John Adams Institute
J.A.I.
for Accelerator
Science

Overview of Future Accelerators

Ken Peach

John Adams Institute for Accelerator Science
University of Oxford & Royal Holloway University of London

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Daresbury

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)
  - EURISOL and Beta Beams
  - “Factories” (φ, τ, c, b)
- **Future Accelerators for other sciences**
  - What is needed and why
  - X-ray sources
  - Neutron sources
  - Nuclear Physics

Will not have time to discuss this

… sorry, because it is important

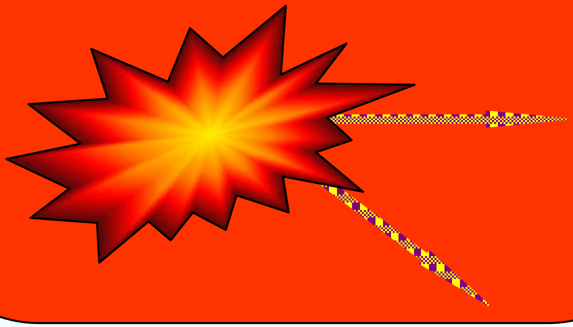
- **Other applications**
  - Accelerators in Medicine
- **Summary**

What is needed, and why

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

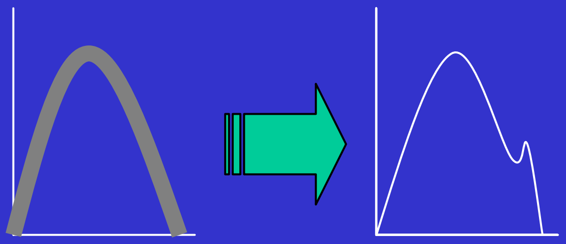
High Energy Frontier

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

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

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

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

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

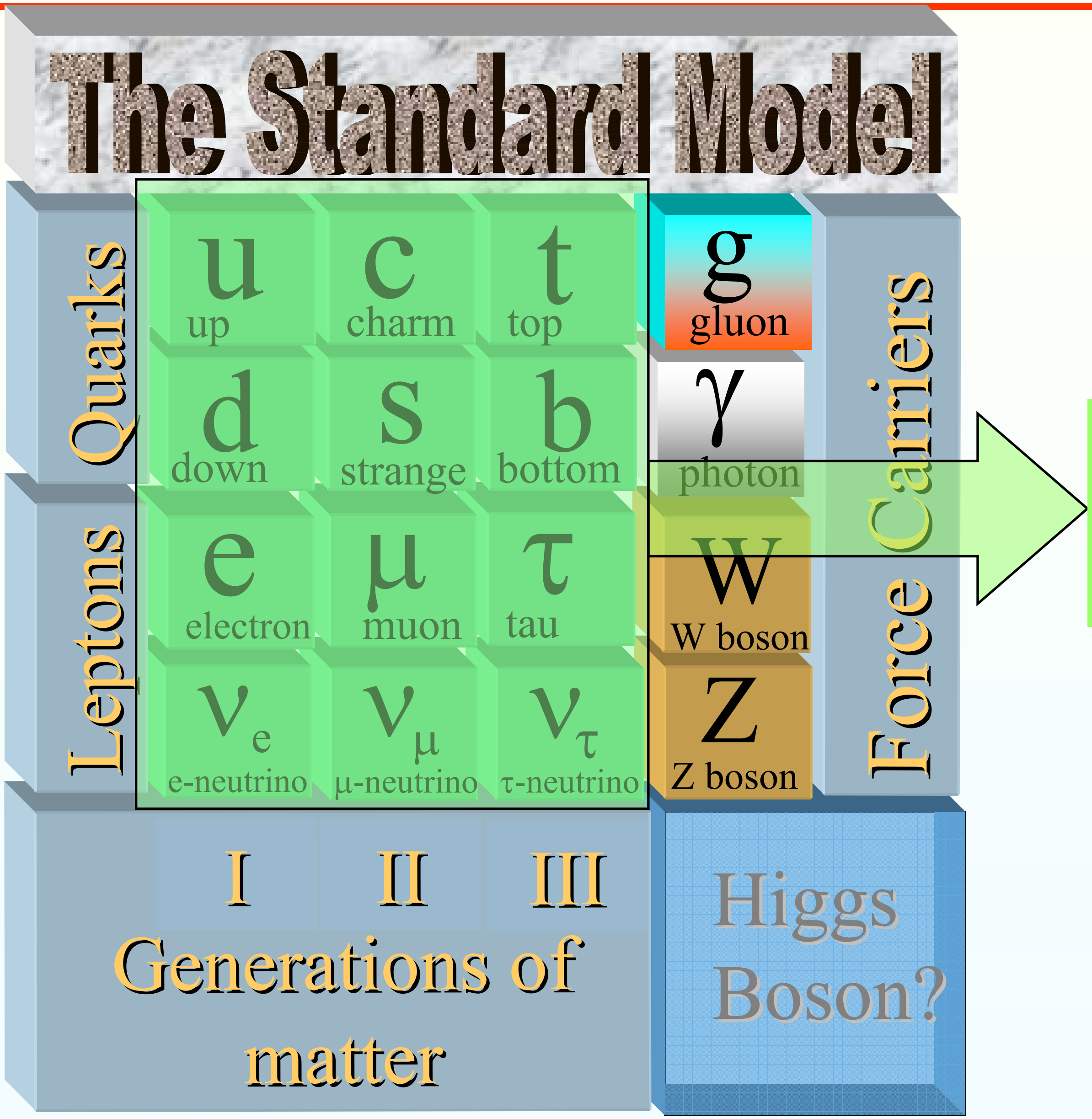
The gauge sector (1)

The flavor sector (2)

The EWSB sector (3)

The ν-mass sector *(4)*

Particles and Forces



The Standard Model

Quarks

u up | c charm | t top

d down | s strange | b bottom

Leptons

e electron | μ muon | τ tau

ν_e e-neutrino | ν_μ μ-neutrino | ν_τ τ-neutrino

I II III

Generations of matter

Force Carriers

g gluon

γ photon

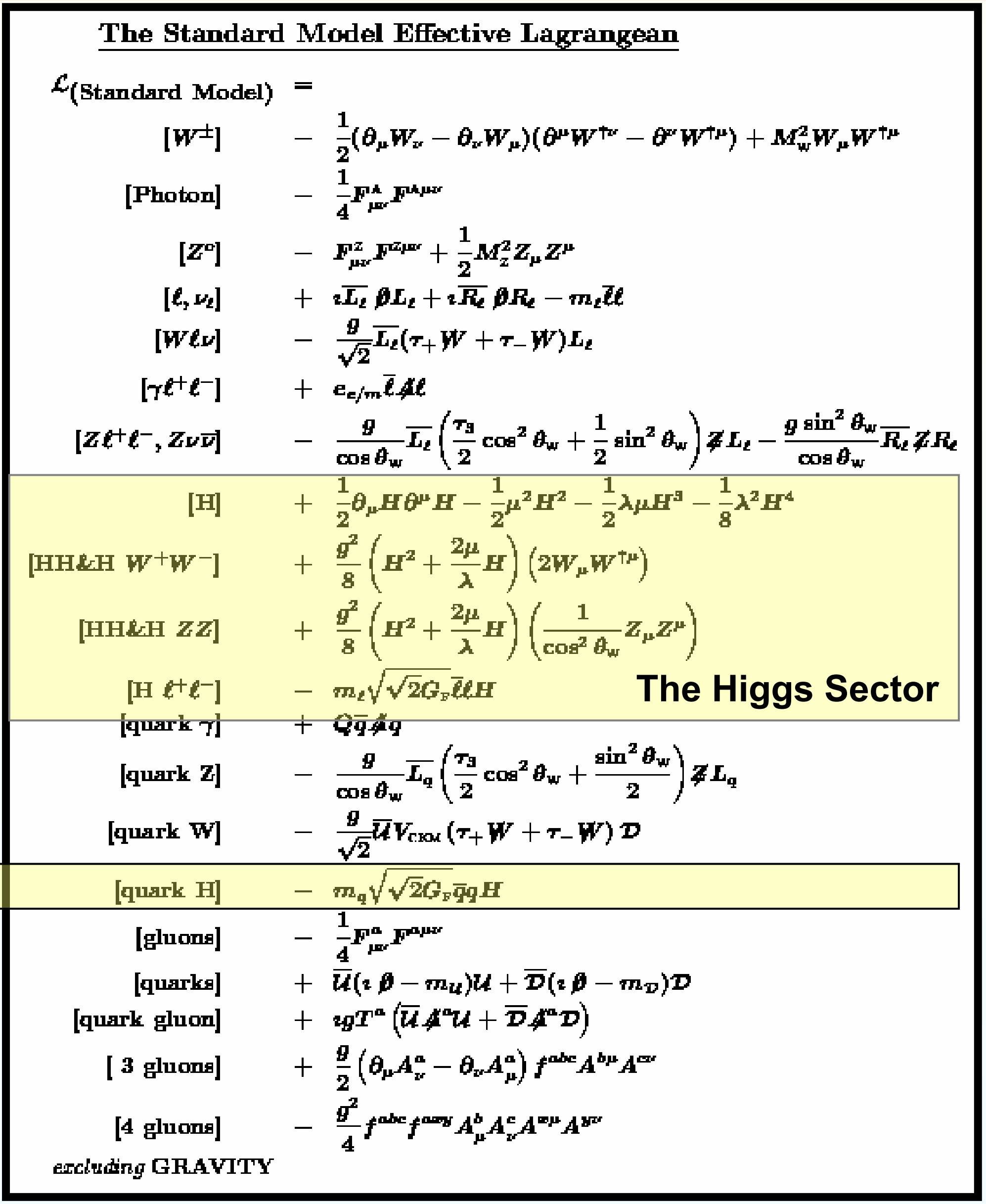
W W boson

Z Z boson

Higgs Boson?

Each with its own 'antiparticle'

The Standard Model



The Standard Model Effective Lagrangean

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

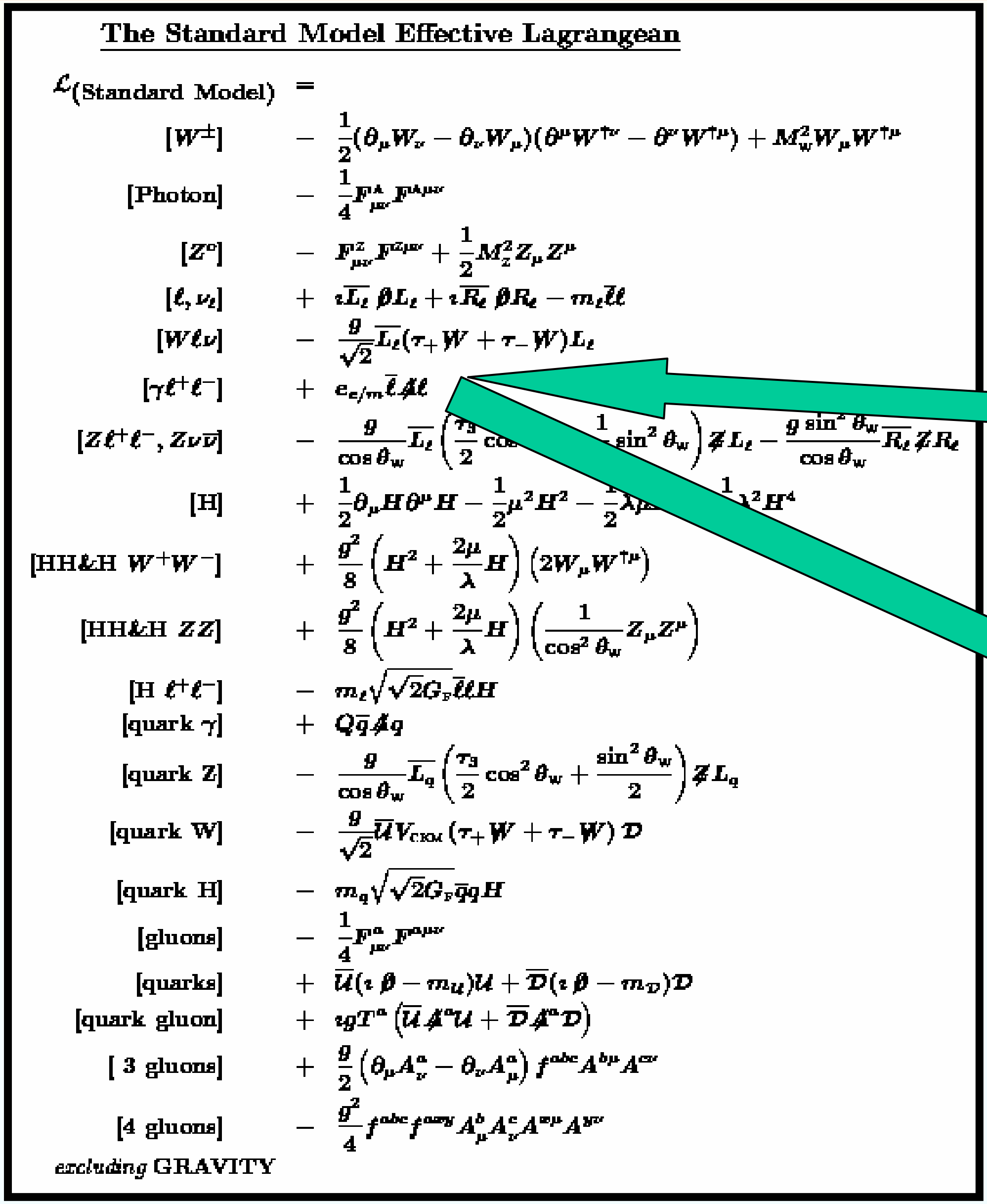
excluding GRAVITY

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_γ, m_g=0)
- 1 Higgs mass
  - M_h
- 3 coupling constants
  - G_F, α, α_s
- 3 quark mixing angles
  - θ_{12}, θ_{23}, θ_{13}
- 1 quark phase
  - δ

The Standard Model in action



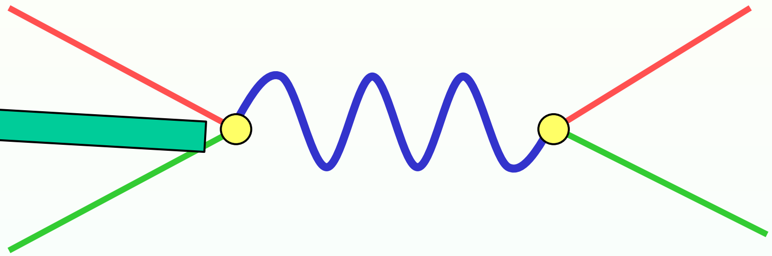
The Standard Model Effective Lagrangean

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

excluding GRAVITY

- **Take a process**

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



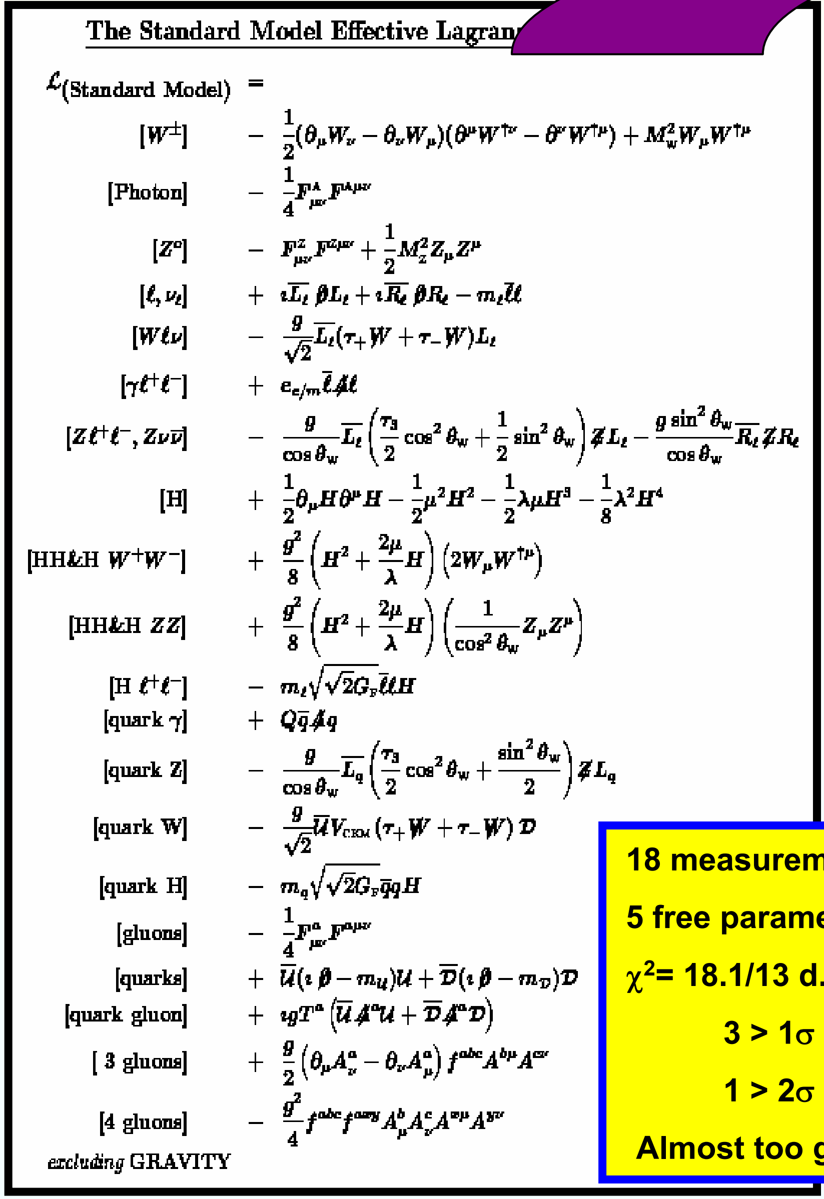
$4\pi\alpha^2/3s$

α 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?



