Hadron Collisions and the LHC

TASI 2006 - Lecture 1

John Conway

If you ask me anything I don't know, I'm not going to answer.

- Yogi Berra

Actually, this is probably not true...Male Answer Syndrome... but there is a lot I do not know about this topic! :)

Outline

A. Overview of the LHC Program

B. Anatomy of a Hadron Collision

C. PDFs and Q^2 Evolution

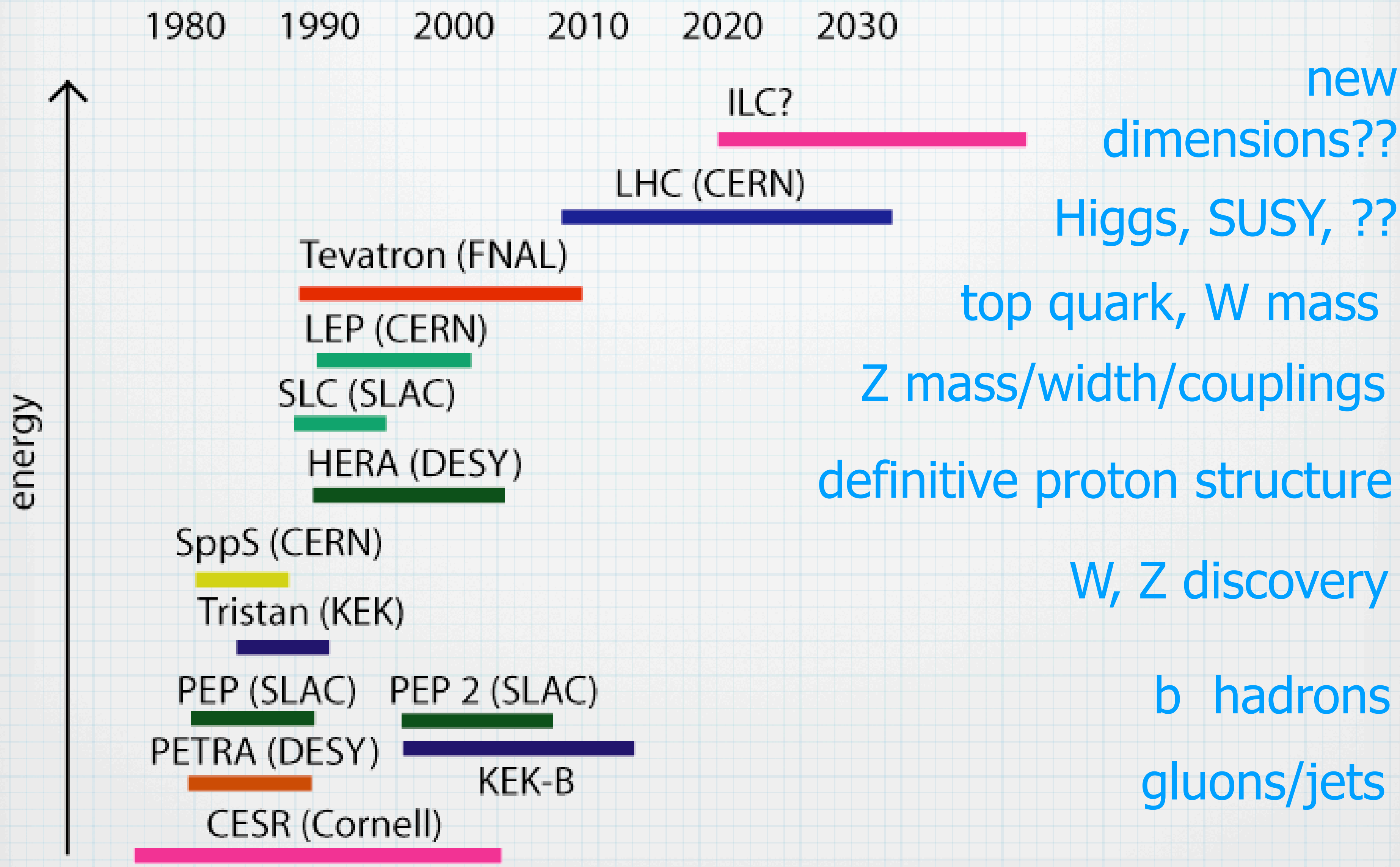
D. Hard Collision Processes

E. LHC Machine Design and Operation

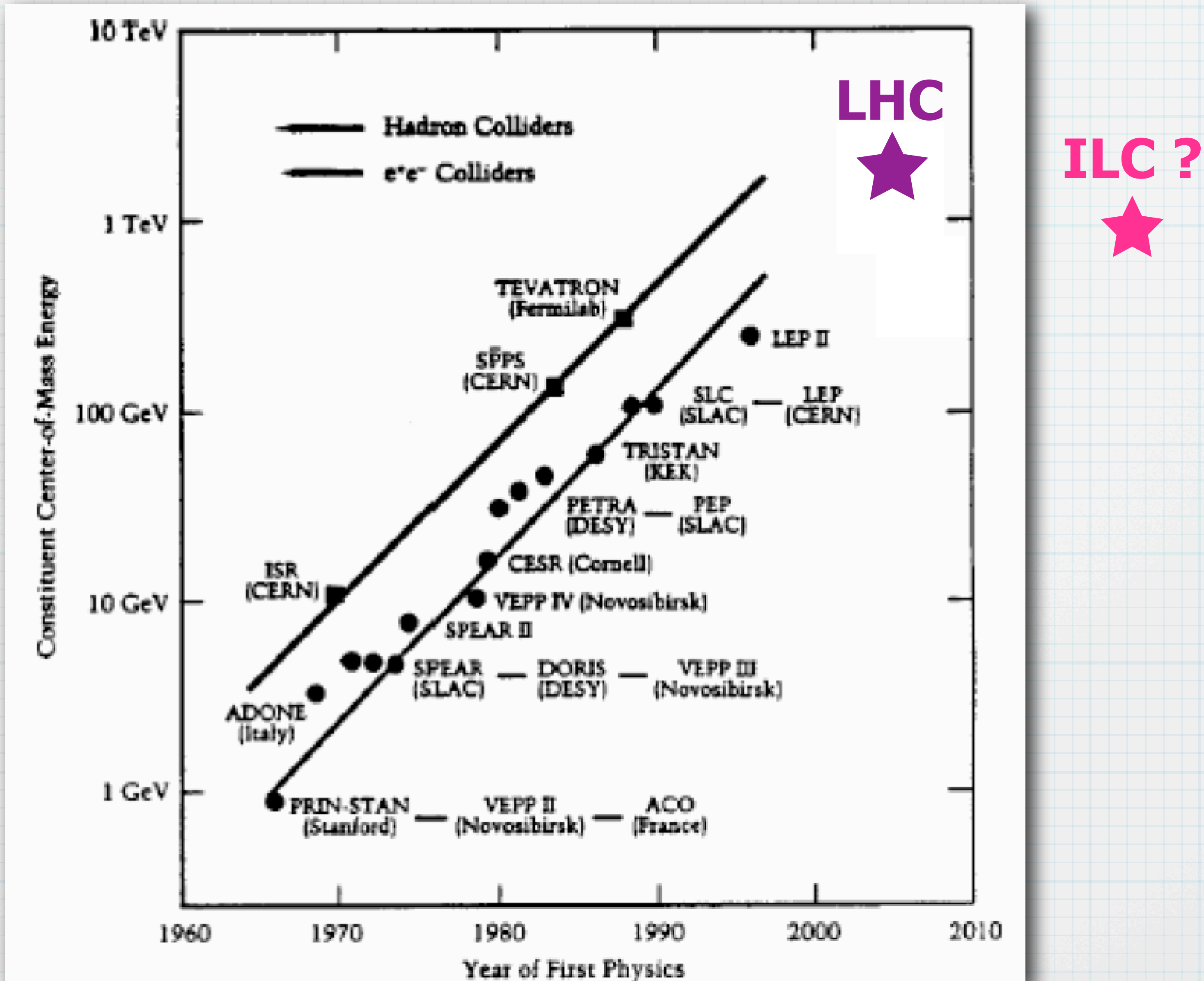
The LHC Program

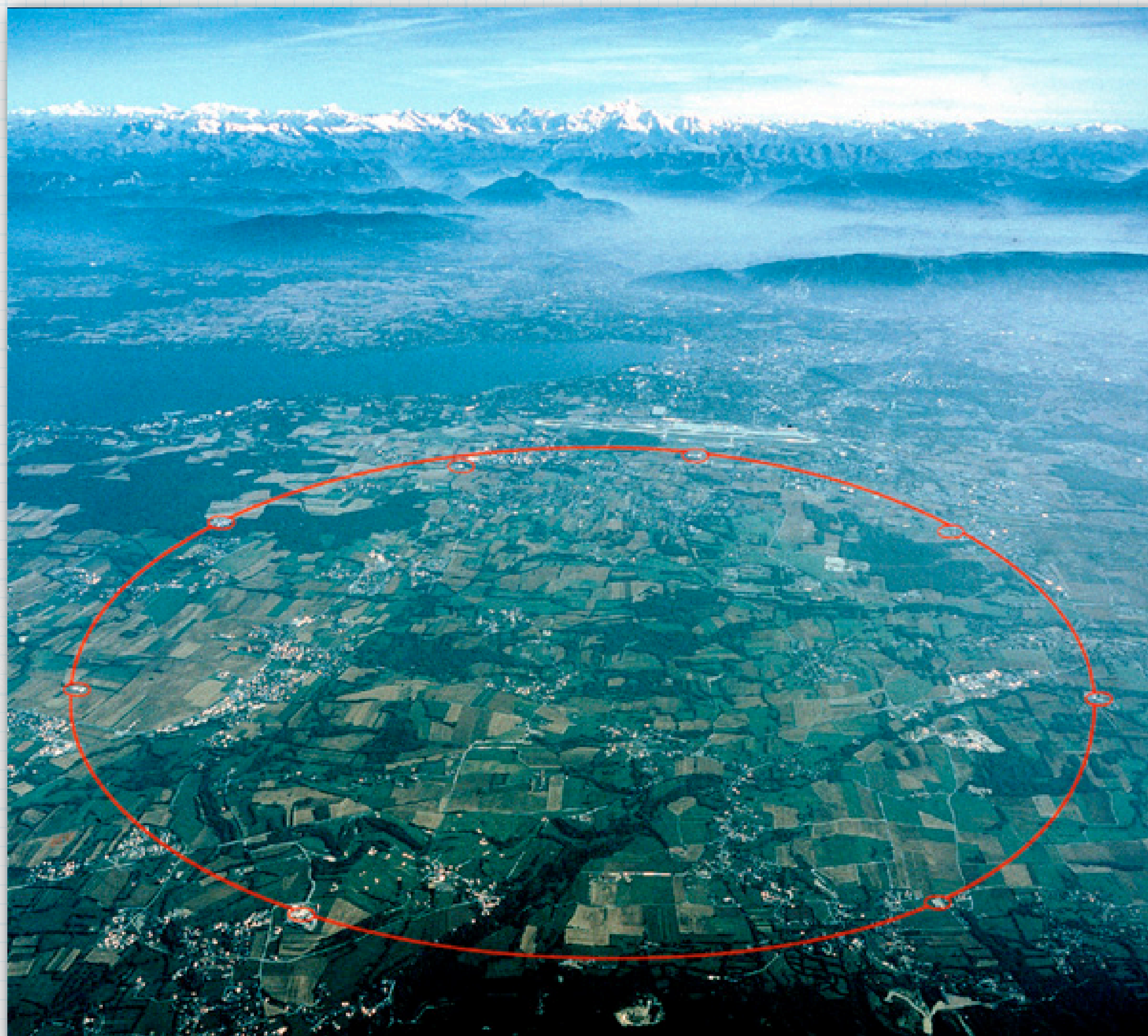
- In 1976, Burt Richter, visiting CERN, designed a large 200 GeV electron position collider: LEP
- He envisioned that come day the concrete/steel LEP magnets could be replaced with SC ones
- Collide protons: more energy!
  - huge cost
  - “dirty” collisions
  - enormous rates
- The lesson: once you have the tunnel...

