Crystal Calorimetry

07/05/2021

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with a ***big thank you*** to all colleagues and crystals/calorimeter experts that helped steering the content of this talk!

ECFA
European Committee for Future Accelerators

ECFA Detector R&D Roadmap Symposium
Task Force 6 - Calorimetry

Outline

- Key features of crystal calorimetry

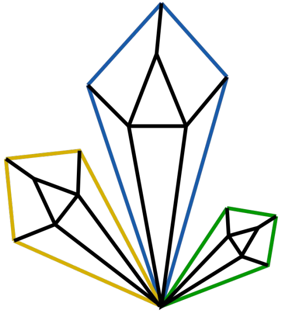
- Today's crystal calorimetry landscape
    - Synergies between existing/proposed calorimeters
    - Technology developments

- New perspectives on crystal calorimetry
    - Maximize information and precision (energy, timing, dual readout)
    - Going granular and big
    - Novel materials and methods

- System aspects & other remarks

Key features of crystals **for calorimetry**

- Large sampling fraction
  - up to homogeneous calorimeters
- **Excellent energy resolution**
  especially for low energy particles
  - to the 1-3% / √(E) level for EM showers
- **Cutting edge time resolution**
  over large areas at contained cost
  - at the O(10) ps level
- **Good radiation tolerance**
  - to withstand harsh radiation environments such as 1 MGy / 10^{15} neq/cm²



Crystals *for* calorimetry

Detector requirements from future experiments

From the Detector R&D requirements ECFA February session

Strong interaction experiments

- Measure low energy photons (down to 10 MeV)
- Photon pointing resolution
- Target energy resolution ~2%√E

‘No-collider’ experiments

- High-intensity and radiation conditions
- Energy resolution, segmentation and timing
- Low energy particles
- Crystal purity

Hadron colliders

- Pileup mitigation through precision timing and granularity
- Radiation tolerance (up 30 MGy for FCC-hh → ~30x HL-LHC)
- Target energy resolution ~10%√E

$\mu^+\mu^-$ colliders

- Mitigation of beam induced background (BIB) through precision timing and granularity
- Target energy resolution ~10%√E

e^+e^- colliders

- Improve Z→ee recoil mass resolution
- Clustering of π^0 photons
- Heavy flavor program (low energy photons)
- Target energy resolution ~3%√E

Crystal synergies for diverse applications

Mu2e

Mu2e-II

TauFV

COMET

'No-collider' experiments

- High-intensity and radiation conditions
- Energy resolution, segmentation and timing
- Low energy particles
- Crystal purity

g-2 experiment

Dark matter detectors
Pure crystal bolometers

EDM searches at COSY
Calorimetric polarimeter

Strong interaction experiments

- Measure low energy photons (down to 10 MeV)
- Photon pointing resolution
- Target energy resolution ~2%√E

Electron Ion Collider (EIC) ECal
(in the backward inner region)

ALICE 3 ECal **& low energy photons**

PANDA ECal **at FAIR**

Hadron colliders

- Pileup mitigation through precision timing and granularity
- Radiation tolerance (up 30 MGy for FCC-hh → ~30x HL-LHC)
- Target energy resolution ~10%√E

HL-LHC: LHCb
calorimeter upgrade
with a crystal SpaCal

FCC-hh: SpaCal or Shashlik
sampling crystal calorimeters

$\mu^+\mu^-$ colliders

- Mitigation of beam induced background (BIB) through precision timing and granularity
- Target energy resolution ~10%√E

ECAL: CRYLIN + crystal timing
segment with fast crystals

e^+e^- colliders

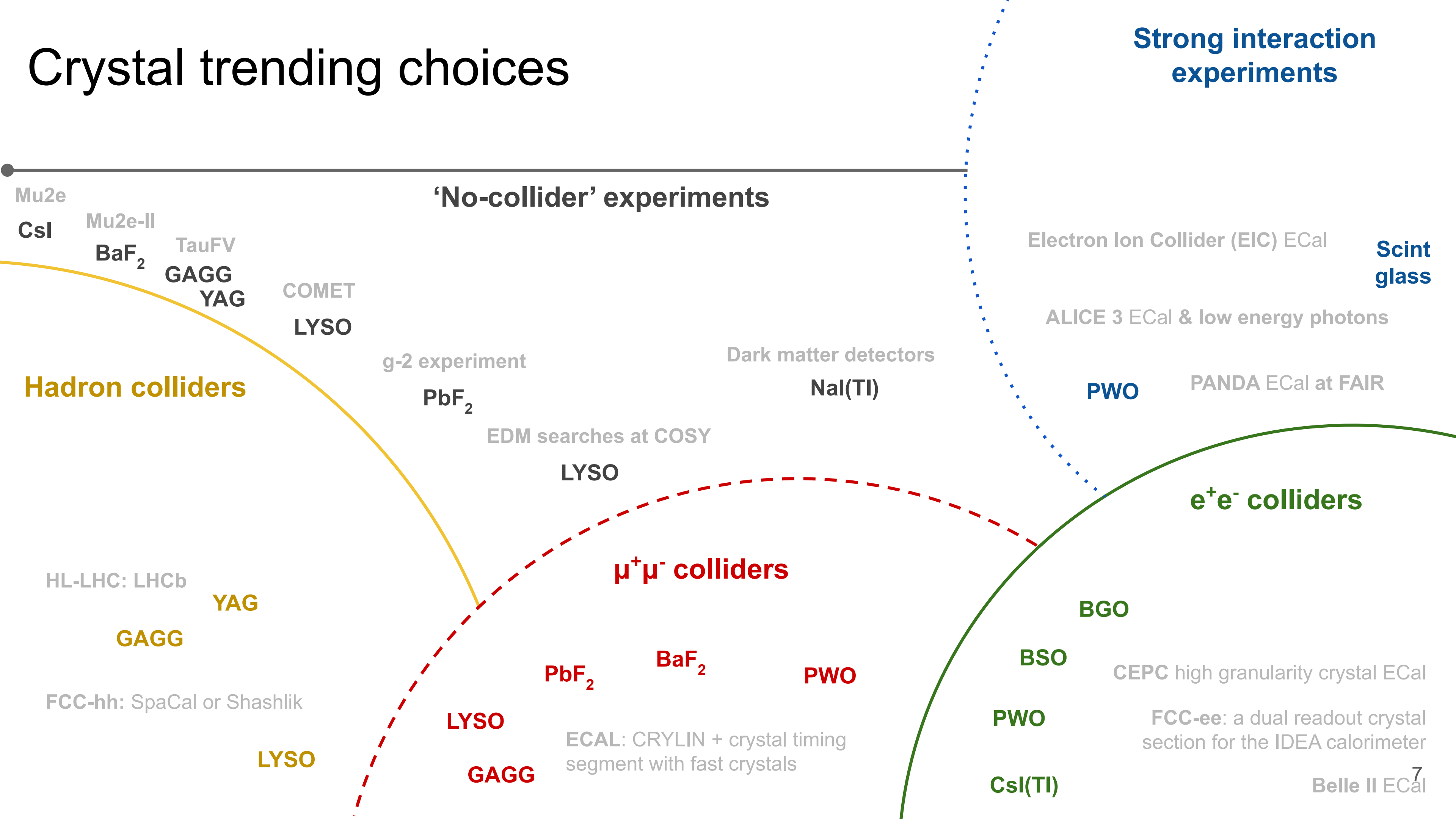
- Improve Z→ee recoil mass resolution
- Clustering of π^0 photons
- Heavy flavor program (low energy photons)
- Target energy resolution ~3%√E

CEPC high granularity crystal ECal

FCC-ee: a dual readout crystal
section for the IDEA calorimeter

Belle II ECal

Crystal trending choices



Strong interaction experiments

‘No-collider’ experiments

Mu2e

CsI

Mu2e-II

BaF_2

TauFV

GAGG

YAG

COMET

LYSO

g-2 experiment

PbF_2

EDM searches at COSY

LYSO

Dark matter detectors

NaI(Tl)

Electron Ion Collider (EIC) ECal

Scint glass

ALICE 3 ECal & low energy photons

PWO

PANDA ECal at FAIR

Hadron colliders

HL-LHC: LHCb

YAG

GAGG

FCC-hh: SpaCal or Shashlik

LYSO

$\mu^+\mu^-$ colliders

PbF_2

BaF_2

PWO

LYSO

GAGG

ECAL: CRYLIN + crystal timing segment with fast crystals

e^+e^- colliders

BGO

BSO

CEPC high granularity crystal ECal

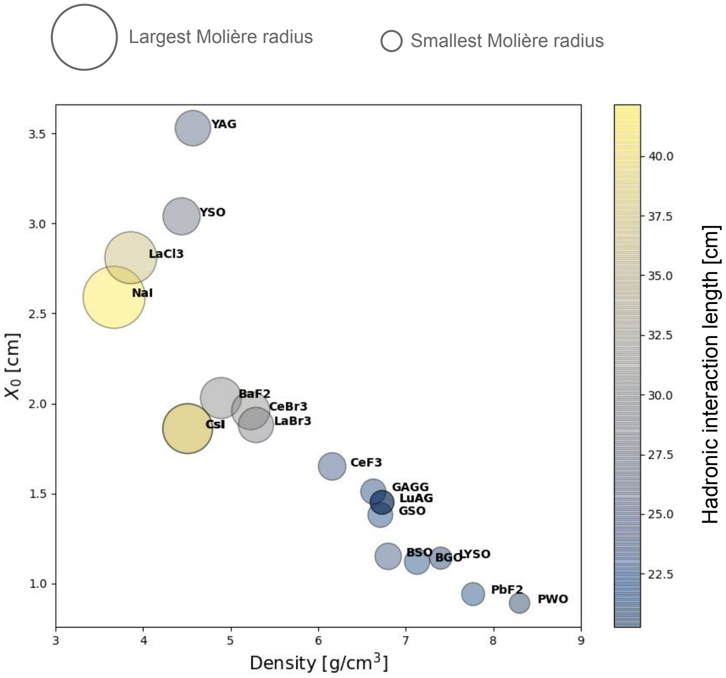
PWO

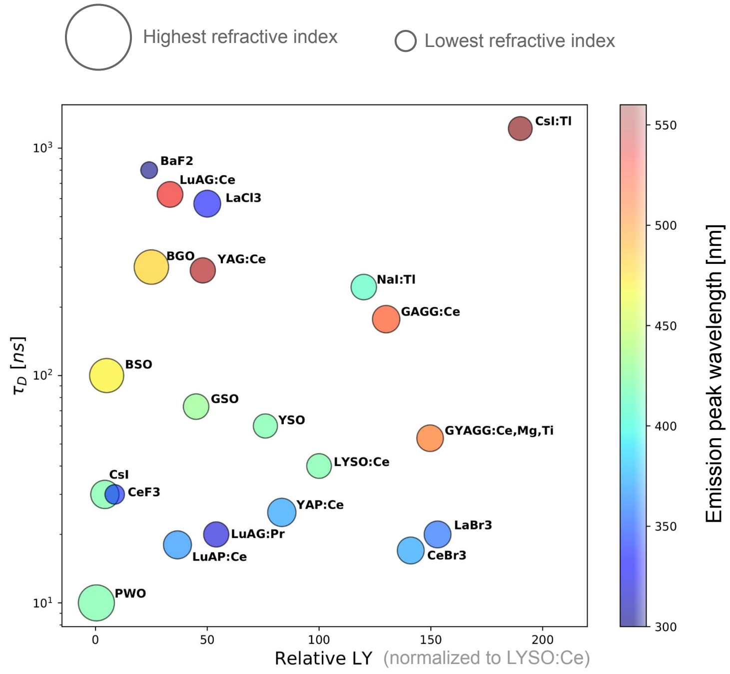
FCC-ee: a dual readout crystal section for the IDEA calorimeter

CsI(Tl)

