An R&T on time resolved pixel detector with BiCMOS (SiGe) technology

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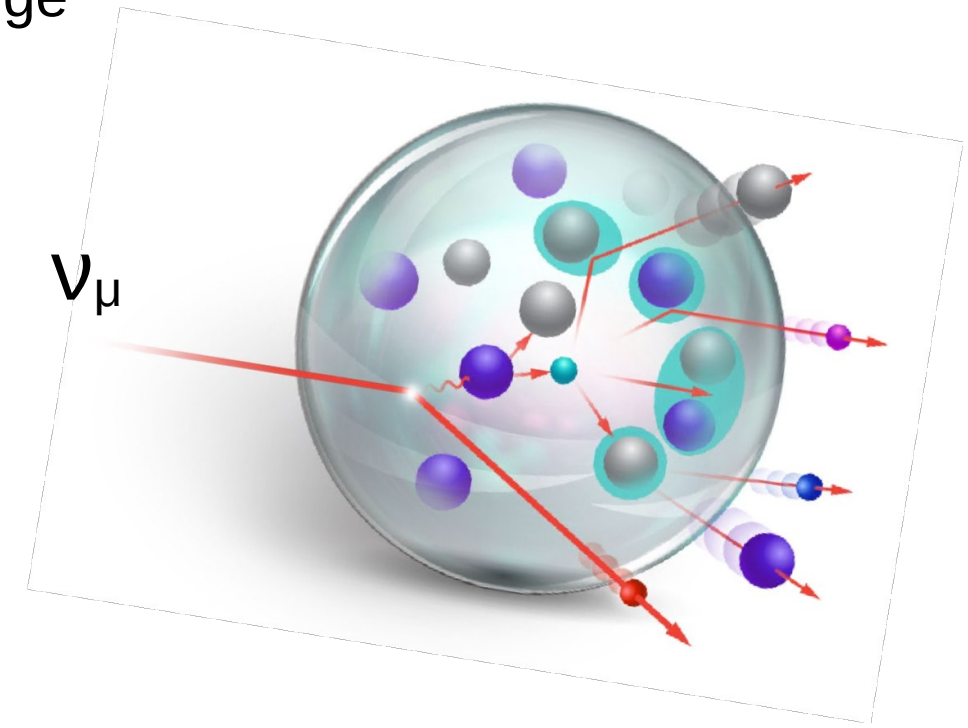
Outline

- **nuSCOPE** project and the need for **4D Tracking**
- **Other applications** of 4D Tracking
- Existing 4D Tracking **technologies**
- **BiCMOS** time resolved pixels
- Discussion on **R&T**

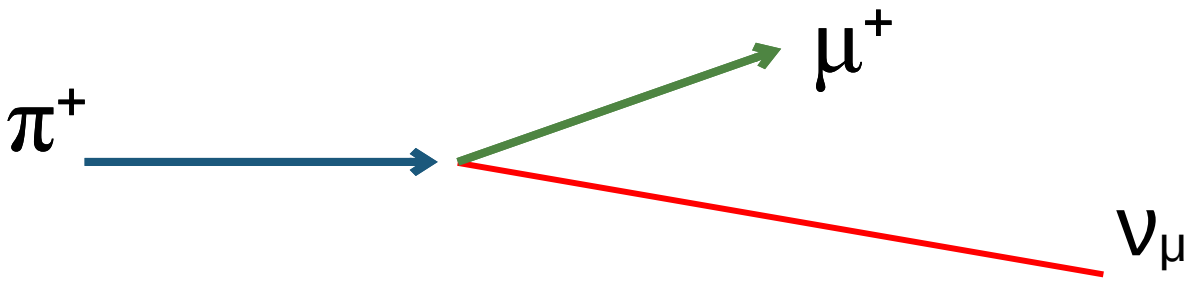
Neutrino Tagging

- Neutrinos studies rely on the reconstruction of neutrino interactions which are complex processes
- Neutrino interaction will be the dominant source of uncertainty at DUNE and HyperK
- Improving our knowledge on them is a major challenge



Neutrino Tagging

- Neutrinos studies rely on the reconstruction of neutrino interactions which are complex processes
- At accelerators, neutrino interaction is only one side of the picture.
  The other side is the neutrino production, which is a simple well controlled process



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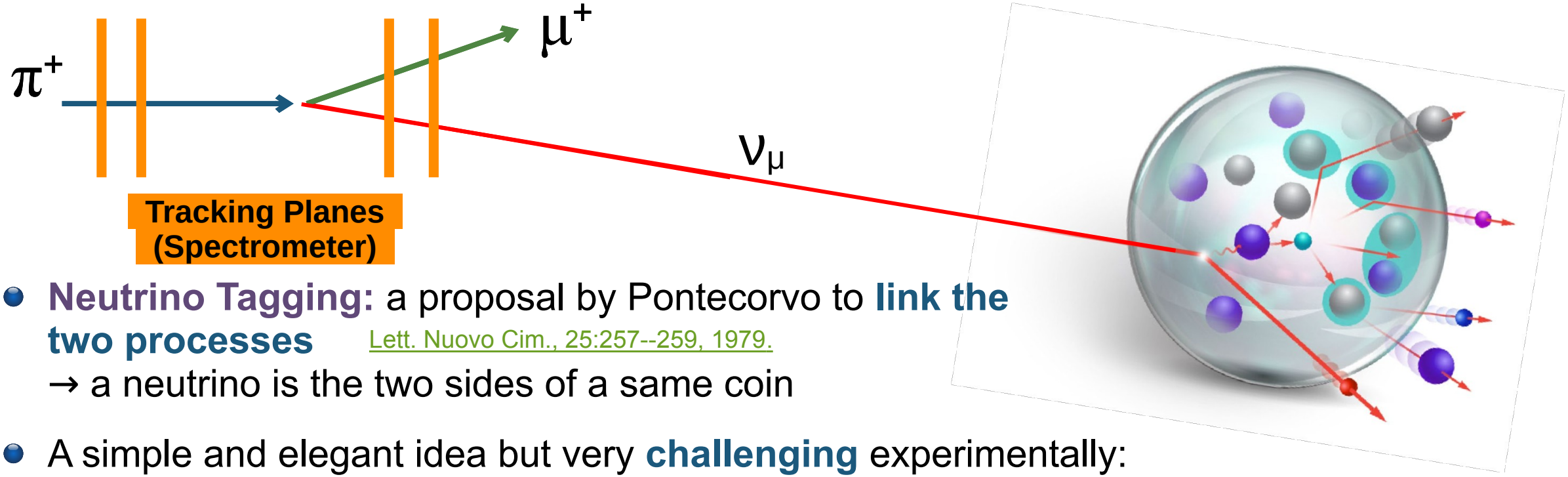
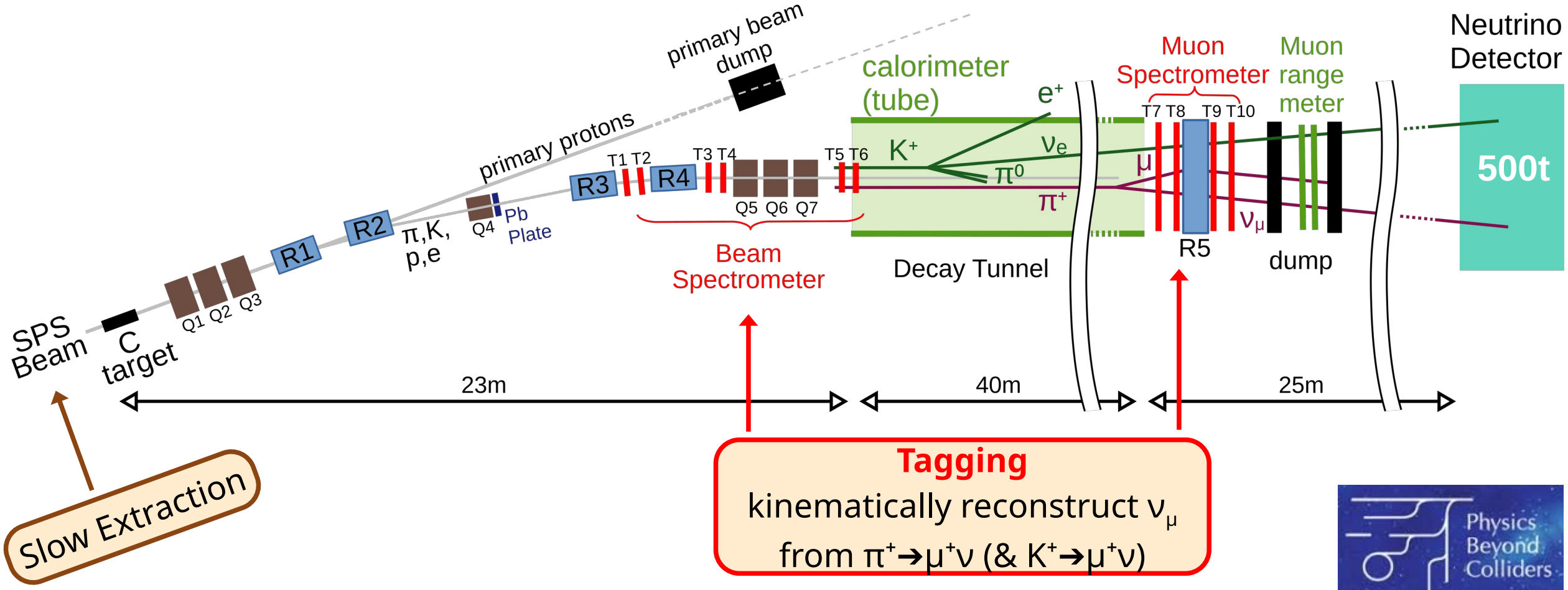


