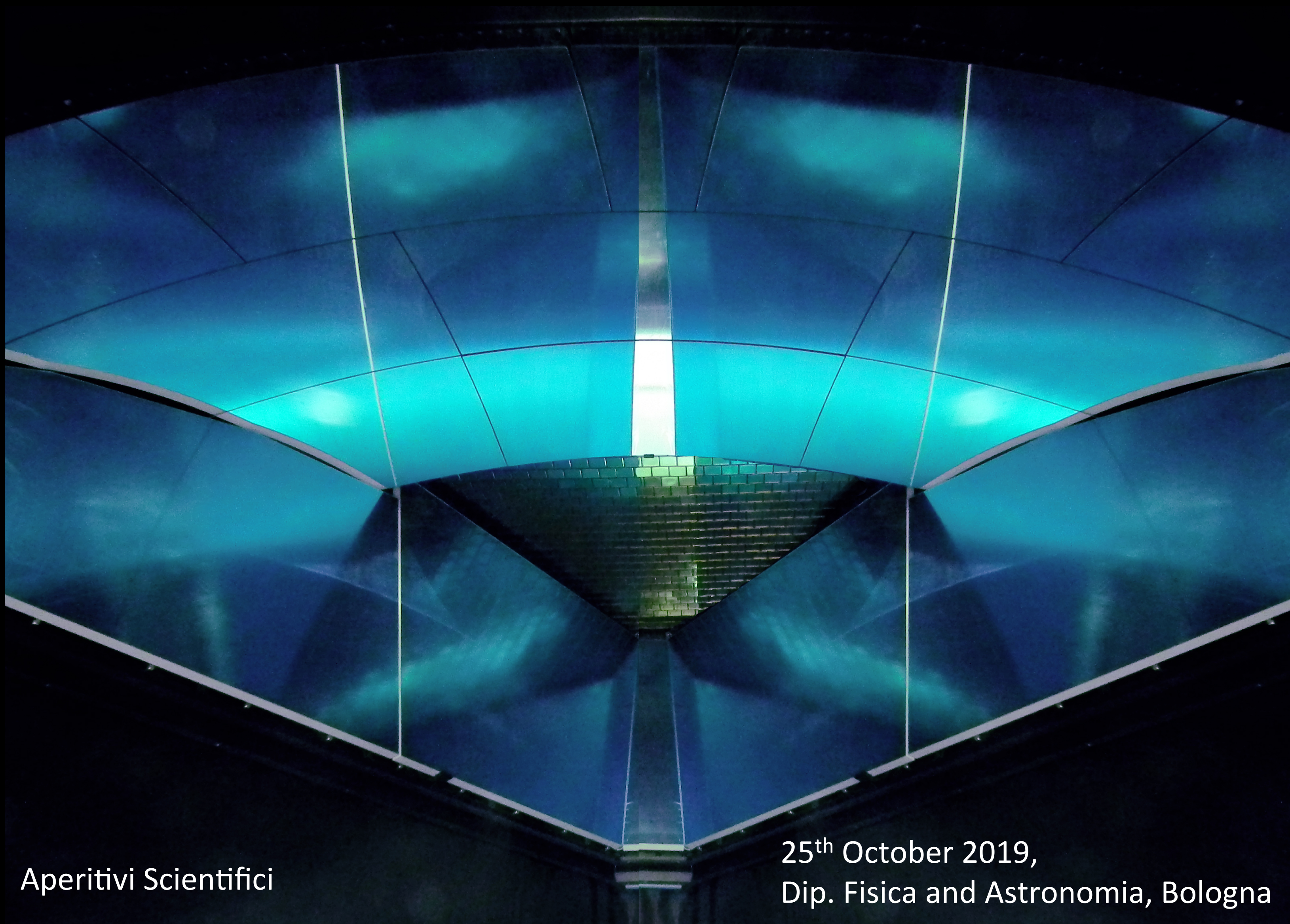
Flavor Separation Instruments for Nucleon Tomography

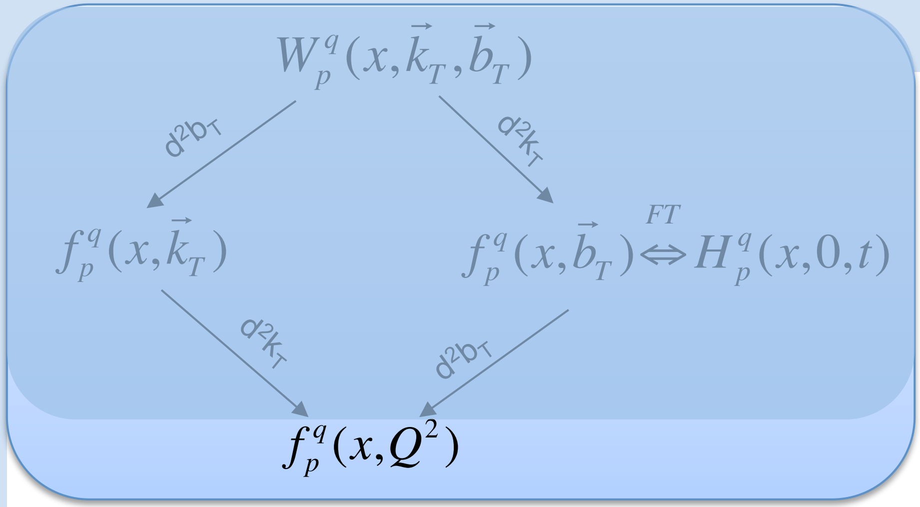
M. Contalbrigo – INFN Ferrara



Aperitivi Scientifici

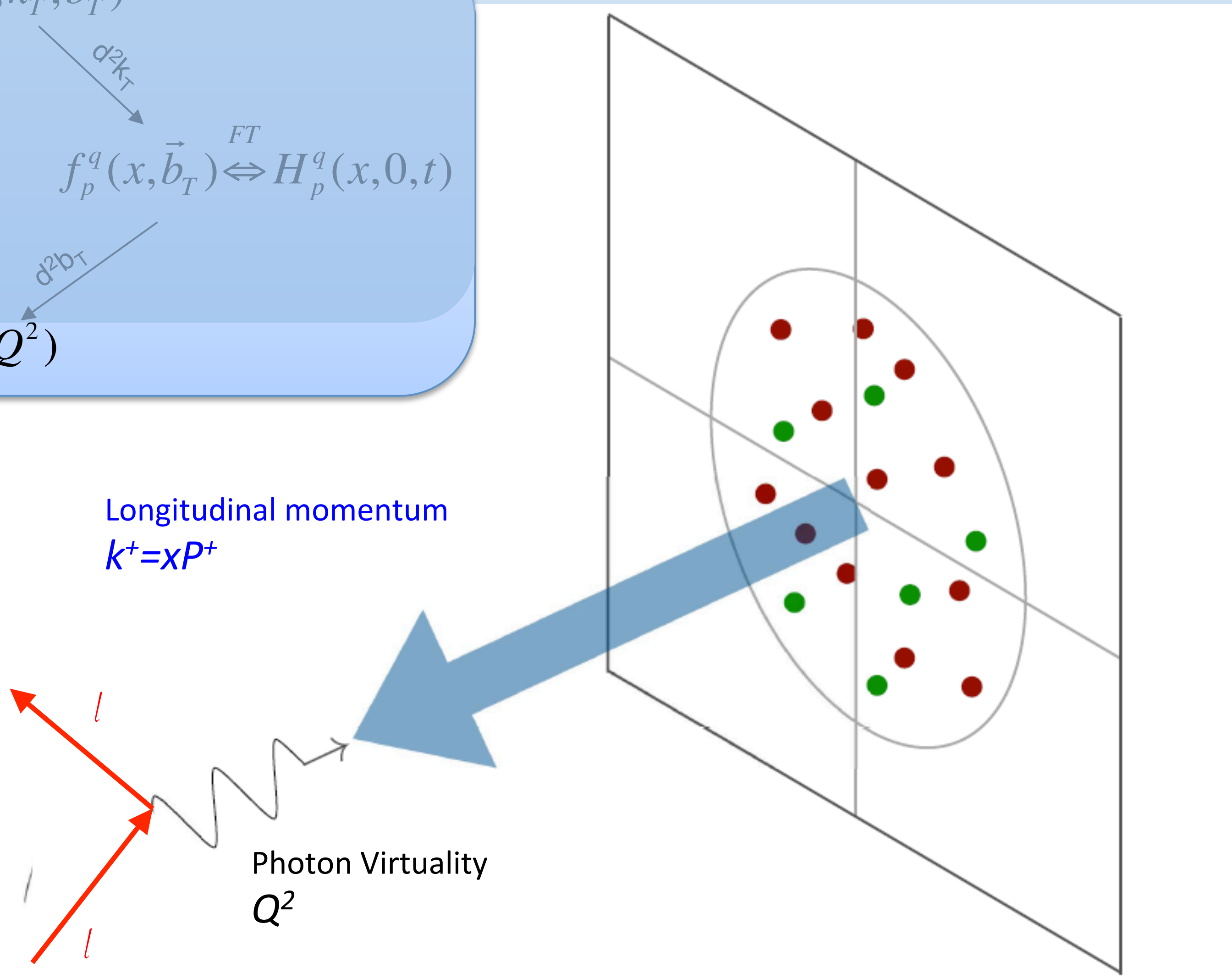
25th October 2019,
Dip. Fisica and Astronomia, Bologna

The Nucleon Structure



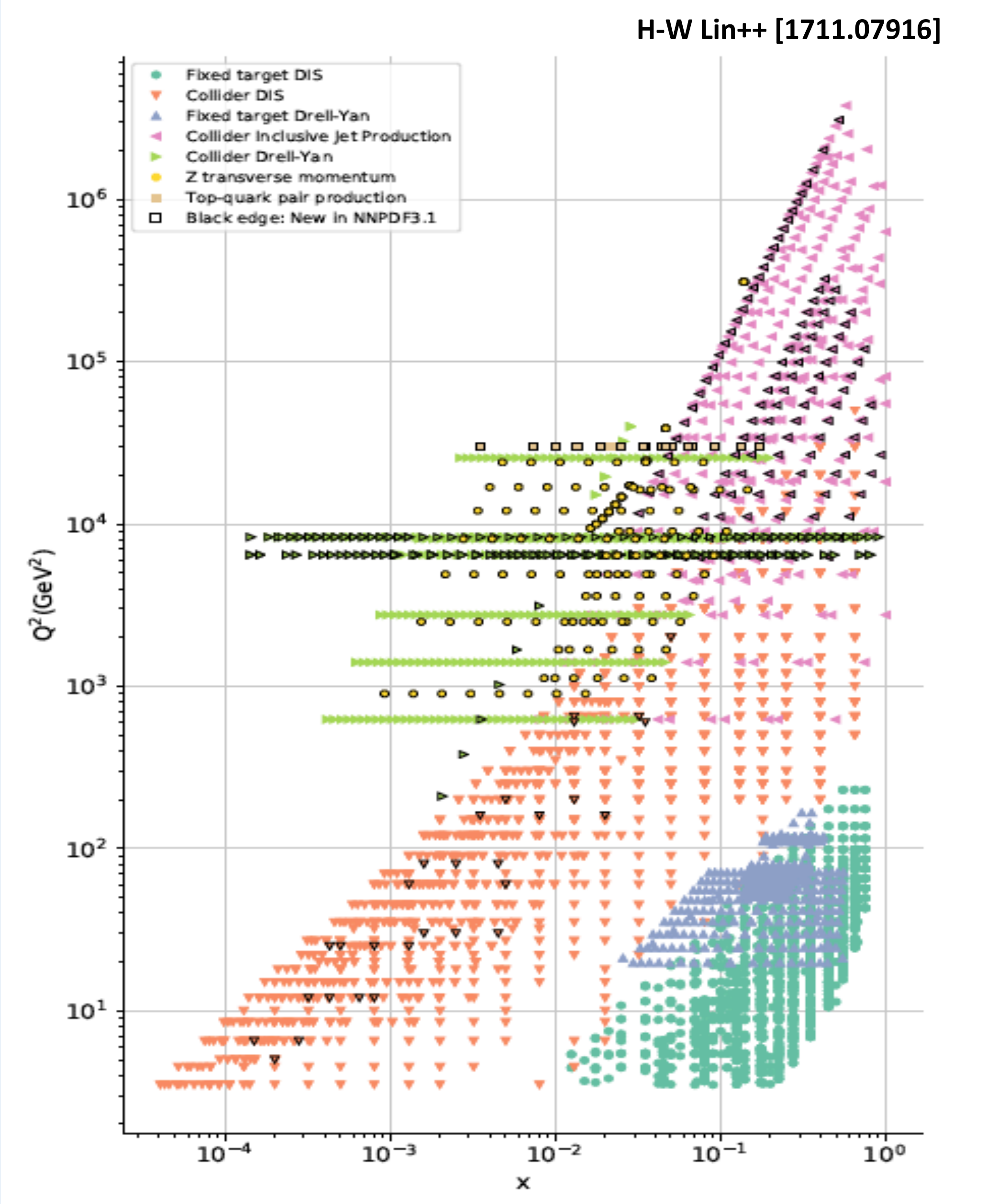
High Energy Probe
Hard Scale

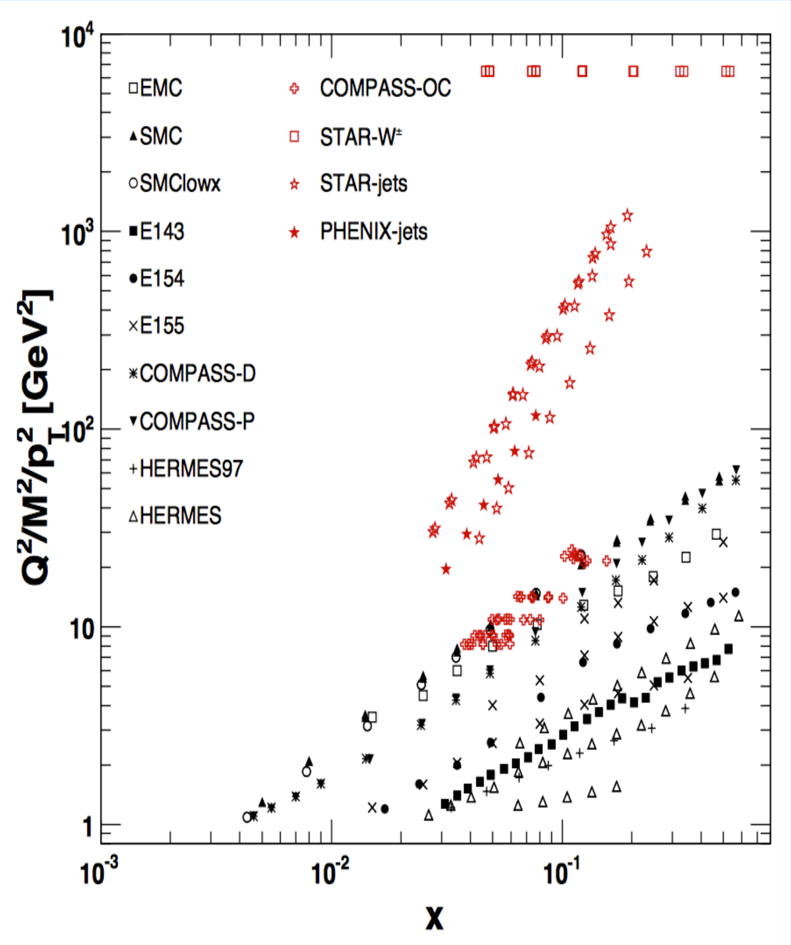
Longitudinal momentum
$k^+=xP^+$



Photon Virtuality
Q^2

Kinematic Coverage

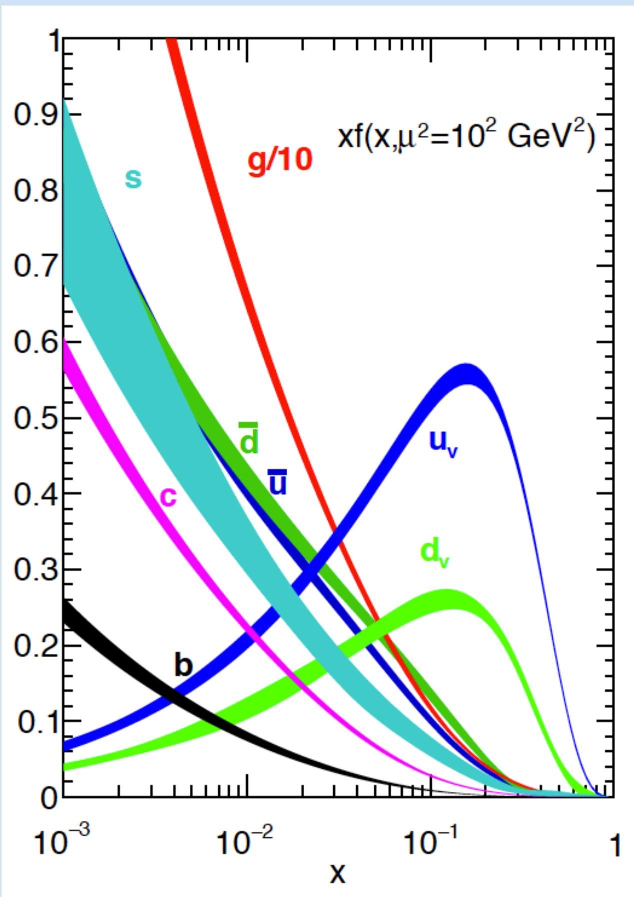




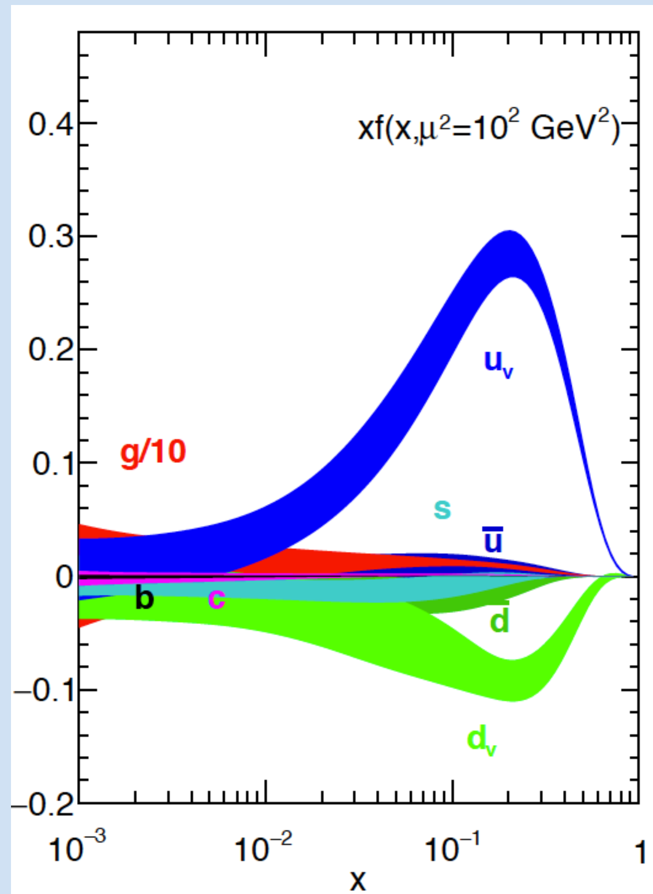
Parton Content

MMHT [arXiv 1412.3989]
HERAPDF2.0 [arXiv 1506.06042]
CT14 [arXiv 1506.07443]
CJ15 [arXiv 1602.03154]
ABMP16 [arXiv 1701.05838]
NNPDF3.1 [arXiv 1706.00428]

BB [arXiv 1005.3113]
LSS [arXiv 1010.0574]
DSSV [arXiv 1404.4293]
BS [arXiv 1408.7057]
NNPDF [arXiv 1406.5539]
JLAM [arXiv 1601.07782]



H-W Lin++ [1711.07916]

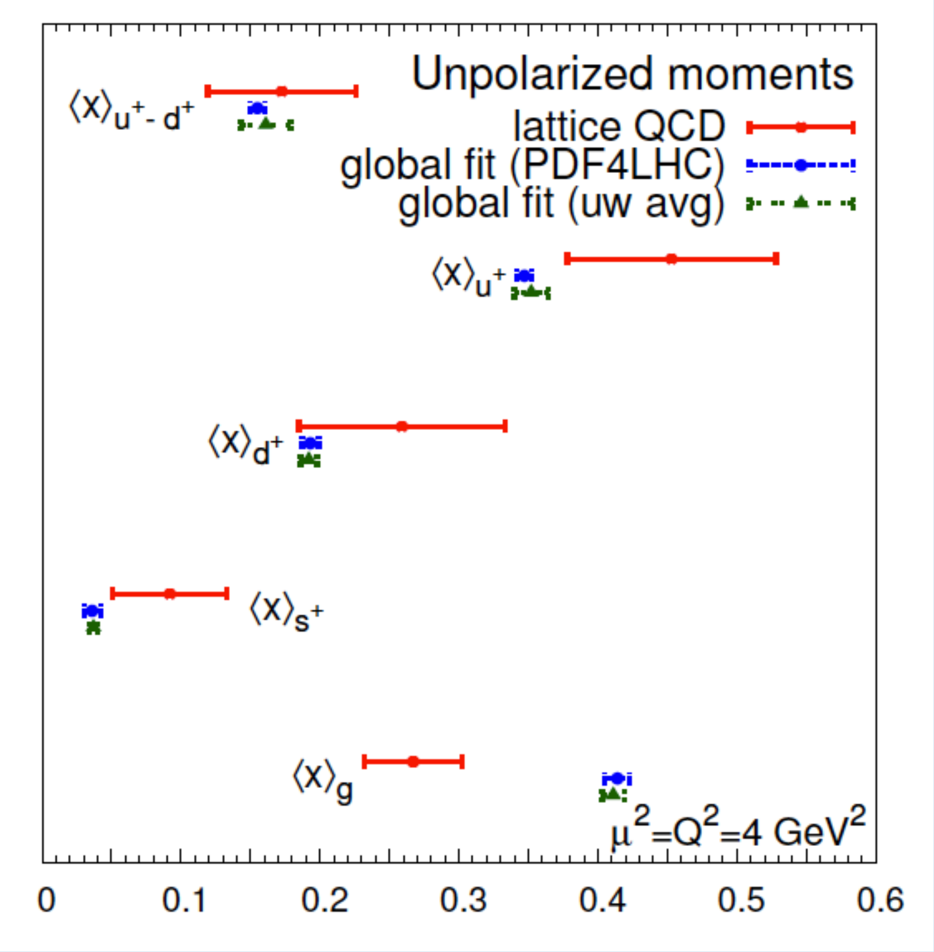


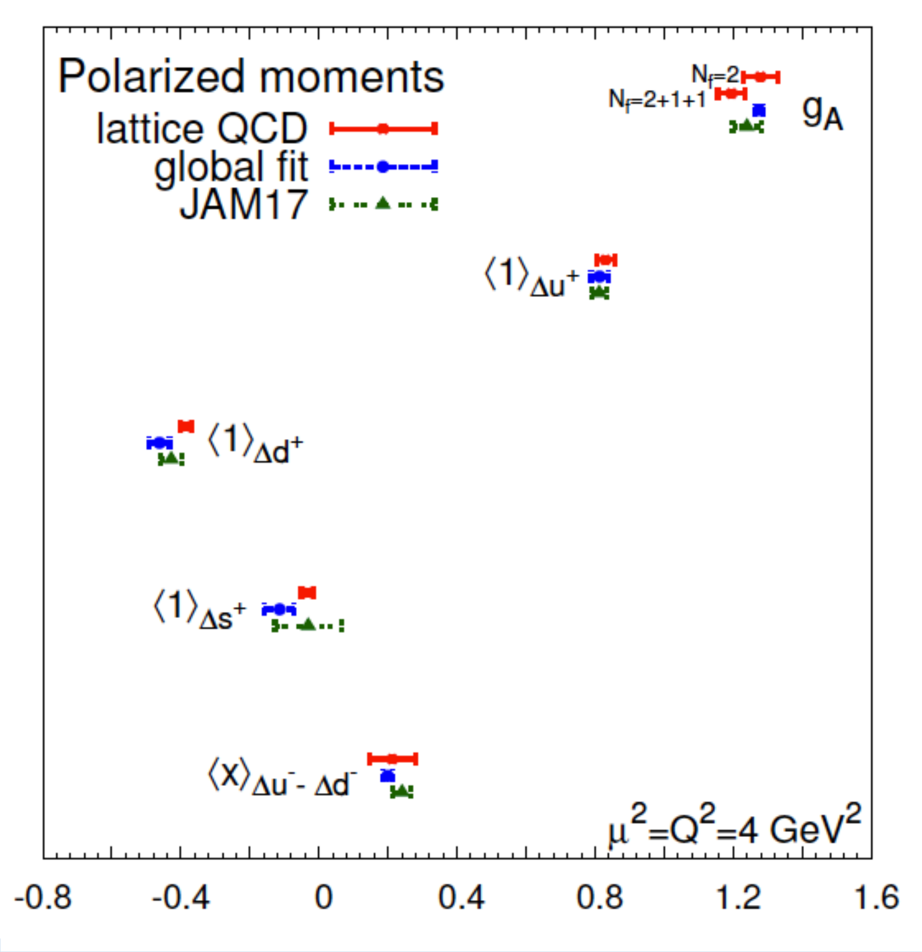
Parton Content & Lattice

Unpolarized moments

Polarized (helicity) moments

H-W Lin++ [1711.07916]





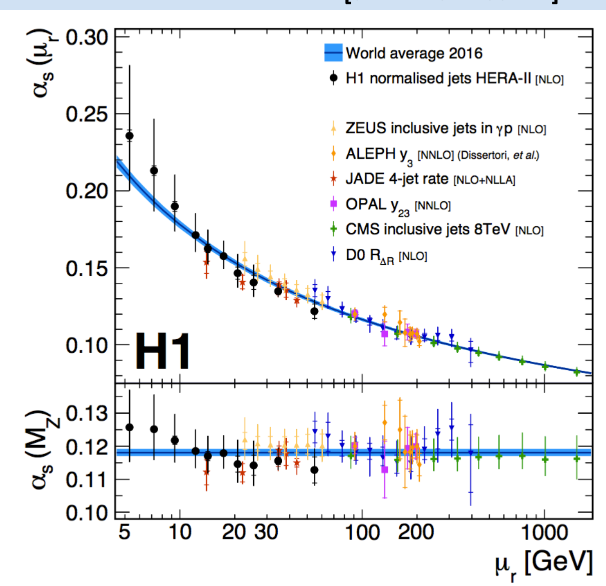
Inclusive Jets @HERA

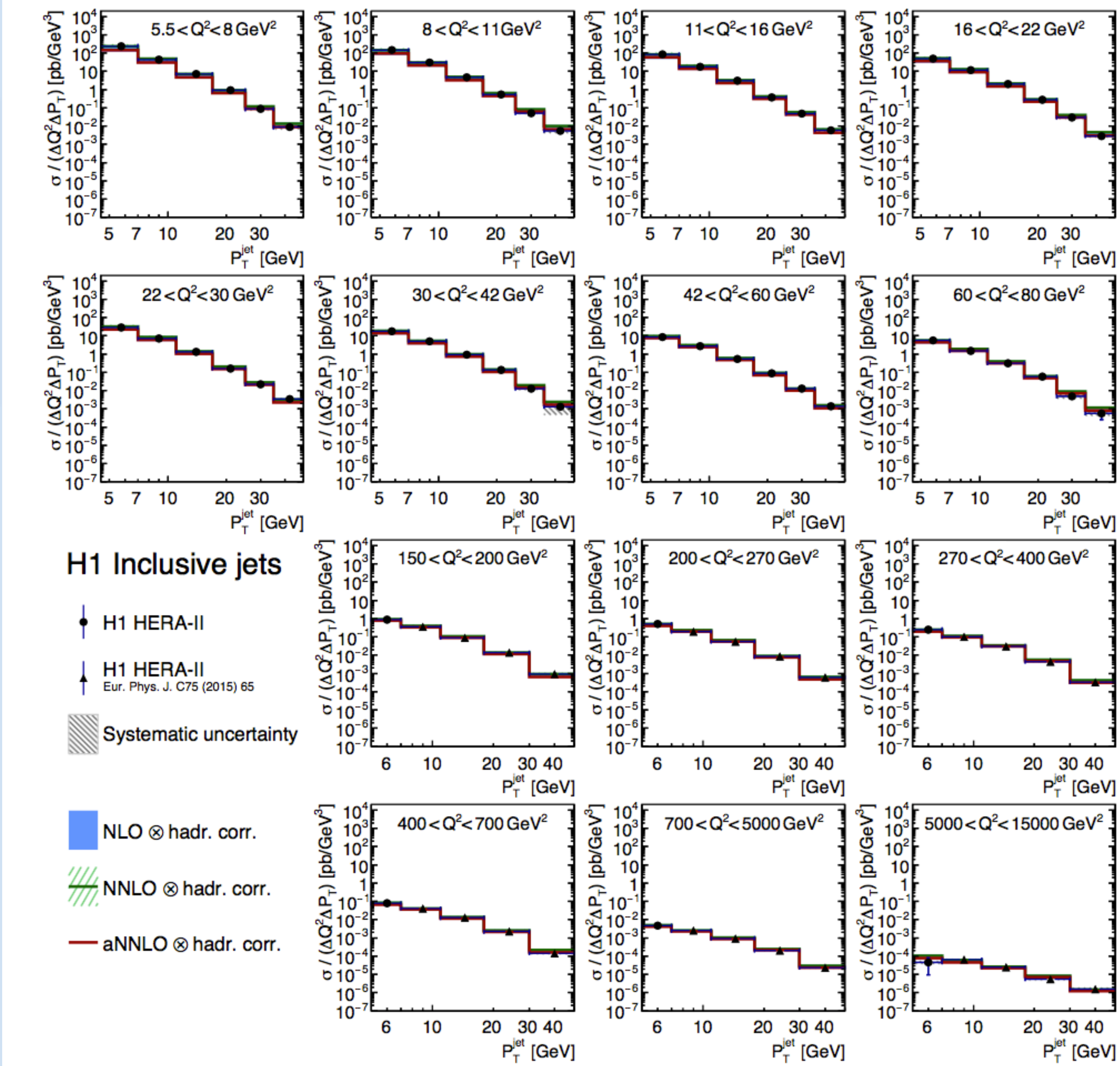
Good perturbative description
(hard gluon emission)

p_T>5 GeV Q^2>5 GeV^2

Part in a p_T<<Q TMD regime

H1 [arXiv: 1611.03421]



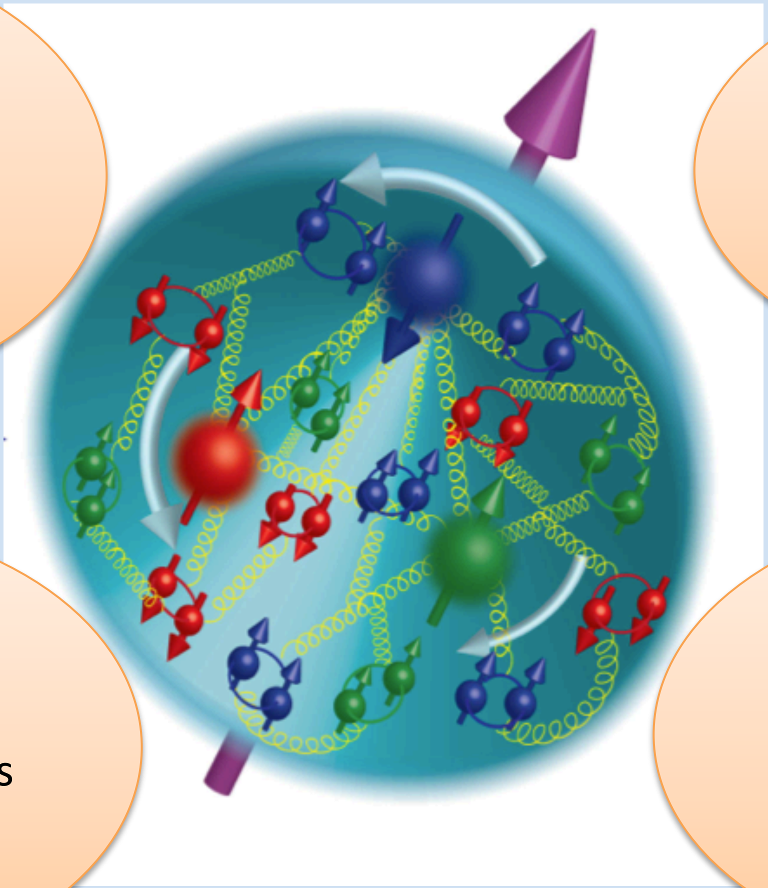


The Strong Force Confined Universe

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q}\left[i\gamma^{\mu}(\partial_{\mu} - igA_{\mu}) - m_q\right] q$$

Dynamic Spin
- Parton polarization
- Orbital motion
- Form Factors
- Magnetic Moment

