Exploring Dense QCD Matter with the CBM Experiment

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Helmholtzzentrum für Schwerionenforschung

63. Cracow School of Theoretical Physics:

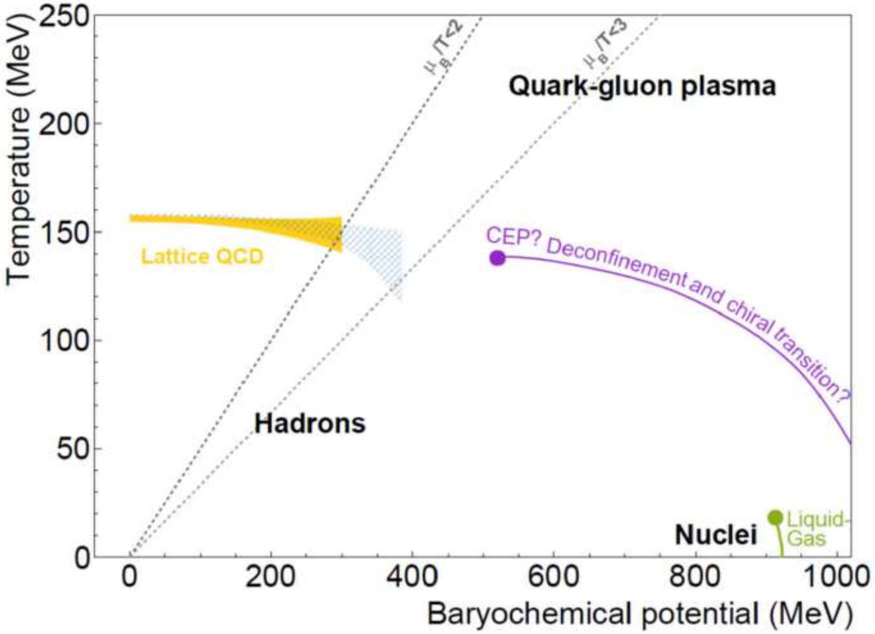
Nuclear Matter at Extreme Densities and High Temperatures

Zakopane, 21 September 2023

Why we are here

CBM = Compressed Baryonic Matter = Nuclear Matter at Extreme Densities (...) = 63th Cracow School

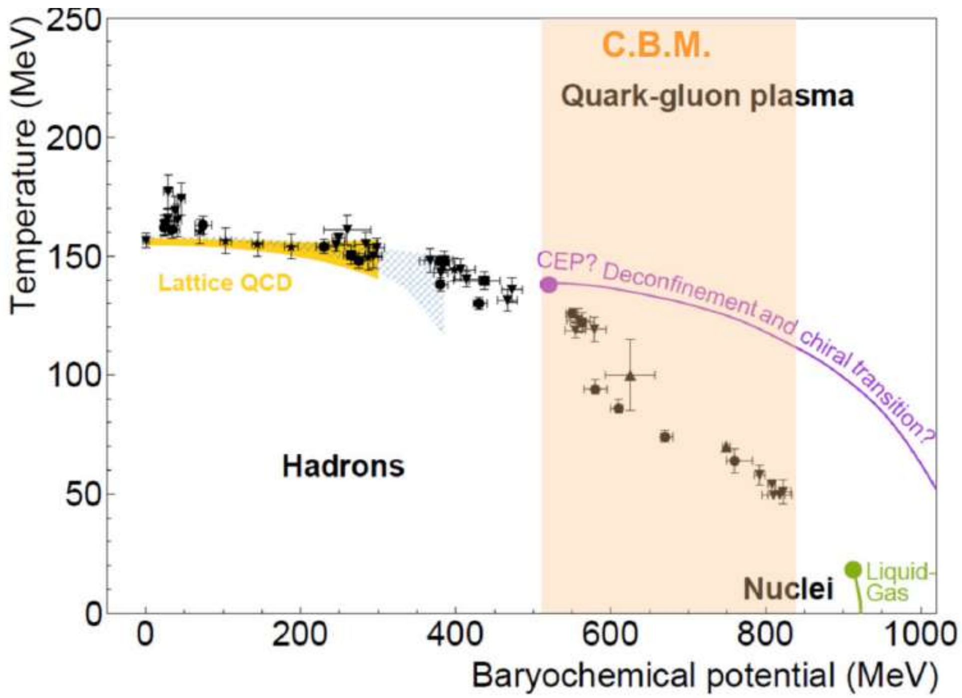
Stolen from: C. Höhne, QM 2023



- Phase structure: 1st-order phase transition? Critical point? If yes, where?
- Equation of state?
- New QCD phases?

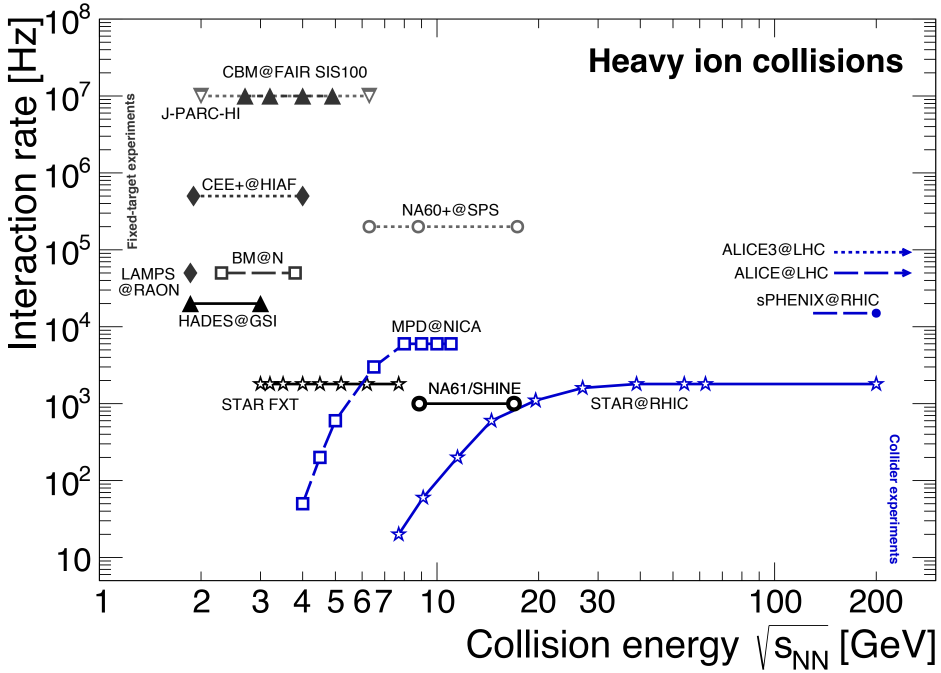
How experiments connect

Stolen from: C. Höhne, QM 2023



- Freeze-out points map the phase diagram
- Variation of collision energy allows to study different regions:
  - High energies (LHC, RHIC): vanishing density, high temperature
  - Lower energies (AGS, FAIR, GSI): high density, moderate temperature
- Caveats:
  - Matter is in equilibrium, nuclear collisions are very dynamic
  - Collision has a trajectory in the phase diagram, not a single point.

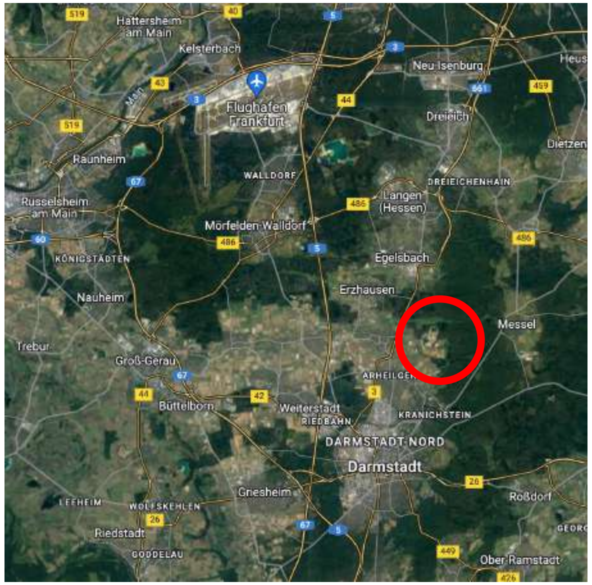
Experimental landscape



- Accelerators / detectors differ: collision energy, interaction rate, collider / fixed-target mode
- Complementarity and competition

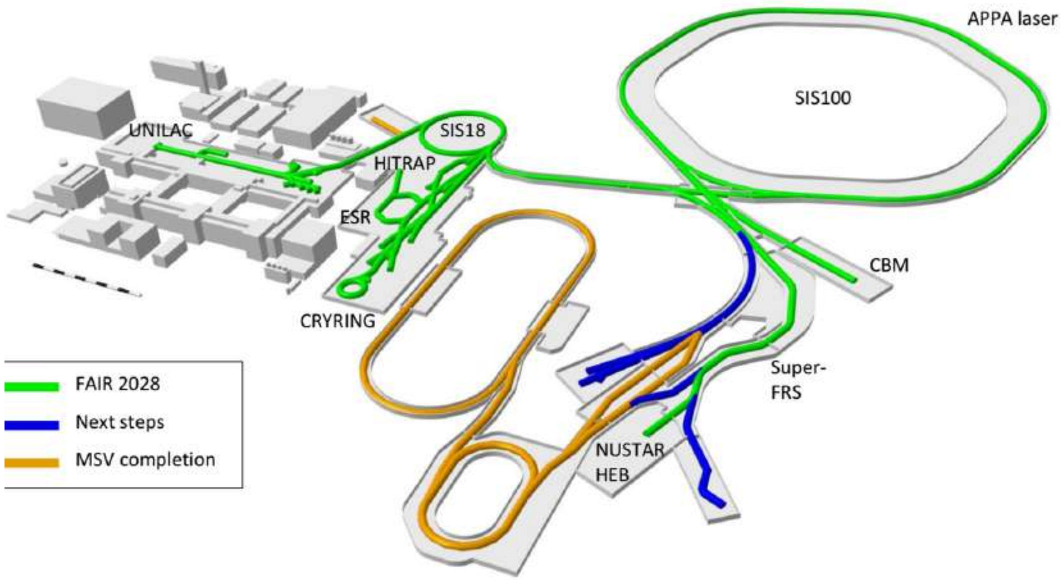
Lecture by C. Blume

What’s FAIR?



- Facility for Anti-proton and Ion Research
- A major new infrastructure for basic and applied research at GSI in Darmstadt, Germany
- 11 international partners - including Poland
- Currently under construction

What's FAIR?

