Accelerators: The Final Frontier?

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October 15, 2007

Knoxville Convention Center
Knoxville, Tennessee

Outline

- Future Accelerators for particle physics
  - What is needed & why
  - The Large Hadron Collider (LHC)
  - The Linear Collider (LC)
  - The Muon Collider (MC)
  - The Neutrino Factory (NF)
- Other scientific applications
  - Light sources, Spallation sources …
- Other Future Accelerators
  - Laser-Plasma accelerators
- Other applications
  - Accelerators in Medicine

No time

- Summary

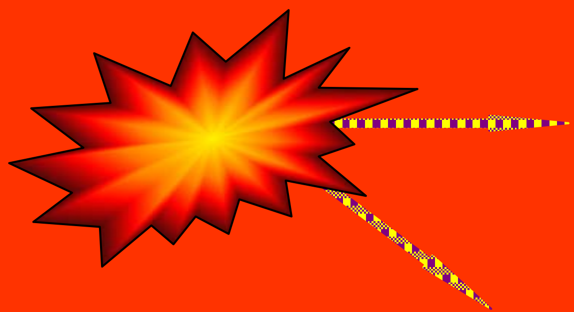
Accelerators for particle physics

What is needed, and why

2 routes to new knowledge about the fundamental structure of the matter

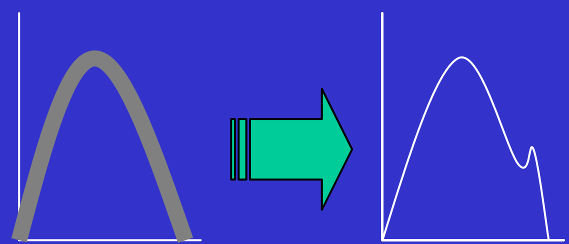
High Energy Frontier

New phenomena (new particles) created when the "usable" energy > mc^2 [×2]



High Precision Frontier

Known phenomena studied with high precision *may* show inconsistencies with theory



The Standard Model

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + i\bar{\psi}D\psi$$

$$+\psi_i\lambda_{ij}\psi_j h + h.c.$$

$$+|D_\mu h|^2 - V(h)$$

$$+\frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j$$

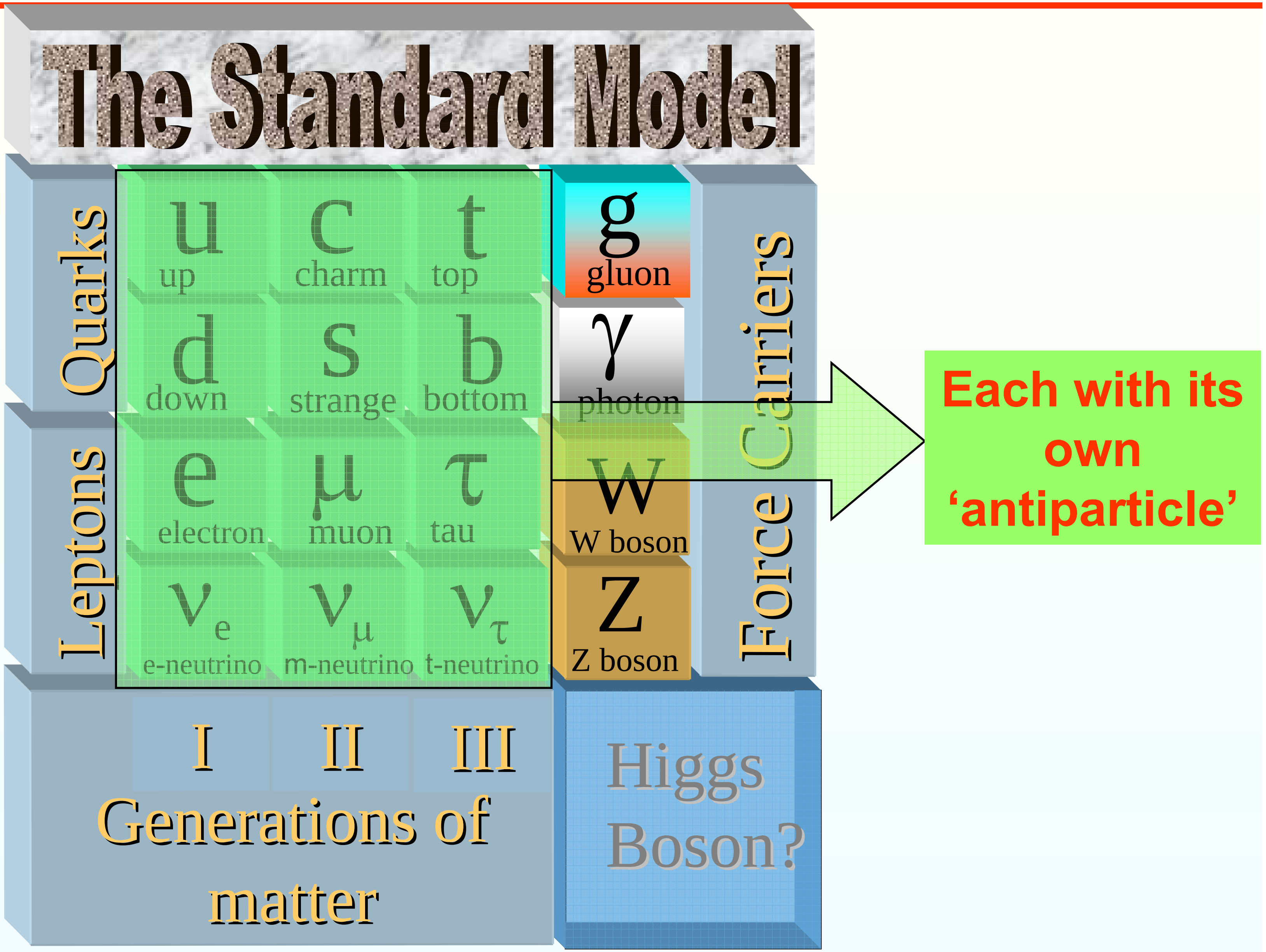
The gauge sector (1)

The flavor sector (2)

The EWSB sector (3)

The ν-mass sector (4)

Particles and Forces



The Standard Model

The Standard Model Effective Lagrangean

$$
\begin{aligned}
&\mathcal{L}_{(\text{Standard Model})} = \\
&[W^{\pm}] \quad - \tfrac{1}{2}(\theta_\mu W_\nu - \theta_\nu W_\mu)(\theta^\mu W^{\dagger\nu} - \theta^\nu W^{\dagger\mu}) + M_w^2 W_\mu W^{\dagger\mu} \\
&[\text{Photon}] \quad - \tfrac{1}{4} F^A_{\mu\nu} F^{A\mu\nu} \\
&[Z^o] \quad - F^Z_{\mu\nu} F^{Z\mu\nu} + \tfrac{1}{2} M_Z^2 Z_\mu Z^\mu \\
&[\ell, \nu_\ell] \quad + \imath \overline{L_\ell} \not\theta L_\ell + \imath \overline{R_\ell} \not\theta R_\ell - m_\ell \bar{\ell}\ell \\
&[W\ell\nu] \quad - \frac{g}{\sqrt{2}} \overline{L_\ell}(\tau_+ \not W + \tau_- \not W) L_\ell \\
&[\gamma\ell^+\ell^-] \quad + e_{e/m} \bar{\ell} \not A \ell \\
&[Z\ell^+\ell^-, Z\nu\bar{\nu}] \quad - \frac{g}{\cos\theta_w} \overline{L_\ell} \left(\frac{\tau_3}{2} \cos^2\theta_w + \frac{1}{2}\sin^2\theta_w \right) \not Z L_\ell - \frac{g \sin^2\theta_w}{\cos\theta_w} \overline{R_\ell} \not Z R_\ell \\
&[\text{H}] \quad + \tfrac{1}{2}\theta_\mu H \theta^\mu H - \tfrac{1}{2}\mu^2 H^2 - \tfrac{1}{2}\lambda\mu H^3 - \tfrac{1}{8}\lambda^2 H^4 \\
&[\text{HH\&H } W^+W^-] \quad + \frac{g^2}{8} \left(H^2 + \frac{2\mu}{\lambda} H \right) \left(2 W_\mu W^{\dagger\mu} \right) \\
&[\text{HH\&H } ZZ] \quad + \frac{g^2}{8} \left(H^2 + \frac{2\mu}{\lambda} H \right) \left(\frac{1}{\cos^2\theta_w} Z_\mu Z^\mu \right) \\
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&[\text{gluons}] \quad - \tfrac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} \\
&[\text{quarks}] \quad + \overline{\mathcal{U}}(\imath \not\theta - m_{\mathcal{U}})\mathcal{U} + \overline{\mathcal{D}}(\imath \not\theta - m_{\mathcal{D}})\mathcal{D} \\
&[\text{quark gluon}] \quad + \imath g T^a \left(\overline{\mathcal{U}} \not A^a \mathcal{U} + \overline{\mathcal{D}} \not A^a \mathcal{D} \right) \\
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&[\text{4 gluons}] \quad - \frac{g^2}{4} f^{abc} f^{axy} A^b_\mu A^c_\nu A^{x\mu} A^{y\nu}
\end{aligned}
$$

excluding GRAVITY

The Higgs Sector

The Parameters

- 6 quark masses
  - m_u, m_c, m_t
  - m_d, m_s, m_b
- 3 lepton masses
  - m_e, m_μ, m_τ
- 2 vector boson masses
  - M_W, M_Z
    - $(m_\gamma, m_g = 0)$
- 1 Higgs mass
  - M_h
- 3 coupling constants
  - G_F, α, α_s
- 3 quark mixing angles
  - $\theta_{12}, \theta_{23}, \theta_{13}$
- 1 quark phase
  - δ

The Standard Model in action

The Standard Model Effective Lagrangean

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\end{aligned}
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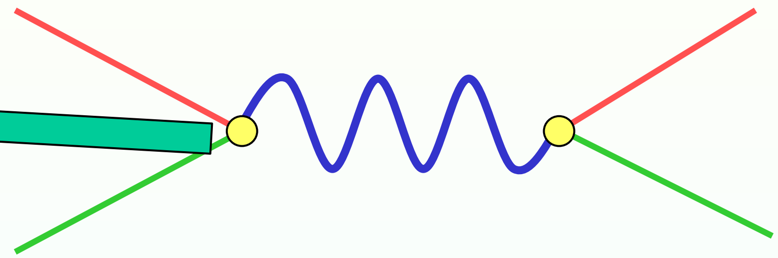
excluding GRAVITY

- **Take a process**

$e^+e^- \rightarrow \mu^+\mu^-$



$4\pi\alpha^2/3s$

a is the fine structure constant

s is the (C.of.M Energy)^2

(neglecting masses and $\sqrt{s} \ll M_Z$)

How good is the Standard Model?

The Standard Model Effective Lagran

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[H]	$+\ \frac{1}{2}\partial_\mu H\partial^\mu H - \frac{1}{2}\mu^2H^2 - \frac{1}{2}\lambda\mu H^3 - \frac{1}{8}\lambda^2H^4$
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[gluons]	$-\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}$
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[4 gluons]	$-\frac{g^2}{4}f^{abc}f^{ars}A^b_\mu A^c_\nu A^{r\mu}A^{s\nu}$

excluding GRAVITY

18 measurements

5 free parameters

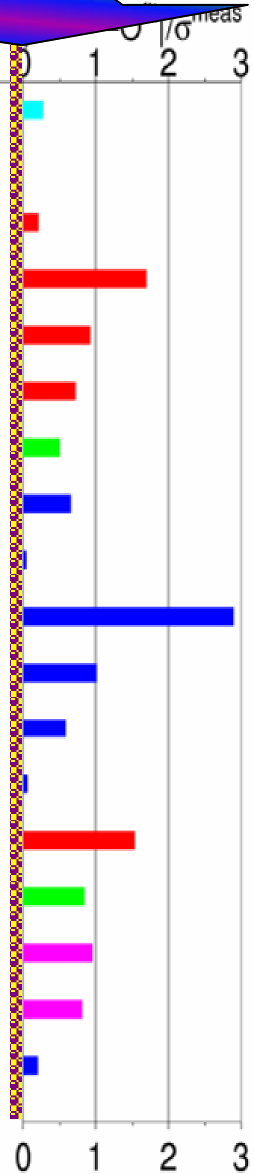
χ^2= 18.1/13 d.o.f.

3 > 1σ

1 > 2σ

Almost too good!

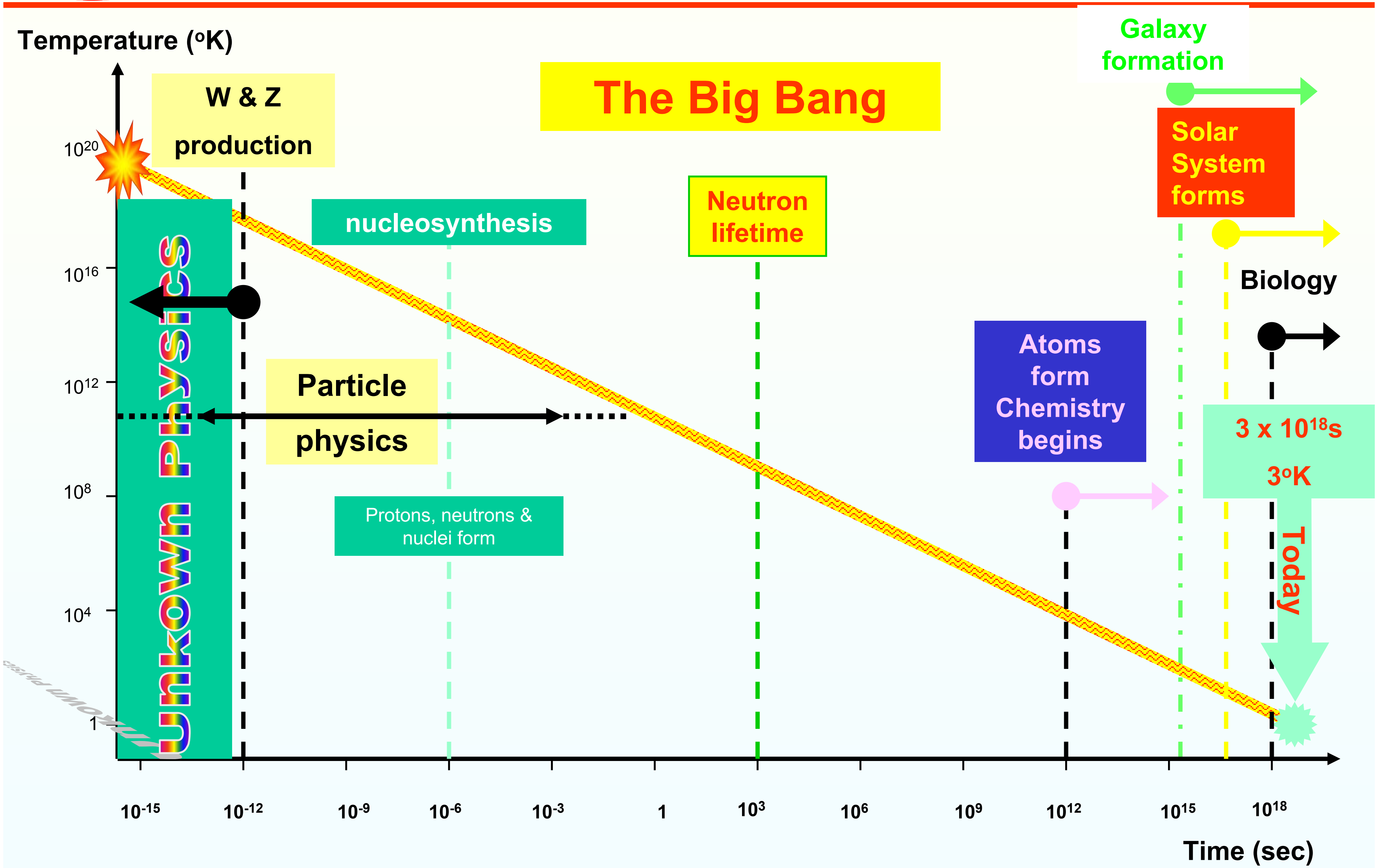
	Measurement	
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



What remains to be done?

