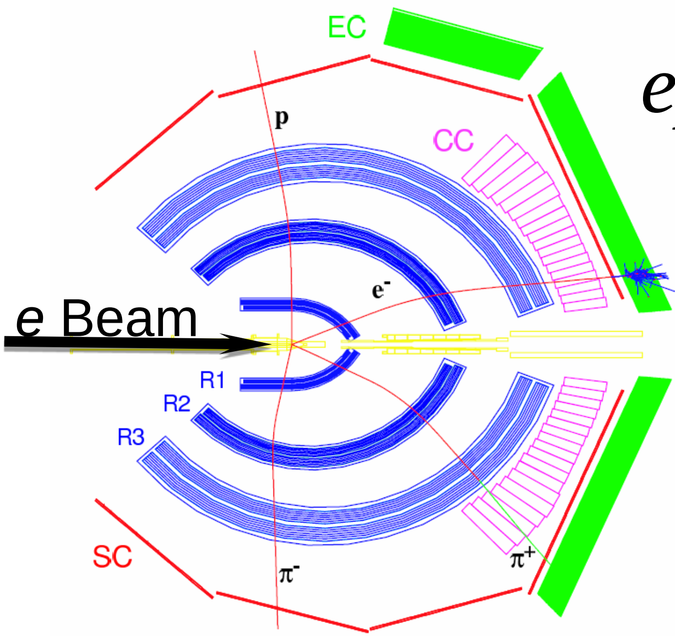


Closest data set to ours is the Hall B Morand data

	Q^2 GeV^2	W GeV	x	$-t$ GeV^2
HERMES (Airapetian et al., 2014)	> 1	3-6.3	0.06-0.14	< 0.2
DESY (Joos et al., 1977)	0.3-1.4	1.7-2.8	0.1-0.3	< 0.5
Zeus (Breitweg et al., 2000)	3-20	40-120	~0.01	< 0.6
Cornell (Cassel et al., 1981)	0.7-3	2.2-3.7	0.1-0.4	<1
JLab Hall C (Ambrozewicz et al., 2004)	~0.5	~1.75	0.2	0.7-1.2
JLab Hall C (Dalton et al., 2005)	5-7	1.5		>4.0
JLab Hall B (Morand et al., 2005)	1.6-5.1	1.8-2.8	0.16-0.64	<2.7
JLab Fpi-2 (2017)	1.6, 2.45	2.21	0.29, 0.38	4.0, 4.74

High t Data from CLAS Hall B (2005)

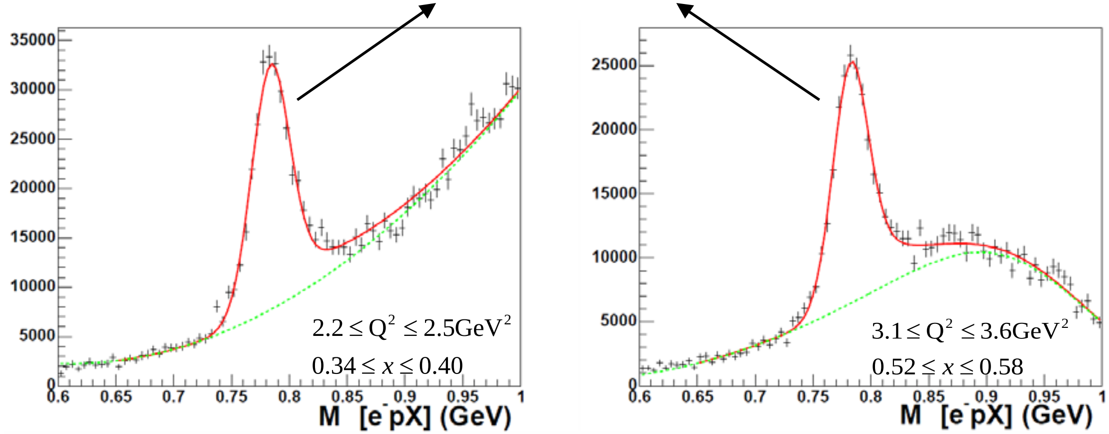
Morand et al., Eur. Phys. J. A 24, 445 (2005).



$$ep \rightarrow ep\omega$$

$$\omega \rightarrow \pi^+\pi^-\pi^0$$

$\omega(782\mathrm{MeV})$



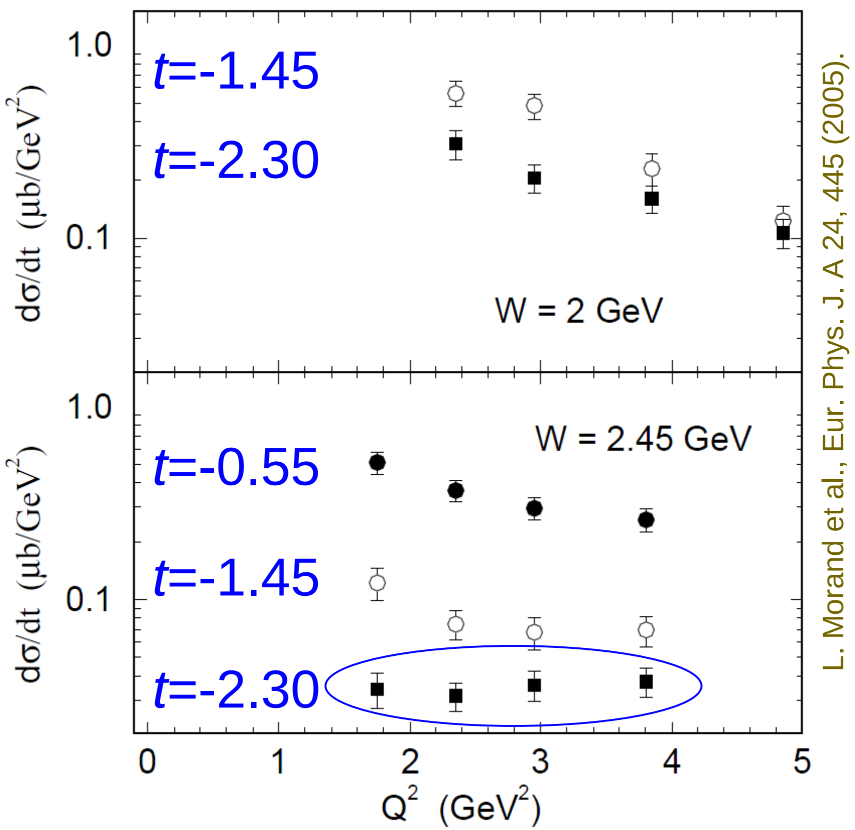
Missing mass reconstruction e^-pX

- Hall B Experiment **e1-6**
  - Oct 2001 – Jan 2002
  - Beam energy: 5.754 GeV
- Kinematic coverage:
  - *W* : 1.8-2.8 GeV
  - Q2: 1.6-5.1 GeV^2
  - ***-t* : < 2.7 GeV^2**
  - *x*: 0.16-0.64
- Event selection:

  $$ep \rightarrow ep\pi^+X$$

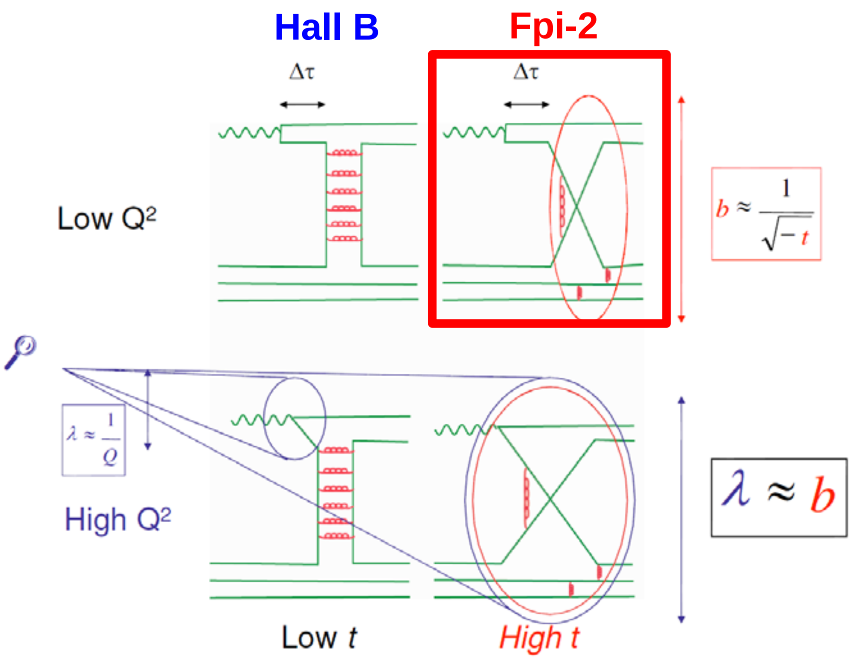
- Reconstructed *e-pX* missing mass consistent with the *ω* mass
- Data published in 2005:
  - Morand et al., Eur. Phys. J. A 24, 445 (2005).

High -*t* Data from CLAS Hall B (2005)

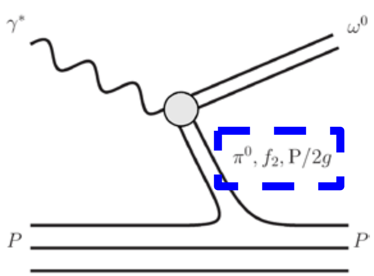


- **Excitement**:
  - **Observation: Q^2 independent cross section at high -*t***
  - **Q^2 dependence of 0**
  - **Possible interoperation: Virtual photon is more likely to couple to a point-like object as -*t* increases.**
- Are we really looking at the point charge like structure within the nucleon?
  - *-t=2.3 high enough?*

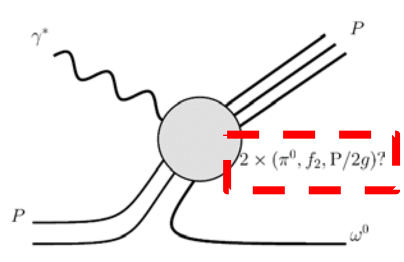
Regge Trajectory Model by JM Laget



Hard Scattering Mechanism schematics

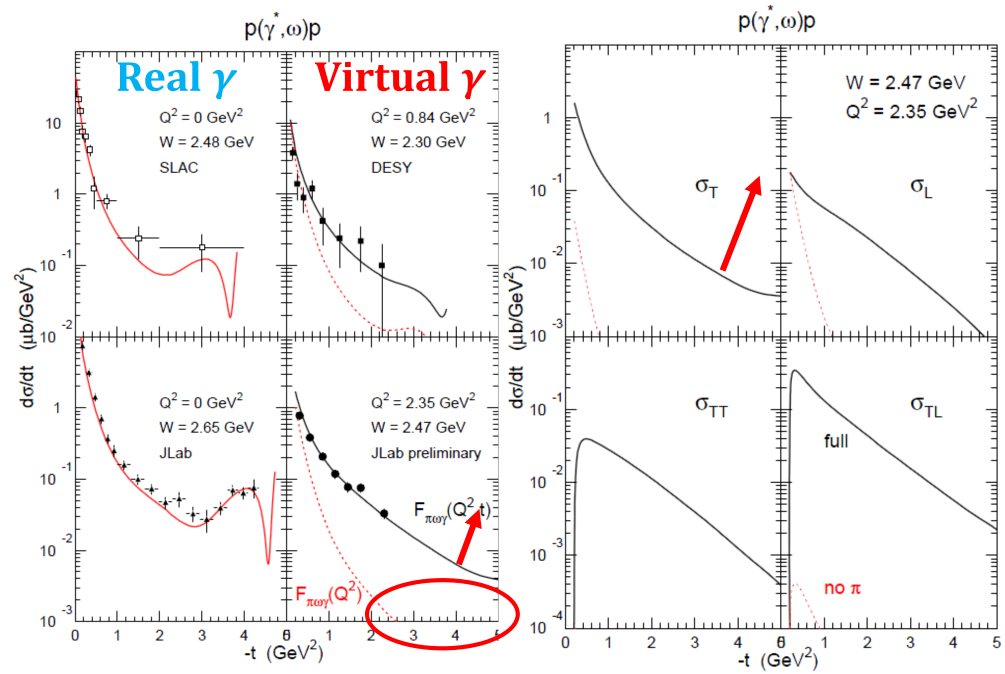


***t*-Channel**
Forward



***u*-Channel**
Backward

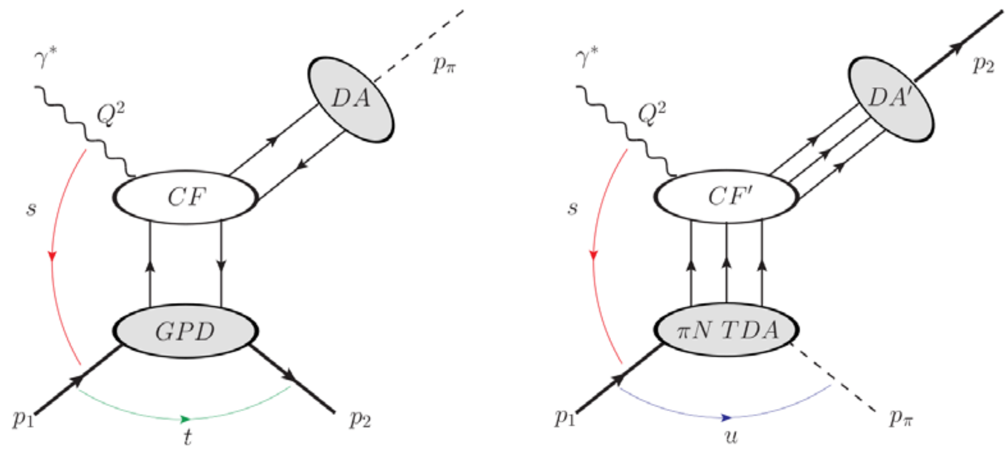
	W (GeV)	*x*	Q^2 (GeV^2)	*-t* (GeV^2)	*-u* (GeV^2)
Hall B	1.8-2.8	0.16-0.64	1.6-5.1	< 2.7	> 1.68
Fpi-2	2.21	0.29	1.6	4.014	0.08-0.13
		0.38	2.45	4.724	0.17-0.24



Fpi2 kinematics: data suggest a u channel peak

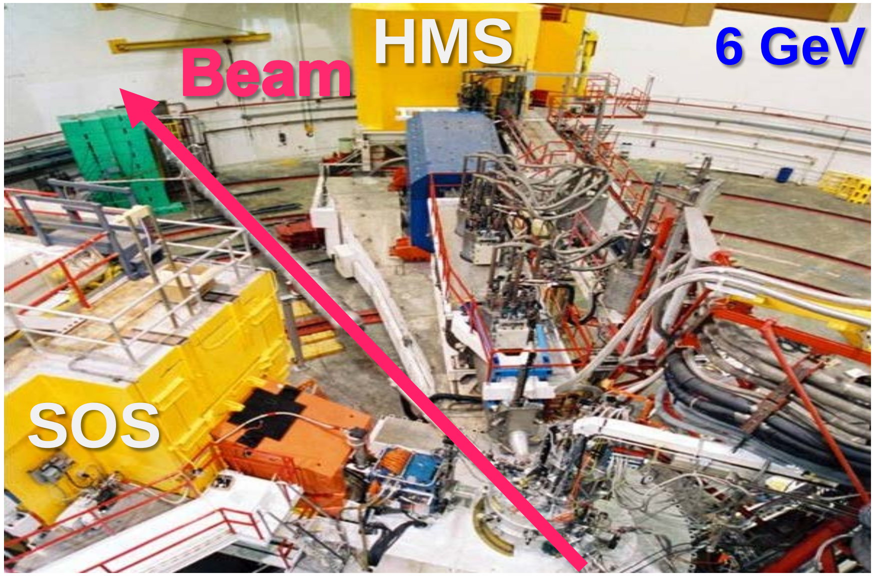
J. M. Laget, Phys. Rev. D 70, 2004

Transition Distribution Amplitude (TDA)



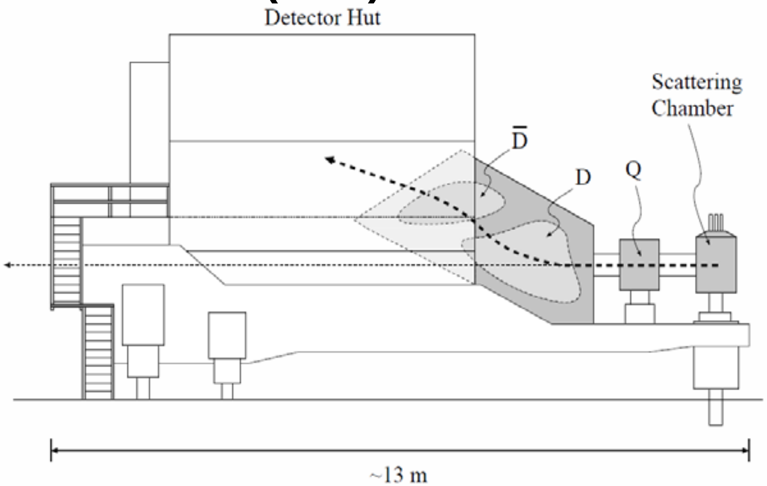
- TDA backward angle analog of GPD
- Interaction of Interest: ***u*-channel pseudocalar** **and** **vector *π* and production**
- Extension of the TDA model to describe the backwards vector meson production
- TDA Factorization **Made two Predictions** (B. Pire, K. Semenov, L. Szymanowski, Phys. Rev. D, **91**, 094006 (2015)).
  - The dominance of the transverse polarization of the virtual photon resulting in the suppression of the longitudinal cross section by at least $1/Q^2$: $\sigma_T > \sigma_L$. (**We can validate this !)**
  - The Characteristic **$1/Q^8$**-scaling behaviour of the σ_T for a fixed Bjorken x (**We can't test this.)**

Experimental Details

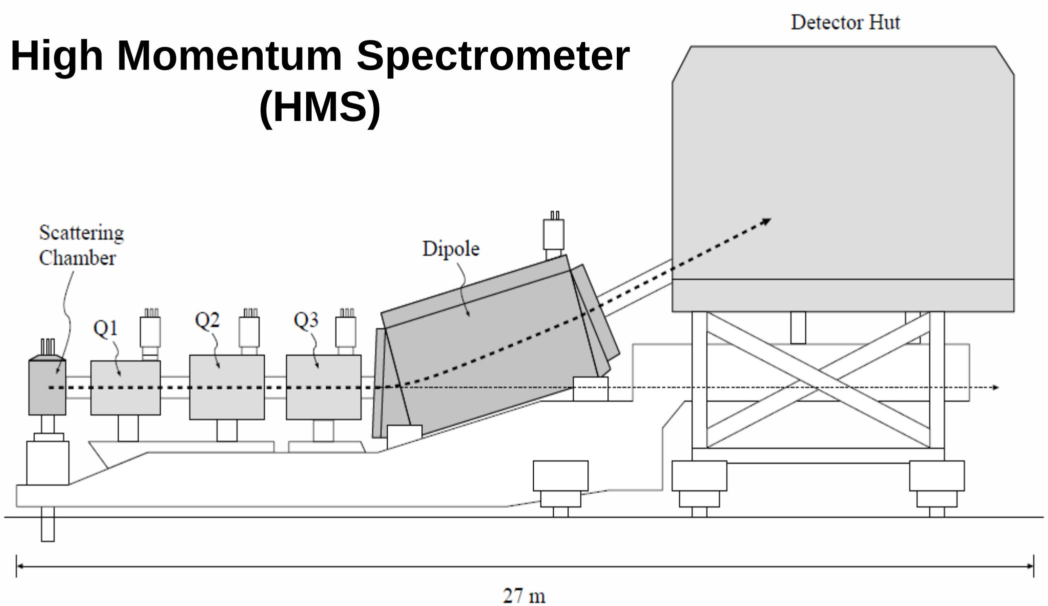


- **HMS (QQQD)**
  - **Angle Acceptance:** 6msr
  - **Momentum:** 0.5-7.5 GeV/c
  - **Momentum Acceptance:** +-9%
  - **Angular, Position Resolution:** 1mr and 1mm
- **SOS (QDDbar)**
  - **Angle Acceptance:** 9msr
  - **Momentum:** 0.1-1.8 GeV/c
  - **Momentum Acceptance:** +-20%

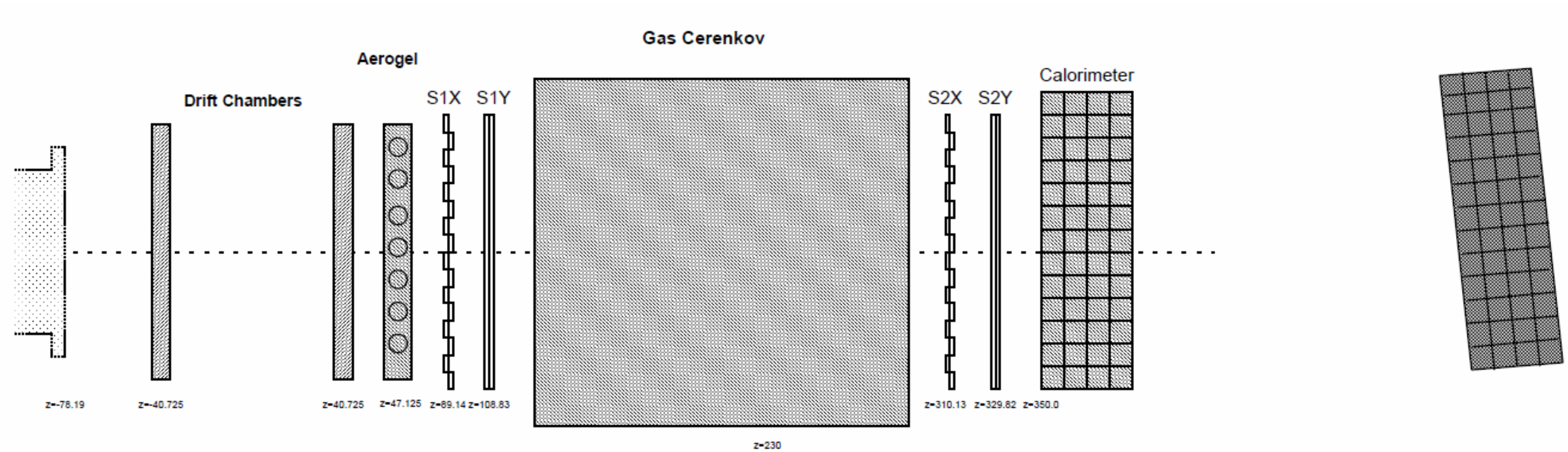
High Momentum Spectrometer (SOS)



