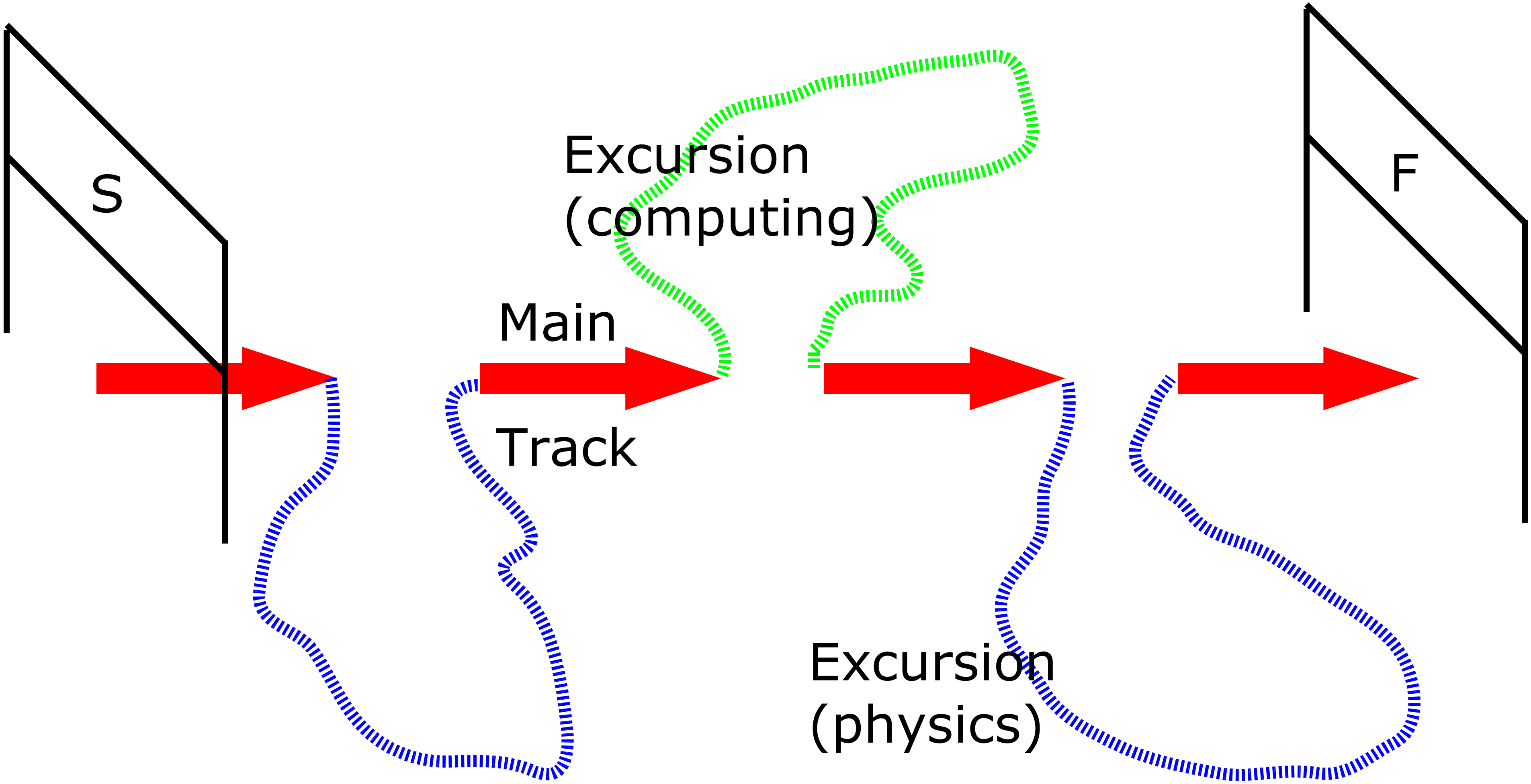
Experiment Simulation

CERN School of Computing 2005
Saint Malo

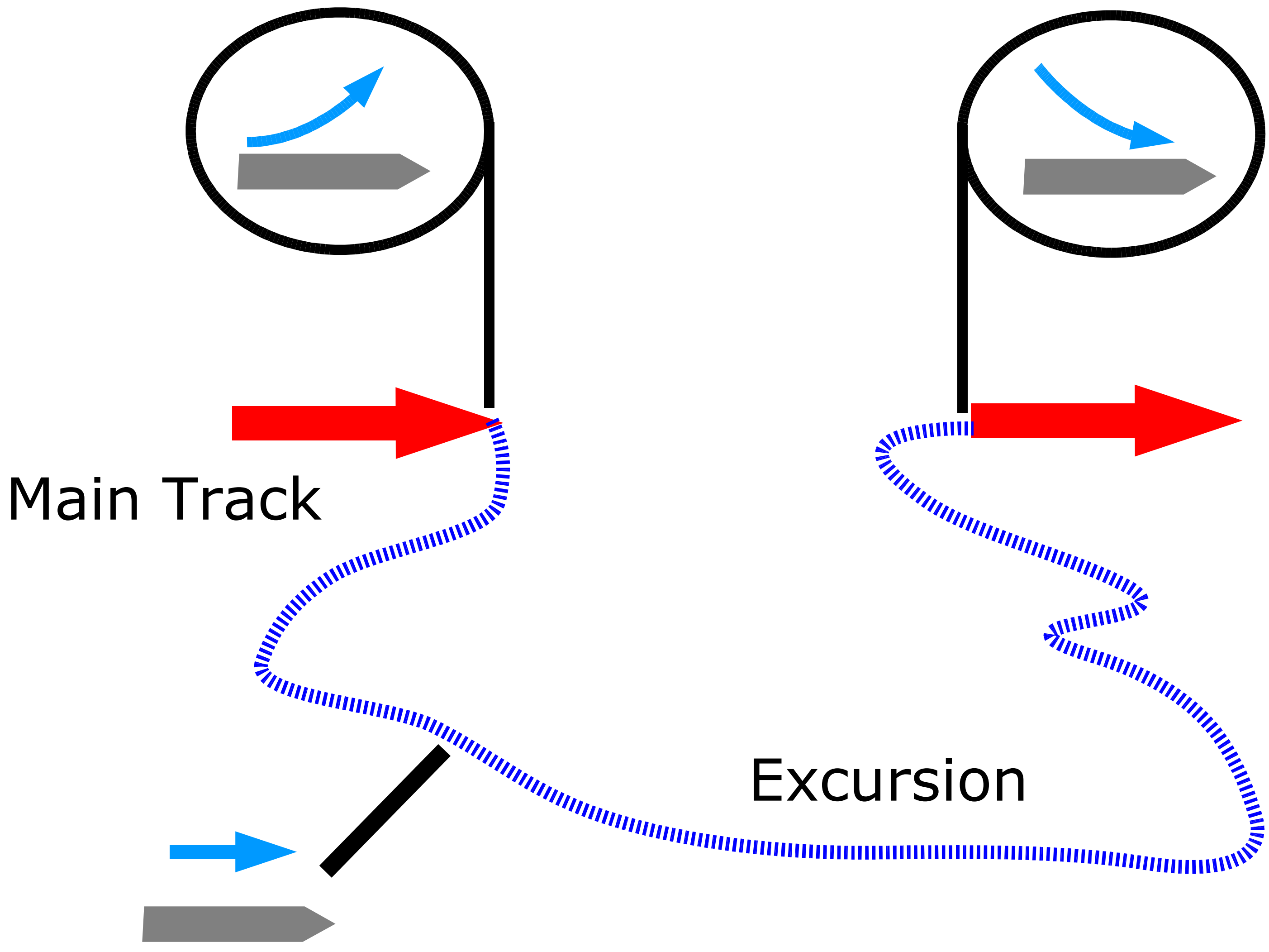
Lecture 1

Martin Liendl
SWX Swiss Exchange

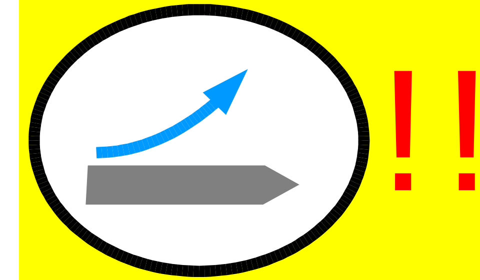
“Strategy”



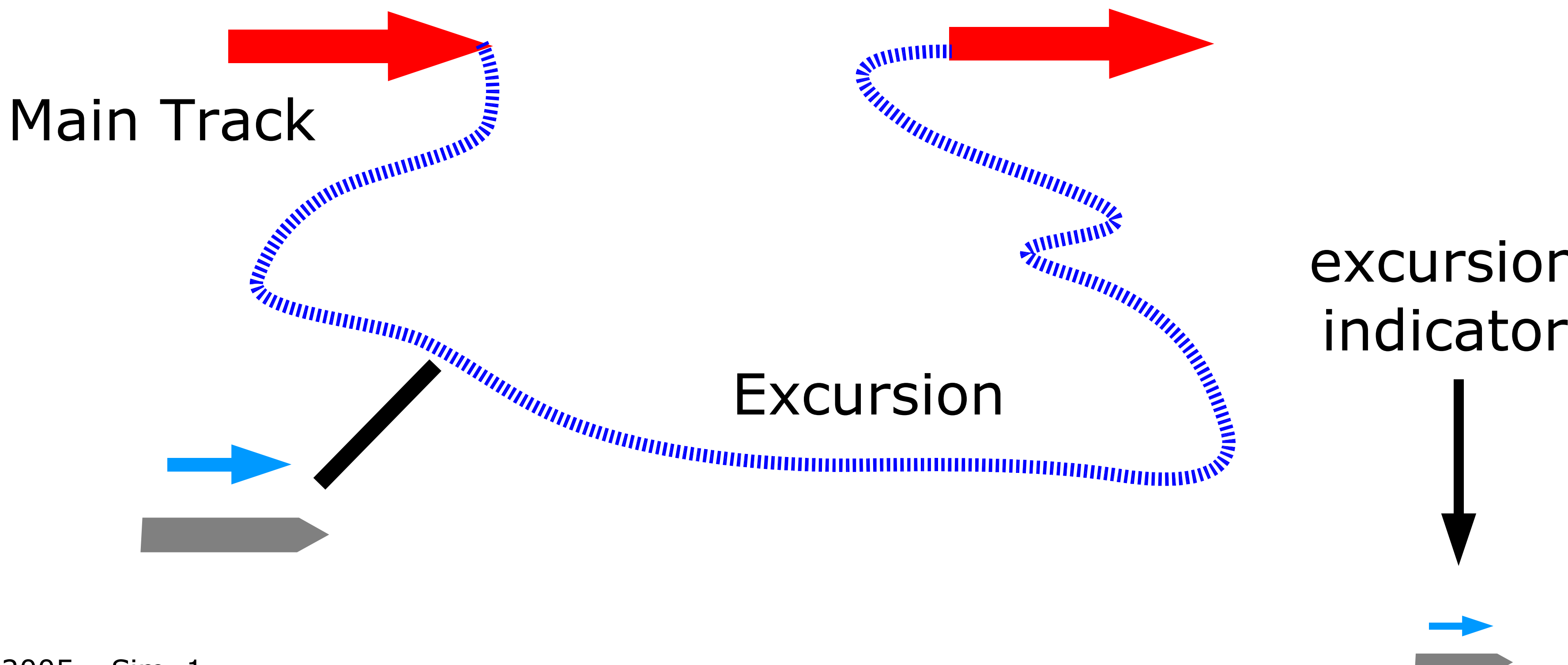
“Strategy”



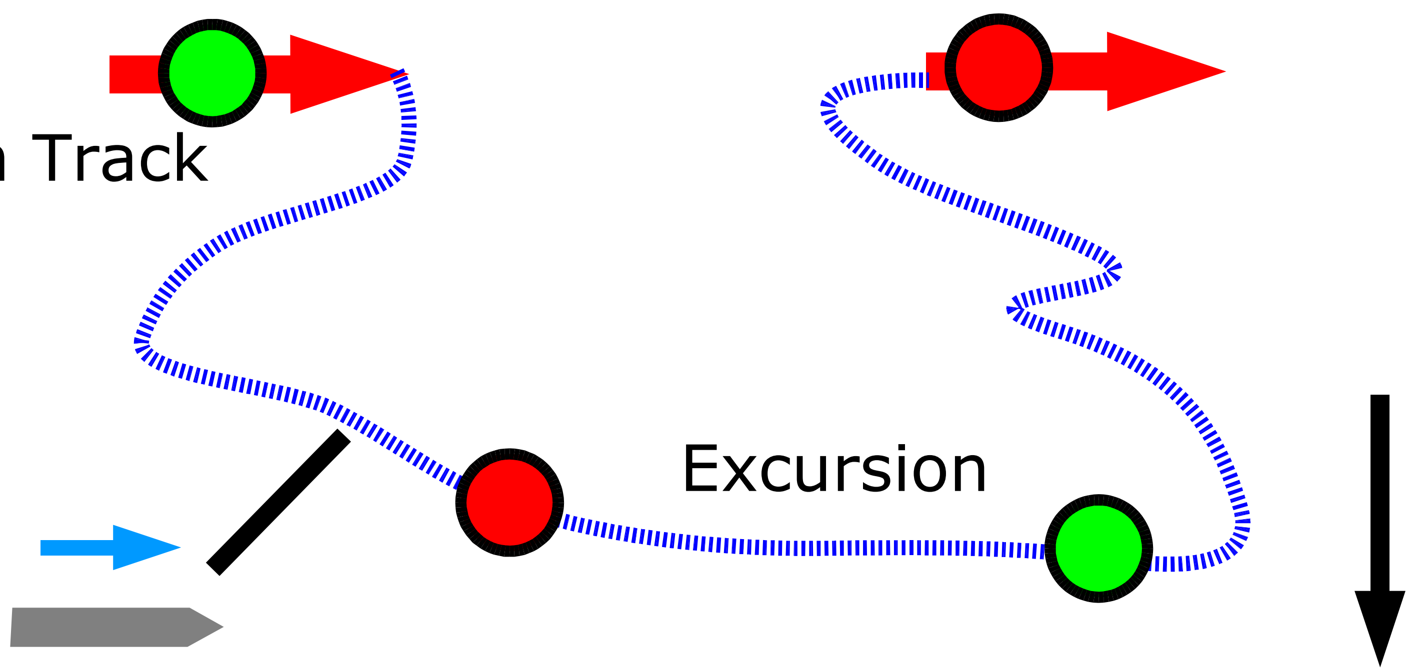
“Strategy”



Now we go on an excursion!



- Slides showing this symbol are not contained in your handouts!
- Slides showing this symbol have been modified from your handouts!
- You can download the updated version of the lectures from the CSC web.



Overview of Lectures

- Experiment Simulation: What and Why
- Passage of Particles through Matter, physics models
- Monte Carlo Methods
- Introduction to GEANT4
- Geometry, Tracking
- Event loop, user hooks
- Introduction to Exercises

always a bit interrelated ...

!!

Why & What

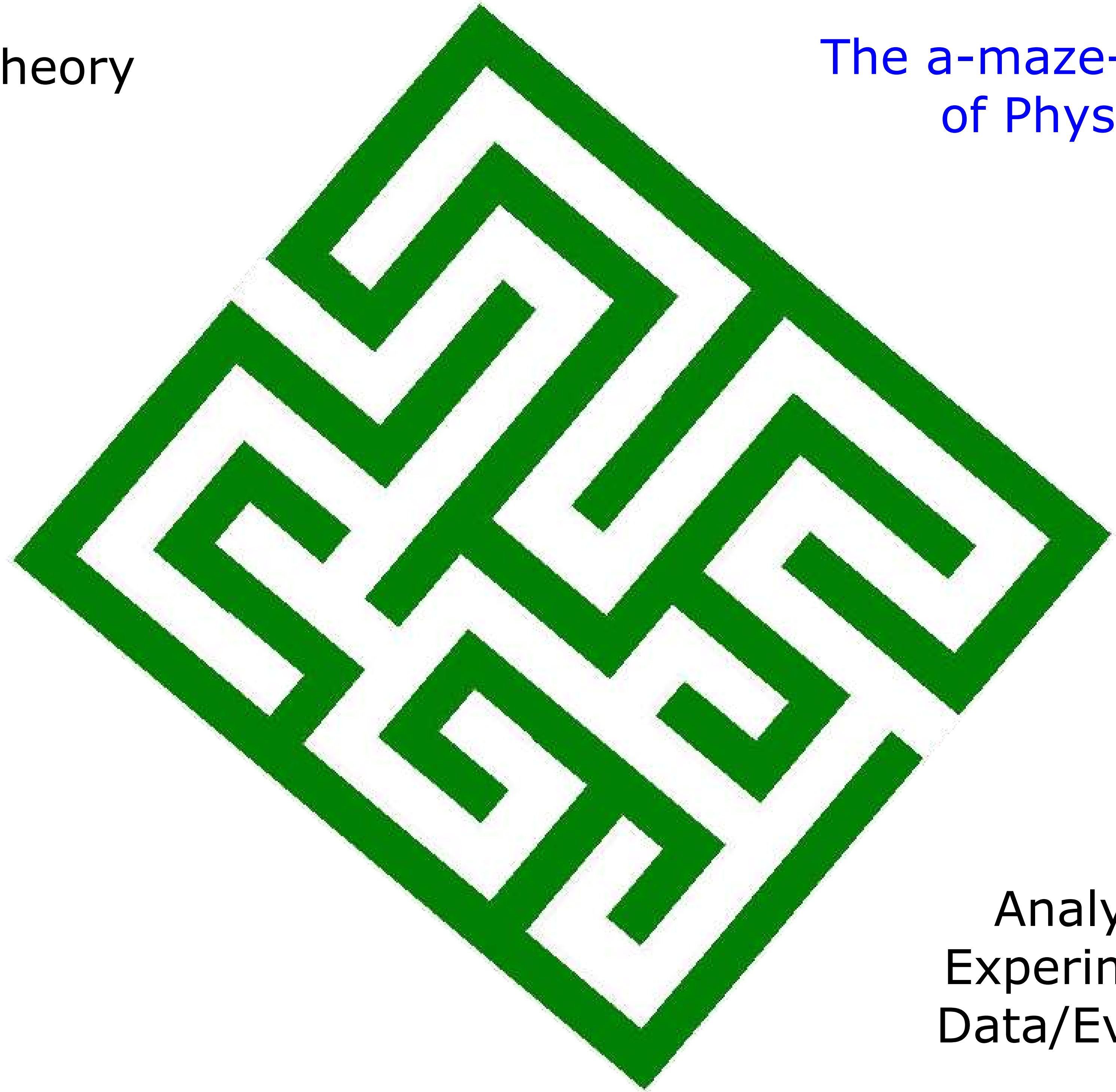
A (by far) non-exhaustive introduction ...

Some general ideas on how high energy physics experiments work in general

Will use (in parallel) a oversimplified "Mickey Mouse"-model to high-light some peculiar aspects

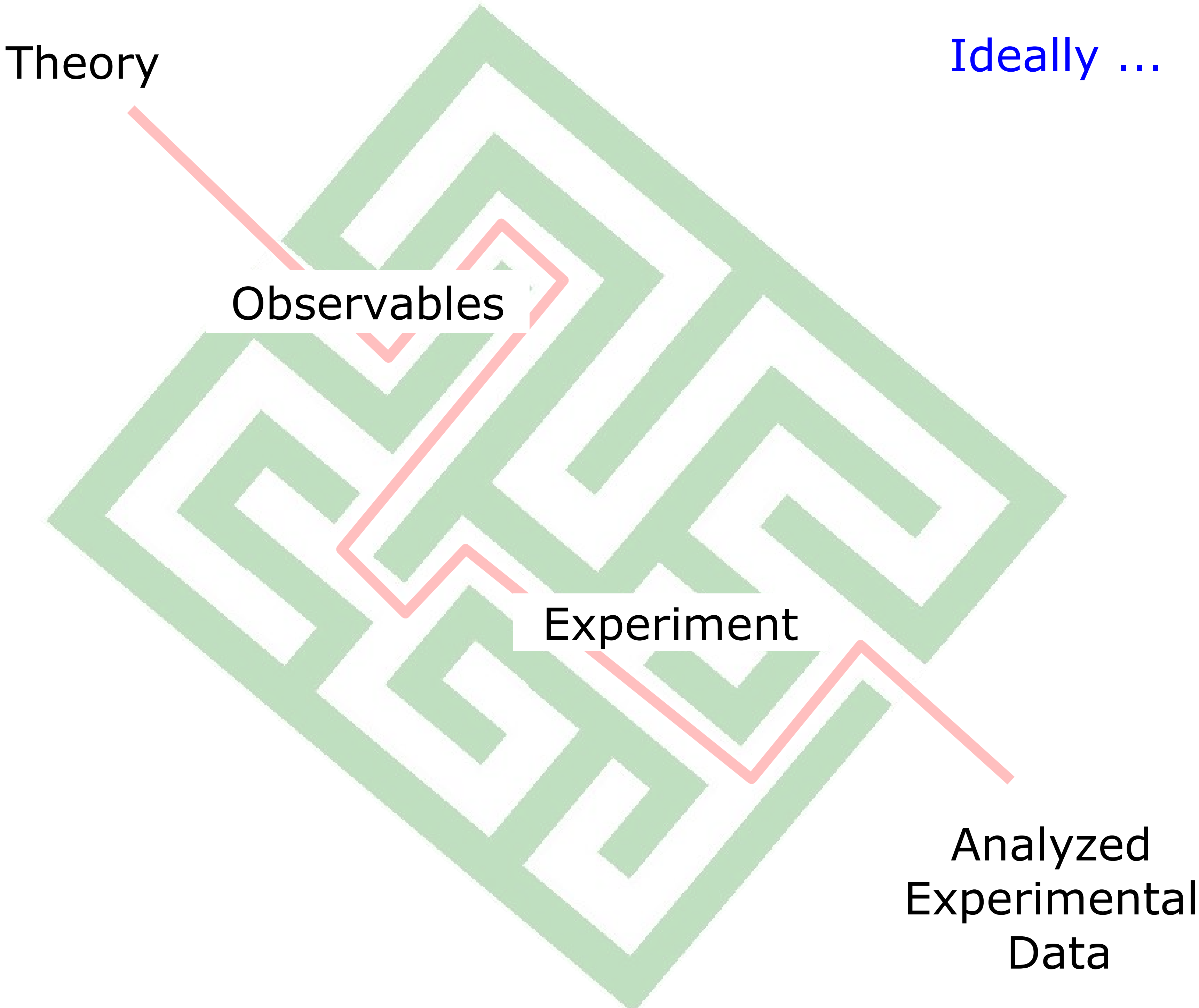
Theory

The a-maze-ing world of Physics ..



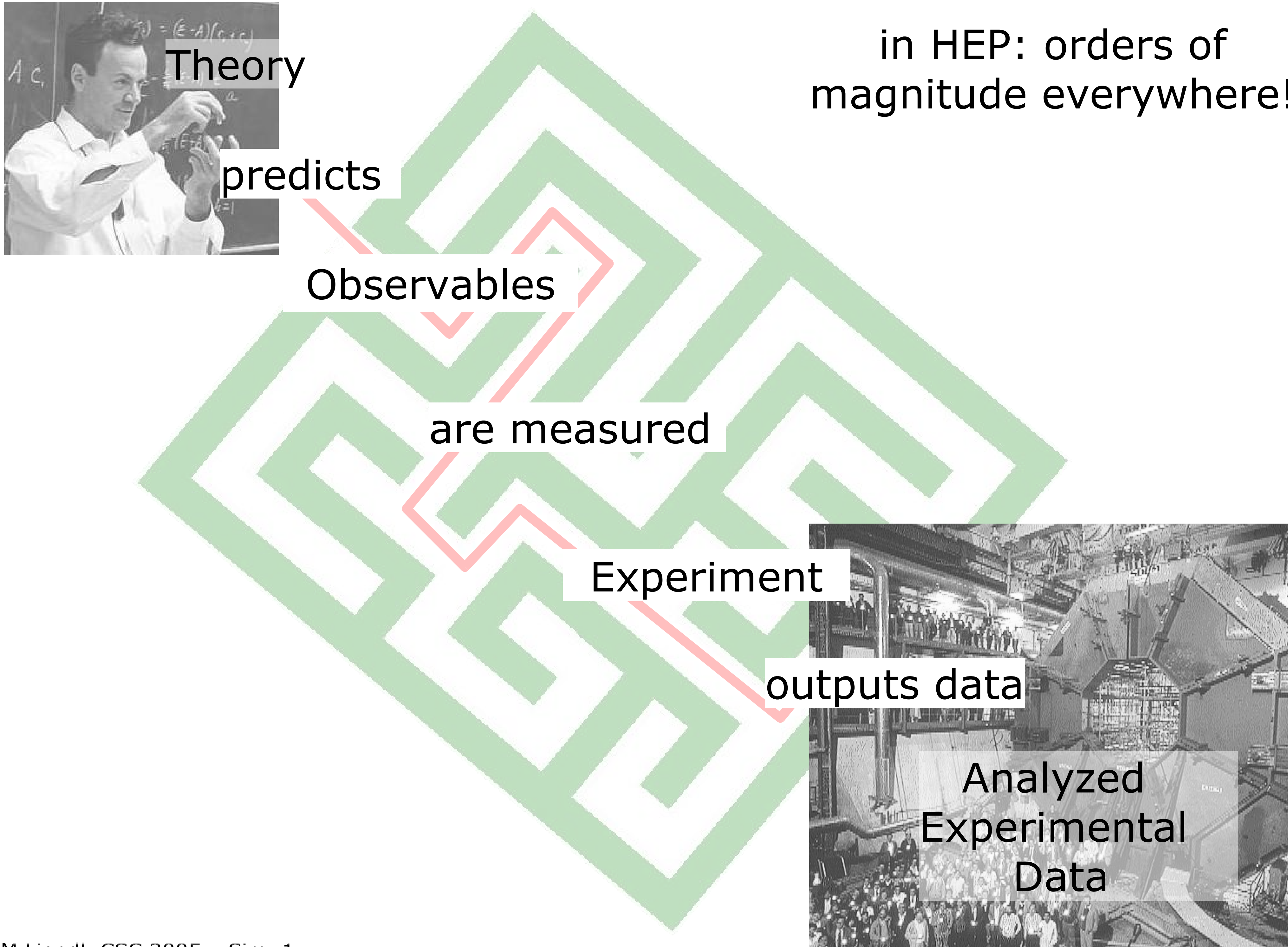
Analyzed Experimental Data/Evidence

Ideally ...



