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The Commonwealth's Flagship Campus

Highlights of the Mini Workshop on Experiments and Detectors

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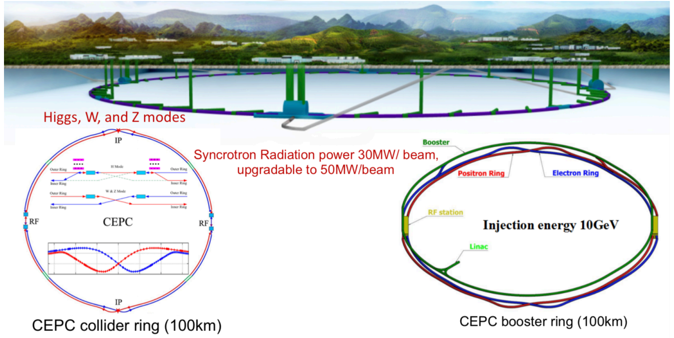
University of Massachusetts Amherst
01/21/2018

Contents

- The workshop happened last week, Thursday and Friday. http://iasprogram.ust.hk/hep/2019/workshop_cc.php
- It was roughly divided in the following parts:
  - Beam energy and backgrounds
  - Vertex detectors
  - Trackers
  - Calorimeters
- I will try to do the summary in the same order

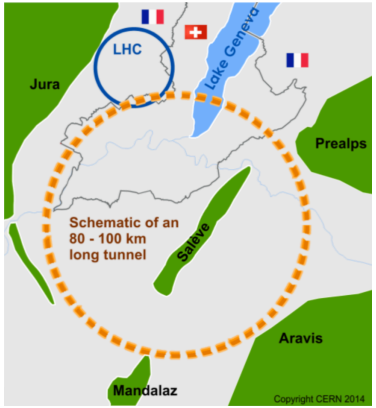
Physics requirements
Future experiments and detectors

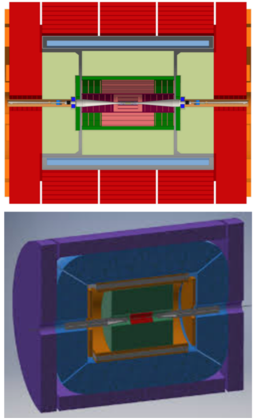
Paolo GIACOMELLI



CEPC collider ring (100km)

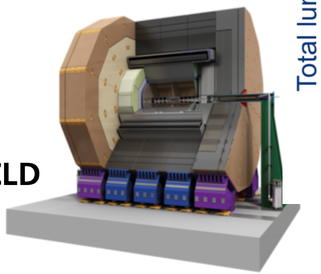
CEPC booster ring (100km)



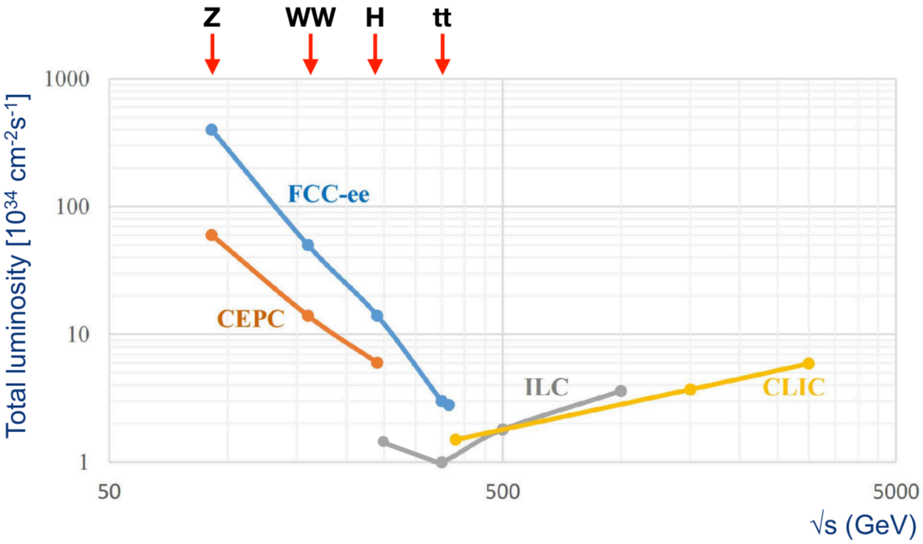


CLD

IDEA



ILD-like



Higher luminosity for circular colliders
Higher energy for linear colliders

Physics requirements

Paolo GIACOMELLI

- Very precise knowledge of beam spread!
  - Can be done with $\mu^+\mu^-$ events
- For all cross-sections Luminometer precision!
  - Acceptance known to ~2μm
- Many measurements require detector acceptance ~5 times better than LEP
  - Acceptance of low p objects must be kept high
- Good π^0 identification and direction
- b/c-tagging much better than LHC
  - High efficiency and purity, little p dependence

Due to extreme statistics, the requirements at the Z are the most demanding ones

- $\Delta p_t/p_t^2$ ~ 2x10^{-5} (GeV^{-1})
- σ(E)/E~10%/$\sqrt{E}$ EM energy resolution
- σ(E)/E~30%/$\sqrt{E}$ for jet energy resolution
- Flavor tagging
  - Decay length
  - Jet kinematic variables
  - Semi-leptonic decays
- Excellent b/c separation (much better than LHC detectors)
- PID for π^{+-} separation from other particles
- Low energy π^0 reconstruction

- 20-50 improvements on all EW observable measurements
- Measure Higgs couplings to ~1% level or better
- Discover possible deviations from the SM
- much more…

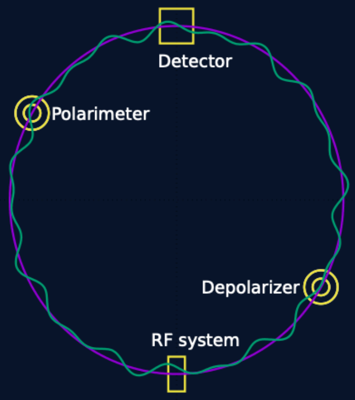
Beam energy calibration

Nikolai MUCHNOI

From FCC-ee CDR

- Beam energy calibration by Resonant Depolarization is the basis for the precise measurements of the Z and W masses with a precision of $\sim$100 keV and $\sim$500 keV correspondingly.
- About 200 polarized pilot bunches/ring will not collide – just used for frequent beam energy measurements by RD.

$$\frac{d\varphi}{d\alpha} = \frac{\Omega}{\omega} = 1 + \gamma \frac{\mu'}{\mu_0}$$



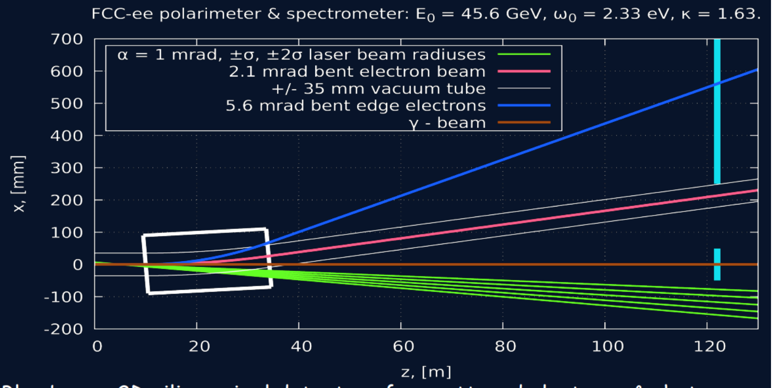
RD approach requires:

- polarized beam,
- polarimeter & depolarizer.

Accuracy limitations ($\Delta E_{cm}/E_{cm} \simeq 1$ ppm):

- rare measurements – interpolation,
- non-flat orbit – $B_{\|}$ affects Ω,
- $E_{beam}(\text{i.p.}) \neq \langle E_{beam} \rangle$,
- collision angle uncertainty, etc.

FCC-ee polarimeter: x-z plane



Blue bars – 2D silicon pixel detectors for scattered electrons & photons.

- Detecting both scattered photons & electrons increases the reliability of beam polarization measurement.
- FCC-ee polarimeter provides $\simeq 1$ % / s accuracy for $\zeta_{\perp}$.

