Dual Readout Calorimetry

For future e^+e^- colliders

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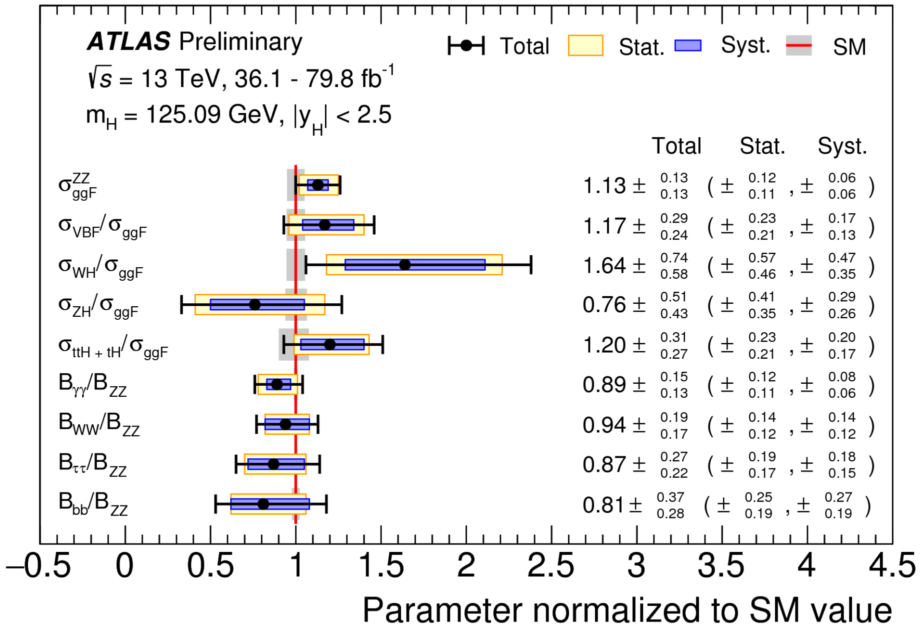
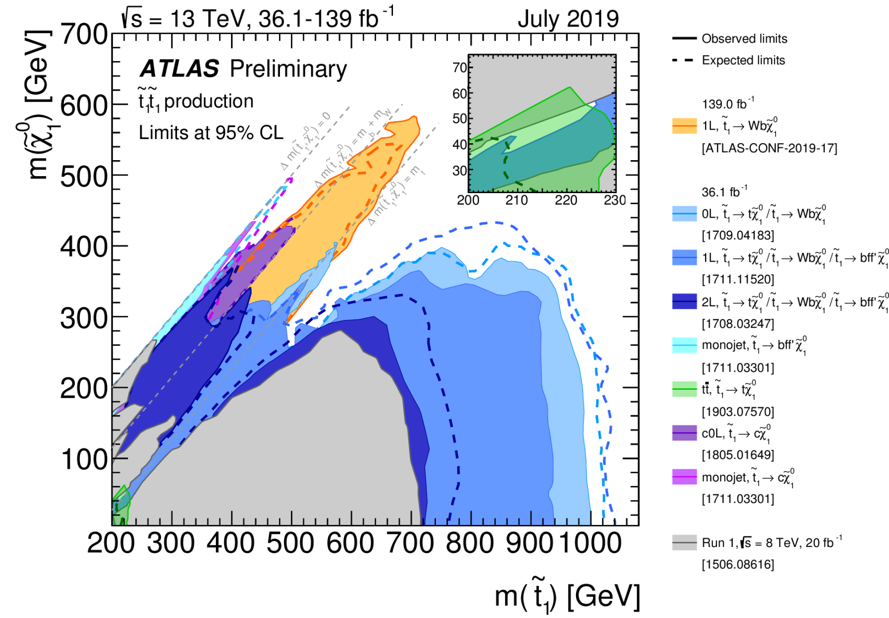
On behalf of IDEA detector group

Seminar - RAL - 23 October 2019

Particle physics in stalemate?





White to move

- We 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

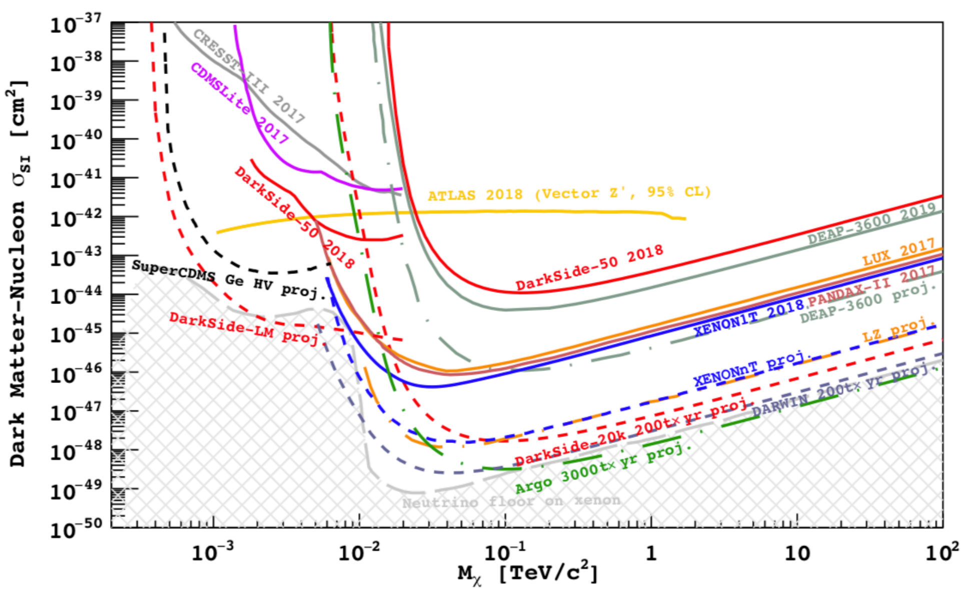
Put the Higgs under the microscope (a e^+e^- Higgs factory)

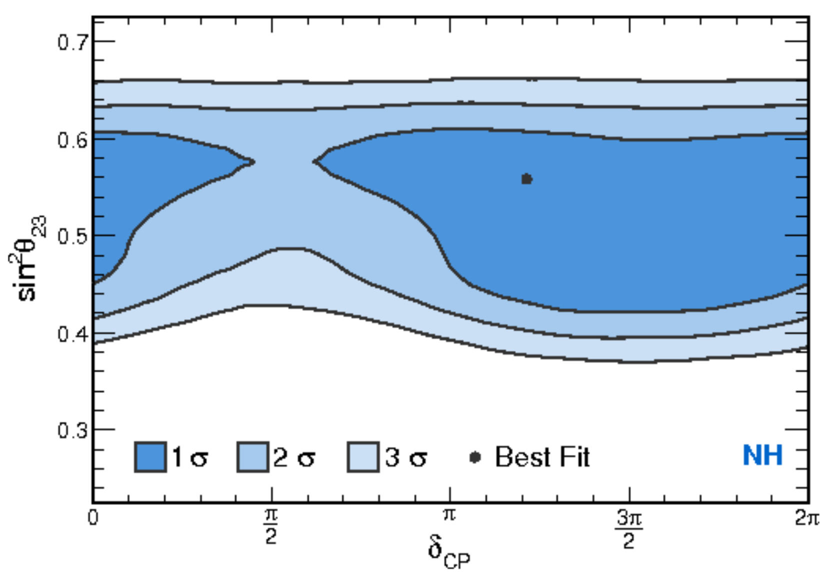
Not really…

- Next move of experimentalists is obvious

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

…while looking for BSM elsewhere



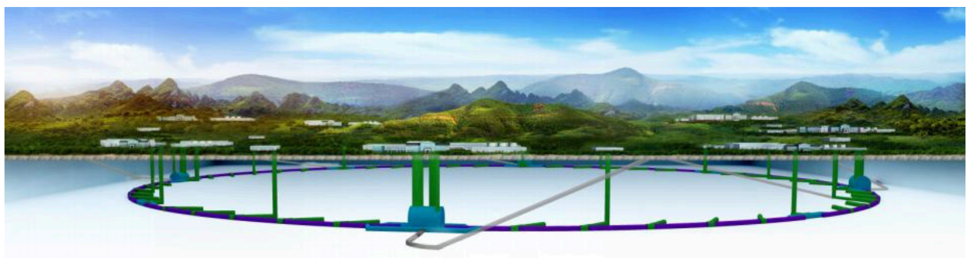


e^+e^- Higgs factories on the table

Circular	Linear

China

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

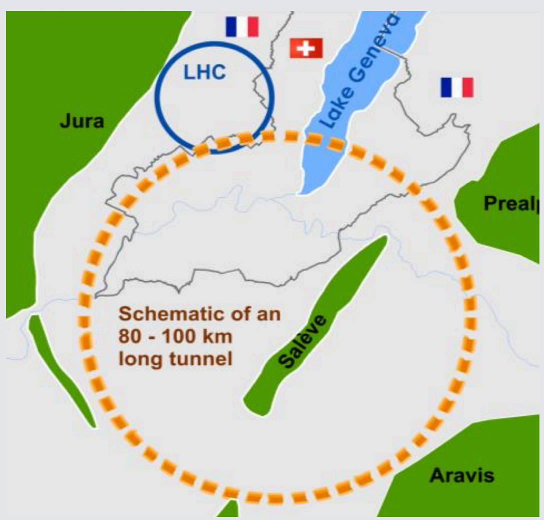


CERN

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

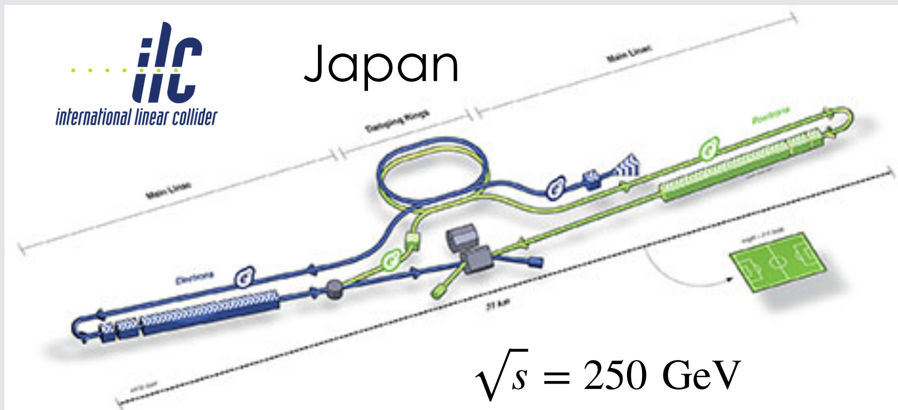
CERN

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



international linear collider

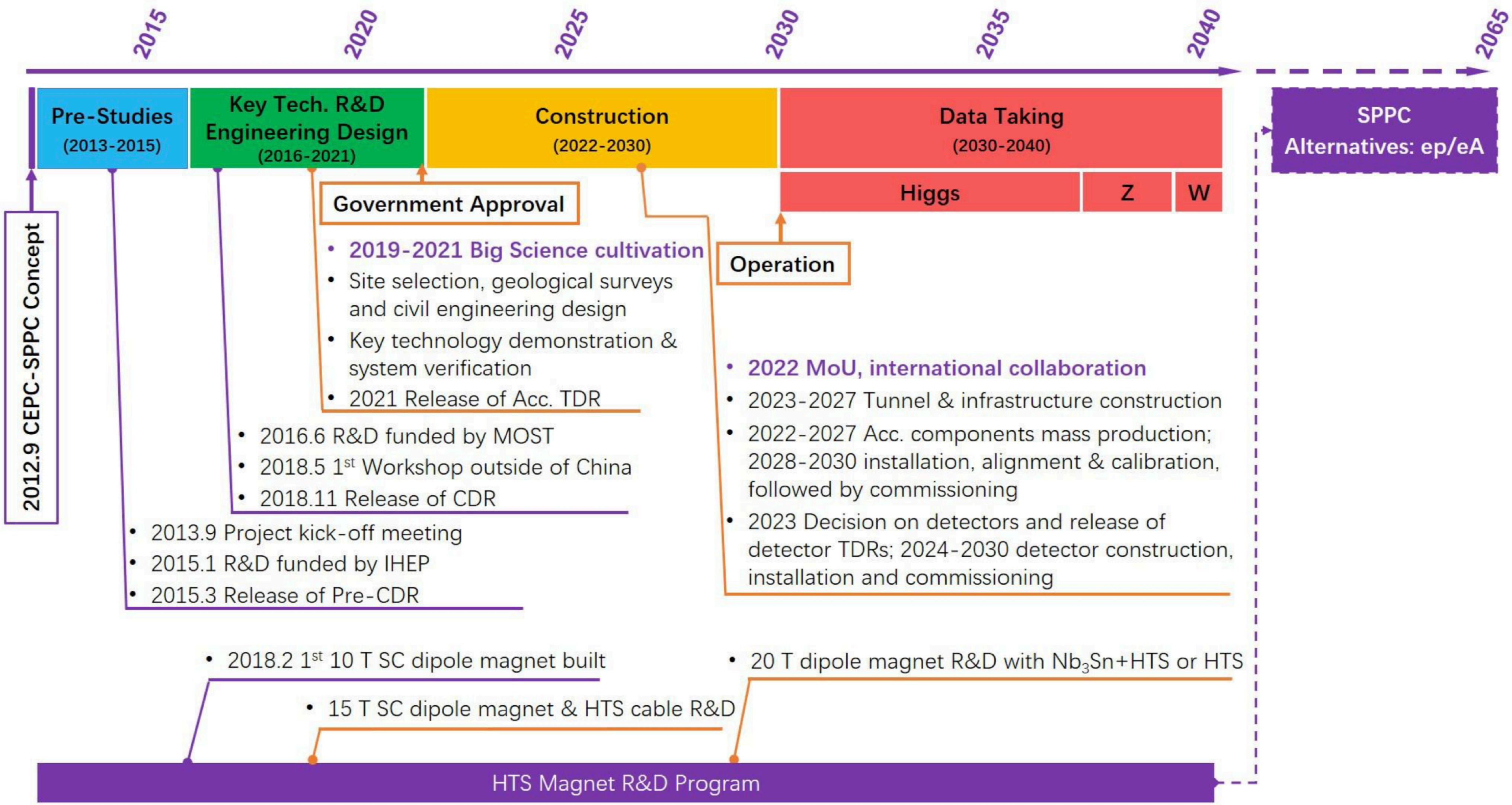
Japan



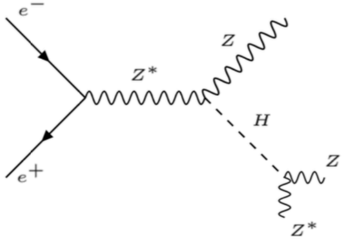
$\sqrt{s} = 250$ GeV

Far future?

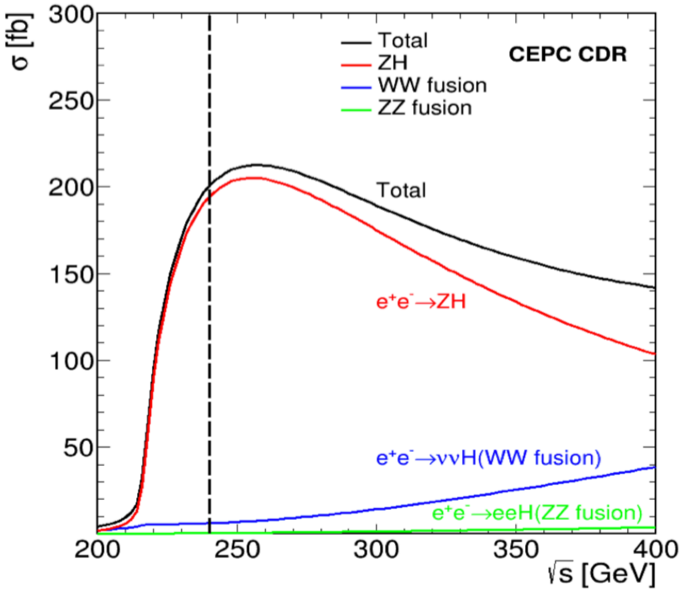
CEPC Project Timeline



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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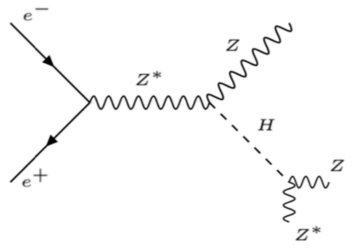

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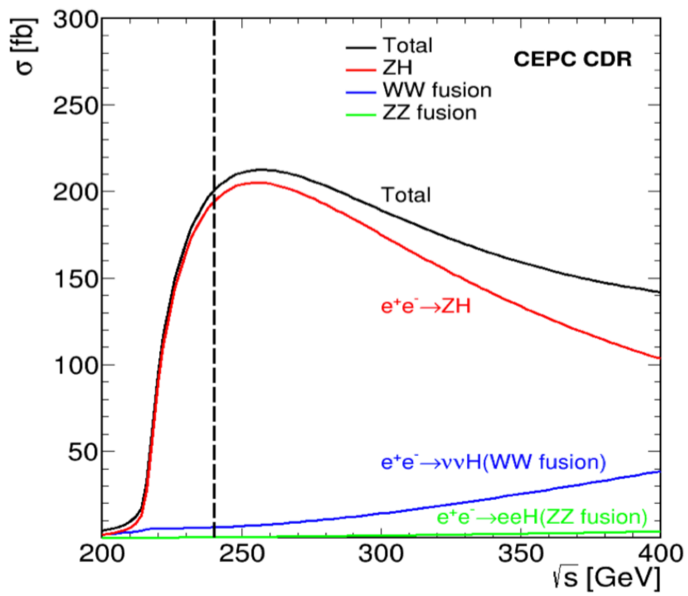
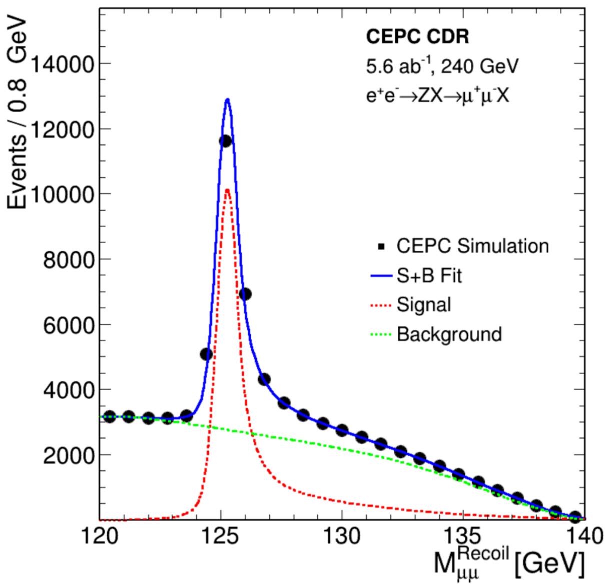
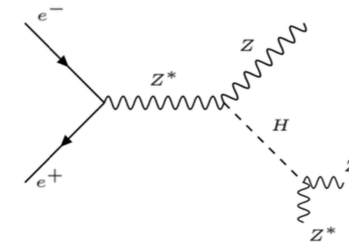
  - Higgs boson tagging gives **unique access** to $e^+e^- \rightarrow ZH$ production cross section





$$M_{\mu\mu}^{\mathrm{Recoil}} = \left(\sqrt{s} - E_{\mu\mu}\right)^2 - p_{\mu\mu}^2$$

e^+e^- at ZH threshold



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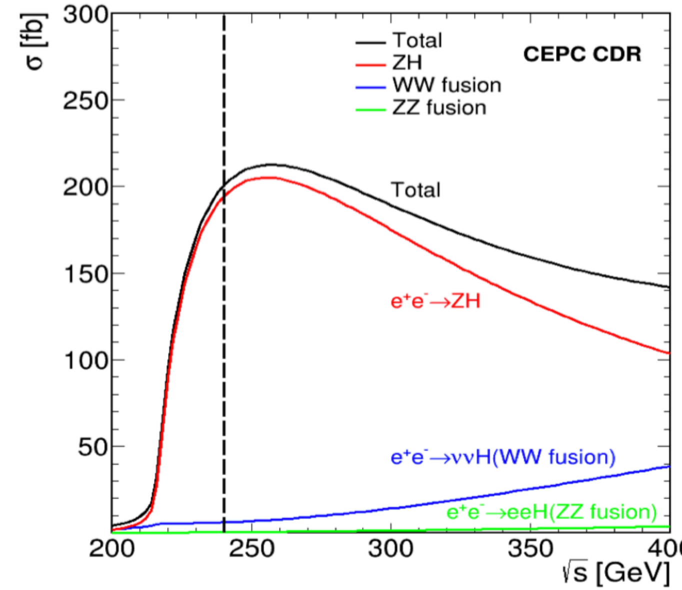

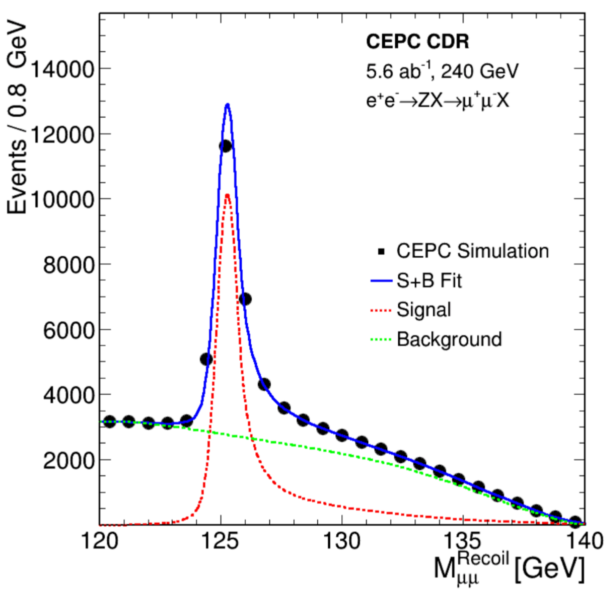

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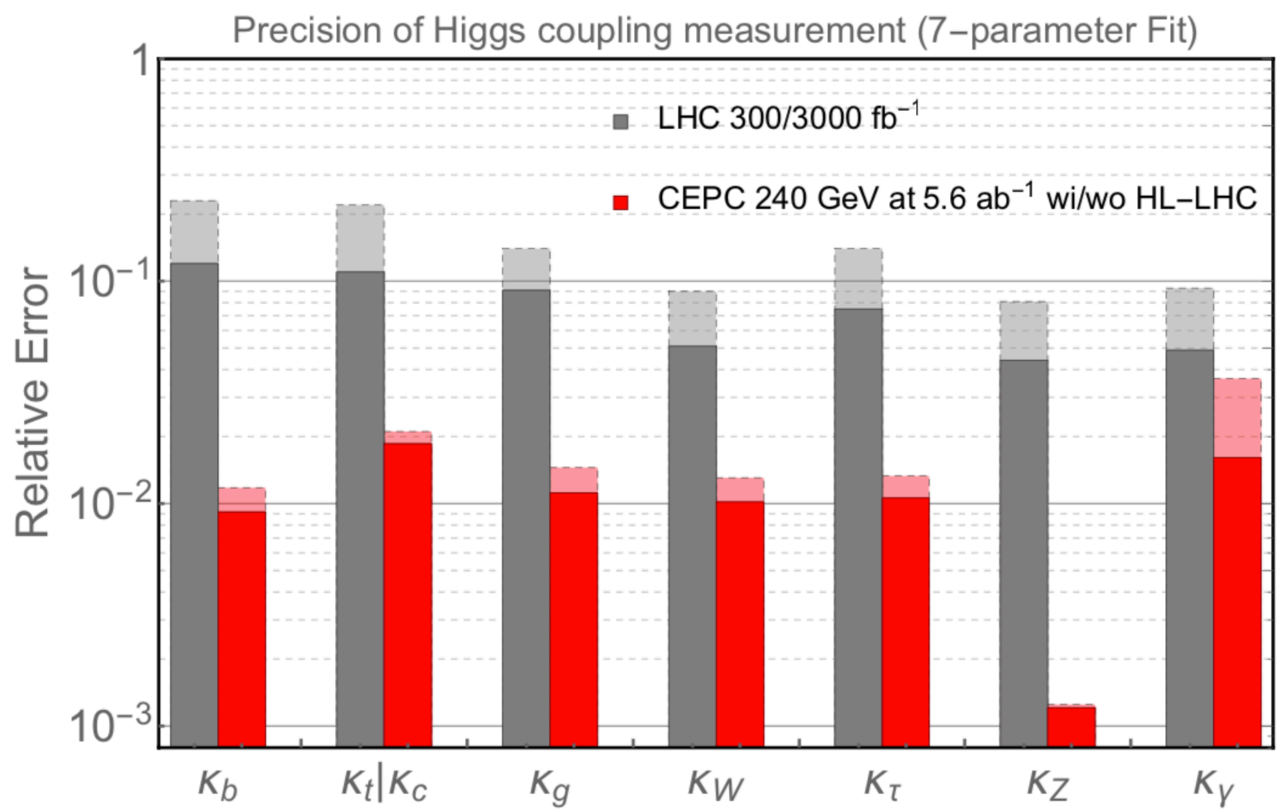
- 3% **model-independent** Higgs boson width measurement from