Age of the Great Colliders



Livingston plot of accelerator history: it's getting harder!

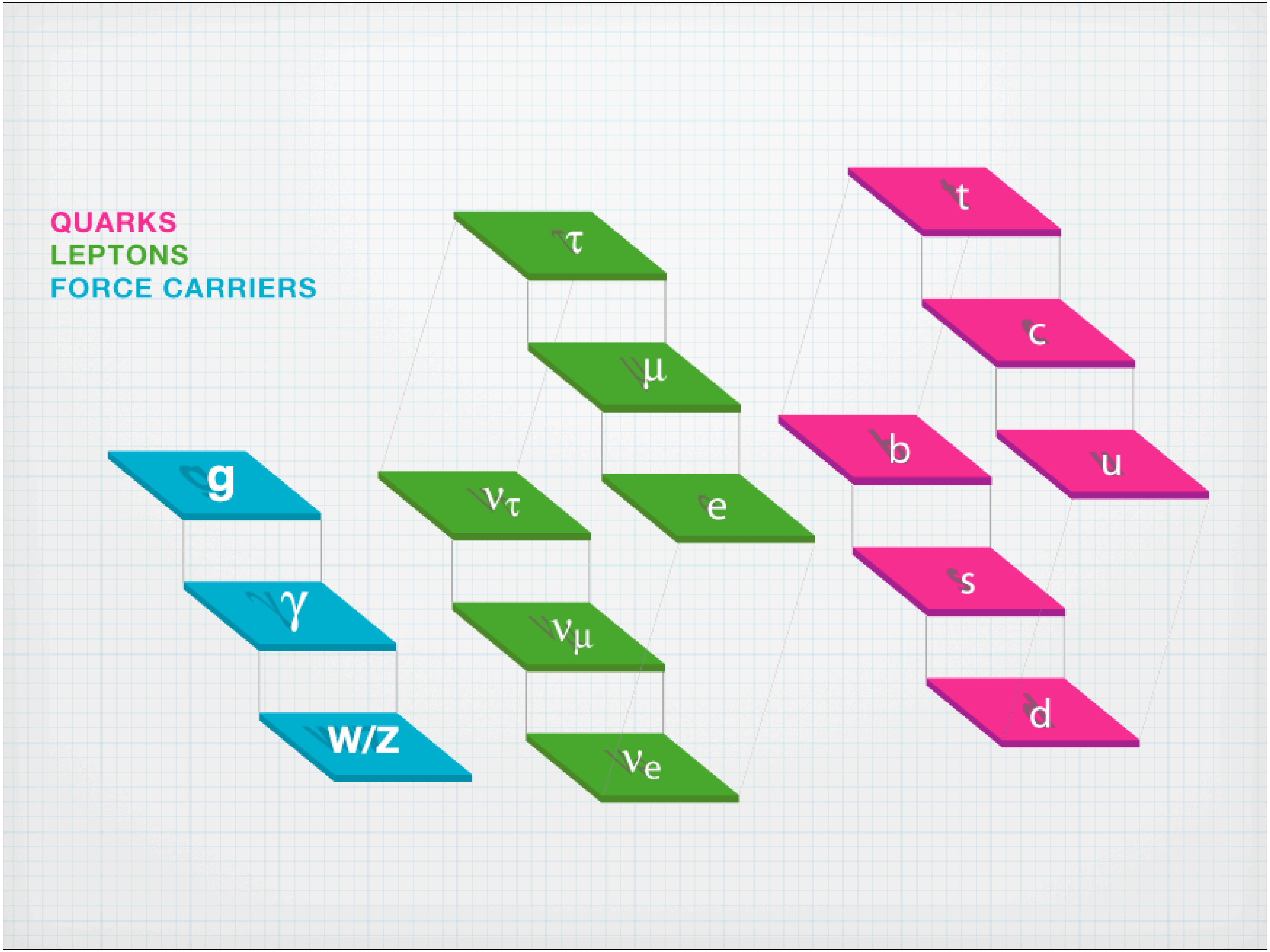




Site of the LHC near Geneva, Switzerland

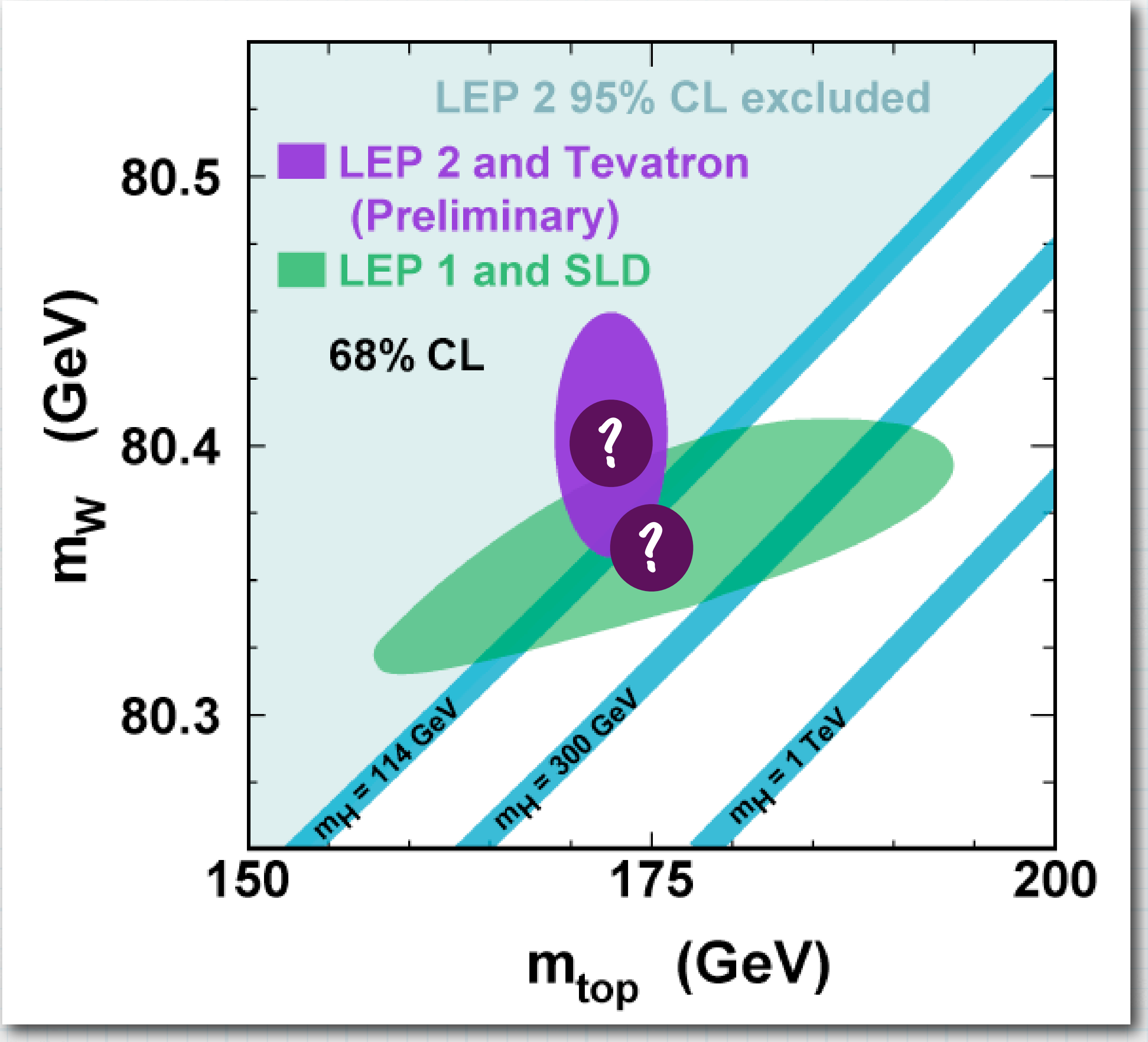
LHC Physics: Questions

- Why are there three generations?
- Are the quark generations related to the lepton ones?
- Why is there a huge range of particle masses?
- What is the nature of electroweak symmetry breaking?
- Is there a Higgs boson at ~120 GeV?
- Are there supersymmetric partners to be found?
- What is the particle nature of dark matter?
- What is the Lagrangian of the world?



