Pixelated readout TPC technology for CEPC

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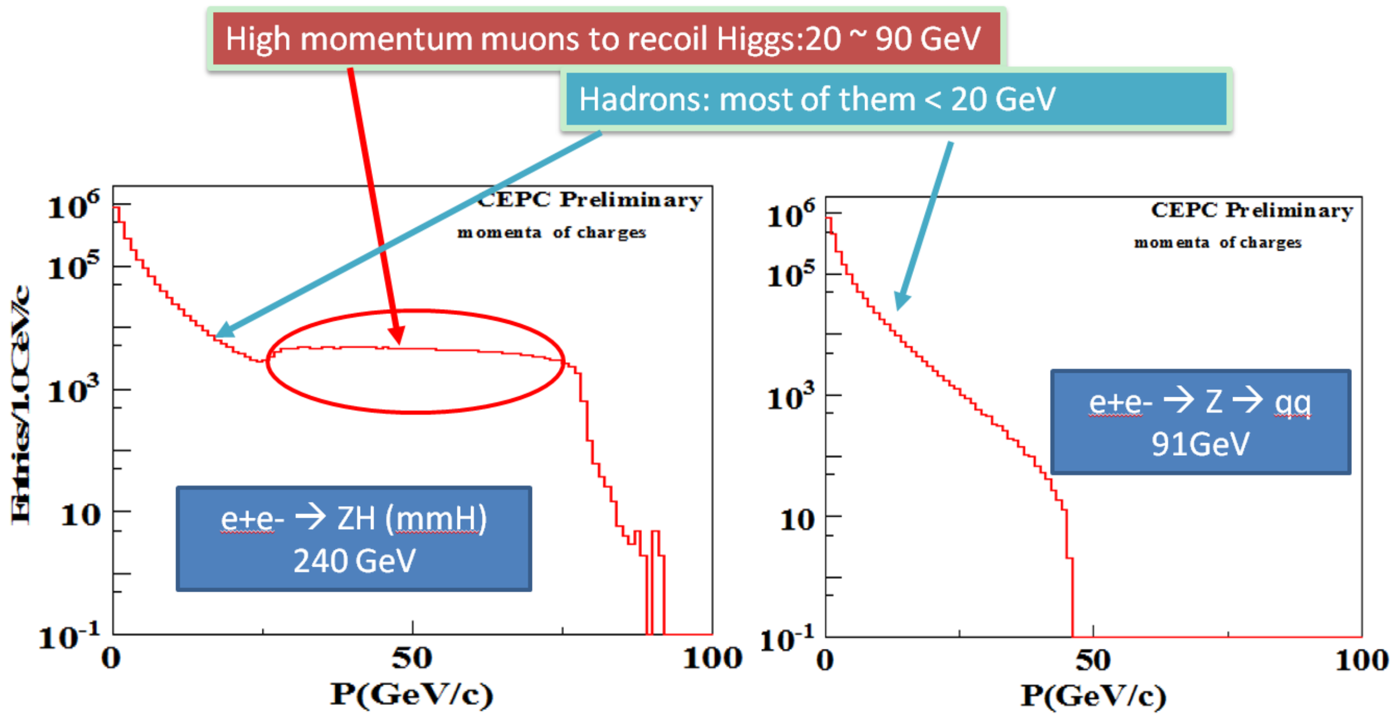
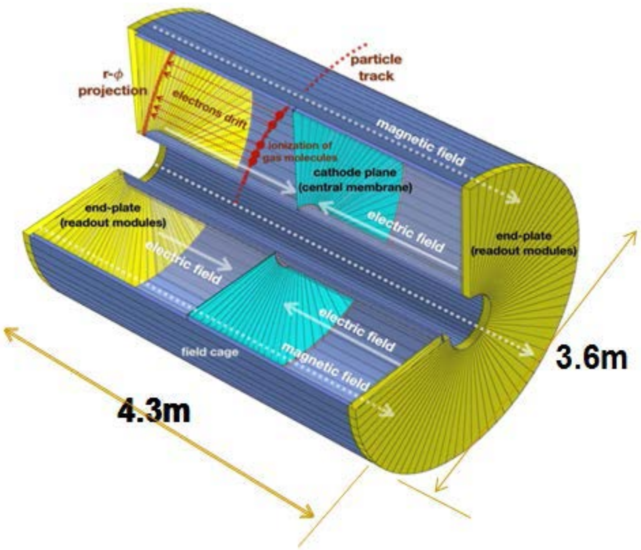
Physics requirements

- Provide decent #Hits (for track finding) with high spatial resolution compatible with PFA design (low material)
  - dP/p ~ 0.1%
- Provide dE/dx + dN/dx ~ 2-3%
  - Essential for Flavor @ Z pole
  - Beneficial for jet & differential at higher energy



Motivation: Challenges of TPC

- **Pad readout TPC** operational at modest Lumi @ Higgs, with 3 T B-field or higher.
- **Pixelated readout TPC** operational at high Lumi (2 E36) @ Z & 2 T B-Field
    - CEPC @ Z pole with 50 MW: 1.92 E36
    - FCC ee @ Z pole 2.3 E36
- Challenges of TPC as main tracker
    - Ion distortion?
    - Material Budget? (Compatibility)
    - Total power & Readout?
    - #Hits & Intrinsic spatial resolution?



Pixelated readout TPC technology

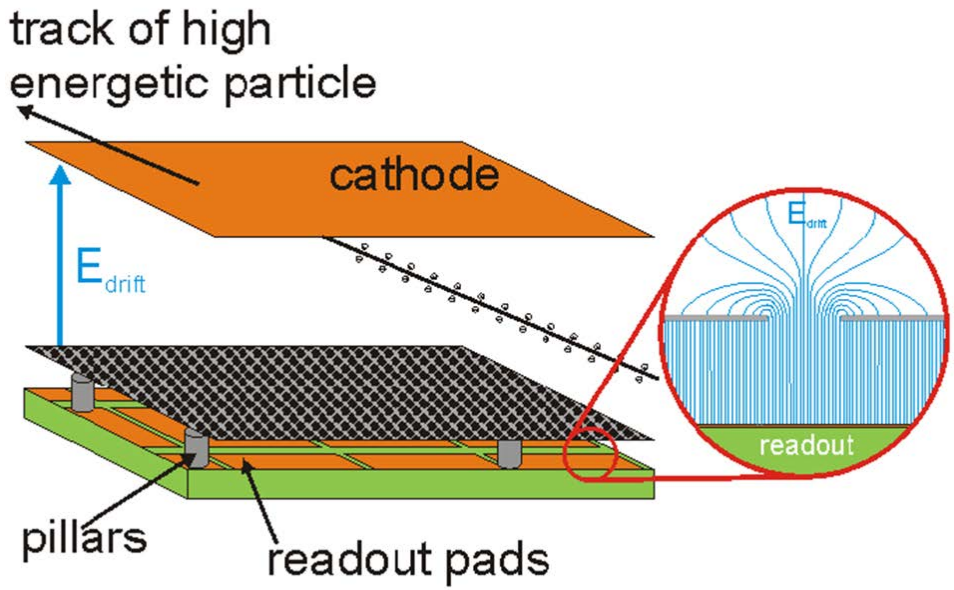
- A pixelated TPC is a good option to provide realistic physics requirements and can work at high luminosity (2 E36) on CEPC.
- Pixelated → better resolution → low gain(<2000) → less distortion
- Pixelated readout TPC is a realistic option to provide at CEPC
  - Can deal with high rates (MHz/cm^2)
  - High spatial resolution → better momentum resolution
  - dE/dx + Cluster counting (In space)
  - Excellent two tracks separation

