Silicon detectors: state of the art & possible options for MUonE

Stefano Mersi, CERN

The Evaluation of the Leading Hadronic Contribution to the Muon Anomalous Magnetic Moment

19 – 23 February 2018

Mainz Institute for Theoretical Physics

This region of the presentation contains complementary information to help those who want to read it off-line

Please ignore this section of the slide… starting from the next one

Outline

MUonE tracker parameters

Figures of merit in silicon detectors

Analytic approach to detector optimization

Overview of current detectors

Initial considerations on detector resolution and systematic errors

Outline

MUonE tracker parameters

Figures of merit in silicon detectors

Analytic approach to detector optimization

Overview of current detectors

Initial considerations on detector resolution and systematic errors

MUonE tracker parameters

60 cm total Be target segmented in 60 stations with **1 cm** target
30 m total detector length

10×10 cm^2 Silicon detectors
Resolve each μ,e track with uniform efficiency
Best possible resolution on θμ,θe

μ rate: **40 MHz** (peak) → 13 MHz (averaged)
μ separation: **25 ns** (peak) → **77 ns** (averaged)

Collect **~3.8×10^{12} events** with E_e>1GeV in ~2 years

Scattering probability (E_e>1GeV): 1.21×10^{-4}/cm
Scattering event rate: **4.8 kHz** per station – **291 kHz** overall
Scattering separation: **206 μs** per station – **3 μs** overall

- The segmentation of Be target, the number of measuring stations (and the number of planes per station) are detector parameters to be optimized.
- Experiment trigger is to be defined: one option is to run **trigger-less**, which would require a major effort in on-line data interpretation: even assuming very large enough buffers each event would have to be analyzed within 77 ns of computing time. Another option is to implement a **(scintillator?) trigger** in each station, possibly replacing the scatterer with the scintillator itself. If an effective trigger can be achieved, this would reduce the number of events to be readout to < 10 kHz

Parameters used here are as follows: **Beam:** 63% beam availability over 2 years, with 4.8s spills every 15s (beam duty cycle 32%) and 40 MHz muon rate
Scattering: σ(μe→μe, Ee>1GeV) = 245 μb, Be electron density = 5×10^{23}/cm^3

Outline

~~MUonE tracker parameters~~

Figures of merit in silicon detectors

Analytic approach to detector optimization

Overview of current detectors

Initial considerations on detector resolution and systematic errors

Relevant figures of merit for silicon detectors

Material amount	→	front-end, mechanics, services
Front-end **response time**	→	front-end
Single-hit **resolution**	→	front-end + sensors
Single-hit **efficiency**	→	front-end (noise) + sensors (signal)
Maximum **readout rate**	→	front-end
Size of active region	→	front-end + sensors

Almost all figures of merit in silicon detectors are determined by the design of front-end electronics. **Radiation damage** is a notable exception, where sensor design is crucial to yield a measurable signal in environments with a high hadron fluence, but this is not relevant for the MUonE experiment.

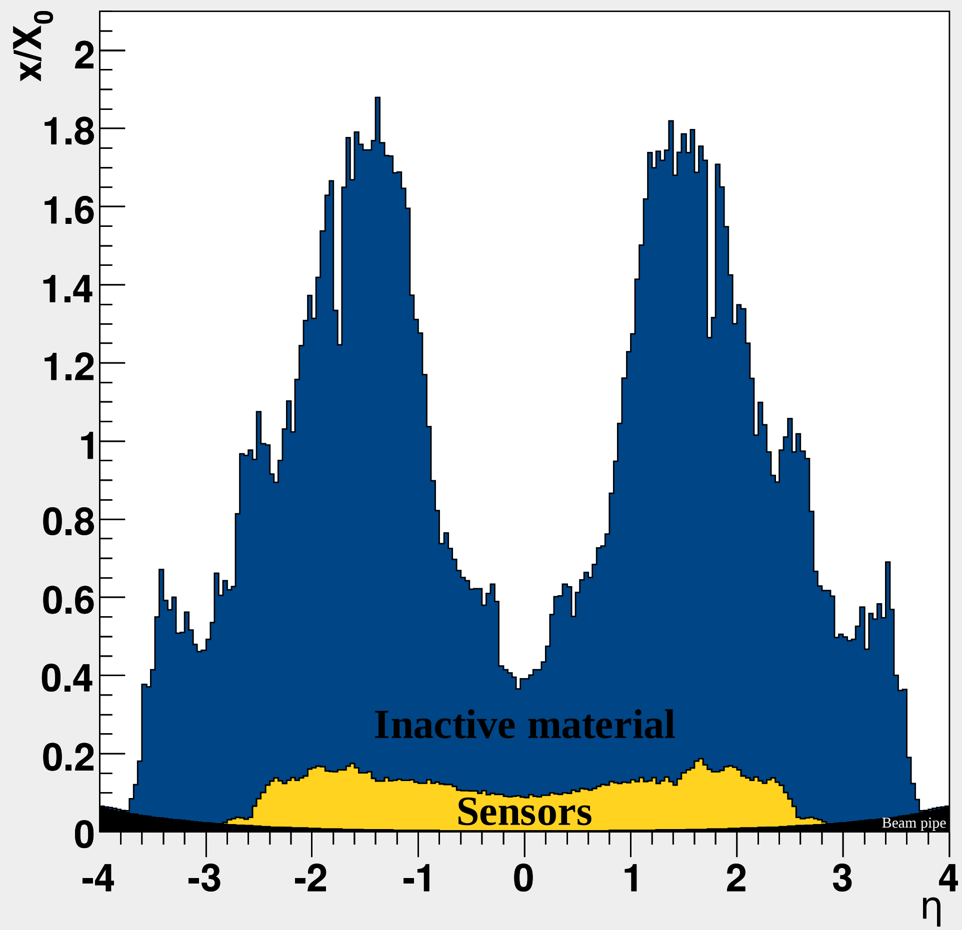
Relevant figures of merit for silicon detectors

Material amount	→	front-end, mechanics, services
Front-end **response time**	→	front-end
Single-hit **resolution**	→	front-end + sensors
Single-hit **efficiency**	→	front-end (noise) + sensors (signal)
Maximum **readout rate**	→	front-end
Size of active region	→	front-end + sensors

Tracking resolution is limited by material

- Most of the material is not in sensors, but still inside the tracking volume
- Best resolution achieved with lighter detectors
- Not necessarily by the highest single-hit resolution

Example: CMS Tracker Material Budget

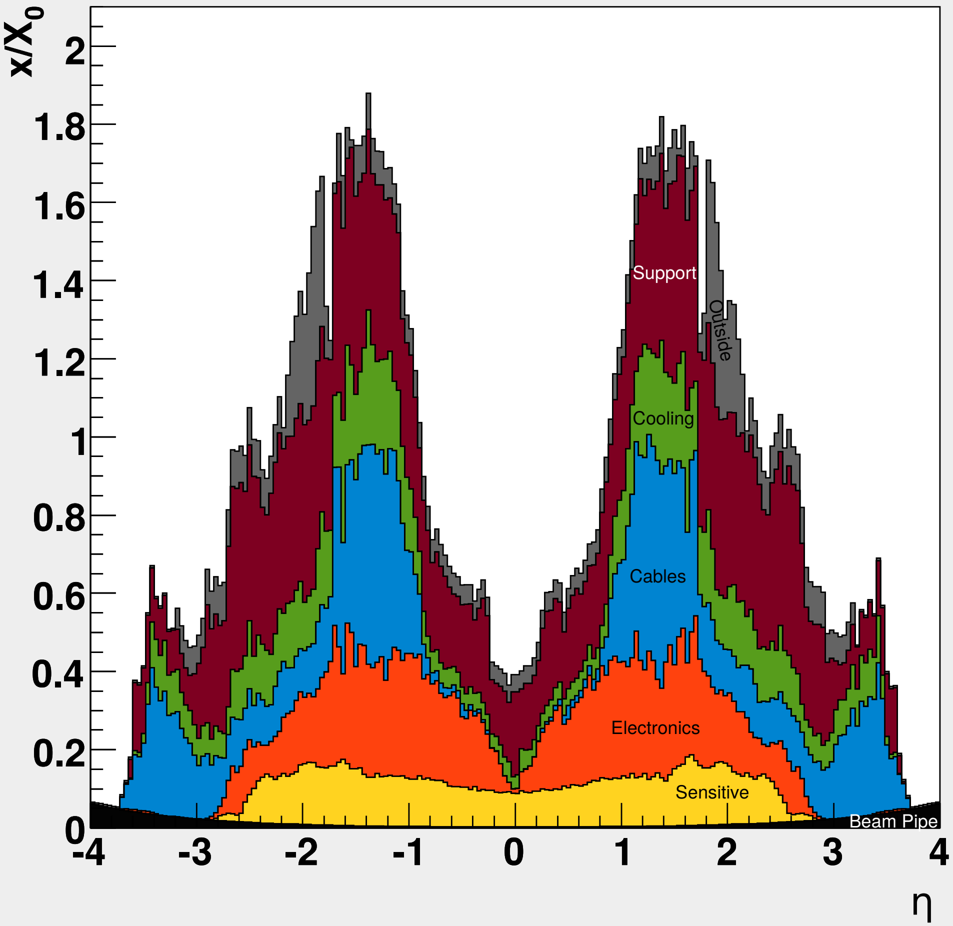


In collider experiments most the material is inside the tracking volume and multiple scattering is the dominant source of uncertainty on track parameters for pT typically up to 10 GeV/c. This means that detector optimization needs to take into account the material amount that goes with the detector.

Material is mainly driven by power

- Material budget spent (~equally) in:
  - **Support structures**
  - **Cooling lines (= power)**
  - **Power supply (& bias)**
  - **Auxiliary electronics**
- Design low-power electronics

Example: CMS Tracker Material Budget



Most of the inactive material is somehow driven by the power consumption in the detector. Therefore a good strategy to minimize the material:

- Design for power-lean front-end electronics
- Design for simple & light support structures
- Design detector modules that require little or no additional auxiliary electronics

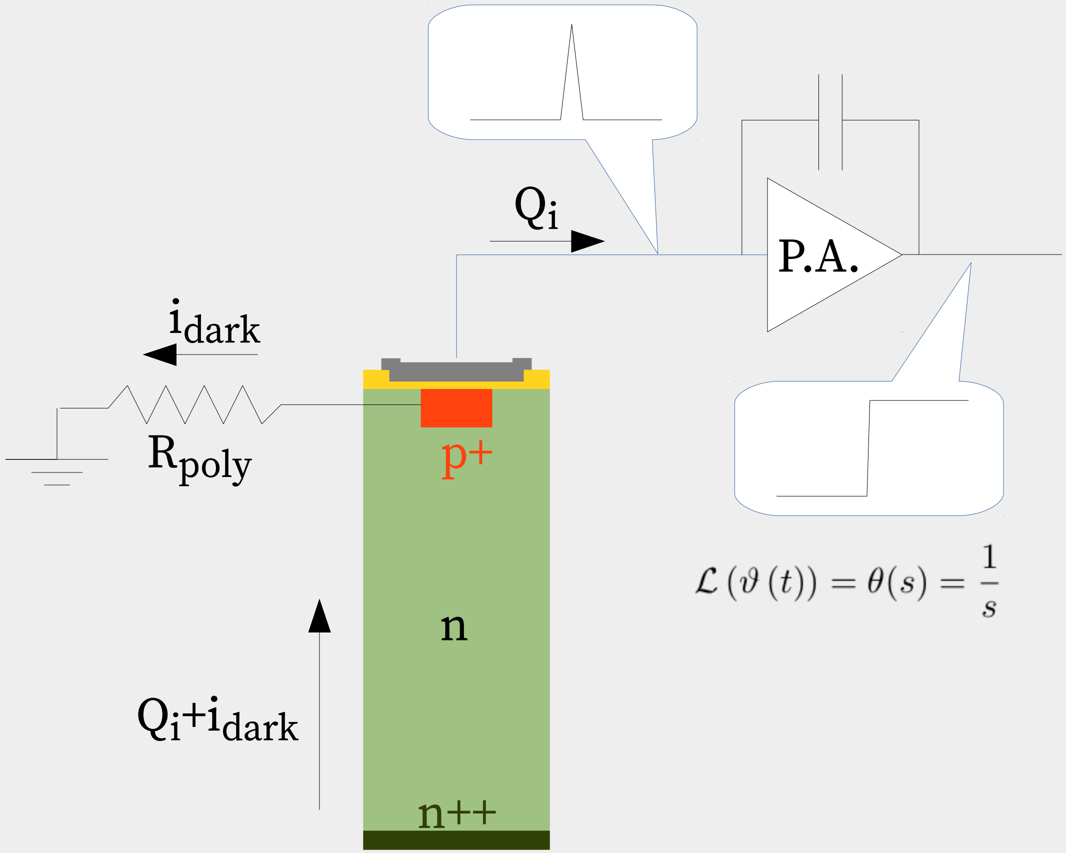
This approach leads away from optimizing the single-hit resolution, for example in HL-LHC CMS Tracker binary readout will be used, losing the charge release information on each hit (no barycenter method)

Relevant figures of merit for silicon detectors

Material amount	→	front-end, mechanics, services
Front-end **response time**	→	front-end
Single-hit **resolution**	→	front-end + sensors
Single-hit **efficiency**	→	front-end (noise) + sensors (signal)
Maximum **readout rate**	→	front-end
Size of active region	→	front-end + sensors

Front-end response time…

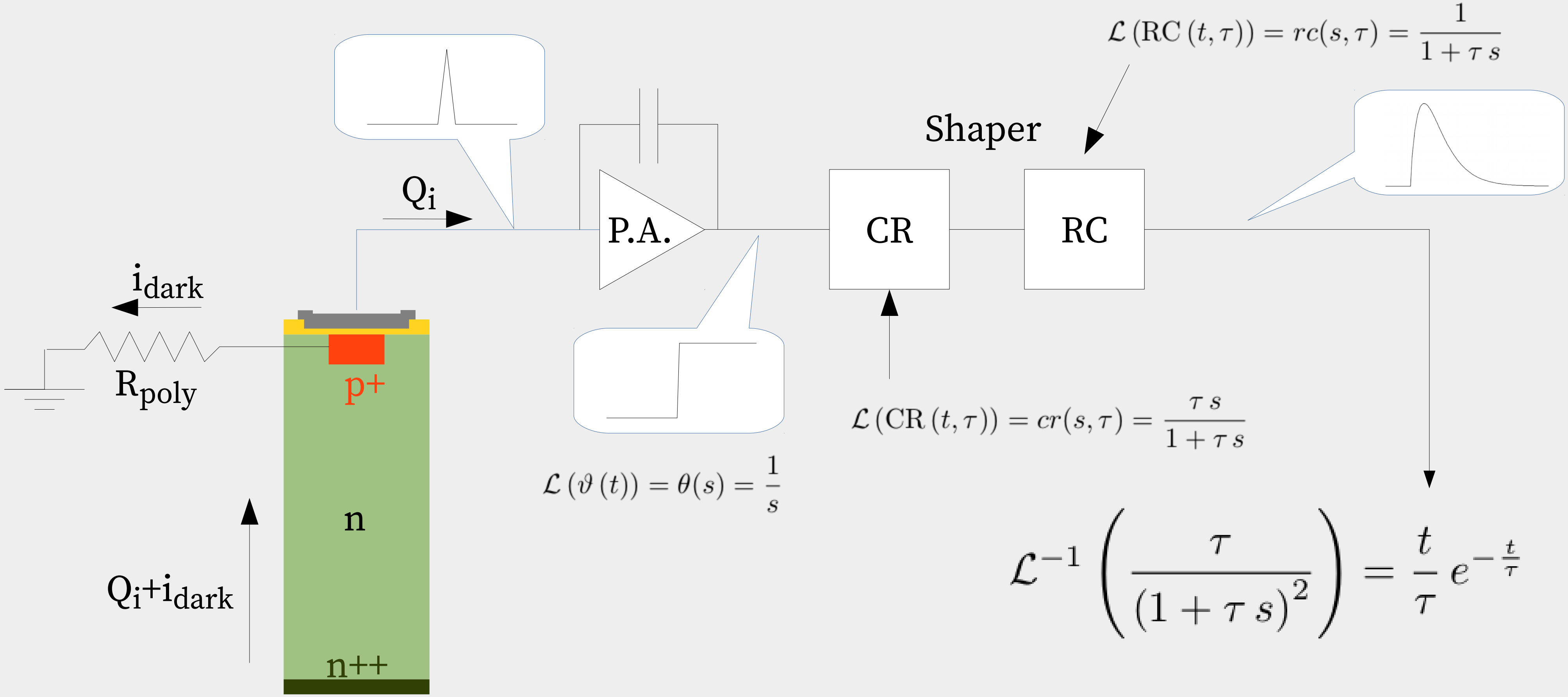
Small signal (ke-): amplification needed



$$\mathcal{L}\left(\vartheta\left(t\right)\right) = \theta(s) = \frac{1}{s}$$

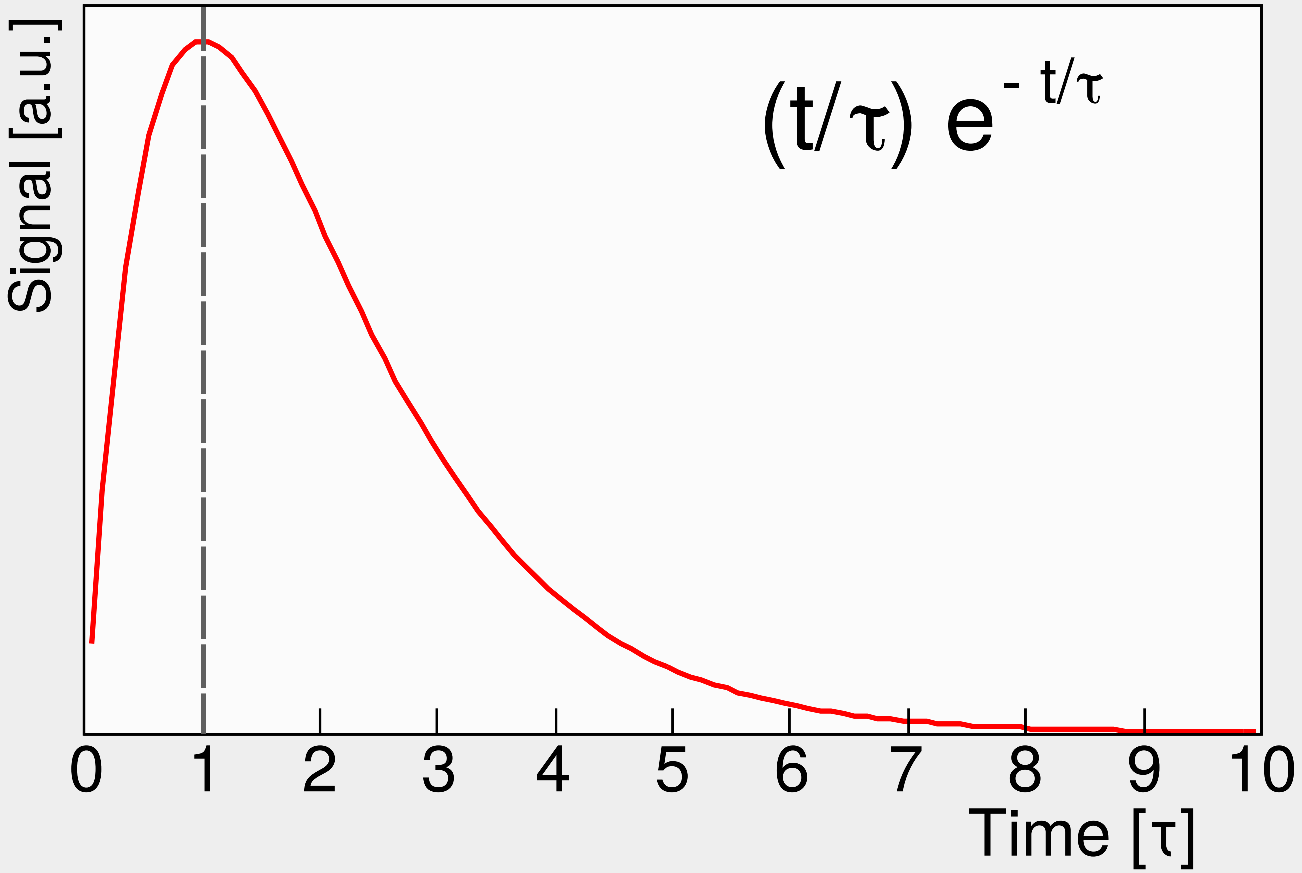
Front-end response time...

