Wstęp do fizyki cząstek elementarnych: część eksperymentalna

System akceleratorowy w CERNie

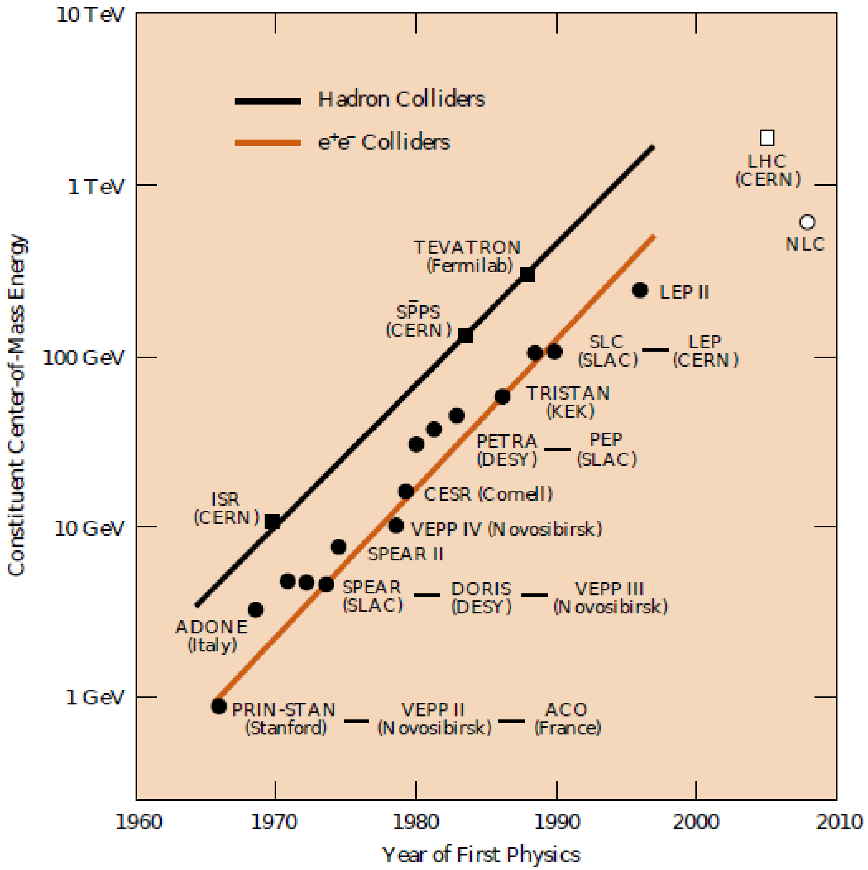
Pierwsze dane LHC

Pomiary Modelu Standardowego

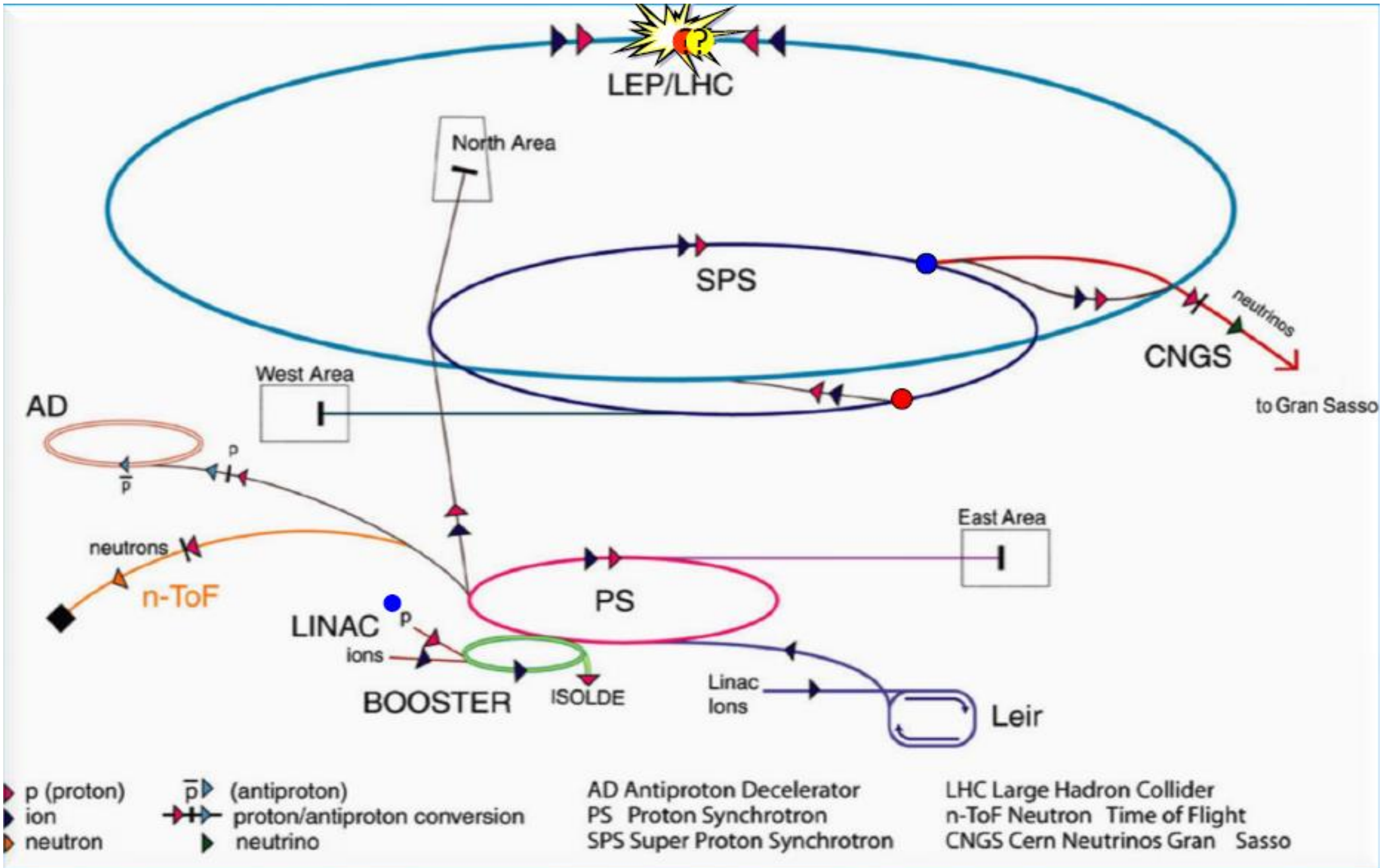
Prof. dr hab. Elżbieta Richter-Wąs

Energy frontier

- Historical progress has been like power law for most of the last 70 years
  - Vast majority of recent machines were synchrotrons
  - Notable exceptions
    - SLC
    - NLC/ILC



CERN accelerator complex



Luminosity frontier

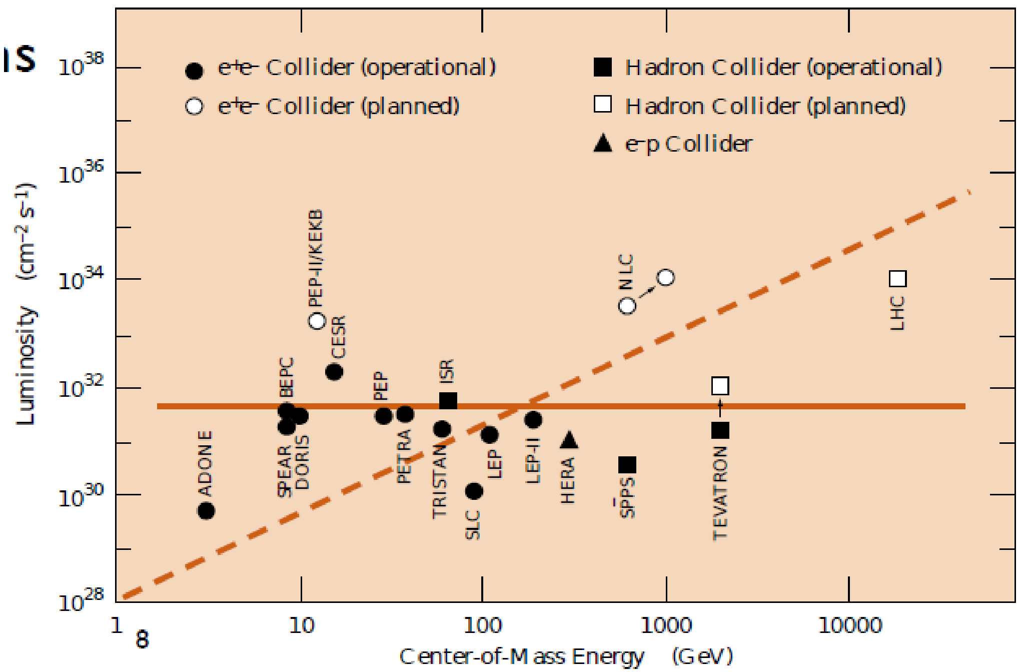
- Need corresponding rise in luminosity (beam intensity)

Number of events — Instantaneous luminosity

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

Cross section — Integrated luminosity

- High luminosity brings all the challenges for the detectors:
  - High event rates
  - Pile up
  - Beam –beam interactions
  - Beamstrahlung



Designing a machine

- Particle species
  - Electron/positrons
  - Protons/antiprotons
  - Muons/antimuons
- Beam energy
- Spin
- Luminosity

- How do you produce antiparticles?
- Ones produced how ones keep them (muon collider)?
- Ones collided what ones does with spent beams?
- Accelerator and detector protection

Accelerator is much more than just….

- Particle production
- Damping, cooling or preparation
- Injection and extraction
- Acceleration
- Collimation (betatron, energy etc.)
- Diagnostics and controls
- Machine (and detector protection)
- Beam delivery and luminosity production
- Technology spin off
  - Lower energy machines, medical applications, applied physics, materials, …..

Acceleration

Lorentz force law

$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

Electric field Velocity Magnetic field

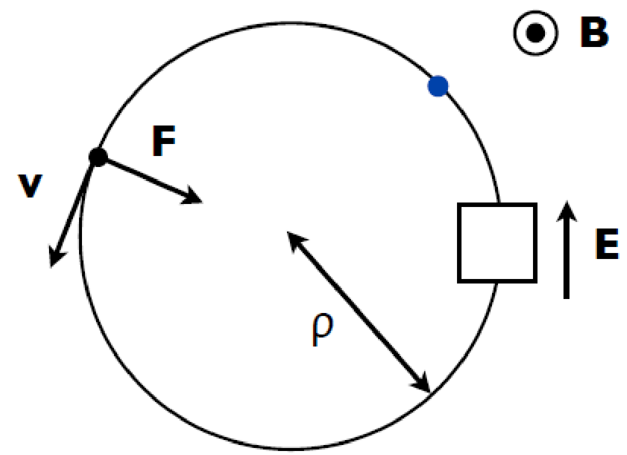
Energy change

$$\Delta E = \int_{\mathbf{r}_1}^{\mathbf{r}_2} \mathbf{F} \cdot d\mathbf{r}$$

- Electric field (either static or more commonly, time varying) to accelerate, or more appropriately, increase energy of beam
- Magnetic part of Lorentz force used to guide and focus
  - Dipole magnets: to bend
  - Quadrupole: to focus or defocus

Synchrotron

- Workhorse of modern particle physics
  - Huge legacy of discovery
  - Increase energy whilst synchronously increasing bending magnet strength
  - Stable storage of high beam current/power
- Magnetic field proportional to momentum



Velocity

$$qBv = \frac{m_0 v^2}{\rho}$$

Magnetic field

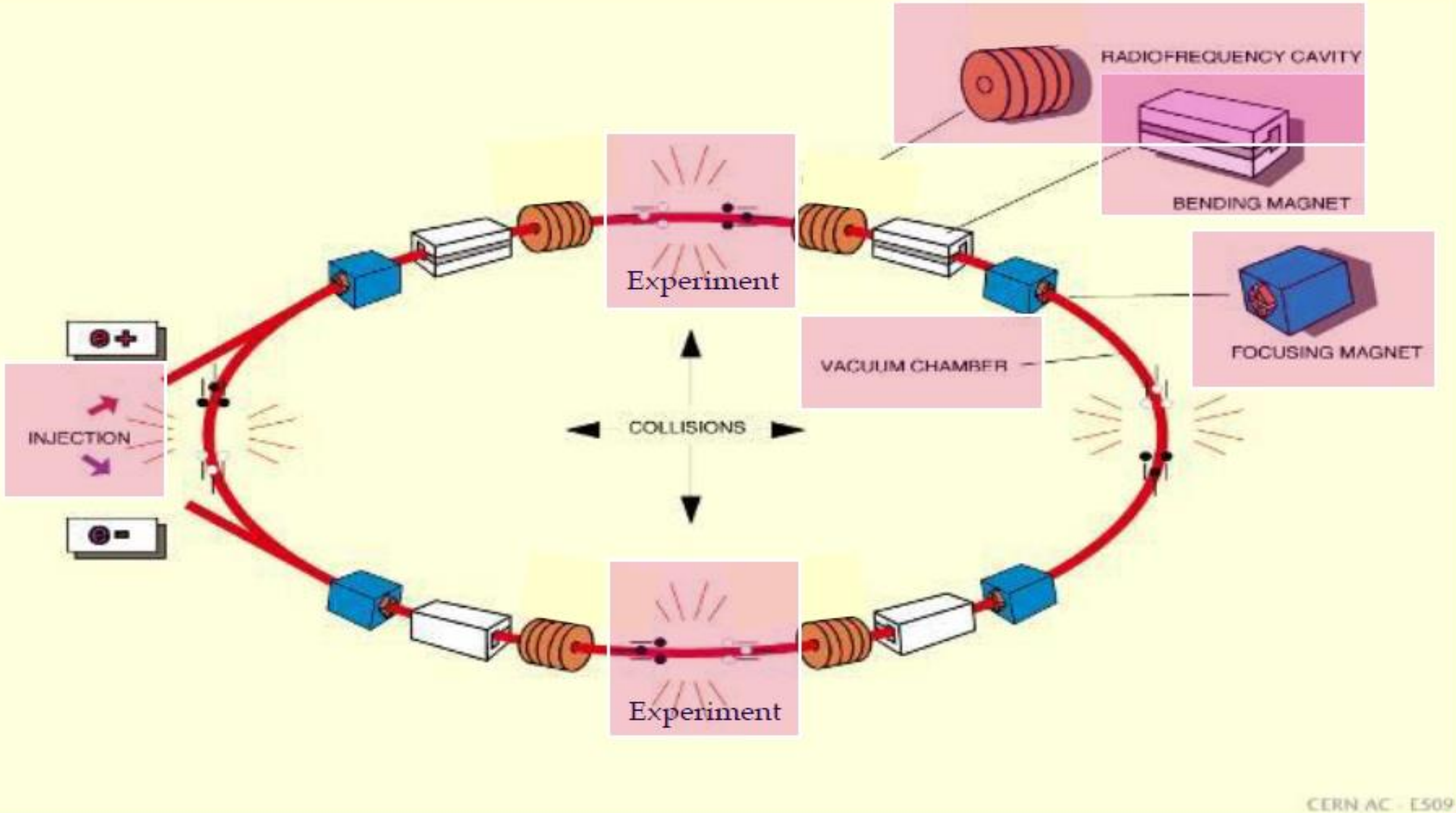
Bending radius

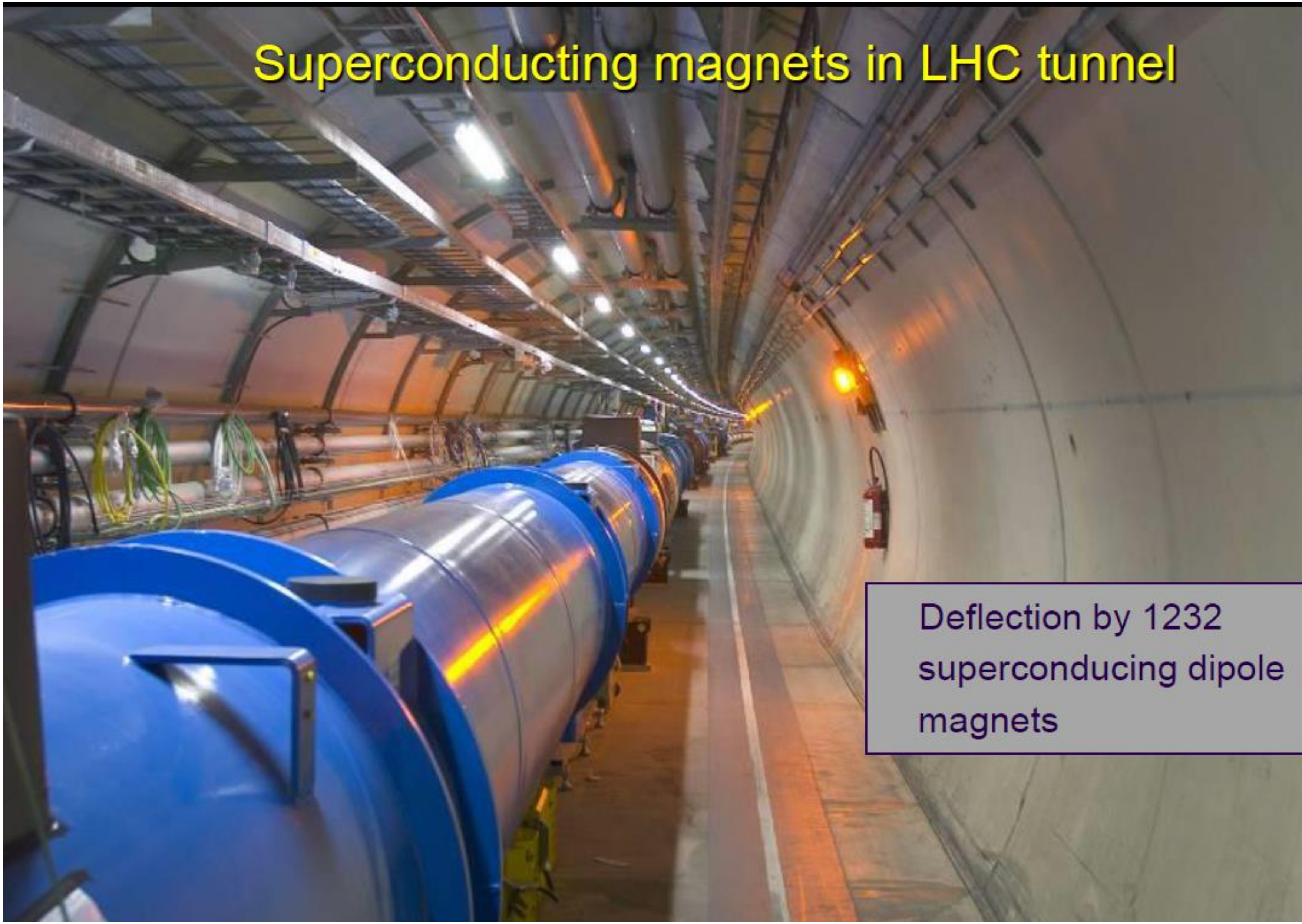
$$B\rho = p/q$$

Momentum

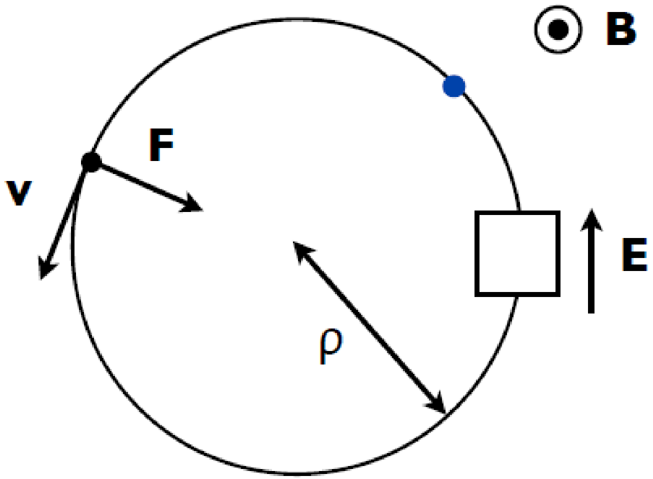
Synchrotron + many passages in RF cavities

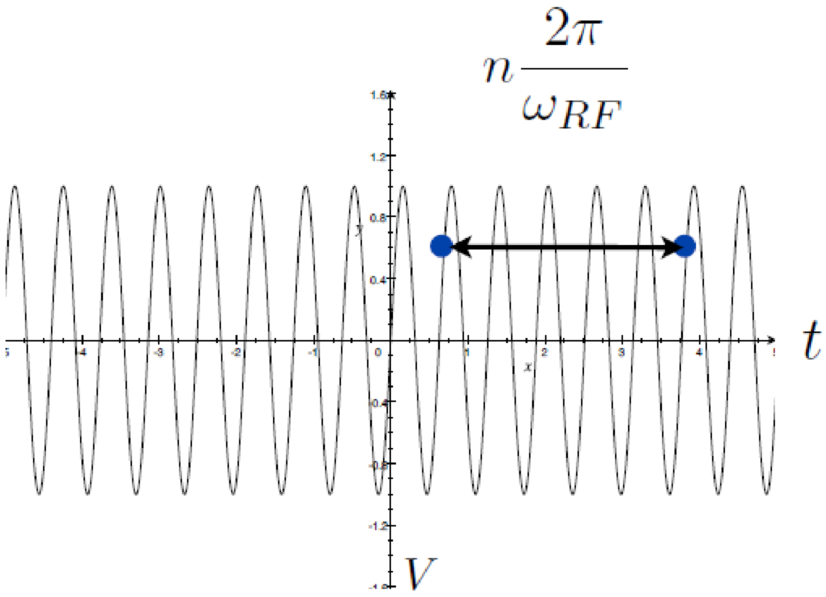
LHC **circular machine** with energy gain per turn ~0.5 MeV
acceleration from 450 GeV to 7 TeV will take about 20 minutes