QUARKS
LEPTONS
FORCE CARRIERS
t
c
u
b
s
d
τ
μ
e
ντ
νμ
νe
g
γ
W/Z

The Billion-Dollar Plot



$$\mathcal{L}_{GWS} = \sum_f (\bar\Psi_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar\Psi_f \gamma^\mu \Psi_f A_\mu) +$$

$$+ \frac{g}{\sqrt{2}} \sum_i (\bar a_L^i \gamma^\mu b_L^i W_\mu^+ + \bar b_L^i \gamma^\mu a_L^i W_\mu^-) + \frac{g}{2c_w} \sum_f \bar\Psi_f \gamma^\mu (I_f^3 - 2s_w^2 Q_f - I_f^3 \gamma_5)\Psi_f Z_\mu +$$

$$-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 - \frac{1}{2}|\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ +$$

$$-ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu|^2 +$$

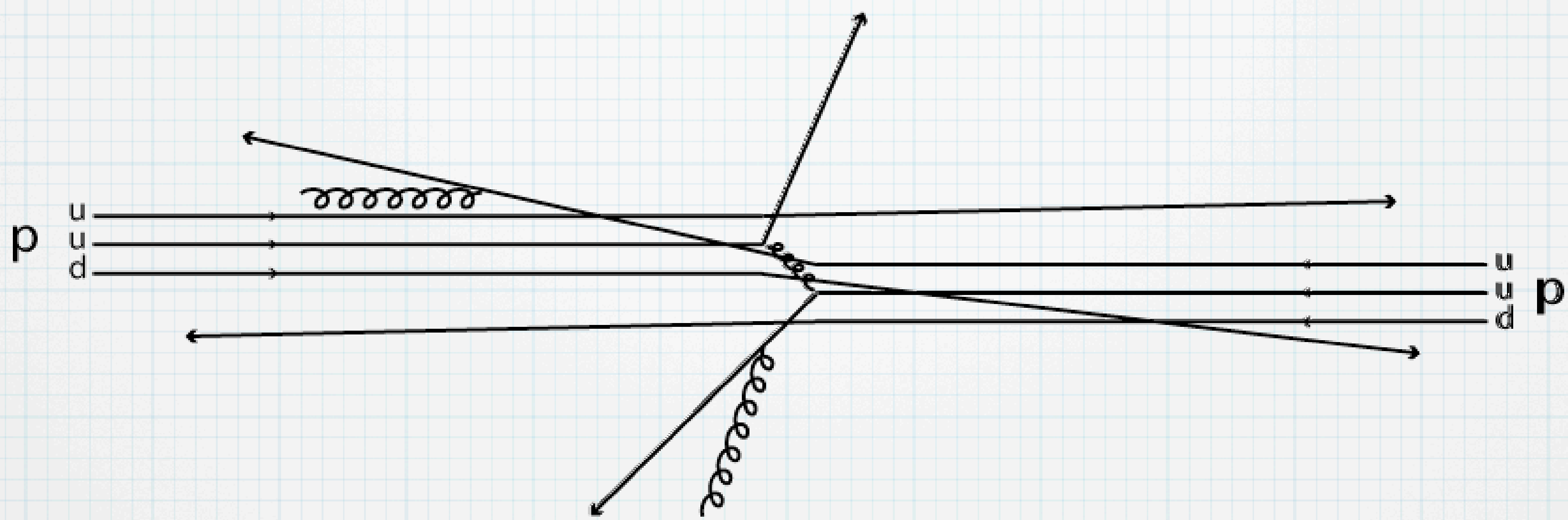
$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 +$$

$$-\frac{1}{2} M_\eta^2 \eta^2 - \frac{g M_\eta^2}{8 M_W} \eta^3 - \frac{g'^2 M_\eta^2}{32 M_W} \eta^4 + |M_W W_\mu^+ + \frac{g}{2} \eta W_\mu^+|^2 +$$

$$+\frac{1}{2}|\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar\Psi_f \Psi_f \eta$$

Is this the theory of everything? Probably not...

Anatomy of a Hadron Collision



- hard collision - governed by PDFs
- initial state/final state radiation (ISR/FSR)
- proton remnants (very forward)
- "underlying event" (color strings breaking)

PDFs and Q^2 Evolution

- PDF - parton distribution function
- measured in many experiments
- evolve with Q^2 - described by DGLAP equations
- functional fits: MRS and CTEQ groups
- uncertainties mean we cannot predict well-understood processes perfectly!
- extrapolation to LHC cross section calculations can vary a lot!

PDFs and Q^2 Evolution

- ad hoc functional form used in fit:

$$f_q(x, Q_0) = Ax^{\alpha}(1-x)^{\beta}e^{\gamma x}(1+Bx)^{\delta}$$

- Q_o = 1.3 GeV (evolve from that)
- light quarks are treated as massless
- use input from neutrino DIS experiments, HERA ep scattering, Tevatron
- Q^2 evolution softens the distributions

Hard Collision Processes

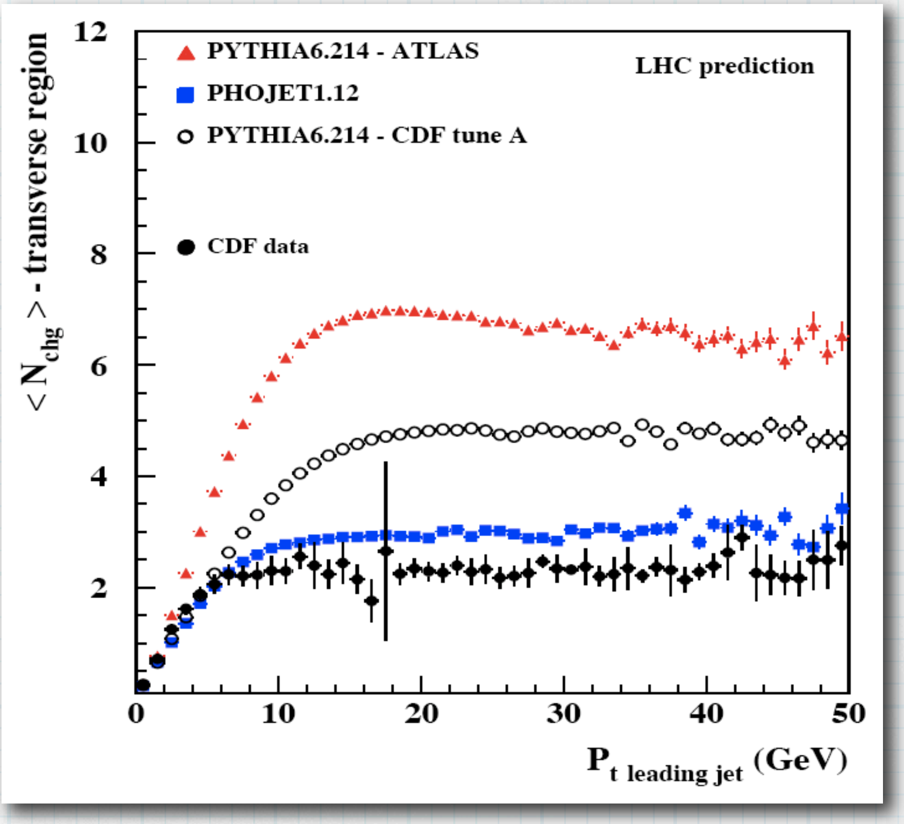
- QCD diagrams dominate
- "Drell-Yan" production of Z/γ* :

$$m^3 \frac{d^2\sigma}{dm\,dx_F} = \left(\frac{8\pi\alpha^2}{9}\right)\left(\frac{x_1 x_2}{x_1 + x_2}\right)\sum_i e_i^2 [q_i^A(x_1)\bar{q}_i^B(x_2) + \bar{q}_i^A(x_1)q_i^B(x_2)]$$

- falling continuum distribution as a function of mass, plus Z resonance
- analogous expression for W production
- antiquarks are non-valence ("sea") quarks!

The Underlying Event

- color strings breaking lead to a sort of cloud of soft mesons in the events
- we often think in terms of the underlying event actually being a min-bias event accompanying the hard collision (or vice versa)
- rule of thumb: number of particles per unit of pseudorapidity is roughly constant...but at what?



Moraes, Buttar, and Clements ATL-PHYS-PUB-2005-15

ΔR

- We tend, at hadron colliders, to use ΔR as a measure of "distance" or separation in direction between particles

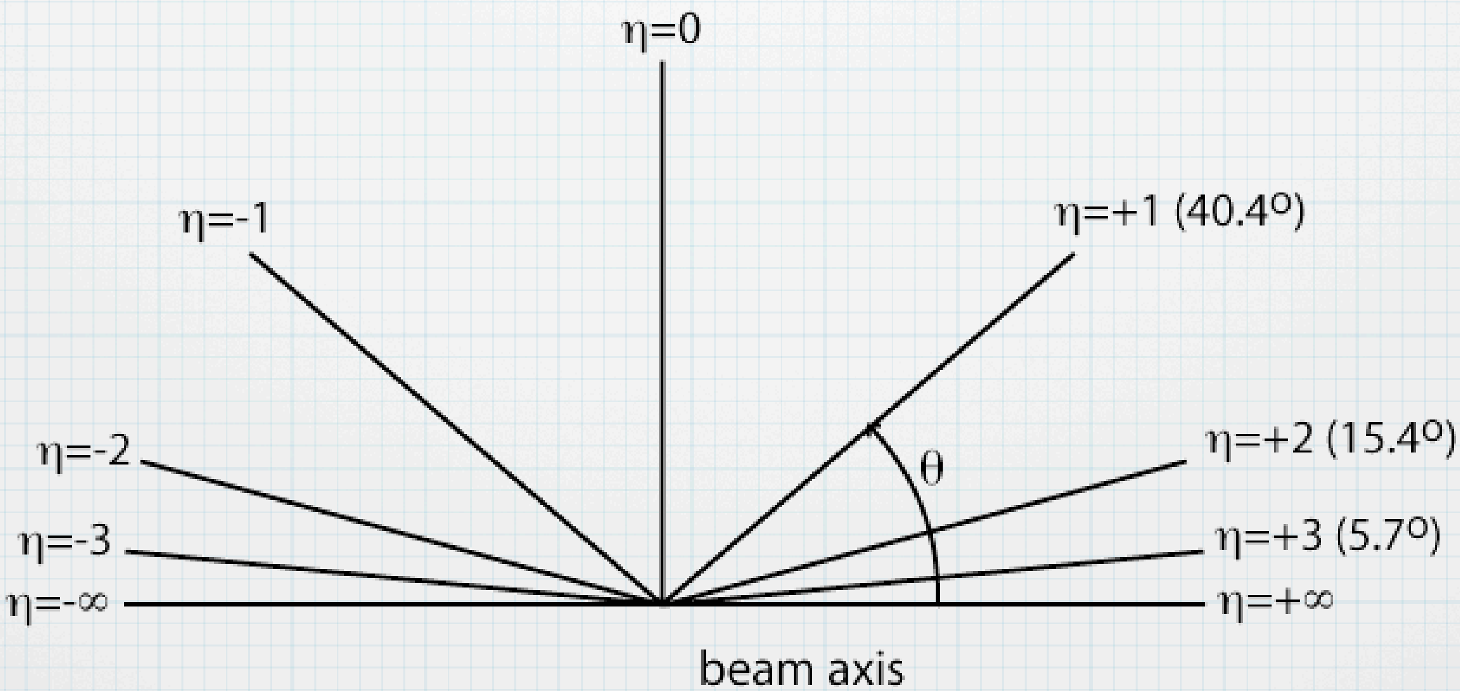
$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

