IFD2015

INFN Workshop on Future Detectors

16-18 December 2015 - Torino - Italy

New Trends in Calorimetry

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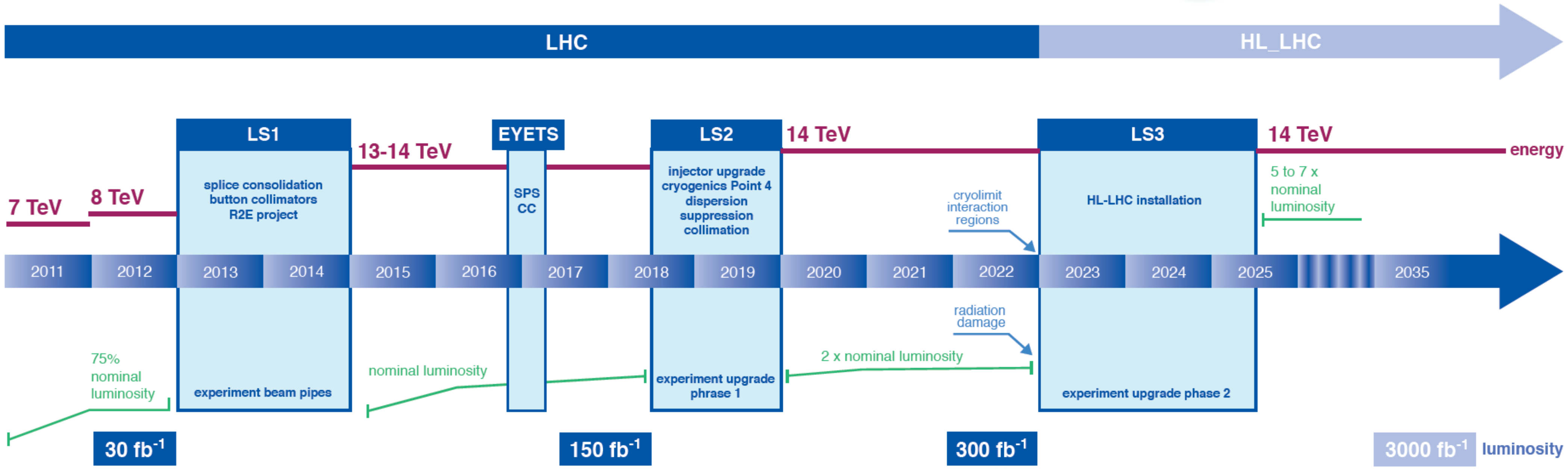
what NEXT?

Upgrades and Future Experiments

High Energy Frontier

LHC / HL-LHC Plan



	E_{cm}, TeV	L_f, km	L, $cm^{-2}s^{-1}$	*Region*
CEPC	0.25	54	$5 \cdot 10^{34}$/IP	China
FCC-ee	0.25	100	$5 \cdot 10^{34}$/IP	CERN
ILC	0.5	36	$2 \cdot 10^{34}$	Japan
CLIC	3	60	$5 \cdot 10^{34}$	CERN
μμ-Collider	6	~20	$2 \cdot 10^{34}$	US ?
SPPC	~50	54	$5 \cdot 10^{34}$	China
FCC-pp/VLHC	100	100	$5 \cdot 10^{34}$	CERN/US

Attilio's talk

	Europe	US	Japan
ν		NOvA, μBoone, ..., DUNE	T2K, HyperK
B	LHCb		Belle II
K	NA62		KOTO TREK-E36
μ	MEG II	Mu2e g-2	COMET DeeMe g-2, EDM

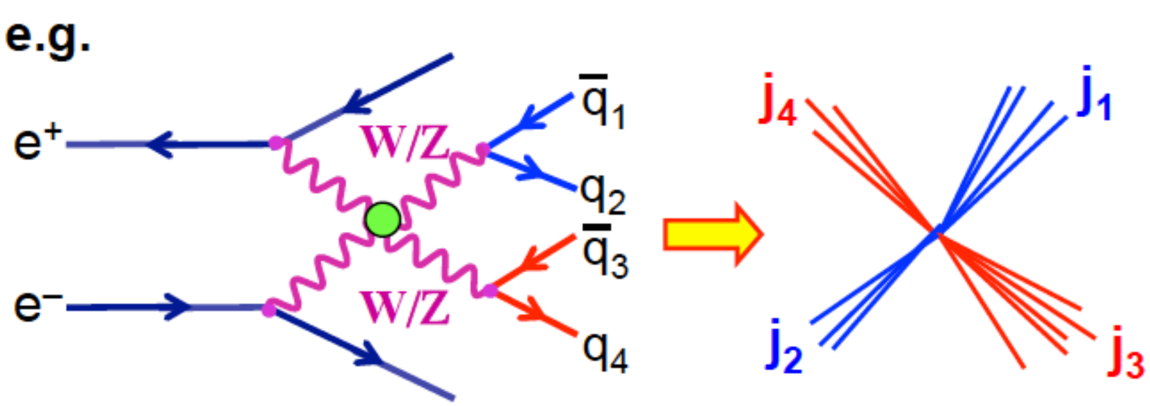
High Intensity Frontier

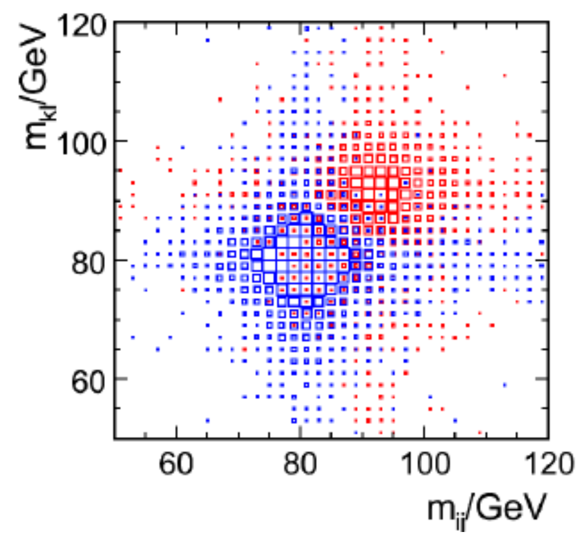
High resolution Calorimetry

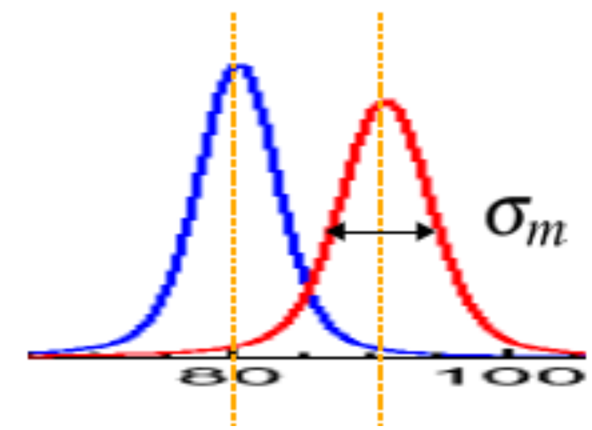
For future colliders, jet energy resolution will be a determinant factor of understanding high energy physics.

⇨

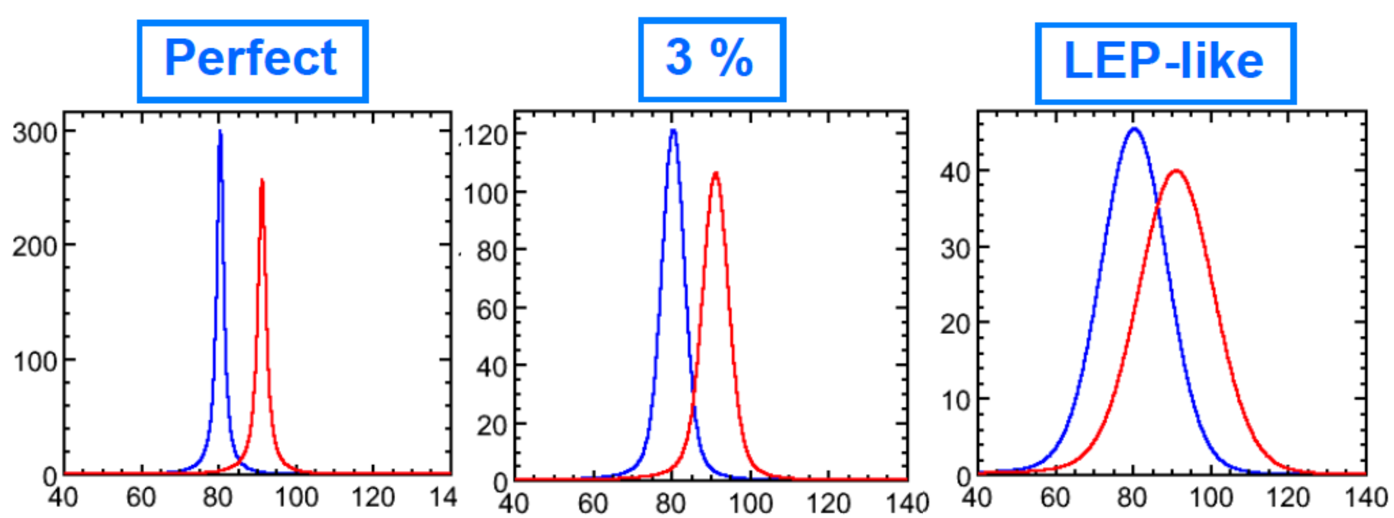
Required to have best possible di-jet mass resolution for narrow resonance observation
At very least one need to distinguish W/Z hadronic decays







$$\text{W/Z sep} = (m_Z - m_W)/\sigma_m$$



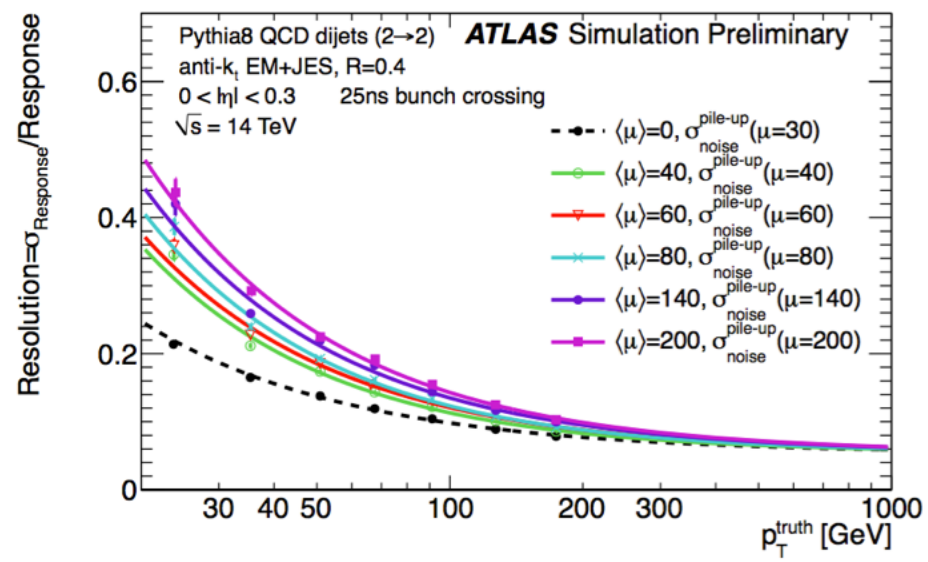
Jet E res.	W/Z sep
perfect	3.1 σ
2%	2.9 σ
3%	2.6 σ
4%	2.3 σ
5%	2.0 σ
10%	1.1 σ

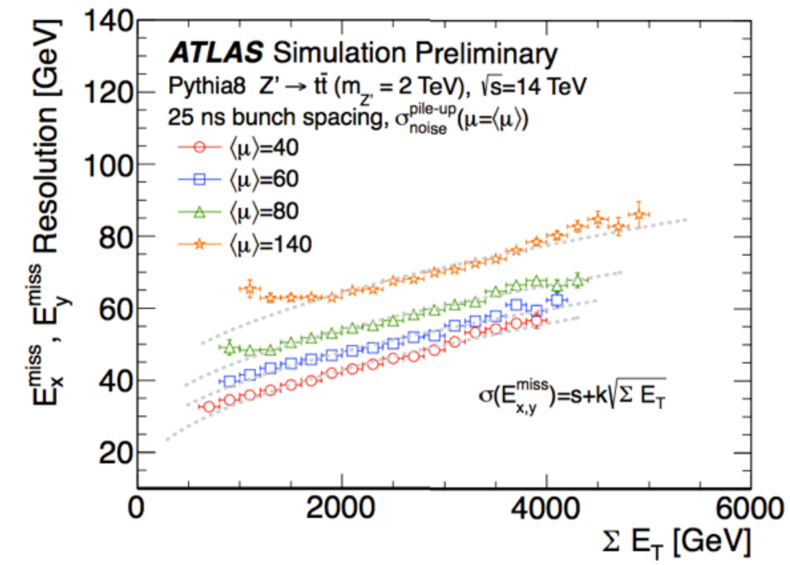
W/Z sep: 3σ

$$\frac{\sigma}{E} \sim \frac{30\%}{\sqrt(E)}$$

High Rate Calorimetry

Jet and E_T^{miss} resolution @high pileup



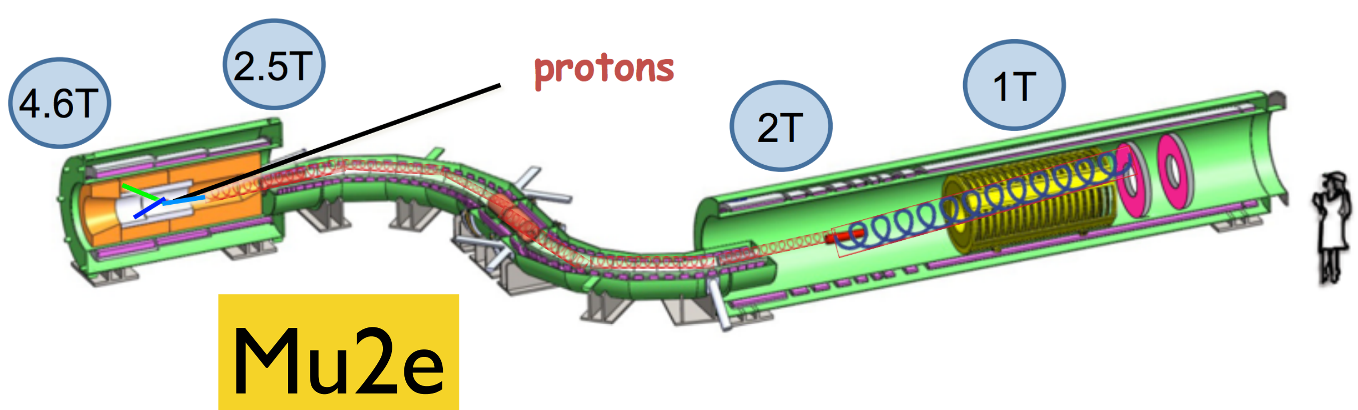


$<\mu> \approx$ 20-40 evts/crossing RunI
$<\mu> \approx$ 50 evts/crossing RunII
$<\mu> \approx$ 60 evts/crossing RunIII
$<\mu> \approx$ 140 evts/crossing HL-LHC

40x10^6 bunch crossing/s
20 collisions/bunch crossing
140 PU evt/bunch crossing

} ~ 10^{10} evt/s ⬇ time scale ~ 100 ps

Charged Lepton Flavor Violation: hint for new physics
rare events ➡ high rate



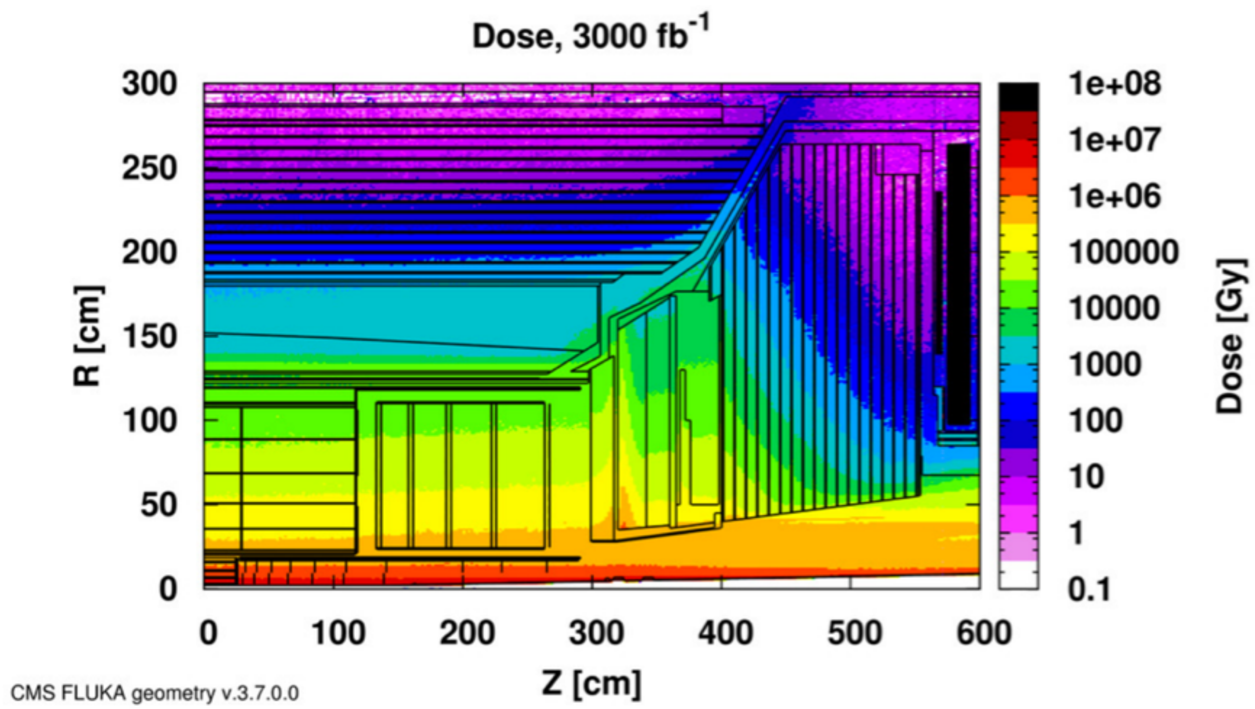
μ^- + (A,Z) ➡ e^- + (A,Z)
the coherent, neutrinoless conversion of a muon to an electron in the field of a nucleus
Negligible in the SM(10^{-52})

for the sensitivity goal ~ 6x10^{17} stopped muons
3 year run (6x10^7sec) ➡ 10^{10} stopped muon/sec

Rad-Hard Calorimetry

Irradiation changes the performance of detectors and electronics

- ✳Total Ionizing Dose (TID)
  - ✳Mainly due to photons, electrons and positrons
  - ✳Measured in Gray (Gy), 1 Gy = 1 J/kg = 100 rad
- ✳ Non Ionizing Energy Loss (NIEL) / equivalent fluence (Φeq)
  - ✳Expressed in 1 MeV neutron equivalent fluence (n/cm^2)
- ✳Thermal neutron fluence



CMS Radiation	LHC (10^{34} $cm^{-2}s^{-1}$, 500 fb^{-1})		HL-LHC (5×10^{34} $cm^{-2}s^{-1}$, 3000 fb^{-1})	
	Barrel (max)	Endcap (max)	Barrel (max)	Endcap (max)
Absorbed dose (rad)	**3.50E+05**	**2.10E+07**	2.10E+06	1.26E+08
Dose rate (rad/h)	25	1512	126	7560
Fast neutrons fluence (E>100KeV, cm^{-2})	**3.00E+13**	**8.00E+14**	1.80E+14	4.80E+15
Fast neutrons flux (E>100KeV, $cm^{-2}s^{-1}$)	6.00E+05	1.60E+07	3.00E+06	8.00E+07
Charged hadrons fluence (cm^{-2})	**4.00E+11**	**5.00E+13**	2.40E+12	3.00E+14
Charged hadrons flux ($cm^{-2}s^{-1}$)	8.00E+03	1.00E+06	4.00E+04	5.00E+06

HL-LHC: a factor 10 wrt RunIII LHC

INFN Istituto Nazionale di Fisica Nucleare

How to cope with physics and performance requirements?

