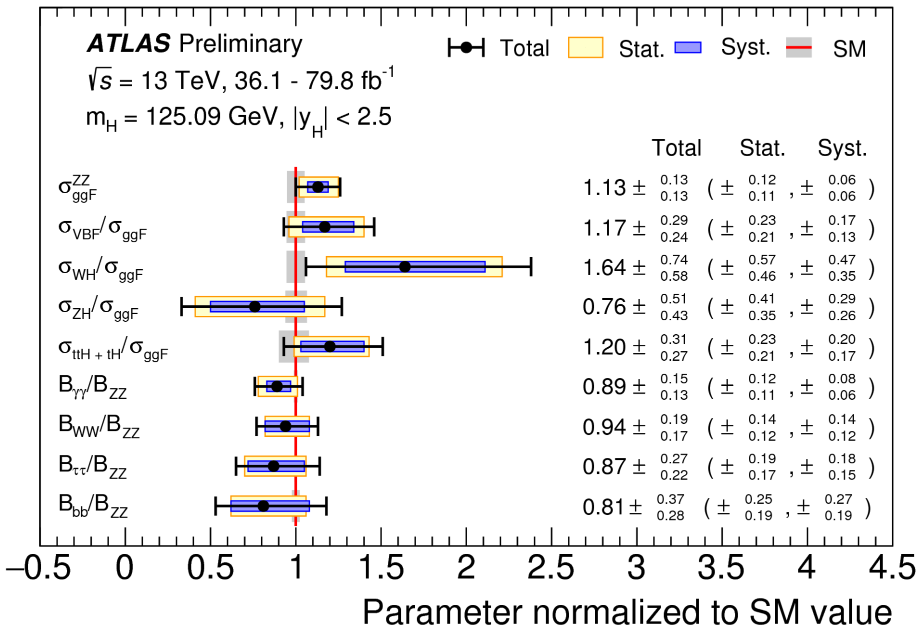
UNIVERSITY OF SUSSEX

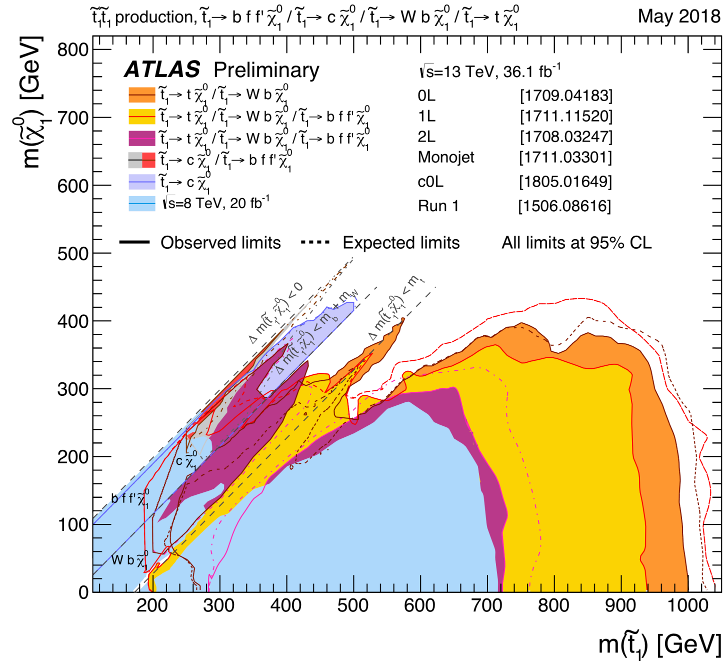
Dual Readout Calorimetry

For future e^+e^- colliders

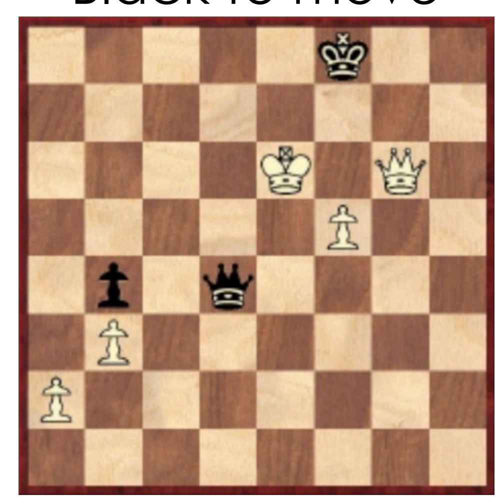
Iacopo Vivarelli
University of Sussex

Particle physics in stalemate?





Black to move



- Did not checkmate fundamental laws of nature
- … but maybe there is no next move that can be done?

Not really…

- Next move of experimentalists is obvious

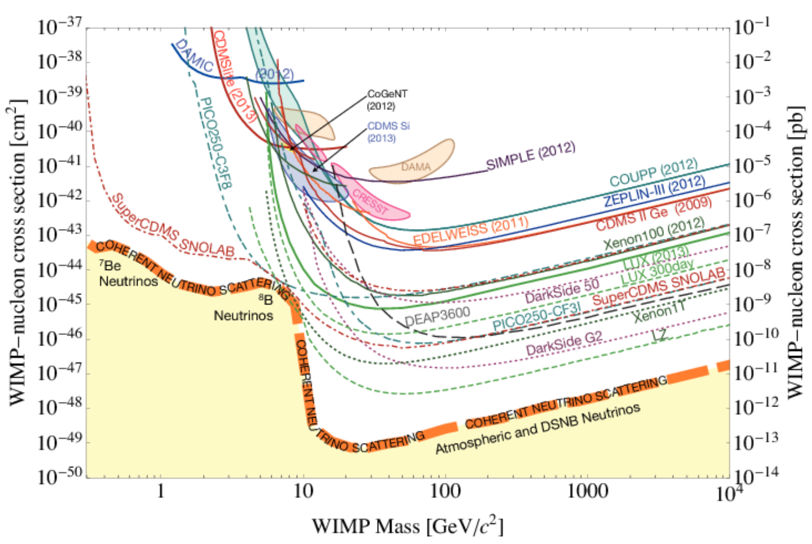
Put the Higgs under the microscope (a e^+e^- Higgs factory)

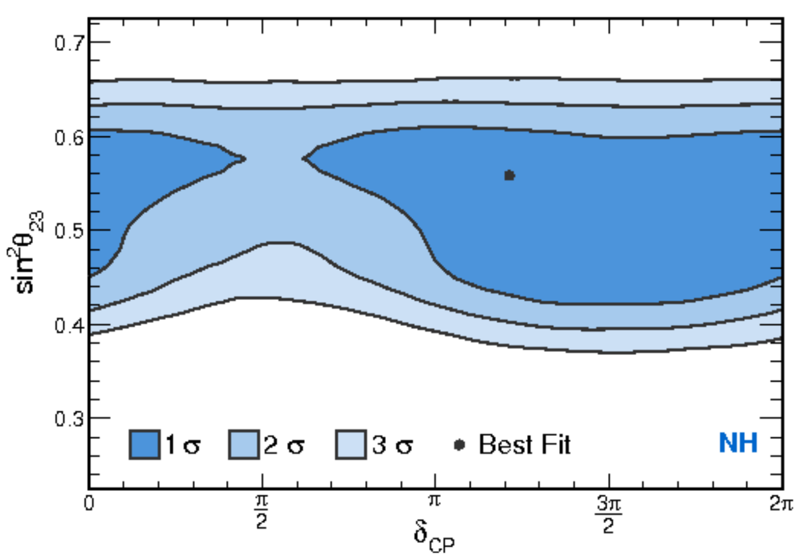
Not really…

- Next move of experimentalists is obvious

Put the Higgs under the microscope (a e^+e^- Higgs factory)

…while looking for BSM elsewhere





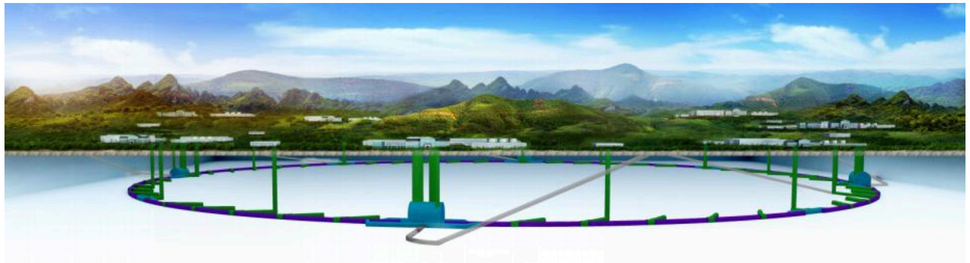
e^+e^- Higgs factories on the table

Circular	Linear

CEPC

China

$\sqrt{s} = 90 - 240$ GeV



CLIC

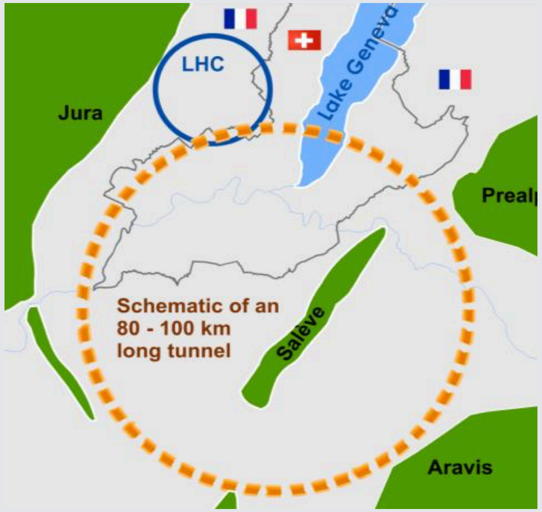
CERN

$\sqrt{s} = 380 - 3000$ GeV

FCC hh ee he

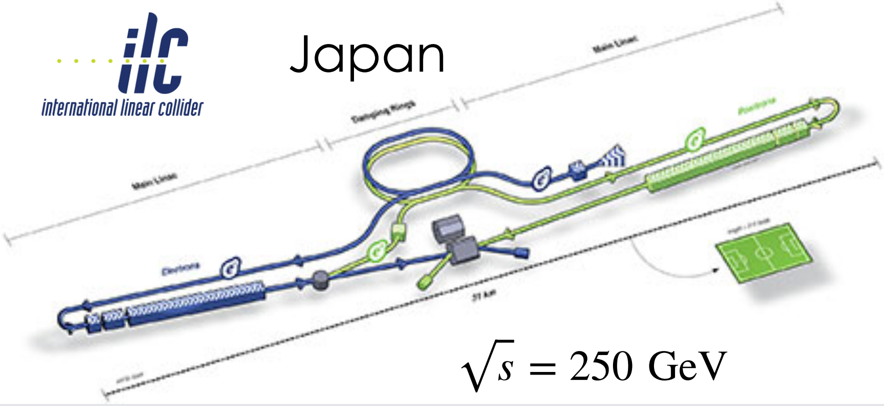
CERN

$\sqrt{s} = 90 - 375$ GeV



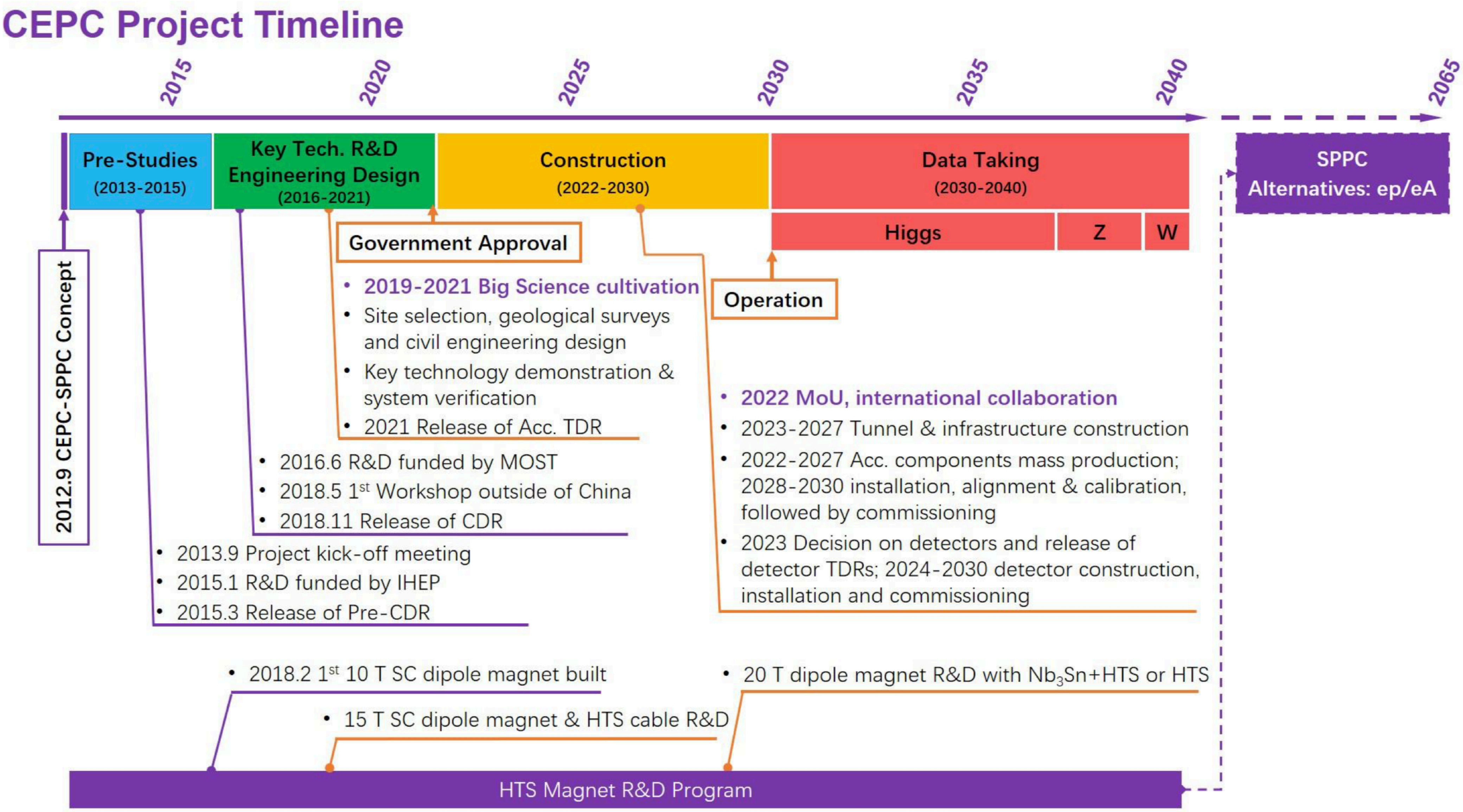
ilc international linear collider

Japan

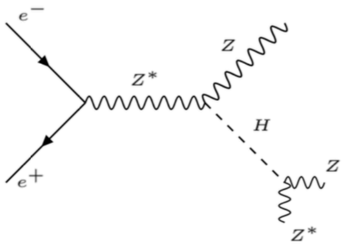


$\sqrt{s} = 250$ GeV

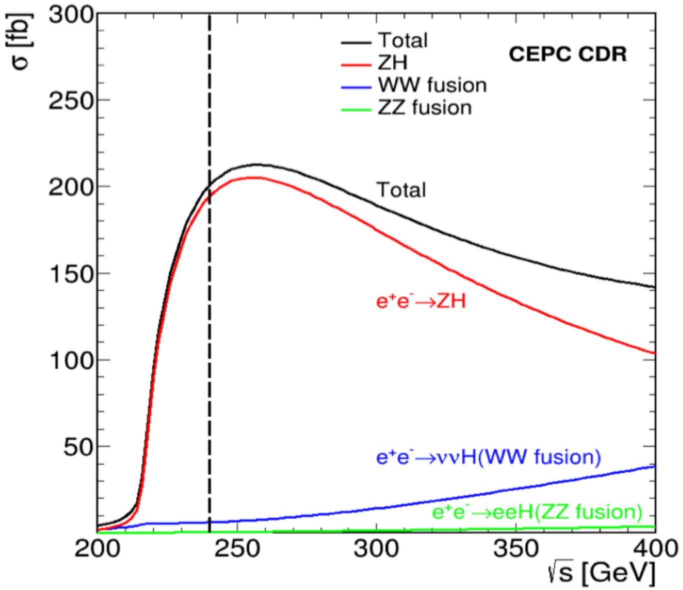
Far future?


CEPC Project Timeline
2015
2020
2025
2030
2035
2040
2065
Pre-Studies
(2013-2015)
Key Tech. R&D
Engineering Design
(2016-2021)
Construction
(2022-2030)
Data Taking
(2030-2040)
SPPC
Alternatives: ep/eA
Higgs
Z
W
Government Approval
Operation
2012.9 CEPC-SPPC Concept
• 2019-2021 Big Science cultivation
• Site selection, geological surveys and civil engineering design
• Key technology demonstration & system verification
• 2021 Release of Acc. TDR
• 2016.6 R&D funded by MOST
• 2018.5 1st Workshop outside of China
• 2018.11 Release of CDR
• 2013.9 Project kick-off meeting
• 2015.1 R&D funded by IHEP
• 2015.3 Release of Pre-CDR
• 2022 MoU, international collaboration
• 2023-2027 Tunnel & infrastructure construction
• 2022-2027 Acc. components mass production; 2028-2030 installation, alignment & calibration, followed by commissioning
• 2023 Decision on detectors and release of detector TDRs; 2024-2030 detector construction, installation and commissioning
• 2018.2 1st 10 T SC dipole magnet built
• 15 T SC dipole magnet & HTS cable R&D
• 20 T dipole magnet R&D with Nb3Sn+HTS or HTS
HTS Magnet R&D Program

e^+e^- at ZH threshold



- For CEPC (but similar number and performance for FCC):
  - **5.6 ab^{-1}** translate in **a million ZH events**



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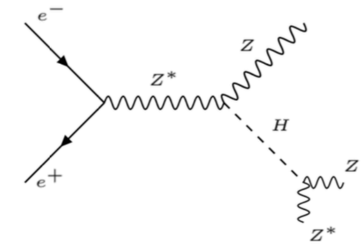

- For CEPC (but similar number and performance for FCC):
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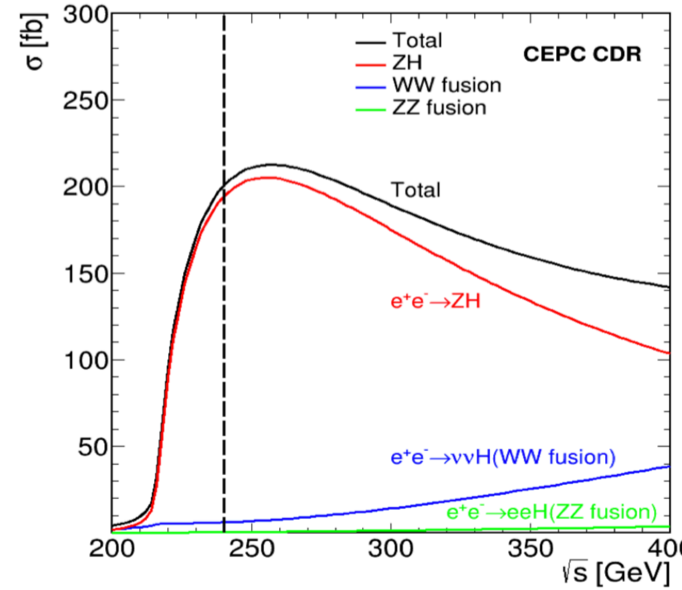
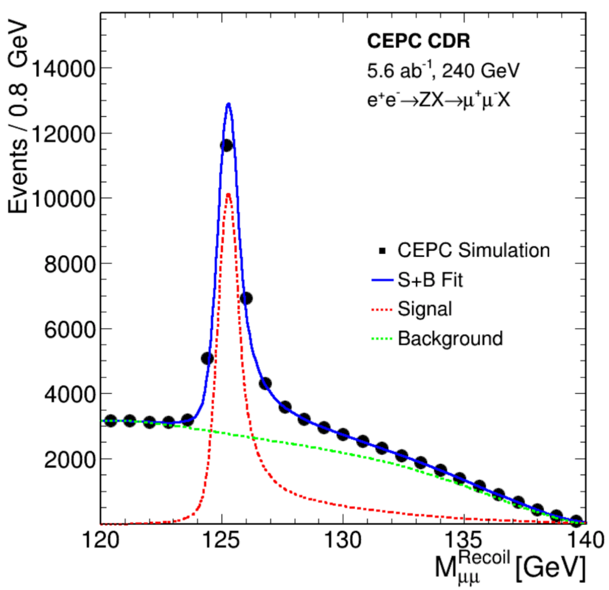
  - Higgs boson tagging gives unique access to $e^+e^-\to ZH$ production cross section





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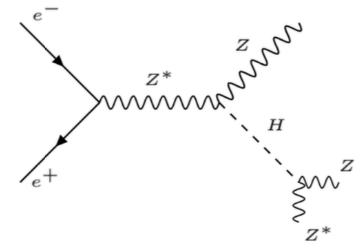

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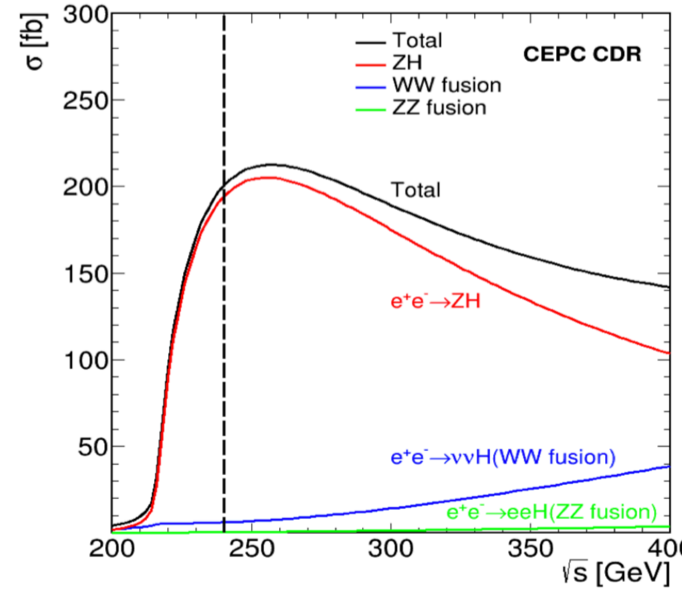
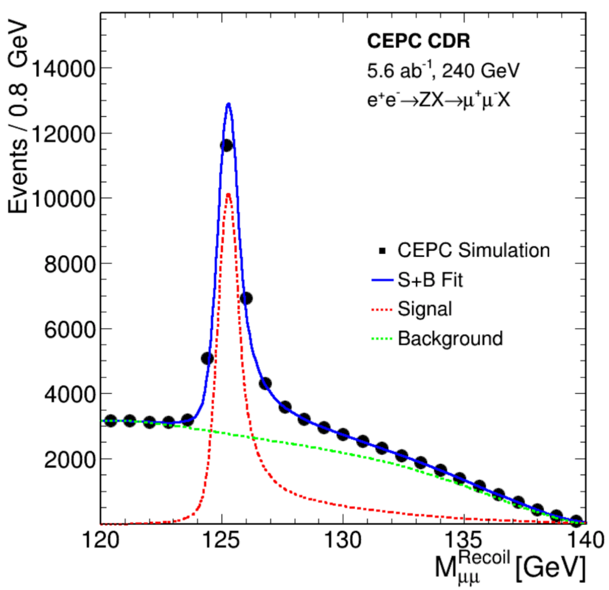


