Experimental methods in particle physics

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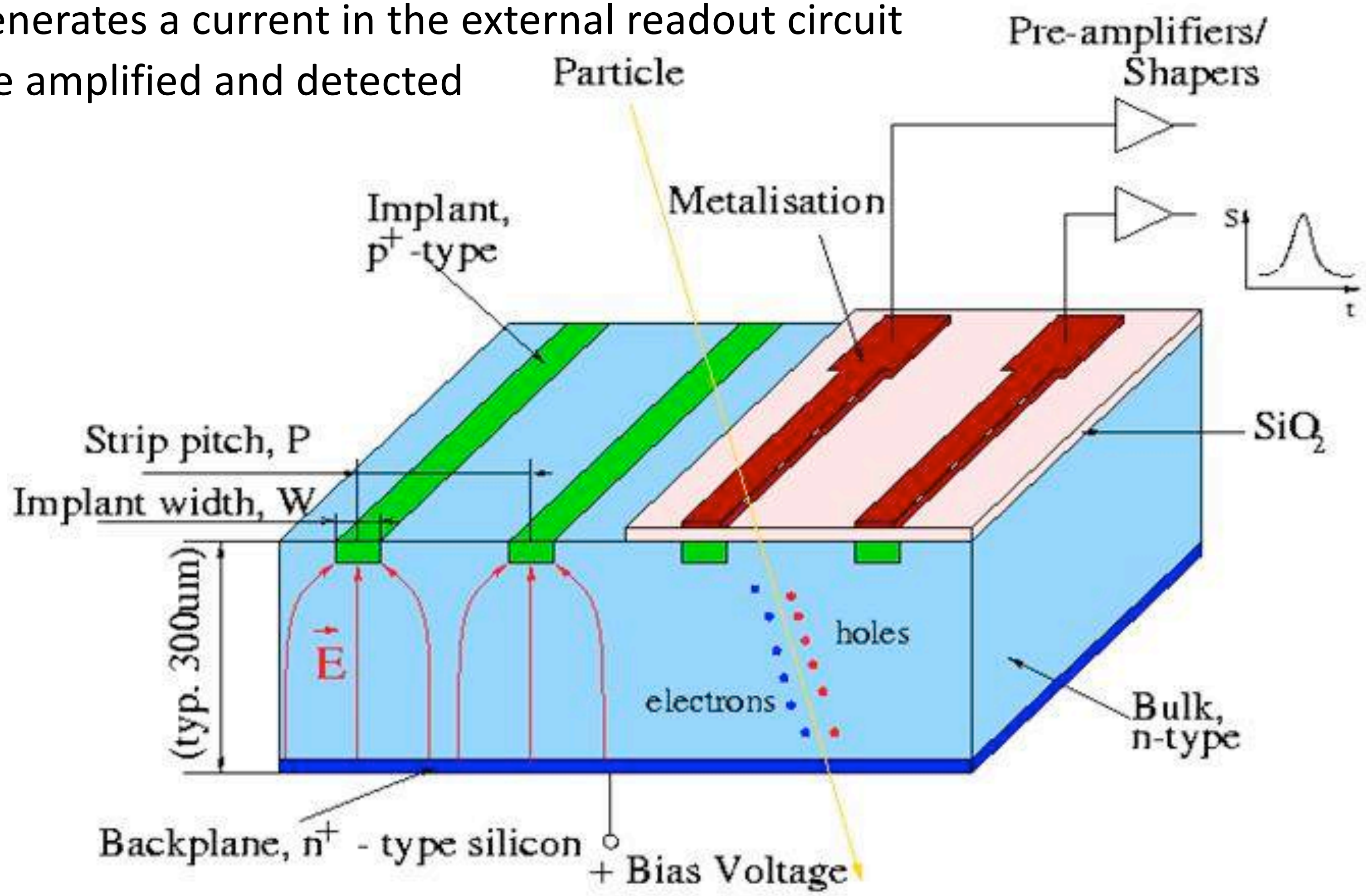
Webpage of lecture:

http://atomfizika.elte.hu/rfkm/rfkm2019.html

Semi-conductor (silicon) detectors

- Principle of ionization chamber
- Reverse bias → wide depletion zone
- Incoming charged particle creates electron - hole pairs
- Charge carriers move in the electrical field
- This movement generates a current in the external readout circuit
- The current can be amplified and detected

- Typical doping:
- p^+: 10^{15} / cm^3
- n: 10^{12} / cm^3



Energy required for creation of an electron-hole pair

Ionization Energy > Band Gap

Formation of e-h pairs requires both

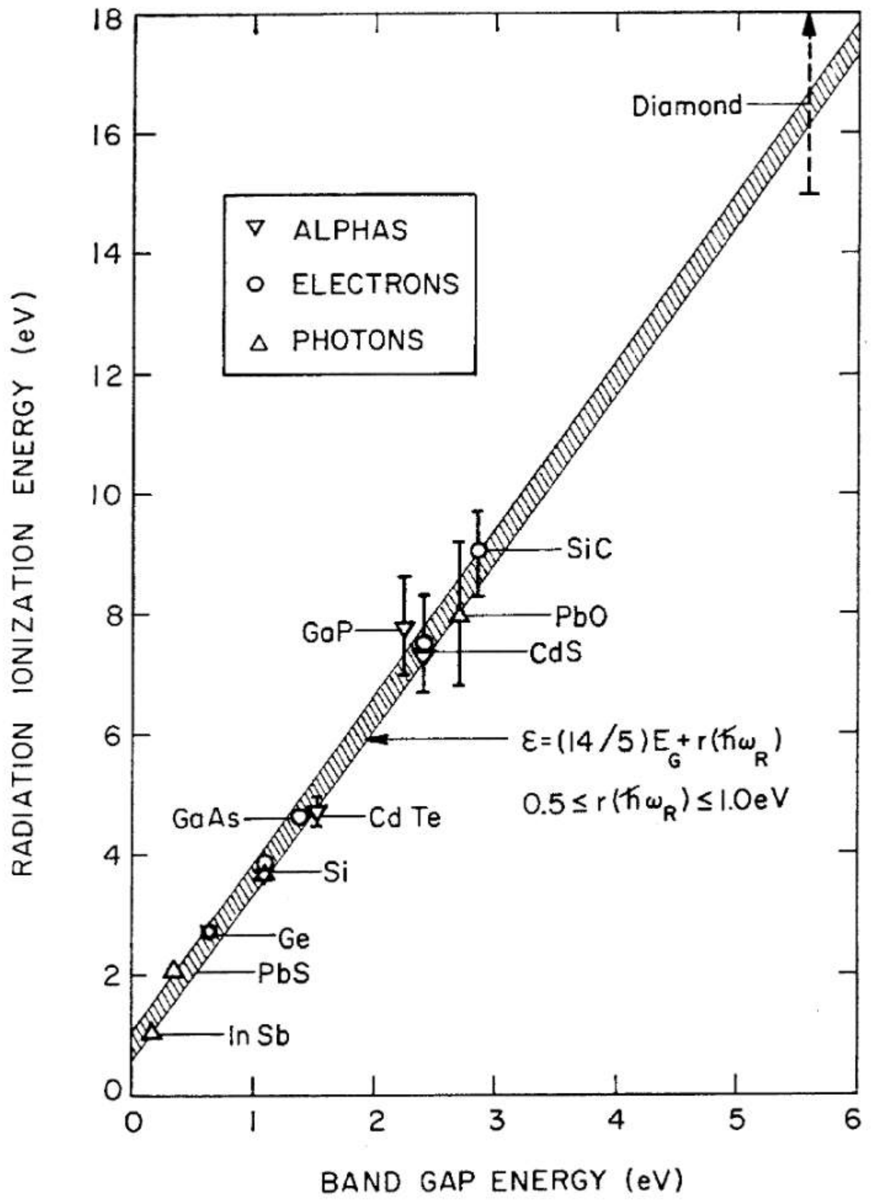
1) Conservation of energy

2) Conservation of momentum

→ additional energy excites phonons

$$\varepsilon_i = C_1 + C_2 * E_g$$

Independent of material and type of radiation



C. A. Klein, J. Appl. Phys. 39,2029 (1968)

Spatial resolution

★ Threshold readout (one strip signal):

➔ position: x = strip position

➔ resolution: $\sigma_x \approx \frac{p}{\sqrt{12}}$

p … distance between strips (readout pitch)

x … position of particle track

★ charge center of gravity (signal on two strips):

➔ position:

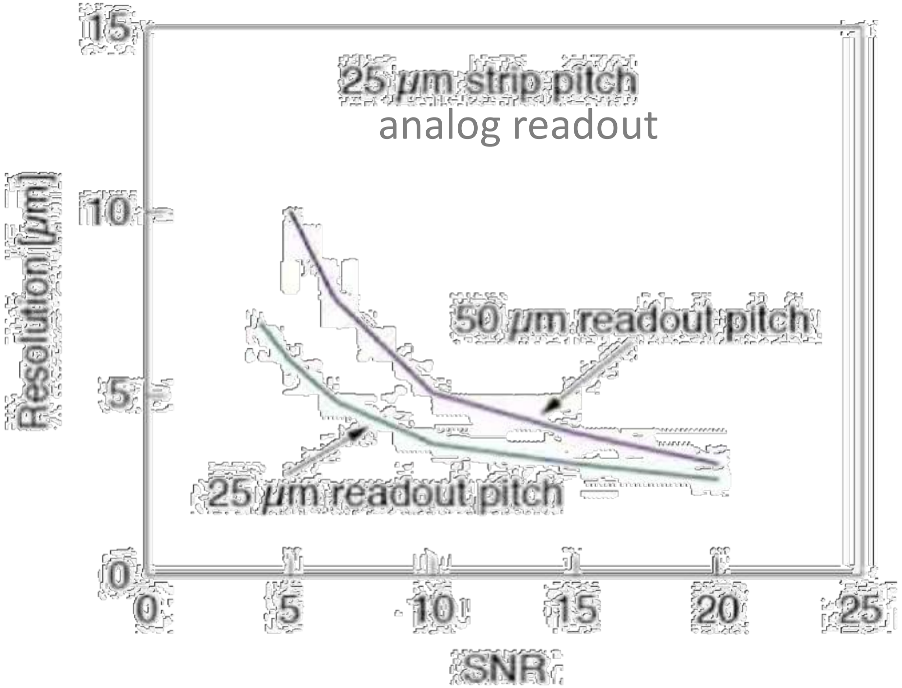
$$x = x_1 + \frac{h_1^2}{h_1 + h_2}(x_2 - x_1) = \frac{h_1 x_1 + h_2 x_2}{h_1 + h_2}$$

➔ resolution: $\sigma_x \propto \frac{p}{SNR}$

x_1, x_2 … position of 1st and 2nd strip

h_1, h_2 … signal on 1st and 2nd strip

SNR … signal to noise ratio

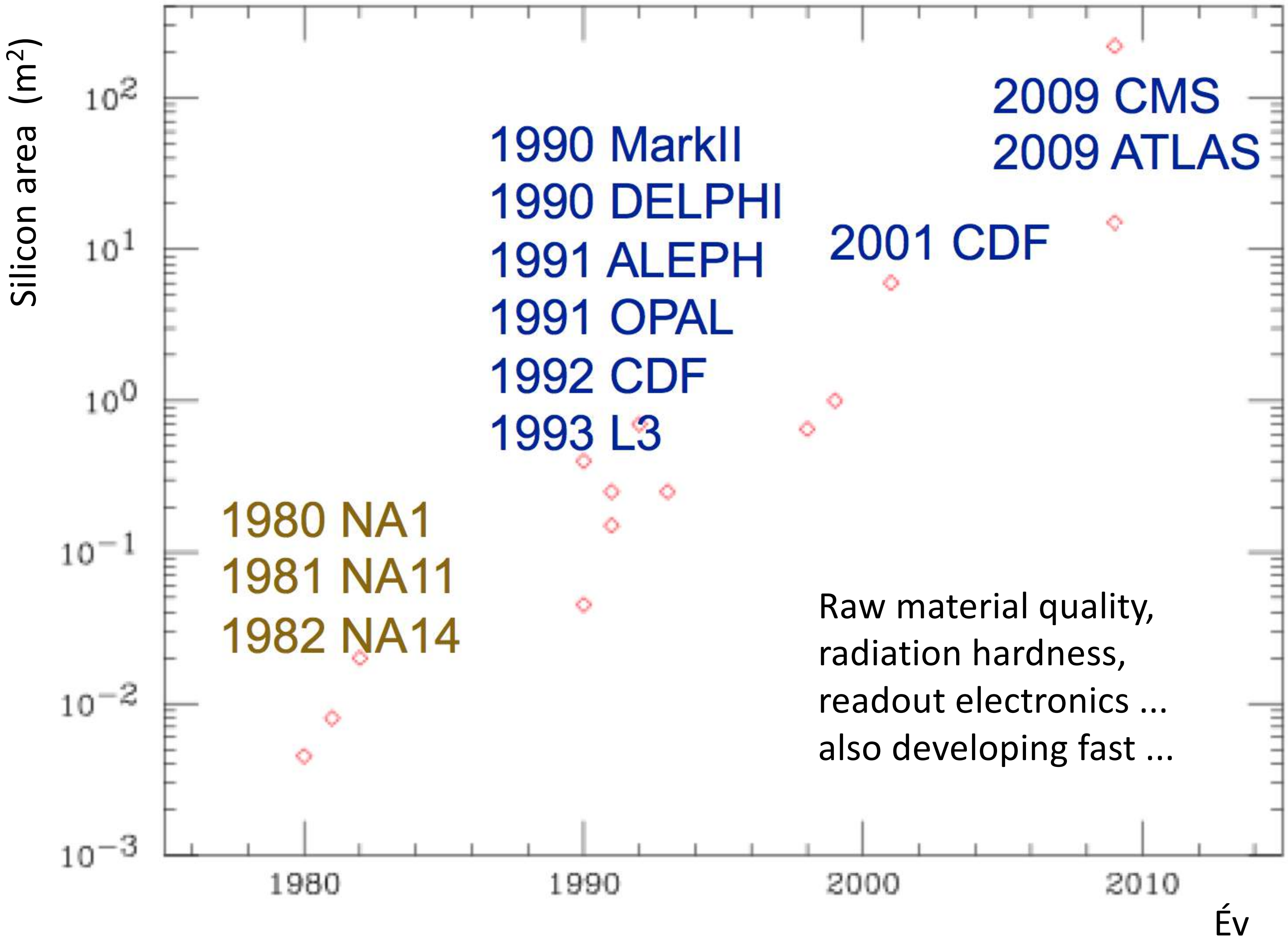


A. Peisert, *Silicon Microstrip Detectors*, DELPHI 92-143 MVX 2, CERN, 1992

Example of a detector with strip pith of 25 μm and analogue readout.
The position resolution is plotted as a function of the SNR.
Bottom curve: every strip is connected to the readout electronics
Top curve: every 2nd strip is connected, one intermediate strip

To benefit from intermediate strips large SNR is required!

Development of Silicon Detectors



Raw material quality,
radiation hardness,
readout electronics ...
also developing fast ...