Beam background

Georgios VOUTSINAS

Synchrotron radiation

- Unlike in linear colliders, SR is expected to be a source of bkg on FCCee detectors
- Main source comes from the last bend, but contribution is expected also from FF quads

Beamstrahlung induced backgrounds: Incoherent Pairs Creation (IPC), Coherent Pairs Creation (CPC), and $\gamma\gamma \to$ hadrons

- Smaller space charge density for FCCee bunches compared to ILC/CLIC bunches
- These backgrounds are expected to be less severe in comparison with linear colliders

Beam−gas interactions

Radiative Bhabhas

Very small backgrounds

Synchroton Radiation Background

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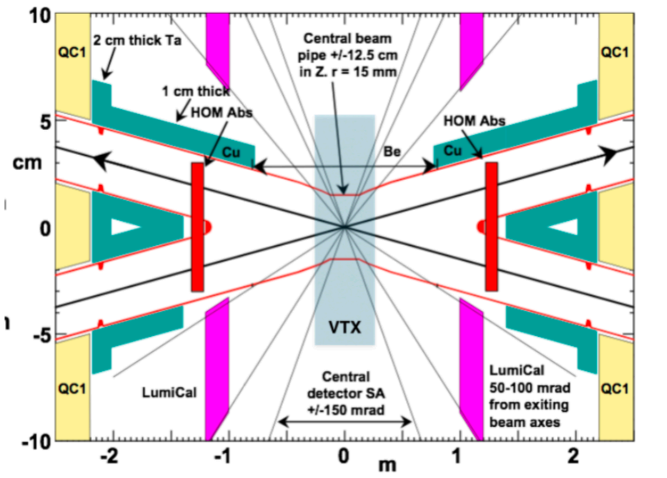
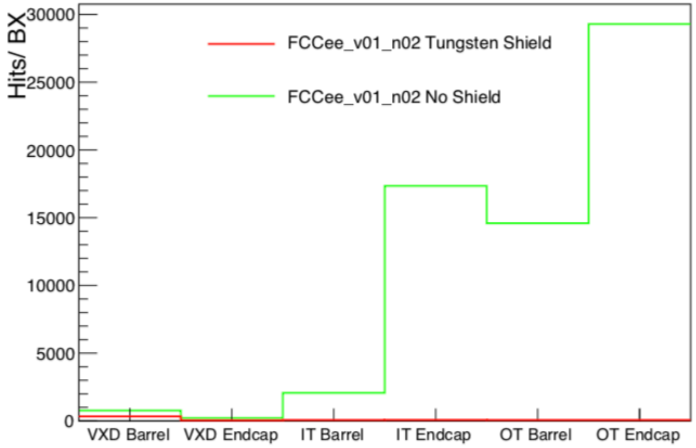


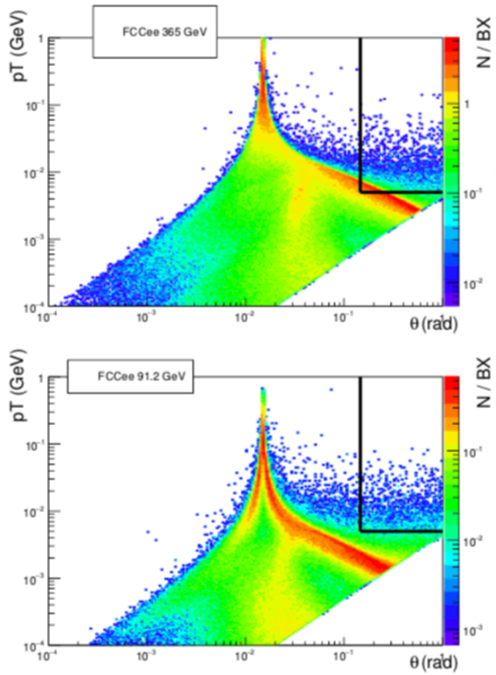
CLD max. occ. / subdetector, IPC & SR		
$\sqrt{s}$ [GeV]	91.2	365
VXDB	$\sim 10^{-5}$	$\sim 4.5 \times 10^{-4}$
VXDE	$\sim 3.8 \times 10^{-5}$	$\sim 4 \times 10^{-4}$
TE	$\sim 1.8 \times 10^{-5}$	$\sim 1.6 \times 10^{-4}$

- A fraction of the last bend and Quad produced SR scatters off the mask and showers into the detector area
- Full simulation studies of SR effect on FCCee detectors showed that proper shielding, it can be reduced to almost negligible levels

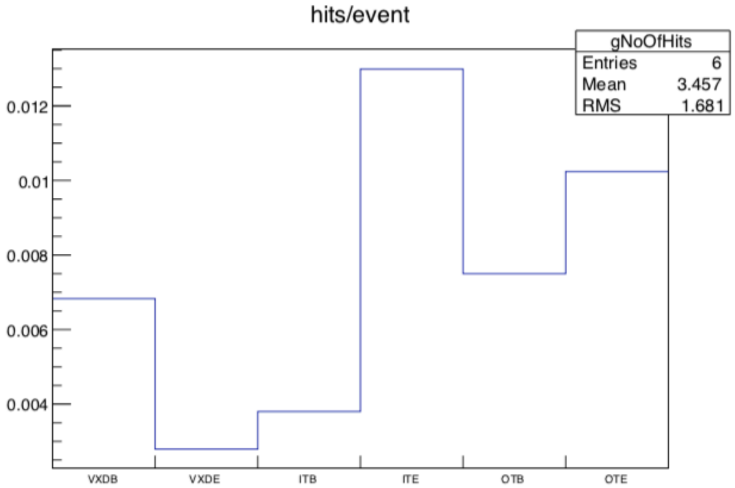


Bremsstrahlung induced background

Georgios VOUTSINAS



ee pairs in these rectangles reach typical VXD



hadrons		
$\sqrt{\hat{s}_{\min}}$ [GeV]	evts Z	evts Top
2	0.00063	0.0078
5	0.00029	0.0043
10	0.00015	0.0027

Vertex detectors

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

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

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

ILD LOI 2009

CDR - 2018

R_{in} [mm]	R_{out} [mm]	n	$\sigma_{single\,point}$ [μm]
16	32.5	3	2.3
16	60.0	3	3.7
16	340	5	6.0
16	340	7	6.9

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

$$\sigma_{m.s.} = R_{beam\,pipe} \times \theta_0 = \frac{b}{p\, sin^{3/2}\theta}$$

The CEPC-CDR baseline vertex detector geometry

	R (mm)	$\lvert z \rvert$ (mm)	$\lvert\cos\theta\rvert$
Layer 1	16	62.5	0.97
Layer 2	18	62.5	0.96
Layer 3	37	125.0	0.96
Layer 4	39	125.0	0.95
Layer 5	58	125.0	0.91
Layer 6	60	125.0	0.90

about 4" 1/4 **about 5"**

(do not forget wafers today are 8" in diameter)

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**

Massimo CACCIA

Vertex detectors: readout rate

CEPC Beam Induced Background at VXD

	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

- **2.4 hits/cm^2/BX**
- **20x20 μm^2 pixels ⇒ 1/4 Megapixel/cm^2**
- **every hit, is generating a 3x3 pixel cluster ⇒ about 20 fired pixels/cm^2/BX**

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

Δt = 85 μs for 1 cm^2 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,

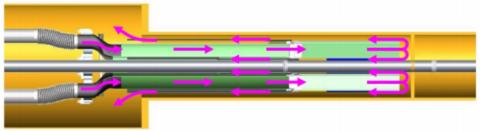
- 2500 pixels (1% of the existing ones) addressed & read-out (effective read-out time ÷ no. fired pixels), namely 34 ns/pixel

Fast reading → More power dissipated (CEPC current estimate <150 mW/cm^2)

Vertex detectors: cooling

Massimo CACCIA
Rafael LOPES DE SA

STAR tracker @RHIC (operational)
170 mW/cm², air cooled

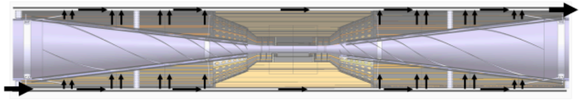


STAR-HFT Heavy Flavour Tagger

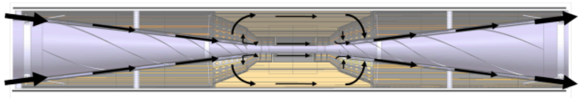
air flow at 10 m/s

TOTAL MATERIAL BUDGET: 0.4% X0, for the 2 layers

CLIC-ILD conceptual design
50 mW/cm² (power pulsing)

