The 12 GeV Upgrade in JLab's Hall C

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The 6th Workshop on Hadron Physics in China
and Opportunities in the US

Lanzhou, China
July 21-25, 2014

Experiments Motivating the Hall C Upgrade

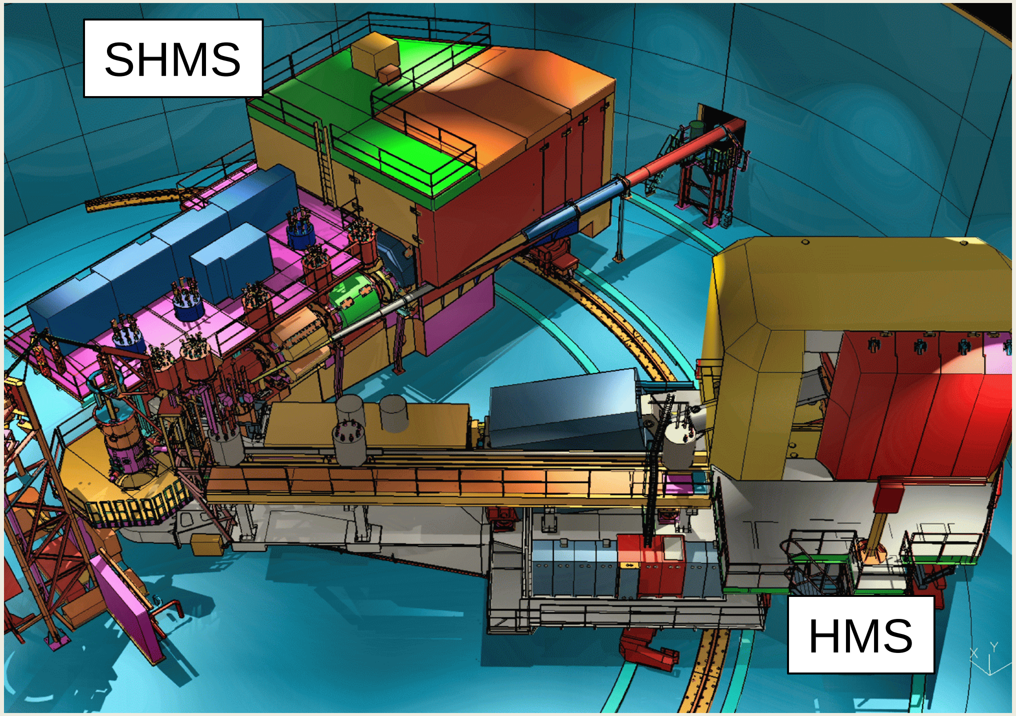
- Pion and nucleon elastic form factors at high momentum transfer
- Deep inelastic scattering at high $x_{Bjorken}$
- Semi-inclusive scattering with high hadron momenta
- Polarized and unpolarized scattering on nuclei

The program demanded a new partner for the existing High Momentum Spectrometer (HMS) suited for detecting charged particles close to the new beam energy, usually close to the beamline:

- Higher momentum capability (11 GeV/c)
- Smaller angle capability (5.5 degrees)
- Particle identification (e, π, k, p)
- Accurate and reproducible angle and momentum settings

The SHMS (Super High Momentum Spectrometer) was designed to meet these requirements.

Hall C Base Equipment at 12 GeV



Hall C will provide 2 moderate acceptance, magnetic focusing spectrometers:

High Momentum Spectrometer:

$d\Omega \sim 6$ msr, $P_{max} = 7$ GeV/c
$\Theta = 10.5$ to 80 degrees

Super-HMS :

$d\Omega \sim 4$ msr, $P_{max} = 11$ GeV/c
$\Theta = 5.5$ to 40 degrees

→ Both spectrometers provide excellent control of systematic uncertainties
→ Kinematic reproducibility, well-understood acceptance

Ideal for:
- precision cross section measurements and response function separations,
- in single arm or coincidence,
- at high luminosity (10^{38}/cm^{2}sec or so).

SHMS Overview

Key Features:

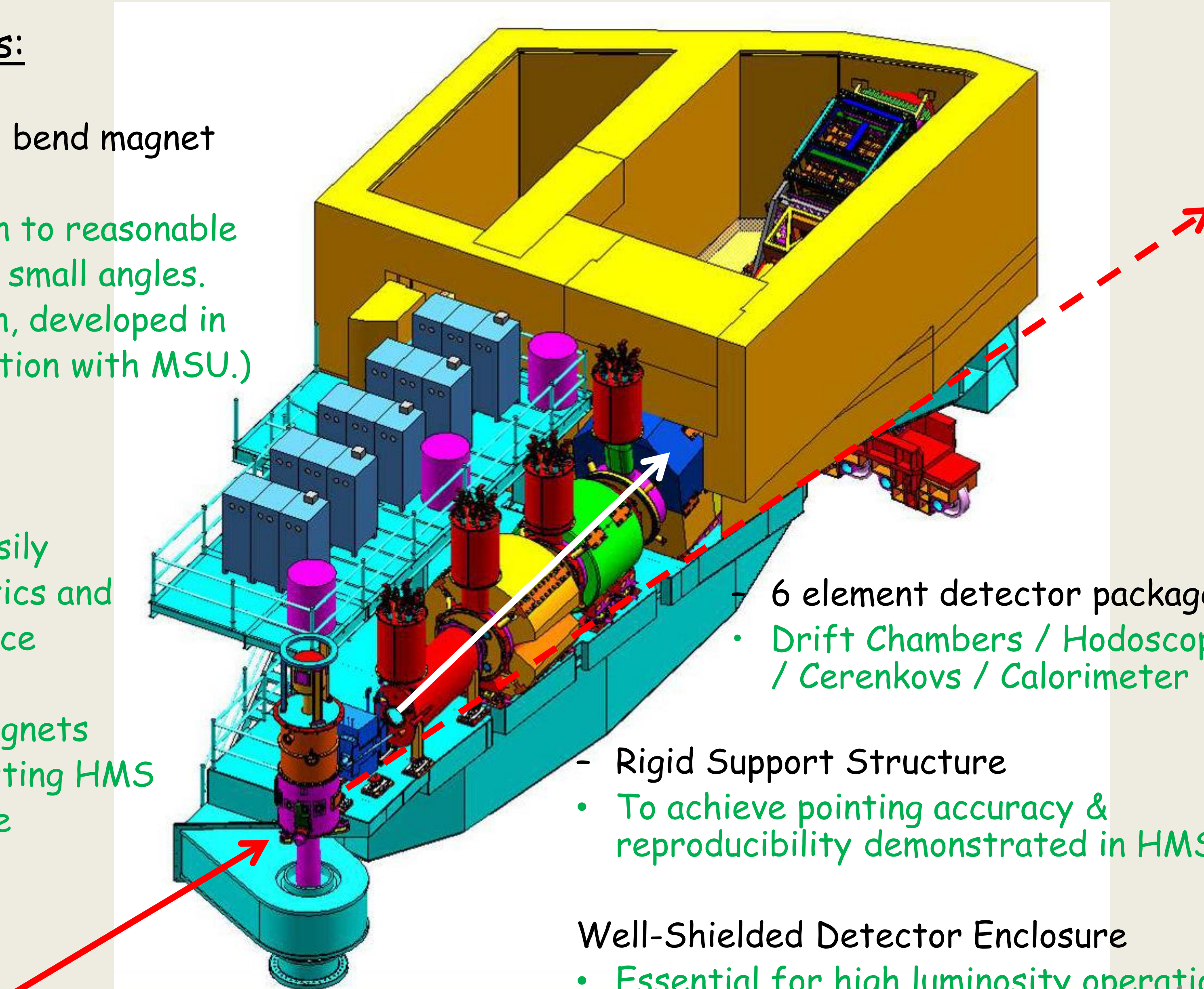
Horizontal bend magnet

- The solution to reasonable acceptance at small angles.
  (New design, developed in collaboration with MSU.)

QQQ-D

- Provides easily calibrated optics and wide acceptance

- Uses SC magnets similar to existing HMS where possible

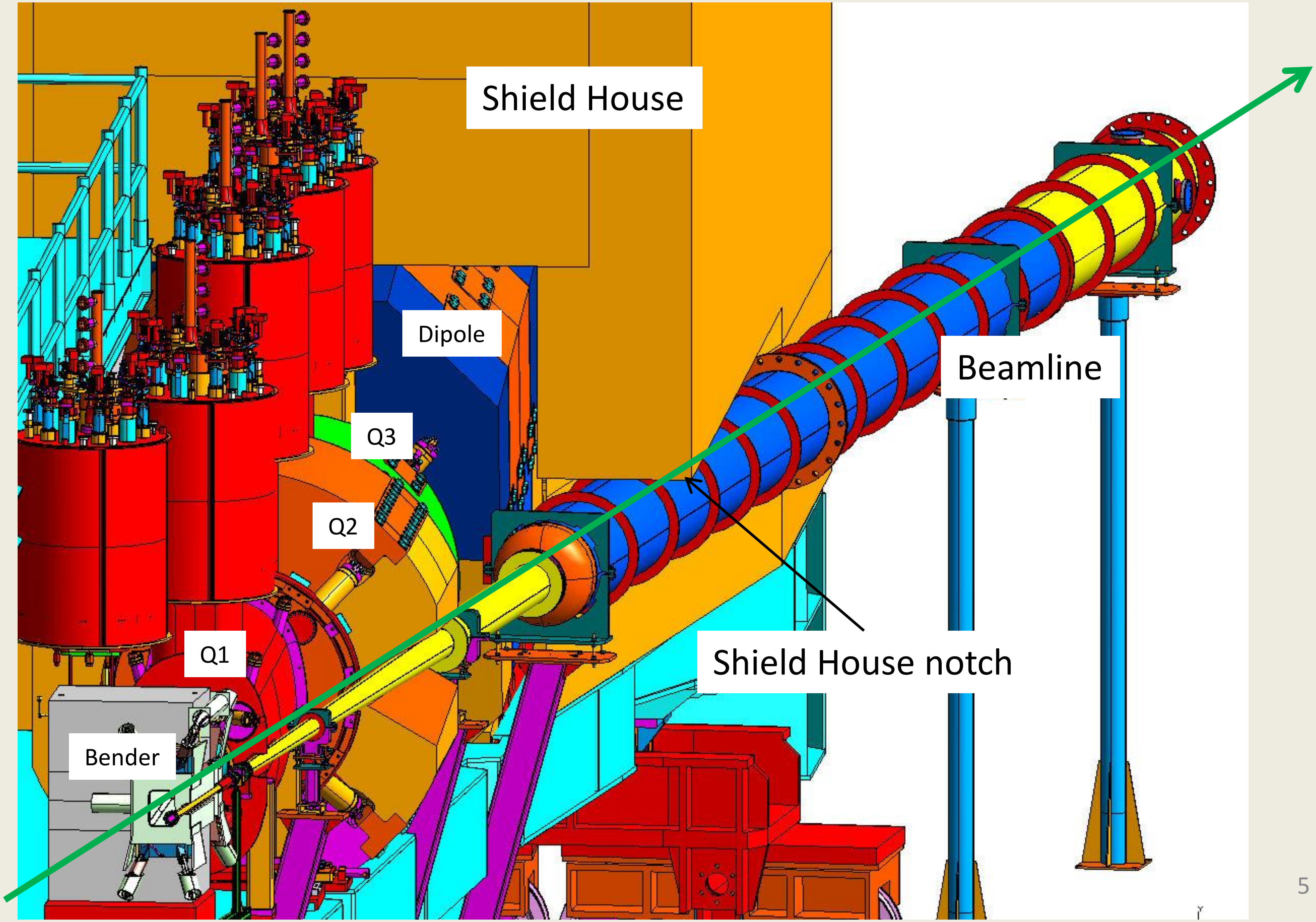


– 6 element detector package
- Drift Chambers / Hodoscopes / Cerenkovs / Calorimeter

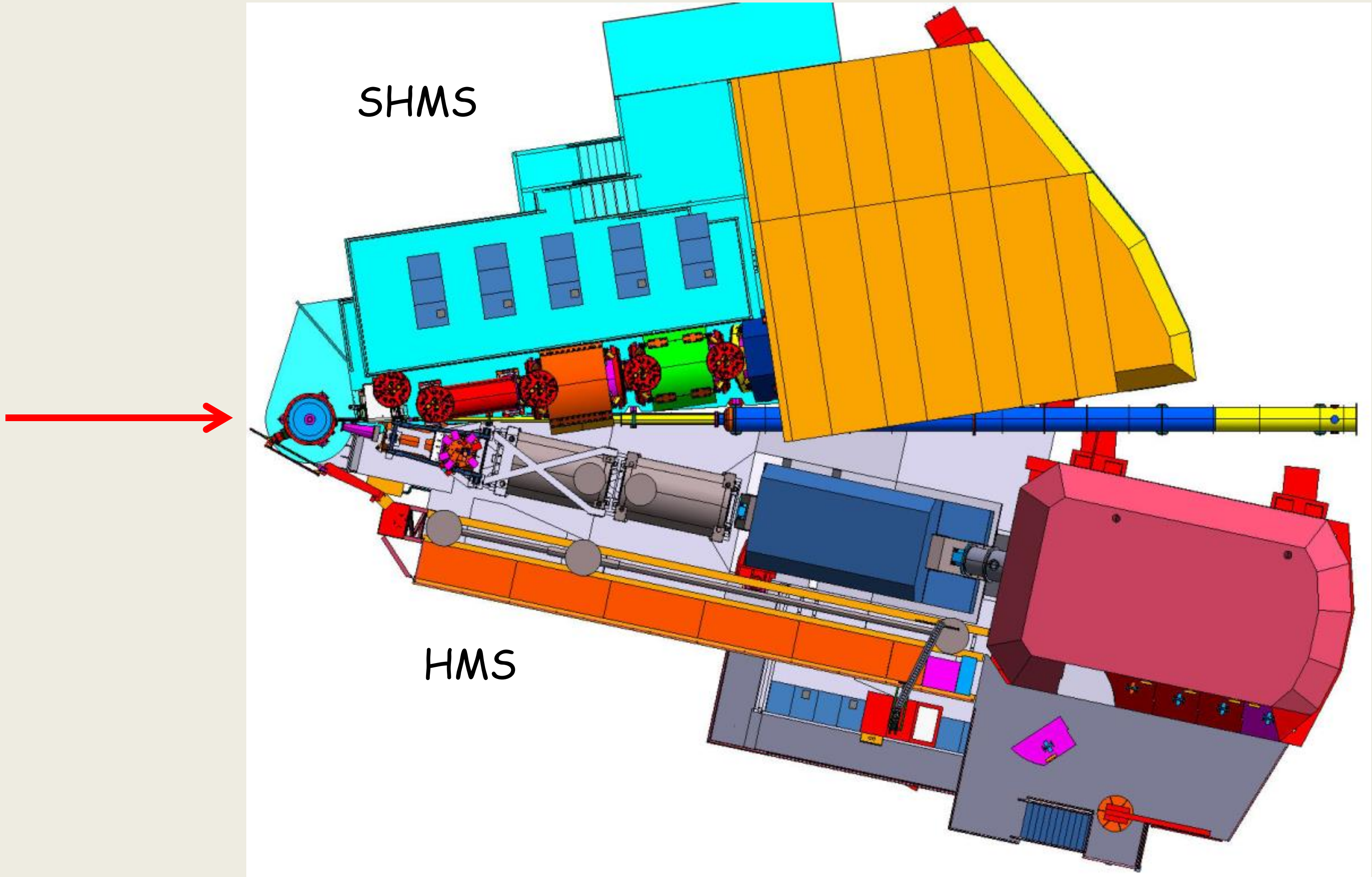
– Rigid Support Structure
- To achieve pointing accuracy & reproducibility demonstrated in HMS