Belle II ECal

A vast technological landscape

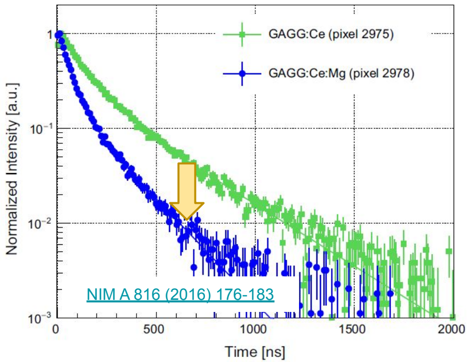




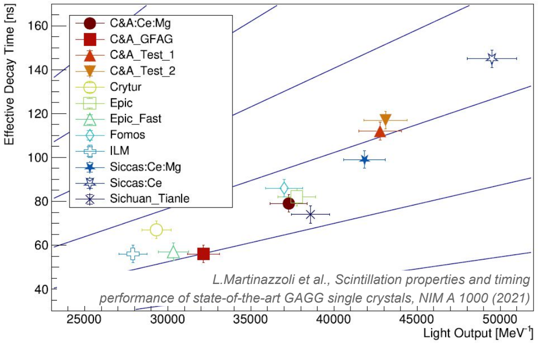
Crystals span a wide range of physical (ρ,X_0,R_M,λ_I) and scintillation properties (LY,λ_{em},n,τ_D)

Crystal technology in continuous **development**

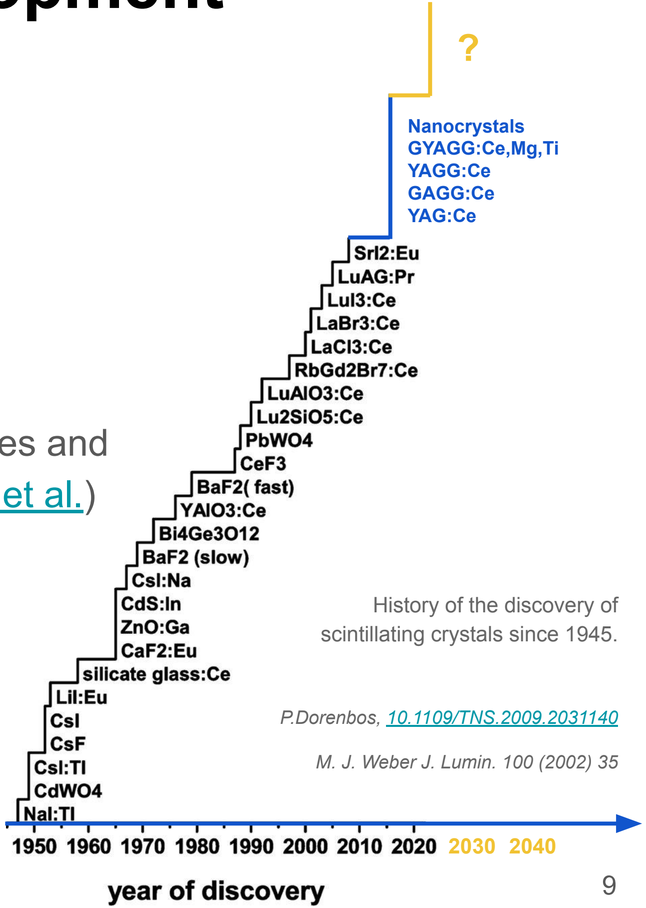
- A crystal with same physical properties can be **doped** differently to achieve a different scintillation performance
  - LuAG **undoped** → excellent Cherenkov radiator
  - LuAG:**Pr** → λ_{em} <370 nm, τ_D<25 ns
  - LuAG:**Ce** → λ_{em} >530 nm, τ_D>100 ns
- Crystal **co-doping** ("defect engineering") also a powerful tool to tune the scintillation parameters
- **Reshuffling crystal matrix composition** to tune physical properties and facilitate the modification of scintillation parameters (G.Dosovitskiy et al.)



NIM A 816 (2016) 176-183



L.Martinazzoli et al., Scintillation properties and timing performance of state-of-the-art GAGG single crystals, NIM A 1000 (2021)



History of the discovery of scintillating crystals since 1945.

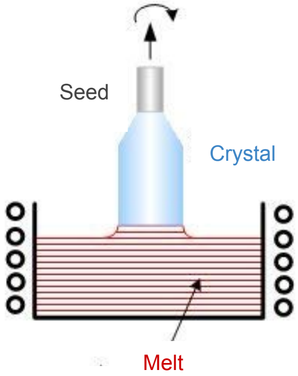
P.Dorenbos, 10.1109/TNS.2009.2031140

M. J. Weber J. Lumin. 100 (2002) 35

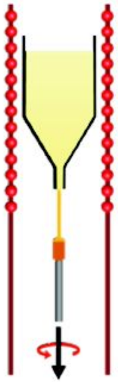
Progress in crystal **manufacturing**

opens new ways for designing crystal based (segmented) calorimeters

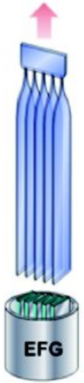
Czochralski / Bridgman
'traditional' ingot growth



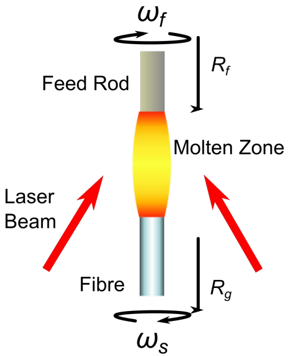
Micro-Pulling Down
(µPD)



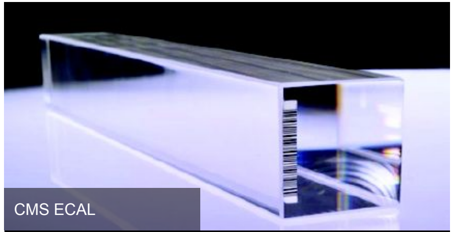
Edge-Defined Film-Fed
Growth (EDG)



Laser-heated pedestal
growth (LHPG)

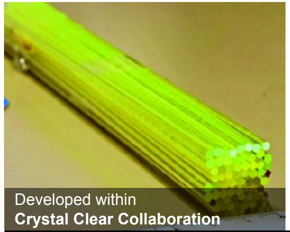


3D printing



CMS ECAL

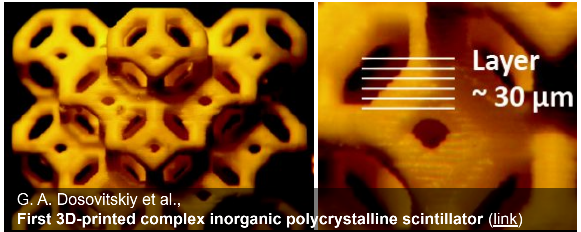
Lead tungstate bulk crystals



Developed within
Crystal Clear Collaboration

https://iopscience.iop.org/article/10.1088/1748-0221/8/10/P10017

Crystal fibers for high granularity



G. A. Dosovitskiy et al.,
First 3D-printed complex inorganic polycrystalline scintillator (link)

3D printed micro structures (for dreaming)

New *and renewed* materials

Cost effective

- Silica doped fibers (SiO_2:Ce, SiO_2:Pr)
  - [F.Cova et al.]
- Heavy scintillating glasses (DSB:Ce, AFO:Ce)
  - [E.Auffray et al.]
- Scintillating ceramics (LuAG:Ce, YAG:Ce, GYAG:Ce)
  - [T.Yanagida et al.]
- Polysiloxane polymers
  - [F.Acerbi et al.]

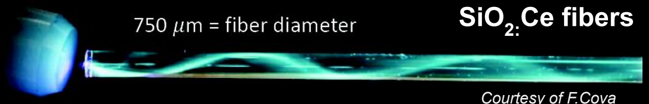
A new look

- PWO → PWO II → PWO III (improving LY by a factor 3, decreasing decay time at the ~2 ns level)
  - [A.Borisevich et al., M.Follin et al.]
- Crossluminescence in BaF_2 and Cherenkov 'rediscovery'
  - [R.Zhu, R.Pots et al., N.Kratocwhil et al., S.Gundacker]

A possible future

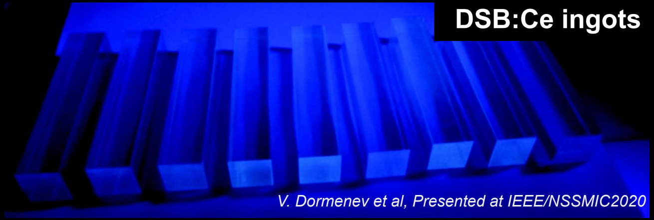
- Nano scintillating crystals (ZnO:Ga, InGaN/GaN QW, perovskites), many developments in Crystal Clear
  - [see E.Auffray @ ECFA Task Force 5]

$SiO_{2:}$Ce fibers



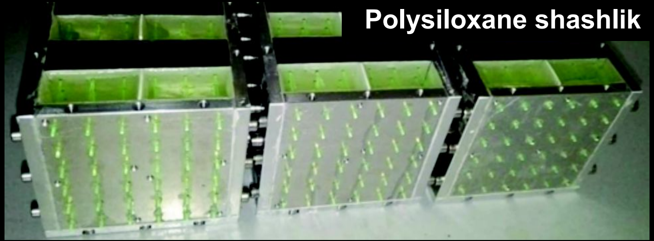
Courtesy of F.Cova

DSB:Ce ingots

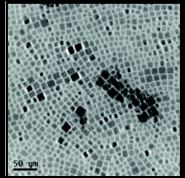


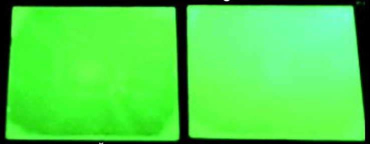
V. Dormenev et al, Presented at IEEE/NSSMIC2020

Polysiloxane shashlik



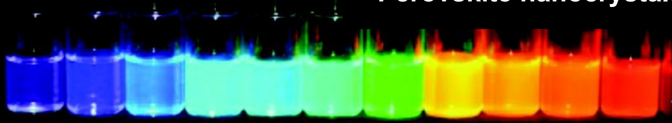
$CsPbBr_3$ nanocrystals





Courtesy V. Čuba, K. Děcká, A. Suchá CTU, Prague

Perovskite nanocrystals



L. Protesescu et al. Nano Lett. 2015, 15, 3692−3696

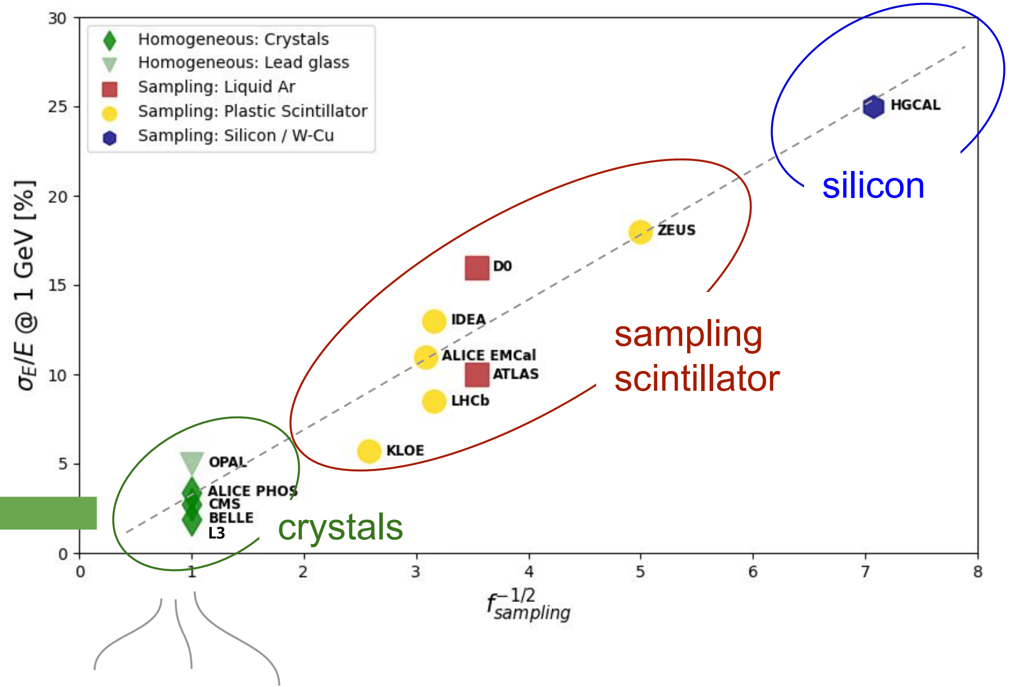
A 20+years long vision for crystal calorimetry