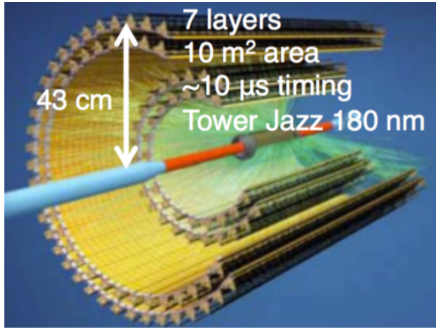


(a) Outer cooling stream

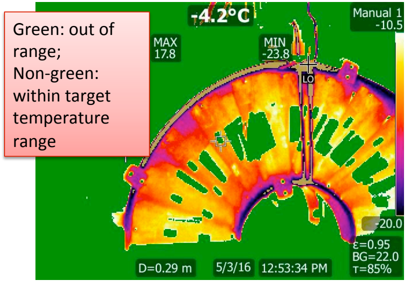


(b) Inner cooling stream

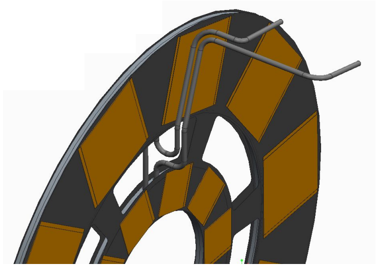
ALICE ITS (to be installed soon)
x/X0 = 0.3% (not good enough for CEPC)
100 mW/cm², liquid cooled



CMS FPIX (operational)
700 mW/cm², 2-phase CO_2 cooled



ATLAS ITk Inner System (design)
700 mW/cm², 2-phase CO_2 cooled



Vertex detectors: new ideas

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Ladislav ANDRICEK
Rafael LOPES DE SA

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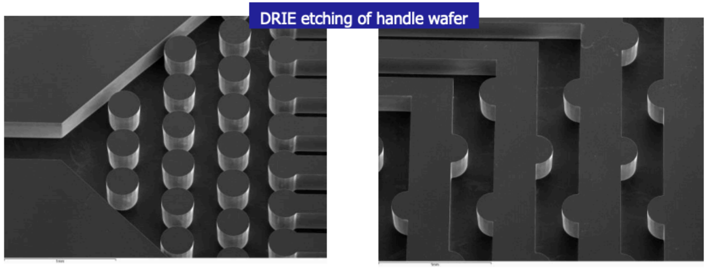
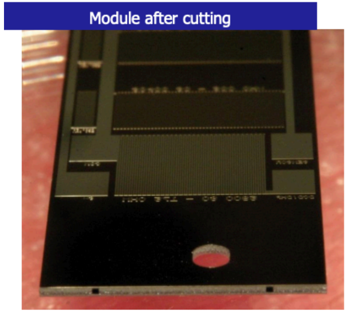
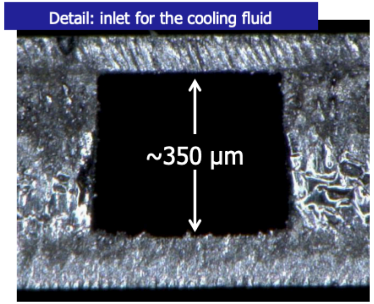
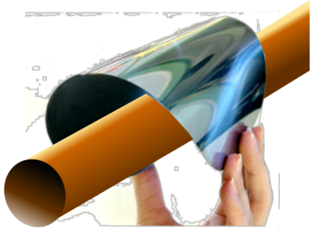
Microchannel cooling





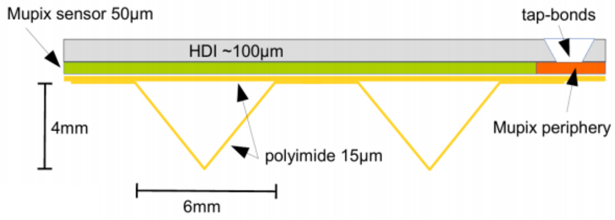


If air cooling works:
(namely if I have a power density **~ 20 mW/cm²**)

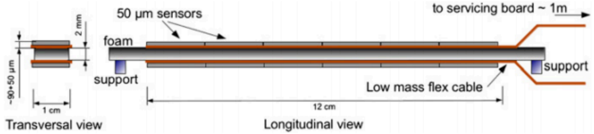


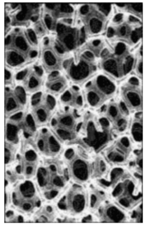
from C. Gargiulo's CERN seminar

Polyimide supports



SiC foam support

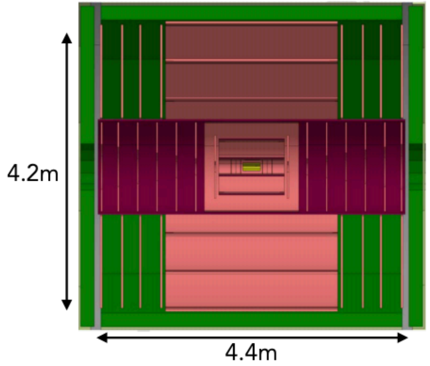




SiC foam, about 2 mm thick

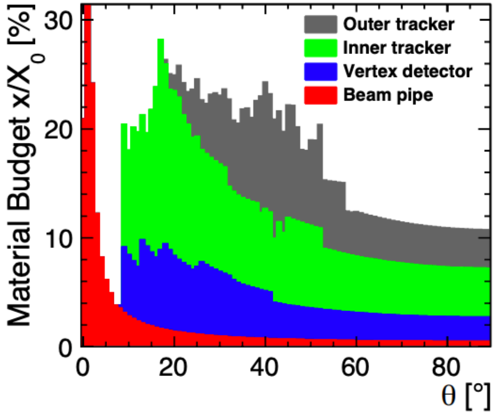
Trackers: full silicon

Emilia LEOGRANDE

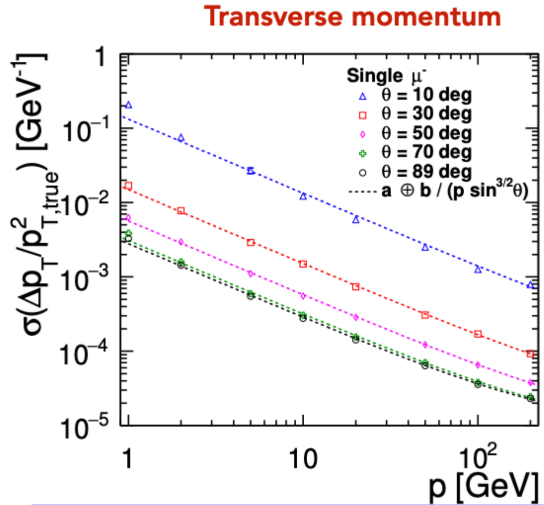


- Inner Tracker: 3 barrel layers + 7 forward disks per side
- Outer Tracker: 3 barrel layers + 4 forward disks per side
- microstrips size (50 μm x 1-10 mm)
  - first inner tracker disk pixelated like vertex detector
- total sensitive area = 195.6 m^2

- lightweight tracker:
  - sensitive thickness: 200 μm per layer
  - 1% X_0 per layer (sensitive + liquid cooling + connectivity) + 2.5% X_0 main support, cooling pipes, cabling routes



CCLD Tracking Performance



Achieved transverse momentum resolution of ~7x10^{-5} GeV^{-1} for 45 GeV muons at normal incidence (corresponding to required accuracy for Z width measurements)

- curves do not saturate at high momenta => resolution dominated by multiple scattering

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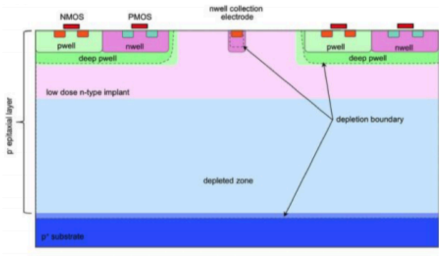
R&D for future silicon trackers and vertex detectors

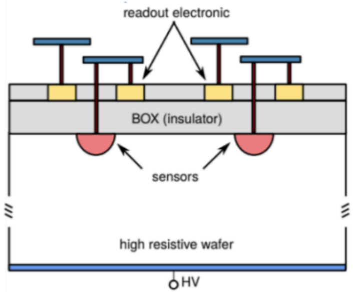
Emilia LEOGRANDE

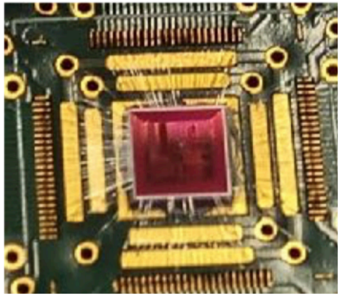
Integrated HR-CMOS



- integrated CMOS sensor on High-Resistivity substrate
- tests with INVESTIGATOR analog prototype chip in TowerJazz 180 nm HR-CMOS process (ALICE development): 20x20 - 50x50 μm^2 pitch
  - for 28x28 μm^2, with *external readout:* **~99.3%** efficiency, **<5 ns** timing, **σ_{SP} ~ 4 μm**
- ongoing work to design *fully integrated* CLICTD chip: 30x300 μm^2 pitch, be thinned to 50-100 μm
- plan to use smaller feature size processes in the future => to become an option for the vertex detector as well

