KLOE-2 Inner Tracker: the First Cylindrical GEM Detector

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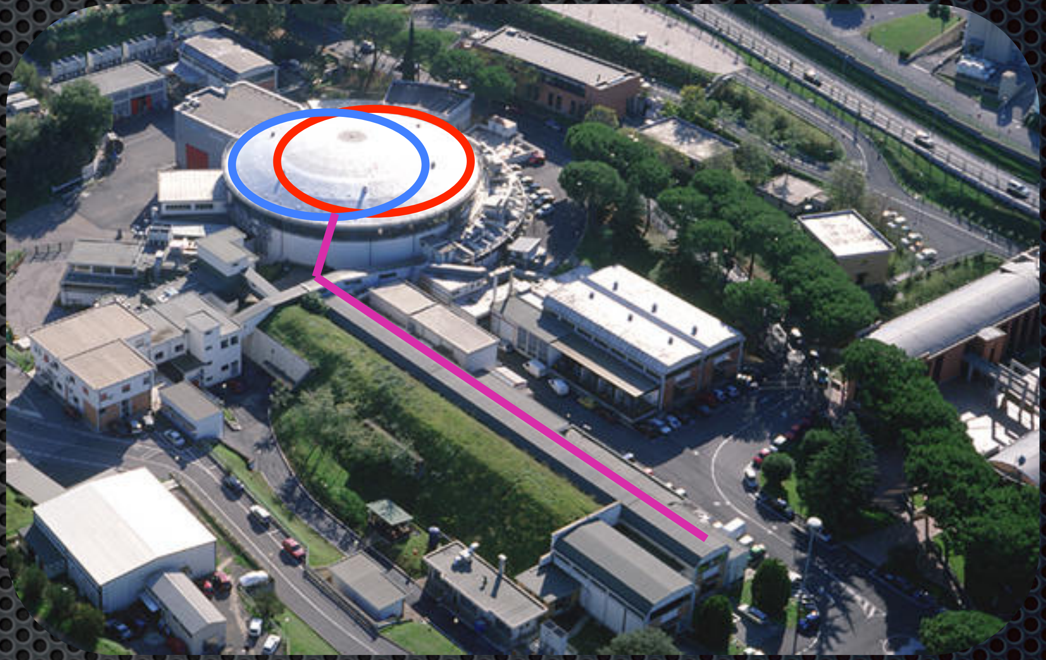
for the KLOE-2 Collaboration

DAϕNE & KLOE

- DAϕNE Frascati ϕ-factory: an e^+e^- collider @ $\sqrt{s}$ =1019.4 MeV = M_ϕ

  Best performance in 2005:
  - L_{peak} = 1.4 × 10^{32} $cm^{-2}s^{-1}$
  - $\int Ldt$ = 8.5 pb^{-1}/day

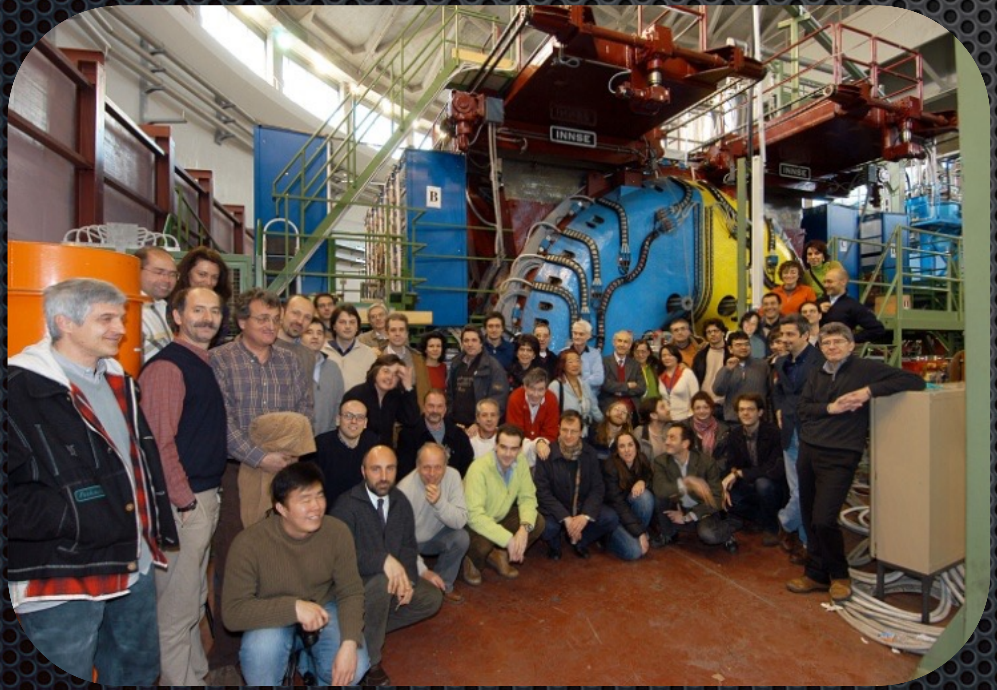
  Presently new crab-waist sextuples configuration

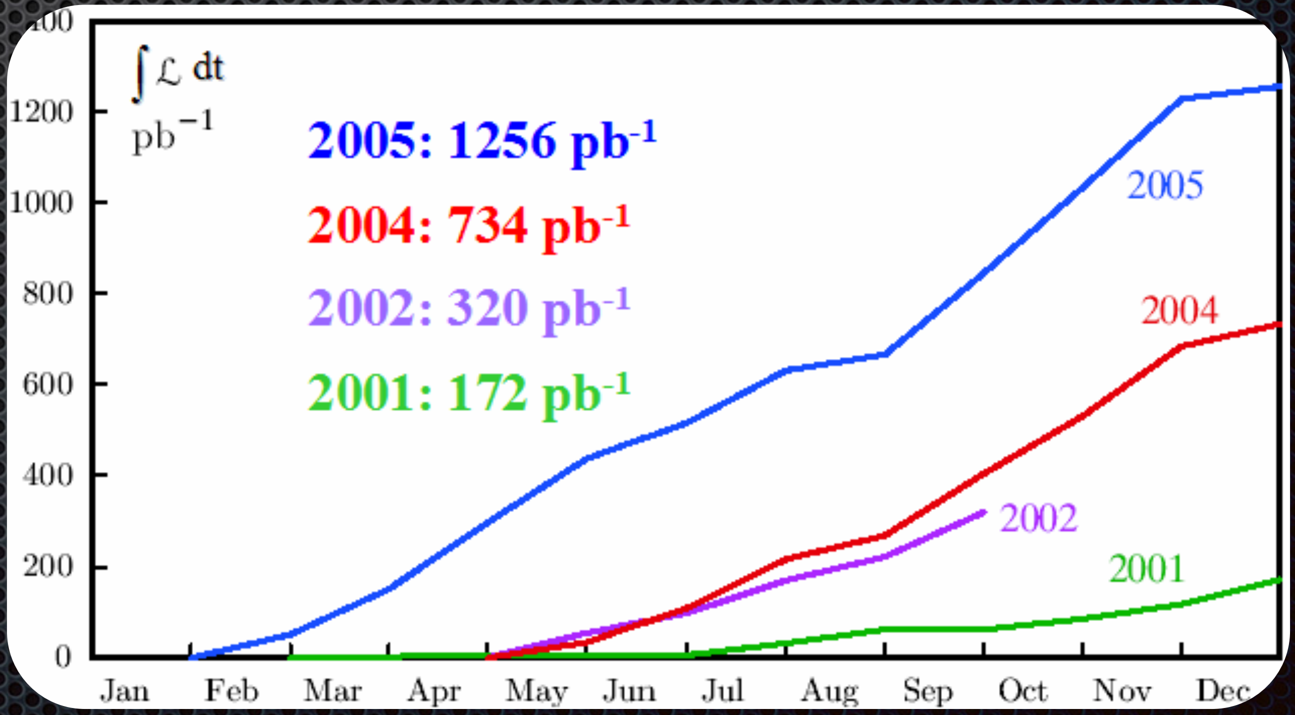


- KLOE has acquired 2.5 fb^{-1} @ $\sqrt{s}$=M_ϕ (2001-05)

+ 250 pb^{-1} off-peak @ $\sqrt{s}$=1 GeV

  Precision Kaon and Hadron Physics with KLOE [Rivista del Nuovo Cimento Vol.31, N.10 (2008)]





- Upgraded detector KLOE-2 Run started in November 2014: goal at least 5 fb^{-1} more

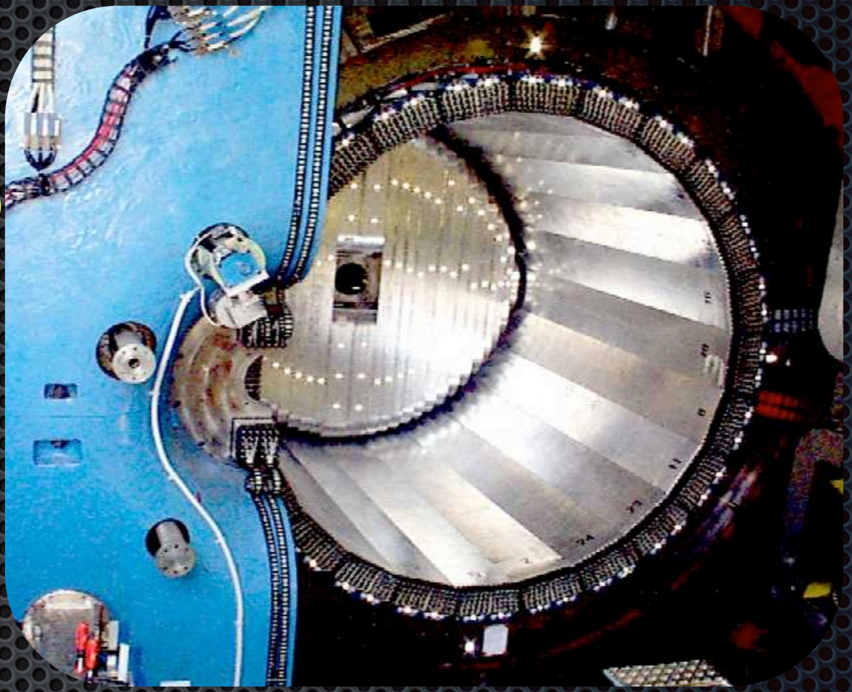
KLOE-2 at DAϕNE

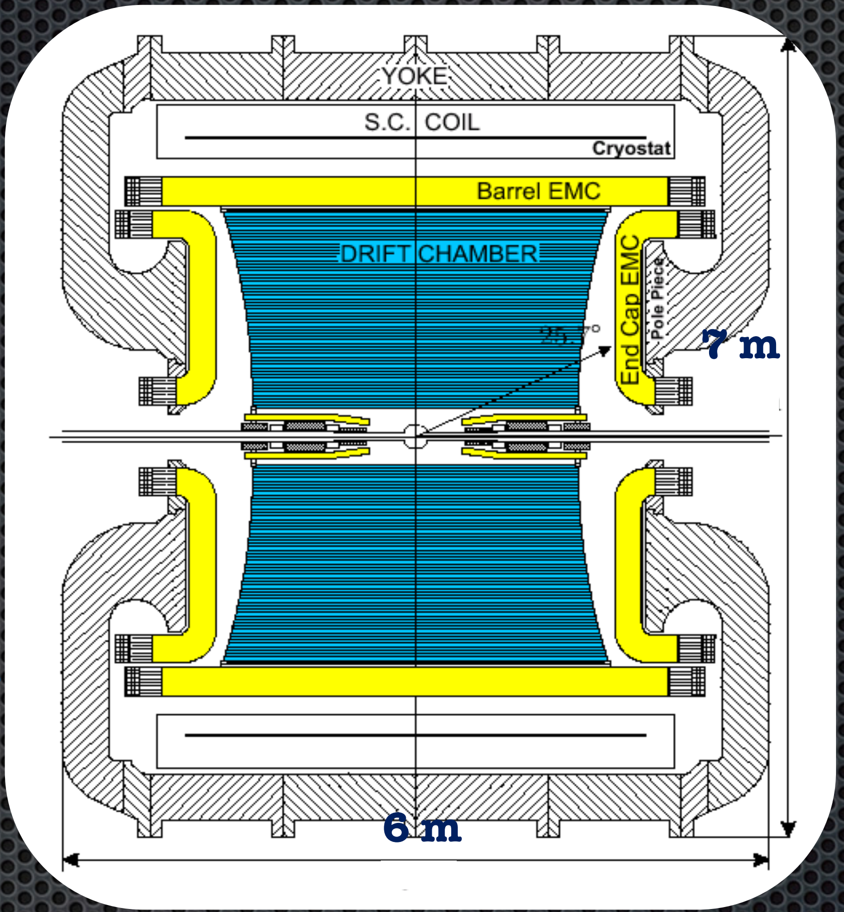
- Calorimeter System
  - EMC – Lead / Scintillating Fibers w PMT

$\sigma E/E = 5.7\% / \sqrt{E(GeV)}$

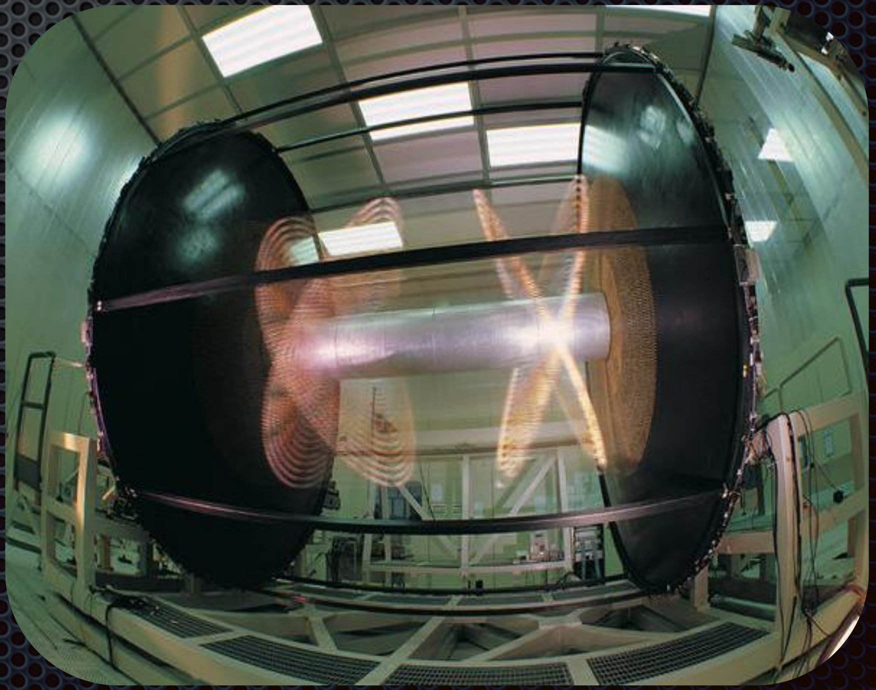
$\sigma t = 54\ ps / \sqrt{E(GeV)} \oplus 140\ ps$

$\sigma vtx(\gamma\gamma)$ ~ 1.5 cm (vertex reso)





- Tracking System
  - DC – He-Iso 90-10
  3.7m x 4m Drift Chamber



- Superconductive Magnet
  - 0.52 T solenoidal field
- DAFNE φ-factory
  - $e^+ e^-$ at 1020 MeV

$\sigma p/p = 0.4\ \%$ ($\theta track > 45°$)

$\sigma hit = 150\ \mu m$ (xy), 2 mm (z)

$\sigma vertex$ ~3 mm

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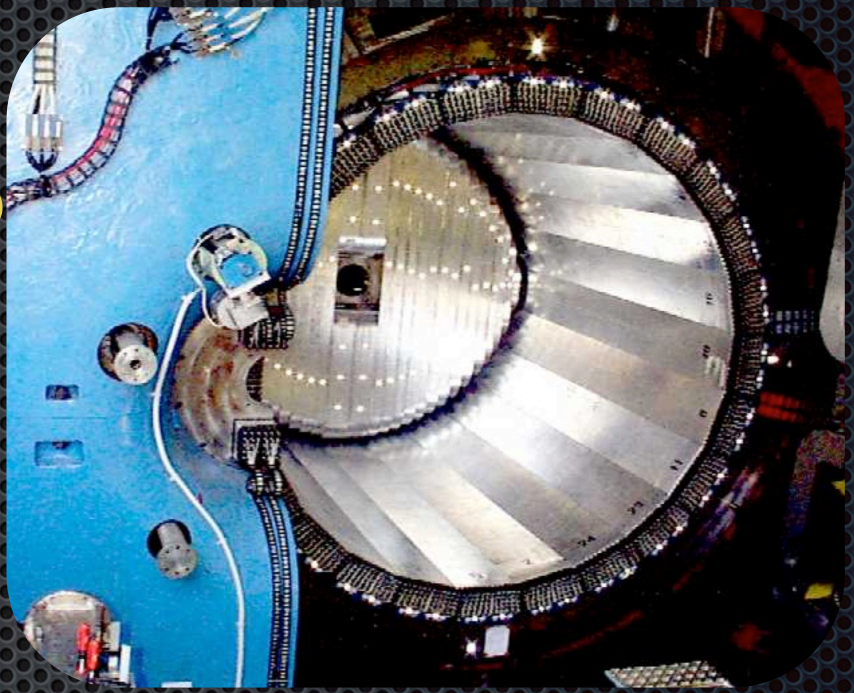

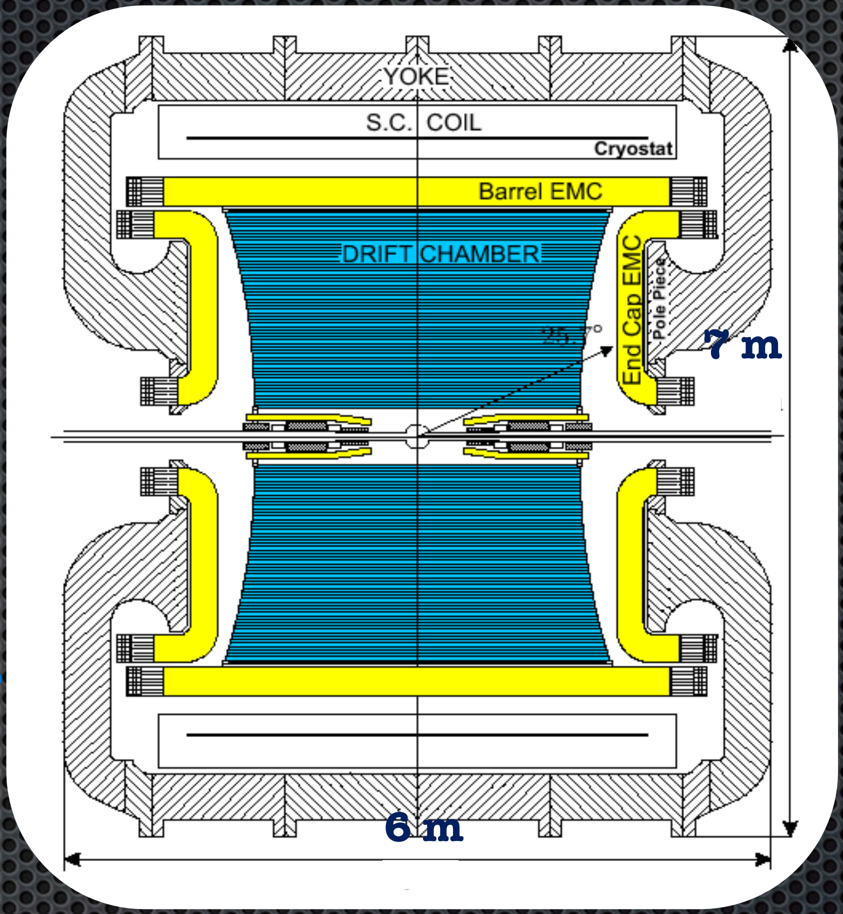

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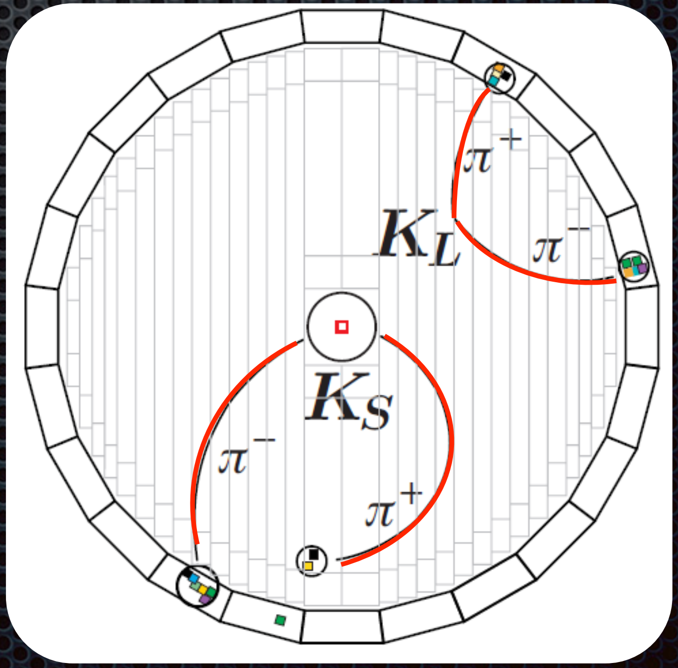

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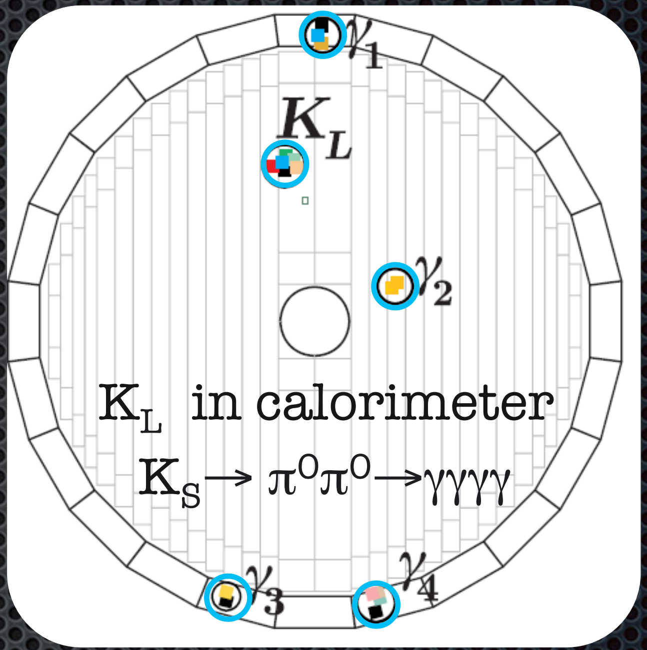

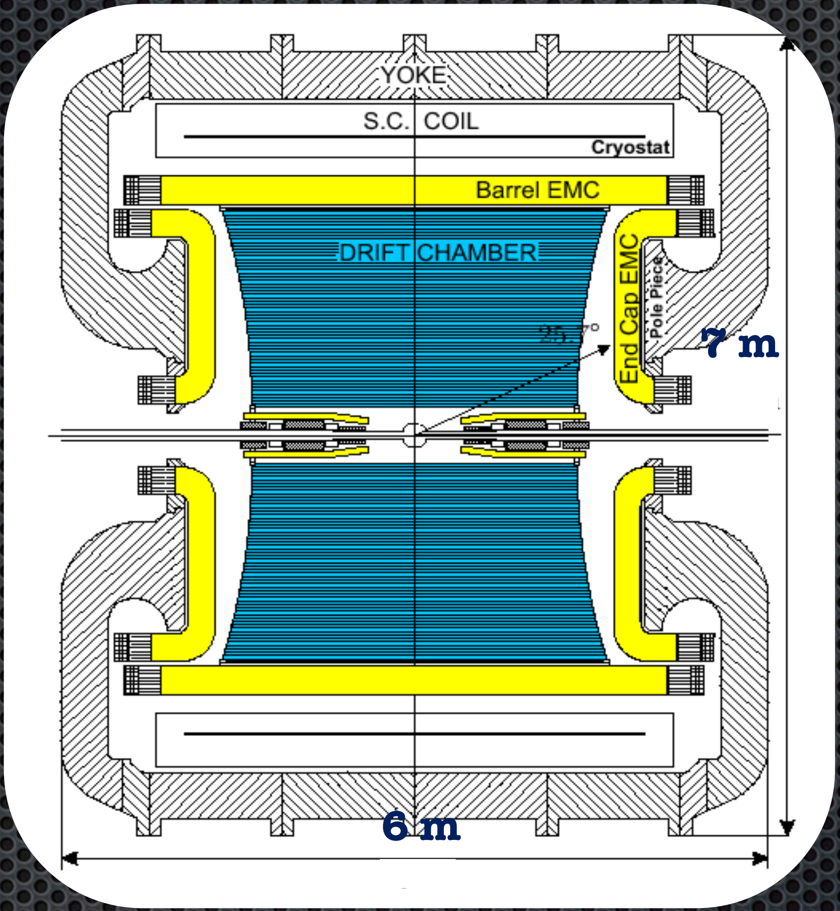

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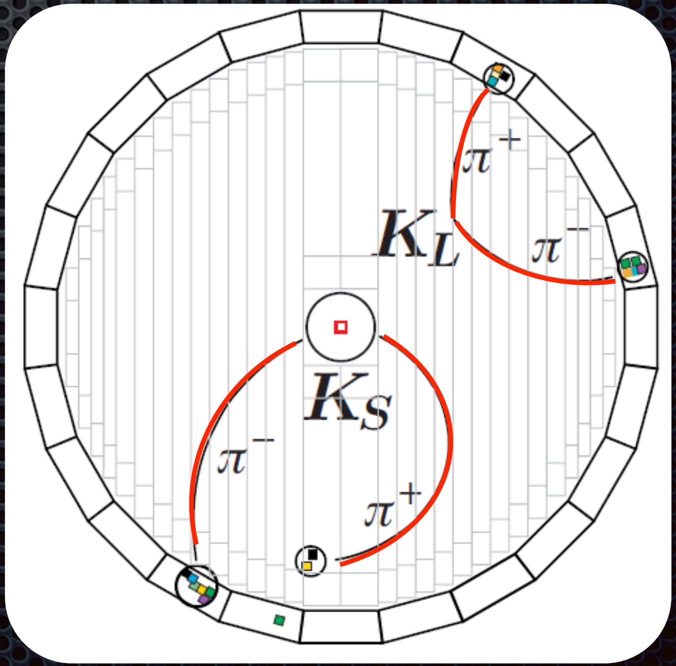

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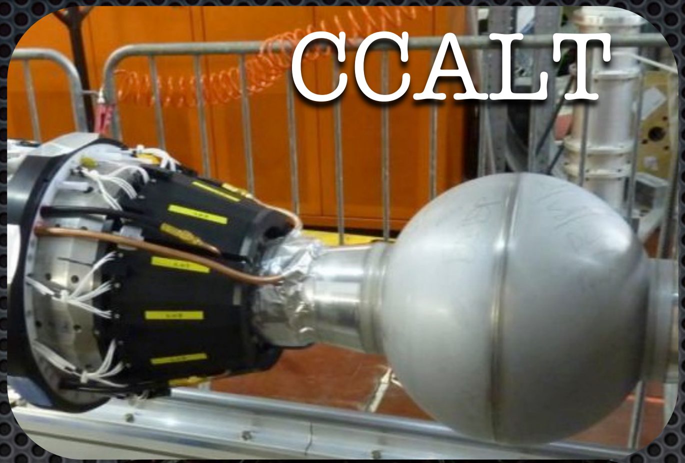
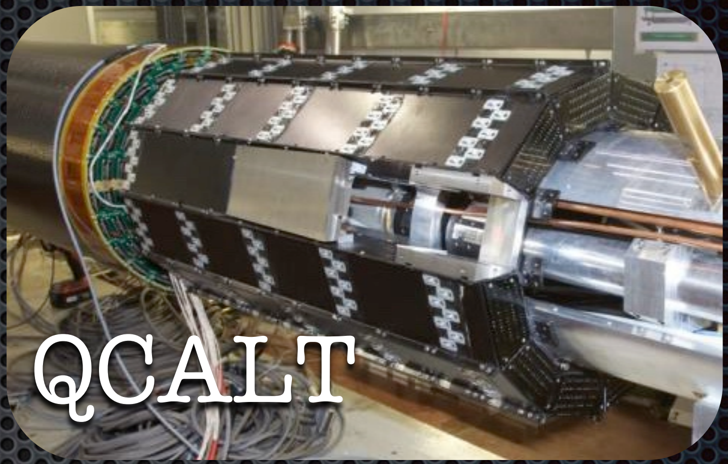
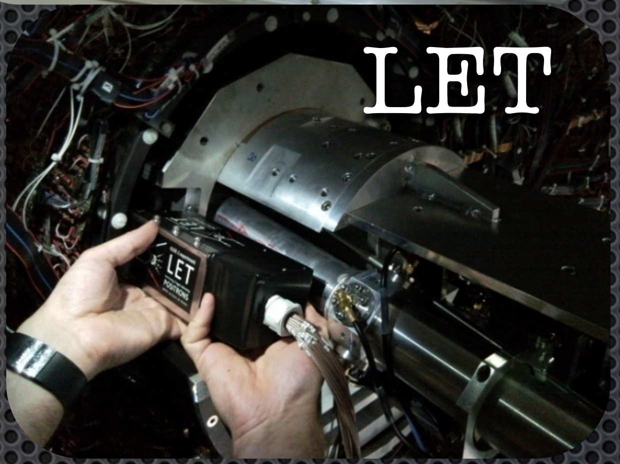
$\sigma vertex \sim 3\ mm$

