Karlsruher Institut für Technologie

DESY

Higgs Boson Physics

L05: From Observable to Measurement

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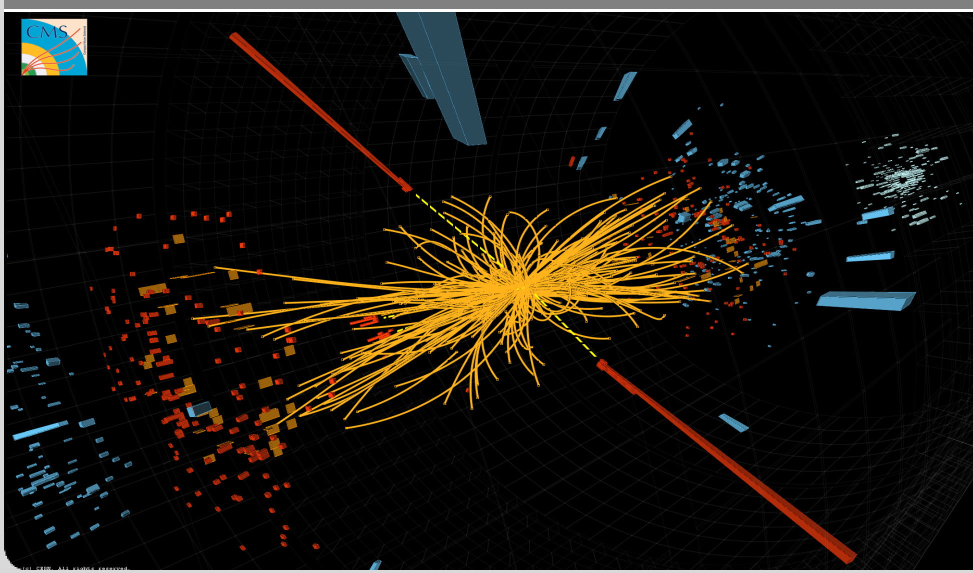
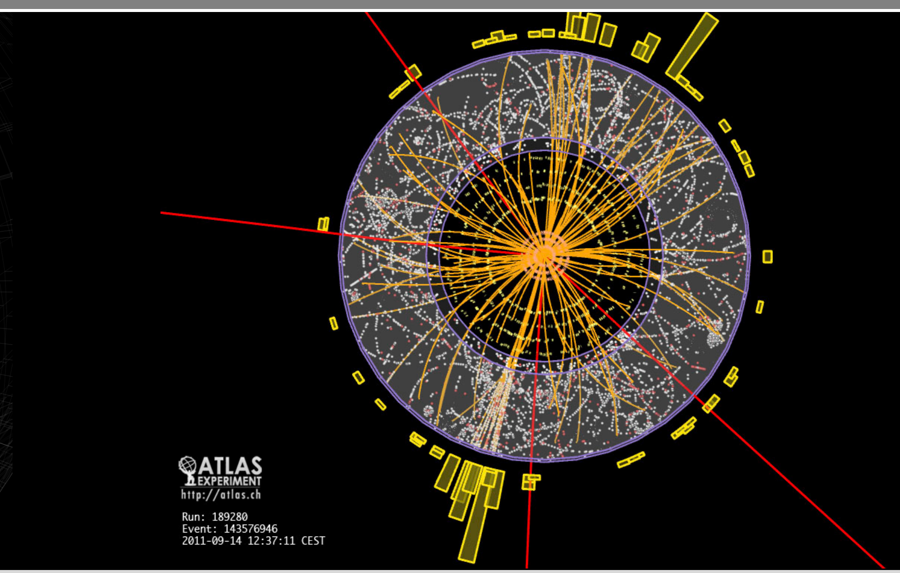
Institut für Experimentelle Kernphysik

Master-Kurs
SS 2015

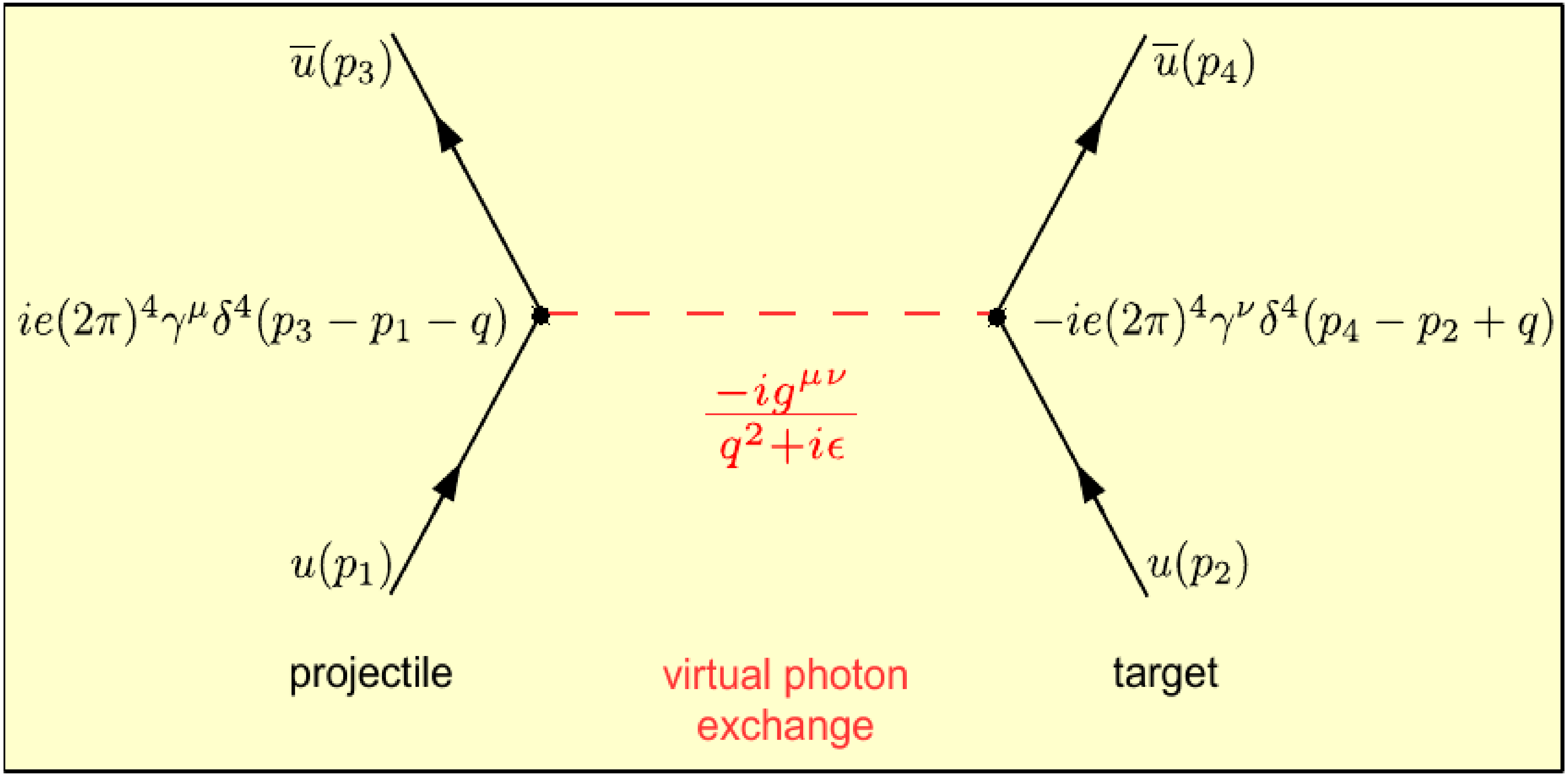




Recap last lecture

Matrix element S_{fi} from Feynman Diagram:

$$i \cdot e^2 \int \frac{d^4q}{(2\pi)^4} (2\pi)^4 \overline{u}(p_3)\gamma_\mu u(p_1)\delta^4(p_3-p_1-q)\frac{-g^{\mu\nu}}{q^2+i\epsilon}\delta^4(p_4-p_2+q)(2\pi)^4\overline{u}(p_4)\gamma_\nu u(p_2)$$



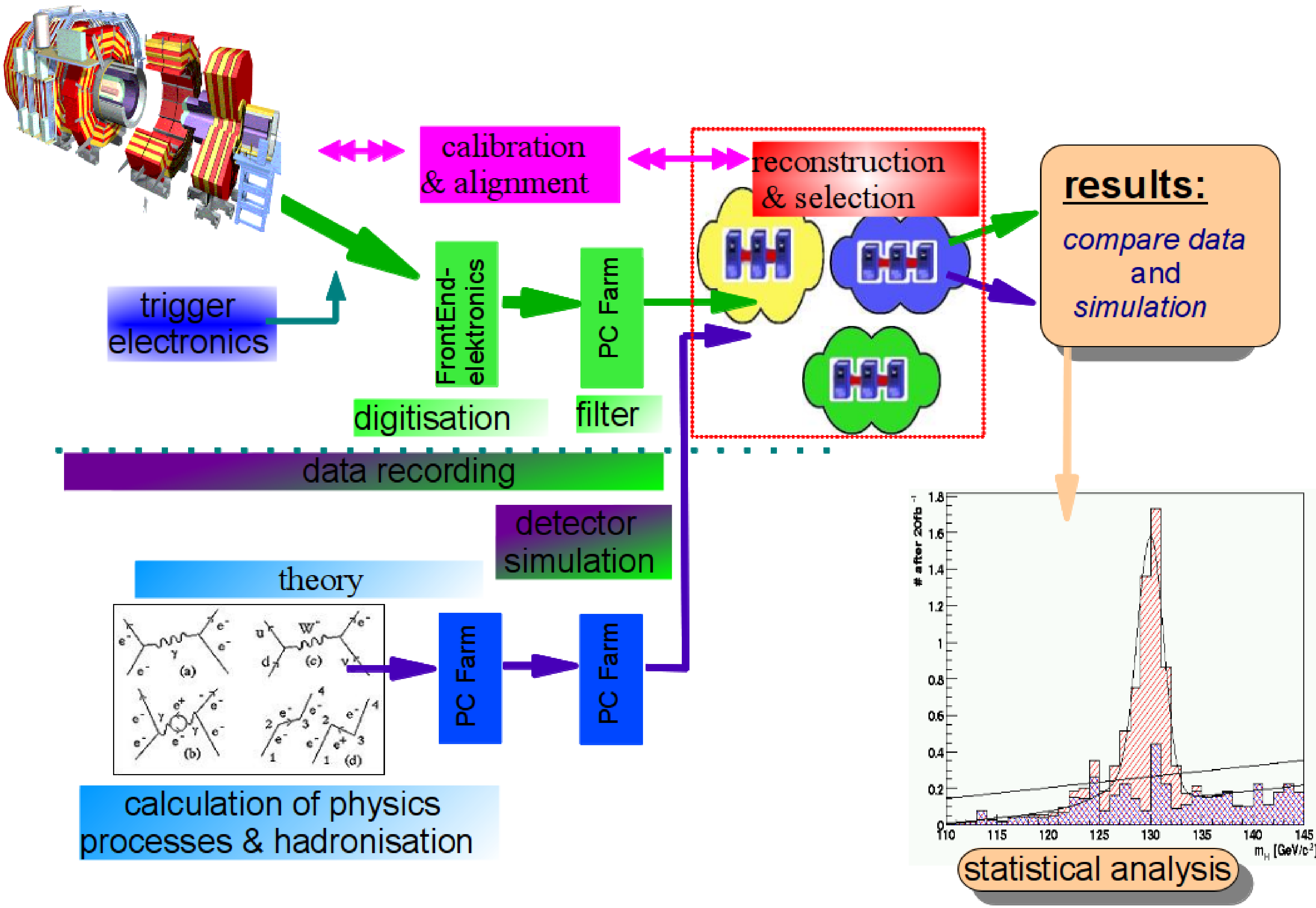
will come back to other topics of last lecture (higher orders) later

Lecture 5

The simulation chain

from S_{fi} to a representation of real data

Overview: Components of Analysis Chain



Components of Analysis Chain

- **Digitizers** record data from detector cells
  - remove empty cells („zero-suppression“ and „noise reduction“
- **Trigger** and **Filter** select „interesting“ events „on-line“
  to be stored for „off-line“ analysis
  (events not stored at this point are lost forever !)
- **Reconstruction** process constructs physical objects
  (electrons, muons, jets, …)
  (this and subsequent steps can be repeated many times)
- **Pre-selection** identifies interesting events and objects in
  events for further processing and analysis
- **Analysis** compares measured distributions with
  theoretical expectations

Experiment

Theory

- **theoretical calculation** of production cross sections
- **hadronisation** of quarks and gluons into jets

- **Detector simulation**

same reconstruction, selection and analysis steps
for simulated events as for real events

The Observable:

the differential cross section

cross section:

transition rate initial → final state

in theory	experimentally

Fermi's golden rule

$$\lambda_{i\to f} = 2\pi |M_{fi}|^2 \rho$$

amplitude or "matrix element" of underlying process

phase space

Cross Section

$$\sigma = \frac{|\mathcal{M}|^2 \cdot [\text{Phase space}]}{[\text{Colliding particle flux}]}$$

$$\sigma = \frac{N_{cand} - N_{bkg}}{\epsilon \cdot f} \frac{1}{T}$$

$\mathrm{N_{cand}}$: number of observed events
N_{bkd} : number of expected background events
ϵ : acceptance · efficiency
f : flux
T : measurement time

Calculation of differential cross sections

want to understand

$$\mathcal{L}_{int} \quad \rightarrow \text{final states}$$

and predict measurable quantities

$$\frac{\partial \sigma}{\partial O_i} \quad = \text{differential cross section}$$

O_i: type,
direction of flight (e.g. azimuthal angle and rapidity)
energy or momentum,
invariant mass of (groups of)
…
final state particles

Rapidity and invariant cross section

In particle reactions, use rapidity, **y**, w.r.t the line of collision of the incident particles: (instead of polar angle θ):

$$y = \tanh^{-1}\beta_z = \frac{1}{2}\ln\left(\frac{1+\beta_z}{1-\beta_z}\right) = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

$$\beta_z = \frac{v_z}{c}$$ is the component parallel to z axis

relation y ↔ β is similar as
α (the angel between a straight line and the x axis) ↔ s (the slope, with α = $\tan^{-1}$(s)):

- angles or rapidities are additive, slopes or (relativistic) velocities are not
  (two subsequent rotations or Lorentz boosts)
- upon a global rotation or Lorentz boost of the coordinate system,
  difference in angles or rapidities remain constant

At hadron colliders,
where the centre-of-mass system of a collision is not at rest,
y is the proper variable

pseudo-rapidity for massless particles: $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$

note: η is easy to measure, y is not !