Theory
Observables
Experiment
Analyzed Experimental Data

in HEP: orders of magnitude everywhere!



OK, fine ...

But why now SIMULATION???

Theory → Observables → Experiment → Analysis

Theory
(a, b, ..)

unknown values for
parameters in theory,
e.g. the mass of the Higgs

change in parameters,
change in prediction
of observables

Observables
(a, b, ..)

Theory
(a, b, ..)

....

Observables
(a)

unknown values for
parameters in theory,
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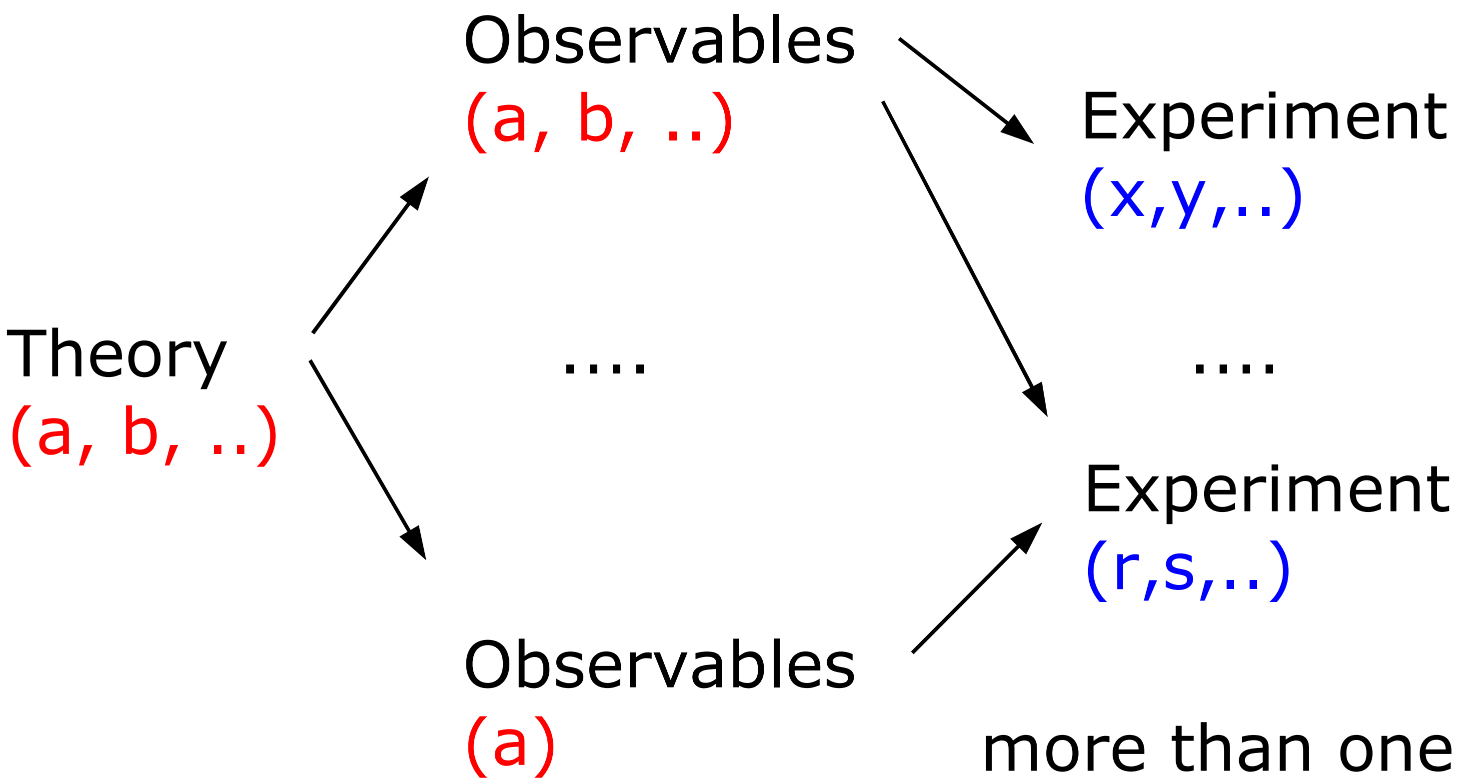
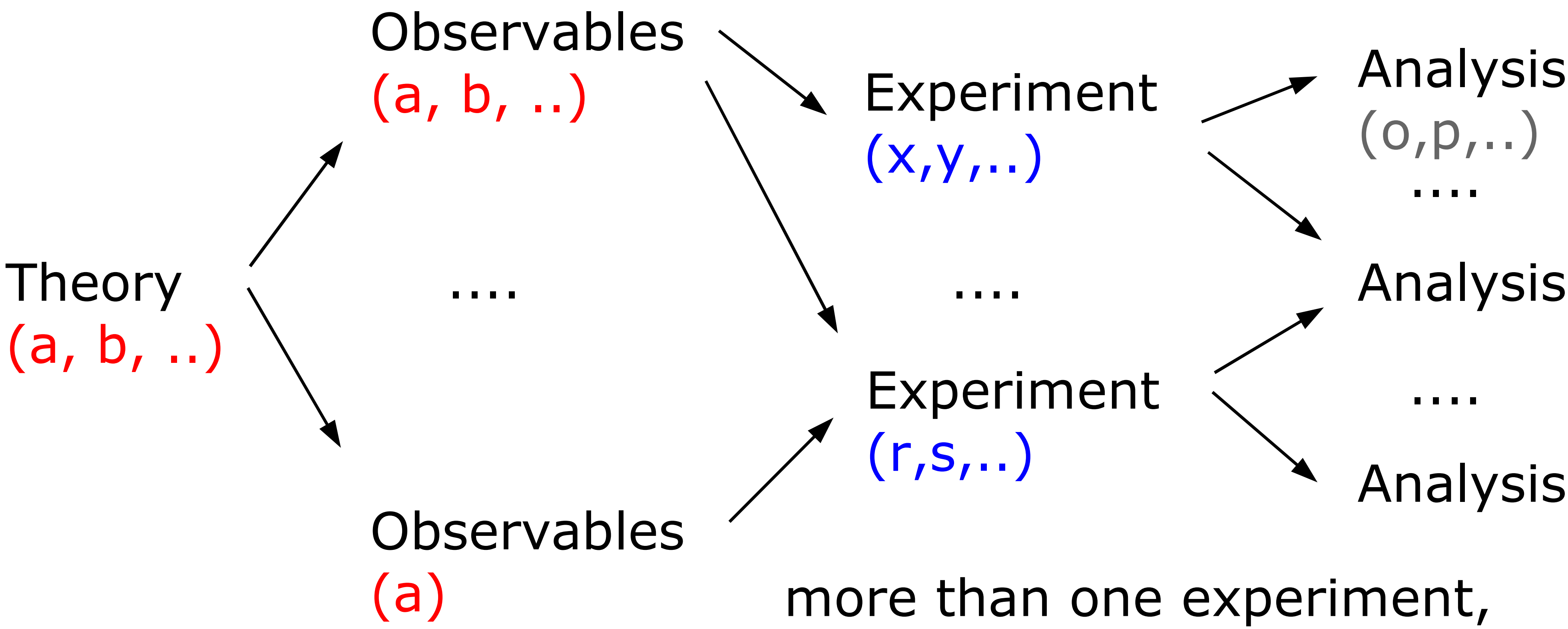


more than one experiment,
gains, gas pressures, voltages, ...
electronic noise, efficiency,
acceptance, dead channels,
machine conditions, ...

unknown values for
parameters in theory,
e.g. the mass of the Higgs

change in parameters,
change in prediction
of observables

choice of algorithm,
“cut” values, ...



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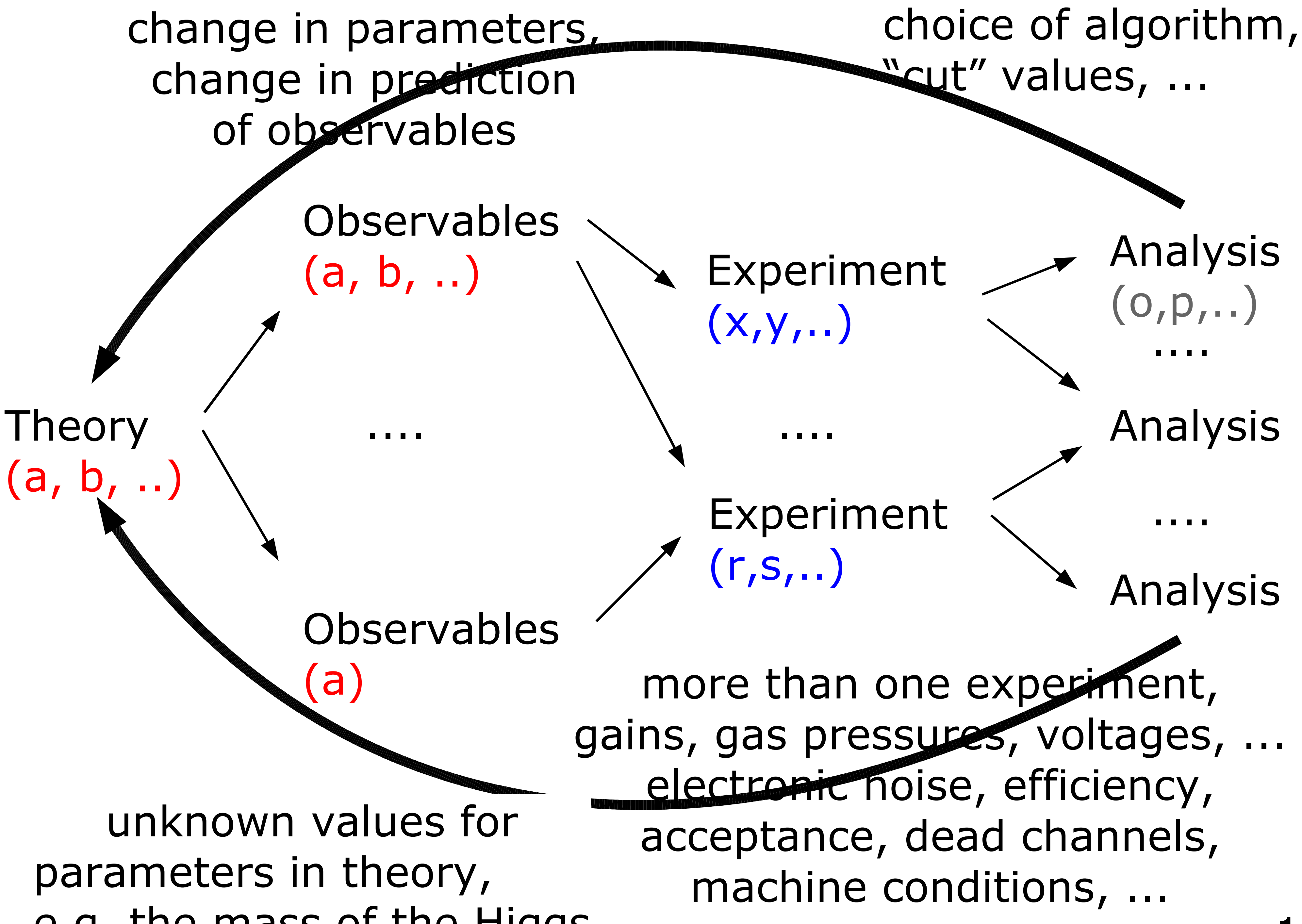
change in parameters,
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of observables
choice of algorithm,
"cut" values, ...
Observables
(a, b, ..)
Experiment
(x,y,..)
Analysis
(o,p,..)
....
Theory
(a, b, ..)
....
....
Analysis
Experiment
(r,s,..)
....
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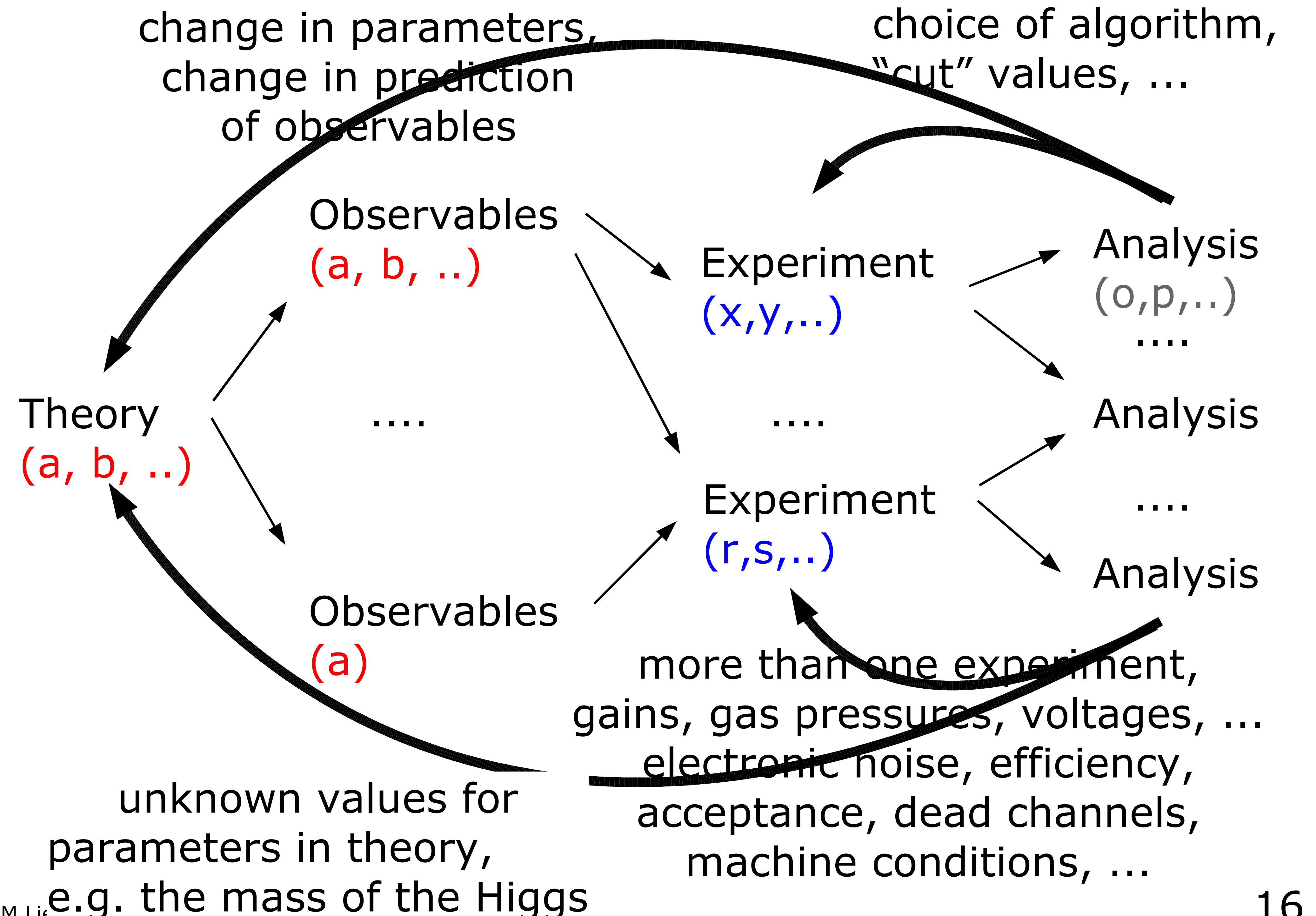
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unknown values for
parameters in theory,
e.g. the mass of the Higgs

change in parameters,
change in prediction

choice of algorithm,
“cut” values, ...

The need for simulation:

Because of the tremendous multiplicity
of possible parameter constellations,
it is impossible to design, operate,
and “understand” today's HEP experiments
without having corresponding simulation
programs capable of “scanning” the
allowed parameter ranges!

Th

(a

gains, gas pressures, voltages, ...
electronic noise, efficiency,
acceptance, dead channels,
machine conditions, ...

unknown values for
parameters in theory,
e.g. the mass of the Higgs

“understanding” your detector

(the – exaggerated simplified - Mickey Mouse case)

The Mickey Mouse Material

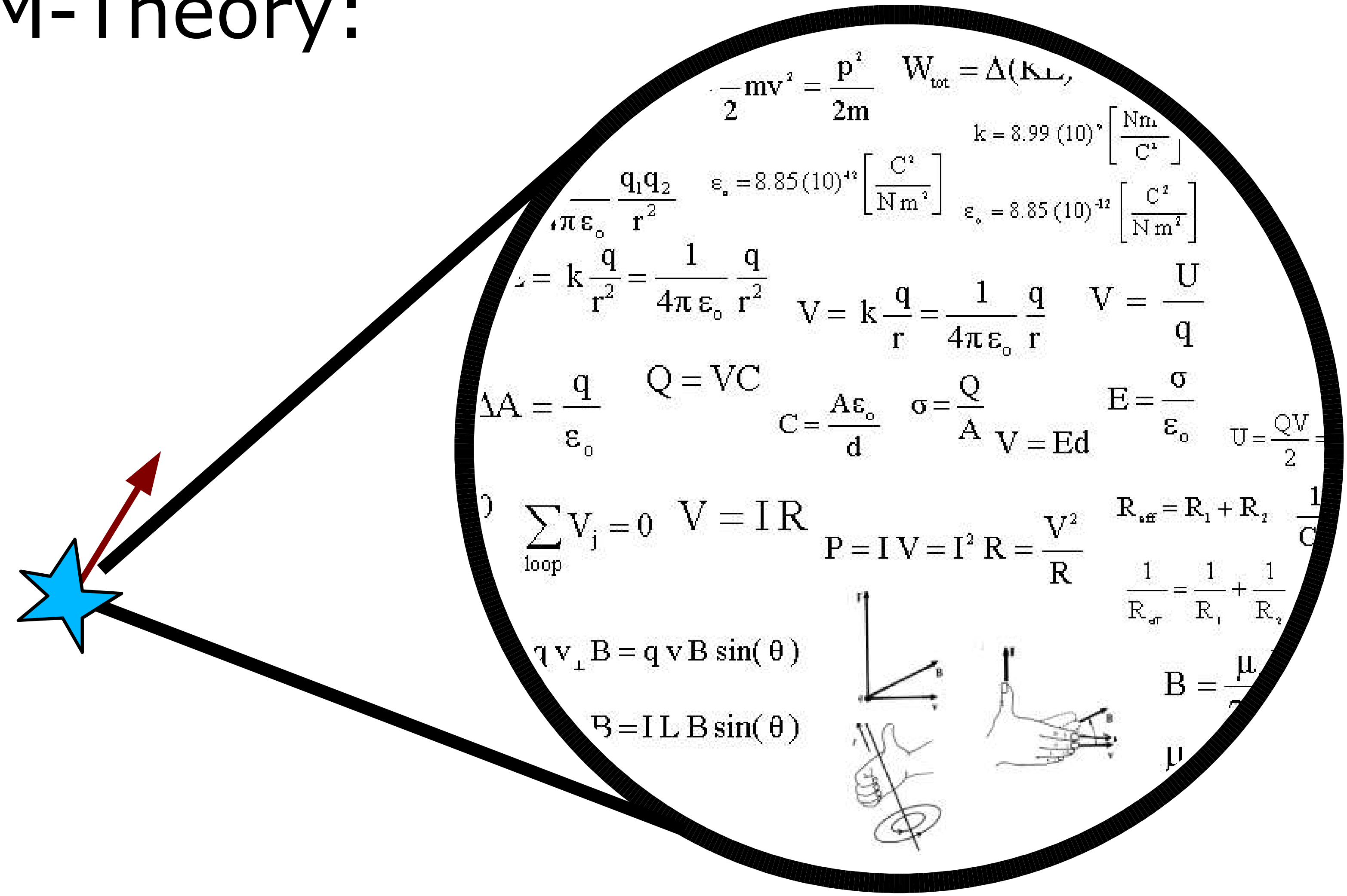
Somewhere in Disney World, Mickey finds ...

... the M-material emits spontaneously electrons into a random direction (2D)

In Mickey's world everything is 2D, of course!

