Karlsruher Institut für Technologie

Higgs Boson Physics

Analysis Techniques

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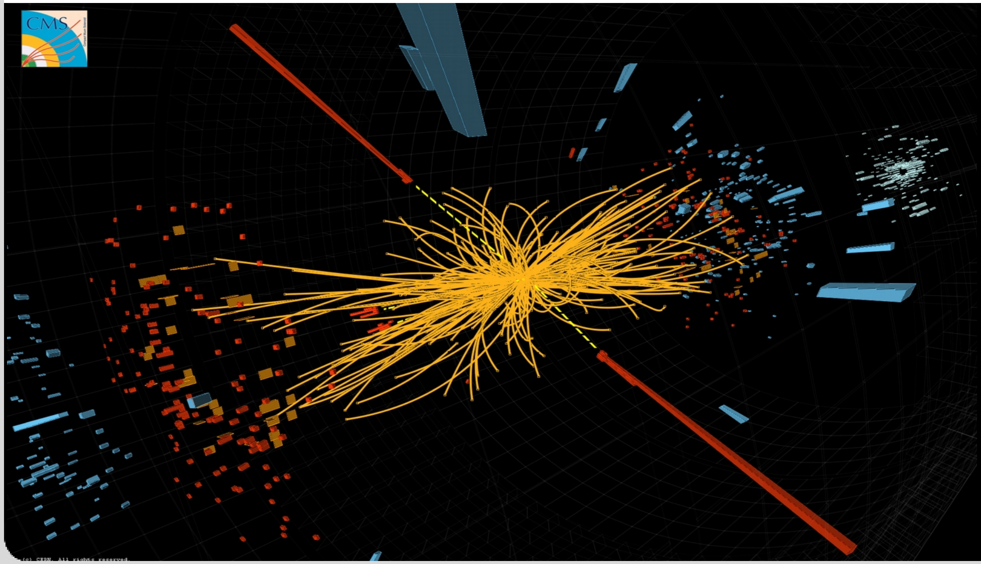
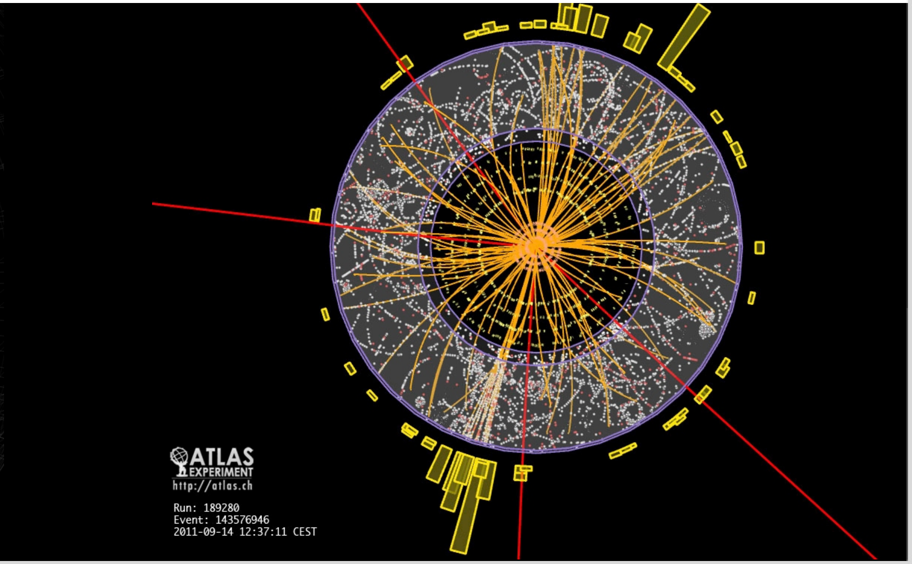
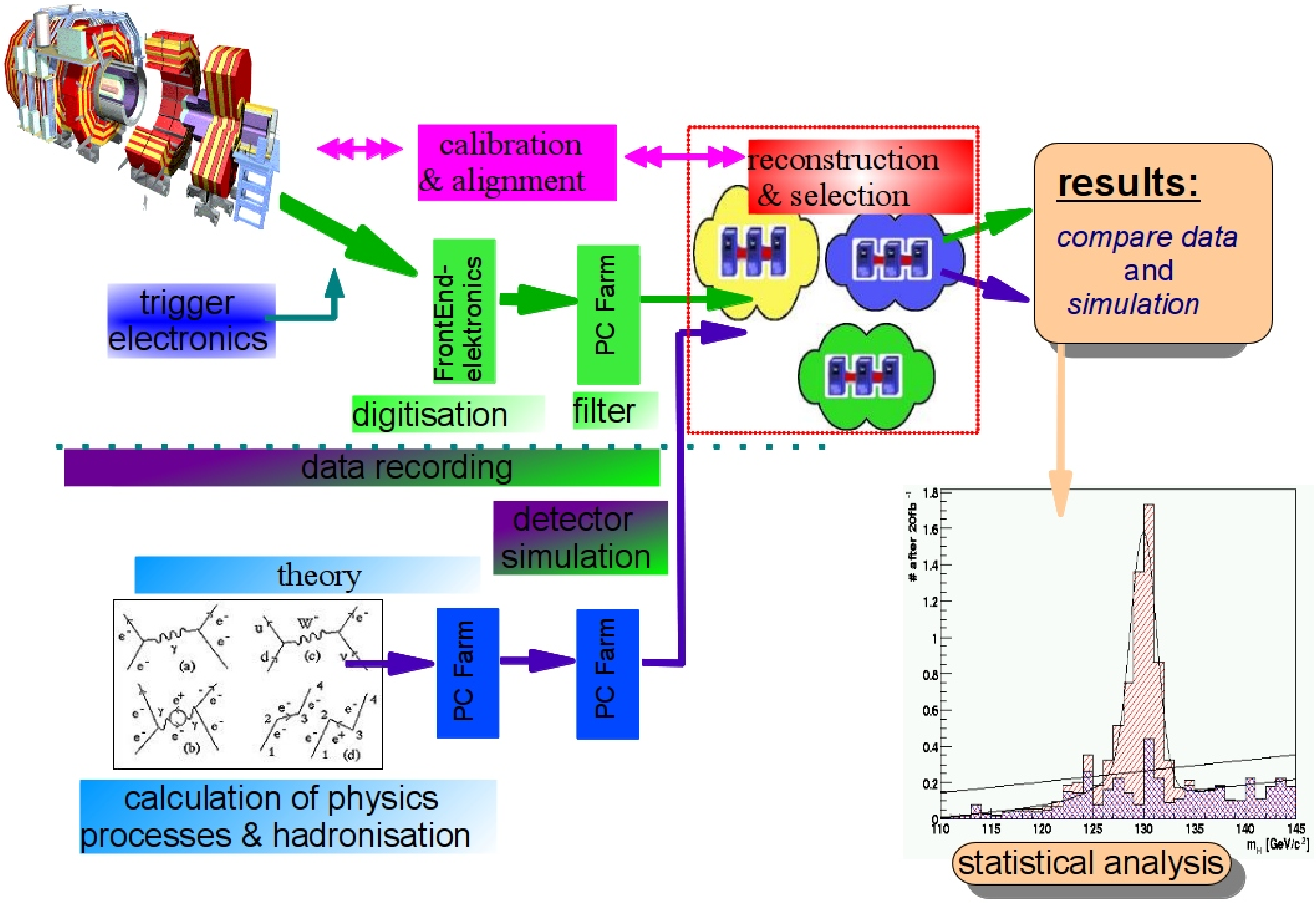
Master-Kurs
SS 2015

Institut für Experimentelle Kernphysik





Recap: Simulation and Analysis Chain



calibration & alignment

reconstruction & selection

results:

compare data and simulation

trigger electronics

FrontEnd-elektronics

PC Farm

digitisation

filter

data recording

detector simulation

theory

PC Farm

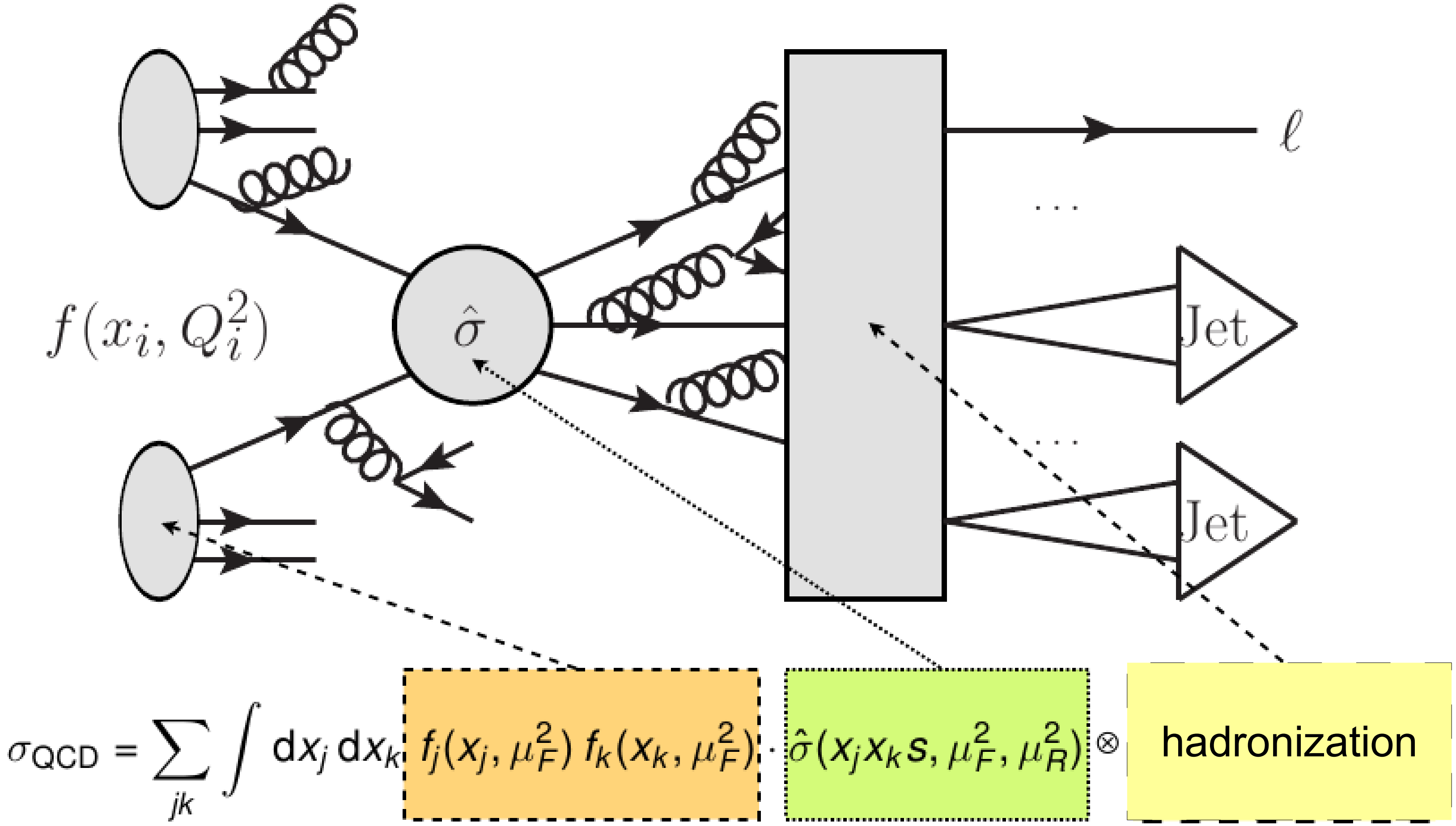
PC Farm

calculation of physics processes & hadronisation

statistical analysis

Recap: Event Simulation

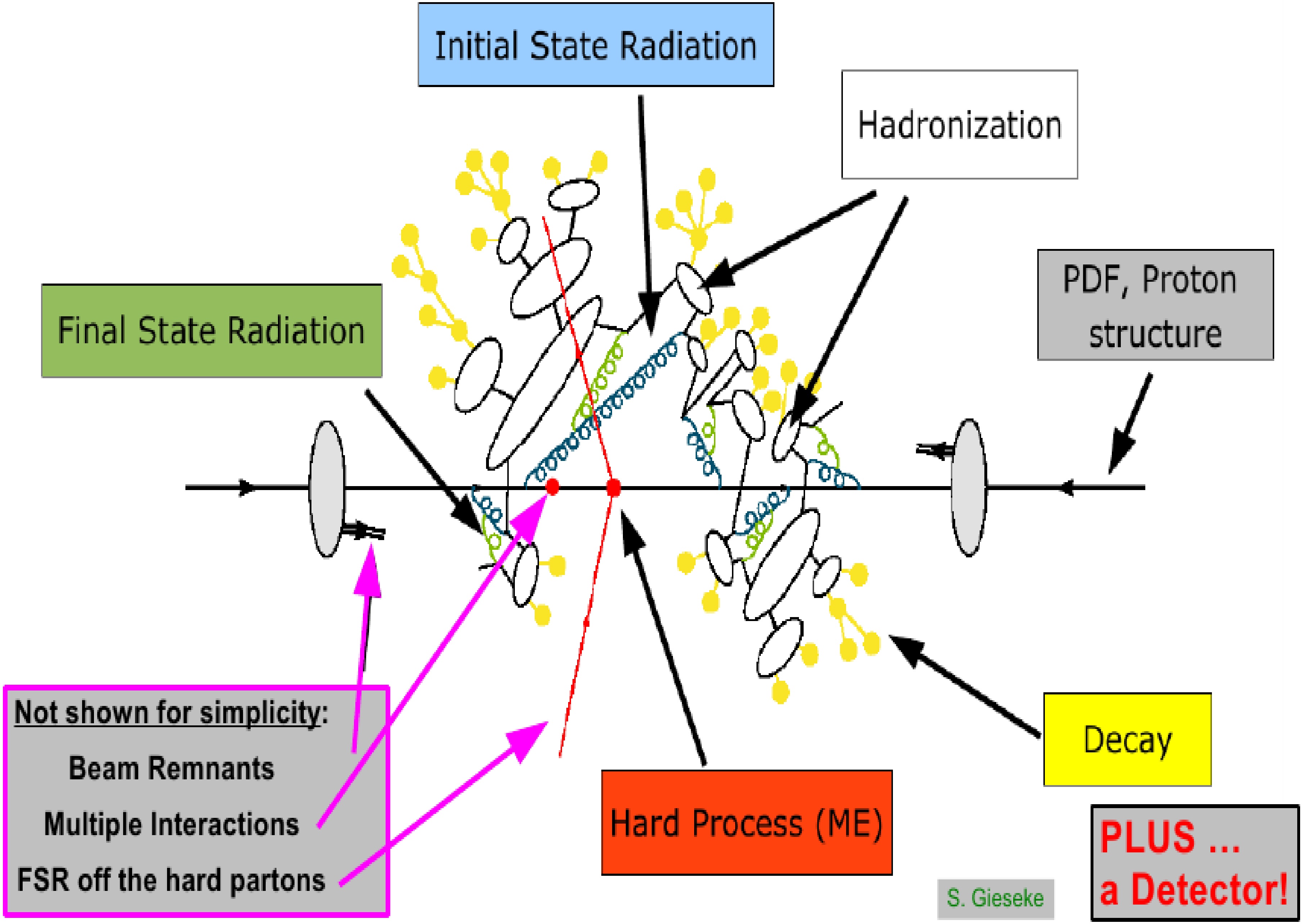
σ = PDFs ⊗ 2→n process ⊗ hadroniszation



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

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

Summary: pp collision



Initial State Radiation

Hadronization

PDF, Proton structure

Final State Radiation

Not shown for simplicity:

Beam Remnants

Multiple Interactions

FSR off the hard partons

Hard Process (ME)

Decay

PLUS ...
a Detector!

S. Gieseke

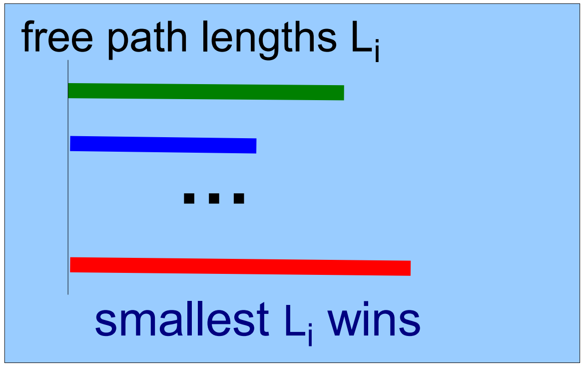
Recap: Detector Simulation

- Generate interaction points along a particle path according to distribution of path length in matter until next interaction (free path length):

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

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

- in case of many competing processes, the one with the smallest free path length is selected to occur



free path lengths L_i

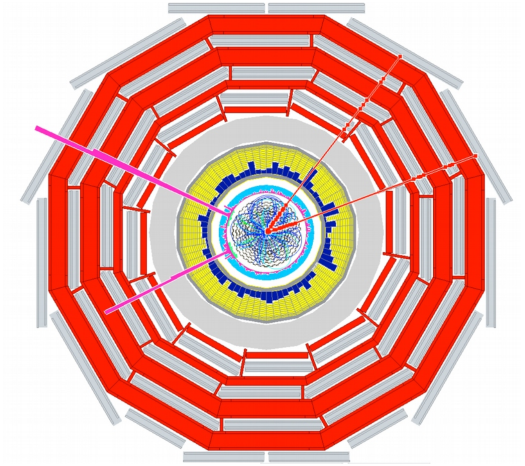
...

smallest L_i wins

- follow each particle, including newly produced daughter particles, until energy is below a cut-off threshold

- calculate deposited energy in detector cells

- simulate observable signal (free charges or light)



