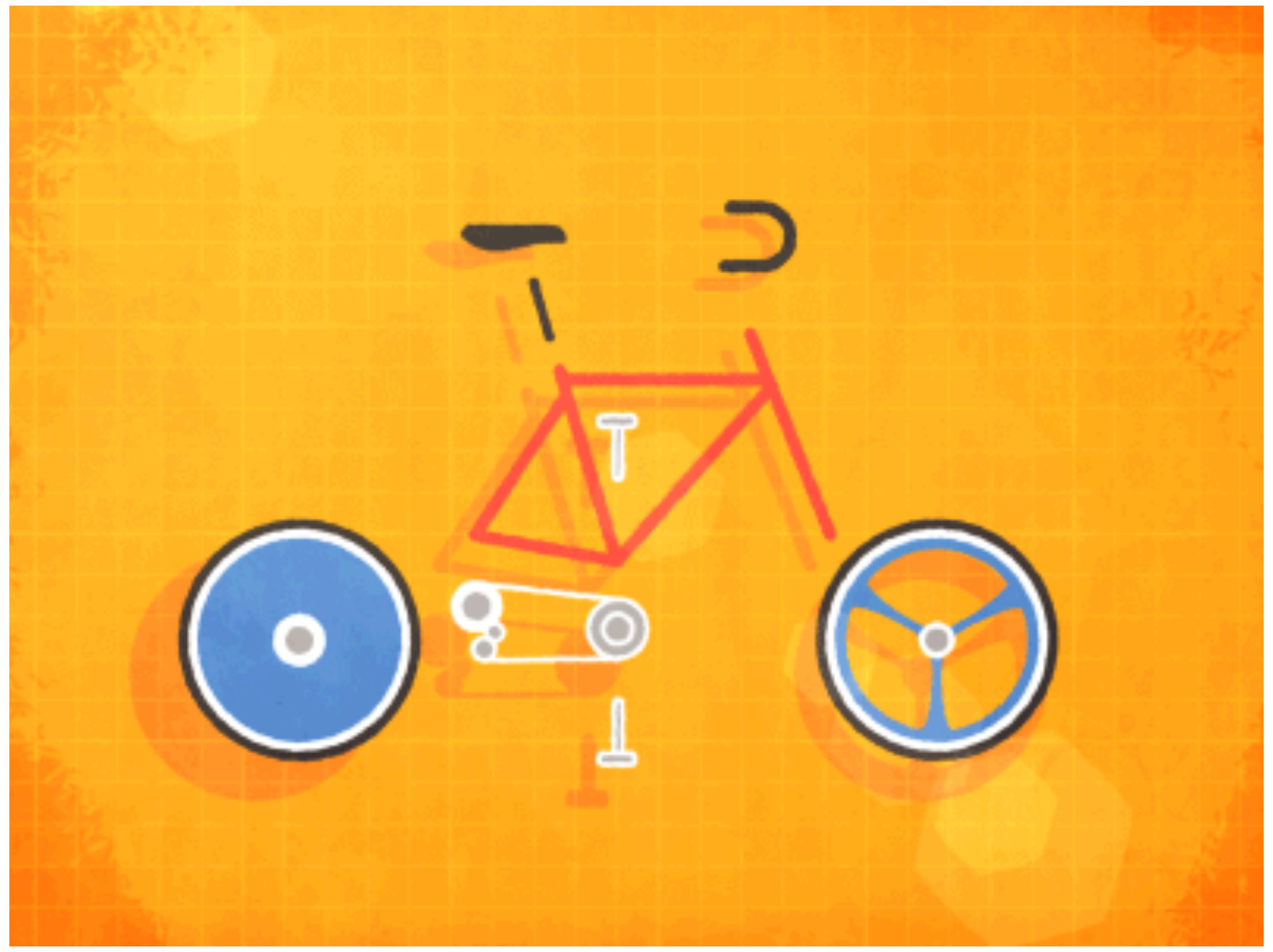
Experiment & sub-detectors: a summary of the key concepts presented and discussed



IAS program in High Energy Physics
HKUST Jockey Club
January 23rd 2019

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* Disclaimer:

Mistakes & misunderstandings are all mine; no fault attributed to the quoted authors/speakers

* Apologies:

- towards authors/speakers not quoted for not being able to fit you in my scheme;
- towards speakers of the session which I was supposed to review but that is taking place AFTER my speech :(

✱ the specs of the racing bicycle we intend to design & build:

What for:

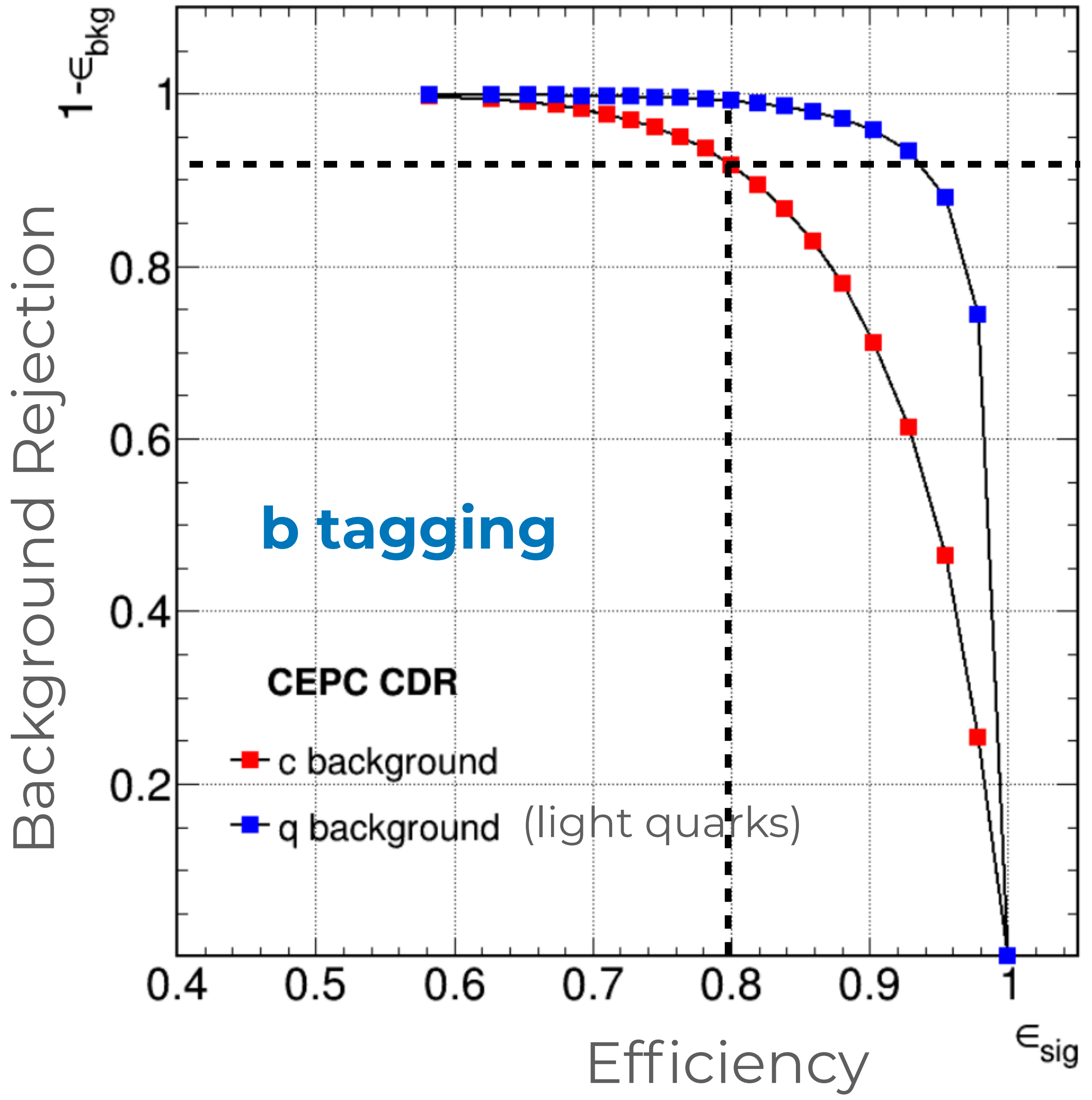
Performance requirement	Detector subsystem	Measurands	Physics process
$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$	Tracker	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$
$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$	Vertex	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	$H \to b\bar{b}/c\bar{c}/gg$
$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV	ECAL HCAL	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	$H \to q\bar{q}, WW^*, ZZ^*$
$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$	ECAL	$\mathrm{BR}(H \to \gamma\gamma)$	$H \to \gamma\gamma$

CAVEAT: the specs are driven by the “high energy” operation; running at the Z pole may require something different and impose complementary constraints.

Contributors:

- Paolo Giacomelli
- Wei-Ming Yao
- Manqui Ruan
- Xin Shi
- Zhijun Liang

Flavour tagging:



✳b tagging:

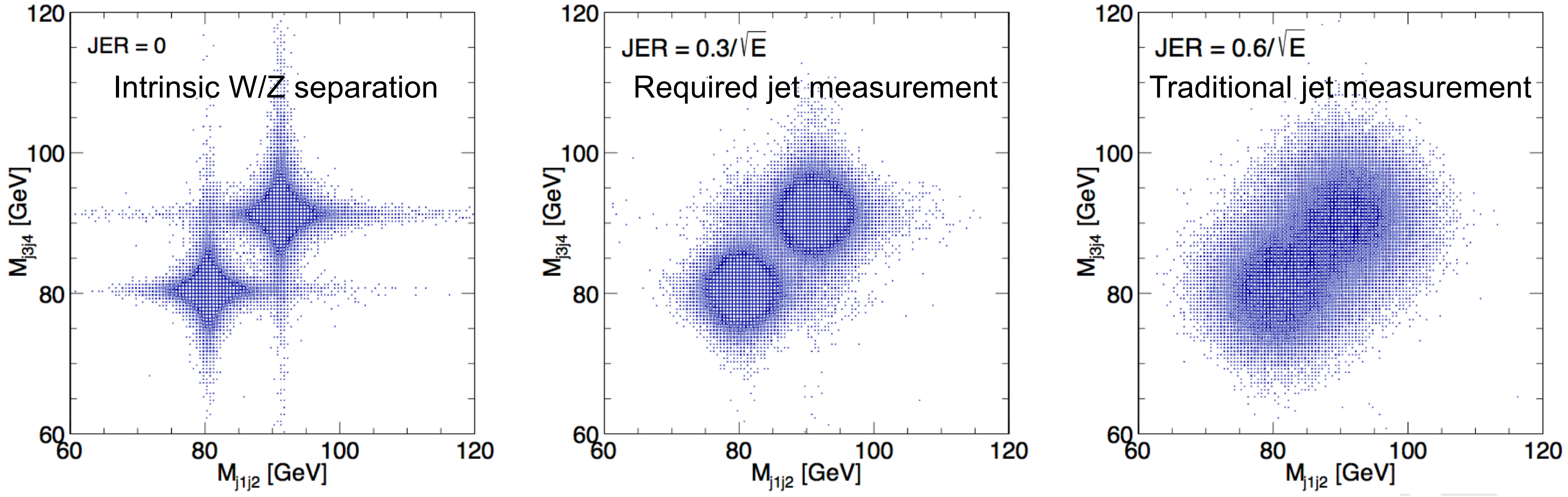
- efficiency: 80%
- purity: 90%

✳c tagging:

- efficiency: 60%
- purity: 60%

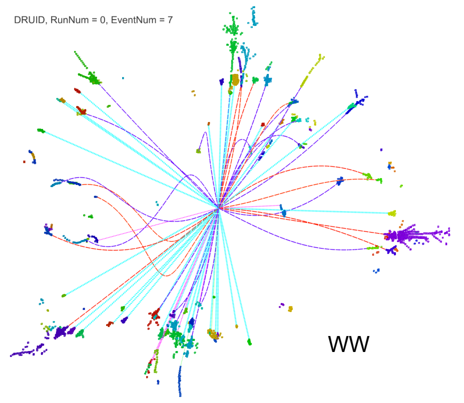
Q: how comes that performance are not incredibly better than DELPHI?

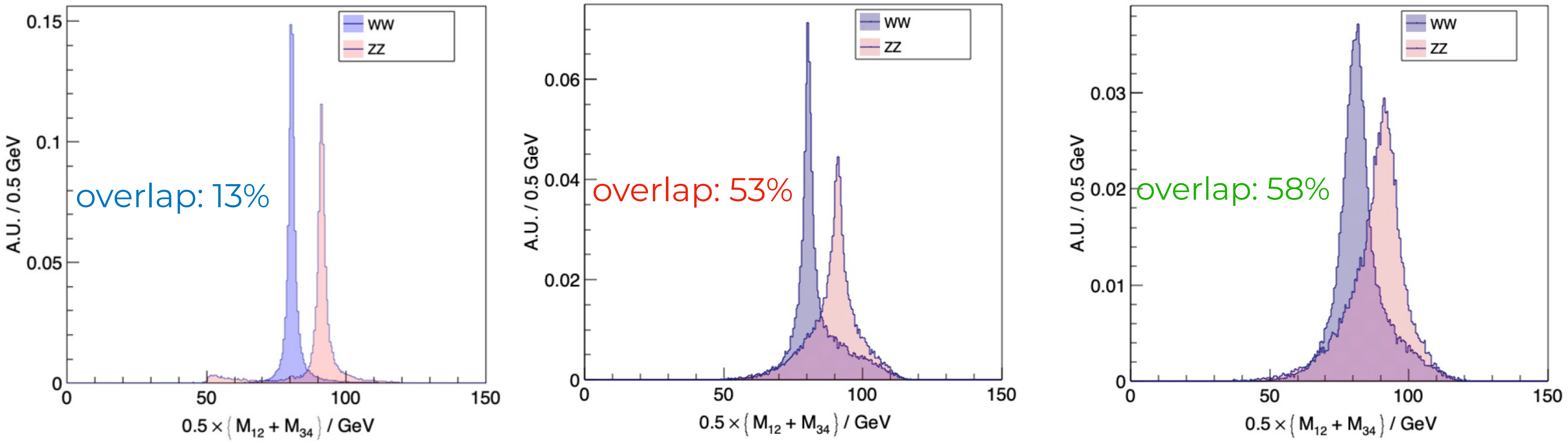
Separation of fully hadronic (4 jet) events from H →WW* or H →ZZ*:



Janbei Liu

but what is actually the most relevant term in spoiling your resolution?





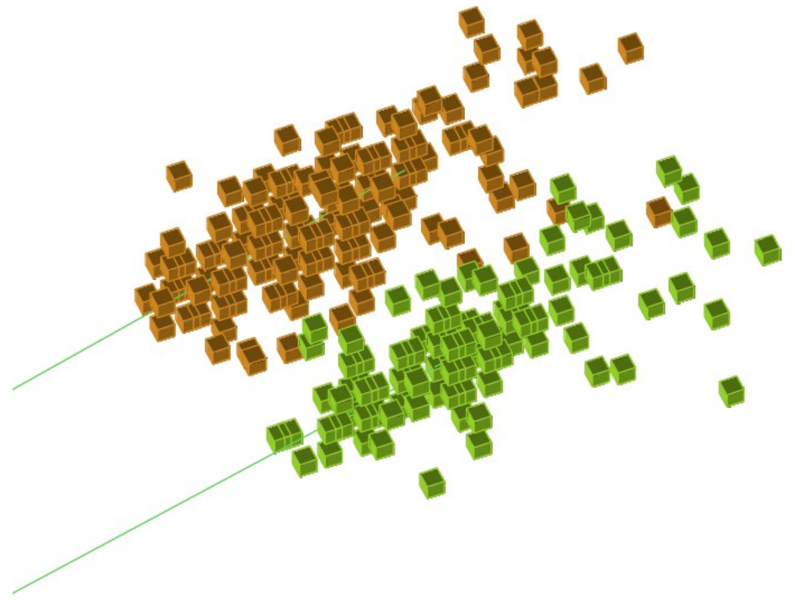
Manqui Ruan

"intrinsic" distribution

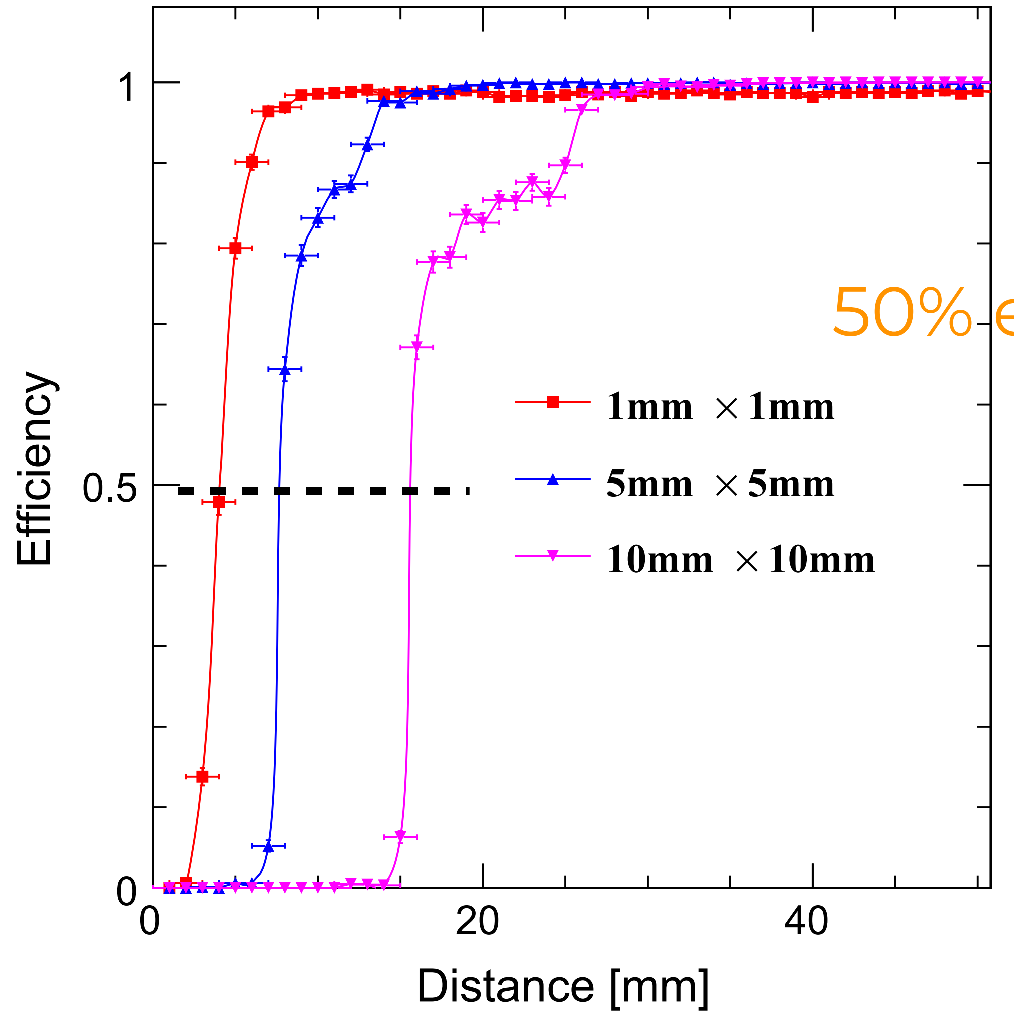
after jet clustering (and a perfect detector)

after jet clustering (and a "realistic"detector)

π^0 reconstruction:



Shoot pair of 5 GeV photons into the e.m. calo and see when they start to be merged as the granularity changes



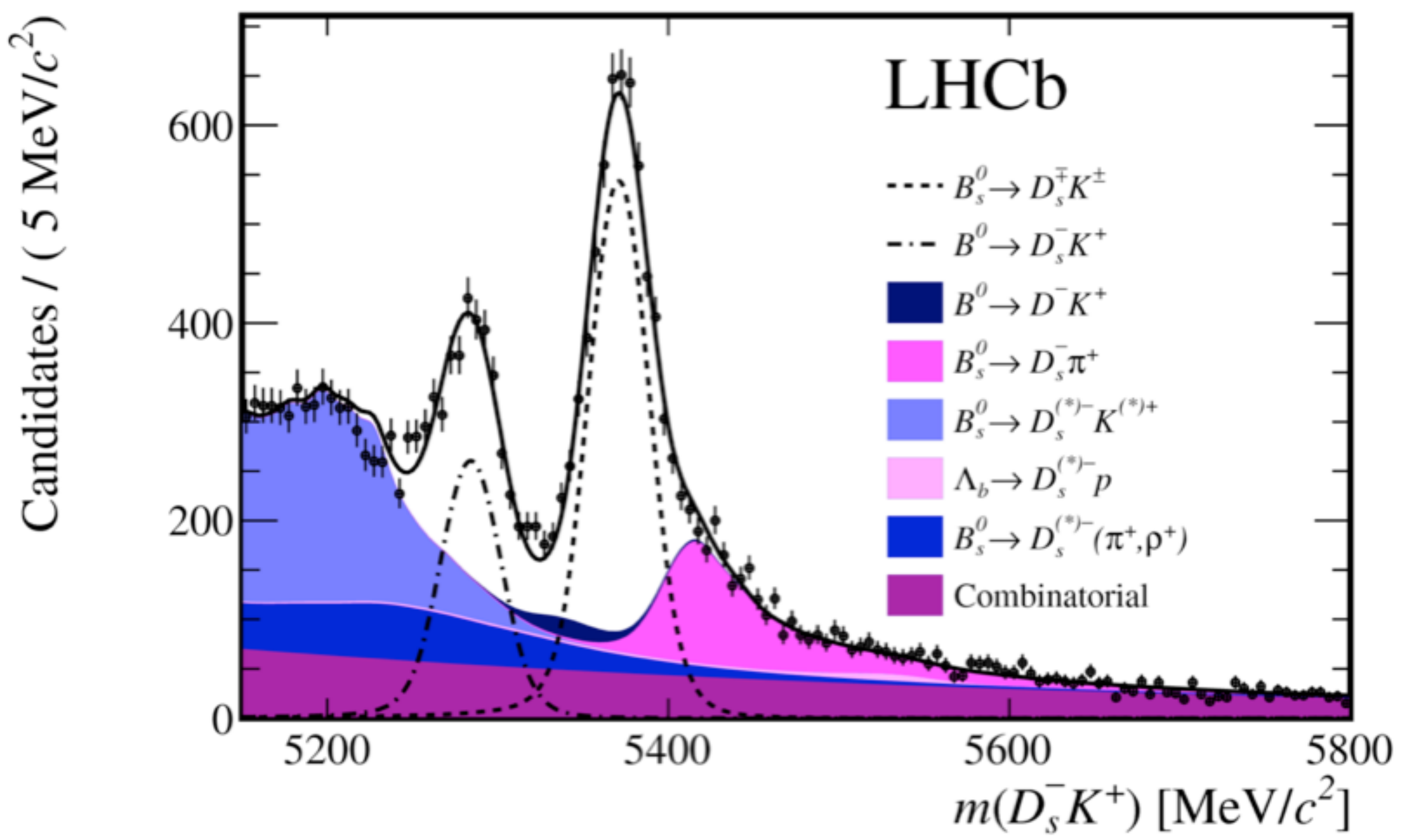
50% efficiency at:

(4 mm)
(9 mm)
(16 mm)

This is for a W base e.m calo with $R_M \approx 1$ cm

Particle identification:

$B_s \rightarrow D_s$ K for CP violation studies



Q: is the current detector good enough for Heavy Flavour Physics at the Z pole?

quoting P. Giacomelli who quotes F. Bedeschi

Anything to win at the High Energy operation (Wei-Ming Yao)? IMPROVED b/c tagging?

still room for optimization:

Xin Shi

Property	Estimated Precision CEPC-v1		Estimated Precision CEPC-v4	
m_H	5.9 MeV		5.9 MeV	
Γ_H	2.7%		2.8%	
$\sigma(ZH)$	0.5%		0.5%	
$\sigma(\nu\bar{\nu}H)$	3.0%		3.2%	
Decay mode	$\sigma \times$ BR	BR	$\sigma \times$ BR	BR
$H \to b\bar{b}$	0.26%	0.56%	0.27%	0.56%
$H \to c\bar{c}$	3.1%	3.1%	3.3%	3.3%
$H \to gg$	1.2%	1.3%	1.3%	1.4%
$H \to WW^*$	0.9%	1.1%	1.0%	1.1%
$H \to ZZ^*$	4.9%	5.0%	5.1%	5.1%
$H \to \gamma\gamma$	6.2%	6.2%	6.8%	6.9%
$H \to Z\gamma$	13%	13%	16%	16%
$H \to \tau^+\tau^-$	0.8%	0.9%	0.8%	1.0%
$H \to \mu^+\mu^-$	16%	16%	17%	17%
$\mathrm{BR}^{\mathrm{BSM}}_{\mathrm{inv}}$	–	$< 0.28\%$	–	$< 0.30\%$

Changes between v1 & v4 (the CDR baseline detector):

1. B-Field reduce from 3.5T to 3T
2. E_{cal} Cell Size increased from 5mm to 10mm
3. H_{cal} Layer number reduced from 48 to 40.

see talk by Gang Li TODAY (afternoon) on the development of software tools

perspectives for the measurements of the EW parameters:

Zhijun Lang

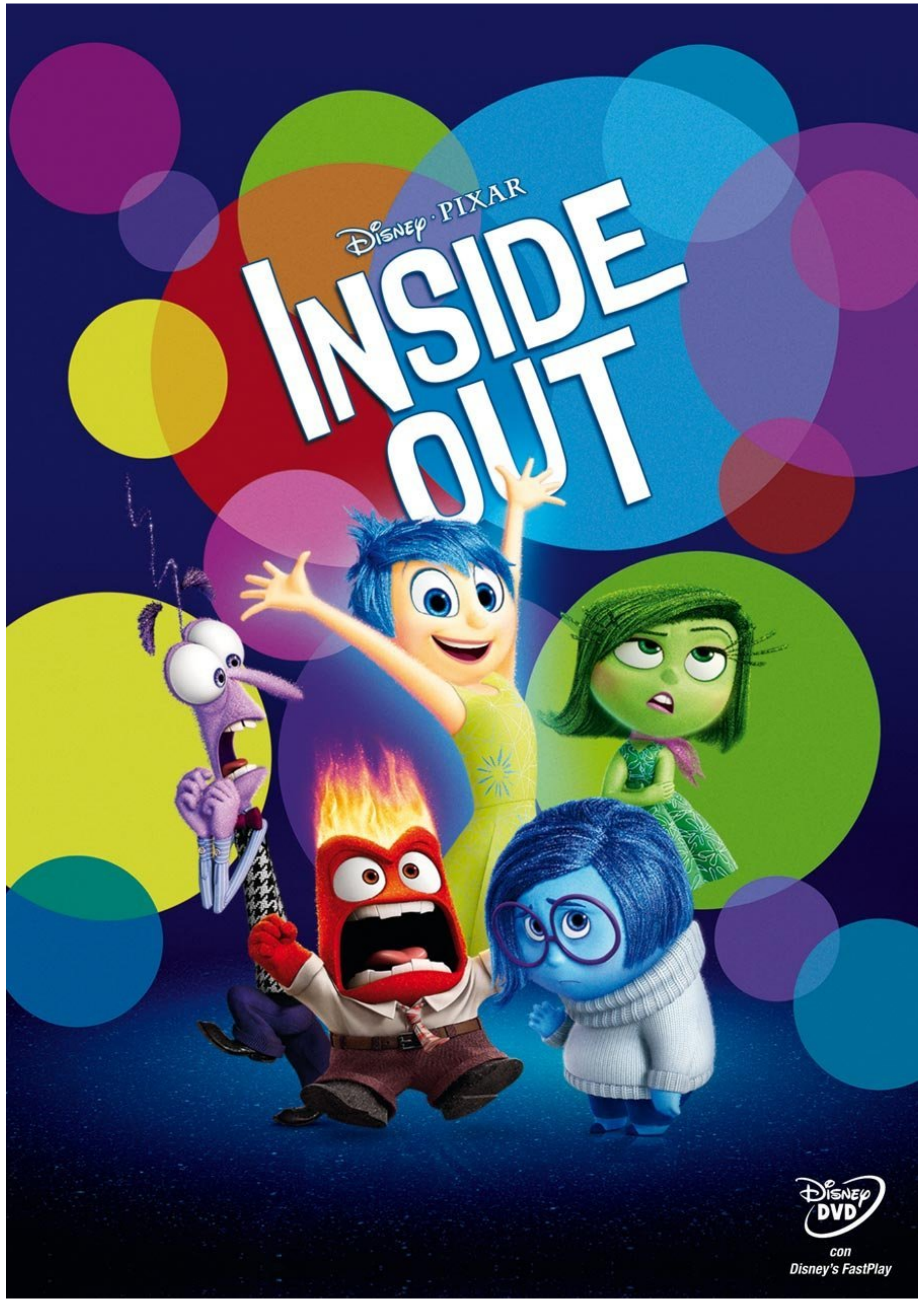
Observable	LEP precision	CEPC precision	CEPC runs	CEPC $\int \mathcal{L}dt$
m_Z	2.1 MeV	0.5 MeV	Z pole	8 ab^{-1}
Γ_Z	2.3 MeV	0.5 MeV	Z pole	8 ab^{-1}
$A_{FB}^{0,b}$	0.0016	0.0001	Z pole	8 ab^{-1}
$A_{FB}^{0,\mu}$	0.0013	0.00005	Z pole	8 ab^{-1}
$A_{FB}^{0,e}$	0.0025	0.00008	Z pole	8 ab^{-1}
$\sin^2\theta_W^{\mathrm{eff}}$	0.00016	0.00001	Z pole	8 ab^{-1}
R_b^0	0.00066	0.00004	Z pole	8 ab^{-1}
R_μ^0	0.025	0.002	Z pole	8 ab^{-1}
m_W	33 MeV	1 MeV	WW threshold	2.6 ab^{-1}
m_W	33 MeV	2–3 MeV	ZH run	5.6 ab^{-1}
N_ν	1.7%	0.05%	ZH run	5.6 ab^{-1}

I personally like the idea that the precision on N_ν comes by the direct measurement through the reaction:

$$e^-e^+ \to \nu\bar{\nu}\gamma \qquad \sigma^0_{\nu\nu\gamma}(s) = \frac{12\pi}{m_Z^2}\frac{s\Gamma_{ee}N_\nu\Gamma_{\nu\nu}}{(s-m_Z^2)+s^2\Gamma_Z^2/m_Z^2}$$

apparently more robust against systematics

A look at the different detector sub-systems



✱ Beam pipe & Vertex Detector; the boundary conditions for the development are determined by:

✳ **the performance:**

$$\sigma_{ip} = a \oplus \frac{b}{p \cdot \sin^{3/2}\theta}$$

- **a** depends on the **single point resolution, the geometry** (Inner & outer layer), the number of layers
- **b** depends on the Coulomb multiple scattering, i.e. t**he material budget in the beam pipe and the detector** [dominated by the closer layer]

✳ **the beam induced background,** dominated by the e+e- following a photon-photon interaction during the beam crossing: process:

	H (240)	**W** (160)	**Z** (91)
Hit Density [hits/cm^2·BX]	2.4	2.3	0.25
TID [MRad/year]	0.93	2.9	3.4
NIEL [10^{12} 1 MeV n_{eq}/cm^2·year]	2.1	5.5	6.2

- constraining the **read-out time** to limit the occupancy at the 1% level

Contributors:

- M.C.
- Emilia Leogrande
- Laci Andricek
- Rafael Coelho
- Ryuta Kuichi
- Yang Zhou

✴ the performance:

$$\sigma_{ip} = a \oplus \frac{b}{p \cdot \sin^{3/2}\theta}$$

Past & future figures:

	Accelerator	a [μm]	b [μm·GeV/c]
	LEP	25	70
	SLC	8	33
	LHC	12	70
	RHIC-II	13	19
ILD LOI 2009	ILC	< 5	< 10
CDR - 2018	**CEPC:**	**5**	**10**

single point resolution & the geometry

$$\sigma^2_{\tilde{y}} = \frac{\sigma^2_{single\,point}}{n} \times \left[1 + 12\frac{n-1}{n+1}\left(\frac{R_{mean}}{\Delta R}\right)^2\right]$$ = 25 μm²

R_{in} [mm]	R_{out} [mm]	n	$\sigma_{single\ point}$ [μm]
16	32.5	3	2.3
16	60.0	3	3.7

the material budget in the beam pipe and the detector:

Machine/Exp.	R_{bp} [mm]	Thickness [mm]	x/X_0 [%]	$b_{beam\ pipe}$ [μm]
LEP/DELPHI	56	1.4	0.40	48
LHC/ATLAS	23.5	0.8	0.23	15
ILC/TESLA Det.	14	0.5	0.14	7
CEPC (CDR2018)	**15**	**0.5**	**0.14**	**8**

$$b \approx 10\mu m \rightarrow x_{VTX\ inner\ layer}/X_0 \leq 0.15\%$$

namely an effective silicon thickness of 140 μm

✴**the beam induced background;** once more, some back-of-an-envelope calculations:

- **2.4 hits/cm²/BX**
- **20x20 μm² pixels ⇒ 1/4 Megapixel/cm²**
- **every hit, is generating a 3x3 pixel cluster ⇒ about 20 fired pixels/cm²/BX**

⇒ targeting 1% occupancy, the maximum number of BX you can integrate is 125, namely

Δt = 85 μs for 1 cm² sensor

meaning that I either have

- ONE full frame read-out in less than 85 μs [independent from the no. of fired pixels]

or, in a data-driven (push) architecture,

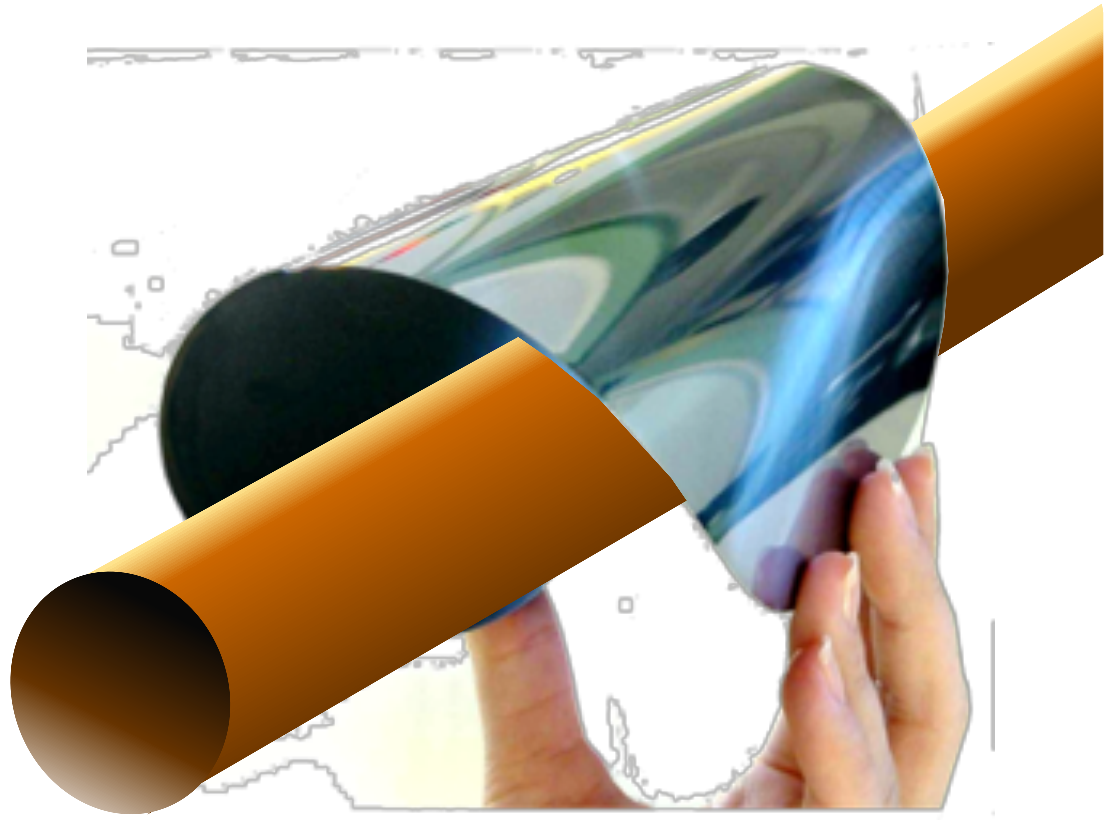
- 2500 pixels (1% of the existing ones) addressed & read-out (effective read-out time ÷ no. fired pixels), namely **34 ns/pixel**

no matter the architecture, you have to be FAST ⇒ “burn” energy ⇒ “grow in mass”

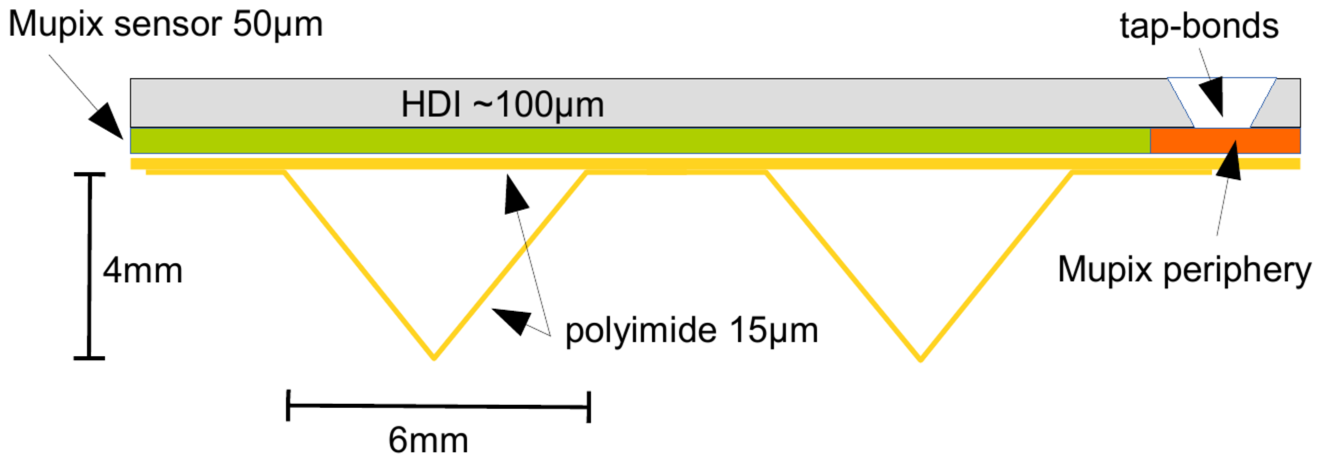
✳ mechanics & integration (Rafael, Laci, M.C.):

- If air cooling works:
(namely if I have a power density **~ 20 mW/cm²**)

- flexible silicon:



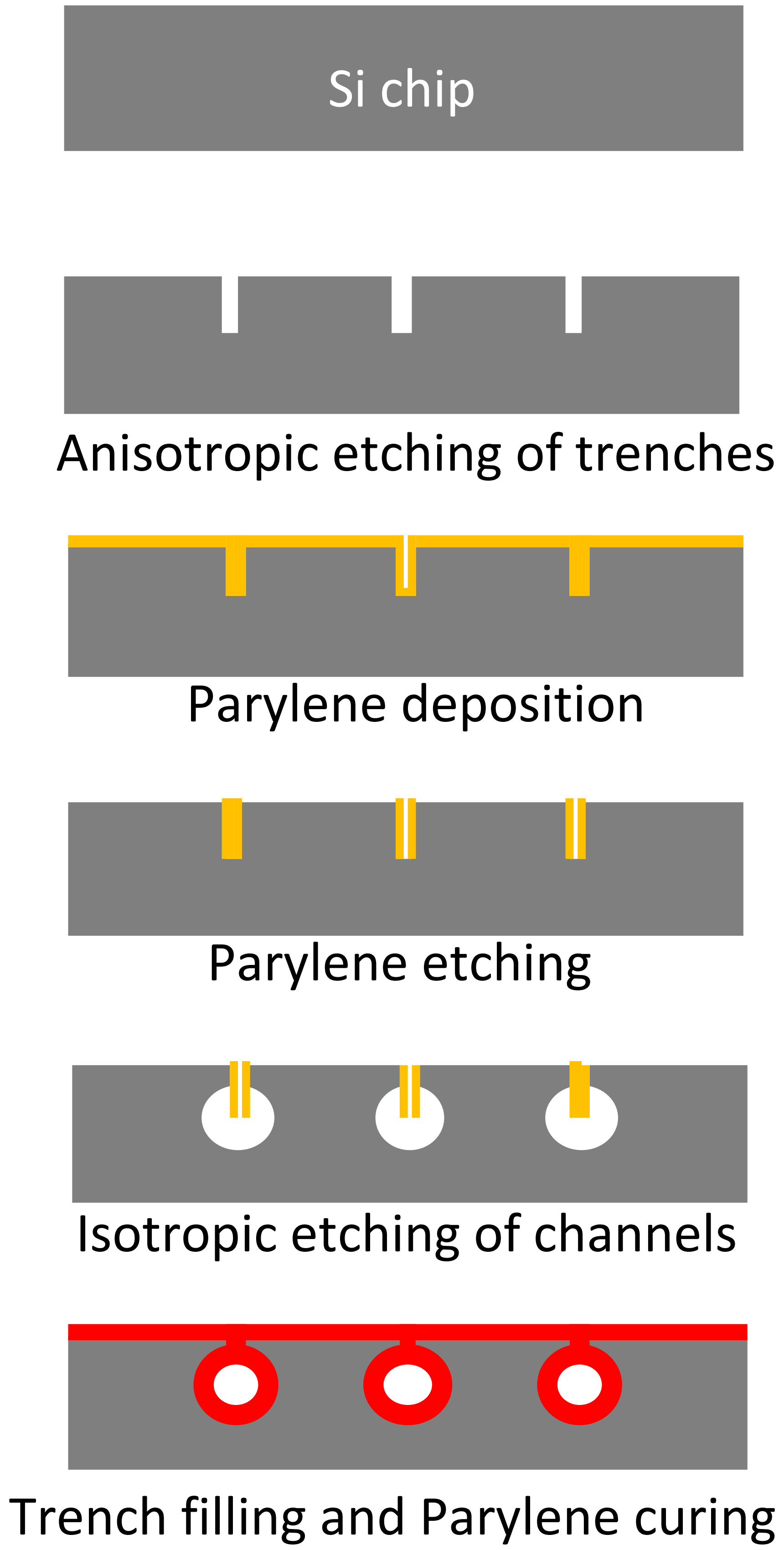
- look at

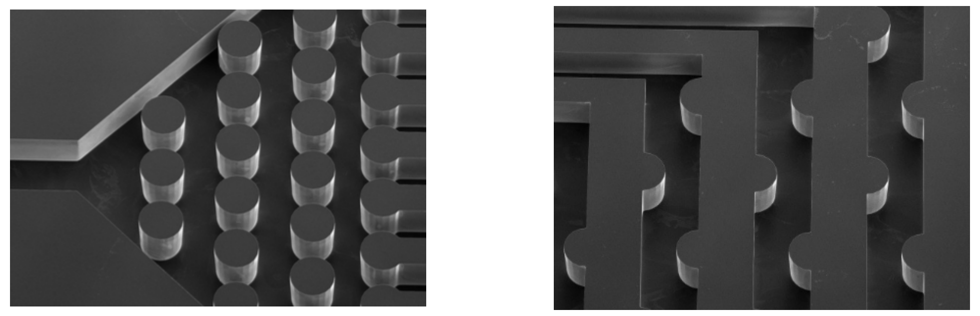


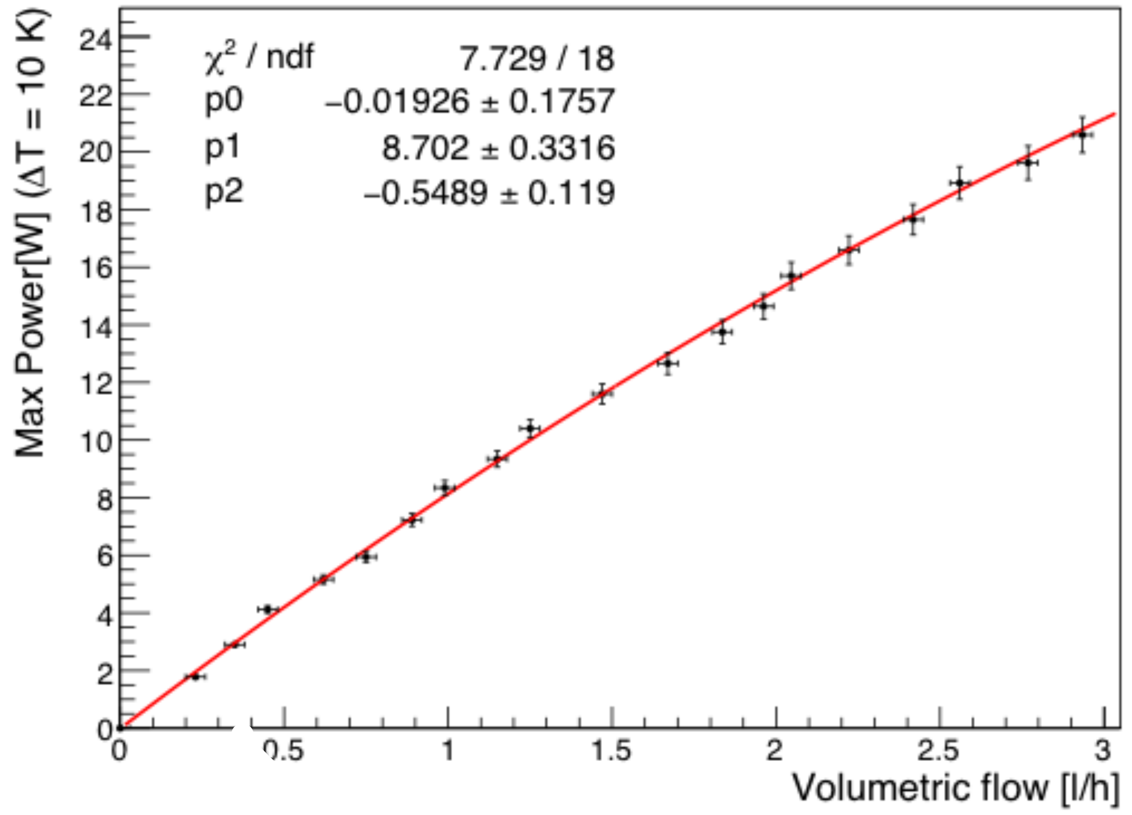
thickness 0.1%X_0/layer

- otherwise:

- start by the integration of cooling pipes in Silicon, pioneered by the DEPFET team at MPI- Munich:

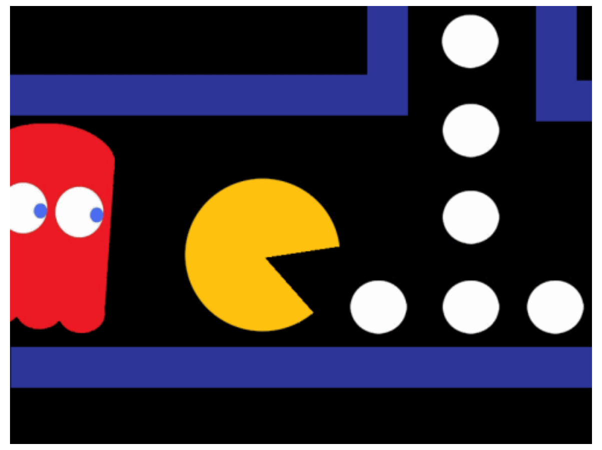






✳ pixel sensors shall be (Laci, Ruyta, Yang, M.C.):

1. Monolithic (or semi-monolithic, e.g. DEPFET)
2. Possibly on high-resistivity substrates
3. Binary ■ □
4. if compliant with the Z-pole run, based on a data driven architecture



✳ there's a tremendous effort around the world, notably in China (Ruyta, Yang):

	Process	Pixel Pitch (μm^2)	Matrix size	R/O architecture
"JadePix1"	CMOS	33x33/16x16	96x160/192x128	Rolling Shutter
"JadePix2"	CMOS	22x22	128x64	Rolling Shutter
"MIC4"	CMOS	25x25	112x96	Asynchronous
"CPV2"	SOI	16x16	64x64	Rolling Shutter

MIC4

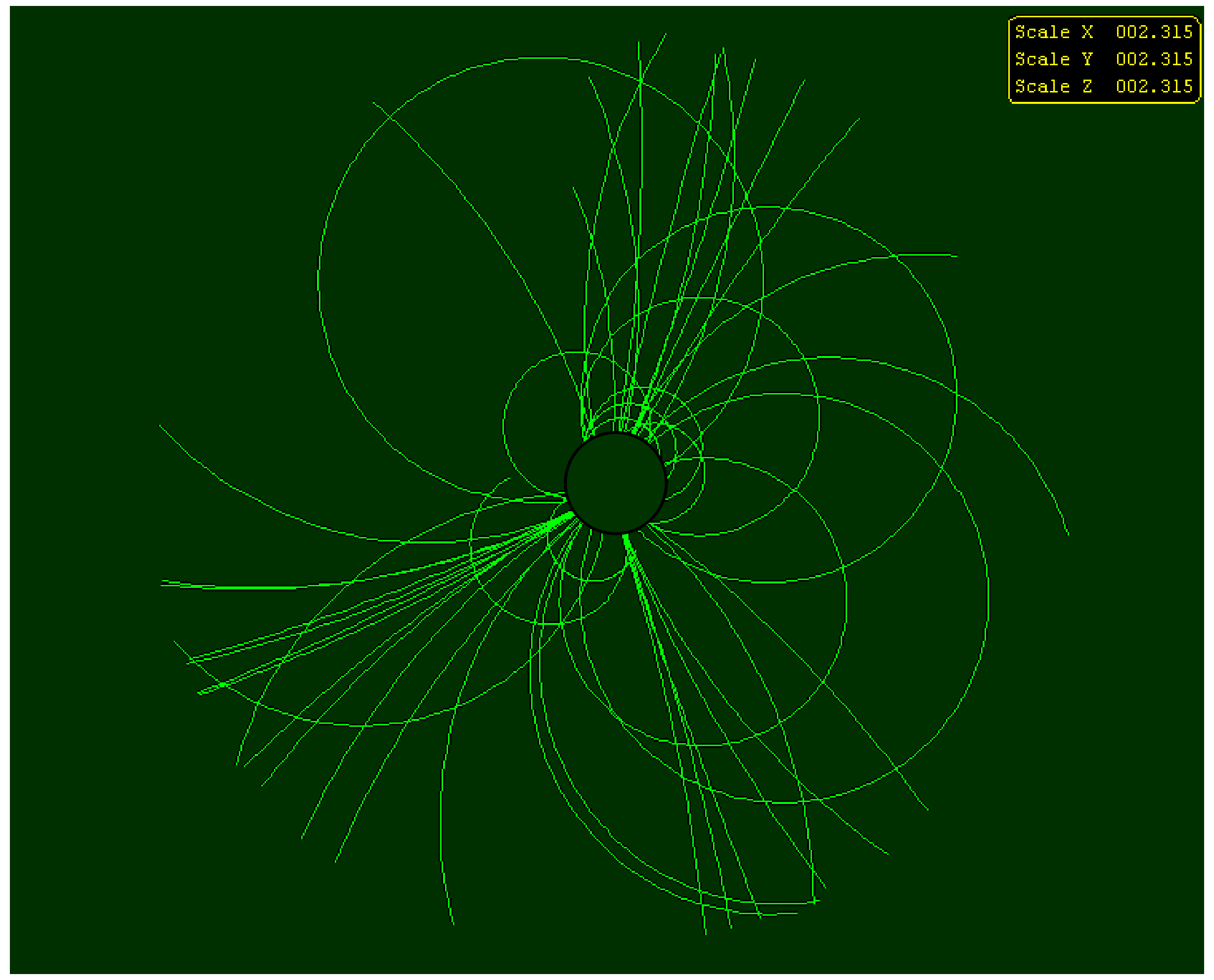
- Chip overview:
  - *3.1 × 4.6 mm²; 128 × 64 pixels*
  - *2 Pixel front-end versions,*
  - *both two pixel versions pitch size=25 μm;*
  - Processing speed: data-driven asynchronous
    - 25 ns/pixel; ⇐
  - Matrix Power:
    - < 20 mW/cm² ; ⇐
  - Data driven readout:
    - Real time readout
    - High speed data link of 1.2 Gbps

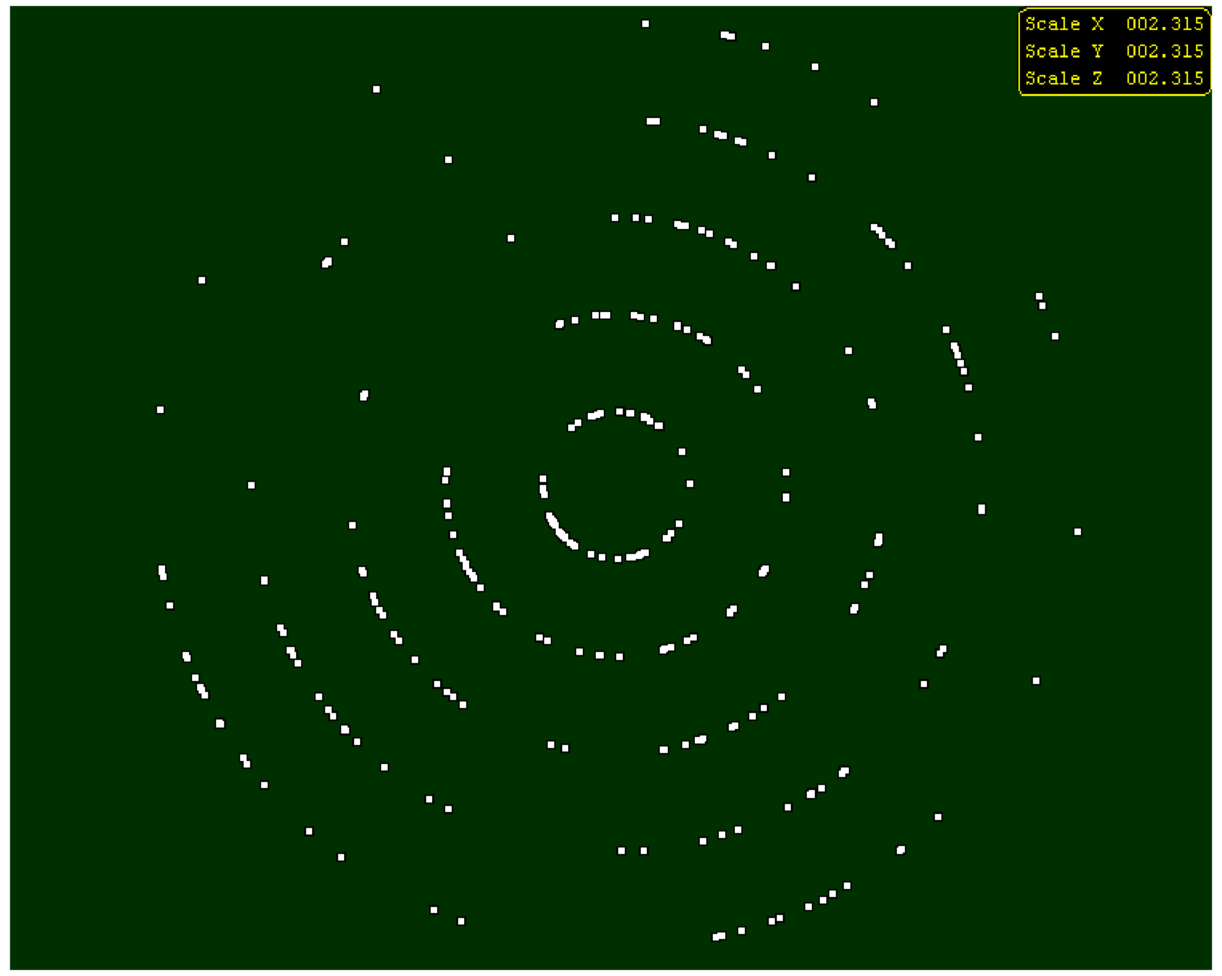
But, as of today, there is NO SENSOR featuring:

- **single point resolution at the 3 μm level**
- **thickness at the 0.1% X_0 level**
- **power dissipation not exceeding 20 mW/cm²**
- **being read-out in less than 80 μs/cm²**
- **scaled-up to "reticle size" area**

✱ Central Tracker:

Having to make a choice based on your own eyes, what would you say?