Well-Shielded Detector Enclosure
- Essential for high luminosity operation

Fussiness Needed for Small Angle Operation

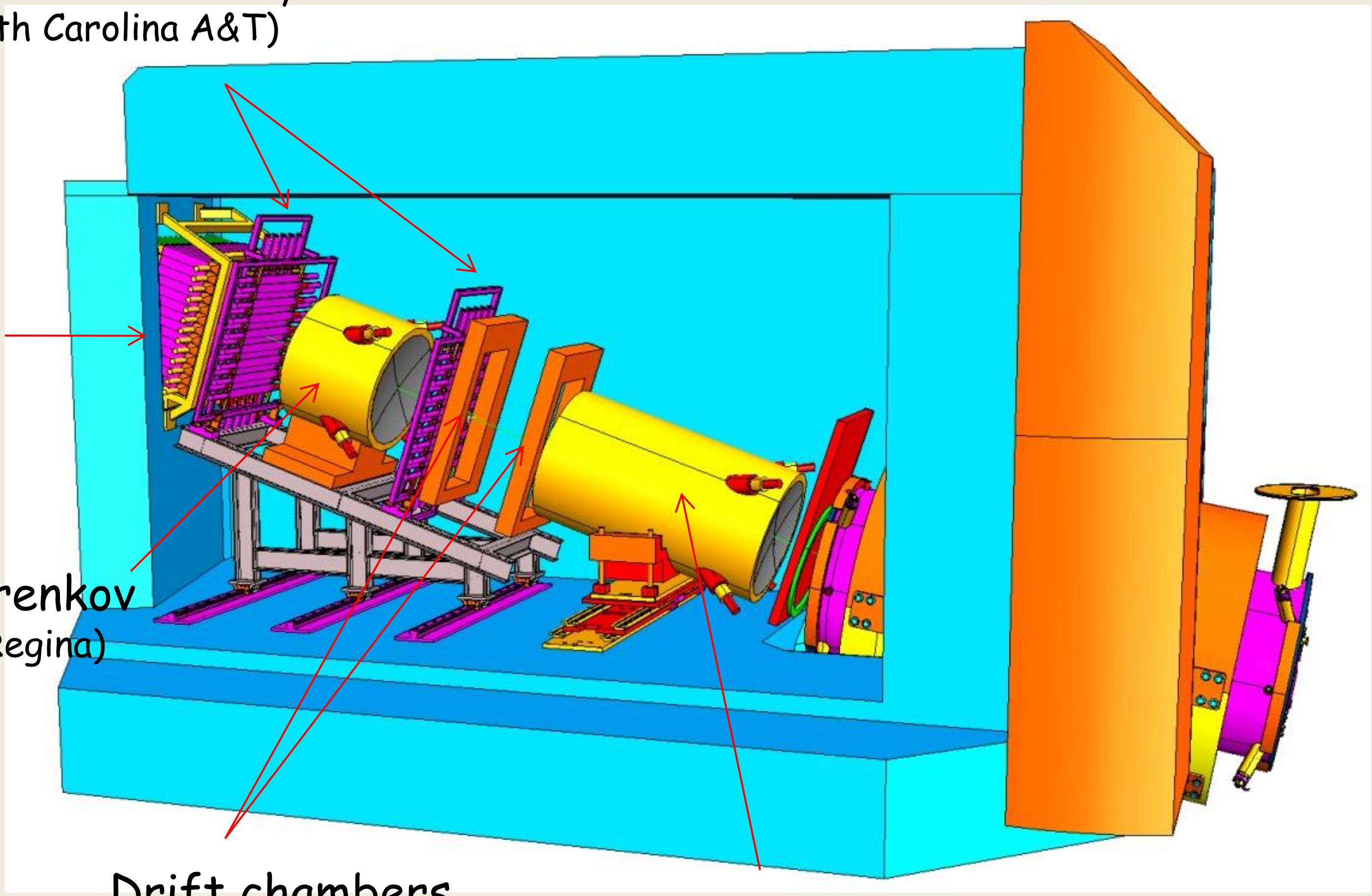


Top View of SHMS-HMS at Small Angle Separation for Coincidence Studies



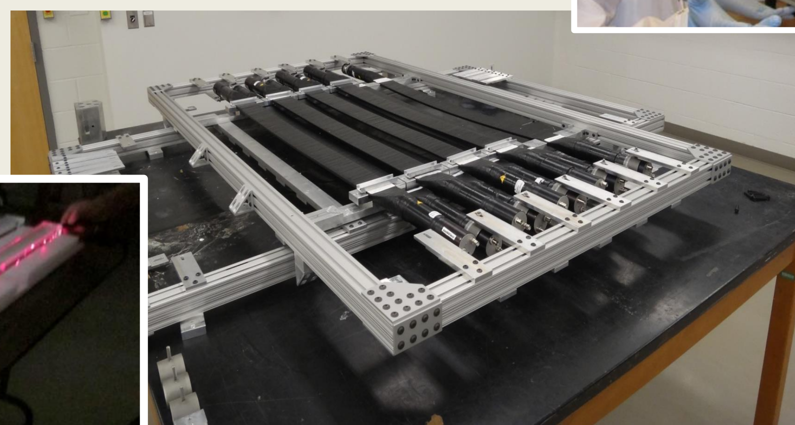
SHMS Detectors

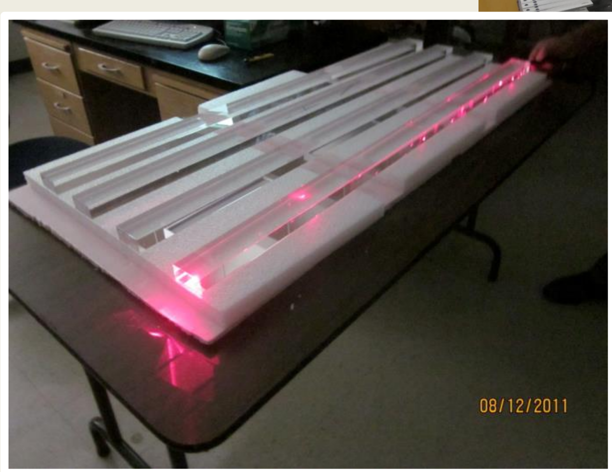
excellent PID over a wide momentum range



"Baby Pictures"

SHMS Detector Construction





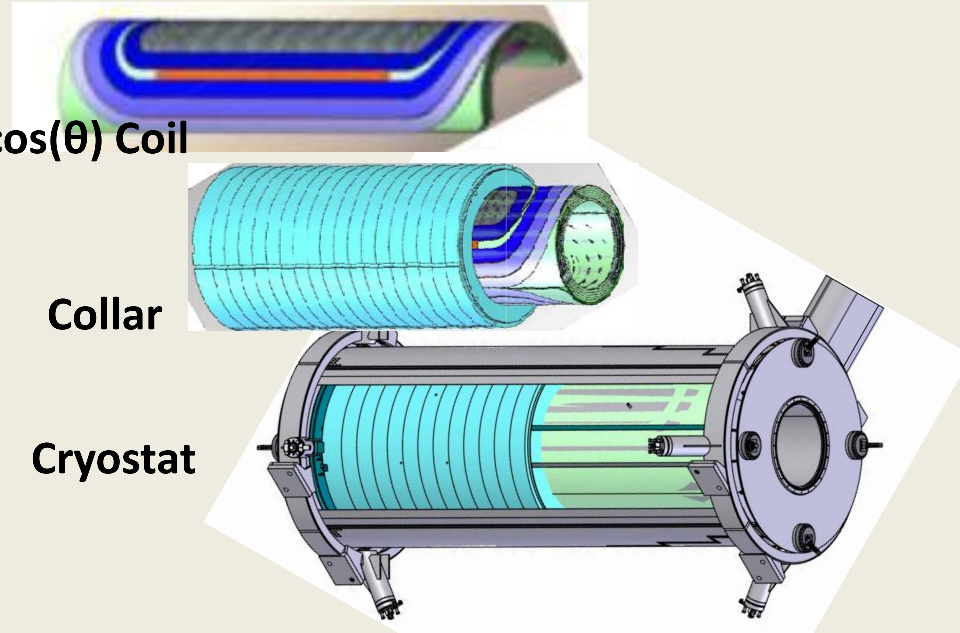
SHMS Dipole

SigmaPhi
Vannes, France

cos(θ) Coil

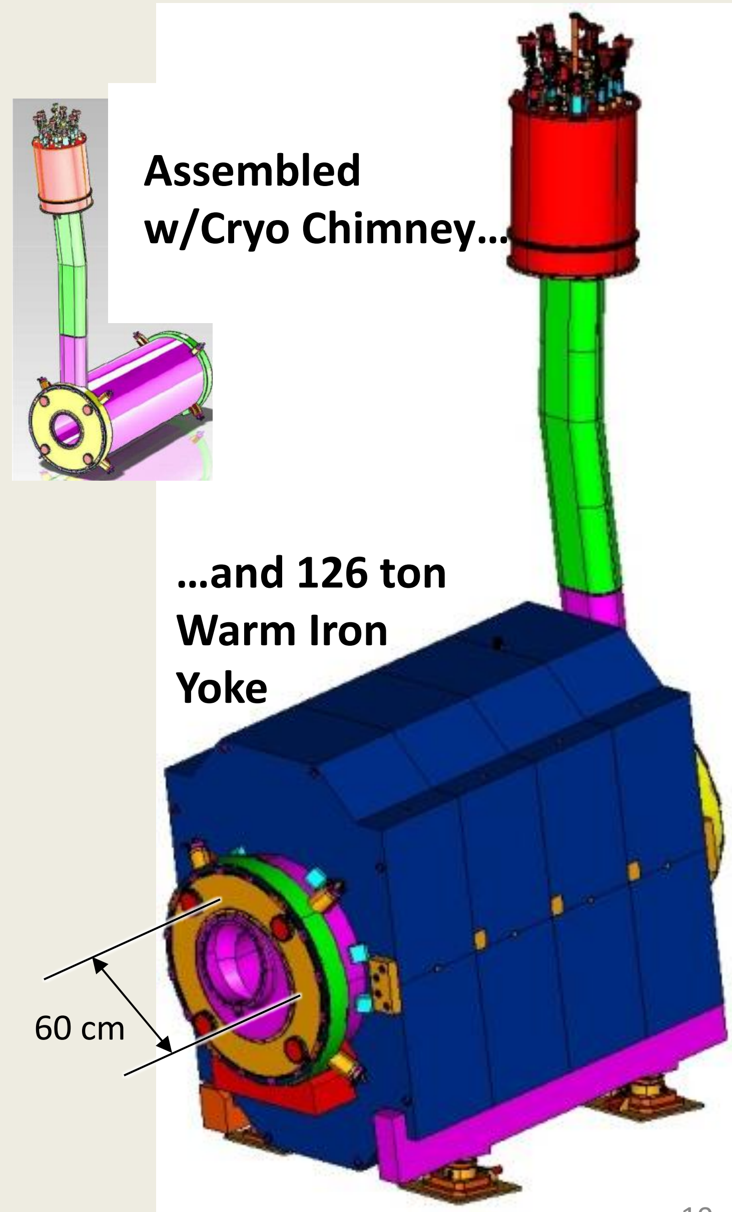
Collar

Cryostat



Prototype Coil on Winding Machine

Assembled
w/Cryo Chimney…



…and 126 ton
Warm Iron
Yoke

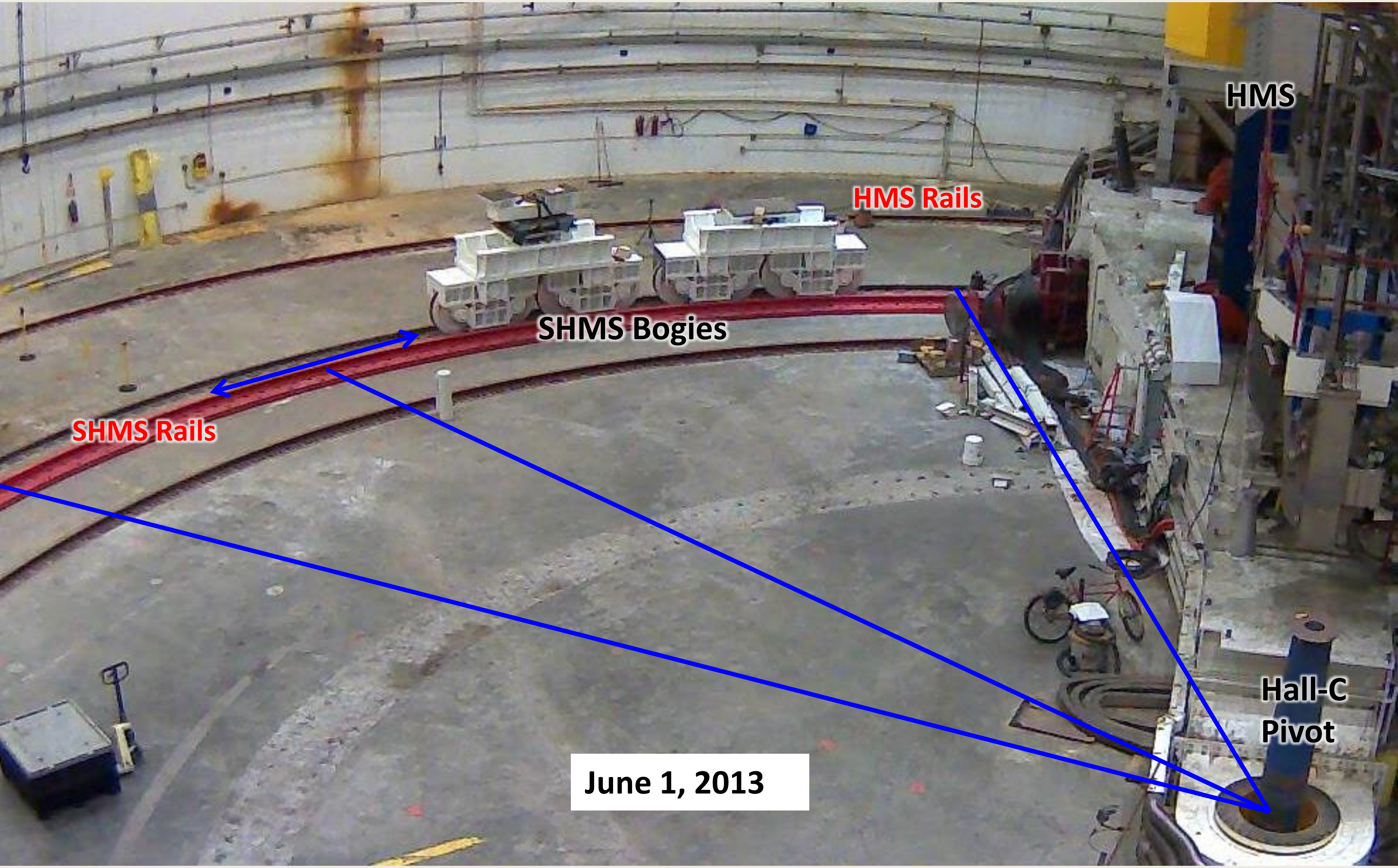
SigmaPhi
Vannes, France

Dipole Magnet

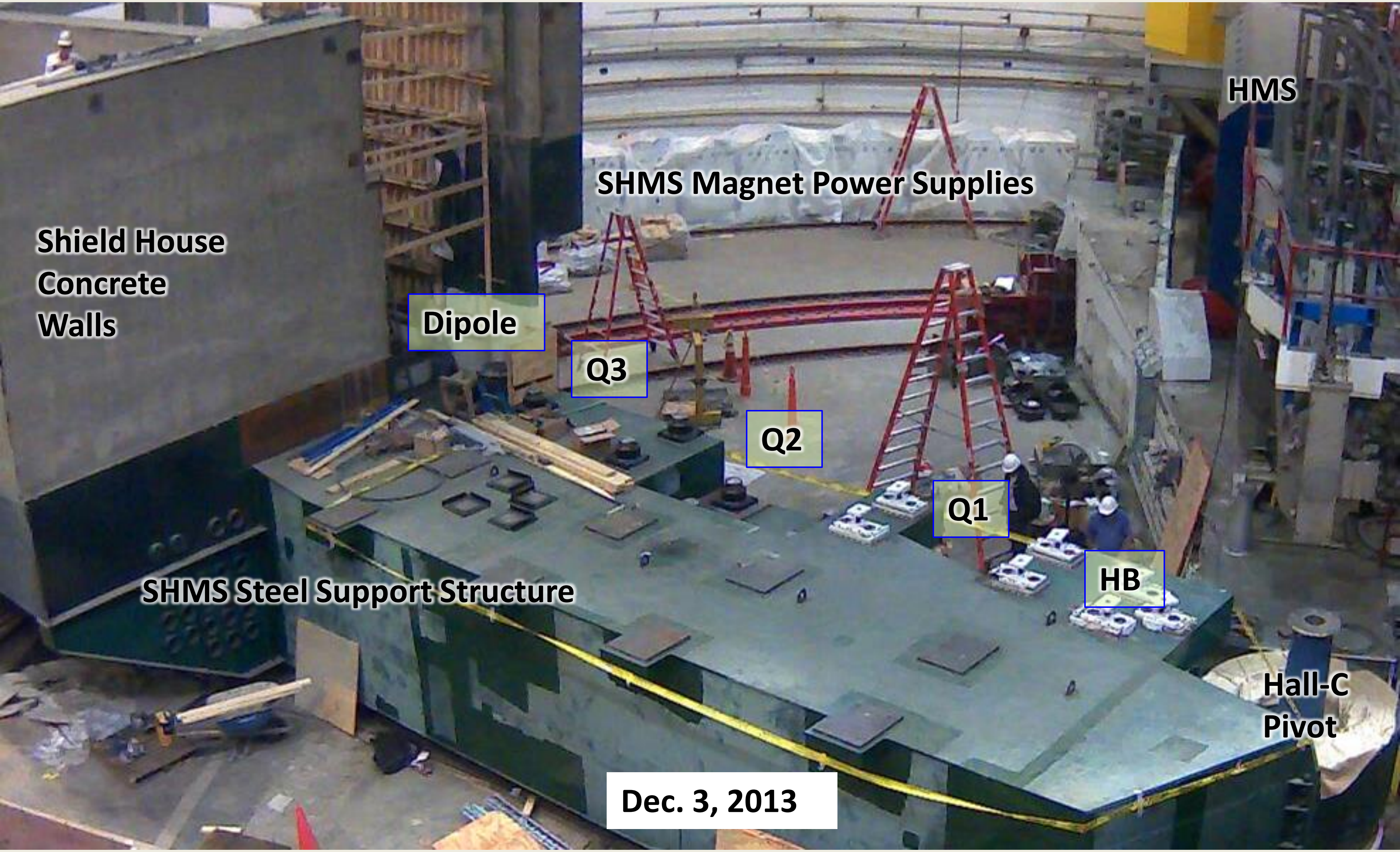
Mold being placed onto Dipole Coil "B" Layers 1&2 in preparation for VPI (May 27, 2014).

Dipole Coil "A" Layer 3 being wrapped and readied for winding layer 4 (May 27, 2014).

Support Structure

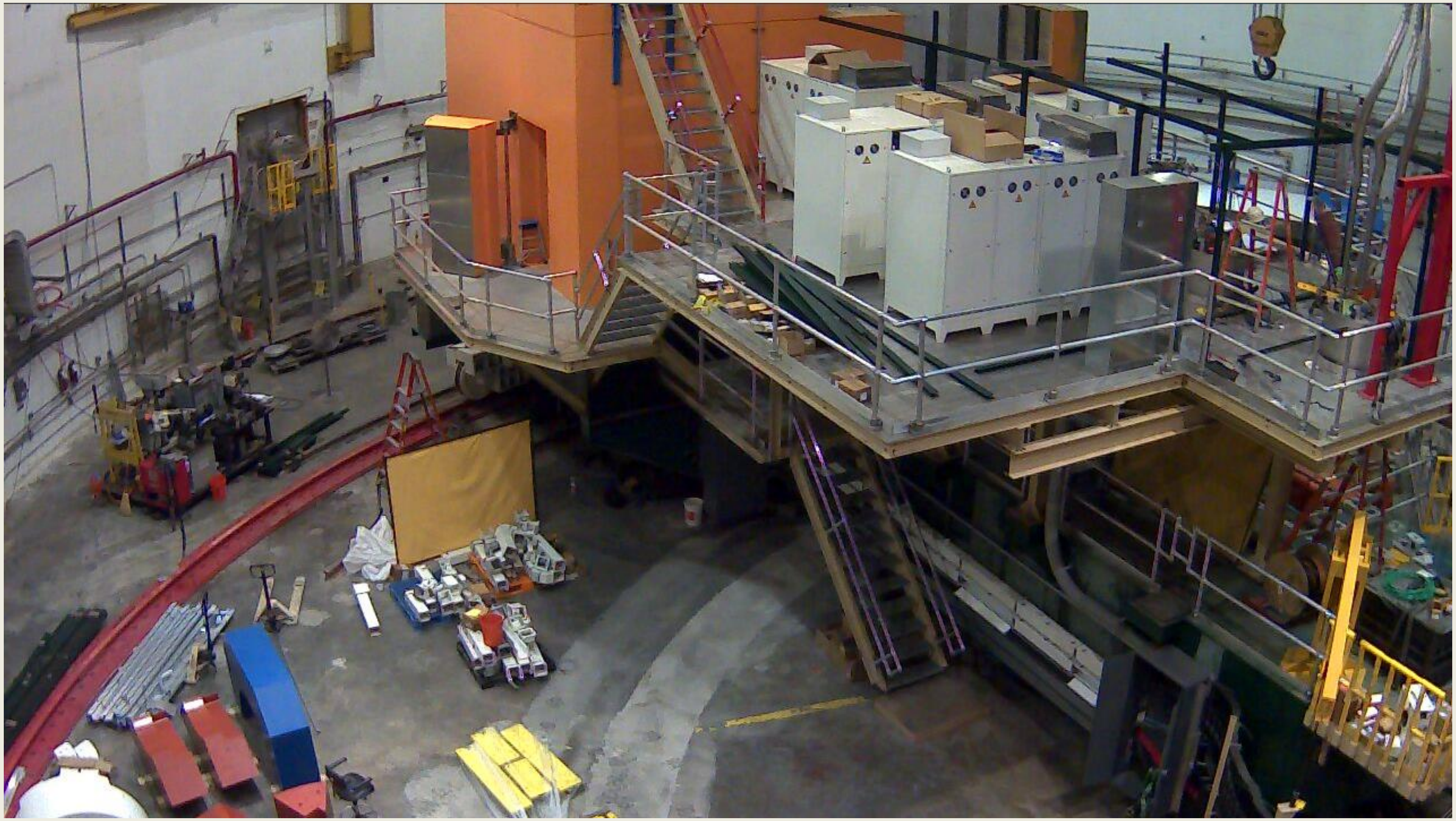


Support Structure



Support Structure

Platform and Shield House



Magnet power supplies are on the platform.