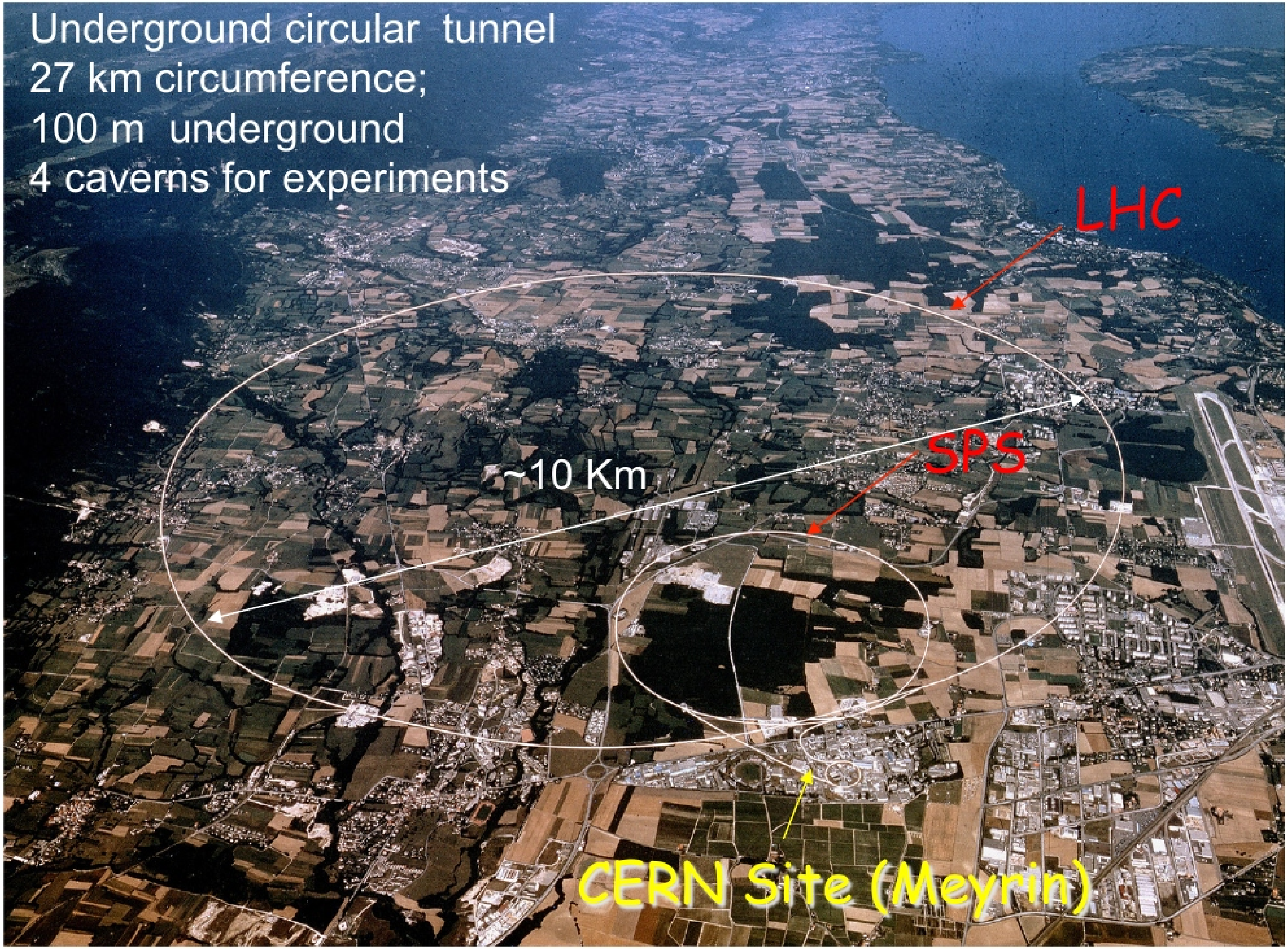
The real experiment and data analysis

Beschleuniger – Detektor – Trigger – Computing - Analyse

Video: CERN-ProcessingLHCdata.mp4

CERN accelerators and the LHC

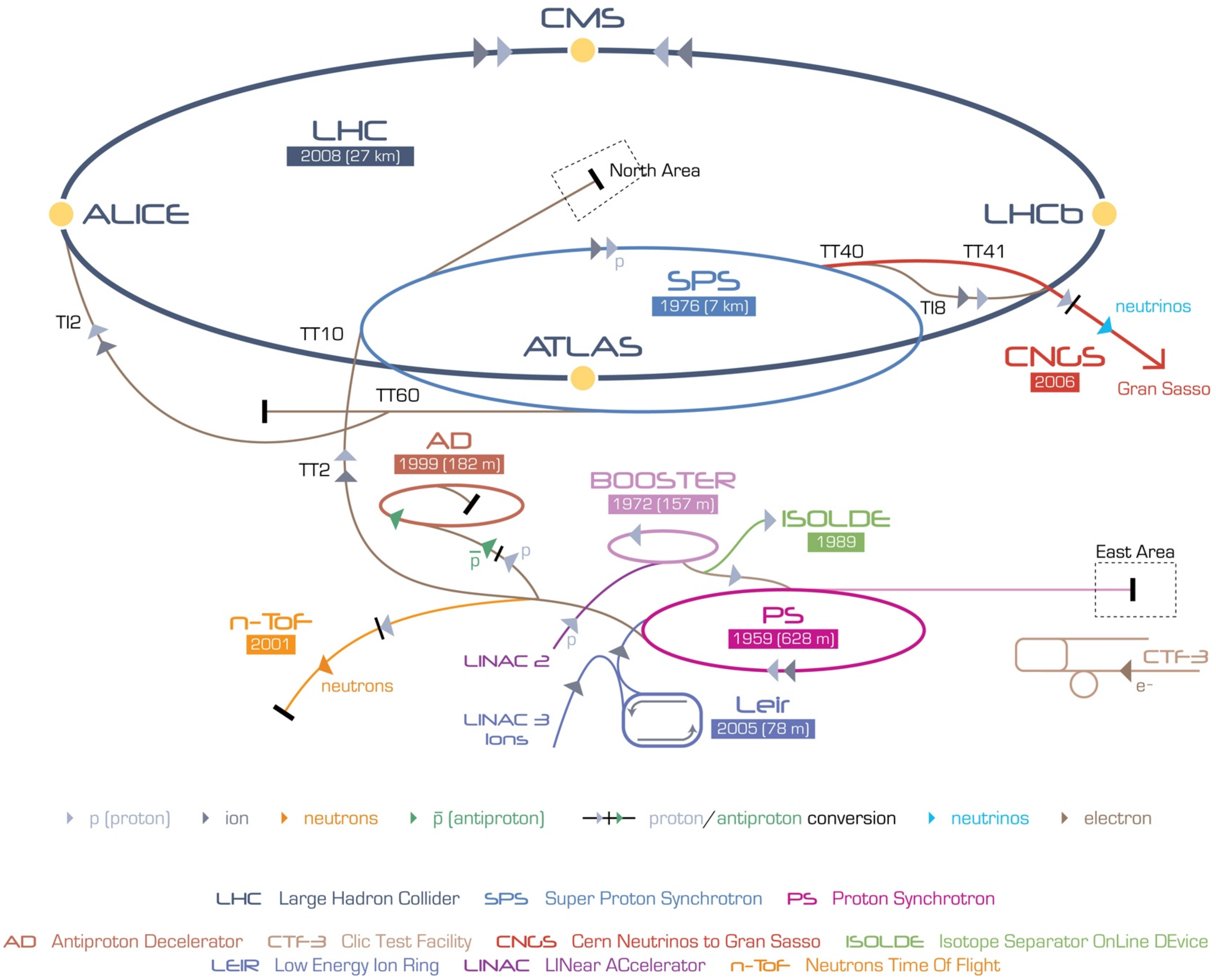
The CERN accelerator complex:



Underground circular tunnel
27 km circumference;
100 m underground
4 caverns for experiments

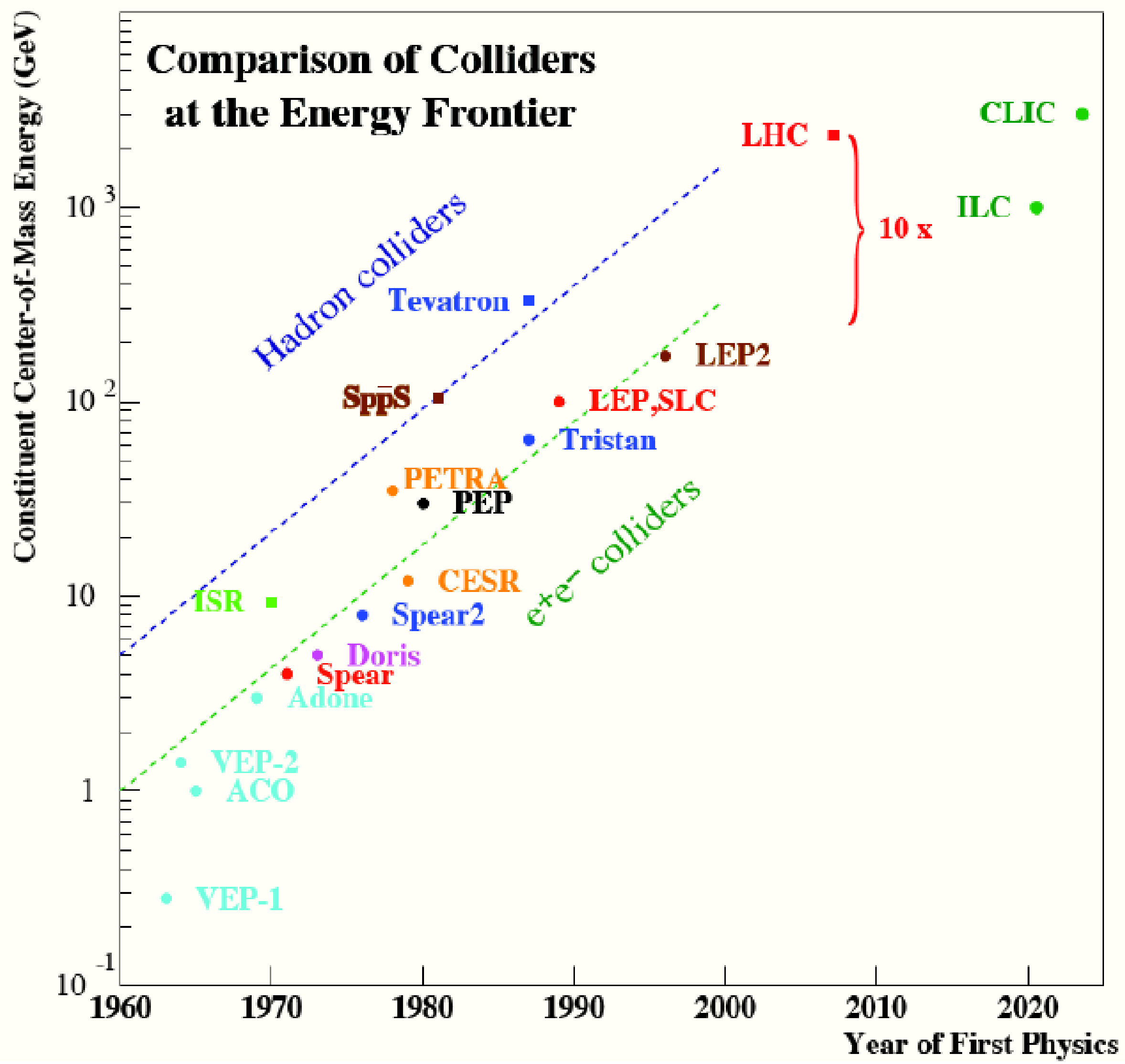
CERN accelerators and the LHC

The CERN accelerator complex:



Übersicht: Beschleuniger

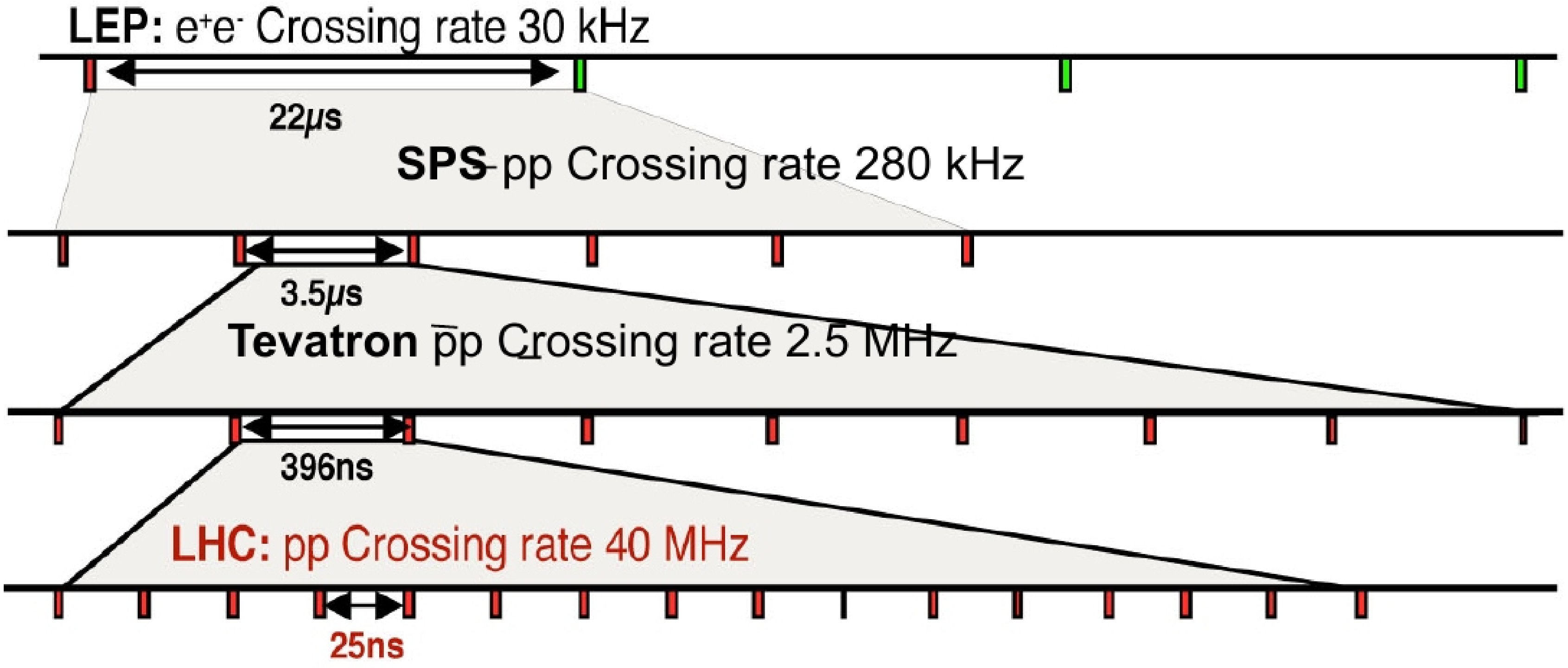
Livingston Plot:



Der LHC ist der bisher leistungsstärkste Beschleuniger mit einer Energie pro Strahl: 3.5 TeV (2010, '11), 4 TeV (2012), 6.5 TeV (2015, '16), evtl. 7 TeV in Zukunft

LHC Parameters

	(2012)
LHC has 3564 bunches (2835 filled with protons)	1400
Crossing rate is 40 MHz	20 MHz
Distance between bunches: 27km / 3600 = 7.5m	15.0 m
Distance between bunches in time: 7.5m / c = 25ns	50 ns
Proton-proton collision per bunch crossing: ~ 20	<35