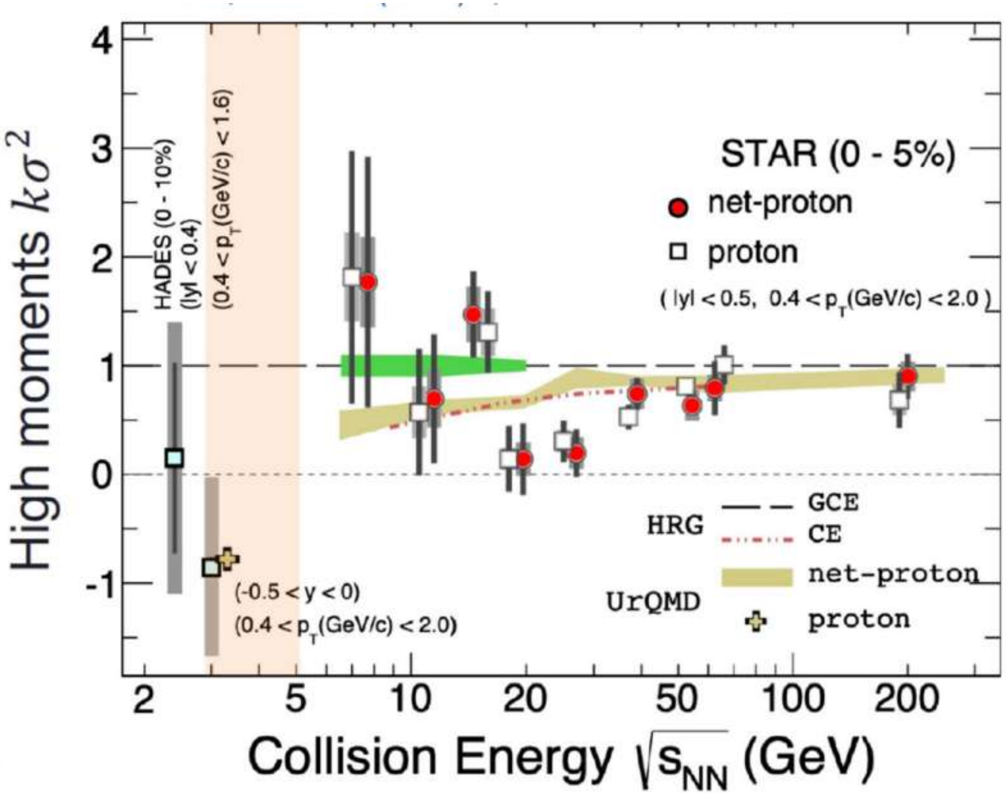


- Complex accelerator facility for a variety of physics
- Including slowly extracted nuclear beams for fixed-target experiments
- Full stripped heavy ions up to p = 12 GeV/c with intensities up to 10^{10} ions / s.
- Symmetric nuclei up to 14 GeV/c; protons up to 30 GeV/c.

CBM energy range:
P = 3.5 - 12 GeV/c
$\sqrt{s_{NN}}$ = 2.3 - 5.3 GeV

Probes: Event-by-event fluctuations of conserved quantities

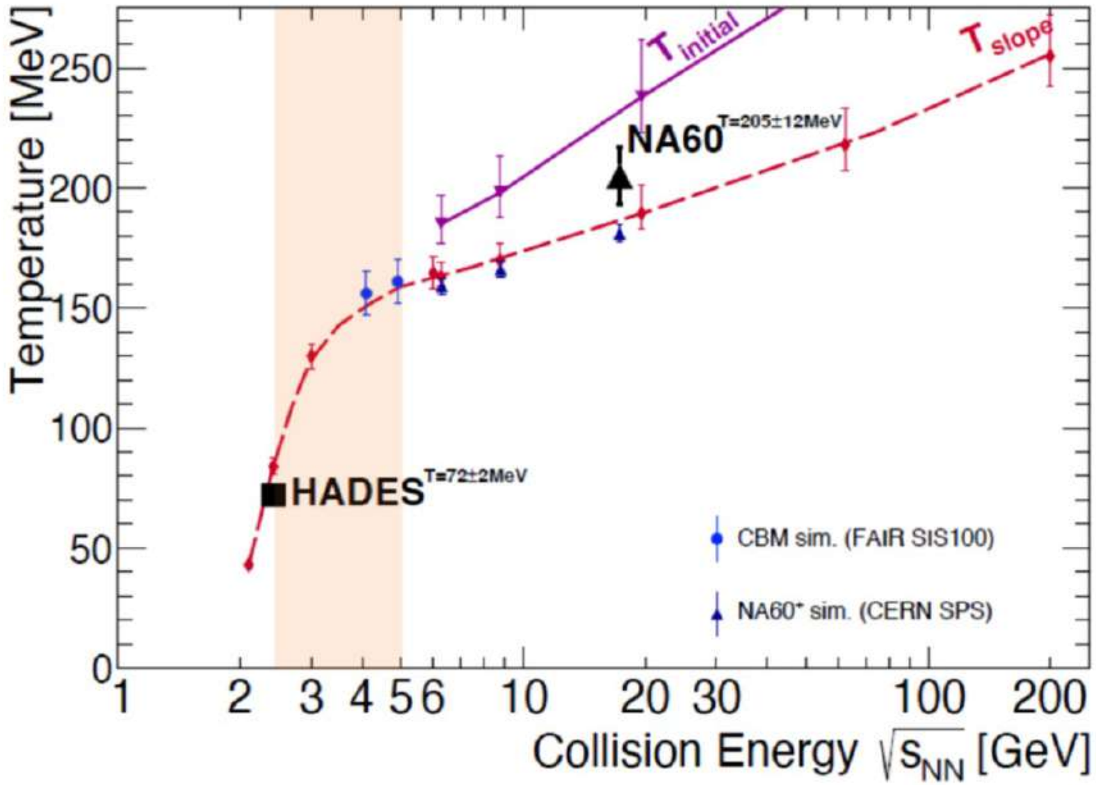
STAR, PRL 128 (2022) 202303
HADES, PRC 102 (2020) 024914



- Discontinuities at CP (or 1st-order phase transition) are expected to manifest in increased fluctuations (here: net-baryon number)
- Observable: cumulant ratios
- Sensitivity increases with order of cumulants: need high statistics
- Difficult experimental systematics.
- Region between HADES and STAR cries for investigation...

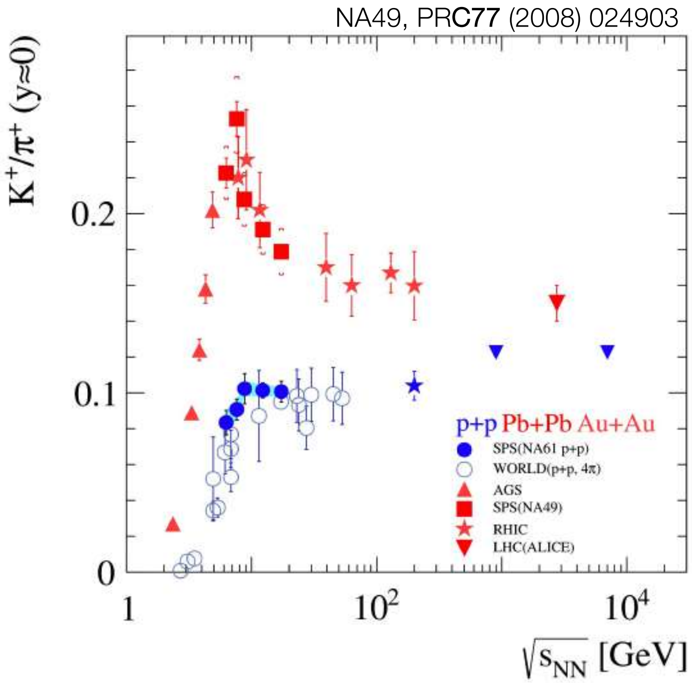
Lecture by A. Rustamov

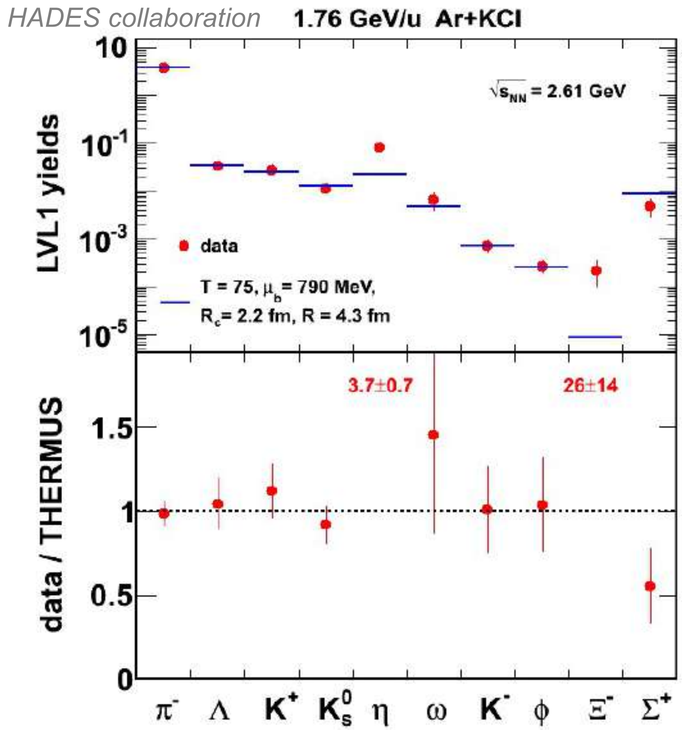
Probes: Lepton pairs



- Unlike hadrons, leptons trace the entire evolution of the fireball.
- Rich information: density, lifetime, temperature...
- Here: “caloric curve”: flattening as signal of phase transition?
- Difficult measurement (abundant background): need to control systematics
- Can be measured with electrons and muons (pros and cons on either side); we want to do both.

Probes: Strangeness

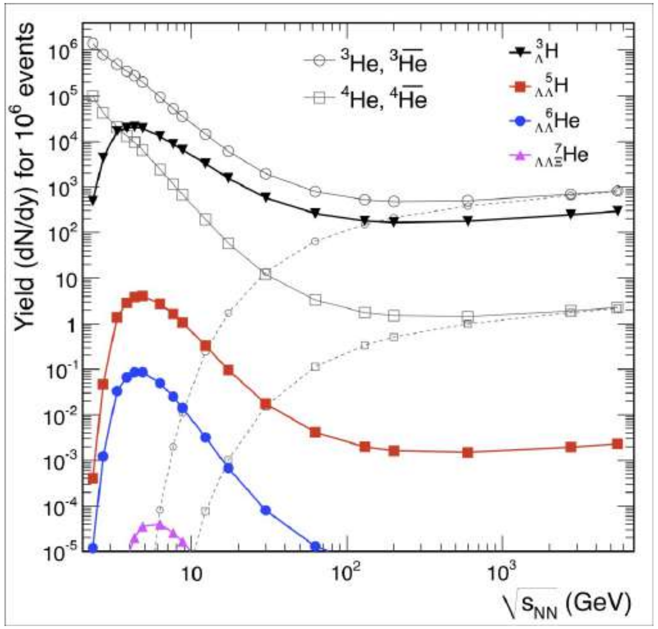




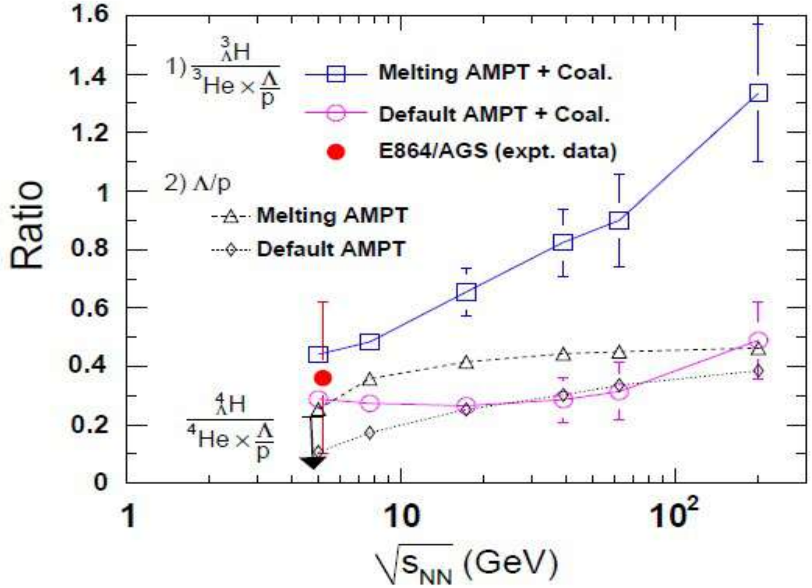
- All understood ?
- Measurements of multi-strange particles are rare; there might be surprises...