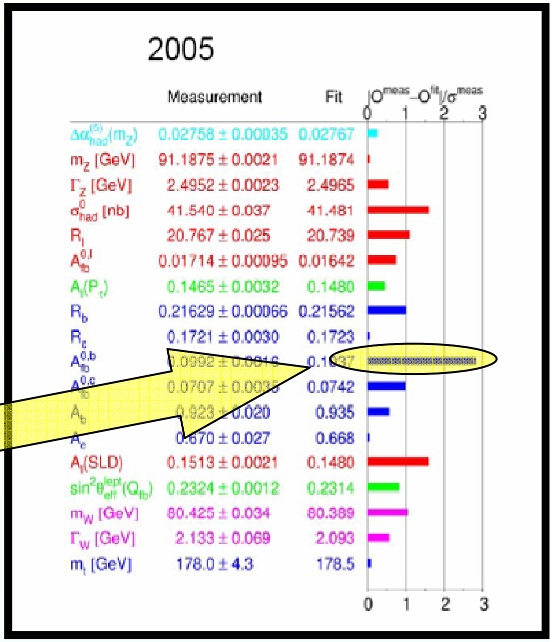
- The Standard Model is a very good *description* of the Universe at the particle scale (~$2M_W$)
  - But does not *explain* many things
    - Why so many particles?
    - Why so many forces?
    - What is mass?
      - Why do particles have the masses they have?
    - How do neutrinos get mass?
      - Are neutrinos different? How do they fit in?
    - What is Dark Matter? Dark Energy?
    - Why is matter different from antimatter?
      - (Where did all the antimatter go?)
    - Where does gravity fit in?

The state of the Universe



What do we need to make progress?

- To reach higher energy
  - To take us beyond the LEP/Tevatron energy scale
    - ~100-200GeV
- To reach higher precision
  - 10 × statistics would make this effect (if real) 8σ



- New types of accelerator
  - Neutrino factories
  - Beta beams
  - Muon colliders …

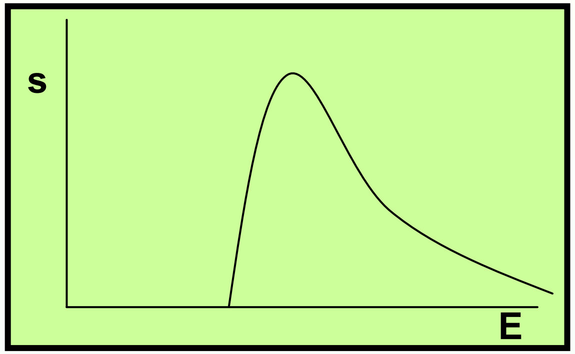
What to accelerate

- **We can accelerate *stable* particles**
  - ***"Stable"* means "with a lifetime long enough to capture and accelerate them**
    - **in practice, > ~μ–second**

- **Hadrons**
  - **p, d, t, α, … nuclei (up to Pb) & antiprotons**
    - **Hadrons contain "partons" (quarks, gluons…)**
- **Leptons**
  - **$e^{\pm}$, $\mu^{\pm}$**
    - **Leptons are "point-like"**
      - **(at our present energy scales)**

Energy and luminosity

- The *Energy* must be sufficiently high that the process of interest can occur



- The *Luminosity* must be sufficiently high that a sufficient number of events are obtained in a "reasonable" time
  - (a few years)

$N_{ev} = L \times \sigma \times t$

$t \sim 10^7$ s/year

$\sigma \sim$ pb (10^{-36} cm^2)

For 1000 events in 1 year requires

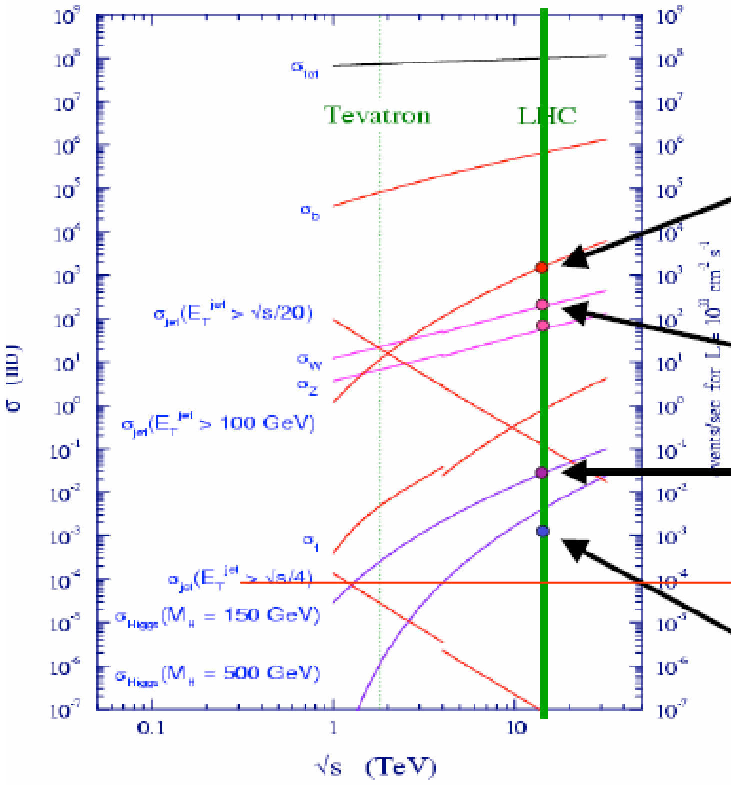
$L \sim 10^{32}$ cm^{2}s^{-1}

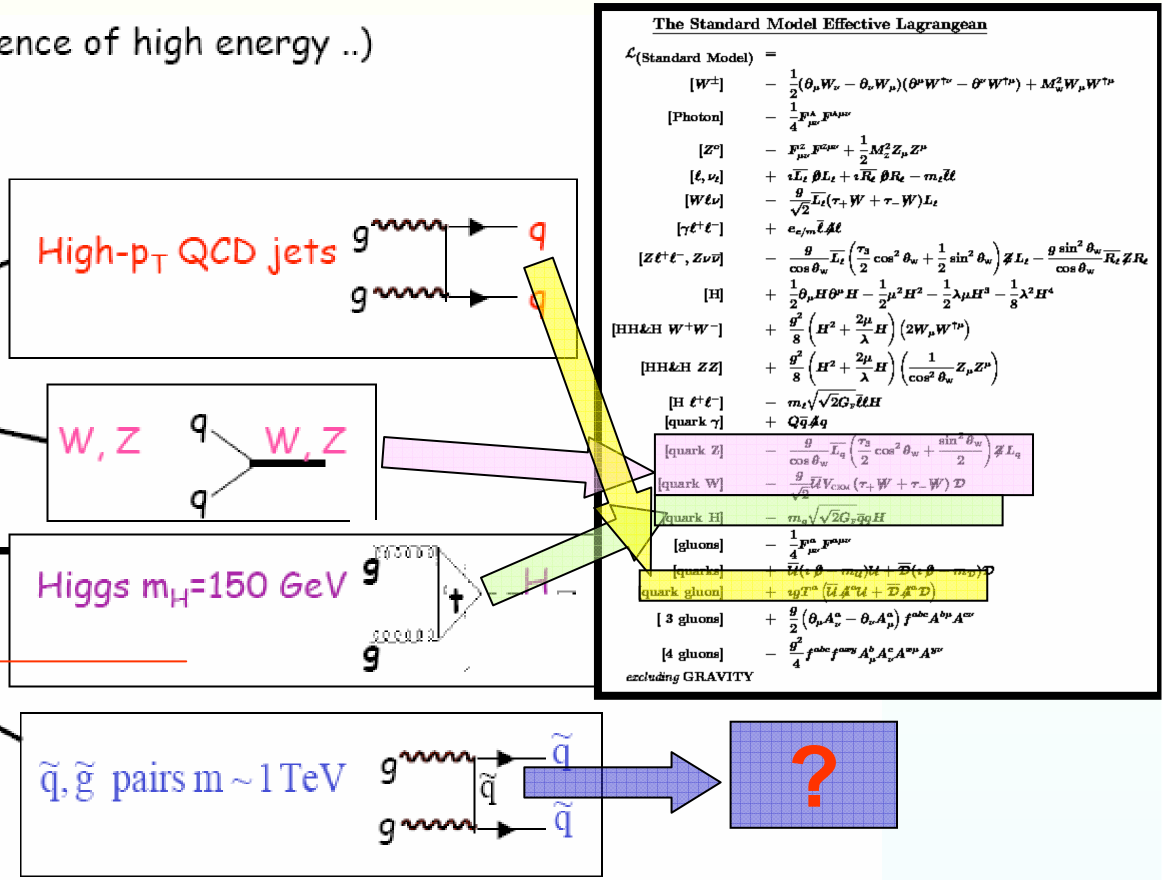
For fixed target (esp. neutrino experiments) the equivalent parameter is

Beam Power or **Protons on Target (POT)**

An example – the LHC

❸ Huge (QCD) backgrounds (consequence of high energy ..)

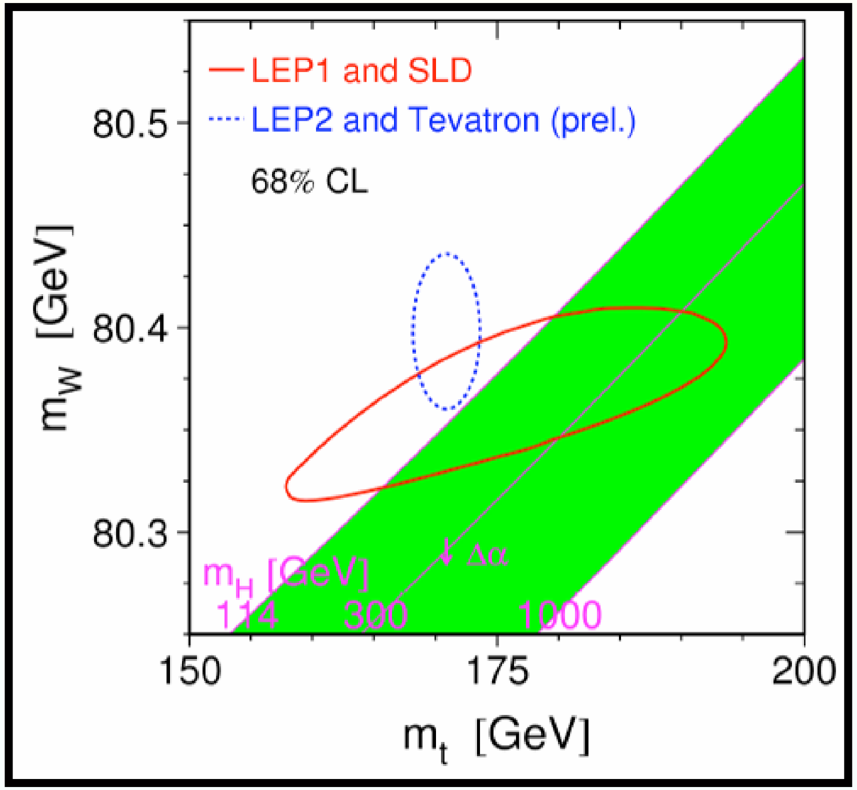


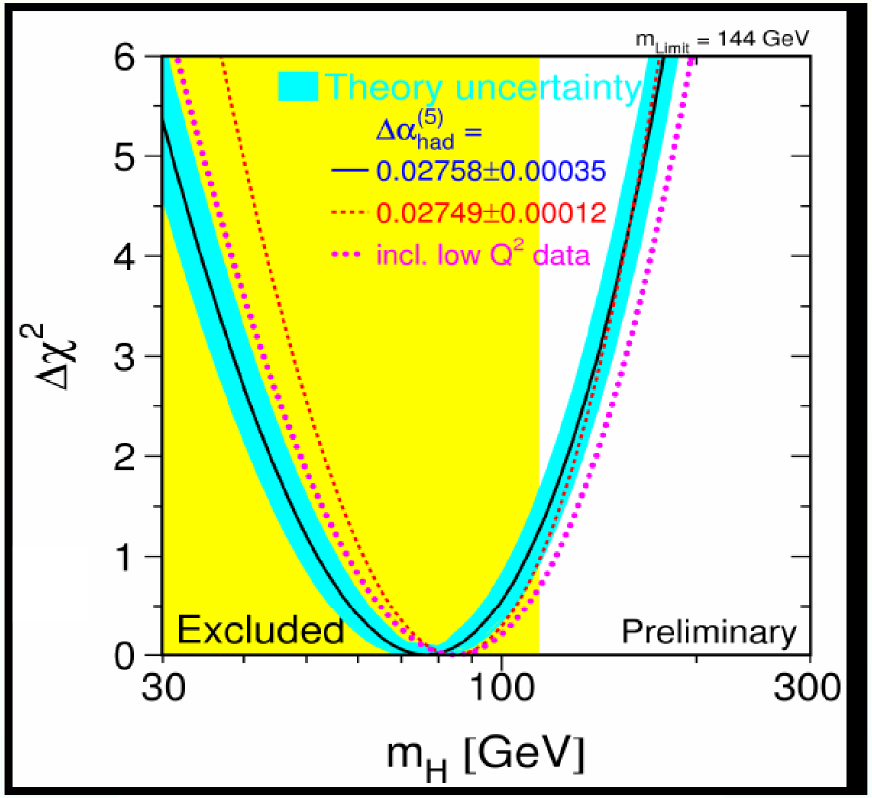


- No hope to observe light objects (W, Z, H ?) in fully-hadronic final states → rely on l, γ
- Fully-hadronic final states (e.g. q* → qg) can be extracted from backgrounds only with hard O(100 GeV) p_T cuts → works only for heavy objects
- Mass resolutions of ~ 1% (10%) needed for l, γ (jets) to extract tiny signals from backgrounds
- Excellent particle identification: e.g. e/jet separation

Gianotti, LP05

What are the big issues?





$M_H = 76^{+33}_{-24}$ GeV

Incl. theory uncertainty:

M_H < 144 GeV (95%CL)

Direct search limit (LEP-2):

M_H > 114 GeV (95%CL)

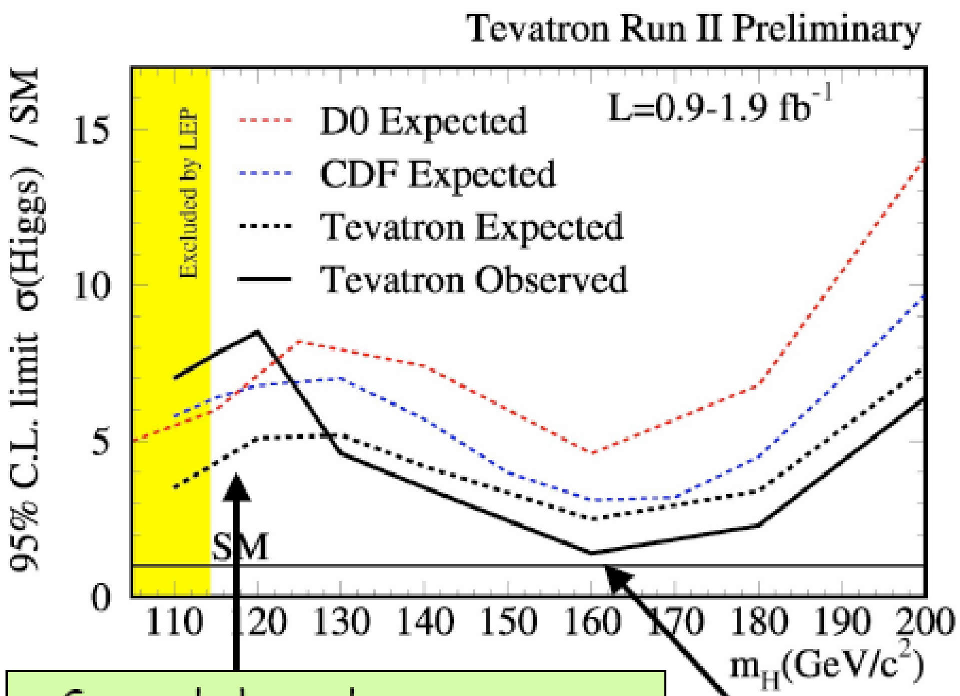
Probability M_H>114 GeV: 15%

Renormalise probability for M_H>114 GeV to 100%:

M_H < 182 GeV (95%CL)

The Tevatron Search

What about the "competition" with Tevatron ?