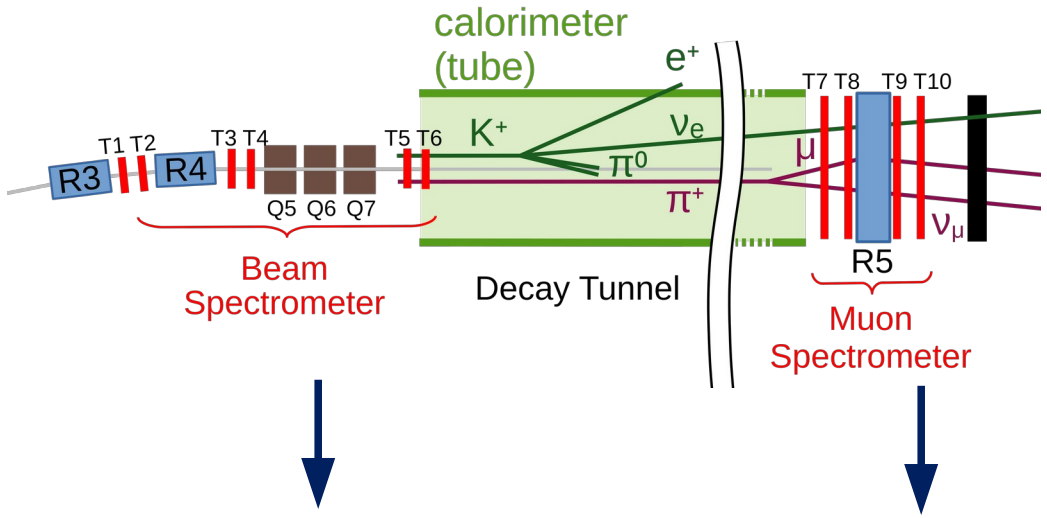
- **Neutrino Tagging:** a proposal by Pontecorvo to **link the two processes** Lett. Nuovo Cim., 25:257--259, 1979.
  → a neutrino is the two sides of a same coin
- A simple and elegant idea but very **challenging** experimentally:
  beam particle rate is tremendously high ($10^{10\text{-}11}$ π/s)

nuSCOPE: a full scale tagged neutrino experiement

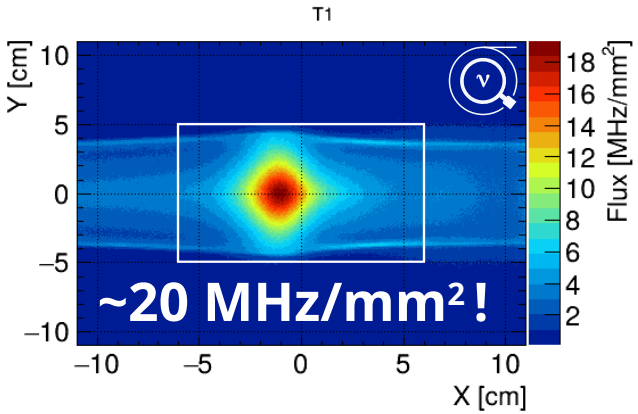
- nuSCOPE is a project for a short baseline neutrino experiment at CERN to implement the neutrino tagging

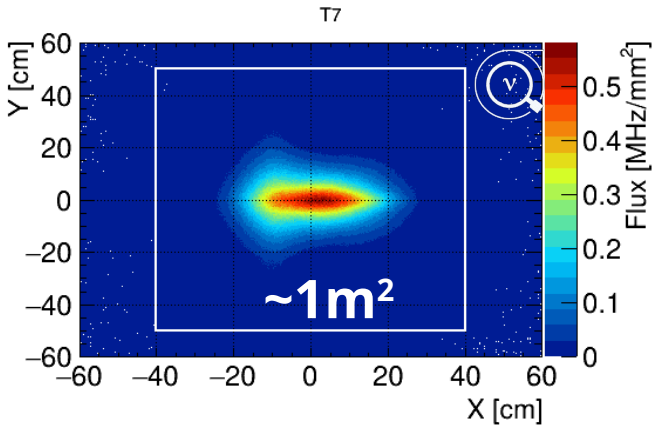


They key technology: high rate time resolved pixels



Specifications [units]	Beam Spectro.	Muon Spectro.	LHCb-VELO (2028)	NA62-GTK (since 2014)
Peak Dose [Mrad]	700	60	$> 10^3$	16
Peak Fluence [1MeVn_{eq}/cm^2]	1×10^{16}	6×10^{14}	5×10^{16}	4.5×10^{14}
Peak Rate [MHz/mm^2]	20	0.6	$10 - 100$	2
Time Resolution [ps]	< 40	< 100	< 50	< 130
Pixel Pitch [μm]	300		45	300
Material Budget [X_0]	$< 1\%$		0.8%	0.5%