Standard charge collection:

Pads (1mm×6mm)/ long strips

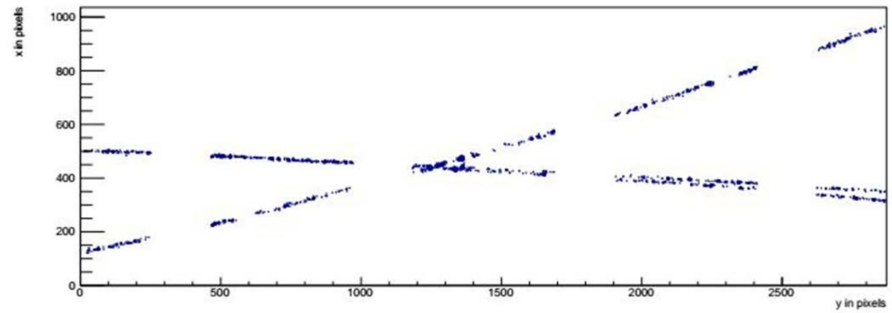
Instead:

Bump bond pads are used as charge collection pads.



Highlight: Good spatial resolution

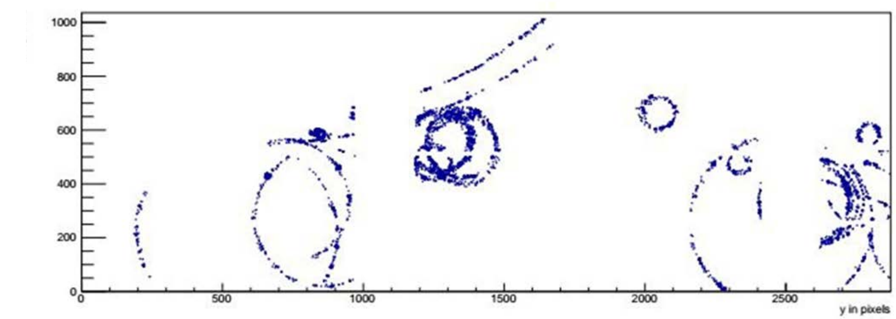
- **Good spatial resolution**
  - **Intrinsic resolution 100um → 16um**
- **Good track reconstruction**
- **Good momentum resolution**



$$\sigma_{r\phi}^{\text{pads}} = \sqrt{\sigma_{r\phi 0}^2 + \sigma_{\phi 0}^2 \sin^2(\phi_{\text{pad}}) + \frac{D_{r\phi}^2}{N_{\text{Eff}}} \sin(\theta_{\text{pad}}) \left(\frac{6\ \text{mm}}{h_{\text{pad}}}\right) \left(\frac{2.0\ \text{T}}{B}\right)^2 L}$$

$$\sigma_{r\phi}^{\text{pixels}} = \sqrt{\sigma_{r\phi 0}^2 + D_{r\phi}^2 \left(\frac{2.0\ \text{T}}{B}\right)^2 L}$$

$$\sigma_z = \sqrt{\sigma_{z0}^2 + D_z^2 L}$$



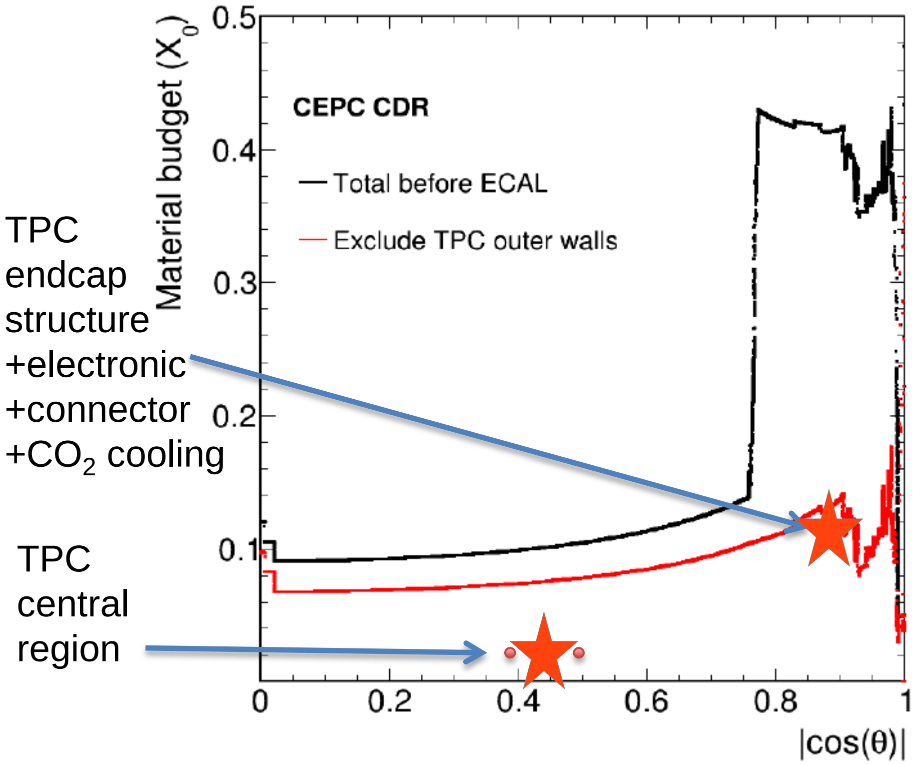
Intrinsic resolution	Pad TPC (1mm×6mm)	Pixel TPC (55um×55um)
$\sigma_{r\varphi 0}$	100um	16um
$\#Hits/track$	~220	~28k
$Gain$	5000	2000