High Resolution

High Rate

Rad-Hard

high resolution
help in the jet measurement (Dual Readout Approach)
reduce dominant source of fluctuation → improve resolution

high granularity
help in the jet measurement (Particle Flow Approach)
reduce cell size → increase number the channels

fast timing
help in reducing pile-up effects (High Energy Frontier)
help in distinguish events (High Intensity Frontier)
faster detectors
faster electronics

new materials & technology
R&D offers new materials and technologies that can be used to reach the goal

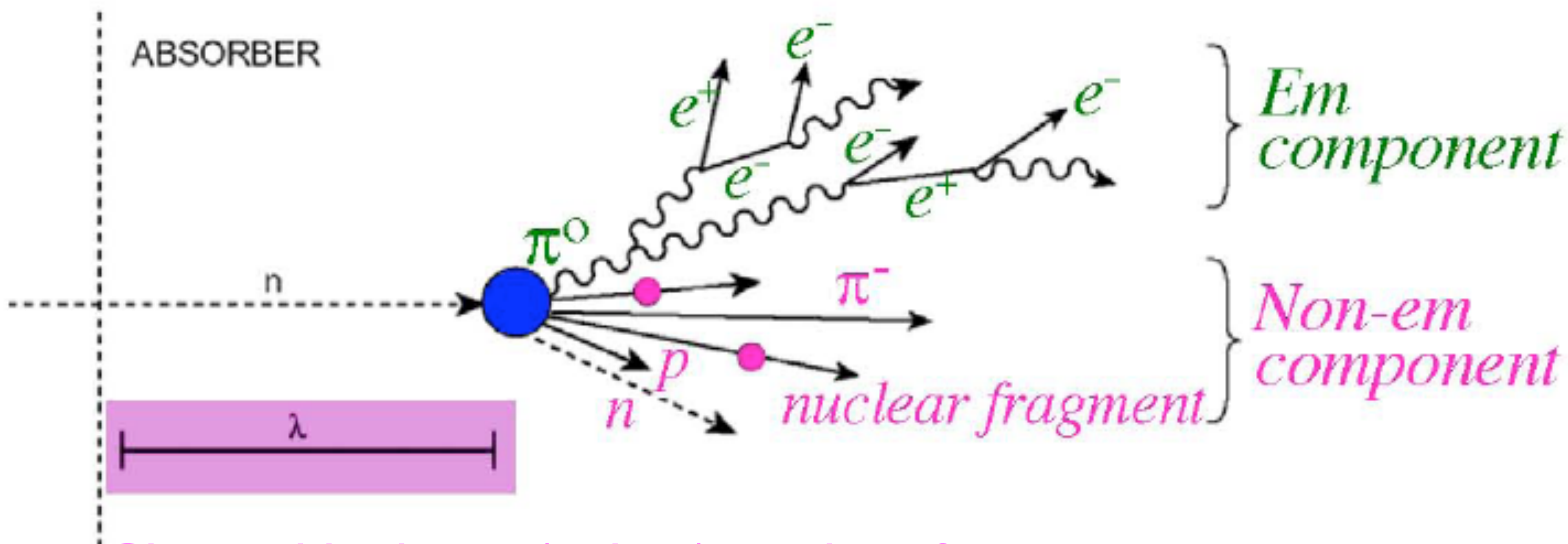
Principle of the Dual Readout method

Study and eliminate/reduce dominant source of fluctuation

Hadronic showers consist of two components

- The calorimeter response to these two components is typically very different
- Hadronic showers are characterized by very large fluctuations due
    - the energy sharing between these two components
    - the fluctuation in the amount of invisible energy

electrons positrons, photons, π^0

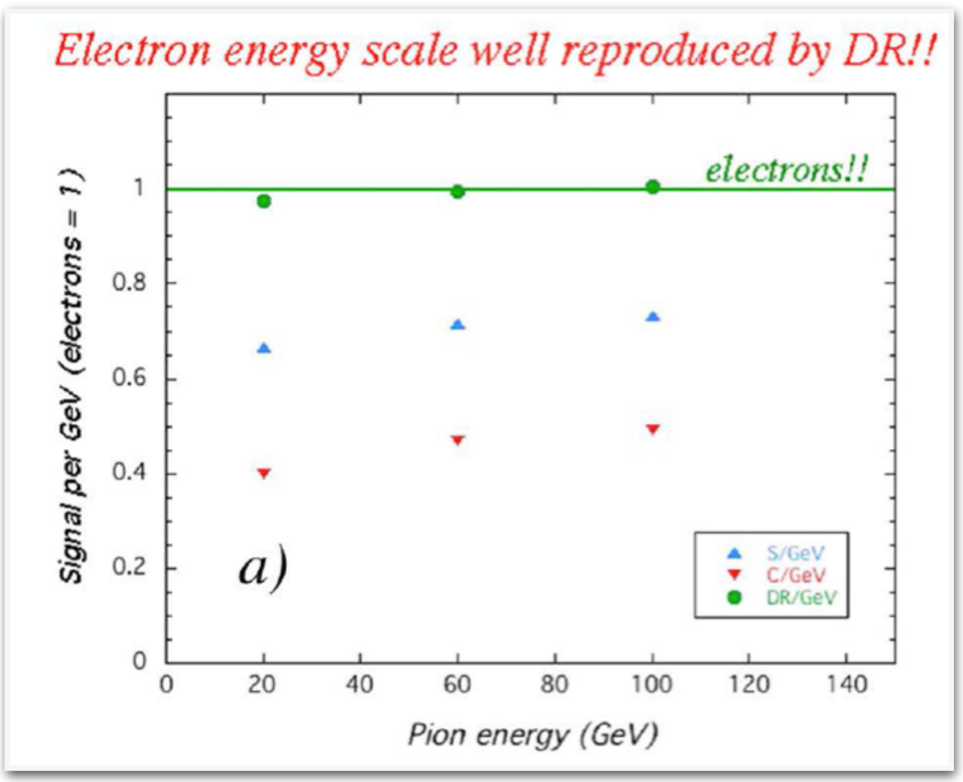


Charged hadrons (π,k…), nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

Principle of the Dual Readout method

Measure the electromagnetic fraction event by event to equalize the response off-line

- Scintillation light to measure all charged particles
- Cherenkov light to measure only relativistic particles, namely only e+ and e- (em component of the hadronic shower).



$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

e.g. If $e/h = 1.3\ (S),\ 4.7\ (Q)$

$$\frac{Q}{S} = \frac{f_{em} + 0.21\ (1 - f_{em})}{f_{em} + 0.77\ (1 - f_{em})}$$

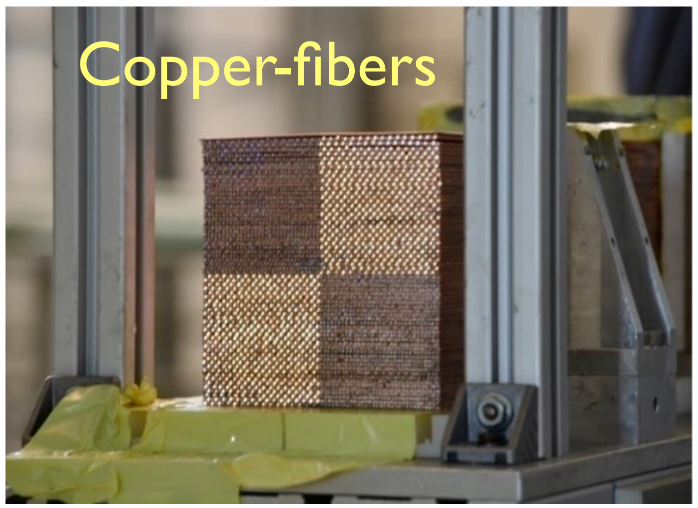
$$E = \frac{S - \chi Q}{1 - \chi}$$

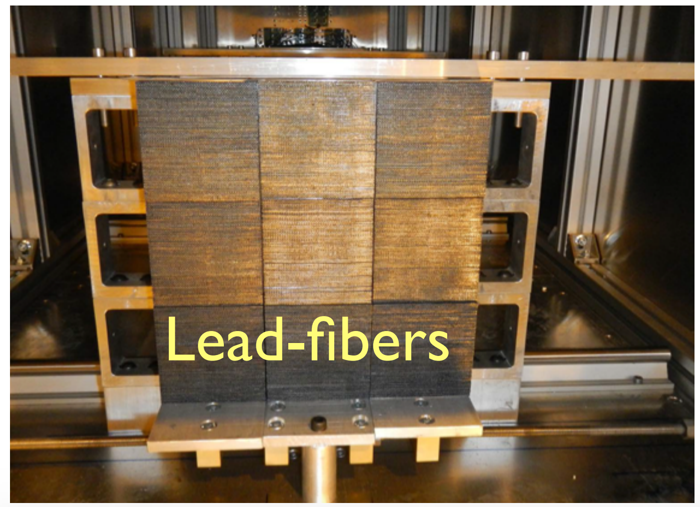
with $\chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

- **Compensation** achieved without construction constraints
- **Calibration** of an hadron calorimeter just with electrons
- **High resolution** EM and HAD calorimetry

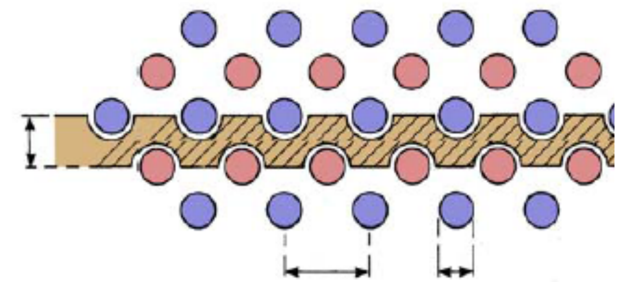
Dual Readout method in sampling calorimeter

In sampling calorimeter with two different types of fibers, Cherenkov and Scintillation are separated by construction





NEW DREAM

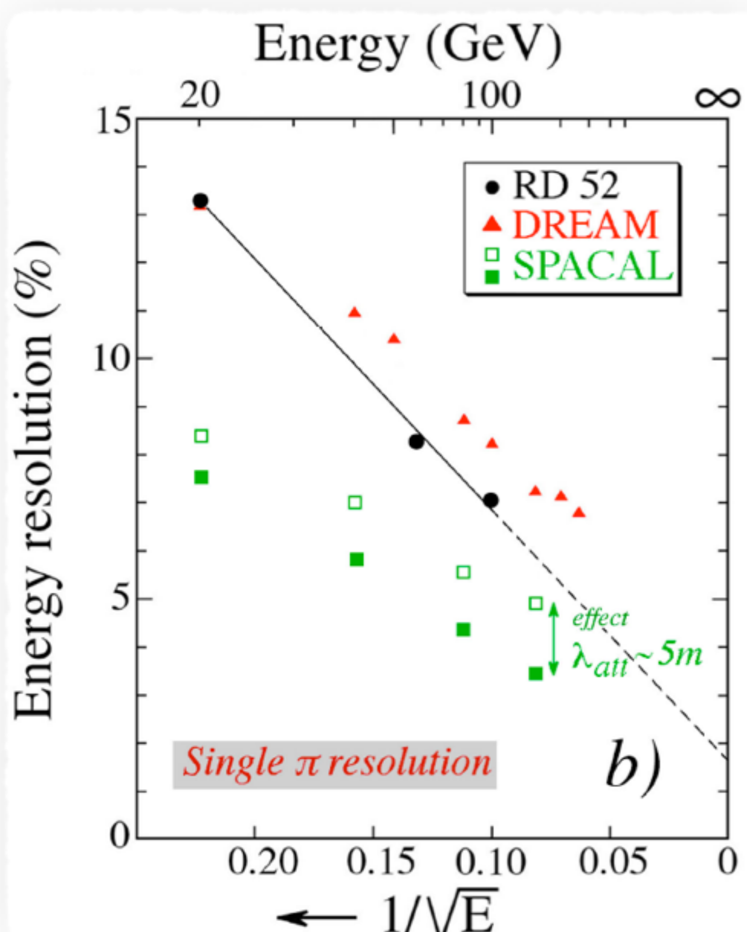


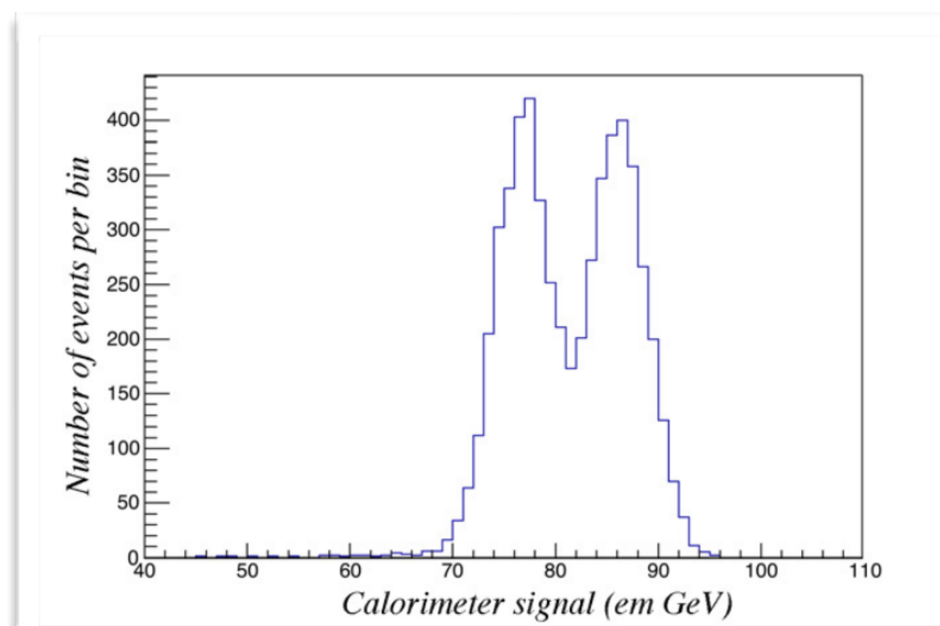
- Each module divided in 4 towers
- Each tower read out by 2 PMTs, one for Cherenkov and one for scintillation

Hadronic Resolution (Pb Module)

$$\frac{\sigma}{E} = \frac{53\%}{\sqrt{E}} + 1.7\%$$

To include corrections on:
- light attenuation
- lateral leakage (~ 6%)



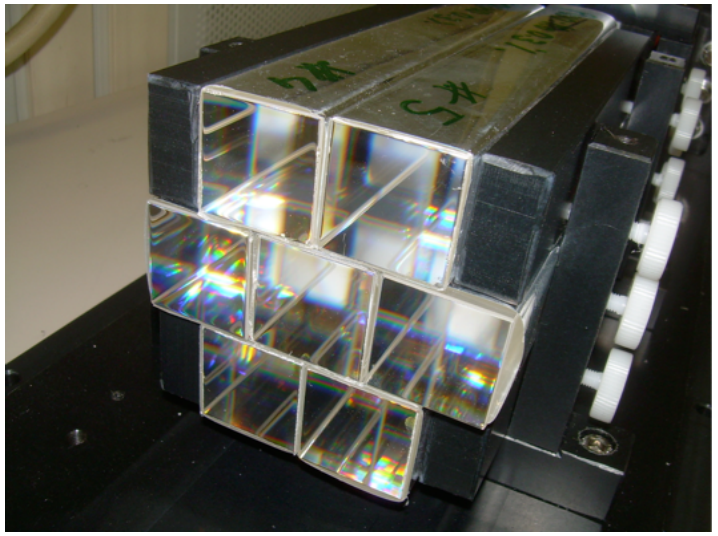


The response curve for a mixture of hadrons with energies corresponding to the W and Z masses (GEANT4 simulation)

Dual Readout method in homogeneous calorimeter

Requirements for using crystals in dual readout based calorimeter:

- Good Čerenkov vs Scintillation separation
- Response uniformity
- High light yield (to reduce contribution of p.e. fluctuation to the resolution)



Separation can be achieved by:

✳ optical filters: exploit different spectral region of Č and S

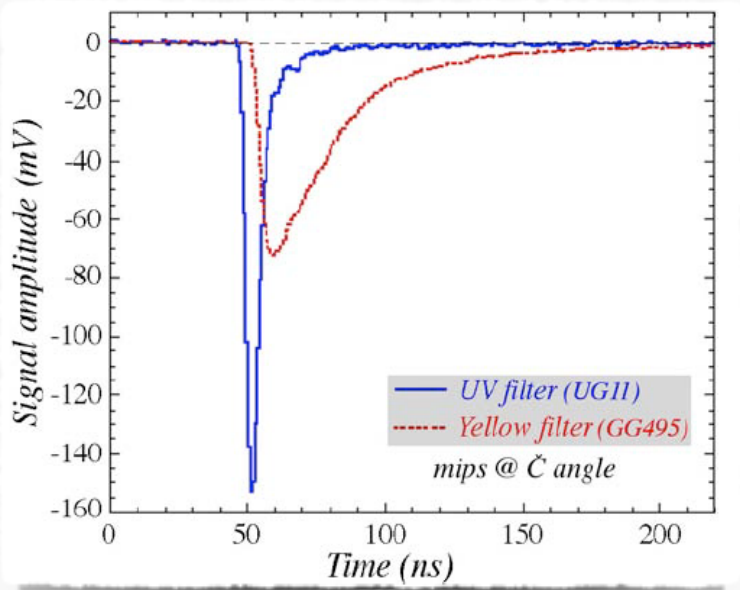
✳ time integration: exploit different time structure of Č and S

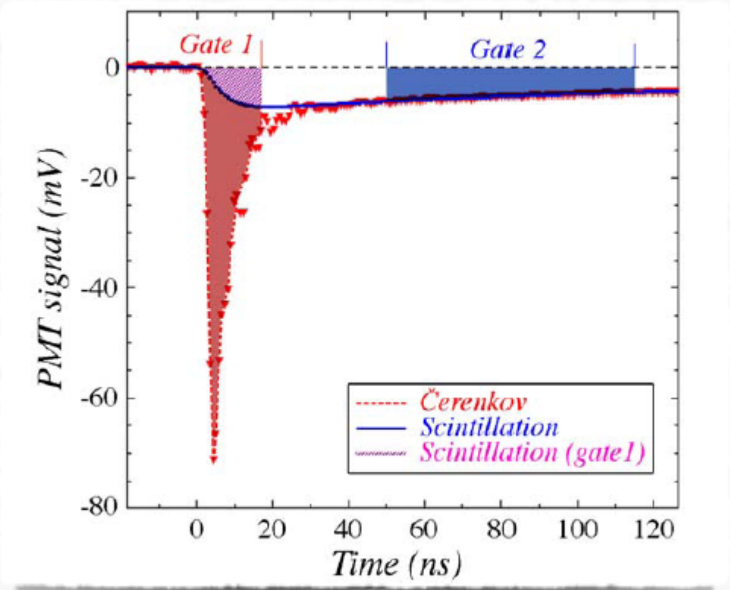
In order to have the best possible separation a crystal must have a scintillation emission:

✳ in a wavelength region far from the Cherenkov one

✳ with a decay time of order of hundreds of nanoseconds

✳ not too bright to get a good C/S ratio (<50% BGO emission)





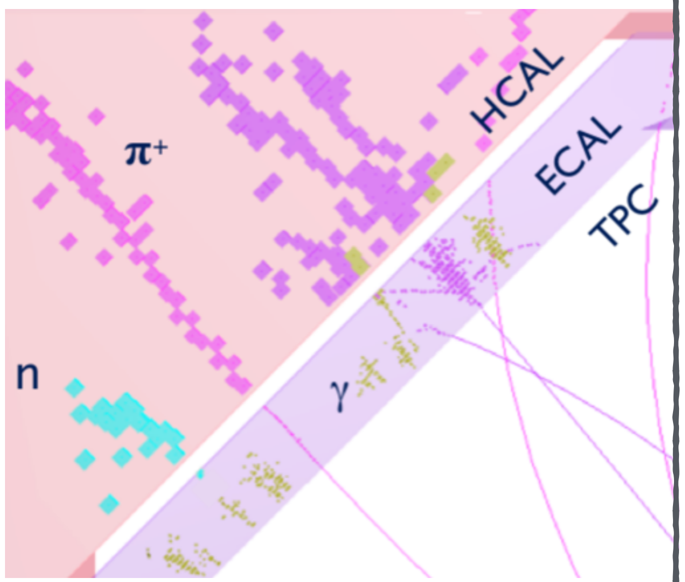
CALOCUBE implemented dual readout

✳CsI(Tl) cube wrapped in black tape

✳2 PhotoTubes, UV filters

Particle Flow & "High granularity paradigm"

Particle Flow combines tracking & calorimeter for optimal jet reconstruction



Jet composition:

charged hadrons ~70%→**tracker** $\sigma(p_T)/p_T \sim 1\%$

photons ~20%→**ECAL** $\sigma(E)/E < 20\%/\sqrt{E}$

neutral hadrons ~10%→**HCAL** $\sigma(E)/E < 60\%/\sqrt{E}$

High granularity to reduce confusion term between close-by showers

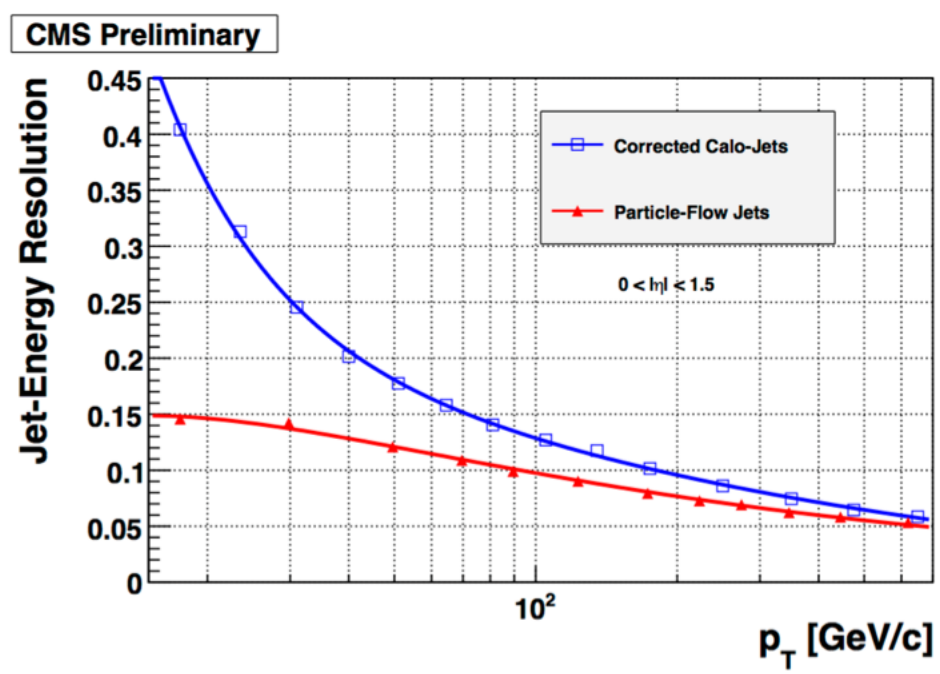
Extreme longitudinal and transverse segmentation to help shower recognition

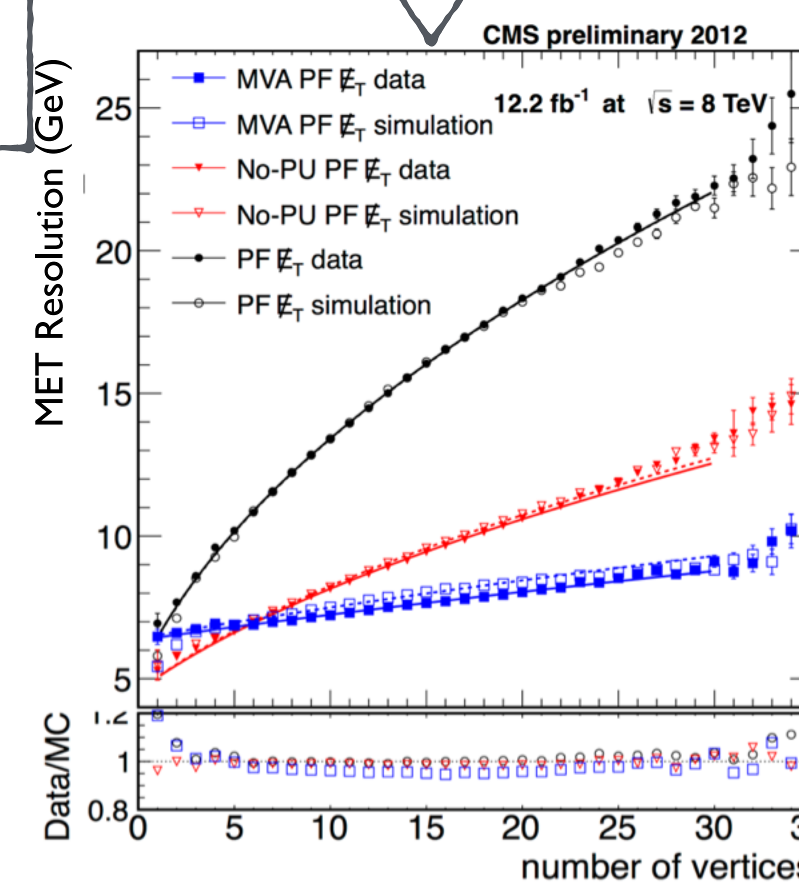
ECAL: small R_M, high λ/X_0 ratio

PF approach also beneficial for PU mitigation (tracks can be easily associated with production vertices)

PF in action already at LHC, CMS (non optimised for PF)

- B=3.8 T
- track $\sigma(p_T)/p_T \sim 1\%$
- photons $\sigma(E)/E \sim 3\%/\text{sqrt}(E)$
- neutral hadrons $\sigma(E)/E \sim 120\%/\text{sqrt}(E)$



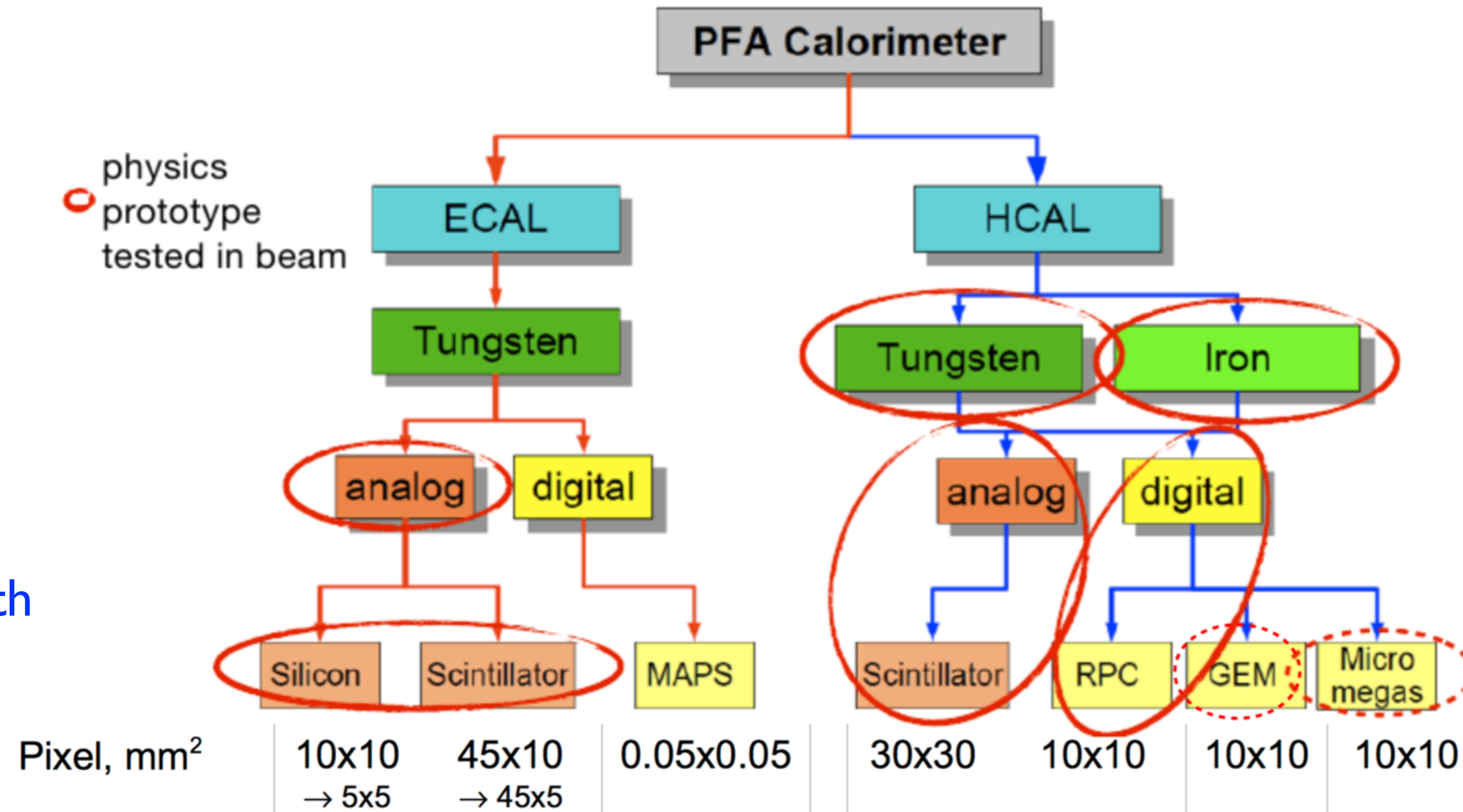


High granularity calorimeter design

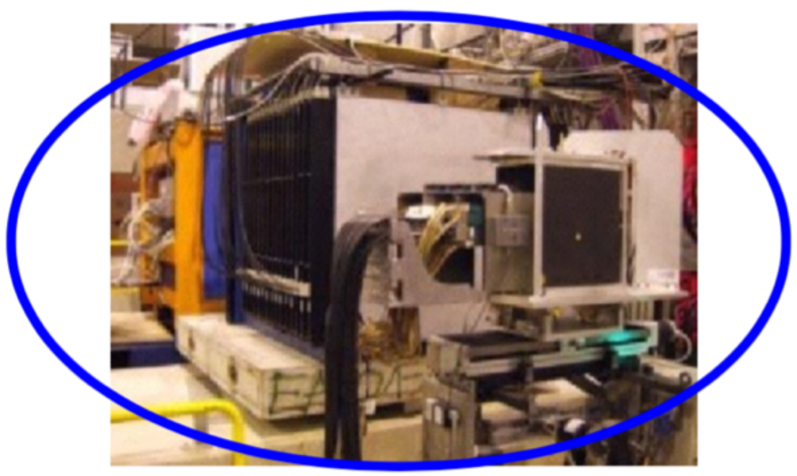
R&D pursued within CALICE collaboration, a 15 year long R&D

R&D moving from 1st generation prototypes demonstrating the PF concept, to 2nd generation prototypes addressing technical issues to demonstrate ILC/CLIC application (mechanics, power, integration…)

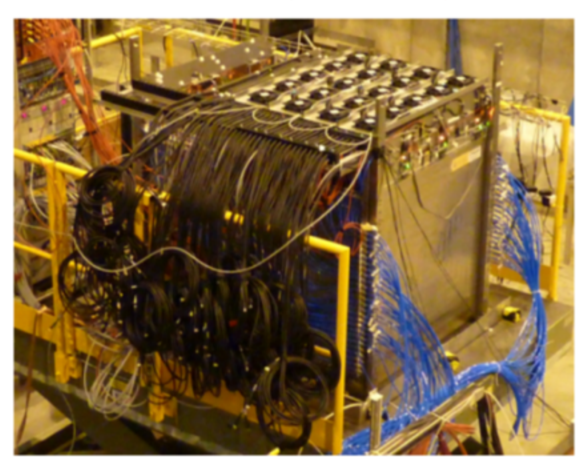
Several designs options investigated with different granularity for ECAL &HCAL: analog, semi-digital, digital



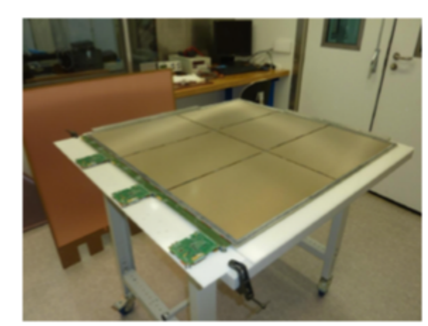
1m³ Sc AHCAL + SiW ECAL



SDHCAL, RPC, 1.3m³



Micromegas:
4 layers x 1m²

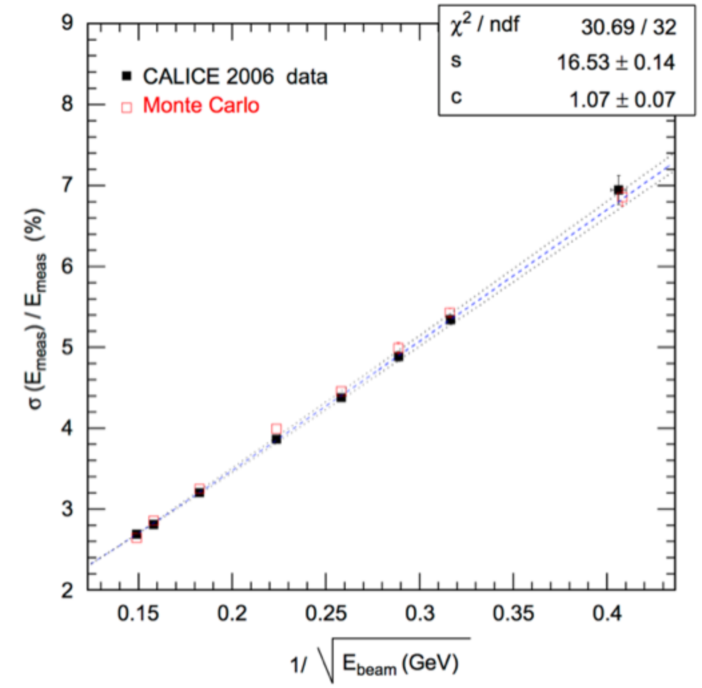


High granularity calorimeter: technologies

Si/W ECAL

- silicon easily segmentable, intrinsically linear (current pixel size 5x5 mm^2)
- require high dynamic range, low noise electronics from 1-1000 MIPs
- power consumption: power pulsing reduce consumption by 1/100 (only for ILC)
- R&D currently targeted on integration for a full scale detector design

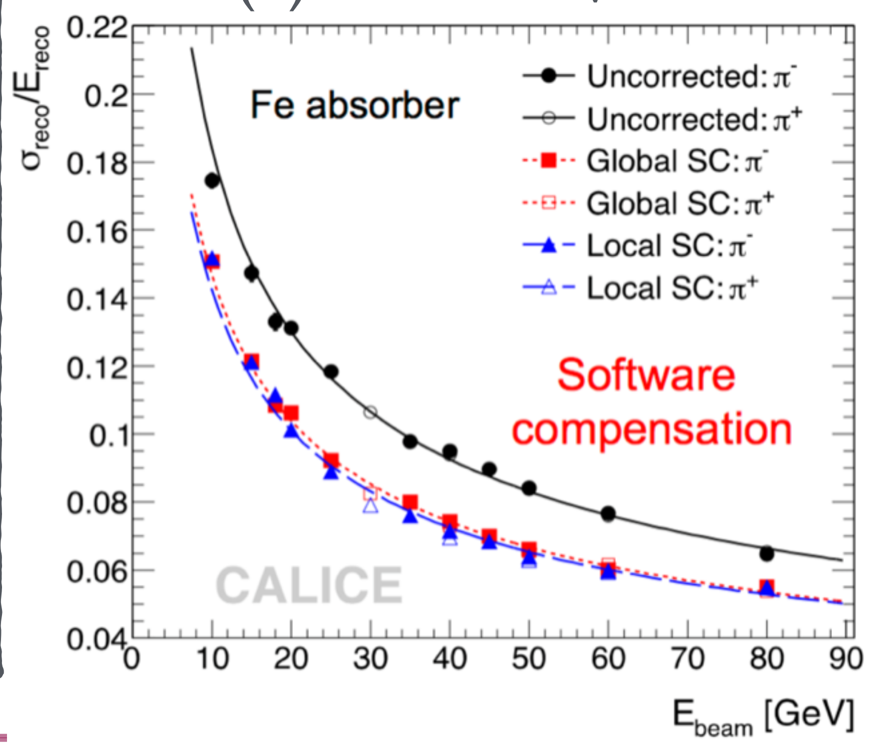
$\sigma(E)/E \sim 16\%/\sqrt{E/GeV}$



AHCAL: Sc w/ SiPM

Scintillator (30x30 mm^2)+ SiPM readout: 8k channels analog readout allows software compensation techniques

$\sigma(E)/E \sim 50\%/\sqrt{E/GeV}$



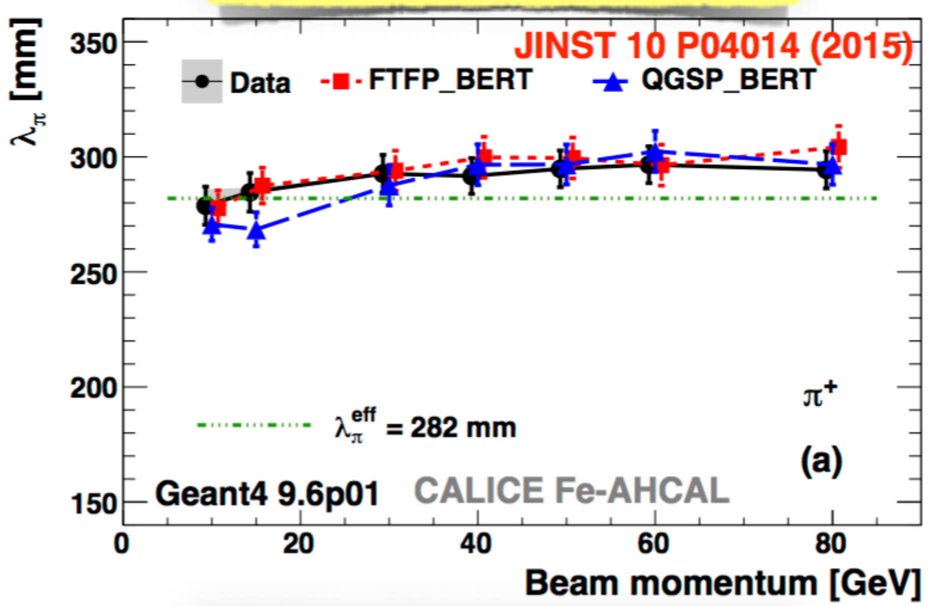
SDHCAL with gas: RPC, Micromegas or GEM

cheaper alternative to scintillator
advantages for 2 bits readout (1, several, many MIPS) over 1 bit
Micromegas and GEM have potential to improve RPC dynamic range & proportionality