- here ϕ is the azimuthal angle around the beam direction, and the pseudorapidity η is related to the polar angle by

$$\eta \equiv -\log\left(\tan\frac{\theta}{2}\right)$$

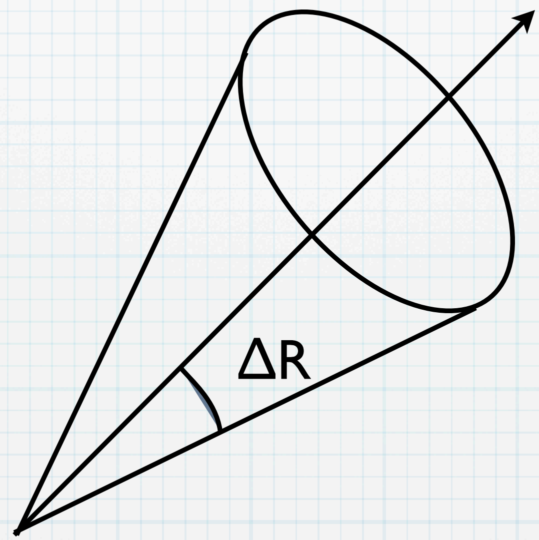
Pseudorapidity

- near $\eta=0$ (or $\theta=90^o$), $\Delta\eta \approx \Delta\theta$
- for large η, the nonlinearity is such that a given $\Delta\theta$ corresponds to a much larger $\Delta\eta$:



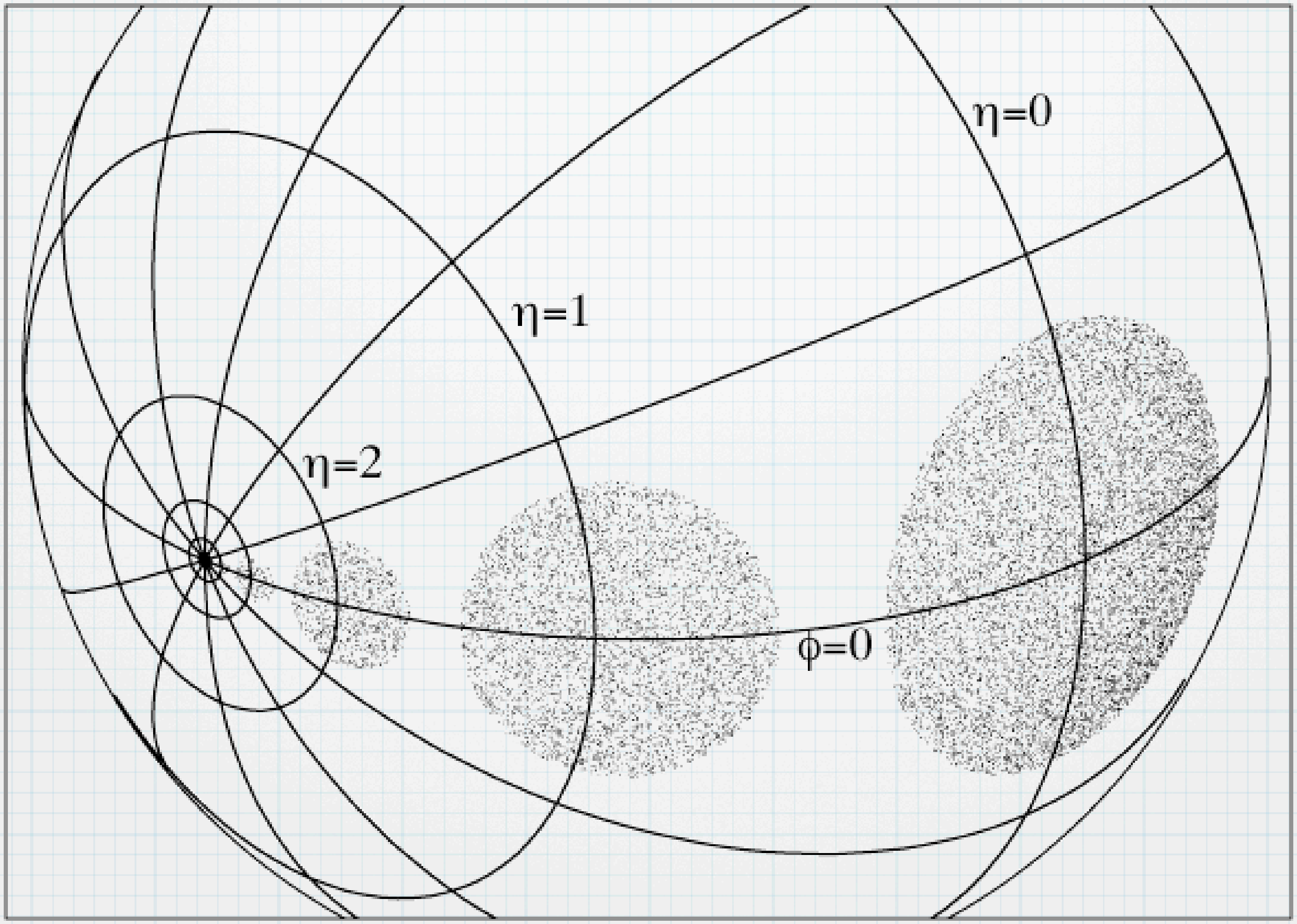
ΔR cones

- we use "cones" in ΔR to associate particles with each other



- we tend to think of these cones as circular and uniform, but they are not

ΔR cones

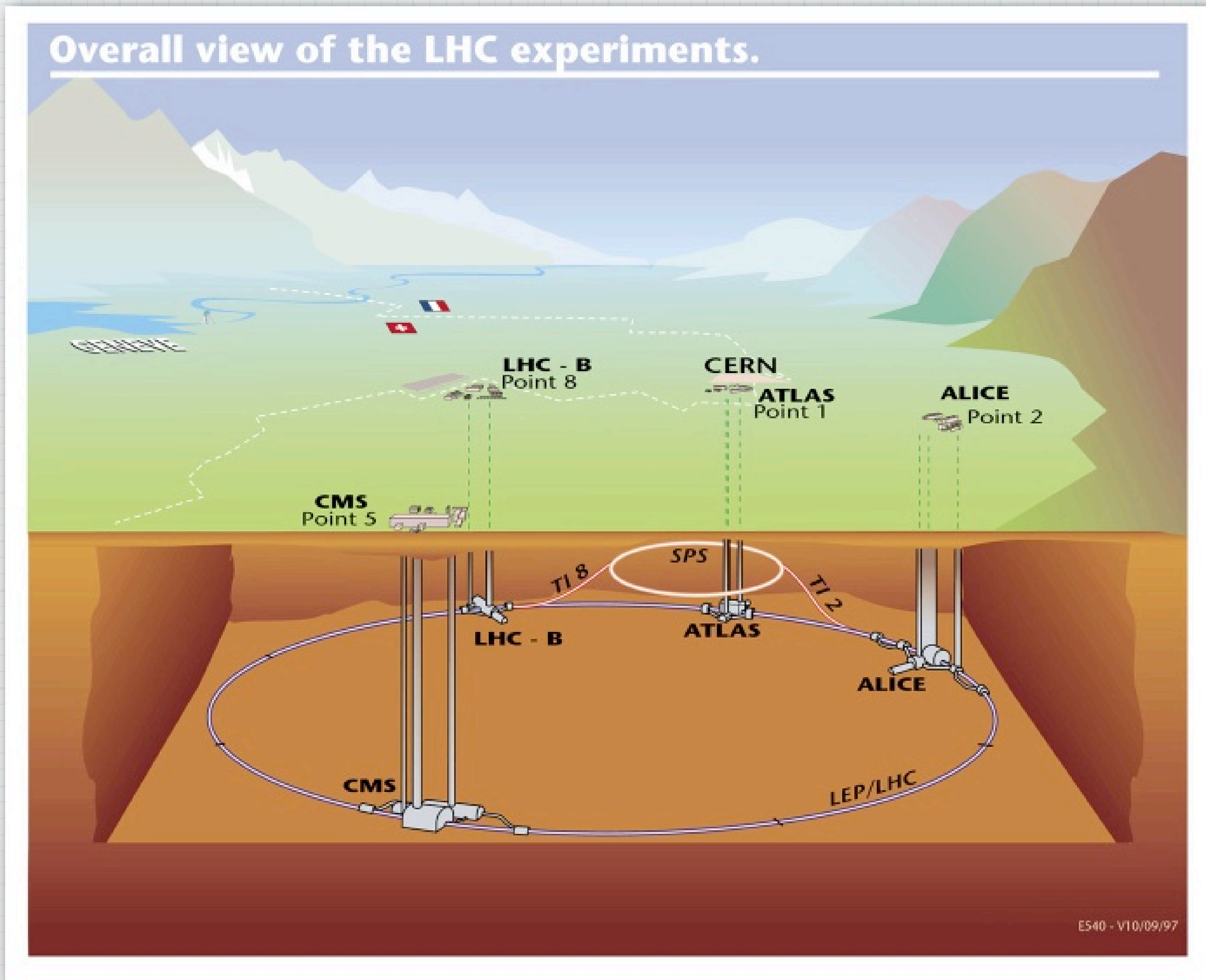


Is ΔR the right thing?