Monolithic SOI sensors





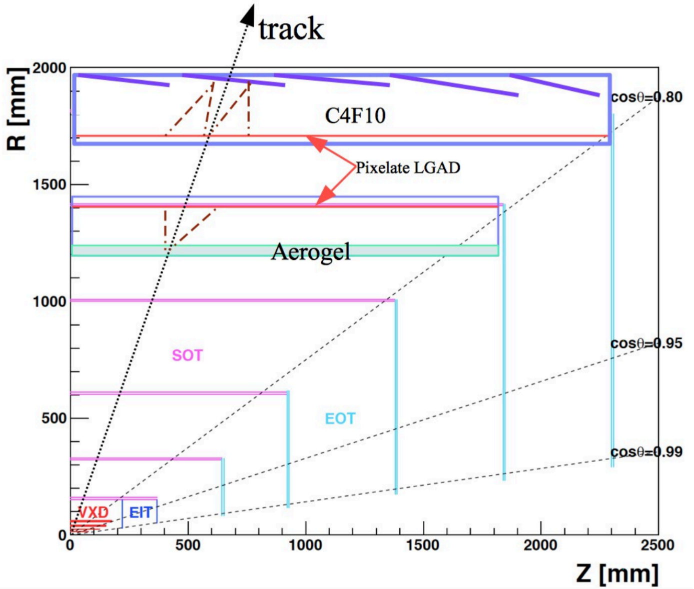
- Silicon-On-Insulator (SOI): sensor and electronics integrated on single wafer with high-resistivity substrate
- Cracow SOI test chip in 200 nm LAPIS SOI process
  - for 500 μm thick sensors and 30x30 μm^2 pitch => **>99%** efficiency, **σ_{SP} ~ 4.5 μm**
- ongoing work is the production of CLICPS vertex test chip, *targeted to Linear Collider* vertex requirements: 20x20 μm^2 pitch, snapshot readout of analog time and charge measurement, >= 100 μm thickness
- promising option for tracker and also for stringent vertex requirements

PID with Silicon Trakers

Wei-Ming YAO

- FST in CDR has few concerns:
  - Limited dE/dx
  - Double sided strip layers with higher material budget
- TOF with LGAD pixelate with 10 ps timing:
  - Replacing outer strip layers with LGAD layer to reduce material budget.
  - Providing timing for PID up to 10 GeV.
- RICH for PID up to 50 GeV:
  - Minimizing material budget
  - Cherenkov light detection:
    - MWPC, SiPM, HPDs...
    - LGAD pixelate detector for tracking and photon.

Do we need to go all the way to 50GeV?

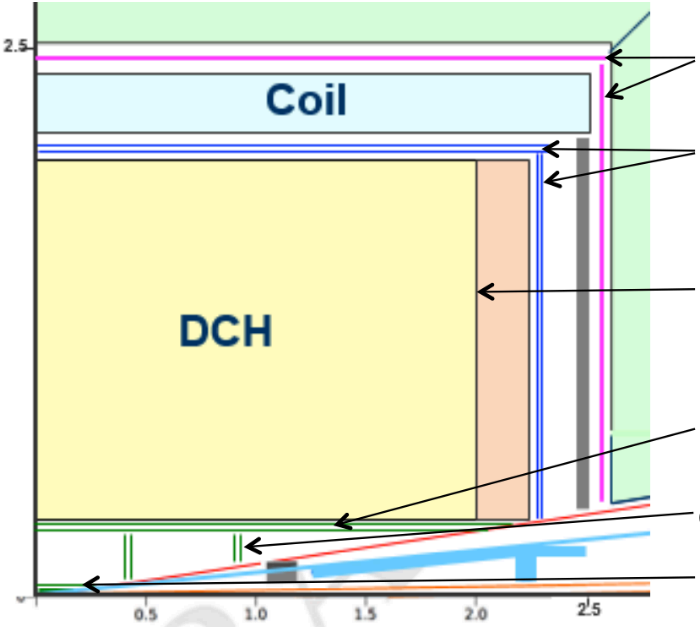


- **Pros: PID will help jet-charge and flavor tagging.**
- **Cons: Additional material budget to degrade the detector performance.**

Francesco GRANCAGNOLO

Trackers: drift chambers

IDEA Drift Chamber (CEPC and FCC-ee)



PSHW: 2 crossed layers of u-well (400 um x 500 mm)
in barrel and forward regions

SOT: 2 crossed Si u-strip (50 um x 100 mm) layers of 0.5% X0
in barrel and forward regions

DCH 56448 (~1.4 cm) cells
(almost the same just minor differences in the overall dimension)

SVX outer: 2 crossed Si u-strip (50 um x 1 mm) layers (0.5 X0)

SVX forward: 4 single Si pixel (50 um x 50 um) layers of 0.3% X0

	R_{in} [mm]	R_{out} [mm]	z [mm]
drift chamber	350	2000	±2000
service area	350	2000	±(2000÷2250)

# of layers	112	min 11.8 mm – max 14.9 mm
# of cells	56448	192 at first layer – 816 at last layer
average cell size	13.9 mm	min 11.8 mm – max 14.9 mm
average stereo angle	134 mrad	min 43 mrad – max 223 mrad
transverse resolution	100 μm	80 μm with cluster timing
longitudinal resolution	750 μm	600 μm with cluster timing

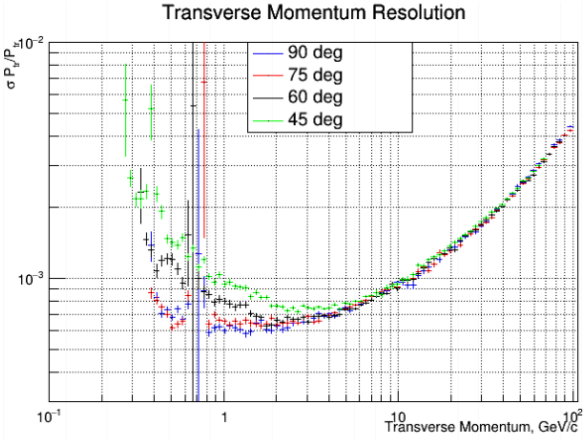
	inner wall	gas	wires	outer wall	service area
thickness [mm]	0.2	1000	1000	20	250
X_0 [%]	0.08	0.07	0.13	1.2	4.5