Probes: Hypermatter

A. Andronic et al., PLB 697 (2011) 203



S. Zhang et al., PLB 684 (2010) 224



In heavy-ion collision: produced through capture of Lambda in light nuclei

Maximum production at CBM energies

Transport models indicate sensitivity to medium properties

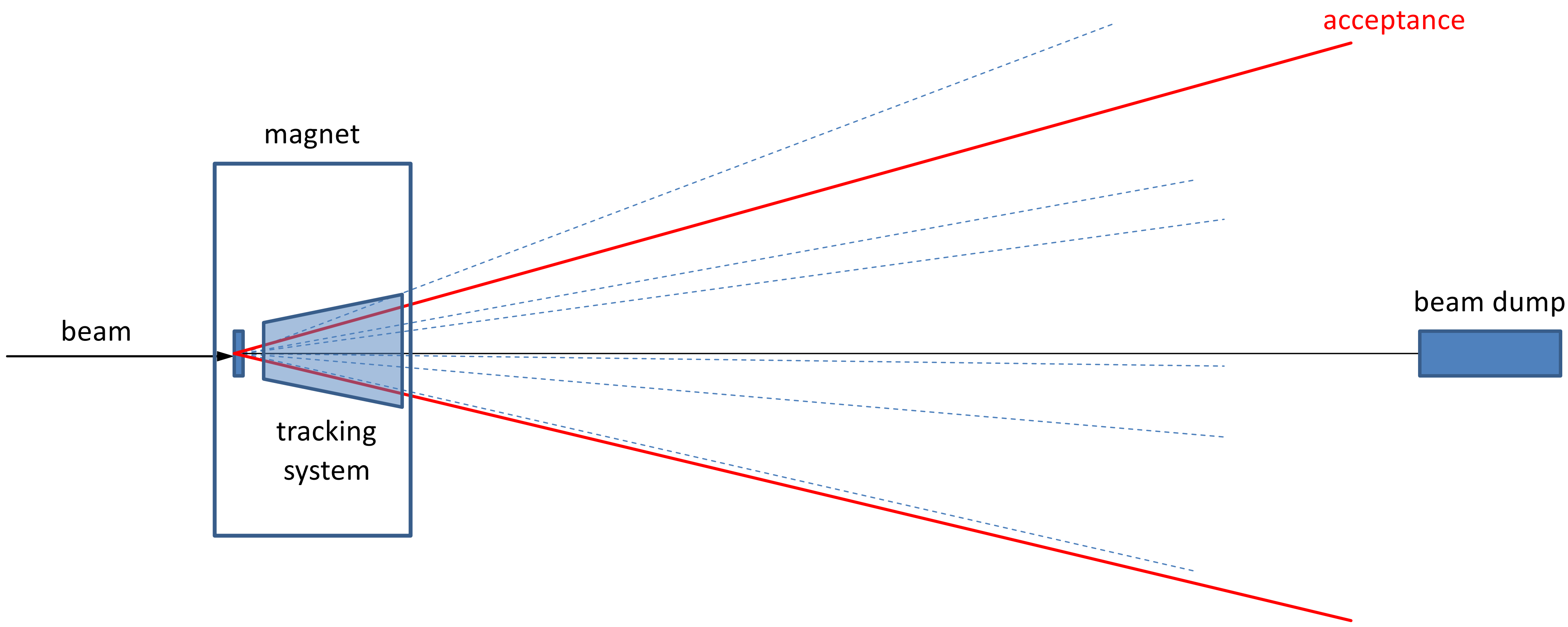
Probes: Not to forget

- Bulk observables (e.g., spectra, flow): partially already measured; repeat / confirm with higher statistics and more systematics (collision energy, system size)
- Stay (as) open (as possible) for new ideas / proposals!

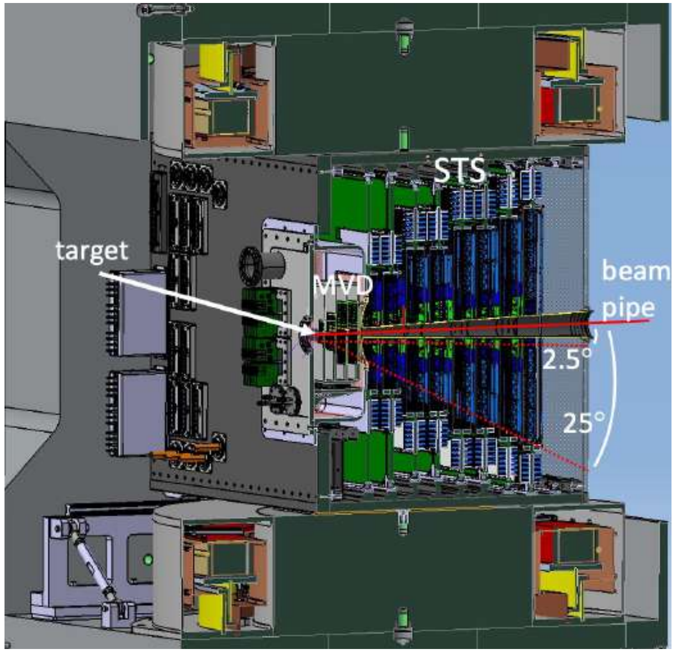
CBM design criteria

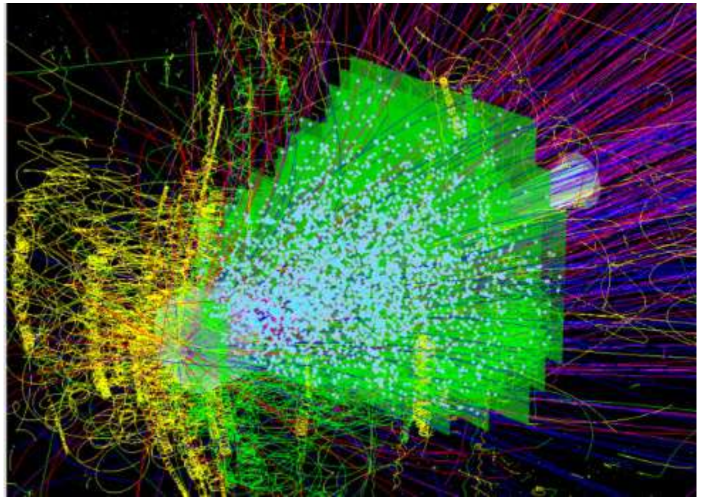
- Measure charged pions, kaons, protons
- Measure electrons and muons
- Reconstruct weak decay topologies (hyperons, hypernuclei)
- In the FAIR-SIS100 energy range
- In a large acceptance
- With high precision
- With high statistics

Designing a fixed-target experiment...



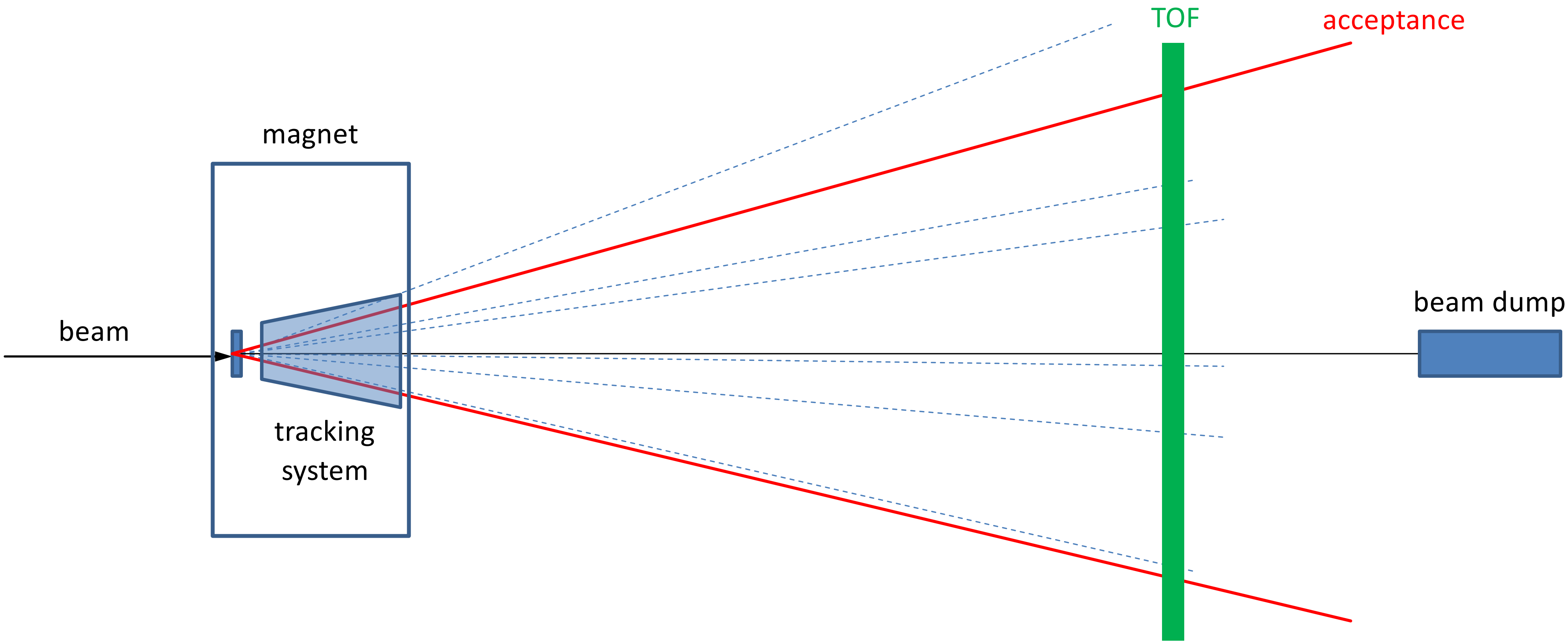
Silicon Tracking Station



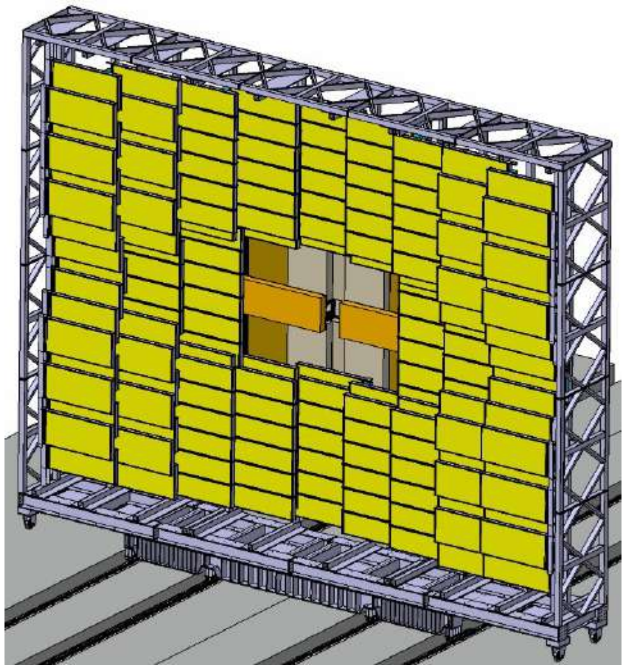


A complicated arrangement of silicon strip and pixel detectors
8 + 4 measurements per track

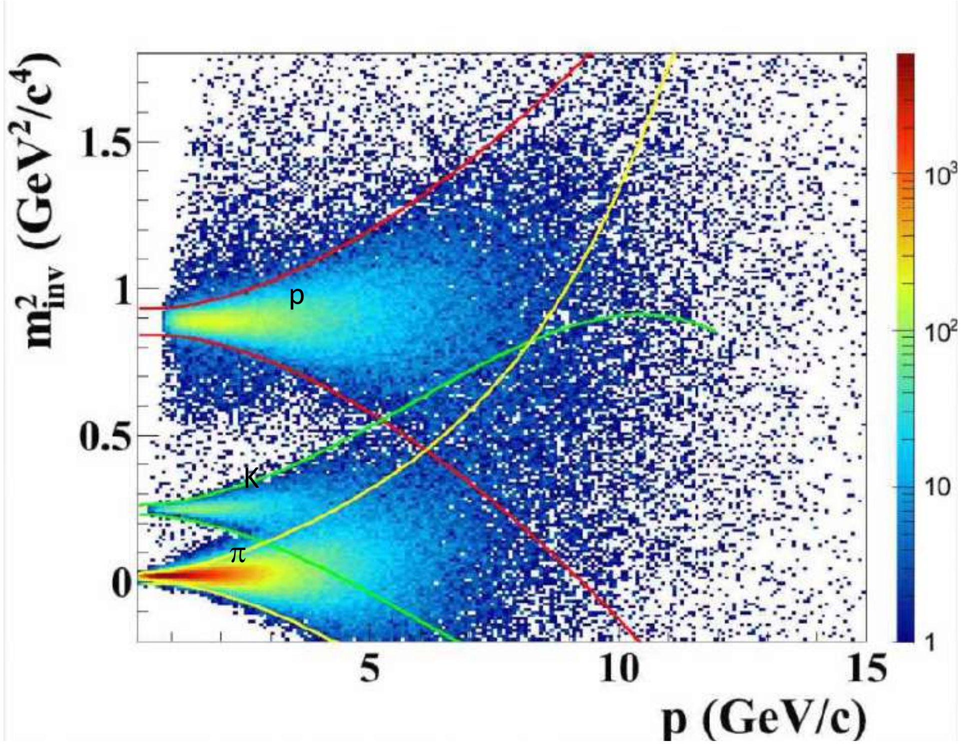
Designing a fixed-target experiment...