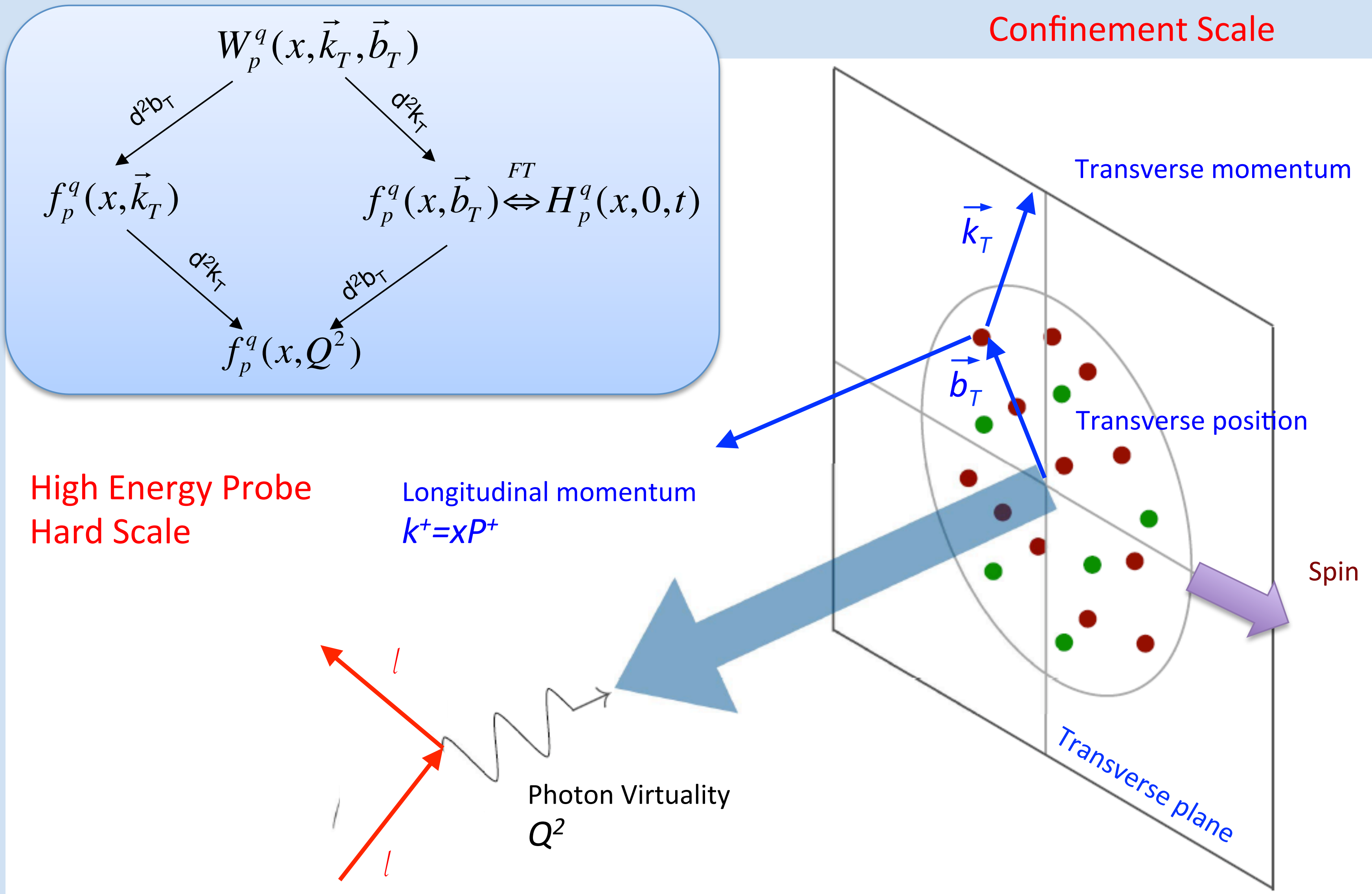
Parton Correlations
- dPDFs
- Short range
- MPI



Hadronization
- Spin-orbit effects
- Parton energy loss
- Jet quenching

Color charge density
- Nucleon tomography
- Diffractive physics
- Gluon saturation
- Color force

The 3D Nucleon Structure



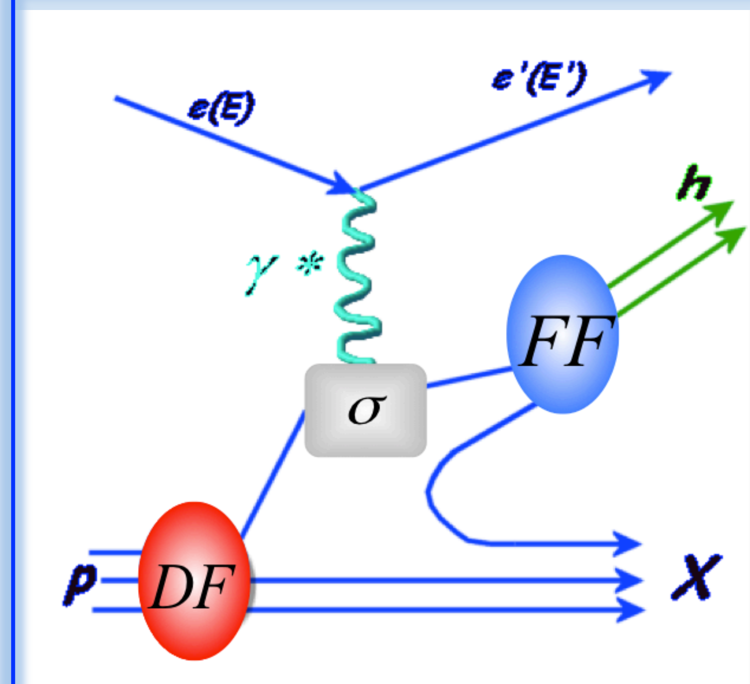
TMDs: Transverse Momentum Parton Distributions

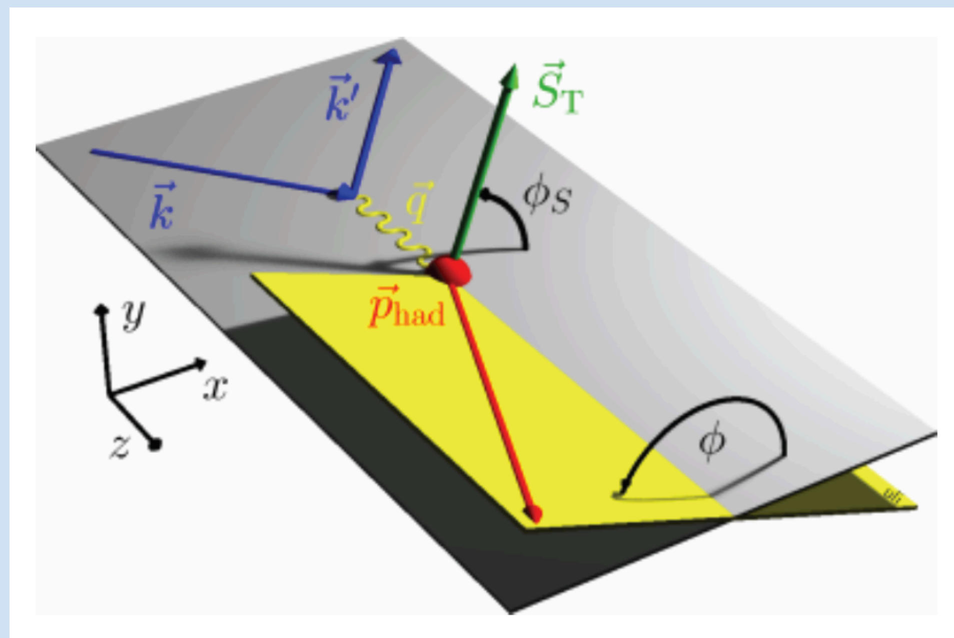
Parton kinematics and flavor from observed hadron kinematics and type

Access to:
3D momentum and spin-orbit effect:

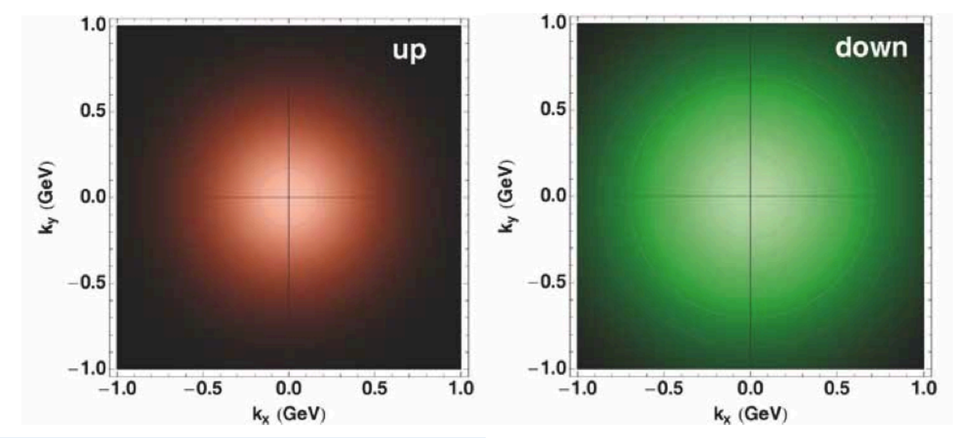
Distribution and fragmentation convoluted:

$$d^6\sigma^h \propto \sum_q e_q^2 q(x,k_T) \otimes D_q^h(z,p_T)$$





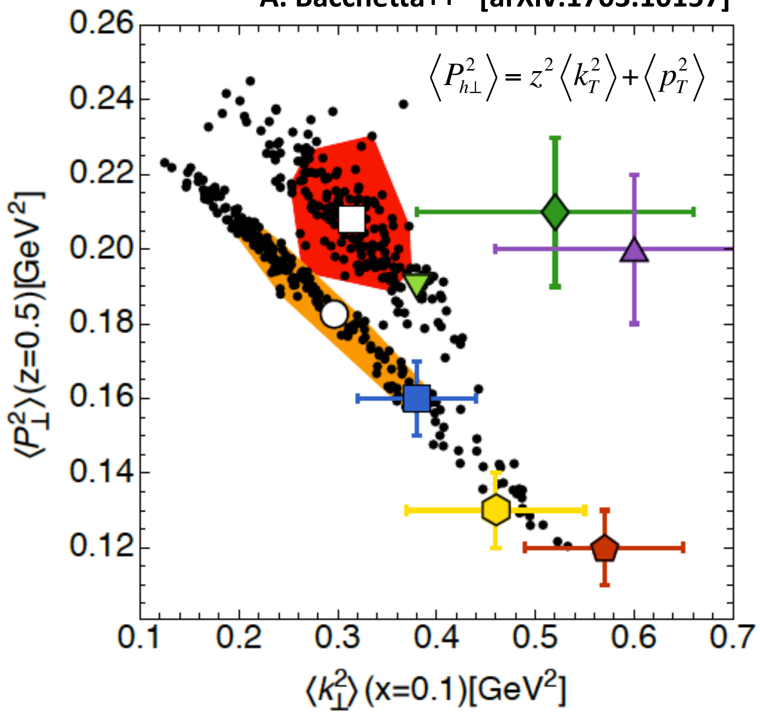
Unpolarised TMDs



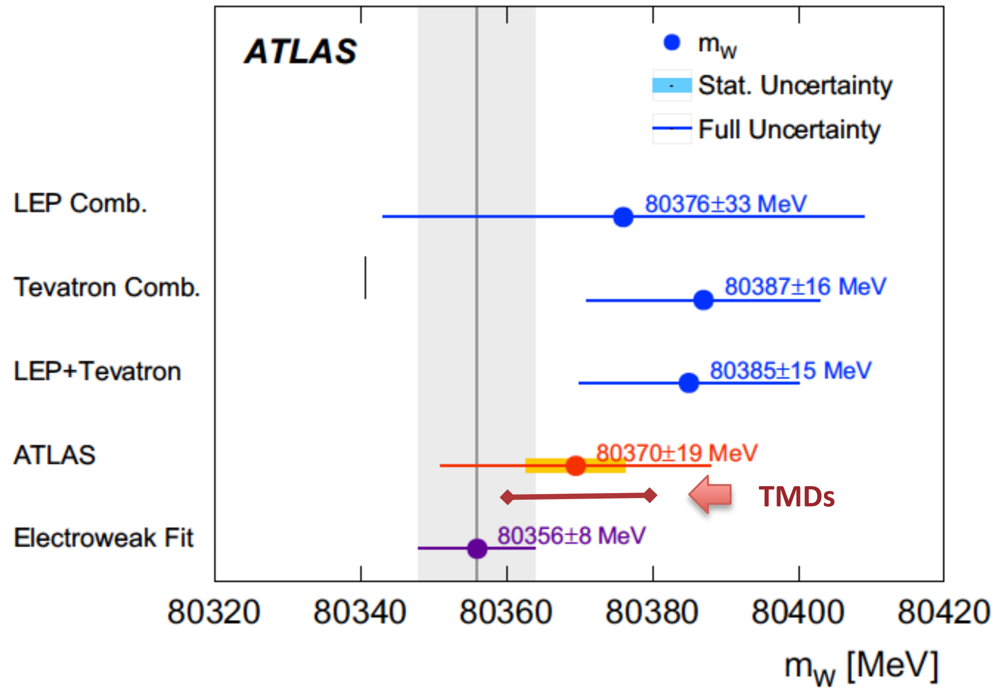
$$m_W = 80370 \pm 7\ (\text{stat.}) \pm 11\ (\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV}$$

+9 / -6 (TMDs)

A. Bacchetta++ [arXiv:1703.10157]

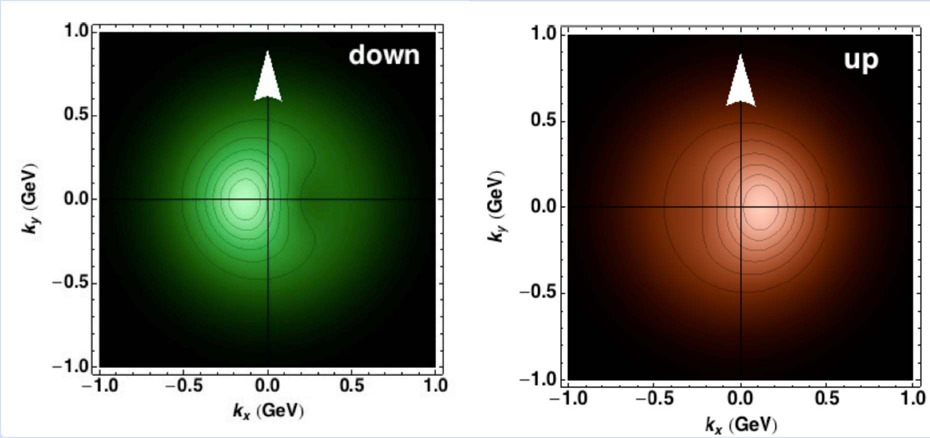


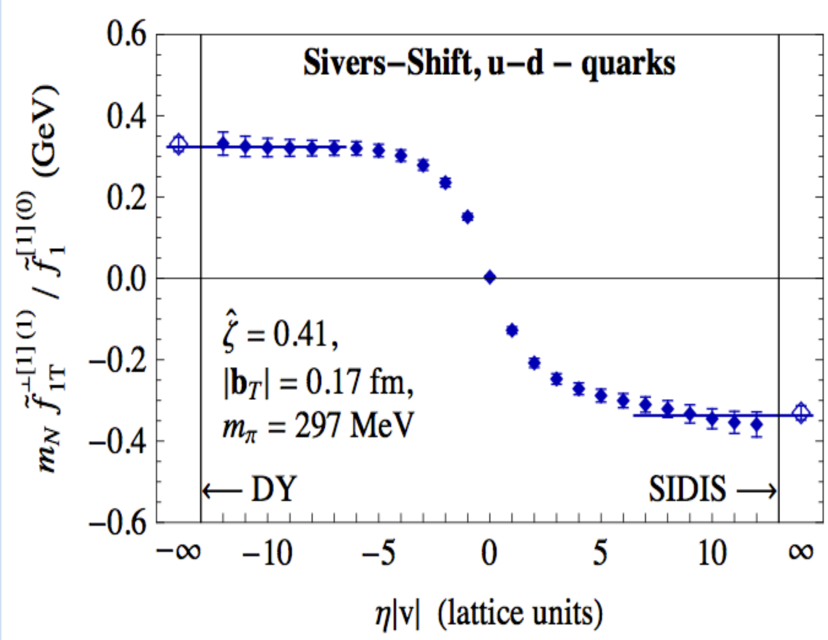
ATLAS++ [arXiv:1701.07240]



Spin-Orbit Effects: Sivers

$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$

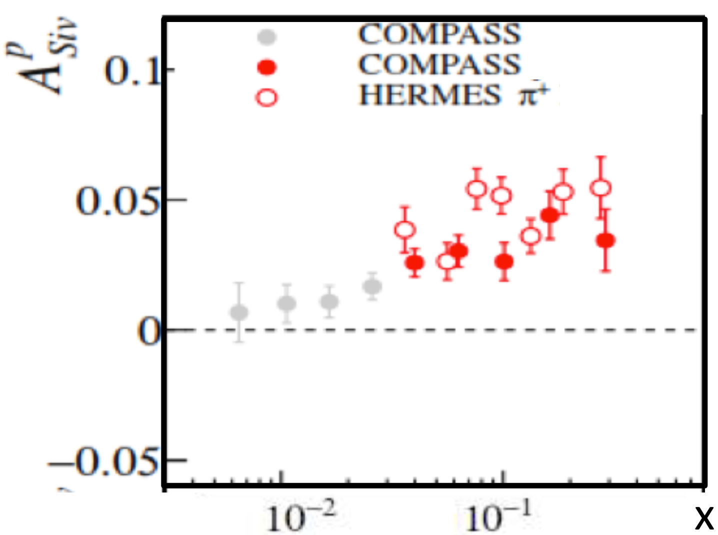


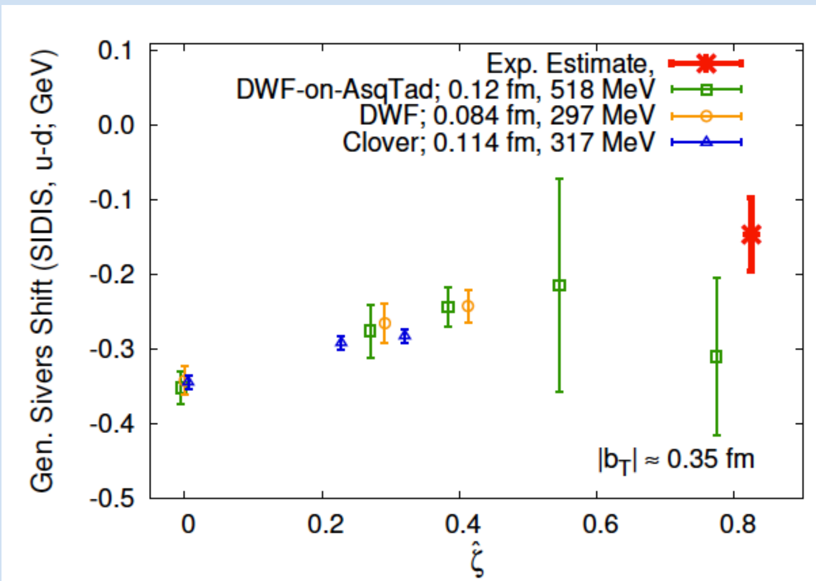


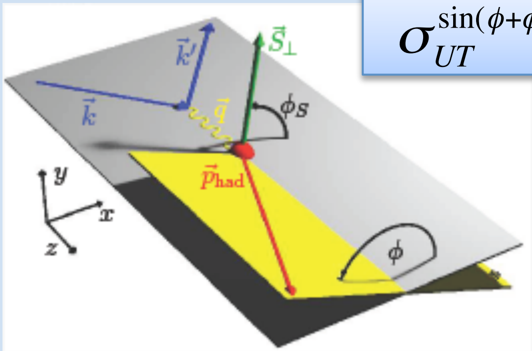
Sivers from polarized SIDIS

HERMES [arXiv:0906.3918]

COMPASS [arXiv:1205.5122]

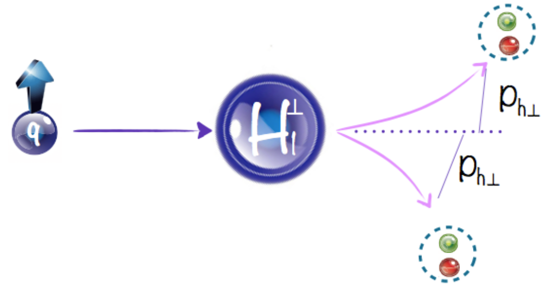




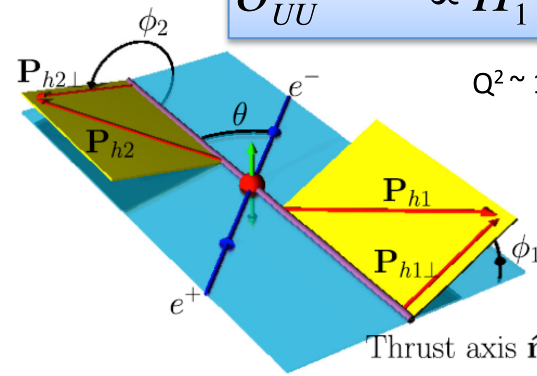


$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^\perp$$

Q^2 ~ 5-7 GeV^2



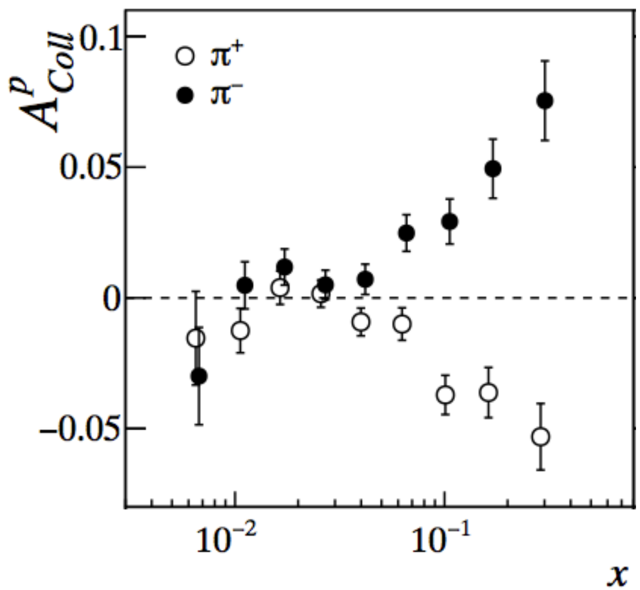
$$\sigma_{UU}^{\sin(\phi_1+\phi_2)} \propto H_1^\perp \otimes H_1^\perp$$

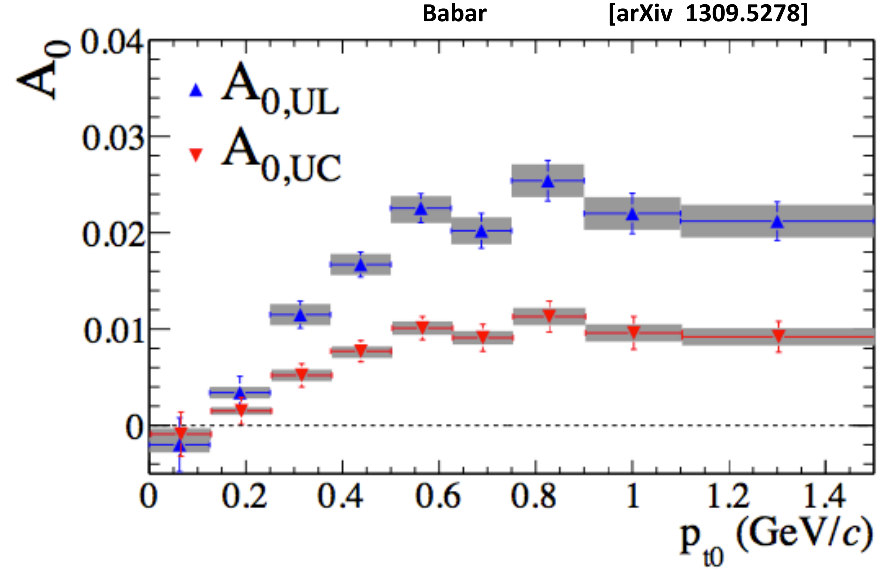


Q^2 ~ 110 GeV^2

HERMES	**[arXiv 0408013]**
HERMES	**[arXiv 0906.3918]**
COMPASS	**[arXiv 1005.5609]**
COMPASS	**[arXiv 1408.4405]**

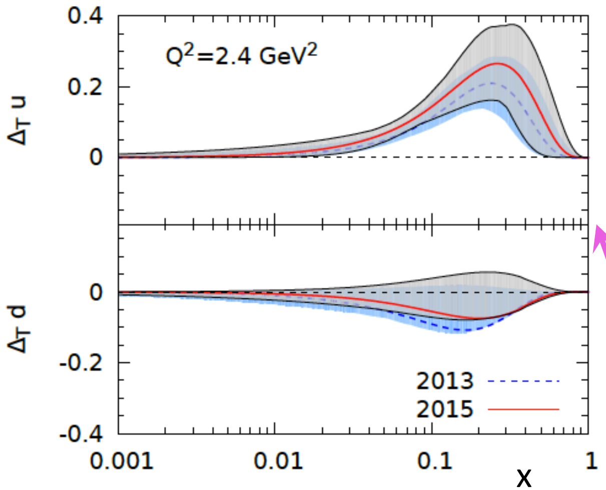
Belle	**[talk at DIS2014]**
BESIII	**[arXiv 1507.06824]**
Babar	**[arXiv 1309.5278]**

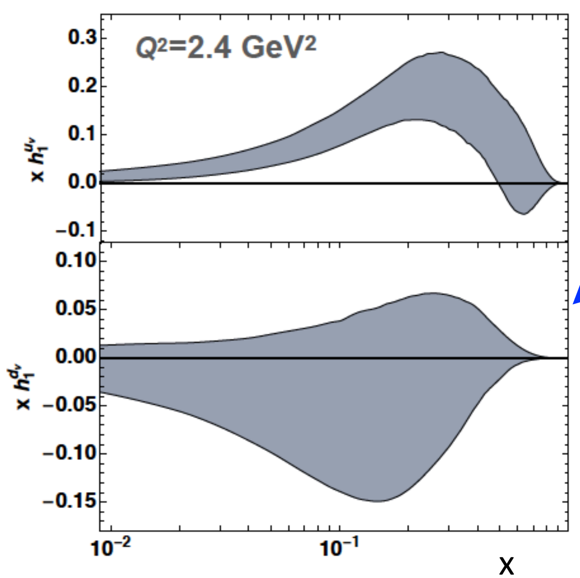


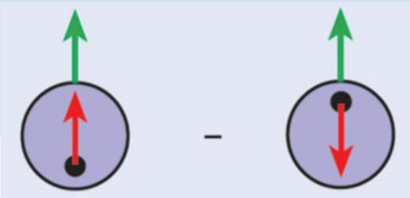


Transversity & Tensor Charge

Distributions:





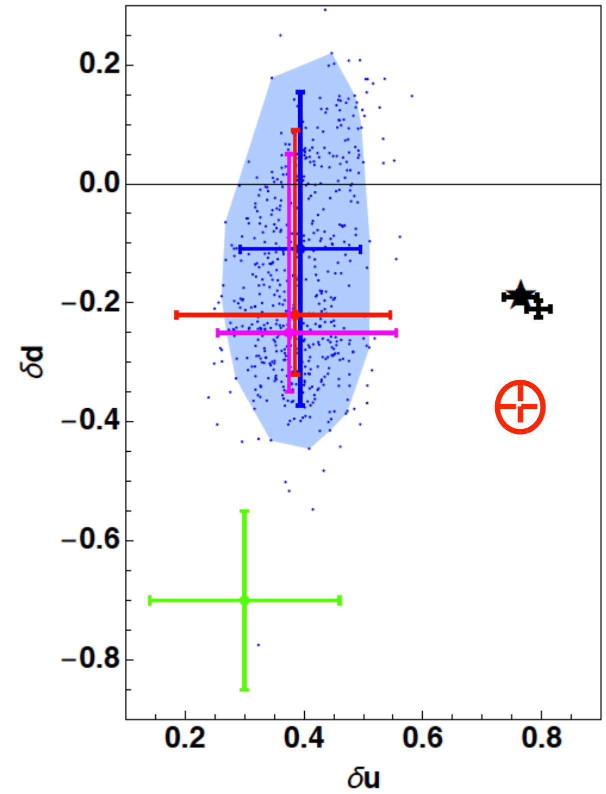


Charges:

$$\delta q \equiv \int_0^1 dx\,[\Delta_T q(x) - \Delta_T \bar{q}(x)]$$

- Helicity
- Alexandrou et al., arXiv:1703.08788
- Gupta et al., arXiv:1806.09006
- Anselmino et al., arXiv:1303.3822
- Kang et al., arXiv:1505.05589
- Lin et al., arXiv:1710.09858
- Radici et al., arXiv:1802.05212

A. Bacchetta @ DIS219



Tensor Charge & BSM Physics

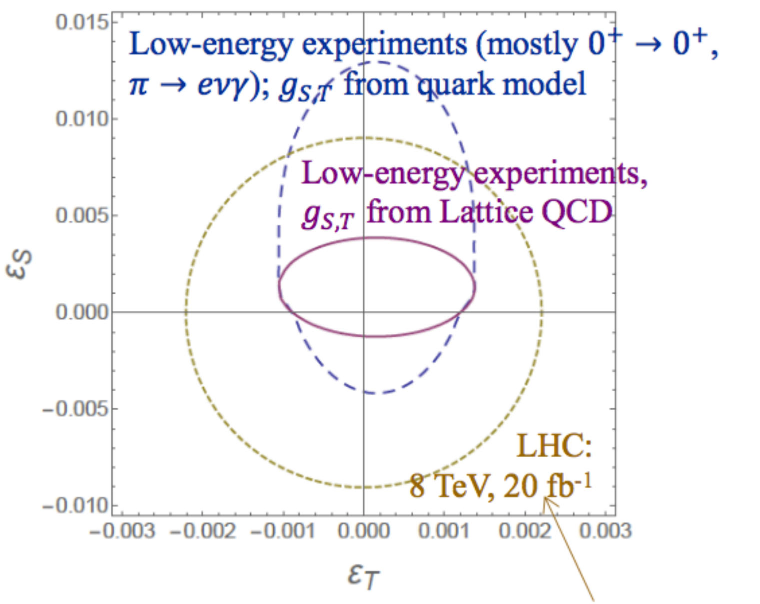
$$\varepsilon_T\, g_T \approx M_W^2 / M_{BSM}^2$$

A. Bychkov++ [arXiv:0804.1815]
B. Pattie++ [arXiv:1309.2499]

current most stringent constraints on BSM tensor coupling from $\pi^+ \to e^+ \nu_e \gamma$ and neutron β-decay is

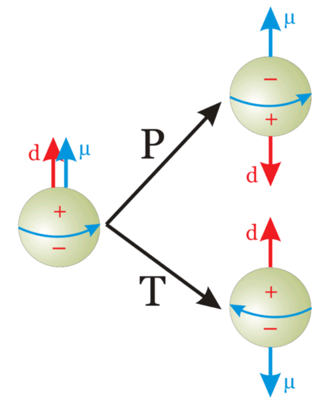
$$|\varepsilon_T\, g_T| \lesssim 5 \times 10^{-4}$$

Baessler++ @ this Conf.