Well-defined sampling time: shaping (amplitude proportional to input charge)



Front-end response time is given by electronics

Time response of preamp+shaper to a pulse signal



Relevant figures of merit for silicon detectors

Material amount → front-end, mechanics, services

Front-end **response time** → front-end

Single-hit **resolution** → front-end + sensors

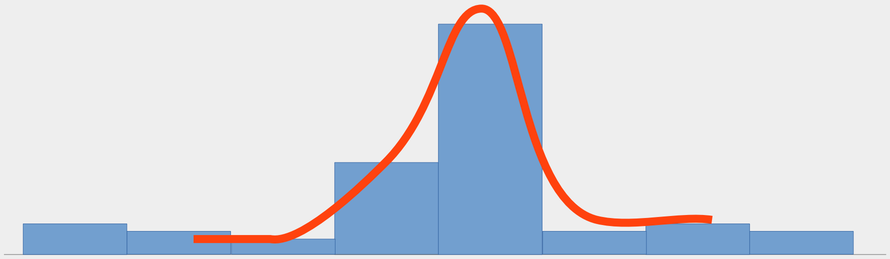
Single-hit **efficiency** → front-end (noise) + sensors (signal)

Maximum **readout rate** → front-end

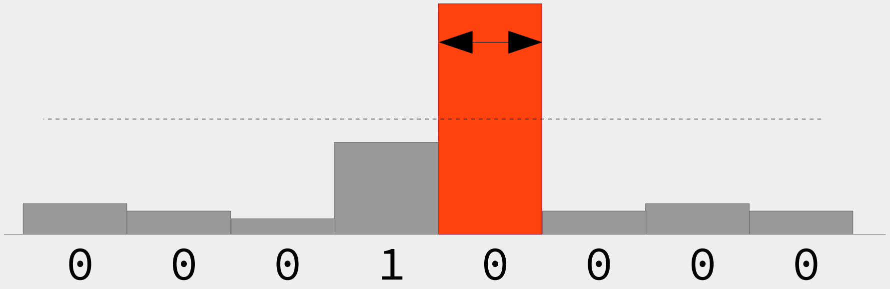
Size of active region → front-end + sensors

Single-hit resolution

- Proportional to segmentation of sensor: pitch
- Readout:
  - Analogue or ADC readout $\sigma = \frac{pitch}{Signal / Noise}$



  - Binary readout: above/below threshold $\sigma = \frac{pitch}{\sqrt{12}}$



Relevant figures of merit for silicon detectors

Material amount	→	front-end, mechanics, services
Front-end **response time**	→	front-end
Single-hit **resolution**	→	front-end + sensors
Single-hit **efficiency**	→	front-end (noise) + sensors (signal)
Maximum **readout rate**	→	front-end
Size of active region	→	front-end + sensors

Efficiency is usually very high (>99%) for **unirradiated detectors**. A Signal/Noise ratio of 10 to 15 is good enough to reach these efficiencies with good noise rejection.

Readout rate is determined by the design of the readout link of the front-ends

Size of the active region per module is limited to ~10× the size of the Read-out chip for pixel detectors and 10×10 cm^2 for strip detectors.

Modules are usually tiled to cover a larger area if needed, but this requires additional mechanics

Outline

~~MUonE tracker parameters~~

~~Figures of merit in silicon detectors~~

Analytic approach to detector optimization

Overview of current detectors

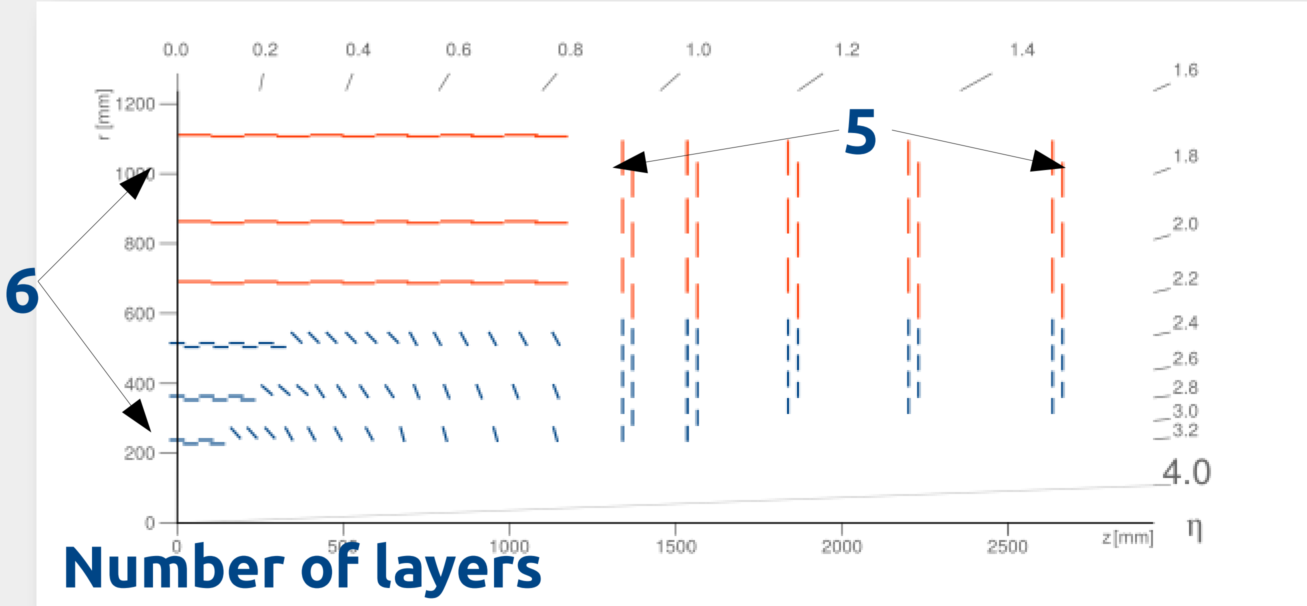
Initial considerations on detector resolution and systematic errors

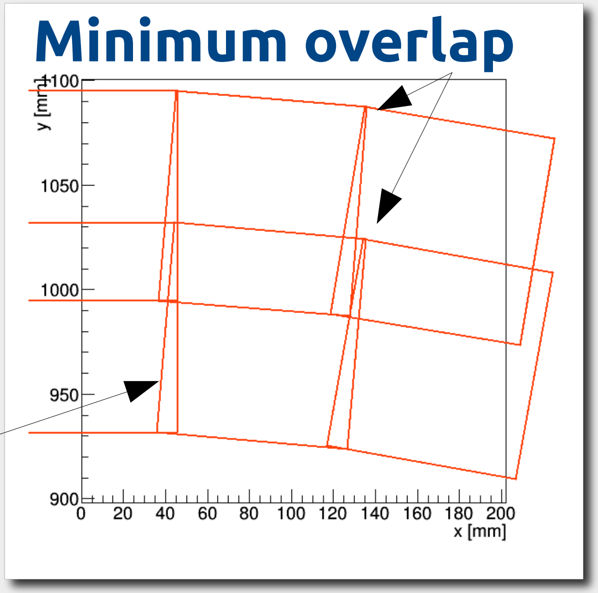
Detector optimization: analytic approach

- Recent experience in optimization of CMS Tracker for HL-LHC based on tkLayout

tkLayout layout building

Based on a simple set of parameters

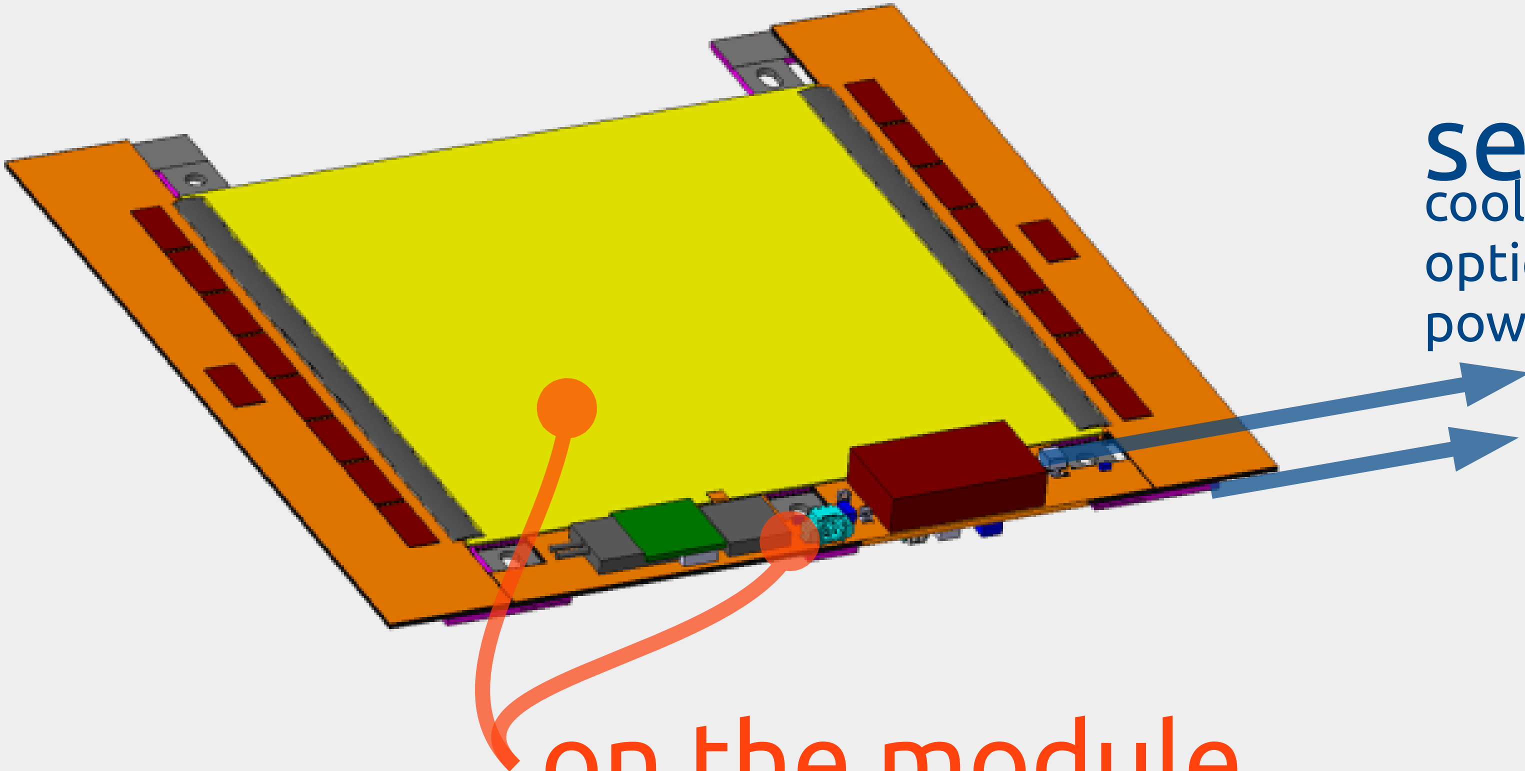




Sensor geometry

(e.g. square ~10×10 cm²)

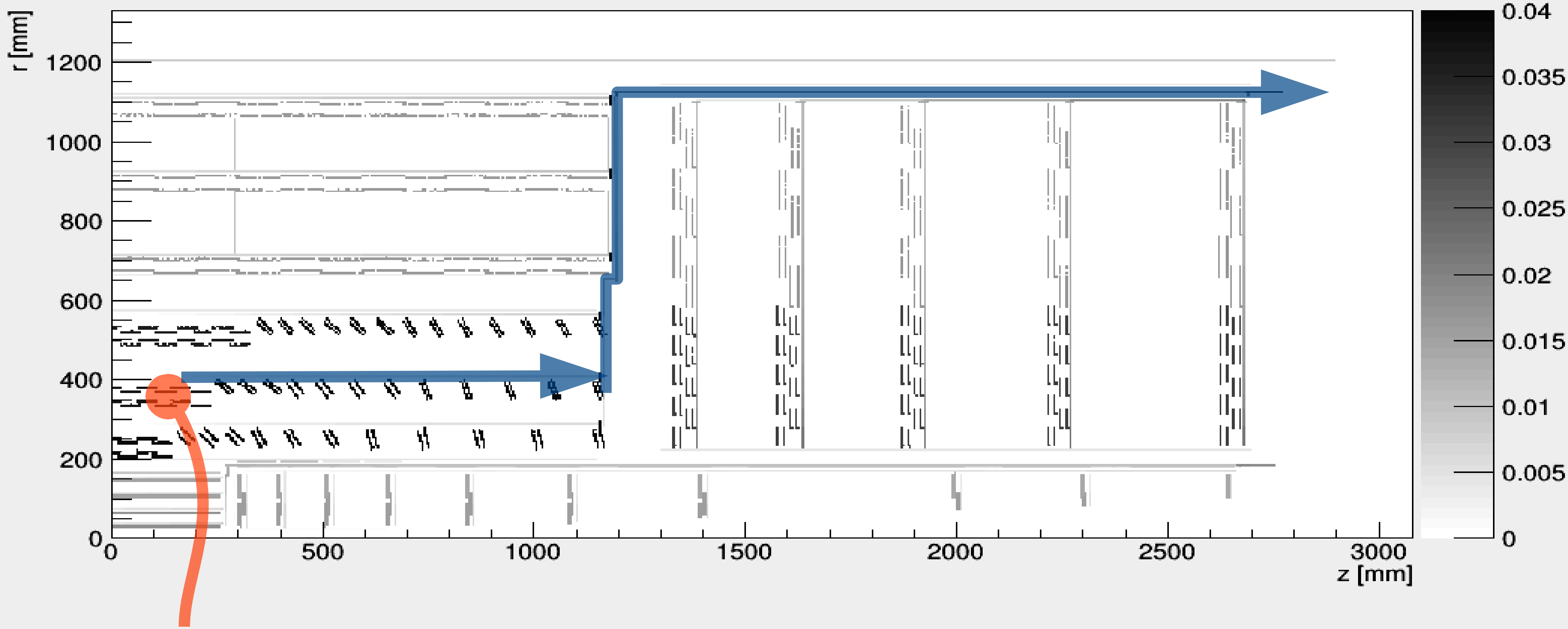
tkLayout material estimation



services
cooling pipes
optical fibres
power cables

on the module
sensor
hybrids & ASICs
cooling contacts

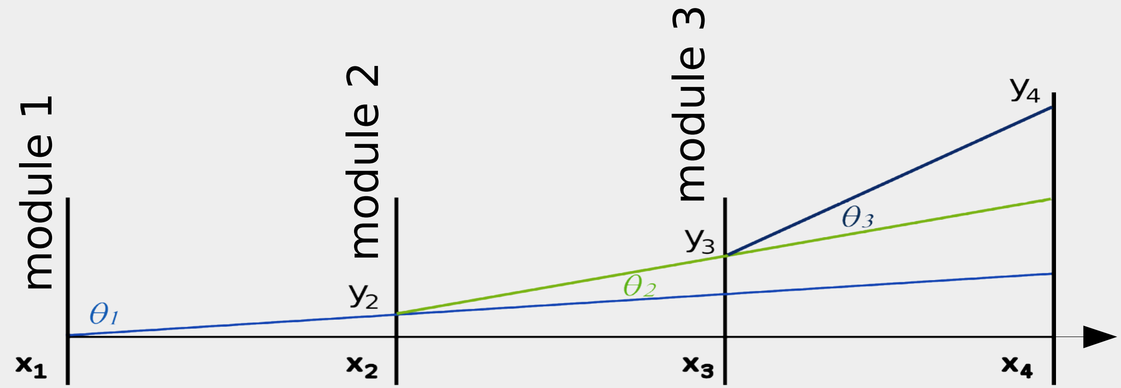
tkLayout material estimation



Material on active elements + Material for services automatically routed

tkLayout μ resolution estimation

- A priori error estimation
  - No Monte Carlo
  - No fit actually done

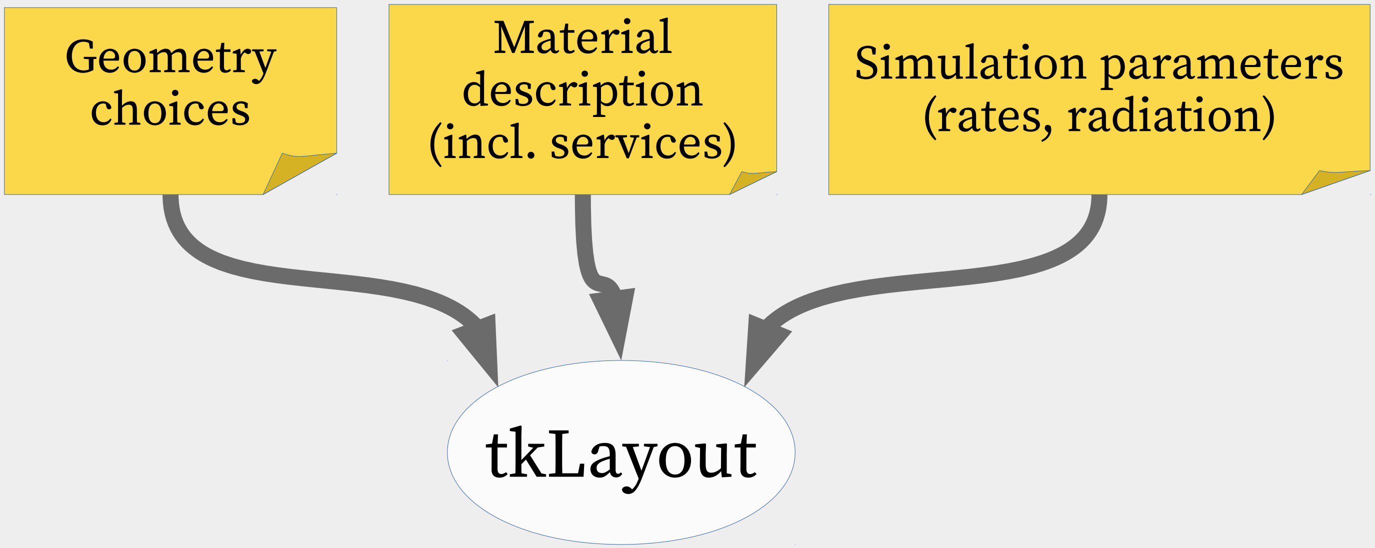


- Error propagation to estimate resolution of track parameters
  - Intrinsic resolution of the measurement point
  - Multiple scattering treated as a (correlated) measurement error

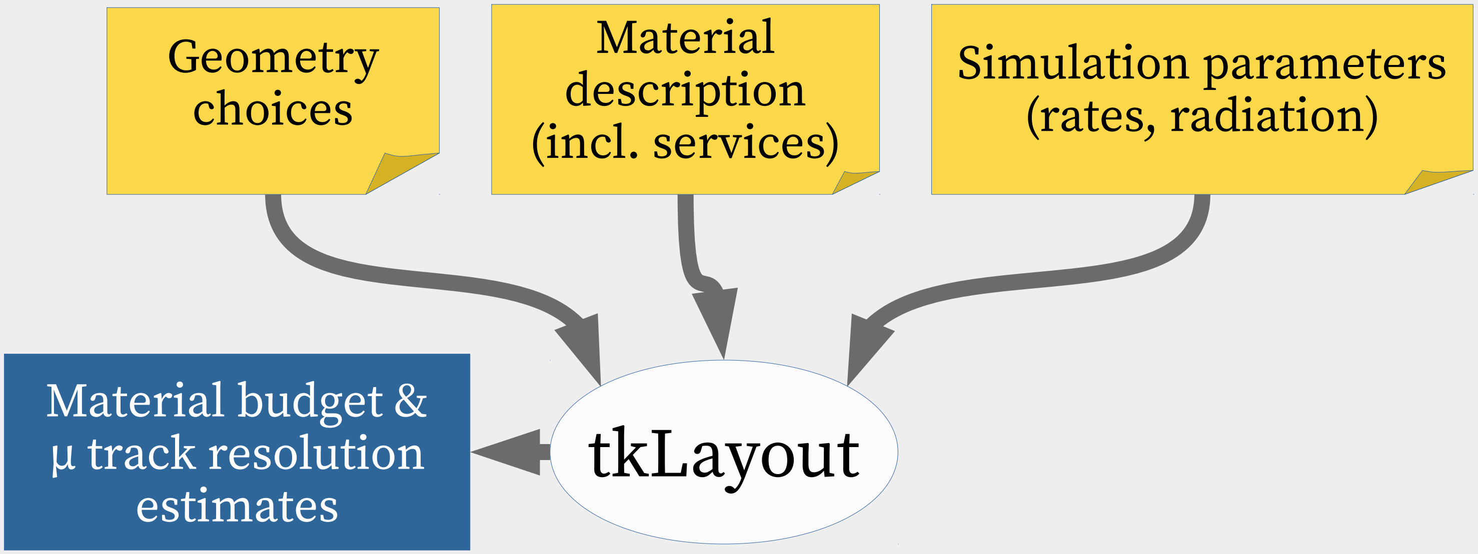
$$\sigma_n^2 = \left\{ \frac{p^2}{12},\ f\left(\text{angle of incidence}\right) \right\}$$

$$\sigma_{n,m} = \langle y_n y_m \rangle = \sum_{i=1}^{n-1} (x_m - x_i)(x_n - x_i)\langle \theta_i^2 \rangle$$