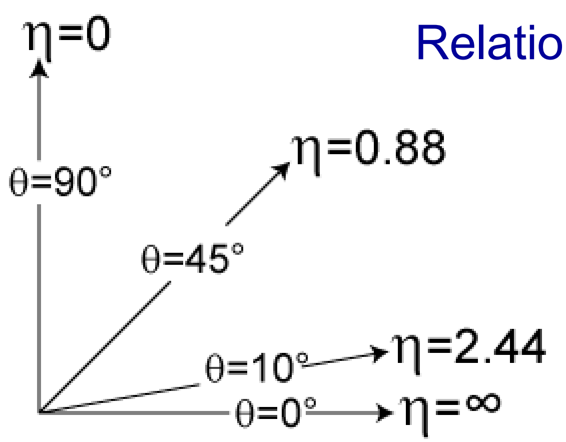
Rapidity and invariant cross section (2)

As a consequence of the above (dy being Lorentz-invariant w.r.t. boosts in z),

$$\frac{d\sigma}{dy}, \frac{d\sigma}{d\phi} \text{ and hence the double-differential cross section } \frac{d^2\sigma}{dy\, d\phi}$$

are Lorentz-invariant w.r.t. boosts in z

$$\frac{d\sigma}{d\eta}$$ is invariant for high-energetic particles with negligible rest mass



Relation between

polar angle (Θ) and

pseudo rapidity (η)

Source: Wikipedia

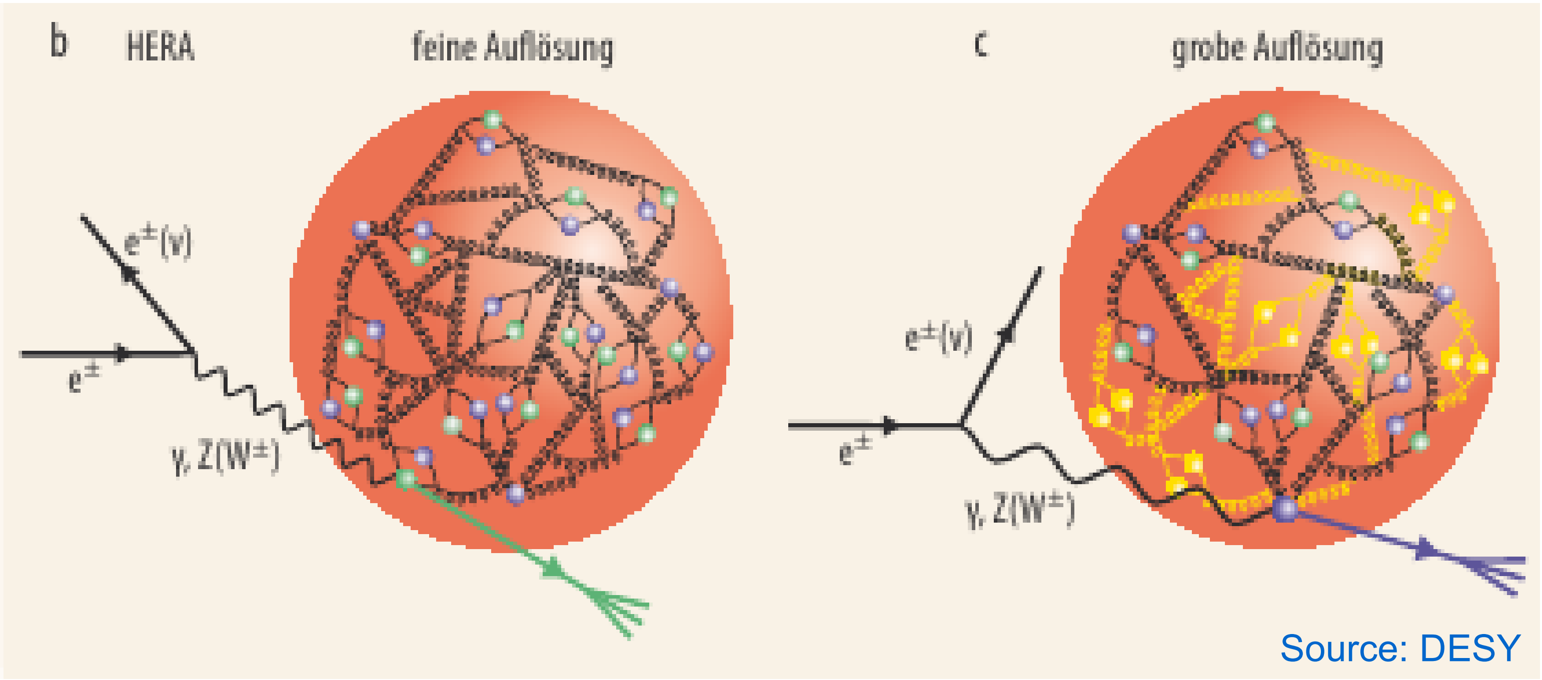
Monte-Carlo Generators

Reprise: the Proton

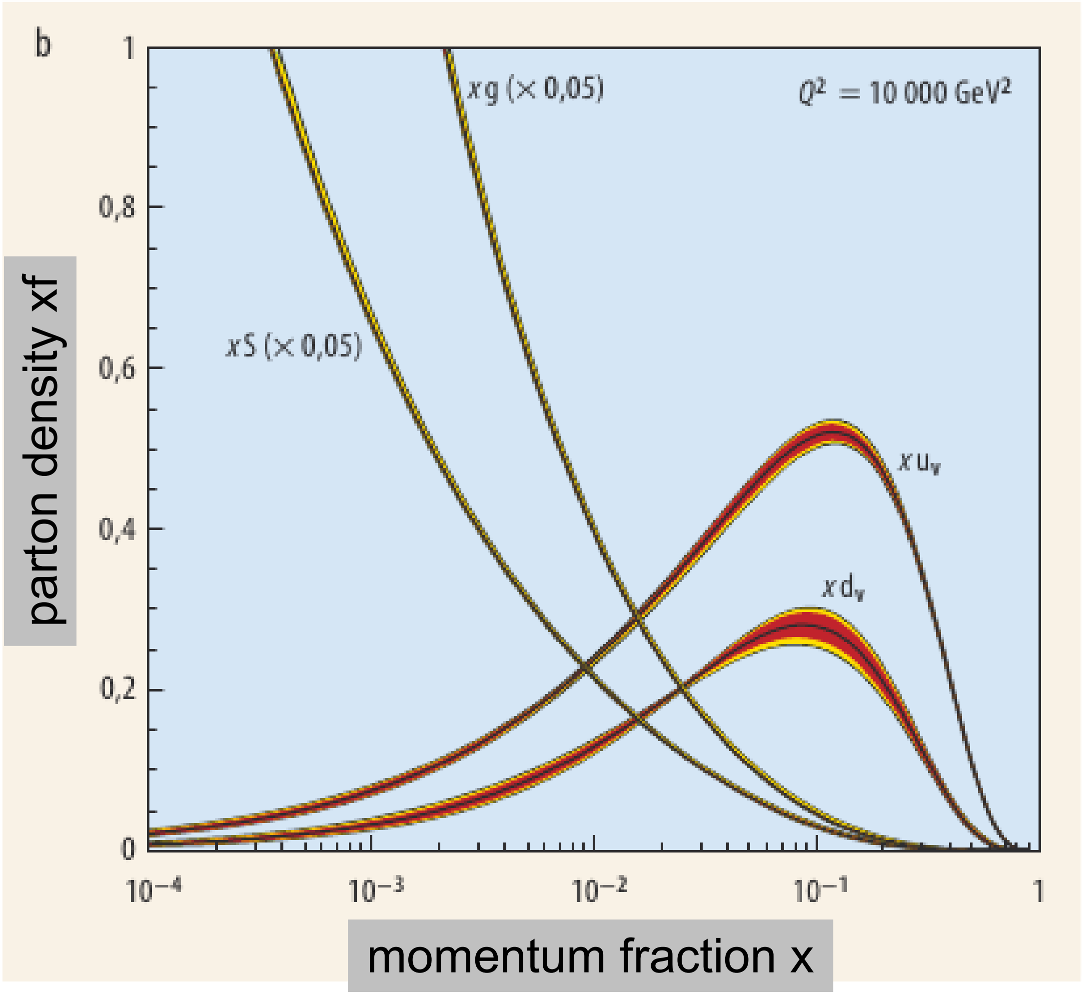
in fact, the proton is complicated:

composed of
- **valence quarks**
- **sea quarks**
- **gluons** (carry 50% of momentum)

Precision study of proton composition in electron-proton scattering
HERA at DESY in Hamburg



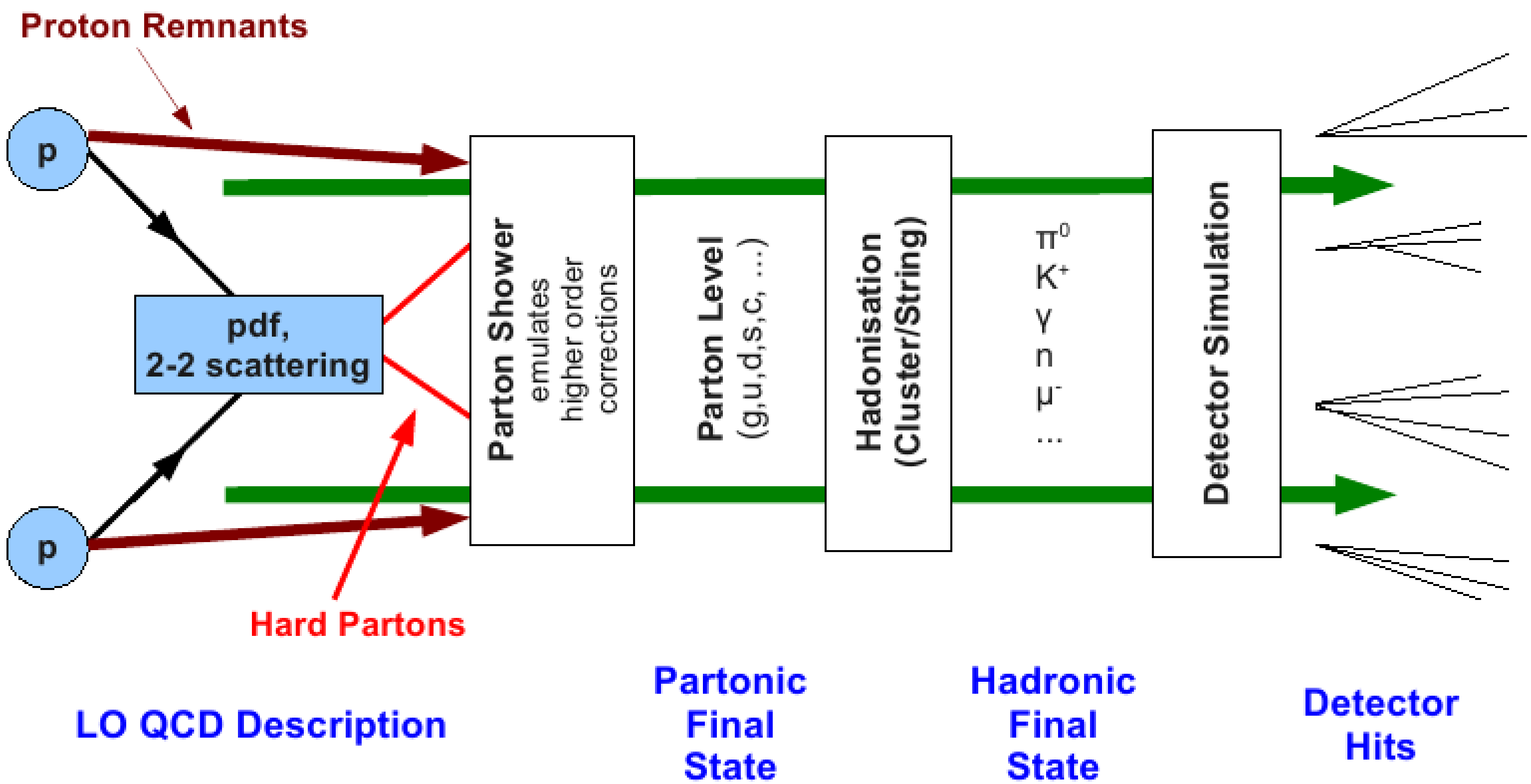
Reprise: Structure Functions



Parton Densitiy Functions (PDFs) have to be taken into account when calculating cross sections at hadron colliders.