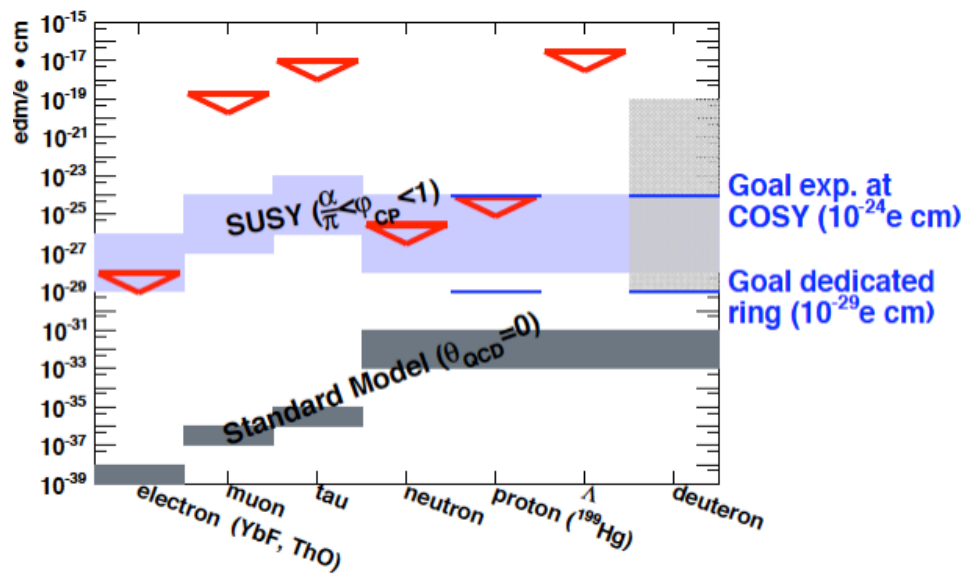
LHC-Search for $pp \to e + \nu$ + other stuff and $pp \to e + e$ + other stuff

EDM violates P and T and CP (if CPT holds)



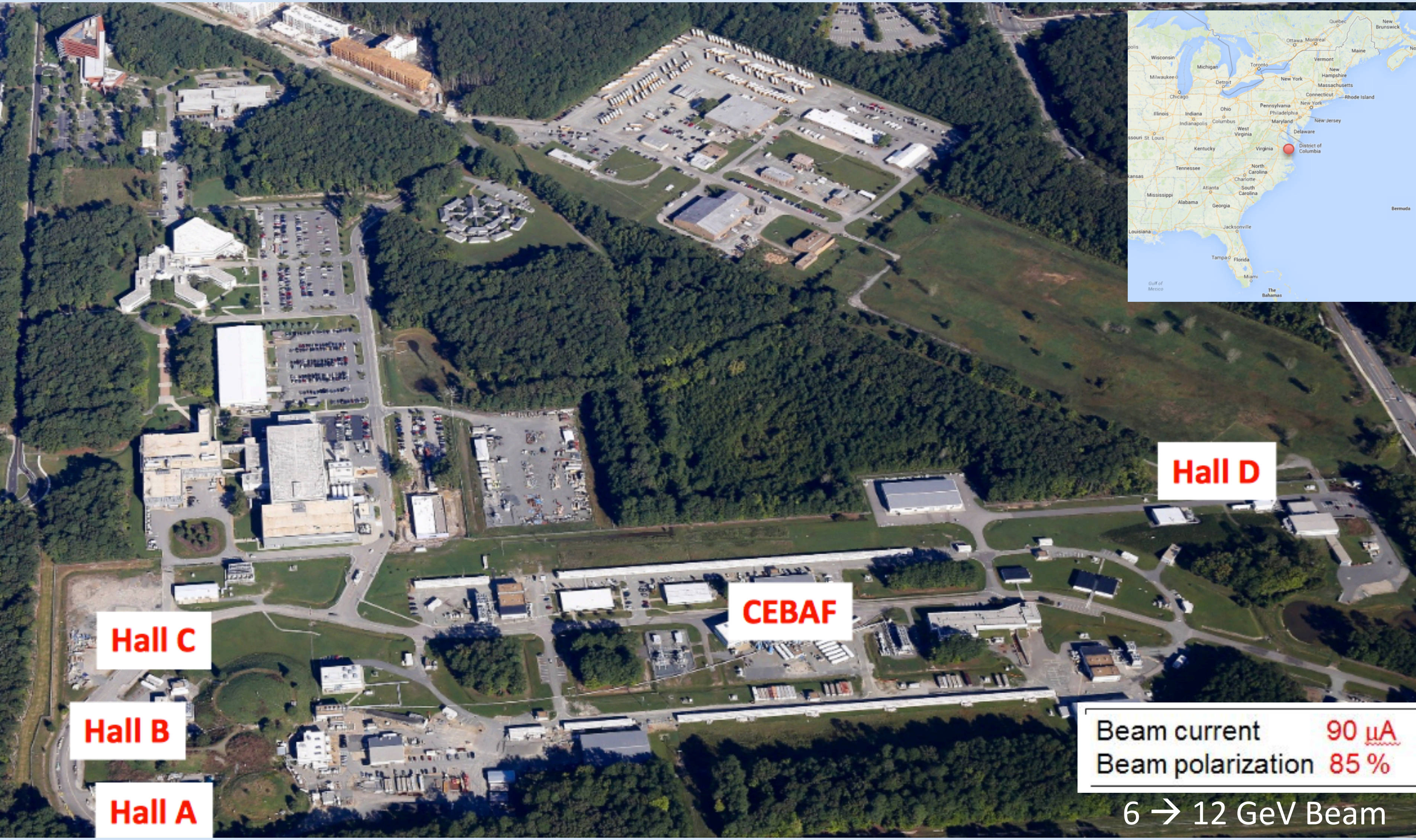
Proton *EDM*: $d_p = d_u\, \delta_T u + d_d\, \delta_T d$

Neutron *EDM*: $d_n = d_u\, \delta_T d + d_d\, \delta_T u$



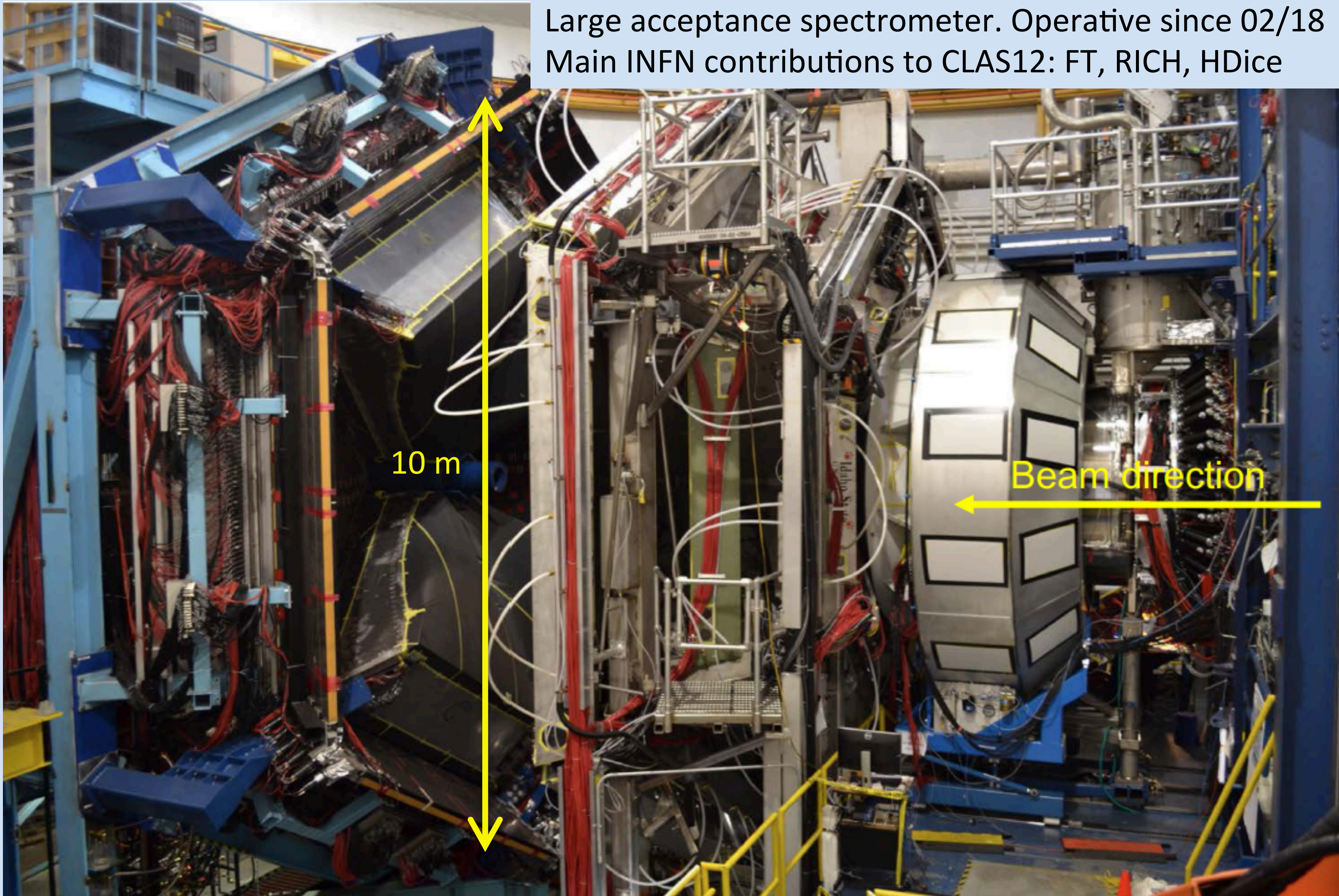
Jefferson Lab

Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

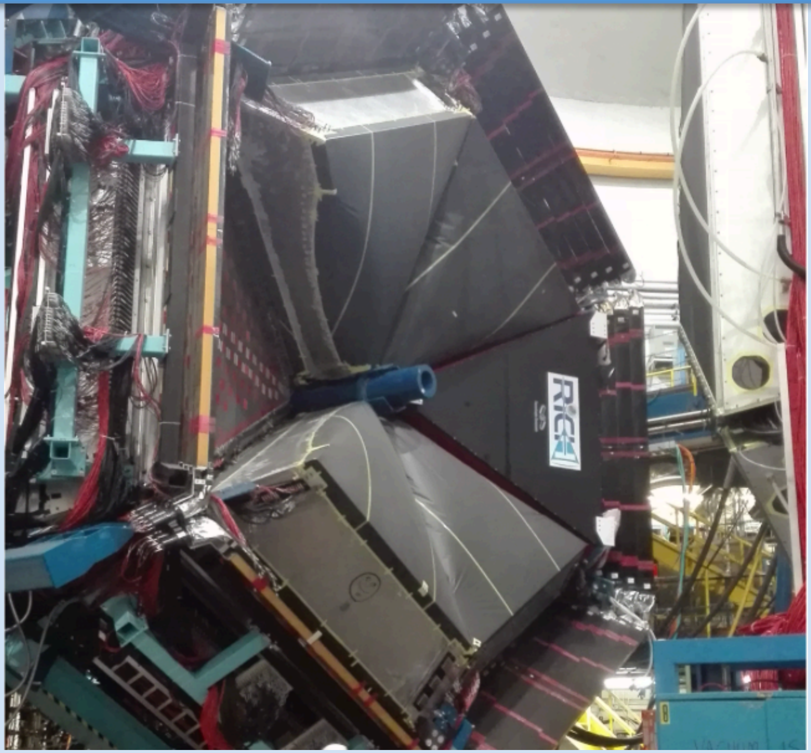


CLAS12 in Hall-B

Large acceptance spectrometer. Operative since 02/18
Main INFN contributions to CLAS12: FT, RICH, HDice

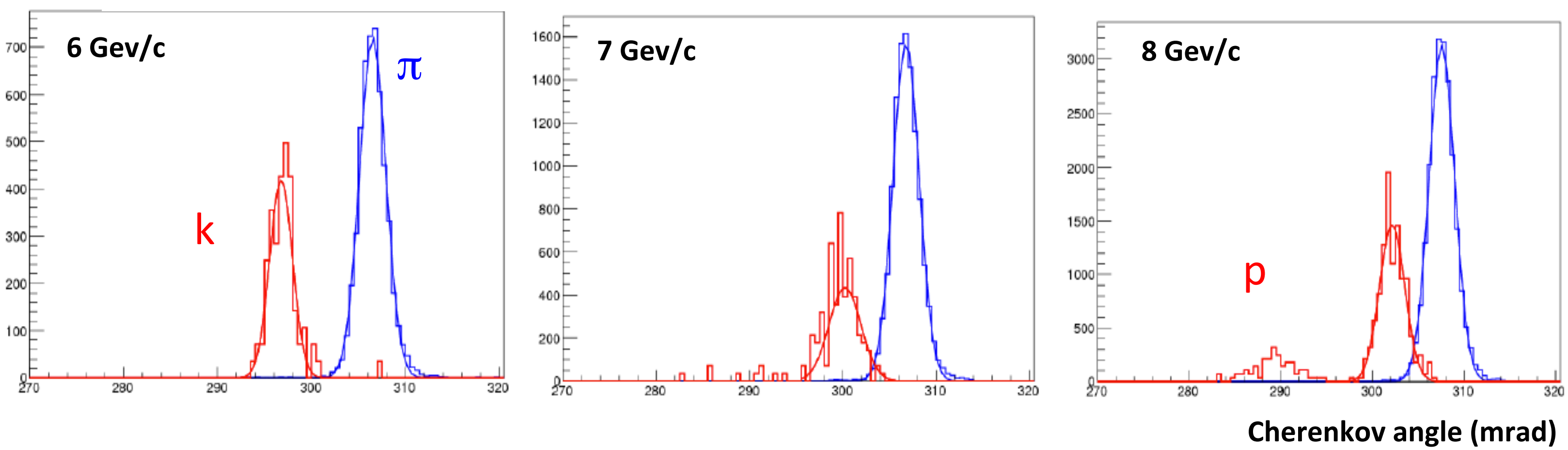


CLAS12 RICH



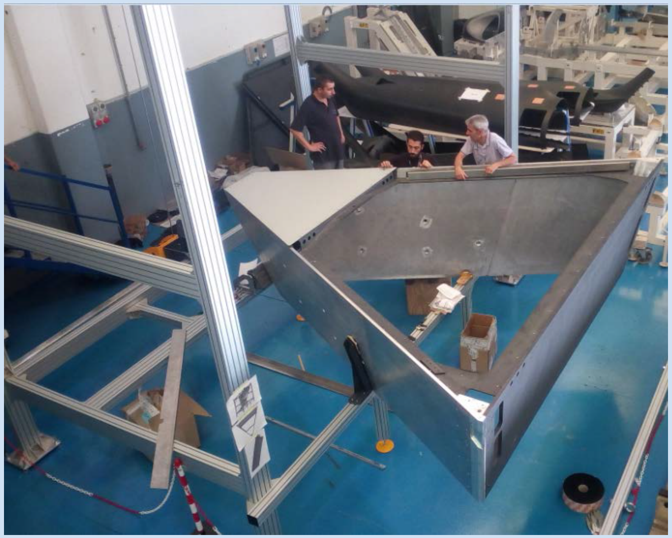
INSTITUTIONS
INFN (Italy) Bari, Ferrara, Genova, L.Frascati, Roma/ISS
Jefferson Lab (Newport News, USA)
Argonne National Lab (Argonne, USA)
Duquesne University (Pittsburgh, USA)
George Washington University (USA)
Glasgow University (Glasgow, UK)
Kyungpook National University, (Daegu, Korea)
University of Connecticut (Storrs, USA)
UTFSM (Valparaiso, Chile)

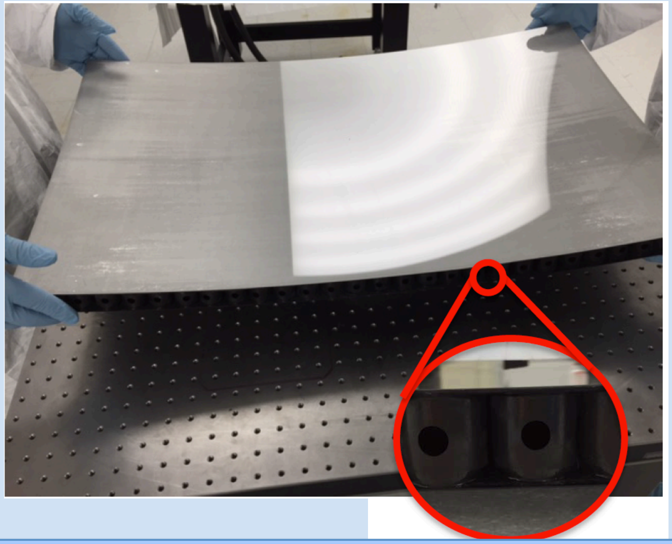
Goal kaon-pion separation up to 8 GeV/c (prototype results):



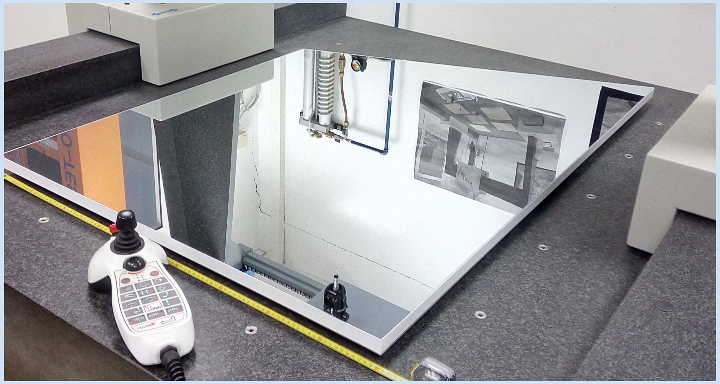
RICH Components

Aeronautic technology for structure
to maximize lightness and stiffness. Trapezoid of composite materials: CFRP inside acceptance, Aluminum outside



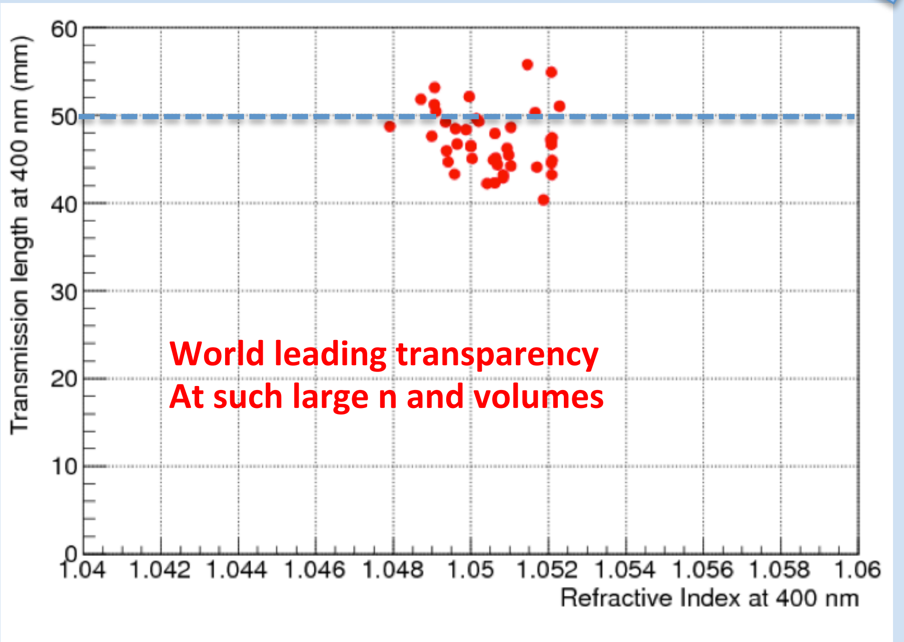


Carbon Fiber Mirrors (spherical)
to maximize lightness and stiffness. Consolidate technology (HERMES, AMS, LHCb) but ~ 30 % material budget reduction



Glass-Skin Mirrors (planar)
Innovative technology never used in nuclear experiments.
1.5 mm outside, 0.7 mm inside acceptance
~ 1/5 cost for squared meter vs CFRP

Large refractive index aerogel radiator
Tiles up to 20x20x3 cm^2 at n=1.05.



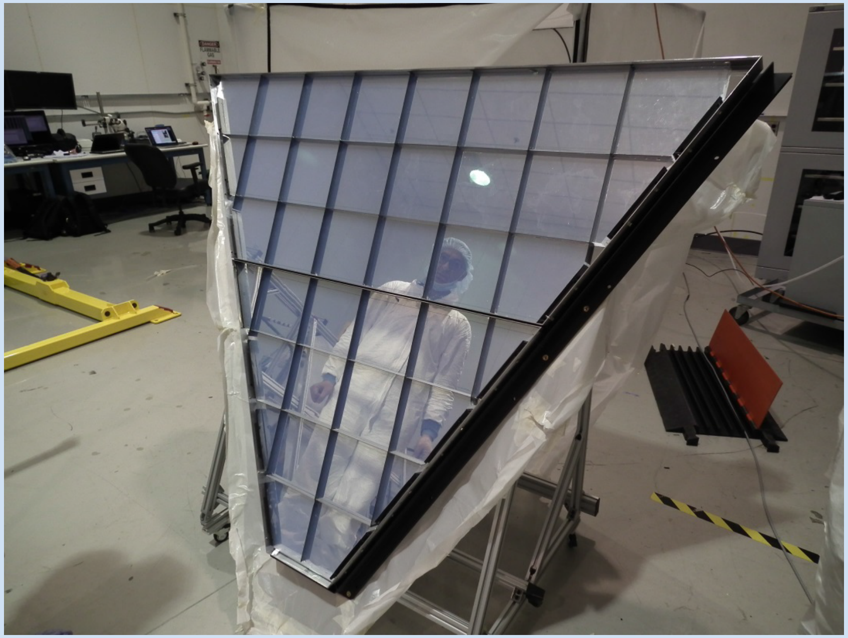
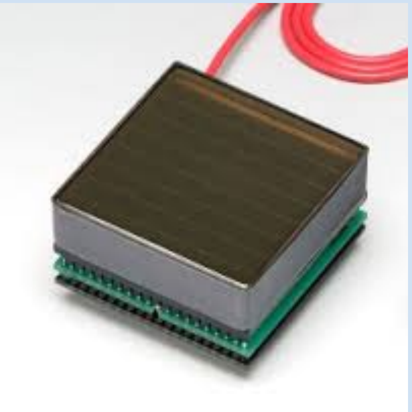


Photo Sensor: MA-PMT

80 H8500 + 350 H12700

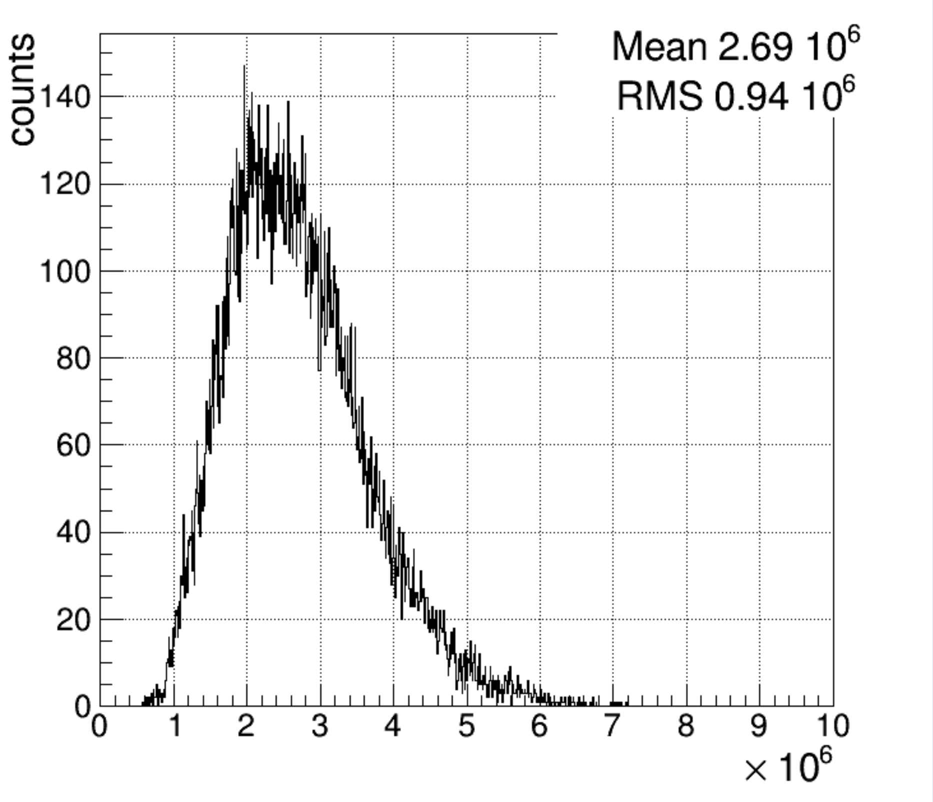
< 1 cm spatial resolution
< 1 ns time resolution
Compatible with the low torus fringe field

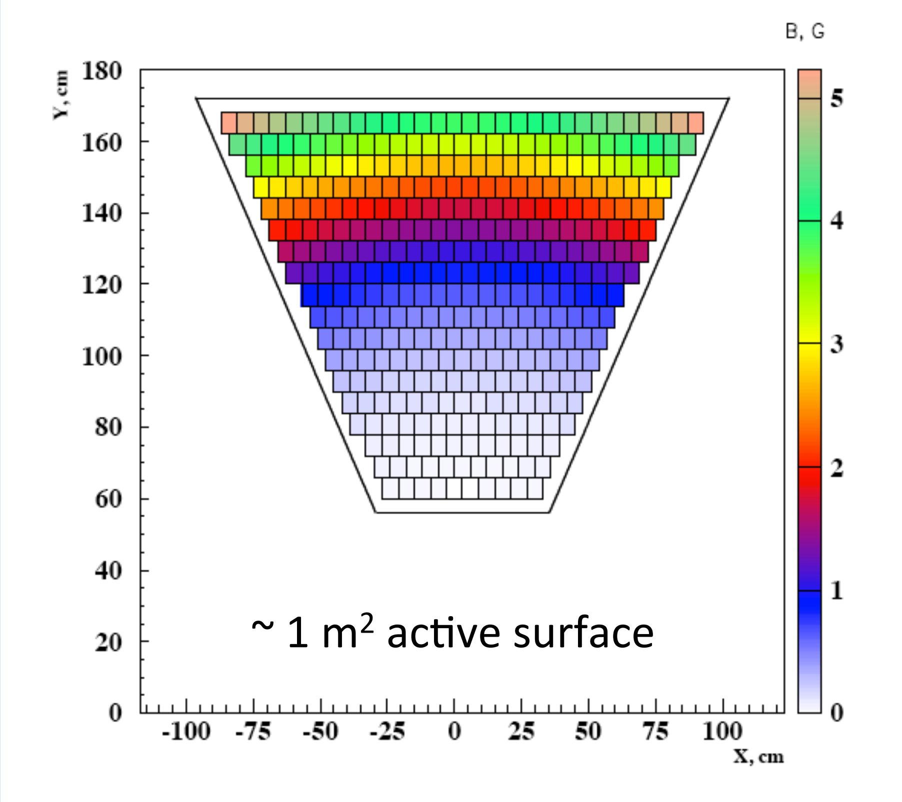
Average MA-PMT gain ~ 2.7 10^6
Corresponds to SPE ~ 400 fC



- ✓ 64 6x6 mm^2 pixels cost effective device
- ✓ High sensitivity on VIS towards UV light
- ✓ Mature and reliable technology
- ✓ Large Area (5x5 cm^2)
- ✓ High packing density (89 %)
- ✓ Fast response

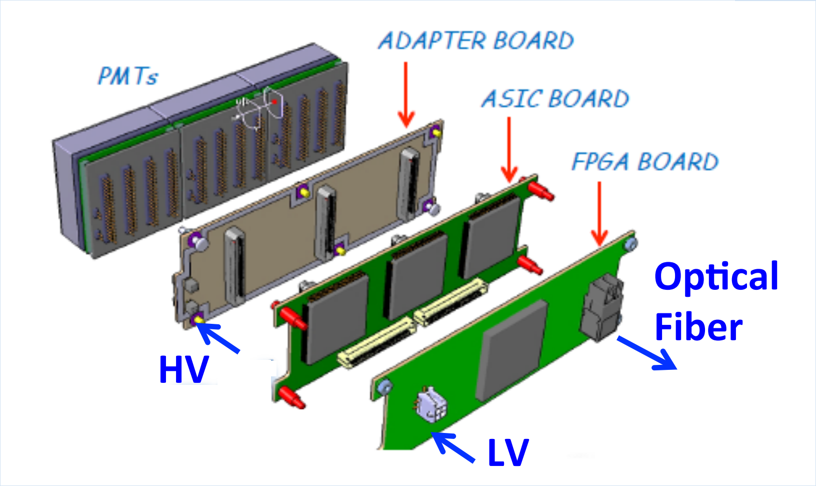
- ✓ Expensive technology

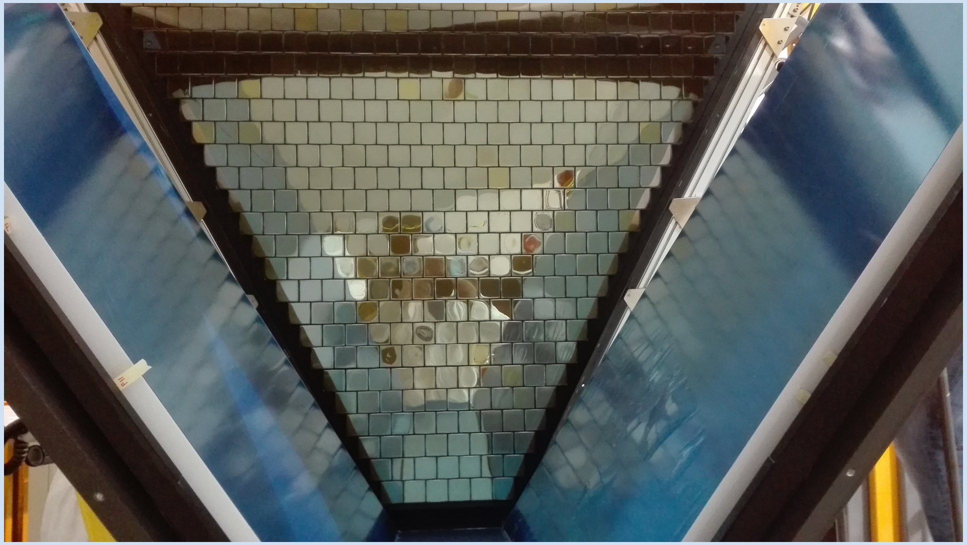




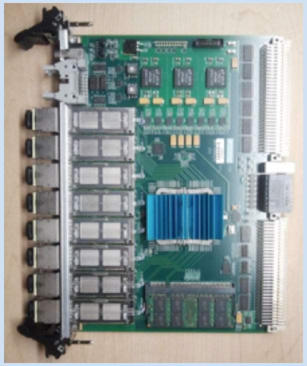
Readout Electronics

Compact (matches sensor area)
Modular Front-End (Mechanical adapter, ASIC, FPGA)
Scalable fiber optic DAQ (TCP/IP or SSP)
Tessellated (common HV, LV and optical fiber)

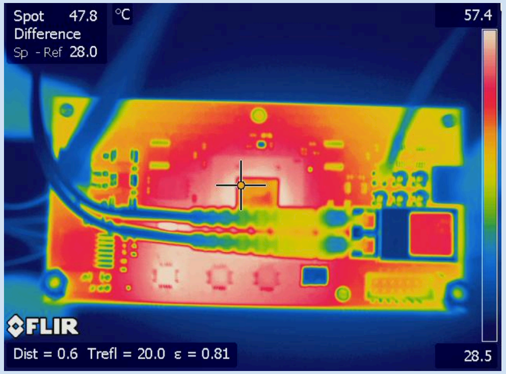


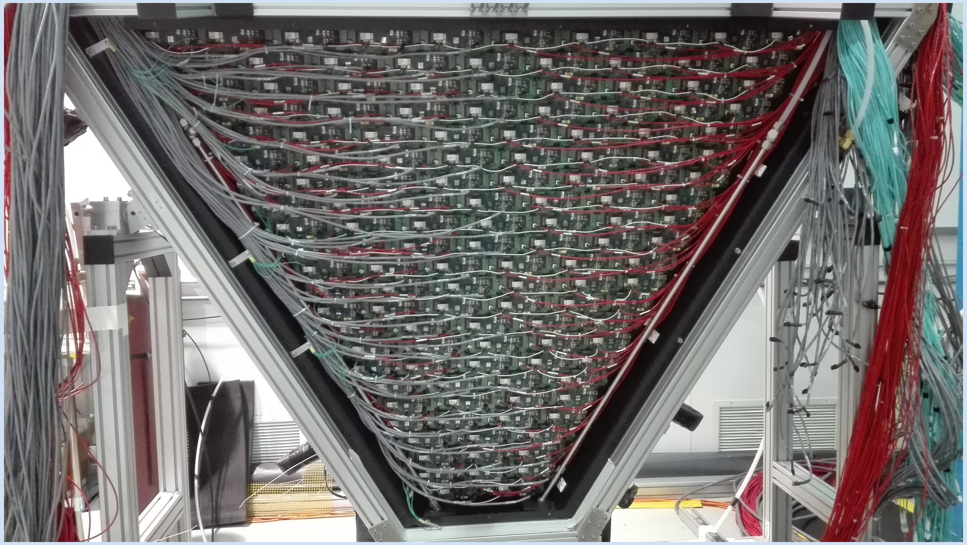


SSP Fiber-Optic DAQ

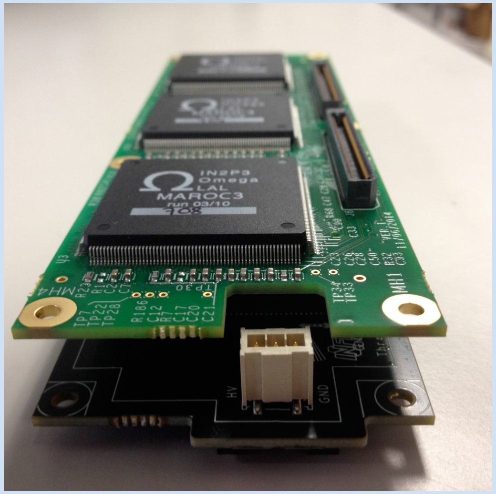


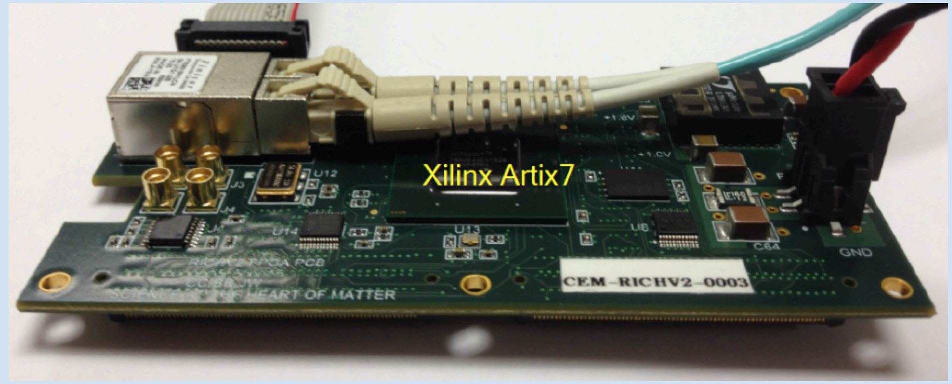
Tile power dissipation ~ 3.5 W





RICH Front-End Electronics





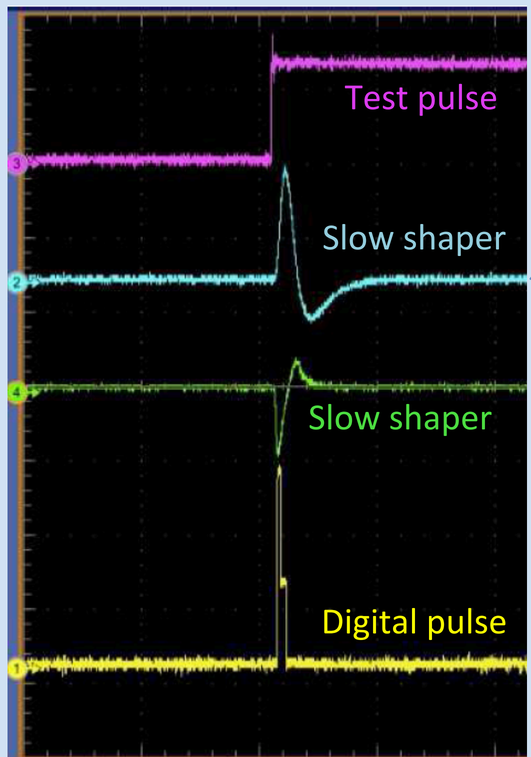
Analog: Charge (1 fC)
Digital: Time (1 ns)