*The SAME event simulated by Graham Wilson in the ILD and SiD detector

Beyond your eyes:

- Gluckstern's formula [PDG] for the curvature resolution δk_{res}:

$$\delta k_{\mathrm{res}} = \frac{\epsilon}{L'^2}\sqrt{\frac{720}{N+4}}$$

- ε single point resolution
- L' projected track length

- dE/dX for Particle ID
- material budget
- robustness
- reliability
- volume
- else…

Not very much on Si Tracking [apart from a presentation on the FCC tailored version of the CLIC detector] but a lot on Gaseous Trackers:

- Paul Colas [TPC]
- Huirong Qi [TPC]
- Piotr Gasik [TPC]
- Franco Grancagnolo [DRIFT CHAMBER]
- Serguei Ganjour [TPC]

✱ Tracking systems at e+e- colliders:

past

SPEAR	MARK2	Drift Chamber
	MARK3	Drift Chamber
DORIS	PLUTO	MWPC
	ARGUS	Drift Chamber
CERS	CLEO1,2	Drift Chamber
PETRA	CELLO	MWPC + Drift Chamber
	JADE	Drift Chamber
	PLUTO	MWPC
	MARK-J	TEC + Drift Chambers
	TASSO	MWPC + Drift Chamber
PEP	MARK2	Drift Chamber
	PEP-4	TPC
	MAC	Drift Chamber
	HRS	Drift Chamber
	DELCO	MWPC + Drift Chamber
TRISTAN	AMY	Drift Chamber
	VENUS	Drift Chamber
	TOPAZ	TPC
BEPC	BES1,2	Drift Chamber

recent past

LEP	ALEPH	TPC
	DELPHI	TPC
	L3	Si + TEC
	OPAL	Drift Chamber
SLC	MARK2	Drift Chamber
	SLD	Drift Chamber
DAPHNE	KLOE	Drift Chamber
VEPP2000	CMD-2	Drift Chamber
PEP2	BaBar	Drift Chamber
KEKB	Belle	Drift Chamber
CESR	CLEO3	Drift Chamber
BEPC2	BES3	Drift Chamber

future

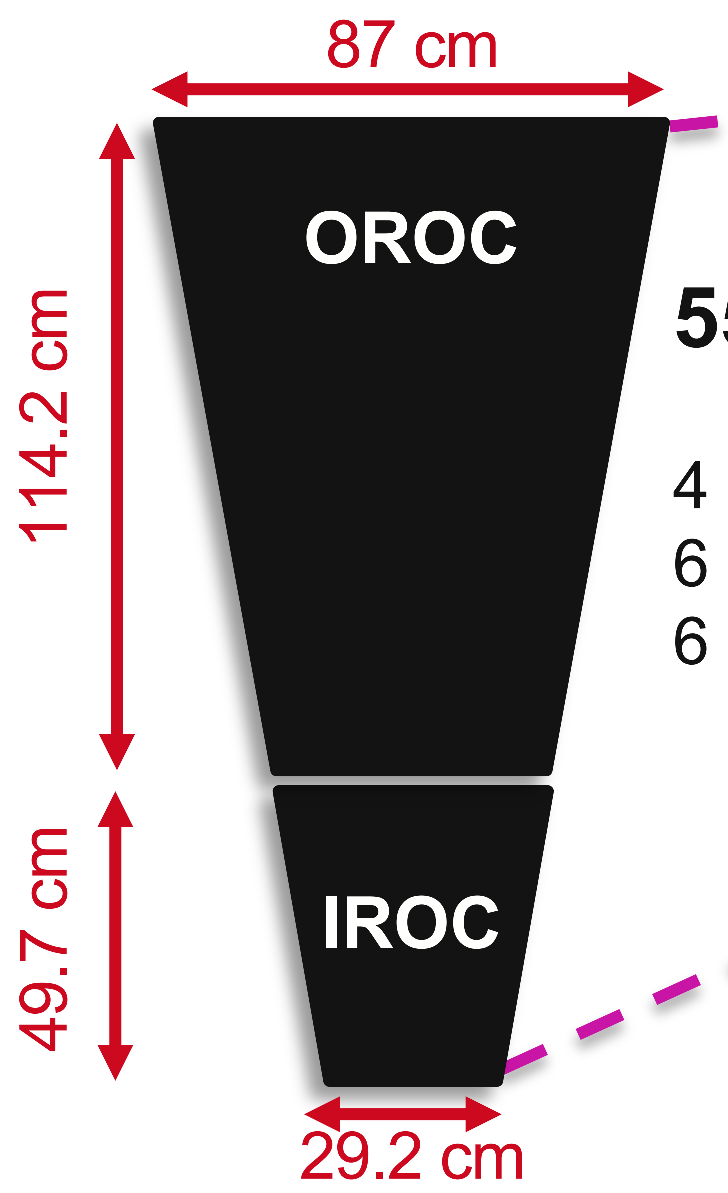
ILC	ILD	TPC
	SiD	Si
CLIC	CLIC	Si
FCC-ee	CLD	Si
	IDEA	Drift Chamber
CEPC	Baseline	TPC / Si
	IDEA	Drift Chamber
KEKB	Belle2	Drift Chamber
SCTF	BINP	Drift Chamber
STCF	HIEPA	Drift Chamber

Franco Grancagnolo

Drift chambers are clearly dominating (by number); however, we have fairly good examples of nicely working TPC's...

THE LARGEST TPC

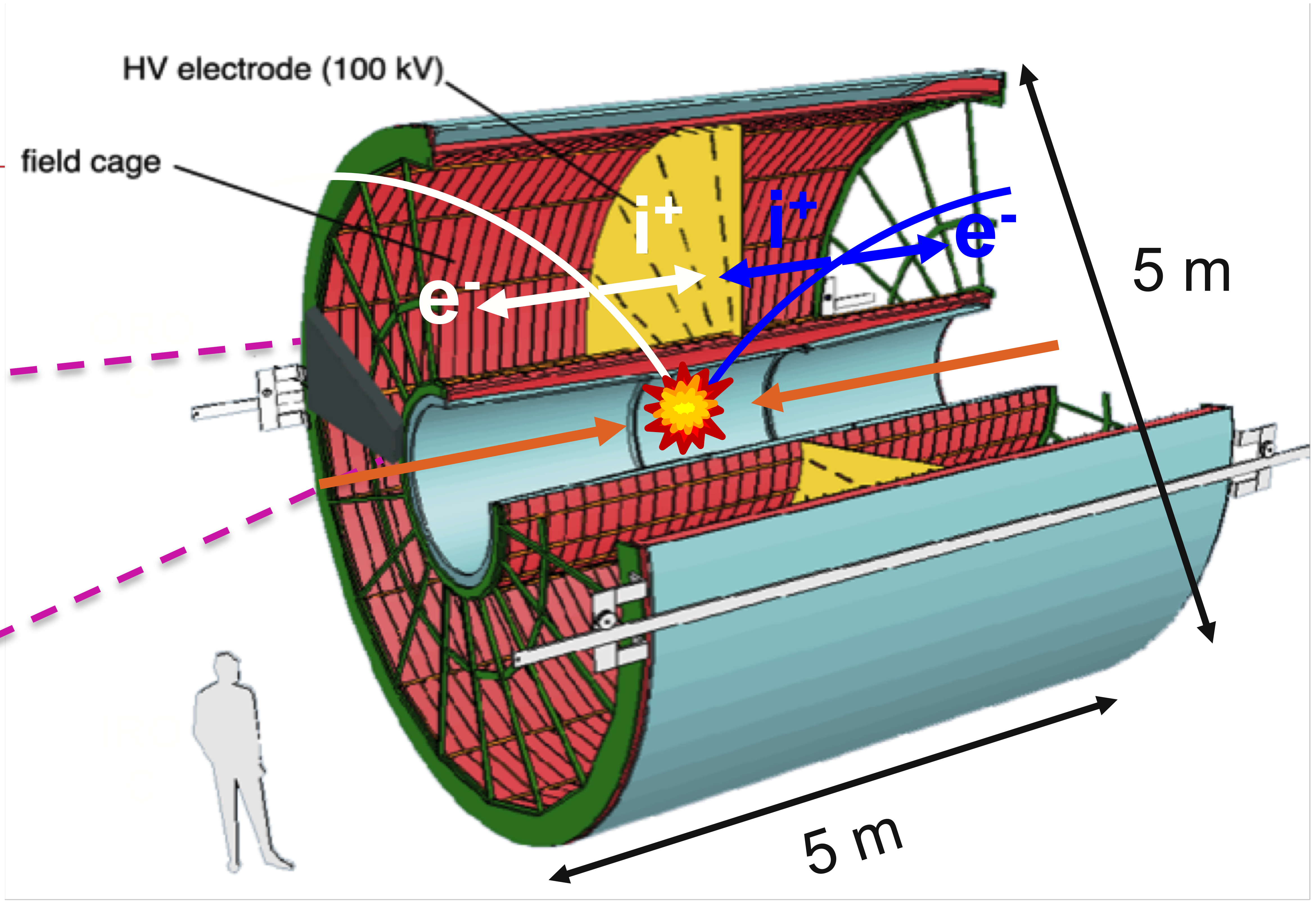
2 x 18
Outer Read Out Chambers



557568 pads

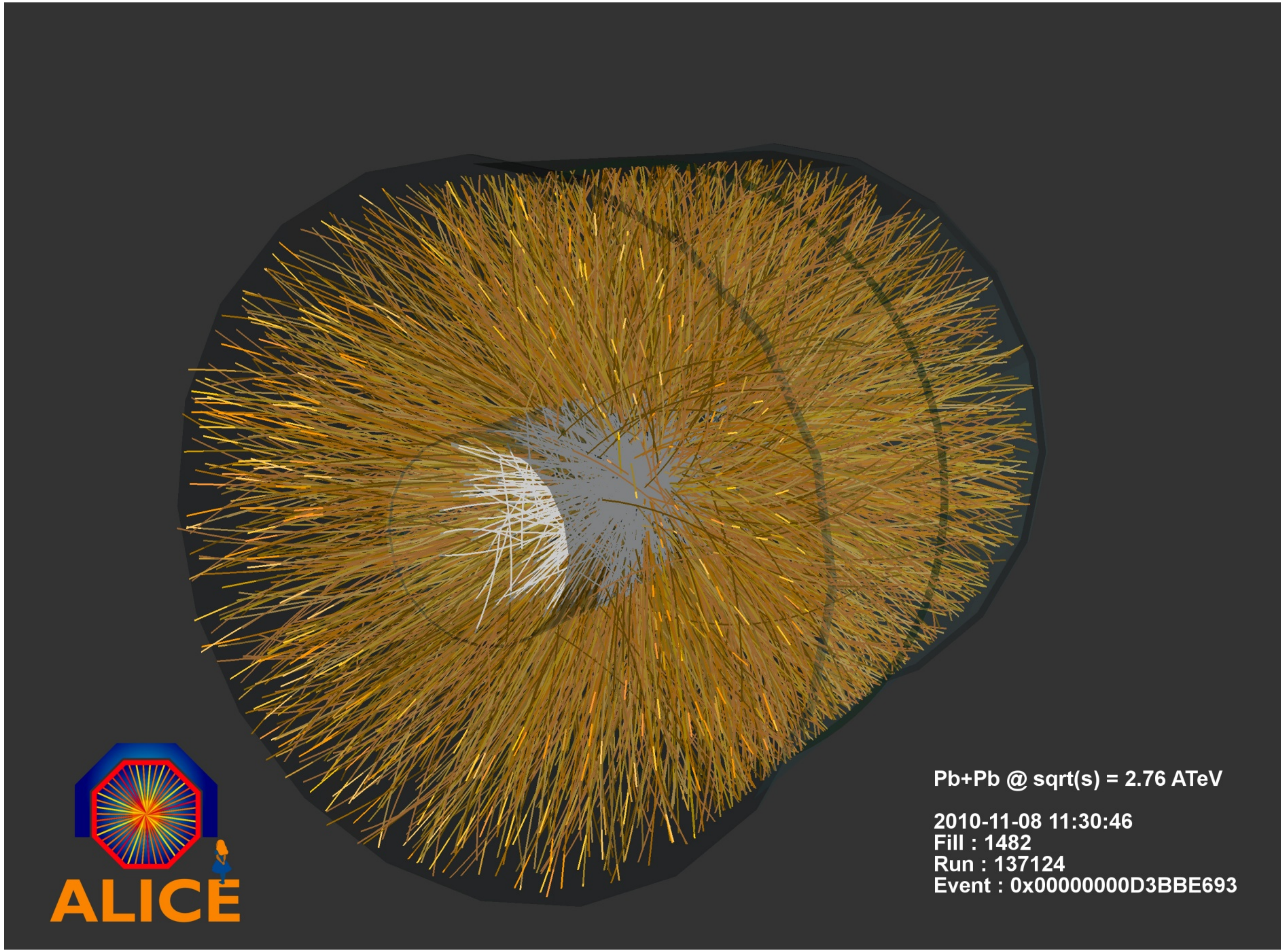
4 x 7.5 mm² (IROC)
6 x 10 mm² (OROC)
6 x 15 mm² (OROC)

2 x 18
Inner Read Out Chambers

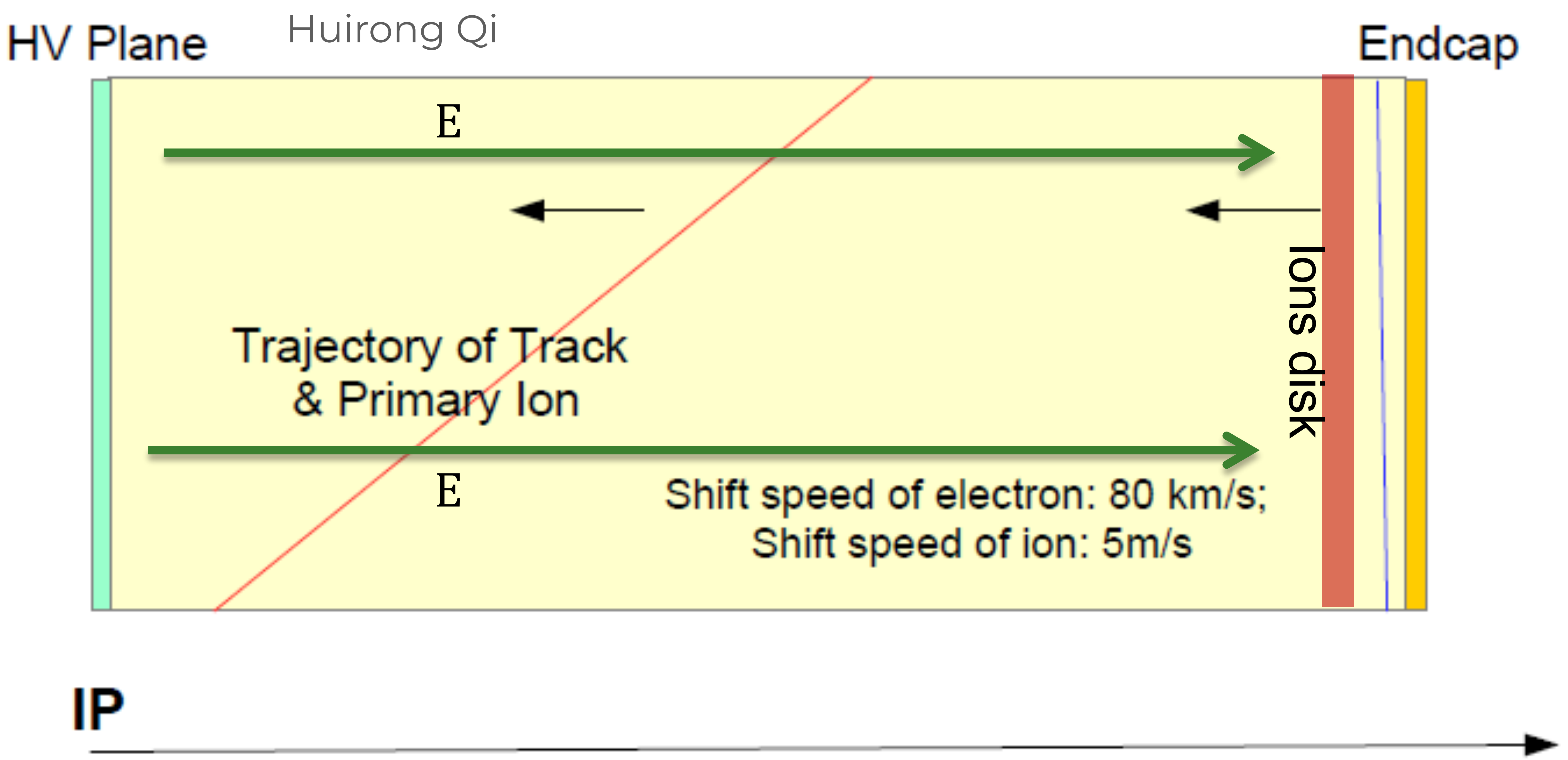


Gas volume:

- ~90 m³
- ~90 µs drift time
- 100 kV at the Central Electrode (E_{drift} = 400 V/cm)



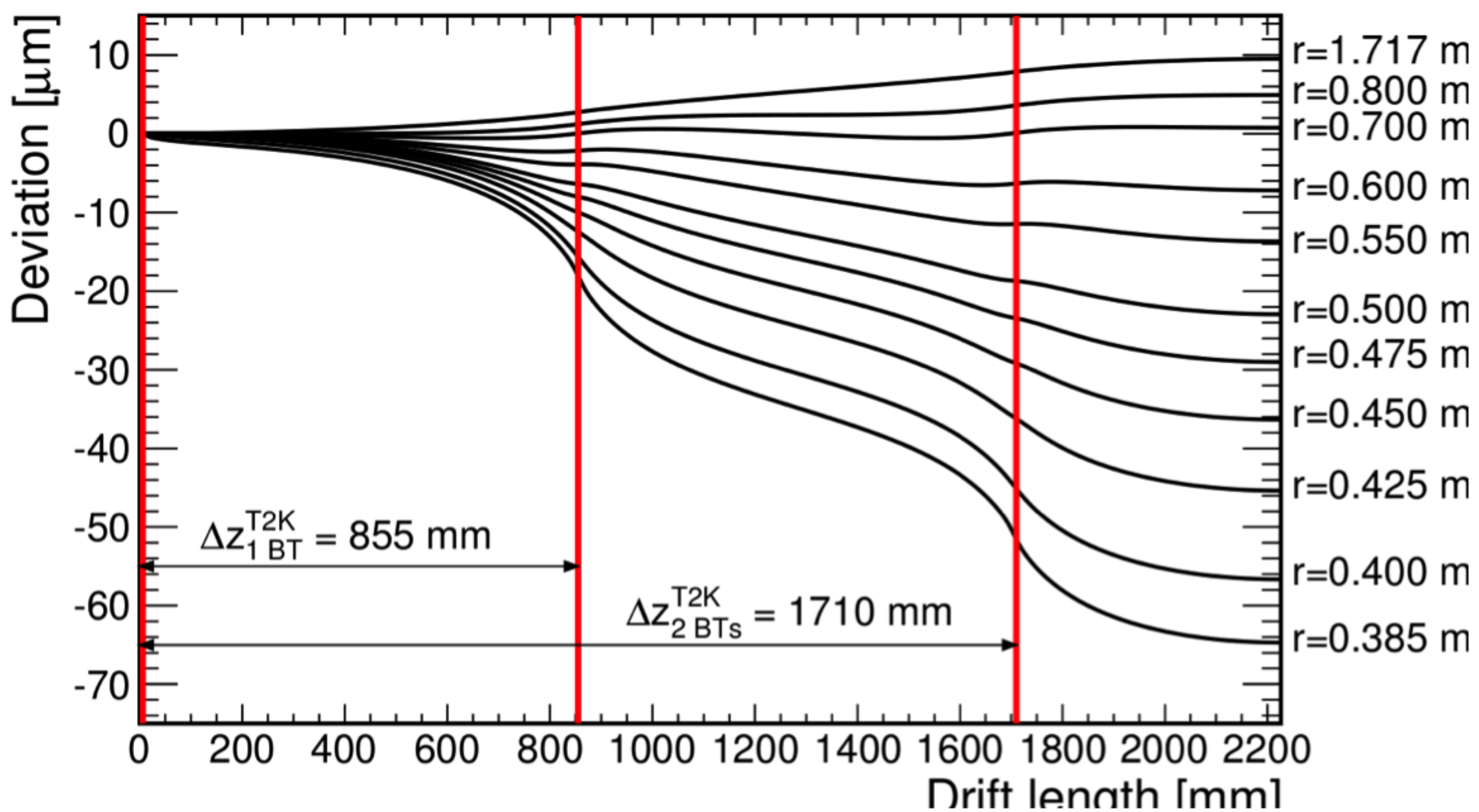
Up to 20 000 tracks/event in the chamber volume and it worked so well because the **ION BACKFLOW** could be reduced by **10^{-5}** by properly "**gating**" the detector for 200-400 μs after 100 μs drift time, **for an effective event rate of a few kHz, a situation not compliant neither with the Run3&4 at LHC (50 kHz collision rate expected) nor with the Z-pole run at CEPC.**



Total ions in chamber: ~ Back flow ions ~(1 + k), k = Gain×IBF + Primary

and it worked so well because the **ION BACKFLOW** could be reduced by **10^{-5}** by properly "**gating**" the detector for 200-400 μs after 100 μs drift time, **for an effective event rate of a few kHz, a situation not compliant neither with the Run3&4 at LHC (50 kHz collision rate expected) nor with the Z-pole run at CEPC.**