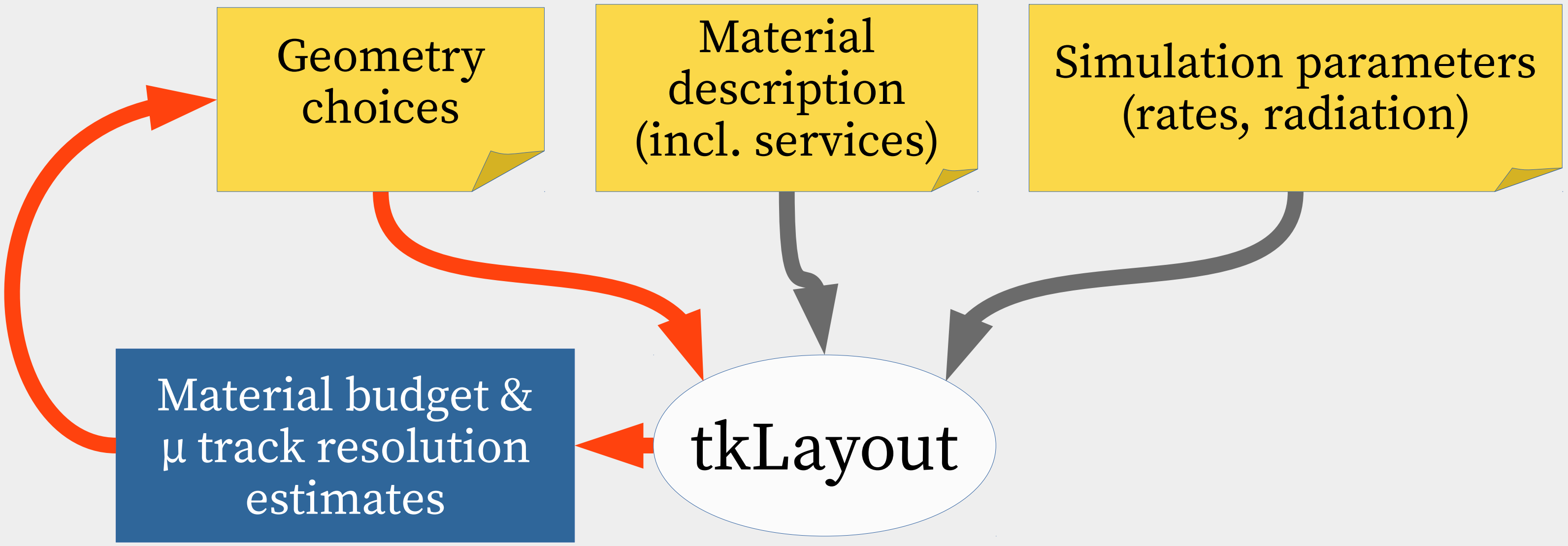
Design optimization work-flow



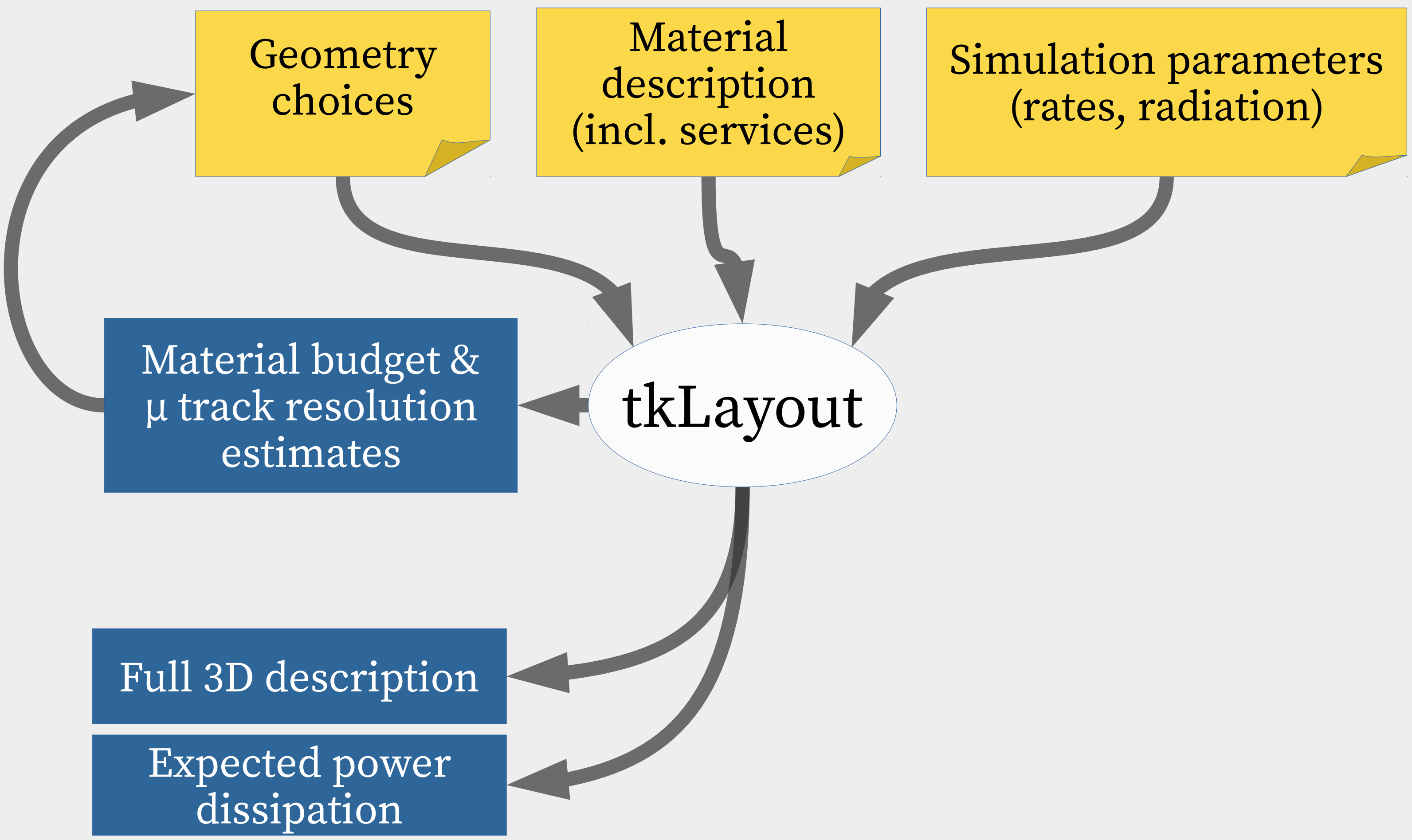
Design optimization work-flow



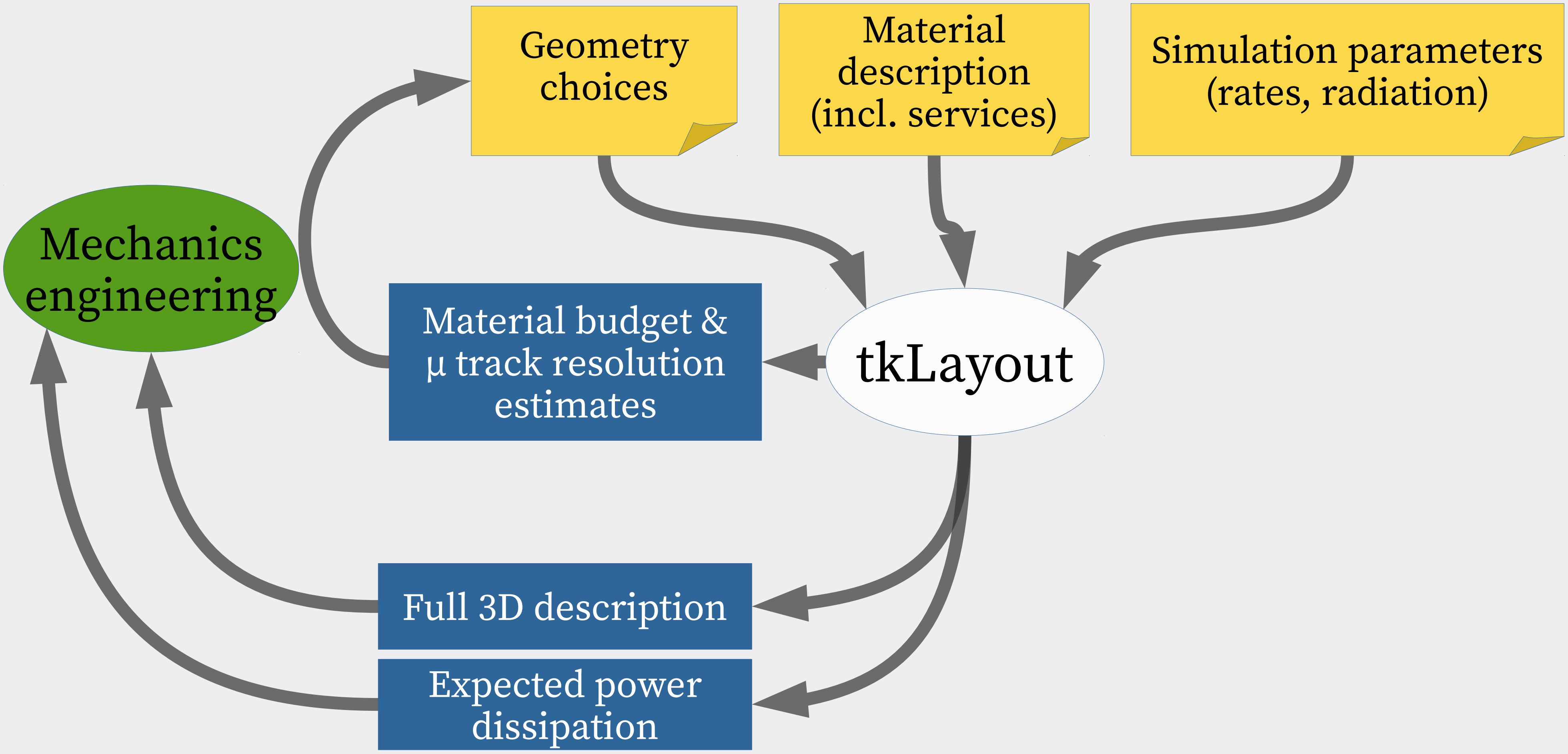
Design optimization work-flow



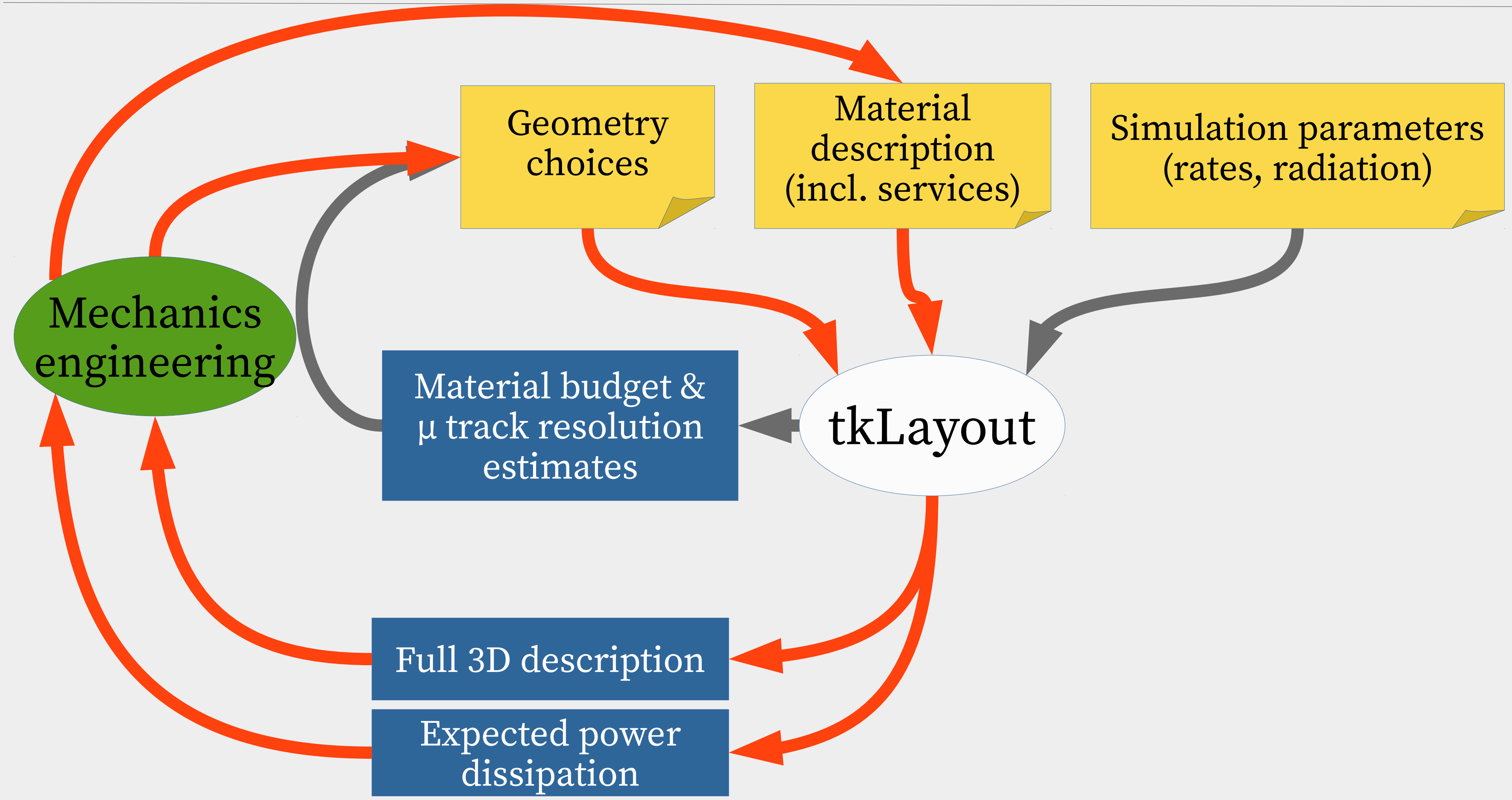
Design optimization work-flow



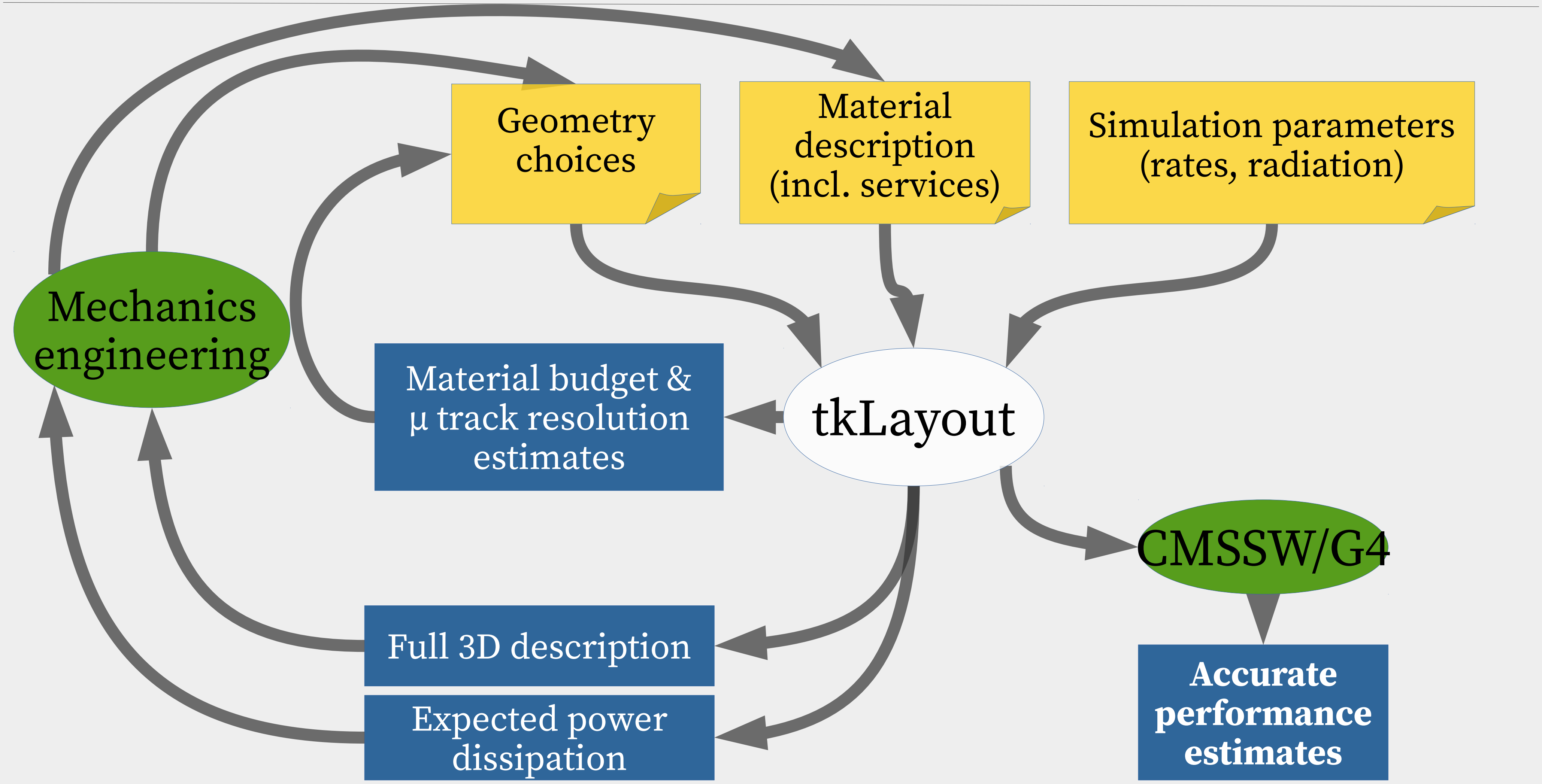
Design optimization work-flow



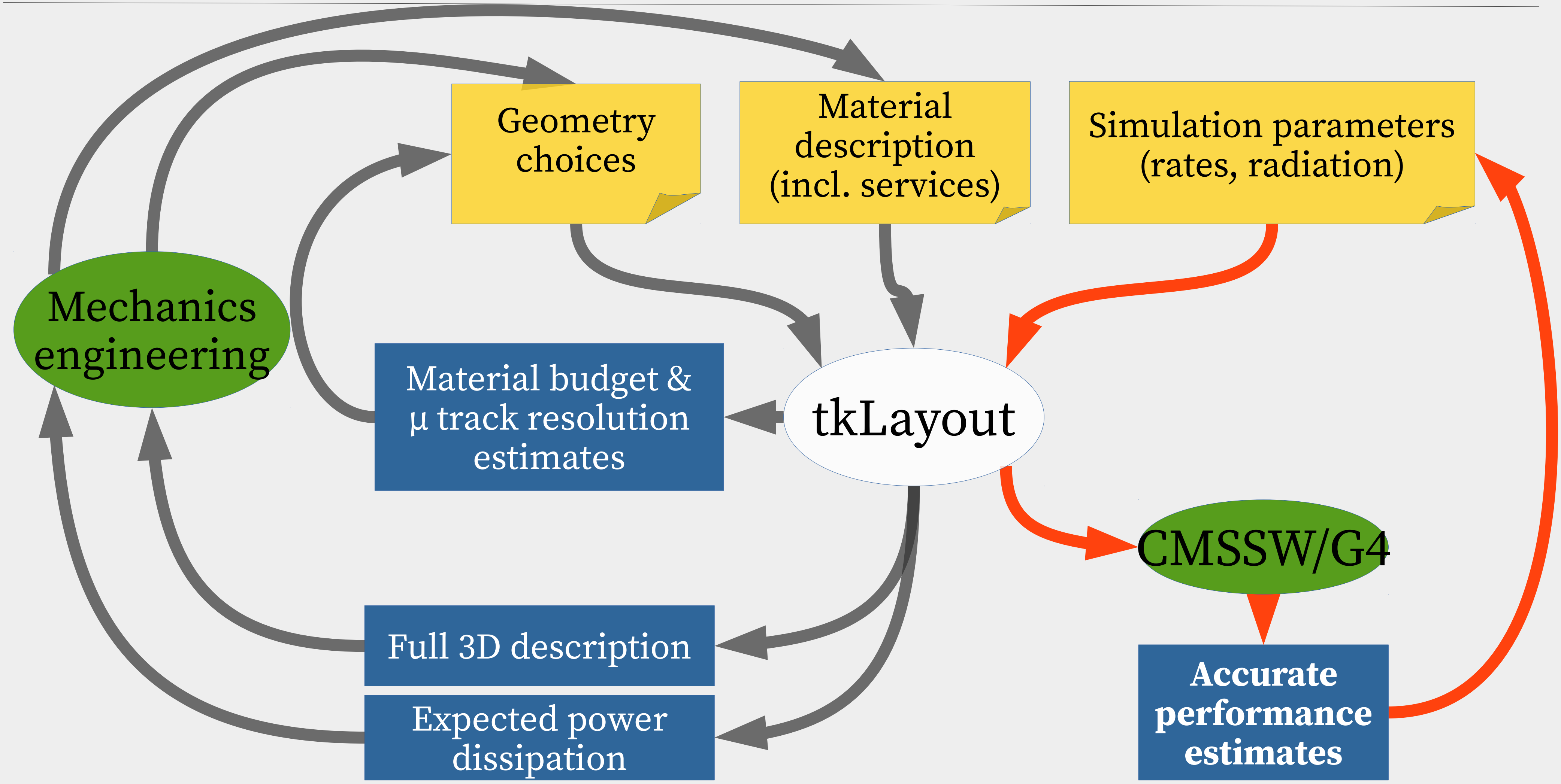
Design optimization work-flow



Design optimization work-flow



Design optimization work-flow



Initial considerations on tracking for MUonE

- Analytic tool should be produced (easy)
- Include tails of multiple scattering: parametrization?
- Main parameters to be optimized:
  - Which detectors
  - Measurement station spacing
  - Thickness of Be targets
  - Number of detector planes per measurement station

An analytic tool to evaluate the tracking resolution can easily be produced. This should be done for MUonE.
Several detector configurations should be studied with a similar tool (even batches of detectors). Evaluation of a single layout takes a few seconds at most.
The effect of tails in the MS distribution should be easy to include analytically, but a parametrization of this effect is needed.

