State-of-the-art in Gaseous Tracking for LC

Precision Time Projection Chamber (TPC)
as a central tracker at LC

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KEK/ IPNS

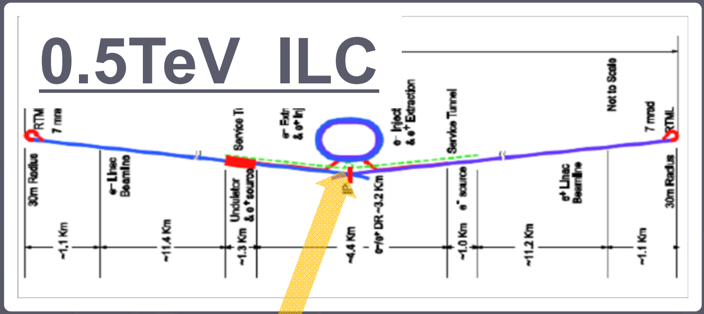
LC special event / IEEE
30 Oct. 2012

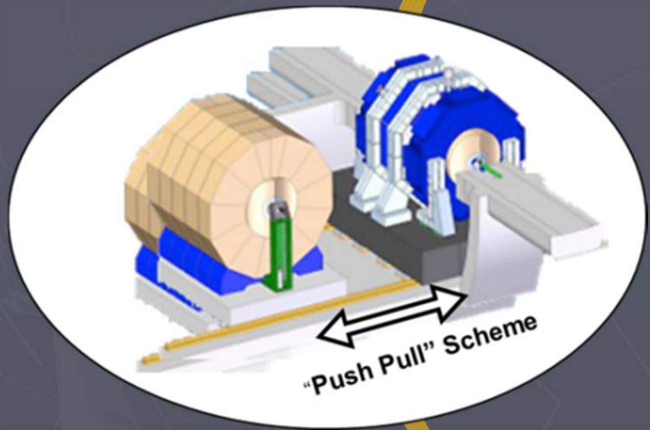
(I apologize that in these slides I could not include proper references.)

Detector at Linear Collider

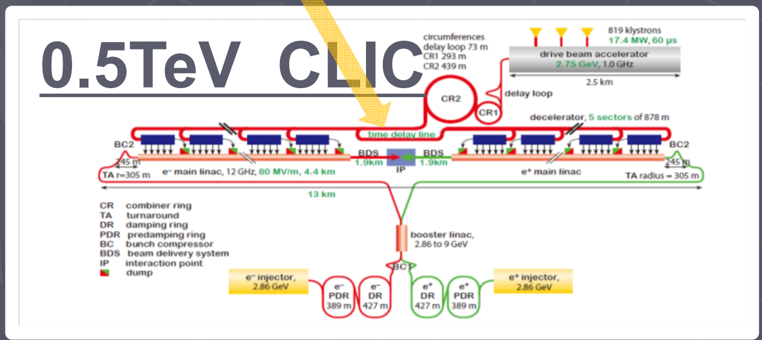
Two detector concepts for the two LC projects

ILC LOI/RDR
CLIC CDR
ILC DBD/TDR
CLIC Program

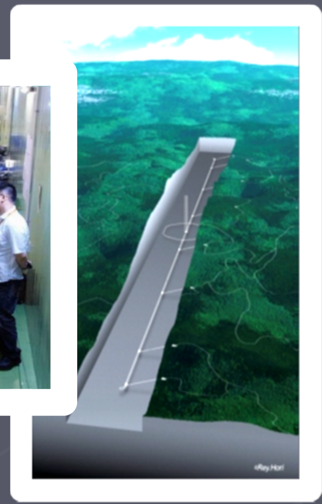




Two detectors
ILD & SiD
on push-pull



S-1 Global cryomodule-assembly

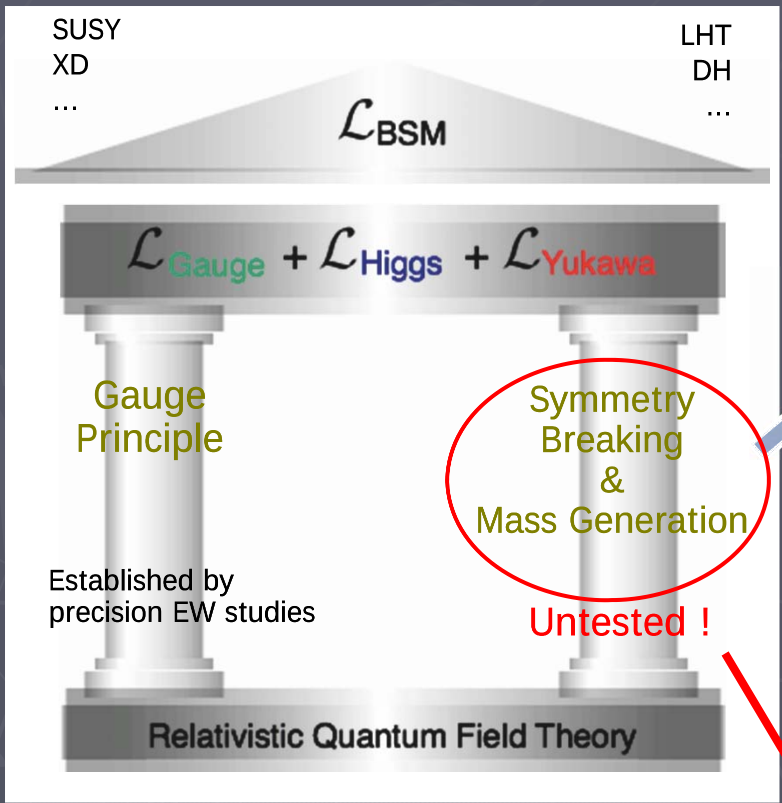


CTF3
Two-beam
Test stand

Primary Goal

Test of the 2nd Pillar of the SM

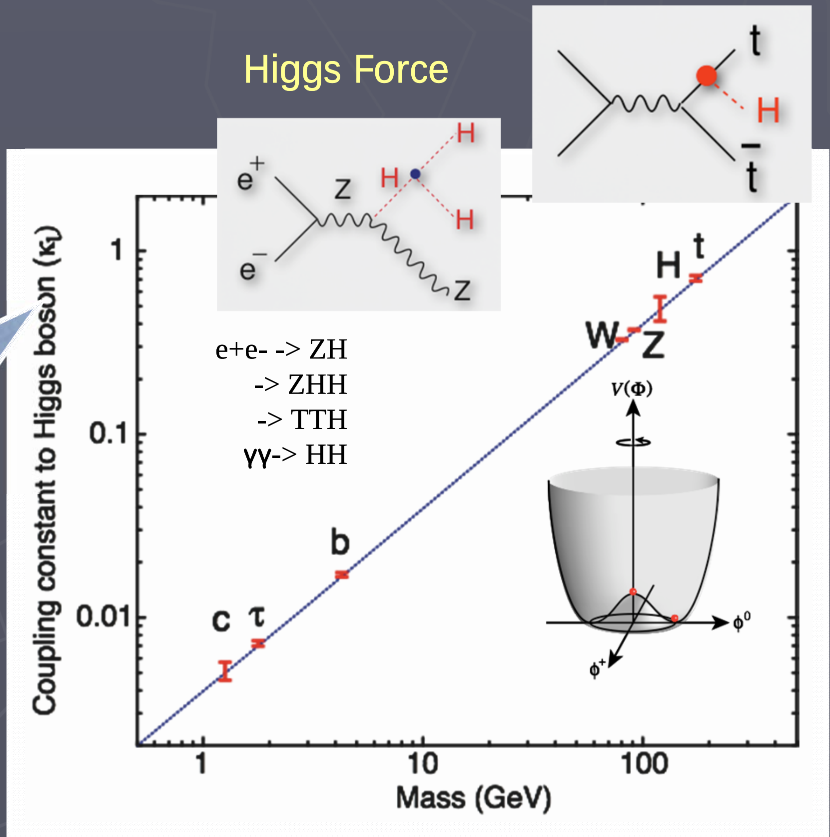
Two Main Pillars of the Standard Model



New Fundamental Forces

Yukawa Force

Higgs Force



We don't know how firm it is! => **Since 4 July '12 we know we will be able to test it !**

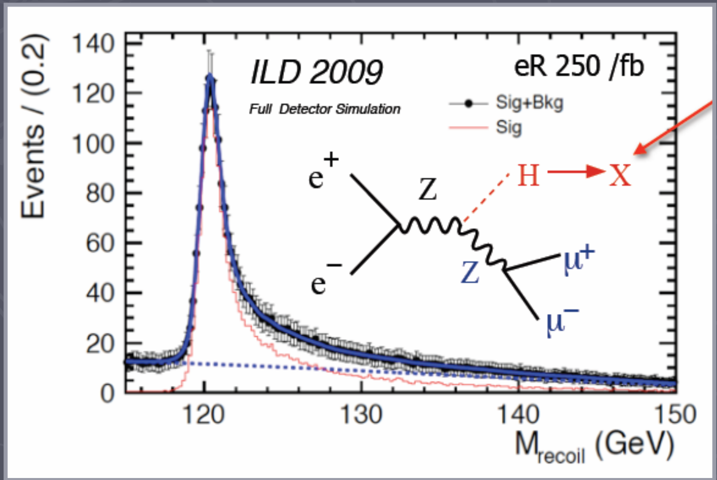
First verify the 2nd pillar, then put the BSM roof!

Detector at Linear Collider (LC)

20 years ago in the KEK green book "JLC-1 Report" (KEK Report 92-16), which proposed 300GeV JLC-1 as the initial stage of JLC 500GeV, and, later in "Particle Experimentation at JLC" (KEK Report 2001-11), we discussed design principles of a detector at the linear collider. They were:

(1) The detector has to measure the mass of Higgs particle down to the machine beam-energy spread. (For ILC, → : $\sigma(1/p_t) < 5 \times 10^{-5}$ /GeV)
(2) Has to separate W and Z by their invariant masses,
(3) Has to tag b-quark by its cascade decay , and c-quark its vertex,
(4) Has to be hermetic in the forward region down to a few 10m rad, and ,
(5) Has to be sufficiently radiation hard.

We should be able to reconstruct any final state in term of patrons; quarks, leptons, and gauge bosons "as if we see the Feynman diagram".