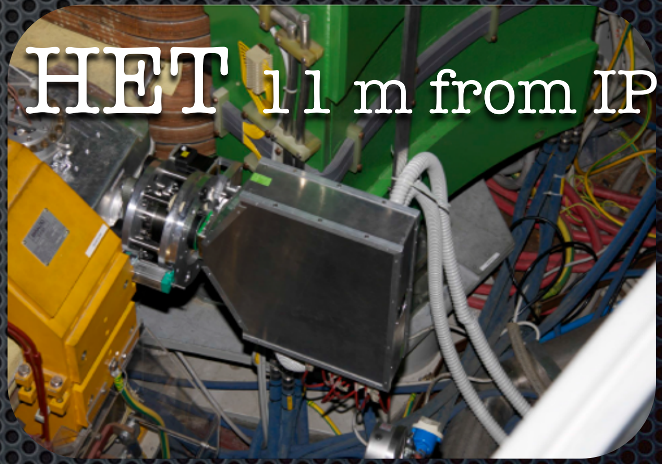
KLOE-2 at DAϕNE

- Calorimeter System
  - EMC – Lead / Scintillating Fibers w PMT Barrel and Endcaps
  - CCALT – LYSO Crystal w SiPM – Low- beta
  - QCALT – Tungsten / Scintillating Tiles w SiPM - Quadrupole Instrumentation
  - LET / LYSO+SiPMs
  - HET / Scint+PMTs









- Tracking System
  - DC – He-Iso 90-10
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  - Inner Tracker – 4 Cylindrical GEM detectors
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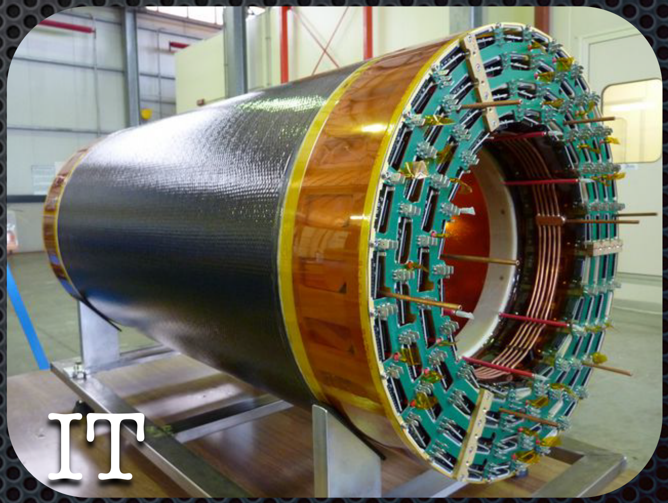
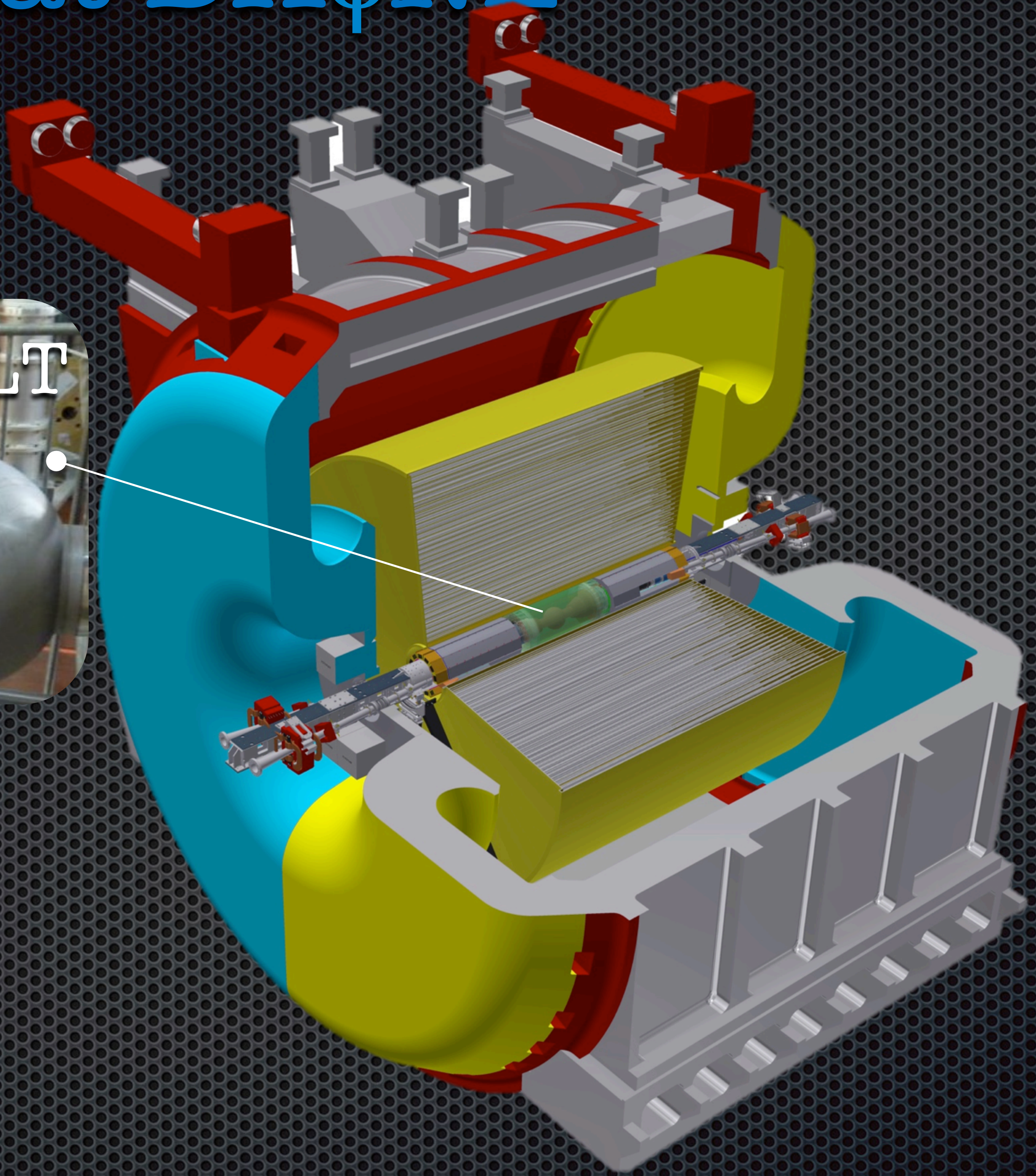


- Physics program [EPJC 68 (2010)]
  - Ks, η, η_S rare decays
  - Quantum Interferometry
  - Dark photon search

(A. Di Domenico A. Gajos Satellite meeting)

KLOE-2 at DAϕNE



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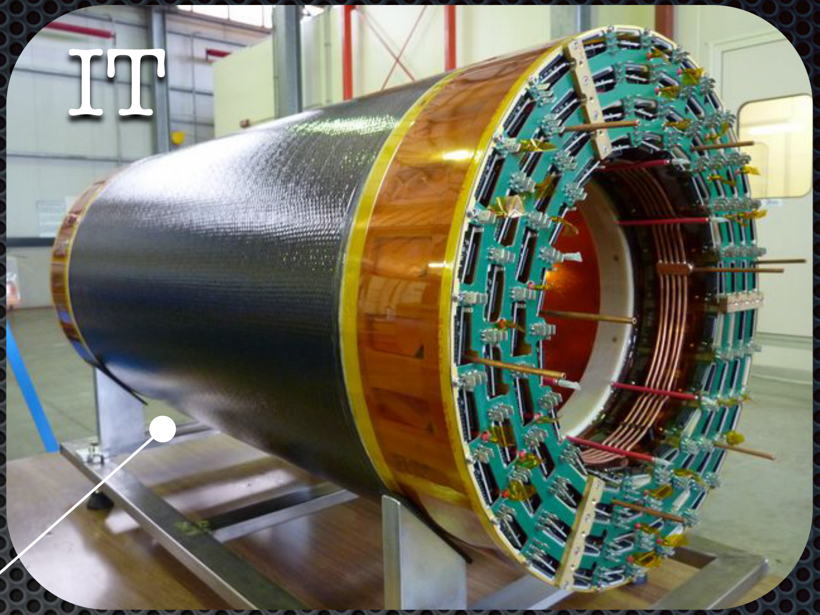

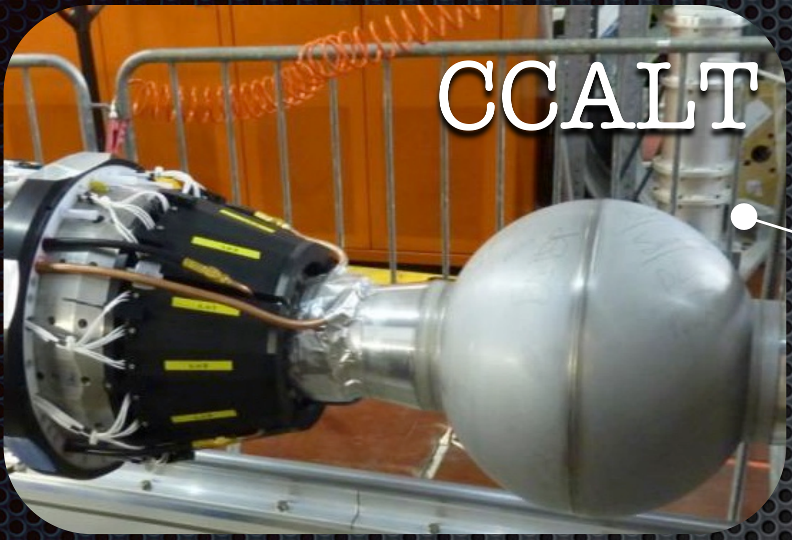

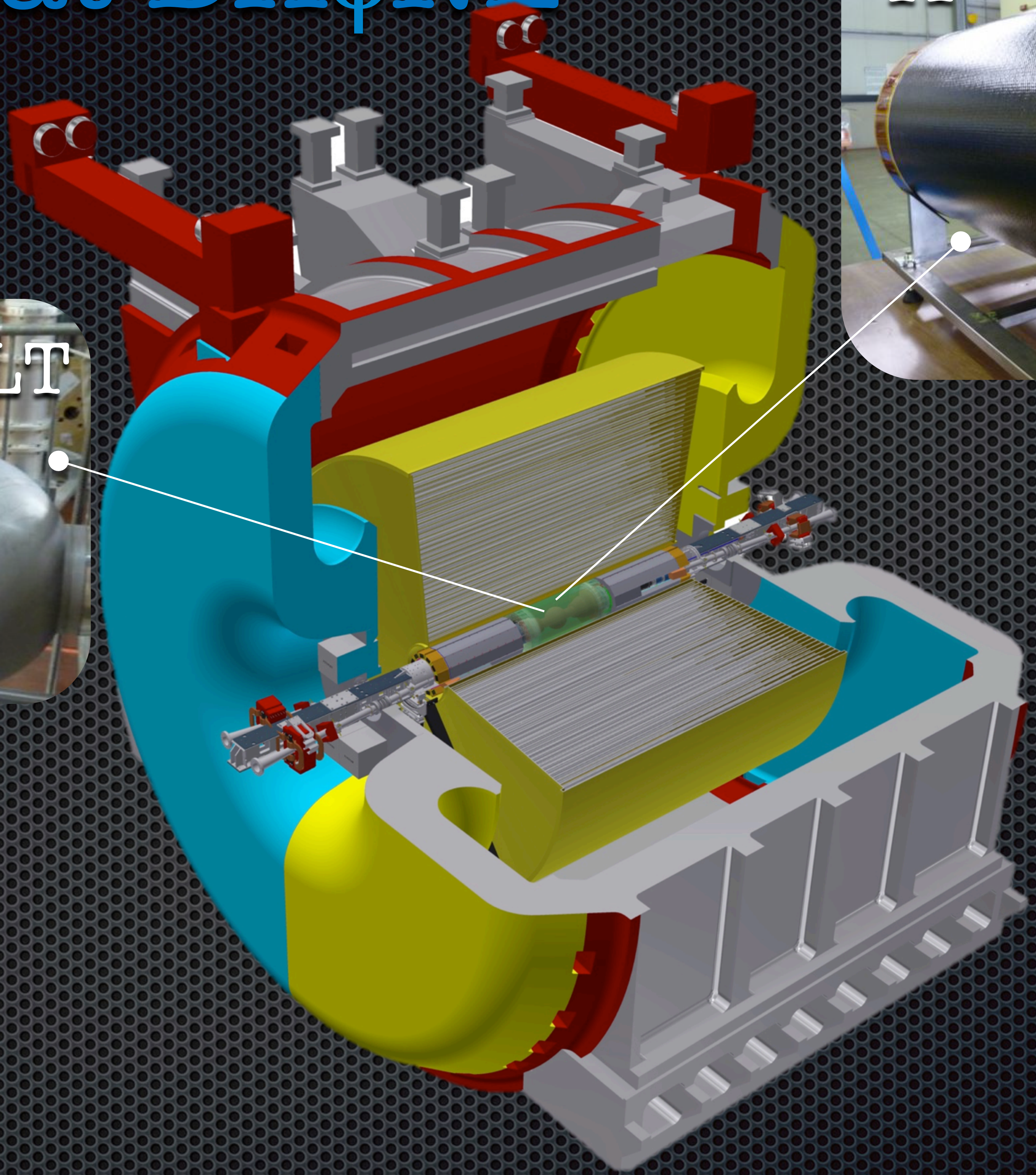

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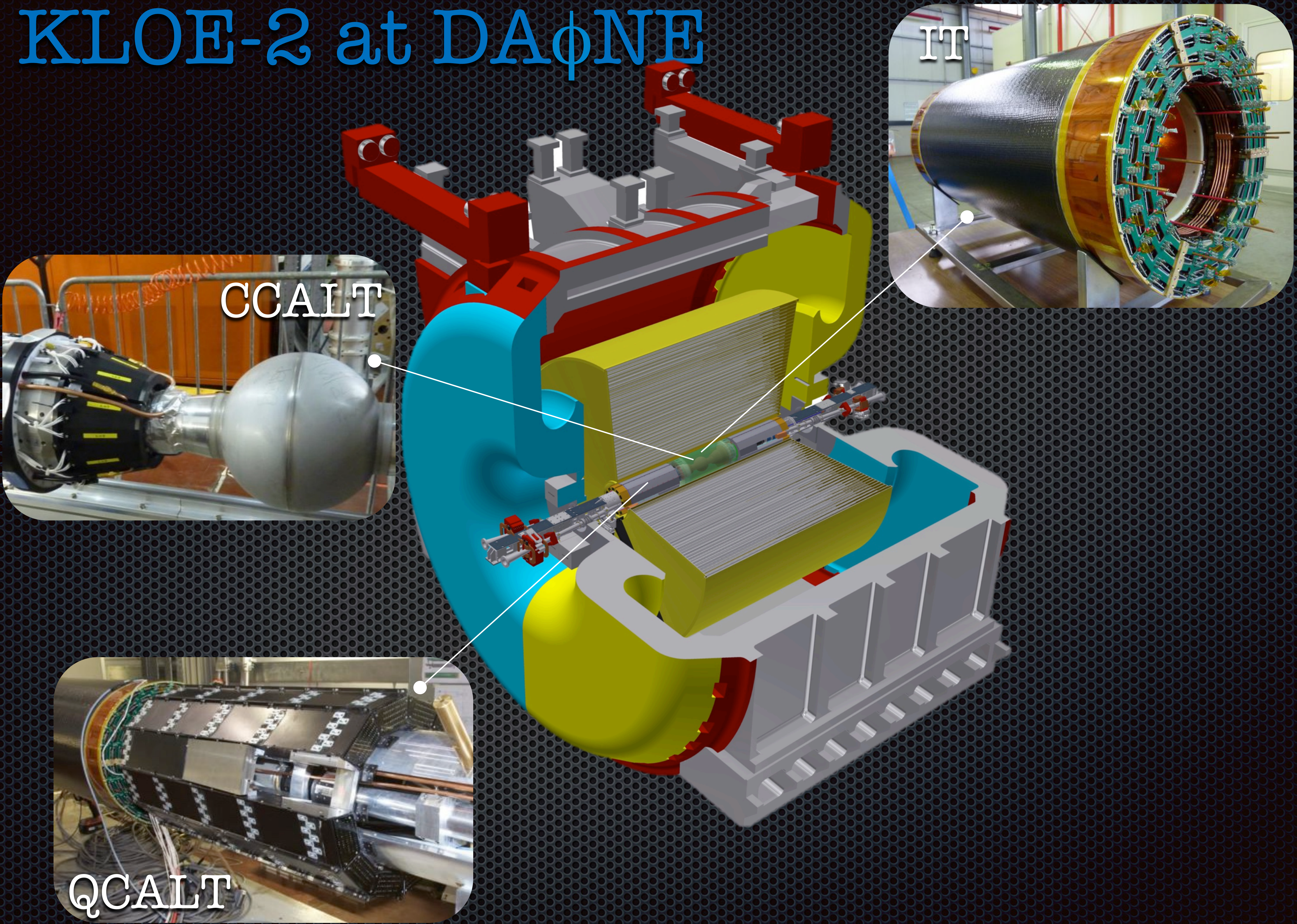

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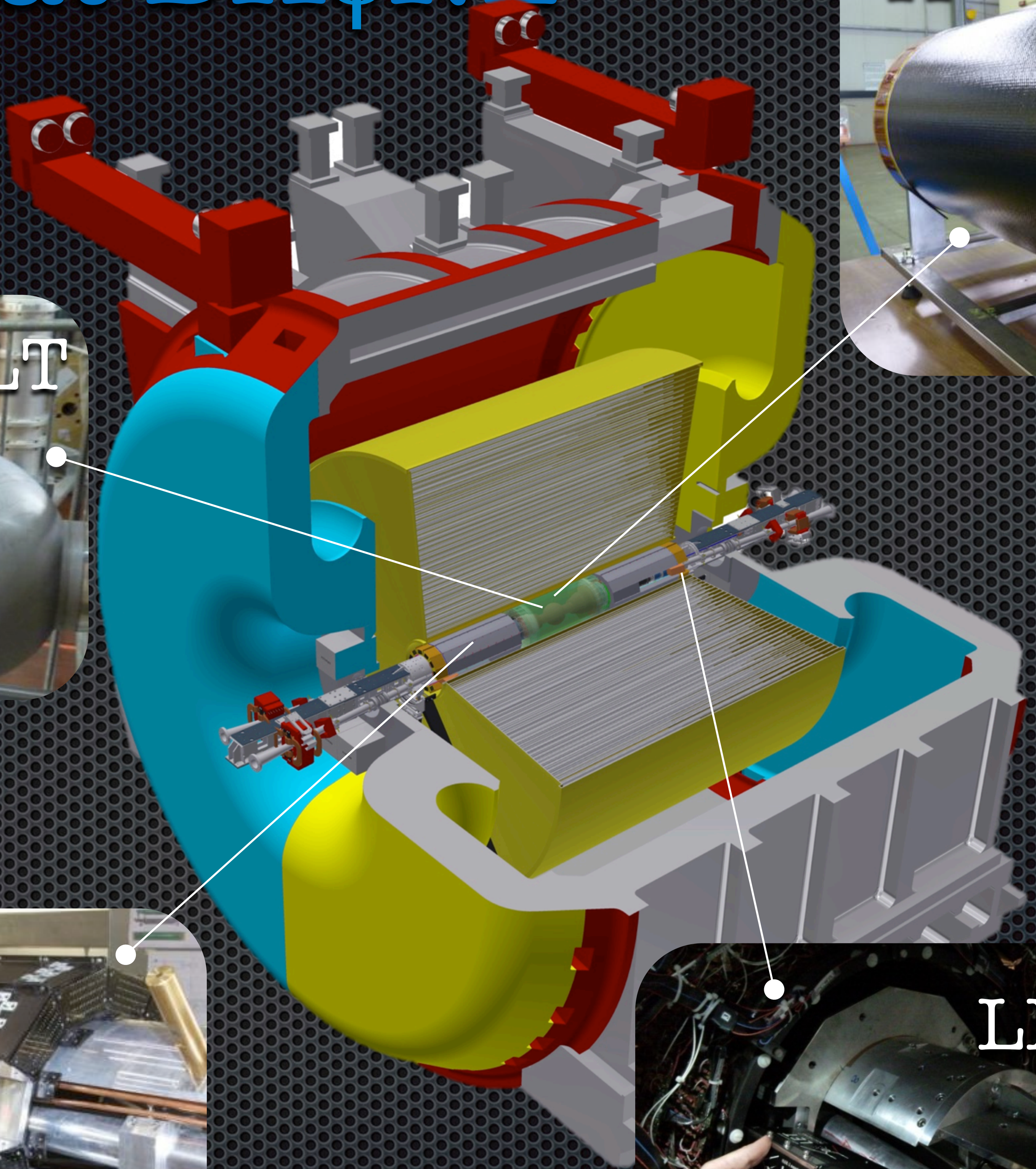

