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Design and Simulation of MAPS-based Inner Tracker for STCF

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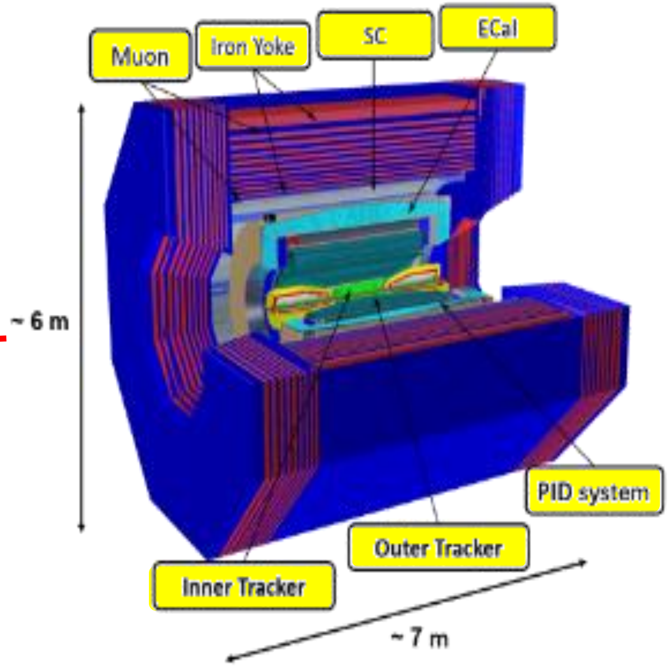
- Introduction to MAPS-based Inner Tracker (ITKM) for STCF
- MAPS sensor simulation and optimization
- ITKM simulation and performance
  - Introduction to OSCAR framework
  - Full simulation process
  - Detector simulation and digitization
  - Reconstruction performance
- Summary

Super Tau-Charm Facility

- **STCF: next generation e^+e^- collider in China**
  - Detailed study of $\tau - c$ physics
  - Precise tests to the SM
  - Searching for new physics
- E_{cm} = **2~7GeV**
- Peaking luminosity > $\mathbf{0.5 \times 10^{35} cm^{-2} s^{-1}}$

Unprecedented high luminosity brings challenges to all detectors, especially Inner Tracker



MAPS-based Inner Tracker

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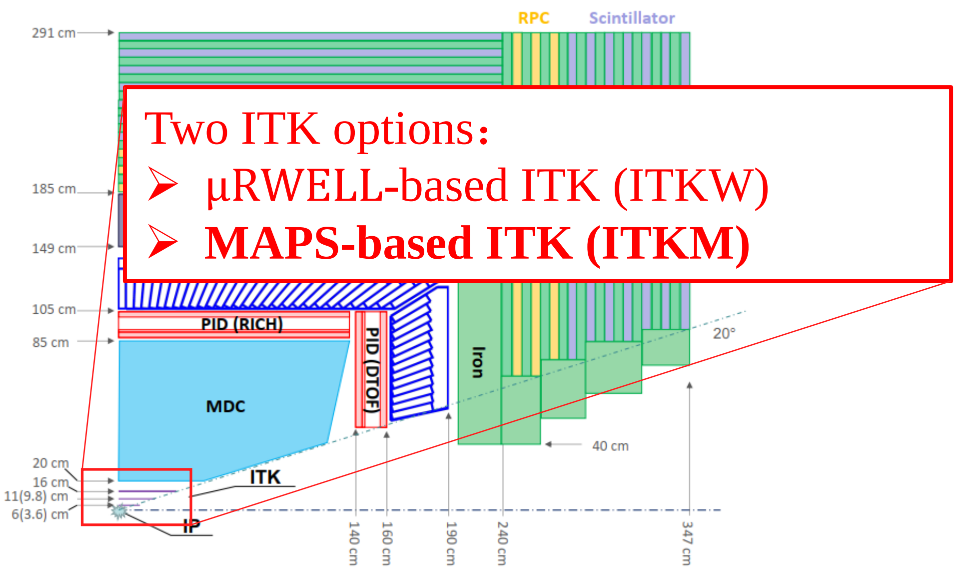
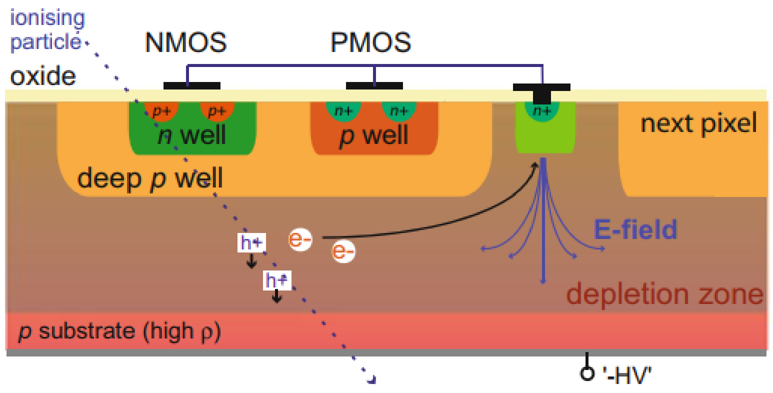
Requirements for Inner Tracker
- 0.3% X_0 per layer
- $\sigma_{r\varphi} < 100\mu m$
- Tracking efficiency >90% @100MeV/c
- Hit rate ~$800\mathrm{kHz/cm^2}$

Requirements for MAPS
- Power consumption < $100\ \mathrm{mW/cm^2}$
- Moderate position resolution
- Good timing of ~50ns
- Detection of energy deposition



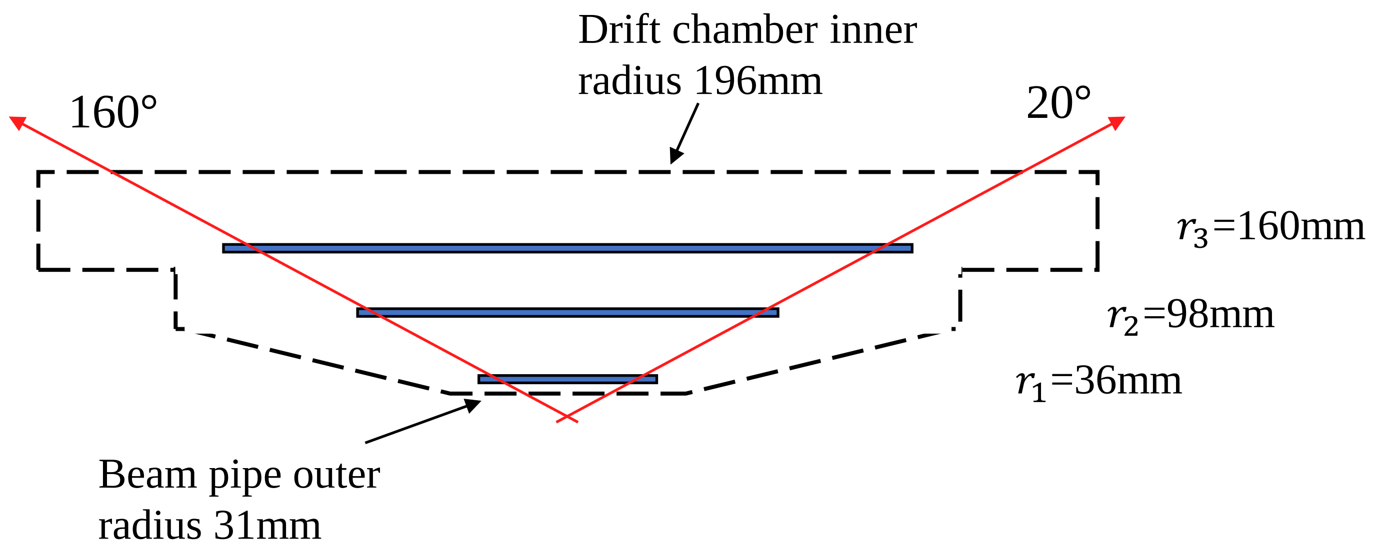
Two ITK options：
- µRWELL-based ITK (ITKW)
- **MAPS-based ITK (ITKM)**

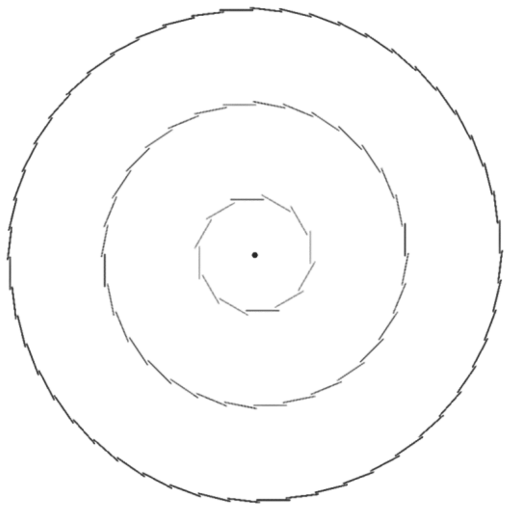


Monolithic **A**ctive **P**ixel **S**ensor
- ✓ Mature CMOS technology
- ✓ Highly integrated
- ✓ Small pixel pitch
- ✓ Low material budget
- ✓ High SNR
- ✓ …

HR-MAPS with pixel size **170µm × 30µm** chosen as the baseline design for ITKM

Preliminary design of ITKM





	Min radius	stave no.	sector no.	Area/cm^2
ITKM1	36mm	12	12	583.9
ITKM2	98mm	32	30	3892.7
ITKM3	160mm	52	48	10120.9

- Covering polar angle 20°-160°
- Total area: 15000 cm^2
- Pixel numbers: 270 million

R&D overview

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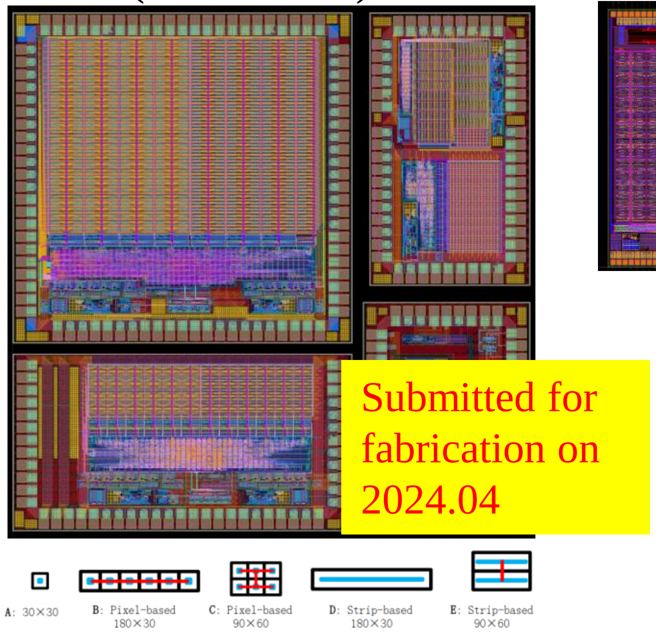
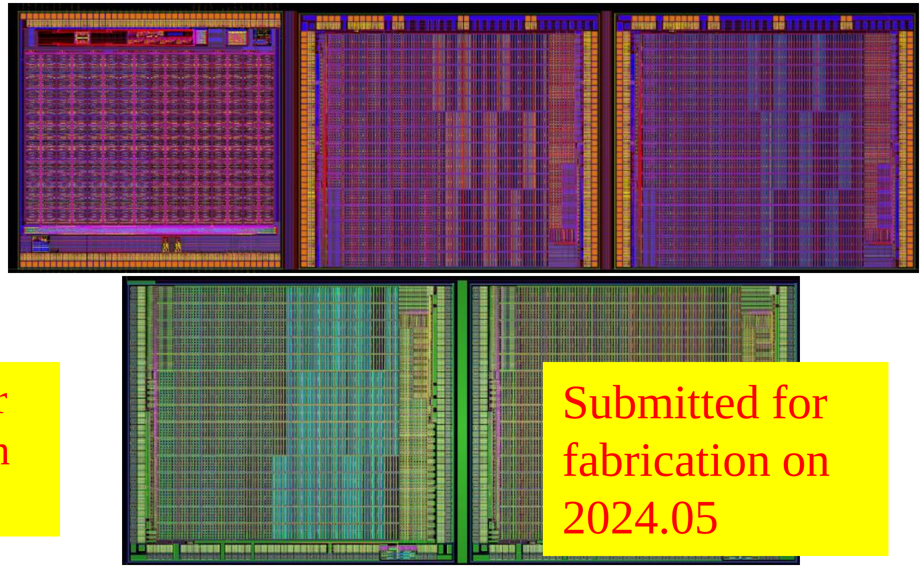
MAPS design going on under three different technologies