The Mickey Mouse Theory

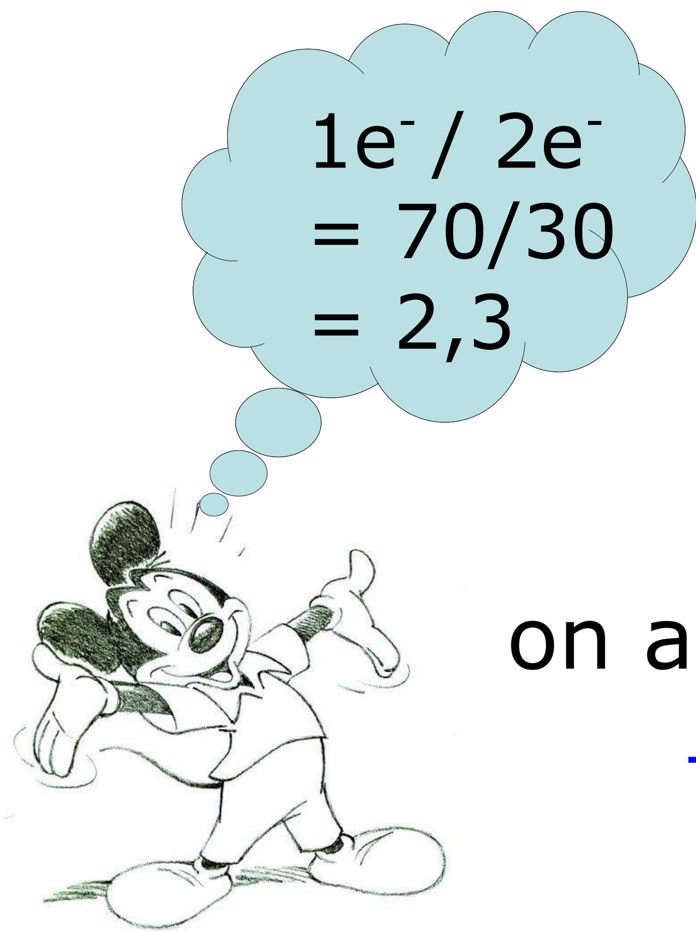
M-Theory:



The Mickey Mouse Theory

M-Theory predicts:

1 cm^2 of M-material emits either one single or two electrons
- at a time
- into a random direction (2D)
- in case of two electrons, they are emitted into opposite direction

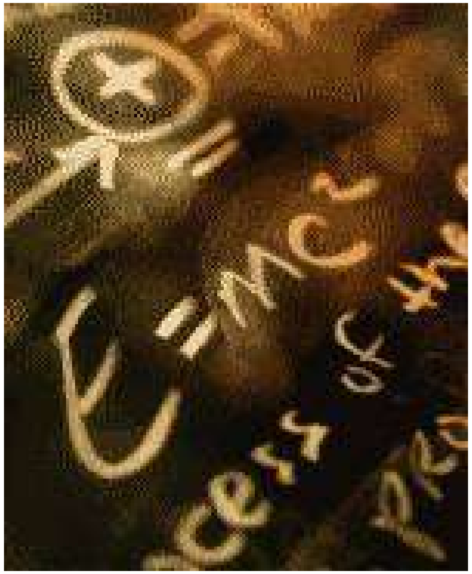


70% of all events are 1e$^-$
30% of all events are 2e$^-$

on average: 1 event / sec per cm^3

Theory predicts Observables

from → to



Mickey´s world

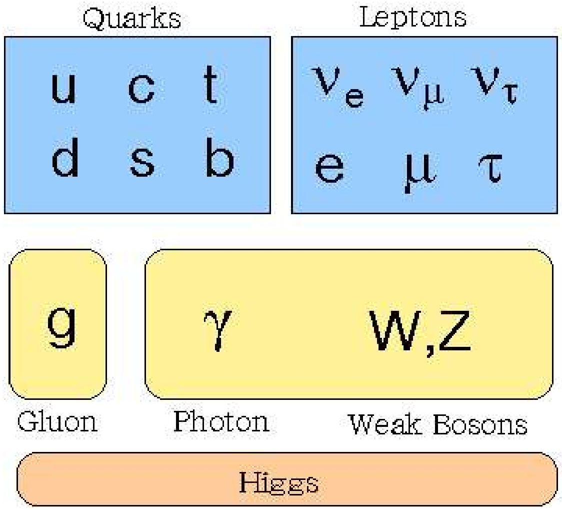
our world

Theory

Exercise 1.1.1.1.1a: Given locality, causality, Lorentz invariance, and known physical data since 1860, show that the Lagrangian describing all observed physical processes (sans gravity) can be written:

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2} m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2} M\phi^0\phi^0 - \beta_h\left[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$

.... (http://nuclear.ucdavis.edu/~tgutierr/files/stmL1.html)

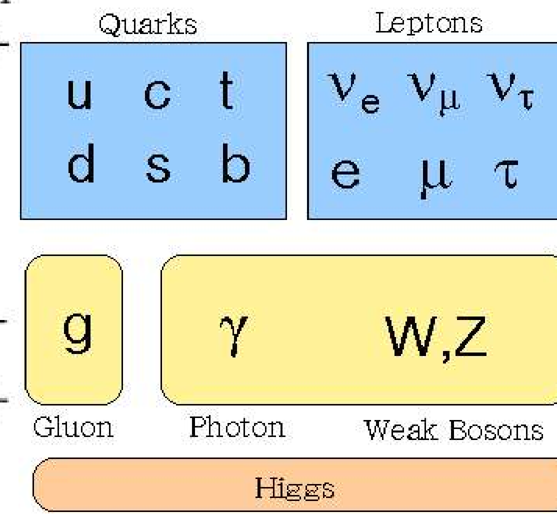


The Standard Model

Theory + Observables

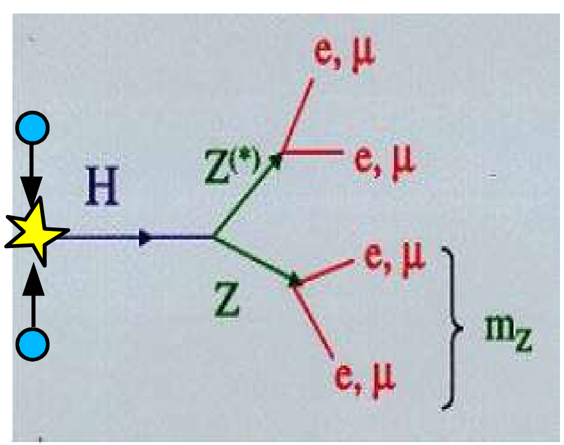
Exercise 1.1.1.1.1a: Given locality, causality, Lorentz invariance, and known physical data since 1860, show that the Lagrangian describing all observed physical processes (sans gravity) can be written:

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h\left[\frac{2M^2}{g^2} +\right.$$
$$\left.\frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+ W^-) - Z^0(W^+ \partial W^- - W^- \partial W^+) + Z^0(W^+ \partial W^- -$$



.... (http://nuclear.ucdavis.edu/~tgutierr/files/stmL1.html
)

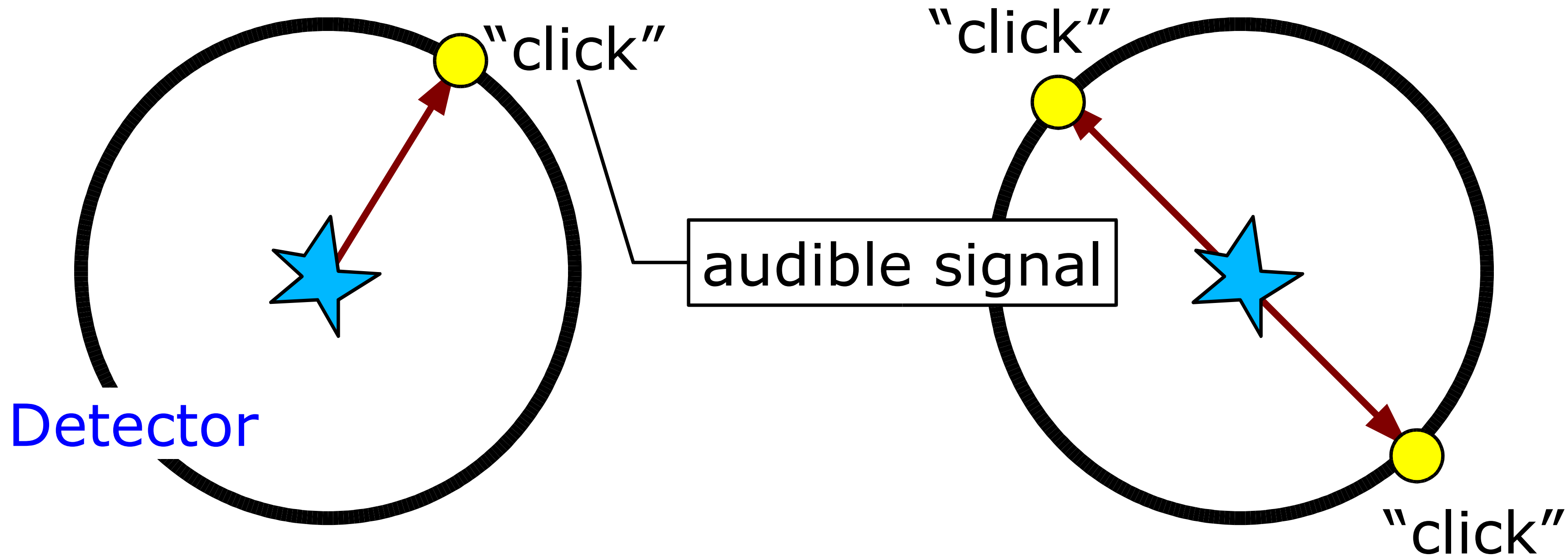
Observables: have a proton-proton collisions to make quarks interact. Sometimes, a Higgs particle will be produced, which decays in Zs, which decay in a pair of leptons ...



The leptons are the observables, because they can be detected by a particle detector, and they live long enough to be detected.

(Example of only one decay channel)

Mickey's "Gedankenexperiment"

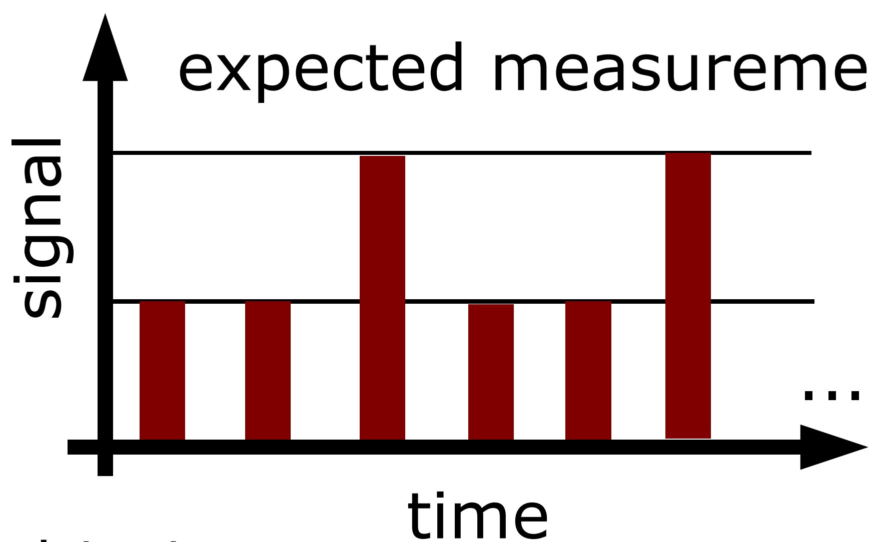


M-Theory says:

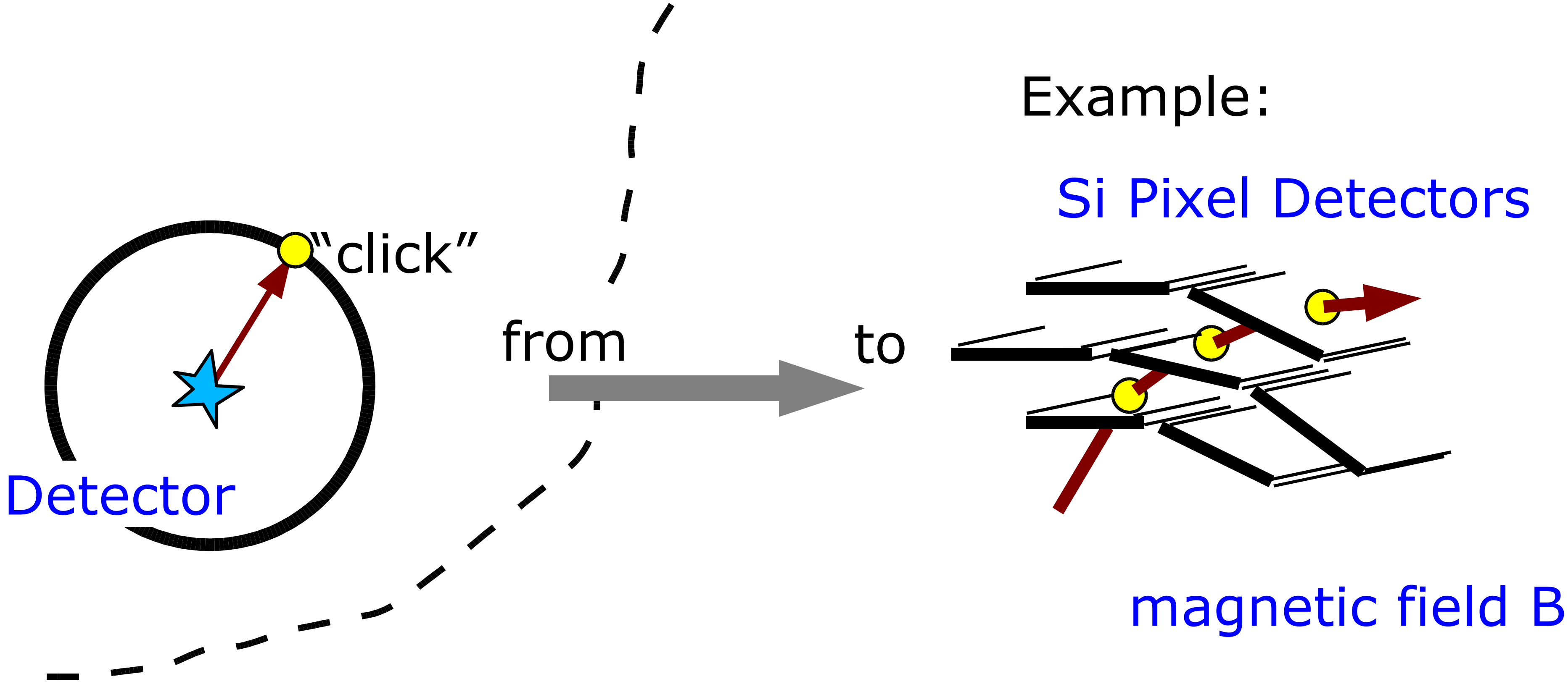
$$1\ e^- / 2\ e^- = 2{,}3$$

If Experiment measures:

1 click / 2 clicks = 2,3



then theory and experiment are consistent.



… - muon interaction with matter:
  . ionization
  . bremsstrahlung
  . Coulomb scattering
- muon interaction with B-field
  . curved flight path

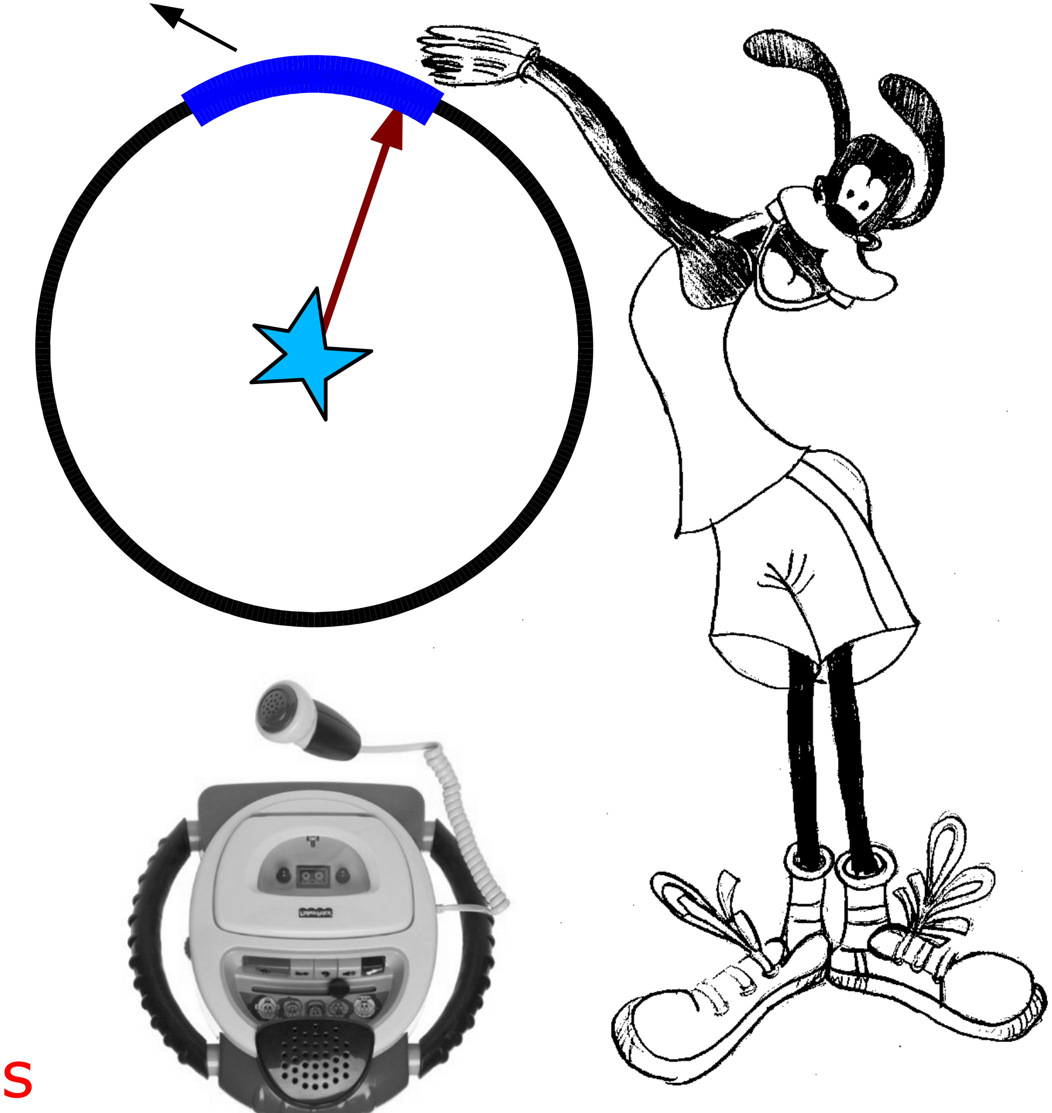
Expected measurement: points on a particle trajectory

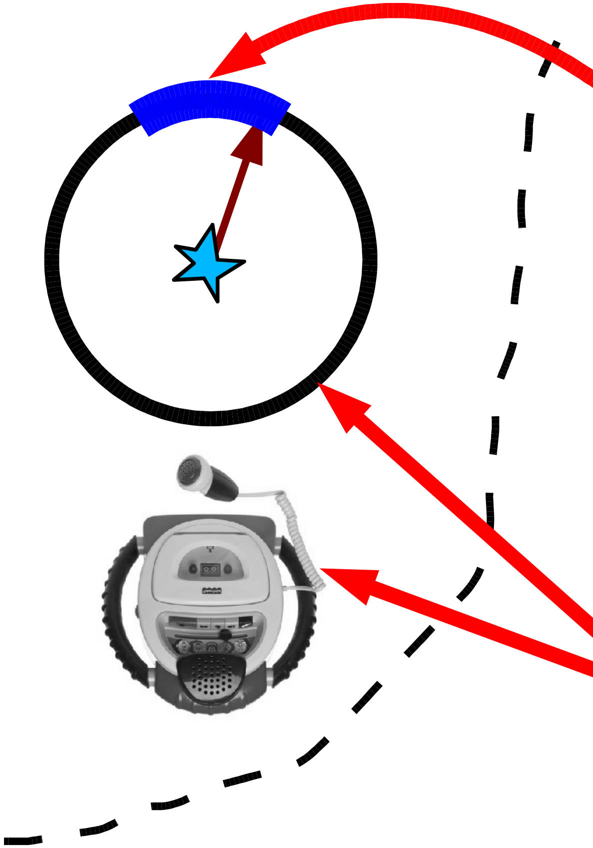
The Mickey Mouse Experiment

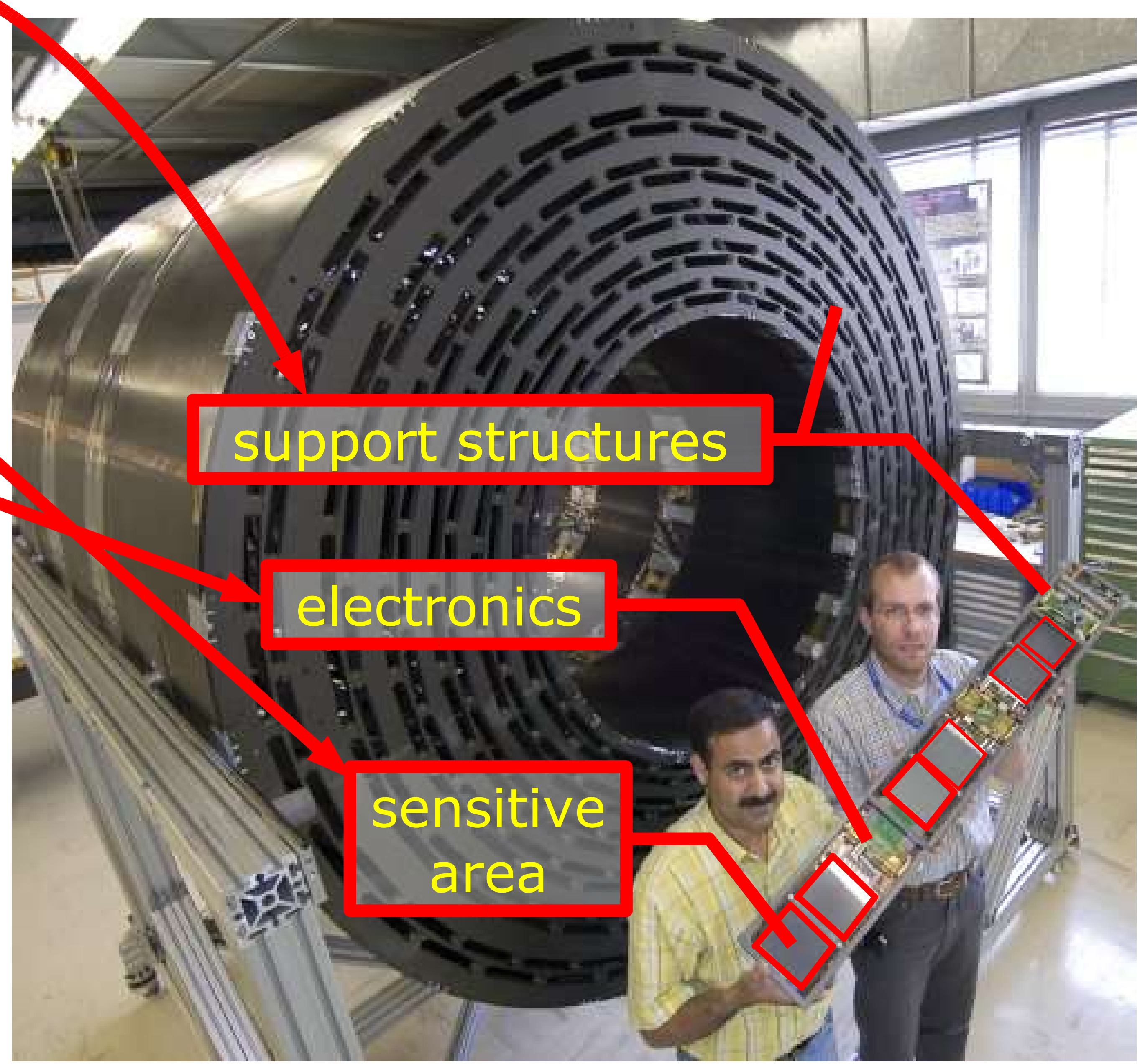
In Disney World,
Goofy builds
the detector.

He has to use
a cooling pipe
taking 20%
of the surface
of the detector´s
sensitive area

Technical Know How
and How To for
measuring observables



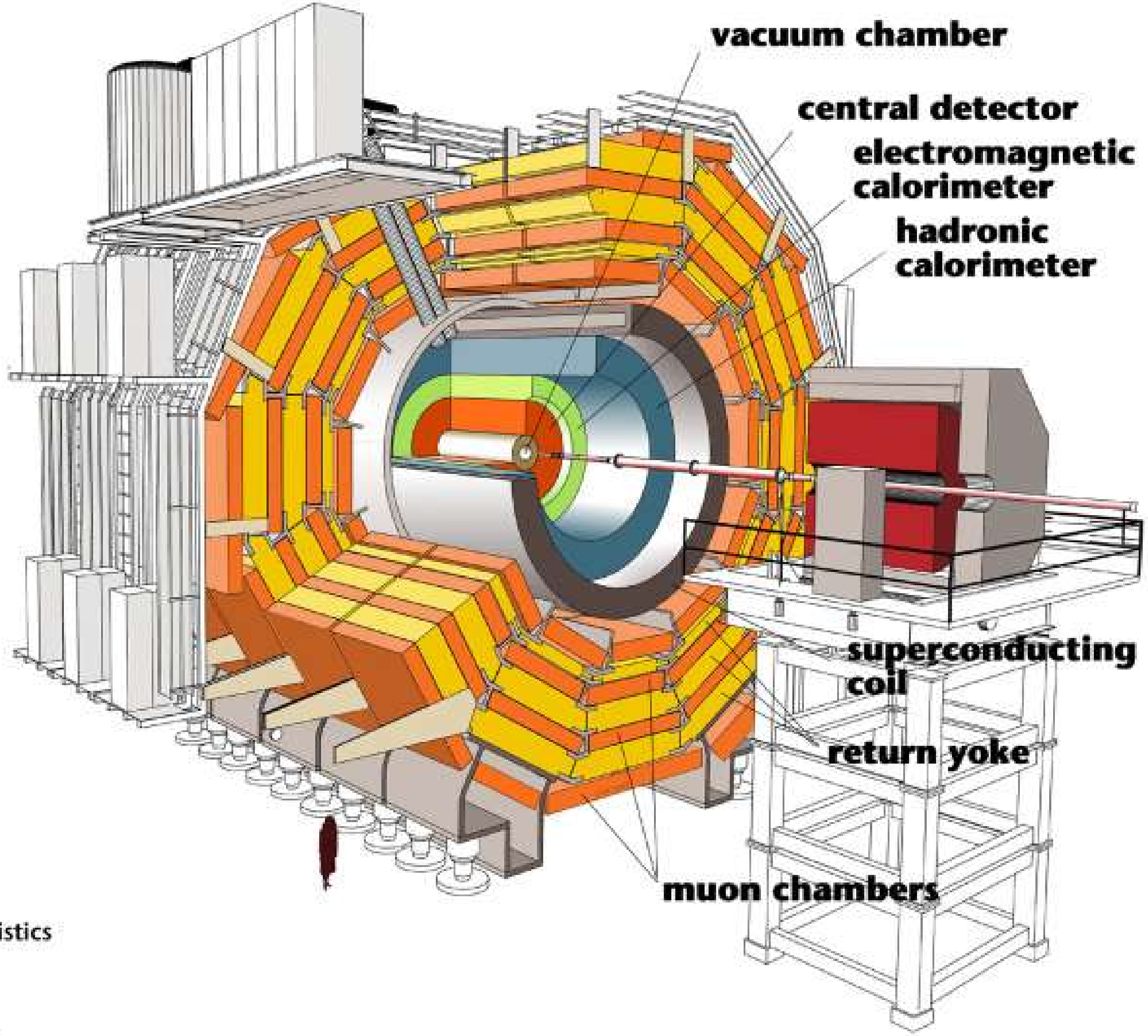




Not shown:
trigger electronics,
data storage, ...

And: it's "only" a part of a sub-detector!