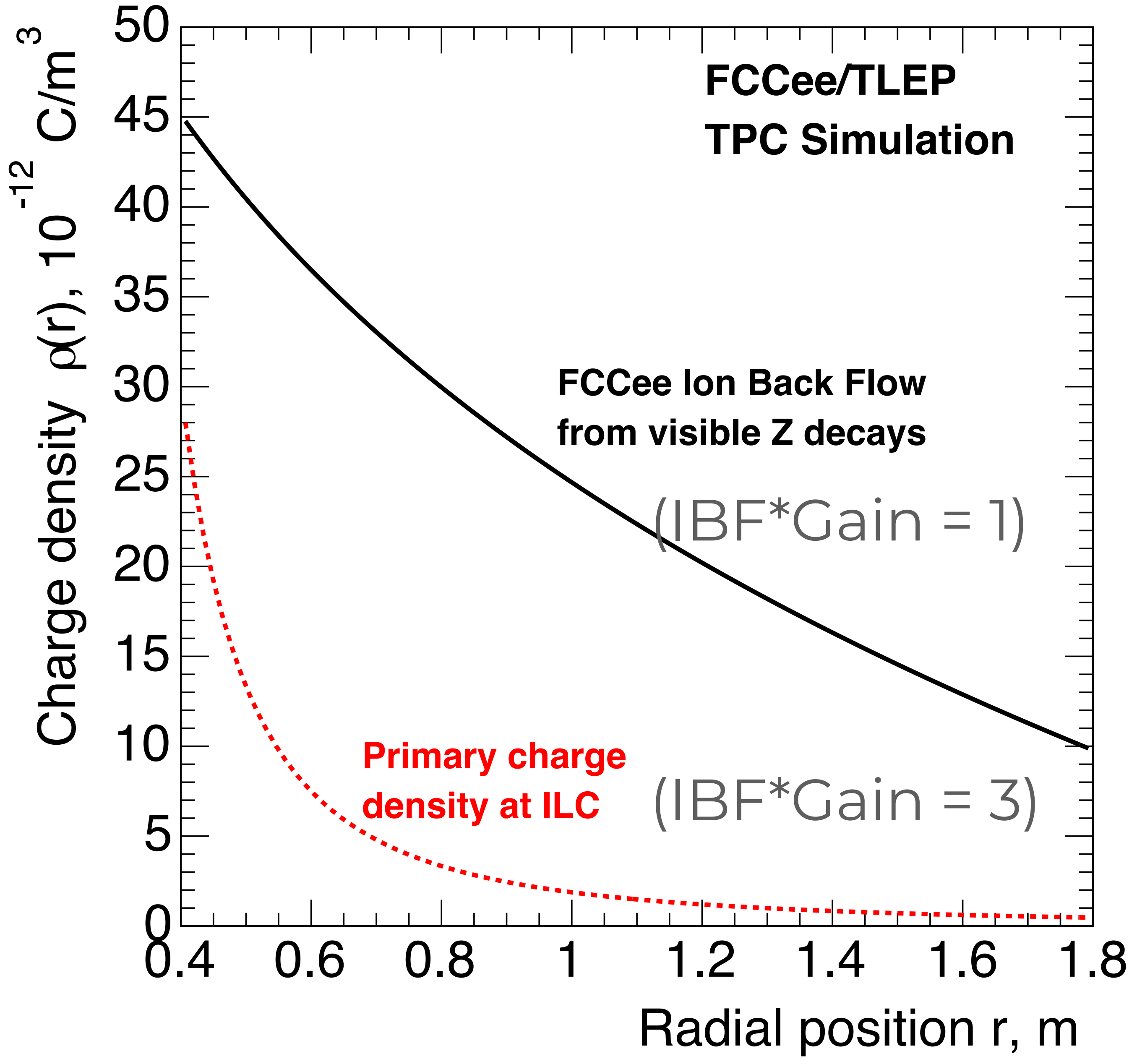
Serguei Ganjour

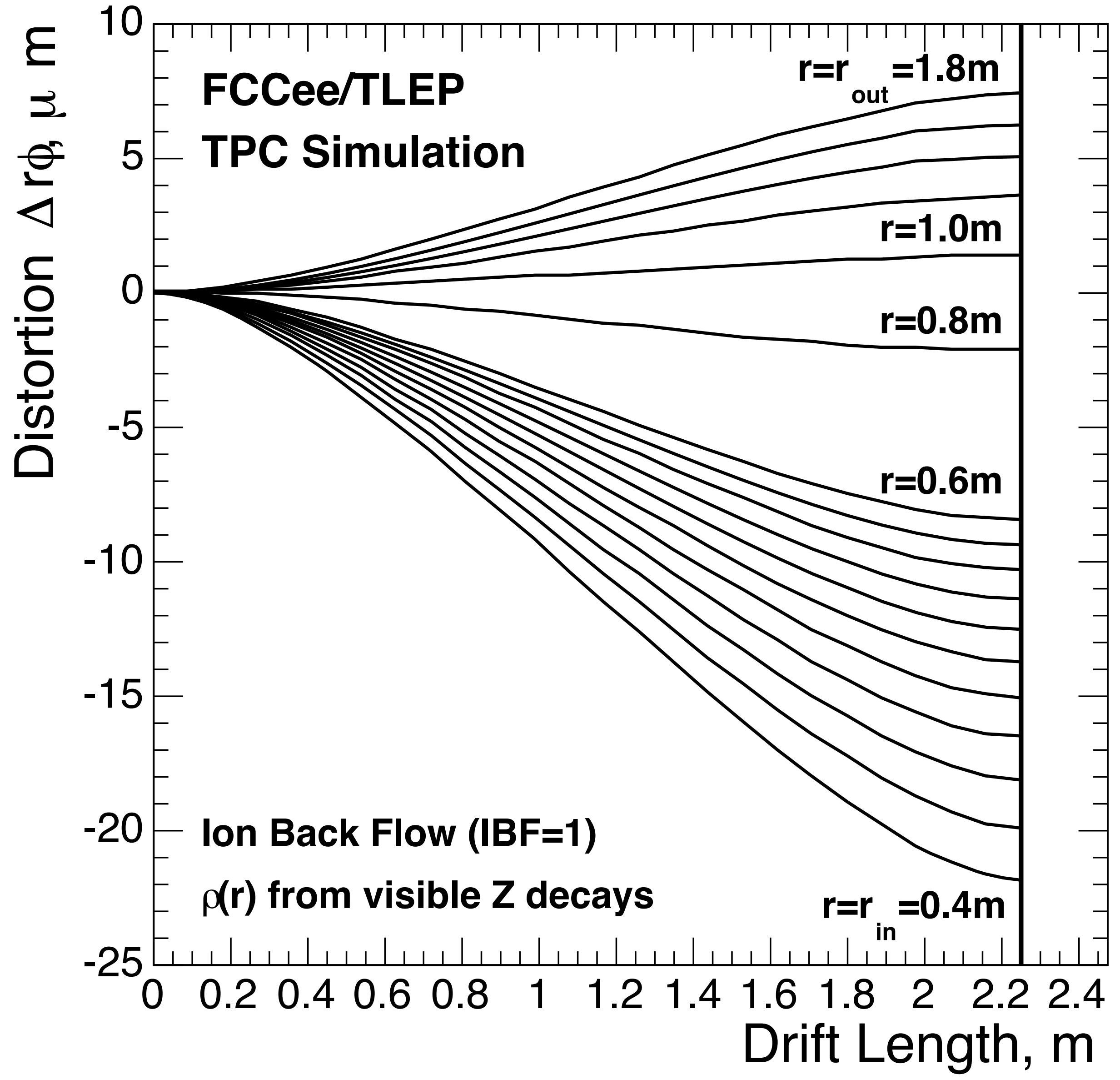


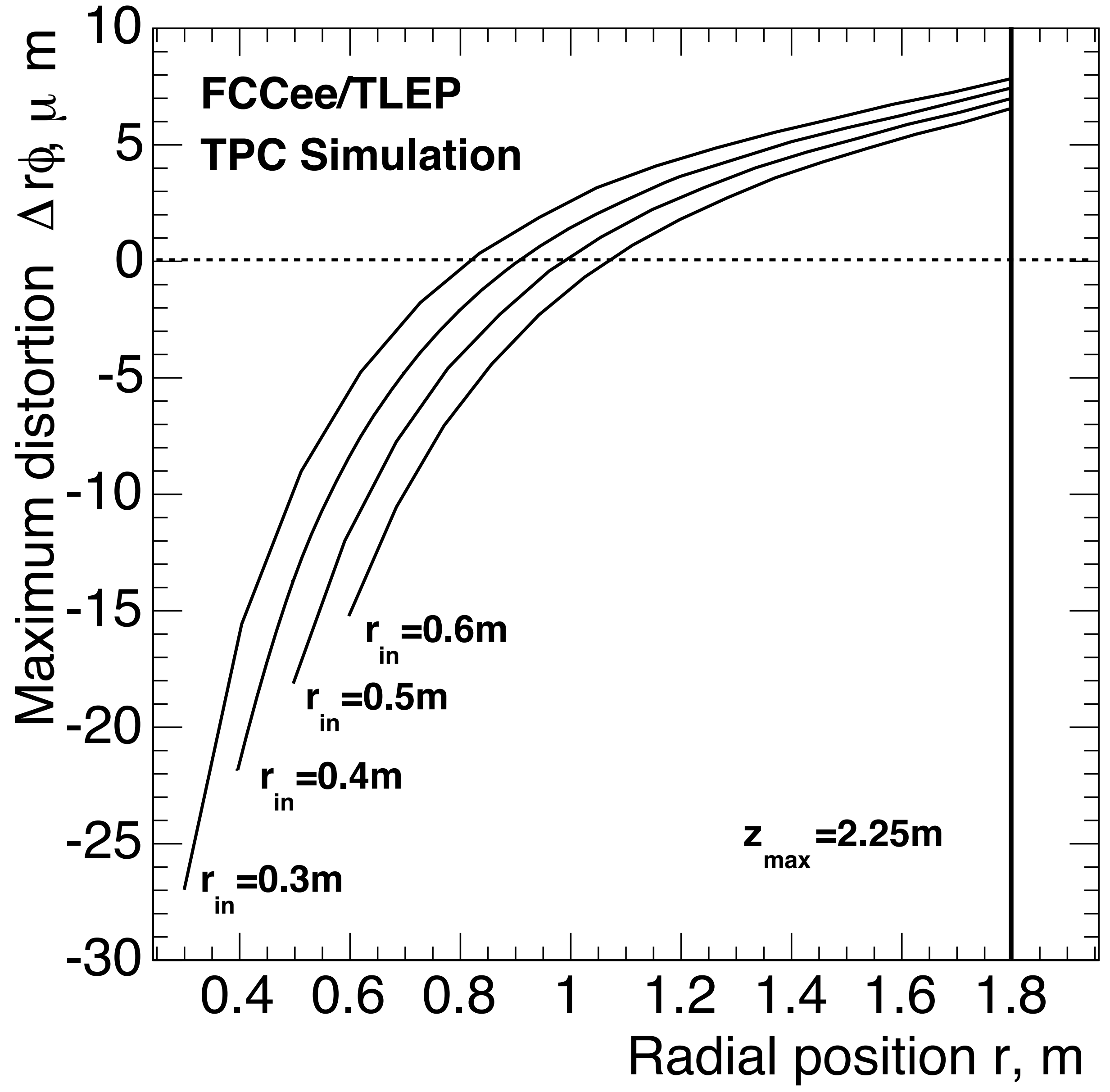
Example of the distortions induced by the ION BACKFLOW with a IBF*Gain = 3 (possible at the ILC)

Situation at the Z-pole, nominal luminosity:

Serguei Ganjour

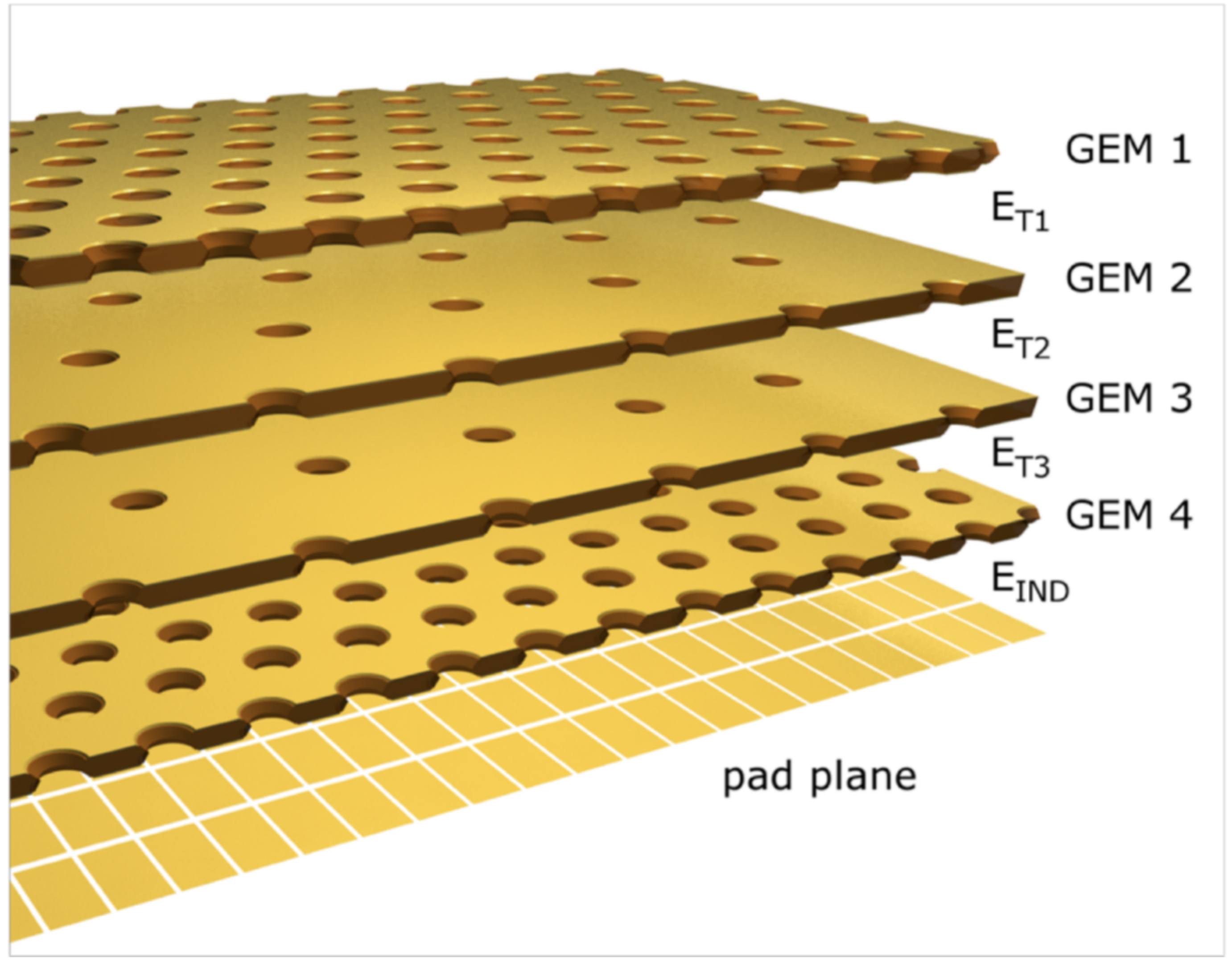






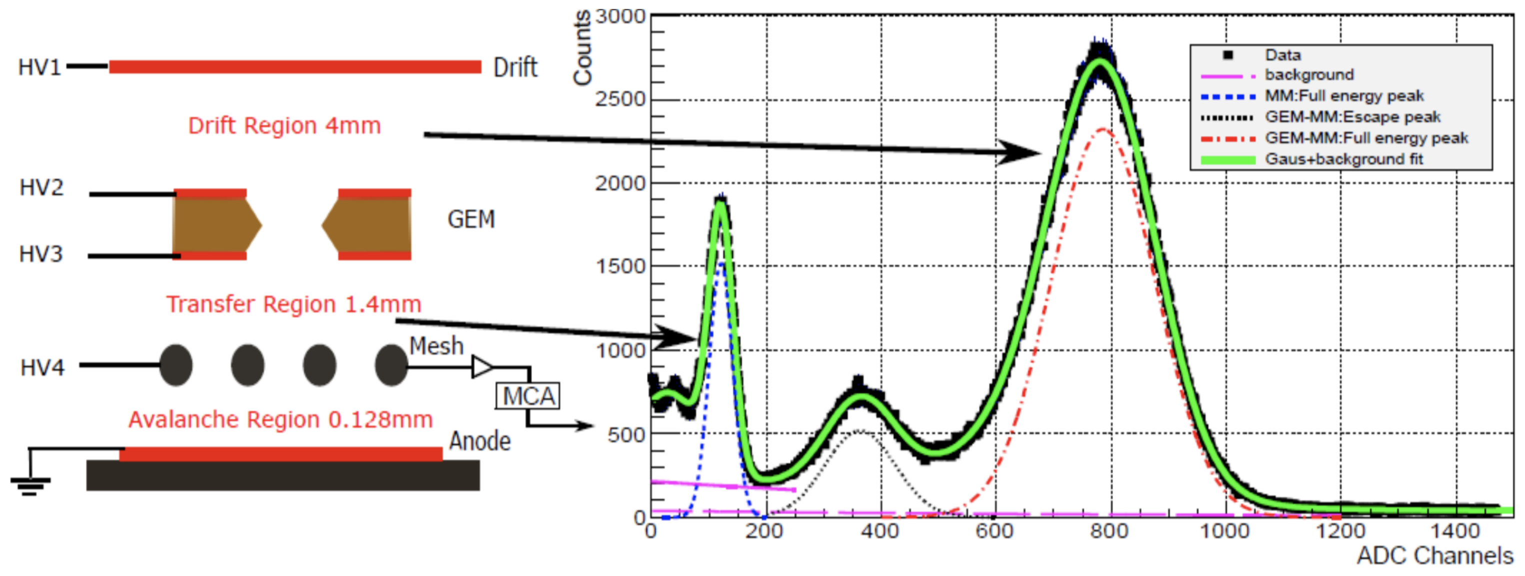
Secondary ions *yield distortions of about 20* μm *for* **IBFxGain=1** *for the case of continious charge density along z axis and corresponds to* $\mathrm{L} = 3 \cdot 10^{35}\mathrm{s}^{-2}\mathrm{cm}^{-1}$ *at 3.5 T magnetic field*

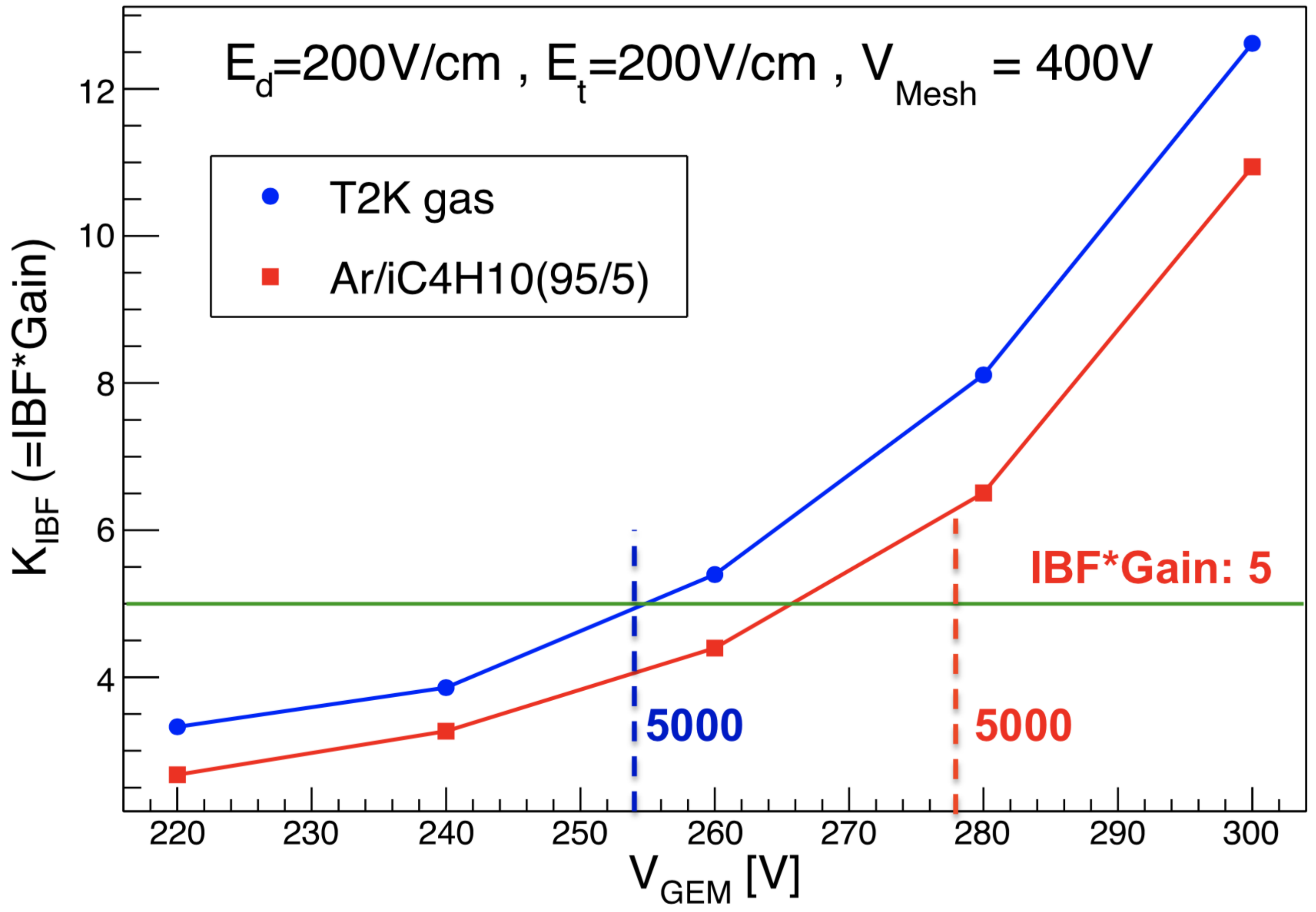
Any way out by now? apparently not …



The ALICE system is at the level of IBF*Gain = 10

Huirong Qi





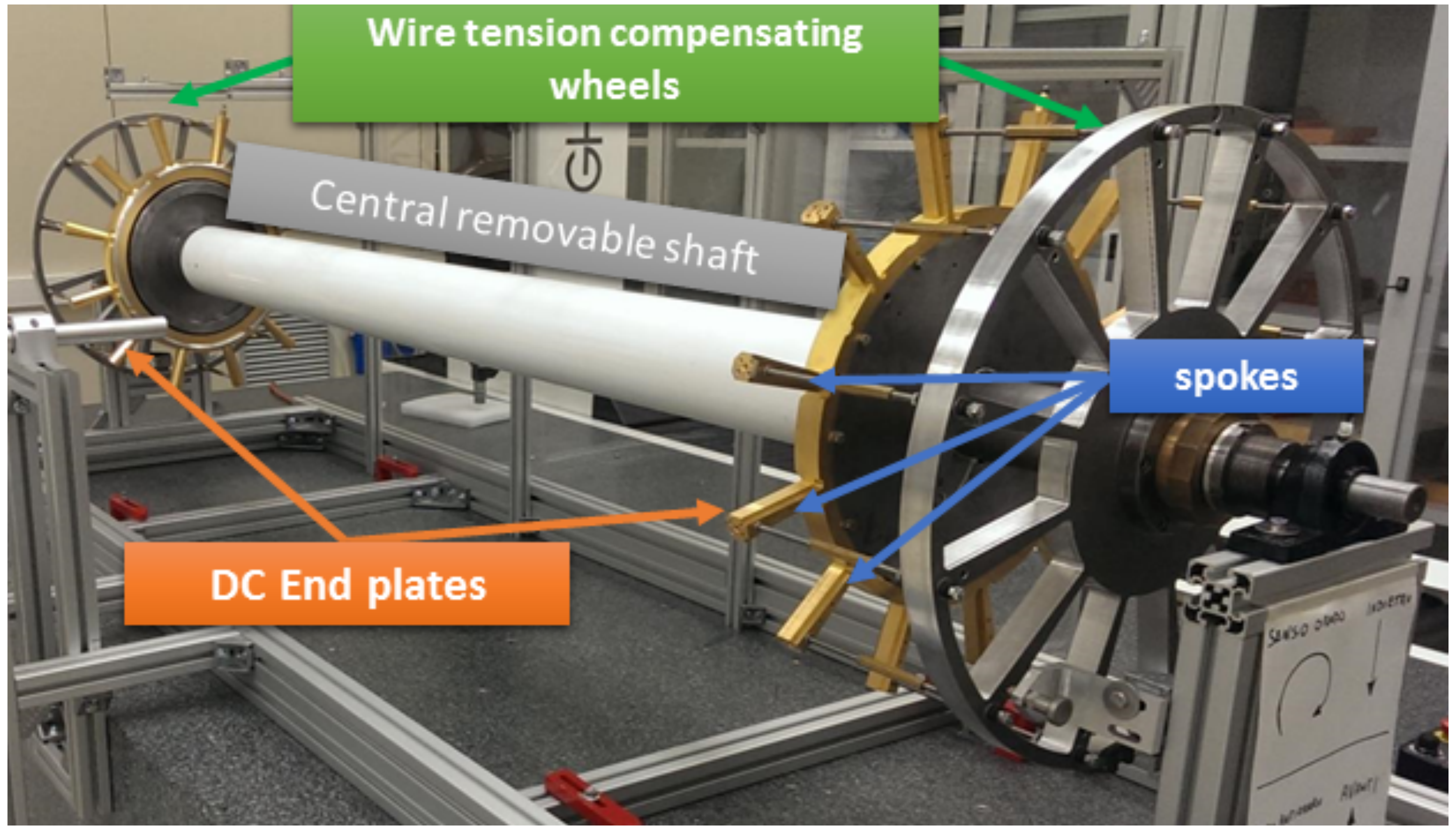
Combined MM+GEM module at IHEP

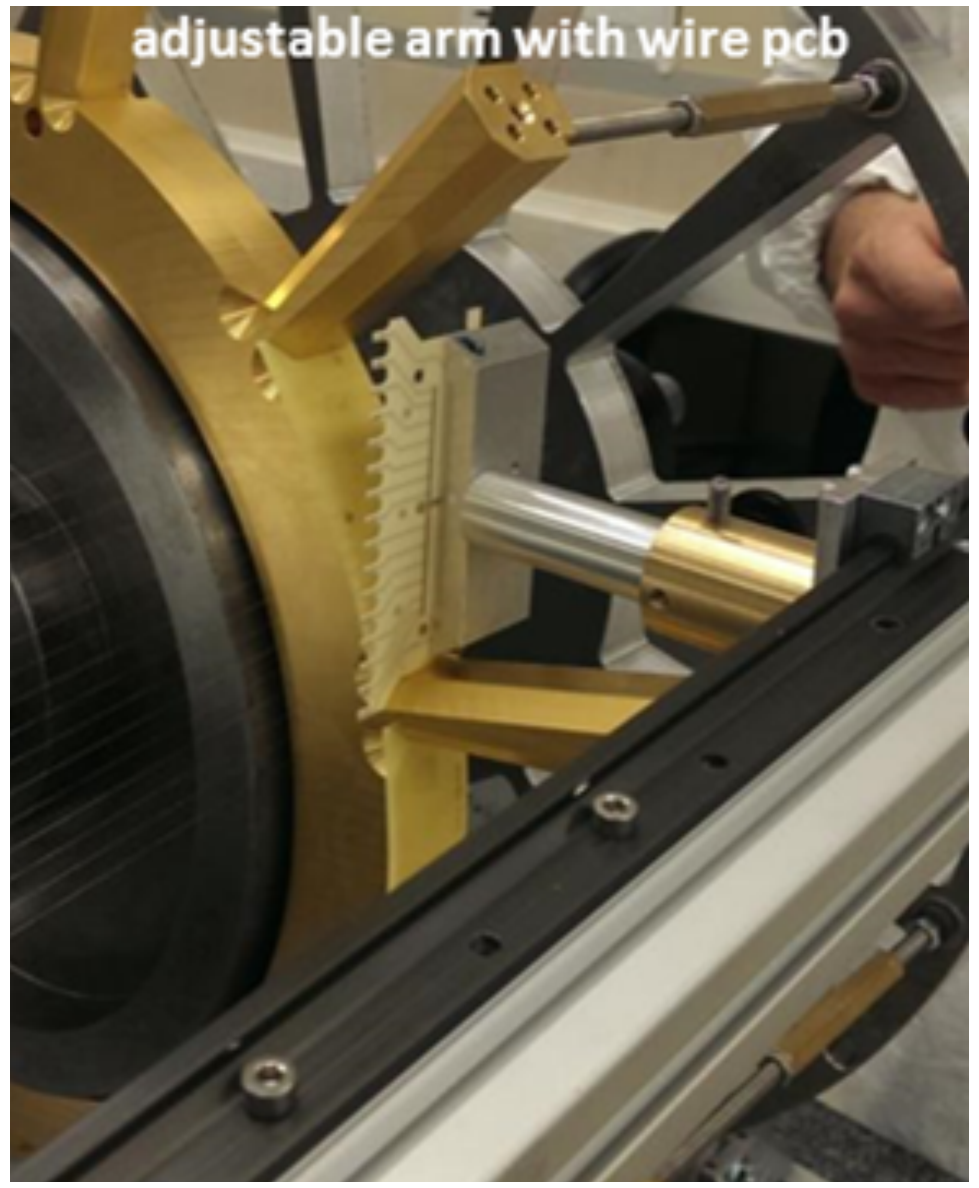
Currently IBF$\sim 10^{-3}$ is feasible, needs more R&D to go beyond