AC Power Feed is in. Branch circuits, lights, etc., going in now.

Signal/HV Cable pulls done.

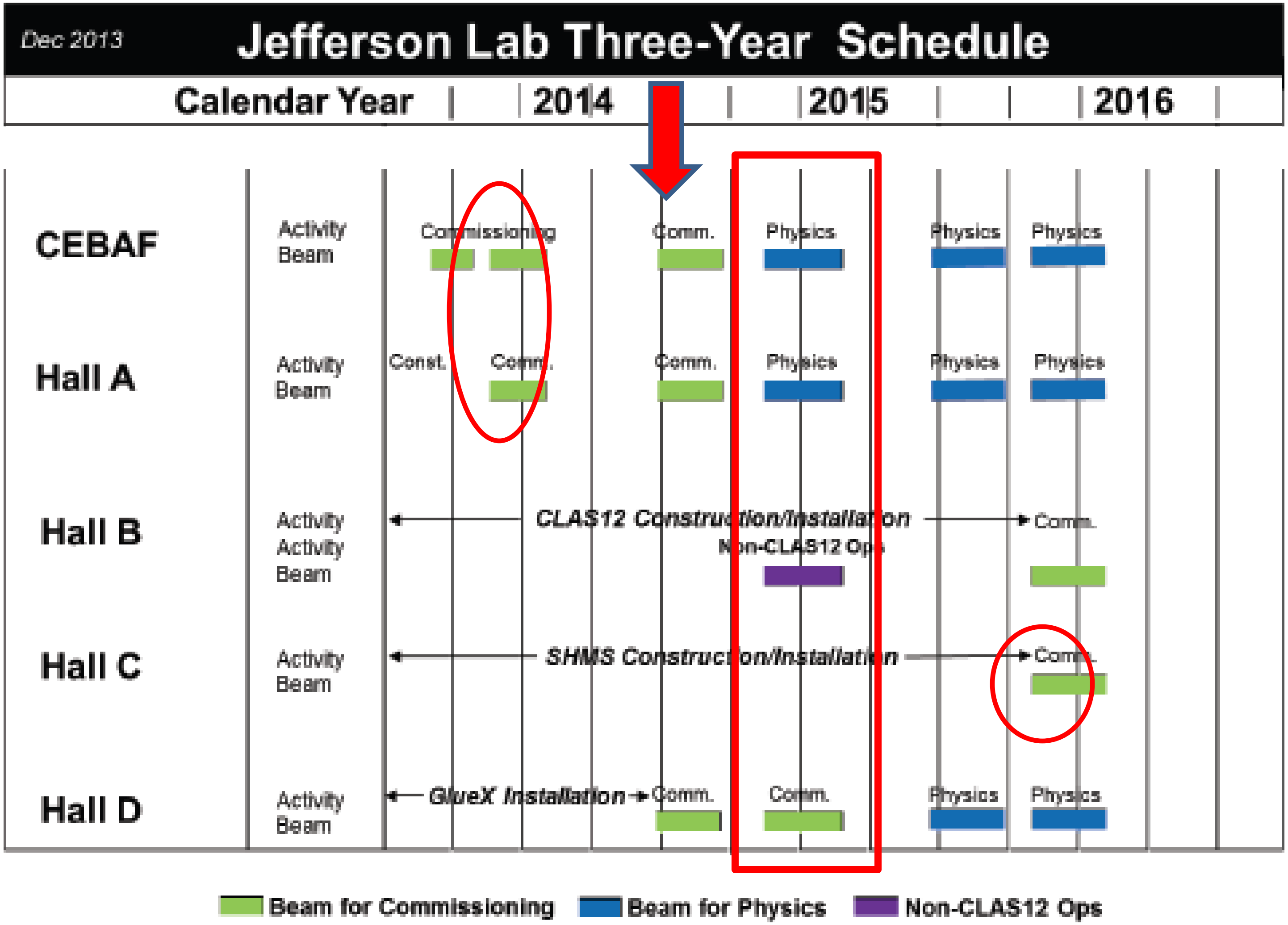
Cryogen distribution cans are installed.

June 2, 2014

Schedule

Mildly obsolete

Three year plan



Approved and Conditional 12 GeV Hall C Experiments

Number	Experiment	Grade	Approved Days	Cond. Days	Non-standard Equipment
E12-06-101	Pion Form Factor	A	52		
E12-06-104	SIDIS R	A-	40		
E12-06-105	x>1	A-	32		
E12-06-121	He3 g_2	A-	29		Polarized He3 target
E12-07-105	(e,e'π) Exclusive Factorizaton	A-	36		
E12-09-011	(e,e'K) Exclusive Factorization	B+	40		
E12-09-017	SIDIS P_t	A-	32		
E12-09-002	Charge Symmetry Violation	A-	22		
E12-10-002	F2 @ large x	B+	13		
E12-10-003	d(e,e'p)	B+	21		
E12-10-008	EMC	A-	23		
E12-06-107	Color Transparency	B+	26		
E12-06-110	He3 A1n	A	36		Polarized He3 target
E12-11-002	He4(e,e'pol(p))	B+	37		FPP in HMS
E12-11-009	Neutron Form Factor	B+	50		Magnet + Neutron polarimeter
E12-11-107	EMC d(e,e' backward p)	B+	40		LAD (Hall B TOF bars)
E12-13-007	SIDIS Pi0	A-	26		Neutral Partical Spect.
E12-13-010	DVCS + Exclusive Pi0	A	53		Neutral Partical Spect.
C12-13-011	Deuteron Tensor SF b1	A-		30	Polarized ND3
			608	30	

Total Days 638 7.3 Years @ 25 Weeks/year

High Impact Experiments (PAC41)

Hall C Early running plans – Year 1

- 2016:
- Precommissioning – detector checkout
- ~25 PAC days – Commissioning "Experiment"
  - 9 days of E12-06-107 search for color transparency
  - A(e,e'p) only – "easy" coincidence measurement
  - E12-10-002 $F_2^{p,d}$ structure functions at large x
  - Momentum scans help understand acceptance
  - 2 days E12-10-108 EMC Effect
  - Integrate light nuclei with F_2 run,
  - Point target helps acceptance studies.
  - 3 days of E12-10-003 d(e,e'p)
  - If time available
  - Push to lower cross sections

JSA

Jefferson Lab

Early running plan – Years 2-3

- 2017:
- E12-09-017 P_t dependence of basic SIDIS cross sections
- Push particle ID capabilities of SHMS
- E12-09-002 Precise $\pi^+\pi^-$ ratios in SIDIS – Charge Symmetry Detector efficiencies
- E12-09-011 L/T separated p(e,e'K+) factorization test
- Easiest L/T separation

- 2018:
- Choose a "High Impact Experiment"?
- E12-06-101 Pion Form Factor (needs well understood SHMS)
- E12-06-105 x>1
- E12-06-110 A_1^n (needs high L ^{3}He)

A_1^n, $F\pi$, GeN?

Example Hall C Experiment

At the 5th Workshop on Hadron Physics in HuangShan last year, I highlighted an experiment to constrain Charge Symmetry Violation in $\pi^{+/-}$ electroproduction.

This year, I've selected the Charged Pion Form Factor whose spokespersons are G. Huber (U. Regina) and D. Gaskell (Jlab).

Slides are from a colloquium by Dave Gaskell.

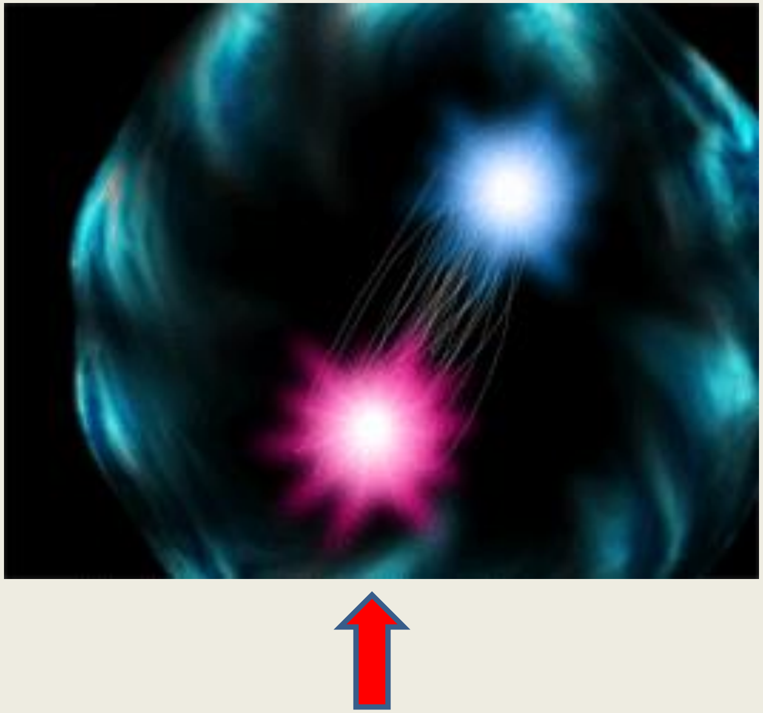
Pion Form Factor

The pion is attractive as a QCD laboratory:

→ Simple, 2 quark system

→ Electromagnetic form factor can be calculated exactly at large momentum transfer (small distances)

→For Q^2 less than the mass of the universe, however, it remains a fun challenge for theorists .



Another perplexing Quark-gluon cartoon to add to Professor Saito's collection.

Downside for experimentalists:

→ No "free" pions

→ Measurements at large momentum transfer difficult

pQCD and the Pion Form Factor

At large Q^2, pion form factor (F_π) can be calculated using perturbative QCD (pQCD)

$$F_\pi(Q^2) = \frac{4}{3}\pi\alpha_s \int_0^1 dx\,dy\,\frac{2}{3}\,\frac{1}{xyQ^2}\,\phi(x)\phi(y)$$

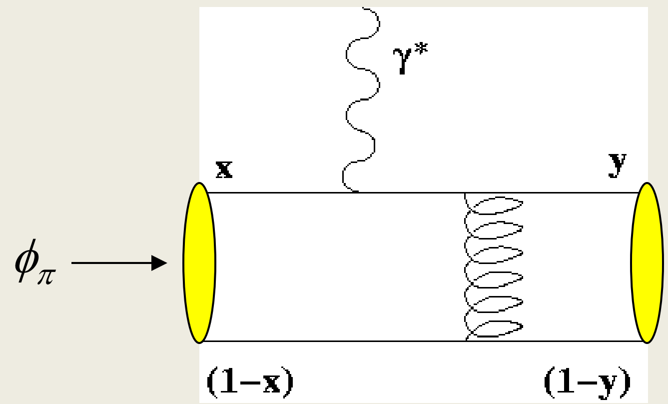
at asymptotically high Q^2,
the pion wave function becomes

$$\phi_\pi(x) \xrightarrow[Q^2\to\infty]{} \frac{3f_\pi}{\sqrt{N_c}}\,x(1-x)$$

and F_π takes the very simple form

$$\boxed{F_\pi(Q^2) \xrightarrow[Q^2\to\infty]{} \frac{16\pi\alpha_s(Q^2)f_\pi^2}{Q^2}}$$

G.P. Lepage, S.J. Brodsky, Phys.Lett. **87B**(1979)359.

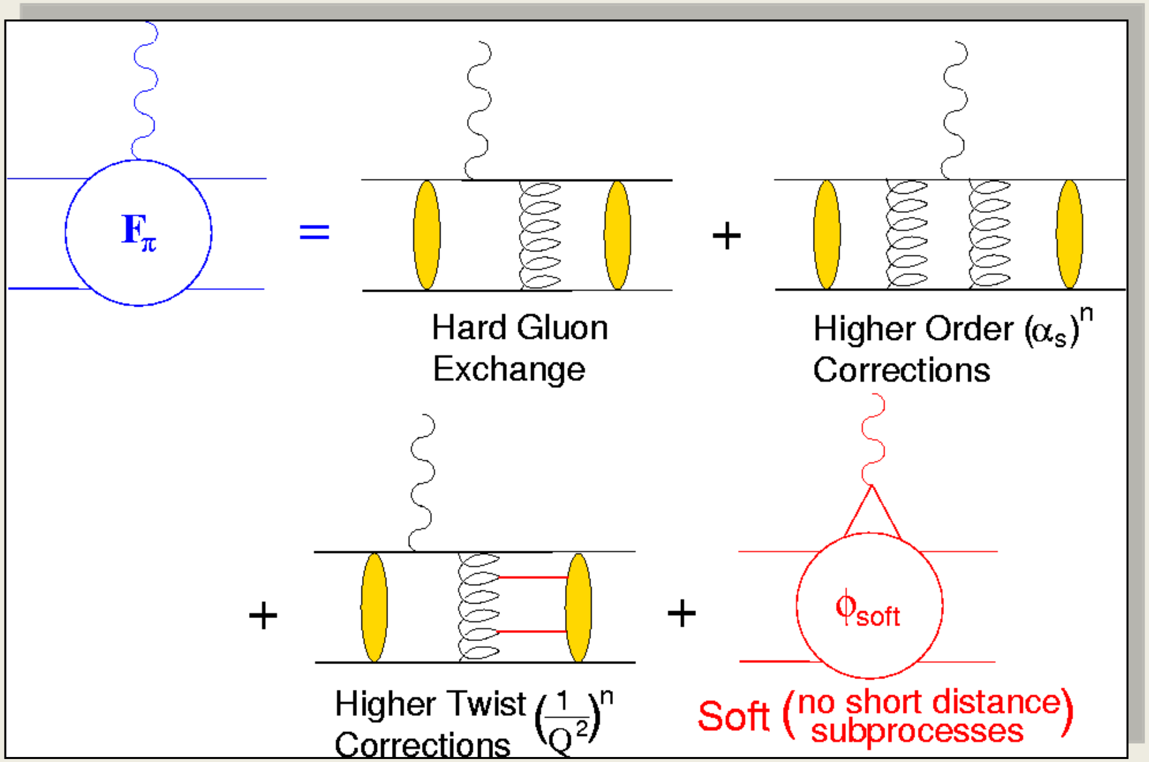


f_π=93 MeV is the $\pi^+ \to \mu^+ \nu$ decay constant.

Pion Form Factor at Finite Q^2

At finite momentum transfer, higher order terms contribute

→ Calculation of higher order, "hard" (short distance) processes difficult, but tractable



There are "soft" (long distance) contributions that cannot be calculated in the perturbative expansion

→Understanding the interplay of these hard and soft processes is a key goal

Measurement of π^+ Form Factor – Low Q^2

At low Q^2, F_π can be measured model-independently via high energy elastic π^- scattering from atomic electrons in Hydrogen

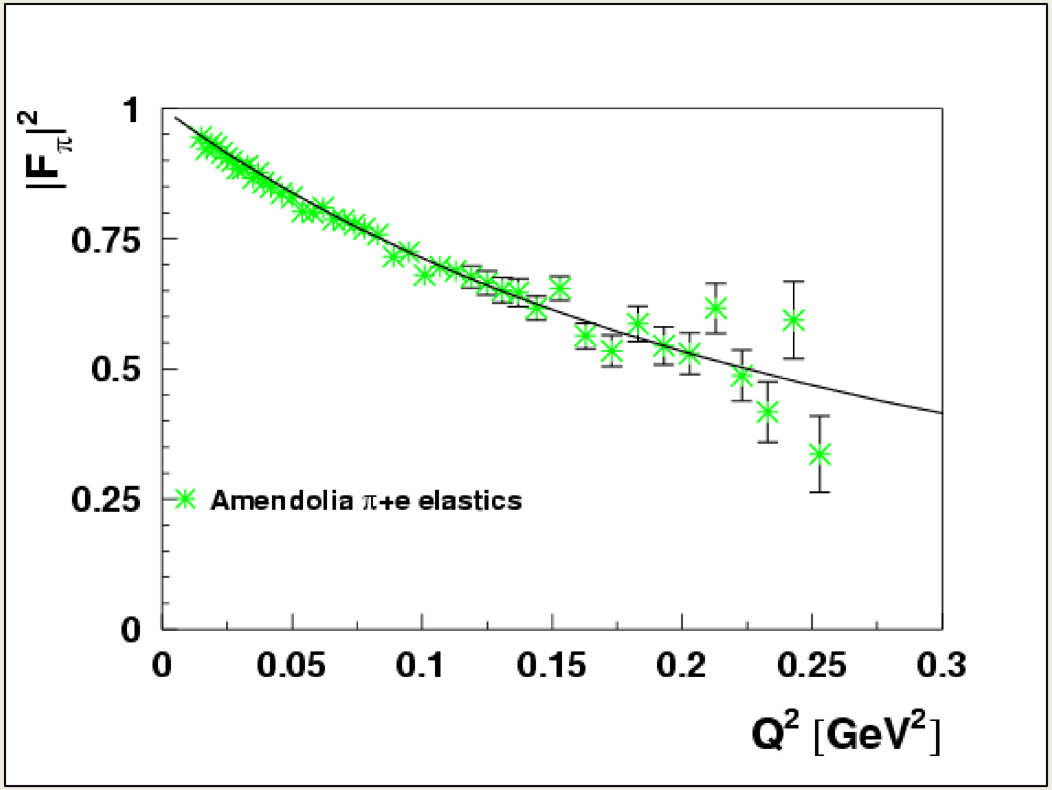
→CERN SPS used 300 GeV pions to measure form factor up to Q^2 = 0.25 GeV^2 *[Amendolia et al, NPB277, 168 (1986)]*

→ Data used to extract pion charge radius

$r_\pi = 0.657 \pm 0.012$ fm

Maximum accessible Q^2 roughly proportional to pion beam energy

Q^2=1 GeV^2 requires 1 TeV pion beam



Measurement of π^+ Form Factor – Larger Q^2

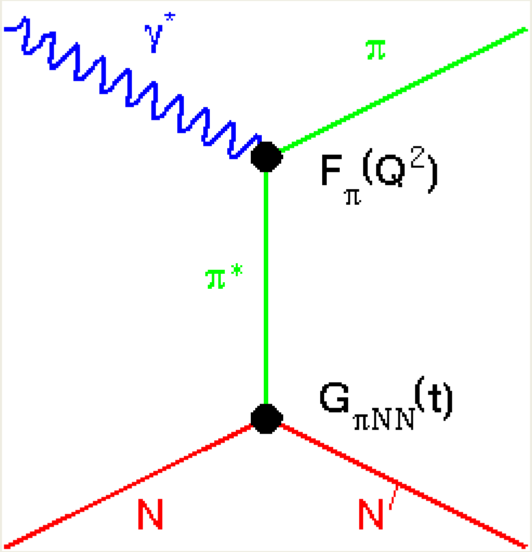
At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion $p(e,e'\pi^+)n$