We need this:

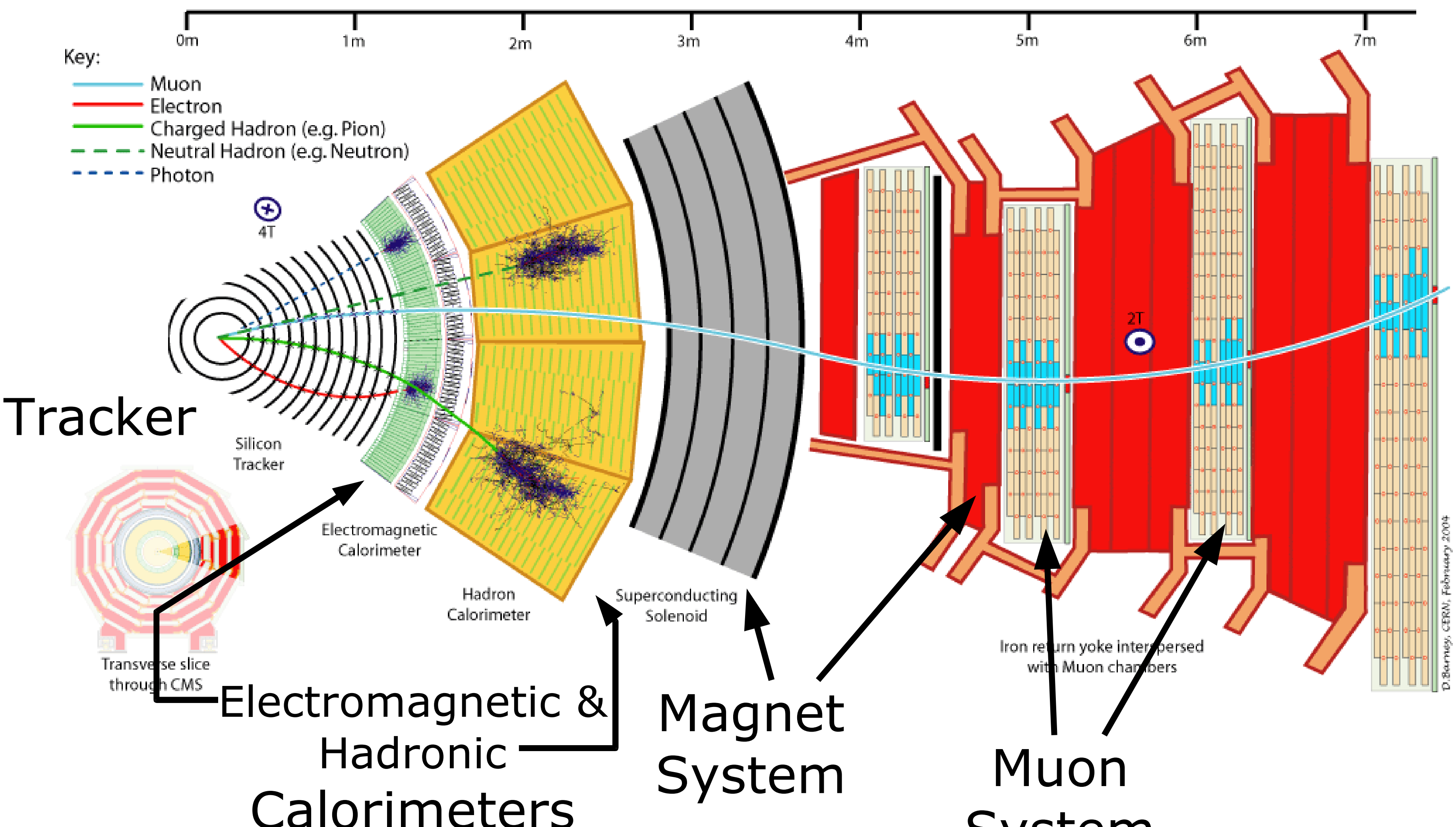


Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

We need this:

Onion shell design exploiting the physics processes of ("long living") particles traversing bulk matter

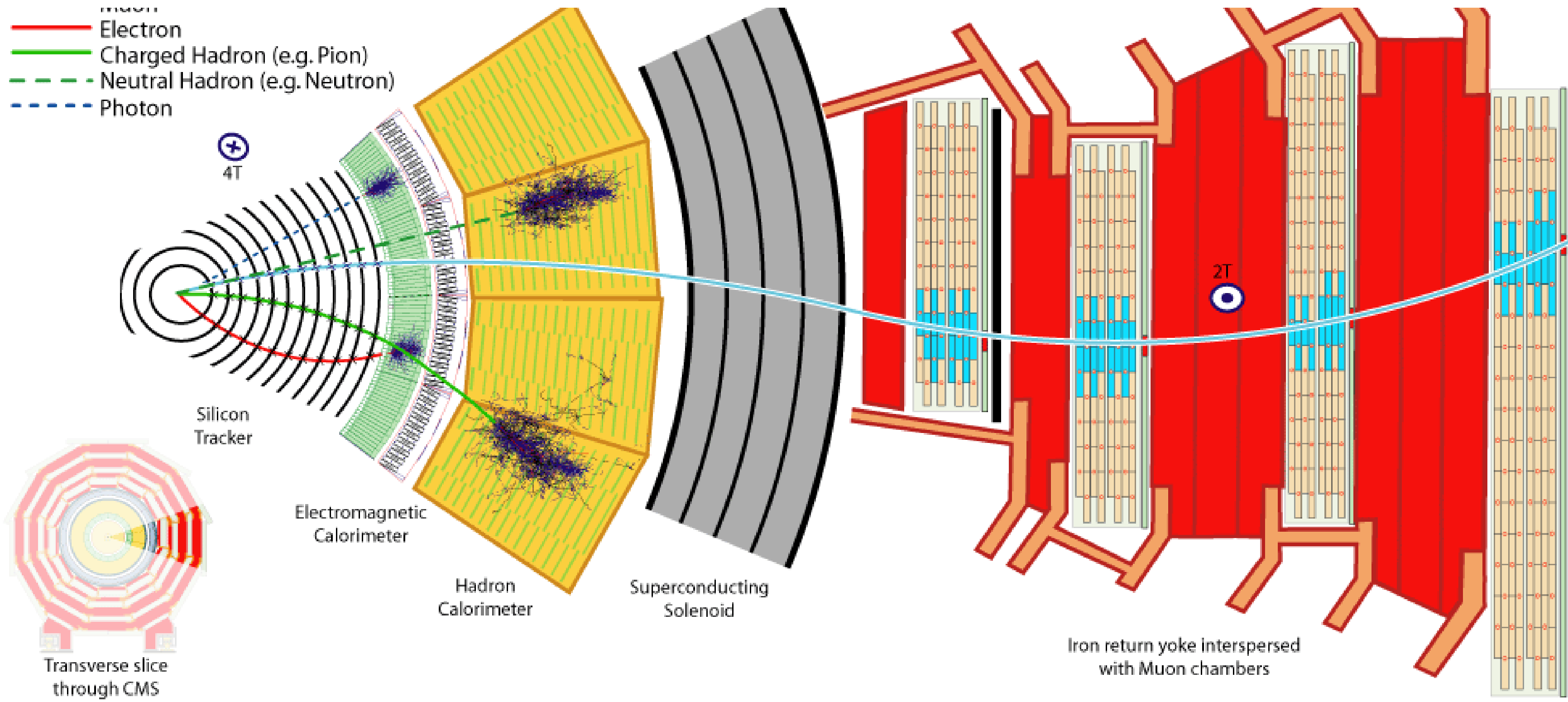


Thousands of channels everywhere!!!
Complex geometry ....

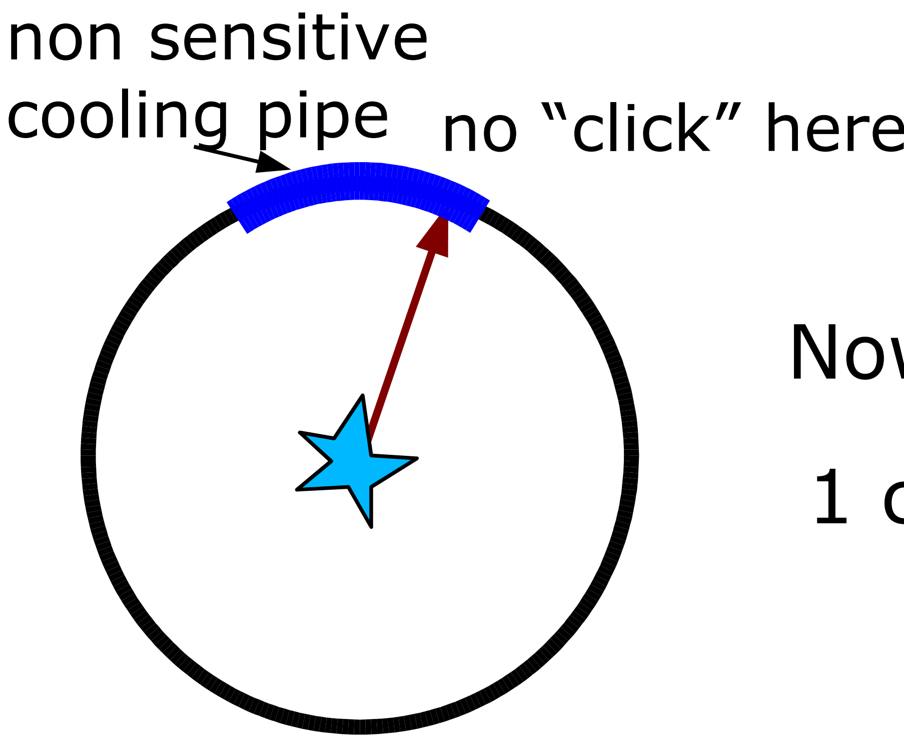
This lectures are mainly about how to simulate particles interacting with and traversing bulk materials:

- how to describe a detector made of bulk materials
- how to track single particles through it
- how to model the physics of their interactions

using the simulation toolkit GEANT4 as an example

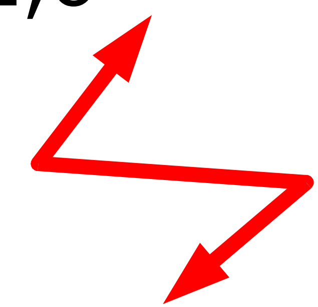


Doing the experiment



Now, Mickey measures:

1 click / 2 clicks = 2,6

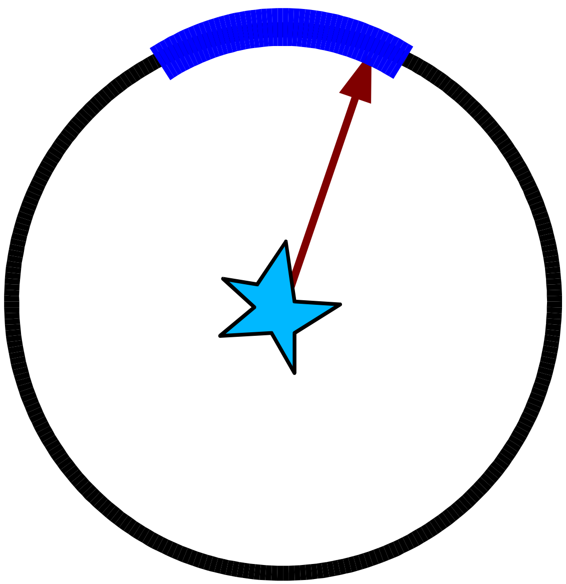


Theory: 1 e^- / 2 e^- = 2,3

Is the experiment still consistent with the theory?

Or does the experiment prove the theory wrong?

The Mickey Mouse Analysis



Thought:

We loose 20% of the sensitive area, thus we measure 20% less events (20% less 1 clicks, 20% less 2 clicks)

but then the ratio between 1 and 2 click counts should be the same!

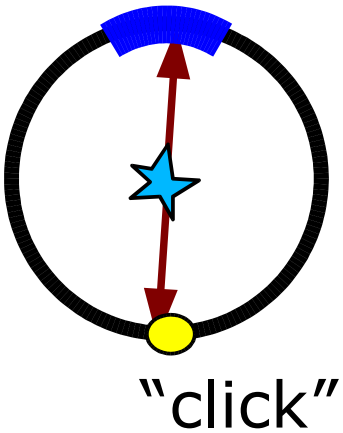
=> the experiment indicates that the theory is not correct!

Theory:
1 e^- / 2 e^- = 2,3

Experiment:
1 click / 2 clicks = 2,6
and thus:
1 e^- / 2 e^- = 2,6

Understand and analyze the measurements

Some 2 e^- events are counted as 1 e^- events!!



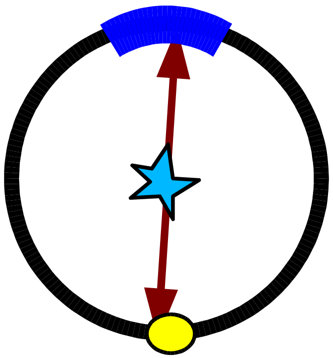
=> 20% of the $1e^-$ events are lost

=> 20% of the $2e^-$ events are counted as $1e^-$

ATTENTION!

Understand
and analyze the
measurements

Some 2 e^- events are counted as 1 e^- events!!



=> 20% of the 1e^- events are lost
=> 20% of the 2e^- events are counted as 1e^-

Assuming the M-Theory:

We have N events per hour, then
0.7N are 1e^- events
0.3N are 2e^- events

Detector sees:

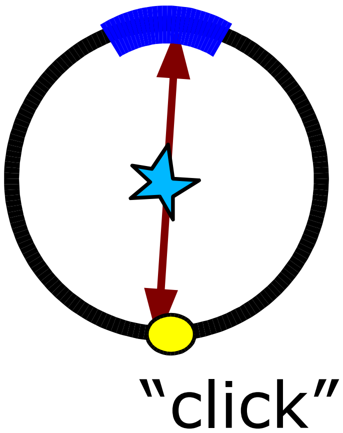
0.7N – 20% 1e^- → 0.56N single clicks (20% less single clicks)
0.3N – 20% 2e^- → 0.24N double clicks (20% less double clicks)
→ (0.3 – 0.24)N = 0.06N doubles counted as singles!

=> additional 0,06N single clicks

single clicks: 0,56N + 0,06N = 0,62N
double clicks: 0,24N

1 click / 2 clicks = 62/24 = 2,6

Some 2 e^- events are counted as 1 e^- events!!



=> 20% of the 1e^- events are lost
=> 20% of the 2e^- events are counted as 1e^-

Assuming the M-Theory:

$$1\ e^- / 2\ e^- = 2,3$$

AND understanding the detector & the measurement, the measured ratio must be bigger to be consistent with the theory:

$$1 \text{ click} / 2 \text{ clicks} = 62/24 = 2,6$$

Efficiency/Acceptance, Background

Mickey needed to know the efficiency/acceptance and background of his detector to interpret the result correctly.

For the same type of event, the acceptance is defined as:

$$\langle N_{measured} \rangle = a \cdot \langle N_{occurred} \rangle + \langle N_{bckgrd} \rangle$$

- $\langle N_{measured} \rangle$: average measured events looking like type X
- a: acceptance
- $\langle N_{occurred} \rangle$: average of real events of type X
- $\langle N_{bckgrd} \rangle$: Background looking like type X

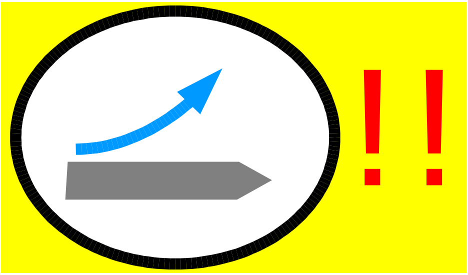
Intuitively, for Mickey's experiment:

acceptance for measuring 1 e^- events = 0.8
acceptance for measuring 2 e^- events = 0.8

Efficiency & Acceptance

If we look only on one particular event, we define:

Detection Efficiency $\varepsilon(x)$:= probability of an event to be detected if it has taken place



$x = (x_1, x_2, ..)$ ... physical variables describing the event (momenta of particles, position of vertices, ...)

Efficiency & Acceptance

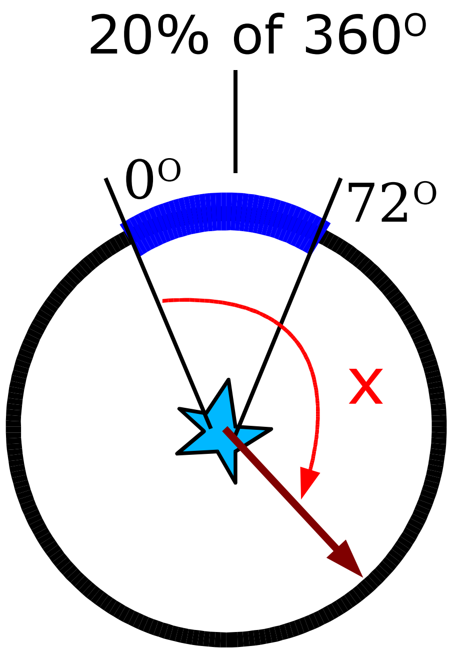
Detection Efficiency $\varepsilon(x)$:= probability of an event to be detected if it has taken place

In Mickey's experiment for $1e^-$ events:

x ... angle of emission

$\varepsilon(x) = 1$, for x within $72^o \rightarrow 360^o$

$\varepsilon(x) = 0$, for x within $0^o \rightarrow 72^o$



Special case of geometrical efficiency!

$x = (x_1, x_2, ..)$ ... physical variables describing the event (momenta of particles, position of vertices, ...)

Efficiency & Acceptance

In Mickey's world, things were simple ...

Detection Efficiency $\varepsilon(x)$:= probability of an event to be detected if it has taken place

triggering

dead time of channels

$$\varepsilon(x) \sim \varepsilon_1(x) \cdot \varepsilon_2(x) \cdot \varepsilon_3(x) \ldots \cdot \varepsilon_g(x)$$

geometrical efficiency

$\varepsilon_g(x) = 1 \leftrightarrow$ particle hit the detector (geometrically)

$\varepsilon_g(x) = 0 \leftrightarrow$ particle missed the detector

$x = (x_1, x_2, ..)$ ... physical variables describing the event (momenta of particles, position of vertices, ...)

Efficiency & Acceptance

The average (expectation value) of $\varepsilon(x)$ is then the acceptance:

Detection Efficiency $\varepsilon(x)$:= probability of an event to be detected if it has taken place

Acceptance a := average efficiency = $\langle\varepsilon\rangle$

$$= \int \varepsilon(x) f(x) dx$$

f(x) ... probability density of event x (quantum theories only give you probabilities!!!)

$x = (x_1, x_2, ..)$ ... physical variables describing the event (momenta of particles, position of vertices, ...)

Efficiency & Acceptance

Prediction of quantum theory

$$\int_{x_1}^{x_2} f(x)dx$$

Probability of x being between x_1 and x_2

ion value) of $\varepsilon(x)$ is then the

probability to detect an occurred event having occurred in any of its possible states

) to be place

:= average efficiency = <ε>

$$a = \int \varepsilon(x) f(x) dx$$

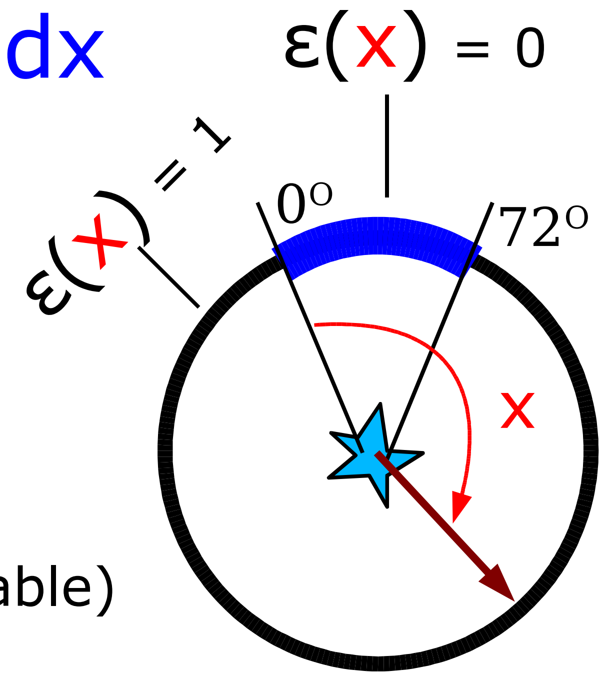
f(x) ... probability density of event x (quantum theories only give you probabilities!!!)

$x = (x_1, x_2, ..)$ ... physical variables describing the event (momenta of particles, position of vertices, ...)

Detection Efficiency $\varepsilon(x)$:= probability of an event to be detected if it has taken place

Acceptance a := average efficiency = $\langle\varepsilon\rangle$

$$a = \int \varepsilon(x) f(x) dx$$



In Mickey's experiment for 1e⁻ events:

- x ... angle of emission
- $\varepsilon(x) = 1$, for x within 72° → 360°
- $\varepsilon(x) = 0$, for x within 0° → 72°
- $f(x) = 1/360°$ (every direction equally probable)

$$a = \int f(x)\varepsilon(x)dx = 1/360^{\circ} \left(\int_{72^{\circ}}^{360^{\circ}} 1\,dx + \int_{0^{\circ}}^{72^{\circ}} 0\,dx \right) = 288/360 = \underline{\mathbf{0.8}}$$

Efficiency & Acceptance

Mickey needed to know the efficiency and acceptance of his detector to interpret the measurement result correctly, and correct it by accounting for background events!

Detection Efficiency ε := probability of an event to be detected if it has taken place

Acceptance a := average efficieny = $\langle\varepsilon\rangle$

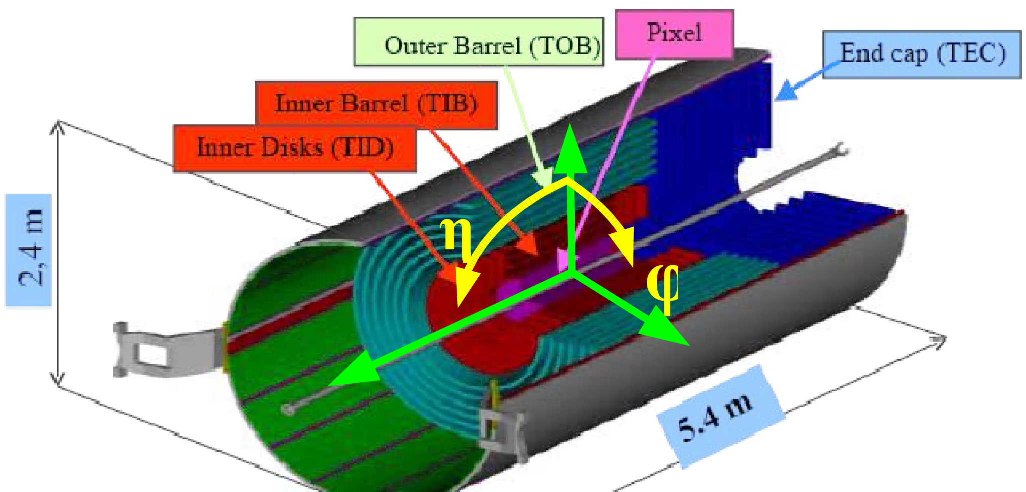
$$\langle N_{measured} \rangle = a \langle N_{occured} \rangle$$ for the same type of event!

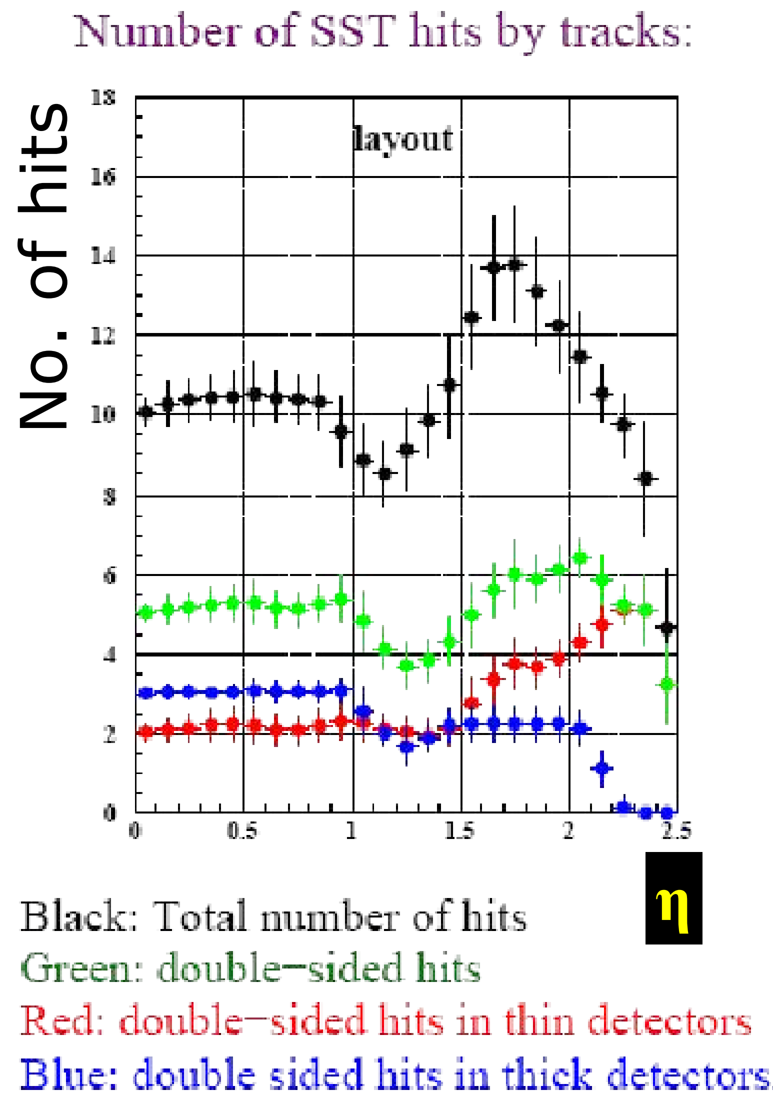
special case: geometrical acceptance ....