Outline

~~MUonE tracker parameters~~

~~Figures of merit in silicon detectors~~

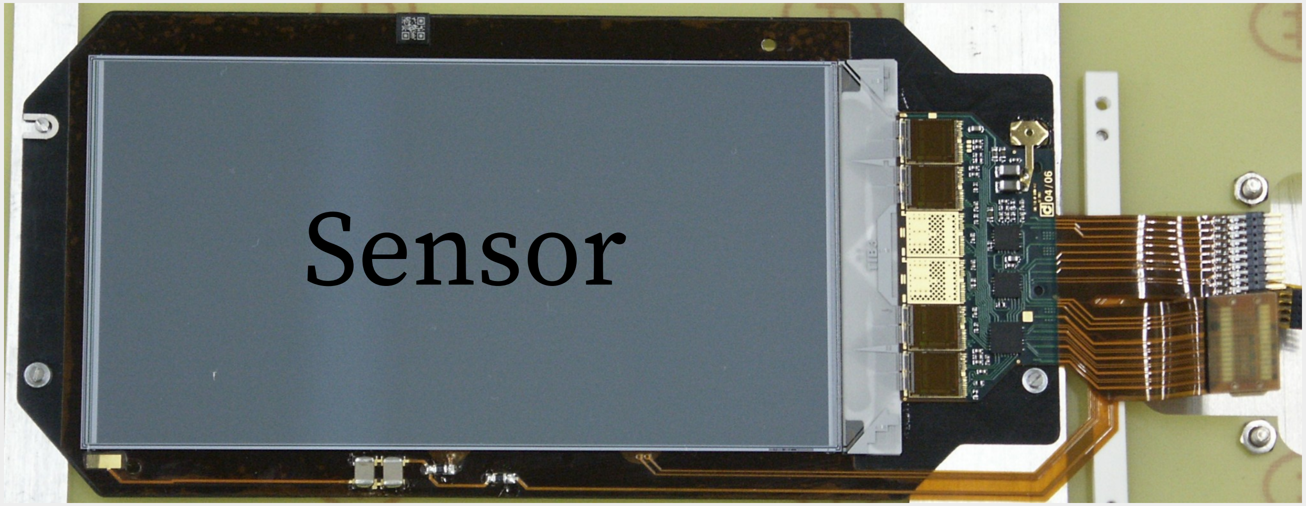
~~Analytic approach to detector optimization~~

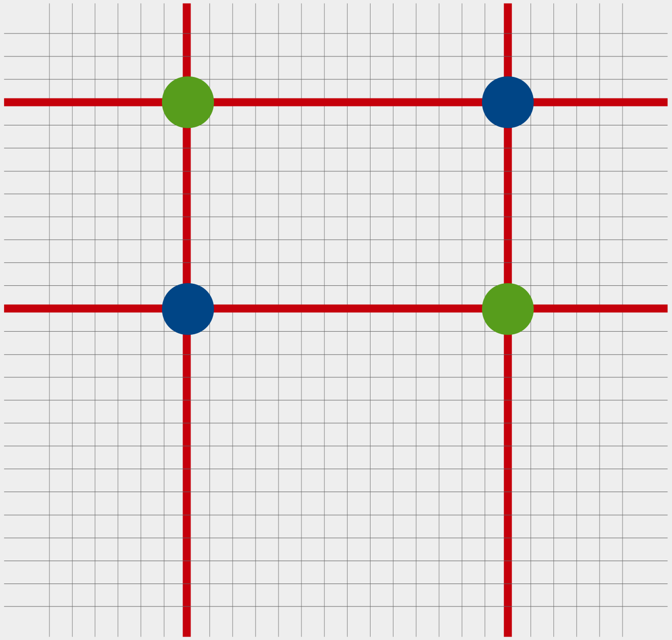
Overview of current detectors

Initial considerations on detector resolution and systematic errors

Strip hybrid detectors

- With large sensors 10×10 cm^2
- no dead material behind sensor
- x,y via two detectors 90°
- Hit position ambiguity
  with >1 track is present

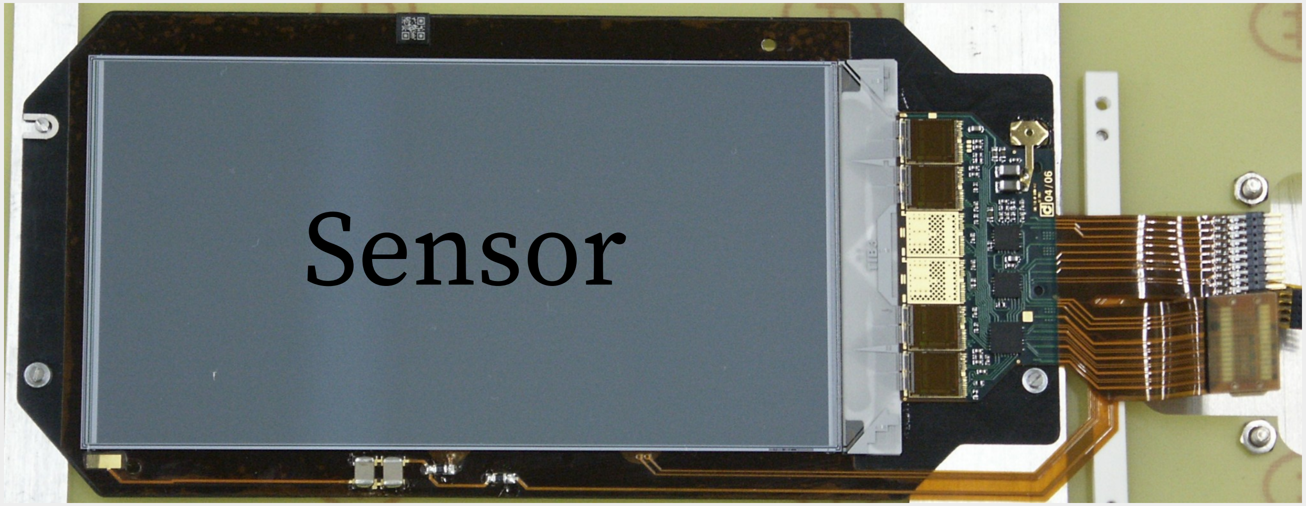




Pair of ● or ● hits?

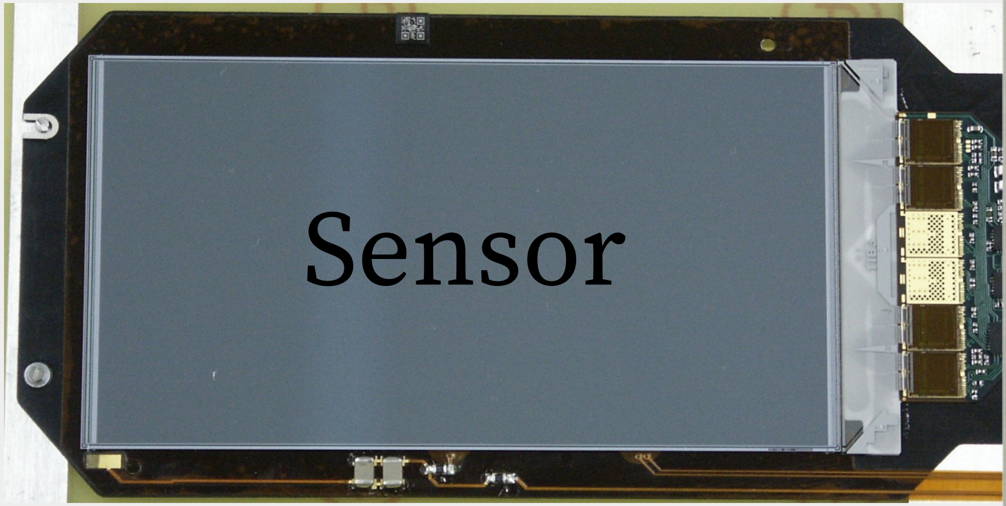
Strip hybrid detectors

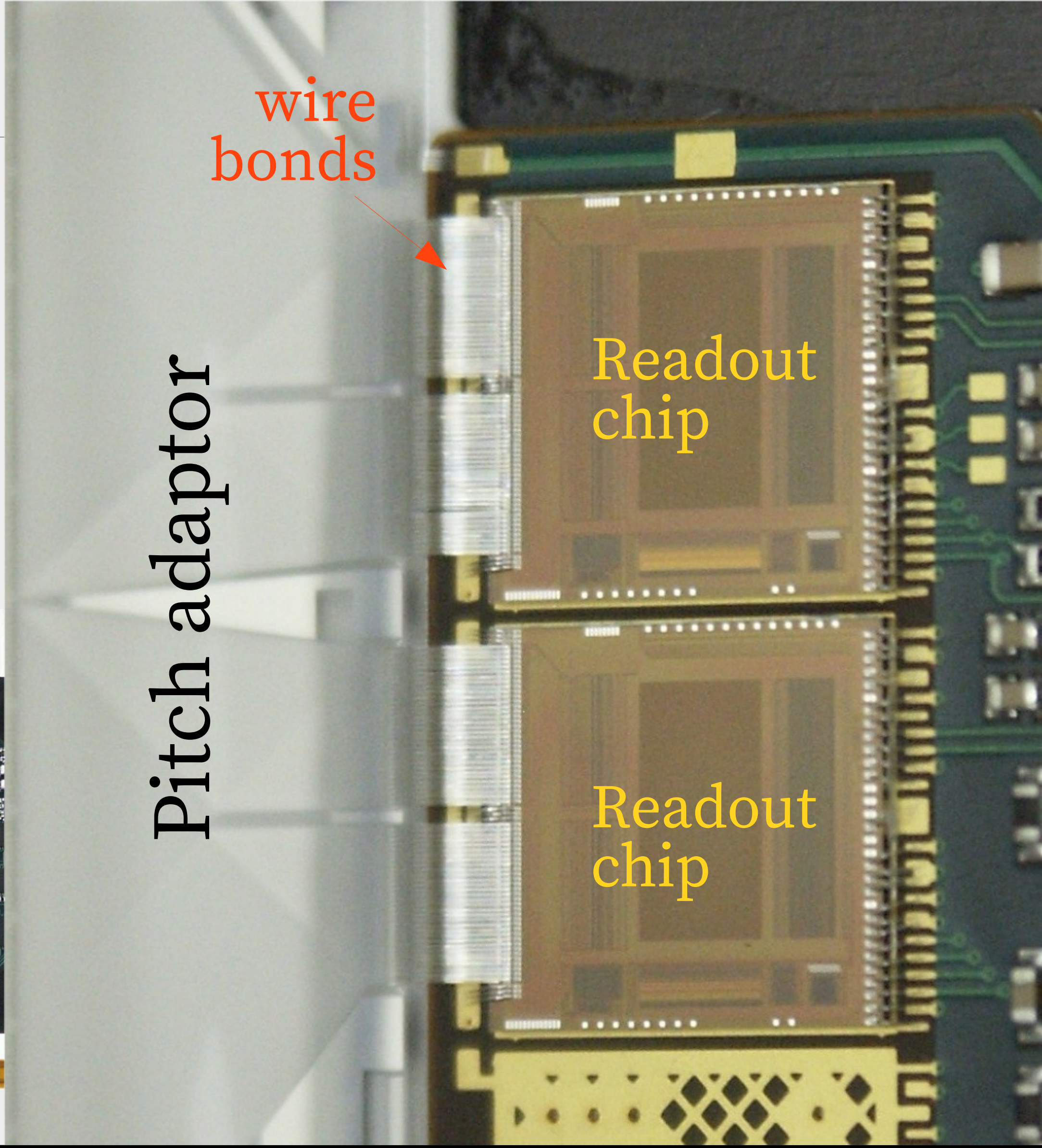
- With large sensors 10×10 cm^2
- no dead material behind sensor
- x,y via two detectors 90°
- Hit position ambiguity with >1 track is present



Strip hybrid detectors

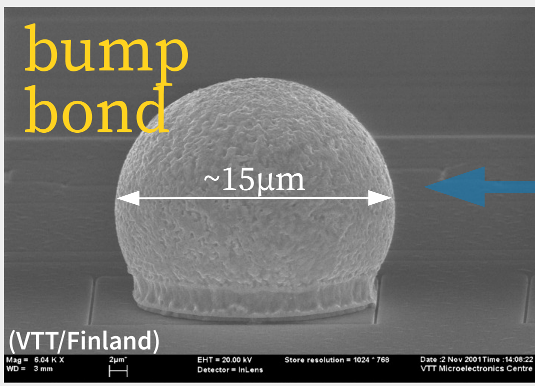
- With large sensors 10×10 cm^2
- no dead material behind sensor
- x,y via two detectors 90°
- Hit position ambiguity with >1 track is present

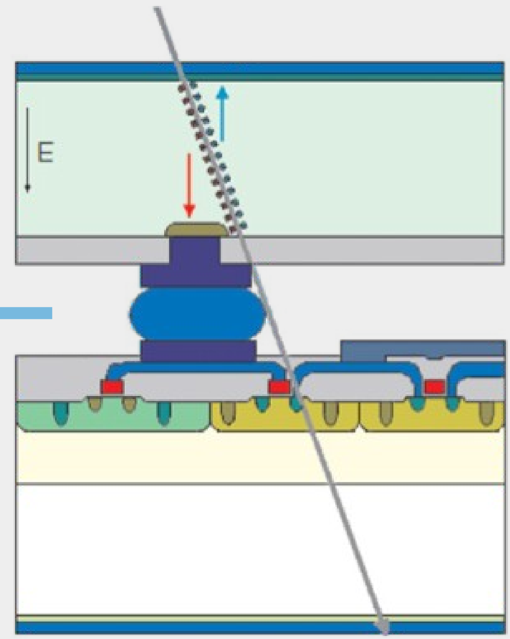




Pixel hybrid detectors

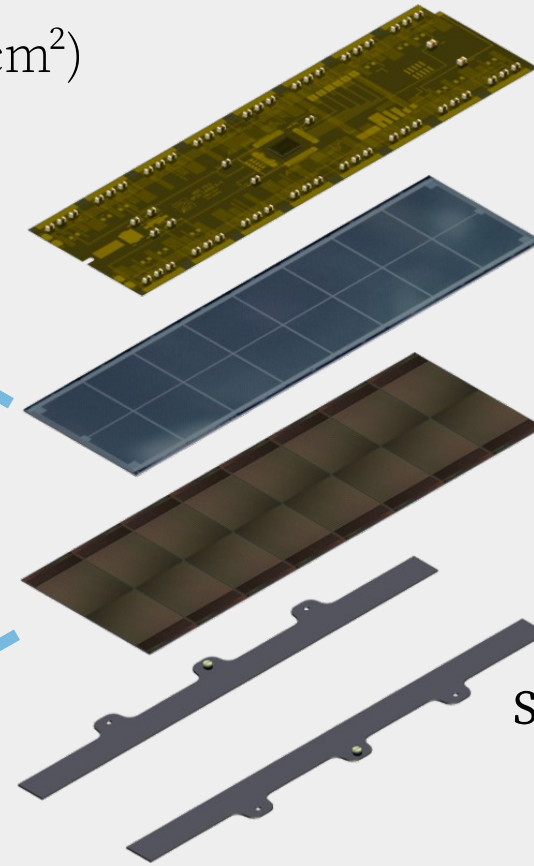
- Front-end electronics right behind the sensor
- Single hit resolution **~10 µm**
- Fast timing (**~25 ns**): high particle rates (100s MHz/cm^2)
- **Thick detectors**: $x/X_0 = 1 \rightarrow 3$ %





P. Riedler

e.g. CMS pixel

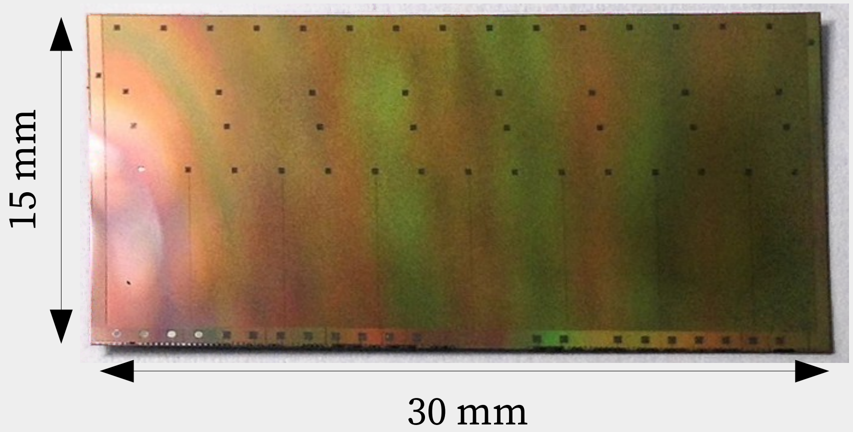


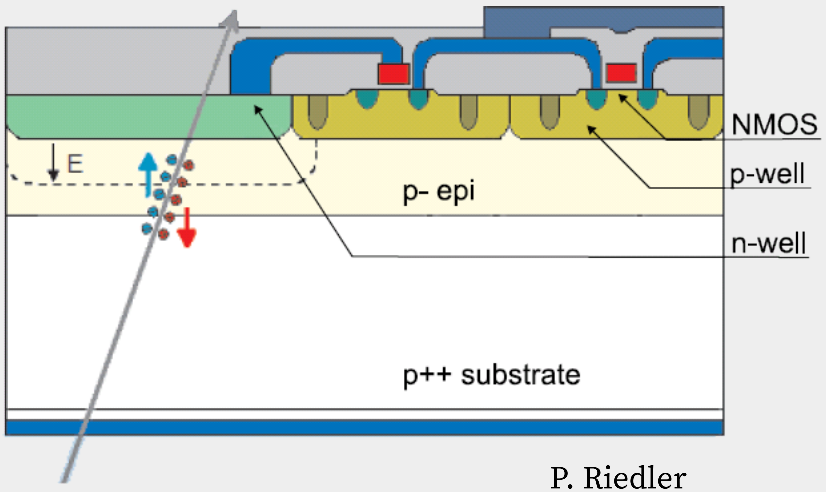
Sensor and ASIC are separate objects. Complex readout with zero-suppression and in-pixel hit buffering is possible. With fast signal shaping these detectors can be designed to work with **very high hit rates**. Since sensor and front-end chip are different objects, the respective design can be individually optimized for radiation environment. Interconnection is needed to connect each pixel in the sensor to a readout cell in the ASIC: fine pitch bump bonding is needed: **limit to the pixel size**. With this approach the detectors material is not negligible: typically x/X_0 = 1 to 3%
This technology choice is favorite at LHC/HL-LHC due to the high particle rate and radiation environment.

Monolithic Active Pixel (MAPS)

- Front-end electronics integrated with sensor
- Single hit resolution **~2 µm**
- Slow timing (**~1 µs**): limited particle rates
- **Thin detectors**: $x/X_0 = 0.3$ %

Alice ITS Chip: ALPIDE





P. Riedler

Charge generation volume integrated into the ASIC. Several variants are possible. In this example CMOS sensor, with on-chip digital readout architecture. Assembly much simpler and cheaper than hybrid pixels. Small pixel features are possible (28×28 µm in Alice ITS upgrade) and very thin detectors are easily implemented with this technique (0.3% in Alice ITS). This technology is limited in particle rate and radiation hardness: so far monolithic CMOS sensors were designed for (relatively) low-radiation environments.