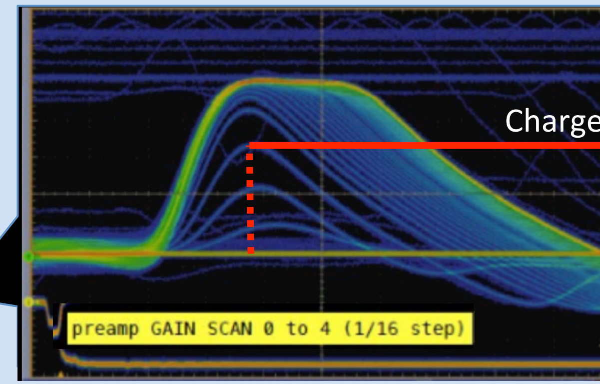
Trigger latency (8 μs)

Optical ethernet (2.5 Gbps)

Trigger: external
internal
self

On-board pulser





Linear response

Multiplexed readout
Limited holding time delays

Used for calibrations

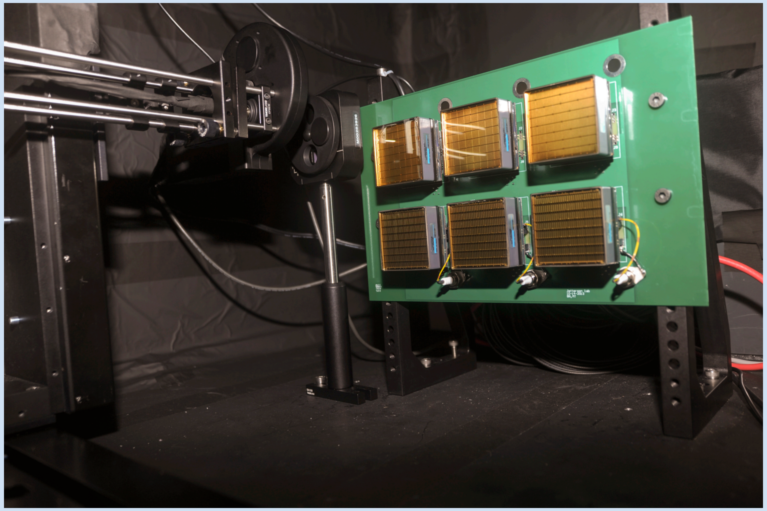
ADC Charge Measurement

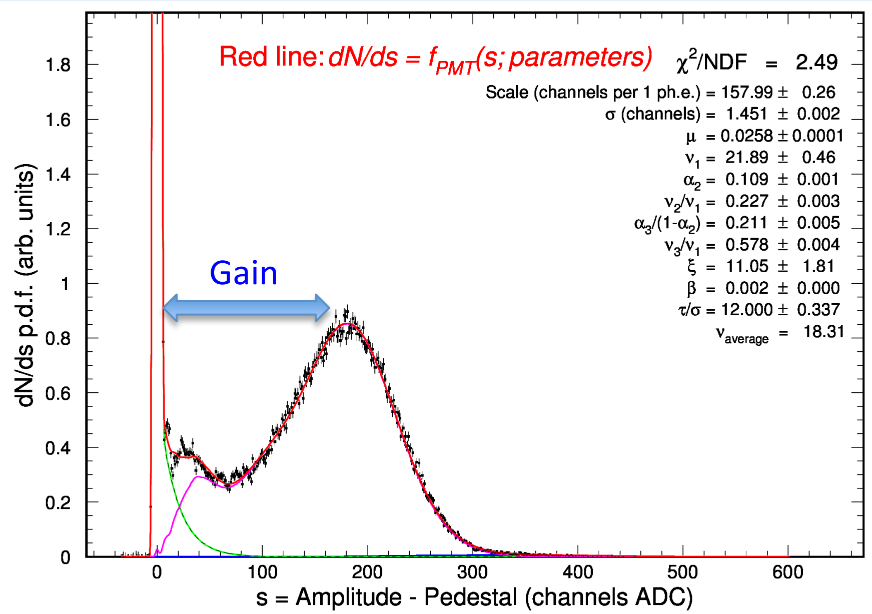
Multiplexed readout up to 50 kHz

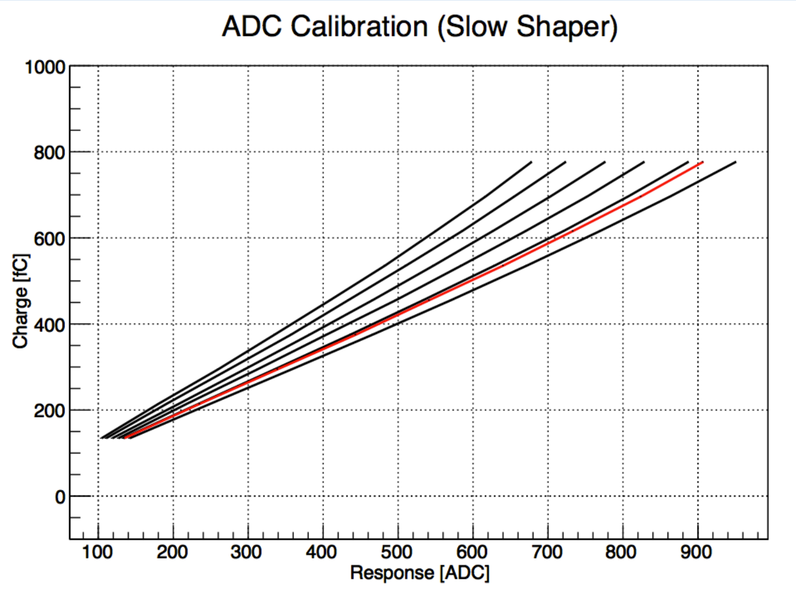
High resolution SPE spectrum

Viable for efficiency and gain monitors

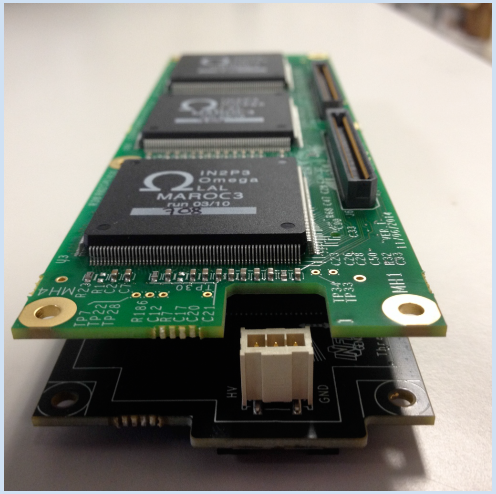
In conjunction with timing, allows the study of PMT discharge and cross-talk

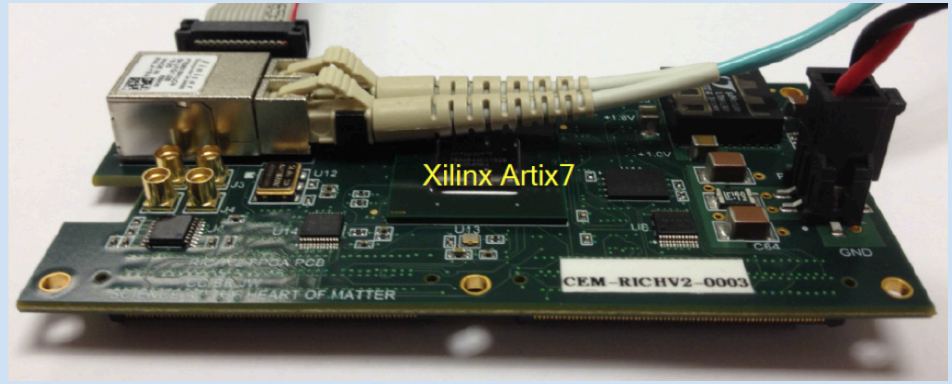






RICH Front-End Electronics





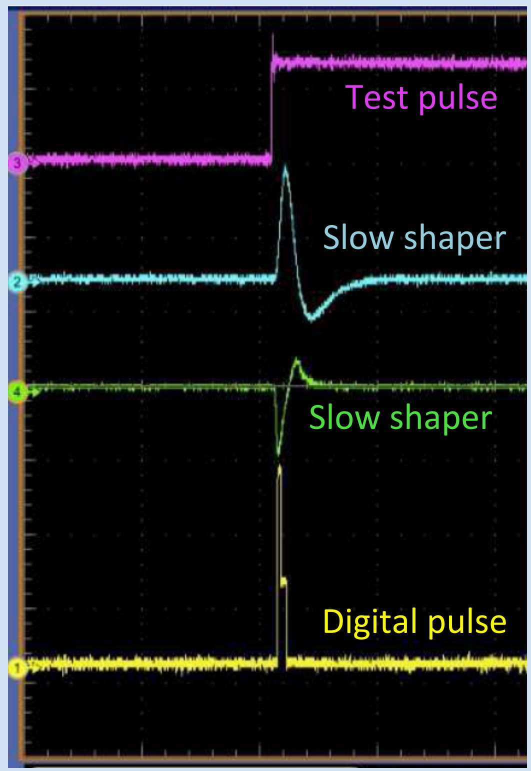
Analog: Charge (1 fC)
Digital: Time (1 ns)

Trigger latency (8 μs)

Optical ethernet (2.5 Gbps)

Trigger: external
internal
self

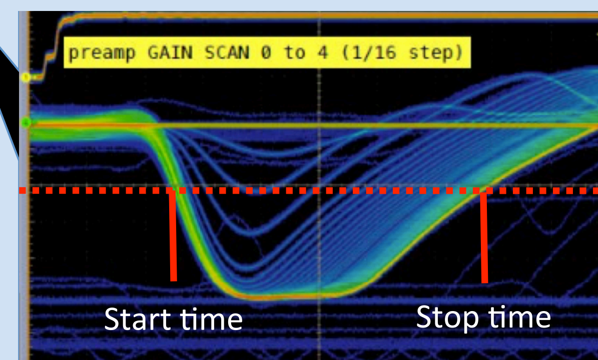
On-board pulser



Digital response
Working in saturated regime

64 parallel channel readout

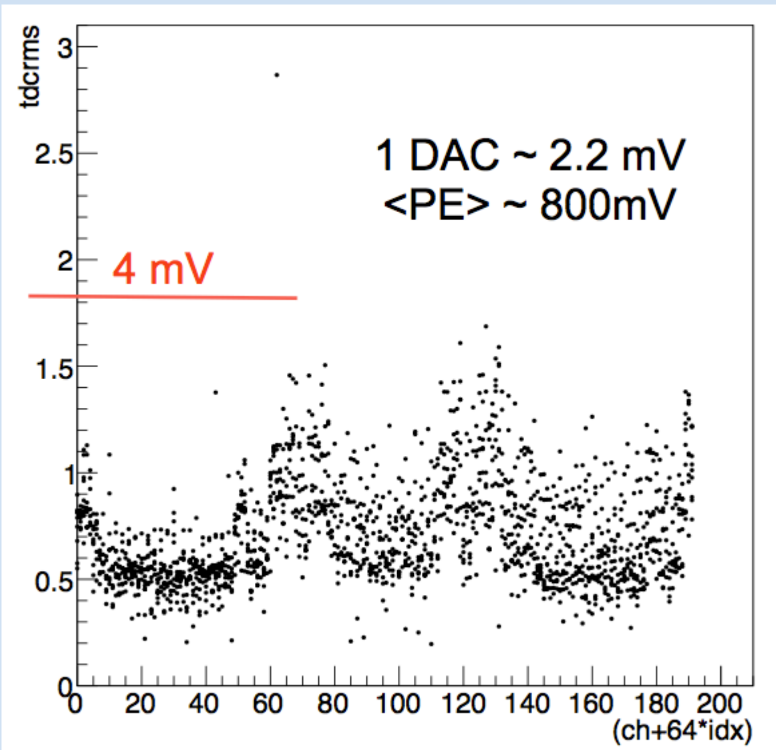
8 μs FIFO and delays
1 ns time resolution



TDC Digital Readout

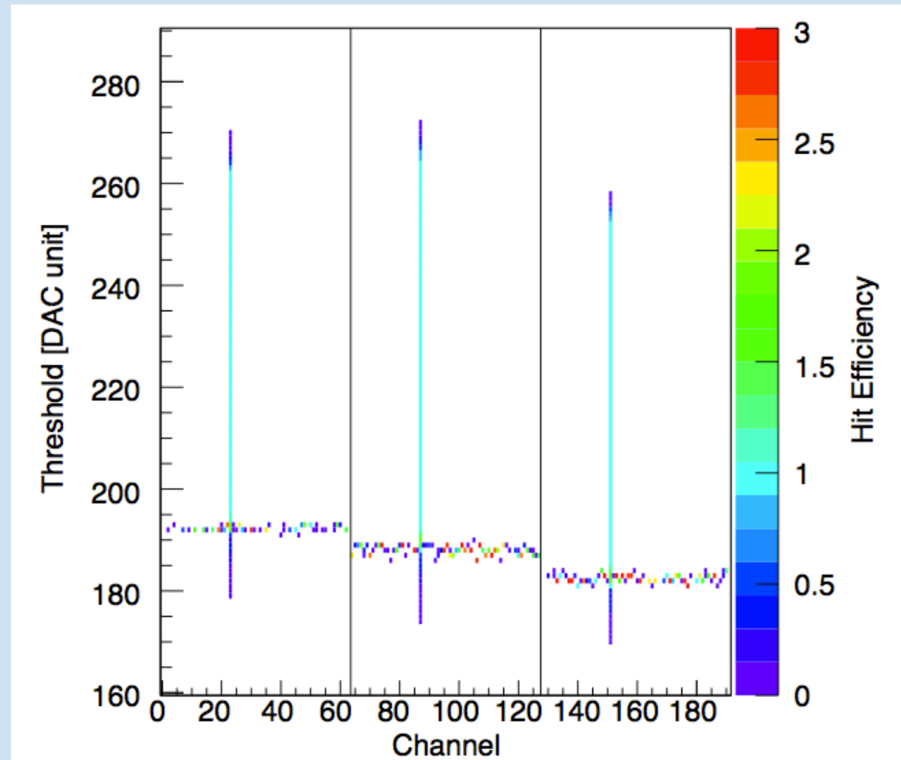
During Acceptance tests

Pedestal rms as seen by a test-point



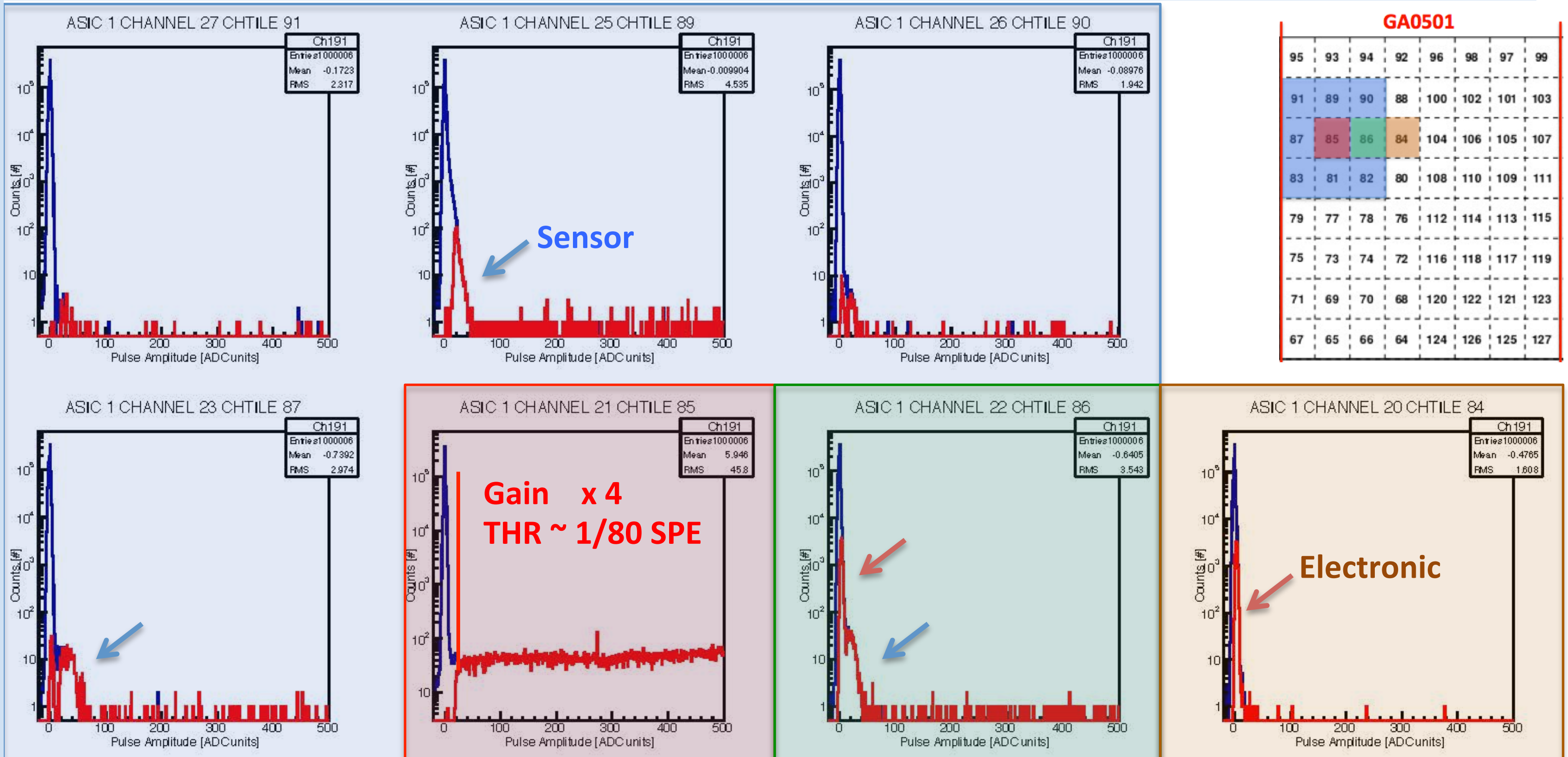
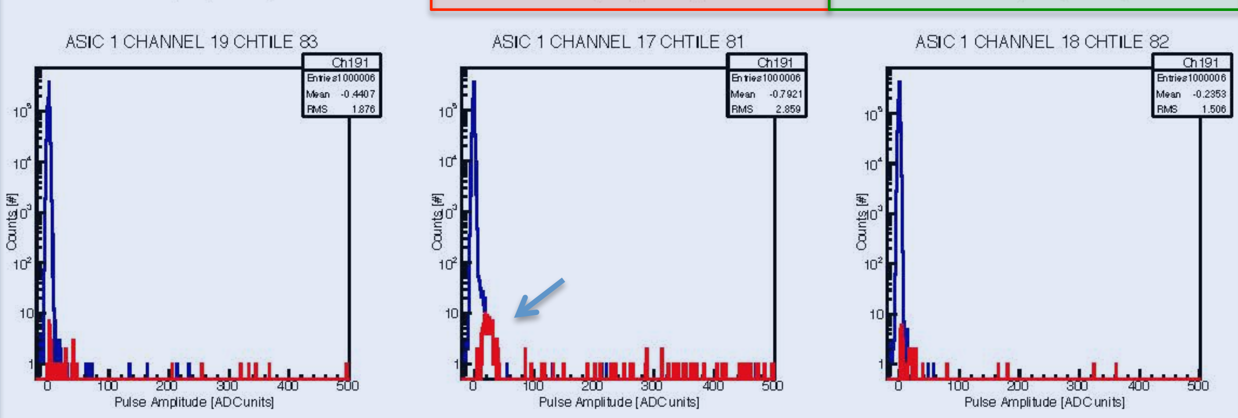
During Internal Pulser Calibration

As seen by RICH readout



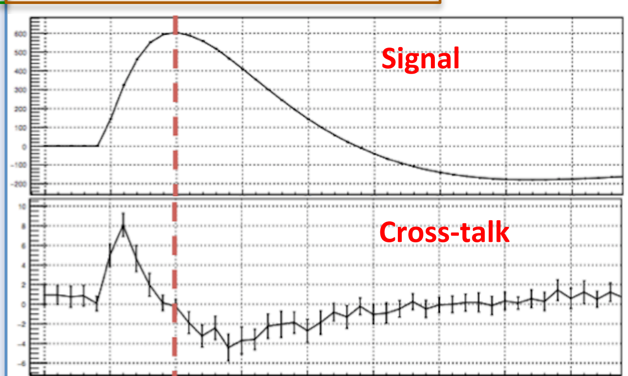
Discrimination down to 20 fC, i.e. few % of SPE, allows sensor characterization

Optical and Electric Cross-talk

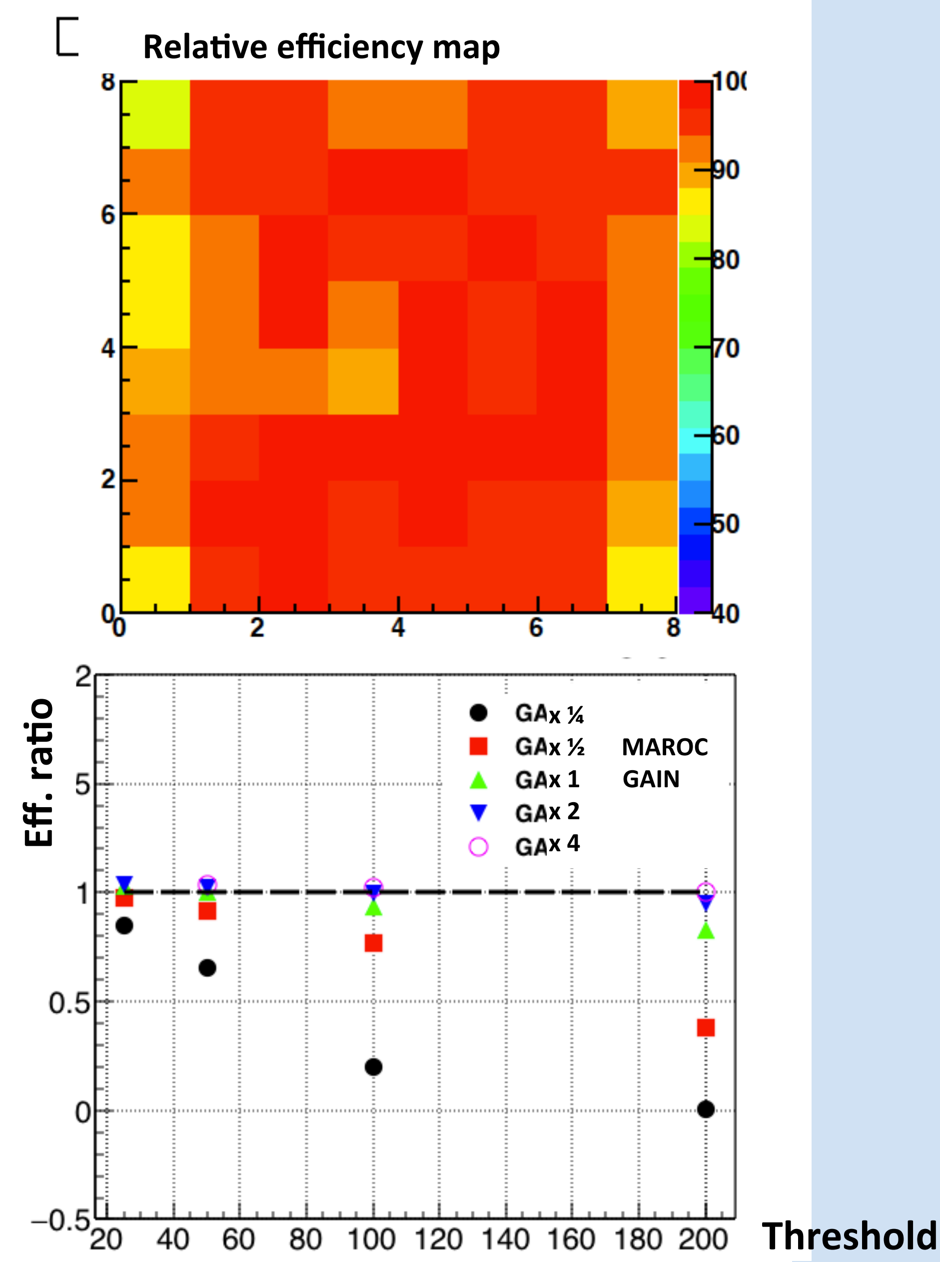



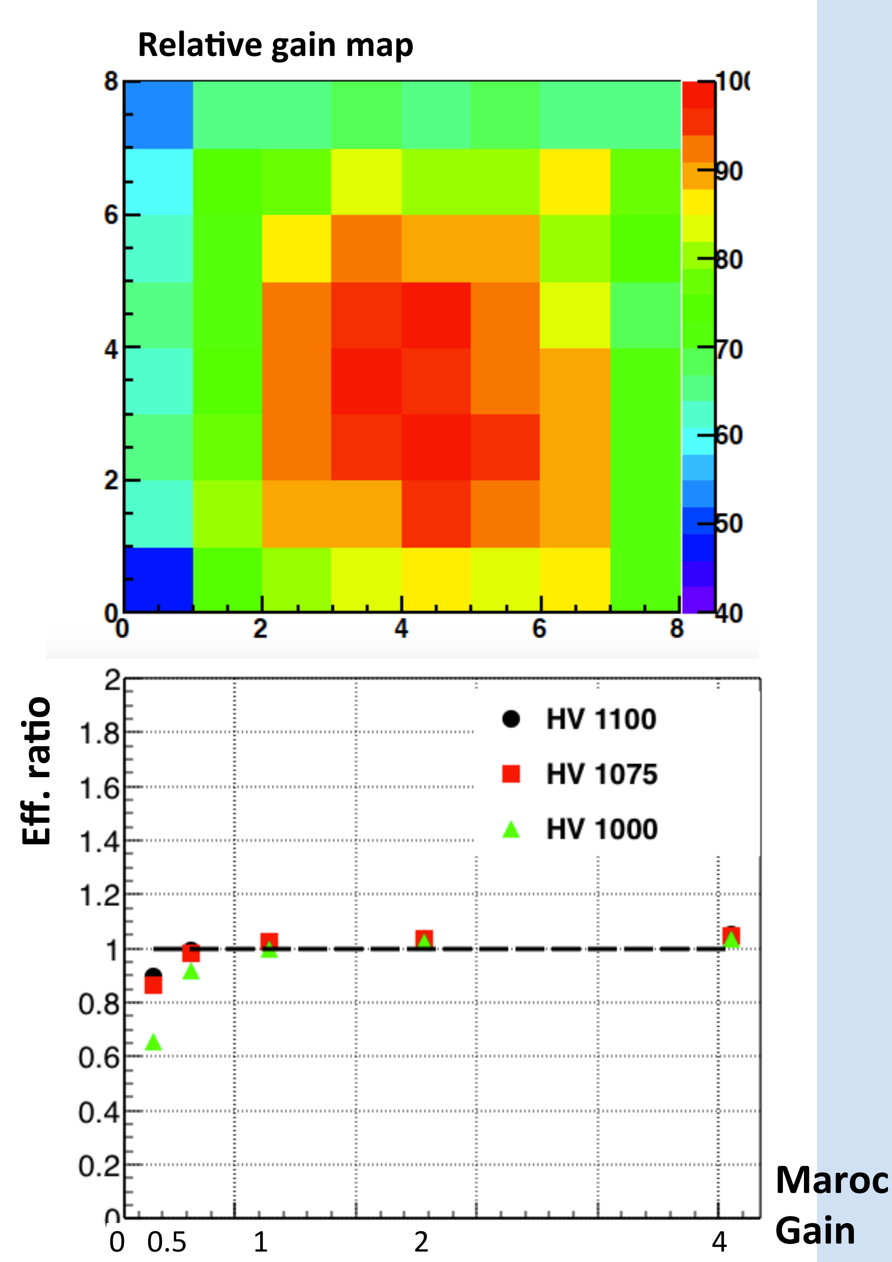
GA0501

95	93	94	92	96	98	97	99
91	89	90	88	100	102	101	103
87	85	86	84	104	106	105	107
83	81	82	80	108	110	109	111
79	77	78	76	112	114	113	115
75	73	74	72	116	118	117	119
71	69	70	68	120	122	121	123
67	65	66	64	124	126	125	127