Development of Silicon Detectors: the beginning

- J. Kemmer 1979

NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 499-502, © NORTH HOLLAND PUBLISHING CO

FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

J KEMMER

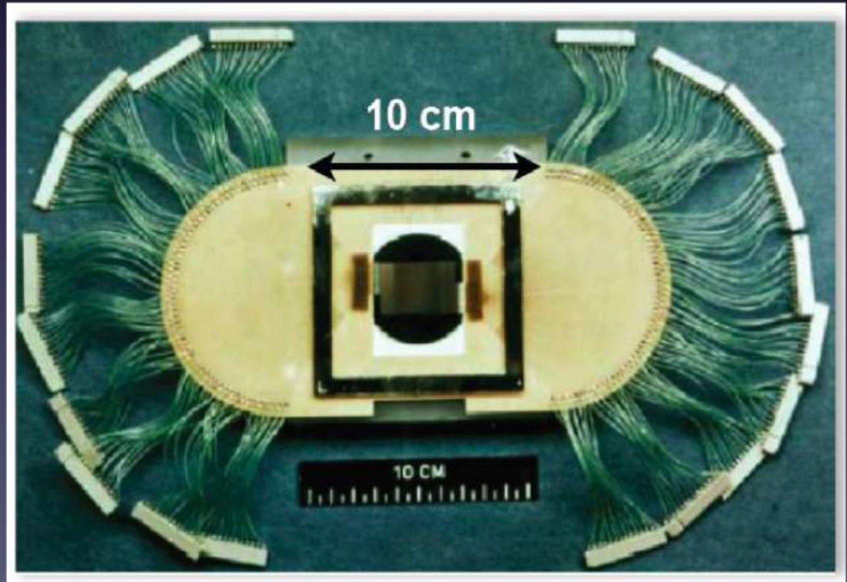
Fachbereich Physik der Technischen Universitat Munchen, 8046 Garching, Germany

Received 30 July 1979 and in revised form 22 October 1979

Dedicated to Prof Dr H -J Born on the occasion of his 70th birthday

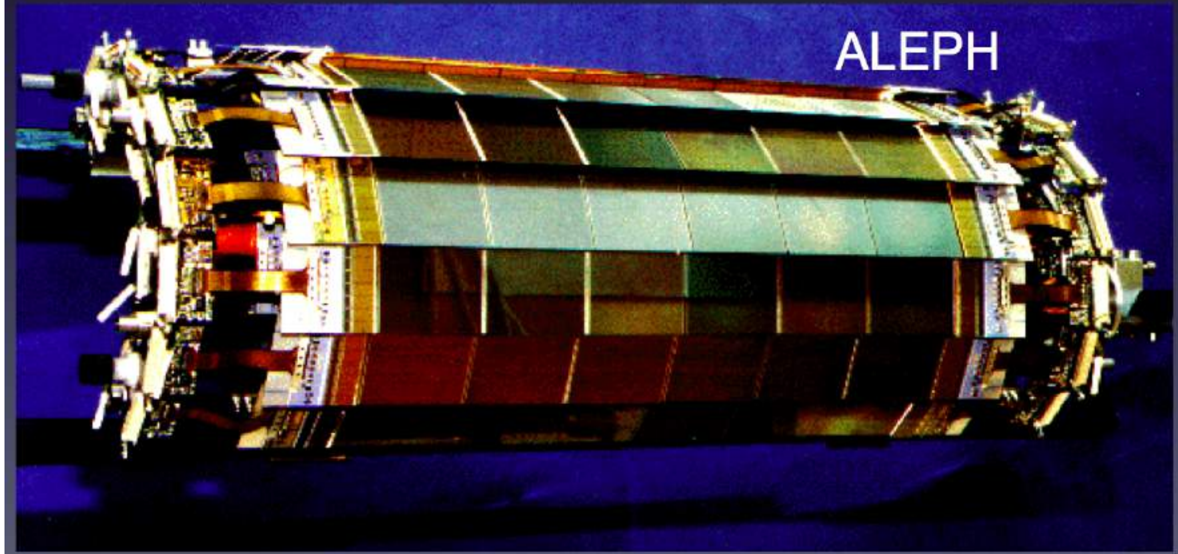
By applying the well known techniques of the planar process oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than 1 nA cm^{-2}/100 μm at room temperature Best values for the energy resolution were 10 0 keV for the 5 486 MeV alphas of ^{241}Am at 22°C using 5×5 mm^2 detector chips

- NA11 at CERN **1983**
  - First use of a position-sensitive silicon detector in HEP experiment
  - Measurement of charm quark lifetimes
  - 1200 diode strips on 24x 36 mm^2
  - 250-500 μm thick bulk material
  - 4.5 μm resolution



Development of Silicon Detectors: LEP@CERN and SLC@SLAC

- **LEP and SLC** **1990s**
  - Readout ASICs at end of ladders
  - Minimize mass inside tracking volume
  - Minimize mass between interaction point and detectors
  - Minimize the distance between interaction point and the detectors
- Enabled measurement of b-quark lifetimes and b-tagging



ALEPH

- 2 silicon layers, 40cm long, inner radius 6.3cm, outer radius 11cm
- 300 μm silicon wafers giving thickness of only $0.015X_0$
- S/N(r-ϕ) = 28:1
- S/N(z)= 17:1
- r-ϕ= 12 μm; z = 14μm

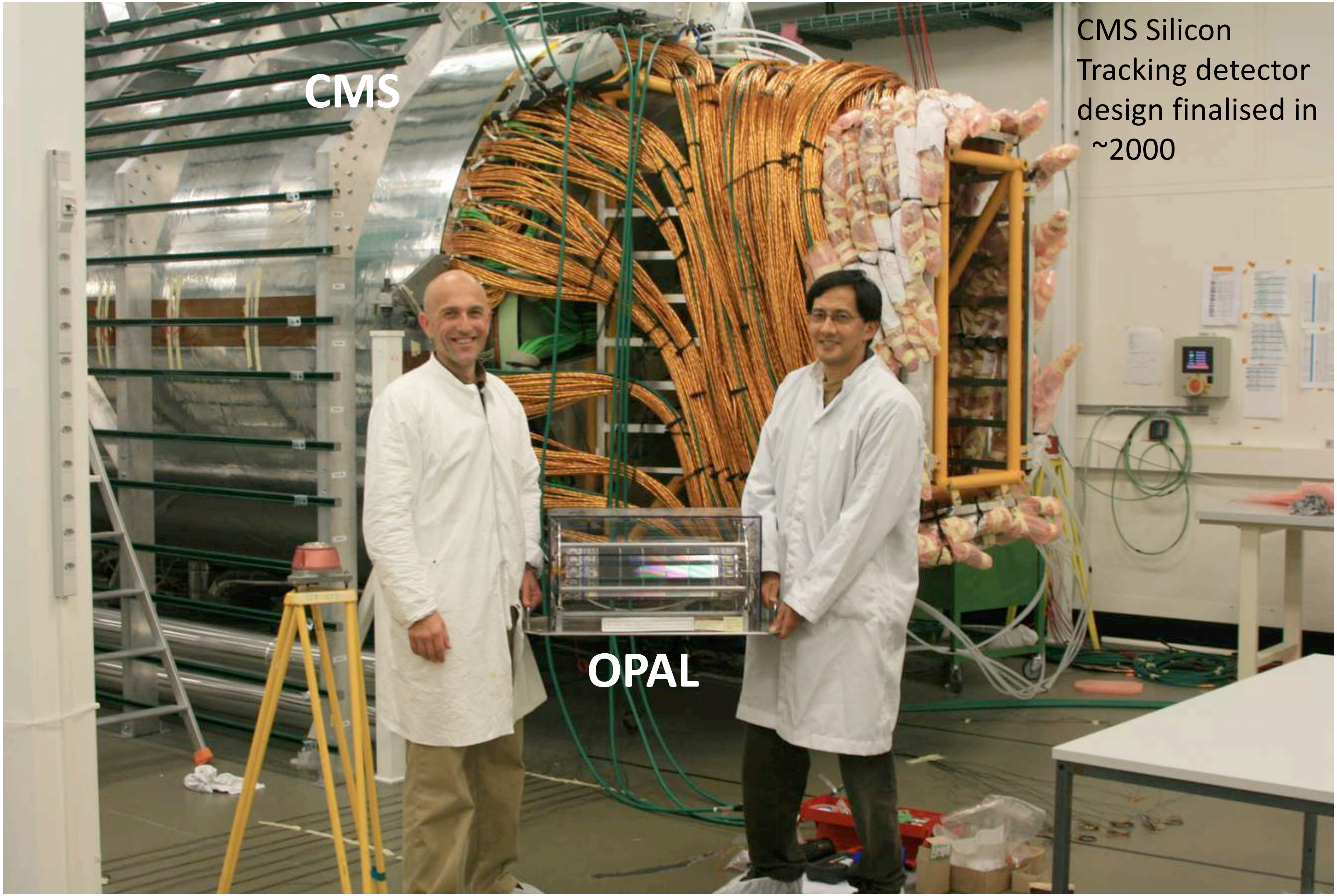
Development of Silicon Detectors: Tevatron@FNAL

From 1990s

- CDF pioneered the silicon vertex detector in the hadron collider environment and pioneered the silicon vertex trigger separating *b*-hadrons
- Emphasis shifted to tracking and vertexing allowing precision measurements in very complex environment
- Cover large area with many silicon layers
- Detector modules including ASIC's and services INSIDE the tracking volume

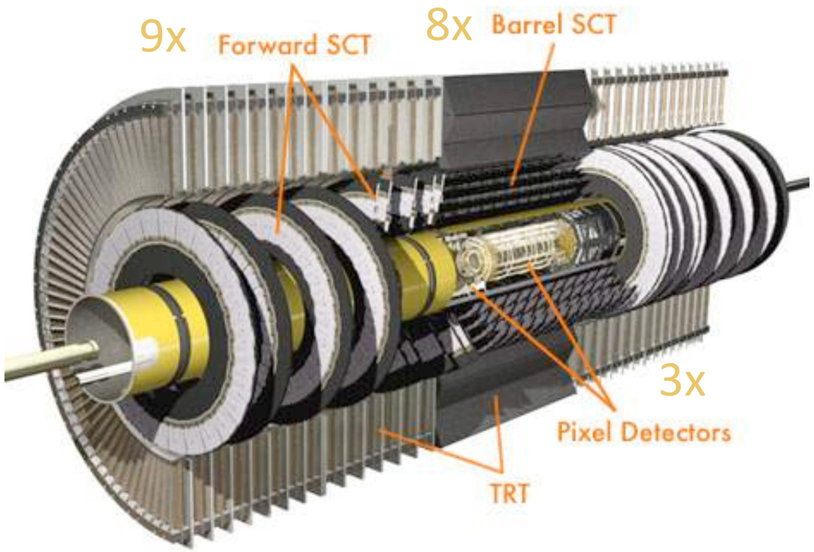
CDF's first Silicon Vertex Detector at the Smithsonian Museum, Washington

Development of Silicon Detectors: from LEP to LHC

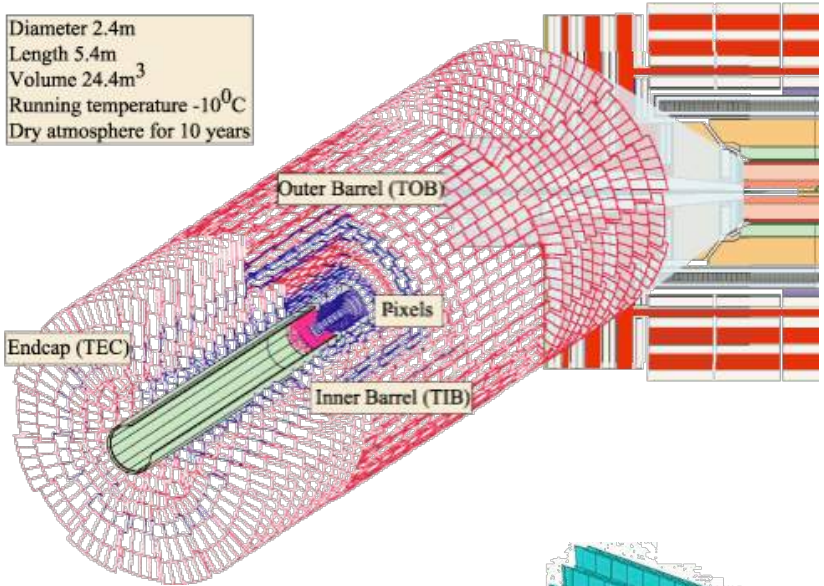


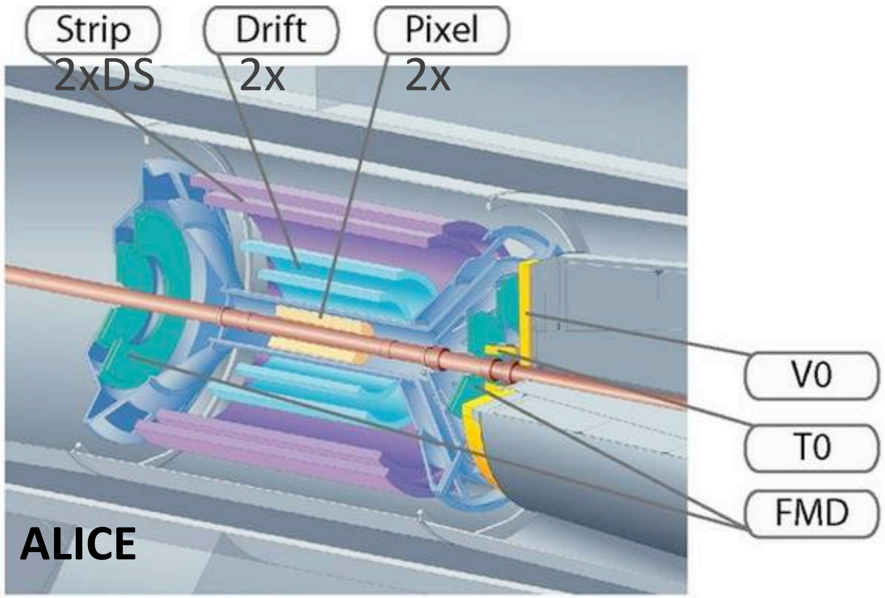
Development of Silicon Detectors: LHC

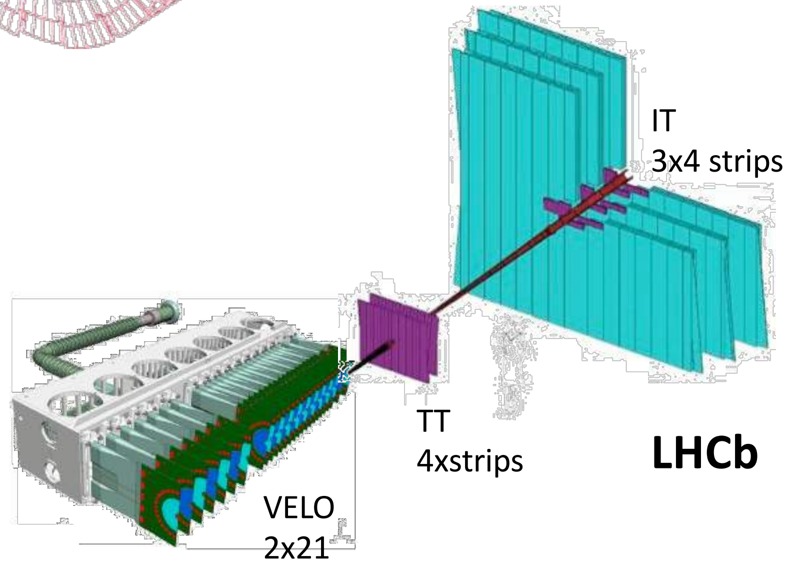
ATLAS: 61 m^2 Si strips, 6M channels
80M pixel channels



CMS 205 m^2 Si strips, 9.3M channels
1 m^2 Si pixels, 66M channels







LHCb experiment

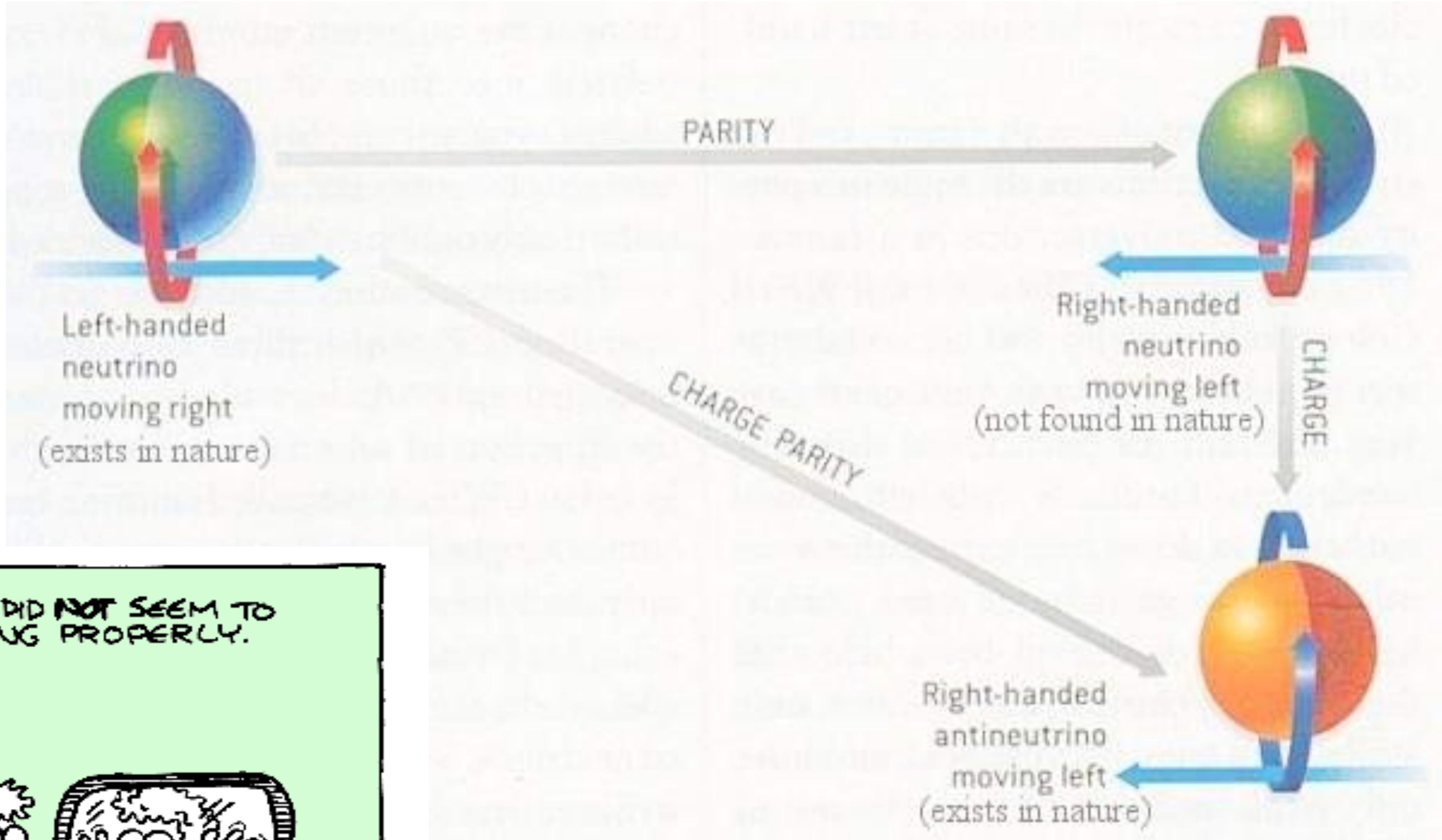
- Study of mater – anti-mater asymmetry
  - Big bang created same amount of matter and anti-matter
  - Why matter dominates in the universe? Where did the anti-matter go?
- Small differences in the properties of matter and anti-matter (e.g. different decay probabilities) could explain
- Study the decay of hadrons containing b-quark or anti-b-quarks

b (beauty, bottom) quark

- 1973 Kobayashi and Maskawa: suggest b quark to explain CP violation (2008 Nobel Prize)
- 1977 Lederman et al. (E288 experiment)
- Q = -1/3
- High mass: m = 4.2 GeV / c2
- Decays via weak interaction (small CKM Vub, Vcb values)
- Lifetime: 10^{-12} s
- b-tagging (secondary vertex)