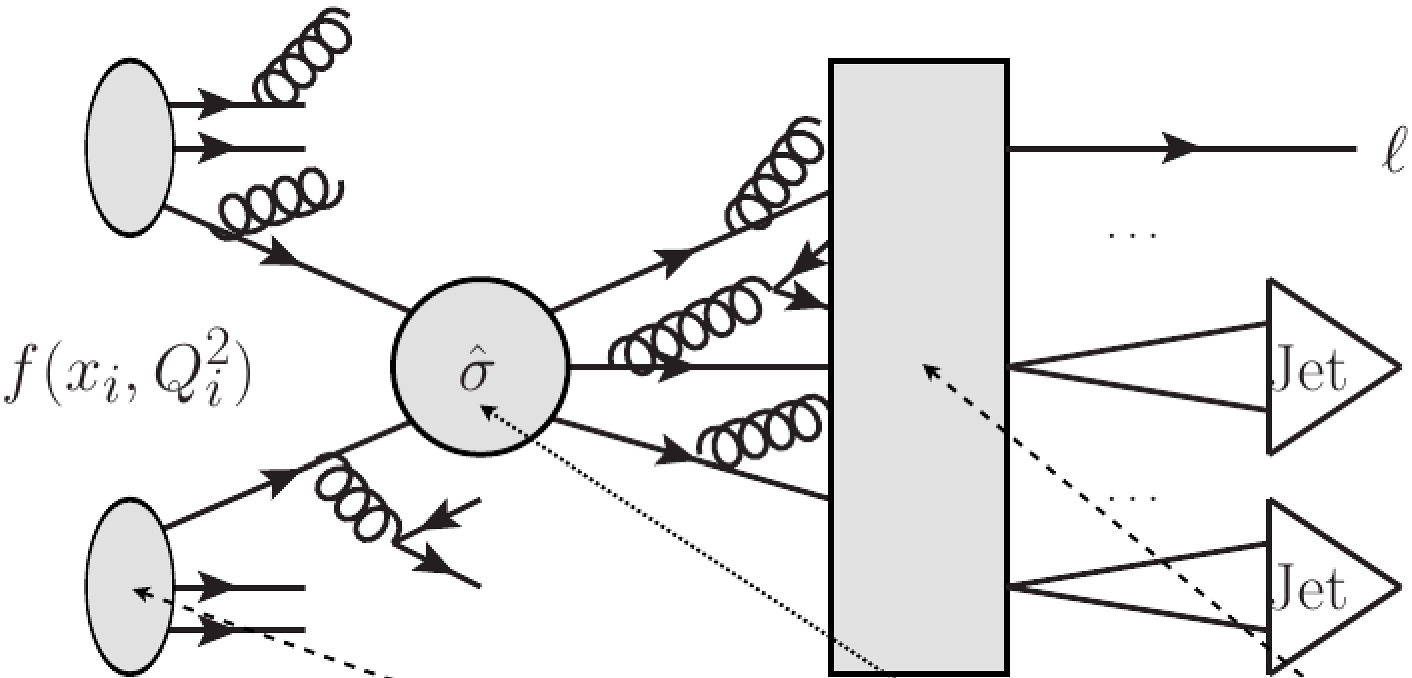
see, e.g., Courses Particle Physics II – Jet Physics

pp → final state is a multi-step process



Calculation of Cross sections

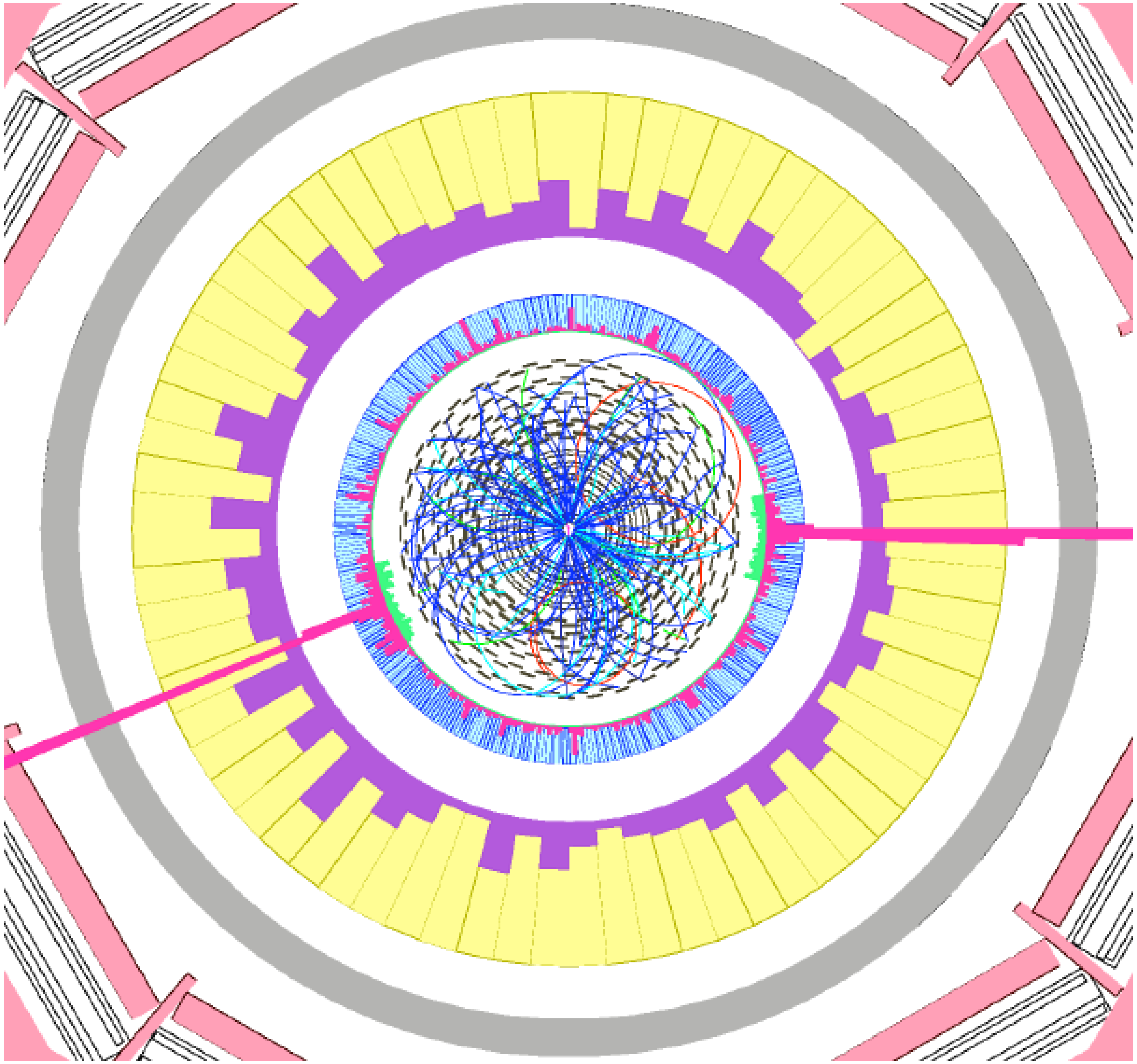
σ = PDFs ⊗ 2→n process ⊗ hadroniszation



$$\sigma_{QCD} = \sum_{jk} \int dx_j\, dx_k\, f_j(x_j, \mu_F^2)\, f_k(x_k, \mu_F^2) \cdot \hat{\sigma}(x_j x_k s, \mu_F^2, \mu_R^2) \otimes \text{hadronization}$$

Complicated process – use MC techniques to calculate cross sections, phenomenological modes to describe hadronization process (quarks → jets)

Example: simulated Higgs Decay in CMS



Can you see the Higgs?

Monte Carlo Generators: School

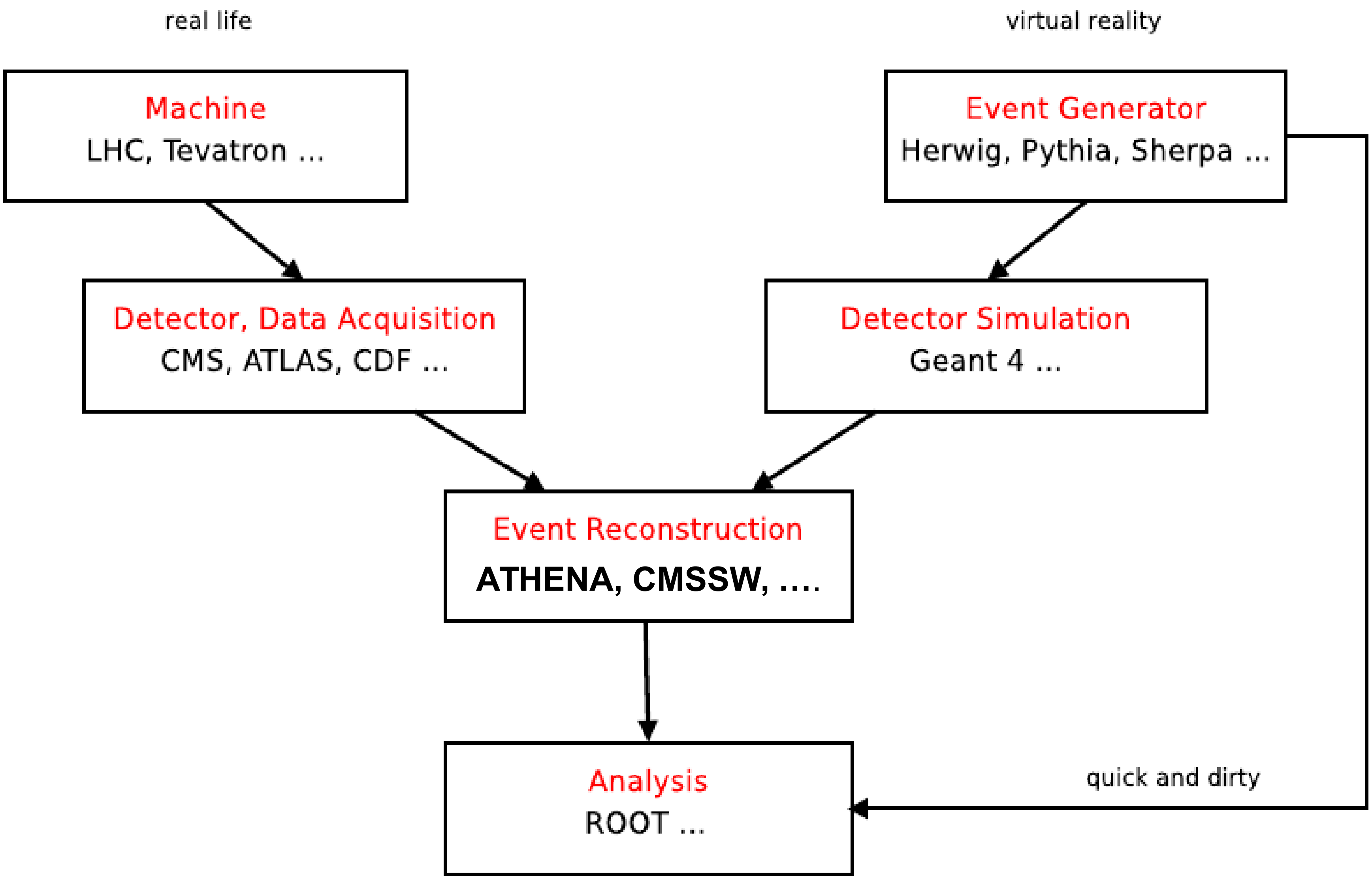
nice lecture, much more detailed than what can be shown here:

Monte Carlo School 2012, Helmholtz Alliance „Physcis at the Terascale“
lecture by Stefan Giesecke, KIT

Technique in particle physics:

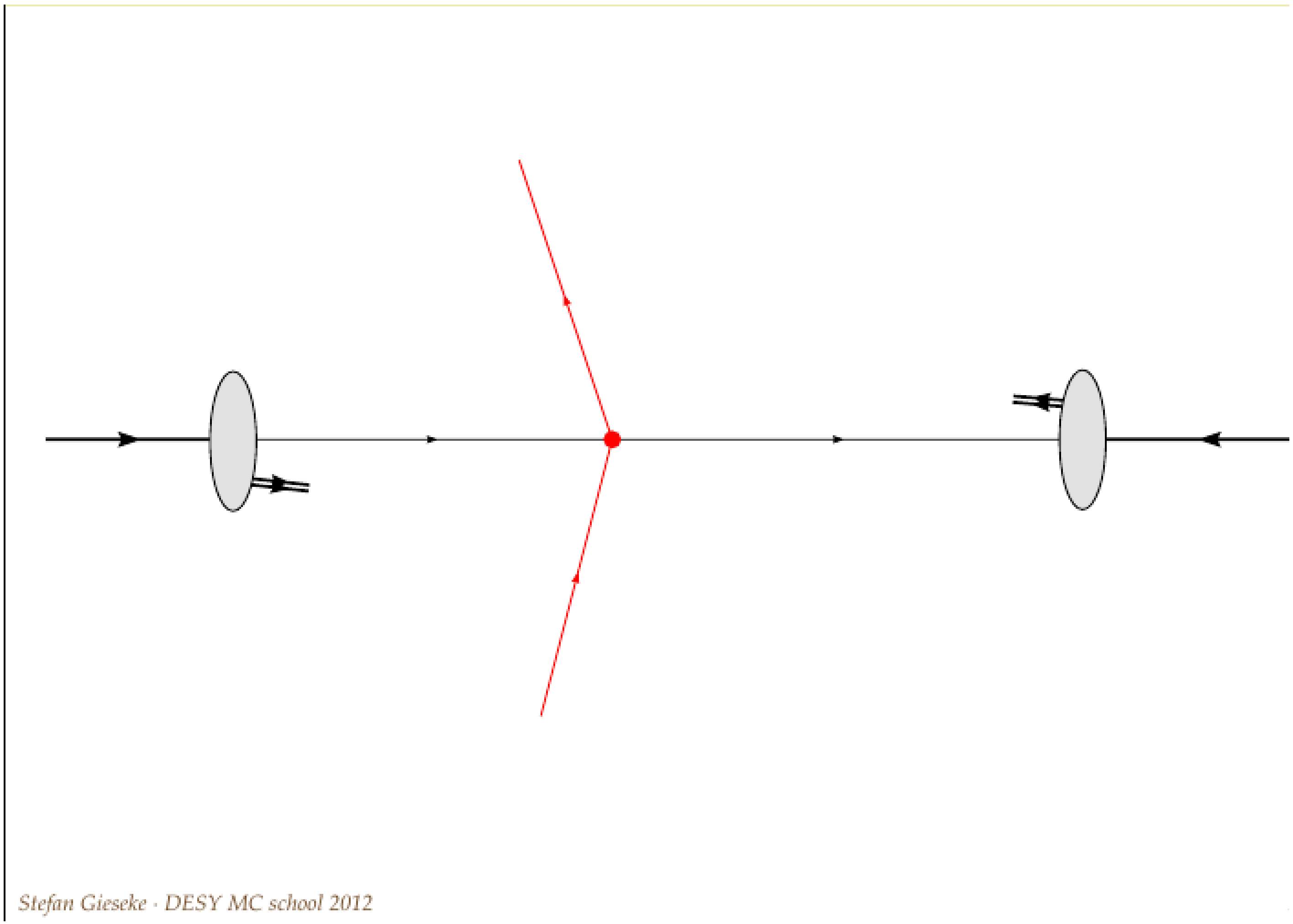
- Generate artificial events
  reflecting all processes in the Lagrangian
  using the Monte Carlo Technique
- obtain arbitrary distributions from simulated final state particles
- and compare with measurements