Crystals in **calorimetry**

- Homogenous crystal calorimeters have a long **history** of **pushing the frontier of high EM resolution**
  - The entire EM shower is sampled
  - Large light signals are produced

$$\frac{\sigma_E}{E} \sim \frac{3\%}{\sqrt{E}}$$

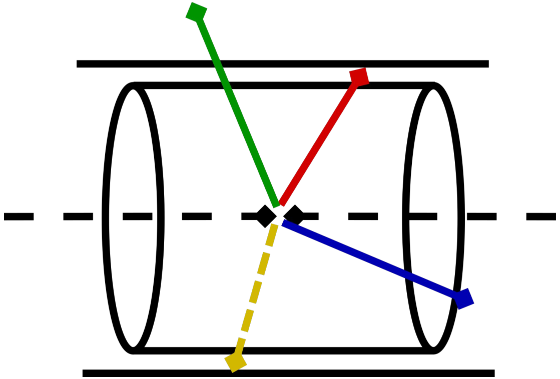
A sample of existing and future calorimeters



PWO, BGO, CsI

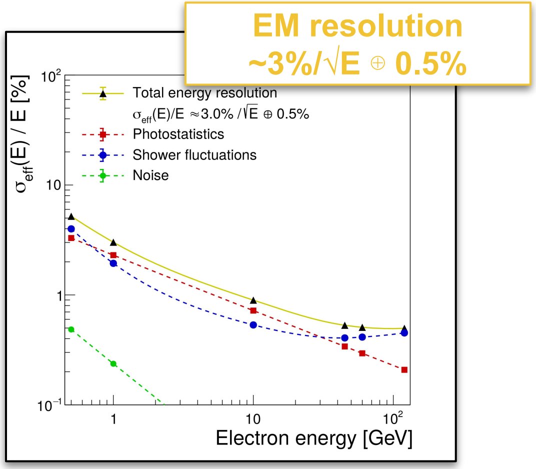
New perspectives for crystal calorimetry

- **Finer granularity**
- **Precision & maximum information**
  - Energy
  - Time
  - Position
  - Composition / particle ID
- **Innovative concepts & methods**

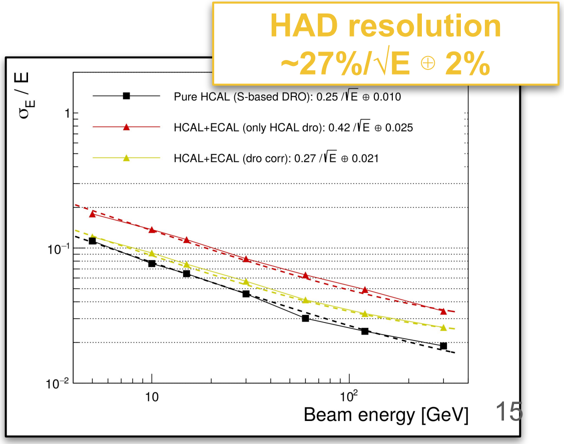


Integration of homogeneous crystals in a **hybrid dual-readout calorimeter**

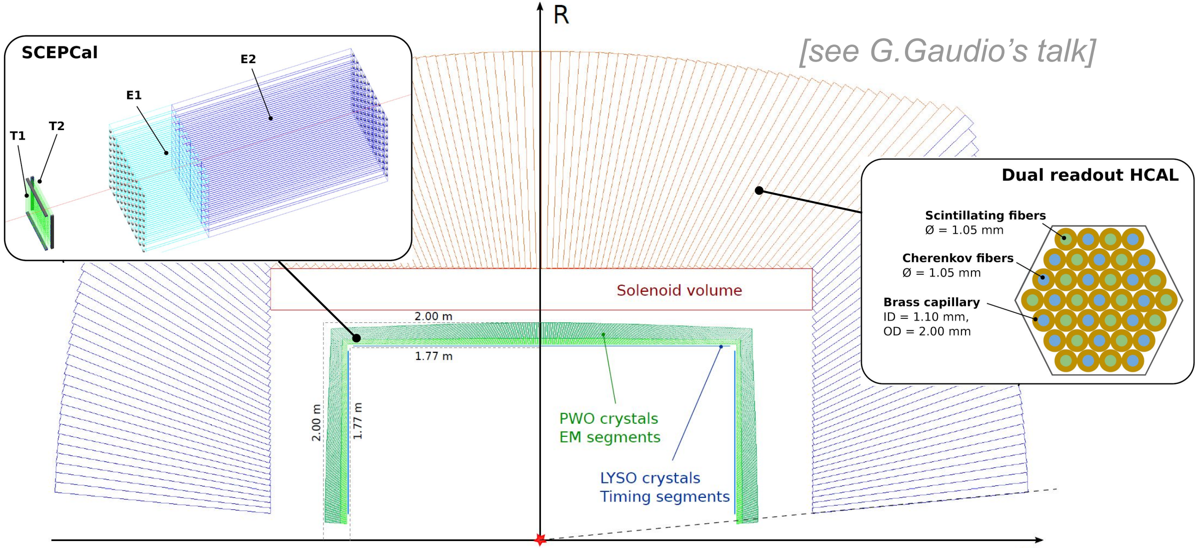
- Achieving **excellent energy resolution** for EM and HAD showers **in a cost-effective way**
- **A EM crystal section with dual readout capabilities**



EM resolution ~3%/√E ⊕ 0.5%



HAD resolution ~27%/√E ⊕ 2%

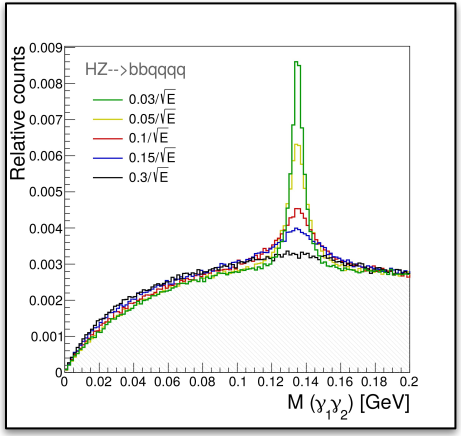


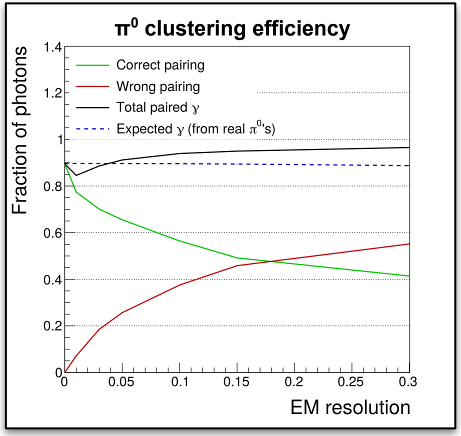
[see G.Gaudio's talk]

https://doi.org/10.1088/1748-0221/15/11/P11005

Integration of **precise** energy measurements in **Particle Flow Algorithms**

- A segmented crystal calorimeter can offer **opportunities to improve performance of particle flow algorithms**, e.g. by exploiting the higher energy resolution for **clustering photons from π^0 decays in multi-jet events**





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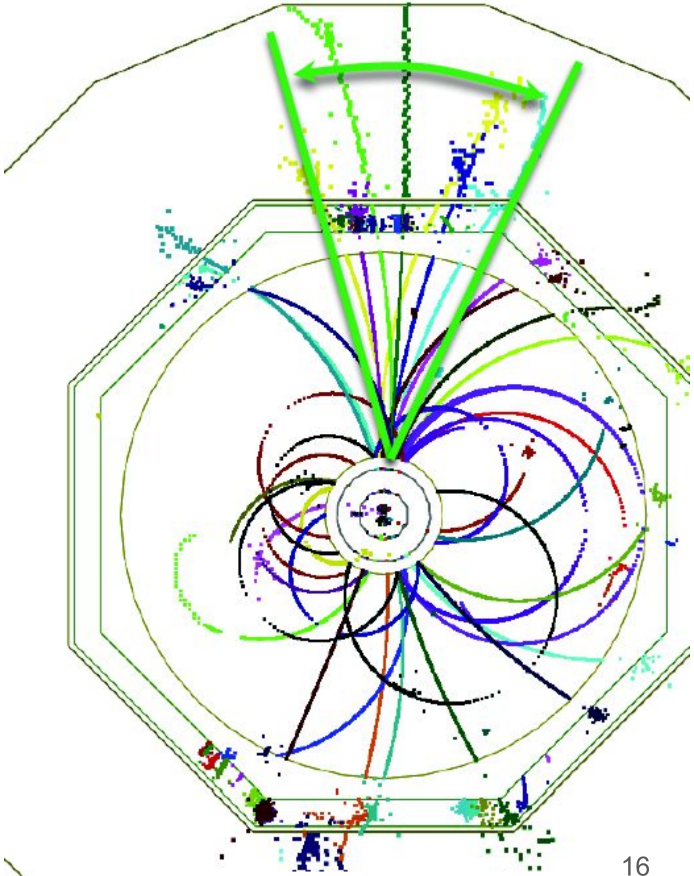
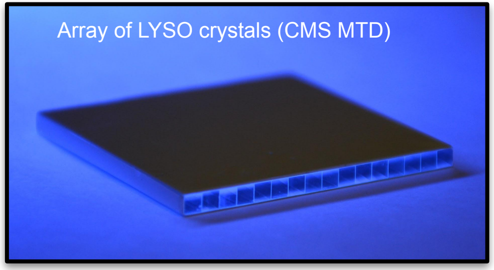


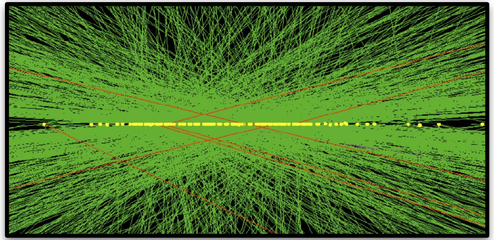
Picture borrowed from Marcel Vos

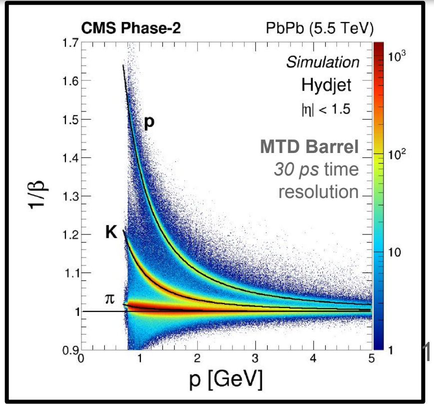
Integration of **precision timing** in crystal calorimeters

[see N.Ackurin's talk]

- Opportunity to integrate precise time and energy measurements with a 'calorimetric' active material (crystals)!
- Two examples from CMS:
  - Time resolution of ~**30 ps for single MIPs** with single **LYSO** layer with SiPMs (see MTD in CMS Phase 2 upgrade)
  - Time resolution of ~**30 ps for EM showers** with the **PWO** ECAL with APDs (see CMS ECAL in Phase 2 Upgrade)
- **An additional powerful handle for event reconstruction**
  - Time-of-flight for heavy ions
  - Search for long lived particles
  - Pileup mitigation
- **Nano crystals** features sub-nanosecond scintillation and may represent a further leap towards precision timing