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[W\ell\nu] & - & \frac{g}{\sqrt{2}} \overline{L_\ell}(\tau_+ \not W + \tau_- \not W) L_\ell \\
[\gamma\ell^+\ell^-] & + & e_{e/m} \overline{\ell} \not A \ell \\
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\end{array}
$$

excluding GRAVITY

$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02768
m_Z [GeV]	91.1875
Γ_Z [GeV]	2.4957
σ^0_{had} [nb]	41.477
R_l	20.744
$A^{0,l}_{fb}$	0.01645
$A_l(P_\tau)$	0.1481
R_b	0.21586
R_c	0.1722
$A^{0,b}_{fb}$	0.1038
$A^{0,c}_{fb}$	0.0742
A_b	0.935
A_c	0.668
A_l(SLD)	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2314
m_W [GeV]	80.374
Γ_W [GeV]	2.091
m_t [GeV]	171.3

18 measurements

5 free parameters

χ^2= 18.1/13 d.o.f.

3 > 1σ

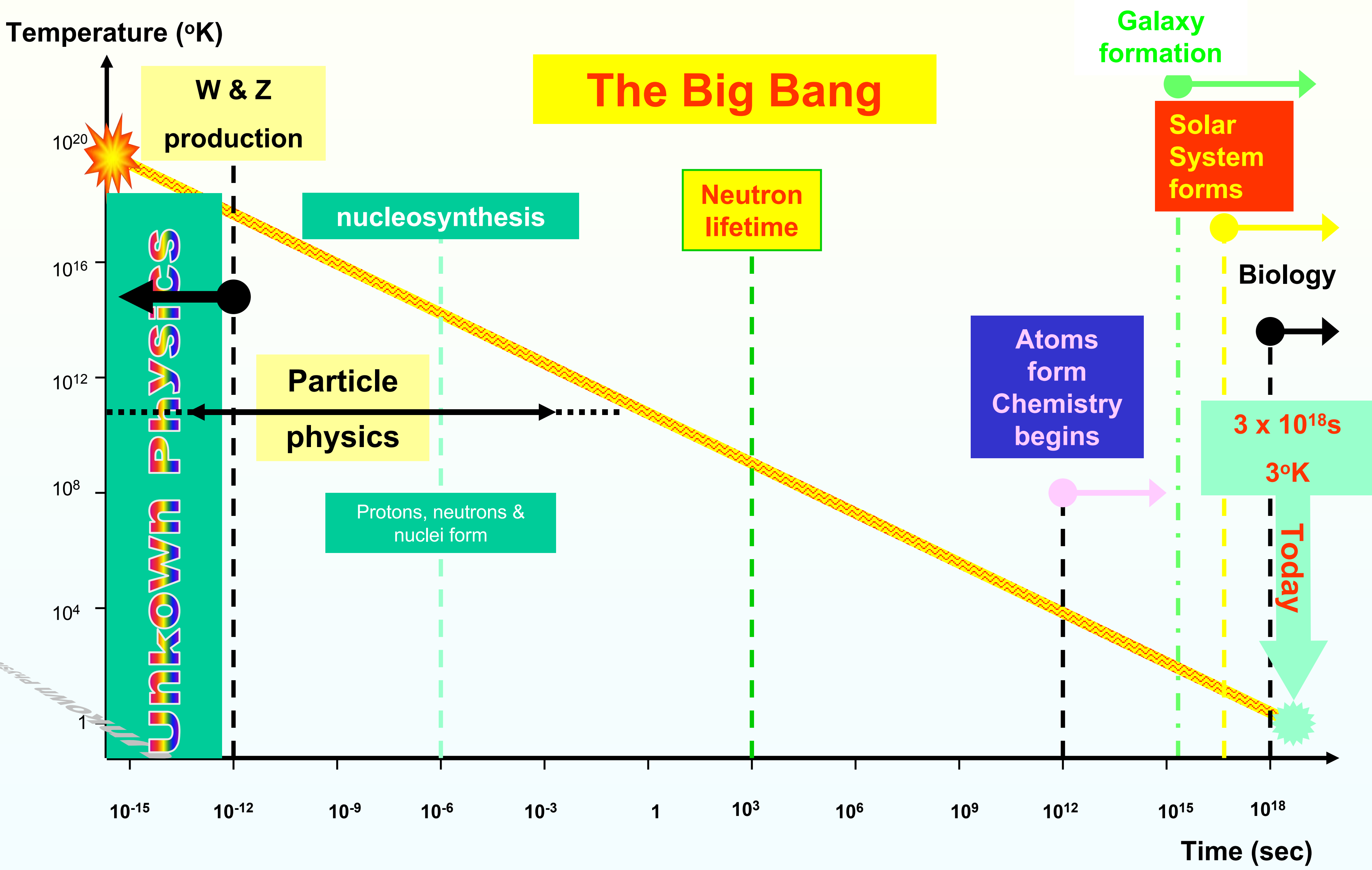
1 > 2σ

Almost too good!

What remains to be done?

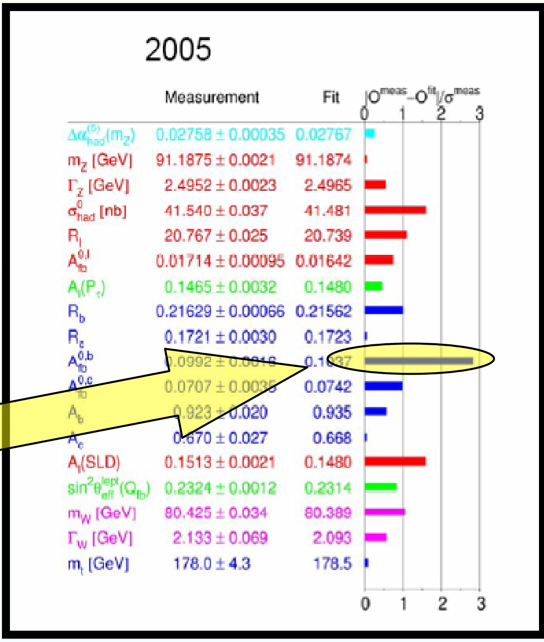
- The Standard Model is a very good *description* of the Universe at the particle scale (~$2M_W$)
  - But does not *explain* many things
    - Why so many particles?
    - Why so many forces?
    - What is mass?
      - Why do particles have the masses they have?
    - How do neutrinos get mass?
      - 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



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	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	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5

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

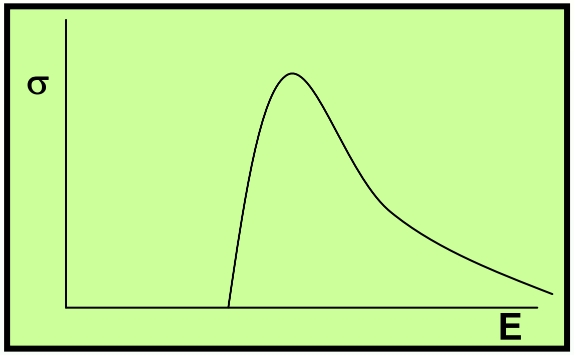
What to accelerate

- 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)

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

Beam Power or Protons on Target (POT)

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

$t \sim 10^7$ s/year

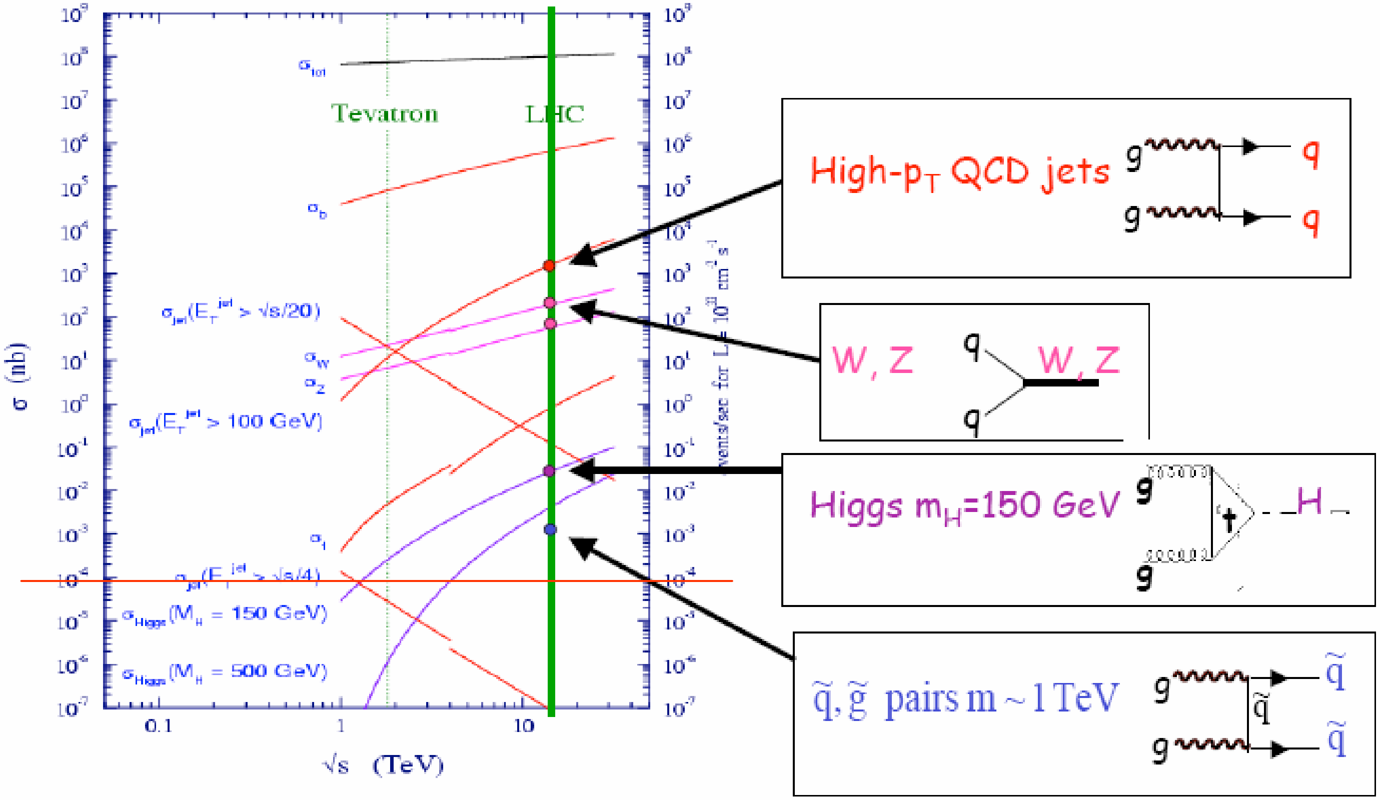
$\sigma \sim$ pb (10^{-36} cm^2)

For 1000 events in 1 year requires

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

An example – the LHC

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



High-p_T QCD jets

W, Z

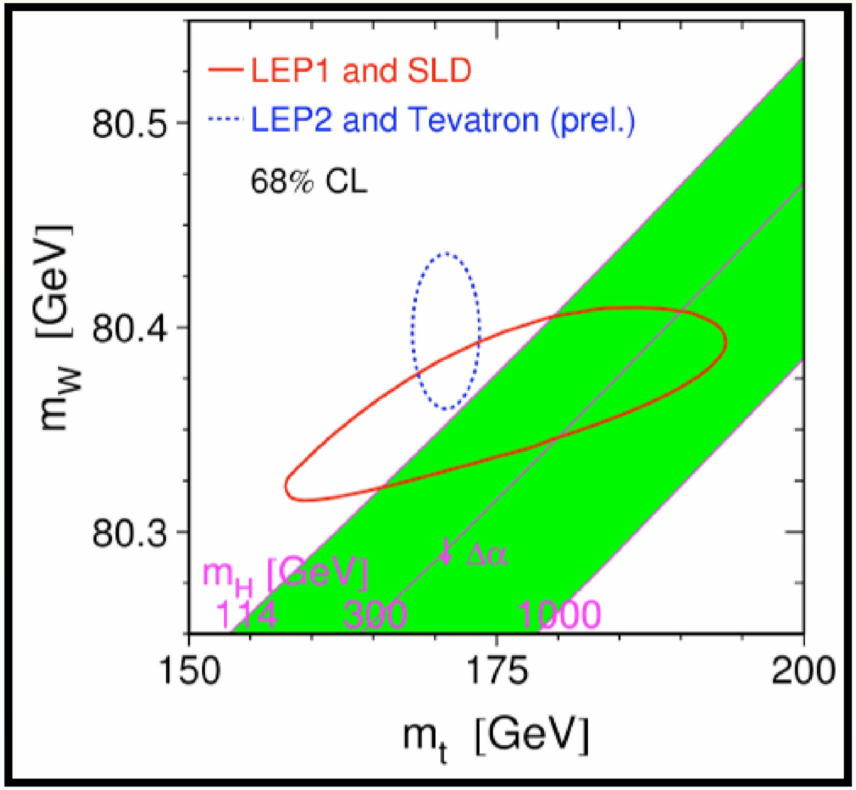
Higgs m_H=150 GeV

$\tilde{q}, \tilde{g}$ pairs m ~ 1 TeV

- No hope to observe light objects (W, Z, H ?) in fully-hadronic final states → rely on l, γ
- Fully-hadronic final states (e.g. $q^* \to qg$) 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?