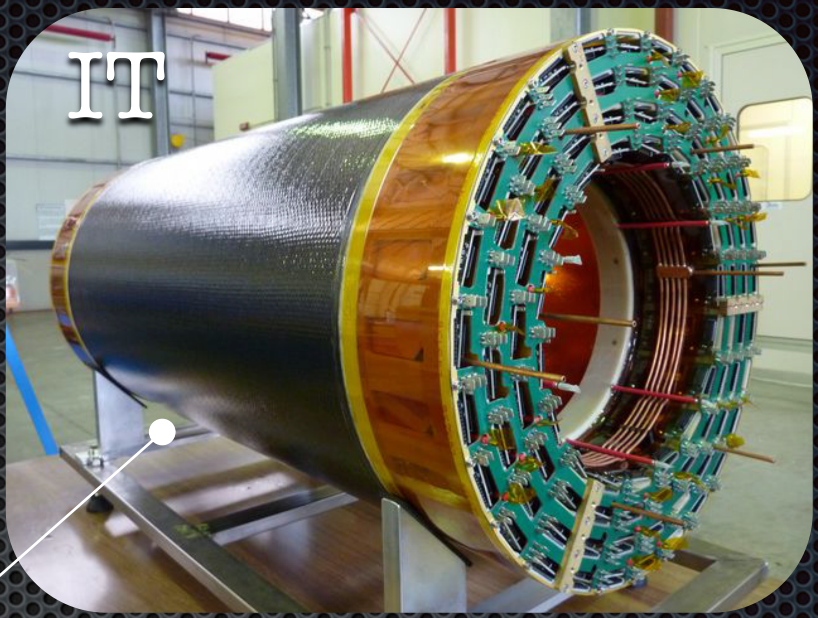

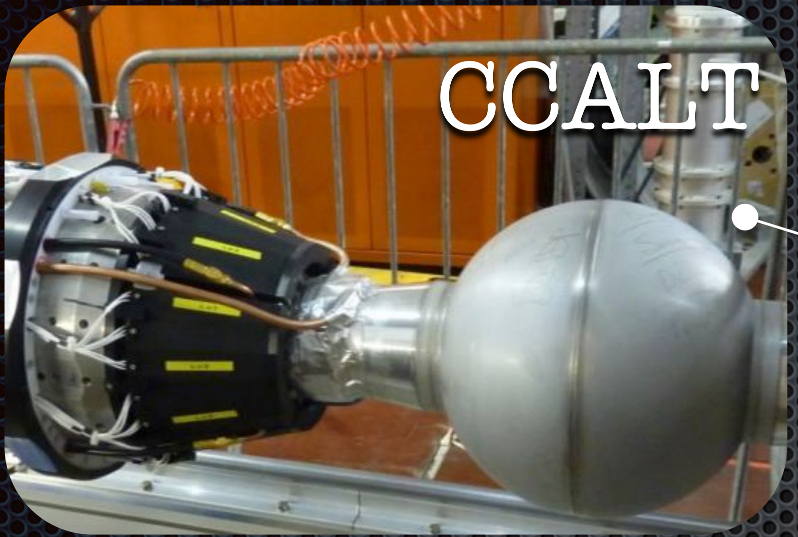

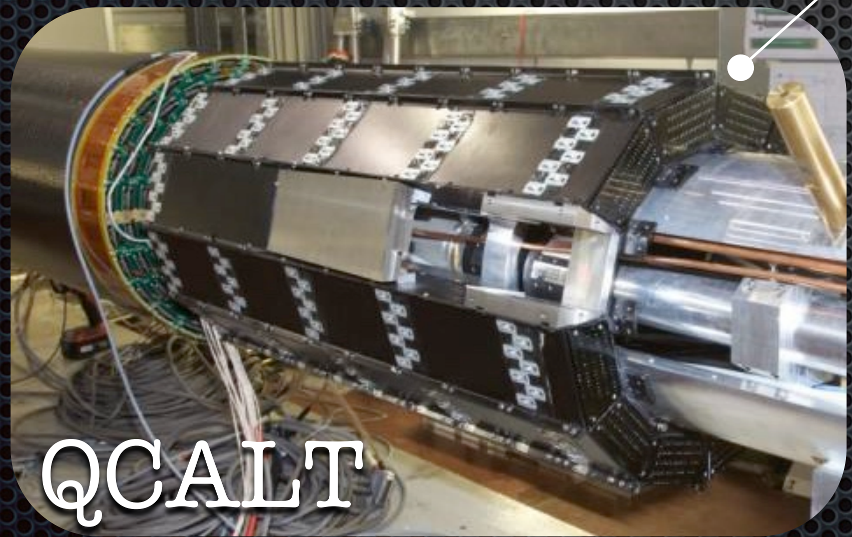

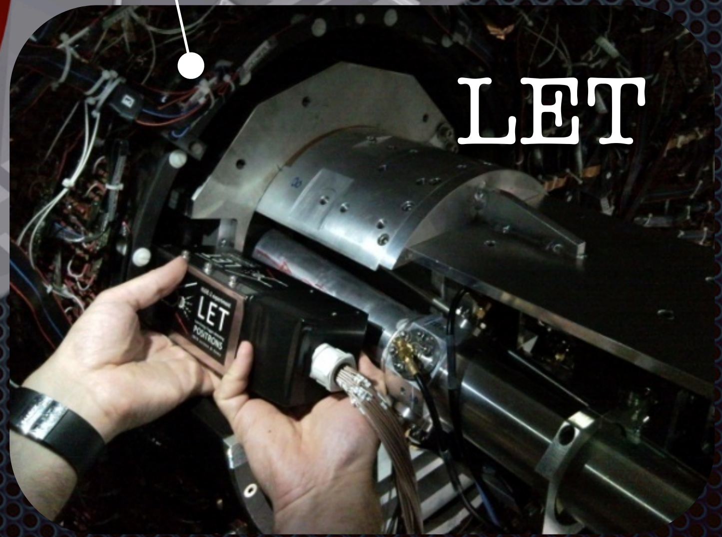

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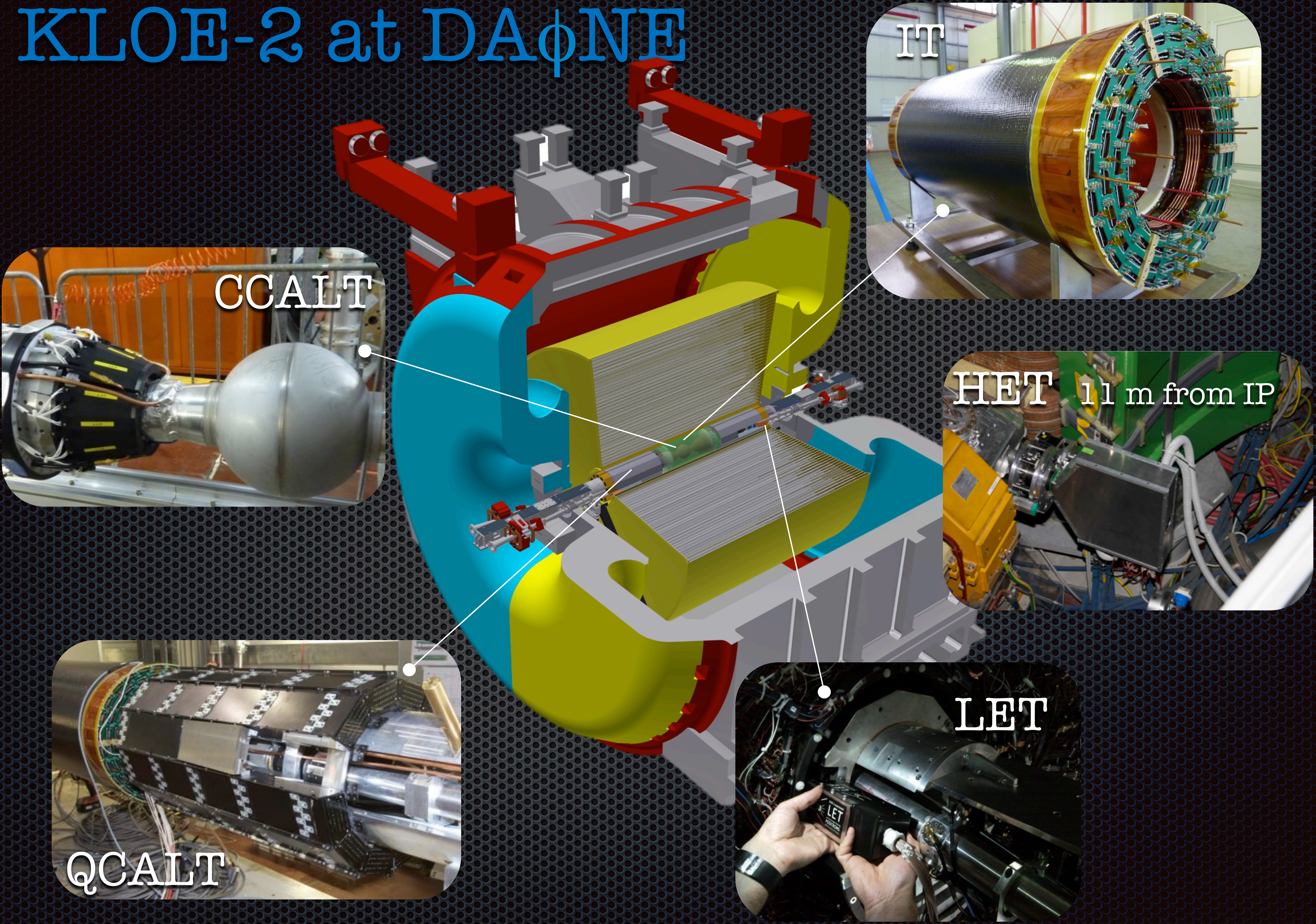
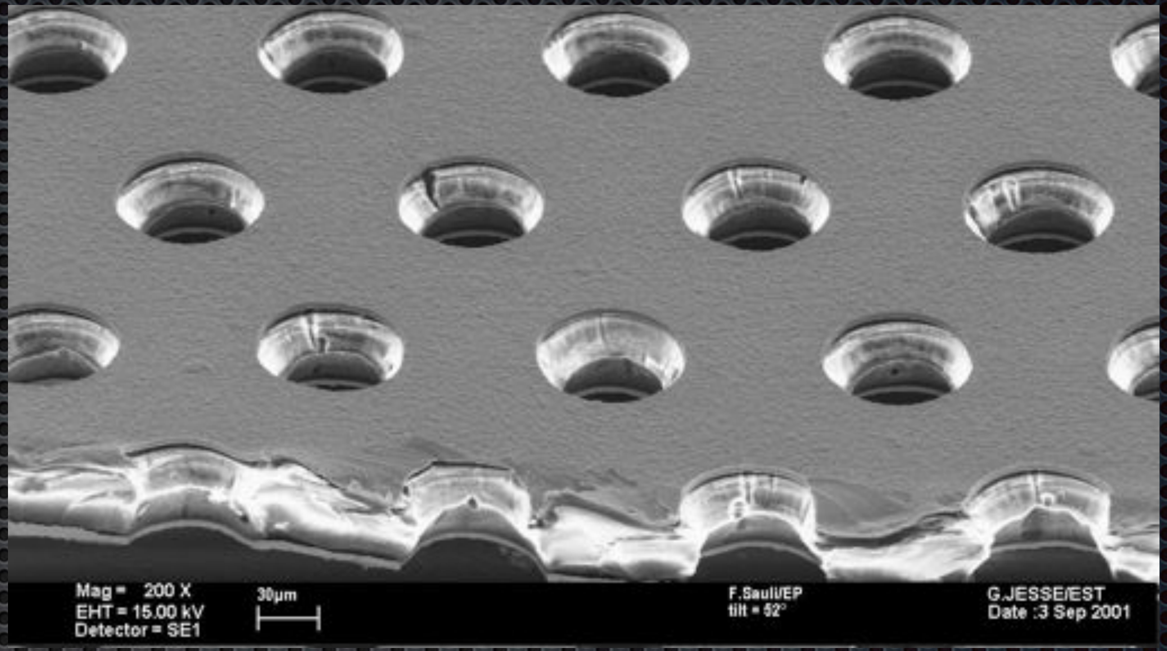
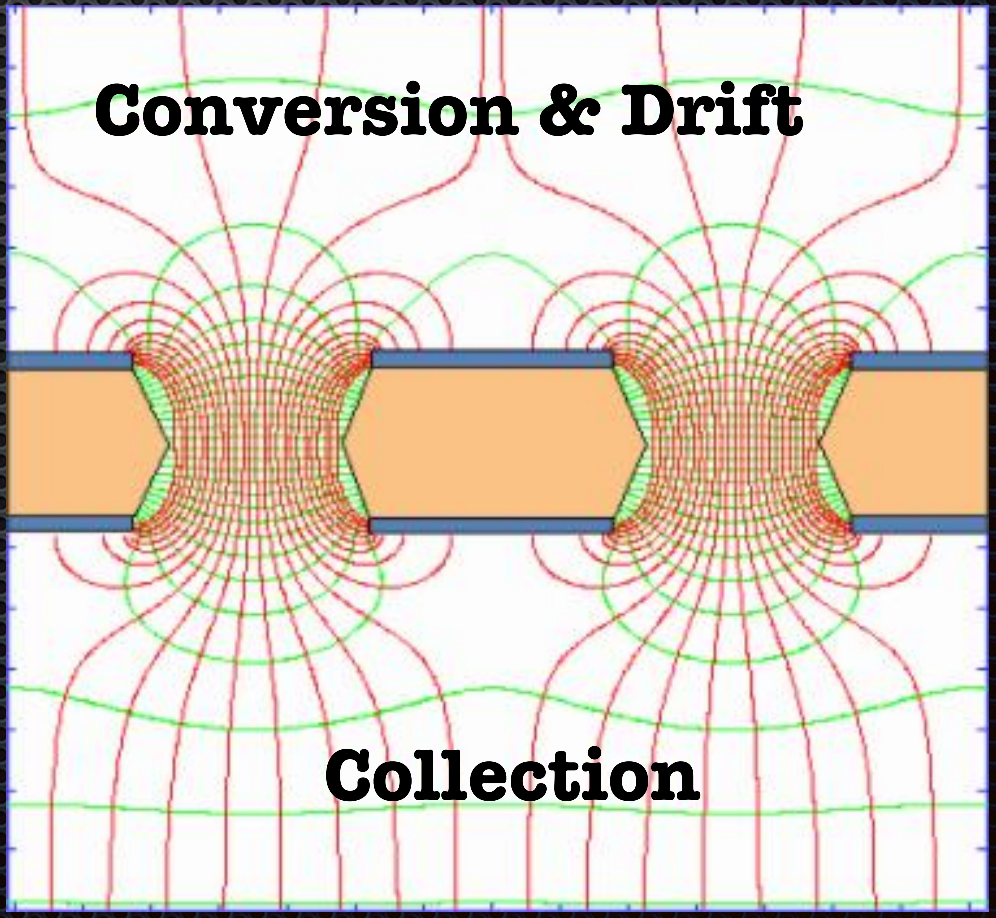


Gas Electron Multiplier (GEM)

- The GEM is a 50 μm thick copper- coated kapton foil, with high density of holes (70 μm ∅, 140 μm pitch) manufactured with standard photo-lithographic technology [F. Sauli, NIM A386 (1997) 531]



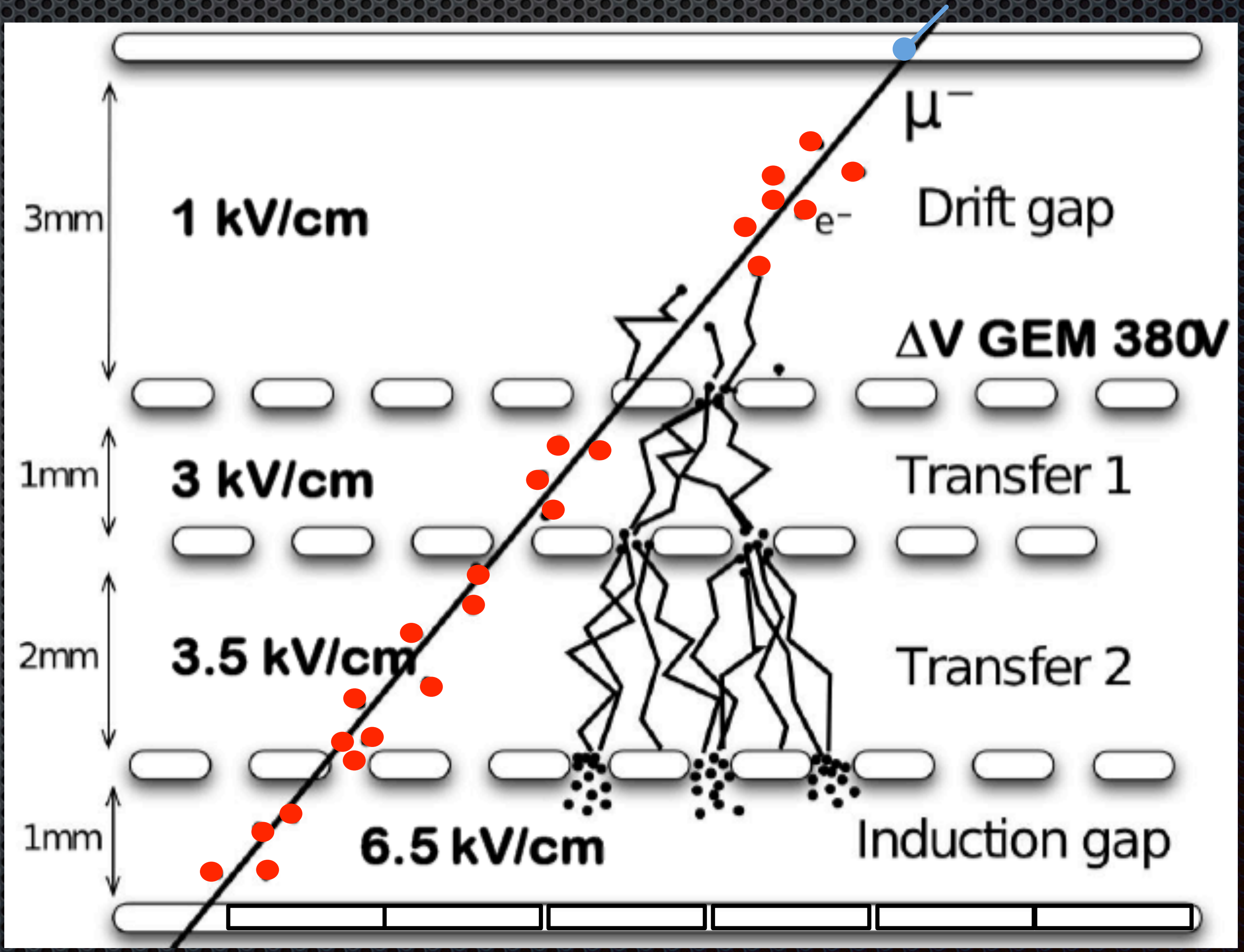
- By applying a difference of potential (400-500 V) between the two copper sides, in presence of external **Drift** and **Collection** fields, an electric field as high as ~100 kV/cm is produced into the **Holes** acting as **Multiplication Stages** for ionization electrons released in the drift gas gap



Gas Electron Multiplier (GEM)

- Gains up to 1000 can be easily reached with a single GEM foil
- Higher gains (and/or safer working conditions) are usually obtained by cascading two or three GEM foils

$G \propto e^{\sum V_{gem}}$



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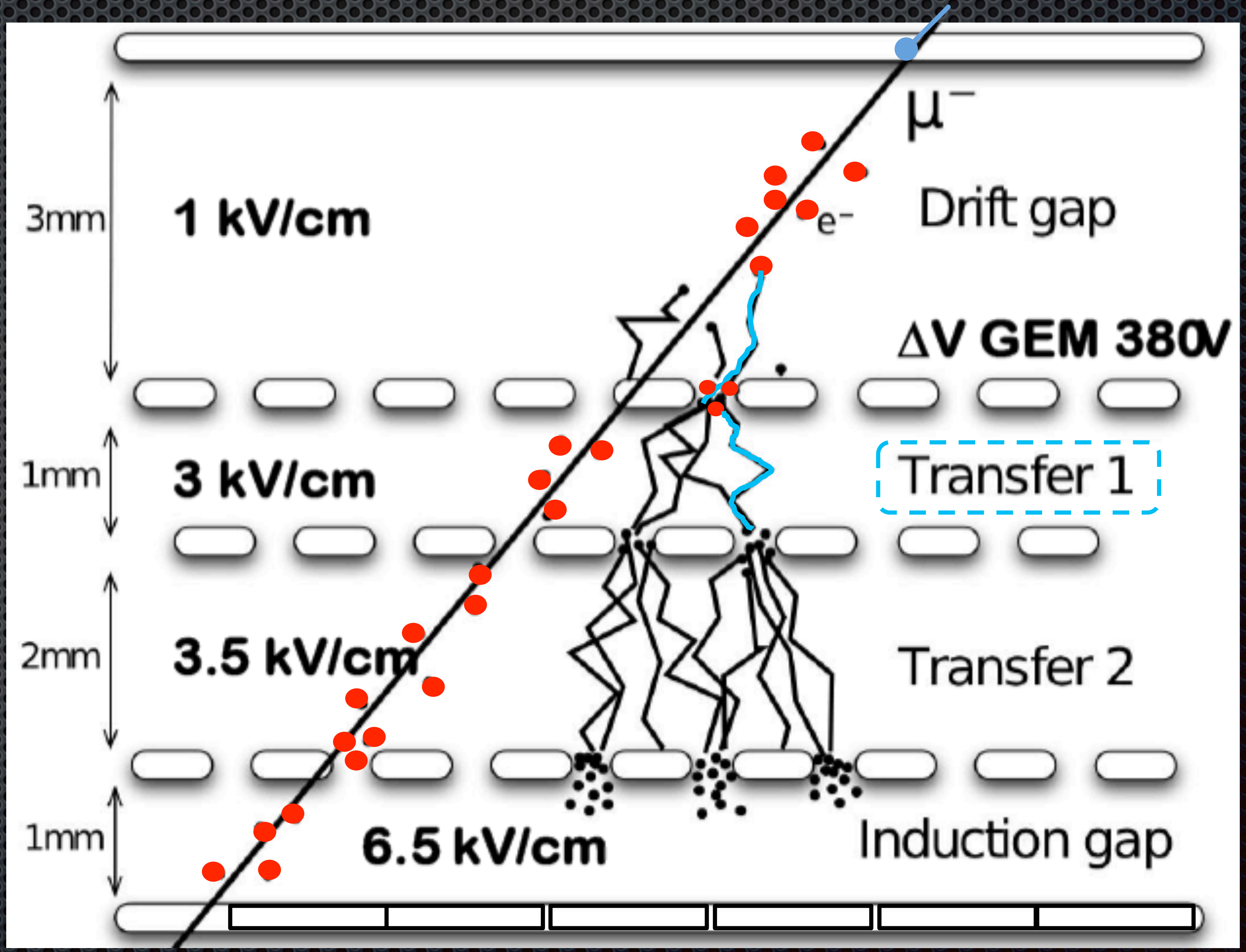

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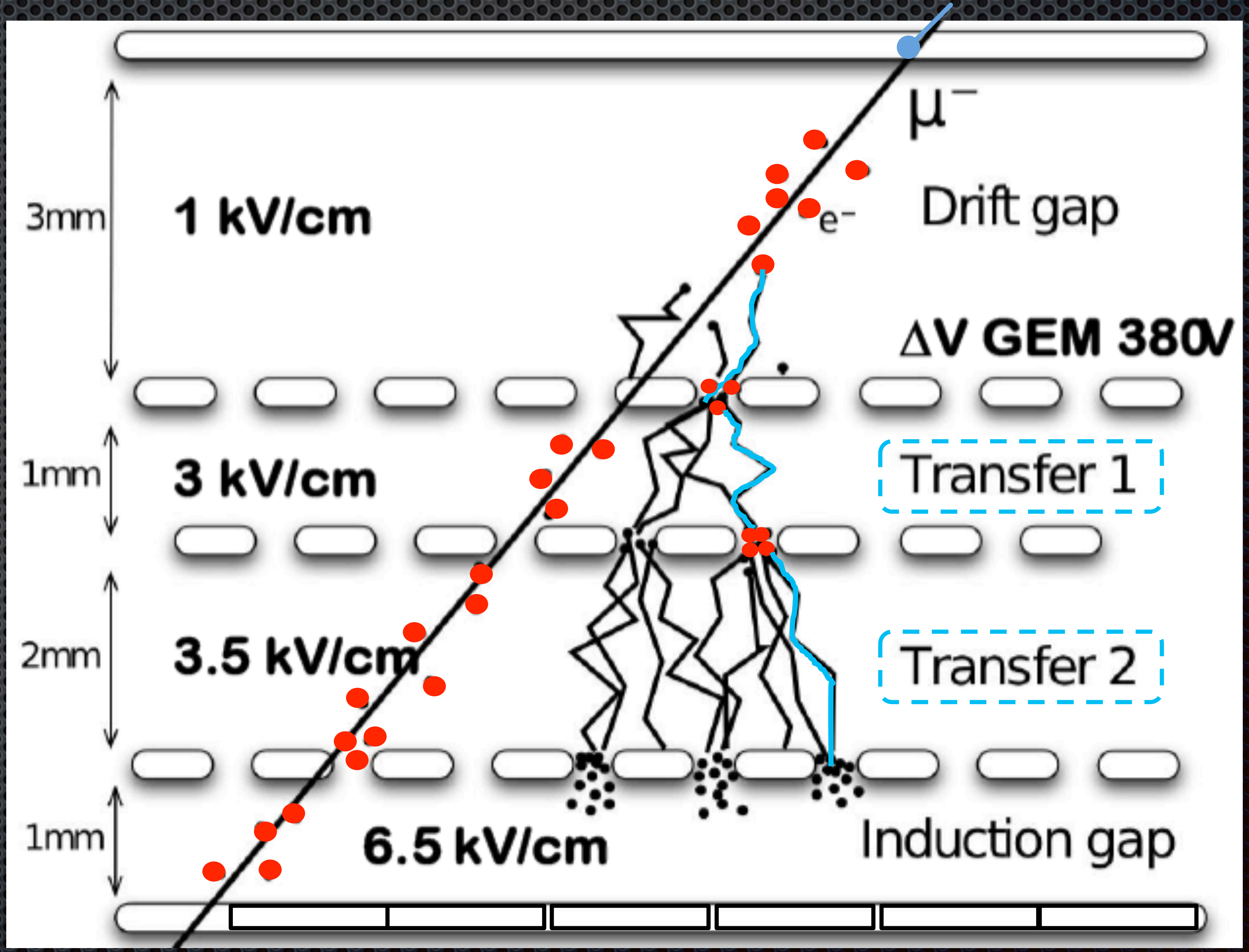

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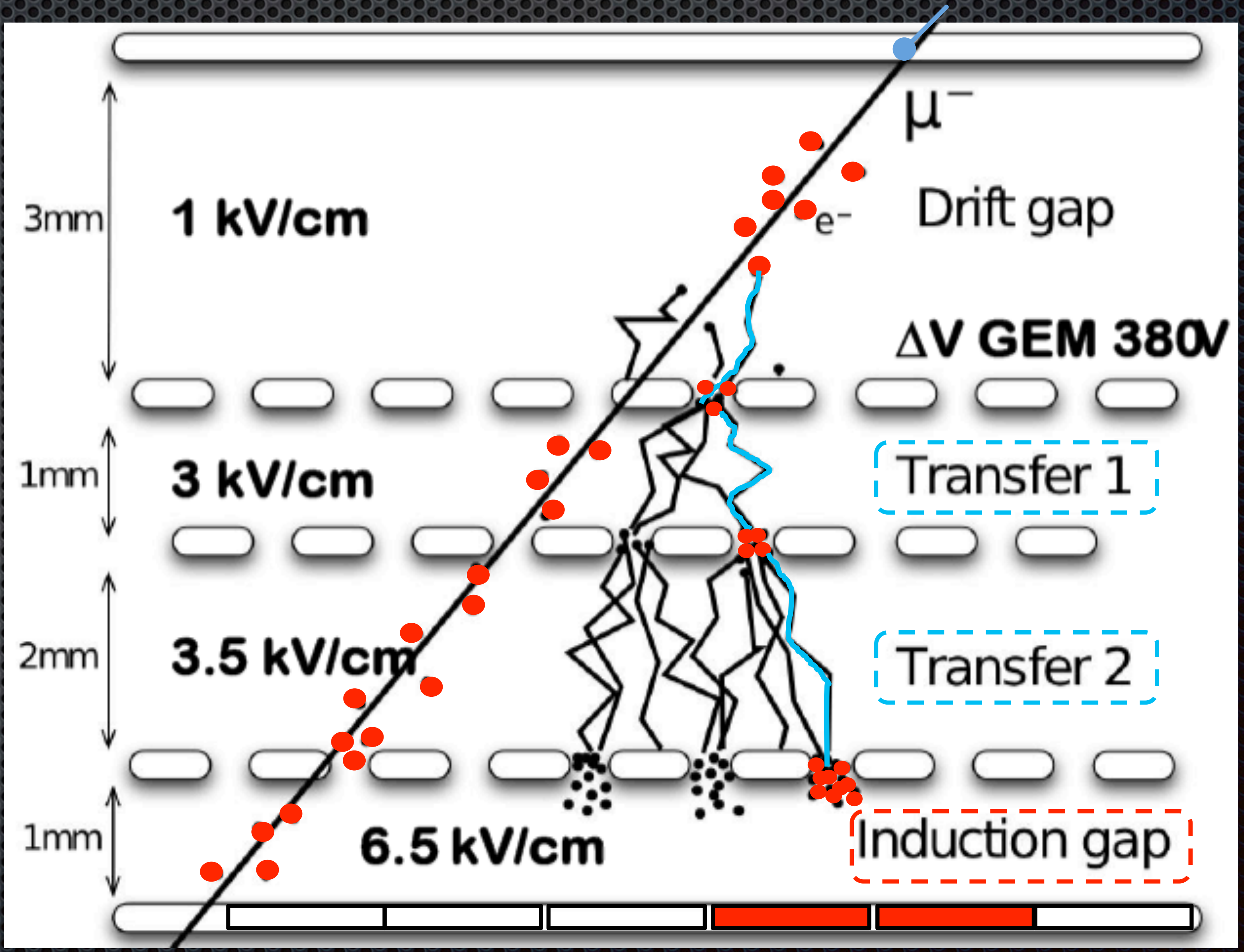
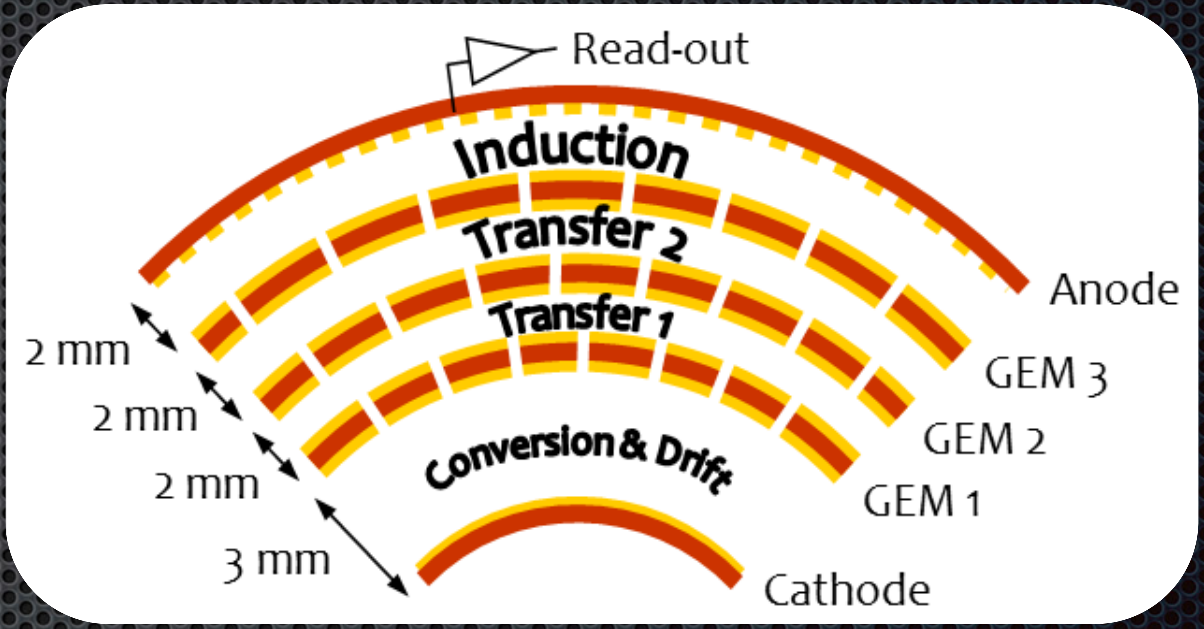