→ $|p\rangle = |p\rangle_0 + |n\,\pi^+\rangle + \ldots..$

→At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L

→In Born term model, $F_\pi^{\,2}$ appears as,

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)}\; g_{\pi NN}^2(t)\, F_\pi^2(Q^2,t)$$



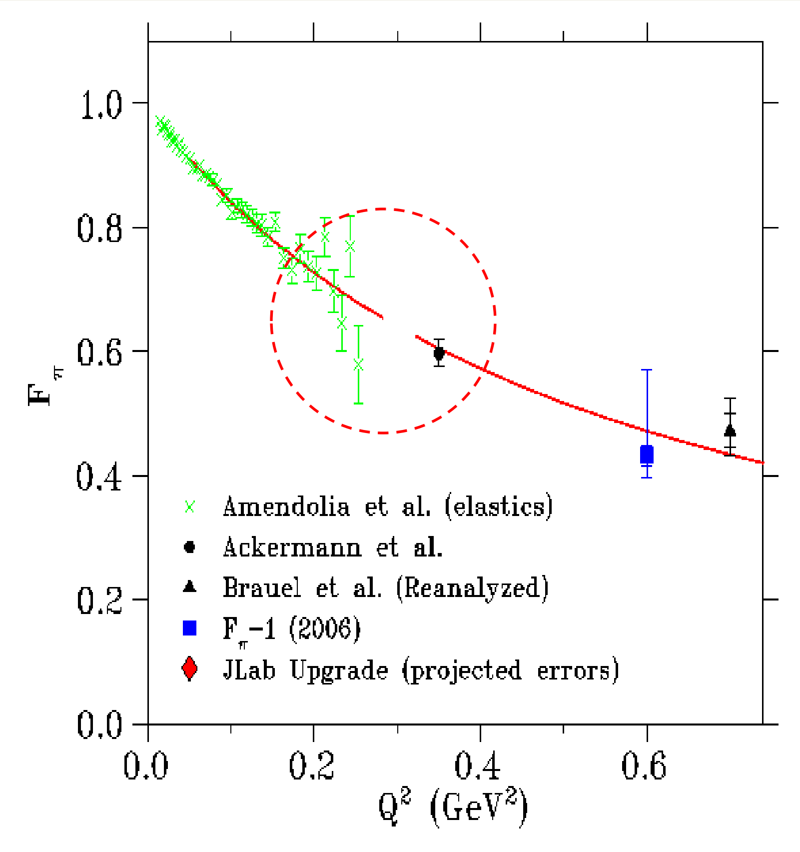
Drawbacks of this technique

1. Isolating σ_L experimentally challenging
2. Theoretical uncertainty in form factor extraction.

Check of Pion Electroproduction Technique

- Does electroproduction really measure the on-shell form-factor?
- Test by making *p(e,e'π^+)* measurements at same kinematics as *π+e* elastics

Can't quite reach the same Q^2, but electro-production appears consistent with extrapolated elastic data



An improved test will be carried out after the JLAB 12 GeV upgrade

→ **smaller *Q^2* *(=0.30* GeV^2)**

→ ***-t* closer to pole (*=0.005* GeV^2)**

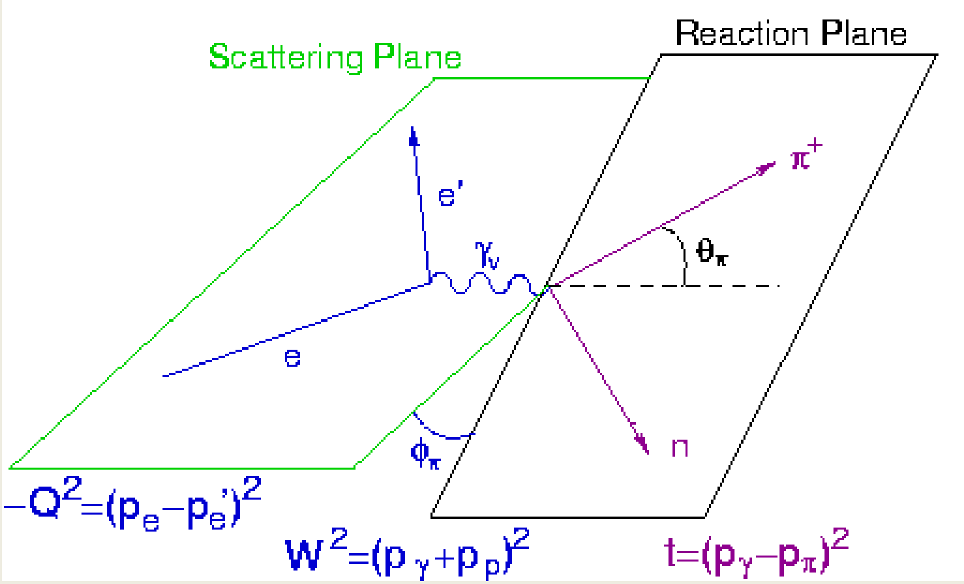
Pion Electro-production Cross Section

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

For electroproduction, $t<0$

Magnitude of $-t$ smallest when pion emitted along direction of virtual photon

At fixed W, $-t_{min}$ increases as Q^2 increases



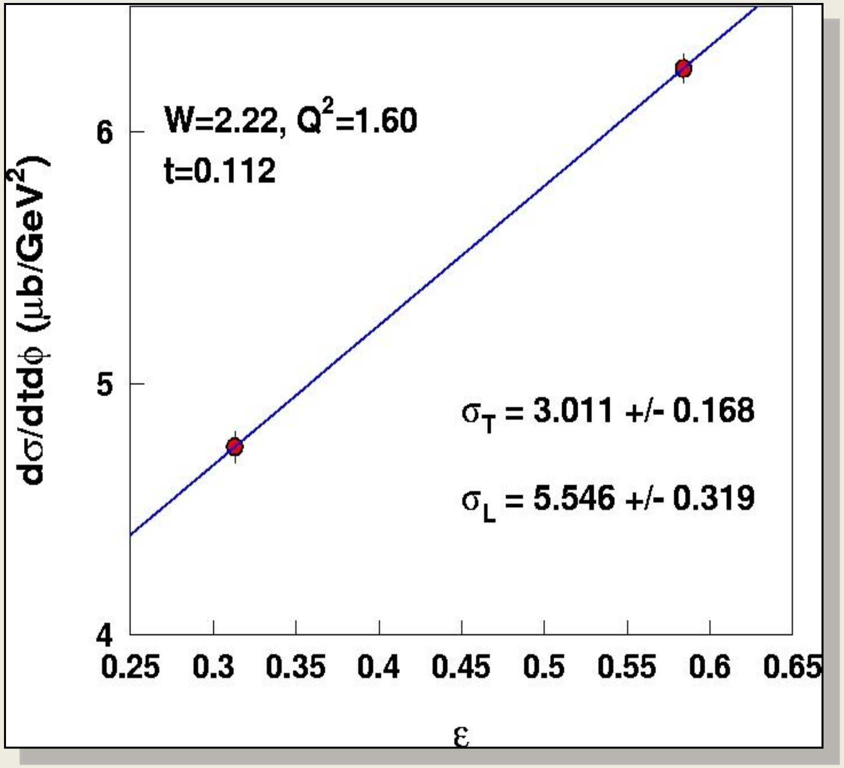
At small $-t$, the pion pole process dominates σ_L

F_π^2 in Born term model

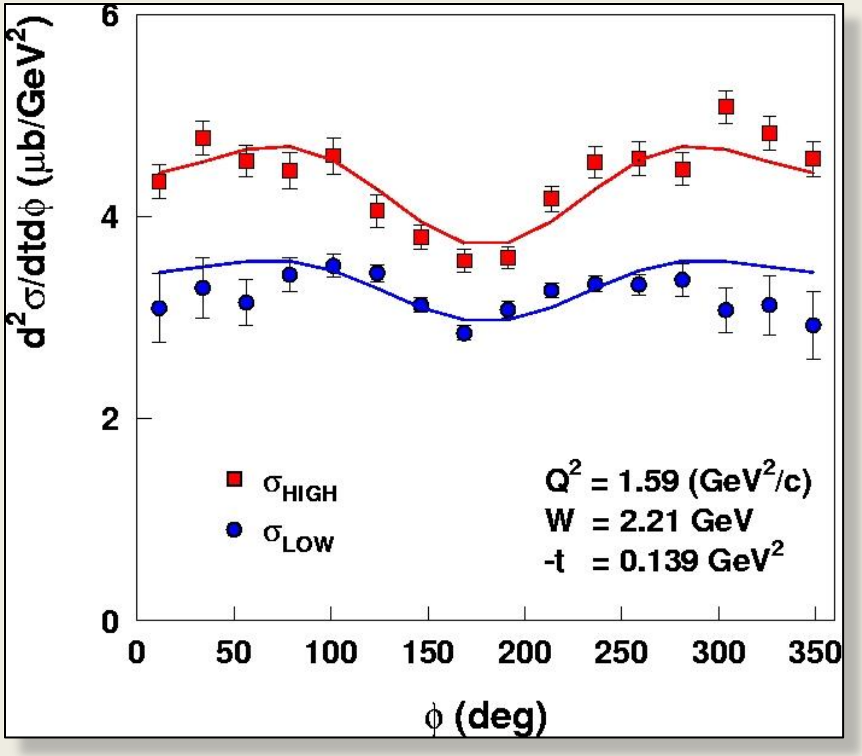
$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)} g_{\pi NN}^2(t)\, F_\pi^2(Q^2,t)$$

Extracting the Longitudinal Xsect σ_L

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

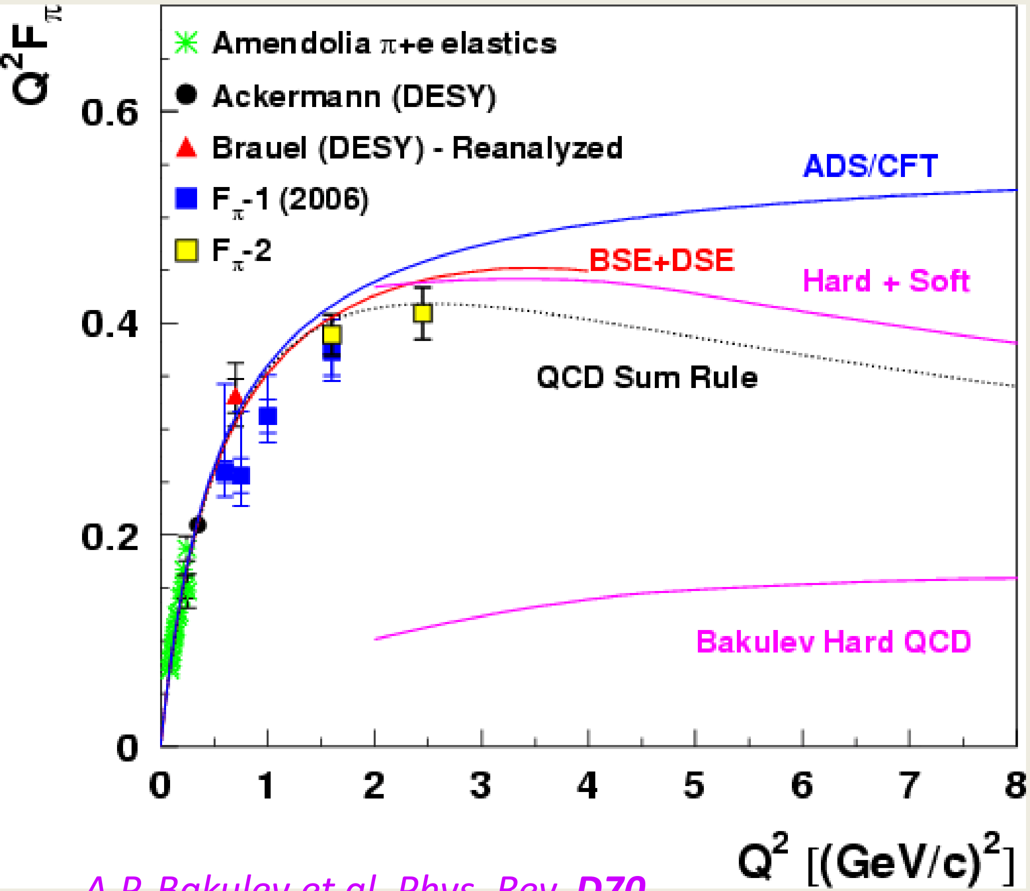


Simple extraction – no ***LT/TT*** terms



4-parameter fit: ***L/T/TT/LT***

$F_{\pi+}(Q^2)$ Models



A.P. Bakulev et al, Phys. Rev. ***D70*** *(2004)*

Maris and Tandy, Phys. Rev. ***C62****, 055204 (2000)*

→ relativistic treatment of bound quarks (Bethe-Salpether equation + Dyson-Schwinger expansion)

Nesterenko and Radyushkin, Phys. Lett. ***B115****, 410(1982)*

→ Green's function analyticity used to extract form factor

Brodsky and de Teramond, hep-th/0702205

→ Anti-de Sitter/Conformal Field Theory approach

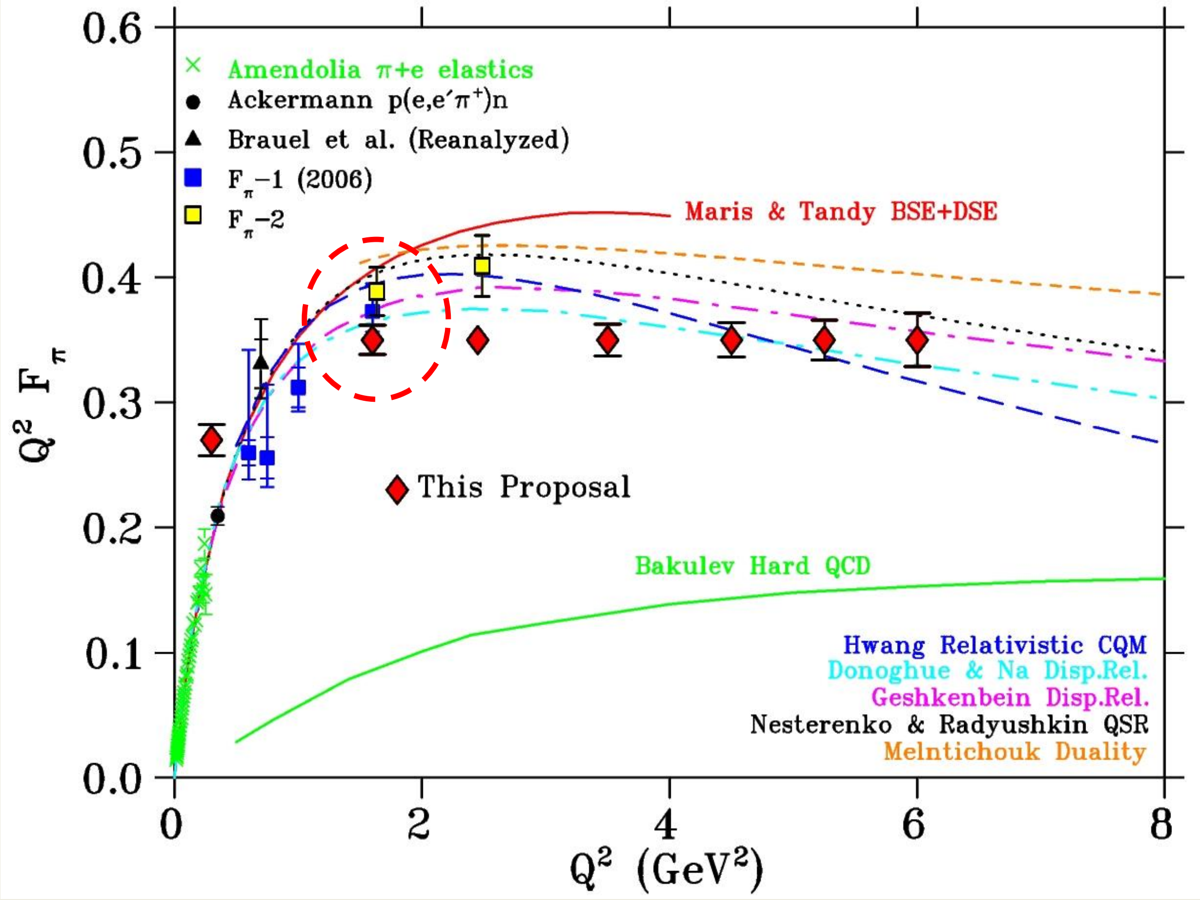
$F_\pi(Q^2)$ after JLAB 12 GeV Upgrade

JLab 12 GeV upgrade will allow measurement of F_π up to $Q^2 = 6$.

No other facility can do this measurement.

New overlap point at $Q^2=1.6$ will be closer to pole to constrain $-t_{min}$ dependence

New low Q^2 point will provide best comparison of the electroproduction extraction of F_π vs elastic π+e data.



Approved with "A" scientific rating – awarded 52 days (G. Huber and D. Gaskell, spokespersons)

Acknowledgements

- Hall A/C colleagues for slides and/or discussions:

Dave Gaskell, Howard Fenker, Cynthia Keppel, and Steve Wood.

- The organizers of this workshop and their support staff.

- Jlab management for supporting this conference and my travel.

Extras

Model for F_π Extraction

Model is required to extract $F_\pi(Q^2)$ from σ_L

Model incorporates π^+ production mechanism and spectator neutron effects:

1. The experimentalist would like to use a variety of models to extract $F_\pi(Q^2)$ from the electroproduction data, so that the model dependence can be better understood.

2. The Vanderhaeghen-Guidal-Laget (VGL) Regge model *[Vanderhaeghen, Guidal, Laget, PRC 57, 1454 (1998)]* is the only reliable model available for our use at present.

3. It would be useful to have additional models for the pion form factor extraction.

The experimental $F_\pi(Q^2)$ result is not permanently "locked in" to a specific model.