$\sigma(1/p_t) = 2\times 10^{-5}$ /GeV)

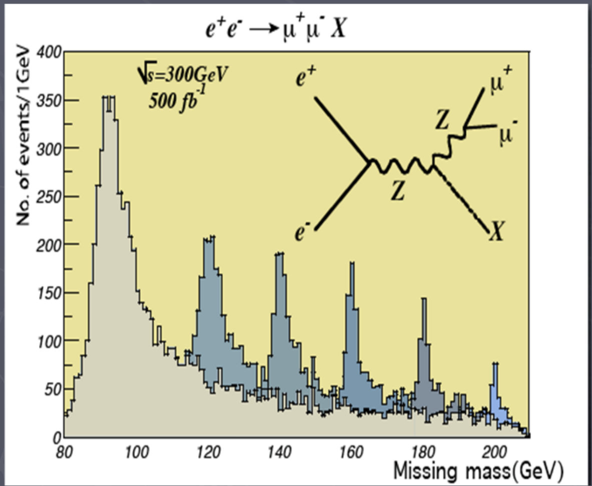
$\Delta m_H \sim 30$MeV (ILD)
→ Higgs cross section $\Delta\sigma_H \sim 2.5\%$

(model independent)

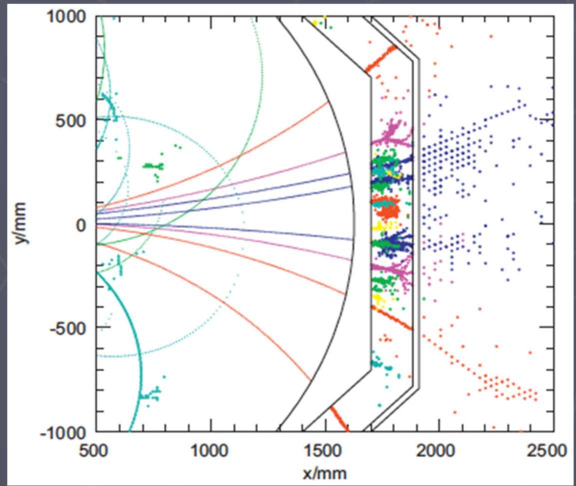
~ 90k Higgs for $250 fb^{-1}$@250GeV, and epol-0.8,ppol+0.3

Requirements to the Central Tracker at LC

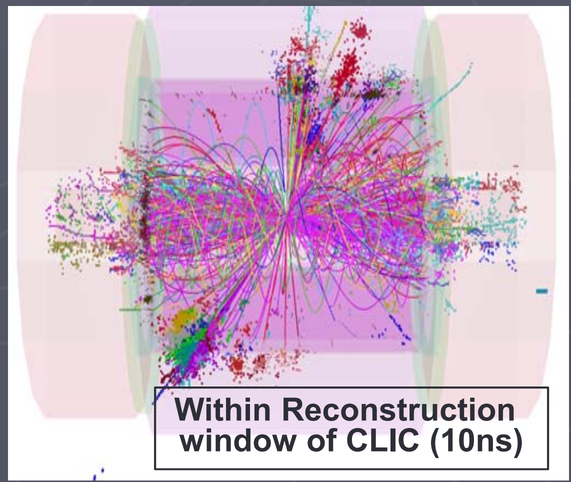
- Momentum resolution: $\sigma(1/pt) = 2 \times 10^{-5}$ /GeV for Higgs mass measurement.
- Tracking efficiency: close to 100% down to low momentum for Particle Flow Algorism (PFA) .
- Minimum material: For the PFA calorimeter behind.
- Time stamping: Desirable to reduce background tracks at HE CLIC.



Higgs mass measurement



PFA:
Matching energy deposits in calorimeter with tracks



High occupancy
$e^+e^- \rightarrow H^+H^- \rightarrow$ 8 jets

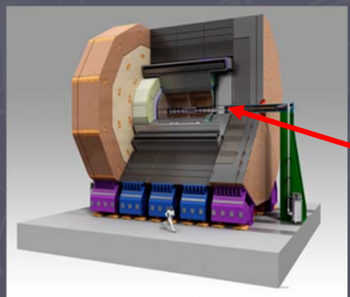
Two Central Trackers for LC

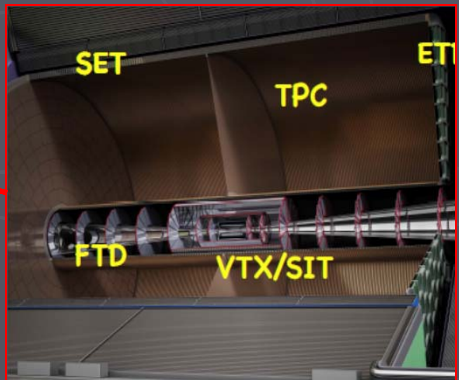
Time Projection Chamber (TPC) (with VTX + SiT)

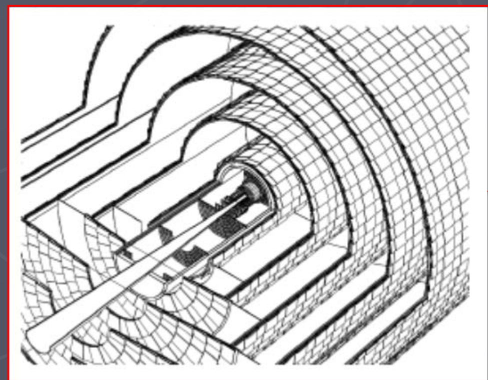
≧200 continuous position measurements along each track in a gas with the point resolution of $\sigma_{r\varphi}$ < 100μm, and a lever arm of around 2m in the magnetic field of 3.5- 4T .

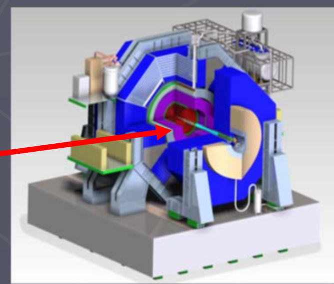
All silicon tracker:

< 10 discrete position measurements of $\sigma_{r\varphi}$~ (10)μm and a lever arm of about 1m in the 5T magnetic field.







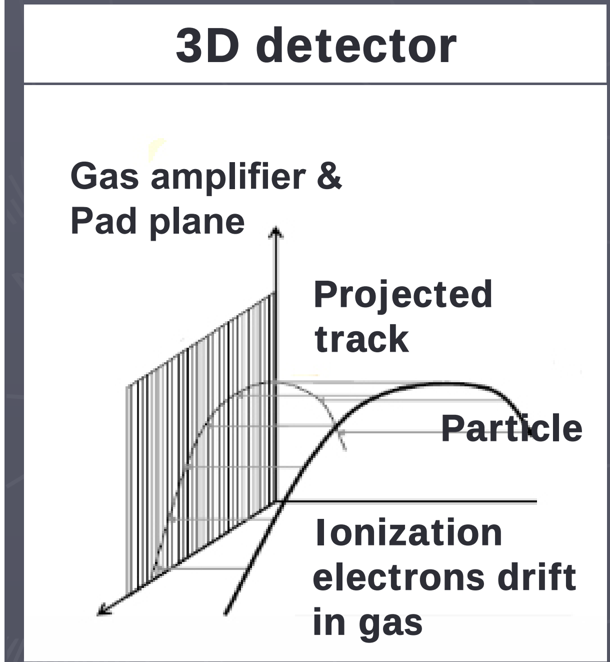


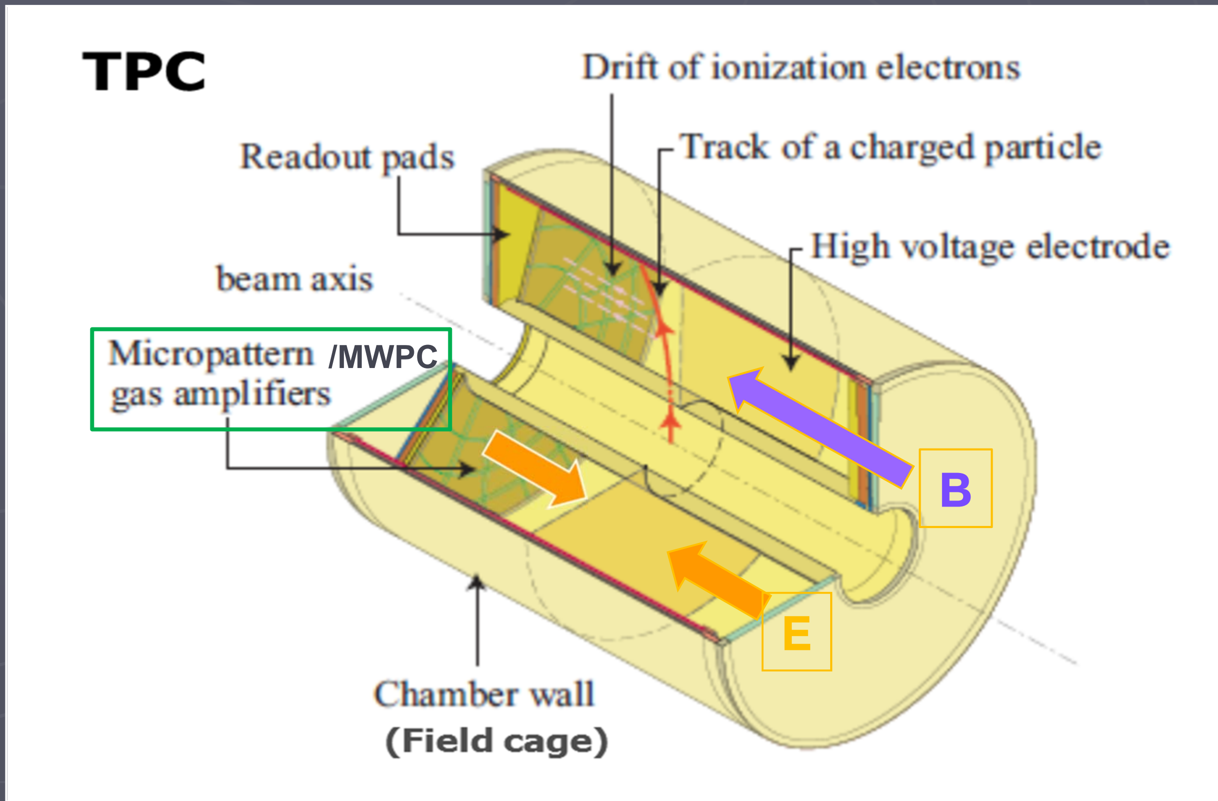
ILD: TPC (+ VTX +SiT)

SiD: silicon tracker

Time Projection Chamber (TPC)

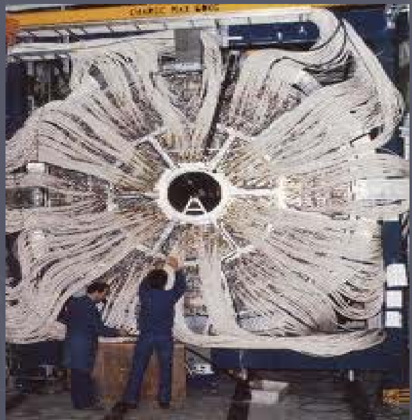
Dr. D. Nygren proposed the "theoretical-at-the-time" (my friend at CERN) 3D gaseous tracker in 1970's, and the first large TPC was built for PEP-4 experiment at SLAC. Since then, no change in the basic principle ("gas physics") and the basic structure of TPC, However, the new devices of gas amplification, Micro Pattern Gas Detectors (MPGD) which appeared in 1990's, and the end-less progress of micro electronics and new materials evolve TPC.