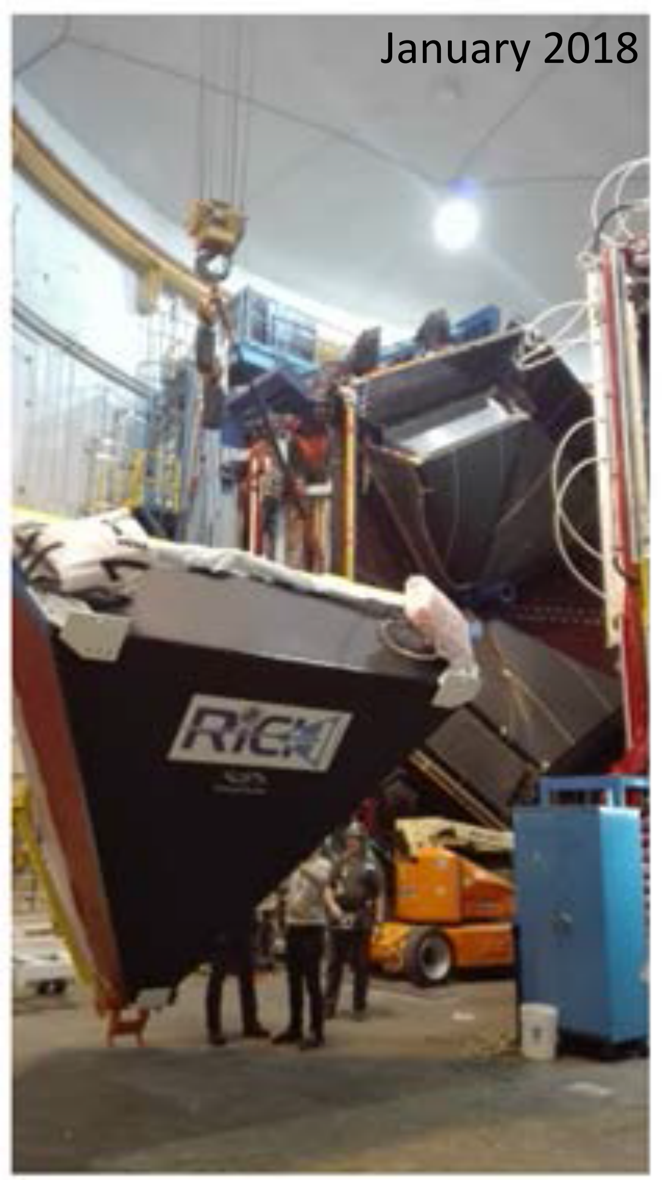


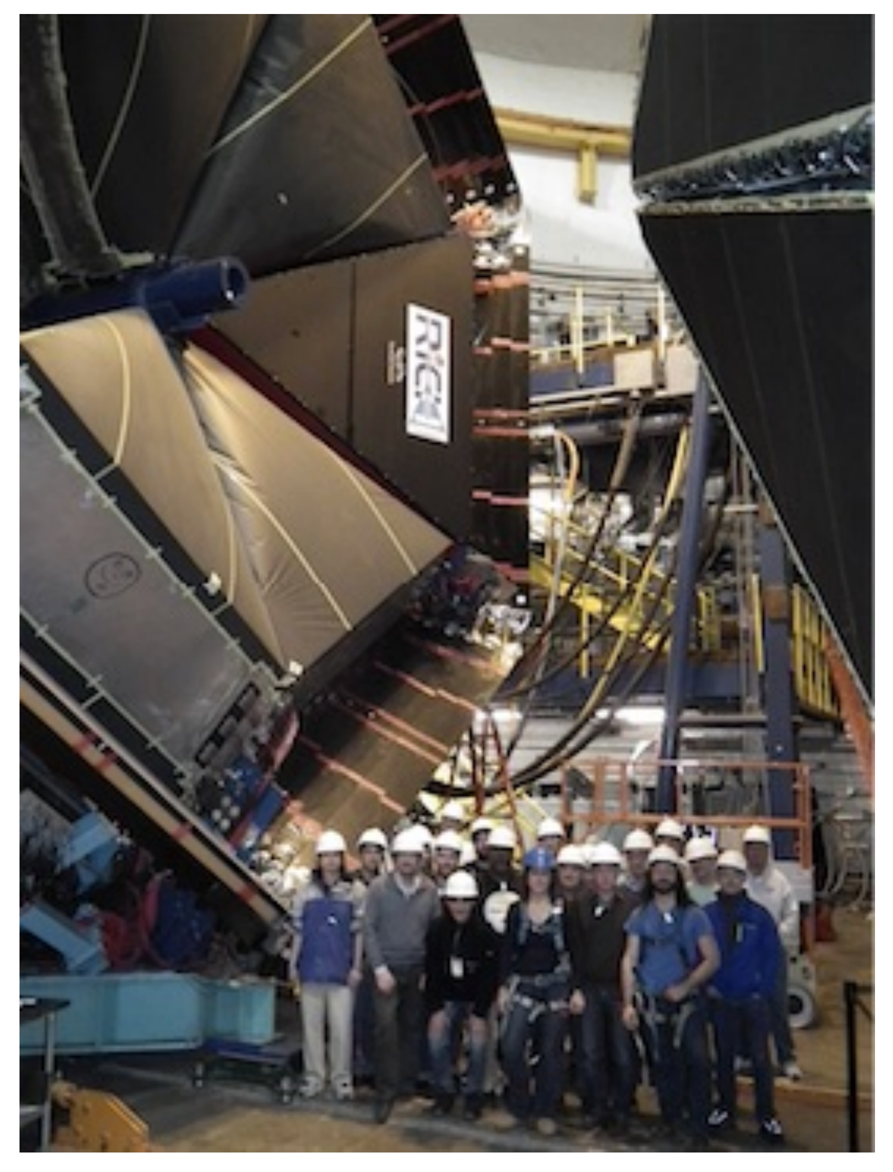
Single Photon Discrimination



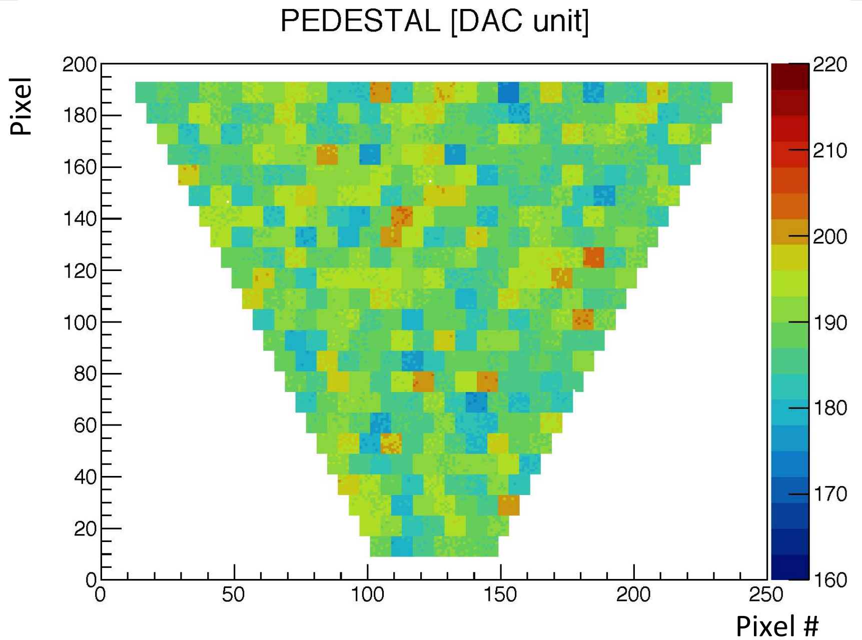


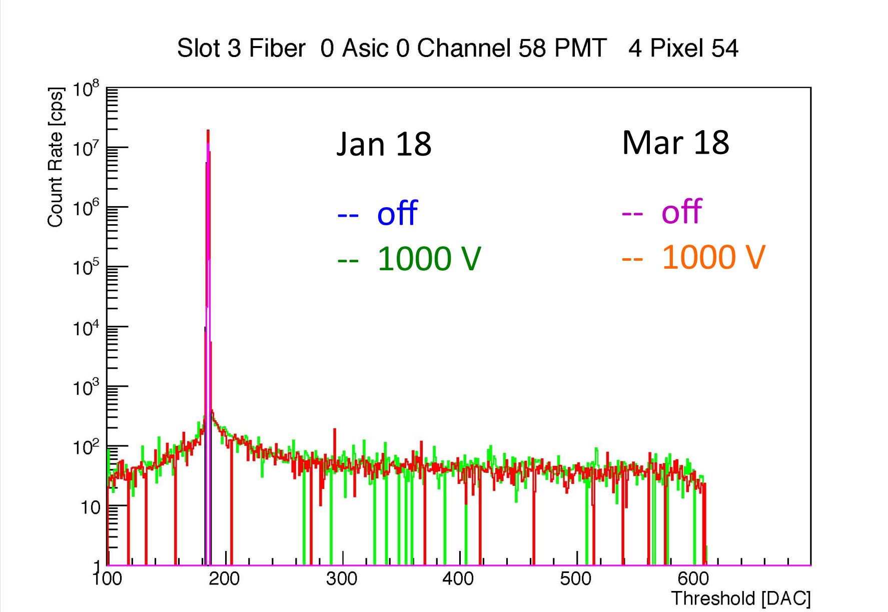
RICH Installation



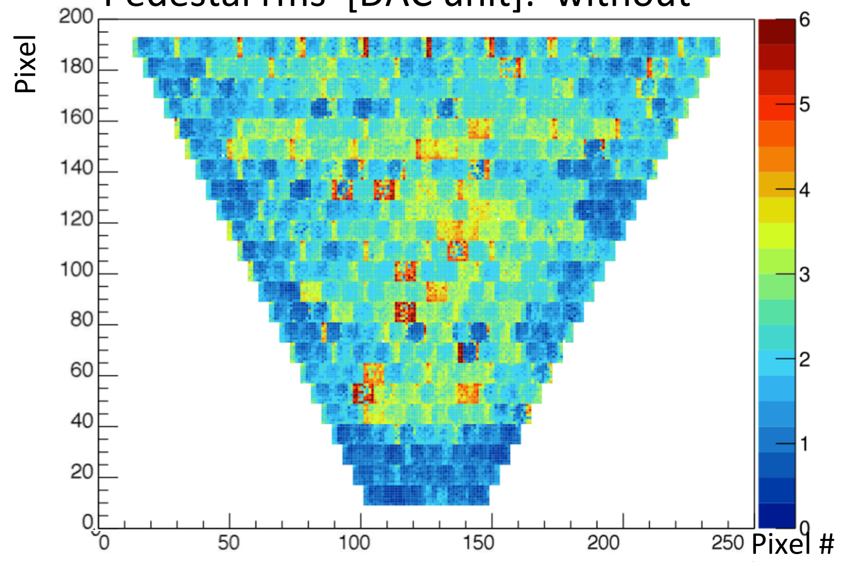


Electronic Pedestal

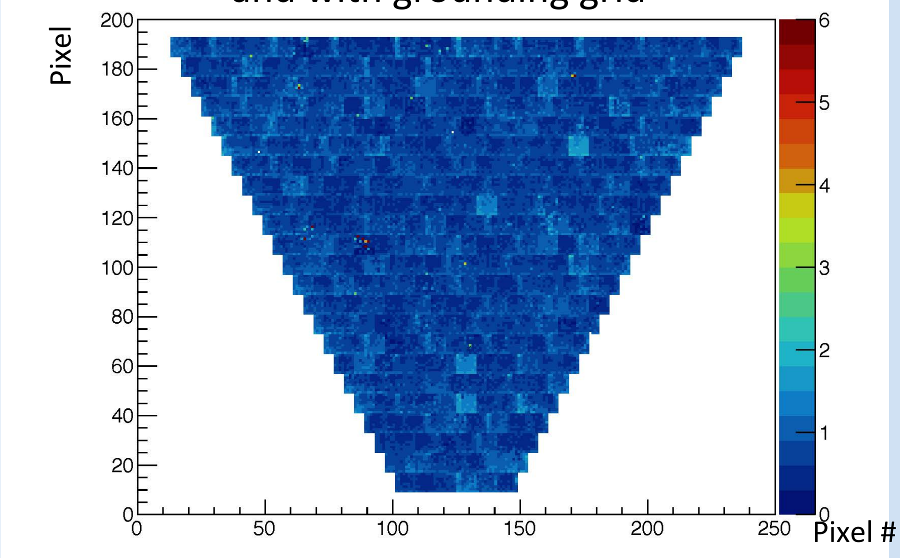




Pedestal rms [DAC unit]: without

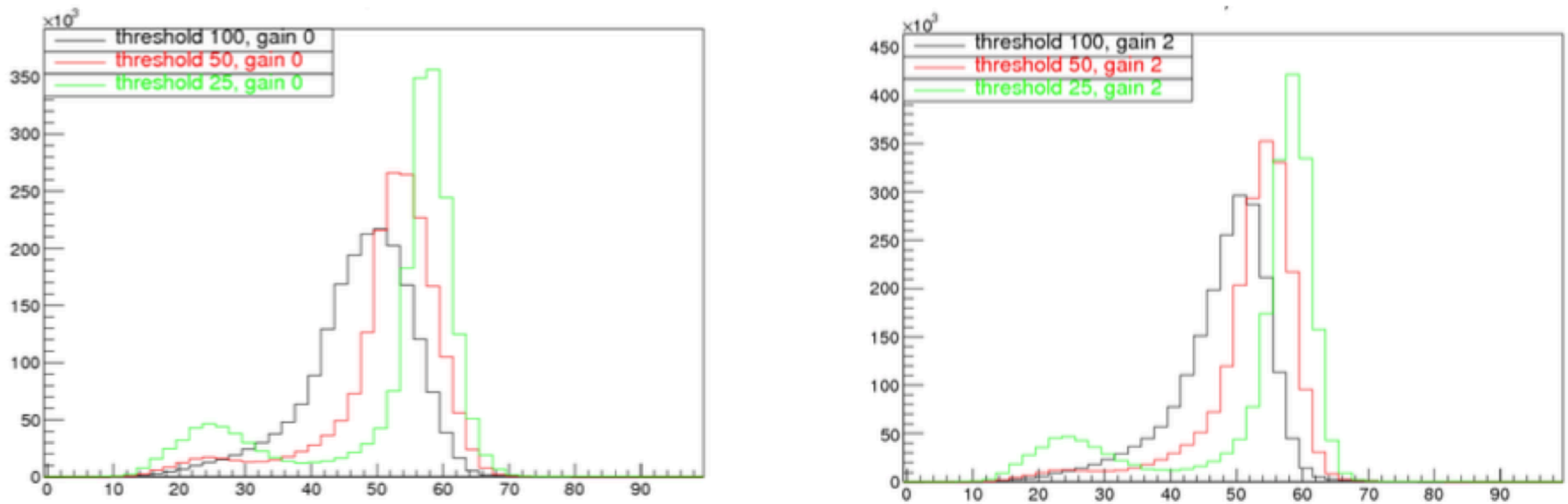


and with grounding grid



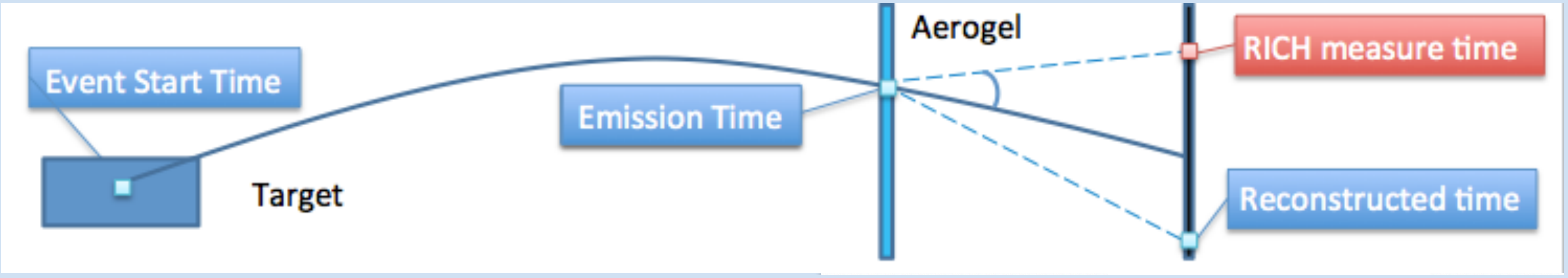
After equalization: distributions narrower and less sensitive to the common threshold
saturate signals and cross-talk well separate

Before equalization **After equalization**



black: high threshold **red: intermediate threshold** **green: low threshold**

Single Photon Time Analysis

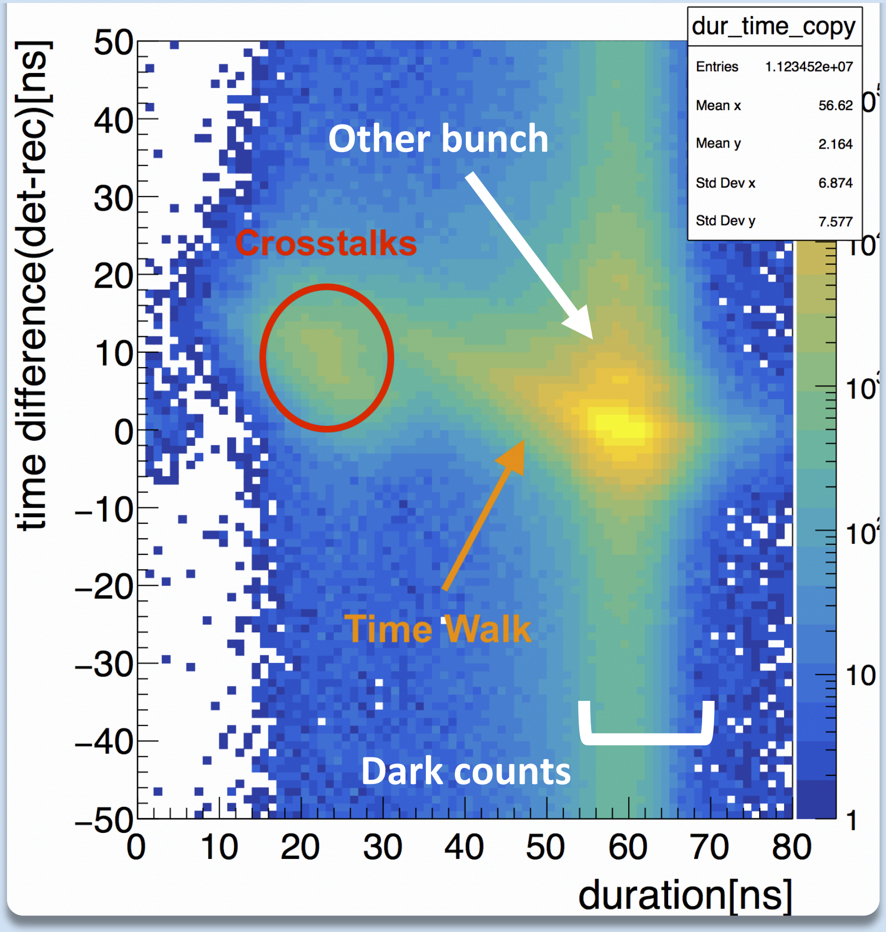


CLAS12 Reconstructed Time and Position:
Photons are traced using information from other CLAS12 detectors

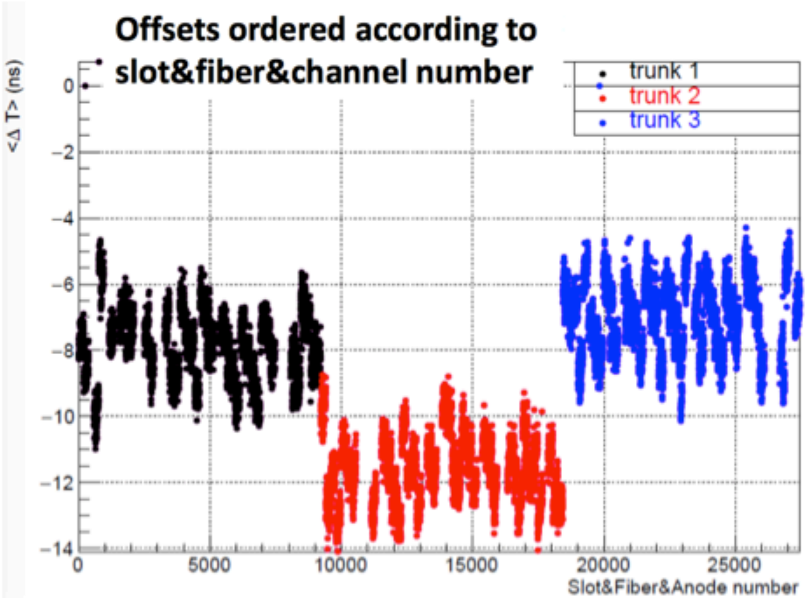
RICH Measured Time and Position:
Defined by the RICH DAQ

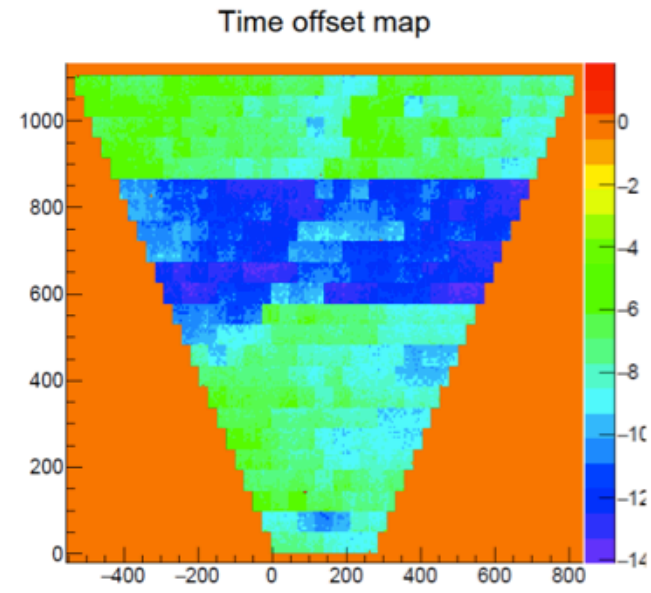
Good photons should match in time and space

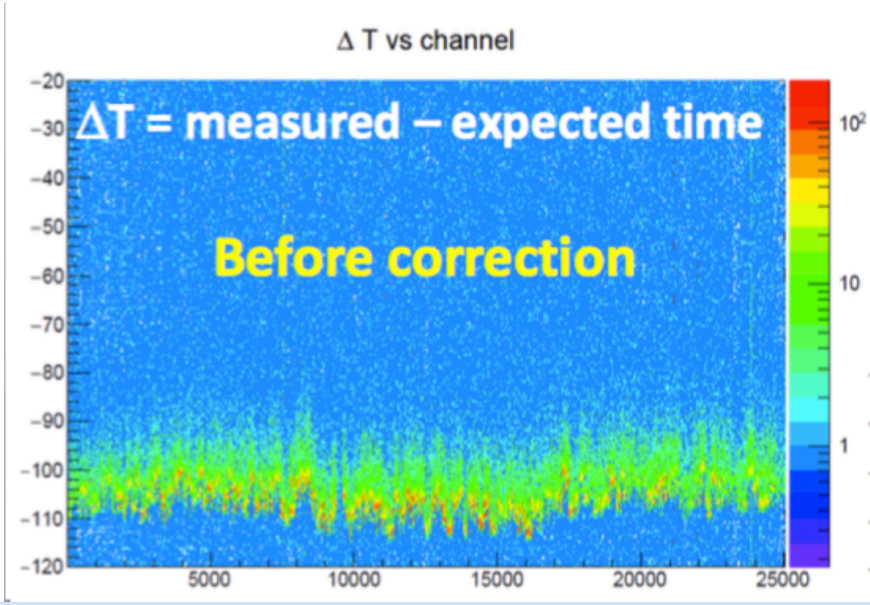
Time analysis allows to separate spurious signals

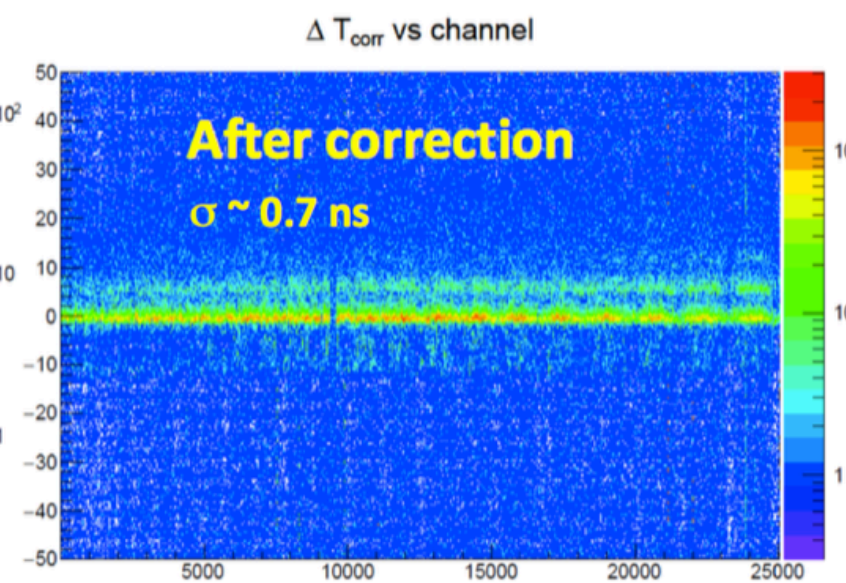


Time Offsets



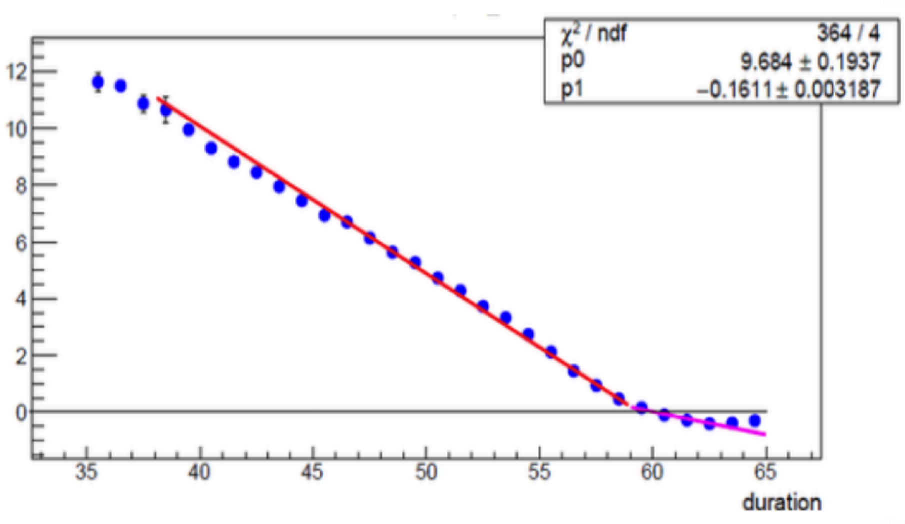


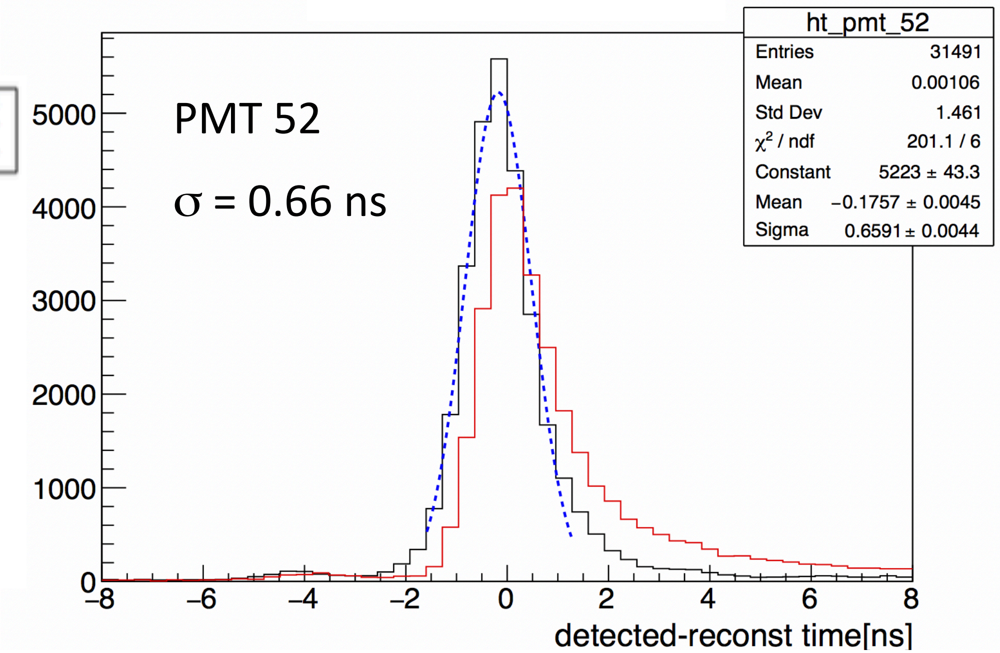




Single Photon Time Resolution

Single-photon time resolution better than the 1 ns specification

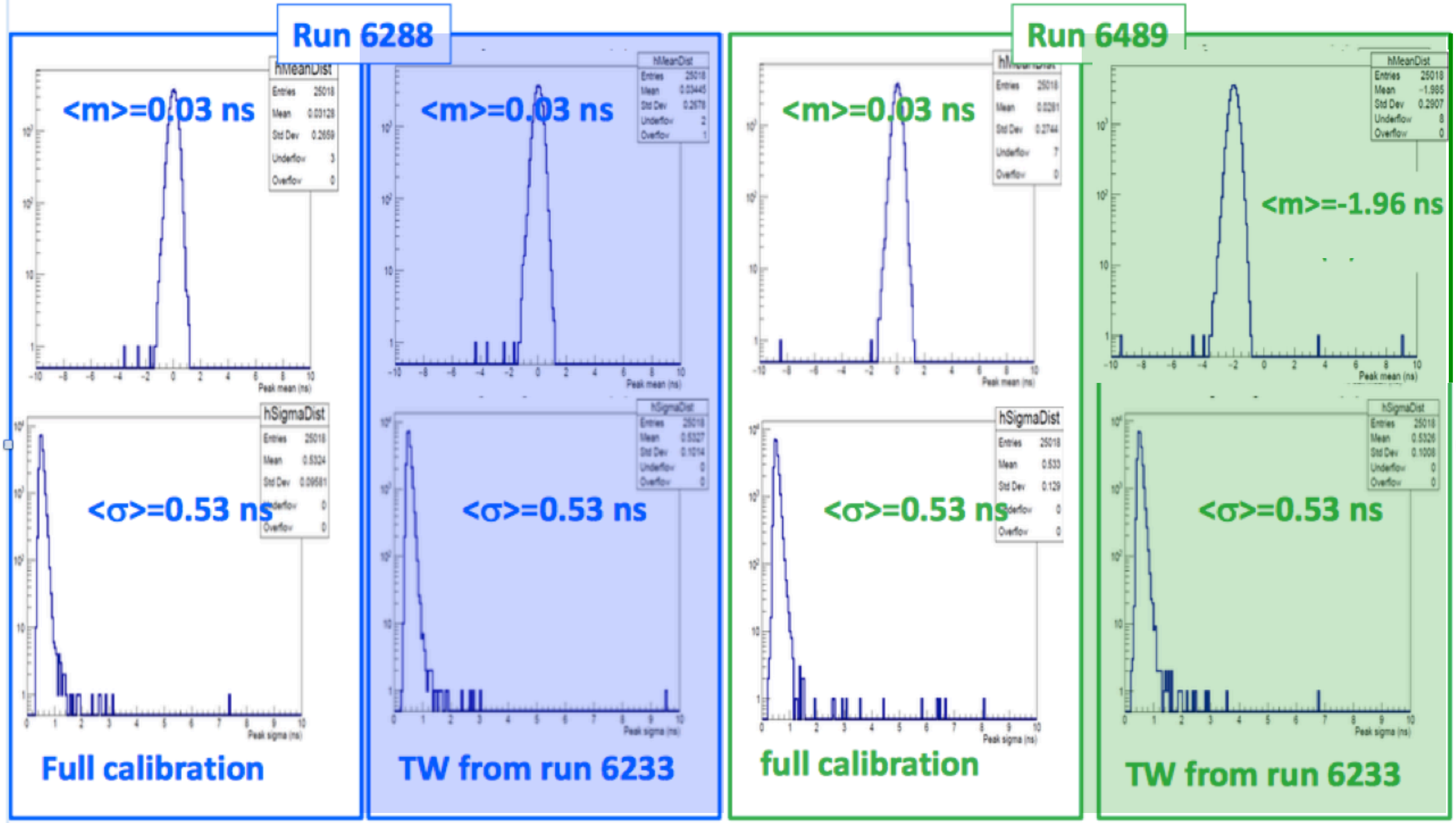




— before time-walk correction

— after time-walk correction

Single Photon Time Resolution



Cherenkov Angle Reconstruction

Analytic solution for direct photons

"Exact" solution for the Cherenkov Angle

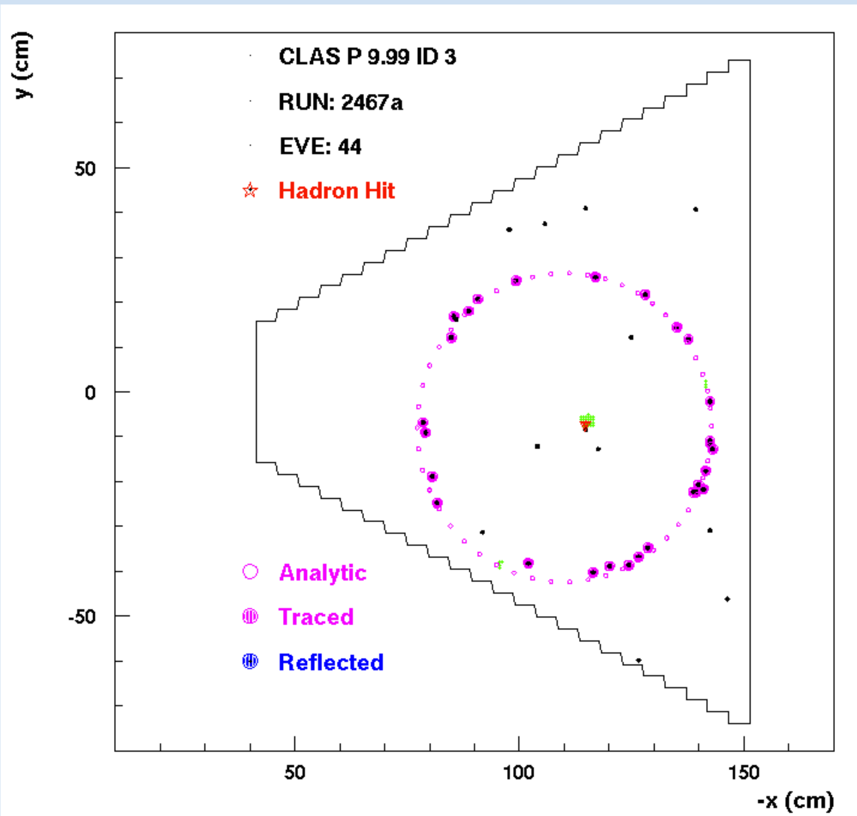
Only direct photons

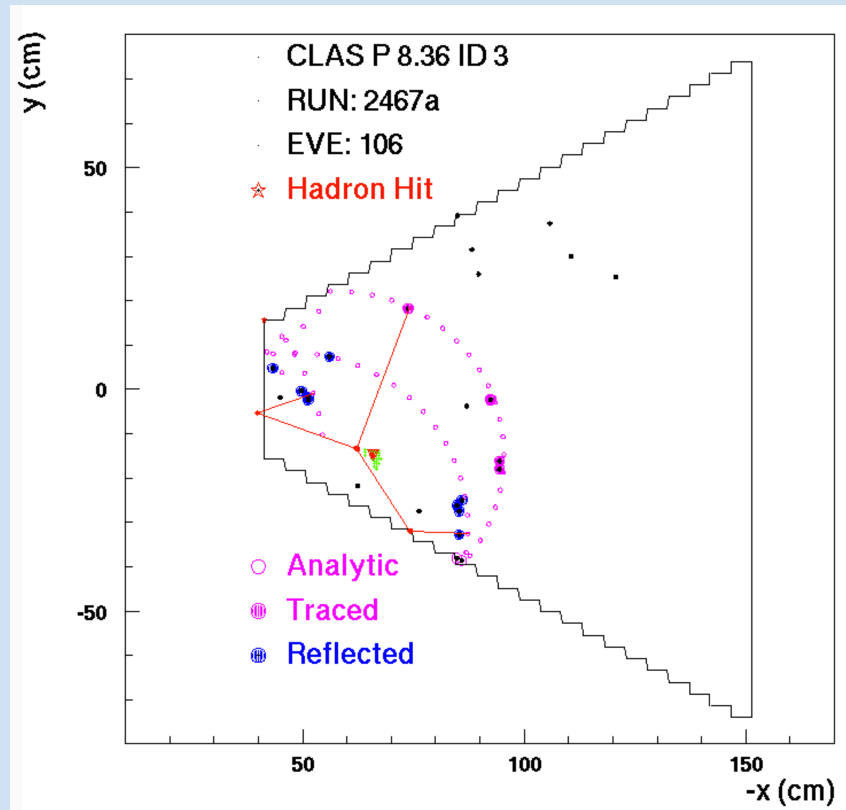
Ray traced solution for direct photons

Assume knowledge of aerogel ref index

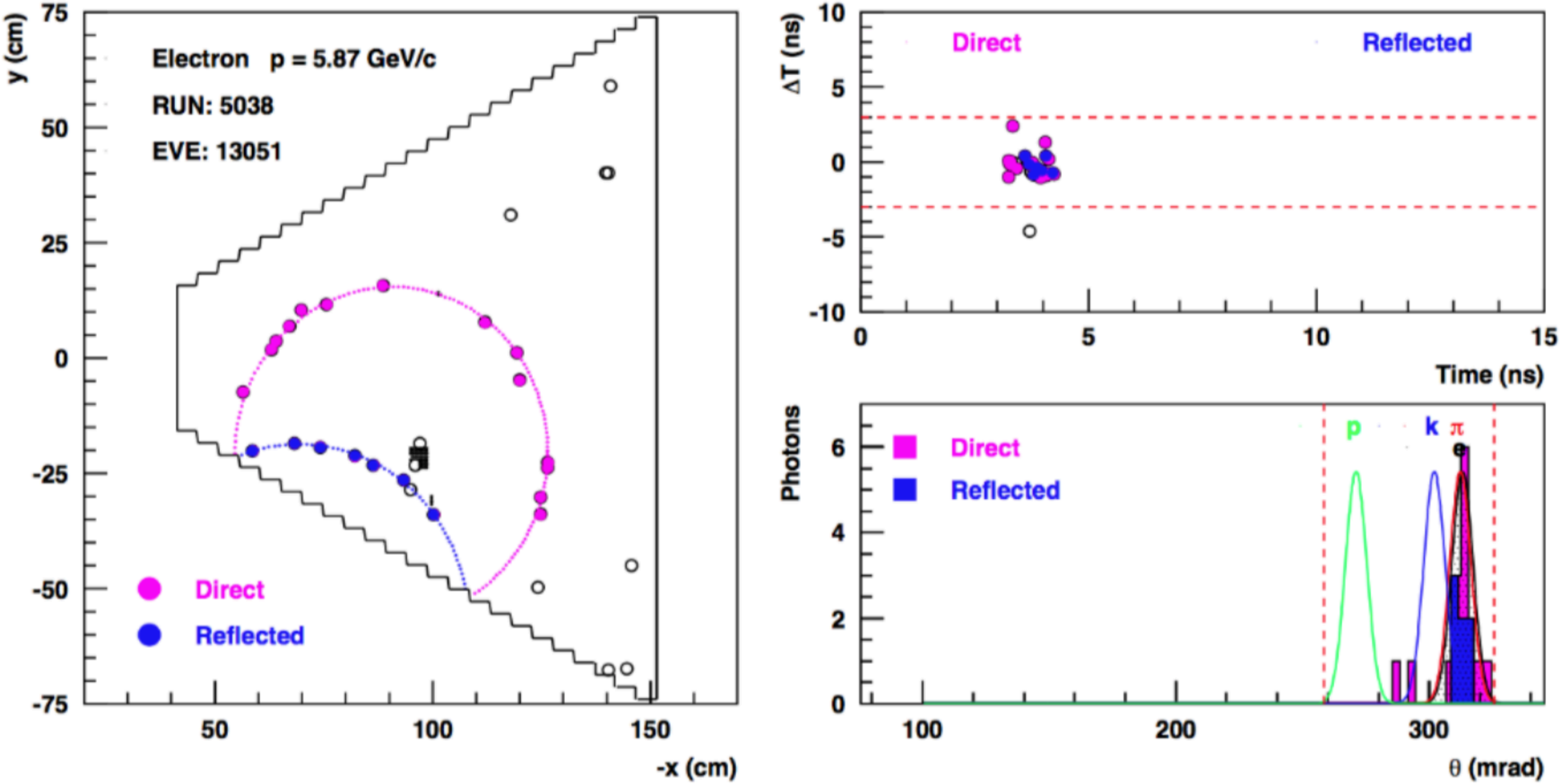
Any photon

GOAL: get a Cherenkov angle estimate for each photon for detailed PID optimization



