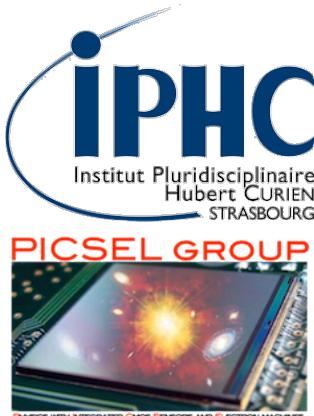


Applications and development of CMOS pixel sensors within the PICSEL group of IPHC

J. Baudot
baudot@in2p3.fr

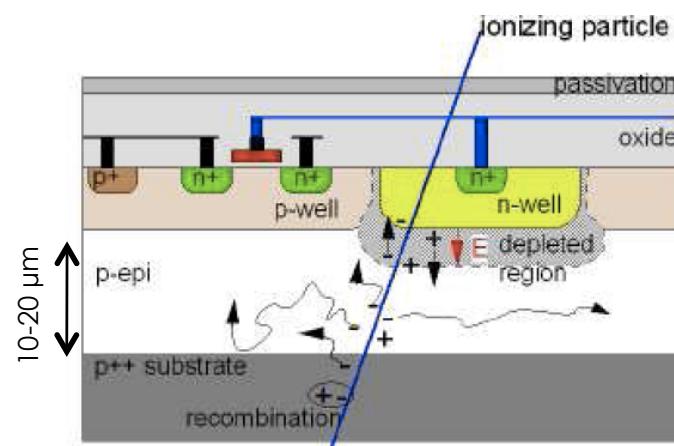
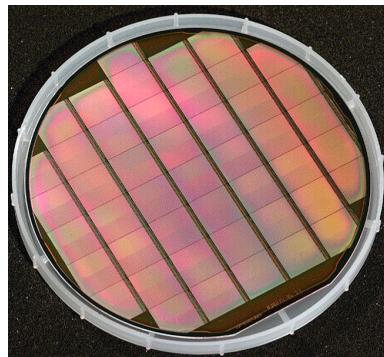
Séminaire “Prospectives”
IPHC, 9 janvier 2015



- Introduction on CPS for vtx det.
- Achievements at IPHC-PICSEL
- Ongoing & foreseen developments
- Applications outside HEP

General web site: iphc.cnrs.fr/PICSEL

CMOS Pixel Sensor: the basic



Useful thickness: 30 μm

- Industrial technology
 - Integrated circuits (chips)
 - Lithography feature size $\ll 1\mu\text{m}$
 - Reticule limits $\approx 25 \times 30 \text{ mm}^2$
- Main features
 - Small pixel size $\leq 50 \mu\text{m}$
 - Signal processing on chip
 - In-pixel amplification \rightarrow SNR: “active”
 - No additional FEE readout: “monolithic”
 - Sensitive layer
 - Thin \rightarrow small signal (MIP 80 e-h/ μm)
 - Low resistivity ($< 100 \text{ }\mu\text{m}$) not fully depleted \rightarrow thermal diffusion of charges
 - Operation at room temperature
- Invention of CMOS sensors for light
 - Early works late 60's
 - 1993 paper by E.Fossum

CPS mainstream

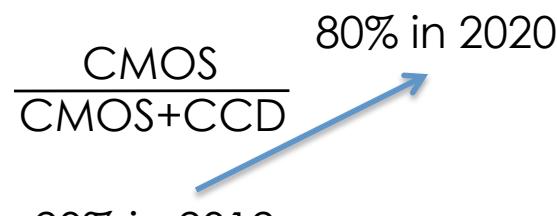


- Main markets

- Customers
(camera, smartphone, ...)
- Industry
- Medical imaging
- Automotive

Pixel size 1-2 µm
Frame rate ~ video
Integration camera (~~single quanta~~)

- CCD vs CMOS



- Sales expectation for 2015:
~700 000 CMOS camera
- Main reason: **cost**

- Tower-Jazz

- Ex: Medical application sensor
 - Few 1000 wafers / year

- SONY

- On a single fabrication site
- Ex: Backside illuminated sensor
 - “stacked” camera
 - (sensor + readout)
 - 60000 wafers / month

→ Main markets = technology drivers

CPS as a pixel detector



■ Full detection chain

sens. layer → q-collect → ampli → analog treat → A-D conv → digital proc

sensor: +FEE

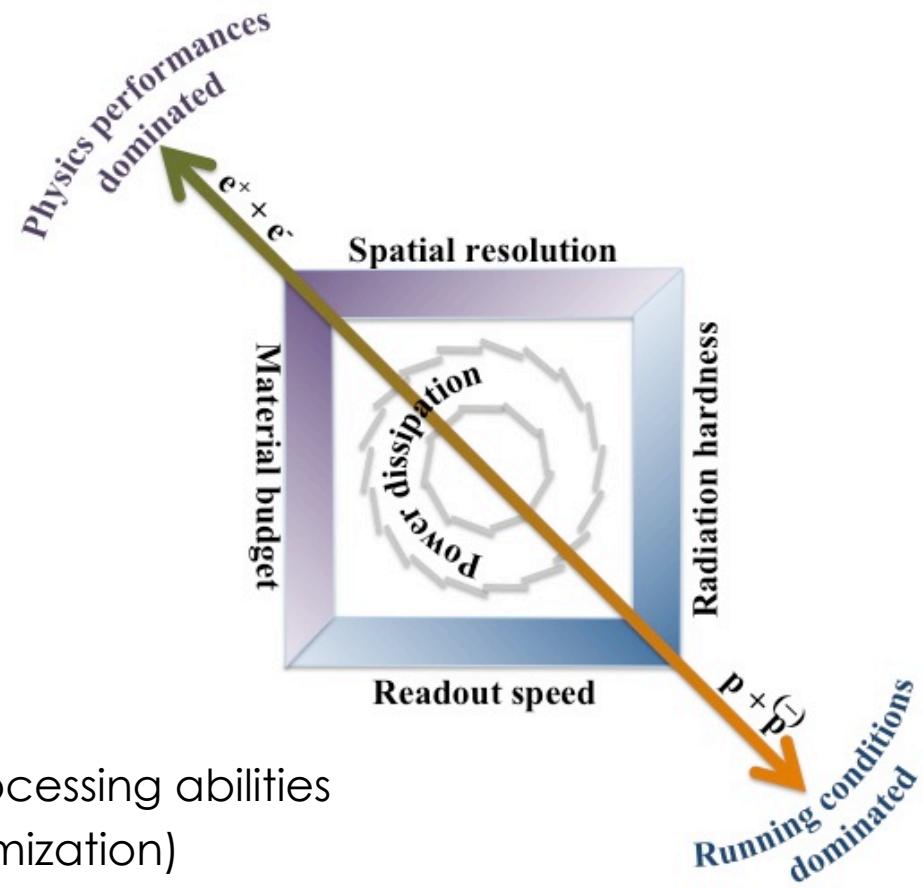
CPS:

■ Figures of merit

- Performances **vs** Conditions

■ Limitations of CPS

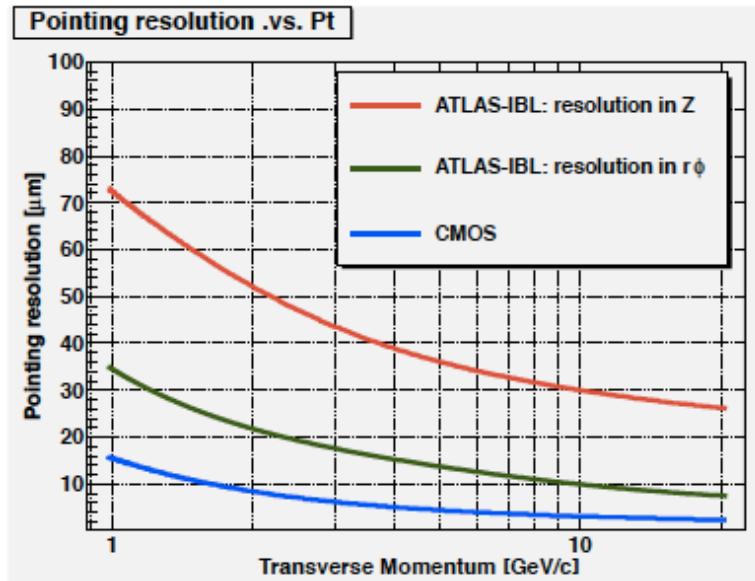
- Same technology for all purposes
- No PMOS transistors in pixel with std techno
- High granularity limits physically processing abilities
- 1 sensor = 1 system (no further optimization)