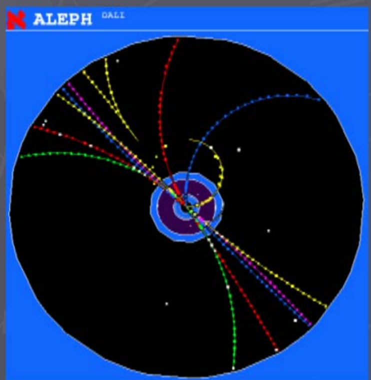




MWPC TPC to MPGD TPC

ALEPH TPC

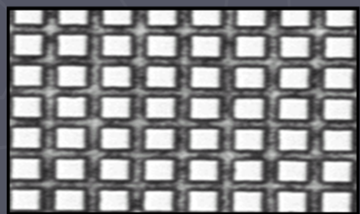


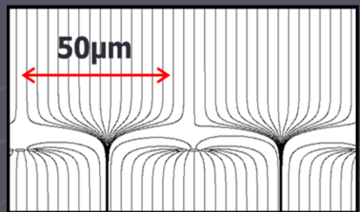


MWPC TPC: Many TPC were built with MWPC technology until now. Among them ALEPH TPC and DELPHI TPC at LEP greatly contributed in establishing the Standard Model. However , the large Ex B effect around the anode wires of MWPC in the high magnetic field limit the rφ resolution even for the narrow anode wire pitch of 1mm.

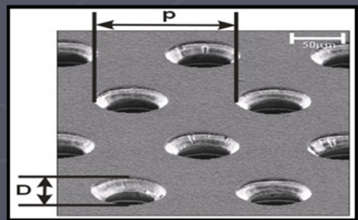
MPGD TPC: The Micro Pattern Gas Detectors (MPGD), which works as an excellent gas electron amplifier, have a finer structure of the order of 100μm achieving O(100μm) resolution.

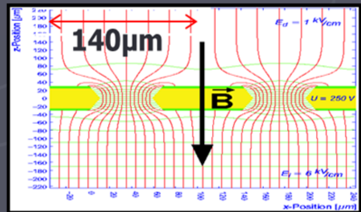
MicroMEGAS

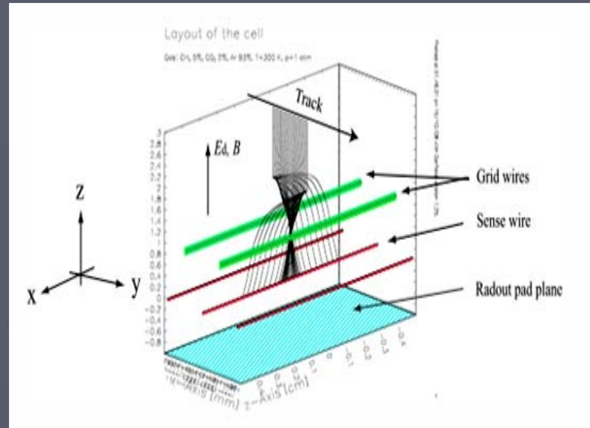




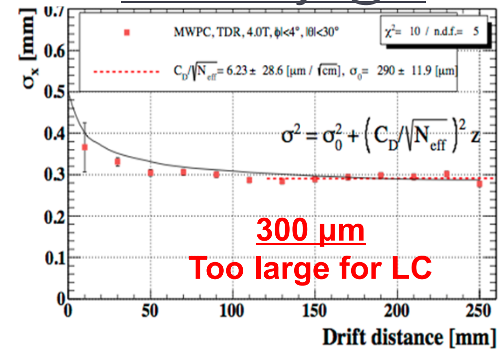
GEM



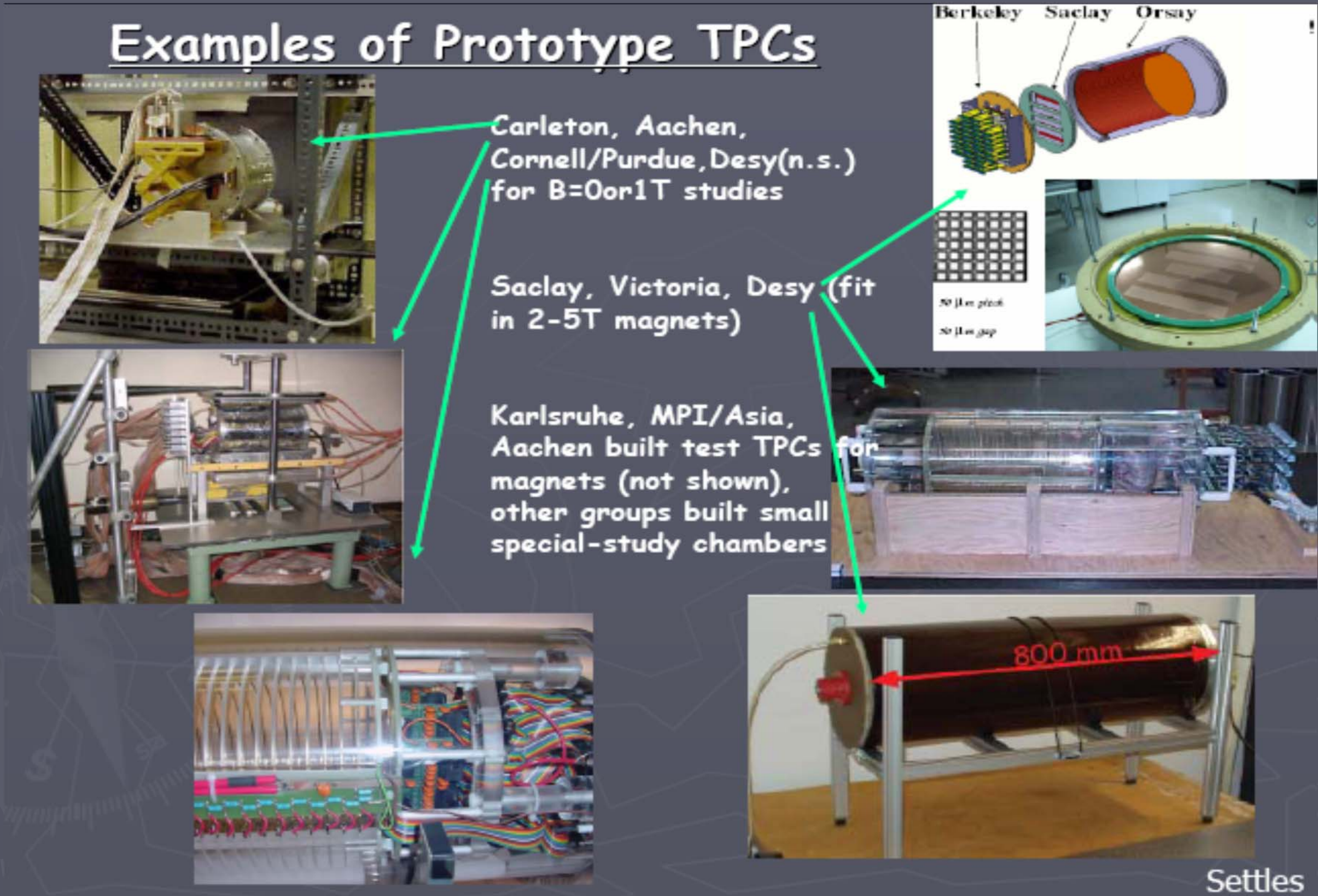




MP-TPC with MWPC: cosmic rays @1T



R&D of MPGD TPC with Small TPC Prototypes



There are / were more.

Options of MPGD TPC

After the initial stage of R&D with many small TPC prototypes, we have four options of MPGD TPC for LC to be tested at Large prototype (LP) TPC

Analog TPC: Subject of the gas gain fluctuation in the gas amplification.

(1) Multi layer GEM with the standard pads to readout the signal charges spread on the pad plane by the diffusion.

(2) MicroMEGAS with resistive-anode pads to spread the very narrow Micromegas charge on the pad plane.

(3) Multilayer GEM with pixel readout to cope with high occupancy.

Digital TPC: Free from the gas gain fluctuation. Expect the improvement of position resolution of 20-30% .

(4) Gridpix: Digital TPC readout by a pixel device with implemented Micromegas mesh (Timepix of the pixel size of 55 μm) detecting individual primary electrons with 100% efficiency. There are a lot of applications of different purposes by its microscopic imaging capability.

Large Prototype Beam Test at DESY

LC TPC Collaboration with EUDET/AIDA

Si strip detector
(EUDET/SiLC/DESY)

Magnet: PCMAG
(EUDET/AIDA, KEK,CERN, DESY)

Field cage & Mechanics
(EUDET: DESY)

Endplate
(LC TPC/Cornell)

Gas system
(EUDET:DESY)

Cathode Laser Calib.
(LC TPC/Victoria)

Beam Trigger
(LC TPC/NIKEFH)

DAQ & Monitoring
(EUDET)

Cosmic trigger
(LC TPC/KEK, Saclay)

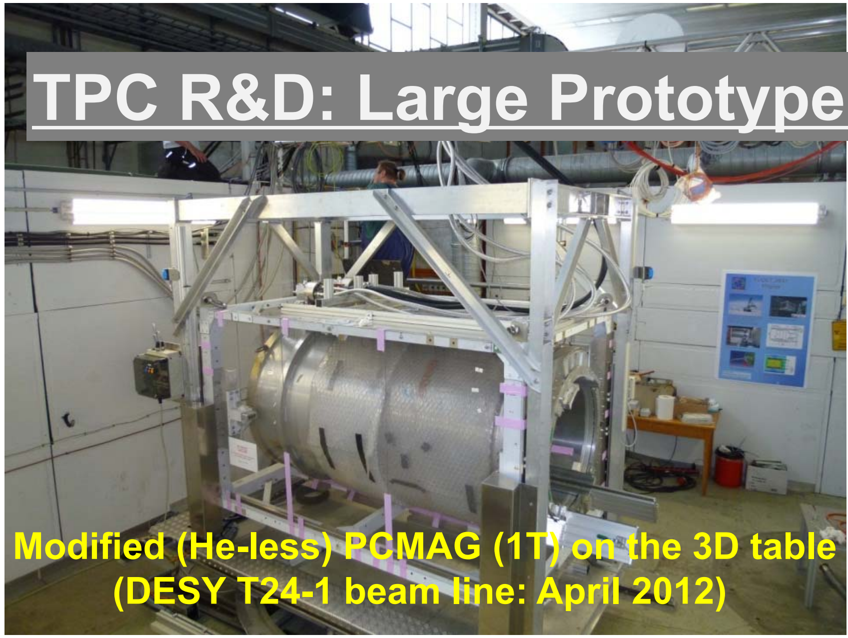
Test beam & Facility
(DESY)