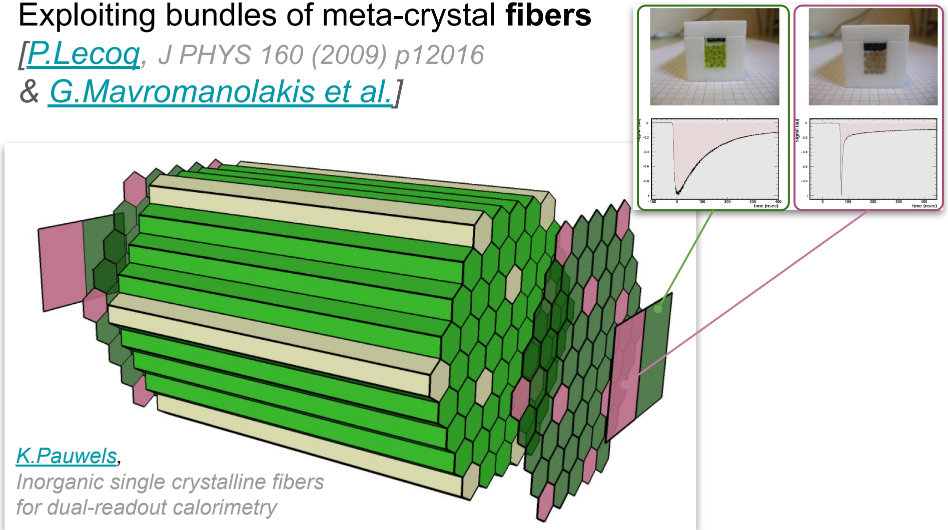




Going **big** for hadrons

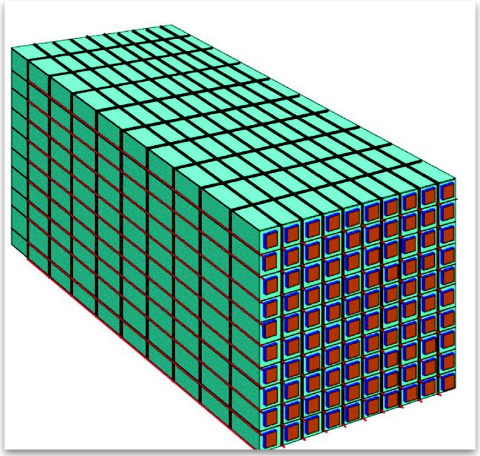
- **Full absorption dual-readout hadron calorimetry could aim at further boosting the energy resolution for hadronic showers→~15%/√E**
- **Major challenges**: requires breakthrough in mass production (quality/uniformity) and cost reduction for high density scintillators (crystals / heavy glasses), challenging to achieve proof-of-concept

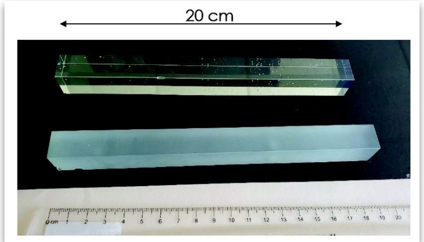
Exploiting bundles of meta-crystal **fibers**
[P.Lecoq, J PHYS 160 (2009) p12016
& G.Mavromanolakis et al.]



K.Pauwels,
Inorganic single crystalline fibers for dual-readout calorimetry

Exploiting **bulk** cost-effective dense scintillators
[CPAD2021, M.Demarteau et al.]



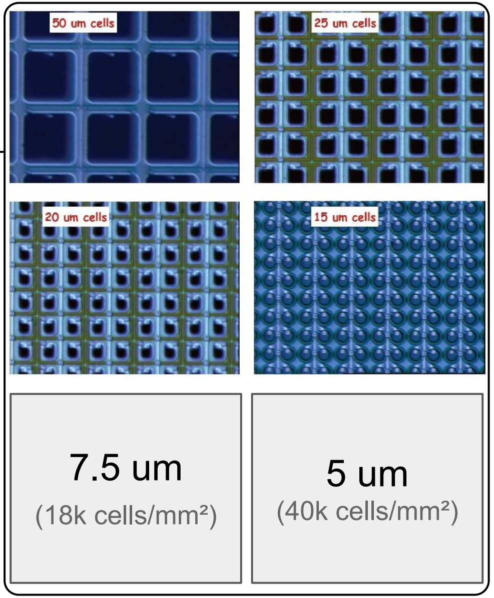


Bulk scintillating glass production as part of EIC R&D

A natural link with photodetector developments

- The way towards more granular, radiation tolerant and performant crystal calorimeters relies on crucial photodetector developments!
  - **SiPMs**
    - A compact and robust solution prone to integration in segmented calorimeters
    - Immune to magnetic fields and low voltage operation
    - *Huge* developments boosting dynamic range, sensitivity and rad-tolerance
    - Not *yet* sufficiently radiation tolerant for future hadron colliders
  - **PMTs**
  - **MCP-PMTs**
  - **MPGDs**

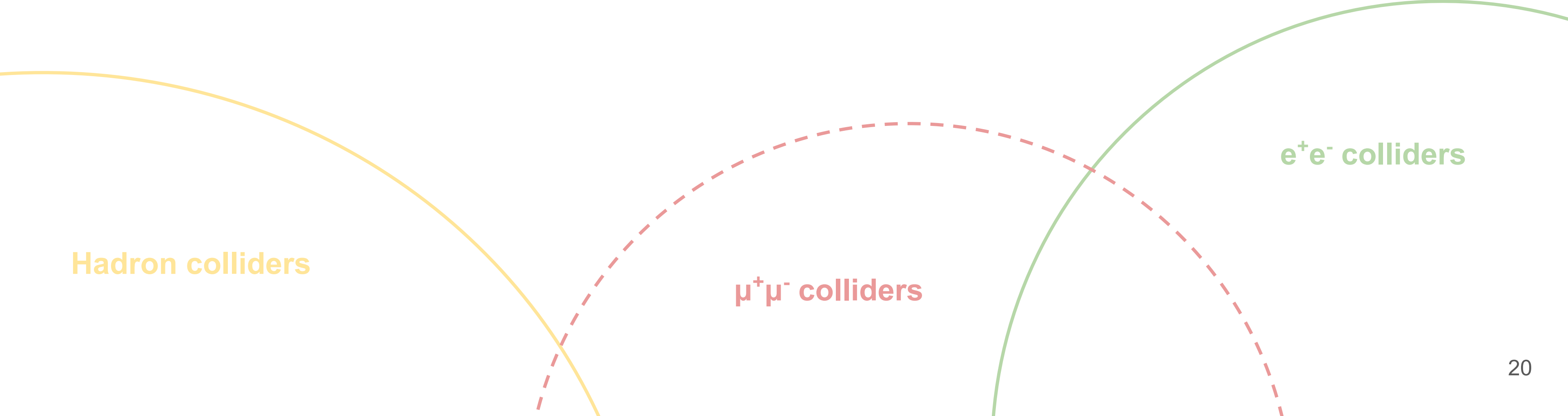
Promising developments towards radiation tolerance and fast timing
[See **Task Force 4** session: https://indico.cern.ch/event/999817/]



- Precision timing

→ requires fast photodetectors with small intrinsic time jitter
→ would welcome enhancement of the sensitivity to the VUV range (e.g. to exploit cherenkov or cross-luminescence)

Three (future?) crystal calorimeter examples



Hadron colliders

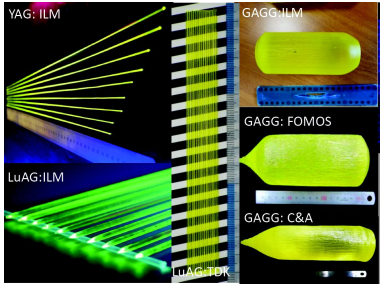
$\mu^+\mu^-$ colliders

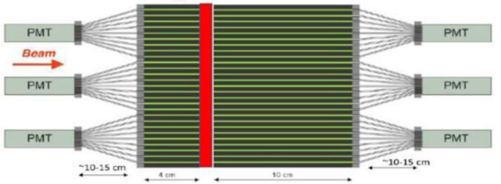
e^+e^- colliders

Radiation tolerant sampling crystal calorimeters

Spaghetti calorimeter (candidate for the LHCb phase II upgrade)

- Crystal fibers inside an absorber ‘groove’ (more details here)
- Co-doped garnet crystals (GAGG, YAG, GYAGG)
- **Possibility to mix different type of fibers** (e.g. Cerenkov, neutron sensitive)
- Targets: $\sigma_E/E\sim10\%/\sqrt{E}$, $\sigma_t\sim O(10)$ps

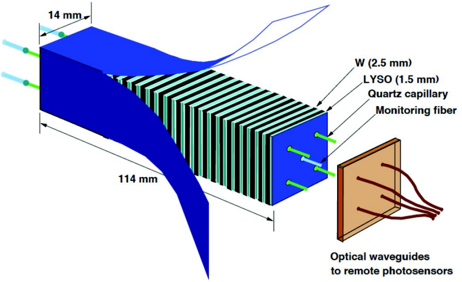




2020 SPACAL-W prototype

Shashlik calorimeter (was candidate for CMS phase II upgrade)

- Crystal slabs interleaved with tungsten slabs and read out with wavelength shifting fibers
- UV-emitting crystals (LYSO, CeF_3)
- SiO2:Ce or LuAG:Ce fibers as WLS
- Targets: 10%/√E, $\sigma_t\sim O(10)$ps
- Ongoing R&D targeting FCC-hh applications with the ***RADiCAL*** detector concept (CPAD 2021)

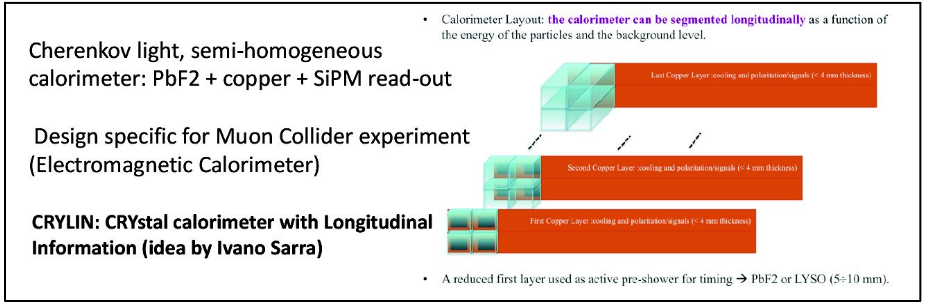


Combining tungsten with radiation tolerant crystals for compact calorimeters at hadron colliders

Fast segmented crystals for BIB mitigation

- **Timing and longitudinal shower distribution** provide a handle to mitigate Beam Induced Background in ECAL
    - Readout energy reduced by 3x with loose timing cuts
    - High granularity + precise timing of each channel would allow to use sophisticated BIB subtraction at the Particle Flow reconstruction level
    - A Cherenkov calorimeter with PbF_2 crystals read out by SiPMs could offer a cost-effective solution
- **Ongoing R&D on rad-hard fast crystals** (e.g. PbF_2, BaF_2, PWO)
- Synergies with KLEVER and LHCb

Detector R&D requirements for muon colliders

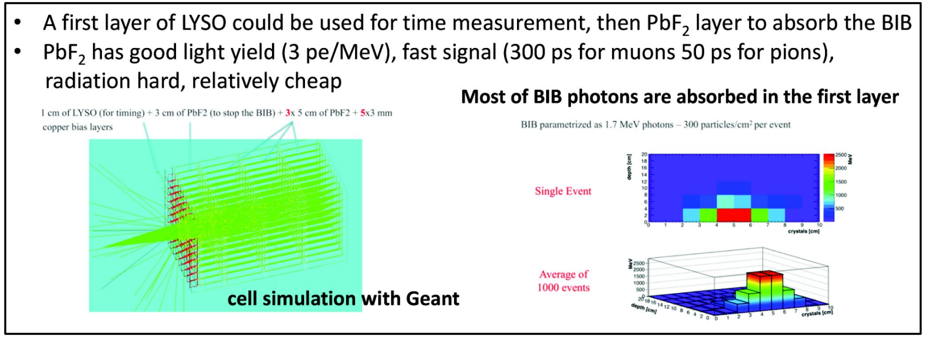


Cherenkov light, semi-homogeneous calorimeter: PbF2 + copper + SiPM read-out

Design specific for Muon Collider experiment (Electromagnetic Calorimeter)

CRYLIN: CRYstal calorimeter with Longitudinal Information (idea by Ivano Sarra)

- Calorimeter Layout: **the calorimeter can be segmented longitudinally** as a function of the energy of the particles and the background level.
- A reduced first layer used as active pre-shower for timing → PbF2 or LYSO (5÷10 mm).