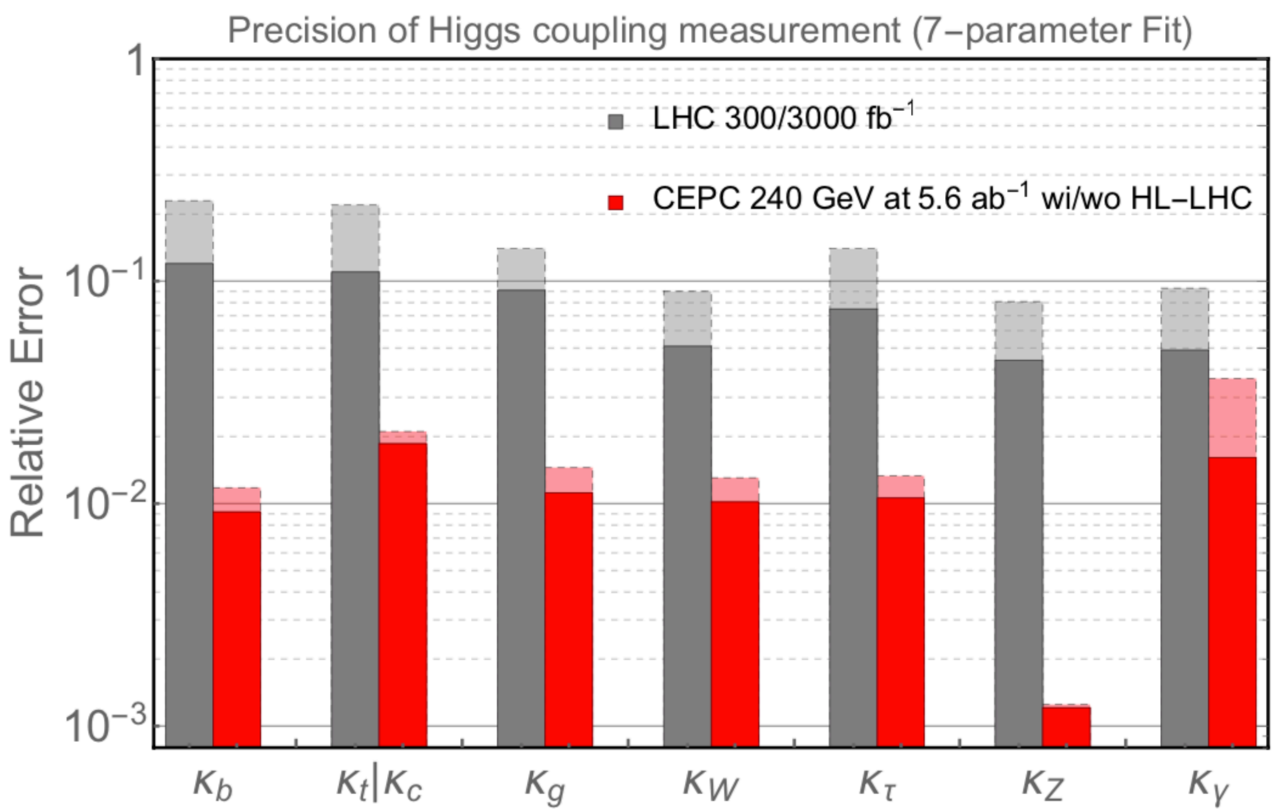


- 3% **model-independent** Higgs boson width measurement from

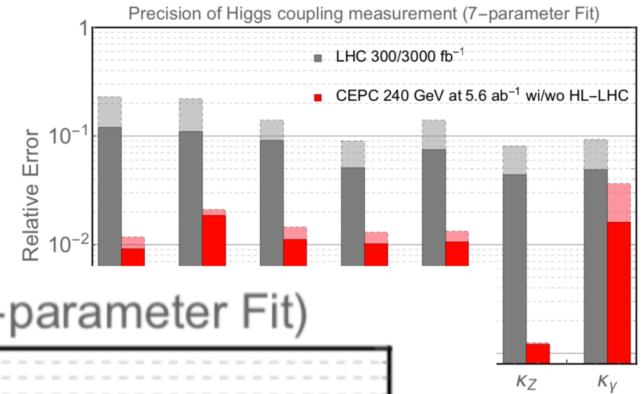
$$\Gamma_H = \frac{\Gamma(H\rightarrow ZZ^*)}{\mathrm{BR}(H\rightarrow ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H\rightarrow ZZ^*)}$$

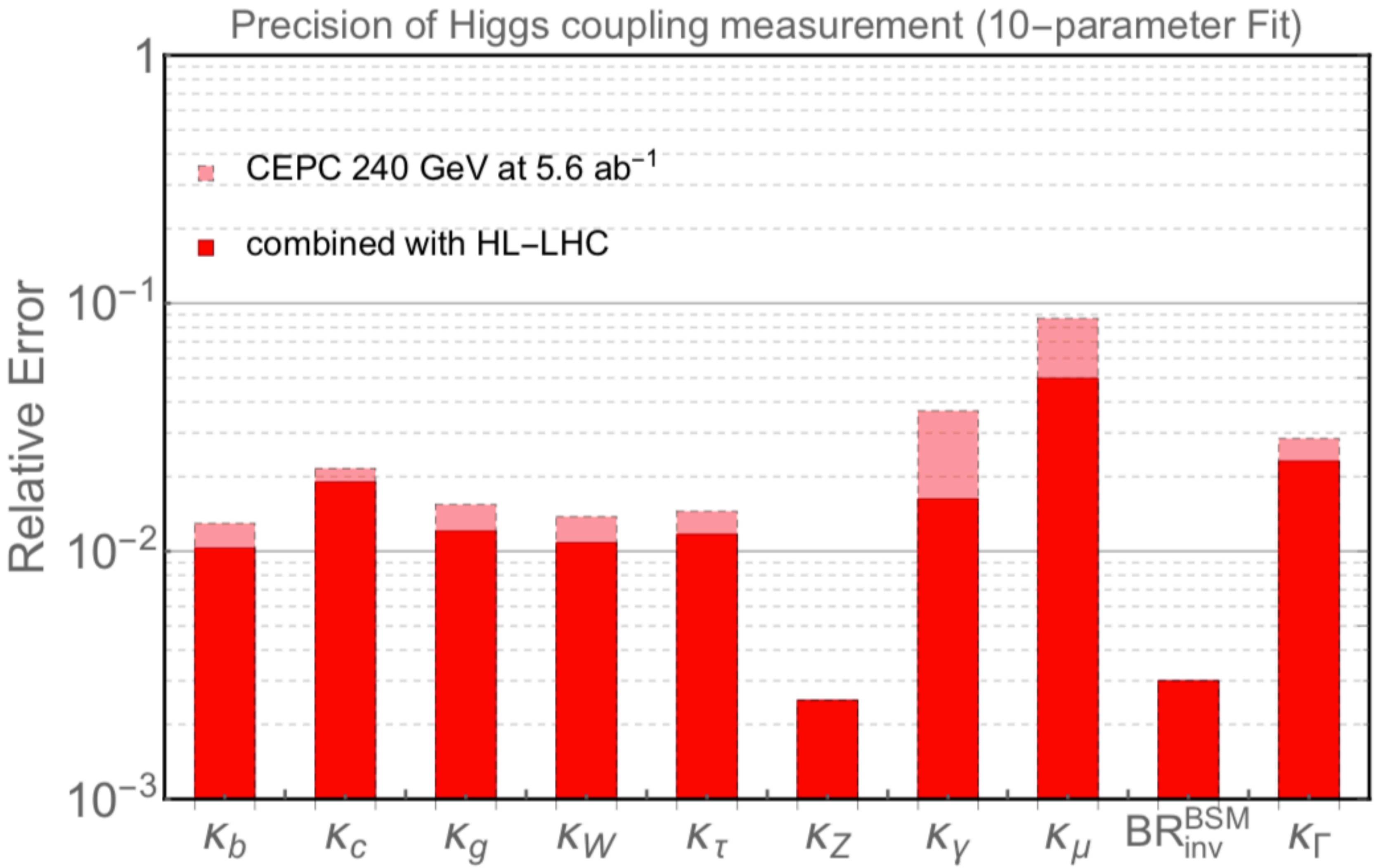
$$\Gamma_H = \frac{\Gamma(H\rightarrow b\bar{b})}{\mathrm{BR}(H\rightarrow b\bar{b})} = \frac{\Gamma(H\rightarrow WW^*)}{\mathrm{BR}(H\rightarrow WW^*)} \propto \frac{\sigma(\nu\bar{\nu}H)}{\mathrm{BR}(H\rightarrow WW^*)}$$

Higgs boson sensitivity



Higgs boson sensitivity





Physics requirements for calorimetry

- **Precision physics** at e^+e^- collider calls for **high-resolution hadronic calorimetry**

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5}$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$		$\oplus 1 \times 10^{-3}/(p_T \sin\theta)$
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\mathrm{m}$
$H \to q\bar{q},\ VV$	$\mathrm{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{\mathrm{jet}}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

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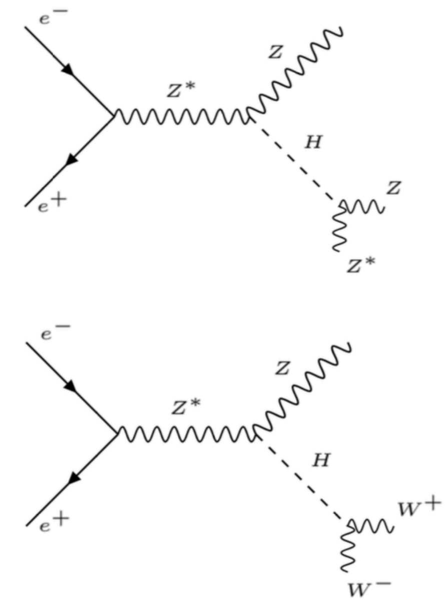

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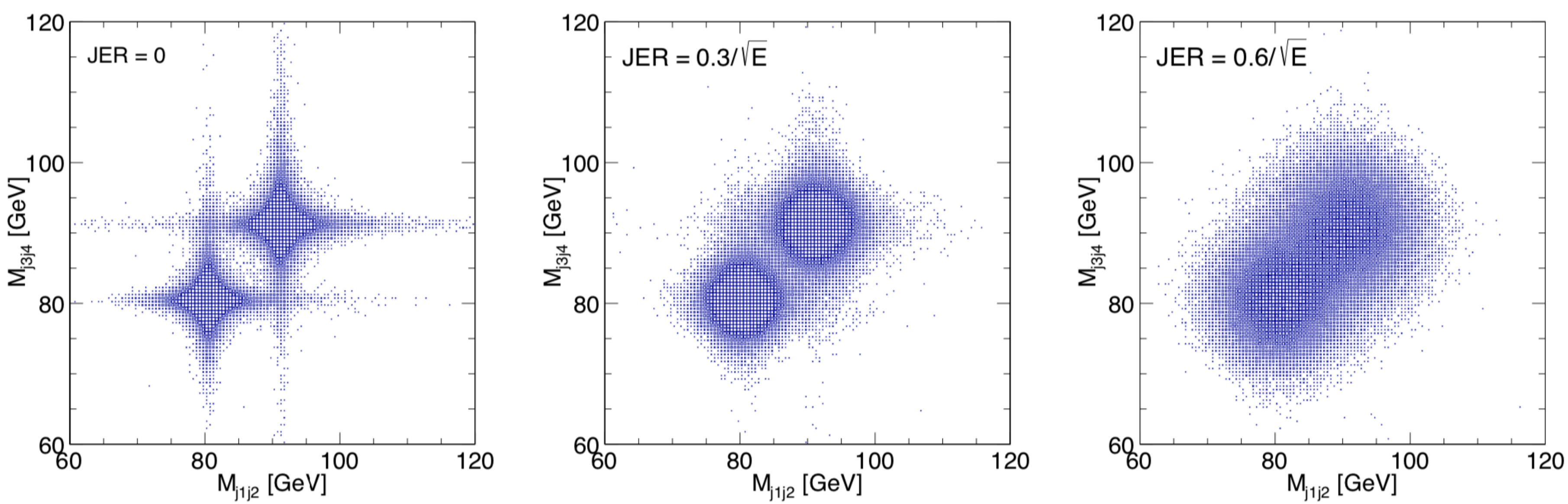
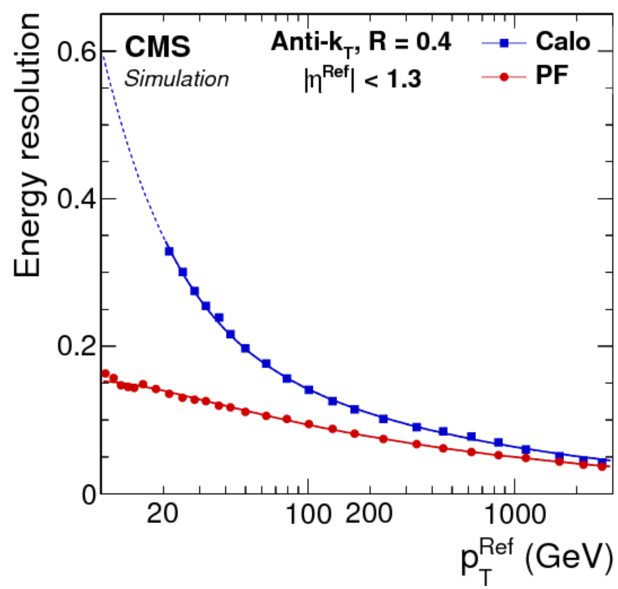


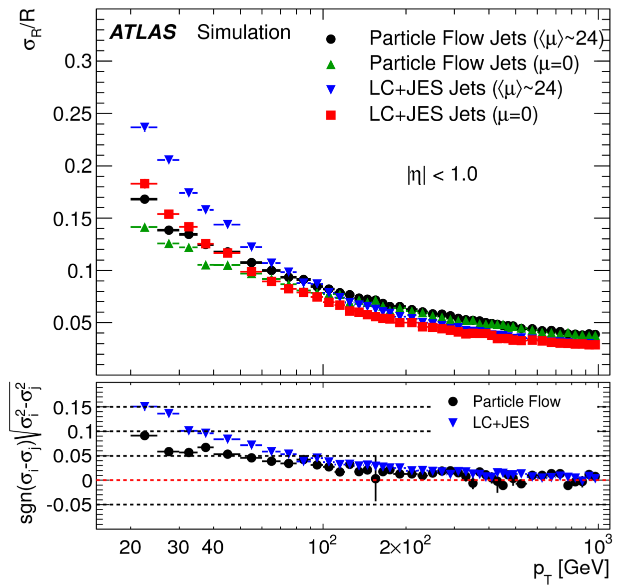
Particle flow approach

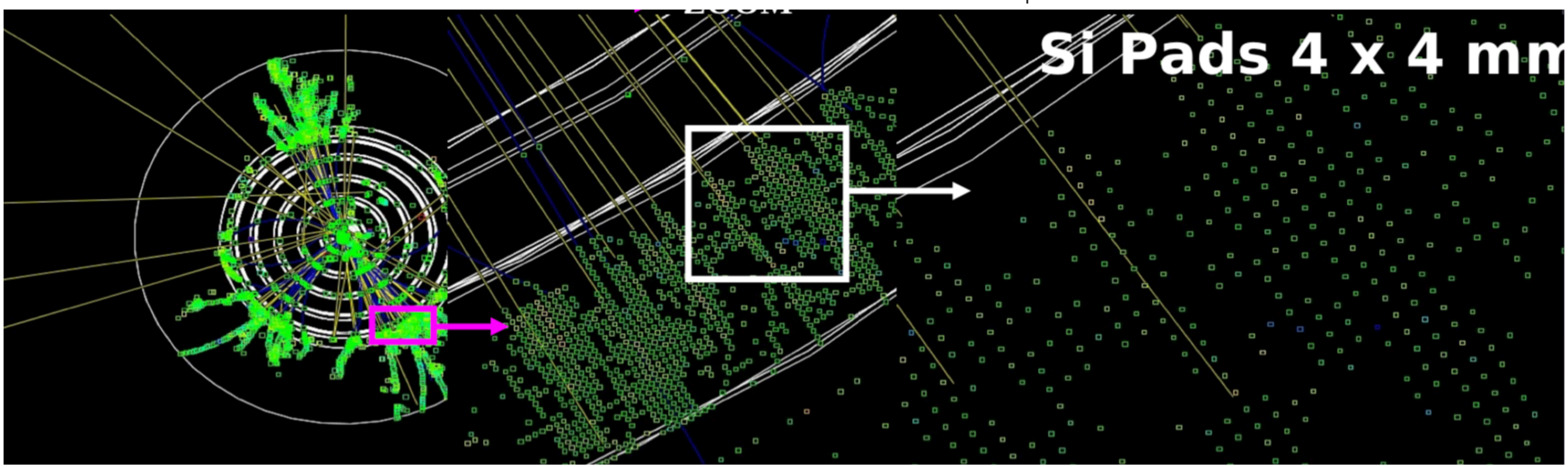
- Basic idea: tracking wins at low particle energy
  - Use **tracks** to measure **charged particles** in the shower

From arXiv:1706.04965



From Eur. Phys. J C77 (2017) 466





From https://warwick.ac.uk/fac/sci/physics/staff/academic/boyd/warwick_week/detector_physics/warwick_lecture_calorimetry.pdf

A different approach

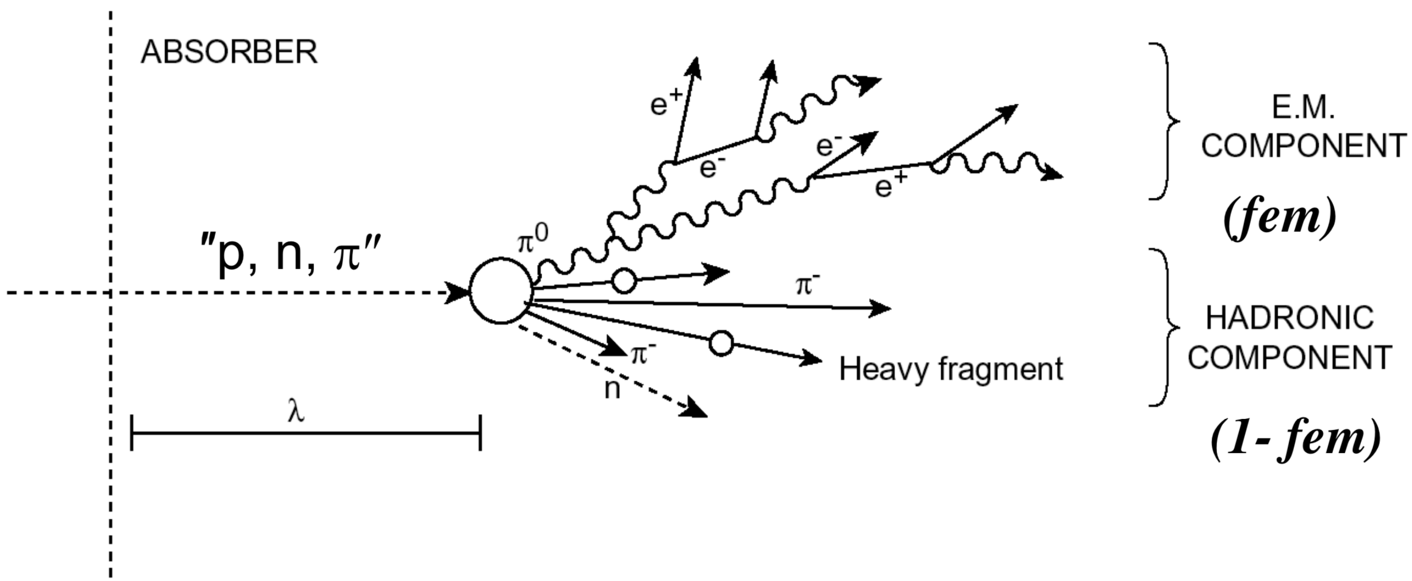
- Attacking the problem from **two sides** always gives opportunities to learn
- Dual readout calorimetry:
  - Excellent **native electromagnetic and hadronic** calorimeter resolution
  - Excellent lateral granularity

Mate in 2

Hadronic Calorimetry - primer

Hadronic Calorimetry - primer

- Hadronic shower:
  - Driven by a relatively **small number** of strong interactions with **nuclei**
  - **Strong** intrinsic interaction intensity, but **small targets** (scale to bear in mind 1 fm = 10^{-15} m)
  - π^0,η^0 production leads to **EM component within hadronic shower**

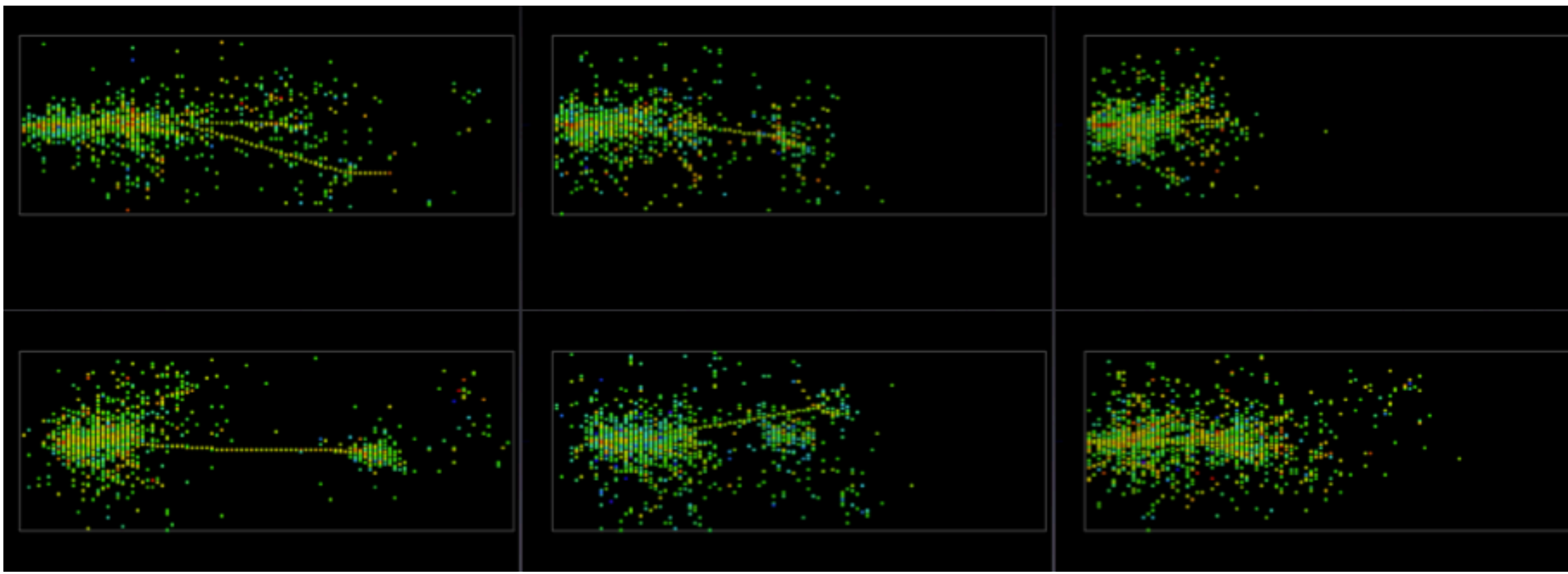


Hadronic showers

- Lots of different physics processes at work in a hadronic shower:
  - EM component: **large fluctuations** in number and energy of π^0,η^0
  - HAD component:
    - **Ionisation** from charged hadrons
    - **Nuclear remnants** (fission, knock-off)
    - Delayed photons
    - **Invisible component** (nuclei breakup)

Hadronic showers

- Large **event-by-event** fluctuations in shape (and energy) deposit
- **Charged hadrons propagate the shower** on large scale (λ_I), **local** EM showers from π^0, η^0.



Why is hadronic calorimetry challenging?