High Momentum Spectrometer (HMS)

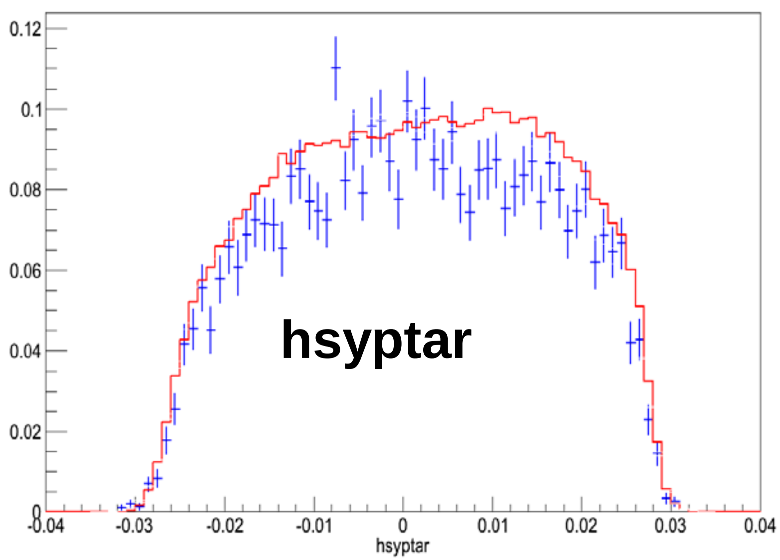


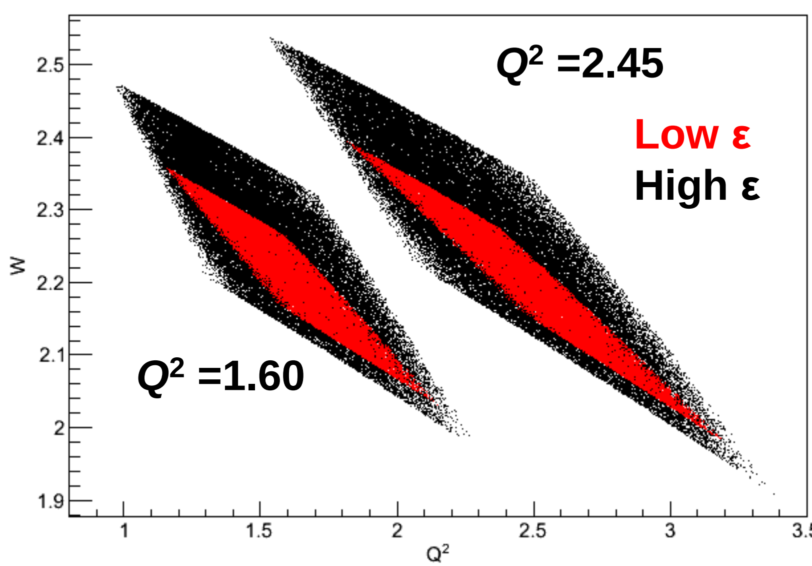
Experimental Setup and Acceptance



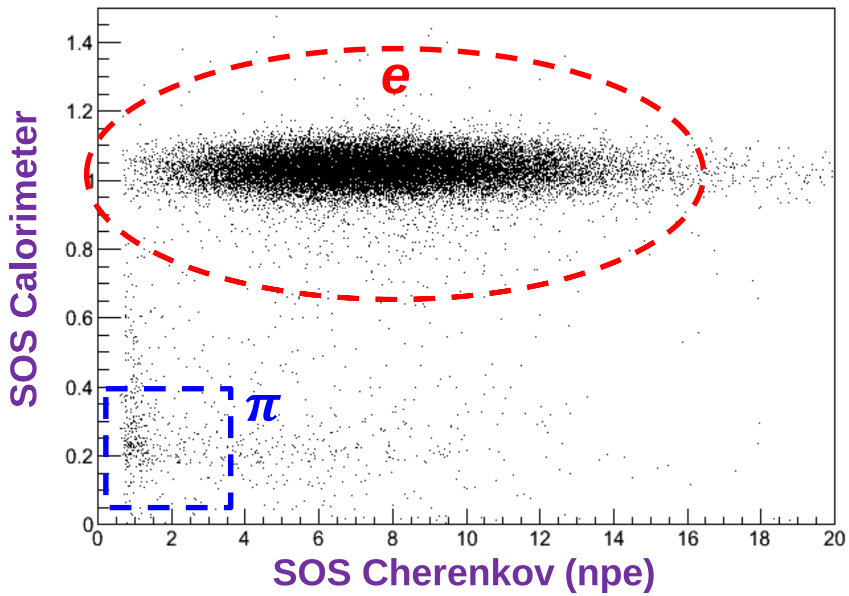
HMS detector (focal plane) layout, SOS is very similar

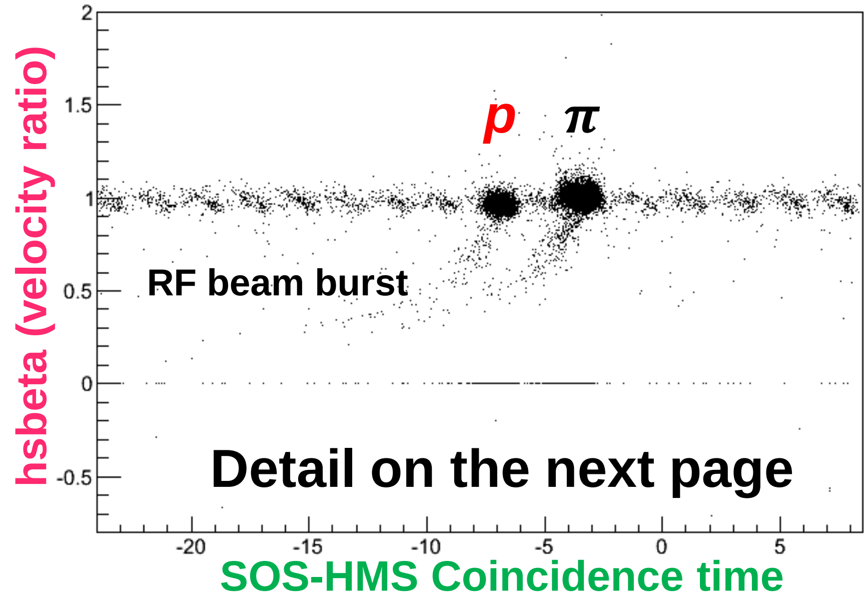
Trigger: 3/4 planes of Hodoscopes





PID Cuts

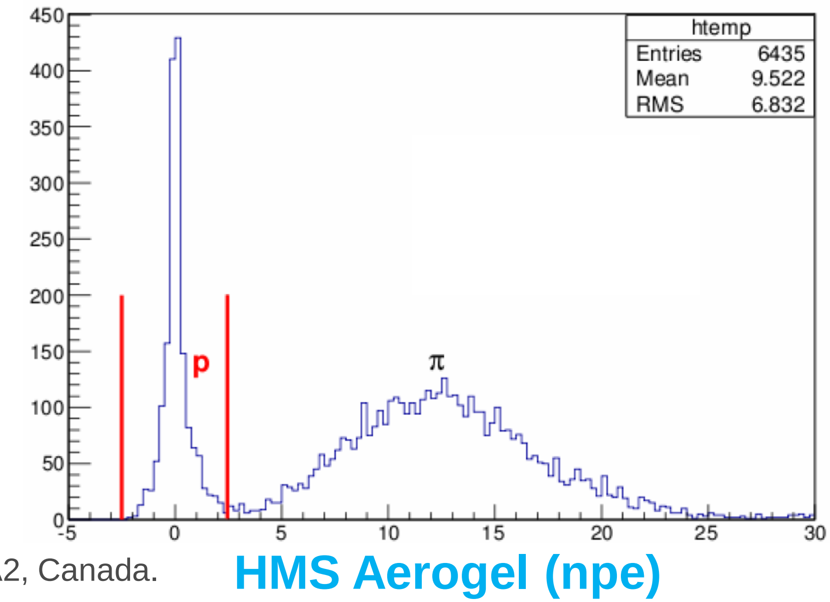




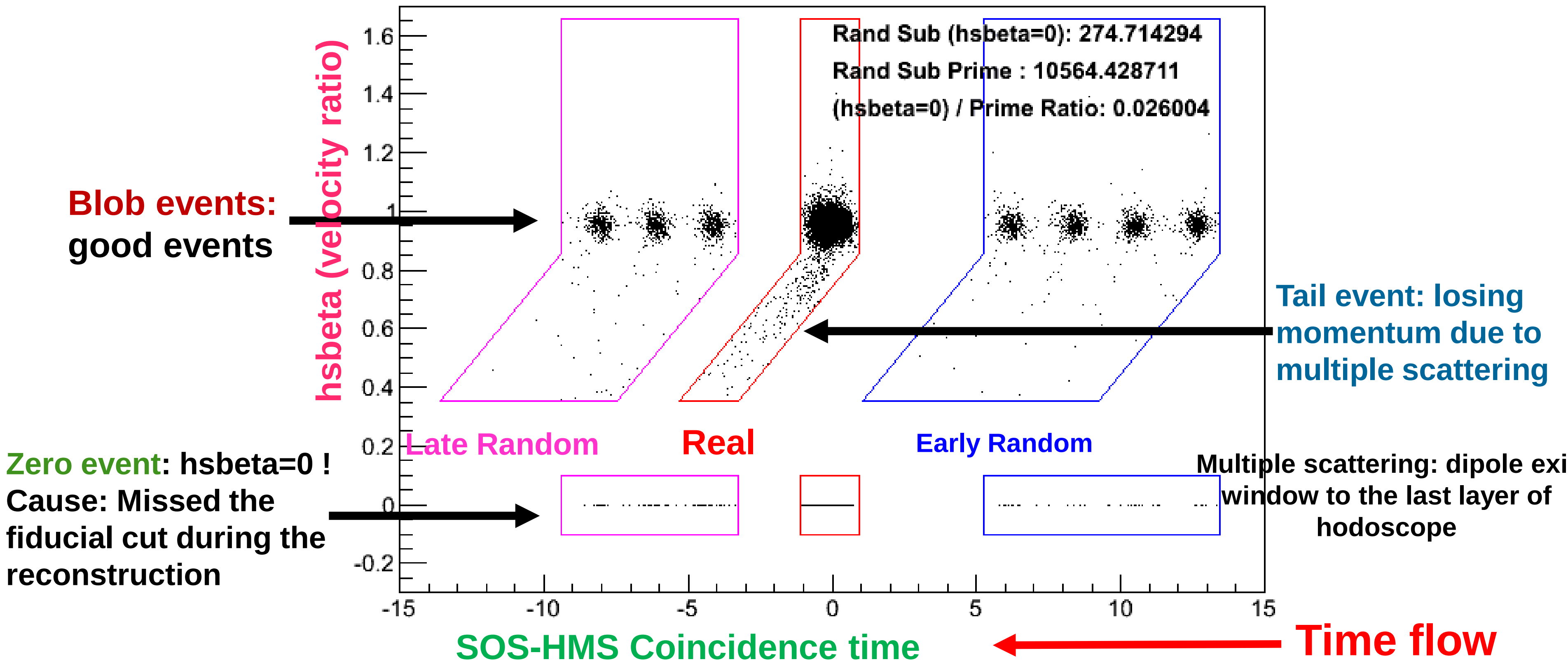
- SOS: select electron
  - **Calorimeter cut**
  - **Cherenkov cut**

99% efficiency

- HMS: select proton
  - **Coincidence timing cut**
  - **Hebeta (particle velocity)**
  - **Aerogel Cut**
  - **Cherenkov Cut: veto e^+**



Coincidence Subtraction

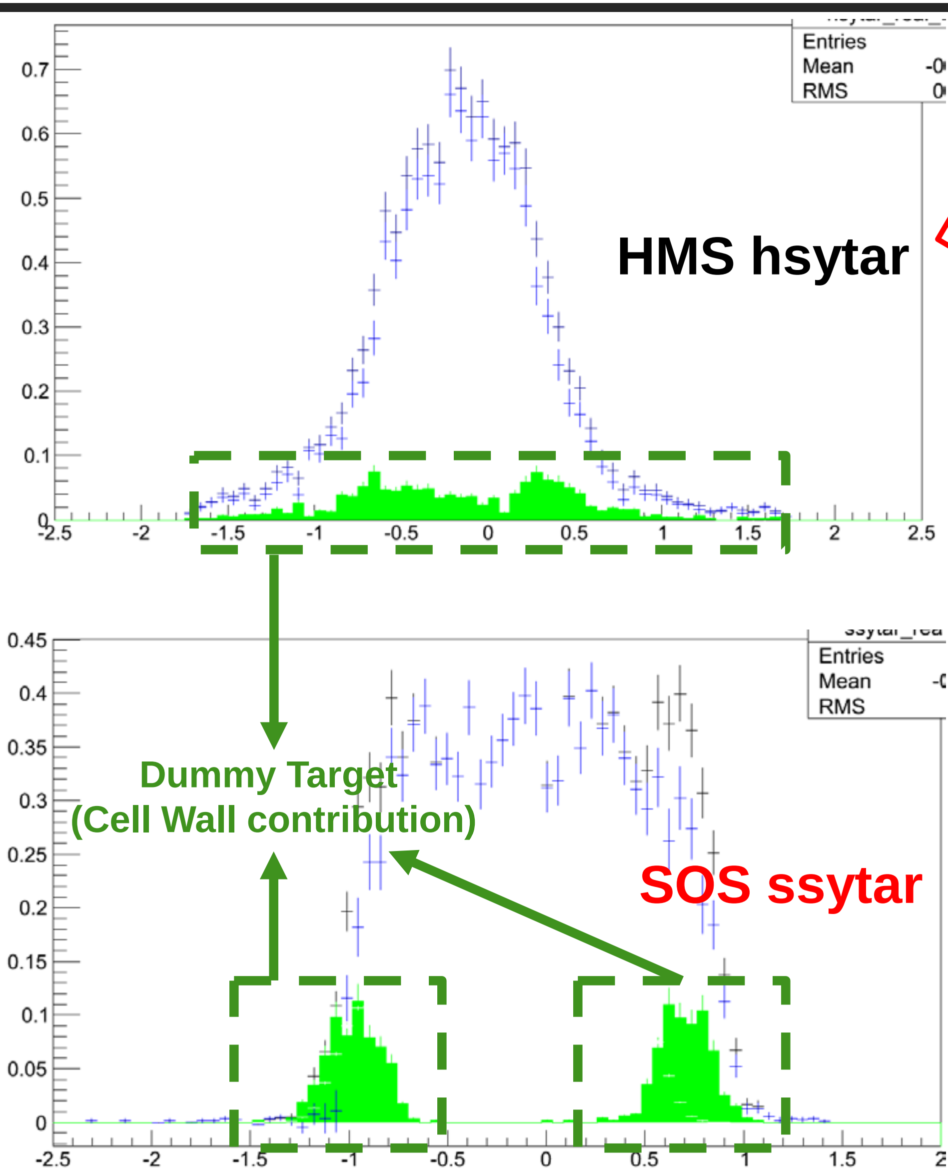


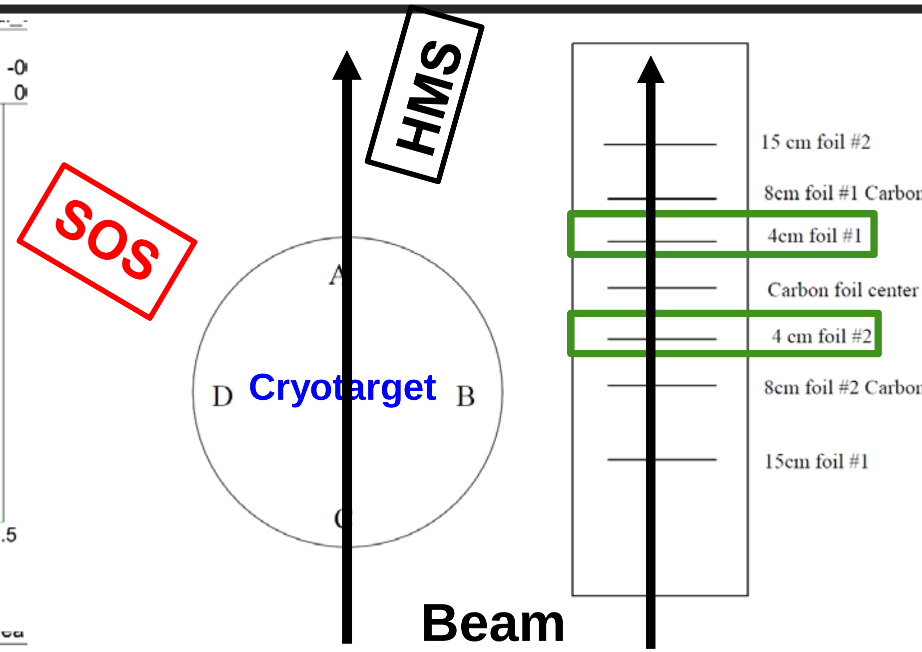
- **Random subtraction:**

$$\text{Coincidence proton} = \text{Real Events} - \left(\frac{\text{Late Random Events} + \text{Early Random Events}}{7}\right)$$

- **Missing proton due to scattering, absorption: ~7%**

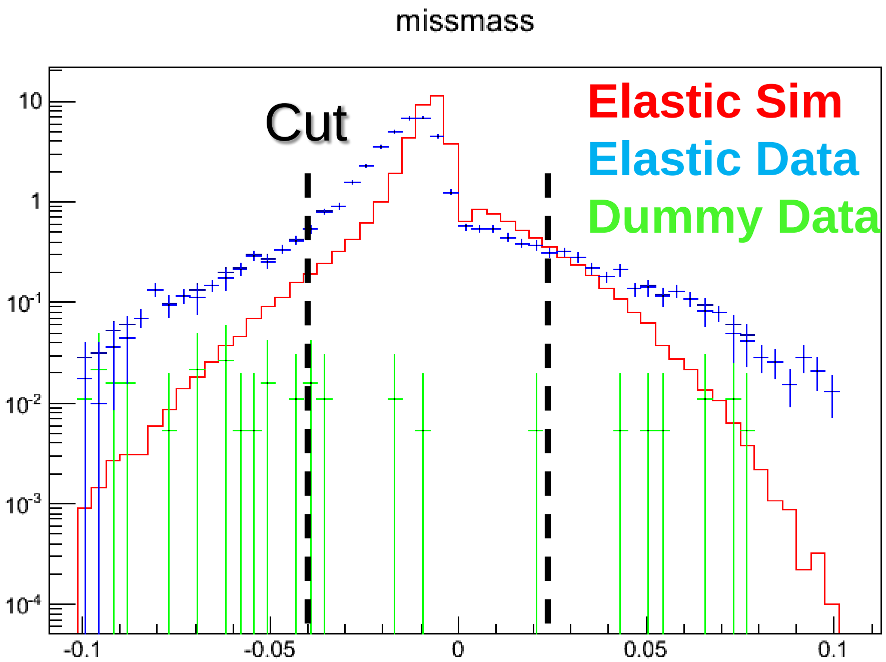
Dummy Subtraction

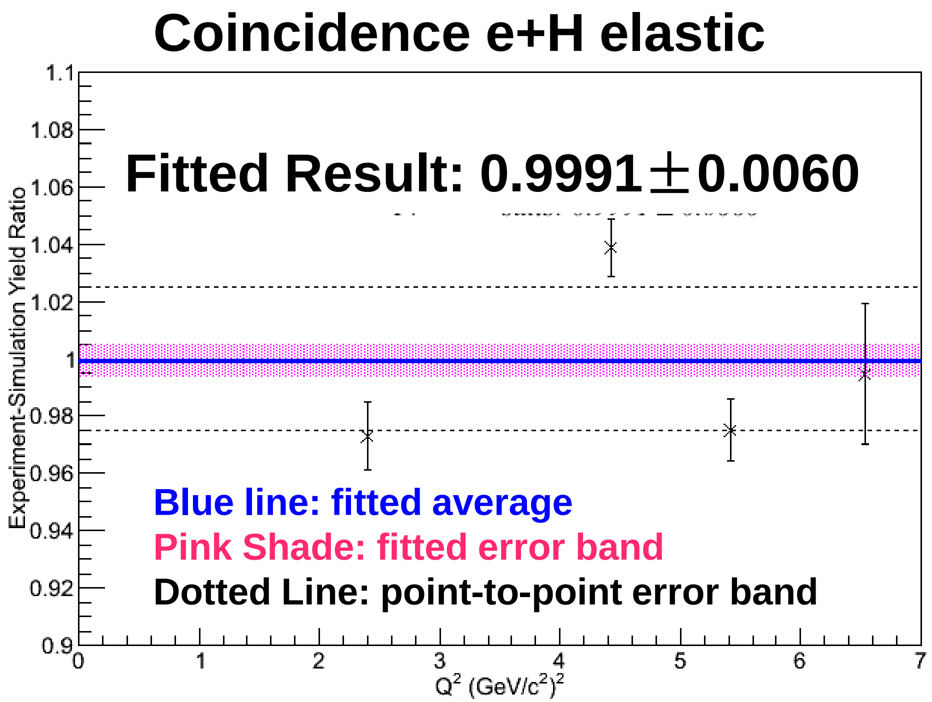




- **Cryotarget**
  - Tuna can shaped
  - With thin Al cell wall
- **Dummy Target**
  - 4cm apart Al sheets
  - Dummy target distribution is corrected for the real/dummy target thickness difference before subtracted from the real proton events