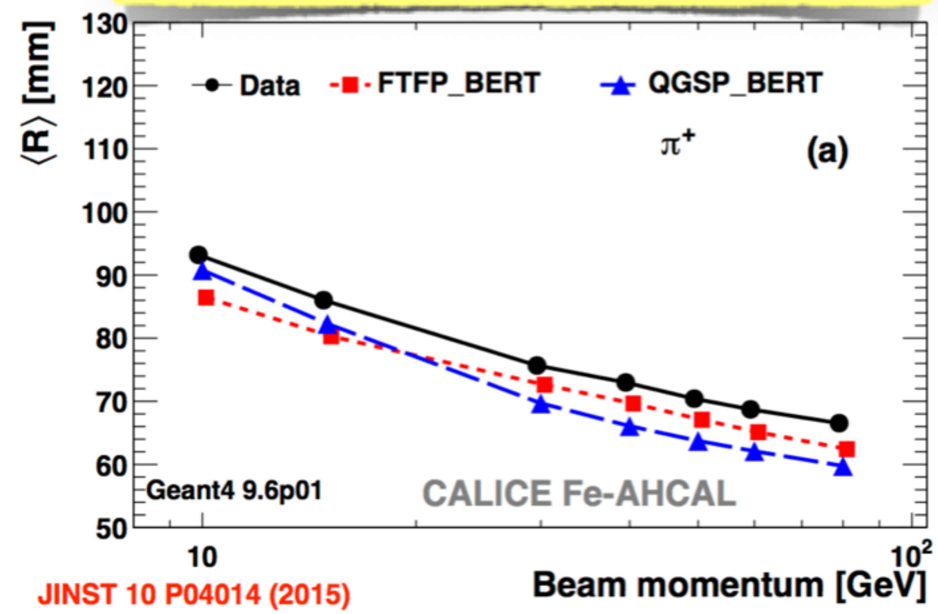
Shower development studies

High granularity prototypes allowed to study in great detail space and time shower evolution

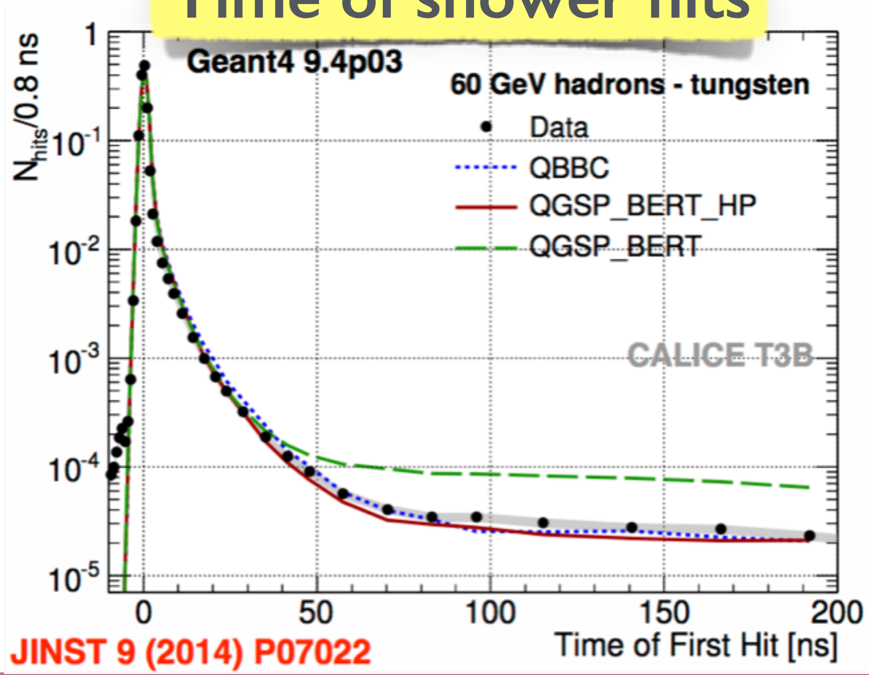
Interaction length



Shower transverse radius



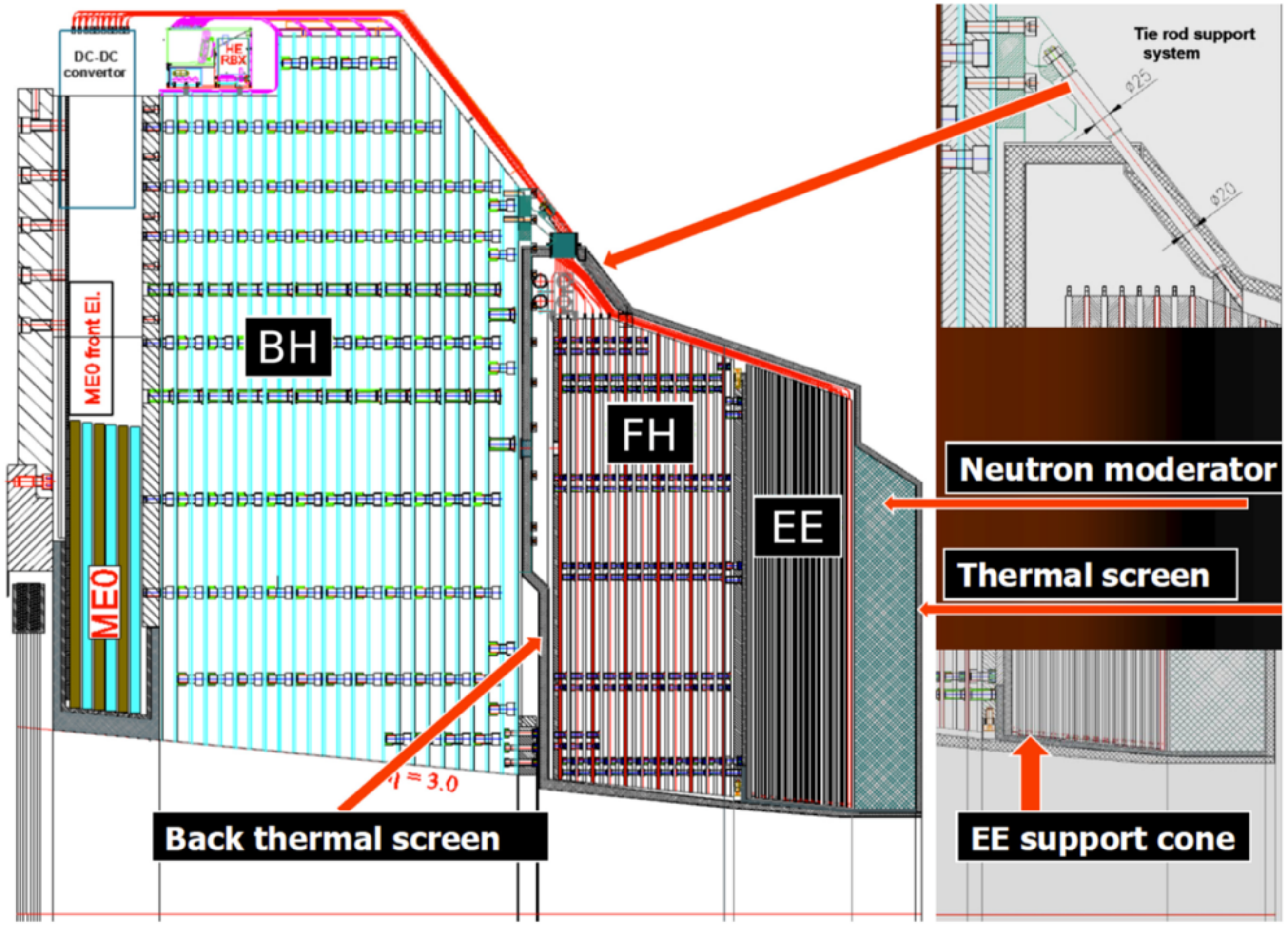
Time of shower hits



Agreement with G4 within 5-10% (studied Fe and W absorbers)

W absorber requires inclusion of neutron processes to reach agreement with data

CMS: HGCAL for HL-LHC



	EE	FH	BH
Absorber	W/Cu	Brass	Brass
Thickness	26 X_0 / 1.5 λ	3.5 λ	5 λ
# long samplings	28	12	12 (readout 2)
Active Material	Si	Si	Sc
Pixel size	10x10 mm²	10x10 mm²	
# channels	4.3M	1.8M	

CMS Phase II upgrade: High Granular CALorimeter for the forward region (1.5 < |η| < 3)

High granularity (transverse & longitudinal) for PF in very dense environment: <PU> at HL-LHC 140-200

New challenges wrt CALICE:

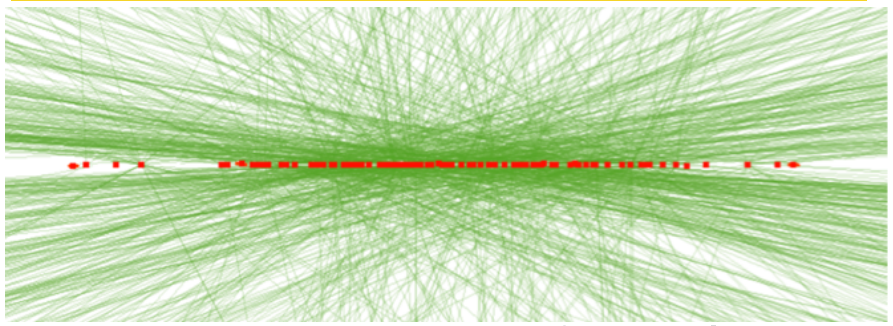
- **Radiation hardness**: fluence up to 10^{16} n cm^{-2} for EE (Si has to be cooled @ -30°C)
- **L1 Trigger + Data transfer**: ~200 Tb/s to be shipped off-detector
- **Engineering & integration**: cooling (~125kW via evaporative CO_2), power distribution, mechanics…

Fast timing: Pile-up mitigation @ HL-LHC

Calorimeter performance (Jets/MET) deteriorates @ 140-200PU

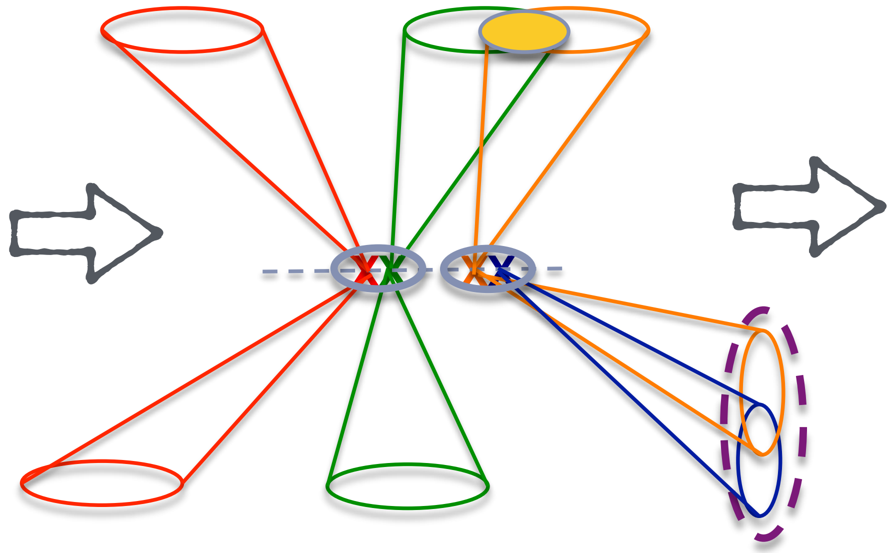
@140 PU ~70 GeV p_T due to PU in a 0.5 jet cone

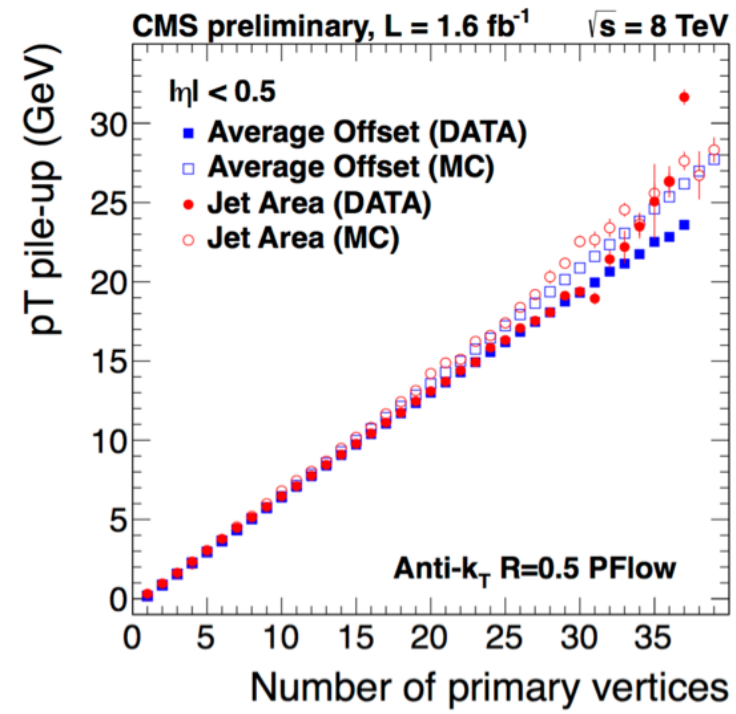
14 TeV pp→ttbar @ 140 PU



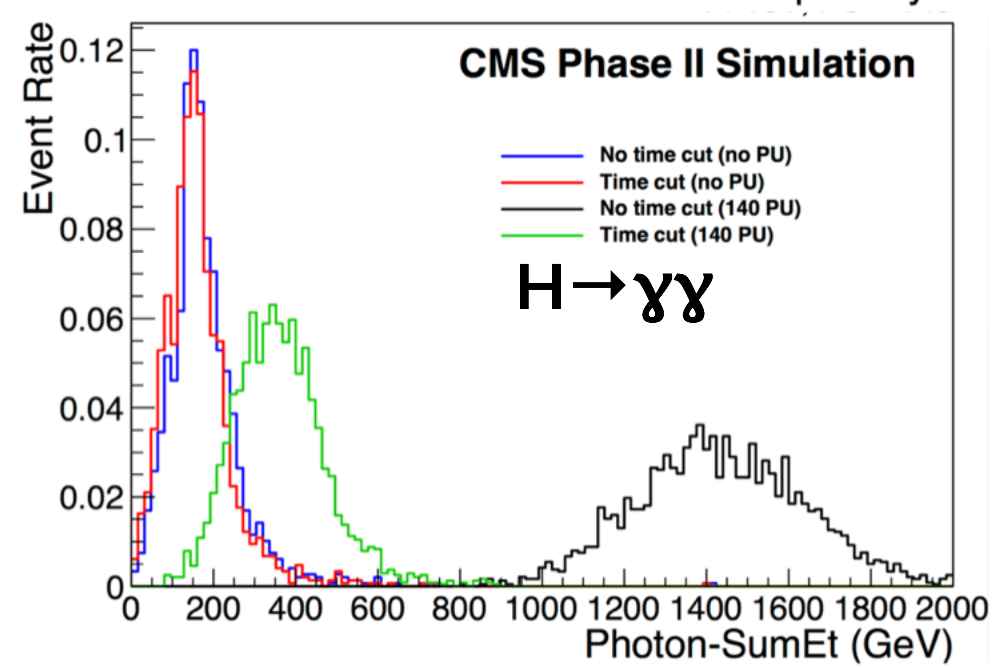
vertex density ~ 1.2 vtx/mm

vertex time spread ~160ps





- Neutrals PU overlap cannot be corrected even with PF approach
- Time of flight information to associate calorimeter energy deposits to primary vertex (assuming knowledge of vertex time): O(30ps)
- Time resolution would reduce PU overlap to RunI levels (PU neutrals rejection ~5)



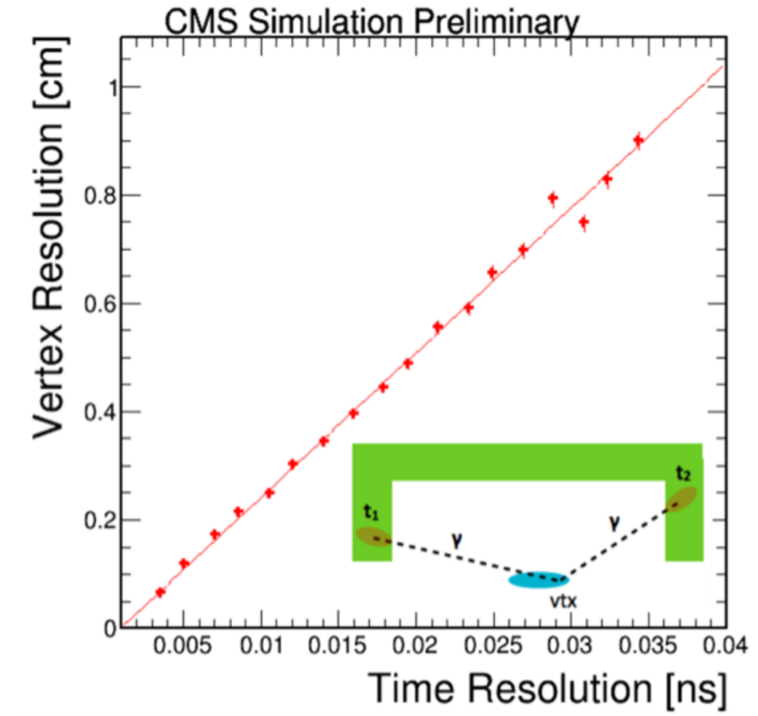
Fast timing: CMS

CMS: developing the idea of "hermetic timing" for γ (possibly up to low p_T) and charged tracks between $0<|\eta|<3$

Opportunistic use of calorimeter upgrades:

- **ECAL EB ($0<|\eta|<1.5$)**: $PbWO_4$+APD upgrade electronics aims at ~30ps above >30-40 GeV γ (no low energy γ PU rejection)
- **HGC EE ($1.5<|\eta|<3$)**: electronics should allow ~50ps for energy hits >10 MIPs (>50 hits above threshold for γ>50 GeV, <50ps also for low p_T γ). Possibility for a MIP fast timing layer