Typically* the calorimeter response to the electromagnetic (e) and hadronic (h) components is different (because of invisible energy)

*This is actually true for non-compensating calorimeter (the vast majority of those in use nowadays)

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The fraction of energy in EM component and HAD component is energy dependent with large fluctuations

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The fraction of energy in EM component and HAD component is energy dependent with large fluctuations

The calorimeter response to hadrons is energy dependent and fluctuates a lot

Calorimeter response to hadrons

- Typically calorimeters are calibrated to the **EM scale**
  - For example: you shoot 20 GeV electrons and want to read 20 GeV
  - Say r is the energy deposit in active material in the calorimeter. Then you choose k such that

$$E_e = ker$$

  - Then the response to a hadron is

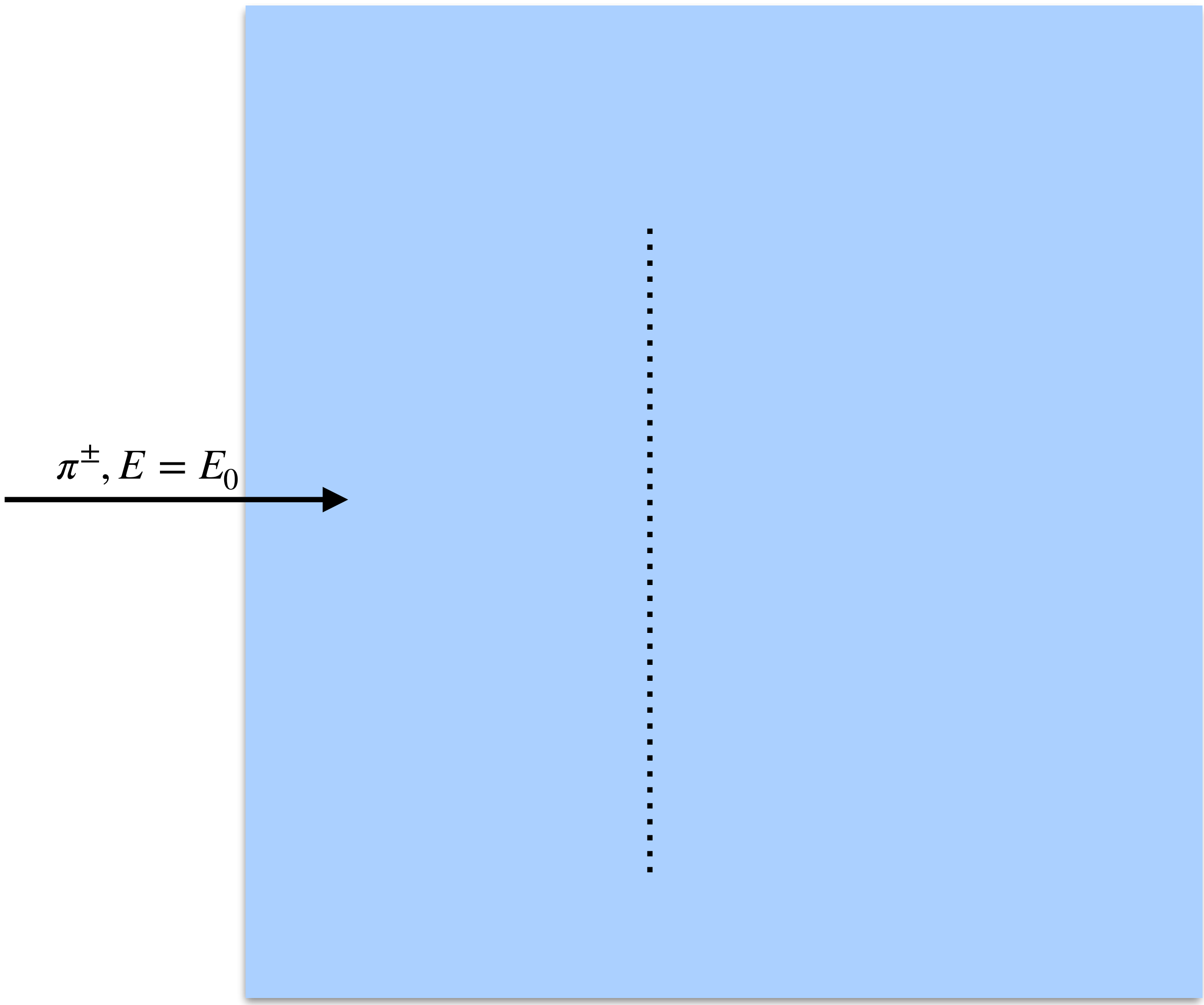
$$E_h = k(ef_{\mathrm{em}} + h(1 - f_{\mathrm{em}}))r$$

  - and with respect to that of an electron of the same energy

$$E_h = E_e(f_{\mathrm{em}} + \frac{h}{e}(1 - f_{\mathrm{em}}))$$

f_{em} energy dependence

- Simple model: **only pions** are produced at each interaction, **respecting isospin symmetry**
- Then the math is:



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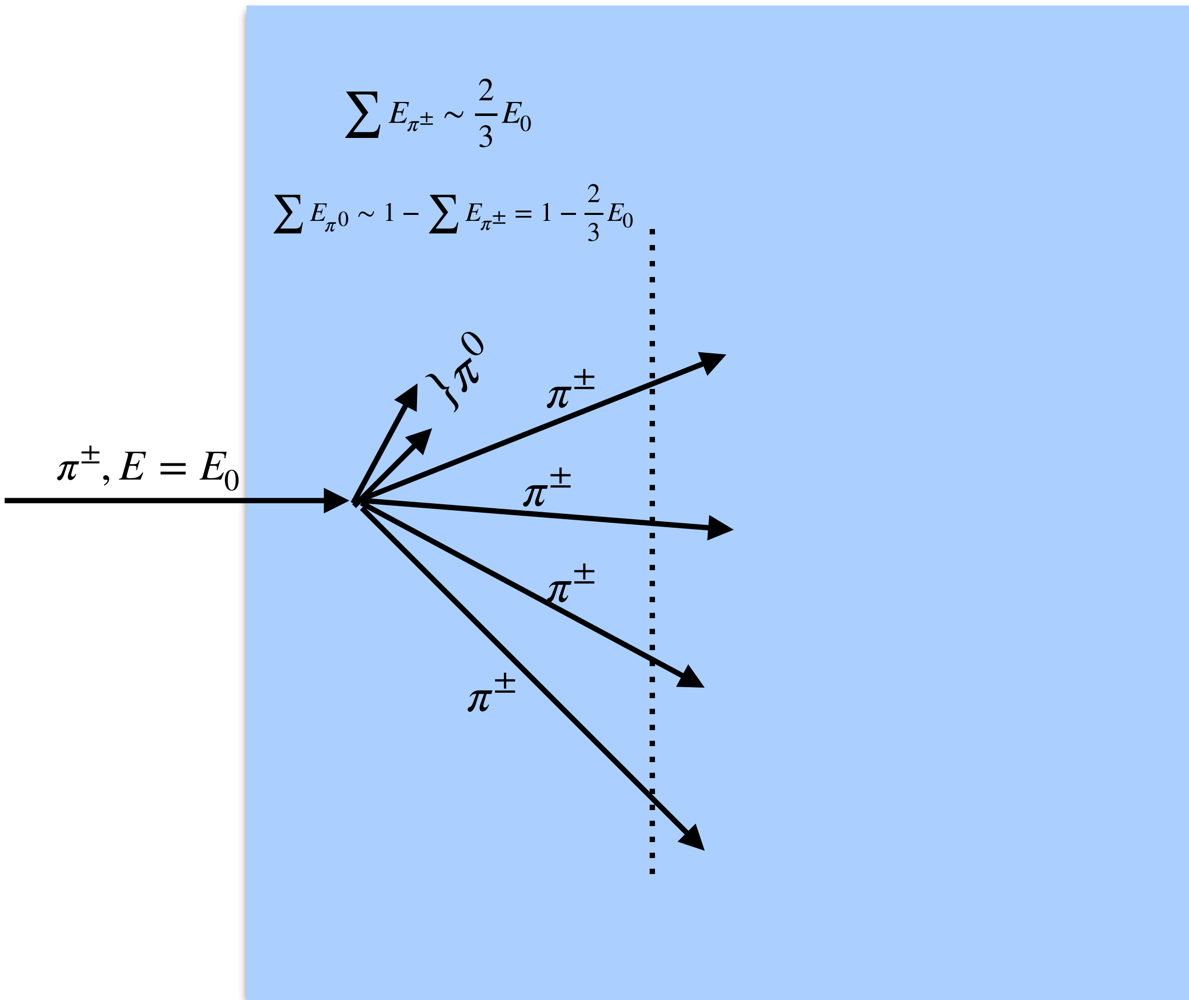

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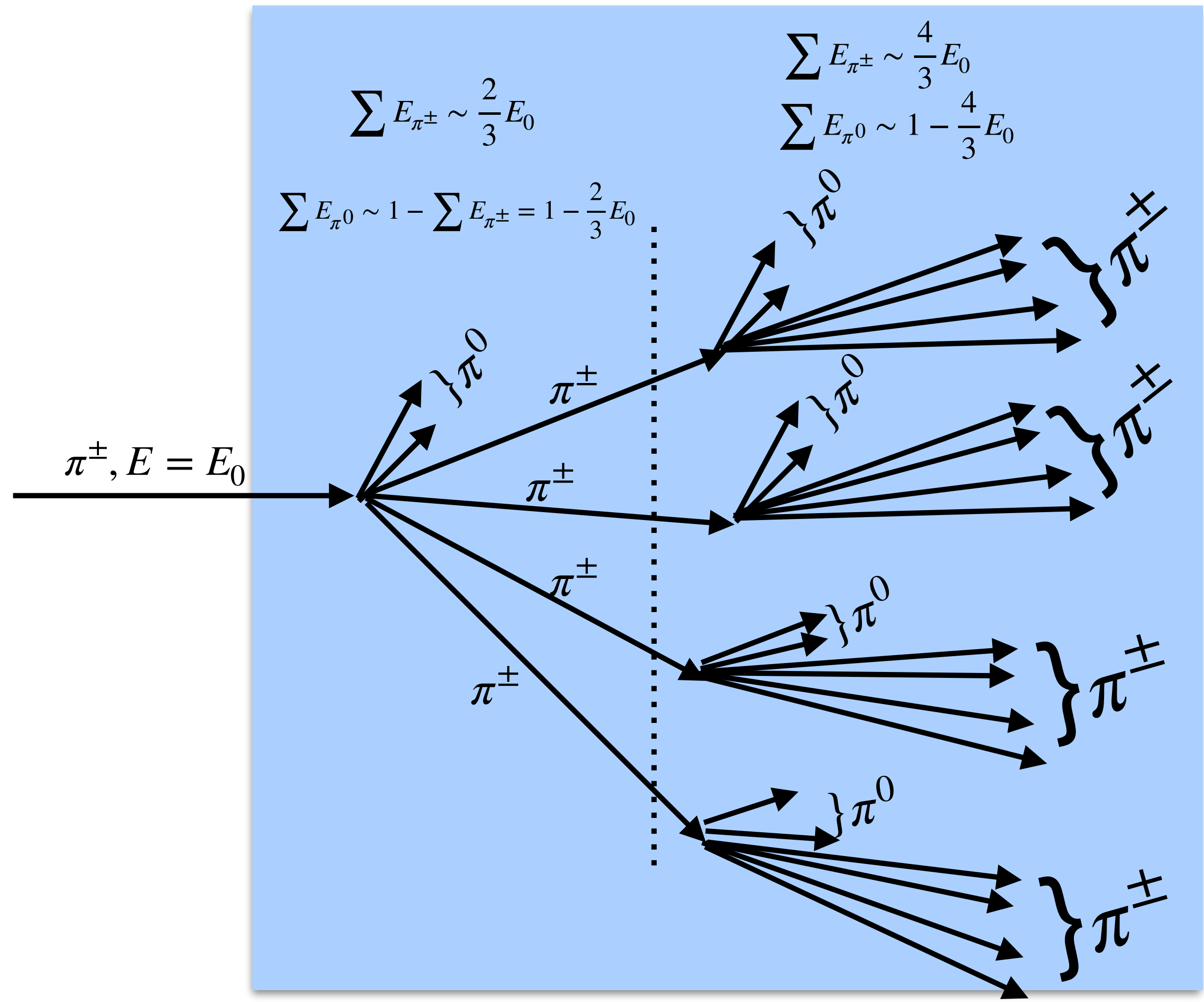


f_{em} energy dependence

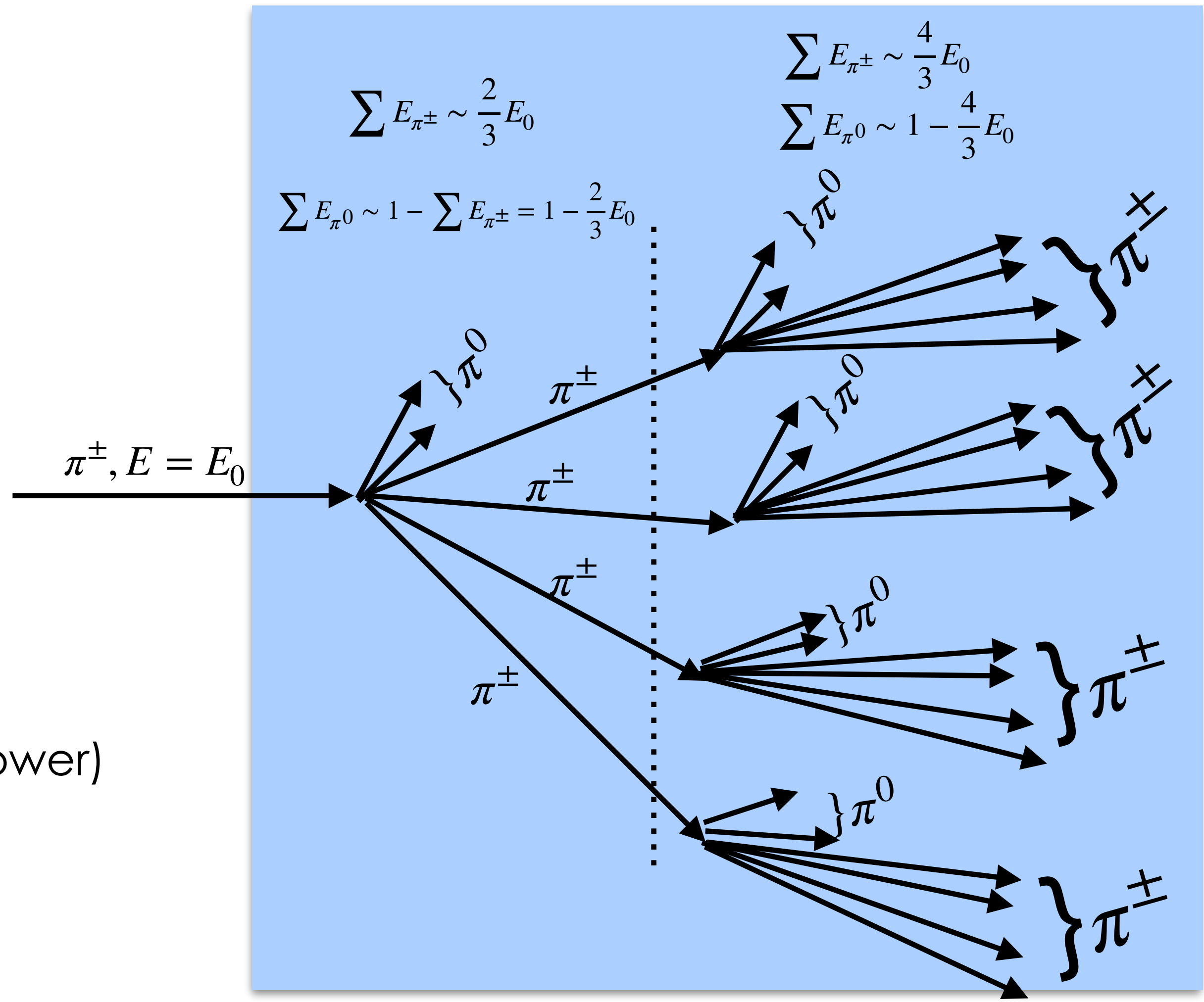
- Simple model: **only pions** are produced at each interaction, **respecting isospin symmetry**
- Then the math is:

$$f_{em} = \frac{E_{em}}{E} = 1 - \left(\frac{2}{3}\right)^n$$

$$\left(\frac{2}{3}\right)^n E = E_{th}$$ (Condition to stop shower)

$$n = p \ln \frac{E}{E_{th}}$$ (for some number p)

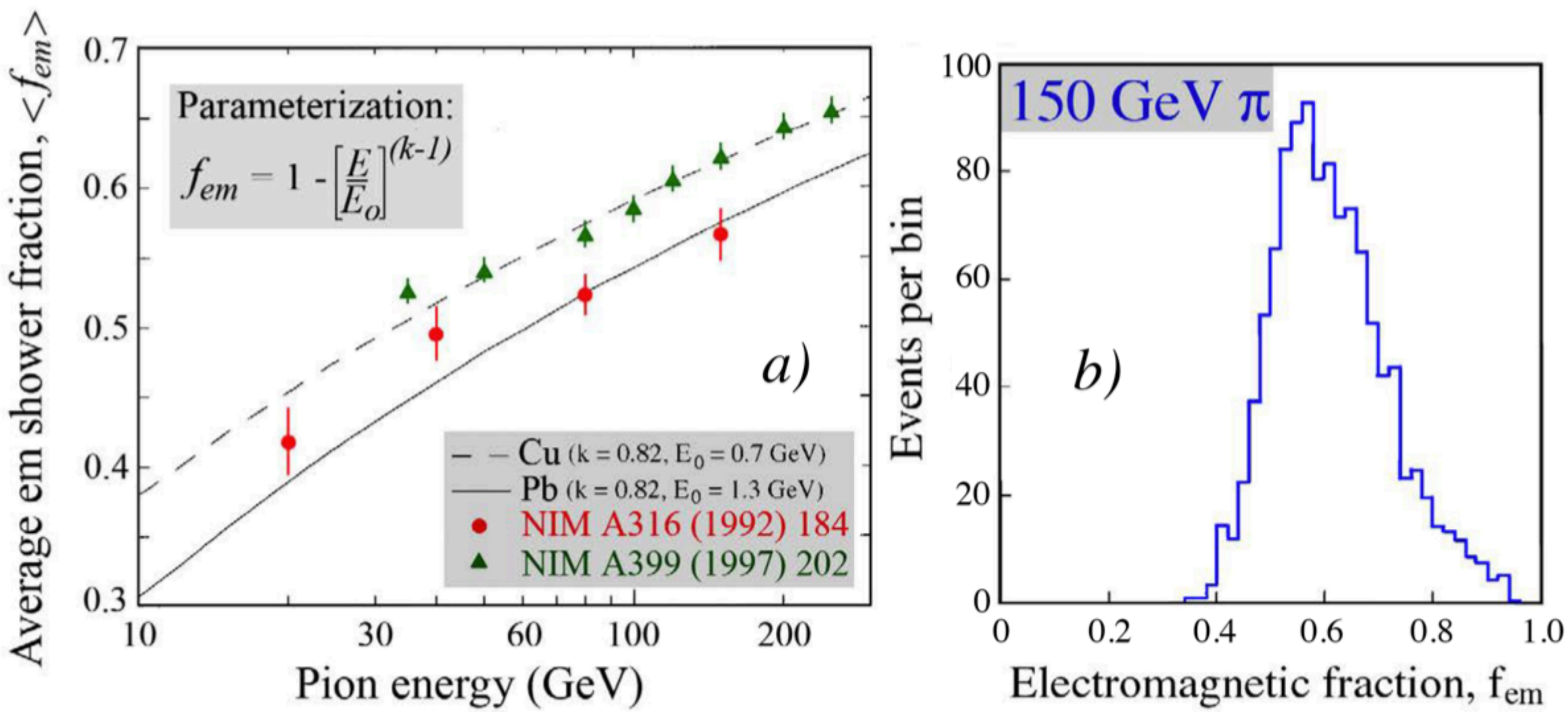
$$f_{em} = 1 - \left(\left(\frac{2}{3}\right)^{\ln \frac{E}{E_{th}}}\right)^p = 1 - \left(\frac{E}{E_{th}}\right)^{k-1}$$ (for some number k)



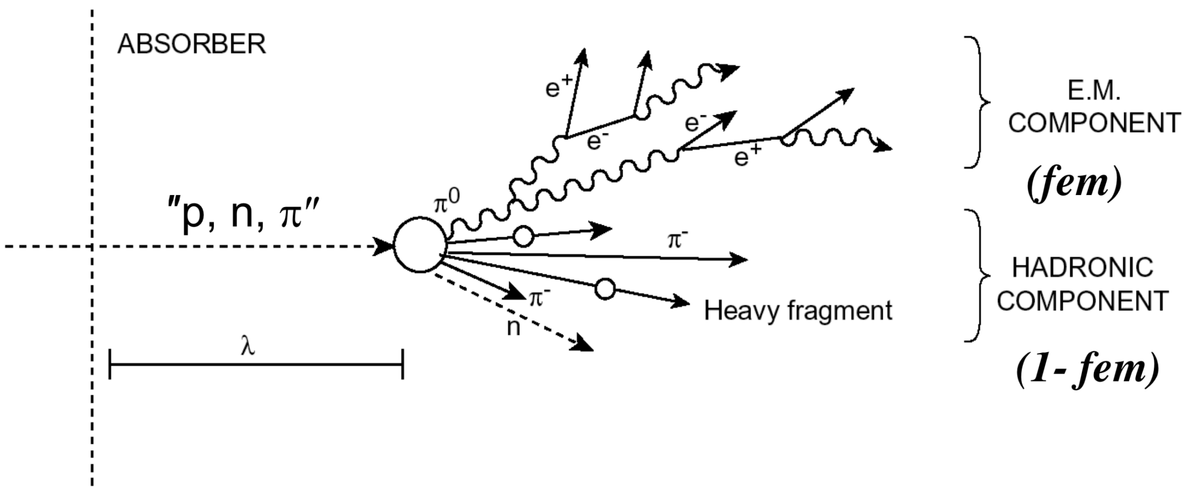
f_{em} energy dependence

$$f_{em} = 1 - \left(\frac{E}{E_0}\right)^{k-1}$$

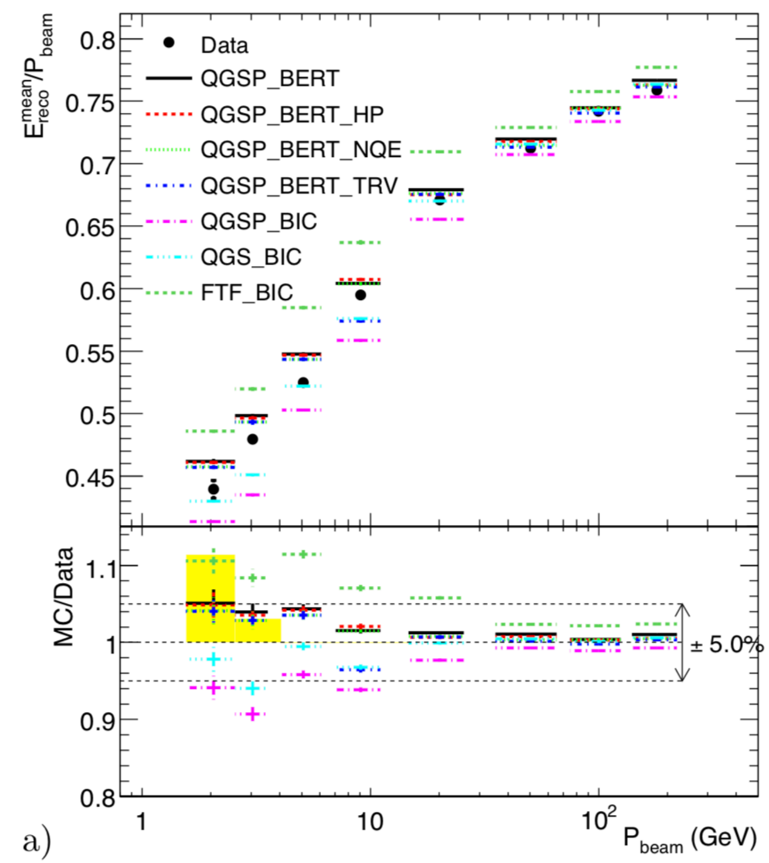
- f_{em} depends on the **incoming particle energy**
- Fluctuations in f_{em} are **large and non-poissonian**



The curse of hadronic calorimetry



ATL-CAL-PUB-2010-001

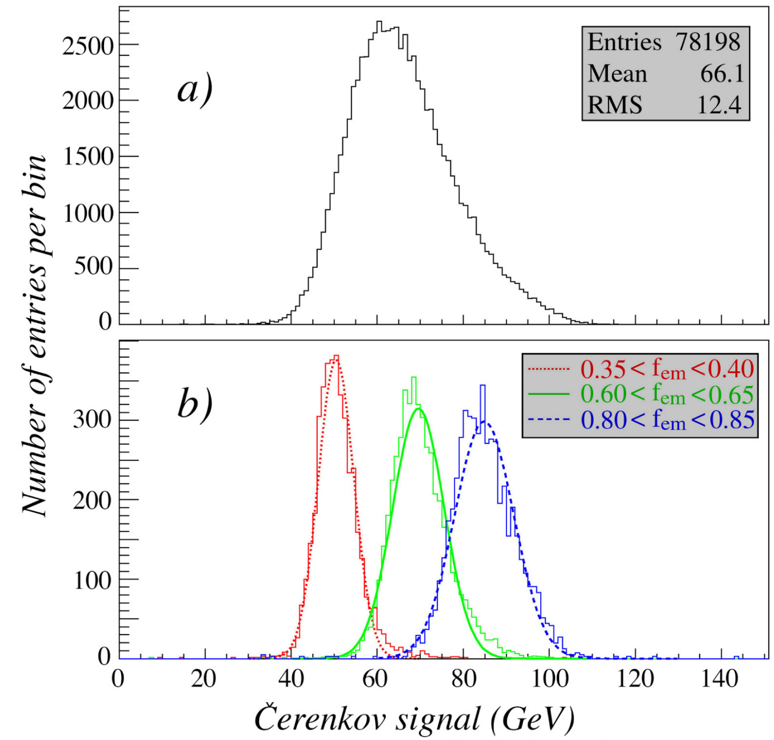


- **Non-compensating calorimeters**: response to em part different from that to non-em part. **h/e < 1**
- <f_{em}> energy dependent ⇒ **Non-linear calorimeter response** to hadrons

$$E_{\text{meas}} = E\left(f_{\text{em}} + \frac{h}{e}(1 - f_{\text{em}})\right)$$

The curse of hadron calorimetry (2)

- Event-by-event **f_{em} fluctuations** dominate the hadronic calorimeter resolution