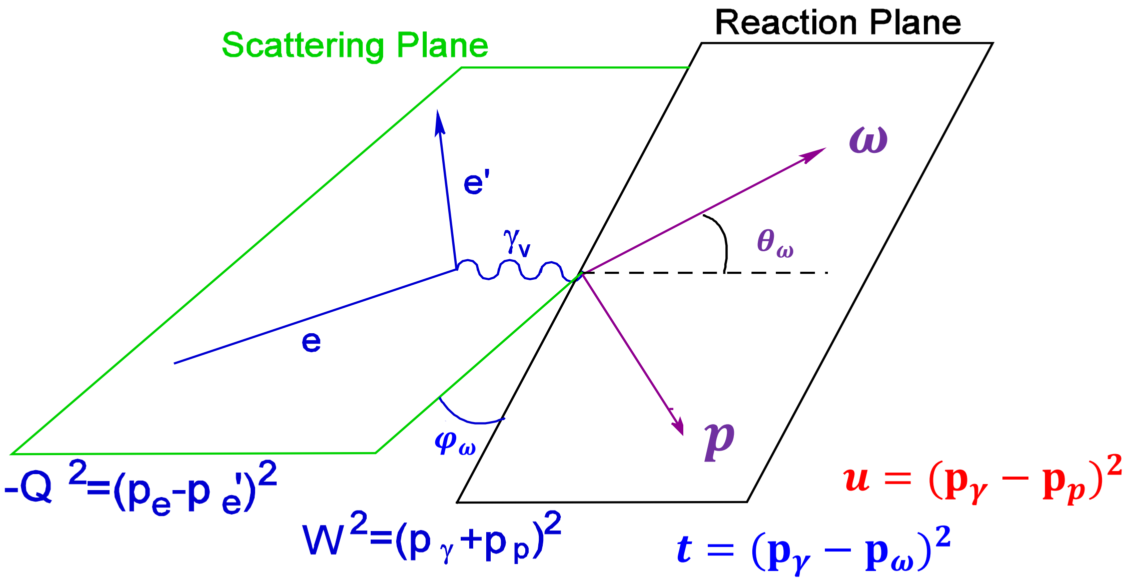
Analysis: e+H Elastic Cross-Section





- Extracted cross section is consistent with Bosted, AMT (Arrington, Melnitchouk, Tjon Phys. Rev. C 76, 035205 (2007)) and Brash empirical e-p elastic cross section parameters.
- ±2.0% (point to point) error from Heep will be included to the final Omega analysis systematics

Rosenbluth Separation



Virtual-photon polarization:

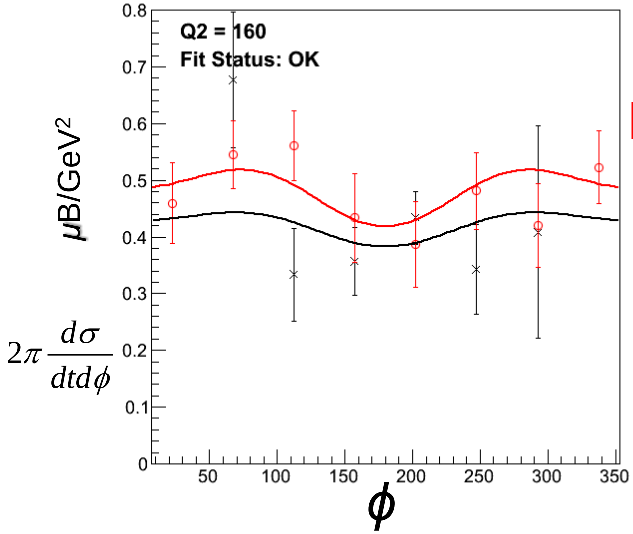
$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$

$$2\pi\frac{d\sigma}{dt\,d\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

- Rosenbluth Separation method requires
  - Separate measurements are taken at different ϵ (virtual photon polarization)
  - All Lorentz invariant physics quantities such as Q^2, *W, t, u*, remain constant
  - Beam energy, scattered e angle and virtual photon angle will change as the result, thus event rates are dramatically different

Separation Method

$$2\pi \frac{d\sigma}{dt d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$



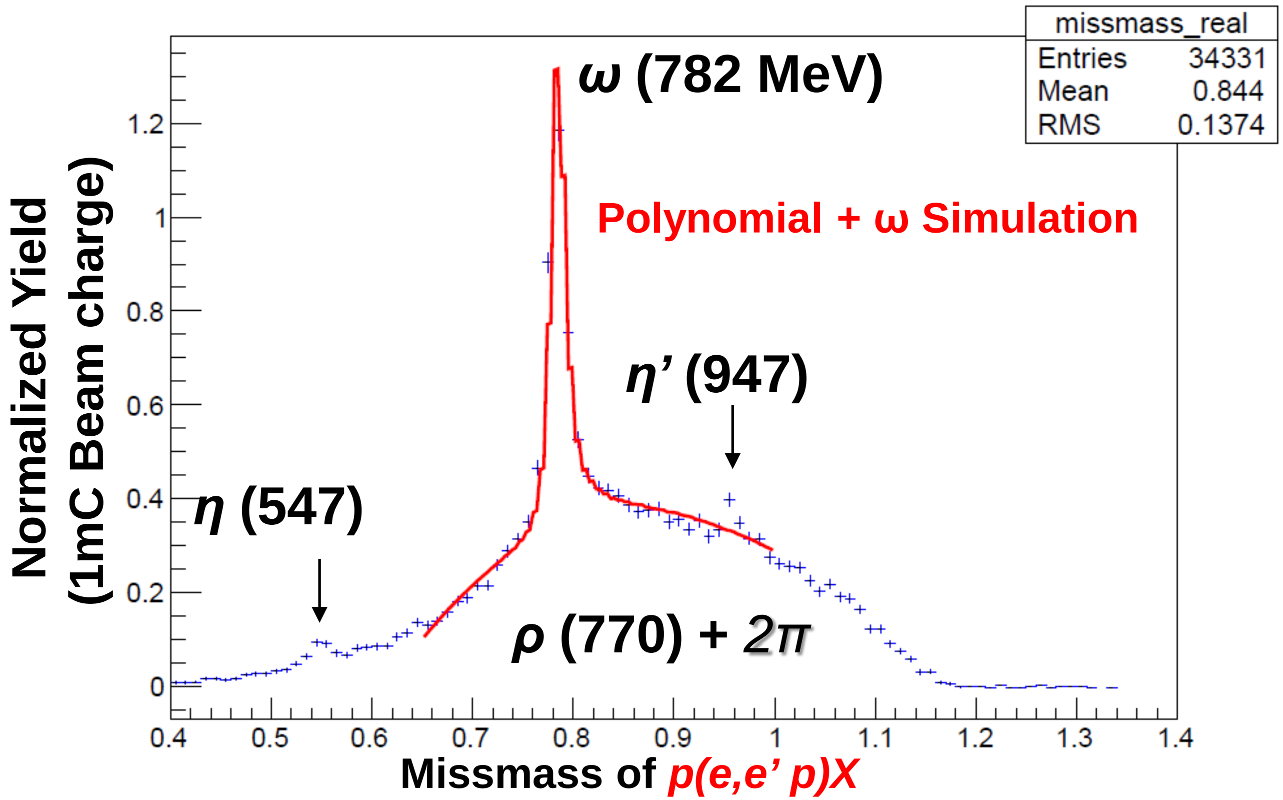
High ε=0.59

Low ε=0.33

E_{beam} GeV	P_{SOS} GeV/c	θ_{SOS} deg	ϵ	P_{HMS} MeV/c	θ_q deg	$\theta_{HMS}-\theta_q$ deg	x GeV/c	P_m deg	θ_{mq}	$-t$ GeV^2/c^2	$-u$ GeV^2/c^2
$Q^2_{nominal}$ = 1.6 GeV^2 $W_{nominal}$ = 2.21 GeV											
3.778	-0.79	43.09	0.328	-9.534	2931	−1.0	0.2855	0.311	9.17	4.014	0.087
						−3.0		0.367	24.59		0.129
4.702	-1.65	25.73	0.5933	-13.281	2931	0.0	0.2855	0.304	0.09	4.014	0.082
						2.7		0.357	22.93		0.121
						−3.0		0.367	24.61		0.129
$Q^2_{nominal}$ = 2.45 GeV^2 $W_{nominal}$ = 2.21 GeV											
4.210	-0.77	51.48	0.270	-9.190	3336	−1.4	0.3796	0.431	10.57	4.742	0.184
						−3.0		0.491	20.82		0.241
5.248	-1.74	29.43	0.554	-13.606	3336	0.0	0.3796	0.415	0.00	4.742	0.169
						−3.0		0.491	20.79		0.241
						3.0		0.490	20.75		0.240

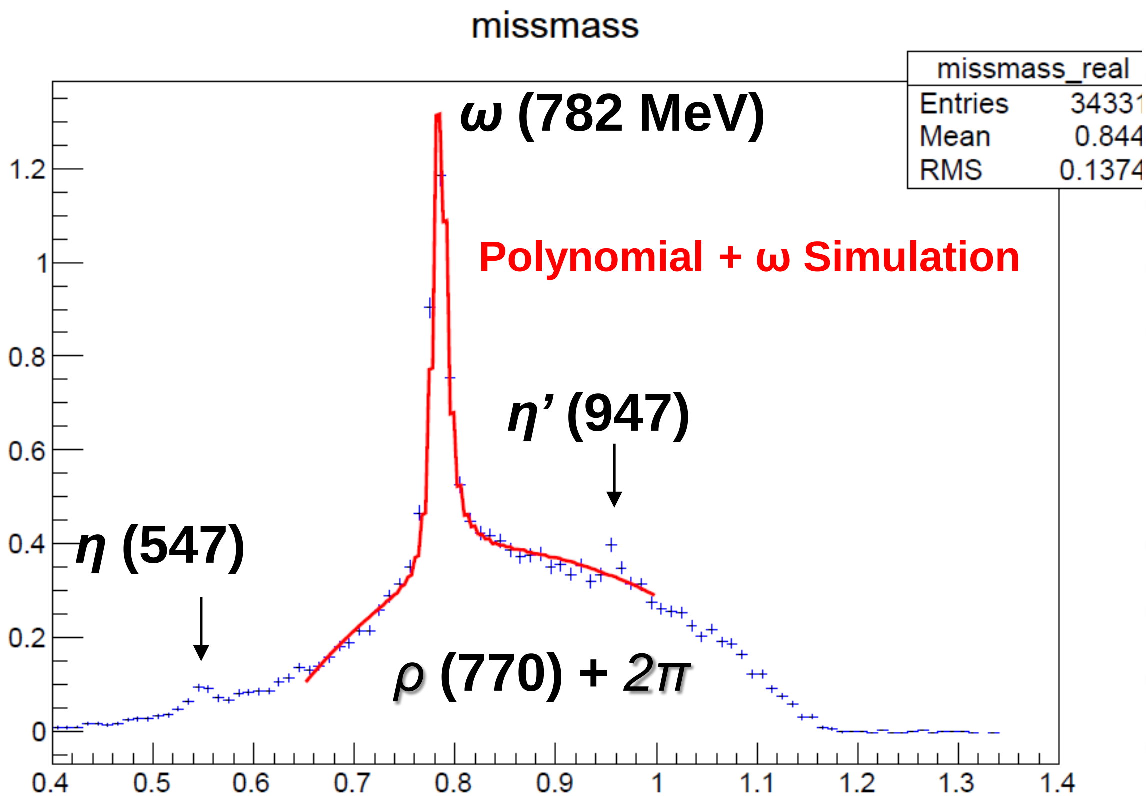
- **L/T separation**
  - Requires detailed comparison at high and low epsilon value
  - High and low epsilon runs involved
- **Simple L/T**
  - $\sigma_{total} = \sigma_T + \epsilon\sigma_L$
    - **Sig_L: difference**
    - **Sig_T: offset**
- ***H(e,e' p):***
  - Over constrained system
  - Determine detector offset
- **Exclusive channel!**
  - *p(e,e' p)ω*
  - We donot detect any part of decayed *ω*
  - Contain physics background

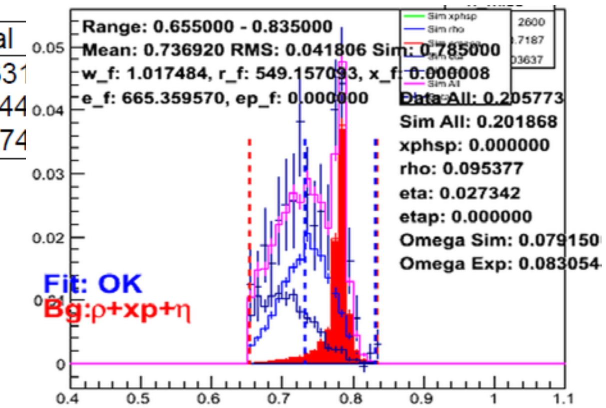
Proof: These are not Elastic Events!



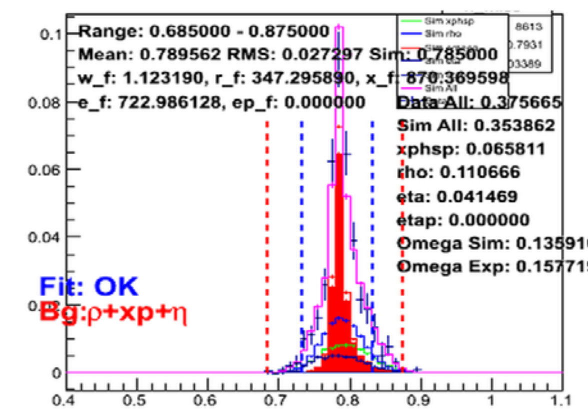
- **Good News!**
  - We see **other Scalar and Vector Mesons:** ***ρ, η, η' , two-π phasespace***
- **Bad News!**
  - Channel is **not clean**!
- **Worse News!**
  - **We can't use Polynomial fit !!**

Missing Mass Distribution

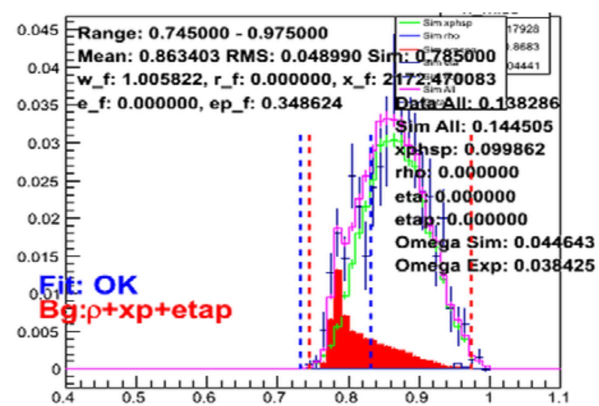




ω @ Right



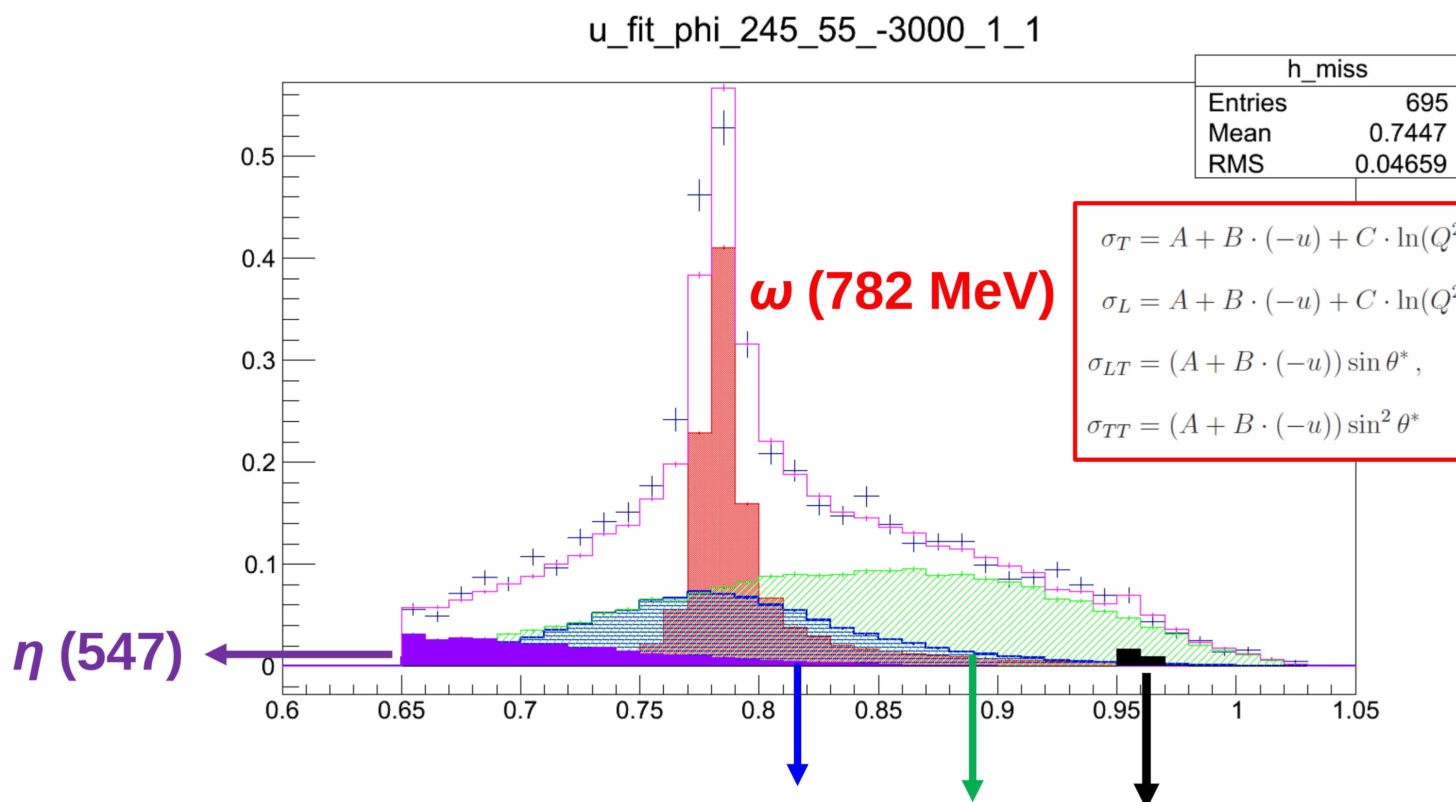
ω @ Center



ω @ Left

- **Most Challenging Issue: Background Subtraction!**
- **Omega is not always in the center**
- **Four sets of Monte-Carlo is used fit the data**
  - ***ω + ρ +* Phase-space + *η or η'***

Physics Background Subtraction



$$\sigma_T = A + B \cdot (-u) + C \cdot \ln(Q^2) + D \cdot (-u) \cdot \ln(Q^2)\,,$$

$$\sigma_L = A + B \cdot (-u) + C \cdot \ln(Q^2) + D \cdot (-u) \cdot \ln(Q^2)\,,$$

$$\sigma_{LT} = (A + B \cdot (-u)) \sin\theta^*\,,$$

$$\sigma_{TT} = (A + B \cdot (-u)) \sin^2\theta^*$$

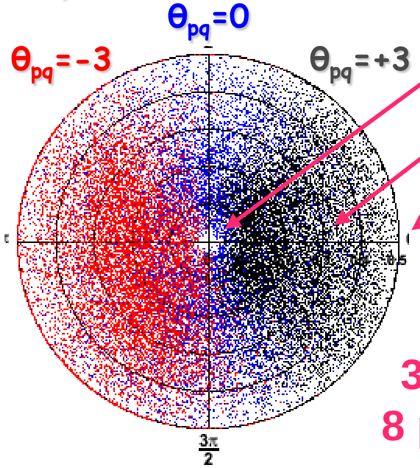
ρ (770) + 2π

HERMES
Imperial parameterization
with Soding factor

η' (947)
Width from PDG with
Ae^{-Bu} dependence

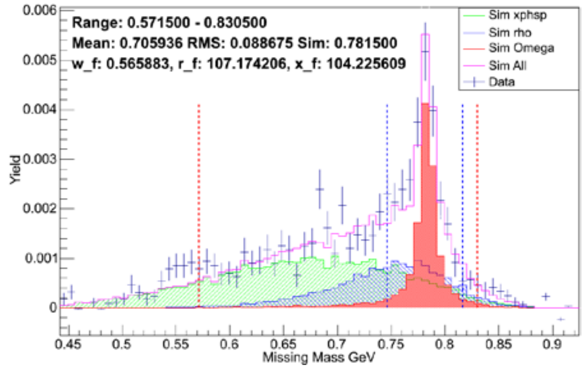
Iterative Procedure (Recipe) to A Full LT Separation

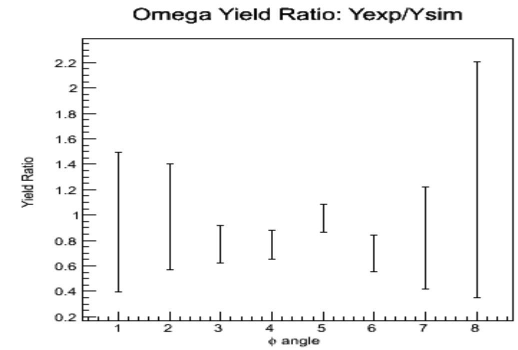
Improve φ coverage by taking data at multiple HMS angles, $-3^o<\theta_{pq}<+3^o$.