Today : ~2.8 fb^{-1} /expt recorded
End 2009: expect 6-7 fb^{-1} /expt
Operation beyond 2009 being discussed

With 7 fb^{-1}:

- 95% C.L. exclusion 150-180 GeV and <135 GeV (if ~4 analysis improvement)
- 2.5 σ evidence 155-170 GeV
- 3σ evidence up to 128 GeV (if ~10 analysis improvement)
- no 5σ sensitivity

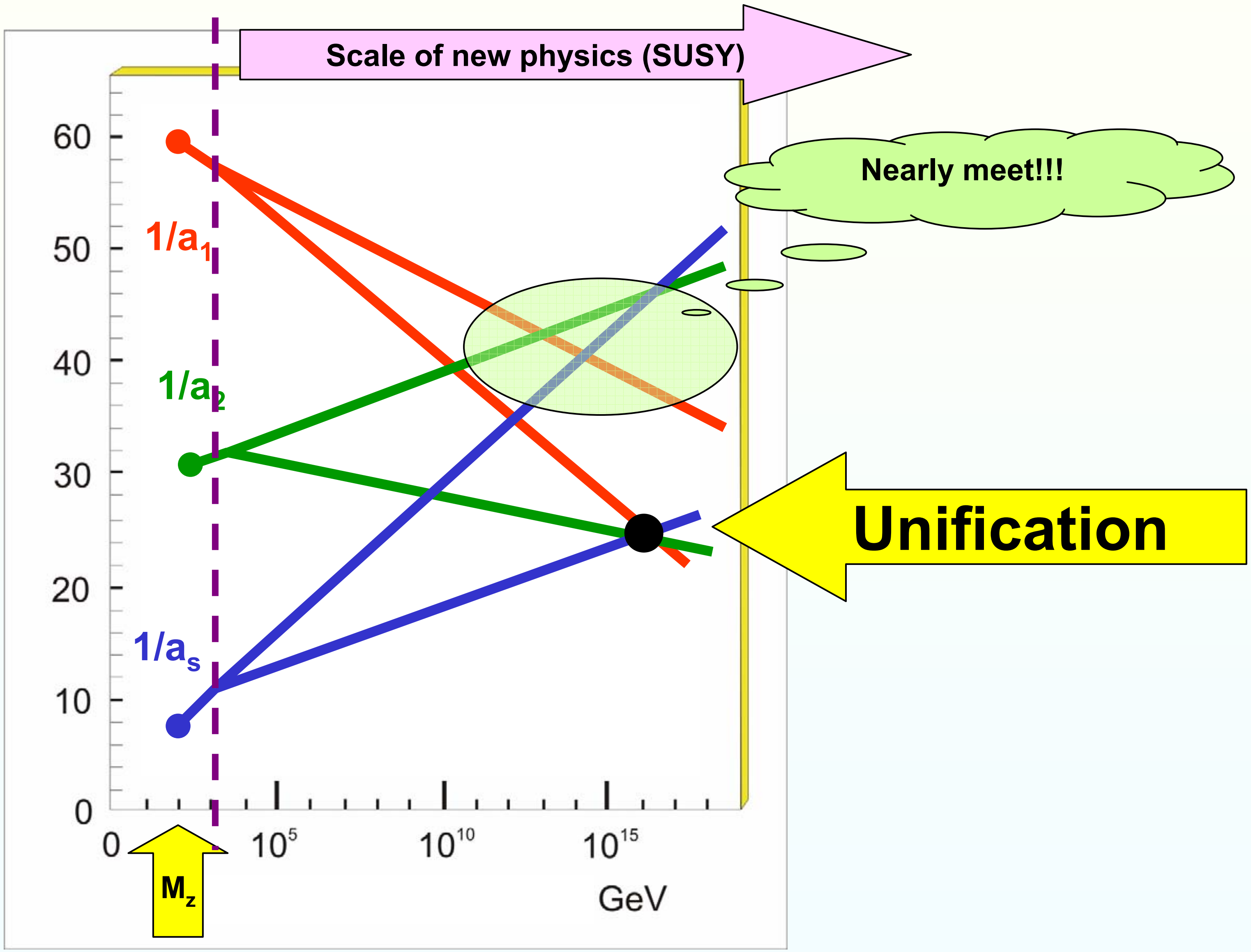
Note: big difference in statistics to go from exclusion to evidence (sophisticated cross-checks required …)

- Several channels: WH → lνbb, ZH → ννbb, etc.
- Expect analysis improvements (b-tagging, mass resolution, ..)
- With 7 fb^{-1} need: ~4 (10) improvement for 95% C.L. (3σ)

- 1 dominant channel: H → WW → lνlν (counting channel)
- 3.8 fb^{-1}/expt for 95% C.L. exclusion (mid 2008 ?)
- end 2009: 2.5σ (6 fb^{-1}) to 3σ (8.5 fb^{-1}) evidence

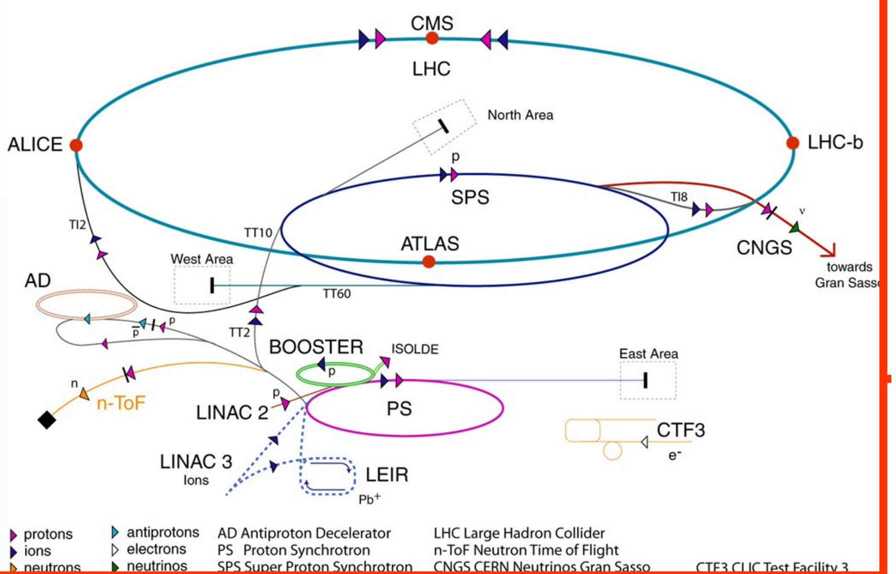
After Gianotti, 07; Plot from Kim LP07

Unification of the forces?

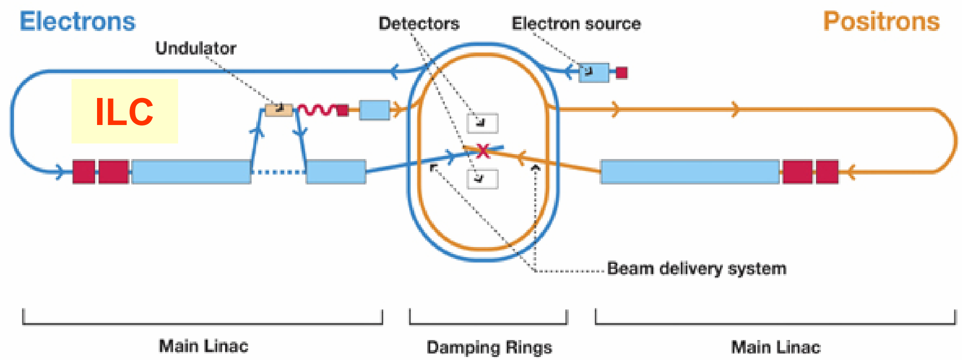


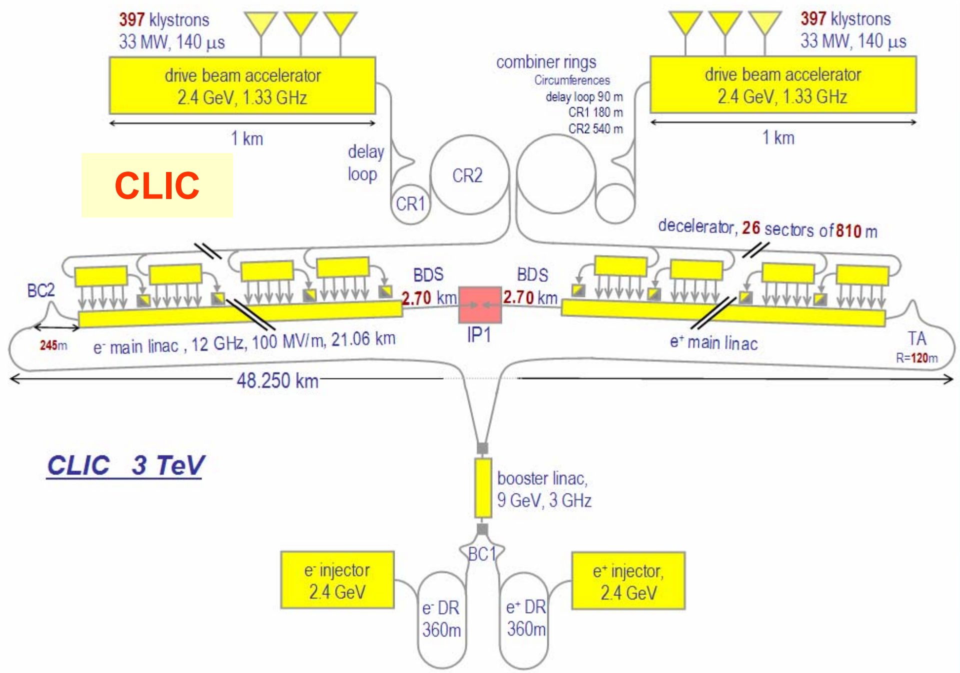
Future Accelerators for particle physics

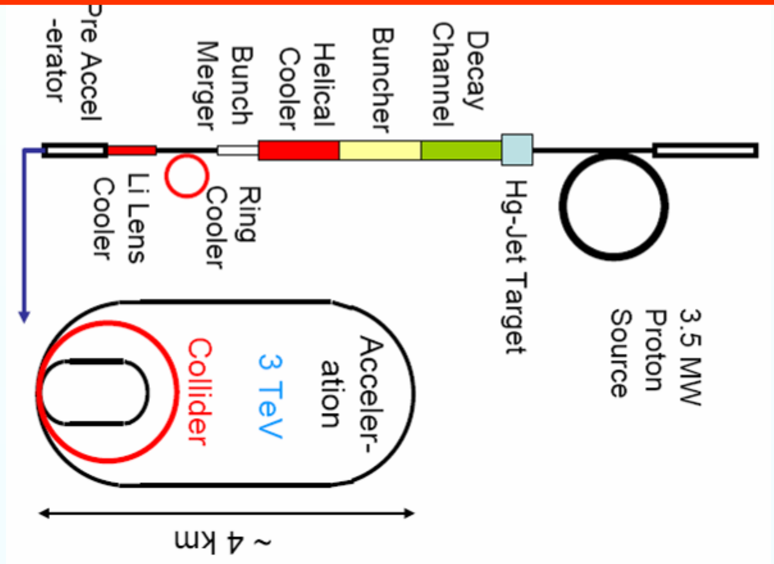
The Large Hadron Collider



The Linear (e+e-) Collider







The Muon Collider

The Large Hadron Collider

The Large Hadron Collider

- **The two main goals are:**
  - Find the Higgs
    - *If it exists!!!*
  - Find the new physics
    - *If it exists!!!*
- **We know ~ the energy scales**
  - $M_H < 250$GeV ; $E_{NP} < 1$TeV
- **pp collisions at high energy**
  - Collision energy ~10% of total energy
    - Need a total collision energy >10TeV
  - Can calculate the cross-sections
    - Need a luminosity > 10^{33}cm^2/s
- **The Large Hadron Collider (LHC) @ CERN**
  - E ~ 14TeV ; L ~ 10^{34}cm^2/s

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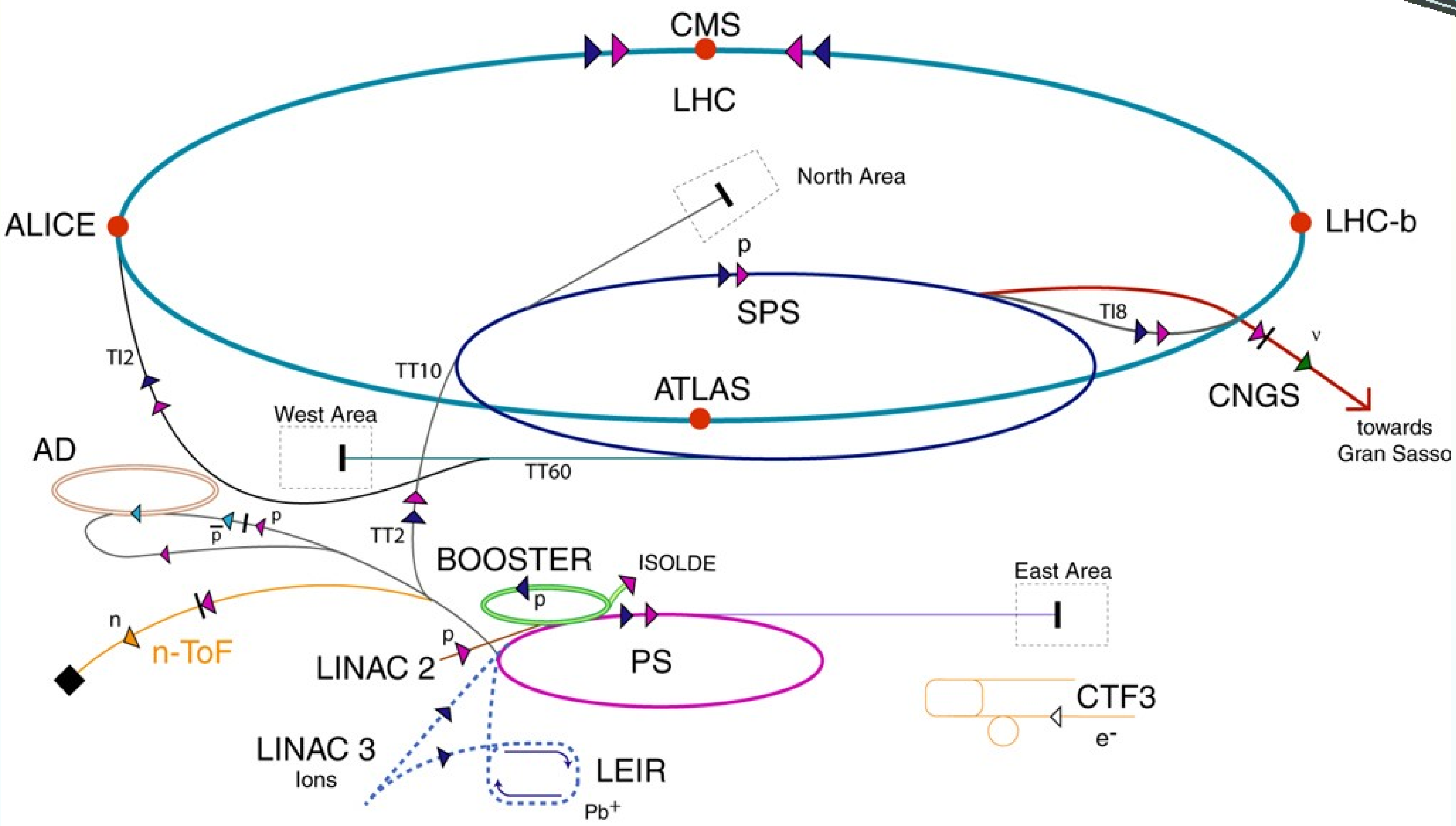
[W\ell\nu] &\quad - \tfrac{g}{\sqrt{2}}\overline{L_\ell}(\tau_+ W\!\!\!\!/ + \tau_- W\!\!\!\!/)L_\ell \\
[\gamma\ell^+\ell^-] &\quad + e_{e/m}\bar{\ell} A\!\!\!/ \ell \\
[Z\ell^+\ell^-, Z\nu\bar{\nu}] &\quad - \frac{g}{\cos\theta_W}\overline{L_\ell}\left(\frac{\tau_3}{2}\cos^2\theta_W + \frac{1}{2}\sin^2\theta_W\right) Z\!\!\!/ L_\ell - \frac{g\sin^2\theta_W}{\cos\theta_W}\overline{R_\ell} Z\!\!\!/ R_\ell \\
[\text{H}] &\quad + \tfrac{1}{2}\partial_\mu H \partial^\mu H - \tfrac{1}{2}\mu^2 H^2 - \tfrac{1}{2}\lambda\mu H^3 - \tfrac{1}{8}\lambda^2 H^4 \\
[\text{HH\&H } W^+W^-] &\quad + \frac{g^2}{8}\left(H^2 + \frac{2\mu}{\lambda}H\right)\left(2W_\mu W^{\dagger\mu}\right) \\
[\text{HH\&H } ZZ] &\quad + \frac{g^2}{8}\left(H^2 + \frac{2\mu}{\lambda}H\right)\left(\frac{1}{\cos^2\theta_W} Z_\mu Z^\mu\right) \\
[\text{H } \ell^+\ell^-] &\quad - m_\ell\sqrt{\sqrt{2}G_F}\,\bar{\ell}\ell H \\
[\text{quark } \gamma] &\quad + Q\bar{q} A\!\!\!/ q \\
[\text{quark Z}] &\quad - \frac{g}{\cos\theta_W}\overline{L_q}\left(\frac{\tau_3}{2}\cos^2\theta_W + \frac{\sin^2\theta_W}{2}\right) Z\!\!\!/ L_q \\
[\text{quark W}] &\quad - \frac{g}{\sqrt{2}}\overline{\mathcal{U}} V_{\text{CKM}}(\tau_+ W\!\!\!\!/ + \tau_- W\!\!\!\!/)\,\mathcal{D} \\
[\text{quark H}] &\quad - m_q\sqrt{\sqrt{2}G_F}\,\bar{q}q H \\
[\text{gluons}] &\quad - \tfrac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} \\
[\text{quarks}] &\quad + \overline{\mathcal{U}}(i\,\partial\!\!\!/ - m_{\mathcal{U}})\mathcal{U} + \overline{\mathcal{D}}(i\,\partial\!\!\!/ - m_{\mathcal{D}})\mathcal{D} \\
[\text{quark gluon}] &\quad + igT^a\left(\overline{\mathcal{U}} A\!\!\!/^a \mathcal{U} + \overline{\mathcal{D}} A\!\!\!/^a \mathcal{D}\right) \\
[\text{3 gluons}] &\quad + \frac{g}{2}\left(\partial_\mu A^a_\nu - \partial_\nu A^a_\mu\right) f^{abc} A^{b\mu} A^{c\nu} \\
[\text{4 gluons}] &\quad - \frac{g^2}{4} f^{abc} f^{axy} A^b_\mu A^c_\nu A^{x\mu} A^{y\nu}
\end{aligned}
$$