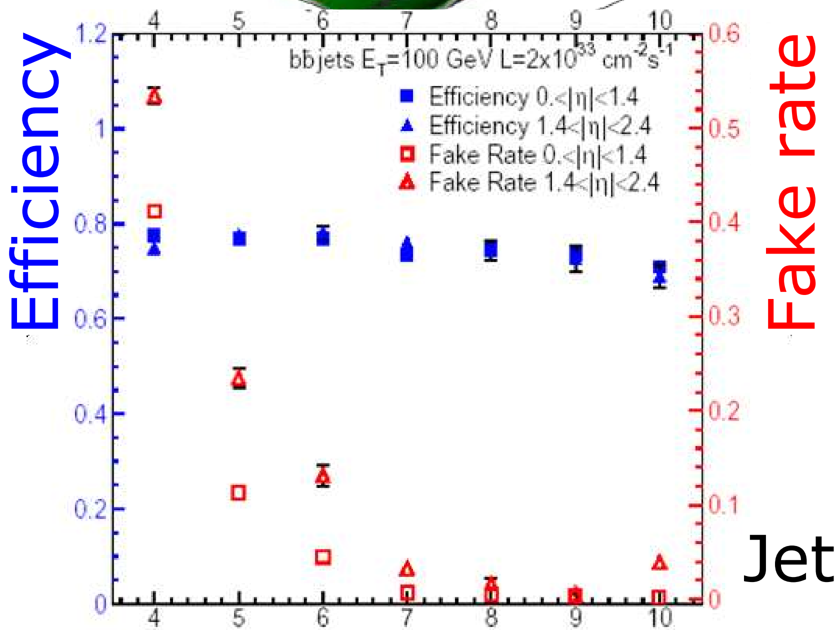
Mickey´s experiment:

a = 0,8 (100% – 20% non sensitive detector)

Example: CMS tracker
average hits around φ by simulation

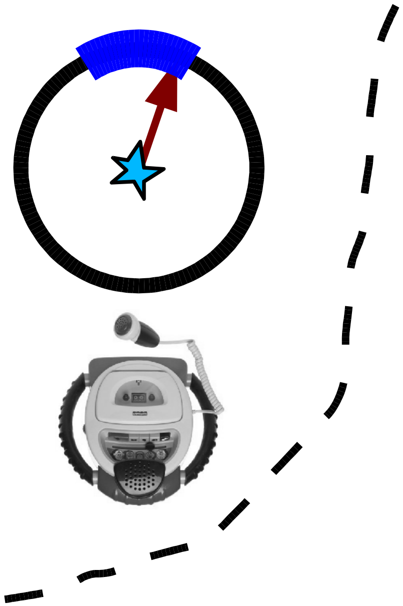


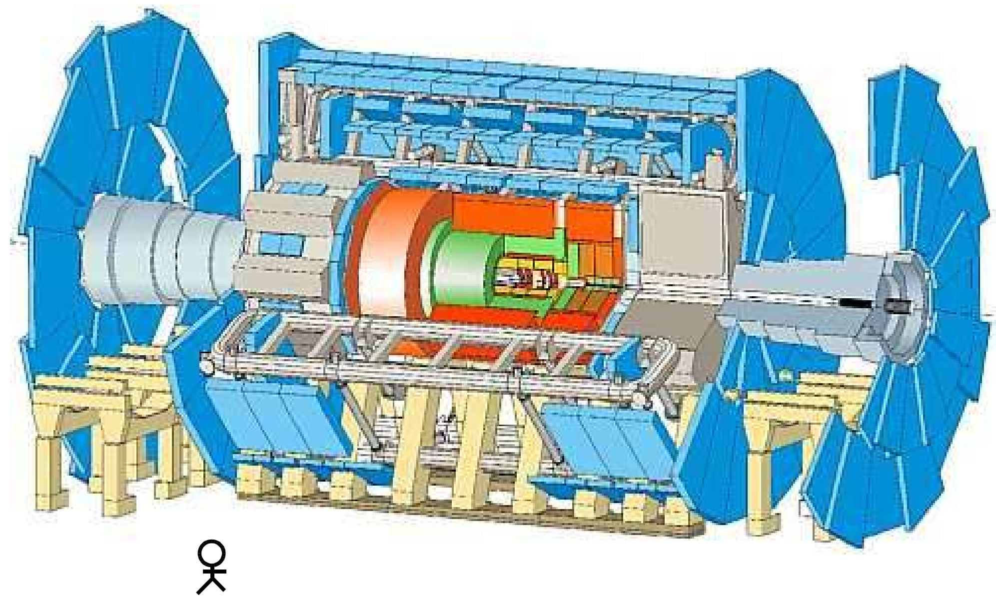




Jet reconstruction efficiency

No. of hits



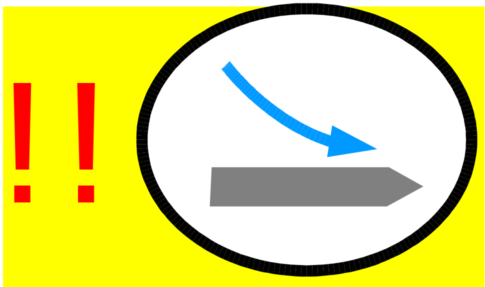


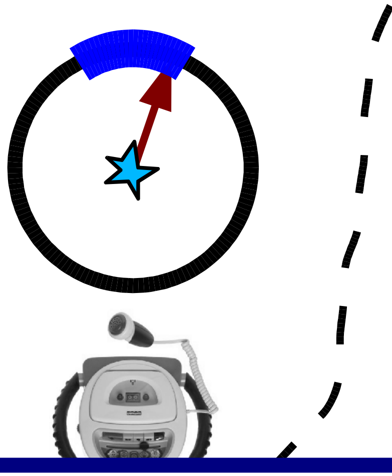
Generally, efficiency depends on many things:

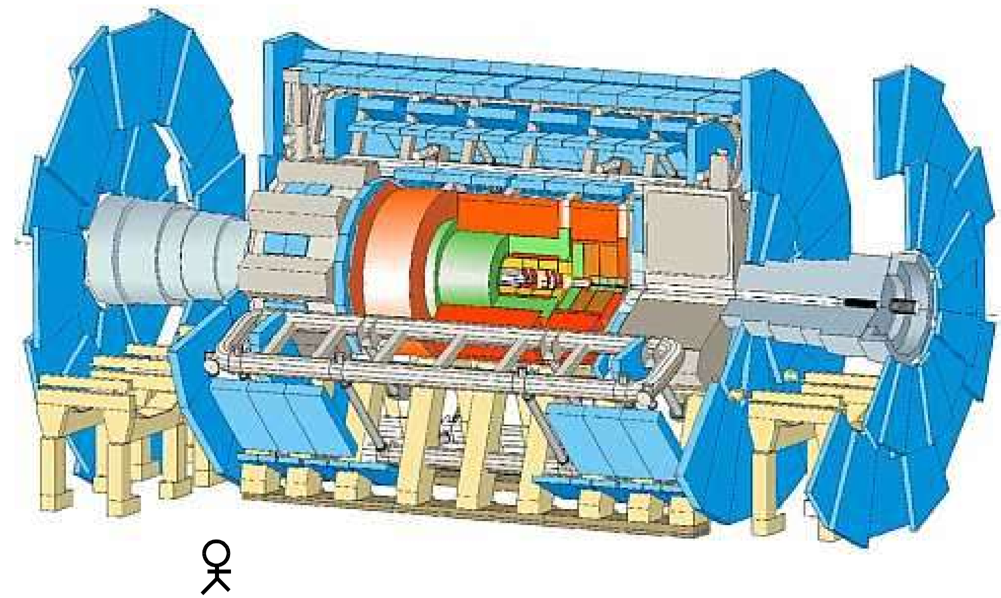
- money
- geometry
- choice of sub-detectors (physical properties, deterioration, ..)
- event type
- trigger efficiencies
- reconstruction & analysis algorithms / SW & computing

How can we design & built a detector "efficiently" enough to measure what we want to measure?

=> <u>simulation studies</u> contribute significantly to the taken decisions







dead time of electronics, selection algorithms (LHC: 10^9 to 100 Hz!!)

epends on many things:

- choice of sub-detectors (physical properties, deterioration, ..)
- event type
- trigger efficiencies
- reconstruction & analysis algorithms / SW & computing

How can we design & built a detector "efficiently" enough to measure what we want to measure?

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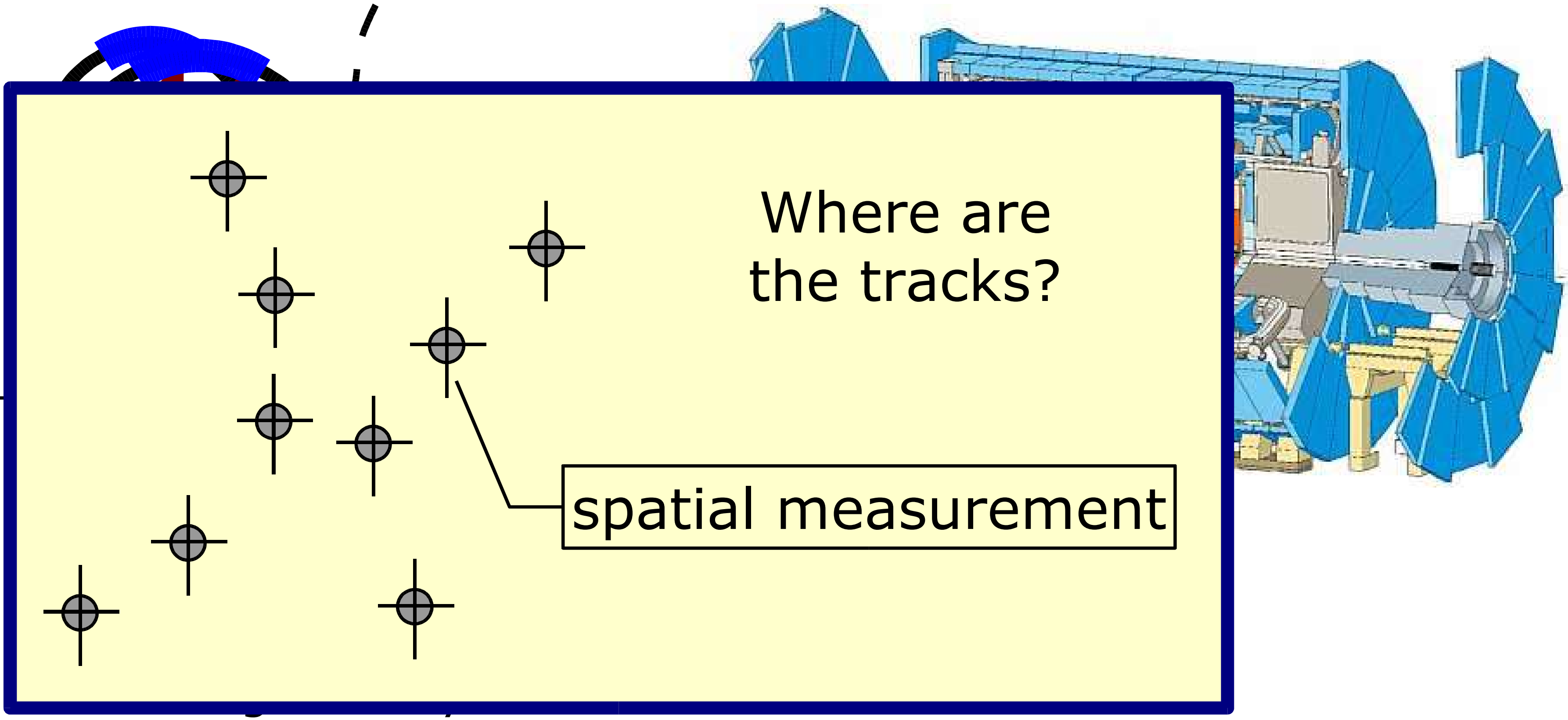
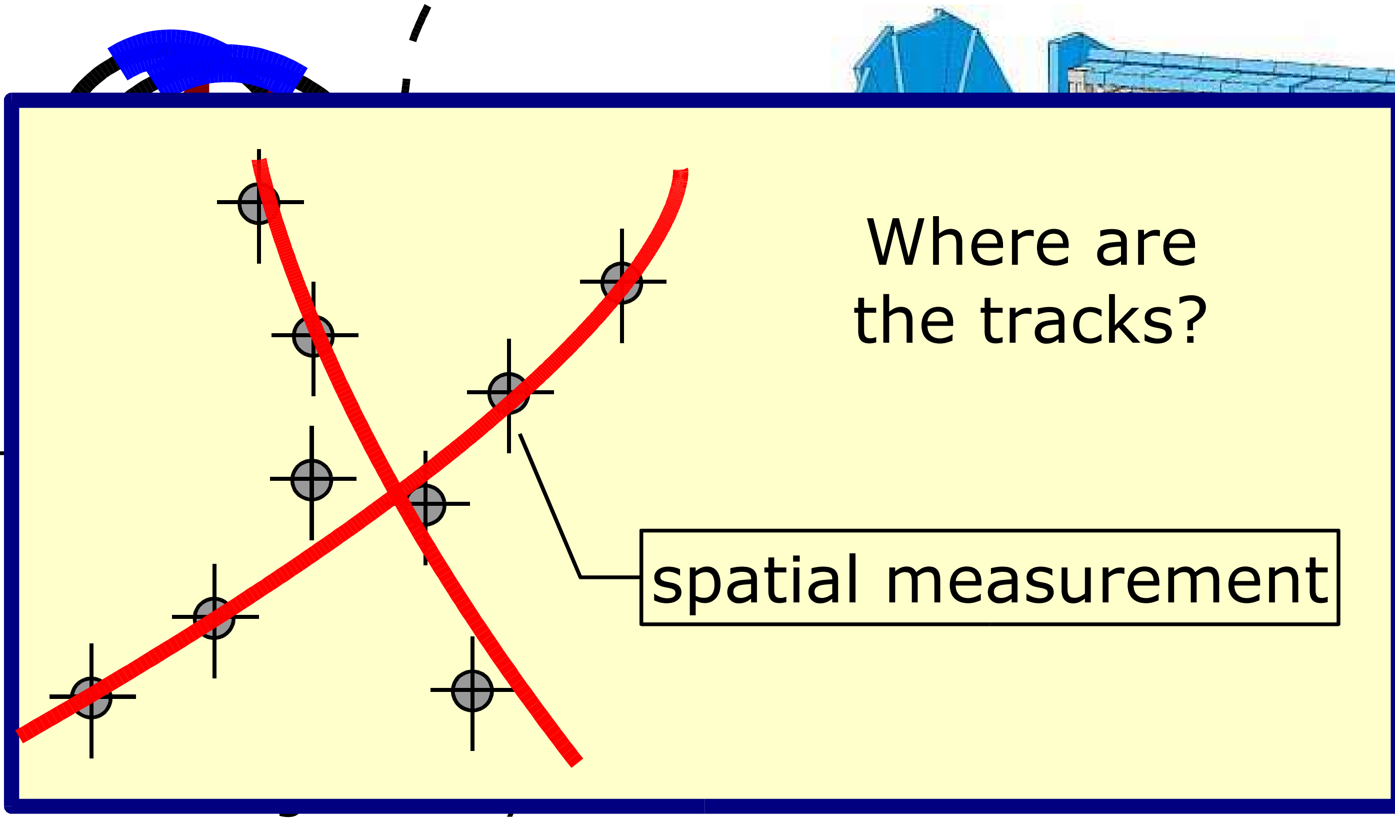
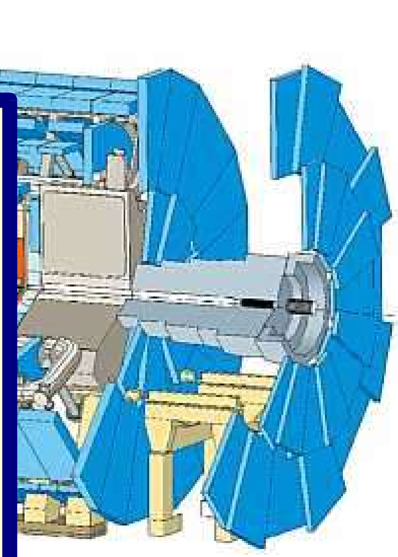


- choice of sub-detectors (physical properties, deterioration, ..)
- event type
- trigger efficiencies
- reconstruction & analysis algorithms / SW & computing

How can we build a detector, that is "efficient" enough to measure what we want to measure?

=> simulation studies contribute significantly to the taken decisions





- choice of sub-detectors (physical properties, deterioration, ..)
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How can we build a detector, that is "efficient" enough to measure what we want to measure?

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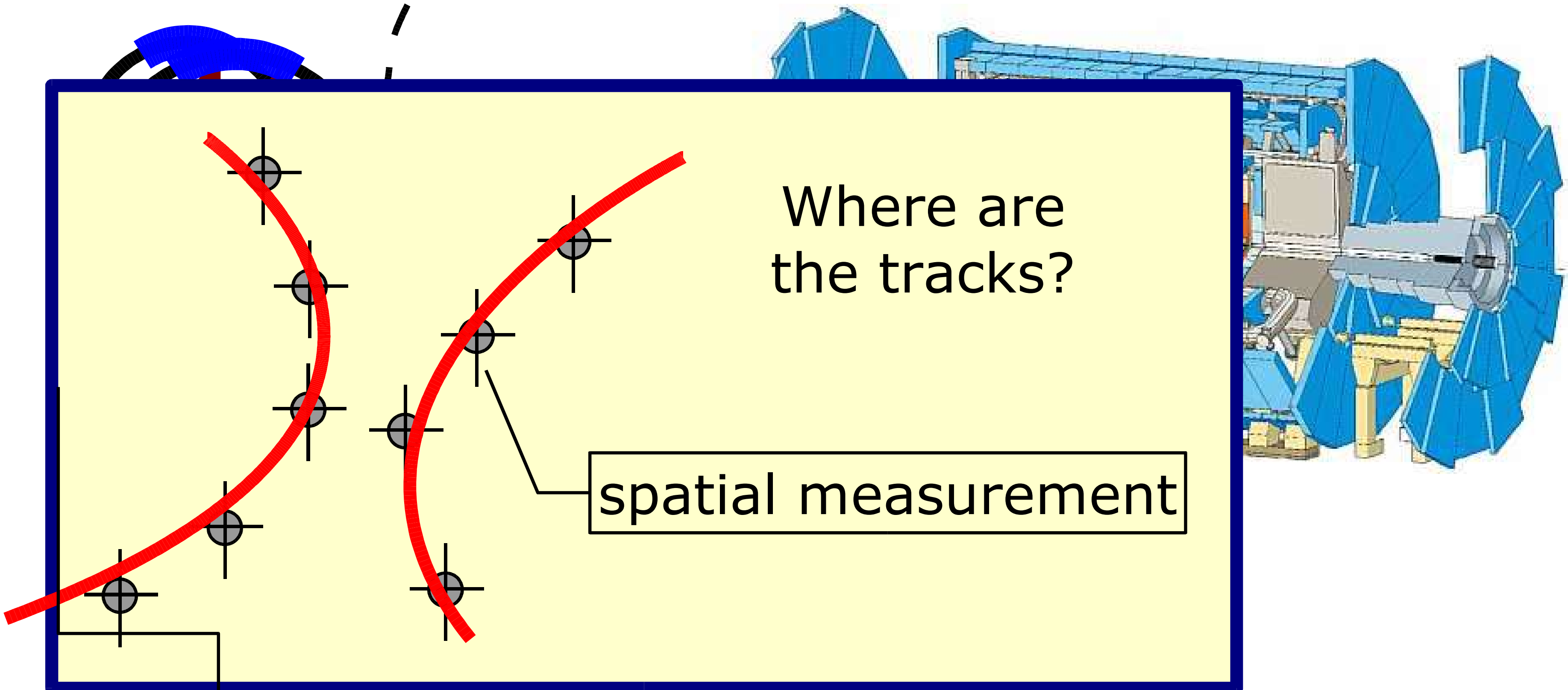

- choice of sub-detectors (physical properties, deterioration, ..)
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How can we build a detector, that is “efficient” enough to measure what we want to measure?

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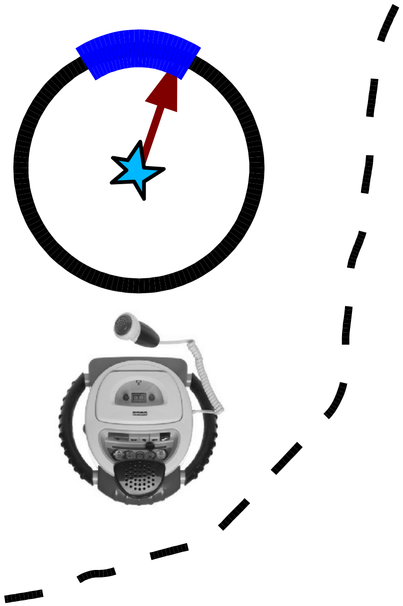
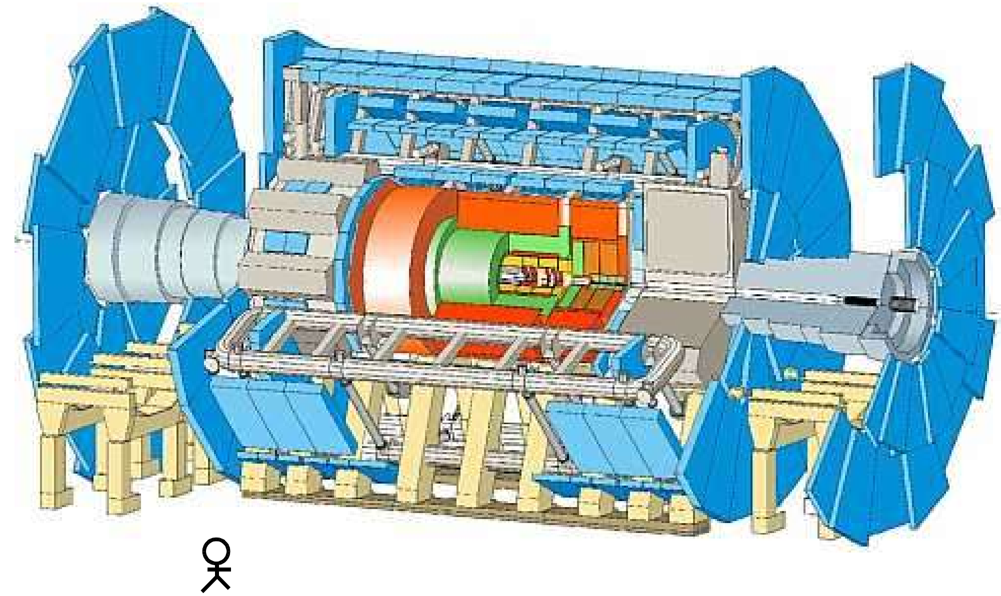
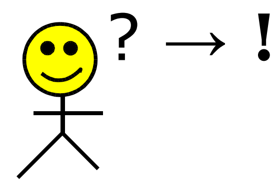






Experiment simulations help to

- design & understand the detector and its data
- verify, train, optimize the event selection (triggering)
- verify, train, optimize the algorithms to reconstruct the physics events from the data

Some thoughts about noise and background ..

- What´s the signal to noise ratio
  - assuming a given theory to be tested?
  - ~ how many signal events, how many background and min. bias events?

In other words: all the additional, unwanted crap being registered in the detector ...

How to split simulation tasks to study these issues ...

Usually, we measure not only the signal!