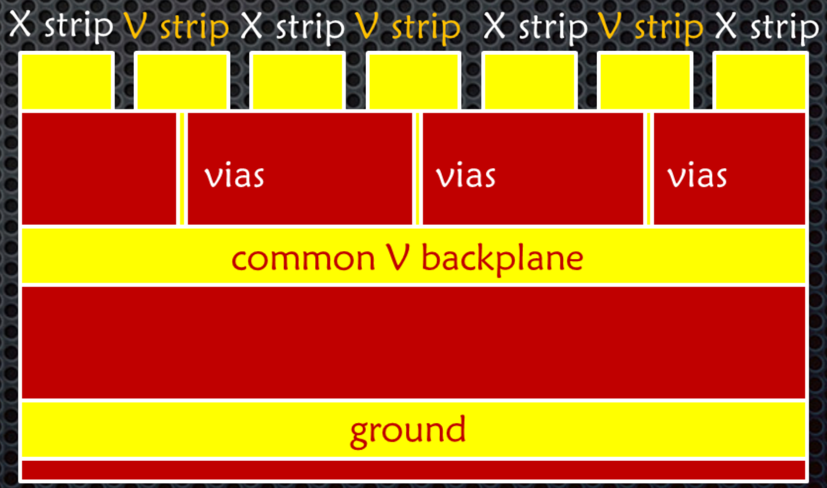
Cylindrical GEM Inner Tracker

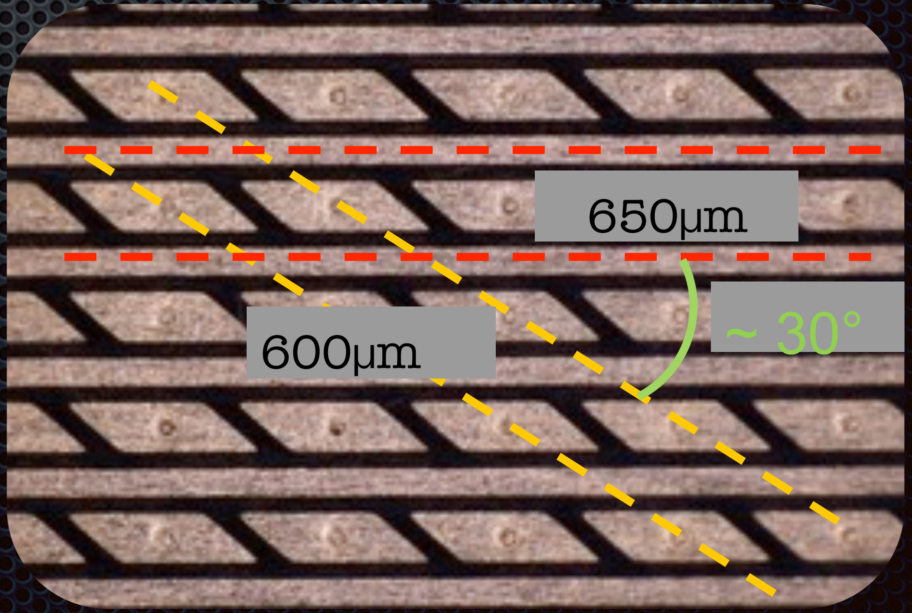
- Improve vertex reconstruction at IP
- First batch ever of GEM foils produced with a single-mask etching developed by CERN-TE-MPE-EM for large area foils
- 70 cm active length
- 650 μm XV pitch strip readout
- 25k chan GASTONE FEE [NIM A 732 (2013)]
- 1600 HV channels
- FEE DAQ system [JINST 08 T04004 (2013)]
- 3/2/2/2 mm triple-GEM layout
- Ar/Iso:90/10 gas mixture
- 12000 gas gain
- 2% X_0 material budget



Kapton/copper multilayer flexible circuit built at CERN TE-MPE-EM
(Tot thickness 300 μm)

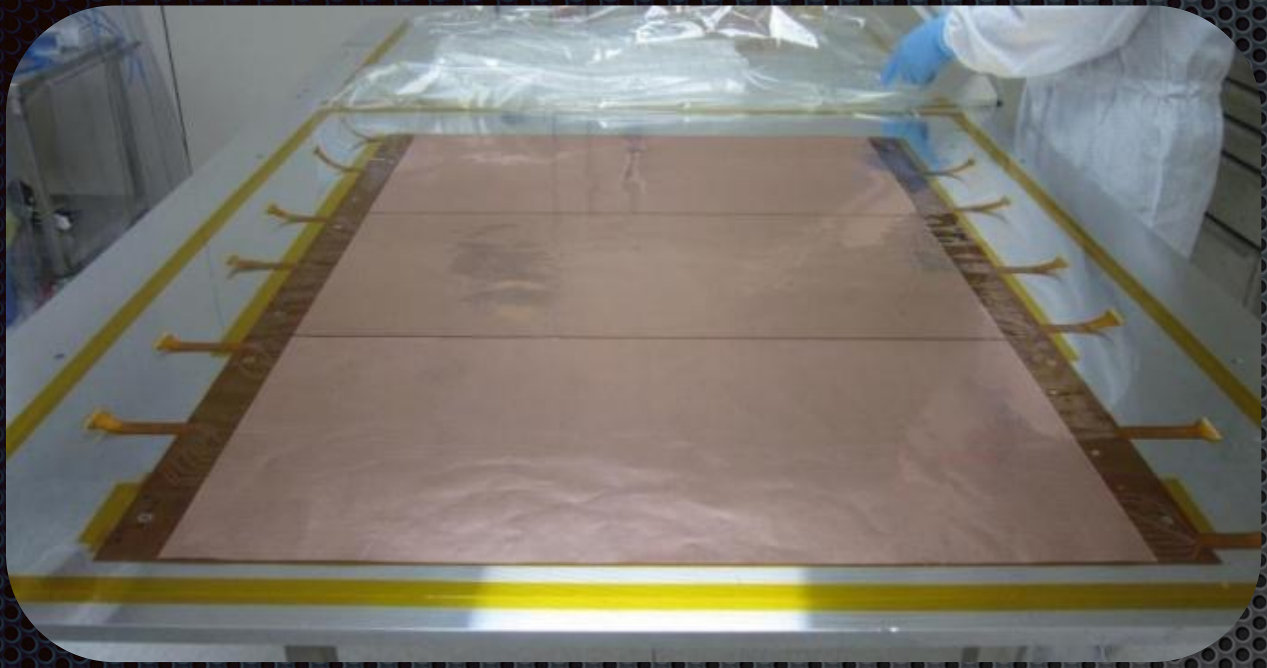
- X-view: longitudinal strips
- V-view: connection of pads through conductive vias and a common backplane





Cylindrical GEM detector construction

- Novel technique developed at LNF and 1st CGEM detector in HEP experiment



- 3 GEM foils spliced together with 3 mm overlap

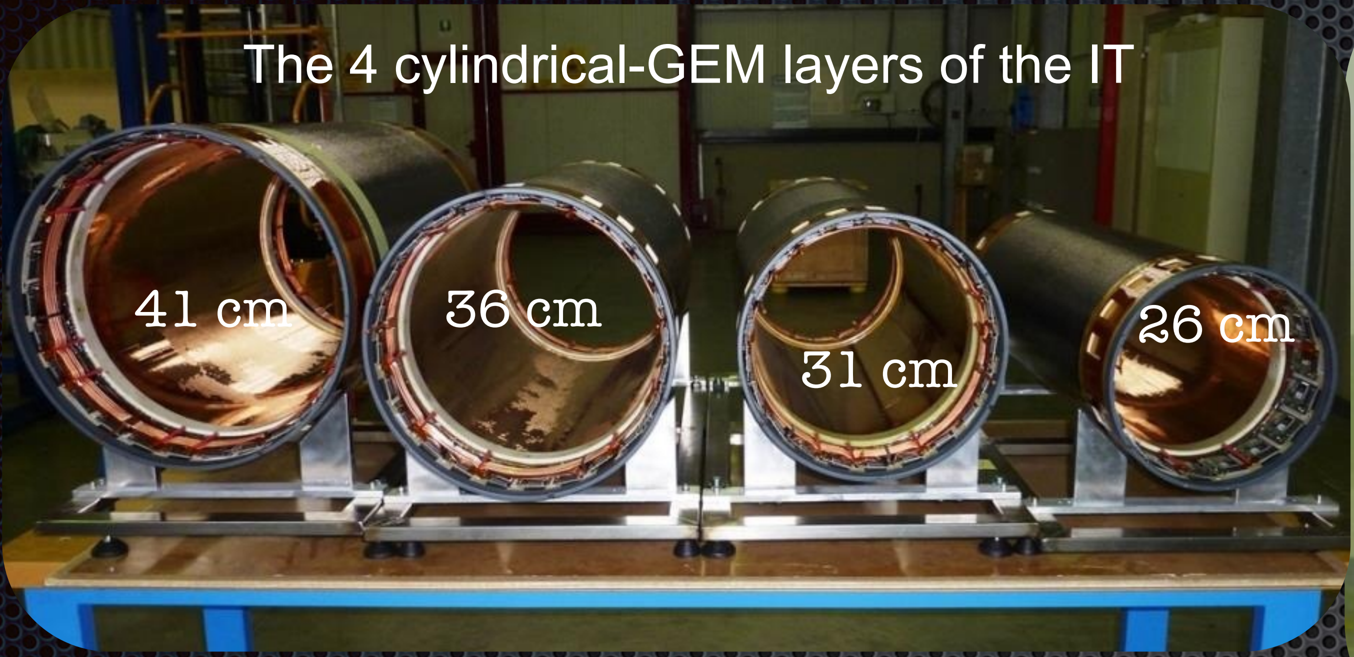
- GEM rolled on a cylindrical mold

- 3 anode readout foils spliced w/o overlap: 6 cm kapton strips glued head-to-head joints

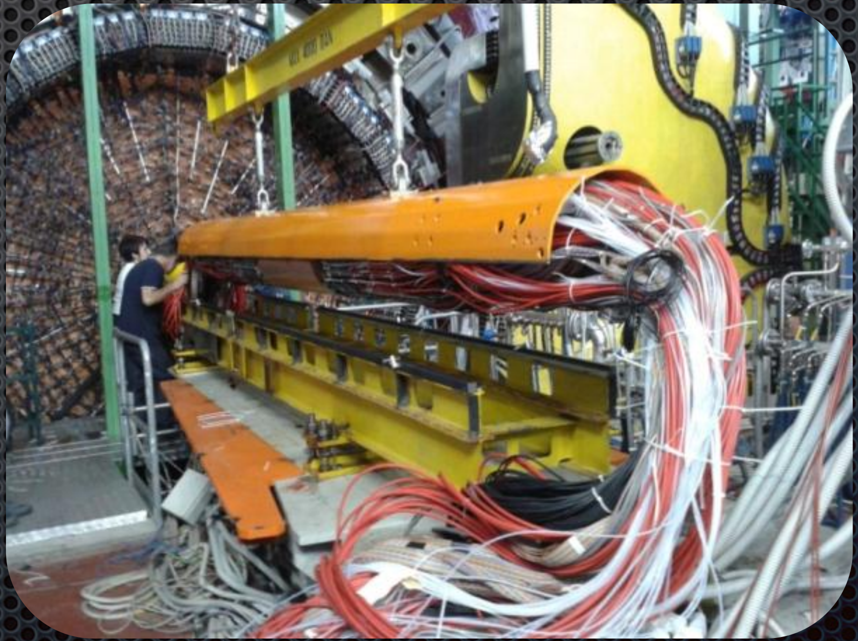
- The GEM mold is fixed at the bottom of the insertion machine. Readout plane is fixed at the top. Electrodes are axially aligned with a precision of 0.1mm/1.5m

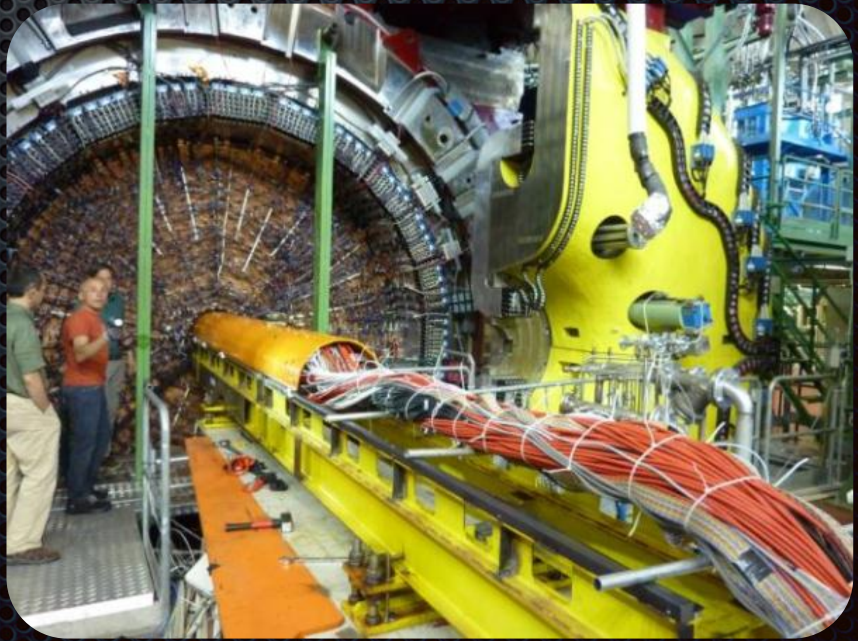
Cylindrical GEM Inner Tracker

◎ Four layers completed and detector integration

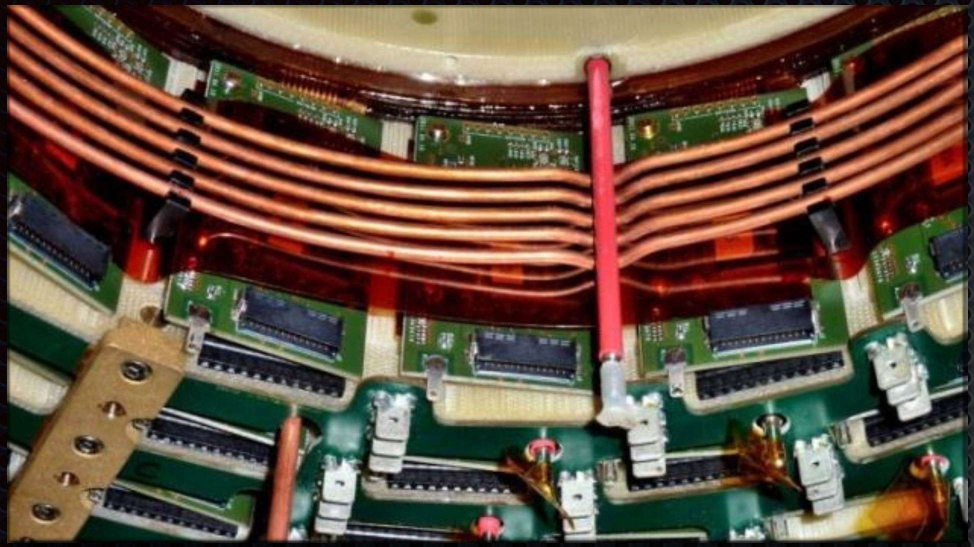


◎ Integration on DAPHNE beam-pipe & insertion in KLOE





Cooling and Temperature control



IT Cables per side:

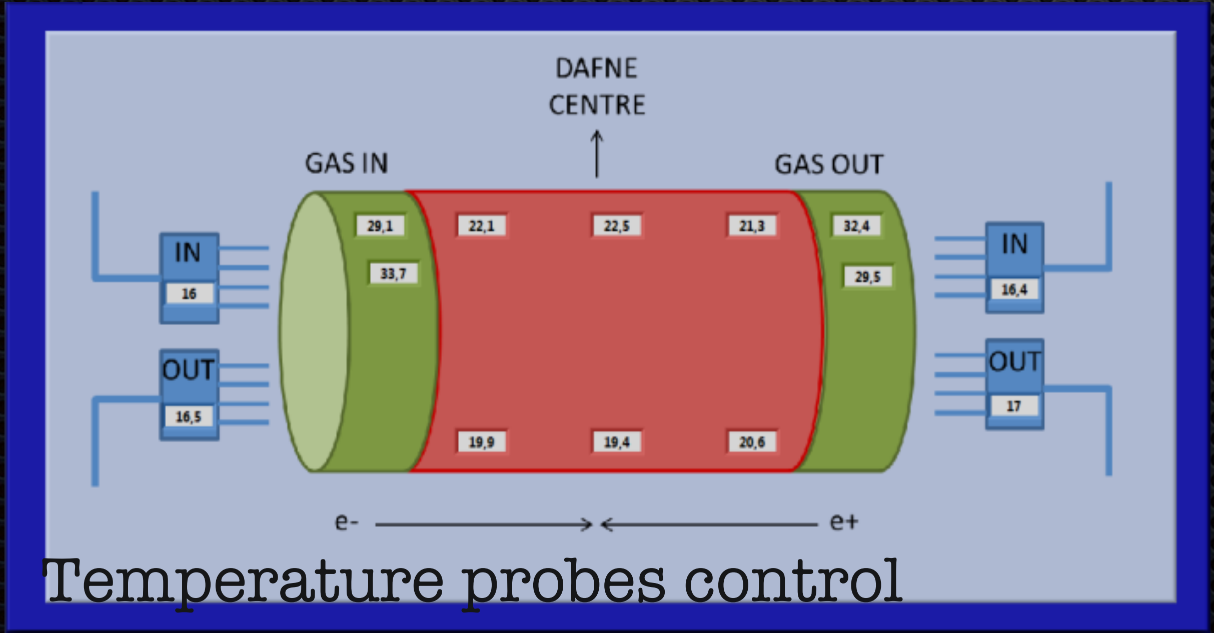
- 90 readout cables
- 69 HV cables
- 36 gas tubes
- 8 cooling tubes
- 6 temp. probes

Heat sources

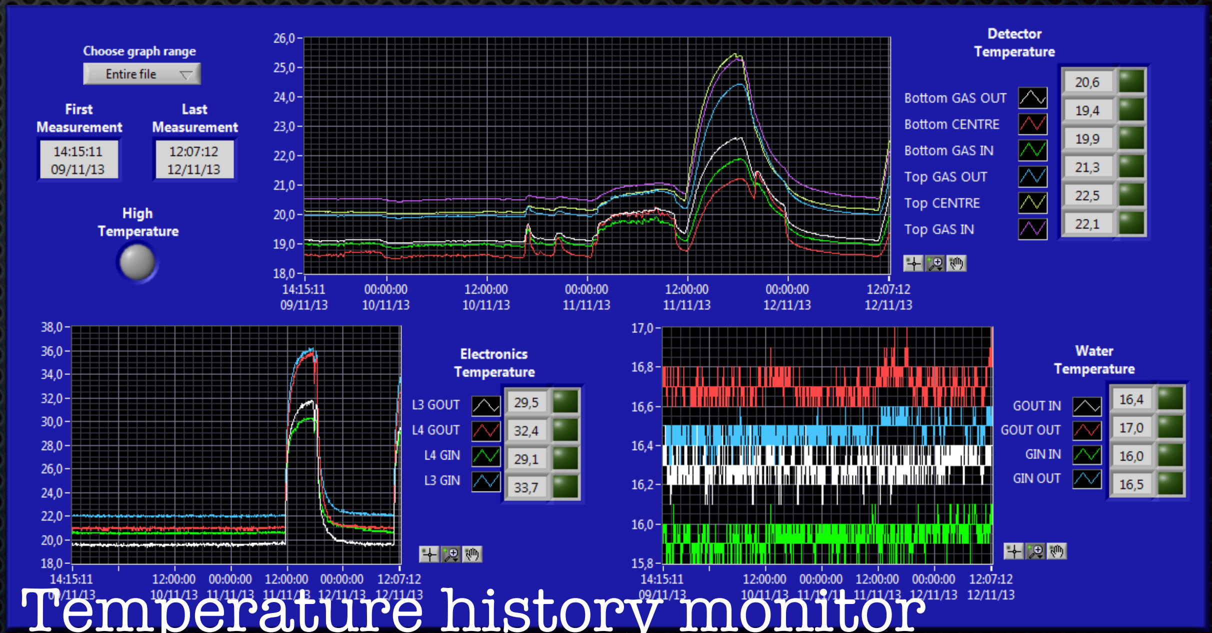
- Beam-pipe (luminosity dependent)
- FEE: 180 chips = 100W per side

Two dedicated cooling systems

- Air blowing between BP and IT
- Water radiators on FEE



Temperature probes control



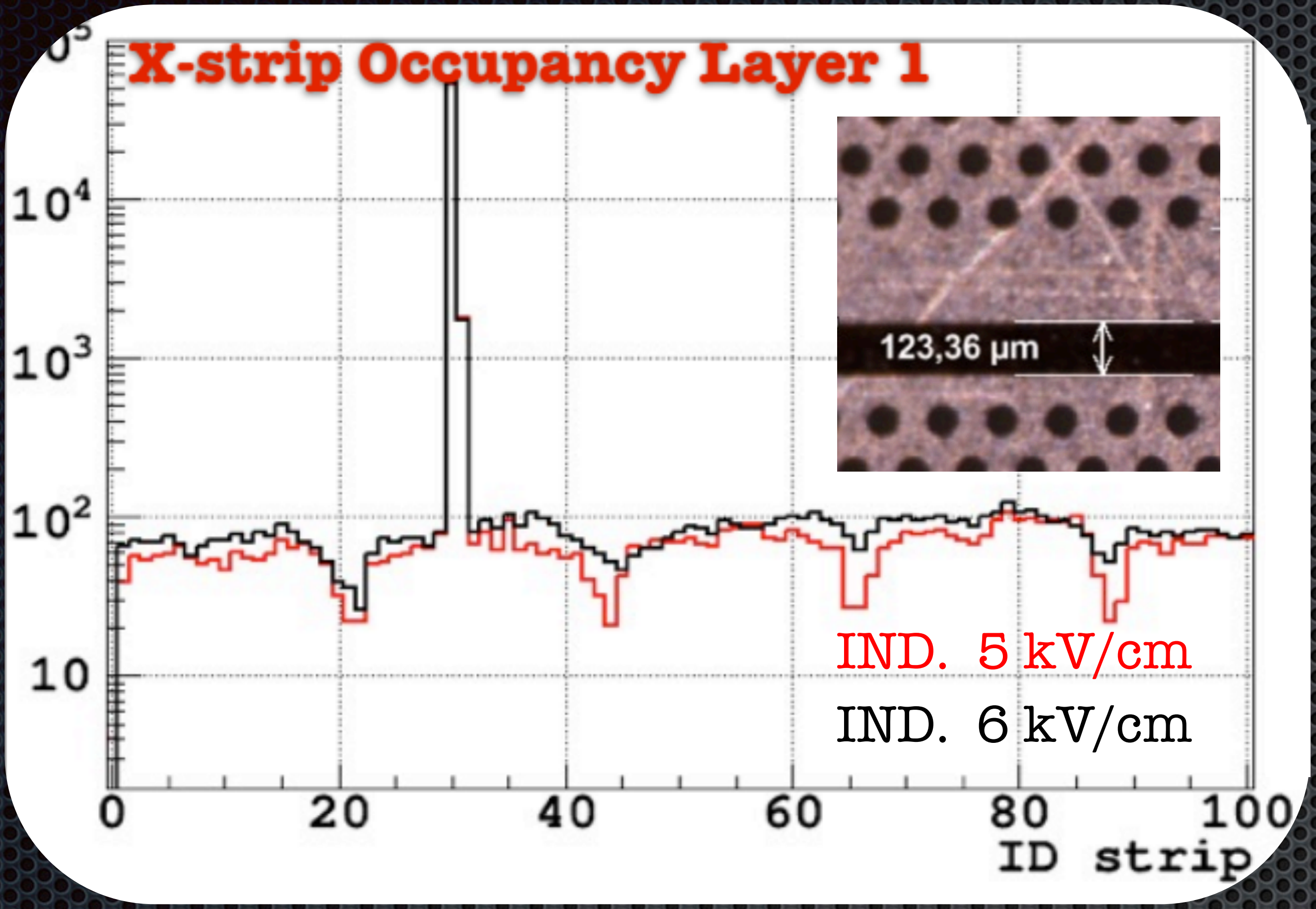
Temperature history monitor

Inner Tracker working point

First CGEM detector used in high-energy physics experiment

Operation point optimization

- Dips show GEM foil micro-sector structure

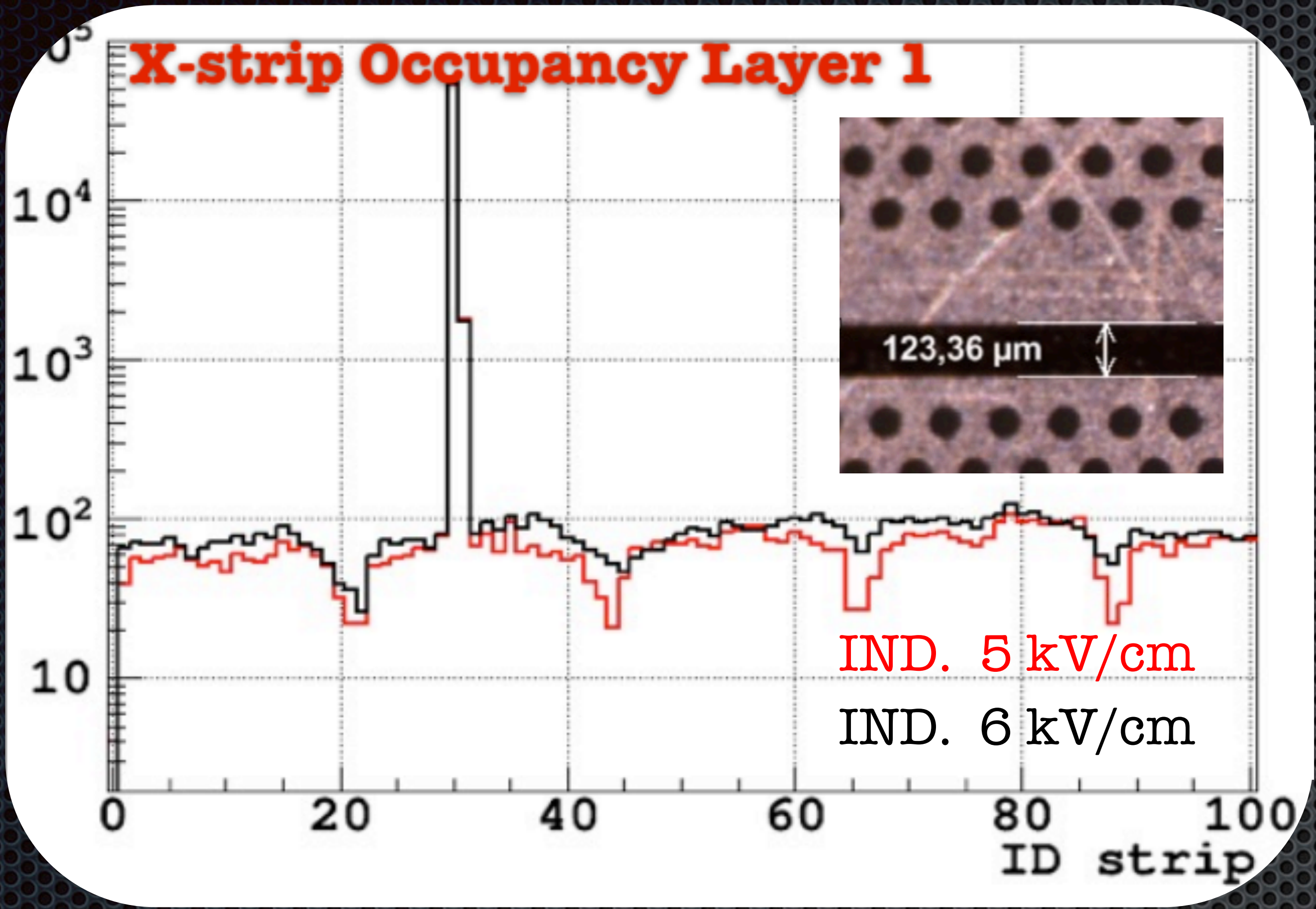


(kV/cm)				(V)		
Drift	T1	T2	IND.	G1	G2	G3
1,5	3	3	5	285	280	265

- Induction field from **5** to **6 kV/cm**

Operation point optimization

- Dips show GEM foil micro-sector structure



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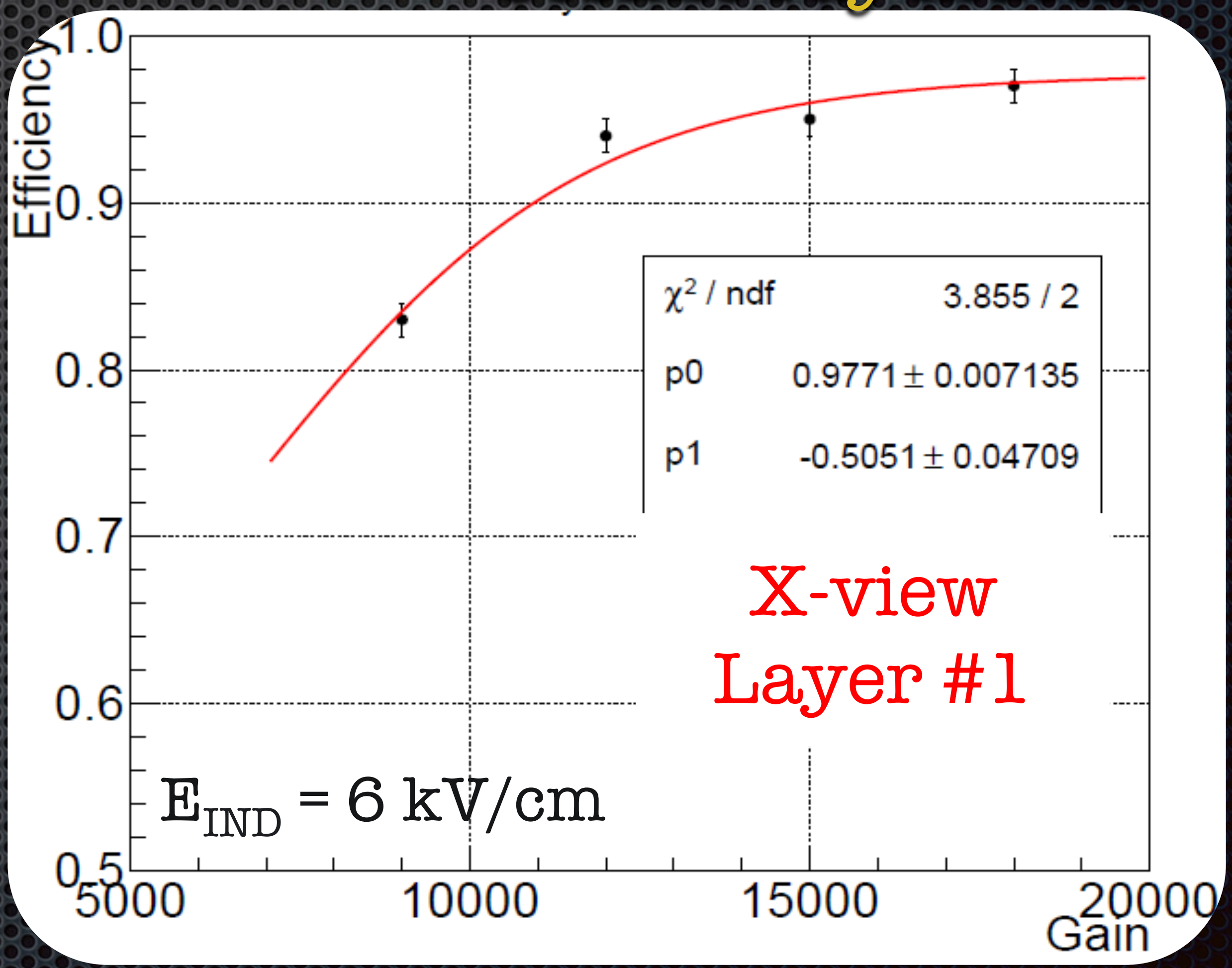
Cosmic-ray muons