Experiment	Detector	Absorber material	*e/h*	Energy resolution (E in GeV)
UA1 C-Modul	Scintillator	Fe	≈ 1.4	80%/√E
ZEUS	Scintillator	Pb	≈ 1.0	34%/√E
WA78	Scintillator	U	0.8	52%/√E ⊕ 2.6%*
D0	liquid Ar	U	1.11	48%/√E ⊕ 5%*
H1	liquid Ar	Pb/Cu	≤ 1.025*	45%/√E ⊕ 1.6%
CMS	Scintillator	Brass (70% Cu / 30% Zn)	≠ 1	100%/√E ⊕ 5%
ATLAS (Barrel)	Scintillator	Fe	≠ 1	50%/√E ⊕ 3%
ATLAS (Endcap)	liquid Ar	Brass	≠ 1	60%/√E ⊕ 3%

N. Akchurin *et al.*, *Nucl. Instr. and Meth.* A537 (2005) 537 .

Dual readout

Dual readout - the principle

- Suppose I read out two signals, S and C, with different h/e. Then:

$$E_S = E\left(f_{em} + \left(\frac{h}{e}\right)_S (1 - f_{em})\right)$$

$$E_C = E\left(f_{em} + \left(\frac{h}{e}\right)_C (1 - f_{em})\right)$$

$$f_{em} = \frac{\left(\frac{h}{e}\right)_C - \left(\frac{h}{e}\right)_S \left(\frac{E_C}{E_S}\right)}{\left(\frac{E_C}{E_S}\right)\left(1 - \left(\frac{h}{e}\right)_S\right) - \left(1 - \left(\frac{h}{e}\right)_C\right)}$$

$$E = \frac{(E_S - \chi E_C)}{1 - \chi}$$

$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C}$$

Depends only on the detector, it can be determined in test beam for example

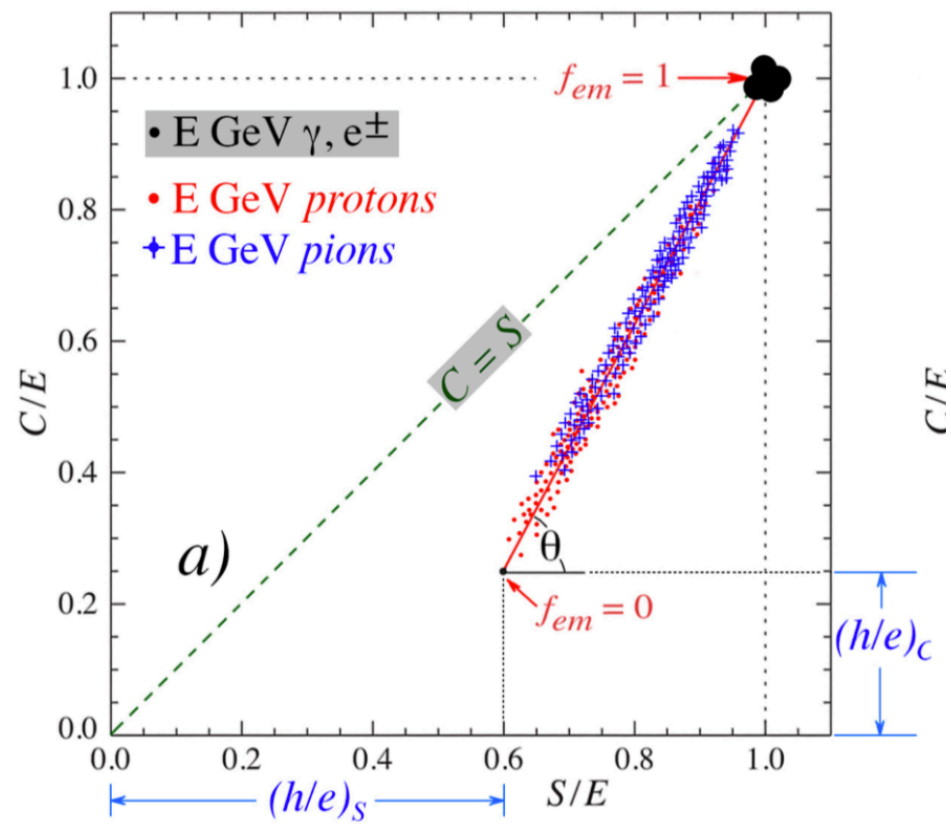
Dual readout - the signals

- In practice, this is realised with:
  - S: **scintillating fiber** signal measuring dE/dx of particles. Sensitive to **all shower components** - h/e < 1
  - C: **undoped fibres** sensitive to **Cherenkov** signal from relativistic particles in the shower (essentially only EM component) - h/e ~ 0.2

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

$$\frac{C}{E} = \left(f_{\text{em}} + \left(\frac{h}{e}\right)_C (1 - f_{\text{em}})\right)$$

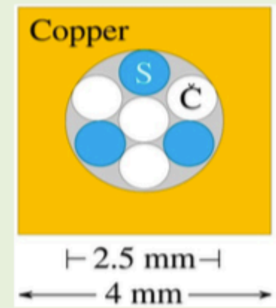
$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C} = \cot\theta$$

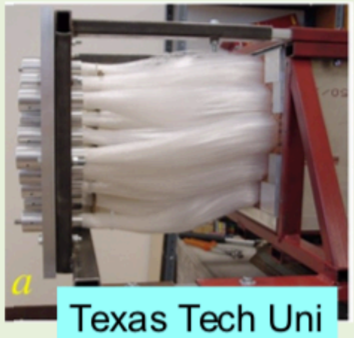


Dual readout calorimeters (PMT readouts)

2003
DREAM

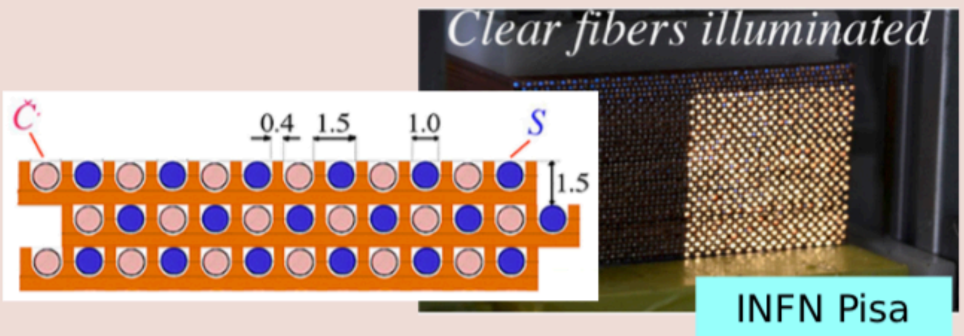
Cu: 19 towers, 2 PMT each
2m long, 16.2 cm wide
Sampling fraction: 2%





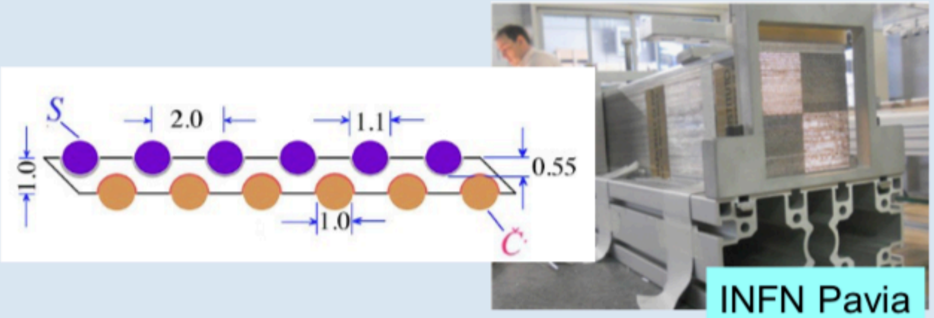
2012
RD52

Cu, 2 modules
Each module: $9.2 \times 9.2 \times 250$ cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}

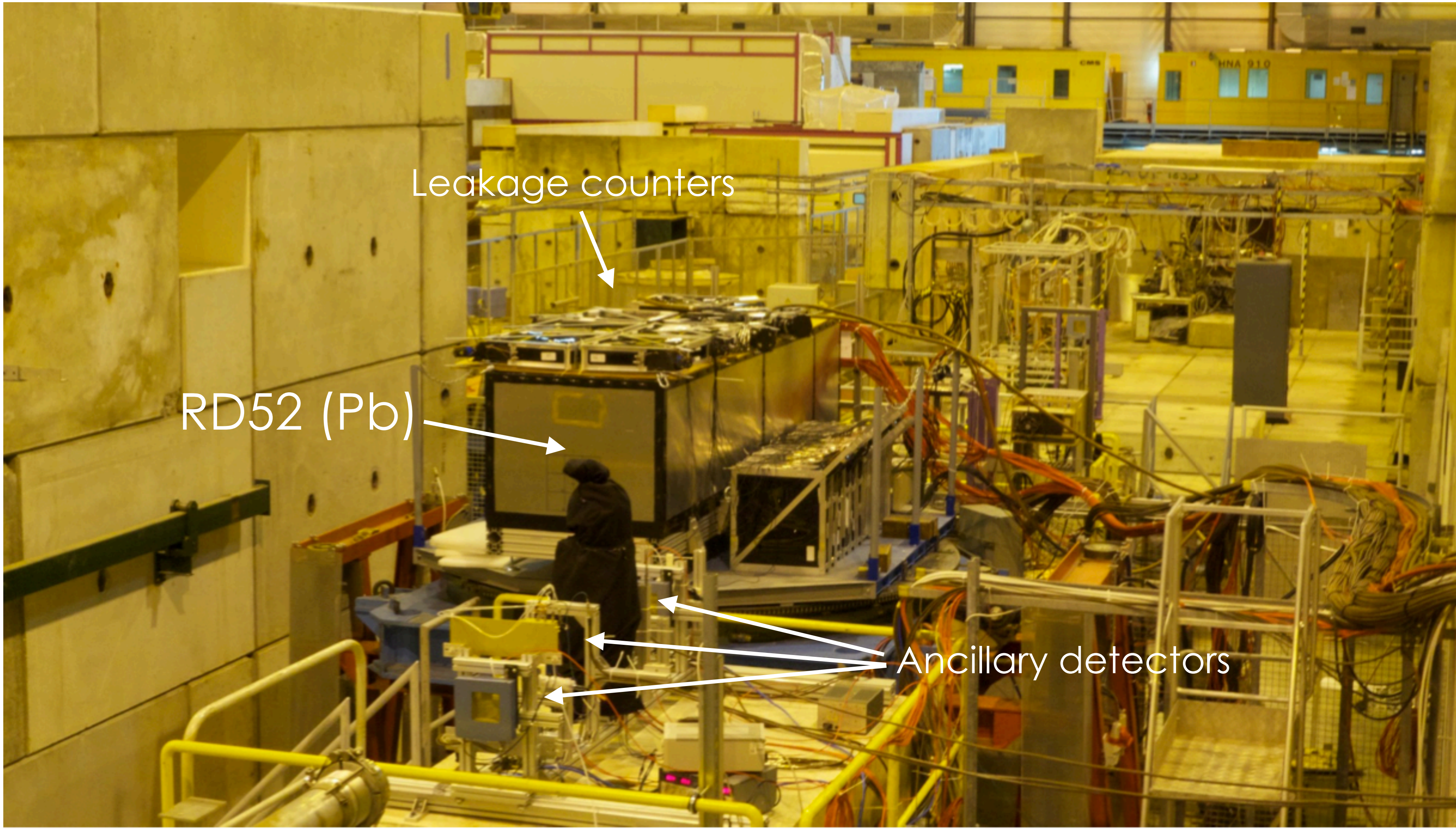


2012
RD52

Pb, 9 modules
Each module: $9.2 \times 9.2 \times 250$ cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}

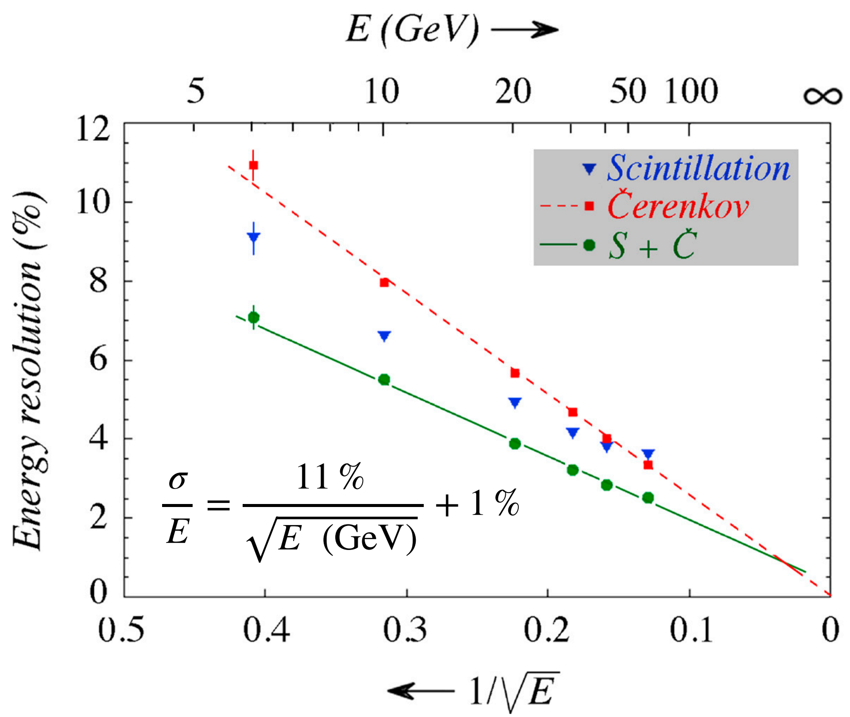


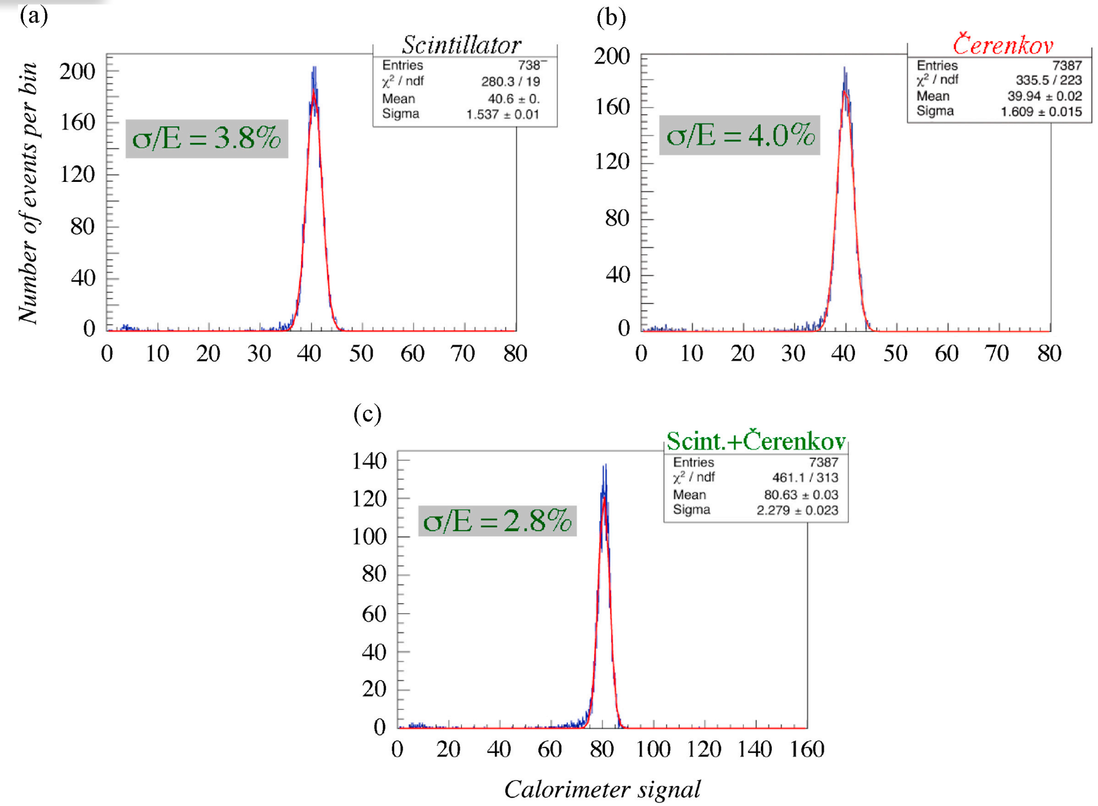
Dual readout calorimeter at work

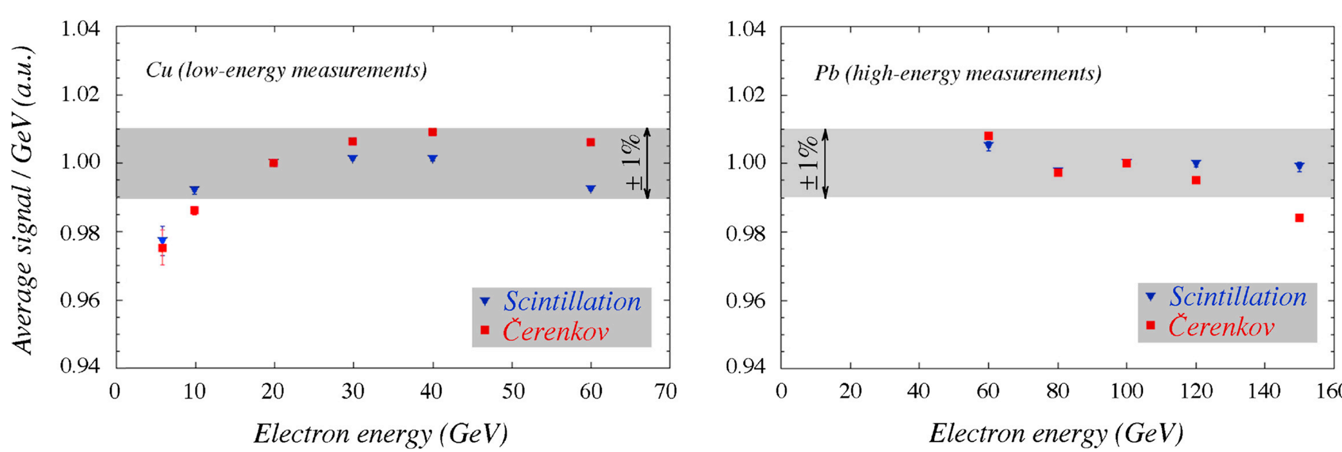


Electron response

40 GeV electrons



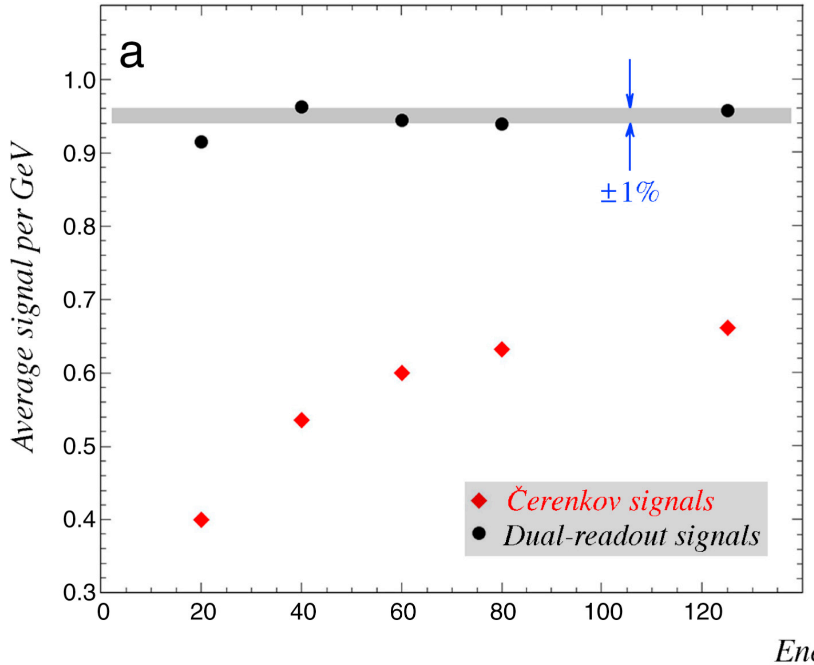




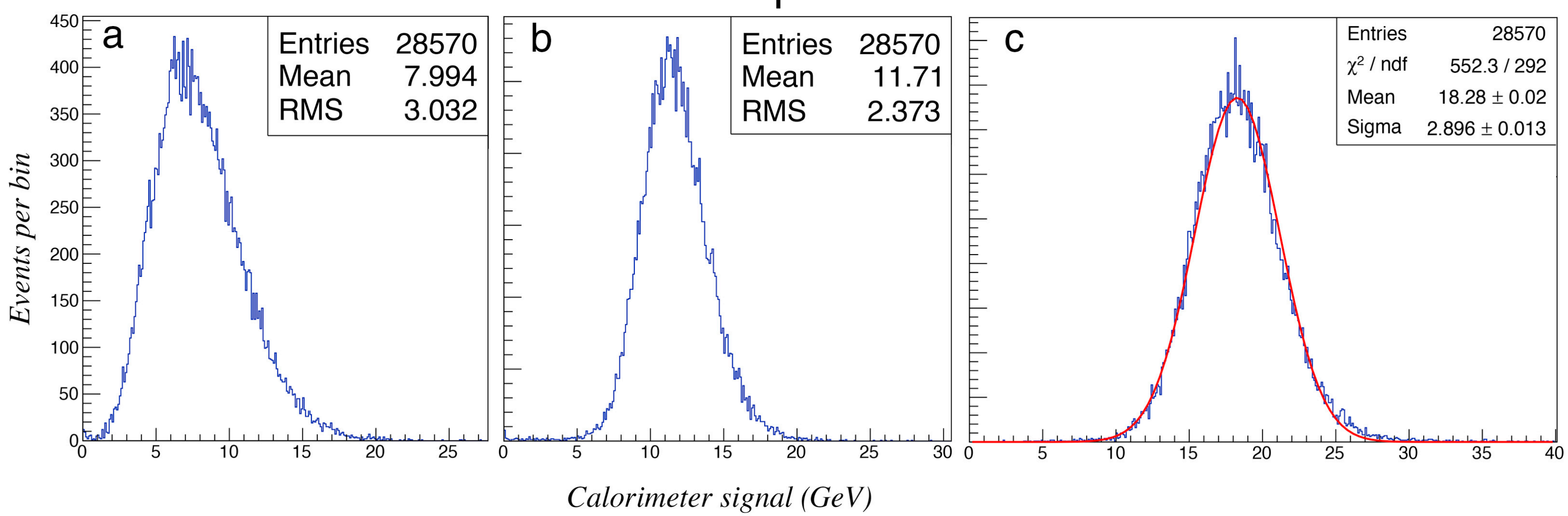
Single hadron response - linearity

NIM A 866 (2017) 76

- Dual readout signal largely recovers linearity while vastly improving resolution