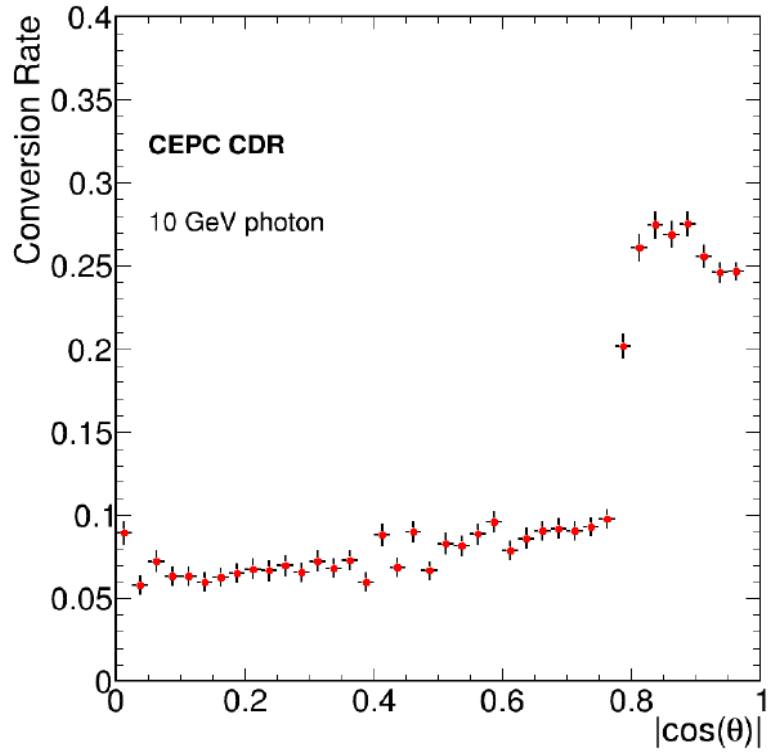
Proposed a feasibility study

- **Feasibility of pixelated readout TPC**
  1. **Material budget of endplate/barrel**
  2. **Ions affect and distortion**
  3. **Occupancy**
  4. **Power consumption**
  5. **Running at 2 Tesla**
  6. **Cost estimation**

#1. Material budget of endplate/barrel (OK)

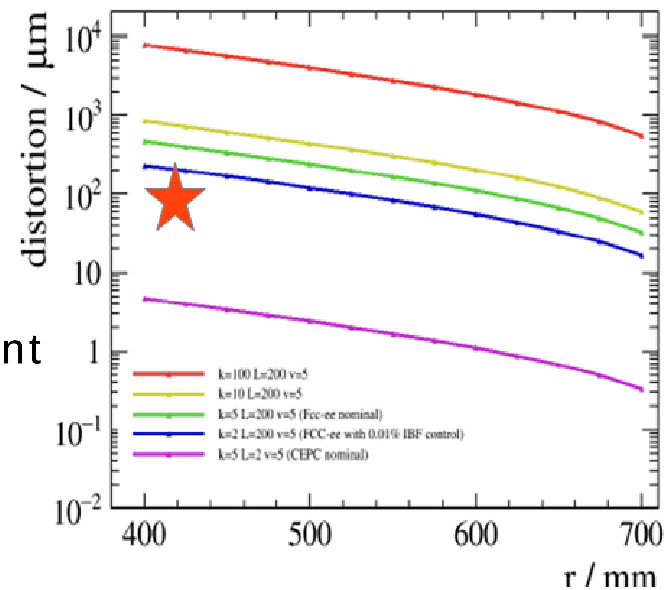
- Typical requirement: ~ 0.1 X_0 at Barrel.
- At CDR setup (Pad TPC): conservative implementation of material budget
  - 0.1 X_0 at Barrel, 0.4X_0 at endplate (sufficient for any readout with cooling)
  - Sizeable effects on detector performance, but tolerable
    - Observed on Photon conversion, PFA, …
- Pixelated readout TPC can reduce the material from CDR setup





#2. Ions affect and distortion

- Distortion: proportional to event rate, ion back flow and gain. Largest distortion occurs at the inner region
- Analysis (cite#1) shows that at
  - IBF×Gain ~ 1
  - Lumi ~ 2E36
  - Hit from Physics event only
  - Distortion ~ 100 micrometer ~ pixelated size
    - Might limit spatial/momentum measurement



- Open question: to be addressed by R&D
  - Correction by at least 1 order of magnitude?

    ==> future simulation studies…
  - In-situ calibration with Laser system/Z->mumu event (cite#2)

    ==> laser system test … collaborative studies with LCTPC
  - Contribution from other sources, especially at Z pole

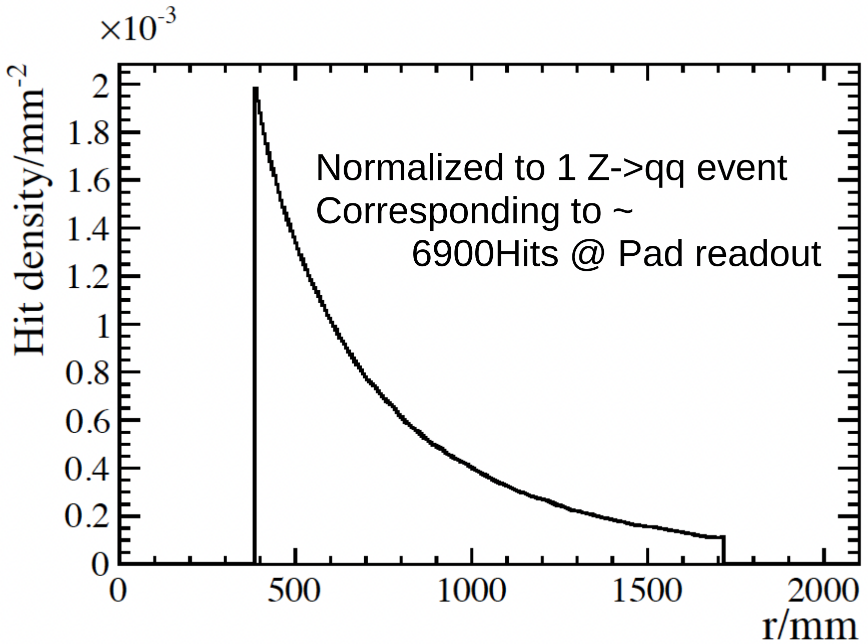
    ==> MDI, Beam background

New strategy and task in LCTPC now

- Cite#1 https://doi.org/10.1088/1748-0221/12/07/P07005
- Cite#2 [Correcting for Distortions due to Ionization]()

#3. Occupancy (Safe)

- Low voxel occupancy : 1E-5 to 1E-6 (cite#3)
- At 2 E36 with Physics event only, even bunch distribution(cite#4).
  - Pad readout (1mm×6mm), inner most occupancy 1 E-4
  - Pixelated readout (55um×55um), much **LOWER** inner most occupancy ~ 1 E-6
- Pixelated readout can easily handle a high hits rate at Z pole.
  - The test beam showed GridPix TPC prototype can handle up to 2.6M hits/s per chip (cite#5).
- Reconstruction algorithm with high Pile Up need to be developed.