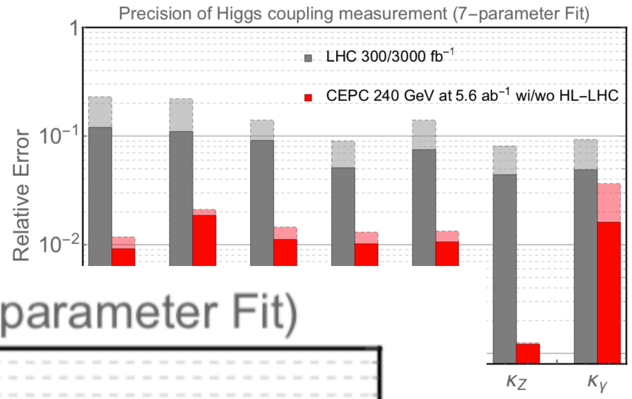
$$\Gamma_H = \frac{\Gamma(H \to ZZ^*)}{\text{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\text{BR}(H \to ZZ^*)}$$

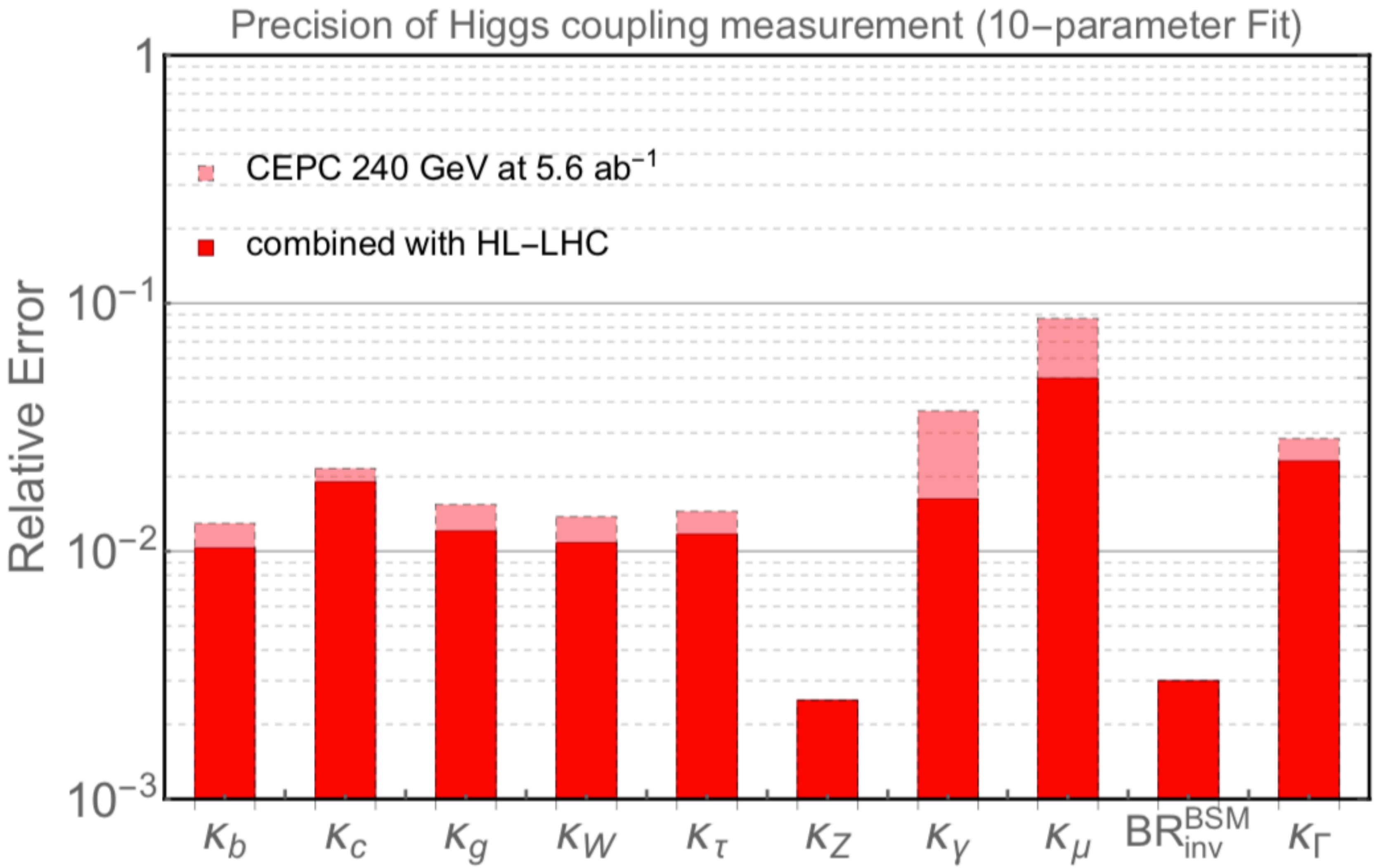
$$\Gamma_H = \frac{\Gamma(H \to b\bar{b})}{\text{BR}(H \to b\bar{b})} = \frac{\Gamma(H \to WW^*)}{\text{BR}(H \to WW^*)} \propto \frac{\sigma(\nu\bar{\nu}H)}{\text{BR}(H \to WW^*)}$$

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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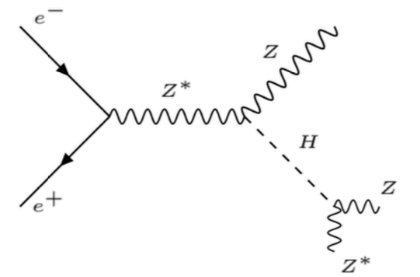

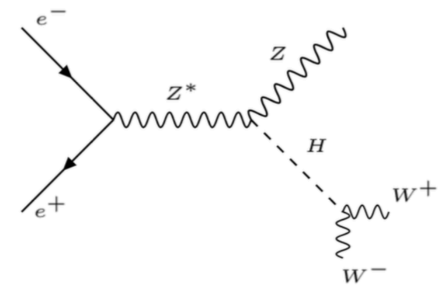

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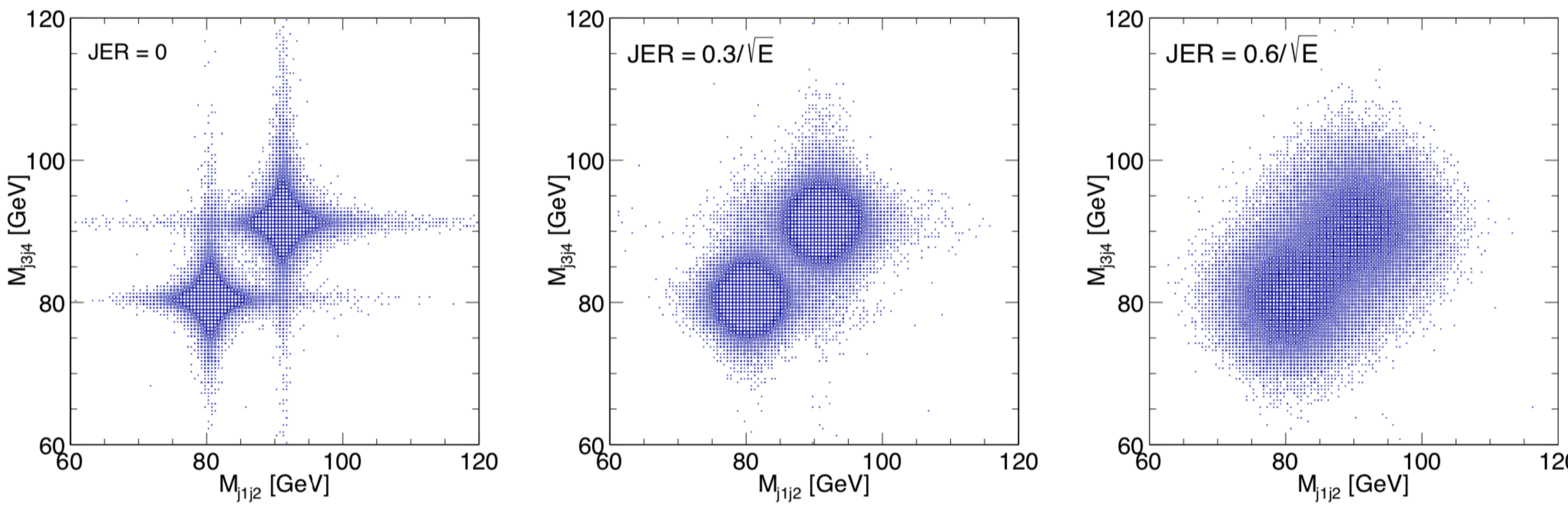
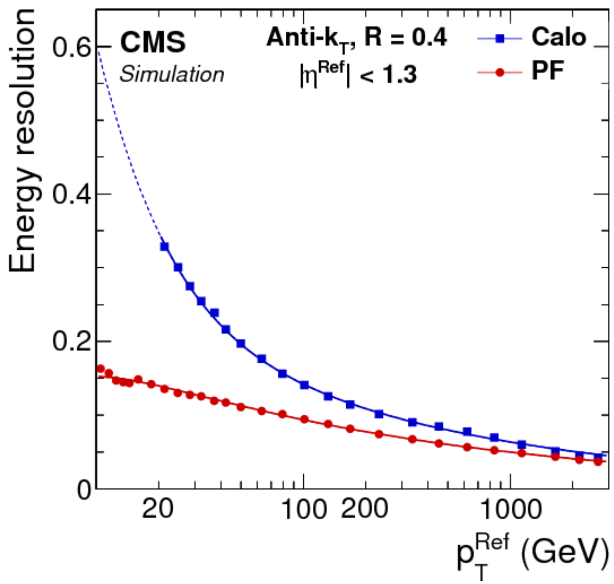


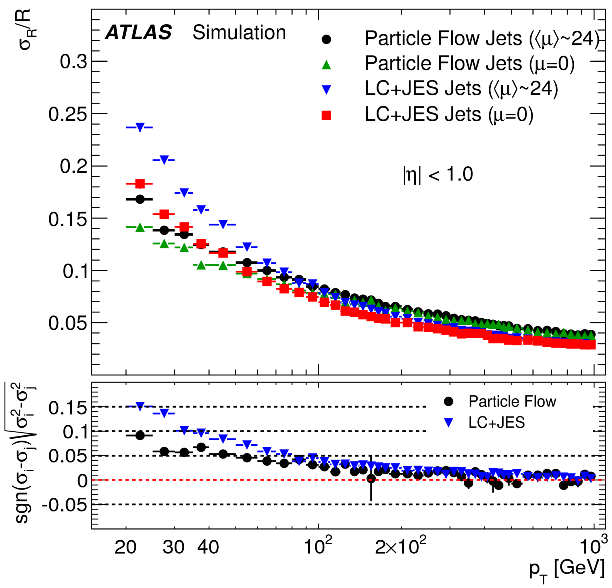
Particle flow approach

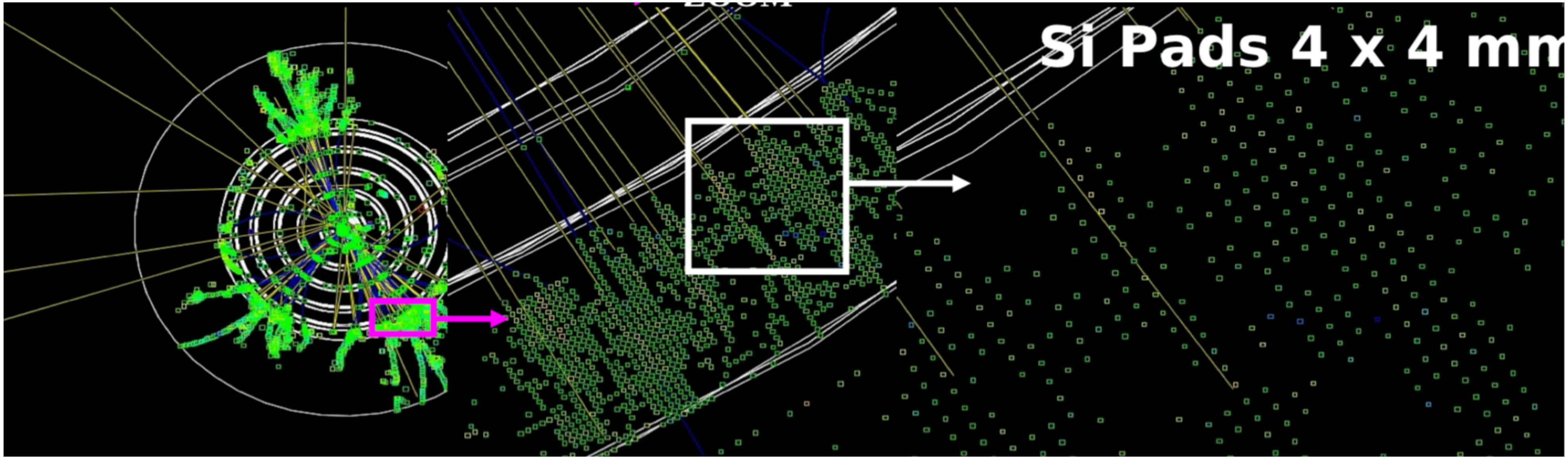
- Basic idea: tracking wins at low particle energy
  - Use **tracks** to measure **charged particles** in the shower

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

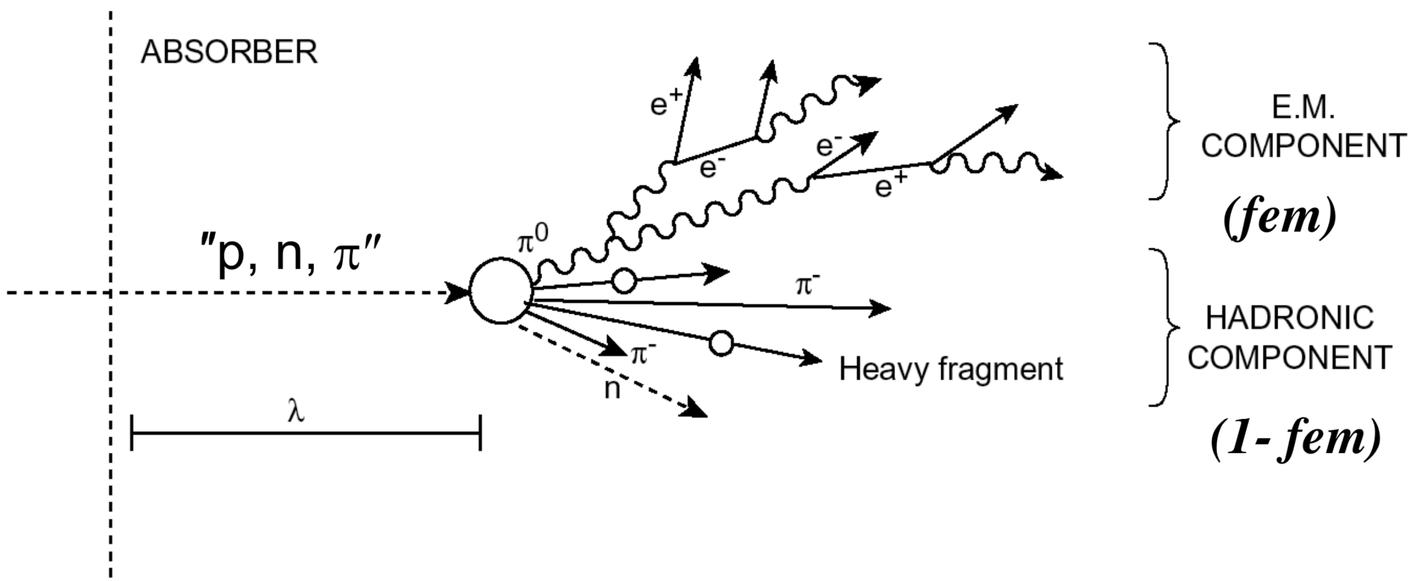
- Attacking the problem from **two sides** always gives opportunities to learn.
- Dual readout calorimetry:
  - Excellent **native electromagnetic and hadronic** calorimeter resolution.
  - Excellent lateral granularity.

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.**

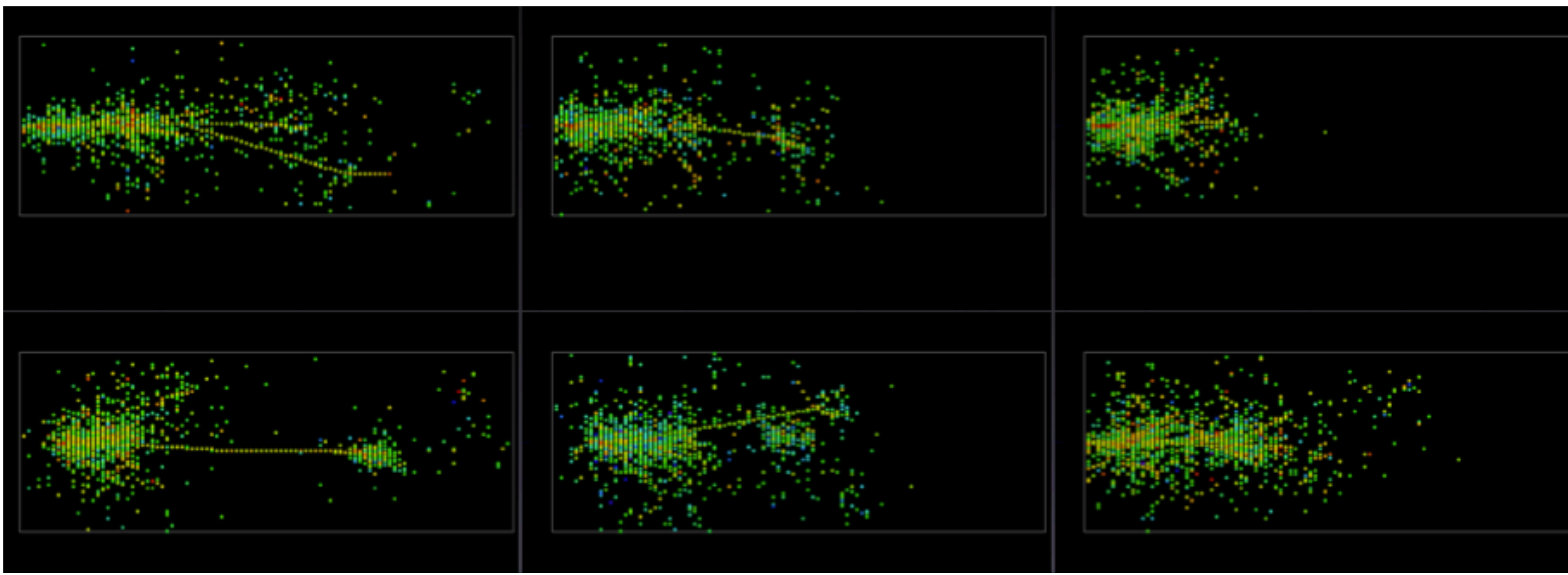


Hadronic showers

- 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

*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 and HAD components 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 **E_{in}=20 GeV** electrons and want to read **20 GeV**
  - Then you choose k such that

$$E_e = keE_{\rm in}$$

  - Then the **response to a hadron** of the same E_{in} is

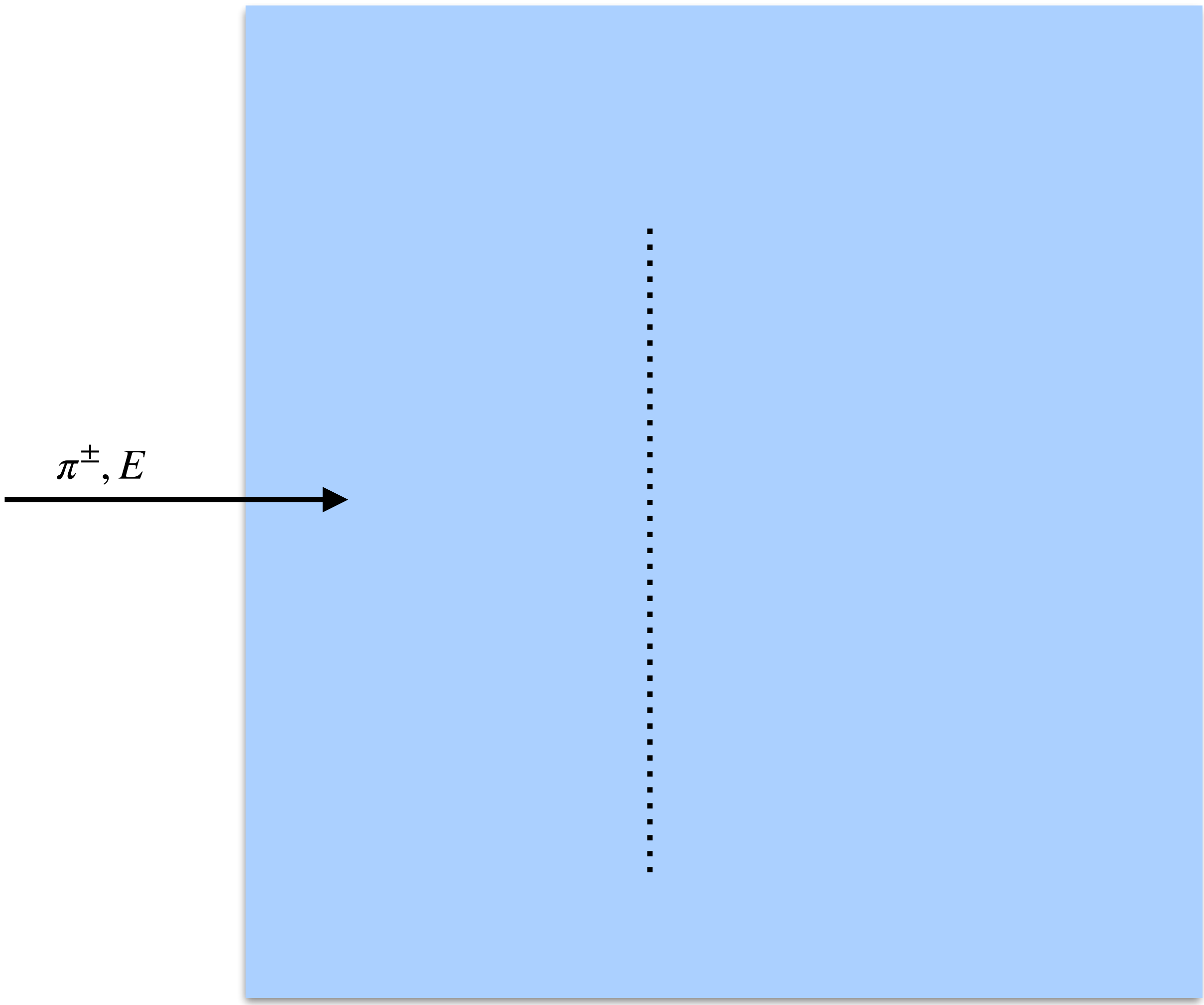
$$E_h = k(ef_{\rm em} + h(1 - f_{\rm em}))E_{\rm in}$$

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

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

f_{em} energy dependence

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



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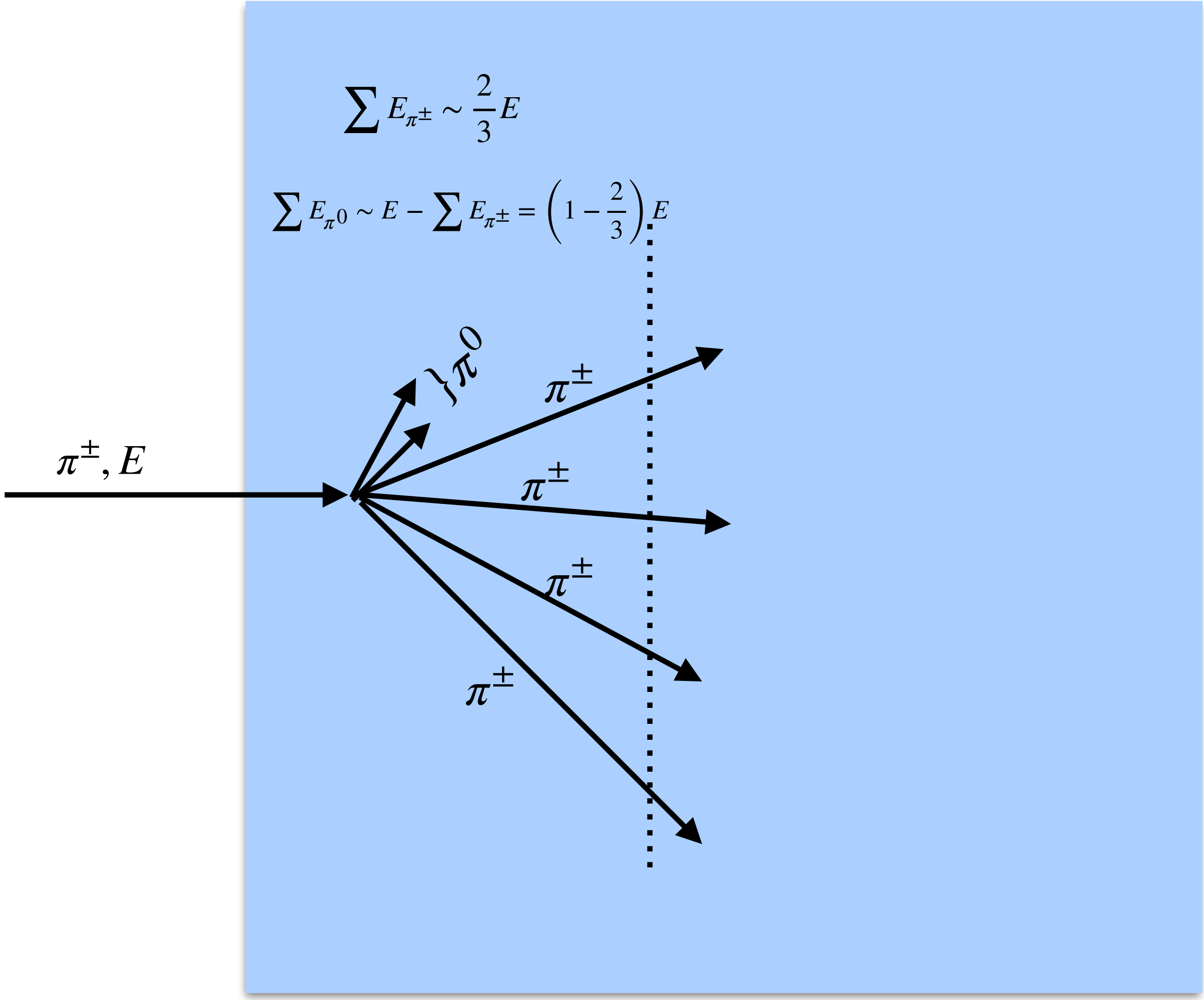