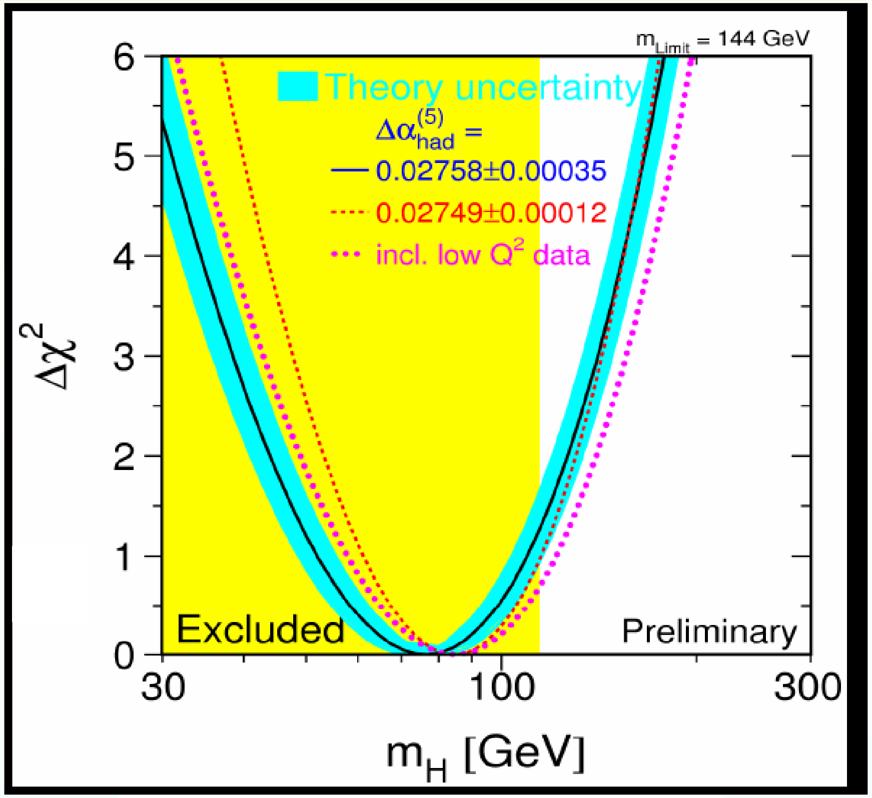
$M_H = 76^{+33}_{-24}$ GeV

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%:

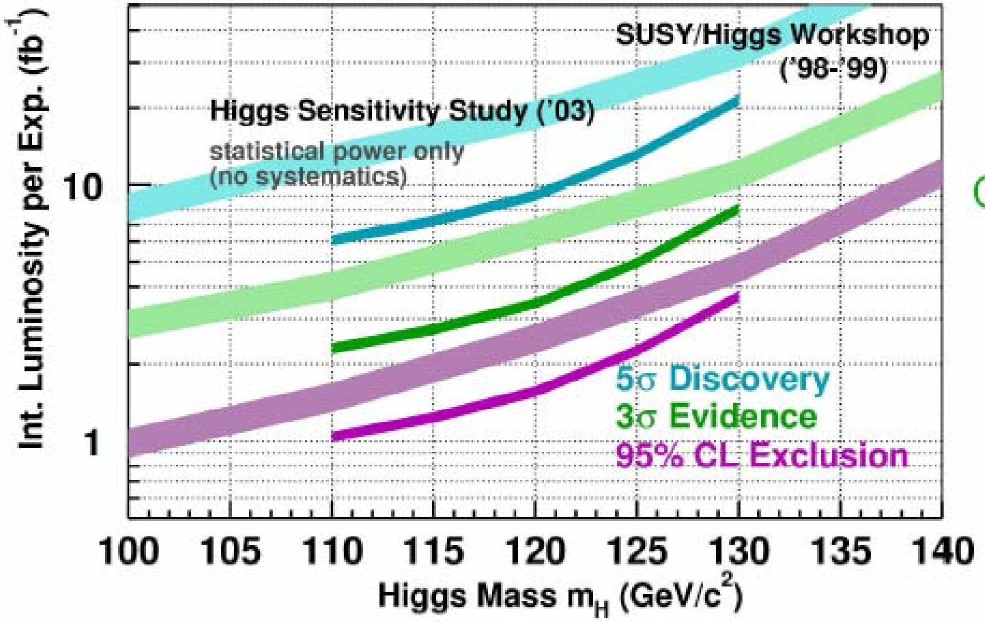
$M_H < 182$ GeV (95%CL)

Wyatt, EPS07

Higgs at the Tevatron

Standard Model Higgs Search

Combining production and decay channels and experiments:



Combined
CDF+DØ
Sensitivity

Expectations:
With 2/fb exclusion up to 123 GeV
With 10/fb discovery up to 121 GeV

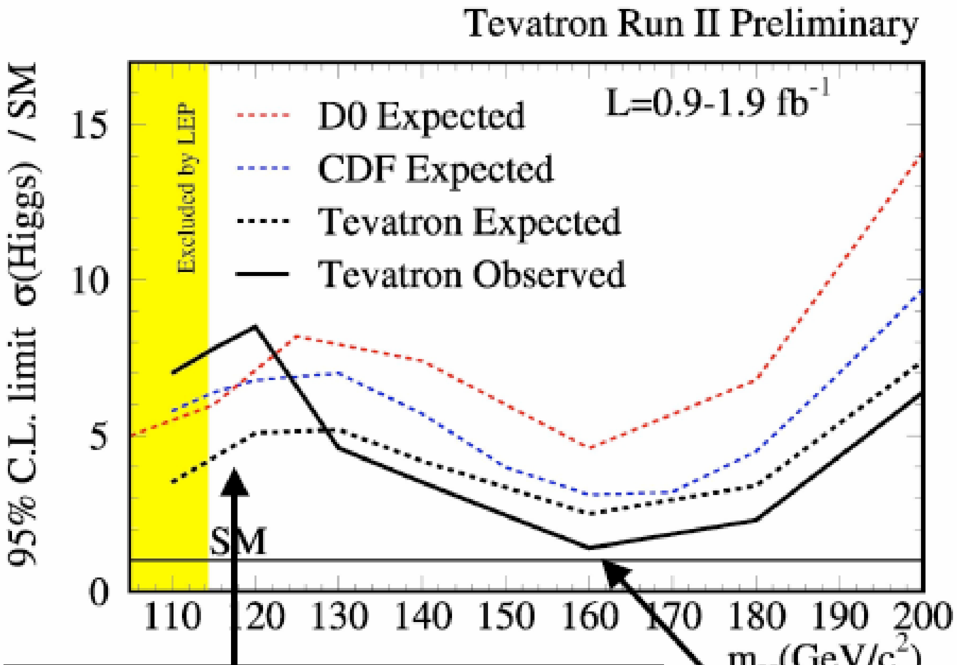
Currently: ~1/fb on tape

This was 3 years ago!!!

Where are they now?

The Tevatron Search today

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

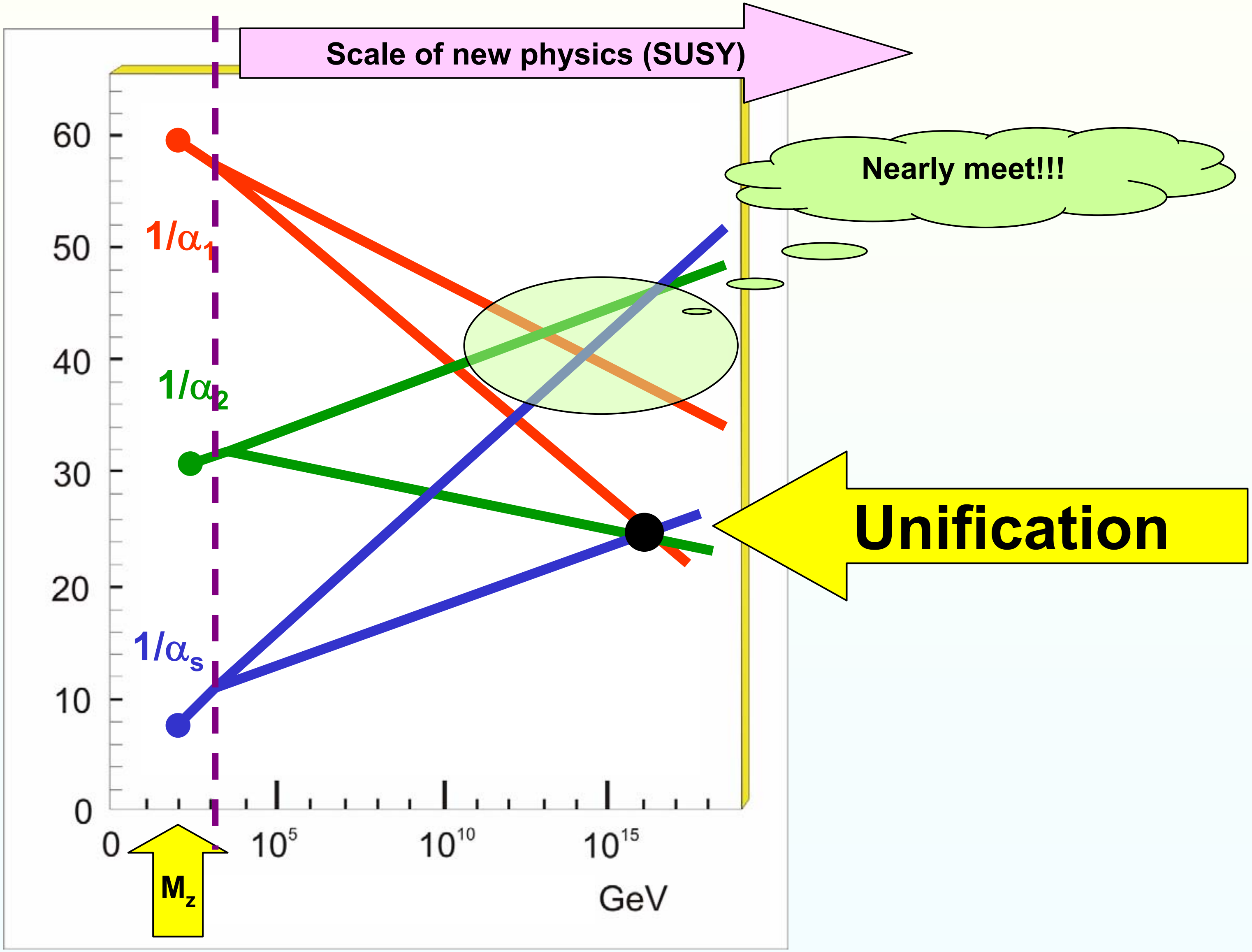
Note: big difference in statistics to go from exclusion to evidence (sophisticated cross-checks required …)

- 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?



Scale of new physics (SUSY)

Nearly meet!!!

Unification

Future Accelerators for particle physics

The Large Hadron Collider

The Linear (e^+e^-) Collider

The Muon Collider

The Neutrino Factory

EURISOL and Beta Beams

"Factories" (ϕ, τ, c, b)

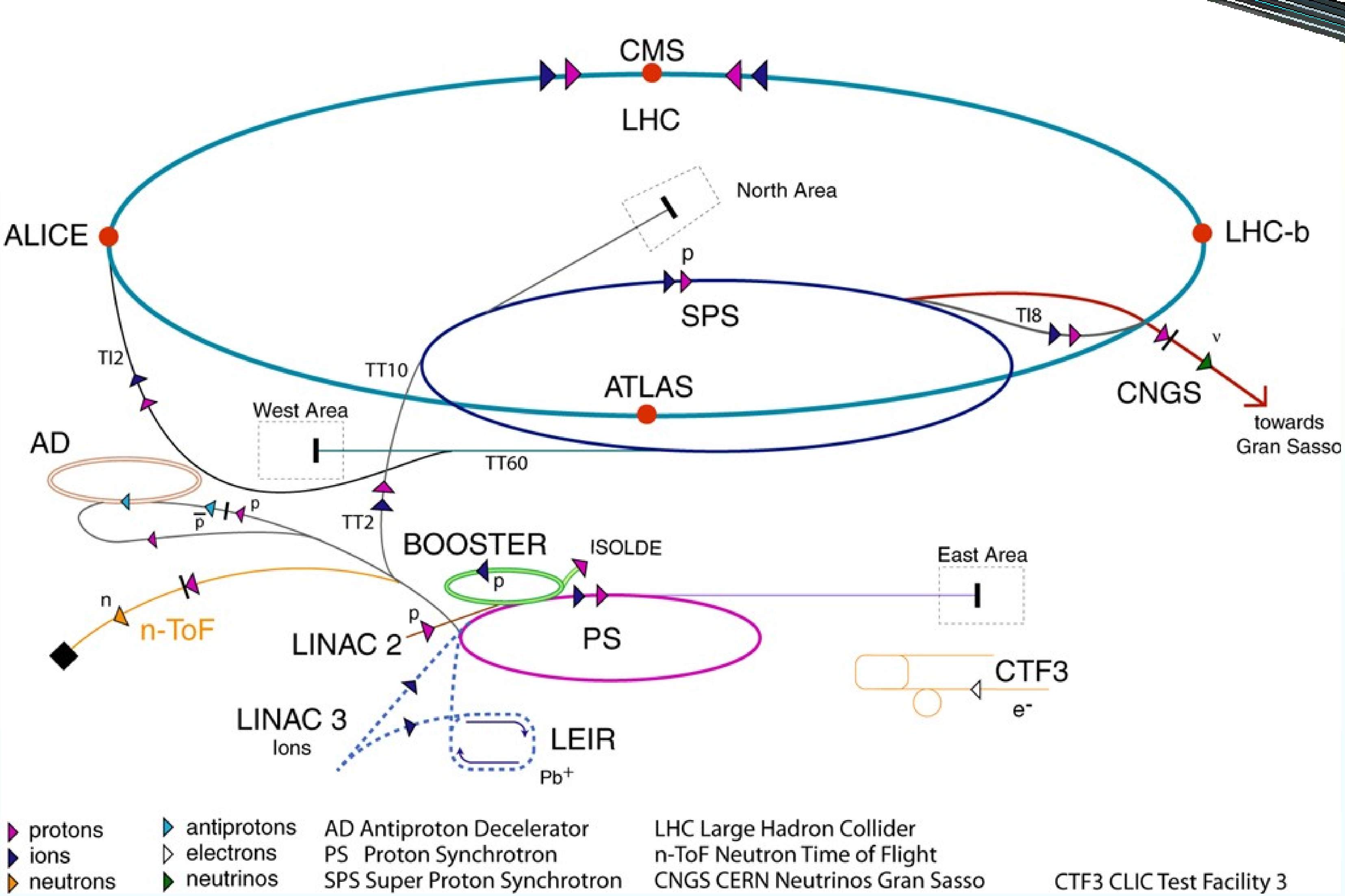
John Adams Institute
J.A.I.
for Accelerator
Science

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 <250GeV ; E_{NP} < 1TeV
- **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 ~ $10^{34}cm^2/s$

The CERN Accelerat Complex



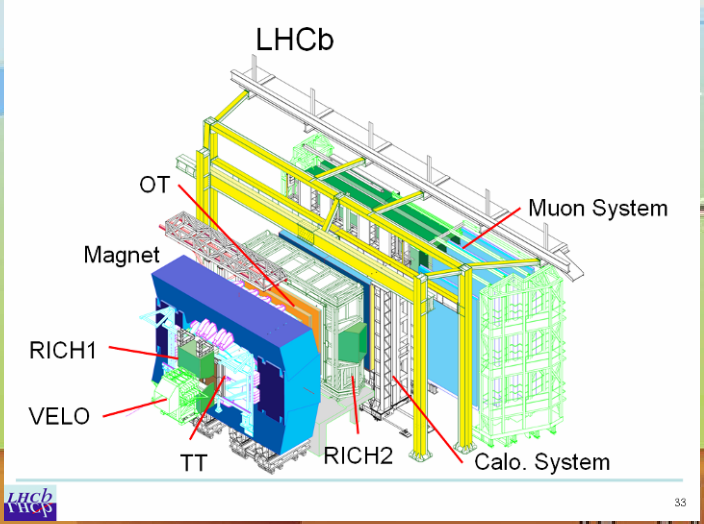
- ▶ protons
- ▶ ions
- ▶ neutrons
- ▶ antiprotons
- ▷ electrons
- ▶ neutrinos

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

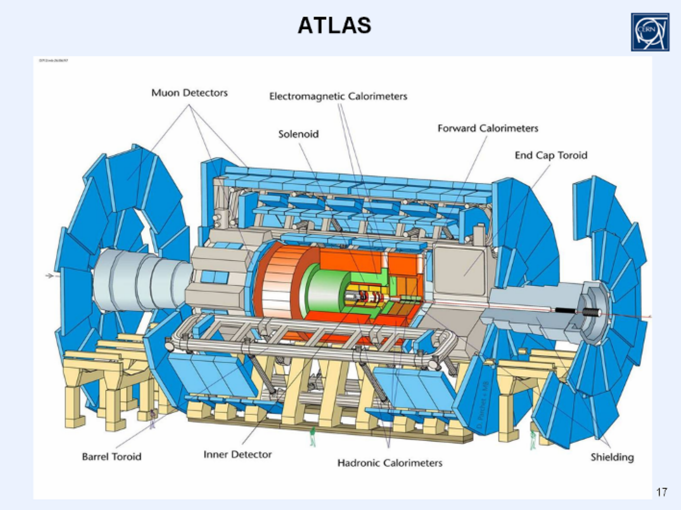
LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS CERN Neutrinos Gran Sasso