CP violation: charge conjugation * parity (reflection in space) not a conserved quantum number (symmetry) in the weak interaction → matter – anti-matter asymmetry

Detour: discovery of parity and CP violation



$\mathbf{L} = \mathbf{r} \times \mathbf{p},$

$P(\mathbf{L}) = (-\mathbf{r}) \times (-\mathbf{p}) = \mathbf{L}.$

CKM matrix

- W boson coupling to left-handed quarks:

$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W_\mu^+ V_{\rm CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

- CKM (Cabibbo – Kobayashi – Maskawa) matrix

$$V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

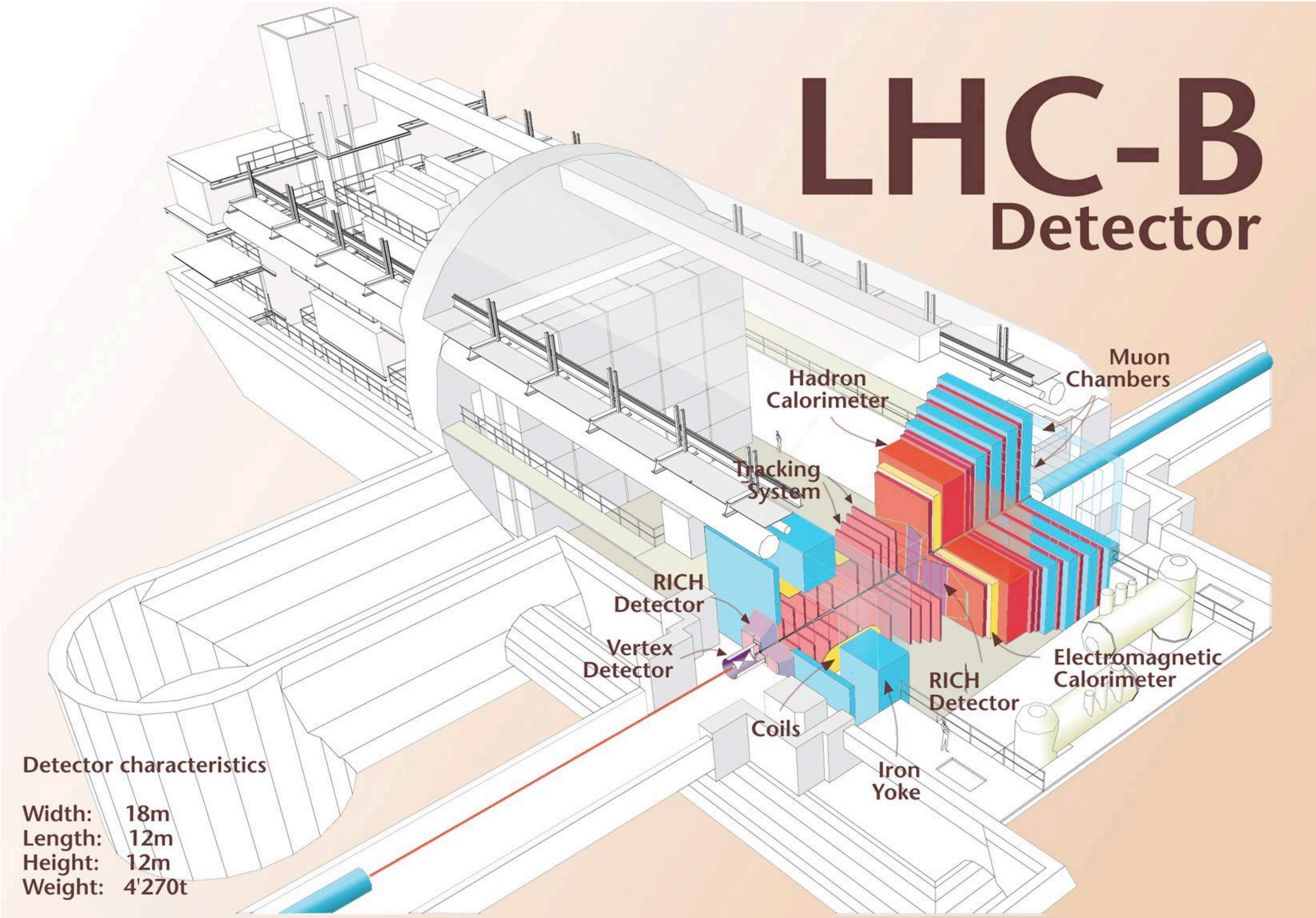
- Unitary
- Can be parametrised with 3 mixing angles (θ_{12}, θ_{13}, θ_{23} : $0 - \pi/2$) and a CP-violating phase (δ):

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij}, \ c_{ij} = \cos\theta_{ij}$$

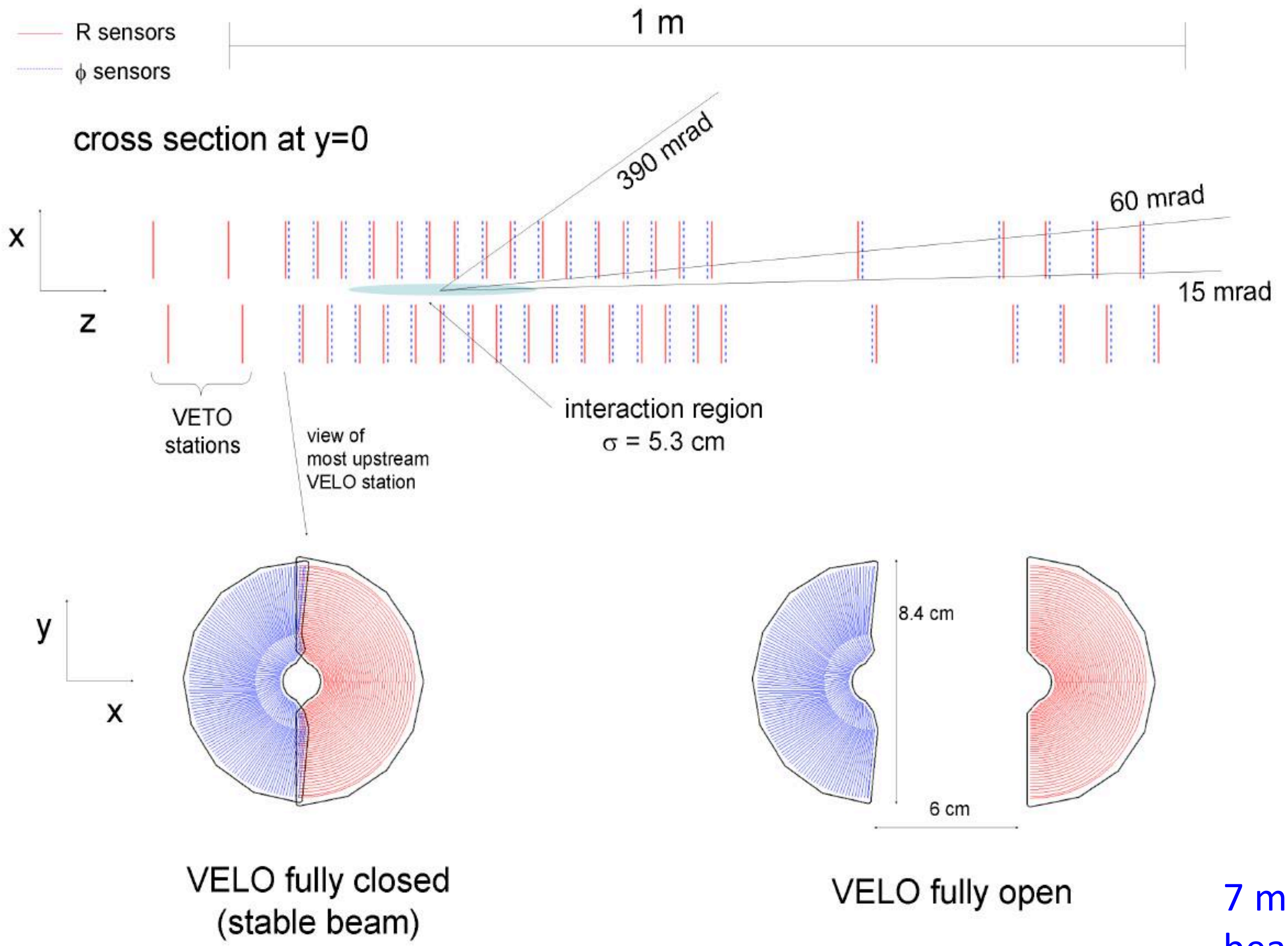
- δ responsible for all CP-violating phenomena in the SM

Back to LHCb



LHC-B
Detector
Muon
Chambers
Hadron
Calorimeter
Tracking
System
RICH
Detector
Vertex
Detector
Coils
Iron
Yoke
RICH
Detector
Electromagnetic
Calorimeter
Detector characteristics
Width: 18m
Length: 12m
Height: 12m
Weight: 4'270t

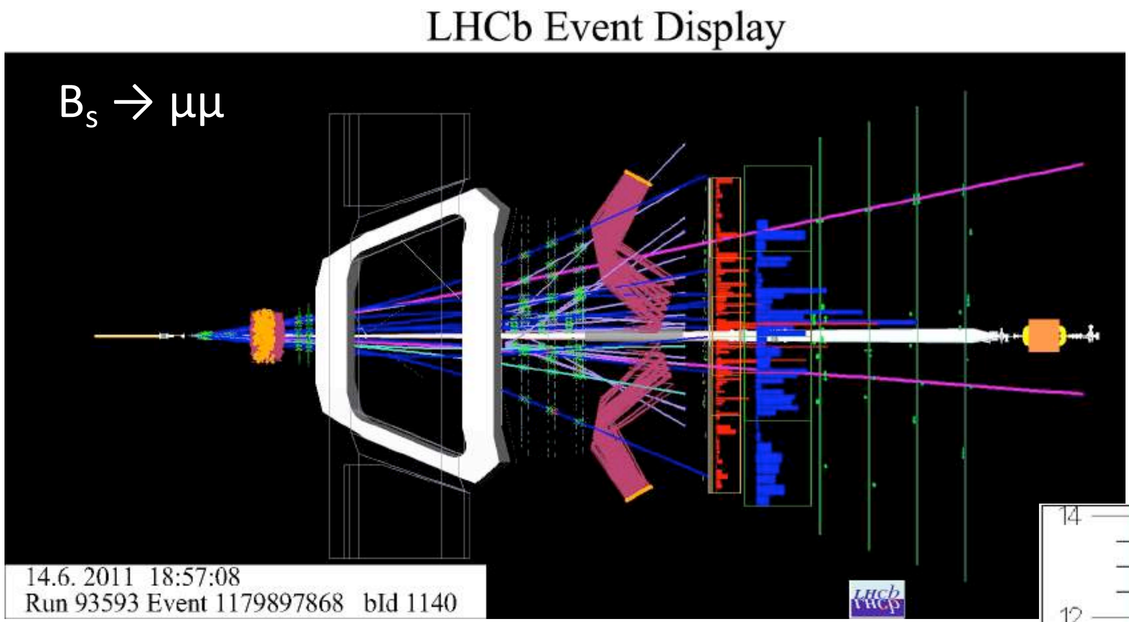
LHCb VELO vertex detector



7 mm from beam line when closed

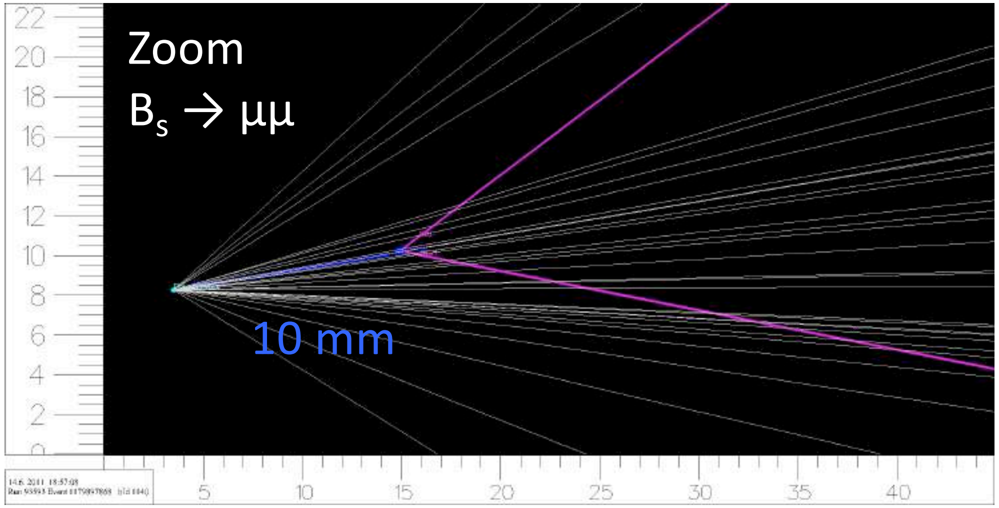
Collider experiment with levelled-luminosity