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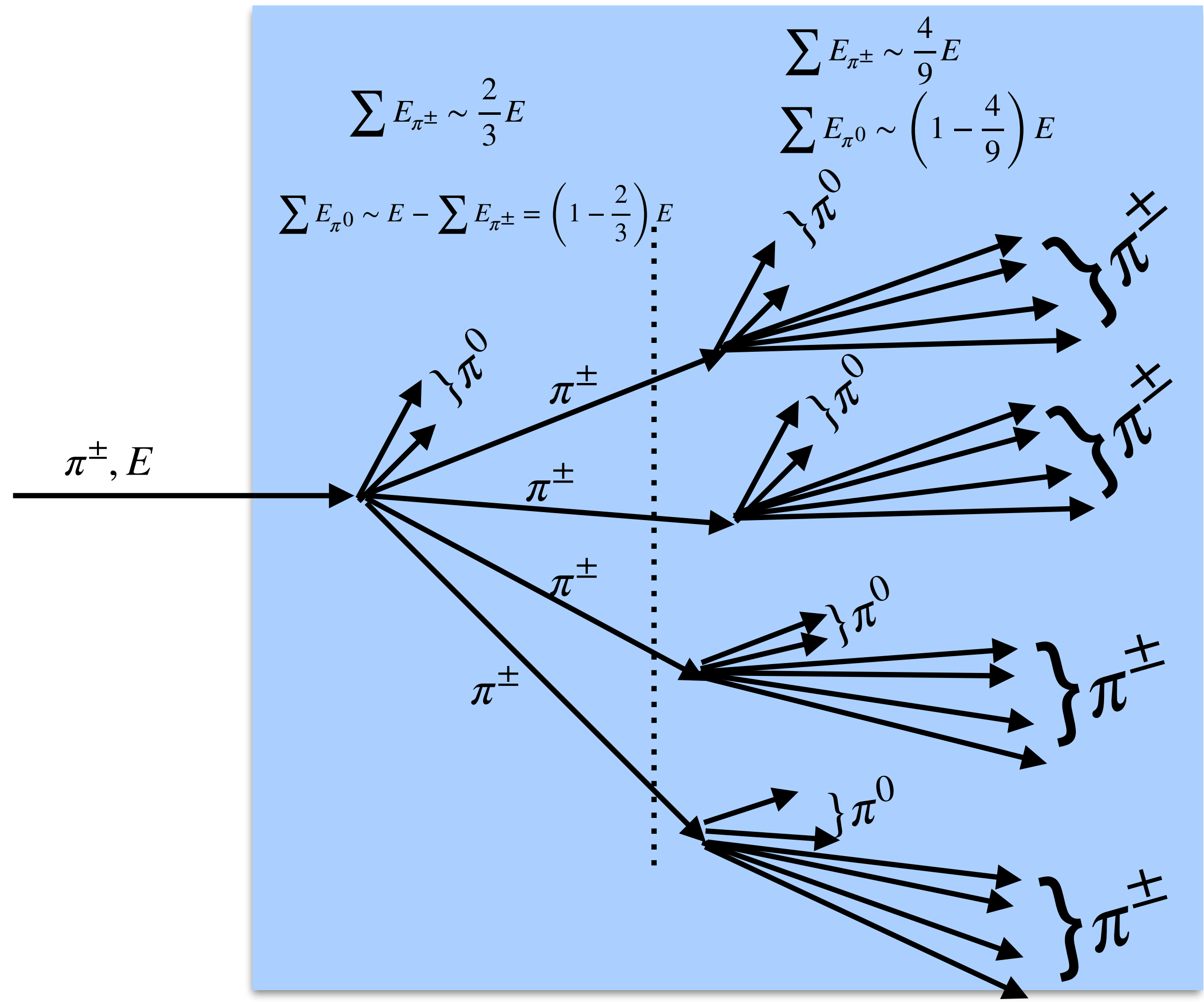

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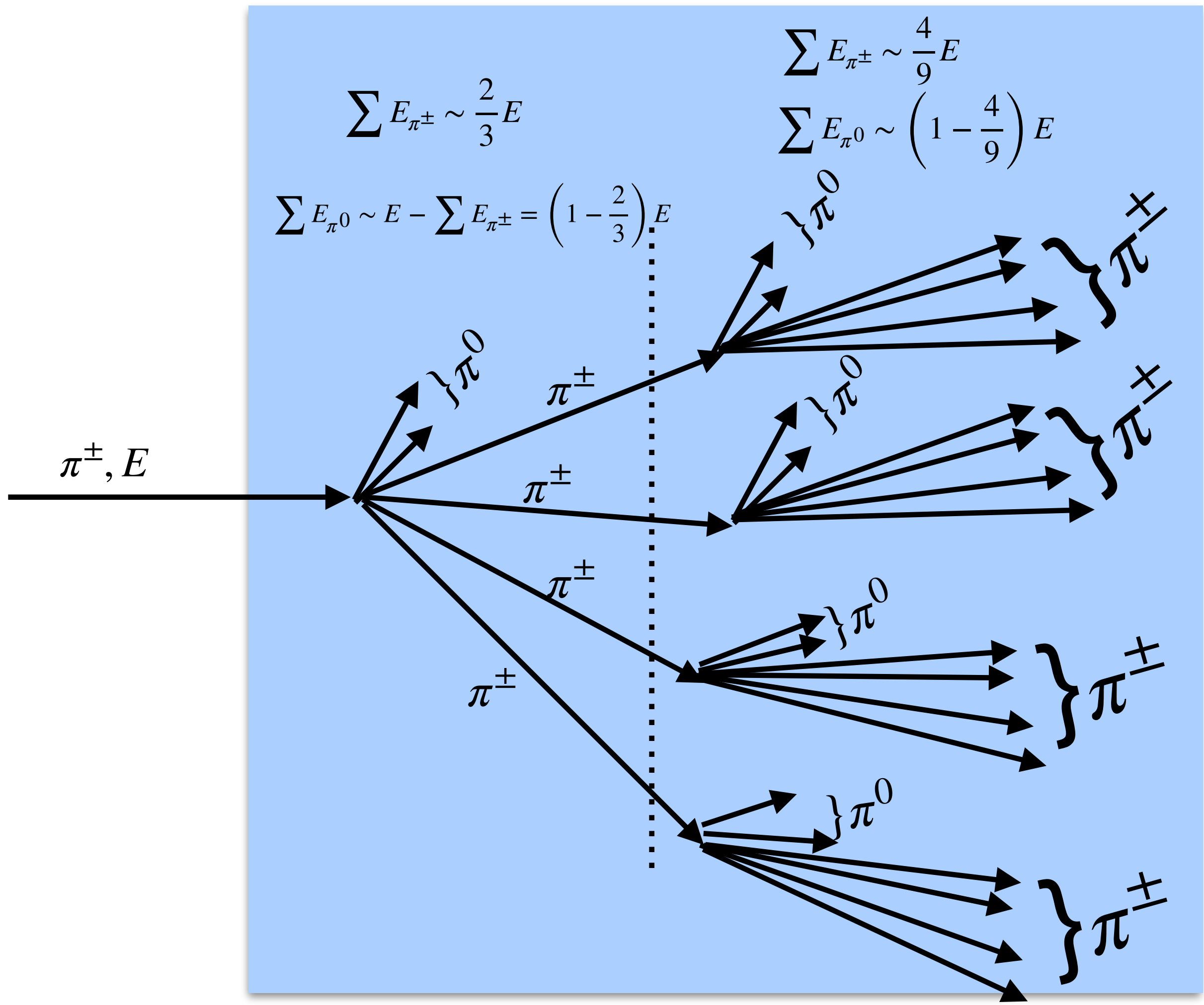
$$f_{\mathrm{em}} = \frac{E_{\mathrm{em}}}{E} = 1 - \left(\frac{2}{3}\right)^n$$



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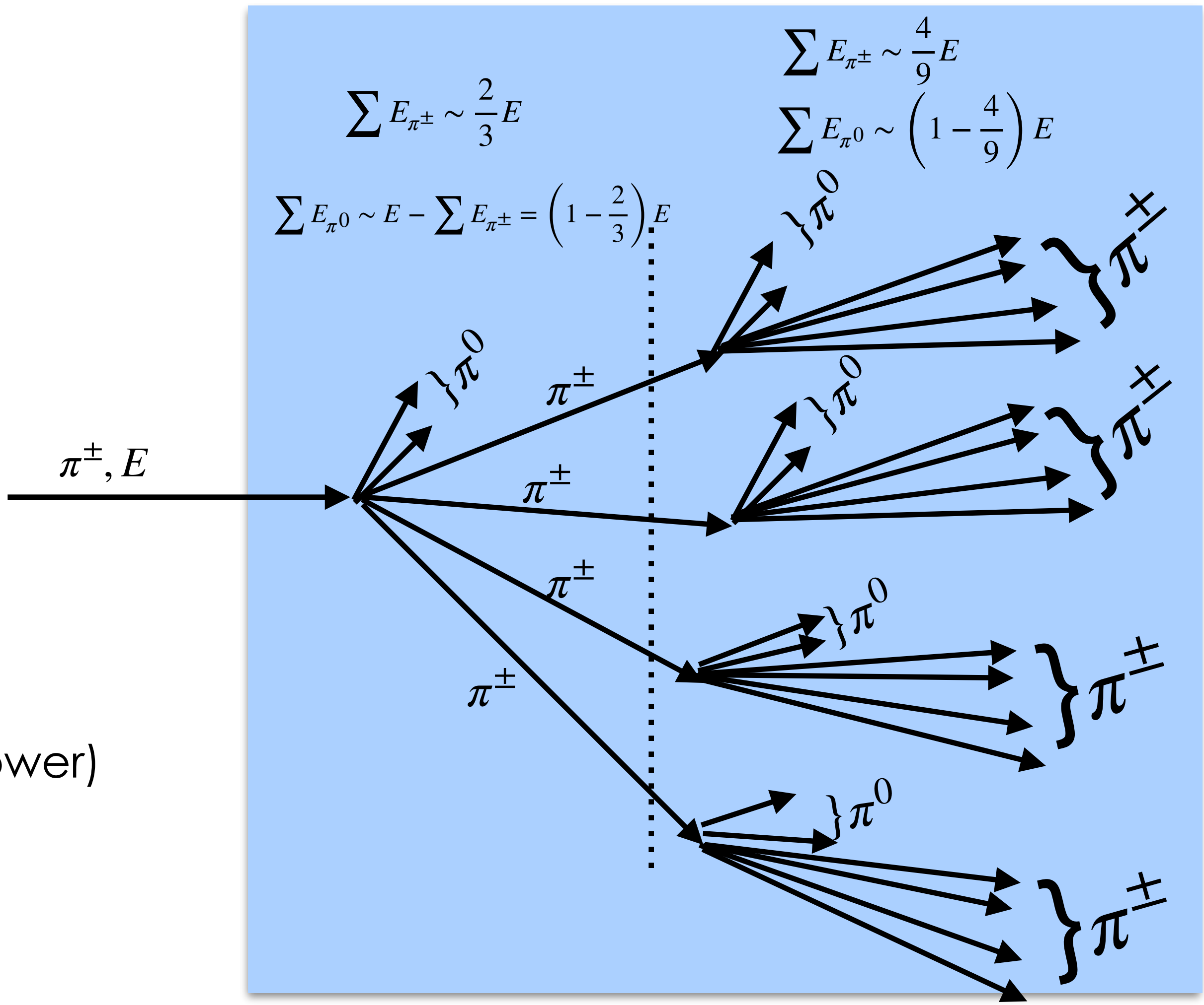
$$\left(\frac{2}{3}\right)^n E = E_{\rm th}$$ (Condition to stop shower)



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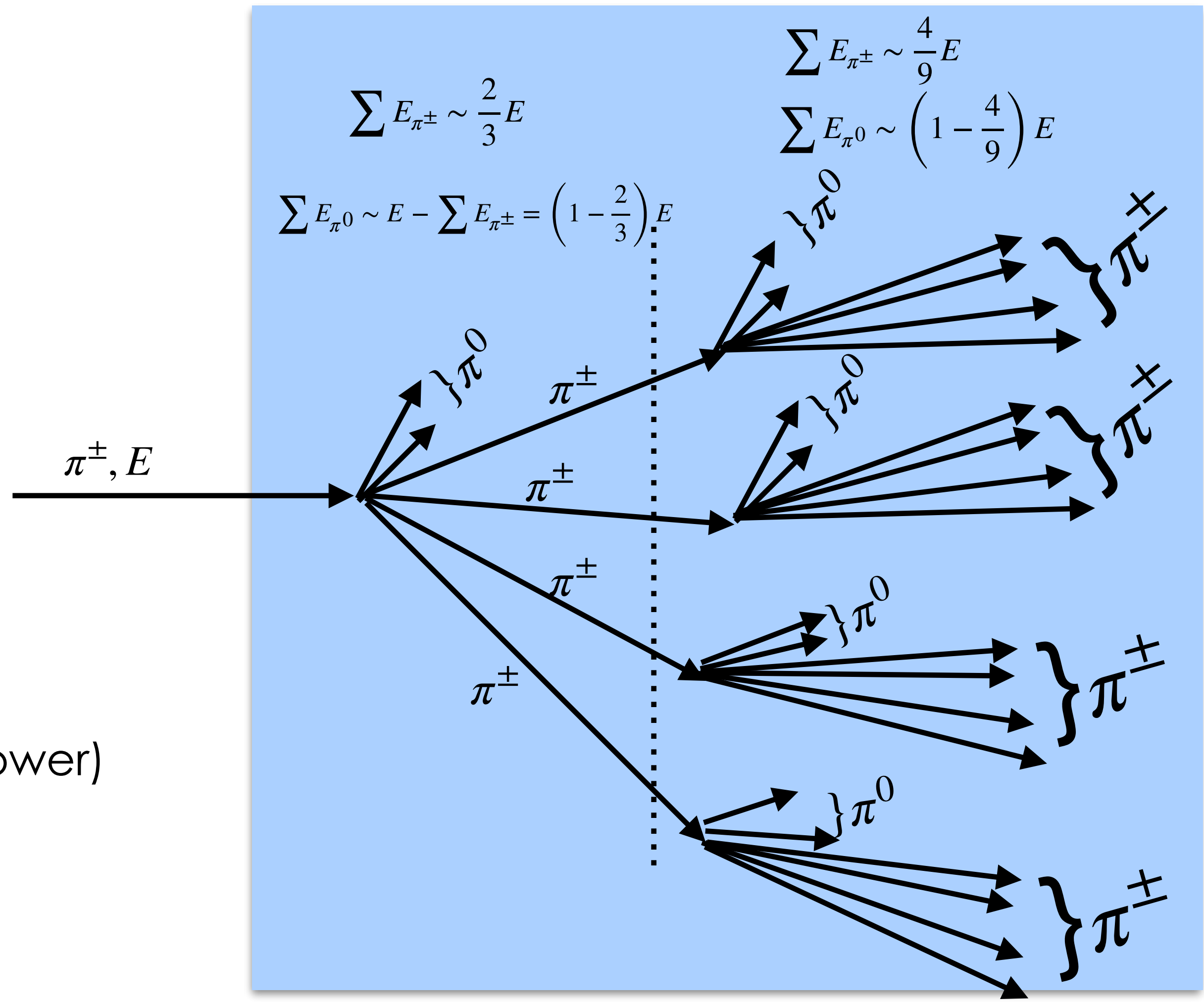
$$n = p \ln \frac{E}{E_{th}}$$ (for some number p)



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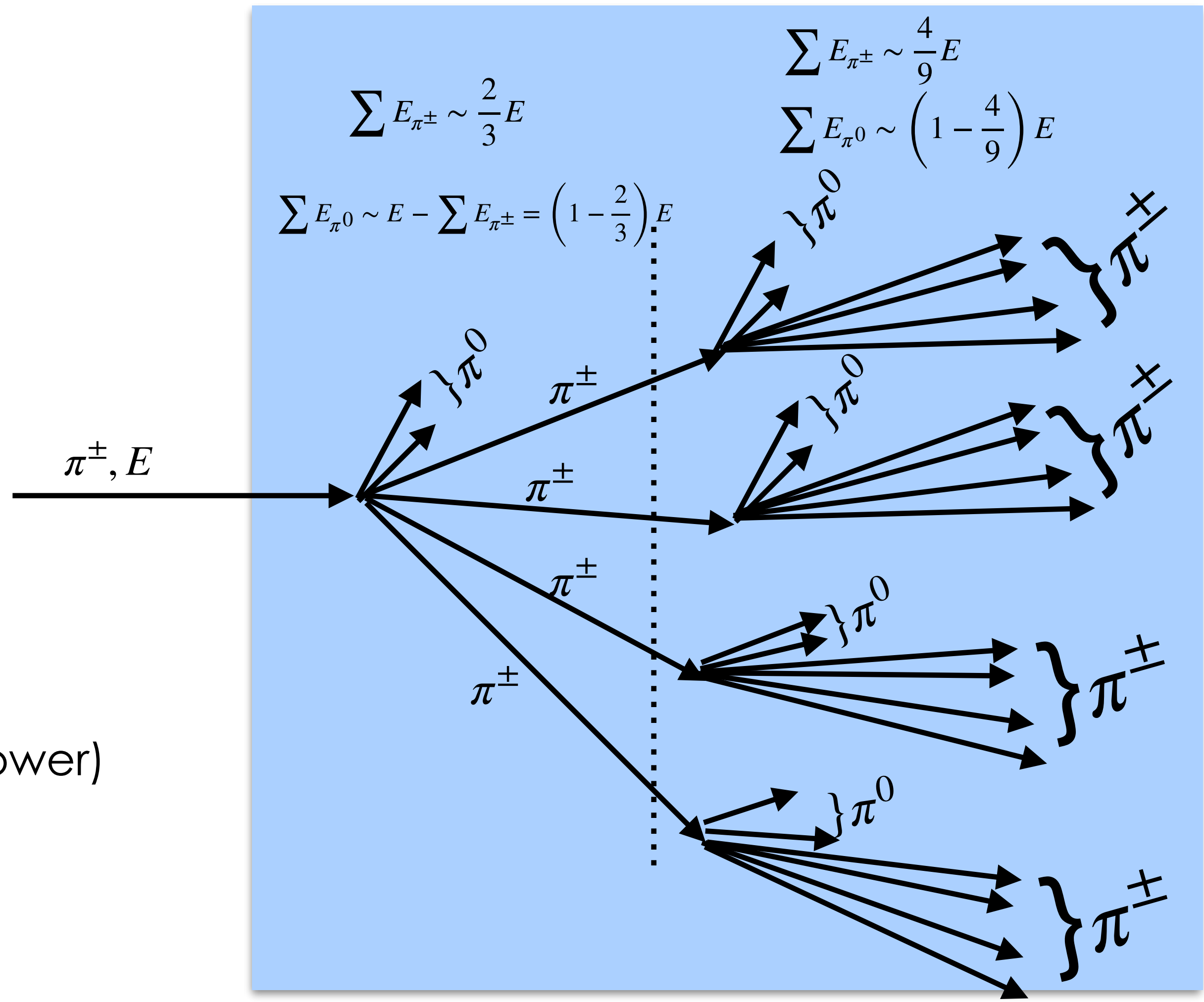
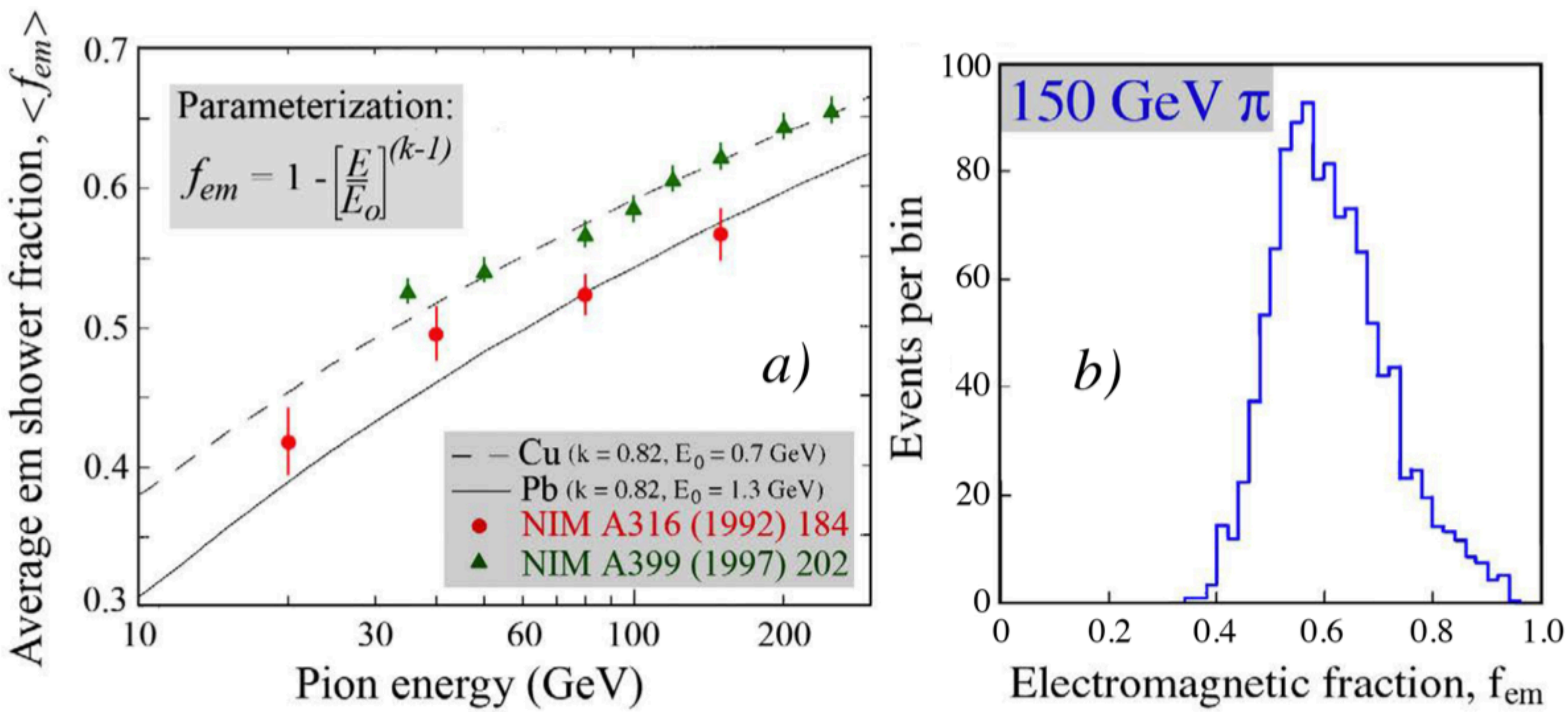
$$f_{em} = 1 - \left(\left(\frac{2}{3}\right)^{\ln \frac{E}{E_{th}}}\right)^p = 1 - \left(\frac{E}{E_{th}}\right)^{k-1}$$ (for some number k)



