ORKA: The Golden Kaon Experiment

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On behalf of ORKA Collaboration

2013 DPF
UC SANTA CRUZ

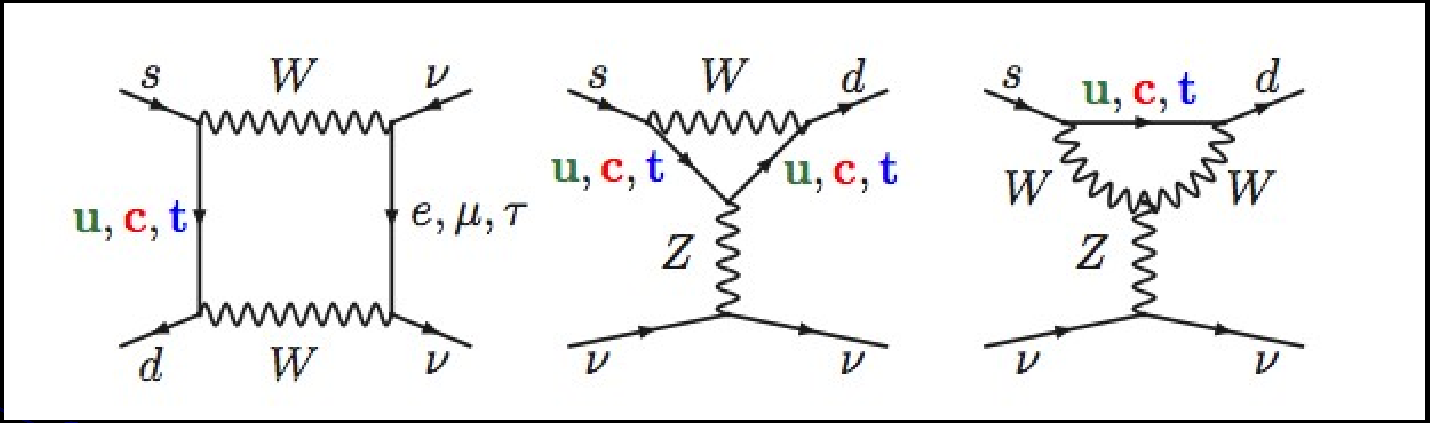
ORKA: The Golden Kaon Experiment

- Precision measurement of $K^+ \rightarrow \pi^+\nu\nu$ BR with ~1000 events at FNAL Main Injector.
  - 10x higher sensitivity than CERN NA62.
- Expected experimental BR uncertainty matches with Standard Model (SM) projected uncertainty.
  - 5σ reach for 35% deviation from BR_{SM}.
- Sensitivity to New Physics (NP) at and beyond LHC mass scale.
  - Explore its flavor structure and higher mass scales.
- Proven technique based on successful previous experiments:
  - 7 candidate events already observed at BNL E787/E949.
  - BR central value ~ twice BR_{SM} although consistent within the uncertainty.
- Granted scientific approval from Fermilab in December 2011.
  - Aggressive detector R&D already underway and site preparation in progress.

Special status: small SM uncertainty and large NP reach
ORKA higher sensitivity allows investigating previous result

$K^+ \to \pi^+ \nu\nu$ In The Standard Model

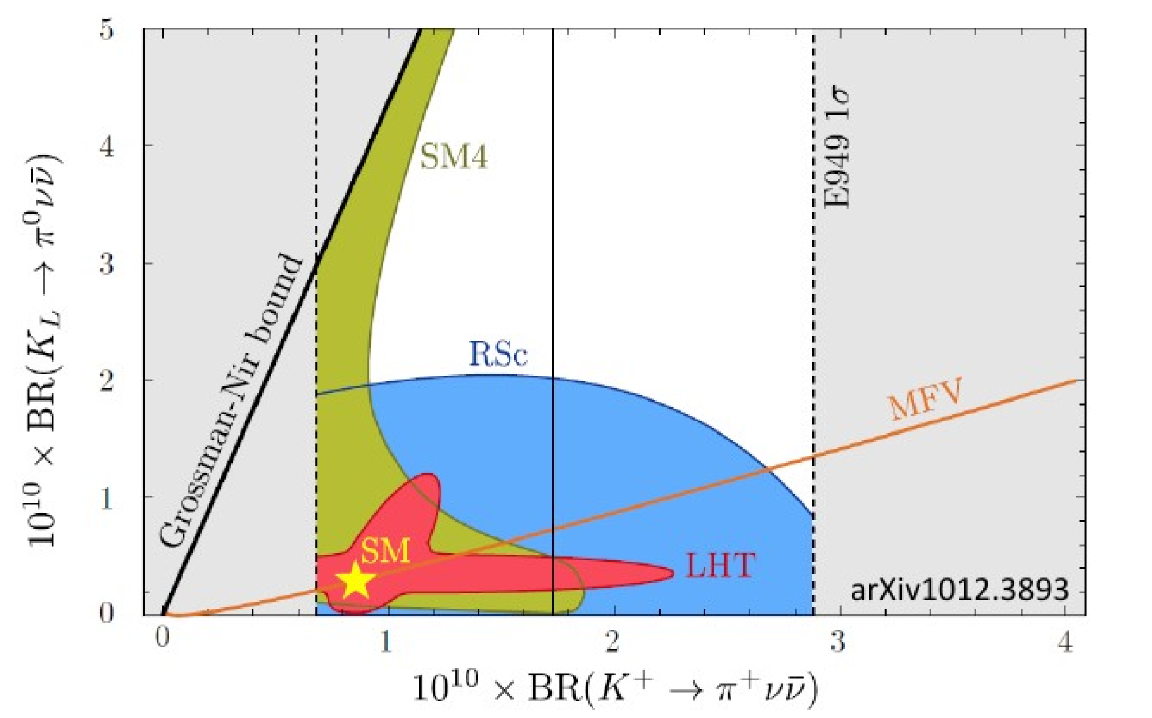
- The $K^+ \to \pi^+ \nu\nu$ decays are the most precisely predicted FCNC decays with quarks
- $B_{SM}(K^+ \to \pi^+ \nu\nu) = (7.8 \pm 0.8) \times 10^{-11}$



- Single effective operator: $(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$
- Dominated by top quark
- Hadronic matrix element shared with $K^+ \to p^0 e^+ \nu_e$
- Dominant uncertainty from CKM matrix elements
- Expect prediction improvement to ~5%

$K^+ \to \pi^+ \nu\nu$ ***"Golden decays"***

$K^+ \to \pi^+ \nu\nu$ Sensitivity To New Physics



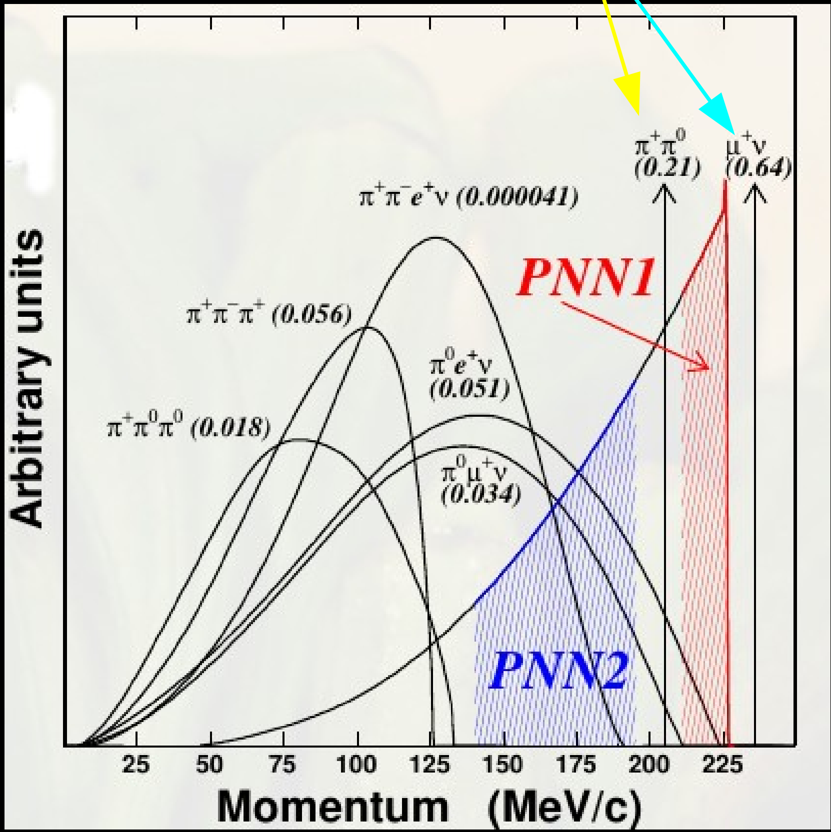
➢ Prediction and measurements at 5% level allows 5σ detection of deviation from the Standard Model as small as 35%.

$K^+ \to \pi^+ \nu\nu$ *BR* has significant power to discriminate among NP models

$K^+ \to \pi^+\nu\nu$ Experimental Challenges

To successfully detect $K^+ \to \pi^+\nu\bar{\nu}$ and separating it from background, mostly $K^+ \to \mu^+ \nu_\mu$ (64%) and $K^+ \to \pi^+ \pi^0$ (21%), the detector must have:

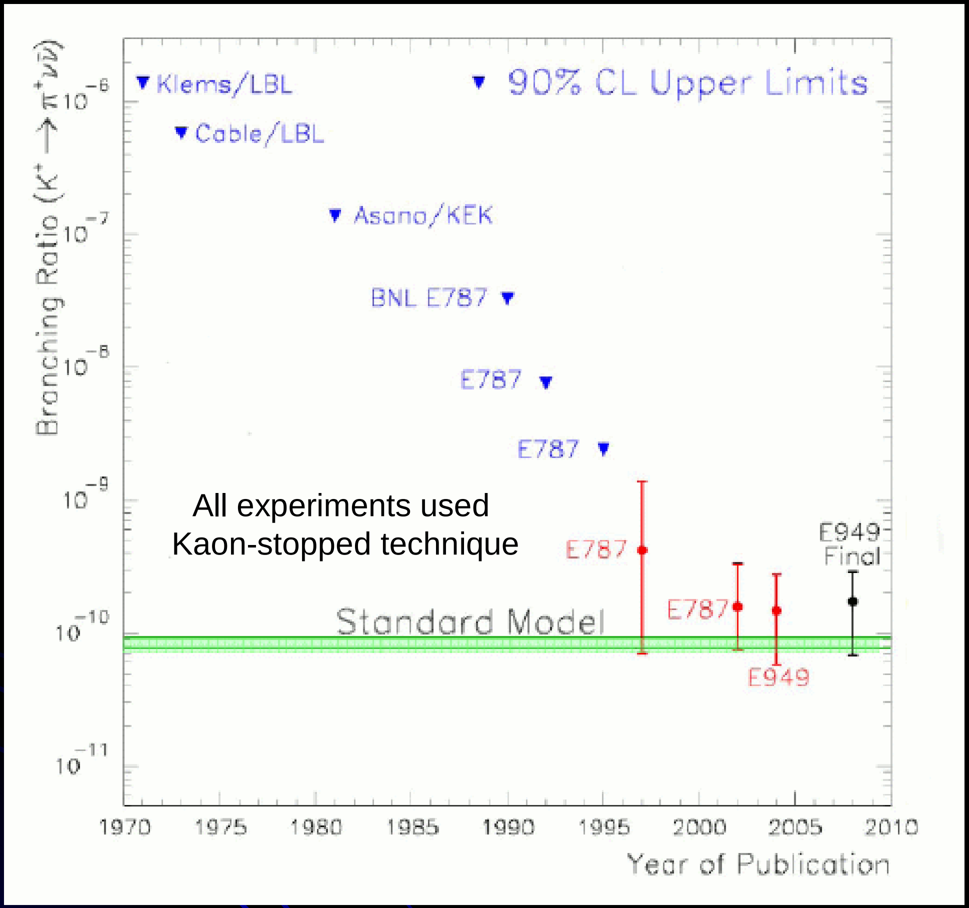
- Powerful π^+ particle identification ($\pi^+ \to \mu^+ \to e^+$) to reject $K^+ \to \mu^+ \nu_\mu$ and $K^+ \to \mu^+ \nu_\mu \gamma$ decays.
- Highly efficient 4π solid-angle photon detection coverage for vetoing $K^+ \to \pi^+ \pi^0$ events and other decays.
- Efficient K^+ identification system for eliminating beam-related backgrounds.

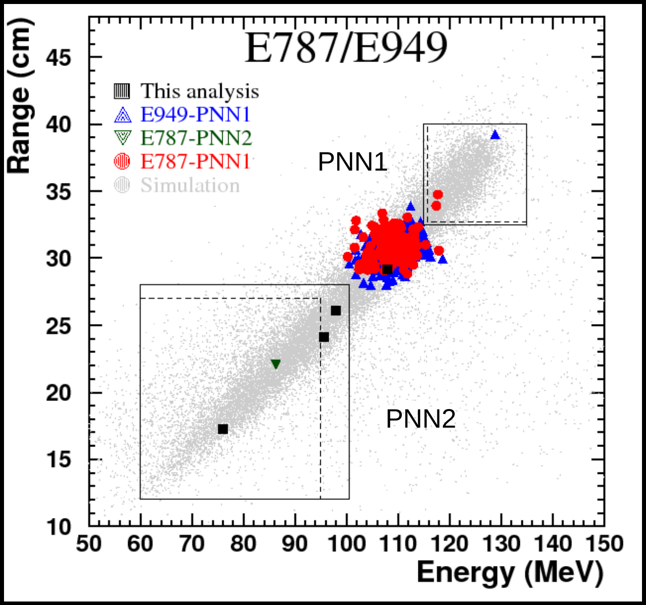


$$K^+ \to \pi^+\nu\nu = \pi^+ + \text{nothing}$$

Experimentally weak signature with background exceeds signal by 10^{10}

$K^+ \to \pi^+\nu\nu$ History





- E787/E949 BNL: 7 events observed

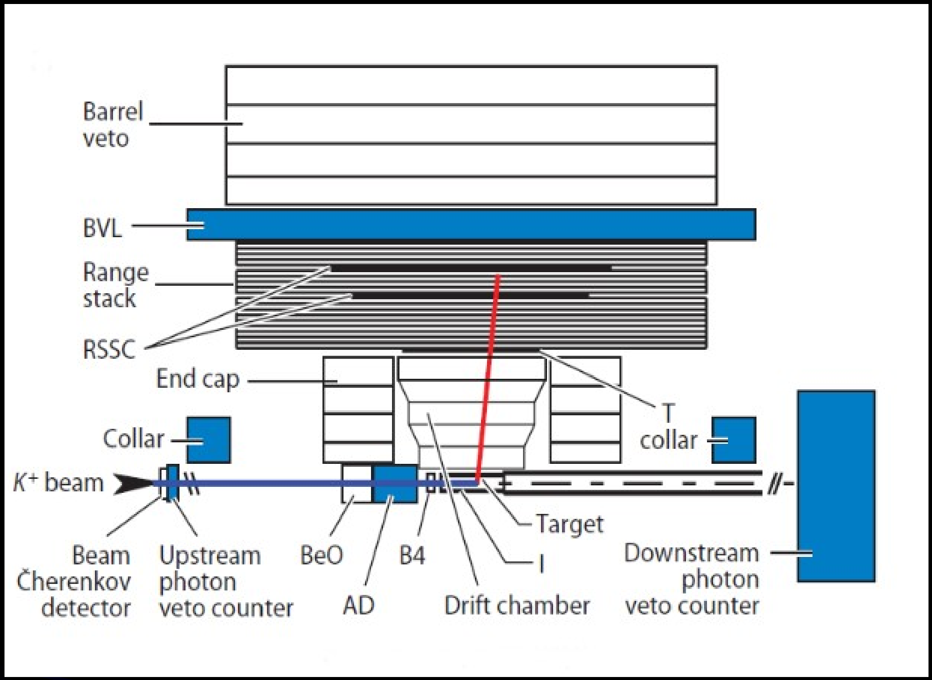
$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

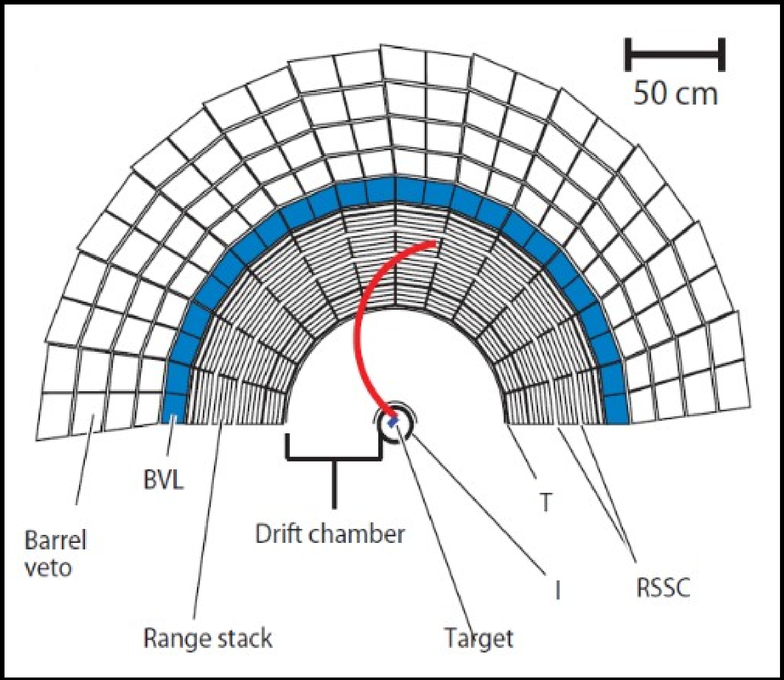
- Standard Model

$$B_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (7.8 \pm 0.8) \times 10^{-11}$$

$K^+ \to \pi^+\nu\nu$ BR$_{exp}$ consistent with SM prediction although ~twice BR$_{SM}$

E747/E949 Experimental Method

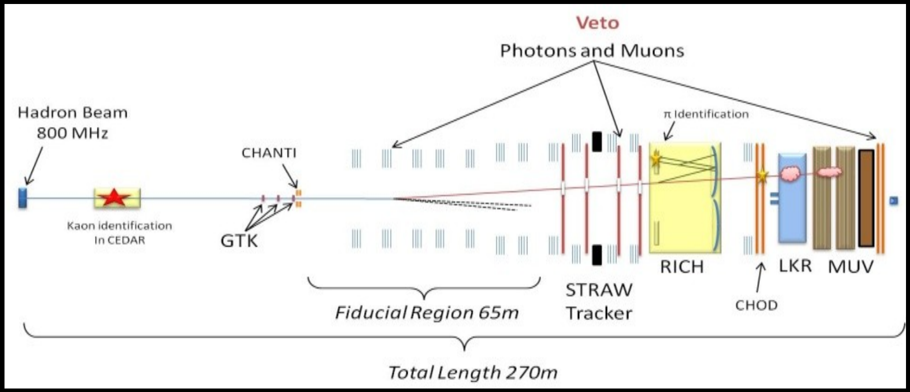




- 710 MeV/c K^+ beam.
- Stop K^+ in scintillating fiber target.
- Wait at least 2 ns for K^+ decay to suppress prompt background.
- Measure π^+ momentum in drift chamber.
- Measure π^+ range and energy in target and range stack.
- Stop π^+ in range stack.
- Observe $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ in range stack.
- Veto photons, charged tracks.

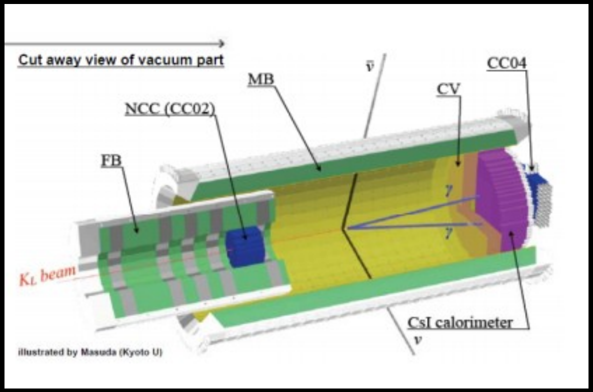
Rare Kaon Decays Worldwide Effort

NA62 @ CERN ($K^+ \to \pi^+ \nu\nu$)



- Complementary technique to ORKA
- Decay-in-flight experiment
- Builds on NA-31/NA-48
- Goal ~100 $K^+ \to \pi^+ \nu\nu$ events (SM) with S/B ~ 10
- Expect 10% measurement of $K^+ \to \pi^+ \nu\nu$ BR
- Expect data taking late 2014

KOTO @ J-PARK ($K_L \to \pi^0 \nu\nu$)

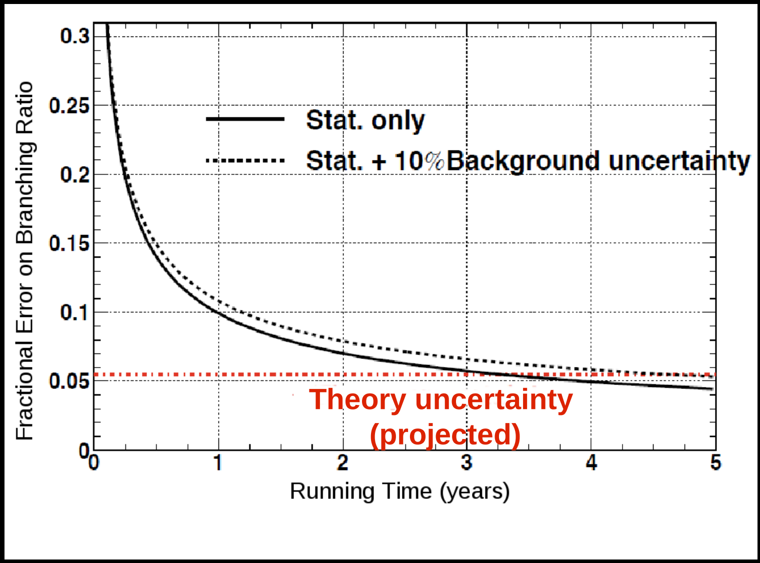


- Pencil beam decay-in-flight experiment
- 2nd generation detector
- Re-using KTeV CsI crystals to improve calorimeter (better resolution and veto power)
- Goal ~3 $K_L \to \pi^0 \nu\nu$ events (SM) with S/B ~ 1
- First run expected this year

World scientific community recognizes tremendous opportunity for NP

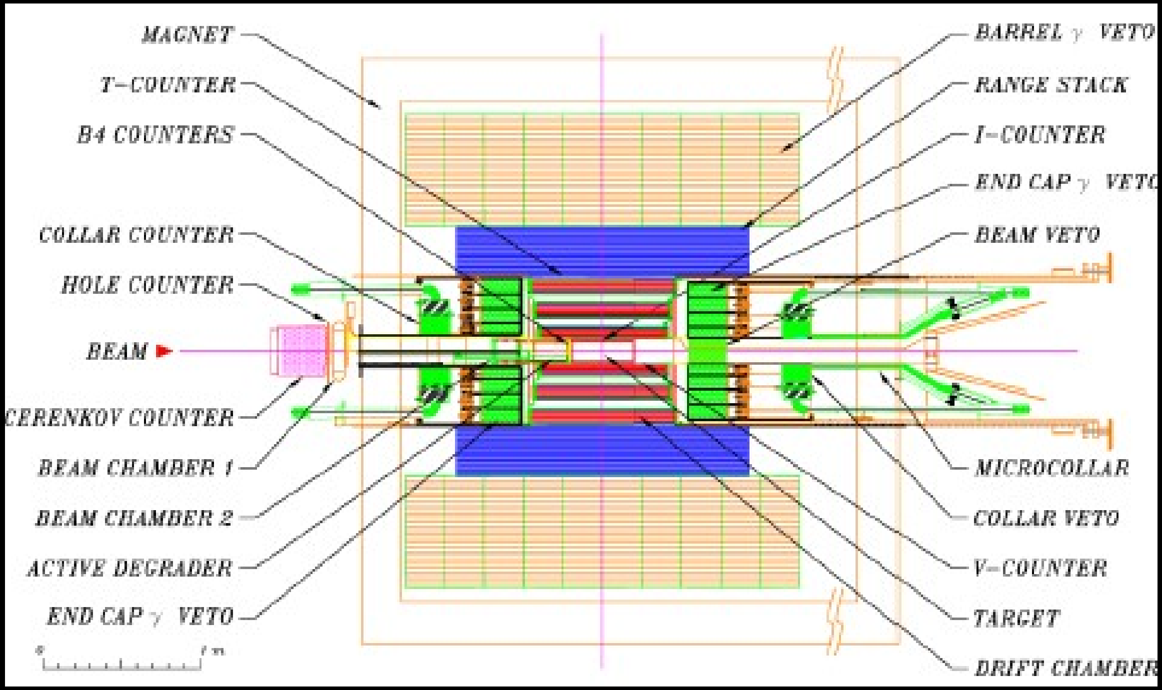
ORKA @ Fermilab

- Stopped-kaon technique complementary to NA62:
  - Low energy products in the final state vs high energy at NA62.
  - Systematic uncertainties completely uncorrelated.
- Total 10^{13} K^+ produced in 5 years:
  - open studies of processes with 10^{-11} -10^{-12} sensitivity.
- Expected ~210 $K^+ \rightarrow \pi^+ \nu\nu$ events per year (SM).
  - 5% uncertainty in 5 years.
- Active and growing international collaboration:
  - 17 institutes from six nations:
    Canada, China, Italy, Mexico, Russia, USA.
  - 6 US Universities, 2 US National Laboratories.