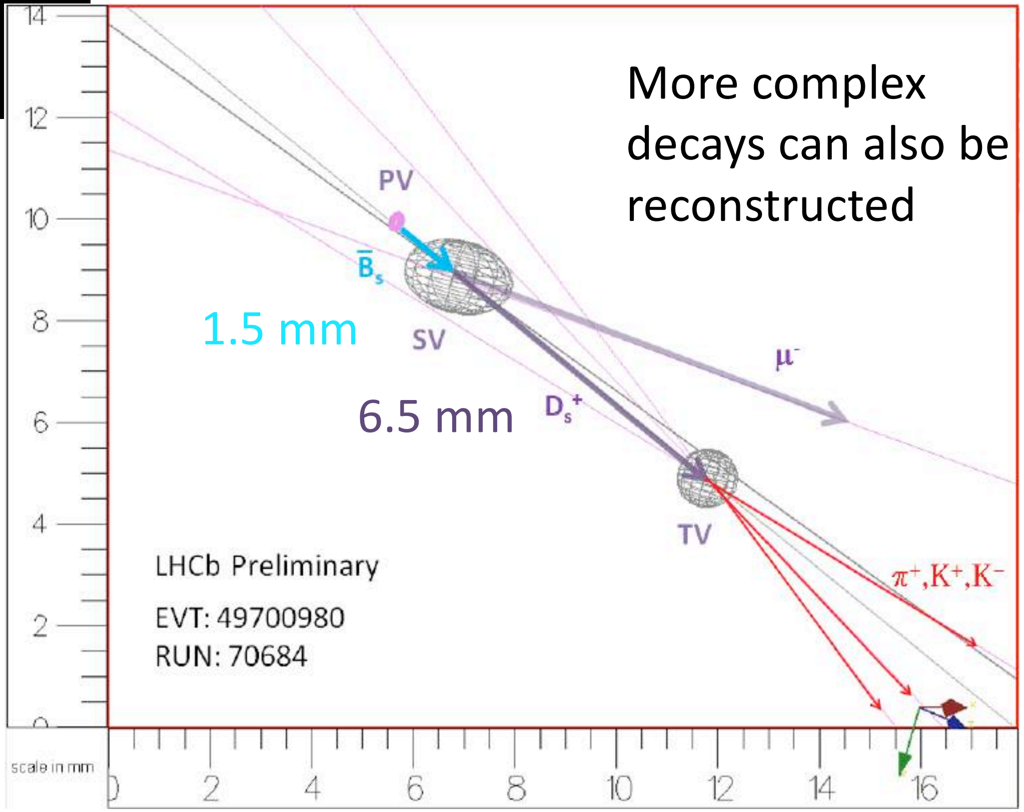
Secondary vertices



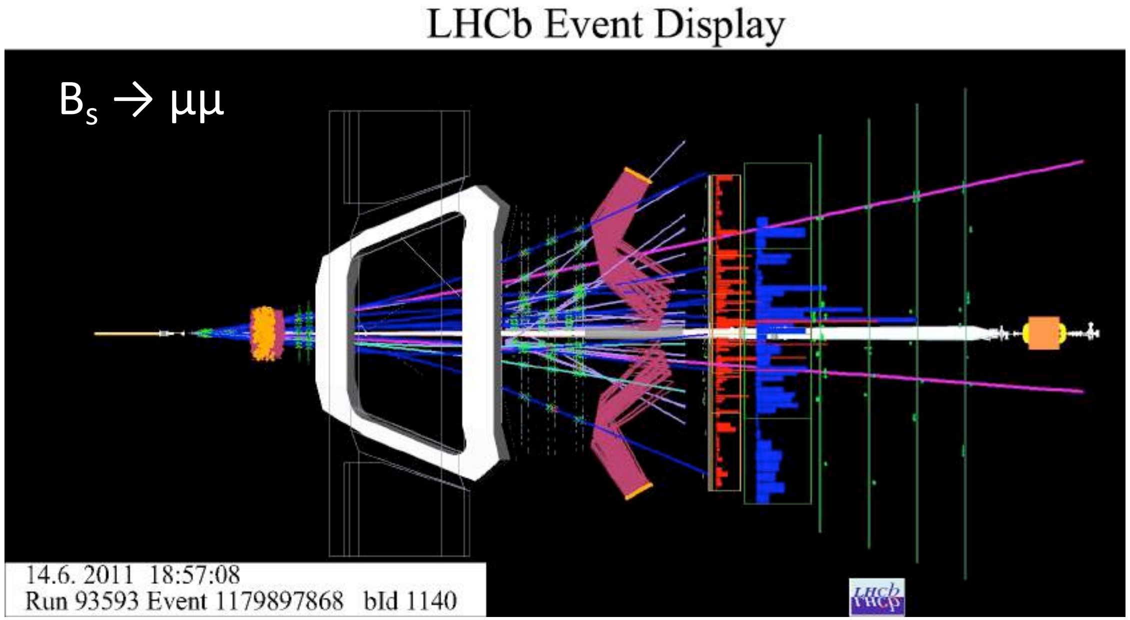
- B hadron lifetime ~ 10^{-12} s
- Decay length= $\beta\gamma c\tau$

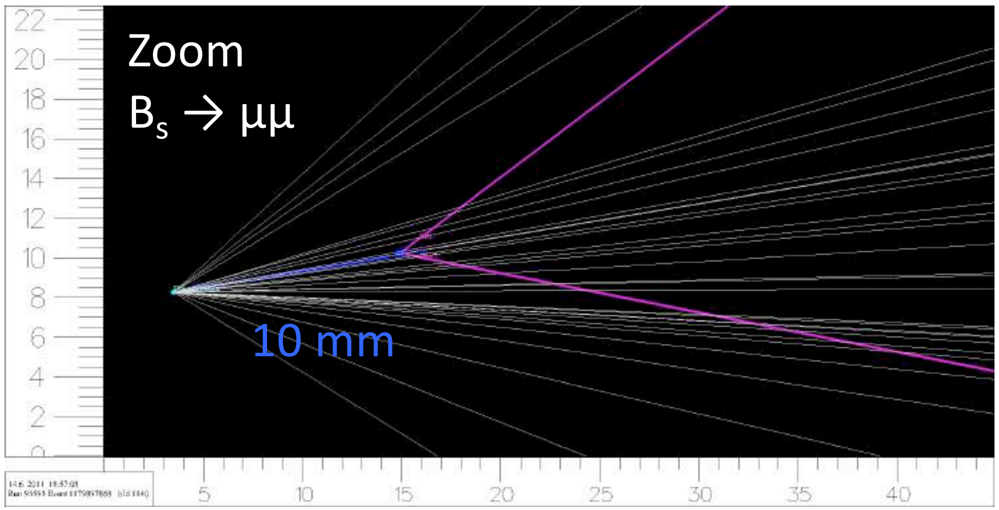
  ~ p/m · 300 μm
- First detector layer a few cm from collision point



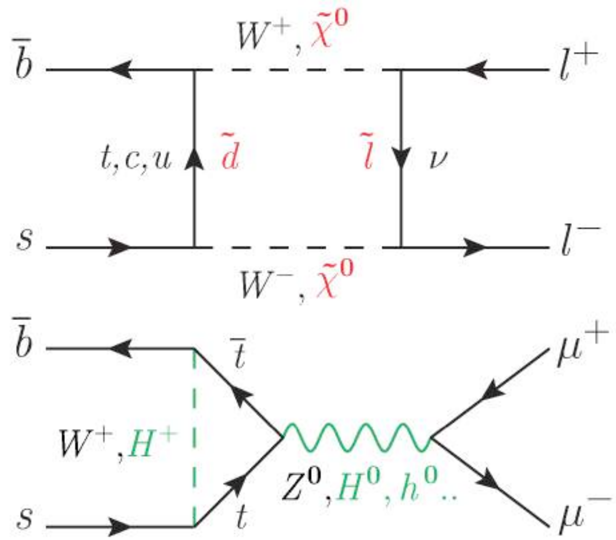


Why interested in $B_s \rightarrow \mu\mu$?

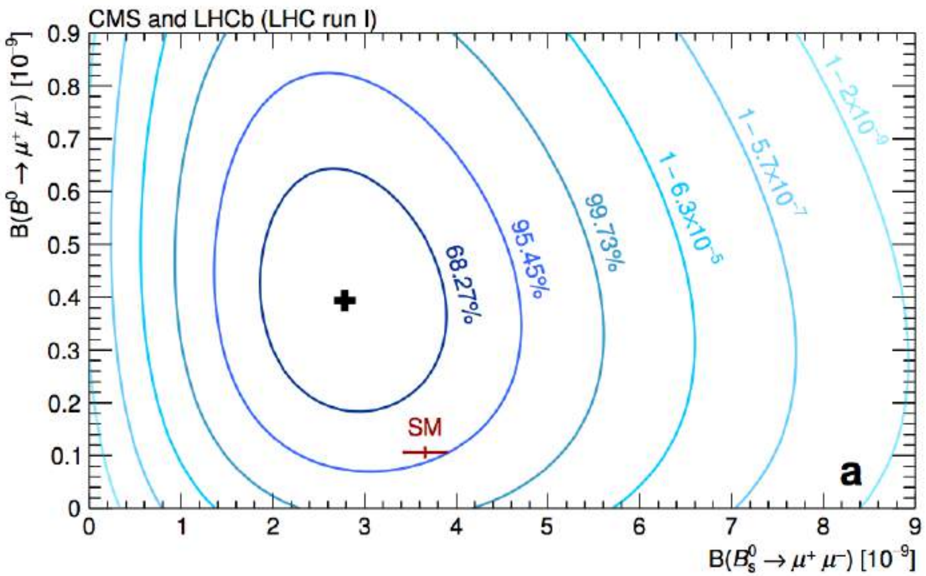




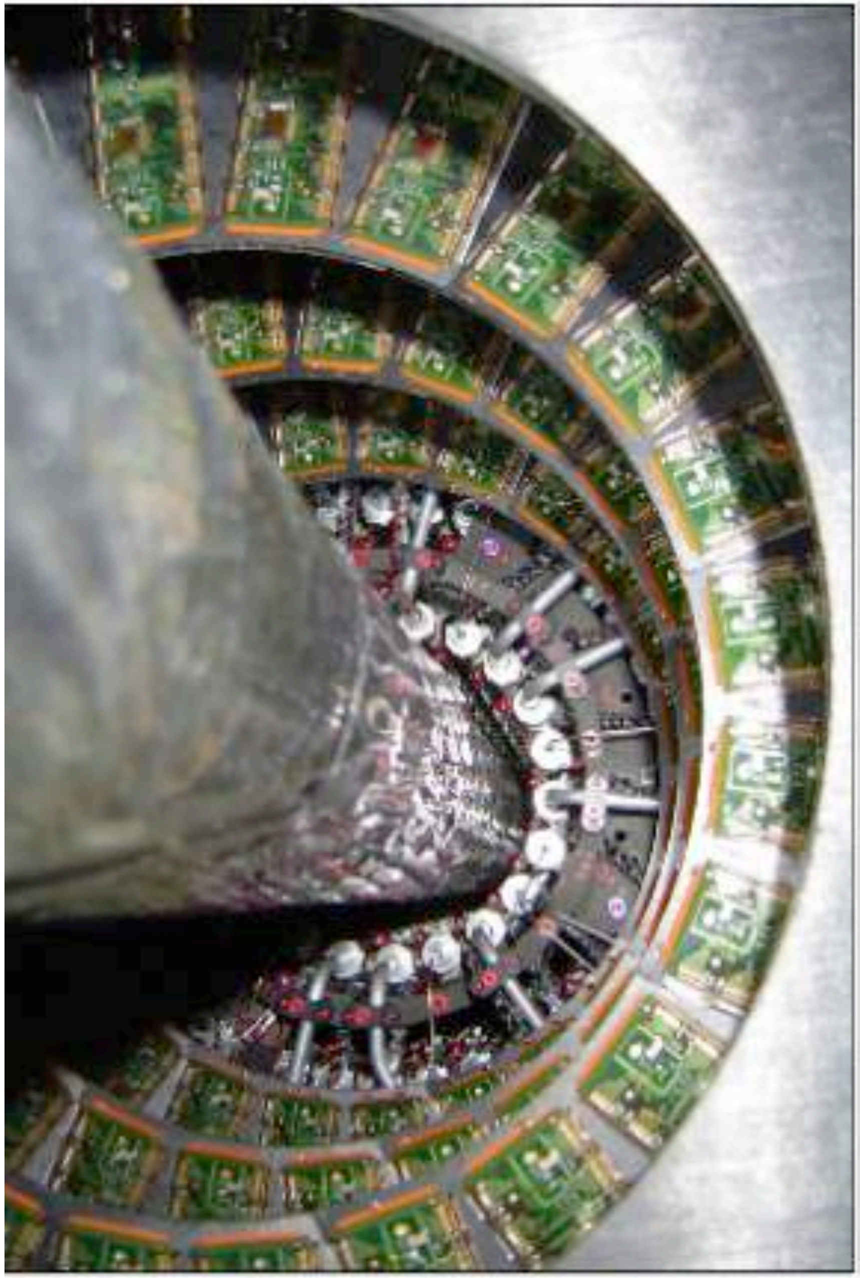
- Possible contribution from New Physics