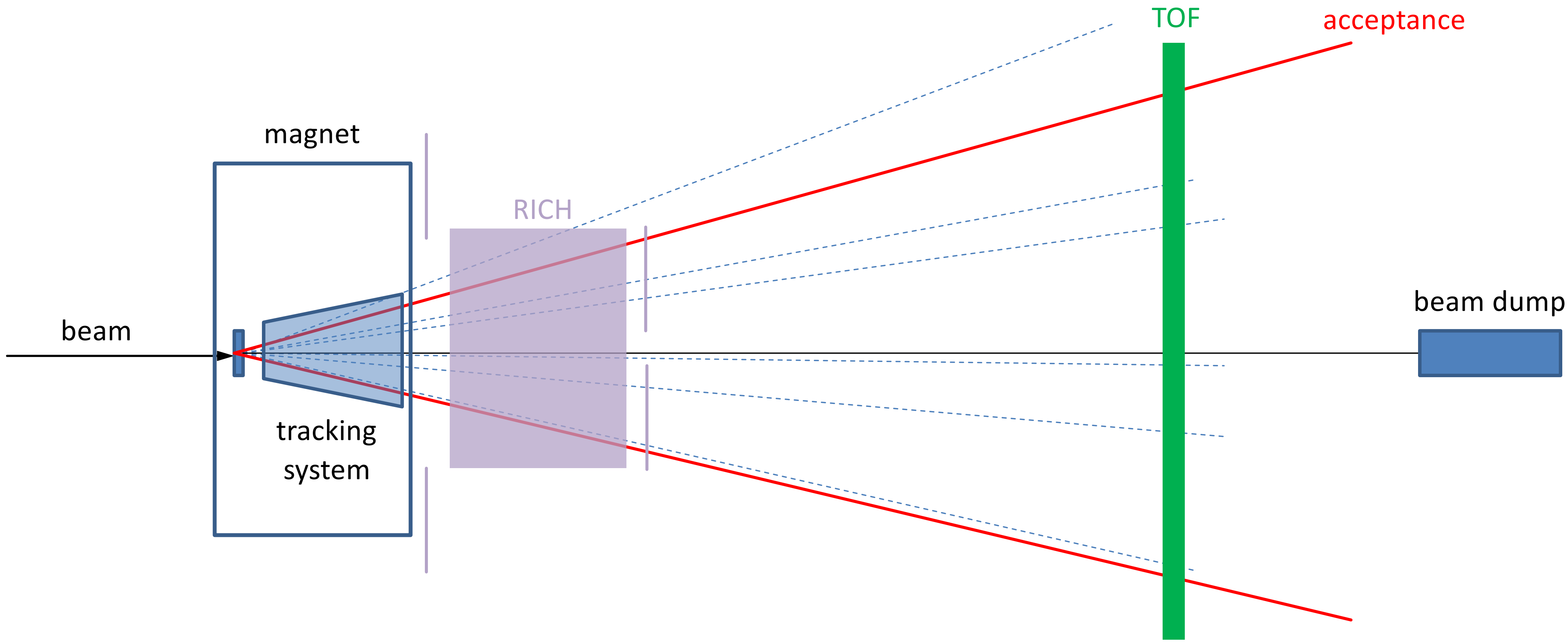
Time-of-flight Detector



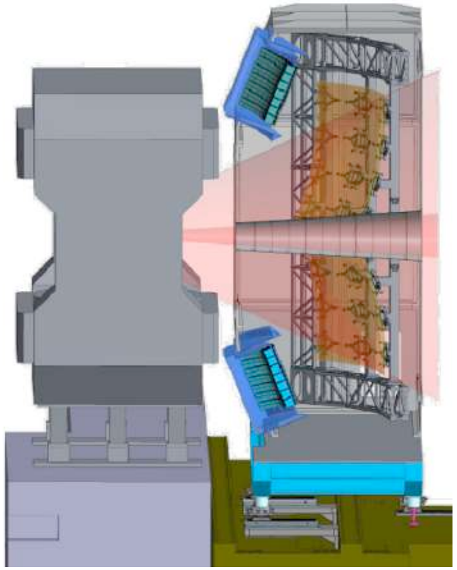
Made of multi-gap resistive plate chambers (RPCs)

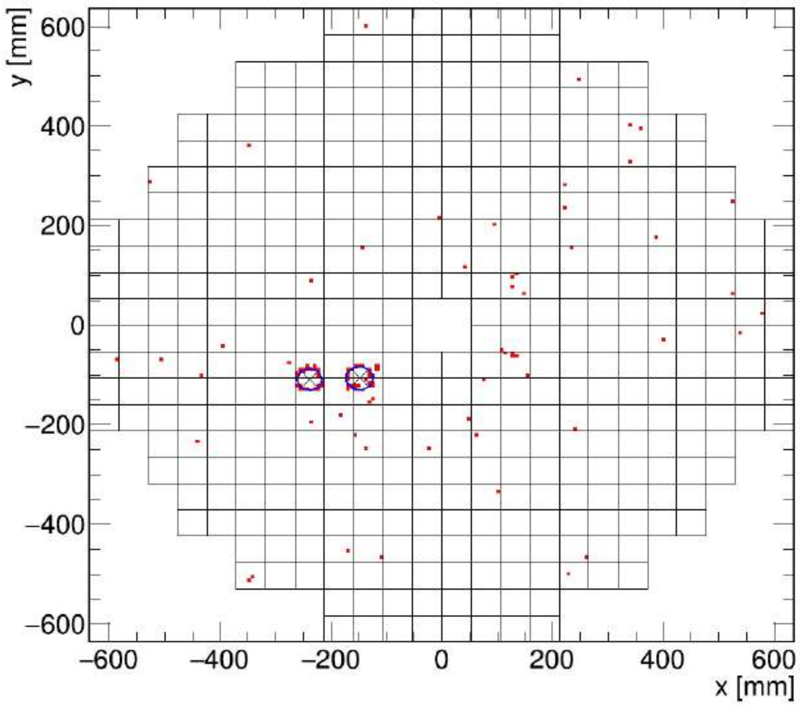


Designing a fixed-target experiment...