excluding GRAVITY

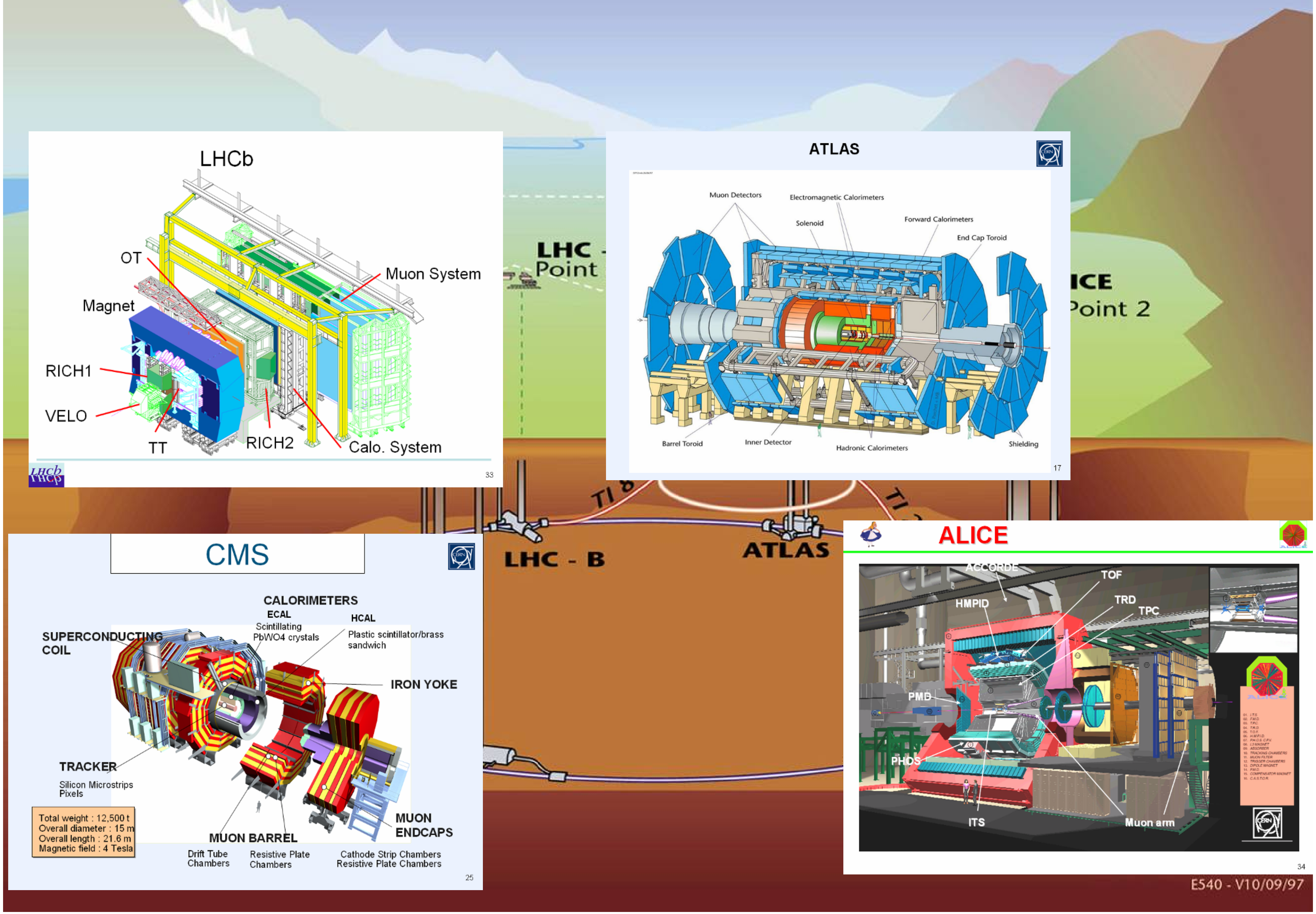
The CERN Accelerat Complex



- protons
- ions
- neutrons
- antiprotons
- electrons
- neutrinos

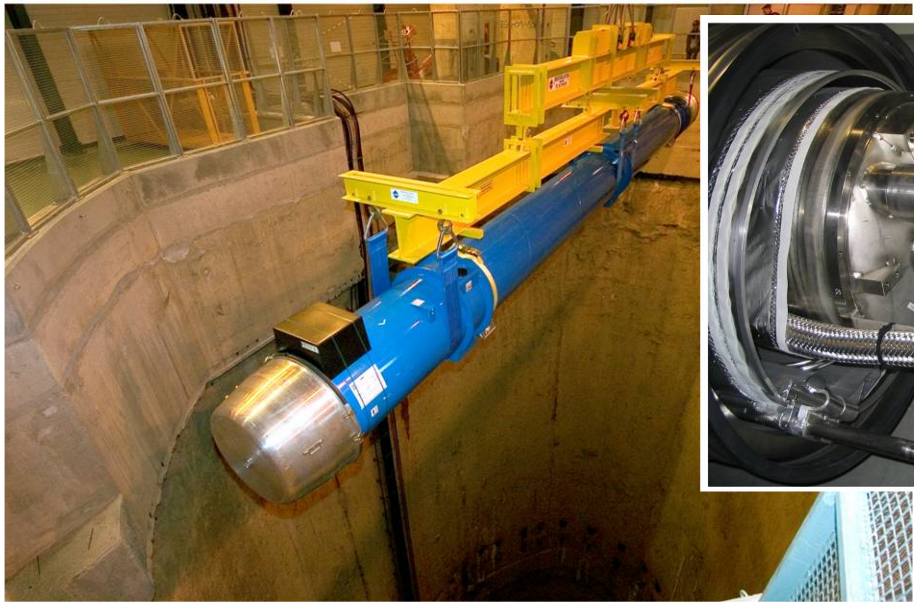
AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron
LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS CERN Neutrinos Gran Sasso
CTF3 CLIC Test Facility 3

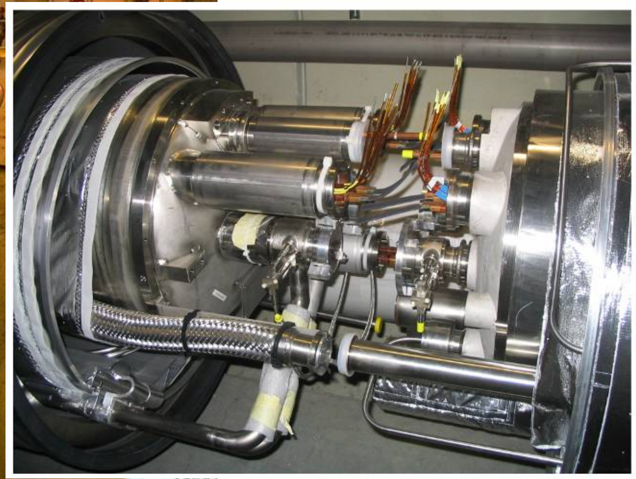
The Large Hadron Collider



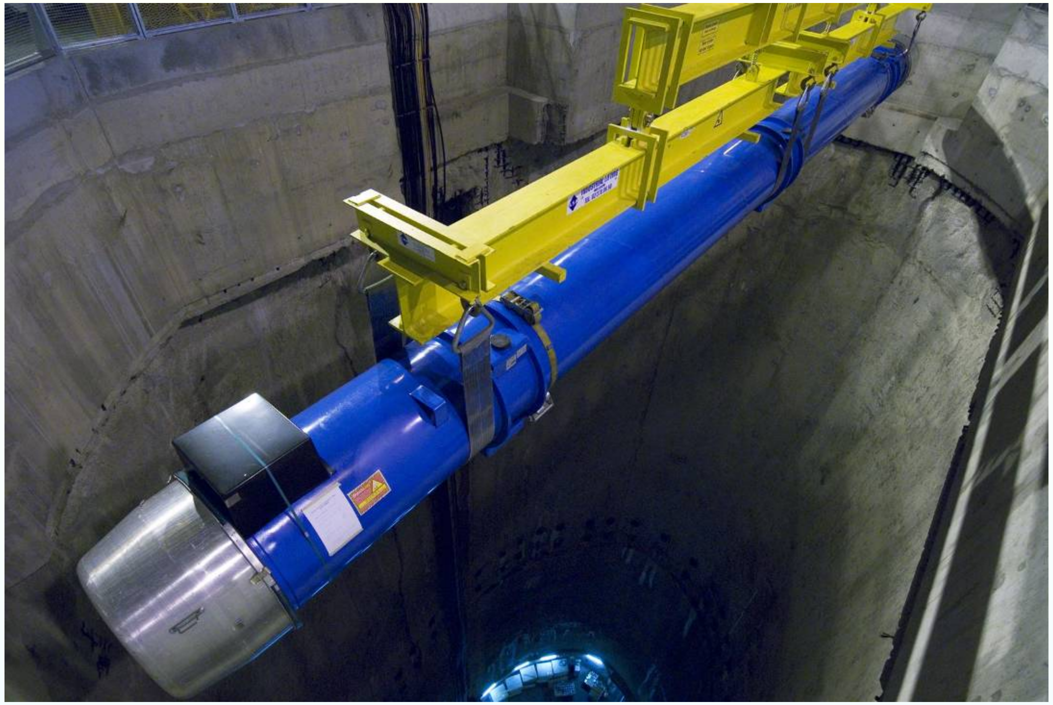
J.A.I.

The LHC installation





Descent of the last magnet, 26 April 2007

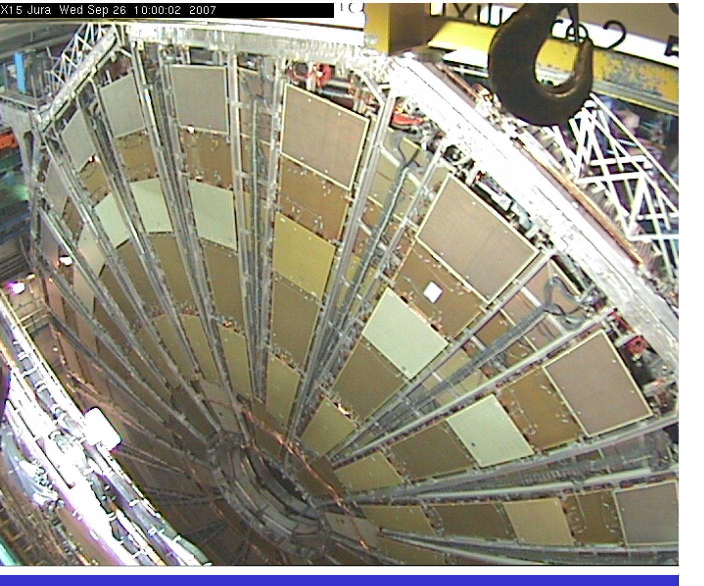


30’000 km underground at 2 km/h!

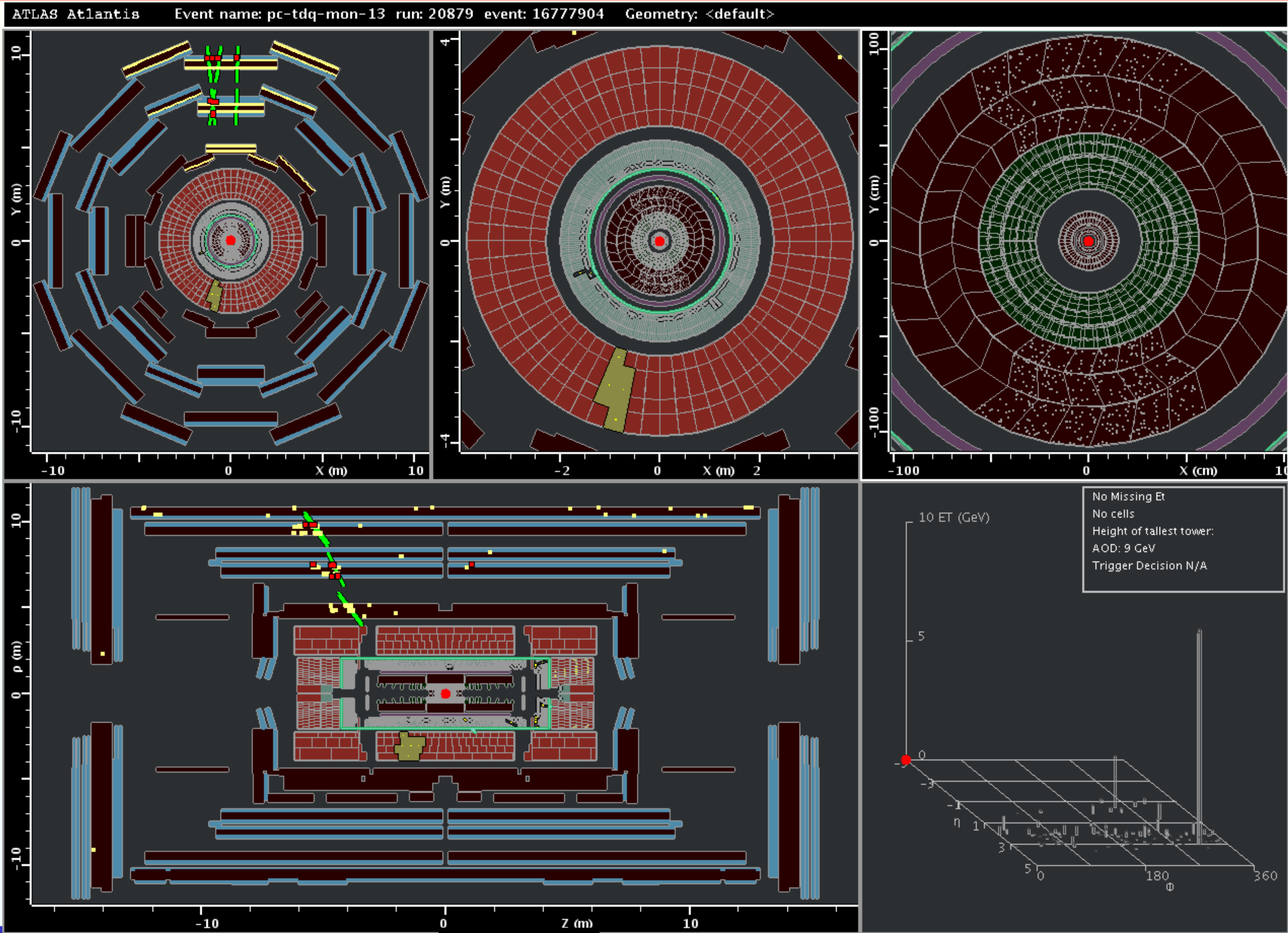
CMS Cavern

ATLAS


UX15 Geneva Wed Sep 26 10:00:03 2007
Charge admissible totale
65 t
Chariot
Palan auxiliaire 1
Palan auxiliaire 2