Steps of MC simulation



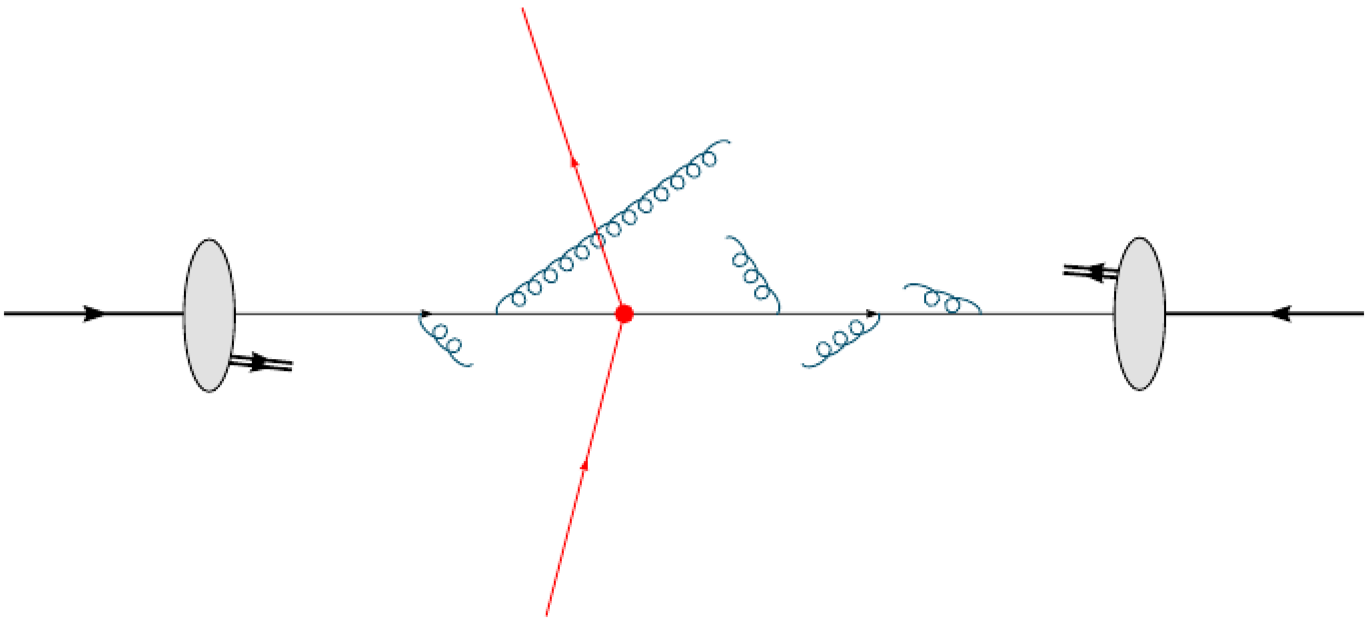
Example: pp collision

Example: pp collision



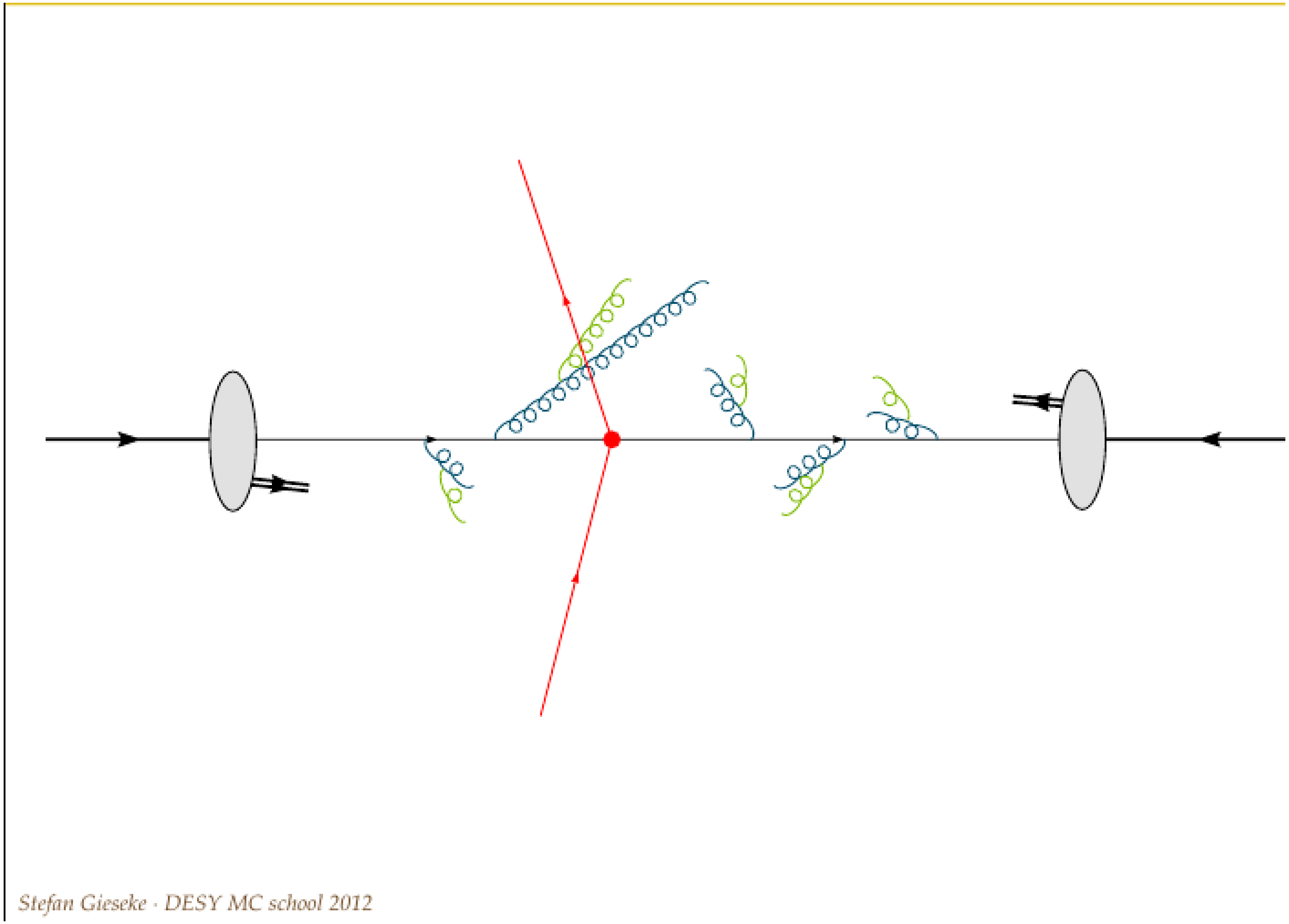
matrix element of hard process

Example: pp collision



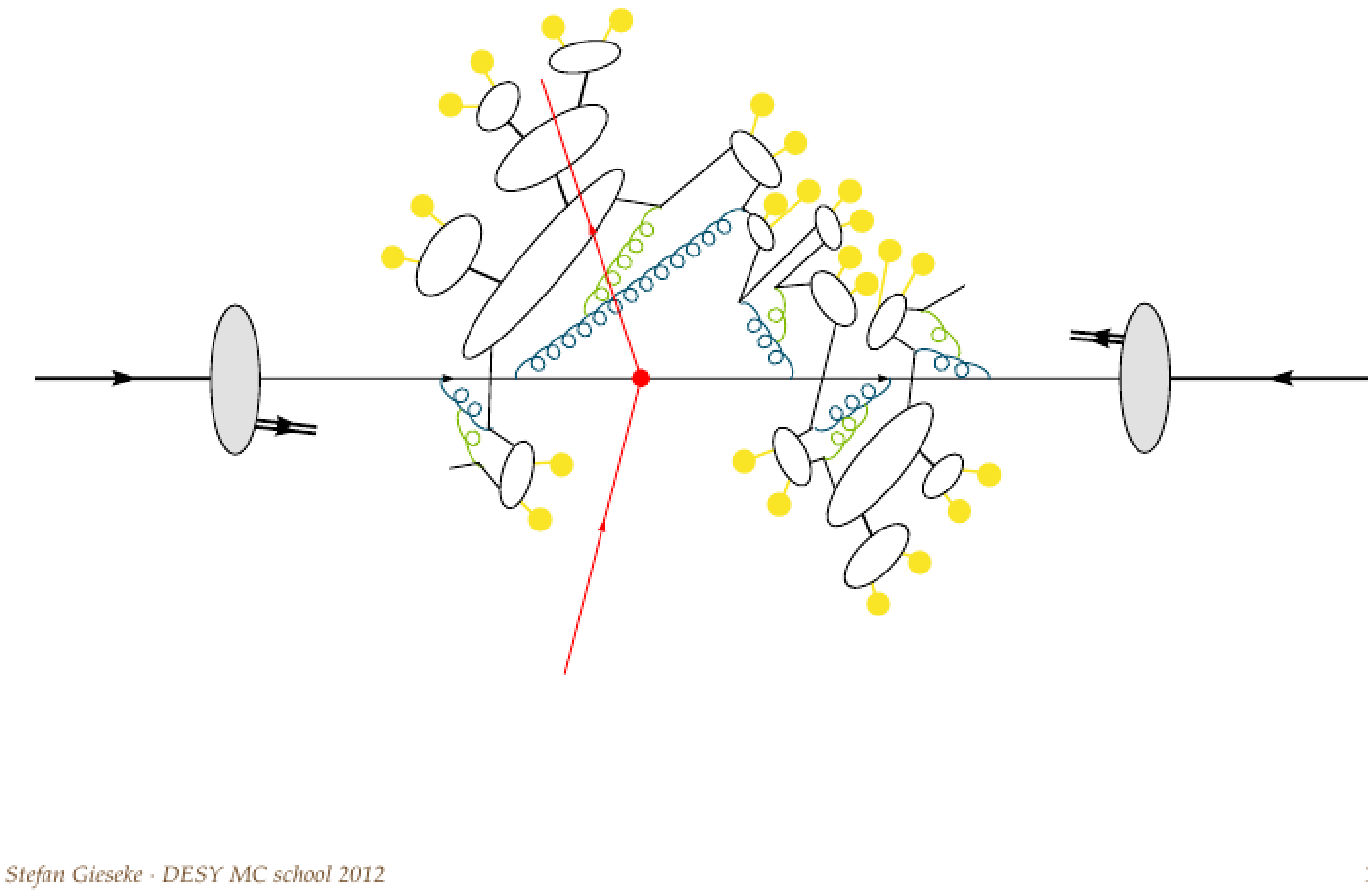
parton shower

Example: pp collision



parton shower

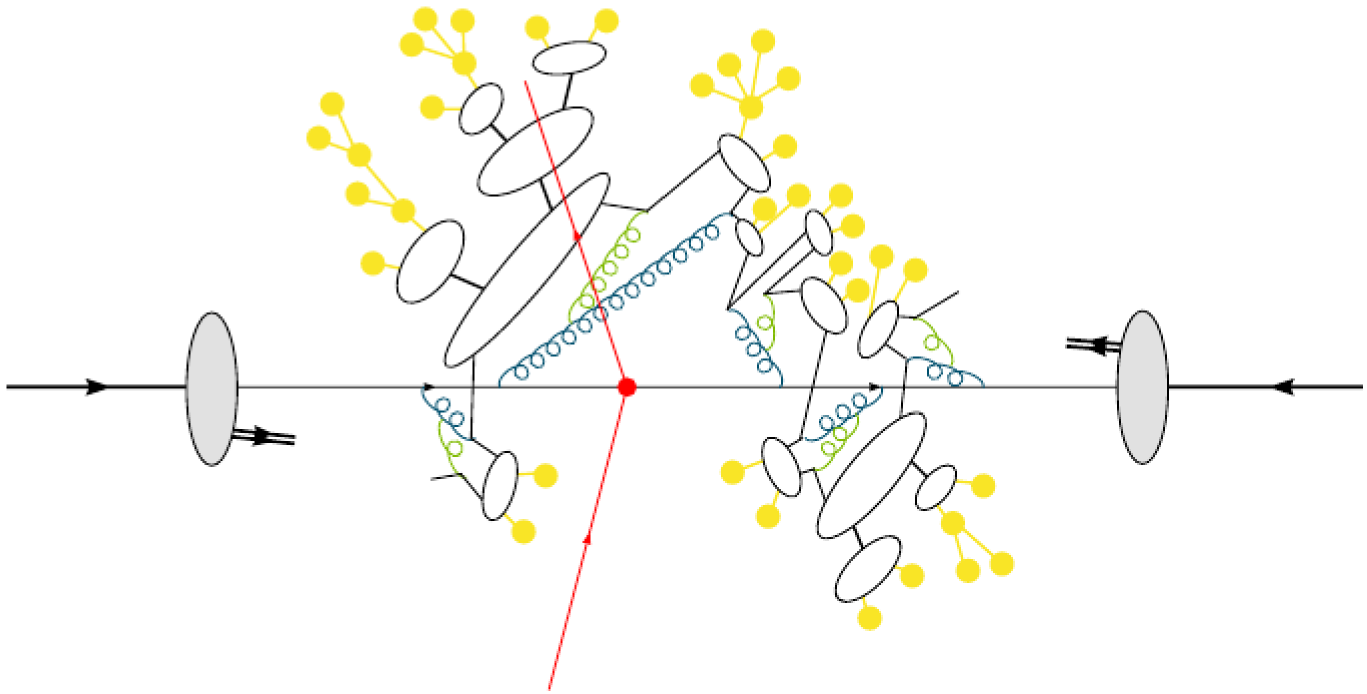
Example: pp collision



hadronization

phenomenological:
Lund string model
(Pythia)
or
cluster hadronisation
(Herwid(++))

Example: pp collision

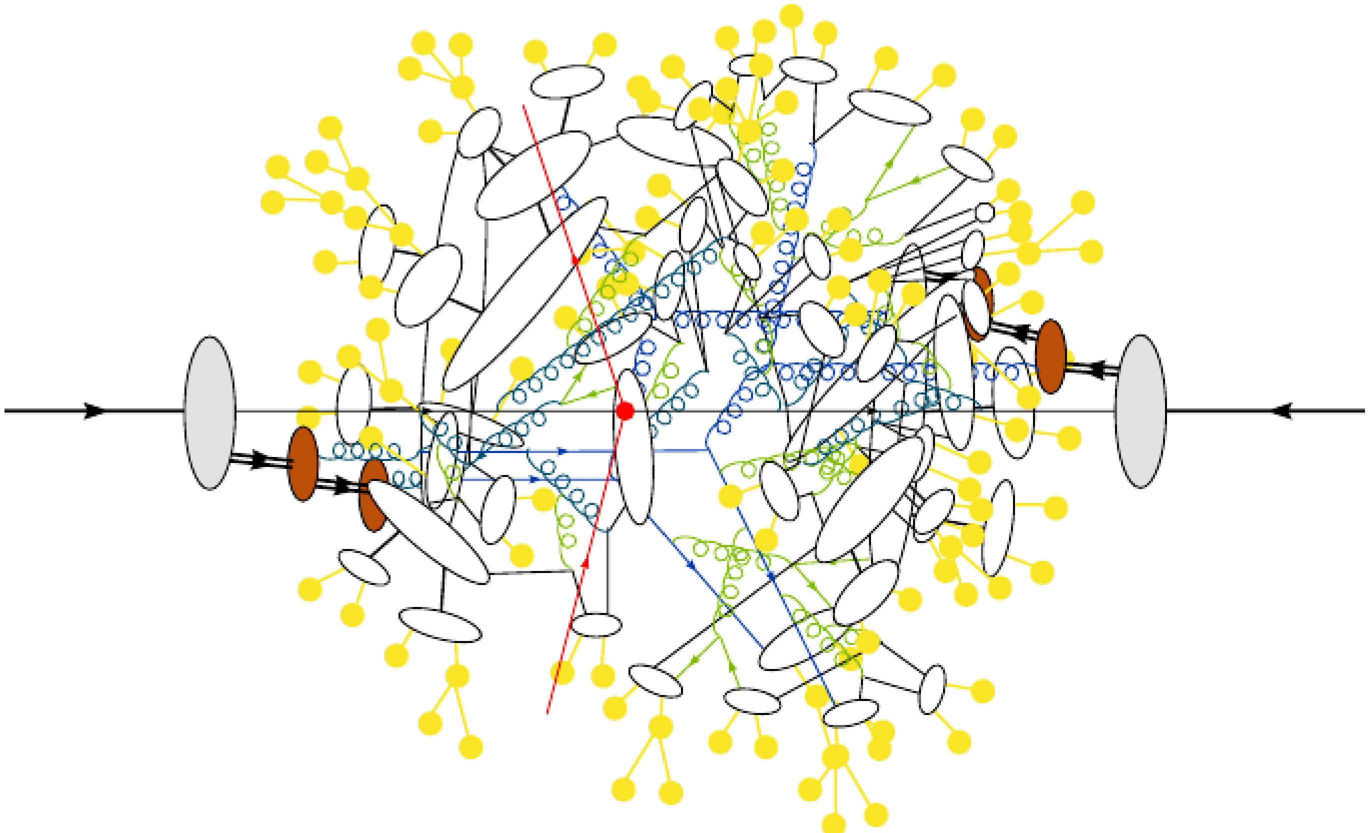


Stefan Gieseke · DESY MC school 2012

hadron decays

tedious -
relies on
measurements

Example: pp collision



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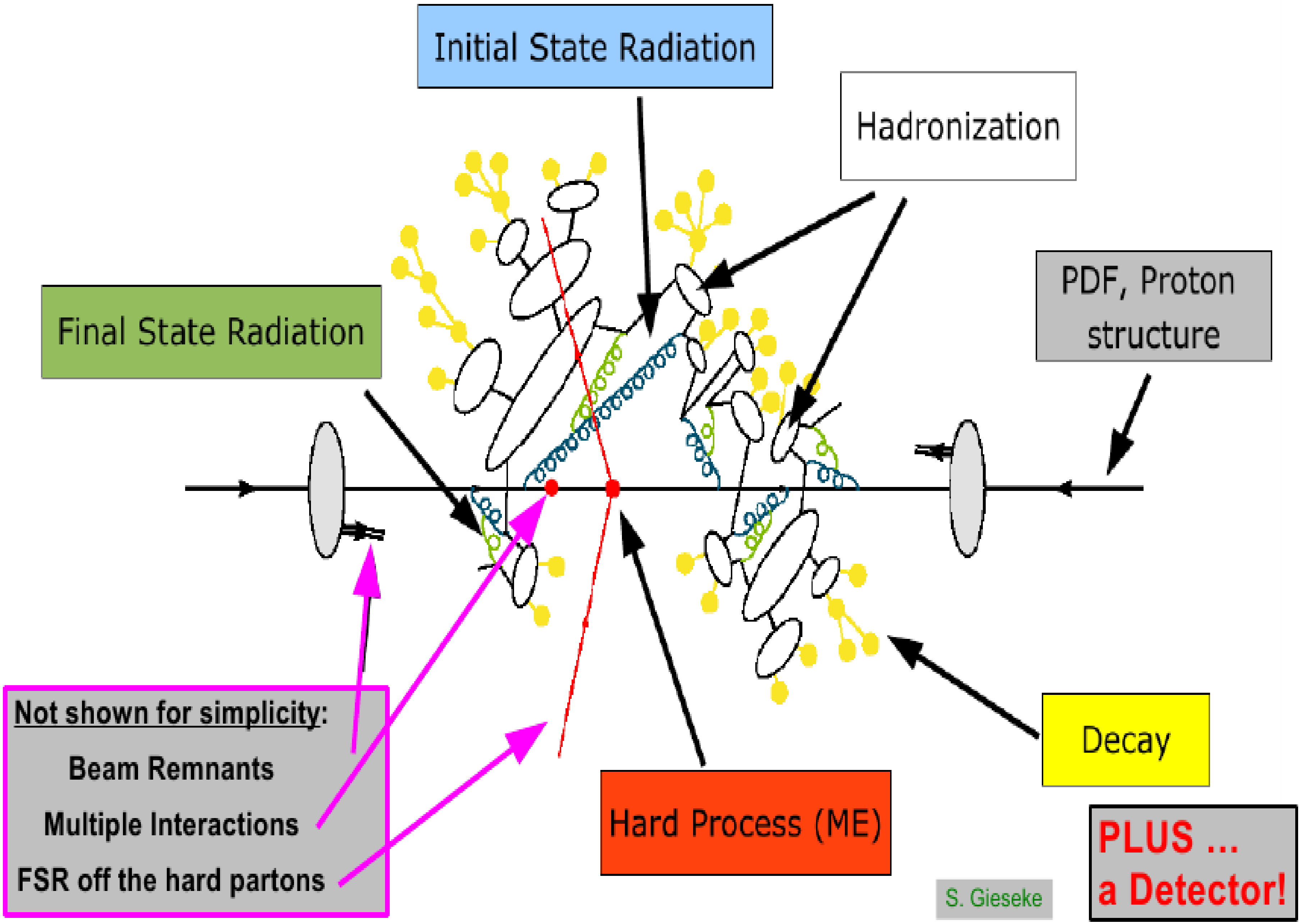
relies on models
& measurements
→ needs „tunig“

Multi-parton interactions and underlying event

Summary: pp collision



Example: pp collision

last step:

– process stable particles through detector simulation
  to obtain „hits“ in detector cells;