Superconducting magnets in LHC tunnel
Deflection by 1232 superconducing dipole magnets

Synchrotron





- Time varying electric field:

$$V(t) = V_0 \sin(\omega_{RF} t + \phi)$$

Angular frequency of accelerating field

- Particle gets a kick every revolution

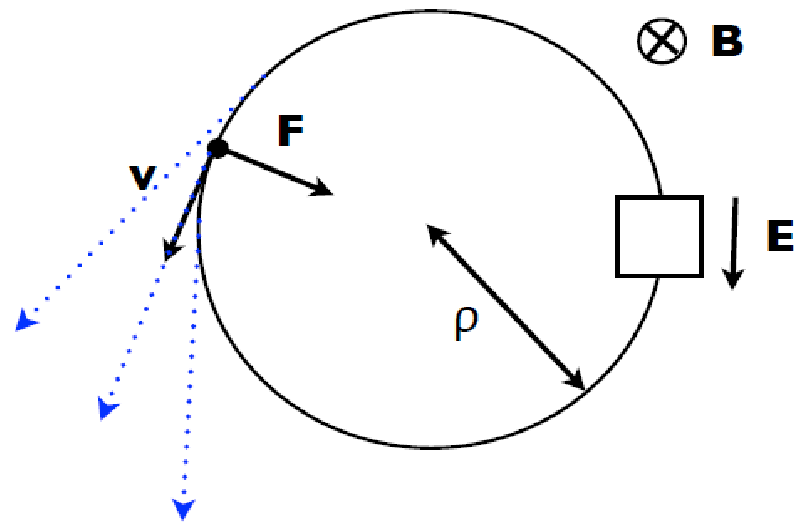
$$\frac{1}{f_{\mathrm{ref}}} = n\frac{2\pi}{\omega_{\mathrm{RF}}}$$

Revolution frequency

Integer

Synchrotron Radiation Limits

- Why not just build bigger LEP?
  - Reuse accelerating section every revolution of particle bunch
  - Power loss due to synchrotron radiation
  - LEP2 was practical limit for electron-positron synchrotron



Power

$$P = \frac{1}{4\pi\epsilon_0}\frac{e^2 v^4}{c^3 \rho^2}\gamma^4$$

Energy loss per turn

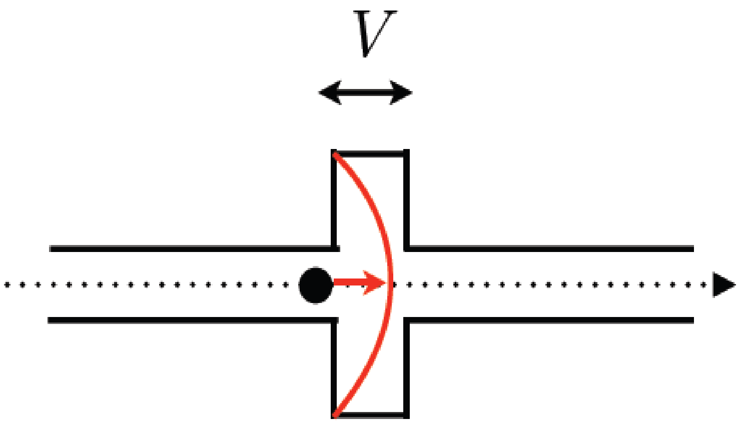
Beam energy

$$W = 8.85 \times 10^{-5} E^4 / \rho$$

Magnetic radius

Absolute Limits on Acceleration

- Need to create large on axis electric fields
  - Accelerating structures:
    - Superconducting (~35 MV/m)
    - Normal conducting (~100 MV/m)
- Beyond these values there is high voltage breakdown

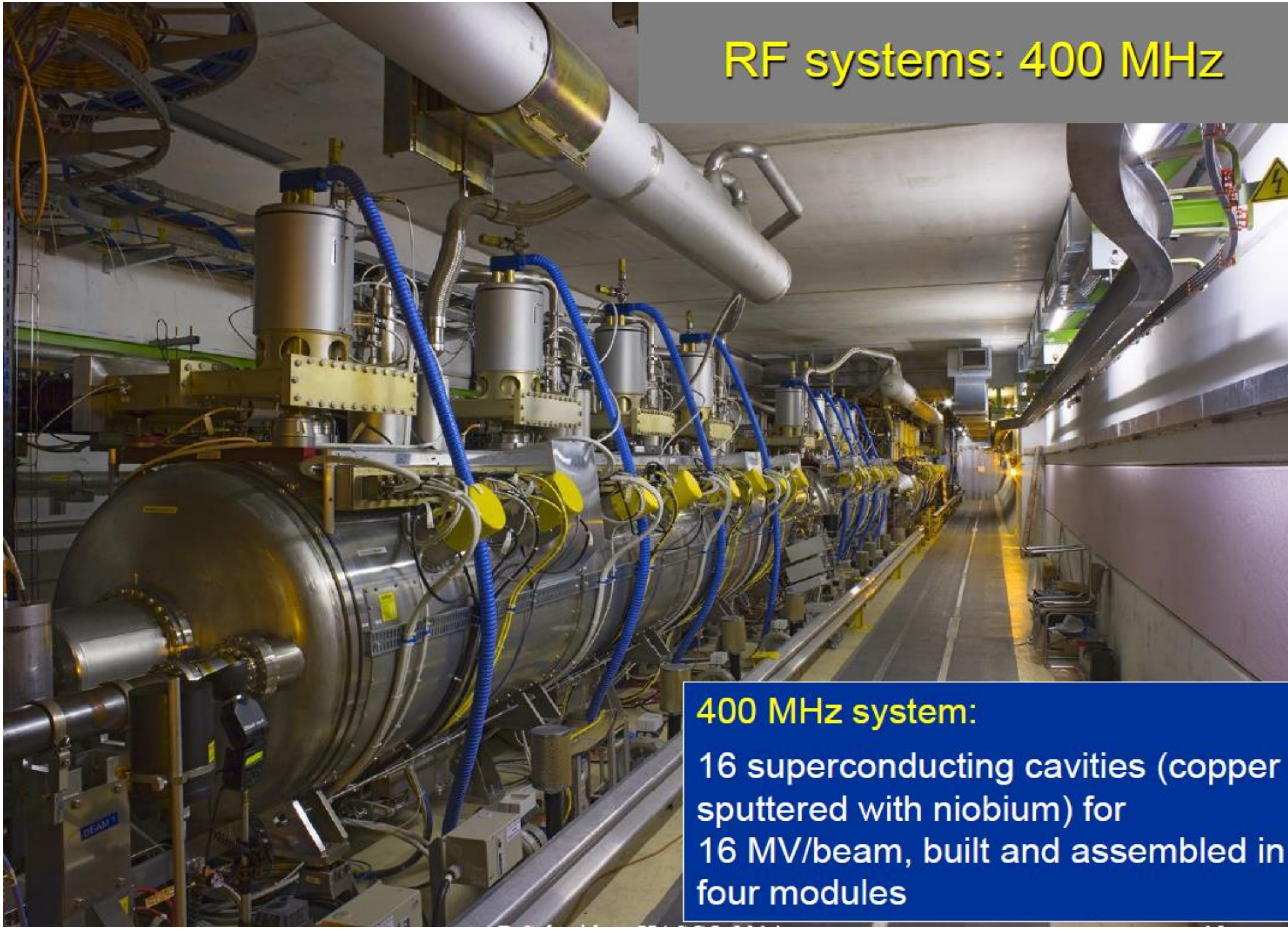


Machine length [m] — Beam energy [MeV]

$$S = \frac{E}{q\, dV/ds}$$

Accelerating gradient [MV/m]

RF systems: 400 MHz

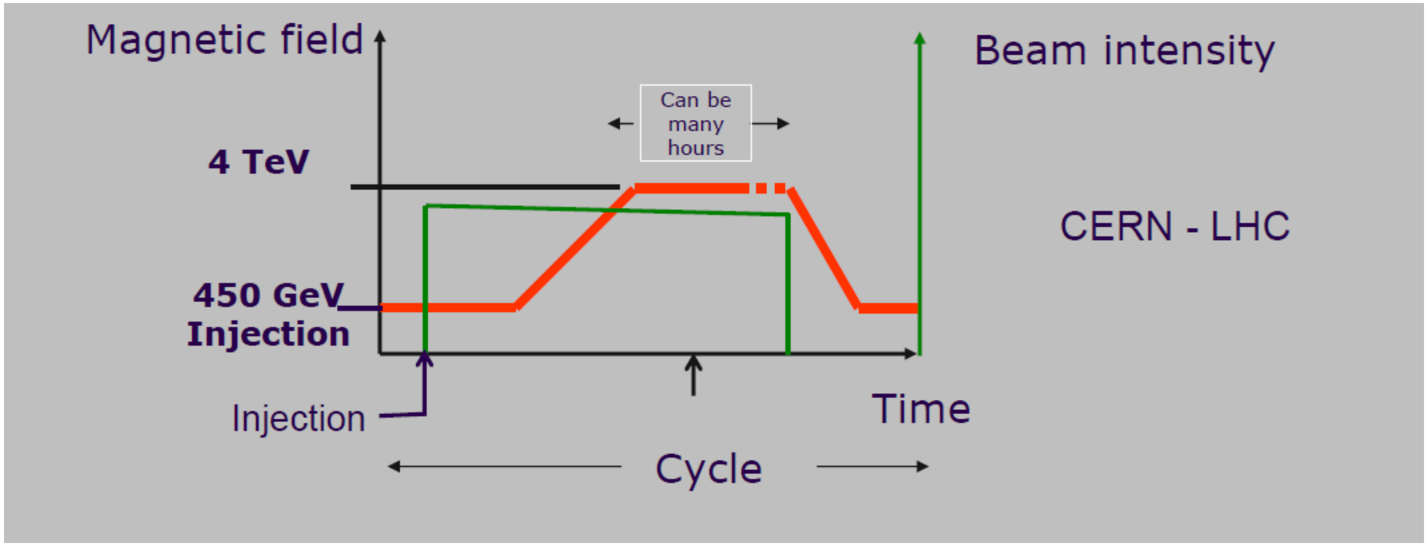


400 MHz system:

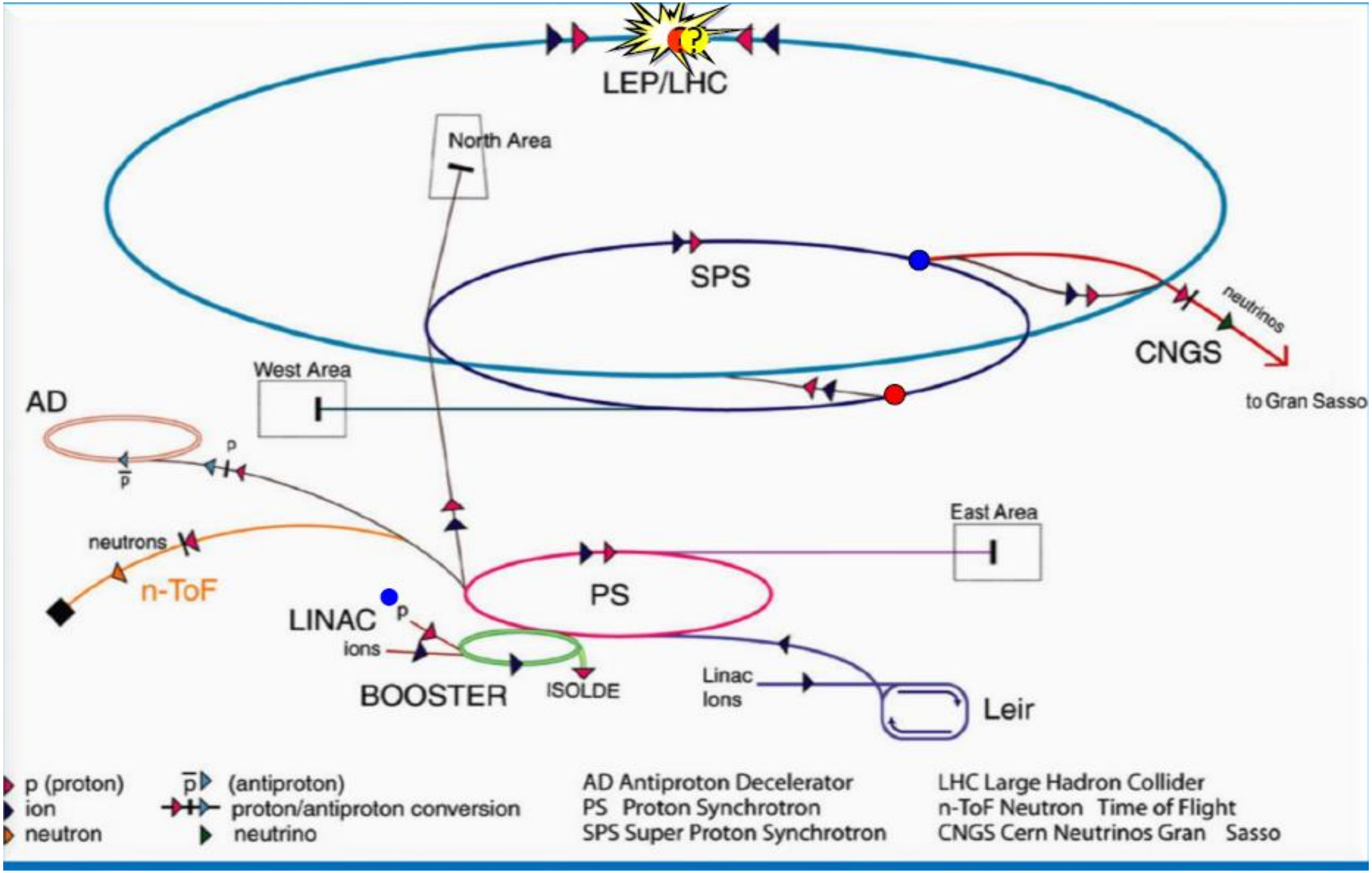
16 superconducting cavities (copper sputtered with niobium) for 16 MV/beam, built and assembled in four modules

Principle of a synchrotron

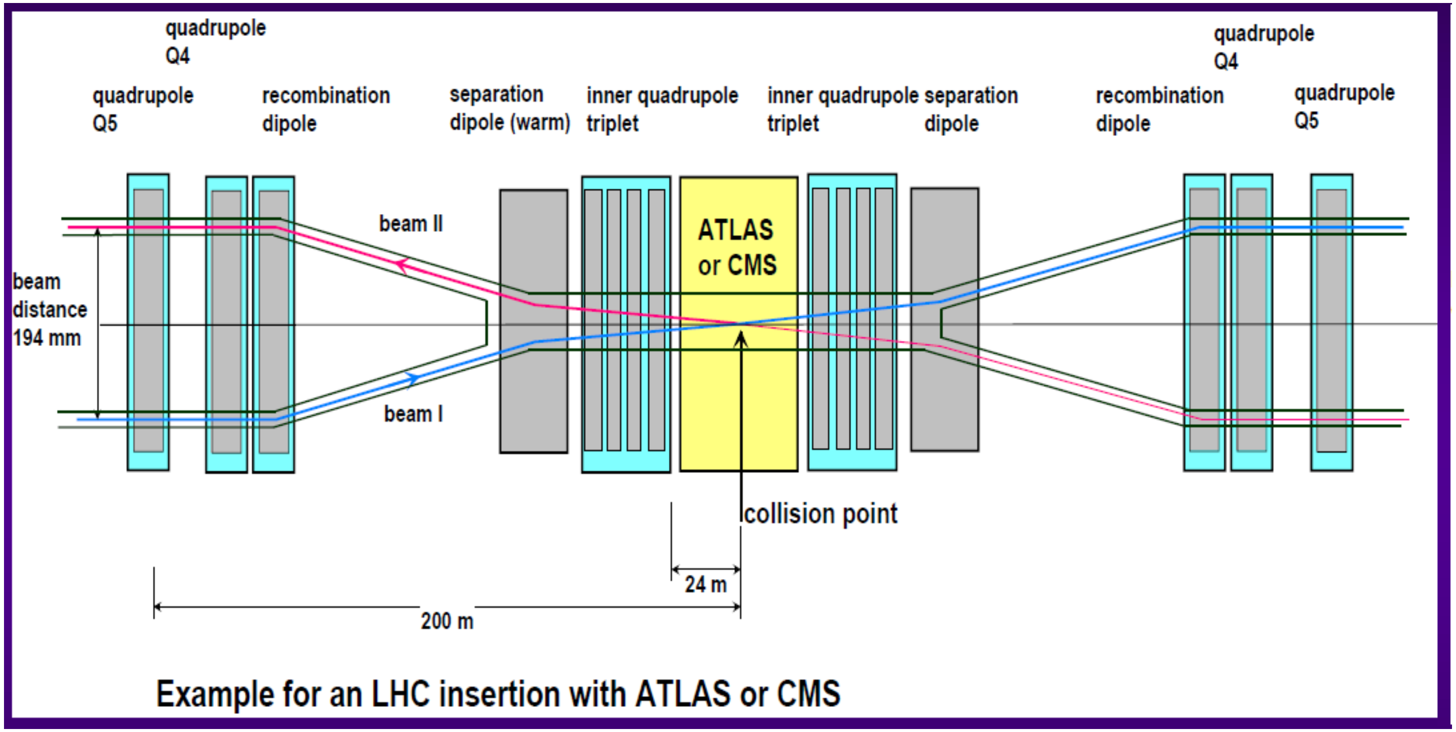
- Injection at low energy
- Ramping of magnetic field and acceleration by RF field. Beams are accelerated in bunches
- Operation (collisions) at top energy



CERN accelerator complex



Experimental long straight section



The 2 LHC beams are brought together to collide in common region. Over ~260m the beams circulate in one vacum chamber with „parasitic" encounters.