ORKA will confirm with a complimentary technique evidence of NP from NA62 or will push the hunt for New Physics to much higher sensitivity.

ORKA 4th Generation Detector



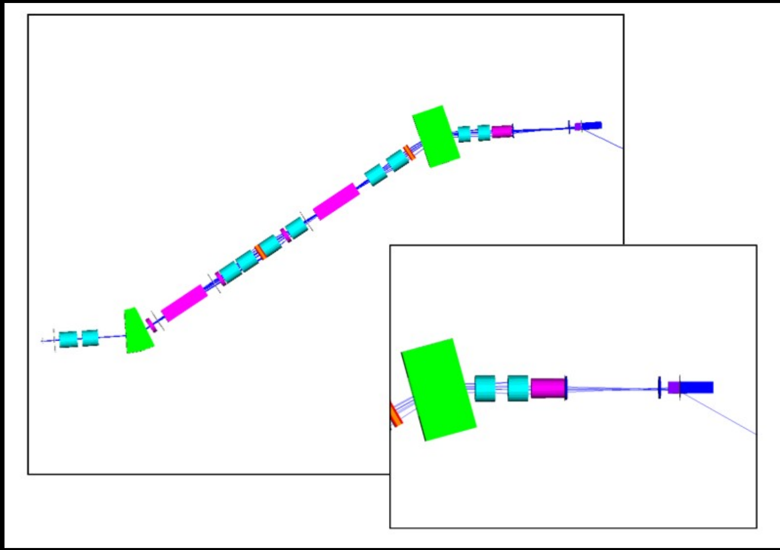
- 4π detector
- Improved stopping target
- Low mass drift chamber
- Finer range stack segmentation
- More efficient photon detectors

- Most of them require considerable R&D

Expected x100 sensitivity with respect to BNL experiments:
x10 from the beam and x10 from the detector

Beam Sensitivity Improvements

- **Primary Beam**
  - 95 GeV/c protons
  - 50-75 kW
  - 48 × 10^{12} protons per spill
  - Duty factor of ~45%
  - # of protons/spill (**×0.74**)



- **Secondary Beam Line**
  - 600 MeV/c K+ particles
  - Increased number of kaons/proton from longer target, increased angular acceptance, increased momentum acceptance (**×4.3**)
  - Larger kaon survival fraction (**×1.4**)
  - Increased fraction of stopped kaons (**×2.6**)
  - Increased veto losses due to higher instantaneous rate (**×0.87**)

Intensity better by a factor of ~10 relative to E949

Detector Sensitivity Improvements

Component	Acceptance factor
$\pi \to \mu \to e$	2.24 ± 0.07
Deadtimeless DAQ	1.35
Larger solid angle	1.38
1.25-T B field	1.12 ± 0.05
Range stack segmentation	1.12 ± 0.06
Photon veto	$1.65^{+0.39}_{-0.18}$
Improved target	1.06 ± 0.06
Macro-efficiency	1.11 ± 0.07
Delayed coincidence	1.11 ± 0.05
Product (R_{acc})	$11.28^{+3.25}_{-2.22}$

Mostly from better hermeticity and granularity

Might require different technology

Acceptance better by a factor of ~11 relative to E949

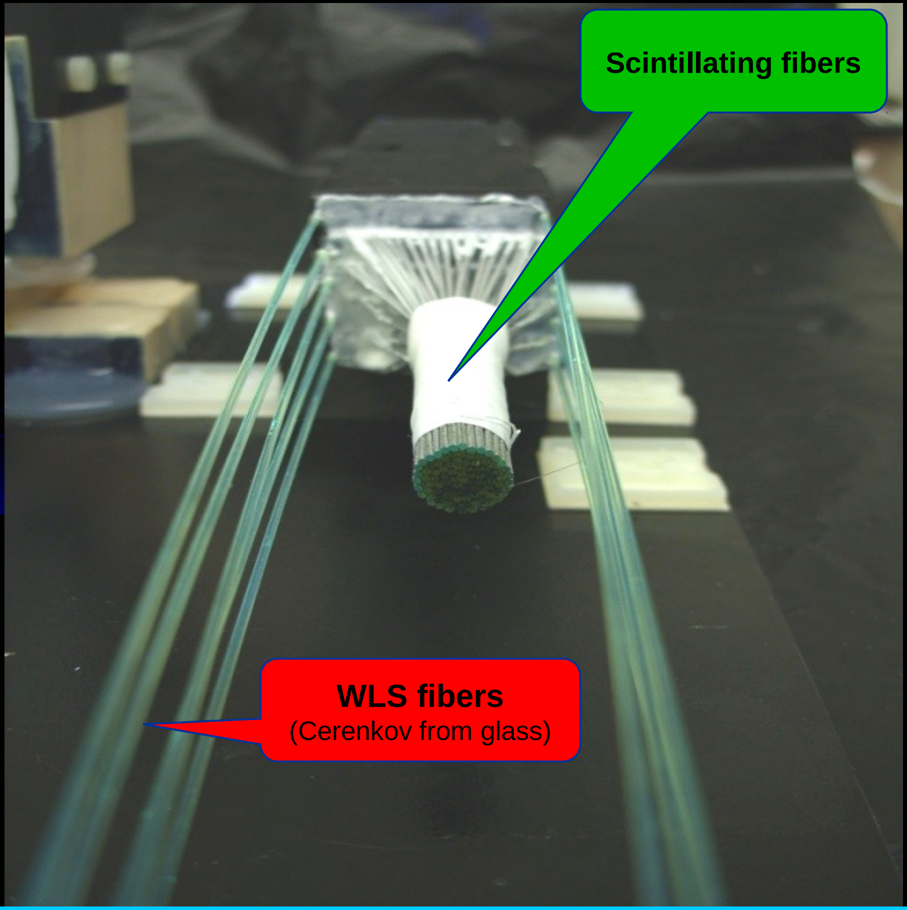
Requirements for ORKA

- π^o rejection > 10^6-10^7 ➡ γ inefficiency < 10^{-3}-10^{-4} above 20 MeV and for impinging angles down to 20°.
  Desirable sensitivity down to few MeV.
- Depth > 20 $X_{o.}$
- Accidentals rate: 0.011/MHz (in order to keep the same rate of accidentals as in E949).
- Desirable: γ/n identification.
- Max decay time for scintillator: 8 nsec (to keep the accidentals down).
- Energy resolution: 10-15% @ 200 MeV (from E949), but needs further studies.

Two technologies proposed for the photon veto: Shashlik and ADRIANO

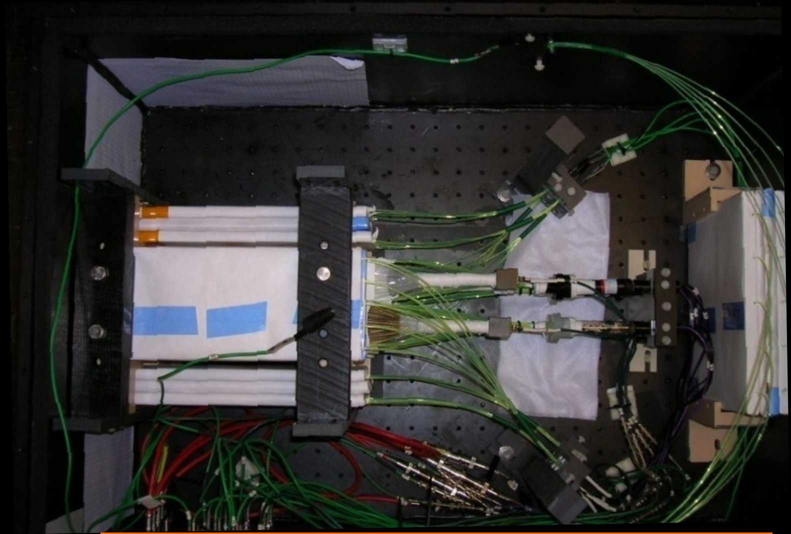
ADRIANO: ***A D***ual-***R***eadout ***I***ntegrally ***A***ctive ***N***on-segmented ***O***ption

- Implementation of the Dual-Readout technique with heavy glasses sandwiched with scintillating fibers/plates.



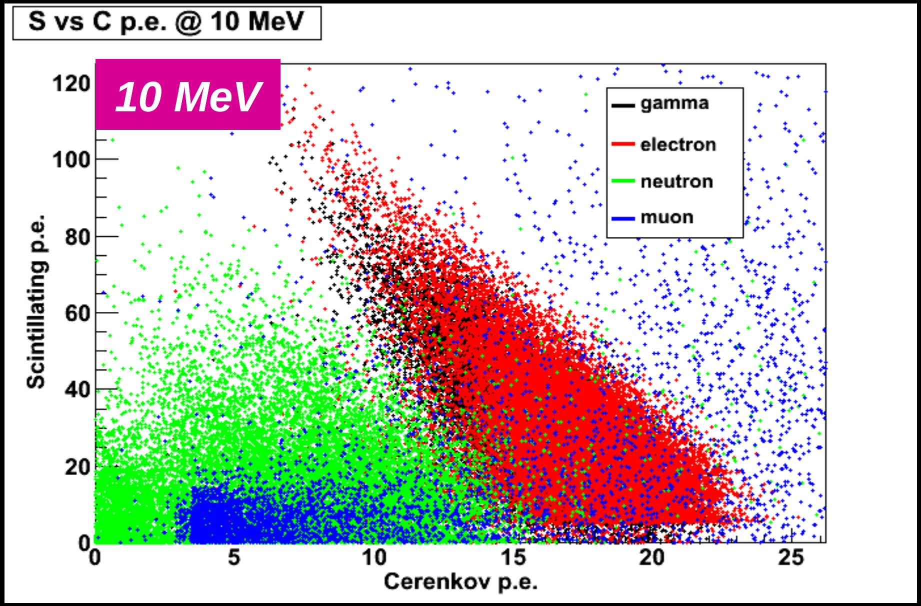
ADRIANO prototype (from T1015 project)

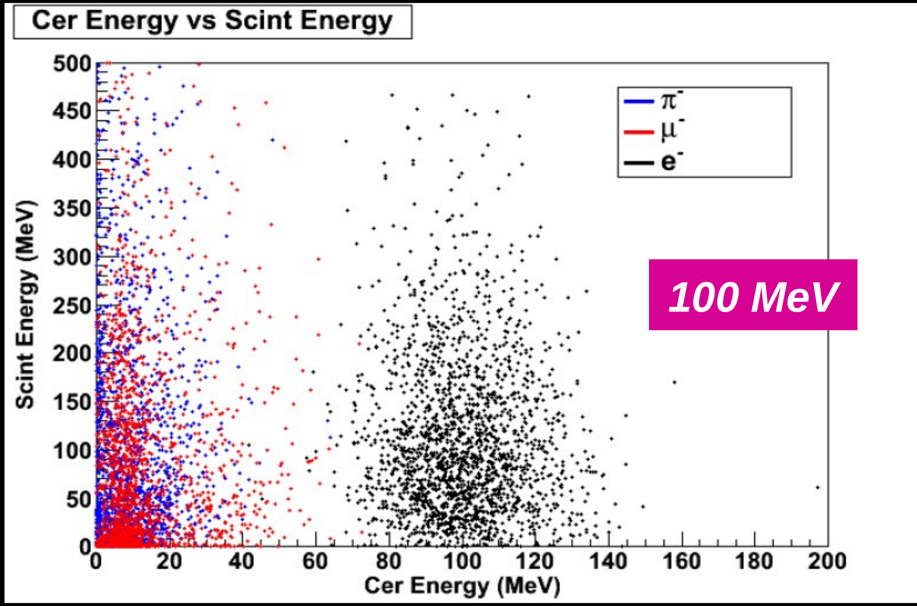
- **Absorber and Cerenkov radiator**: lead glass or bismuth glass (ρ > 5.5 gr/cm3)
- **Cerenkov light collection:** WLS fiber optically coupled to glass
- **Scintillation region**: scintillating fibers or scintillating plates
- **Particle ID**: from S vs Č
- **Readout**: front and back SiPM
- **R&D**: T1015 Collaboration (FNAL-INFN)



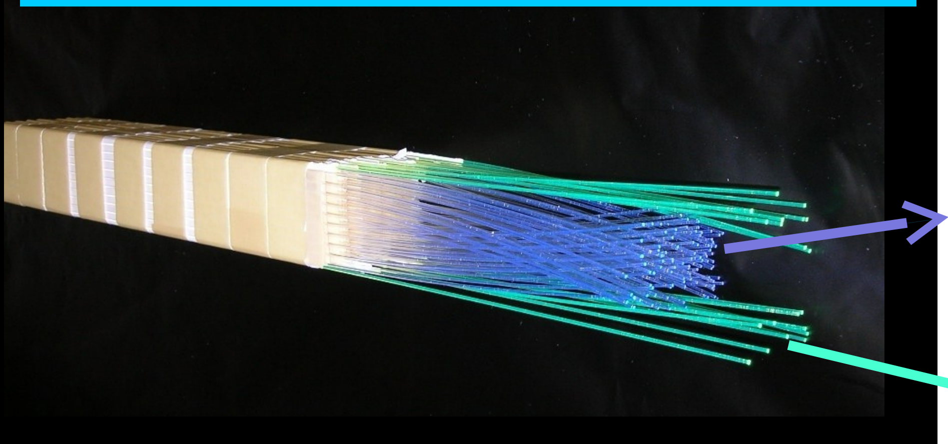
April 2012 Test Beam at FNAL (4 prototypes – 25 cm long)

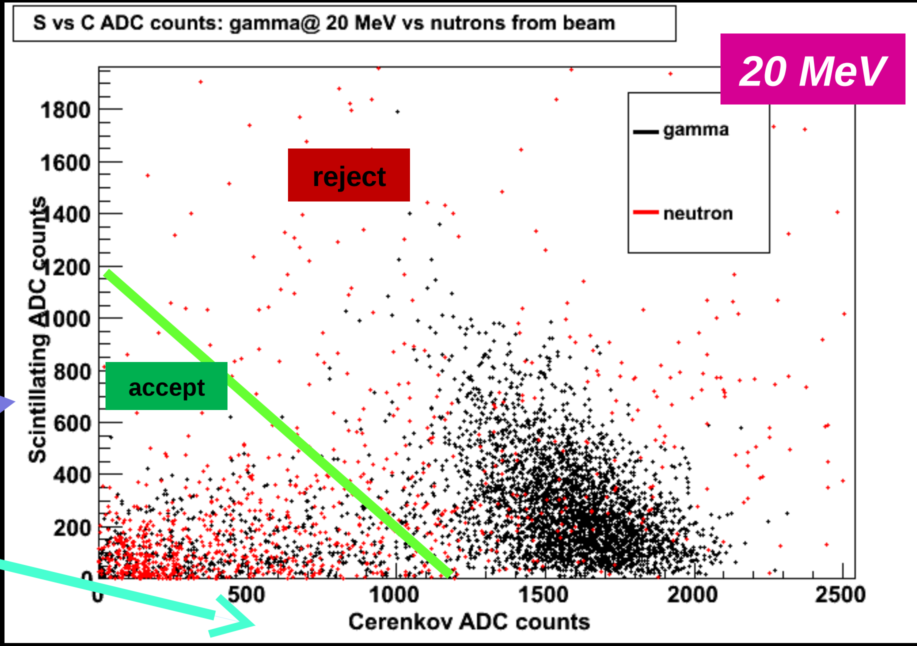
Particle ID with ADRIANO





n vs γ discrimination very important at ORKA
to mitigate accidental veto of good events





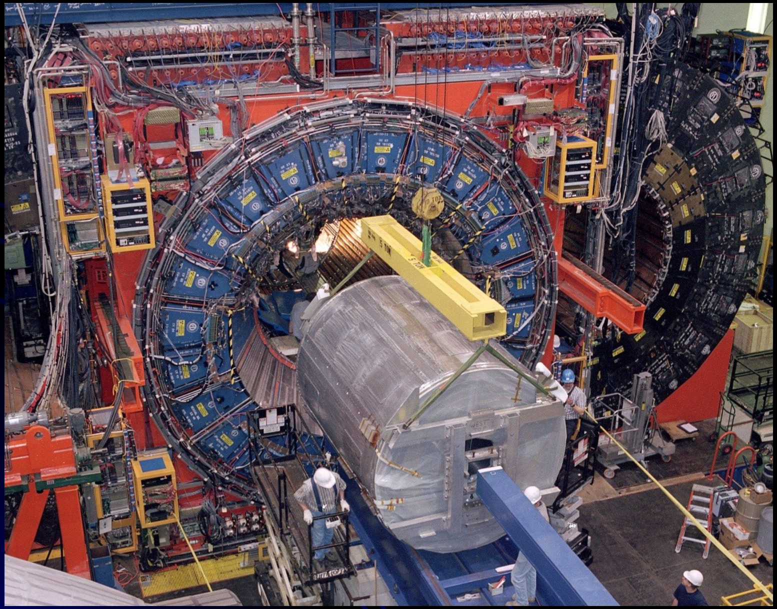
ORKA Detector R&D Program

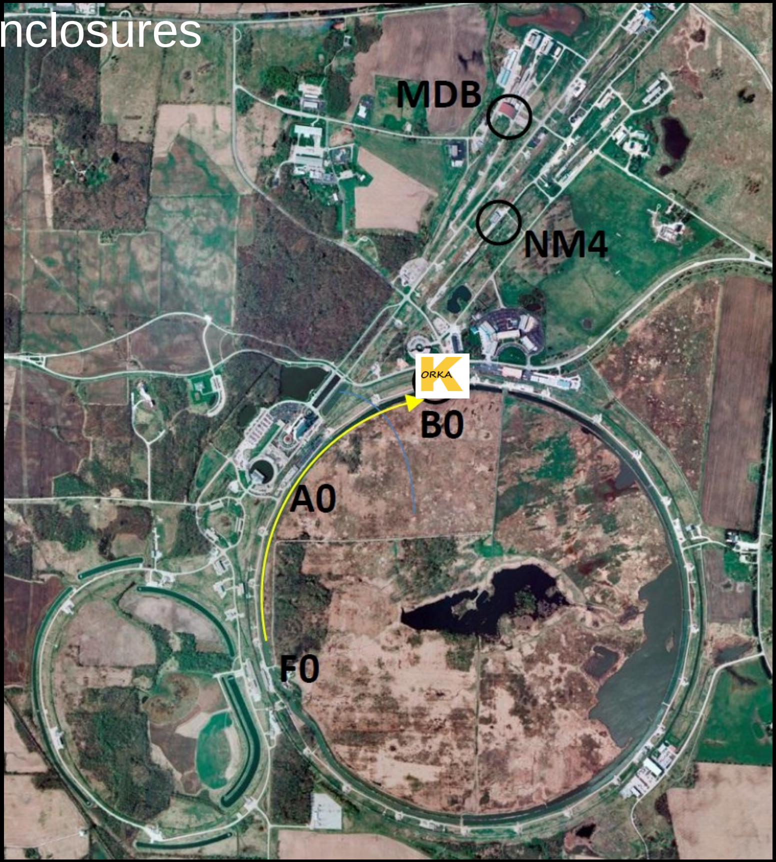
- Scintillating fiber target
  - Stopping power
  - optical coupling
  - single/double end readout
- Drift chamber
  - low mass
  - cell size
  - # layers
  - gas
  - endplates
  - supports
- Tracking with GEM
  - Gas electron multiplier
  - Low cost, low HV, high gain
- Range stack
  - Segmentation
  - Readout
- K^+ beam line design
- ADRIANO fully-active calorimeter
  - Cerenkov light from layers of lead glass
  - Scintillation light from layers of plastic scintillator
  - Potential to improve photon-veto efficiency
  - Potential for particle identification
- SiPM readout
  - Double-pulse resolution
  - Temperature performance
  - Linearity response
  - Coupling to scintillating fibers
  - Radiation hardness
- Front-end electronics
  - Fast wave-form digitizer (500Mhz)
  - Electronics for SiPM
- DAQ
  - Triggerless system
  - High-rate digitizers
  - Long time depth for muon decay

Very rich program and opportunity on detector R&D

ORKA Site Selected: CDF HAll

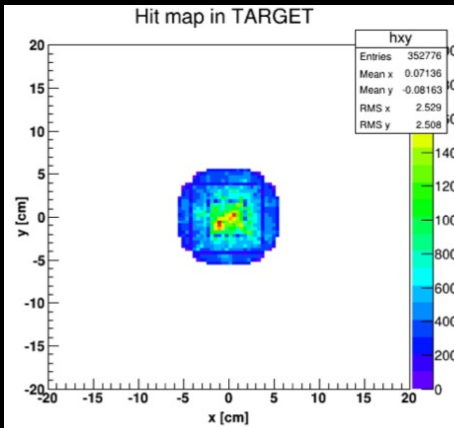
- **CDF (B0):**
  - ORKA detector inside CDF solenoid
  - Re-use CDF solenoid, cryogenics and infrastructures
  - Well shielded transport and experimental enclosures
  - Required new line from A0 to B0.