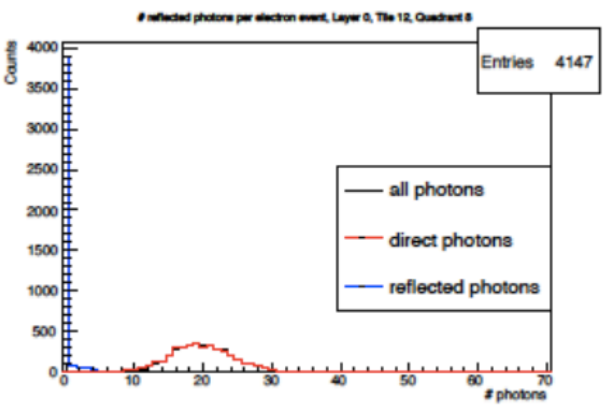


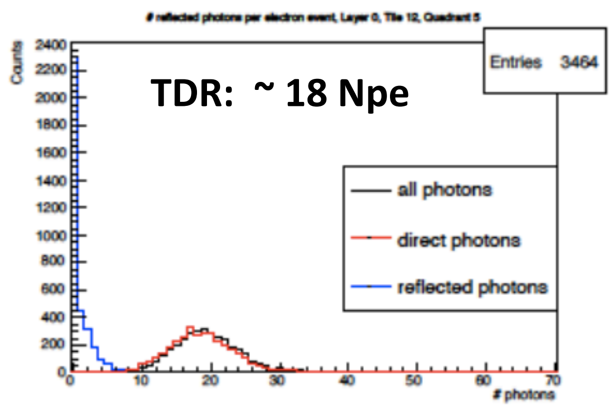
Cherenkov Angle Reconstruction

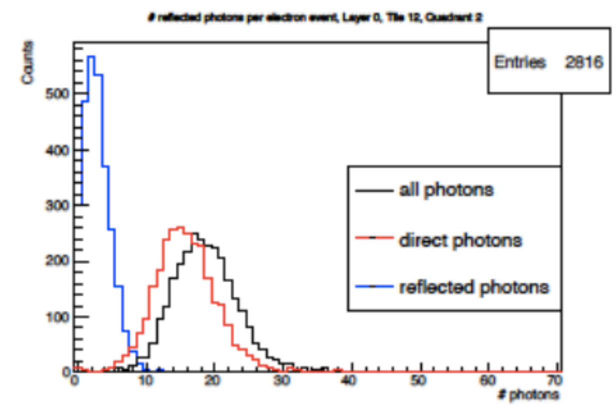


Cherenkov Angle Resolution

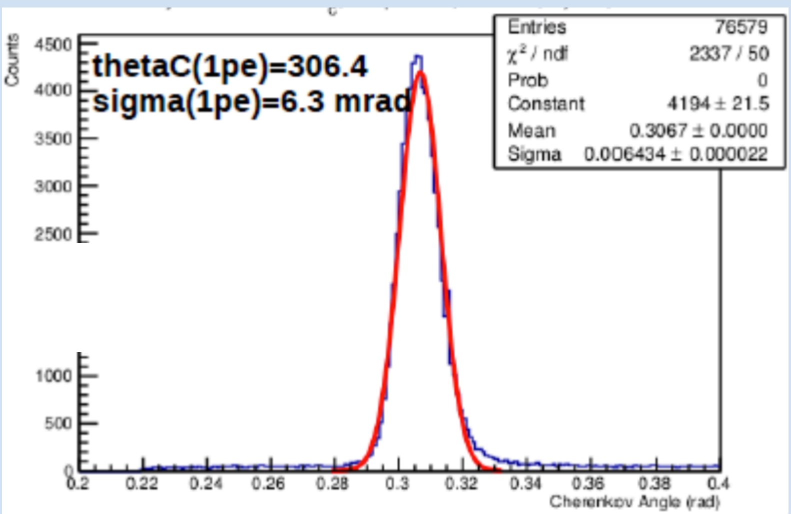
RGA data, direct photons   No alignment of internal components
Number of photons and single photon resolution close to TDR

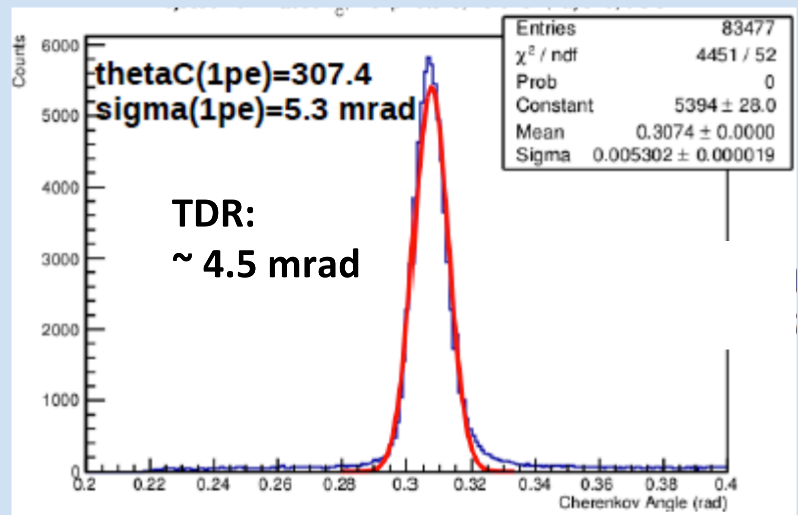






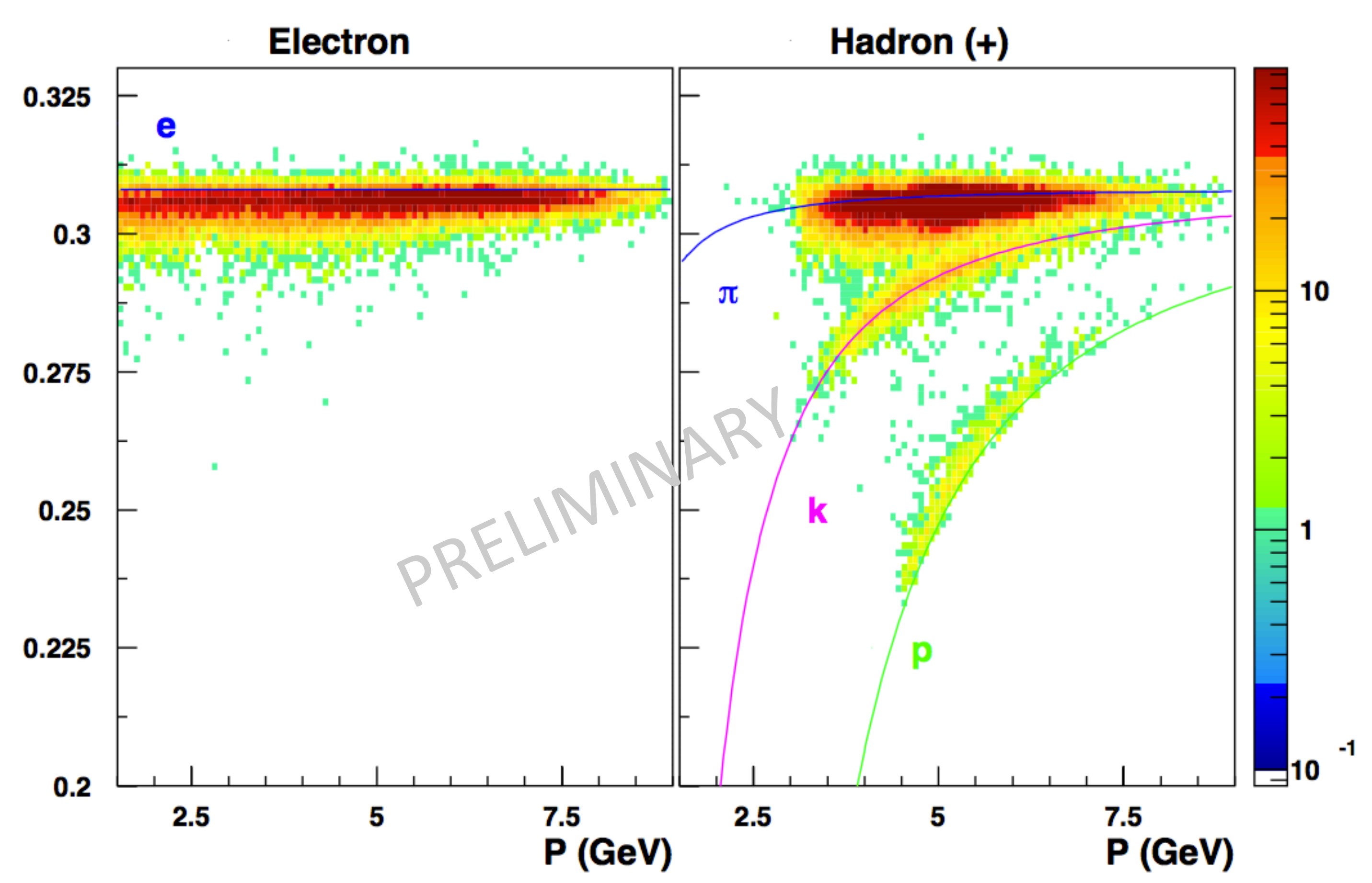
Raw RICH alignment (not for internal components)

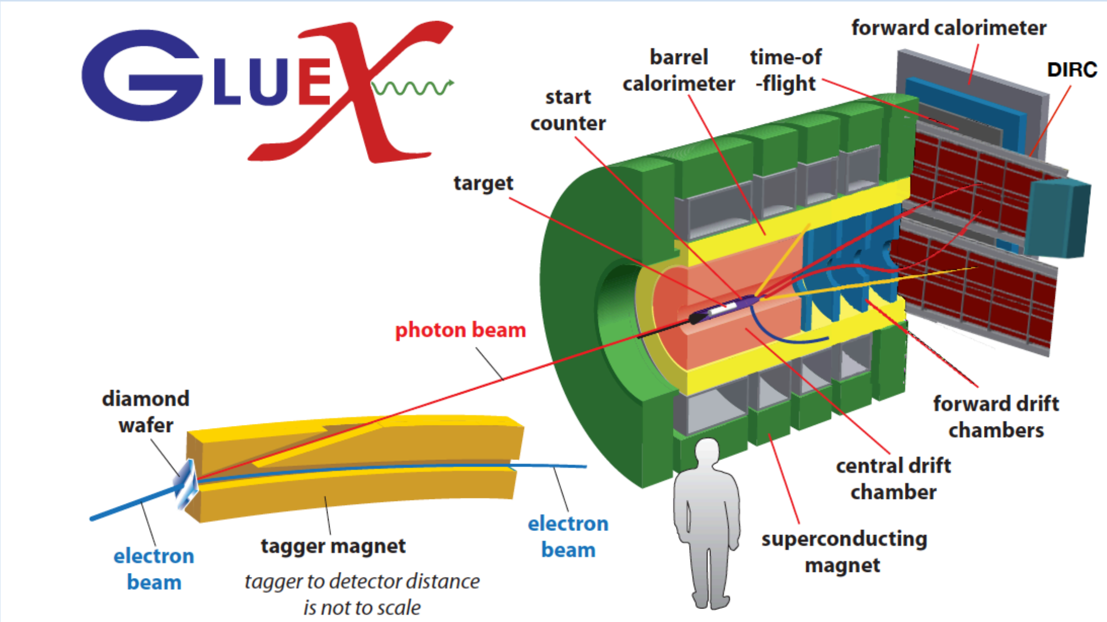


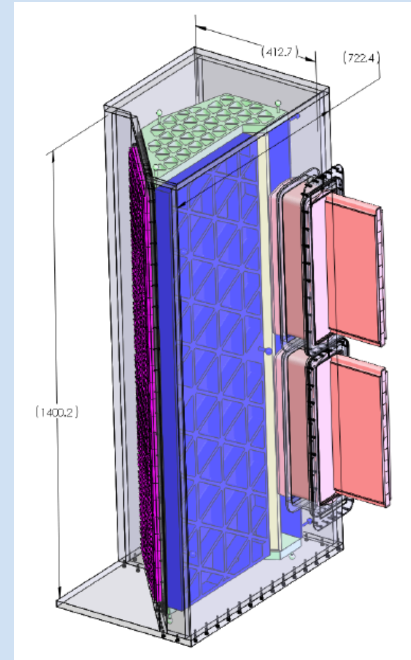


Hadron Separation

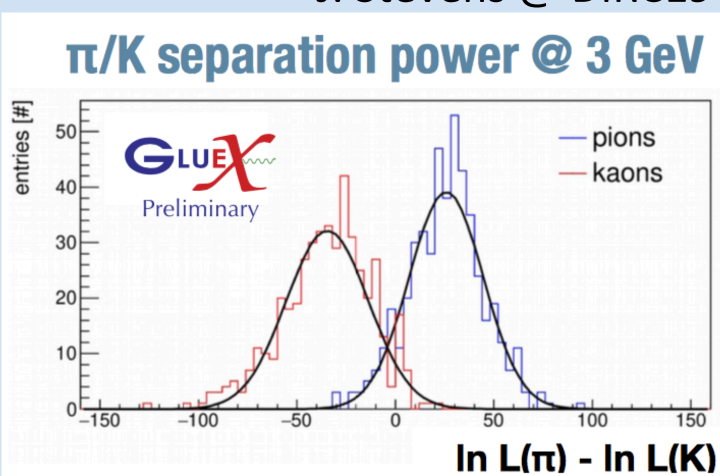
Hadron separation, direct photon, RGA data, raw alignment

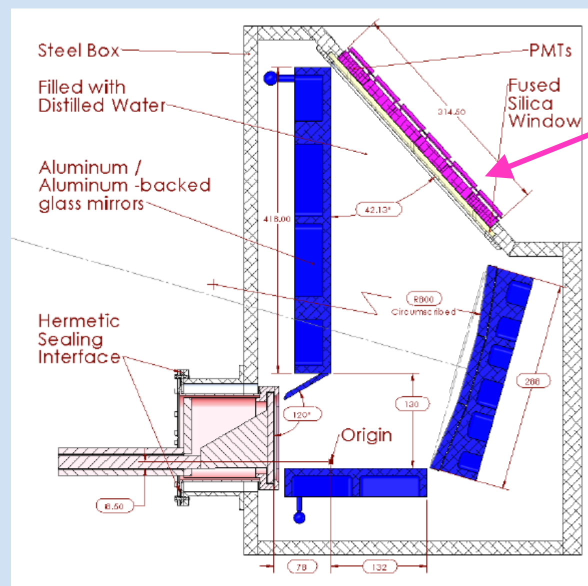






J. Stevens @ DIRC19





H12700 + CLAS12 readout

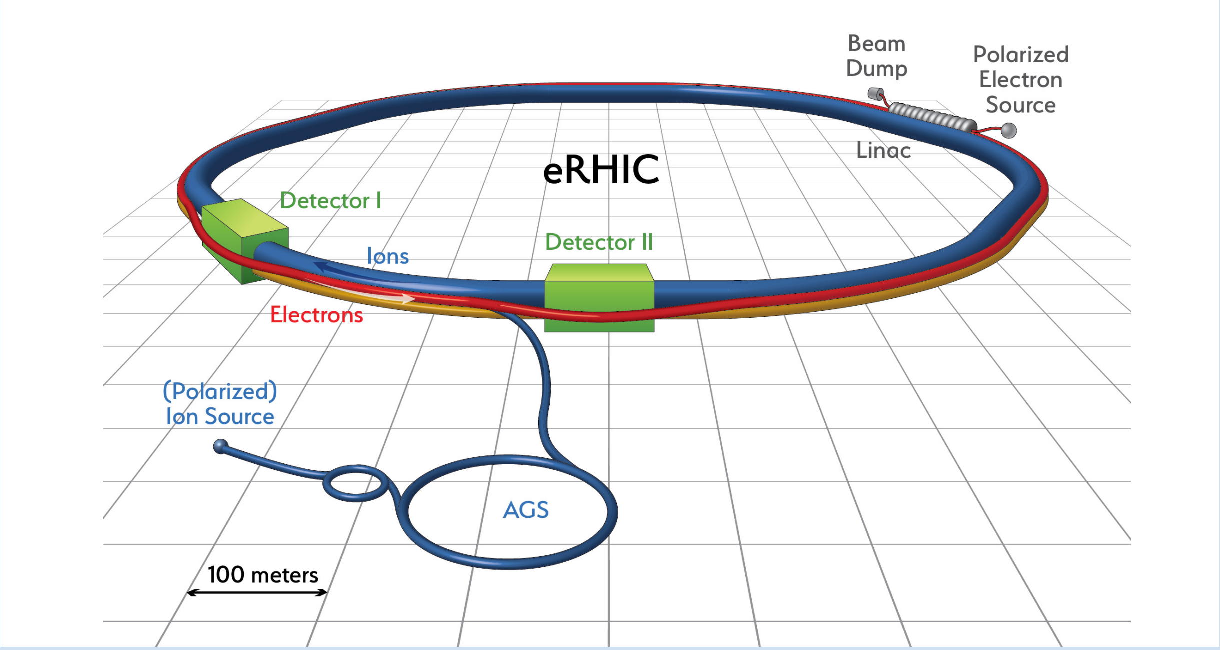
The Future: EIC

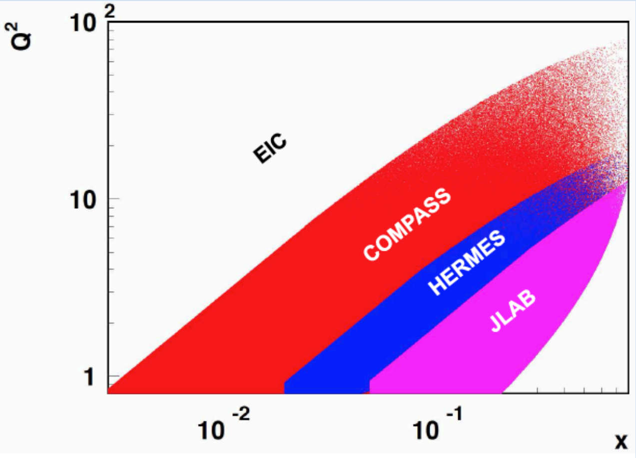
The ultimate machine fro QCD

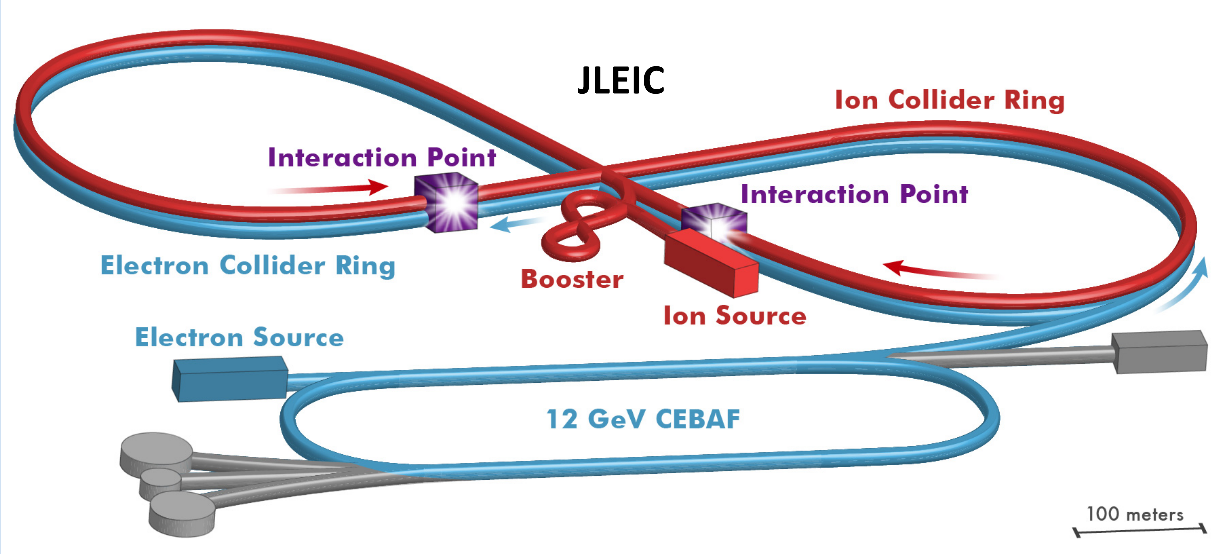
Well Beyond HERA:

- x 1000 Lumi
- Variable CM energy
- Polarized Beams
- Ion Beam
- Precision Detectors

CD0 + Site Decision Expected Soon







EIC Detector Challenges

Specific requirements to move beyond the longitudinal description

- Resolve partons in nucleons

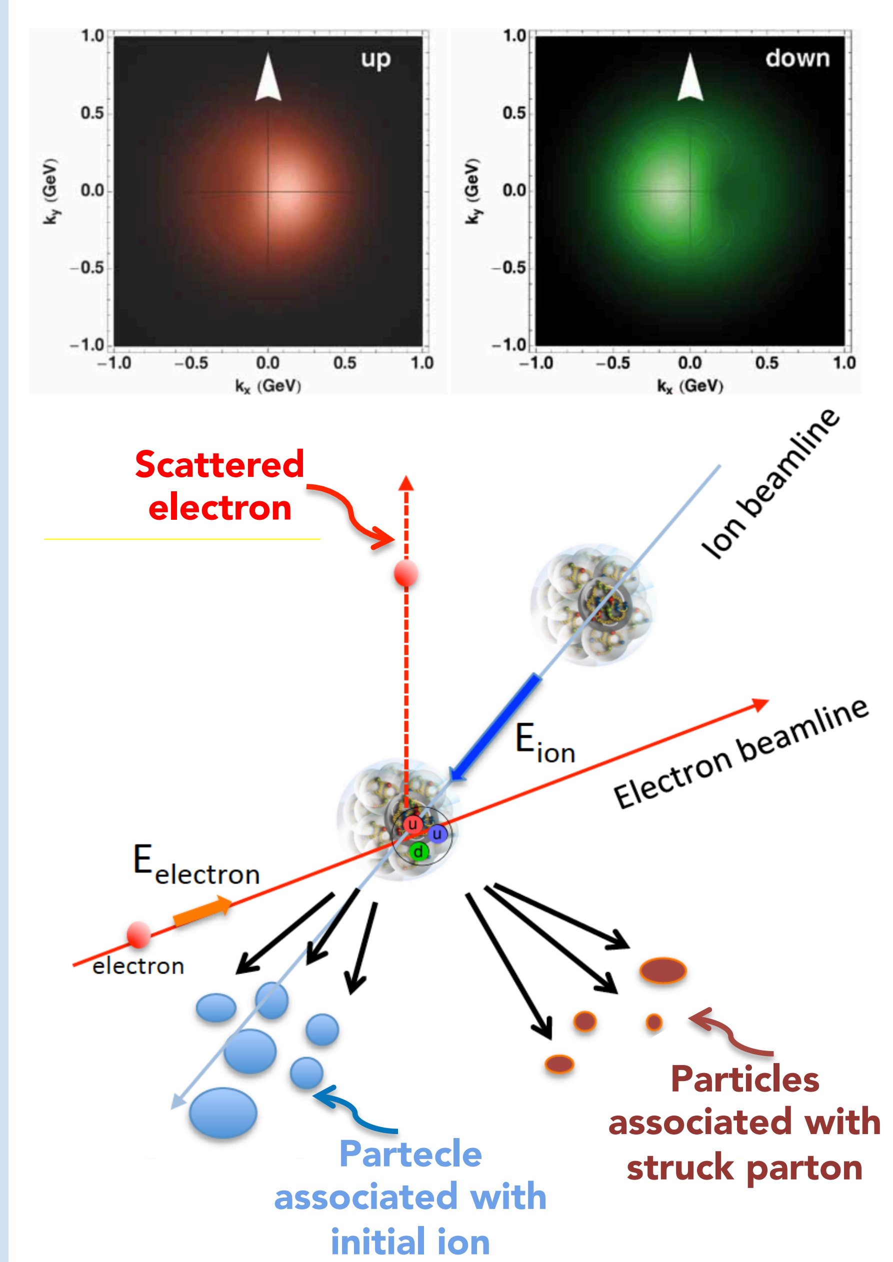
➔ high beam energies and luminosities Q^2 up to **~1000 GeV²**

- Need to resolve quantities (k_t, b_t) of the order **a few hundred MeV** in the proton Correlated quantitites, multi-D analyses

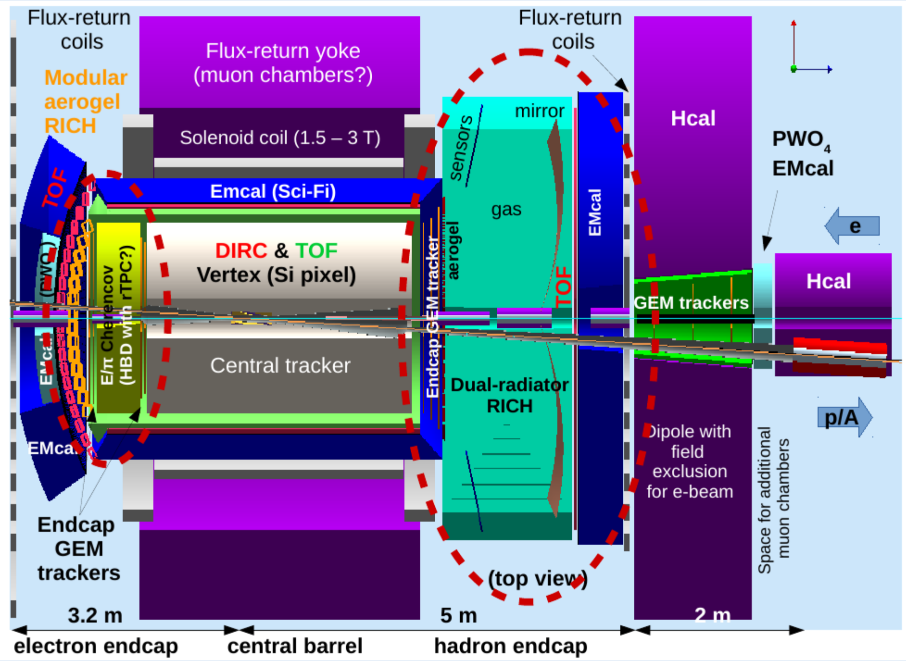
➔ High Granularity, wide dynamic range

- Need to detect **all types of remnants** to seek for correlations:
  - scattered electron
  - particles associated with initial ion
  - particles associated with struck parton

➔ Large acceptance, Forward particle detection, Excellent PID



Particle Identification @ EIC



Asymmetric detector

Compact solutions to contain the cost

New high-tech materials

New technologies with emerging markets in medical imaging and homeland security

Activity linked to eRD14 EIC R&D consortium

e-endcap:

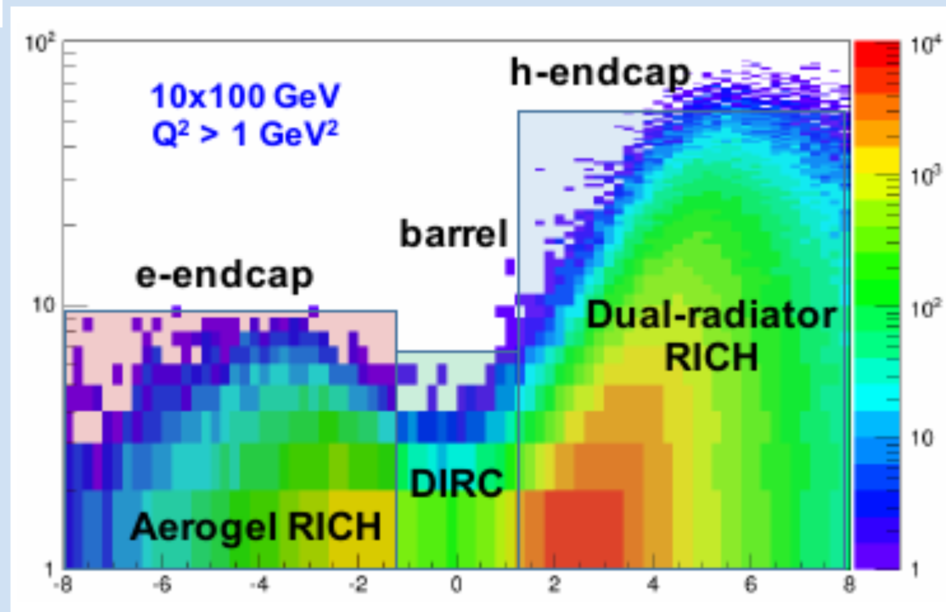
medium momentum (< 10 GeV/c)
aerogel modular Cherenkov

h-endcap:

medium and high momentum (3-50 GeV/c)
dual radiator Cherenkov

Sensors

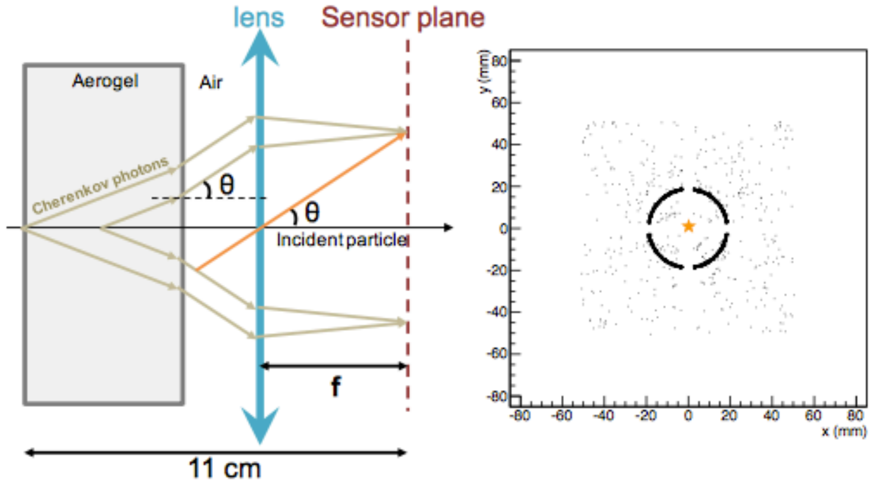
Workign at 1 T magnetic field ?
Radiation Tolerant ?