Examples of recent tracker designs

Alice Inner Tracker System: ALPIDE
- MAPS
- Low power ← long integration time in front-ends
- Simple electronics ← integration of sensor with amplifiers
- Very light support structures

LHCb upgrade: VELOpix
- Hybrid pixels
- Auxiliary material outside tracking volume
- Very fast electronics: every event is recorded

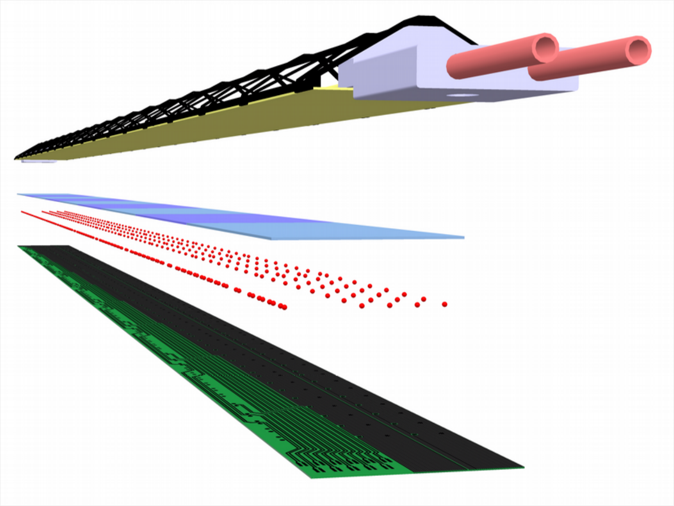
CMS Outer Tk for HL-LHC: CBC
- Hybrid strip
- Binary readout (no ADC to reduce bandwidth → power)
- Target: LS3

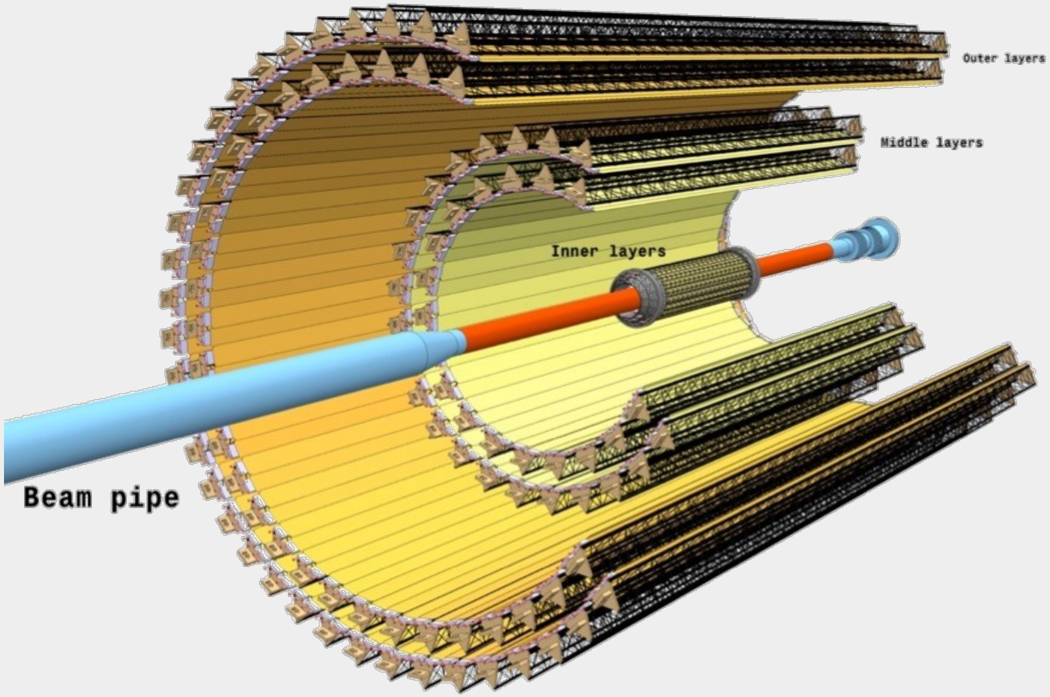
CMS Inner Tk for HL-LHC: RD53
- Hybrid pixel
- 4 bits ADC to reduce bandwidth & power
- Target: LS3

Examples of recent tracker designs

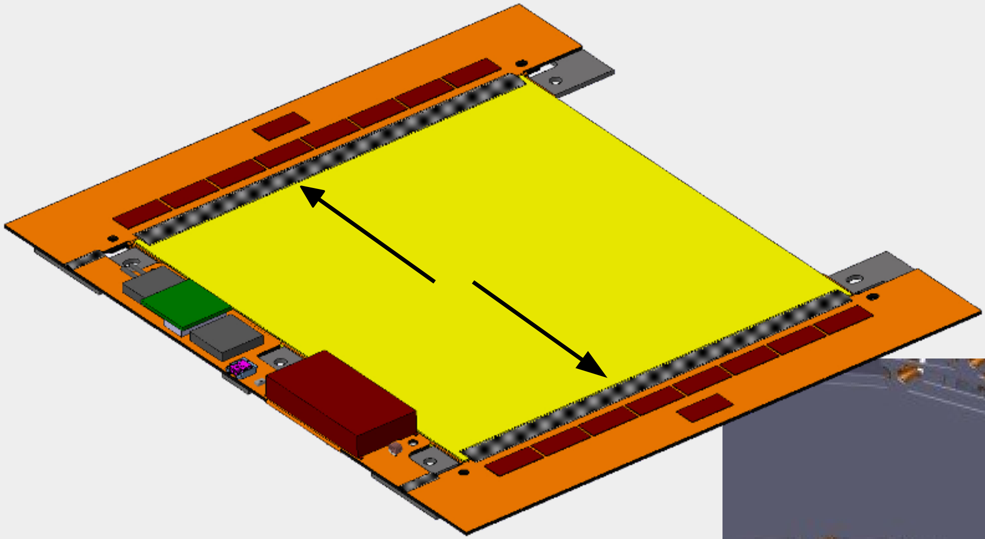
Alice Inner Tracker System: ALPIDE

- MAPS
- Low power ← long integration time in front-ends
- Simple electronics ← integration of sensor with amplifiers
- Very light support structures



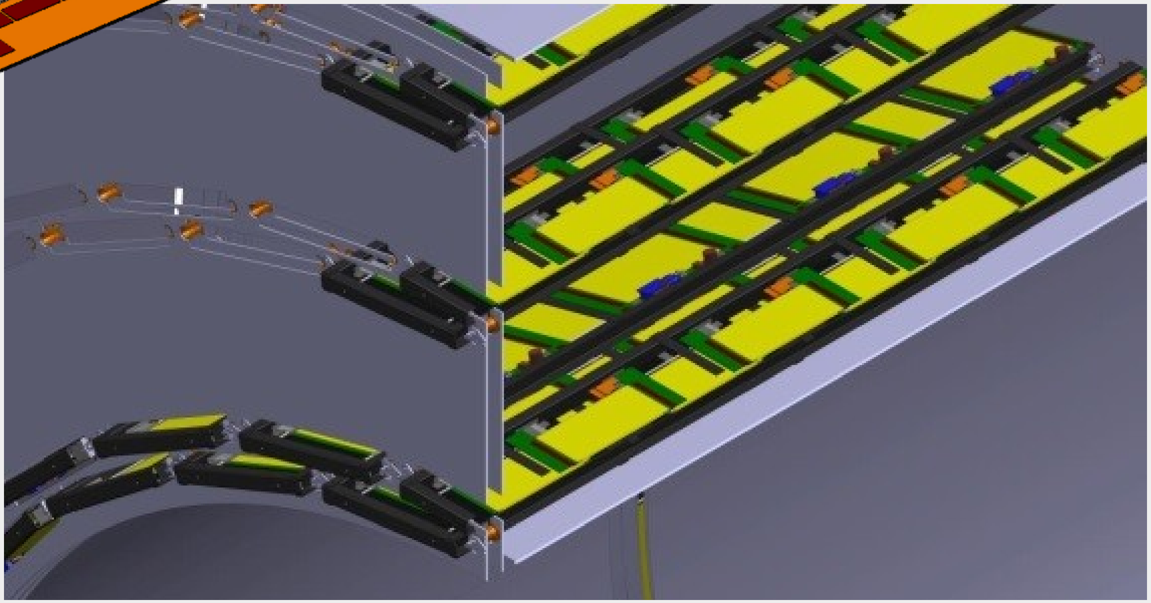


Examples of recent tracker designs



CMS Outer Tk for HL-LHC: CBC

- Hybrid strip
- Binary readout (no ADC to reduce bandwidth → power)
- Target: LS3



Outline

~~MUonE tracker parameters~~

~~Figures of merit in silicon detectors~~

~~Analytic approach to detector optimization~~

~~Overview of current detectors~~

Initial considerations on detector resolution and systematic errors

Detector procurement

	ALICE Upg Inner	**ALICE** Upg Outer	**CMS** Upg 2S	2×**CMS** Upg 2S	**CMS** Upg PS	**CMS** Upg Pixel	2×**CMS** Current	**Mimosa26**	**LHCb** VELO-pix
Technology	MAPS	MAPS	Hybrid strip	Hybrid strip	Hybrid strip/px	Hybrid pixel	Hybrid strip	MAPS	Hybrid pixel
active x [cm]	27	21	10	10	10	33	10	1.06	4.246
active y [cm]	1.5	3	10	10	5	44.2	10	2.12	1.408
pixel size x [µm]	30	30	90	90	100	50	90	18.4	55
pixel size y [µm]	30	30	50000	90	1400	50	50000	18.4	55
σx [µm]	2	2	26	26	29	7	18	3.2	12
σy [µm]	2	2	14434	26	404	7	18	3.2	12
Material [x/X_0]	0.3%	0.8%	2.3%	4.5%	3.8%	2.0%	4.5%	0.10%	0.94%
Sensor mat. [x/X_0]	0.3%	0.8%	0.3%	0.6%	3.8%	2.0%	0.6%	0.10%	0.94%

In HEP experiments a large effort is needed to produce new detectors. Most of the effort goes into the design, production and qualification of the front-end electronics, which is also expensive. Using already-existing front-ends is a good way to contain cost and risks.

Here a few detectors are compared. New detector productions could be easily incremented by a few units to cover for MUonE needs, but it is also possible that older detectors (e.g. APV25) can be adapted, possibly with a new sensor production.

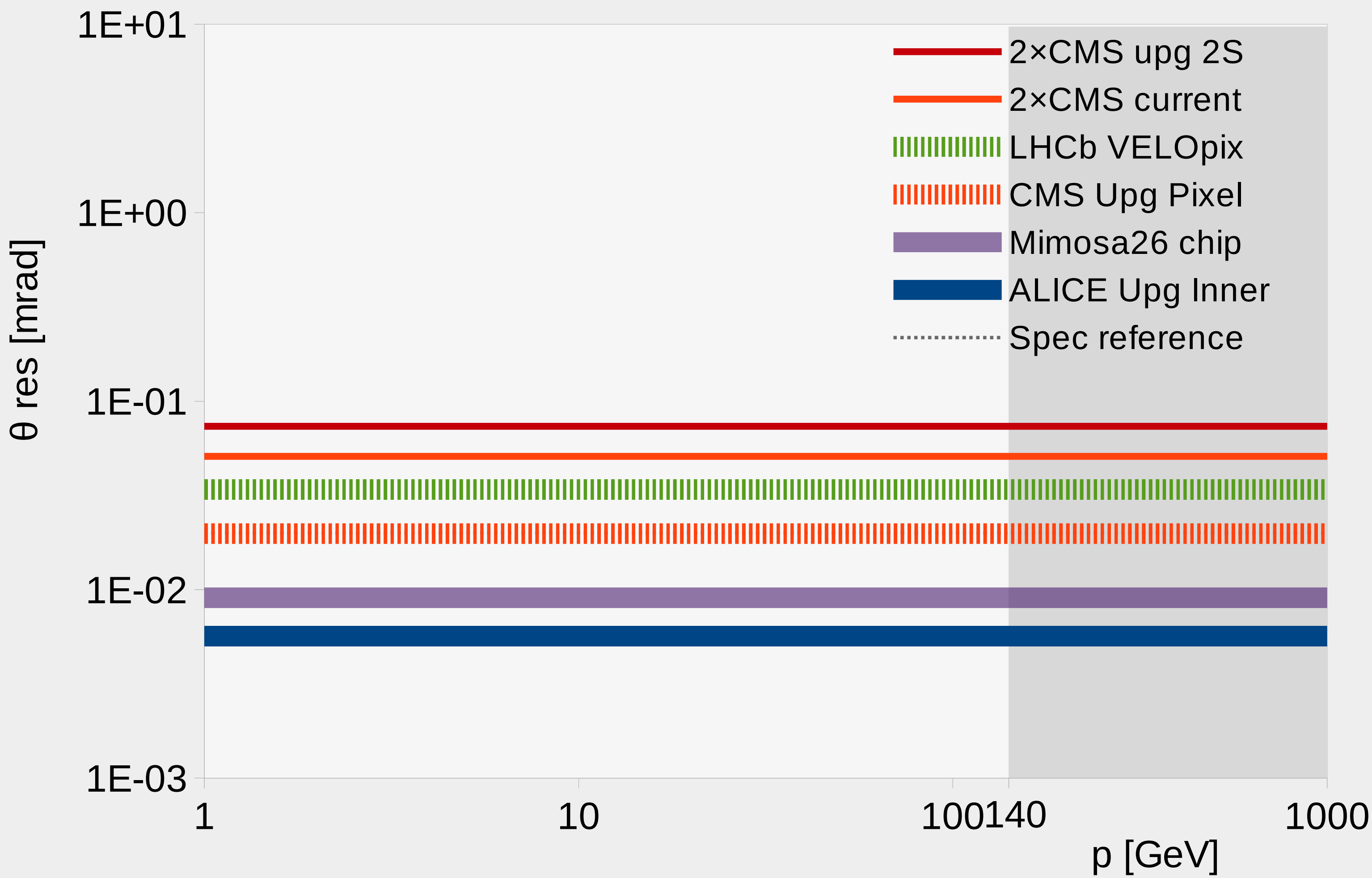
For simplicity, from here on I am going to focus on a subset of these detectors.

Simple analytic considerations

Resolution on scattering angle assumptions:

- 2 measurement planes
- 0.5 m apart
- Scattering on:
  - No plane (ideal resolution)
  - First detector plane (pure tracker resolution)
  - First plane + ½ Be target (includes “average” MS in target)
- Core of MS only considered (no tails)

Purely geometric resolution is ideal



Angle resolution:

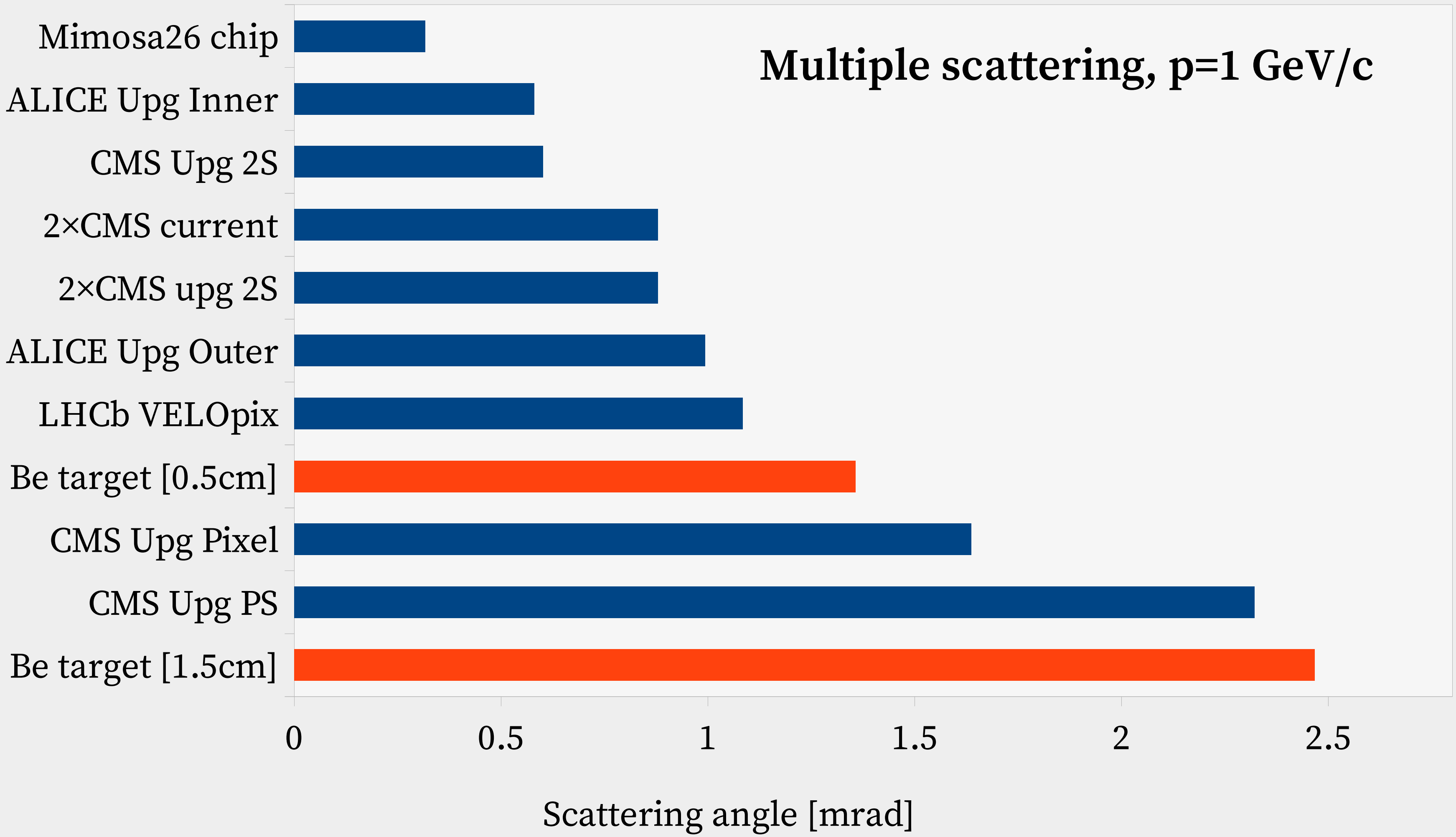
$$\Delta\theta^2 = \Delta\theta_I^2$$

Angle intrinsic resolution:

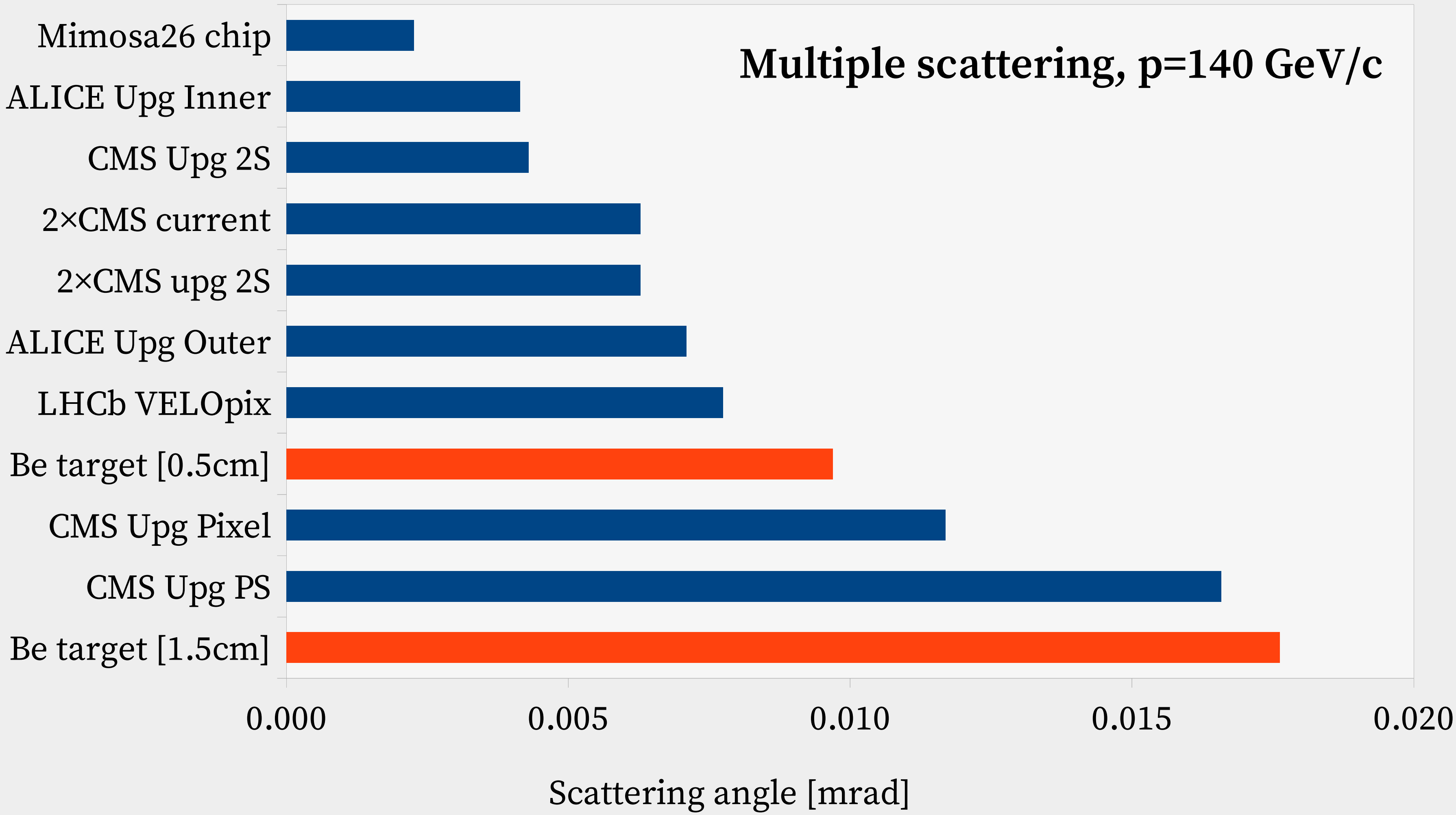
$$\Delta\theta_I = \frac{\Delta x\sqrt{2}}{0.5\,\mathrm{m}}$$