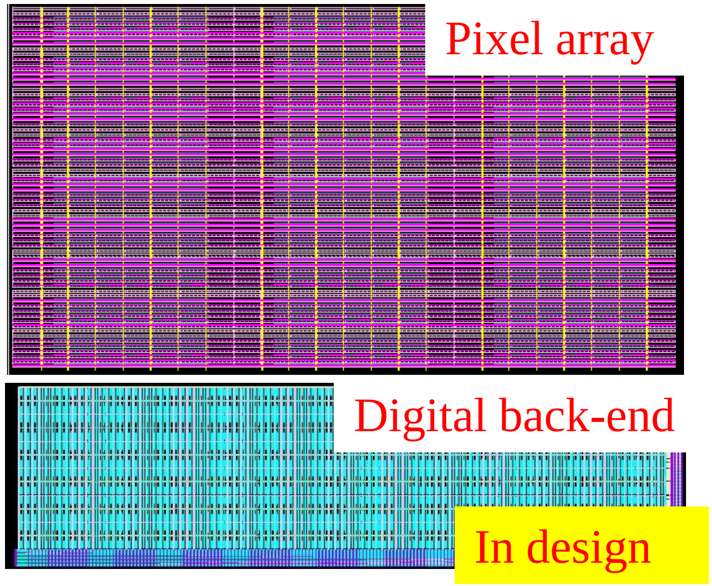
TJ180nm
- Widely used in HEP (ALPIDE, OBELIX)
- **Baseline techno**
- Low res substrate + high res (>$1k\Omega\cdot cm$) EPI



FCIS/BCIS90nm
- **Domestic techno**
- Low res substrate & EPI



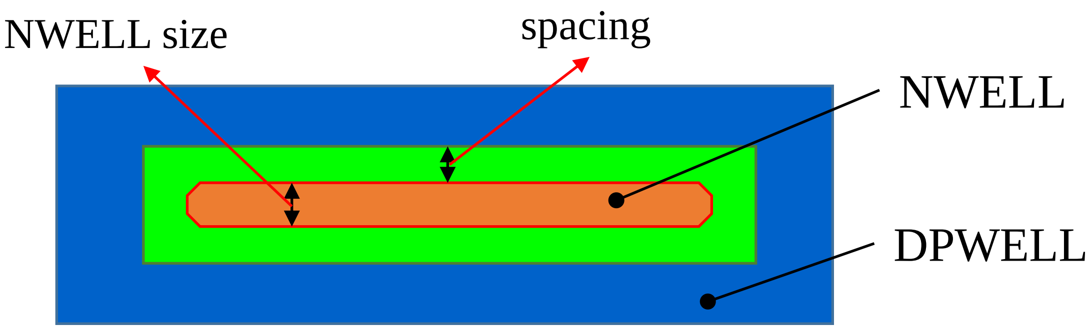
GSMC130nm
- **Domestic techno**
- High res substrate, no EPI



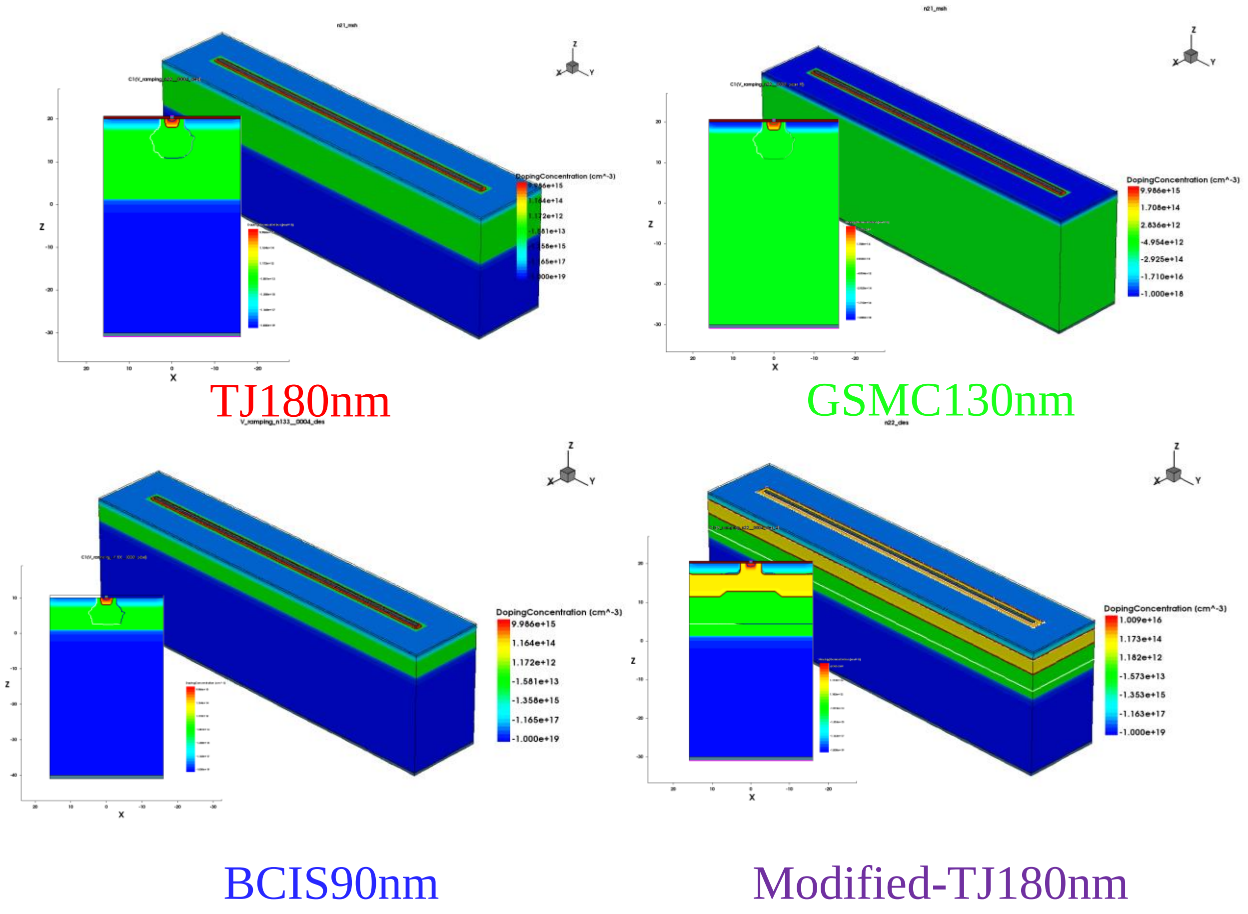
See Dongwei's talk for details

MAPS sensor simulation

- TCAD simulation in different technologies
- Pixel size: 170μm × 30μm
- NWELL size 2μm
- NWELL-DPWELL spacing 2μm
  - TJ180nm
  - GSMC130nm
  - BCIS90nm
  - Modified-TJ180nm (N-blanket design)



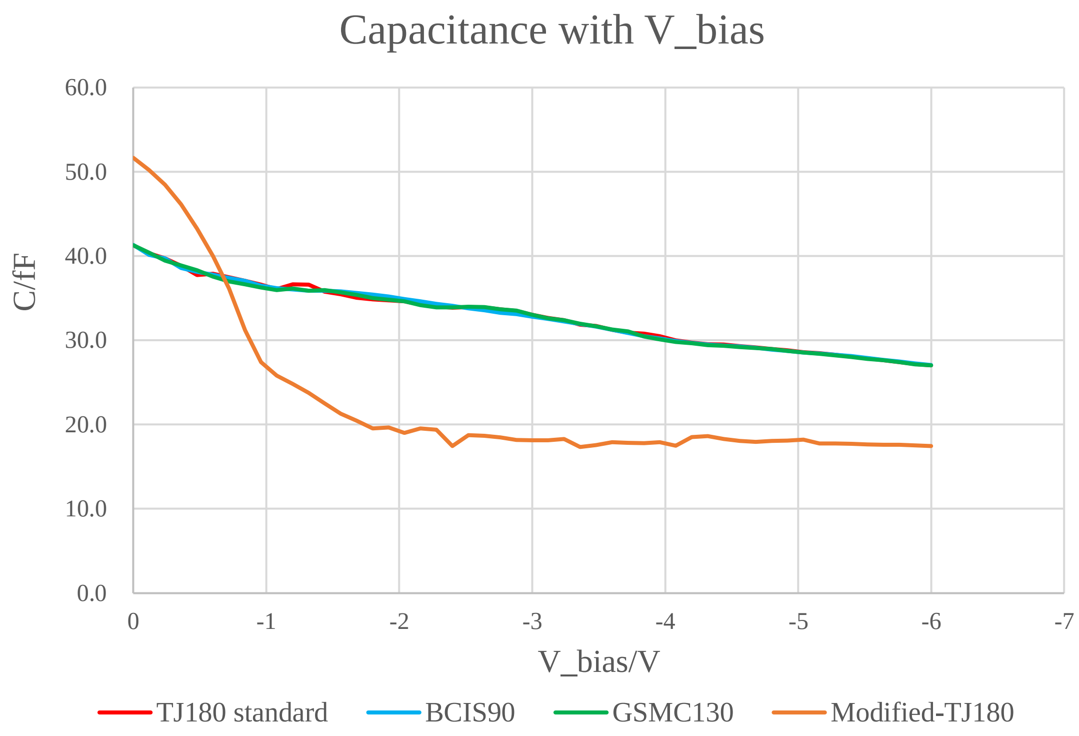
Doping profile



Sensor capacitance simulation

- Nwell voltage set to 0.8V, substrate voltage scanned from 0 to -6V

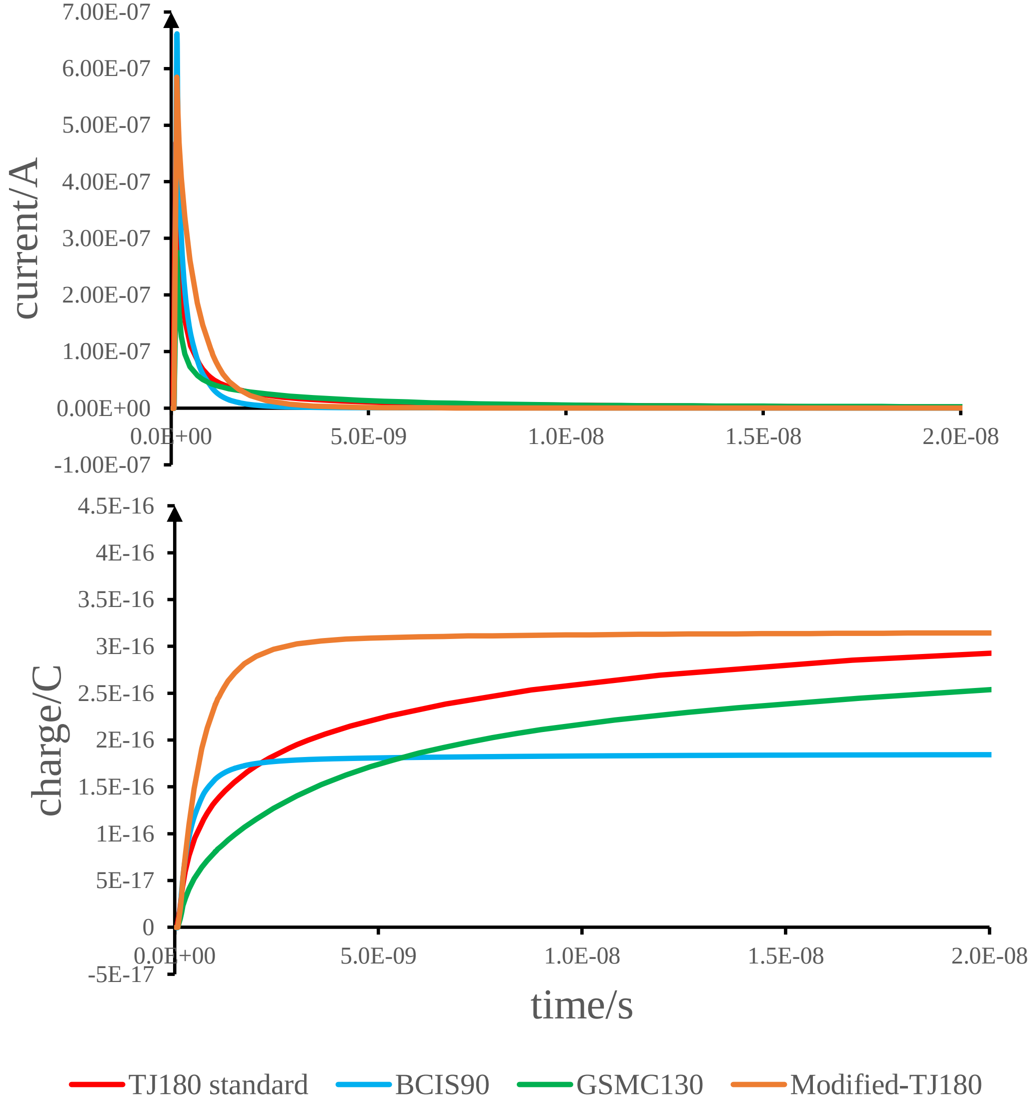
Techno	Capacitance @ $V_{sub} = -6V$
TJ180nm	**27.0fF**
GSMC130nm	**27.1fF**
BCIS90nm	**27.0fF**
Modified-TJ180nm	17.4fF