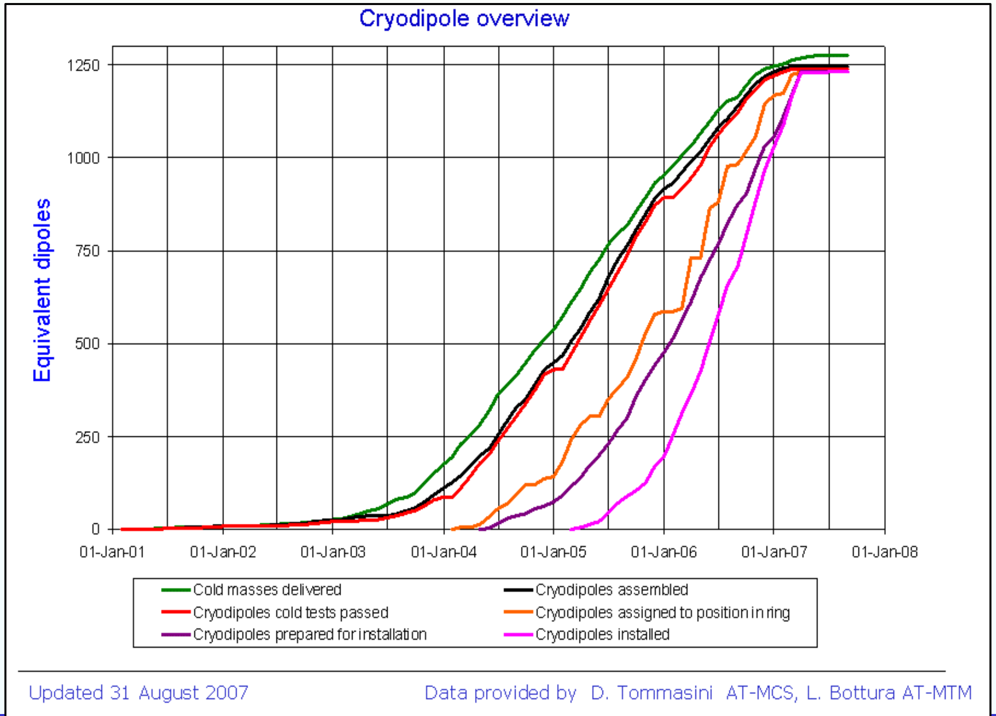

UX15 Jura Wed Sep 26 10:00:02 2007

Already taking "data" (cosmics)



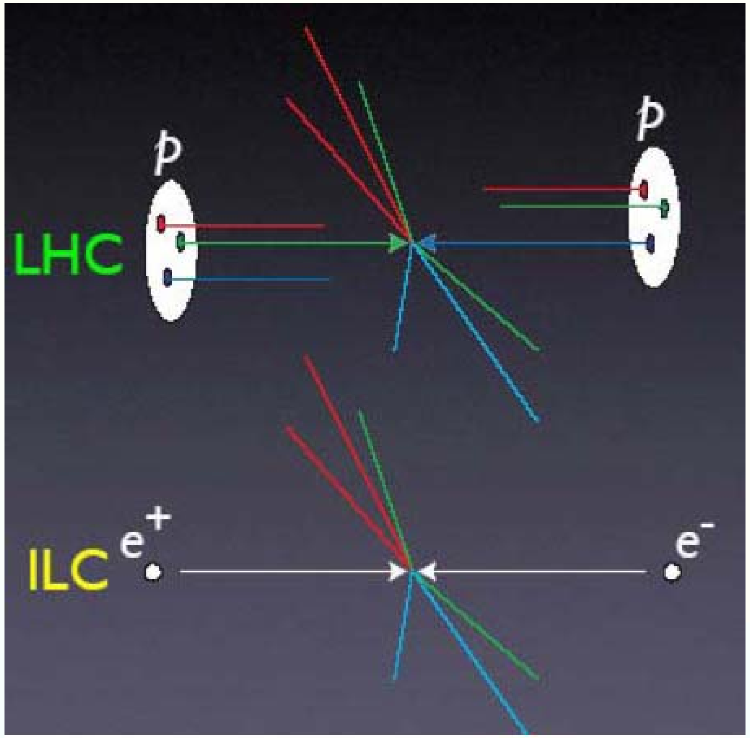
LHC status

- **Machine installed, commissioning**
- **Experiments nearly installed, commissioning**
- **Due for completion in Spring 2008**
- **First collisions end summer 2008**
- **First results 2009**
  - **Higgs, SUSY**
    - **or something else**



The Linear (e^+e^-) Collider

Why an e+e- collider?



- **elementary particles**
- **well-defined**
  - **energy,**
  - **angular momentum**
- **uses full COM energy**
- **produces particles democratically**
- **can mostly fully reconstruct events**

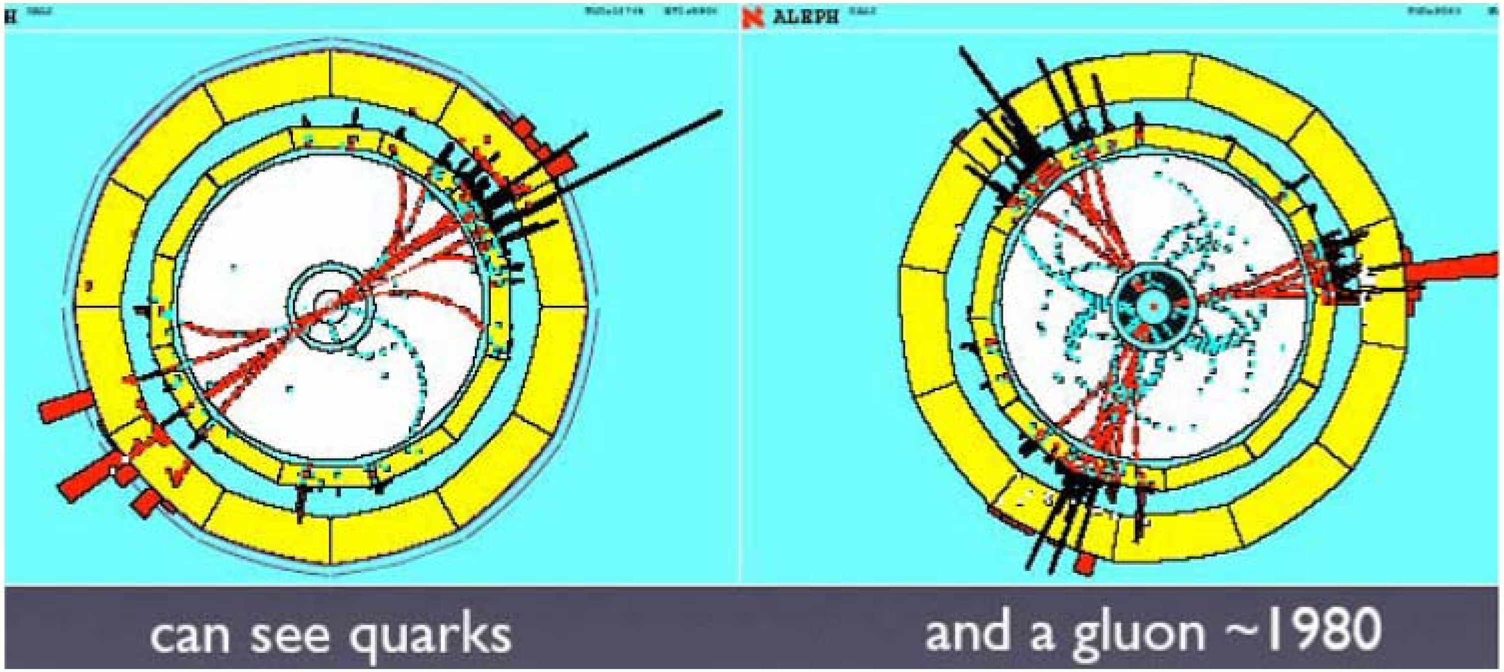
The Standard Model Effective Lagrangean

$$
\begin{aligned}
\mathcal{L}_{(\text{Standard Model})} &= \\
[W^\pm] \quad & - \frac{1}{2}(\partial_\mu W_\nu - \partial_\nu W_\mu)(\partial^\mu W^{\dagger\nu} - \partial^\nu W^{\dagger\mu}) + M_W^2 W_\mu W^{\dagger\mu} \\
[\text{Photon}] \quad & - \frac{1}{4} F^A_{\mu\nu} F^{A\mu\nu} \\
[Z^o] \quad & - F^Z_{\mu\nu} F^{Z\mu\nu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu \\
[\ell, \nu_\ell] \quad & + i\overline{L_\ell}\, \partial\!\!\!/ L_\ell + i\overline{R_\ell}\, \partial\!\!\!/ R_\ell - m_\ell \bar{\ell}\ell \\
[W\ell\nu] \quad & - \frac{g}{\sqrt{2}} \overline{L_\ell}(\tau_+ W\!\!\!\!/ + \tau_- W\!\!\!\!/) L_\ell \\
[\gamma\ell^+\ell^-] \quad & + e_{e/m} \bar{\ell} A\!\!\!/ \ell \\
[Z\ell^+\ell^-, Z\nu\bar{\nu}] \quad & - \frac{g}{\cos\theta_W} \overline{L_\ell} \left(\frac{\tau_3}{2}\cos^2\theta_W + \frac{1}{2}\sin^2\theta_W\right) Z\!\!\!/ L_\ell - \frac{g\sin^2\theta_W}{\cos\theta_W} \overline{R_\ell} Z\!\!\!/ R_\ell \\
[\text{H}] \quad & + \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\mu^2 H^2 - \frac{1}{2}\lambda\mu H^3 - \frac{1}{8}\lambda^2 H^4 \\
[\text{HH\&H } W^+W^-] \quad & + \frac{g^2}{8}\left(H^2 + \frac{2\mu}{\lambda}H\right)\left(2W_\mu W^{\dagger\mu}\right) \\
[\text{HH\&H } ZZ] \quad & + \frac{g^2}{8}\left(H^2 + \frac{2\mu}{\lambda}H\right)\left(\frac{1}{\cos^2\theta_W} Z_\mu Z^\mu\right) \\
[\text{H } \ell^+\ell^-] \quad & - m_\ell \sqrt{\sqrt{2}G_F}\, \bar{\ell}\ell H \\
[\text{quark } \gamma] \quad & + Q\bar{q} A\!\!\!/ q \\
[\text{quark Z}] \quad & - \frac{g}{\cos\theta_W} \overline{L_q} \left(\frac{\tau_3}{2}\cos^2\theta_W + \frac{\sin^2\theta_W}{2}\right) Z\!\!\!/ L_q \\
[\text{quark W}] \quad & - \frac{g}{\sqrt{2}} \overline{\mathcal{U}} V_{\text{CKM}} (\tau_+ W\!\!\!\!/ + \tau_- W\!\!\!\!/)\, \mathcal{D} \\
[\text{quark H}] \quad & - m_q \sqrt{\sqrt{2}G_F}\, \bar{q} q H \\
[\text{gluons}] \quad & - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} \\
[\text{quarks}] \quad & + \overline{\mathcal{U}}(i\partial\!\!\!/ - m_{\mathcal{U}})\mathcal{U} + \overline{\mathcal{D}}(i\partial\!\!\!/ - m_{\mathcal{D}})\mathcal{D} \\
[\text{quark gluon}] \quad & + igT^a\left(\overline{\mathcal{U}} A\!\!\!/^a \mathcal{U} + \overline{\mathcal{D}} A\!\!\!/^a \mathcal{D}\right) \\
[\text{3 gluons}] \quad & + \frac{g}{2}\left(\partial_\mu A^a_\nu - \partial_\nu A^a_\mu\right) f^{abc} A^{b\mu} A^{c\nu} \\
[\text{4 gluons}] \quad & - \frac{g^2}{4} f^{abc} f^{axy} A^b_\mu A^c_\nu A^{x\mu} A^{y\nu}
\end{aligned}
$$

excluding GRAVITY

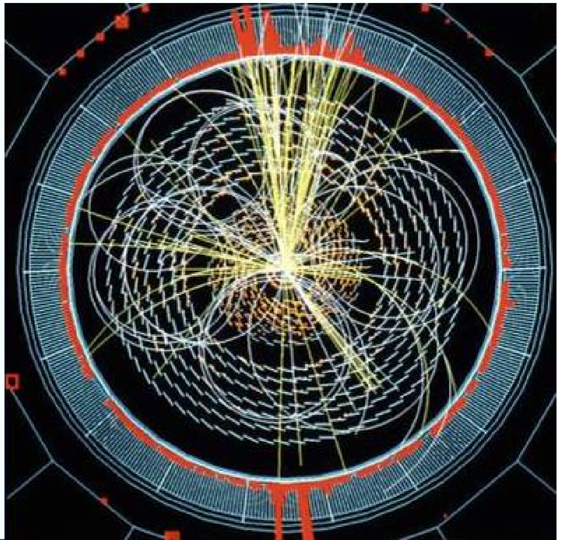
After Barry Barish

Why an e+e- collider?



⇓ **LEP**

LHC ◊



After Barry Barish

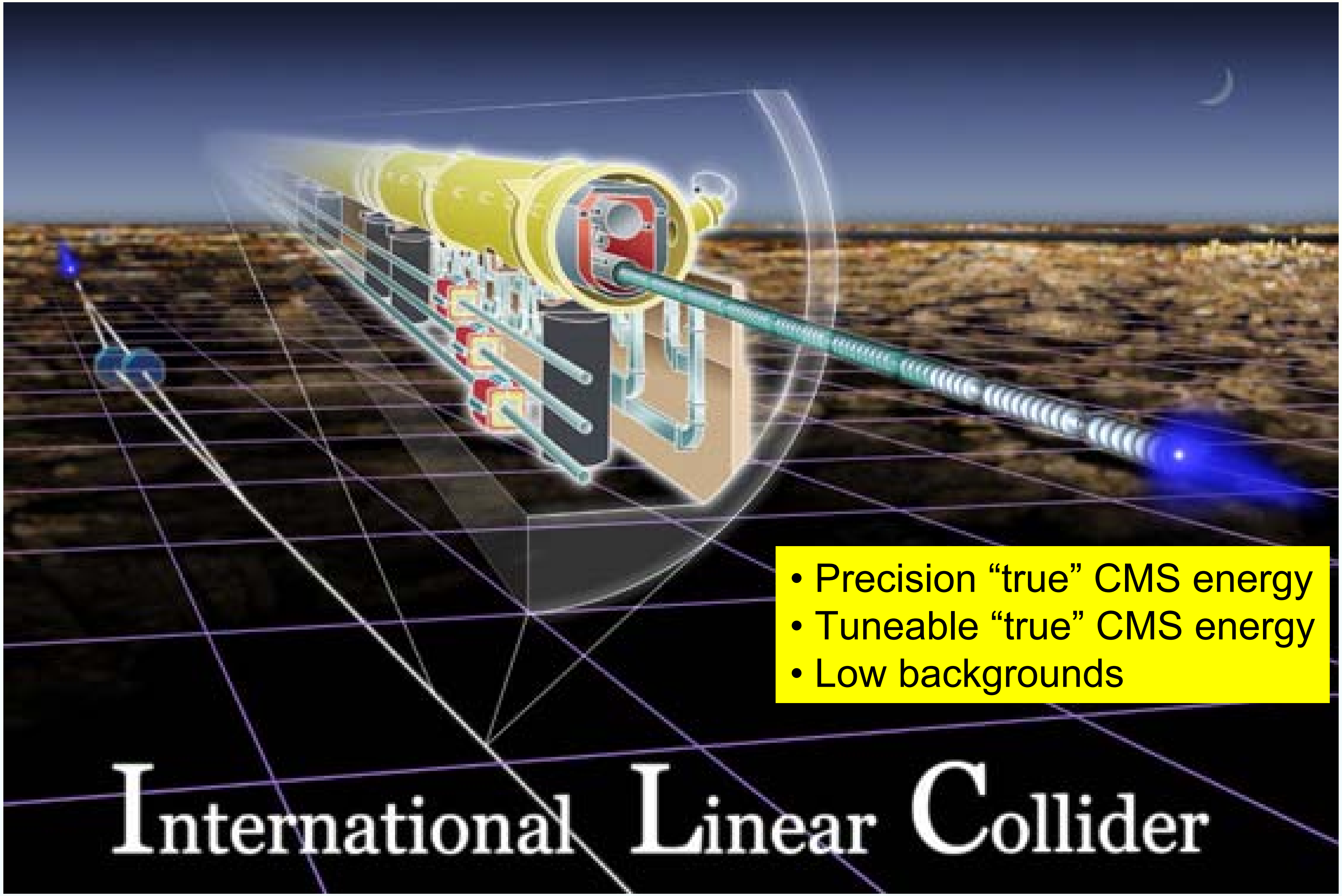
Why a *linear* e+e- collider?