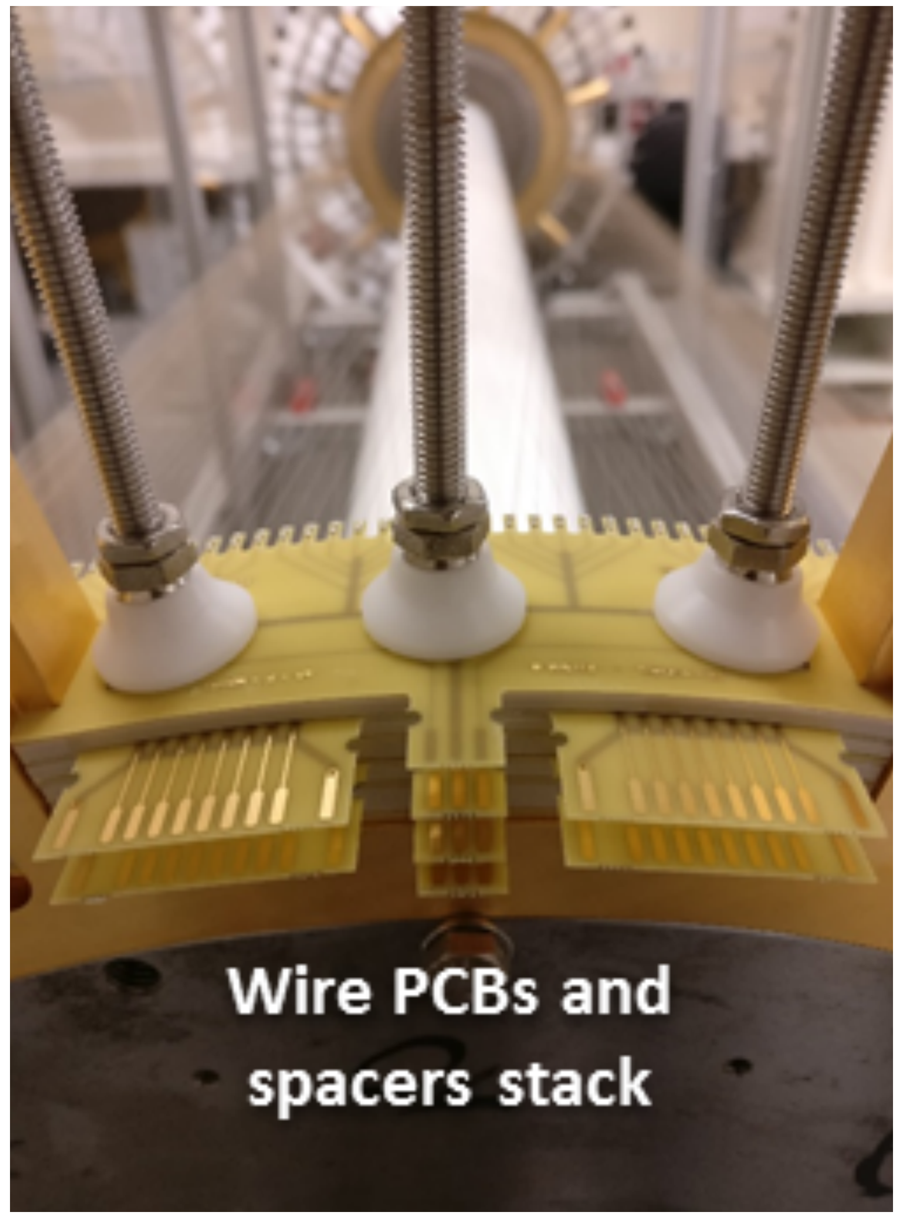
According to Serguei, you need to win another order of magnitude!

Any alternative? The main tracker of the IDEA detector concept is the BIG brother of the KLOE/MEGII chamber:

Franco Grancagnolo

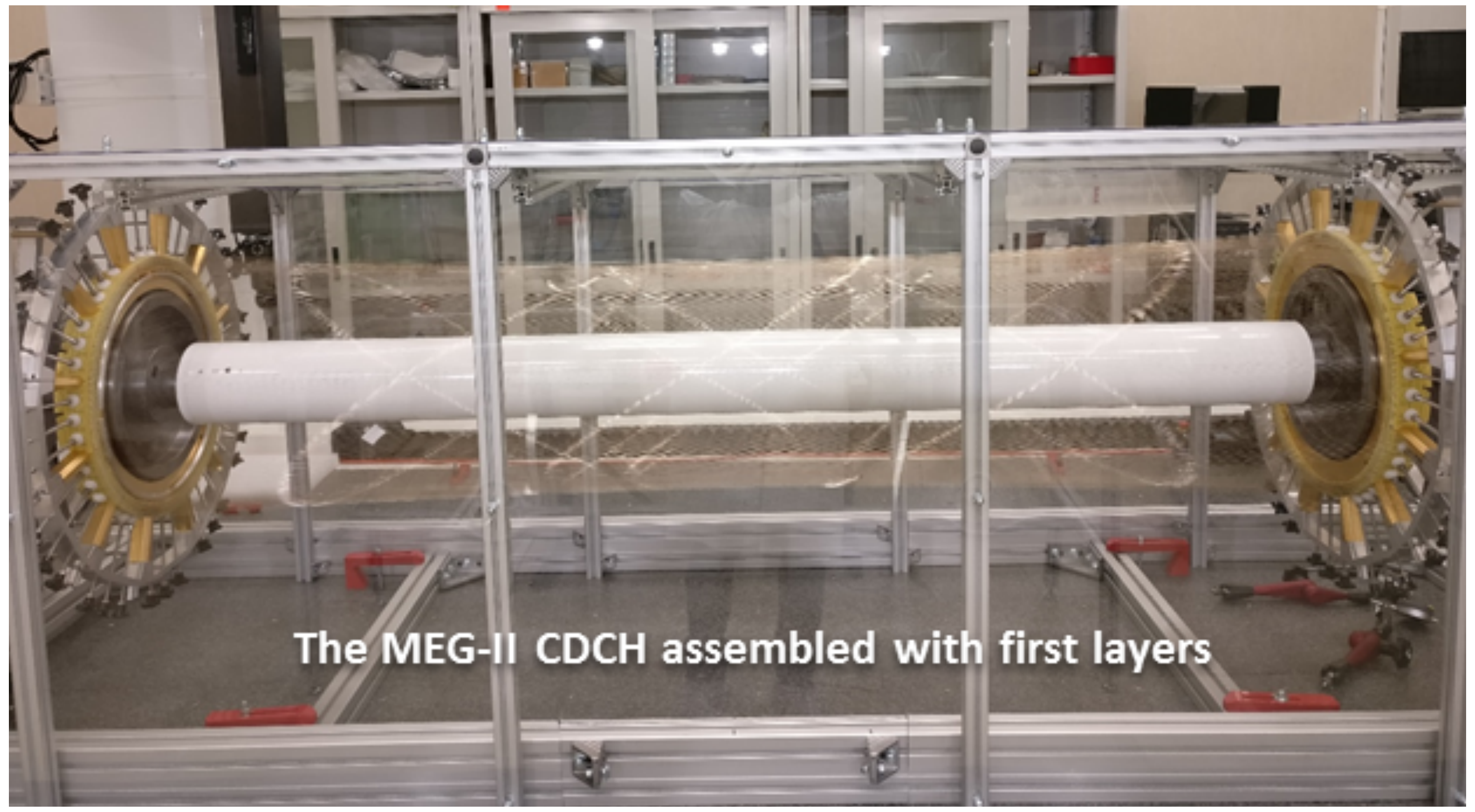




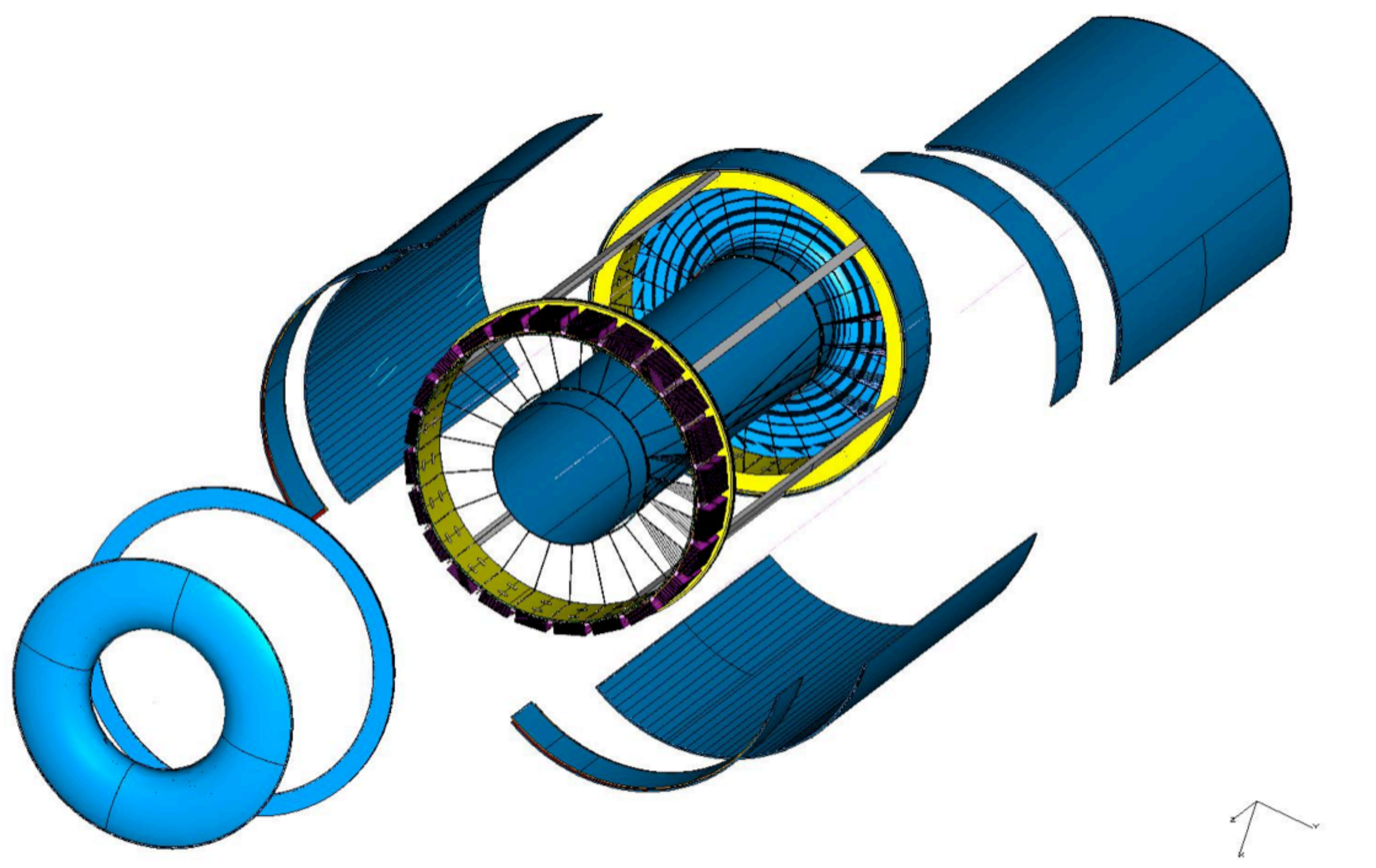


Dimensions of the MEG II chamber:

- $L = 193$ cm
- $R_{in} = 17$ cm
- $R_{out} = 30$ cm
- 10 layers for each 30° azimuthal sector

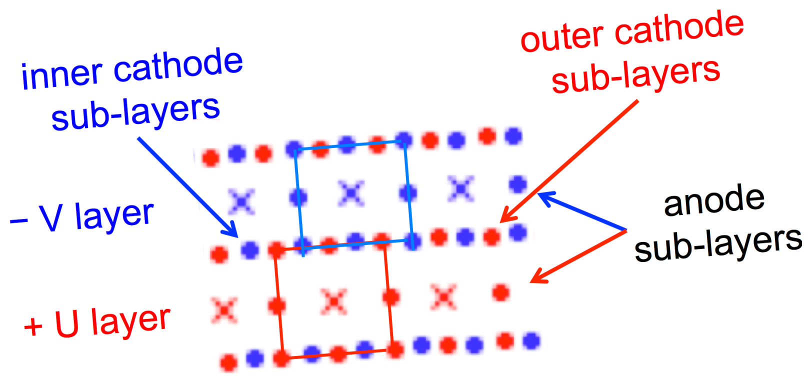


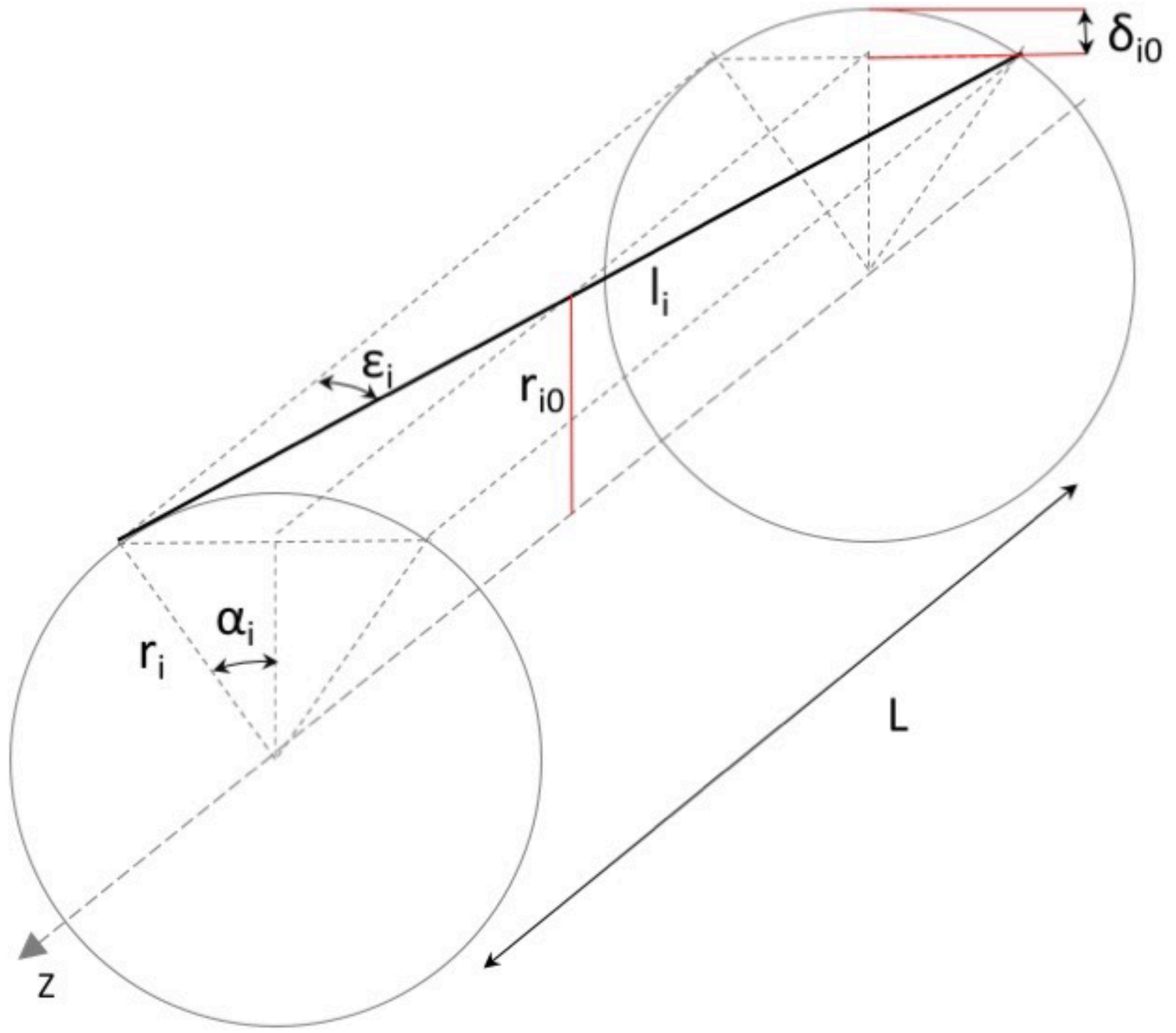
Any alternative? The main tracker of the IDEA detector concept is the BIG brother of the KLOE/MEGII chamber:



The IDEA drift chamber by numbers:

- L =   400 cm
- R_{in} =   35 cm
- R_{out} = 200 cm
- 112 layers for each 15° azimuthal sector
- 56 448 squared drift cells of about 12-13.5 mm edge
- **max drift time: 350 ns in** 90%He-10%iC_4H_{10}



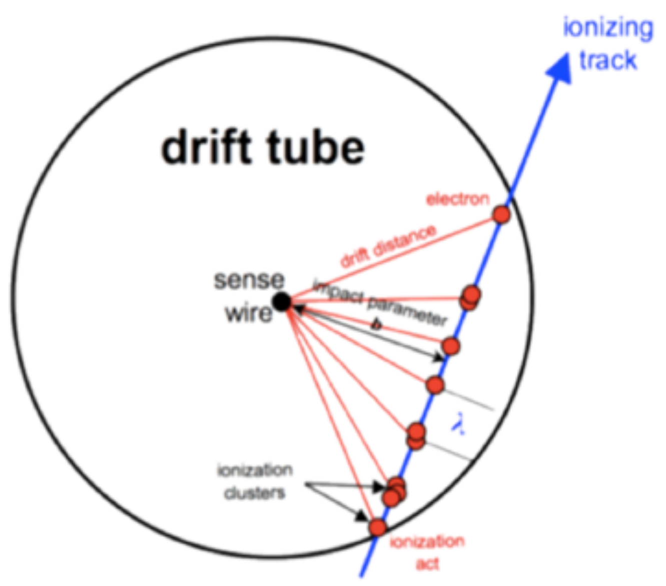


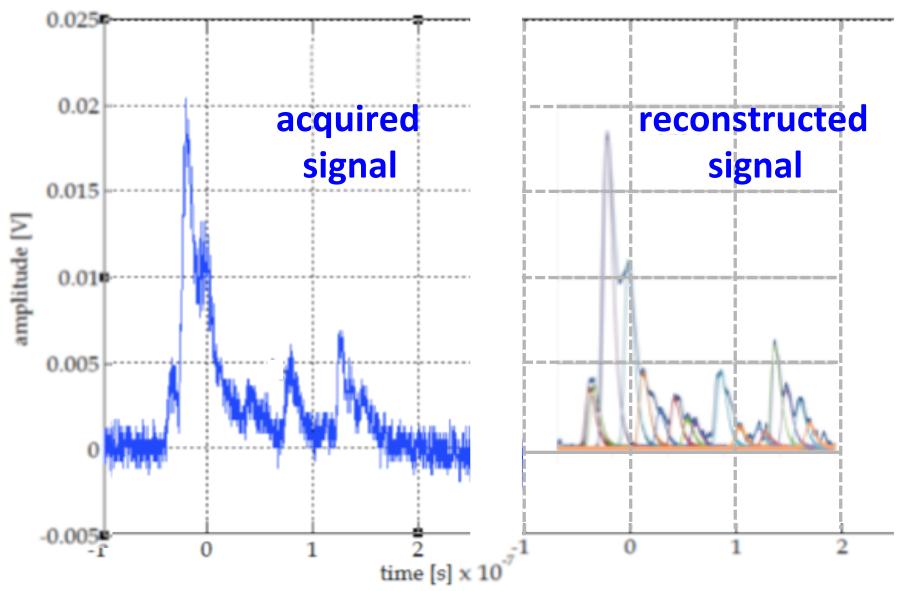
- The stereo angle α is generated stringing the wire between spokes @ 2 sectors (30°) distance
- α ∈ [20 mrad (1.1°); 180 mrad (10.3°)], increasing with R
- the electrostatic stability is achieved when the wire tension is about 25g, for a total load of about 7,7 tons!

strong points of the DRIFT chamber:

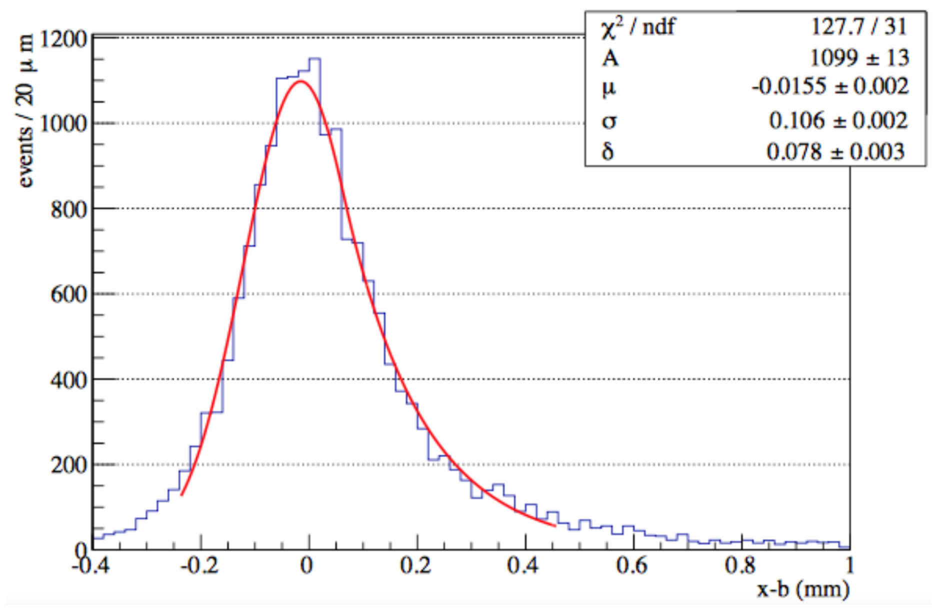
strong but light:

- 1.6% X_o in the barrel [a few % for the TPC]
- 5% X_o in the fwd/bkwd directions (end plates included)





- record the time of arrival of electrons generated in every ionisation cluster (≈12cm-1)
- reconstruct the trajectory at the position most likely generating the sequence



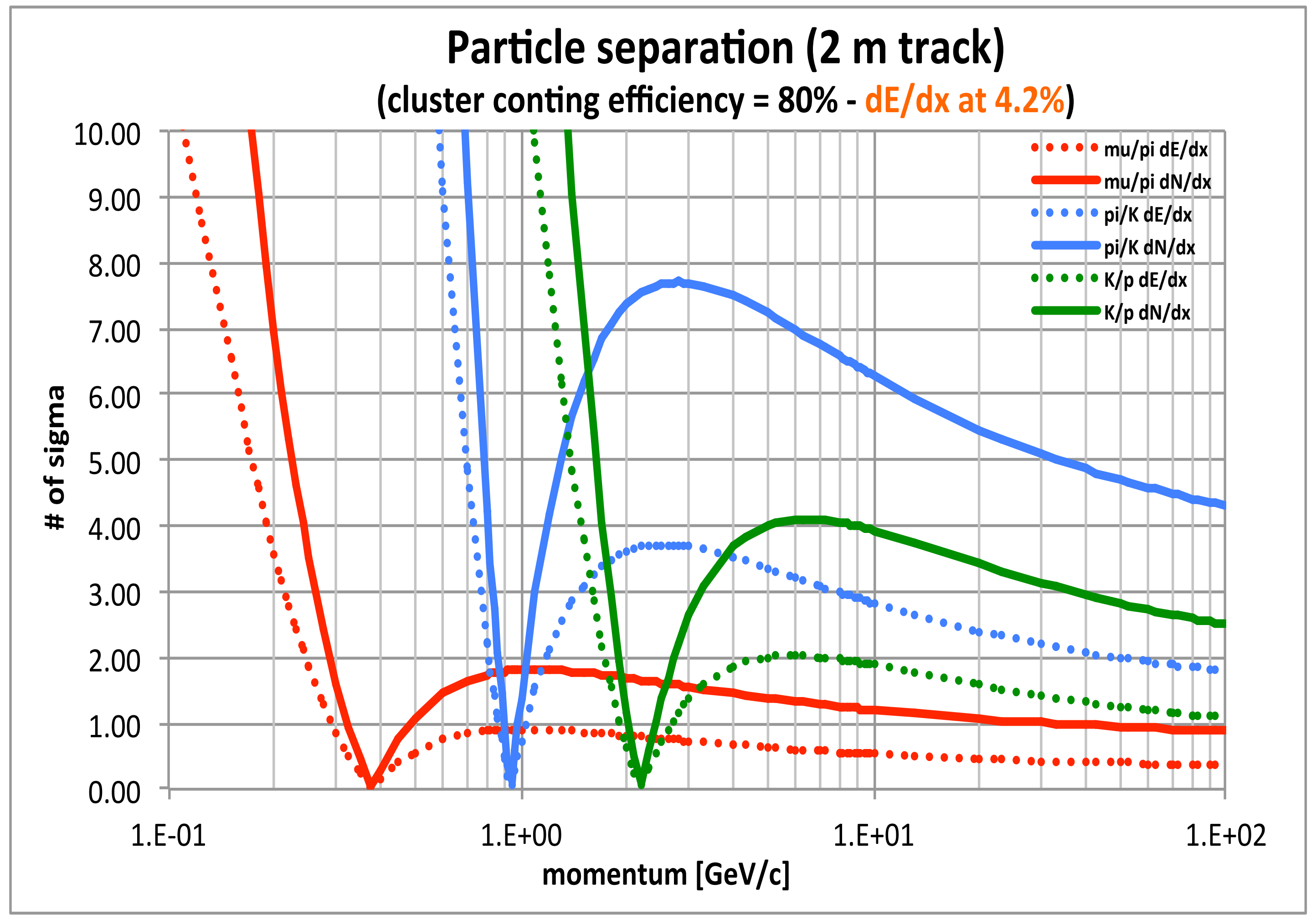
measured resolution for the MEGII prototype, corresponding to