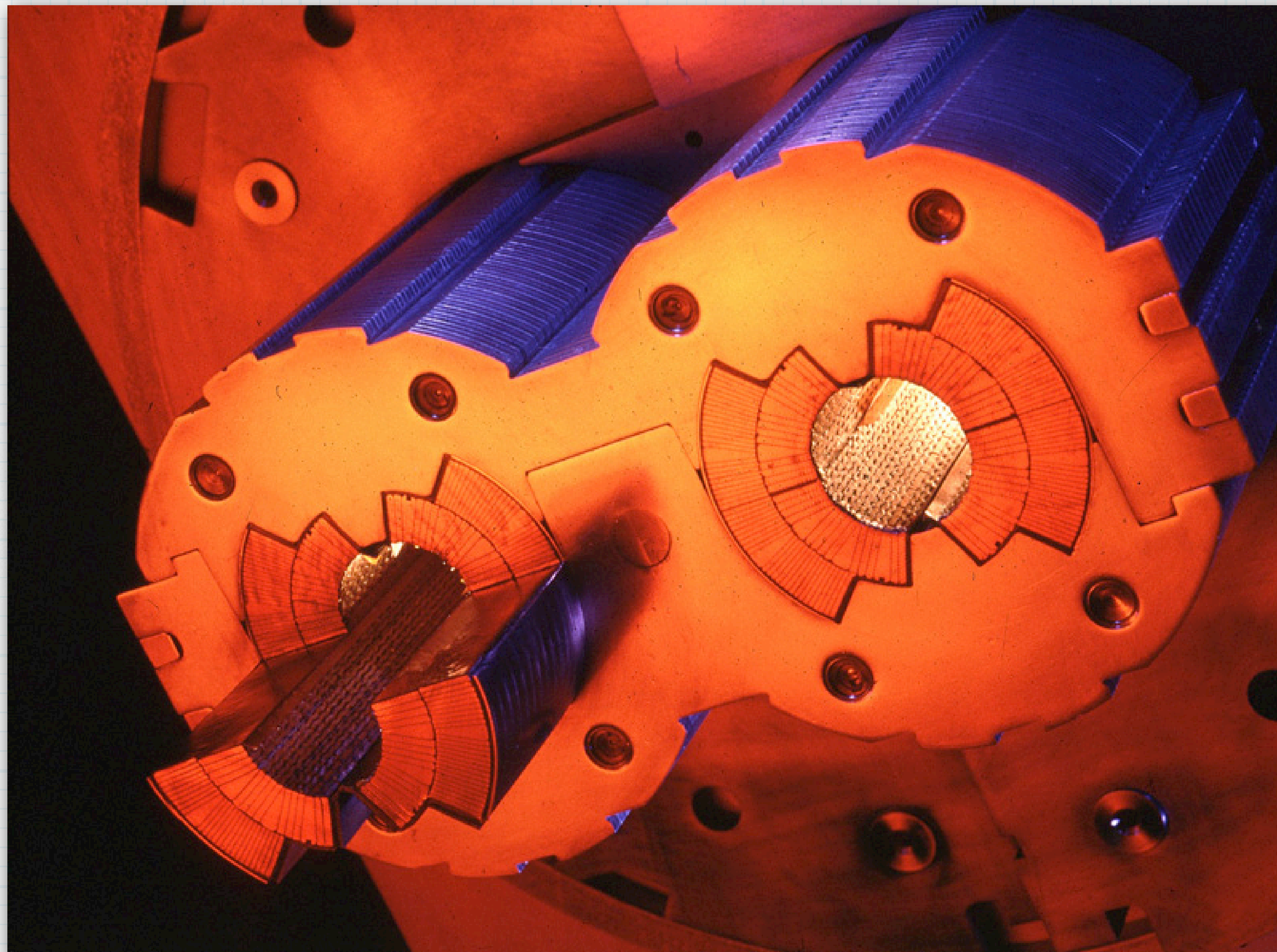
- Typical applications of ΔR cones include
  - lepton isolation (e.g. e isolation in $W \to e\nu$)
  - jet reconstruction
  - tau reconstruction ($\tau \to h\nu$)
- Is it desirable to use ΔR in any or all of these cases?
- let's look at some actual (well, simulated) 14 TeV pp collisions...

The LHC Machine

- 27 km circumference
- 100-150 m underground
- dipole bend radius ~ 2.8 km
- SC dipole field ~8.4 Tesla
- 1232 dipoles (14.3 m length)
- 2-in-1 “cosθ” design
- plane of machine tilted at 1.4^{o} (Jura)
- eightfold symmetry
- four experiments: ATLAS, CMS, ALICE, LHC-B



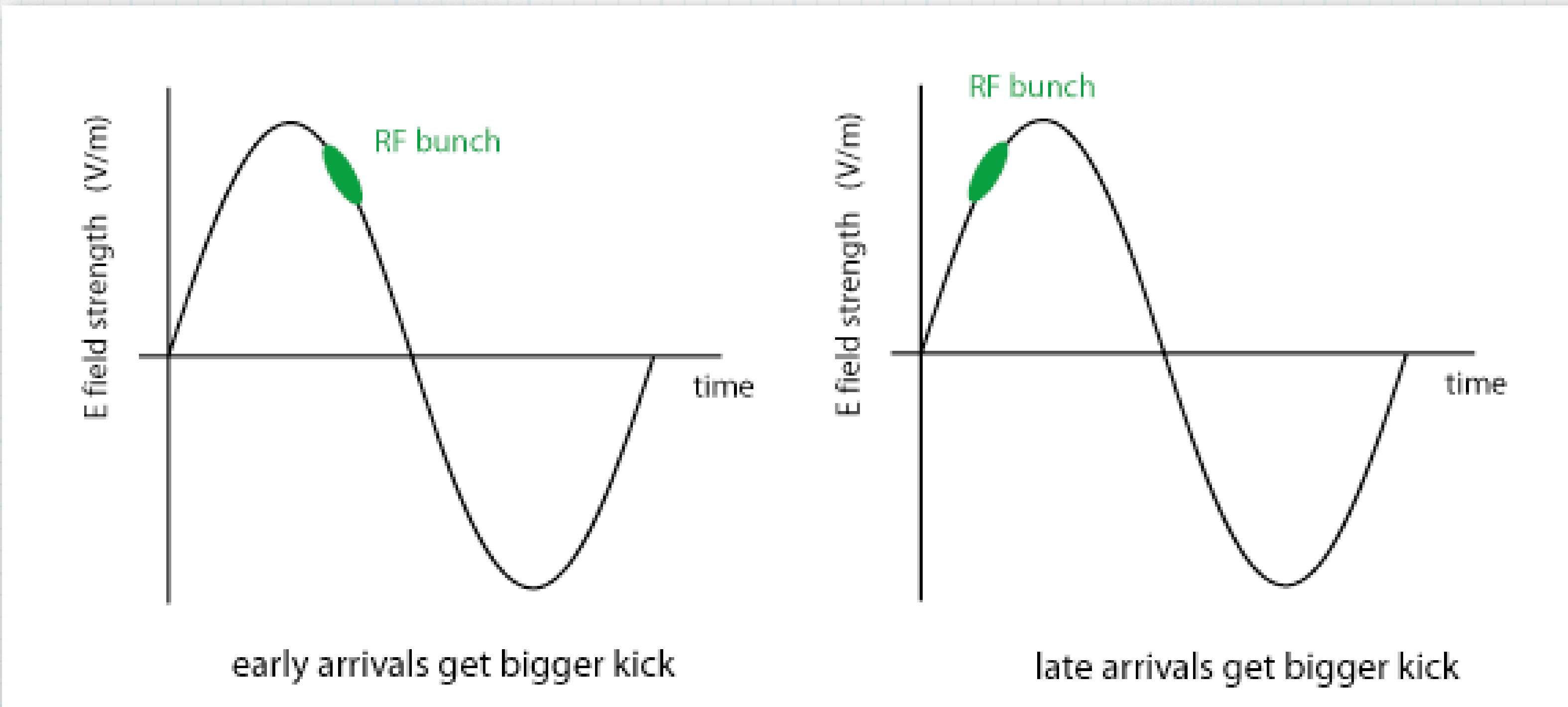
Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
E540 - V10/09/97



LHC 2-in-1 design - note cosθ current density

LHC: Synchrotron

- LHC is actually two accelerators - synchrotrons
- particle bunches arrive at a certain moment at an RF station which has a longitudinal E field; phasing?



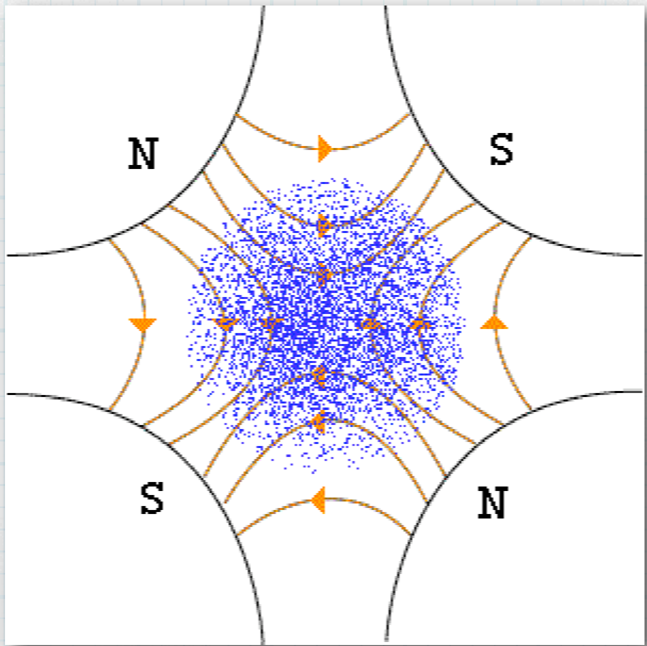
- 400 MHz (2.5 nsec) SC at Point 4 (42 cm separation)

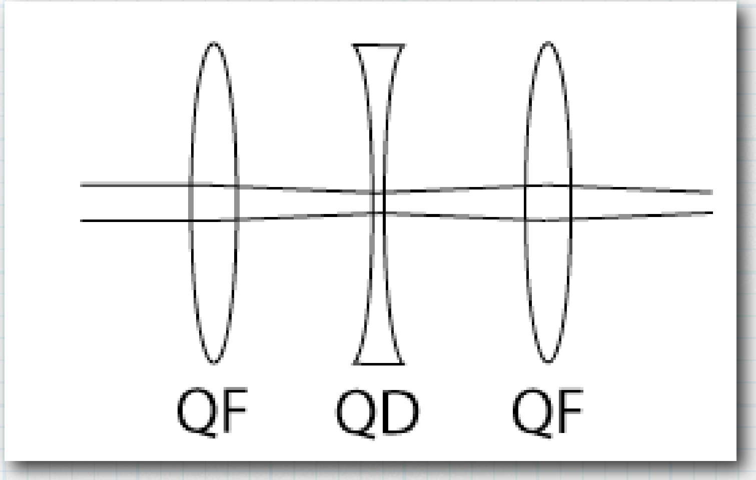
LHC bunch structure

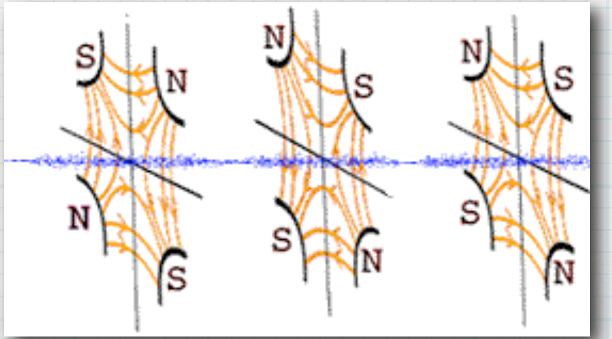
- machine frequency = c/26659 m = 11.25 kHz
- 88.9 μs per turn
- design: 24.95 ns bunch spacing
- 2808 bunches maximum due to abort/injection gaps
- initially: 75 ns bunch spacing (936x936 bunches)
- later: 25 ns bunch spacing
- bunch length?