Benefits for vertexing / tracking

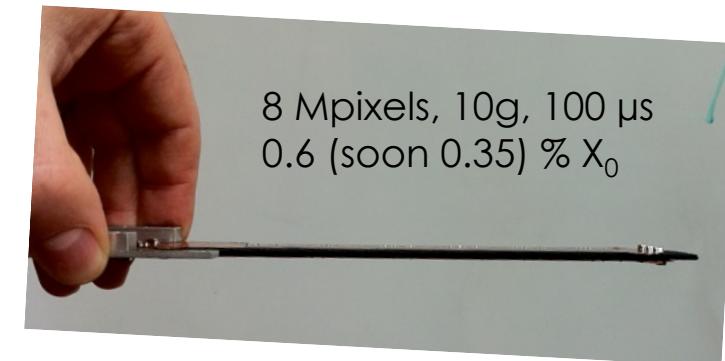
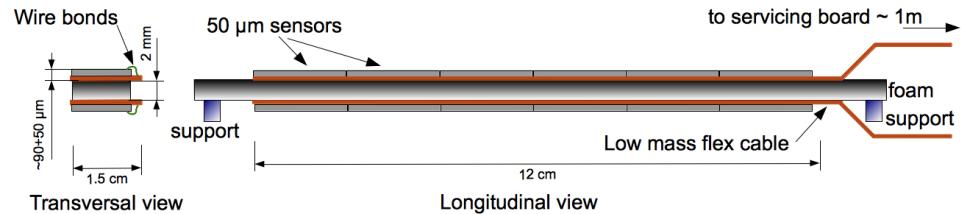


■ As single layer



■ As n-tuplet layers

- Doublets = PLUME project
 - Double-sided layer



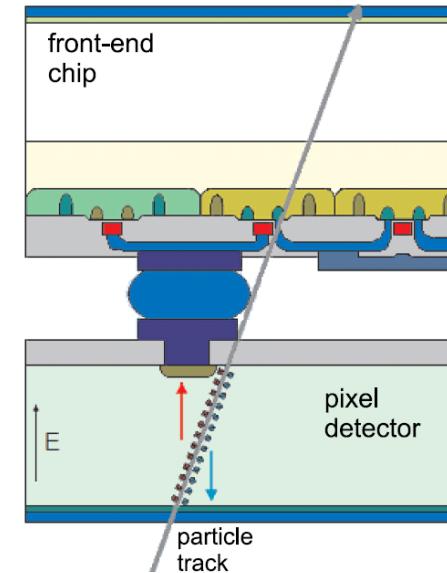
- Triplets
 - Track (helix) seed
 - Idea from Mu3e

Other pixel technologies



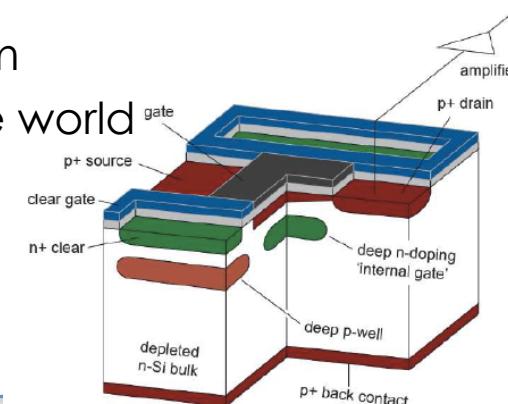
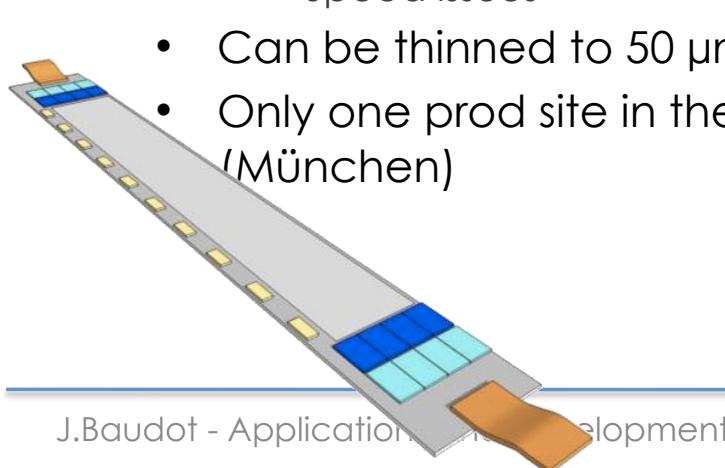
■ CCD

- (very-)Small & thin pixels possible
- Internal read-out BUT
 - slow & requires Front-End Elec.
- $T_{op} \sim -40^\circ\text{C}$
otherwise rad. tolerance issue



■ DEPFET

- Small pixels possible
- Fully depleted sens. layer
- Internal amplification BUT
 - External read-out (3 ≠ chips)
 - Speed issues
- Can be thinned to 50 μm
- Only one prod site in the world
(München)



■ Hybrid pixel

- Small pixel not possible
- Fully depleted sens. layer
- FEE on top of sensor
 - Increased mat. Budget
 - BUT powerful processing

What is read-out speed ?



- Which is the good figure of merit?
 - Time to read one frame
 - Time of arrival of the hit
 - Duration of signal integration
 - Number of hits registered / unit of time
- Triggered exp. with high event rate
 - Compulsory
 - Precision on arrival time
 - Short integration \ll trigger rate
 - “standard” strategy
 - Fast signal **shaping**
 - Ex: strips, hybrid-pixels @ LHC
- Triggered exp. with low event rate or un-triggered exp.
 - Main specification
 - # hits registered / u.time
 - **Integration strategy**
 - Correlated double sampling (CDS)
 - Ex: ILC, heavy-ion coll.
- Note:
 - Mixing two strategies on different detection layers: possible
 - Ex: Belle-II

IPHC-PICSEL CPS activities



■ Motivation for CPS

- Matches main specifications for ILC
 - High spatial resolution ($\approx 3 \mu\text{m}$)
 - Low material budget ($\lesssim 0.2 \% X_0/\text{layer}$)
- LHC-type pixels has opposite optimization: $10-15 \mu\text{m}$, budget $\lesssim 1 \% X_0$

■ 1998-1999: start of pioneering work

- Single particle detection with
 - High efficiency (SNR)
 - Single point resolution at few μm level
- Question 1 : which CMOS technology ?
- Question 2 : which read-out architecture ?

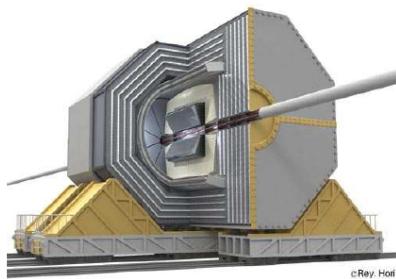
PICSEL strategy



EUDET 2006/2010
Beam Telescope



ILC >2025
International Linear Collider



EUDET (R&D for ILC, EU project)

STAR (Heavy Ion physics)

CBM (Heavy Ion physics)

ILC (Particle physics)

HadronPhysics2 (generic R&D, EU project)

AIDA (generic R&D, EU project)

FIRST (Hadron therapy)

ALICE/LHC (Heavy Ion physics)

EIC (Hadronic physics)

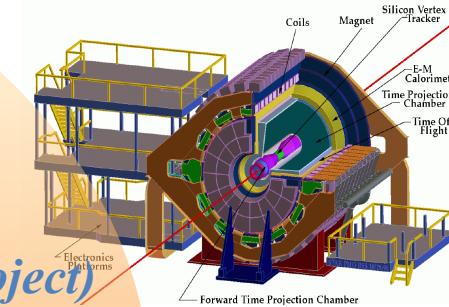
CLIC (Particle physics)

Belle II (Particle physics)

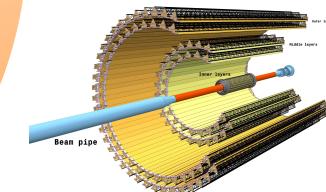
...

→ **Spinoff:** Interdisciplinary applications, biomedical, space ...

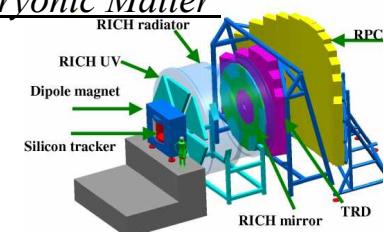
STAR 2014
Solenoid Tracker At RHIC



ALICE 2018
A Large Ion Collider Experiment at LHC



CBM >2018
Compressed Baryonic Matter



PICSEL CPS architecture



■ Driving ideas

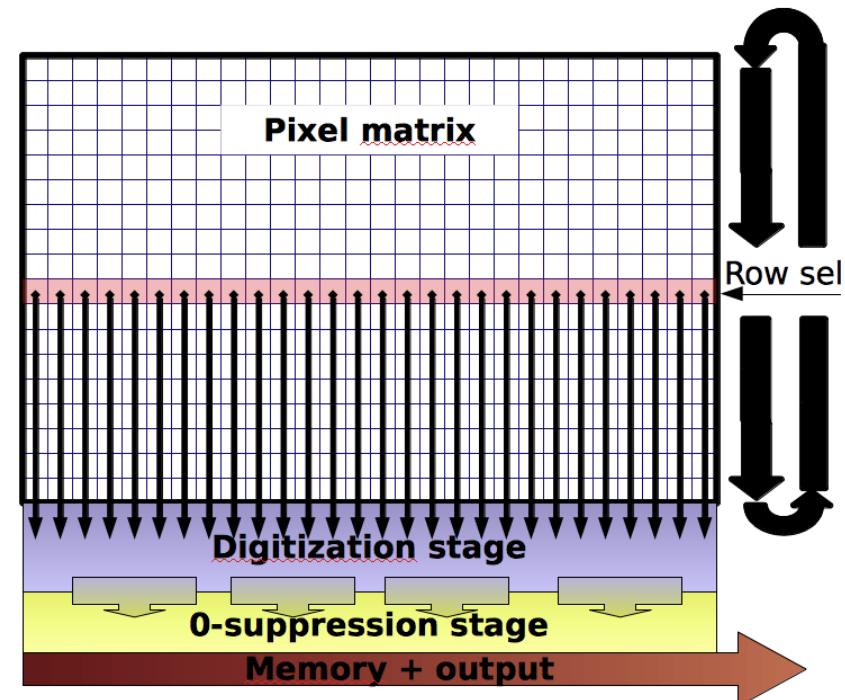
- Read-out acceleration ← limit data output + read-out parallelisation
 - Discrimination & zero suppression
- Power dissipation mitigation ← limit #pixels read simultaneously
 - Rolling-shutter