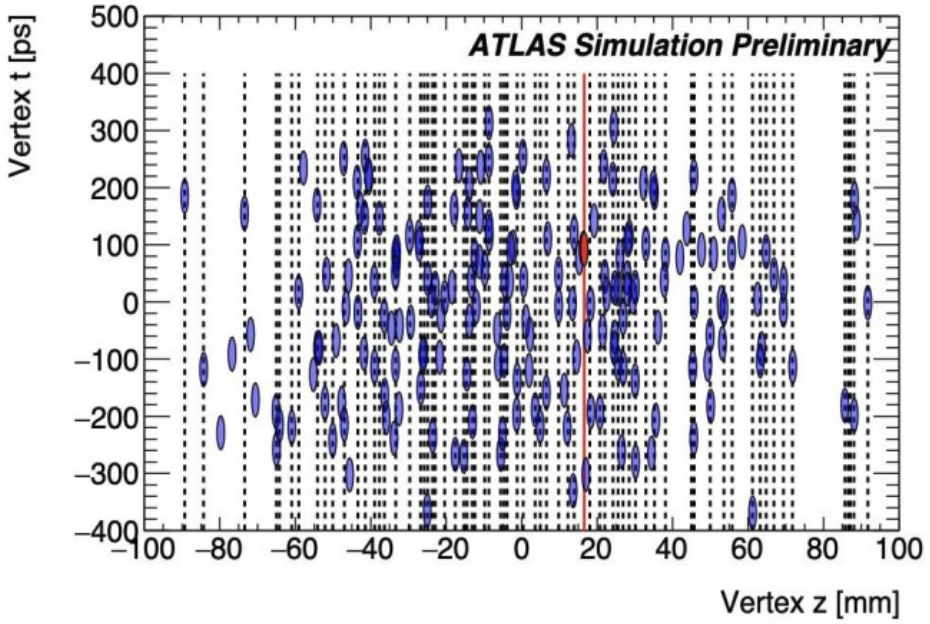


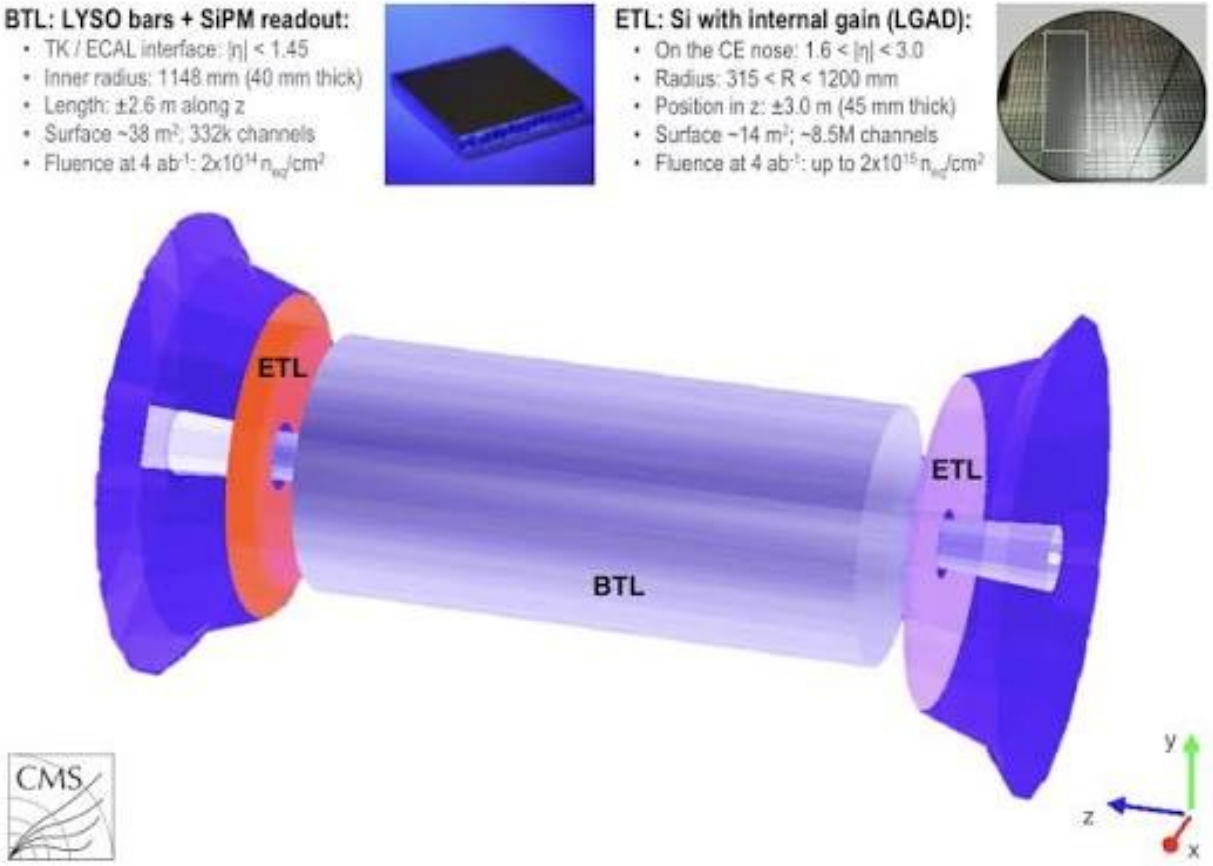
- **Beam Spectrometer**
  - **Time reso & rate beyond state of the art (NA62) by factor 10**
  - **Aligned with LHCb upgrade and other R&Ds**
- **Muon Spectrometer**
  - Time reso and material budget challenging on such **large scale**

Applications with similar specs. – HL-LHC

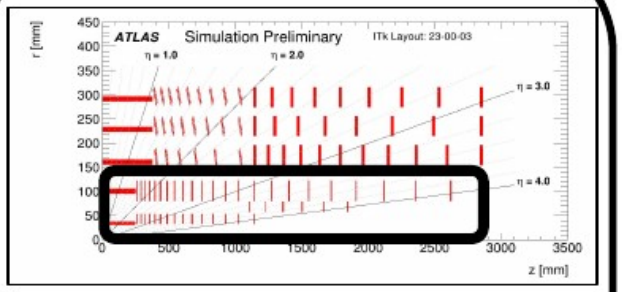
4D Tracking at HL-LHC (ATLAS and CMS)

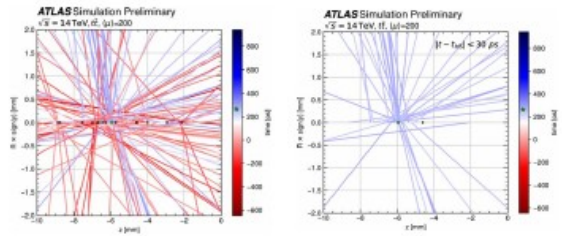
- primary vertices are overlapping in space...
- .. but can be resolved with time
- luminous region is about 180ps
- 30 ps allows pileup reduction by 6



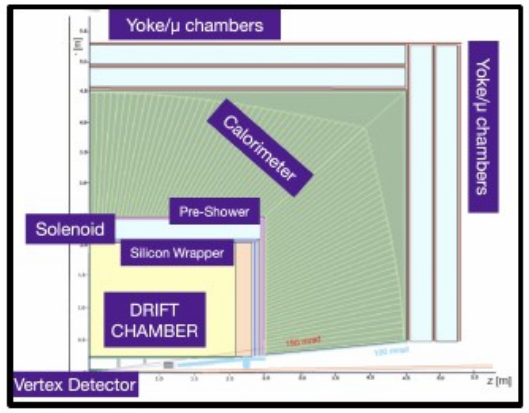


Applications with similar specs. – Future Colliders

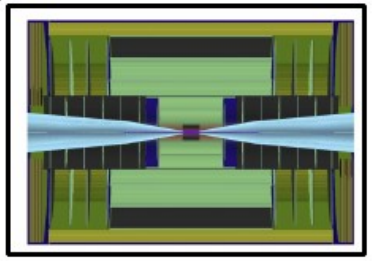


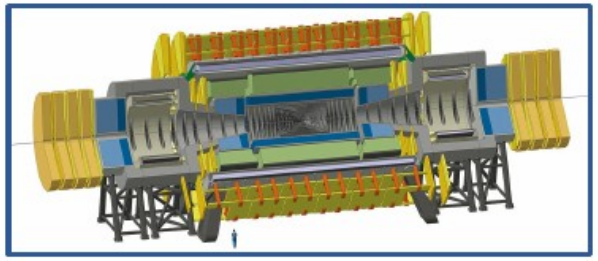


HL-LHC: (*2035*) 4D tracker inner system replacement



FCCee/ILC: (*2040*) Timing layers for flavor tagging, particle ID, and LLP searches