Strong Focusing

- want beam bunches as small (dense!) as possible in all three dimensions
- quadrupole magnets interspersed among dipoles







Beta and Tune

- betatron oscillations: departure of particle from nominal orbit path β_x and β_y
- betatron oscillations decrease with beam energy
- betatron oscillations excited by machine imperfections
- want minimal x-y coupling in betatron oscillations
- want number of betatron oscillations per turn (the "tune") in machine to be <u>non-integer</u>
- interaction region: "low-beta insertion" in straight section
- trade angular spread for IP size!

Luminosity

- "fundamental equation of high energy physics"

$$N = L\sigma\epsilon$$

event rate (s^{-1})

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

cross section (cm^2)

efficiency

- 1 fb = 10^{-39} cm^{-2} 1 year ~ 10^7 s
- 10^{33} $cm^{-2}\ s^{-1}$ ~ 10 fb^{-1} per year

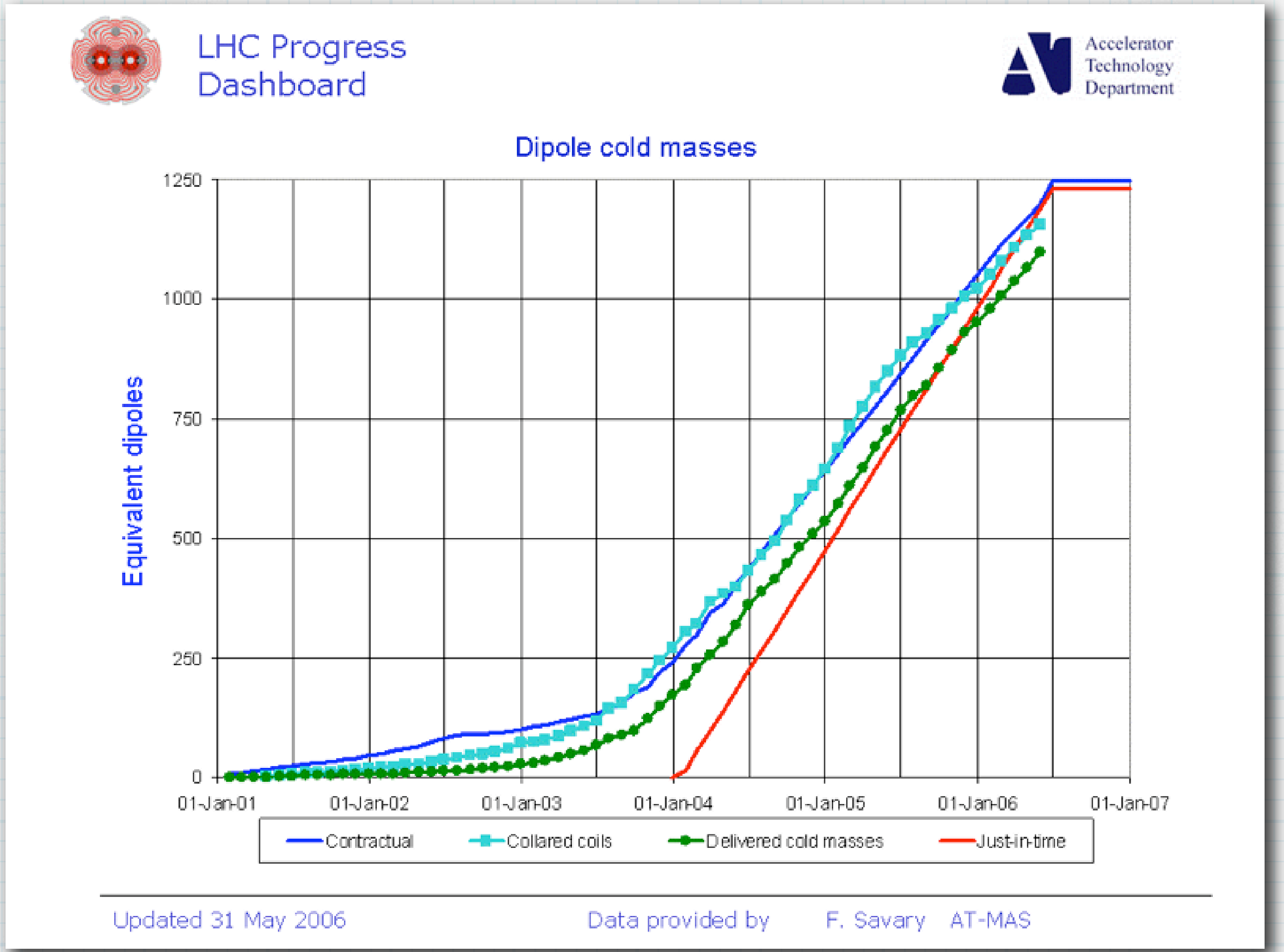
Luminosity

- luminosity depends on beam parameters:

$$L = \frac{f \sum_{i=1}^{n_b} N_{1i} N_{2i}}{4\pi\sigma_x\sigma_y} \approx \frac{f n_b N^2}{4\pi\sigma_x\sigma_y}$$

- assume f = 11.25 kHz, n_b = 2800, N=10^{11} p/bunch
- for 10^{34} we need 15 μm rms spot size
- (Tevatron beam size ~ 35 μm)

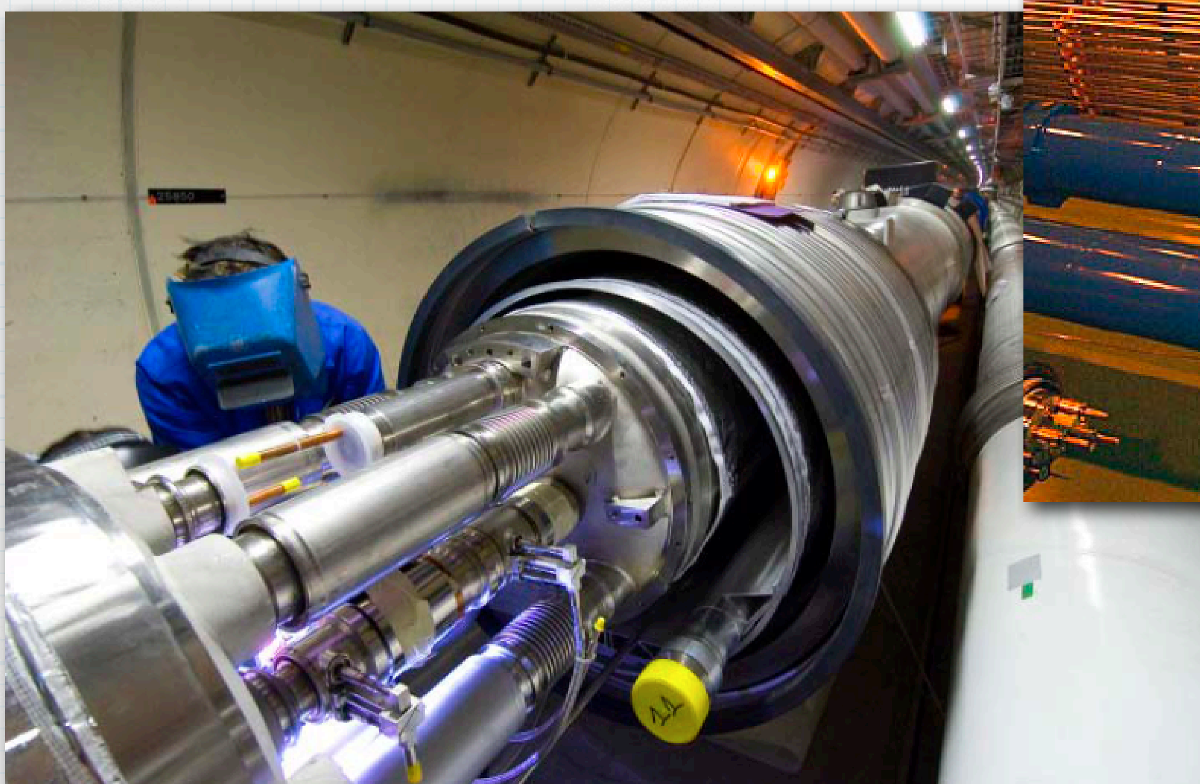
LHC "Dashboard"