The crossing angle of about 300μrad

Luminosity

- What luminosity is required for measurement?
  - Need some knowledge of x-section
- Simple relationship between number of particles, frequency of collision and beam sizes

Luminosity [s⁻¹ m⁻²]

Bunch populations

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

Frequency of collisions [Hz]

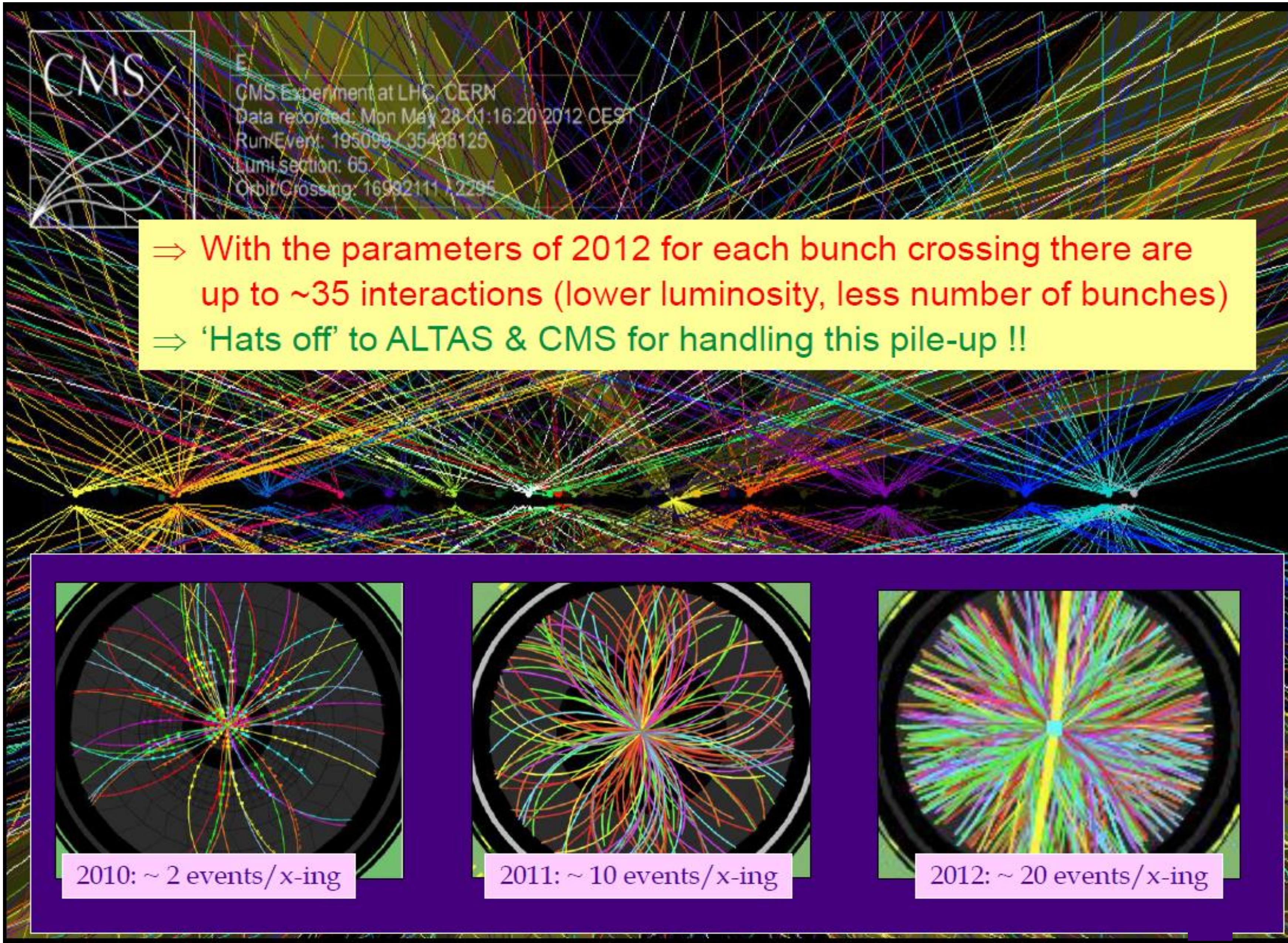
Beam r.m.s. sizes [m]

$$\sigma = \sqrt{\epsilon\beta}$$

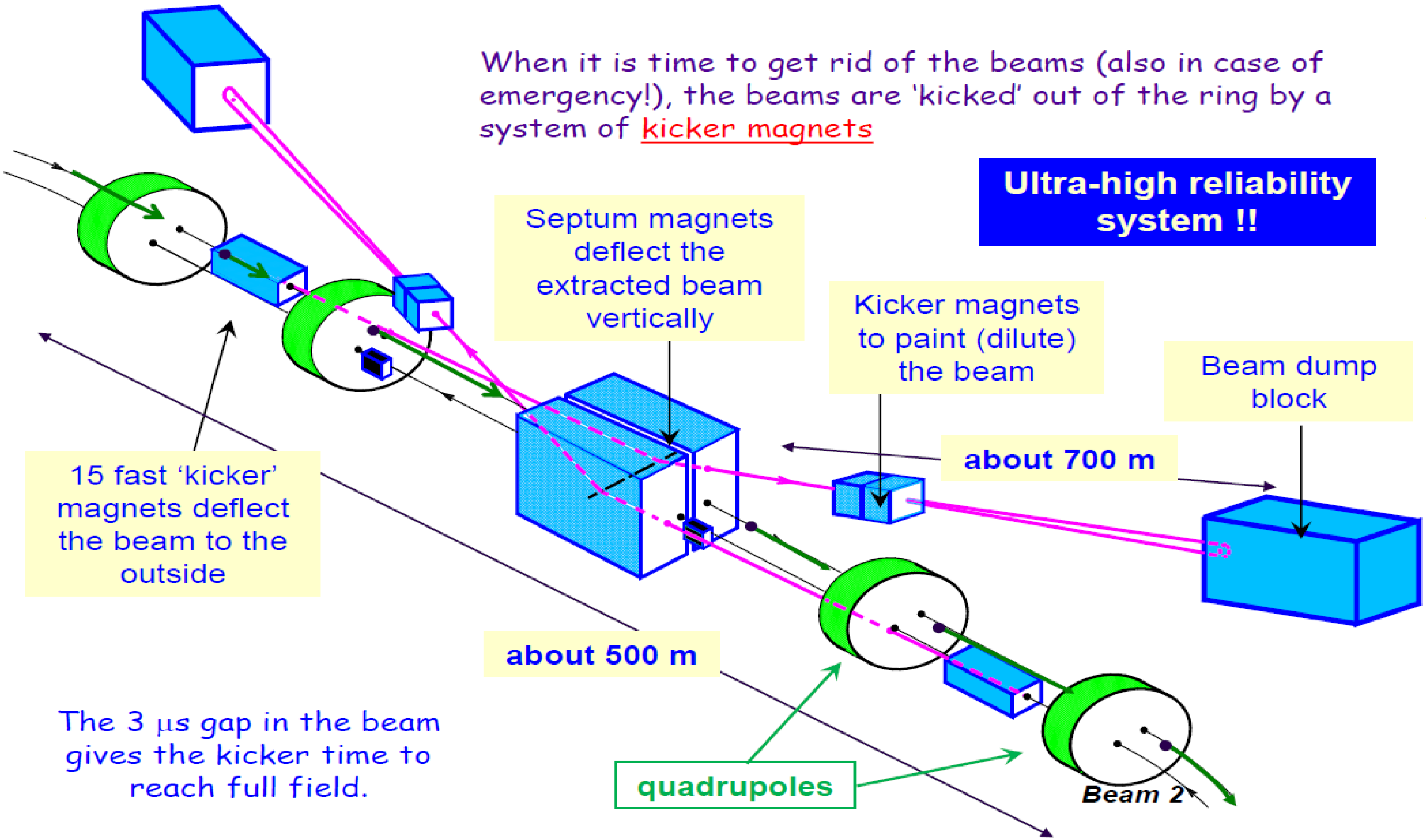
Emittance [m]

Beta function [m]

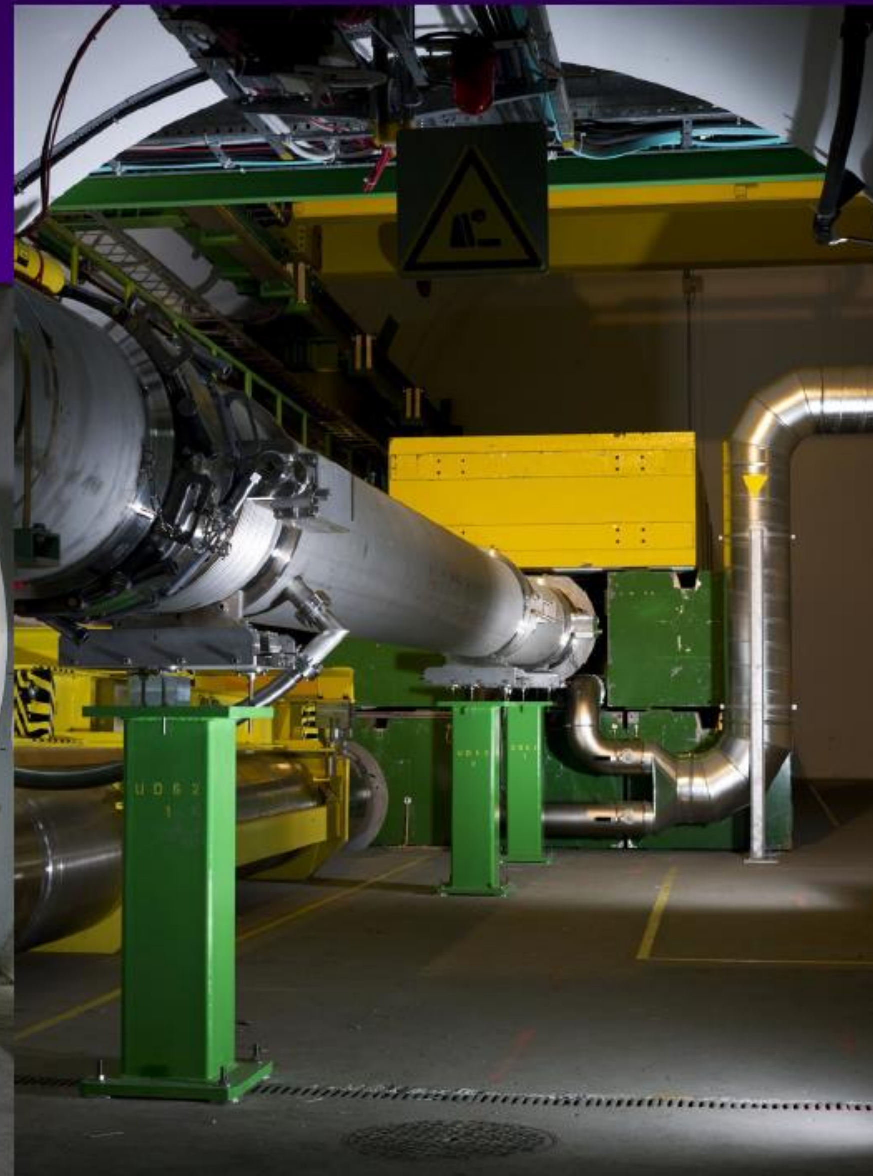
$$\mathcal{L} = f \frac{N_1 N_2}{4\pi\sqrt{\epsilon_x\beta_x^*\epsilon_y\beta_y^*}}$$


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
⇒ With the parameters of 2012 for each bunch crossing there are up to ~35 interactions (lower luminosity, less number of bunches)
⇒ 'Hats off' to ALTAS & CMS for handling this pile-up !!
2010: ~ 2 events/x-ing
2011: ~ 10 events/x-ing
2012: ~ 20 events/x-ing

Layout of beam system dump



Dump line

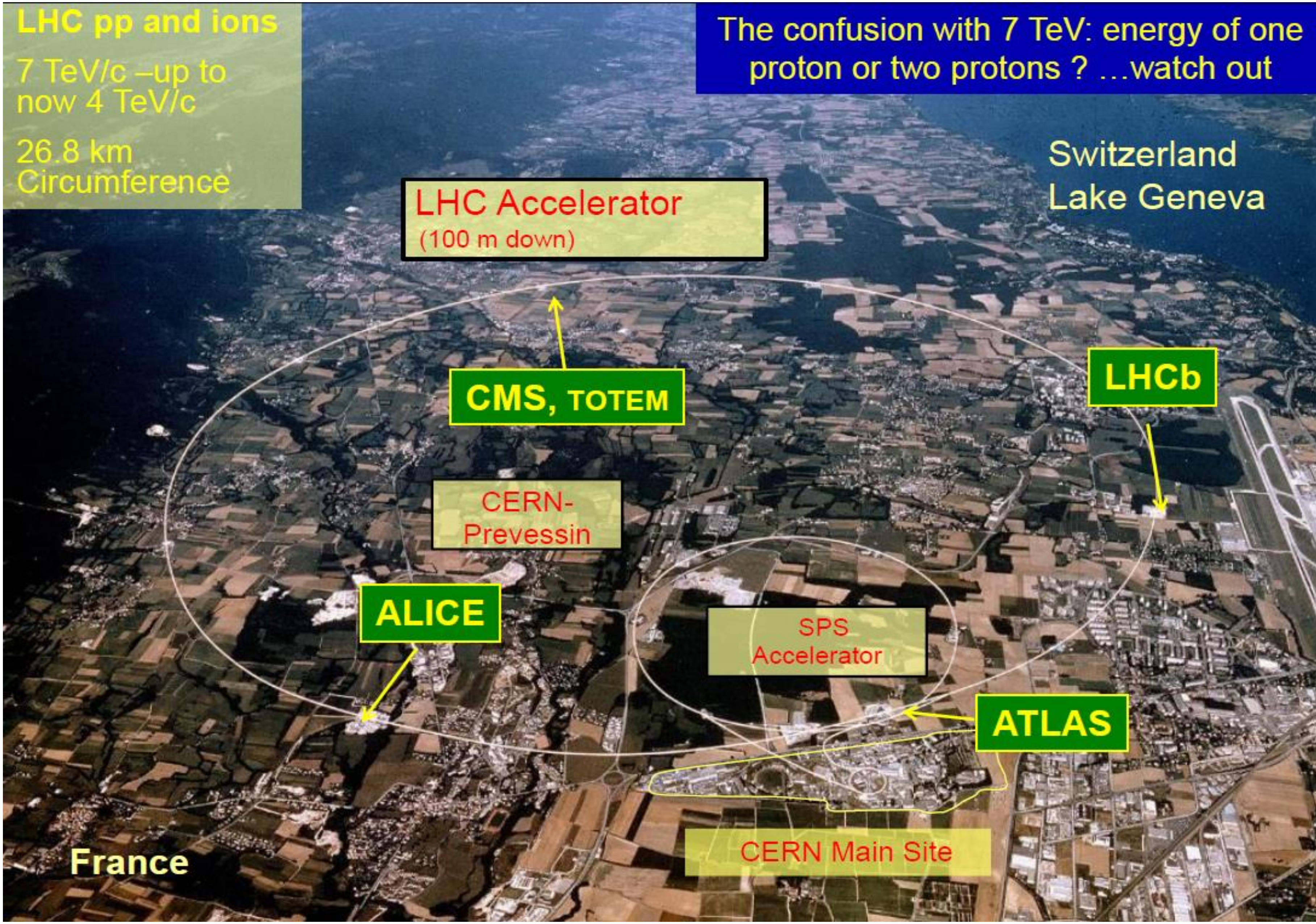


Beam Loss Monitors

- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- There are **~3600 chambers** distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !
- Very important beam instrumentation!

The LHC: just another collider?

	Start	Type	Max proton energy [GeV]	Length [m]	B Field [Tesla]	Lumi $[cm^{-2}s^{-1}]$	Stored beam energy [MJoule]
TEVATRON Fermilab Illinois USA	1983	p-pbar	980	6300	4.5	$4.3\ 10^{32}$	1.6 for protons
HERA DESY Hamburg	1992	p – e+ p – e-	920	6300	5.5	$5.1\ 10^{31}$	2.7 for protons
RHIC Brookhaven Long Island	2000	Ion-Ion p-p	250	3834	4.3	$1.5\ 10^{32}$	0.9 per proton beam
LHC CERN	2008	Ion-Ion p-p	7000 Now 4000	26800	8.3	10^{34} Now 7.7×10^{33}	**362 per beam**
Factor			7	4	2	**50**	**100**



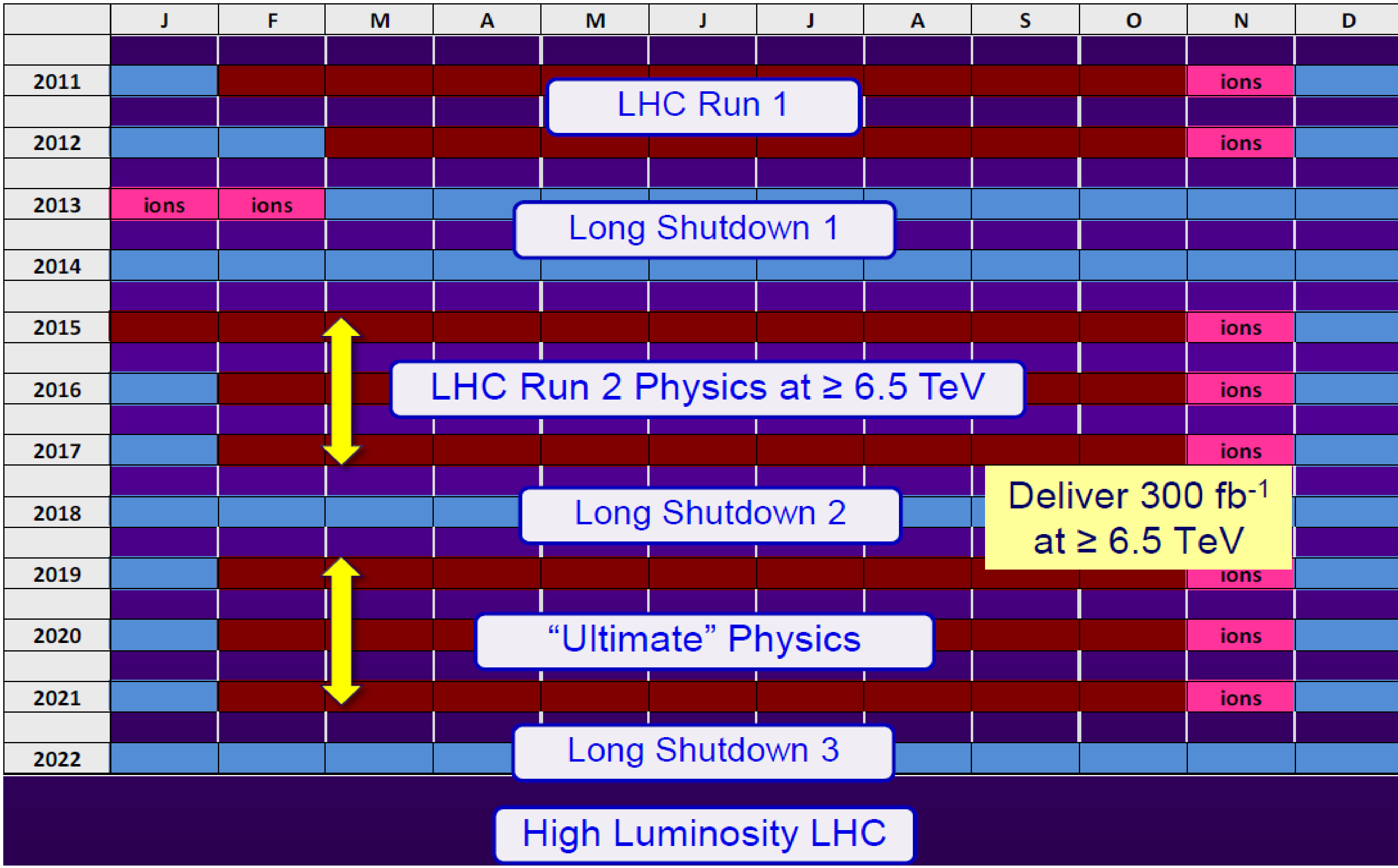
LHC pp and ions
7 TeV/c –up to now 4 TeV/c
26.8 km Circumference
The confusion with 7 TeV: energy of one proton or two protons ? …watch out
Switzerland
Lake Geneva
LHC Accelerator
(100 m down)
CMS, TOTEM
LHCb
CERN-Prevessin
ALICE
SPS Accelerator
ATLAS
CERN Main Site
France

Summary: 2010 - 2012

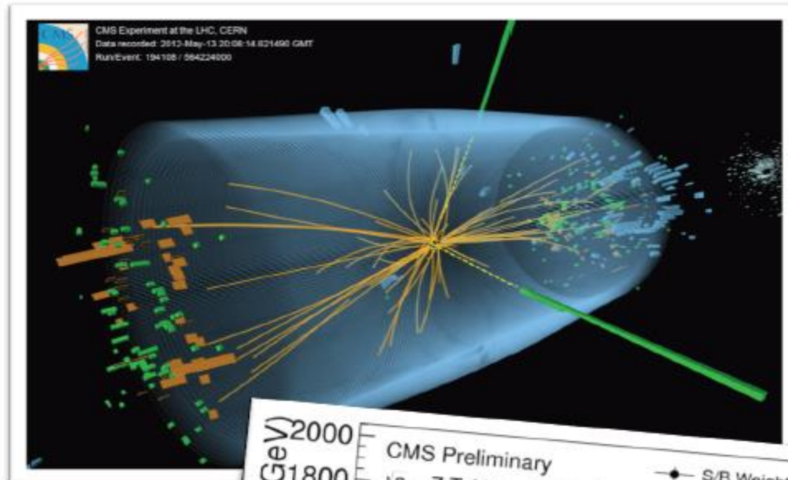
$$L = \frac{k N_b^{\,2} f \gamma}{4\pi \beta^* \varepsilon^*} F$$

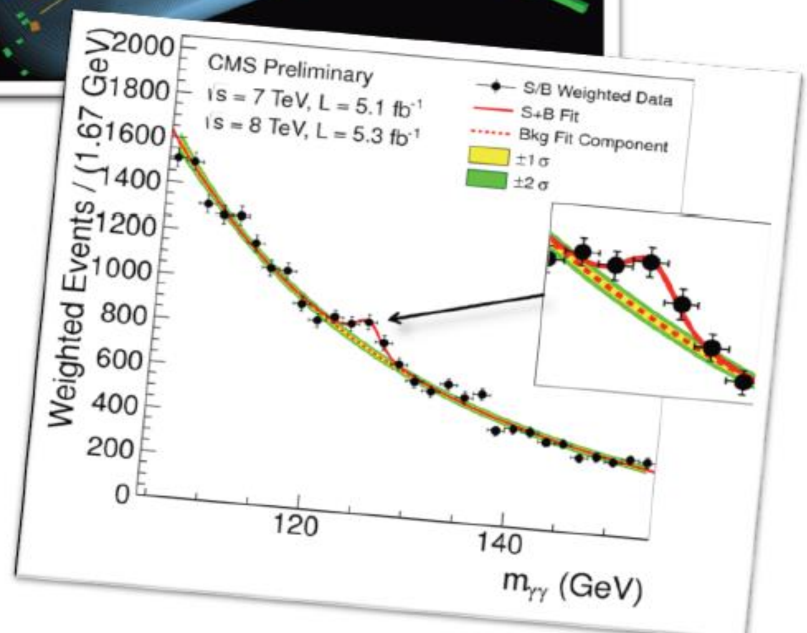
Parameter	2010	2011	2012	Nominal
Energy [TeV]	3.5	3.5	**4.0**	7.0
N_b [10^{11} p/bunch]	1.2	1.45	**1.6**	1.15
k (no. bunches)	368	1380	**1380**	2808
Bunch spacing [ns]	150	75 / 50	**50**	25
Stored energy [MJ]	25	112	**140**	362
ε^* [μm]	2.4	2.4	**2.5**	3.75
β^* [m]	3.5	1.5 → 1	**0.6**	0.55
Crossing angle [μrad]	200	240	**290**	285
L [10^{34} cm^{-2}s^{-1}]	0.02	0.35	**0.76**	1.0
Beam-beam parameter/IP (ΔQ_{bb})	-0.0054	-0.0065	**-0.0069**	-0.0033
Average Pile-up @ beg. of fill	8	17	**38**	26