- A first layer of LYSO could be used for time measurement, then PbF_2 layer to absorb the BIB
- PbF_2 has good light yield (3 pe/MeV), fast signal (300 ps for muons 50 ps for pions), radiation hard, relatively cheap

Most of BIB photons are absorbed in the first layer

BIB parametrized as 1.7 MeV photons – 300 particles/cm² per event

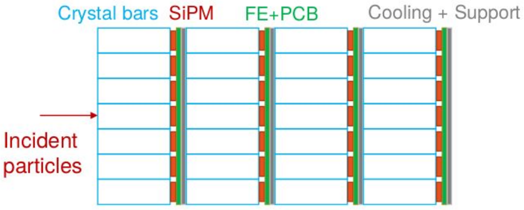
cell simulation with Geant

Exploiting crystal timing and longitudinal segmentation for BIB rejection at muon collider

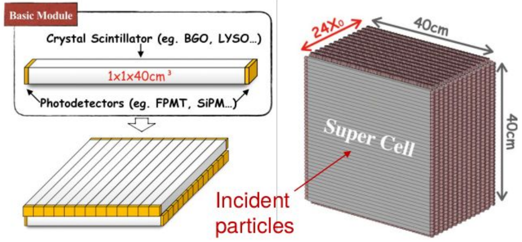
High granularity crystal calorimeter for CEPC

Y.Liu, Detector concept with crystal calorimeter @IAS Conference 2021

Design 1

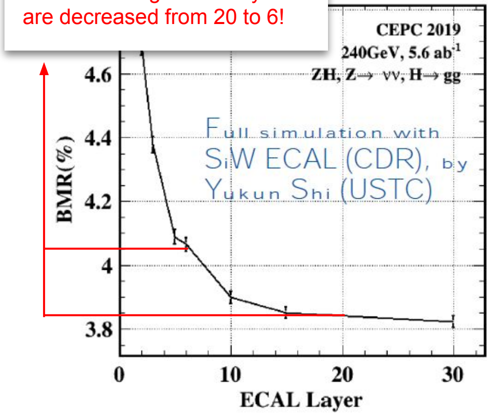


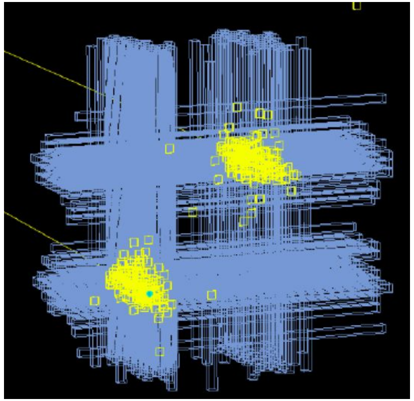
Design 2

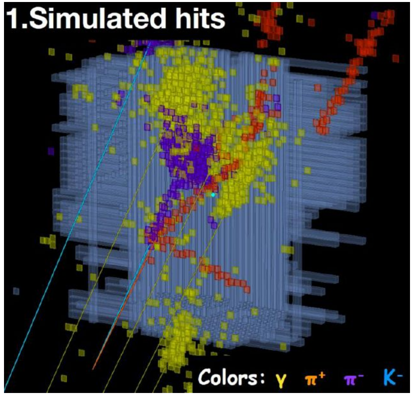


Evaluating optimal crystal configuration for granular 3D imaging

PFA performance not too affected if longitudinal layers are decreased from 20 to 6!







Developing precision particle flow optimized for crystal calorimetry

Merging high granularity and high energy resolution for precision physics at e^+e^- colliders

System aspects & other remarks

System aspects

- **Cost**
  Historical limitation for large volume instrumentation
- **Integration and calibration**
  Challenged by high granularity, channel count and radiation effects
- **Validation**
  Where to exploit collaboration and synergies

- Decrease cost of crystal production
- Optimize calorimeter design
- Develop new cheaper materials
- Collaboration with vendors
- Synergies with other ‘customers’

- Uniformity and quality for mass production
- Photodetectors (compact, low power)
- Fast readout electronics (ASICs)
- Clock distribution
- Cooling infrastructures
- Calibration and monitoring

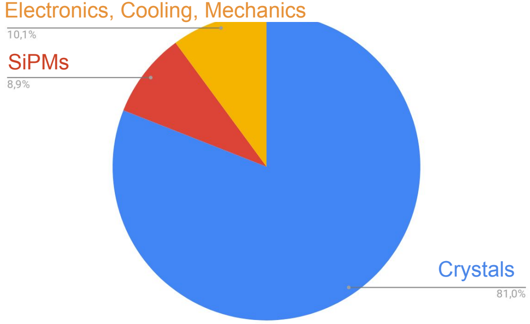
- Simulation software
- Prototypes
- Test beam and irradiation facilities

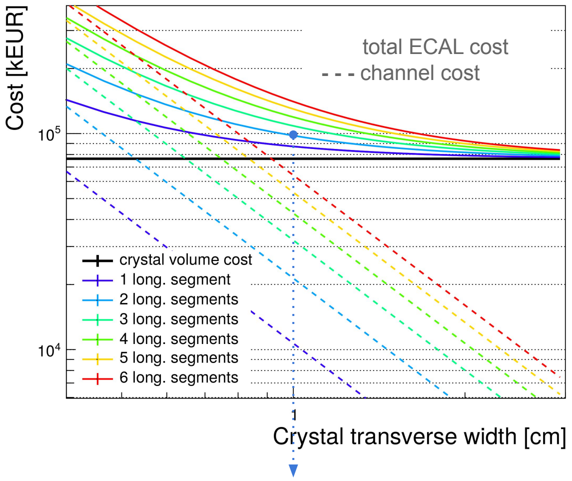
Cost aspects

- Cost typically dominated by crystal volume→granularity can be optimized with moderate cost impact

- **Competitions between vendors is a powerful handle for cost reduction and high quality mass production**
  - Collaboration with industrial partners
    (since the R&D phase and on cost reduction)
  - Synergies with medical applications
    (a more attractive market for industries)
  - High quality production accessible/achievable
    (example: more than 15 vendors of high quality packaged LYSO crystals worldwide, ~2 in Europe, most in Asia)

Costing exercise for an hermetic calorimeter
(R=1.8 m, 1 cm² transverse granularity,
2 longitudinal layers, 22X_0, ~600k channels / layer)





For 1 cm², 2 layers
cost <95M€

Examples of collaborations and networks **fostering crystal R&D**

Crystal Clear Collaboration
https://crystalclear.web.cern.ch/

Calvision proposal

Maximal Information Calorimetry

https://cds.cern.ch/record/2003266

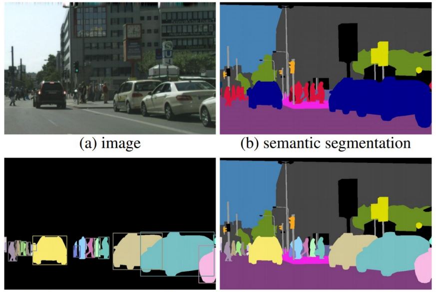
Advanced European Infrastructures
for Detectors at Accelerators

- **Large HEP experiments collaborations** (LHC detectors, CEPC, FCC)
- **National & international networks and consortia between academic institutes**
- **Projects & networks between academic institutes and industries/manufacturers**

A **look over the fence**

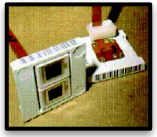
(possible synergies outside particle physics)

- **Pattern recognition** with neural networks
  - Already exploiting developments from non-particle physics community (e.g. car vision)
- **Medical imaging** radiation detectors
  - Positron Emission Tomography scanners: a market driving application (an opportunity for cost reduction)
  - A large community developing crystal+SiPM innovative detectors for TOF-PET scanners
  - Strong and fertile historical collaboration (e.g. within the Crystal Clear Collaboration)
- **Homeland security, oil well logging**, gamma cameras, …


(a) image (b) semantic segmentation
(c) instance segmentation (d) panoptic segmentation

https://towardsdatascience.com/panoptic-segmentation-with-upsnet-12ecd871b2a3

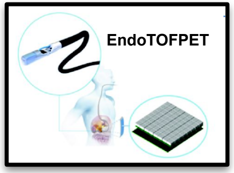
APDs developed for CMS ECAL...



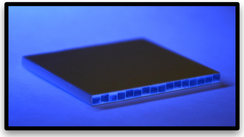
Used in ClearPEM (Mammography scanner)

Crystal Clear

LYSO+SIPM+electronics for time-of-flight in PET scanner...



...a starting point for the CMS barrel timing layer



In brief...

- Crystal technology in continuous development offers **key features** for future calorimeters at a wide range of particle physics experiments
  - Energy resolution
  - Fast and precision timing
  - Radiation tolerance
  - Fine granularity
- Potential **synergies in R&D** goals between projects and with other fields should be exploited to boost technological development, reduce cost and improve mass production capabilities
  - R&D on similar crystals
  - Link to photodetectors
  - Collaboration with vendors
- **New perspectives** on crystal calorimetry should be explored
  - Potential of dual-readout
  - Integration with particle flow
  - Inclusion of time information

Crystal life (re)cycle

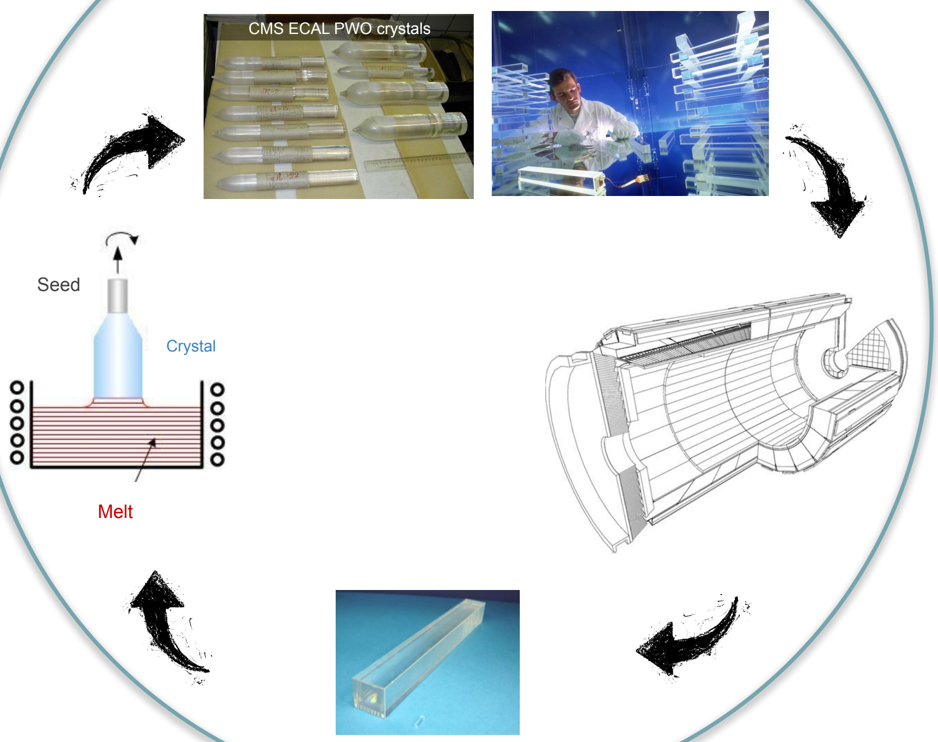
- Crystals can be annealed at high temperature or re-melt and re-grown (all radiation induced damage recovered!)
- Despite 20+ years long experiments… is it worth thinking **what could happen to all crystals from ‘old’ detectors?**
  - **cost saving opportunity?**
  - **limit impact on environment?**
  - requires R&D and infrastructure?
- >800 BGO crystals recovered from L3 for the PADME and FOOT experiments

Dark Matter

Hadron therapy

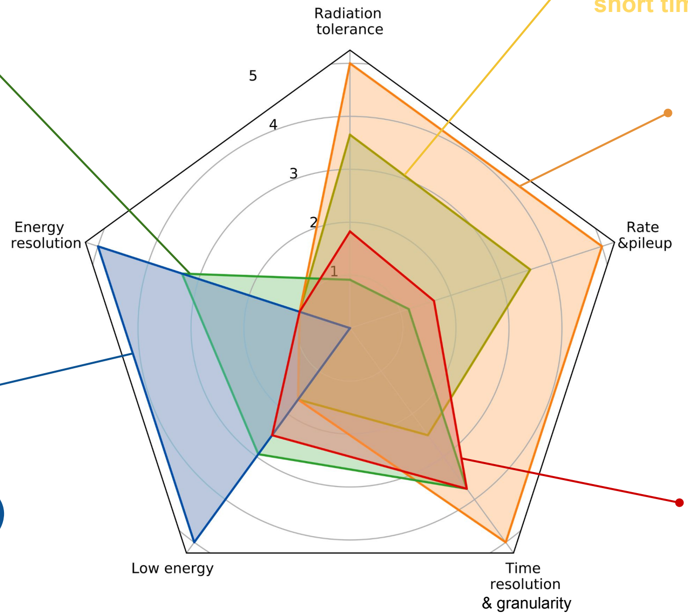
Collider physics

A crystal is forever?