Sensor signal simulation

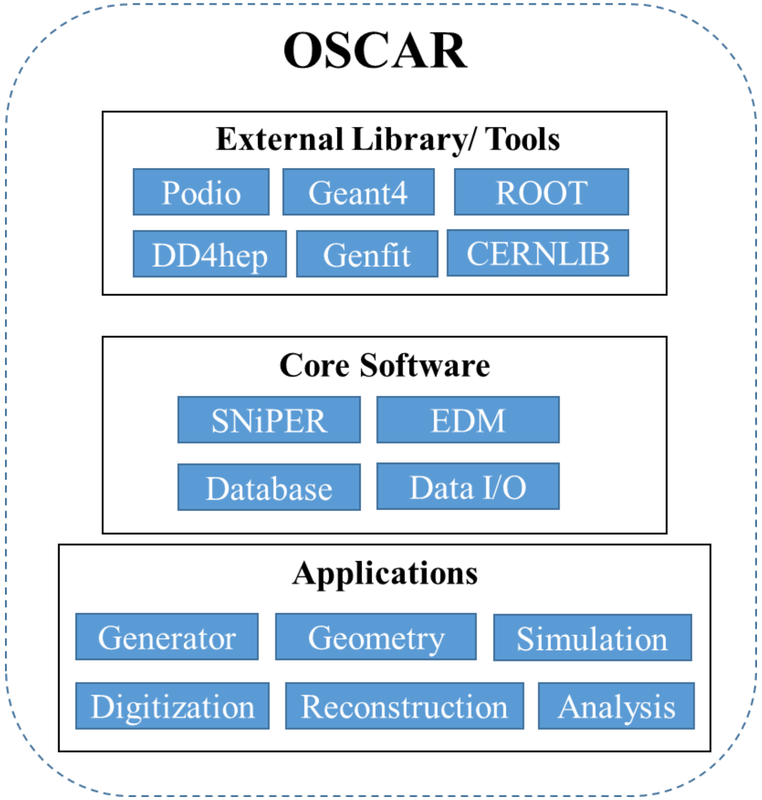
- **Ionization injection from center of pixel**
- Ionization density $80e^{-}/\mu m$
- Thresholds vary across different technologies

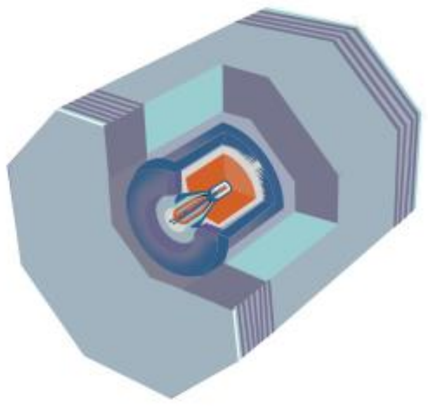
Techno	Collected charge (e)	Collection time(ns)	TOA @ threshold(ns)
TJ180nm	**2039.81**	**20.56**	**0.21**
GSMC130nm	**2477.65**	**89.72**	**0.30**
BCIS90nm	**1153.17**	**1.28**	**0.16**
Modified-TJ180nm	1969.85	1.81	0.20

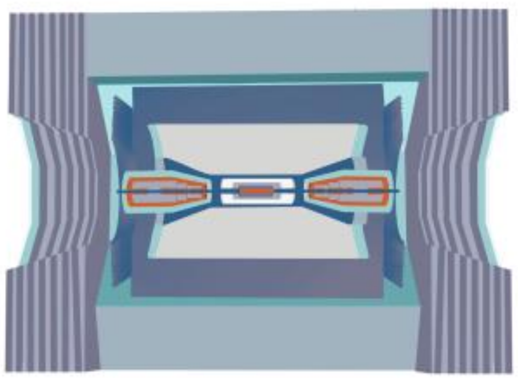


Introduction to OSCAR

- The Offline Software of STCF (**OSCAR**) is designed for detector design, MC data production and physics analysis at STCF
- External libraries & tools
  - Podio, G4, ROOT, DD4hep …
- Core software
  - common platform for the offline software
  - underlying framework: SNiPER
- Applications
  - STCF specific application software

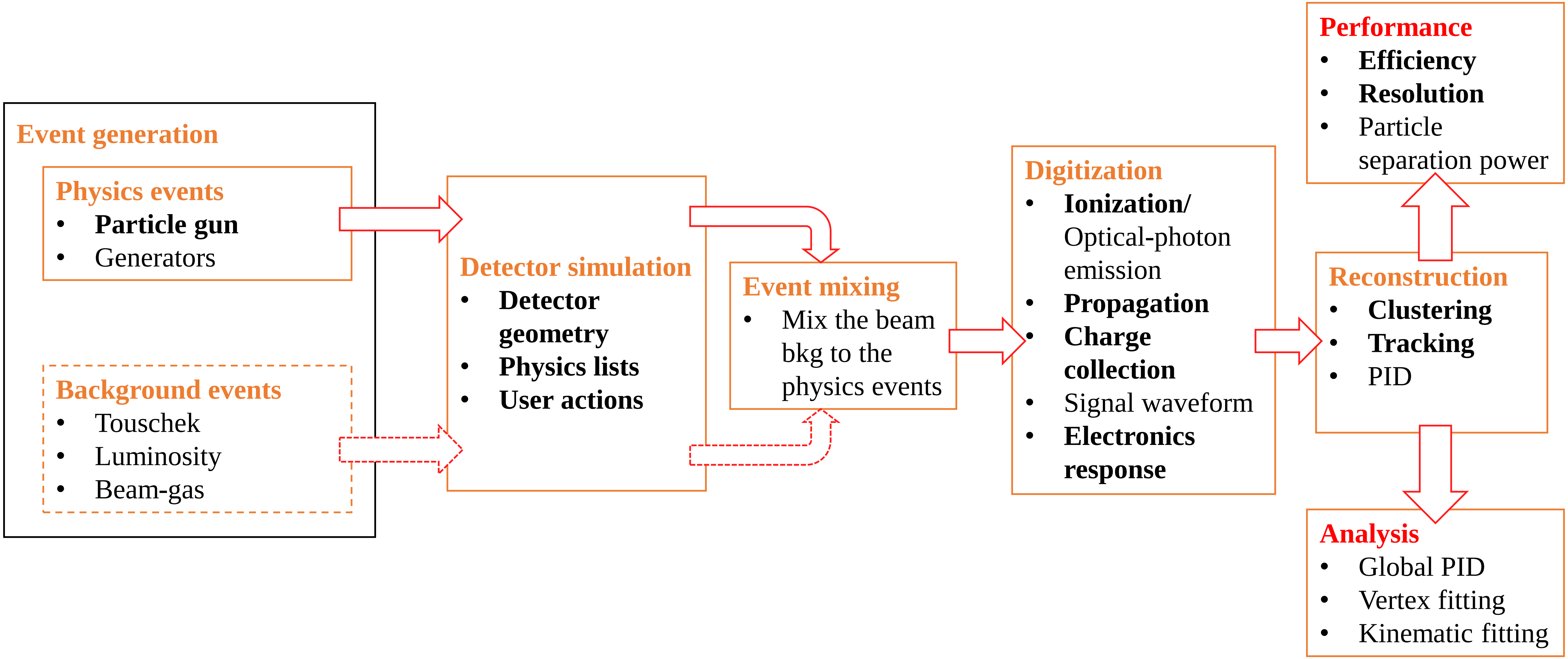






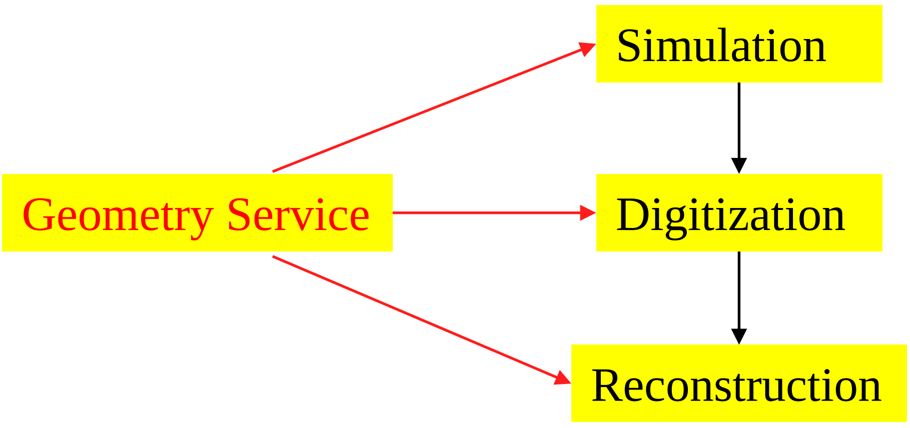
OSCAR is now the common platform for full simulation of all sub-detectors

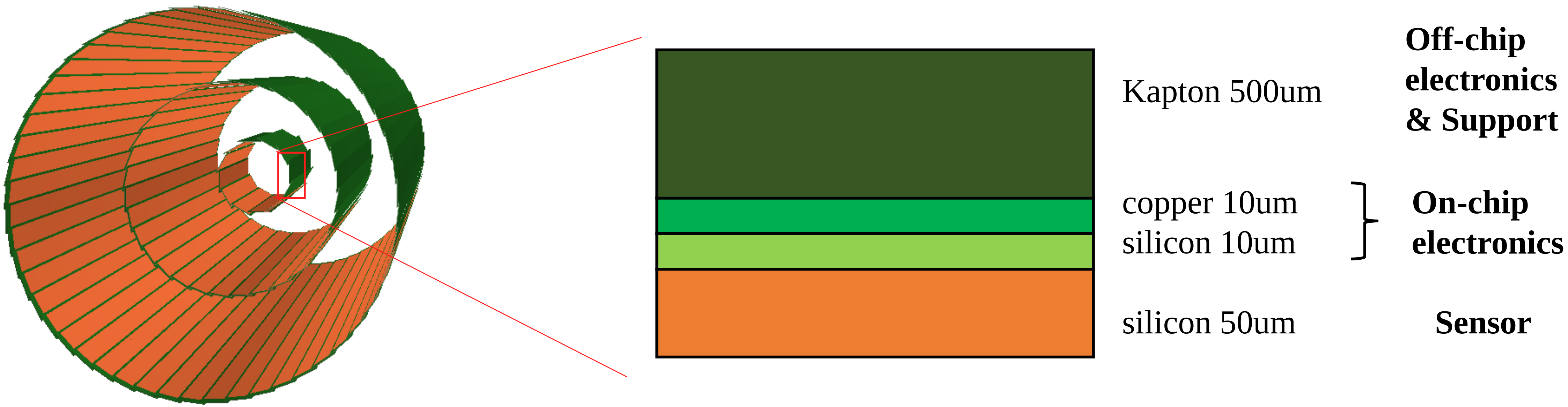
Full simulation process under OSCAR



ITKM geometry

- Geometry constructed by DD4hep
- ➢ Stave width 2.2cm
- ➢ Chip size 2cm × 2cm
- ➢ Pixel geometry: 170μm × 30μm TJ180nm techno
- ➢ Material budget **0.31%** $\boldsymbol{X_0}$ per layer





Simulation and digitization of ITKM

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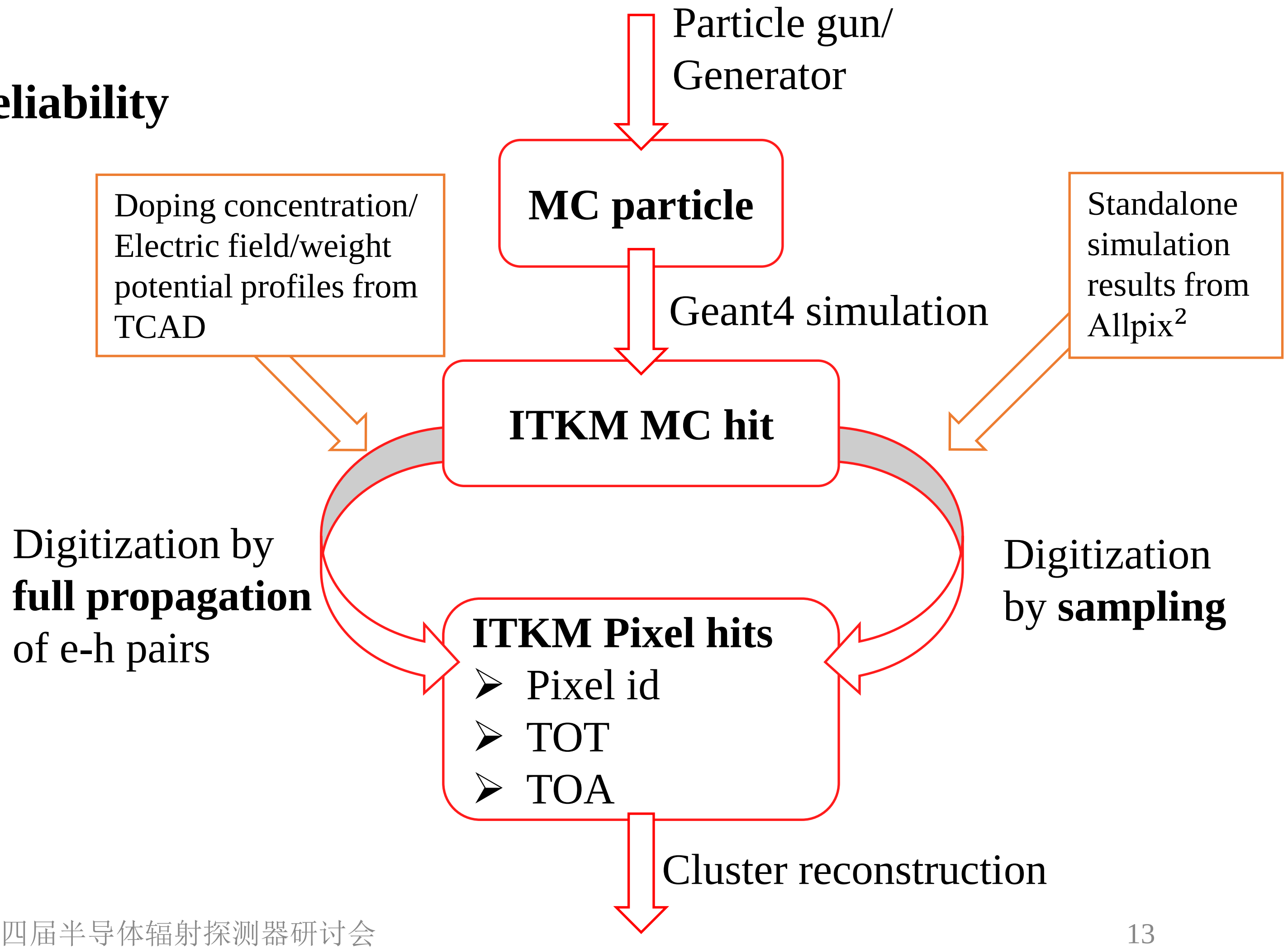
- **Digitization** is the bridge between simulation and reconstruction
- **Its accuracy largely determines the reliability of the full simulation**