Synchrotron Radiation!

or rather

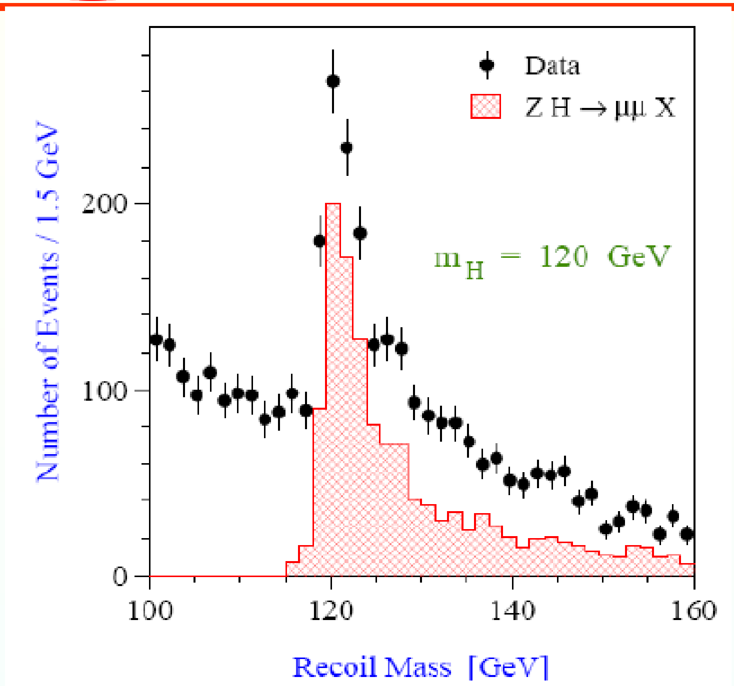
the lack of it in a linear machine

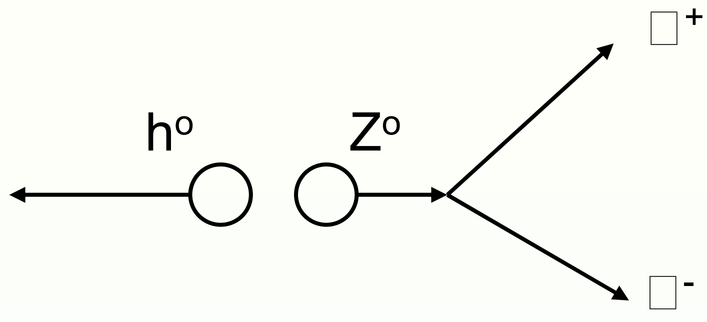
Key ILC Properties



- Precision “true” CMS energy
- Tuneable “true” CMS energy
- Low backgrounds

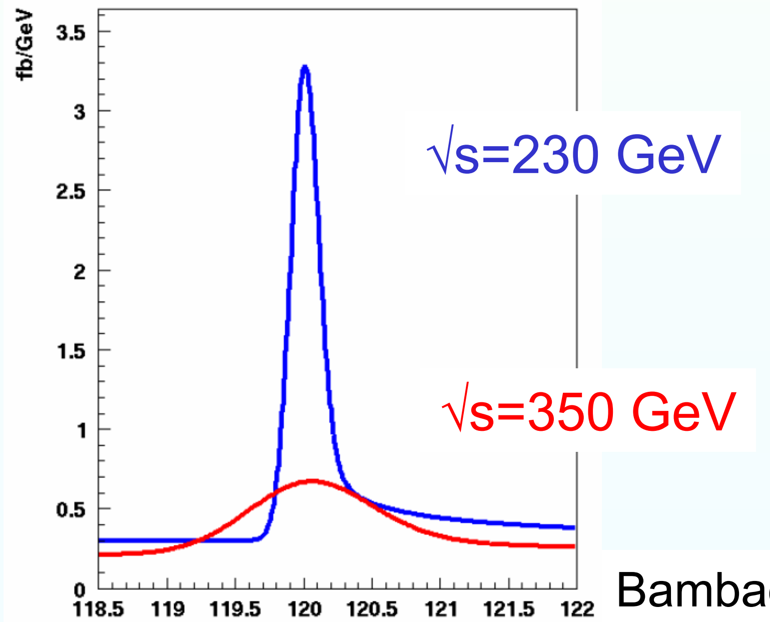
Invisible Higgs?





Measure recoil against Z^0

120 GeV Higgs:
Advantages of running at lower than top threshold:



Bambade et al.

RDR vs ILC Physics Goals

- E_{cm} adjustable from 200 – 500 GeV
- Luminosity → $\int Ldt$ = 500 fb^{-1} in 4 years
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarization of at least 80%

- The machine must be upgradeable to 1 TeV

The RDR Design meets these "requirements," including the recent update and clarifications of the reconvened ILCSC Parameters group!

7-Feb-07
GDE/ACFA Closing Beijing

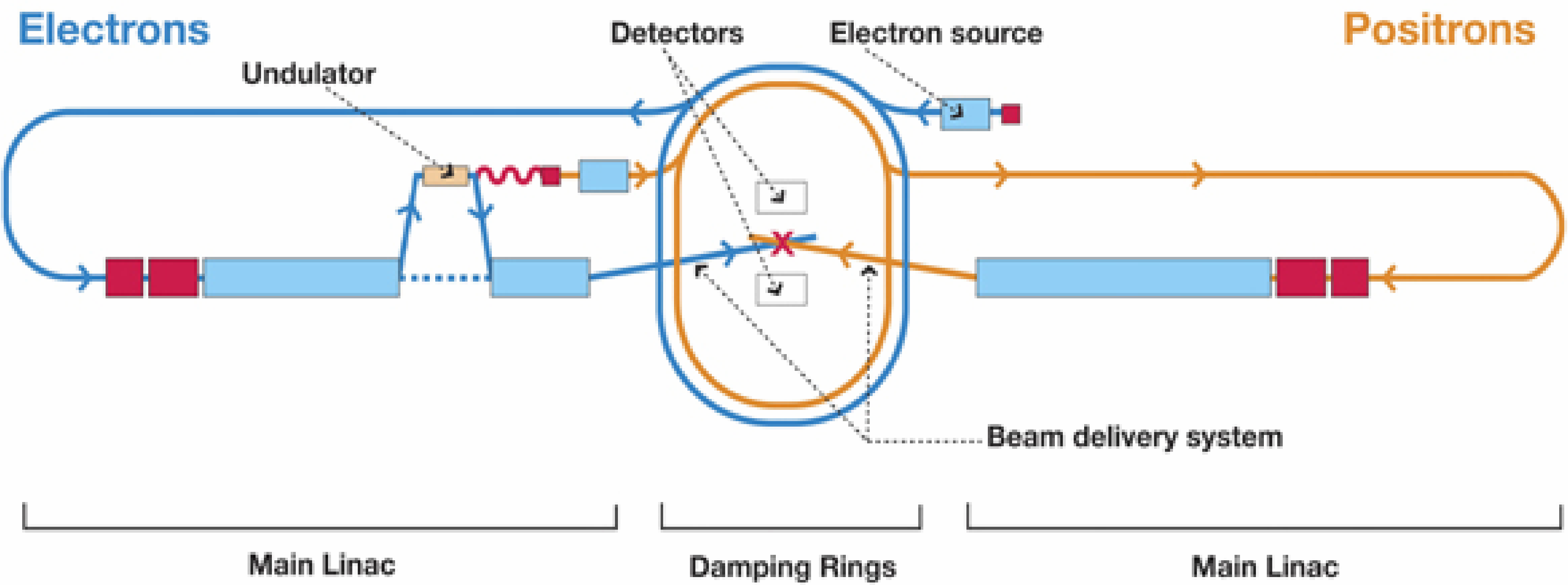
Global Design Effort

6

B. Barish, Beijing 2007

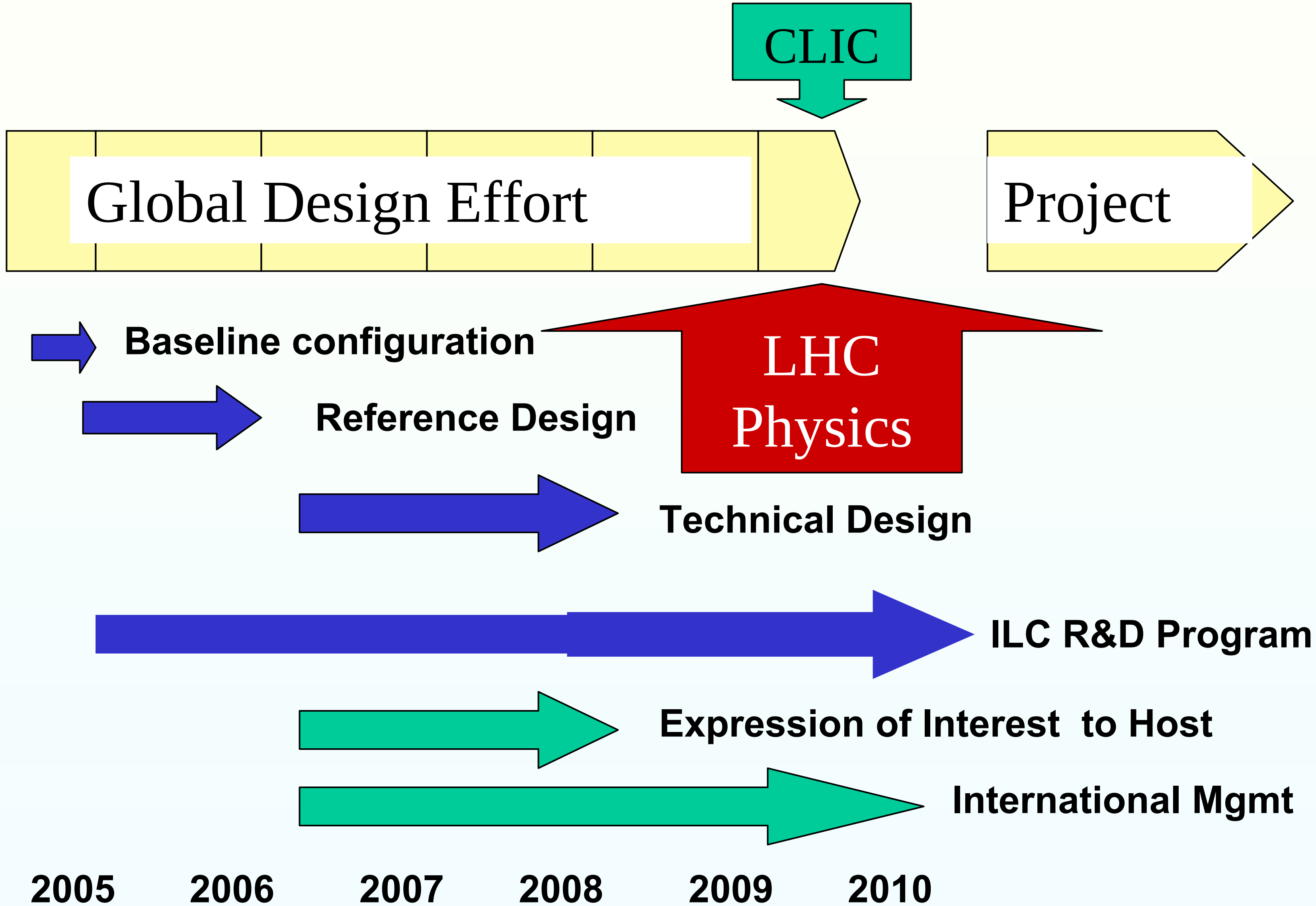
ILC Layout

500 GeV machine



The ILC Plan and Schedule

(B.Barish/CERN/SPC 050913)