- Extrapolate cosmic-ray muon DC tracks to IT with straight-line approximation
- Look for reconstructed IT clusters close to expected positions from DC track

$\varepsilon_{(5\ kV/cm)} = 86\ \%$ → $\varepsilon_{(6\ kV/cm)} = 94\%$ @ G = 12000

- Compromise between good efficiency and stable detector operation with beams

Operation with collisions (I)

One day @ KLOE-2
(with calibration time)

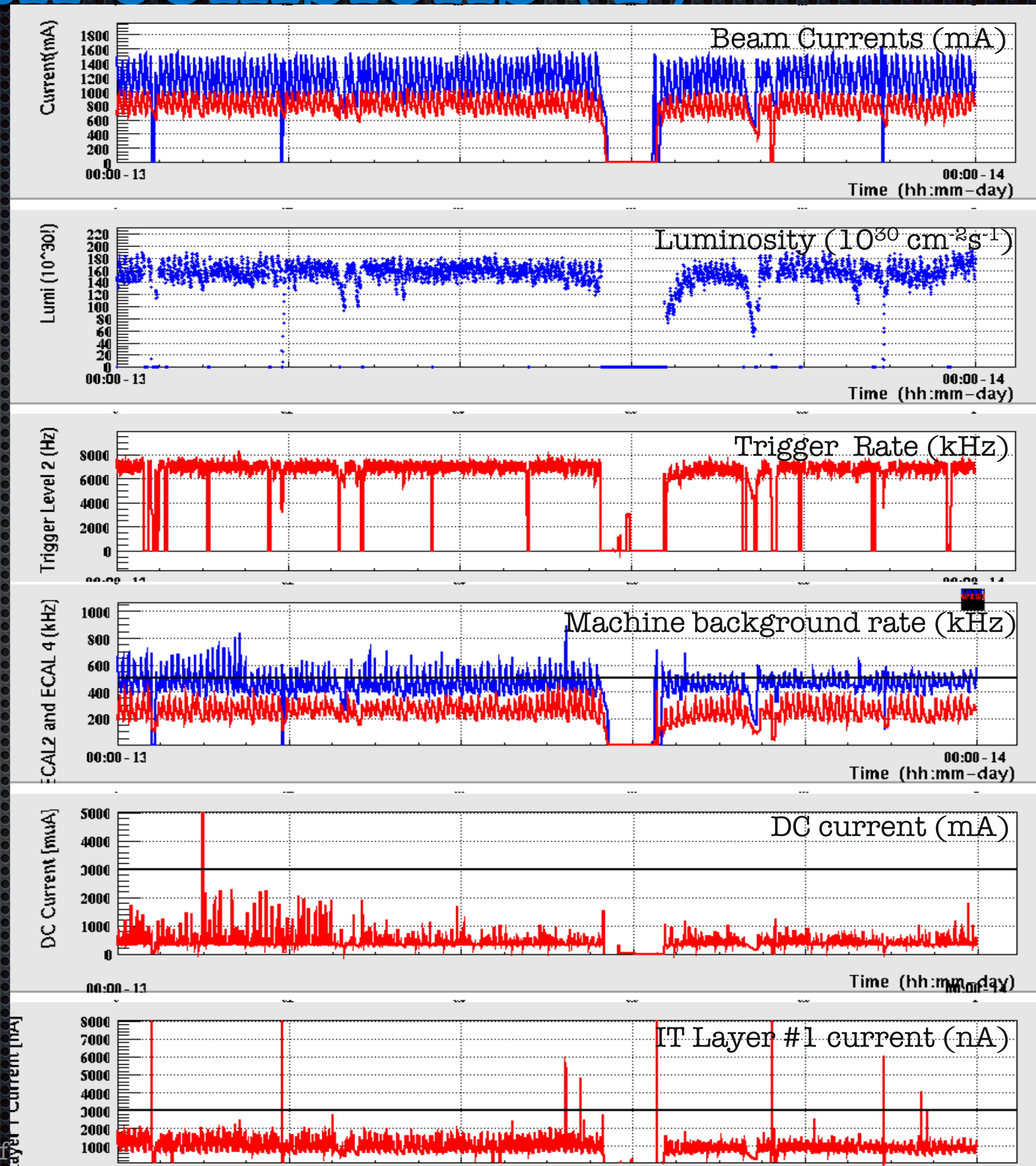
L2 Trigger rate
7 kHz

Important improvement in normal collision operation:
- injection optimization
- online feedback to DAFNE from 3 background limits

EMC EndCaps < 500 kHz

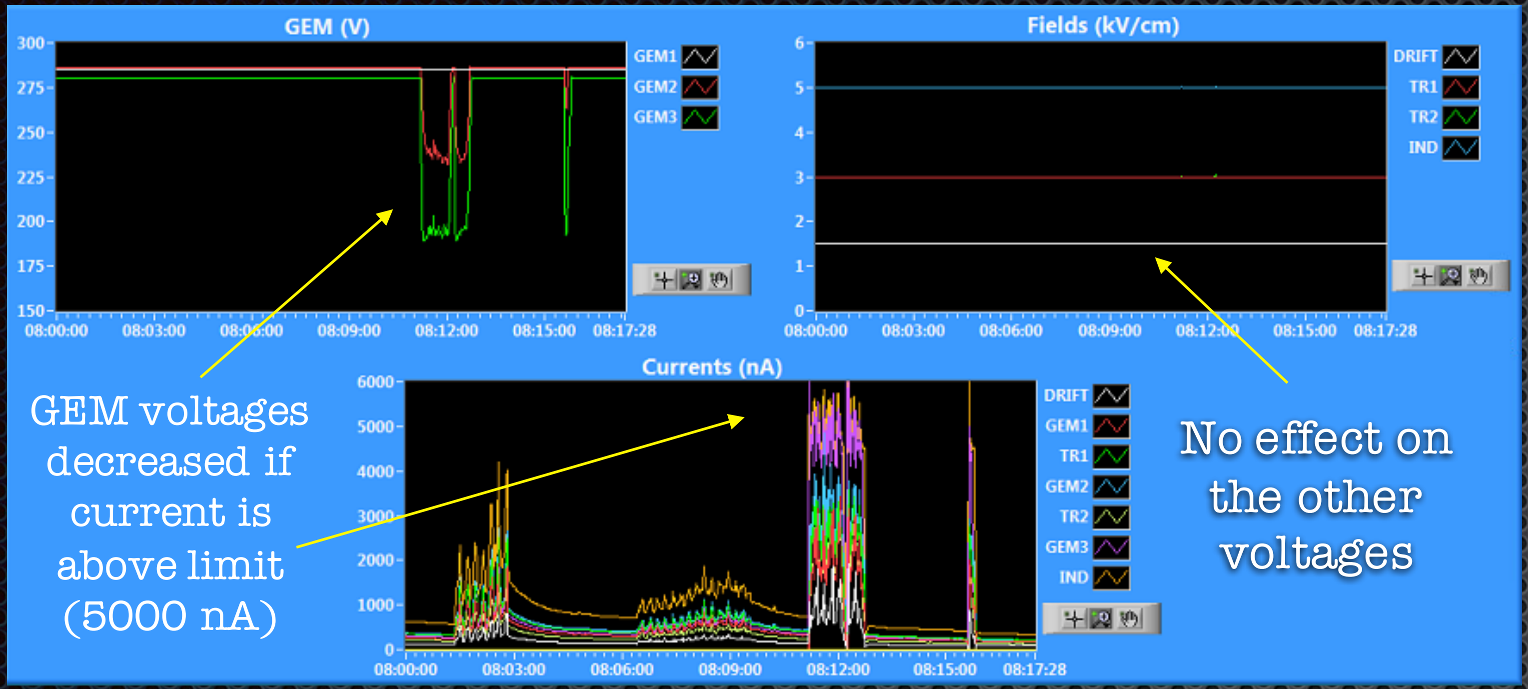
DC total current < 3000 μA

IT L1 current < 3000 nA



Operation with collisions (II)

- IT Online monitoring



Old HV scheme:
7 independent channels per layer
possible increase of discharge propagation among GEM stages when current saturates for one electrode

New HV scheme:
1 common channel for all layers with Dedicated CAEN Board successfully tested and installed in Sep 2016 on all layers for safer operation with collisions

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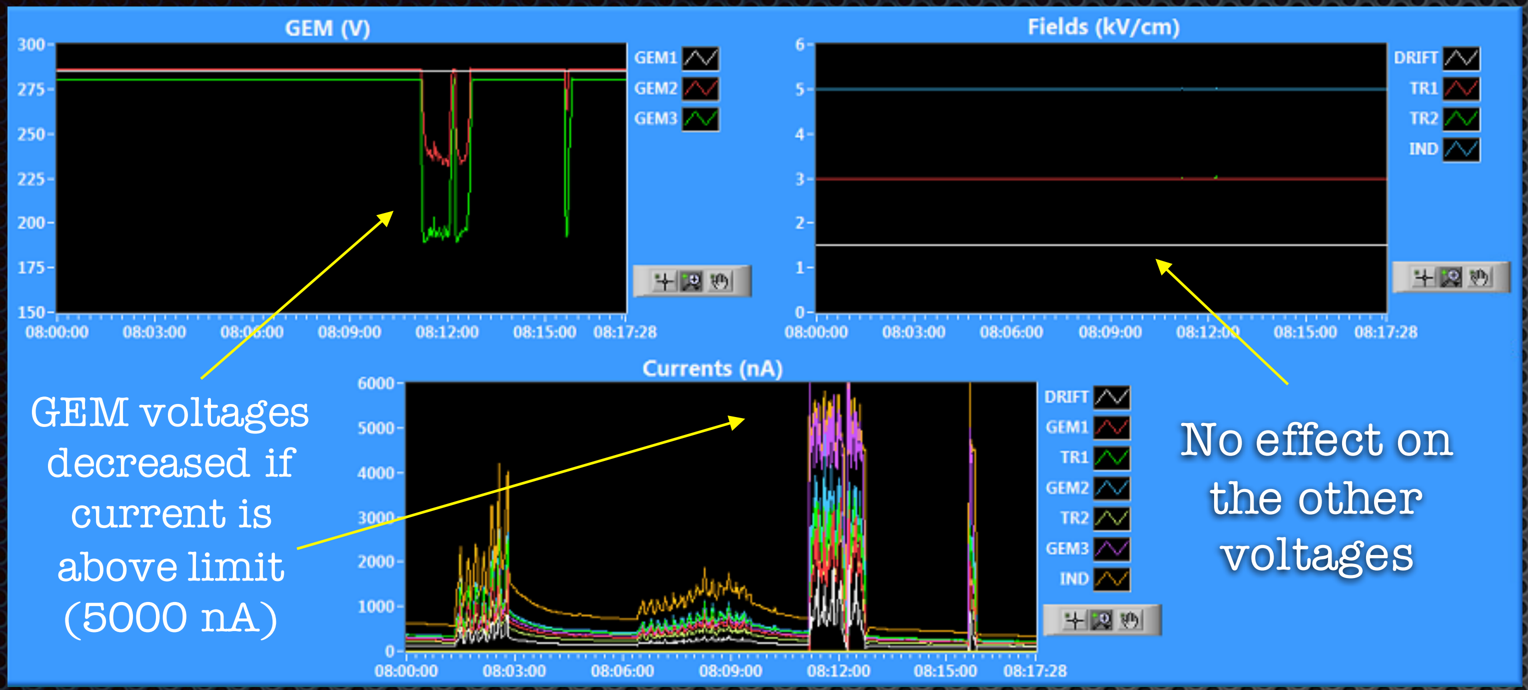


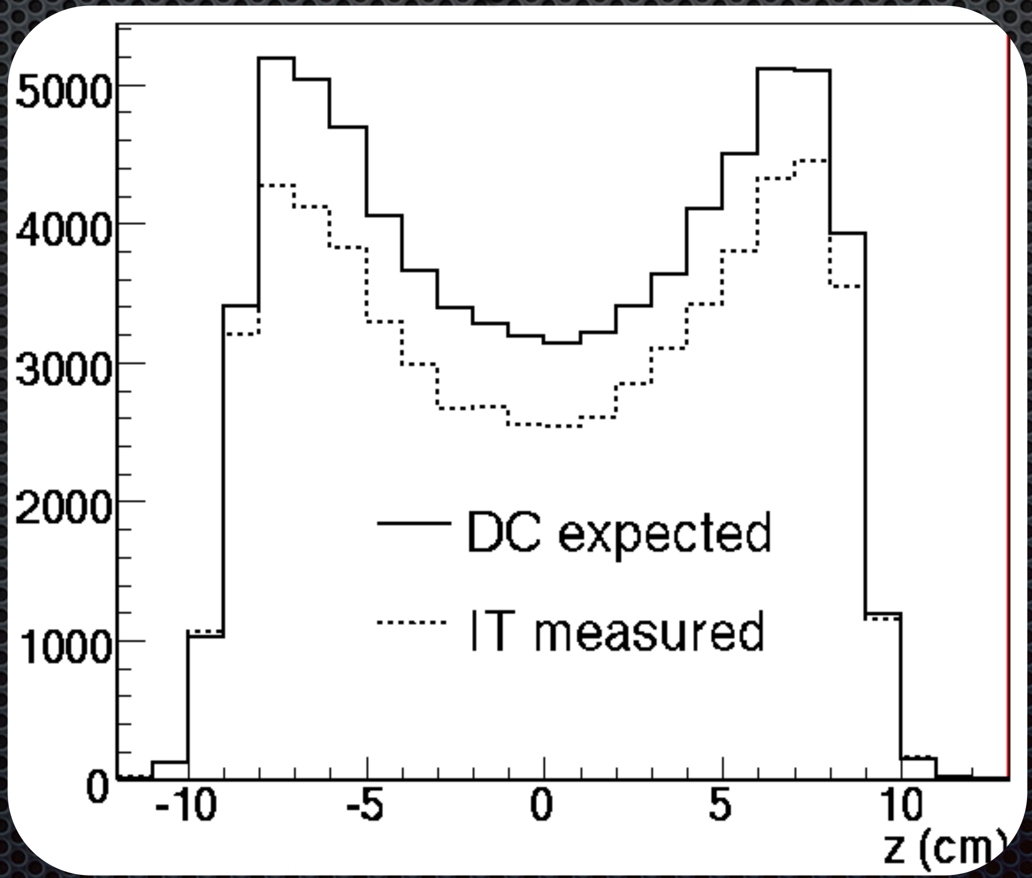
Old HV scheme:
7 independent channels per layer possible increase of discharge propagation among GEM stages when current saturates for one electrode

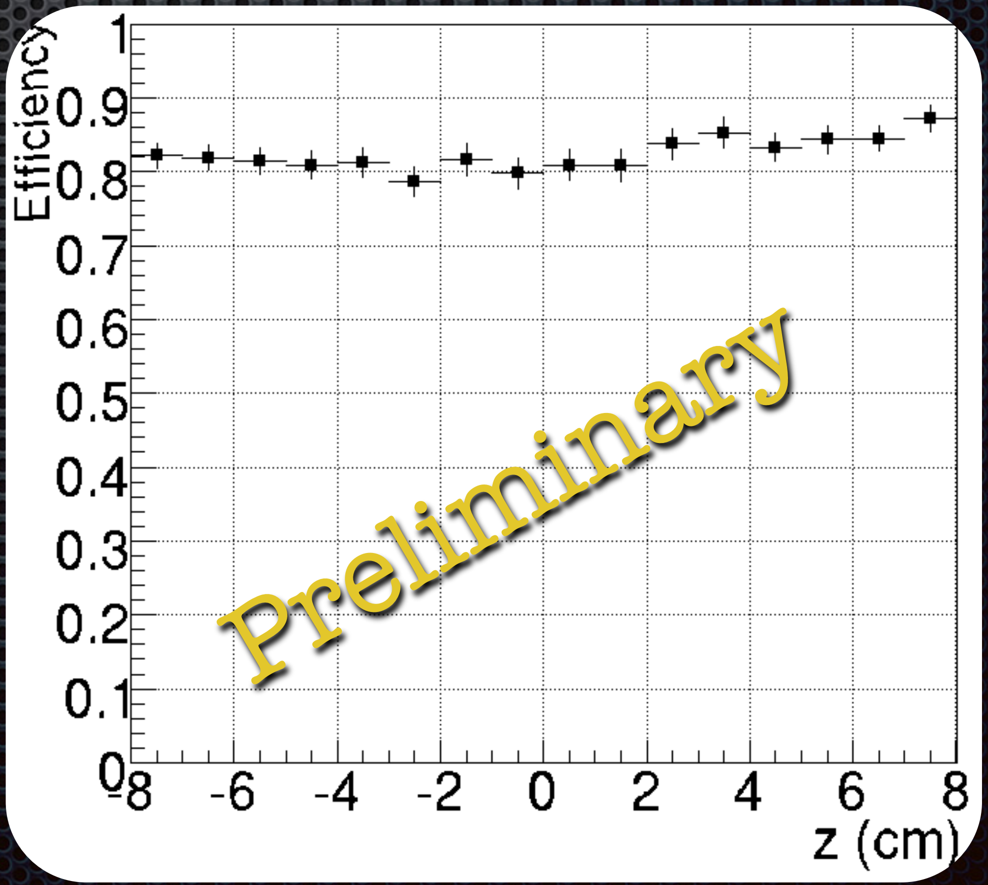
New HV scheme:
1 common channel for all layers with **Dedicated CAEN Board** successfully tested and installed in Sep 2016 on all layers for safer operation with collisions

- **Efficiency with Bhabha scattering events**

Selected using DC information:

- 2 tracks
- R_{PCA} < 5 cm & abs(z_{PCA}) < 5 cm
- p_T > 300 MeV





Align & Calibrate CGEM detector

Challenging. Never done before.

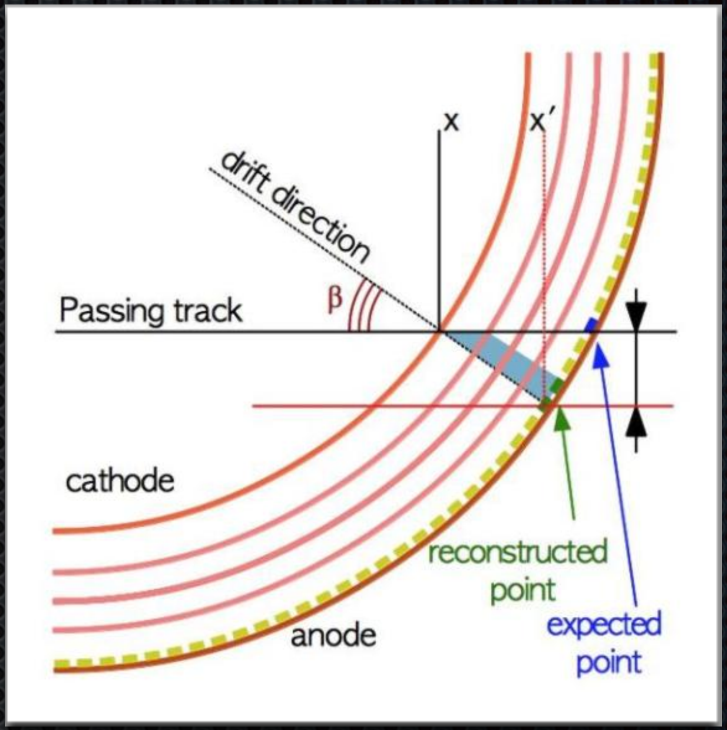
Detector Calibration strategy

1. NON-RADIAL TRACKS

The angle formed by a track and the radial E-field direction introduces: **shift & spread** of the e- cloud

2. MAGNETIC FIELD

0.52 T B-field orthogonal to Triple-GEMs E-fields: **shift** $\Delta x(\alpha_L)$ and **larger spread of the electron cloud**



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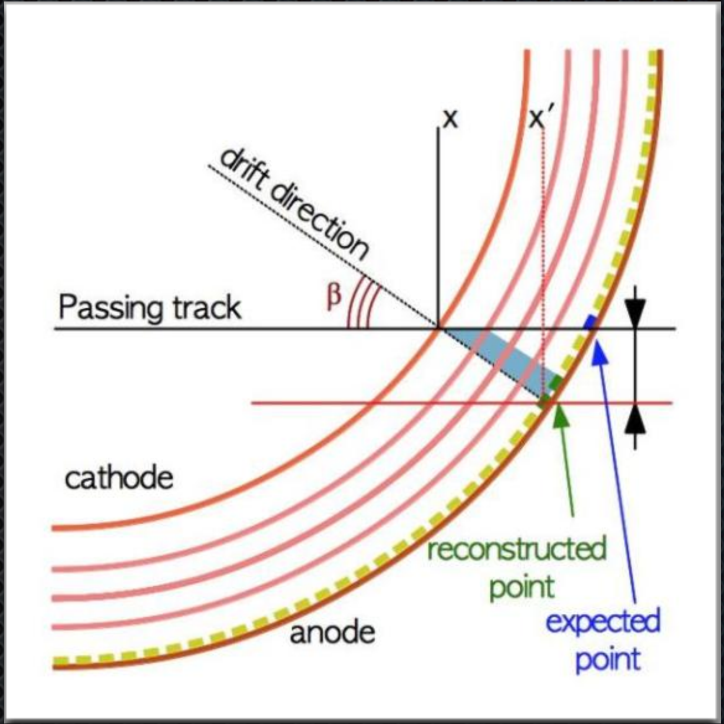
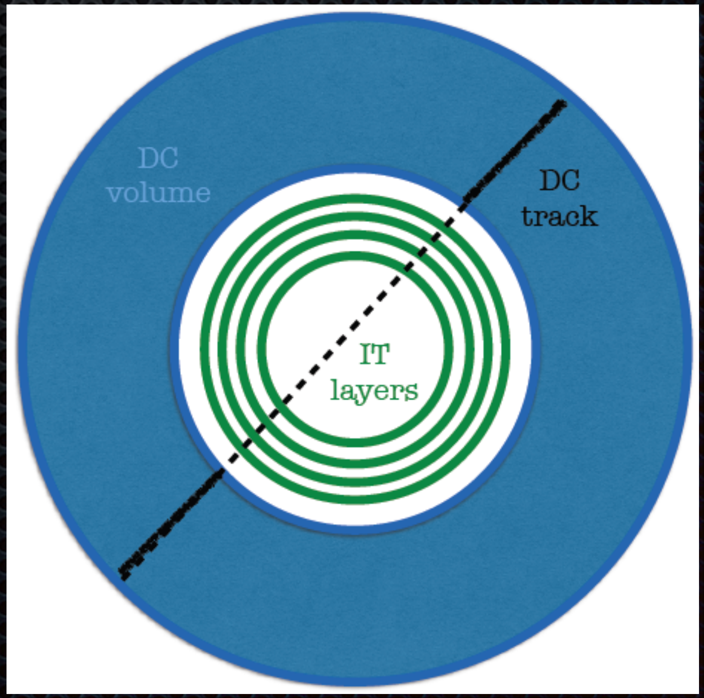


- Cosmic-ray muon data acquired with B-field OFF
  - Calibration of Non-radial track effect
  - Select DC tracks crossing IT at 2 points
  - Corrections as a function of track parameters
  - Shifts and rotations to align the IT



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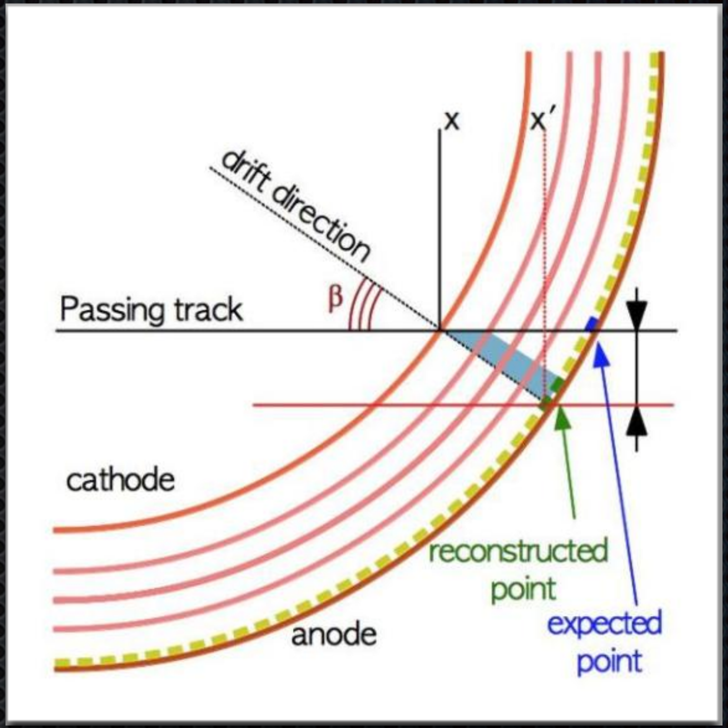
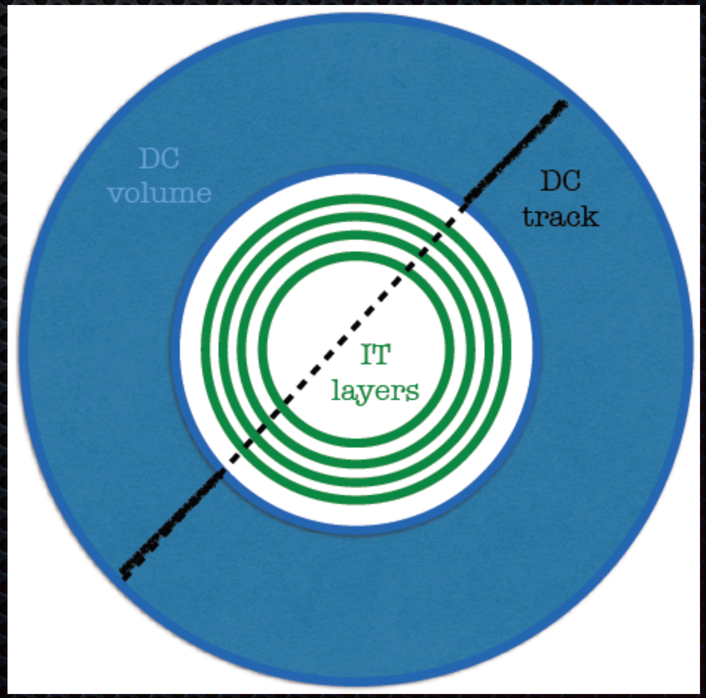