Two different digitization methods implemented under OSCAR framework



Simulation settings

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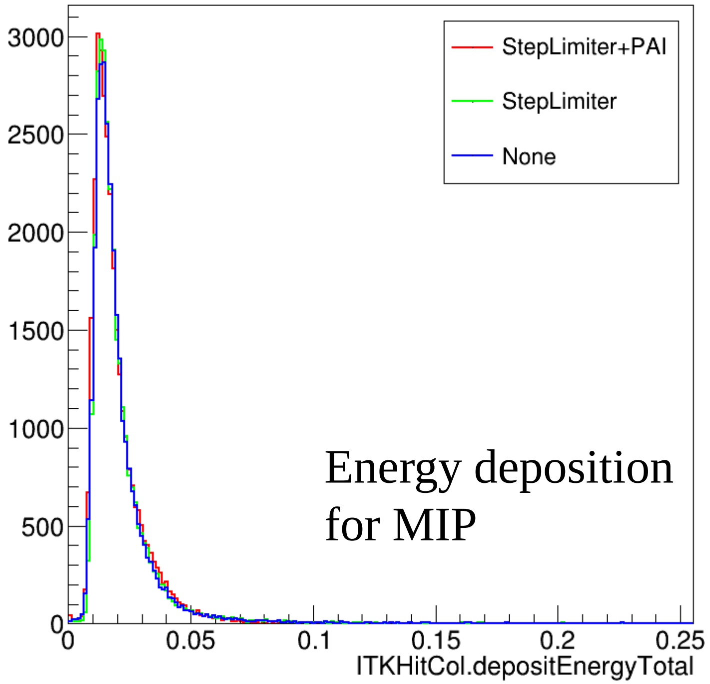
In order to precisely simulate the ionization in 50μm silicon layer:

- Step limit in SV set to 10μm
- Geant4 PAI model registered

All step information in SV is saved for the purpose of digitization



	Average steps per hit	Average secondaries per hit
StepLimiter+PAI	7.11	0.041
StepLimiter	7.14	0.0061
None	1.00	0.0056

- Energy deposition does not vary much with model settings, MPV is about 15keV
- “StepLimiter+PAI” provides more steps as well as more accurate generation of secondaries

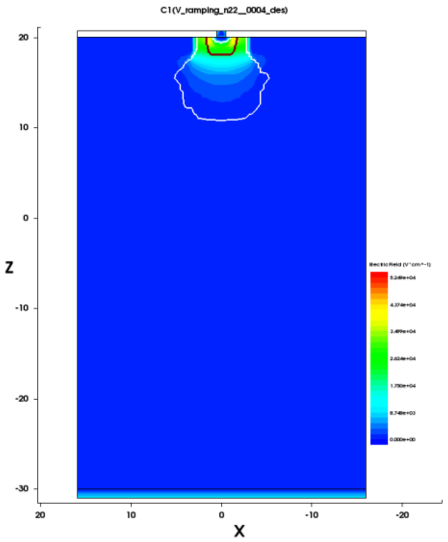
Digitization method 1

- ➢ "Full propagation" method

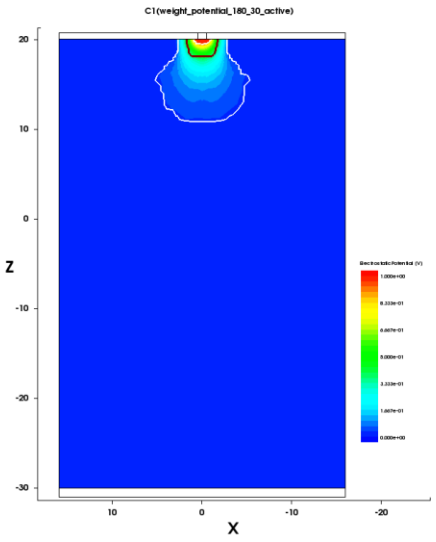
Precisely simulate the signal generation process in MAPS

1. **Generating e-h pairs** according to deposit energy
2. **Simulation of e-h propagation**, including:
   - ➢ Drift
   - ➢ Diffusion
   - ➢ Recombination
   - ➢ Trapping & Detrapping
3. **Inducing charge** on electrode according to Ramo-Shockley theorem

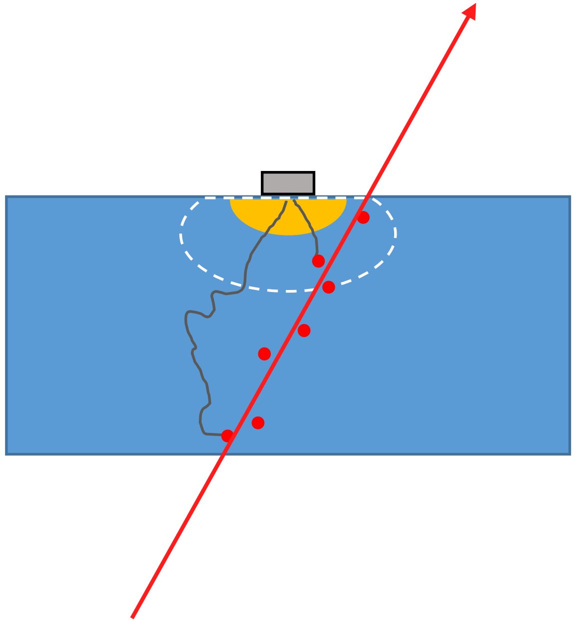
collected charge



electric field



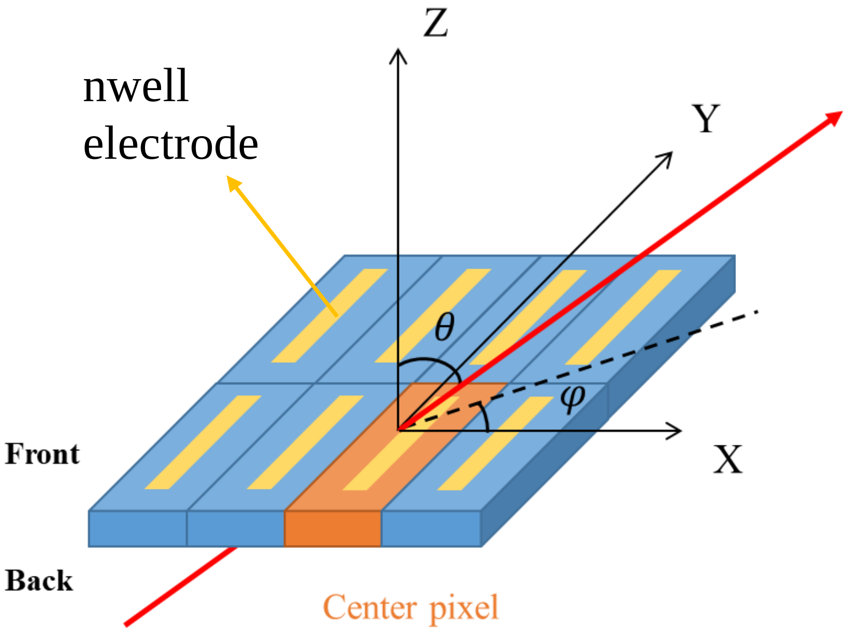
weight potential

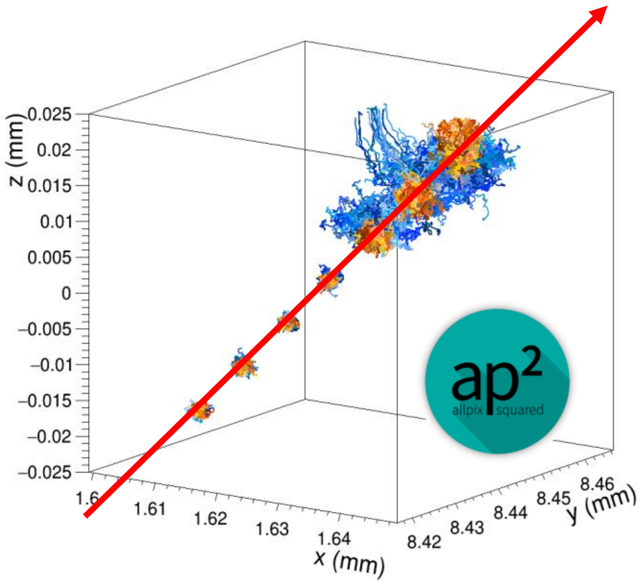


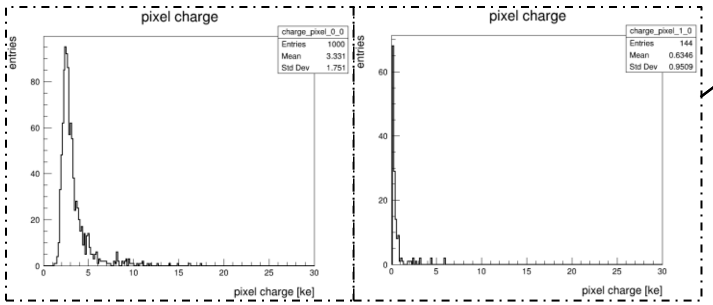
Digitization method 2

- “Sampling” method

Pursue faster processing speed with the help of standalone simulation results







Incidence parameters are separated into a series of bins:

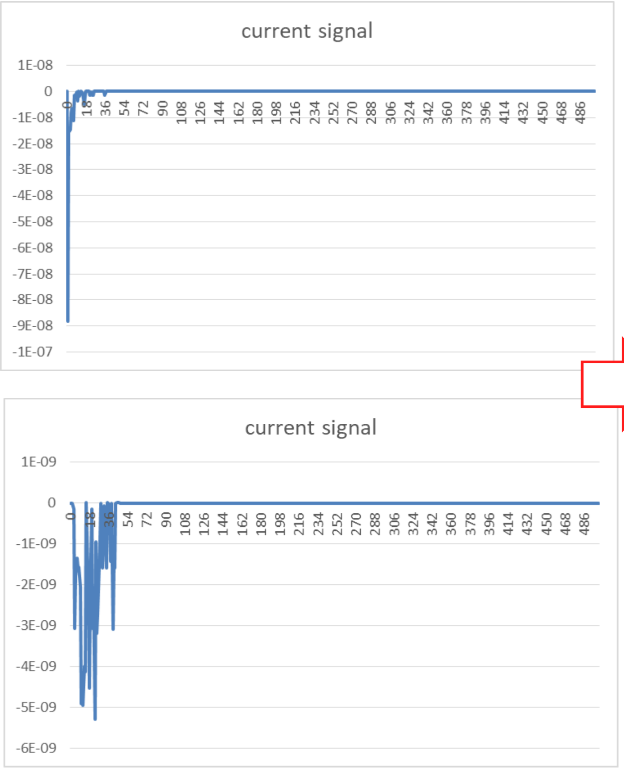
- ***θ*** (5 bins, 0-90°)
- ***φ*** (6 bins, 0-360°)
- **Energy deposit** (5 bins, 0-120keV)
- **Position** (5×5 bins)