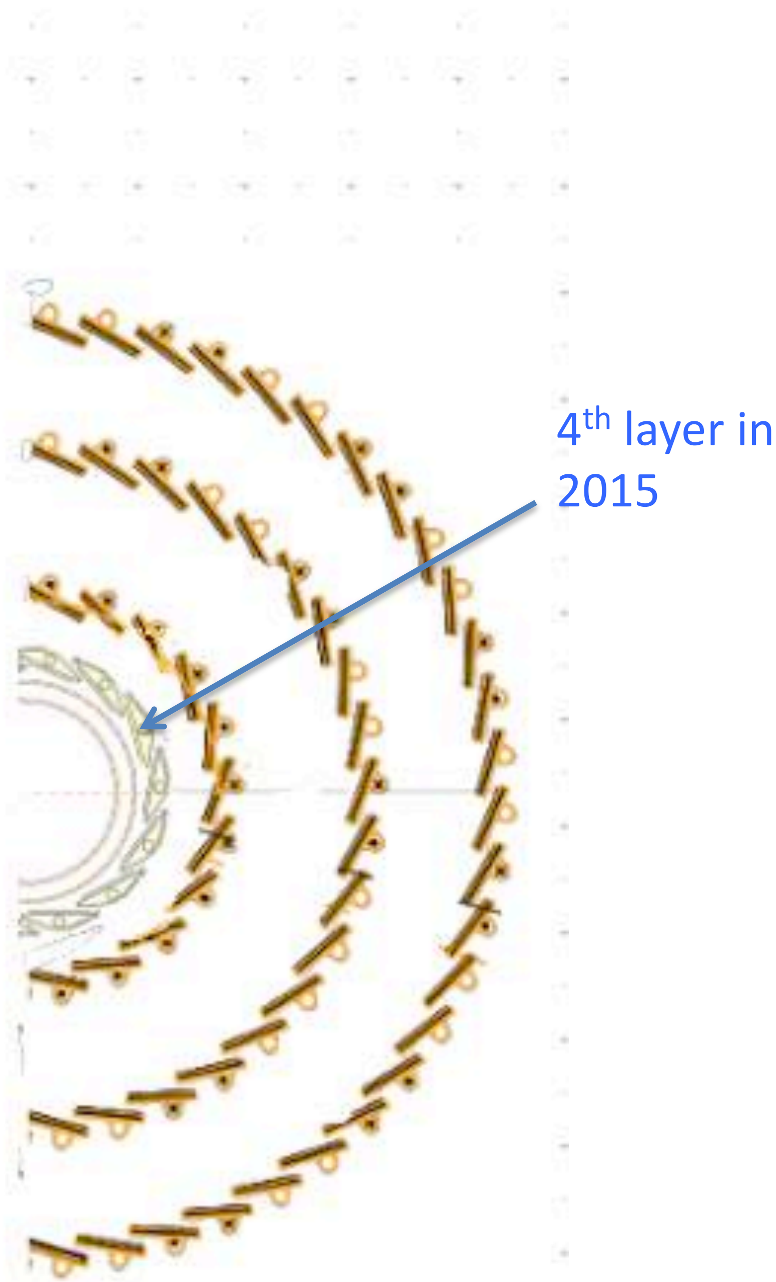


- Discovery or limit on new models



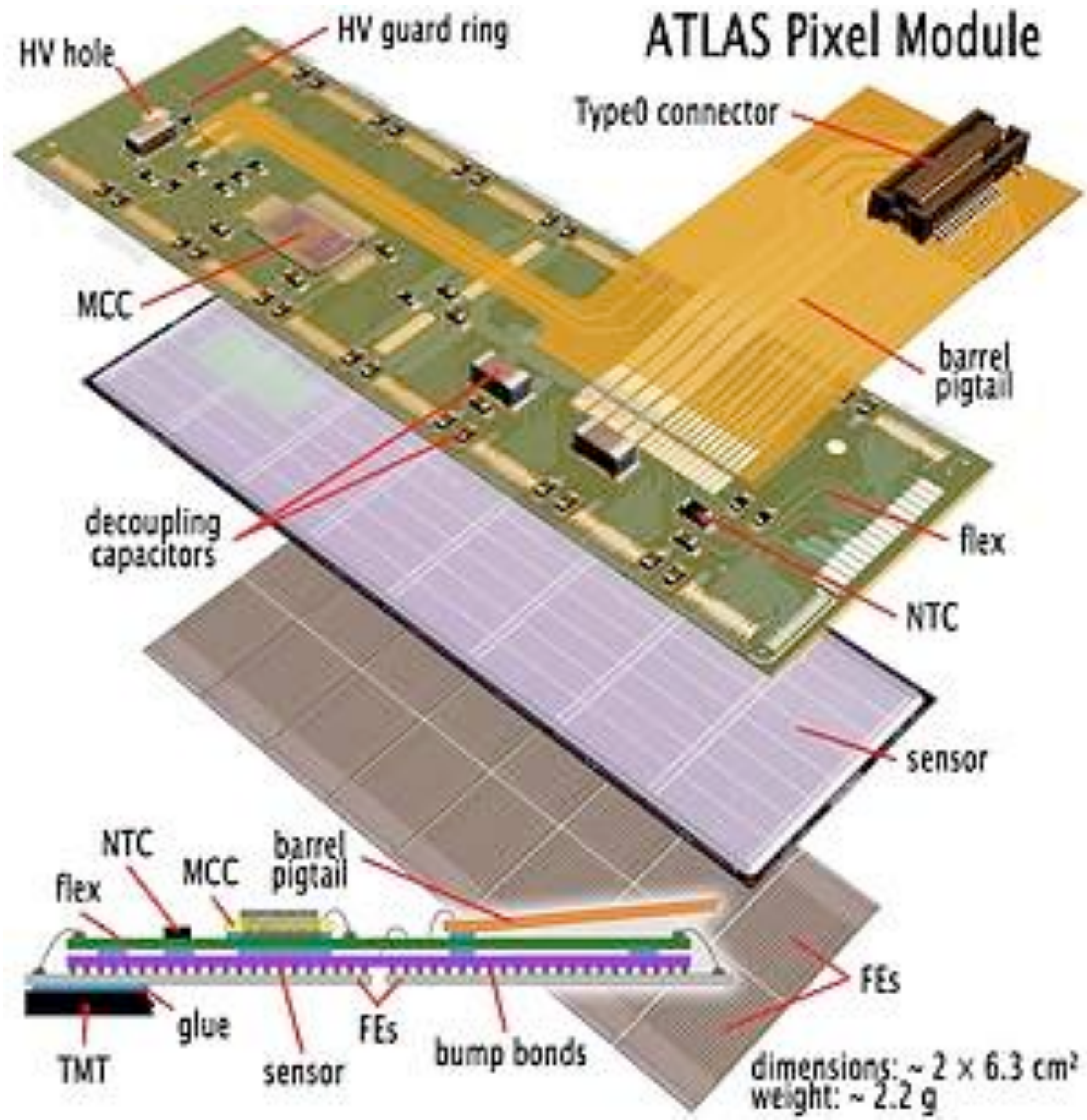
ATLAS Pixel detektor



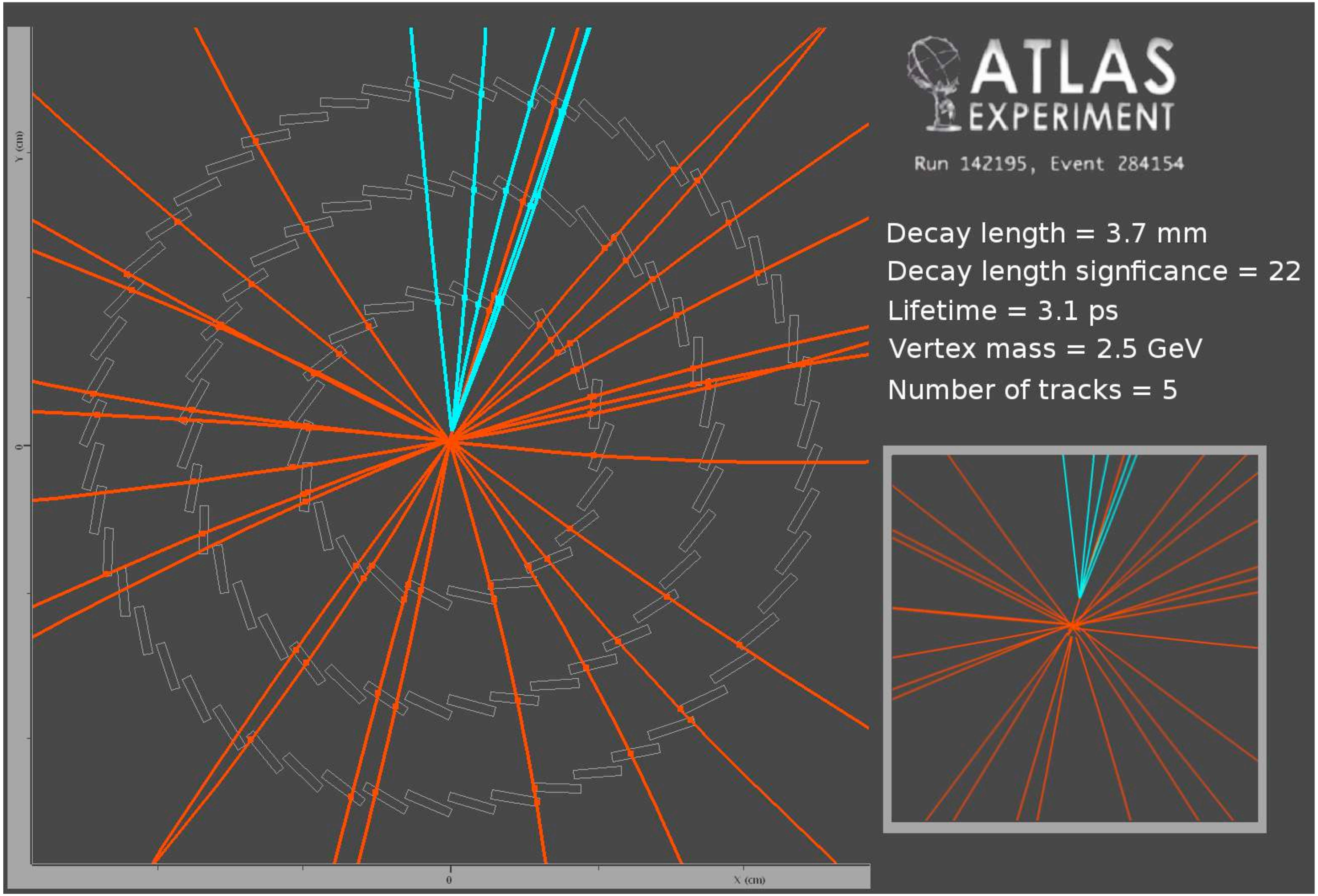


ATLAS Pixel detector

- Module size: 16.4mm × 60.4mm
- Weight: 2.2 g
- 1744 module
- Each module:
  – 47000 pixels
  – 16 "front-end" chips
    - 2880 channels / chips
    - Signal gain
    - Digitized on positive trigger signal
    - Sends a signal to the MCC
  – Module control chip (MCC)
    - Serialization
    - Sends signal to the DAQ system
    - Generates control signals for front-end chips
  – High-density circuit (flex)
  – Pigtail and connector
    - Power supply
    - I / O

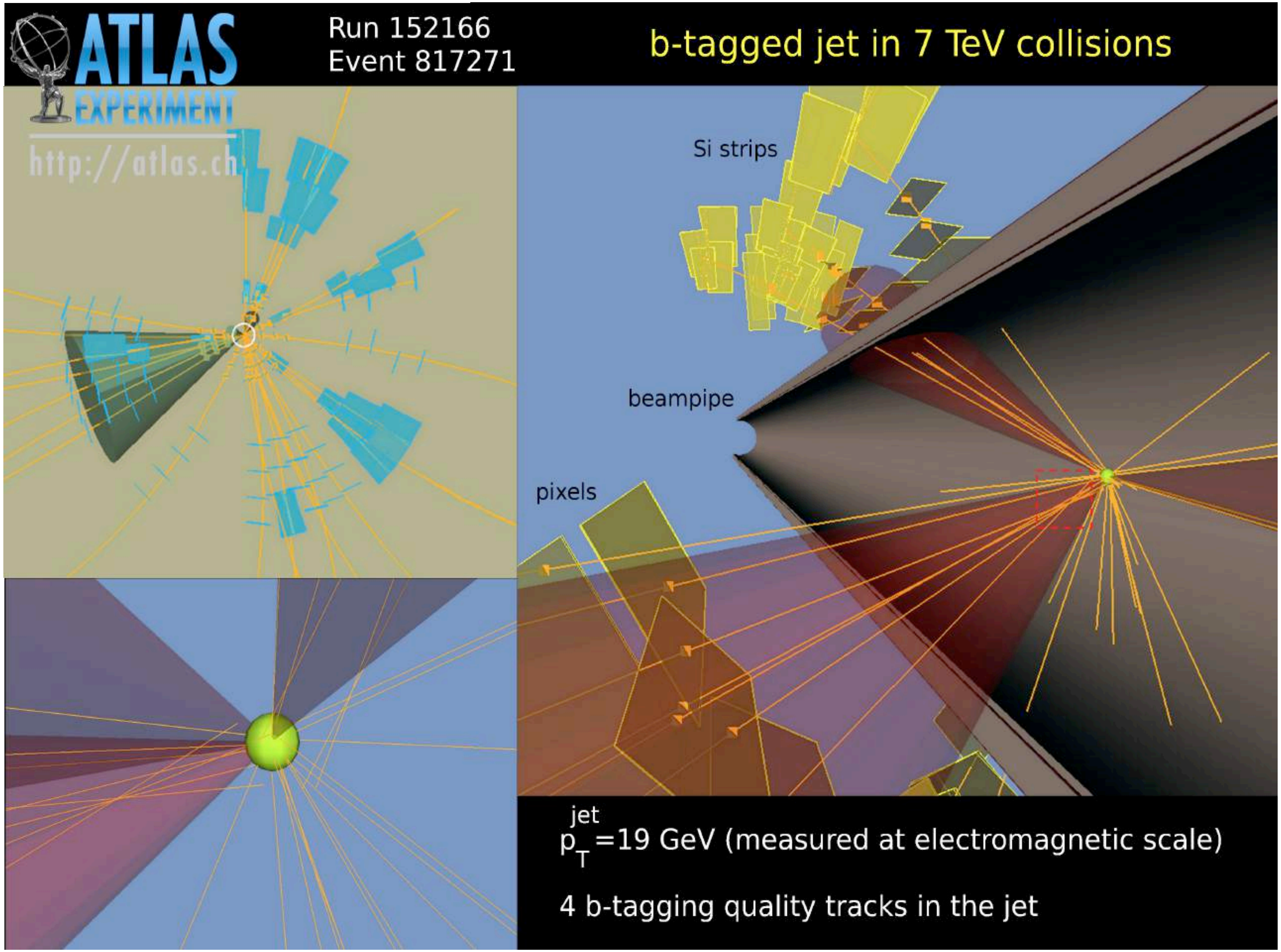


b-jet tagging

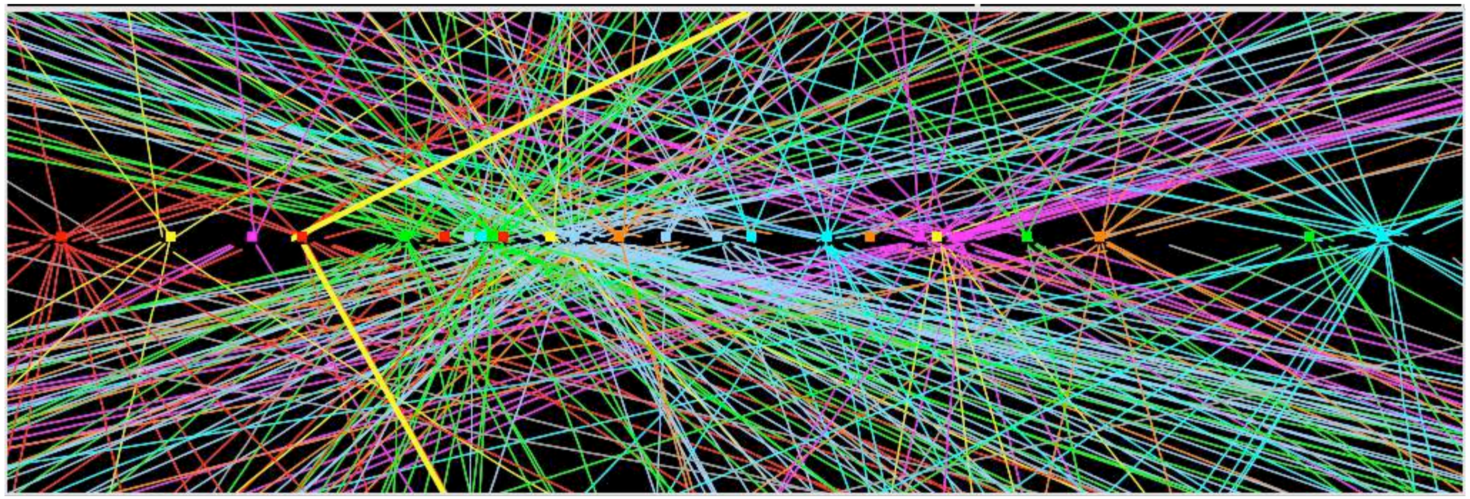


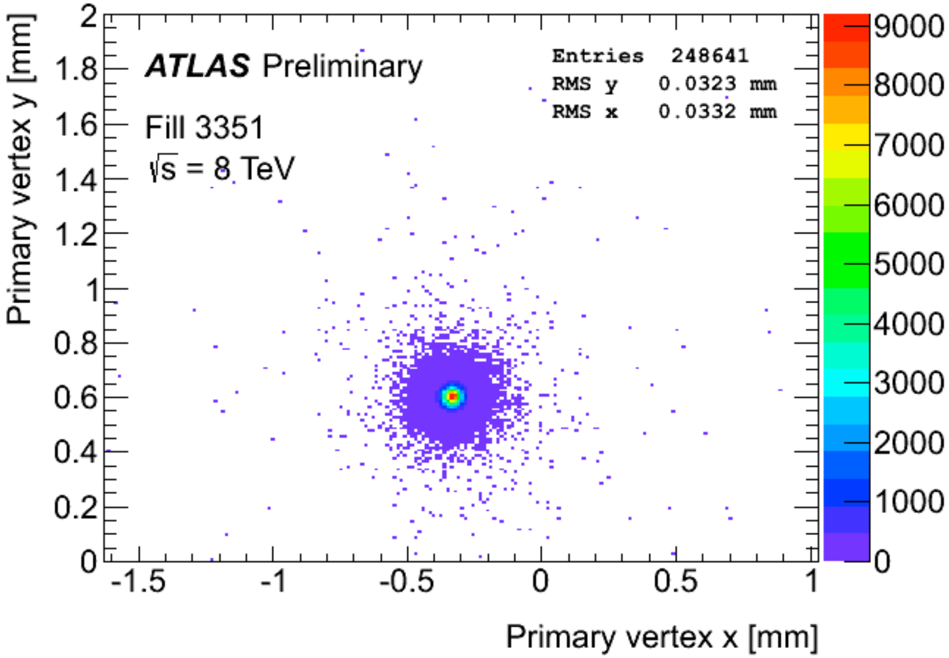
Event display of a b-jet candidate event. Only tracks in the barrel region with p_T > 500 MeV are displayed. The detector elements shown are the three barrel layers of the Pixel detector.

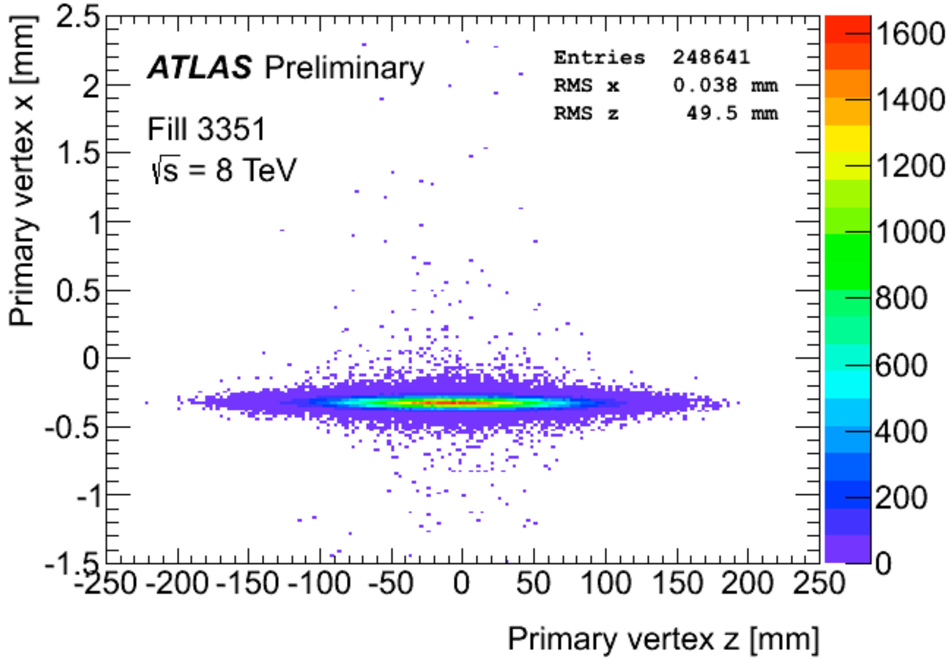
b-jet tagging



LHC beam spot size







Semi-conductor or gaseous ionisation detector?