$\sigma_{xy} \approx 100\ \mu m$

$\sigma_z \approx 1000\ \mu m$

cluster counting for improved spatial resolution:

it is essentially based on the well known method of measuring the [truncated] mean dE/dX but it replaces the measurement of an ANALOG information with a DIGITAL one, namely the number of ionisation clusters per unit length:



$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 0.41 \cdot n^{-0.43} \cdot \left(L_{track}[m] \cdot P[atm]\right)^{-0.32}$$

- ≈ 4%

from *Walenta parameterization (1980)*

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = \left(\delta_{cl} \cdot L_{track}\right)^{-1/2}$$

- ≈ 2%

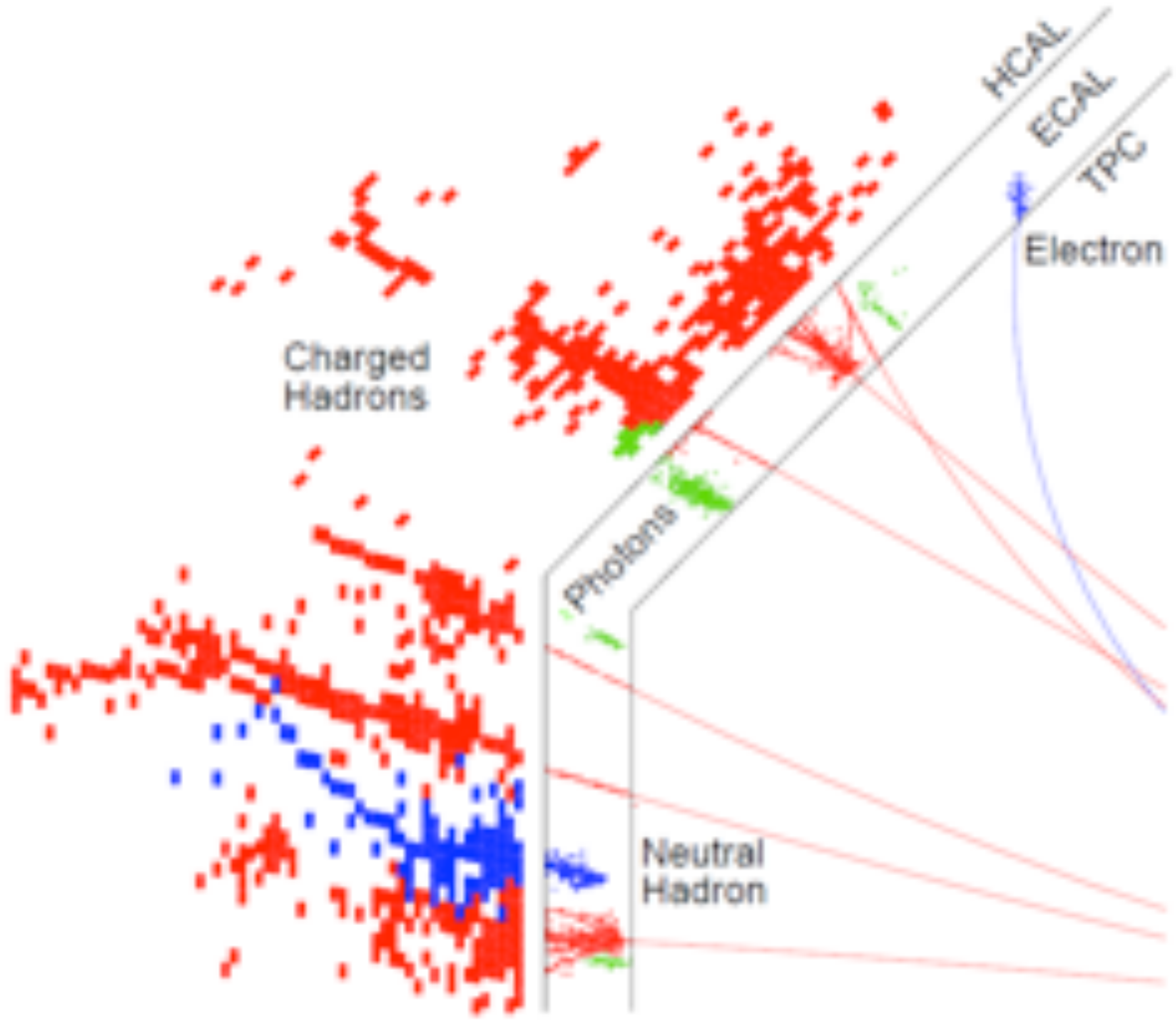
from *Poisson distribution*

✱ Last but not least: the Calorimeters!

Contributors:

- J.C Brient
- Jianbei Liu
- Roberto Ferrari
- Sarah Eno
- Mingyi Dong
- Boxiang Yu
- Gabriella Gaudio

✳ Particle flow paradigm:



Jianbei Liu

As long as you have an imaging detector reconstructing the shower development, make the best possible use of the reconstructed tracks, match them to the showers and assign the energy measurement accordingly:

- Charge particles (65%): use the momentum [$\sigma_E/E \approx 0.1\%$]
- Neutral Hadrons (10%): Hadron calorimeter [$\sigma_E/E \approx 45\%$]
- Photons (25%); EM Calorimeter [$\sigma_E/E \approx 20\%$]

[numbers by Sarah Eno]

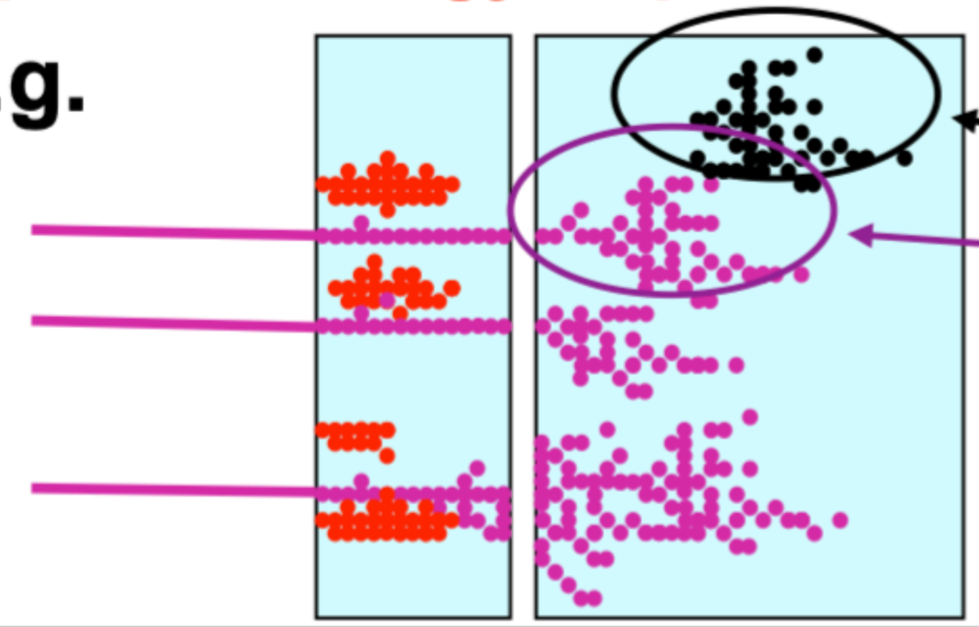
Why separation is a "must have":

Reconstruction of a Particle Flow Calorimeter:

★ **Avoid double counting of energy from same particle**

★ **Separate energy deposits from different particles**

e.g.

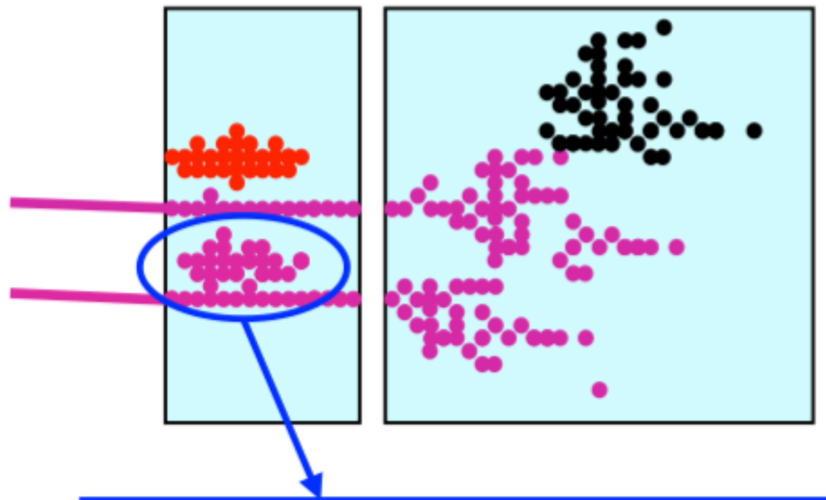


If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution not the intrinsic calorimetric performance of ECAL/HCAL

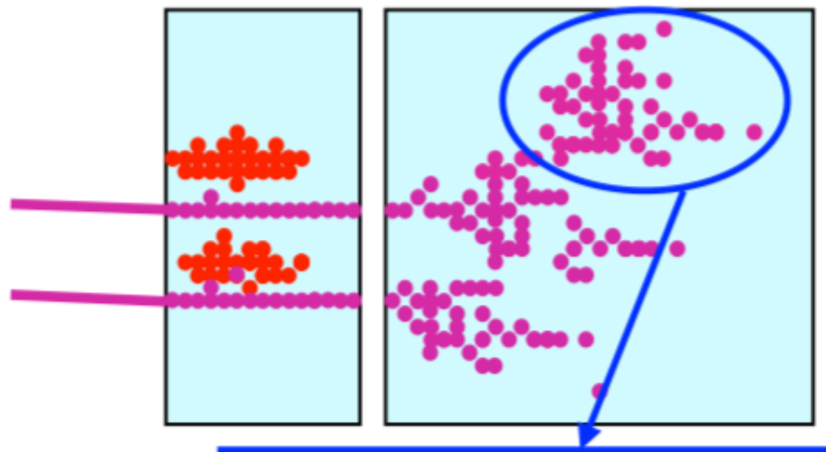
Three types of confusion:

i) Photons



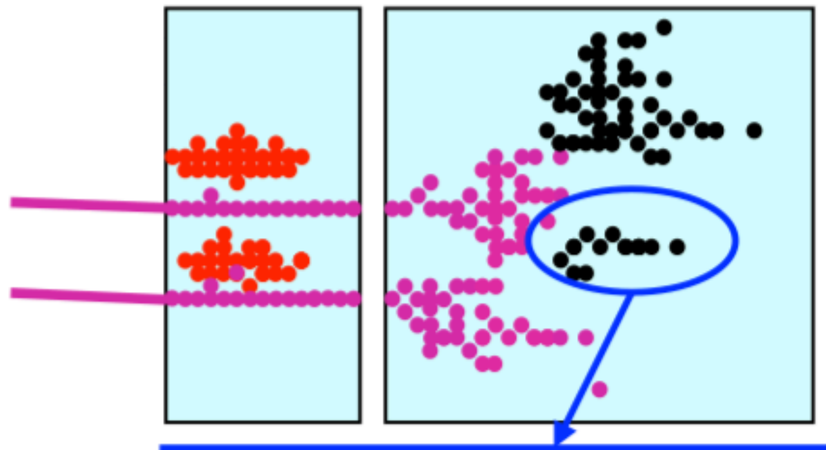
Failure to resolve photon

ii) Neutral Hadrons



Failure to resolve neutral hadron

iii) Fragments



Reconstruct fragment as separate neutral hadron

credits: Mark Thomson

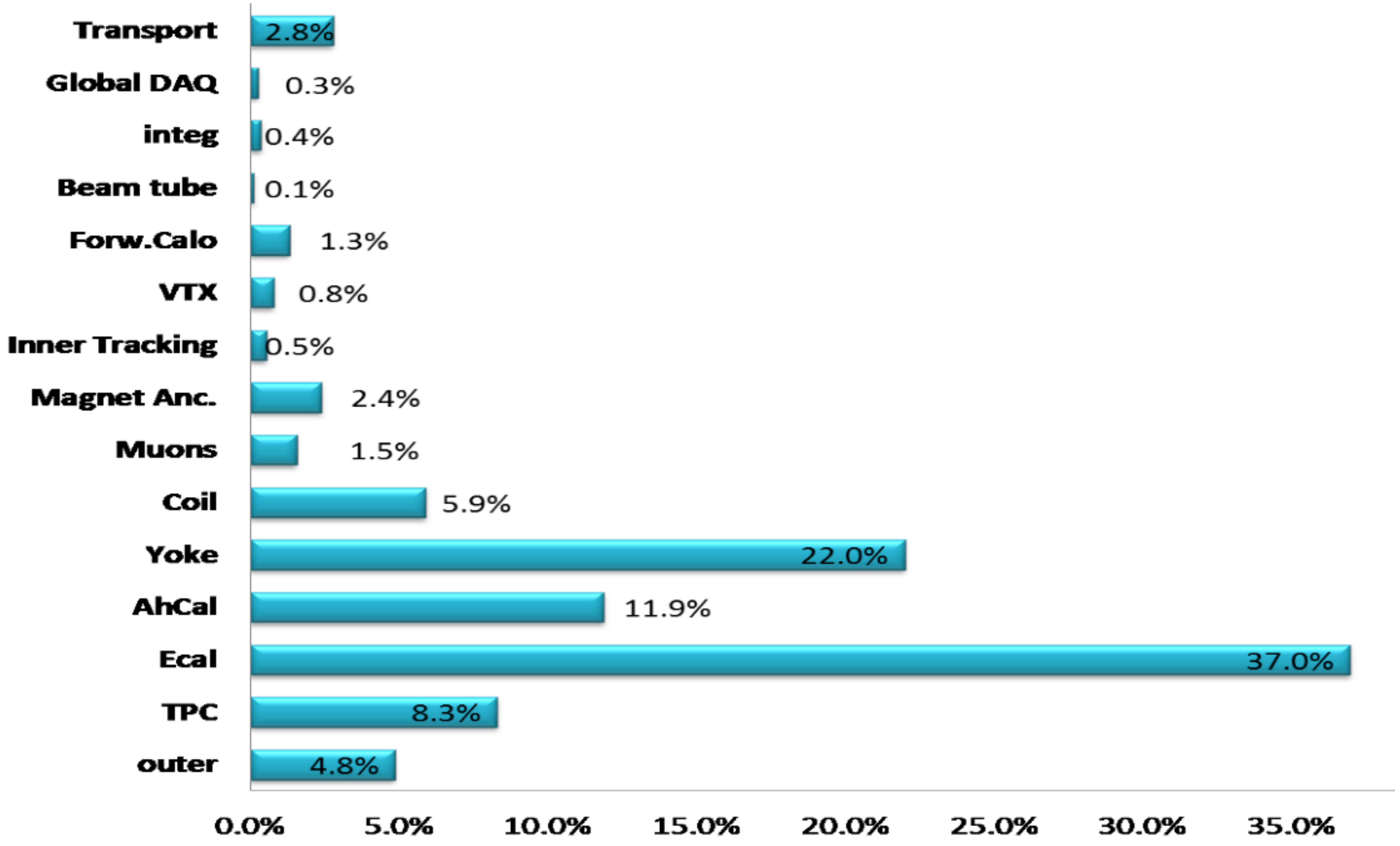
$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{E}{100}\right)^{+0.3} \%$$

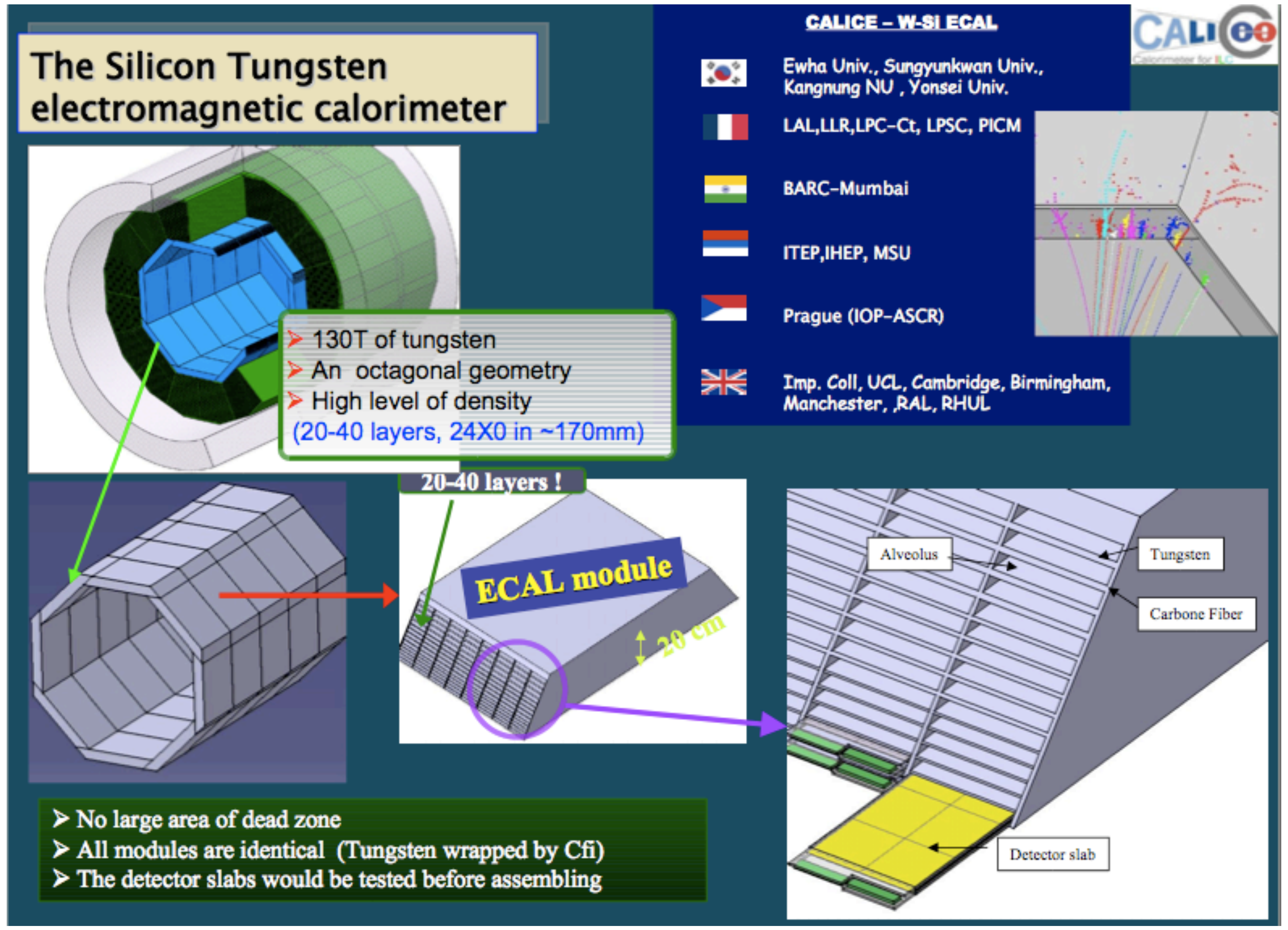
Resolution | Tracking | Leakage | Confusion

Total Resolution	3.1 %
Confusion	2.3 %
i) Photons	1.3 %
ii) Neutral hadrons	1.8 %
iii) Charged hadrons	0.2 %

Granularity does not come for free, neither in terms of complexity not cost:

Why silicon





- ❖ 130T of Tungsten (watch the commodity market..)
- ❖ 3000 m^2 of pixelated Silicon
- ❖ 250 Mpixel (well calibrated and stable…)

opening slide by JC Brient

Today: reduced to 100 Millions….

Why Silicon?

	Np.e. /MIP	linearity	Longitudinal segmentation	Timing (ps) at mip	cost
Scintillator (3 mm & SiPM)	10-20	<1000 mip	***	?? (pb related to noise)	**
Silicon (300µm)	24000	No limit	***	$30/(\text{Nlayer})^{1/2}$	*
Shashlik type	***	Yes	*	30	***

Good S/N @mip for <1mm thickness, timing measurement, small pixel size, .. → Silicon

Why Tungsten?

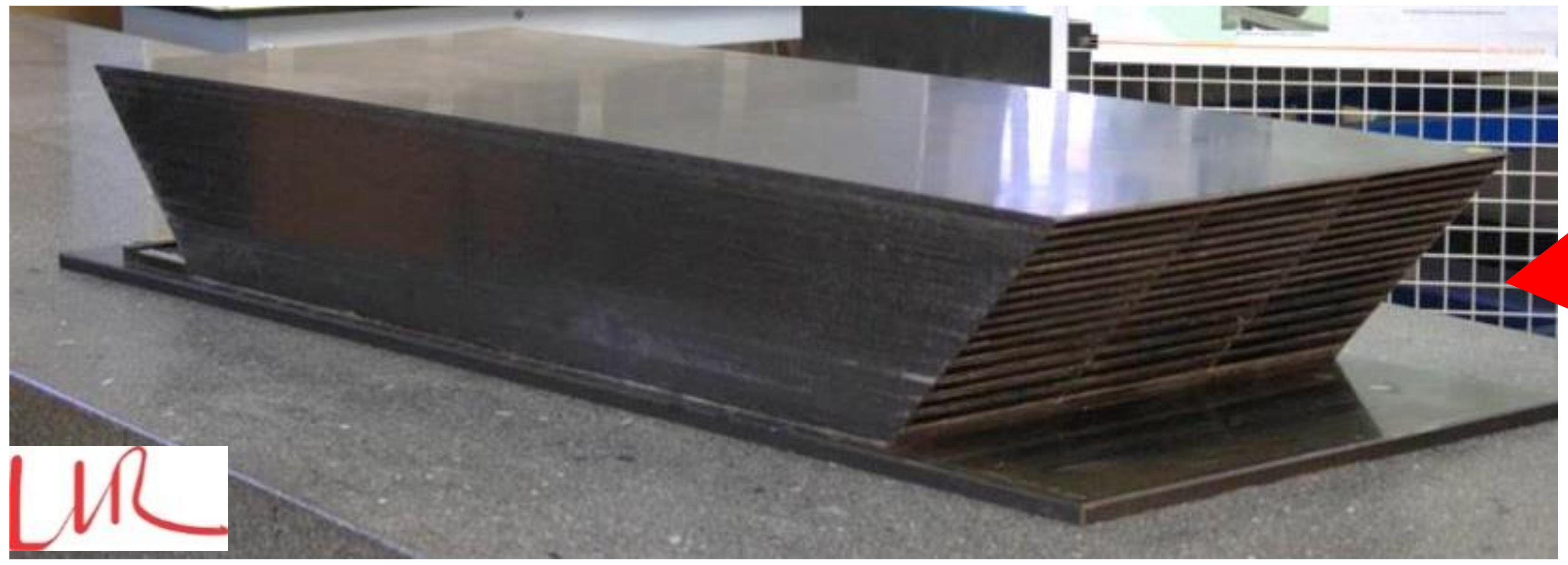
	X0 (cm)	λ_I (cm)	Ratio	Molière Rad (cm)	Mechanics	cost
Fe	1.76	16.8	9.5	1.69	***	***
Cu	1.43	15.1	10.6	1.52	***	*
W	0.35	9.6	27.4	0.93	**	*
Pb	0.56	17.1	30.5	1.00	*	***