CTF3 CLIC Test Facility 3

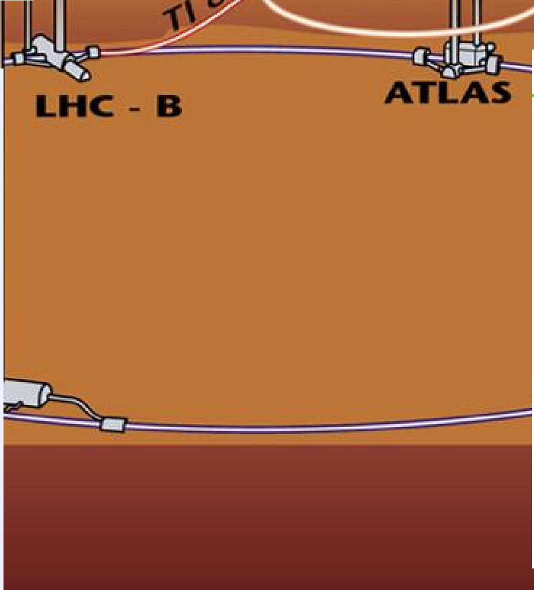
The Large Hadron Collider

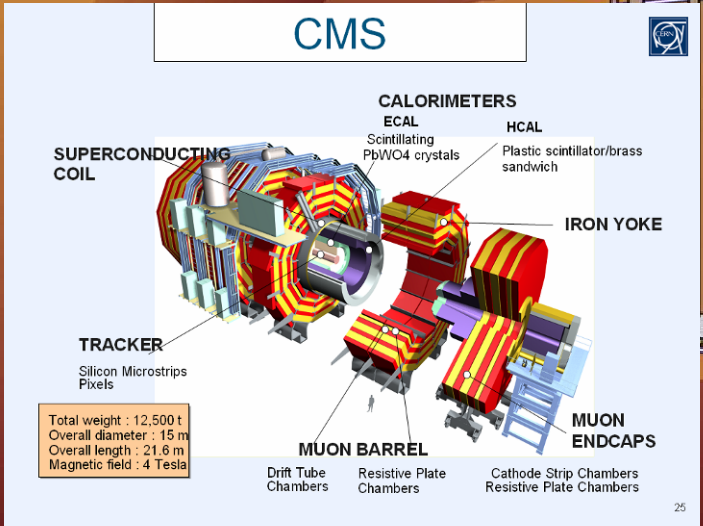


LHCb



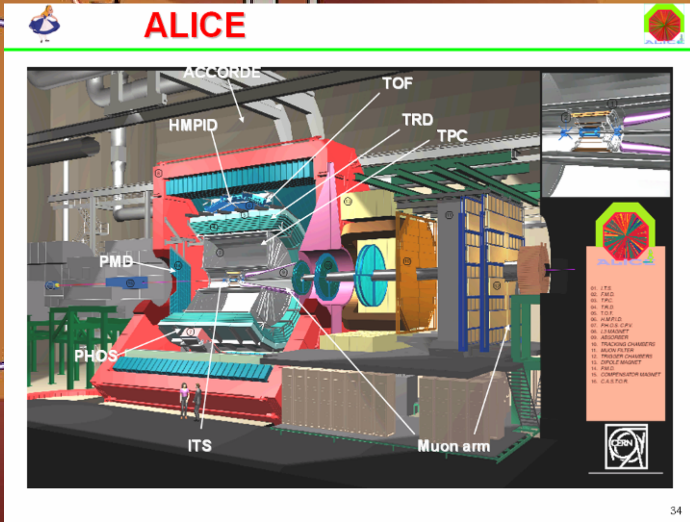
ATLAS





CMS

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

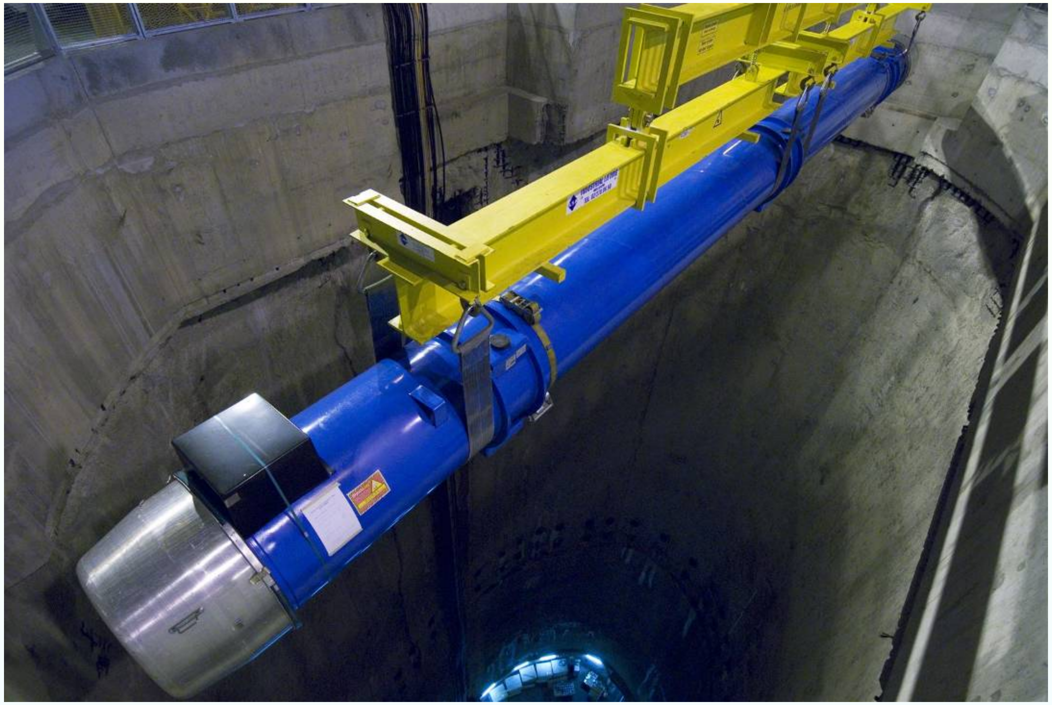


ALICE

The LHC installation

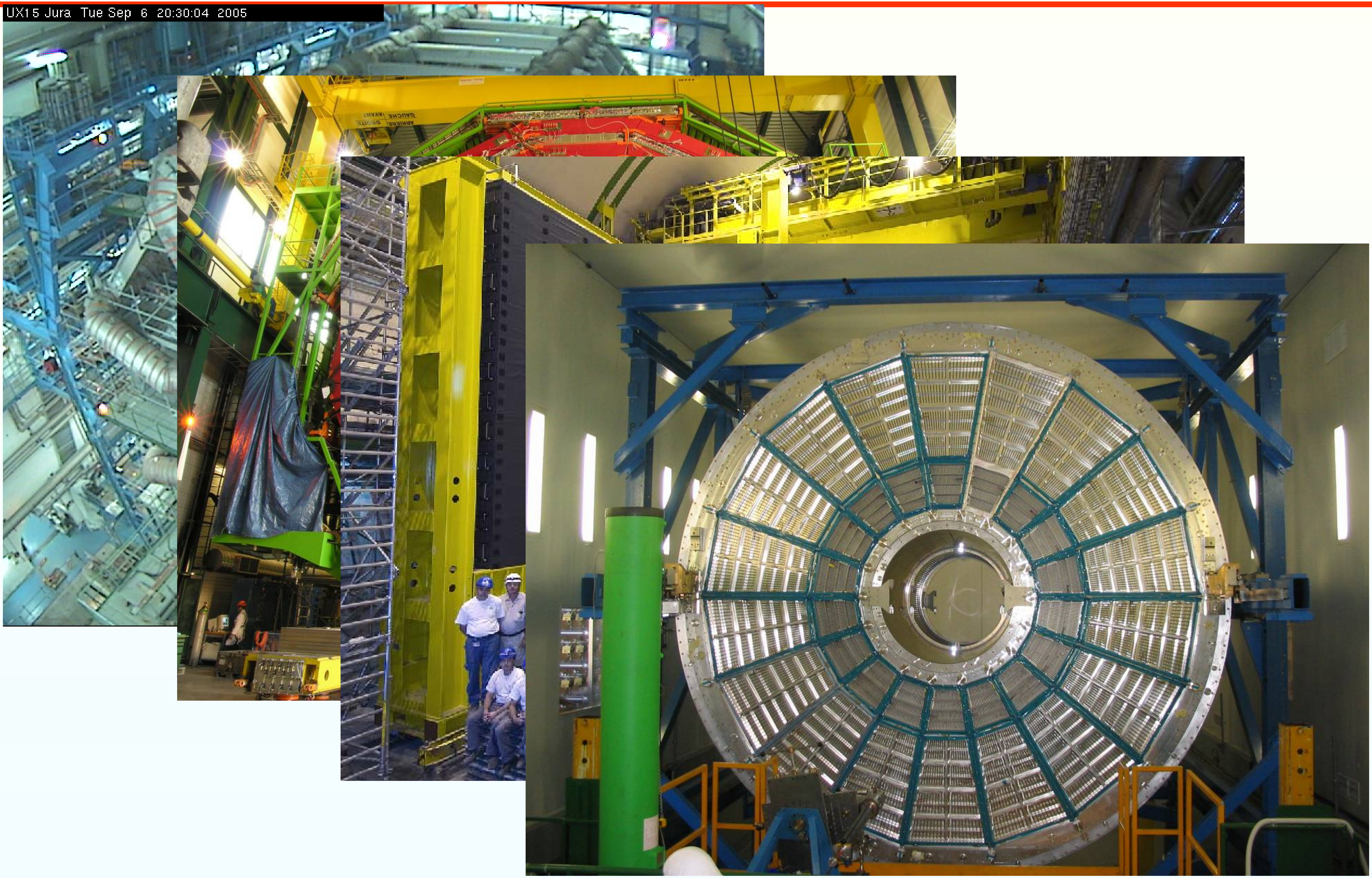
After Evans

Descent of the last magnet, 26 April 2007



30’000 km underground at 2 km/h!

ATLAS, CMS, LHCb, ALICE

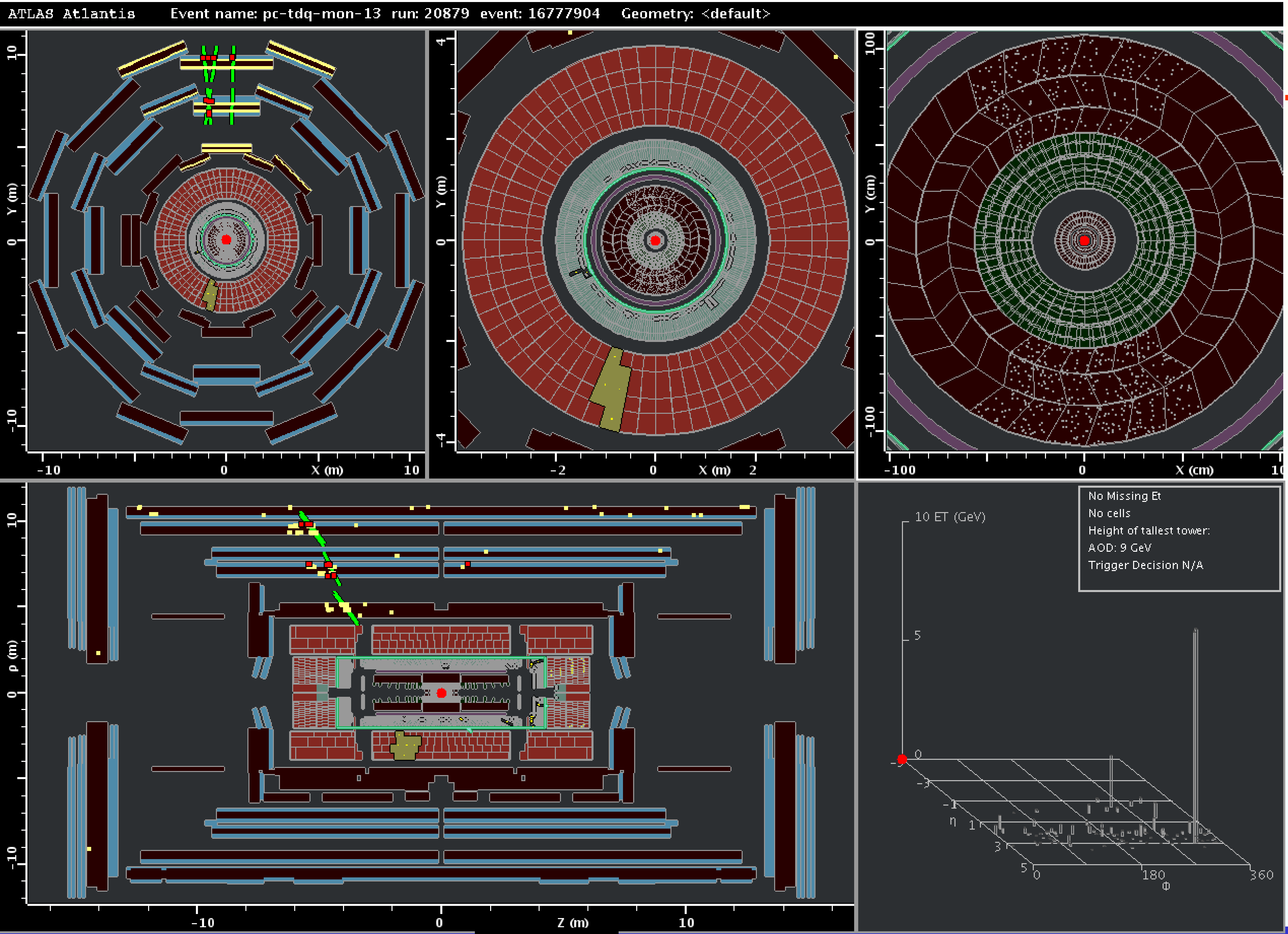


CMS Cavern


September 2007

ATLAS


UX15 Geneva Wed Sep 26 10:00:03 2007
Charge admissible totale
65 t
Chariot 65
Palan auxiliaire 1 5
Palan auxiliaire 2 5
UX15 Jura Wed Sep 26 10:00:02 2007

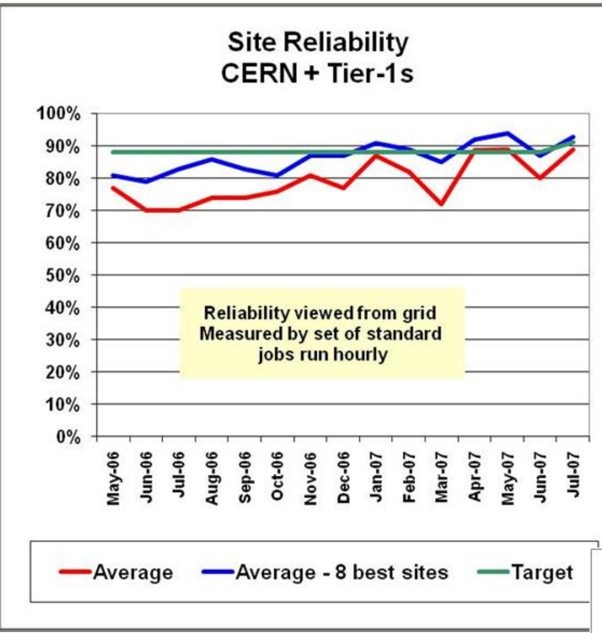


ATLAS Atlantis Event name: pc-tdq-mon-13 run: 20879 event: 16777904 Geometry: <default>

No Missing Et
No cells
Height of tallest tower:
AOD: 9 GeV
Trigger Decision N/A

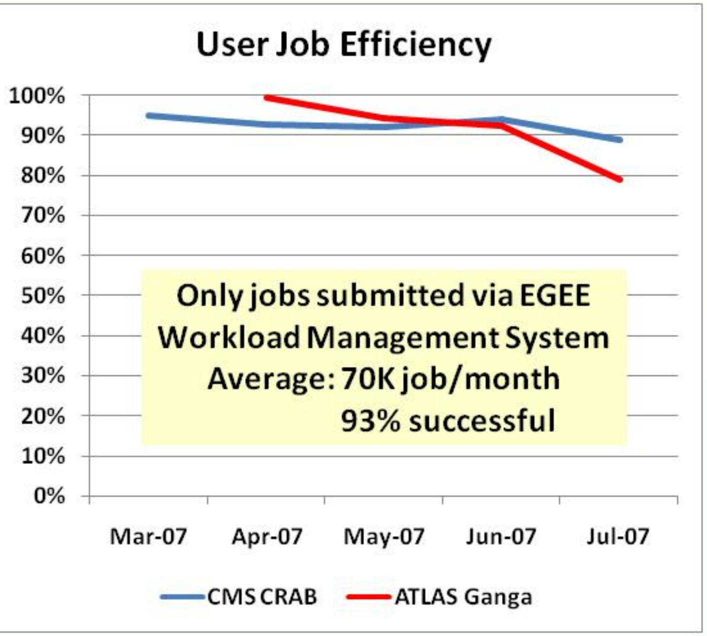
After Engelen

LCG


Site Reliability
CERN + Tier-1s

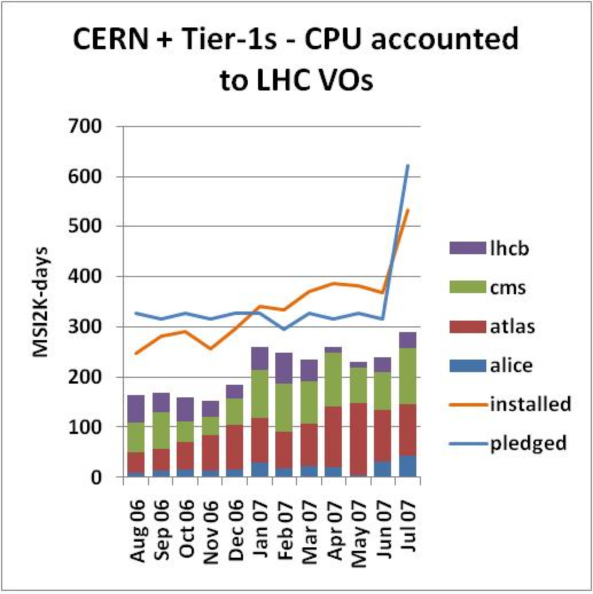
Reliability viewed from grid
Measured by set of standard
jobs run hourly