Additional material

Over-simplified and qualitative representation of requirements for crystal calorimeters at future colliders



HL-LHC

Tough challenges on a short timescale

FCC-hh

Setting the toughest challenge on radiation tolerance and pileup conditions

e^+e^- colliders

Precision physics may benefit from exploiting the best possible energy and time resolution

Strong interaction experiments (e.g. EIC)

Requiring the highest energy resolution for low energy photons

$\mu^+\mu^-$ colliders

High beam induced background rate, need for ambitious time resolution

Major **R&D challenges**

- Enhance the performance of crystal based calorimeters in terms of **time resolution**, **radiation tolerance** and **particle ID** (e.g. dual readout, pulse shape discrimination) with R&D on new materials but also exploring new calorimeter concepts

- Establish a strong and wide collaboration within the field and beyond, including crystal manufacturers, to identify new materials, techniques and processes to **reduce cost and improve mass production** (quality and uniformity on large number of finely granular crystal elements)

- Explore further the **potential of enhanced crystal calorimetry** to improve object reconstruction and and extend the landscape of physics goals at detector colliders

Validation of new calorimetry concepts

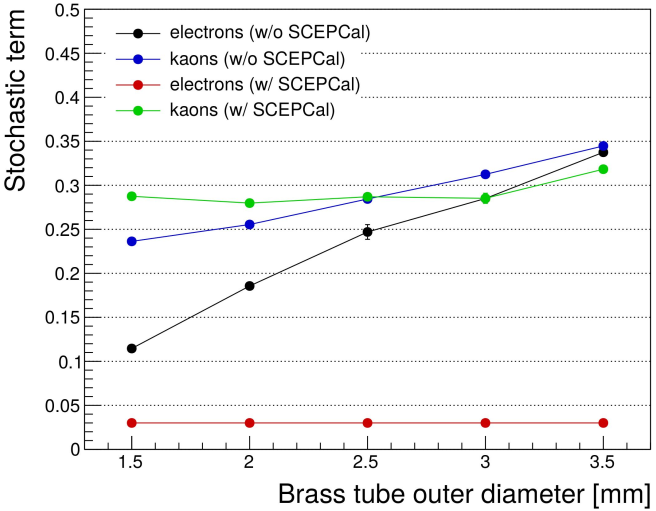
(stating the obvious)

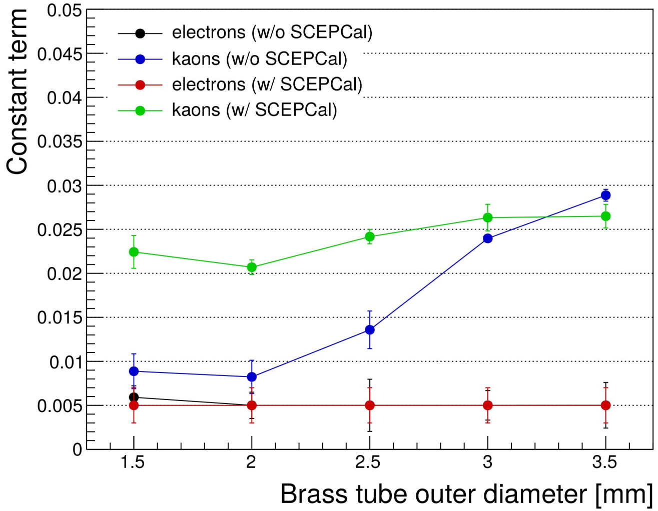
- Crystal applications mostly focused on **EM shower** (or MIPs) detection (because of cost implications) → **require relatively small size prototypes**
- Crystals for instrumentation of **larger volumes** (e.g. homogeneous hadron calorimeter) **prohibitive without development of cost effective materials**
- Validation of new EM crystal calorimeter concepts and their integration with a hadronic section should exploit **larger collaborations to optimize resources and infrastructure** (e.g. test beam facilities)
- Prototypes with enhanced granularity and timing should exploit **synergies with electronics development, clock distribution, cooling infrastructures**, etc.

Miscellanea

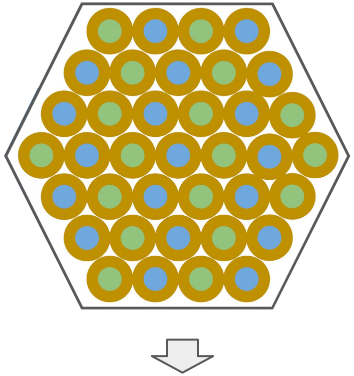
Example of **cost/performance optimization** in a crystal + fiber hybrid dual-readout calorimeter

- **Brass tube outer diameter** (OD) **can be increased to 3/3.5 mm with marginal impact on the hadron resolution**
- Relative channel reduction and cost decrease approximately with ~1/OD^2

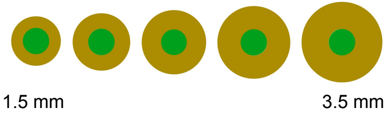




Brass capillaries
“Nominal” dimension
OD=2 mm, ID=1.1 mm



Active fiber diameter unchanged
Brass tube outer diameter varied



INTELUM project

Intelum project: tackling the calorimetry challenge for future high-energy colliders

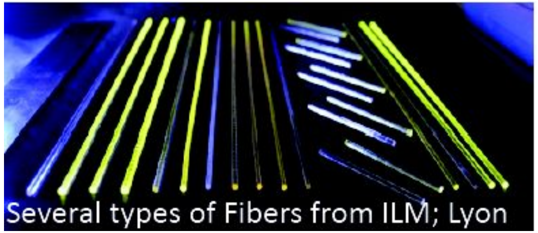
INTELUM was a four-year Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE) project coordinated by CERN. The project was focused on international and intersectoral mobility to develop advanced scintillating and Cerenkov fibres for new hadron and jet calorimeters for future colliders.

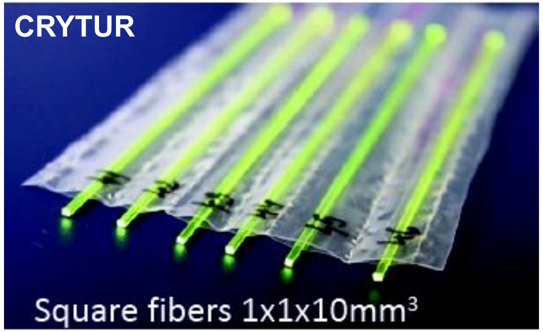
It aimed at developing low-cost, radiation-hard scintillating and Cherenkov crystal and glass fibres for the next generation of calorimeter detectors for future high-energy experiments. This new technology could also have important applications in the medical imaging field.

https://cds.cern.ch/record/2003266

http://www.intelligentsia-consultants.com/index.php/en/news/13-category-eng/news-eng/178-intelum-2019

Intelum


Several types of Fibers from ILM; Lyon



Square fibers 1x1x10mm^3

SPACAL-W: radiation hardness of garnets

Courtesy of A.Schopper

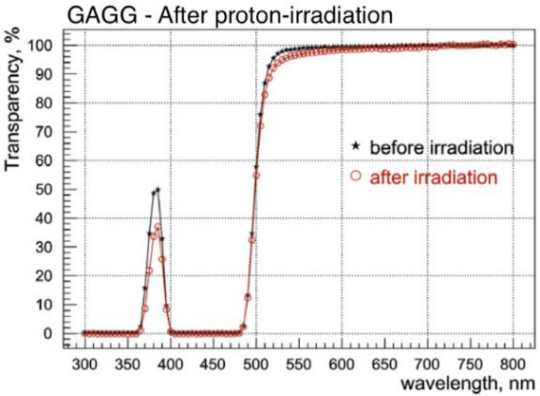
- Garnet crystals are radiation hard

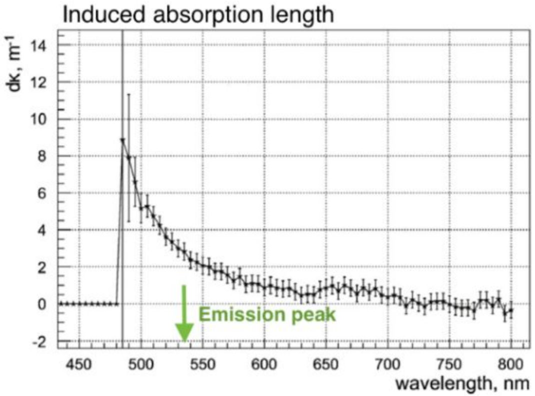
- GAGG irradiated with protons of 24 GeV/c
  - ✓ Fluence of 3.1×10^{15} cm^{-2}
  - ✓ 910 kGy dose
  - ✓ Induced absorption below 4m^{-1} at the emission peak

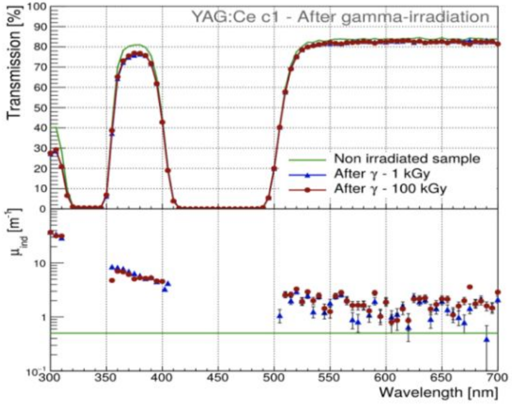
See: *V. Alenkov et al., NIM A 816 (2016) 176*

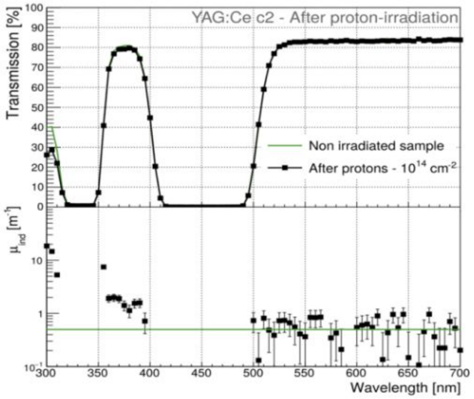
- YAG and LuAG tested with both gamma and proton radiation to lower doses