F_π Extraction from JLab data

VGL Regge Model

Feynman propagator replaced by π and ρ Regge propagators

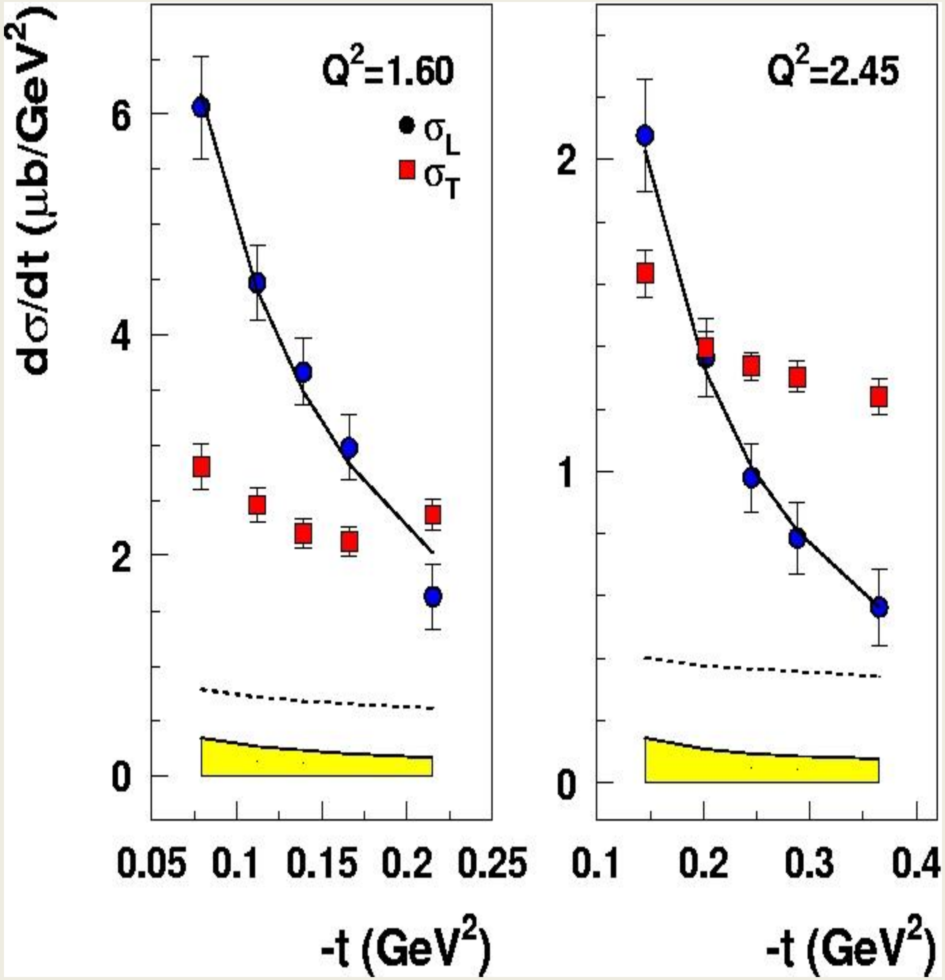
→Represents the exchange of a series of particles, compared to a single particle

Model parameters fixed from pion photoproduction

Free parameters: Λ_π, Λ_ρ (trajectory cutoff)

$$F_\pi(Q^2) = \frac{1}{1 + Q^2/\Lambda_\pi^2}$$

Horn et al, PRL97, 192001,2006



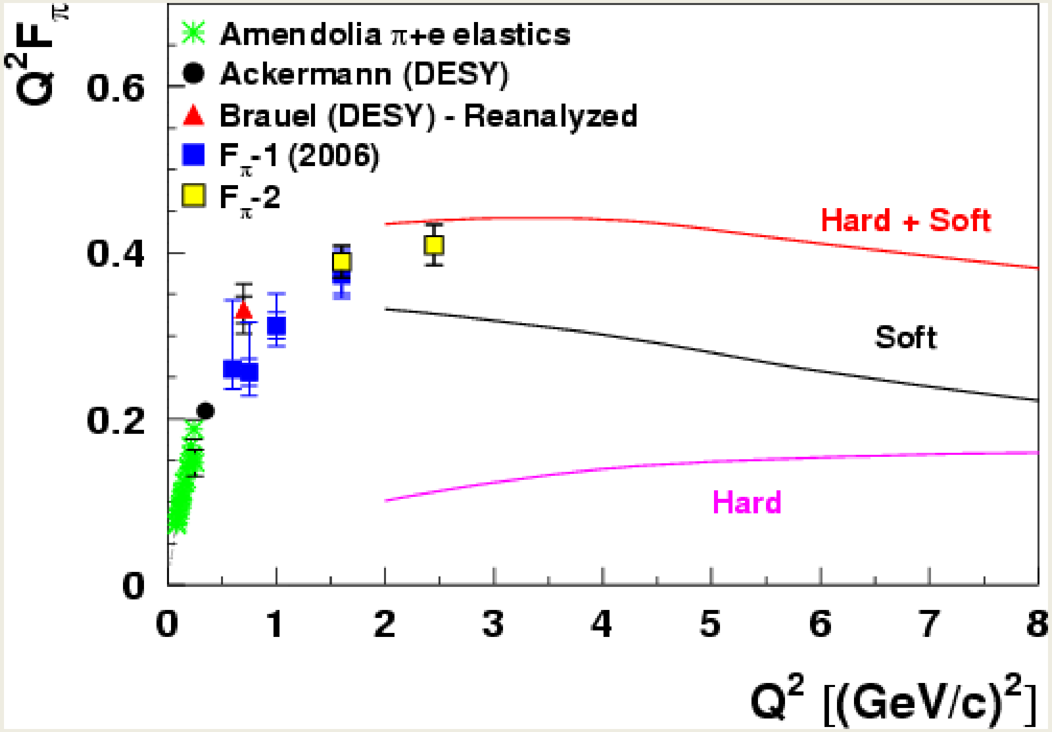
Λ_π^2=0.513, 0.491 GeV^2, Λ_ρ^2=1.7 GeV^2

pQCD and the Pion Form Factor

Calculation including only perturbative contributions dramatically under-predicts form factor

Good agreement with data only achieved after including "soft" model dependent contribution

→Modeled using "local duality" – equivalence of hadronic and partonic descriptions



$$F_\pi = \int (\text{Free quark spectral density})$$

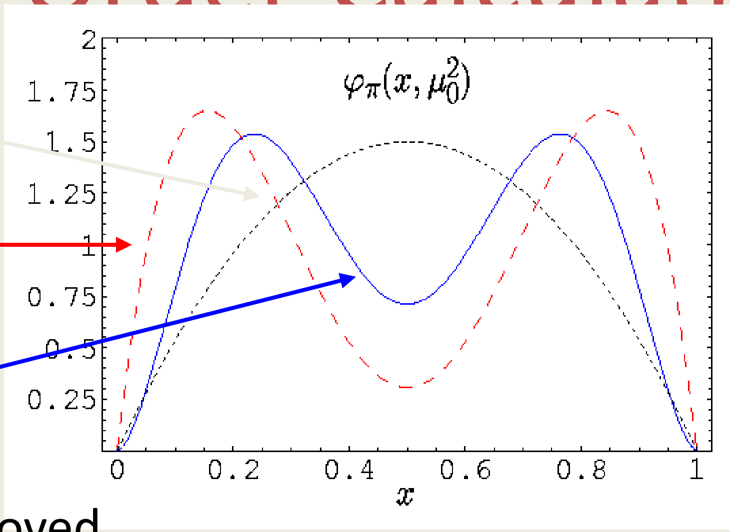
A.P. Bakulev, K. Passek-Kumericki, W. Schroers, & N.G. Stefanis, PRD **70** (2004) 033014.

pQCD Higher Order Calculation

Asymptotic DA

Chernyak-Zhitnitsky DA (QCD sum rule)

Improved DA



Asymptotic form of F_π can be improved

→Include higher order terms, i.e., more than just 1 gluon exchange

→Use pion wave function (Distribution Amplitude) more appropriate to lower Q^2

DA constrained by $\gamma^*\gamma \rightarrow \pi^0$ (old) transition form factor data

Even this improved calculation dramatically underpredicts F_π at moderate Q^2

A.P. Bakulev, K. Passek-Kumericki, W. Schroers, & N.G. Stefanis, PRD **70** (2004) 033014.

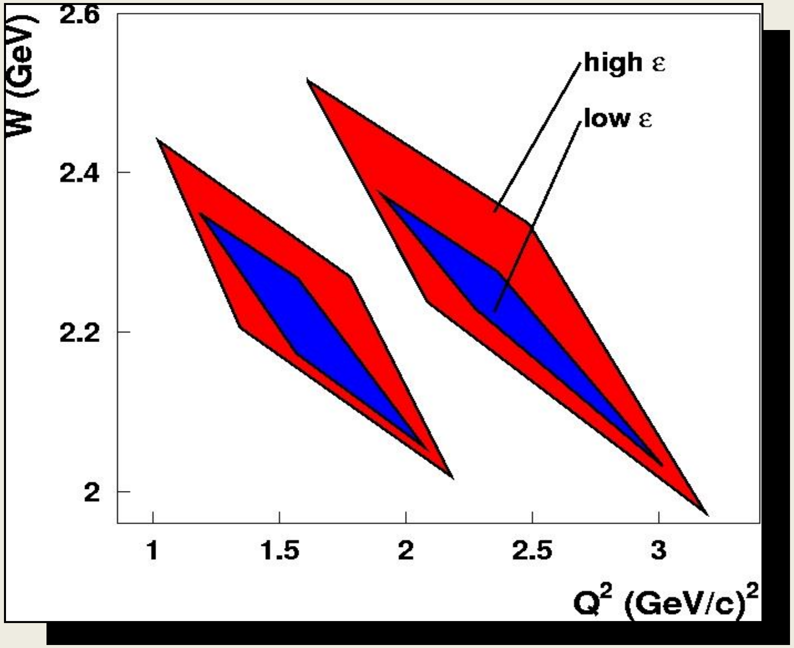
Rosenbluth Separation and Kinematics

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

To isolate $\boldsymbol{\sigma_L}$, need to vary virtual photon polarization, $\boldsymbol{\varepsilon}$
→ Make measurements at multiple values of electron beam energy and scattering angle

$$\sigma_L = \sigma_L(Q^2, W, -t)$$

At each value of $-t$, must keep Q^2 and W constant



Proposing Experiments at Jlab 12 GeV

If you have a great idea for one of our end-stations, you can propose it to our Program Advisory Committee (PAC). Your proposal will be judged on the merit of the physics as well as the technical feasibility. An internal co-spokesperson may be helpful but is *not* required.

A tremendous amount of information can be gain from our website at

http://www.jlab.org/

and looking under topics such as “Nuclear Physics”, “Experiment Research”, and “12 GeV Upgrade”.

Proposals now mostly fall into two categories: standard 12 GeV equipment, or major new apparatus. Proponents are expected to help build or commission standard 12 GeV equipment as well as new apparatus.

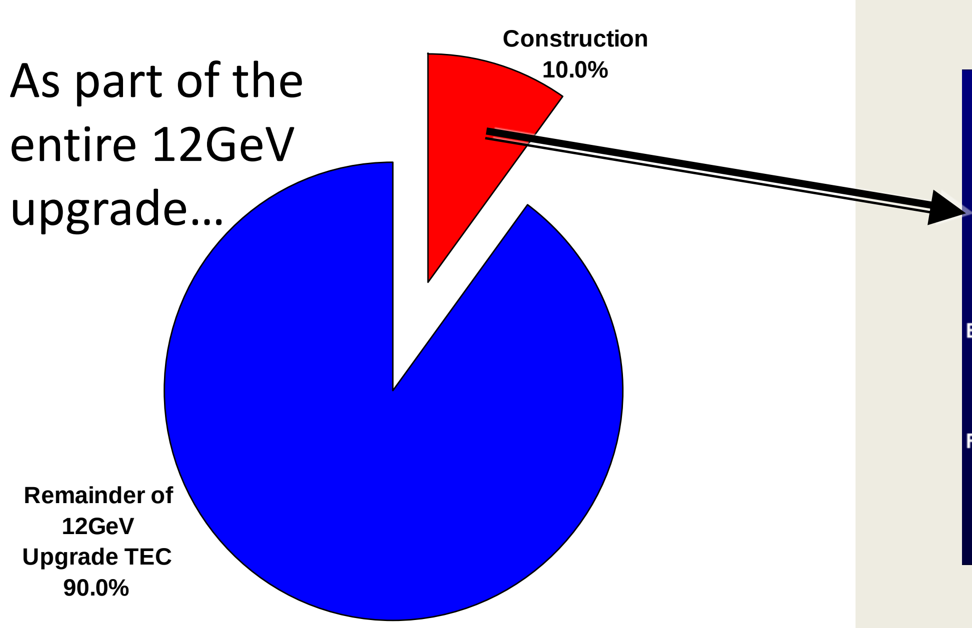
Of course, funding, manpower (both collaboration and Jlab), and multi-endstation scheduling issues will eventually be looked at carefully.

SHMS Design Parameters

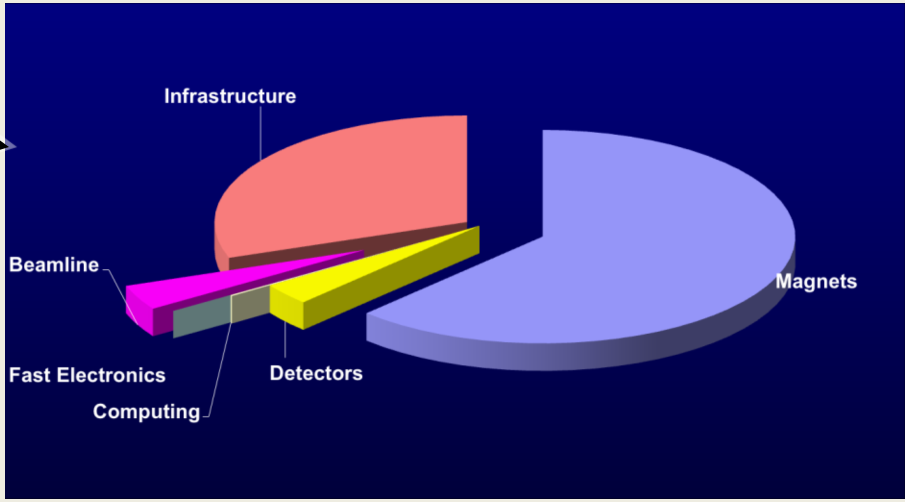
Parameter	SHMS Design
Range of Central Momentum	2 to 11 GeV/c for all angles
Momentum Acceptance δ	-10% to +22%
Momentum Resolution	0.03-0.08% (SRD: "<0.2%")
Scattering Angle Range	5.5 to 40 degrees
Solid Angle Acceptance	>4.5 msr for all angles (SRD: ">4.0 msr")
Horizontal Angle Resolution	0.5 - 1.2 mrad
Vertical Angle Resolution	0.3 - 1.1 mrad
Vertex Length Resolution	0.1 - 0.3 cm

Hall C Upgrade Costs

As part of the entire 12GeV upgrade…

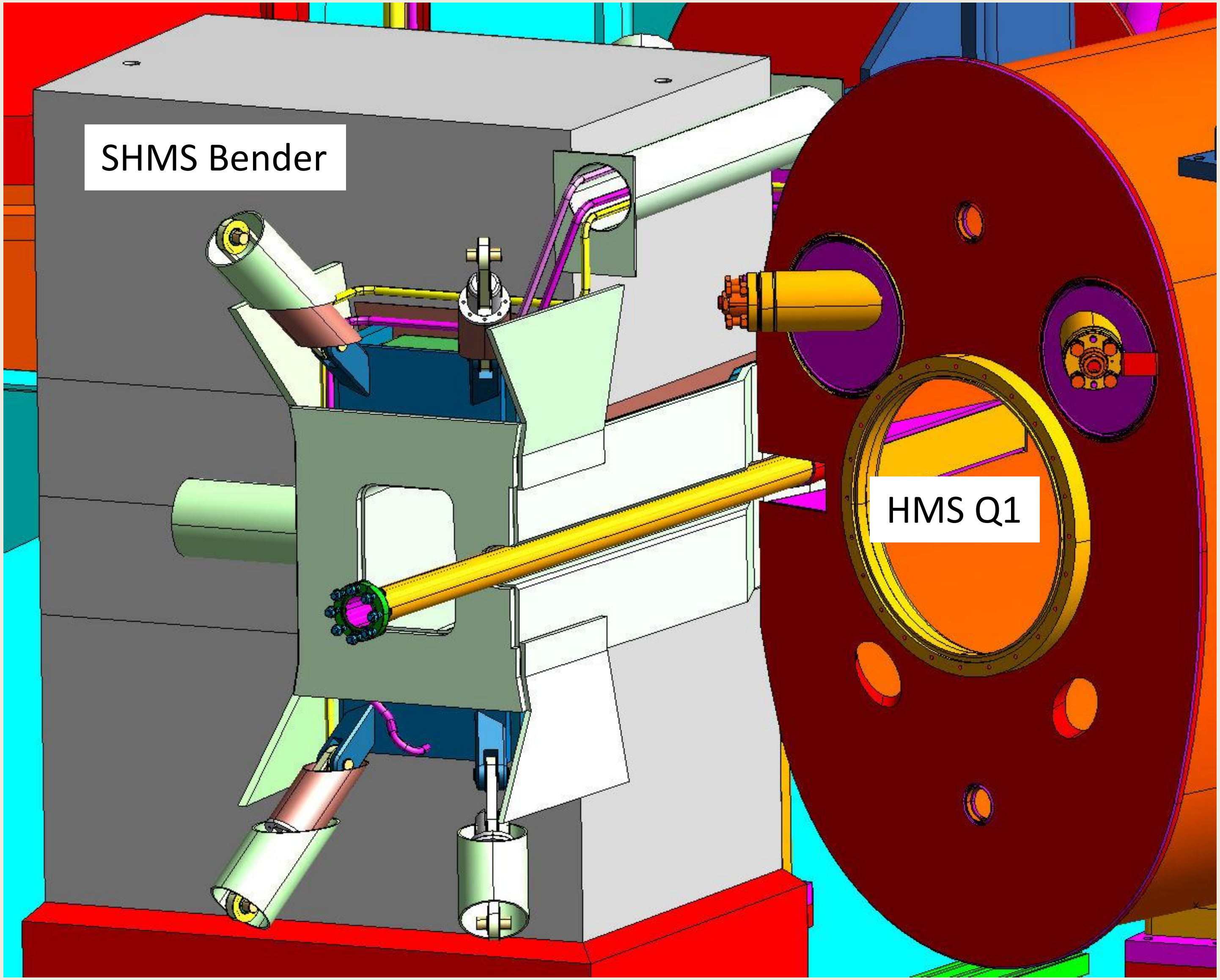


By Subsystem…



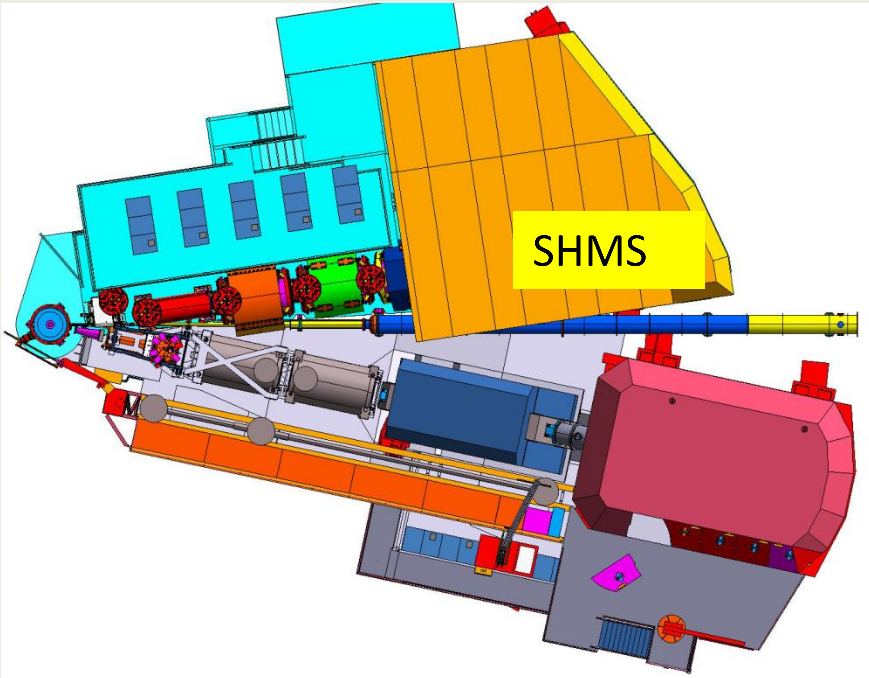
WBS 1.4.3	Hall C Construction	FY09 $K Direct
1.4.3.1	Magnets	12,249
1.4.3.2	Detectors	649
1.4.3.3	Computing	32
1.4.3.4	Electronics	-
1.4.3.5	Beamline	751
1.4.3.6	Infrastructure	5,989
	Total	19,670