BACKGROUND distorting the measurement!

measured events looking like events of type E

$$\langle N_{measured} \rangle = a \langle N_{occured} \rangle + \langle N_{background} \rangle$$

$$\langle N_{unwanted} \rangle = \langle N_{min.bias} \rangle + \langle N_{noise} \rangle$$

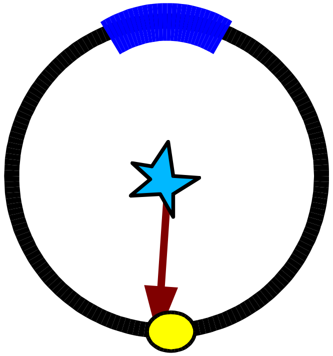
inevitably detected events

from events of type E

from similar but not interesting events of type X

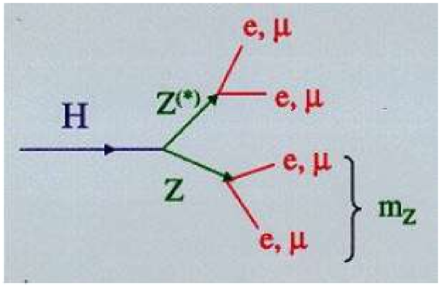
from not interesting events

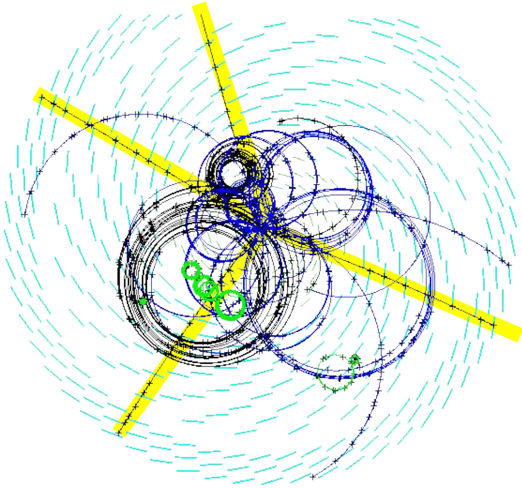
from somewhere else



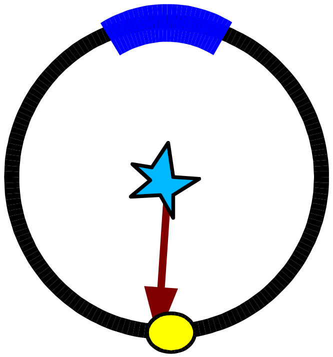
"click"

Signal



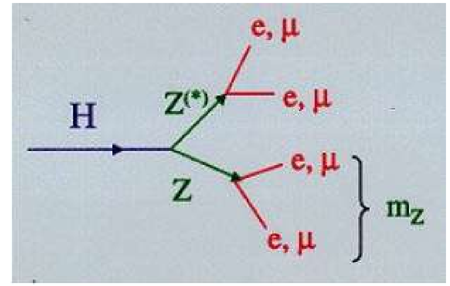


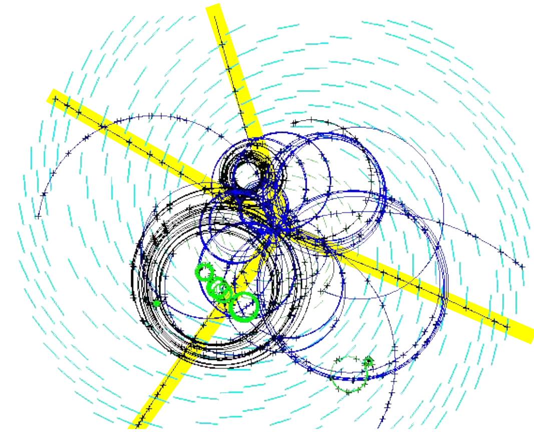
What we wish to measure!



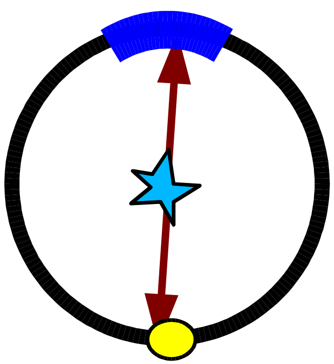
"click"

Signal



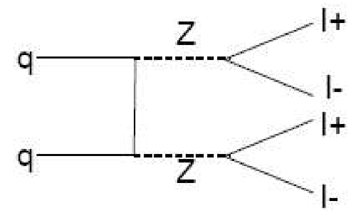


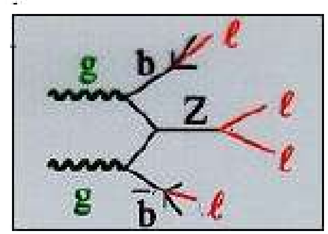
+ What we actually measure ...

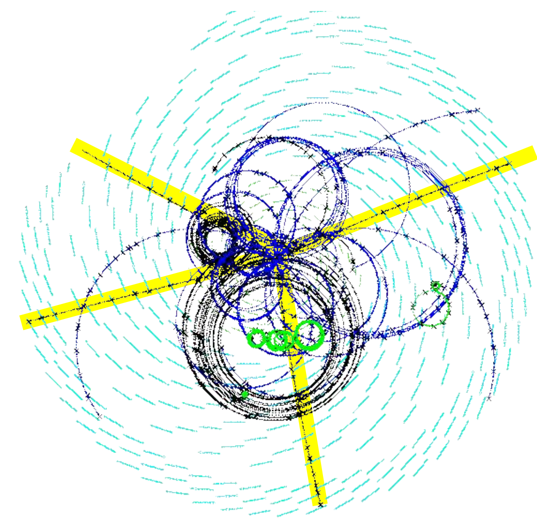


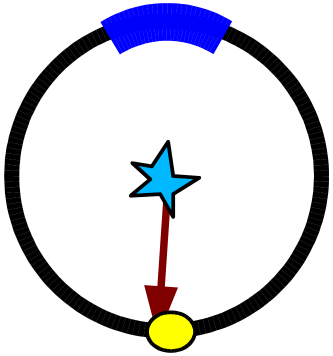
"click"

Back-
ground



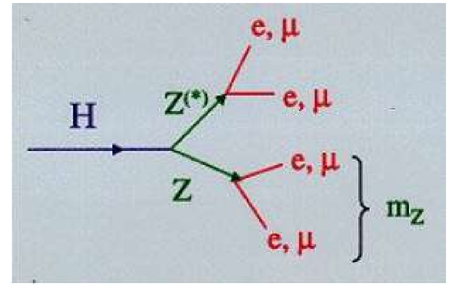


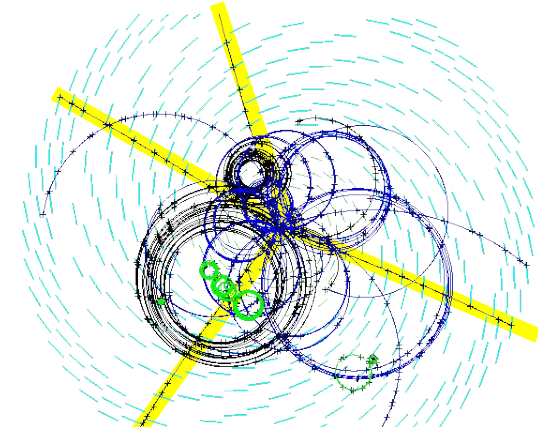




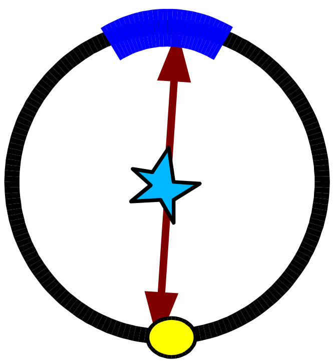
"click"

Signal



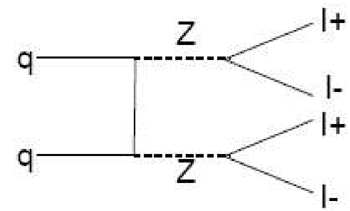


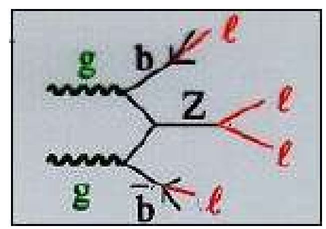
\+ What we actually measure ...

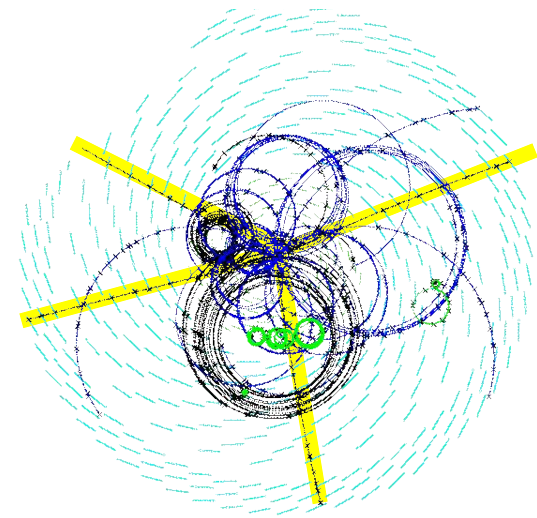


"click"

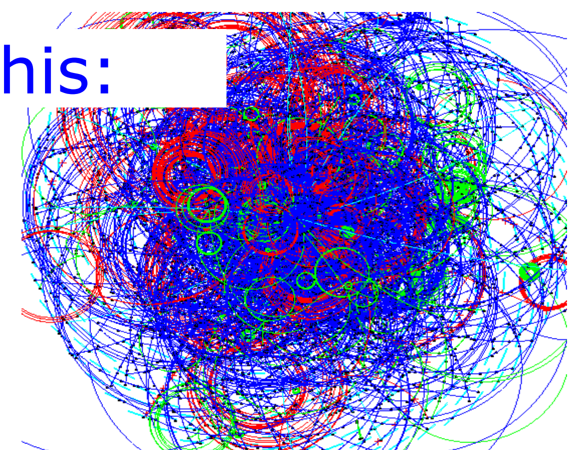
Back-
ground







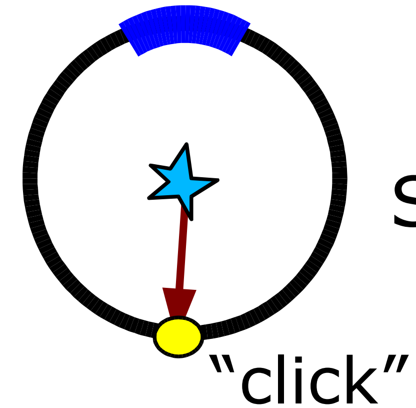
... if we manage to ignore this:



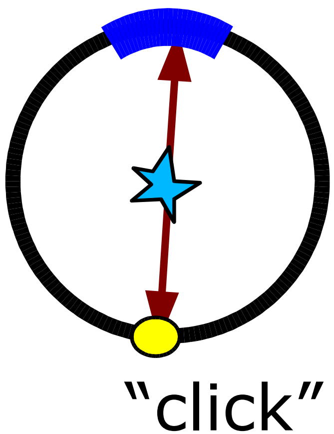
Mickey
was lucky!

= minimal bias events
and noise data

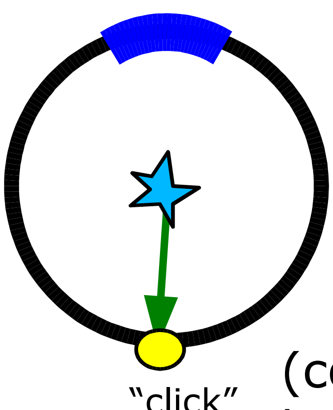
The four types of data



Signal



Back-
ground

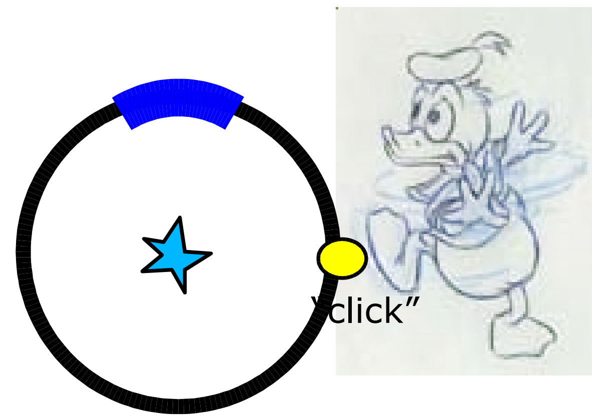


Minimal bias

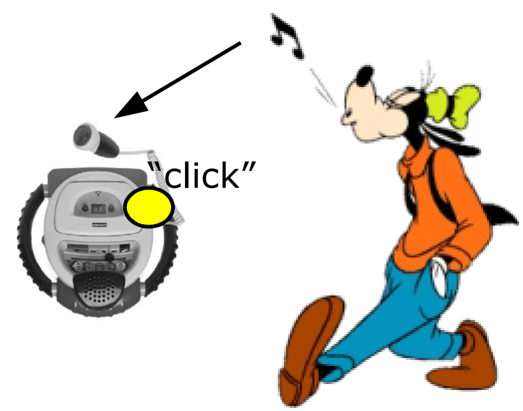
emission of
a "Pianissimon"

(comes from the interaction,
but is not signal nor background)

Noise



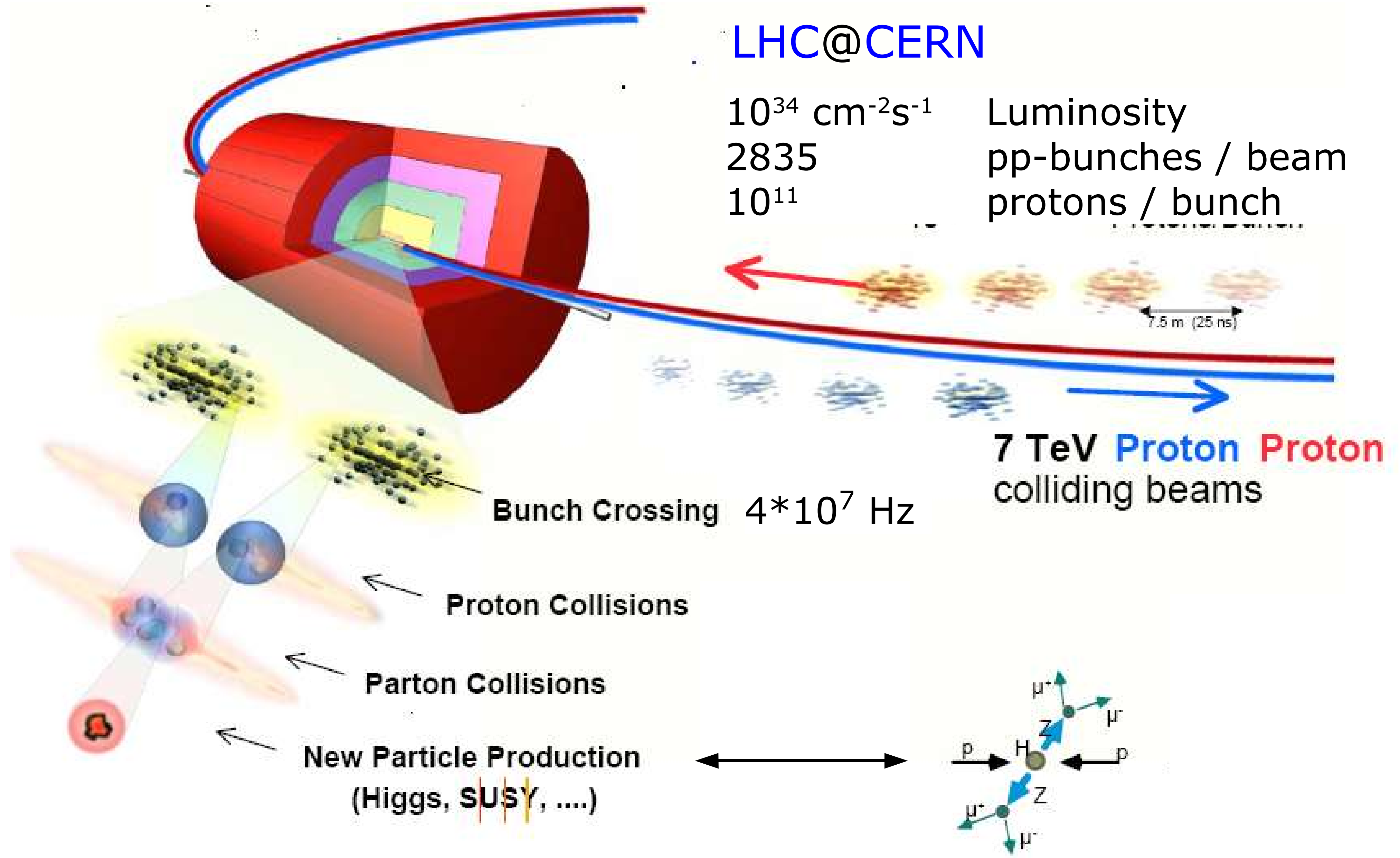
(comes from somewhere else)



Let´s see this for LHC@CERN!

... want to get a feeling of orders of magnitude for signal and background events, to see, why accurate simulations studies are required!

Rare and exotic birds ...



Very simple formula:

luminosity ($cm^{-2}s^{-1}$)

acceptance

$(0 \leq a \leq 1)$

time (s)

number of measured events

$$N(T) = a \cdot \sigma \cdot \int L(t) \cdot dt$$

reaction cross section (cm^2)

number of events measured in the time interval [0,T]

(ignoring background ..)

σ ... cross section: measures the interaction strength of two colliding particles; it depends on the physics nature of the particle collision

L ... Luminosity: measures the crossing rate and beam density; it depends on the accelerator design

luminosity ($cm^{-2}s^{-1}$)

$$N(T) = a \cdot \sigma \cdot \int L(t) \cdot dt$$

reaction cross section (cm^2)

number of events measured in the time interval [0,T]

Interaction Rate

Simply get the time derivative of the number of events!

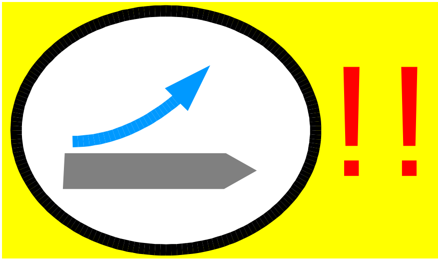
luminosity ($cm^{-2}s^{-1}$)

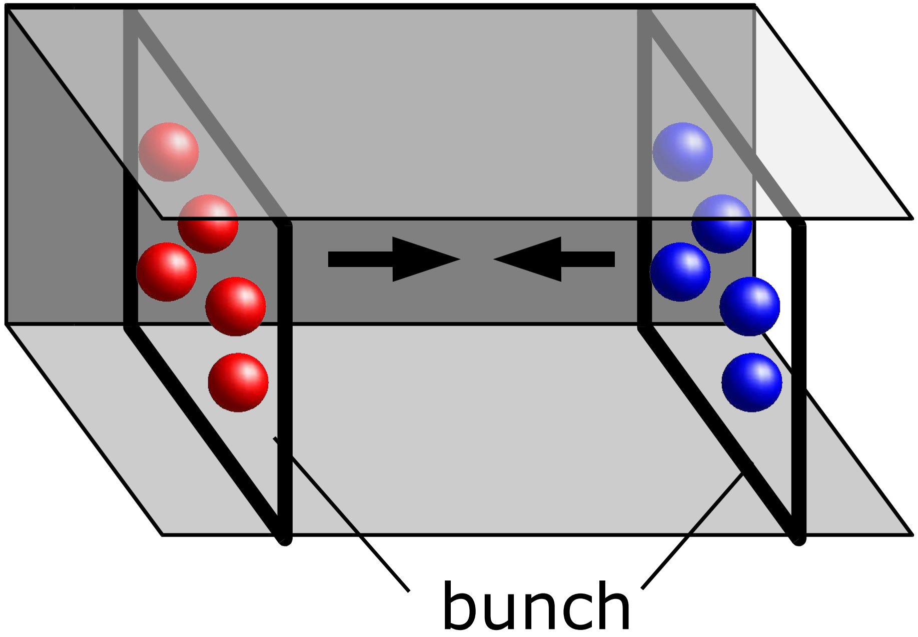
$$\frac{dN(t)}{dt} = \sigma \cdot L(t)$$

reaction cross section (cm^2)

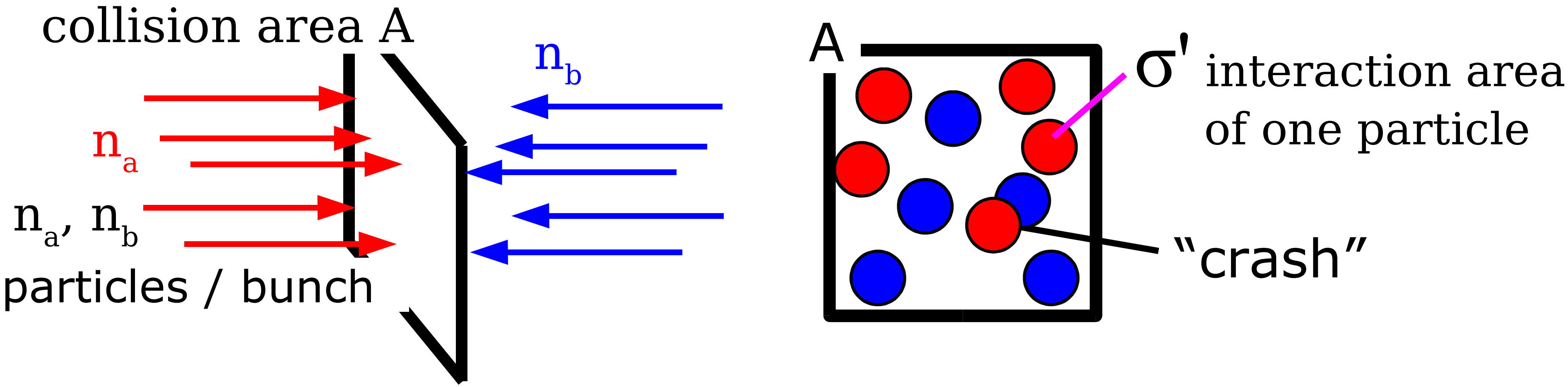
frequency: number of interactions per second

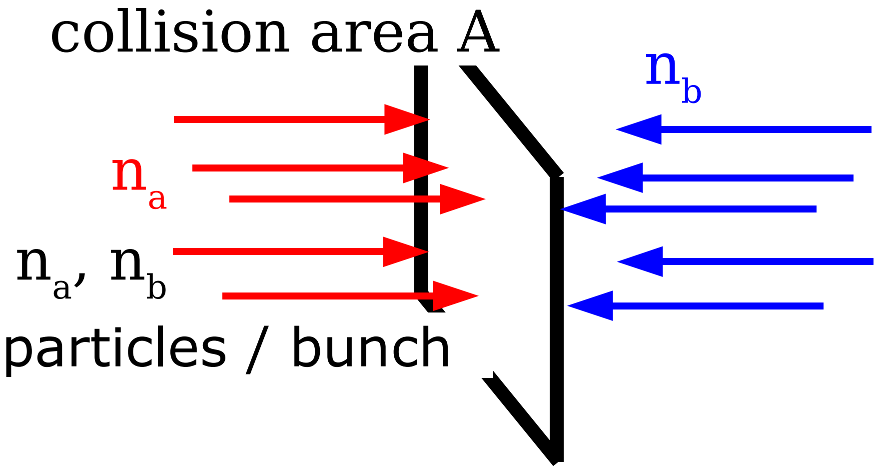
Let´s look at one LHC bunch crossing:

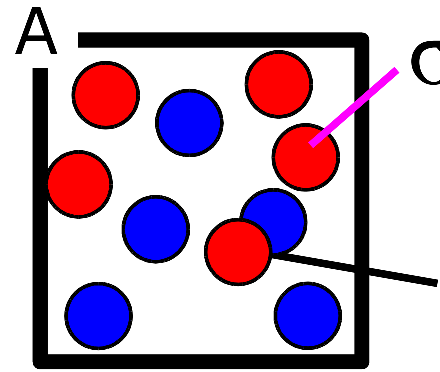




simplification:
all protons of one bunch considered to be in the same plane

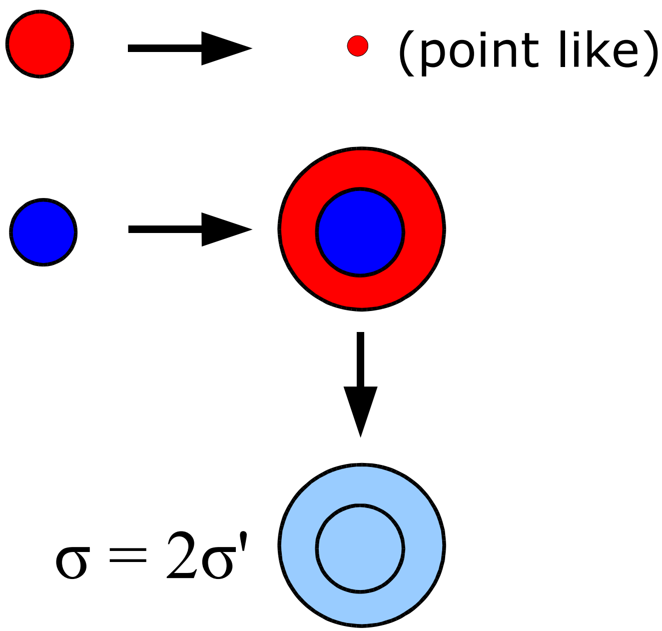


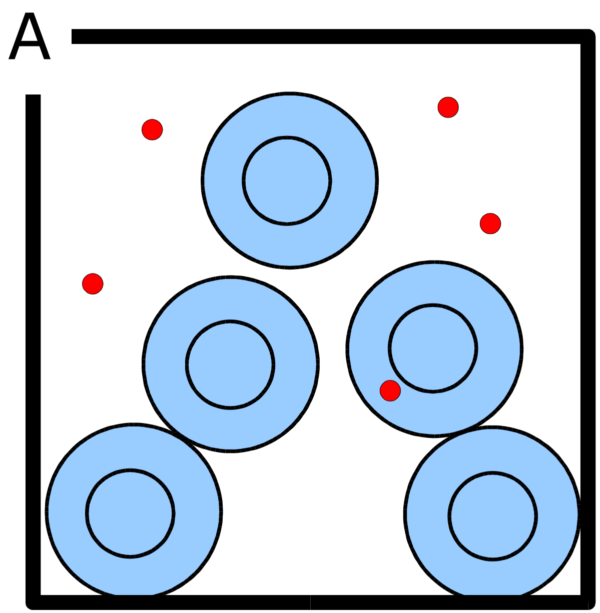




σ' interaction area of one particle

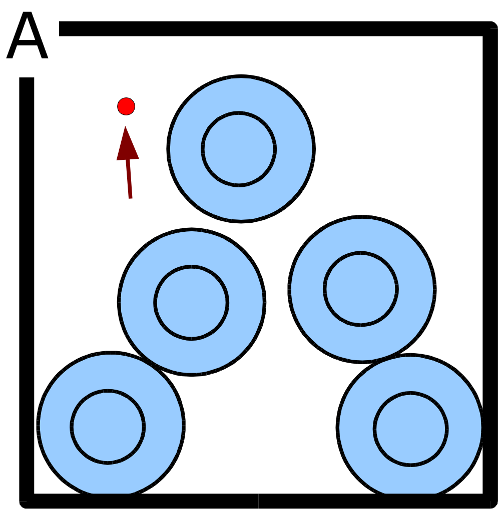
equivalent:





$\sigma = 2\sigma'$ interaction area for a two particle interaction

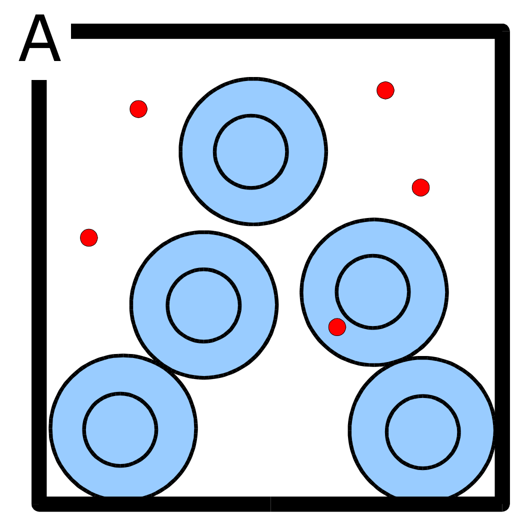
$n_b \cdot \sigma$ ... total interaction area in one bunch crossing



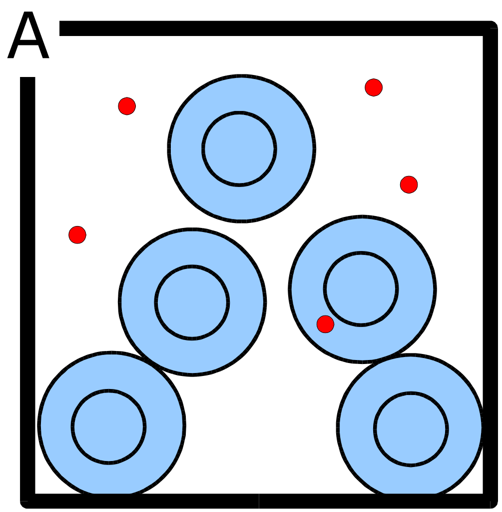
$n_b \cdot \sigma / A$ ... probability **w**, that one red particle will interact with a blue particle in one bunch crossing

average number of collisions with n_a red particles in one bunch crossing is:

$$n = n_a \cdot w = n_a \cdot n_b \cdot \sigma / A$$

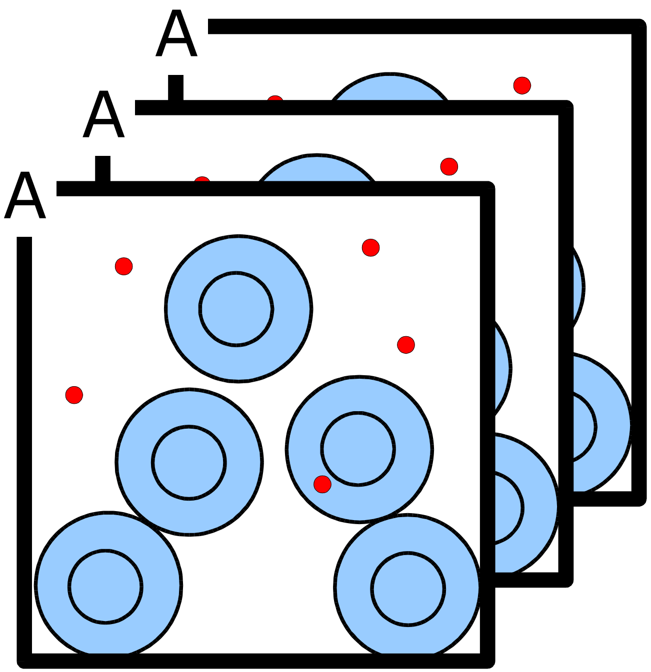


we have f bunch crossings per second:



$n = n_a \cdot w = n_a \cdot n_b \cdot \sigma / A$

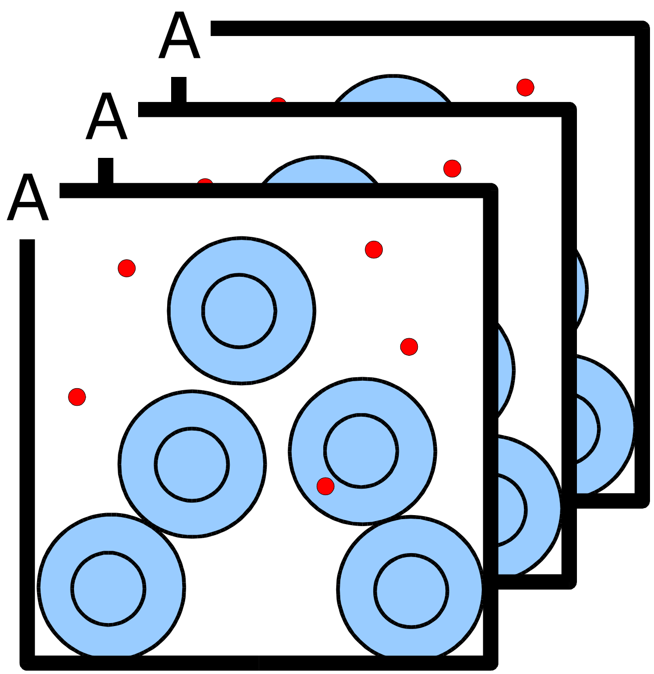
avg. number of interactions per bunch crossing



Interaction rate:

$$\frac{d\,n(t)}{d\,t} = f \cdot n_a \cdot w = \sigma \cdot \underbrace{f \cdot n_a \cdot n_b / A}_{\text{luminosity}}$$

$= \sigma \cdot L$



Interaction rate:

$$\frac{d\,n(t)}{d\,t} = f\cdot n_a\cdot w = f\cdot n_a\cdot n_b\cdot\sigma / A$$

$$= \sigma\cdot L$$, factorization into physics & beam

Luminosity:

$$L = f\cdot n_a\cdot n_b / A$$

defined by beam properties only!

$$N'(t) = \sigma\cdot\int L(t)\cdot dt = \sigma\cdot L\cdot t$$

Number of interactions in the time interval (0, t).

$$N(t) = a\cdot N'(t)$$

acceptance (a)

Number of observed interactions in the time interval (0, t).

LHC@CERN:

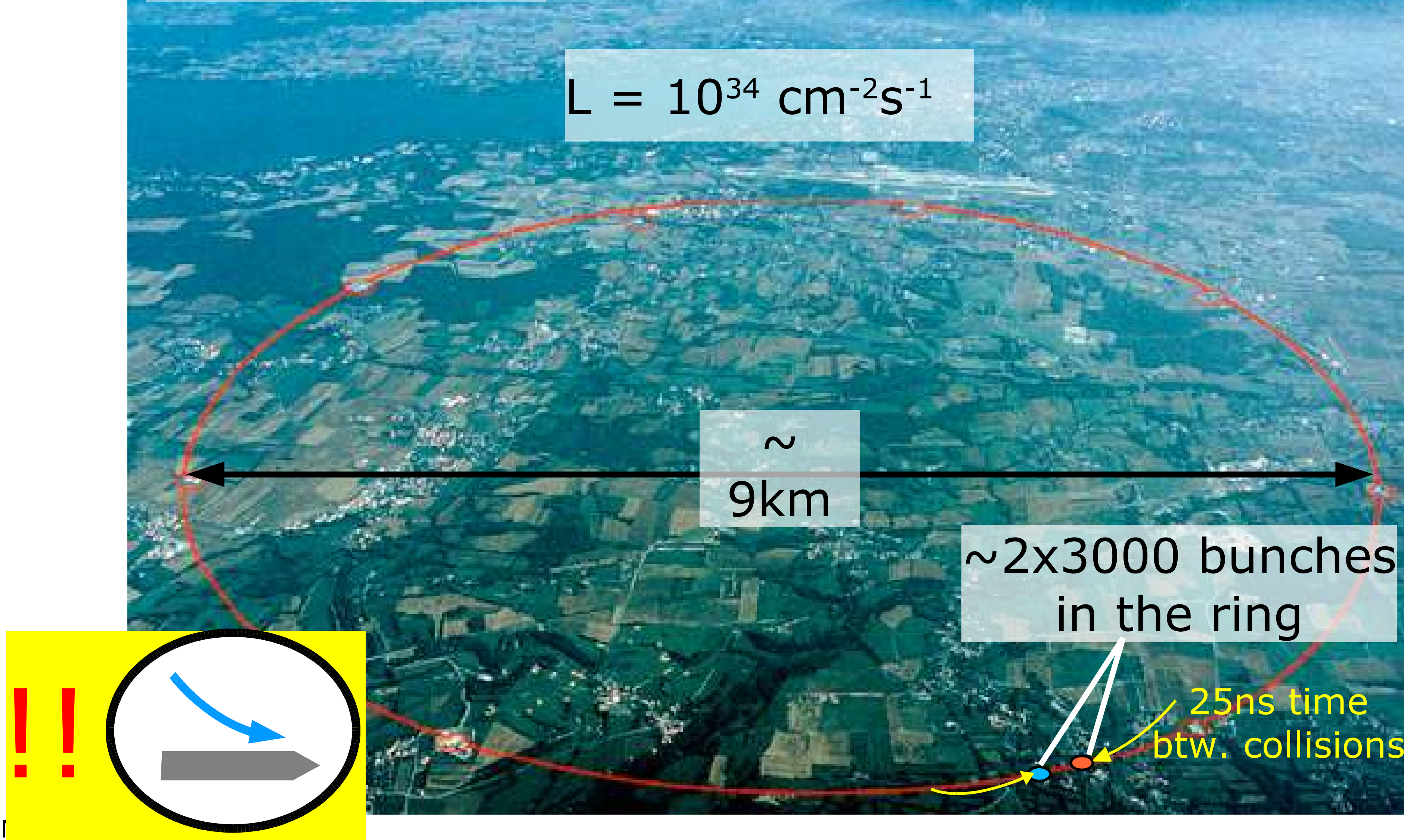
$n_a = n_b \sim 10^{11}$ protons/bunch

Luminosity:

$$L = f \cdot n_a \cdot n_b / A$$

$f = 40$ MHz $= 40 \cdot 10^6$ Hz

$L = 10^{34}\ \mathrm{cm^{-2}s^{-1}}$



Cross Section(s)

Remember? interaction rate: $\frac{d\,n(t)}{d\,t} = \sigma \cdot L$

σ ... total interaction cross section (cm^2, barn, ..)

well known processes

$$\sigma = \sigma_1 + \sigma_2 + \ldots + \sigma_{Higgs}$$

unknown

yet undetermined process(es)

$$\sigma_X = \sigma_X(E, m, \text{“theory”}, \ldots)$$

Remember: theories have unknown parameters ....

Theory → Observables → Experiment → Analysis

(a, b, ..)

Theories have unknown parameters ....

Theory → Observables → Experiment → Analysis
(a, b, ..)

$$\sigma_X = \sigma_X(E, m, \text{“theory”}, \ldots)$$

In HEP, these parameters are determined by the same experiment that should verify/falsify the theory!!

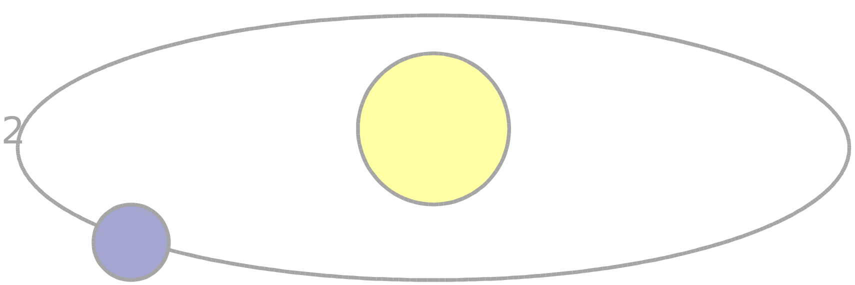
Parameters also mean: experiments must work accurate over the possible ranges of these parameters.

Classical example:

$$F_g = G \frac{m_1 m_2}{r^2}$$

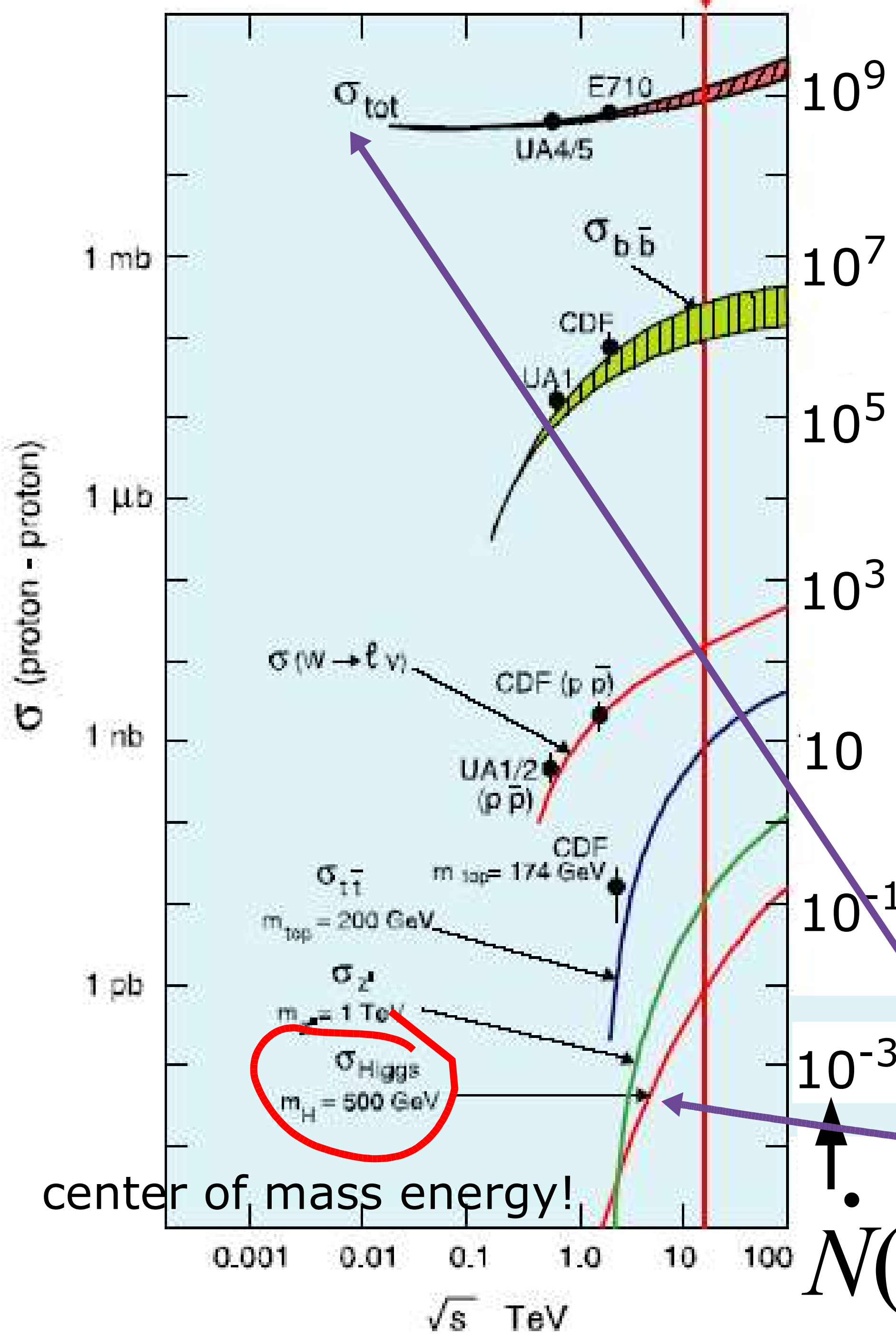
Parameters: G, m_1, m_2

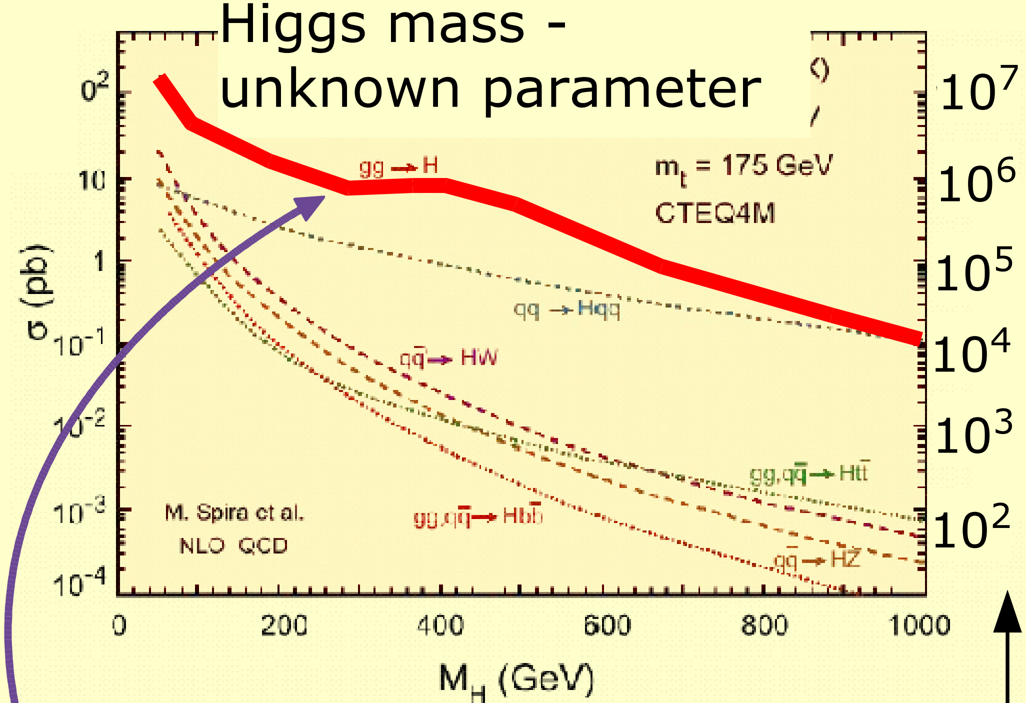
Observables:
revolution time, path,
pendulum freq.



Experiments: pendulum, system earth-sun, moon-earth, ...

1 year LHC at highest $L = 10^{34}\ cm^{-2}s^{-1}$





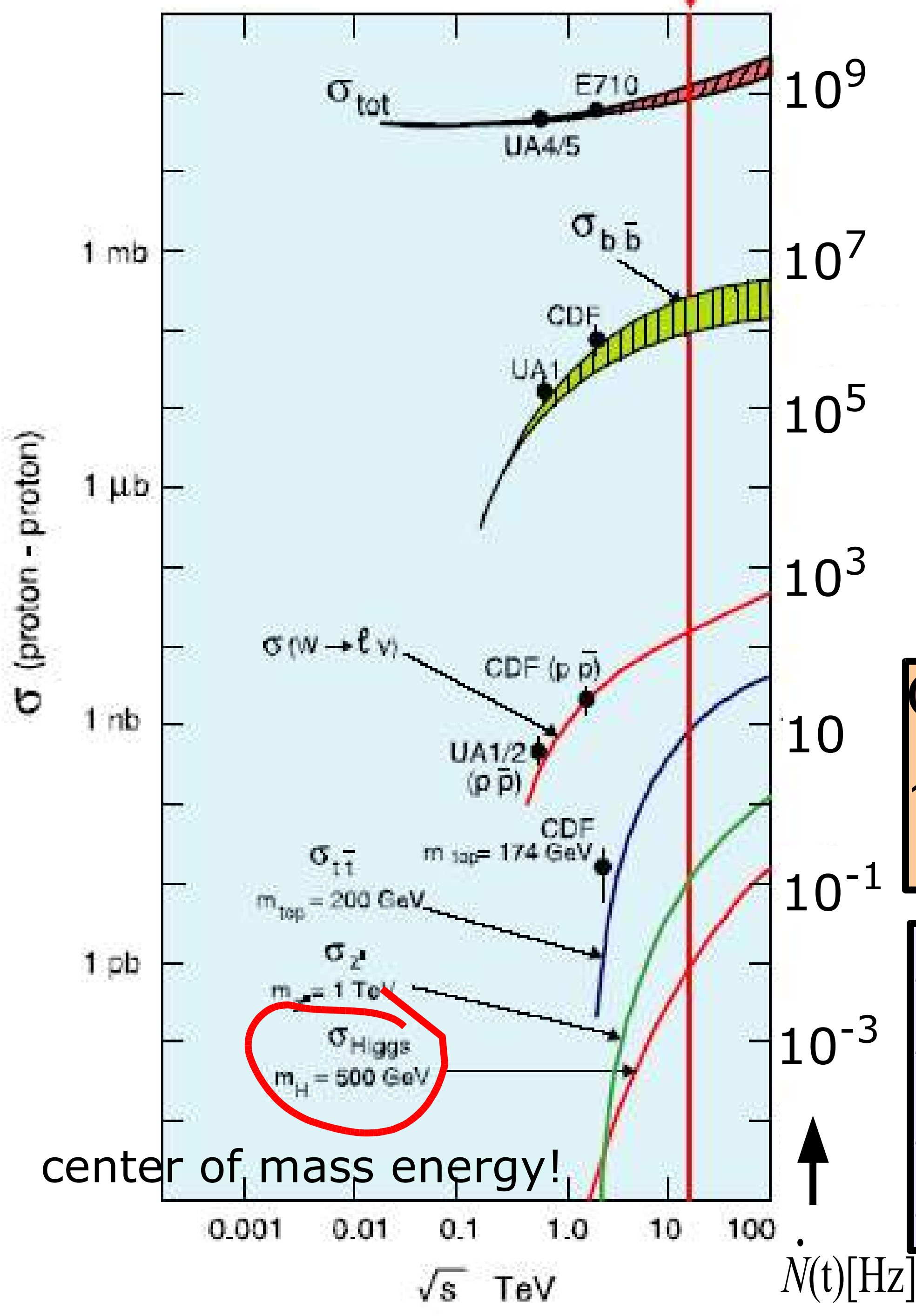
$$N(t) = \sigma \cdot L \cdot t$$

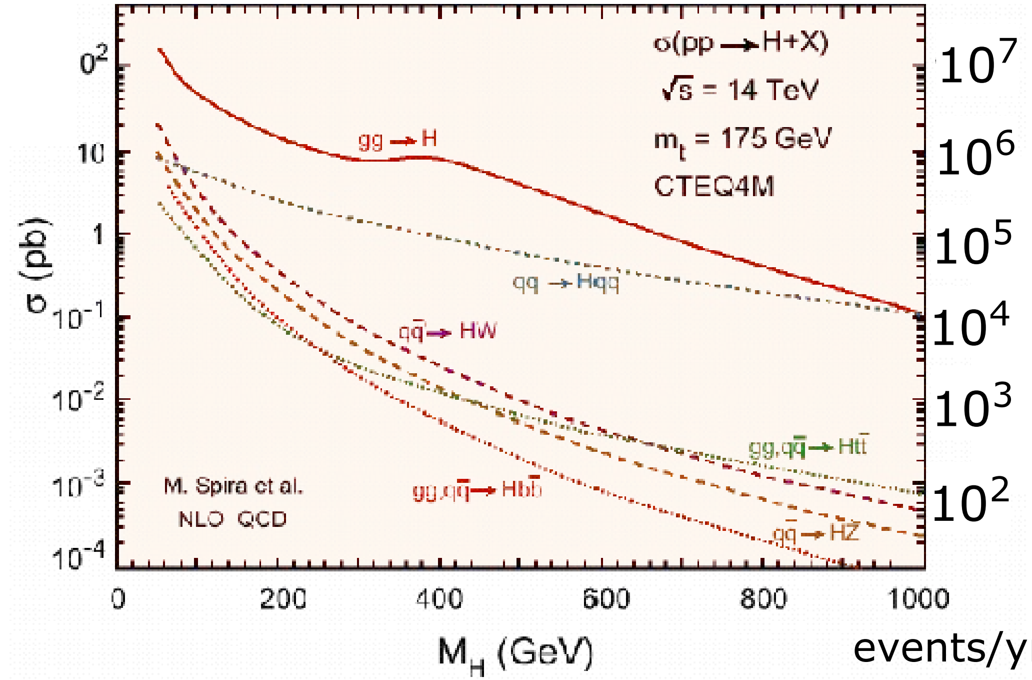
$$\sigma_{Higgs} = \sigma_{Higgs}(m_{Higgs})$$

$$\sigma = \sigma_1 + \sigma_2 + .. + \sigma_{Higgs}$$

$$\dot{N}(t)[Hz] = \sigma \cdot L$$

1 year LHC at highest L = 10^{34} cm^{-2}s^{-1}





Collisions of bunches a ~3000p:

~20 simultaneous interactions every 25ns!