– run reconstruction software
  to obtain „reconstructed objects“

– run selection procedures („Analysis“)
  to obtain „identified reconstructed objects“

in total:

true properties of objects from hard process at parton level are folded with

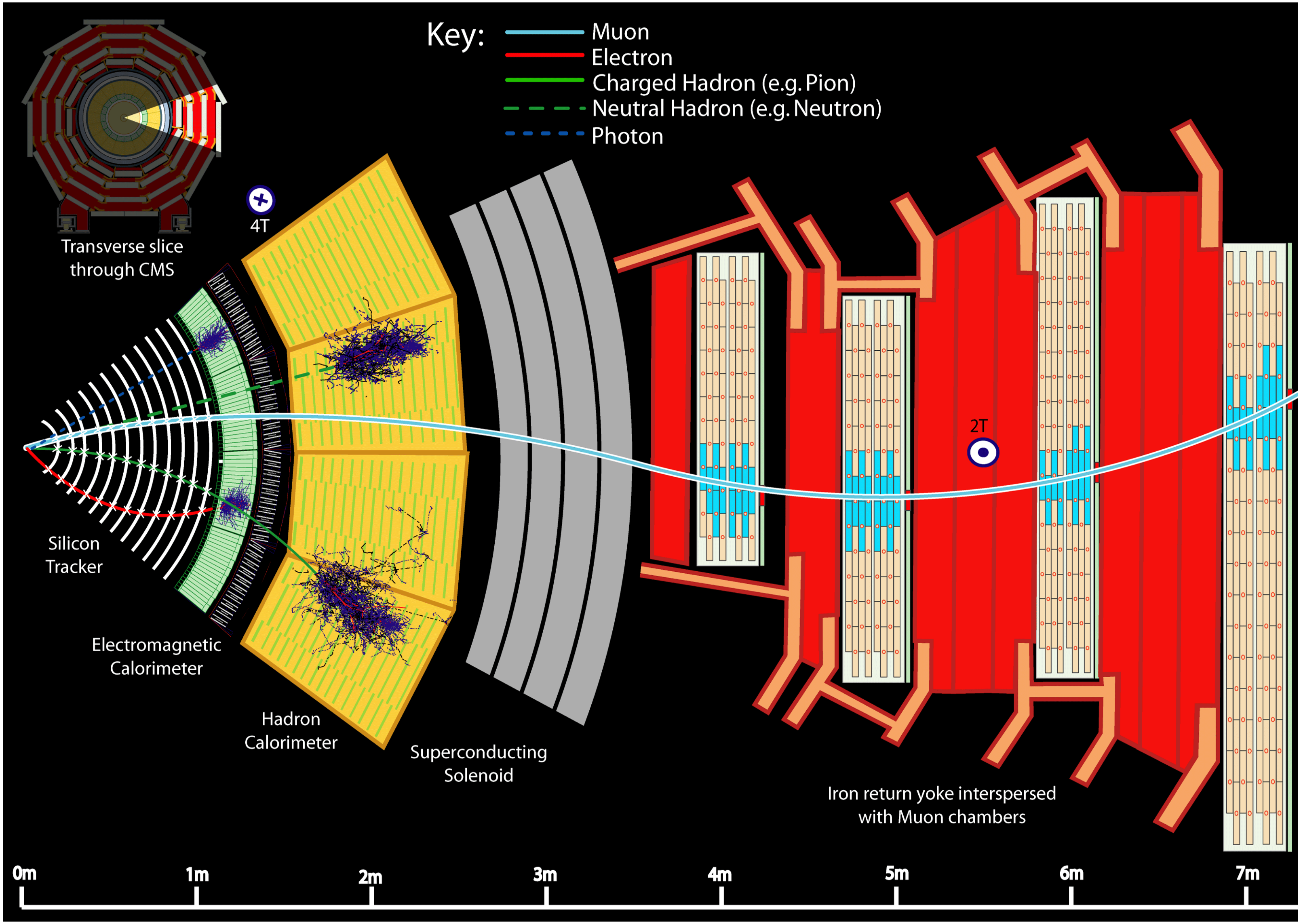
- parton distribution functions,
- hadronization effects,
- detector acceptance and efficiency,
- reconstruction efficiency and resolution,
- identification efficiency and purity

to obtain **reconstructed properties**

all steps involve multi-dimensional integrations;
Monte Carlo is the only choice !

Detector Simulation

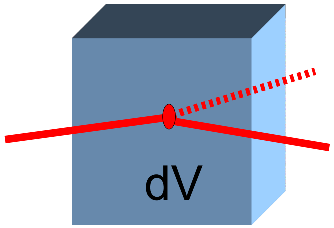
Stable Particles in a Detector



Detector registers only „stable particles“,
i.e. with life times long enough to traverse the detector

7 stable particles:
γ, e, μ , p, n, $\pi^{\pm}$, $K^{\pm}$

Basics: Detector simulation



Tracking of individual interactions of particles

Starting point:
ONE interaction of a SINGLE particle
in a volume element $dV = A\,dL$

Interaction probatility w depends on

- cross section σ of a process and
- number N of particles in volume element

$$dN = A\,dL\,\rho\,N_A\,/\,m_{Mol} = \rho_n\,A\,dL$$

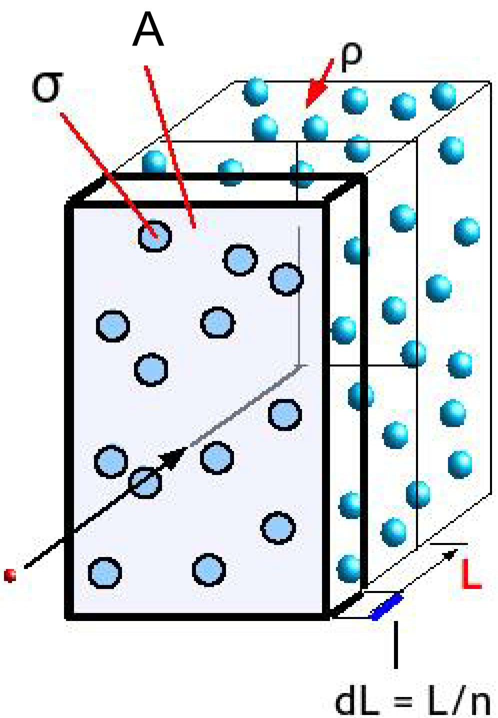
$$\rightarrow \quad dw = \rho_n\ \sigma\,dL$$

Probability, to pass fraction of length L/n without interaction:

$$1 - dw = 1 - \rho_n\ \sigma\,L\,/n$$

Probatility to pass length L without interaction:

$$P_{o\text{-}ww} = (1 - \rho_n\ \sigma\,L\,/n\,)^n \quad \rightarrow \quad \exp(-\rho_n\,\sigma\,L\,)$$



$P_{o\text{-}ww}(L)$ describes the free path length in material

Basics: detector simulation (2)

By differentiation one obtains from $P_{o\text{-}ww}$ the probability density of the path in matter to the first interaction:

$$w(L) = \rho_n \sigma \exp\left(-\rho_n \sigma L\right) = \frac{1}{\lambda} \exp\left(-L/\lambda\right)$$

$\lambda = (\rho_n\ \sigma)^{-1}$: **interaction length**

The **interaction length** in materials with multiple components is given by the inverse sum over the individual densities and interaction lengths

$$\lambda = \left(\sum_j [\rho_{n_j} \sigma(Z_j, E)]\right)^{-1} = \left(\sum_j \frac{1}{\lambda_j}\right)^{-1}$$

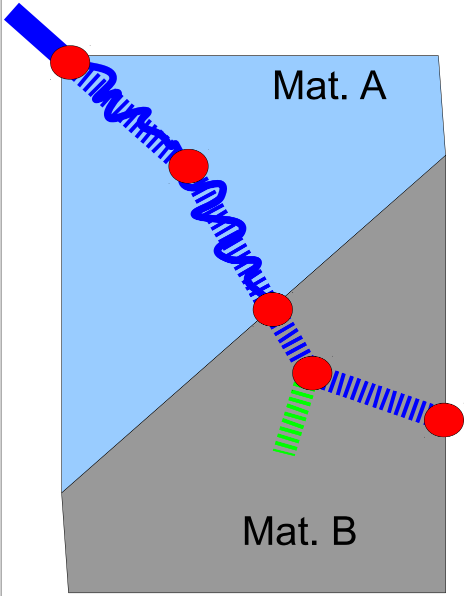
λ is an important property of materials

Clearly, λ depends on the kind of processes considered !

Basics: detector simulation (3)

a simple algorithm for tracking of particle reactions:

1. choose particle from list of particles
2. set initial parameres of particle *(type, position, four-moment)*
3. calculate λ from ρ_n and σ for given material
4. generate random paht lenth L according to density $w(L)$
5. propagate particle by length L or to the next material boundary,
   taking into account deflections from multiple scattering
   and electrical or magnetic fields
6. if still inside the same material:
   let process take place at calculated position and
   – add newly generated particles to list
   – if original particle still exists
   is its energy > given "cut off"
   ? yes: go to 2
   ? no: done with this object; add energy as energy deposit to material element and remove particle from list



eventually, additional random numbers are needed:

– energy loss of particle along path,
– new parameters of particle at the end of the step
– initial parameters of new particles

Basics: detectors imulation (4)

What if there are **many Processes** *1, …, p* ?

1., 2. as above

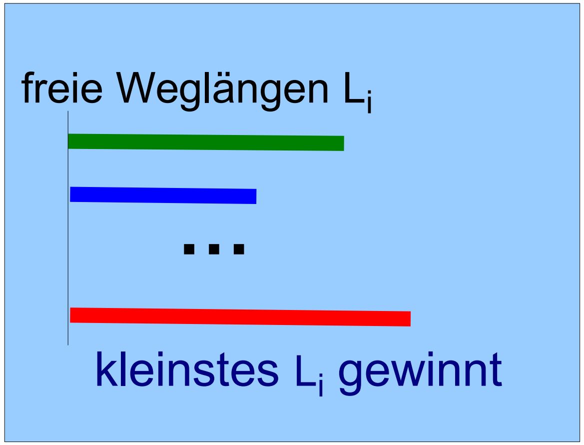
3.' determine all interaction lengths $\lambda_1 , \dots , \lambda_p$

4.' draw *p* random numbers and caclulate L_p ,

determine $L_i = \min(L_p)$, $1 \le i \le p$

5.' propageta particle by length L_i

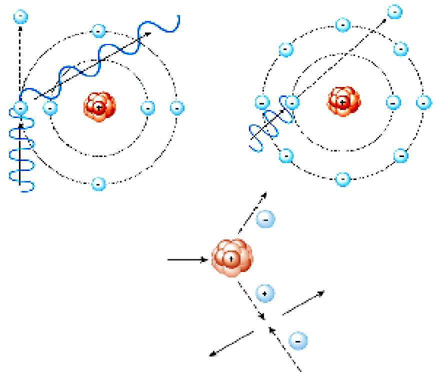
6.' let process i take place



Detector simulation – wrap up

what's needed:

– a list of relevant processes for each particle type
(for short-lived particles, their lifetime and decay topologies also is such a „process“)

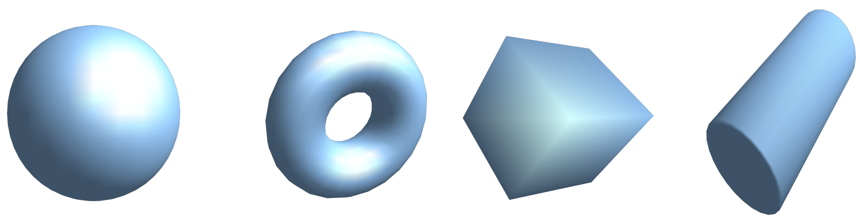


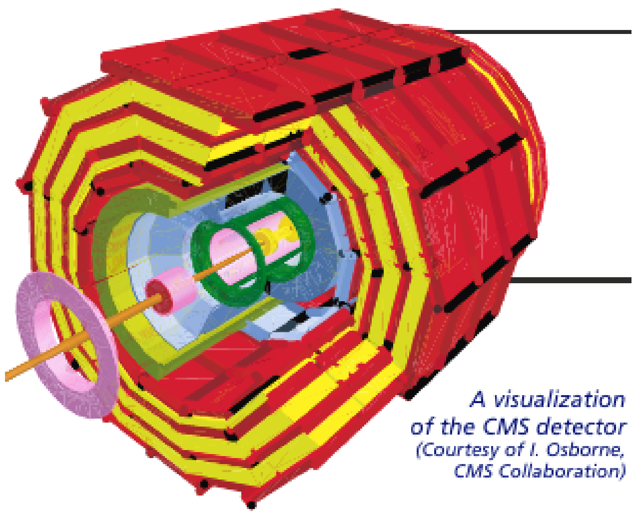
– properties of materials

– cross section for each process depending on parameters of particle and material properties

– propagation rules for particles in materials and fields

– treatment of boundaries:
→ geometrie of detektor volumes and description of complex detectors





A visualization of the CMS detector (Courtesy of I. Osborne, CMS Collaboration)

– recording of energy deposited in volume elements and simulation of the amount of generated charge or light

– for short-lived particles:
list of life times and branching fractions

This, and a lot more, is provided by the simulations framework GEANT

The simulation framework Geant

Geant 4 - a world-wide Collaboration

- open-source Tool-Kit from particle physics
- definition of gemometres and materials
- Tracking of particles in material taking into account a large number of physics processes
- visualisation
- Open interfaces for input/output, storage of geerated data („persistence“)

Began 1994 as a development project, first release 1998
predecessor: Geant 3 (FORTRAN package), applications in nuclear, particle and astro particle physics, medicine and many others

see http://geant4.cern.ch/
documention, tutorials, code …

at EKP, we packed Geant4 in a virtual machine

Own applicatoins

Geant4 is a very powerful and hence complex tool
→ familiarization takes much time

Geant4 is used by all experiments in particle physics for

– design of detectors prior to construction

– generation of „simulated data“ for the development of reconstruction algorithms and analysis strategies