Bender Fit to HMS Q1

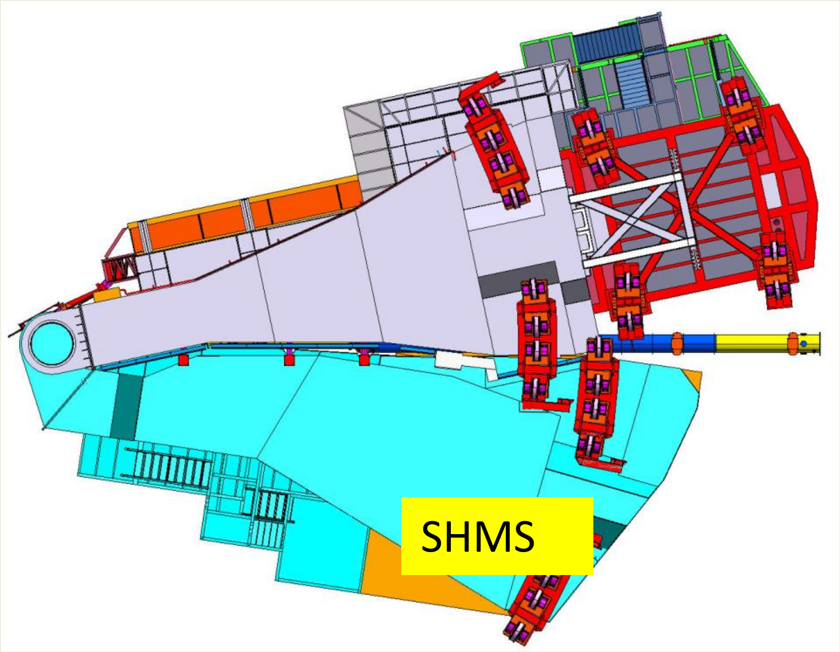


Getting Both Spectrometer to Small Angles

<u>Top View</u>

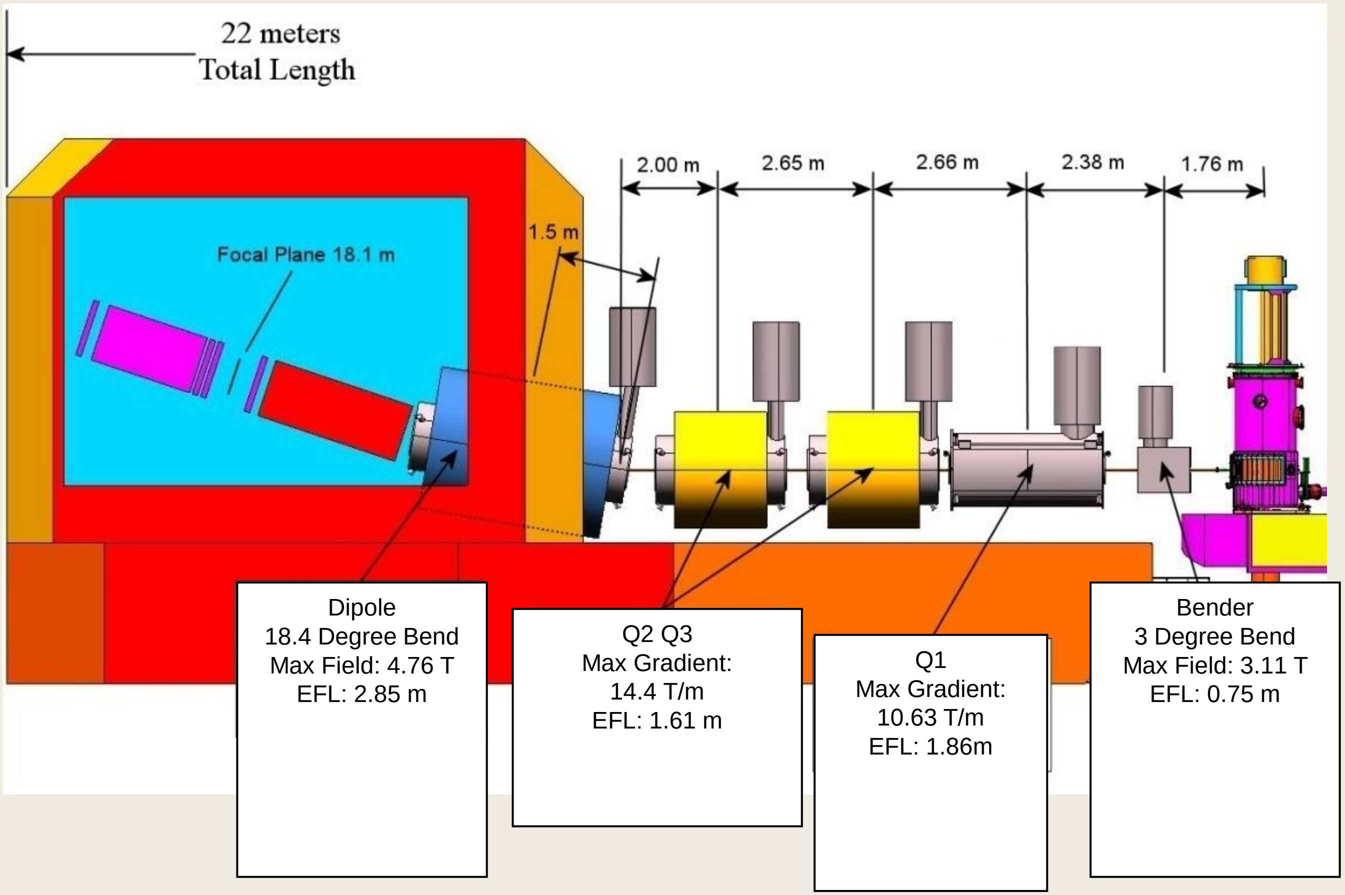


<u>Bottom View</u>

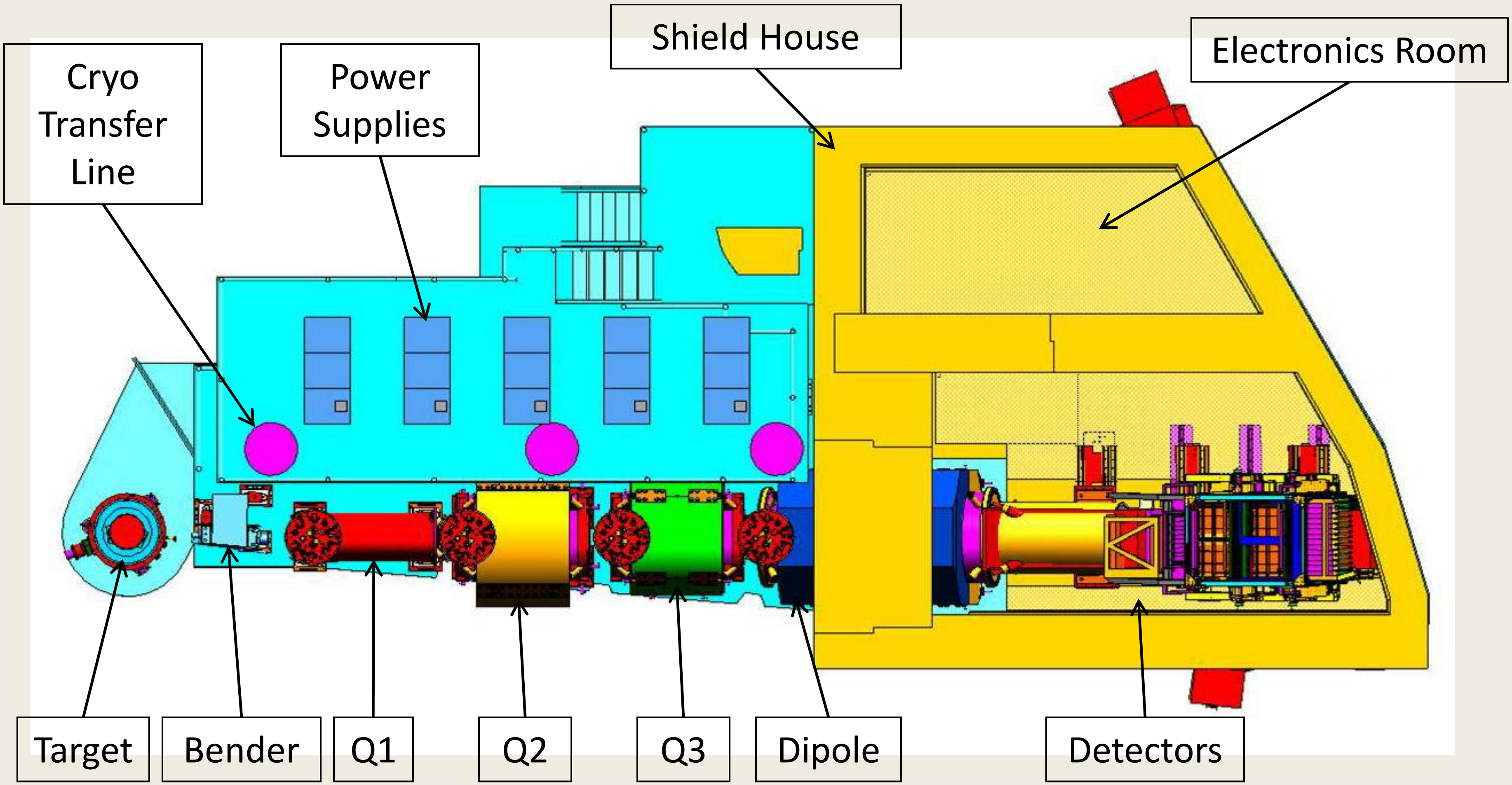


… an incredible 3-dimensional jigsaw puzzle for our engineers and designers.

SHMS Elements

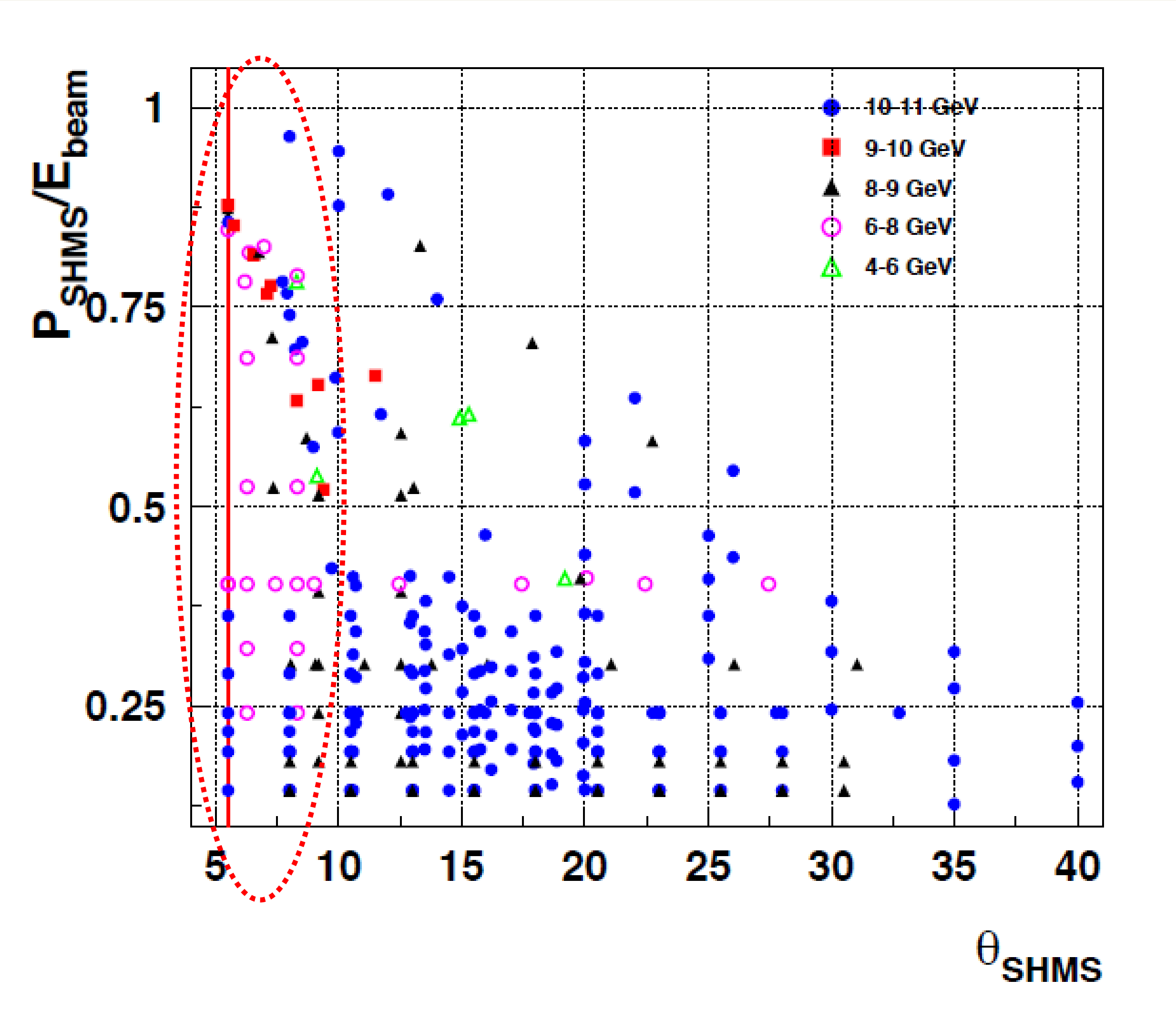


SHMS



Cryo Transfer Line
Power Supplies
Shield House
Electronics Room
Target
Bender
Q1
Q2
Q3
Dipole
Detectors

Kinematics of Some Approved Hall C Proposals



Summary

I've tried to introduce some of the standard apparatus for Hall C at 12 GeV. More detailed information on the SHMS can be obtained at

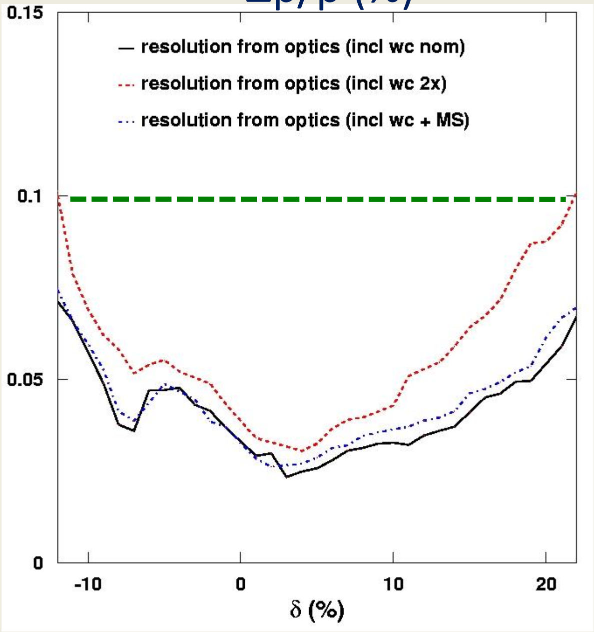
http://www.jlab.org/Hall-C/upgrade/index.html

SHMS Experiment Resolution Requirements

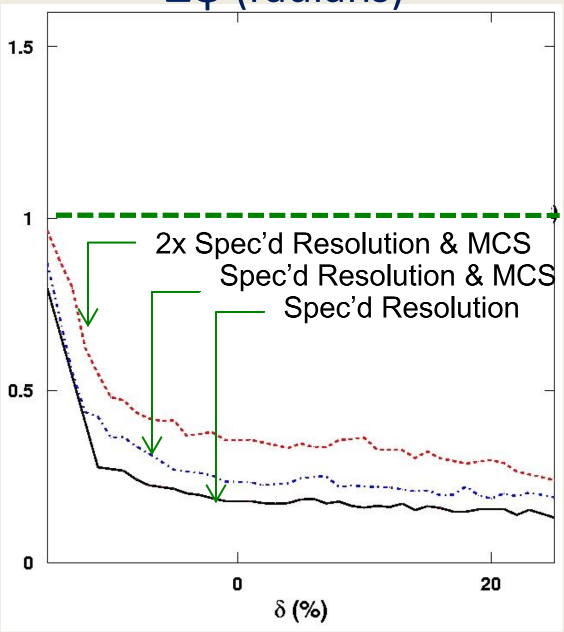
Experiment	p (GeV/c)	Δp/p (%)	Δθ (rad)	Δφ (rad)
Pion Form Factor (12-06-101)	**2.2-8.1**	**$2x10^{-3}$**	**$1.5x10^{-3}$**	**$1.5x10^{-3}$**
Transition Form Factors*	1.0-8.5	$1x10^{-3}$	$1.0x10^{-3}$	$1.0x10^{-3}$

* Not yet submitted to PAC

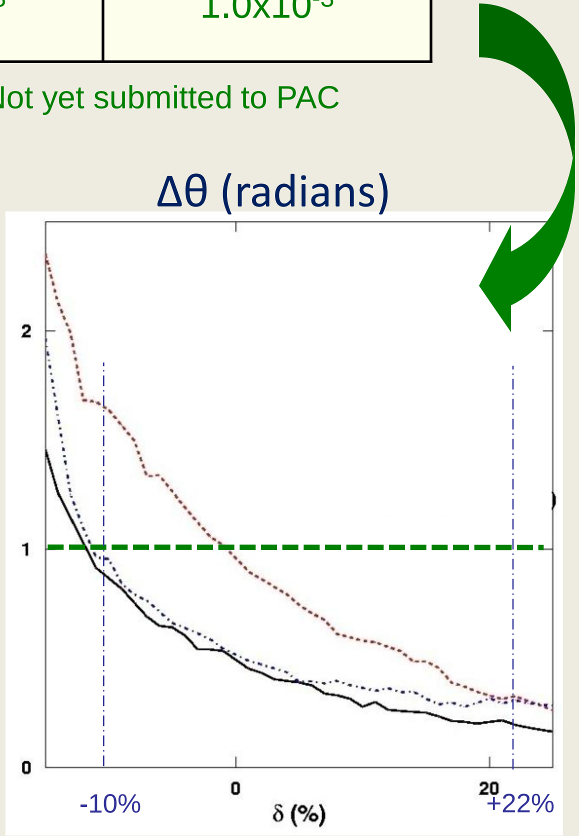
Δp/p (%)