Drift chamber - performance

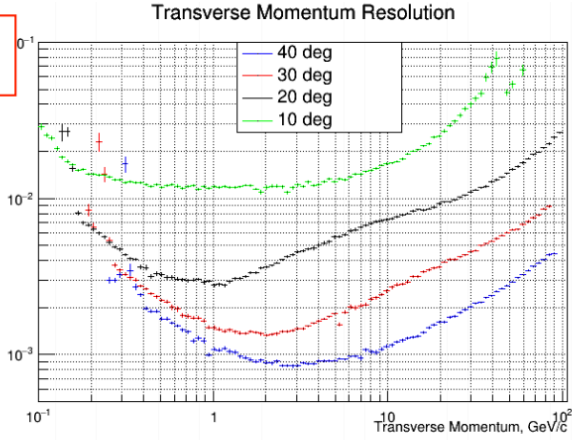
Francesco GRANCAGNOLO

Barrel

Forward

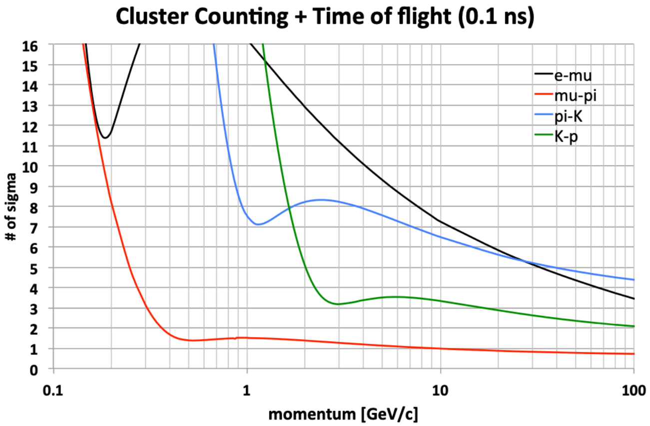


p_t



IDEA	$0.1p_t \oplus 0.7$	0.74×10^{-3}	2.2%

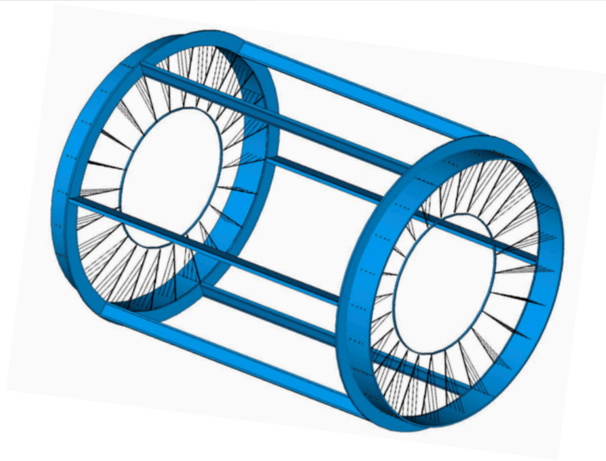
PID with dN/dx and timing



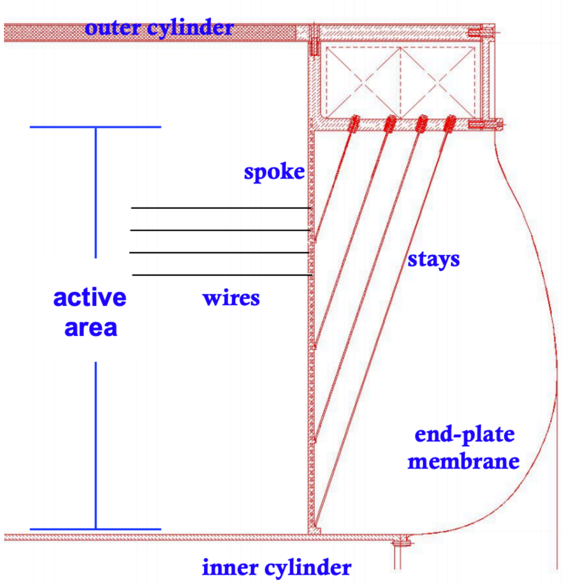
Good PID with cluster counting and timing

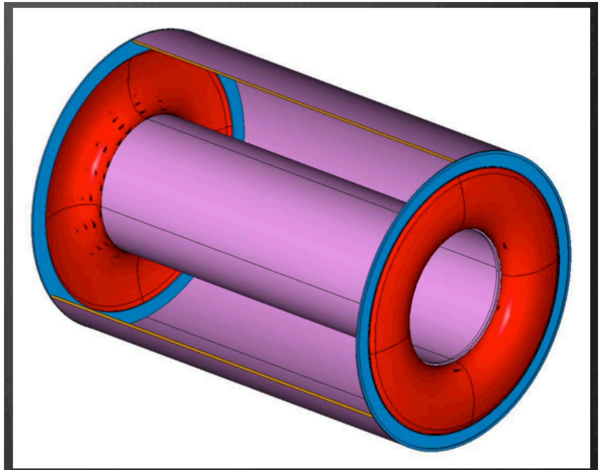
Drift chamber structure

Francesco GRANCAGNOLO



Wire support:
Wire cage structure not subject to differential pressure can be light and feed-through-less.





Gas containment:
Gas envelope can freely deform without affecting the internal wire position and tension.

Very light wire cage structure

Wire tension compensation

Huirong QI

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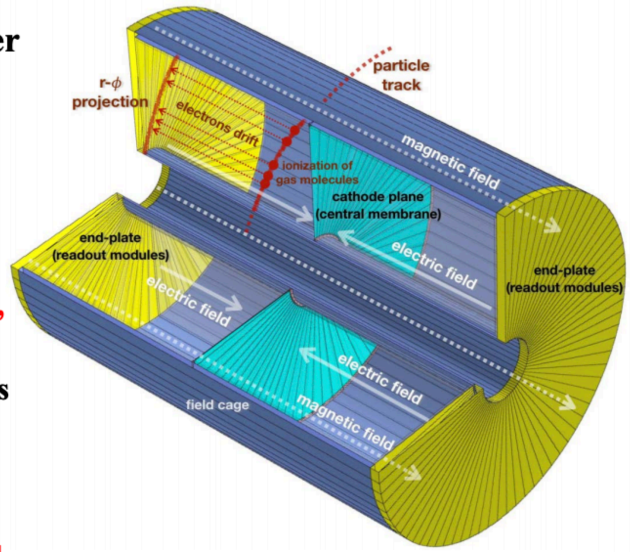
Trackers: TPC

Why use TPC detector as the tracker detector?

- Motivated by the H tagging and Z
- TPC is the perfect detector for HI collisions …(ALICE TPC…)
- Almost the whole volume is active
- Minimal radiation length (field cage, gas)
- Easy pattern recognition (continuous tracks)
- PID information from ionization measurements (dE/dx)
- Operating under high magnetic field
- MPGD as the readout



Overview of TPC detector concept

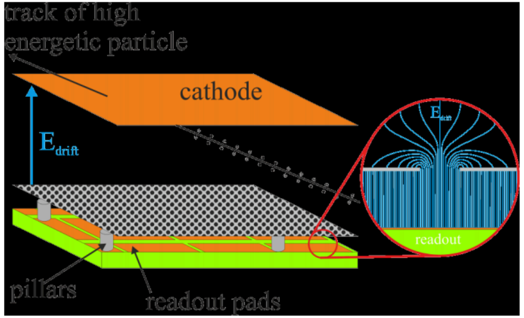
TPC detector concept:

- Under 3 Tesla magnetic field (Momentum resolution: ~10^{-4}/GeV/c with TPC standalone)
- Large number of 3D space points(~220 along the diameter)
- dE/dx resolution: <5%
- ~100 μm position resolution in rφ
  - ~60μm for zero drift, <100μm overall
  - Systematics precision (<20μm internal)
- TPC material budget
  - <$1X_0$ including outer field cage
- Tracker efficiency: >97% for pT>1GeV
- 2-hit resolution in rφ : ~2mm
- Module design: ~200mm×170mm
- Minimizes dead space between the modules: 1-2mm