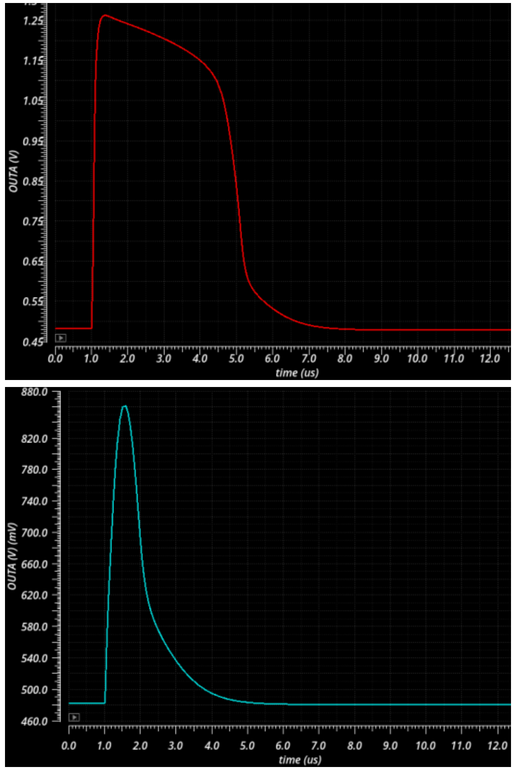
Sampling from **Allpix^2** result datasets

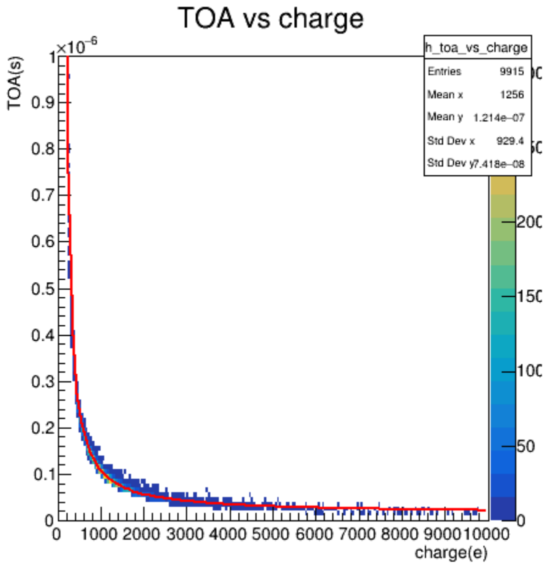
collected charge

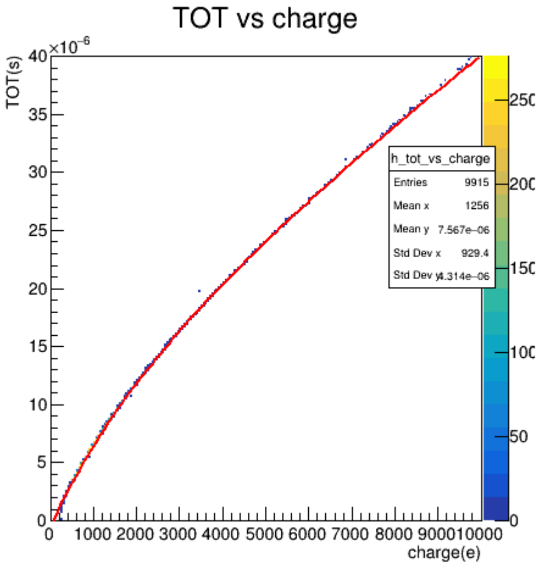
Electronics response

- A series of sensor signals from randomly incident particles are fed to electronics simulation
- Voltage signals after analog front end are obtained
- TOA and TOT information is recorded



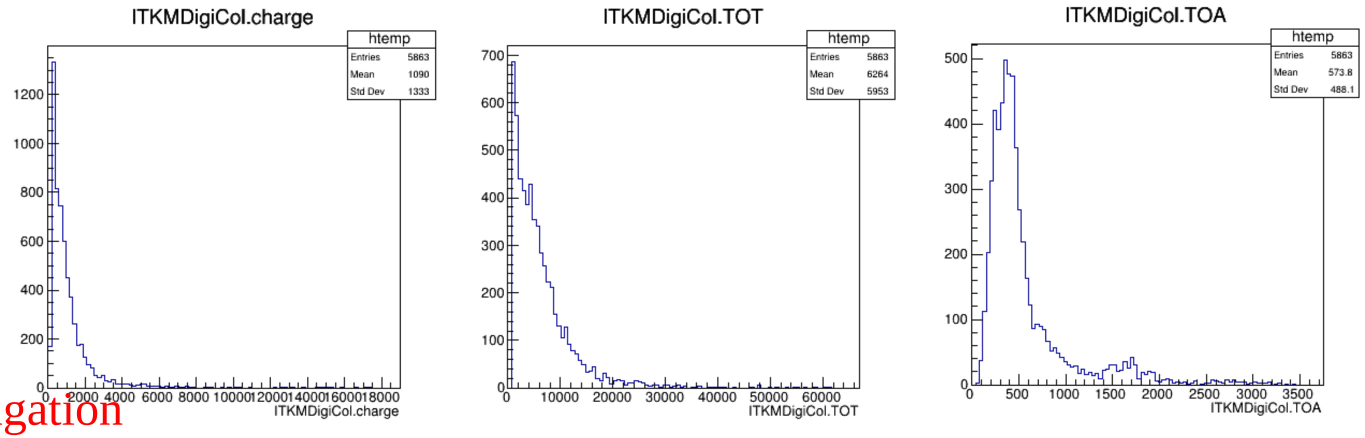




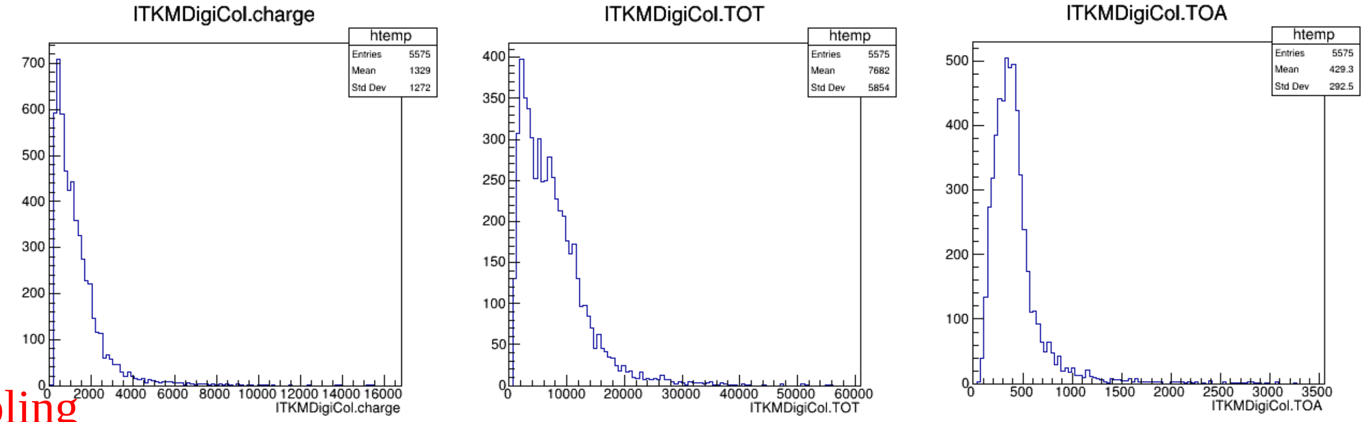


- ➢ Relationship between TOA/TOT and collected charge obtained
- ➢ Given a charge value, the TOA/TOT is calculated with a Gaussian smearing

Digitization performance



Full propagation



Sampling

Method	Full propagation	Sampling
Memory usage	1.1G	Negligible
Time cost	48ms/hit	0.5ms/hit
Average collected charge per pixel	$1080e^{-}$	$1329e^{-}$
Average cluster size after reconstruction	1.835	1.755

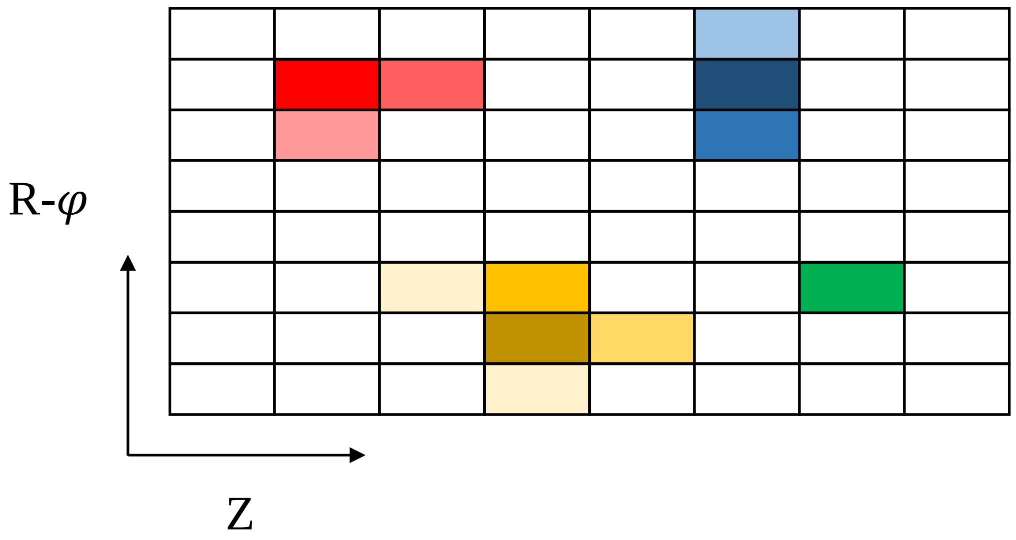
More accurate for small signals

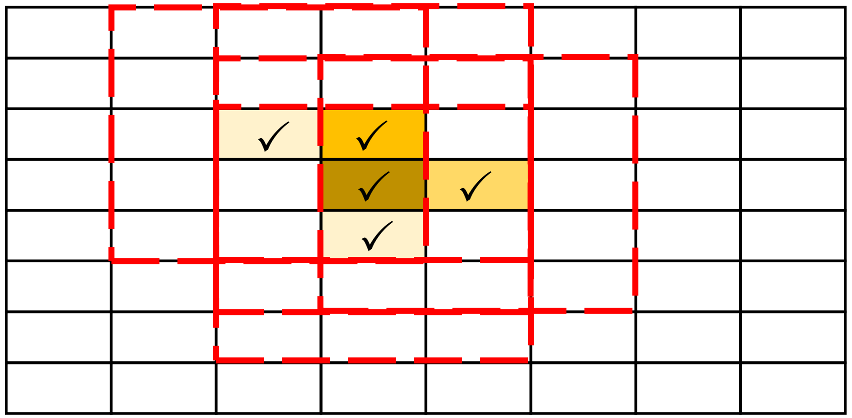
Faster, less memory usage

Optimization for both methods is in progress

Cluster reconstruction

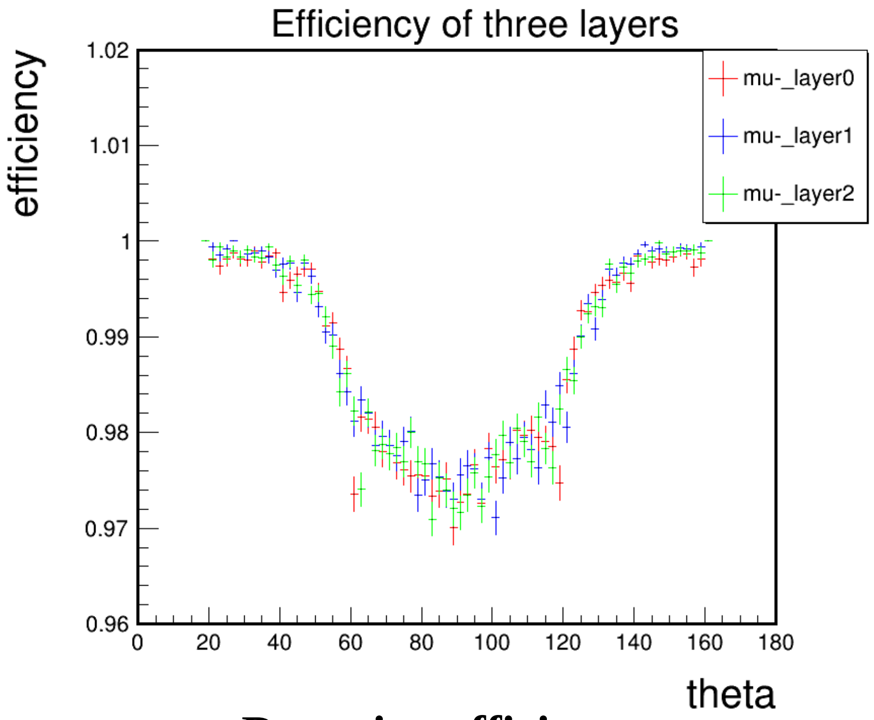
- **Cluster finding**: hit pixels inside 3*5(z*rphi) range classified as one cluster
- **Cluster position reconstruction**: charge centering (TOT converted to charge)