Δϕ (radians)



Δθ (radians)



Misc shms detector slides

P… he SH… ctors

Noble Gas Cerenkov

Drift Chambers

Trigger Hodoscopes

- 3 Planes Scintillator
- 1 Plane Quartz

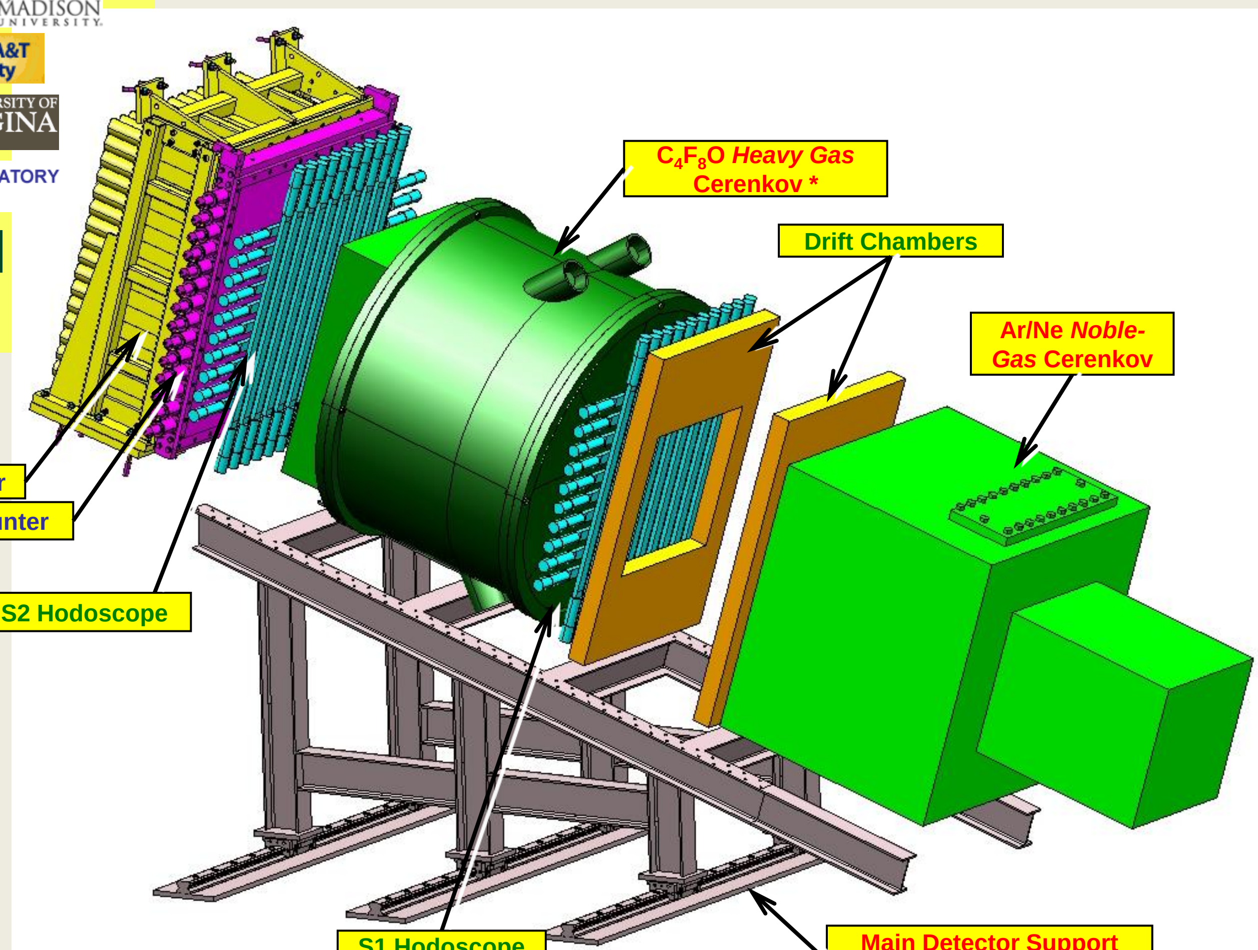
Heavy Gas Cerenkov*

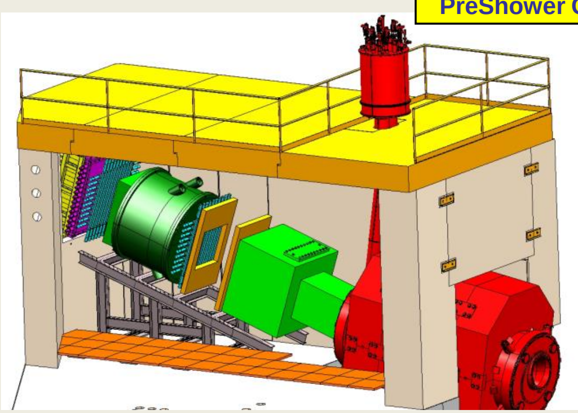
Calorimeter

Detector Frames

*HGC is largely funded by NSERC grant to U. Regina

(Funding Color Codes)
12 GeV Project Funded
NSF MRI Funding
Gift from NIKHEF and NSL





The SHMS Detector System

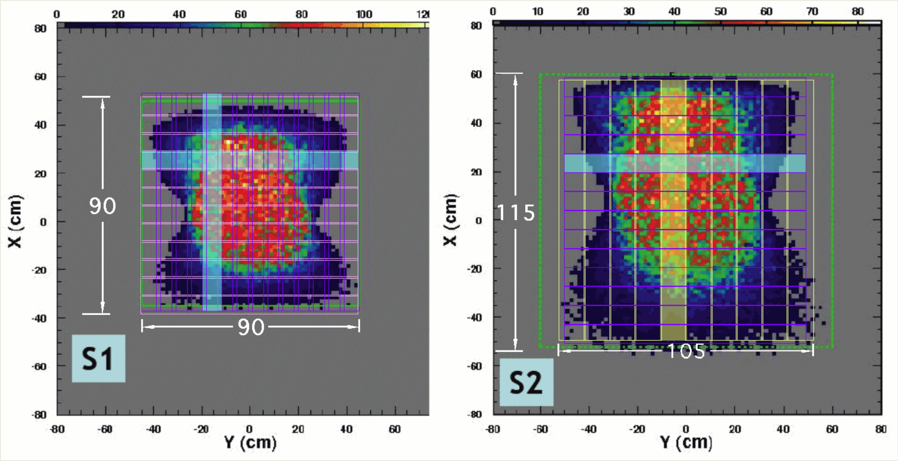
Trigger Hodoscopes: basic trigger; efficiency determination.

- 3 Planes Scintillator Paddles + 1 Plane Quartz Bars

S1X: 12 bars 8cm x 110 cm x 5mm
S1Y: 14 bars 8cm x 90cm x 5mm
S2X: 14 bars 8cm x 105cm x 5mm

S2Y: 10 quartz bars: 11cm 115cm x 2.5 cm

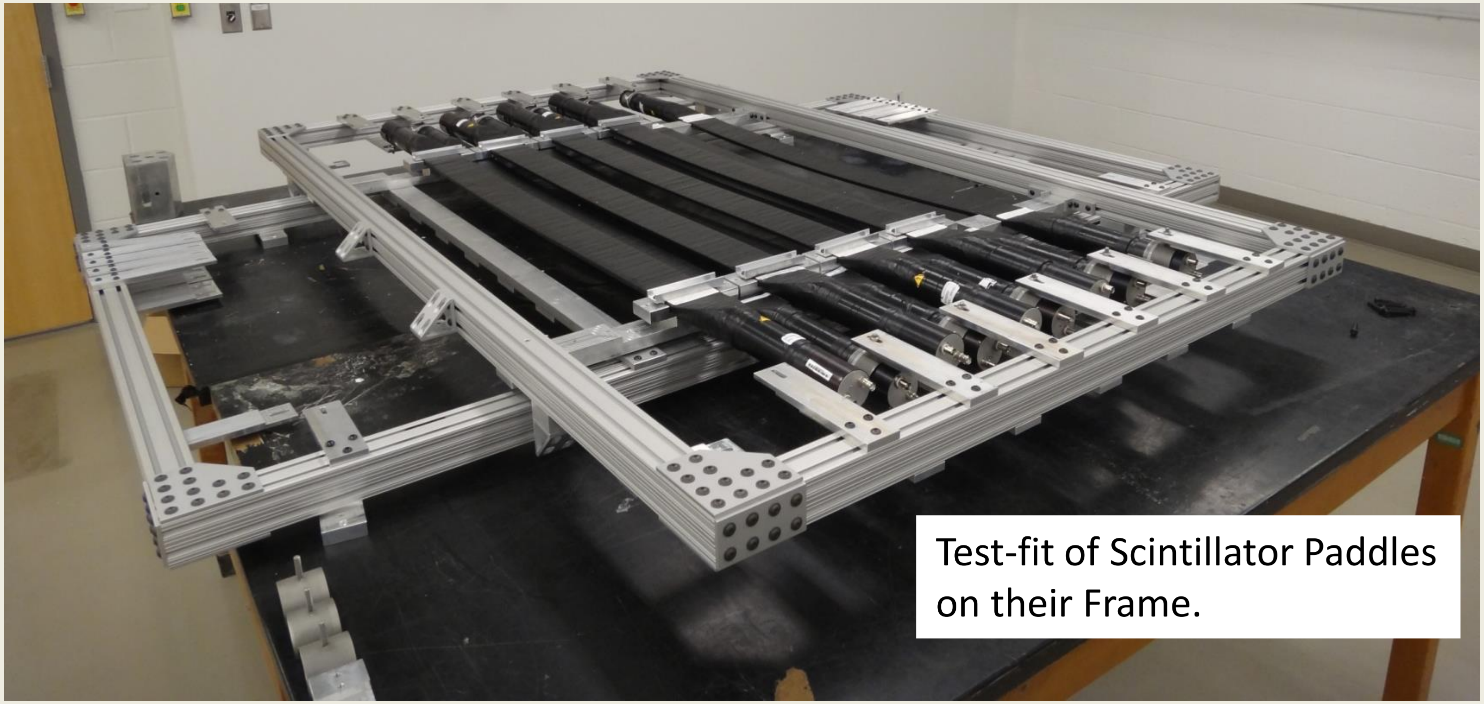
0.5 cm overlap / 2 PMTs on each bar



Detector Frames

"FRAMES" HOLD DETECTOR ELEMENTS TOGETHER AS A UNIT

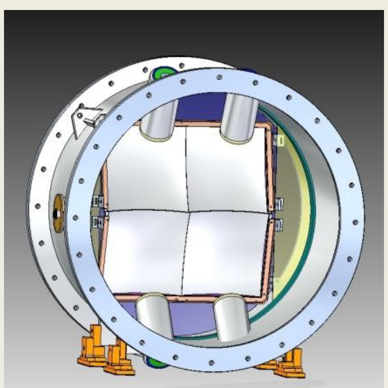
- Frames for Hodoscopes and for Drift Chambers
- Responsibility: College of William and Mary
- Funded by NSF MRI 2008-2011
- Status
  - Complete



Test-fit of Scintillator Paddles on their Frame.

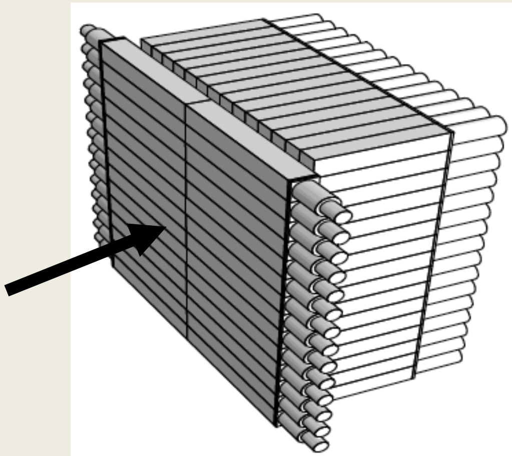
Heavy-Gas Cerenkov

- Sub-atmospheric to Atmospheric C_4F_8O
- Responsibility: University of Regina
- Funding:
  - Almost entirely on NSERC grant
  - 12-GeV scope: Mirror aluminization & related items
- Status
  - Arrived at JLab in June, 2013.
    - Mirrors Installed & Aligned. Windows attached. Tank leak-checked.
  - Complete



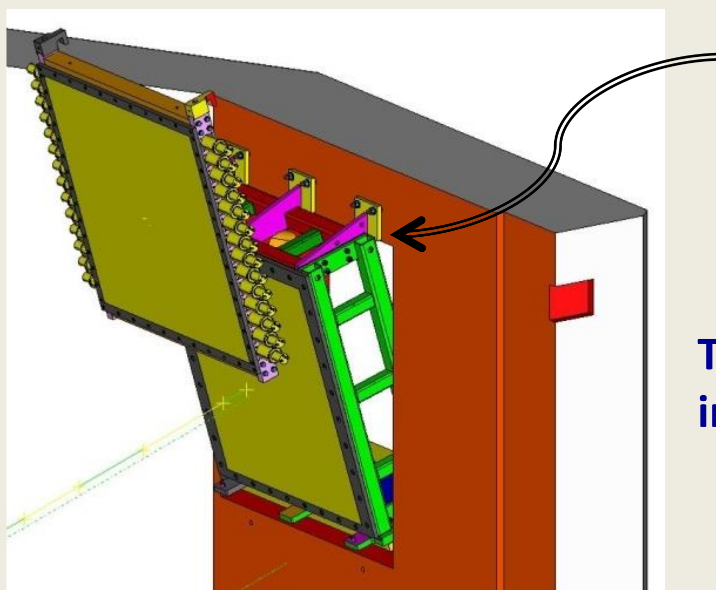
Calorimetry

- Shower Counter: 228 HERMES Pb-Glass Blocks
  - Sit in a window in the rear wall of the SHMS shield house
- Preshower: 24 re-used SOS Pb-Glass Blocks
  - Sit in frame attached to interior of rear shield house wall
- Provided by Yerevan / NSL. HERMES blocks arrived in 2008.
- Yerevan team has…
  - Characterized performance of each module and logged results to database.
  - Revised optical joints, wrapping, etc.
  - Optimized MC and analysis software.
- Status: Complete



HERMES Modules

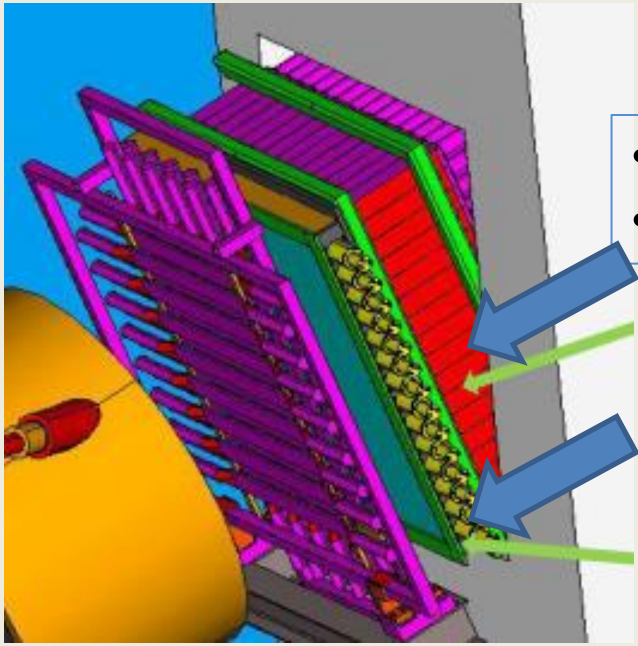
Preshower Counter



This detector has been ready to install since 2010.