See: *M. T. Lucchini et al., IEEE Trans. on Nucl. Sci., 63 (2016), 2*





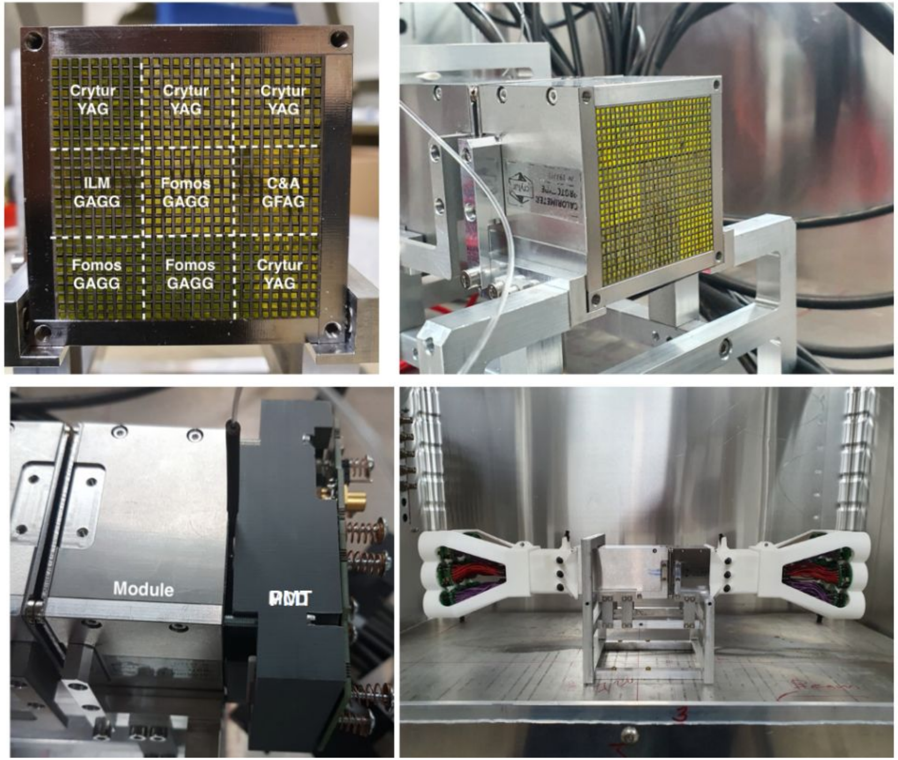




SPACAL-W: the 2020 prototype

Courtesy of A.Schopper

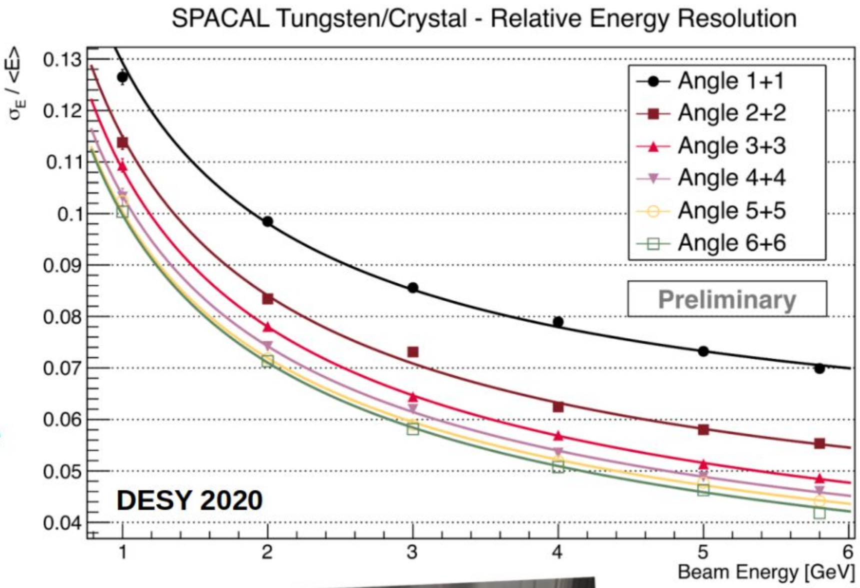
- ➢ SPACAL prototype tested at DESY in 2020 with electrons of 1-5.8 GeV
  - ✓ Crystal garnet fibres with 1x1 mm^2 square section, 4 and 10 cm length
  - ✓ Tungsten absorber with hole pitch of 1.7 mm
  - ✓ Longitudinal segmentation at the shower maximum
- ➢ Two photodetectors employed:
  - ✓ Hamamatsu R12421 and PMMA light guides
  - ✓ Hamamatsu R7600U-20 metal channel dynodes (MCD) PMTs in direct contact
- ➢ 4 garnet types tested:
  - ✓ Crytur - YAG
  - ✓ Fomos - GAGG
  - ✓ ILM - GAGG
  - ✓ C&A - GFAG

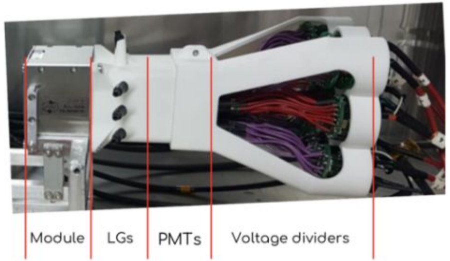


SPACAL-W: energy resolution

Courtesy of A.Schopper

- Energy resolution measured at DESY for electrons up to 5.8 GeV
  - ✓ Measurements performed at several vertical and horizontal incidence angles
  - ✓ Hamamatsu R12421 and PMMA light guides readout
- Energy resolution improving for increasing angles
  - ✓ Preliminary fit results to low energy data give sampling term of 10.6% and constant term of 1.9% ± 0.5% at 3°+3°
- Test beam scheduled at SPS for July/August 2021 with e^- up to 100 GeV to measure precisely the constant term and improve it finely tuning the calibration



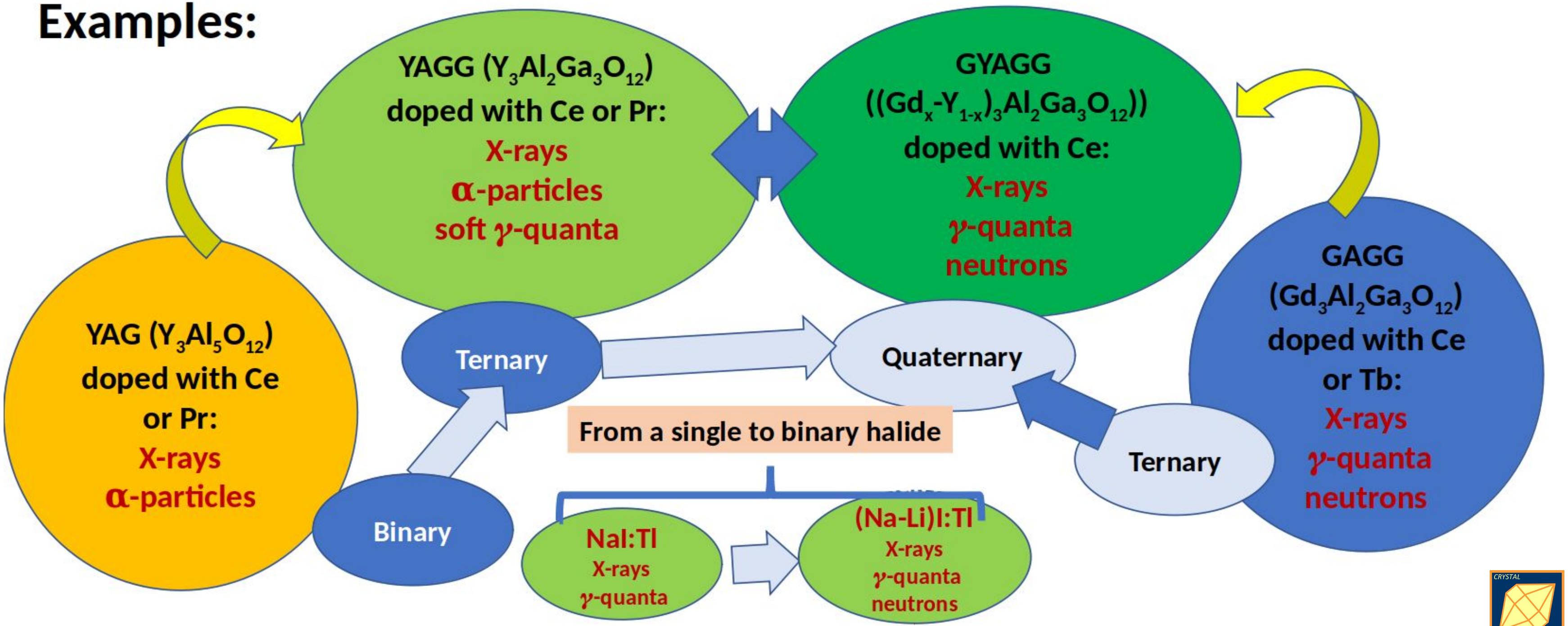


Courtesy of M.Korjik
and G.Tamulaitis

Multipurpose scintillation materials

Materials allowing one to focus on the detection of the specified kind of ionizing radiation by reshuffling their composition

Examples:



YAG ($Y_3Al_5O_{12}$)
doped with Ce
or Pr:
X-rays
α-particles

YAGG ($Y_3Al_2Ga_3O_{12}$)
doped with Ce or Pr:
X-rays
α-particles
soft γ-quanta

GYAGG
($(Gd_x\text{-}Y_{1-x})_3Al_2Ga_3O_{12}$))
doped with Ce:
X-rays
γ-quanta
neutrons

GAGG
($Gd_3Al_2Ga_3O_{12}$)
doped with Ce
or Tb:
X-rays
γ-quanta
neutrons

From a single to binary halide

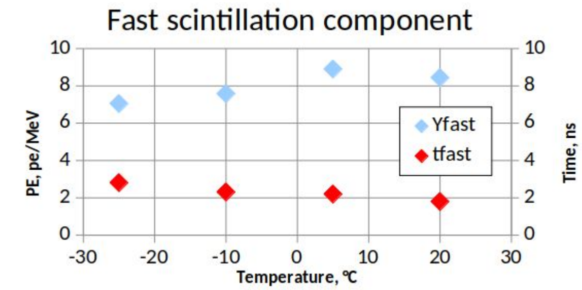
NaI:Tl
X-rays
γ-quanta

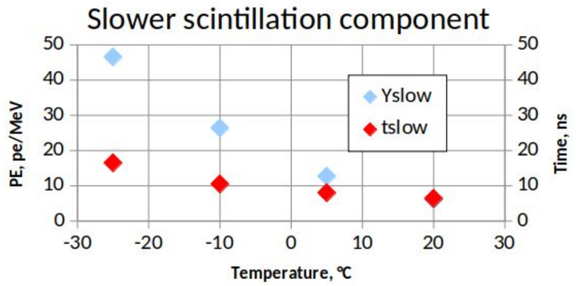
(Na-Li)I:Tl
X-rays
γ-quanta
neutrons

*Courtesy of M.Korjik
and G.Tamulaitis*

Towards PWO-III technology

PWO-II: FAIR (Darmstadt), Jefferson Lab, CEA (Saclay)


Fast scintillation component


Slower scintillation component

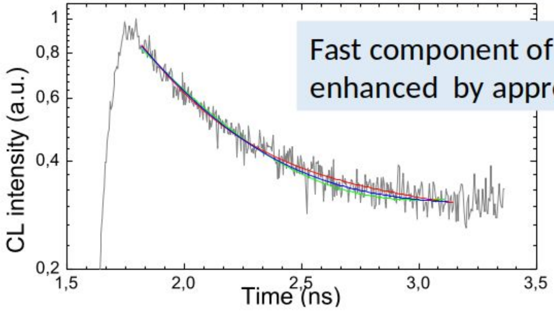
Parameters of scintillation pulse of PWO-II
as a function of temperature

Essential idea for PWO-III : reoptimising the crystal techology to redistribute scintillation in favor of the fast component, make it faster than 1 ns

Expected results:

- 90% of light in 2 ns
- weak temperatre dependence of LY
- LY ~ 15-20 PE/MeV for the length ~20·X_0

First reslts on shortening the scintillation pulse



Fast component of 300 ps is enhanced by appropriate doping

Scintillation of PWO after 20 ps 10 keV electron pulse excitation

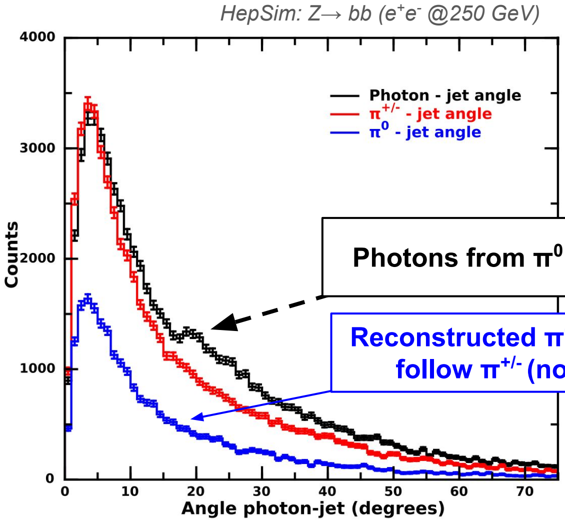
See more details on PWO-II *in M. Follin et al. “Scintillating properties of today available lead tungstate crystals”,*
arXiv identifier 2103.13106 .