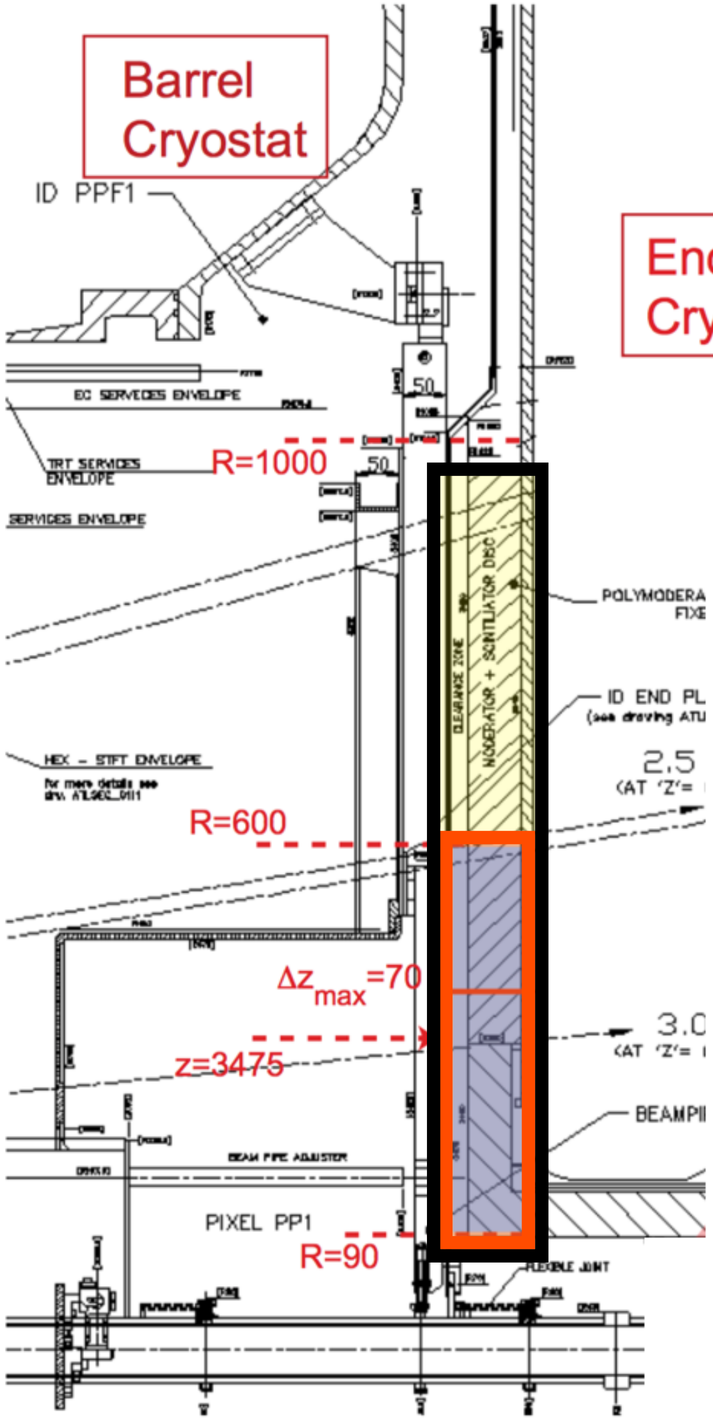
high energy γ fast timing: di-photon H→γγ vertex location



Also studying a dedicated timing detector in the tracker volume. 2 options:

- **Fast timing layer in tracker (MIP)**: Low-Gain avalanche detectors, hyper fast APD, MPGD
- **Pre-shower in front of EB (MIP+γ)**: small crystal (e.g. LYSO)+SiPM, I-MCP

Fast timing: ATLAS



ATLAS: high granular fast timing detectors in the region between barrel & endcap cryostat
baseline 4 layers @ 2.5<|η|<4.3, possibly a 3-4 X_0 pre-shower using W absorber

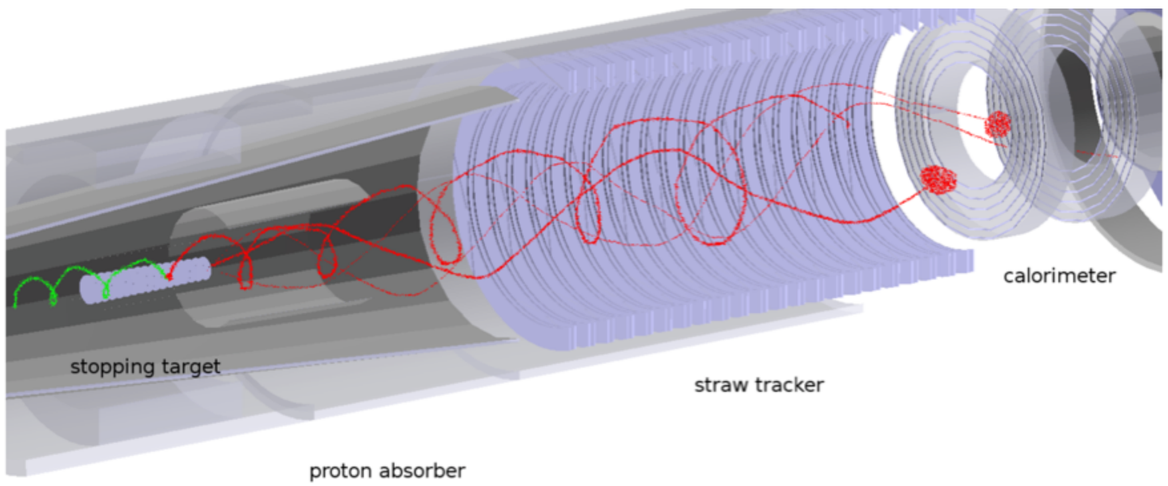
Table 3: Possible performance of several detector technologies to be deployed for a timing detector after a dedicated and successful R&D program is completed.

	Area [mm^2]	Resolution/MIP Time [ps]	Resolution/MIP Space [μm]	Noise [e$^-$ rms]	Efficiency/MIP	Max. Dose [Mrad]
Hybrid pixel	20×20	100	10	100	1	1000
HVCMOS pixel	20×20	100	10	30-100	1	1000?
Low-Gain Avalanche Detector		10	10-50	-	1	100?
Poly-diamond strips	5×5	100	10	500	1	1000?
Photocathode MCP	50×50	10	100		photon statistics	0.3?
Fiber bundle	1000×50	50	100		photon statistics	10-100?
Ionization MCP	200×200	30	100	100	0.7	100?

Similar technologies & requirements to what is being considered for CMS:
possibility for R&D synergies, also on specific aspects i.e. clock distribution

Other fast timing applications: Mu2e

Mu2e search for coherent stopped μ νless conversion $\mu^- N \rightarrow e^- N$ $E(e^-)=104.97$ MeV

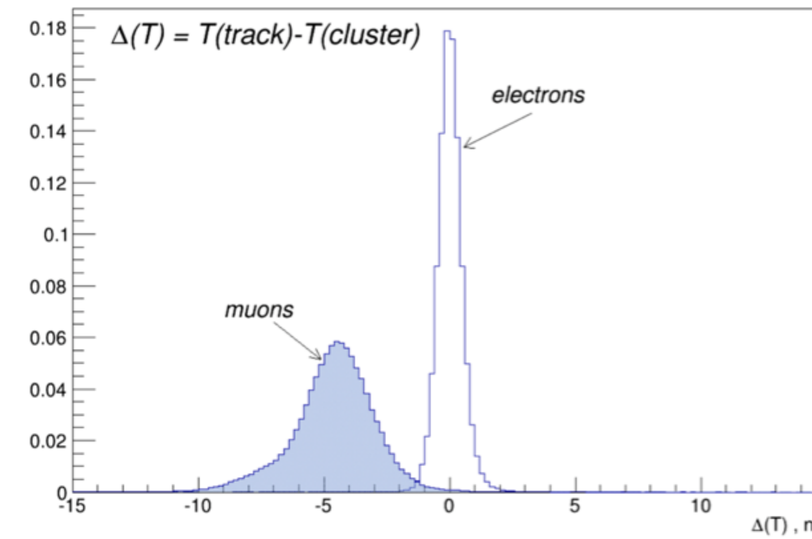


BaF_2 calorimeter: 1650 xtals ($30 \times 30 \times 200 mm^3$)

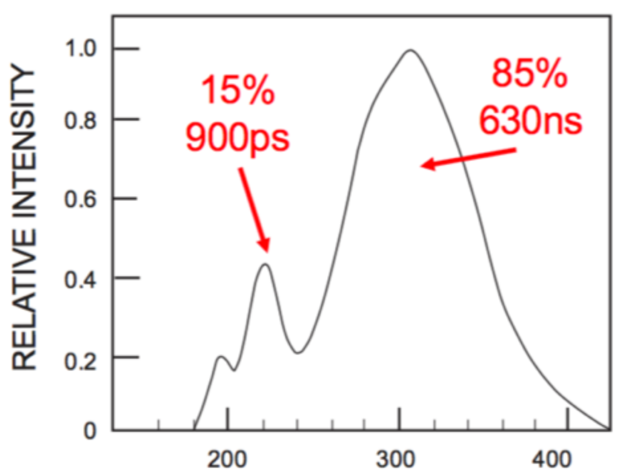
$\sigma(E)/E$ @ 100 MeV < 5%

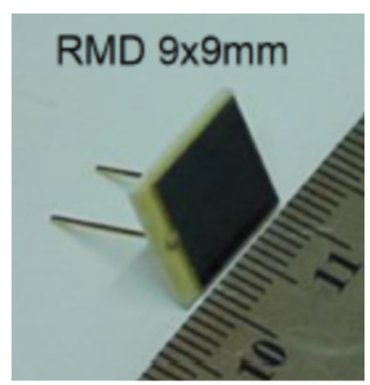
$\sigma(t)$<500ps to reduce background and help track pattern recognition

10^{10} $\mu\ s^{-1}$



BaF_2 emission spectrum

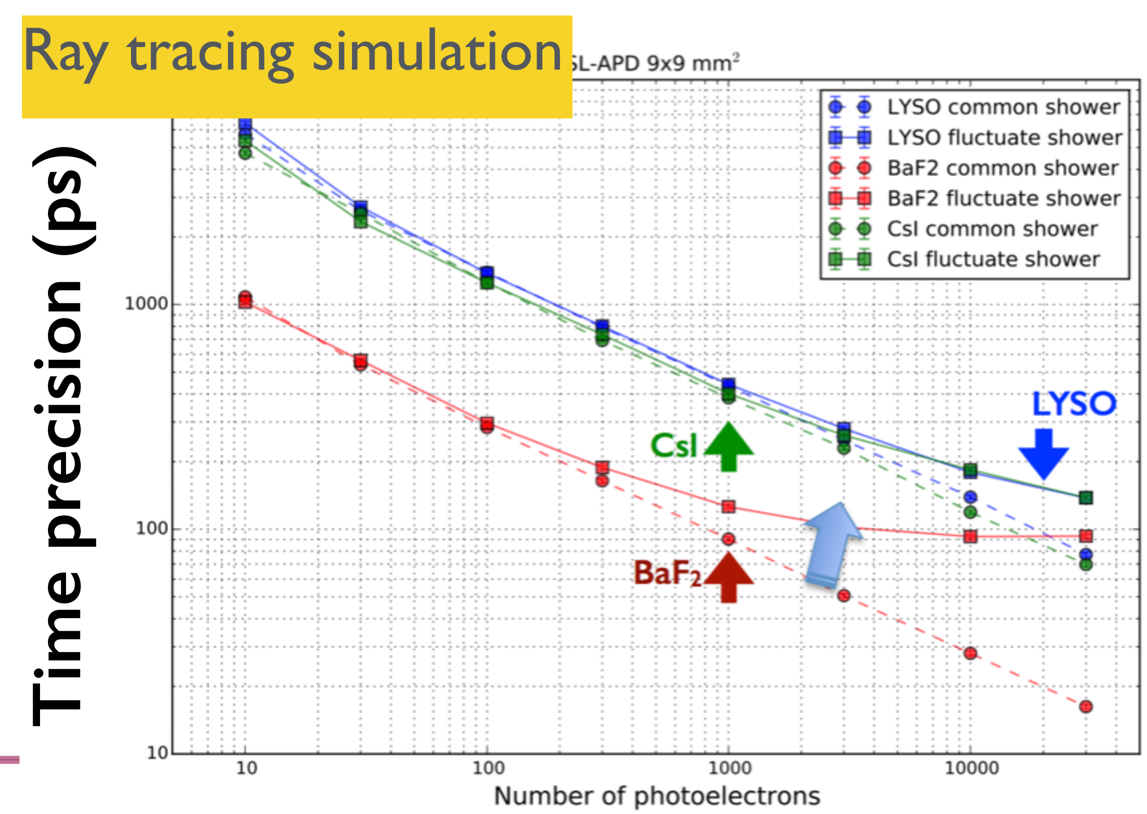




Developed solar blind APD to suppress BaF_2 slow component (>280nm)

QE(@220nm)=60%

QE(@300nm)=0.1%

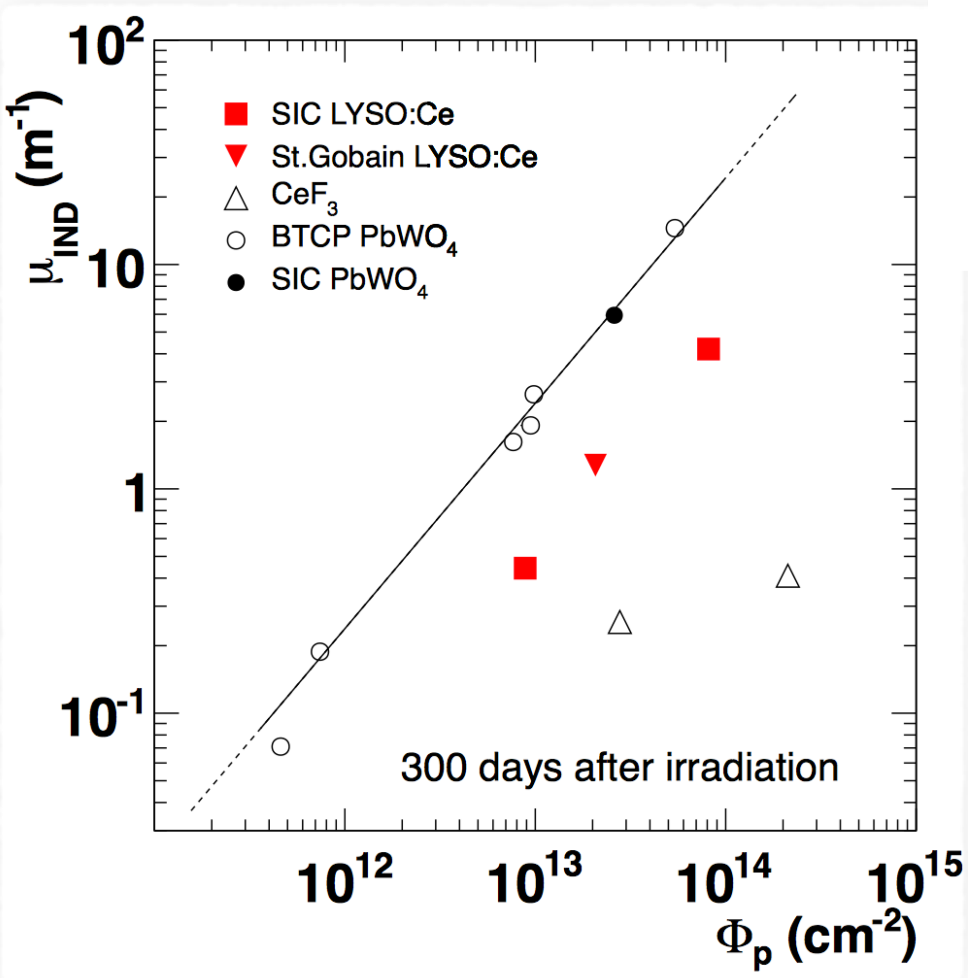


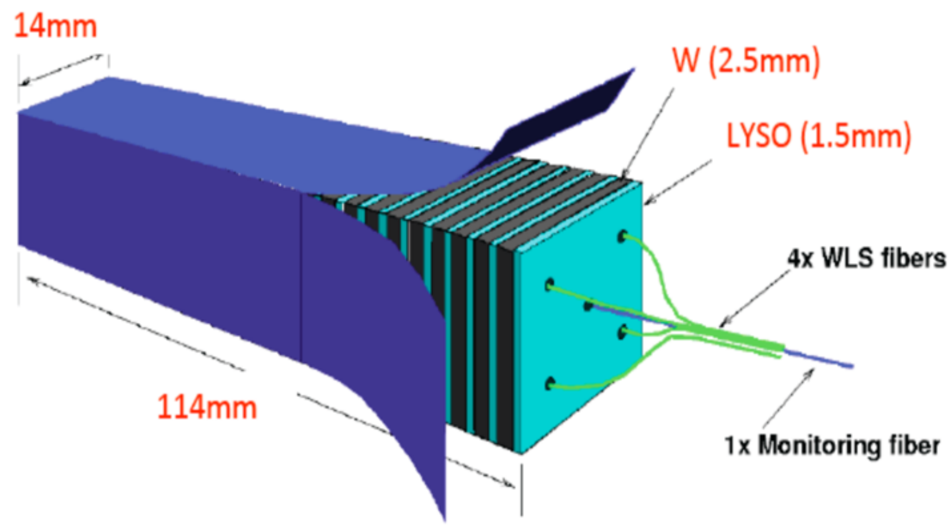
R&D: Rad-hard optical calorimeters

R&D for optical calorimeters who can cope with O(300 kGy) & O(10^{14-15}) hadrons cm^{-2}

Shashlik design to minimise the optical path in the scintillator. Also rad-hard WLS fibres & photodetectors

hadron damage for $PbWO_4$, LYSO, CeF_3





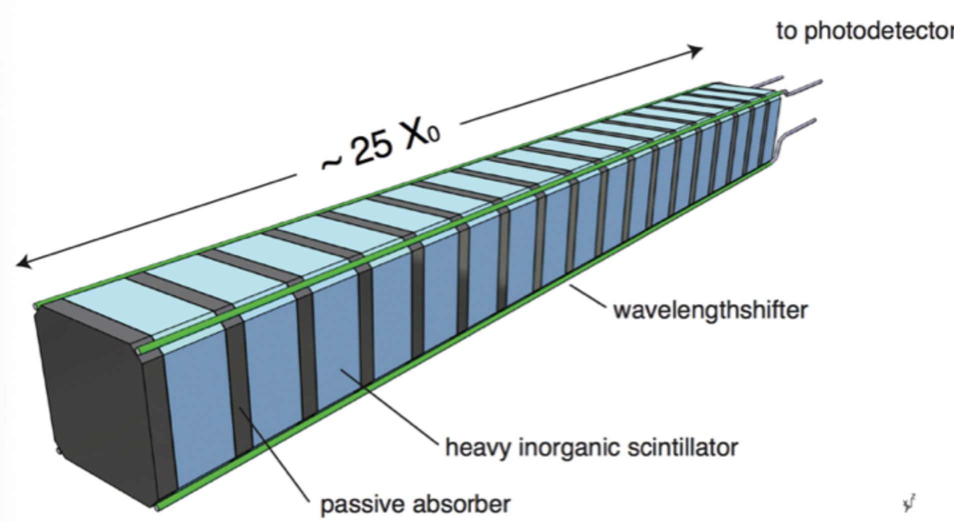
W/LYSO shashlik cell designed for CMS EE:

$14 \times 14 \times 114\ mm^3$

Quartz capillaries with WLS liquid

R&D for InGaAs SiPM

$\sigma(E)/E \sim 10\%/\sqrt{E/GeV}$



W/CeF_3 as an alternative:

CeF_3 excellent hadron damage radiation hardness

Can use SiO_2:Ce as radiation hard WLS

Ceramics: a rad-hard material for calorimeters

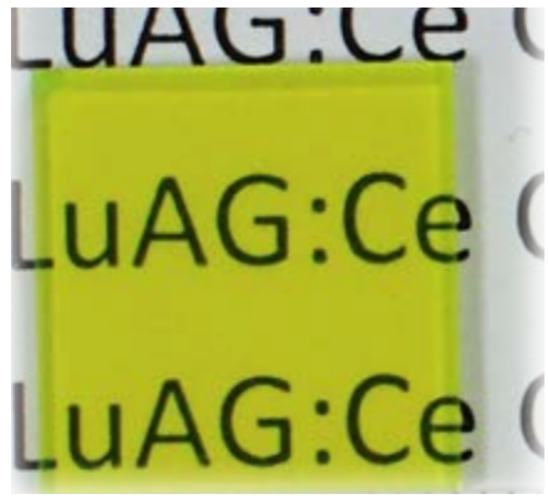
Development of scintillating ceramics (LuAG:Ce, YAG:Ce) could provide a cost-effective solution for calorimeters:

e.g LuAG:Ce

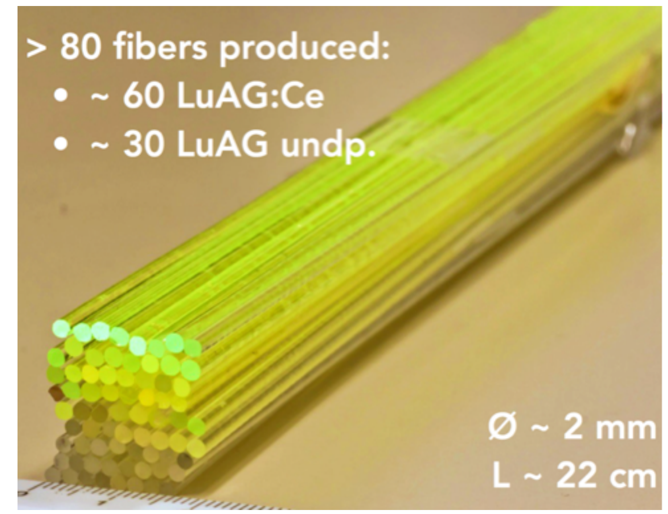
LY ~ 20 kɣ/MeV

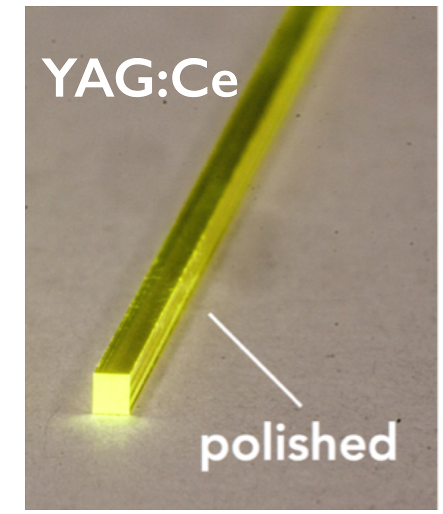
ρ = 6.76 g/cm^3

X_0 = 1.45 cm



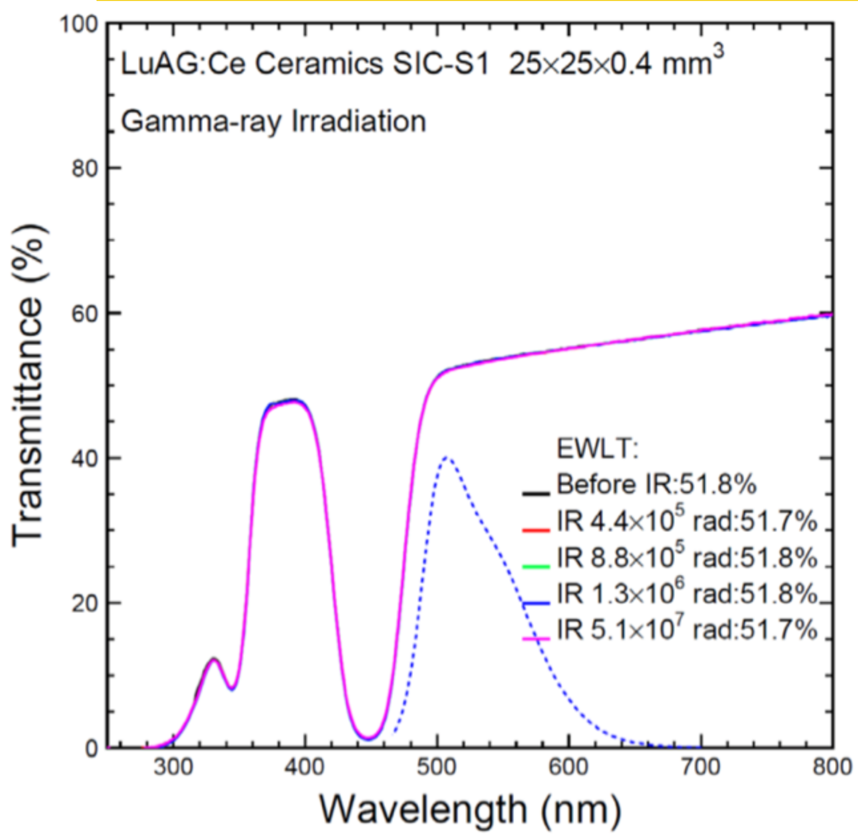
Also available as crystal fibres



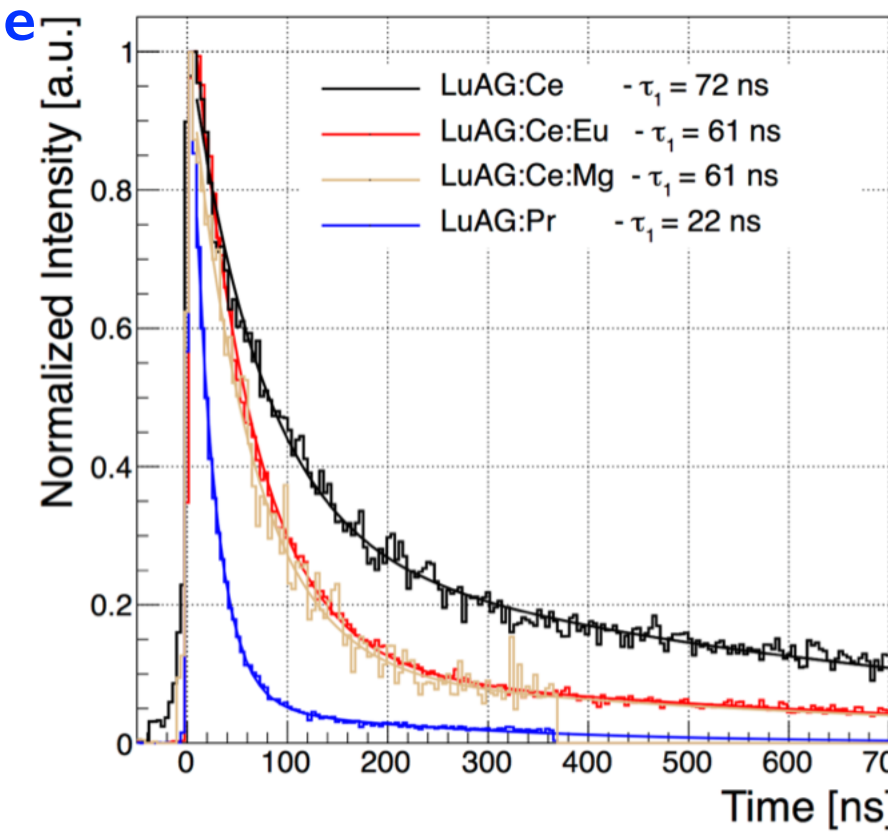


irradiation up to 50 Mrad

Excellent radiation hardness



Relatively fast, possible ways to improve response time (Ce co-dopants, Pr)

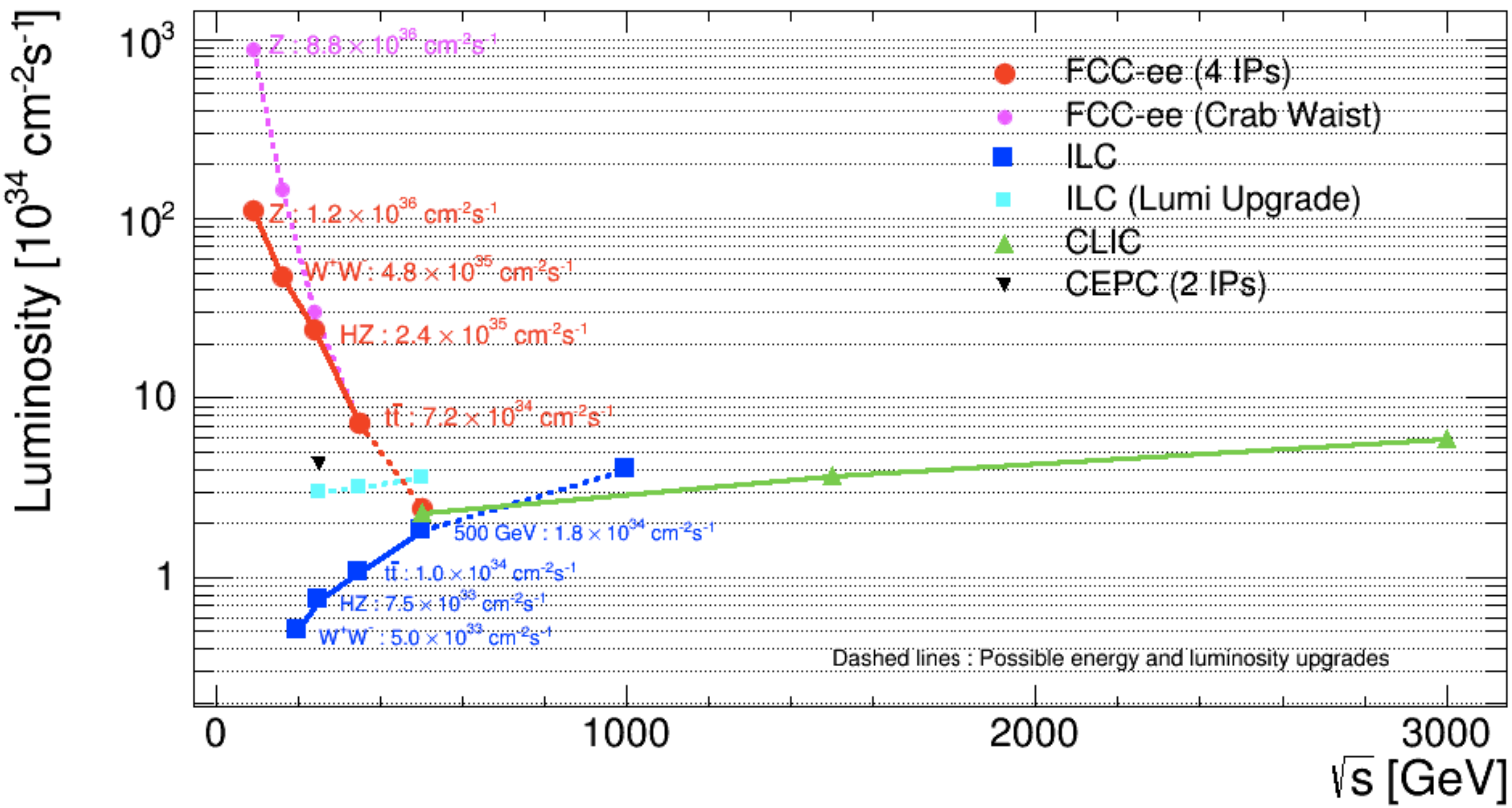


Summary & conclusions

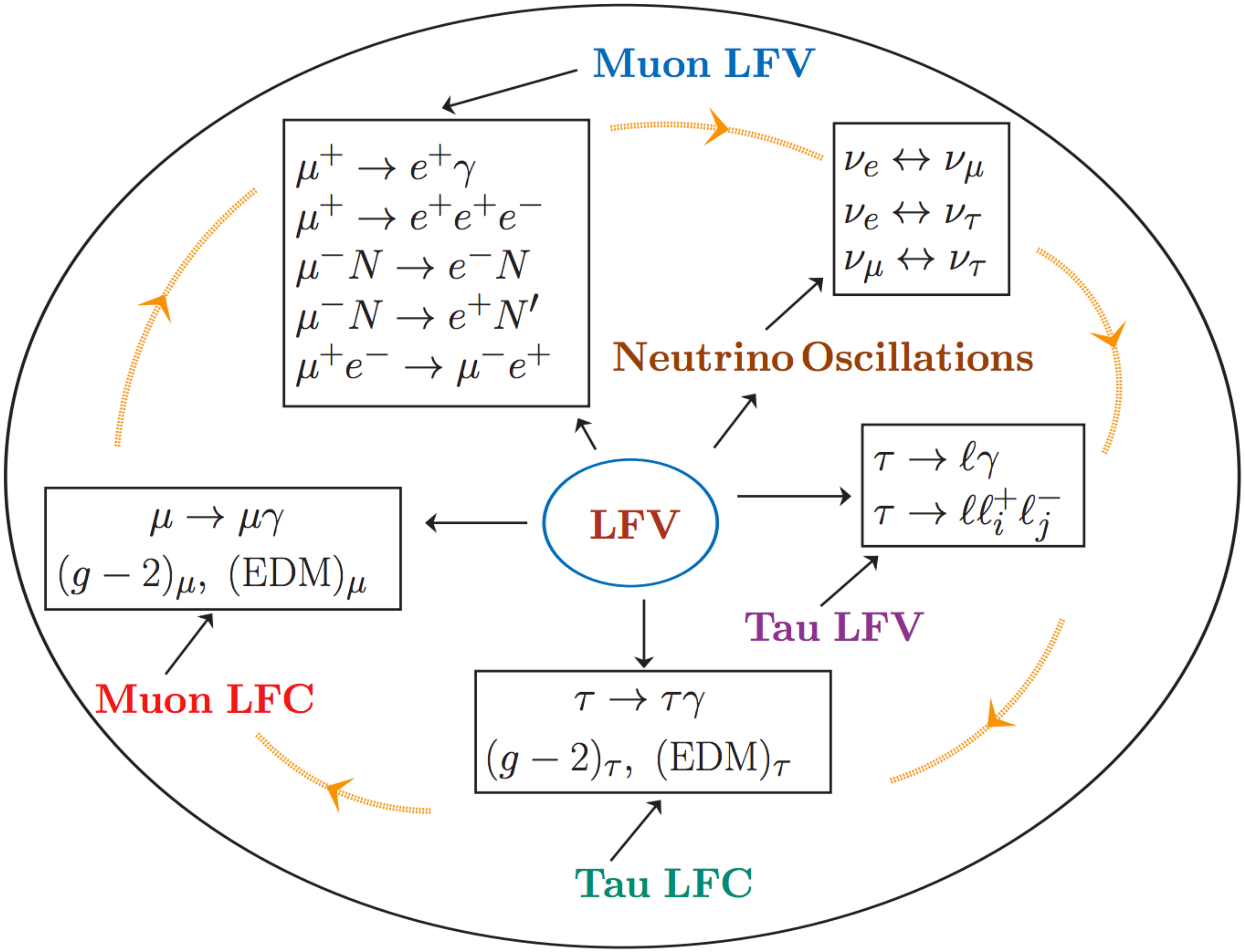
- High energy & high intensity frontiers driving R&D directions for calorimetry:
- >10 years old ideas are reaching maturity and start to be integrated into full scale detectors: dual readout & high granularity
- Particle flow approach beneficial for jet resolution but also to cope with high pile-up
- Extremely fast detectors: a new concept of integrated "5D calorimetry" (space, energy, time) is surfacing. Beneficial for the new challenging rates (10^{10} events/sec), benefit from R&D for rad hard & fast O(10ps) sensors
- Radiation hard optical calorimeters. Still some work to be done, need radiation hard O(10^{16} n/cm^{-2}) photodectors. New interesting scintillators (ceramics) appearing on the market

Back-up

e+ e- colliders



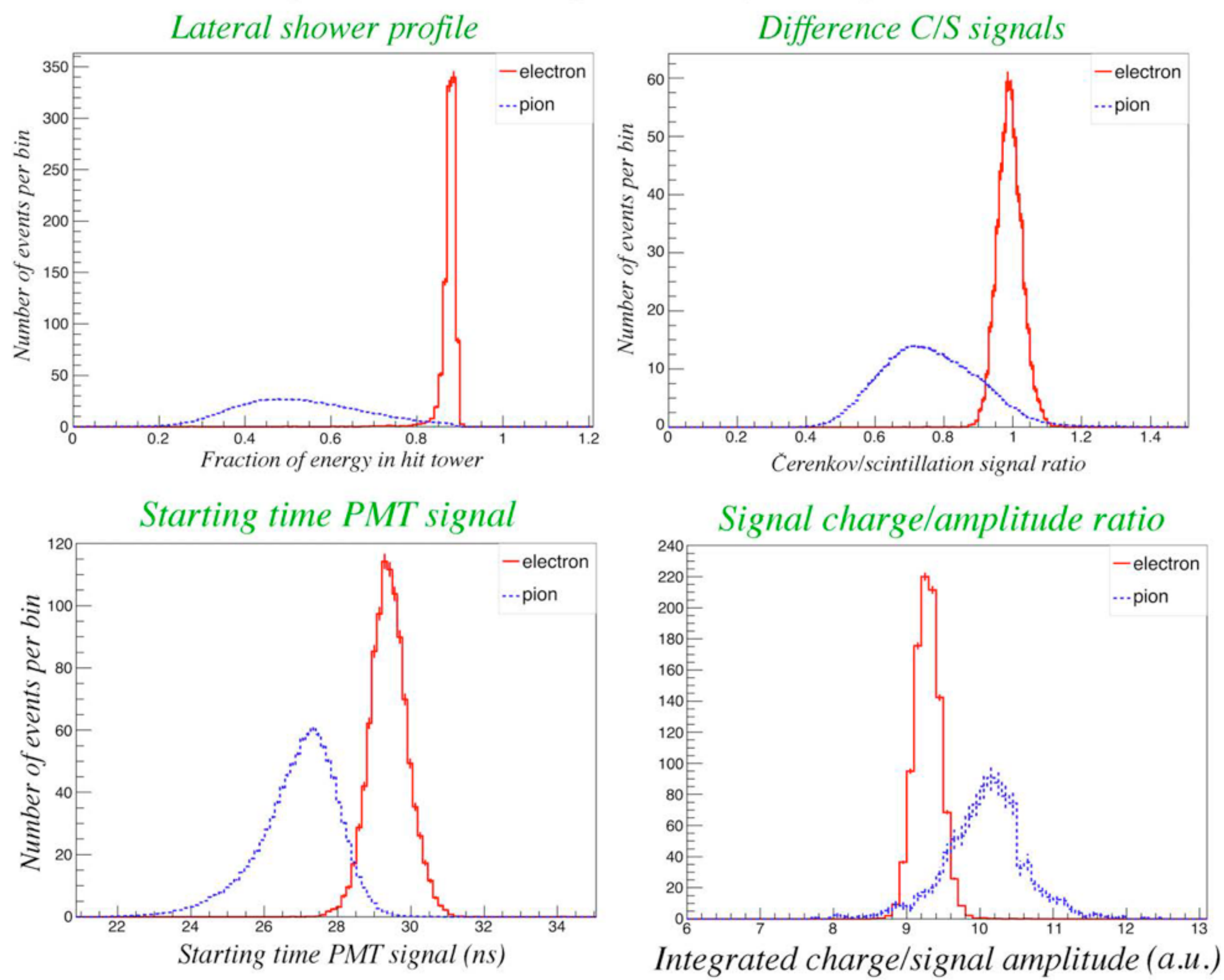
LFV



Muon LFV
$\mu^+ \to e^+\gamma$
$\mu^+ \to e^+e^+e^-$
$\mu^- N \to e^- N$
$\mu^- N \to e^+ N'$
$\mu^+ e^- \to \mu^- e^+$
$\nu_e \leftrightarrow \nu_\mu$
$\nu_e \leftrightarrow \nu_\tau$
$\nu_\mu \leftrightarrow \nu_\tau$
Neutrino Oscillations
LFV
$\mu \to \mu\gamma$
$(g-2)_\mu,\ (\mathrm{EDM})_\mu$
$\tau \to \ell\gamma$
$\tau \to \ell\ell_i^+\ell_j^-$
Tau LFV
Muon LFC
$\tau \to \tau\gamma$
$(g-2)_\tau,\ (\mathrm{EDM})_\tau$
Tau LFC