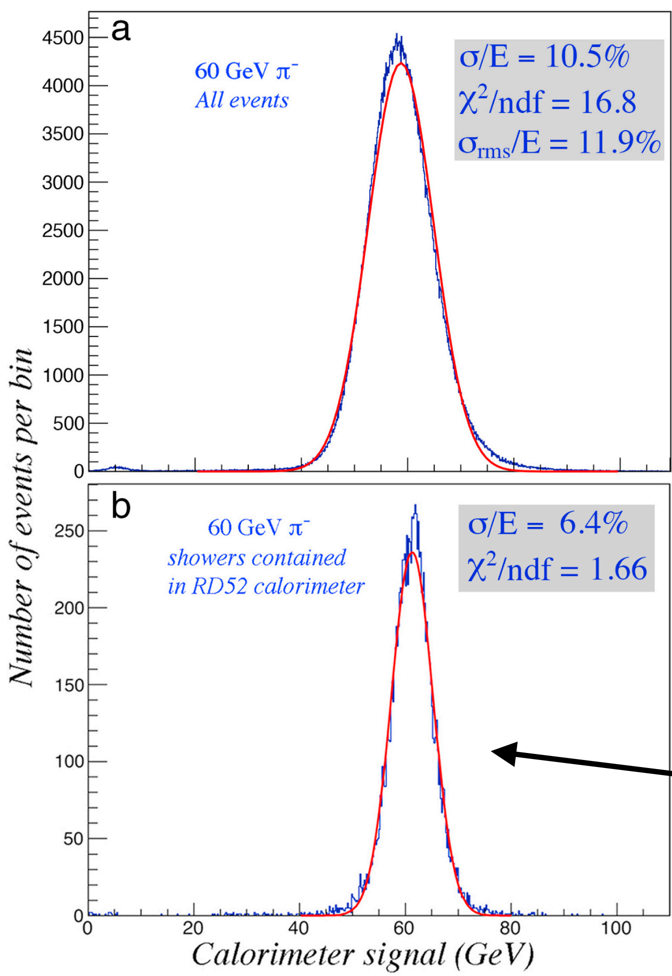


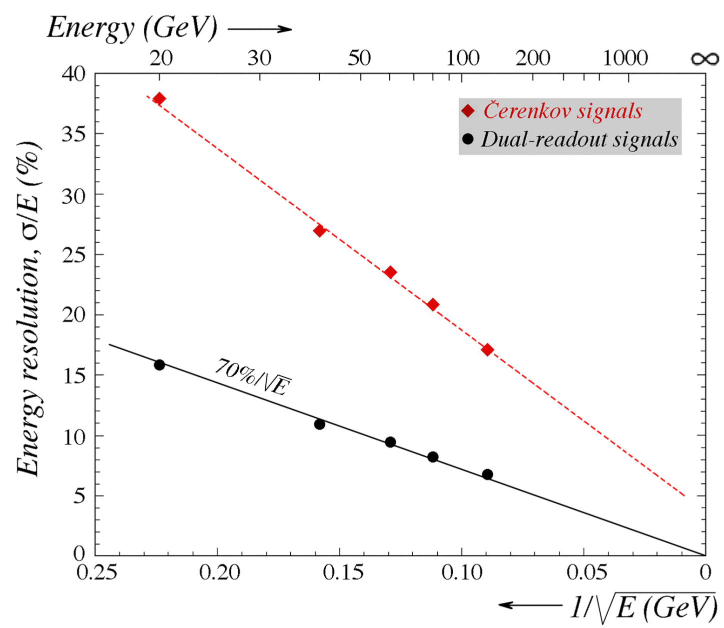
20 GeV pions



Single hadron response - resolution

- Curse of calorimeter R&D: a fully containing calorimeter is expensive

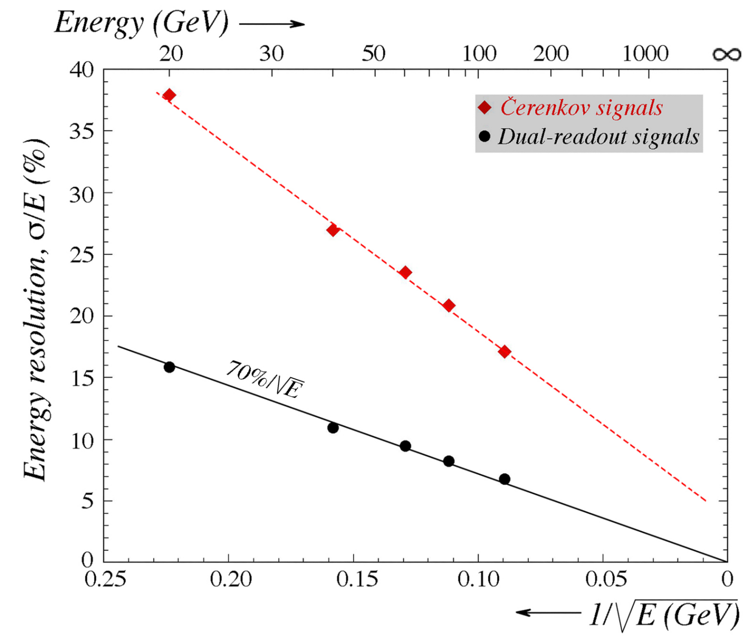




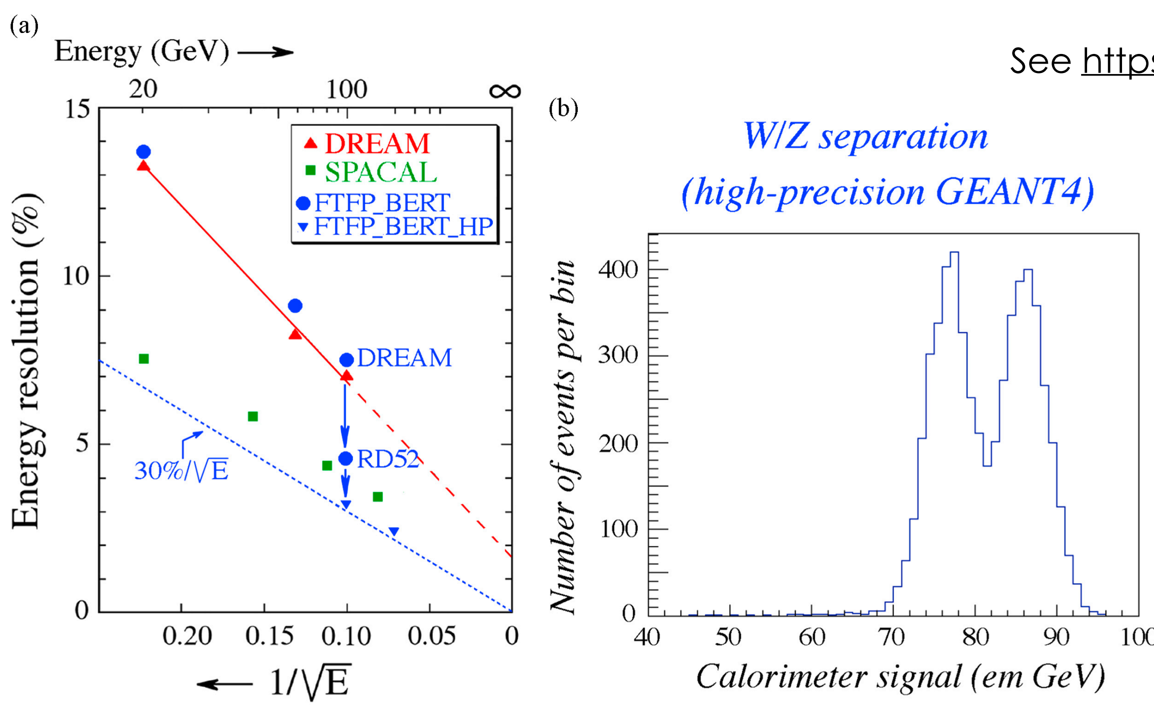
No signal in leakage counters

Performance of Dual Readout

- **Hadronic resolution** comparable to **compensating calorimeters**.
  - Resolution at TB (dominated by leakage). G4 estimate **with full containment** $\frac{\sigma}{E} = \frac{34\,\%}{\sqrt{E}}$

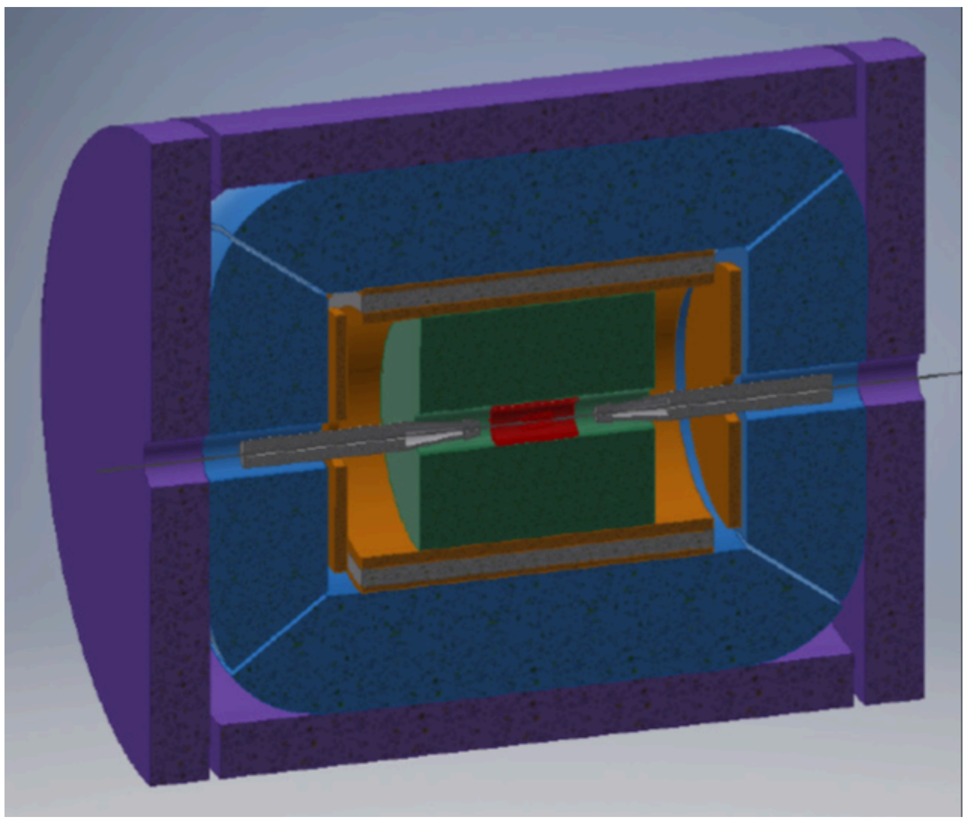


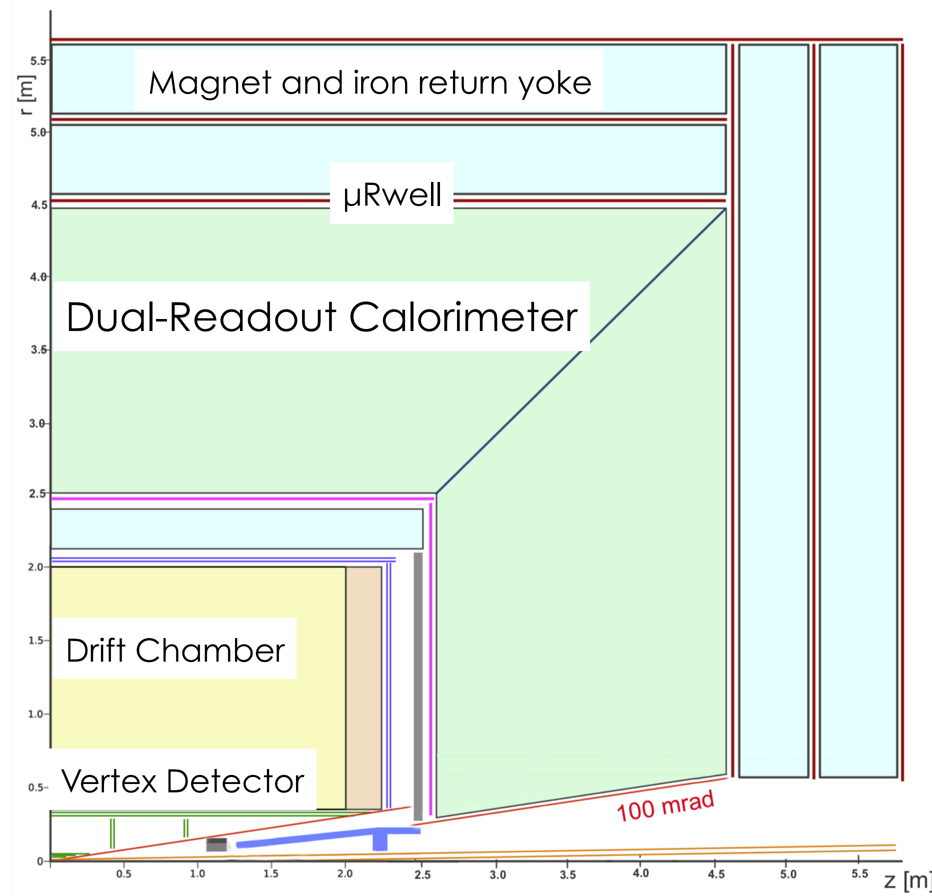
See https://doi.org/10.1016/j.ppnp.2018.07.003



Recent results

A practical implementation: IDEA

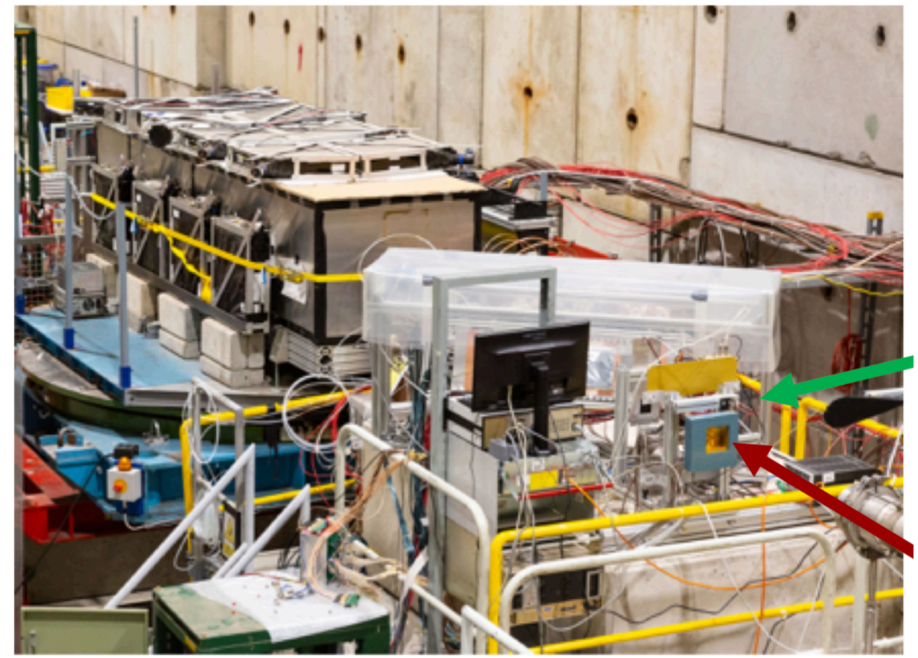


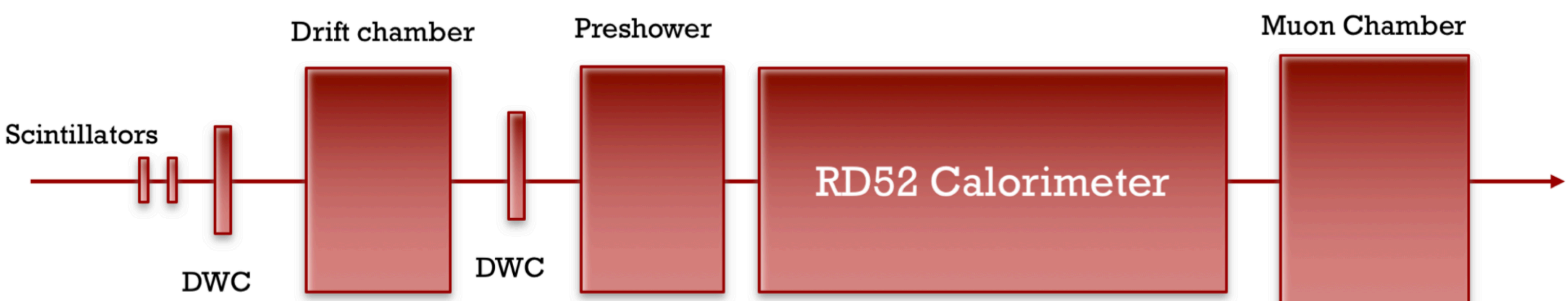


See here for additional information

IDEA slice on beam (2018)

- A full **combined test** of IDEA:
  - Drift chamber prototype
  - GEM as preshower + μRWell for μ detection
  - Several calorimeter options tested on beam





From PMTs to SiPM

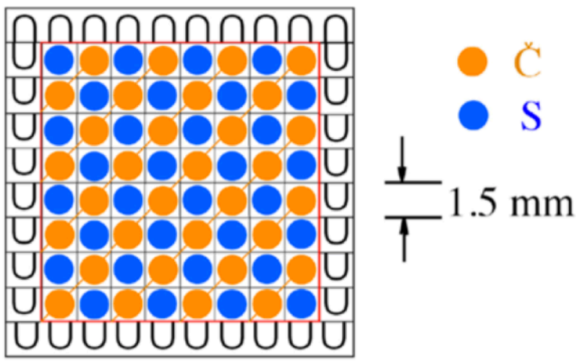
SiPM pros:

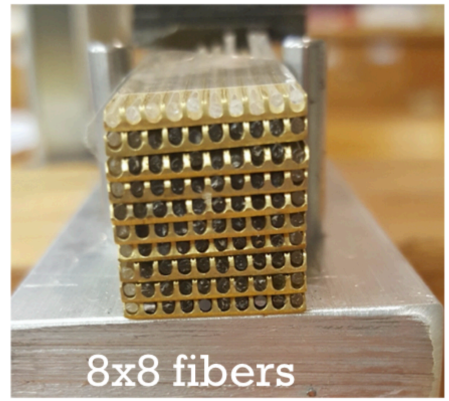
- Compact readout
- Resilience to magnetic field
- Large light yields
- High readout granularity (particle flow "friendly")
- Photon counting (calibration)
- High timing resolution

SiPM cons:

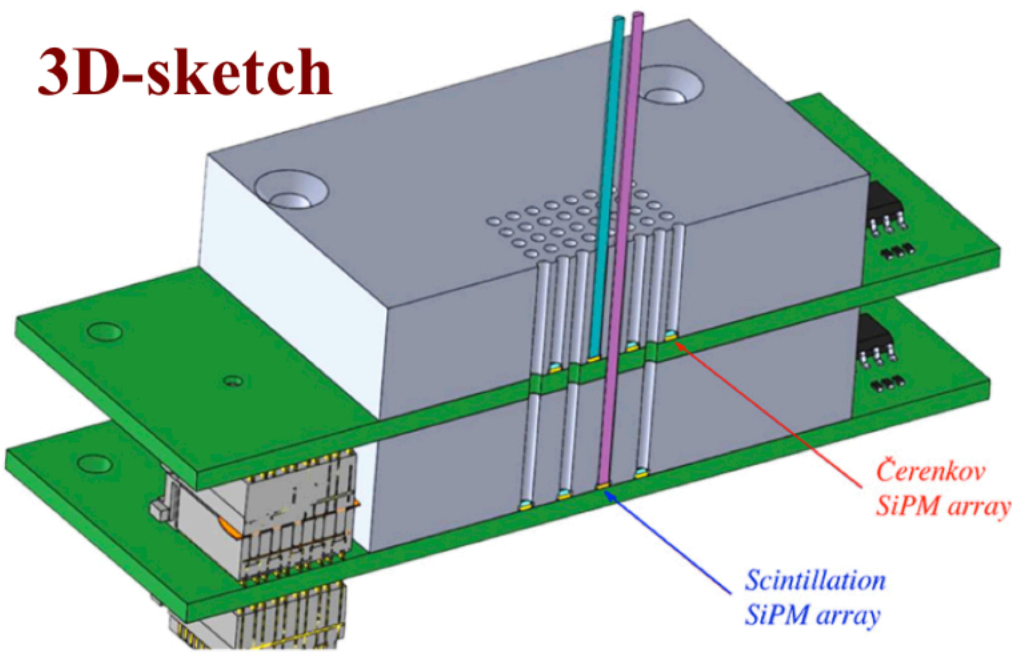
- Signal saturation/dynamic range
- Cross talk between C and S signals
- Instrumental effects

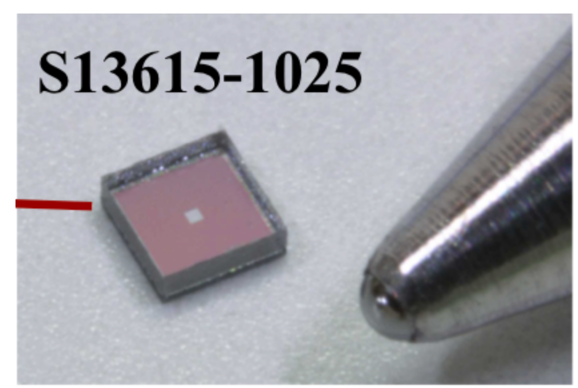
SiPM dual readout



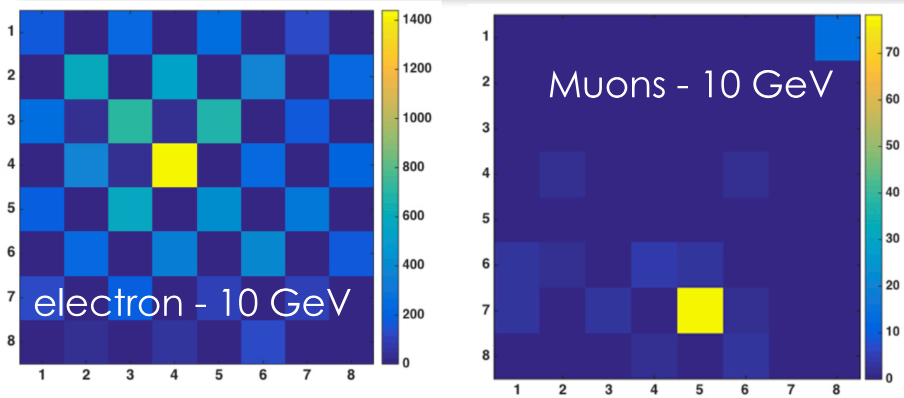


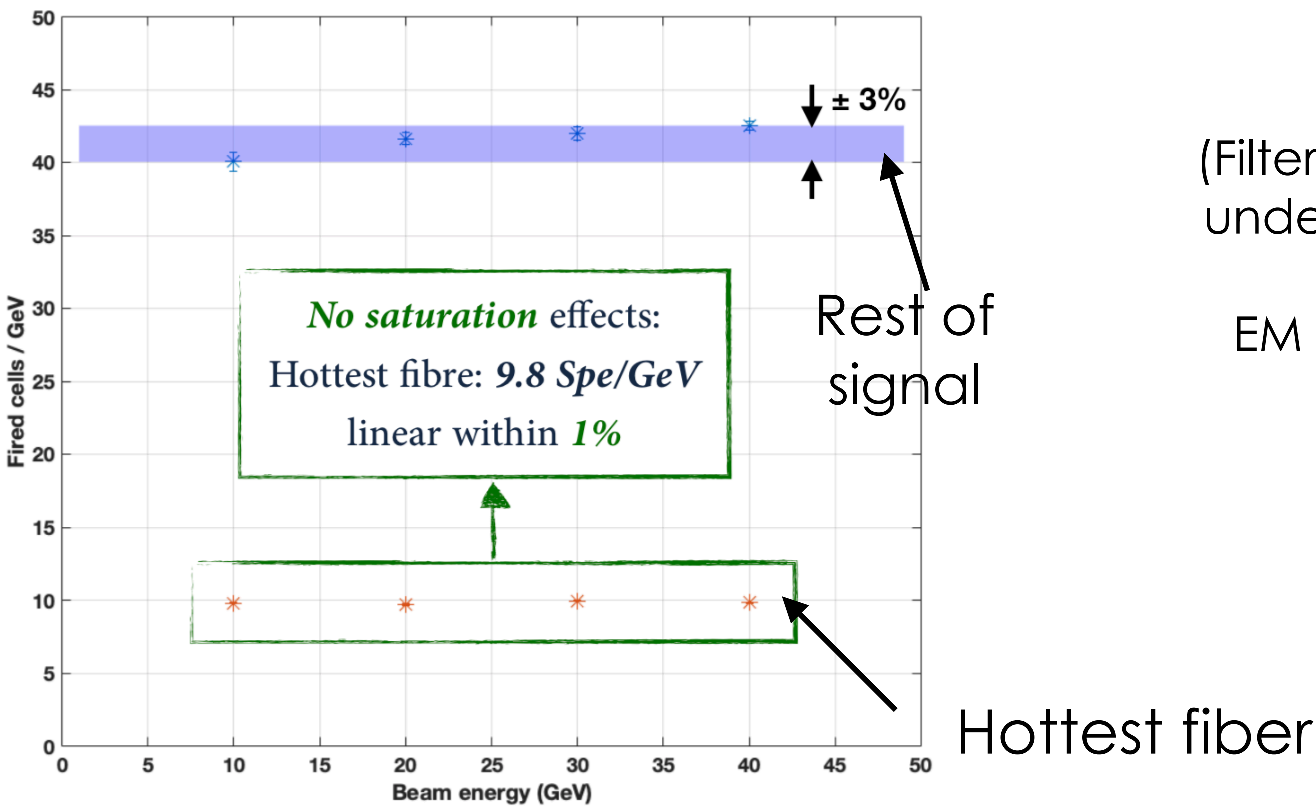
- Single fibre readout with **HAMAMATSU SiPM**
- Readout for Cherenkov and Scintillation light separated to minimise cross talk (the latter expected to be ~ 50 times larger if not attenuated)





SiPM dual readout





Operating with 5.5 V_{OV} - PDE ~ 22%

Cherenkov light yield (70 Spe/GeV) ~ a factor 2 larger than what measured with PMT

(Filtered) scintillation light yield under control (~95 Spe/GeV).