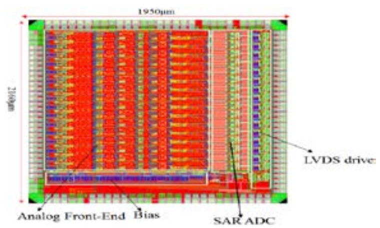


Marlin TPC software package

- Cite#3 Occupancy in the CLIC
- Cite#4 https://doi.org/10.1088/1748-0221/12/07/P07005
- Cite#5 GridPix detectors

#4. Power consumption

- Pixelated readout TPC@55um×55um**@NIKHEF**
  - Total channels: 10^9
  - Total power: 200 kW
    - Power consumption of Gridpix: ~1A@2V (2W) depending on rate
    - 1W/cm^2, No optimization
  - Next plan of total power: <100kW
    - TPX4: <500mW/cm^2 (plan)



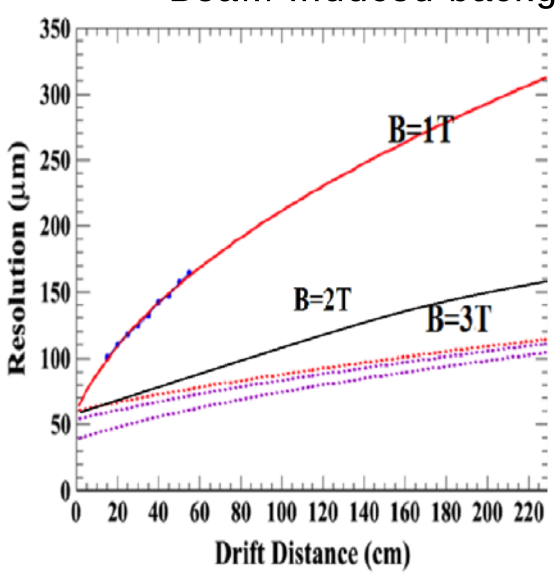
	AGET	PASA+ALTRO	Super-ALTRO	SAMPA
TPC	T2K	ALICE	ILC	ALICE upgrade
Pad尺寸	6.9x9.7 mm^2	4x7.5 mm^2	1x6 mm^2	4x7.5 mm^2
通道数	1.25 x 10^5	5.7x 10^5	1-2 x 10^6	5.7 x 10^5
读出结构	MicroMegas	MWPC	GEM/MicroMegas	GEM
增益	0.2-17 mV/fC	12 mV/fC	12-27 mV/fC	20/30 mV/fC
成型方式	$CR-(RC)^2$	$CR-(RC)^4$	$CR-(RC)^4$	$CR-(RC)^4$
达峰时间	50 ns-1us	200 ns	30-120 ns	80/160 ns
ENC	850 e @ 200ns	385 e	520 e	482 e @ 180ns
波形采样方式	SCA	ADC	ADC	ADC
采样率	1-100 MSPS	10 MSPS	40 MSPS	10 MSPS
精度	12 bit(external)	10 bit	10 bit	10 bit
功耗	<10 mW/ch	32 mW/ch	47.3 mW/ch	17 mW/ch
CMOS工艺	350 nm	250 nm	130 nm	130 nm

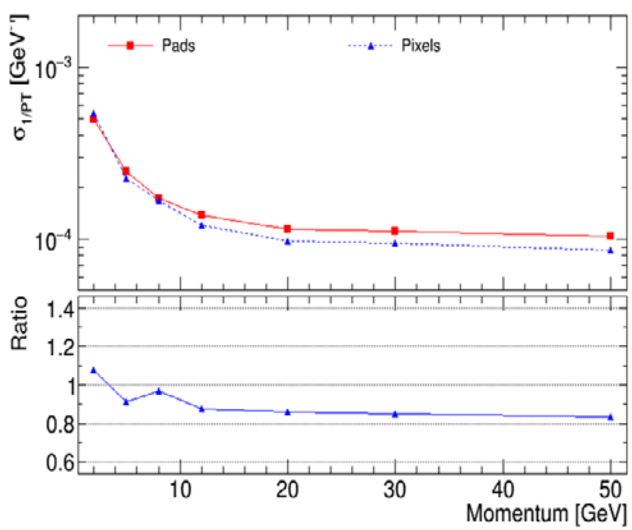
- Pad readout TPC@1mm×6mm**@IHEP**
  - Total channels: 10^6
  - Total power: <12 kW
    - 48mW/cm^2
    - WASA ASIC chip: 3.5mW/ch@40 MS/s(cite#6)
- To be addressed by R&D**@IHEP/Tsinghua**
  - Optimization pixelated readout @300um×300um
  - Total channels: 10^8
  - Total power:<20 kW
    - <100mW/cm^2
- 2-phase CO_2 Cooling is optional**@IHEP**

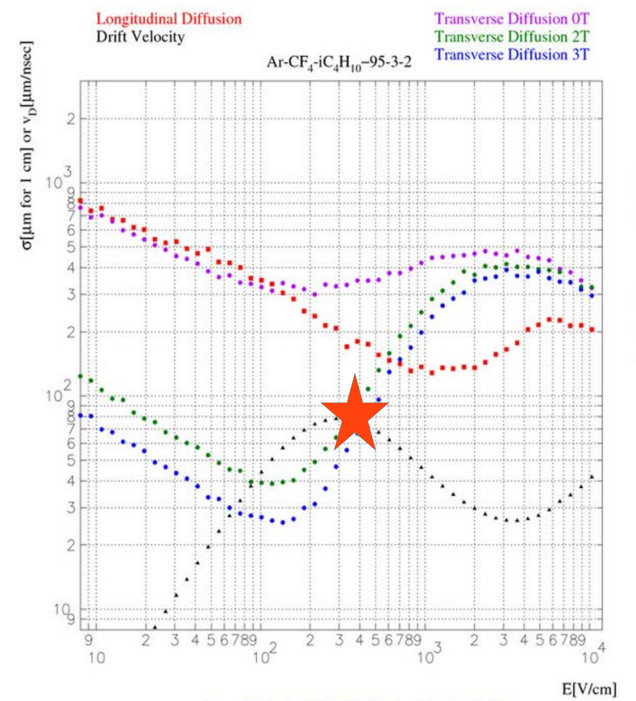
- Cite#7 Low power WASA chip

#5. Running at 2 Tesla

- TPC can work well at the 2 T B-field **without any E×B effect**.
- Momentum resolution is better (>20%) compared with the pad readout technology at the same geometry.
  - Pixelated technology: ~10,000hits/track; Pad: 220hits/track
  - Transverse diffusion constant is same level at 2 T & 3 T
- Open question: to be addressed by R&D
  - **Optimized TPC geometry** at 2 T B-field
  - Beam induced background at 2 T B-field