The next years



Experiment = probing theories with data



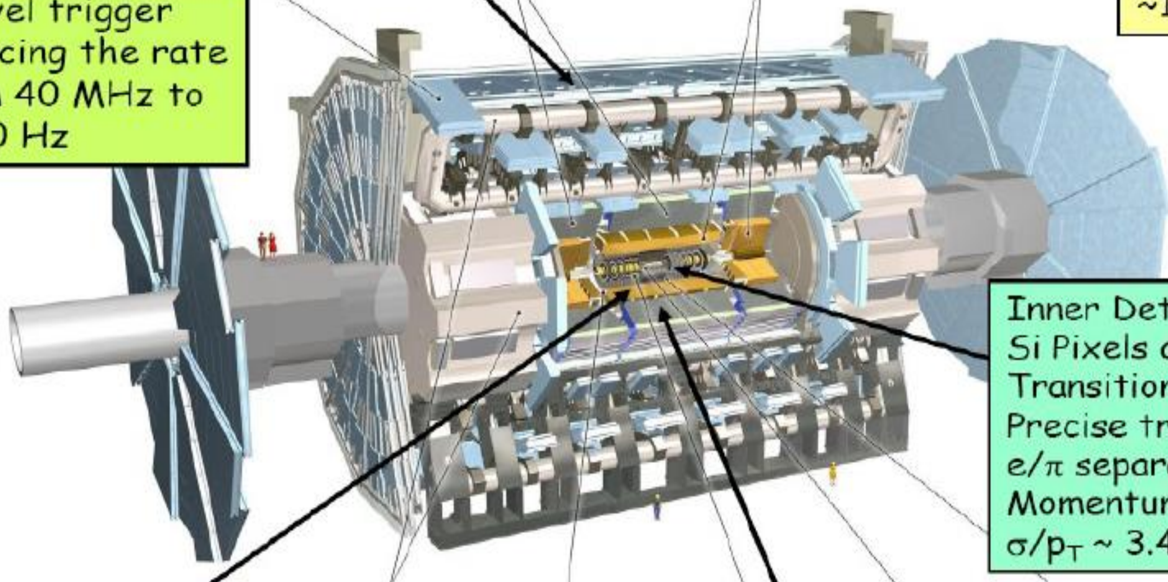


The ATLAS detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels

3-level trigger reducing the rate from 40 MHz to ~200 Hz



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels and strips (SCT) +
Transition Radiation straws
Precise tracking and vertexing,
e/π separation (TRT).
Momentum resolution:
$\sigma/p_T \sim 3.4\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

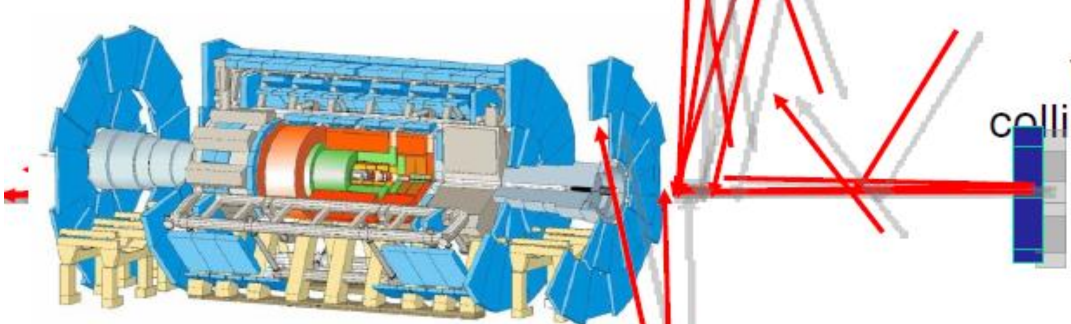
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: ~ 1% at 100 GeV, 0.5% at 1 TeV

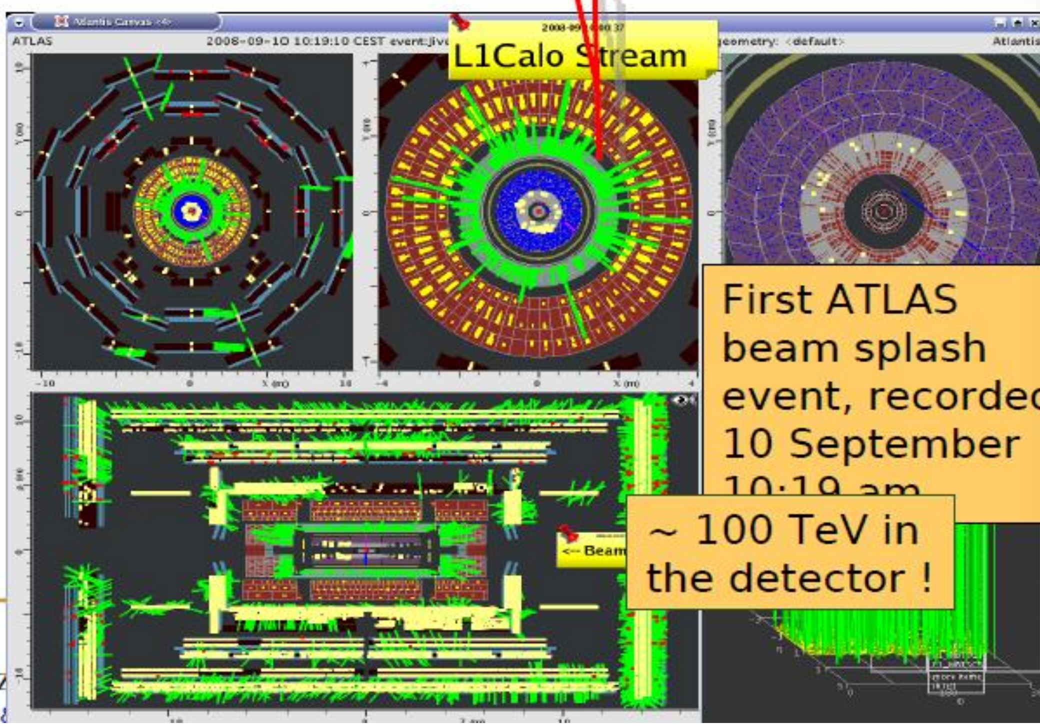
HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Tilecal Fe/scintillator (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$


Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan
Morocco
Netherlands
Norway
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR
ATLAS
Collaboration

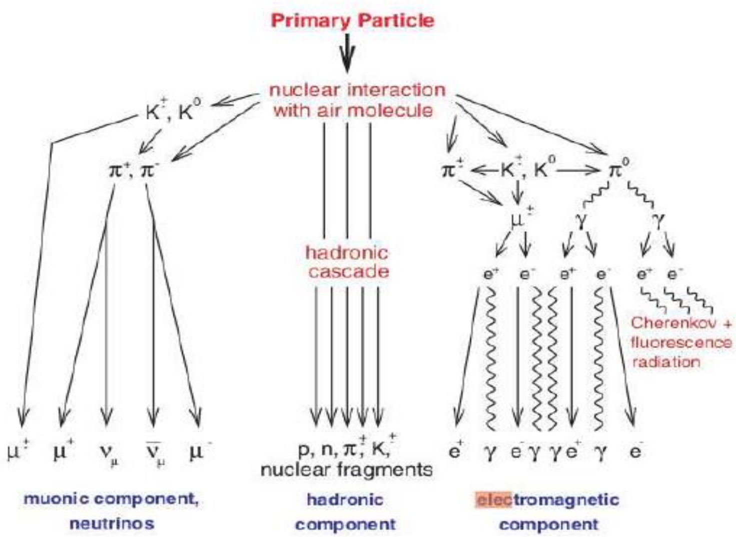
2008

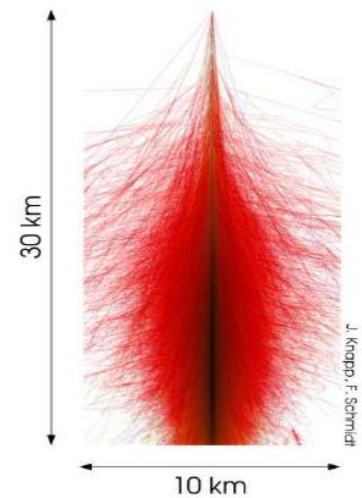
Beam bunches ($2x10^9$ protons at 450 GeV) stopped by (closed) collimators upstream of experiments →
"splash" events in the detectors (debris are mainly muons)



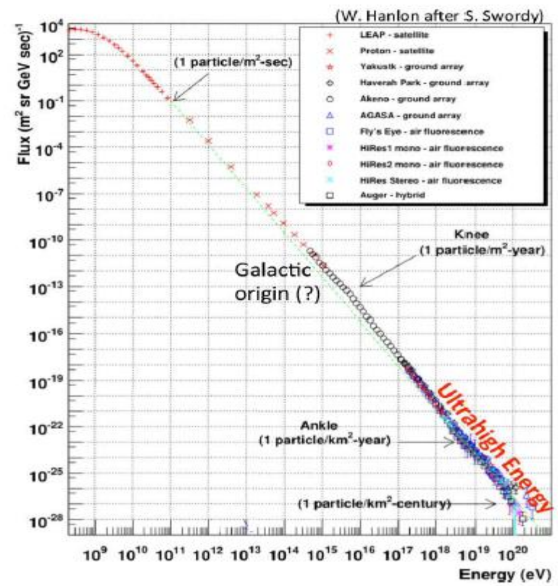


Cosmic rays





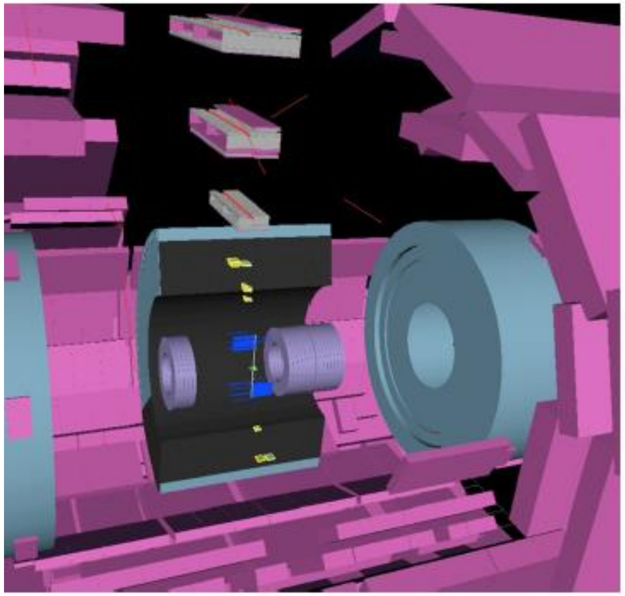
Simulation proton 10^{14} eV



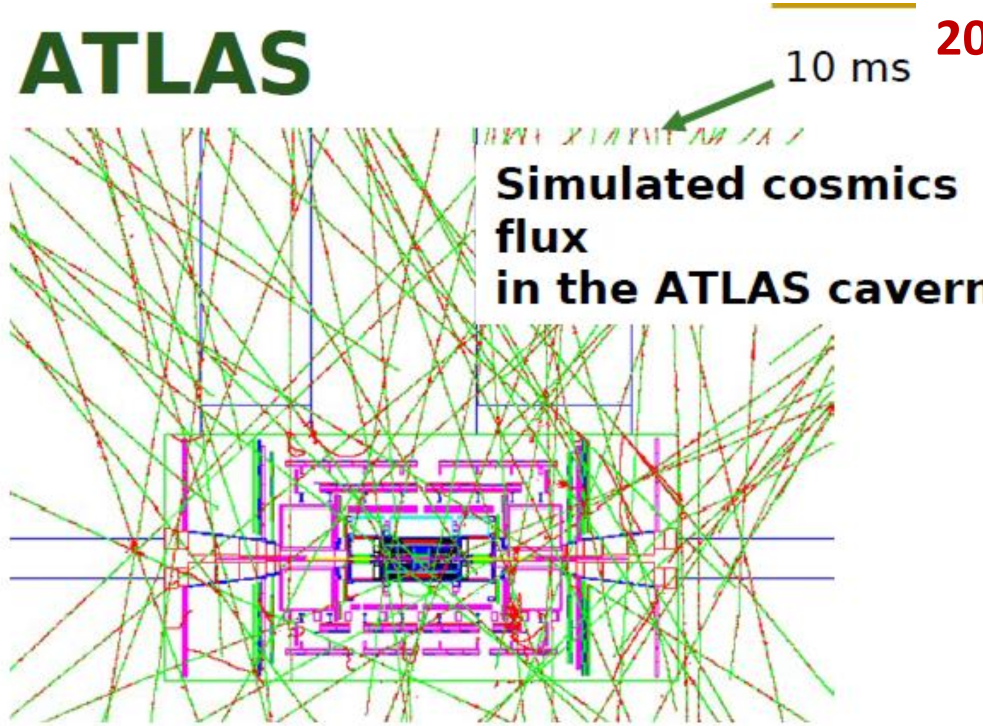
- The most penetrating component of atmospheric showers: the muon component
- At sea level muons represent about 80% of the cosmic ray flux
    - averaged over all energies
    - above E ≈ 1 GeV they contribute almost 100%
- Below 1 GeV the energy spectrum of muons is almost flat
- Above 100 GeV falls exponentially
- It extends to extremely high energies
- The average cosmic ray muon energy is 4 GeV

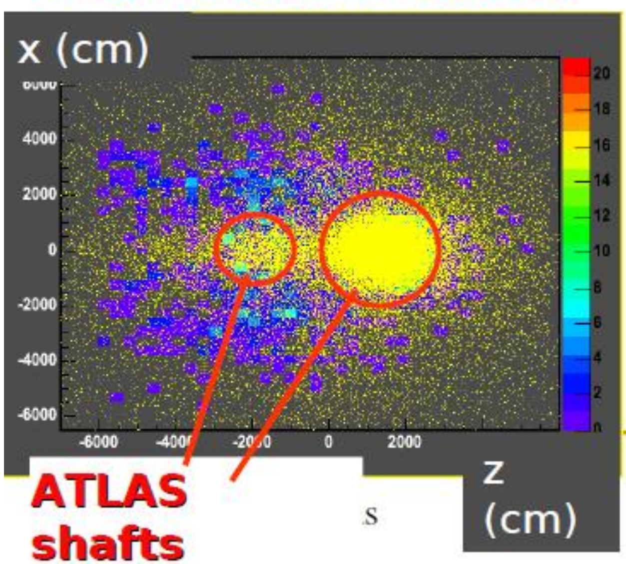
Cosmic Muons in ATLAS

2008



Real Cosmic Event



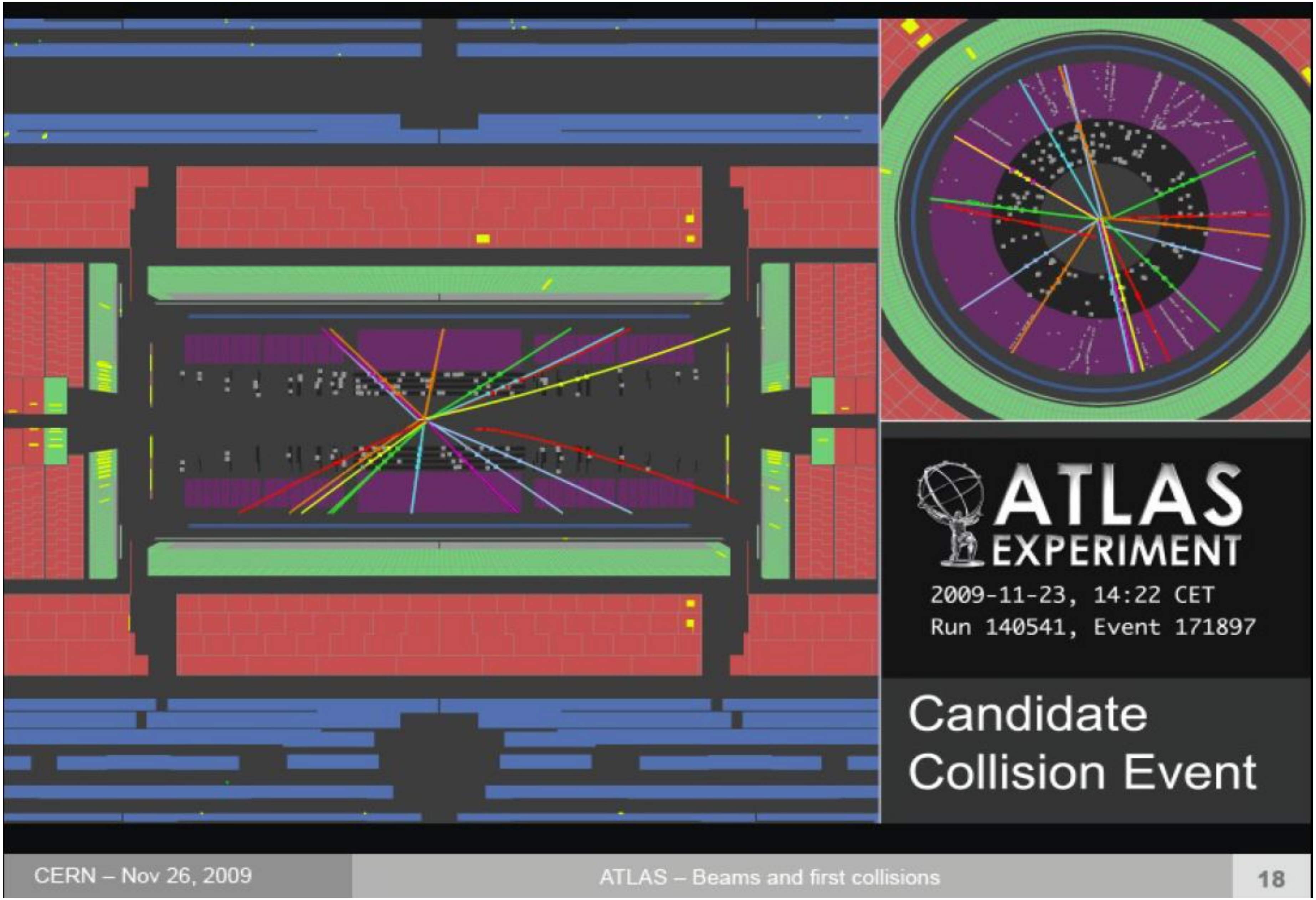


Muon impact points extrapolated
to surface as measured by
Muon Trigger chambers
(RPC)

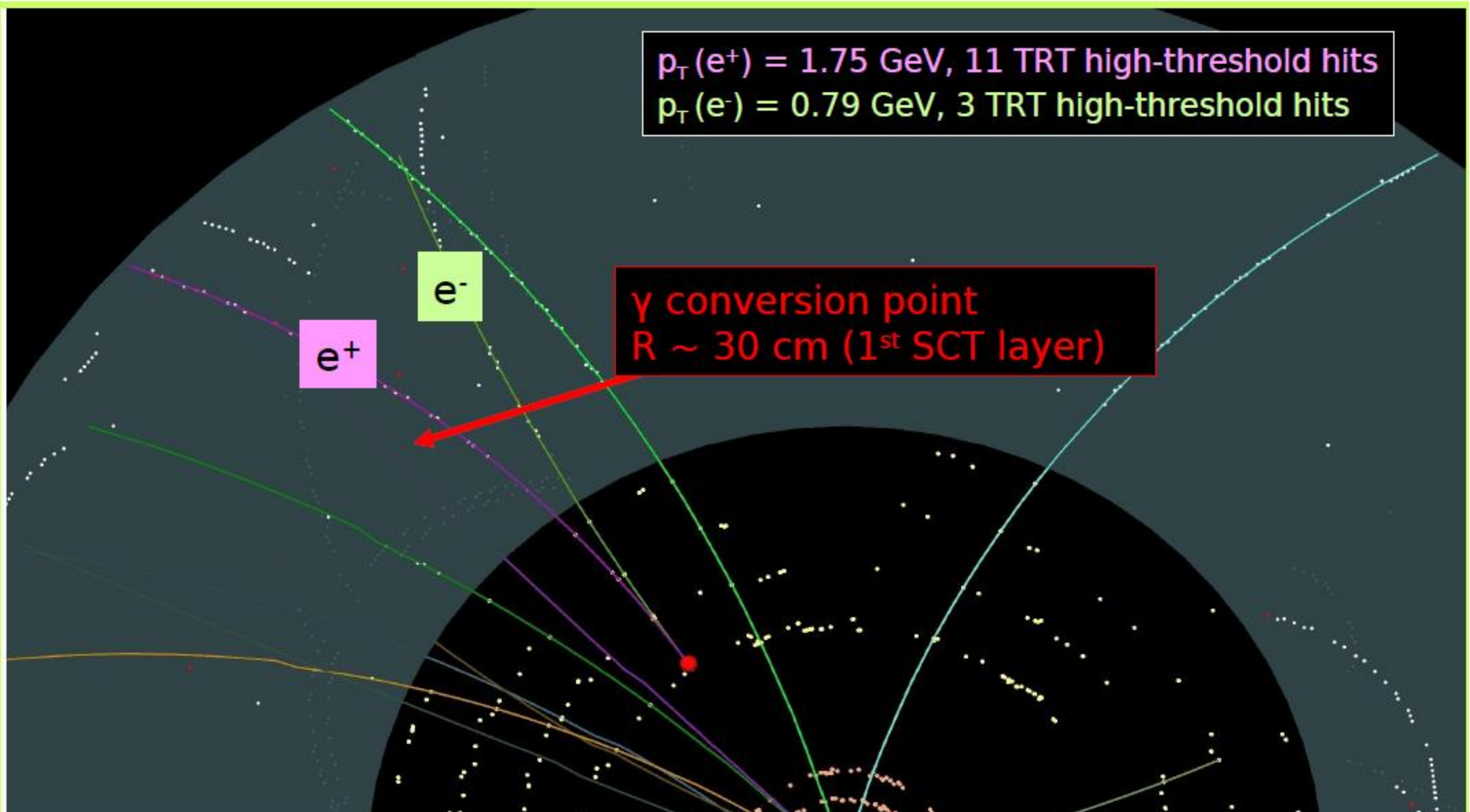
(Calorimeter trigger also

Rate ~100 m below ground:
~ O(15 Hz) crossing Inner Detector

First collisions in ATLAS (2009)