Some physics cases for precision calorimetry

(at future Higgs factories)

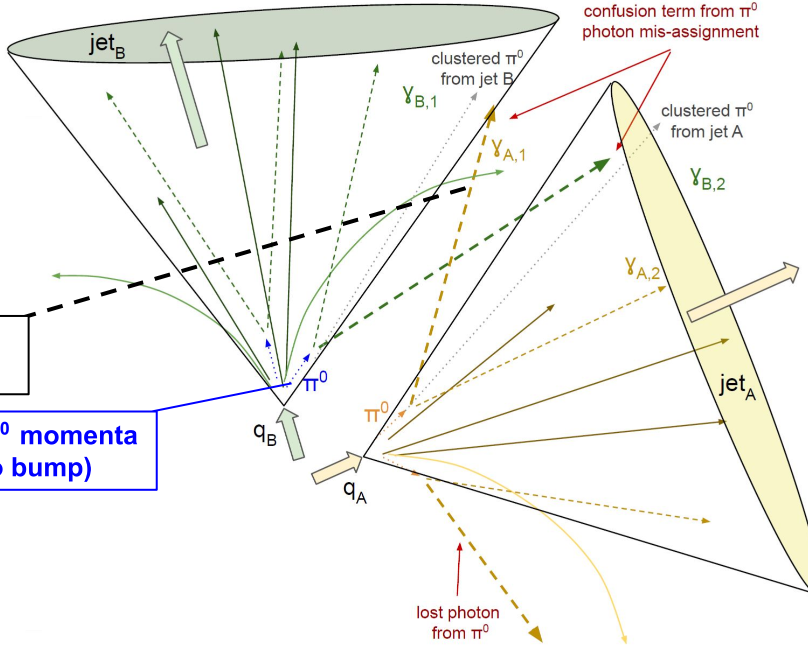
High photon resolution potential for PFA

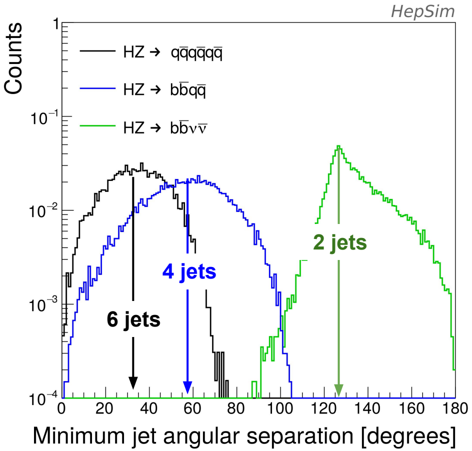
- **Many photons from π^0 decay** are emitted **at a ~20-35° angle** wrt to the jet momentum and can get scrambled across neighboring jets
- Effect **particularly pronounced in 4 and 6 jets topologies**



Photons from π^0

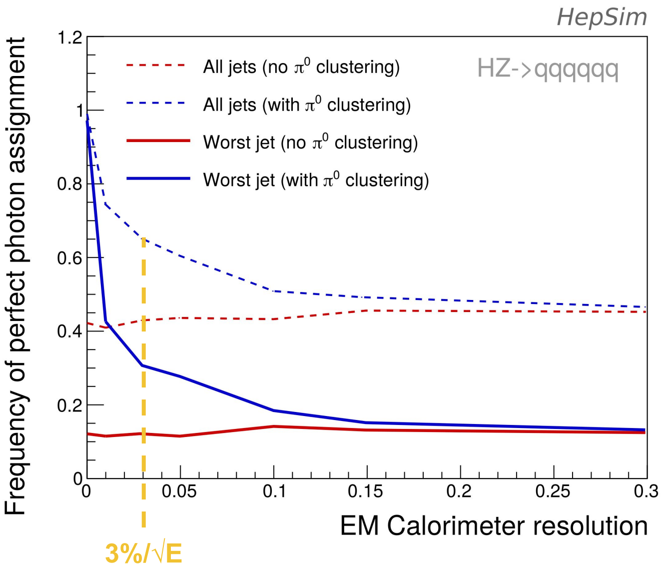
Reconstructed π^0 momenta follow $\pi^{+/-}$ (no bump)

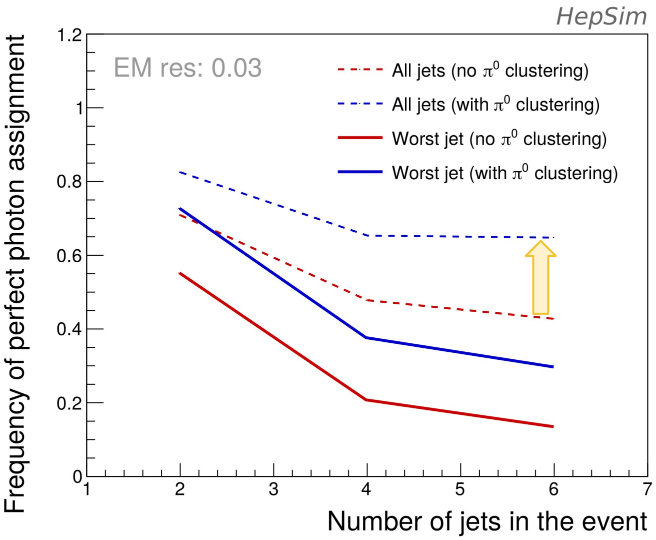




Improvements in photon-to-jet correct assignment

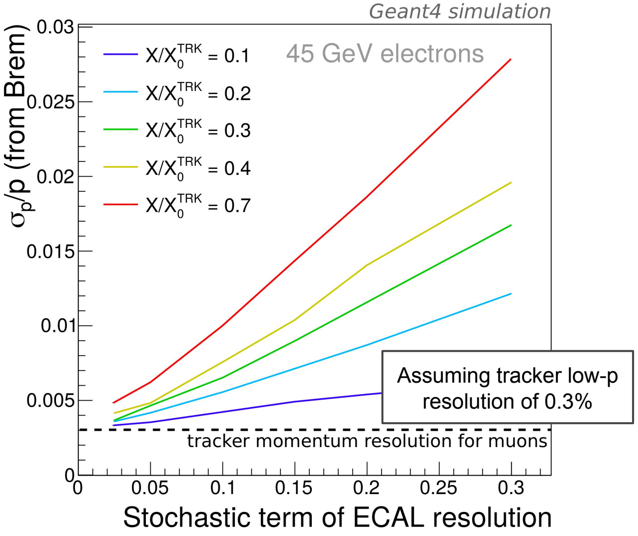
- **High e.m. resolution enables** photons **clustering into π^0's** by reducing their angular spread with respect to the corresponding jet momentum
- **Improvements in the fraction of photons correctly clustered to a jet** sizable only for e.m. resolutions of ~3%/√(E)





Recovery of Bremsstrahlung photons

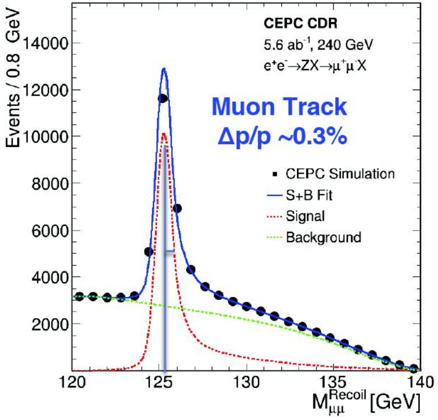
- Reconstruction of the Higgs boson mass and width from the recoil mass of the Z boson is a key tool at e^+e^- colliders
- Potential to **improve the resolution of the recoil mass signal from Z→ee decays** to about 80% of that from Z→ μμ decays [with Brem photon recovery at EM resolution of 3%/√E]



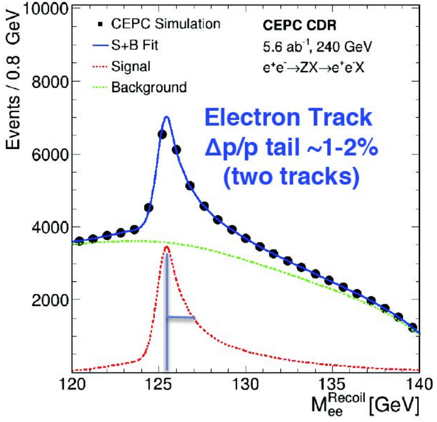
Assuming tracker low-p resolution of 0.3%

Example from ***CEPC CDR***

Z→$\mu^+\mu^-$ Recoil



Z→e^+e^- Recoil



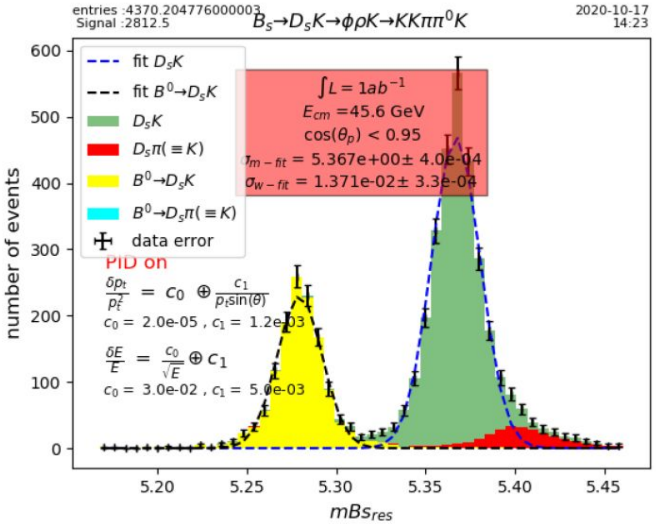
~80% of resolution recovery with 3%/√(E)

Studies of CP violation and EW physics at e^+e^- colliders

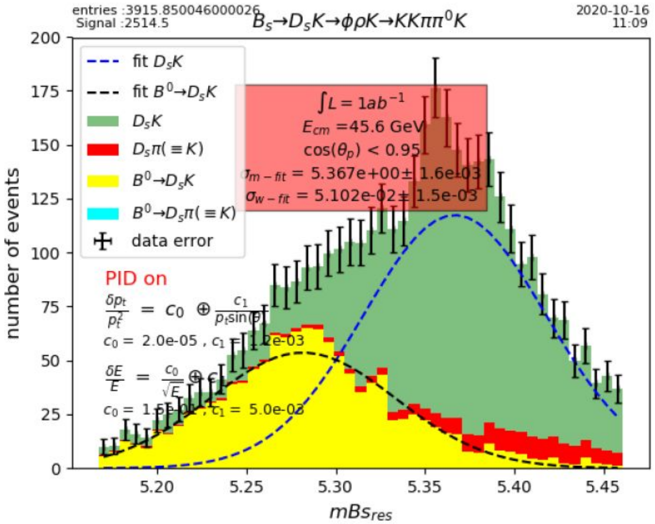
$\overline{\mathrm{B_s}}$ decay Mode	Decay Mode	Final State	Number of $\overline{\mathrm{B_s}}$ decays
$D_s^+K^-$	$\mathrm{D_s^+} \rightarrow \phi\pi$	$\mathrm{K^+K^-\pi^+K^-}$	$\sim 5.2\ 10^5$
$D_s^+K^-$	$\mathrm{D_s^+} \rightarrow \phi\rho$	$\mathrm{K^+K^-\pi^+K^-\pi^0}$	$\sim 9.8\ 10^5$

EM energy resolution at 3%/√E is required to study B_s decay final states with multiple neutrals

$$\frac{\delta E}{E} = \frac{0.03}{\sqrt{E}} \oplus 0.005$$



$$\frac{\delta E}{E} = \frac{0.15}{\sqrt{E}} \oplus 0.005$$



See **R. Aleksan's** talk @ 4th FCC Physics and Experiments Workshop