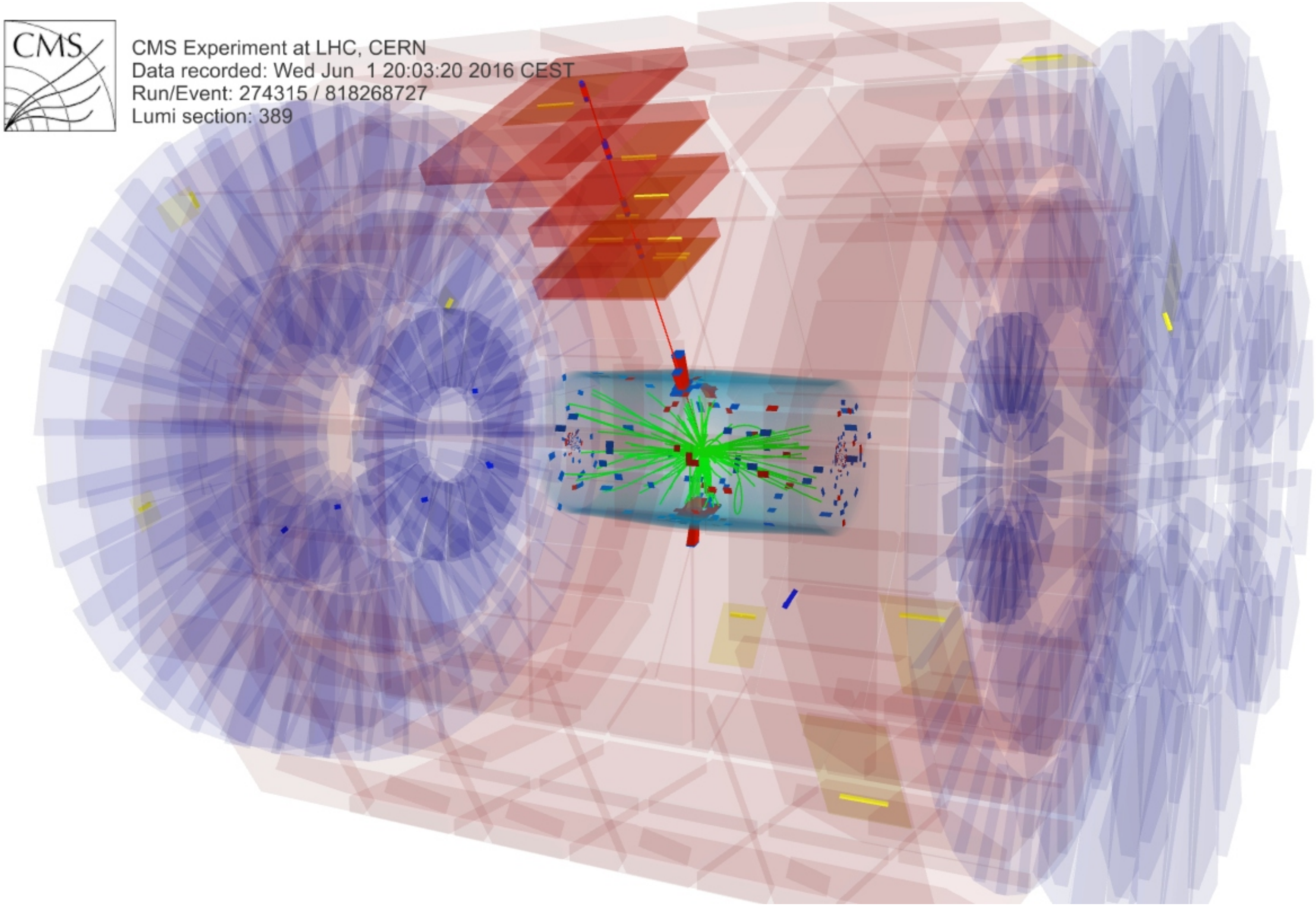
LEP: e^+e^- Crossing rate 30 kHz

SPS pp Crossing rate 280 kHz

Tevatron $\bar{p}p$ Crossing rate 2.5 MHz

LHC: pp Crossing rate 40 MHz

A live-view on the LHC



http://www-ekp.physik.uni-karlsruhe.de/~quast/CMSMonPage16/cms-event.html

Luminosität (aus VL. Teilchenphysik I)

Luminosität (Collider, Kreisbeschleuniger, 2 Bunches)

$$L = \frac{f}{4\pi} \cdot \frac{N_1 \cdot N_2}{\sigma_x \cdot \sigma_y}$$

f: Umlauffrequenz

$$\sigma_x = \sqrt{\epsilon_x \cdot \beta_x}\ ,\ \sigma_y = \sqrt{\epsilon_y \cdot \beta_y}$$

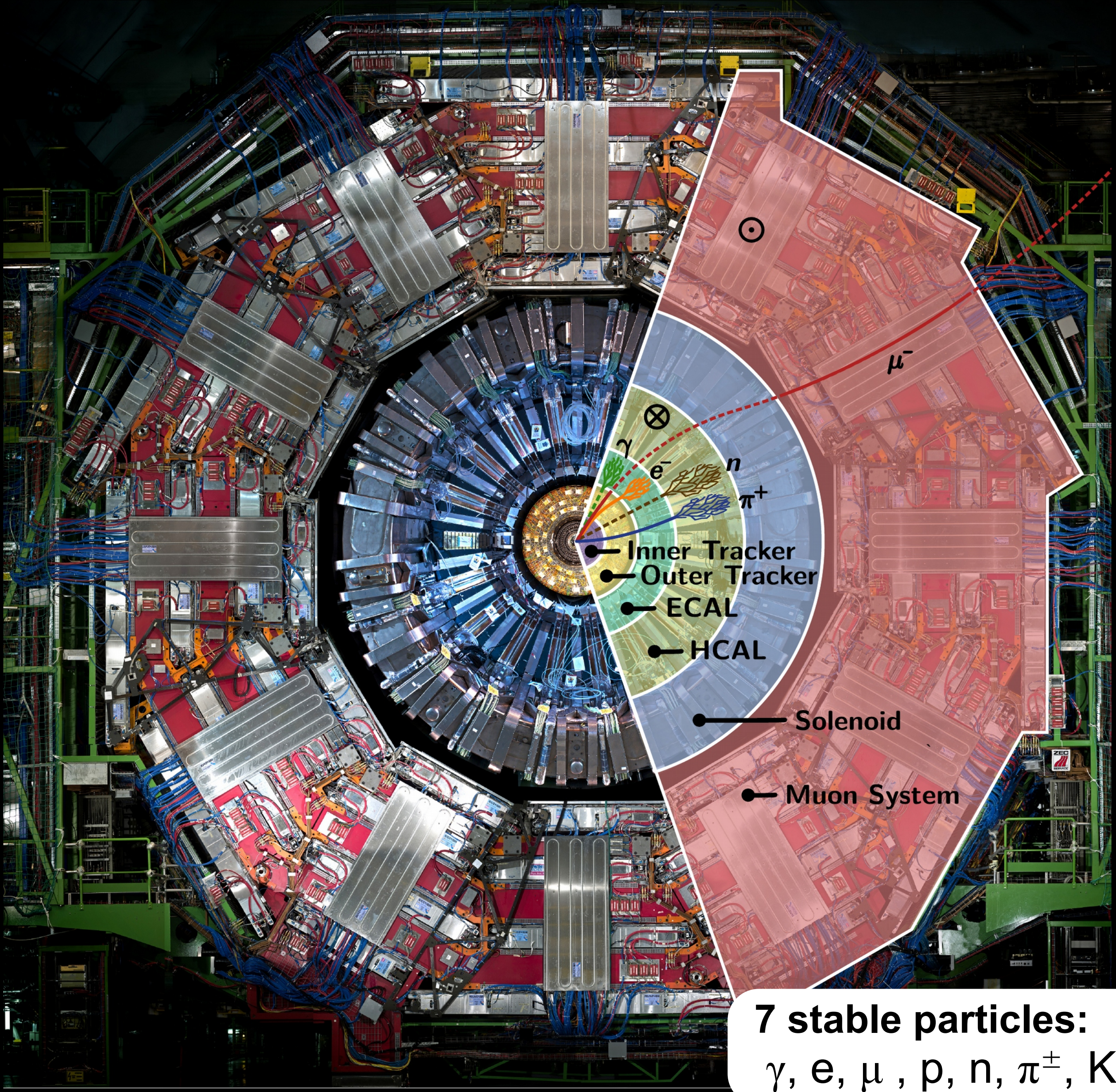
Luminosität (Collider, Kreisbeschleuniger, n_B bunches)

$$L = \frac{f}{4\pi} \cdot \frac{\gamma \cdot n_B \cdot N_1 \cdot N_2}{\epsilon_n \beta^*} \cdot F$$

Lorentzfaktor: $\gamma = E/m_0c^2$
F: Reduktionsfaktor aufgrund des Kreuzungswinkels der Strahlen
LHC: f=11246 Hz

	LHC design	**LHC 2010**
Instantane Luminosität [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	$\sim 10^{34}$	$\sim 2.0 \cdot 10^{32}$
Anzahl der Bunche pro Strahl, n_B	2808	312
Teilchenanzahl pro bunch, $N_1=N_2$	$1{,}15 \cdot 10^{11}$	$1{,}15 \cdot 10^{11}$
Separation der Bunche [ns]	25	75
Norm. transversale Emittanz, $\varepsilon_n=\gamma\varepsilon$ [µm]	3,75	1,6
Betafunktion am WP, β* [m]	0,55	3,5
Kreuzungswinkel der Strahlen [µrad]	285	100

Particle reconstruction



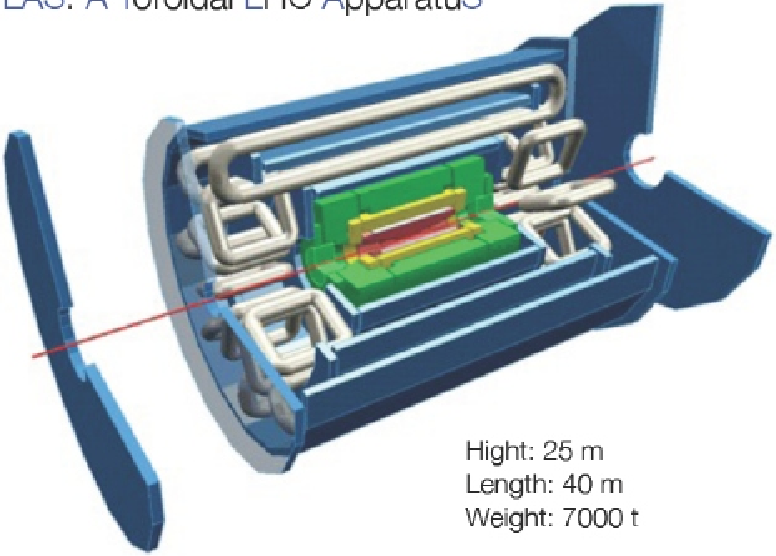
Detector registers only „stable particles“, *i.e.* those with with life times long enough to traverse the detector

7 stable particles:

γ, e, μ , p, n, $\pi^{\pm}$, $K^{\pm}$

The Tow big LHC Experiments

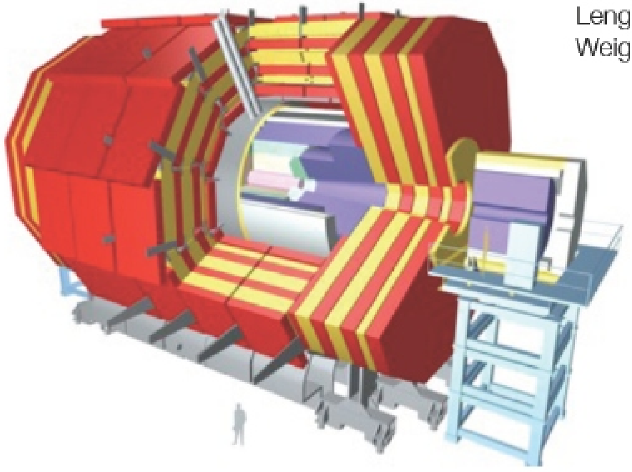
ATLAS: A Toroidal LHC ApparatuS

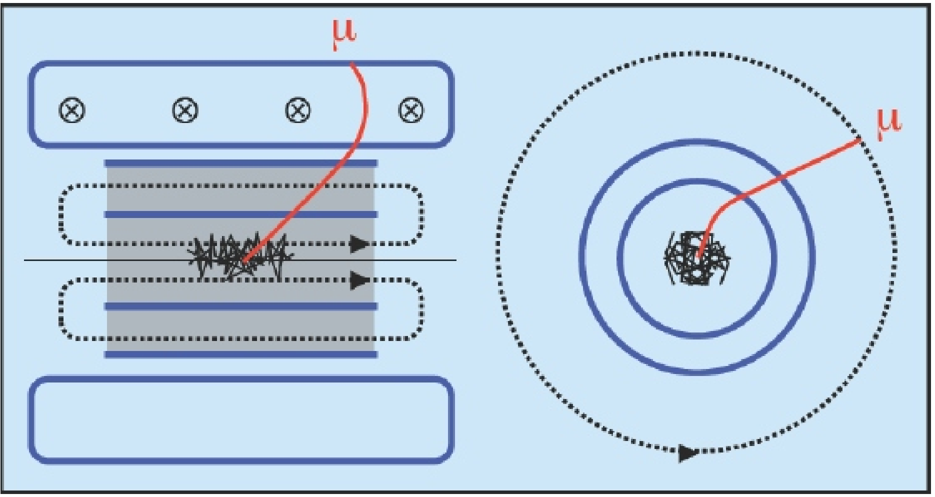


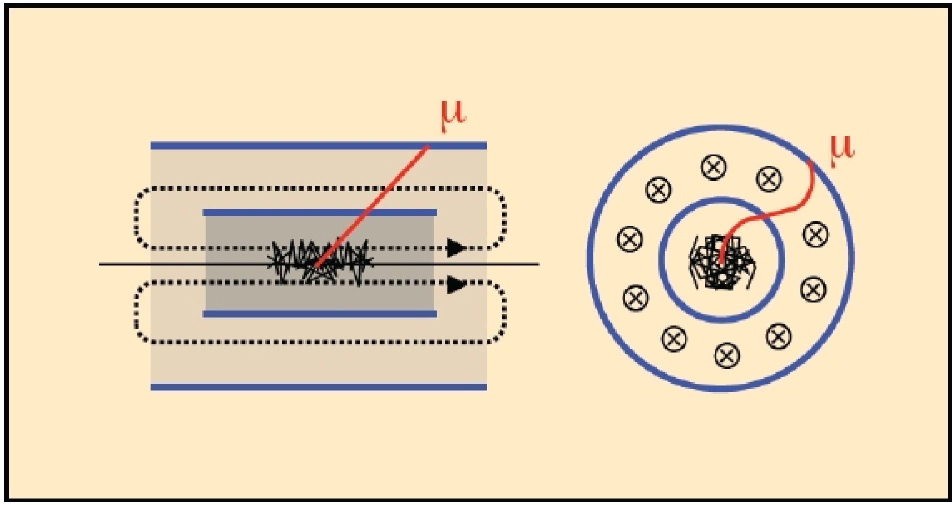
Hight: 25 m
Length: 40 m
Weight: 7000 t

CMS: Compact Muon Solenoid

Hight: 15 m
Length: 22 m
Weight: 12500 t





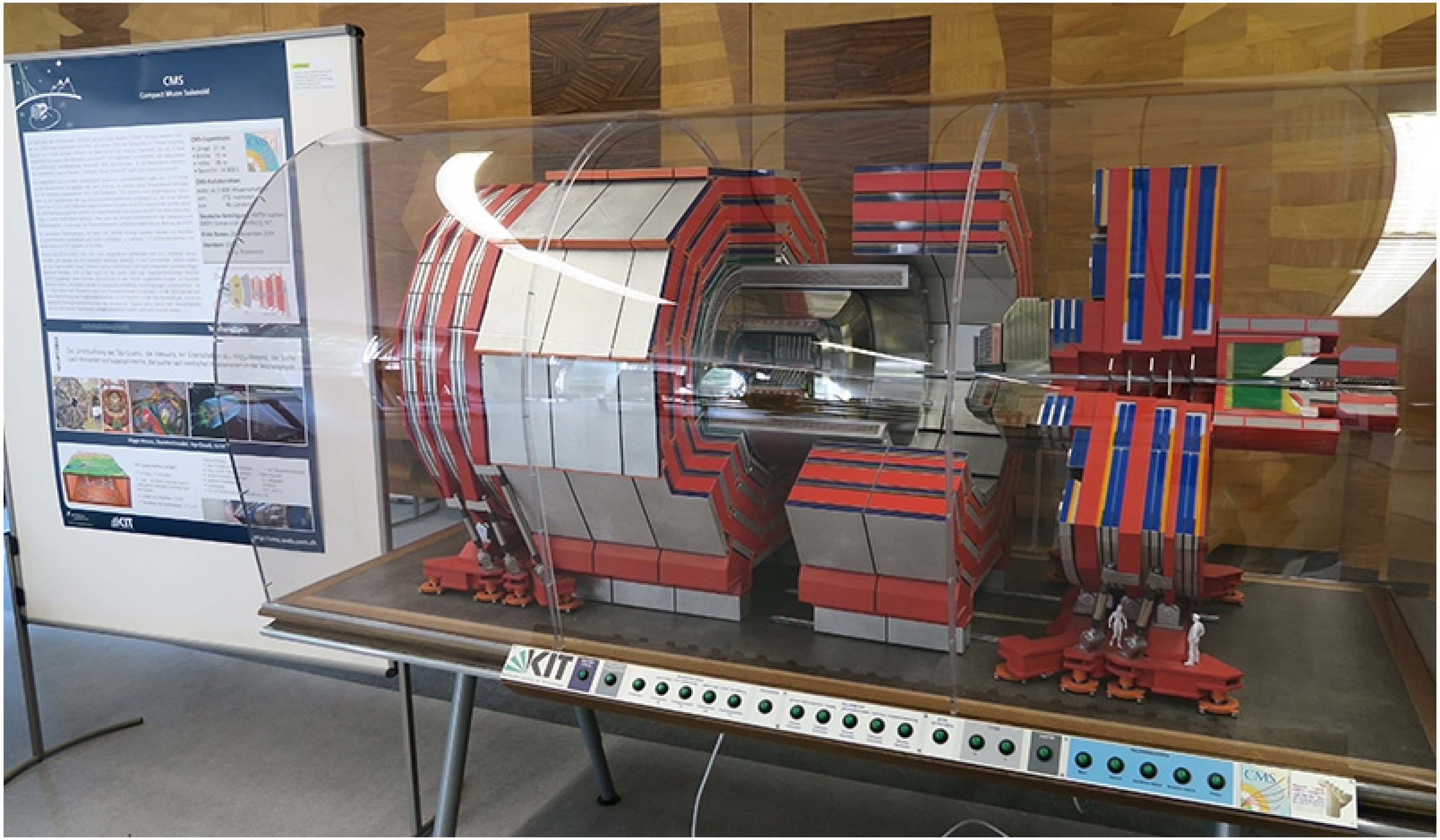


Comparison of Concepts

ATLAS		CMS
Silicon pixels; Silicon strips; Transition Radiation Tracker; 2 T magnetic field	Inner Detector	Silicon pixels, Silicon strips, 4 T magnetic field
Lead plates as absorbers; active medium: liquid argon; outside solenoid	Electrom. Calorimeter	Lead tungsten ($PbWO_4$) crystals; both absorber and scintillator; inside solenoid
Central region: Iron absorber with plastic scintillating tiles; Endcaps: copper and tungsten absorber with liquid argon	Hadronic Calorimeter	Stainless steel and copper with plastic scintillating tiles
Large air-core toroid magnet; muon chambers: drift tubes and resistive plate chambers; 0.5 T magnetic field	Muon Chambers	Magnetic field from return yoke (solenoid field: 4 T); muon chambers: drift tubes and resistive plate chambers

Exkursion:

CMS-Modell Foyer des Physikhochhauses



Overview: 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

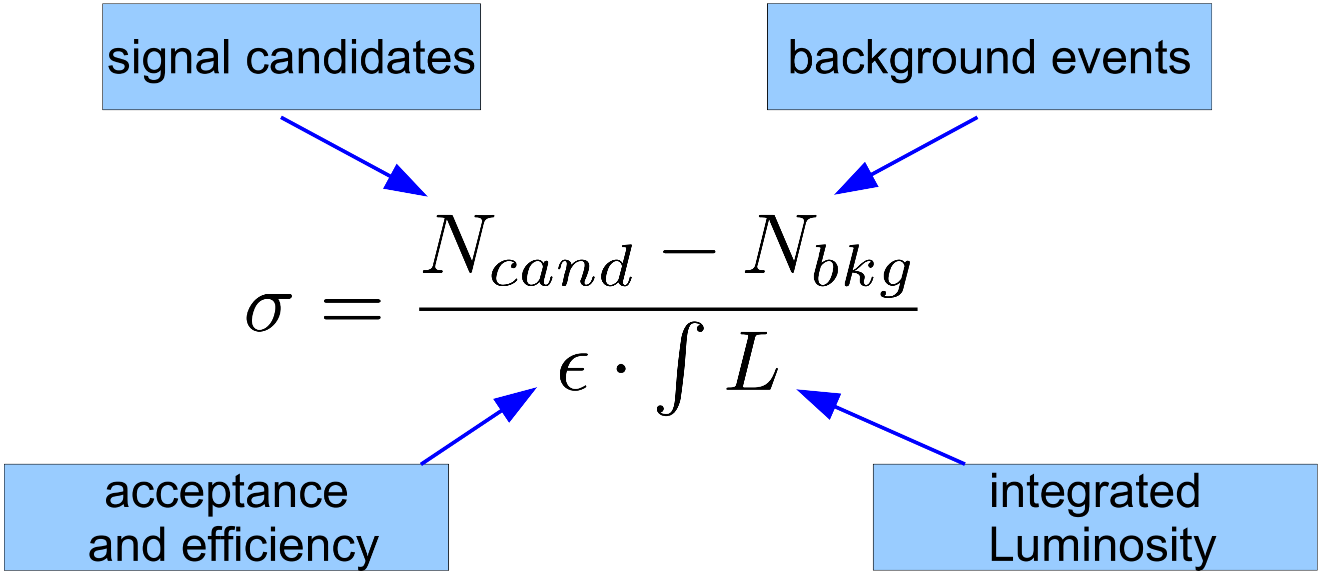
  ⟶ selection efficiency and purity

- **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 minimize

- 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, $N = \int \mathcal{L}\, dt \cdot \sigma$