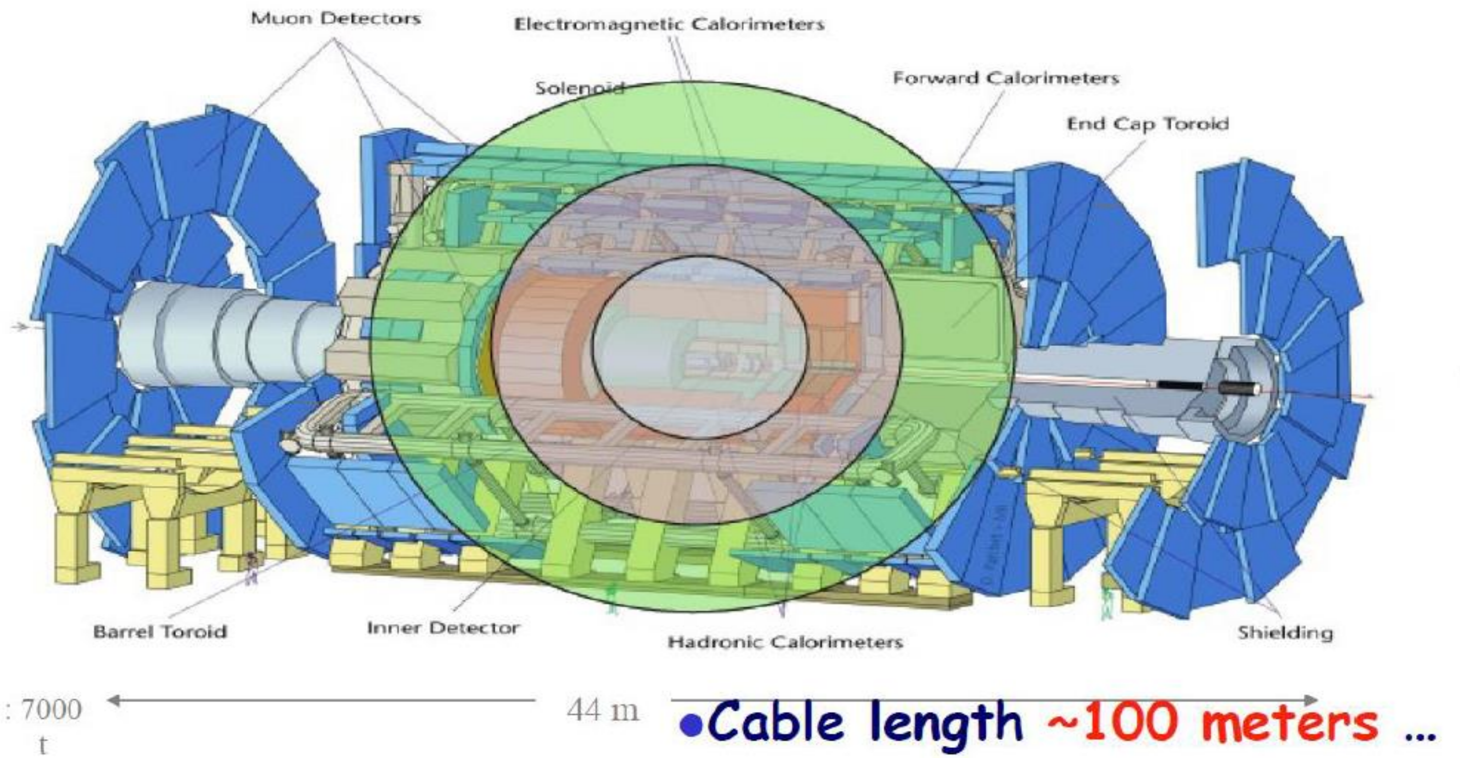
$\gamma \rightarrow e^+e^-$ conversions



Trigger system

- **Interactions every 25 ns …**
  - In 25 ns particles travel 7.5 m

c=30cm/ns; in 25ns, s=7.5m



- **Cable length ~100 meters …**
  - In 25 ns signals travel 5 m

Trigger system

Jak w ciągu 1 sekundy wybrać 1 spośród 10^7 ?

Co to znaczy niewielka część?

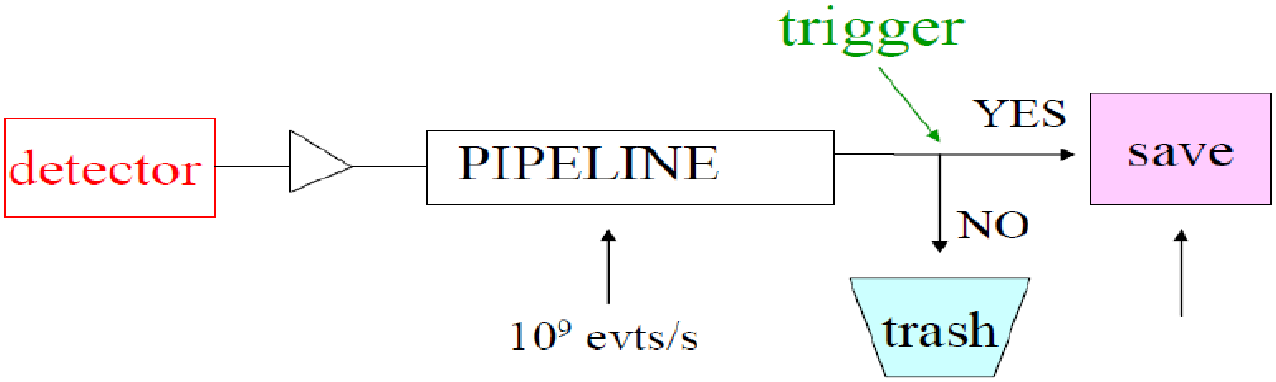
- 25ns ⇒ 40 x 10^6/s zderzeń
- 23 oddział/zderzenie ⇒ 23 x 40 x 106 /sek ~ 10^9 /sek oddział
- możemy zarejestrować tylko ~ 100/sek zderzeń ⇒ **redukcja 10^7**

Ile informacji trzeba przetworzyć?

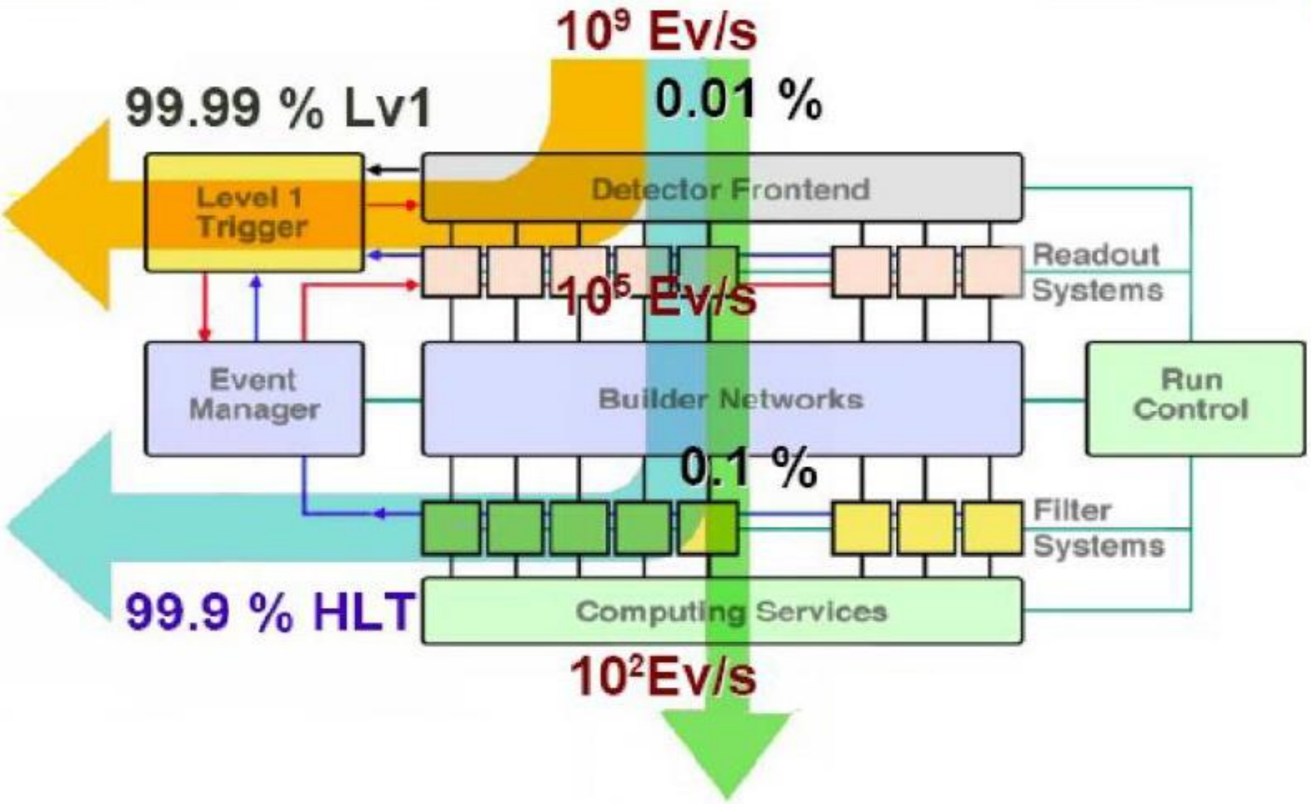
trigger elektron: 8bit x 40MHz x 7500 ~ 3 000 Gbit/sek

Czy można podjąć decyzje w 25ns?

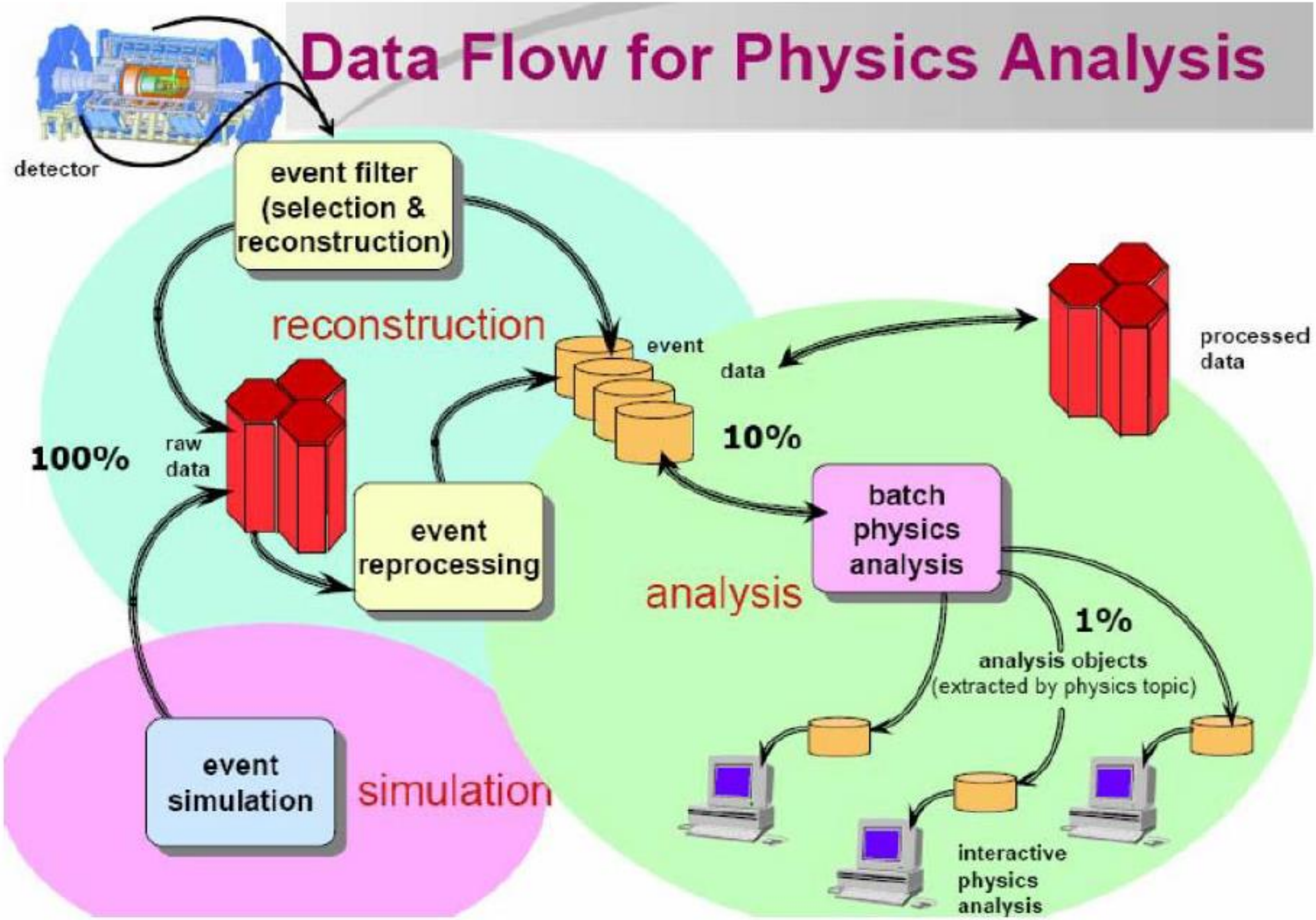
nie można: czas rejestracji w detektorze dłuższy (ok. 50 x 25ns)
informacje trzeba wysłać do procesora (ok. 15 x 25ns)
informacje trzeba przetworzyć (ok. 10 x 25ns)