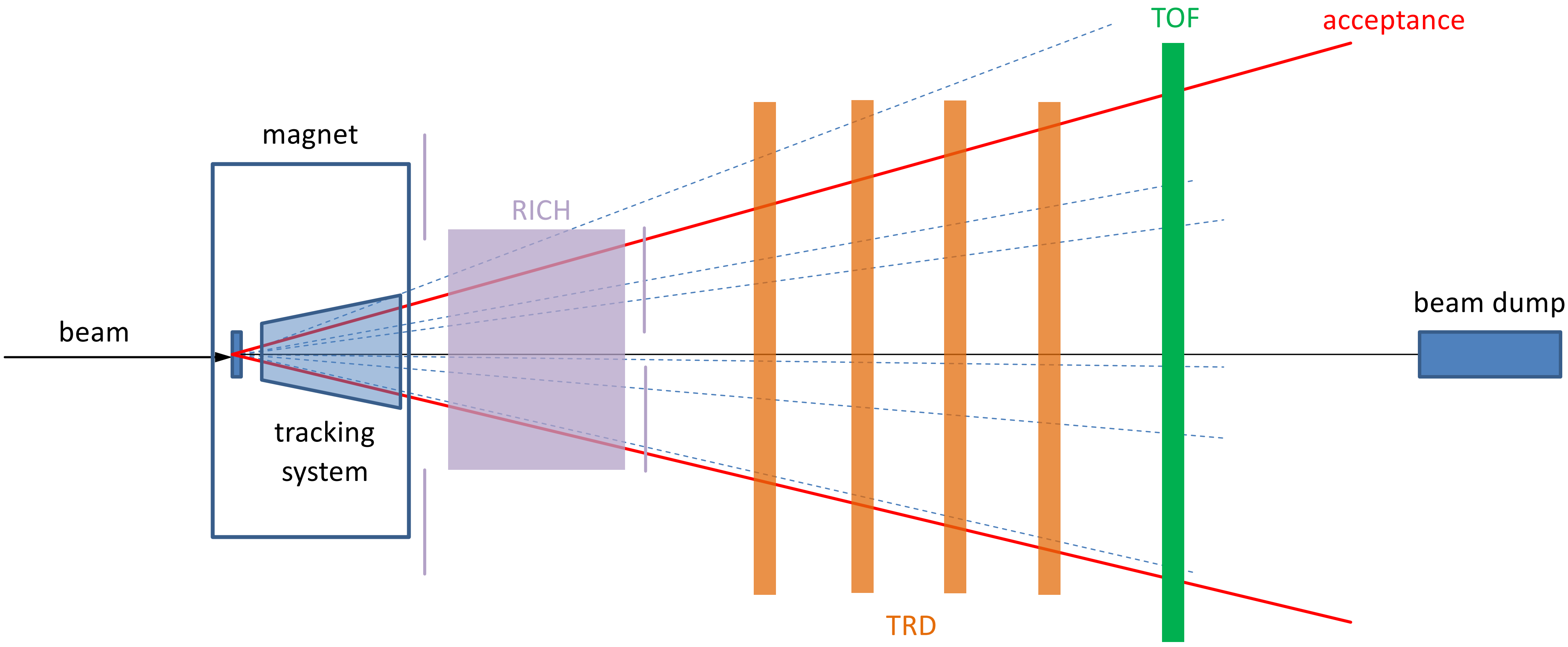
RICH detector



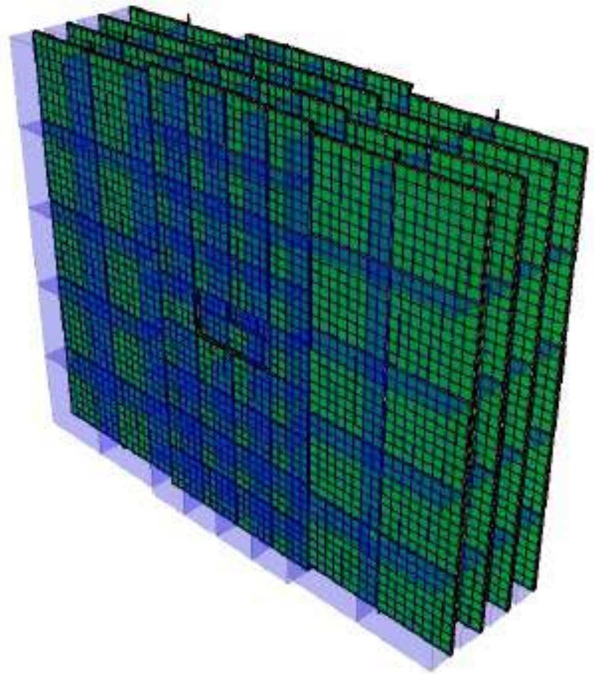


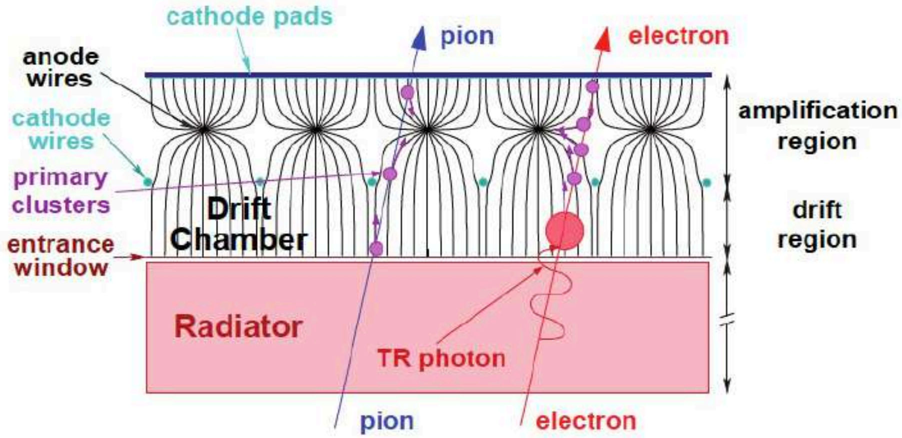
Ring Imaging Cherenkov Detector
Measurement principle: electrons make Cherenkov in the radiator, others not
Radiation focused to rings in the photodetector plane

Designing a fixed-target experiment...



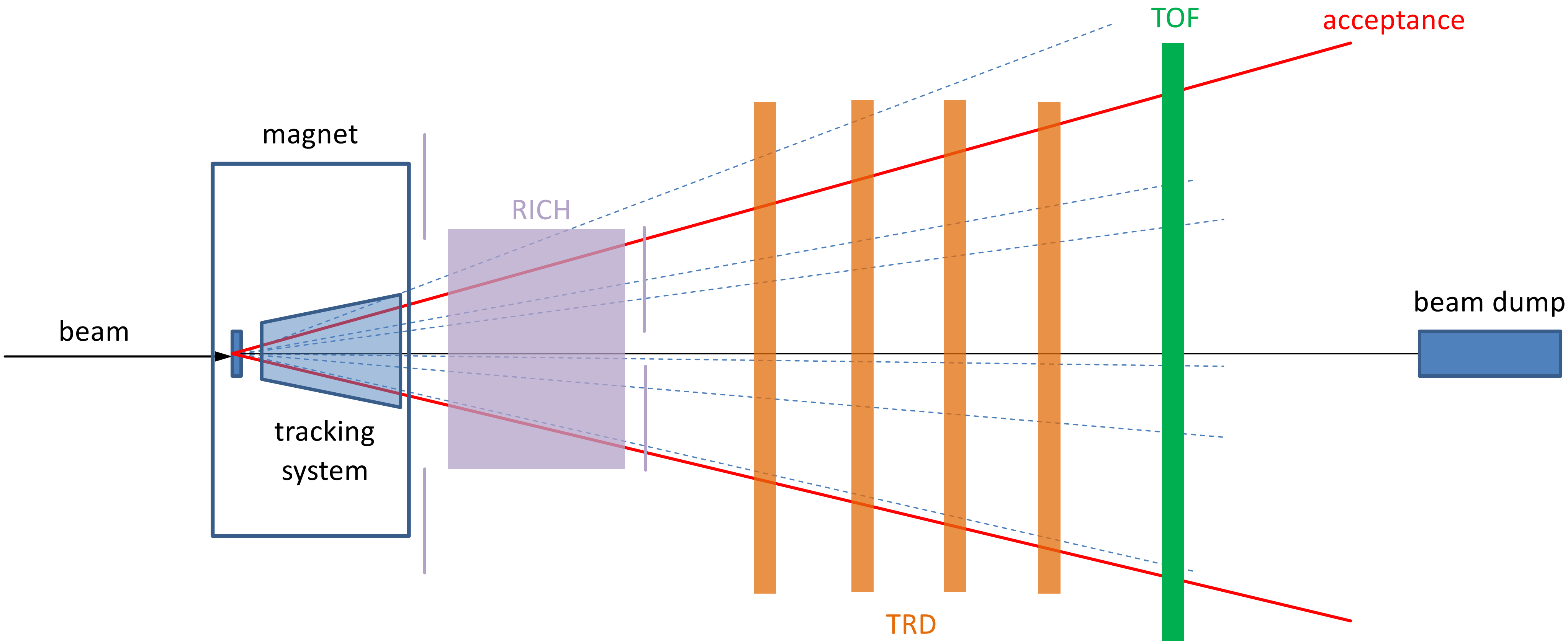
TRD



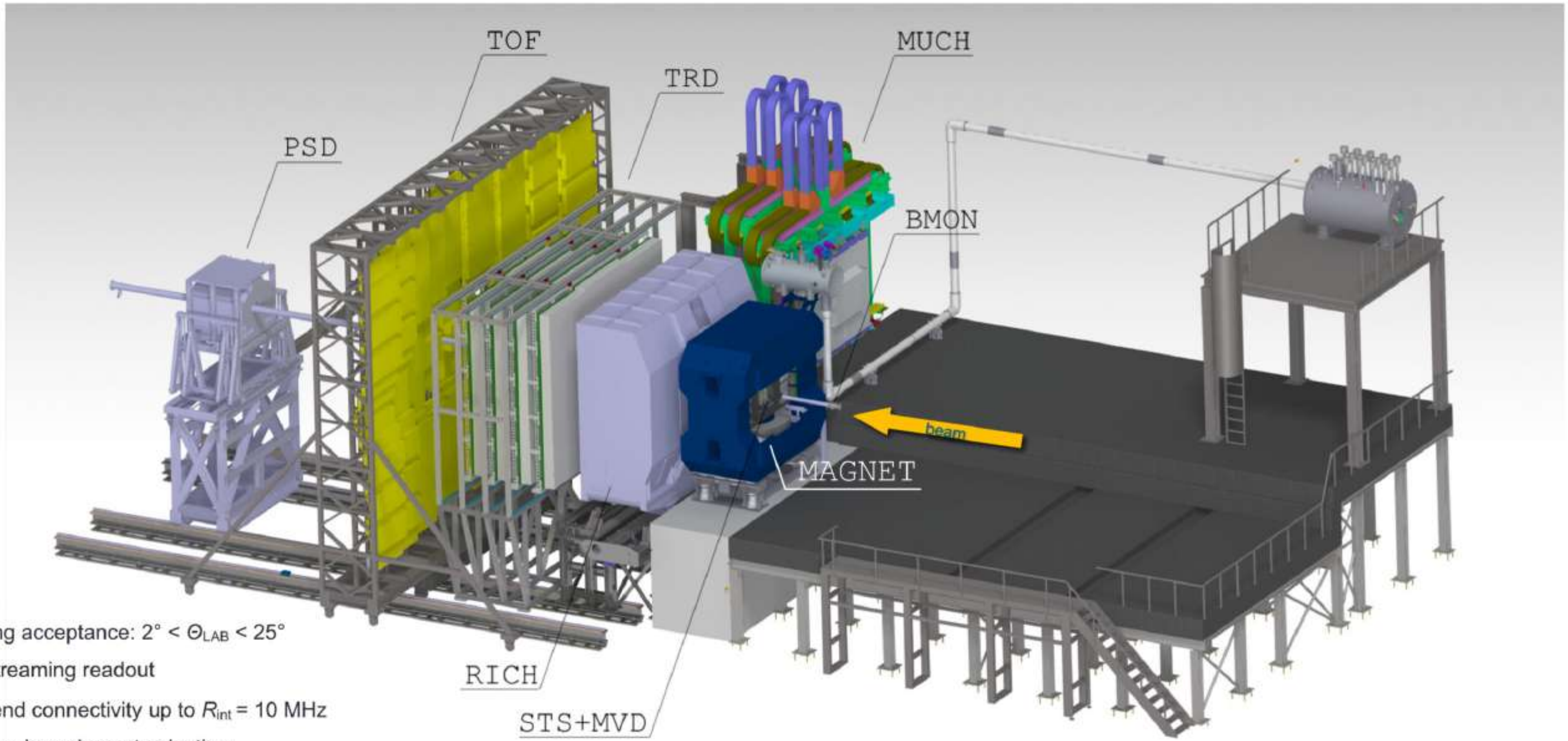


Transition Radiation: charged particles passing through inhomogeneous material
Probability increases with gamma factor: electrons make it, others not

Splendid! Our sketchy experiment...



...and CBM as it will be



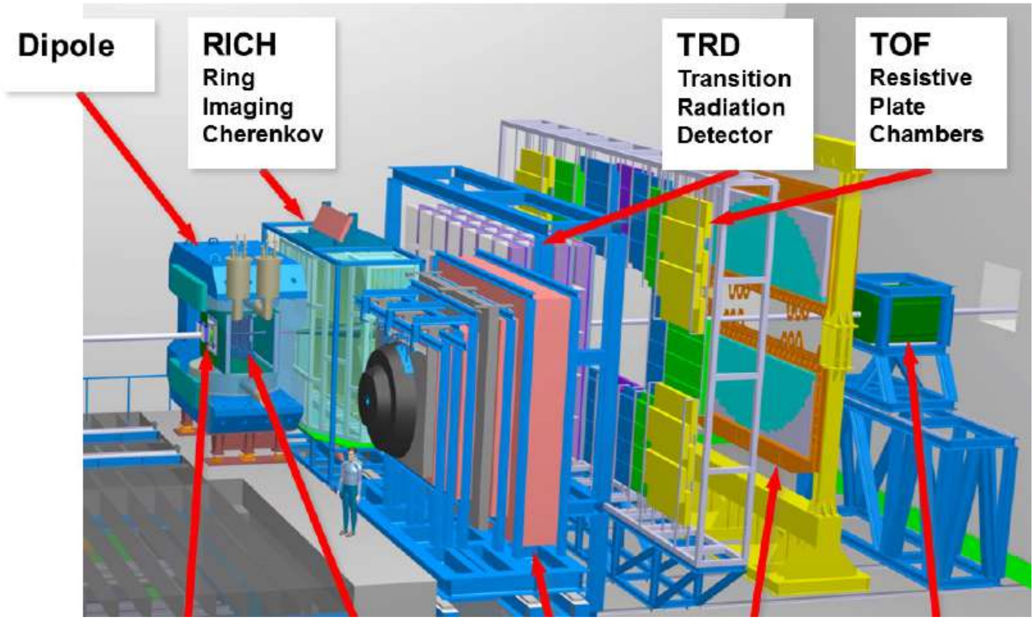
Tracking acceptance: 2° < Θ_{LAB} < 25°

Free streaming readout

Front-end connectivity up to R_{int} = 10 MHz

Software-based event selection

The muon setup

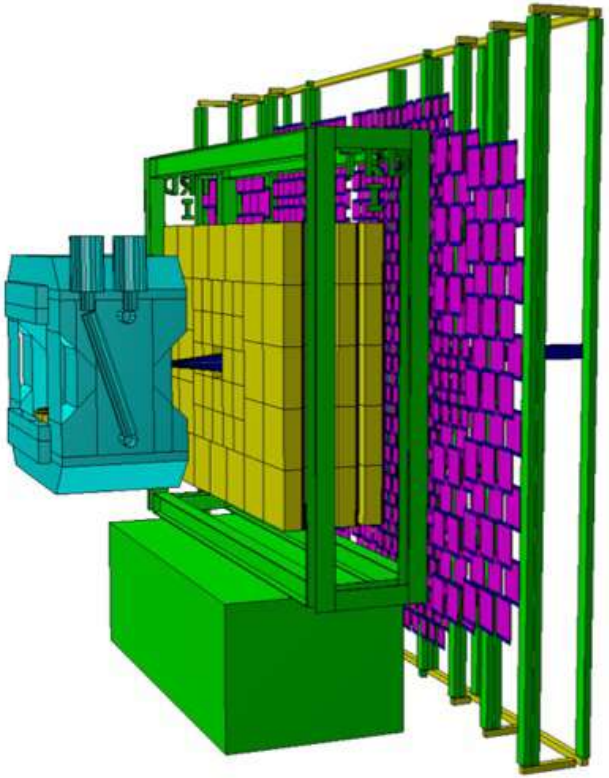


Muon Detection System

- Principle of identifying muons: survival of the fittest
- Put some massive absorber: muons are likely to make it through, others get absorbed.
- In our case: need “active” absorber (alternating absorber and detector layers) to follow the trajectory through the system.
- Excludes any other measurement: dedicated setup / run
- Can replace the RICH (on a rail system)