Ionization chambers can be made with any medium that allows charge collection to a pair of electrodes

The medium can be: *Gas*, Liquid, Solid

	gas	liquid	solid
density	low	moderate	high
atomic number Z	low	moderate	moderate
ionization energy ε_i	moderate	moderate	low
signal speed	moderate	moderate	fast

Desirable properties:

Low ionization energy → Increased charge yield *dq/dE*

Gas ~ 30 eV
Solid ~ 3-4 eV

Superior resolution

$$\frac{\Delta E}{E} \sim \frac{1}{\sqrt{N}} \sim \frac{1}{\sqrt{E/\epsilon_i}} \sim \sqrt{\epsilon_i}$$

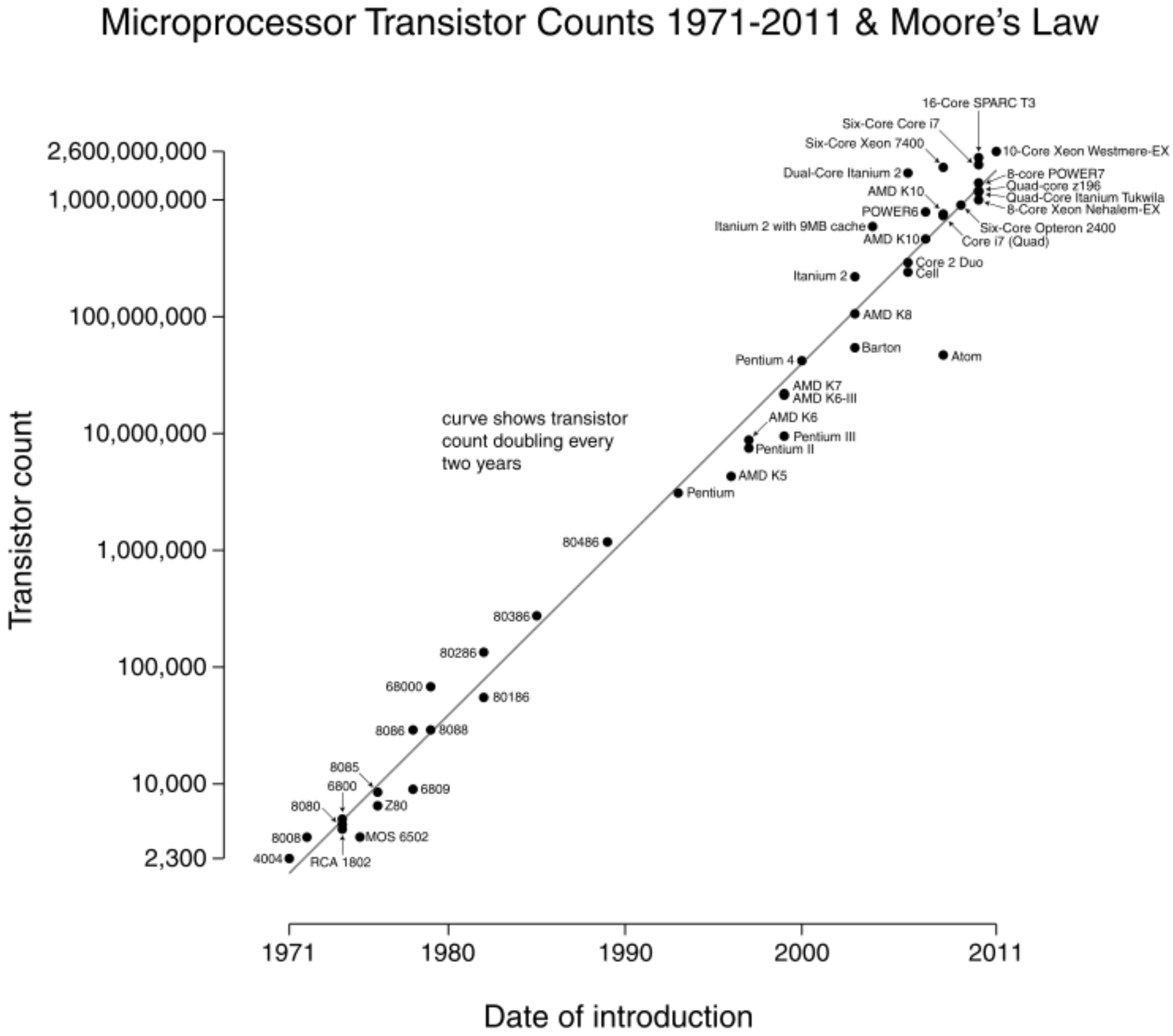
High field in detection volume → Fast response

Gas ~ 10 ns – 10 μs
Solid < 20 ns

Improved charge collection efficiency

Why silicon?

- A common element on Earth
- Utilizes the fast (exponential) development of integrated circuit technology
- Moore's law still in effect

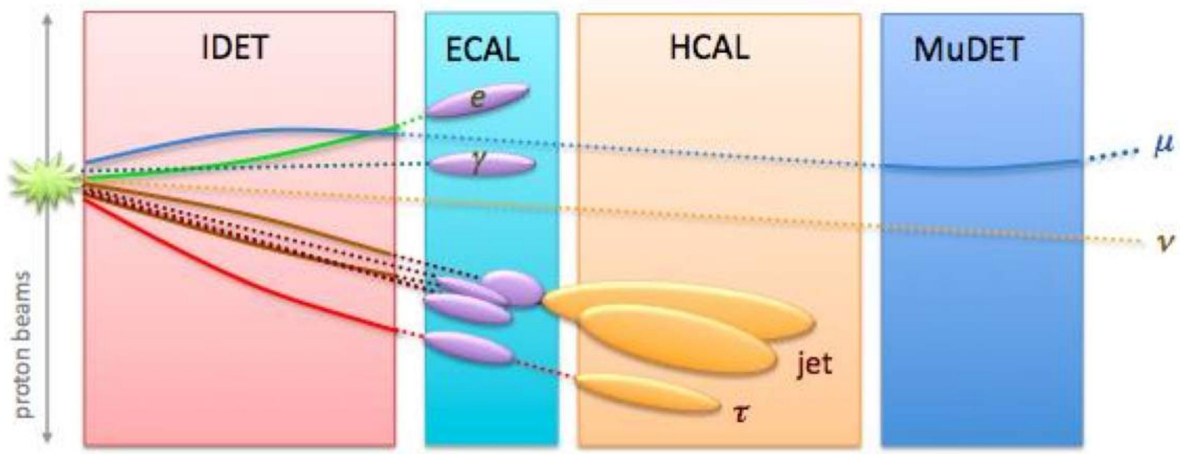


Event reconstruction

- Calibration (e.g. energy calibration of calorimeters)
- Determination of detector element positioning (alignment)

- Reconstruction of data from individual detectors
  - Track finding
    - Finding the path of charged particles in the detector
  - Calorimeter cluster finding
    - Finding energy deposits by charged and neutral particles

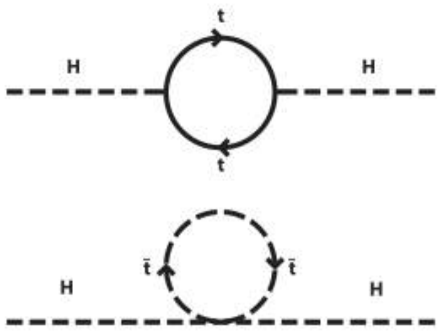
- Combined reconstruction
  - Electron / photon identification
  - Muon identification
  - Tau identification
  - Jet reconstruction
  - Missing energy



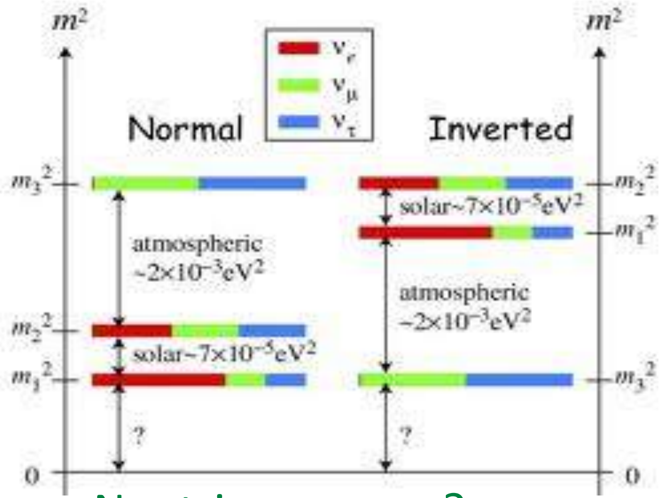
Beyond the Standard Model

Standard Model complete with Higgs boson and describes well collider experiments

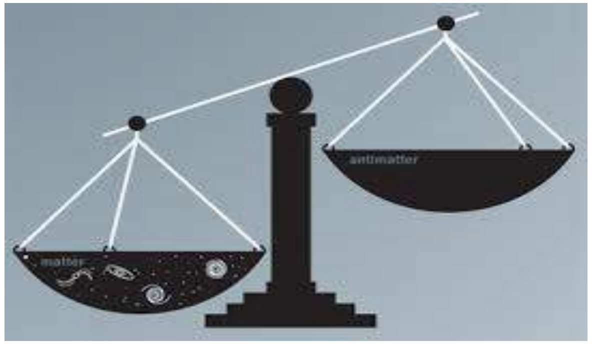
A number of open questions point beyond it and need a more fundamental theory



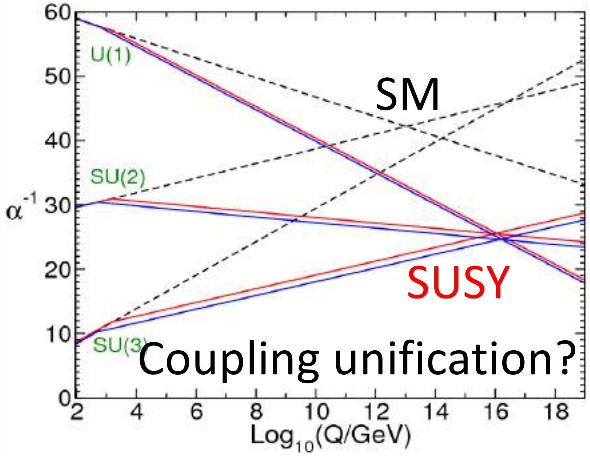
Higgs mass stabilisation?
(Hierarchy problem)



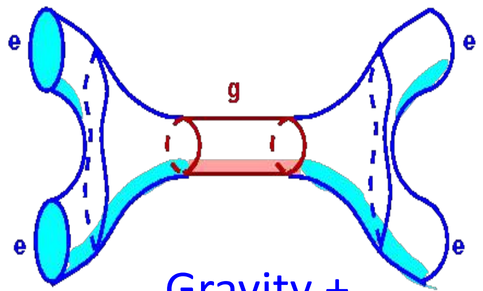
Neutrino masses?



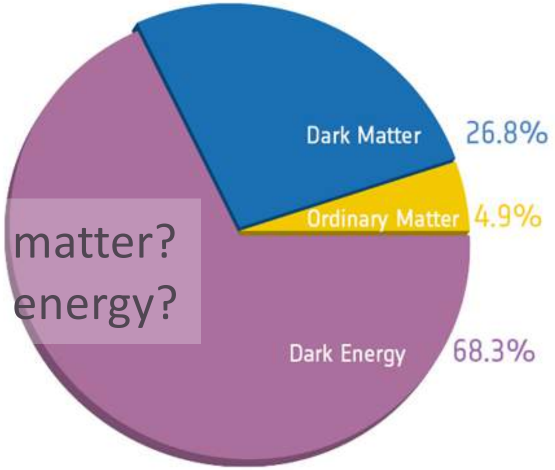
Matter – antimatter asymmetry?



Coupling unification?



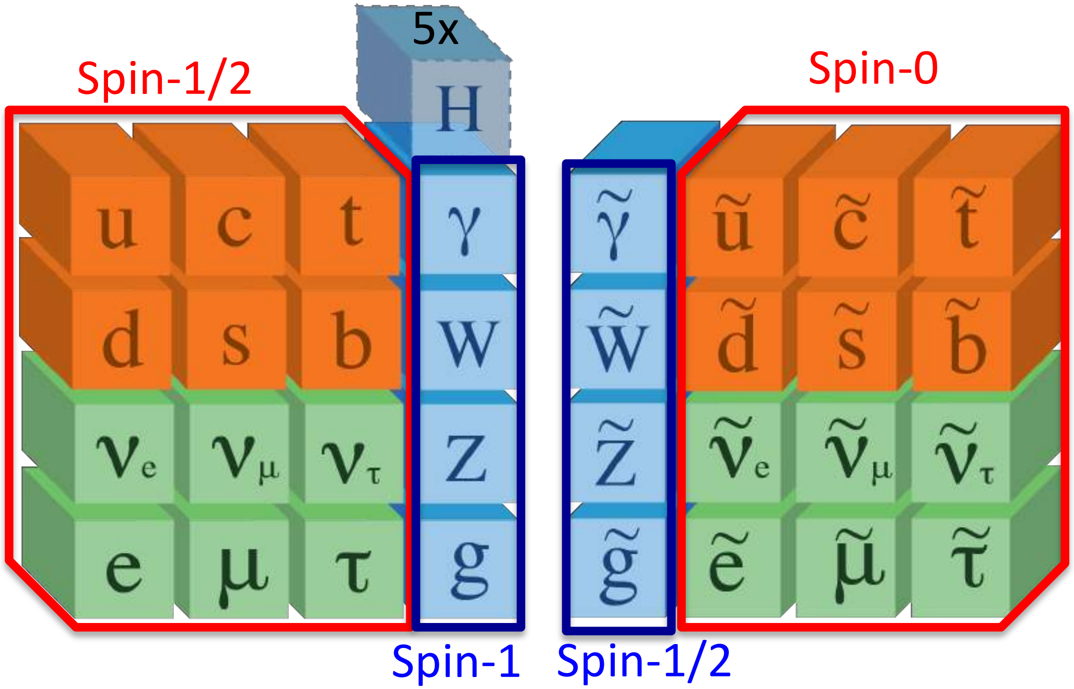
Gravity +
gauge interactions



Dark matter?
Dark energy?

Supersymmetry (SUSY)

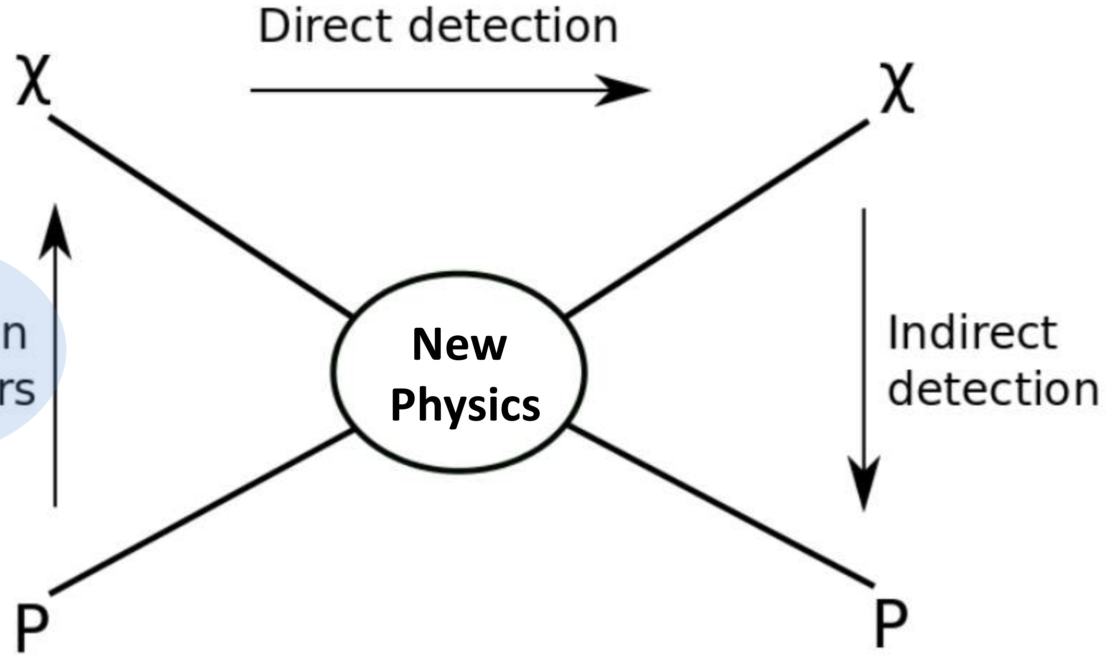
- Most general symmetry of space-time
- Symmetry between the constituent (fermionic) and the mediator (bosonic) particles
- Predicts a new, heavy partner for each particle: Particle ↔ partner, anti-particle ↔ anti-partner, $X_L, X_R \leftrightarrow \tilde{X}_1, \tilde{X}_2$



- The lightest supersymmetric particle, if electrically neutral, is a good dark matter candidate
- The coupling constant of EM, weak and strong interactions meet with good precision at high energy (~ 10^{16} GeV) in the presence of SUSY, thanks to the contribution of many new particle
- SUSY can protect the Higgs mass from vacuum fluctuations up to Planck scale

How to search for dark matter?