■ Key elements

- In-pixel CDS → discri possible
- Column // read-out
BUT one row at a time
- Synchronous digitization
 - discriminator (1bit)
- Synchronous zero-suppression
 - address pixels per group

■ Distinct features

- Read-out time = integration time
- Insensitive area aside the pixel matrix
- Counting rate ← size and speed zero-supp. stage



State-of-the-art CPS



MIMOSA 26 2006

1152x576 ~ 0.7 Mpixels
pitch 18.4x18.4 μm^2

- Sensitive area 10.6x21.2 mm²
- Total area 13.7x21.5 mm²
- Readout time 112 μs

- Technology: AMS 0.35 μm
- Sensitive layer: 400 $\Omega\cdot\text{cm}$



2008-2011

MIMOSA 28

960x928 ~ 0.9 Mpixels
pitch 20.7x20.7 μm^2

- Sensitive area 19.7x19.2 mm²
- Total area 20.2x22.7 mm²
- readout time 200 μs
- Power diss ~ 150 mW/cm²

- EUDET Telescope

- Dozen of versions throughout world

- Hadrontherapy

- FIRST @ GSI
- Ion vertex imaging

- STAR-PXL

- 1st CPS-based vertex detector

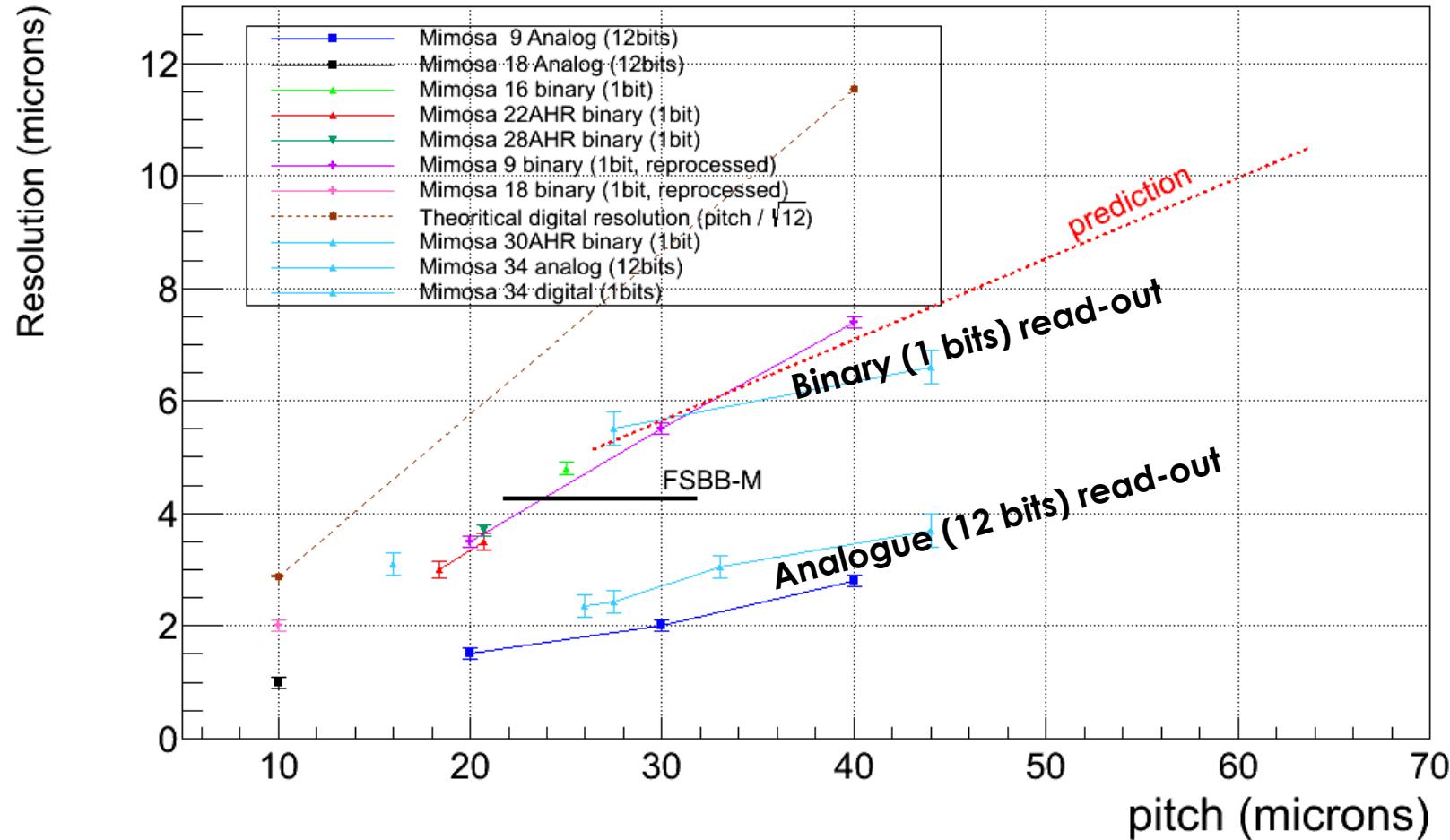
- AIDA Large area telescope

→ Counting rate: > 10⁶ hits/cm²/s