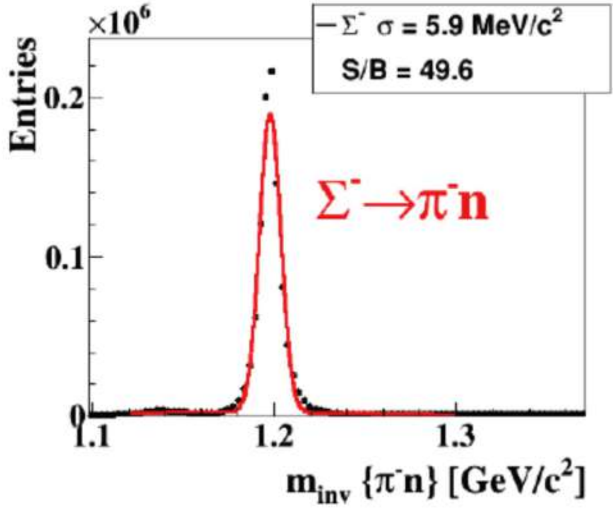
Does this experiment do what it is supposed to do?

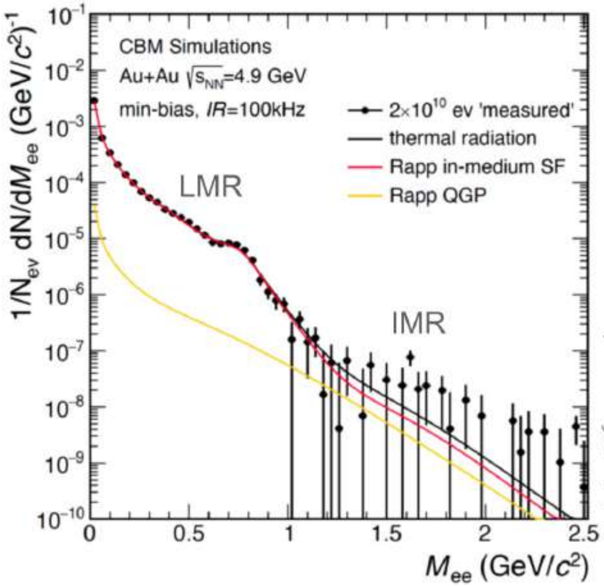
- To verify the experiment design and to study its performance, the whole thing has to be simulated.
- Requires a software model of the detector: geometry, materials, detailed detector and electronics response.
- No model, no experiment...

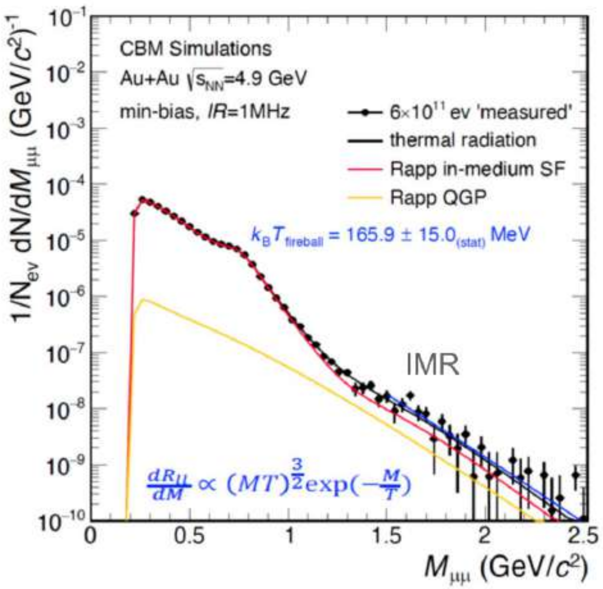


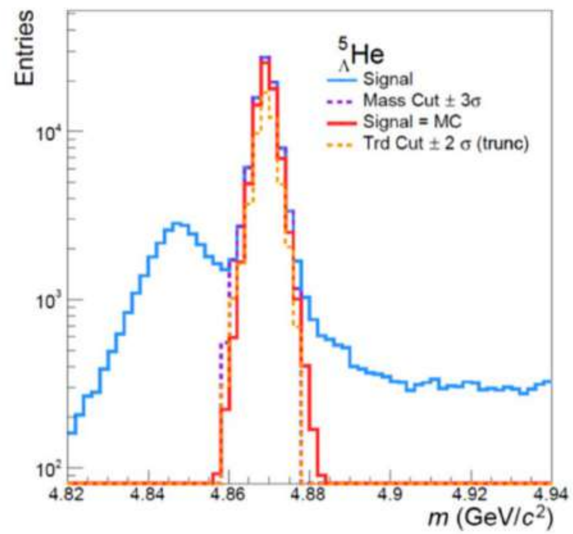
What we can expect

- Performance studies: simulated data
- Sensitivity matches our expectations: the concept looks ok!





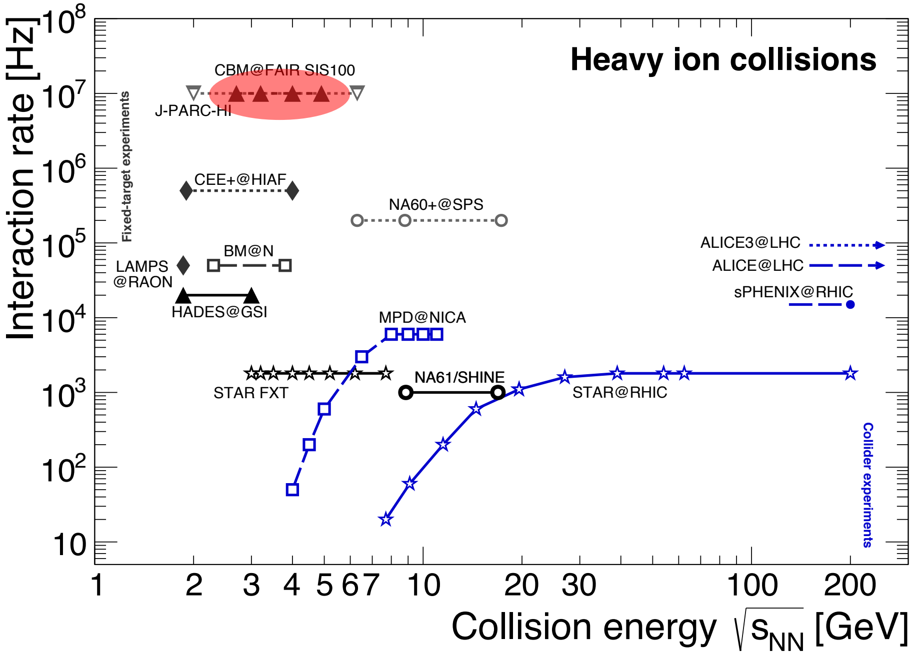


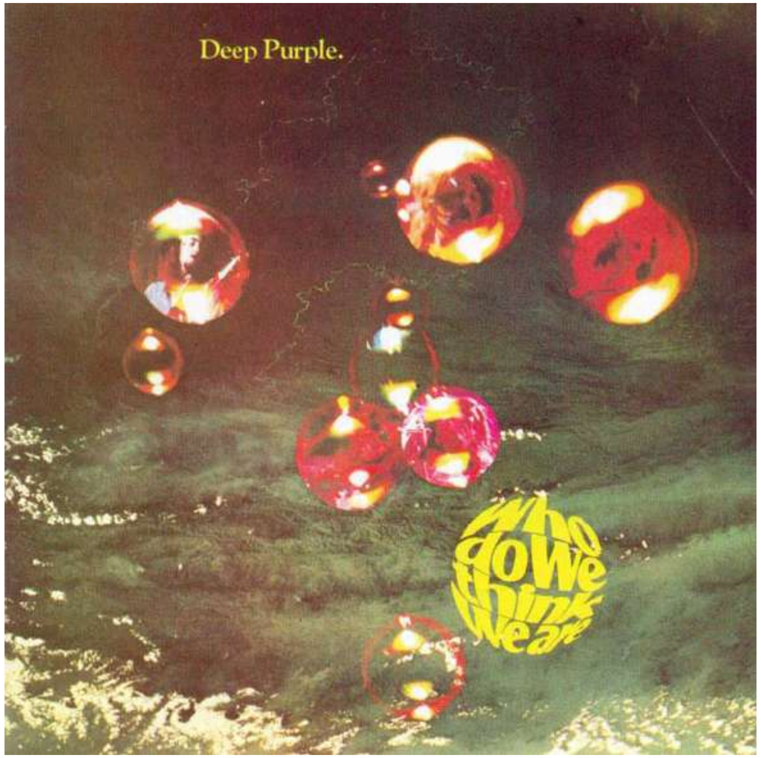


Rare probes, high rates

- Some of the (most interesting) probes are extremely rare. See, for instance, anti-hyperons or multi-strange hyper-nuclei (expected multiplicities may be 10^{-6} or worse).
- Decent measurement in reasonable time necessitates high interaction rates.
- Current heavy-ion experiments run with very moderate rates (100 Hz - several kHz).
- CBM is designed to cope with extreme interaction rates.

The high-rate frontier





10 million collisions per second? Really? Come on!

Is that possible?

If yes, why was it not done before?

Why 10^7?

Rate issues

- Radiation load on detectors and front-end electronics
  Difficult, but not unsurmountable.
- Fast timing response of detectors and electronics
- HUGE data rate coming off the detectors

What's so special about 10 MHz?

Temporal extension of a collision event

- Typical dimension of the experimental setup: 10 m
- TOF for a fast pion (speed of light): 30 ns
- TOF for a slow proton (p = 0.5 GeV): 67 ns
- The event extends over ~40 ns.