Particle ID in sampling dual readout calorimeter

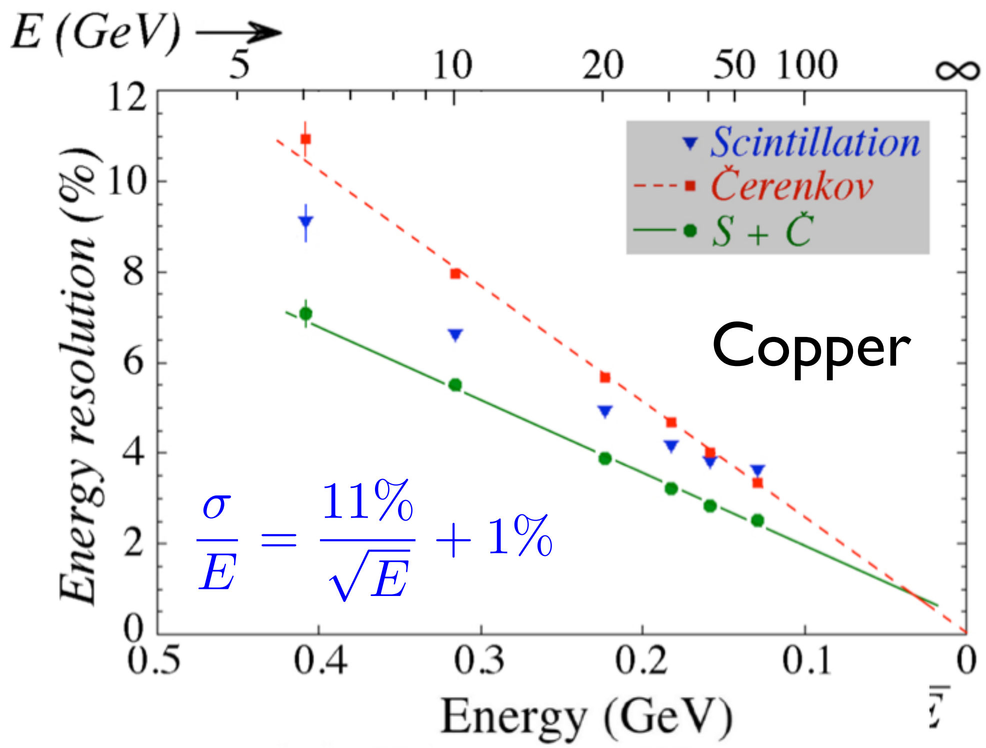
Methods to distinguish e/π in longitudinally unsegmented calorimeter

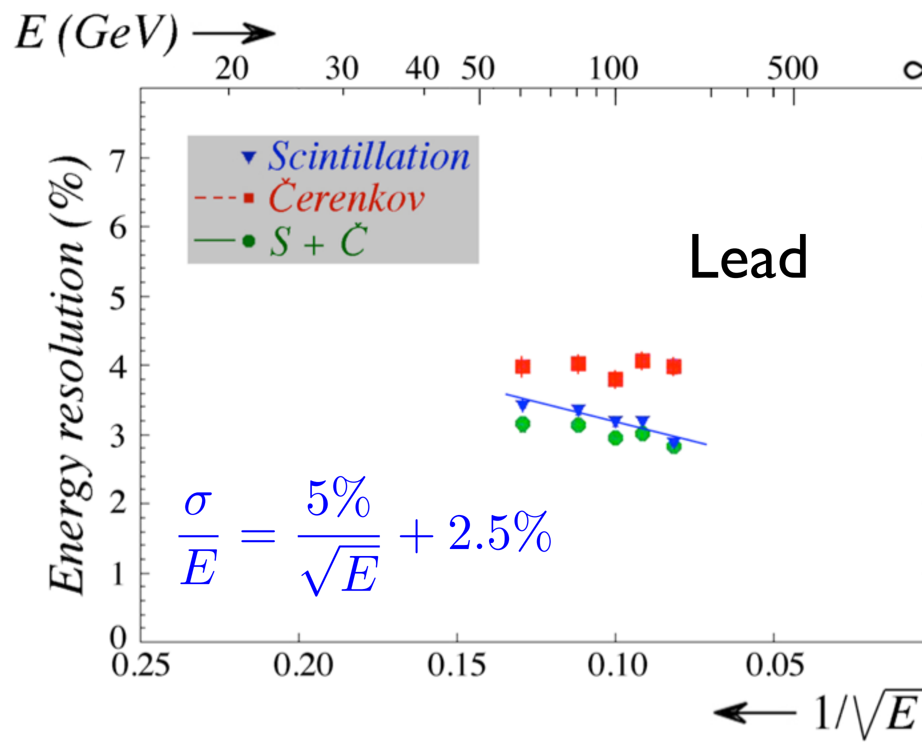


Combination of cuts: >99% electron efficiency, <0.2% pion mis-ID

Dual Readout method in sampling calorimeter

Electromagnetic Resolution

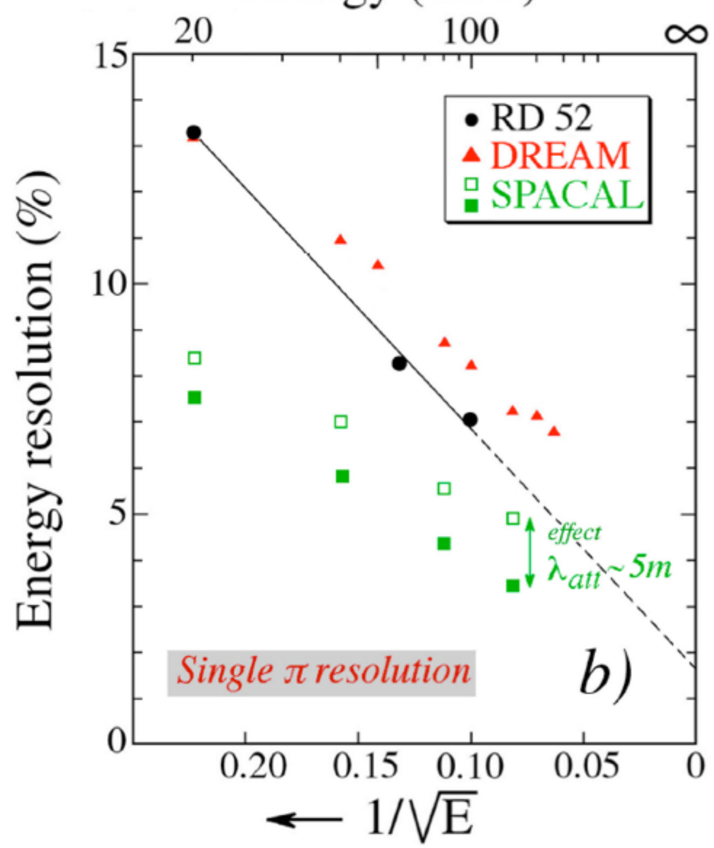


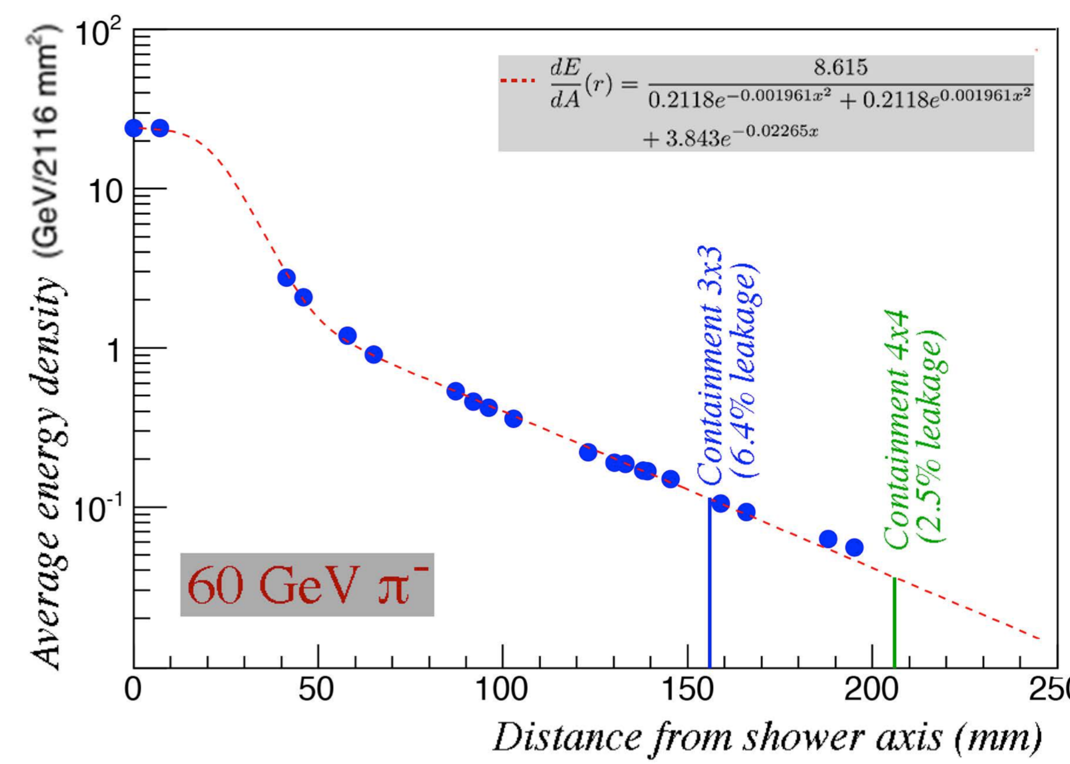


Hadronic Resolution (Pb Module)

$$\frac{\sigma}{E} = \frac{53\%}{\sqrt{E}} + 1.7\%$$

To include corrections on:
- light attenuation
- lateral leakage





Dual Readout method in homogeneous calorimeter

Motivations:

- high density scintillating crystal widely used in particle physics experiment: ensure excellent energy resolution for electromagnetic showers
- calorimeters with a crystal EM compartment usually have a poor had. resolution due to
  - fluctuation of the starting point of the hadronic shower in the EM section
  - different response to the em and non-em component of the shower in the two calorimeters

Dual readout applied to an hybrid system:

Measuring fem on an event-by-event basis allows to correct for such fluctuations and allows to eliminate the main reasons for poor hadronic resolution

Properties	Čerenkov	Scintillation
Angular distribution	Light emitted at a characteristic angle by the shower particles that generate it $\cos\theta = 1/(n\beta)$	Light emission is isotropic: excited molecules have no memory of the direction of the particle that excited them
Time structure	Instantaneous, short signal duration	Light emission is characterized by one or several time constants. Long tails are not unusual (slow component)
Optical spectra	$\frac{dN_C}{d\lambda} = \frac{k}{\lambda^2}$	Strongly dependent on the crystal type, usually concentrated in a (narrow) wavelength range
Polarization	polarized	not polarized

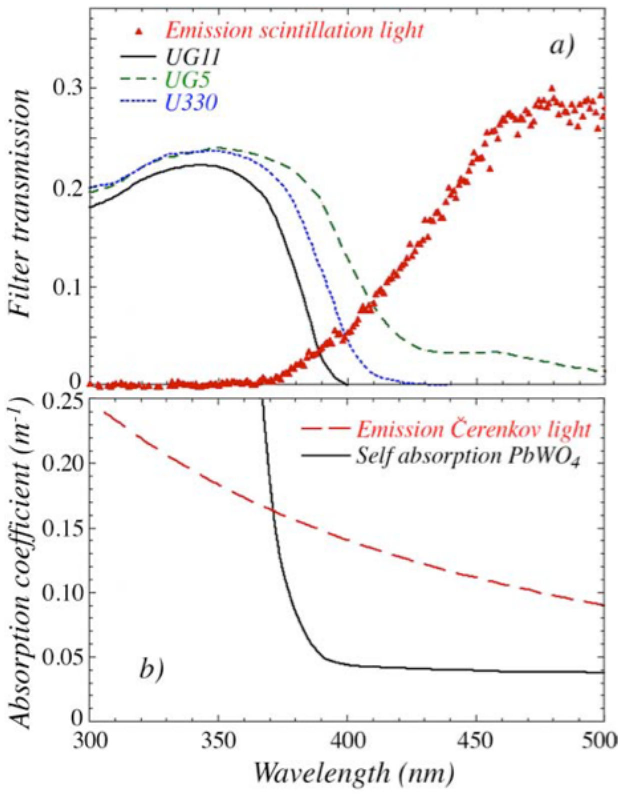
Results from DREAM Crystal TB

Praseodymium doped $PbW0_4$

Praseodymium doping causes:

- ★ shift of the S spectra to higher λ (emission in the red region)
- ★ too long S decay time (~μs)
- ★ shift of the absorption cut-off to higher λ

The high wavelength shift allow for higher cut-off filters, resulting in ***no light attenuation*** effect. The ***too long tail*** in scintillation emission is not suitable for fast calorimetry.

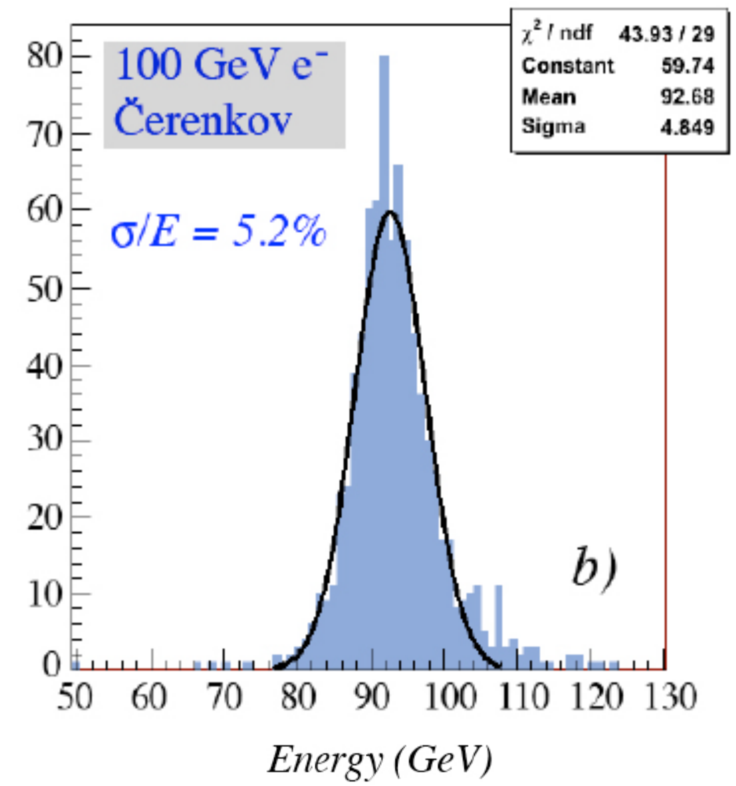


Molybdenum doped $PbW0_4$

Molybdenum doping causes:

- ★ shift of the S spectra to higher λ wrt undoped crystal
- ★ longer S decay time (50 ns)
- ★ shift of the absorption cut-off to higher λ

This allows to obtain a ***very good C/S separation*** using filters. Very narrow window where C light can be collected results in ***strong light attenuation*** .

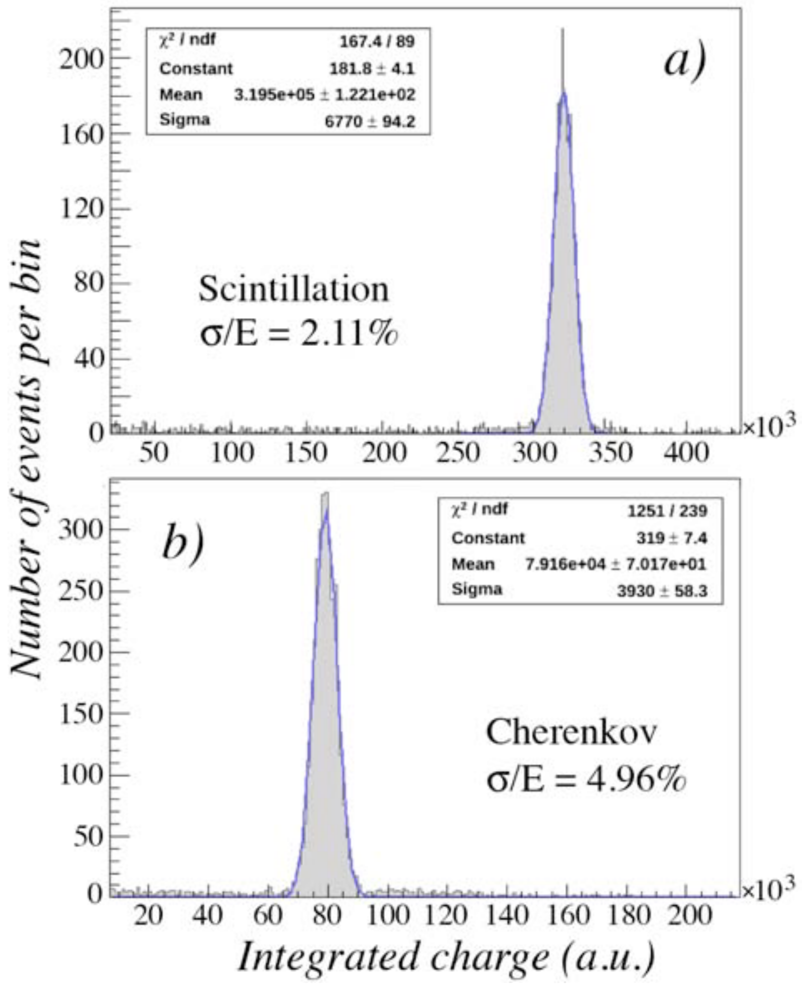


BGO Matrix results

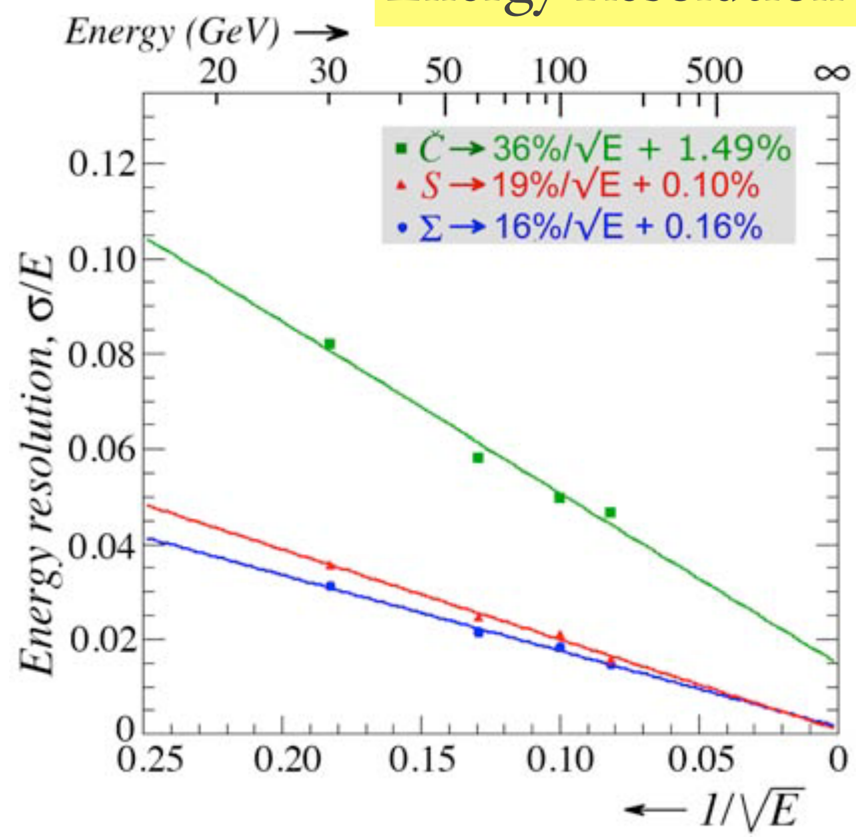
Resolution obtained from distribution of integrated charge