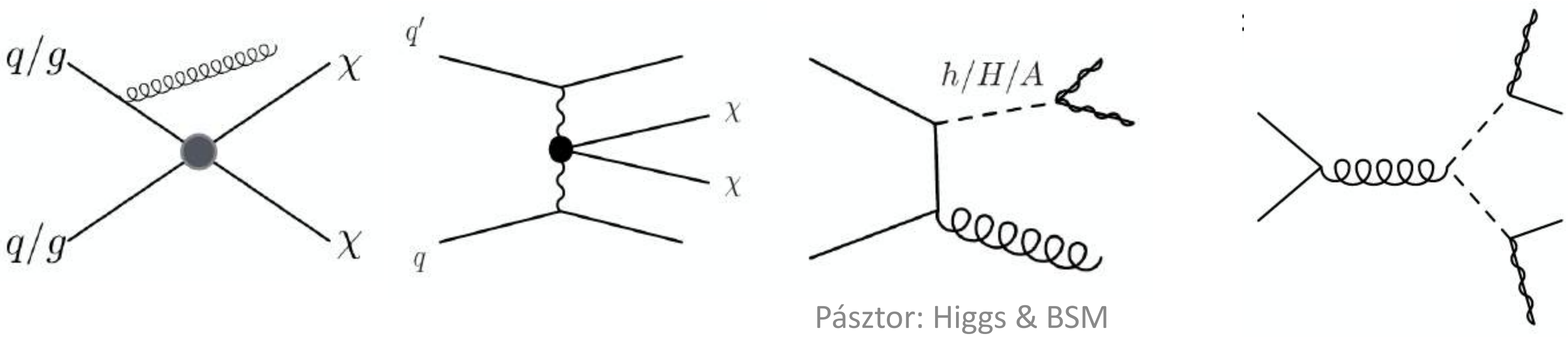
Nuclear recoil
Measurement with ionization, scintillation,... detectors
(pl. DAMA, CDMS,...)



Production at colliders

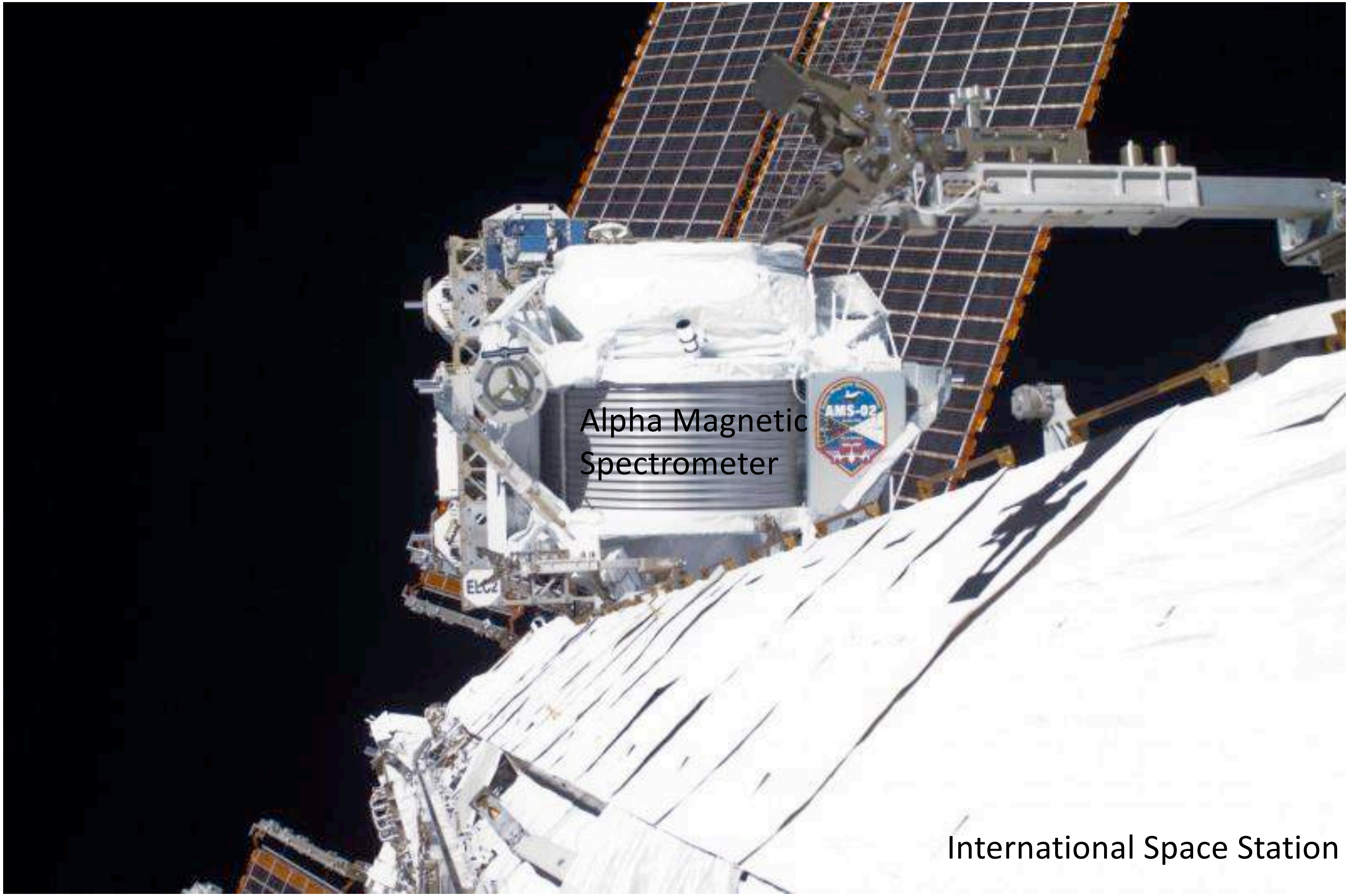
Missing energy
e.g.
$pp \to \chi\overline{\chi} + x$
x= photon, Z, Higgs, jet(s)...

High-energy photon, neutrino, anti-matter (e.g. AMS)



AMS on the helmet of an astronaut

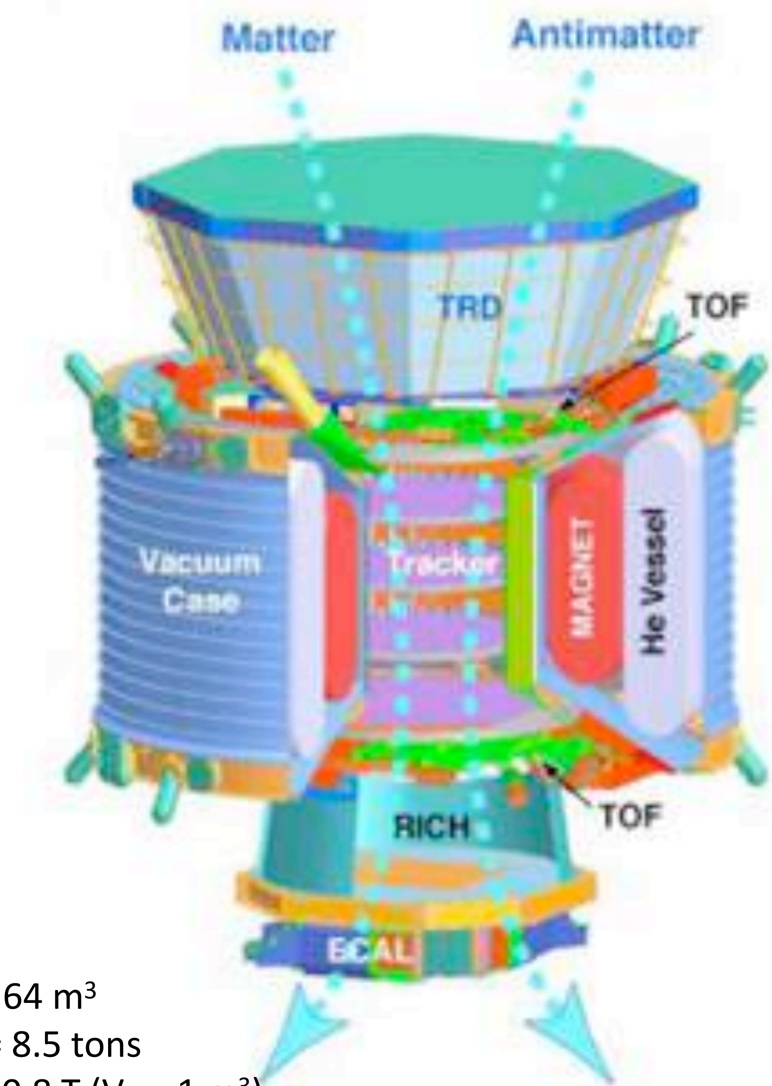
AMS on the ISS

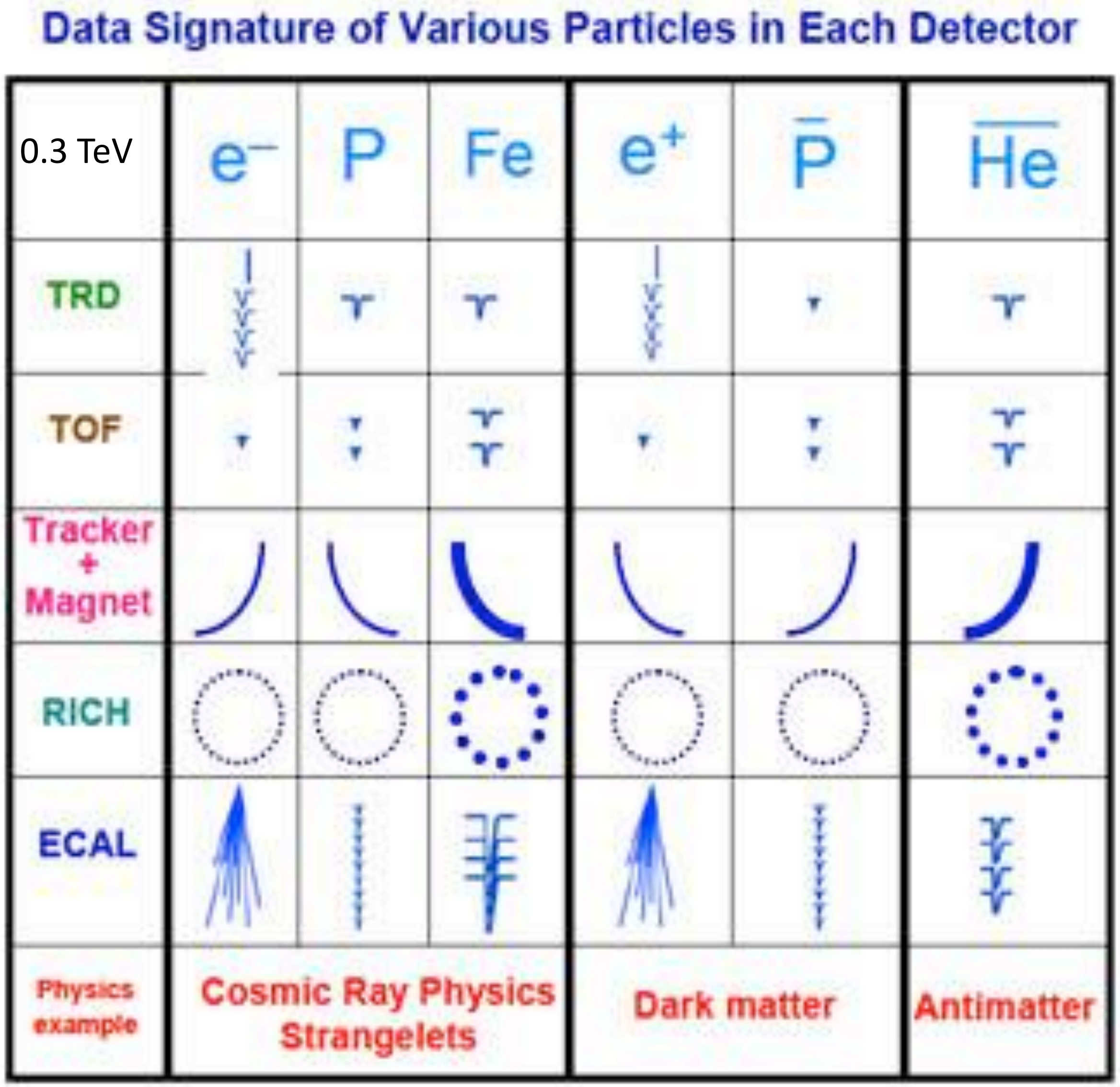


Az AMS experiment

AMS: A TeV Magnetic Spectrometer in Space

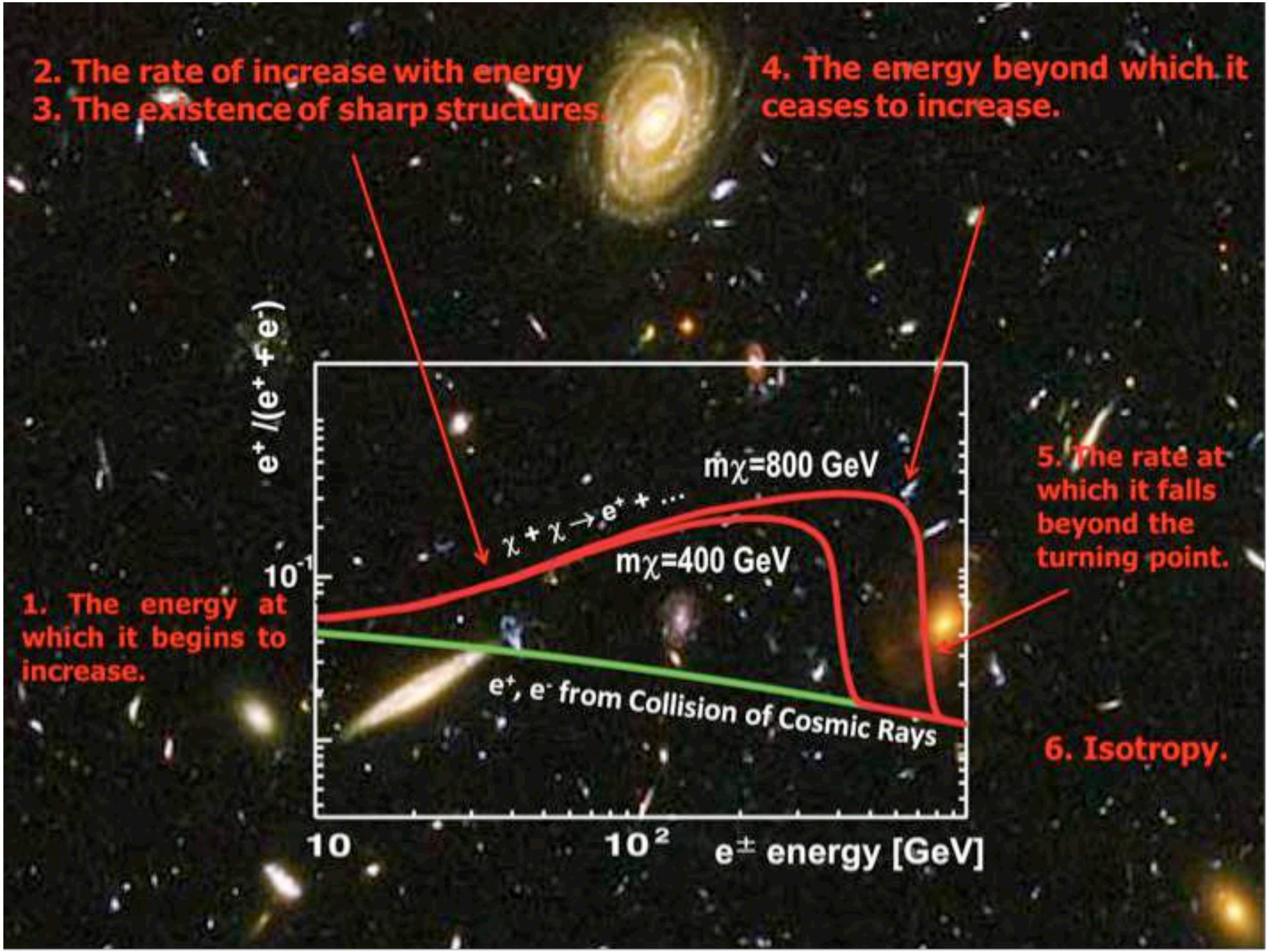
2 star tracker + GPS system:
precise position measurement





V = 64 m^3
m = 8.5 tons
B = 0.8 T (V_B = 1 m^3)
300 000 channel → 9 Mbps average data download speed