Next PID Solutions: Modular RICH

Smaller, but thinner ring improves PID performance and reduces length

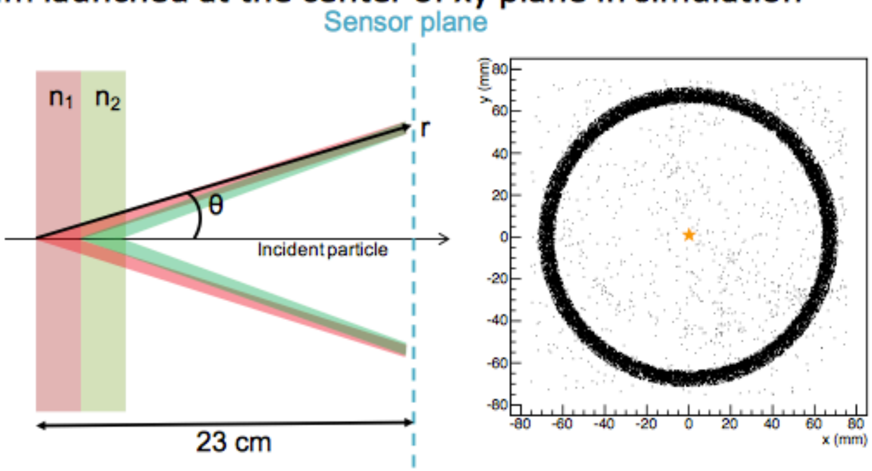
Lens-Based mRICH Design



- 9 GeV/c pion beam launched at the center of xy plane in simulation
- **Smaller and thinner** ring image

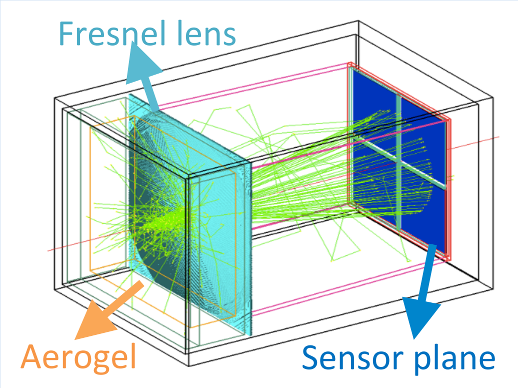
9 GeV/c pion beam launched at the center of xy plane in simulation

Two-Layer Proximity Focusing Design (BELLE-2 ARICH)



- EIC mRICH designed for K/pi ID up to 10 GeV/c
- BELLE-2 ARICH aims to separate pion and kaon up to 4 GeV/c

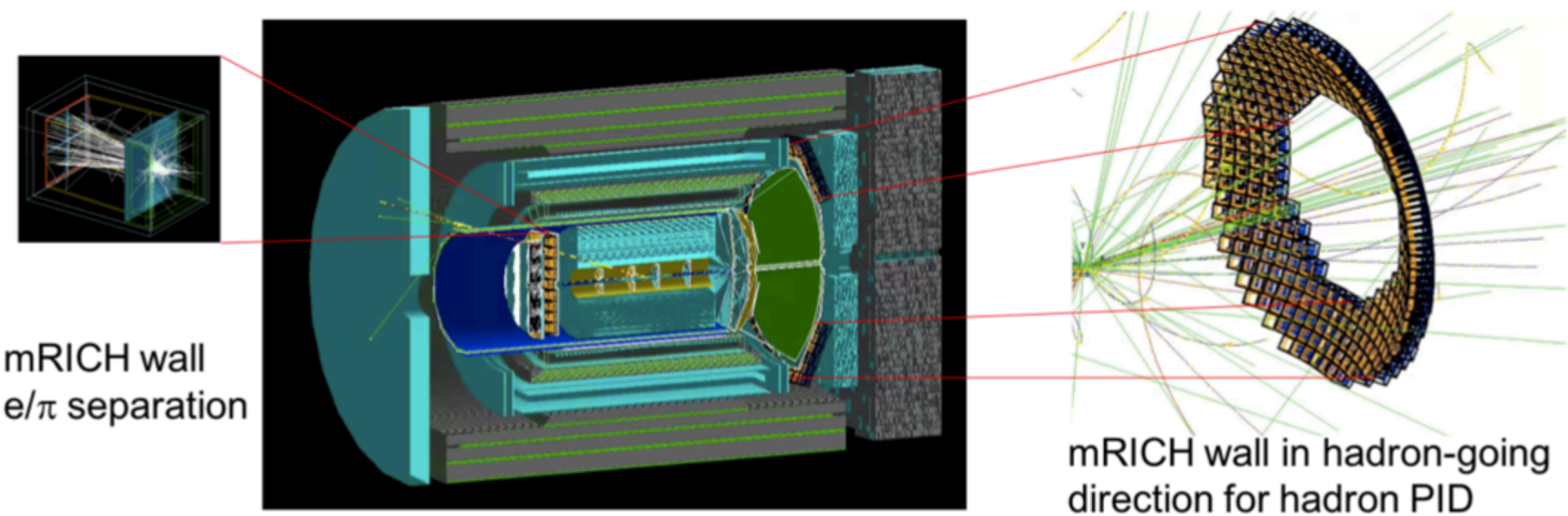
Compact / modular solution for few-GeV range



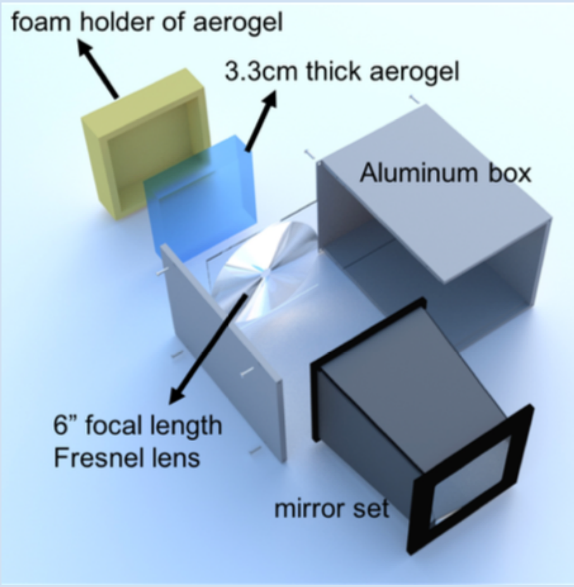
mRICH: An aerogel RICH with Fresnel lens focalization for compact and projective imaging

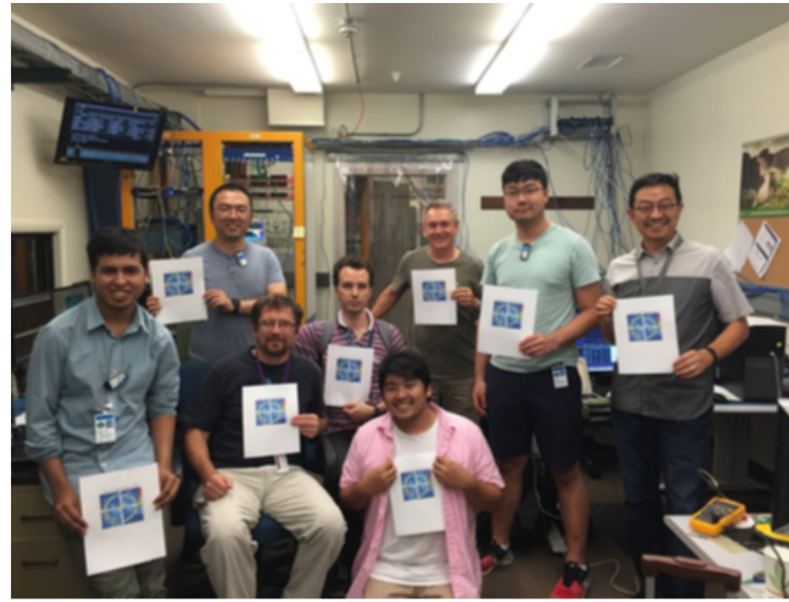
π/K sepration up to ~ 10 GeV/c

Proposed also for sPHENIX @ BNL

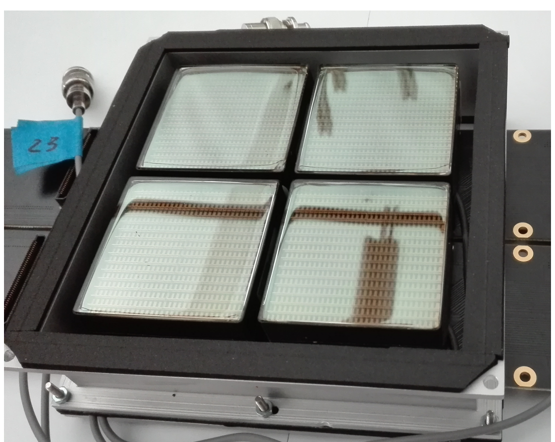


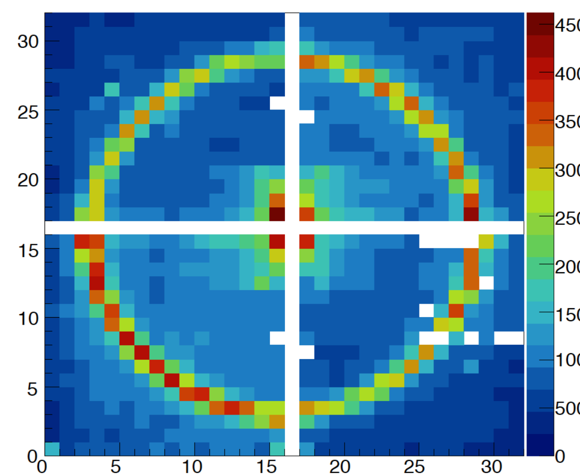
mRICH Test Beam

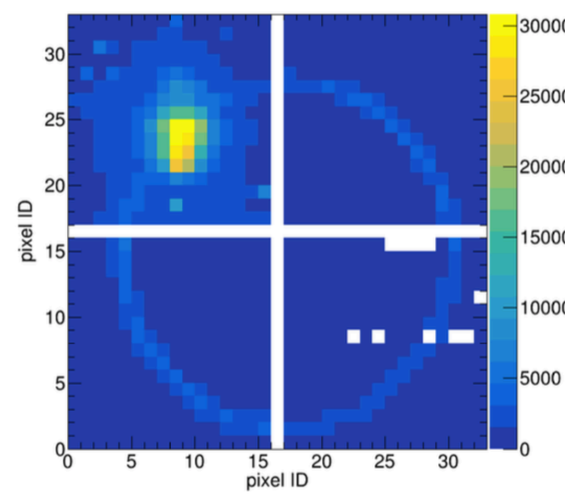




H13700 to reach the 3 mm spatial resolution

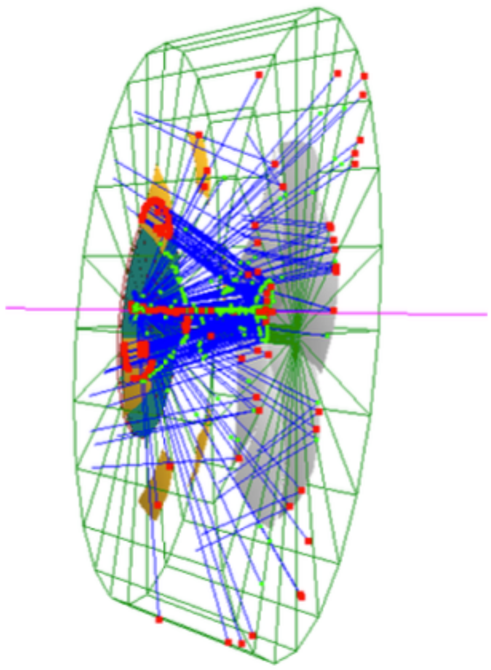




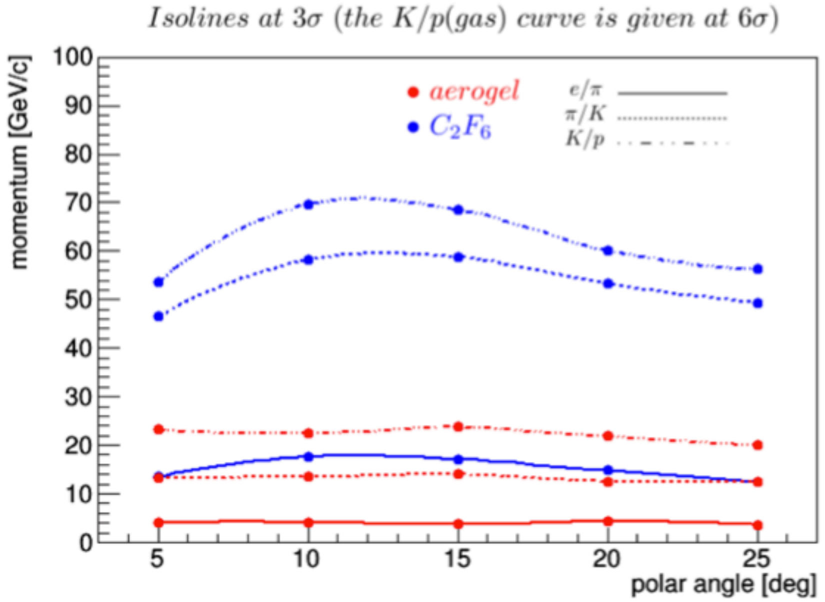


Next PID Solutions: Dual Radiator RICH

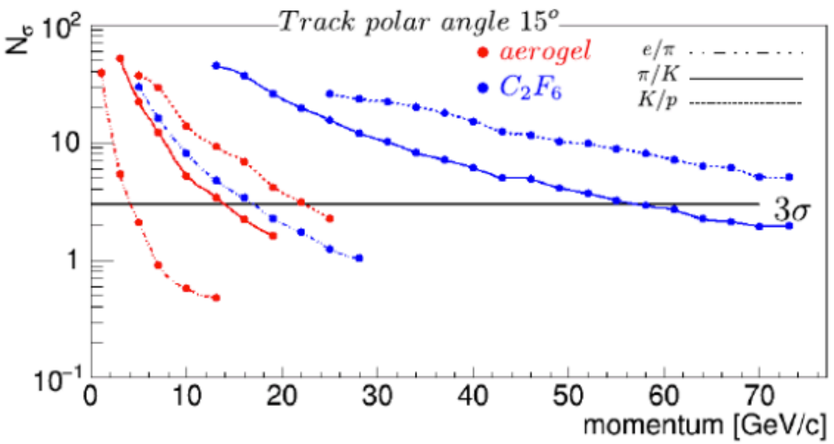
Solution optimized for JLEIC



- Aerogel (n=1.02) & C_2F_6 gas
  - Continuous coverage
- Outward reflecting mirrors
  - Sensors away from the beam
  - No scattering in aerogel
- Sector-based 3D focusing
  - Reduced photosensor area
  - LAPPDs or SiPMs



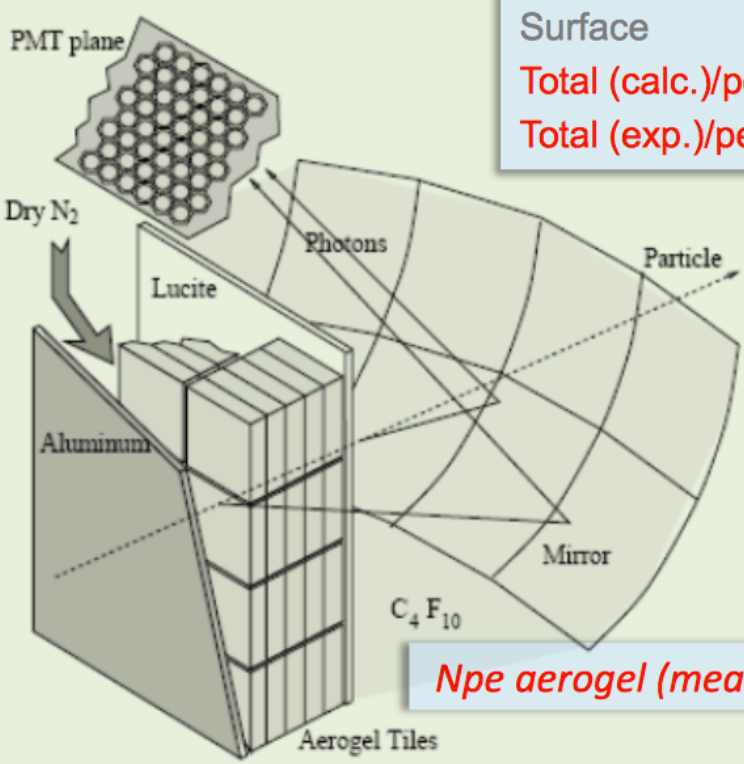
Geant4 simulation includes magnetic field



Dual RICH So Far

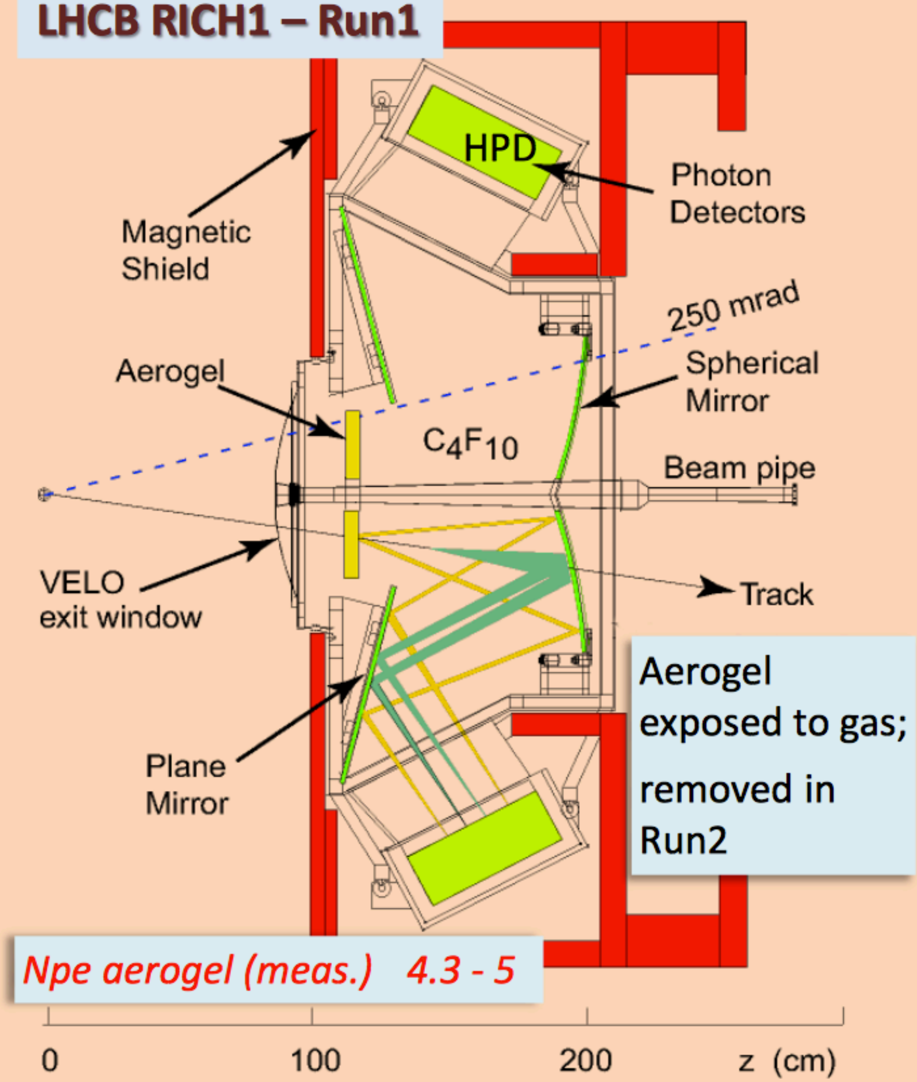
HERMES RICH

Angular resolution	
Pixel	2.3
Chromatic	**1.3**
Point emiss.	0.7
Mirror	0.6
n spatial disp.	0.5
Forw. scatt.	0.4
Surface	0.4
Total (calc.)/pe	2.9
Total (exp.)/pe	3.3



Npe aerogel (meas.) ~10

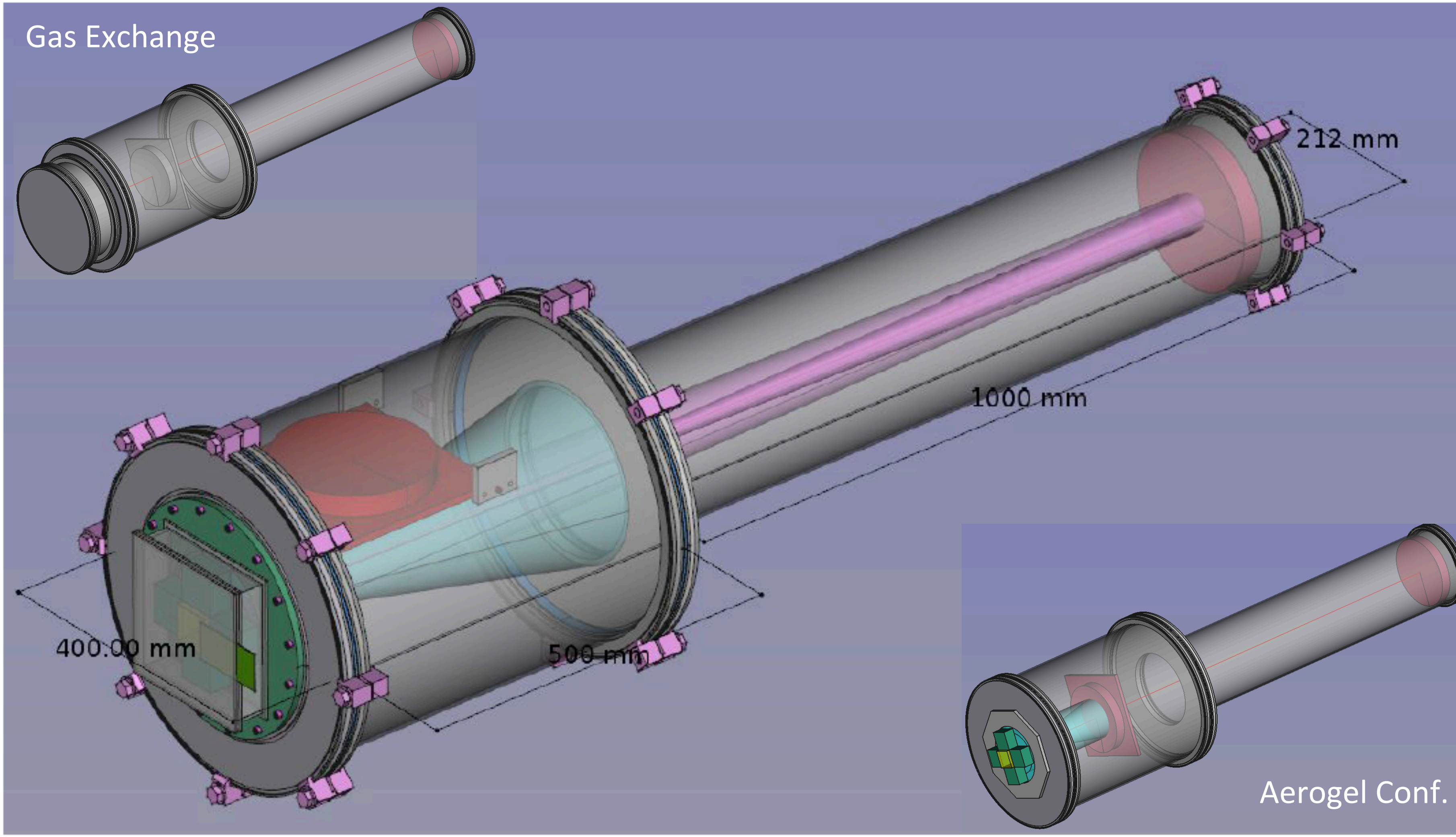
LHCB RICH1 – Run1



Aerogel exposed to gas; removed in Run2

Npe aerogel (meas.) 4.3 - 5

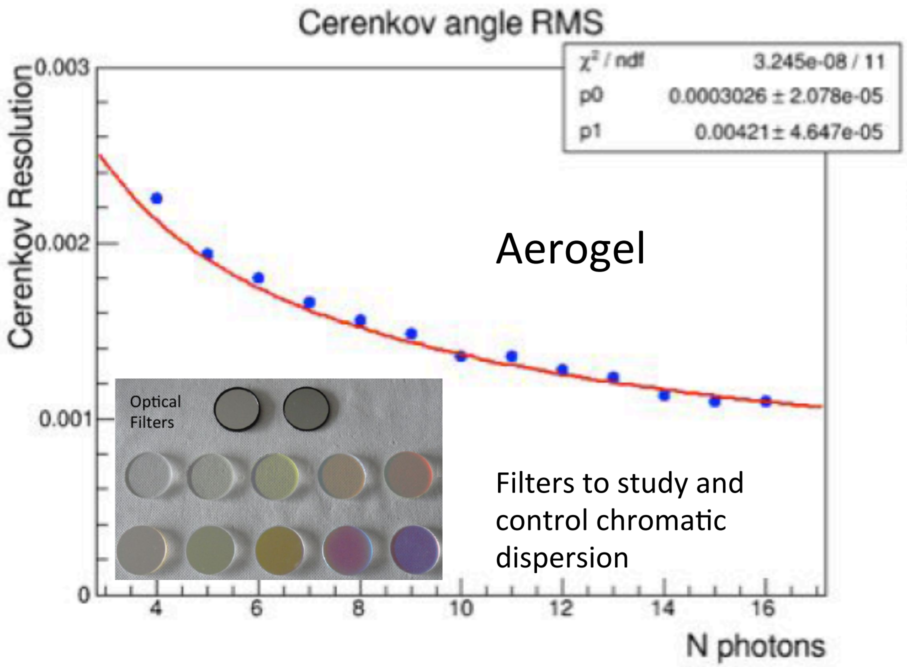
dRICH Prototype Design

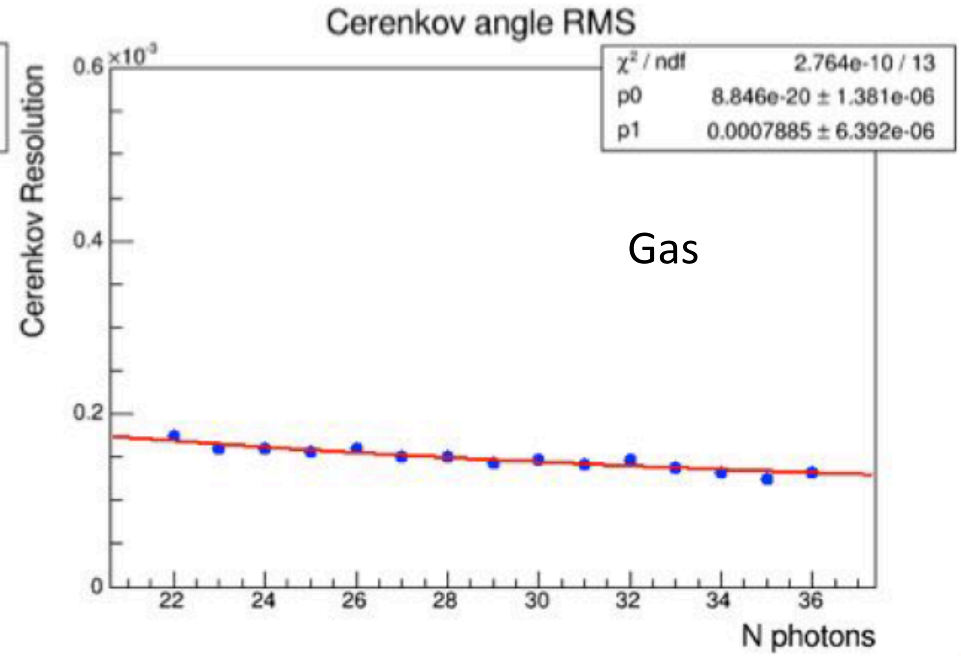


Commercial vacuum technology for safety and cost effectiveness
Overlapping rings for parallel beam particles

dRICH Prototype Performance

Montecarlo simulation





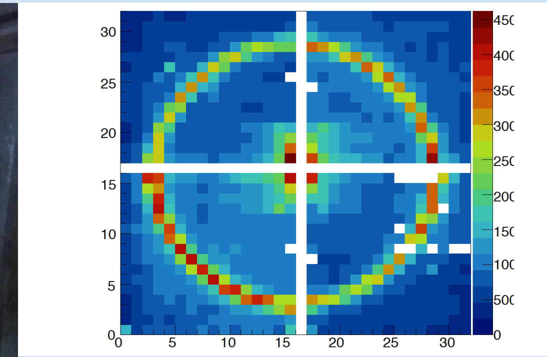
1 p.e. Error (mrad)	Aerogel	@EIC	C_2F_6 Gas	@EIC
Chromatic error	3.2	(2.9)	0.51	(0.8)
Emission	0.5	(0.5)	0.5	(1.2)
Pixel	2.5	(0.5)	0.42	(0.5)

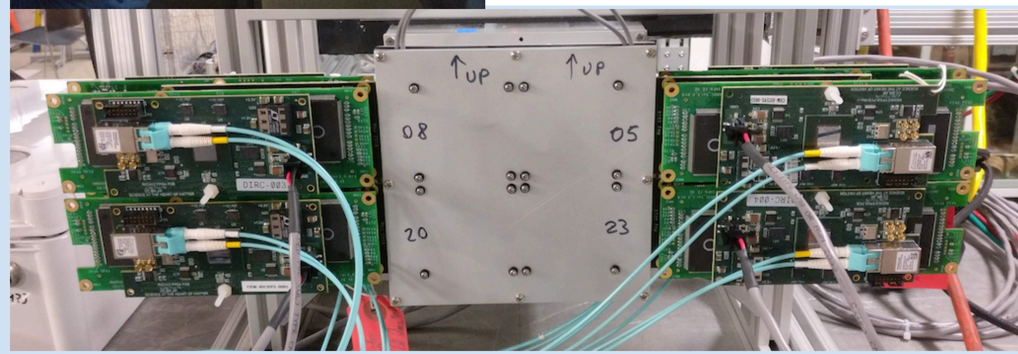
Development: Sensor and Readout

Readout Independent element for flexibility: supports various detectors with integrated cooling

Reference:
MAROC + SSP/VSX

Dedicated:
SiREAD + SSP/ethernet

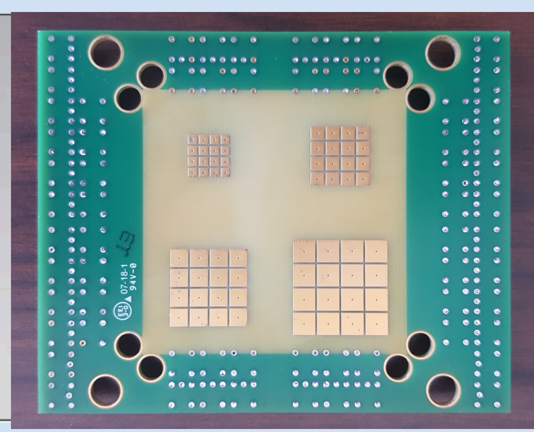




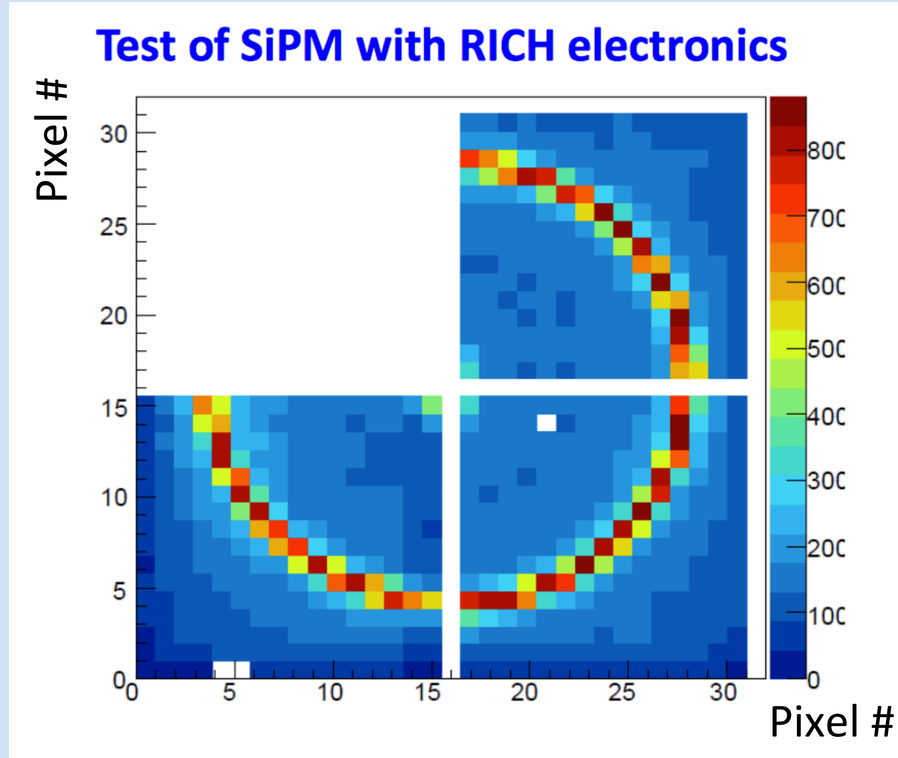
Sensors Reference MA-PMTs

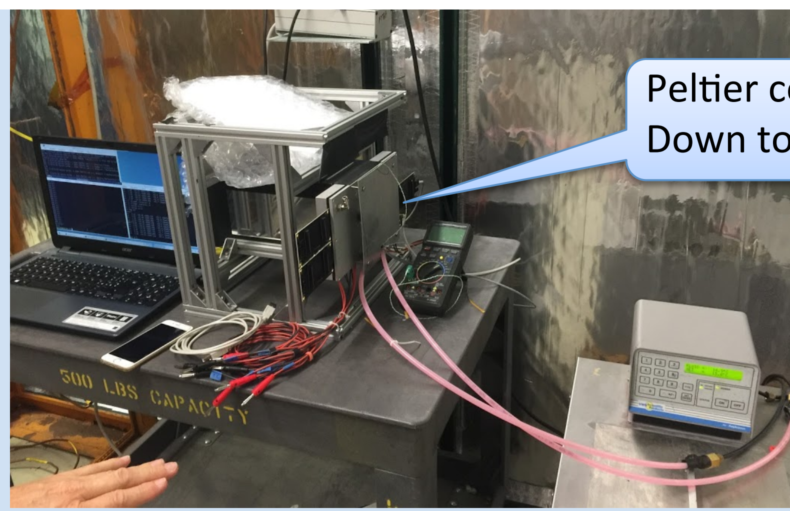
B-field tolerant: MCP-PMTs (LAPPDs)