- Čerenkov energy resolution shows a constant term of about 1.5%
- good linearity (within ± 3%)
- Čerenkov light yield about 6 p.e./GeV

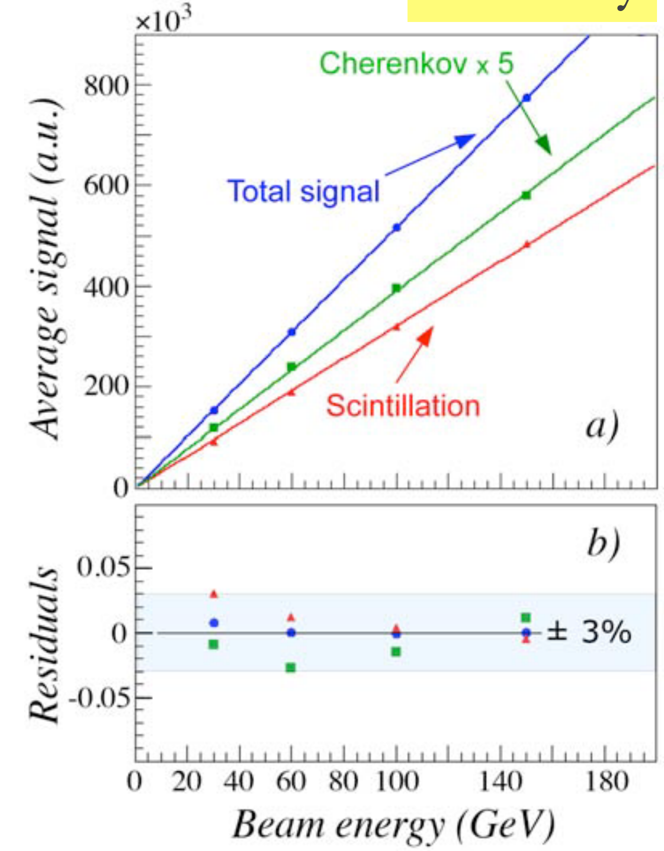
100 GeV electron



Energy Resolution



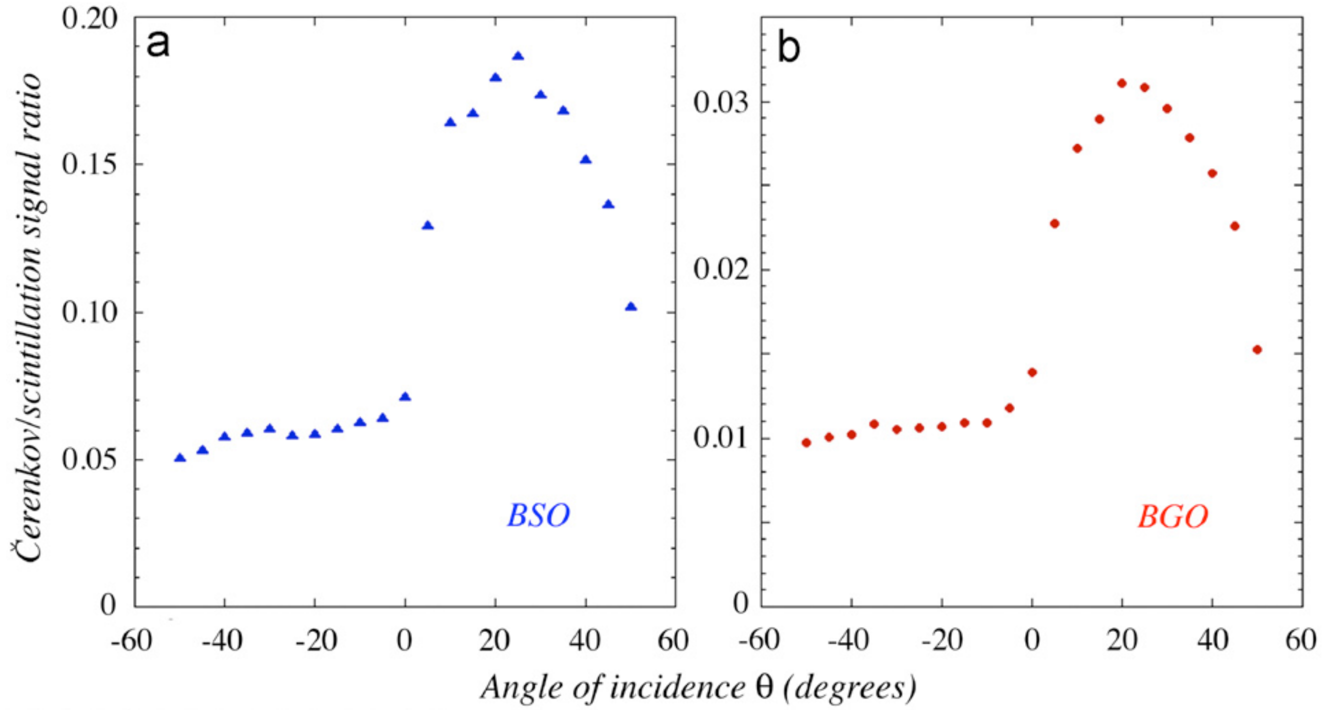
Linearity



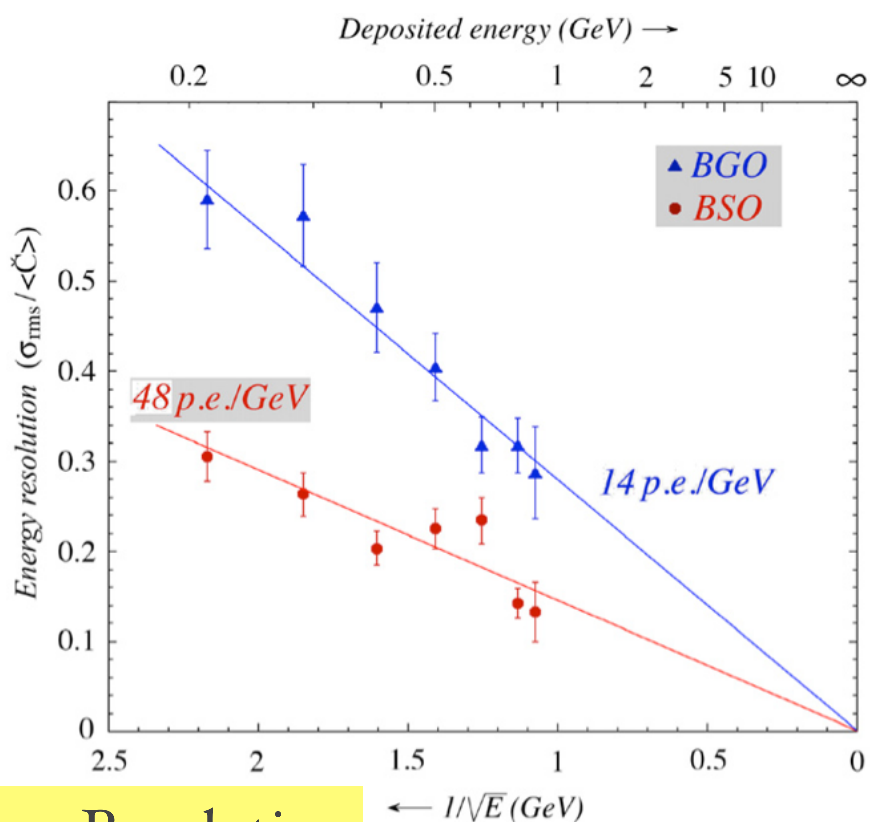
BGO vs BSO for dual readout use

INFN Istituto Nazionale di Fisica Nucleare

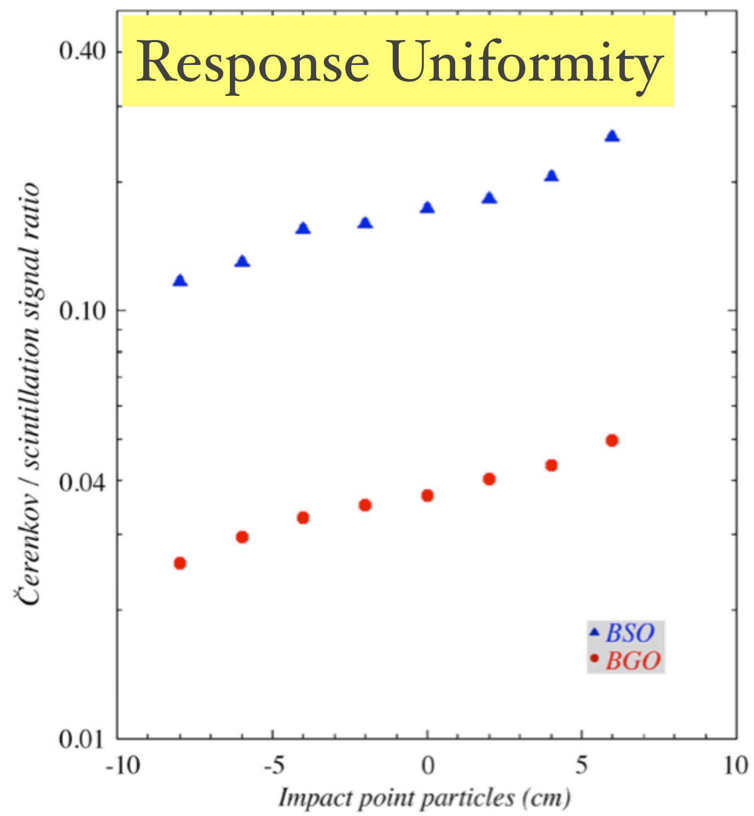
Crystal	Density ($g\ cm^{-3}$)	Radiation length (mm)	Decay constant (ns)	Peak emission (nm)	Refractive index n	Relative light output
BSO	6.80	11.5	~ 100	480	2.06	0.04
BGO	7.13	11.2	~ 300	480	2.15	0.15



purity of the $\check{C}$ signal obtained with filters: separation power better by a factor of 6



Energy Resolution



- $\check{C}$ light yield: p.e. detected per unit deposited energy 2-3 times larger in BSO
- light attenuation length for $\check{C}$ light: mostly the same in both crystals

Use of dual readout method

LuAG and Ce:LuAG

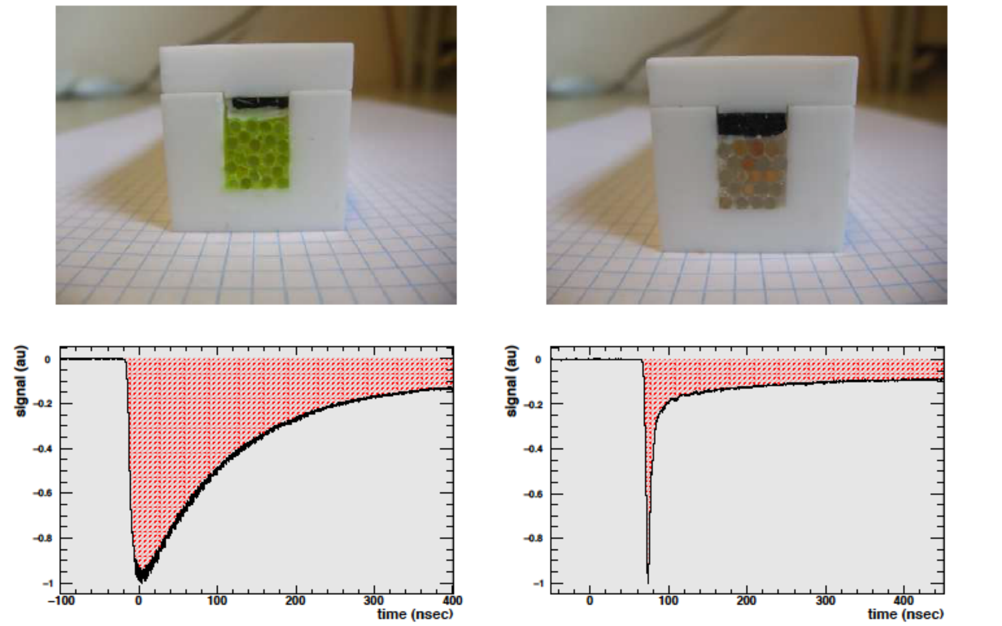
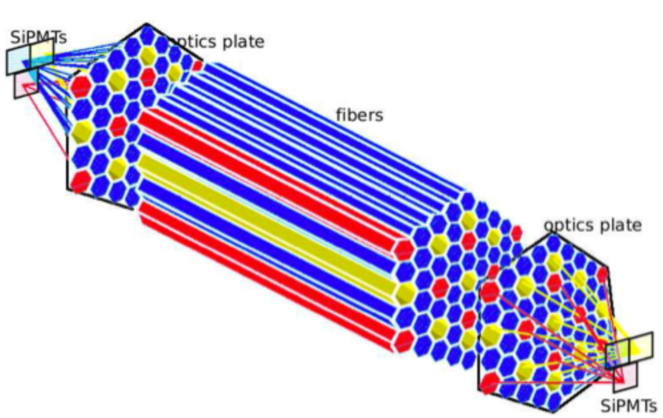
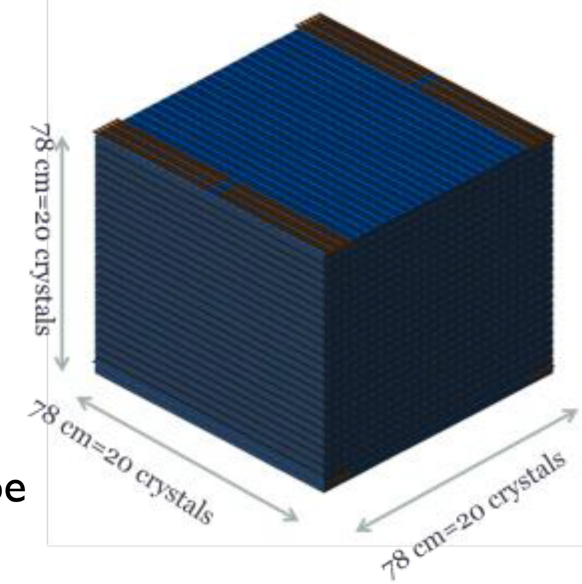


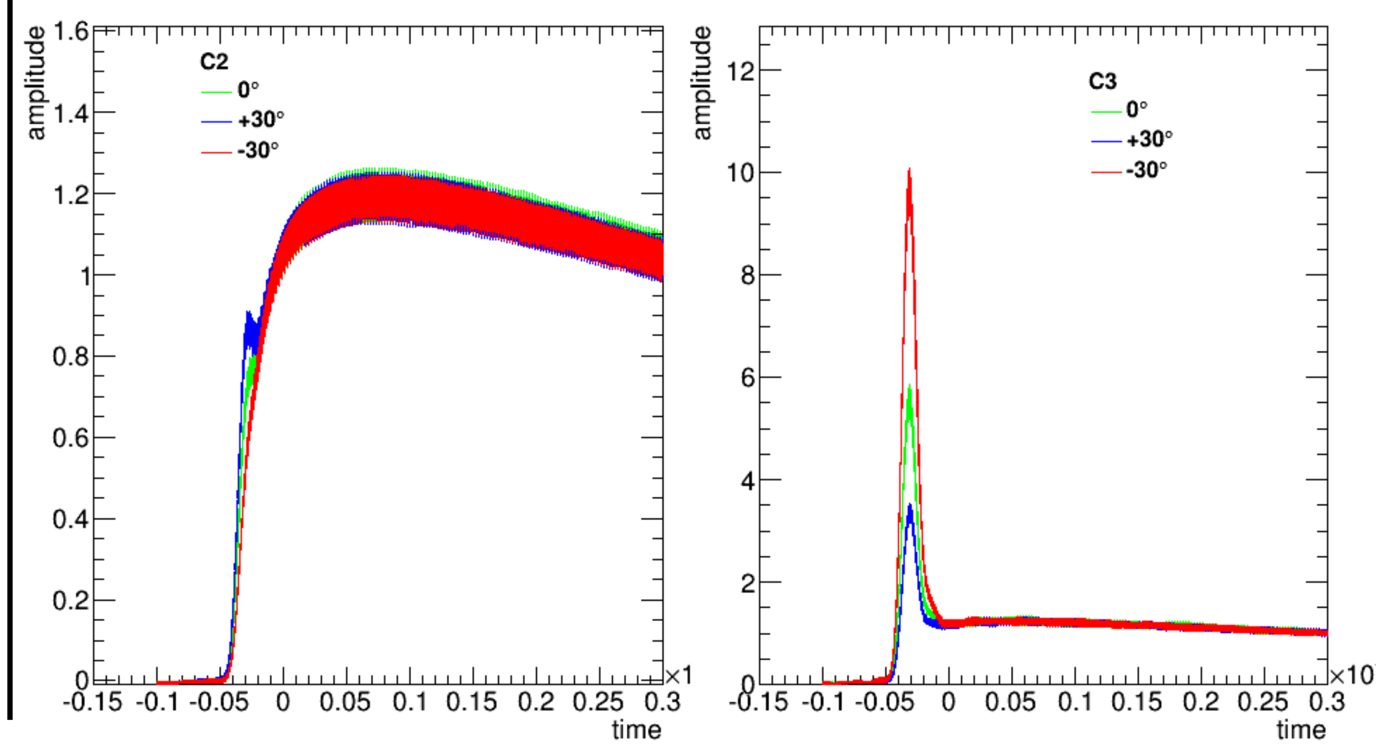
Figure 5. Bundles of Ce doped (top left) and undoped (top right) LuAG fibers and corresponding typical signal pulses recorded (bottom row). Each fiber measures 2 mm in diameter and 80 mm in length.



CaloCube



- ✶500 MeV electrons
- ✶CsI(Tl) cube wrapped in black tape
- ✶2 PhotoTubes, UV filters
- ✶Signal time profile averaged over many events



TEST BEAM AT FRASCATI BTF (SEP. 2013)

Figure of Merit for Timing

FoM is calculated as the LY in 1st ns obtained by using light output and decay time data measured for 1.5 X_0 crystal samples.

Crystal Scintillators	Relative LY (%)	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF_2	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180	53.8	5.4	75.3
CeF_3	7.3	100	30			208	6.8	0.7	8.6
BGO	21	100	300			350	1.2	0.1	2.5
PWO	0.377	80	30	20	10	9.2	0.42	0.04	0.4
$LaBr_3$:Ce	130	100	20			3810	185.8	19.0	229.9
$LaCl_3$:Ce	55	24	570	76	24	1570	49.36	5.03	62.5
NaI:Tl	100	100	245			2604	10.6	1.1	14.5
CsI	4.7	77	30	23	6	131	7.9	0.8	10.6
CsI:Tl	165	100	1220			2093	1.7	0.2	4.8
CsI:Na	88	100	690			2274	3.3	0.3	4.5