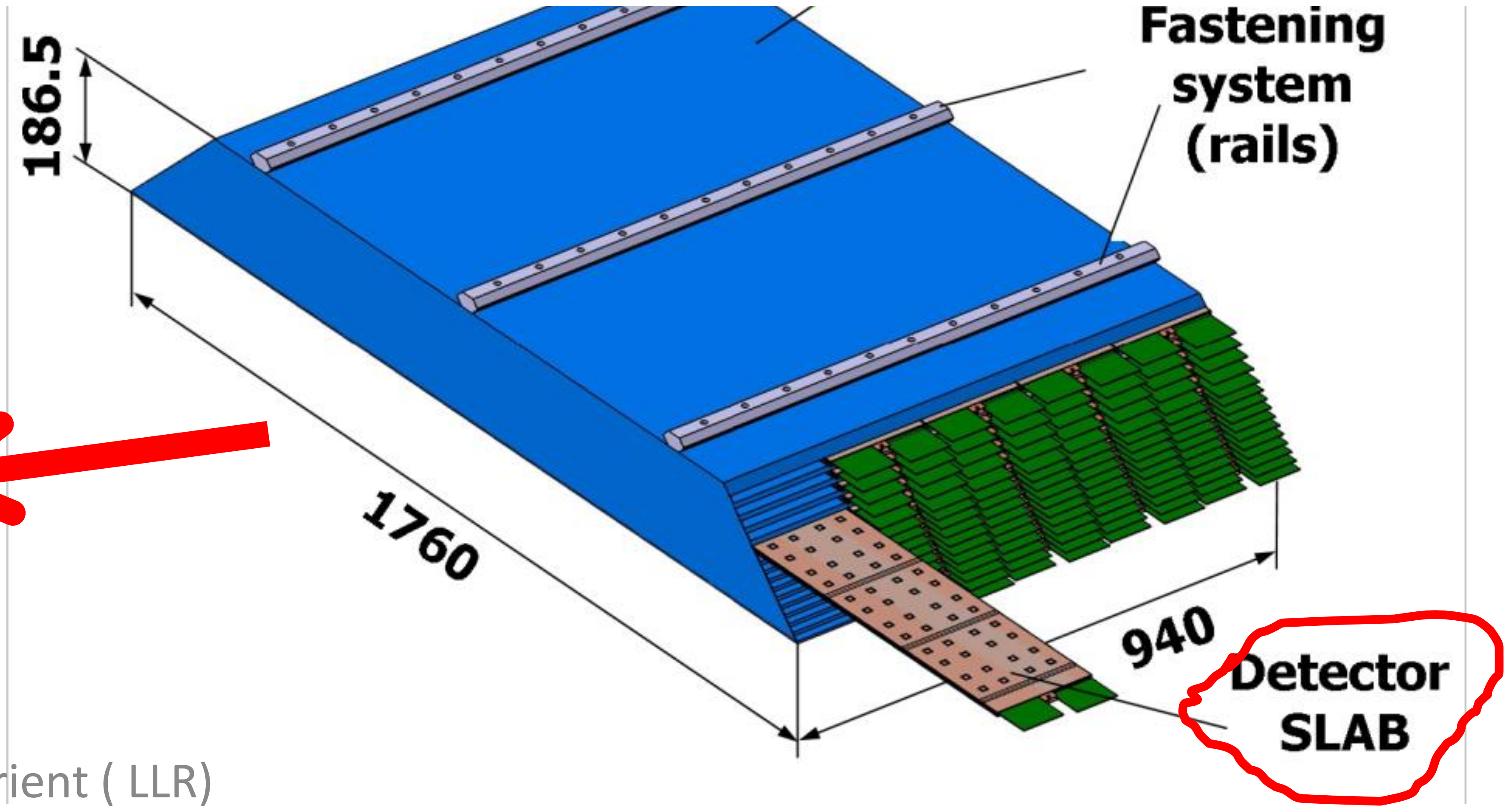
Good ratio, small Molière radius and good mechanical behaviour → Tungsten

JC. Brient

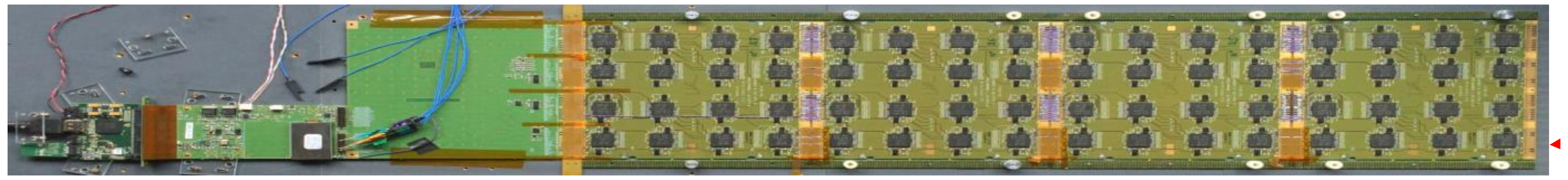
Prototyping certainly advanced:

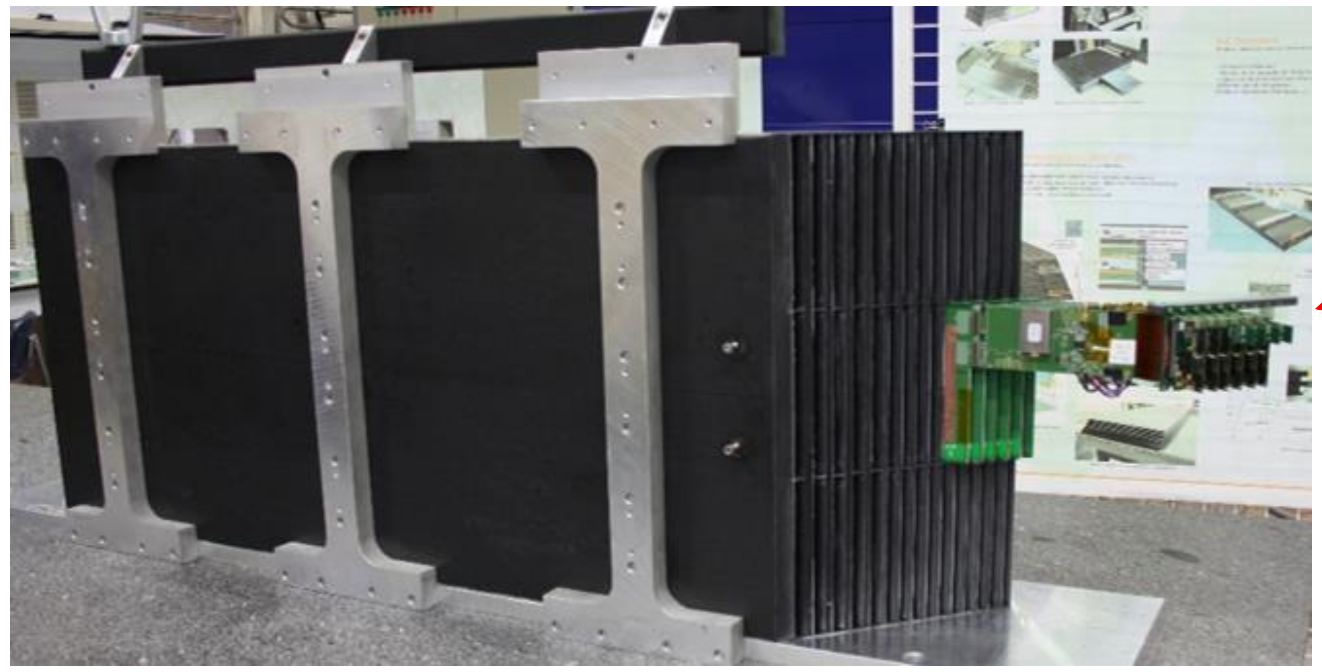
Carbon fiber –Tungsten structure with Alveola to slide in the active layers.

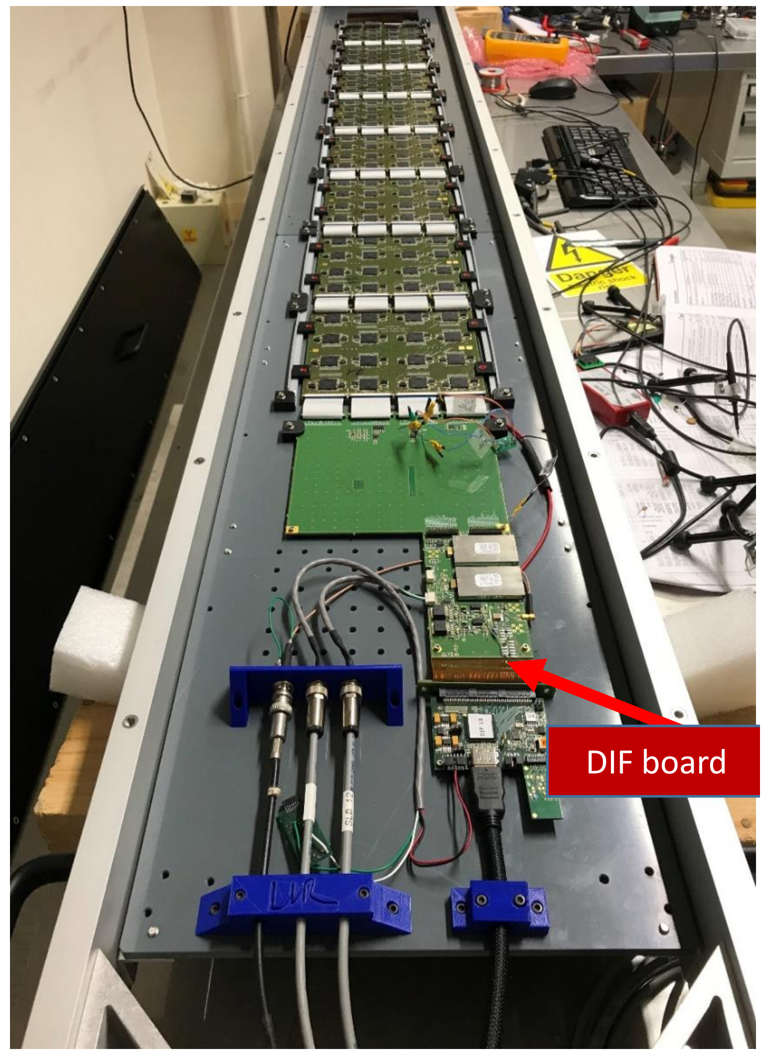




J.-C. Brient (LLR)

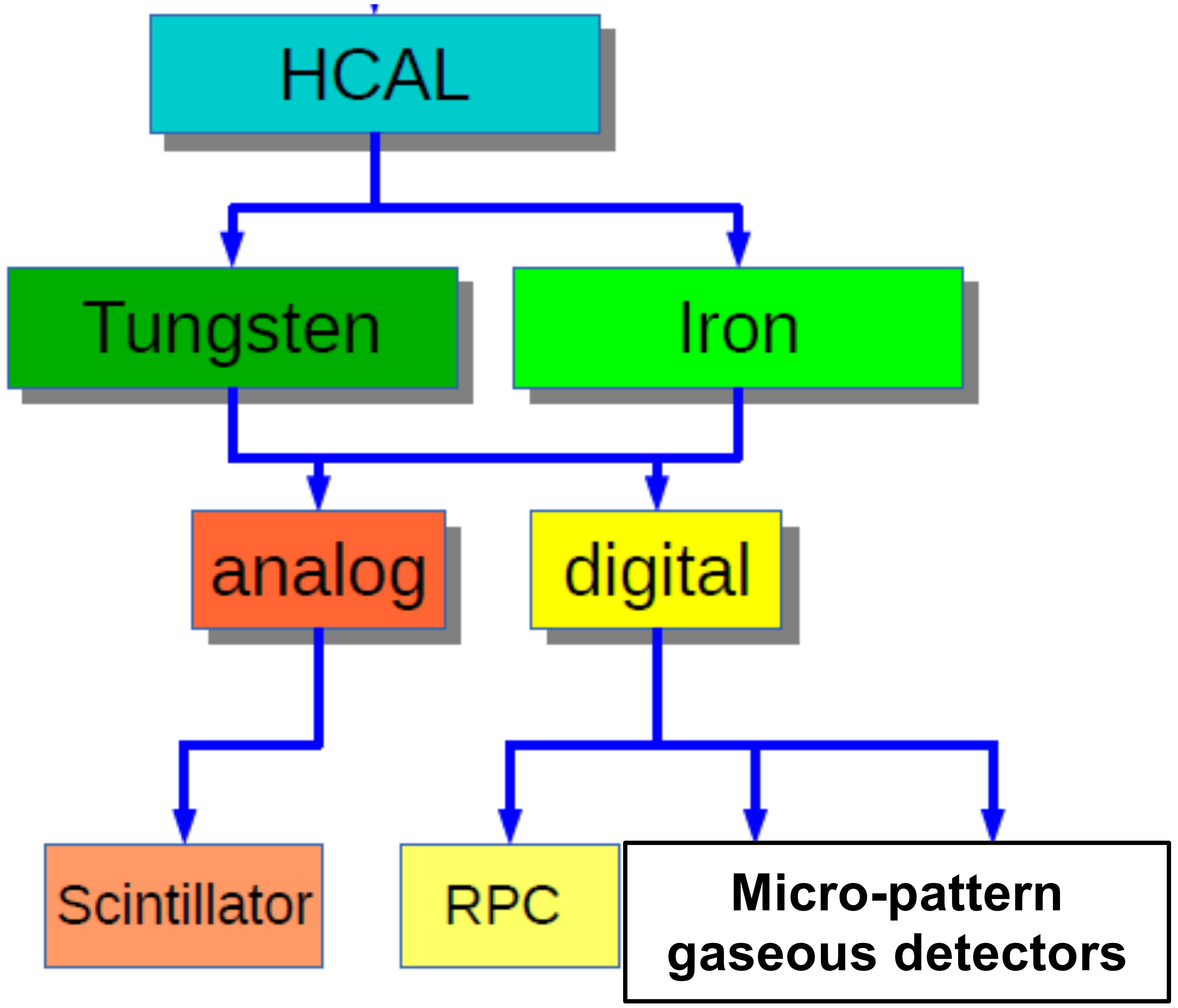






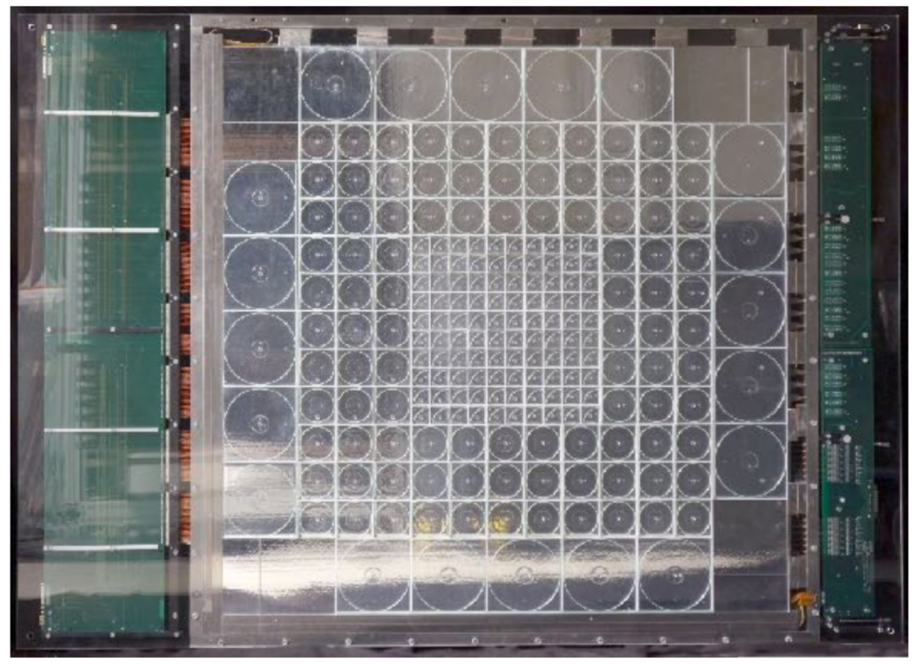
On beam at DESY in 2018

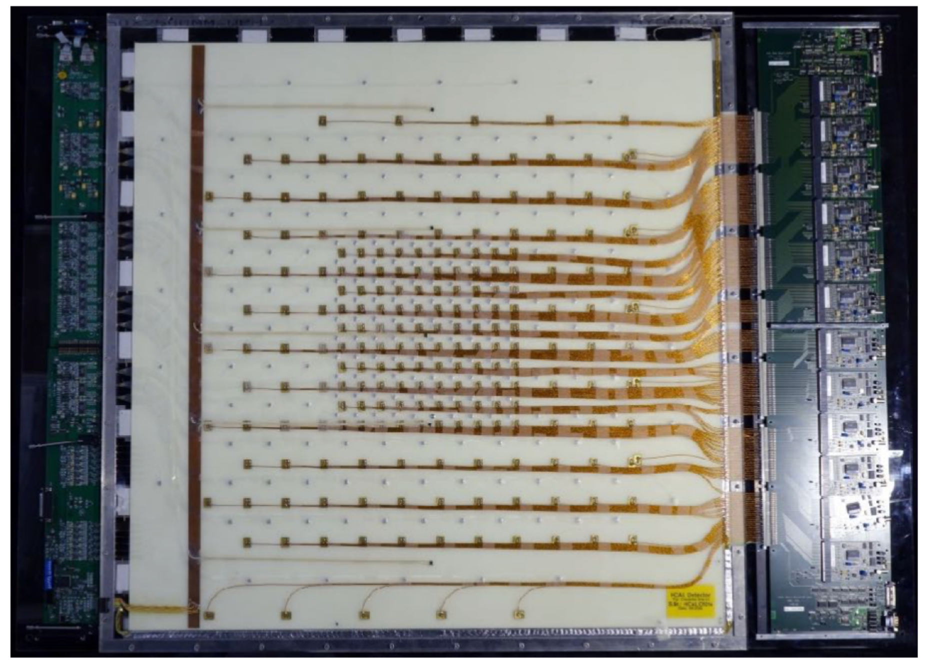
Moving on to the Hadron Calorimeter [JIanbei Liu]:

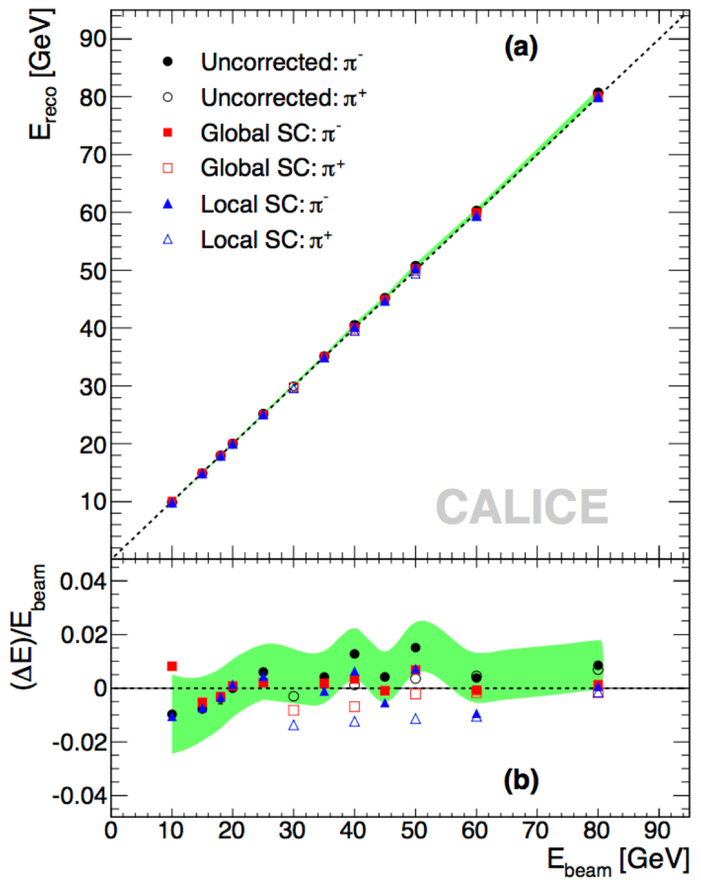


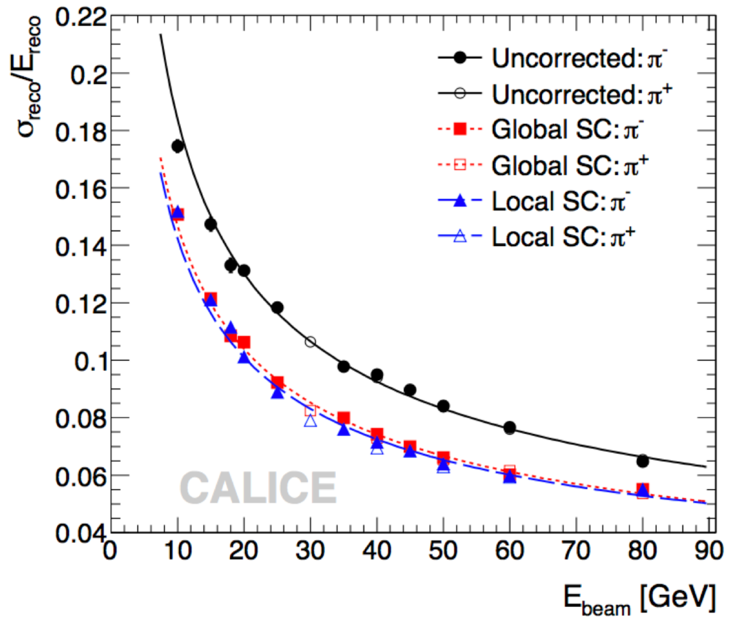
Analog HCAL:

- Rapid development of SiPM technology made a scintillator-based PFA calorimeter possible.
- A large-scale physics prototype was built
  - scintillator tiles in varying size, WLS+SiPM, FEE not imbedded
  - 38 layers, cross-section: $1{\times}1 m^2$, volume: $1 m^3$, ~7.6 k channels
  - tested with both tungsten and steel absorber









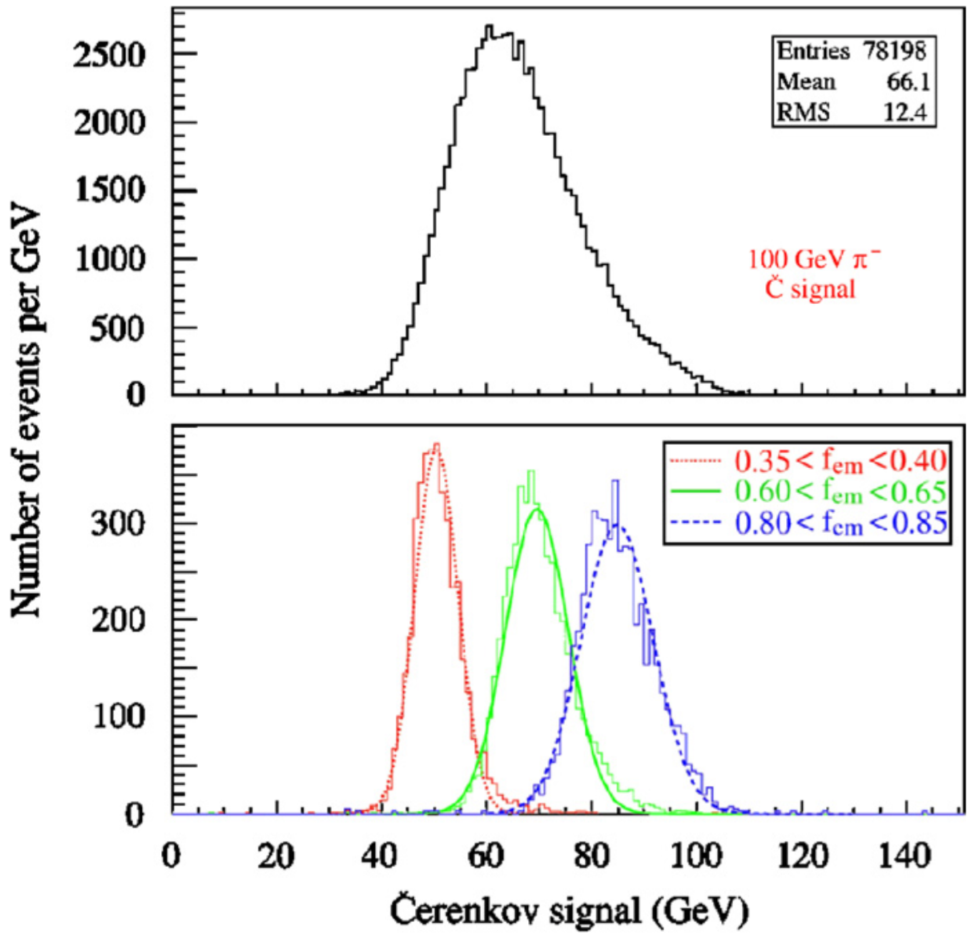
fit results	stochastic	constant
initial	57.6%	1.6%
global SC	45.8%	1.6%
local SC	44.3%	1.8%

Any alternative? Dual Readout calorimetry [Roberto Ferrari & Gabriella Gaudio]

We know that:

- Calorimetry is a "fluctuation game" [leakage, sampling, e.m. fraction, invisible energy, noise];
- **In hadron initiated showers, the main fluctuations in the event-to-event response are due to:**
  - **the share between the e.m. and and hadronic component**
  - **the fluctuations in the "invisible energy"**

and the e.m. component is giving a significant contribution, growing with energy:



R. Wigmans, NIM A572 (2007) 215-217

an example of the improvement that can be expected in the measurement of a sample of 100 GeV π's if $f_{e.m.}$ is NOT measured (top plot) or if $f_{e.m.}$ bins are singled out

We also know that:

- if you embed in the same calorimeter a detector responding primarily to the e.m. fraction and detector responding to the total dE/dX, you can single out $f_{e.m.}$.