No scattering: resolution does not depend on p

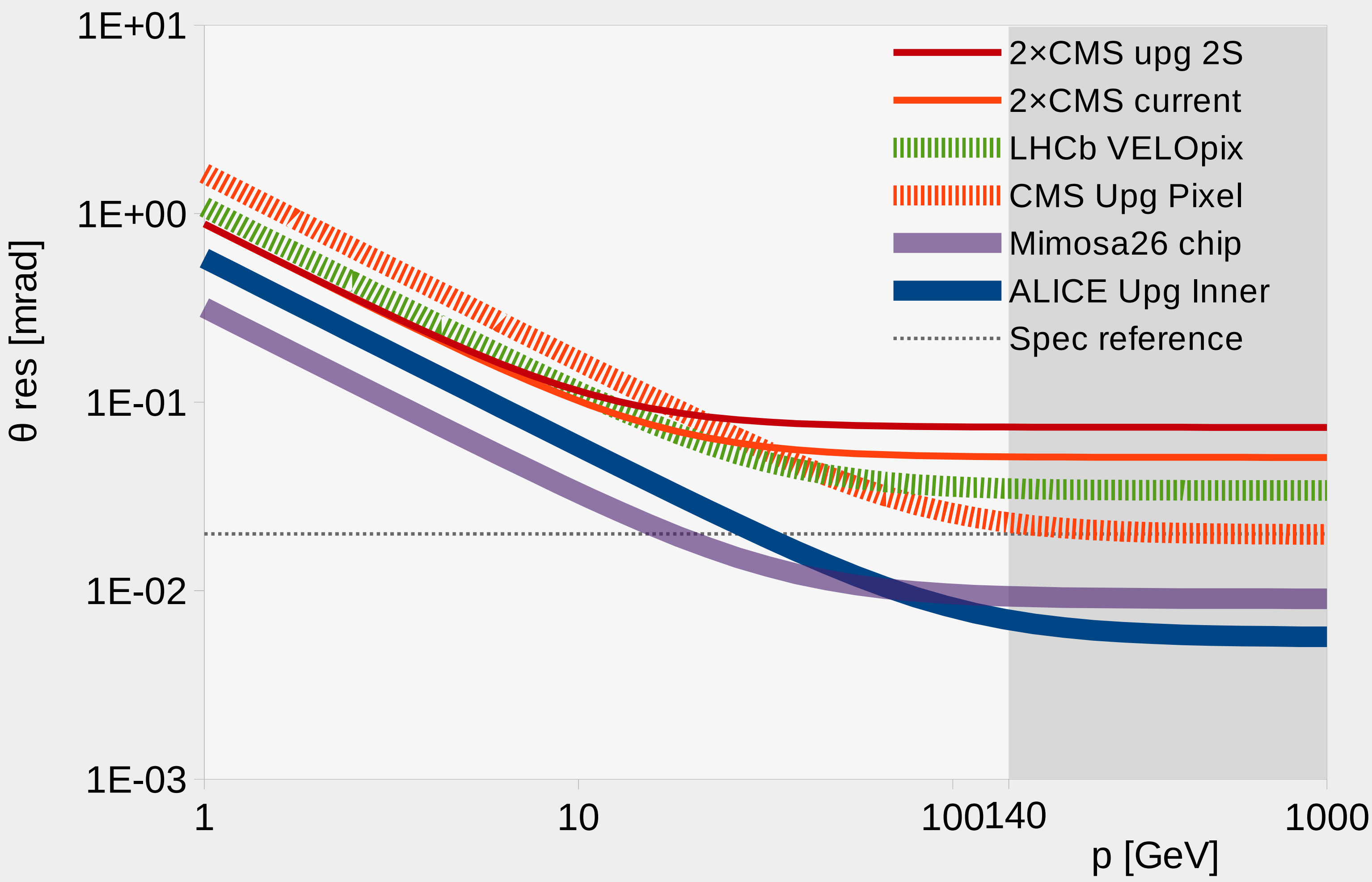
Multiple scattering angle



Multiple scattering angle



Resolution dominated by MS up to 10~100 GeV/c



Angle resolution:

$$\Delta\theta^2 = \Delta\theta_I^2 + \Delta\theta_{MS}^2$$

Angle intrinsic resolution:

$$\Delta\theta_I = \frac{\Delta x \sqrt{2}}{0.5\,\mathrm{m}}$$

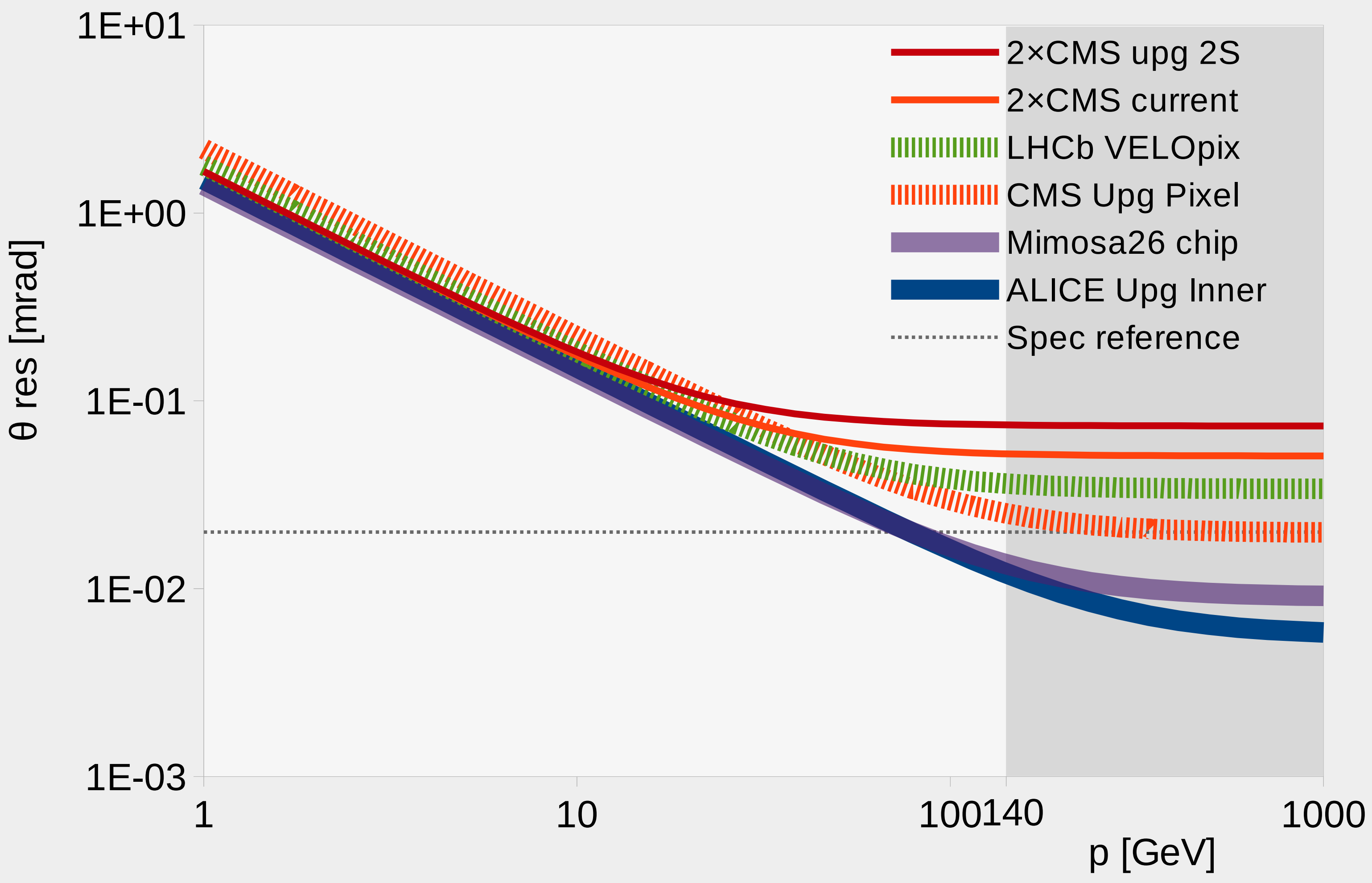
MS angle:

$$\Delta\theta_{MS} = \frac{13.6}{p/\mathrm{MeV}} \sqrt{m} \times (1 + 0.038 \ln m)$$

Scattering material: first layer only

$$m = \left(\frac{x}{X_0}\right)_{\mathrm{det}}$$

Resolution dominated by MS up to 20~260 GeV/c



Angle resolution:

$$\Delta\theta^2 = \Delta\theta_I^2 + \Delta\theta_{MS}^2$$

Angle intrinsic resolution:

$$\Delta\theta_I = \frac{\Delta x\sqrt{2}}{0.5\,\mathrm{m}}$$

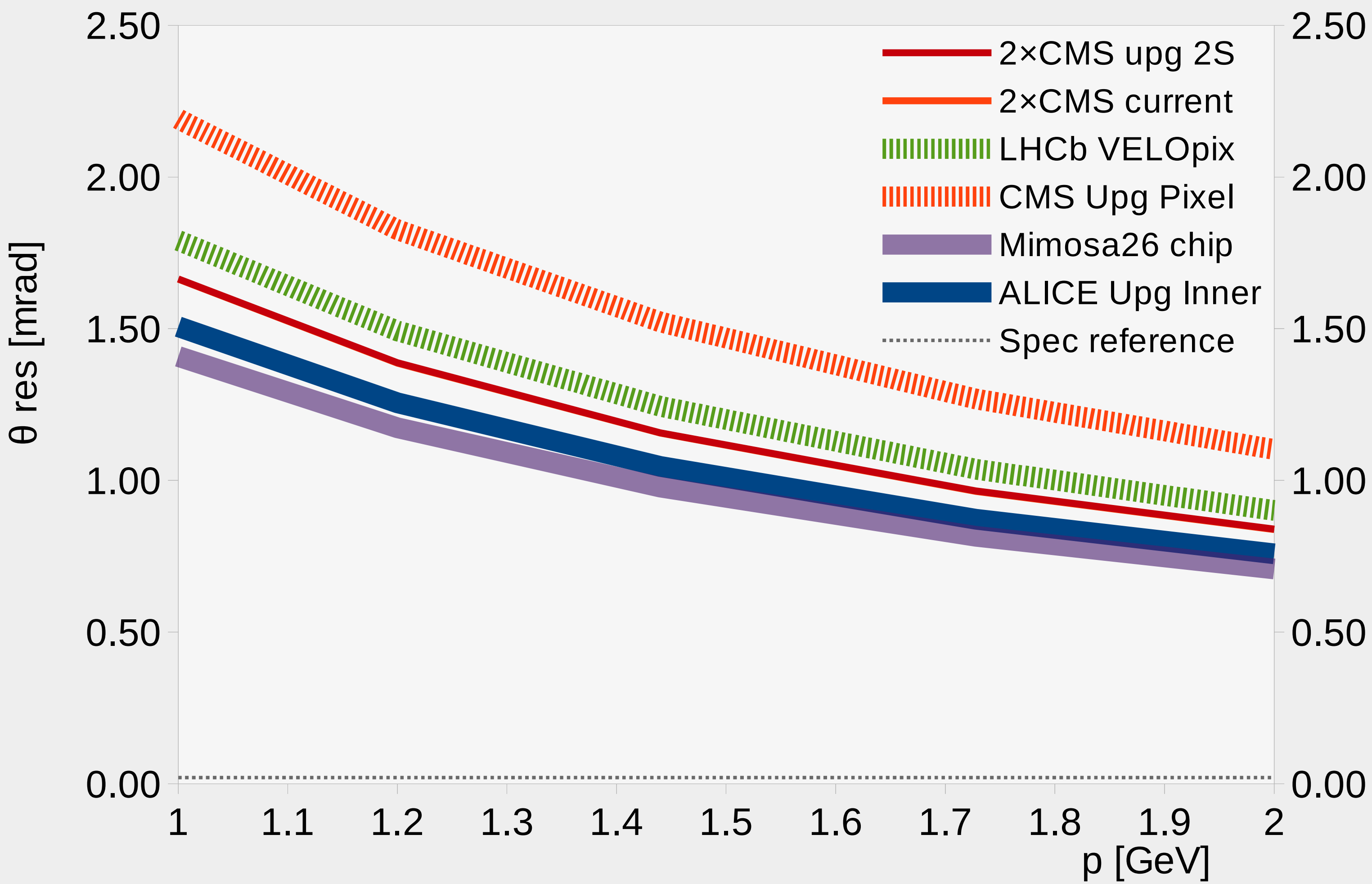
MS angle:

$$\Delta\theta_{MS} = \frac{13.6}{p/\mathrm{MeV}}\sqrt{m}\times(1+0.038\ln m)$$

Scattering material: first layer + 0.5 cm Be

$$m = \left(\frac{x}{X_0}\right)_{\mathrm{det}} + \left(\frac{0.5\,\mathrm{cm}}{35\,\mathrm{cm}}\right)_{\mathrm{Be}}$$

Normalization region: similar performance



Angle resolution:

$$\Delta\theta^2 = \Delta\theta_I^2 + \Delta\theta_{MS}^2$$

Angle intrinsic resolution:

$$\Delta\theta_I = \frac{\Delta x\sqrt{2}}{0.5\,\mathrm{m}}$$

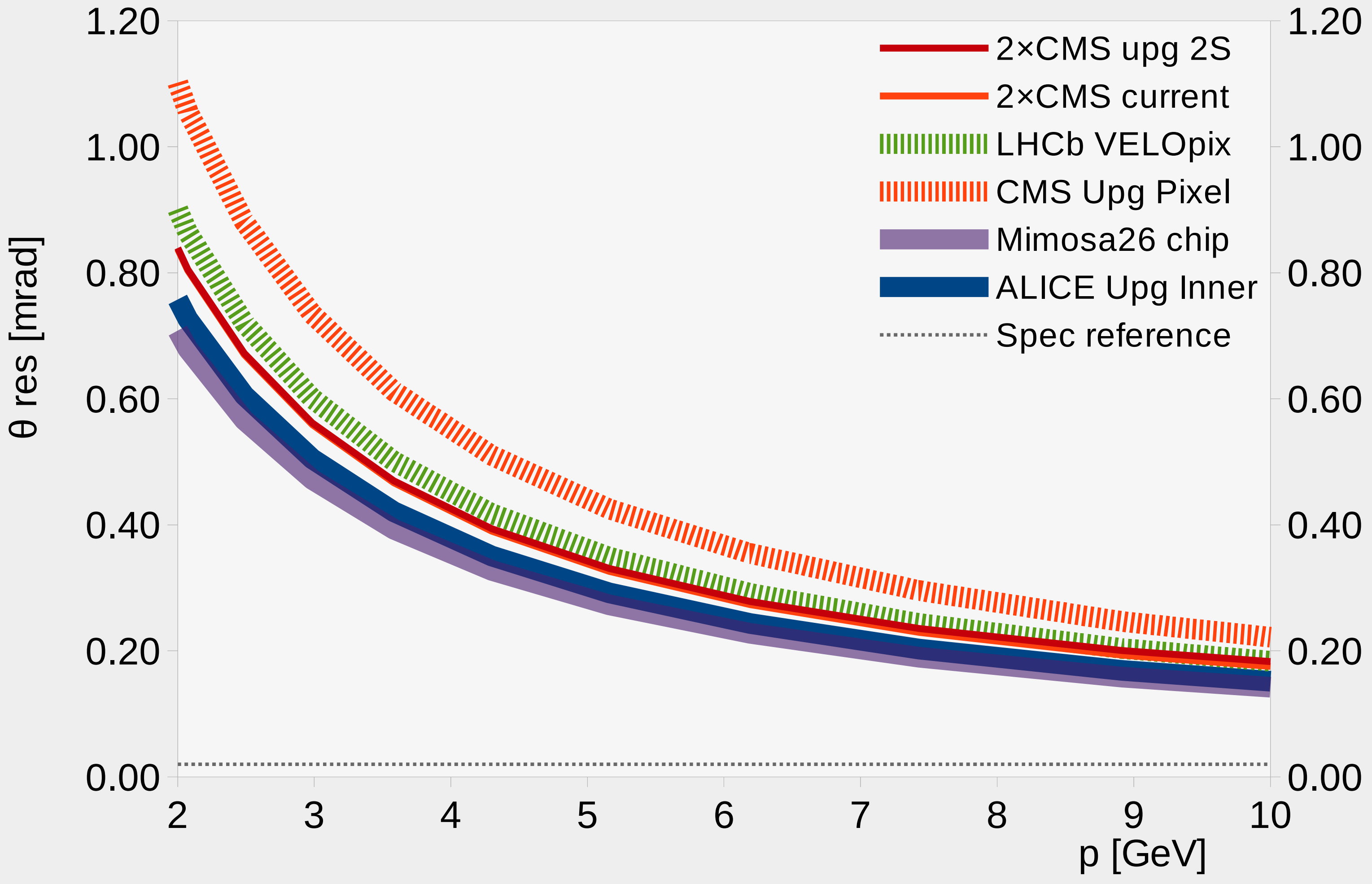
MS angle:

$$\Delta\theta_{MS} = \frac{13.6}{p/\mathrm{MeV}}\sqrt{m}\times\left(1+0.038\ln m\right)$$

Scattering material: first layer + 0.5 cm Be

$$m = \left(\frac{x}{X_0}\right)_{\mathrm{det}} + \left(\frac{0.5\,\mathrm{cm}}{35\,\mathrm{cm}}\right)_{\mathrm{Be}}$$

Signal region (0.3<x<0.6): similar performance



Angle resolution:

$$\Delta\theta^2 = \Delta\theta_I^2 + \Delta\theta_{MS}^2$$

Angle intrinsic resolution:

$$\Delta\theta_I = \frac{\Delta x\sqrt{2}}{0.5\,\mathrm{m}}$$

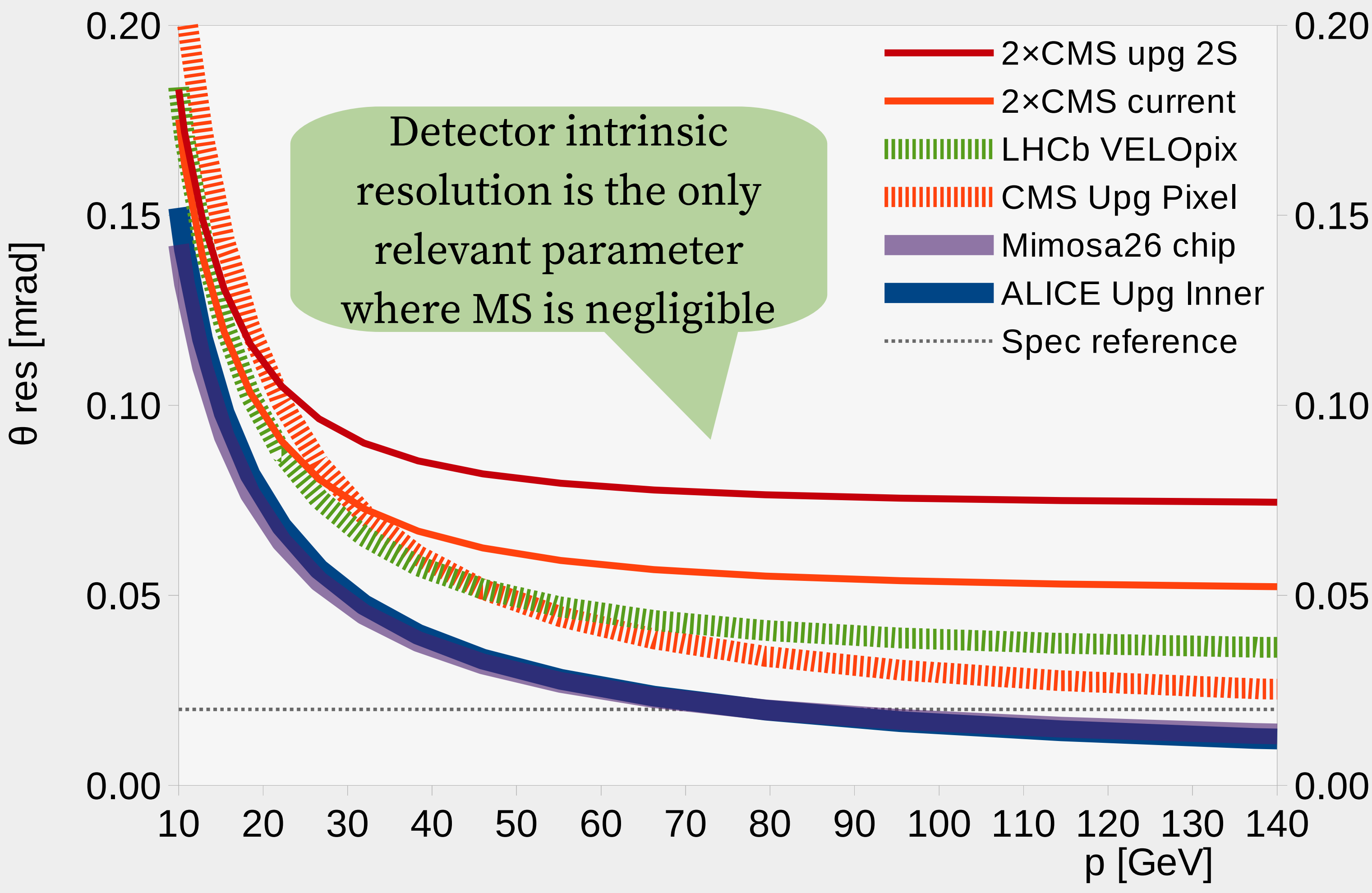
MS angle:

$$\Delta\theta_{MS} = \frac{13.6}{p/\mathrm{MeV}}\sqrt{m}\times\left(1+0.038\ln m\right)$$