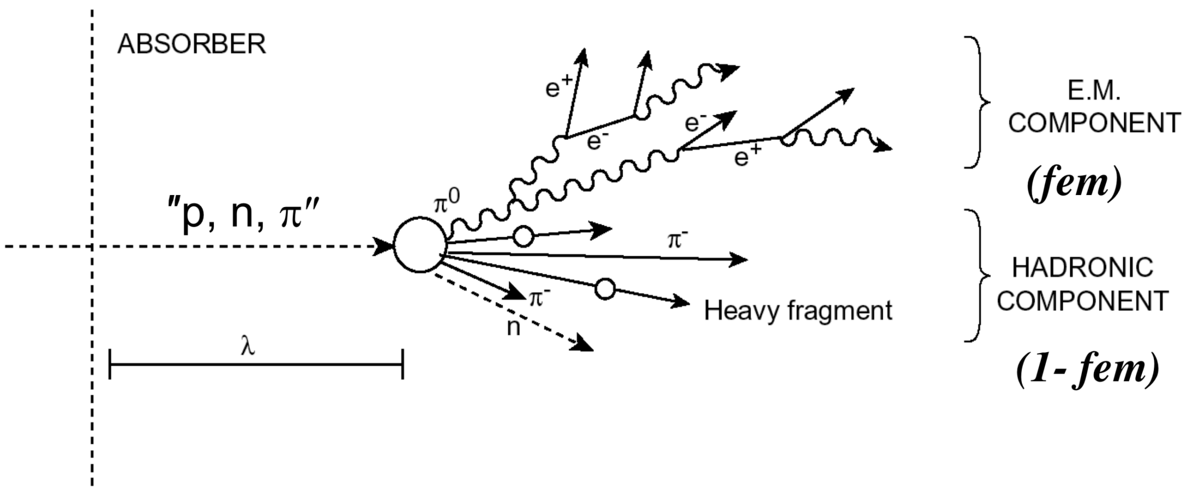
f_{em} energy dependence

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

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



The curse of hadronic calorimetry



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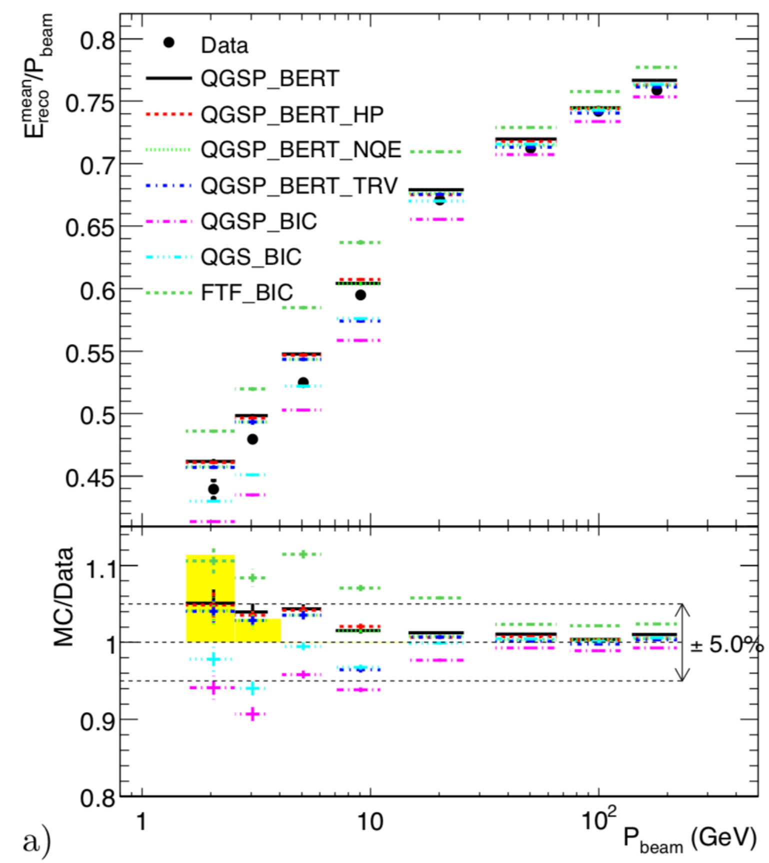
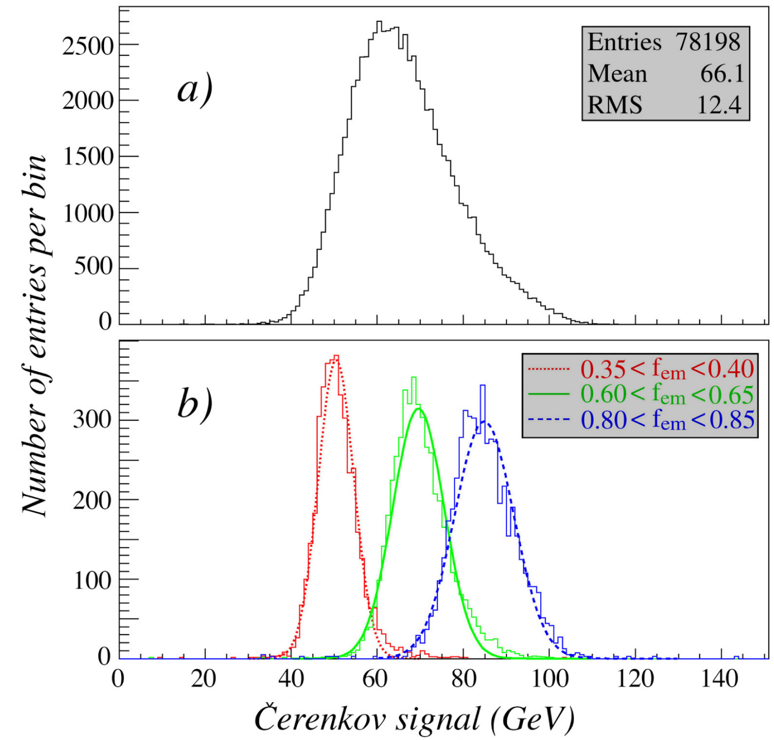


- **Non-compensating calorimeters**: response to em part different from that to non-em part. **h/e < 1**
- $\langle f_{em} \rangle$ energy dependent ⇒ **Non-linear calorimeter response** to hadrons.

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

The curse of hadron calorimetry (2)

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



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

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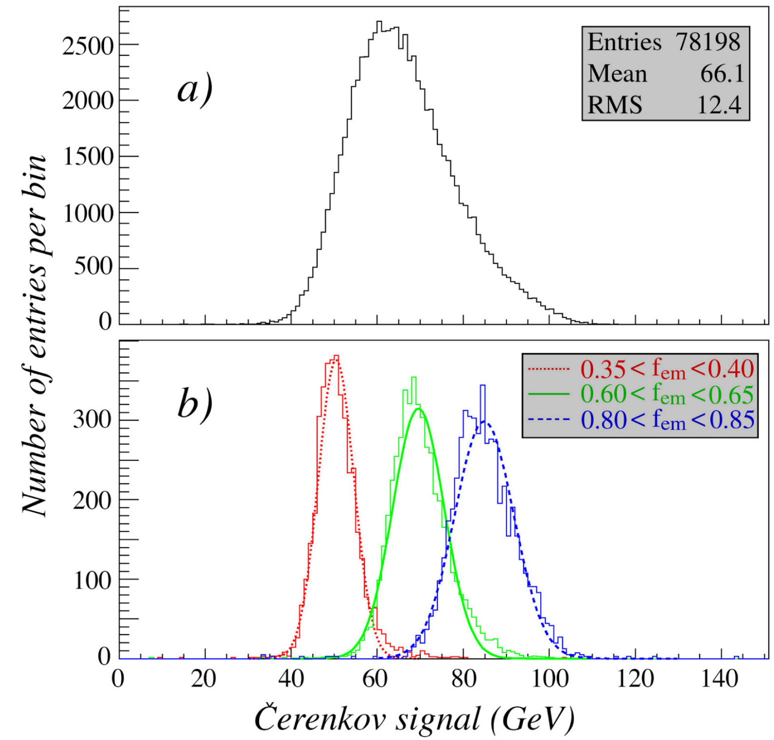

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Experiment	Detector	Absorber material	*e/h*	Energy resolution (E in GeV)
UA1 C-Modul	Scintillator	Fe	≈ 1.4	$80\%/\sqrt{E}$
ZEUS	Scintillator	Pb	≈ 1.0	$34\%/\sqrt{E}$
WA78	Scintillator	U	0.8	$52\%/\sqrt{E} \oplus 2.6\%$*
D0	liquid Ar	U	1.11	$48\%/\sqrt{E}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

Dual readout

Dual readout - the principle

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

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

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

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

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

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

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

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

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

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

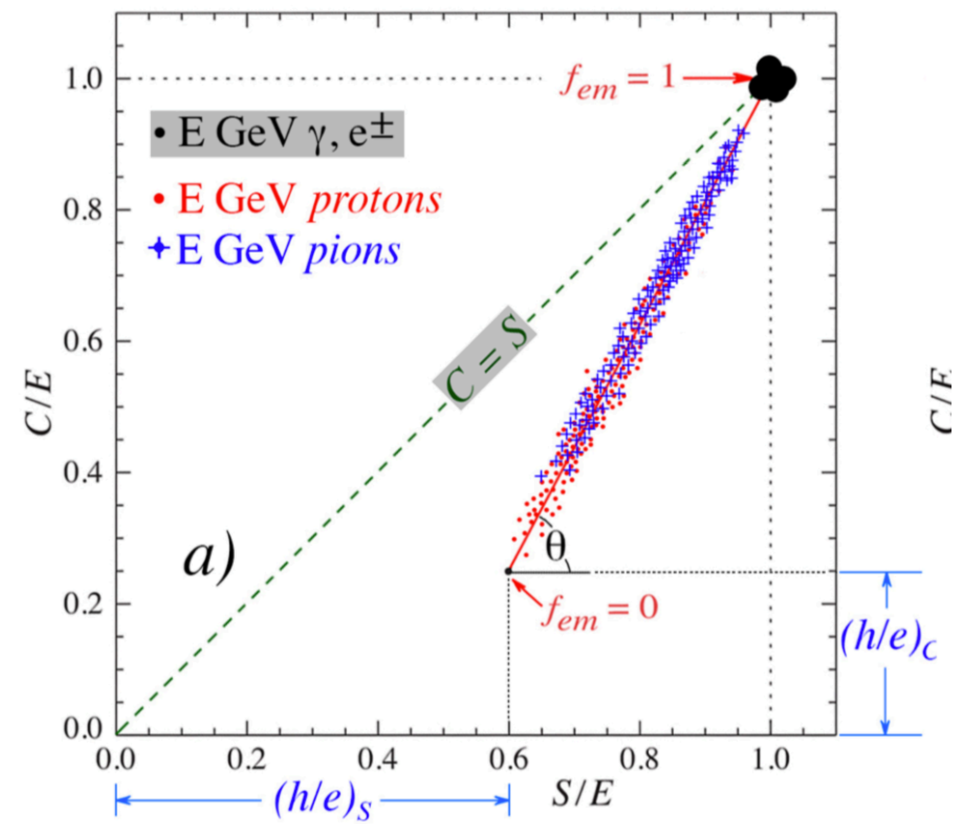
Dual readout - the signals

- 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 .

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

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

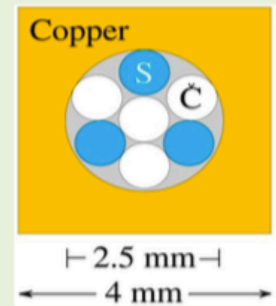
$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C} = \cot\theta$$



Dual readout calorimeters (PMT readouts)

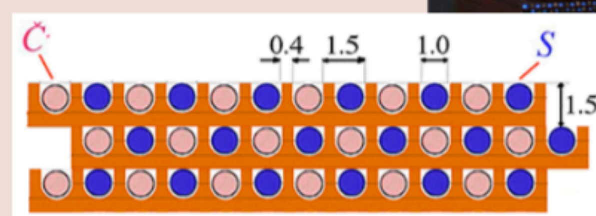
2003
DREAM

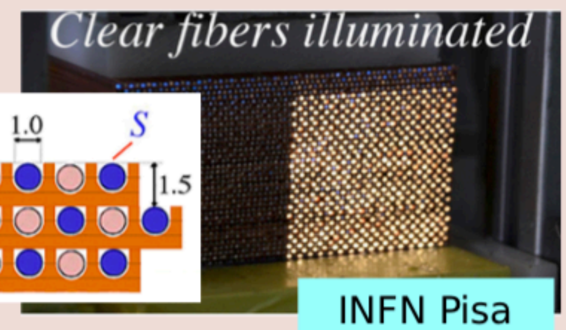
Cu: 19 towers, 2 PMT each
2m long, 16.2 cm wide
Sampling fraction: 2%



2012
RD52

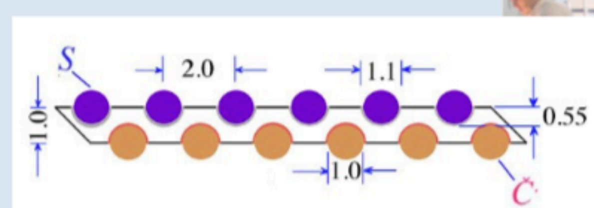
Cu, 2 modules
Each module: $9.2 \times 9.2 \times 250$ cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}



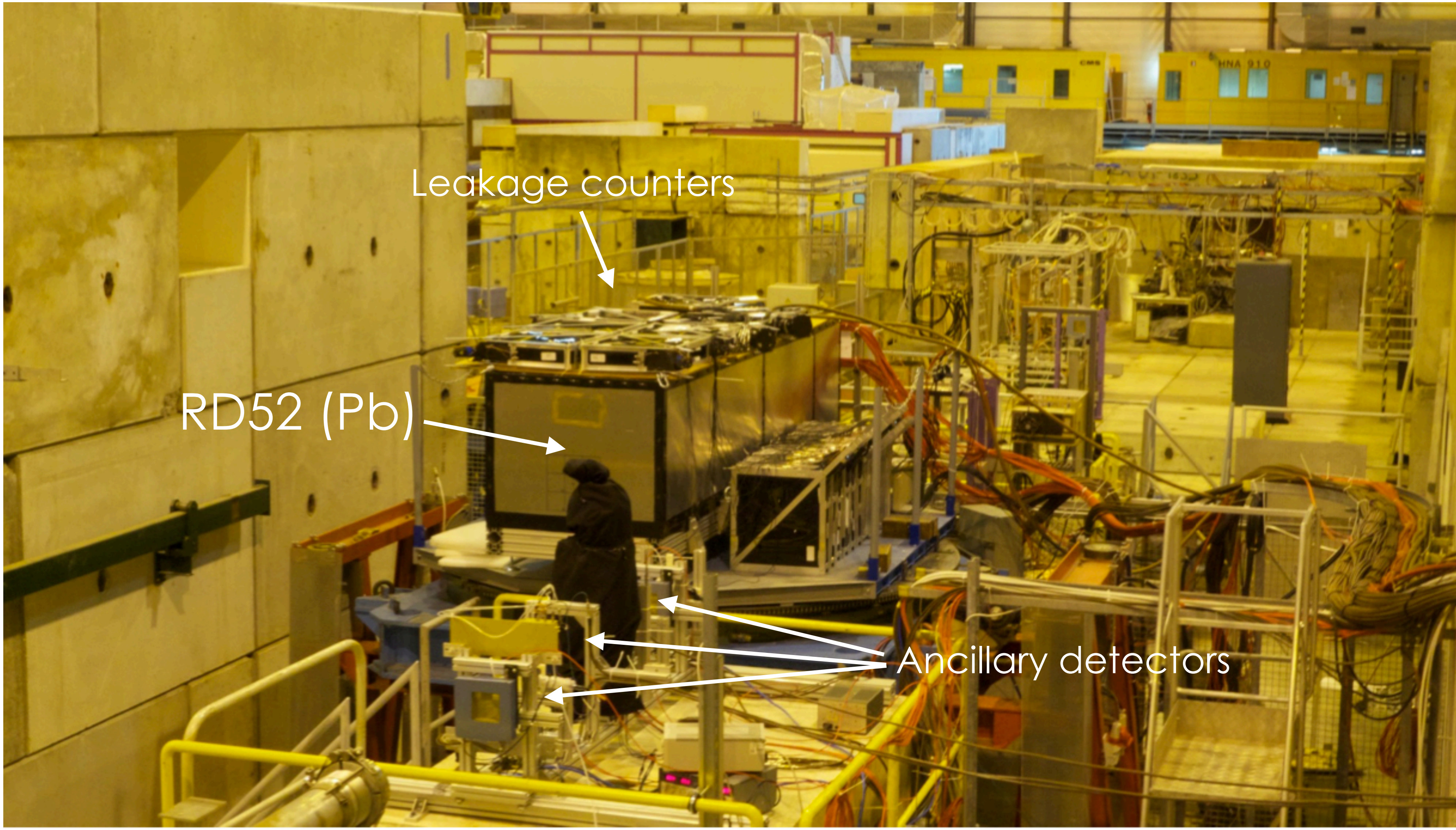


2012
RD52

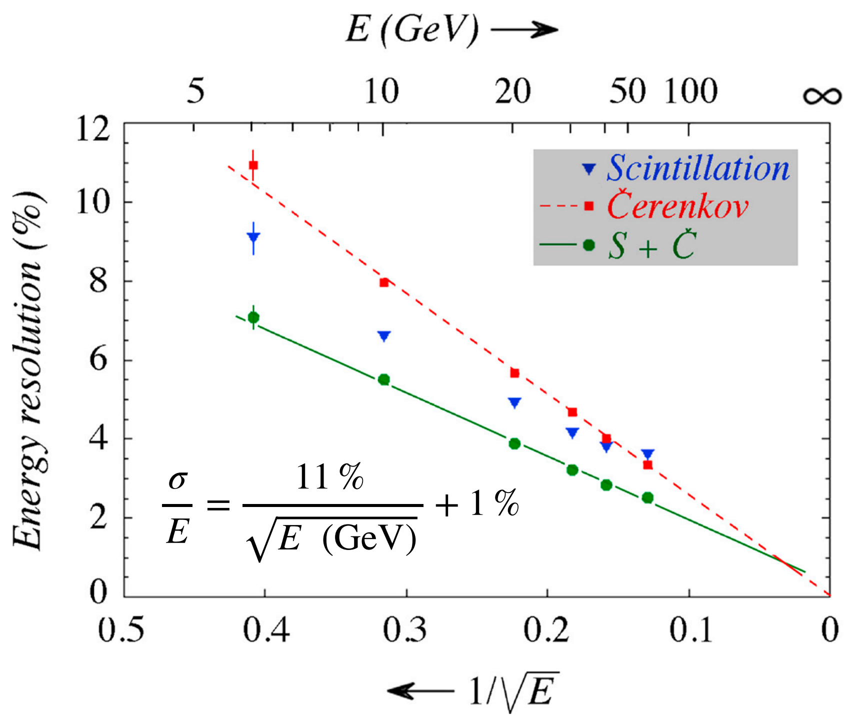
Pb, 9 modules
Each module: $9.2 \times 9.2 \times 250$ cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}



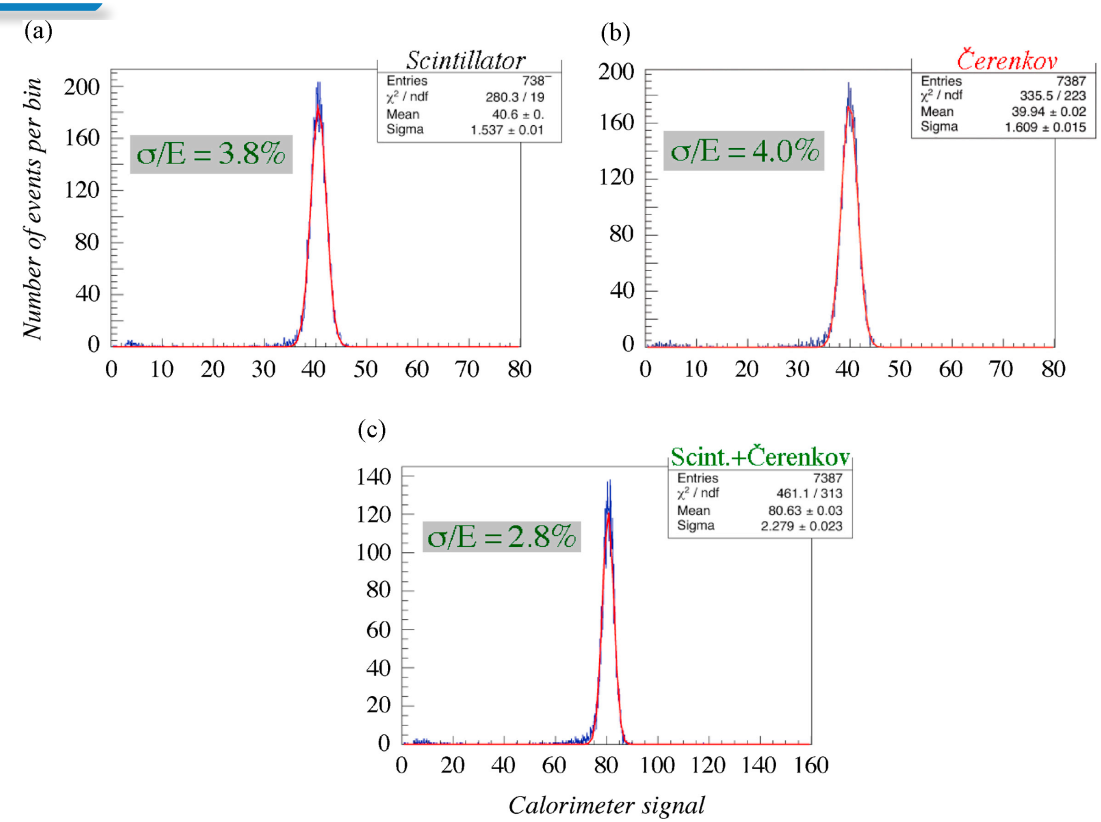
Dual readout calorimeter at work

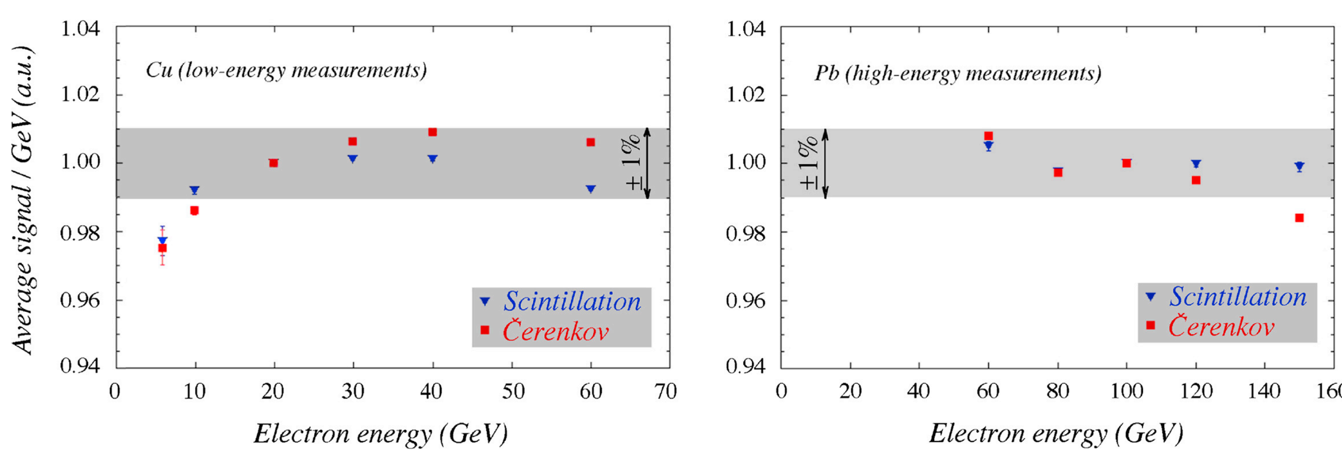


Electron response



40 GeV electrons

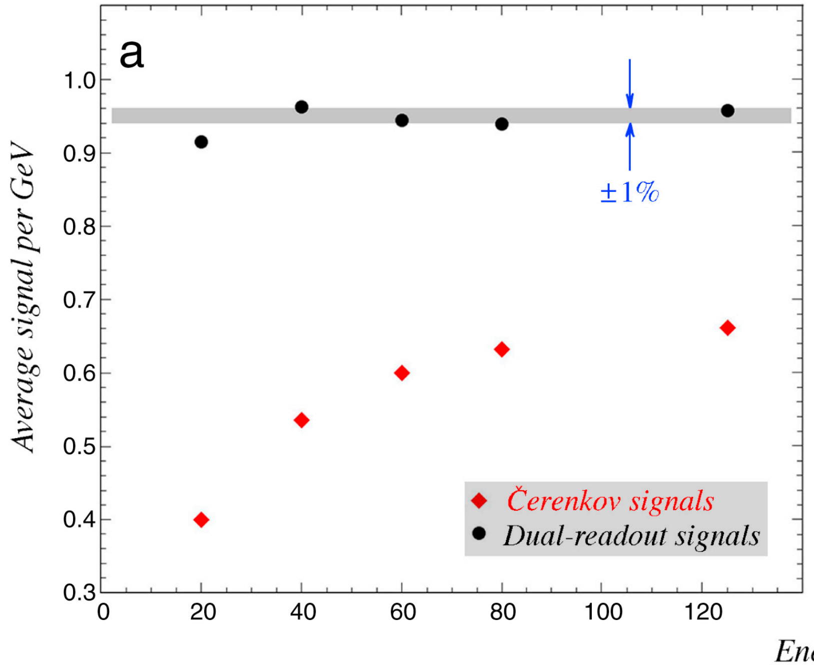




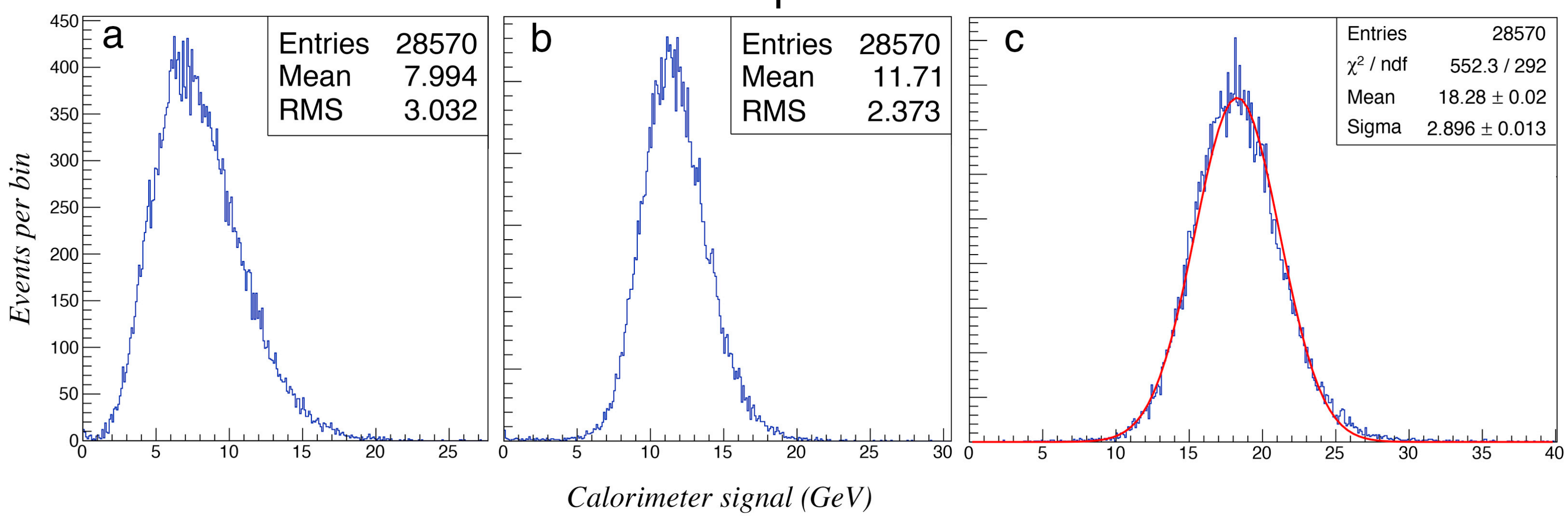
Single hadron response - linearity

NIM A 866 (2017) 76

- Dual readout signal **largely recovers linearity** while vastly improving resolution.