Published!
NIM A 719 (2013) 85

Calorimeter (NSL Yerevan)

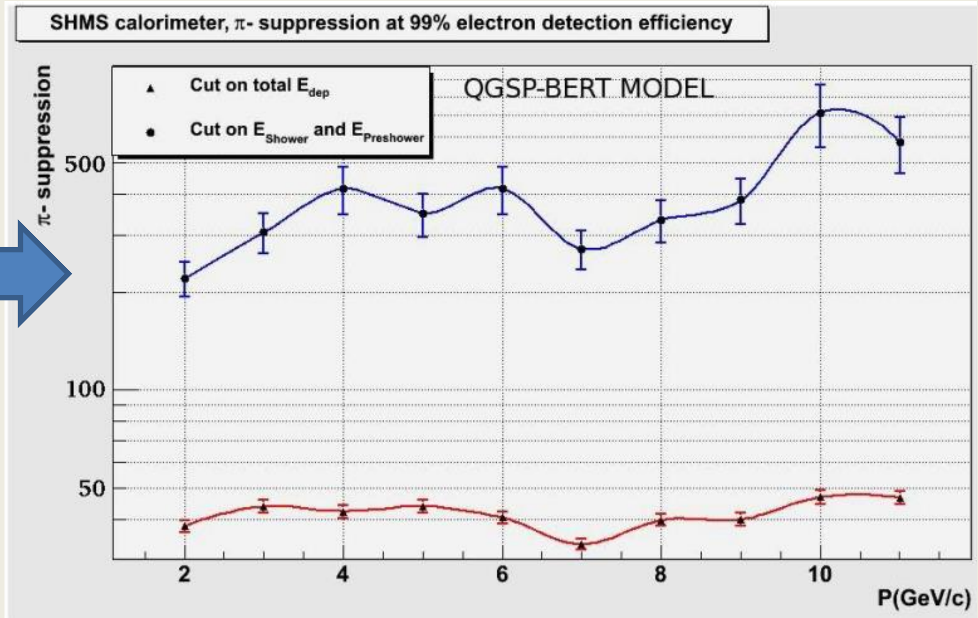


- Shower made from 250 blocks from Hermes
- Refurbished and tested

- Preshower made from 30 blocks from Hall C SOS
- Each 10x10x70 cm^3

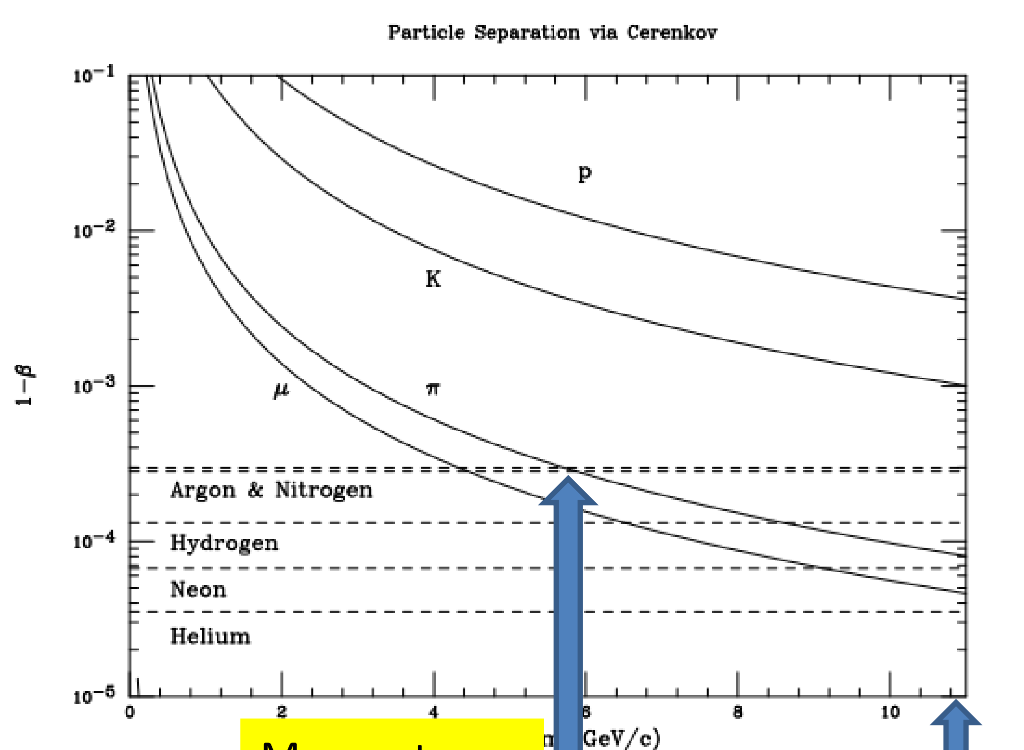
GEANT4 simulation
of π^- suppression

250:1 at all momentum



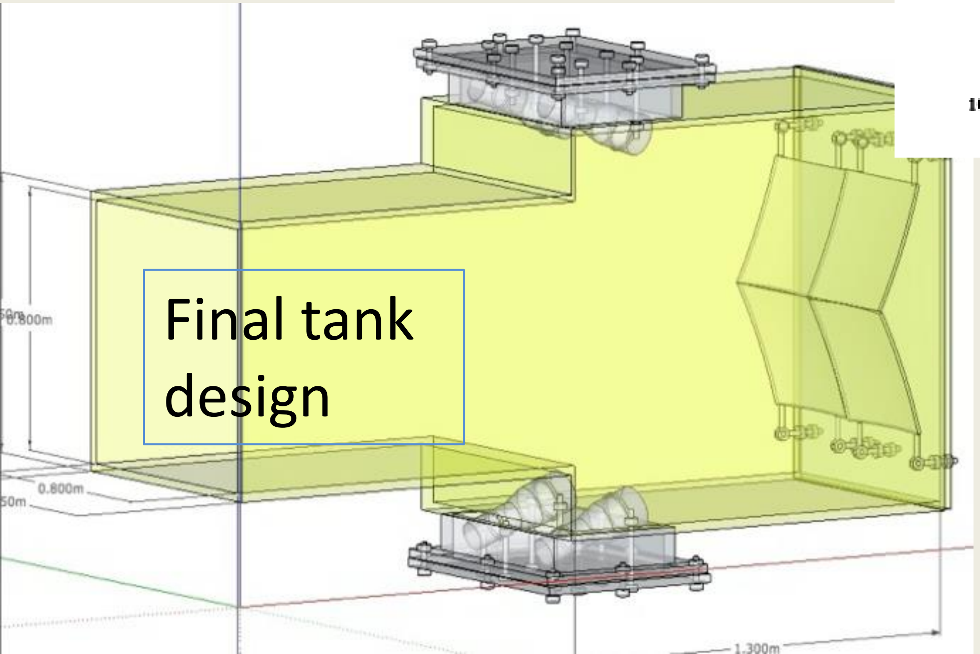
Noble Gas Cerenkov (U. of Virginia)

- e/π^- PID 50:1 discrimination
- Operate at STP
- Placed in front of drift chamber
  - Use only at high momentum so multiple scattering is reduced
- When not is use replace by vacuum pipe



Momentum

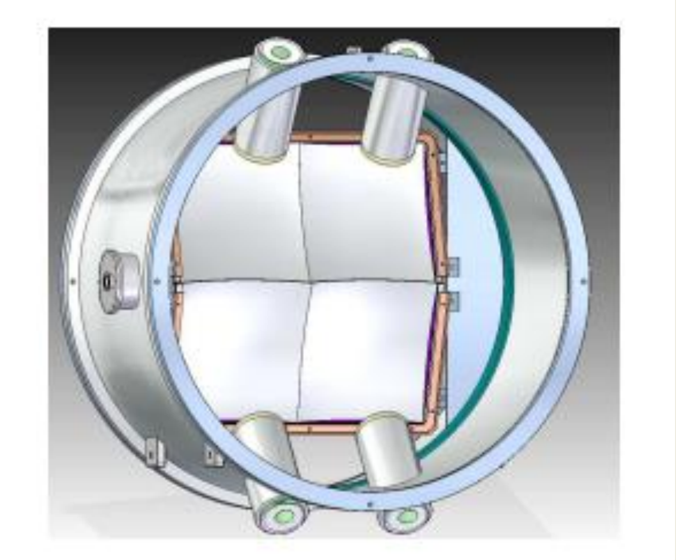
- Argon π threshold at 6 GeV/c
- Add Neon to extend reach to 11



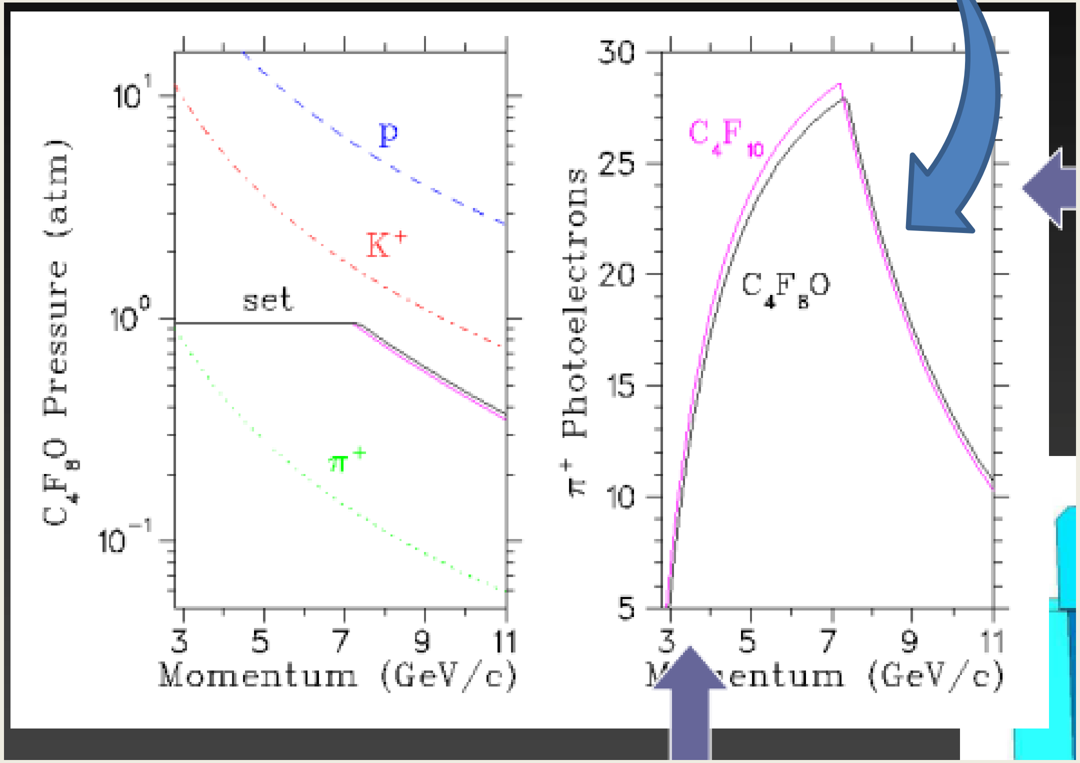
Final tank design

Heavy Gas Cerenkov (U. of Regina)

- π^+/K separation above 3.4 GeV/c
- Rejection factor of 1000:1
- Vary gas pressure with momentum to keep π^+/K separation

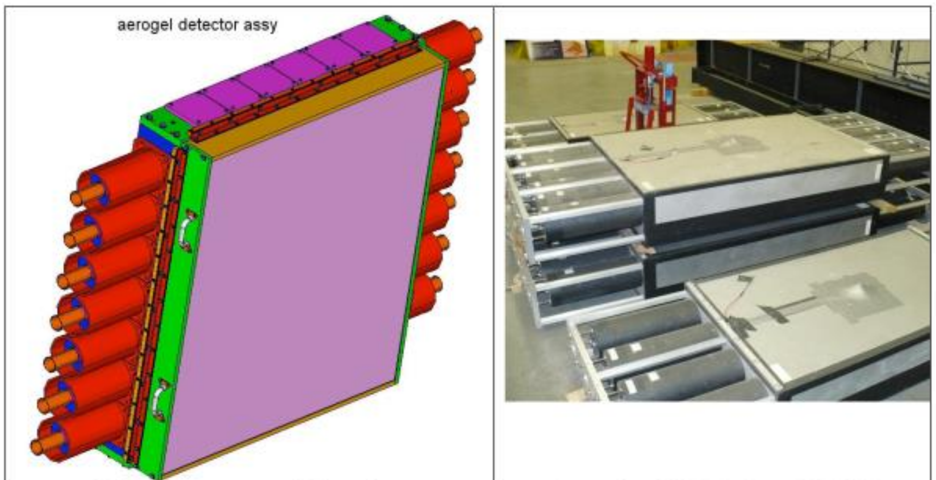


Front view

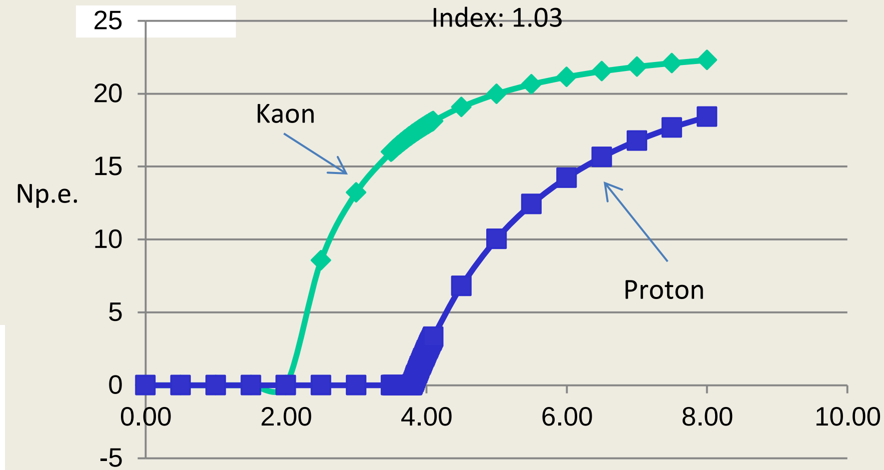


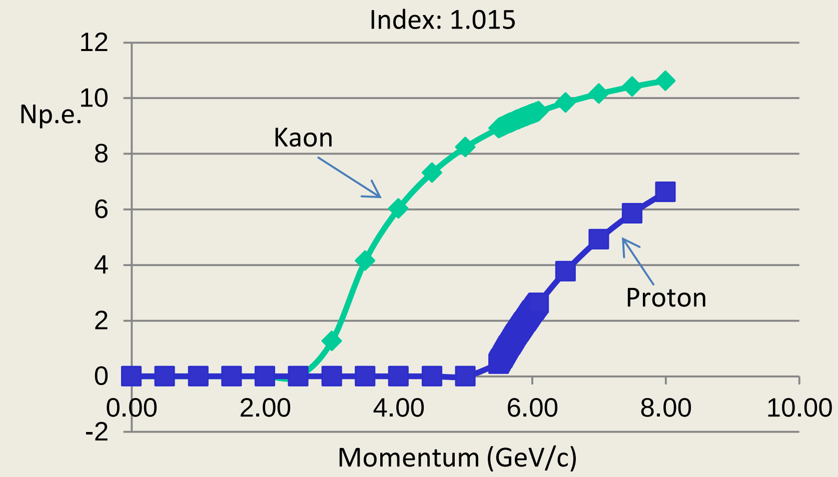
Aerogel Detector

- K/p PID in 2-6 GeV/C range 1000:1
- Need two indices of refraction to cover different momentum regions
- Using aerogel and PMTs from BLAST at MIT-BATES



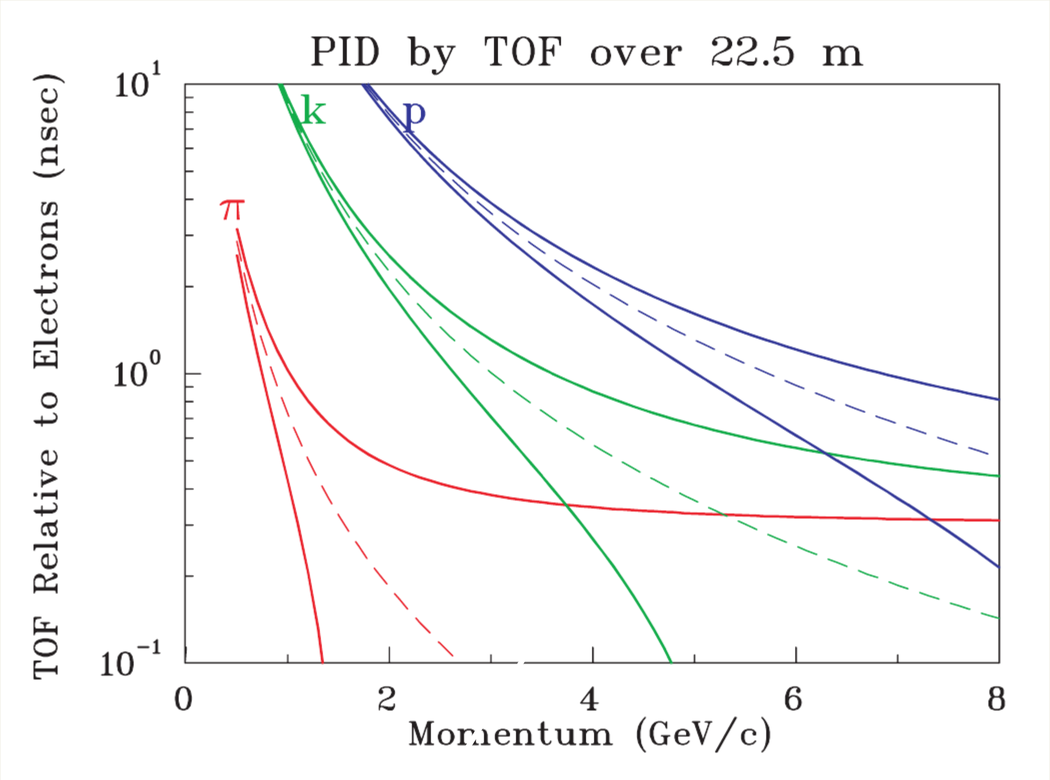
SHMS kaon aerogel Cerenkov | Aerogel and PMTs from BLAST experiment at Bates ready for shipping.





Particle ID: Limitations of TOF

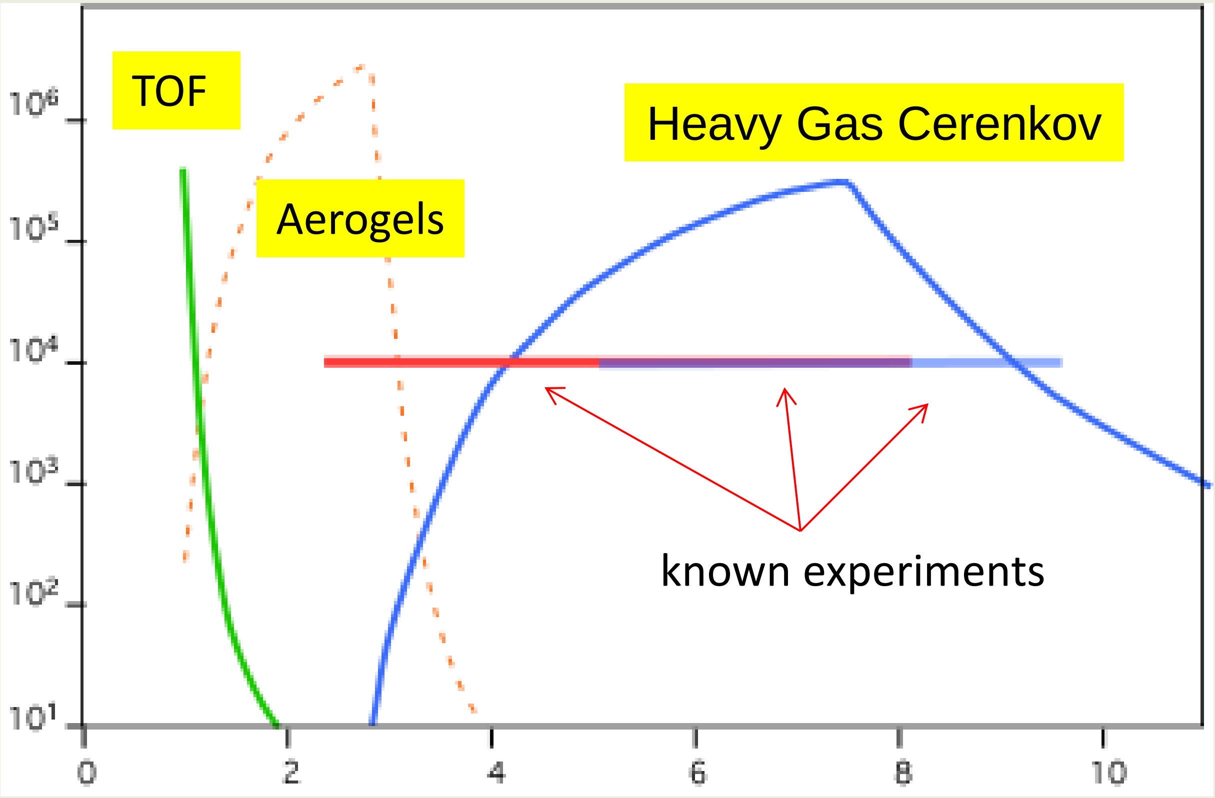
- TOF over the short ~2.2m baseline inside the SHMS hut will be of little use for most of the momentum range anticipated for the SHMS.
- Even over a 22.5m distance from the target to the SHMS detector stack, TOF is of limited use.



Effect of finite timing resolution (±1.5σ with σ=200ps). Separation <3σ to the right of where lines intersect.

SHMS Particle Identification: +hadrons

Rejection Power



Momentum (GeV/c)