3 u bins
8 phi bins

Background Subtraction





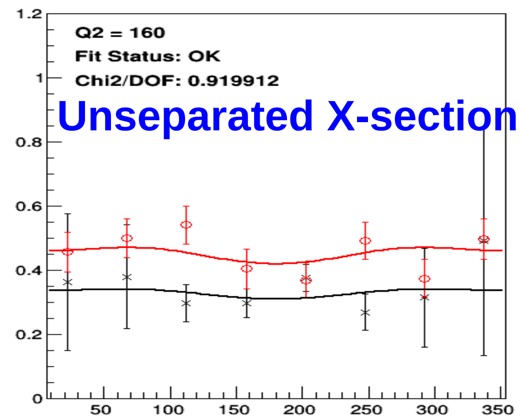
For each HMS setting, form ratio:

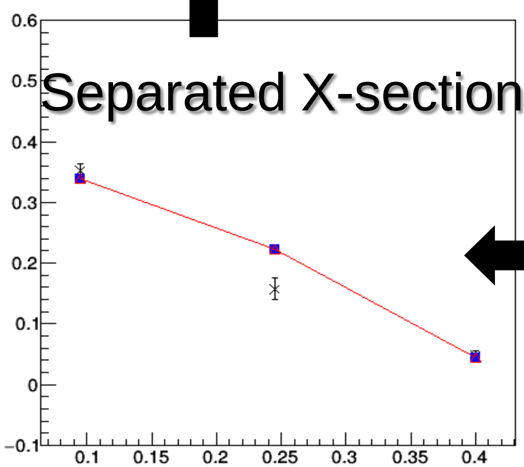
$$R = \frac{Y_{Exp} - Y_{\rho\ \mathrm{sim}} - Y_{Xspace\ \mathrm{sim}} - Y_{\eta\ \mathrm{sim}}}{Y_{\omega\ \mathrm{sim}}}$$

Combine ratios for settings together, propagating errors accordingly.

$$\frac{d^2\sigma}{dtd\varphi}_{EXP} = R\,\frac{d^2\sigma}{dtd\varphi}_{SIMC}$$

Empirical Model

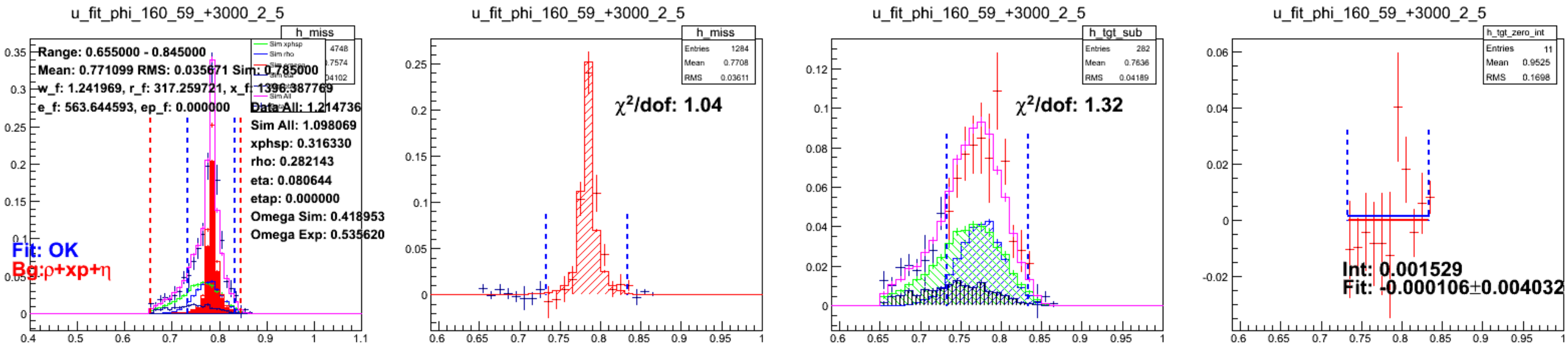




Extract **T, L, LT, TT** via simultaneous fit

$$2\pi\frac{d\sigma}{dtd\phi} = \frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Missing Mass Distribution Background Extraction



Omega

Background Sum

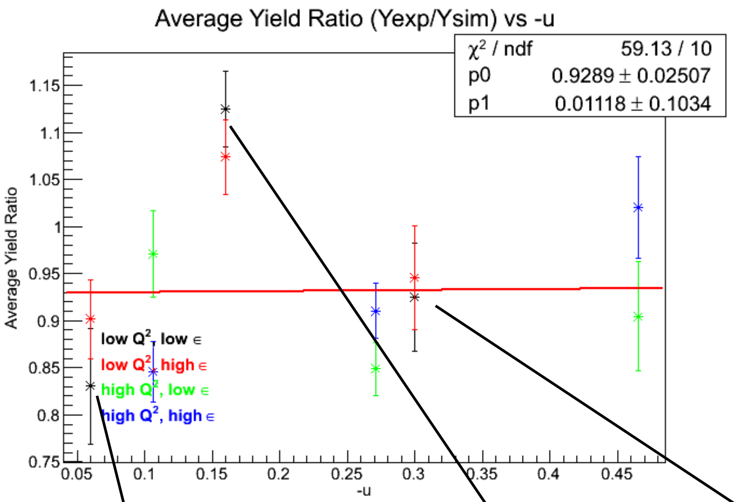
Zero= Data – Omega- Bg

Data (blue point)
Xspace Sim (green)
ρ Sim (light blue)
ω Sim (red)
η or η' (black)
Simulation Sum (pink)

$$R = \frac{Y_{Exp} - Y_{\rho\ \mathrm{sim}} - Y_{Xspace\ \mathrm{sim}} - Y_{\eta\ \mathrm{sim}}}{Y_{\omega\ \mathrm{sim}}}$$

- **Fitting Limits (red dashed line):**
  - **Not fixed, fit 95% data distribution**
- **Integration Limits (blue dashed line):**
  - **Fixed for all u-phi bins!**
- **Bin Exclusion criteria:**
  - **Radiative tail exceeds 50% total ω sim**
  - **Less that 100 raw counts**

Yield Ratio and Simulated Cross-Section



$$\sigma_T = A + B \cdot (-u) + C \cdot \ln(Q^2) + D \cdot (-u) \cdot \ln(Q^2)\,,$$

$$\sigma_L = A + B \cdot (-u) + C \cdot \ln(Q^2) + D \cdot (-u) \cdot \ln(Q^2)\,,$$

$$\sigma_{LT} = (A + B \cdot (-u)) \sin\theta^*\,,$$

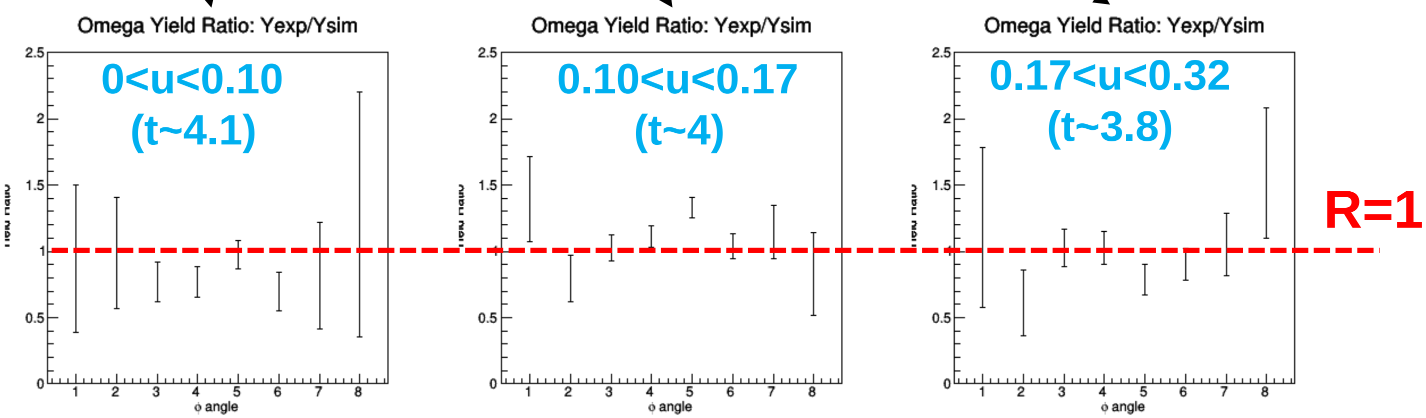
$$\sigma_{TT} = (A + B \cdot (-u)) \sin^2\theta^*$$

$$2\pi \frac{d\sigma}{dt\,d\phi} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Model Cross Section

$$\left.\frac{d^2\sigma}{dt\,d\varphi}\right._{EXP} = R \left.\frac{d^2\sigma}{dt\,d\varphi}\right._{SIMC}$$

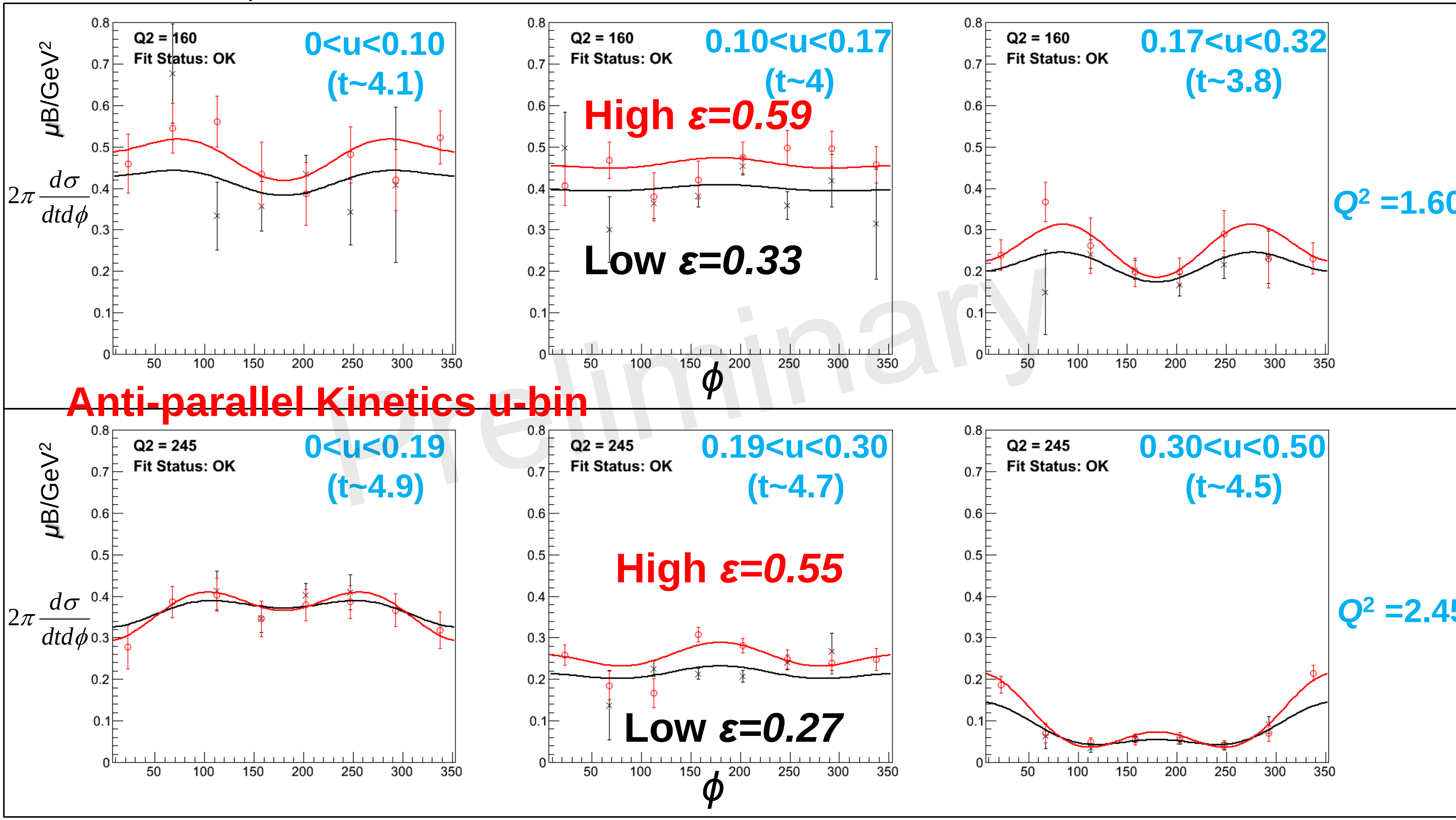
Exp/Sim Yield Ratio



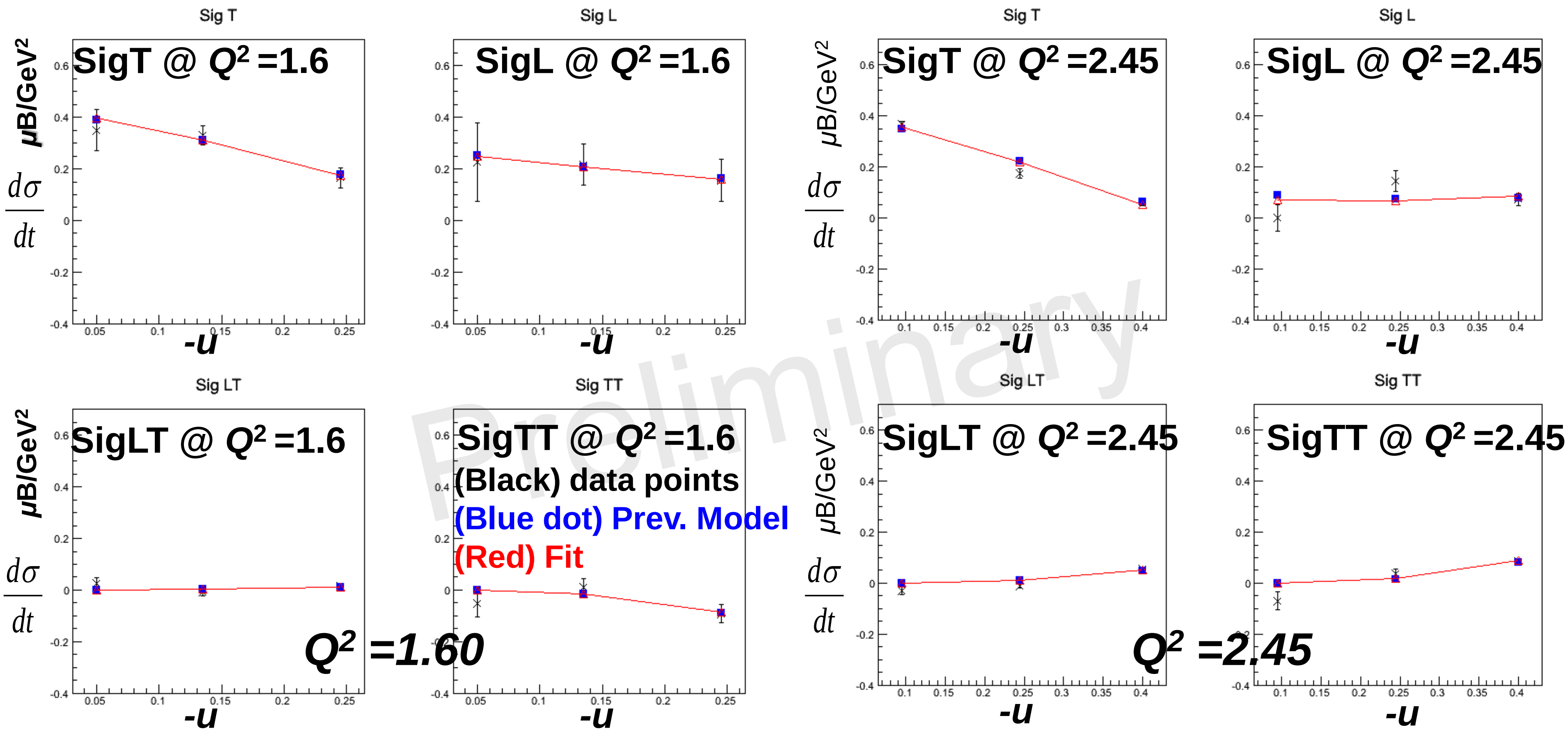
Q^2=1.6, Low *ε=0.33*

Unseparated Cross Section (Money Plot)

$$2\pi \frac{d\sigma}{dt\,d\phi} = \frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

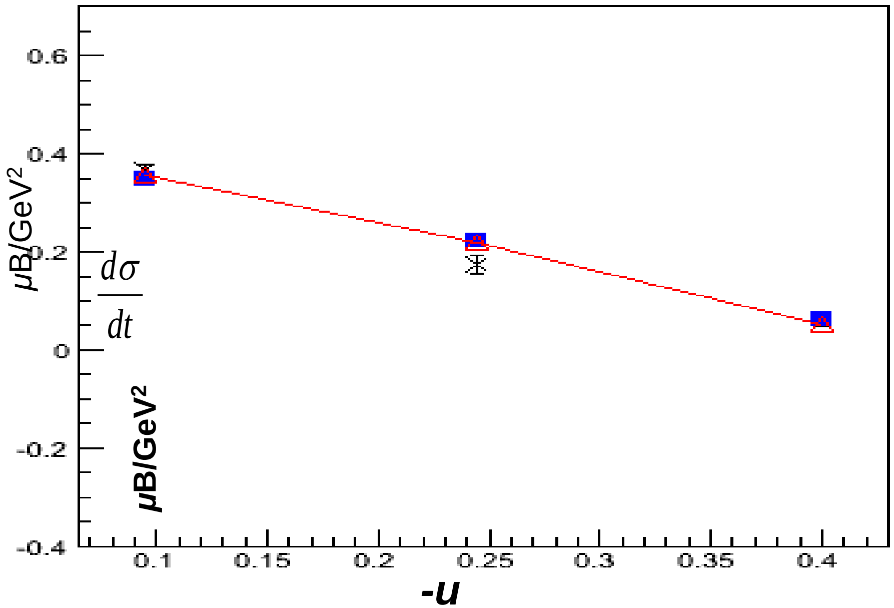


Separated Cross Section

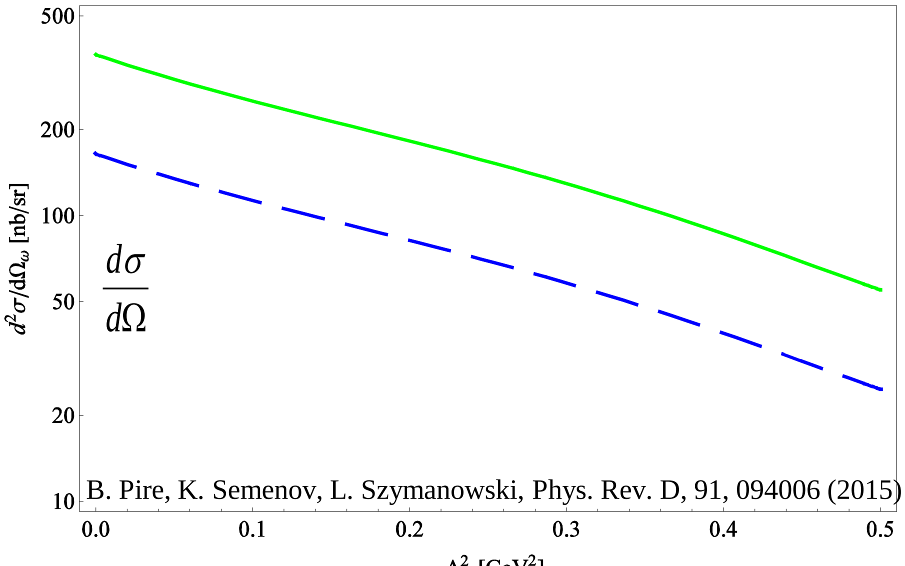


- **Observations:**
  - **SigT dominate SigL at 2.45 at u~0: validated the TDA prediction ($\sigma_T > \sigma_L$) for Q^2 =2.45**
  - **SigT behave differently at different Q^2.**
  - **LT and TT are small**

TDA Prediction (Private Communication)



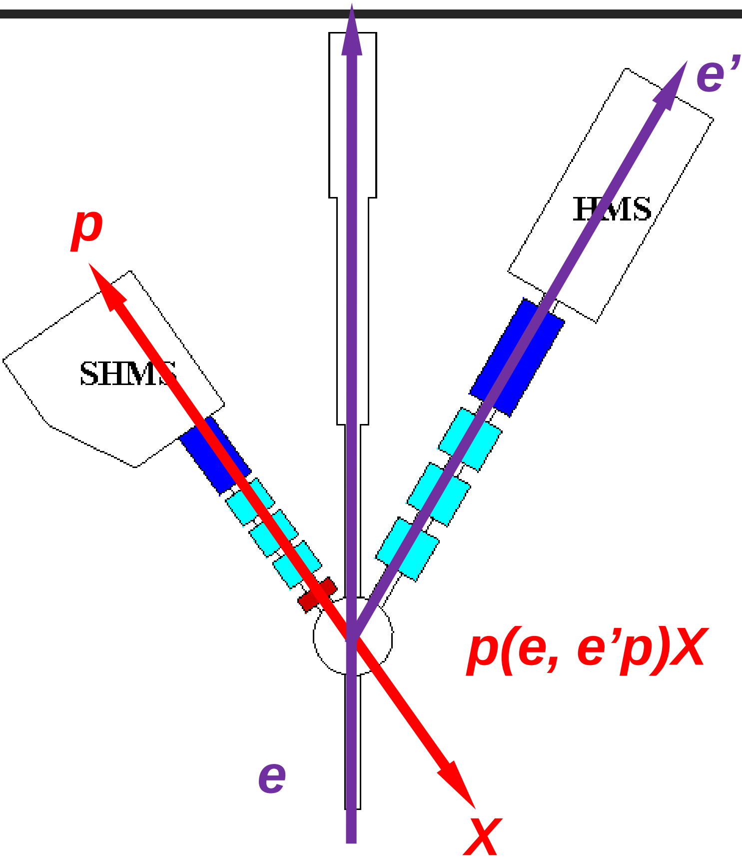
- Top: separated cross section at W=2.21,Q^2=2.45

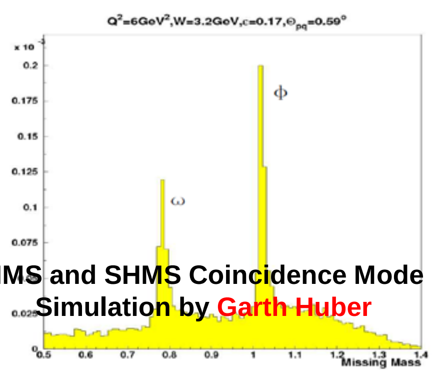


B. Pire, K. Semenov, L. Szymanowski, Phys. Rev. D, 91, 094006 (2015)

- Bottom:TDA calculation for cross section at W=2.21 Q^2=2.45 (private communication)

Future Backward Meson Production Opportunities





HMS and SHMS Coincidence Mode Simulation by Garth Huber

- Potential LOI (2018):
  - **Backward π^0** production at Hall C.
- Other extreme forward angle physics program
  - Some u-channel ω data from 6 GeV Era
  - 12 GeV Commissioning experiment at Hall C include Kaon Form Factor experiments.
- Fpi 12 experiment (for free)
  - η, η', ω, $\phi(s\bar{s})$, ρ
  - ω, $\phi(s\bar{s})$ production ratio would yield valuable information.