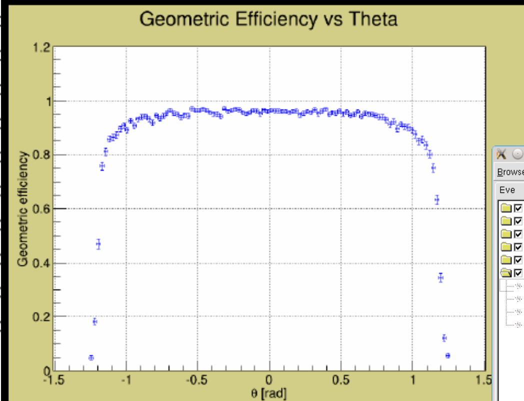


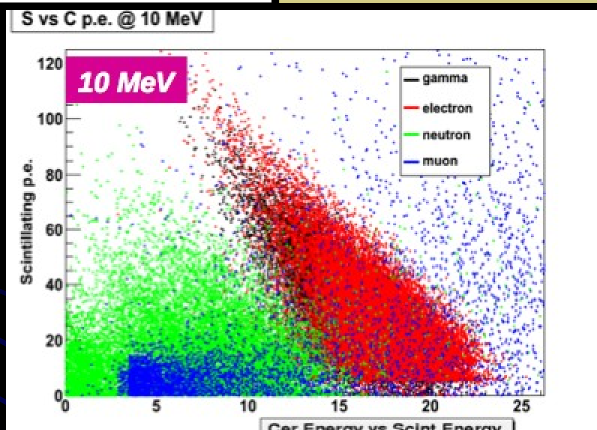


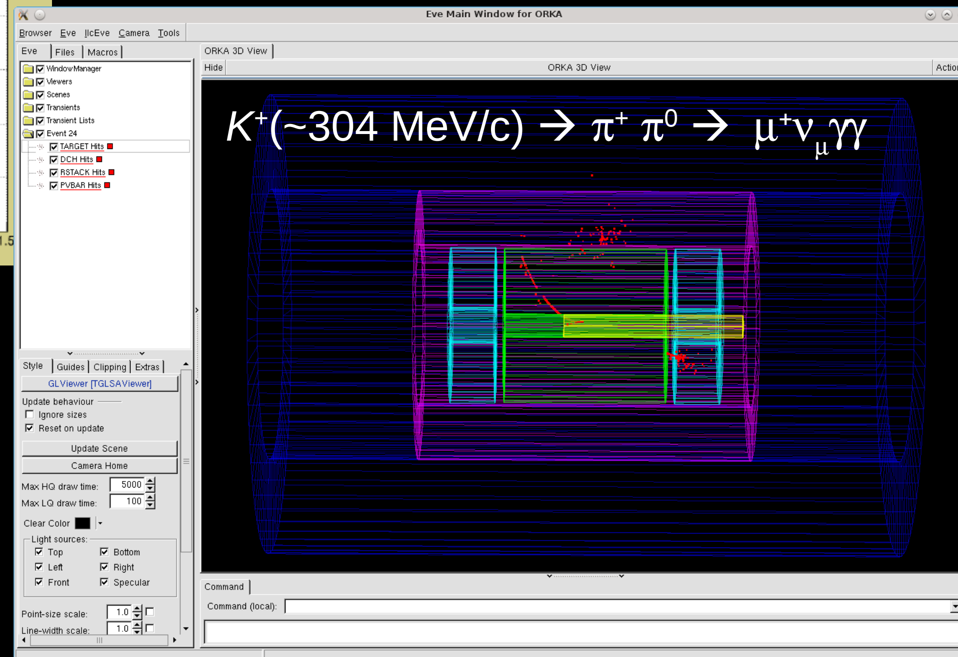
Preparations of CDF hall have begun

ORKA Simulations









- Full simulation and digitization implemented in ILCRoot framework
- Evaluate detector technology options
- Optimize detector design and study detector performance
- Verify acceptance increase relative to BNL E949

ILCroot framework full in place for physics and detector studies

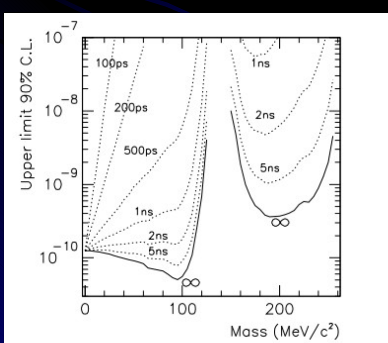
ORKA: Not Only $K^+ \to \pi^+ \nu\nu$

- While optimized for $K^+ \to \pi^+ \nu\nu$, ORKA is capable of making precise measurements of many other physics processes.

Process	Current	ORKA	Comment
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events	
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$	$K^+ \to \pi^+ \nu\bar{\nu}$ is a background
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+ \pi^0 X^0$	$<\sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$	
$K^+ \to \mu^+ \nu_{heavy}$	$< 2 \times 10^{-8} - 1 \times 10^{-7}$	$< 1 \times 10^{-10}$	150 MeV $< m_\nu <$ 270 MeV
$K^+ \to \mu^+ \nu_\mu \nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$	
$K^+ \to \pi^+ \gamma\gamma$	293 events	200,000 events	
$\Gamma(Ke2)/\Gamma(K\mu 2)$	$\pm 0.5\%$	$\pm 0.1\%$	
$\pi^0 \to \nu\bar{\nu}$	$< 2.7 \times 10^{-7}$	$< 5 \times 10^{-8}$ to $< 4 \times 10^{-9}$	depending on tech nique
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$	

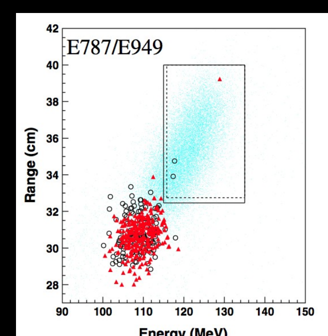
Interesting process for further investigation

$K^+ \to \pi^+ X^0$



Many models for X^0.
familon, axion, sgoldstino, dark matter ....

Upper limit on $K^+ \to \pi^+ X^0$
where X has a lifetime or is stable.

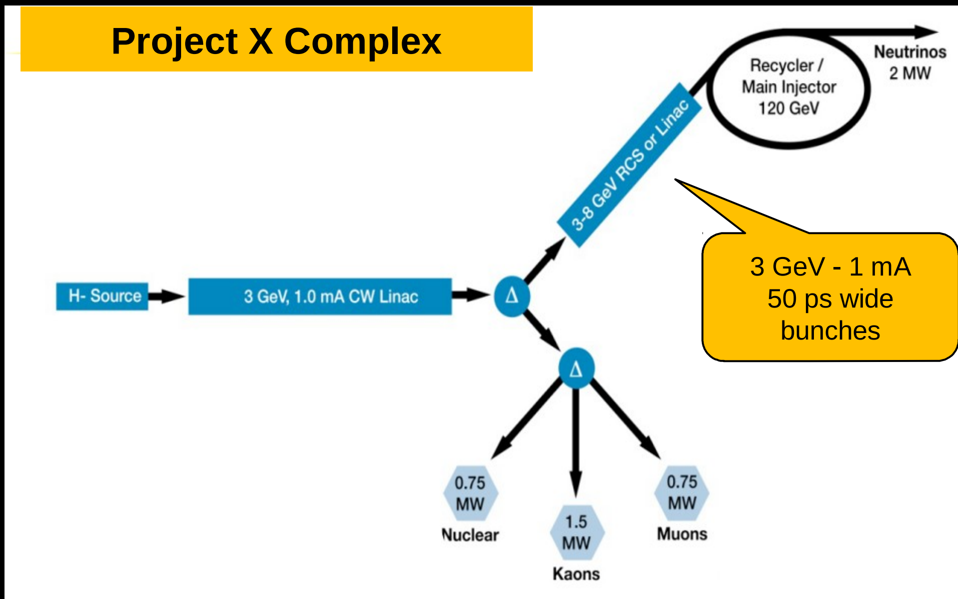


One event seen in E949 $K^+ \to \pi^+ \nu\nu$ PNN1 signal region is near kinematic endpoint

Corresponds to a massless X^0

Wide range of BSM processes accessible by ORKA

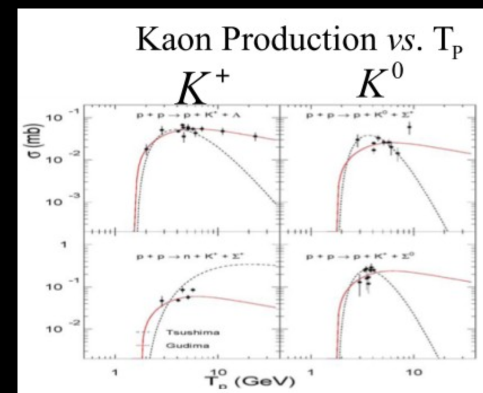
ORKA at Project X



K production (<1 GeV): $\frac{\sigma_K^{3\,\text{GeV}}}{\sigma_K^{24\,\text{GeV}}} \sim \frac{1}{10}$

p beam intensity: $\frac{\text{Proj. X}}{\text{AGS}} \sim 300$

K flux: $\frac{\text{Proj. X}}{\text{AGS}} \sim 30$



- Project X will open the opportunity to study the charged and the neutral channel

$B_{SM}(K^+ \to \pi^+ \nu\nu) = (7.8 \pm 0.8) \times 10^{-11}$

Goals	NA62	ORKA	ORKA@PX
Events/yr	40	200	340
S/B	5	5	5
Precision	10%	5%	3%

$B_{SM}(K^+ \to \pi^+ \nu\nu) = (2.8 \pm 0.4) \times 10^{-11}$

Goals	KOTO phase II	ORKA2@PX
Events/yr	1	200
S/B	1	5 -10
Precision	1	5%

Richer physics program at Project X era

Conclusions

- ORKA aims to precisely measure the $K^+ \to \pi^+ \nu\nu$ branching ratio (BR) at the Fermilab Main Injector.
- This decay is highly suppressed in the Standard Model (SM), but has minimal theoretical uncertainty, thus making this measurement a tremendous potential for discovery of New Physics (NP).
- The certainty with which the SM contribution to $K^+ \to \pi^+ \nu\nu$ can be predicted and the precision measurement at the same level will permit a 5σ discovery for NP with only a 35% deviation from the BR_{SM}.
- However the small BR and the weak experimental signature make this measurement very challenging.
- The need for a 4th generation detector is a good training for future generation of physicists and open for opportunities of international collaborations.
- In recognition of the unique sensitivity in the quark flavor physics and the opportunity to probe many models of NP beyond the direct search of the LHC, the latter FNAL director has granted scientific approval to the ORKA proposal.
- Detector R&D and site preparation already started.
- Project X will provide an unprecedented opportunity to discover New Physics with rare kaon decays.

Scientific community, FNAL management and US funding agencies are enthusiastic about ORKA and working to find a way to make it possible.

Backup Slides

ORKA Critical Experimental Issue

- Proposed Photon Veto based on Shashlik calorimeter

  155 interleaved layers of 0.8 mm lead and 1.6 mm scintillator.

  23 X_0 depth.

  - About 2/3 of energy lost in Pb absorber
  - Need to set threshold at 1pe
  - No energy measurement

- Estimated accidental losses based on E949:

$$\mathcal{S} = e^{\lambda(R_{\mathrm{ORKA}} - R_{\mathrm{E949}})}$$

- Using: λ = -0.345/MHz R_{ORKA}= 26.2 MHz R_{E949}=8.4MHz

$$\mathcal{S} = 0.54 \text{ with respect to E949}$$

Forget about expected sensitivity

Needed dedicated simulations to fully understand and optimized the detector

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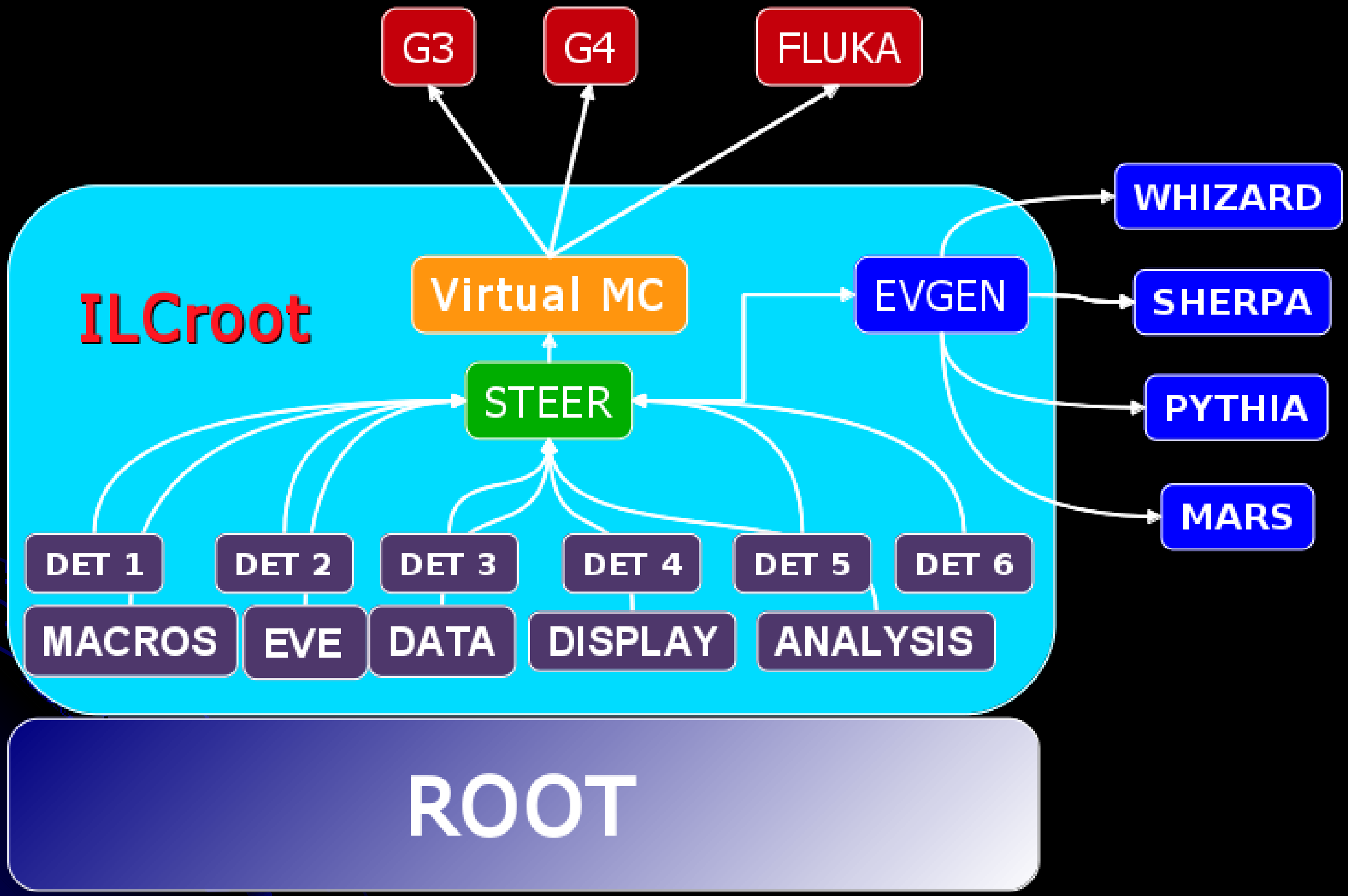
Needed dedicated simulations to fully understand and optimized the detector

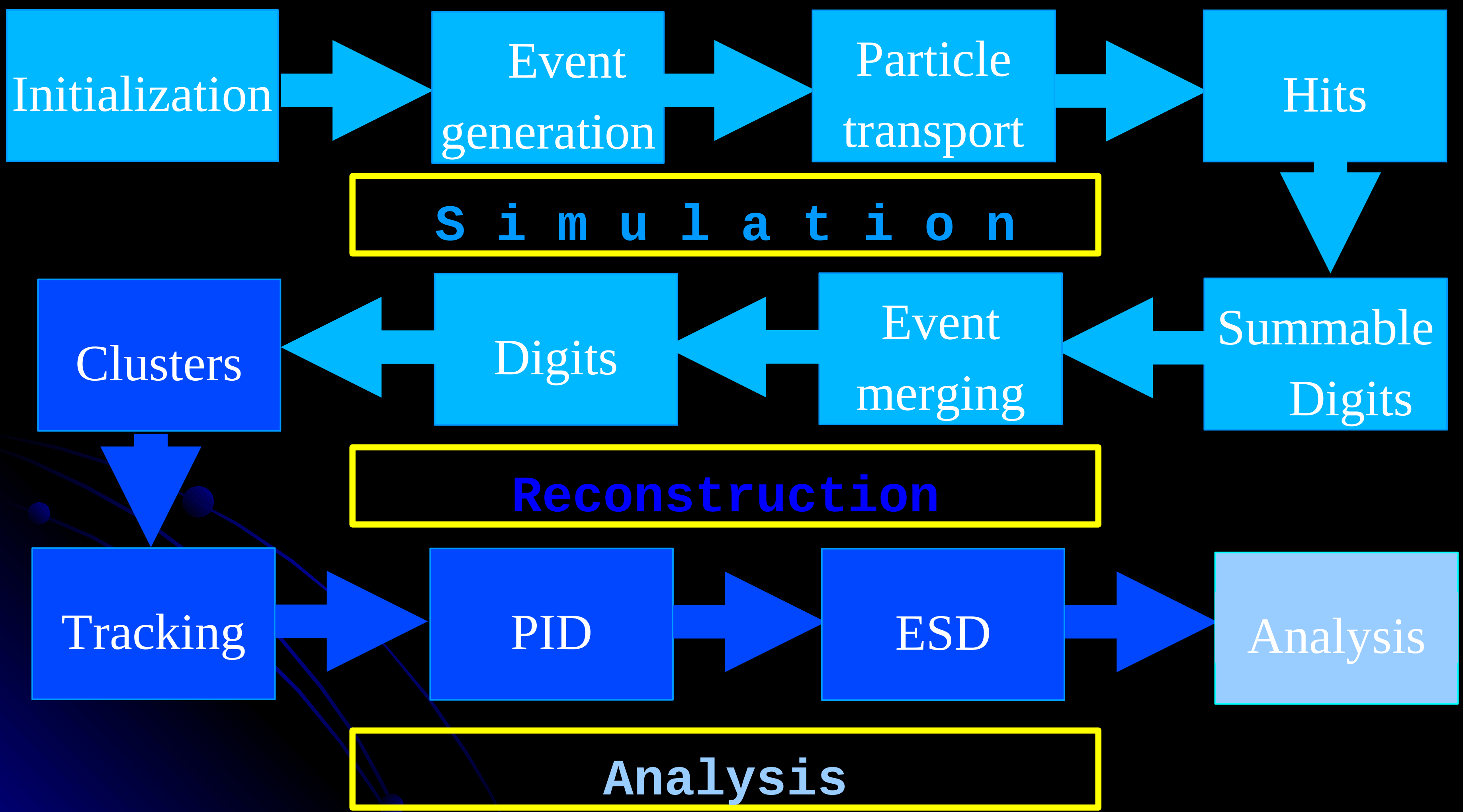
ILCroot: root Infrastructure for Large Collider

- **CERN** architecture (based on Alice's Aliroot).
- Six MDC have proven robustness, reliability and portability.
- Uses **ROOT** as infrastructure.
  - All ROOT tools are available (I/O, graphics, PROOF, data structure, etc.).
  - Extremely large community of users/developers.
  - Growing number of experiments/projects have adopted IlcRoot: Opera, CMB, Panda, ILC 4th Concept, Muon Collider, ORKA
- Include **interfaces** to read external event generator outputs (Pythia, Whizard) and MARS (for the Muon Collider background).
- Virtual Geometry Modeler (VGM) for geometry .
- **Virtual Montecarlo** allows to use several MonteCarlo (Geant3, Geant4, Fluka) The user can select at run time the MonteCarlo to perform the simulations without changing any line of the code.
- **Single framework**, from generation to reconstruction through simulation. Don't forget analysis!!!
- IlcRoot successfully adopted for the ILC and actually used for the MuC detector studies for Snowmass.
  (**LoI** studies for the ILC (4Th Concept) completed based on IlcRoot).