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#6. Cost estimation

- The total cost of a pad or a pixel readout is **at same level .**
  - The cost goes comparably to pad technology for massive production referred to Gridpix chip of NIKHEF
- All readout options need CO_2 cooling and electronics and that drives the TPC readout cost. (cite#7)

Including the cooling system

TPC COST ESTIMATION(unit: *10K RMB) **Total: 180 Millions RMB**

ITEM	DEVICE ITEM	TYPE	UNIT	Quantity	Prive/	Total
3.1	TPC detector (TPC)					18000.00
3.1.1	Chamber					3600.00
3.1.1.1	Fieldcage		set	1	1200.00	1200.00
3.1.1.2	Connector		set	1	800.00	800.00
3.1.1.3	Barrel		set	1	1000.00	1000.00
3.1.1.4	Support device		set	1	600.00	600.00
3.1.2	Readout					2500.00
3.1.2.1	MPGD detector		set	1	800.00	800.00
3.1.2.2	Support board		set	2	600.00	1200.00
3.1.2.3	Readout board		board	200	2.50	500.00
3.1.3	Electronics					10000.00
3.1.3.1	FEE ASIC readout		channel	1200000	0.002	2400.00
3.1.3.2	Cables		set	50000	0.03	1500.00
3.1.3.3	Optical driver		set	50000	0.03	1500.00
3.1.3.4	Optical link, connectors		set	500	1.00	500.00
3.1.3.5	DAQ		set	5000	0.30	1500.00
3.1.3.6	Crate and controller		set	50	20.00	1000.00
3.1.3.7	Cooling sytem		set	1	1600.00	1600.00
3.1.4	Calibration					500.00
3.1.4.1	Calibration system		set	1	500.00	500.00
3.1.5	HV and Gas system					1400.00
3.1.5.1	HV and low power		set	1	800.00	800.00
3.1.5.2	Gas system		set	1	300.00	300.00
3.1.5.3	Monitor system		set	1	300.00	300.00

- Cite#7 Cost estimation of ILD concept

Feasibility of pixelated readout

- **Feasibility of pixelated readout TPC**
  - **Material budget of endplate/barrel √**
  - **Occupancy √**
  - **Power consumption √**
  - **Cost estimation √**
  - **Running at 2 Tesla √ (need R&D)**
  - **Ions affect and distortion √ (need R&D)**

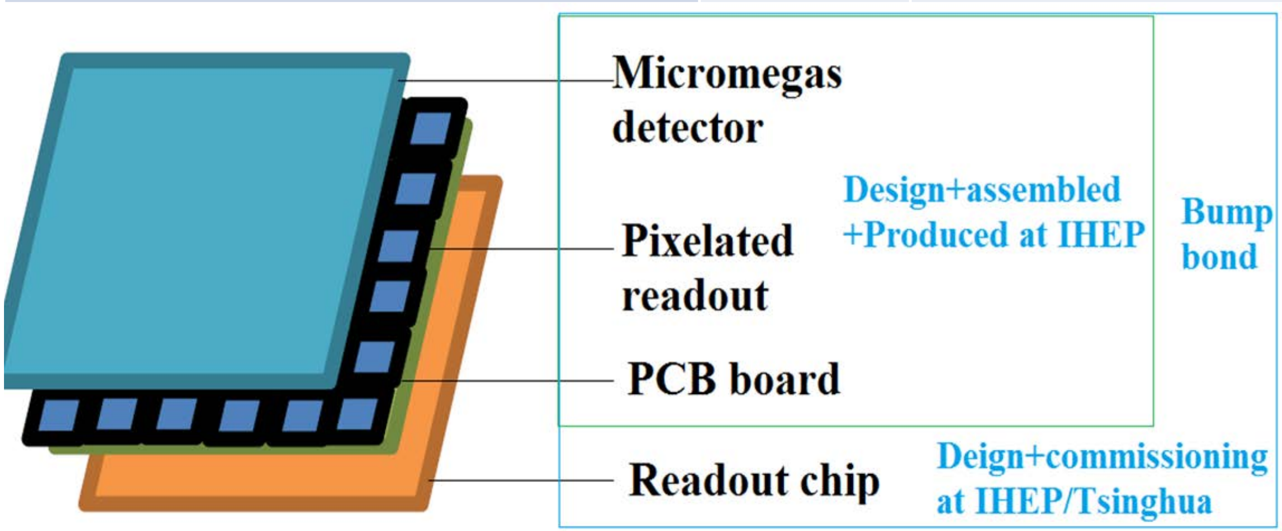
Prototype R&D plan

- **Advantage and realized R&D**
  - **Prototype R&D plan**
  - **Improved dE/dx**
  - **Optimization of cluster/pixel size**

Prototype plan #1

- **Realization of pixelated technology collaborated with Tsinghua**

Bump bond pixelated readout with Micromegas detector	Module size	To be addressed by R&D
• **≥300um×300um** • Developed the readout chip by Deng Zhi (Tsinghua) • Developed the Micromegas detector sensor at IHEP • Development of the new module and prototype	1-2 cm^2	• Research on pixelated readout technology realization • Optimization of cluster profile and pad size • Study of the ‘dN_{cl}+dx’
	100 cm^2	• Study the distortion using UV laser tracks and UV lamp to create ions disk • In-situ calibration with UV Laser system • Study of the ‘$dE/dx+dN_{cl}/dx$’



Tsinghua University
University

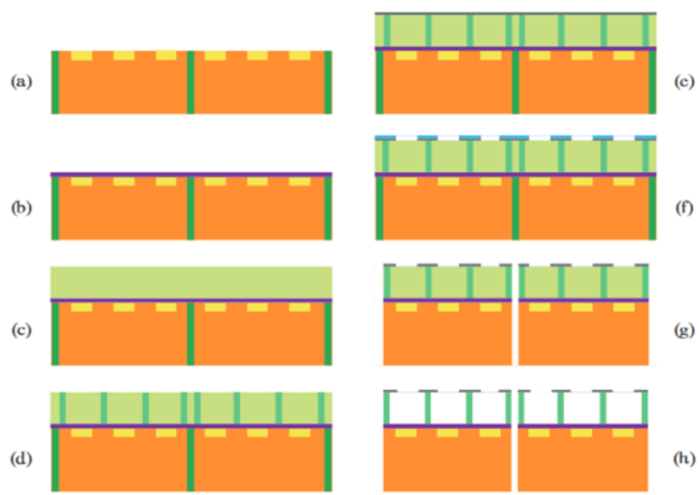
Prototype plan #2

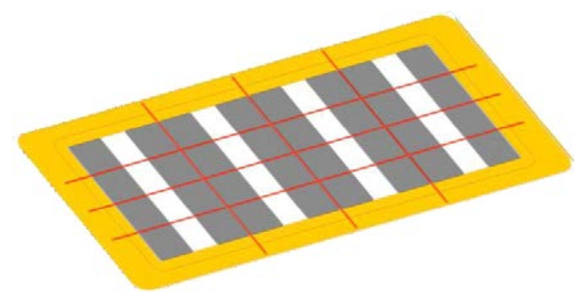
- **Realization of pixelated technology using GridPix chip collaborated Bonn**
  - **200um×200um and smaller**
  - Design the different readout pixelated size
  - Collaborated with Bonn University to produce the new prototype (Peter, Jan and Jochen from Bonn)
  - Study using UV laser tracks