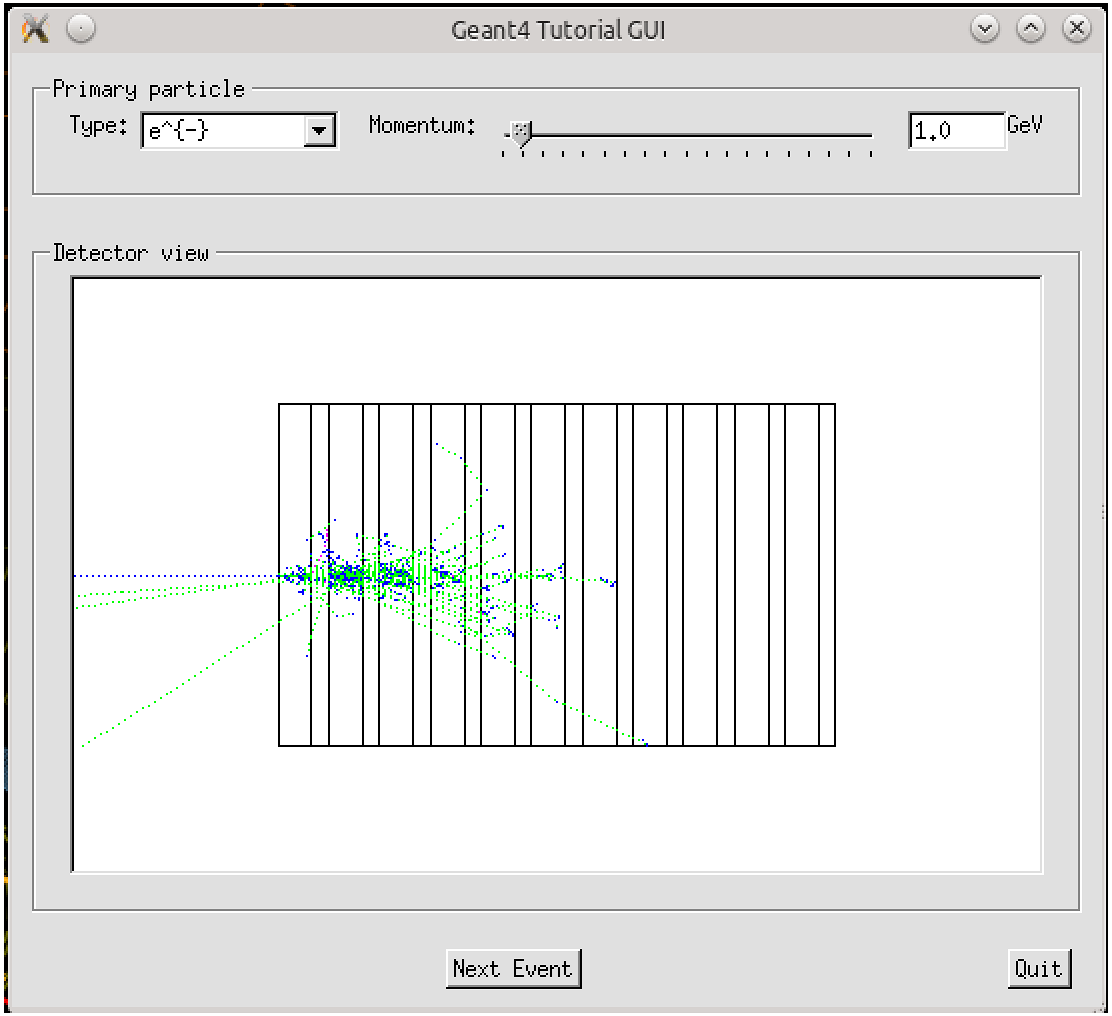
– determination of detector response to assumed scenarios of “new physcs”

– securing proper understanding of „known“ physics when analysing experimental data

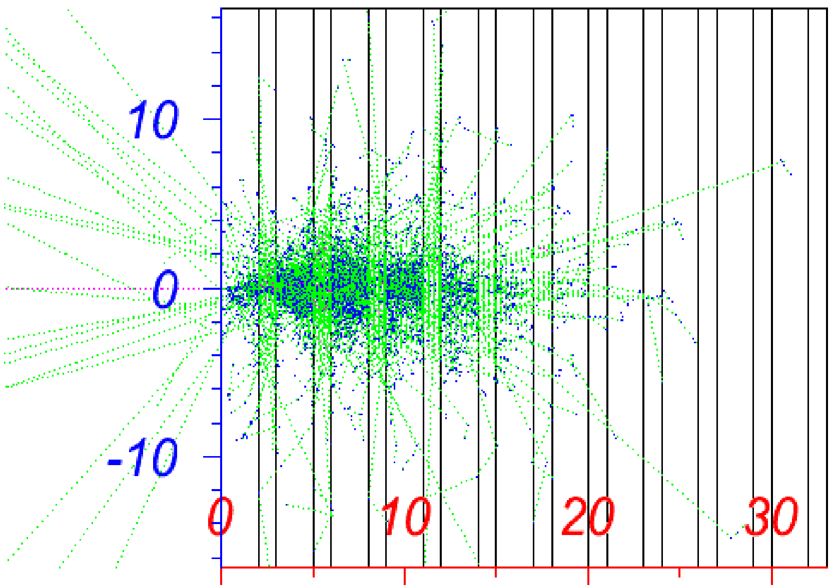
Simulated Data
are an important component in any phase of an experiments.

Eigene Übungen

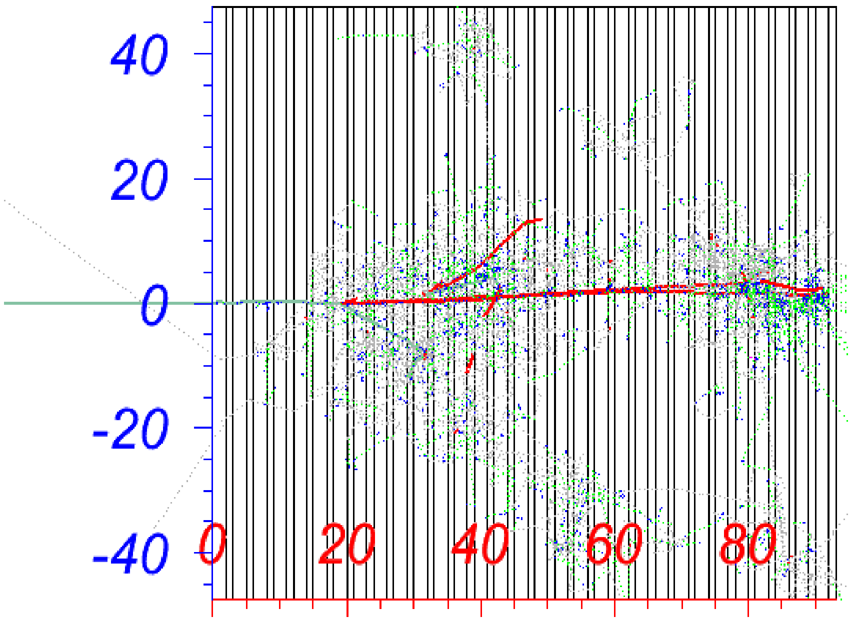
graphical interface with
shower of an elektrons
of 1 GeV energy



Simulation mit Geant4



Shower of an electron of E=10 GeV
in a lead -scintillator sandwich
calorimeter, simulated with geant4



Shower of a pions of E=10 GeV
in a lead scintillator sandwich
calorimeter, simulated with geant4

more on Geant, see Course Particle Physics II – Detectors

Detector Simulation – the last step

- follow each particle through the material of each detector component
- simulate energy deposit in each sensor
- convert energy deposit to detectable signal
  - free charges
  - photons (=visible light) from excitations,
  - eventually light from other processes (Cherenkov-light, transition radiation …)
- final result of simulation:

signal (in mV)
per detector cell

"The Event"
(here an example from the BaBar experimen@SLAC)

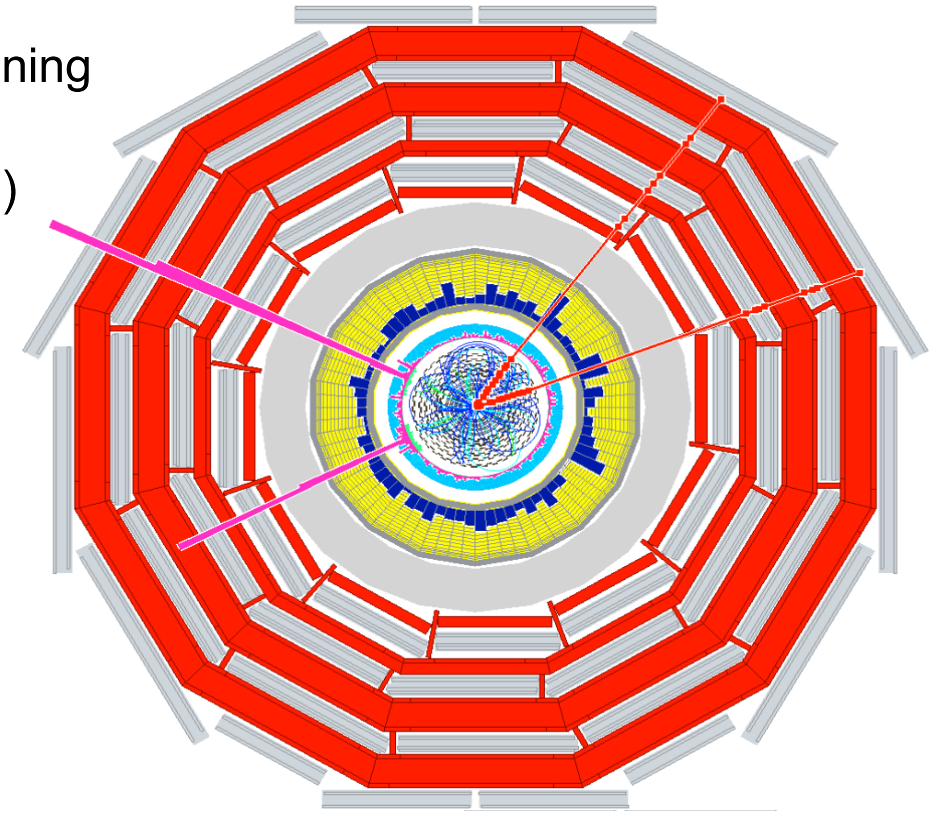

```
0x01e84c10:  0x01e8 0x8848 0x01e8 0x83d8 0x6c73 0x6f72 0x7400 0x0000
0x01e84c20:  0x0000 0x0019 0x0000 0x0000 0x01e8 0x4d08 0x01e8 0x5b7c
0x01e84c30:  0x01e8 0x87e8 0x01e8 0x8458 0x7061 0x636b 0x6167 0x6500
0x01e84c40:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c50:  0x01e8 0x8788 0x01e8 0x8498 0x7072 0x6f63 0x0000 0x0000
0x01e84c60:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c70:  0x01e8 0x8824 0x01e8 0x84d8 0x7265 0x6765 0x7870 0x0000
0x01e84c80:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c90:  0x01e8 0x8838 0x01e8 0x8518 0x7265 0x6773 0x7562 0x0000
0x01e84ca0:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cb0:  0x01e8 0x8818 0x01e8 0x8558 0x7265 0x6e61 0x6d65 0x0000
0x01e84cc0:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cd0:  0x01e8 0x8798 0x01e8 0x8598 0x7265 0x7475 0x726e 0x0000
0x01e84ce0:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cf0:  0x01e8 0x87ec 0x01e8 0x85d8 0x7363 0x616e 0x0000 0x0000
0x01e84d00:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d10:  0x01e8 0x87e8 0x01e8 0x8618 0x7365 0x7400 0x0000 0x0000
0x01e84d20:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d30:  0x01e8 0x87a8 0x01e8 0x8658 0x7370 0x6c69 0x7400 0x0000
0x01e84d40:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d50:  0x01e8 0x8854 0x01e8 0x8698 0x7374 0x7269 0x6e67 0x0000
0x01e84d60:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d70:  0x01e8 0x875c 0x01e8 0x86d8 0x7375 0x6273 0x7400 0x0000
0x01e84d80:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d90:  0x01e8 0x87c0 0x01e8 0x8718 0x7377 0x6974 0x6368 0x0000
```

Last step: Event reconstruction

- apply thresholds to suppress "noise" (i.e. "fake" hits)
- convert signal (mV) in each detector cell to energy deposit (using "calibration constants" of each cell)
- apply pattern recognition to hits above threshold, search for
  - "track segments" (circular arc) in tracking detectors
  - "clusters" in calorimeters
- attempt "particle identification" by combining information from sub-detectors
- cluster particles into jets ("jet algorithms")
- store reconstructed objects and their properties, final result:

reconstructed event

reconstructed objects only approximately correspond to true properties,
as in real life !