- Cosmic-ray muon data acquired with B-field OFF
  - Calibration of Non-radial track effect
  - Select DC tracks crossing IT at 2 points
  - Corrections as a function of track parameters
  - Shifts and rotations to align the IT

- Cosmic-ray muon data acquired with B-field ON
  - Calibration of Non-radial track & B-field effects
  - Corrections, Shifts and rotations from B-field OFF sample
  - Study and apply B-field effects corrections



Detector Calibration strategy

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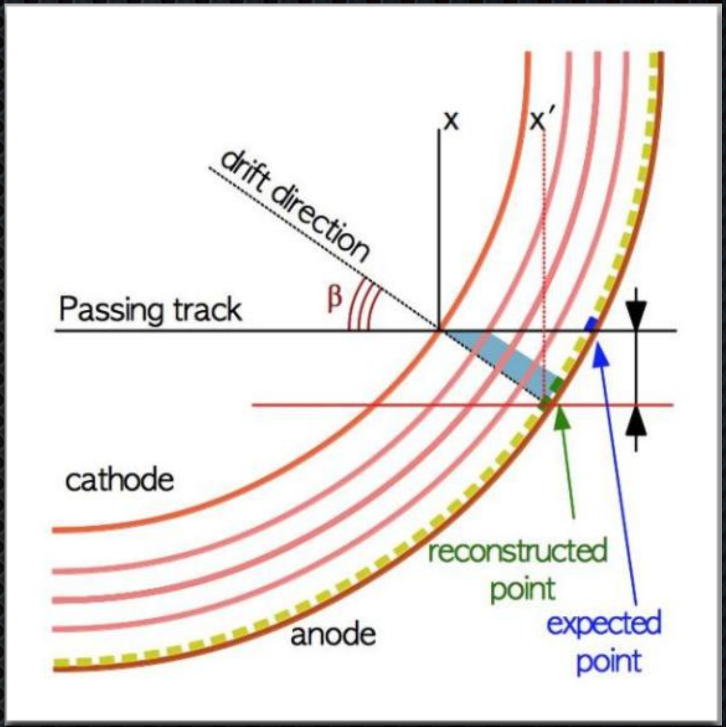
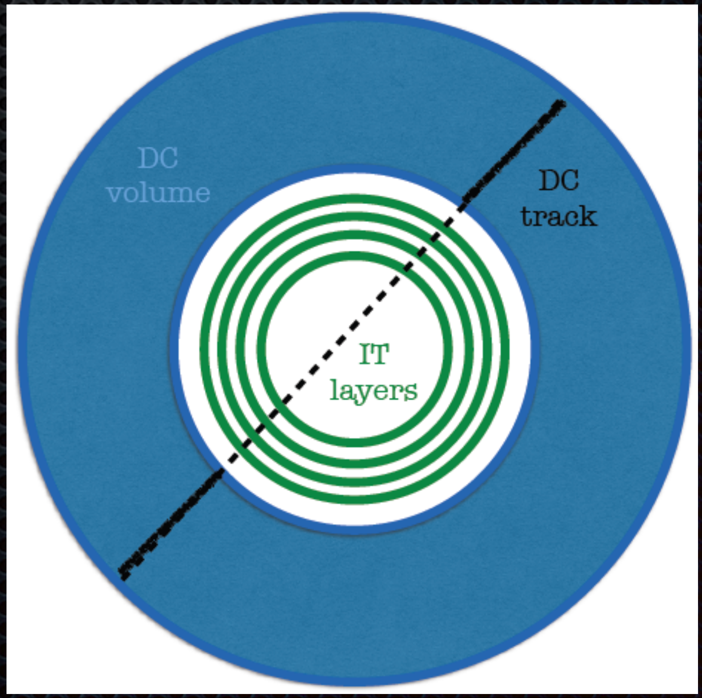


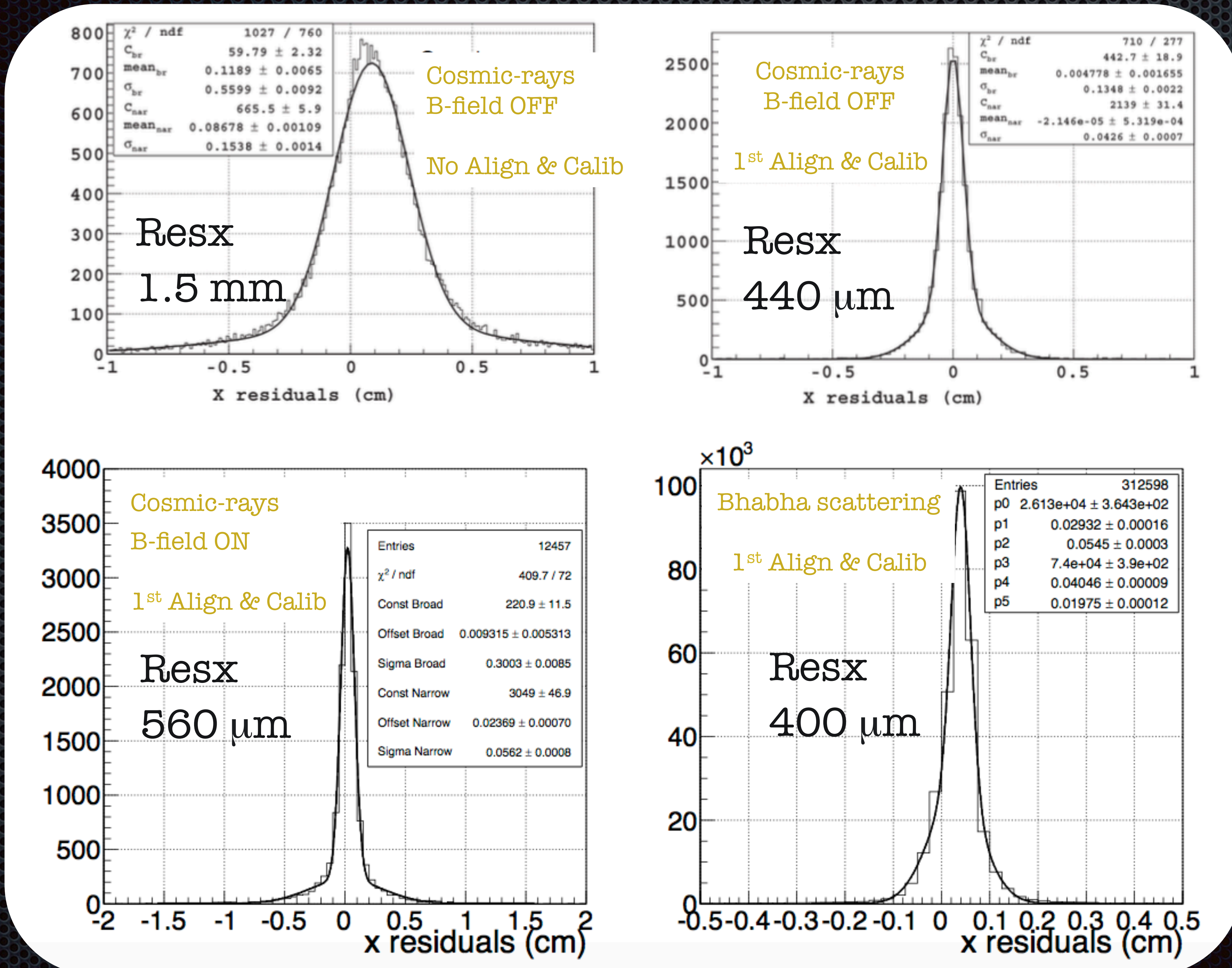
- Cosmic-ray muon data acquired with B-field OFF
  - Calibration of Non-radial track effect
  - Select DC tracks crossing IT at 2 points
  - Corrections as a function of track parameters
  - Shifts and rotations to align the IT



- Cosmic-ray muon data acquired with B-field ON
  - Calibration of Non-radial track & B-field effects
  - Corrections, Shifts and rotations from B-field OFF sample
  - Study and apply B-field effects corrections
- Bhabha scattering events
  - Check calibration of Non-radial track & B-field effects
  - Corrections , Shifts and rotations from cosmic-ray muons with B-field ON sample

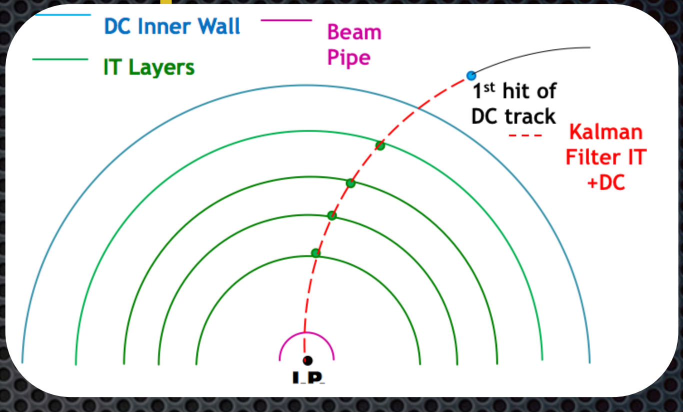
Detector Status: IT Calibration (II)

- Path to 1st Alignment & Calibration: Layer #4



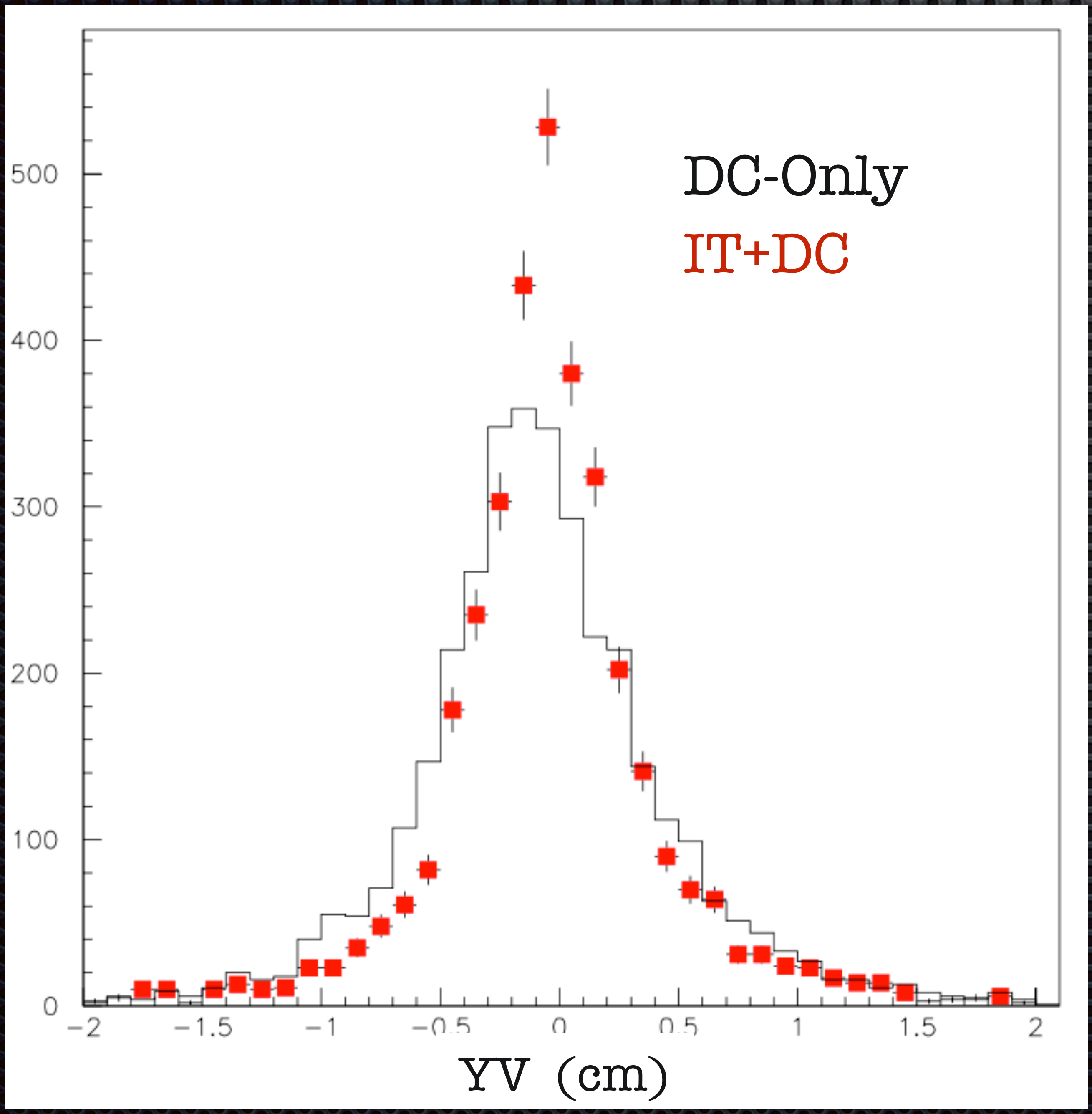
Tracking with IT+DC

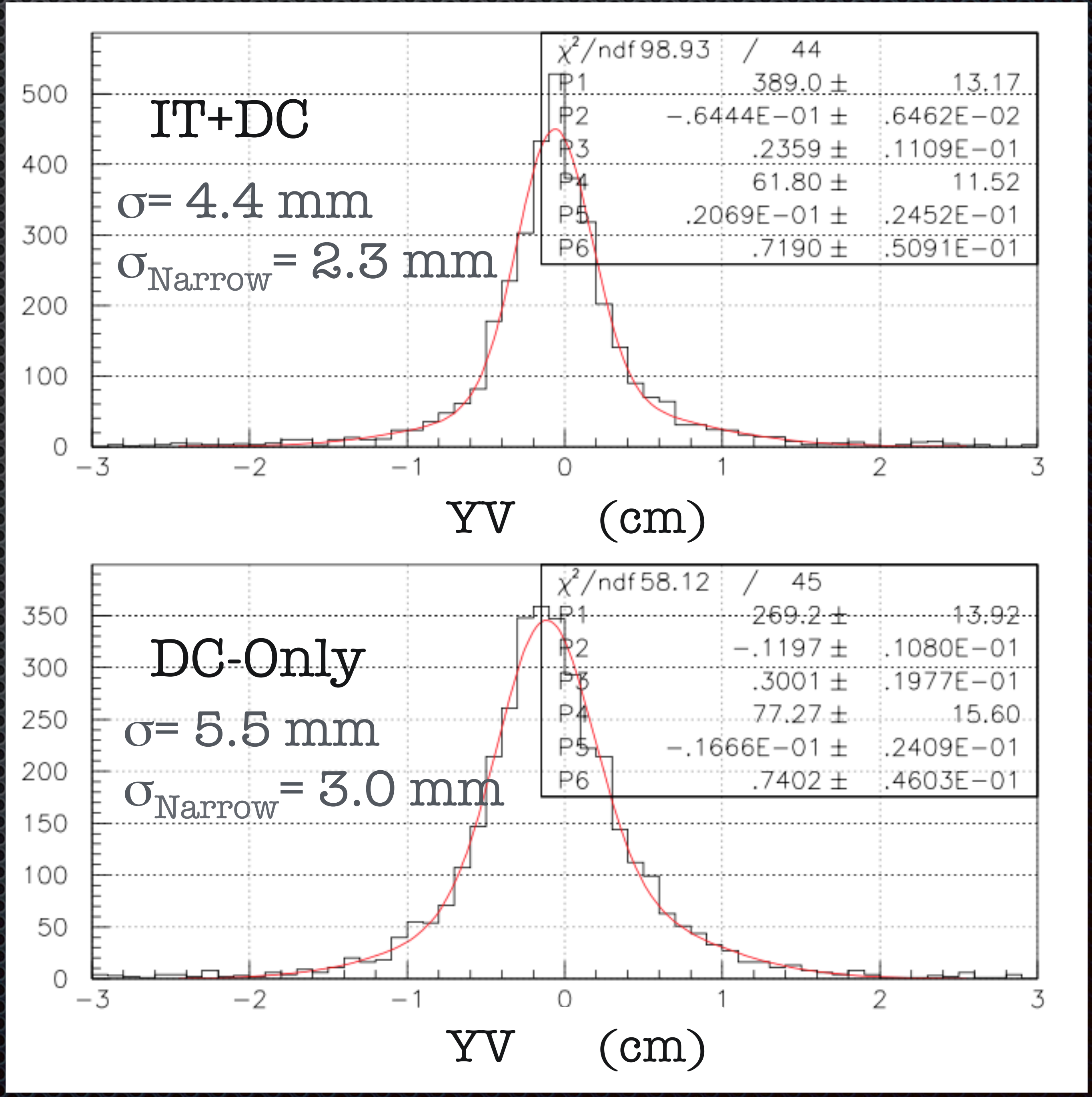
IT+DC Tracking & Vertex: $\phi \rightarrow \pi^+\pi^-\pi^0$



Vertex resolution figure of merit with decay at IP:

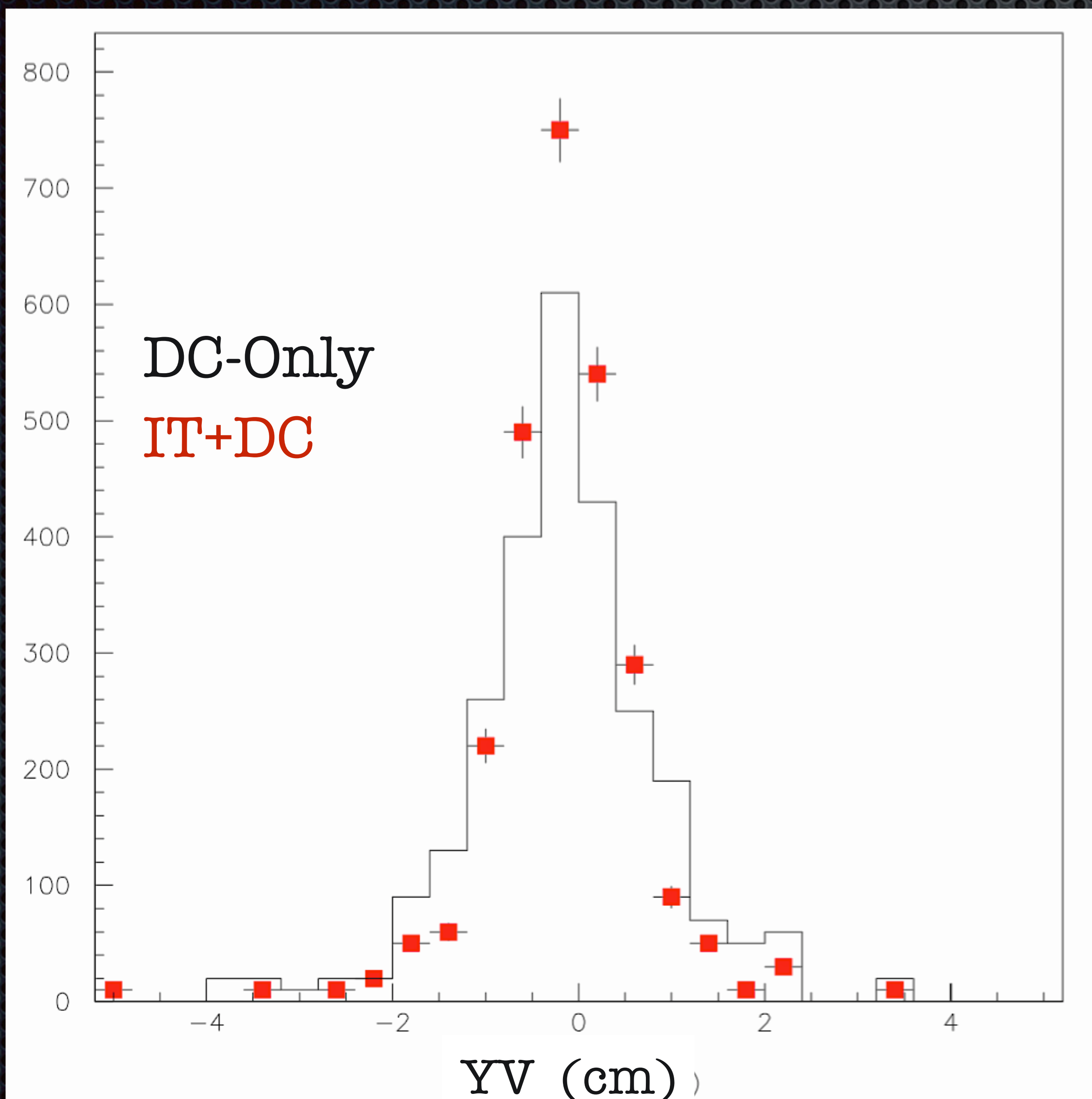
- 2 tracks from IP with $p_T > 100$ MeV
- YV negligible contribution from beam size (tens of μm)

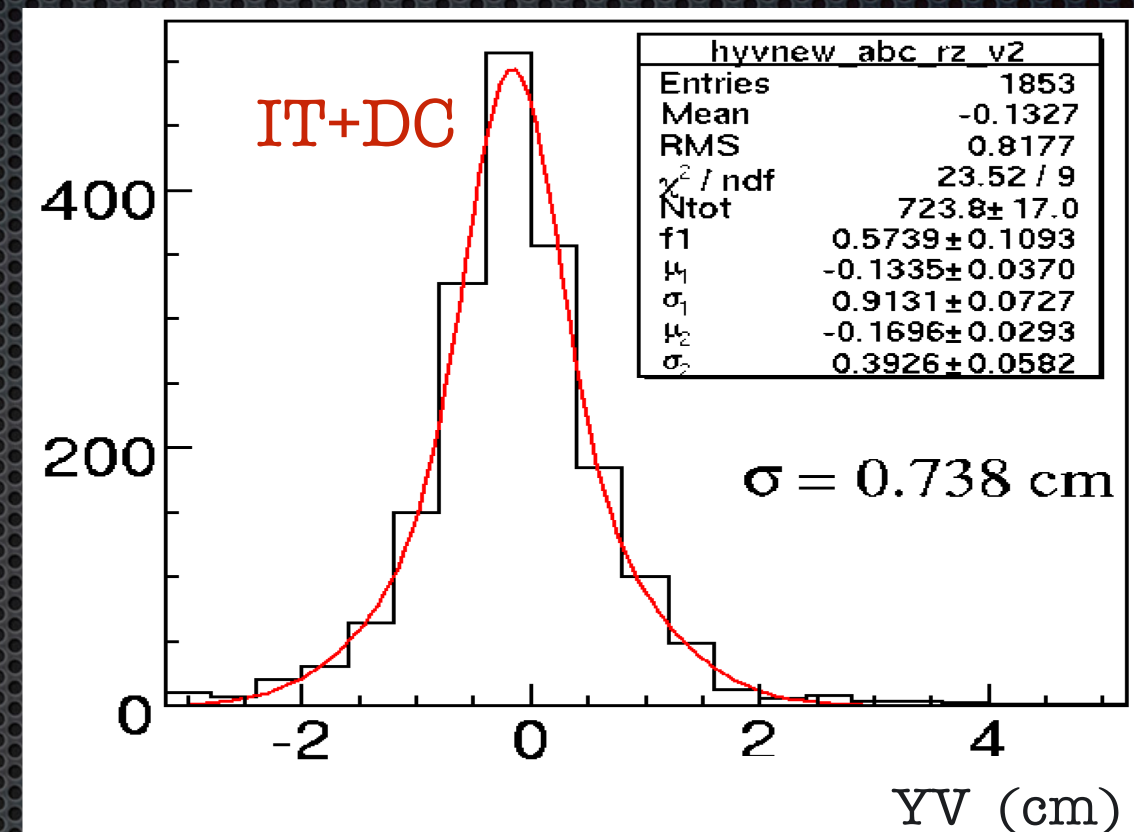


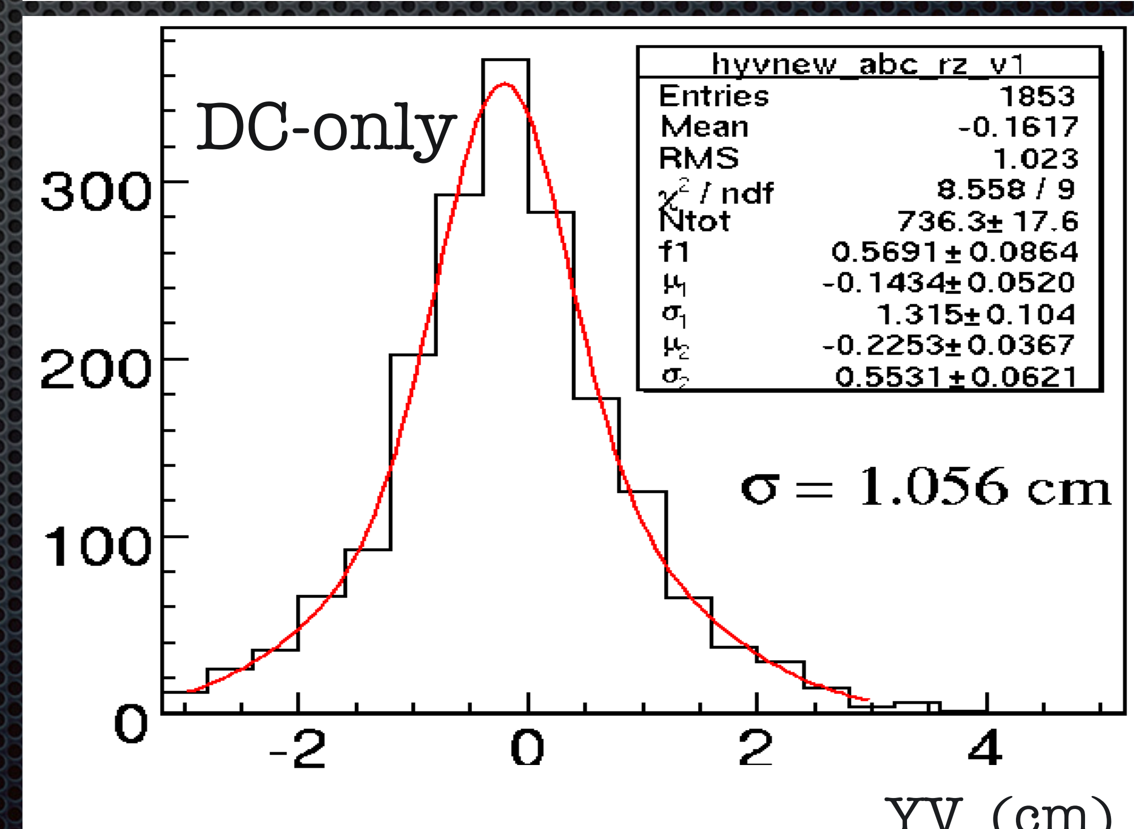


IT+DC Tracking & Vertex: Ks $\rightarrow \pi^+\pi^-$

- 2 tracks from IP with $p_T > 10$ MeV
- YV contributors: vtx resolution $\oplus$ Ks lifetime