10 TeV muon and hadron colliders (*2050+*) Full 4D tracker for BIB rejection (muC) and pileup suppression (FCC-hh) at extremely high radiation environments

See: LHCb Velo Upgrade 2 ICHEP Talk

Credits: Ariel Schwartzman

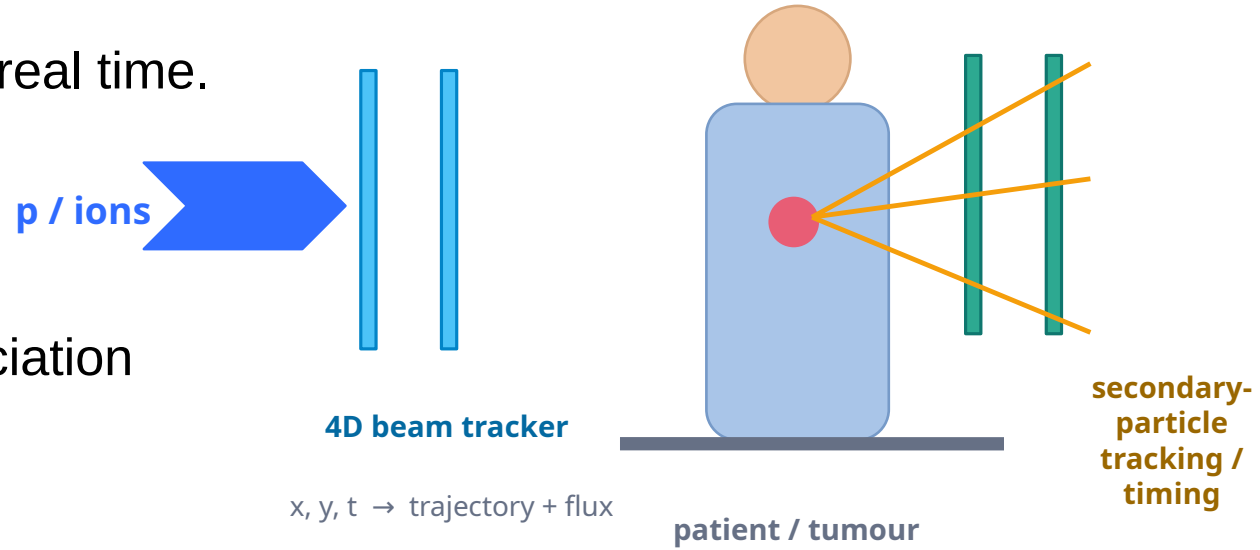
Specifications for Future Colliders

- Sensors and electronics capable of reaching 30-50ps time resolution per track under a high radiation environment (10^{16} n_{eq}/cm^2) and ~10 MGy
- Small pitch: ~50μm^2, high occupancy
- Low power to minimize additional material
- Data transmission for ToA and ToT and bandwidth requirements
  - TDC range → power
  - on-chip data reduction schemes?
    - provide single time for clusters
    - 4D clustering
    - …

Credits: Ariel Schwartzman

Applications with similar specs. – Medicine

- **Real-time beam monitoring and dosimetry**
  - Count and localise particles bunch-by-bunch;
    detect beam motion and intensity changes in real time.
- **Proton/ion radiography and CT**
  - Track particles before & after the patient
    Precise timing (<100ps) enables proton association
    and residual energy measurement with TOF



- **Range / in-vivo verification**
  - Time-tag prompt secondaries / PET products and correlate
    them with the incident particle to constrain where dose is deposited.
  - 100 ps demonstrated at reduced intensity;
  - 10 ps: could potentially extend proton tagging
    toward clinical intensities (~100 MHz/mm² peak).

Existing Technologies

Technology	Key projects	Gain	Typical pitch	Timing [ps]	Radiation tolerance [n_{eq}/cm^2]	Thickness [µm]	Cost	Maturity
LGAD	UFSD, HGTD, ETL	Yes	~1 mm ➔50µm with TI	20–30	10^{15}	sensor >50 asic >100	$$$	very mature, used in experiments
3D trench	TimeSPOT LHCb U2	No	55 µm not larger (timing)	~10–30 external readout	$>10^{16}$	sensor >150 asic >100	$$$$	small sensors ASIC in R&D
HV-CMOS / DMAPS	CACTUS	No	~0.5–1 mm smaller possible	~50–100 external TDC	10^{15}	>150	$	small ASIC with limited digital circuitry
Fast SiGe BiCMOS monolithic	MONOLITH	No	~100 µm smaller possible	~20-40 external TDC	10^{16}	>50	$$	full scale ASIC for FASER preshower (100ps)
SiGe Monolithic avalanche	PicoAD	Yes	~100 µm smaller possible	~15–25 external TDC	R&D	>50	$$	small ASIC with limited digital circuitry

not exhaustive

Existing Technologies

Very promising solution:
- excellent time resolution
- excellent material budget (monolithic)
- pixel pitch compatible with tracking applications
- high radiation hardness
- high band width
- cheap

Match the specs of both nuSCOPE spectrometers and of many longer term applications (FCC)