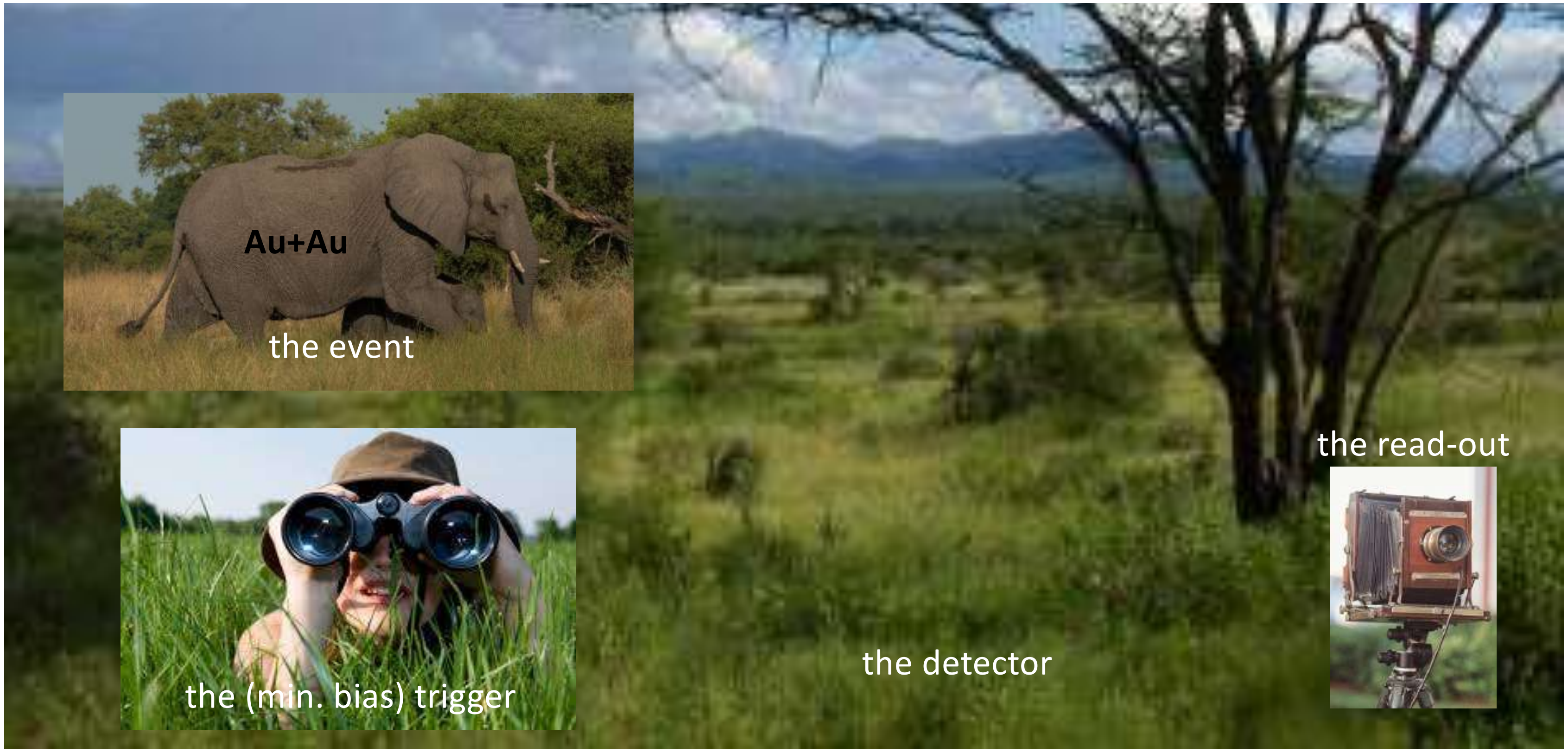
Temporal separation of two events

- Sequence of beam particles (and thus, collisions) is stochastic.
- Poisson process: $P(\Delta t) \sim e^{-t/R}$
- Mean value is 1/R (=100 ns at 10 MHz)
- But: large fraction of event pairs with smaller separation!

At about 10 MHz, the two time scales become comparable: overlapping events (pile-up) become the regular case.

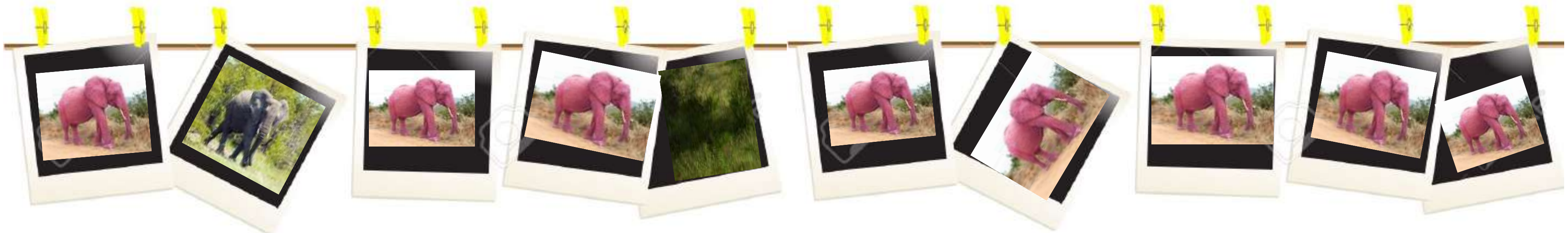
The hunt for rare probes

Triggering on elephants: conventional approach



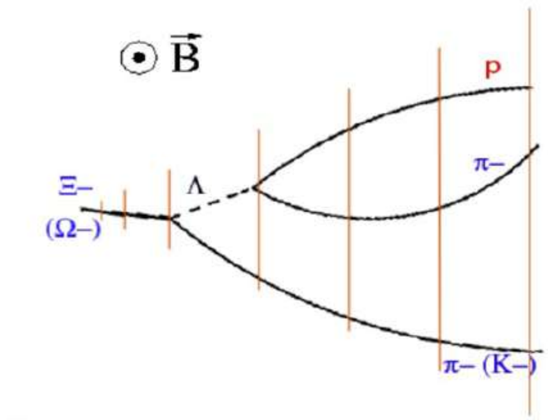
Searching elephants: conventional approach

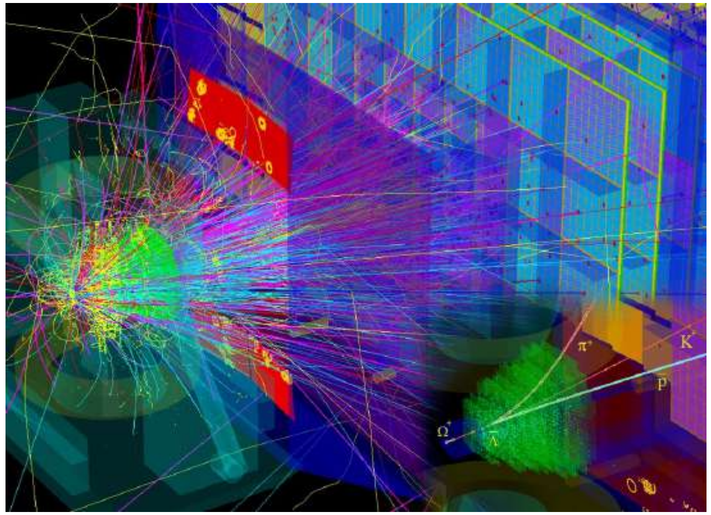
- Problem: too many photos of (uninteresting) grey elephants. Costly...
- Can’t we trigger on pink elephants only? (High-level trigger)



Nice! But does not work for us.

Problem 1: Interesting events are not pink





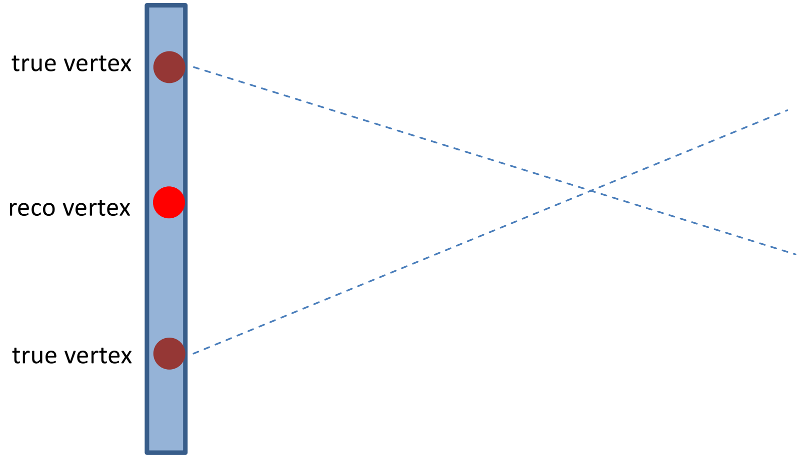
Complicated event topology!

Trigger decision requires track reconstruction and detection of the decay topology.

No chance to realize that in hardware logic. Has to be done in software.

Problem 2: Event overlap (pile-up)

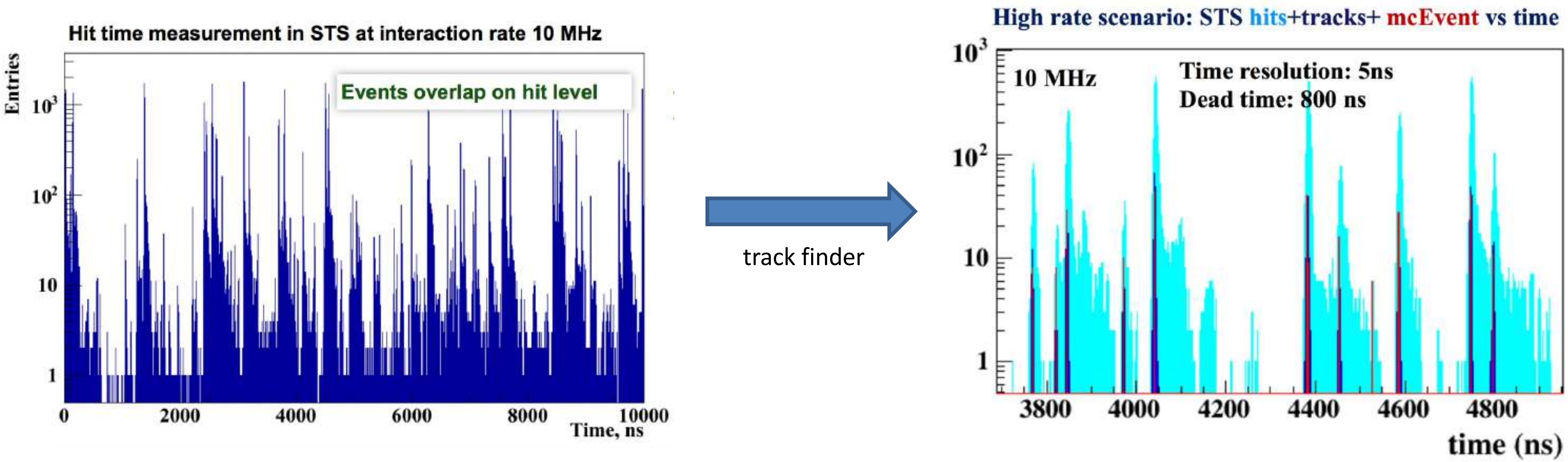
- Hard to detect by simple means.
- Disentangling pile-up events requires close inspection.
- Not to be realized in a hardware trigger; to be done in software.



Pile-up can spoil the physics - and the trigger!

- Two peripheral events on top of each other may look like one central event.
- Two primary tracks from different events my look like secondary tracks -> may fake a decay trigger

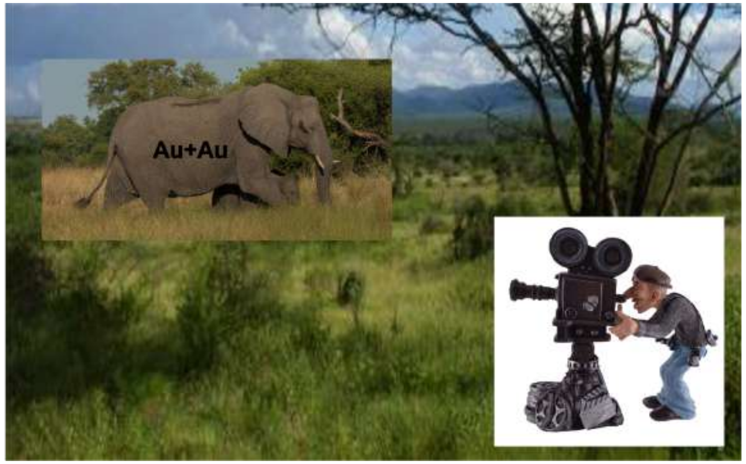
Resolving event pile-up



- Reliable event resolution requires track reconstruction.
- Tracking operates on stream of detector hits, without event association.
- Needs a 4d track model (x, y, z, t, q/p); sophisticated algorithm.
- Reduces the temporal event extension from ~40 ns to ~3 ns.
- Runs in software - noy way to have it in hardware.