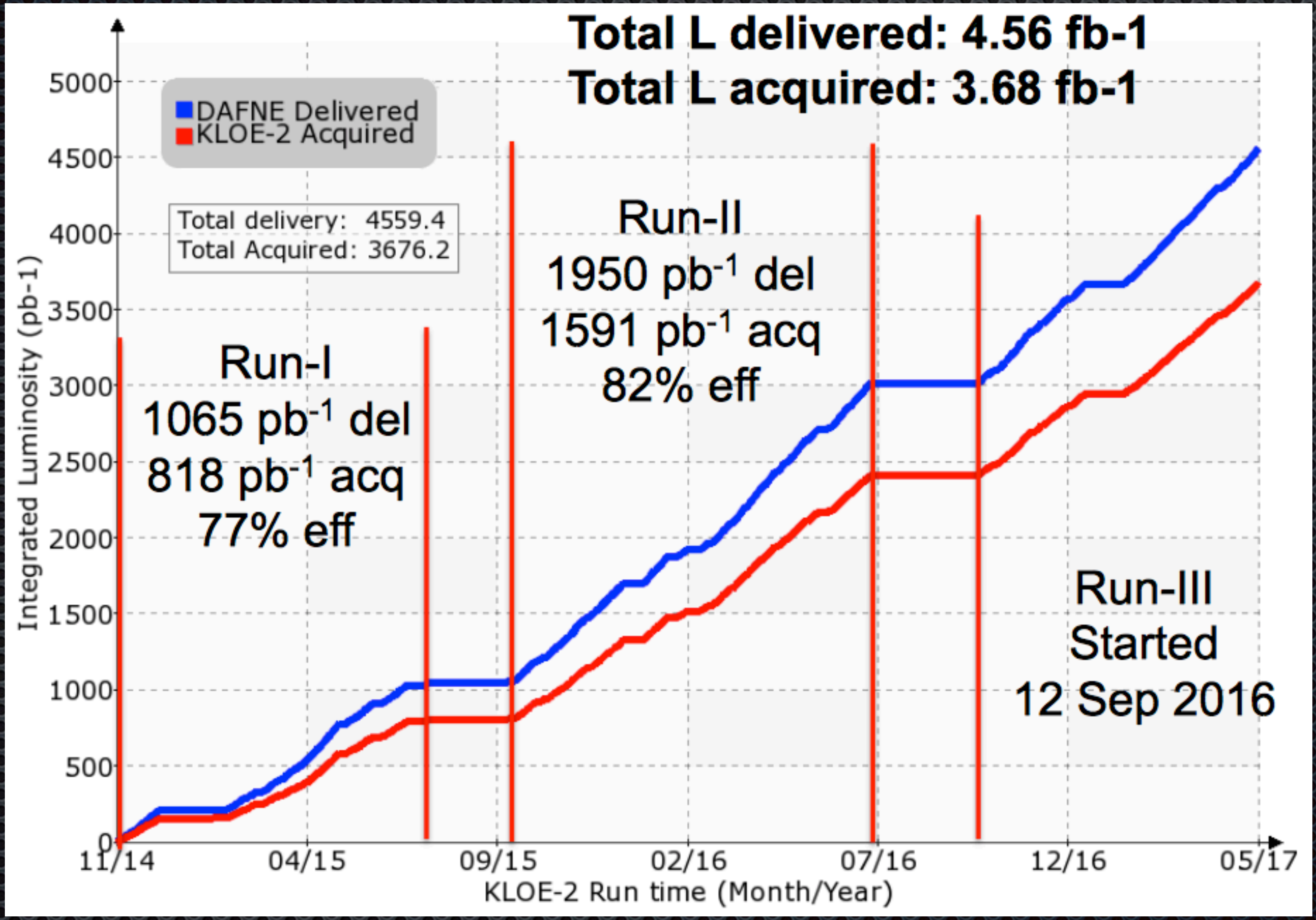






KLOE-2 Status & Plans

- KLOE-2 Run started in November 2014
  Daily record : 13 (11.0) pb^{-1} delivered (acquired)
  Peak Luminosity: $2.2x10^{32}$ cm^{-2} s^{-1}
- KLOE-2 Target >= 5 fb^{-1} acquired Luminosity by end of March 2018



- Intermediate L Milestone additional 2 fb^{-1} delivered L by July 2017

KLOE-2 Physics updated wrt EPJC (2010) 68, 619

KAON Physics:

- CPT and QM tests with kaon interferometry
- Direct T and CPT tests using entanglement
- CP violation and CPT test:
  $K_S \to 3\pi^0$
  direct measurement of $Im(\varepsilon'/\varepsilon)$ (lattice calc. improved)
- CKM Vus:
  K_S semileptonic decays and A_S (also CP and CPT test)
  $K\mu3$ form factors
- χpT : $K_S \to \gamma\gamma$
- Search for rare K_S decays

Dark forces:

- Improve limits on:
  $U\gamma$ associate production
  $e^+e^- \to U\gamma \to \pi\pi\gamma, \mu\mu\gamma$
- Higgstrahlung
  $e^+e^- \to Uh' \to \mu^+\mu^- +$ miss. E
- Leptophobic B boson search
  $\phi \to \eta B$, $B \to \pi^0\gamma$, $\eta \to \gamma\gamma$
  $\eta \to B\gamma$, $B \to \pi^0\gamma$, $\eta \to \pi^0\gamma\gamma$
- Search for U invisible decays

Hadronic cross section

- Measurement of a_μ^{HLO} in the space-like region using Bhabha process
- ISR studies with 3π, 4π final states
- F_π with increased statistics

Light meson Physics:

- η decays, ω decays, TFF $\phi \to \eta e^+e^-$
- C,P,CP violation:
  improve limits on $\eta \to \gamma\gamma\gamma$, $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^0\pi^0\gamma$
- improve $\eta \to \pi^+\pi^- e^+e^-$ (non-CKM CP viol.)
- χpT : $\eta \to \pi^0\gamma\gamma$
- Light scalar mesons: $\phi \to K_S K_S \gamma$ (1st obs?)
- $\gamma\gamma$ Physics: $\gamma\gamma \to \pi^0$ and π^0 TFF
- light-by-light scattering
- axion-like particles

Conclusions

◎ The KLOE detector has been upgraded with several new sub-detectors for the new data taking campaign within the KLOE-2 project started on Nov 2014

◎ $\int Ldt = 3.7\ fb^{-1}$ acquired

◎ The goal is to acquire at least $\int Ldt = 5\ fb^{-1}$ by the end of March 2018

◎ KLOE-2 experiment is fully operational and its new detectors are being successfully commissioned

◎ KLOE-2 Inner Tracker is the First CGEM detector used in high-energy physics experiment

◎ 1^{st} Detector Alignment and calibration performed
Challenging. Never done before.

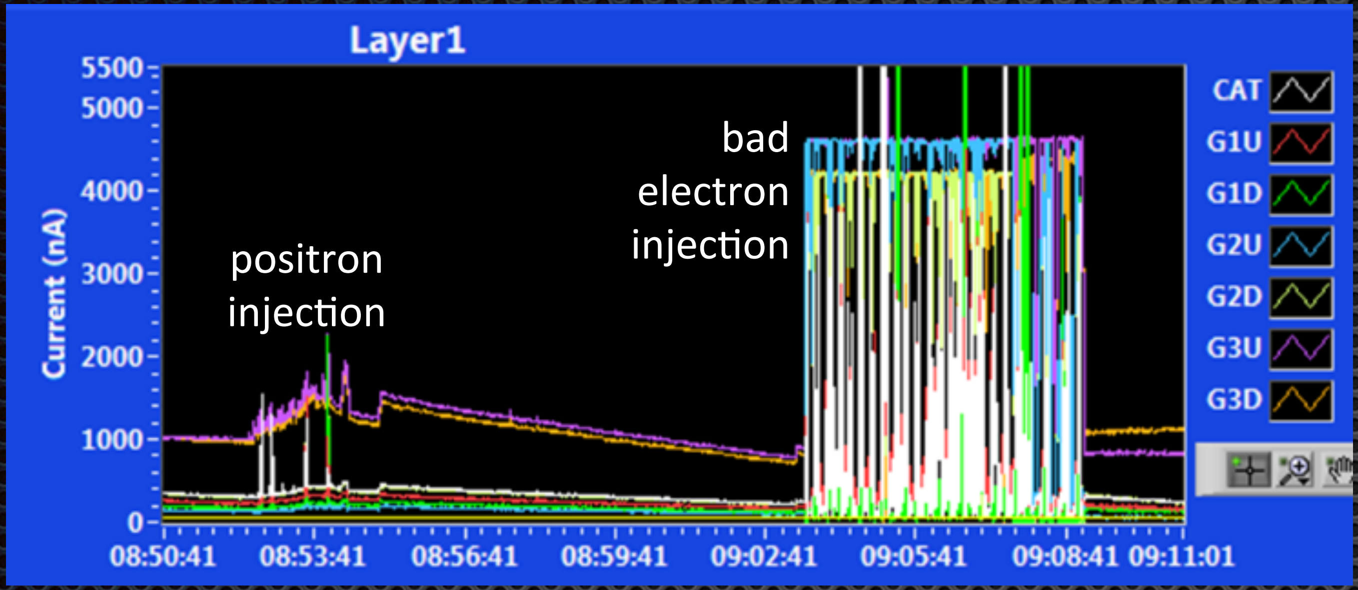
◎ Results from IT+DC integrated tracking and vertexing using 1^{st} align & Calib parameters with $\phi\to\pi^+\pi^-\pi^0$ and $K_S\to\pi^+\pi^-$ samples are good and will improve with refined alignment and calibration we are presently working on

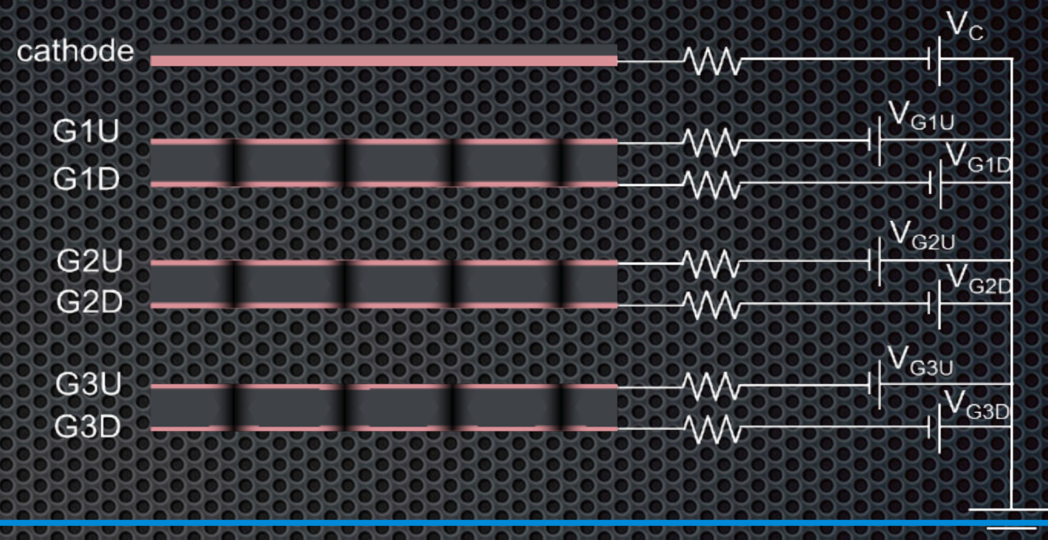
Spare Slides

Operation with collisions (I)

Run-I HV scheme

- 7 independent channels referred to ground
- Current limit only to top GEM faces
- Software common trip





IT current saturation with e- injection decrese of V_{top} and increase of fields w possible propagation of discharge between GEM stages

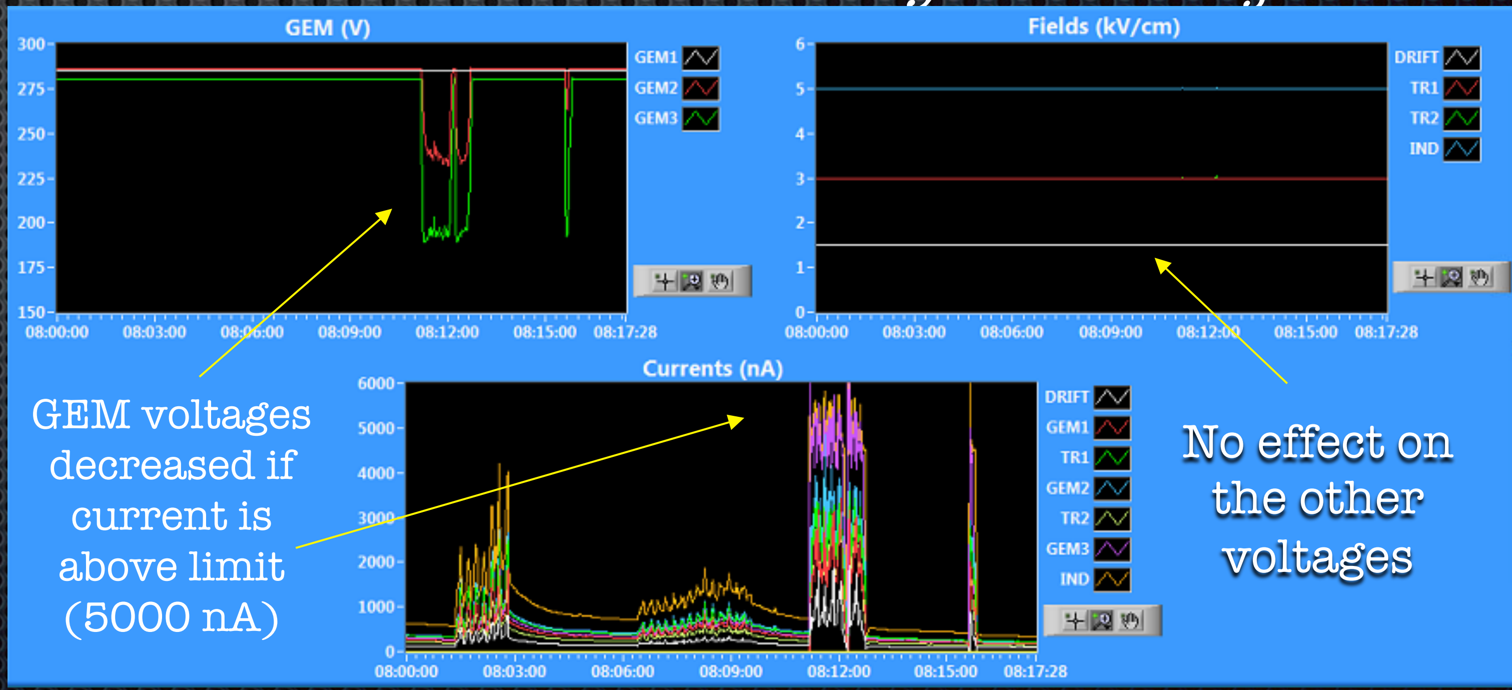
Run-II HV scheme (Oct '15)

- single current generator channel
- passive voltage divider

Dedicated CAEN Board

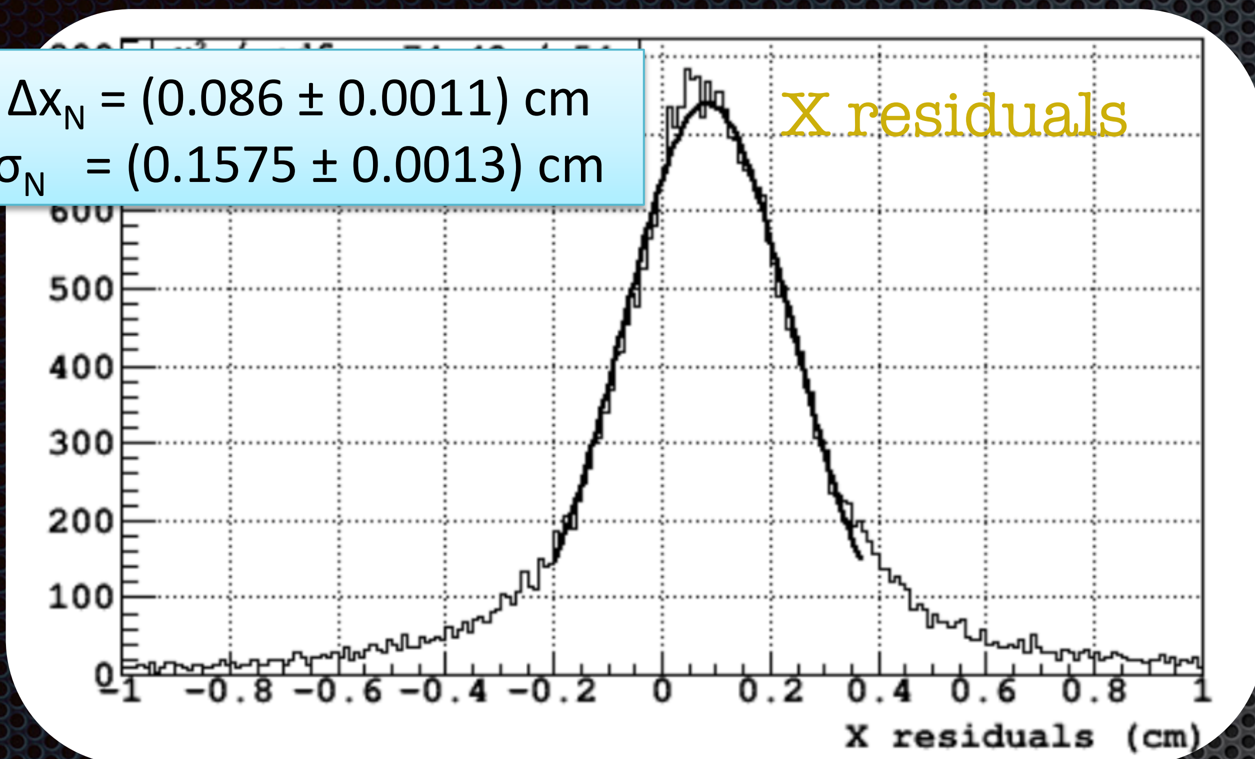
- Individual floating channels system allows safe operation & single voltages adjustment
- 1 board borrowed from CAEN succesfully tested on Layer3 since November 2015
- All 4 layers instrumented (Sep '16)

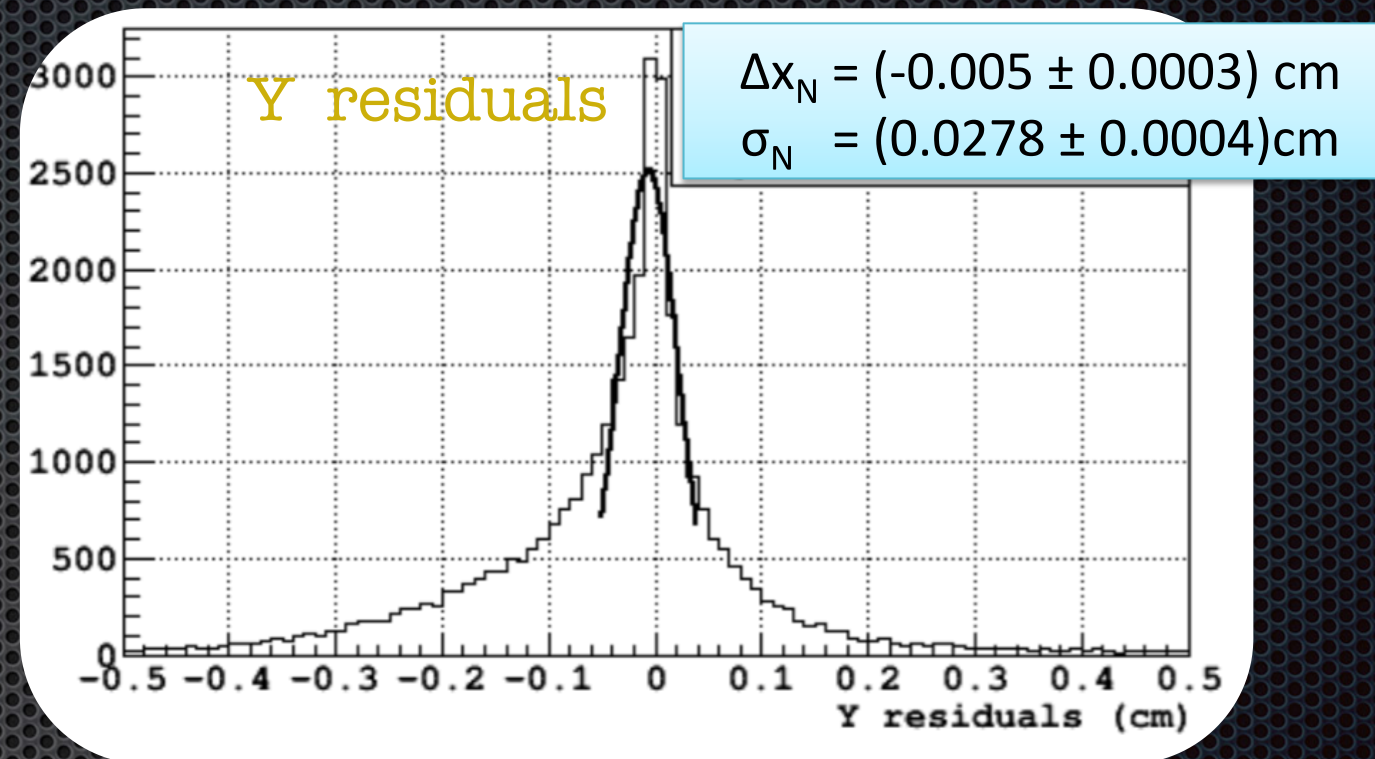
HV CAEN A1515CG on Layer #3 w injections



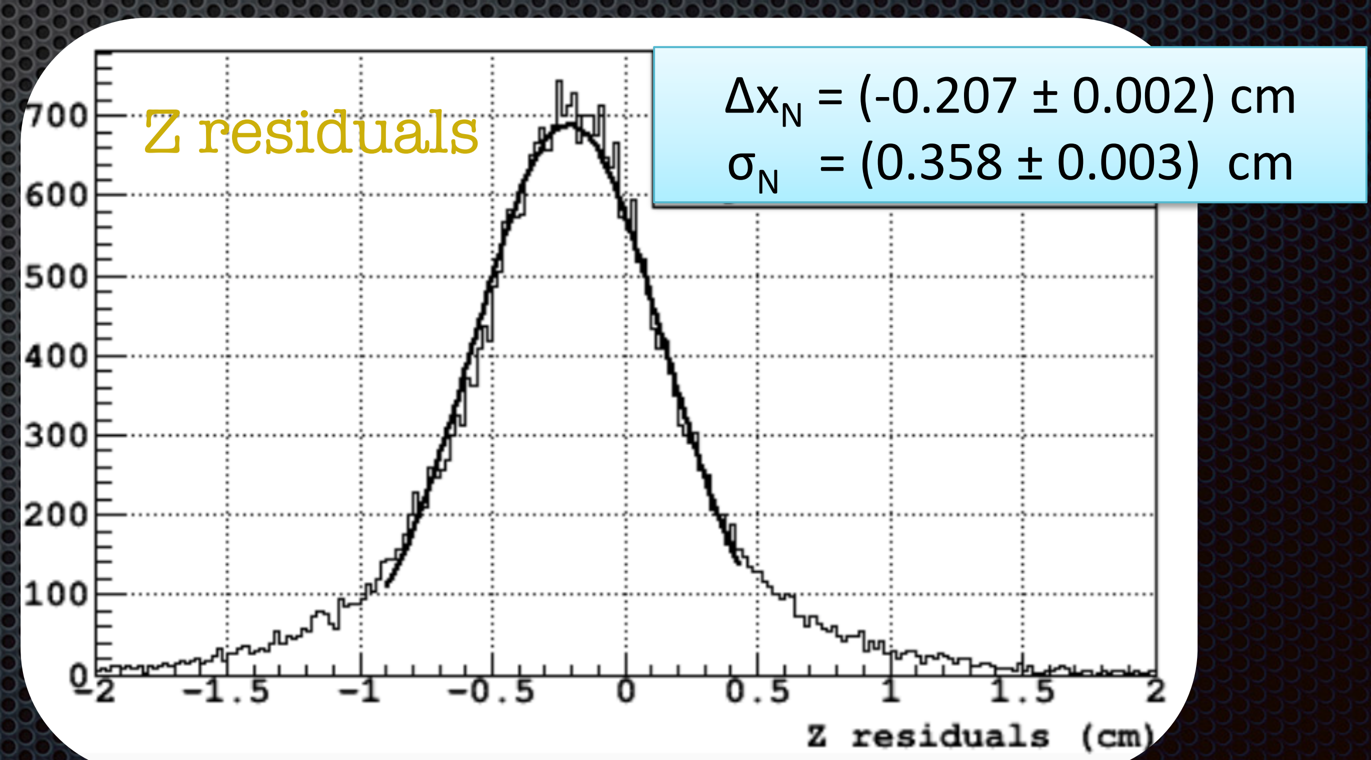
Starting point: Layer #4 residuals

Cosmic-ray muons with B OFF





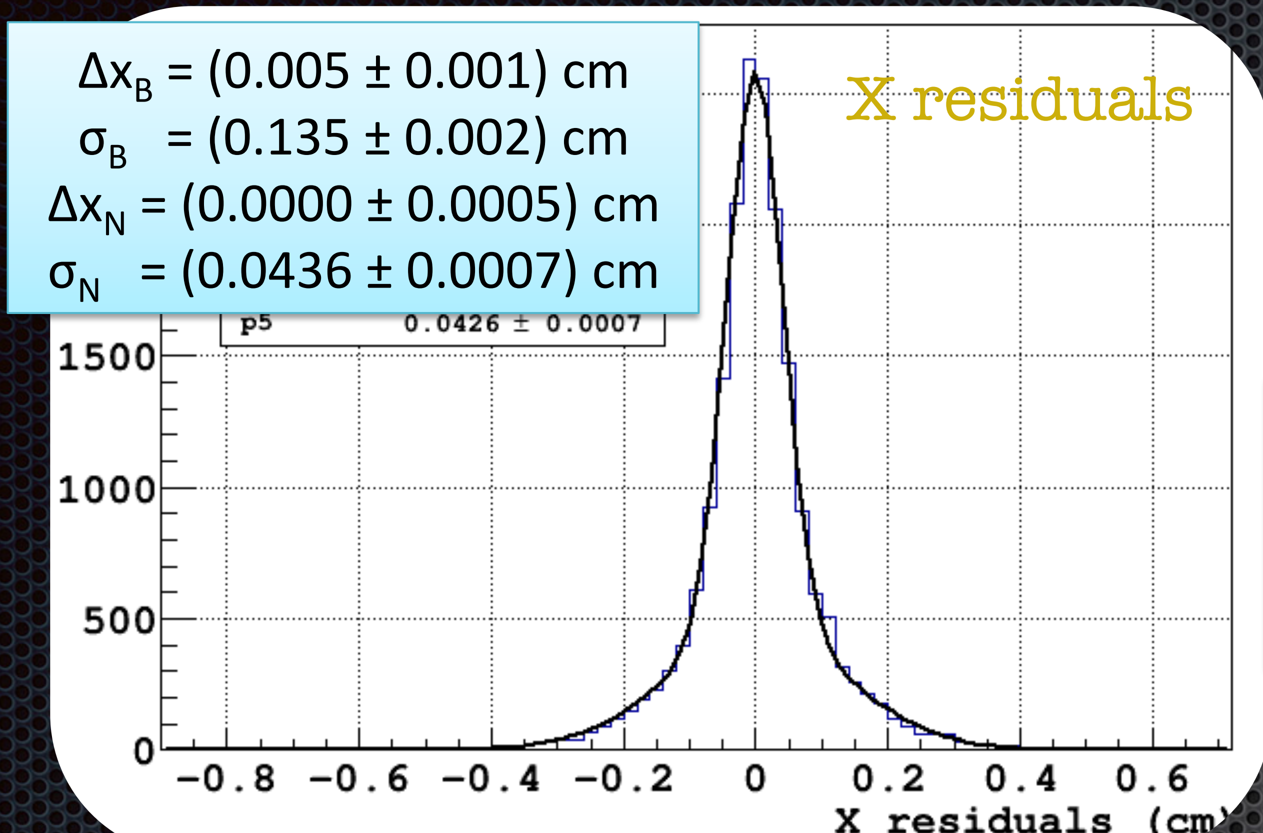
- Starting point before align & calib
  - Resx = 1.5 mm
  - Resy = 280 μm
  - Resz = 3.6 mm
  - Δx = 860 μm
  - Δy = - 50 μm
  - Δz = 2 mm