~10^5 Higgs / year

~10^{16} something else / year

~0.01 Higgs per second

~1.000.000.000 Interactions/sec

Observables → Discovery

Because of the quantum character of the physics:
- we talk of event rates
- there is no such a thing than “single measurement of THE Higgs particle”

$$\dot{N}(t) = \sigma \cdot L$$

Count sufficiently enough events of (indirect) decay products of the particle looked for in as many decay channels as possible!

The count must be <u>statistically significant</u> compared to the background noise (5 sigma) to claim “discovery”.

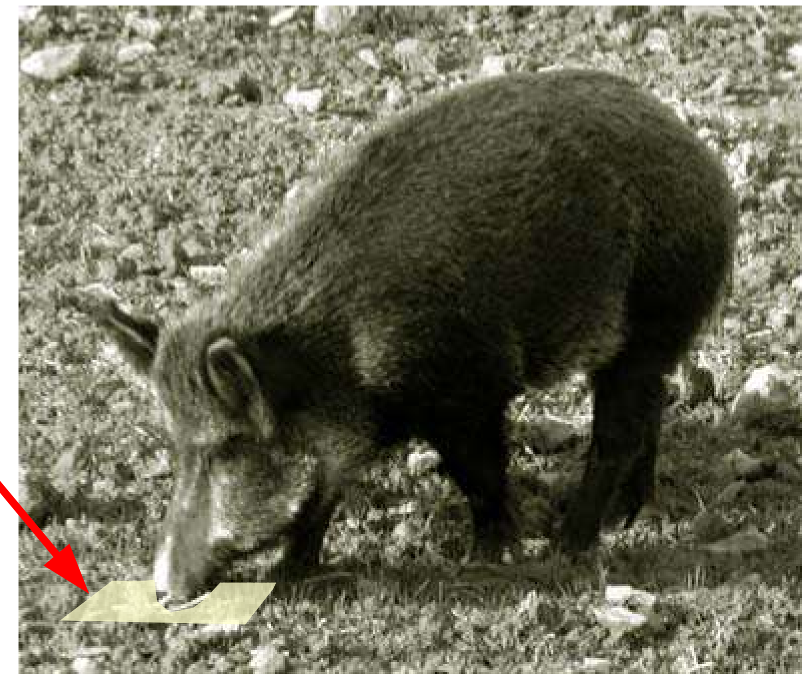
To be <u>really confident</u>:
Discovery in many decay channels, in more than one experiment!

The "Truffles Pig"

~10^5 Higgs / year
~10^{16} something else / year

→ **1** Higgs event in **10^{11}** events

1 event .. $1 dm^2 = 10 \times 10\ cm^2$



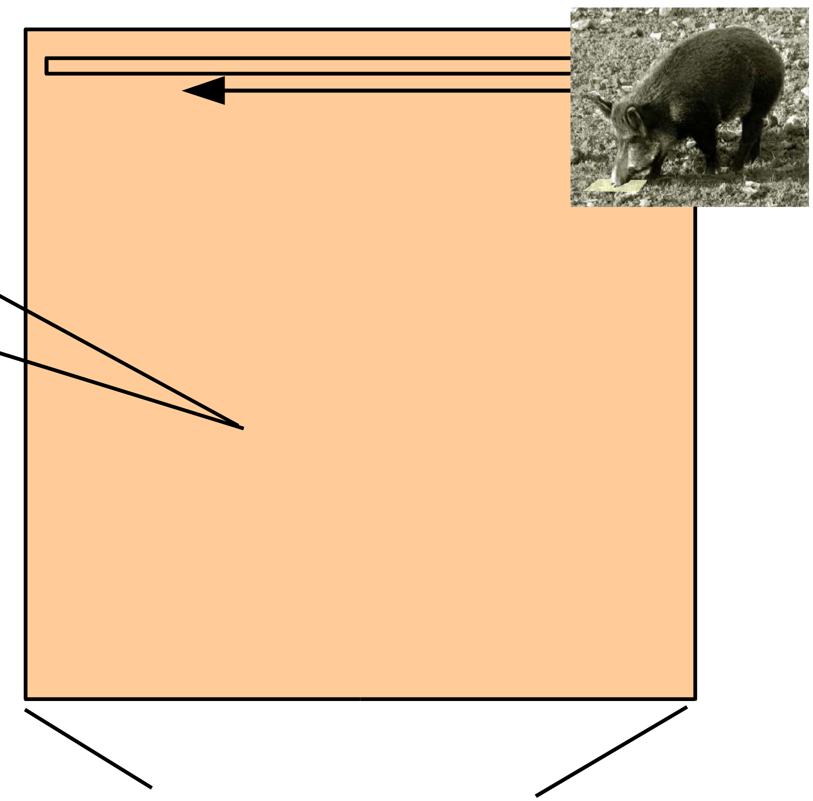
10^{11} events .. $10^{11} dm^2 \sim 3 \cdot 10^5 \times 3 \cdot 10^5\ dm^2$

... just to visualize these numbers ...

The "Truffles Pig"

~10^5 Higgs / year
~10^{16} something else / year

→ **1** Higgs event in **10^{11}** events



1 event …. 10 x 10 cm^2

10^{11} events .. $10^{11} dm^2$ ~
$3\cdot10^5$ x $3\cdot10^5$ dm^2 =
30 x 30 km^2 !!

Find a **1 dm^2** area in a square of **30 x 30 km^2** !

(and search the area in ~1.5 minutes)

... and all this only if the Standard Model Higgs is “real”!

Experiments also search for evidence of other theories beyond the Standard Model:
- even more undefined parameters!!!

... and all this only if the Standard Model Higgs is "real"!

Experiments also search for evidence of other theories beyond the Standard Model:
- even more undefined parameters!!!

Event Simulations ("Generators")

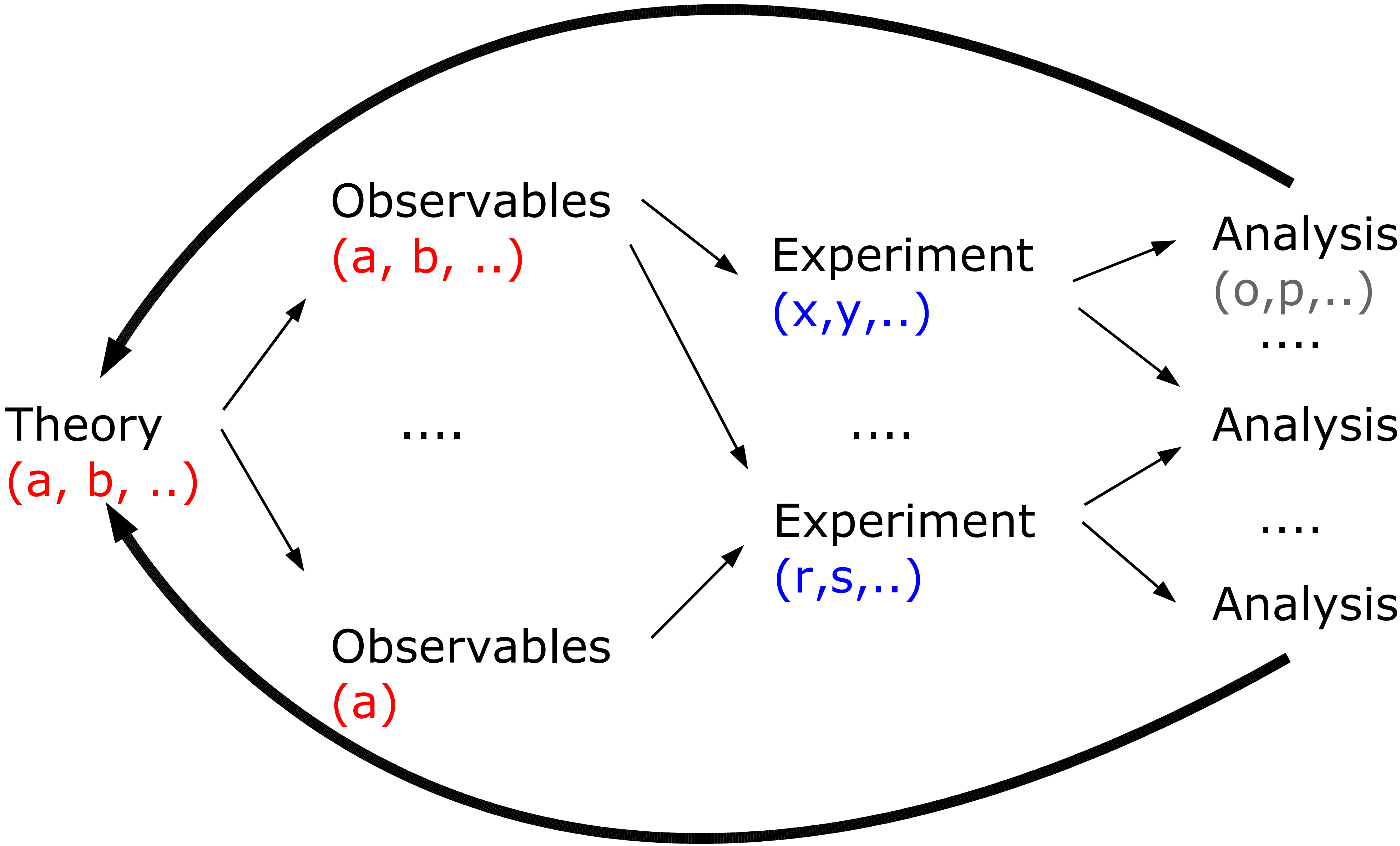
are used to generate amounts of samples of p-p collisions covering the parameter spaces of these theories!

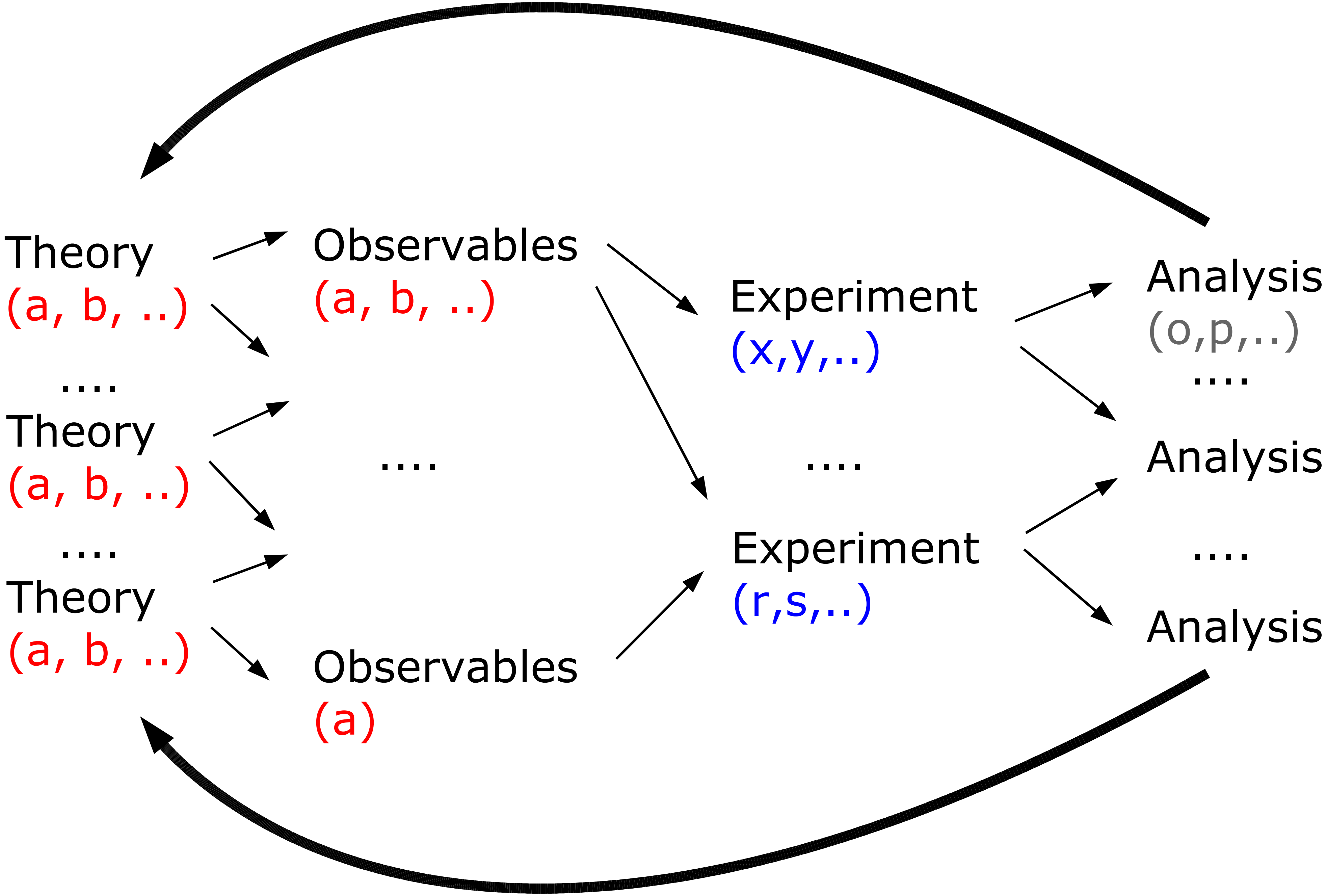
Special sampling methods are applied to correctly mix huge amounts of minimum bias events ("noise") to all the various kinds of signal events ....

We won´t cover Generators here ...

Simulation for ...

- Covering the parameter space of the physics theories to be tested in experiment
  - Various Generator codes exist
  - For LHC: quark-quark interactions up to 14 TeV center of mass energy
- Design, build, and understand detectors
  - Efficiency and acceptance calculations among various design options
  - Various levels:
    - Choice of “sensitve” material and geometrical layout – passage of particles through matter
    - Conversion of particle interactions to electronic measurement signals (ADC, TDC) and then physical quantities – digitization
    - Reconstruction of higher level physical objects (trajcks, energy clusters, ...)


Observables
(a, b, ..)
Experiment
(x,y,..)
Analysis
(o,p,..)
....
Theory
(a, b, ..)
....
....
Analysis
Experiment
(r,s,..)
....
Analysis
Observables
(a)


Theory
(a, b, ..)
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Theory
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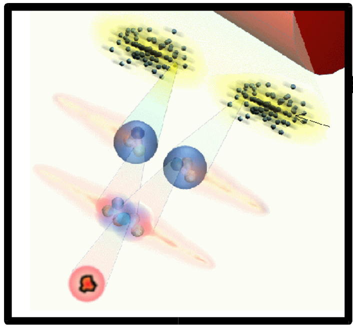
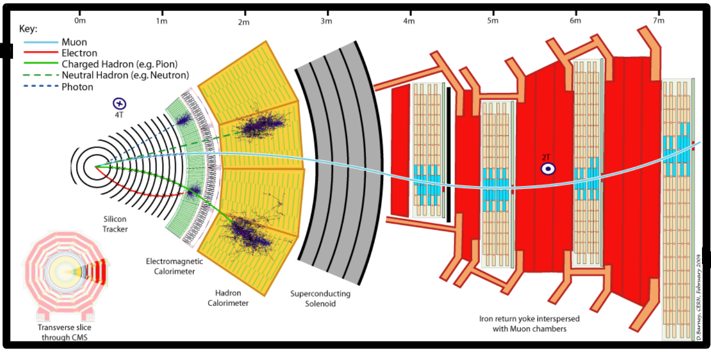




Theory
(a, b, ..)
Generator
....
Theory
(a, b, ..)
Generator
....
Theory
(a, b, ..)
Generator

Observables
(a, b, ..)

....

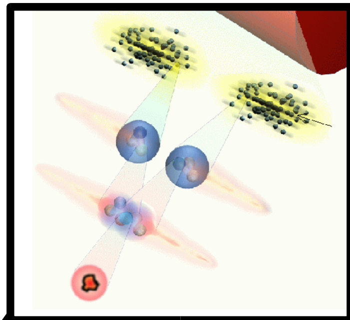
Observables
(a)

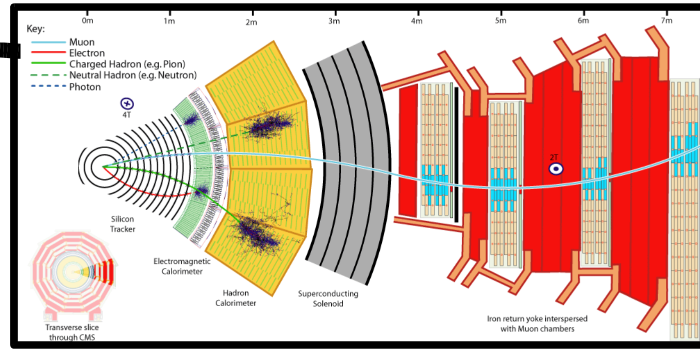
Exp. simulation
Experiment
(x,y,..)

....

Exp. simulation
Experiment
(r,s,..)

Analysis
(o,p,..)
....
Analysis
....
Analysis





Theory
(a, b, ..)
Generator
....
Theory
(a, b, ..)
Generator
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Theory
(a, b, ..)
Generator

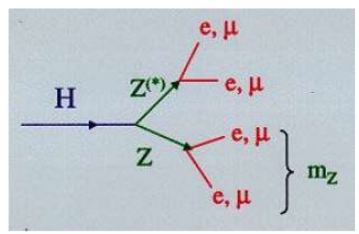
Observables
(a, b, ..)

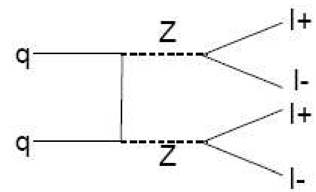
Exp. simulation
Experiment
(x,y,...)

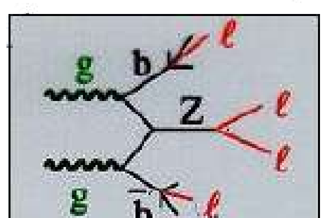
n

Analysis
(o,p,..)
....
Analysis
....
Analysis

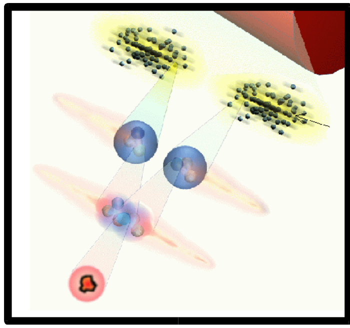
Input

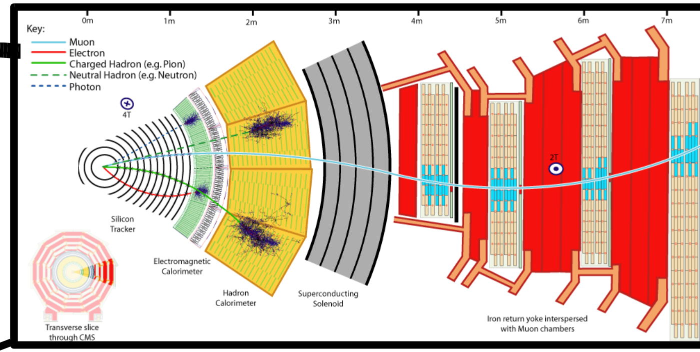






Output





Theory
(a, b, ..)
Generator
....

Observables
(a, b, ..)

Exp. simulation

Experiment
(x,y,..)

Analysis
(o,p,..)
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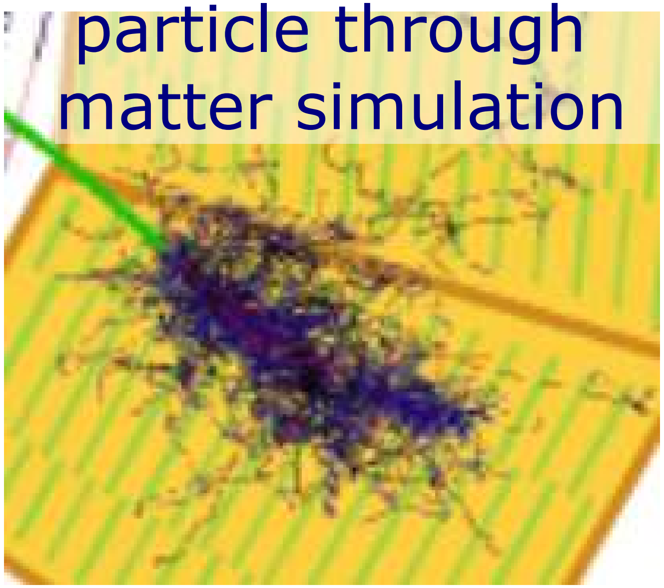
particle through matter simulation



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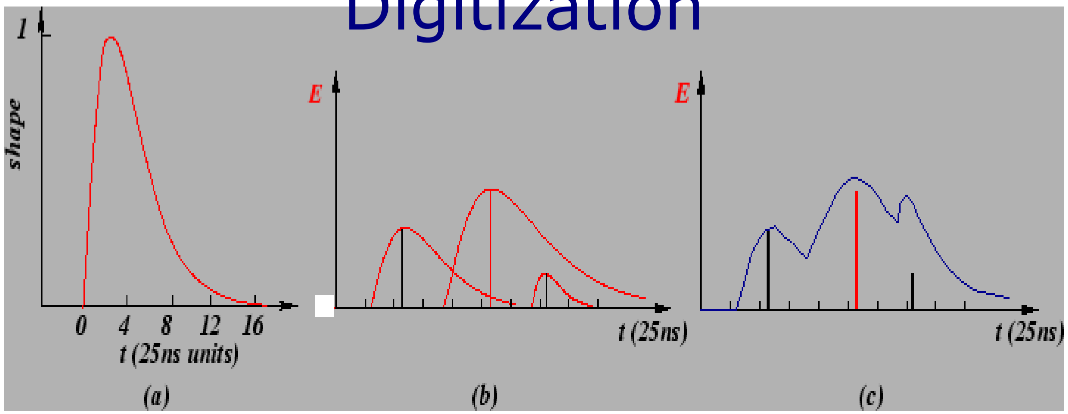
Digitization



signal recorded by electronics
(not in these lectures, highly experiment specific)

GEANT4 – this lectures

What is GEANT4

"Geant4 is a toolkit for simulating the passage of particles through matter. It includes a complete range of functionality including tracking, geometry, physics models and hits." [1]

[1] NIM A506 (2003), 250-303

GEANT comes from GEometry ANd Tracking.

The history of GEANT goes back to the 1970s (CERN)

Official homepage: http://www.cern.ch/geant4

Geant4 is the C++ successor of the FORTRAN Geant3 (and much more).

1994–1998: R&D phase, ~100 scientists from >10 experiments world wide; first production release in 1998; today's (2005) release: GEANT4.7.1
=> more than 10 years of work!!

Areas of application: high energy physics, medical application, space science

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GEANT comes from GEo

The history of GEANT go

Official homepage: http:

Geant4 is the C++ succe

ch more).

So, it's a Pop-Star! ;-)

(Pop ... particles over particles)

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=> more than 10 years of work!!

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Summary -1-

- **Need of simulation**
  - understanding the experiment
  - complexity of physics: generators
  - complexity of detectors:
    - passage of particles through matter (GEANT4)
    - response simulation (elect. measurement signals)
- **Basic design of a collision detector**
  - onion shell design, what is measured where
- **Concept of cross-section**
- **Types of data:**
  - signal and background
  - minimum bias events
  - noise