SiPMs



Development: SiPMs





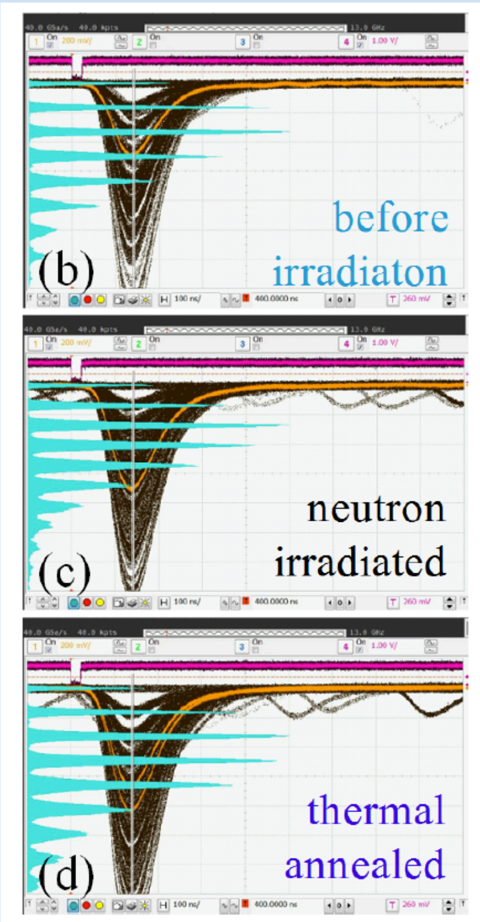
Peltier cell cooling
Down to -30° in N_2

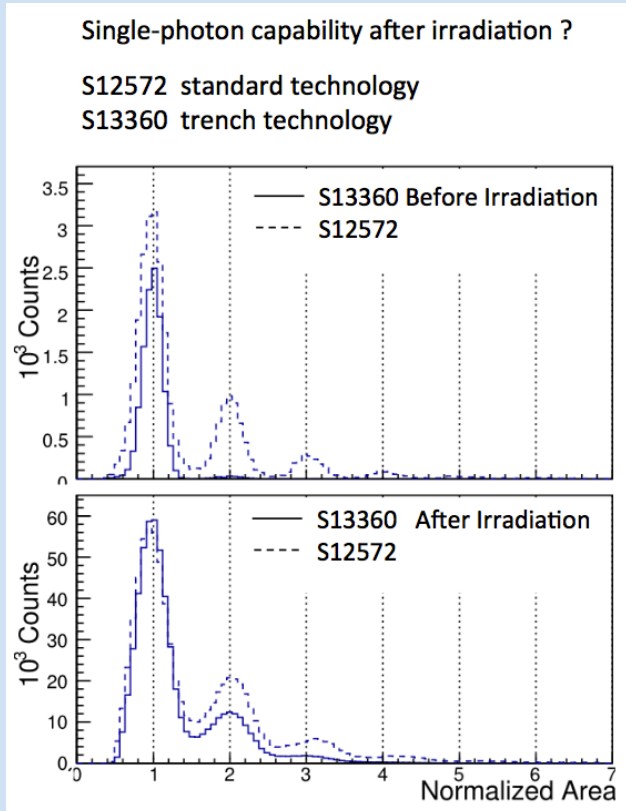
SiPM Radiation Tolerance

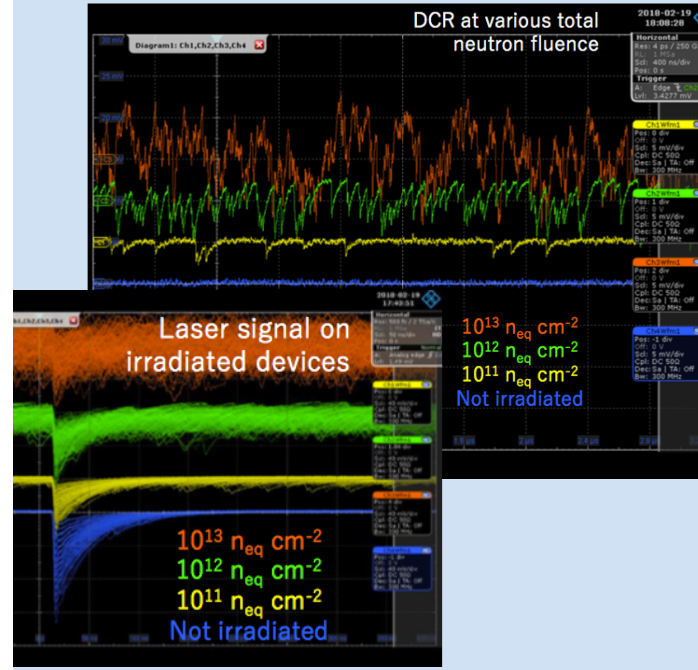
T. Tsang et al.
JINST 11 (2016) P12002

I. Balossino et al.
NIMA 876 (2017) 89

Paolo Carniti
@ RICH 2018







T= 84 K
10^9 n_{eq} cm^2
Annealing at 250 °C

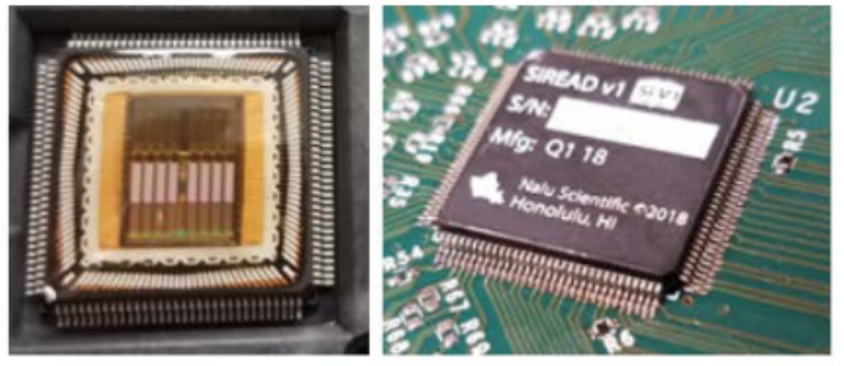
T= 0 C
few 10^9 n_{eq} cm^2

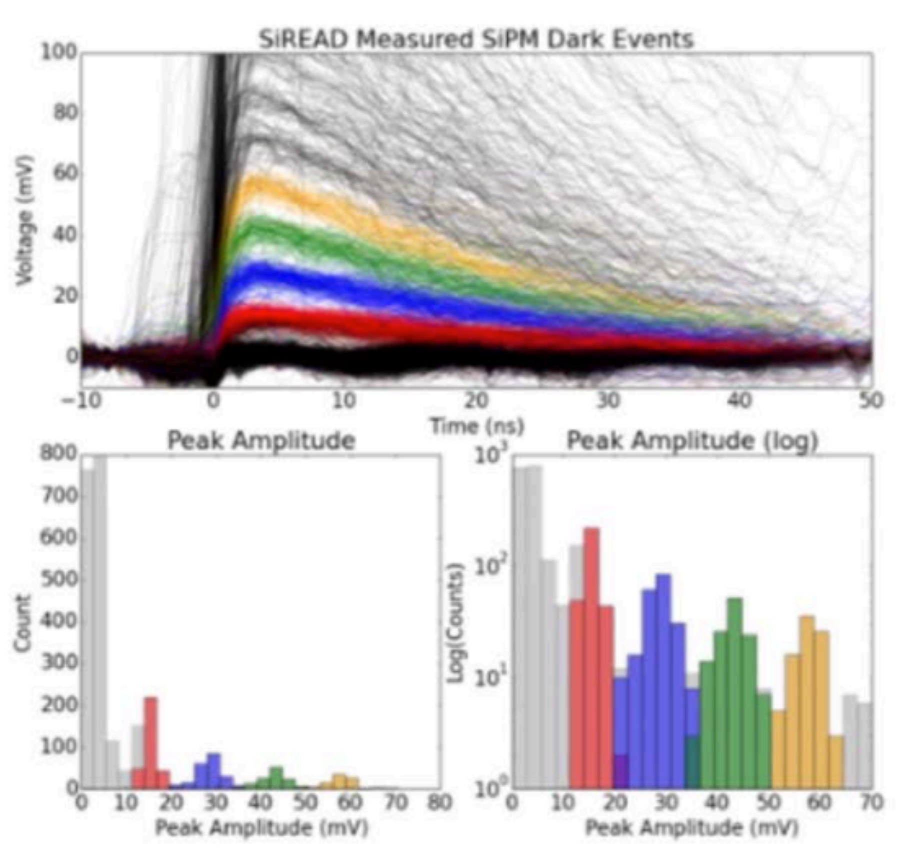
SiPM: Hamamatsu S13360-1350CS (50 μm cells)

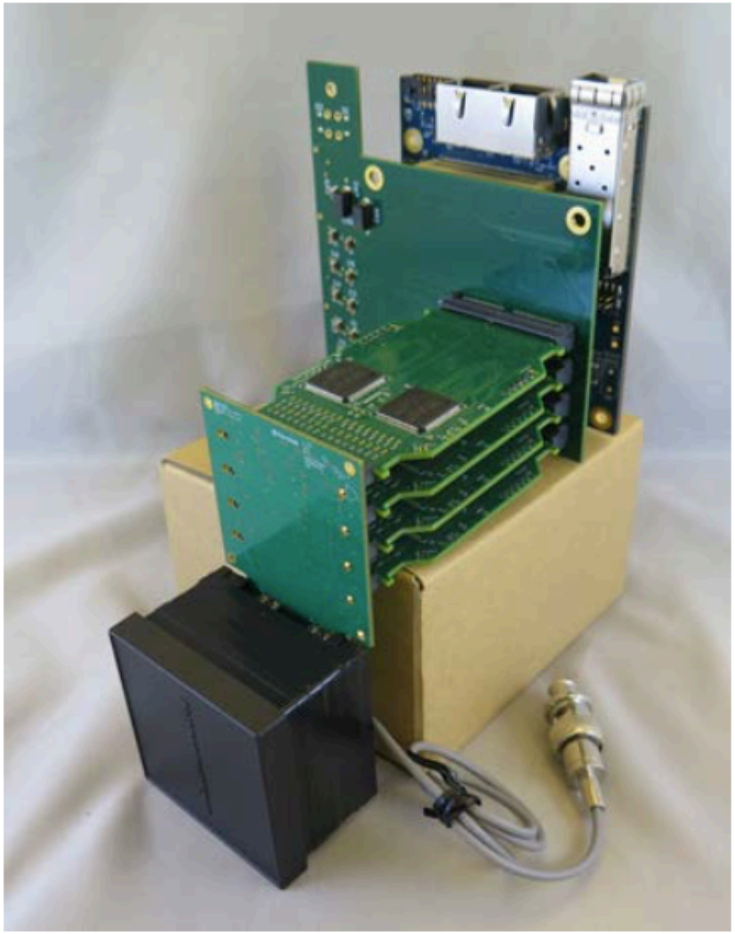
Temperature: –30 °C

Bias: V_{BR} + 1.5 V

Development: SiREAD Chip (HU)

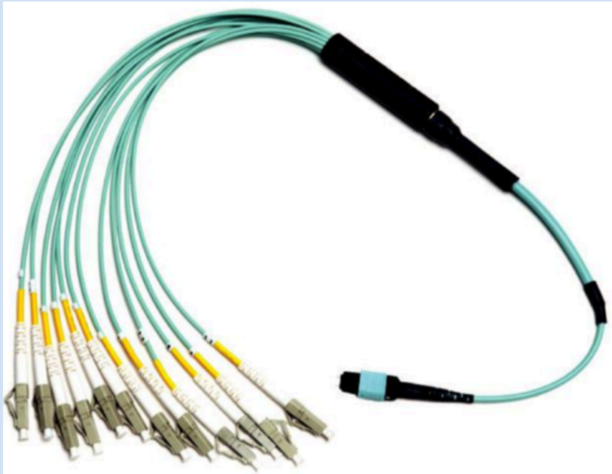






Photograph of the first generation of 256-anode 2" PMT readout for use with mRICH prototype in the Fermilab beam test facility.

Development: Back-End (JLab)



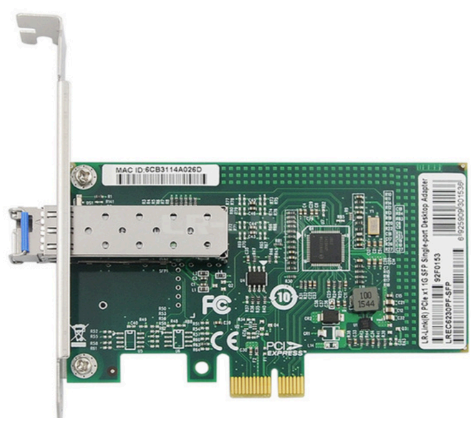
Optical ethernet (2.5 Gbps)

Small setups:
TCP/IP
Optical bridge / PC Desktop

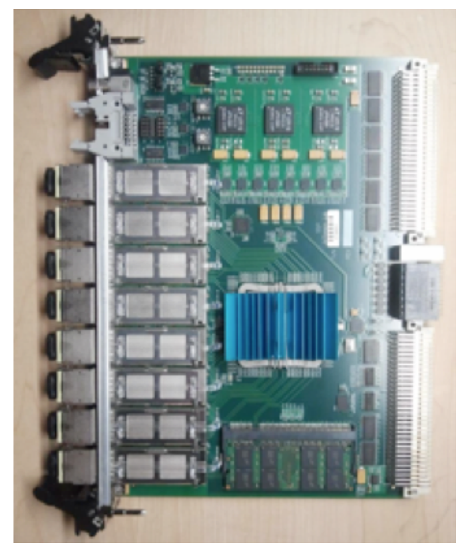
Full experiment:
SSP protocol
SSP board / VSX crate

Next:
Ethernet Switches

Optical bridge / PC Desktop
Few FPGA units ~ 500 channels



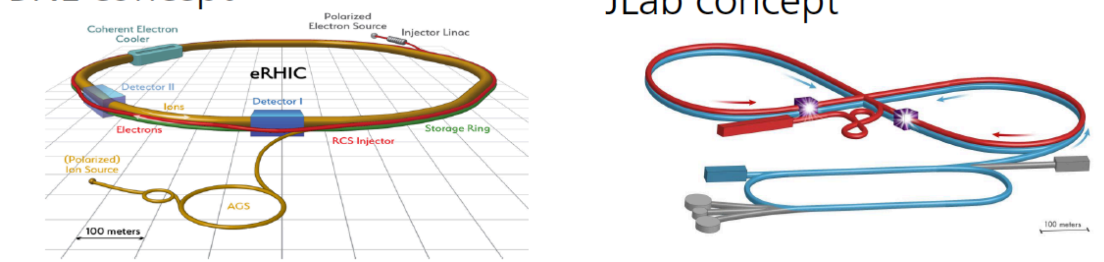
SSP board / VSX crate
2 RICH sectors ~ 50 k channels

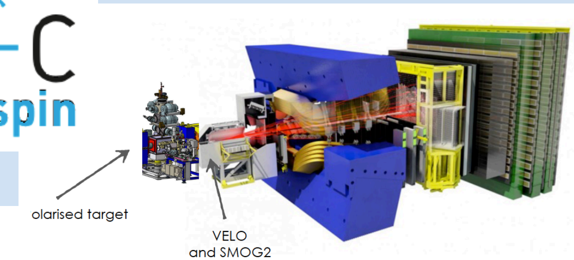


Nucleon Structure Landscape

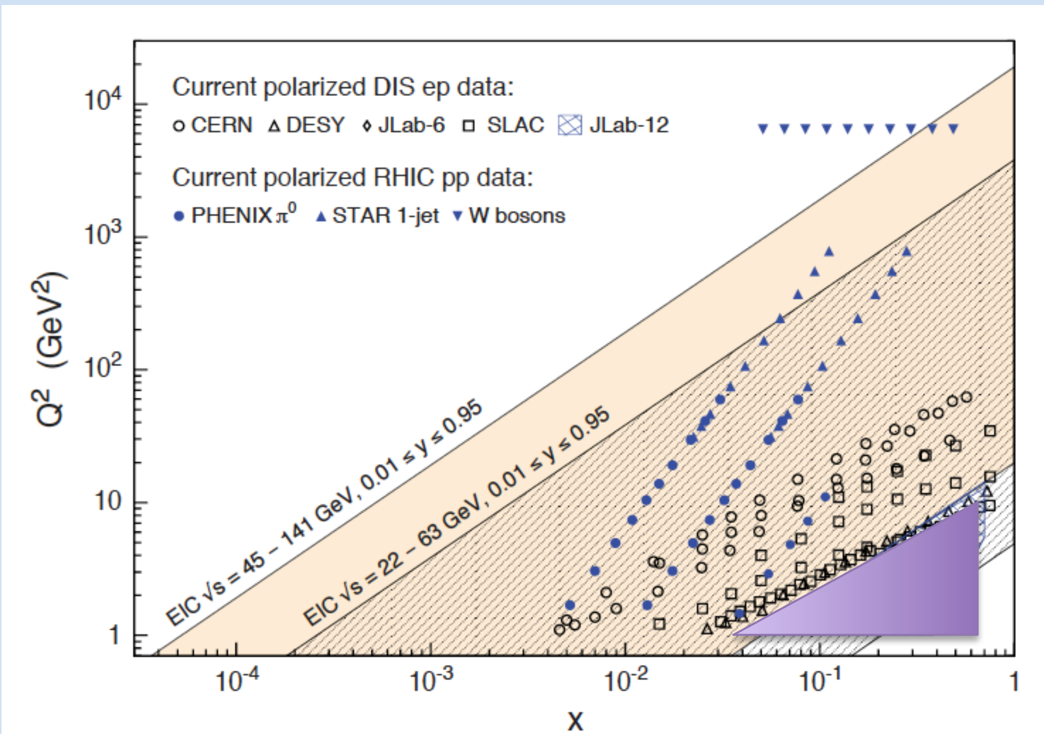
BNL concept

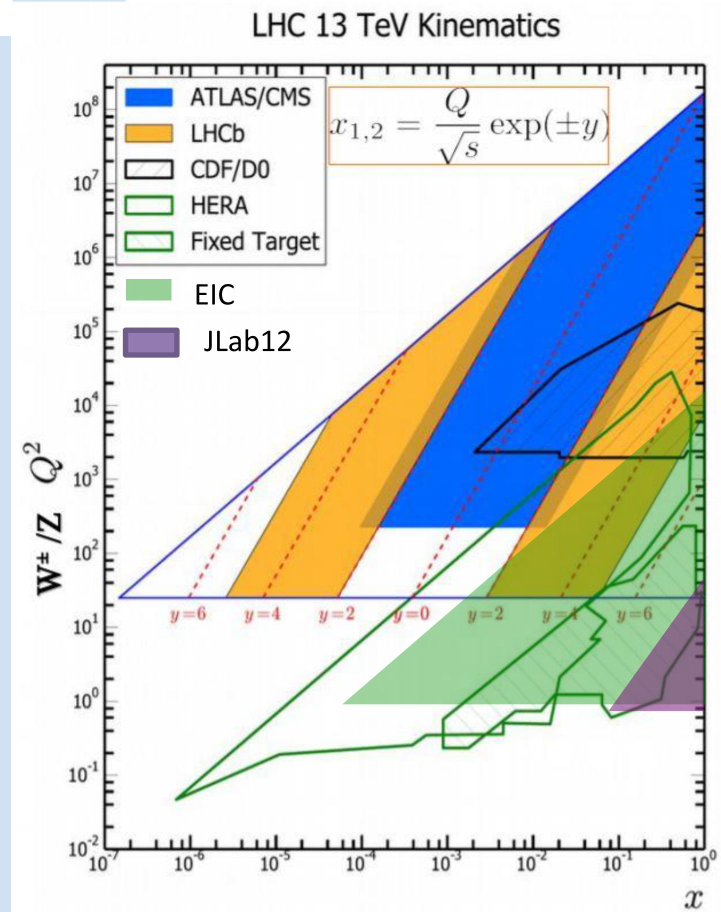
JLab concept

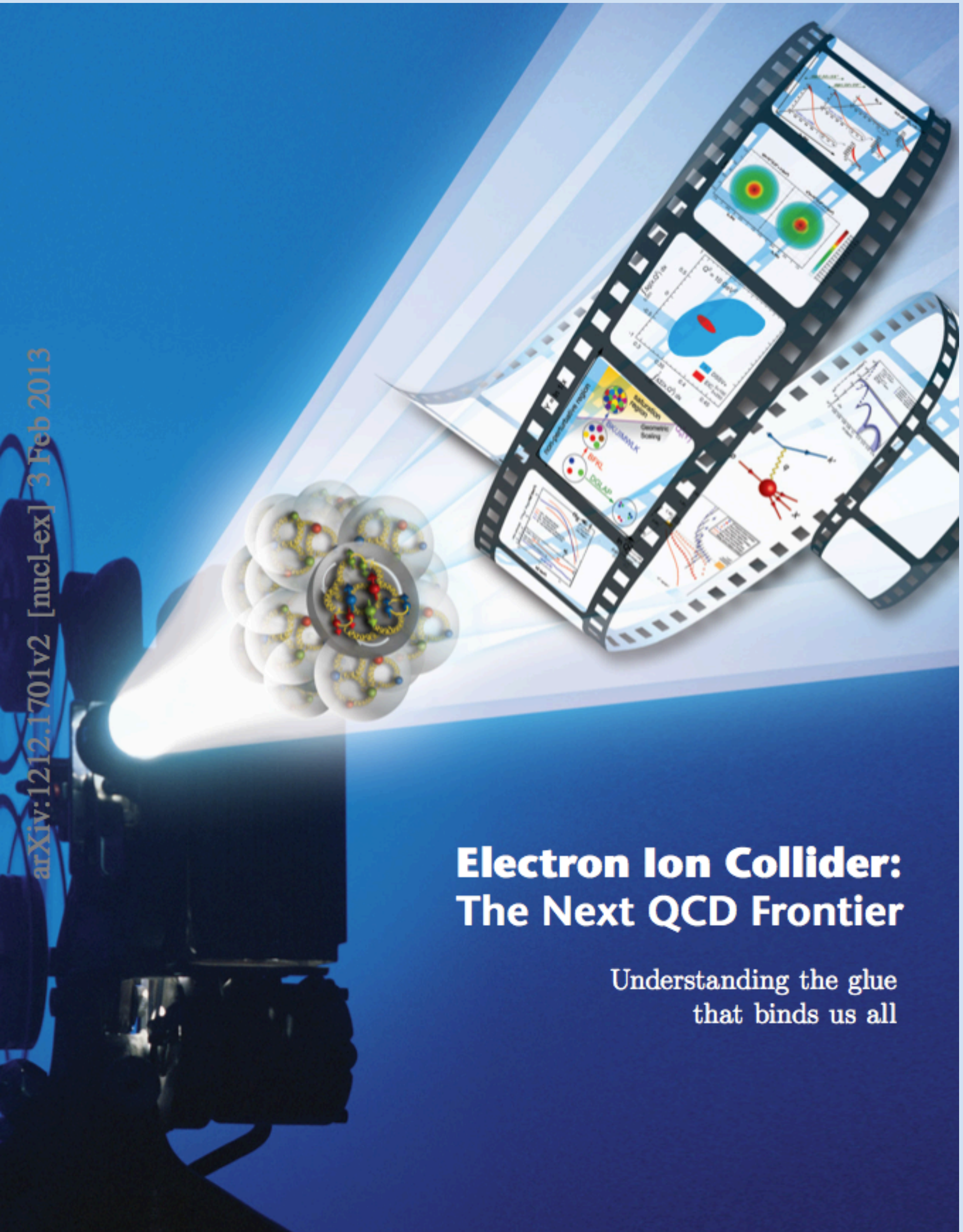




Data in the much needed "intermediate" energy region matching "pure" pQCD with "pure" TMD regime.







The Next QCD Frontier

EIC (and JLab) is a unique opportunity
for a comprehensive QCD study
and possible breakthroughs

Potential impact on many
fields of investigation

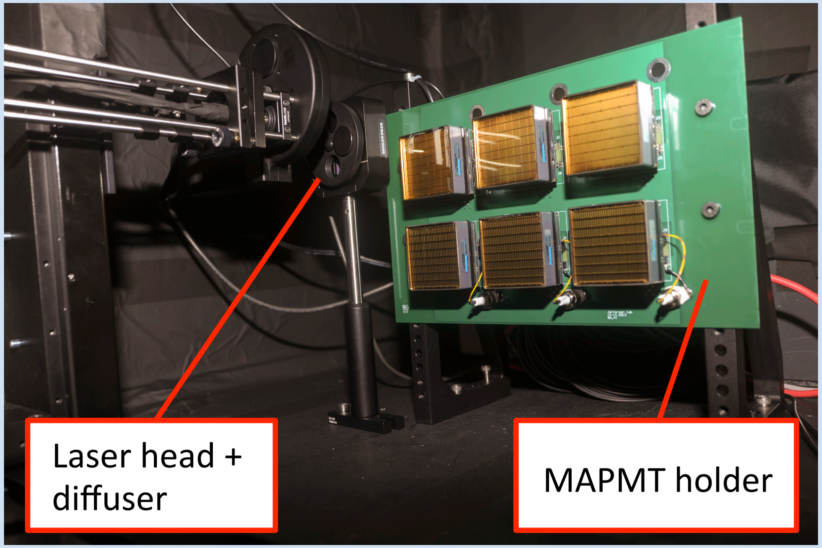
EIC offers immediate opportunities
for supported R&D activities
on science and technology

PID is crucial to achieve
flavor separation

Seek for cost-effective
solutions with potential application
In other fields

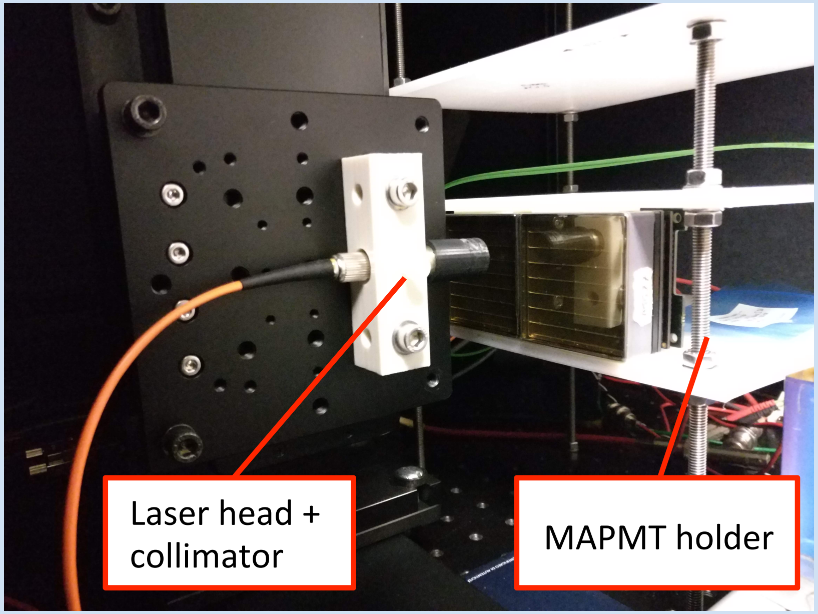
Pulsed Laser Test Benches

Detailed characterization
Sensors: gain, efficiency, cross-talk, radiation tolerance
Electronics: gain, cross-talk, thresholds, time resolution



JLab

632 nm picosecond pulsed laser light
Light diffuser to illuminate the whole MAPMT surface
Standardized system with CLAS12 electronics
H8500 6x6 mm^2 pixel sensor so far



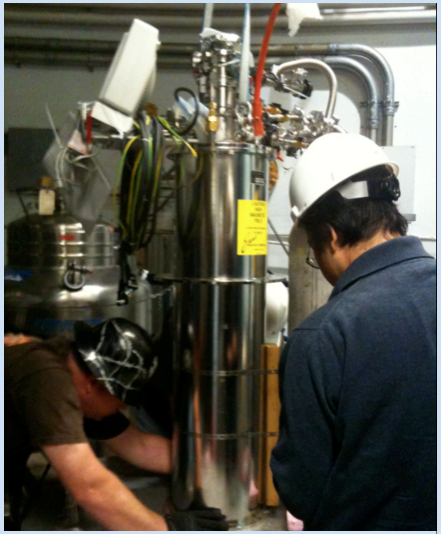
INFN

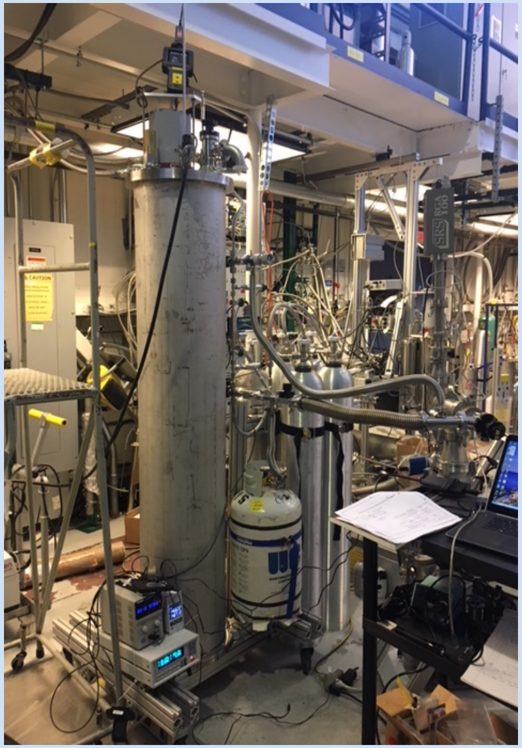
632 nm and 407 nm picosecond pulsed laser light
Light concentrator to scan the sensor surface
Flexible layout supporting various sensors and
Front-End electronics

HDice: Frozen Spin Polarized Target

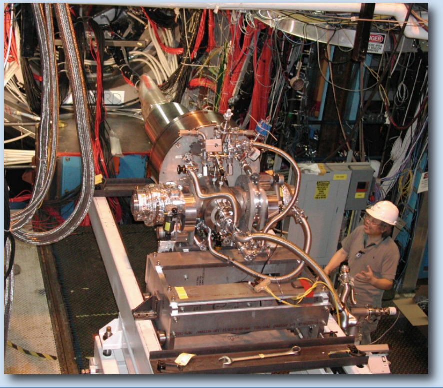
Polarized targets of solid HD in frozen spin mode.
Longitudinal and Transverse Polarizations: up to 60% H or 35% D.
Physics program rated as High-Impact by PAC41

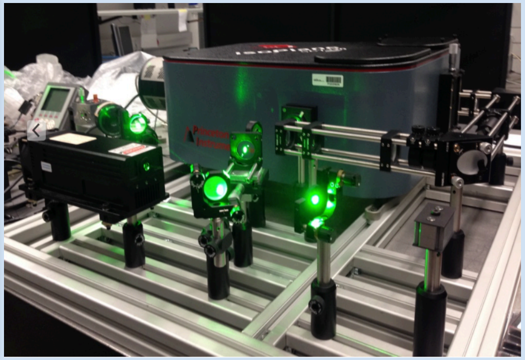
Advantages:
- ✓ Dilution factors ~ 1
- ✓ Low holding magnetic fields

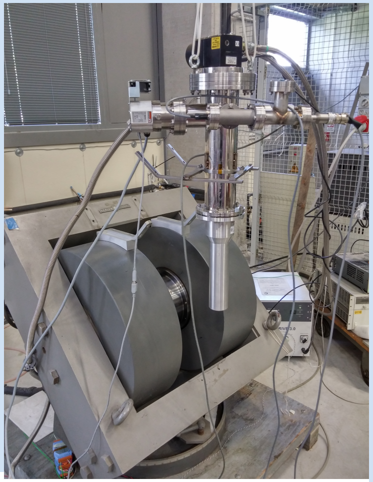




RM1: dewars & cryostats
HD gas purity by Raman distillation and analysis







FE: frozen B field on a bulk SC MgB_2 magnet