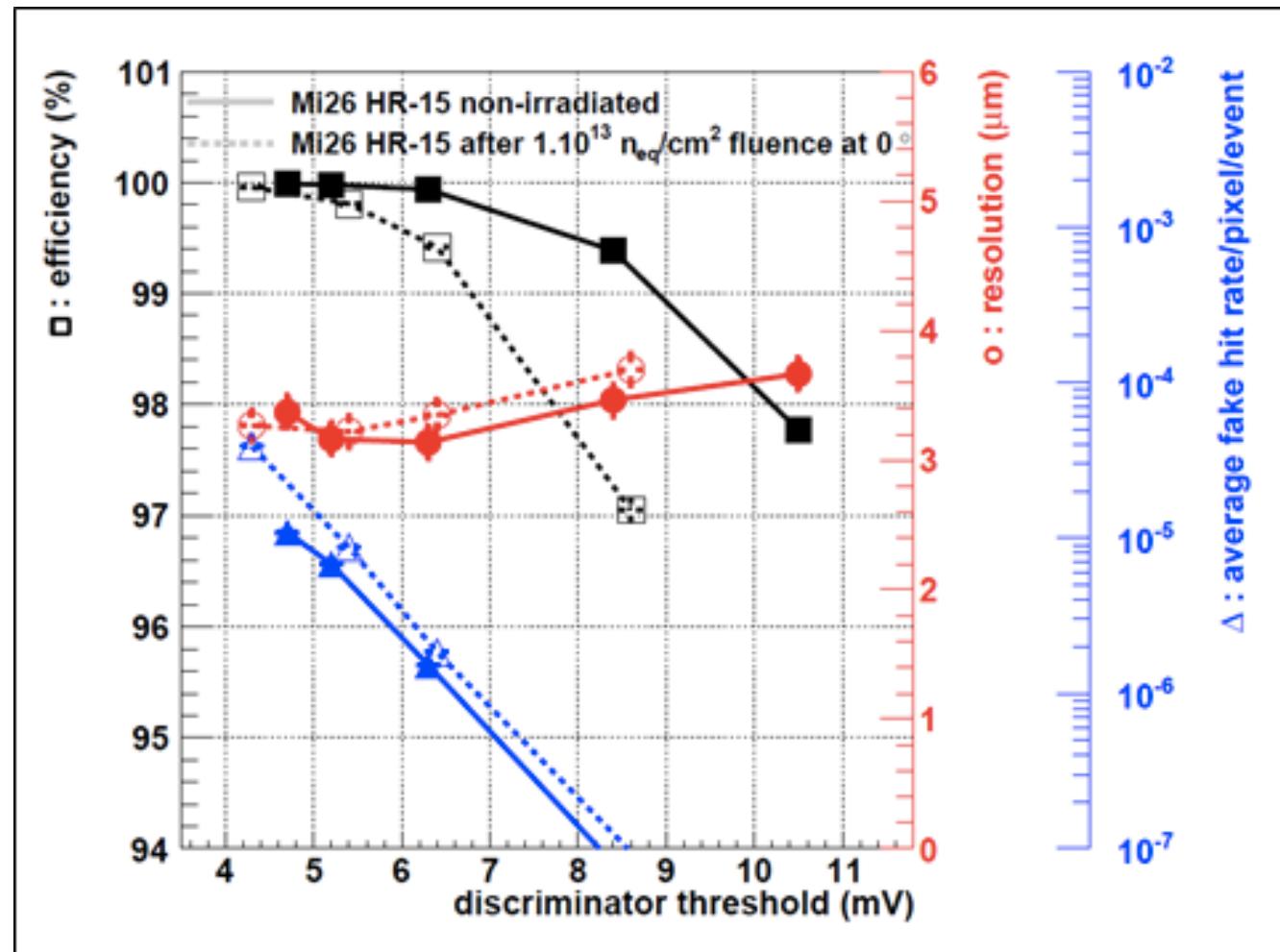
Spatial resolution performances



Mimosa resolution vs pitch



Detection efficiency

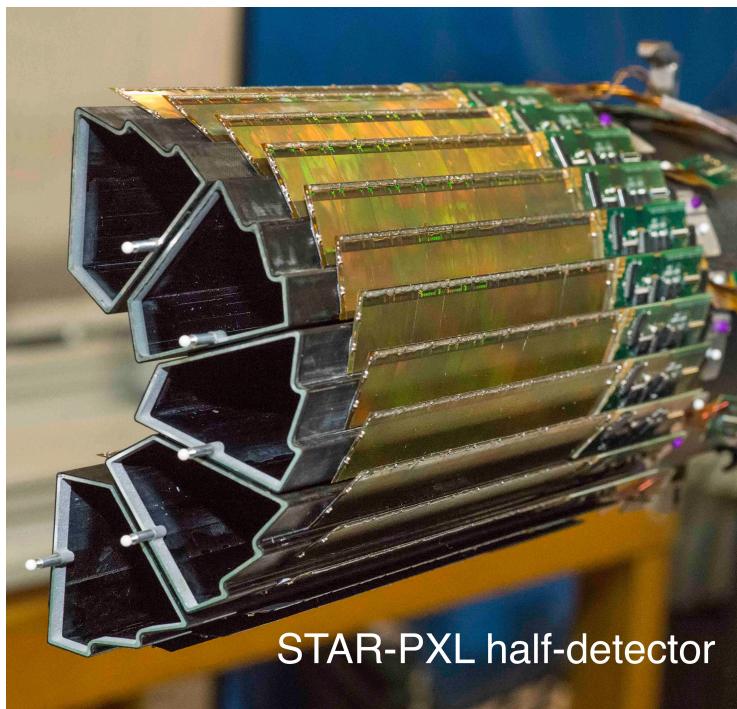


STAR-PXL achievements

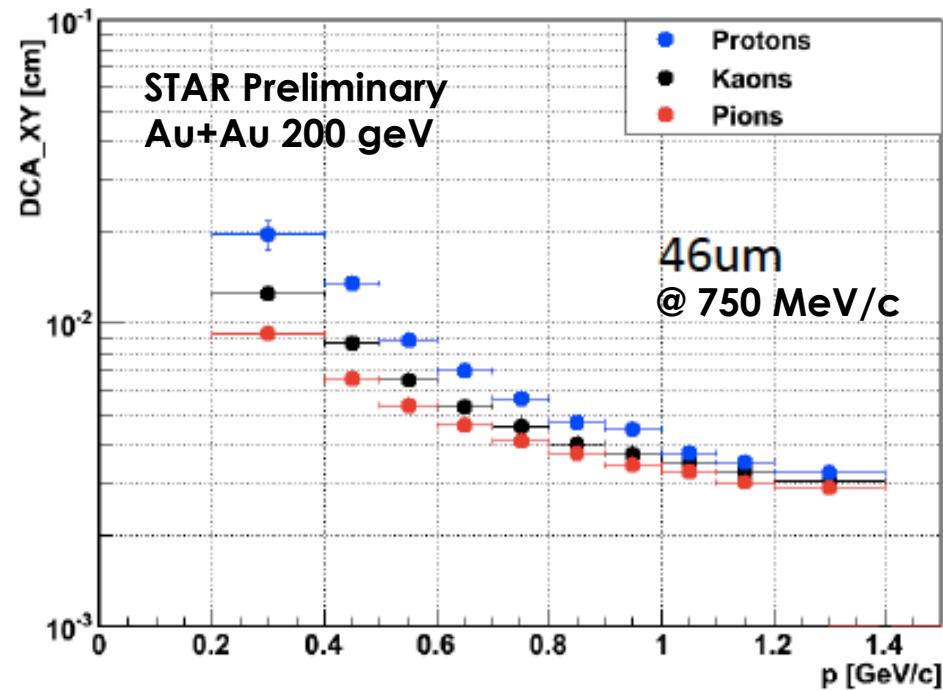
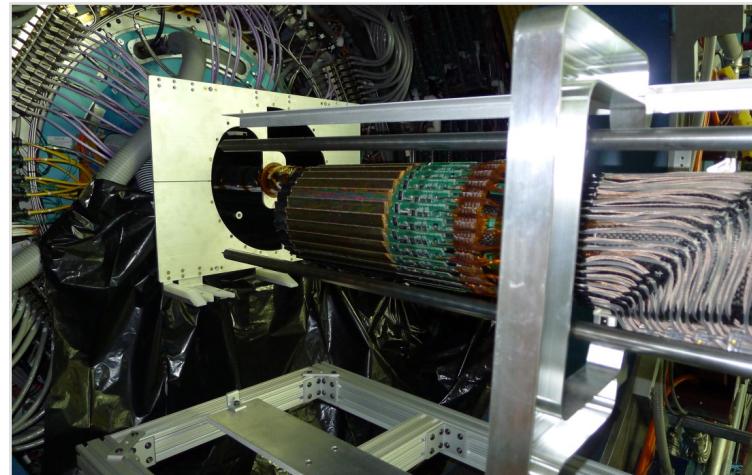


- 400 MIMOSA-28 sensors
- 360 10^6 pixels
- Air flow cooling $T_{op} \leq 35^\circ\text{C}$
- $\sigma_{s.p.} \approx 4 \mu\text{m}$
- mat. budget = 0.39 % X_0 / layer
- Read-out time $\sim 190 \mu\text{s}$

→ Installed January 2014
for 4 months physics run



STAR-PXL half-detector



Next order

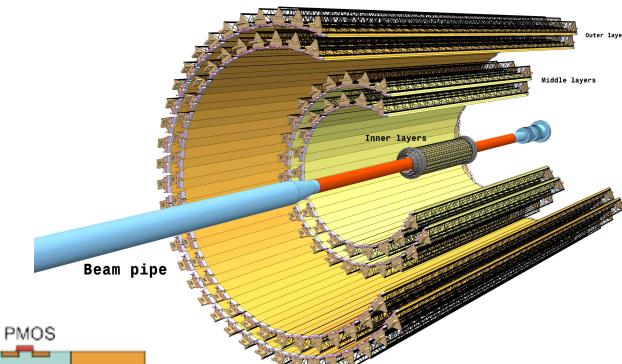


Motivations

- CBM @ FAIR & ALICE @ LHC
 - Faster x10 → 10-30 µs
 - Rad. Tol. X10-100

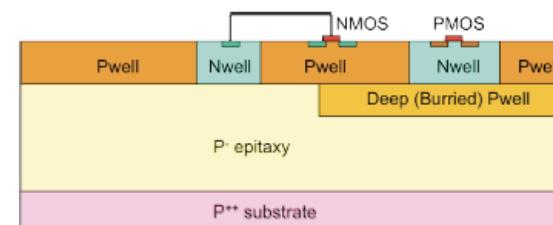
New ITS for ALICE

- First full vtx detector in CPS techno
- 10 m² – 25 10⁹ pixels

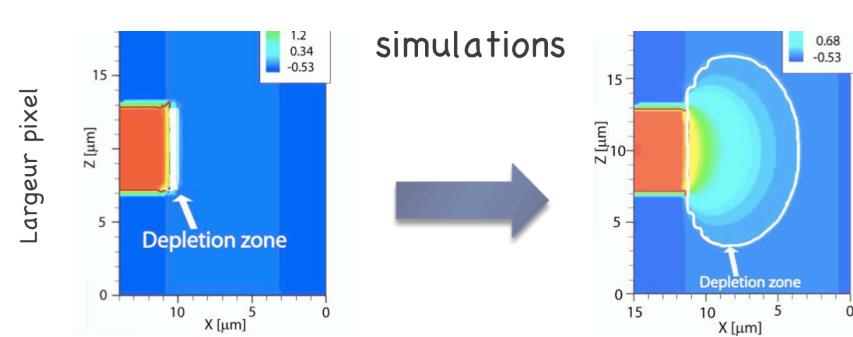


Upgraded CMOS technologies

- Smaller feature size: 0.18 µm
- More metal layers
- More doped layer variants
- Increased processing power