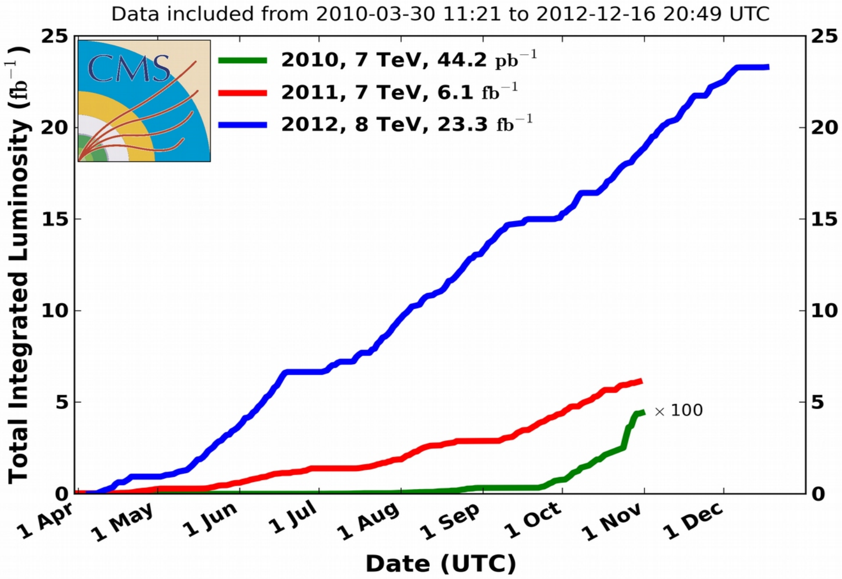
$\mathcal{L}$ is a property of the accelerator:

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

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

$\int\mathcal{L}$ recorded by the CMS experiment during LHC Run 1



The total integrated Luminosity of 29.4 fb^{-1} corresponds to 1.8 ·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:

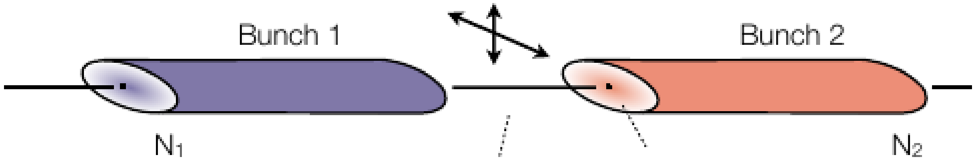
$$\int L = N_{ref} \,/\, \sigma_{ref}$$

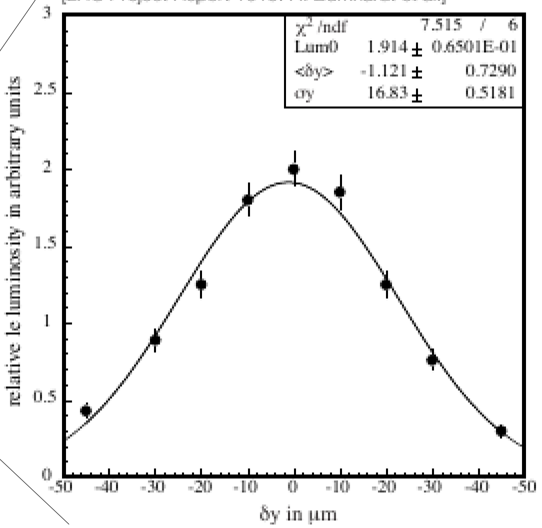
absolute value from

- 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





[LHC Project Report 1019: H. Burkhardt et al.]

relative methods:

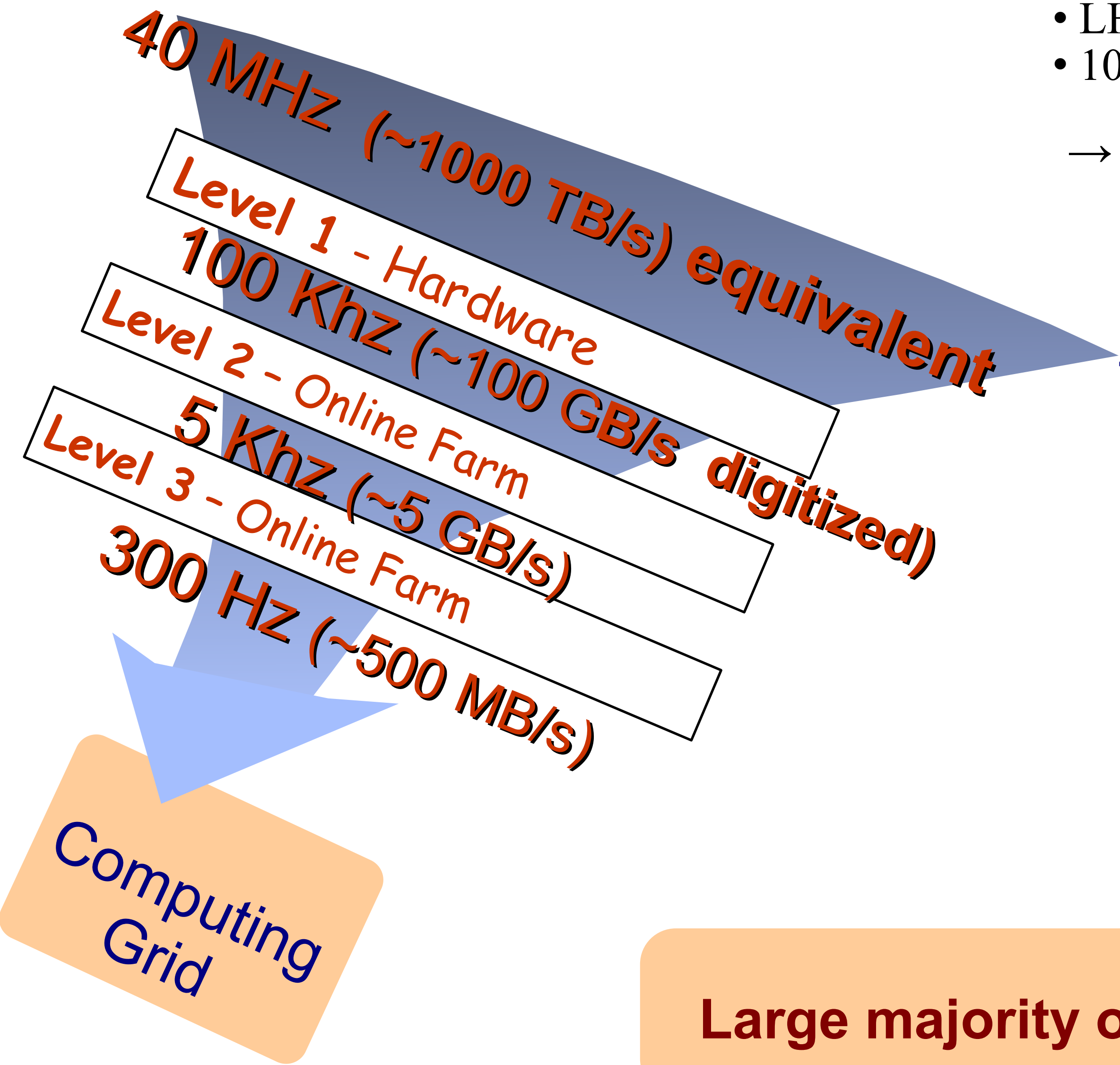
- particle counting or current measurements in detector components with high rates

  (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)

Trigger

Online Data Reduction



40 MHz (~1000 TB/s) equivalent

Level 1 - Hardware

100 Khz (~100 GB/s digitized)

Level 2 - Online Farm

5 Khz (~5 GB/s)

Level 3 - Online Farm

300 Hz (~500 MB/s)

Computing Grid

- ~ 100 million detector cells
- LHC collision rate: 40 MHz
- 10-12 bit/cell

→ **~1000 Tbyte/s raw data**

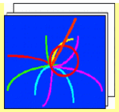
Zero-Suppression & **Trigger** reduce this to „only“ some 100 Mbyte/s

i.e. 1 /sec

Large majority of events is not stored!

CMS Trigger & Data Acquisition

every 25 ns



40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

DAQ accepts
Level-1 Rate of 100kHz

1 Terabit/s
(50000 DATA CHANNELS)

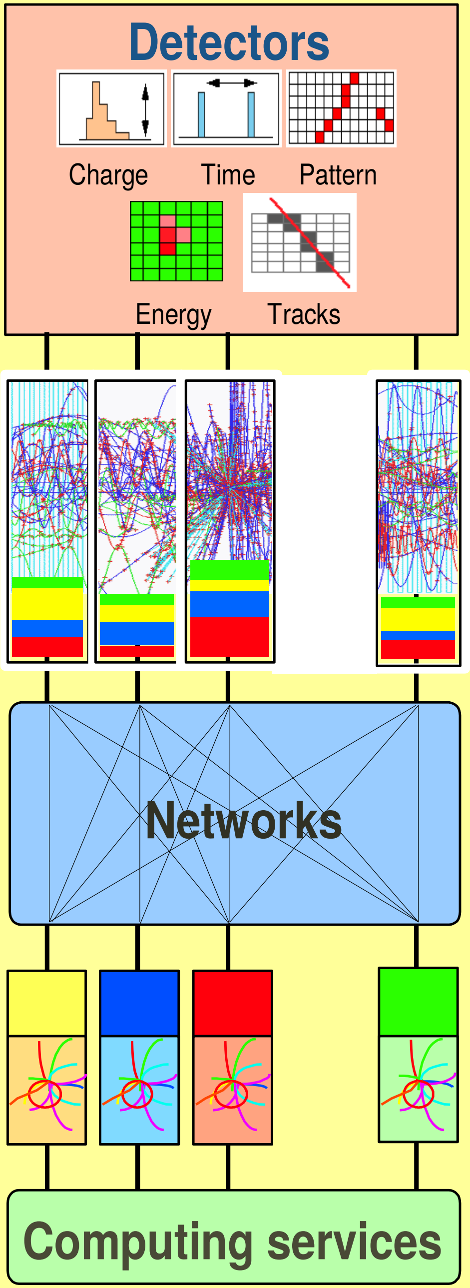
500 Gigabit/s

HLT (High Level Trigger) designed for O(100Hz)