Thank You

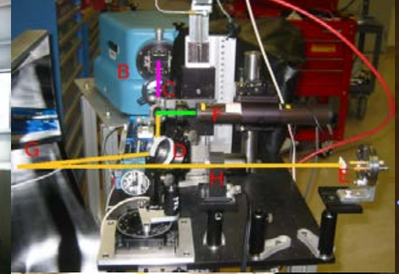
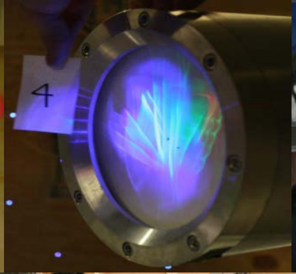
- **Greatest gratitude to the TDA group providing the calculation to fit our data and inspiring inputs from Christian Weiss. Valuable comments from Kijun Park were very important during analysis.**

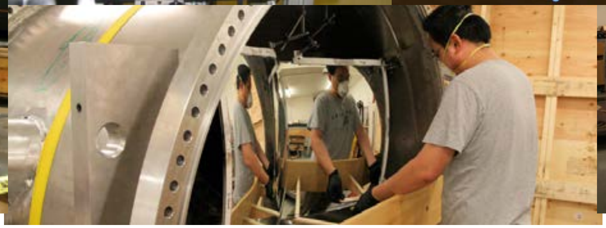
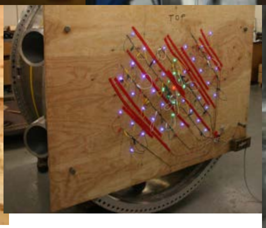
- **Data Nturple were generated by Tanja Horn, Great work**

- **Many thanks to my graduate student colleagues**

- **Fantastic support from colleagues, staff scientist and technicians from Regina and Jefferson Lab**

- **Special thanks to my wife: Noemi Ochoa Gamboa**

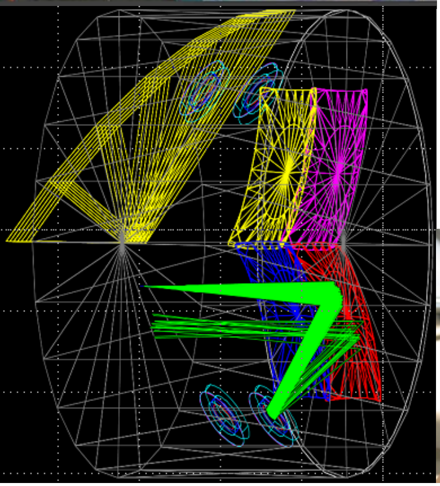
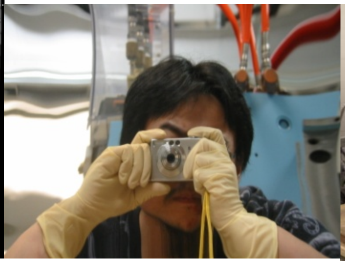




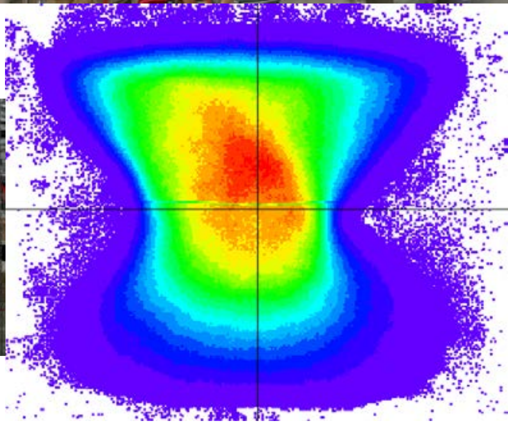





Heavy Gas Cherenkov Detector, My contributions to the 12 GeV upgrade


NSERC CRSNG

Jefferson Lab

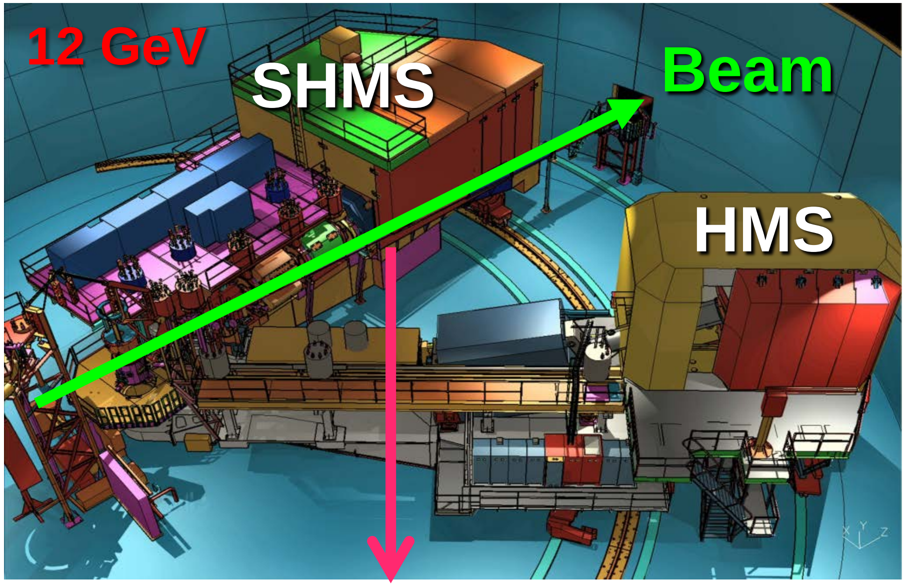



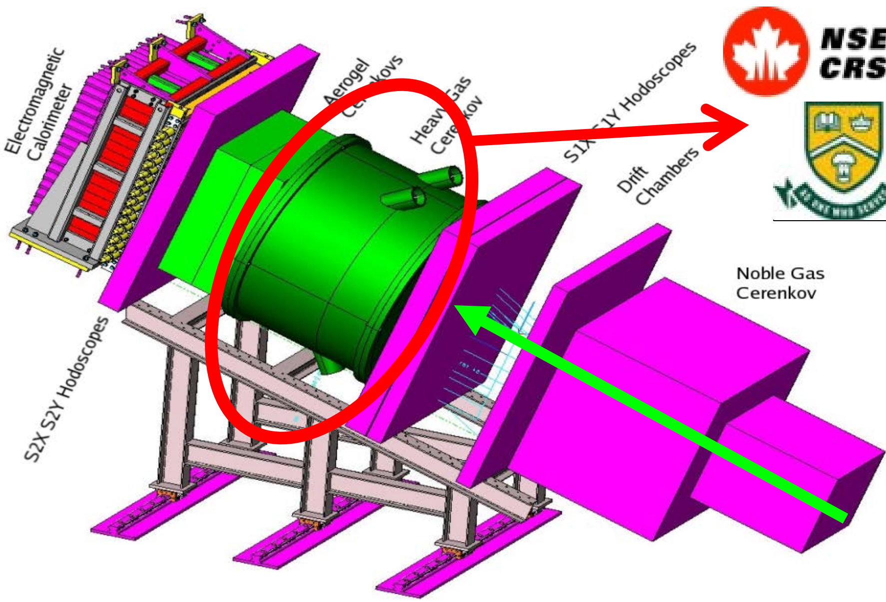



Department Seminar, October 16, 2015.

Wenliang Li, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.

Hall C Configuration

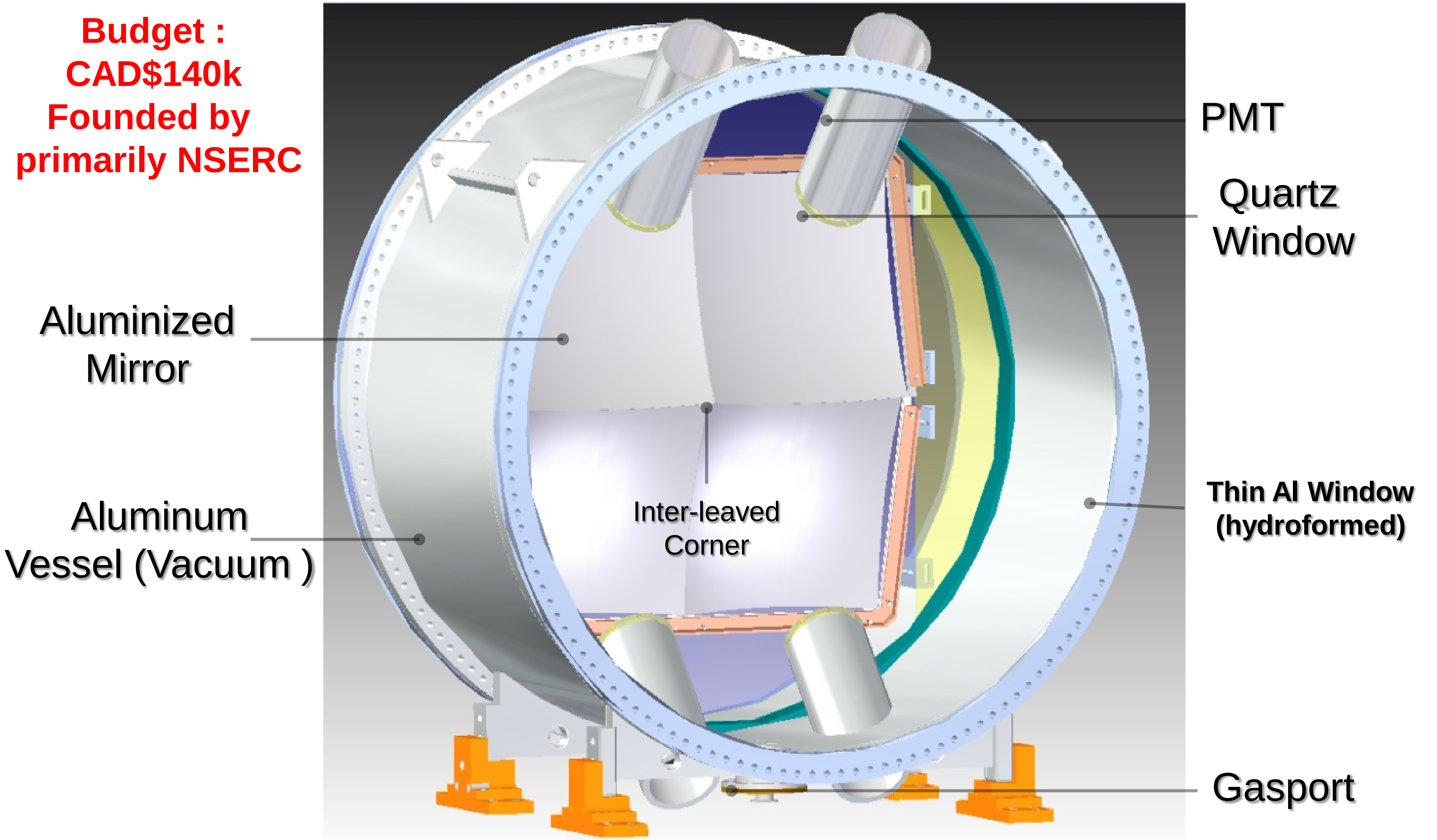




- **Noble Gas Cerenkov Detector**
  - e/π separation at high momentum.
- **Wire-chamber (Focal point)**
  - Momentum Determination
- **Hodoscopes**
  - Trigger
- **Heavy Gas Cherenkov Detector**
  - π/K separation for p>3.4 GeV/c.
- **Aerogel Cerenkov Detector**
  - Depending on material K/p separation or π/K at low momentum.
- **Lead Glass Calorimeter**
  - e/π Separation

Detector Design

Budget : CAD$140k Founded by primarily NSERC



My Role on the detector R&D projects

- Only graduate student on the.
  - **Good**: complete exposure to a successful detector R&D project. Involvement at every single stage of the project. Interact and learn from other experts/technicians. Share responsibility which is unusual for a master student.

- **Helping with project management:** making manufactural inquiries, double checking blue prints and budgets. Help keeping track of project schedule. Jump through administrative and safety red tapes. **(2010-2013)**

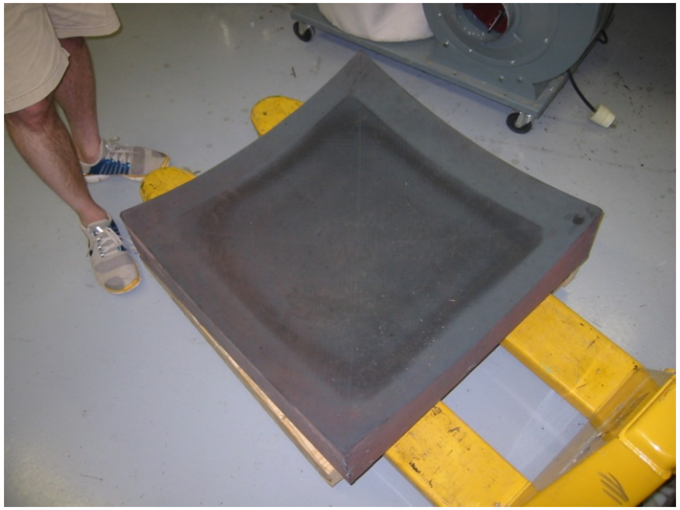
- **Complete variety of sub projects R&D (2010-2013)**

- **Software simulation**: developing and maintaining the detector Geant4 simulation to simulate detector performance. **(2010-present)**

- **Retired from R&D front line, tutoring summer and new students (2014-present).**

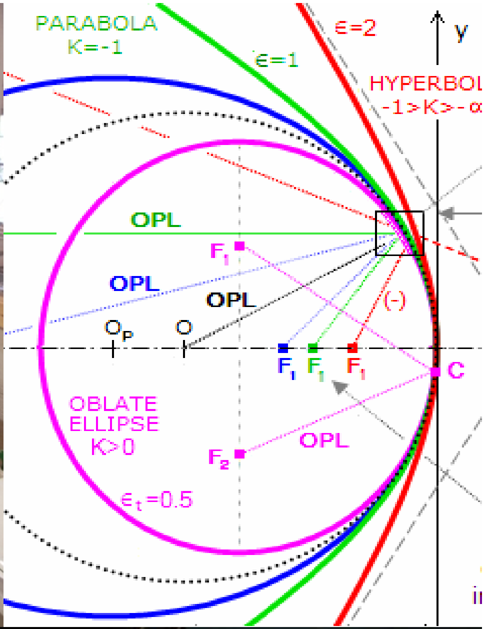
- **Listed as the HGC detector expert for Hall C (carry unique responsibility).**

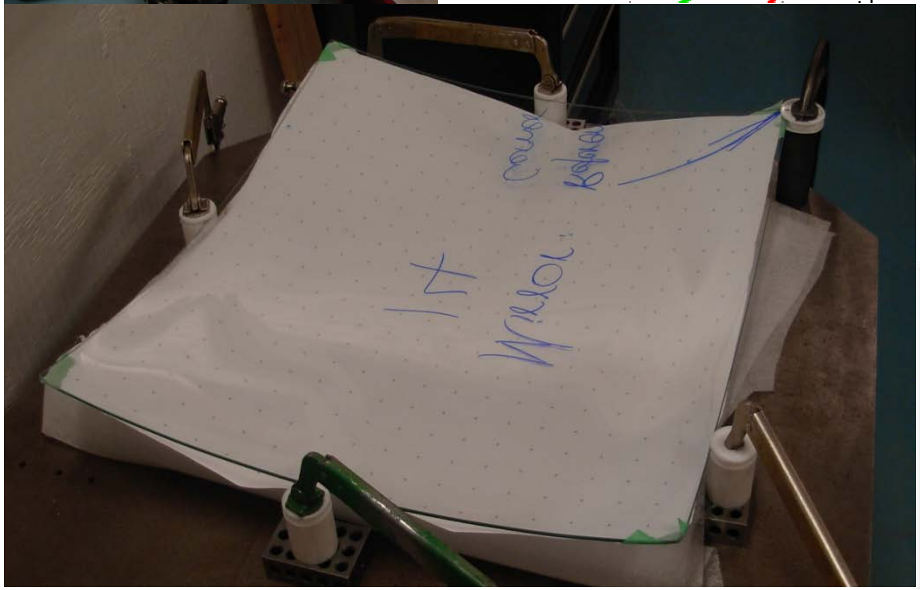
Sub Project 1: Mirrors



- Slumping Glass Technique:
  - Machine a metal mold
  - Place pre-cut glass onto the mold
  - Place mold into the oven
  - Glass gradually slumps to the mold curvature
- Select the best mirrors for the HGC detector
- 15 mirrors ordered

Sub Project 1: Mirror Selection





- Classification of curvature using telescope equation:

$$z = \frac{(x - x_{off})^2 + (y - y_{off})^2}{R + \sqrt{R^2 - (1-\kappa)[(x - x_{off})^2 + (y - y_{off})^2]}} + z_{off}$$

***R*: Radius of Curvature**

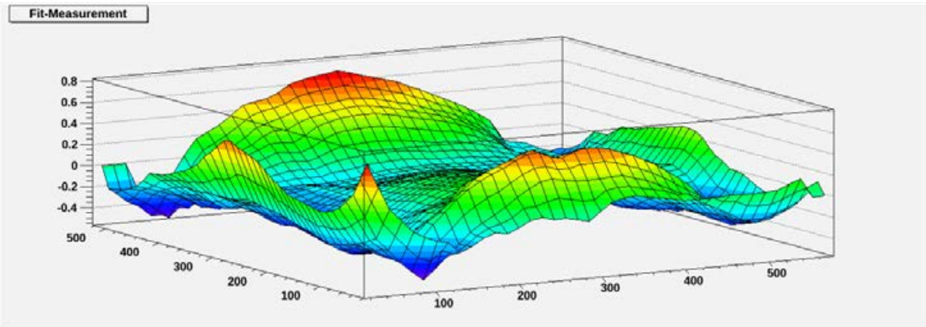
***K*: Conic Constant**

K = 0: Sphere

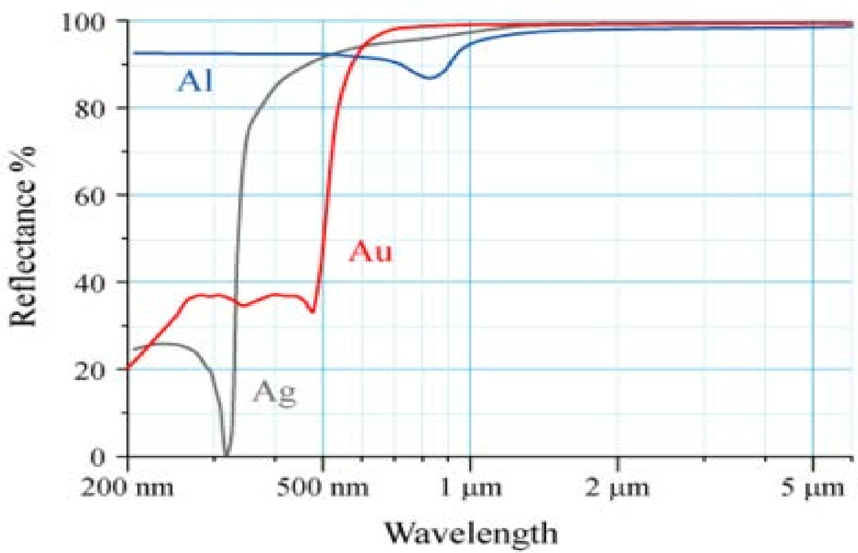
K < 0: Prolate Ellipsoid

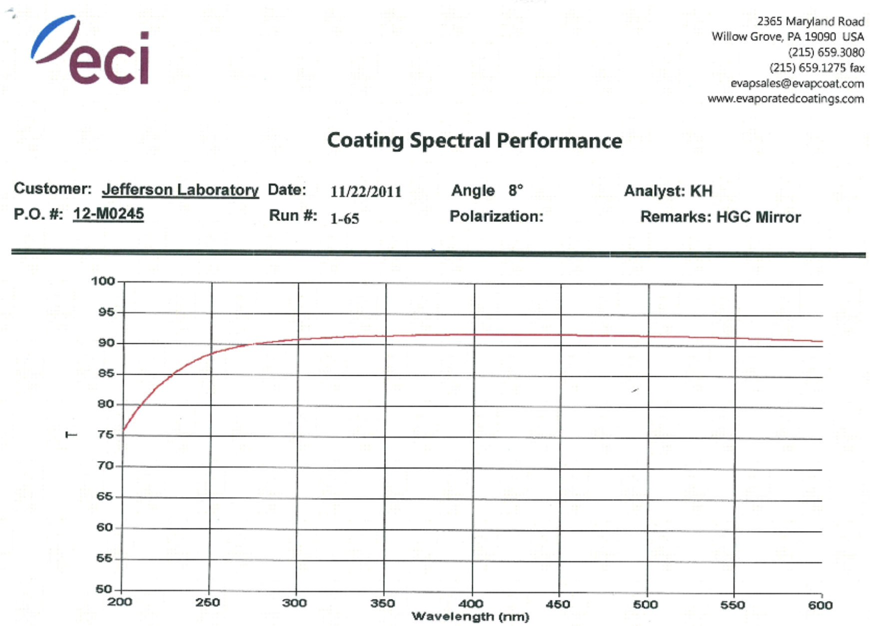
K > 0: Oblate Ellipsoid

- Mirrors are classified based on their fitted *R* and ***K*** values
- Difference between fit and real mirror measurement is along *the edges and corners*



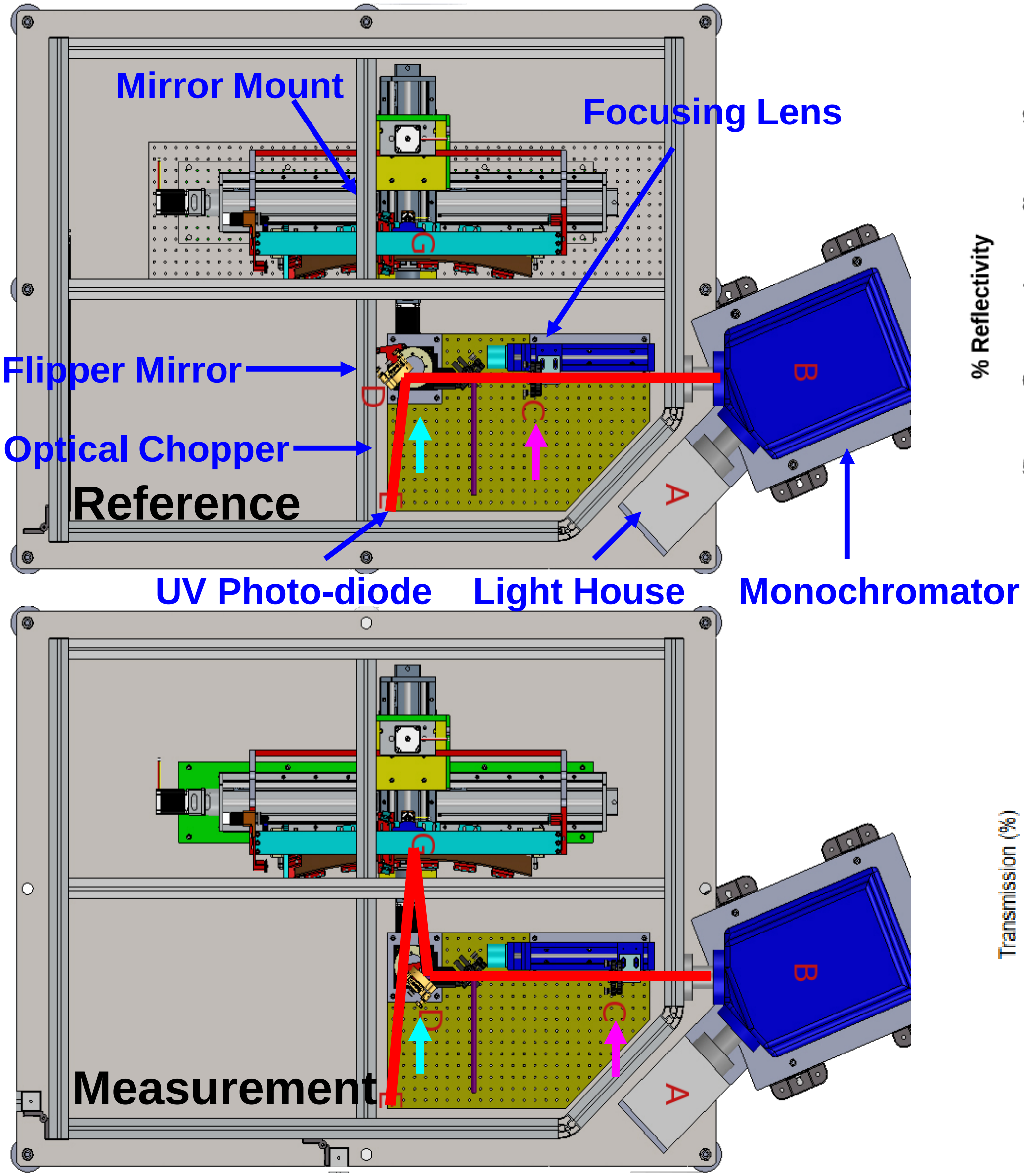
Sub Project 2: Mirror Aluminization Reflectivity