The way out: continuous read-out

- No hardware trigger.
- Autonomous, self-triggered front-end electronics.
- Signals are generated by a detector element on activation above threshold.
- All signals time-stamped, collected by the data acquisition and pushed to further treatment.



It’s that easy?

- We did not invent continuous (triggerless) readout.
- But were probably the first in our field to plan an experiment that way.
- Meanwhile, the concept is followed by most experiments in planning and by several upgrades (ALICE, LHCb, ...)
- It’s NOT easy!
  - You have only the time information to associate measurements to events.
  - Central clock distribution, synchronisation: tedious business
  - **For CBM: archiving the entire detector data is prohibitive.**

The data challenge: back-of-the-envelope

- Raw data size: ~100 kB / event (min. bias Au+Au @ 12 GeV/u).
- 10^7 events/s -> 1 TB/s raw data rate from the detector.
- Archival rate: 100 GB/s surely possible; 1 TB/s on the high side
- Data volume:
  - Assuming 2 months of operation per year (5×10^6 s): 5 EB / year!

The experiment data must be reduced in real-time by 3 orders of magnitude.

Experiment →  → Online Data Processing →  → Storage

~ 1 TB/s

~ 1 - 3 GB/s

Online Data Selection

- Time and charge calibration
- Cluster and hit reconstruction
- Track reconstruction
- Event construction
- Event analysis (w.r.t. trigger signature) and trigger decision

- Traditionally done offline
- To be done in real-time
- Needs very fast algorithms
- Massively parallel computing (multi-core, GPU) in the GSI Data Centre

Selectivity and operation modes

Not all observables require or allow a highly selective trigger:

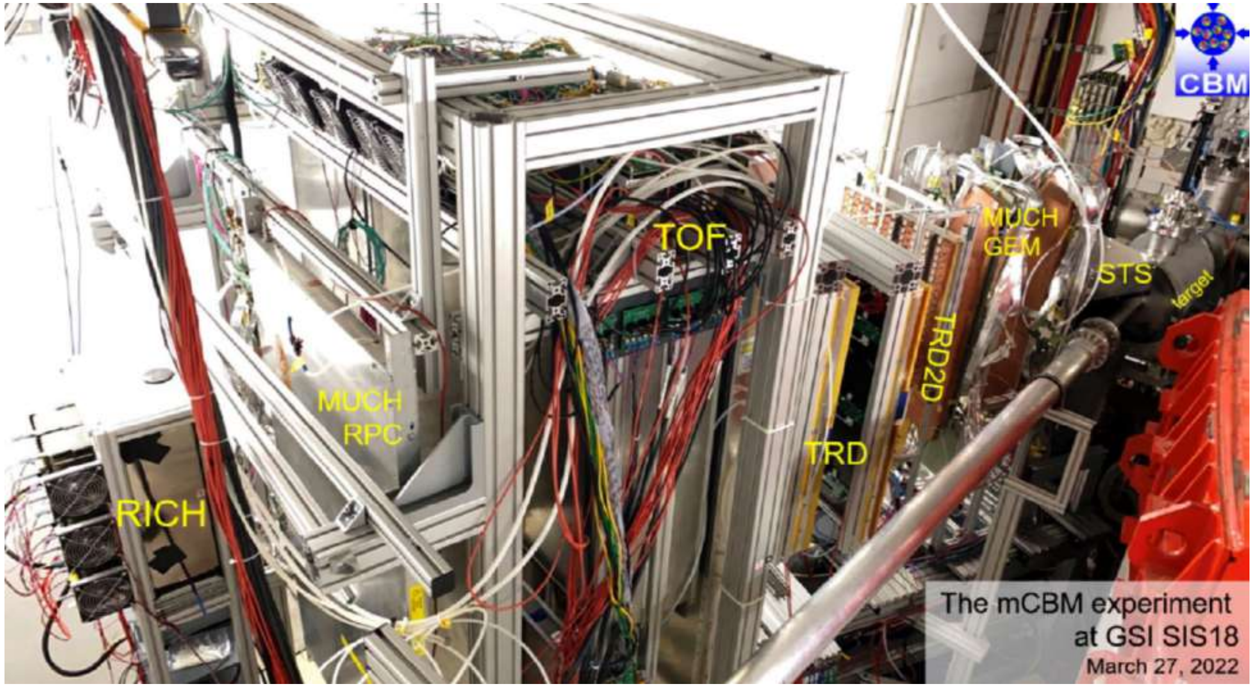
- Some have no trigger signature: fluctuations, low-mass electron pairs
- Some are not rare: all bulk observables
- Some allow lesser selectivity: high-mass electron pairs

Recordable min. bias rate
(w/o online selection):
10^5 events/s

Of course, CBM can also be operated at lower rates!

N.b.: High-rate operation allows to take selective (triggered) data together with min. bias (downscaled to saturate the bandwidth).

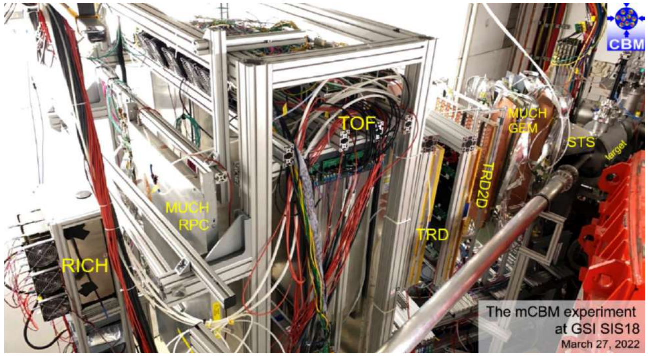
Our testbed: mCBM

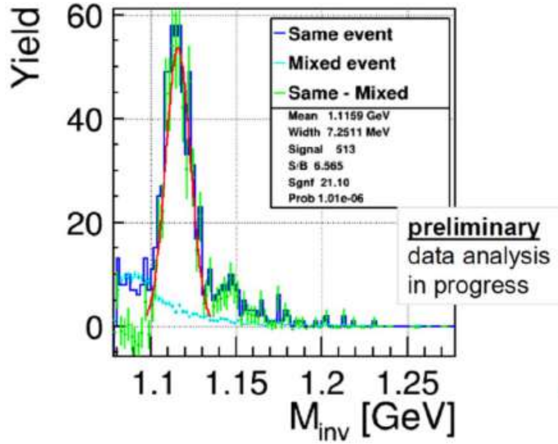


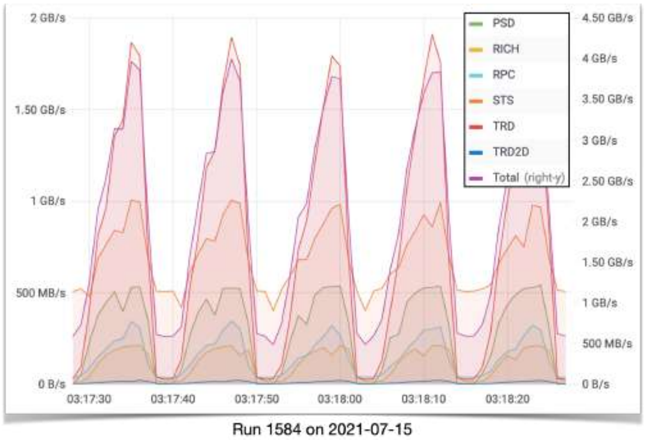
- A full-system sandbox with detector prototypes / pre-series components
- Study detectors after integration
- Verify free-streaming read-out and data transport and online data processing
- Benchmark online data processing
- Gain operational experience

- First runs 2021, 2022 (w/o online processing, all data to disk)
- Next benchmark run: 2024, applying online data selection

Our testbed: mCBM



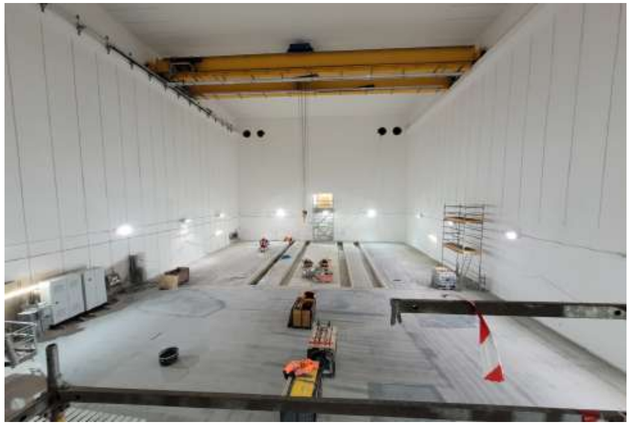




- First runs 2021, 2022 (w/o online processing, all data to disk)
- Next benchmark run: 2024, applying online data selection
- Trying to see Lambdas in real-time

So: Where are we?

FAIR construction site: tunnel for SIS100 is ready; first installations started

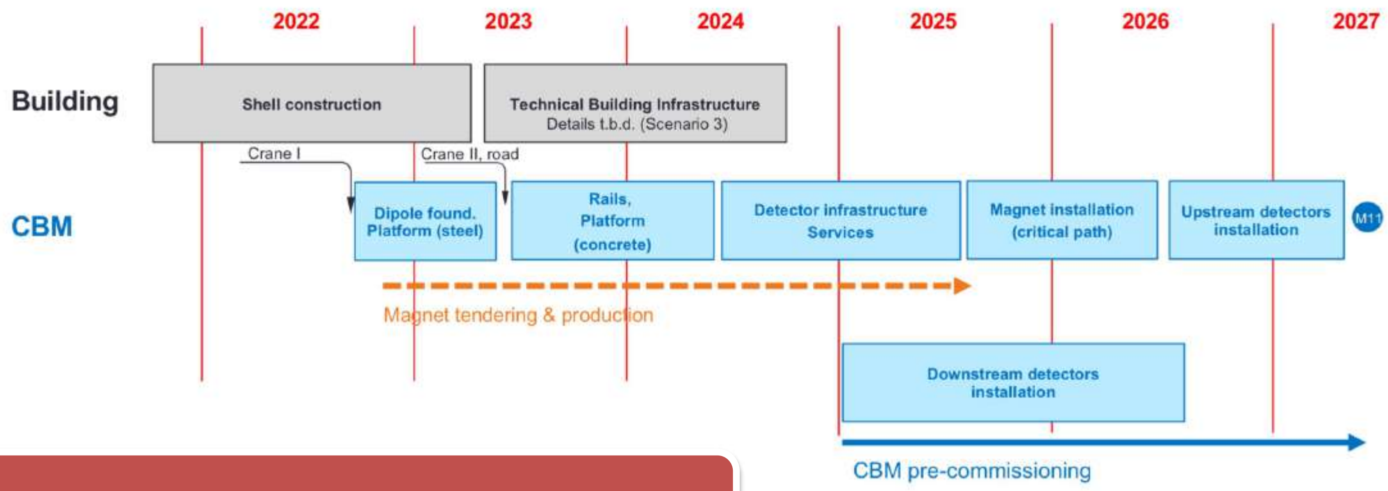


Building for CBM is ready; no infrastructure yet

So: When?

From our side:

- Detector series production has started
- Magnet will be contracted these days
- Cooperation with Russia frozen; Russian contributions / components / manpower has to be replaced.



Current planning: Ready for beam in mid-2027

Dramatis Personae

Latest head count: 323 persons, 47 institutes