- suppression factor ~1000

~2000 CPUs

Gigabit/s SERVICE LAN



16 Million channels
3 Gigacell buffers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

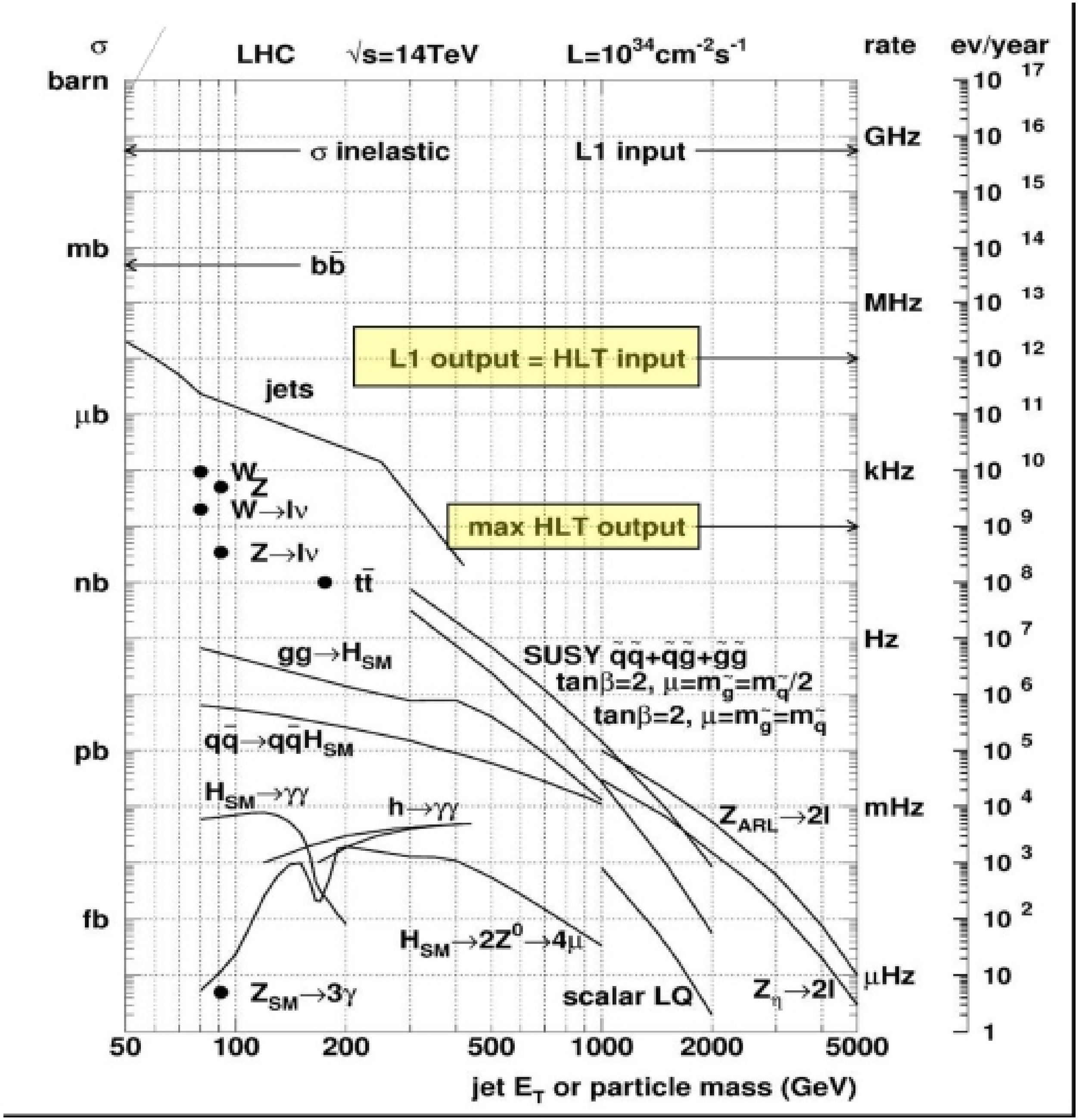
EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

5 TeraIPS

EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

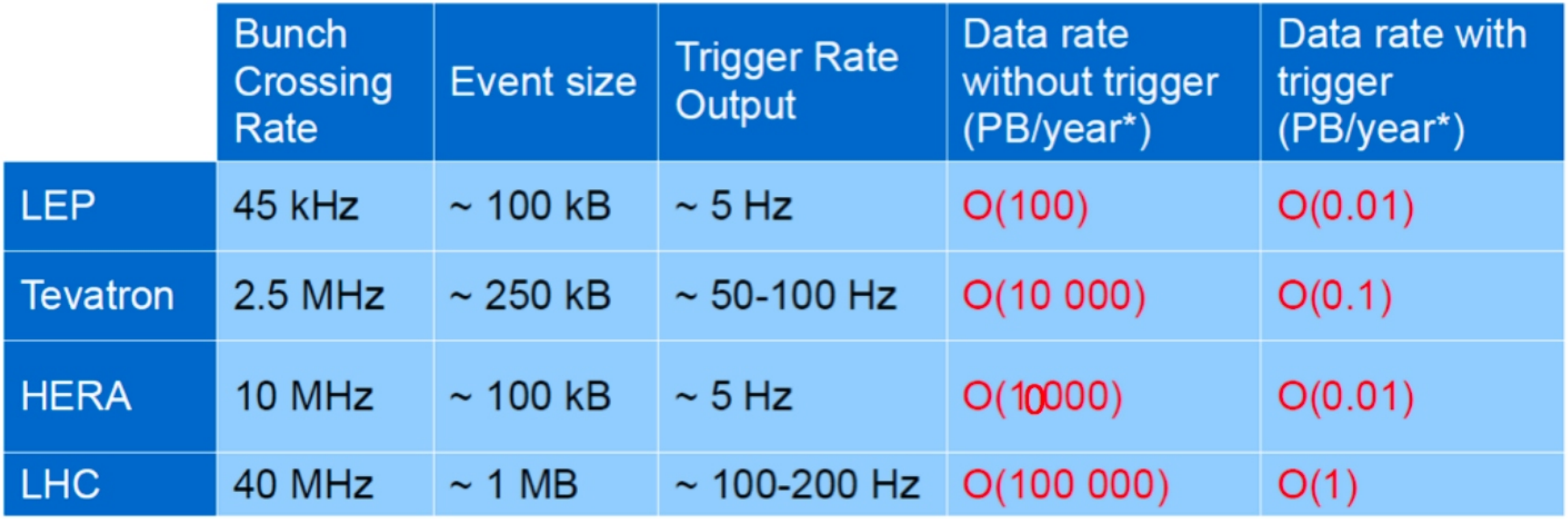
Petabyte ARCHIVE

Trigger Rate vs. Cross section



Much of the
"interesting physics"
limited by maximum
possible trigger rate !

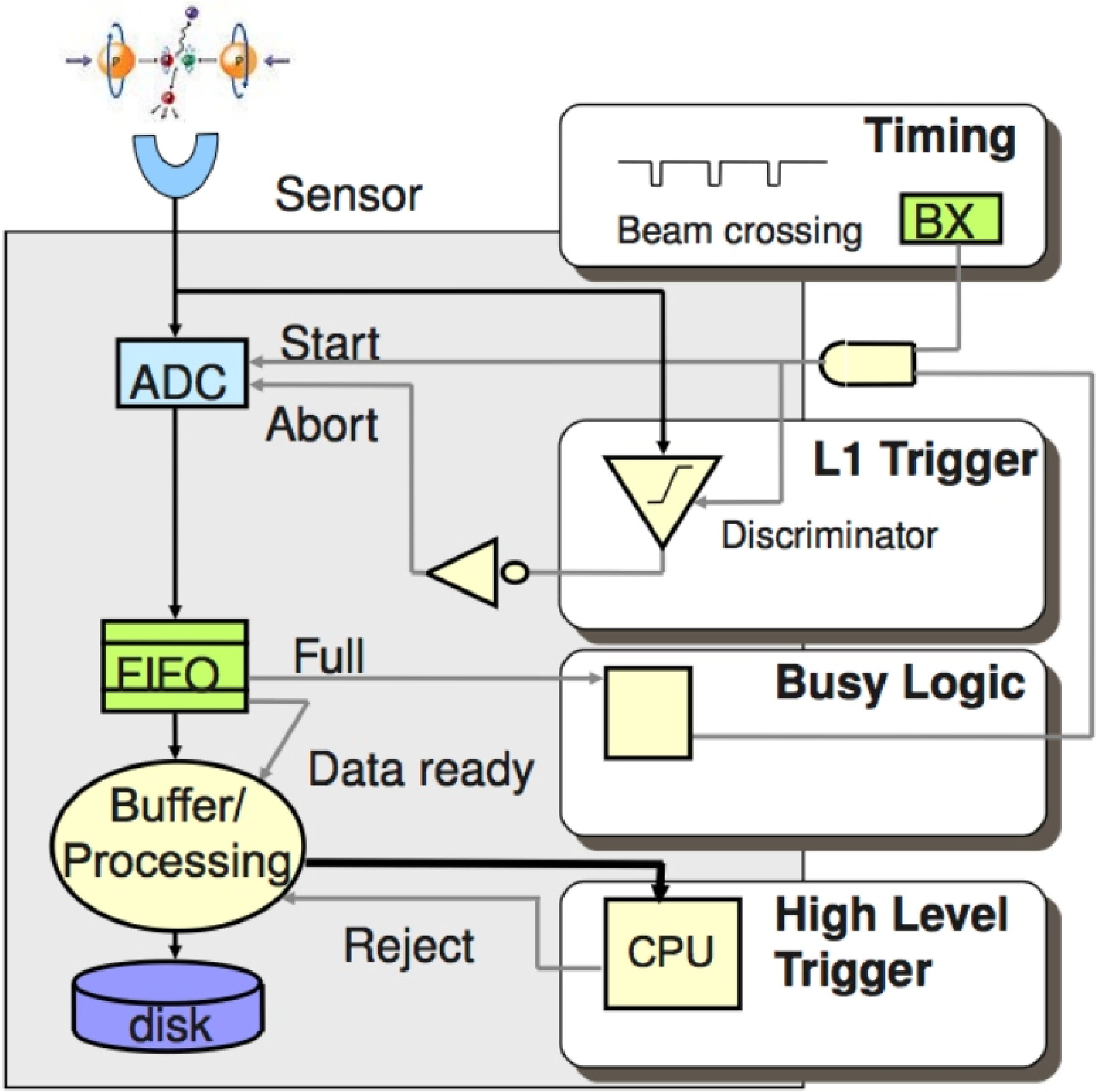
The need for a Trigger ….