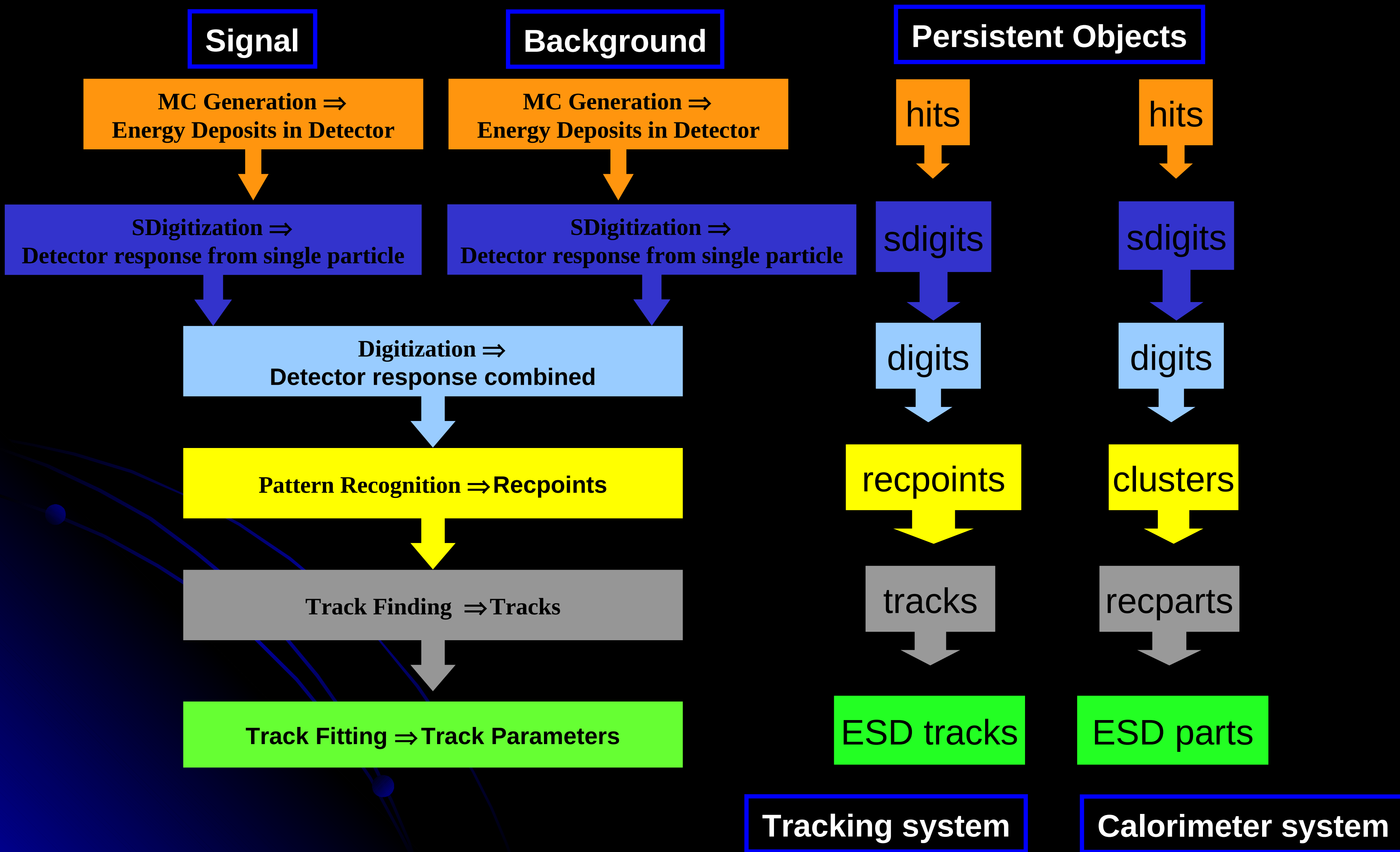
ILCroot Framework



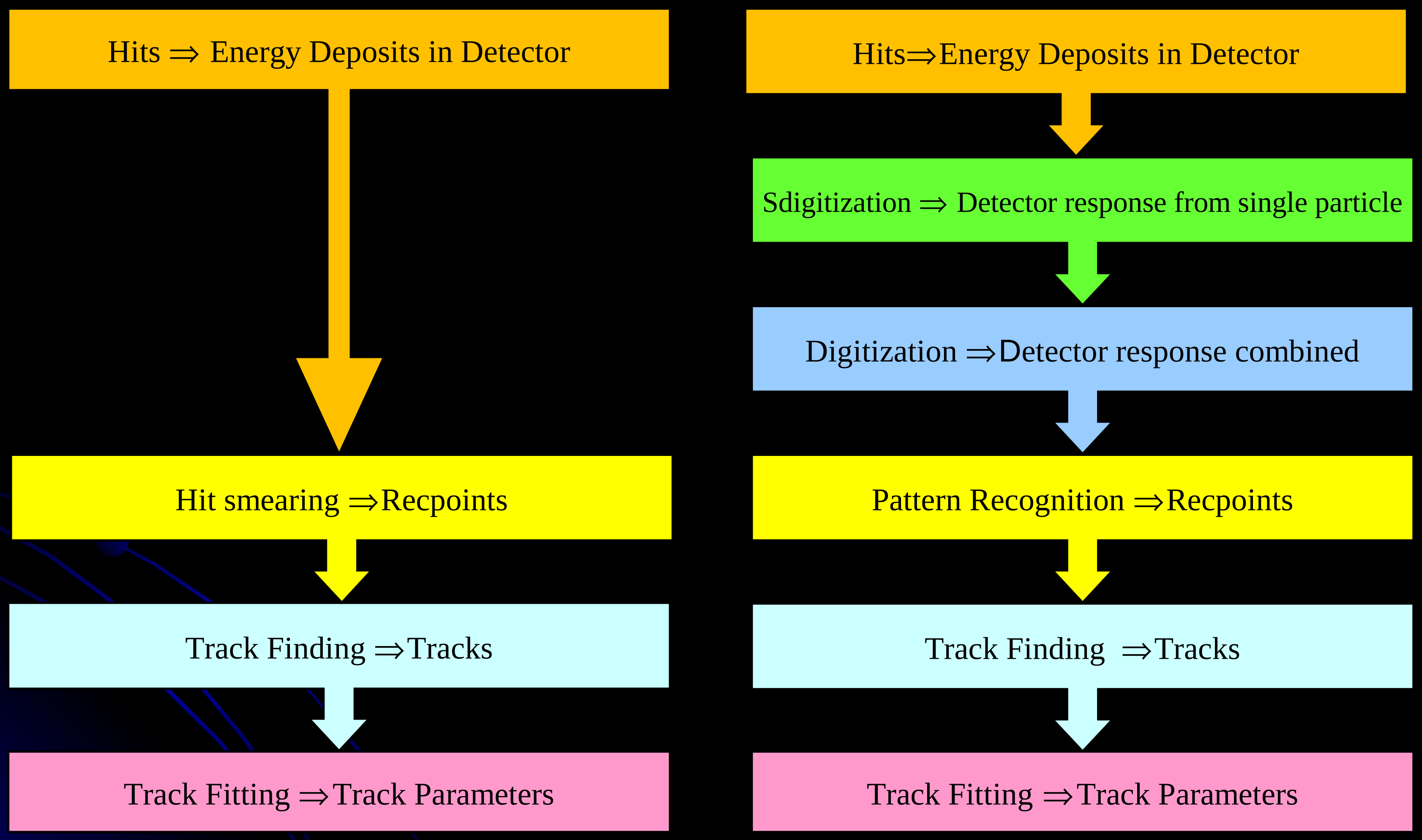
ILCroot Flow Control



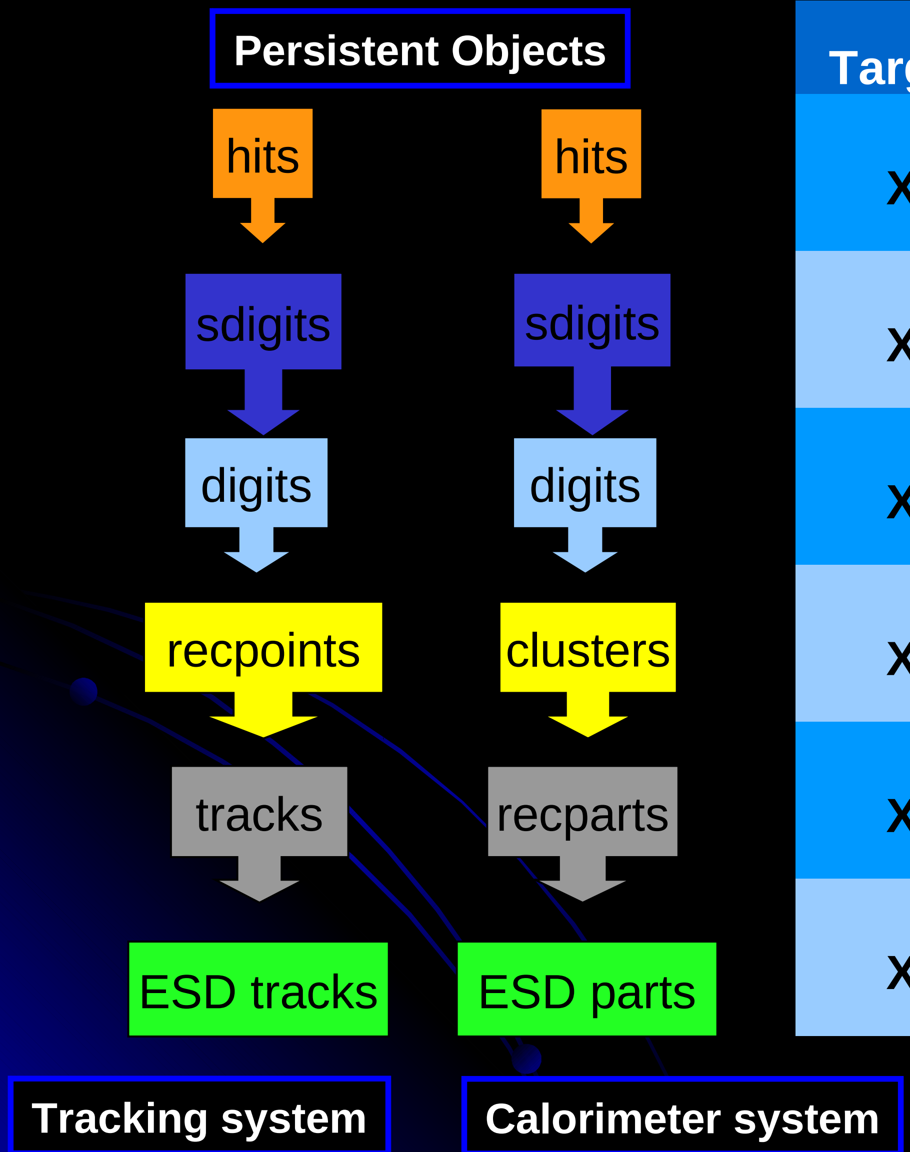
ILCroot Simulation steps



ILCroot Fast vs Full Simulation



Detector Simulation Status



Target	DCH	RS	PVBAR	PVEC
X	X	X	X	X
X	X	X	X	X
X	X	X	X	X
X	X		X	
X	X		X	
X	X		X	

ADRIANO: simulation chain

Hits:
Pacticles interaction with media.
Relevant output: **photons**

SDigits:
Is the ideal contribution to Digits originate by each Hit.
Is ideal detector response without Front End Electronics effects.
Relevant output: **p.e.**

Digits:
is the sum of all SDigits belonging to the same electronics channel.
it takes into account Front End Electronics.
Relevant output: **ADC counts**

Hits production in ADRIANO

- **Scintillating component.**
  - Select charged particles.
  - Get energy deposition (dE).
  - Apply Birk's correction to dE.
  - **Apply decay time in scintillator and in WLS.**
- **Cerenkov component.**
  - Cerenkov angle evaluated via Sellmeier dispersion relation and particle beta.
  - Cerenkov photons generated with appropriate wavelength spectra in 5nm bins.

$$dN_{\gamma} = 2\pi L_{step}\,\alpha \sin^2(\theta_C)\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

  - **Apply decay time in WLS.**
- **Both components.**
  - Calculate light-yield.
  - Hits merged within the same channel, from same primary and within 1ps time window.
- **Used parameters.**
  - Scintillator Light Yield Mean: 133 photons/MeV (take into account reflection, absorption and WLS collection efficiency).
  - DecayTime WLS: 2.4 ns
  - DecayTime scintillator: 2.4 ns

SDigits production in ADRIANO

- **Scintillating and Cerenkov component.**
  - Apply WLS attenuation length.
  - Apply WLS → SiPM collection efficiency.
  - Apply SiPM detection efficiency (PDE).
  - Apply Poisson smearing.
  - **Update time with travel time of light in WLS.**

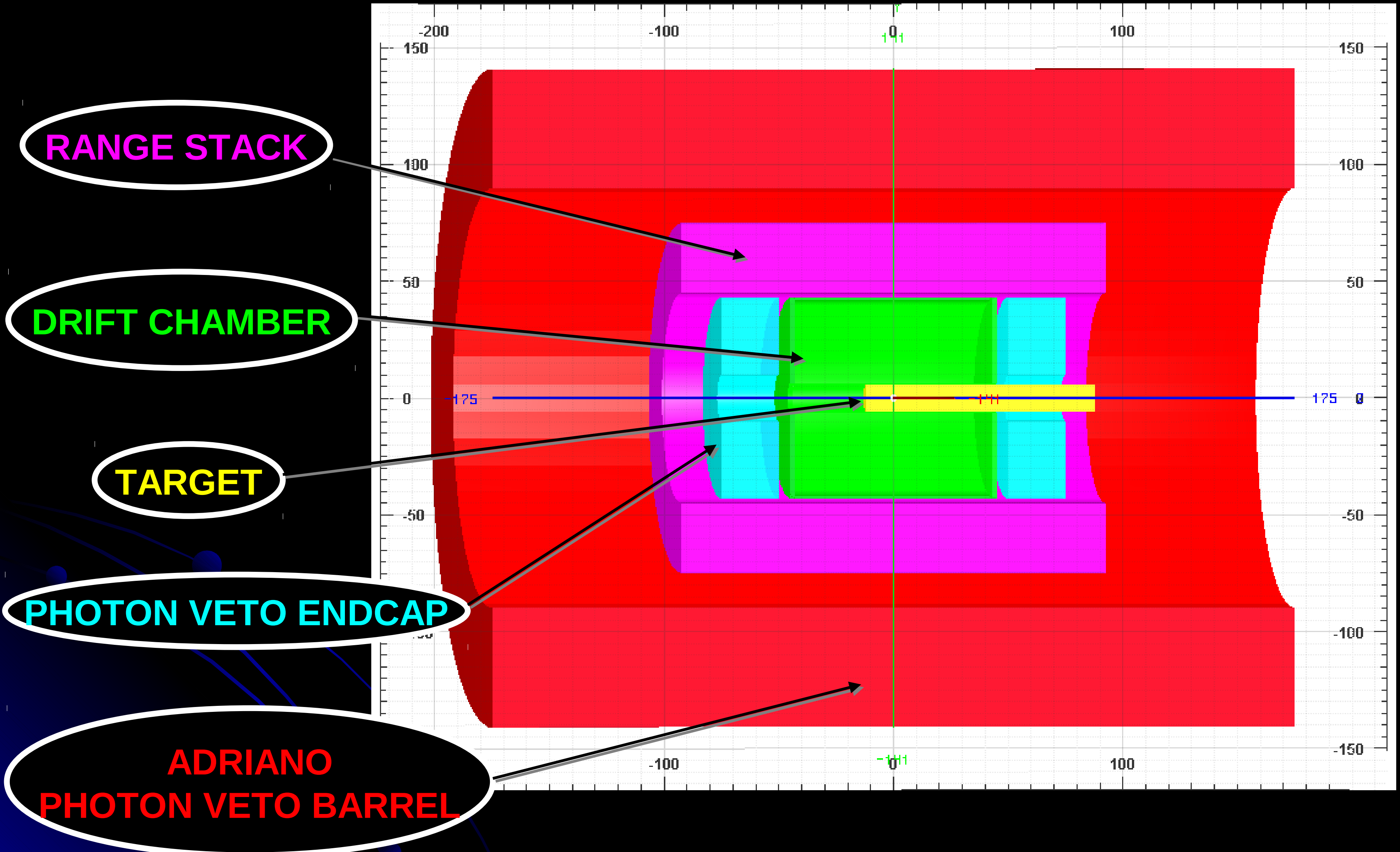
- **Used parameters.**
  - WLS attenuation length: 450 cm.
  - WLS → SiPM collection efficiency: 90%.
  - PDE $\simeq$ 20% (depend on light wavelength).

Digits production in ADRIANO

- **Scintillating and Cerenkov component.**
  - Limit number of p.e. to total number of SiPM pixels.
  - Apply shot noise.
  - Apply Excess Noise Factor (ENF).
  - **Apply z position fluctuation (From KLOE $\propto$ 1/sqrt(E[GeV])).**
  - Apply electronic gain and convert p.e. in ADC counts.
  - **Apply electronic rise time.**
  - Remove Digits below threshold.

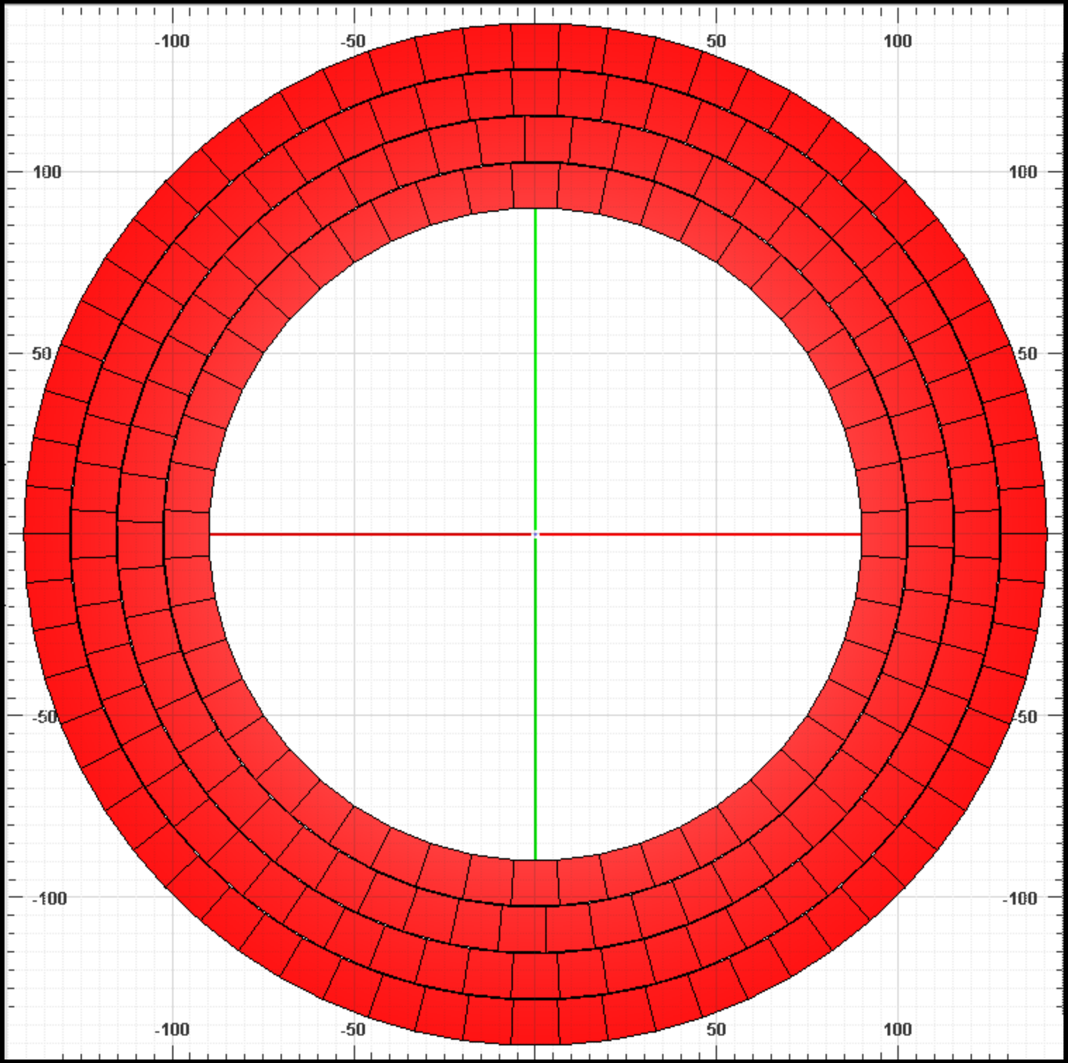
- **Used parameters.**
  - Number of SiPM pixels = 6400.
  - SiPM shot noise = 0.1 p.e.
  - ENF = 1.016.
  - Z position fluctuation = 6mm/sqrt(E[GeV]).
  - Electronic gain = 10 (can be different for Cer and Sci signal).
  - ADC width = 0.1 p.e. (can be different for Cer and Sci signal).
  - Electronic RiseTime = 0.5 ns.
  - ADC threshold = 4 ADC counts. (can be different for Cer and Sci signal).

ORKA Detector in ILCroot

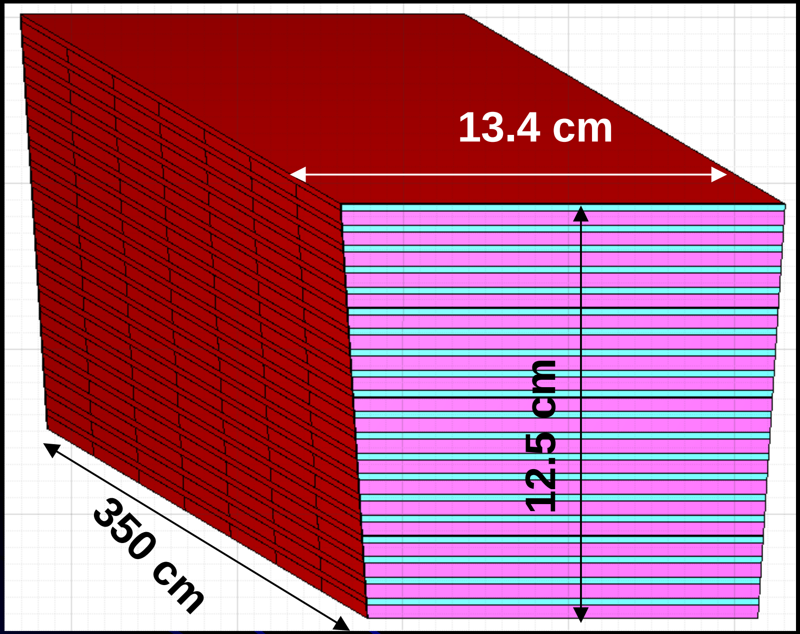


ADRIANO Photon Veto Barrel Geometry

- PV Barrel divided into 4 layers 12.5 cm thick.
- Z = 350 cm.
- $R_{in} \simeq 89.7$ cm.
- $R_{out} \simeq 140.8$ cm.
- Each layer subdivided in cells with similar transverse section.
- Cells per layer {48, 54, 60, 66}
- Cells staggered to avoid aligned cracks.
- Open space between layers filled with Plexiglas



ADRIANO Photon Veto Barrel Geometry



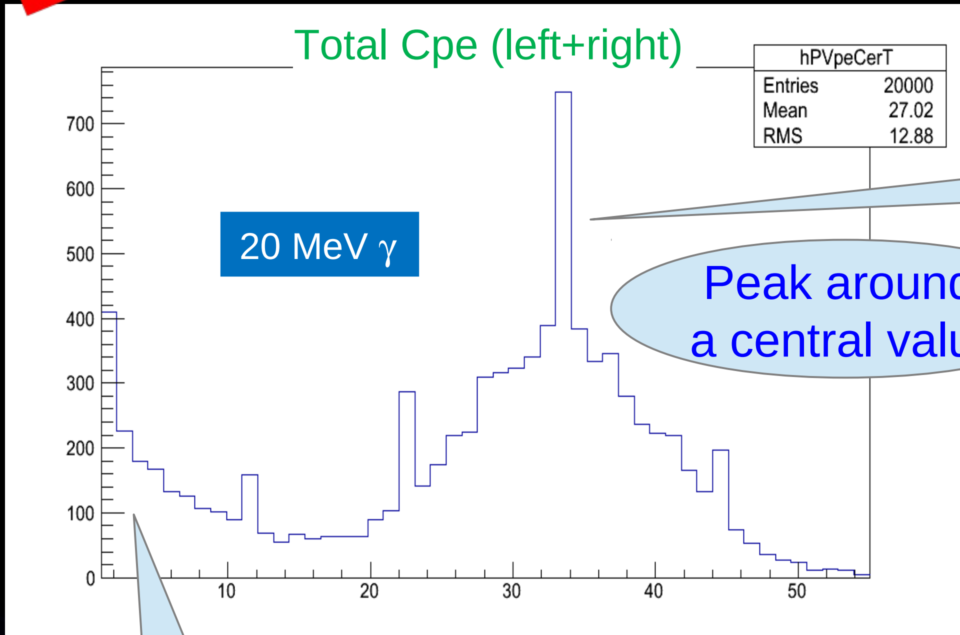
- Elementary cell has trapezoidal shape:
- Major base = 13.4 cm.
- Thickness = 12.5 cm.
- 20+20 alternated tiles optically de-coupled lead-glass (4.2 mm thick) scintillator (2.0 mm thick)
  + glue (25 μm thick).
- lead-glass made in 7 glued segments (50 cm long) along z.
- Photons collected in lead-glass and scintillator by distinct WLS.
- Each cell divided into 3x2x2 channels/side (ϕ, R, Cer/Sci). Readout on both sides.

Advantages of ADRIANO For ORKA

1. Energy from Cerenkov signal is narrower and picked also at low energy.
2. Integrally active detector has lower inefficiency than sampling calorimeters.
3. Left-right reading of Cerenkov signal provide z-component measurement (important for π^0 reconstruction).
4. PID from S vs C helps in reducing accidentals from neutrons.