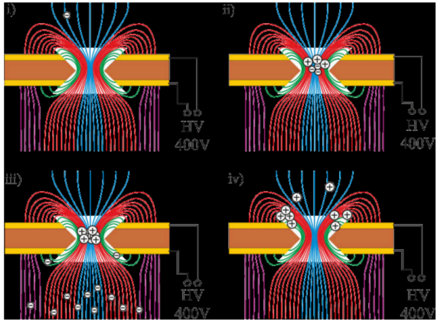
UMassAmherst

TPC trackers: technologies

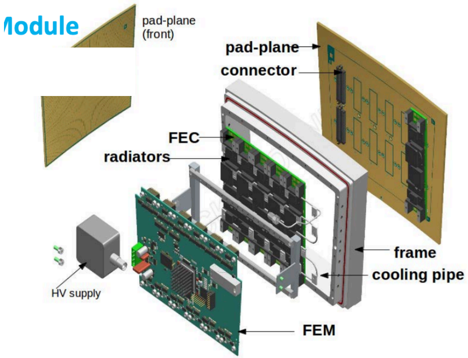
Micromegas : Micromesh gaseous chamber



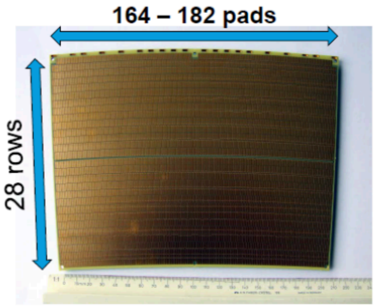
GEM : Gas Electron Multiplier



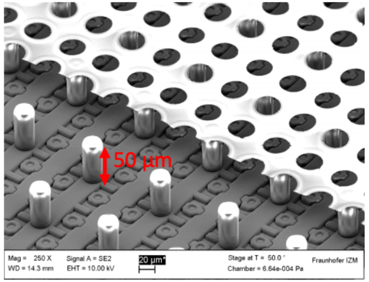
SACLAY Micromegas

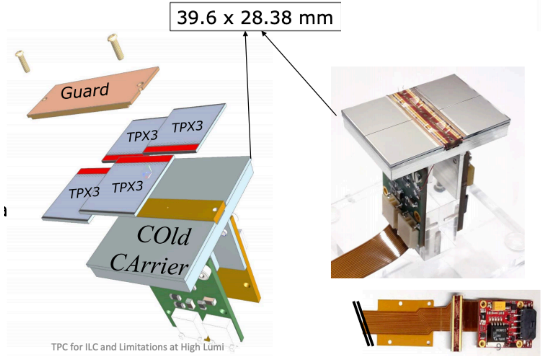


DESY GridGEM



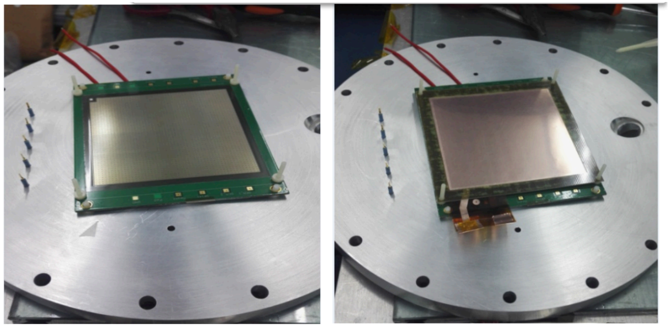
Gridpix: "digital TPC"



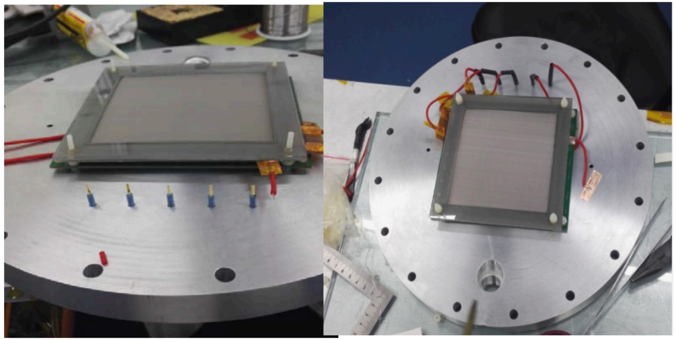


TPC trackers: technologies (2)

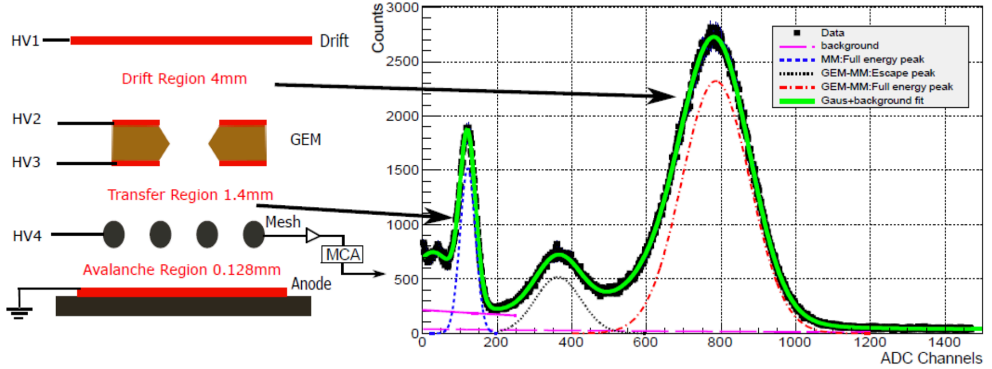
Huirong QI



Micromegas(Saclay) GEM(CERN)



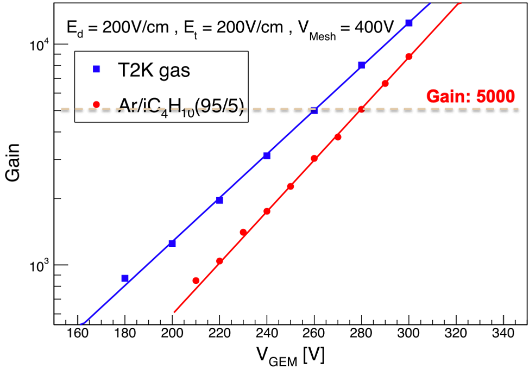
Cathode with mesh GEM-MM Detector

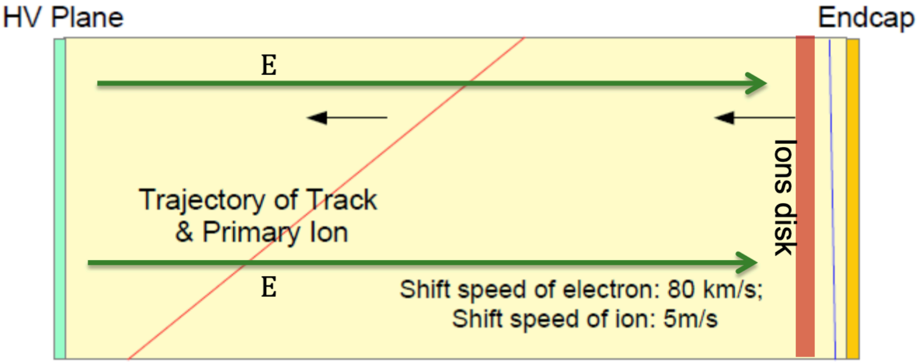


Huirong QI

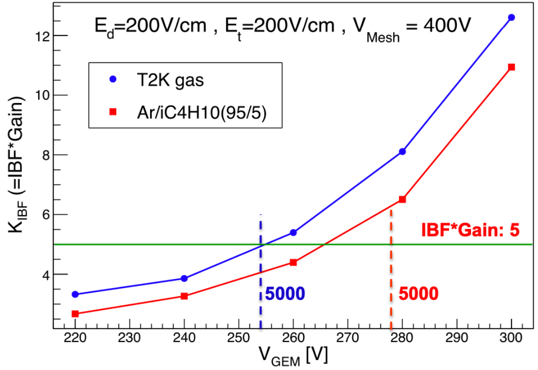
UMassAmherst

TPC trackers: Ion Back Flow (1)





To conclude, the TPC will be able to be used if the Gain×IBF can be controlled to a value smaller than 5.



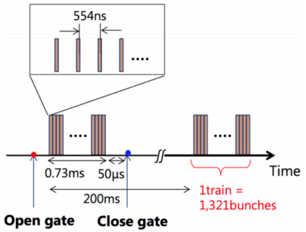
	ALICE TPC	CEPC TPC
Maximum readout rate	>50kHz@pp	w.o BG?
Gating to reduce ions	No Gating	No Gating
Continuous readout	No trigger	Trigger?
IBF control	Build-in	Build-in
IBF*Gain	<10	<5
Calibration system	Laser	NEED

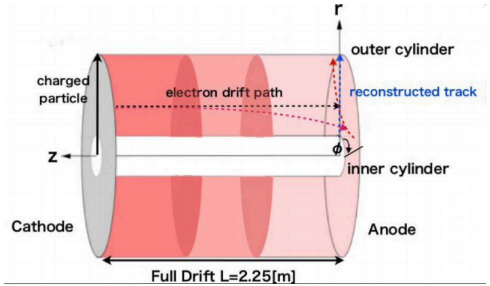
TPC trackers: Ion Back Flow (2)

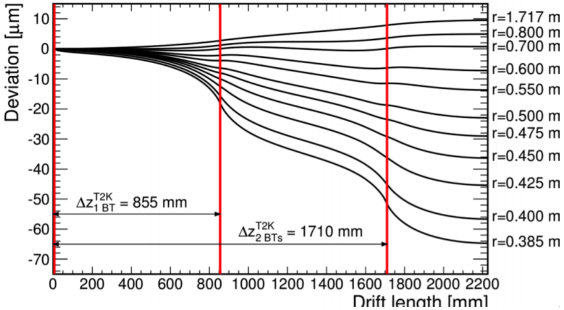
Paul COLAS

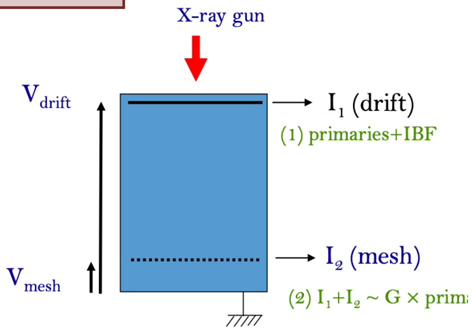
Piotr GASIK

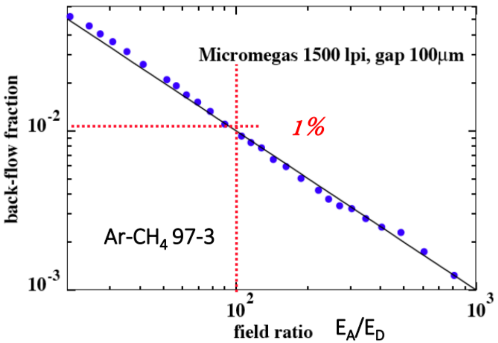
At the ILC, the bunch trains last about 1ms every 200 ms, giving rise to ion disks slowly drifting to the cathode