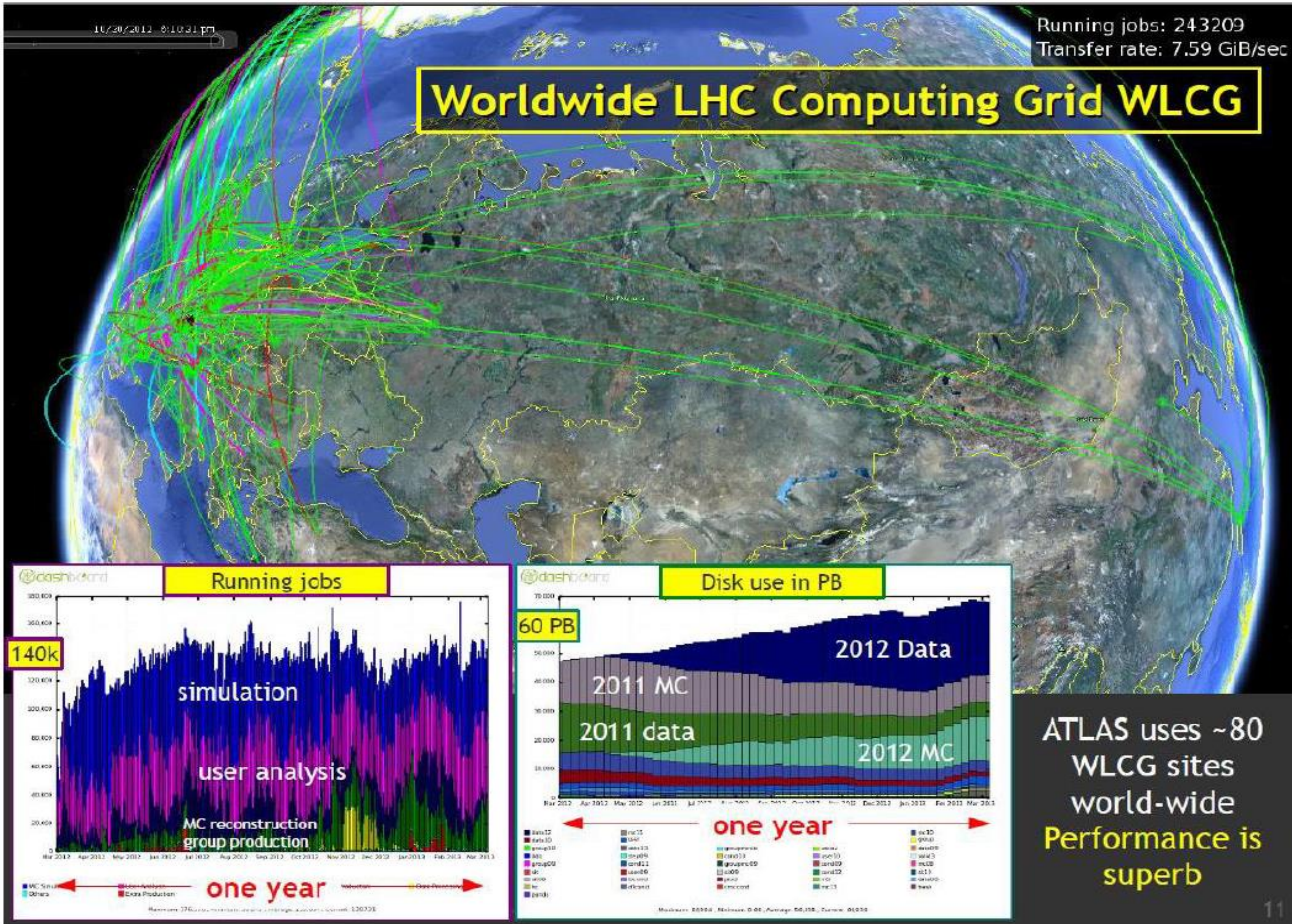


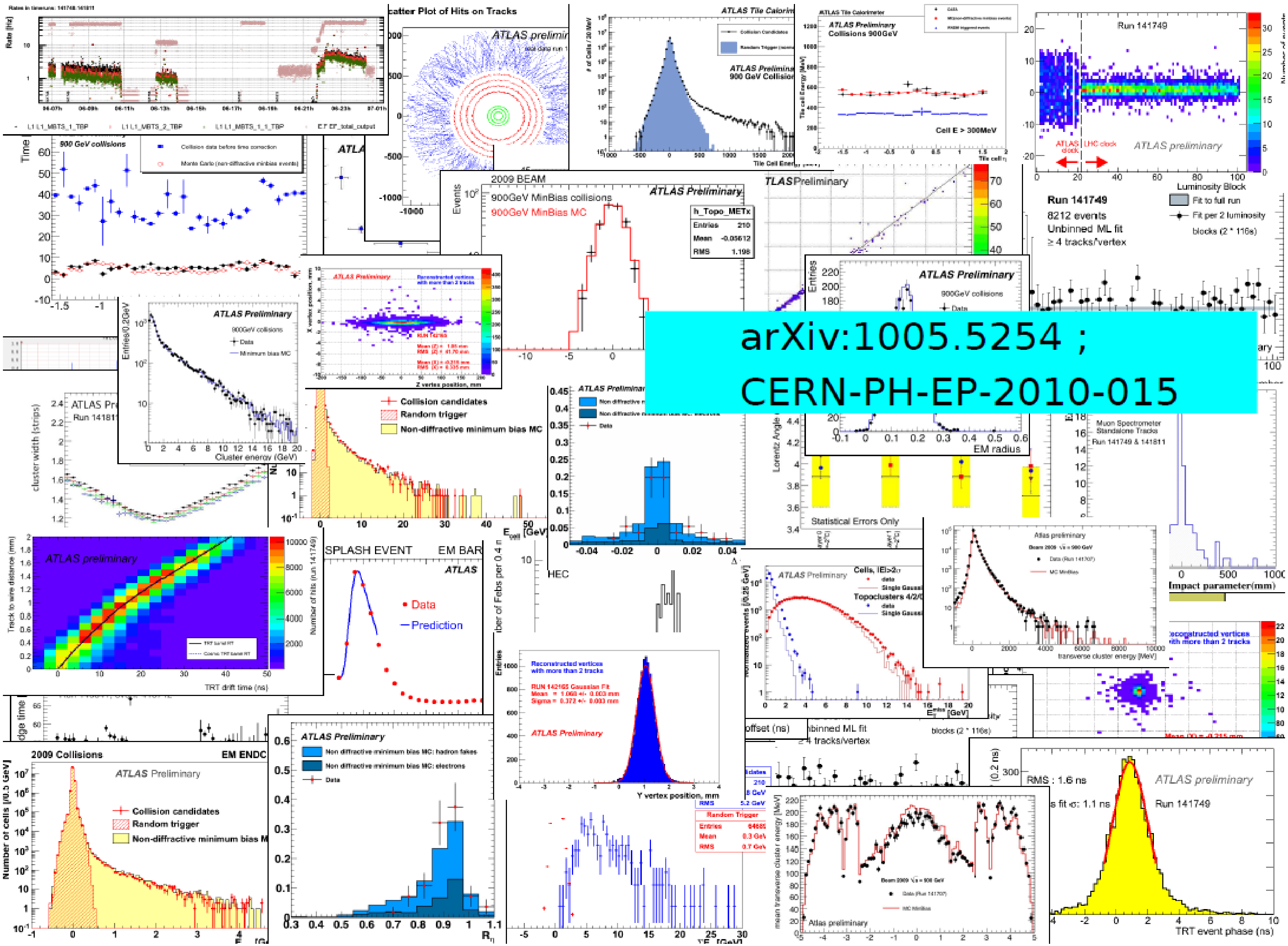
Trigger system



Data Flow for Physics Analysis

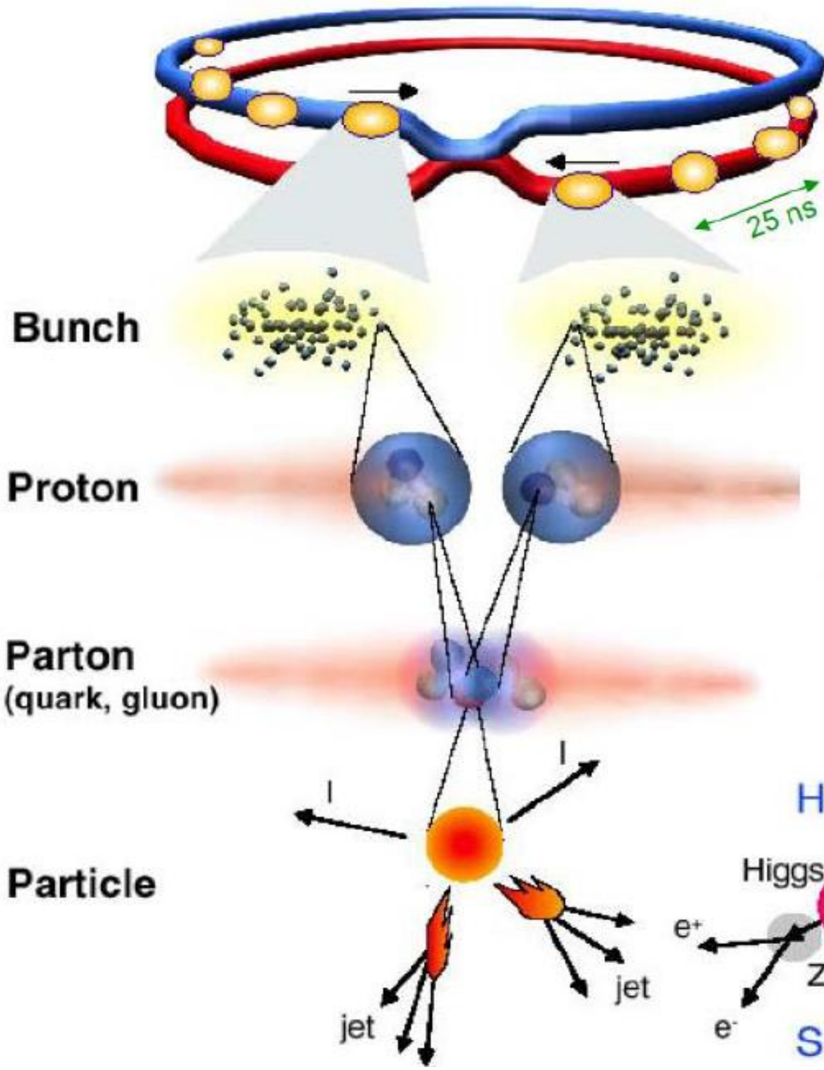



Running jobs: 243209
Transfer rate: 7.59 GiB/sec
Worldwide LHC Computing Grid WLCG
Running jobs
140k
simulation
user analysis
MC reconstruction
group production
one year
Disk use in PB
60 PB
2012 Data
2011 MC
2011 data
2012 MC
one year
ATLAS uses ~80
WLCG sites
world-wide
Performance is
superb
11



arXiv:1005.5254 ;
CERN-PH-EP-2010-015

Collisions at LHC

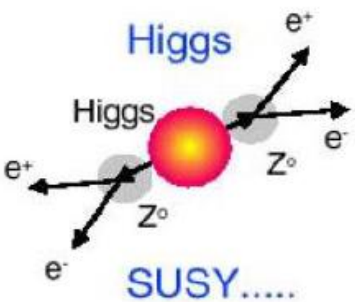


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

In the experiments:

10^9 pp interactions per second

~ 1500 particles (p,n, π) produced in the detectors at each bunch-crossing

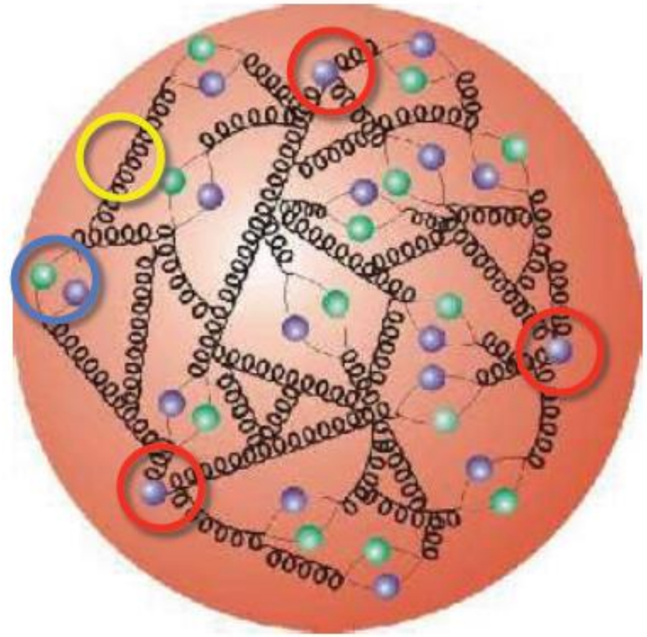


Selection of 1 in 10,000,000,000,000

Inner structure of a proton

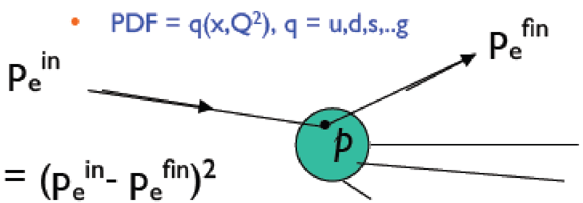
protons have substructures

- ✓ partons = quarks & gluons
- ✓ 3 valence (colored) quarks bound by gluons
- ✓ Gluons (colored) have self-interactions
- ✓ Virtual quark pairs can pop-up (sea-quark)
- ✓ p momentum shared among constituents
  - described by p structure functions



Parton energy not 'monochromatic'

- ✓ Parton Distribution Function
  - PDF = $q(x,Q^2)$, q = u,d,s,..g

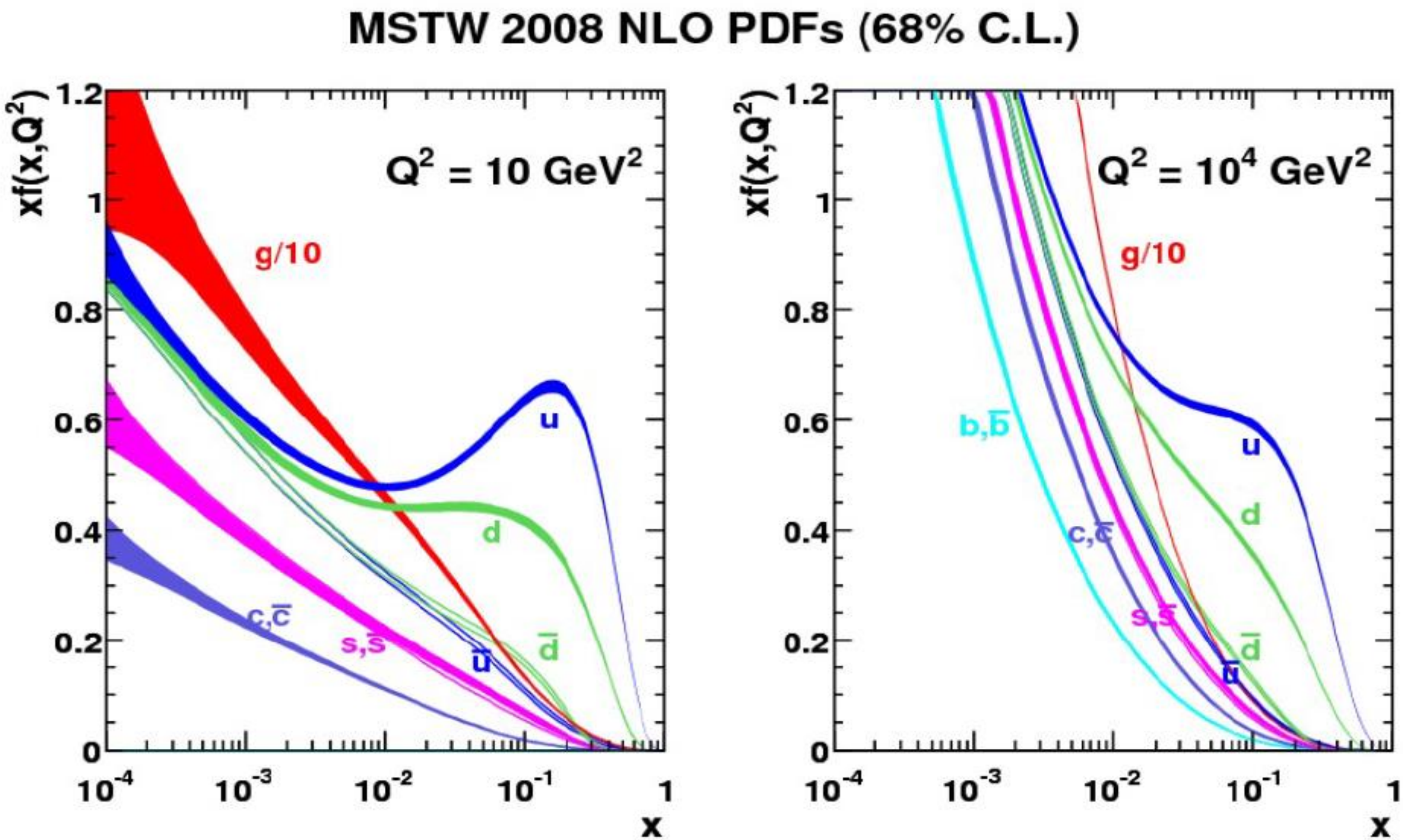


$Q^2 = (p_e^{in} - p_e^{fin})^2$

Kinematic variables

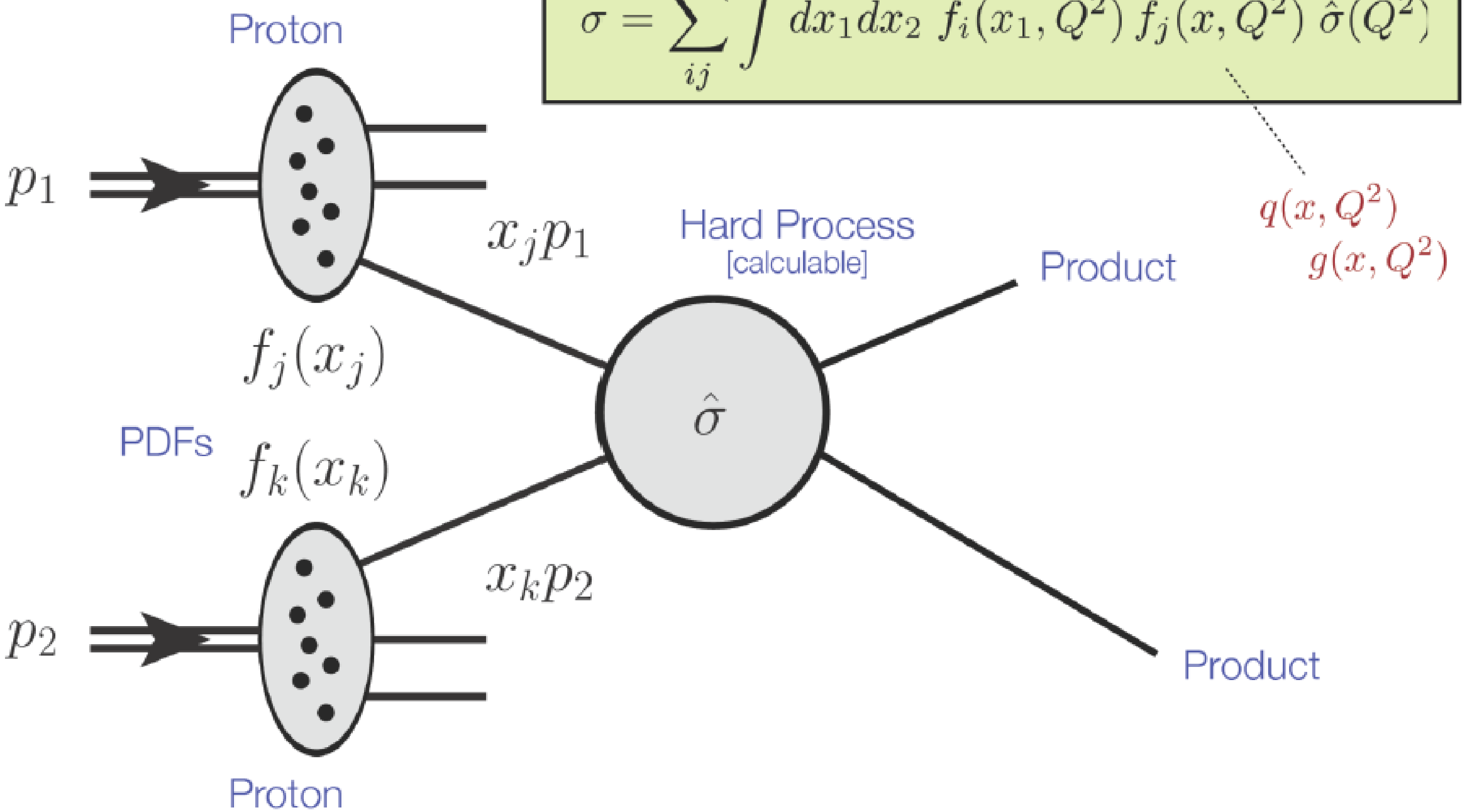
- ✓ Bjorken-x: fraction of the proton momentum carried by struck parton
  - $x = p_{parton}/p_{proton}$
- ✓ Q^2 : 4-momentum^2 transfer

Inner structure of a proton



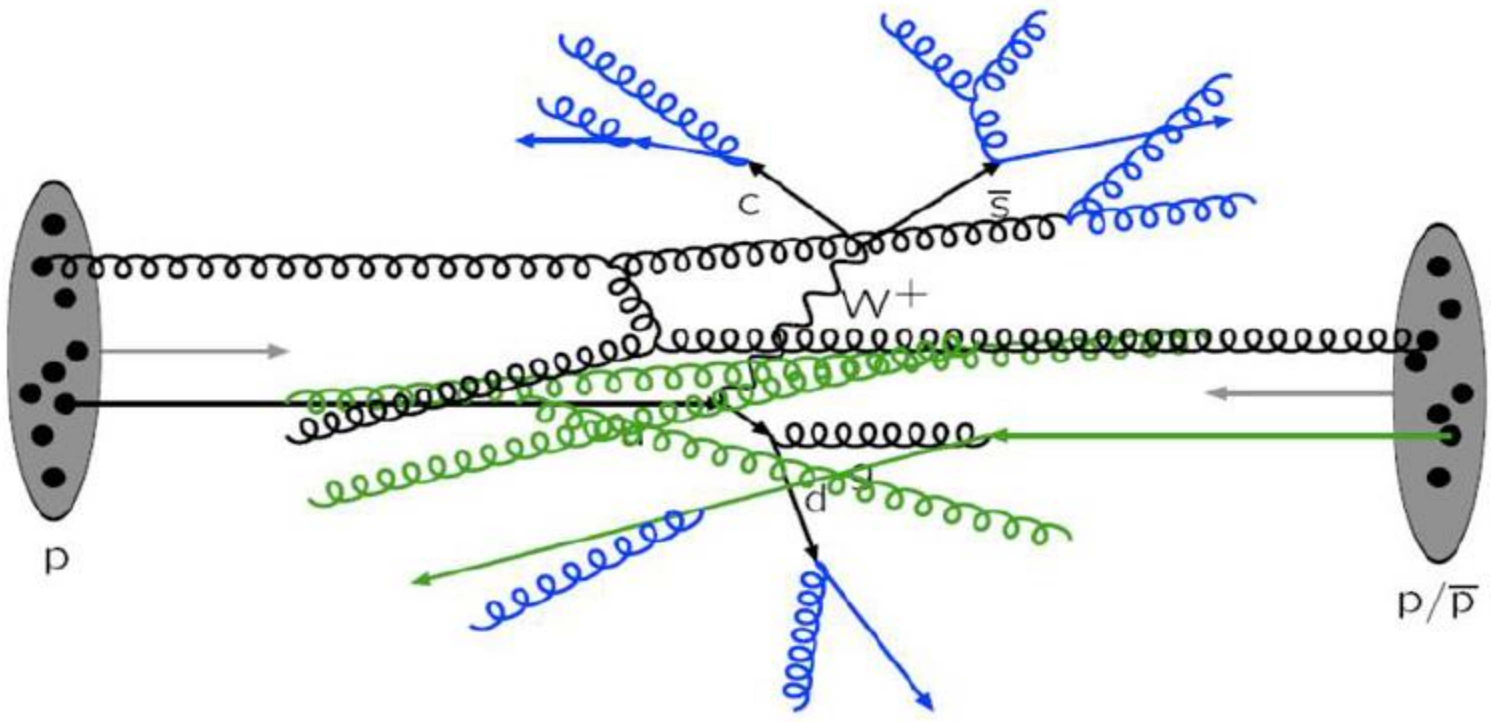
Proton-proton scattering at LHC

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2)\, f_j(x, Q^2)\, \hat{\sigma}(Q^2)$$

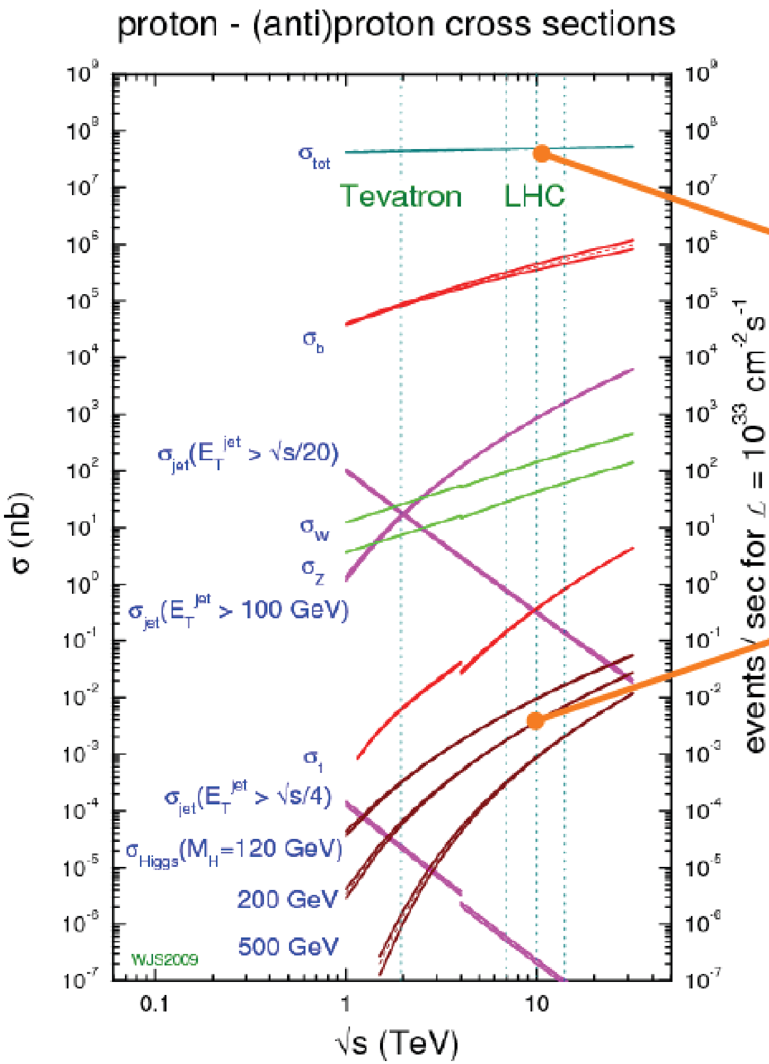


Proton-proton scattering at LHC

- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction ["underlying event"]