Reliability


User Job Efficiency

Only jobs submitted via EGEE
Workload Management System
Average: 70K job/month
93% successful

Efficiency

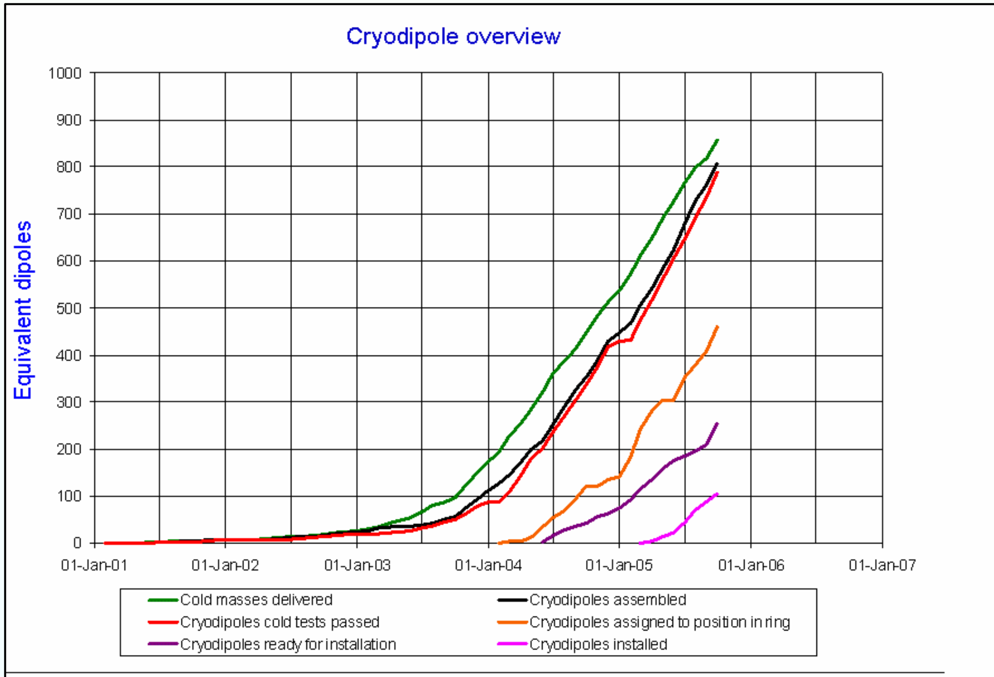

CERN + Tier-1s - CPU accounted to LHC VOs

Capacity

LHC status

Two Years Ago

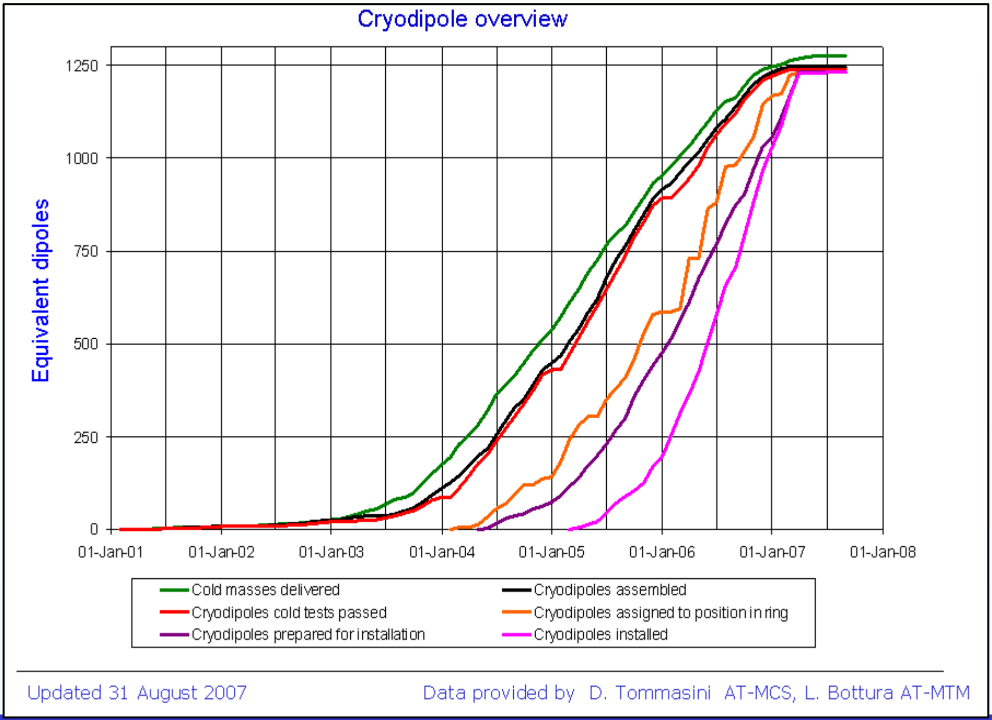
- Machine, experiments now installing
- Due for completion in summer 2007
- First collisions end summer 2007
- First results 2008
  - Higgs, SUSY
    - or something else



Updated 30 Sep 2005 Data provided by D. Tommasini AT-MAS, L. Bottura AT-MTM

LHC status Today

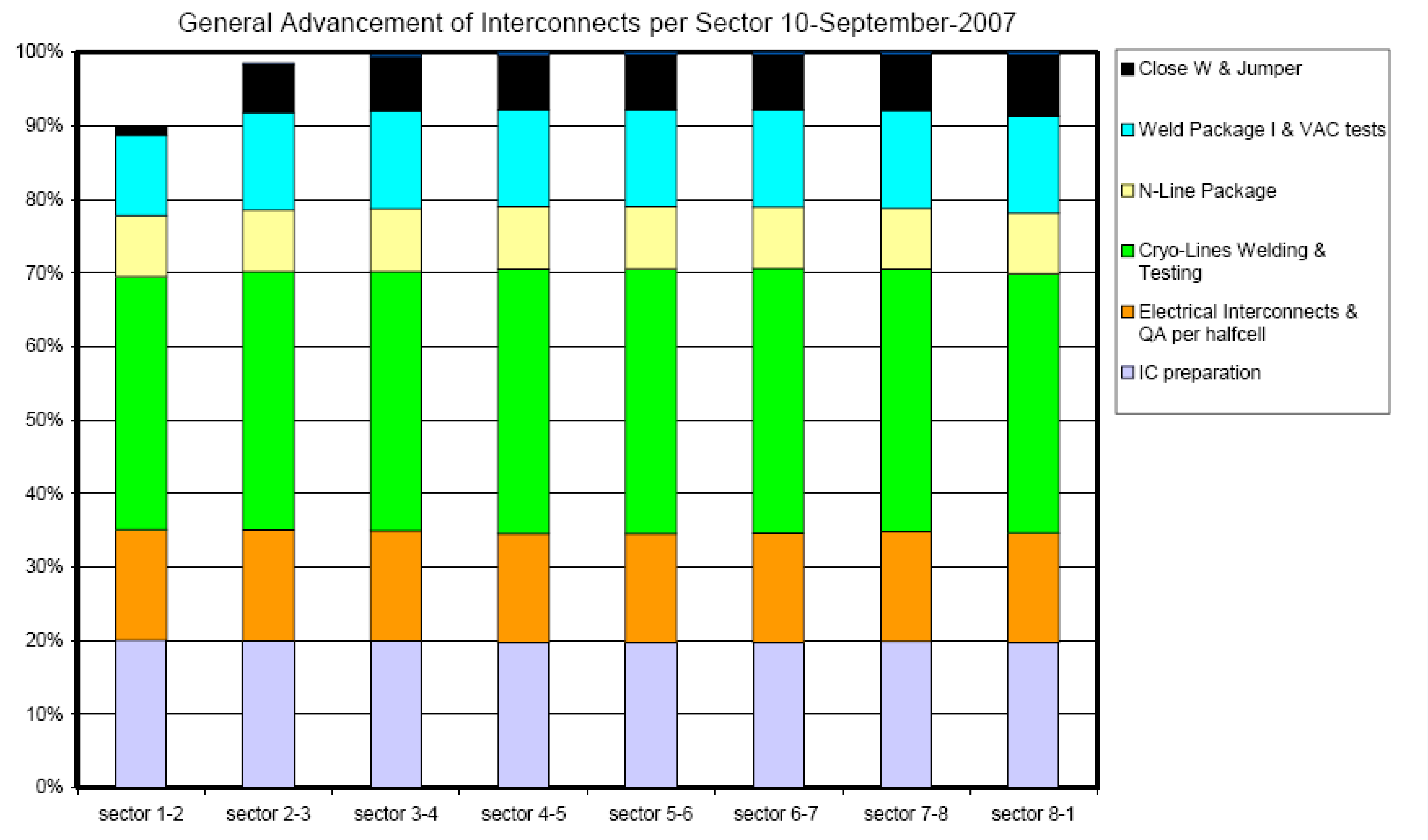
- Machine installed, commissioning
- Experiments nearly installed, commissioning
- Due for completion in ~~summer 2007~~ May 08
- First collisions end summer 200~~7~~ 8
- First results 200~~8~~ 9
  - Higgs, SUSY
    - or something else