This was proposed (and successfully demonstrated in a series of different implementations) using Cherenkov light [produced by relativistic particles and dominated by the e.m. shower component] and scintillation => DUAL READOUT CALORIMETRY

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

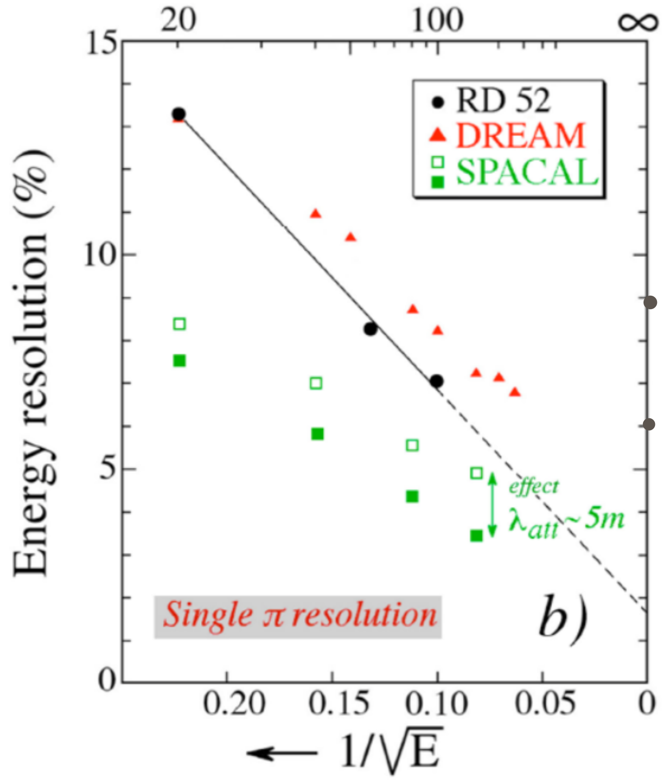
$$C = E \times [\ f_{em} + (h/e)_C \times (1 - f_{em})\ ]$$

$$E = (S - \chi C) / (1 - \chi)$$

$$\chi = (1 - (h/e)_S) \ / \ (1 - (h/e)_C) = (E - S) / (E - C)$$

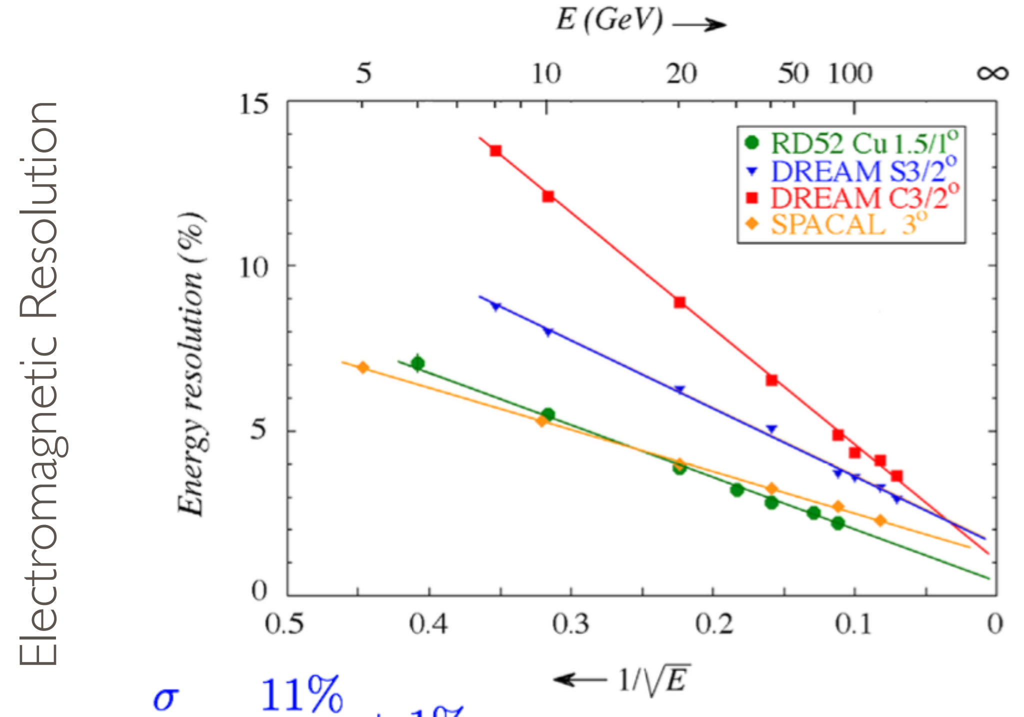
Two exemplary results from the DREAM/RD52 calorimeters:

[NIM A537 (2005) 537-561 - NIM A735 (2014) 130-144 - NIM A732 (2013) 475]

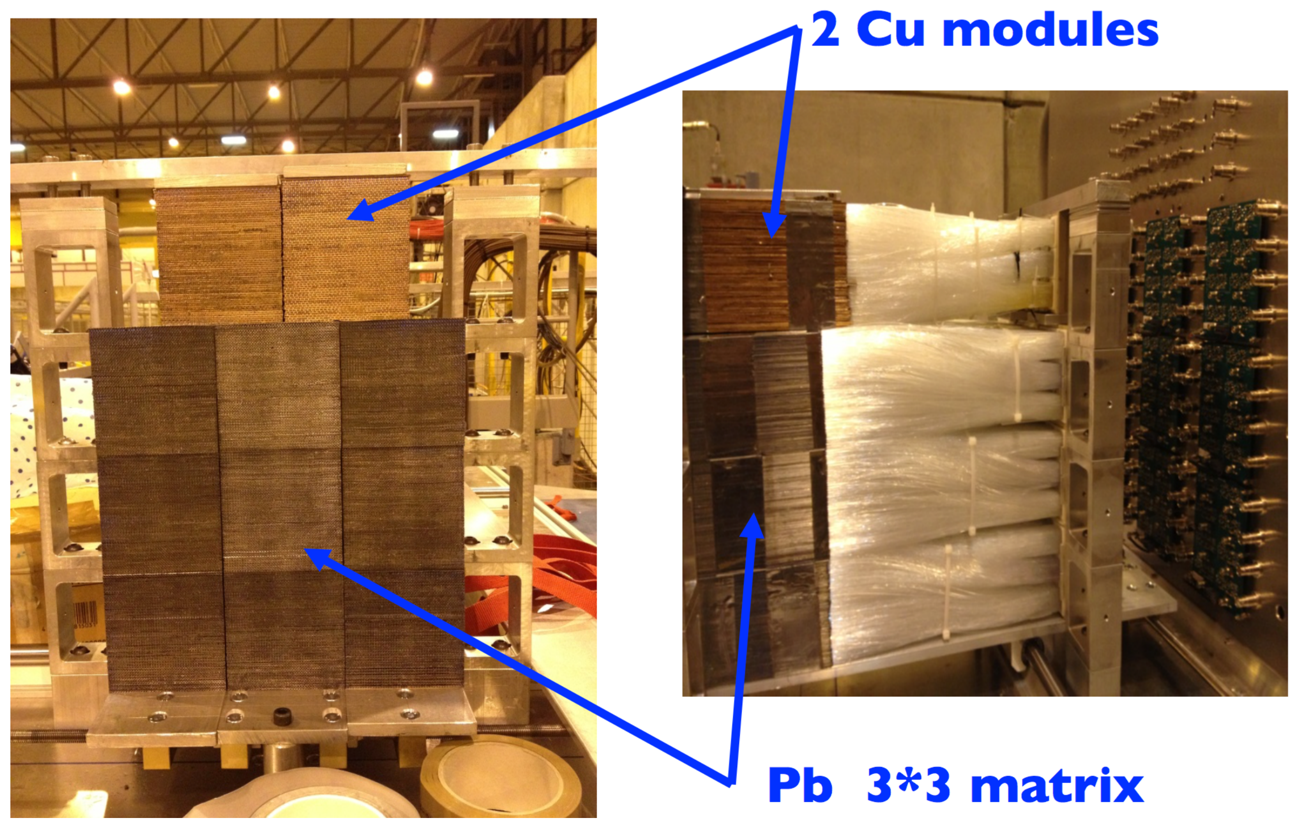


$$\frac{\sigma}{E} = \frac{53\%}{\sqrt{E}} + 1.7\%$$

referred to the RD52 calo with Pb converter affected by lateral leakage and light attenuation

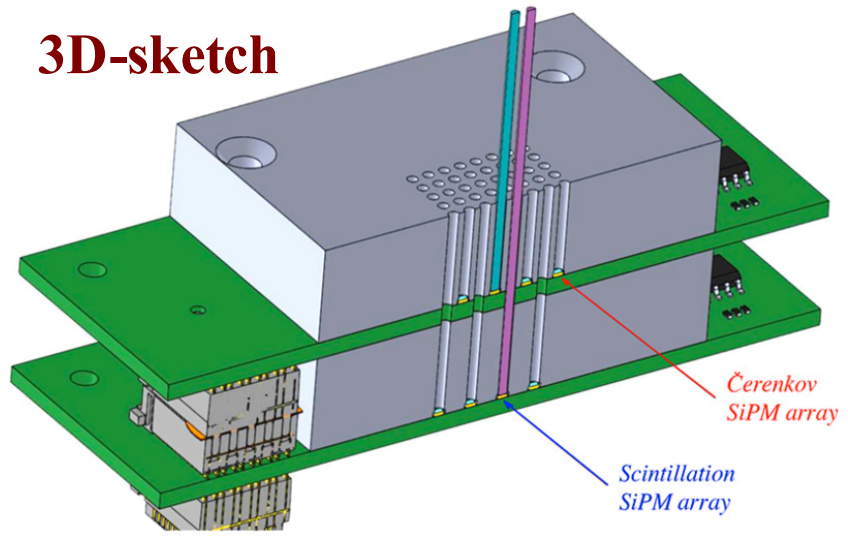


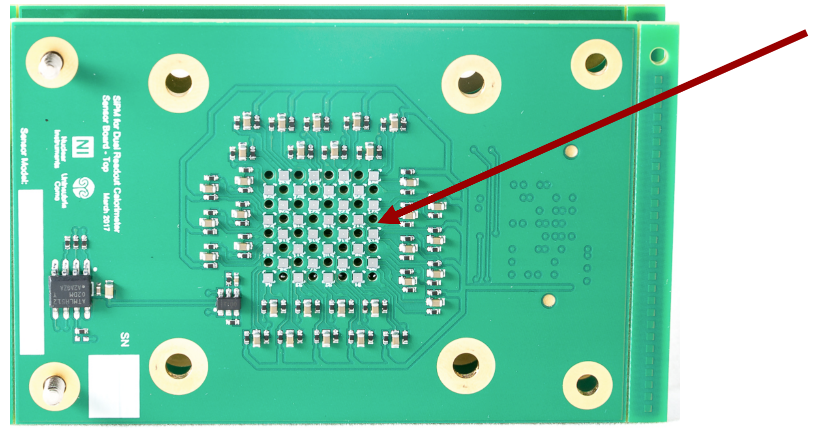
$$\frac{\sigma}{E} = \frac{11\%}{\sqrt{E}} + 1\%$$

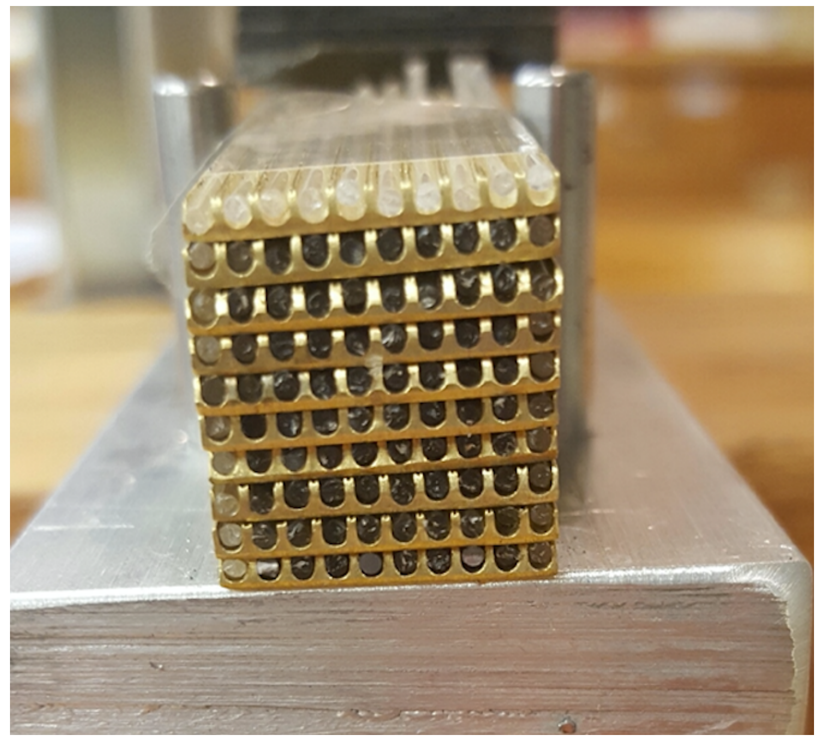


So far, the idea of integrating such a detector concept in a 4π detector turned the DREAM into a nightmare

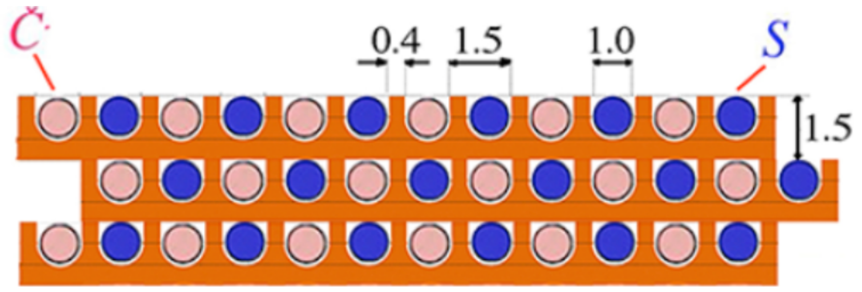
And it was so until when the Silicon age entered the photonics world and PMT were replaced by SiPM:





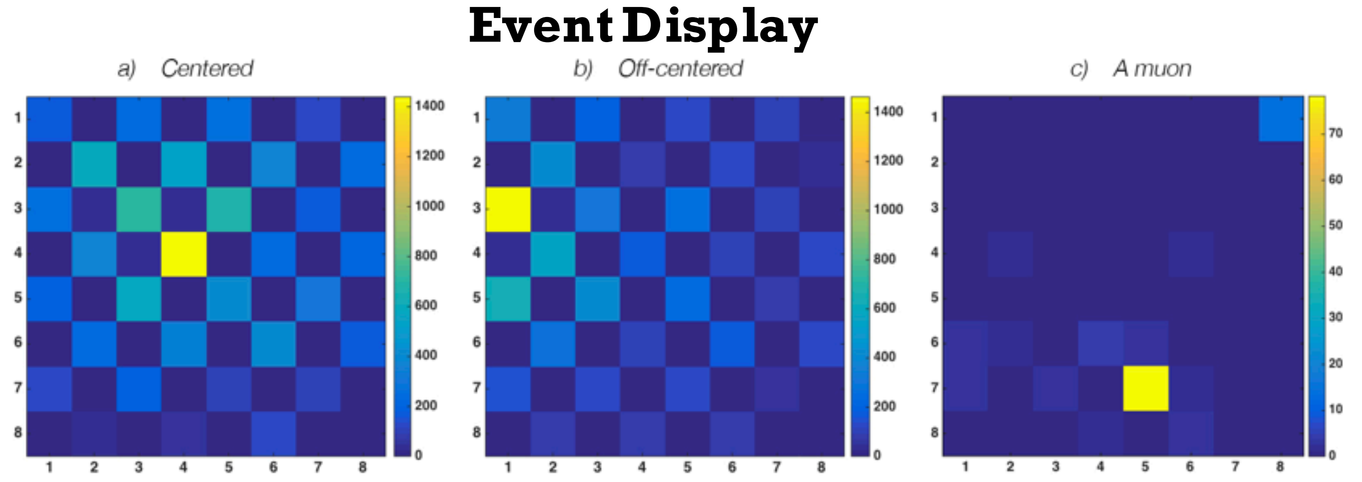


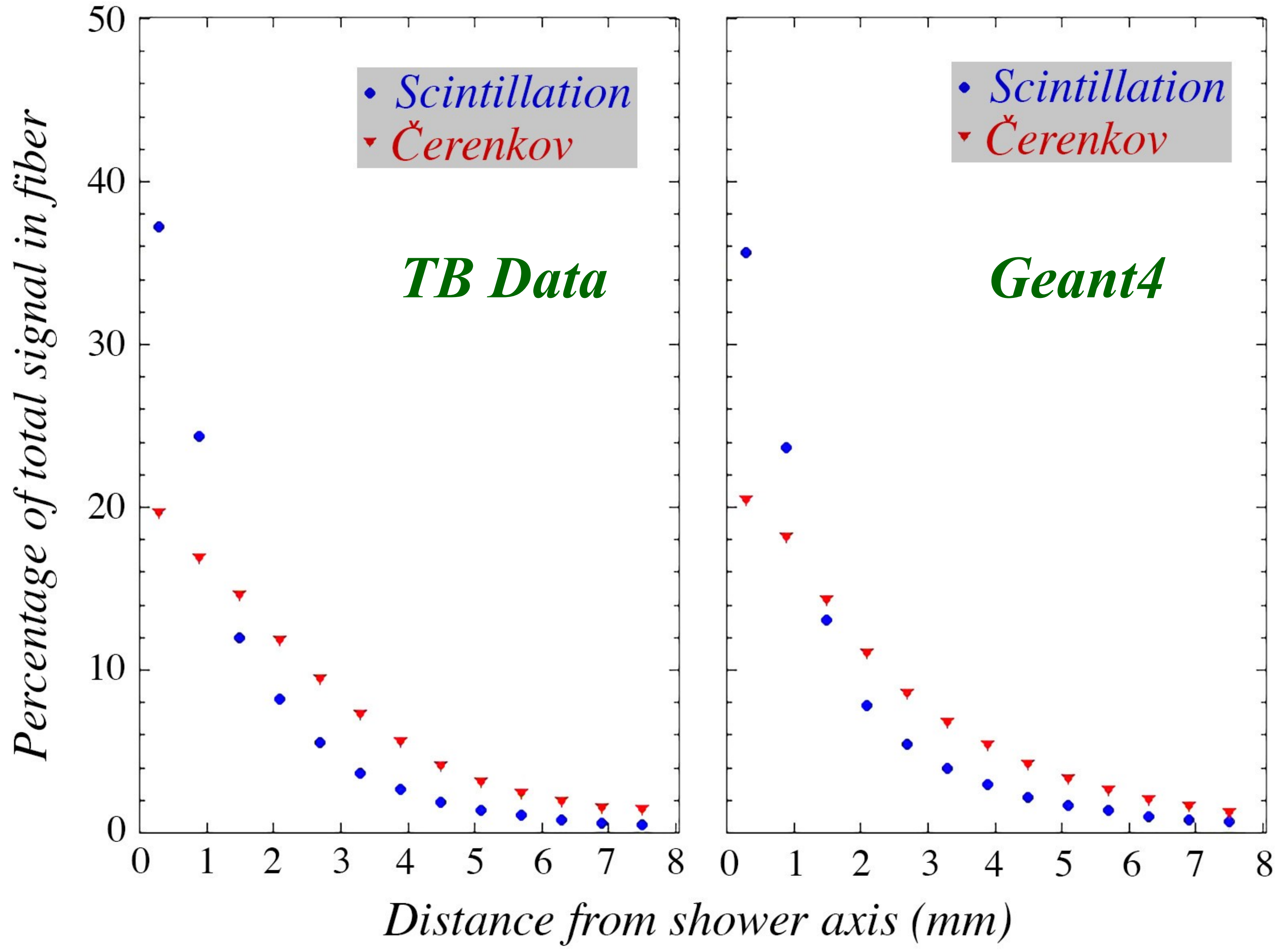
10x10 fibers



[sampling fraction 4.5%]

Test beam 2017 results:





more info:

- our NIM paper, available on the ArXiv: 1805.03251

A non exhaustive list:

1) absorber
2) longitudinal segmentation
3) alternative approaches (i.e. tiles vs. fibres)
4) front-end electronics (ASIC)
5) feature extraction
6) machine learning for jets

Lead:

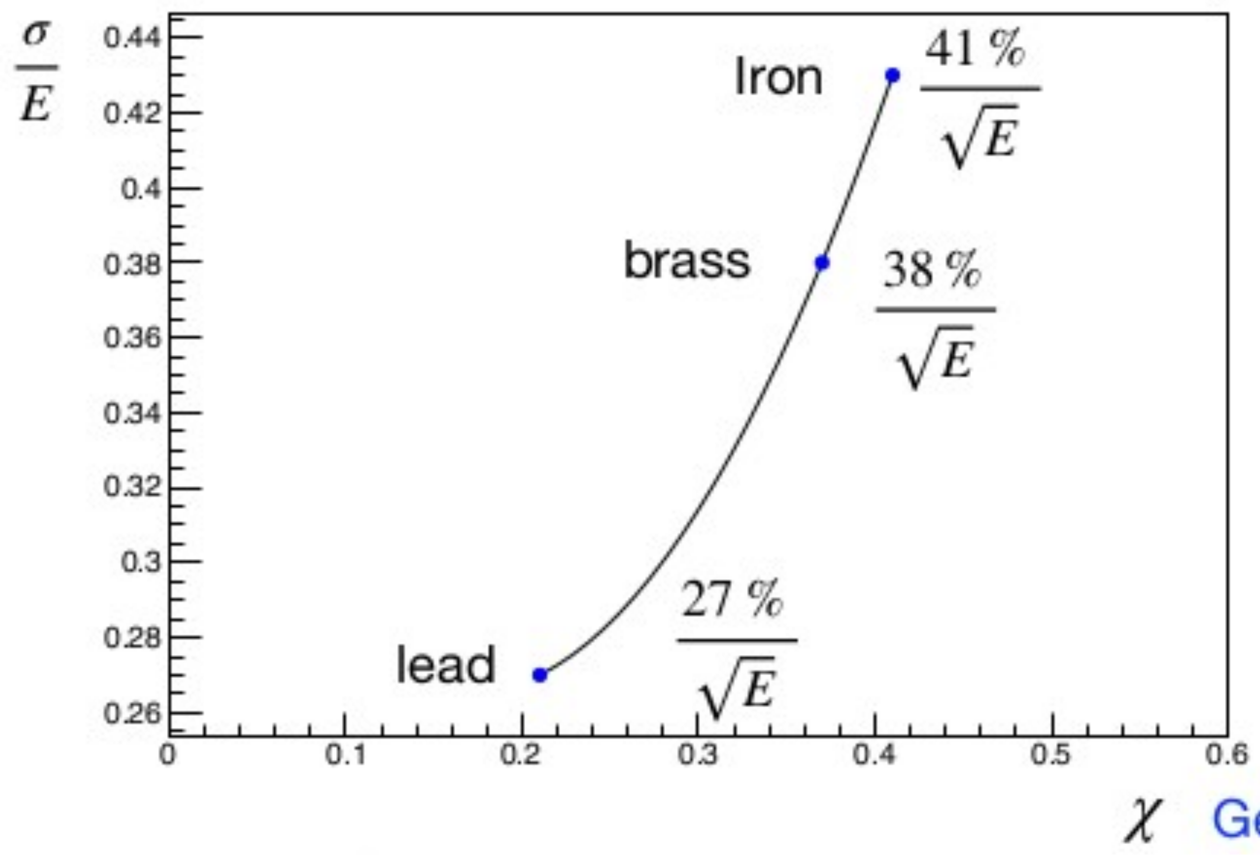
(-) ~ 60% more mass

(+) a factor of ~ 3 in longitudinal separation of em and hadronic showers

absorber : active volume = 62 : 38

	Iron	Brass (Cu260)	Lead
ρ (gr/cm^3)	5.31	5.71	7.46
λ_N (cm)	23.7	23.3	24.7
χ_0 (cm)	2.75	2.35	0.9
R_M (cm)	2.48	2.38	2.32
$\rho \times \lambda_N^3$ (kg)	71	72	113
$\lambda_N : \chi_0$	8.6	9.9	27.6

Hadronic resolution vs. χ



Geant4 - Preliminary

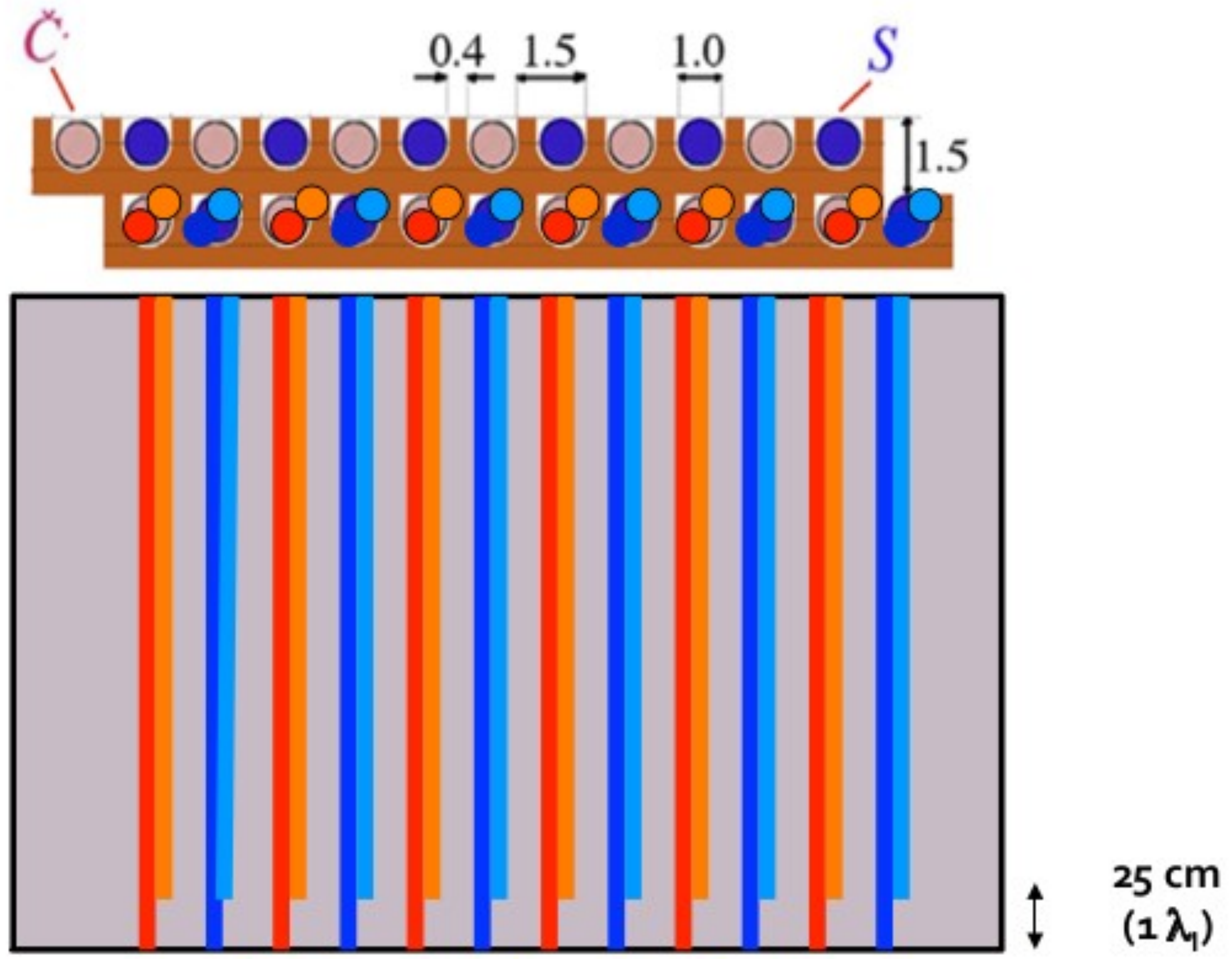
A non exhaustive list:

1) absorber
2) longitudinal segmentation
3) alternative approaches (i.e. tiles vs. fibres)
4) front-end electronics (ASIC)
5) feature extraction
6) machine learning for jets

different-length (staggered) fibres ?

(at least) 4 kind of fibres:

S-short, S-long,
C-short, C-long



short fibres → hadronic compartment(s)