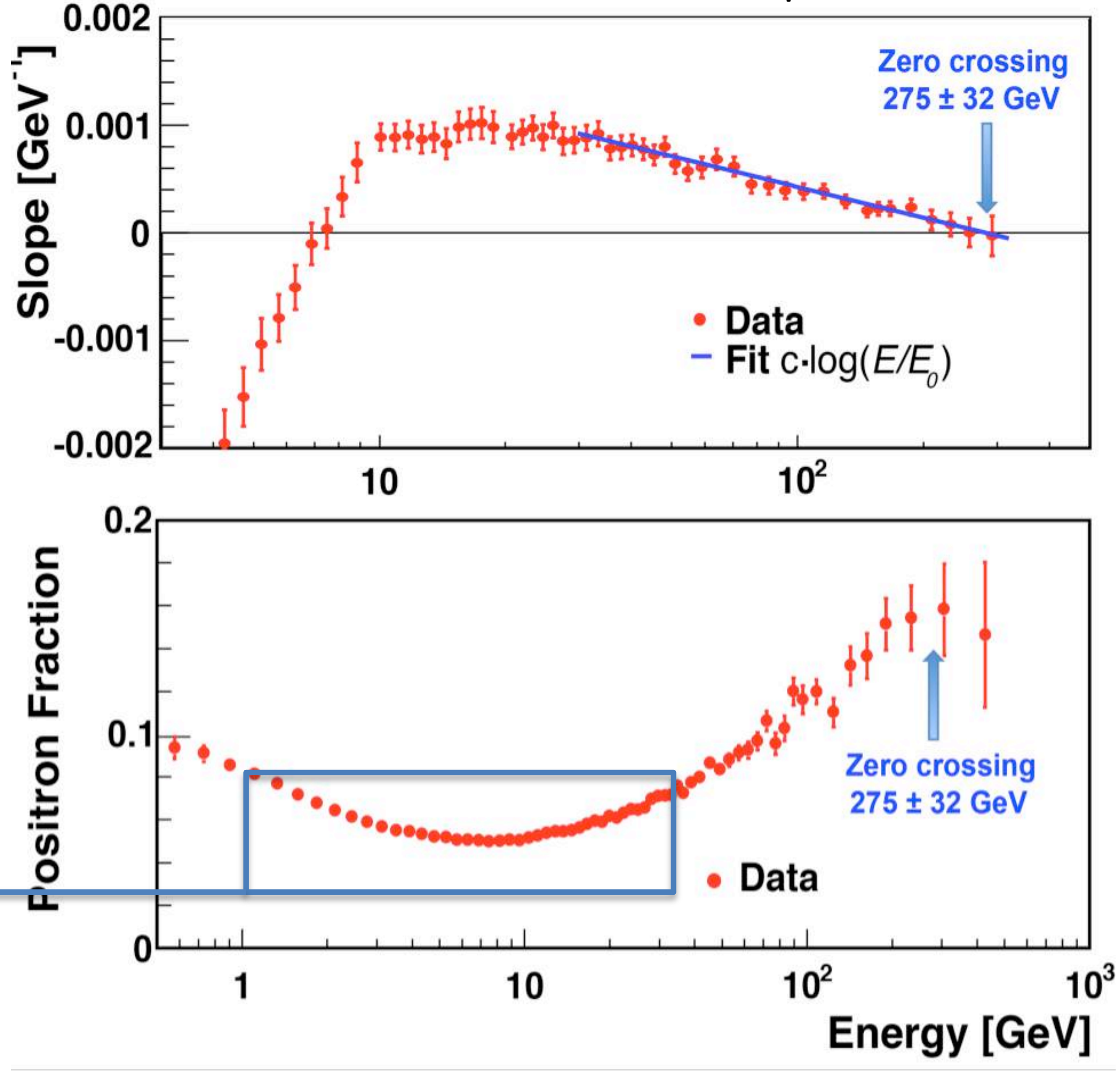
AMS dark matter search

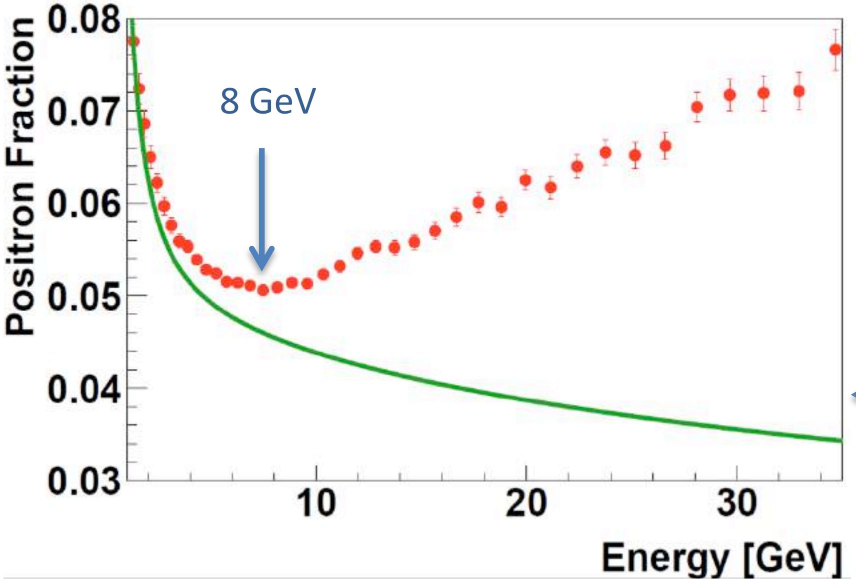


AMS: dark matter search

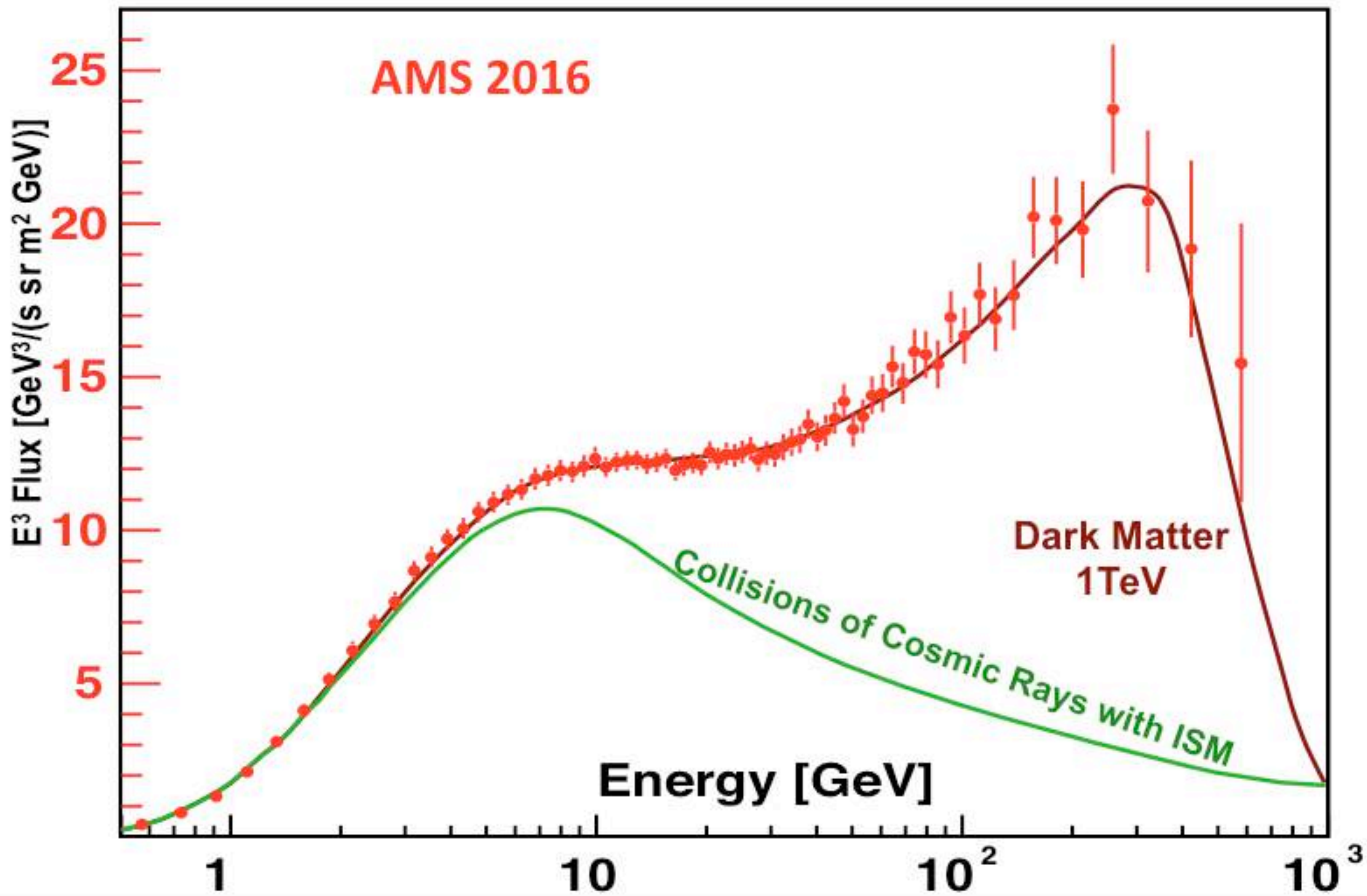
- Discovering a new phenomenon?
- Consistent with the annihilation of neutralinos of mass m = 1 TeV
- Positrons from astrophysical sources (e.g. pulsars)?
- Need new measurements (slope of drop ...,? Anti-proton quotient)

September 2014





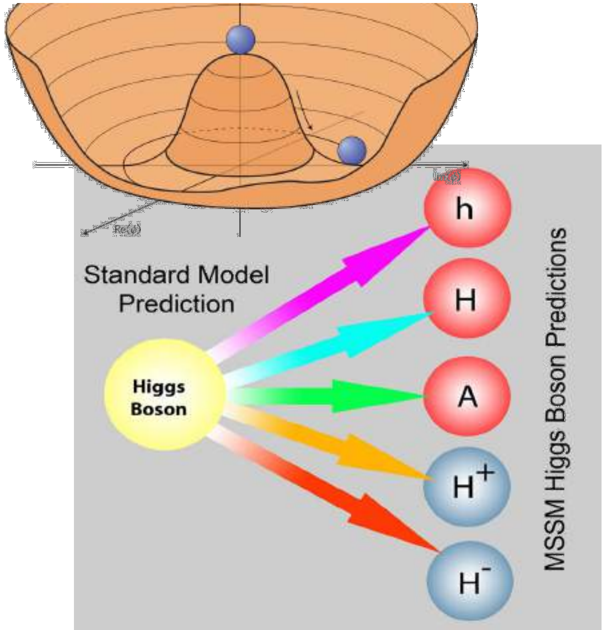
AMS 2016 update



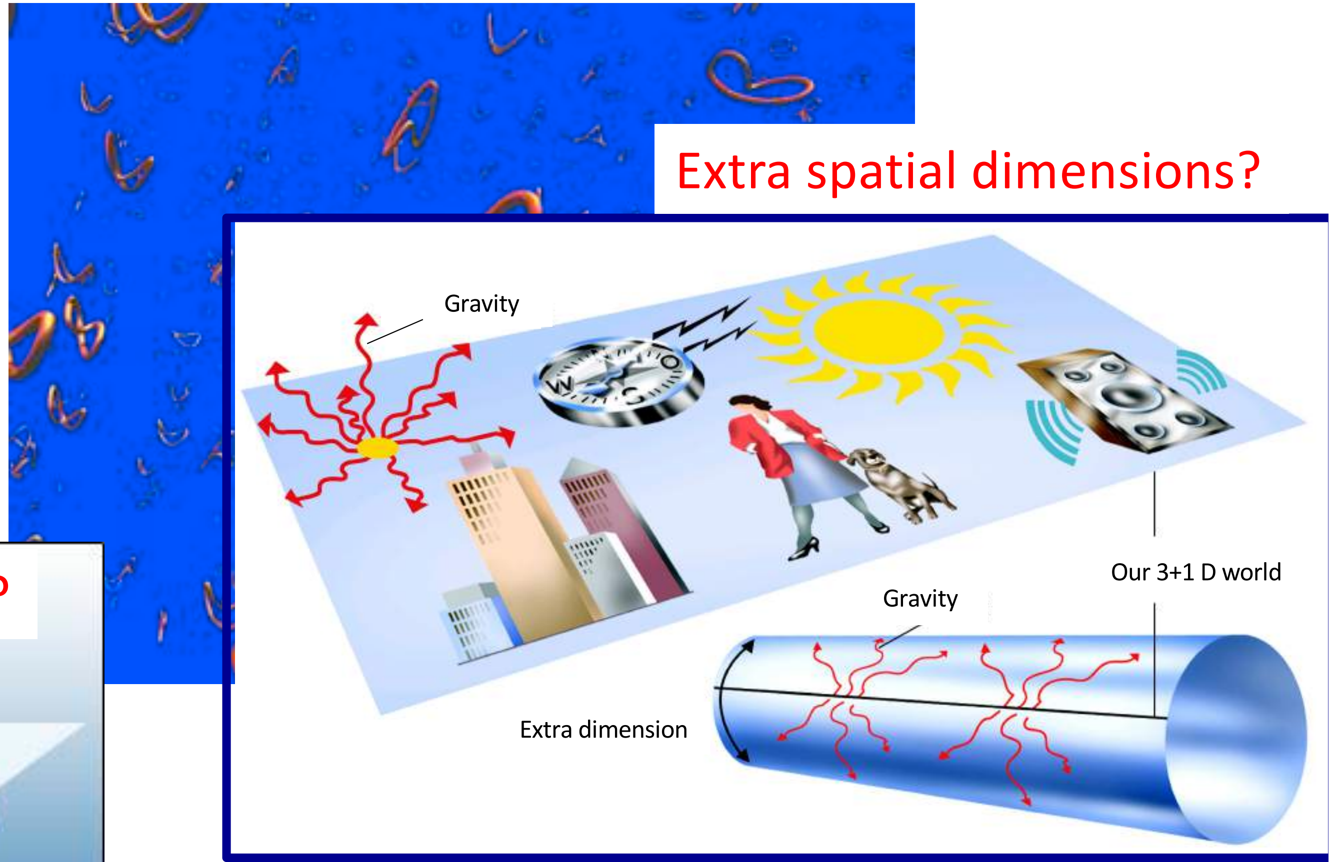
Still more data needed to understand source of the shape…
New Physics or astrophysical phenomena (e.g. pulsars) ?

What brings the future

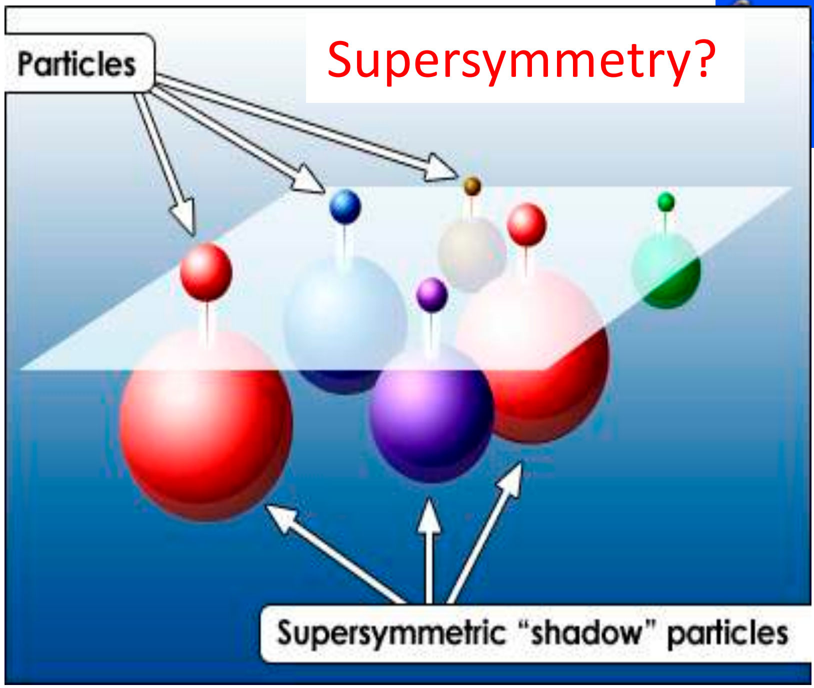
More Higgs particles?



Extra spatial dimensions?



Supersymmetry?



New interactions? Unexpected surprises?

Homework #10

- A photomultiplier have 14 dynodes and are operated at a total operation voltage of 2000 V, with an amplification factor of 4. Calculate the signal height in Volts for one input electron if the total time of travel is 5 ns and the resistance is 50 Ω.
- A photomultiplier tube with 25% quantum efficiency detects light from an organic scintillator with a density of 1.15 g cm^{-3} and $4x10^3$ photons being emitted per MeV of particle energy loss. Only 5% of scintillation photons reach the PMT due to losses in the scintillator and light guide. How thick scintillator layer is required to detect minimum ionizing particles with an efficiency of at least 99%?
- A detector has an efficiency of 95% and a fake rate, i.e. how many times there is a signal without any incoming particle, of 1%. Calculate the efficiency and fake rate of a stack of three such identical detector layers if a signal is defined as (a) a logical OR of the three detector layers; (b) a logical AND of 2 or more layers.
- Derive the formula for the spatial resolution σ (defined as the RMS of the residuals between the measurement and the actual point of impact) in the case of threshold (also called digital) readout of a Silicon detector with a pitch size p: $\sigma = p/\sqrt{12}$.
- How can dark matter be observed by particle physics experiments?