University of Bonn
University

Production of GridPixes

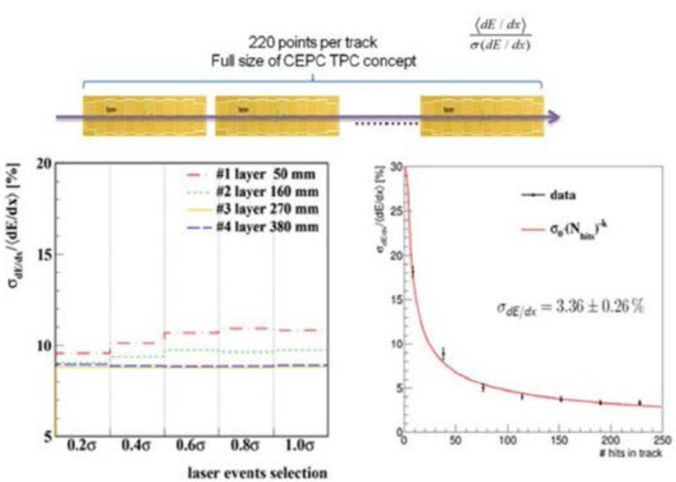
a) Cleaning
b) Deposition of Protection layer
c) SU-8 covering
d) Exposure with mask
e) Aluminium layer is deposited
f) Another layer of photoresist is applied, exposer with a mask creates a hole pattern, and the holes are chemically etched
g) The wafer is diced
h) The unexposed SU-8 is resolved



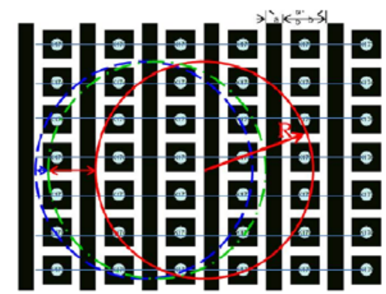


Study the cluster/pixel size

- **R&D plan will mainly focus on making pixelated TPC work**
- **Using the existing UV laser TPC prototype**
- **Some key issues R&D**
  - **– improve the laser track resolution and cluster size**
  - **– improved dE/dx to 2% level (TOA+TOT methods)**
    - Pixel size:(300μm or similar level size)
    - Micromegas + WASA ASIC Chips (Gain: 40mv/fC)
    - Almost without IBF (Gain< 2000)

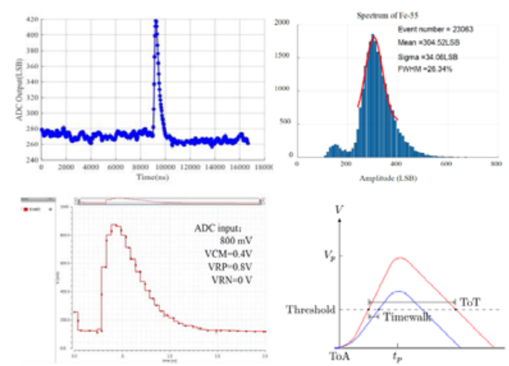


Resuls of the laser TPC prototype



Drift length of Z position	Profile of the electrons cluster(single event)	Minimum electrons cluster	Maximum electrons cluster
10.30mm	1.06 mm	3	6
7.30 mm	0.85 mm	3	6
5.84 mm	0.76 mm	3	6
3.65 mm	0.60 mm	2	4
1.46 mm	0.38 mm	1	4

Electron cluster profile



10bit TOT + 12bit TOA

dE/dx along drift length

$dE/dx + dN_{cl}/dx$

Summary

- Pad readout TPC can operate @ CEPC W/Higgs operation, with 3 T B-field or higher.
  - A laser TPC prototype has been successfully developed and studied at IHEP in the last 6 years. Ionback flow can be reduced to 1 level at gain 2000.
- High Lumi operation (2 E36) @ Z with 2 T B-Field is challenge for gaseous.
  - Material budget, construction cost, power & cooling, Occupancy is OK.
  - Further study is needed to better understand the Distortion (induced by ion charge) and beam background:
    - Geometry Optimization
    - Distortion correction & in-situ calibration
    - Beam background validation & simulation
- Pixelated readout TPC is promising, compared to Pad readout:
  - Much Lower Occupancy;
  - Lower Ion backflow;
  - High Precision;
  - Potential for dN/dx, essential for PID
- R&D plan focus on the Pixelated TPC readout & prototype, optimization to the local configuration (for dN/dx, power consumption, …) and global geometry optimization (inner Radius, etc)
- Good International/domestic Partners: LCTPC, CEA-Saclay, NIKHEF, Tsinghua…

Many Thanks

- Especially thanks to Jianchun, Manqi, Gang, Joao, Xinchou, Zhiyang, Chang Yue, Liwen, Deng Zhi
- Especially thanks to some good inputs from Ron Settle, Peter Kluit, Fujji Keisuke, Paul Colas, Jan Timmermans, Jochen kaminski from LCTPC