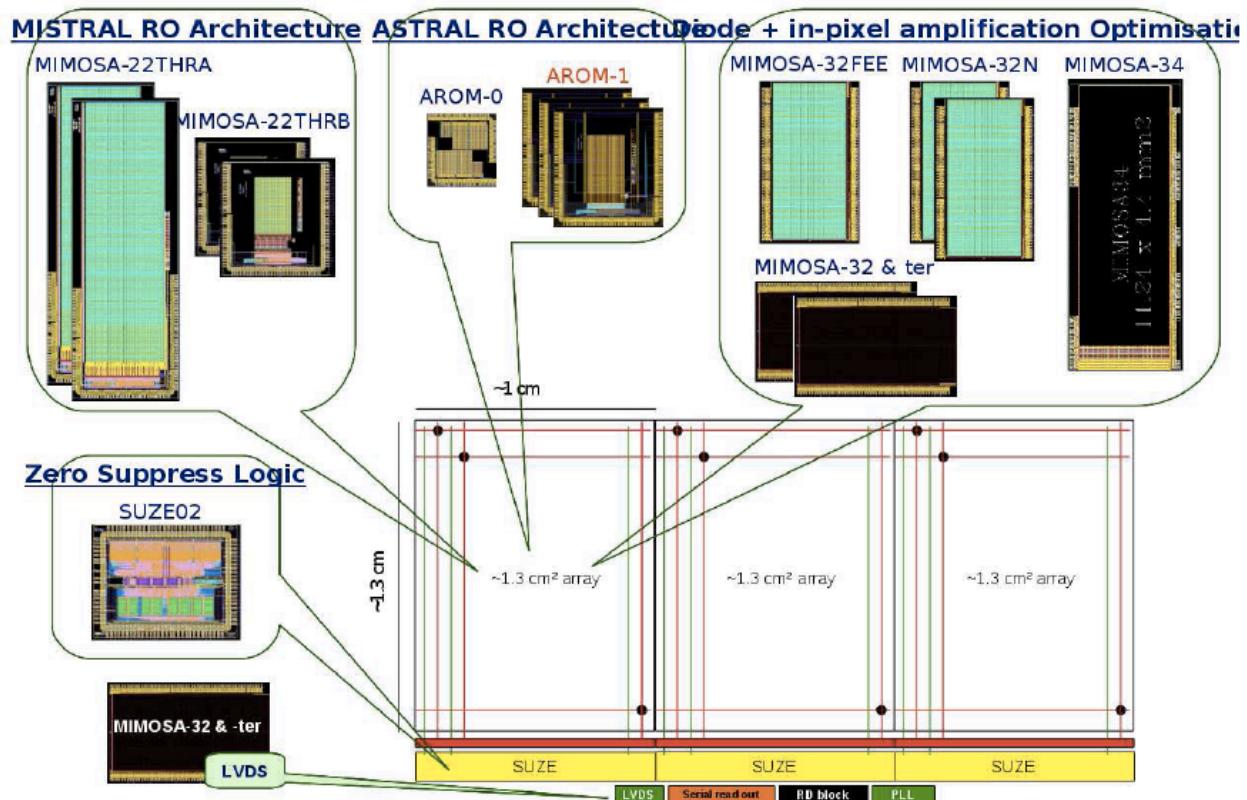
- Sens. layer with higher resistivity
- Increased non-ionizing fluence tolerance



Next order with PICSEL+ALICE



- Tower-Jazz techno
Work started in 2011



- 2 architectures
 - Still rolling shutter with column // Read-out
 - **ASTRAL**: in-pixel discriminator 15 μ s, ~ 75 mW/cm²
 - For inner layers
 - **MISTRAL**: column-level discriminator 20 μ s, ~ 100 mW/cm²
 - For outer layers

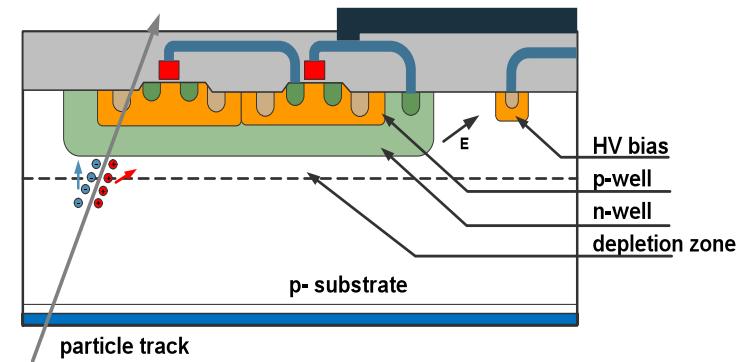
Next to Next order



PICSEL projects

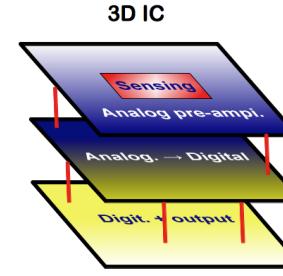
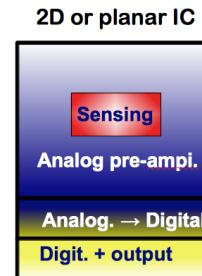
- CBM >2018:
 - “Extrapolation” of MISTRAL
- Belle-II:
 - Exploitation of PLUME ladder
- ILC:
 - New double-sided layers with complementary optimization

Layer	σ_{sp} MIMOSA/AROM	t_{int} MIMOSA/AROM	Occupancy [%] 1 TeV (0.5 TeV)	Power inst./average
VXD-1	3 / 5-6 μm	50 / 2 μs (8 μs)	4.5(0.9) / 0.5(0.1)	250/5 W
VXD-2	4 / 10 μm	100 / 7 μs (100 μs)	1.5(0.3) / 0.2(0.04)	120/2.4 W
VXD-3	4 / 10 μm	100 / 7 μs (100 μs)	0.3(0.06) / 0.05(0.01)	200/4 W



CMOS technology progresses

- Targets fully-depleted sens. layer
- “std” CMOS process with specific bias
- HV-CMOS
 - RD53 program for LHC
 - CLIC
- FD-SOI, HD-SOI
- Ultimately 3D technology



MAPS for low energy X-rays



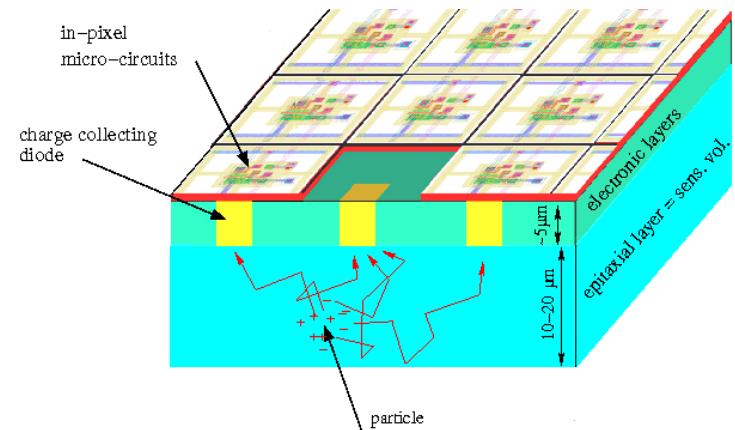
General remarks

■ Pros

- Low cost and complexity comparing to hybrid-pixels
- Full depletion of 50 μm sensitive layer
 - Recently available from several foundries
 - Low energy X-rays applications possible ($\sim 1\text{keV}$)
- Excellent energy resolution from Si
- Integration over small pixels \rightarrow count rate \approx hybrid-pixels
- 4 side buttable (flip chip to PCB)
- No high voltage needed

■ Cons

- Limited to low energy X-rays only
 - for 50 μm of Si thickness
the absorption efficiency at 10keV is 30%
 - \rightarrow stacking sensors might be useful



Low noise operation example



^{55}Fe with V foil

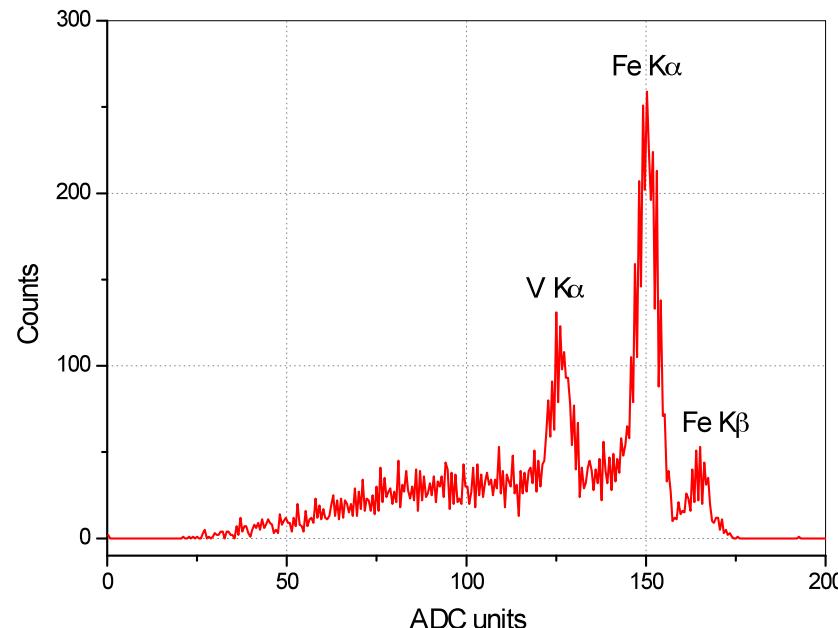
Pegasus 2 – designed in TOWER-JAZZ 0.18 μm
Analog readout

Standard source follower pixel:

Gain $17 \text{ uV/e-} \Rightarrow C_{\text{in}} = 9.38 \text{ fF}$

ENC 17 e- (base)

28 e- (Fe peak)