MPGD Detector Modules
(LC TPCs)

Two types of Readout electronics
(EUDET/AIDA ; LC TPC/Lund, DESY, KEK, Scalay)

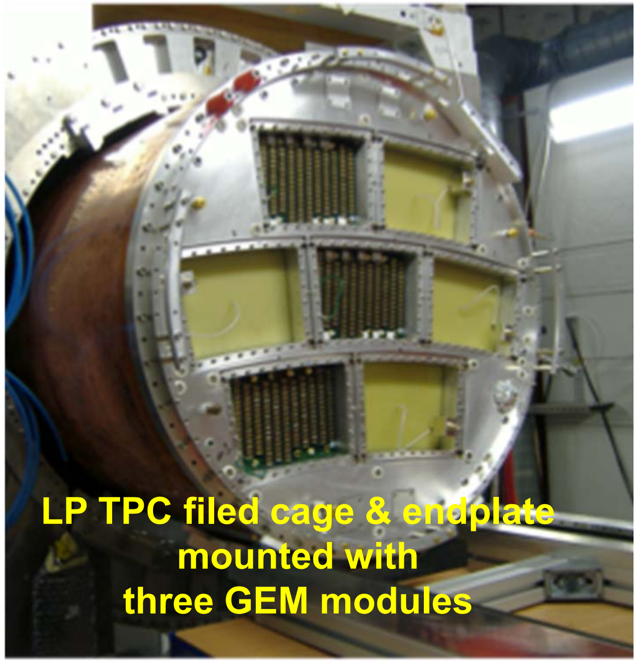
Software development
(EUDET/AIDA & LC TPCs)

TPC R&D: Large Prototype (LP) TPC

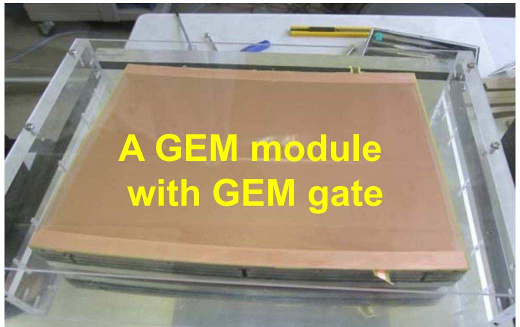


Modified (He-less) PCMAG (1T) on the 3D table
(DESY T24-1 beam line: April 2012)

DESY test beam set upwith 8,00ch
PCA16- ALTRO readout electronics



LP TPC filed cage & endplate
mounted with
three GEM modules



A GEM module
with GEM gate

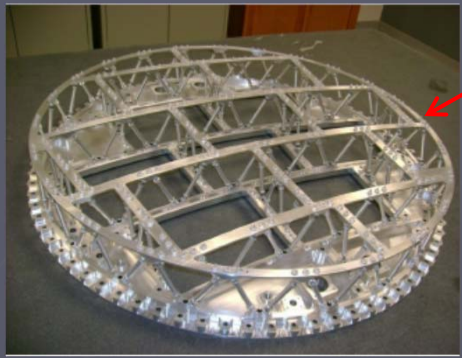
Beam test of 6 Micromegas

PCA16 + ALTRO
readout electronics

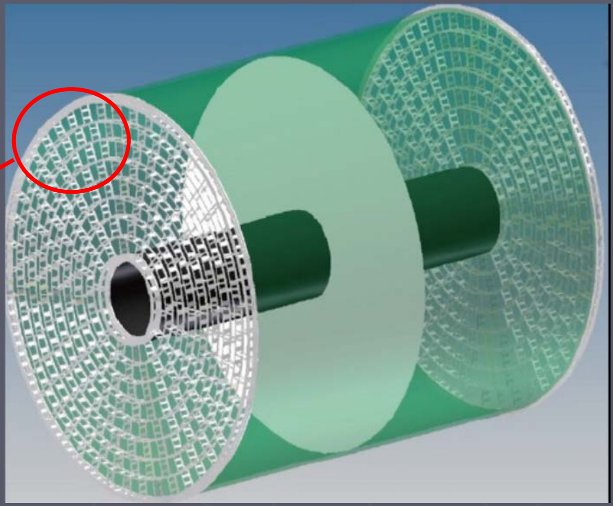
TPC Large Prototype

Field Cage & Endplate

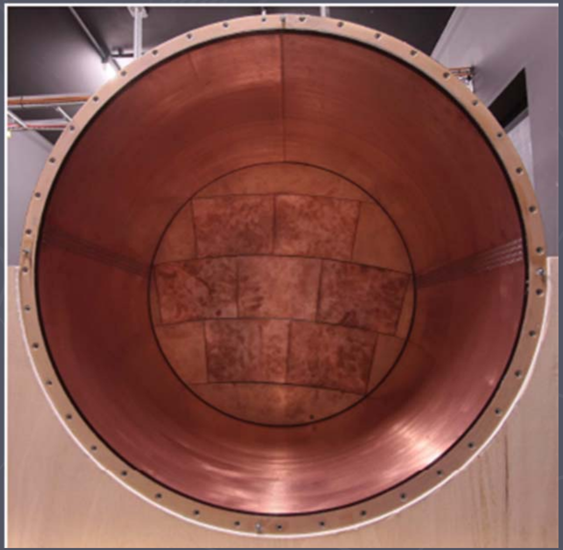
Current LP Endplate
With termination plates

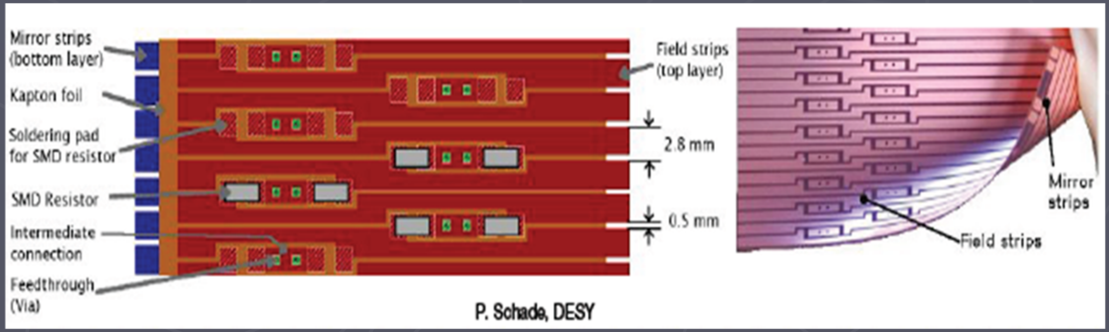


New Lighter LP Endplate
(Space frame)



ILD TPC
with the space frame end-plates

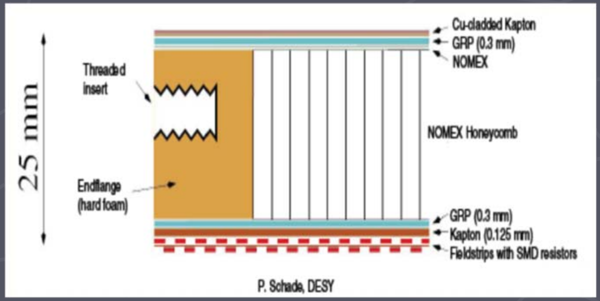




LP Field Cage

Nomex_honycomb complex
- L=61 cm, D =72 cm.
- 1.2% X_0 @21kV

25mmt
Model of the inner FC

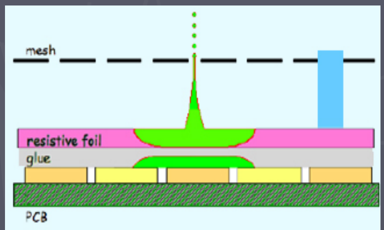


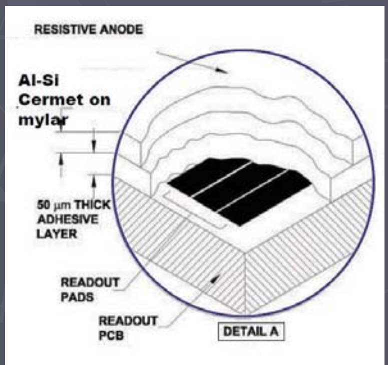
Micromegas with Resistive Anode

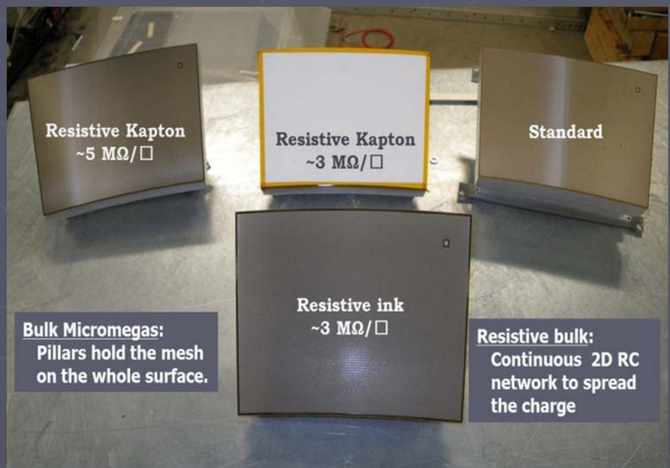
- Very narrow signal of Micromegas O(10μm) need to be broadened by a resistive layer (RC net work) on the pad PCB to match with the width of readout pad.
- The point resolution and the double hit separation can be controlled separately by tuning R of the resistive anode and the pad width.

- Micromegas mesh, a thin woven mesh of stainless steel) wire, is supported at the distance of about 100μm from the pad plane by tiny pillars (the bulk Micromegas).
- With only one electrode (mesh) thus one HV connection make the structure simple.

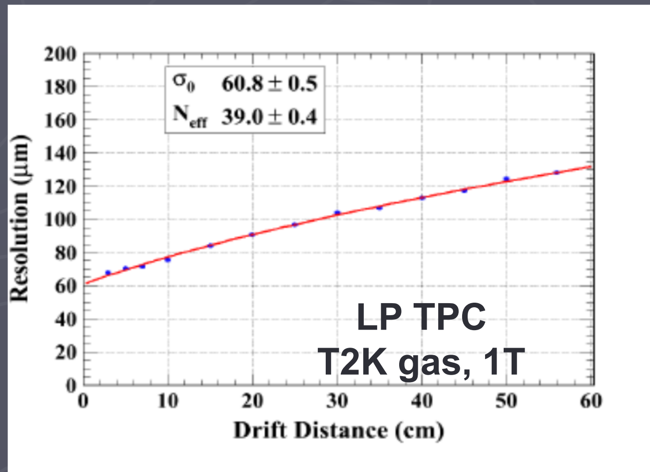
- May need to confirm of the effect of the pedestal rise due to the resistive anode in high occupancy.