http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/DashBoard/index.asp

Dipole storage
before installation

Dipole installation in tunnel



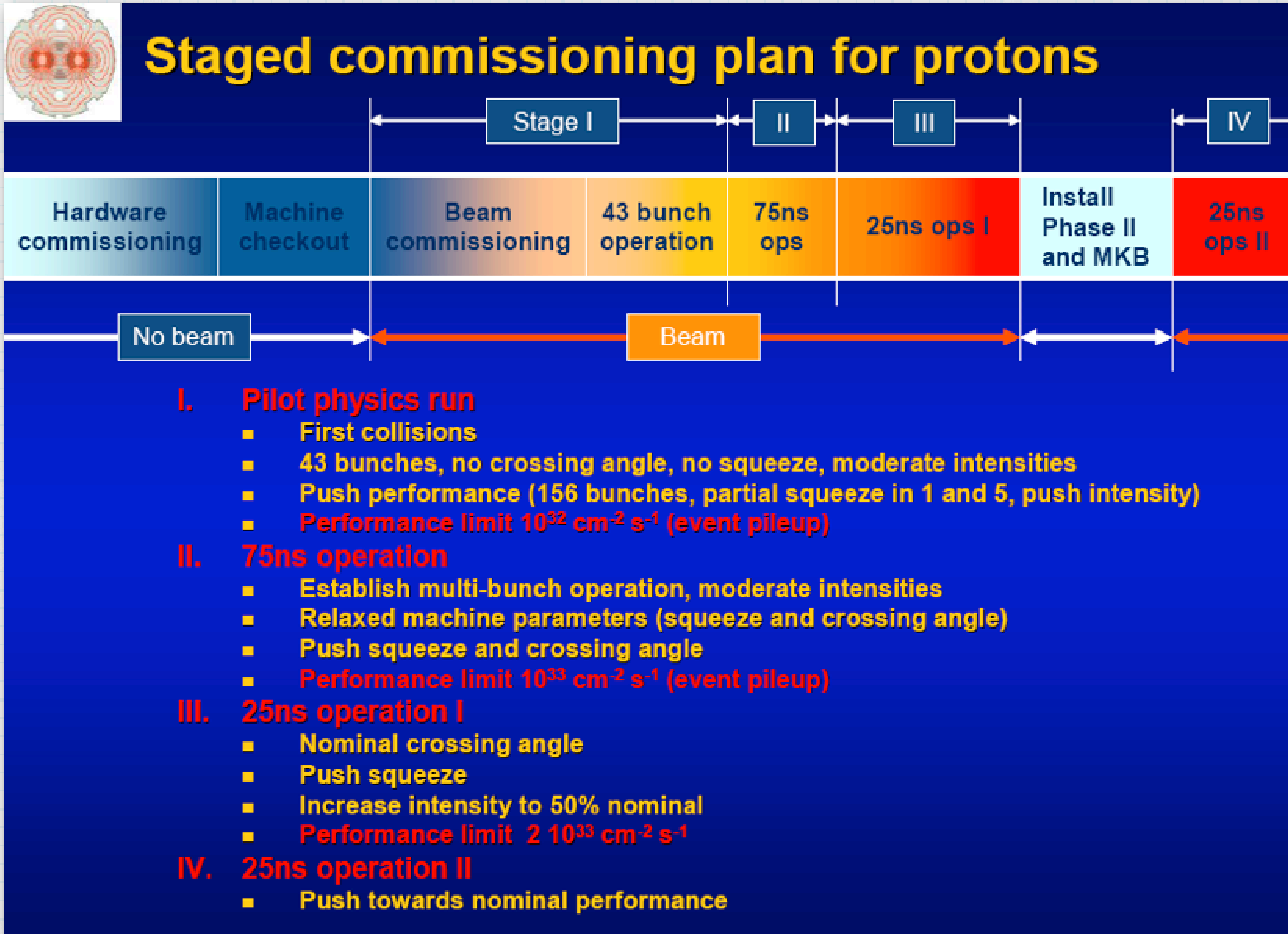
Birth of The LHC

- date of “first beam” has long been July 1, 2007
- this could mean
    - vacuum in beam pipe
    - one bunch circulating at low energy
    - no collisions
- recent change: moved to November, 2007
- initial energy: 0.9 TeV (435 GeV beam energy)
- first real physics running in 2008

Prediction is very difficult, especially about the future.

- Niels Bohr

My guess:

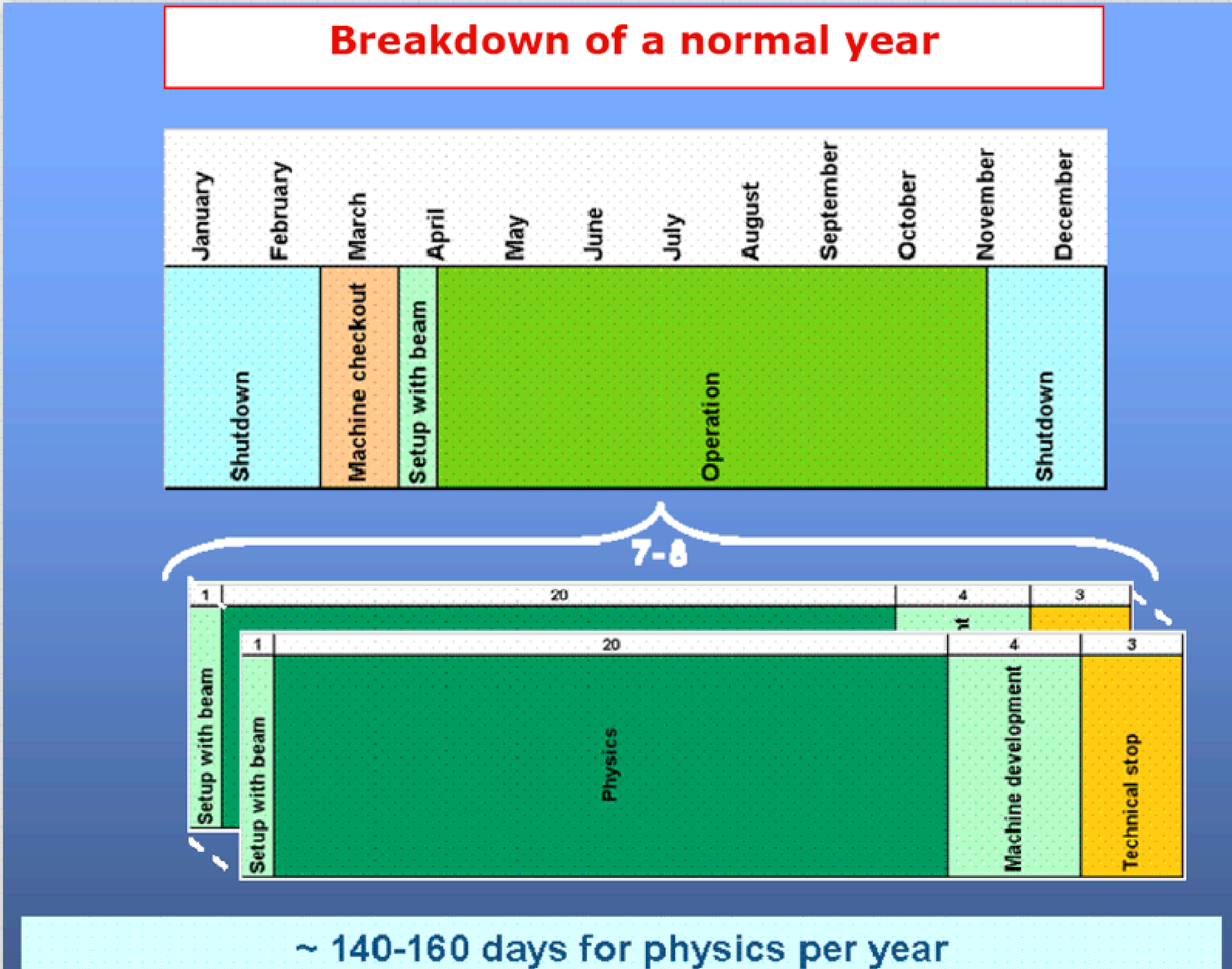


2007

2008

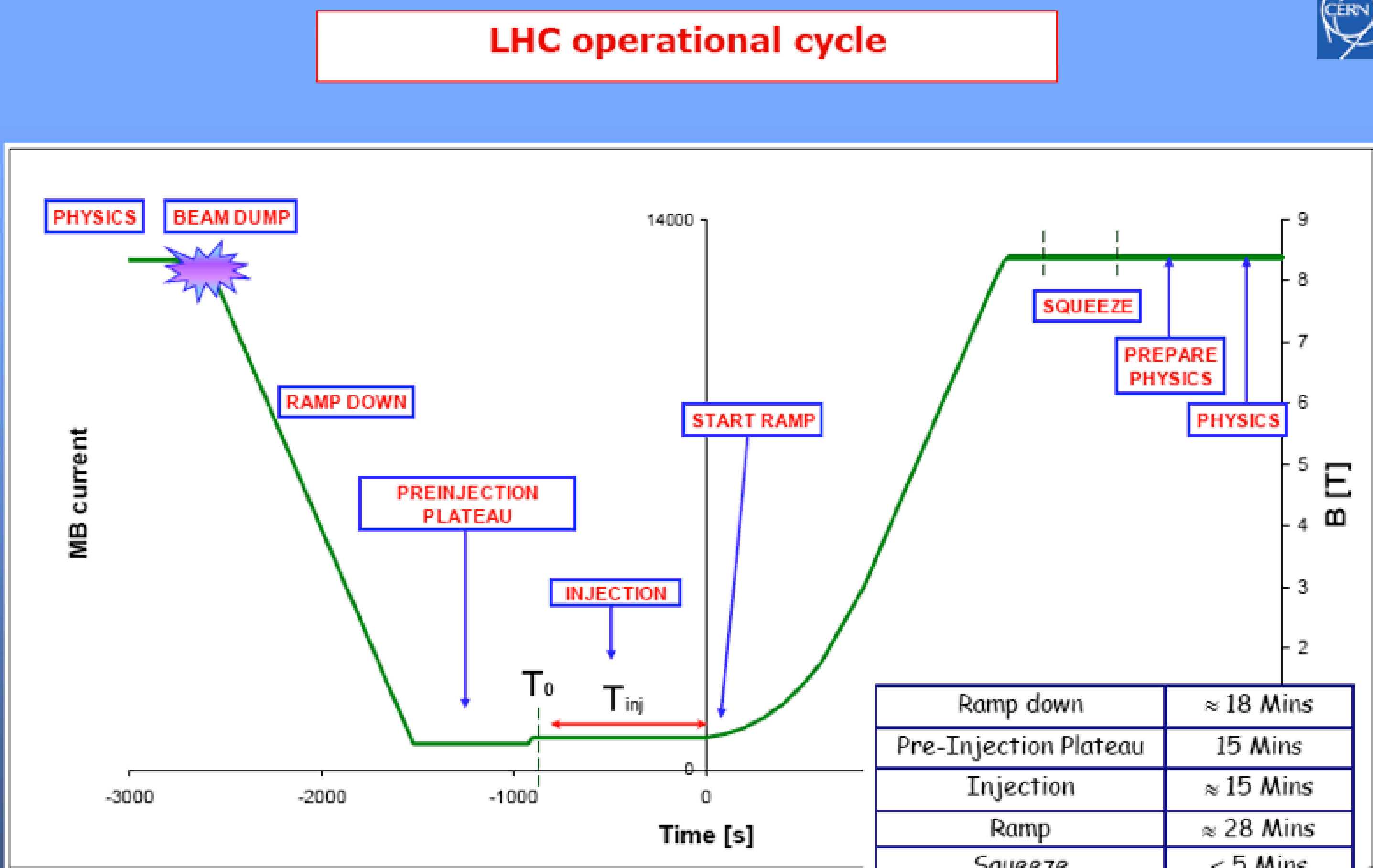
2009

from Lyn Evans, LHCC report, March 2006



from Lyn Evans, LHCC report, March 2006

LHC Daily Operations



Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

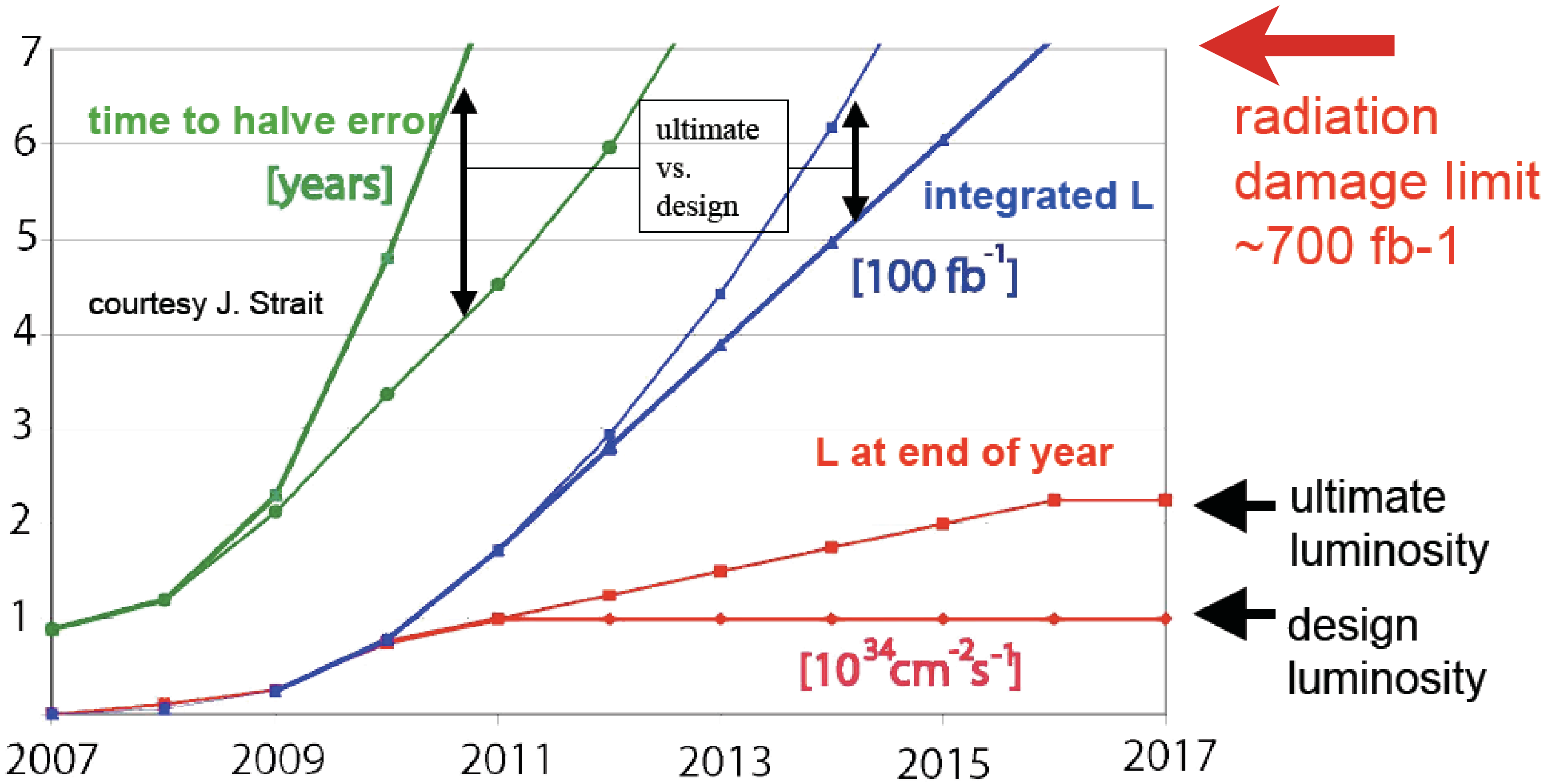
from Lyn Evans, LHCC report, March 2006

Other random LHC facts

- bunch length: 8 cm
- crossing angle: 285 μrad
- stored energy, per beam: 300 MJ (150 sticks dynamite)
- interactions per crossing at 10^{33}: 2.1
- operating temperature: 1.9 K
- power consumption: 120 MW

SuperLHC

- after ~500 fb^{-1} (roughly 2012-13?) the experiments will require major upgrades
  - radiation damage to inner detectors
  - improved readout
  - improved triggering
- major upgrade for accelerator too!
- goal for SuperLHC: 10^{35} cm^{-2} s^{-1}



(1) ***LHC IR quads life expectancy*** estimated <10 years from radiation dose

(2) the ***statistical error halving time*** will exceed 5 years by 2011-2012

(3) therefore, it is reasonable to plan a ***machine luminosity upgrade based on new low-β IR magnets before ~2014***

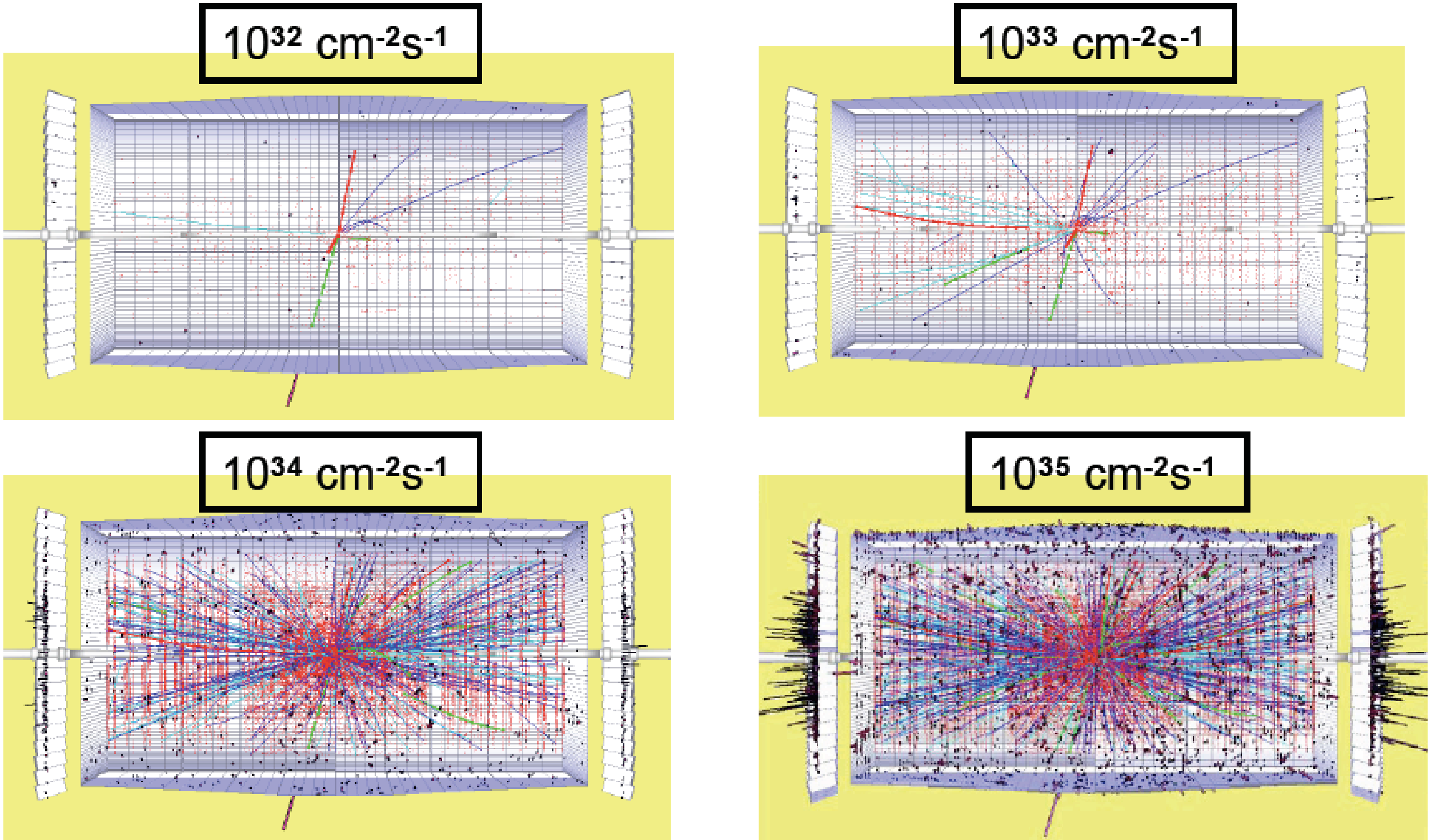
SLHC

parameter	symbol	nominal LHC	ultimate LHC	shorter bunches
#bunches	n_b	2808	2808	5616
protons/bunch	N_b [10^{11}]	1.15	1.7	1.7
bunch spacing	Δt_{sep} [ns]	25	25	12.5
average current	I [A]	0.58	0.86	1.72
norm. transv. emittance	ε_n [μm]	3.75	3.75	3.75
longit. profile		Gaussian	Gaussian	Gaussian
rms b. length	σ_z [cm]	7.55	7.55	3.78
beta at IP1&IP5	β^* [m]	0.55	0.5	0.25
crossing angle	θ_c [μrad]	285	315	445
Piwinski parameter	$\theta_c\sigma_z/(\sigma^*2)$	0.64	0.75	0.75
luminosity	L [10^{34} cm^{-2}s^{-1}]	1.0	2.3	9.2
events/ crossing		19	44	88
length luminous region (rms)	σ_{lum} [mm]	44.9	42.8	21.8

very difficult!

Wesley Smith, Snowmass LC Workshop 2005

$H \rightarrow ZZ \rightarrow \mu\mu ee$, $M_H = 300$ GeV for different luminosities in CMS



Holy crap!