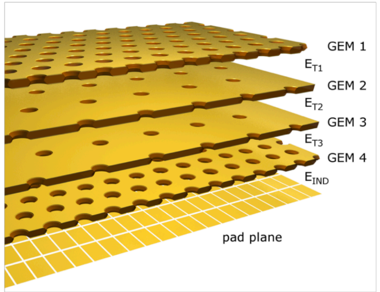


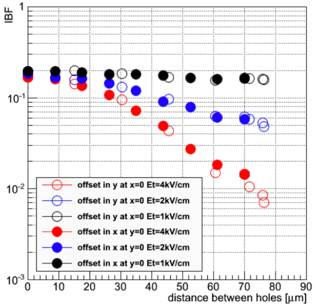






Caveats : if too much intensity of the gun is used, space charge affects the electric field and gives rise to underestimate of the backflow! See M. Ball et al, JINST 2013 (MPGD2013, Zaragoza)





Calorimetry
EM high granularity calorimeter

Jean-Claude Brient

	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/(Nlayer) $^{1/2}$	*
Shashlik type	***	Yes	*	30	***

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

	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

Calorimetry
EM SiW calorimeter

Jean-Claude Brient

CMS HGCAL

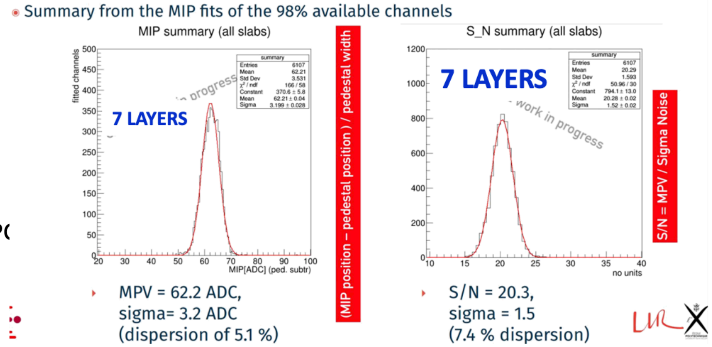
- Readout every 25 ns, active cooling , large number of layers
- High level of radiation (10^{16} n/cm²/year) … variation of the gain of the diodes
- The pile-up mitigate the power of PFA

FCCee/CEPC

- Readout every 25 ns (hypothesis)
- No problem of radiation
- Need active cooling (It allows pixels size of 6x6 mm – see my presentation at CEP(workshop 2017)
- Small pixel allows time measurement /particle (like in ATLAS or CMS)
- Small pixel allows to run at Z Pole (occupancy)… to be studied !!

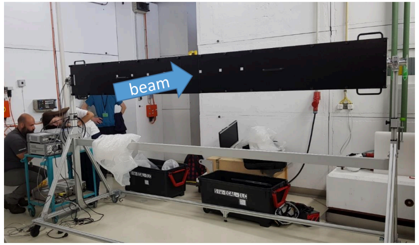
MIP CALIBRATION RESULTS

CALICE ECAL SiW Test Beam at DESY - 2017

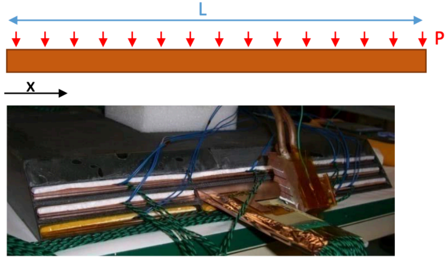


S/N ~ 20

Test Beam DESY July 2018

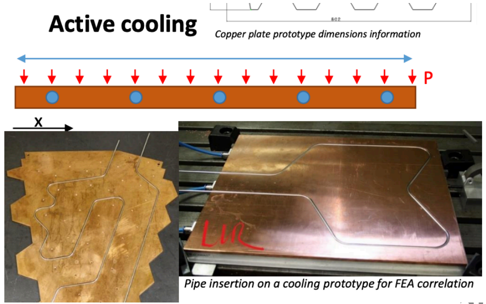


Passive cooling



Passive cooling ramp set up test on a 3 layers prototype

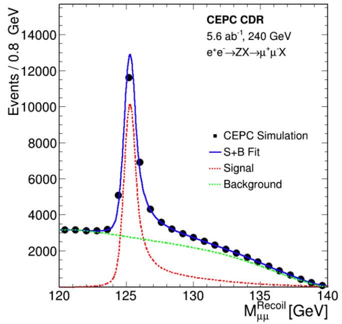
Active cooling

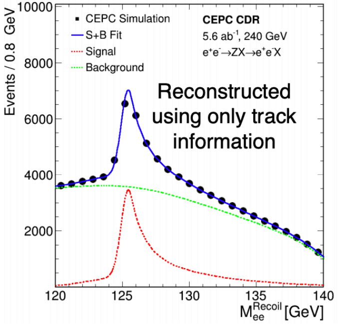


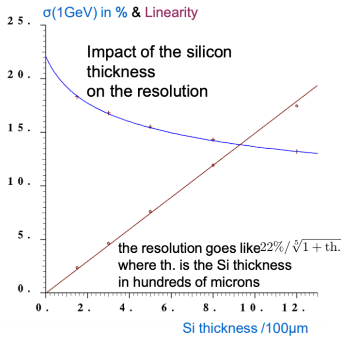
Pipe insertion on a cooling prototype for FEA correlation

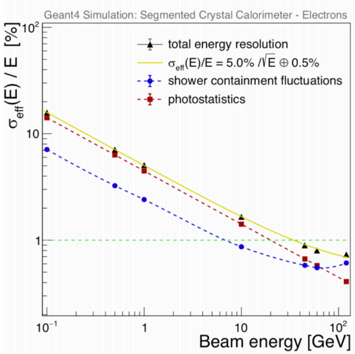
Calorimetry
EM crystal calorimetry

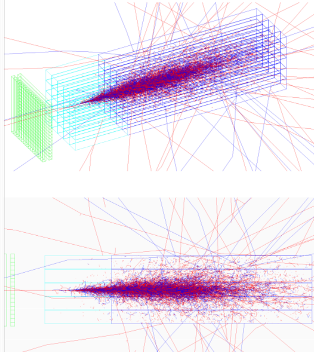
Sarah ENO







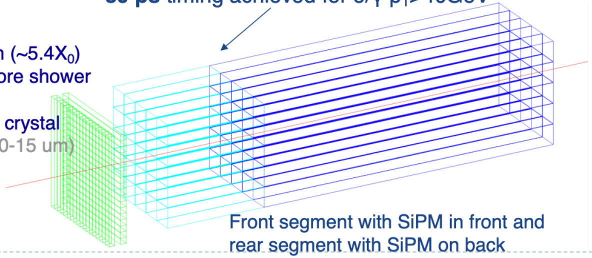




- **Timing layer (2 layers):**
  - LYSO:Ce crystals
  - SiPMs
  - 3x3x54 mm³ active cell
  - 3x3 mm² SiPMs (15-25 um)

- **ECAL layer:**
  - PbWO crystals
  - front segment 5 cm (~5.4X_0)
  - rear segment for core shower
  - (15 cm ~16.3X_0)
  - 10x10x200 mm³ of crystal
  - 5x5 mm² SiPMs (10-15 um)