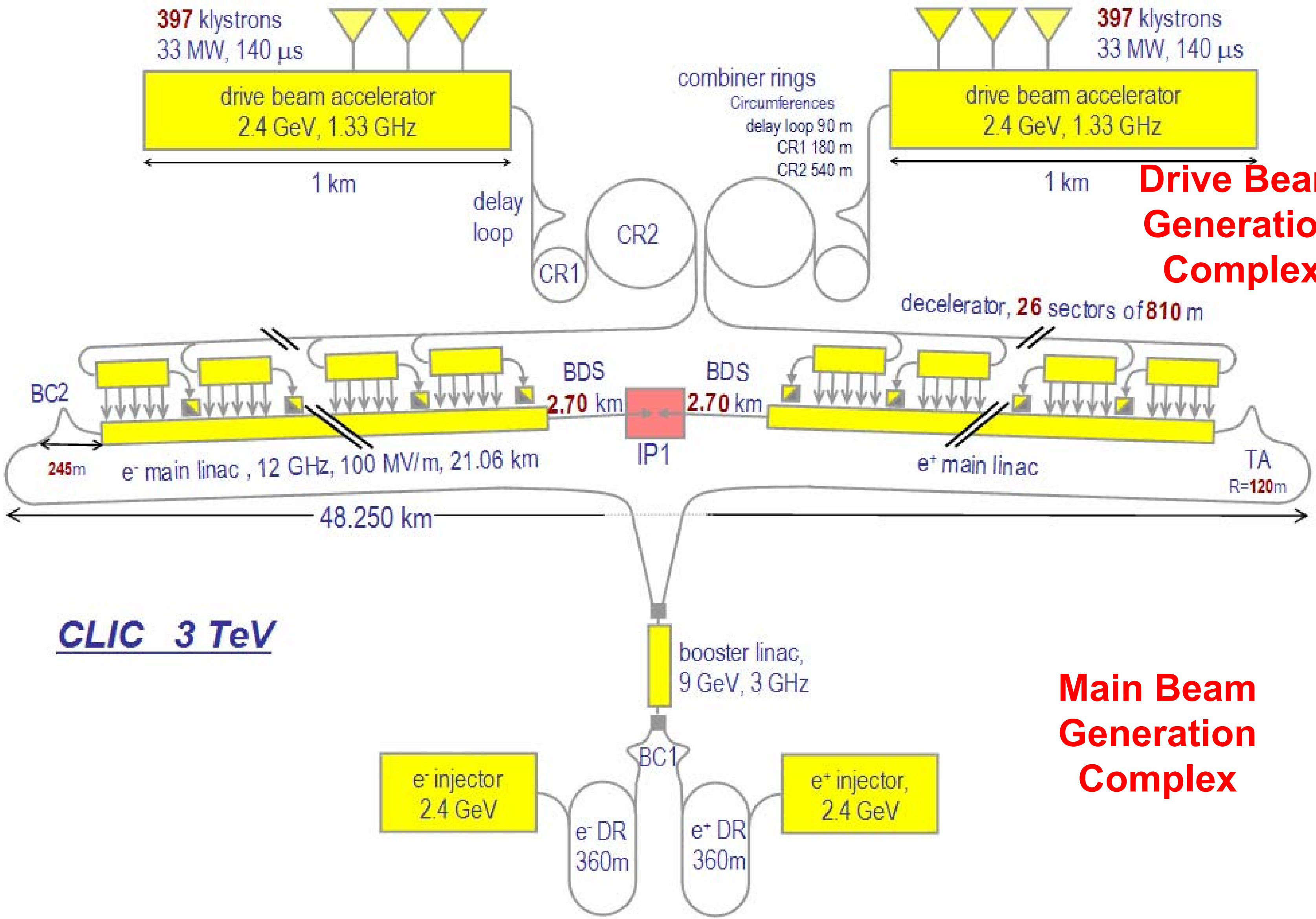
CLIC

Compact

LInea

Collider

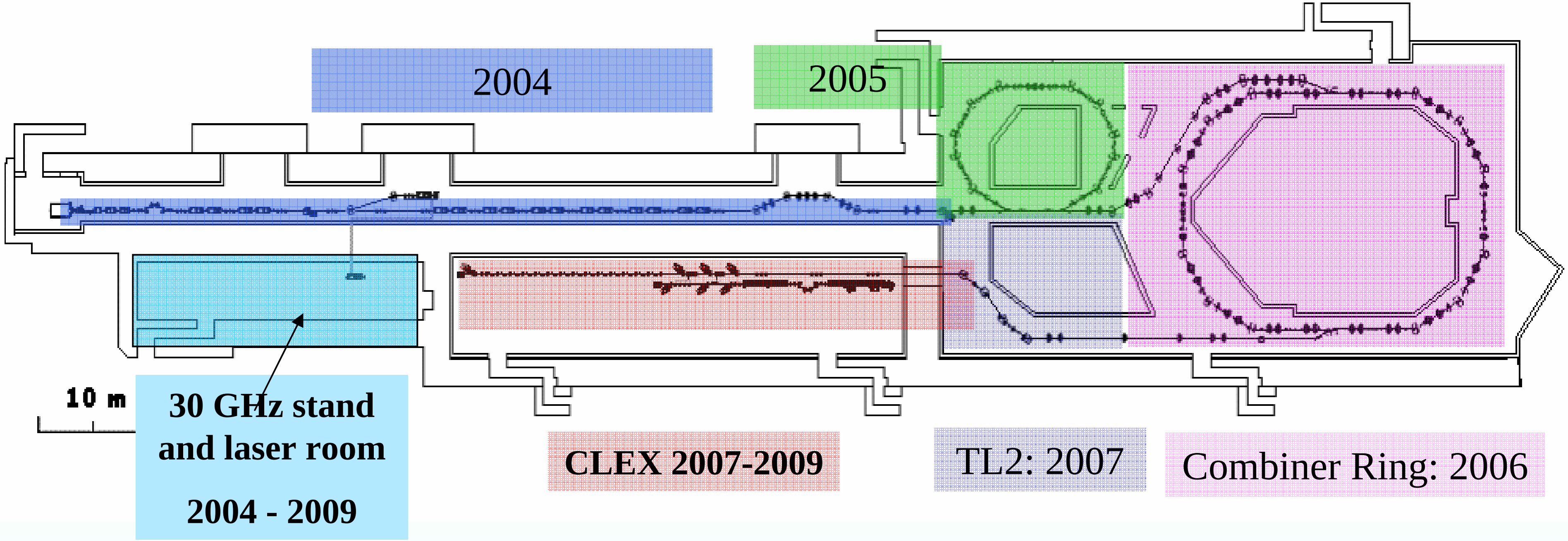
CLIC – overall layout



Drive Beam Generation Complex

Main Beam Generation Complex

CLIC Test Facility (CTF3)



Key issues

From 2005: Accelerating structures Development& Tests (R2.1)

2007- 2008: Drive beam generation scheme (R1.2)

2008- 2009: Damped accelerating structure with nominal parameters (R1.1)
ON/OFF Power Extraction Structure (R1.3)
Drive beam stability bench marking (R2.2)
CLIC sub-unit (R2.3)

New CLIC Parameters (December 2006)

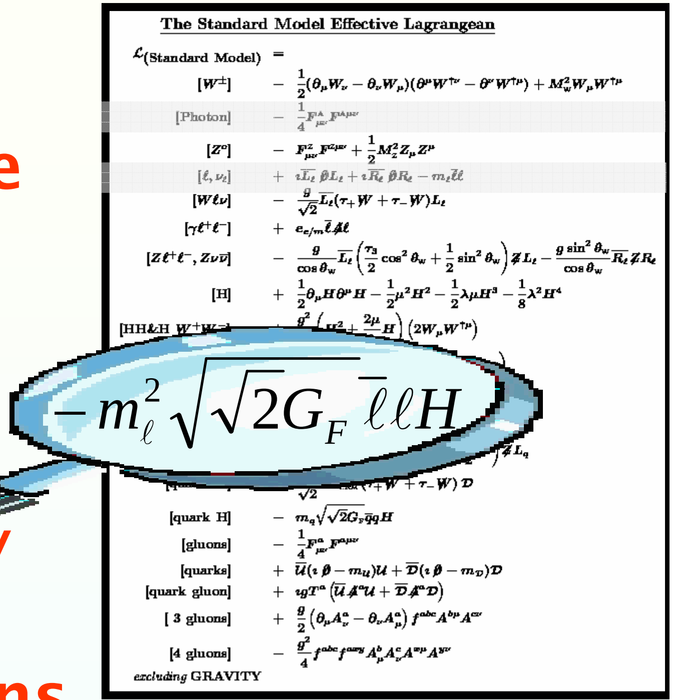
Main Linac RF frequency	**30 GHz → 12 GHz**
Accelerating field	**150 MV/m → 100 MV/m**
Overall length @ E_{CMS}= 3 TeV	**33.6 km → 48.2 km**

- **Substantial cost savings and performance improvements for 12 GHz / 100 MV/m indicated by parametric model (flat optimum in parameter range)**
- **Promising results already achieved with structures in test conditions close to LC requirements (low breakdown rate) but still to be demonstrated with long RF pulses and fully equipped structures with HOM damping.**
- **Realistic feasibility demonstration by 2010**

The Muon Collider

A *Muon* Collider???

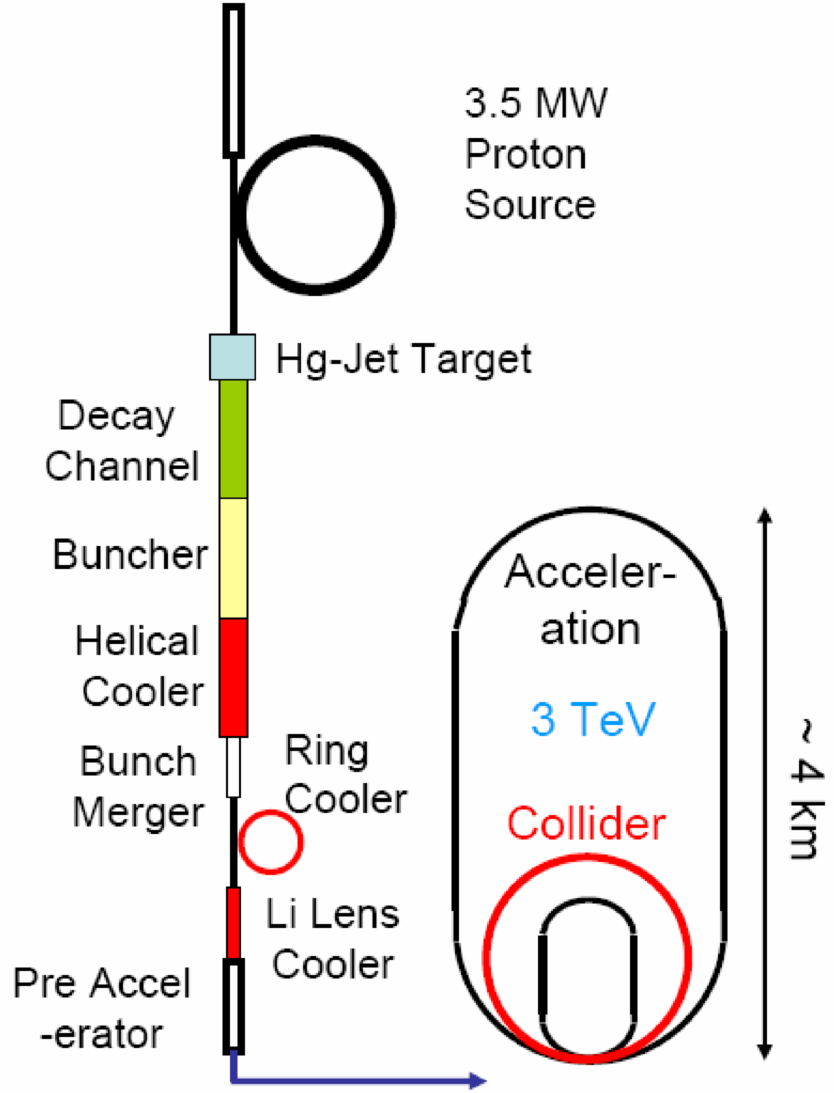
- **Why?**
  1. For some processes, muons are better than electrons
     - $\sigma(\mu^+\mu^- \rightarrow H)$ is $(m_\mu/m_e)^2 \times \sigma(e^+e^- \rightarrow H)$
       - (40000 times larger)
  2. If CLIC does *not* work, this may be the only route to multi-TeV collisions under clean conditions



- **Why not?**
  - Muon lifetime is only 2μsec!
  - Need to produce, collect, cool and accelerate large numbers ($>>10^{13}$) muons per second

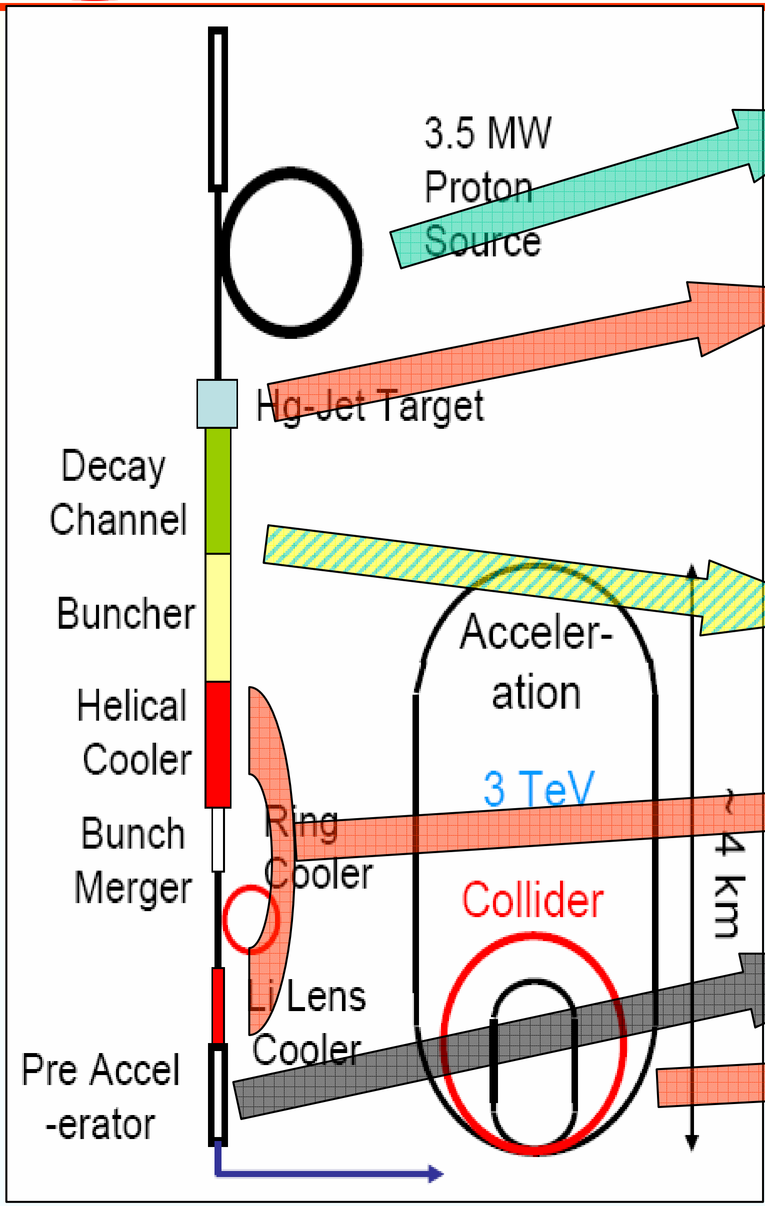
Main Components of a Muon Collider

- Proton Driver
  - primary beam on production target
- Target, Capture, and Decay
  - create π; decay into μ
- Bunching & Phase Rotation
  - reduce ΔE of bunch
- Cooling
  - reduce 6D emittance
- Acceleration
  - 130 MeV $\rightarrow$ up to 1.5 TeV
- Storage Ring
  - store for ~1000 turns
  - One IP



Steve Geer

Challenges for the Muon Collider



- **Proton Driver**
  - ~4MW, 1ns bunches
- **Target**
  - ~4MW, 1ns bunches
  - “open” geometry
- **Muon Collection and bunching**
- **Bunch cooling & compression**
- **(Acceleration)**
- **Collider**

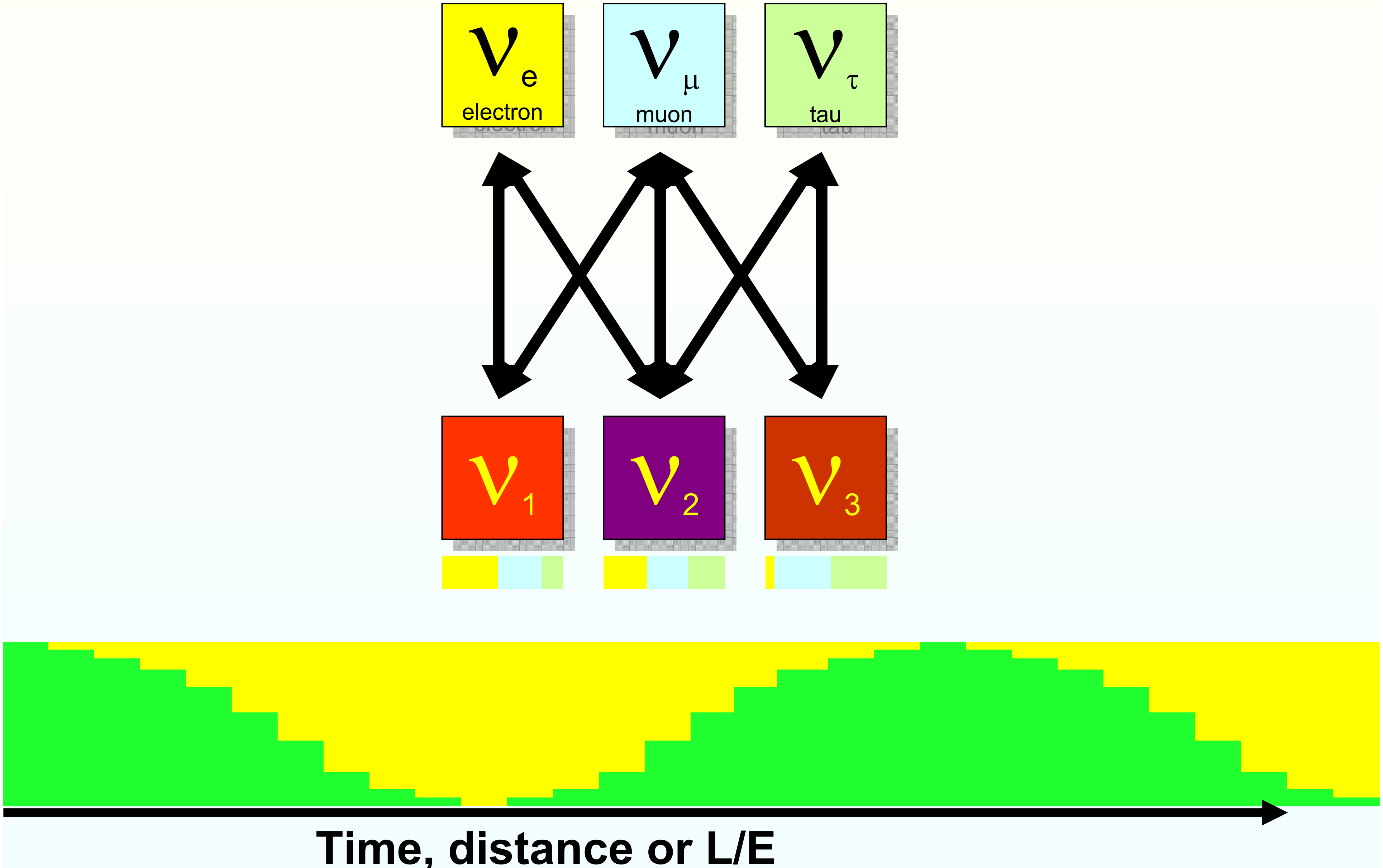
All are needed for a Neutrino Factory

Neutrino Factory

- **1950's and early 60's**
  - **Nature (and existence) of the neutrino**
    - (Reines & Cowan, Lederman, Schwartz and Steinberger)
- **Late 1960s, 1970s, 1980s**
  - **Structure of the nucleon**
    - F_2, xF_3 etc
  - **Structure of the weak current**
    - Neutral currents, $sin_2\theta_w$ etc
- **Now, and future**
  - **Nature of the neutrino**
    - Neutrino Mass and Neutrino Oscillations
    - Standard Model assumption of massless neutrinos is *wrong!*
      - Note: difficult to add neutrino mass to SM *a la Higgs*
      - Lack of Charge → additional mass-like (Majorana) terms
- **New Physics at last!!!!**