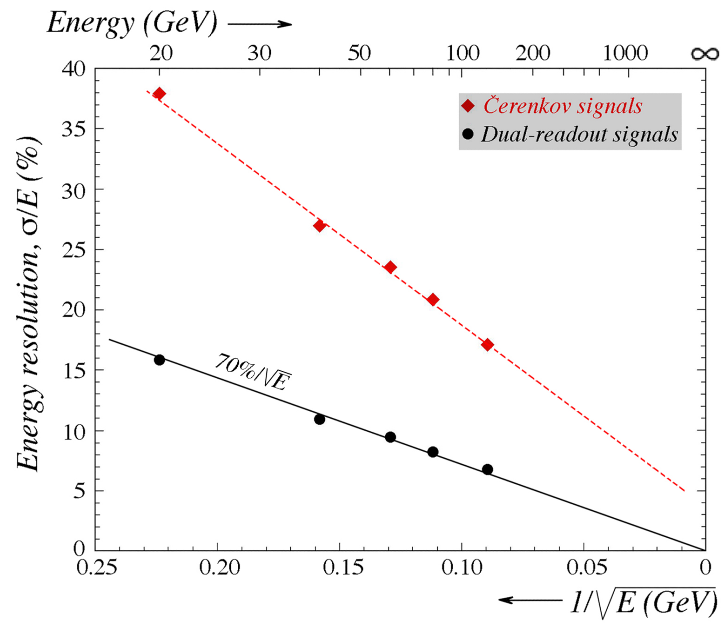


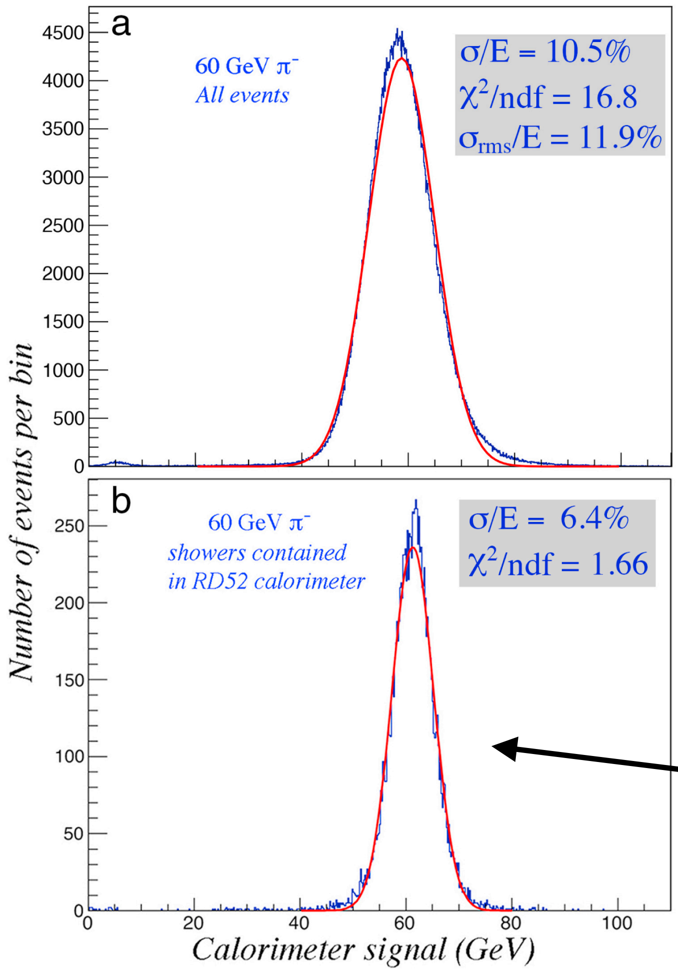
20 GeV pions



Single hadron response - resolution

- Problem of calorimeter R&D: a **fully containing calorimeter** is **expensive.**

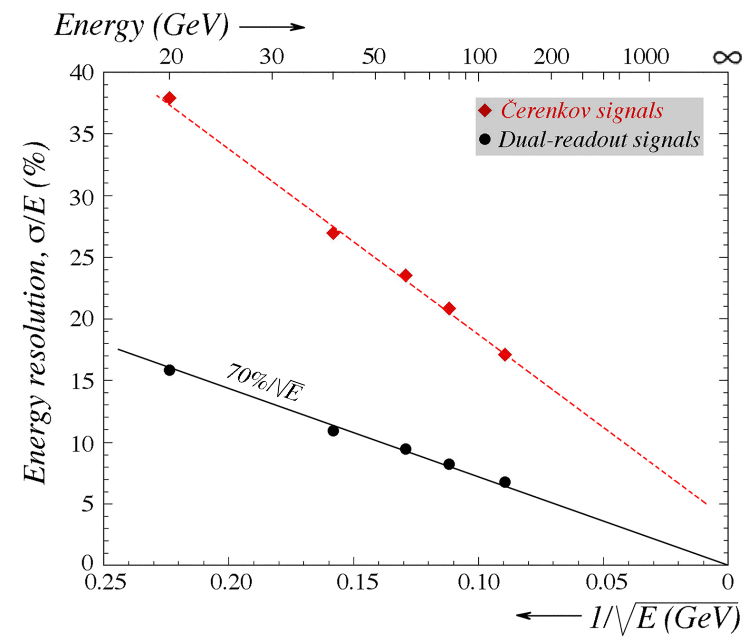




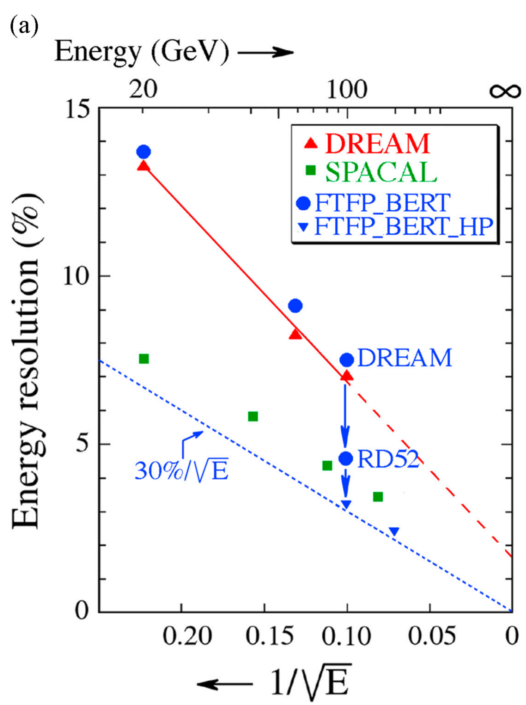
No signal in leakage counters

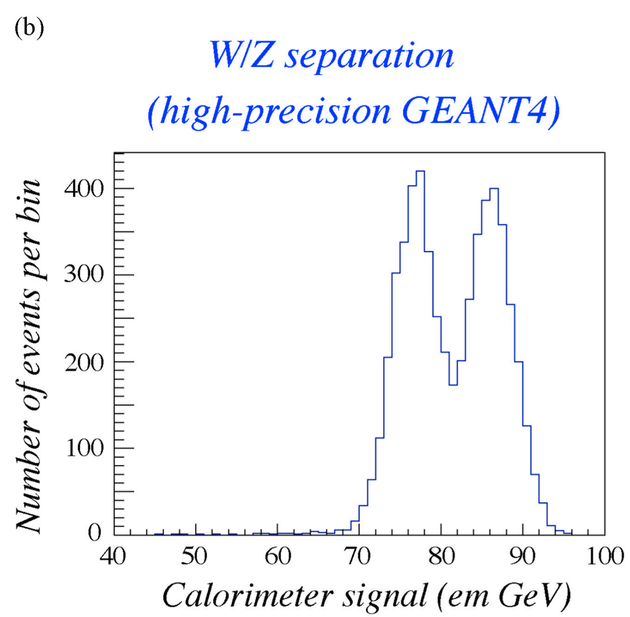
Performance of Dual Readout

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



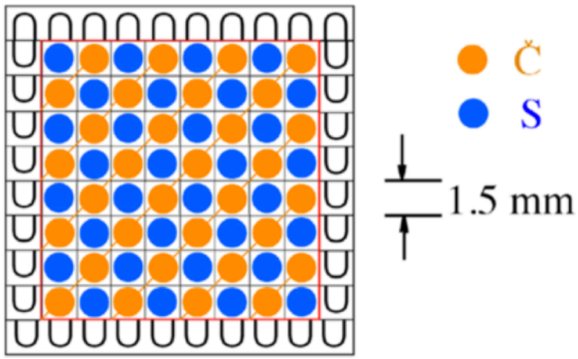
See https://doi.org/10.1016/j.ppnp.2018.07.003

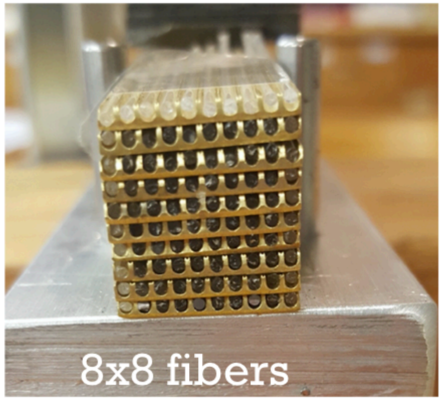




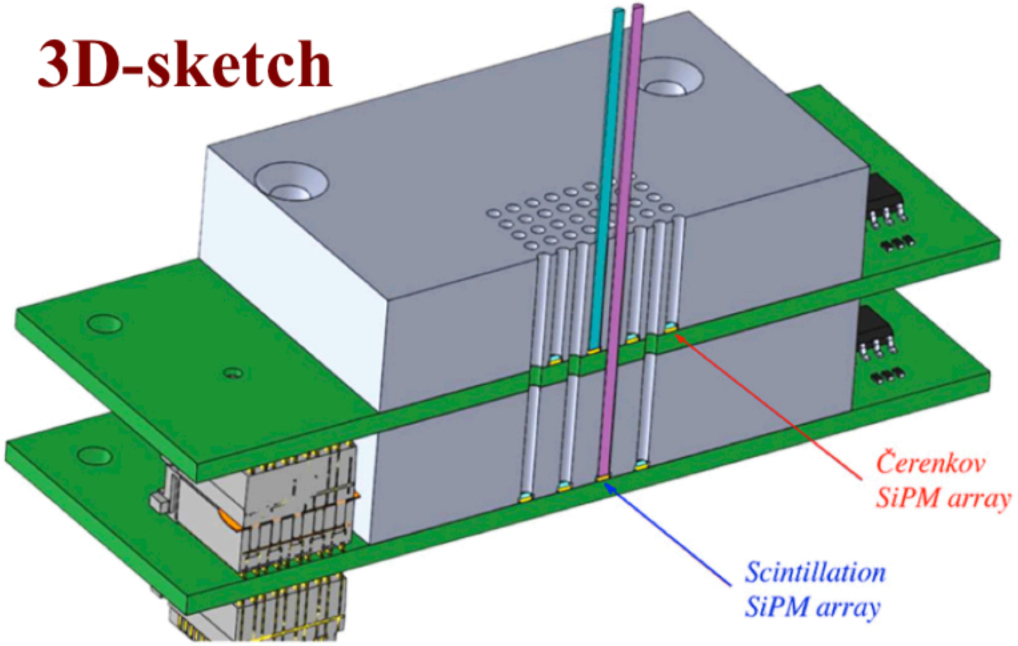
Recent developments

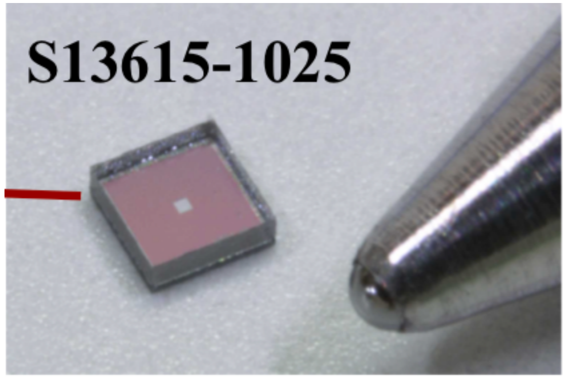
SiPM dual readout





- 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).





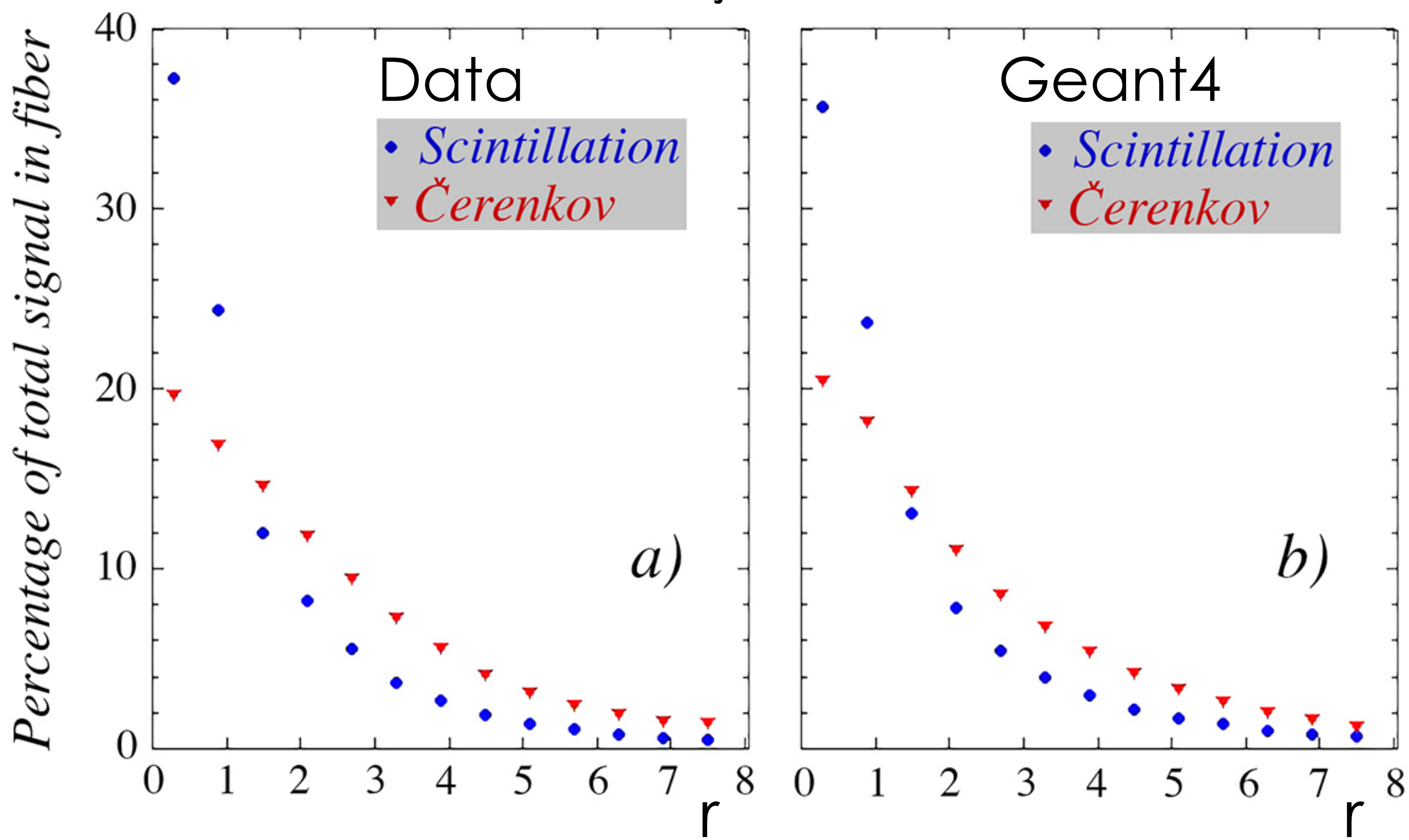
SiPM dual readout (shower shape)

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

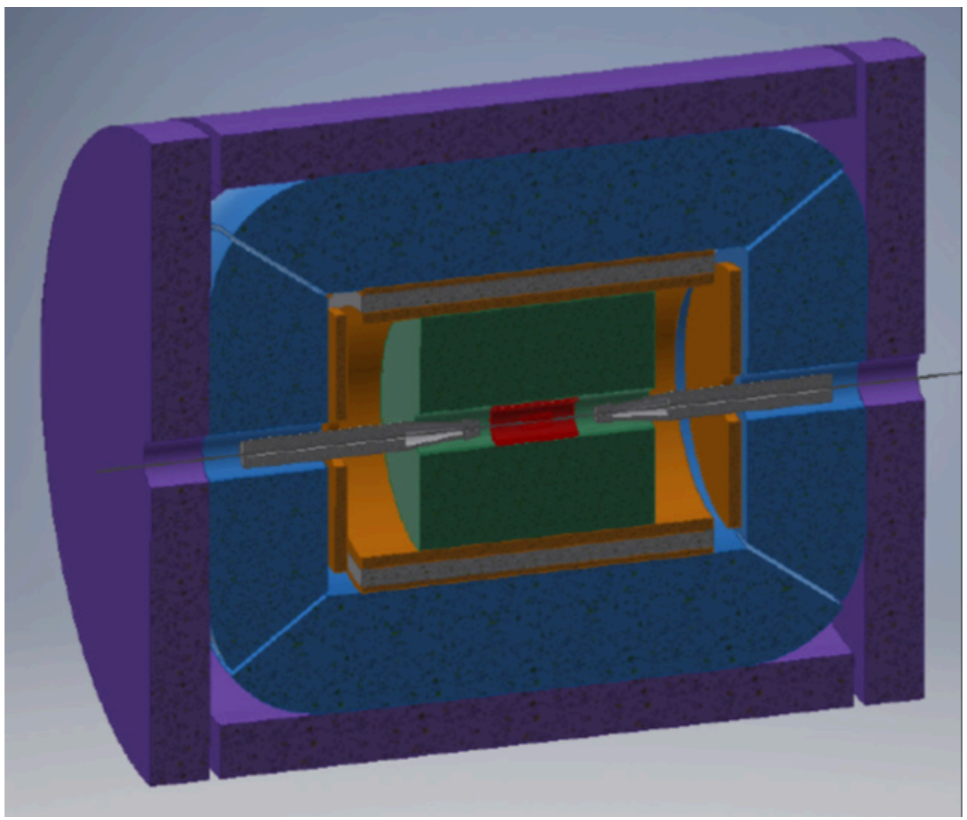
Doi:10.1016/j.nima.2018.05.016

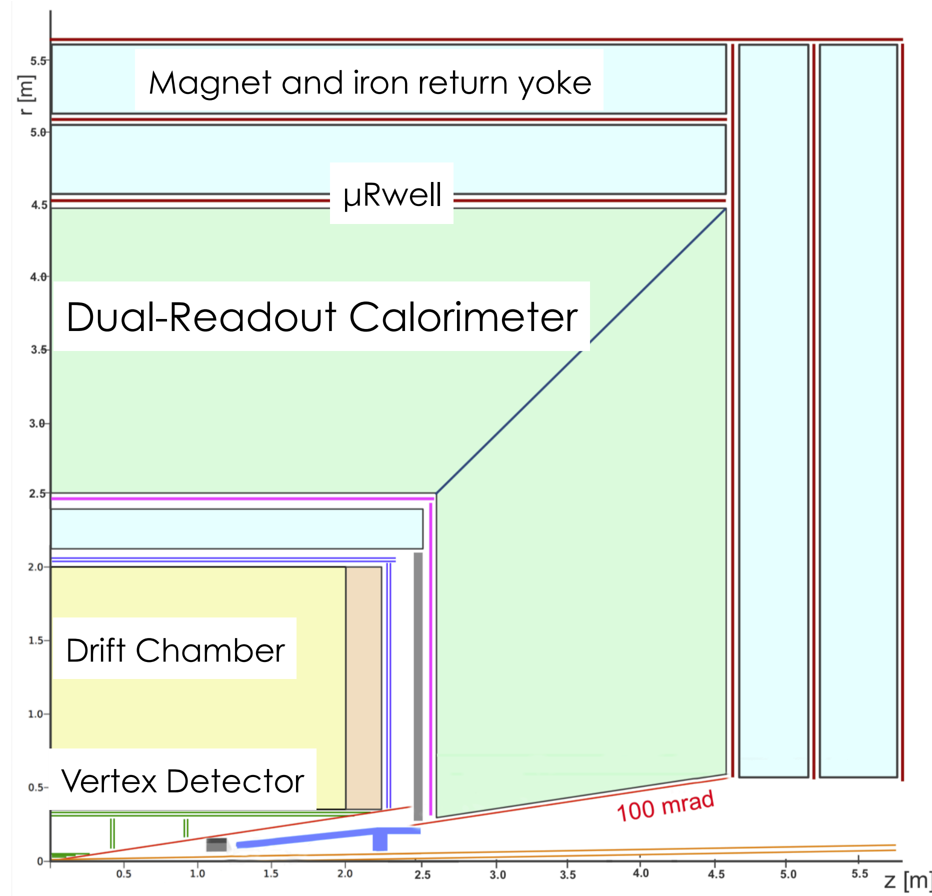
$$\bar{x} = \frac{\sum_i x_i E_i}{\sum_i E_i}; \bar{y} = \frac{\sum_i y_i E_i}{\sum_i E_i}$$

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



A practical implementation: IDEA

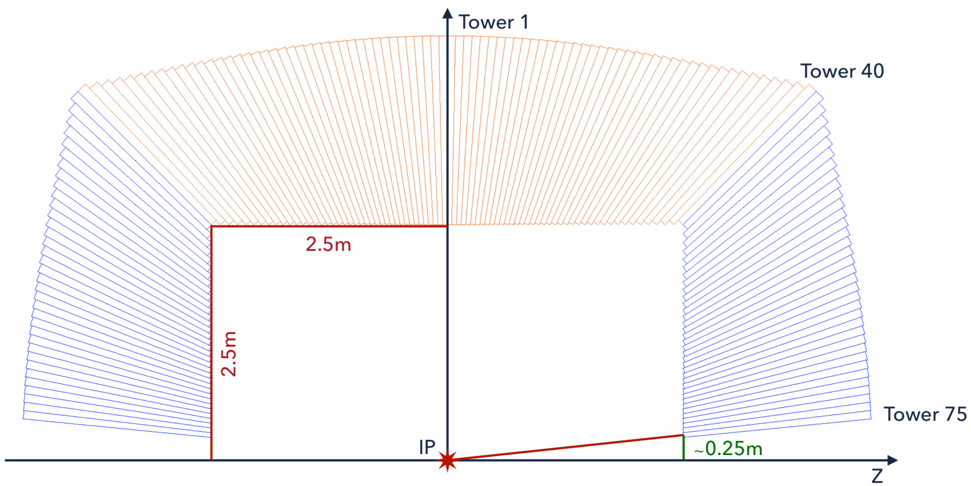


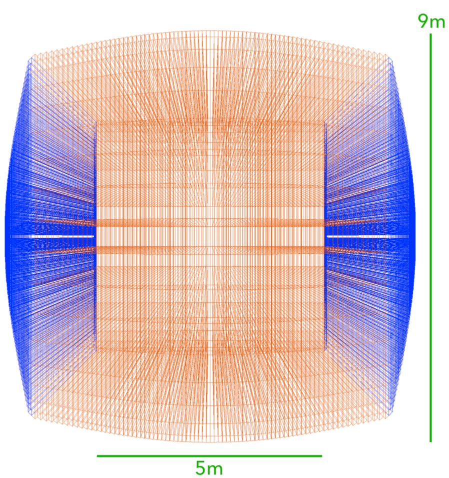


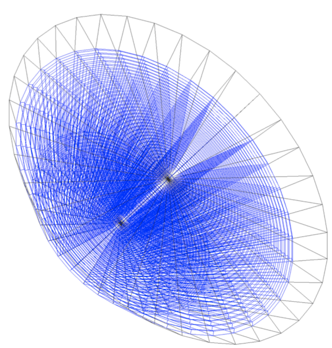
See here for additional information

Simulation

Work in progress







- Full G4 simulation of "final" geometry **is available**:
  - Cu absorber, 1 mm fibers, 1.5 mm pitch
- Also existing parametrised simulation for physics studies