Scattering material: first layer + 0.5 cm Be

$$m = \left(\frac{x}{X_0}\right)_{\mathrm{det}} + \left(\frac{0.5\,\mathrm{cm}}{35\,\mathrm{cm}}\right)_{\mathrm{Be}}$$

Signal region (x>0.6): MAPS > pixel > strips



Angle resolution:

$$\Delta\theta^2 = \Delta\theta_I^2 + \Delta\theta_{MS}^2$$

Angle intrinsic resolution:

$$\Delta\theta_I = \frac{\Delta x \sqrt{2}}{0.5\,\mathrm{m}}$$

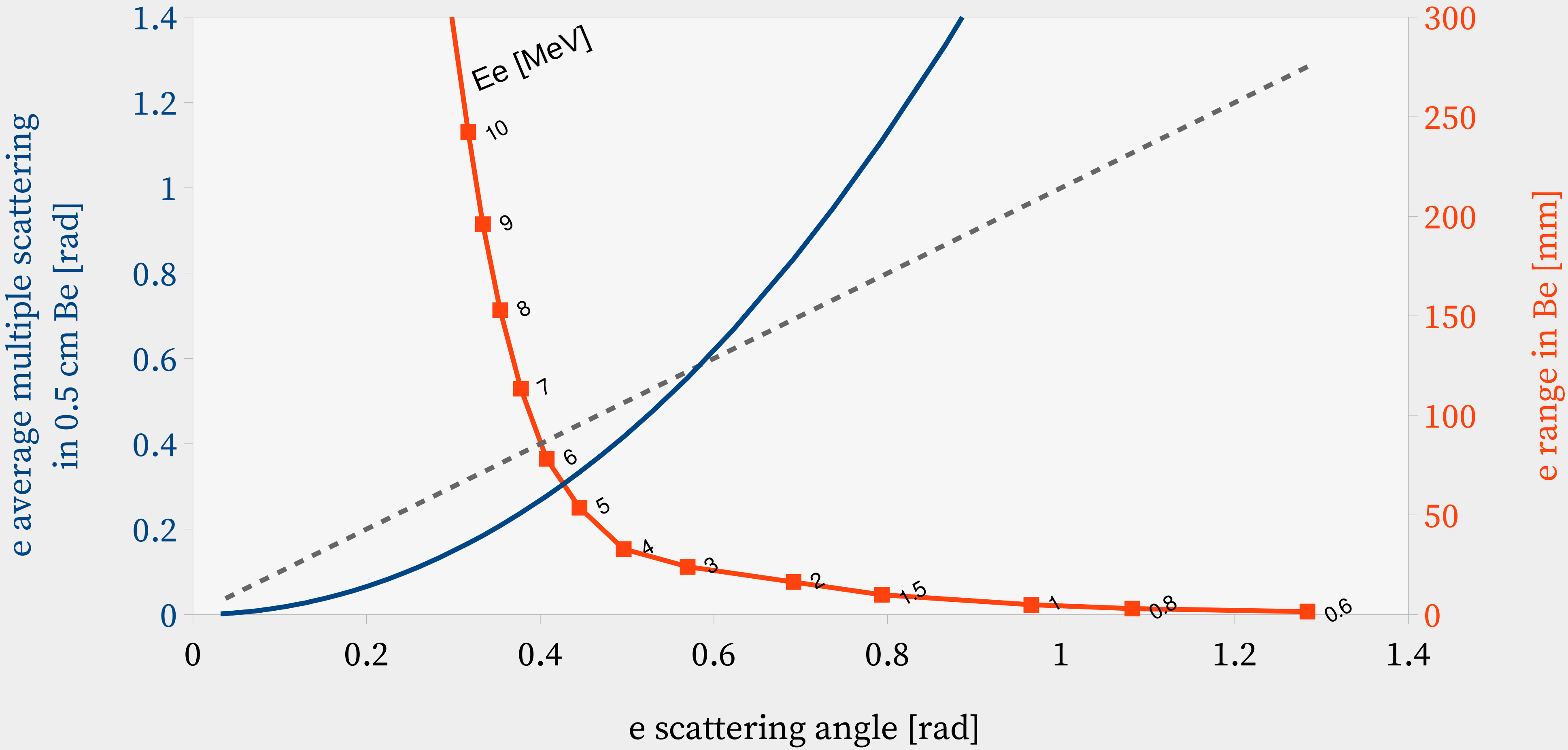
MS angle:

$$\Delta\theta_{MS} = \frac{13.6}{p/\mathrm{MeV}} \sqrt{m} \times (1 + 0.038 \ln m)$$

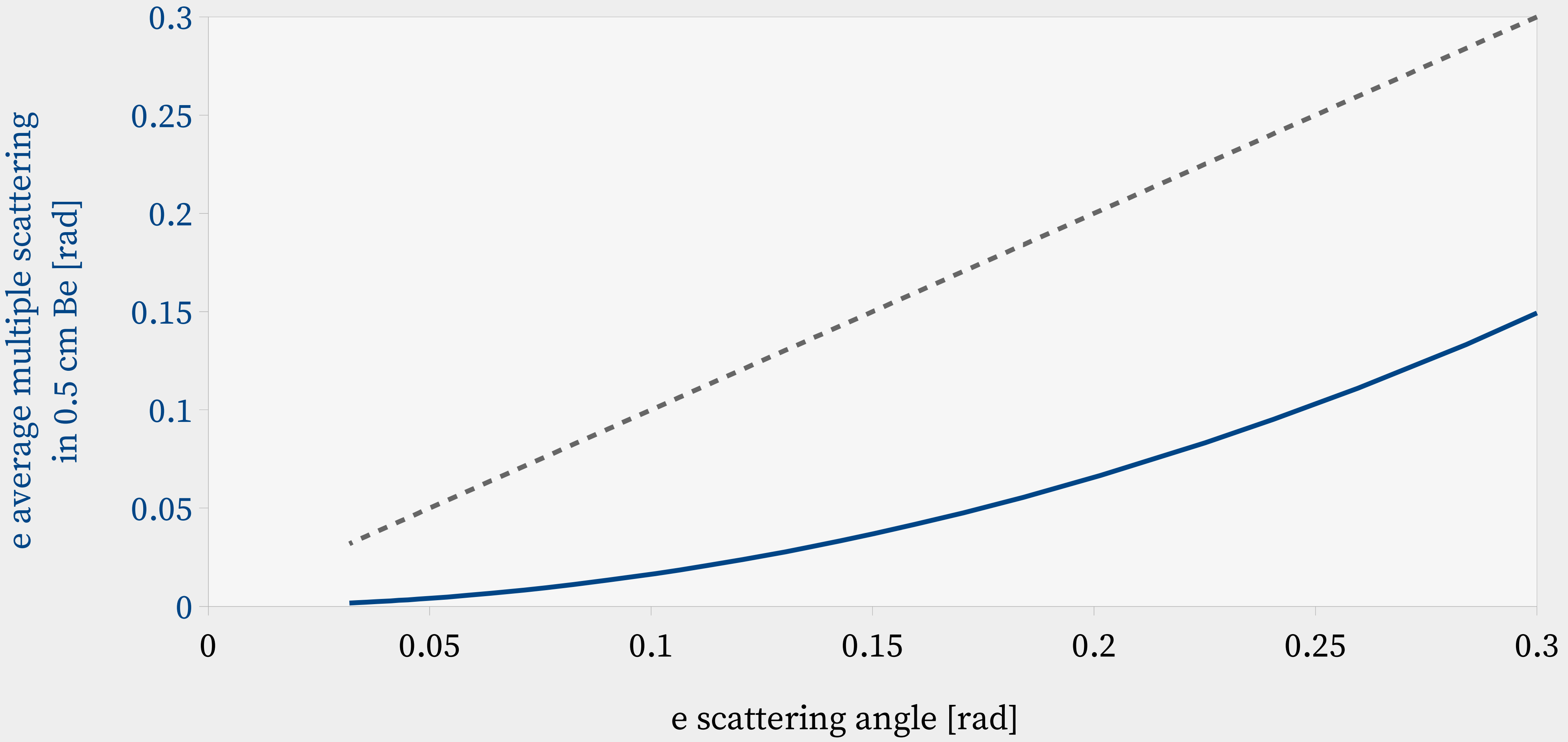
Scattering material: first layer + 0.5 cm Be

$$m = \left(\frac{x}{X_0}\right)_{\mathrm{det}} + \left(\frac{0.5\,\mathrm{cm}}{35\,\mathrm{cm}}\right)_{\mathrm{Be}}$$

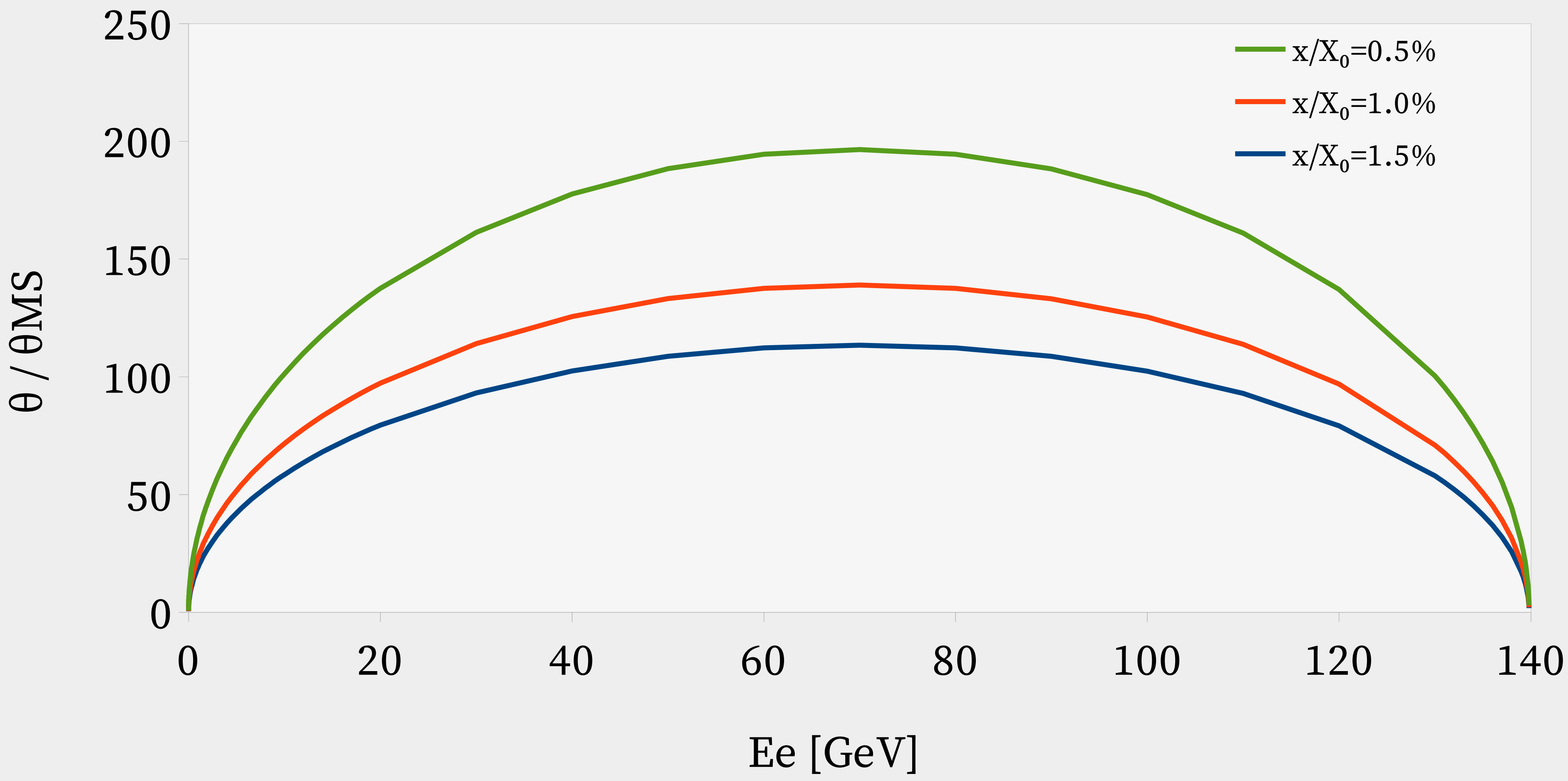
Contamination from low energy electrons



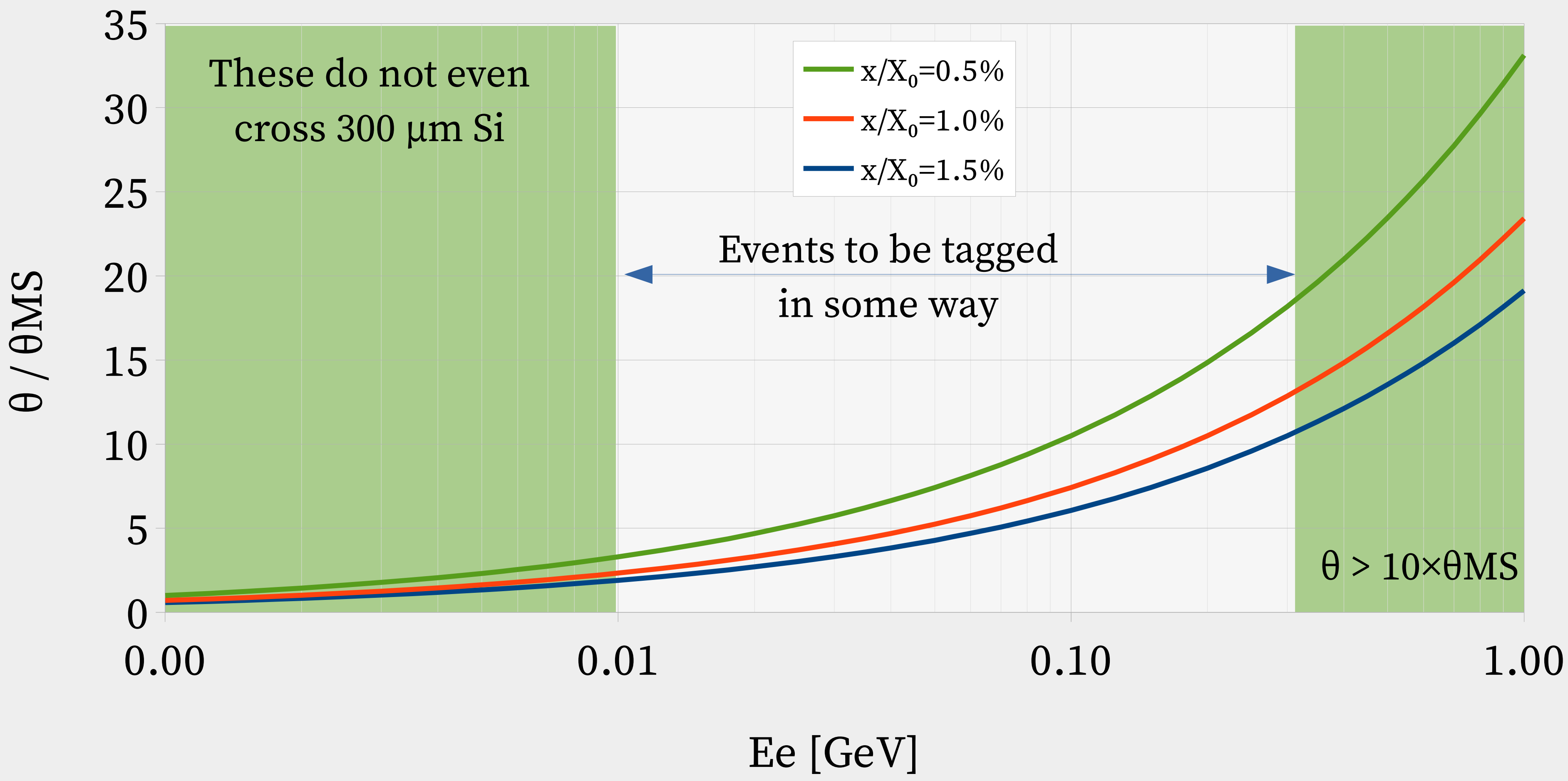
Small contamination from low energy electrons