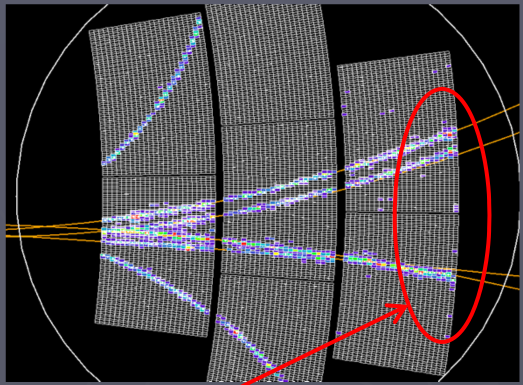
LP Modules with different resistive anodes. So far the carbon-loaded Kapton seems to be stable

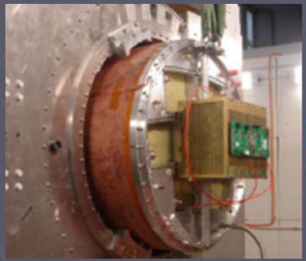


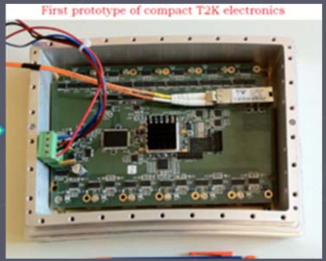
Position resolution
Micromegas with resistive anode

New Micromegas LP module with Compact T2K Electronics

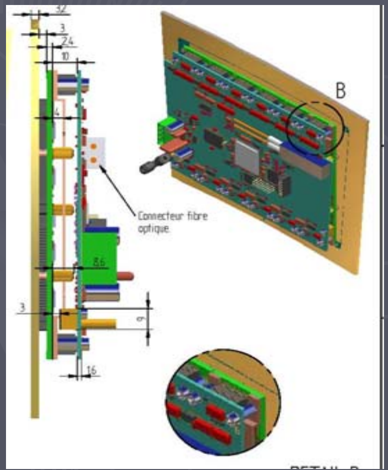
- Compact T2K electronics (1,700ch) mounted on directly the backside of each Micromegas module
- One step toward the final assembly of ILD TPC.
- New resistive anode with improved grounding .
- Beam tested successfully in Aug. 2012.



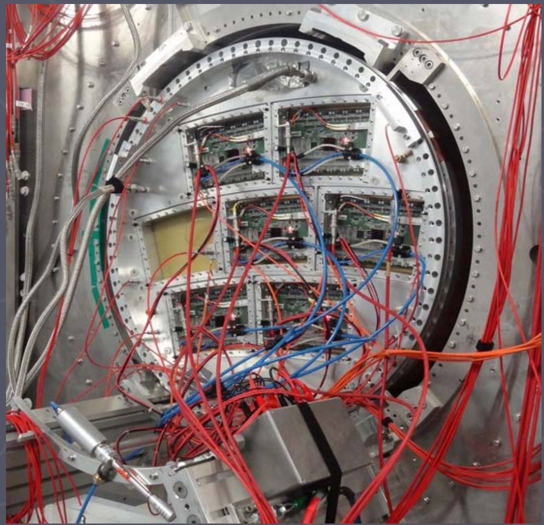




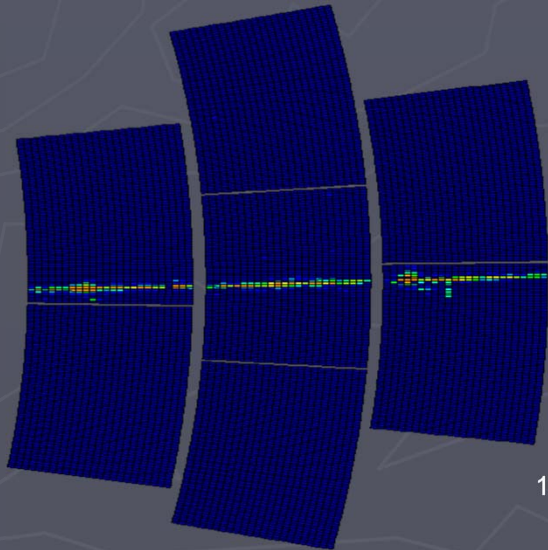
Problem of fitting Rotaion by the non uniform B field (intended), and probably the ExB distortion at the boundaries. We are now facing to the traditional TPC problem!



Double deck
Behind the module

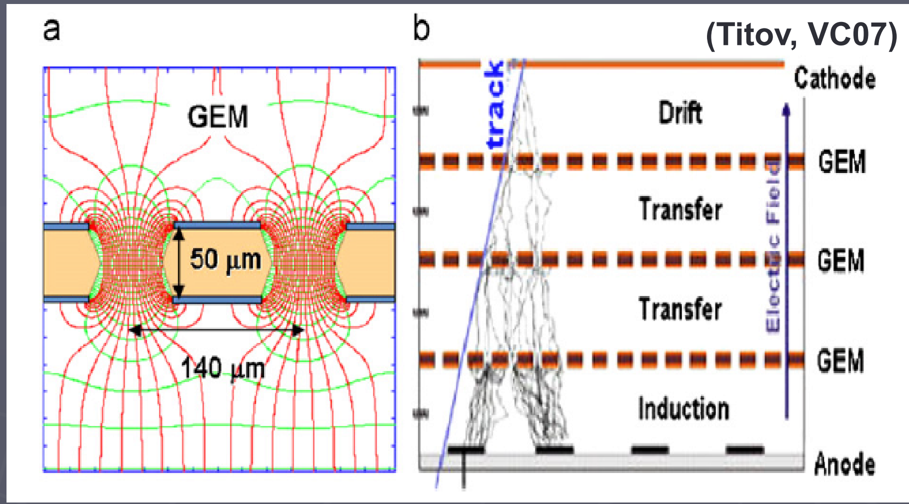


6 modules mounted on the LP TPC



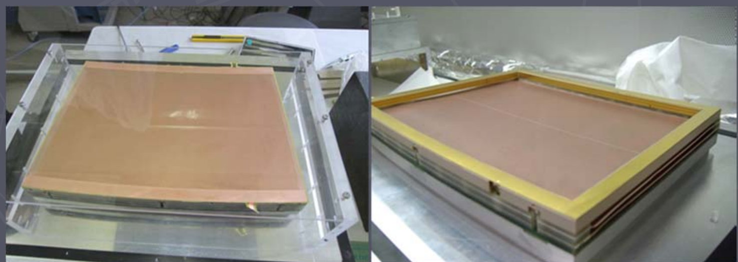
Multilayer GEM for TPC

- 2-3 layers of GEM provide sufficient gas gain O(1,000) for low noise electronics.
- The gaps between GEMs and the voltages across the gaps determine the signal spread on the pad plane, which determine the point resolution and the double hit separation simultaneously (for a given pad width in accordance to the drift distance).

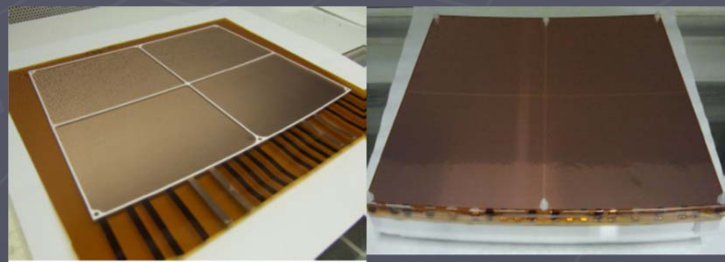


(Titov, VC07)

- Two types of LP modules (23 x 17 cm^2) tested and successfully reached down to the point resolution of 100μm at LP-TPC (60cm drift, 1T). Many HV connections and the protection of the edge of the GEM electrodes may be engineering issues.



<u>Asian GEM module:</u> Double thick (100μm) GEM without the side GEM support. With/without a thin-GEM ion gate (50% electron transmission)



DESY GEM module: Triple CERN GEM with thin (1mm) ceramic GEM frame (white).

Resolution Formula for GEM TPC

K. Fujii
R. Yonamine

Since TPC operates on the nice and old "gas physics"; ionization, diffusion, gas amplification and fluctuation etc, we have derived for the GEM TPC (the option (1)) the full analytic presentation of the point resolution.

1. Charged particles ionize gas molecules. The electrons generated in this process are called seed electrons.

- Primary Ionization $P_{PI}(N)$: collision between incident particle and gas molecules
- Secondary Ionization $P_{SI}(M)$: further ionization by primary ionized electrons

N : # of primary clusters M : cluster size

2. The seed electrons drift toward the readout plane while diffusing.

$$P(\Delta x; \sigma_d) \frac{1}{\sqrt{2\pi}\sigma_d} \exp\left[-\frac{1}{2}\left(\frac{\Delta x}{\sigma_d}\right)^2\right]$$

$$\sigma_d^2 = C_d^2 \, z$$

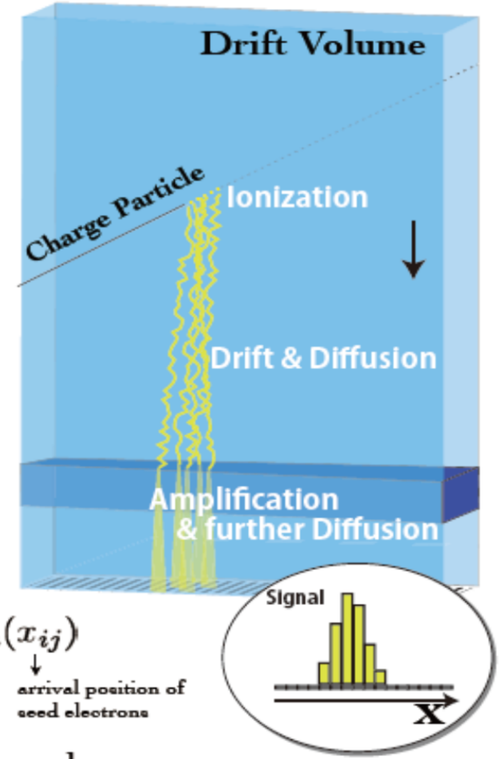
3. The Seed electrons are multiplied by a gas amplification device.

Polya distribution

$$P_G(G/\bar{G};\theta) = \frac{(\theta+1)^{\theta+1}}{\Gamma(\theta+1)}\left(\frac{G}{\bar{G}}\right)^{\theta} \exp\left(-(\theta+1)\left(\frac{G}{\bar{G}}\right)\right)$$

4. There may be further charge spread after gas amplification, and the charge spread is expressed by pad response function $F_a(x_{ij})$ and its width is specified by σ_{PRF}.
This process is detector-specific.

x_{ij} ↓ arrival position of seed electrons



5. Finally the gas-amplified signals are readout with finite-width pads. We measure the coordinate of seed electrons with the charge centroid method.