Cross-sections at LHC



10^8 events/s

$\sim 10^{10}$

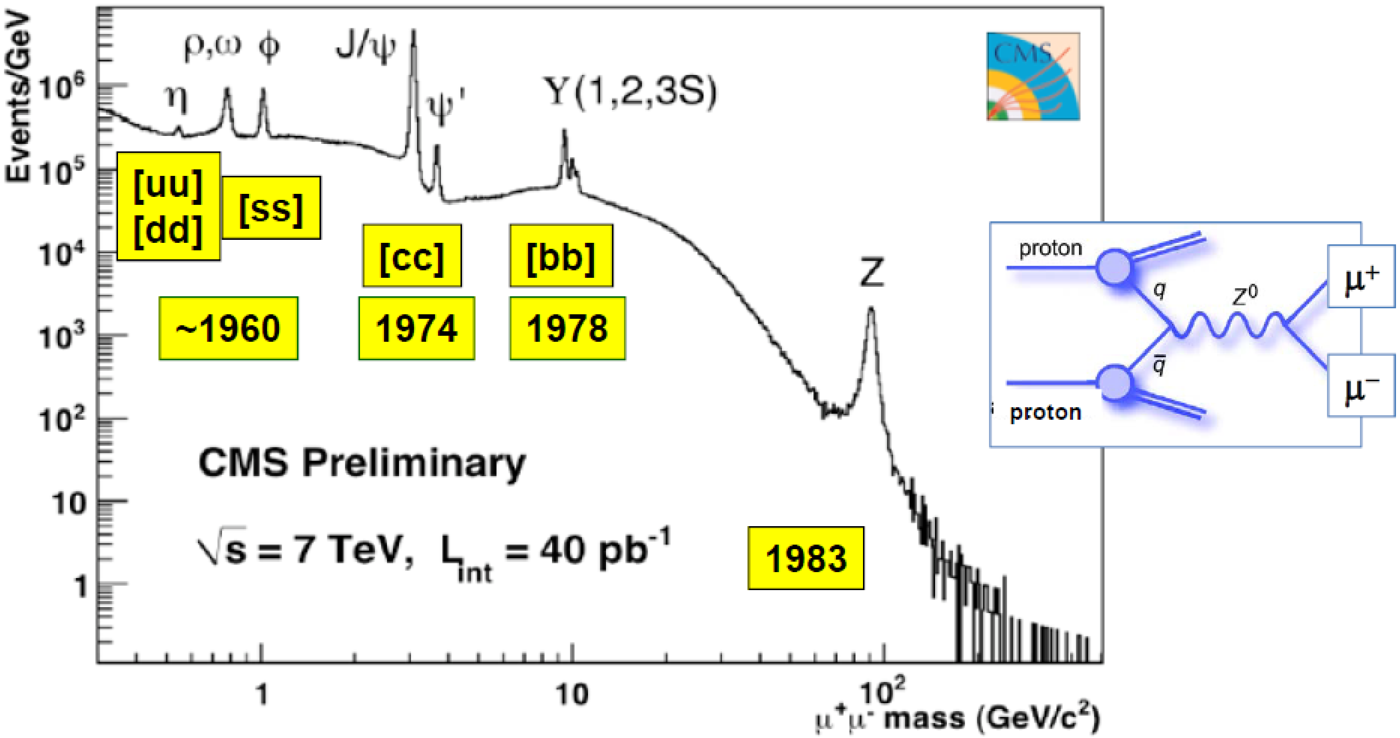
10^{-2} events/s ~ 10 events/min

[m_H ~ 120 GeV]

0.2% H → γγ
1.5% H → ZZ

Year 2010: Retracing history of particle physics

2010 Data corresponding to ~40 pb^{-1} collected
→ re-discovery of the Standard Model



The di-muon spectrum recalls a long period of particle physics:
Well known quark-antiquark resonances (bound states) appear "online"

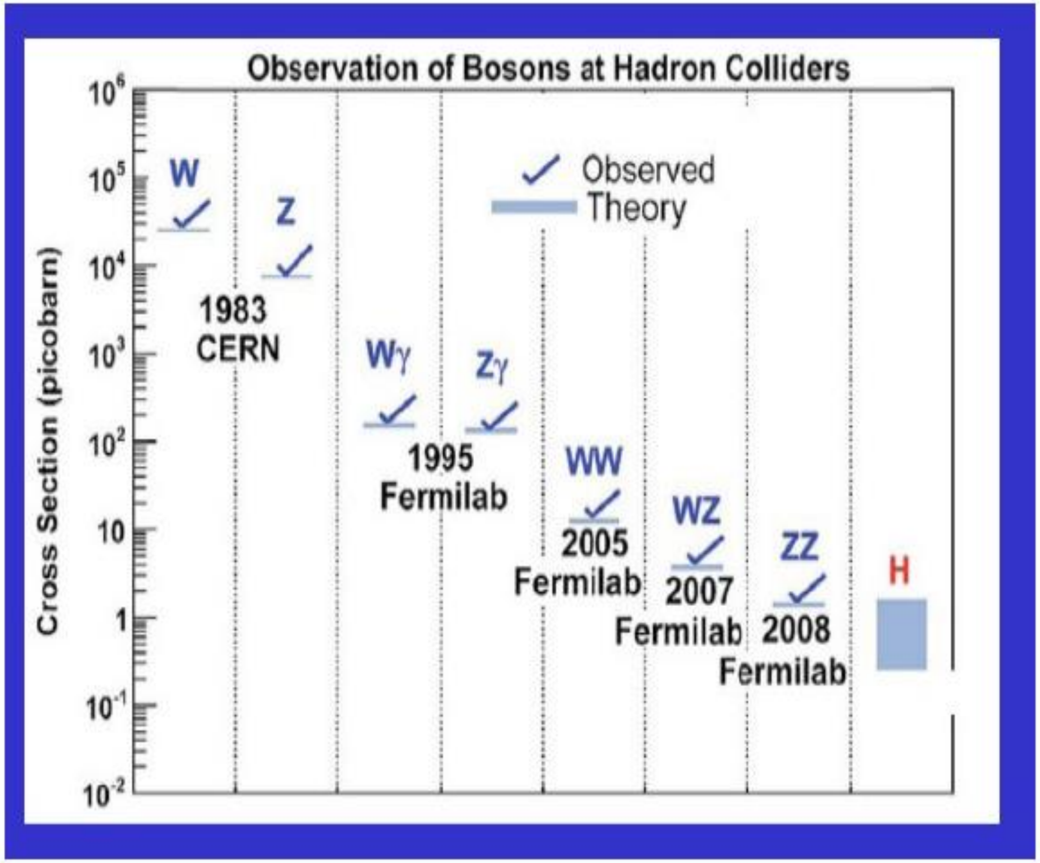
Bosons at hadron colliders

The primary decay chanel is through leptonic decays:

- BR(W→e ν) ~ 10%
- BR(Z→ ee) ~ 3%

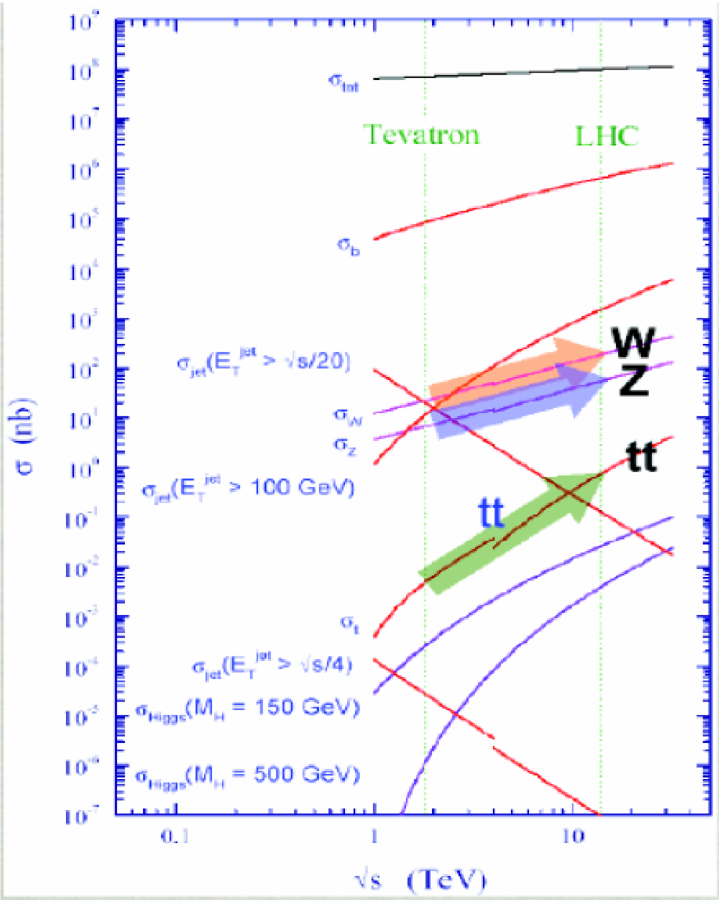
- It means that we are probing σ x BR values orders of magnitude smaller
- At LHC cross-section 5-10 x higher than at Tevatron at Fermilab.

2010

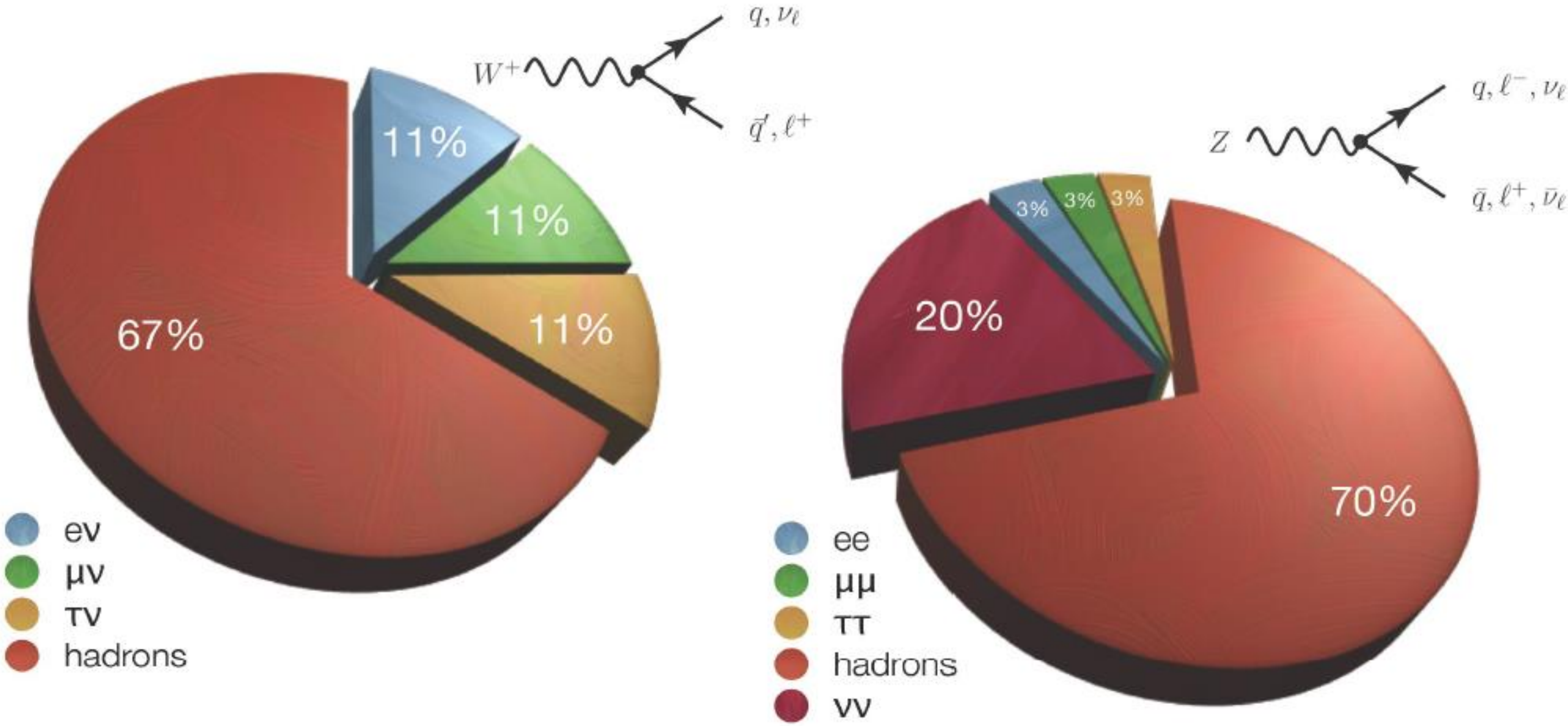


Bosons and top quark at LHC

- Well measured by previous experiments
- Still educational at LHC
  - Cross-sections
  - New PDF constraints
- „Standard candles" for high p_T analyses
  - Calibration, alignment
  - Independent luminosity measurements

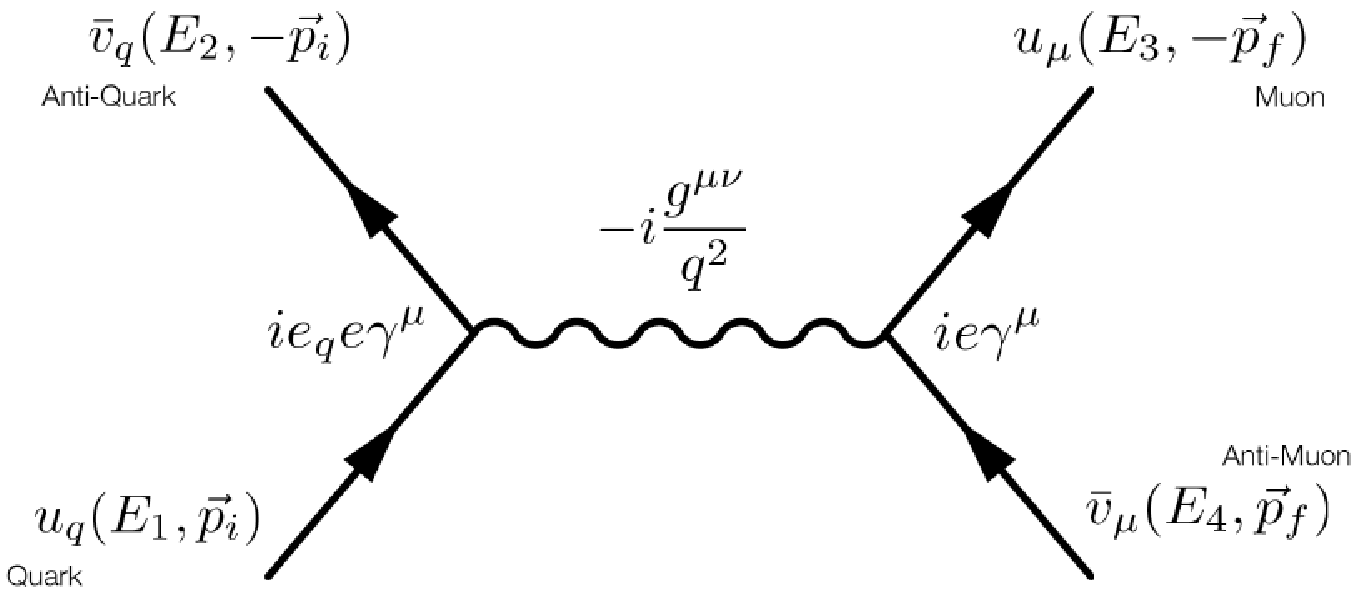


W and Z boson decays



Leptonic decays (e/μ): very clean, but small(ish) branching fractions
Hadronic decays: two-jet final states; large QCD dijet background
Tau decays: somewhere in between…

Example: Drell-Yan process

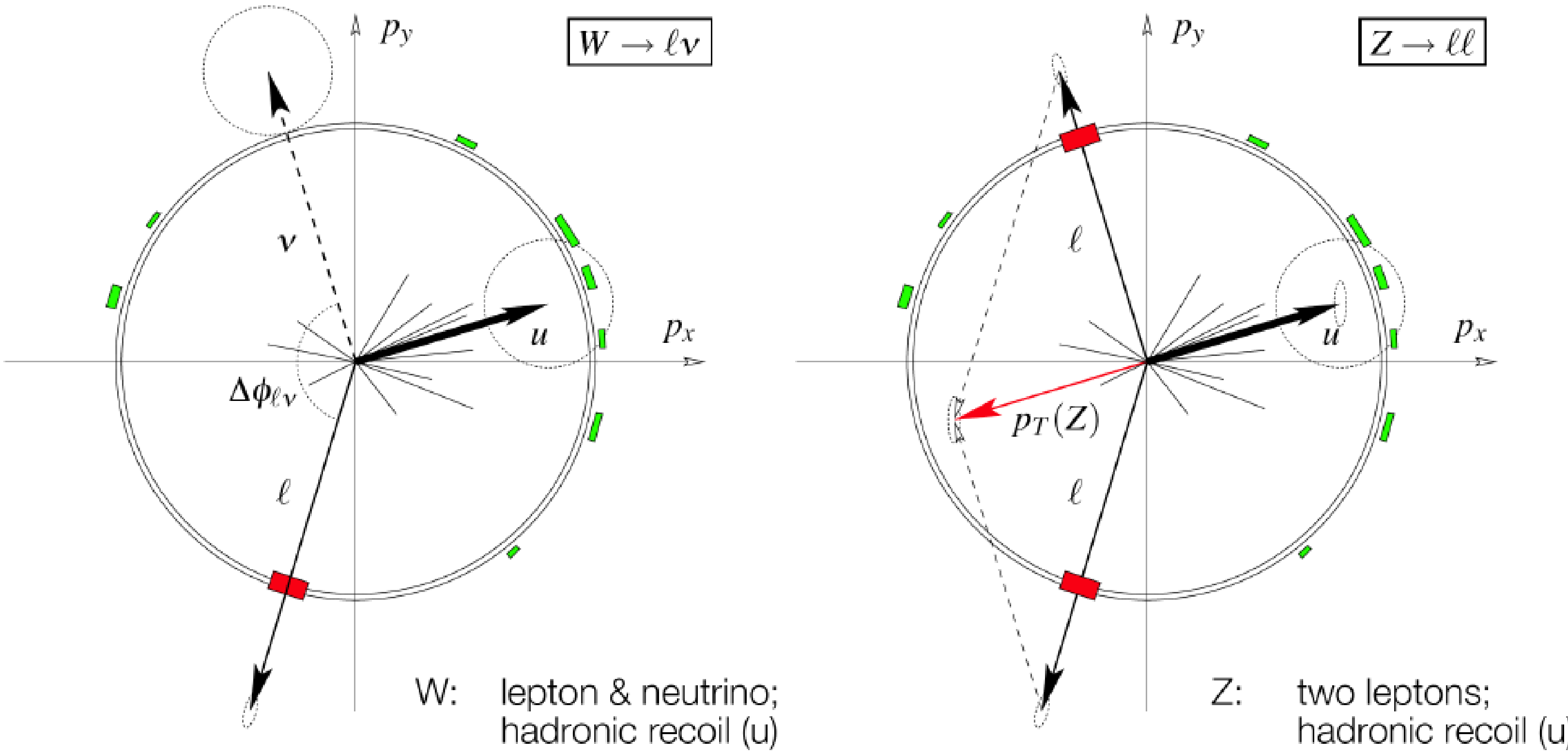


Averaging over initial spins

Summing over initial and final spins

$$|M_{fi}|^2 = \frac{1}{(2s_q+1)^2} \cdot \sum_{s_q, s'_q} \sum_{s_\mu, s'_\mu} |M_{fi}|^2$$

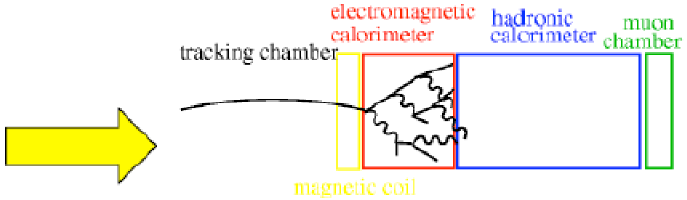
W and Z boson signatures



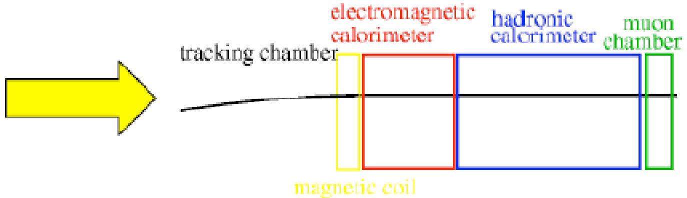
Additional hadronic activity ➛ recoil, not as clean as e^+e^-
Precision measurements: only leptonic decays