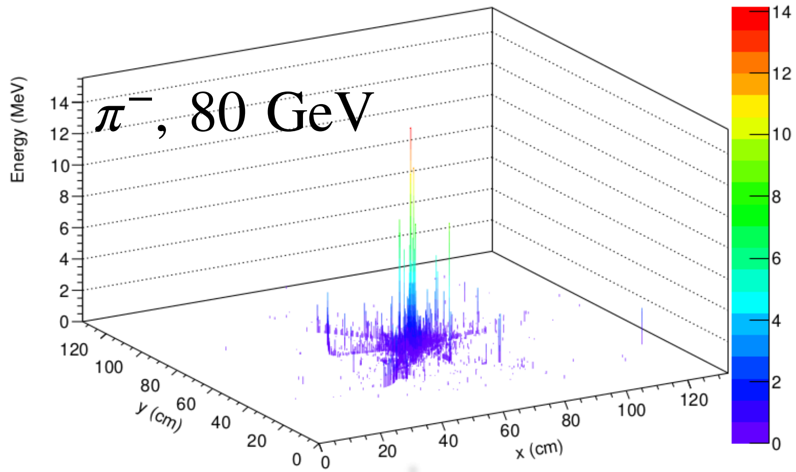
75 projective elements x 36 slices

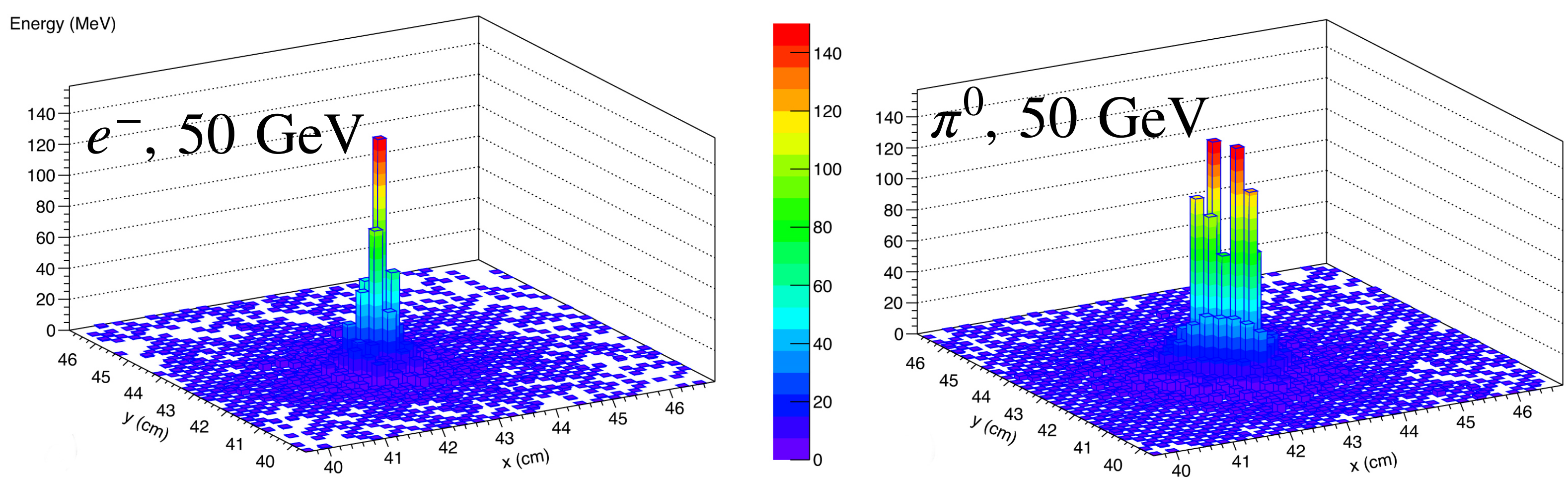
Tower size: $\Delta\theta = 1.125^\circ$ $\Delta\phi = 10^\circ$

Read out the single fibre: 130 M channels

Shower shape

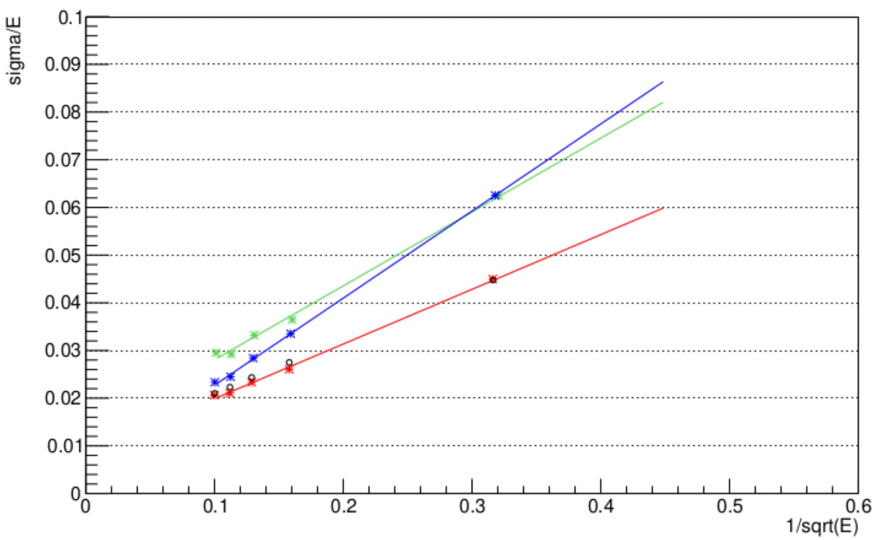
- Single particle shower shape
  - Using full implemented granularity



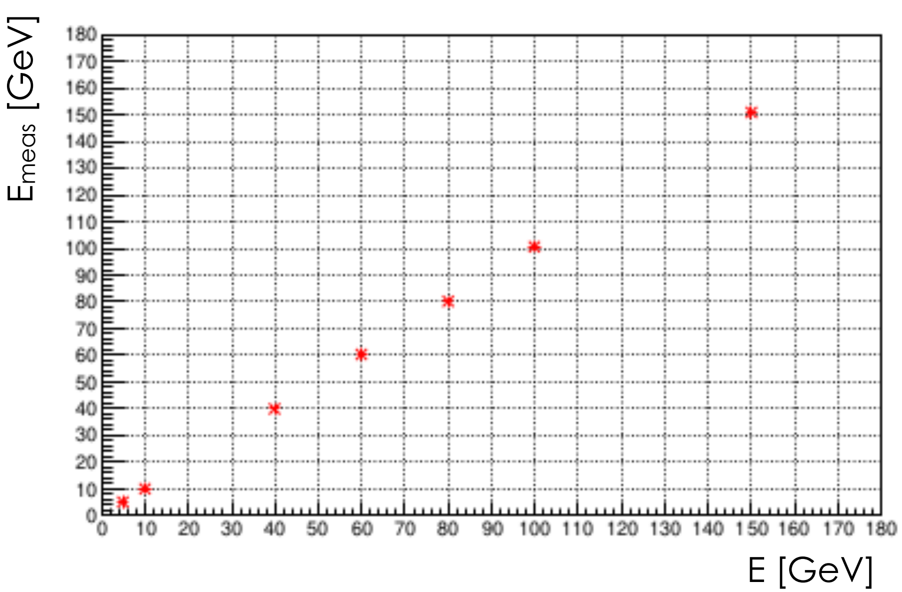


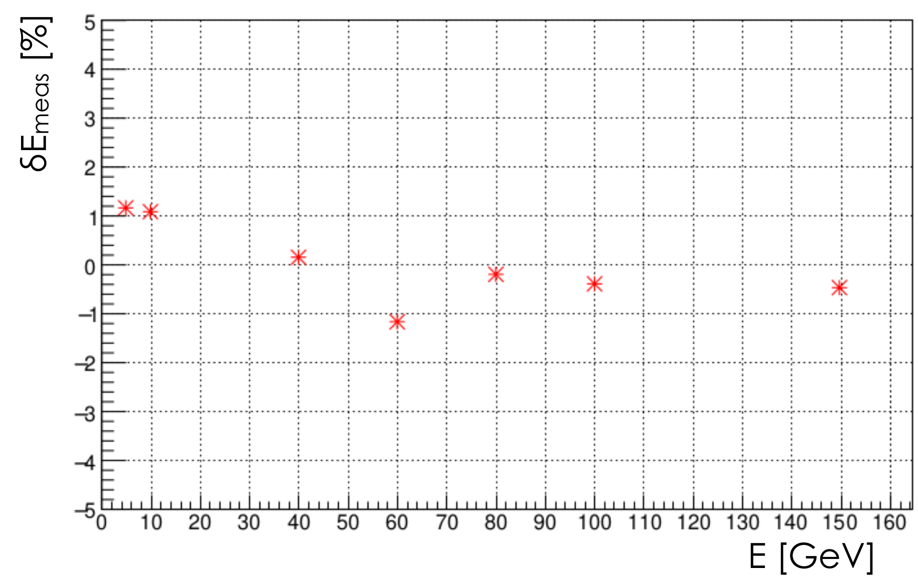
Electron response

Work in progress



- Scintillation (S): $\frac{\sigma}{E} = \frac{15.5\,\%}{\sqrt{E}} + 1.2\,\%$
- Cherenkov (C): $\frac{\sigma}{E} = \frac{18.3\,\%}{\sqrt{E}} + 0.5\,\%$
- Dual Readout: $\frac{\sigma}{E} = \frac{11.0\,\%}{\sqrt{E}} + 0.8\,\%$

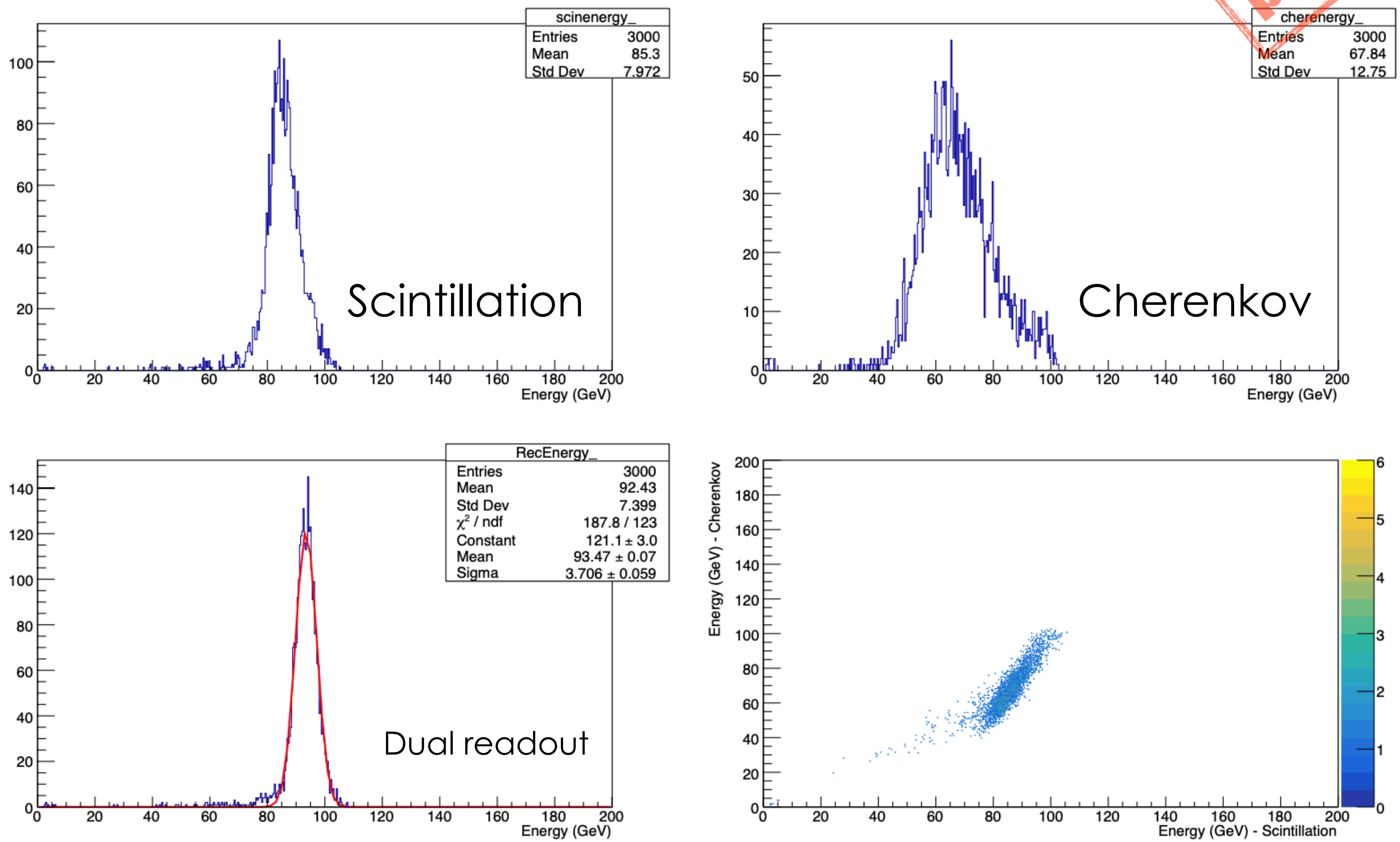




Hadron response

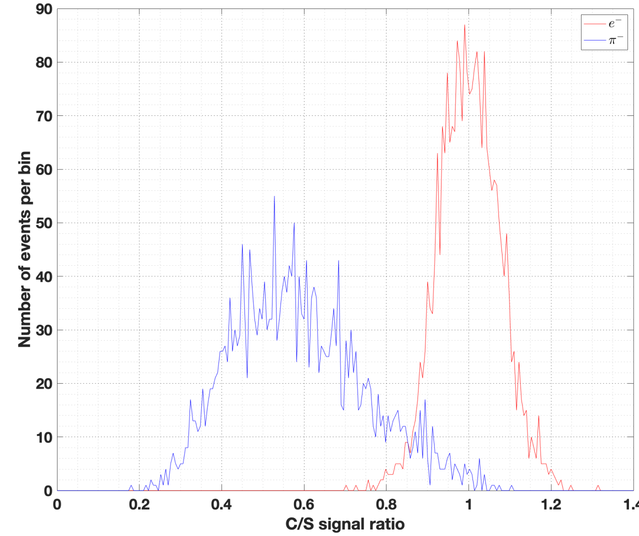
Work in progress

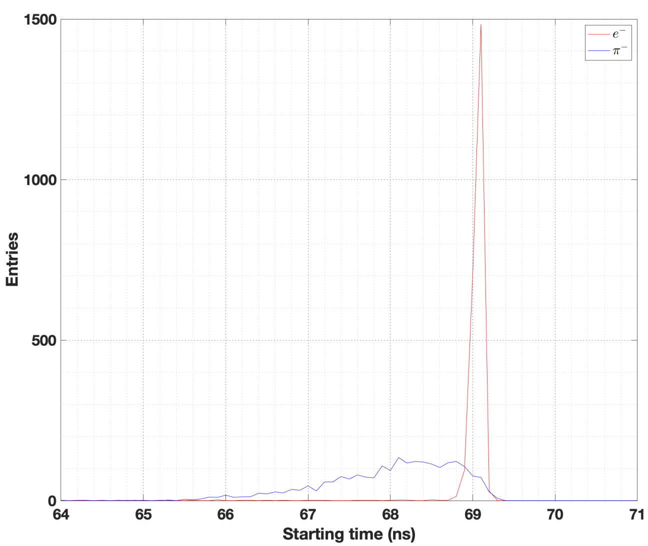
100 GeV pions

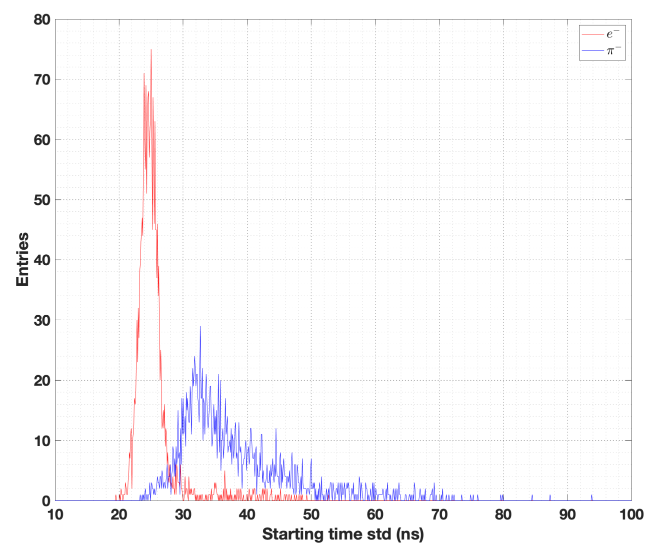


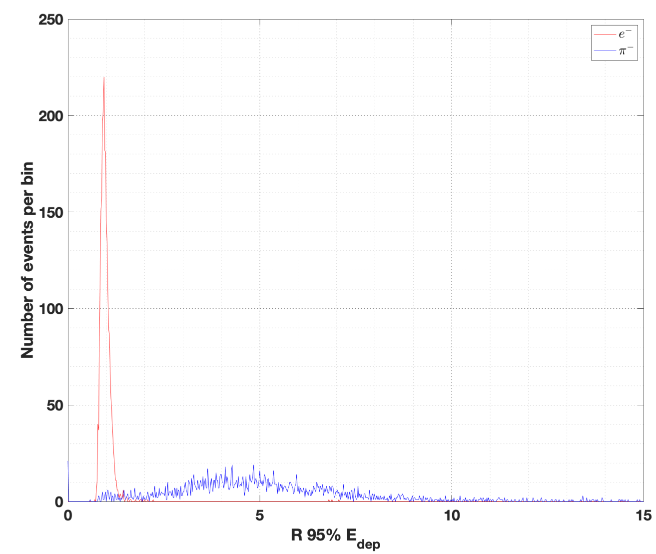
Particle identification

- Compare **electron and pion** shower shapes (20 GeV)
- Consider also **Time of arrival** of signal to SiPM (fiber propagation and SiPM + electronics time response parametrised in full sim)









Particle identification

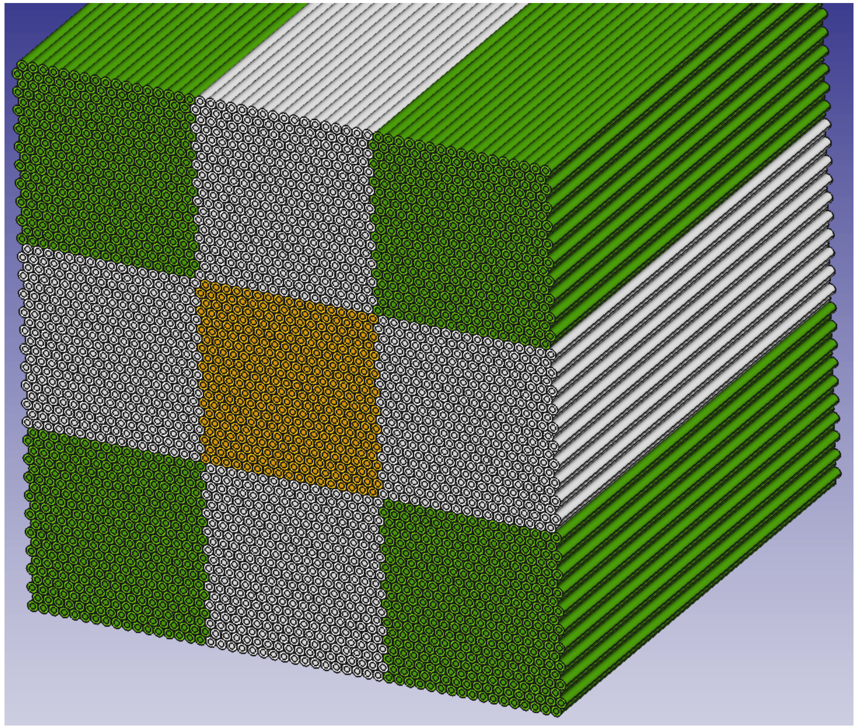
	C/S ratio	Time of Arrival (ToA)	σ(ToA)	R_{95} (S&C)
Cut value	> 0.86	> 68.9 ns	< 28.2 ns	< 1.4^{o}
ε(e)	97.3%	94.2%	92.2%	98.9%
R(π)	15.2	12.5	20.8	35.7

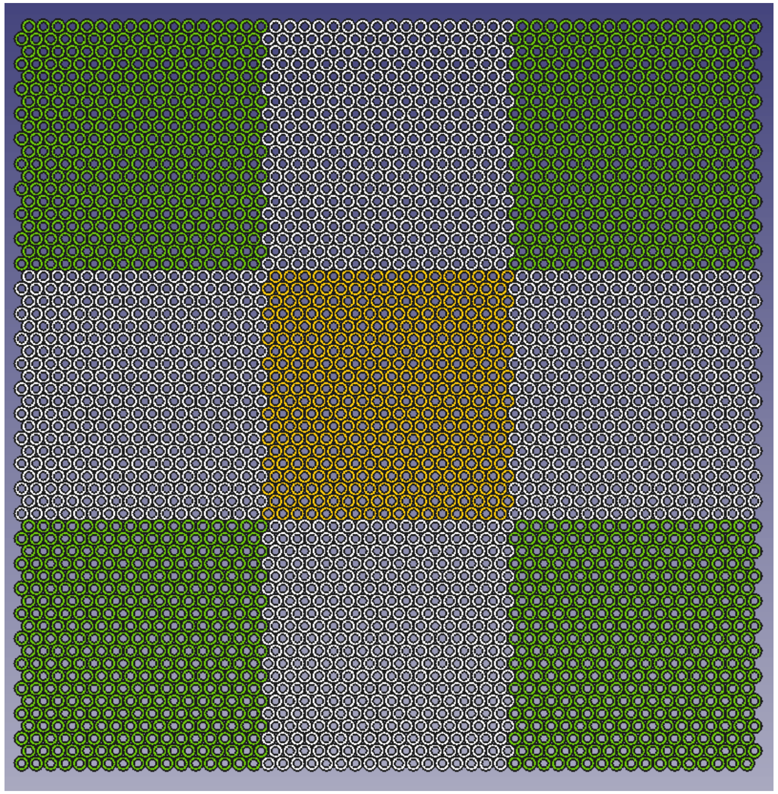
- **Correlations** between these variables **are weak** (and more variables can be explored)
  - We estimate pion rejection of at least R(π) = 10^2 for ε(e) = 90%.
  - A <u>very old study</u> with the ATLAS calorimeter quotes R(π) = 3.2% (90% efficiency, calo only, test beam, still E = 20 GeV)

Outlook

2020 target

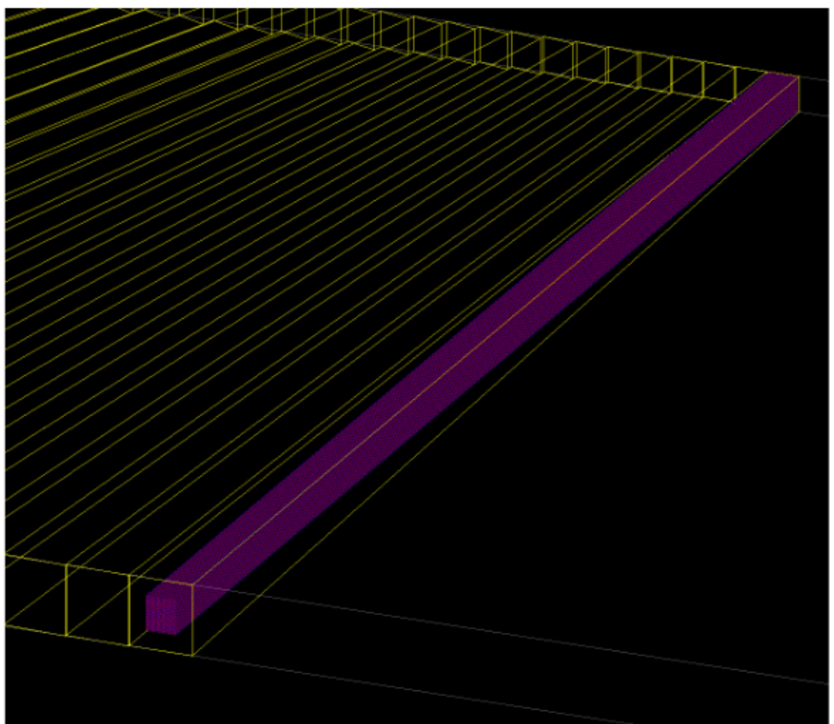
- Build a 10 x 10 x 100 cm^3 prototype:
  - Use **2 mm diameter** tubelets (CuZn37, glued with araldite)
    - 60 horizontal layers of 51 tubes
    - 9 readout towers of 17x20 tubes each
    - **SiPM** readout for the **central tower**, PMs (with reduced granularity) otherwise





Open issues

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



- 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

SiPM readout (2):

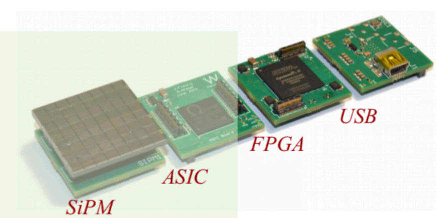
digitiser (ASIC) & feature extraction (FPGA)

→ 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 **~ 100 M€**.
  - Large number of channels (o(130 M)) **completely dominating the cost.**
  - Current estimates tell us **70% of the cost will be optical fibres and SiPM**, with the rest being FE electronics and absorber.
- Actively looking at **ways of reducing these costs**:
  - Channel grouping: how much can we group together without hampering particle ID?

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 **2020 prototype** to develop readout model and tubelet mechanical construction + test EM performance.
- Towards a **full scale prototype** - some open questions still to be addressed.
  - Lots of space for collaborations.