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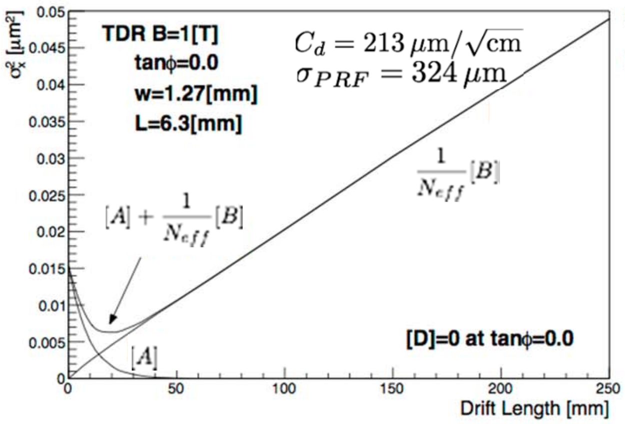
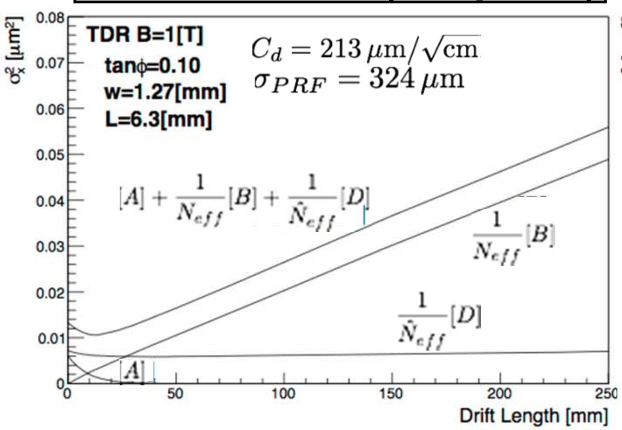
Some Examples from the Resolution Formula

Perpendicular track



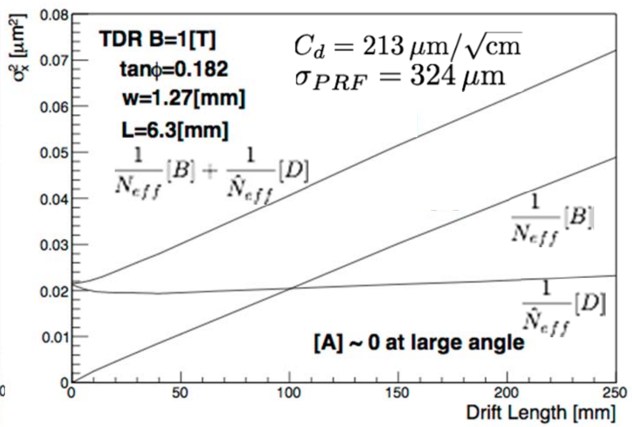
[D] is invisible.

Inclined track (tanφ=0.1)



[A] becomes smaller.
[D] becomes visible.

Inclined track (tanφ=0.18)



[A] becomes invisible.
[D] becomes sizable.

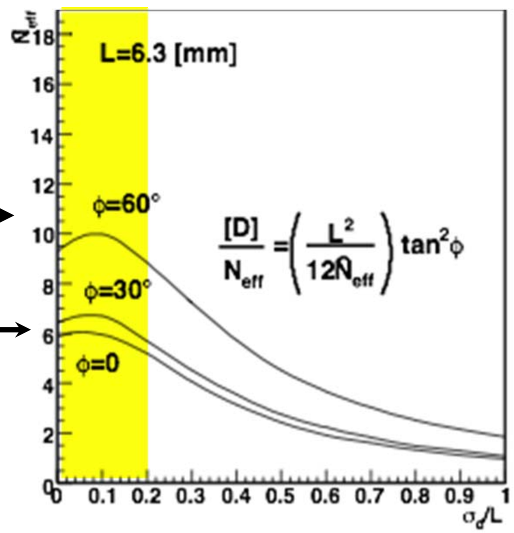
The σ_d/L will not exceed 0.2 for the LC-TPC.

$\hat{N}_{eff}$ is roughly constant in this range.

[D] term contribution is determined not by N_{eff} but by $\hat{N}_{eff}$

$\hat{N}_{eff} \ll N_{eff}$ → **σ_x quickly deteriorates with angle.**

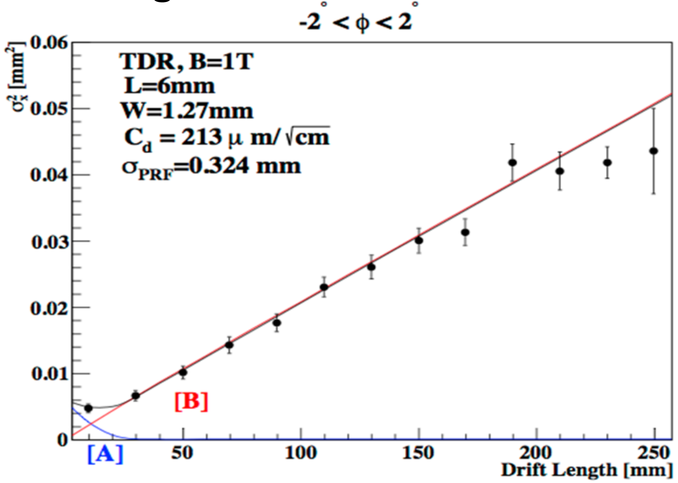
tanφ=0.18 -->φ=10°



Comparisons with Results of GEM TPC Prototypes

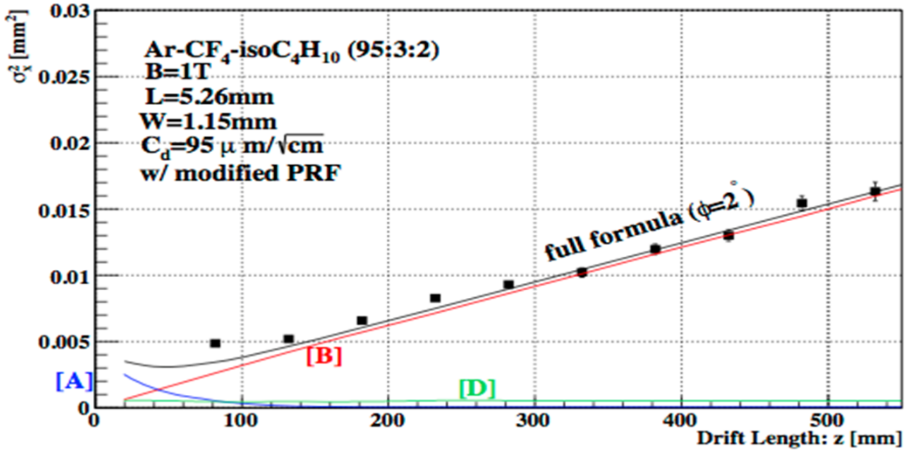
MP-TPC@KEK

TDR gas/1T/ALEPH Electronics

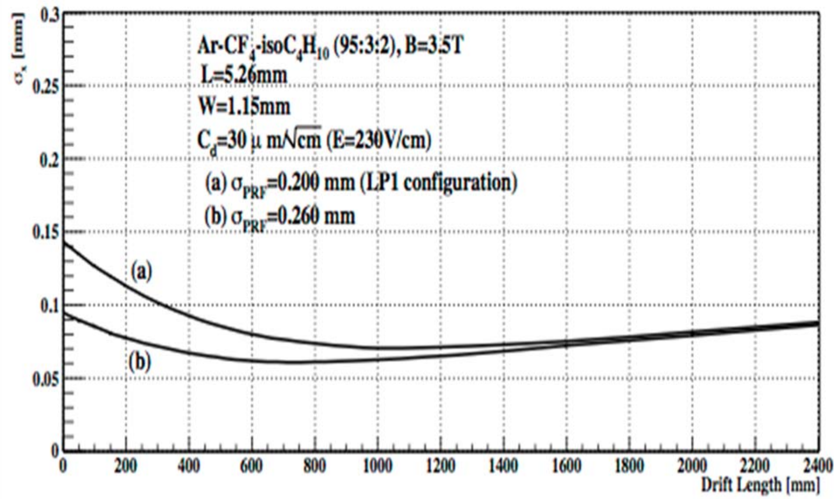


Asian GEM module@LP-TPC

T2K gas/1T/PAC16 + ALTRO electronics



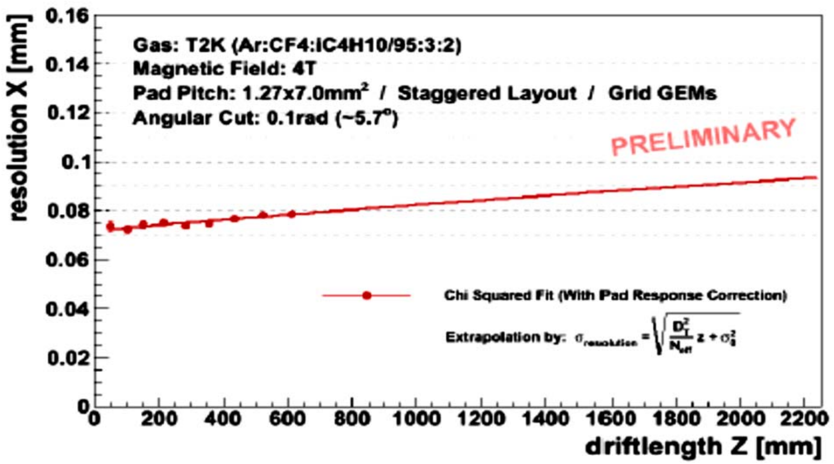
Extrapolation to ILD TPC (2.2m drift, 3.5T)



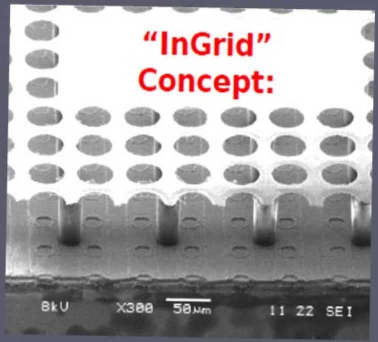
Measurement at 4T

DESY midi-TPC@DEST 5T magnet

T2K gas, 4T , and ALEPH electronics

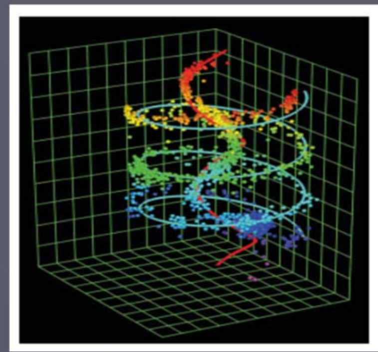


Digital TPC with Gridpix

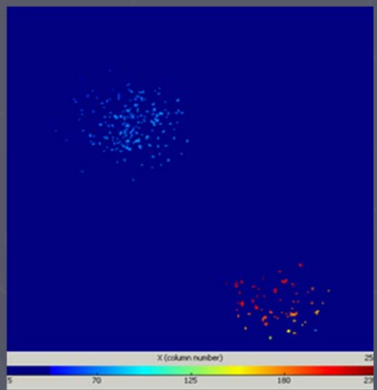


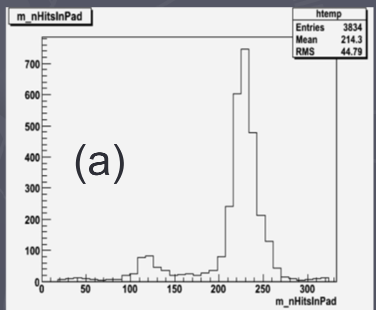
Gridpix

- Grodpix: Micromegas mesh is built on Timepix chip by a wafer post-process (MESA, IZN-Berlin) providing the ideal alignment of grid holes to the pads of the pixel chip (55-60μm).
- aSi or Si_3N_4 protection layer to prevent damage of spark.
- The gain of 5,000 – 10,000.
- Close to 100% efficiency to detect each primary electron (fig. a).
- LP module with 8 Gridpix tested. Analysis are underway.
- Timepix-III is under design with variable pixel size and the capability of silicon trough holes.
- However, still need another iteration for the application to large TPC (ILD TPC) with deeper time counting and multi-hit capability.