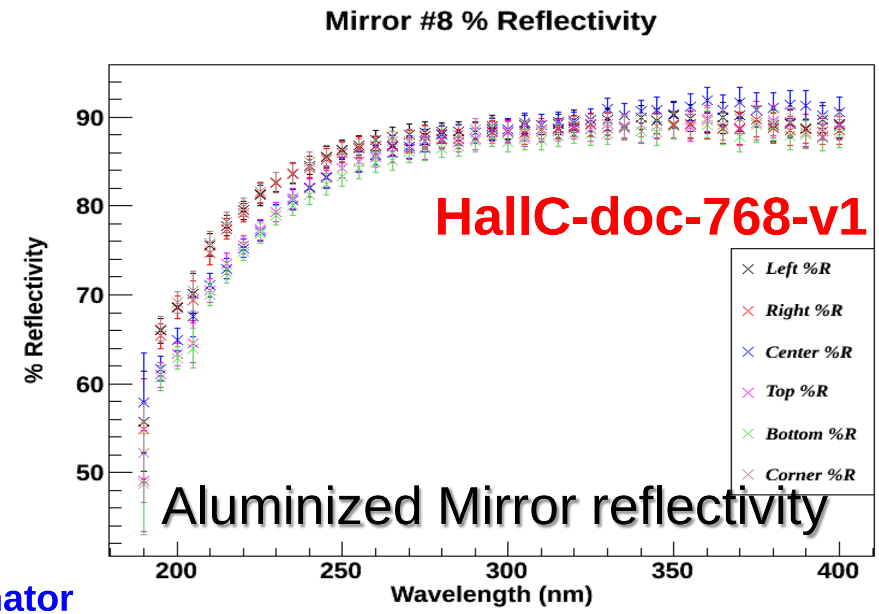


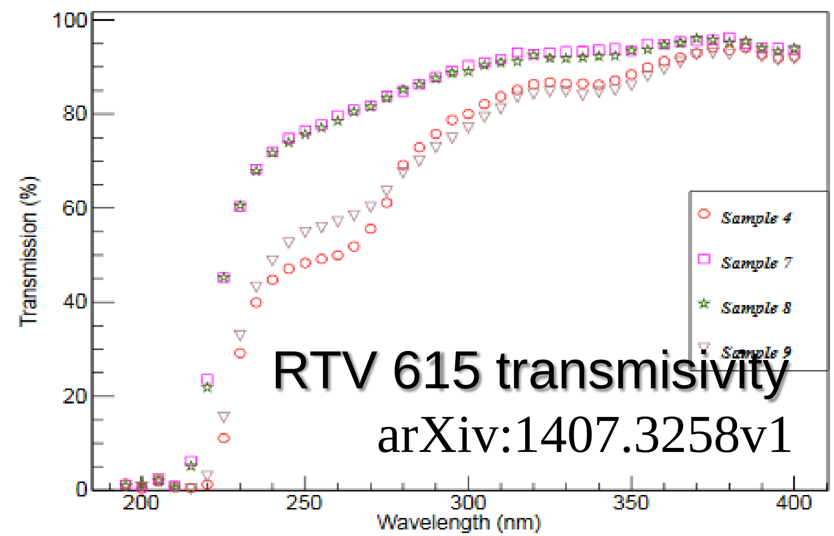


- Why Aluminization?
- Manufacture choices:
  - @ Cern: $5000/piece
  - @ ECI: $4000/lot (6 mirrors)
- Generated Cherenkov photon wavelength
  - 180-600 nm
- Mirror reflectivity setup @ Jefferson Lab were used
- Aluminized mirror requirement
  - 70% Reflectivity @ 200nm
  - 90% Reflectivity @ 300nm

Sub Project 2: Reflectivity Setup

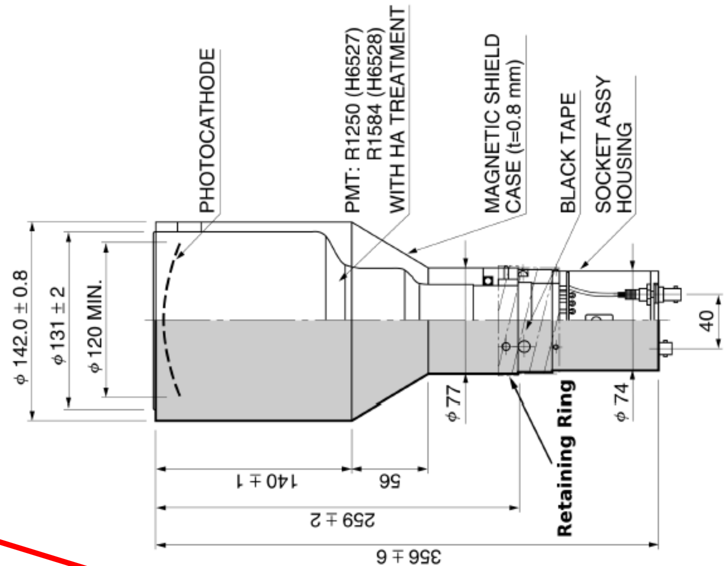


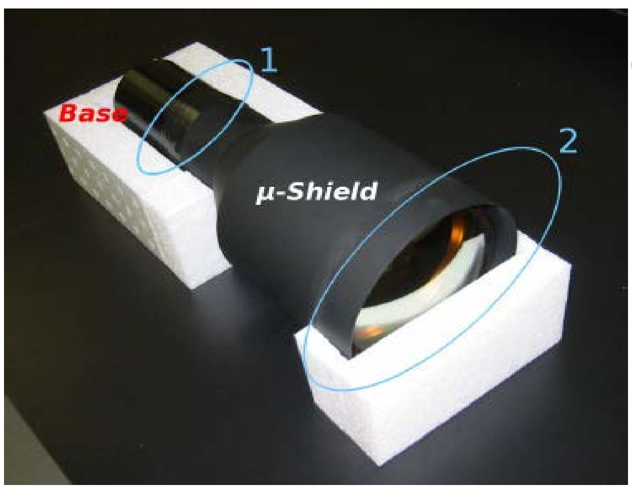


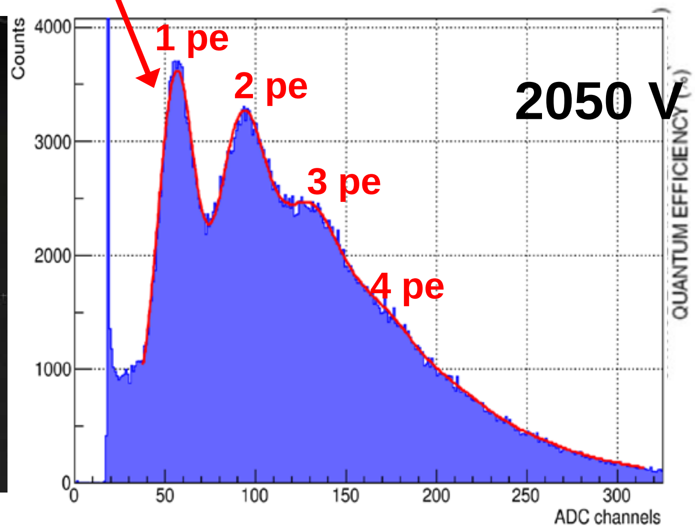


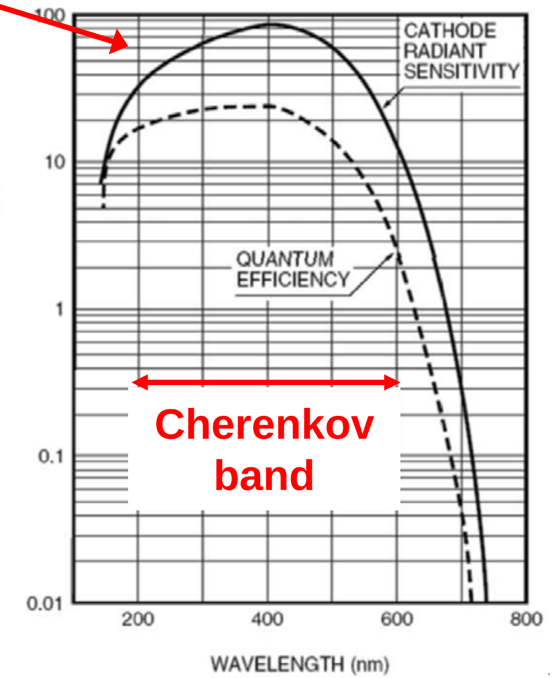
Sub Project 3: PMTs

- **Basic working principle**
  - Photoelectric effect: convert photon to analog signa
  - Widely used by Particle physics detectors for many years: hodoscopes, calorimeters, etc
- **Hamamatsu 5” PMT**
  - Cost: $4400 each (2009); over $10k (now)
  - Recommended Voltage: -3000 V
  - **Good**:
    - High cathod sensitivity, constraint on quantum efficiency
    - Good photon electron resolution
  - **Bad:**
    - **Come with some wired problem! Discharge and Ringing**

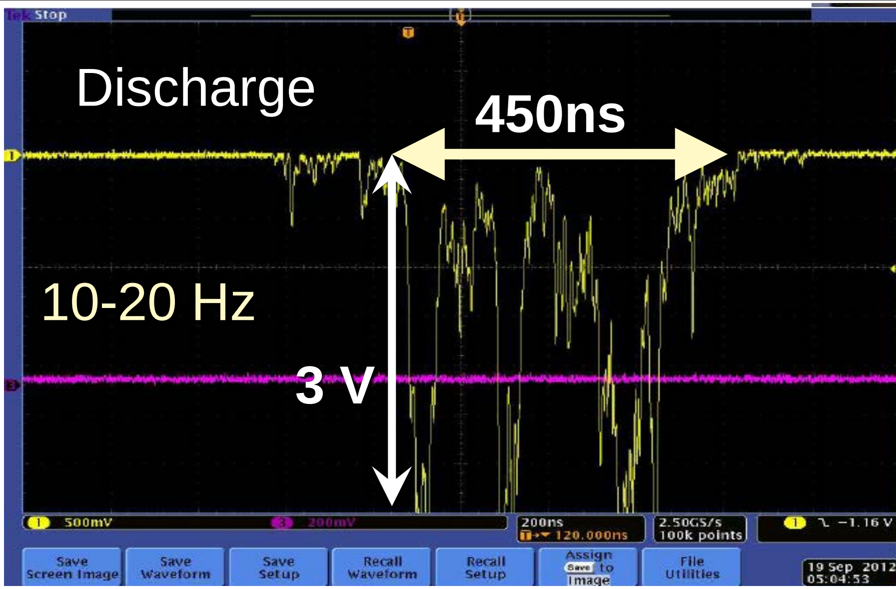


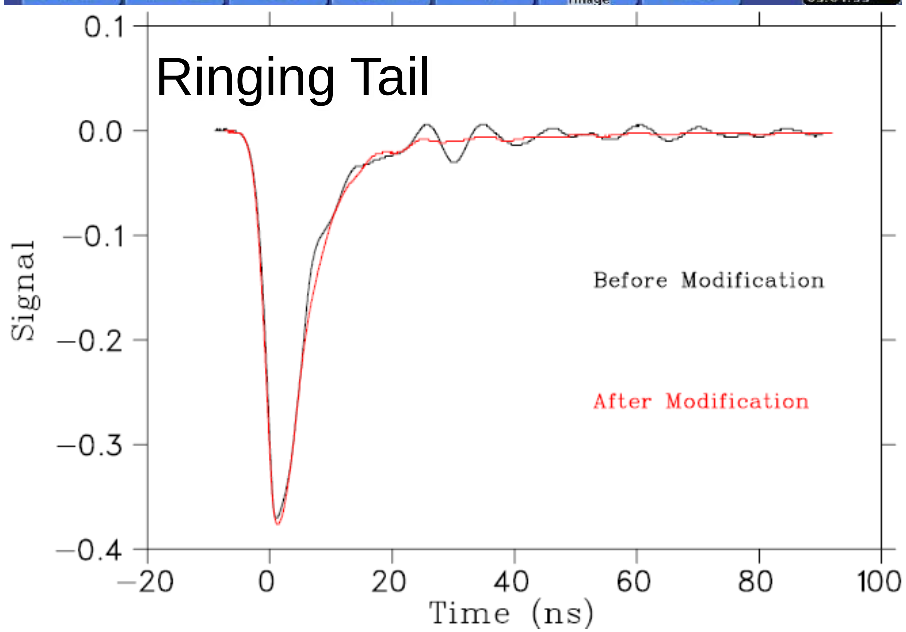






Sub Project 3: PMT Modifications

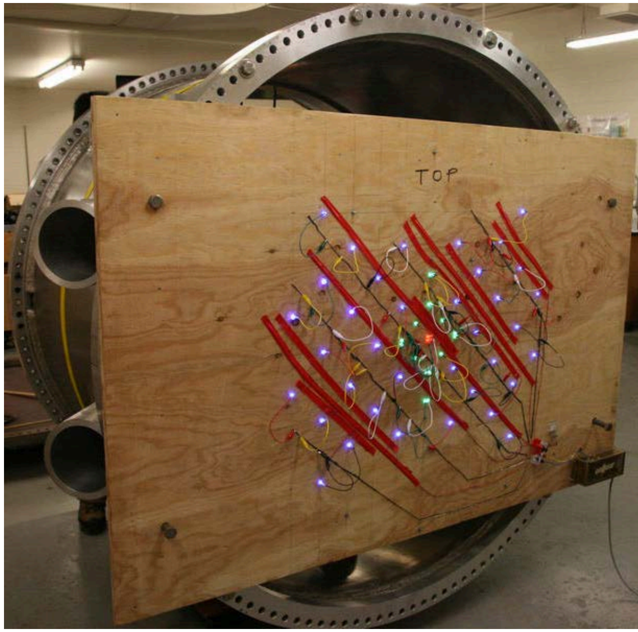


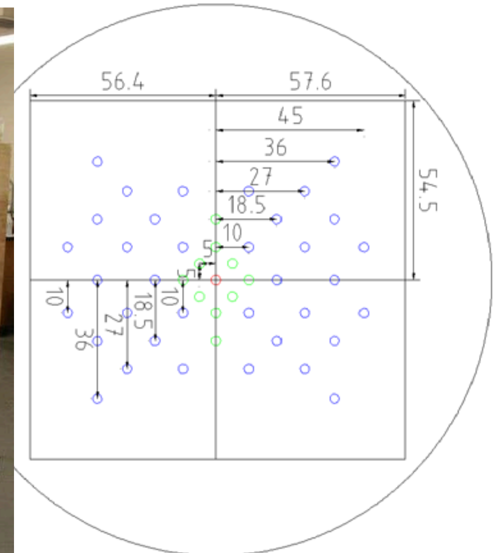


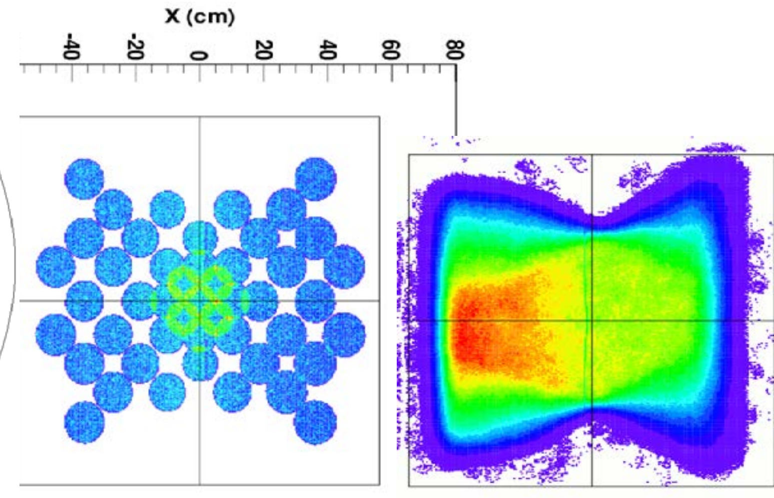
- Hamamatsu R1584 5” PMT @ 2000V (recommended) two disturbing characteristics:
  - Discharge
  - Ringing
- Solutions:
  - Add more insulation to eliminate the discharge
  - Modified the base circuit board to suppress the ringing
- R1584 from 20 years ago do not have these characteristics

arXiv:1311.6761v1

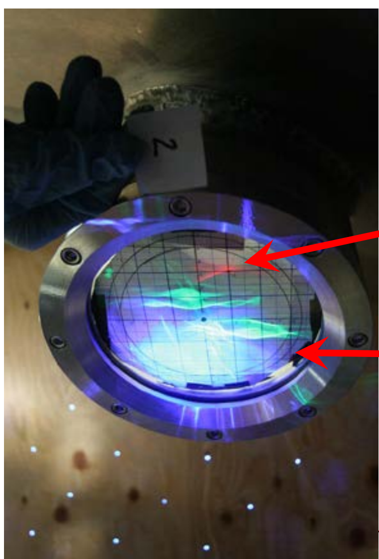
Sub Project 4: Detector Alignment

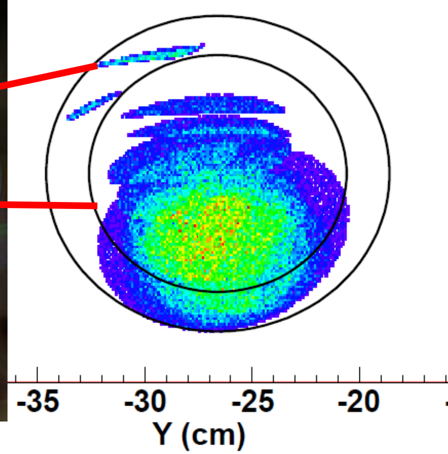






Geant 4 simlation



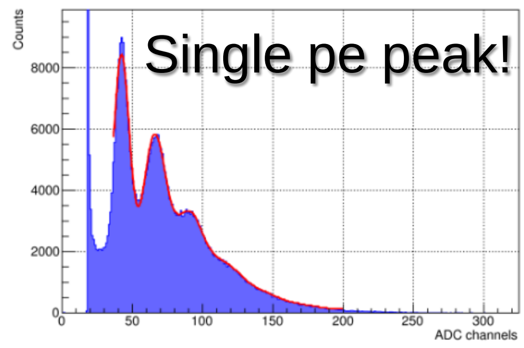


- **LED alignment Array (Xmas tree)**
  - Colored LEDs: **Red**, **Blue** and **Green**
  - Replicate photon envelope
  - Compared to MC

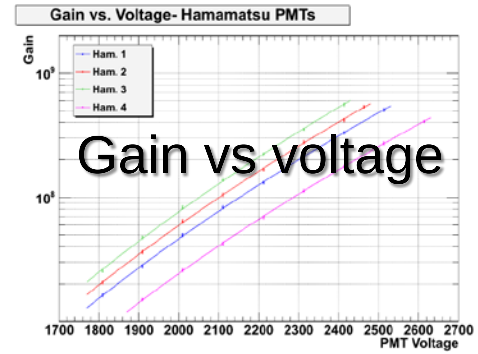
- **Significantly helped us aligning the detector**

Student Projects Under My Assistance in Supervision

- **Alex Fisher (2012)**
  - Studying and measuring gain of Hamamatsu PMTs
  - **HallC-doc-738-v1**



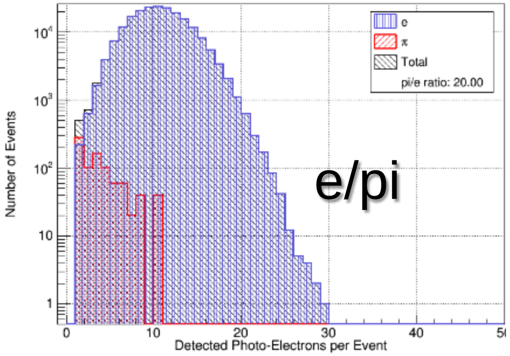
(a) 2050 V



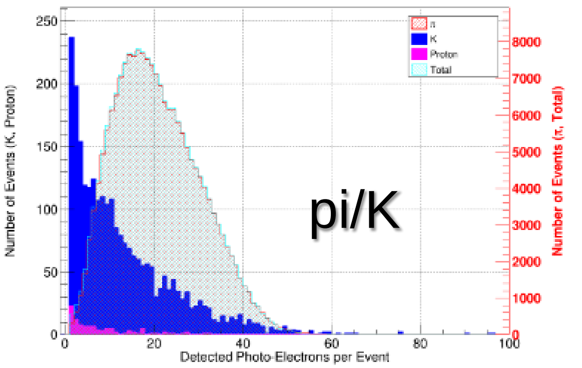
- **Thomas Fitz-Gerald (2013)**
  - Help the HGC assembly at Jefferson Lab

- **Matt Stugari (2016)**
  - Detector performance simulation with CO2 and C4F10
    - e/pi performance
    - Pi/K performance
  - **HallC-doc-804-v2**
  - **HallC-doc-804-v2**