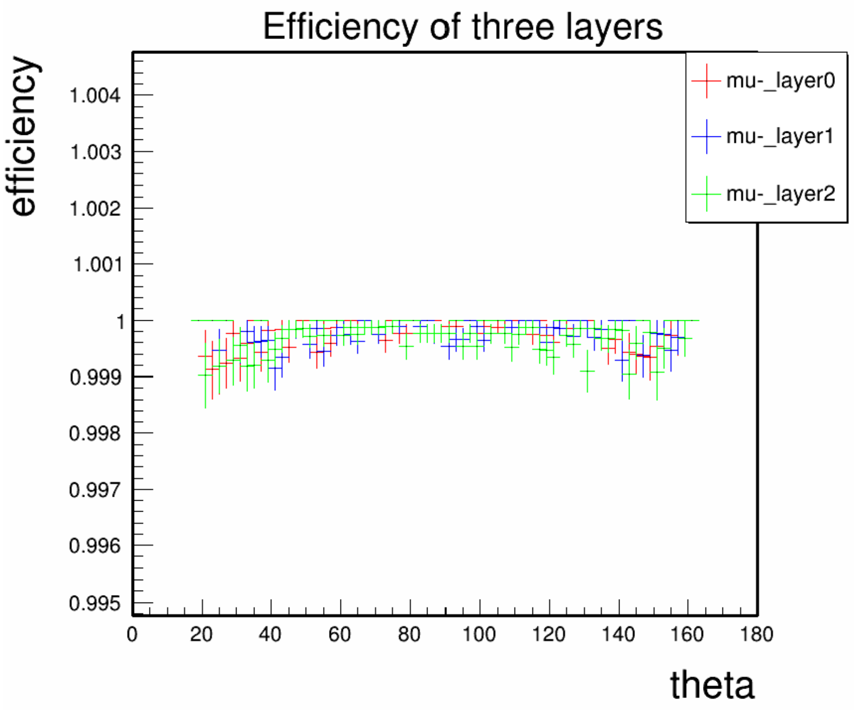


Efficiency

- Simulation settings:
  - ➢ 1GeV/c muon, θ range 20°-160°
  - ➢ Pixel threshold: 300e



Detection efficiency vs. polar angle



Clustering efficiency vs. polar angle

- Average detection efficiency 98.5%
- Average clustering efficiency >99.9%

Position resolution

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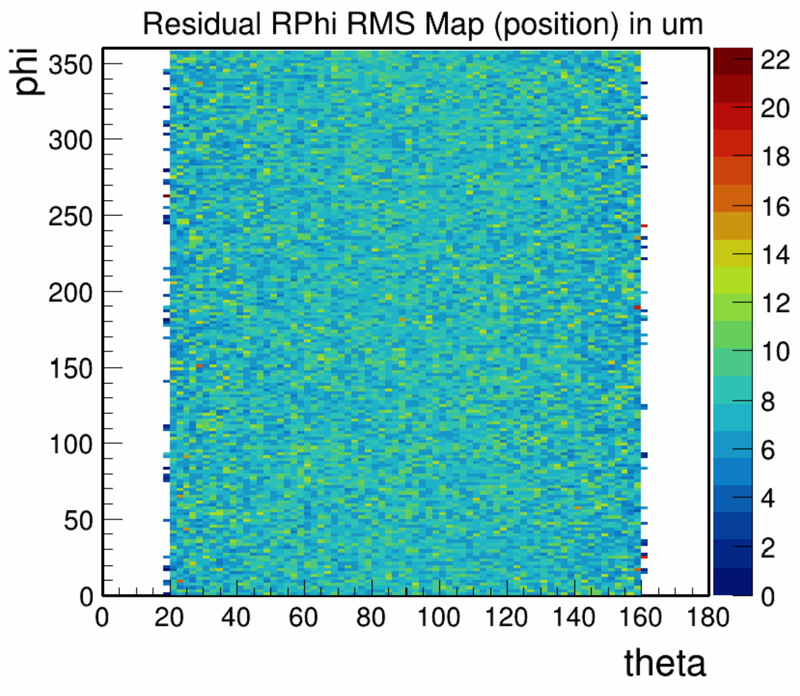
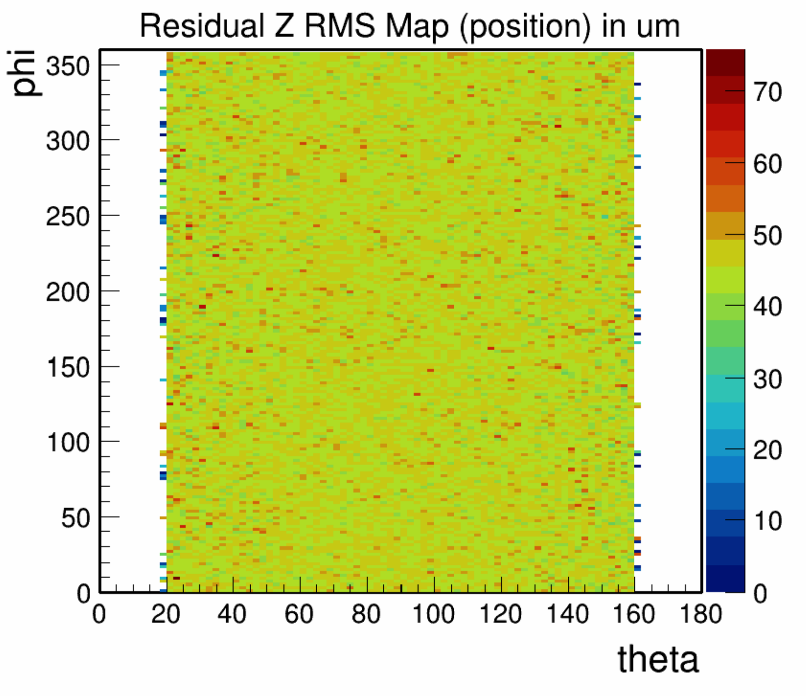
- Simulation settings:
  - ➢ 1GeV/c muon, θ range 20°-160°
  - ➢ Pixel threshold: 300e



Residual RMS (rphi)



Residual RMS (z)

- $\sigma_z = 37.4\mu m$
- $\sigma_{rphi} = 6.4\mu m$

✓ No correlation between pixel position and position resolution

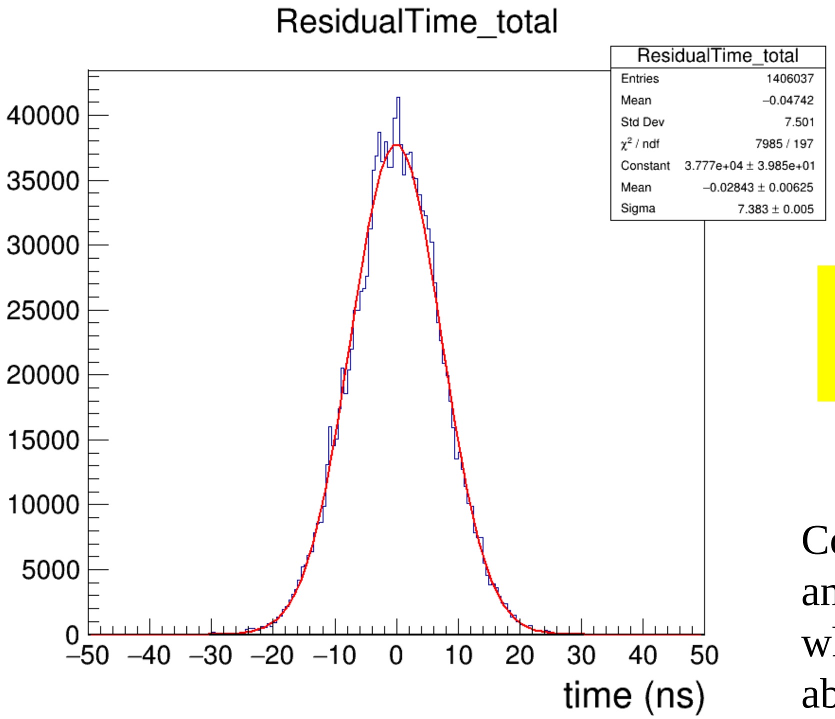
✓ The resolution is better than (pixel pitch)/$\sqrt{12}$ due to the charge information

Timing performance

- Simulation settings:
  - 1GeV/c muon, θ range 20°-160°
  - Pixel threshold: 300e

Method

- Pixel with **largest** charge (TOT) is chosen as "seed"
- Seed pixel's TOA **calibrated by TA-relationship** gives the time stamp of this cluster
- Compared with the MC hit time to get residual



Time resolution ~7.4ns

Contributions from noise and TDC not included, which are simulated to be about **30ns**

Summary

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- MAPS-based inner tracker for STCF is under R&D in USTC, aiming at :
  - $\sigma_{r\varphi} < 100\mu m$
  - material budget 0.3% X_0 per layer
- TCAD simulation conducted for 4 different technologies:
  - TJ180nm standard, BCIS90nm, GSMC130nm, TJ180nm modified
- ITKM full simulation chain is accomplished under OSCAR framework
  - Two different digitization methods implemented and their performance well studied
  - Cluster reconstruction of 1GeV/c muons shows good performance of ITKM:
    - ✓ Average detection efficiency 98.5%
    - ✓ Position resolution: $\sigma_z = 37.4\mu m$, $\sigma_{rphi} = 6.4\mu m$
    - ✓ Time resolution (sensor only) 7.4ns

In the future:

- Track reconstruction study
- MAPS sensor structure optimization
- ITKM geometry optimization

Thanks!

Backup

Features at Tau-Charm energy region

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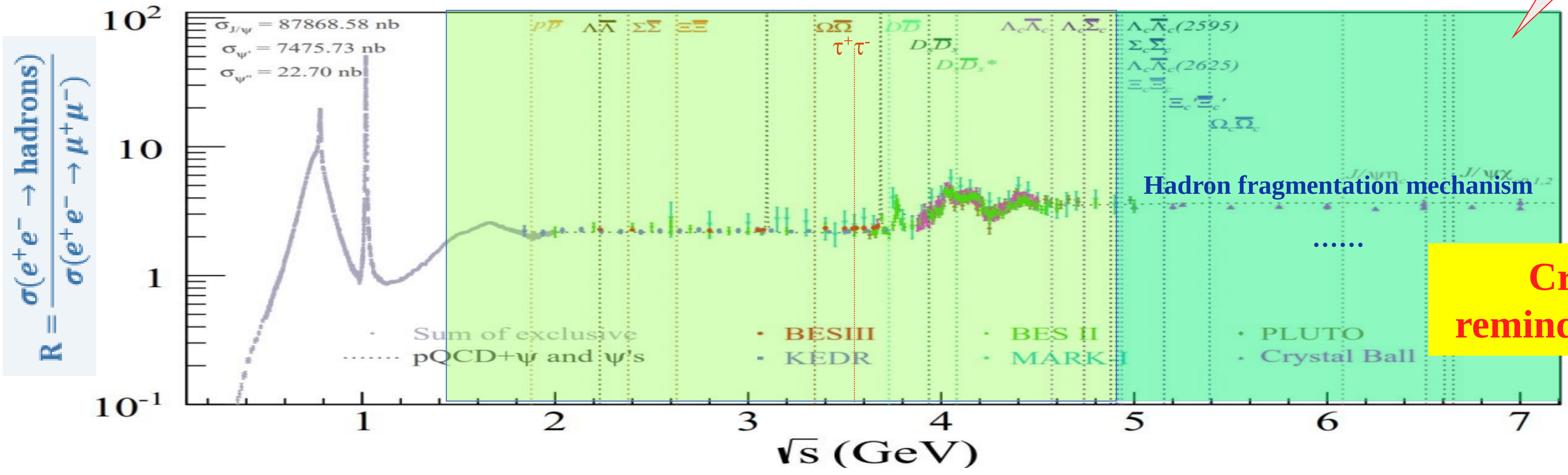
- Tau-Charm energy region (2-5GeV):
  - Transition region between perturbative and non-perturbative QCD
  - Rich of resonances structures
  - Threshold of pair production of hadrons and tau leptons
  - Mass location where exotic hadrons, gluonic matter and hybrid exist
- **Rich physics programs in the tau-charm region to be explored**

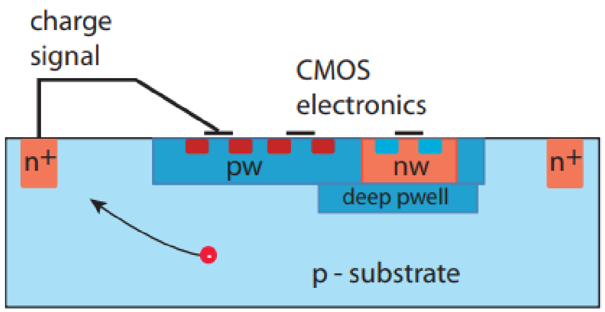
No e^+e^- Collider
Opportunity for future TCF

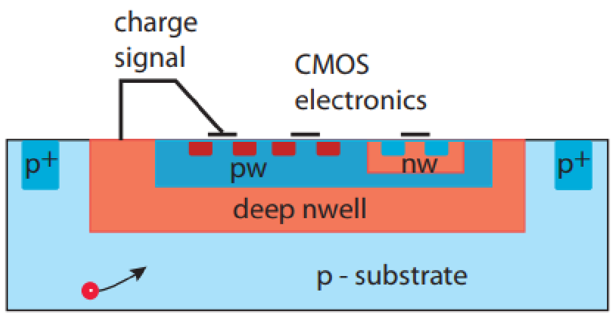


Crucial to meet the reminding challenges of SM

Considerations for STCF MAPS

HR-MAPS or **HV-MAPS**?