Preliminary

Čerenkov signal is narrower



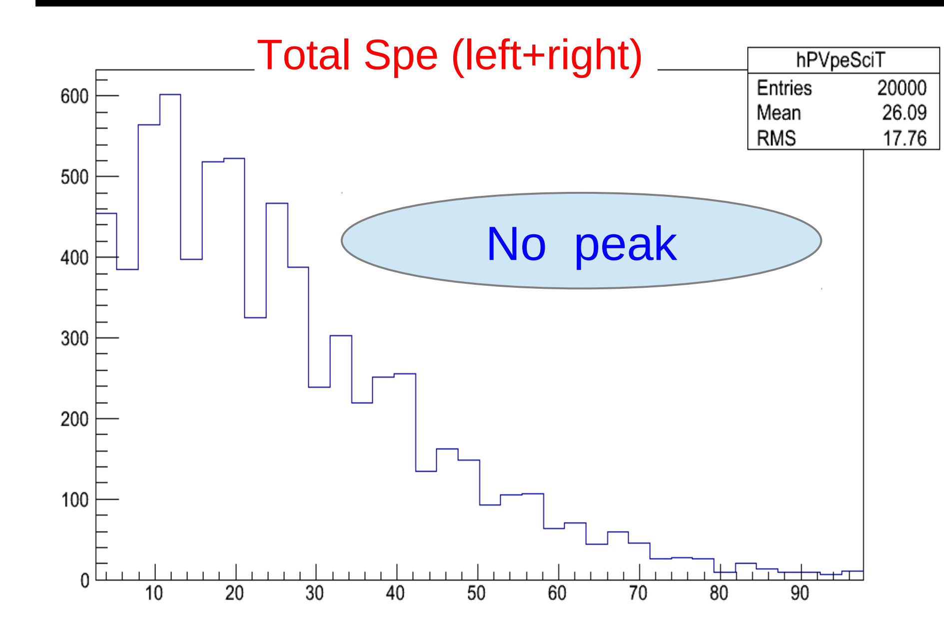
γ interacting in ADRIANO

Peak around
a central value

Same situation as Shashlik

A binomial component
appears at low energies
in the scintillating signal

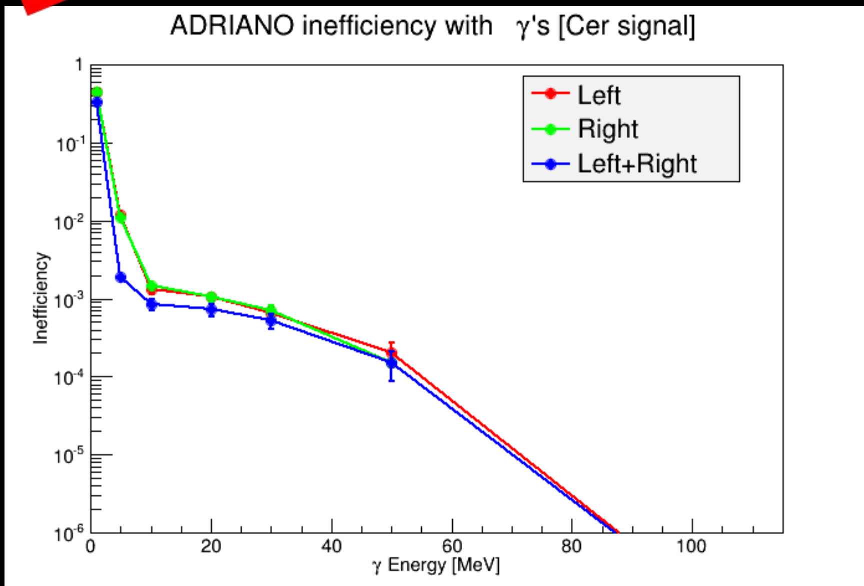
γ interacting before ADRIANO

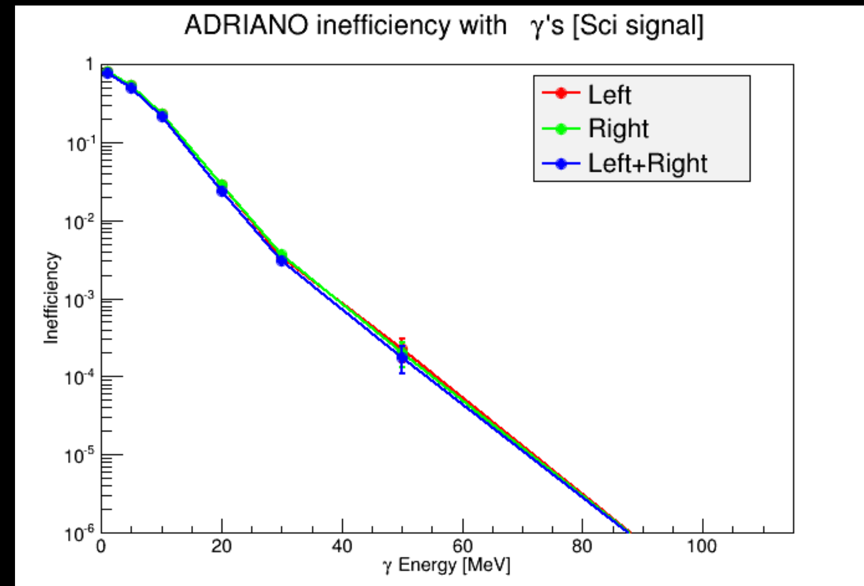


No peak

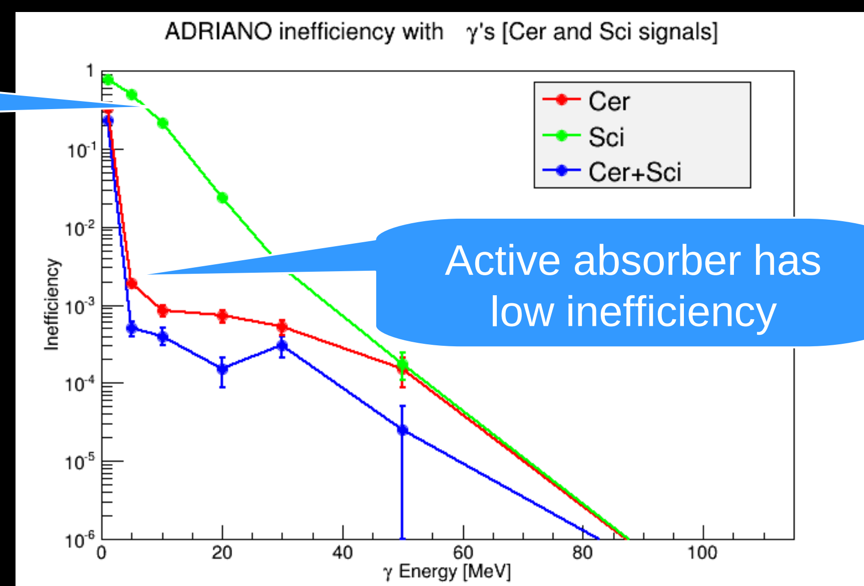
Preliminary

Integrally active detector has lower inefficiency





Scintillating signal suffers at low energy from sampling mechanism



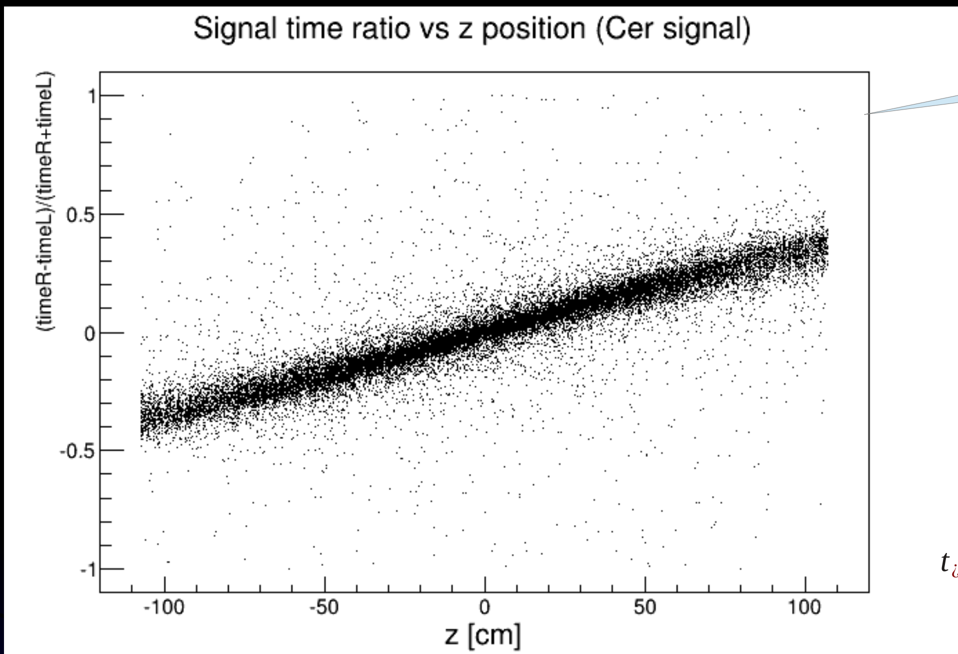
Active absorber has low inefficiency

Integrally active detector has lower inefficiency

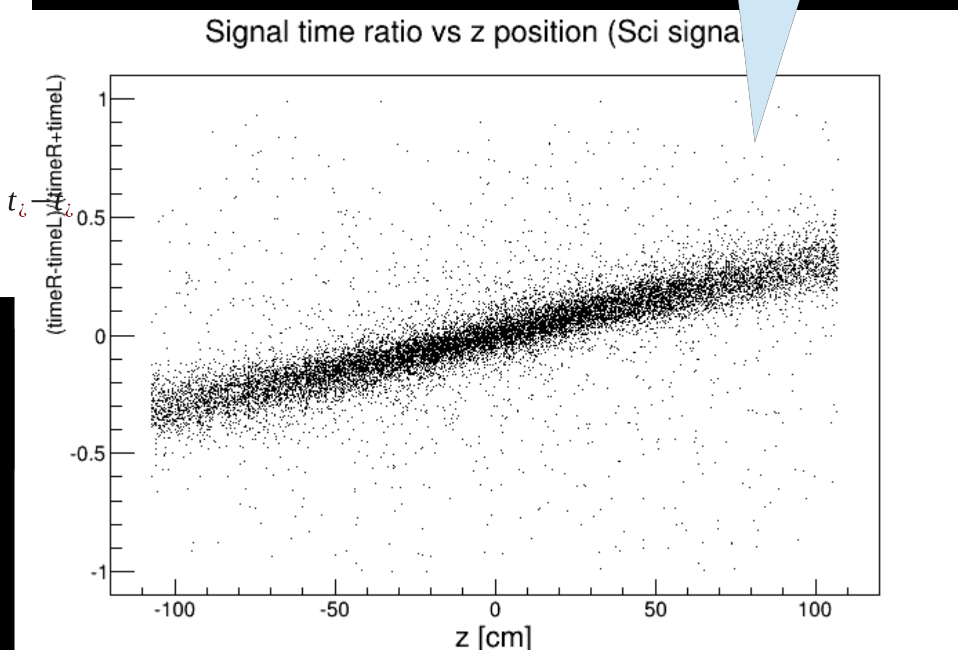
Preliminary

Left-right reading of Cerenkov signal provide z-measurement

Lead glass



Scintillator

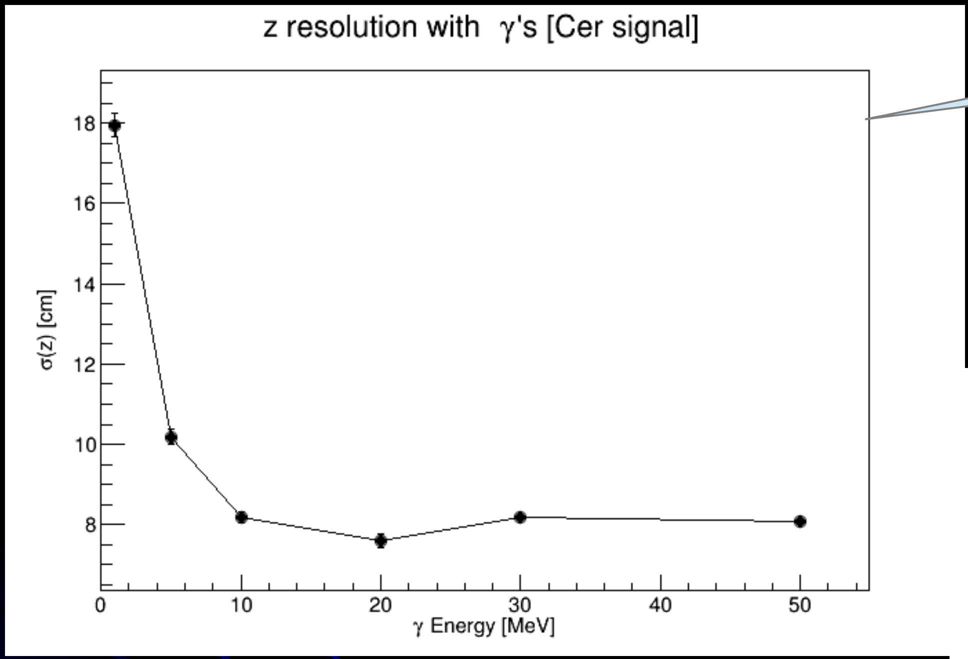


Time difference from the readout both sides for z measurement

$$z \propto \frac{t_R - t_L}{t_R + t_L}$$

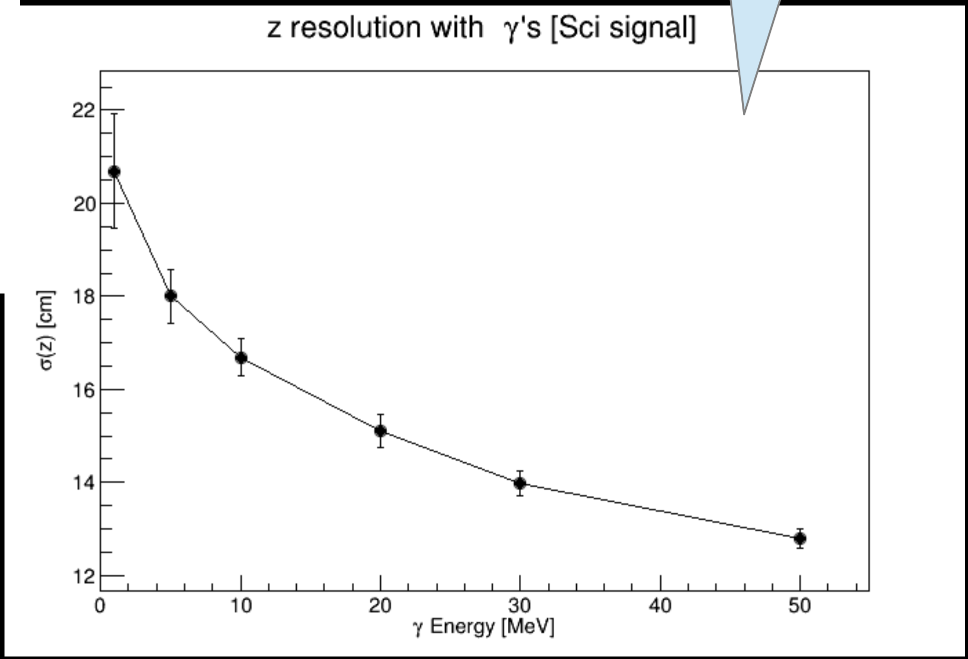
Preliminary

Left-right reading of Cerenkov signal provide z-measurement



Lead glass

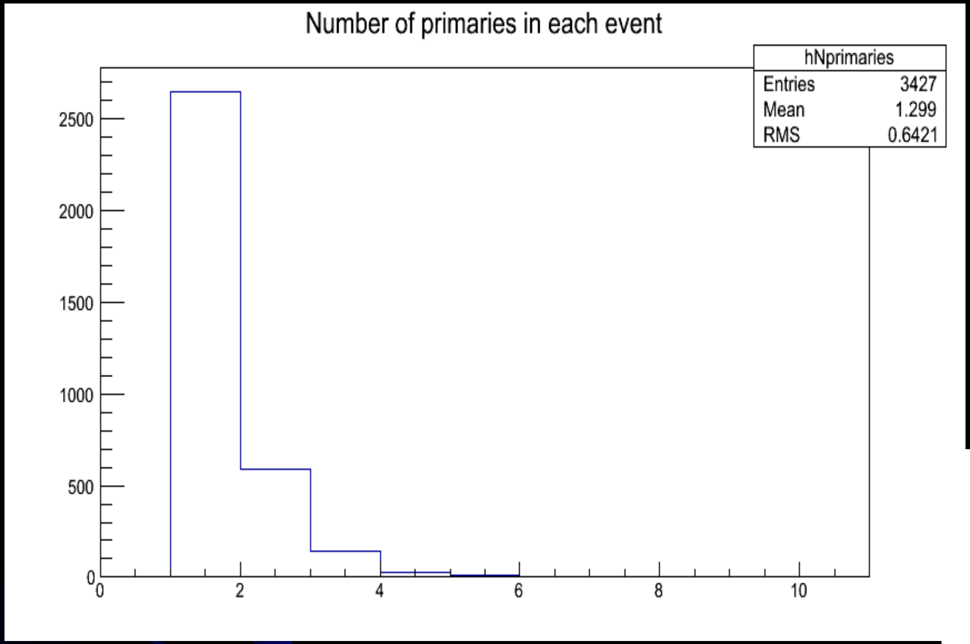
Scintillator



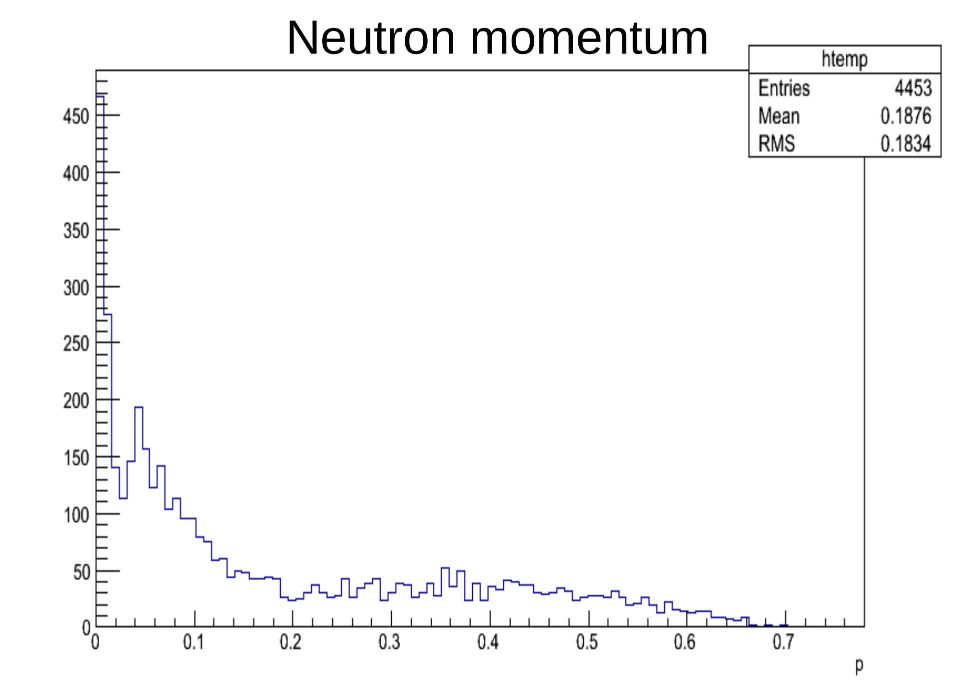
Cer time give better resolution.

Čerencov signal is promt. Only decay time from WLS.

PID from sci vs cer

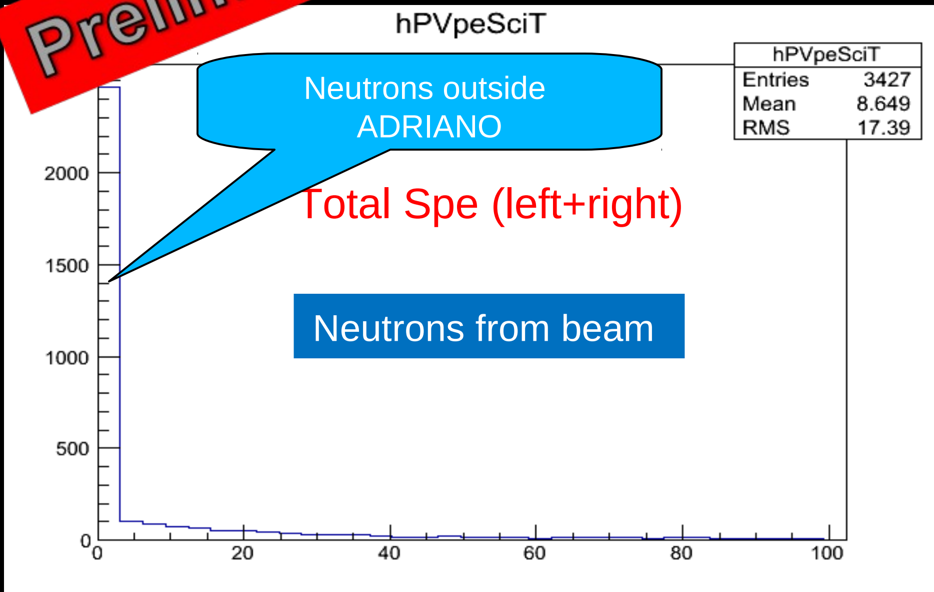


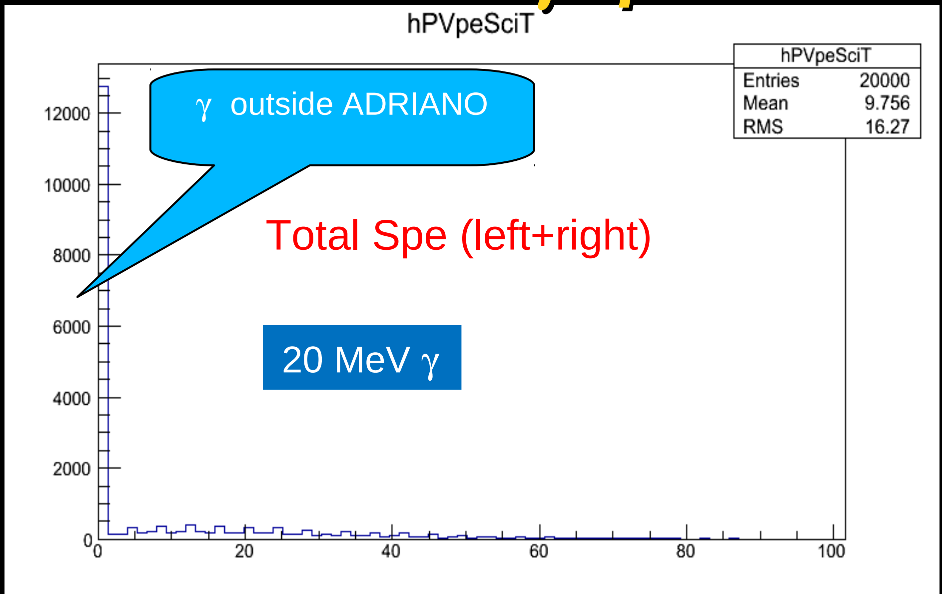
(Preliminary study by J. Jensen for Kaon beam)



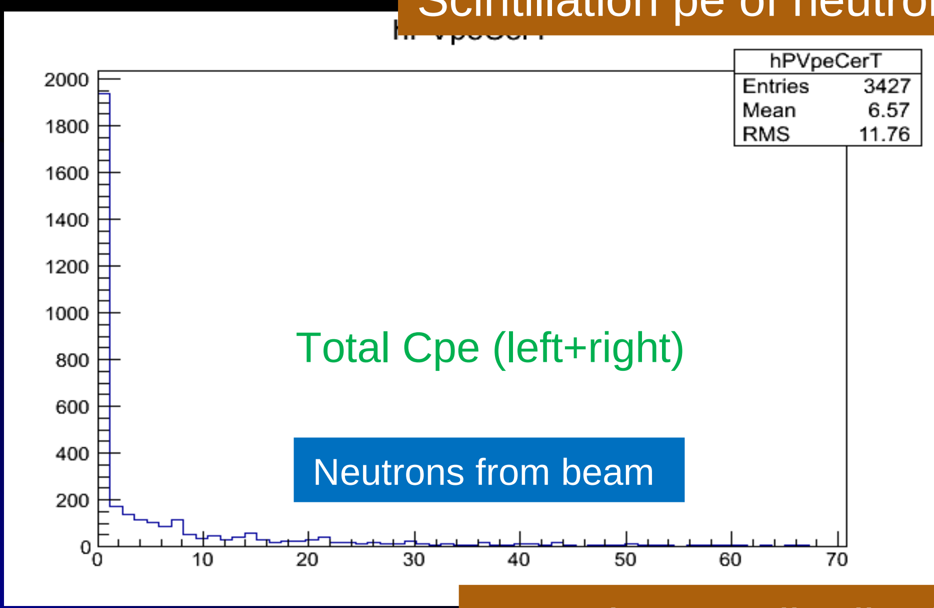
Neutron effects in ADRIANO vs 20 MeV γ: pe/evt