Technology	Key					Thickness [µm]	Cost	Maturity
LGAD						sor >50 asic >100	$$$	very mature, used in experiments
3D trench	L				>10^{16}	sensor >150 asic >100	$$$$	small sensors ASIC in R&D
HV-CMOS / DMAPS	CA			~50–100 external TDC	10^{15}	>150	$	small ASIC with limited digital circuitry
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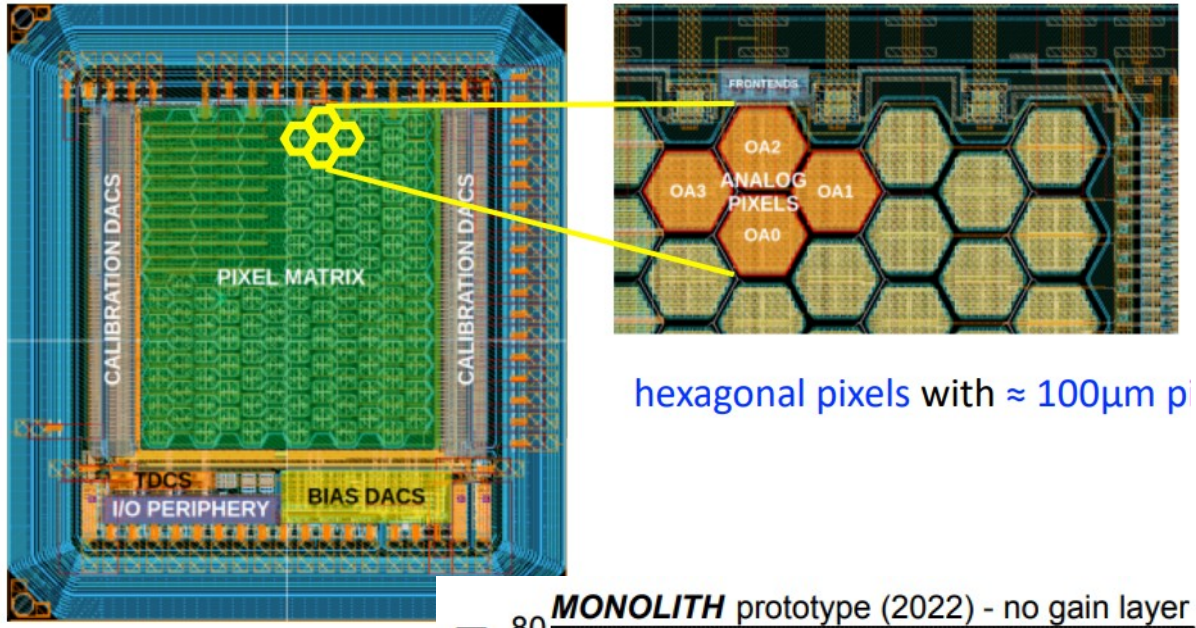
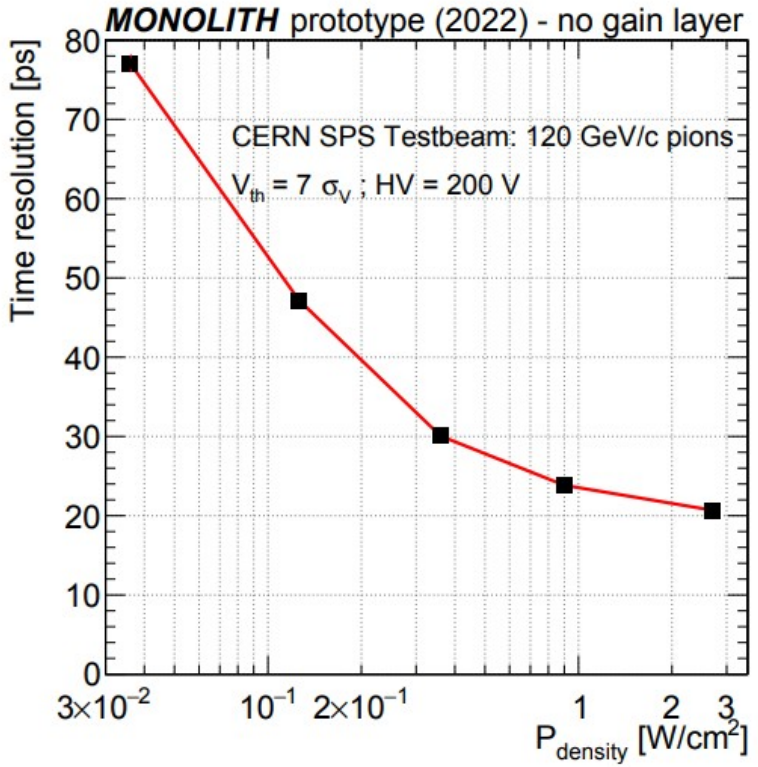
Status of MONOLITH



hexagonal pixels with ≈ 100µm p

- ASIC produced using **wafers** with 50 µm thick epilayer (350Ωcm)
- ASICS **contains**:
  - **144 hexagonal pixels of 65µm side** (i.e. pitch of 100µm)
  - including **4 analog pixels,** with electronics outside the pixel (preamp connected to analog driver with differential output)
- **Time resolution** measured on analog pixels connected to **fast scope** in a **beam test** with 120 GeV/c pions
- Time resolution **as good as 20ps** (after TW correction)
- Little dependence on hit position



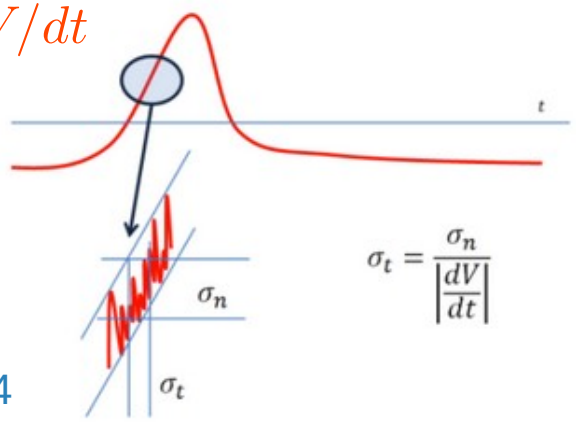
Project Website HERE

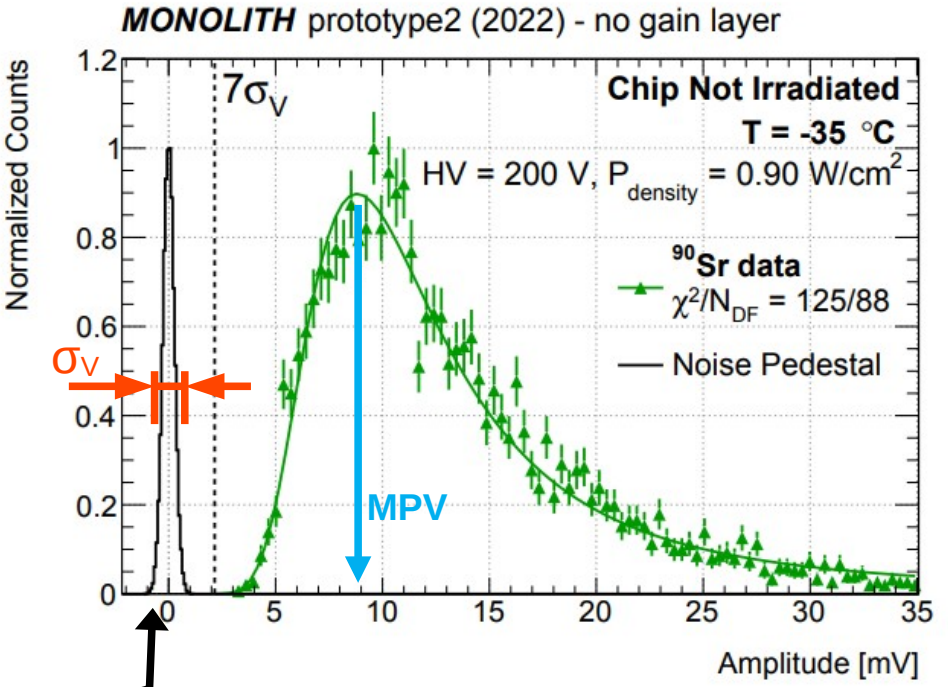
MONOLITH

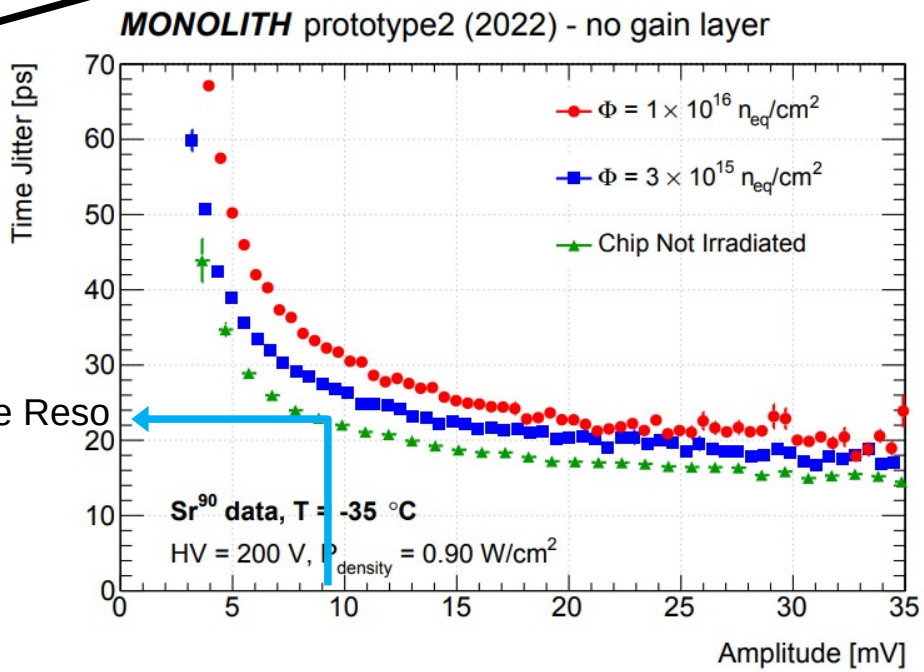
S. Zambito et al 2023 JINST 18 P03047

Performance after irradiation (1)