Motivation of TPC technology

CEPC Accelerator TDR Design

2018 CDR Baseline Design

	Higgs	W	Z (3T)	Z (2T)
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5 × 2			
Piwinski angle	3.48	7.0	23.8	
Particles /bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number	242	1524	12000 (10% gap)	
Bunch spacing (ns)	680	210	25	
Beam current (mA)	17.4	87.9	461.0	
Synch. radiation power (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compaction (10^{-5})	1.11			
β function at IP β_x^*/β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance x/y (nm)	1.21/0.0024	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.109	0.013/0.123	0.004/0.06	0.004/0.079
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz)	650			
Harmonic number	216816			
Natural bunch length σ_z (mm)	2.72	[illegible]	[illegible]	
Bunch length σ_z (mm)	4.4	[illegible]	[illegible]	
Damping time $\tau_x/\tau_y/\tau_E$ (ms)	[illegible]	[illegible]	849.5/849.5/425.0	
Natural Chromaticity	[illegible]	[illegible]	-491/-1161	-513/-1594
[illegible]	363.10 / 365.22			
[illegible]	0.065	0.040	0.028	
[illegible] (2 cell) (kw)	0.46	0.75	1.94	
Natural energy spread (%)	0.100	0.066	0.038	
Energy spread (%)	0.134	0.098	0.080	
Energy acceptance requirement (%)	1.35	0.90	0.49	
Energy acceptance by RF (%)	2.06	1.47	1.70	
Photon number due to beamstrahlung	0.082	0.050	0.023	
Beamstruhlung lifetime /quantum lifetime[†] (min)	80/80	>400		
Lifetime (hour)	0.43	1.4	4.6	2.5
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP (10^{34} cm^{-2}s^{-1})	3	10	17	32

[†] include beam-beam simulation and real lattice

2021 Improved Design

	ttbar	Higgs	W	Z
Number of Ips		2		
Circumference [km]		100.0		
SR power per beam [MW]		30		
Half crossing angle at IP [mrad]		16.5		
Bending radius [km]		10.7		
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	[illegible]
Beam size at IP (sigx/sigy) [um/nm]	39/113	15/36	[illegible]	[illegible]
Bunch length (SR/total) [mm]	2.2/2.9	[illegible]	[illegible]	2.5/8.7
Energy spread (SR/total) [%]	[illegible]	[illegible]	[illegible]	0.04/0.13
Energy acceptance (DA/RF) [%]	[illegible]	[illegible]	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	[illegible]	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/0.9	-/-/5.8
Qx/Qy/Qs	0.12/0.22/0.078	0.12/0.22/0.049	0.12/0.22/	0.12/0.22/
Beam lifetime (bb/bs)[min]	81/23	39/18	60/717	80/182202
Beam lifetime [min]	18	12.3	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

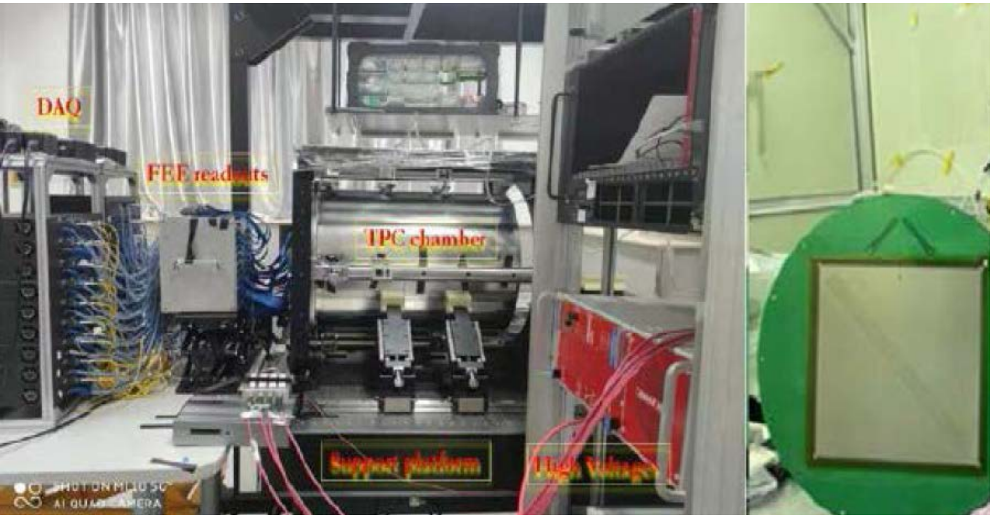
67%⇑ 259%⇑

Even higher↑

- https://indico.cern.ch/event/1129966/contributions/4747428/attachments/2404058/4112102/ECFAMIniWS-2.pdf
- CEPC Study Group. "CEPC Conceptual Design Report: Volume 2-Physics & Detector." arXiv:1811.10545 (2018).

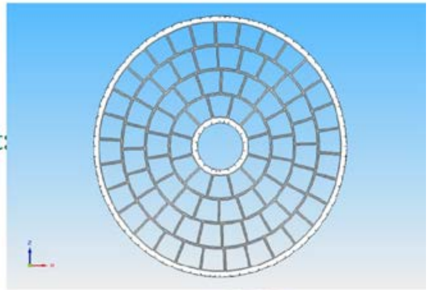
Pad TPC technology

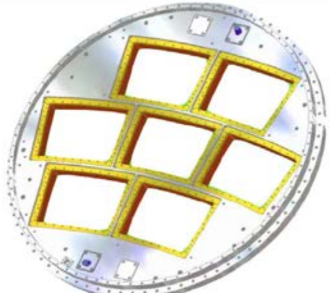
- At a circular collider CEPC there is place for different experiments, one of the detector concept could use a TPC as the main tracker.
- For Higgs, W and top running **no problem** for all TPC read out technologies.
- Laser TPC prototype has been successfully developed **in last 6 years** at IHEP.



Pad TPC for collider

- Active area: $2 \times 10m^2$
- One option for endplate readout:
  - GEM or Micromegas
  - 1×6 mm^2 pads
  - 10^6 Pads
  - 84 modules
  - Module size: $200 \times 170mm^2$
  - Readout: Super ALTRO
  - CO_2 cooling