Cryodipole overview

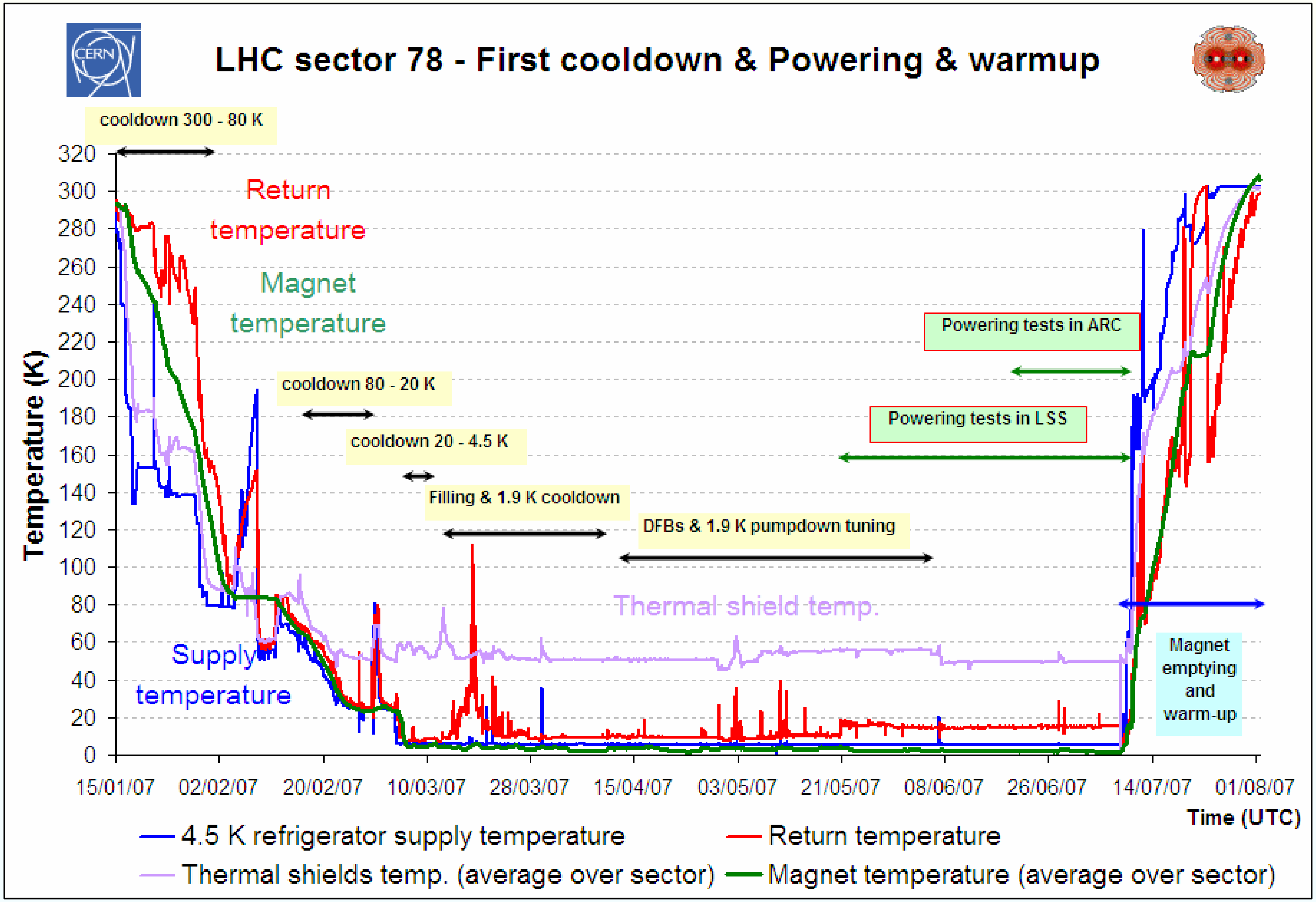
Updated 31 August 2007

Data provided by D. Tommasini AT-MCS, L. Bottura AT-MTM

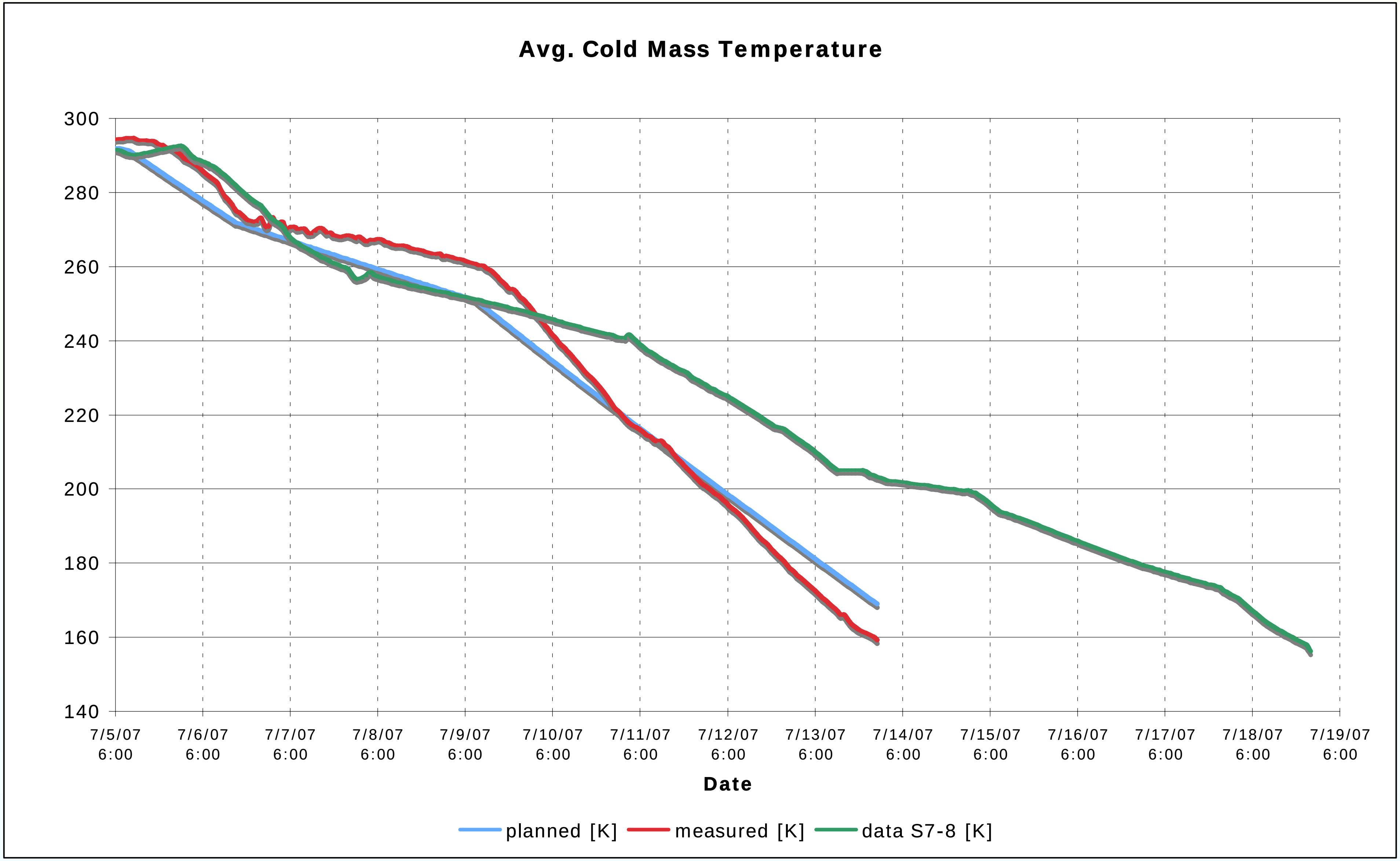
Magnet interconnections



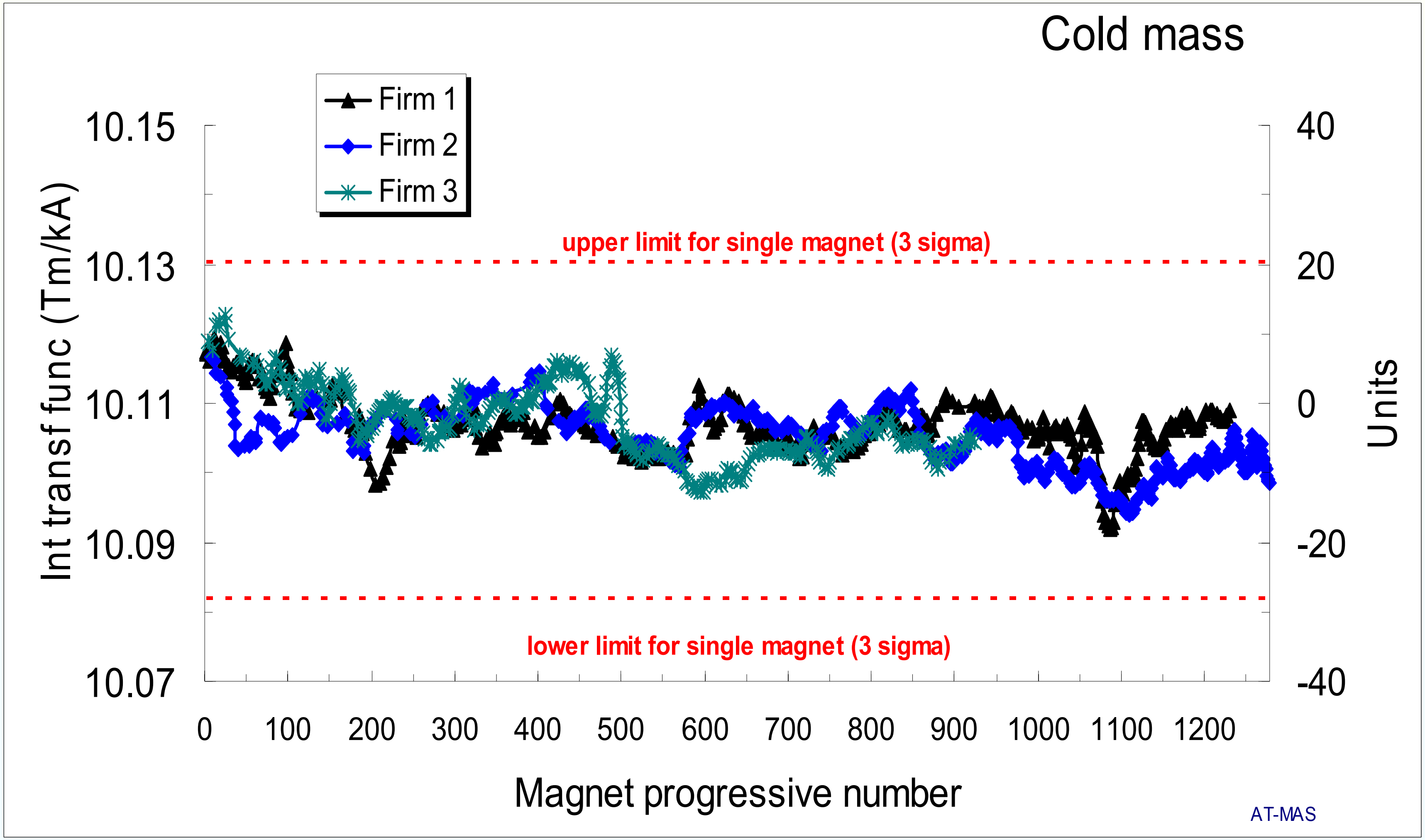
First cooldown and warm up of Sector 7-8



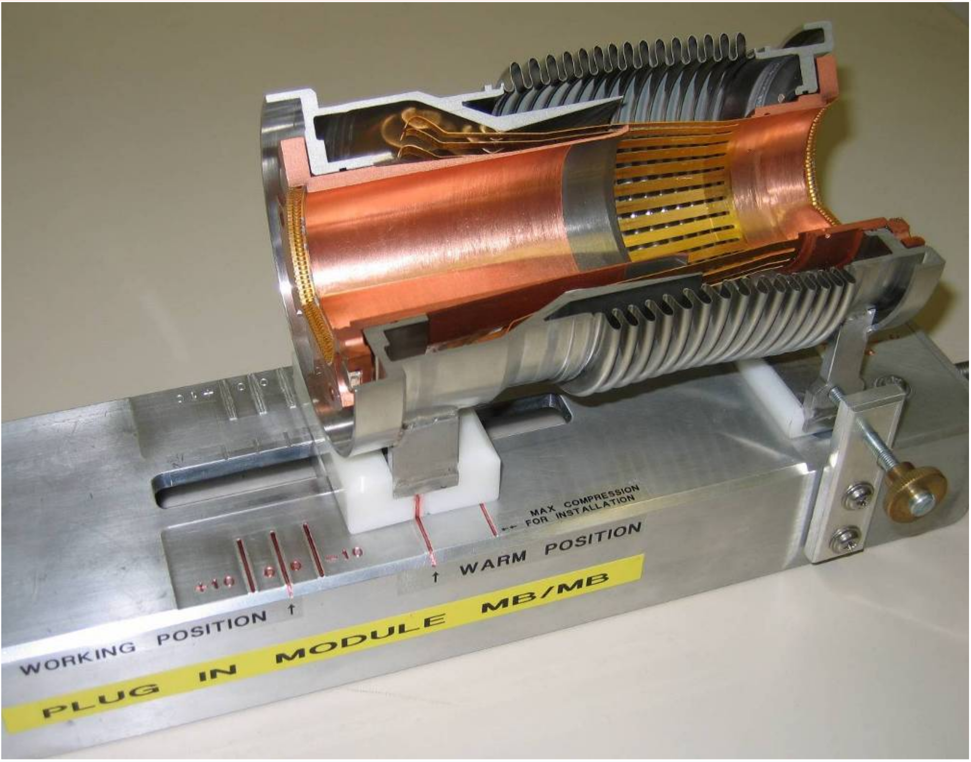
Cooldown until Saturday 14-7-7 - Cooldown speed

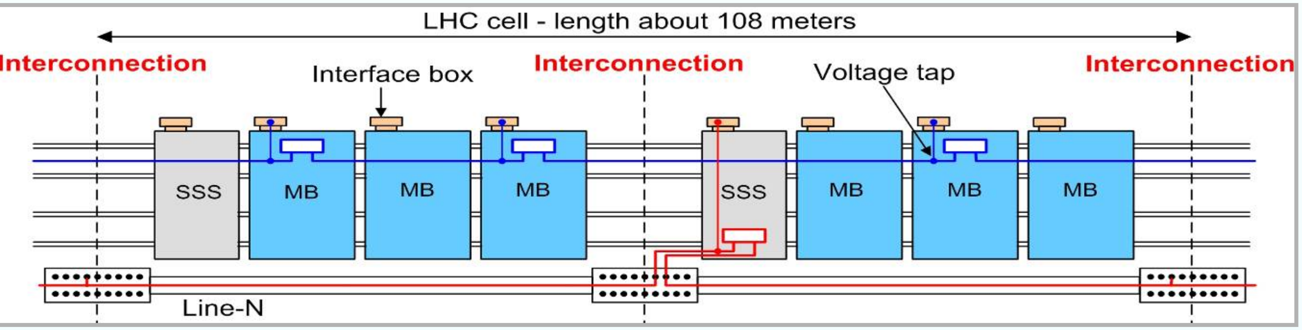


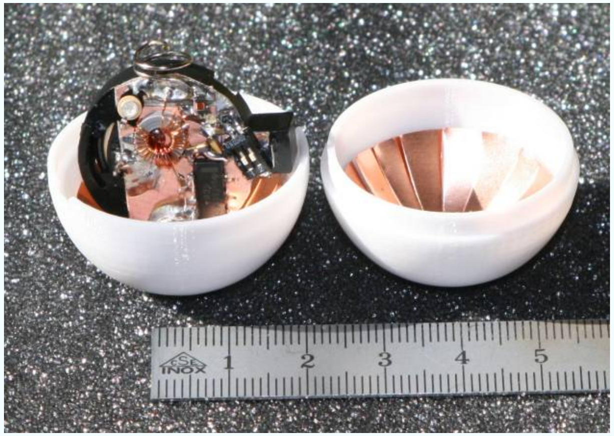
Bending strength of dipoles



Module at room temperature …





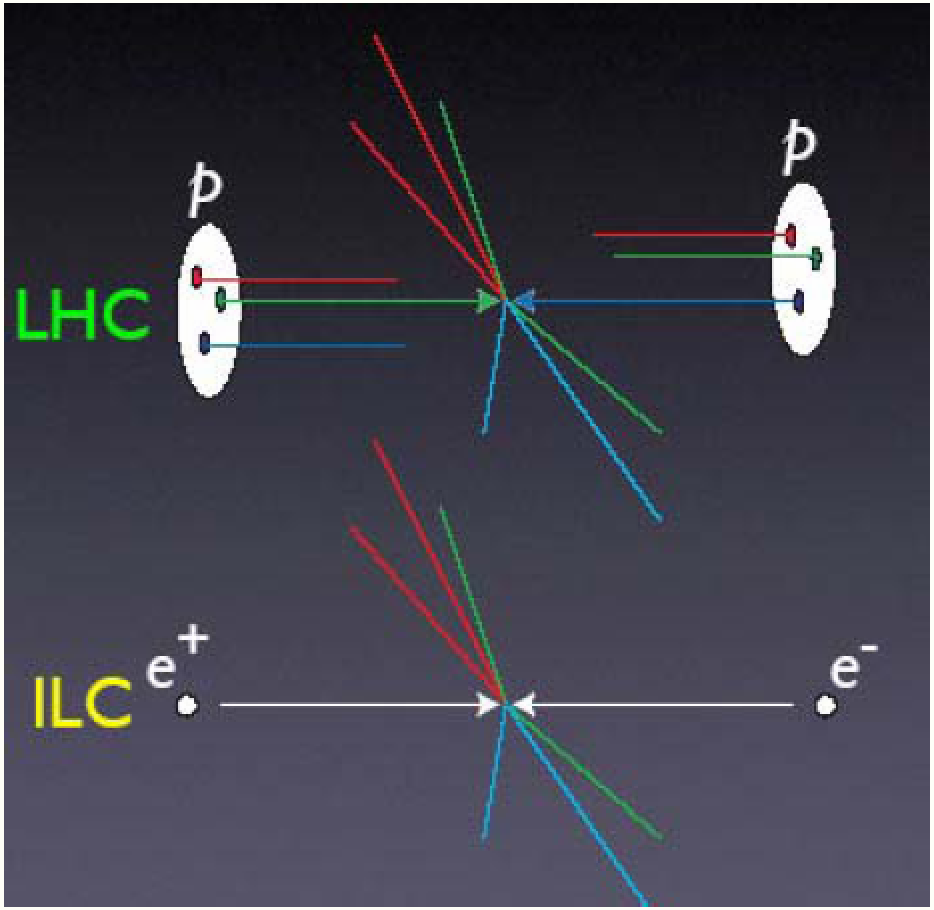


After Evans

The Linear (e^+e^-) Collider

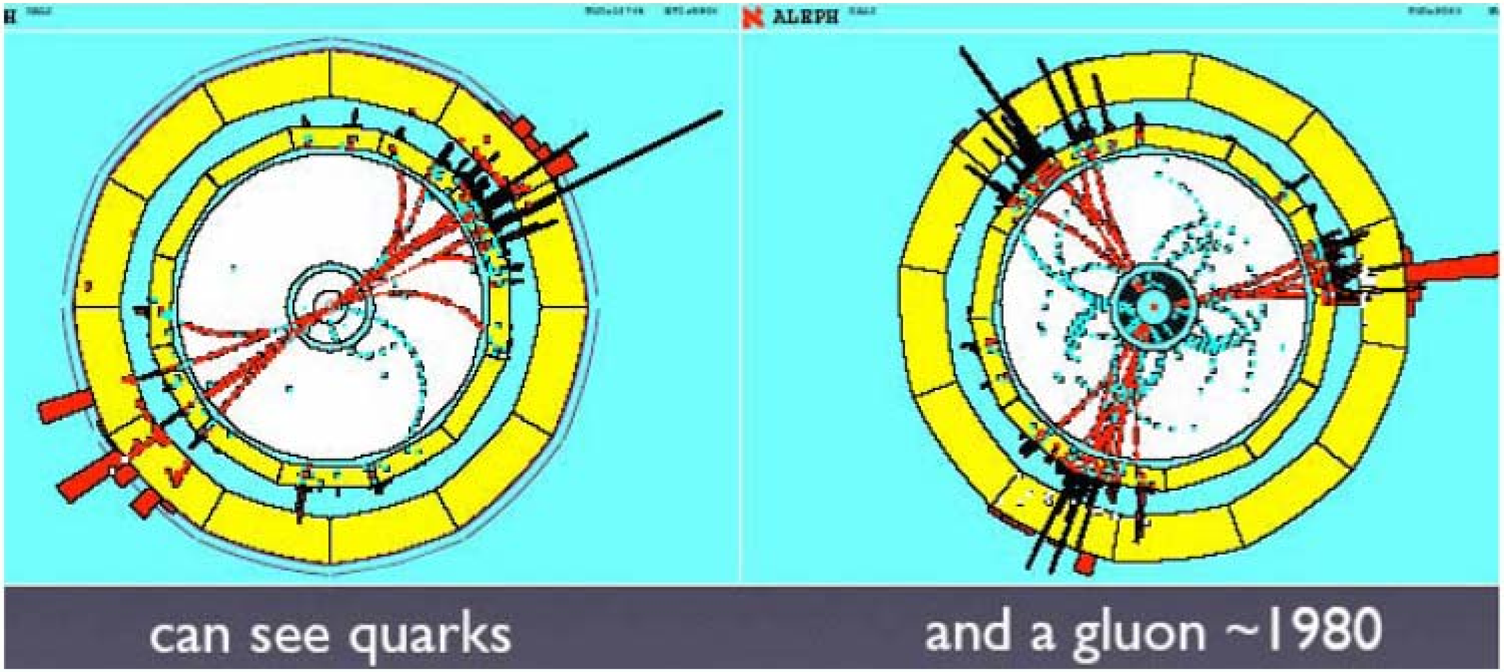
Why an e+e- collider?