- **Same devices** were tested in **irradiation**
  - **70MeV** proton up to **10^{16}** n_{eq}/cm^2 at CYRIC in Japan (1.5μA)
  - chips **powered** during irradiation
  - chips kept **cold** (-35°C) after irradiaton
- **Time resolution measurement**
  - power density fixed at 0.9 W/cm²
  - measured with ^{90}Sr as the **average time jitter** at the **most probable signal amplitude**
  - signal time jitter defined as $\frac{\sigma_V}{dV/dt}$ with **σ_V** the voltage noise



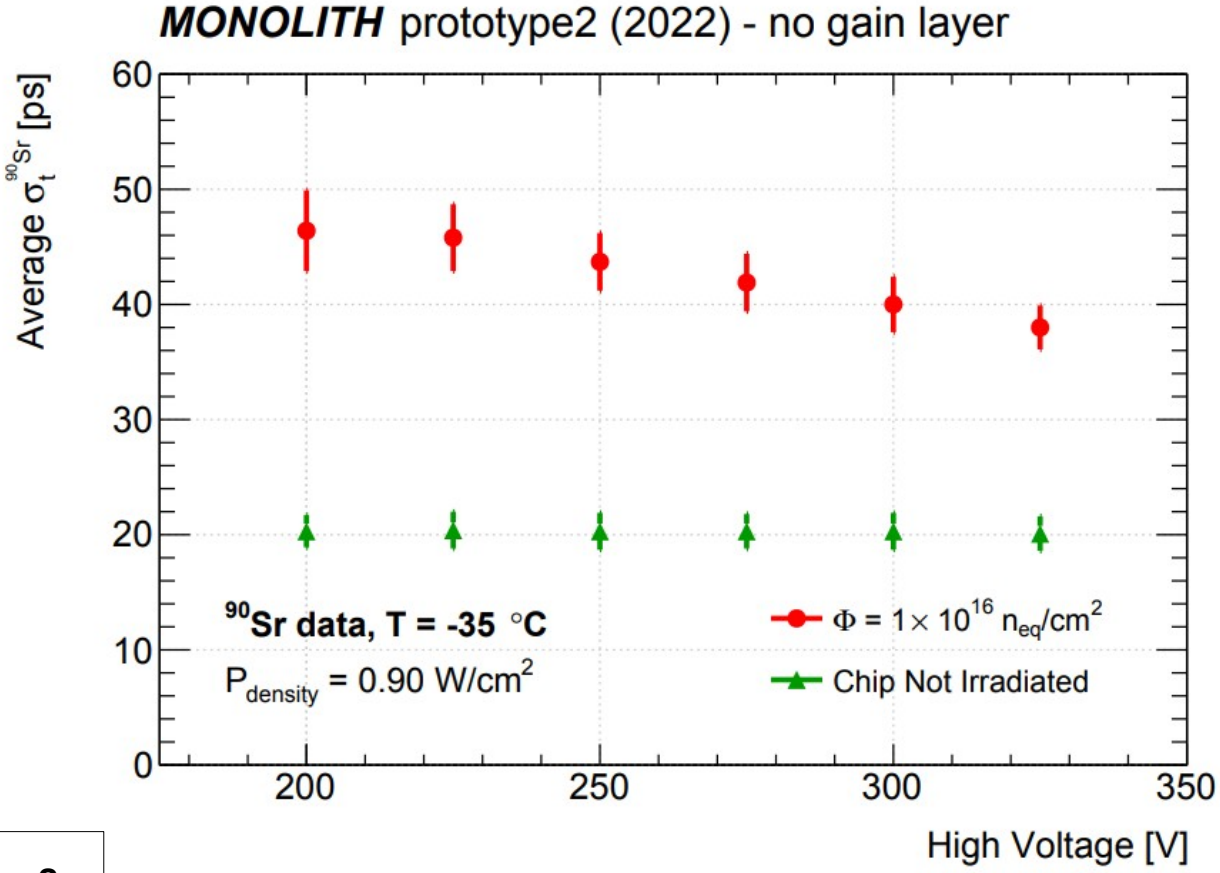




M. Milanesio et al 2024 JINST 19 P01014

Performance after irradiation (2)

- **Same devices** were tested in **irradiation**
  - **70 MeV** proton up to **10^{16}** n_{eq}/cm^2 at CYRIC in Japan (1.5μA)
  - chips **powered** during irradiation
  - chips kept **cold** (-35°C) after irradiaton
- **Time resolution measurement**
  - power density fixed at 0.9 W/cm²
  - Temperature -10°C
  - measured with ^{90}Sr as the **average time jitter** at the **most probable signal amplitude**
  - signal time jitter defined as $\frac{\sigma_V}{dV/dt}$ with σ_V the voltage noise



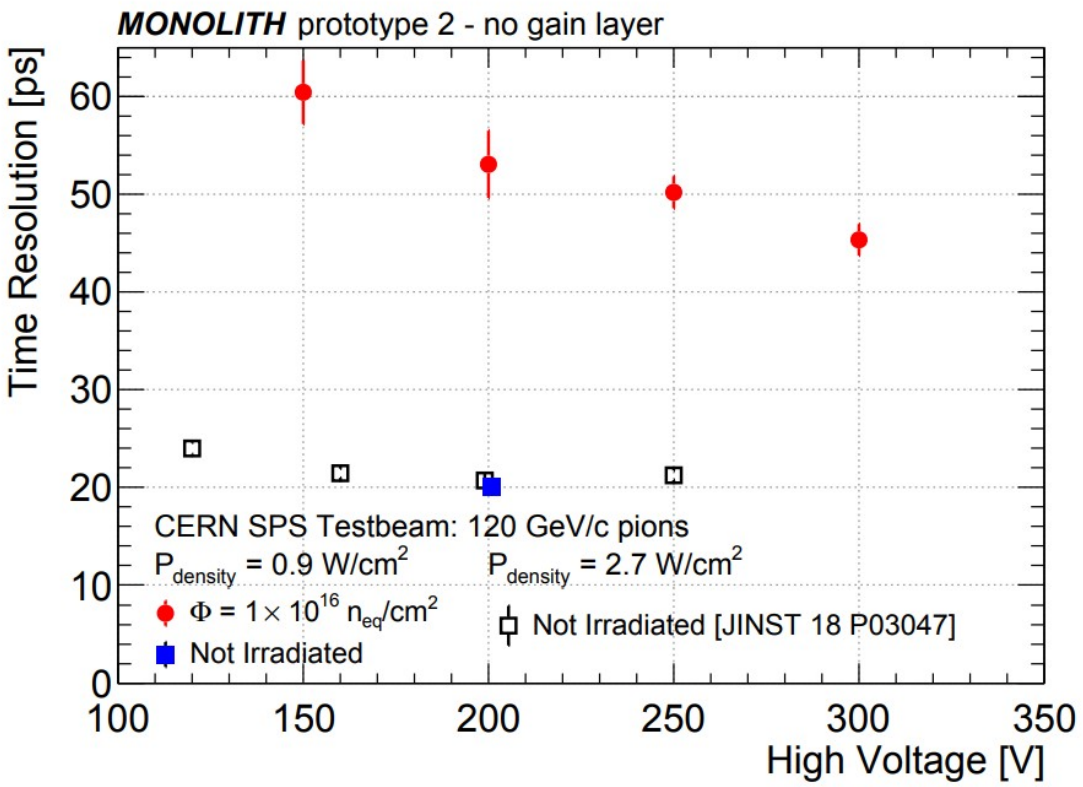
Time resolution of 40 ps after 10^{16} n_{eq}/cm^2