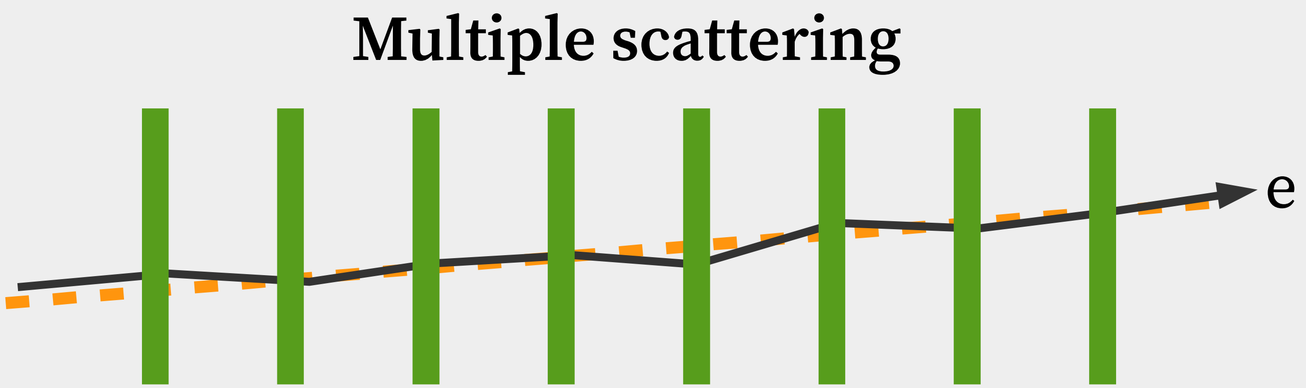
Low energy electrons should be tagged

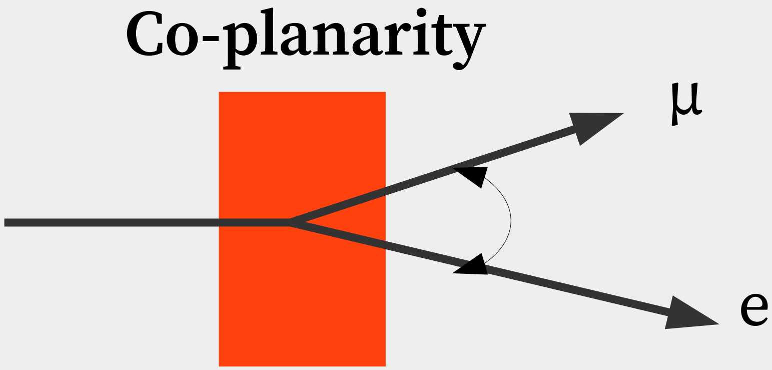


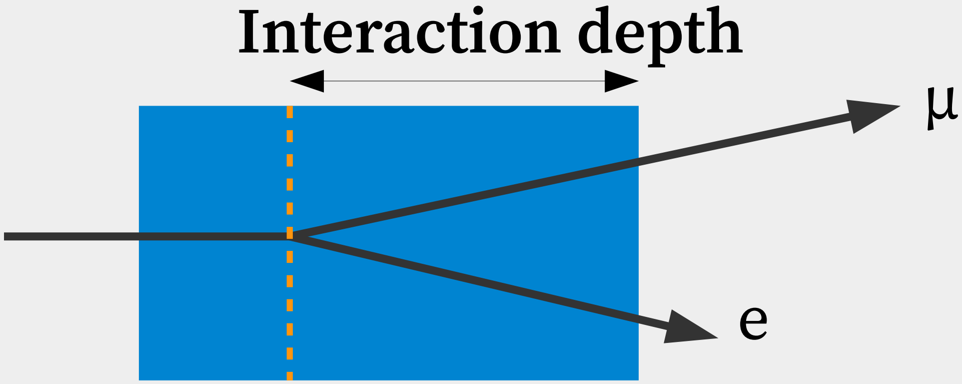
Low energy electrons should be tagged



Not only the track angle

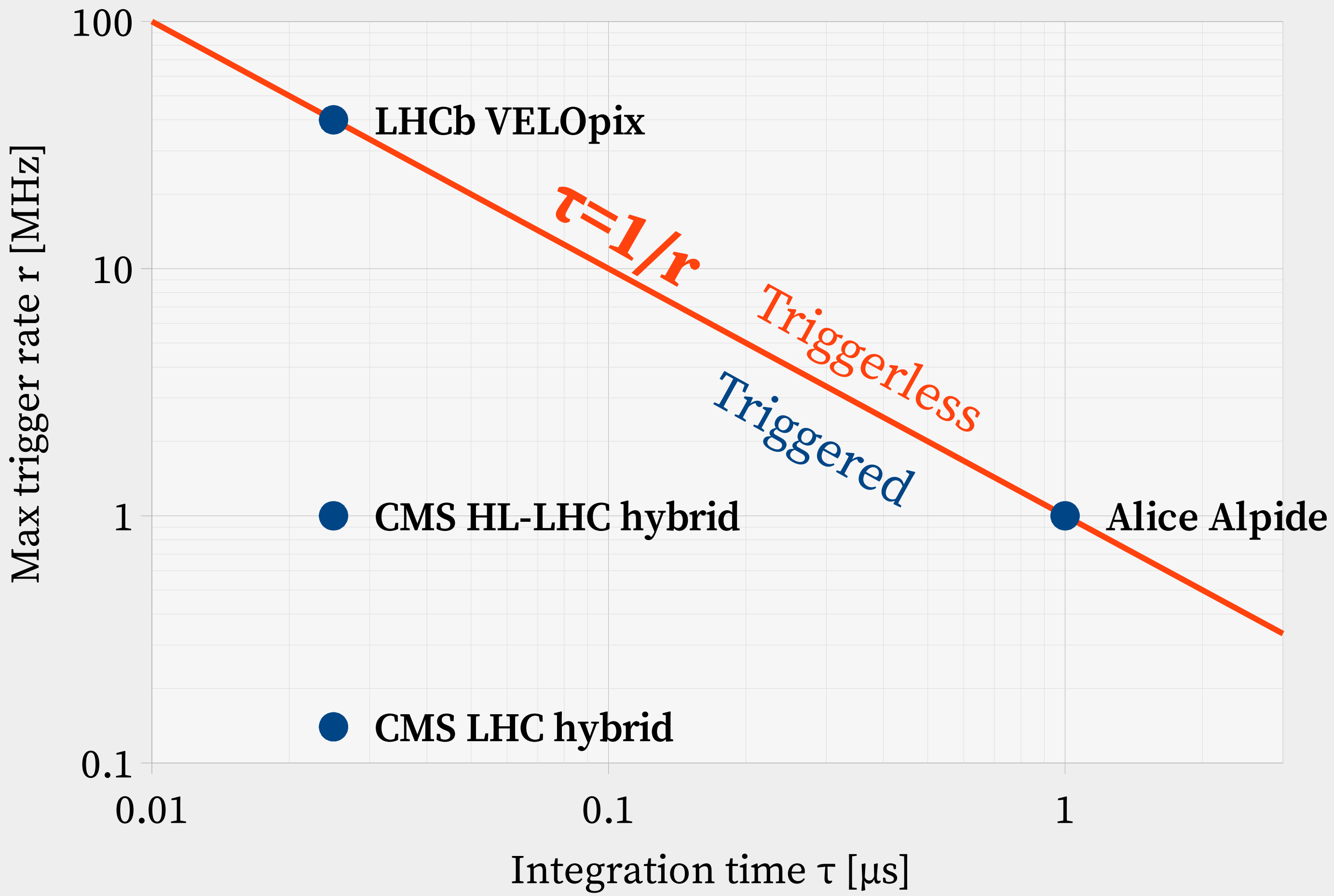




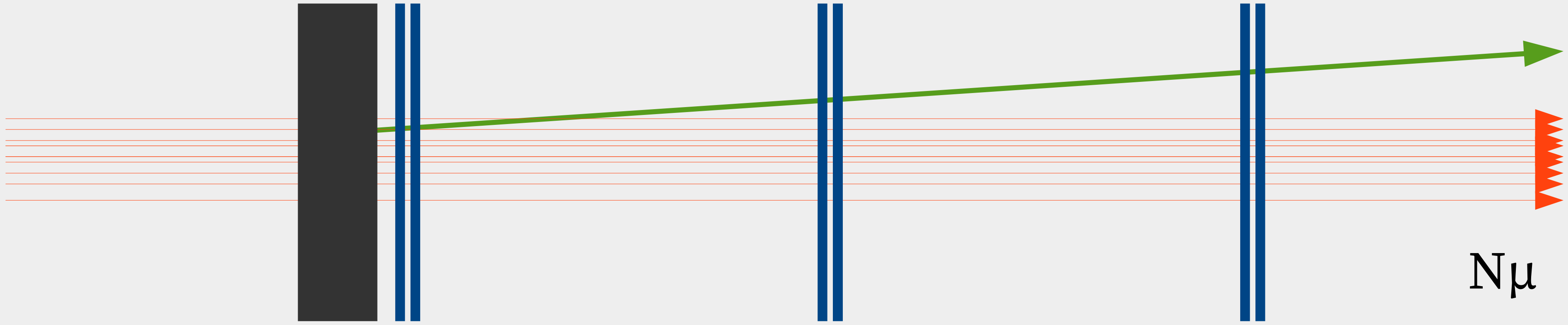


The tracker provides more information on the track than just its angle. These three parameters can be used as input to a global track quality parameter. Usually **dE/dx** is another discriminator, but unfortunately it is not significant in our range of energies

τ and trigger rate define operation mode



Pile-up in the detector



$N\mu = r \times \tau$

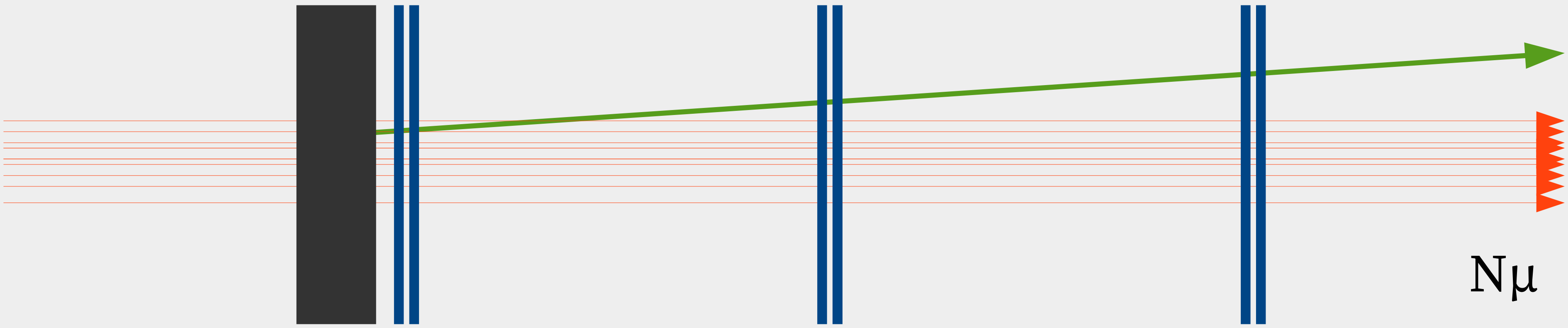
e.g. $N\mu = 10\ \mathrm{MHz} \times 25\ \mathrm{ns} = 0.25$

e.g. $N\mu = 10\ \mathrm{MHz} \times 1\ \mu\mathrm{s} = 10$

The pile-up is the number of events that you expect to see if triggering randomly.

If the incoming particles are not correlated in time with a bunch structure, and if an efficient trigger is used to select one particle, then one expects to record the signal from that particle, plus Nμ other from the pile-up

Pile-up in the detector



$N\mu = r \times \tau$

e.g. $N\mu = 40\ \mathrm{MHz} \times 25\ \mathrm{ns} = 1$

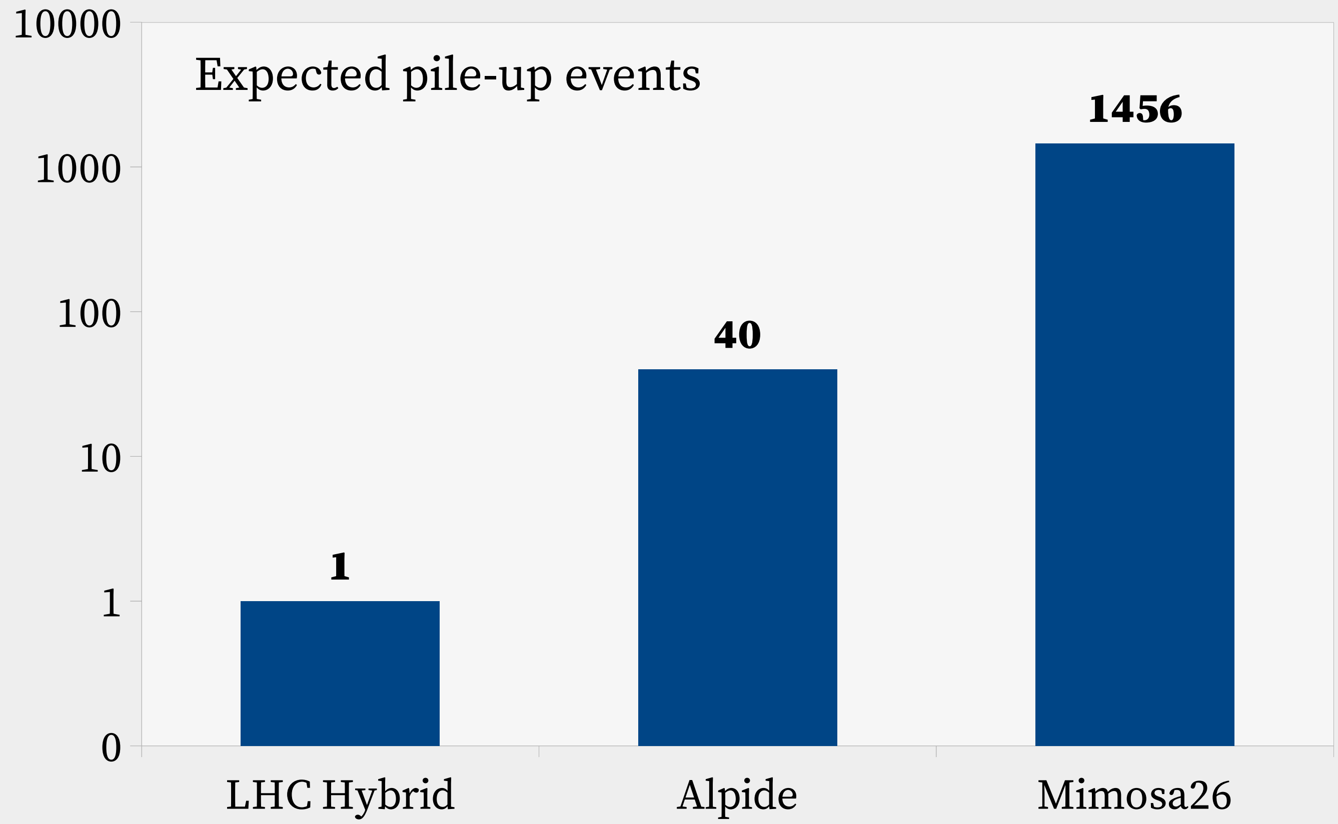
e.g. $N\mu = 40\ \mathrm{MHz} \times 1\ \mu\mathrm{s} = 40$

The pile-up is the number of events that you expect to see if triggering randomly.

If the incoming particles are not correlated in time with a bunch structure, and if an efficient trigger is used to select one particle, then one expects to record the signal from that particle, plus Nμ other from the pile-up

Detector integration time

- Hybrid pixels & strips for (HL-)LHC: 25 ns
- ALPIDE: 1 μs
- Mimosa26: 112 μs



Systematics: accurate material budget map

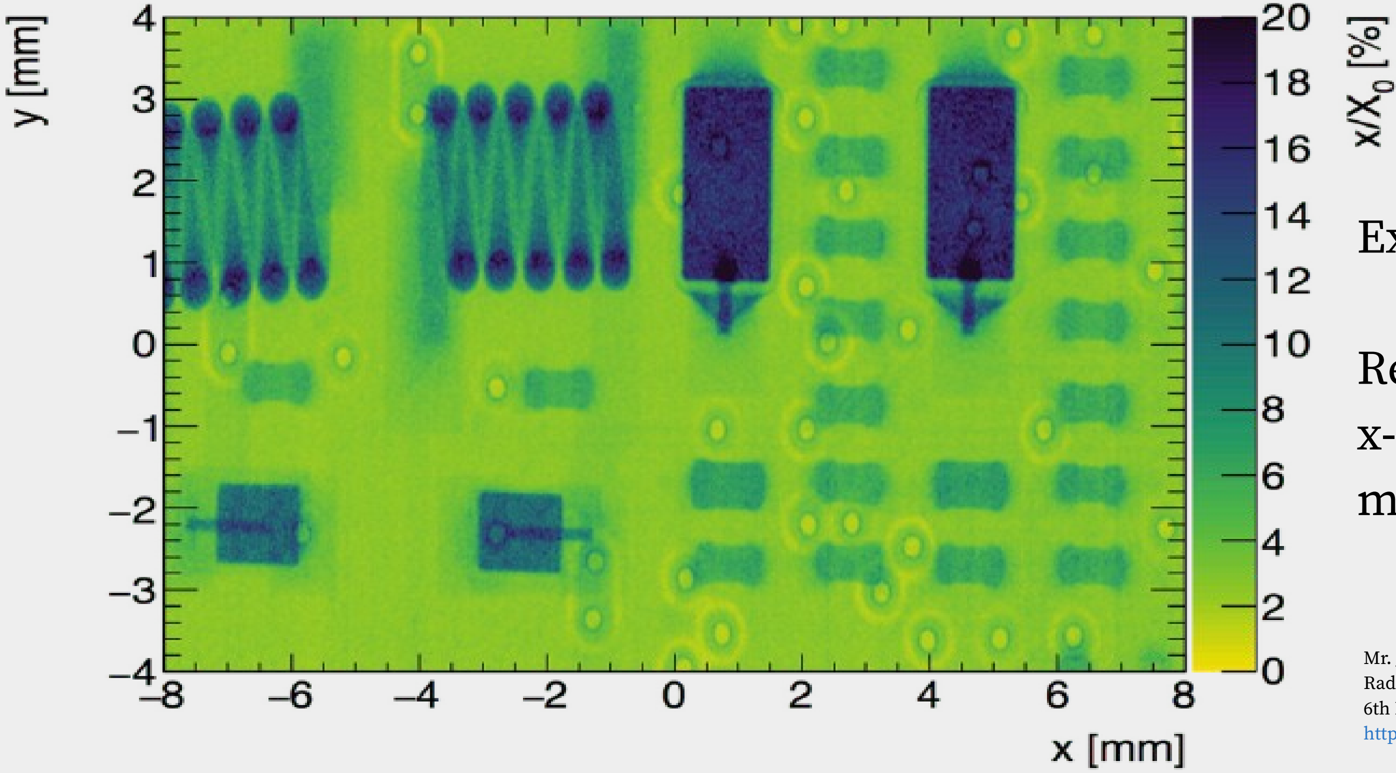
New technique recently developed at DESY: measurement of scattering angle on each point

Object placed in a 3 GeV electron beam inside a Mimosa telescope

DESY: 1-3 GeV electrons with a Mimosa-26 telescope is available: measurement of material amount by measuring the electron scattering on a surface.

Systematics: accurate material budget map

New technique recently developed at DESY: measurement of scattering angle on each point



Exact material distribution

Reveals internal structure (like x-ray), but provides direct measure of x/X_0

Mr. Jan-Hendrik Arling (DESY), Ms. Michaela Queitsch-Maitland (DESY), Radiation length measurements for the ATLAS ITk Strip Detector
6th Beam Telescopes and Test Beams Workshop 2018
https://indico.desy.de/indico/event/18050/other-view?view=standard

DESY: 1-3 GeV electrons with a Mimosa-26 telescope is available: measurement of material amount by measuring the electron scattering on a surface.

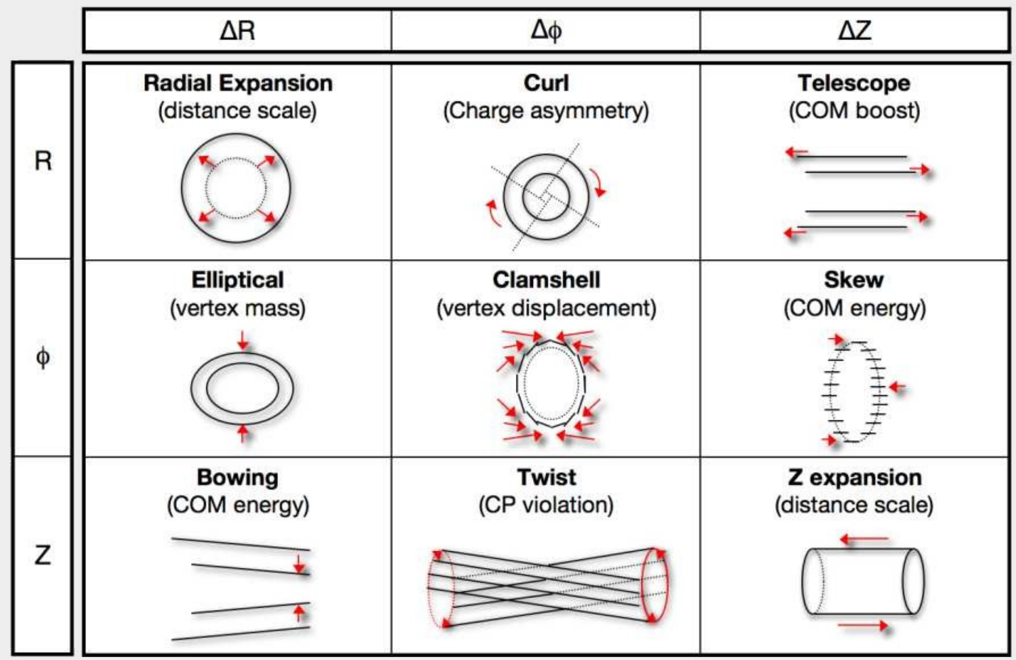
Systematics: track-based “alignment”

Software **track-based “alignment”** is needed to reach nominal accuracy. Mis-alignment can be the biggest systematic uncertainty.

Pitfall: **weak modes**

Physics processes used in CMS and ATLAS to control weak modes.

Different strategy needed in MUonE?



Weak modes in ATLAS
C. Escobar, Vertex 2008

A software technique named “alignment” was developed to accurately determine the actual position of detector modules, which consists in varying the detector position to minimize the χ^2 over a large sample of tracks.

This is always needed to reach nominal accuracy, as no mechanics assembly procedure can reasonably reach the detector resolution.

A detector mis-alignment can be the biggest systematic uncertainty.

Unfortunately the tracks χ^2 distribution is invariant to certain detector movements, which are called weak modes.

CMS and ATLAS found several physics process which are sensitive to these modes (e.g. in CMS: reconstructed Z mass should be independent to the track directions). This aspect should be taken into account in designing the MUonE detector.

Main tracking-related systematics

- Detector mis-alignment
- Multiple scattering parametrization
- Uniformity of tracking efficiency
- Uniformity of material budget

These should be studied through dedicated beam tests with particles of known energy

Outline

~~MUonE tracker parameters~~

~~Figures of merit in silicon detectors~~

~~Analytic approach to detector optimization~~

~~Overview of current detectors~~

~~Initial considerations on detector resolution and systematic errors~~


That's all Folks!