EM stochastic term ~ 10% is achievable

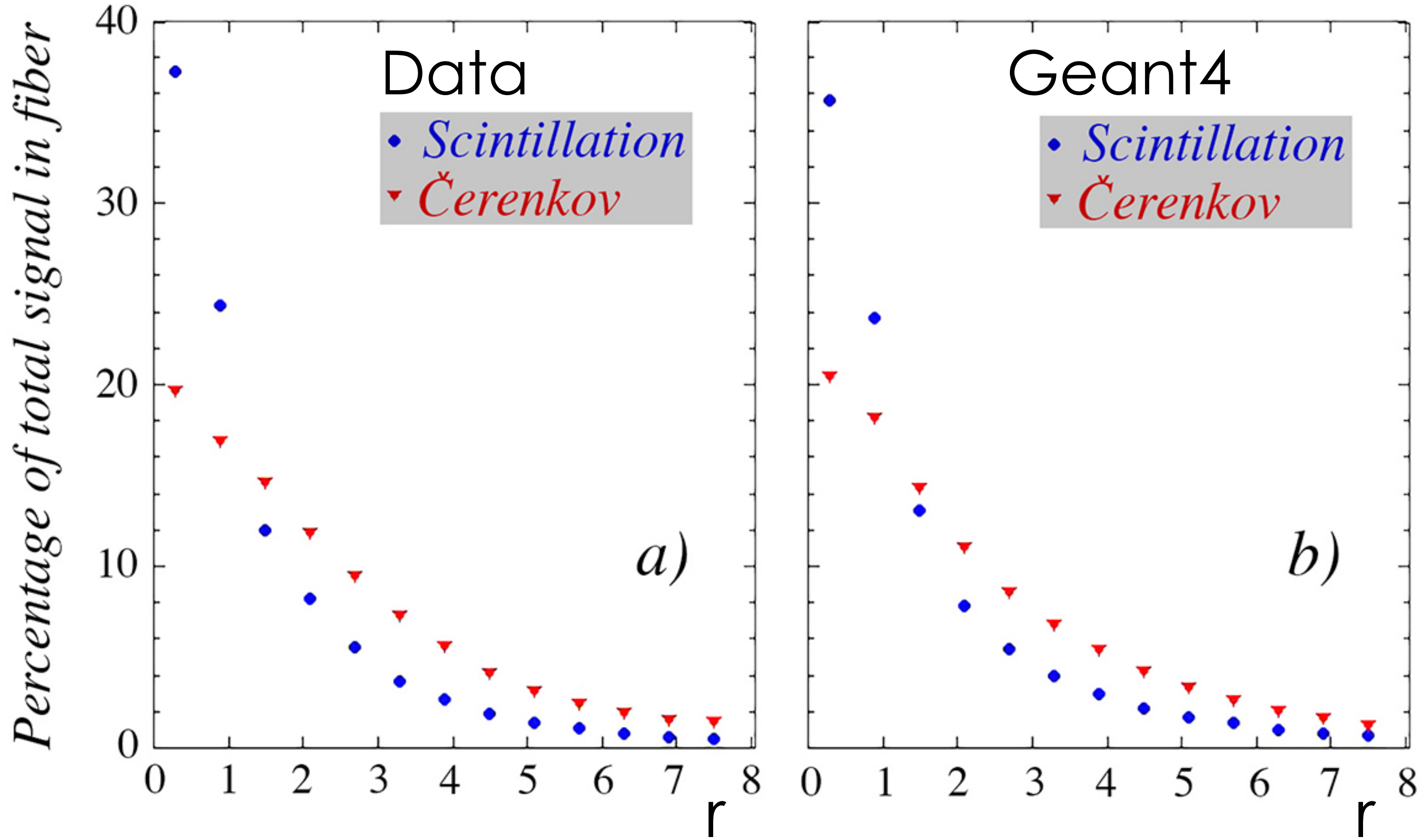
SiPM dual readout (shower shape)

- Readout of single fibre gives **unprecedented lateral segmentation**
- Em lateral shower shape measured with **~ 1 mm precision**.

$$\bar{x} = \frac{\sum_i x_i E_i}{\sum_i E_i}; \bar{y} = \frac{\sum_i y_i E_i}{\sum_i E_i}$$

$$r = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2}$$

Doi:10.1016/j.nima.2018.05.016

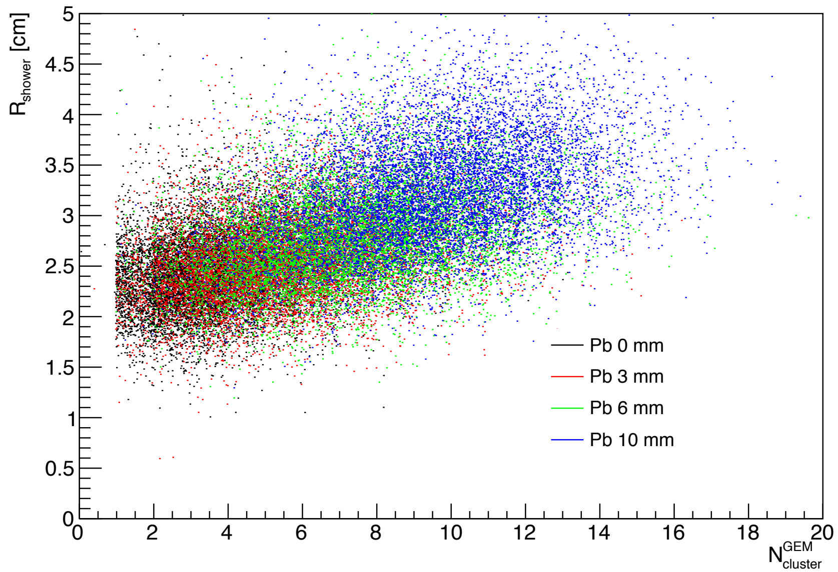


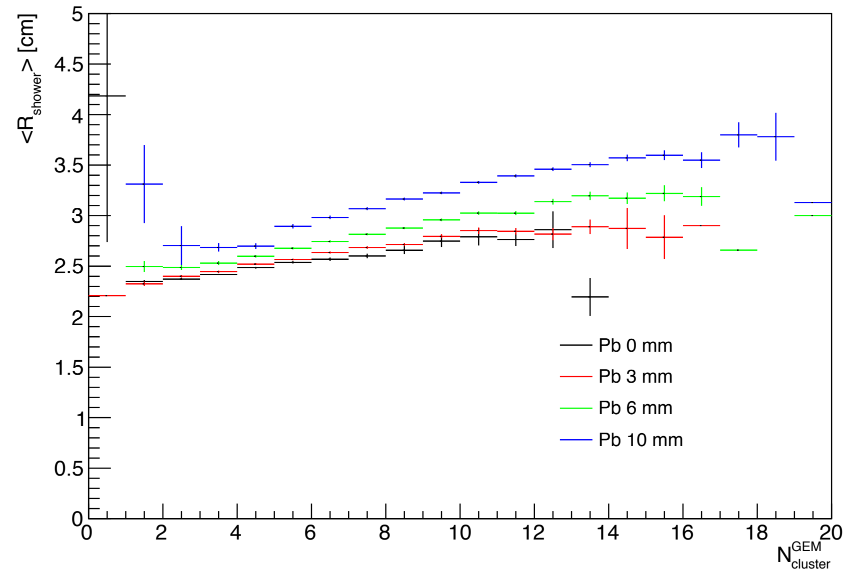
Combined measurements (RD52)

- RD52 performance studied in detail elsewhere
  - Focus on DAQ combination and combined runs with GEM-based preshower

$$R_{\text{shower}} = \frac{\sum_{\text{ch}} E_{\text{ch}} \cdot \sqrt{x_{\text{ch}}^2 + y_{\text{ch}}^2}}{\sum_{\text{ch}} E_{\text{ch}}}$$

Shower width from 5 mm Pb + additional material correlates with number of clusters in GEM preshower





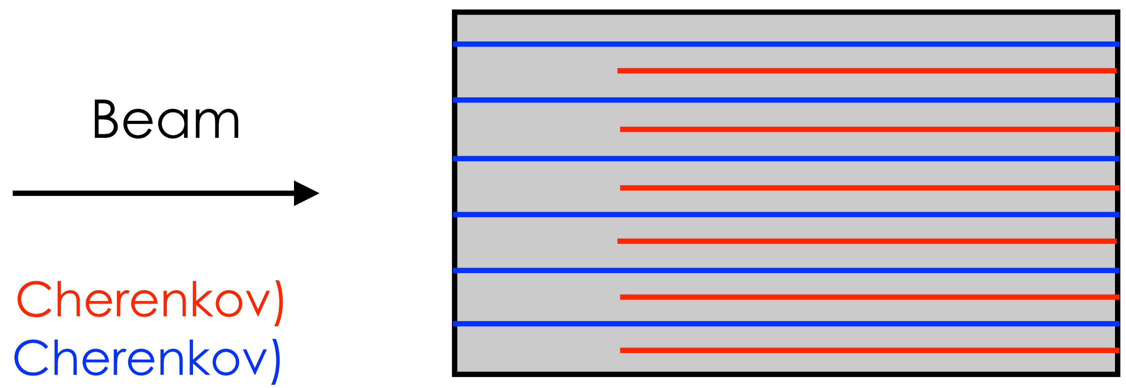
Longitudinal segmentation (standalone test)

- Particle identification (e.g. hadronic tau decay) may benefit from **longitudinal segmentation**.
- "Staggered" option tested on beam

"HAD" section: E(short fibres)
"EM" section: E (long fibres) - E (short fibres)

- Challenge: calibration of the short section.

View from above

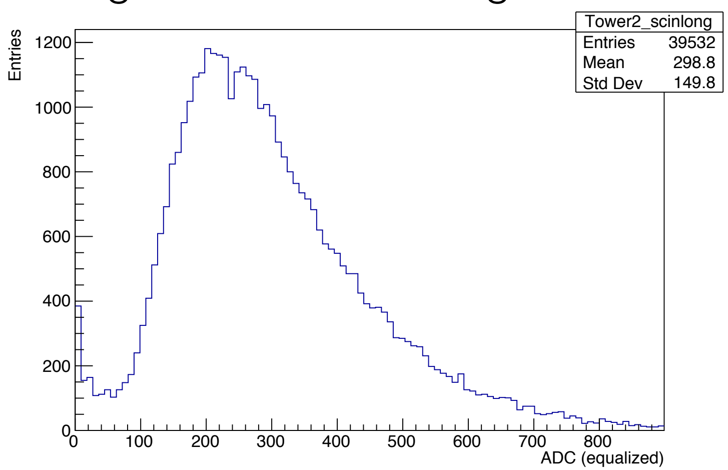


Red: short fibres (scintillation and Cherenkov)
Blue: long fibres (scintillation and Cherenkov)

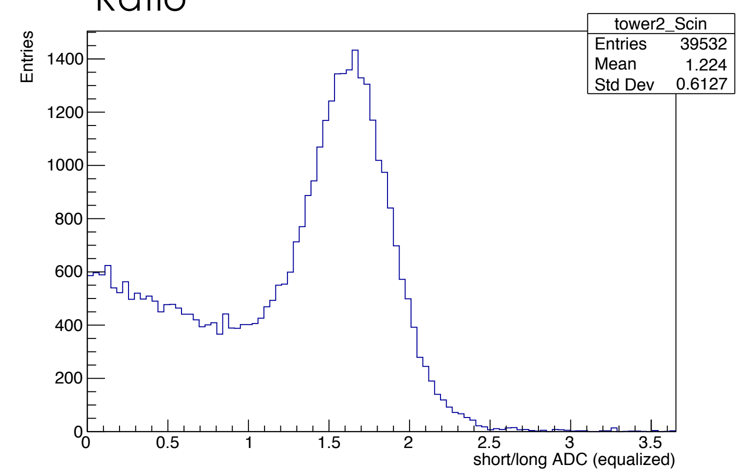
Longitudinal segmentation

- Problem: how do we calibrate short section?
  - Idea: **propagate calibration** from long section **using hadrons**.

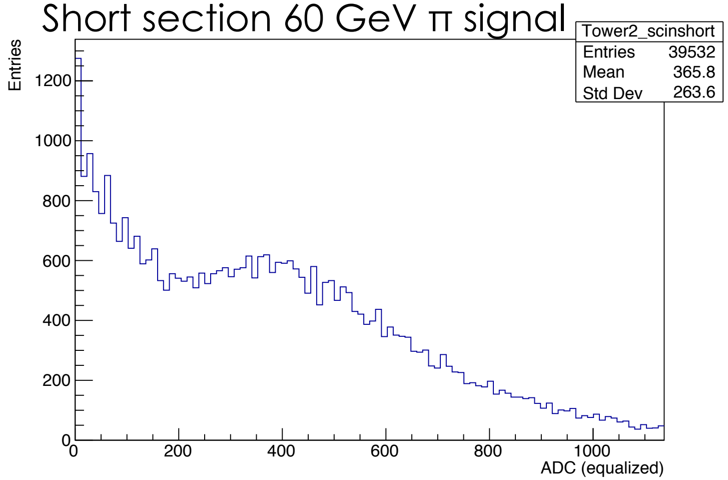
Long section 60 GeV π signal

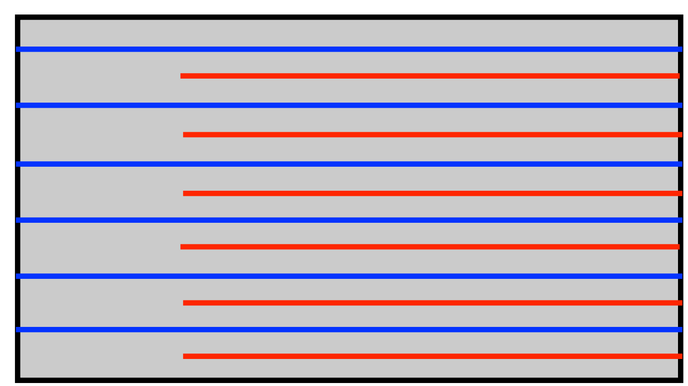


Ratio



Short section 60 GeV π signal



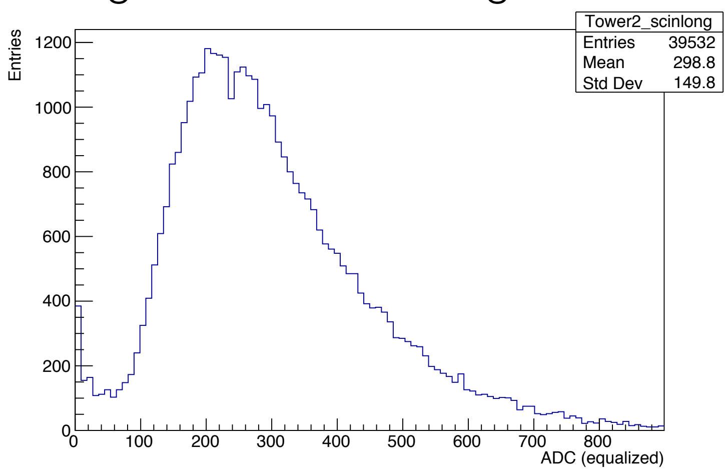


Scintillation fibers

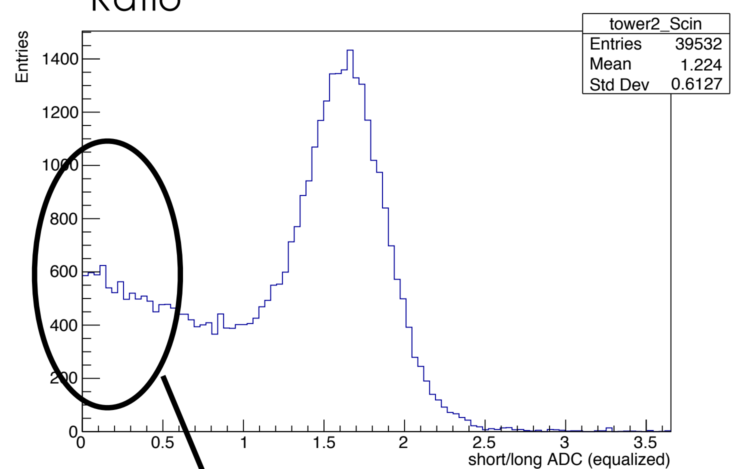
Longitudinal segmentation

- Problem: how do we calibrate short section?
  - Idea: **propagate calibration** from long section **using hadrons**.

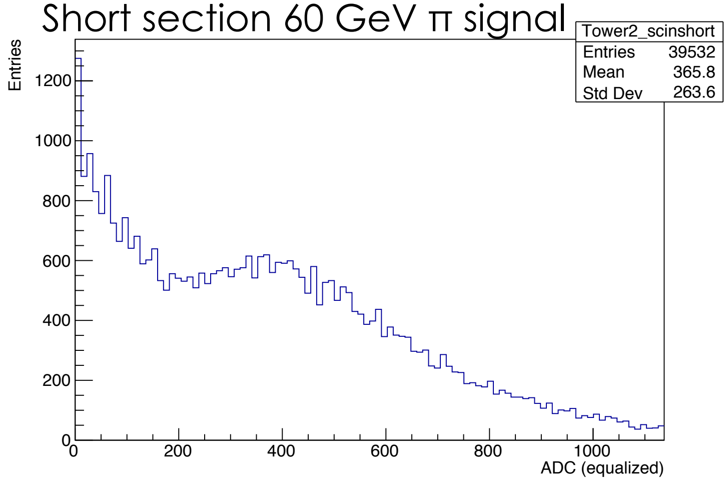
Long section 60 GeV π signal

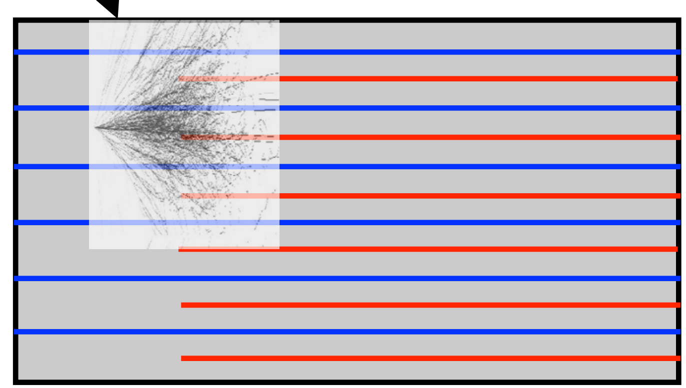


Ratio



Short section 60 GeV π signal



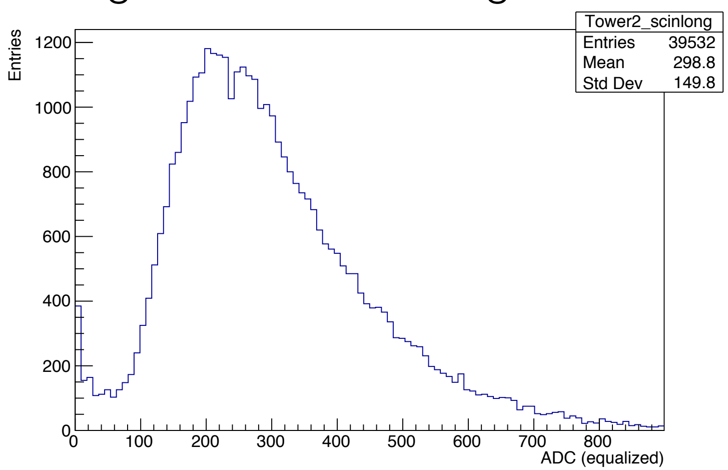


Scintillation fibers

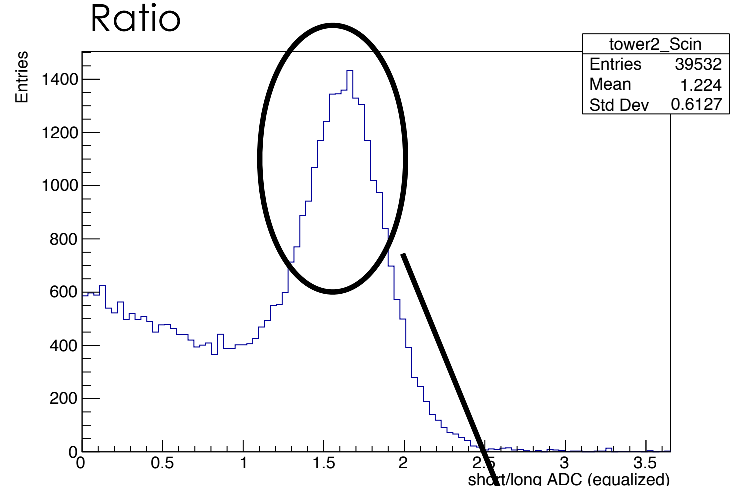
Longitudinal segmentation

- Problem: how do we calibrate short section?
  - Idea: **propagate calibration** from long section **using hadrons**.

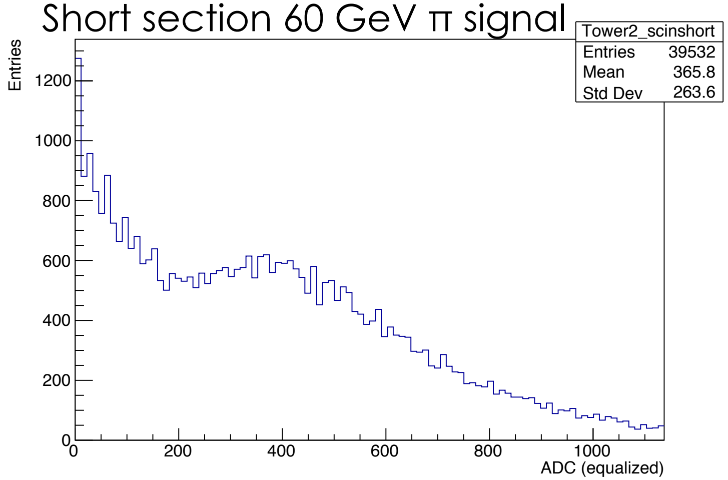
Long section 60 GeV π signal

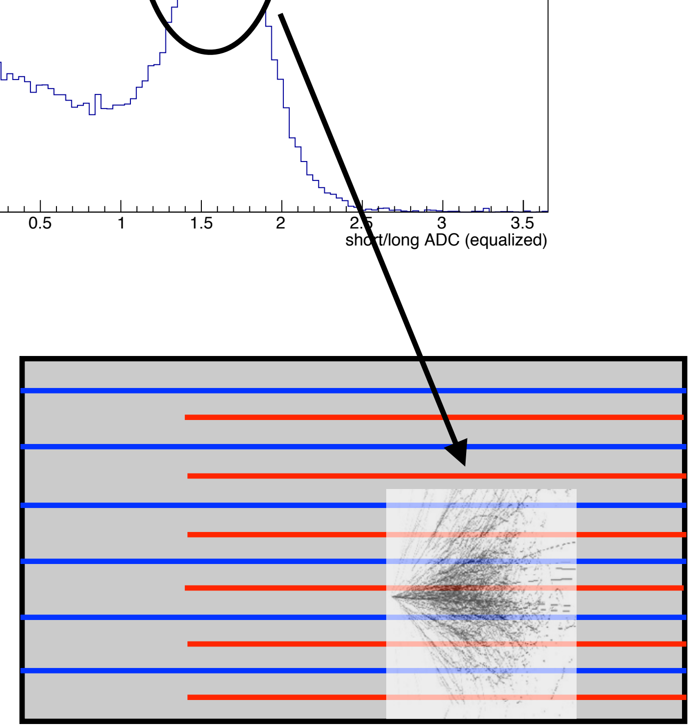


Ratio



Short section 60 GeV π signal



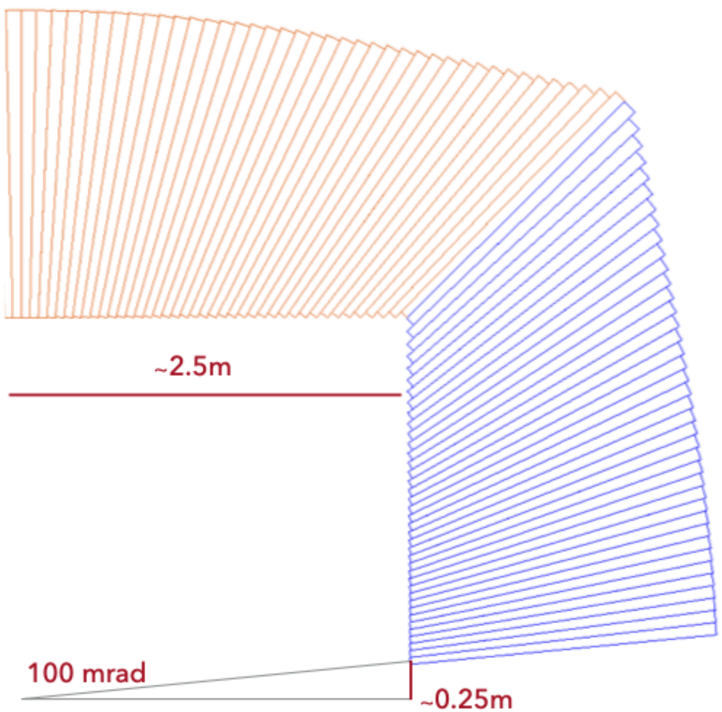


Scintillation fibers

Open questions

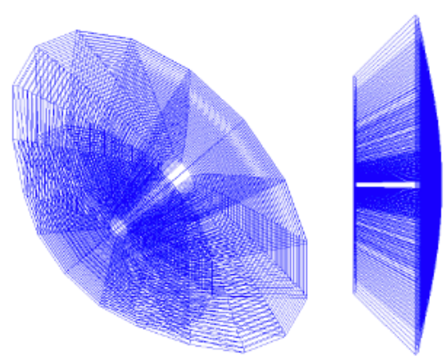
Simulation

- Final choices need **reasonably well understood G4** simulation
- Existing fast sim + **full G4 sim projective geometry**