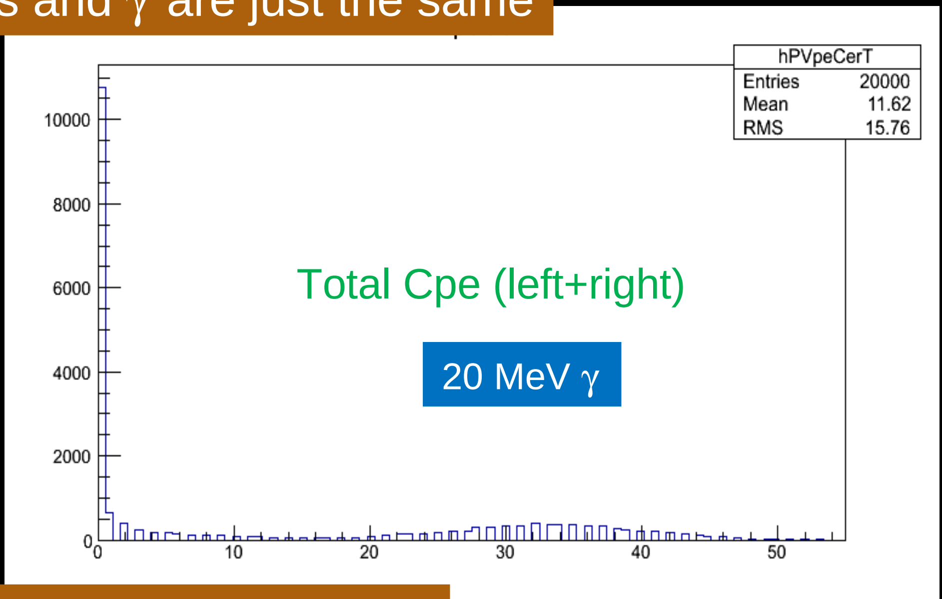
Preliminary





Scintillation pe of neutrons and γ are just the same

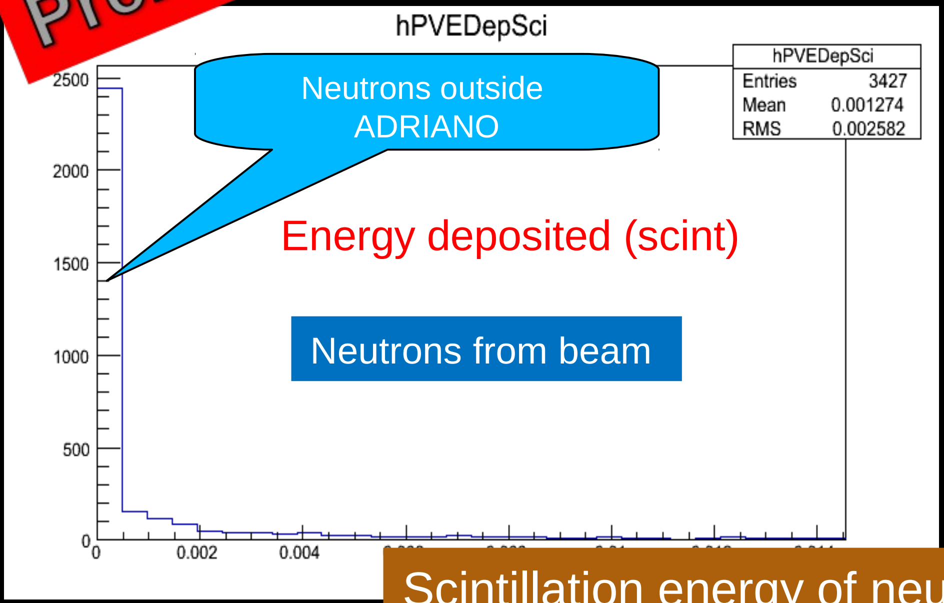


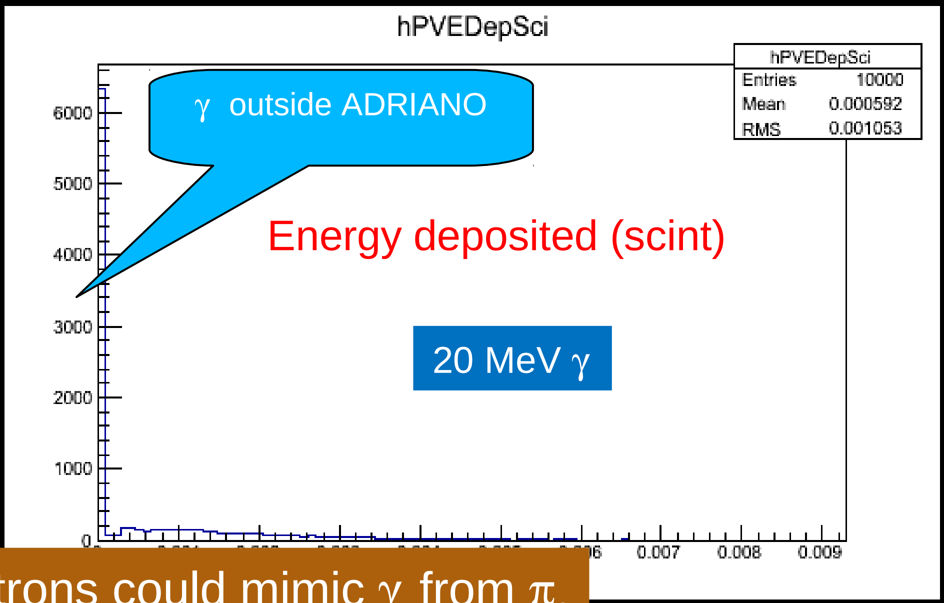


Cerenkov pe distributions are very different

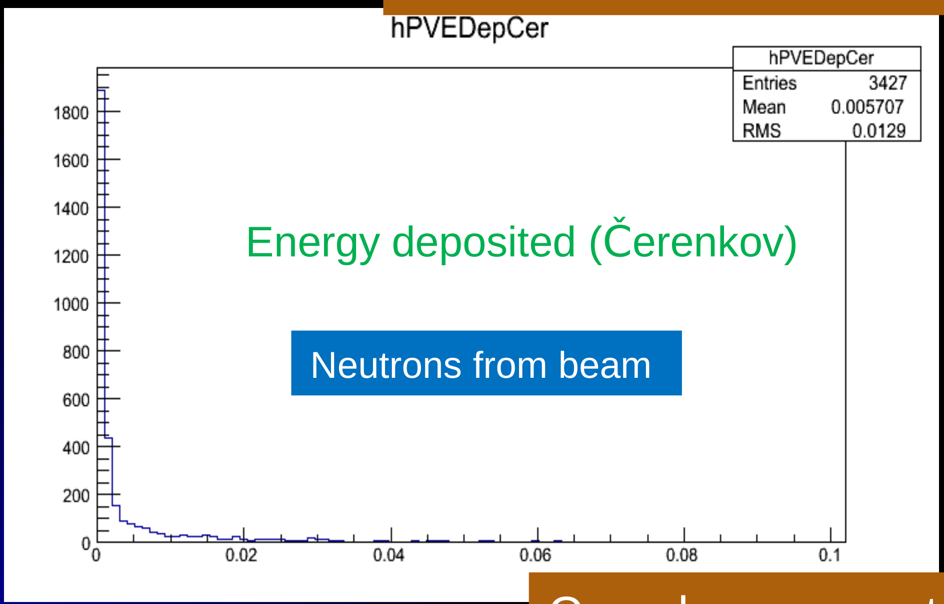
Preliminary

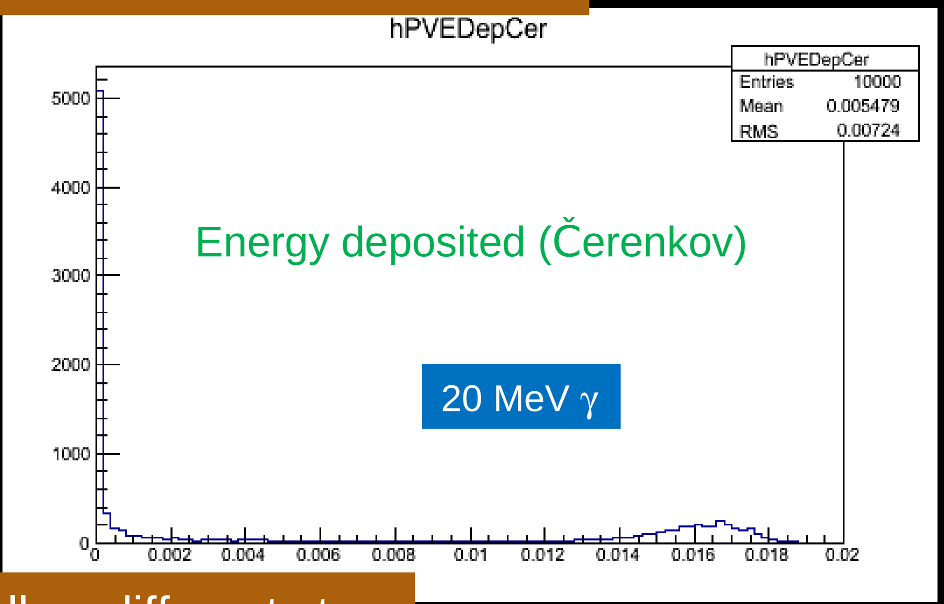
...n effects in ADRIANO vs 20 MeV γ : Edep/evt





Scintillation energy of neutrons could mimic γ from π_o

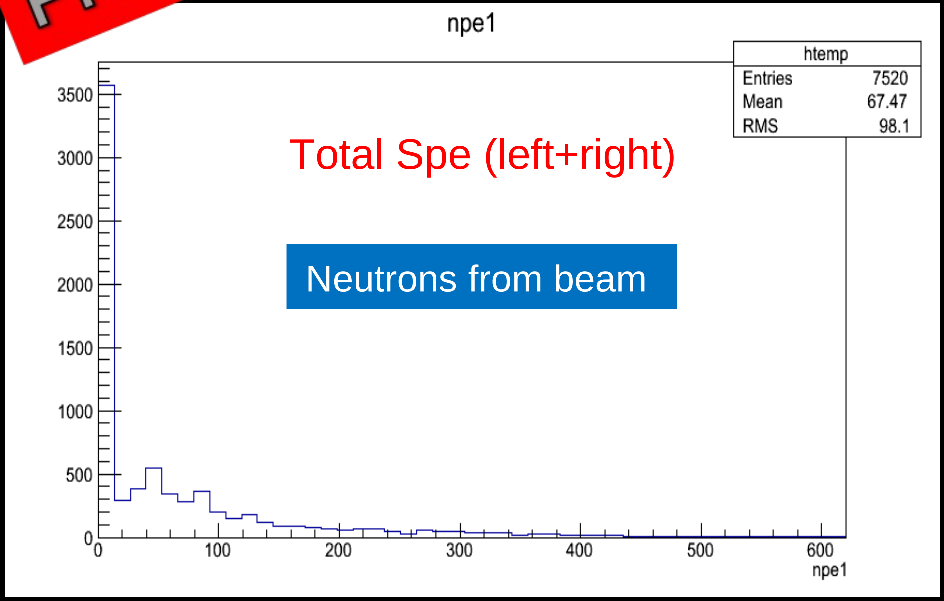


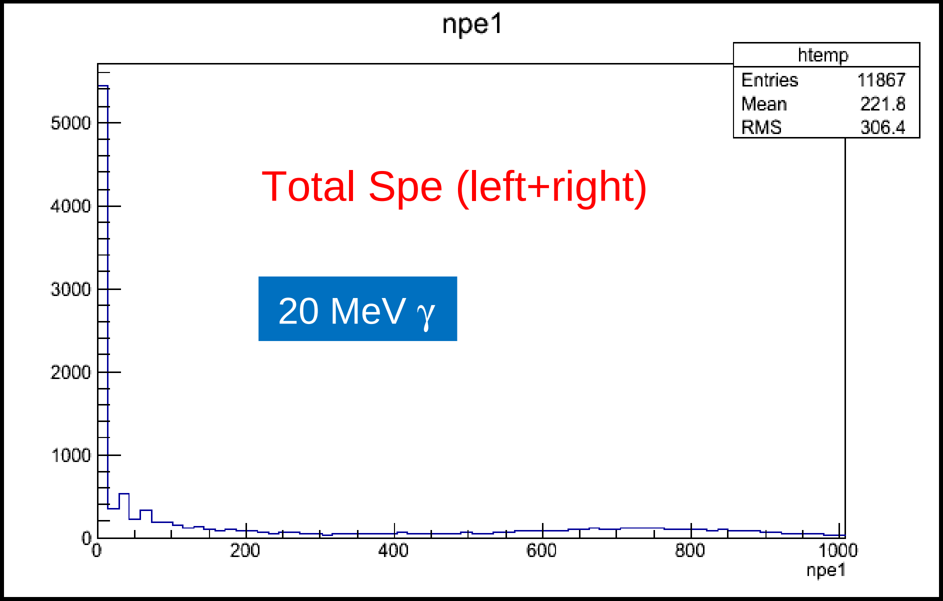


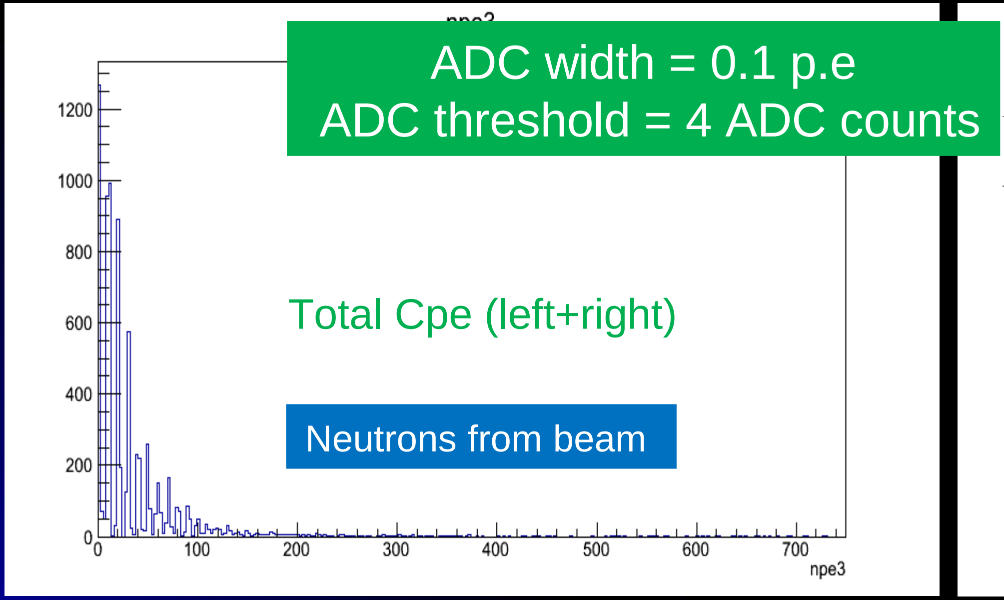
Cerenkov energy tells a different story

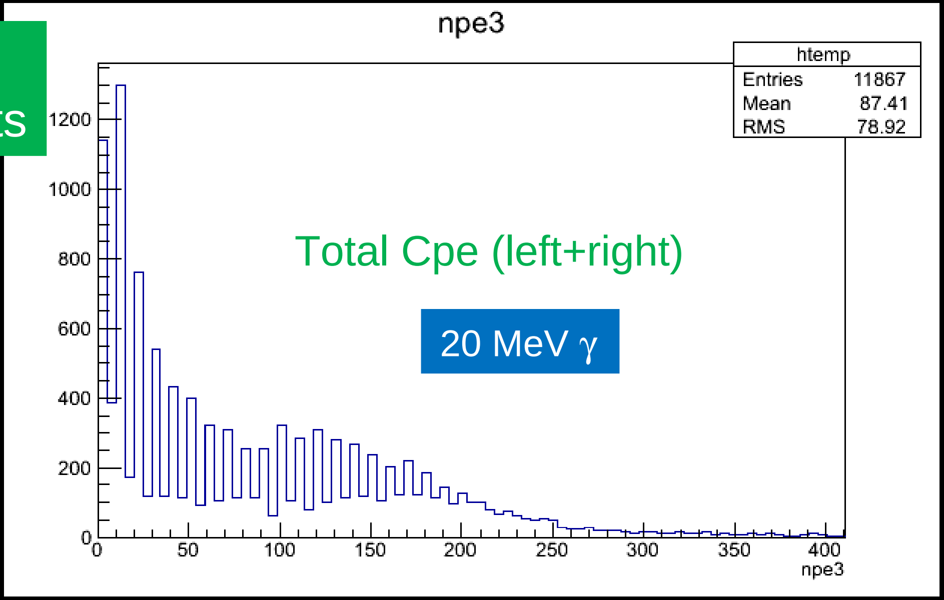
Preliminary

Neutron effects in ADRIANO vs 20 MeV γ: ADC count









Summary

- Dual-readout technique improves the energy resolution of a hadronic calorimeter.
- It is one of the two approaches for a calorimeter at future Lepton Colliders.
- ADRIANO technique overcomes limits of sampling calorimeters.
- Intense R&D ongoing at Fermilab and Italy.
- Proposed a modified version of ADRIANO calorimeter for ORKA photon veto Barrel.
- Two options under study:

A) ADRIANO in dual-readout mode

B) ADRIANO in single readout mode

- Intense simulation activity in progress using IlcRoot framework.
- Future test beams at FNAL and University of Naples already planned.
- Approved project between University of Naples and INFN to build a “neutron line” at an extisting TANDEM facility with tagged neutrons from nuclear reaction in 2MeV-12 MeV range ($D+D \rightarrow He^3 + n$).

Photon Veto or Calorimeter

It depends on the process!

Process	Current	ORKA
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \pi^0 X^0$	$<\sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$
$K^+ \to \mu^+ \nu_{heavy}$	$< 2 \times 10^{-8} - 1 \times 10^{-7}$	$< 1 \times 10^{-10}$
$K^+ \to \mu^+ \nu_\mu \nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$
$K^+ \to \pi^+ \gamma\gamma$	293 events	200,000 events
$\Gamma(Ke2)/\Gamma(K\mu2)$	$\pm 0.5\%$	$\pm 0.1\%$
$\pi^0 \to \nu\bar{\nu}$	$< 2.7 \times 10^{-7}$	$< 5 \times 10^{-8}$ to $< 4 \times 10^{-9}$
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$

Photon Veto or Calorimeter

Photon veto required here

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Photon Veto or Calorimeter

Energy measurement required here

Process	Current	ORKA
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$
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Technologies For Barrel

Shashlyk

Pro

- Cheap
- Well established technology
- Extensive test beam

- Cons
  - Sampling fluctuations
  - Inadequate for E_{γ}<50 MeV see KOPIO R&D
  - Large inefficiency for low energy photon

ADRIANO in dual-readout mode

- Pro
  - Integrally active calorimeter
  - Higher detection efficiency
  - S vs C provides PID

- Cons
  - More expensive
  - Novel technology
  - Tested only at high energy (500 MeV)

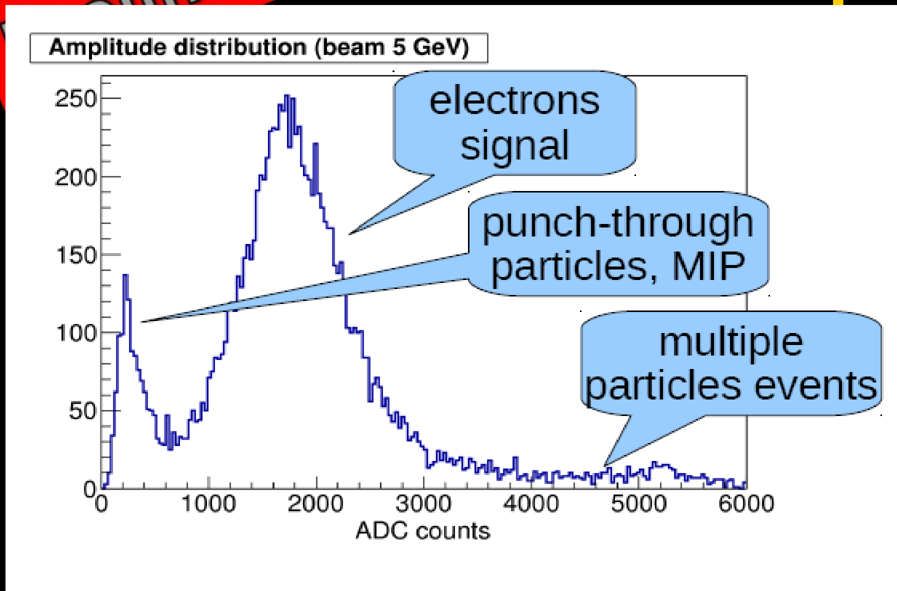
ADRIANO in single readout mode

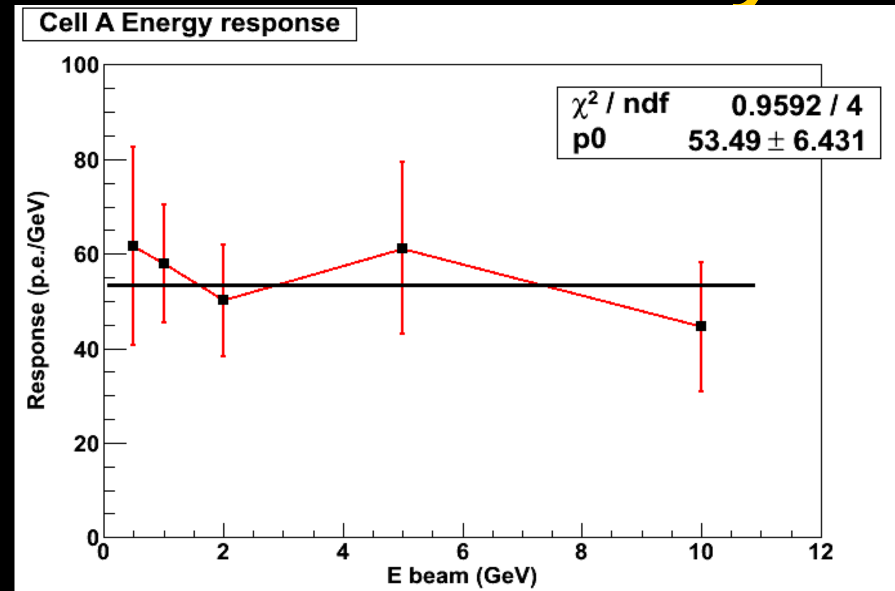
- Pro
  - Integrally active calorimeter
  - Highest detection efficiency

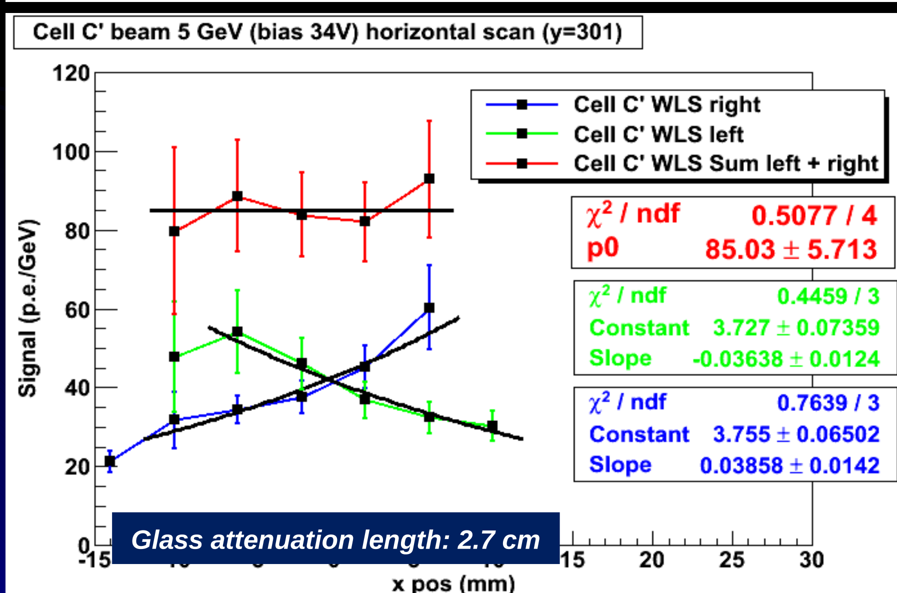
- Cons
  - Also expensive
  - Untested technology
  - No PID

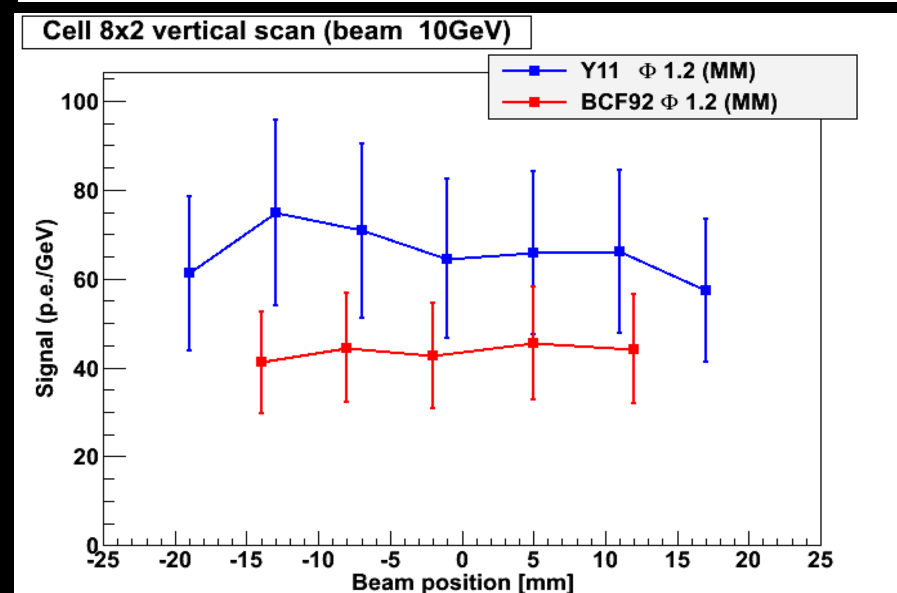
Detector Response Uniformity

Preliminary







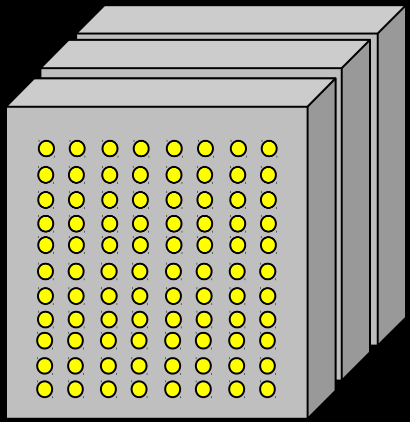


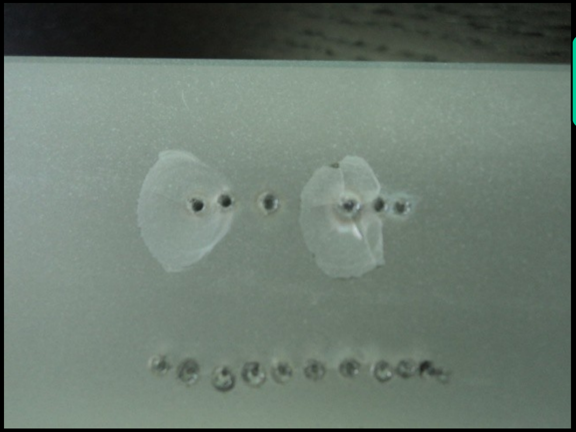
Very Intense R&D within T1015 Collaboration

- 5 test beams scheduled in 2011-2012 at FTBF
- Several cells in different configurations (40x40x250 mm^3)
- Many variants of ADRIANO
- Tested: glass, fibers, coating, optical coupling, PMT vs SiPM, etc.