Fantastic work!
Turned HGC to CO2 GC

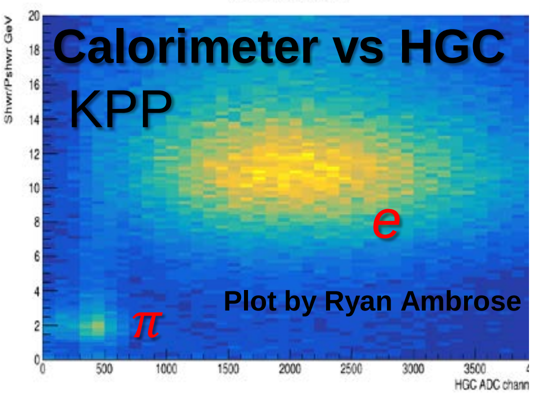


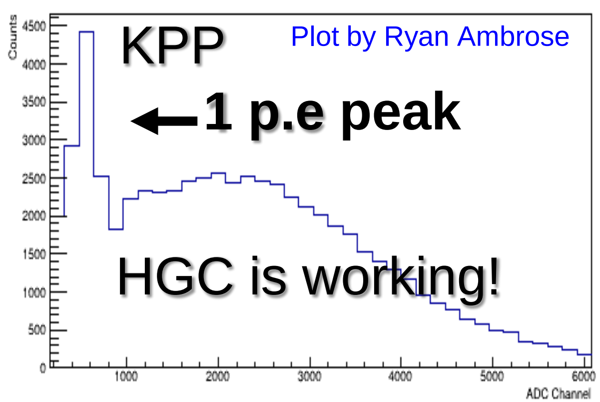
(b) CO_2 @ $P = 0.50$atm & $p = 3$GeV/c



(b) C_4F_{10} @ $P = 0.95$atm & $p = 3$GeV/c

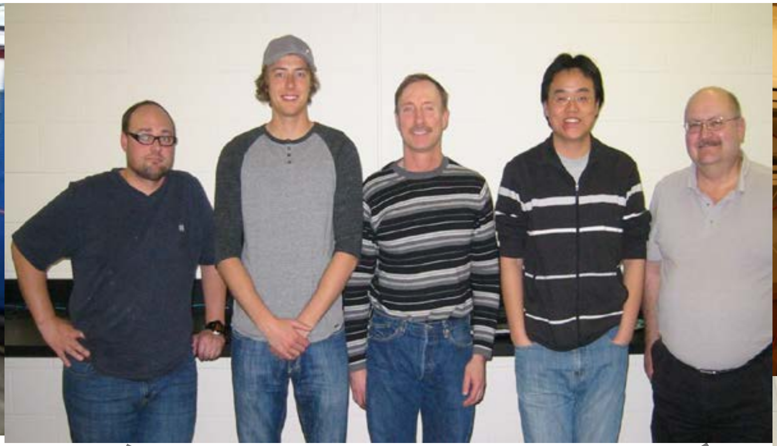
Detector Status and Updates

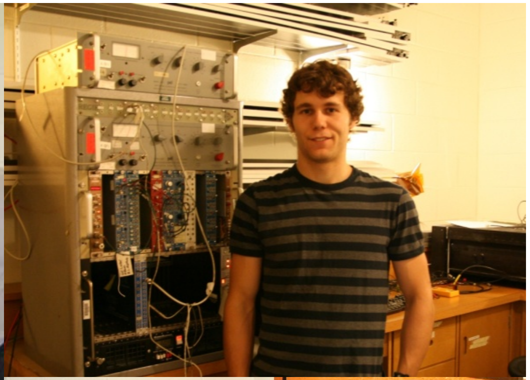


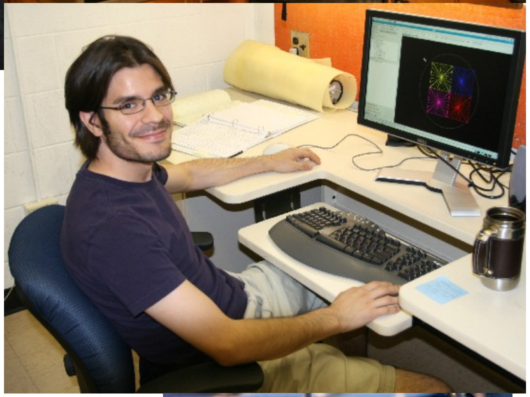


- April, 2013 Hydroforming completed
- June, 2013: Detector finished aligned and assembled at Regina
- July, 2013: Detector was shipped to Jefferson Lab
- August, 2013: Detector was re-assembled at Jefferson Lab
- April, 2015: Detector installed
- **March 2017: Calibration underway by new grad student: Ryan Ambrose**
- **Remain as one of HGC detector expert throughout 12 GeV era**

Thank you

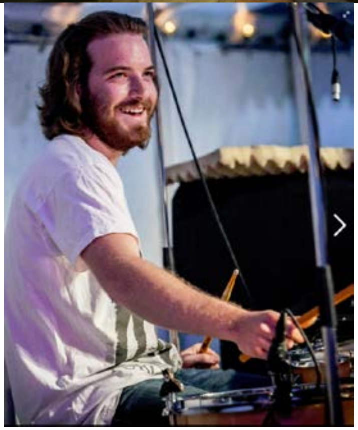






- HGC Construction Team at UofR
  - Leader: **Garth Huber**
  - Grad-Student: Wenliang (Bill) Li
  - Technician: **Derek and Keith**
  - Undergraduate Students: **Thomas, Lee, Alex, Paul, Matt**

Success Project, strong leadership by Garth, fantastic group Effort! Great support from Hall C staff scientists and Technicians

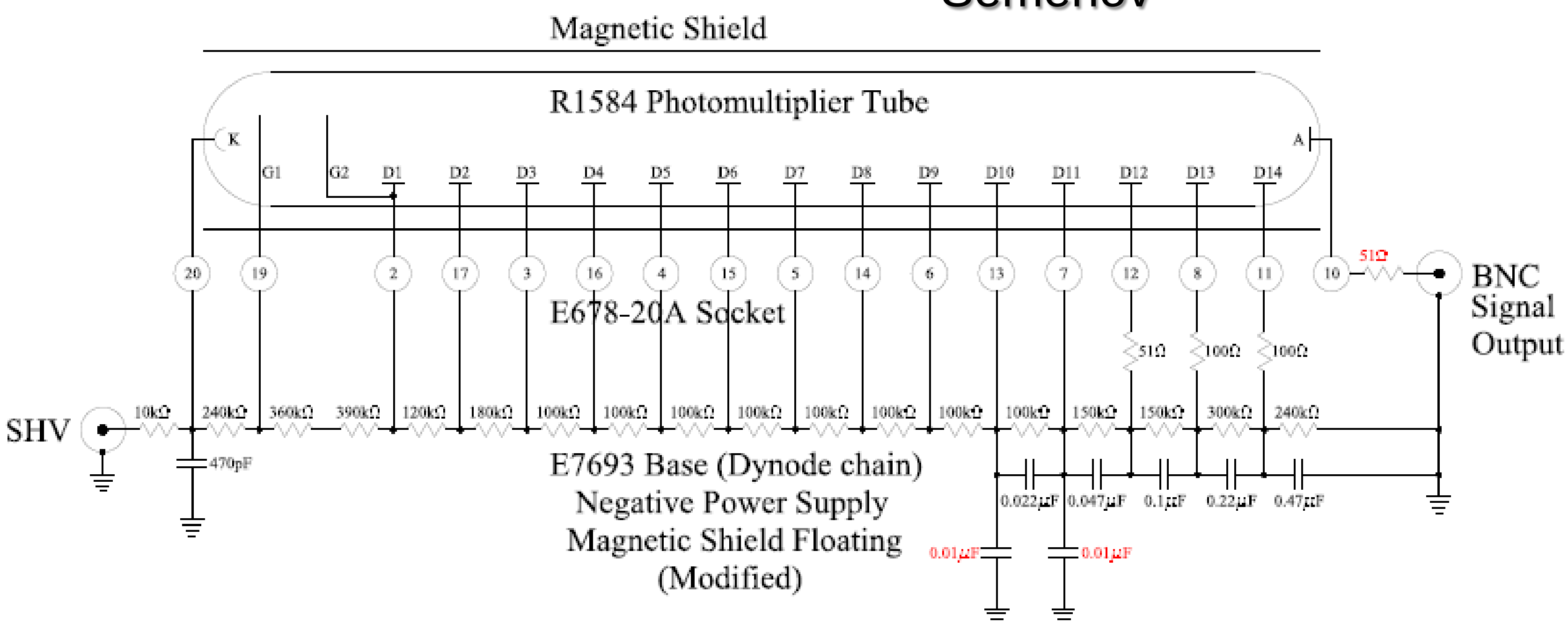


I would love to provide detailed information on any R&D sub project

Backup slides

PMT Modification

Credit to Keith and Dr Andrei Semenov



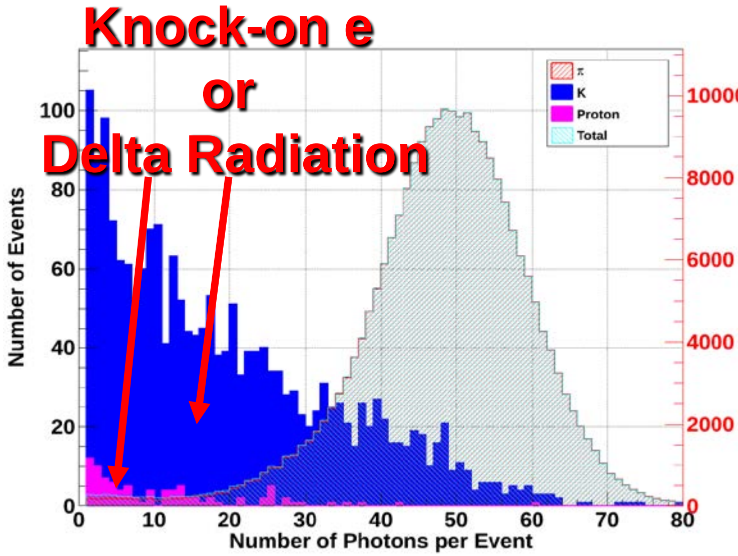
0.01µF Capacitors added on recommendation of Dr. A. Semenov, Dept. of Physics, U of R.
51Ω resistor is a common impedence matching technique.

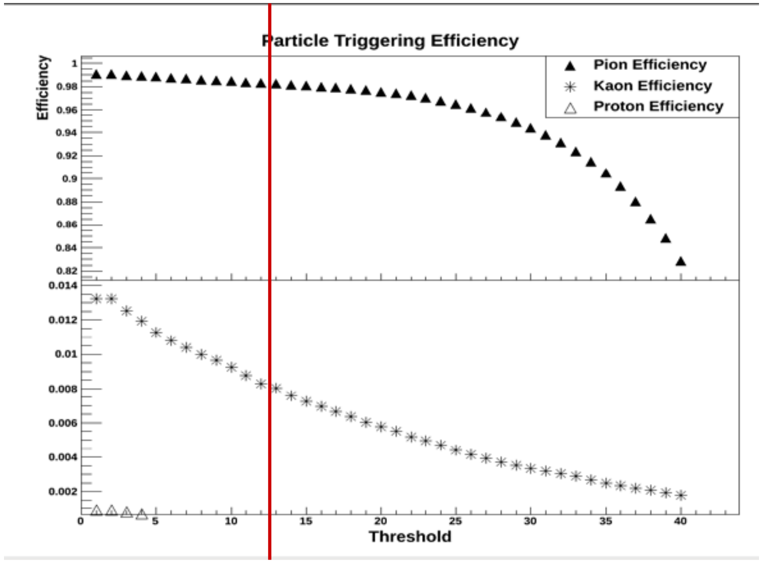
Expected Performance

- **K and P should not Cherenkov**
  - Not directly
  - 250000 Event at 7GeV momentum
  - Delta radiation is possible

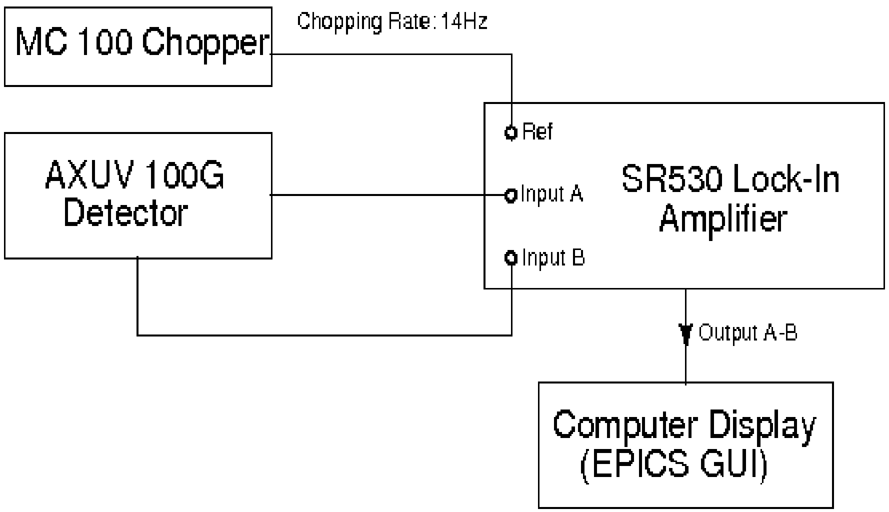
- **Simulation at 7 GeV:**
  - π: 250000
  - p: 100000 Events
  - K: 100000 Events

- **Performance at 7 GeV:**
  - Cut at 10 photo-e:
  - 98% detected pion
  - 0.8% detected Kaon
  - No Proton
  - 1% missing pion





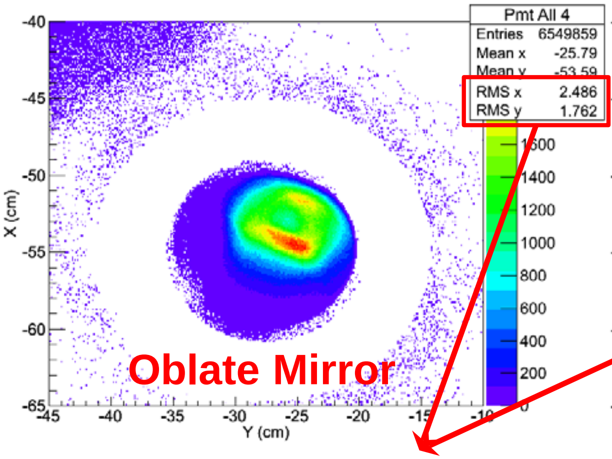
Lock-in Technique

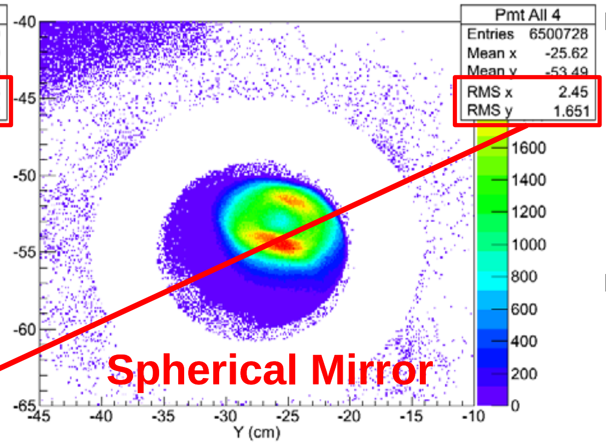


- **MC 100 Optical Chopper:**
  - Chop the light signal
  - gate Generation for SR 530
- **AXUV-100 Photo-diode**
- **SR530 Lock-in amplifier:**
  - Output: Signal Subtraction (A-B)

- **The lock-in technique is used to measure very small AC signals in large background at narrow bandwidth.**
- **Advantages:**
  - Measure Reflectivity at any possible on the Mirror
  - No PMT
  - No Dark Box required
    - Requires a constant background
  - No Vacuum Chamber required
  - If N_2 is used, lower wavelength is possible.

Spherical vs Oblate Mirrors

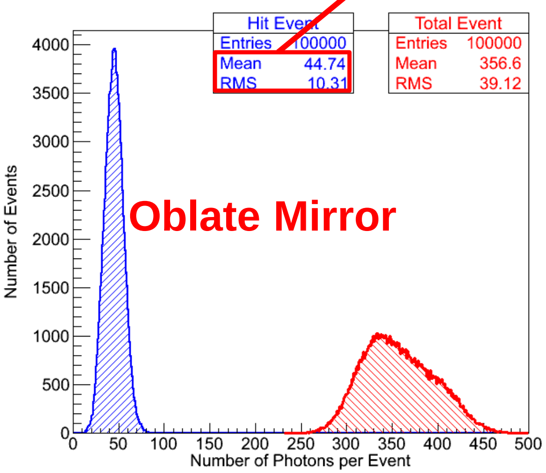


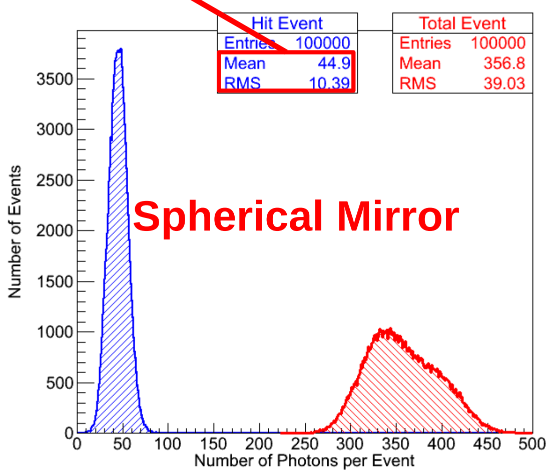


Oblate Mirror has larger focus spot

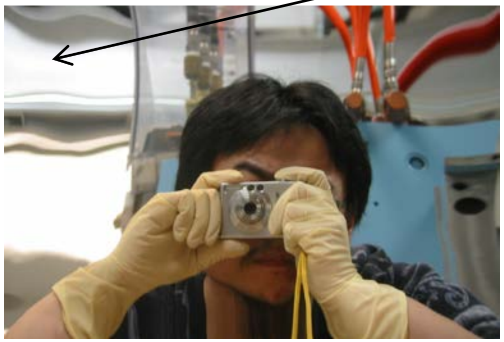
7 GeV pion simulation

Oblate Mirror has lower focusing Efficiency

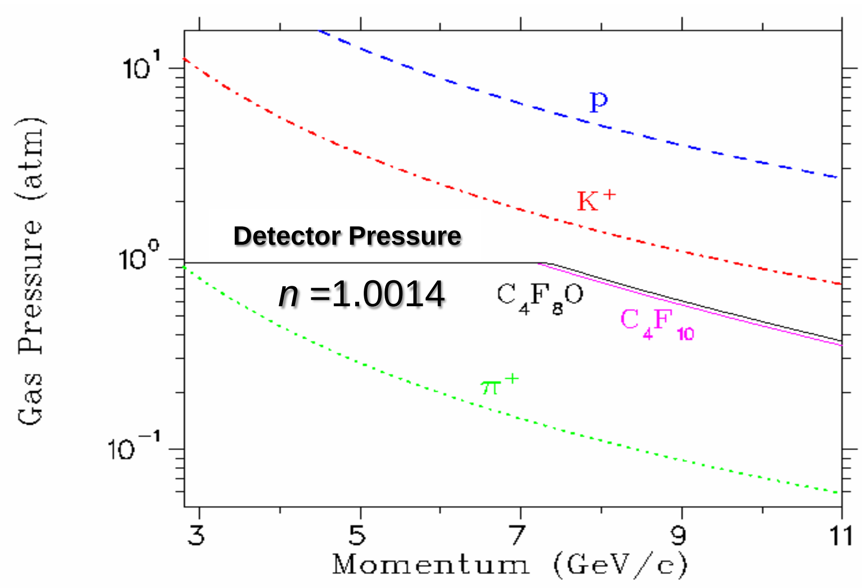


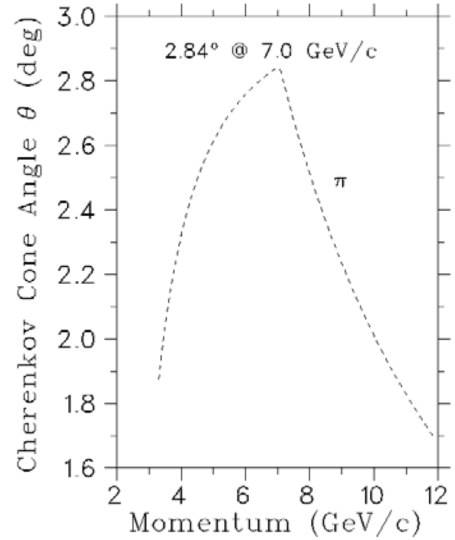


- Oblate vs Spherical Mirrors
  - Spot Size is slightly worse
  - Detection Efficiency is slightly worse
- Oblate mirrors (slumped): $8k/lot
- Spherical mirrors (polished) : $100k/lot (Hall B number)
- Conclusion: Oblate mirror is sufficient for the threshold Cherenkov detector
  - Concern: corner optical aberration