New facilities allow old physics to be done much better

Neutrino Mixing



Neutrino Mixing

Atmospheric | 3G | solar | Majorana

$$U_{MNS}=$$

$$\begin{bmatrix}1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23}\end{bmatrix}\otimes\begin{bmatrix}c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{bmatrix}\otimes\begin{bmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{bmatrix}\otimes\begin{bmatrix}1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta}\end{bmatrix}$$

$$=\begin{bmatrix}c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -c_{23}s_{12}-s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12}-s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12}-s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12}-s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23}\end{bmatrix}\otimes\begin{bmatrix}1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta}\end{bmatrix}$$

$$\left|\Delta m^2_{32}\right| = 2.4(1^{+0.21}_{-0.26})\times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.44(1^{+0.41}_{-0.51})$$

$$\Delta m^2_{21} = 7.92(1\pm 0.09)\times 10^{-5}\,\mathrm{eV}^2$$

$$\sin^2\theta_{12} = 0.314(1^{+0.18}_{-0.15})$$

$$\sin^2\theta_{13} < 3.2\times 10^{-2}$$

$Sign(\Delta m^2_{32})$ unknown

δ, α, β unknown

masses $< O(1\mathrm{eV})$

2σ

Lisi, NuFACT05

Parameters of neutrino oscillation

$c_{ij}=\cos\theta_{ij}$

$s_{ij}=\sin\theta_{ij}$

1 absolute mass scale m_{ν_e}

2 squared mass diffs $\Delta m^2_{12}, \Delta m^2_{23}$ $\begin{cases}\Delta m^2_{ji} = m^2_j - m^2_i \\ \Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}\end{cases}$

3 mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$

1 phase δ (always $\sin\theta_{13} e^{i\delta}$)

2 Majorana phases α, β

Measuring the Parameters

$$P\left(\nu_\mu \Rightarrow \nu_e\right) =$$

$$4c_{13}^2 s_{12}^2 \left(c_{12}^2 c_{23}^2 - s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13} \boxed{\cos\delta}\right)\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$+ 8c_{13}^2 s_{12}s_{13}s_{23}\left(c_{12}c_{23}\boxed{\cos\delta} - s_{12}s_{13}s_{23}\right)\cos\left(\frac{\Delta m_{32}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$+ 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right)\left(1 + \left(1 - 2s_{13}^2\right)\frac{2a}{\Delta m_{31}^2}\right)$$

$$- 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\left(\frac{\Delta m_{32}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$- 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\left(\frac{\Delta m_{32}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)\left(1 - 2s_{13}^2\right)\frac{aL}{4E}$$

$\nu_\mu \Rightarrow \bar{\nu}_\mu \quad \Leftrightarrow \quad a \Rightarrow -a$

a =2□2 $G_F n_e E_n$ = 7.6 10^{-5} r E

Where is the electron density ; r is the density (g/cm^3) ;   E is the neutrino energy (GeV)

c_{ij}=cosq$_{ij}$, s_{ij}=sinq$_{ij}$

(Richter: hep-ph/0008222)

What to Measure?

Neutrinos

ν_e disappearance

$\nu_e \rightarrow \nu_\mu$ appearance

$\nu_e \rightarrow \nu_\tau$ appearance

ν_μ disappearance

$\nu_\mu \rightarrow \nu_e$ appearance

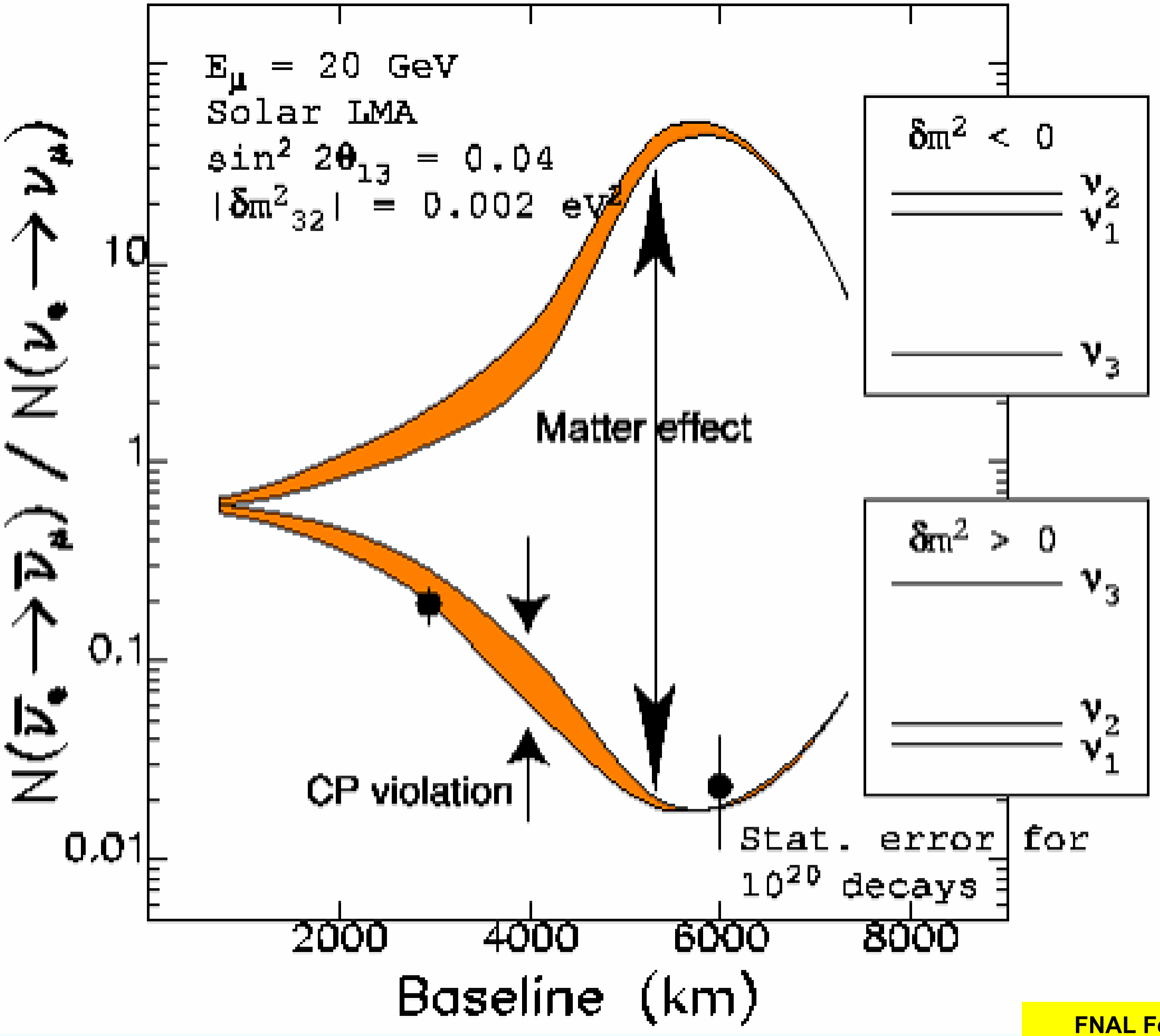
$\nu_\mu \rightarrow \nu_\tau$ appearance

… and the corresponding antineutrino interactions

Note: the beam requirements for these experiments are:

high intensity	**known flux**
known spectrum	**known composition** (preferably no background)

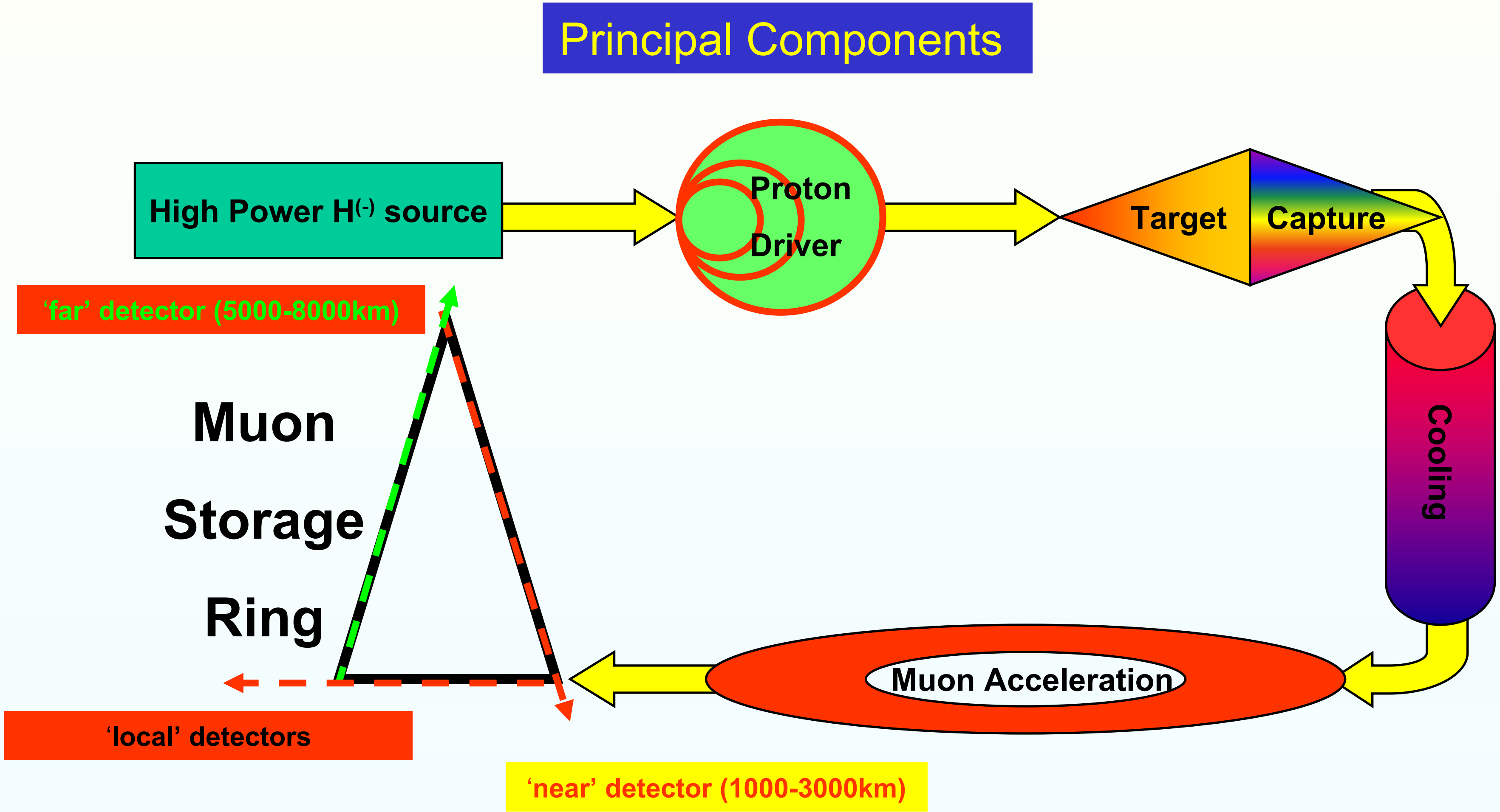
CP-violation



FNAL Feasibality Study 1

A Neutrino Factory is …

… an accelerator **complex** designed to produce $>10^{20}$ muon decays per year directed at a detector thousands of km away



Neutrino Factory Challenges

- **Parameters**
  - Need to know that θ_{13} is not zero
    - Other parameters well known to fix (E_μ,L)
- **Technology**
  - Proton driver
    - RCS or LINAC?
  - Proton energy?
    - HARP, E910, MIPP
  - Target
    - MW beam power
      - Mercury, solid, liquid-cooled, pellet, …
  - Pion/muon collection and/or cooling
    - Magnetic Horns or Solenoids?
    - Phase Rotators, FFAG's, cooling?
  - RF and acceleration
    - RLA's or FFAG's?
  - Muon Storage Ring
    - Racetrack, triangular or bow-tie
    - Conventional or FFAG?

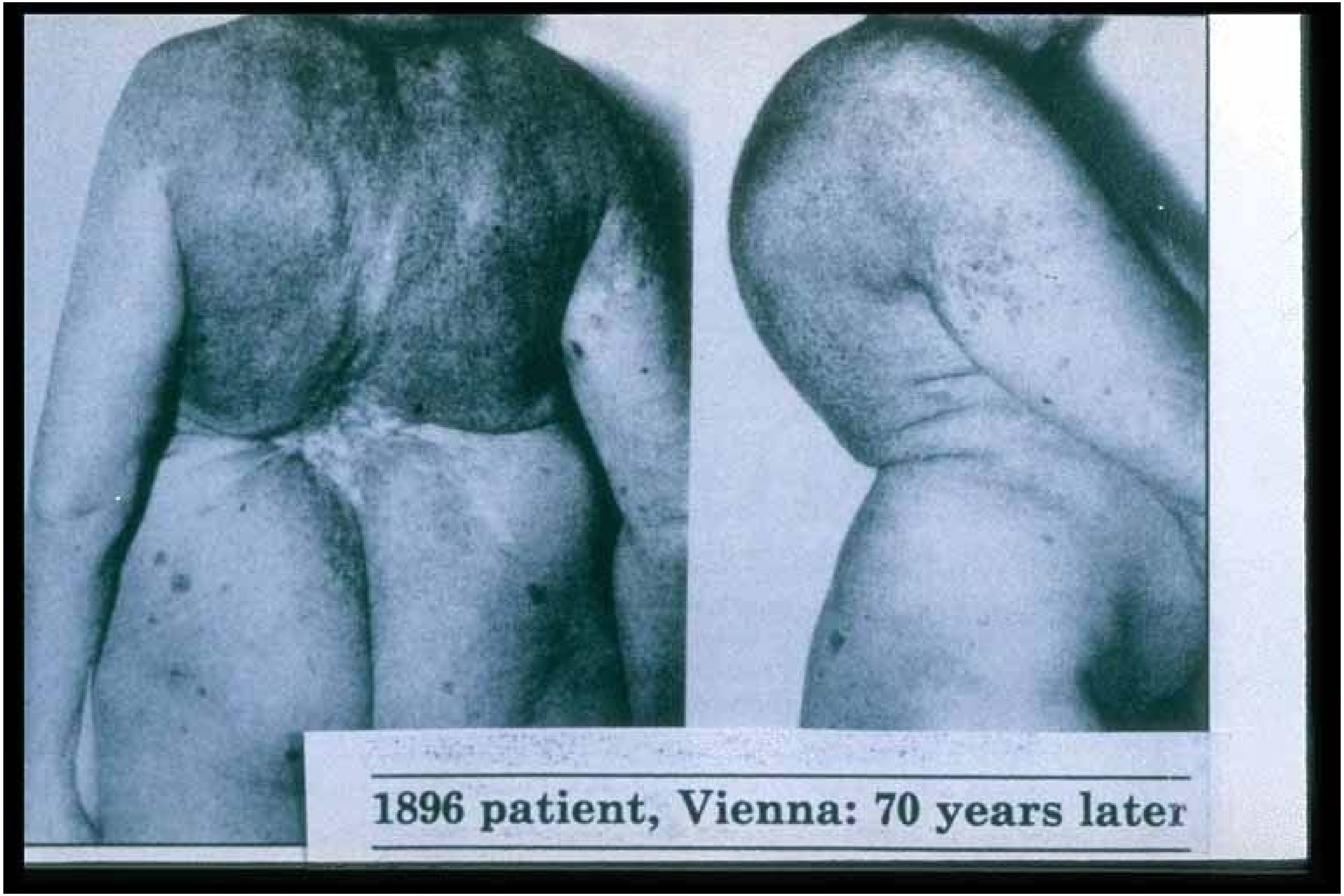
- **Other uses of high power protons & muons?**

Other future uses of accelerators

- Other scientific applications
  - Light sources, Spallation sources, FELs, ERLs …
- Other Future Accelerators
  - Laser-Plasma accelerators
- Other applications
  - Accelerators in Medicine

All have challenges
&
push technologies

X-ray therapy began within months of Roentgen's discovery



Slide from Gillies McKenna, Oxford

Conclusion

- Particle Accelerators have an exciting future
  - In particle physics
    - LHC, LC, CLIC, NF, factories …
  - In other sciences
    - Light sources, FELs, spallation sources
  - In society
    - Medical accelerators (isotopes, hadron-therapy…)
- And they are *fun too!*