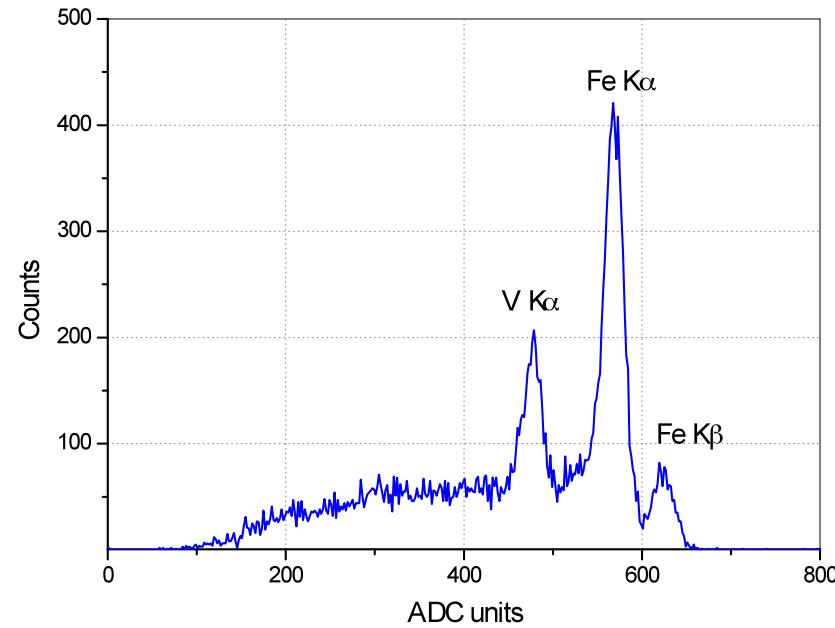


Amplifier pixel:

Gain 70 uV/e-

ENC 16 e- (base)

30e- (Fe peak)



MAPS for low energy X-rays



Parameters planned for SOLEIL synchrotron

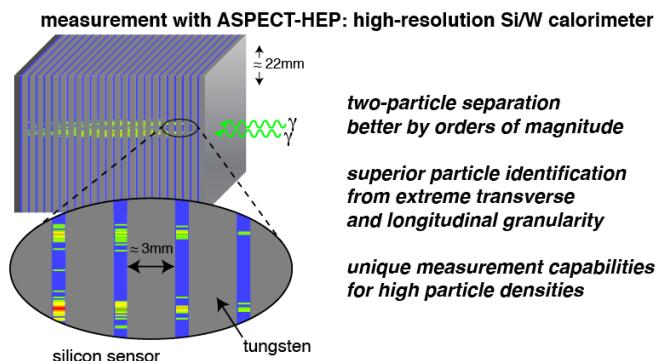
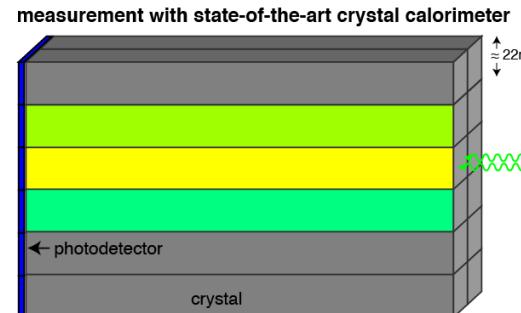
- Energy resolution → noise level $\sim 20 \text{ e}^- \text{ rms}$
- Position resolution → pixel size $\sim 25 \times 25 \mu\text{m}$
- Frame rate » kHz (with matrix of 512x512 pixels)
- Readout choice:
 - Analog readout
 - With integration and monochromatic X-rays -> able to count as fast as hybrids – but need off chip ADCs
 - Digital readout
 - no off chip ADCs needed

Digital Calorimetry

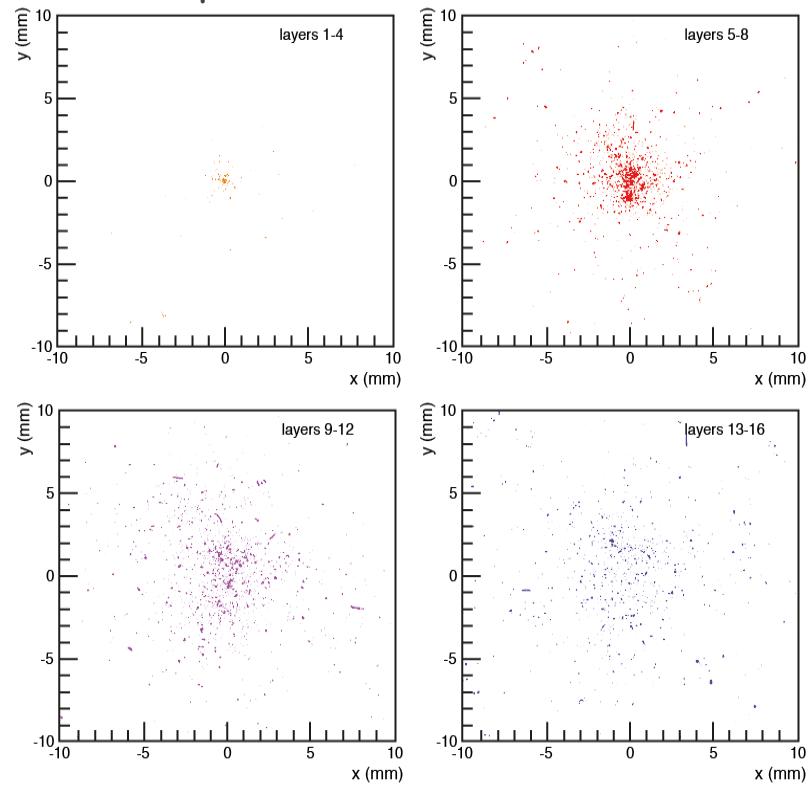


► Projet ALICE-FOCAL

- ▶ Utrecht-NIKHEF + Bergen groups
- ▶ Mesure γ directs vers l'avant p+p, p+A, A+A
- ▶ Granularité \ll rayon de Molière
- ▶ Mesure énergie = comptage des particules



Développement longitudinal
gerbe d'électron à 200 GeV
Avec 25 couches basées
sur capteur prototype
pixel $30 \times 30 \mu\text{m}^2$ mais lent



- ▶ Nécessite capteurs avec temps d'intégration $< 50 \mu\text{s}$

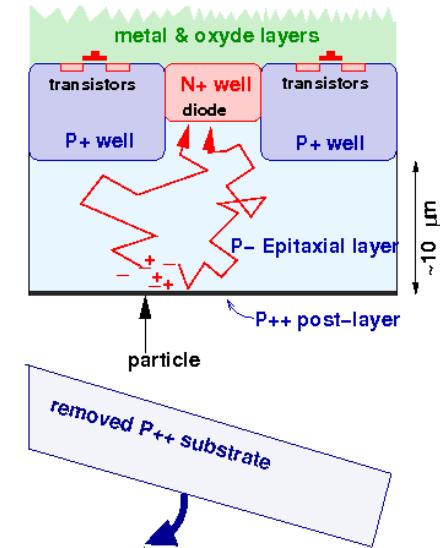
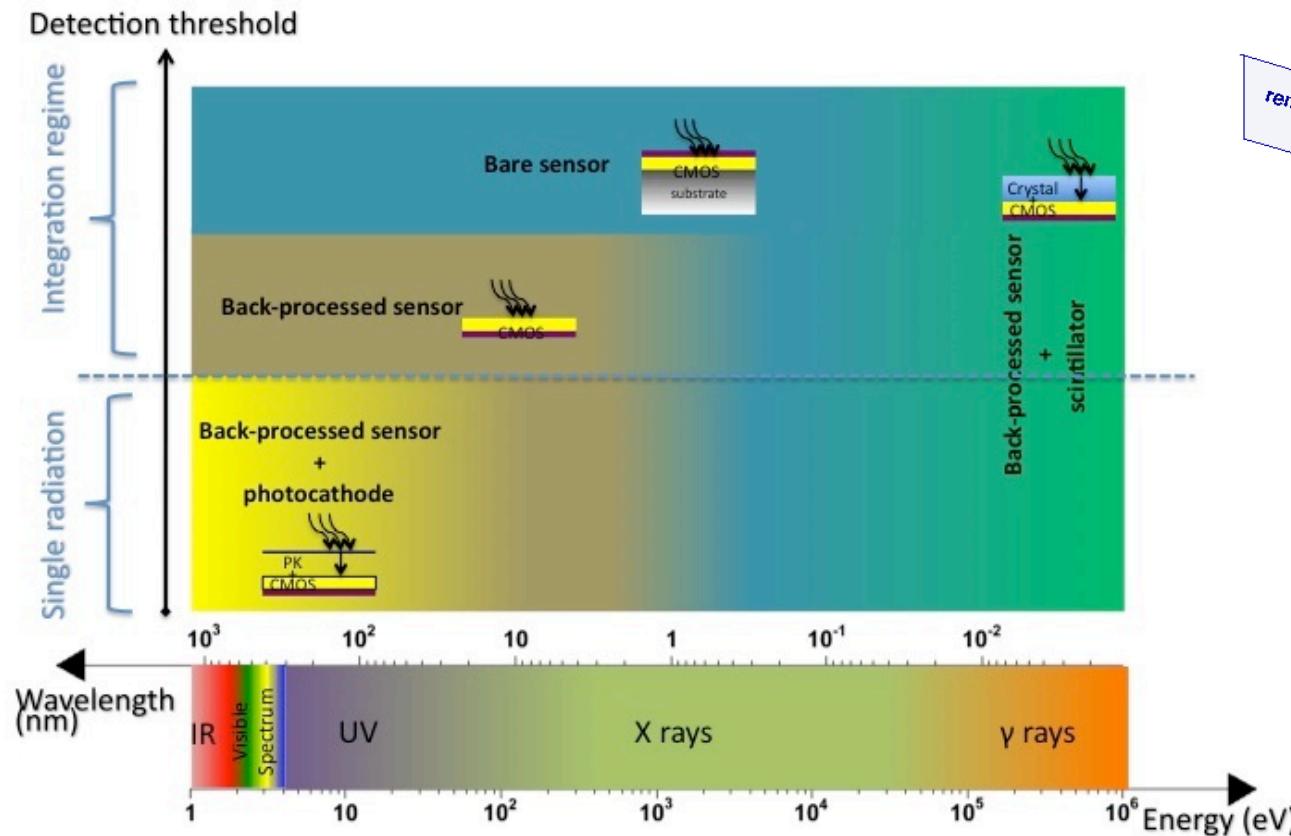
Sensitivity to radiations