-

Fabrication Technology #4: Laser + diamond drilling

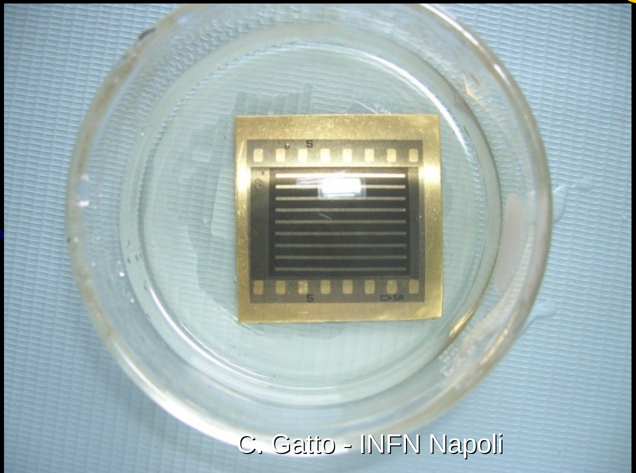




Nd-YAG laser

Fabrication Technology #5: Photo-etching

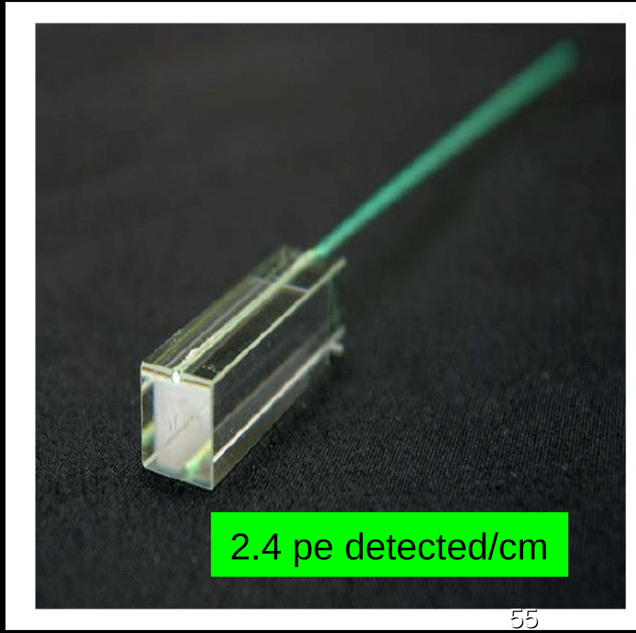
Early stages of R&D



ADRIANO Simulations in ILCroot

- **ILCroot: C++ Software architecture based on root, VMC & Aliroot**
  G3, G4, Fluka + all ROOT tools (I/O, graphics, PROOF, data structure, etc)
  - ***Single framework, for generation, simulation reconstruction and analysis***
- *ADRIANO* is a melting pot of well established experimental methodologies
- All algorithms are implemented parametrically
- Use known experimental setups to normalize the overall results:
  - ***DREAM for scintillating light production (fiber calorimeter is OK, BGO+fibers not quite there)***
  - ***CHORUS for instrumental effects with sci-fibers***
  - ***R. Dollan Thesis for WLS light collection with SF57***

Instrumental effects included in ILCroot:
- SiPM with ENF=1.016
- Fiber non-uniformity response = 0.6% (scaled from CHORUS)
- Threashold = 3 pe (SiPM dark current < 50 kHz)
- ADC with 14 bits
- Constant 1 pe noise.



Next: New Glasses R&D in T1015

- **Research mostly carried at Department of Materials and Environmental Engineering at Uni-Modena (Italy)**
- Heavy glasses with ***no-Pb*** (Cerenkov only)
  - ***Mostly Bi based (heavier, less environmental issues, higher n_D, lower softening point for molding)***
  - ***WO_2 under study (just purchased a 1600 °C furnace)***
  - ***Goal is >8 gr/cm^3***
- Rare earths doped scintillating heavy glasses:
  - ***Ba-Bi-B matrix to accomodate Ce_2O_3 :***
  - ***Density achieved up to now: 7.5 gr/cm^3 (see next slide)***
  - ***Several rare earth oxides tested: Dy_2O_3 promising***
  - ***Lithium content for neutron sensitivity***
- Organic scintillator doped heavy glasses:
  - ***Requires low melting point glass matrix (< 500 °C)***
  - ***Currently under R&D at DIMA: P-T-F-P glass (up to 5.8 gr/cm^3)***

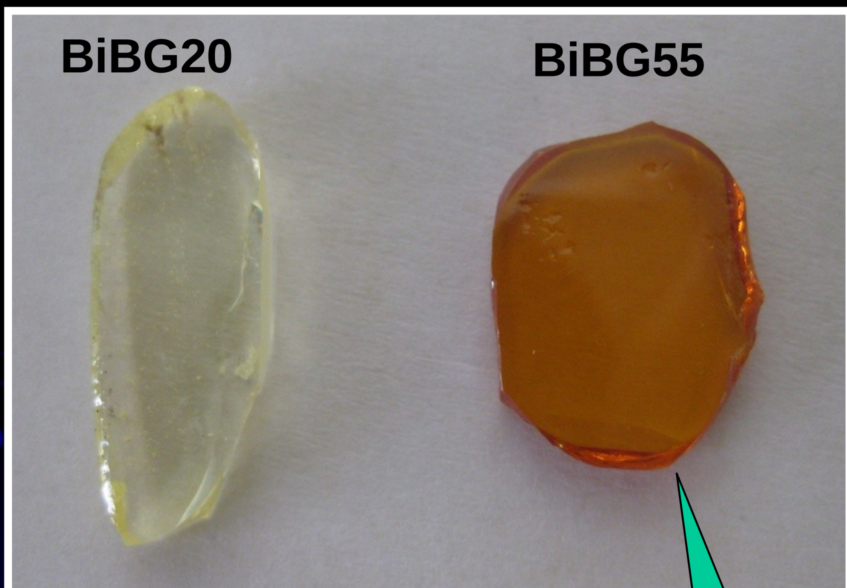
See D. Groom talk at CALOR2012

Consuelo Mugoni

Bismuth Borate Glasses BiB-G

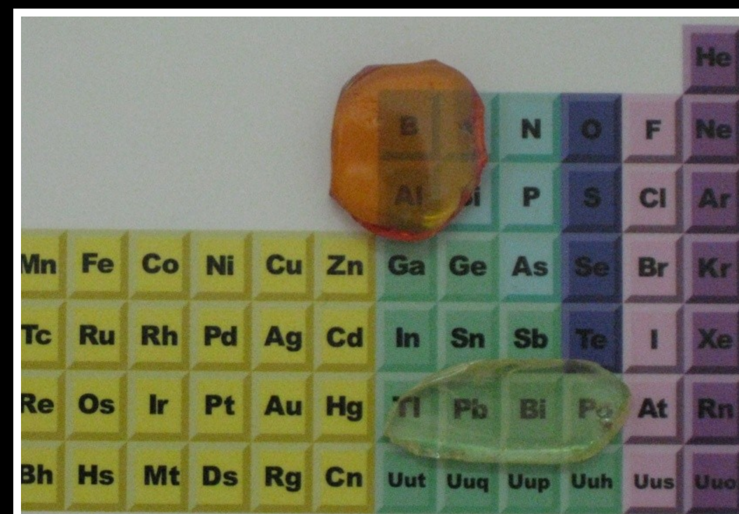
Goal *High density glasses by melt quench method*

- ***Two compositions (BiBG20 and BiBG55) with different Bi_2O_3 content***



Bi_2O_3 mol%

Dark color due to Bi_2O_3 not pure enough

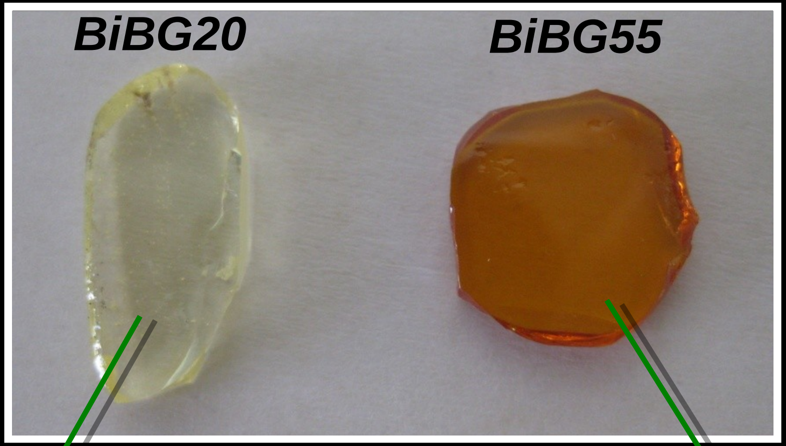


DENSITY

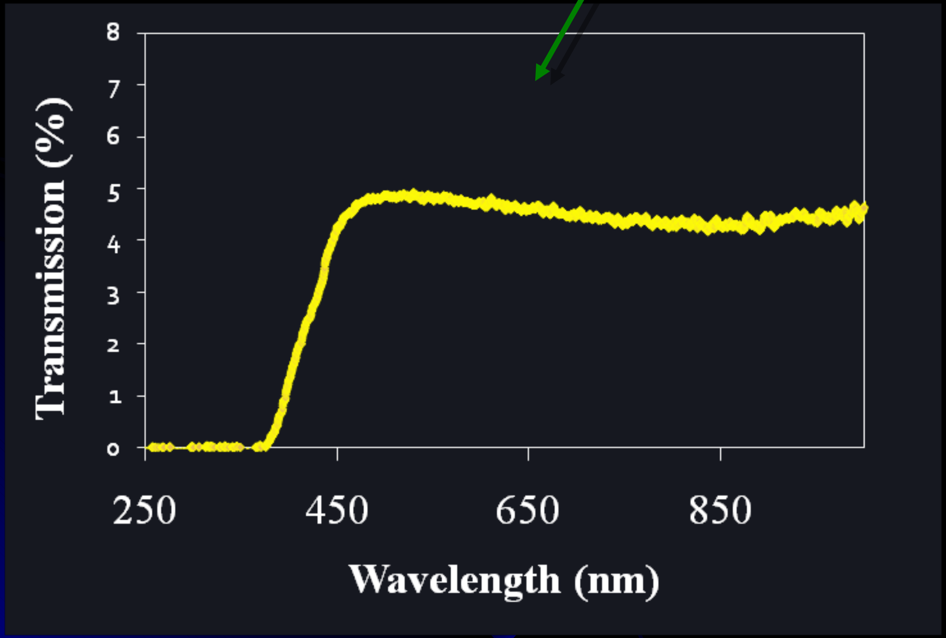
Glass	ρ (g/cm³)
BiBG 20	4.57
BiBG 55	7.48

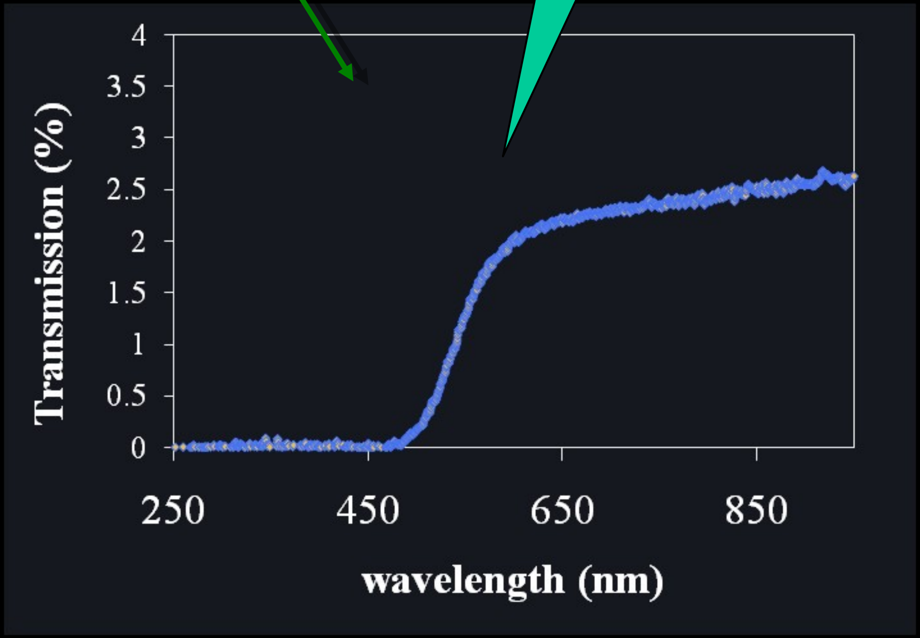
exp.error ± 0.01

Transmission Spectra



No absorption bands



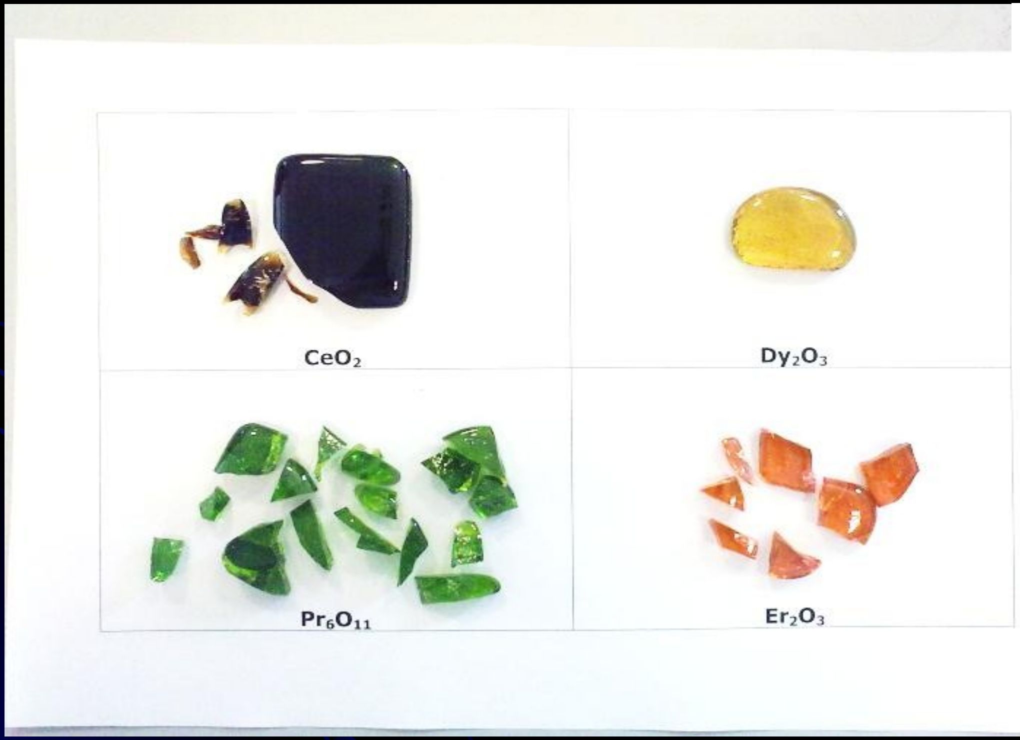


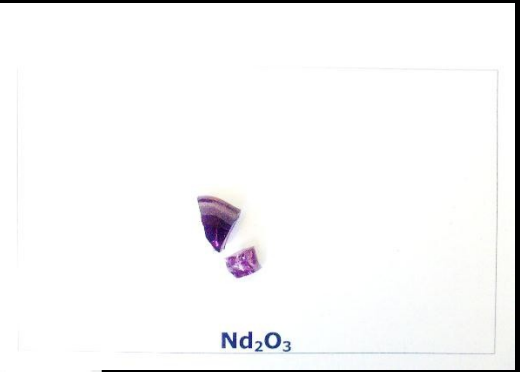
thickness c.a 0.3 cm

thickness c.a 0.3 cm

Rare Earth Heavy Glasses

- Rare earths oxides + Ho_2O_3 + ZnO + P_2O_5+B_2O_3+SiO_2
- R.e. considered: CeO_2, Dy_2O_3, Nd_2O_3, Pr_6O_{11}, Er_2O_3



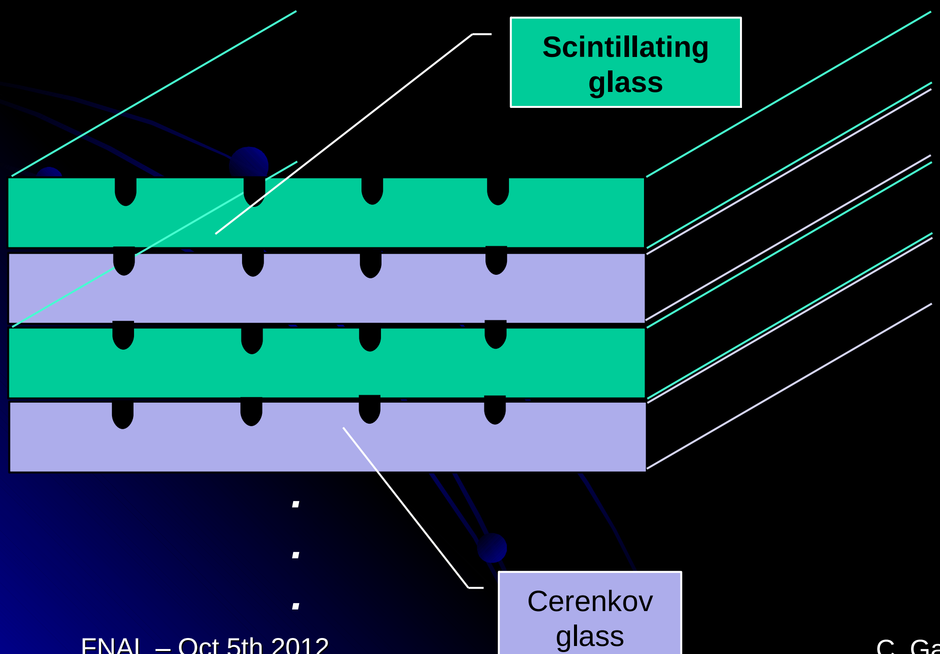


Composition	Density (g/cm^3)
CeO_2	3,3776
Pr_6O_{11}	3,7445
Dy_2O_3	3,8851
Er_2O_3	4,0690
Nd_2O_3	4,2441

Department of Materials and Environmental Engineering

ADRIANO II: aka Glass-only ADRIANO

- Advantages:
  - ***No density dilution from scifi plastic***
  - ***Excellent EM calorimeter***
  - ***Easier to build***
  - ***Cheaper (scifi are expensive!)***
  - ***Requires Li or H in the glass (see D. Groom talk at CALOR2012)***



SCG1- tested at FTBF

Light yield: > 600 pe/Gev (FEE saturating)

T1015 Collaboration at FNAL (28 scientists)

<u>Institution</u>

INFN Trieste/Udine and University of Udine
Fermilab
INFN NA
Lecce University
INFN and University
Roma I

University
of Salerno

University
of Modena

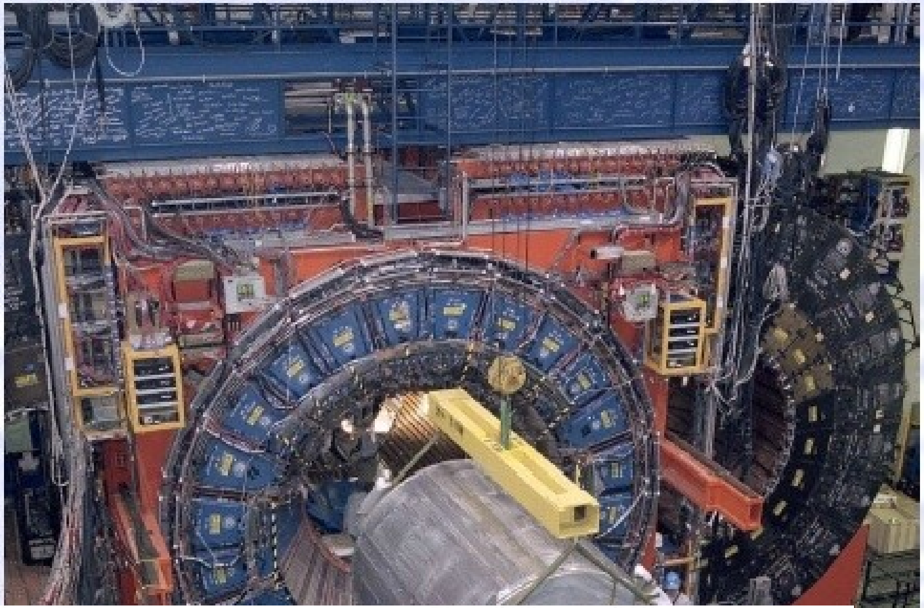
<u>Collaborator</u>

Diego Cauz
Anna Driutti
Giovanni Pauletta
Lorenzo Santi
Walter Bonvicini
Aldo Penzo
Erik Ramberg
Paul Rubinov