Barrel (right): 40 towers
Inner length 2.5m
Tower height 2.0m

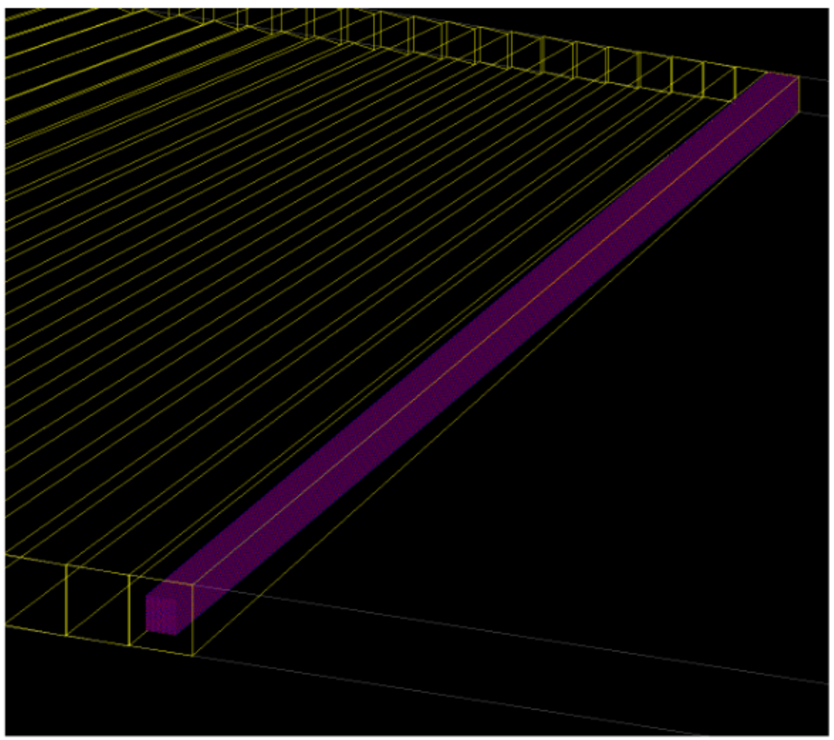
Endcap (right): 39 towers
Inner length 2.25m
Tower height 2.0m



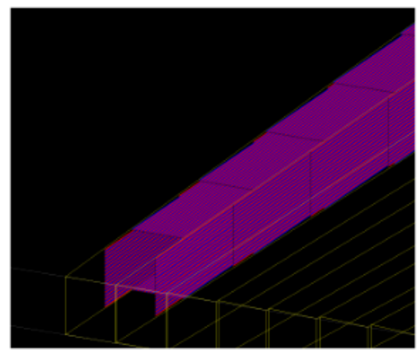
- Open points:
  - Reliability of G4 to reproduce χ value.
  - More structured software effort for full IDEA project

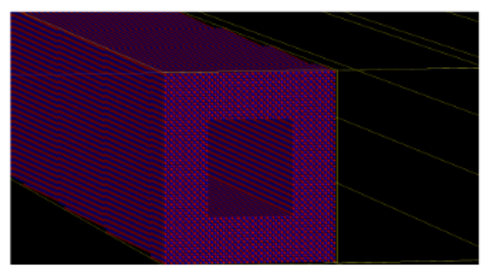
Absorber and layout

- Copper/brass calorimeter would **avoid problems with e/mip**
  - But lead more cost-effective
  - Options to be finalised with G4 simulation



Courtesy of L. Pezzotti





70447104 fibers in the barrel

- Readout with **longitudinally distributed fibres** is the baseline:
  - Excellent lateral segmentation and **electronics all outside the calorimeter**
  - But **large number of fibres/ SiPM** readout channels needed
- Other options being investigated:
  - Tiles
  - More creative options

Longitudinal segmentation - use timing?

- Profit from **excellent SiPM time resolution** - derive **energy deposit longitudinal position** with time
- More studies with simulation needed

SiPM readout (2):

digitiser (ASIC) & feature extraction (FPGA)

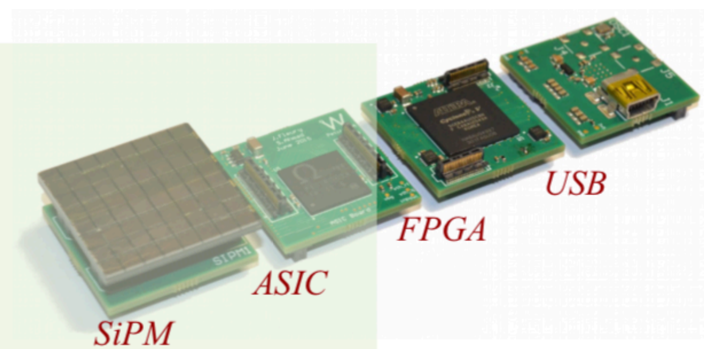
→ started investigating

→ time stamps w/ O(100 ps res)

→ get shower longitudinal development

[$\Delta x \sim 5$ cm $\Rightarrow \Delta t \sim 100$ ps]

→ started looking at neural network implementation



Costs

- Total foreseen cost at the moment ~ 150 M€.
  - Dominated by optical elements (fibre + SiPM)

	Unit cost	Quantity	Total (M€)
Fibres	0.25 €/m	190 M x 1.2 m	57.4
SiPM	0.25 € each	190 M	47.7
Absorber	2000 €/ton	3.4 kton	6.7
Front-end	-	-	17.9

- Actively looking at ways of reducing these costs

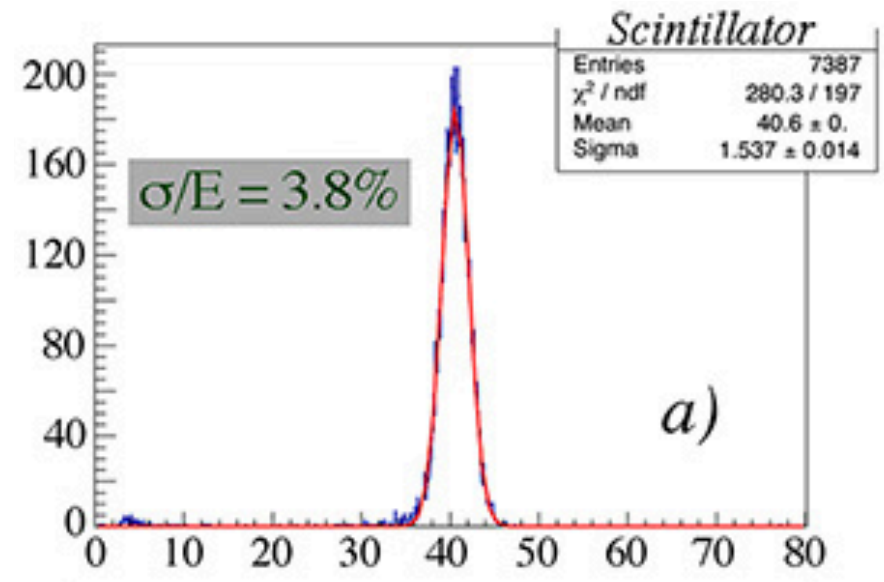
Summary

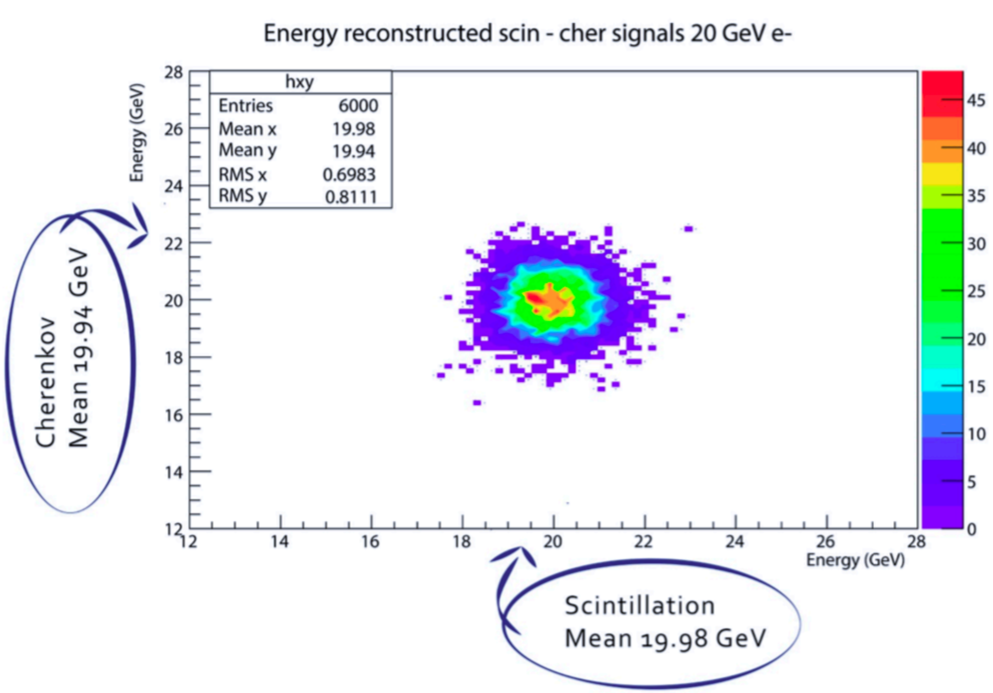
- Dual readout:
  - **Complementary** principles w.r.t. particle flow.
  - Excellent EM and HAD **native resolution.**
  - Could be combined with pFlow approach if need be.
- Towards a prototype. Help welcome on each of the open questions

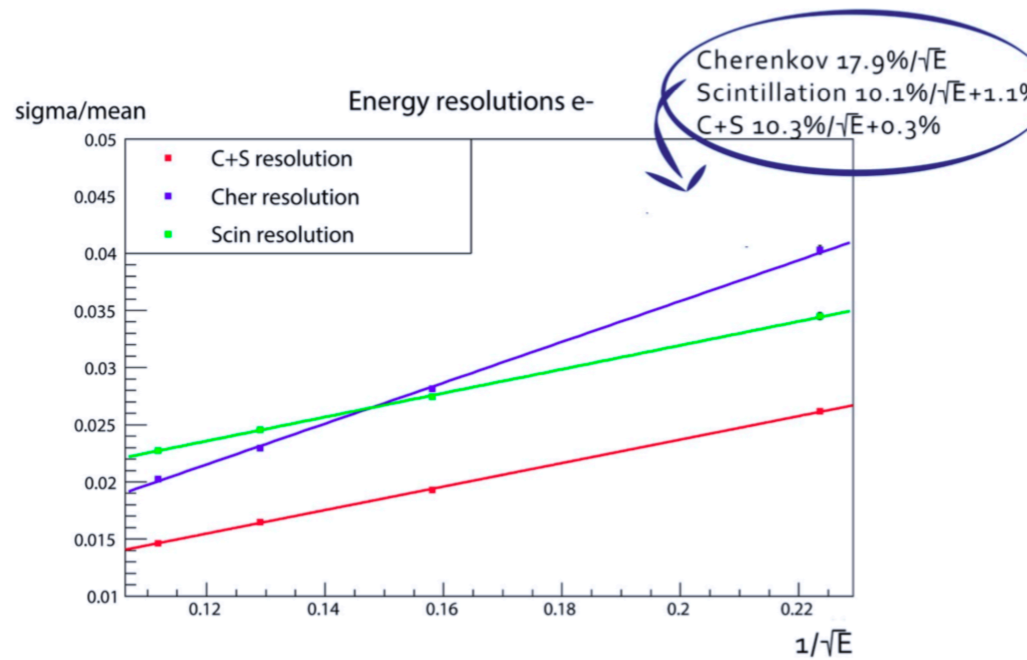
Backup

EM performance

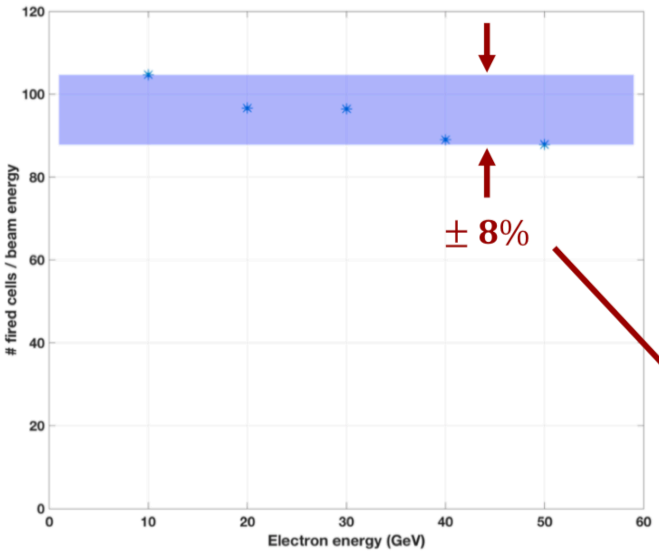
- Excellent e and γ calorimeter performance thanks to high sampling fraction.
  - EM and HAD calorimetry in one device.





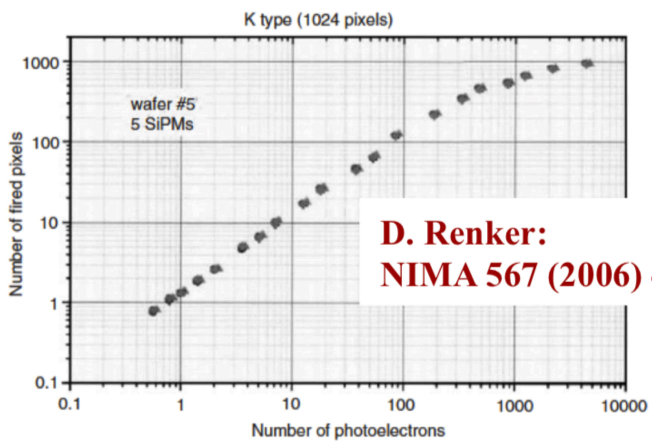


Results from 2017 test beam



- Detector operated at 0.5V over breakdown (PDE ≈ 2%)
- Temperature stability correction:
  - < 0.5°C during a single run (negligible)
  - < 2°C during the full scan (considered)
- PDE correction for temperature variation

$$N_{fired} = N_{total} \times \left[1 - e^{-\frac{N_{photons} \times PDE}{N_{total}}}\right]$$

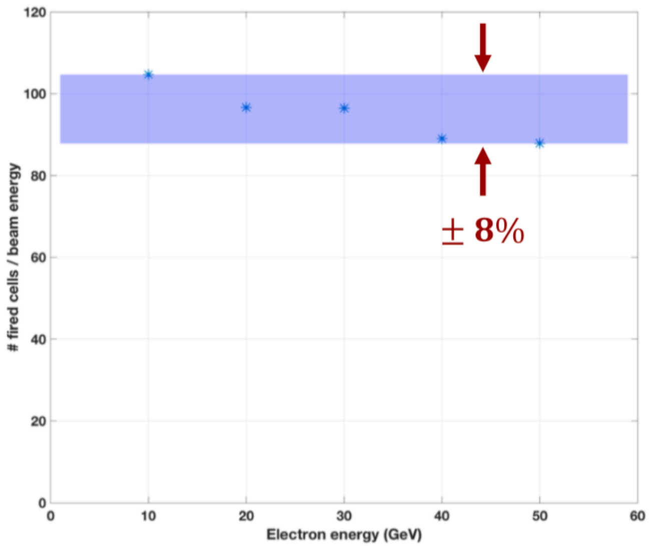


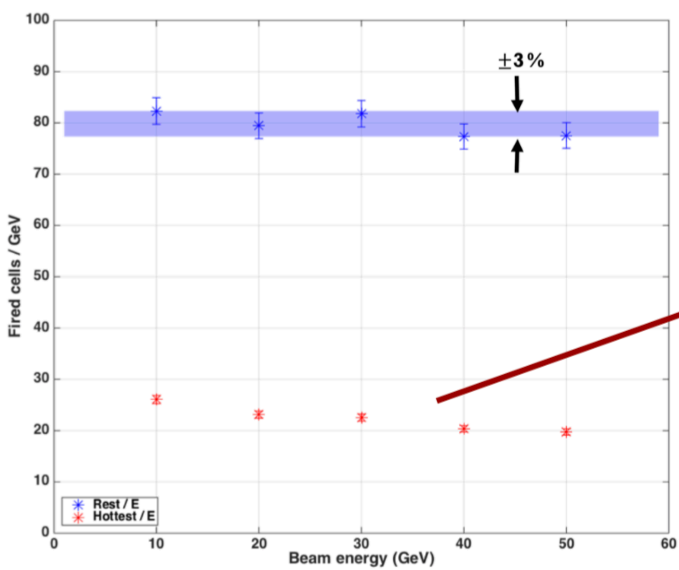
Even if the SiPMs are not saturated with this setting, they are working in a strongly non linear regime: a correction is required

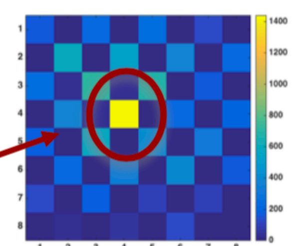
Valid as a first approximation: the light uniformly illuminate the SiPMs, all photons come at the same time and spurious effects are negligible

Scintillation light

Results from 2017 test beam







- Detector operated at 0.5V over breakdown (PDE ≈ 2%)
- Temperature stability correction:
  - < 0.5°C during a single run (negligible)
  - < 2°C during the full scan (considered)
- PDE correction for temperature variation

Once the correction is applied, the linearity is improved even if it is not fully recovered

(i.e. signal from the seed)

To reduce this effect we decided to attenuate the scintillating light using a yellow filter

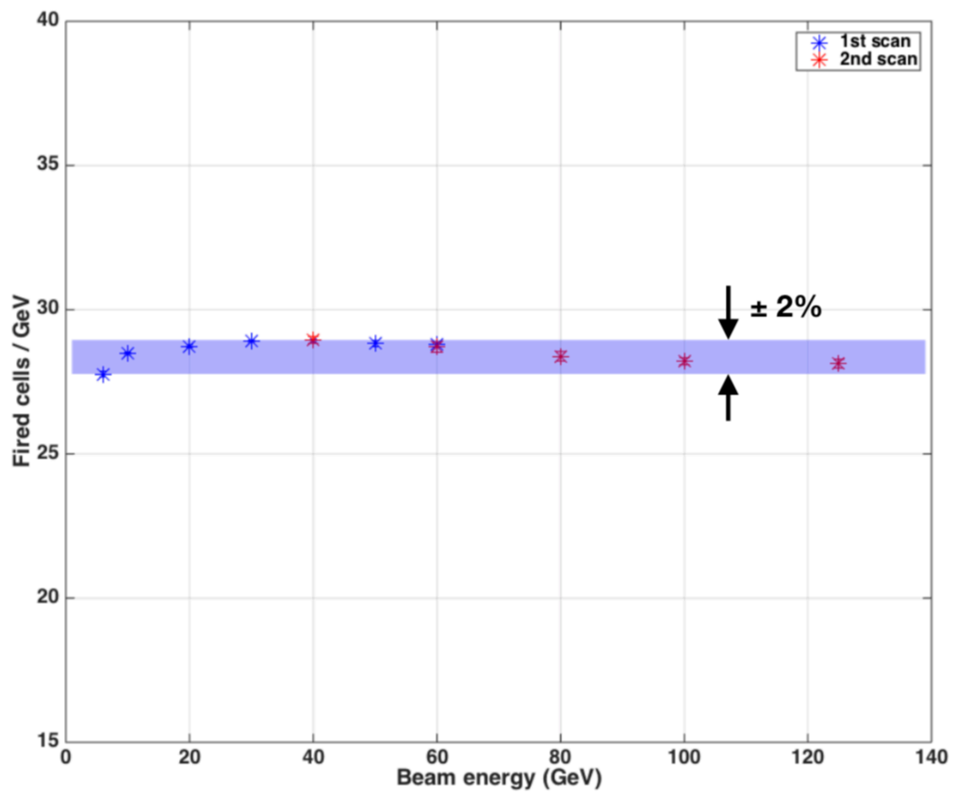
Cherenkov light

Cherenkov light yield:

V_{Bias} = 5.5 V_{ov} (57.5 V) and ***PDE ~ 25%.***

~ 28.6 Cpe/GeV, 2% linear from 6 to 125 GeV.

Correcting for 36% e.m. energy containment: ~ ***69 ± 5 Cpe/GeV.***



More than ***2 times larger*** than what measured with the previous* PMT-based modules.

Example:

Stochastic term of RD-52 e.m. resolution could be improved from ~14%/√E up to ~***12.5%/√E***.

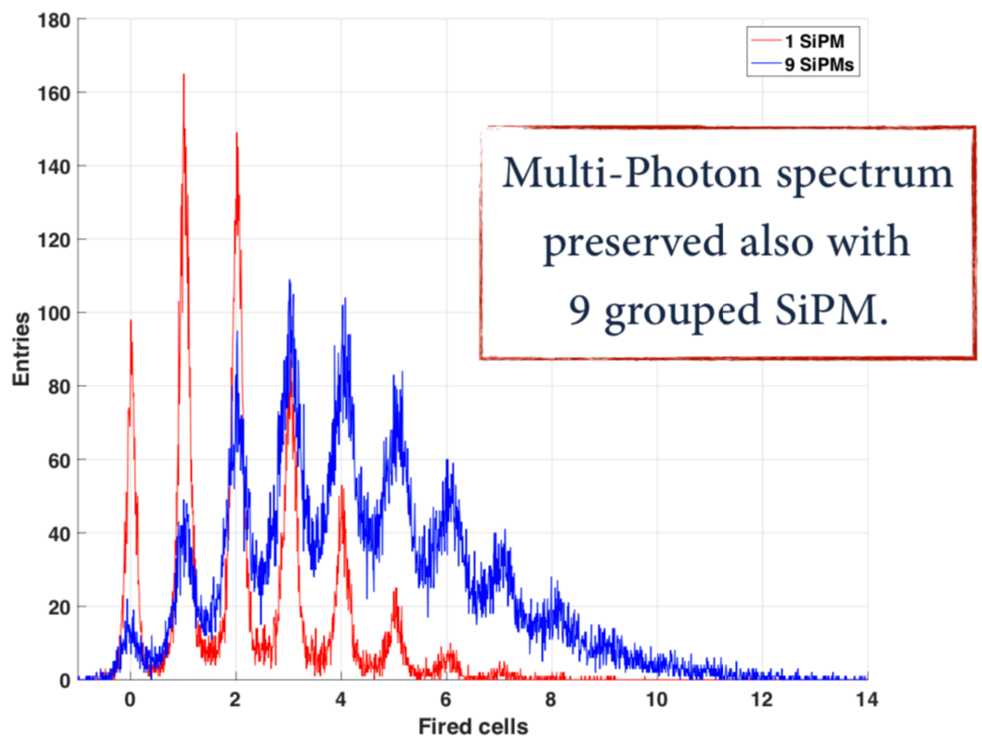
(sampling fluctuations: ~ 9%/√E).

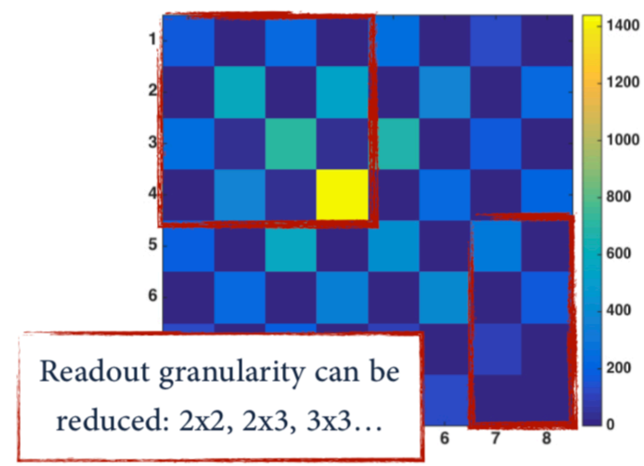
Grouping channels

In a full scale module, the number of ***readout channels*** will be of the order of ***10^8***.