Backup

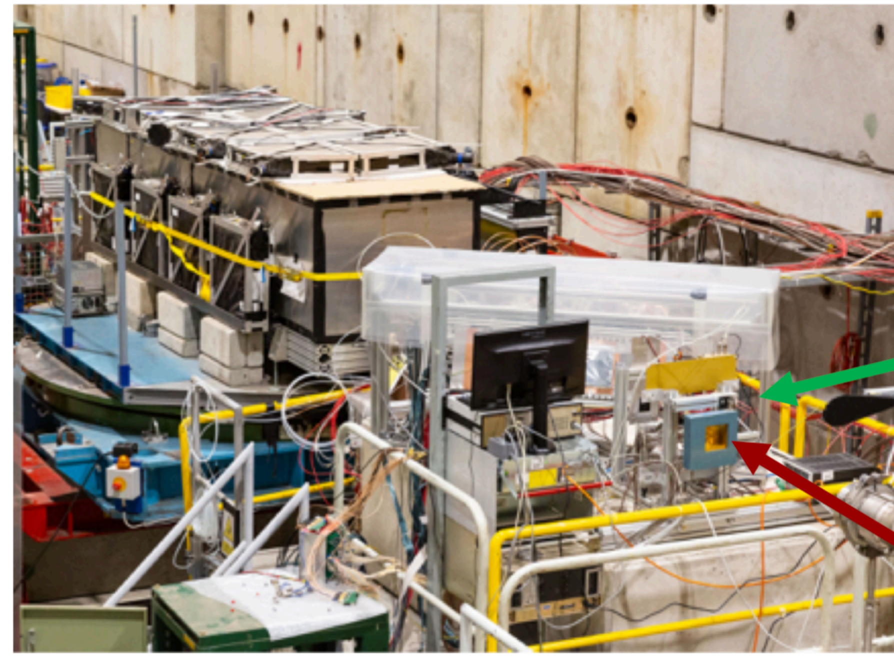
From PMTs to SiPM

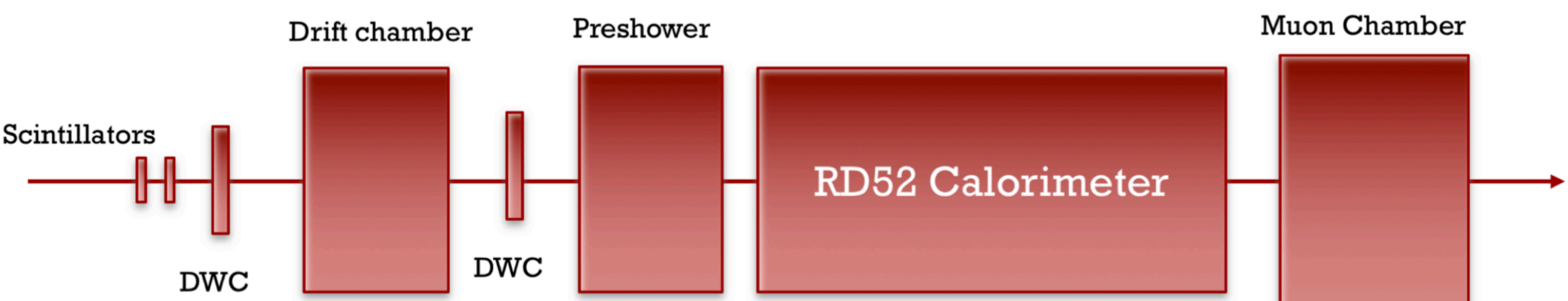
SiPM pros:
- Compact readout
- Resilience to magnetic field
- Large light yields
- High readout granularity (particle flow "friendly")
- Photon counting (calibration)
- High timing resolution

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

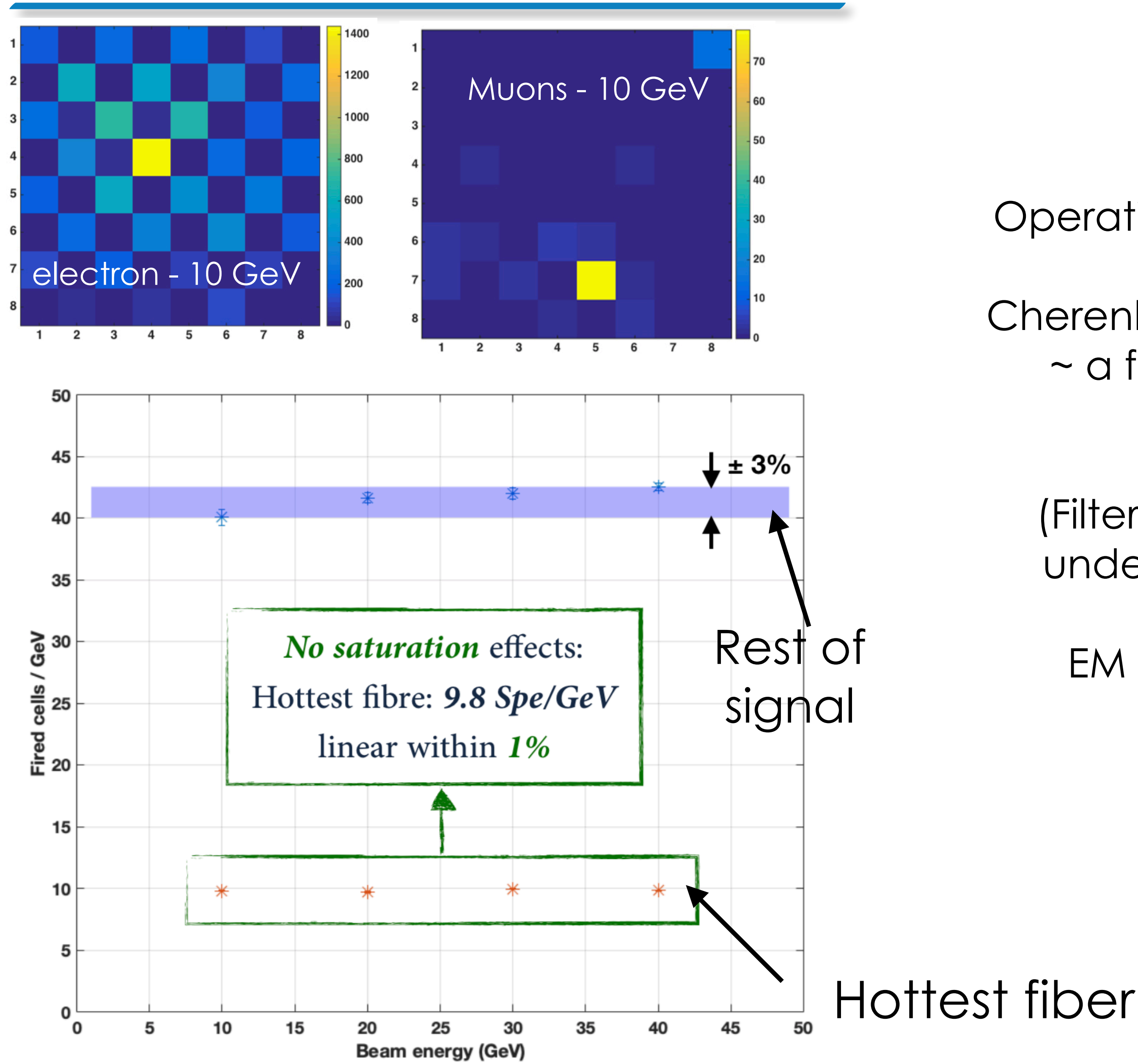
IDEA slice on beam (2018)

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





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).

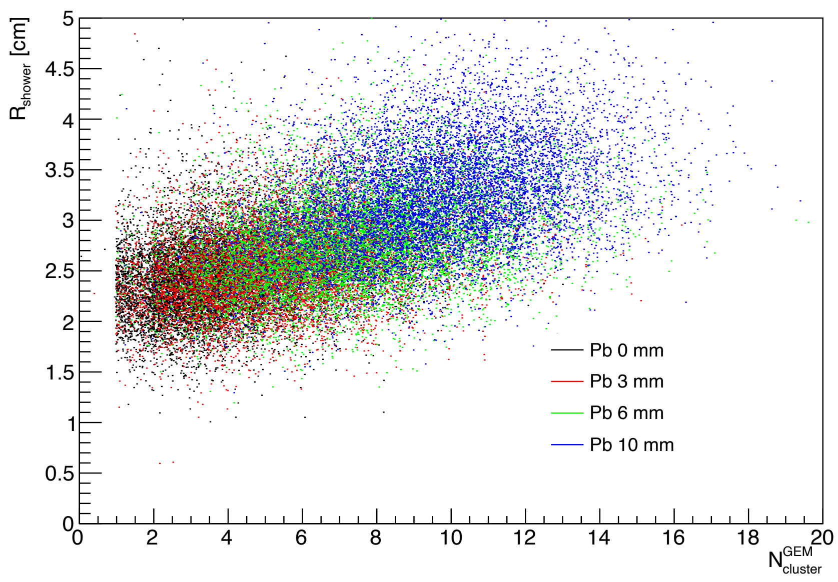
EM stochastic term ~ 10% is achievable

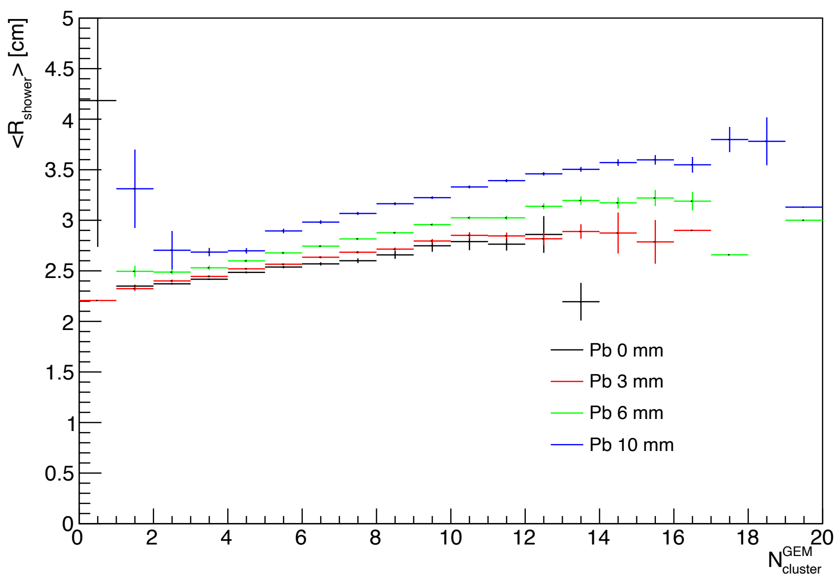
Combined measurements (RD52)

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

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

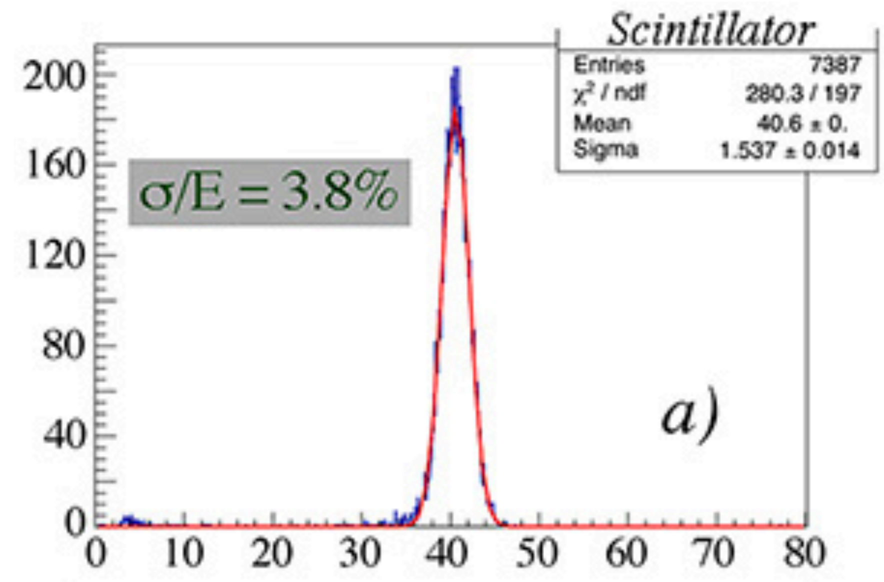
Shower width from 5 mm Pb + additional material correlates with number of clusters in GEM preshower

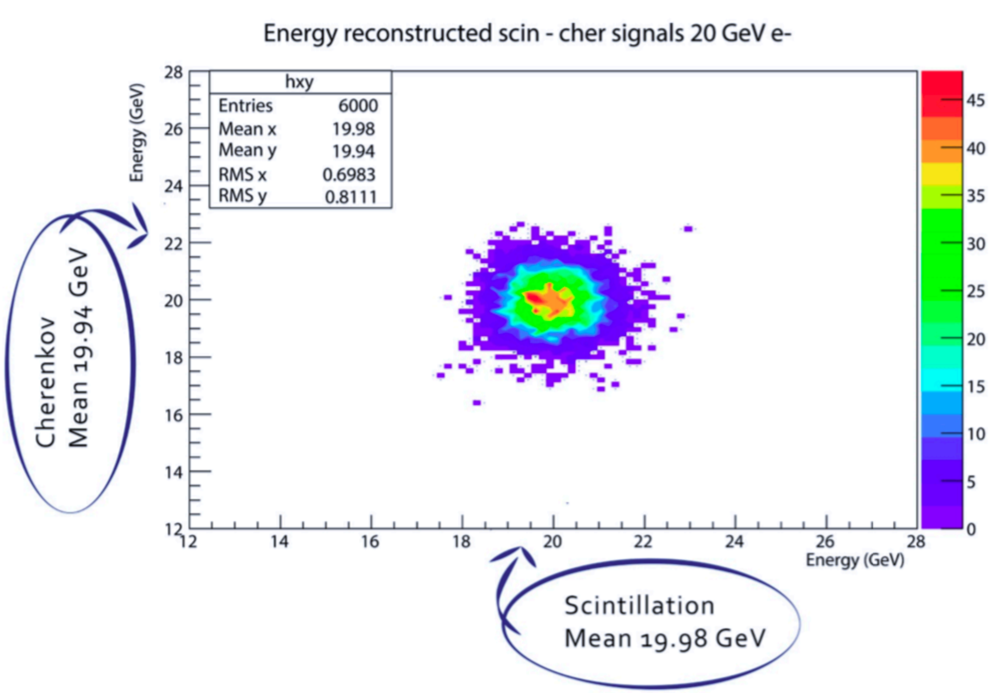


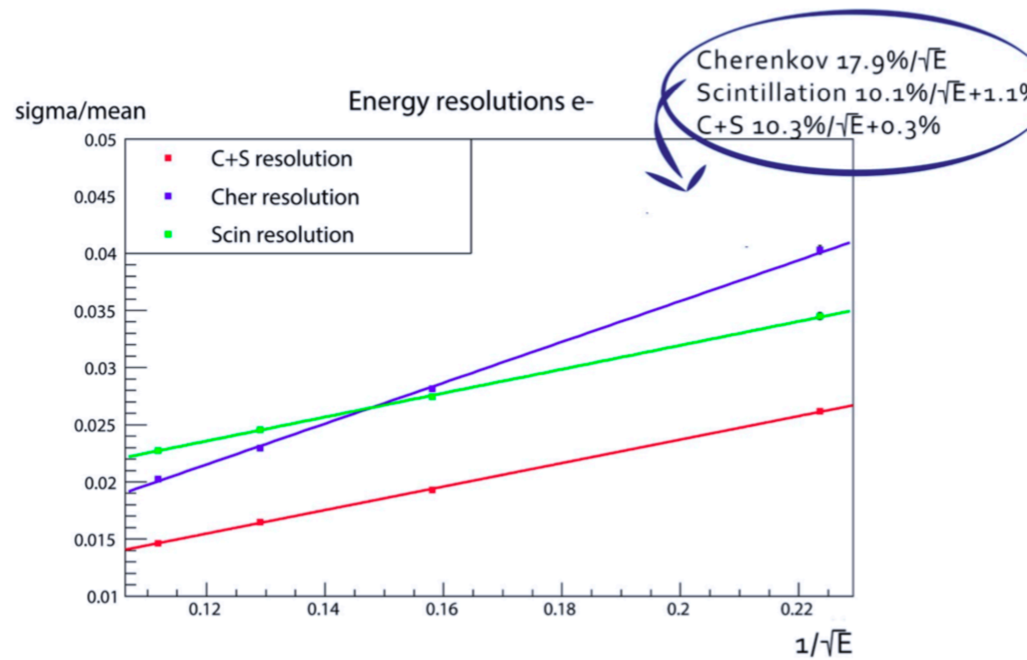


EM performance

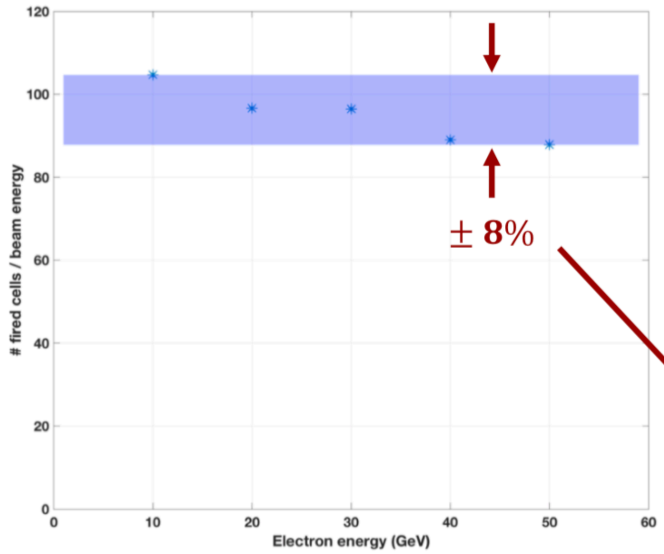
- Excellent e and γ calorimeter performance thanks to high sampling fraction.
  - EM and HAD calorimetry in one device.







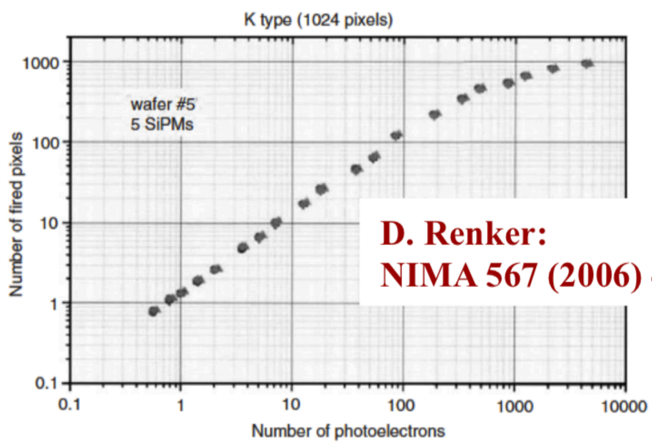
Results from 2017 test beam



- 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

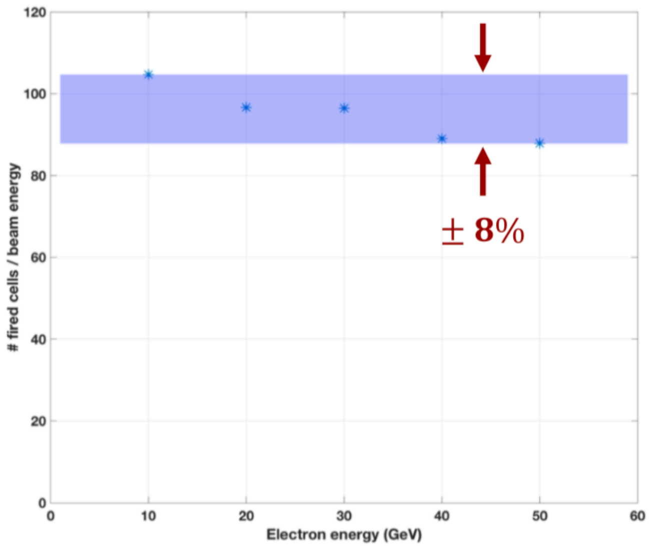


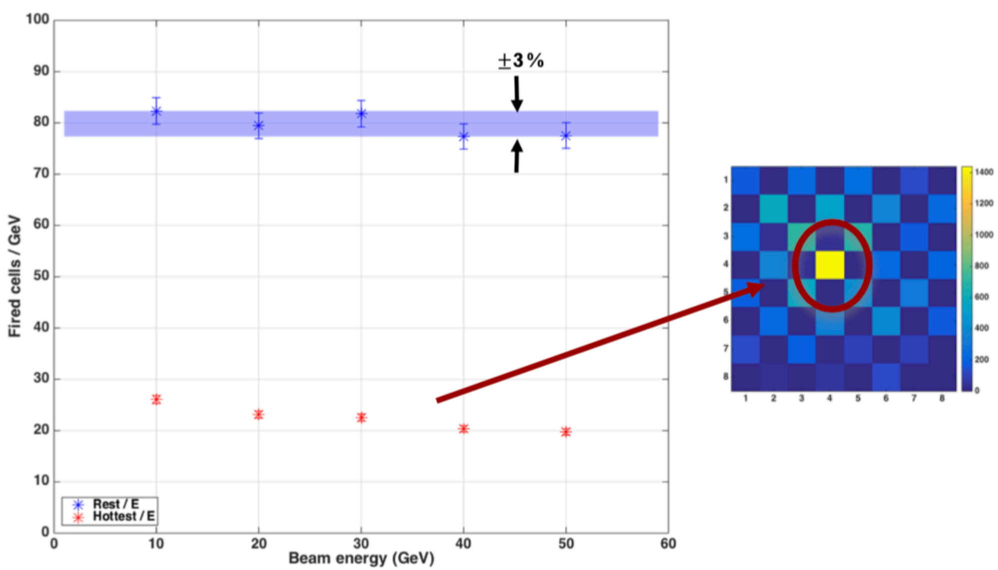
D. Renker: NIMA 567 (2006) 48–56

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

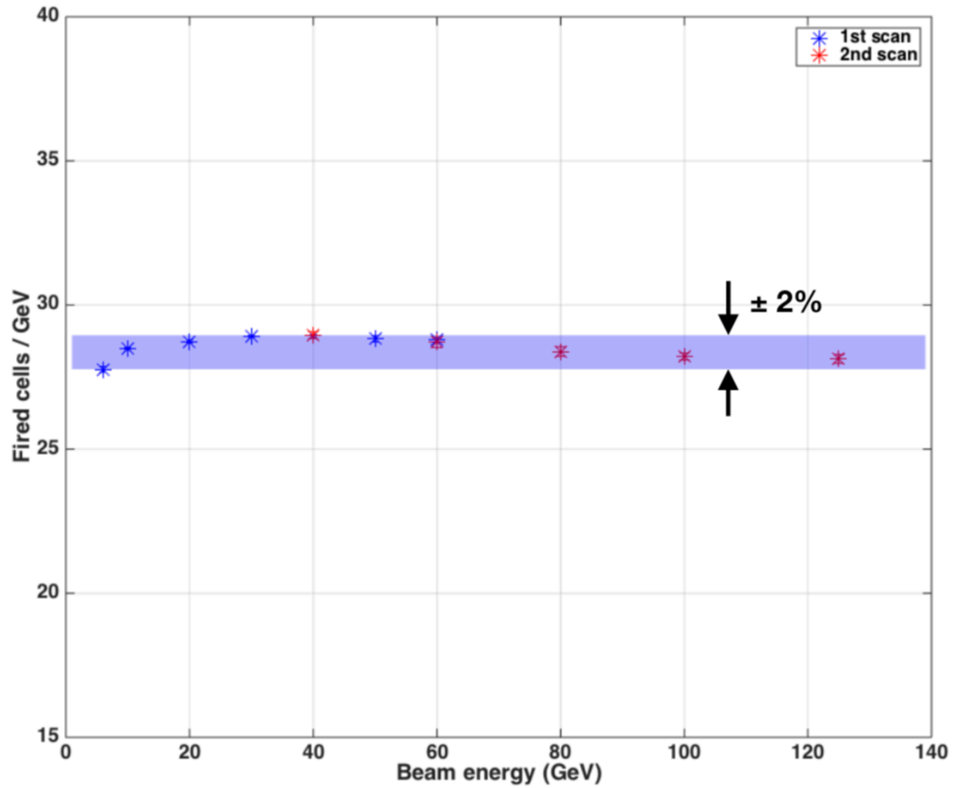
Cherenkov light

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***.

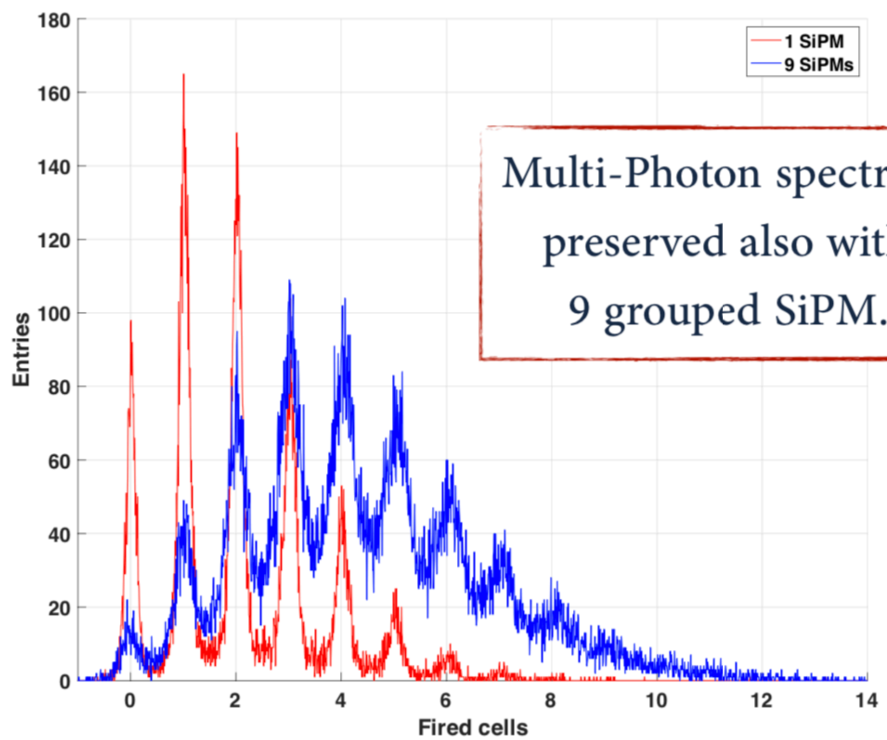
(sampling fluctuations: ~ 9%/√E).