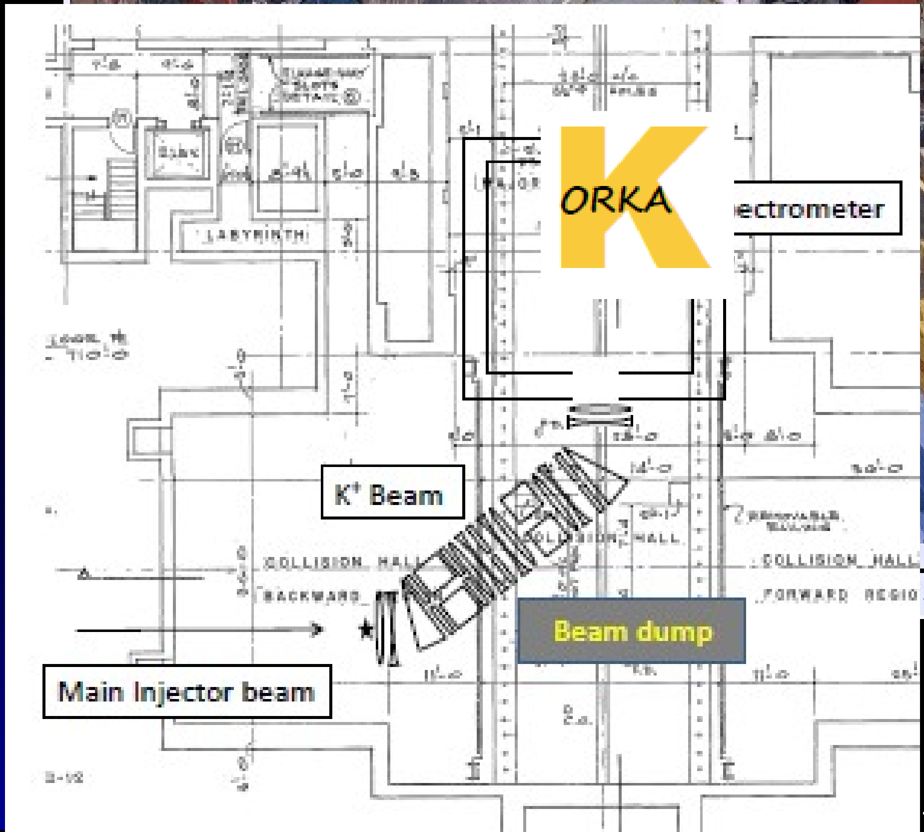
Hans Wenzel
Gene Fisk
Aria Soha
Anna Mazzacane
Benedetto Di Ruzza
Corrado Gatto
Vito di Benedetto
Antonio Licciulli
Massimo Di Giulio
Daniela Manno
Antonio Serra
Maurizio Iori
Michele Guida
NEITZERT Heinrich Christoph
SCAGLIONE Antonio
CHIADINI Francesco
Cristina Siligardi
Monia Montorsi
Consuelo Mugoni
Giulia Broglia

Future Prospects & Conclusions

- **Cerenkov ligth yield <u>more than adequate for 30%/sqrt(E)</u> calorimetry. Our goal is to make it even better for EM calorimetry**
- Precision molding is (at present) the preferred construction technique: two molds (37 cm long) under construction (flat and grooved)
- **Year 2013 program:**
  - ***14cm x 14cm x 74cm ADRIANO module (total 18 cells)***
  - ***9.2 cm x 4.6 cm x 37 cm module with scintillanti plates***
  - ***9.2 cm x 4.6 cm x 37 cm S+C module (for ORKA experiment)***
  - ***Test beam of scintillating glass module***
- **Ohara sponsorship/partership for bismuth optical glass (6.6 gr/cm^3, n_d = 2.0) in progress: two strips (total 1.4 Kg) provided at no cost**
- New Ohara heavy glass tested in 2012 at FNAL
  - ***7.54 gr/cm^3 ; n_d = 2.24***
- *ADRIANO*2 (Cerenkov + <u>scintillating glass</u>)
- **Heading toward a large prototype**
  - ***1,800 PMT appropriated from CDF***
  - ***2 ton SF57 left from NA62 calorimeter construction***

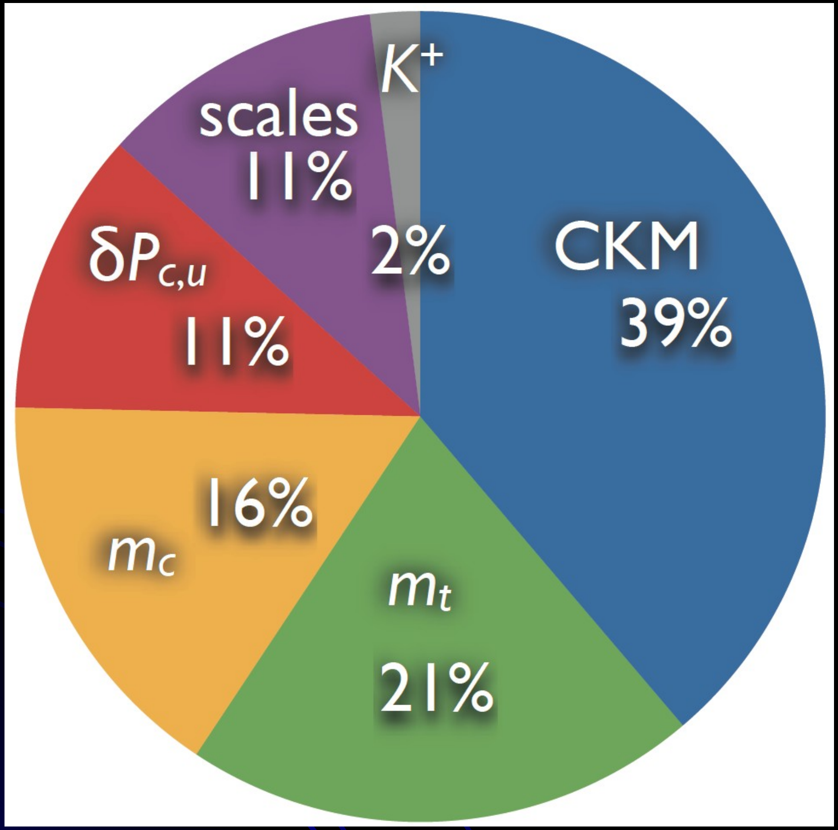


The ORKA new detector payload replaces the CDF tracker volume.



Summary of SM Theory Uncertainties

CKM parameter uncertainties dominate the error budget today.



With foreseeable improvements, expect total SM theory error ≤6%.

SM accuracy of <5%, motivates 1000-event experiments (ORKA proposal)

Unmatched by any other FCNC process (K or B).

30% deviation from the SM would be a 5σ signal of NP

Ex.:

$$M_{\rm NP} = \frac{4\pi}{\Lambda^2} C \overline{d}_L \gamma_\alpha s_L \overline{\nu} \gamma^\alpha \nu,$$

For Re(C)~Im(C)~O(1), a 10% measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ or $K_L \to \pi^0 \nu\bar{\nu}$ would probe $\Lambda \sim O(3{,}000\ \text{TeV})$

SM theory error for $K_L^0 \to \pi^0 \nu\bar{\nu}$ mode exceeds that for $K^+ \to \pi^+ \nu\bar{\nu}$.

J. Brod, M. Gorbahn, and E. Stamou, Phys. Rev. D83, 034030 (2011) [arXiv:1009.0947 [hep- ph]].

$K^+ \to \pi^+ \nu\bar{\nu}$ Prospects

$$Now:\quad \mathrm{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05}\, x10^{-10}$$

(7 events)

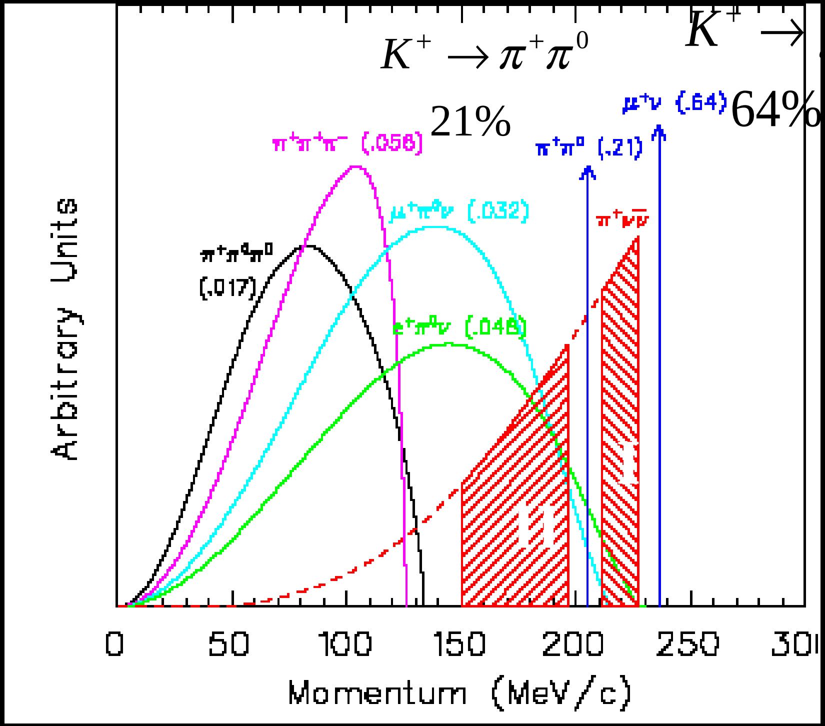
Future: Sensitivity at SM $0.78x10^{-10}$

Goals	NA62 CERN	ORKA	ORKA at Proj. X
Events/ yr	50	210	340
S/N	5	5	5
Precision	10%	5%	2%

Special Features of Measuring

$K^+ \to \pi^+ \nu \bar{\nu}$

Experimentally weak signature with background processes exceeding signal by $>10^{10}$



Determine everything possible about the K^+ and π^+

* π^+/μ^+ particle ID better than 10^6 (π^+ - μ^+ - e^+)

Eliminate events with extra charged particles or ***photons***

* π^0 inefficiency $< 10^{-6}$

Suppress backgrounds well below the expected signal (S/N~10)

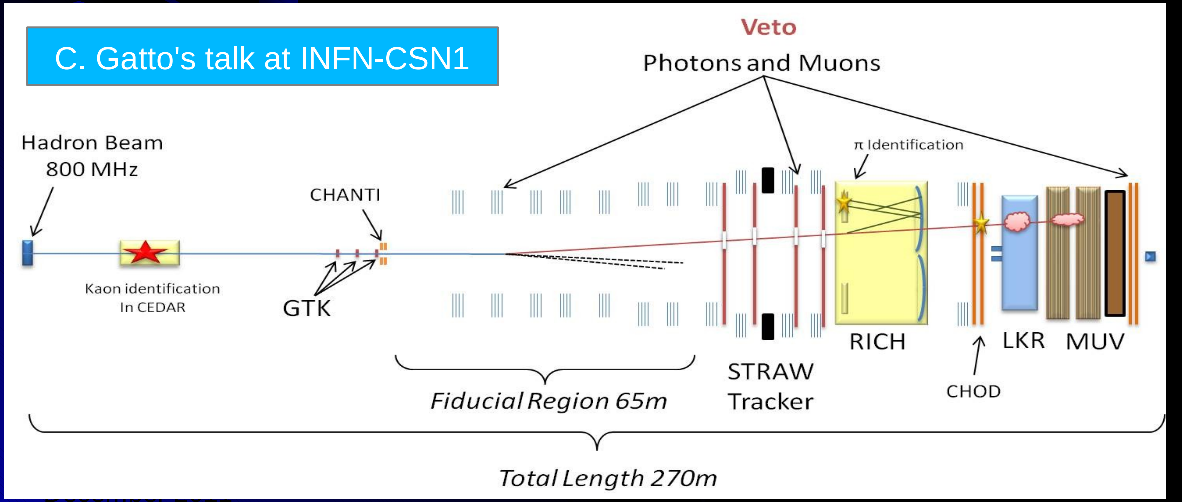
* Predict backgrounds *from data*: dual independent cuts
* Use "Blind analysis" techniques
* Test predictions with outside-the-signal-region measurements

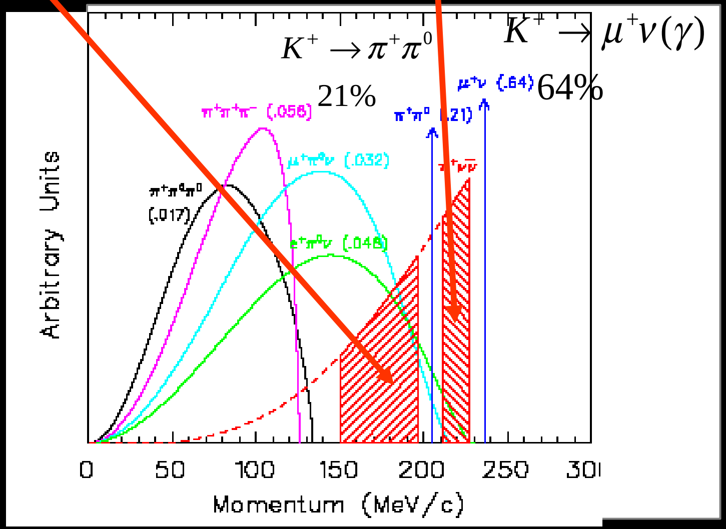
Evaluate candidate events with S/N function

NA62 vs ORKA

	NA62	ORKA
Technique	In-flight decay	Stopped K
Beam	Unseparated p/K (60% K)	Pure K
Phase space targeted	Lower region	Higher region
E/p detected	O(10 GeV)	1-230 MeV
Critical issues	PID up to 35 GeV (1-ε ~ 10^{-5})	Accidentals in PV
Advantages	No tagging of π->μ->e chain (higher rate)	High precision P measure
Notes	Running must be coincident with LHC, splits run-time with CNGS.	Splits run-time with NOVA.
First results	2017	2020
Sensitivity goal	~80 events	~1000 events

C. Gatto's talk at INFN-CSN1





Dual Readout Calorimetry

i.e.: two distinct calorimeters sharing the same absorber

$$E_S = \left[fem + \frac{(1-fem)}{\eta_S} \right] \cdot E_{HCAL}$$

$$E_C = \left[fem + \frac{(1-fem)}{\eta_C} \right] \cdot E_{HCAL}$$

$$\left(\eta_S = \left(\frac{e}{h} \right)_S \quad ; \quad \eta_C = \left(\frac{e}{h} \right)_C \right)$$

fem is:

1) Energy dependent -> the calorimeter is non linear
2) Fluctuating event-by-event -> the energy resolution is non gaussian if $\eta_s \surd\neq \eta_c$

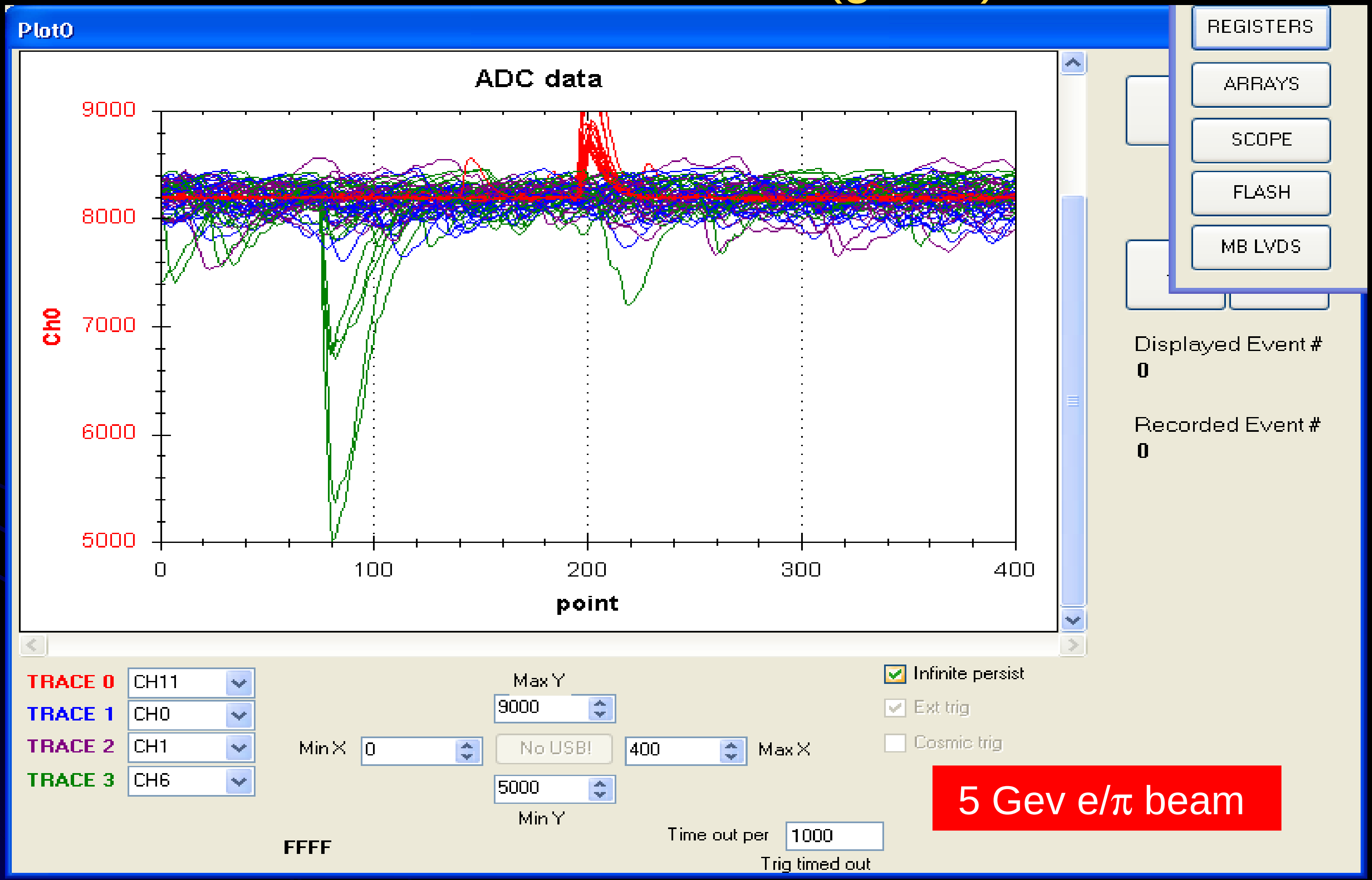
If $\eta_s \surd\neq \eta_c$ then the system can be solved for E_{HCAL}

$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S}$$

We are measuring fem event-by-event

Waveforms from TB4 DAQ:

SiPM with INFN light concentrator (blue) vs direct fiber readout (green)



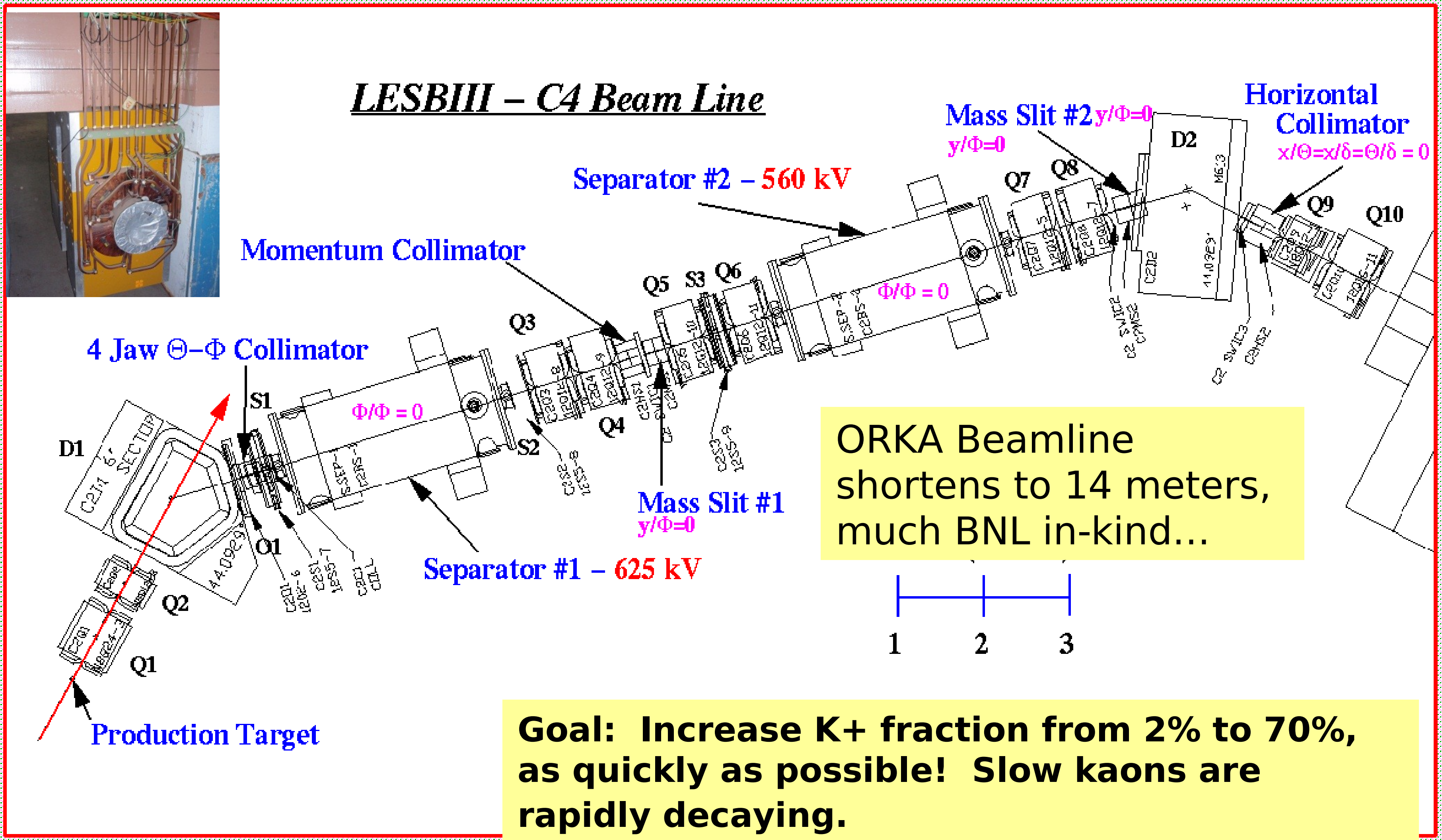
ORKA Roadmap in Particle Physics

2017, first results from the NA62 CERN experiment:

- **Evidence of new physics?:** ORKA will embark on confirming with a completely different method, provide definitive measurement.
- **No evidence of new physics?:** ORKA will push the hunt for new physics to much higher sensitivity.

-

separated charged beam on a stopping target.



ORKA Beamline shortens to 14 meters, much BNL in-kind…

Goal: Increase K+ fraction from 2% to 70%, as quickly as possible! Slow kaons are rapidly decaying.

Sensitivity Frontier of Kaon Physics Today

- CERN NA62: 100 x 10^{-12} measurement sensitivity of $K^+ \to e^+\nu$
- Fermilab KTeV: 20 x 10^{-12} measurement sensitivity of $K_L \to \mu\mu ee$
- Fermilab KTeV: 20 x 10^{-12} search sensitivity for $K_L \to \pi\mu e$, $\pi\pi\mu e$
- BNL E949: 20 x 10^{-12} measurement sensitivity of $K^+ \to \pi^+\nu\bar{\nu}$
- BNL E871: 1 x 10^{-12} measurement sensitivity of