▶ Particules chargées

- ▶ Sensible à tous les rayonnements chargés
- ▶ Efficacité seulement limitée à basse énergie (4 keV/e-)

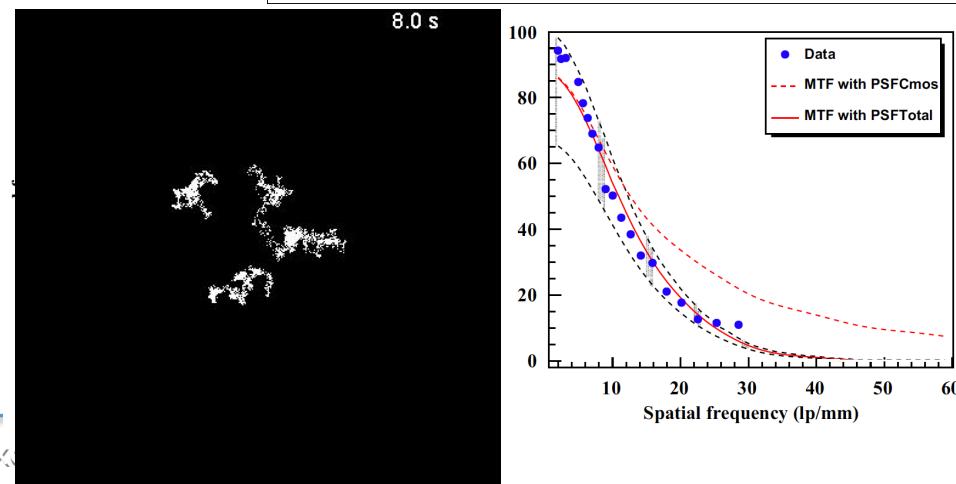
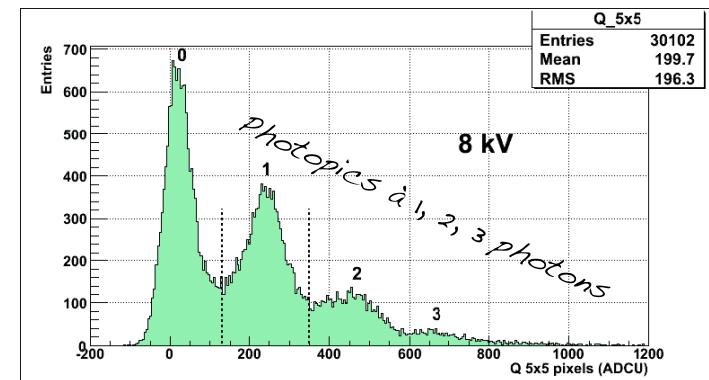
▶ Photons



Hybrid-photodetector



- ▶ Caméra ebCMOS
 - ▶ Photo-détecteur hybride
 - ▶ Collaboration IPN-Lyon (Rémi Barbier) & PHOTONIS
- ▶ Performances de LUSIPHER
 - ▶ Capteur LUCY, 400x800 pixel 10 μm , 600 fps
 - ▶ Photocathodes QE \sim 15-25 % @ 480 nm
 - ▶ Dark count \sim 15 Hz/mm²
- ▶ Applications
 - ▶ Suivi de sources lumineuses très faibles
 - ▶ Bioluminance sous-marine (ANTARES)
- ▶ Perspectives
 - ▶ Dvpmt technique stoppé par manque partenaire
 - ▶ Actuellement marché occupé EMCCD
 - ▶ Potentiellement remplacable par SiPM numériques

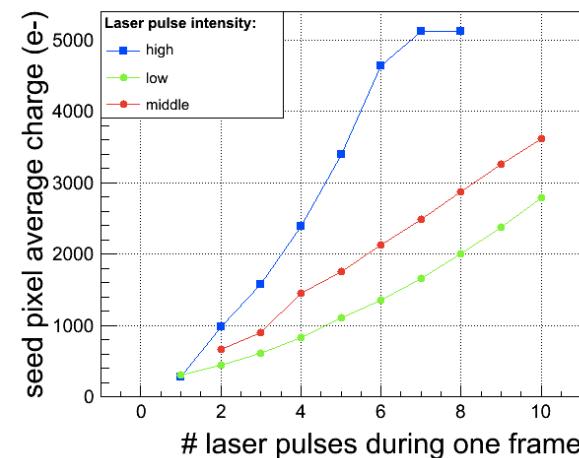
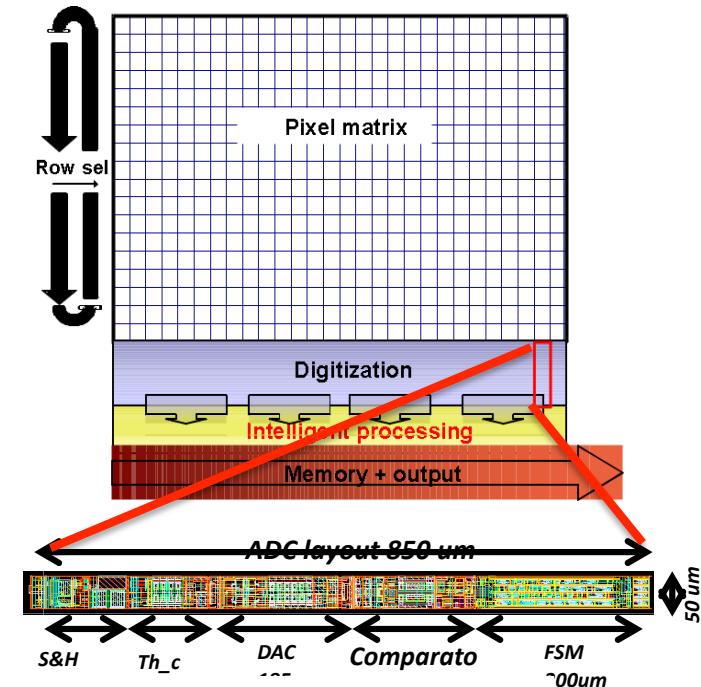