Low material budget

- Power consumption < 100 mW/cm^2
- Thin silicon layer ~ 50 μm

High hit rate

- Fast readout

Moderate timing of ~50ns

- Fast charge collection
- Record TOA & TOT information

Moderate position resolution requirements

- Enlarge pixel size if necessary (especially in z direction)

Other considerations

- Technology availability
- Cost-effective

HR-MAPS with pixel size **170μm × 30μm** chosen as the baseline design

Comparison of TCAD and Allpix^2 signals

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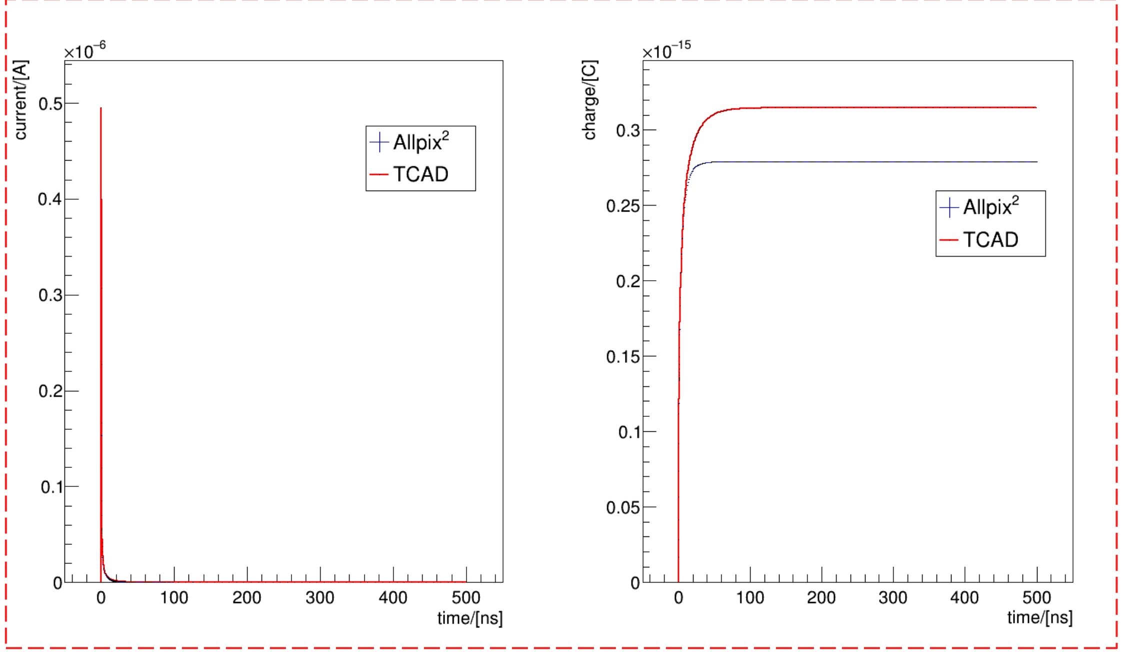
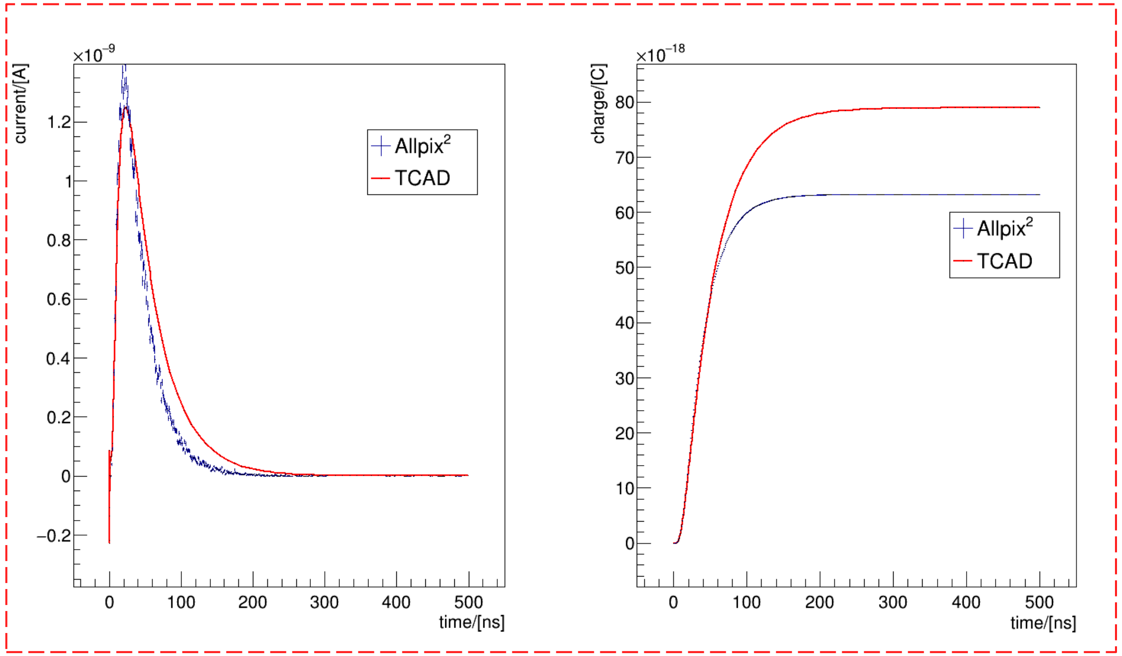
- TJ180nm techno, nwell size $2\mu m$, spacing $2\mu m$
- nwell 0.8V, substrate -6V
- Ionization density $80e^{-}/\mu m$

```
[DepositionPointCharge]
source_type = "mip"
model = "spot"
spot_size = 0.0354um
# position = 1596um 8441.75um
position = 1611.96um 8526.1675um
# position = 0 0
number_of_steps = 100
number_of_charges = 80/um
```

Settings in Allpix^2



Injection from pixel center



Injection from pixel corner

Details of digitization

- Three digitization options available:
  - 0: sampling
  - 1: Full sim based on Allpix^2, only electron propagation considered (default for now)
  - 2: Full sim based on Allpix^2, both electron & hole propagation considered

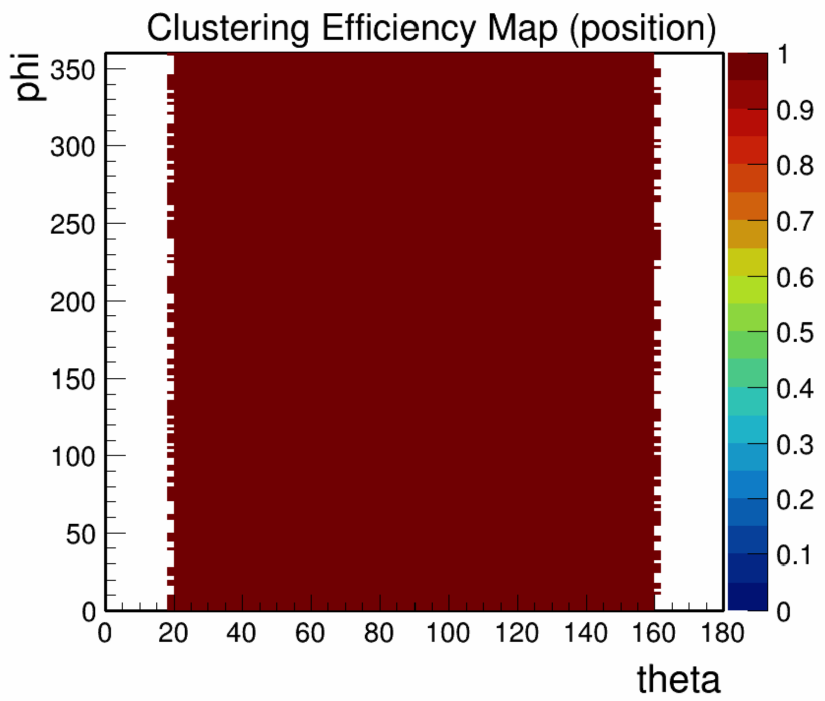
More accurate
but
Slower

- Optional physics models for different physics process

```
# set physics models for full digitization
# modility model: jacoboni/canali/canali_fast/hamburg/hamburg_highfield/masetti/masetti_canali(default)/arora/ruch_kino/quay/levinshtein/constant
ITKMDigi.property("mobility_model").set("masetti_canali")
# recombination model: srh/auger/srh_auger(default)/constant/none
ITKMDigi.property("recombination_model").set("srh_auger")
# multiplication model: massey/massey_optimized/overstraeten/overstraeten_optimized/okuto/okuto_optimized/bologna/none(default)
ITKMDigi.property("multiplication_model").set("none")
# trapping model: ljubljana/kramberger/dortmund/krasel/cmstracker/mandic/constant/none(default)
ITKMDigi.property("trapping_model").set("none")
# detrapping model: constant/none(default)
ITKMDigi.property("detrapping_model").set("none")
```

Clustering efficiency

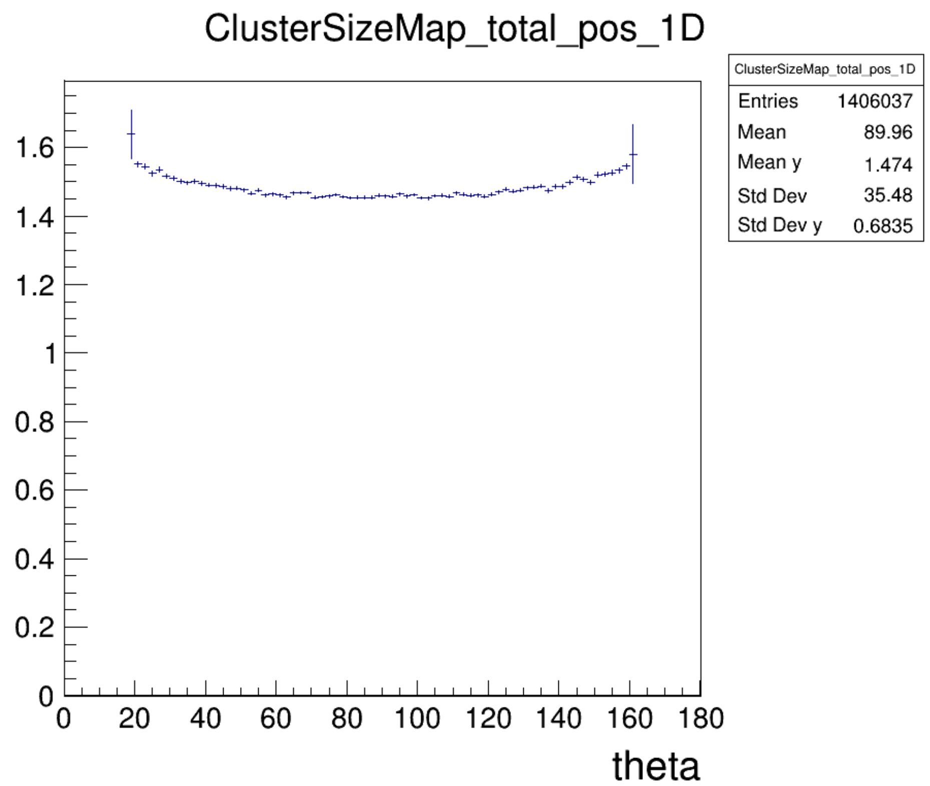
- Simulation settings:
  - 1GeV/c muon, θ range 20°-160°
  - Pixel threshold: 300e



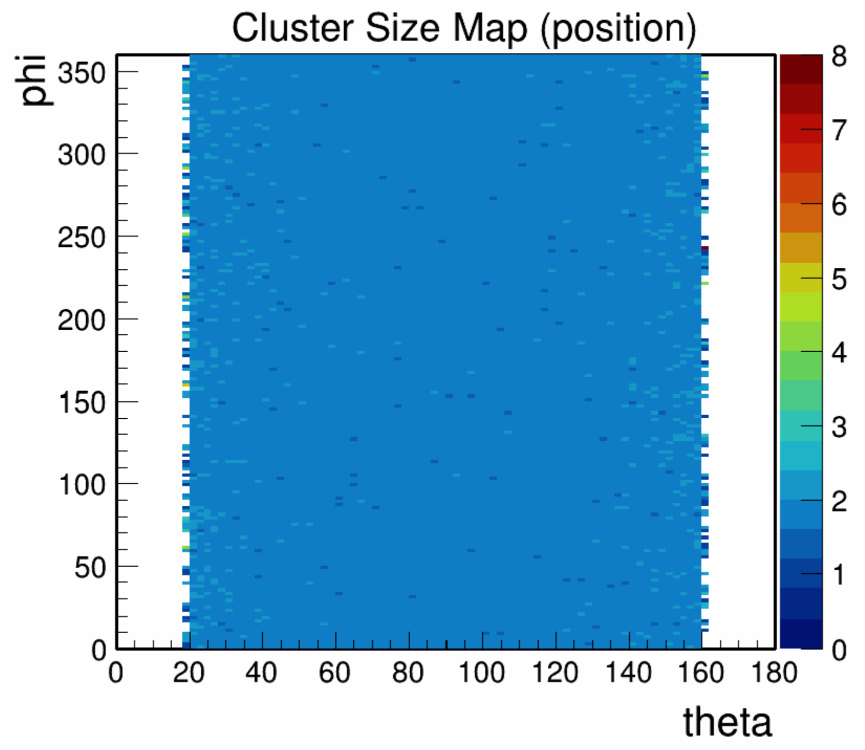
Average Efficiency vs.
polar & azimuthal angle