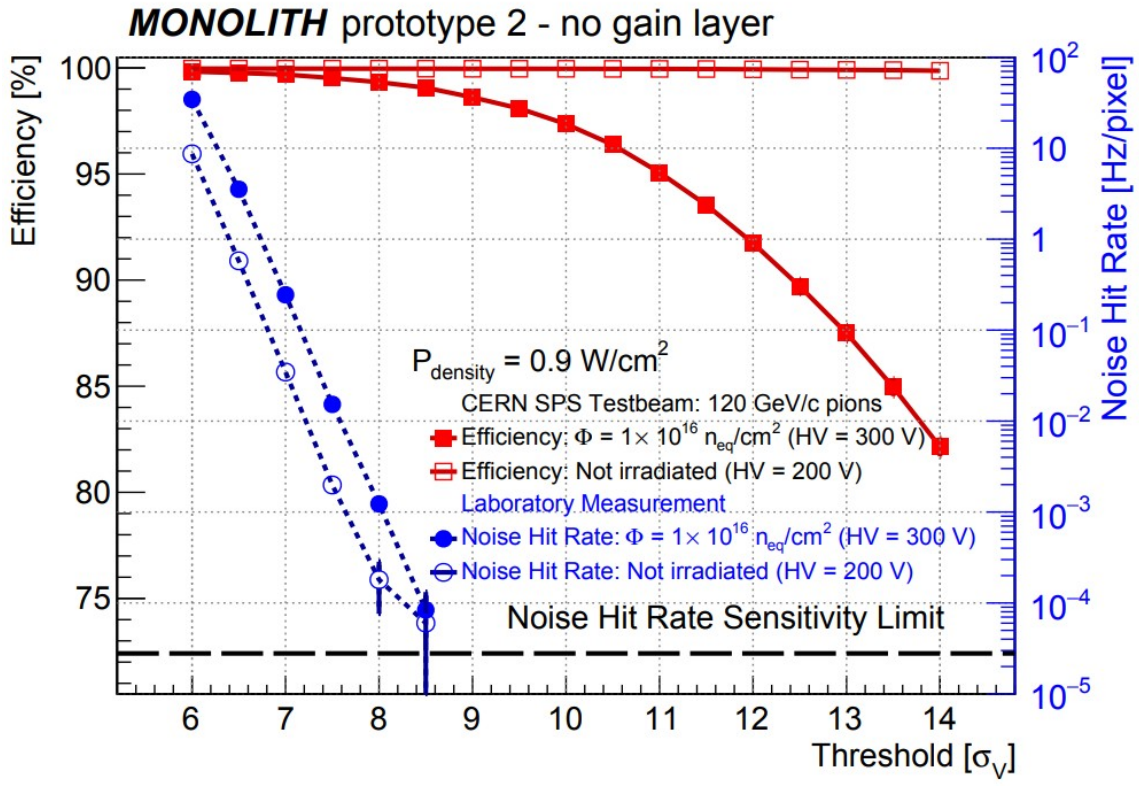
M. Milanesio et al 2024 JINST 19 P01014

Performance after irradiation (3)

- Results have been confirmed in a test beam at SPS (120 GeV/c pion)