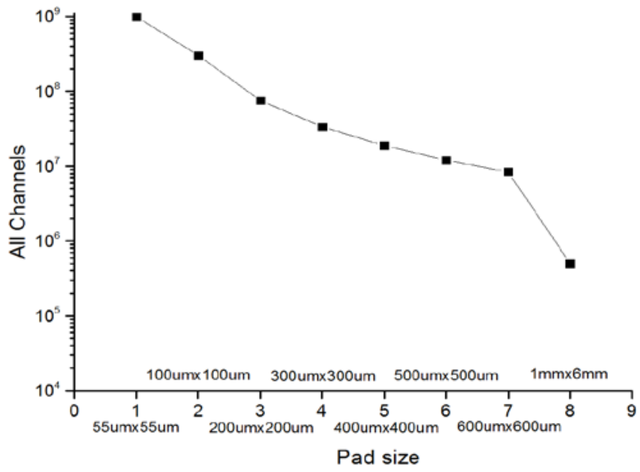


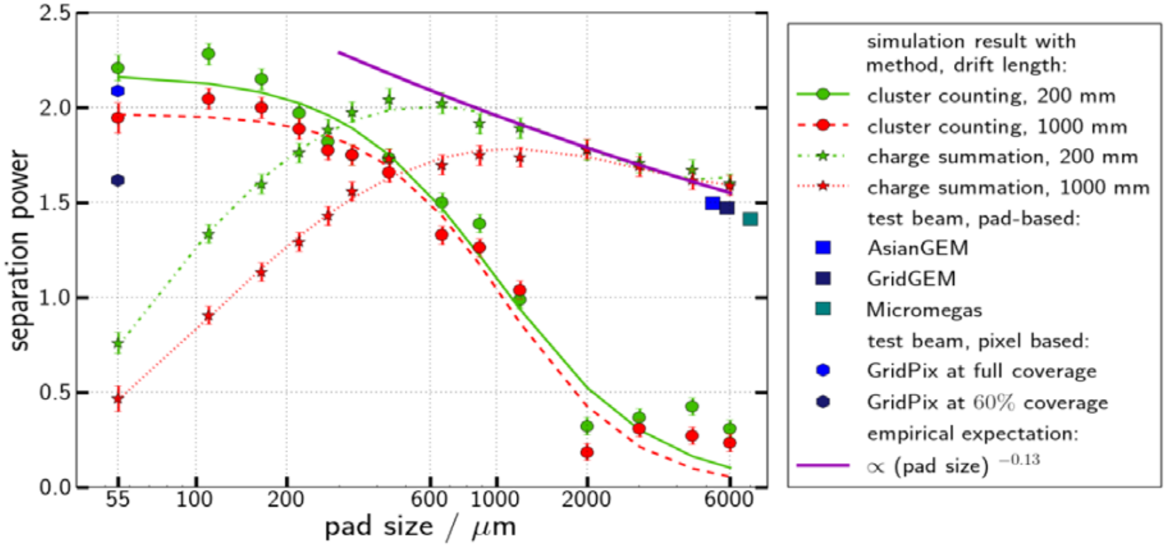
- https://agenda.linearcollider.org/event/5504/contributions/24543/attachments/20144/31818/PositiveIonEffects-kf.pdf
- https://indico.fnal.gov/event/46746/contributions/208077/attachments/141125/177798/LCTPC.pdf
- Di Meglio, Alberto, et al. CERN Quantum Technology Initiative Strategy and Roadmap. No. CERN-OPEN-2021-012. 2021
- arXiv:1902.01987 [physics.ins-det, 2019] Yuan, Zhiyang, et al. International Journal of Modern Physics A 36.22 (2021): 2142015.
- Chang, Y., et al. "Performance of the continuous ions suppression TPC prorotype for circular collider." Journal of Instrumentation 15.09 (2020): C09065.

First step: Optimization of pixelated size

Using the TPC prototype

- **Pixelated size should be optimized**
  - From 55um×50um to 300um×300um
  - All of channels will be reduced from 10^9 to 10^7
  - Based on the existing Prototype and experimental data results, the pad size could be estimated about 300um×300um or 200um×200um





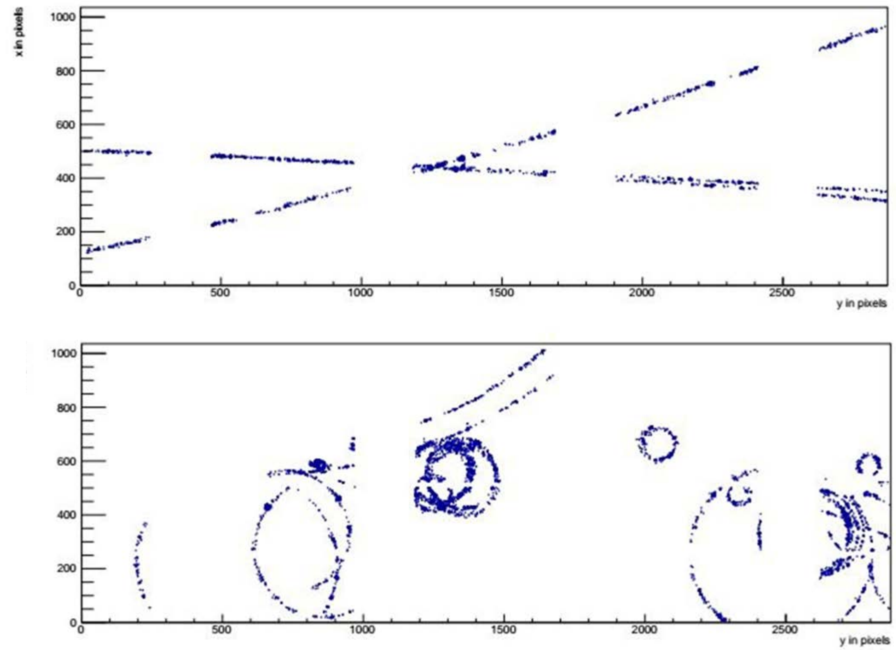
- https://agenda.linearcollider.org/event/9533/contributions/49862/attachments/37746/59205/2022_01_13%20LCTPC%20Collaboration%20Meeting.pdf
- https://wiki.classe.cornell.edu/pub/ILC/WWS/TrackCornellSim/TPC_Detector_Resp_Sim_LCWS_Paris_19_Apr_2004.pdf
- http://w4.lns.cornell.edu/~dpp/linear_collider/images/talks/20070531-Peterson-LCWS07-SimRecon.pdf

Gridpix Cost

- For the prototype, as know the costs, but they will go down substantially because of prices going down for large numbers. E.g. for 1 module of 100 chips we need 1 wafer 3000 euro plus post processing 3000 euro. (reference from NIKEHF GridPix)

Highlight: Good spatial resolution

- **Good spatial resolution**
  - **Intrinsic resolution 100um → 16um**
- **Good track reconstruction**
- **Good momentum resolution**



$$\sigma_{r\phi}^{\text{pads}} = \sqrt{\sigma_{r\phi 0}^2 + \sigma_{\phi 0}^2 \sin^2(\phi_{\text{pad}}) + \frac{D_{r\phi}^2}{N_{\text{Eff}}} \sin(\theta_{\text{pad}}) \left(\frac{6\text{ mm}}{h_{\text{pad}}}\right) \left(\frac{2.0\text{ T}}{B}\right)^2 L}$$

$$\sigma_{r\phi}^{\text{pixels}} = \sqrt{\sigma_{r\phi 0}^2 + D_{r\phi}^2 \left(\frac{2.0\text{ T}}{B}\right)^2 L}$$

$$\sigma_z = \sqrt{\sigma_{z0}^2 + D_z^2 L}$$

Intrinsic resolution	Pad TPC (1mm×6mm)	Pixel TPC (55um×55um)	Pixel TPC (300um×300um)
$\sigma_{r\varphi 0}$	100um	16um	**85um**
$\#Hits/track$	~220	~28k	**~5k**
$Gain$	5000	2000	**<2000**