Résultats obtenus par R.Barbier et al. @ IPNL

Spatial dosimetry

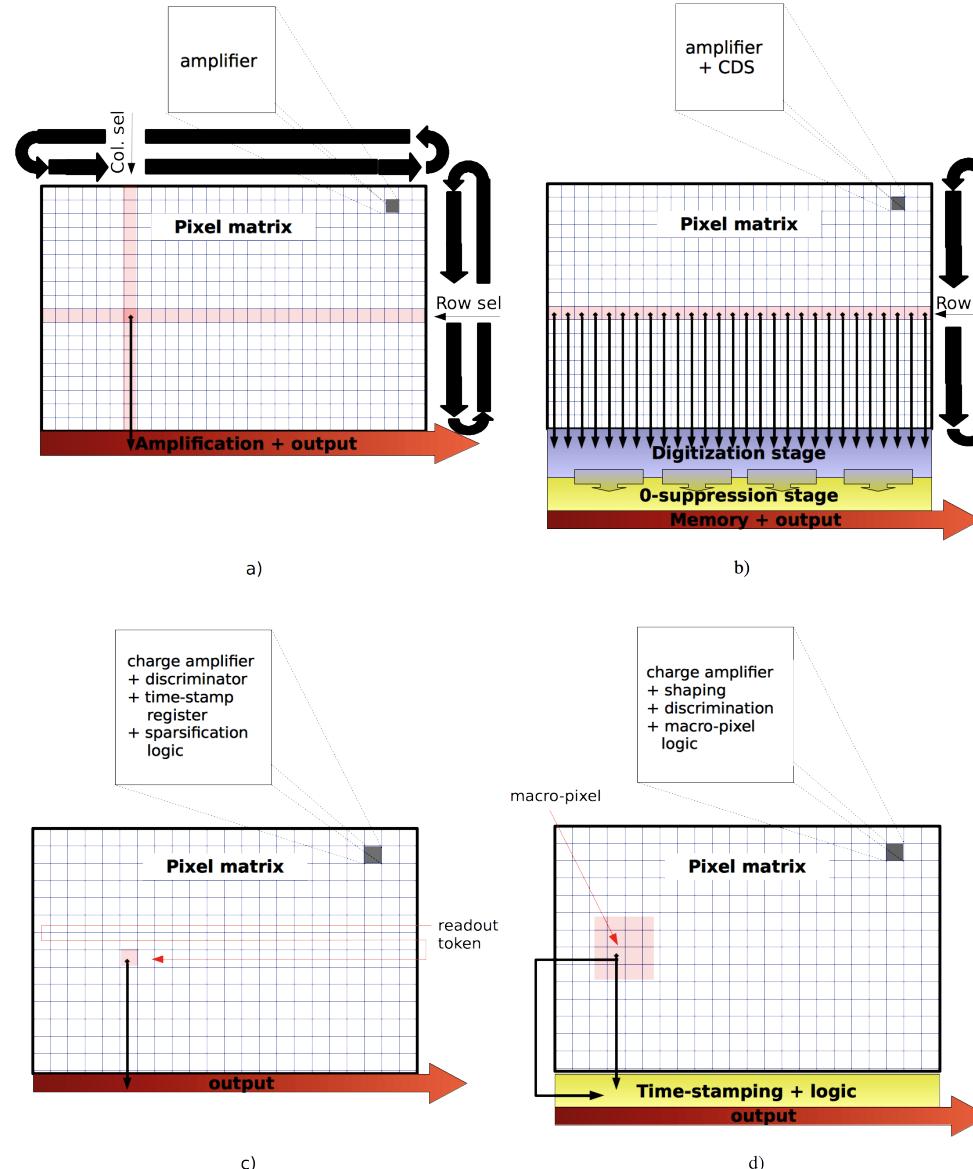


- ▶ Comptage des flux par particules
 - ▶ Satellites « Medium Earth Orbit »
 - ▶ Electrons: 100 keV-7 MeV;
 $10^4 \rightarrow 10^7$ particles/cm²/s
 - ▶ Protons: 100 keV - 400 MeV;
 $10^3 \rightarrow 10^4$ particles/cm²/s
- ▶ Contraintes
 - ▶ Poids, encombrements, consommation
 - ▶ Information temps réel
- ▶ CPS bien adapté
 - ▶ Si mesure énergie déposée
 - ▶ Architecture MIMOSA 26 + ADC + logique « clusterisation »
 - ▶ Prototype COMETH



BACKUPs

Readout architectures



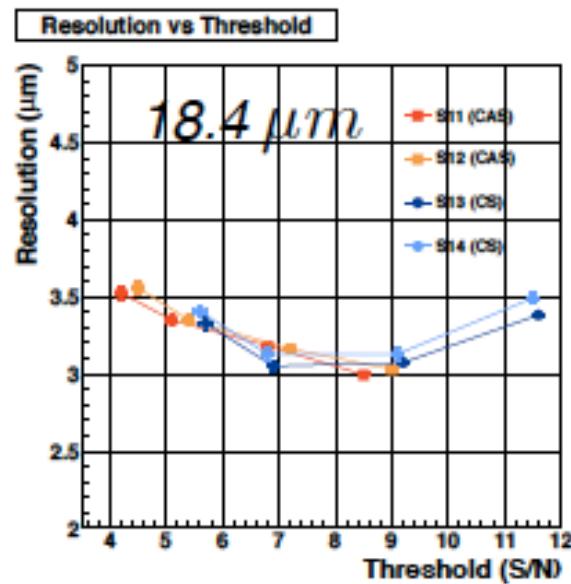


	SLD	CMS	STAR	CBM	ALICE	Belle-II	ILD	CLIC
collision	e ⁺ +e ⁻	p+p	A+A p+p	A+A	A+A p+p	e ⁺ e ⁻	e ⁺ e ⁻	e ⁺ e ⁻
résolution (μm)	2	13	< 10	~5	~5	< 10	≤ 3	≤ 3
Budget matière (% X0)	0.4	~2	~0.3	~0.3	~0.3	~0.2	≤ 0.2	≤ 0.3
densité impacts (10⁶ s⁻¹cm⁻²)	O(20)		O(0,1)	O(1-10)	O(1)	100	O(0,2)	O(1)
temps d'intégration	0,2 s	25 ns	200 μs	~10 μs	<30 μs	~1 μs	O(10)μs	
radio-tolérance (Mrad) (n_{eq}/cm²)	-	100 < 10¹⁵	O(0,2) O(10 ¹²)	O(30) < 10¹⁴	O(0,7) O(10 ¹³)	O(20) < 10 ¹³	O(0,1) < 10 ¹²	O(20) < 10 ¹⁴
Puissance diss. (W/cm²)	-		0.1	1-2	~0.3	~2	0.1	0.1

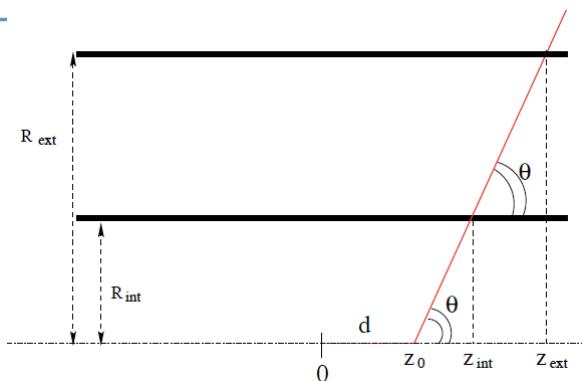


- Pixel multiplicity in hits
- Basic of silicon depletion
 - Formula for 2D-geometry
 - For 5 V bias

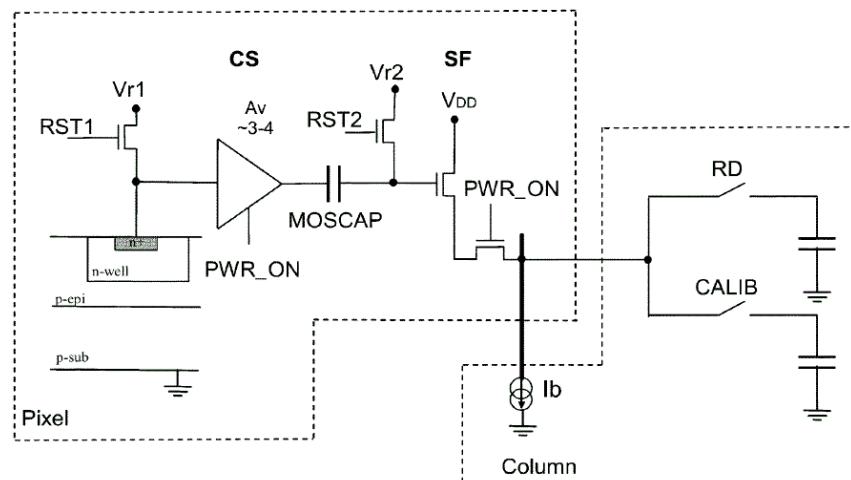
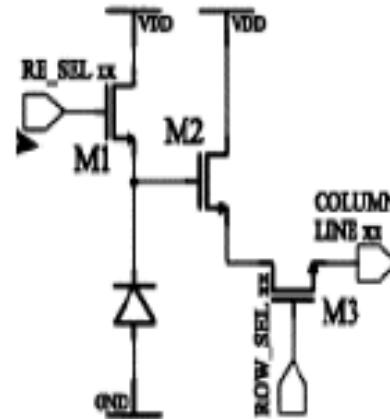
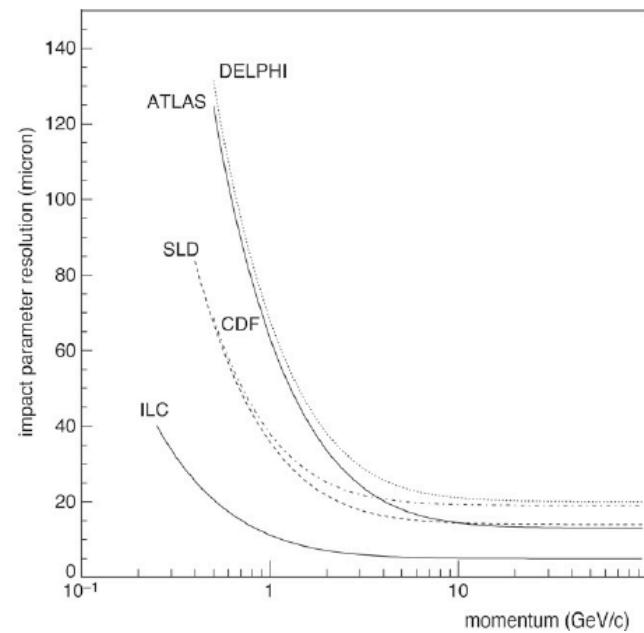
$$d = \sqrt{2\mu\varepsilon V\rho}$$



Resistivity ($\Omega \cdot \text{cm}$)	Depleted depth (μm)
50	8
1000	35



$$\sigma_{IP} \propto \frac{\sqrt{R_{\text{ext}}^2 \sigma_{\text{int}}^2 - R_{\text{int}}^2 \sigma_{\text{ext}}^2}}{R_{\text{ext}} - R_{\text{int}}} \oplus \frac{R_{\text{int}} \sigma_{\theta(\text{ms})}}{p \sin^{3/2}(\theta)}$$



Tracking with doublets