T. Moretti et al 2024 JINST 19 P07036

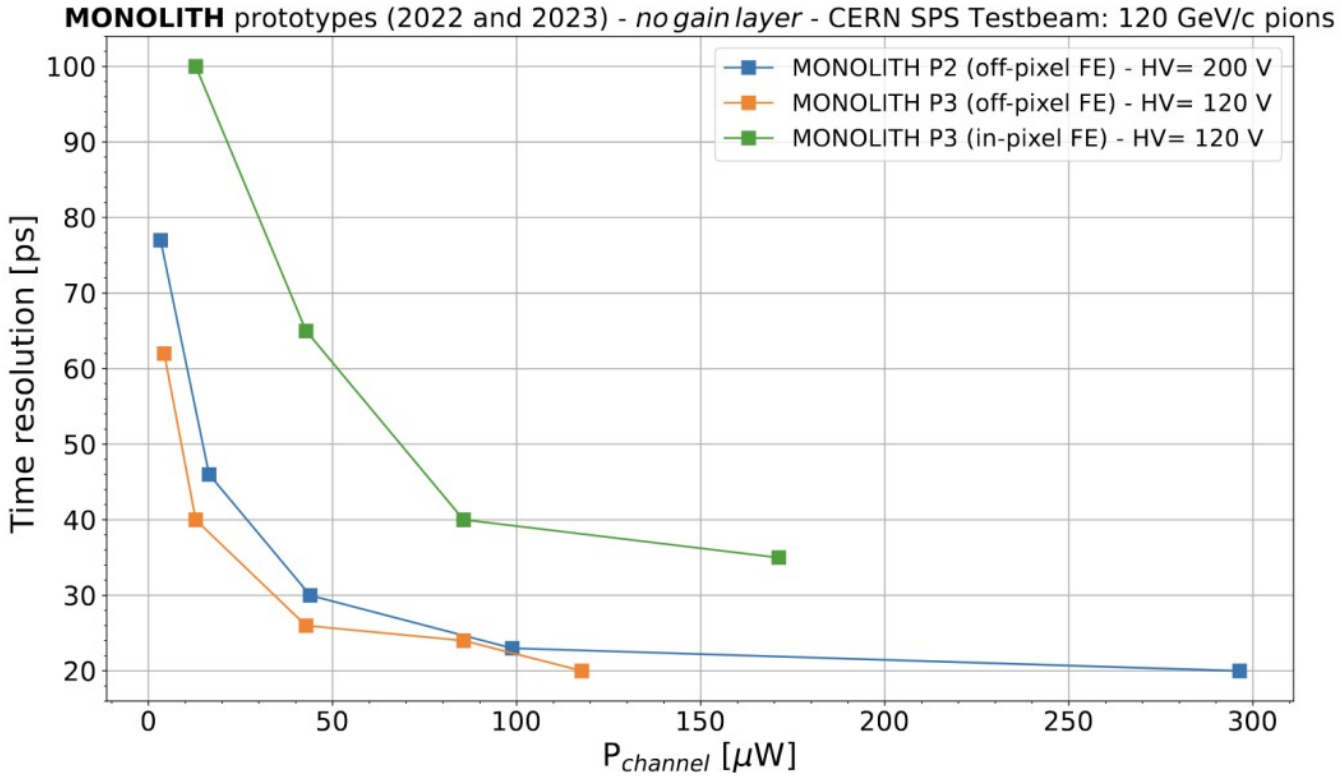




MONOLITH v3

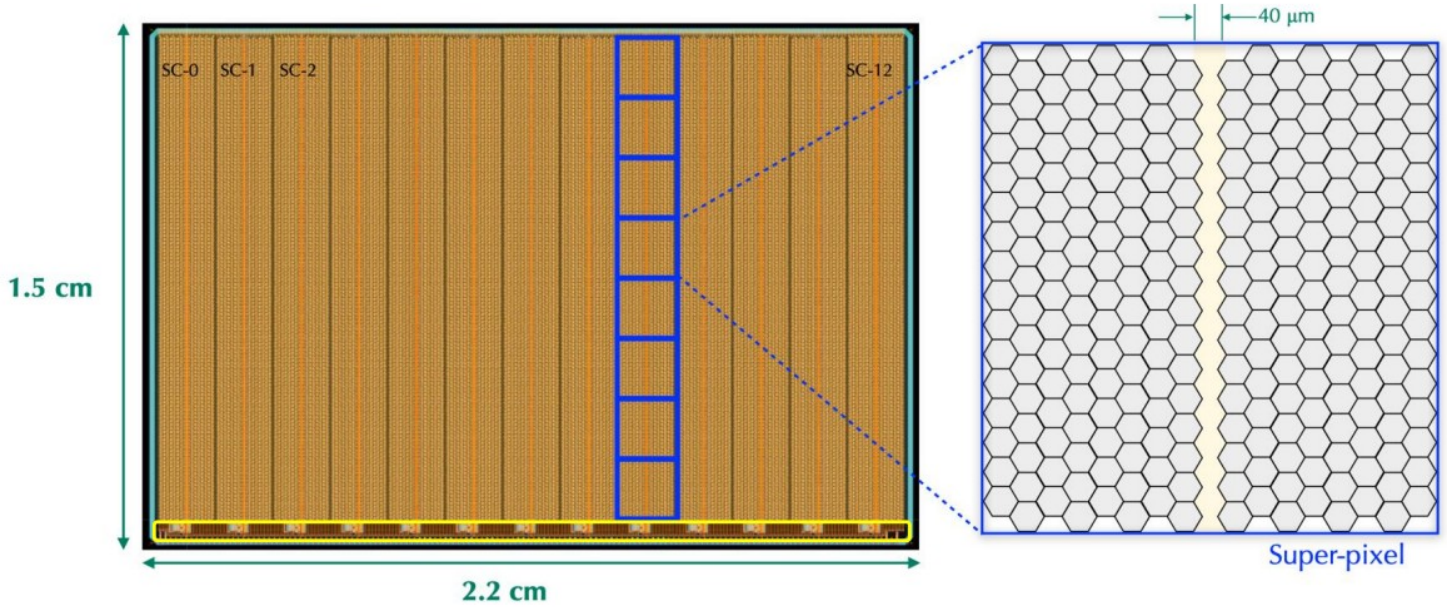
More info at TWEPP 22 and FEE 26

- A 3rd version of the desmonstrator ASIC was produced
  - with 50 µm pitch pixel
  - pre-amp + discriminator inside the pixel
  - not much documentation on these results

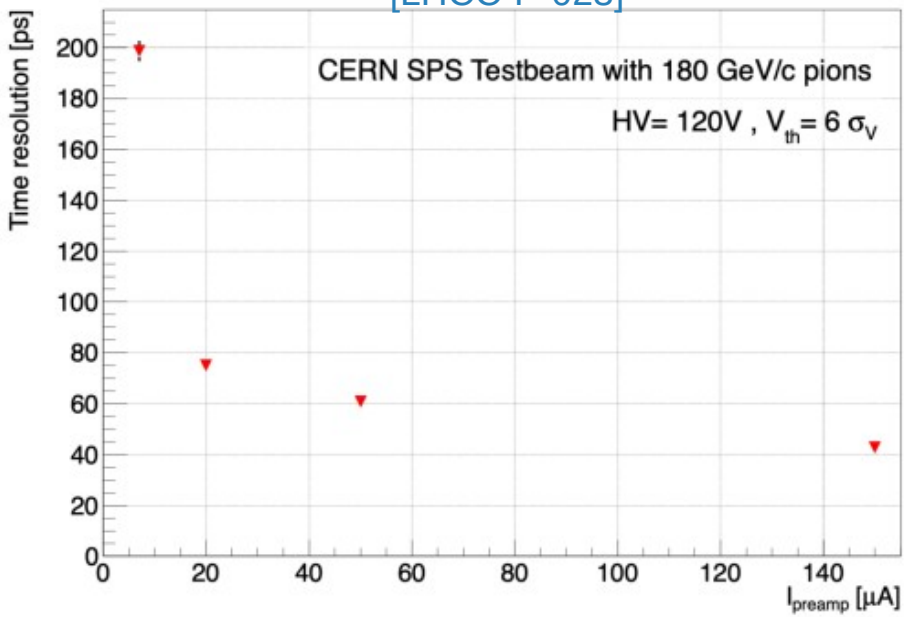


FASER Chip

- Pre-shower application (time resolution <300ps and **low rate**)
  - time resolution <300ps
- A **full reticle chip** (1.5 x 2.2cm2)
  - Active region divided in 8 super-pixels of 16x16 pixels
  - Digital column (40μm) in the middle with readout logic



Results on asic prototype
[LHCC-P-023]



R&T Main Goal / Practical Aspect for Submission

Main goal: **Bridge the gap between the current MONOLITH chips and a full scale ASIC for high intensity tracking application**

Submission Timeline

- **Phase1**

Pour la phase 1 (du 6 juillet au 30 septembre 2026), la lettre d'intention attendue est un document d'environ 2 pages explicitant :

- Un court descriptif du projet
- Les motivations incluant le ou les verrous technologiques à lever avec une estimation des TRL avant/après
- Le déroulement méthodique du projet (phases et résultats attendus à décliner en jalons et livrables)
- Quelques éléments d'organisation (membres confirmés ou en cours, découpage en lots de tâches, plan de financement et des principales dépenses…)

- **Phase2**
  - Detailled project: https://atrium.in2p3.fr/nuxeo/site/doc/54756d13-7db8-4a4d-8d54-d098bc22308b
  - **Submission** from Oct 7th to **Nov. 6th 2026**, **Final decision** on Nov. 30th
- Funding available early 2027
- **Today:** -Identify interested persons
  -Define Content and Work Packages
  -Find date for a follow-up meeting (next week) to converge on the Letter of Interest

Proposal for an R&T at IN2P3

Goal: **Bridge the gap between the current MONOLITH chips and a full scale ASIC for high intensity tracking application**

R&T (3-4y) could include:

- **Test after irradiation of existing chips** (from Geneva)
- **First Submission** and **tests** of key circuits (6.2 kEurs/mm^2, 6 months)
  - Pixel matrix
  - Power
  - Monitoring
  - Analog (Discriminator, Amplifier, TDC)
  - Pixel Digital Part (Triggerless readout)
  - EoC Digital Part (Clock distribution, Serialiser)
- Possibly **second submission** and **tests**
  - demonstrator of a full scale ASIC 2x2mm (2x2mm^2 so ~25kEur)
  - with corrections based on previous tests

Europractice Calendar

IHP MPW	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
IHP SG13S SiGe:C Bipolar/Analog, Ft/Fmax= 250/340GHz, 7M/MIM, optional with TSV					5		27				6	