Cluster size

- Simulation settings:
  - 1GeV/c muon, θ range 20°-160°
  - Pixel threshold: 300e



Cluster size vs. polar angle

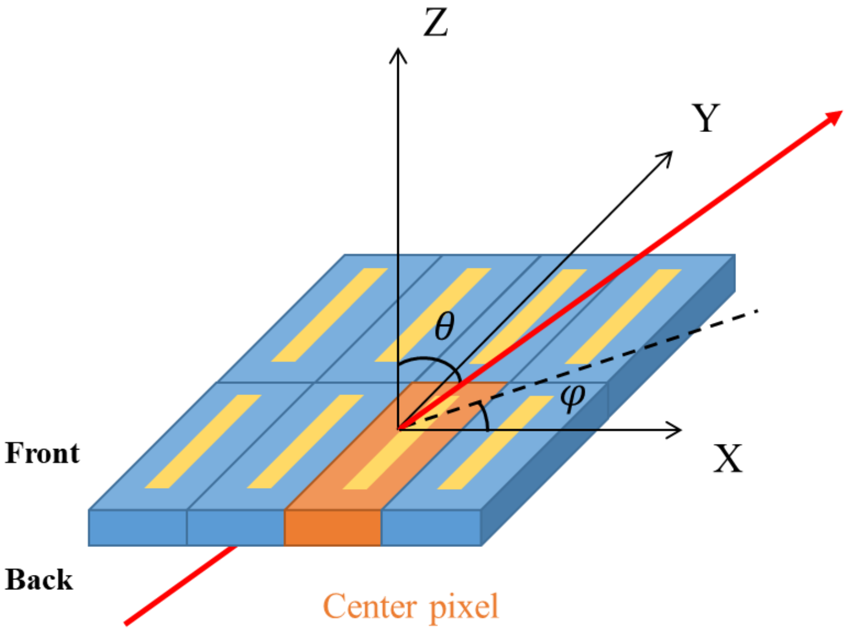


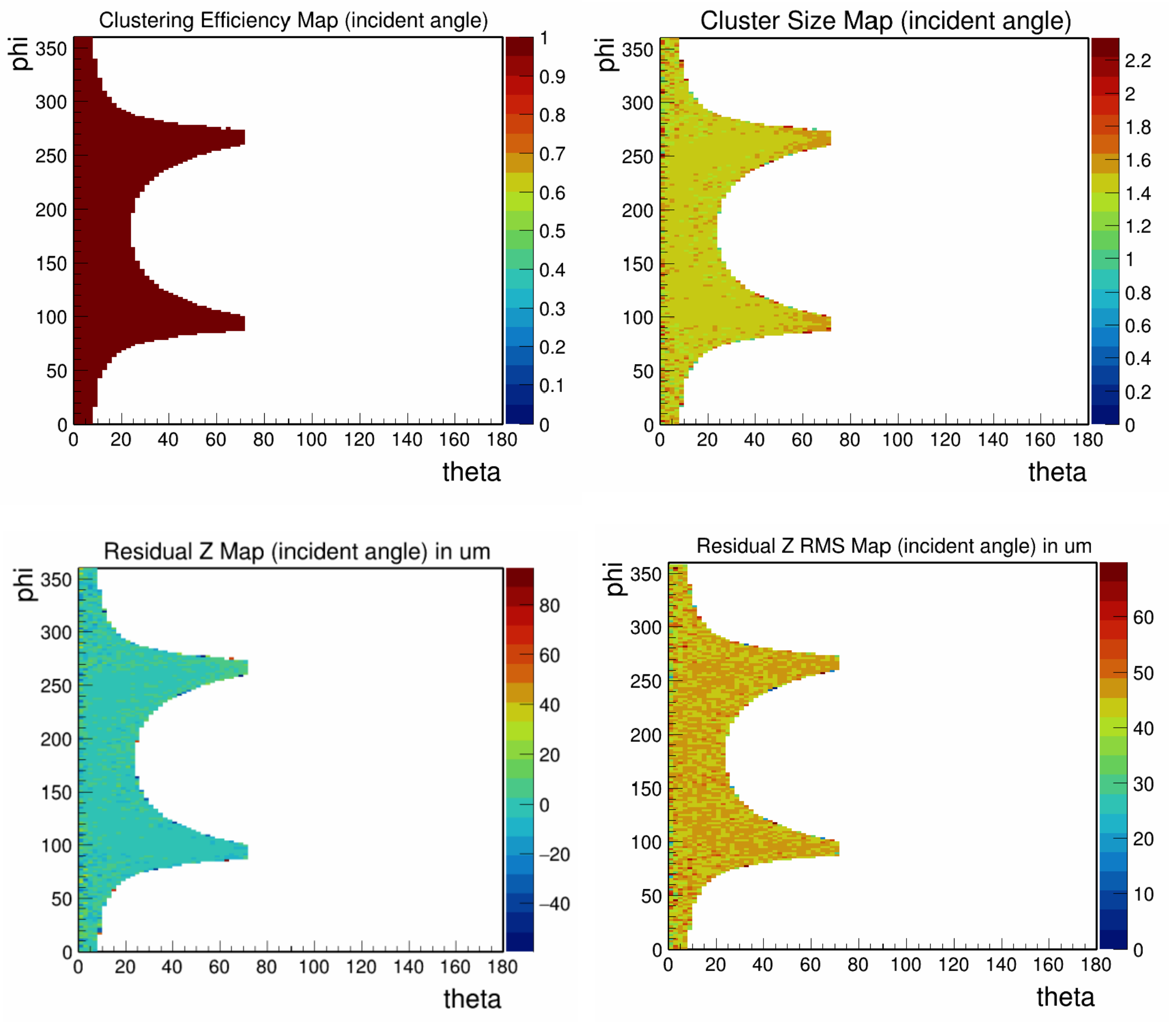
Cluster size vs. polar & azimuthal angle

Average cluster size 1.47

Clustering performance in local coordinate

- Simulation settings:
  - 1GeV/c muon, θ range 20°-160°
  - Pixel threshold: 300e





ITKM background estimation

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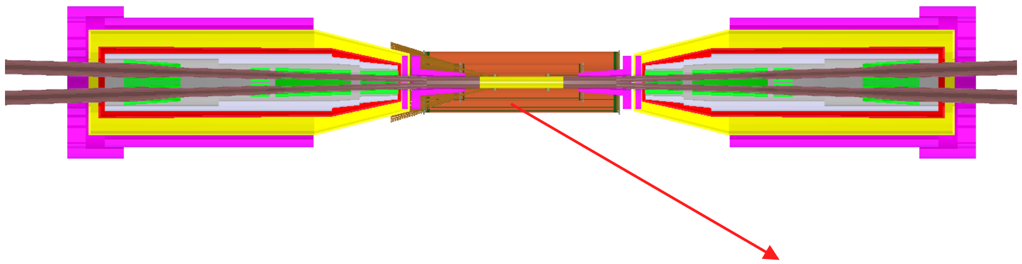
University of Science and Technology of China

- Background simulation carried out under OSCAR framework
- Three types backgrounds combined: **Touschek (main background), Luminosity, Beam-gas**
- Latest bkg generators and MDI design
- **Simulation + Digitization** to get the background hit rate in terms of fired pixels



	Total hit rate / Hz	Arevage hit rate per unit area / (kHz/cm^2)	Maximum hit rate per unit area / (kHz/cm^2)
ITKM1	2.4E+08	411.7779	440.78
ITKM2	47691165	12.25144	14.66
ITKM3	47566214	4.699801	5.47

Preliminary results on track reconstruction

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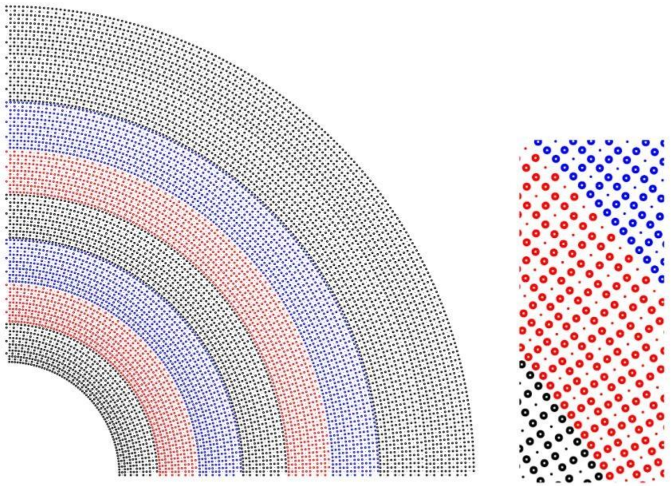
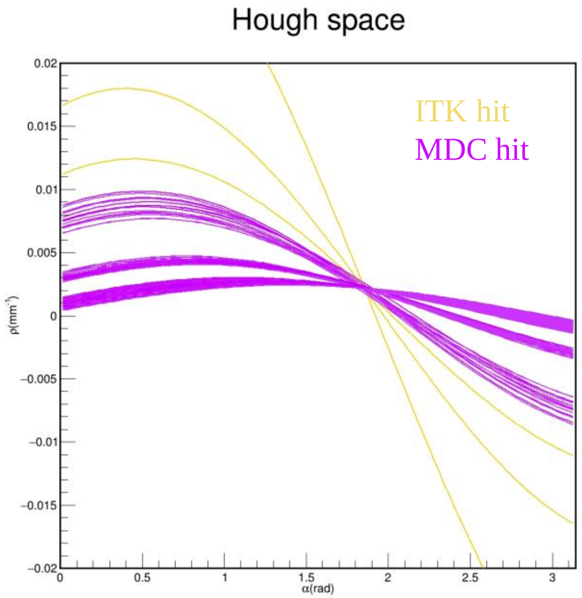
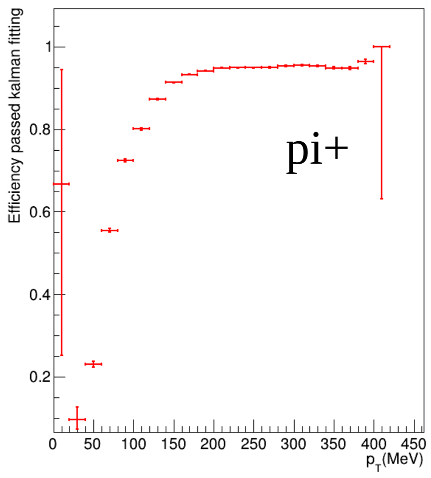
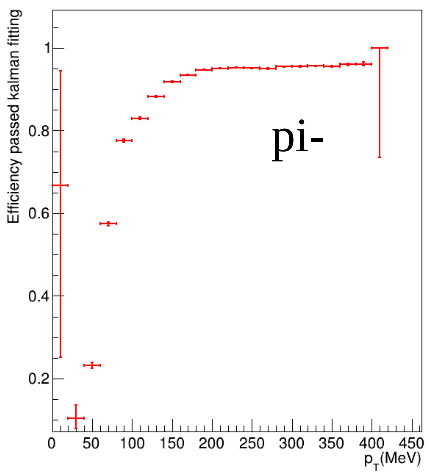
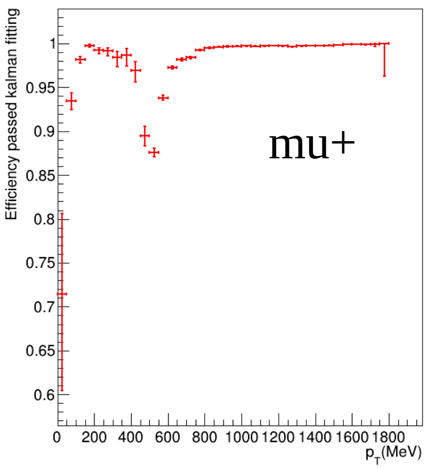
- ITKM and MDC(Drift Chamber) together form the tracking system of STCF
- Basic idea of track finding: conformal transform + Hough transform
- Track fitting uses generic track-fitting toolkit Genfit2

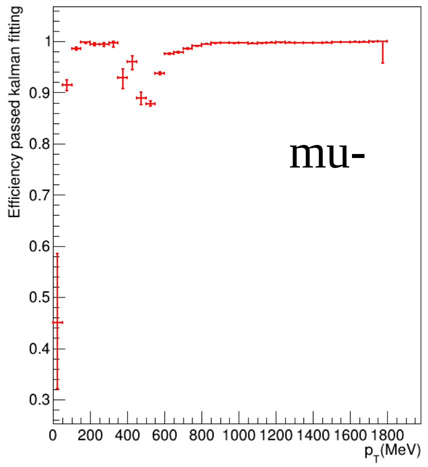












Tracking efficiency for $\psi(3686) \rightarrow \pi^+ \pi^- J/\psi(\mu^+ \mu^-)$