< 5%/sqrt(E) (+) 1%
~30 ps timing achieved for e/γ p_T>40GeV



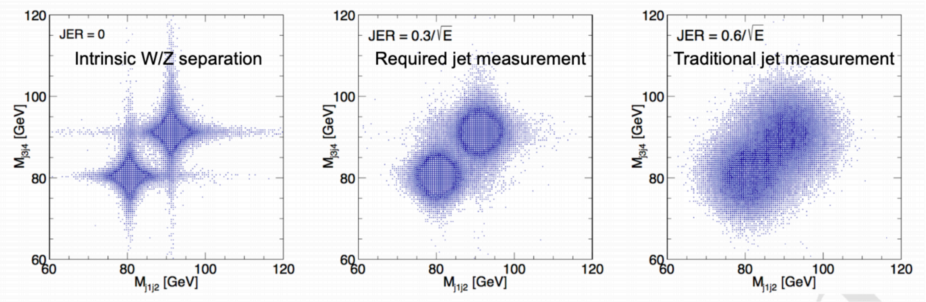
Front segment with SiPM in front and rear segment with SiPM on back
→ Avoids dead material at shower max

7

Calorimetry
HAD high granularity calorimeter

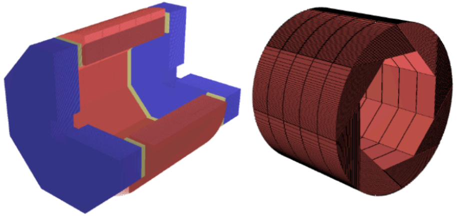
Jianbei LIU

- Figure of merit: separating W and Z bosons in their hadronic decays .
- This translates into a jet energy resolution requirement of ~ 3-4% over a wide jet energy range (~ 30% /√E).
  - A factor of two improvement w.r.t. traditional jet measurement

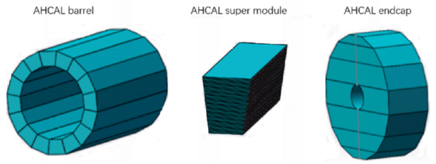


WW→4j and ZZ→4j

SDHCAL



AHCAL



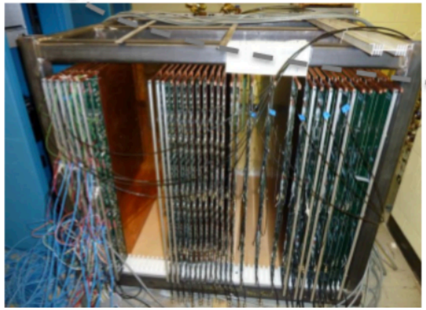
Both adapted from ILD

- Absorber
  - Fe, 40 layers × 2cm, $5\lambda_I$
- Active layer
  - SDHCAL
    - glassRPC, 6mm thick
    - cell-size: 1cm×1cm
  - AHCAL
    - Sci+SiPM, ~5mm thick
    - cell-size: 3cm×3cm

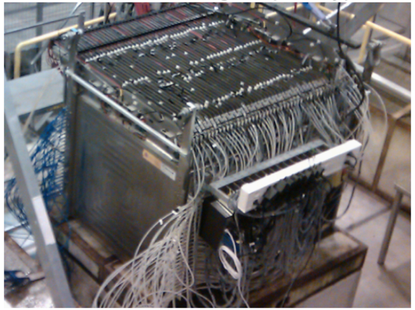
Calorimetry
HAD high granularity calorimeter

Jianbei Liu

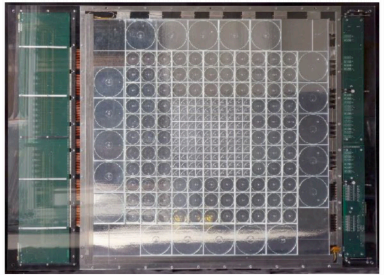
RPC HCAL Prototype

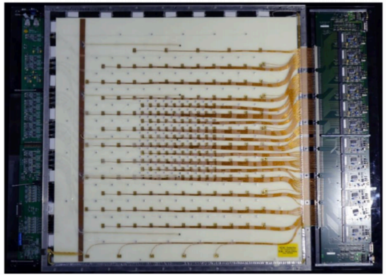


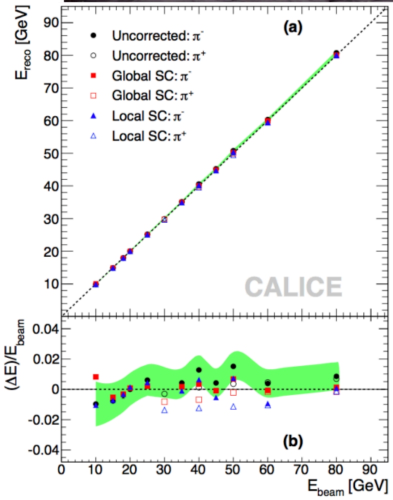
SDHCAL Prototype

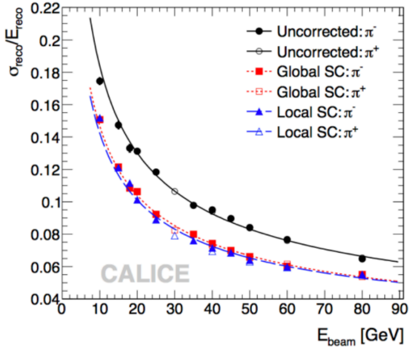


Sci-AHCAL Prototype





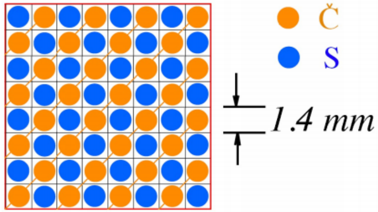


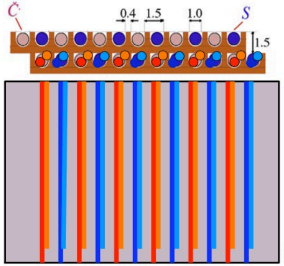


fit results	stochastic	constant
initial	57.6%	1.6%
global SC	45.8%	1.6%
local SC	44.3%	1.8%

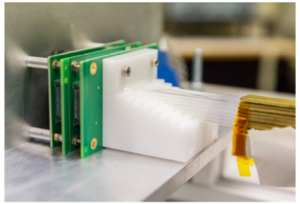
Dual readout calorimetry

Roberto FERRARI





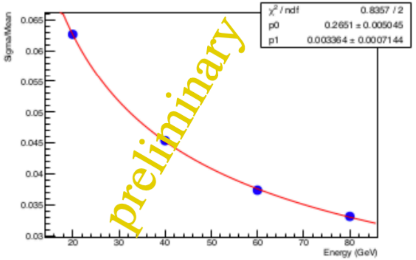
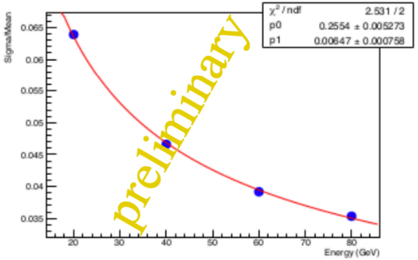
Light sensors (SiPM)



SiPM + :

- + *compact readout (no fibres sticking out)*
- + *longitudinal segmentation possible*
- + *operation in magnetic field*
- + *larger light yield (main limitation to Čerenkov signal)*
- + *high readout granularity → particle flow "friendly"*
- + *photon counting (calibration)*

Hadron resolution

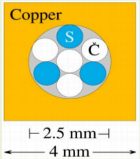
DR method	Machine Learning
	

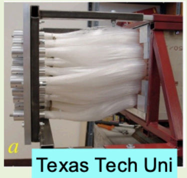
$$\frac{\sigma}{E} = \frac{26.5\,\%}{\sqrt{E}} + 0.3\,\%$$

$$\frac{\sigma}{E} = \frac{25.5\,\%}{\sqrt{E}} + 0.6\,\%$$

2003 DREAM

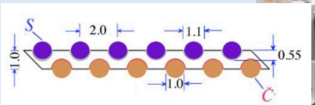
Cu: 19 towers, 2 PMT each
2m long, 16.2 cm wide
Sampling fraction: 2%





2012 RD52

Pb, 9 modules → 36 towers
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}



Conclusions

- Intense two days about detectors for future circular e^+e^- colliders.
- Vertex:
  - Very strict requirements may require new mechanical designs to keep material under $x/X0 < 0.1\%$ per layer.
- Tracker:
  - Both silicon, TPC and drift chambers are potential solutions for future detectors.
  - Strict requirements for momentum resolution and PID
- Calorimeters:
  - High granularity is a requirement for particle flow reconstruction.
  - EM calorimeter based on Si+W has excellent segmentation. Homogeneous crystal calorimetry with dedicated timing layer is an option with excellent resolution.
  - Dual readout calorimeters are an attractive possibility with SiPM readout.