CMS: simulated Higgs → 2e4μ decay with hits and reconstructed objects

Recap: what we have up to now

After

- precise (including next-to-leading order) cross sections of signal and background processes
- generation of a large number of representative single "events" in an "event generator"
- simulation of parton showers and hadronization
- simulation of detector response ("hits")
- reconstruction of physics objects from the hits

application of (soft) selection criteria to roughly represent the acceptance *(see later)* of the detector

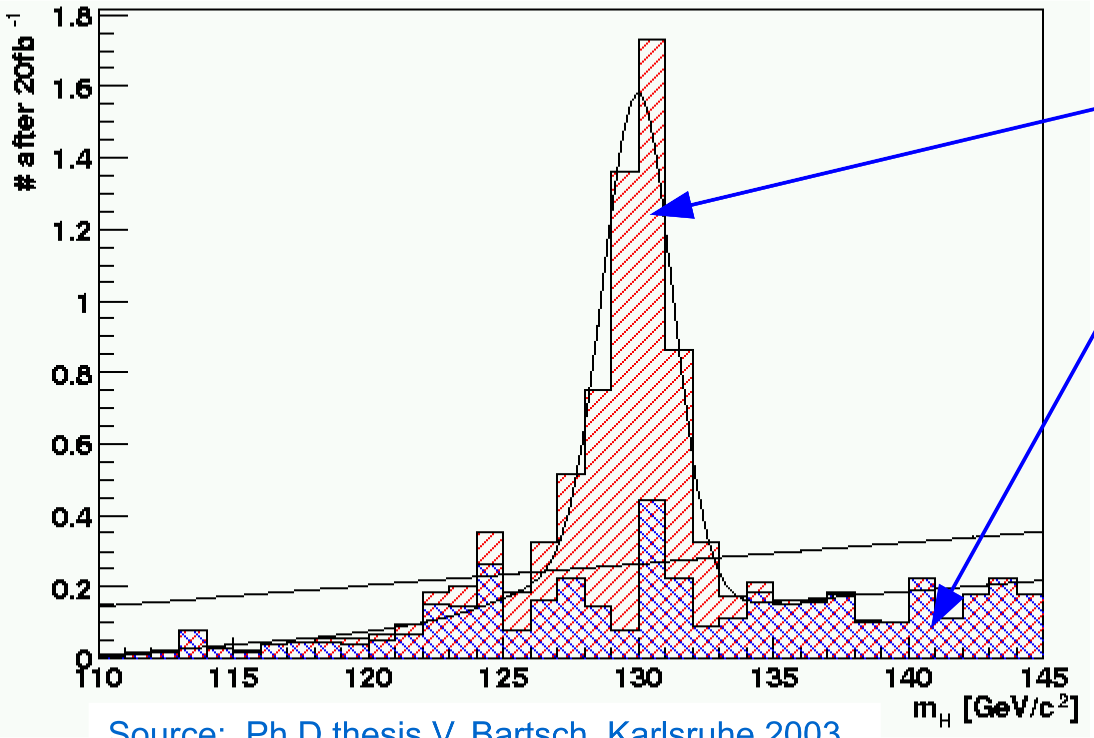
obtain samples of

simulated signal and background events

From these, obtain distributions of (reconstructable) variables to design an analysis and determine its selection and background rejection efficiencies *(see later)*

Example: Expected Distributions of Signal and Background

Early Study of H → ZZ



Source: Ph.D thesis V. Bartsch, Karlsruhe 2003

Distribution(s) of

- – signal events
- – background events

from scaled MC

Used to formulate
„signal+background“ (S+B)
and
„background-only“ (B)
hypotheses for

- – comparison with data and
- – statistical inference

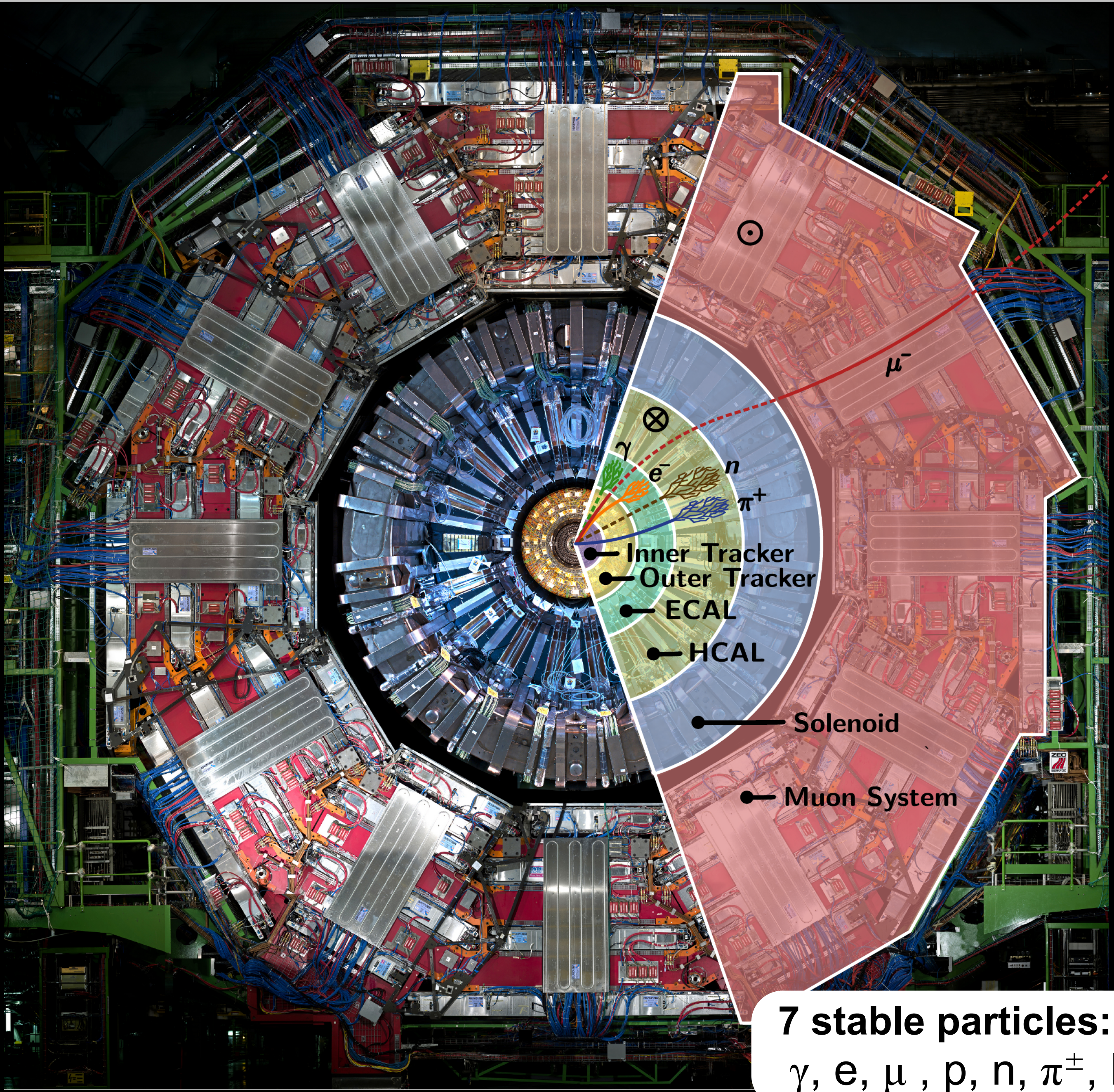
Hint: in the real experiment, only very small numbers are expected to be observed (see y-axis), and therefore statistical fluctuations will be large

– the question will be:
are they best described by the S+B or the B-only shape?

→ need for sophisticated statistical treatment (see later)

The real experiment and data analysis

Particle reconstruction



Detector registers only „stable particles“, i.e. those with with life times long enough to traverse the detector

7 stable particles:
γ, e, μ , p, n, $\pi^{\pm}$, $K^{\pm}$

Steps of Event selection

- **hardware Trigger** and **on-line selection** identify „interesting“ events with particles in the sensitive area of the detector (events not selected are lost)

  ⟶ detector acceptance and online-selection efficiency

- physics objects are **reconstructed** off-line

  ⟶ reconstruction efficiency

- **Analysis** procedure identifies physics processes and rejects backgrounds

  ⟶ selection efficiency and purity

- **statistical inference** to determine confidence intervals of interesting parameters (production cross sections, particle properties, model parameters, ...)

All steps are affected by systematic errors !

Cross section measurement

Master formula:

signal candidates

background events

$$\sigma = \frac{N_{cand} - N_{bkg}}{\epsilon \cdot \int L}$$

acceptance and efficiency

integrated Luminosity

product of many factors:
- detector acceptance
- trigger efficiency
- reconstruction efficiency
- selection efficiency
- background rejection efficiency

usually determined using well-known reference reaction:

$$\int L = N_{ref} \, / \, \sigma_{ref}$$

Cross Section measurement: errors

by error propagation →

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{\delta N_{cand}^2 + \delta N_{bkg}^2}{(N_{cand} - N_{bkg})^2} + \left(\frac{\delta\epsilon}{\epsilon}\right)^2 + \left(\frac{\delta\int L}{\int L}\right)^2}$$

This is the error you want to <u>minimize</u>

- with signal as large as possible
- background as small as possible
- nonetheless, want large efficiency
- luminosity error small (typically beyond your control, also has a "theoretical" component)

(Integrated) Luminosity

Luminosity, $\mathcal{L}$, connects event rate, r, and cross section, **σ**:

$$r = \mathcal{L} \cdot \sigma$$, unit of [$\mathcal{L}$] = cm^{-2}/s oder 1/nb /s

Integrated luminosity, $\int \mathcal{L}\, dt$, is a measure of the total number of events at given cross section, $N = \int \mathcal{L}\, dt \cdot \sigma$

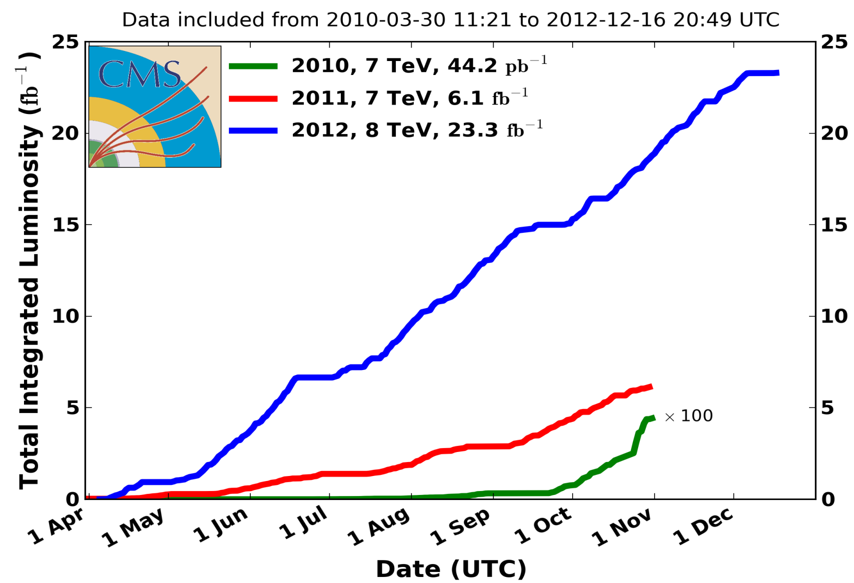
$\mathcal{L}$ is a property of the accelerator:

$$\mathcal{L} = \frac{f_{\text{rev}} n_b {N_p}^2}{4\pi A_{\text{bunch}}} = \frac{f_{\text{rev}} n_b {N_p}^2}{4\pi \epsilon \beta^*}$$

f_{rev}: revolution frequency of beams
n_b: number of bunches
N_p: number of particles in a bunch
A_{bunch}: area of bunches
ε: emittance of beam
β*: beta-function at collision point

LHC design Luminosity: 10^{-34} /cm²/s

∫$\mathcal{L}$ recorded by the CMS experiment



The total integrated Luminosity of 29.4 fb^{-1} corresponds to $1.8 \cdot 10^{15}$ pp collisions (assuming 60 mb inelastic pp cross section)

Determination of Luminosity

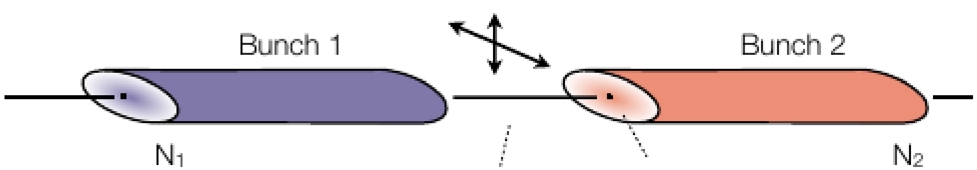
Luminosity is, however, not determined from machine parameters
(precision only ~10%)

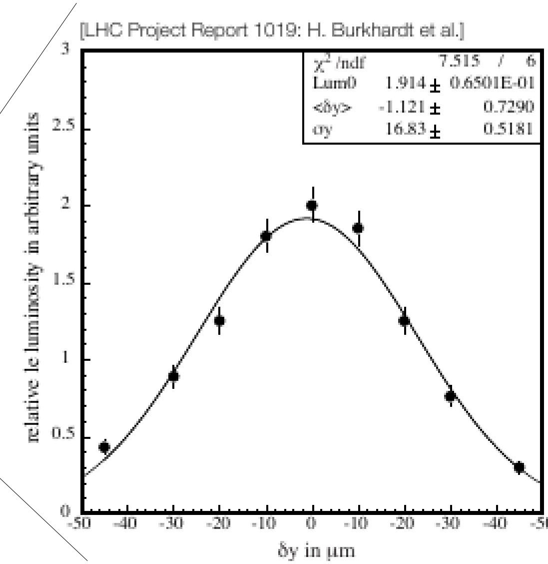
but by simultaneous measurements of a **reference reaction** with well-known cross section:

$$\int L = N_{ref} \,/\, \sigma_{ref}$$

absolute value from
- elastic proton-proton scattering at small angles
- production of W or Z bosons
- production of photon or muon pairs in $\gamma\gamma$-reactions
- ...

measurement of luminous beam profile:
- van-der-Meer scans by transverse displacement of beams, record $\mathcal{L}$ vs. δx, δy





relative methods:
- particle counting or current measurements in detector components with high rates
  (need calibration against one of the absolute methods)

accuracy on $\int\mathcal{L}$ (CMS experiment): 2.2% (7 TeV, 2011) and 2.6% (8TeV, 2012)