Cherenkov @ Jefferson Lab: Hall C





Cherenkov Threshold

$$v > \frac{c}{\sqrt{\epsilon_r(\omega)}} = \frac{c}{n(\omega)}$$

Cherenkov Angle

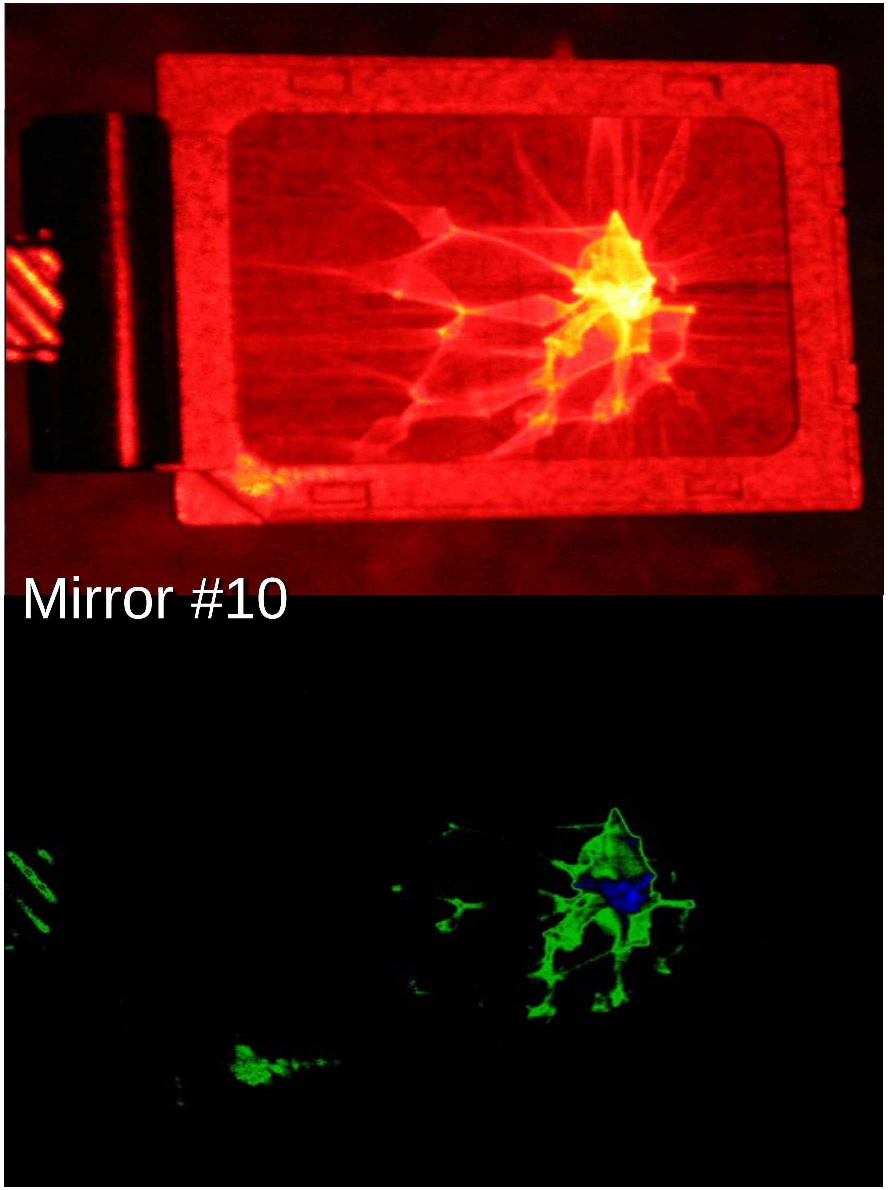
$$\cos\theta_C = \frac{1}{\beta\sqrt{\epsilon_r(\omega)}} = \frac{1}{\beta n}$$

- Spectrometer Momentum is define by the dipole setting
- Cherenkov medium: $C_4F_{10}O$ gas
- Refractive Index to Pressure:

$$P = \frac{(n-1)}{(n_{1\,\mathbf{atm}}-1)}$$

- Detector Pressure
  - 1 atm for 3–7 GeV/c Momenta
  - Reduced pressured at 7GeV/c or higher Momenta

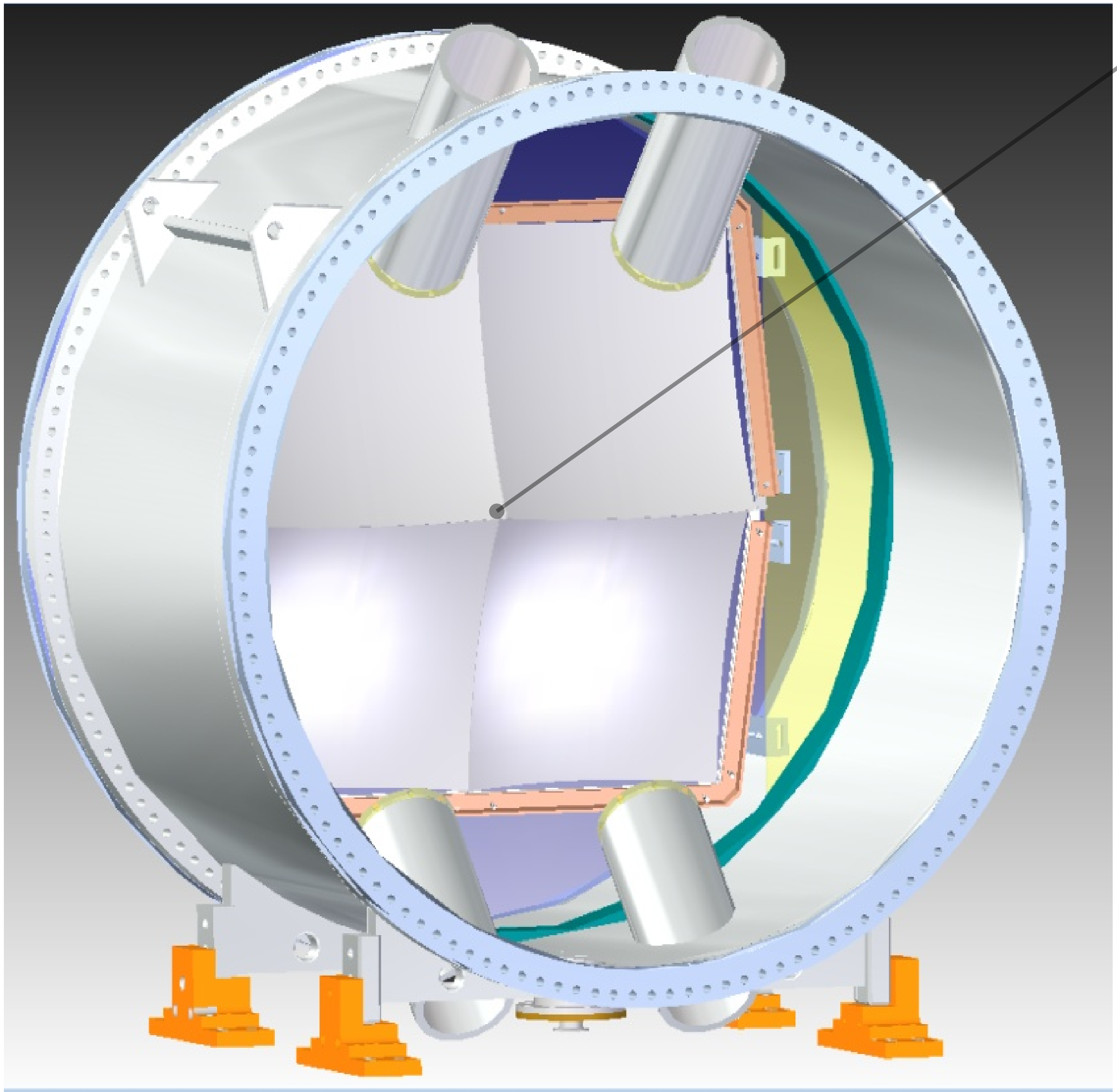
Sub Project 1: Optical Test & Overall Results



Mirror #	90% Fit R (cm)	90% Fit κ	# of Failed Criterion	FR/2−FL (cm)	Blue-Green Ratio	Overall Ranking
1	118.397	1.95	5	1.15	0.09	Bad
2	113.124	1.06	5	2.24	0.39	Average
3	117.110	1.70	5	2.99	0.70	Average
4	122.392	2.29	6	4.80	0.08	Bad
5	113.331	0.76	5	-0.14	0.14	Average
6	112.906	0.94	2	-0.36	0.15	Good
7	113.538	1.13	3	0.79	0.12	Reserve
8	114.325	1.26	4	1.01	0.15	Average
9	114.372	1.30	4	1.62	0.12	Reserve
10	112.035	0.42	0	-0.79	0.14	Good
11	111.766	0.75	1	0.73	0.12	Good
12	112.117	0.84	1	0.24	0.12	Good
13	122.464	2.43	6	3.19	0.01	Bad
14	117.964	1.59	6	3.41	0.14	Bad
15	113.674	1.17	5	2.10	0.18	Average

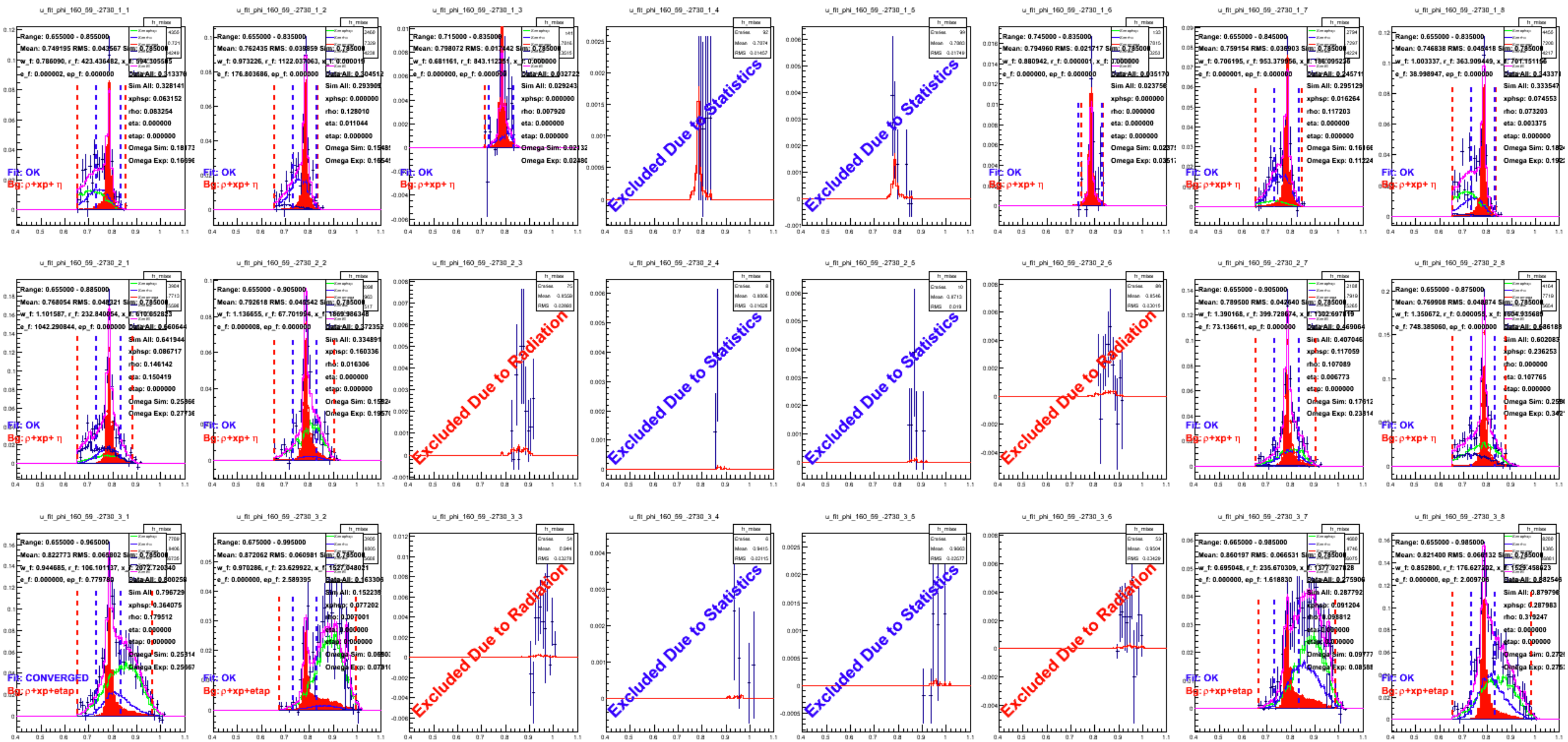
- **Optical (defused Laser Beam) Test**
  - **Measured focused spot distance and obtained focal length. Then the focal length is compared with the fitted radius.**
  - **Photographic processing obtained Blue-Green Pixel Ratio**
- **Overall Results**
  - Mirrors with better fitted K and R values had better reflected spot in the optical test.
  - Best 4 mirrors has ***0<K<1*** (Oblate) and 110cm <***R < 115cm***

Sub Project 1: Mirror



- **4 Aluminized Mirrors**
  - Dimension: 60cm x 55cm.
  - Curvature Radius: 110cm
  - Top two mirrors: 16 degree
  - Bottom two mirrors: 20 degree to the vertical plane
- **Manufacturing technique:**
  - Slumped Glass: $8k (15 pieces)
    - Pro: cheap
    - Con: quality may vary
  - Polished Plastic: $100k (4 pieces)
    - Pro: perfect quality
    - Con: expensive

Missing Mass Distribution Background Extraction

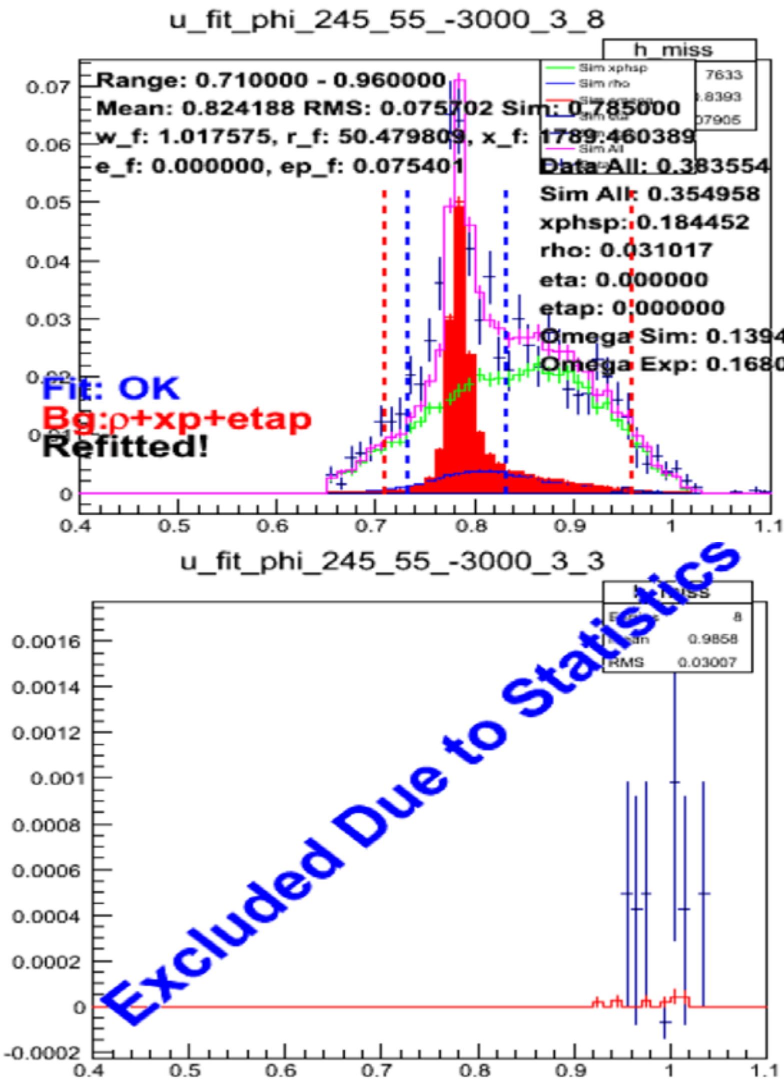


- Integration limits and fitting limits
- Exclusion criteria
  - Exclude the radiative only omega bins
  - Exclude the low statistics bins

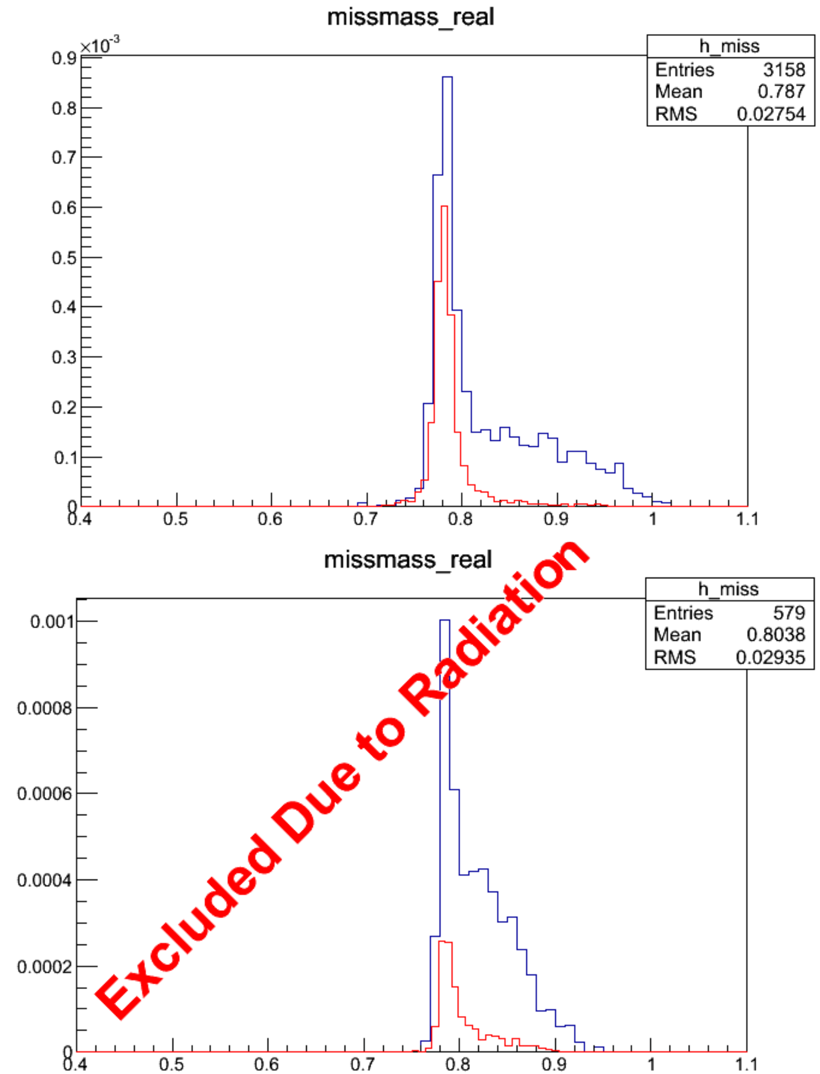
Wenliang Li, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.

Bin Exclusion criteria

- Low Statistics

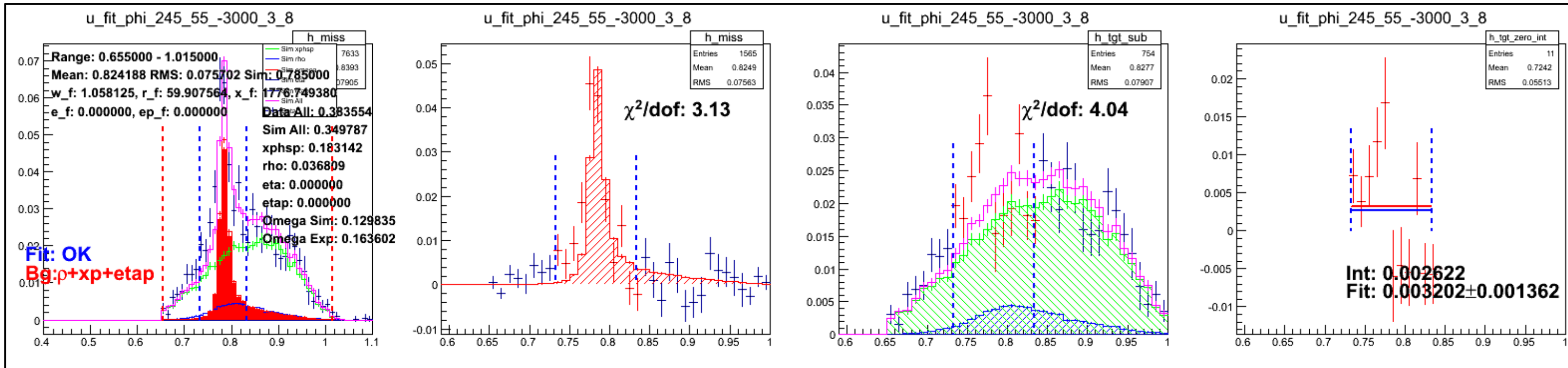


- Radiative Tail

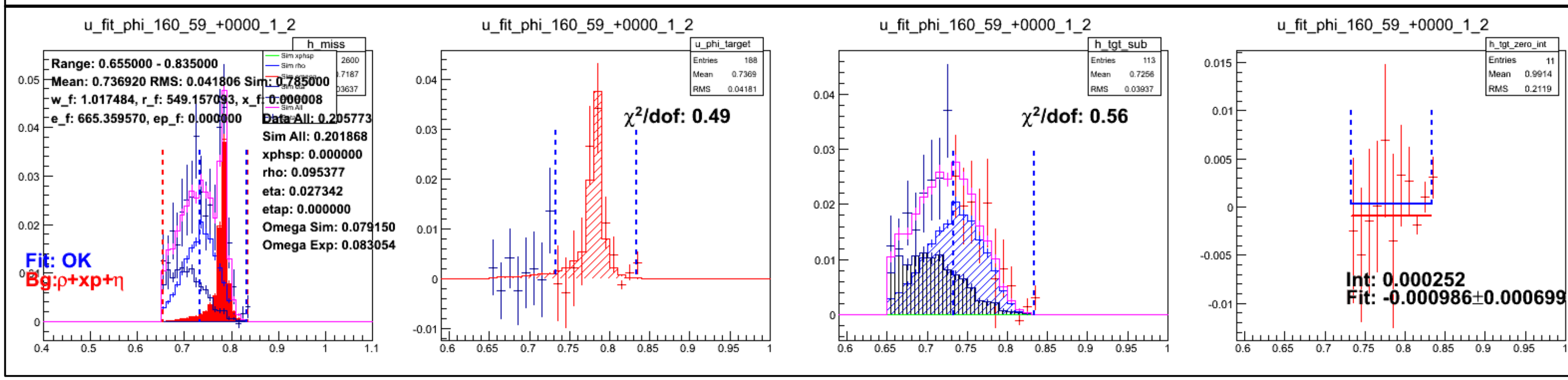


Wenliang Li, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.

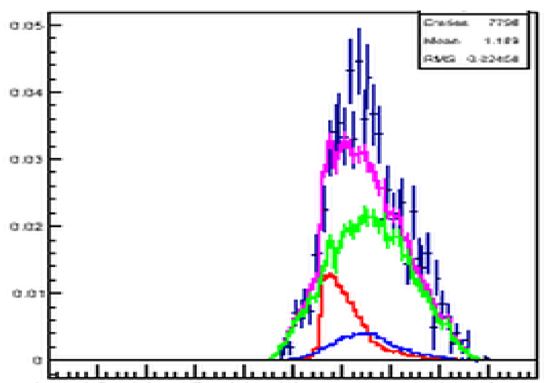
Background Extraction and Check



Worse example



Missmass edge example



Reconstructed Missing Energy For the worse example