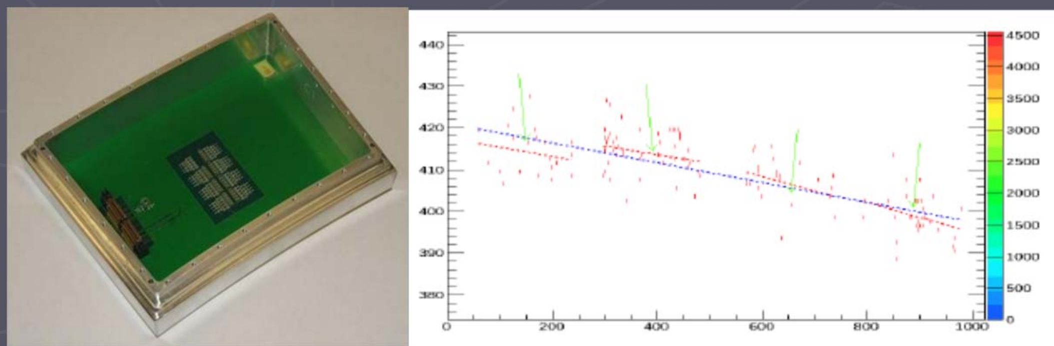


Two electrons (^{90}Sr) dancing in a 5 cm^3 Gridpix TPC

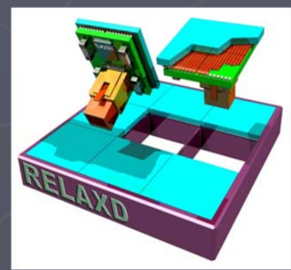




Electrons from an X-ray conversion



LP module with 8 Gridpix and a recorded event



With Timepix-III?

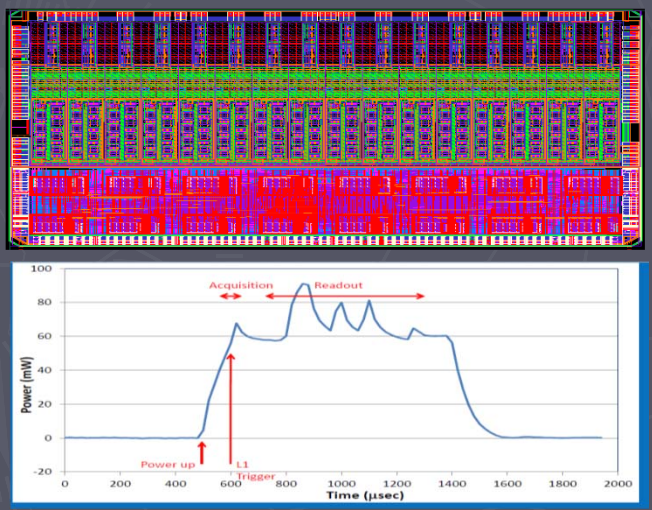
TPC Electronics for Pad Readout

T2K electronics with After chip: Nice results from R&D. Can not be use for ILD TPC because of the sampling depth.

PAC16 low-noise preamplifier with ALTRO used for GEM modules in the LP- TPC beam test .

S-ALTRO16 : The first low-noise digital-analog mix chip . Unfortunately only 16ch.
To be used for LP beam test.
Power pulsing has been tested successfully at chip level. For the ILC 50Hz cycling the reduction factor of around 60 is foreseen
ADC takes too much power (30-40mW)

GdSP: New digital-analog chip for MPGD TPC readout (Alice TPC and LC TPC under the collaboration with CMS. Test structure submission in 2013.



S-ALTRO16

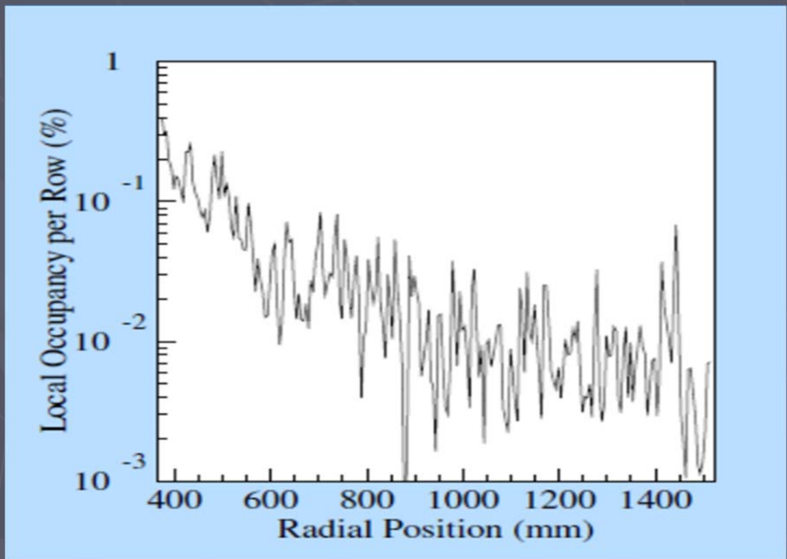
Parameter	VFAT2 (IBM 0.25)	SALTRO (IBM 0.13)	VFAT3 / GdSP (IBM 0.13)
Linear range	+- 12fC	150fC	Max 200fC
Input capacitance (pF)	20	0-20	5 – 10 – 30 – 60
Noise	~500e- ⊕ 40-60e-/pF @ 25ns	~ 650e- ⊕ 15e-/pF @ 120ns	< SAltro /VFAT

Parameter	VFAT2	SALTRO	VFAT3 / GdSP
Power (mW/channel)	1.5 (IBM 250nm) (incl. comparator)	10	<< 1

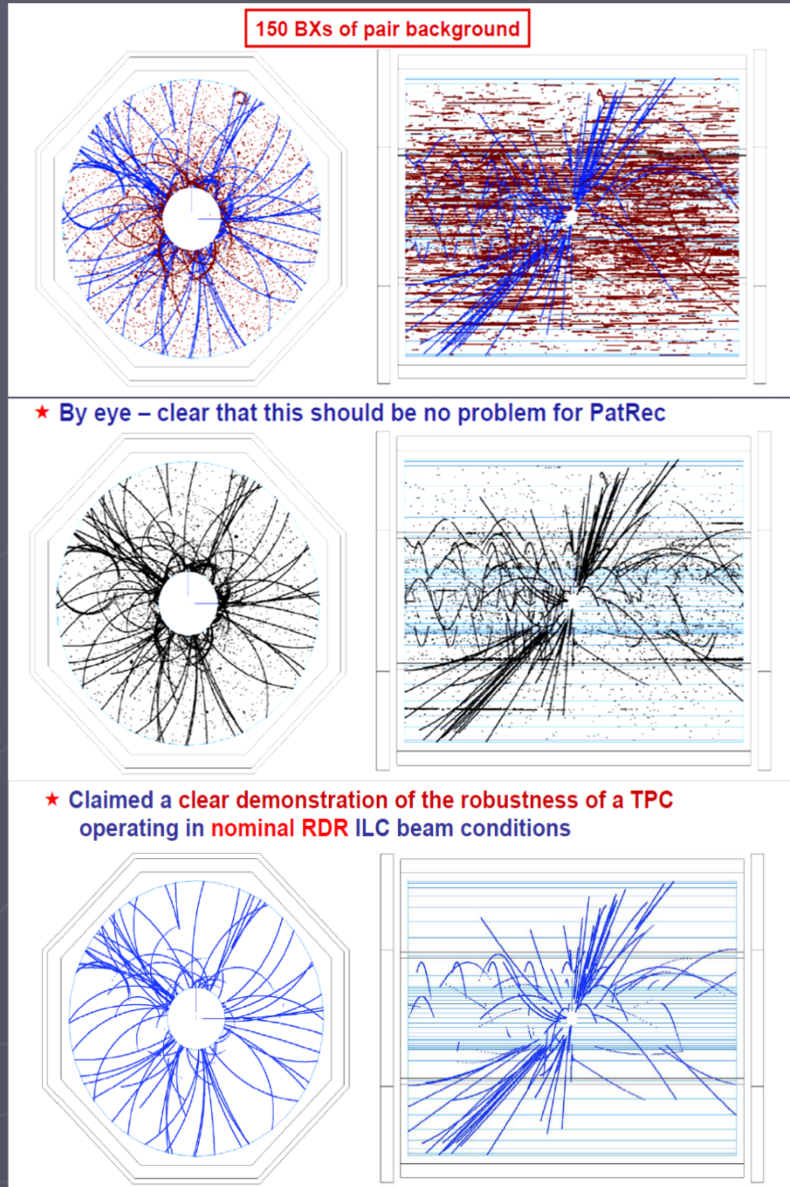
GdSP Specification

Beam Backgrounds for TPC at 500GeV ILC

- No two photon background included in this plot (2010). But the contribution is not significant at 500GeV.
- np scattering gives negligible contribution.
- Occupancy stays well below 1%.
- No problem to reconstruct events removing many micro curlers.