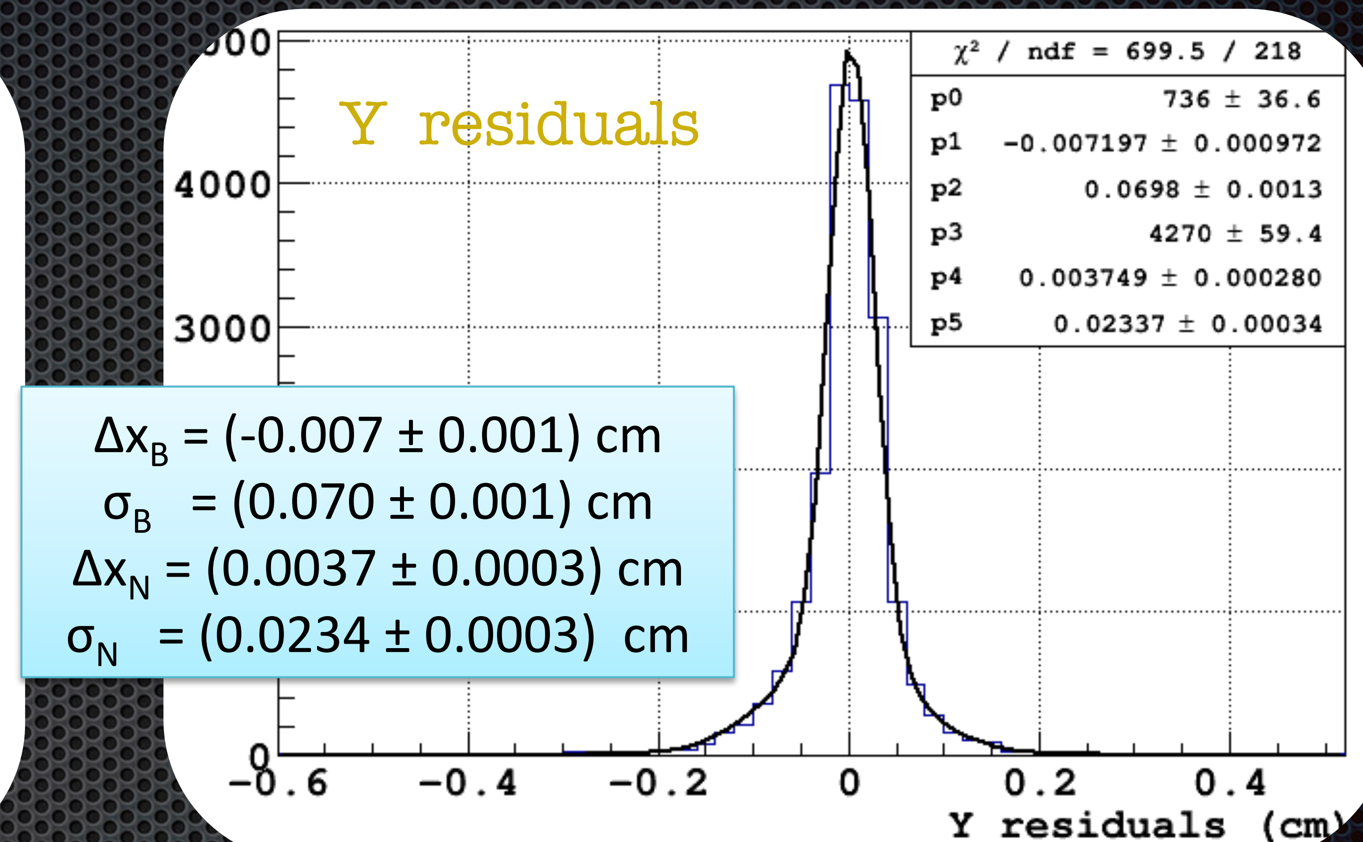


Convolution of DC + IT resolution

Detector Status: IT Calibration (I)

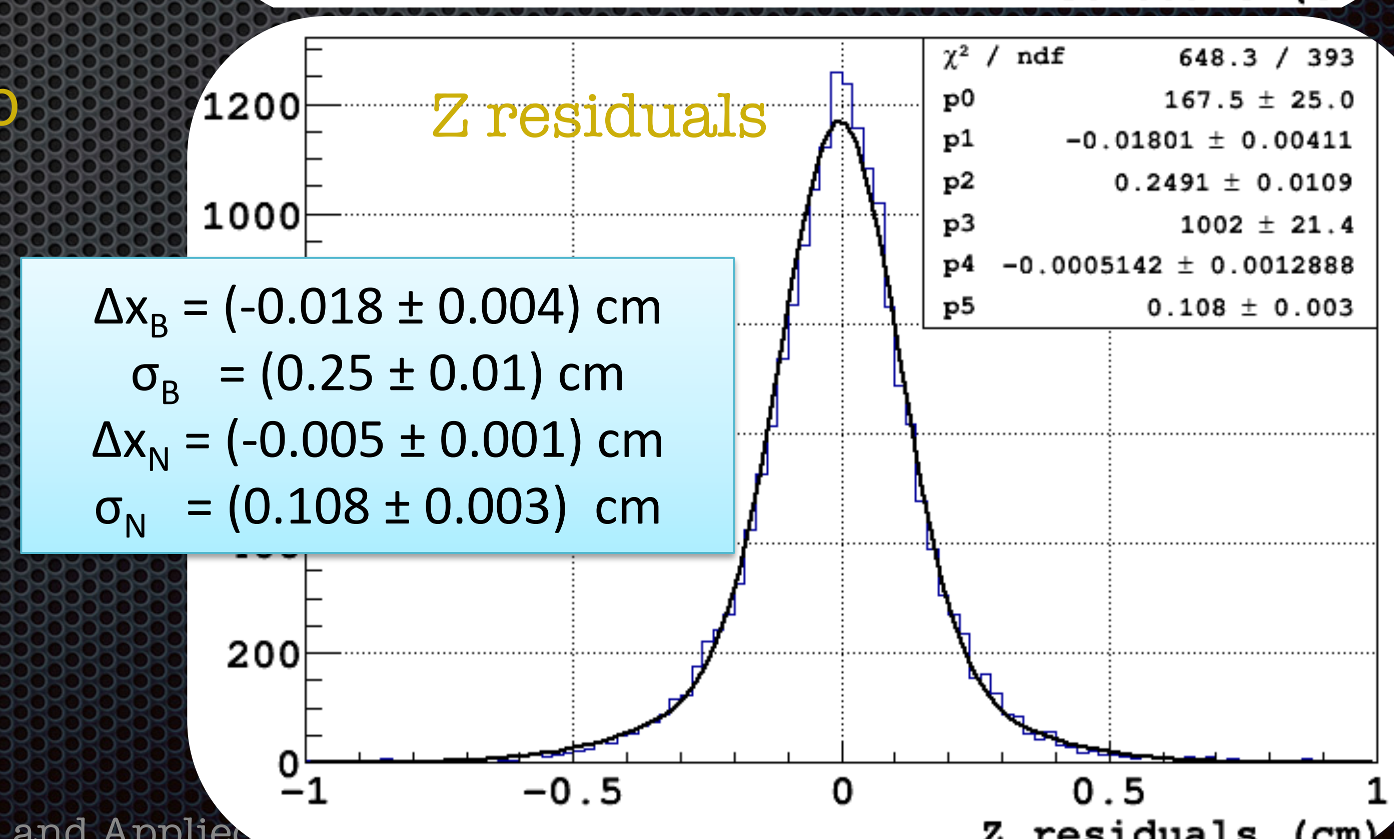
- Layer #4 residuals: 1st align & calib using cosmic-ray muons with B OFF





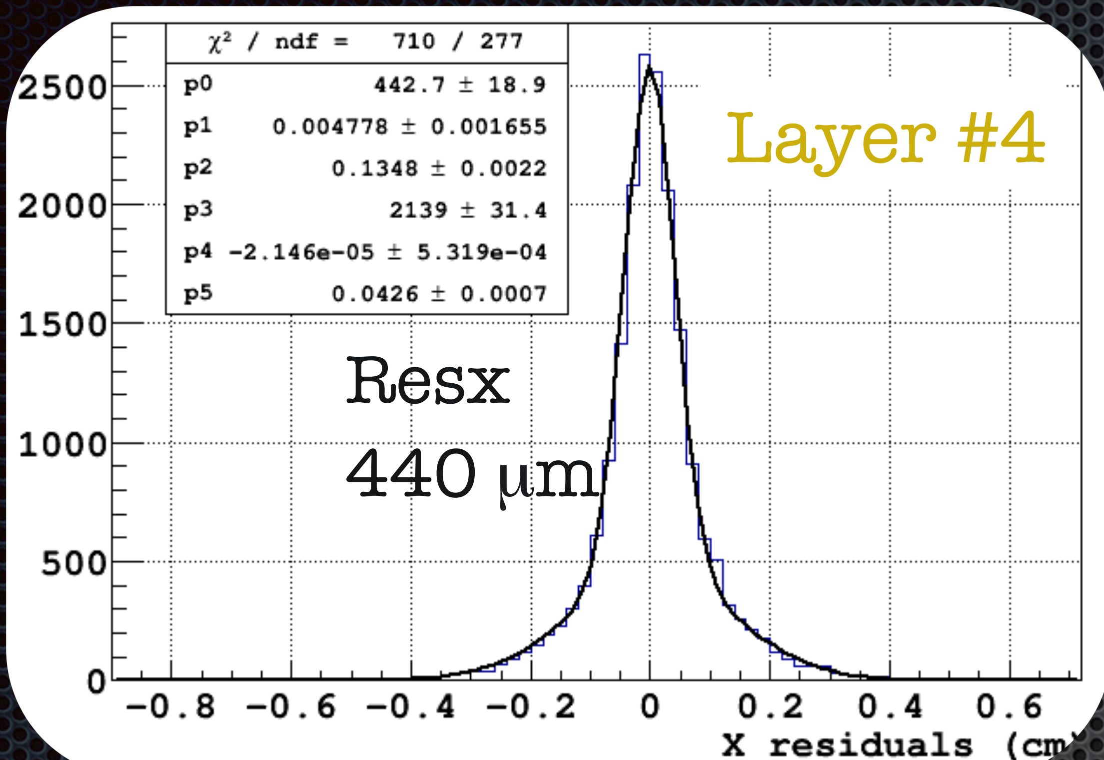
- Improvement with 1st align & calib
  - Resx = 1.5 mm => 440 μm
  - Resy = 280 μm => 240 μm
  - Resz = 3.6 mm => 1.1 mm
  - Δx = 860 μm => 50 μm
  - Δy = - 50 μm => -50 μm
  - Δz = 2 mm => 5 μm

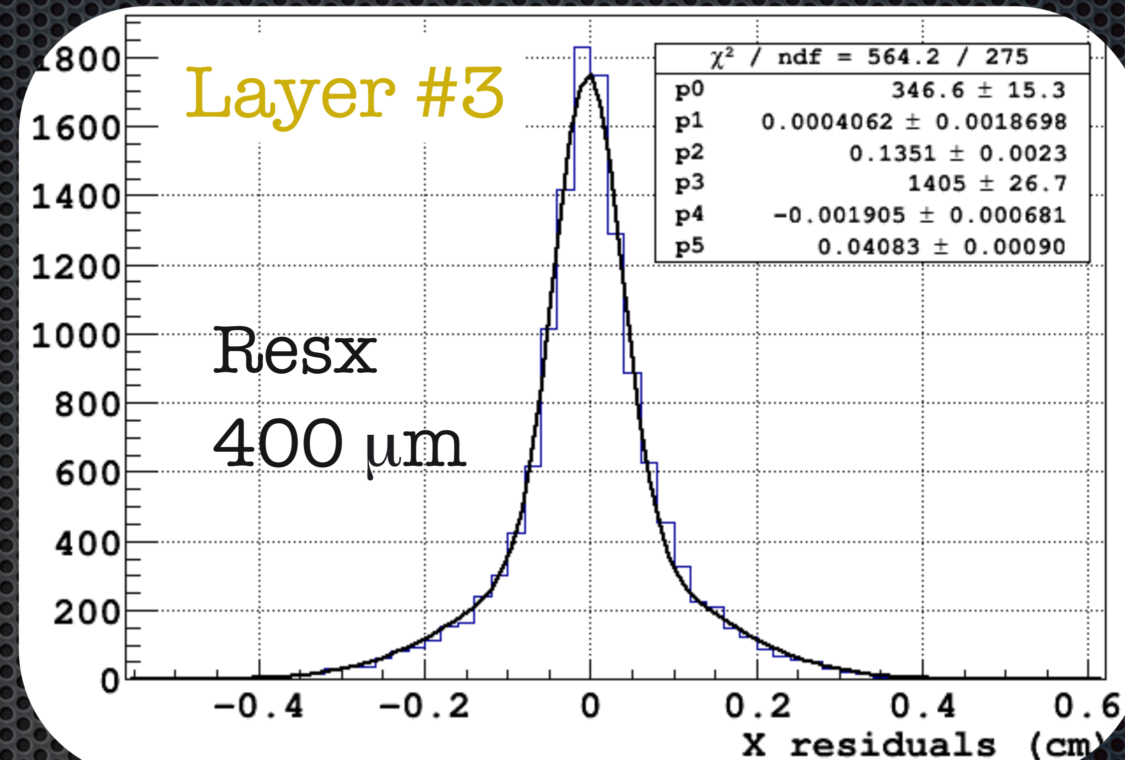
Convolution of DC + IT resolution

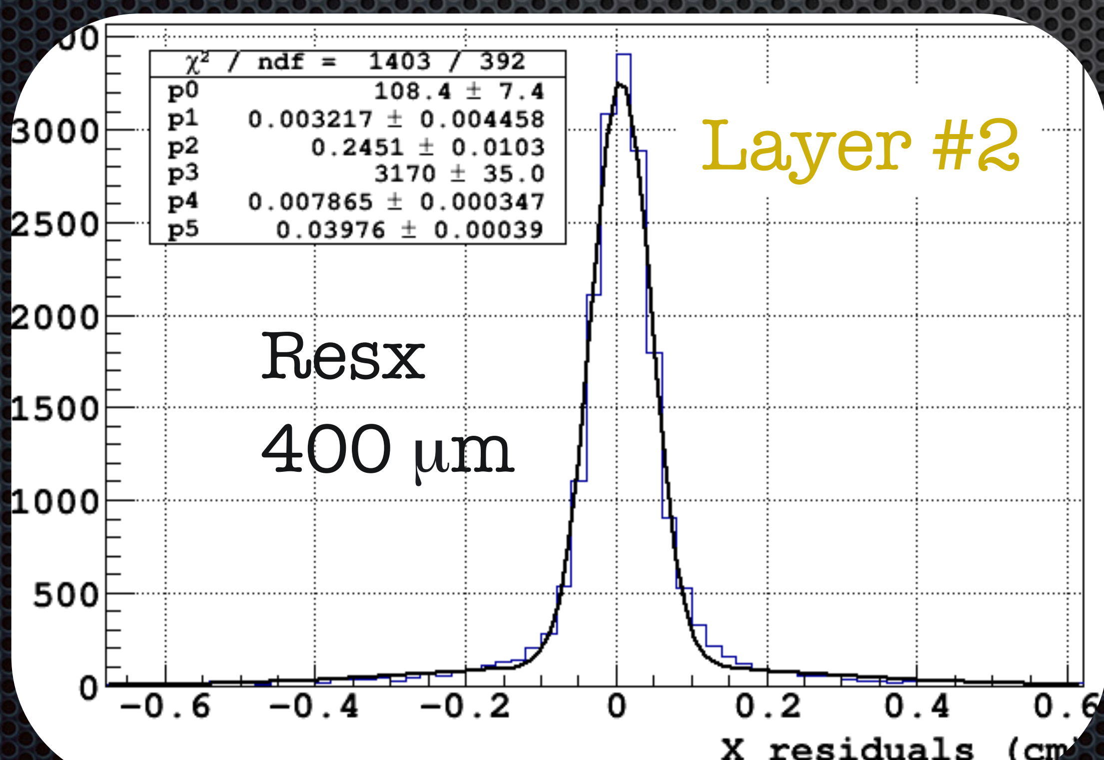


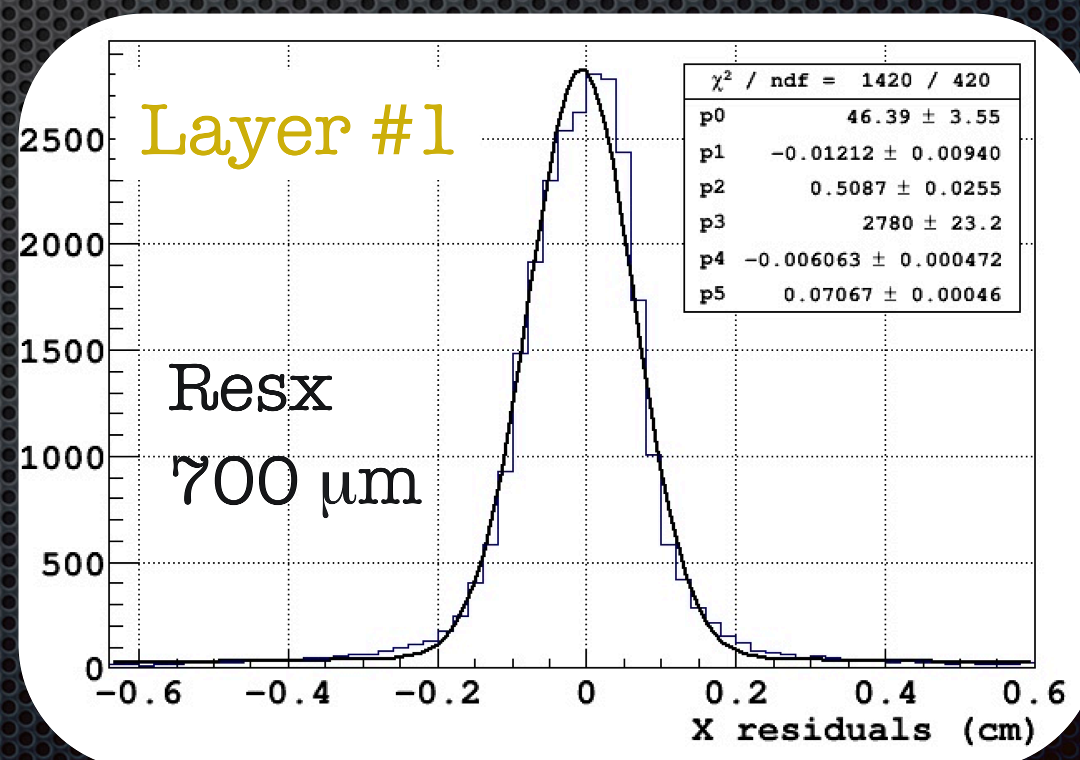
Detector Status: IT Calibration (II)

- 1st align & calib for all layers using cosmic-ray muons with B OFF



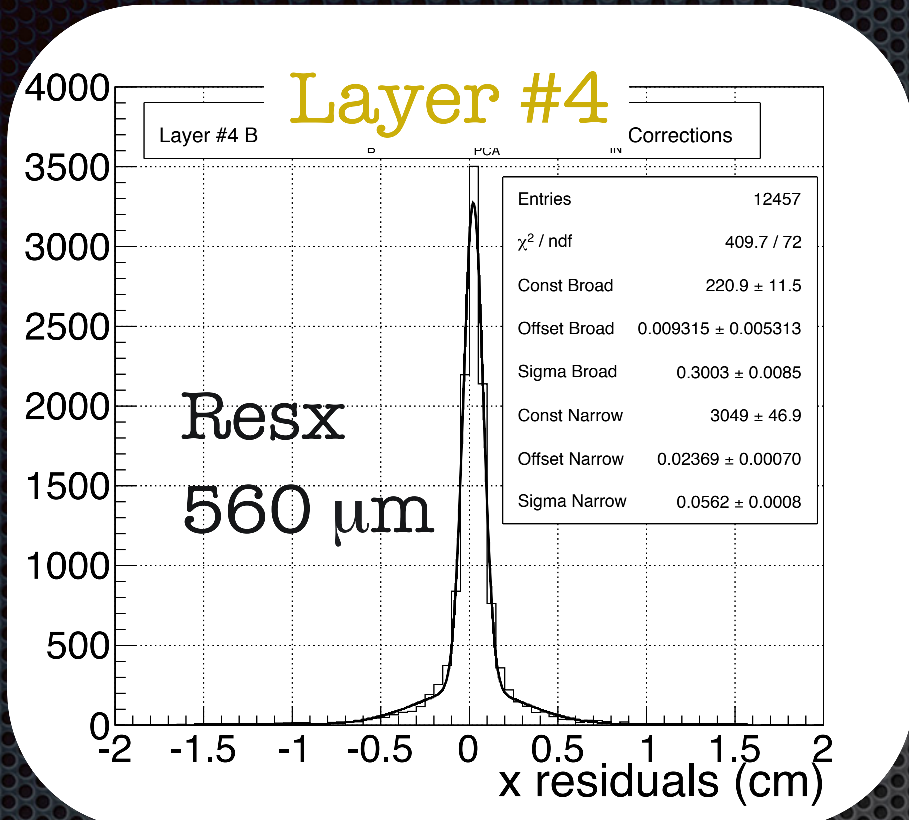


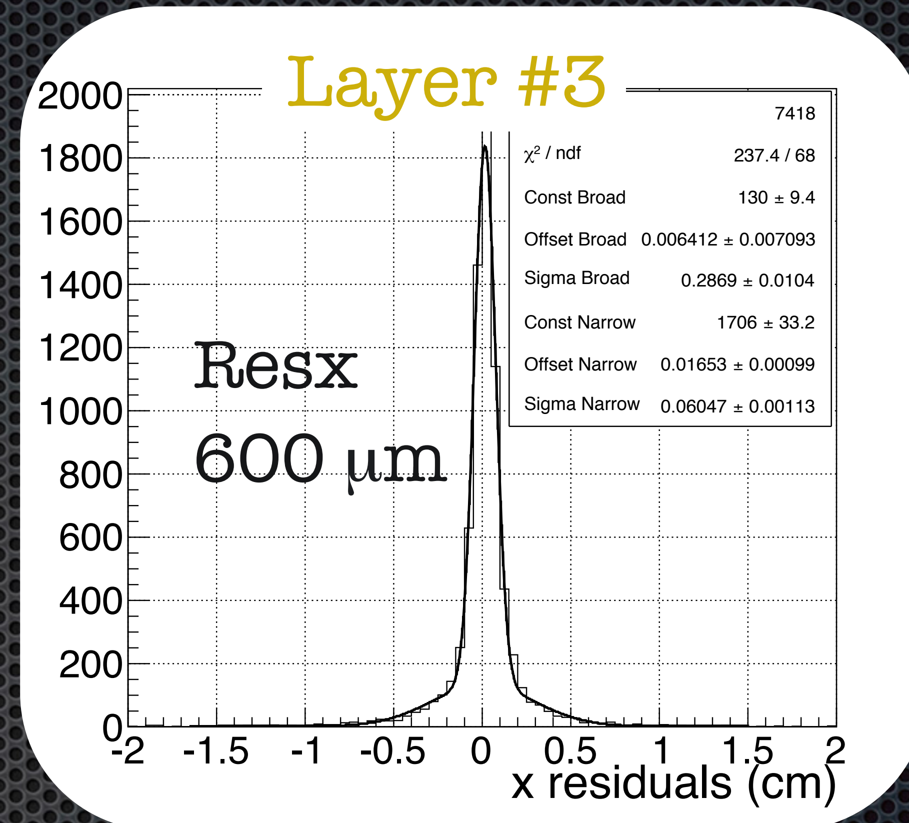


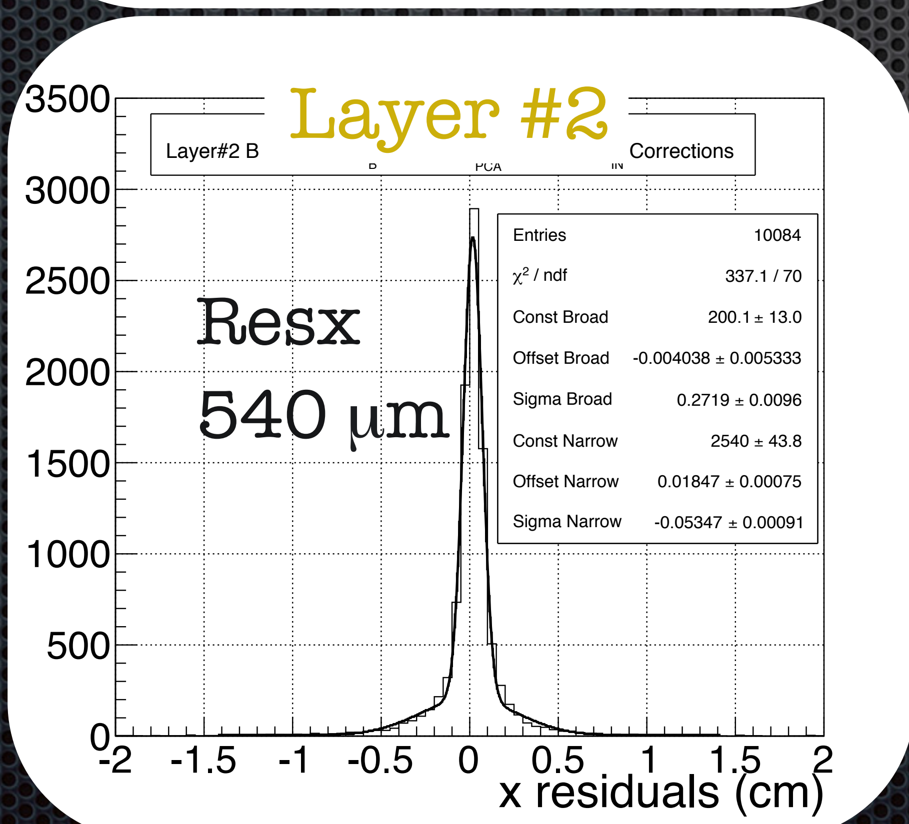


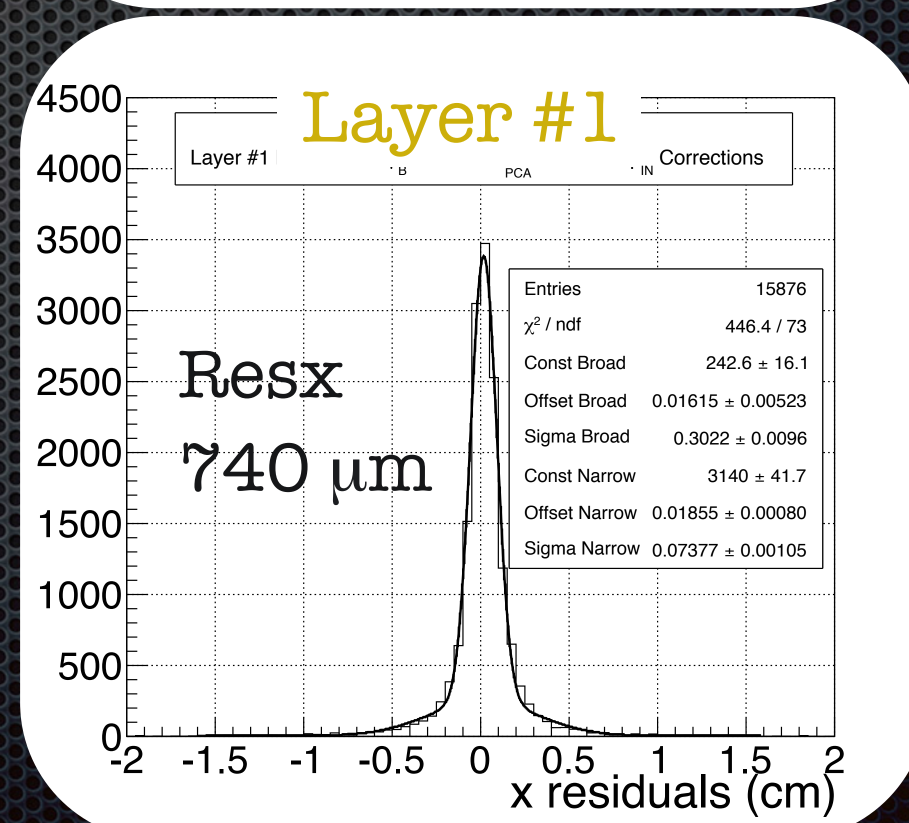
Detector Status: IT Calibration (III)

- 1st align & calib for all layers using cosmic-ray muons with B ON









Detector Status: IT Calibration (IV)

- Checking 1st align & calib with Bhabha scattering events