The possibility to **sum up the analog output** is under study:

- Number of SiPM that can be grouped guarantying the ***Multi-Photon spectrum***.
- SiPM *dynamic range*: sensors have to operate in a ***linear regime***.





SiPM number	1	4	8
Space granularity (mm²)	4.5	18	36

Outline

- Why dual readout?
- Towards a combined detector: IDEA test beam
  - Combined data taking with old prototypes
  - SiPM readout
  - Longitudinal segmentation
- Summary

EM showers: relevant numbers

- Radiation length X_0: typical scale of longitudinal shower development

$$X_0 \sim 1433 \frac{A}{Z(Z+1)(11.32 - \ln Z)} \left(\frac{\mathrm{g}}{\mathrm{cm}^2}\right) \implies \sim \frac{1}{Z}$$

- Critical energy E_C (below which ionisation takes over bremsstrahlung)

$$E_C \sim \frac{160\ \mathrm{MeV}}{(Z+1.24)} \implies \sim \frac{1}{Z}$$

- Moliére radius R_M (typical scale of lateral shower development)

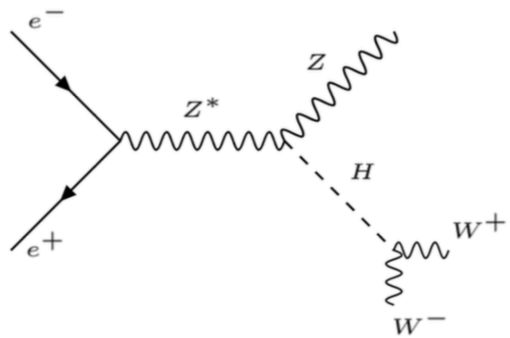
$$R_M \sim \frac{X_0 \times 21.2\ \mathrm{MeV}}{E_C} \implies \sim const$$

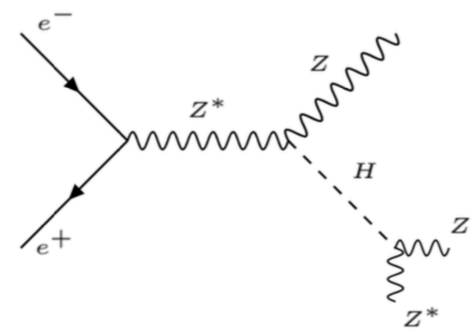
- Shower depth (shower maximum), where the multiplication process stops

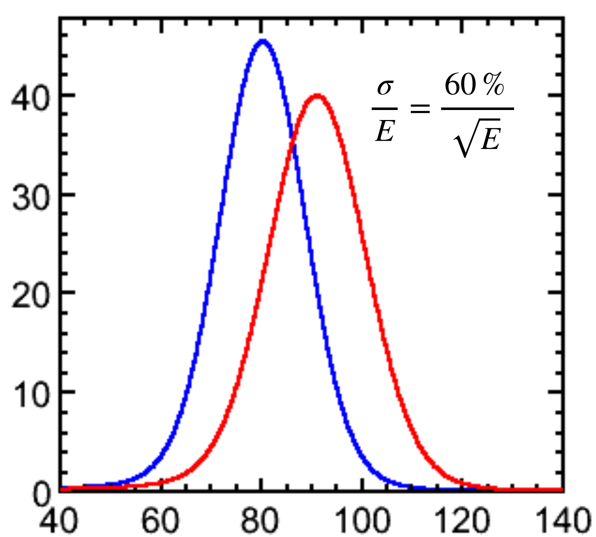
$$X_{\max} = X_0 \frac{\ln\left(\frac{E}{E_C}\right)}{\ln 2} \implies \sim \frac{1}{Z}, \sim \ln E$$

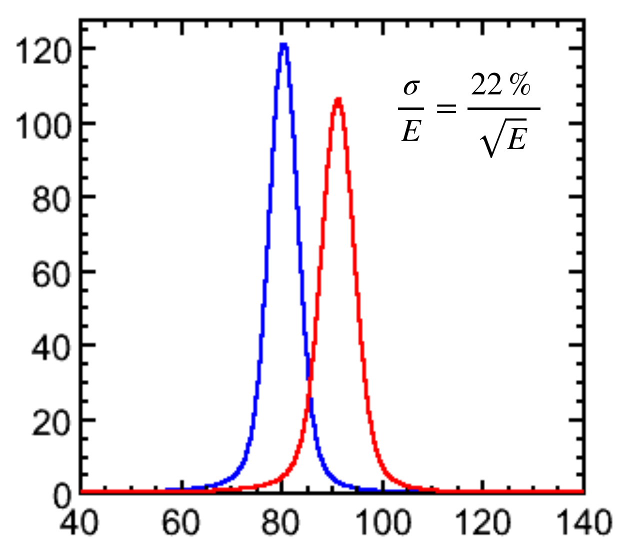
Reminder: why dual readout?

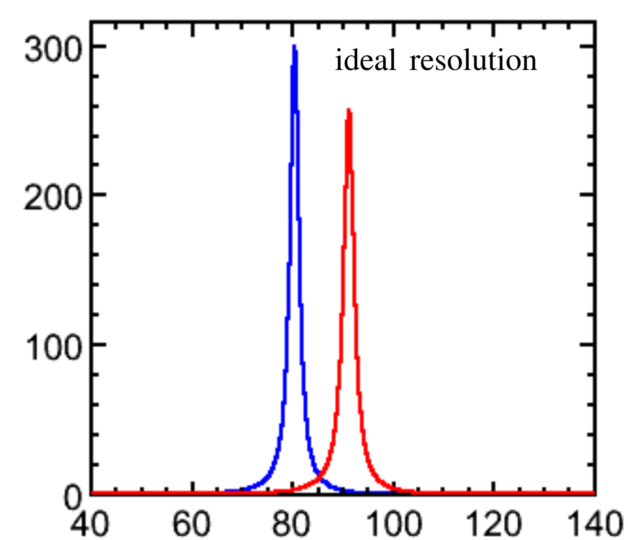
- Precision physics at e^+e^- collider calls for high-resolution hadronic calorimetry



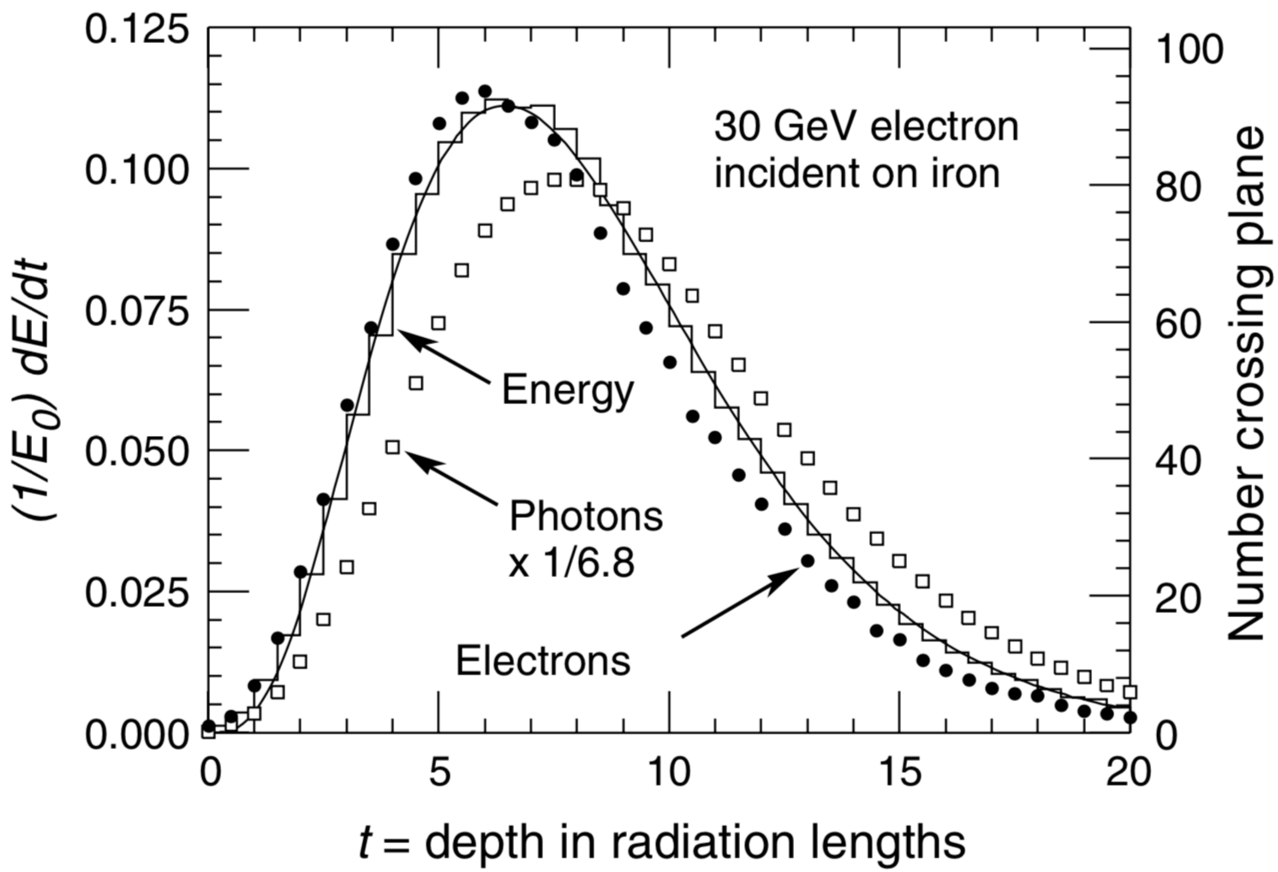








EM shower



- Large number of particles involved
- Regular shape
- Small event-by-event fluctuations

f_{em} energy dependence

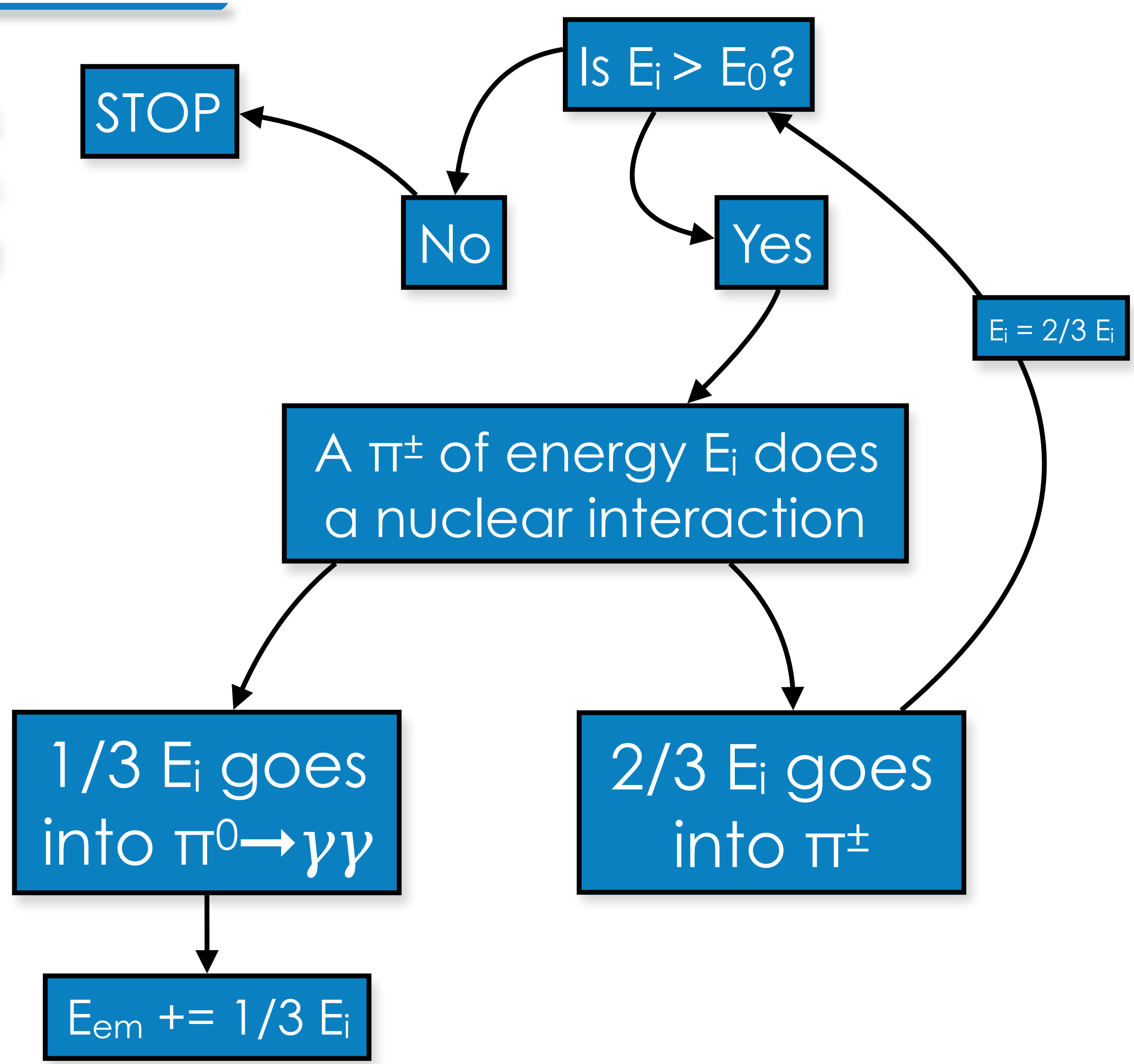
- Simple model: **only pions** are produced at each interaction, **respecting isospin symmetry**
- Then the math is:

$$f_{em} = \frac{E_{em}}{E} = 1 - \left(\frac{2}{3}\right)^n$$

$$\left(\frac{2}{3}\right)^n E = E_0$$

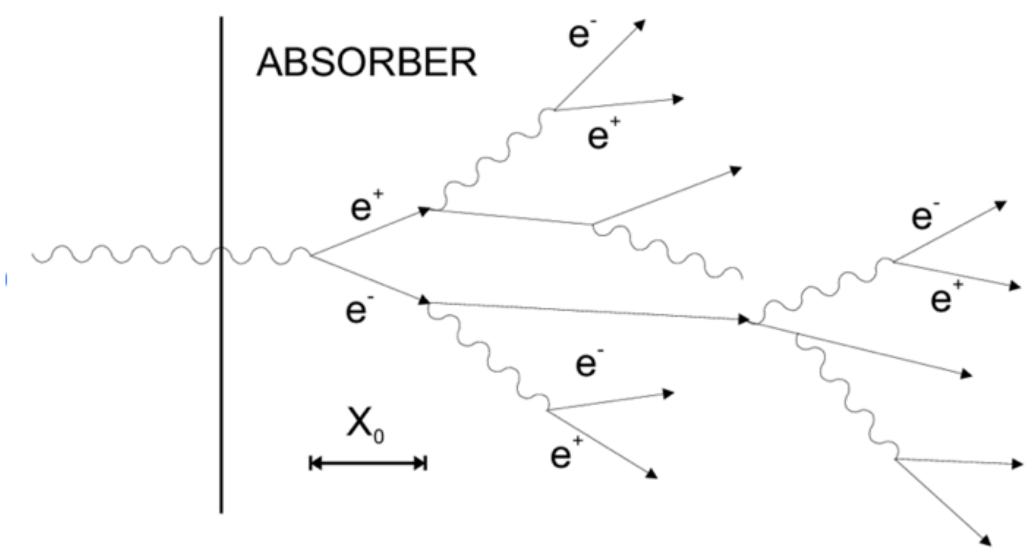
$$n = p \ln \frac{E}{E_0}$$ (for some number p)

$$f_{em} = 1 - \left(\left(\frac{2}{3}\right)^{\ln \frac{E}{E_0}}\right)^p = 1 - \left(\frac{E}{E_0}\right)^{k-1}$$ (for some number k)



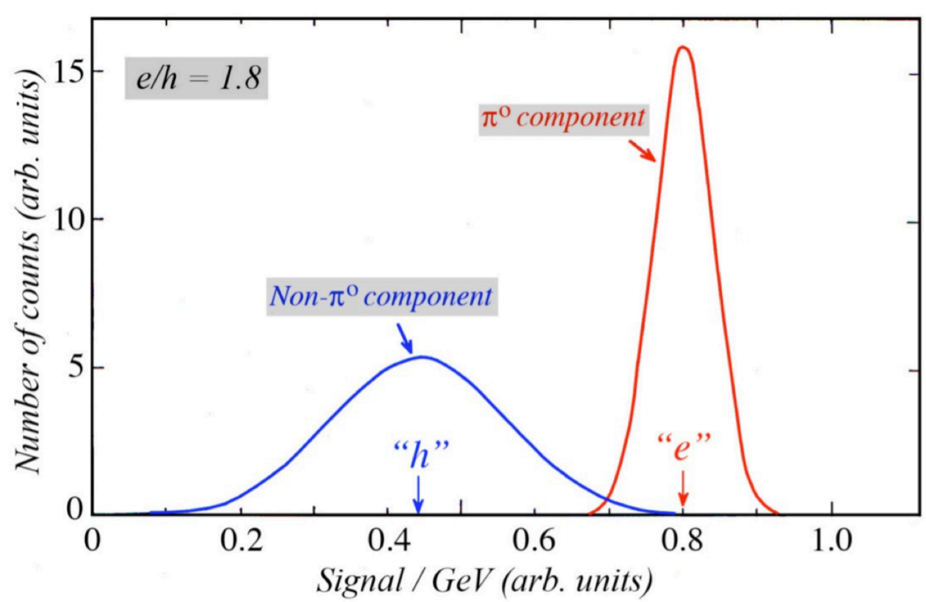
Calorimetry - a primer

- Electromagnetic shower:
  - Driven by **EM interactions with atom EM field**
  - **Moderate** intrinsic interaction intensity, but **big targets** (scale to bear in mind ~ 10^{-10} m)
  - Main mechanisms at work: **bremsstrahlung, pair production, ionisation**.
  - **Lots of particles** involved

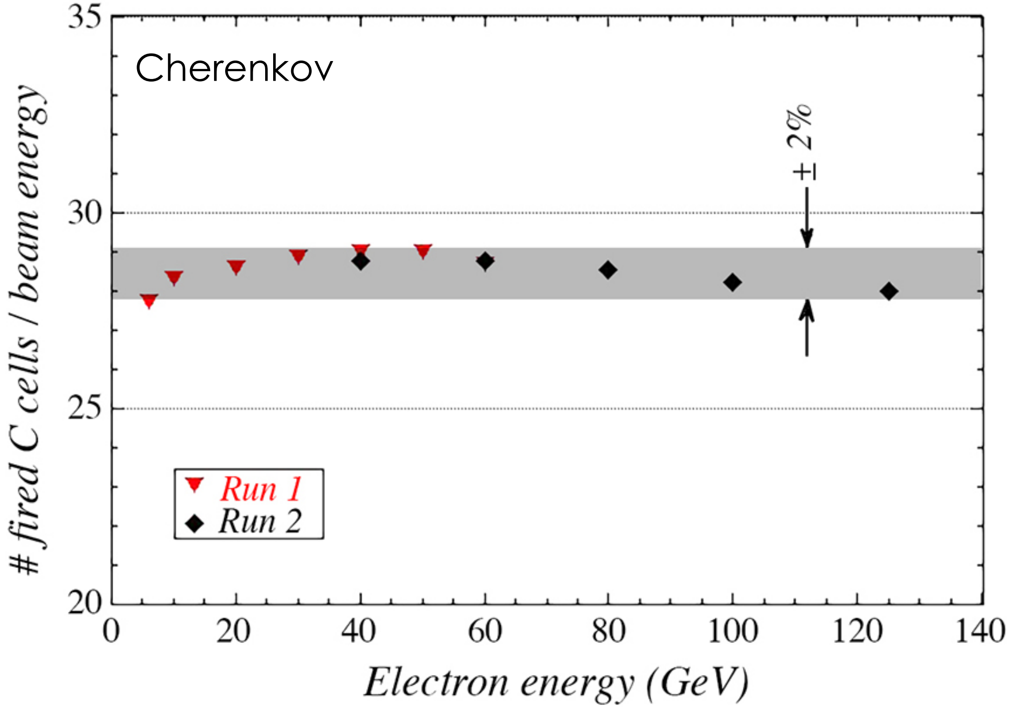


Measuring hadronic showers

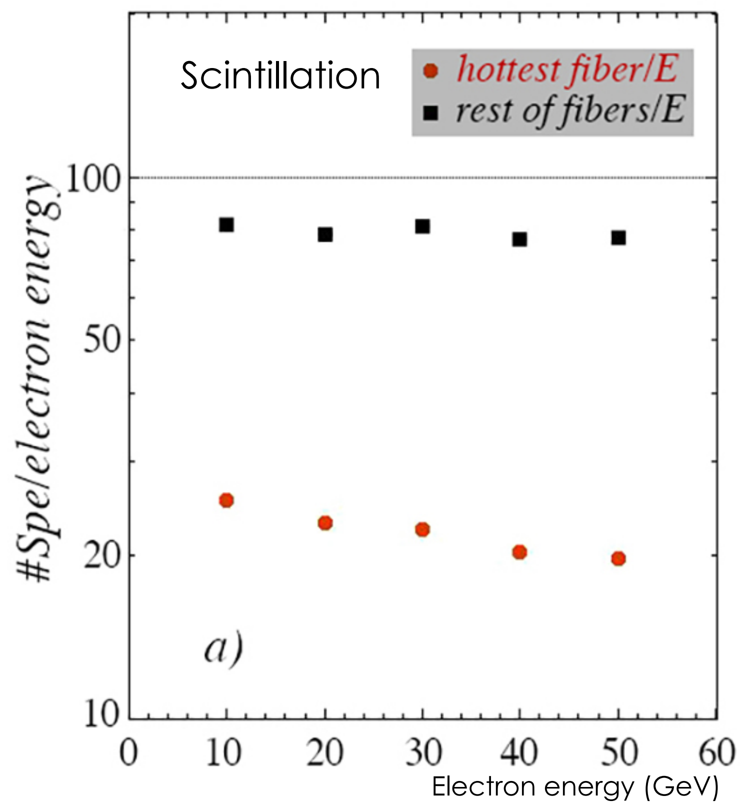
- Definitions:
  - **e** is the efficiency of the measurement of the **EM component**
  - **h** is the efficiency of the measurement of the **HAD component**
- e/h is a characteristic number **of the calorimeter**
  - Normally **e/h > 1** (mostly because of invisible component), and the calorimeter is said to be **non-compensating**.



SiPM readout - results (test beam 2017)

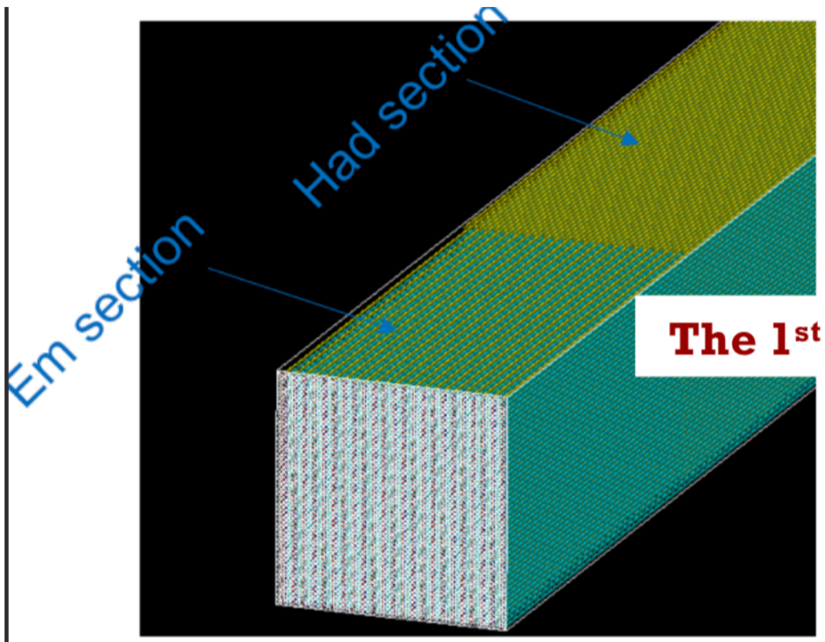


- Cherenkov light yield linear with beam energy over a wide range
- Light yield 28 Spe/GeV:
  - After correcting for containment ~ 55 Spe/GeV.
- Scintillation response showing evidence of saturation (addressed in 2018 test)



Calorimeter options used during TB

- **RD52 module** (combined data taking with other sub detectors)
- **SiPM-based** readout (standalone)
- **“Staggered"** module (standalone)



The 1st time on beam