Lepton identification

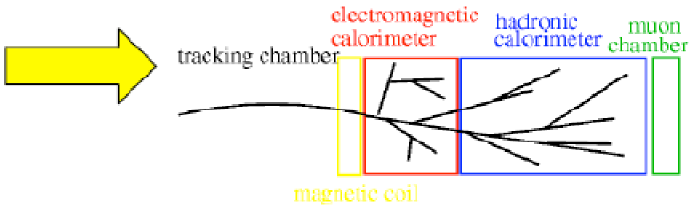
- Electron:
  - Compact electromagnetic cluster in calorimeter
  - Matched to track



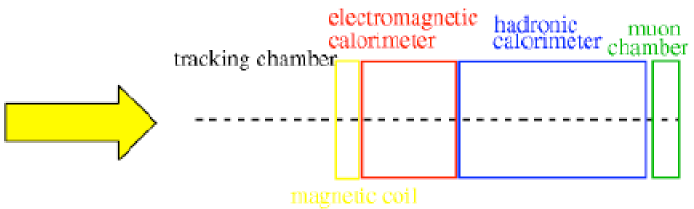
- Muons:
  - Track in the muon chambers
  - Matched to track



- Taus:
  - Narrow jet
  - Matched to one or three tracks

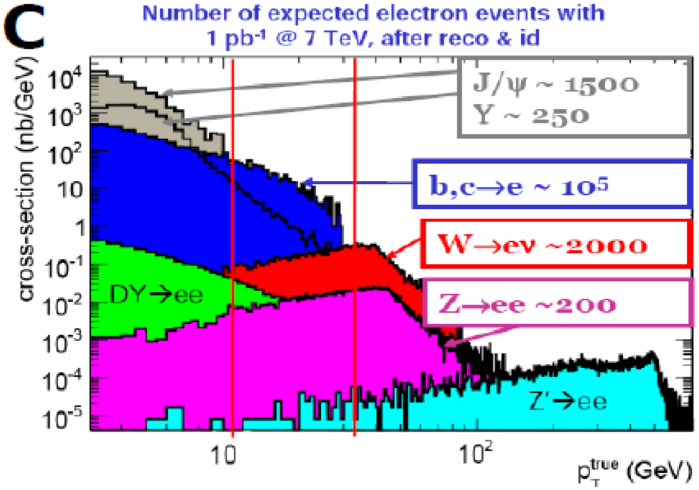


- Neutrinos
  - Imbalanse in transverse momentum
  - Inferred from total transverse energy in detector



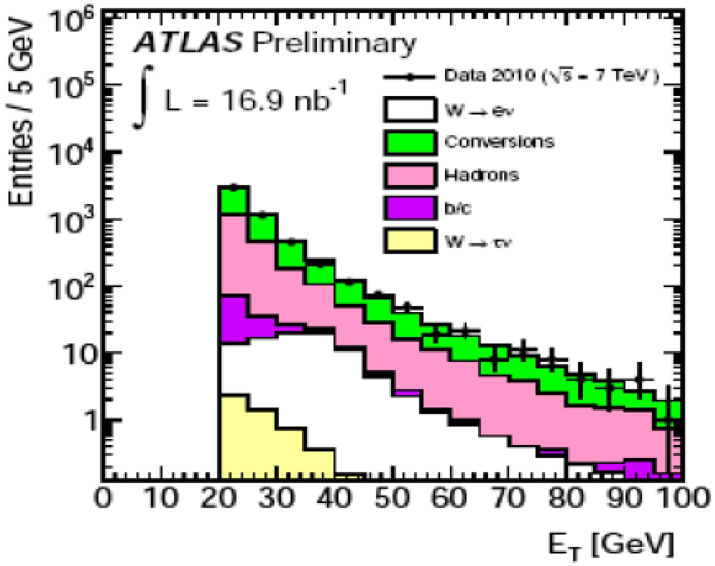
Electrons and jets

MC



- There is also lot of true electrons from semileptonic decays inside jets

DATA: loose electron ID



- Jets can look like electrons
  - Photon conversion from π^0's
  - Early showering charged pions
- And there is lot of jets
- Difficult to model in Monte Carlo
  - Detailed simulation in tracking and calorimeter volume

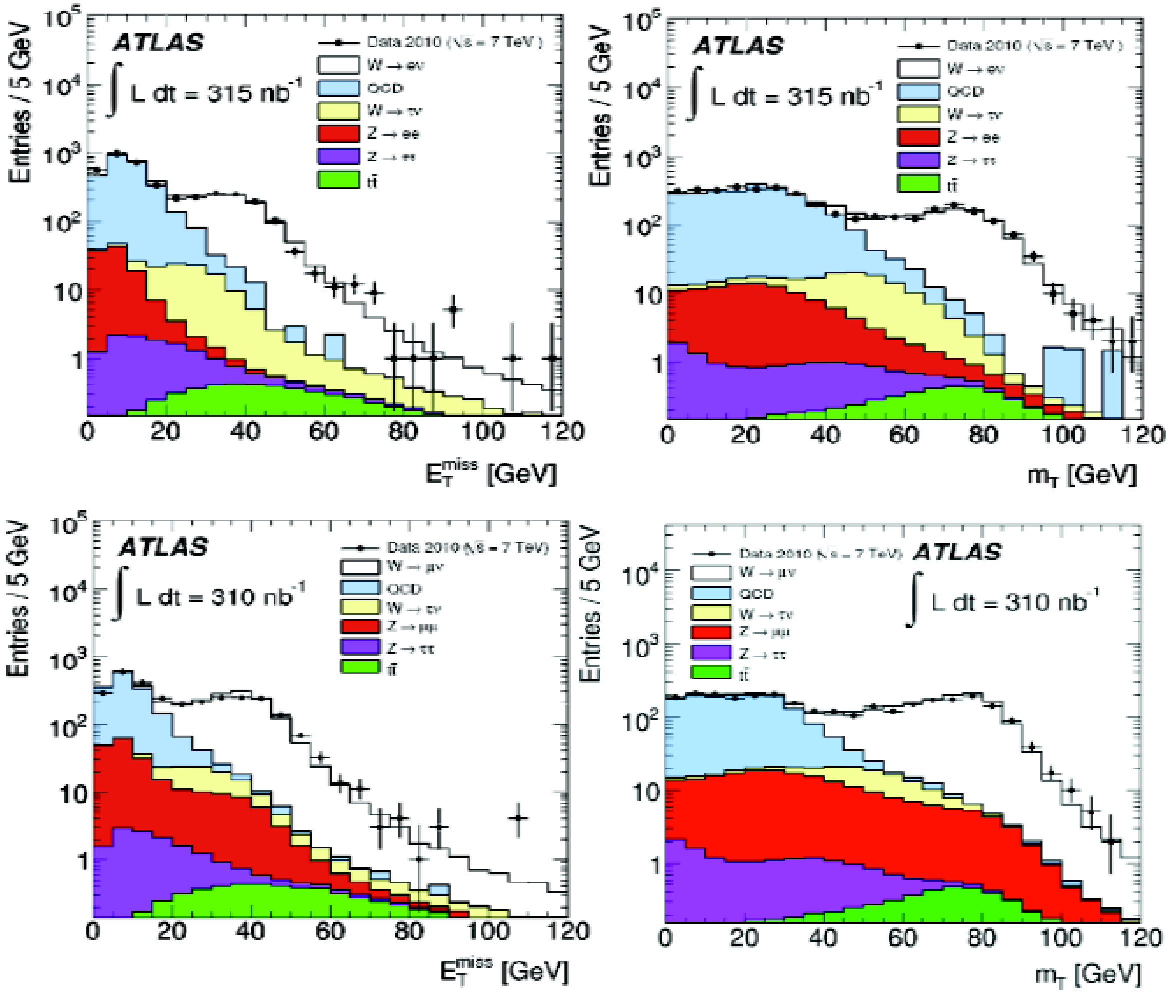
W selection (2010)

Electrons:

- $E_T > 20$ GeV
- *Tight ID*
- Missing $E_T > 25$ GeV
- $m_T > 40$ GeV
- *1069 Candidates*

Muons:

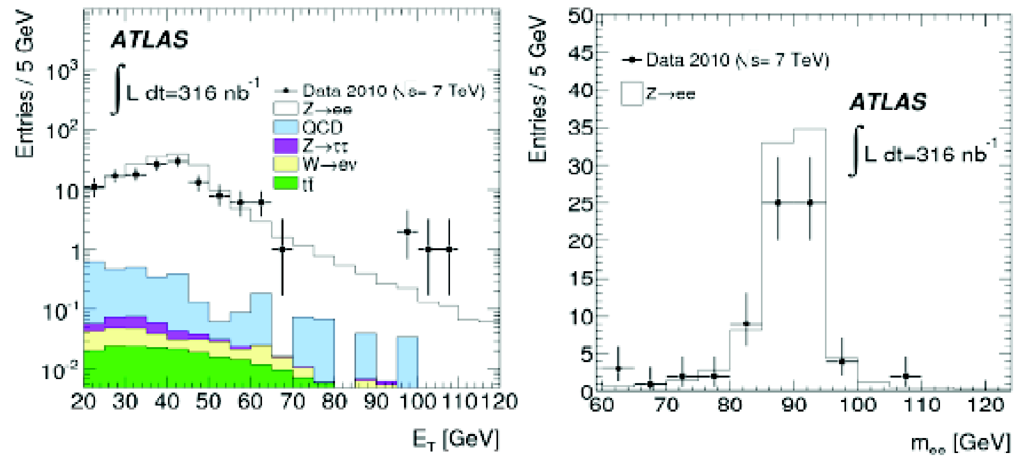
- $p_T > 20$ GeV
- *Track isolation*
- Missing $E_T > 25$ GeV
- $m_T > 40$ GeV
- *1181 Candidates*



Z selection (2010)

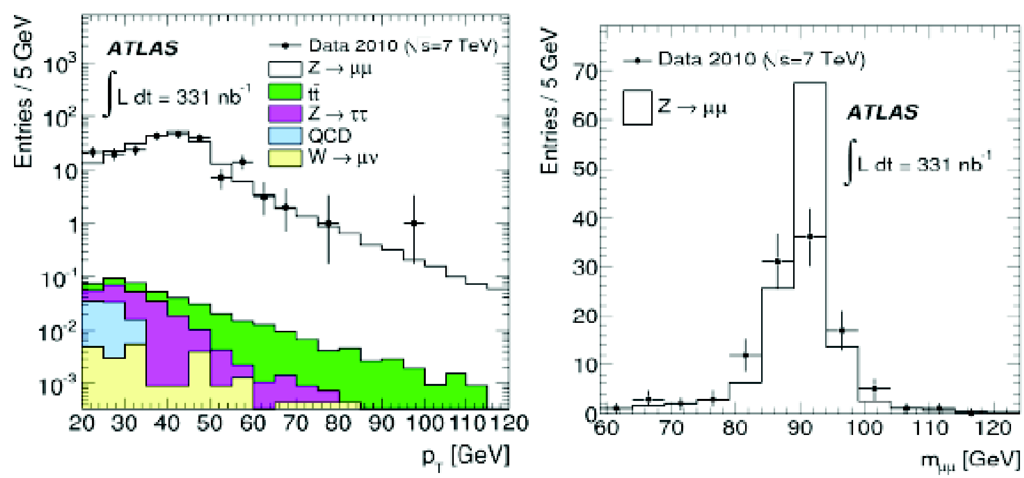
2 Electrons :

- $E_T > 20$ GeV
- Opposite charge
- Medium ID
- $66 < m_{ee} < 116$ GeV
- ➢ 70 Candidates



2 Muons :

- $p_T > 20$ GeV
- Track isolation
- Opposite charge
- $66 < m_{\mu\mu} < 116$ GeV
- ➢ 109 Candidates



W backgrounds

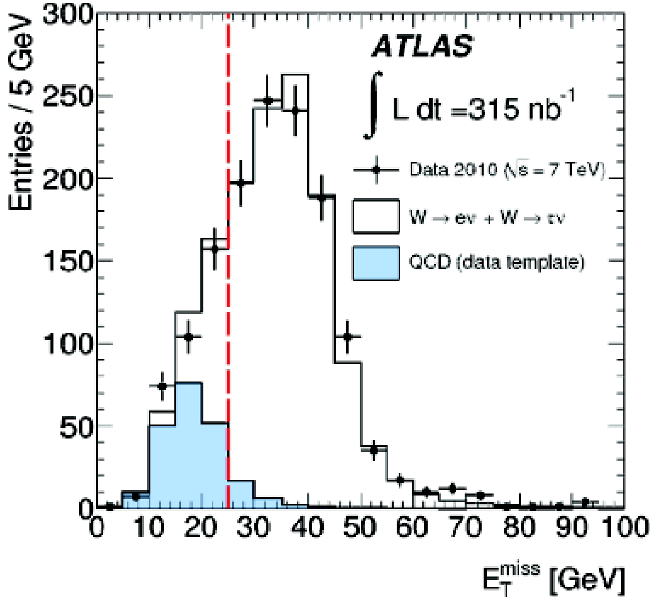
Electrons:

- EW + top background: W→ $\tau\ \nu$ + Z →e^+e^- + $t\bar{t}$

  $N_{EW+TOP} = 33.5 \pm 0.2(stat) \pm 3.0(syst)$

- QCD background is estimated with the template method using the missing energy distribution.

  $N_{QCD} = 28.0 \pm 3.0(stat) \pm 10.0(syst)$



Muons:

- EW + top background: Z → $\mu^+\mu^-$ + W→ $\tau\ \nu^-$ + $t\bar{t}$

  $N_{EW+TOP} = 77.6 \pm 0.3(stat) \pm 5.4(syst)$

- QCD background estimated from comparison of events seen in data after the full selection to number of events observed if the isolation is not applied.

  $N_{QCD} = 22.8 \pm 4.6(stat) \pm 8.7(syst)$

$$N_{loose} = N_{nonQCD} + N_{QCD}$$
$$N_{iso} = \epsilon^{iso}_{nonQCD} N_{nonQCD} + \epsilon^{iso}_{QCD} N_{QCD}$$

Cross-section & Luminosity

Number of observed events

just count …

Background

measured from data or calculated from theory

$$\sigma = \frac{N^{\text{obs}} - N^{\text{bkg}}}{\int \mathcal{L}\,\mathrm{d}t \cdot \varepsilon}$$

Luminosity

determined by accelerator, triggers, …

Efficiency

many factors, optimized by experimentalist

W cross-section measurement

The total cross section for each lepton channel can be obtained by:

$$\sigma_W \times BR(W \to l\nu) = \frac{N_W^{obs} - N^{bkg}}{A_W C_W L_{int}}$$

A_W is the geometrical acceptance calculated at generator level:

$$A_W = \left(\frac{N^{acc}}{N^{all}}\right)_{gen}$$

MC	A_W $W^+ \to e^+\nu$	A_W $W^- \to e^-\nu$	A_W $W \to e\nu$	A_W $W^+ \to \mu^+\nu$	A_W $W^- \to \mu^-\nu$	A_W $W \to \mu\nu$
PYTHIA MRST LO*	0.466	0.457	0.462	0.484	0.475	0.480
PYTHIA CTEQ6.6	0.479	0.458	0.471	0.499	0.477	0.490
PYTHIA HERAPDF1.0	0.477	0.461	0.470	0.496	0.479	0.489
MC@NLO HERAPDF1.0	0.475	0.454	0.465	0.494	0.472	0.483
MC@NLO CTEQ6.6	0.478	0.452	0.465	0.496	0.470	0.483

W cross-section measurement

The total cross section for each lepton channel can be obtained by:

$$\sigma_W \times BR(W \to l\nu) = \frac{N_W^{obs} - N^{bkg}}{A_W C_W L_{int}}$$

A_W is the geometrical acceptance calculated at generator level:

$$A_W = \left(\frac{N^{acc}}{N^{all}}\right)_{gen}$$

MC	A_W $W^+ \to e^+\nu$	A_W $W^- \to e^-\nu$	A_W $W \to e\nu$	A_W $W^+ \to \mu^+\nu$	A_W $W^- \to \mu^-\nu$	A_W $W \to \mu\nu$
PYTHIA MRST LO*	0.466	0.457	0.462	0.484	0.475	0.480
PYTHIA CTEQ6.6	0.479	0.458	0.471	0.499	0.477	0.490
PYTHIA HERAPDF1.0	0.477	0.461	0.470	0.496	0.479	0.489
MC@NLO HERAPDF1.0	0.475	0.454	0.465	0.494	0.472	0.483
MC@NLO CTEQ6.6	0.478	0.452	0.465	0.496	0.470	0.483

C_W correction factor and uncertainties

$$\sigma_W \times BR(W \to l\nu) = \frac{N_W^{obs} - N^{bkg}}{A_W C_W L_{int}}$$

- C_W is a factor correcting for reconstruction, identification and trigger efficiencies of the lepton.

	$W \to e\nu$	$W \to \mu\nu$
C_W	0.66	0.76

- Components to systematic uncertainties, are summarized below:

Parameter	$\delta C_W/C_W(\%)$
Trigger efficiency	<0.2
Material effects, reconstruction and identification	5.6
Energy scale and resolution	3.3
E_T^{miss} scale and resolution	2.0
Problematic regions in the calorimeter	1.4
Pile-up	0.5
Charge misidentification	0.5
FSR modelling	0.3
Theoretical uncertainty (PDFs)	0.3
Total uncertainty	7.0

Electrons

Parameter	$\delta C_W/C_W(\%)$
Trigger efficiency	1.9
Reconstruction efficiency	2.5
Momentum scale	1.2
Momentum resolution	0.2
E_T^{miss} scale and resolution	2.0
Isolation efficiency	1.0
Theoretical uncertainty (PDFs)	0.3
Total uncertainty	4.0

Muons

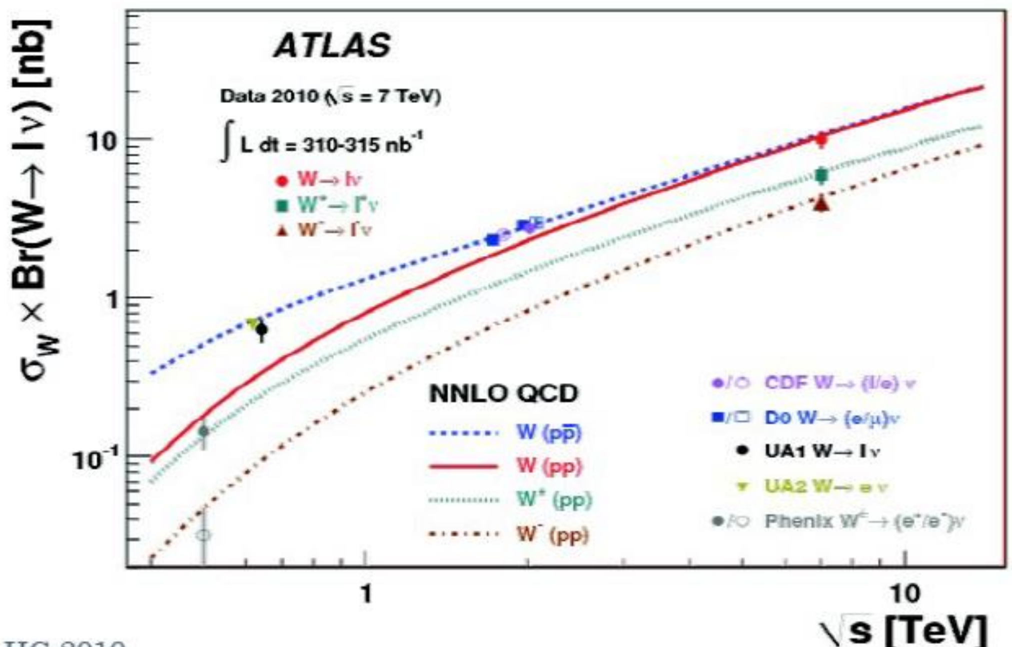
W cross-section measurement

$L \approx 310 - 315\ nb^{-1}$

Theory prediction : 10.46 ± 0.42 nb

$\sigma_W \times BR(W \to e\nu) = [10.51 \pm 0.34(stat) \pm 0.81(sys) \pm 1.16(lumi)]\ nb$

$\sigma_W \times BR(W \to \mu\nu) = [9.58 \pm 0.30(stat) \pm 0.50(sys) \pm 1.05(lumi)]\ nb$



Jose E. Garcia - HEP-LHC-2010

Z cross-section measurement

$L \approx 310 - 315\ nb^{-1}$

Theory prediction : 0.96 ± 0.04 nb for [66 – 116] GeV mass window

$$\sigma_Z \times BR(Z \to e^+e^-) = [0.75 \pm 0.09(stat) \pm 0.08(sys) \pm 0.08(lumi)]\, nb$$

$$\sigma_Z \times BR(Z \to \mu^+\mu^-) = [0.87 \pm 0.08(stat) \pm 0.06(sys) \pm 0.10(lumi)]\, nb$$