Occupancy for 100BT

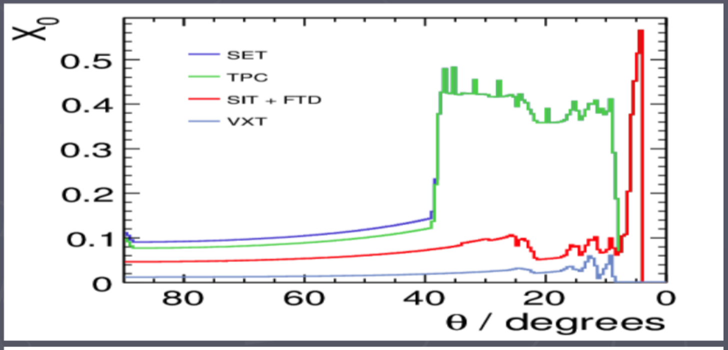


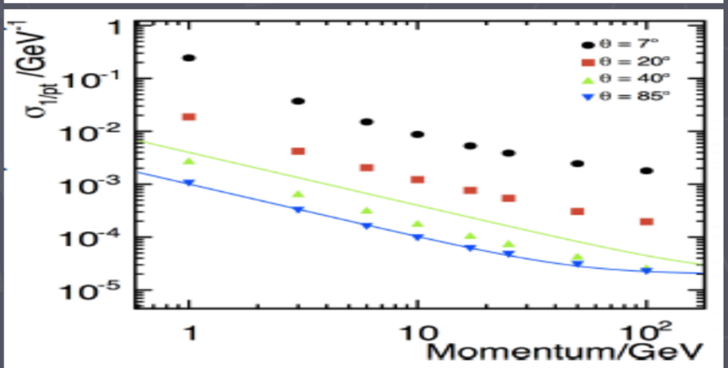
Tracking: New ILD Tracking Code
TPC, Si-tracker and Forward tracker

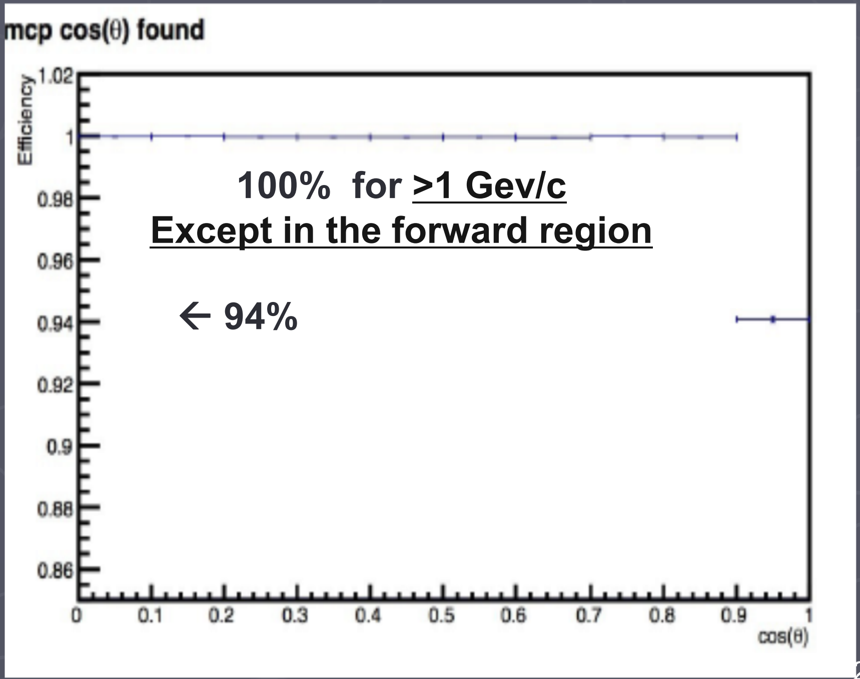
ILD material budget — TPC in the endplate 25% X_0 (nominal)
15% (LOI) → 25%(DBD)
No sizable effect in PFA resolution
Better to improve : full surface mounting of electronics and cooling (of the pad planes)

Momentum resolution: As the specification.

Tracking efficiency: 100% > 1GeV except in the forward region

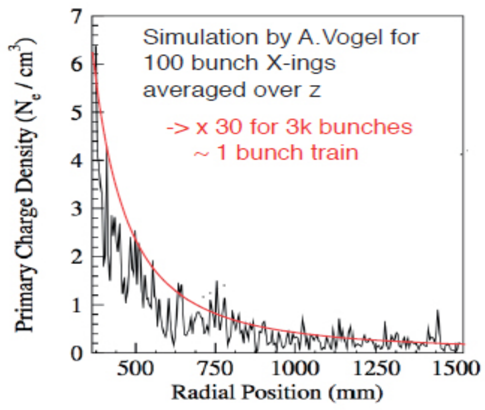






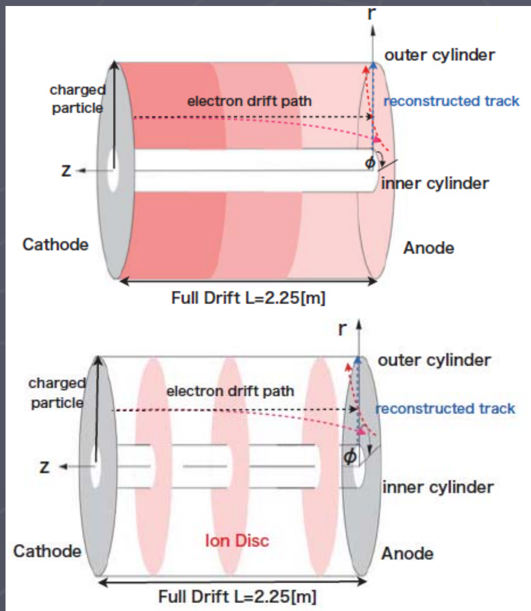
Positive Ions and Ion gate for 500GeV ILC

- Solve the Passion equation for a given ion density distribution with proper boundary conditions. Then , estimate the distortion of drift electron trajectory by the Langevin equation.
- Estimate the effect of he primary ions and the secondary ions from the amplification w/wo a gating device.
- For the ion feed back ration of $>10^{-3}$ (measured both for the triple GEM and Micromesh) and the gas gain of 1,000, we need an ion gate device.
- The current options of the ion gate we know of:
  - Wire gate: Known to work but introduce mechanical complication.
  - Very thin GEM gate: Stop ions alright, but the electron transmission of only 50%@ 1T.
- TPC measures also the ion density, thus "in principle" software correction is possible to some level.



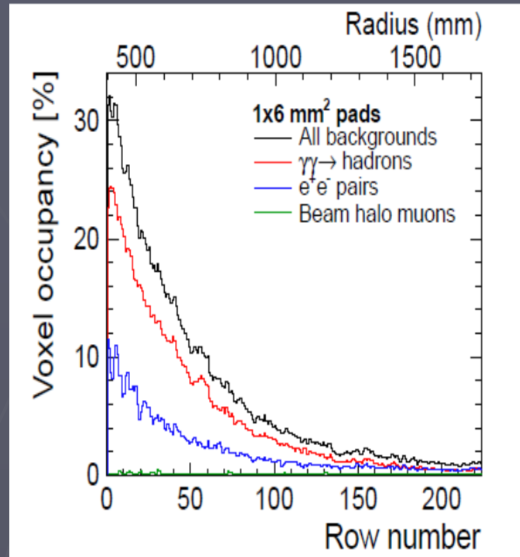
No two-photon hadron BG included.
-> underestimate

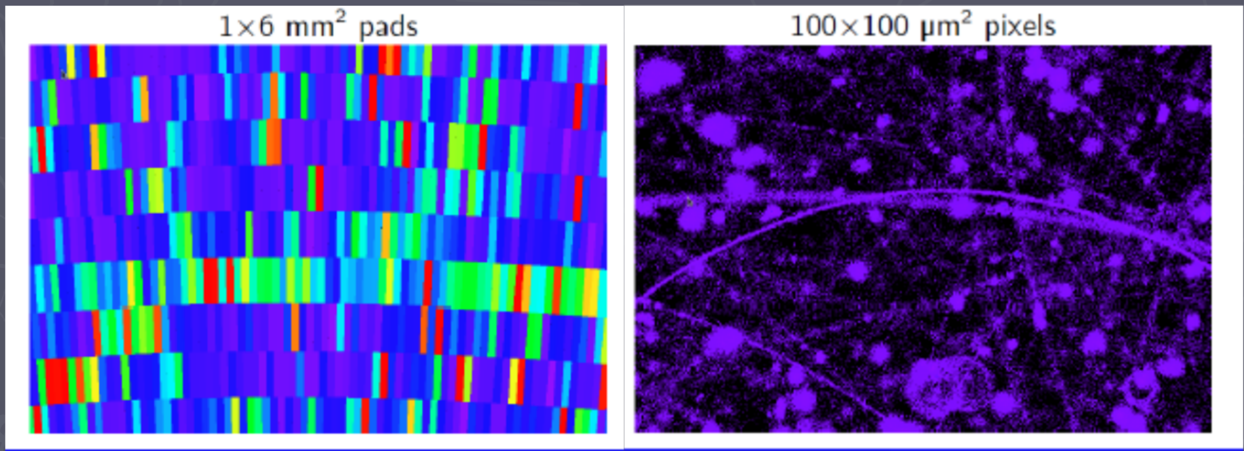
	without Gating Device	with Gating Device
Primary Ion	8.5 μm	8.5 μm
Secondary Ion	60 μm	0.01 μm
sum	70 μm	8.5 μm

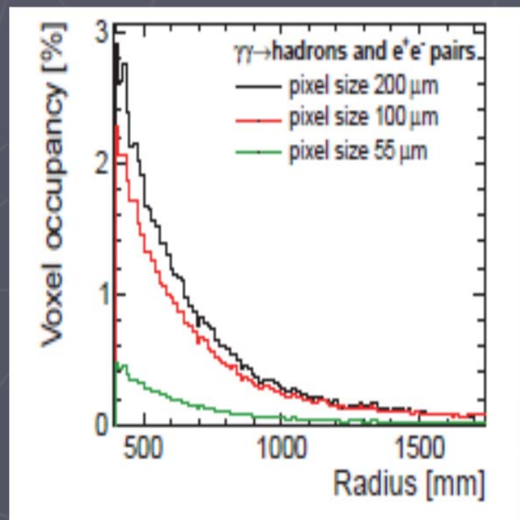


<u>3TeV CLIC</u>
TPC Occupancy and Positive ions

<u>At 3TeV CLIC</u>: 1 train = 312BX (156ns)
300k Incoherent pairs/BX
3.2 two-photon hadrons events/BX
1 beam-halo muon/BX
30% occupancy with the pad readout (1mm x 6mm)
A study with the "Ideal" pixel device (< 200μm)
Data size and pattern recognition are issues.
Distortion of the primary ions has to be addressed.







On right: We see many micro curlers but also tracks. There should be a way to find tracks if the data size (i.e. memory size) issue is solved.

Personal and Tentative Conclusion

At the 500GeV LC, the pad-readout MPGD TPCs satisfy the requirements. Then we need to focus more on engineering aspects for stable and reliable operation solving the "old distortion problem of TPC".

We need to come up with a design of gate device. The default option is the old wire gate known to work.

To reduce the material budget in the TPC endplate, we need some drastic(?) approach to electronics mounting and cooling.

For the high energy LC (3TeV CLIC), we probably need a TPC with pixel readout of < a few 100μm.

There the occupancy and the effect of (primary) ion have to be addressed carefully to judge if TPC, as a very nice 3D detector, might still be one of the best detectors.