Grouping channels

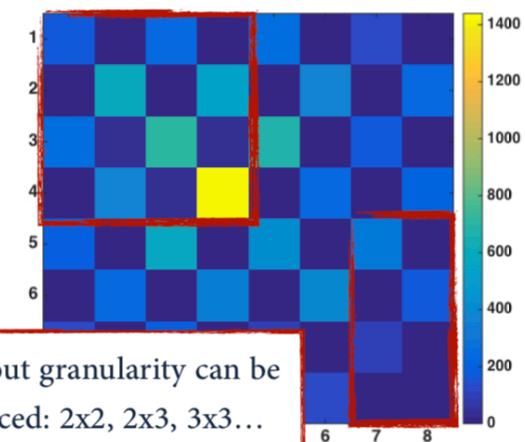
In a full scale module, the number of ***readout channels*** will be of the order of ***10^8***.

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***.



Multi-Photon spectrum preserved also with 9 grouped SiPM.

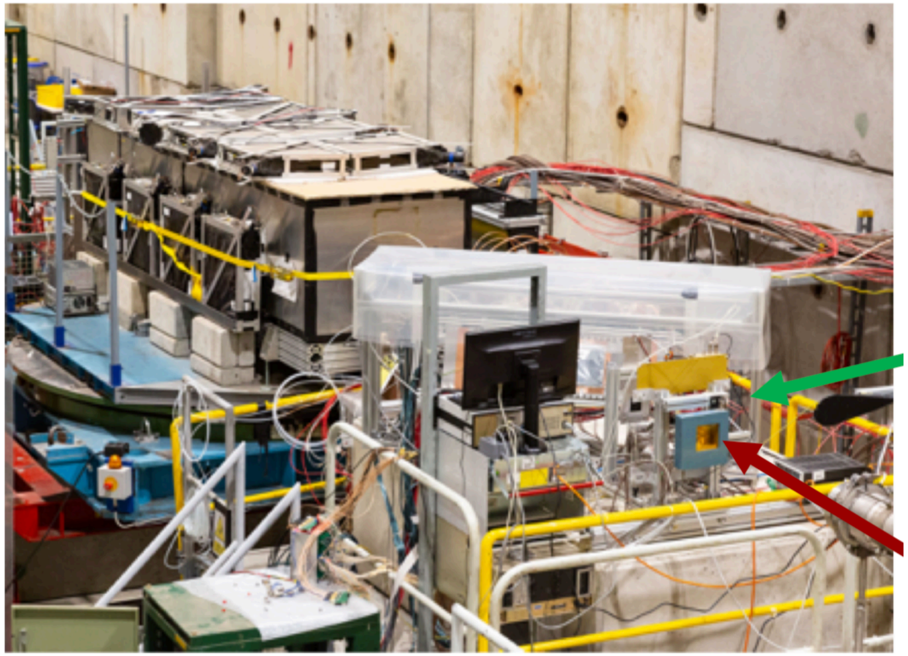


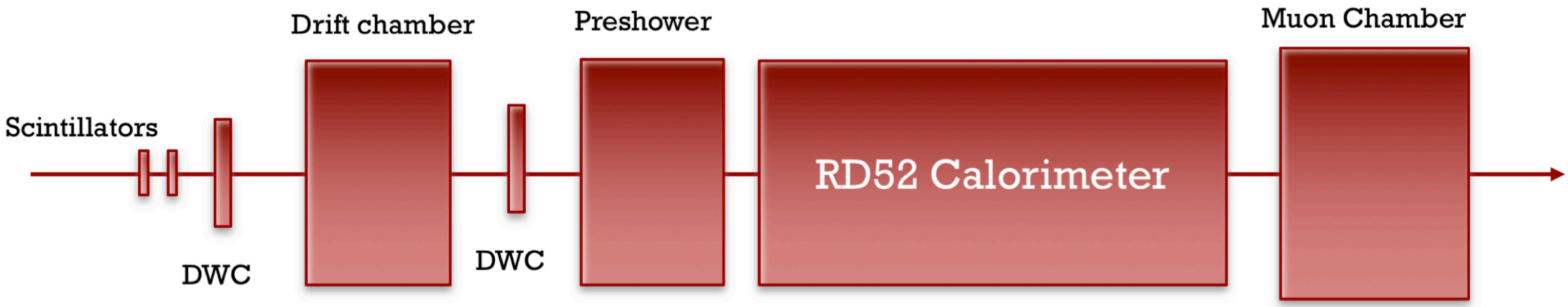
Readout granularity can be reduced: 2x2, 2x3, 3x3…

SiPM number	1	4	8
Space granularity (mm^2)	4.5	18	36

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





EM showers: relevant numbers

- Radiation length X_0: typical scale of longitudinal shower development

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

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

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

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

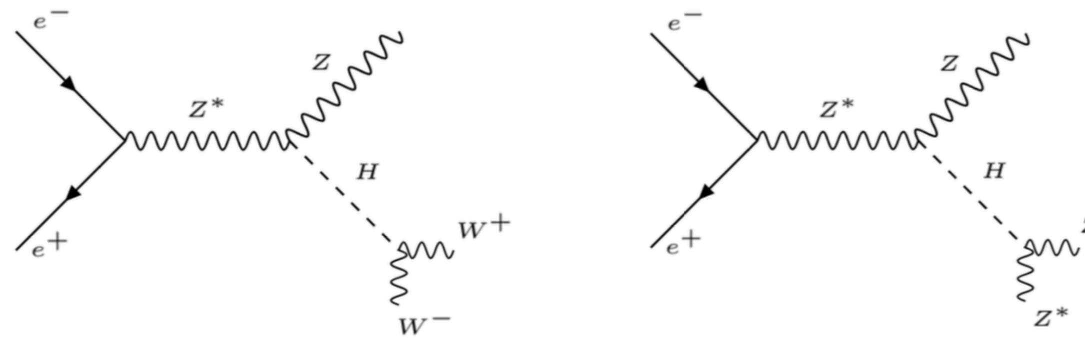
$$R_M \sim \frac{X_0 \times 21.2\ \mathrm{MeV}}{E_C} \Longrightarrow \sim const$$

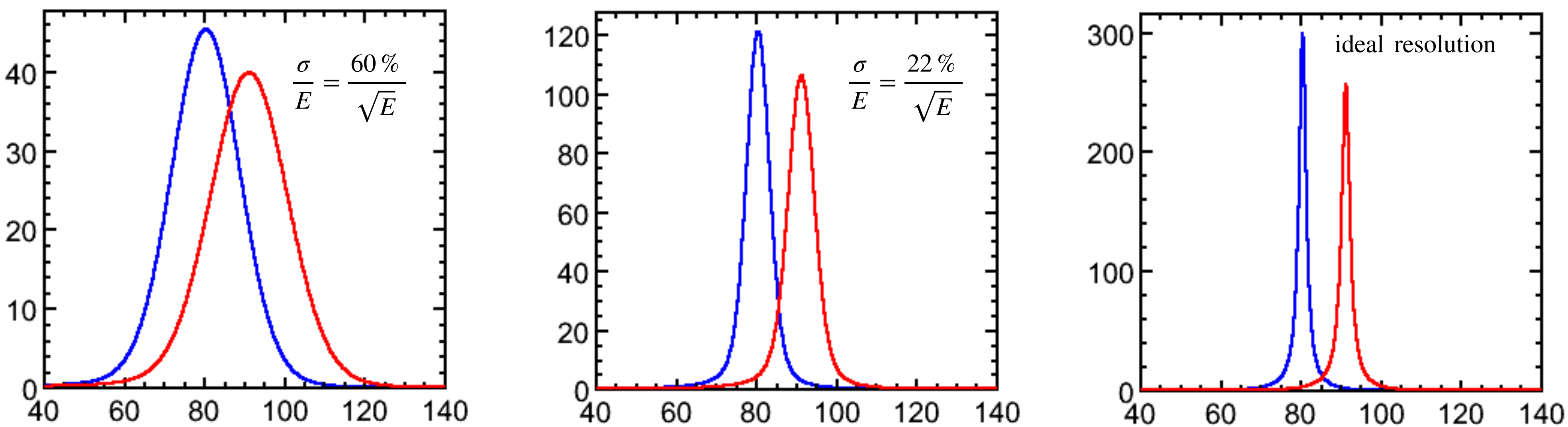
- Shower depth (shower maximum), where the multiplication process stops

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

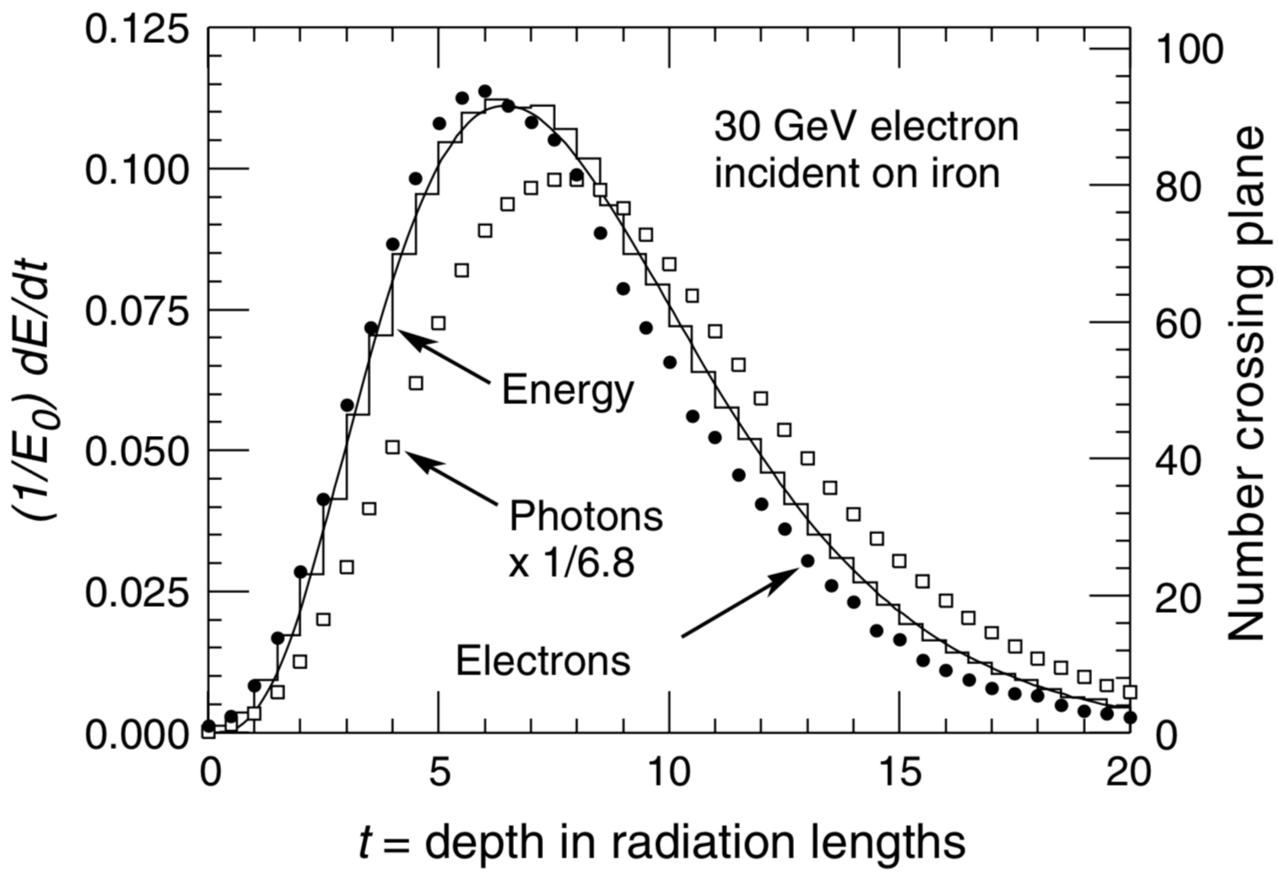
Reminder: why dual readout?

- 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

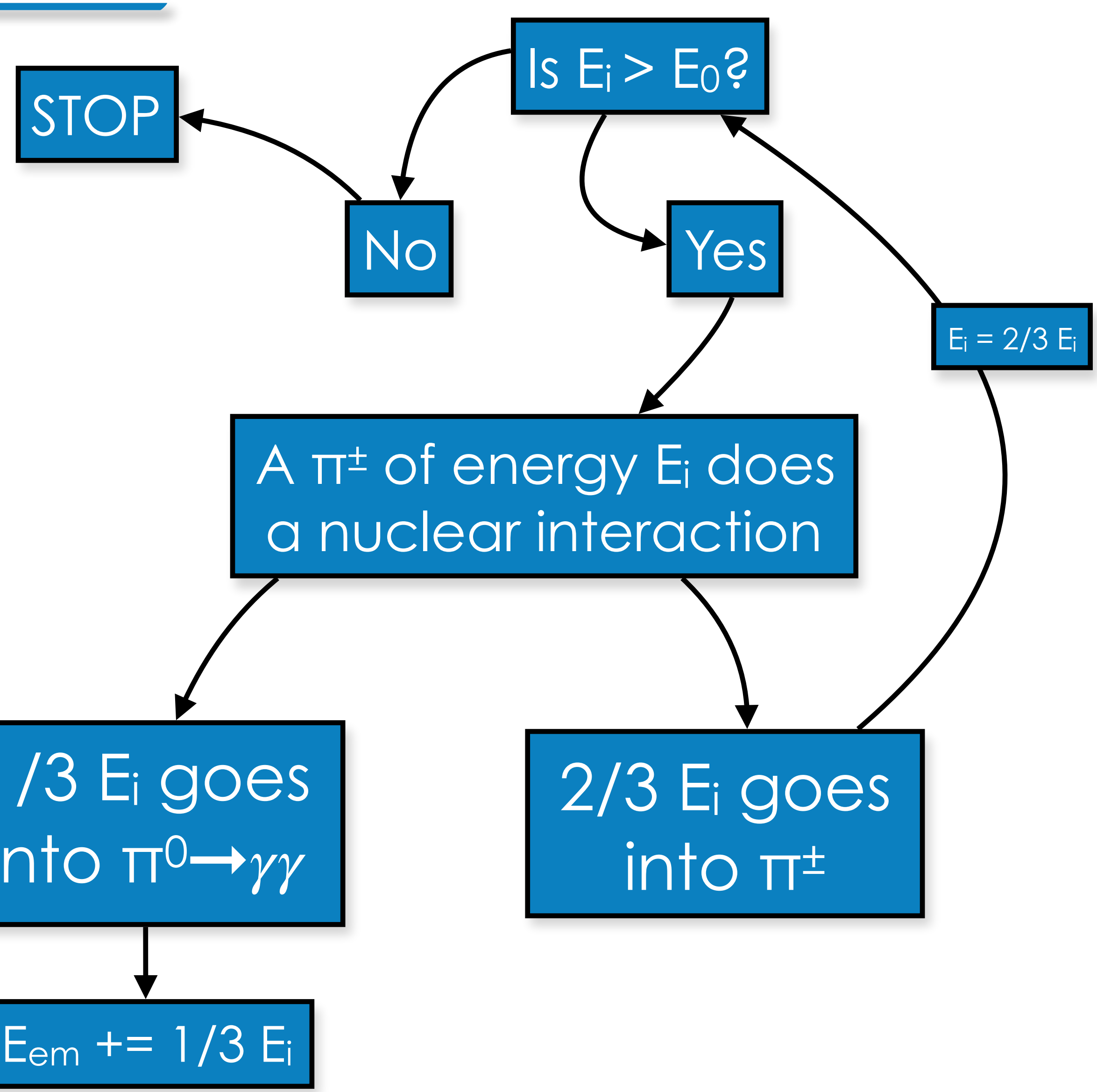
- Simple model: **only pions** are produced at each interaction, **respecting isospin symmetry**
- Then the math is:

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

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

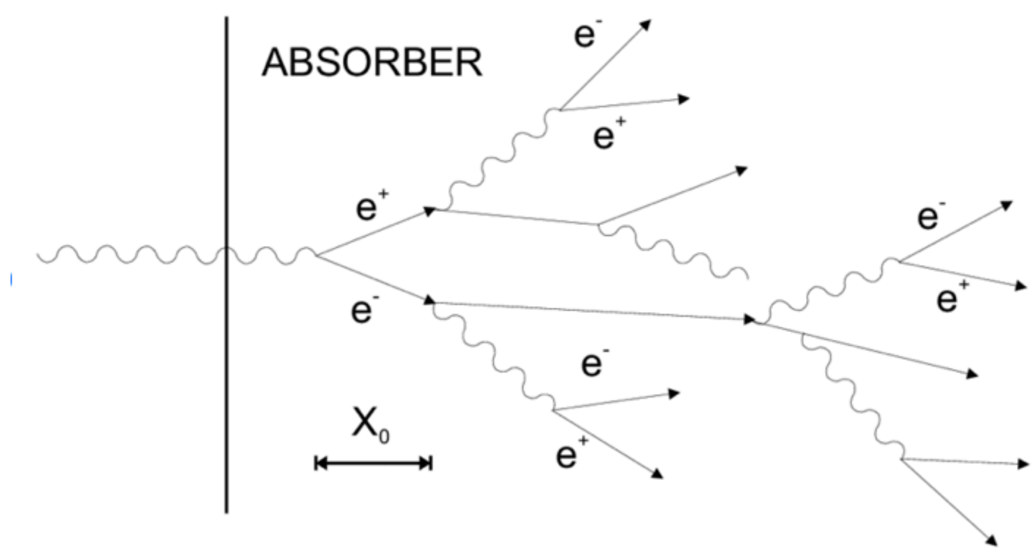
$$n = p \ln \frac{E}{E_0}$$ (for some number p)

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



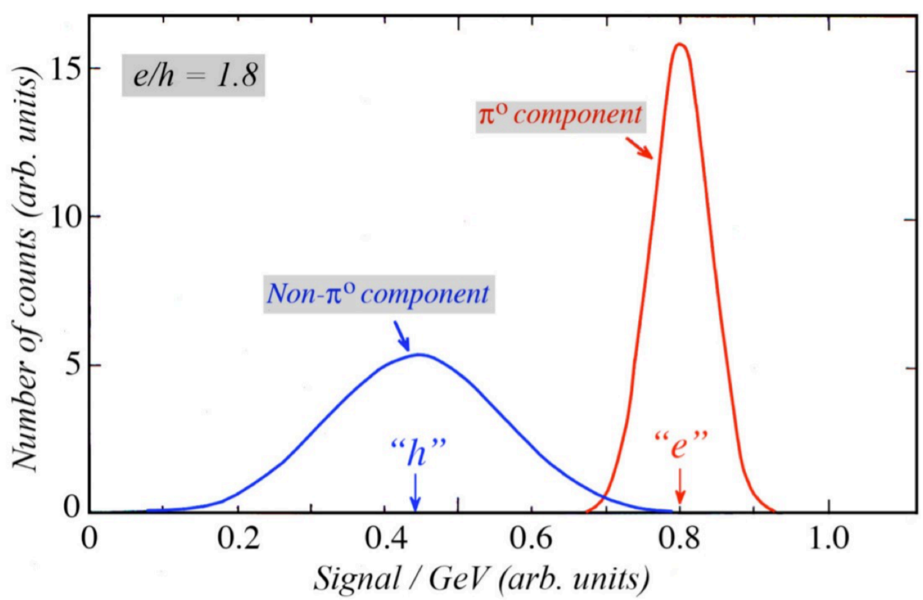
Calorimetry - a primer

- 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

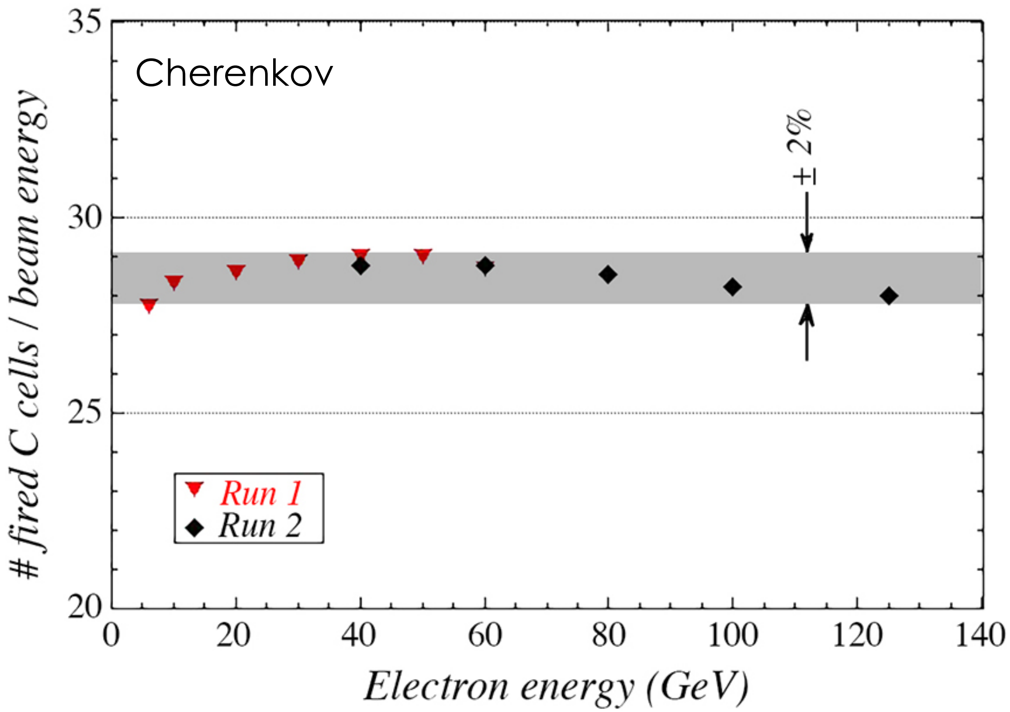


Measuring hadronic showers

- 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**.

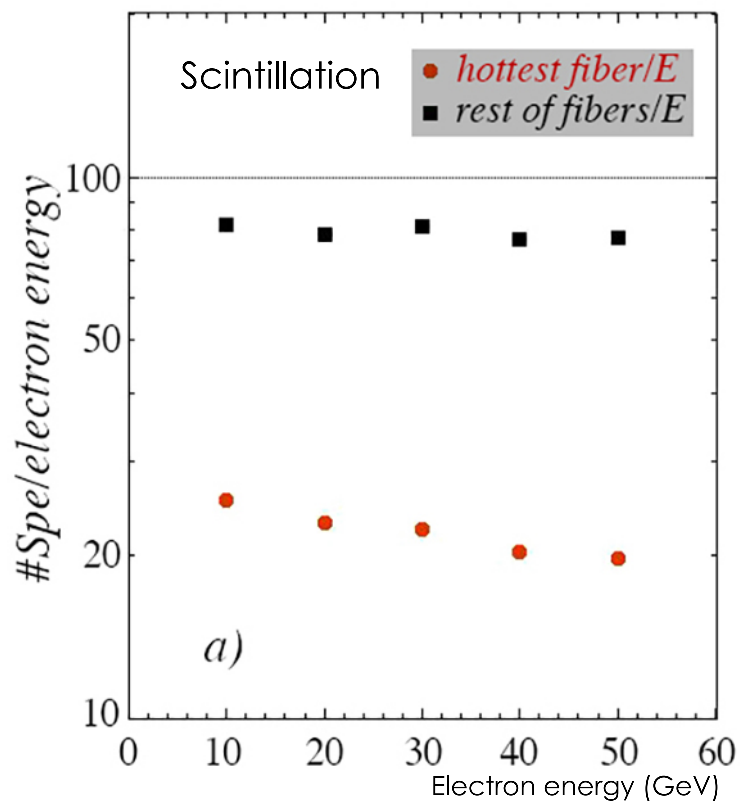


SiPM readout - results (test beam 2017)



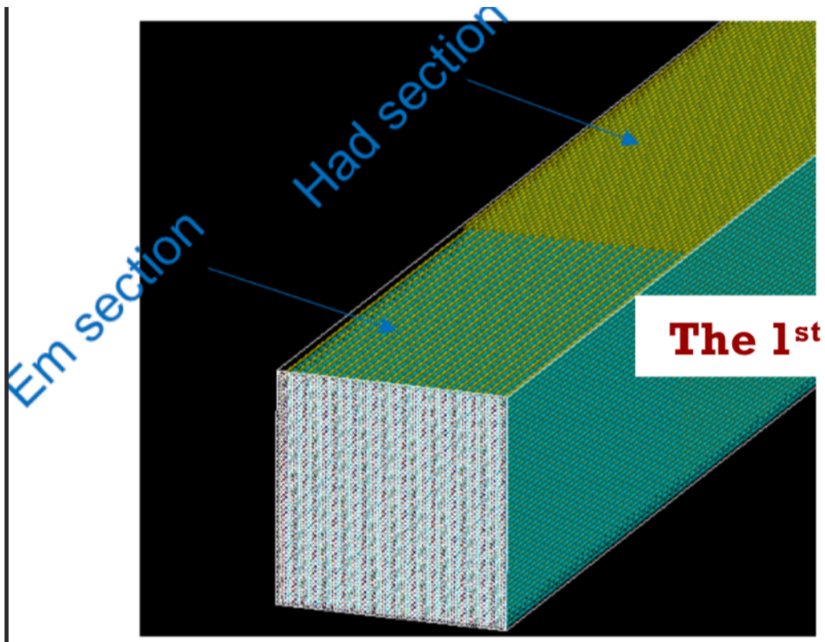
- Cherenkov light yield linear with beam energy over a wide range
- Light yield 28 Spe/GeV:
  - After correcting for containment ~ 55 Spe/GeV.

- 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