	Bunch Crossing Rate	Event size	Trigger Rate Output	Data rate without trigger (PB/year*)	Data rate with trigger (PB/year*)
LEP	45 kHz	~ 100 kB	~ 5 Hz	O(100)	O(0.01)
Tevatron	2.5 MHz	~ 250 kB	~ 50-100 Hz	O(10 000)	O(0.1)
HERA	10 MHz	~ 100 kB	~ 5 Hz	O(10000)	O(0.01)
LHC	40 MHz	~ 1 MB	~ 100-200 Hz	O(100 000)	O(1)

assumed data volumes without triggering

A simple Sketch of a trigger logic



Level 1
Hardware Trigger

Level 2
Software Trigger

Example of L1 Trigger and "Trigger Menu"

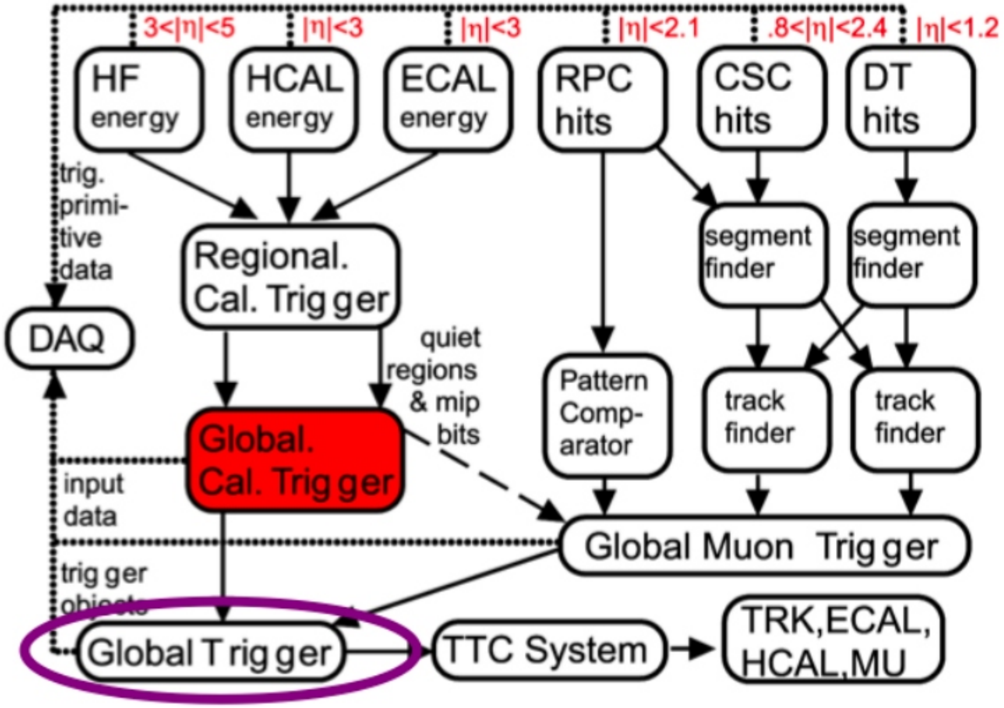
Multiple sources of L1 triggers combined in one place
for final decision of "accept" or "reject" (global/central trigger)
- also includes busy logic

Can either be big OR of input triggers, require combinations of certain trigger objects or even some topological cuts

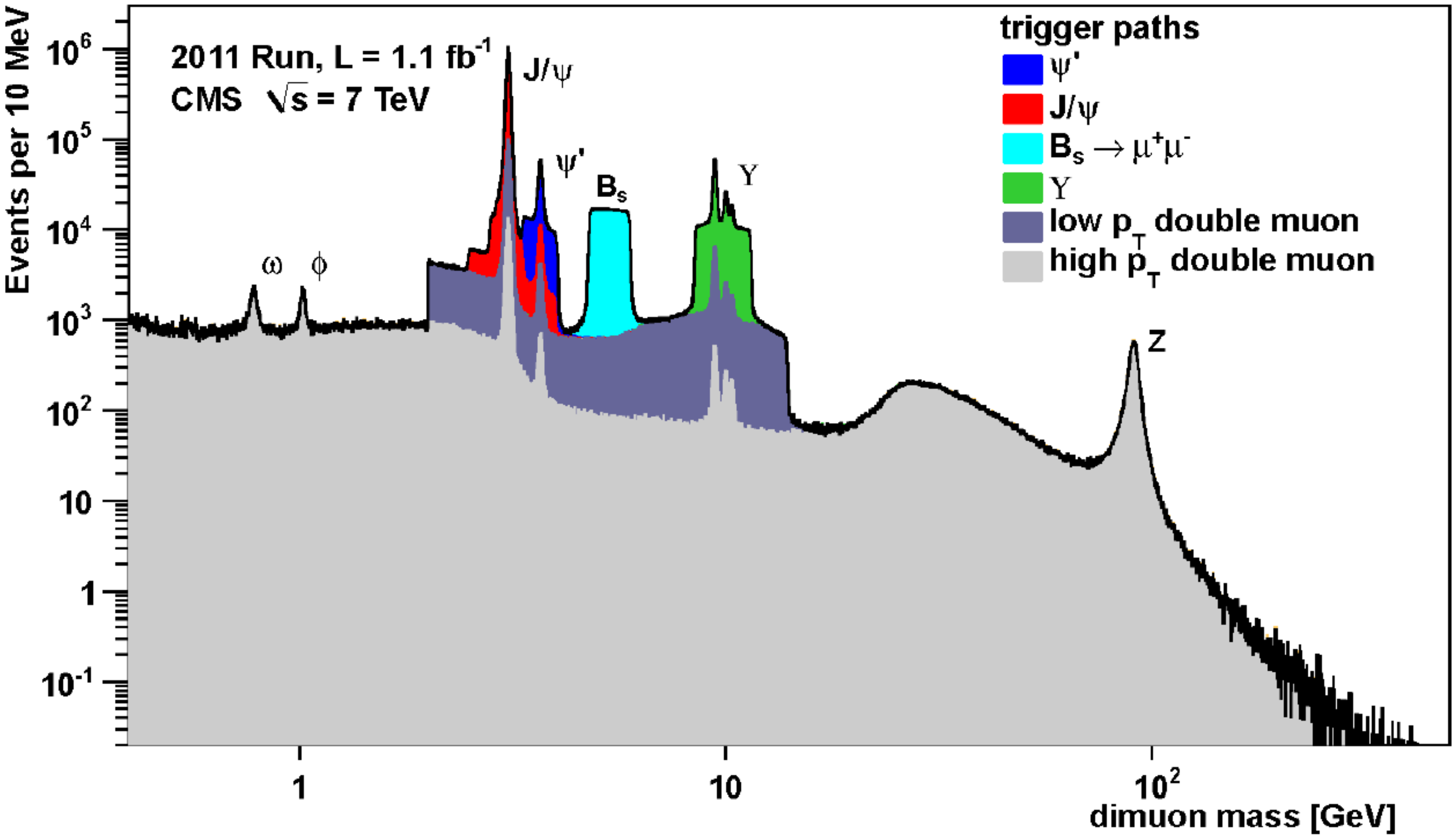
Example:
trigger menu for isolated muons:

- 1 muon with p_T>20 GeV, or
- 2 muons with p_T>5 GeV, or
- 1 electron with p_T>7 GeV and 1 muon with p_T>5 GeV, or
- 1 muon above 15 GeV and no jet within $\Delta\phi$ of 0.2 rad,

Example: CMS L1 Trigger



The Power of Trigger Flexibility



Efficiently triggering di-muon resonances in CMS

What is easy to trigger ?

Trigger thresholds rise as luminosity goes up,
and are a topic of permanent debate !

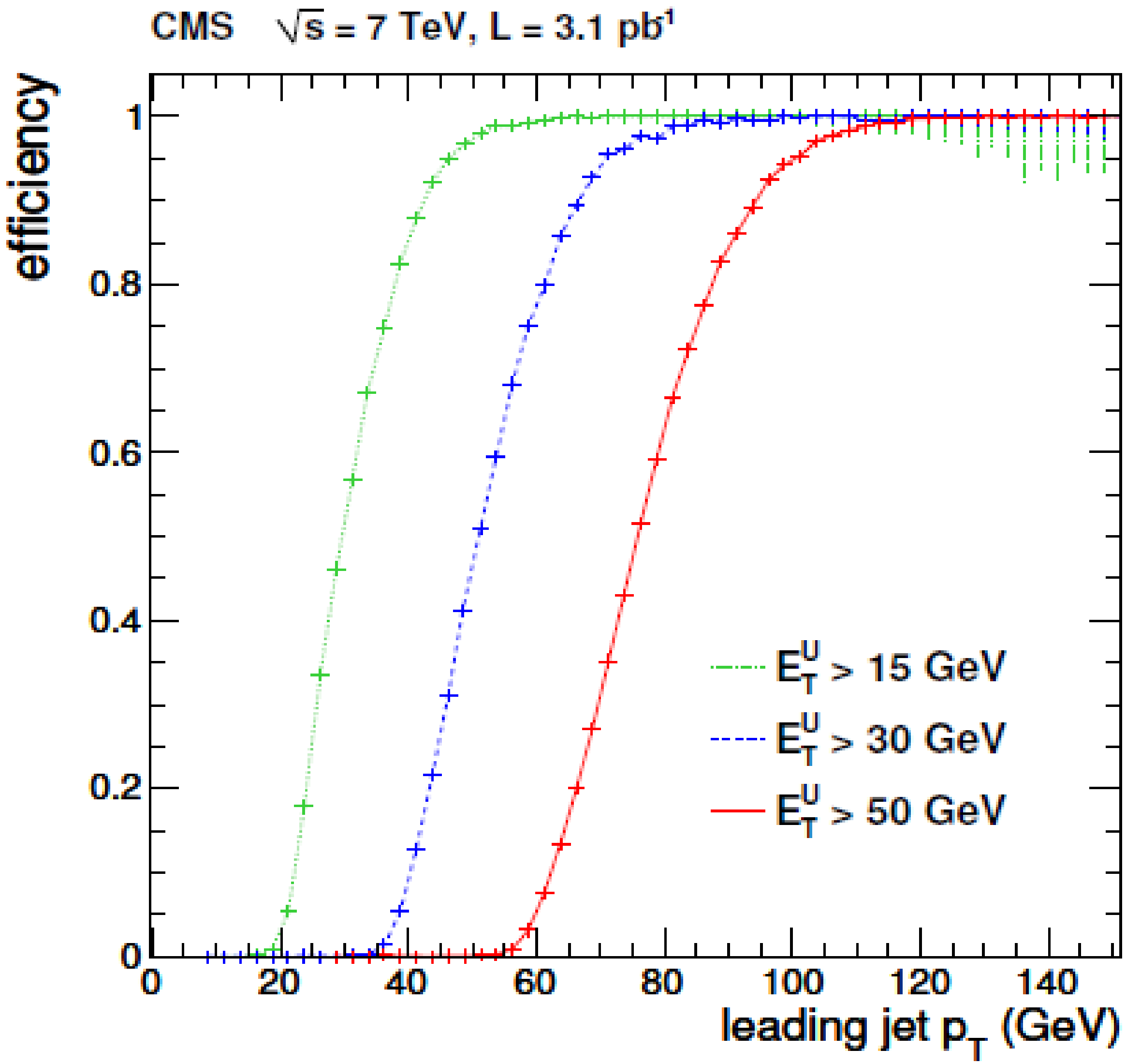
- isolated leptons with large transverse momentum > ~20 GeV (from W, Z, top)
- di-lepton events with transverse momentum > ~10 GeV
- jets with very high transverse momentum (several 100 GeV)
- events with large missing energy (~100 GeV)
- isolated photons with transverse energy >~50 GeV

lower-threshold triggers typically pre-scaled

Rest is difficult and probably not in recorded data !

for analysis, must know trigger efficiencies

Example: trigger "turn-on" for jets



typical knee-shaped trigger efficiency curves (CMS, 2010), rising from 0 to 1 to come next week:

Data Analysis