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



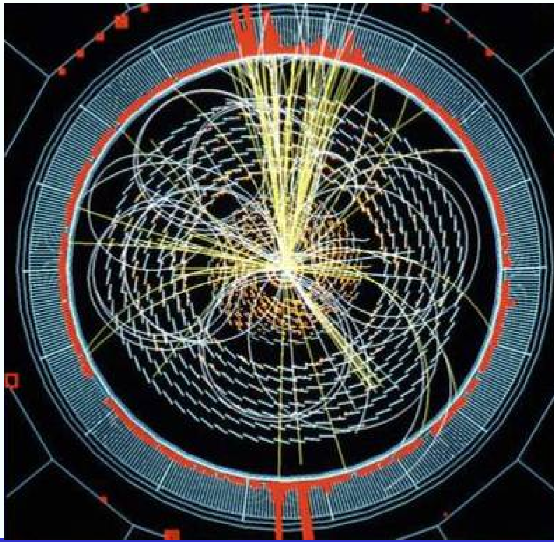
After Barry Barish

Why an e+e- collider?



← LEP

LHC →



After Barry Barish

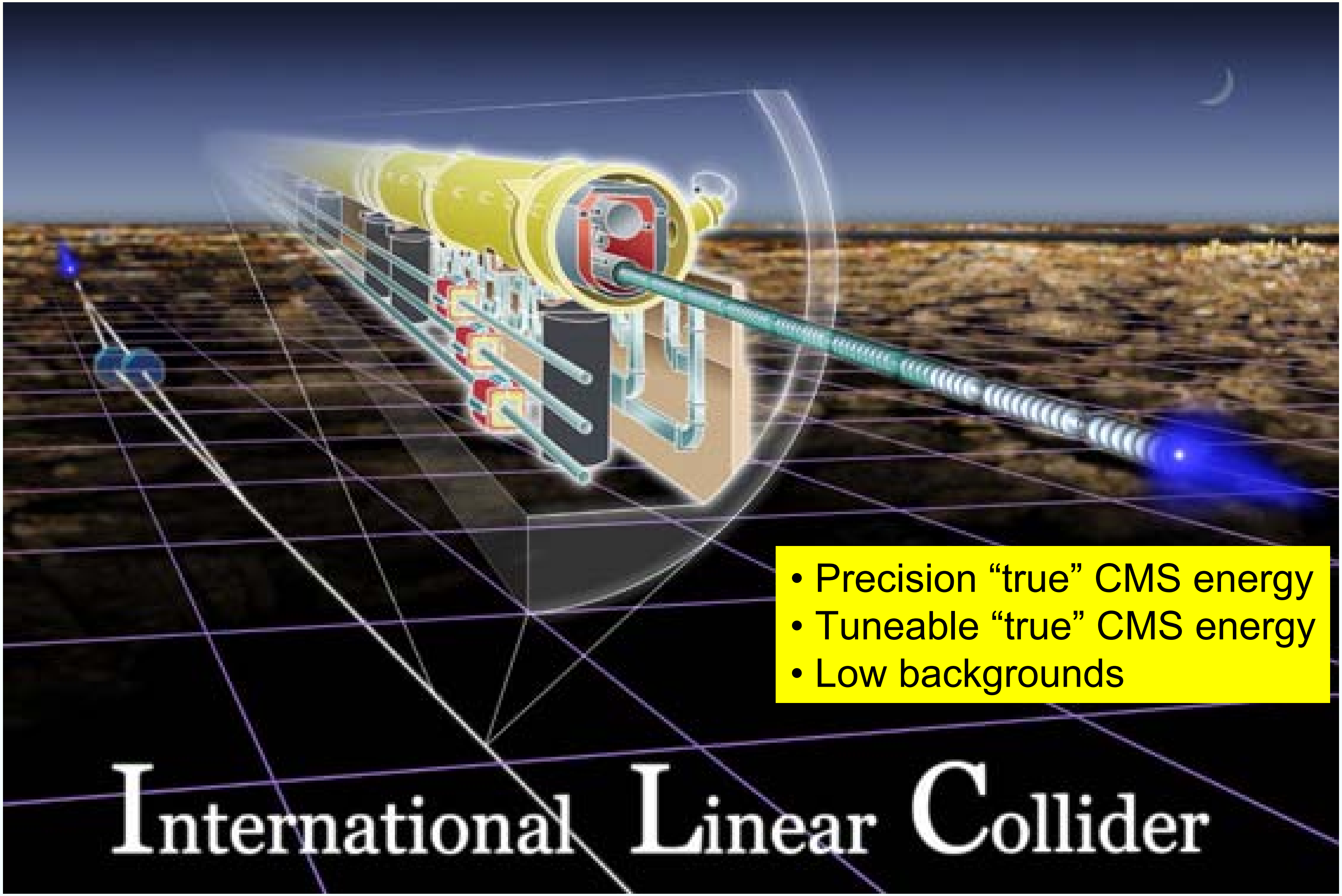
Why a *linear* e+e- collider?

Synchrotron Radiation!

or rather

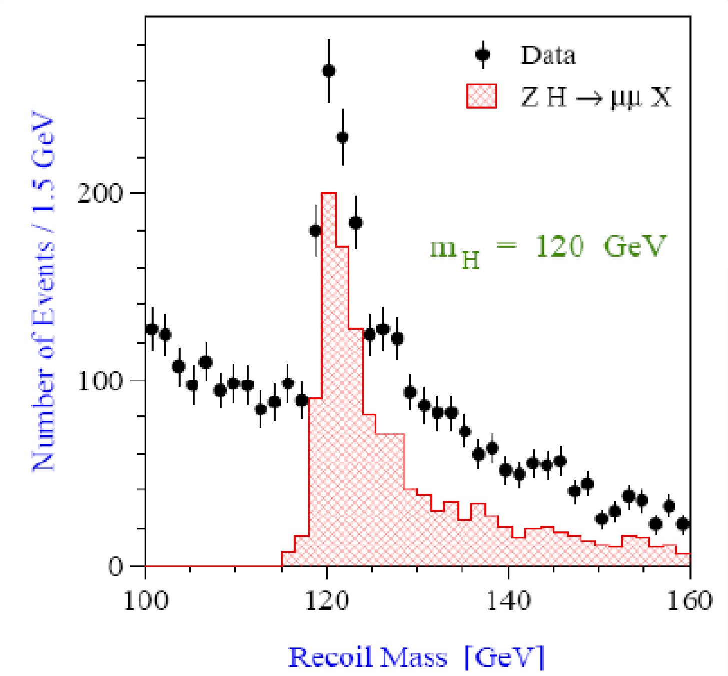
the lack of it in a linear machine

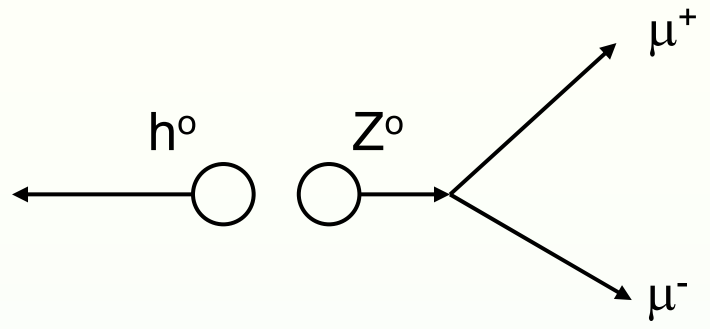
Key ILC Properties



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

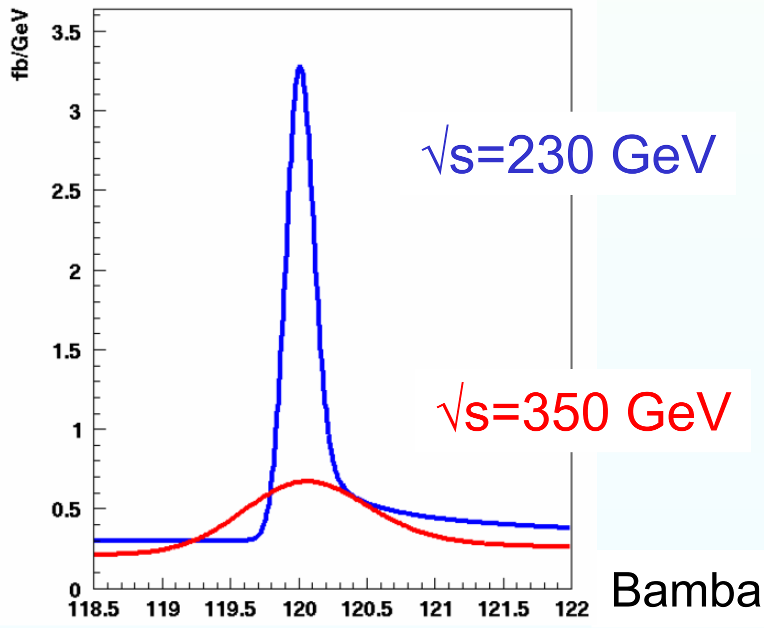
Invisible Higgs?



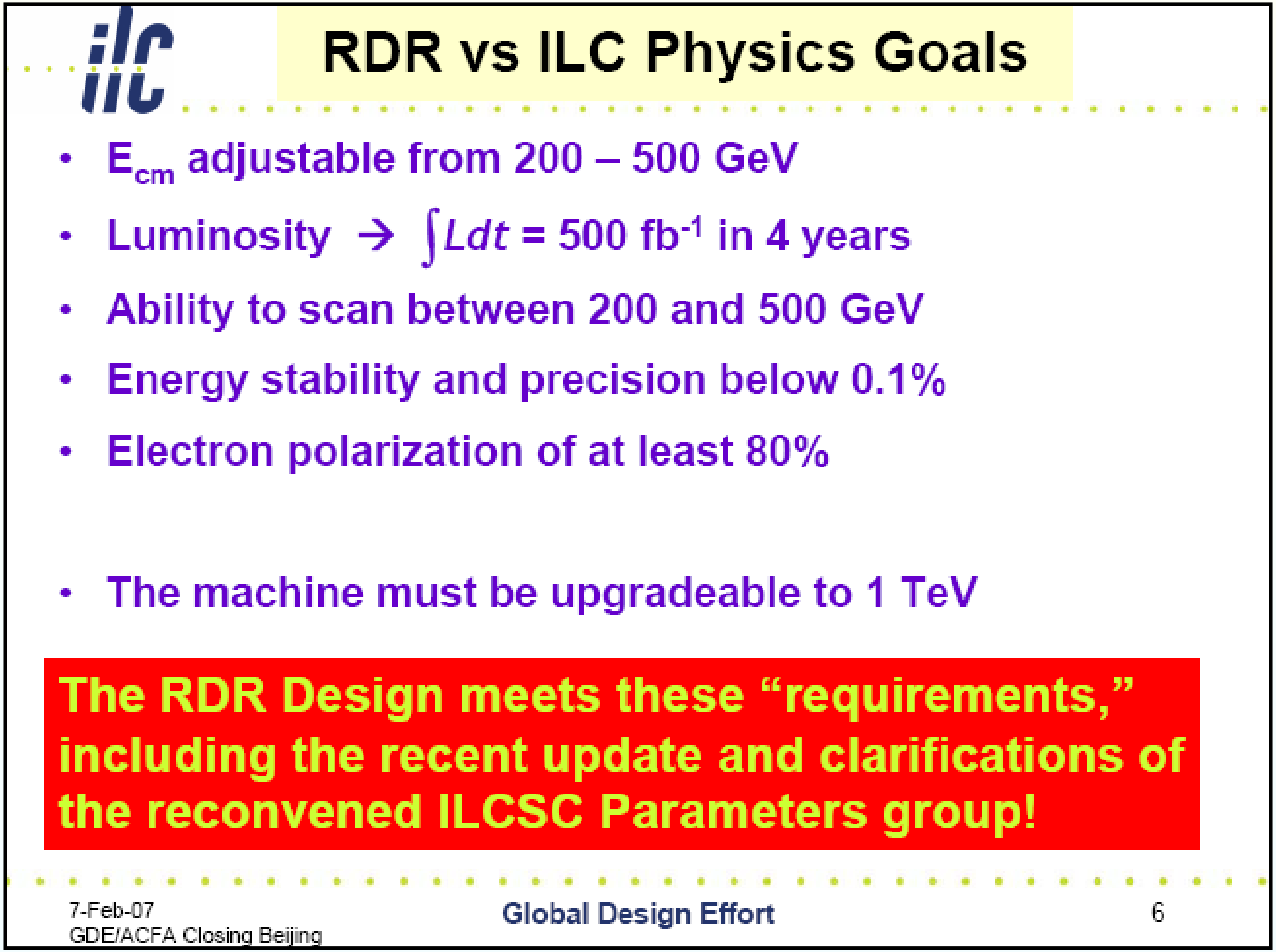


Measure recoil against Z^0

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 → $\int L dt$ = 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!

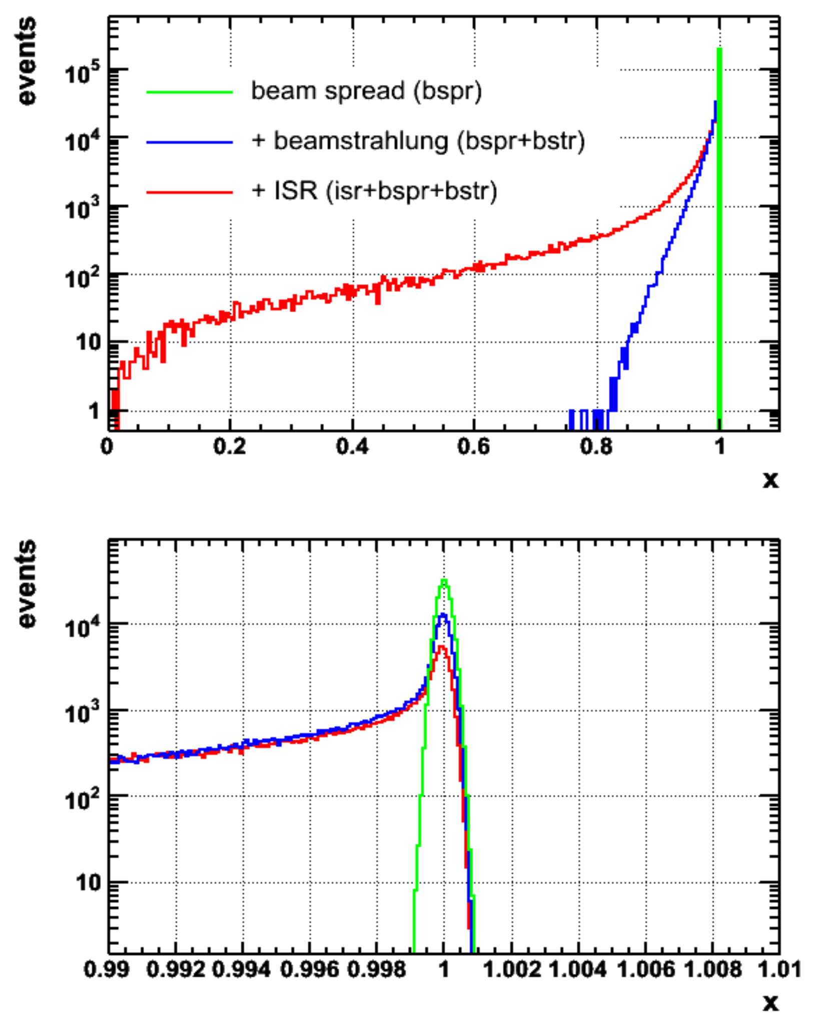
7-Feb-07
GDE/ACFA Closing Beijing

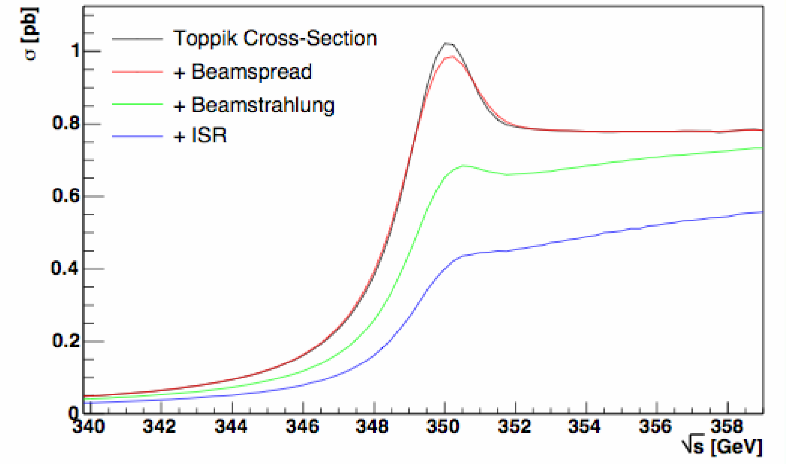
Global Design Effort

6

B. Barish, Beijing 2007

ILC energy spectrum; impacts physics output:





Need for:

- Energy measurement accuracy 10^{-4}
- Stability and ease of operation
- Minimal impact on physics data taking

Luminosity

Efficiency

$$L = \frac{\eta P_{\mathrm{electrical}}}{\mathrm{E}_{\mathrm{CM}}} \sqrt{\frac{\delta}{\varepsilon_{n,y}}}\, H_D$$

Beamstrahlung parameter

$$\delta \propto E_{\mathrm{CM}} \frac{N^2}{\sigma_z \sigma_x^2}$$

Disruption parameter

Trade-off between
- Luminosity
- beam energy precision (beamstrahlung δ)
- backgrounds (related to H_D)
- running cost

ILC Parameter Plane

500 GeV CMS

	Nominal	Low Q	Large Y	Low P	
Number of Particles	2	1	2	2	10^{10}
Number of bunches	2625	5120	2625	1320	
Bunch interval (buckets)	369(480)	189(246)	369(480)	480(624)	ns( )
Average current	9.0	9.0	9.0	6.8	mA
Norm.emittance at IP x/y	10/0.04	10/0.03	10/0.08	10(0.036)	μm
Beta at IP x/y	20/0.4	11/0.2	11/0.6	11/0.2	mm
Rms beamsize at IP x/y	639/5.7	474/3.5	474/9.9	474/3.8	nm
Rms bunch length	300	200	500	200	μm
Disruption param x/7	0.174/19.4	0.108/14.6	0.520/24.9	0.211/26.1	
Beamstrahlung param Υ	0.048	0.050	0.038	0.097	
Energy loss by beamstr.	2.4	1.7	2.7	5.5	%
# of photons of beamstr.	1.32	0.91	1.77	1.72	
Pinch enhancement	1.71	1.48	2.18	1.64	
Geometric luminosity	1.20	1.35	0.935	1.21	10^{34}
Luminosity	2.0	2.0	2.0	2.0	10^{34}

After Blair

ILC Parameter Range

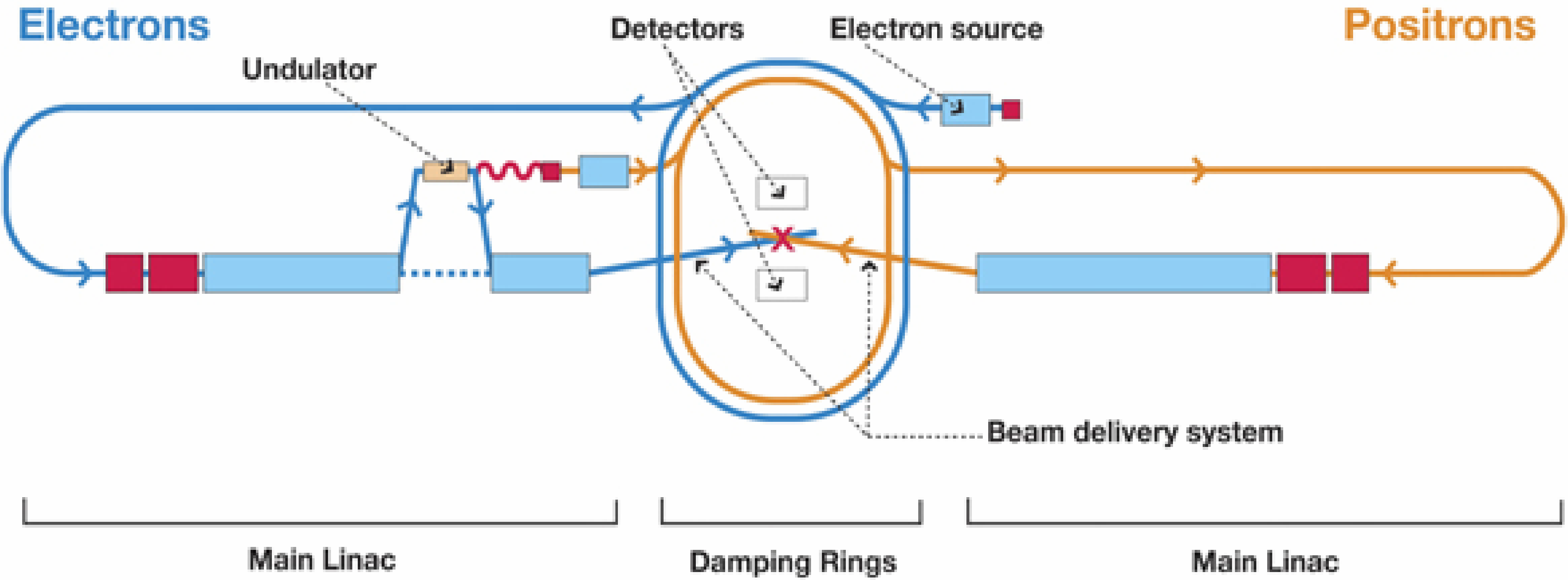
	min	-	nominal	-	max	
Number of particles	1	-	2	-	2	10^{10}
Number of bunches	1320	-	2625	-	5120	
Linac bunch interval	189	-	369	-	480	ns
DR bunch interval	3.08	-	6.15	-	12.3	ns
Bunch length	200	-	300	-	500	µm
Vertical emittance	0.03	-	0.04	-	0.08	µm
Beta at IP (x)	11	-	11	-	20	mm
Beta at IP (y)	0.2	-	0.4	-	0.6	mm

Special challenges in red

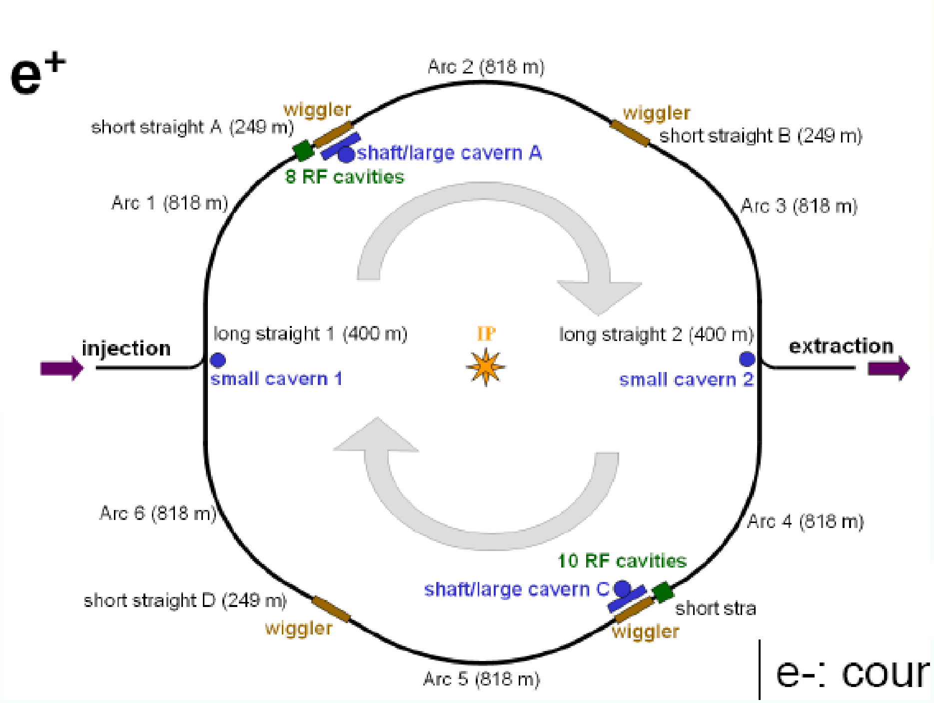
After Blair

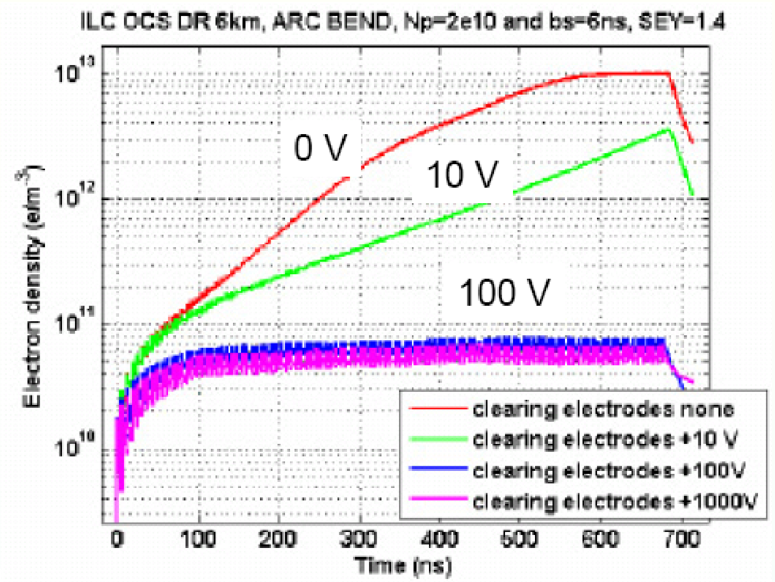
ILC Layout

500 GeV machine



DR Challenges





Electron cloud: suppression with clearing electrodes?

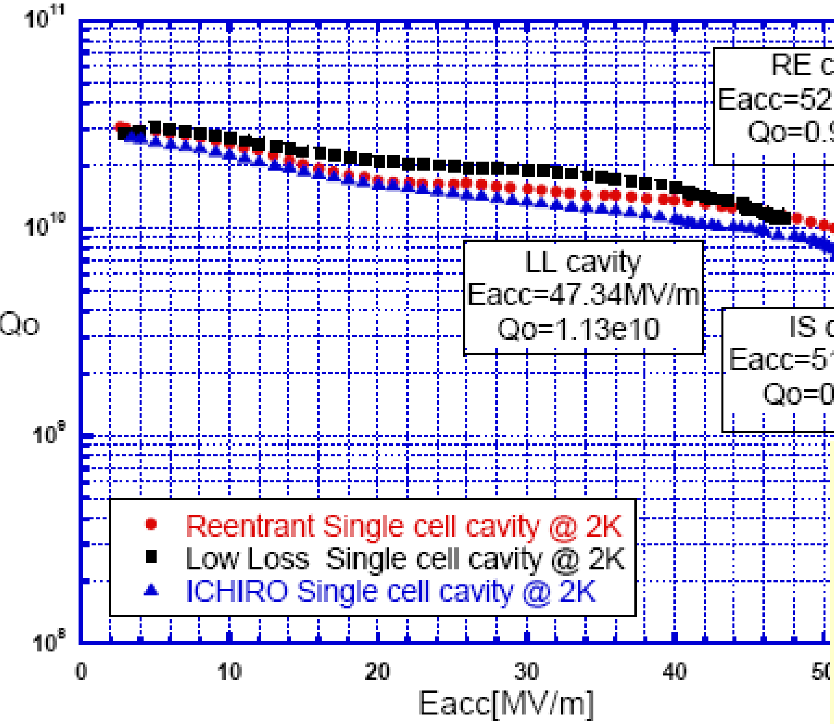
- Fast ion effects in electron DR:

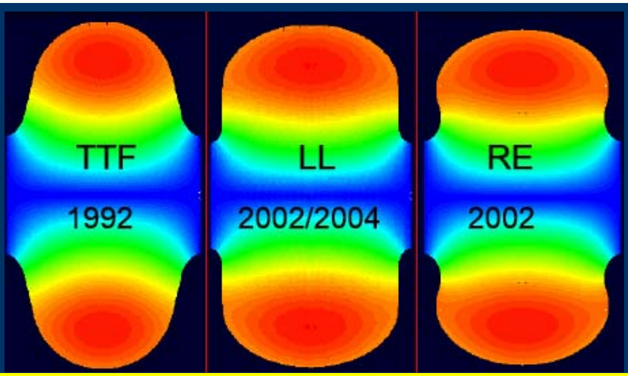
  feedback, vacuum design (1nTorr), train gaps?
- Long-range wake fields can drive multi-bunch instabilities,
- Short-range wake fields can drive single-bunch instabilities
- Requires: Fast kicker: 5ns rise time, 30 ns fall time…

  (one train of 2625×369ns →290 km !)

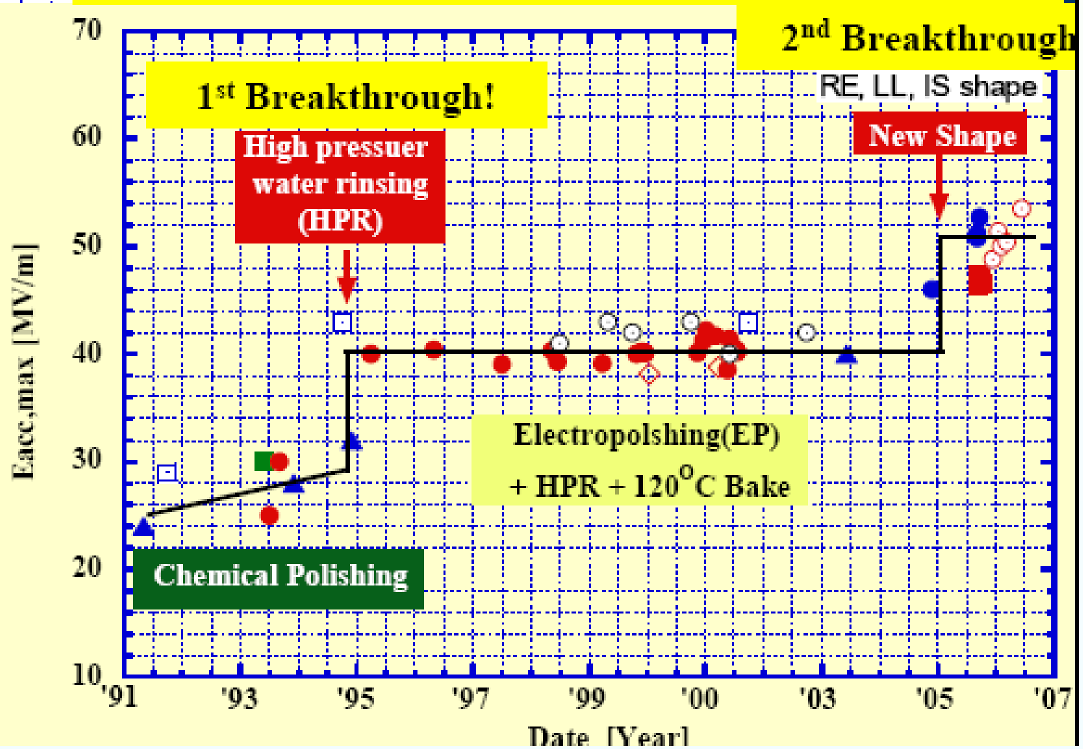
“The DR have more accelerator physics than the rest of the accelerator…”

Higher Gradients?





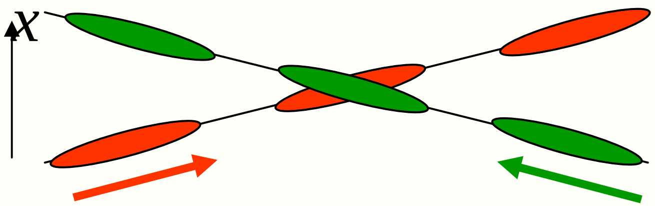
Break-through by new-shapes



RE, LL and ICHIRO Single-cell (IS) achieved 45MV/m

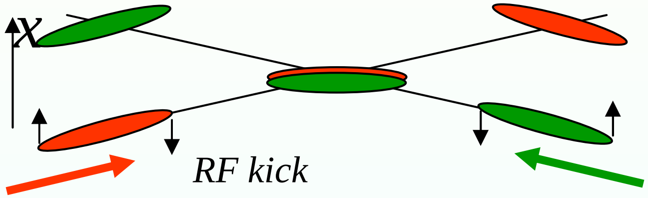
saeki

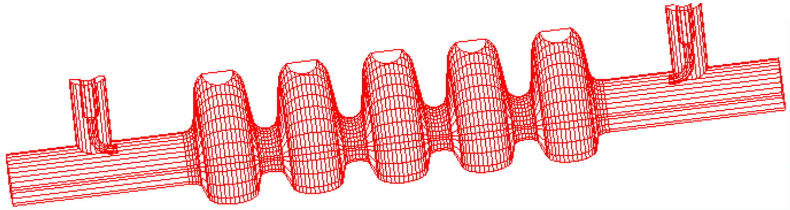
Crab crossing



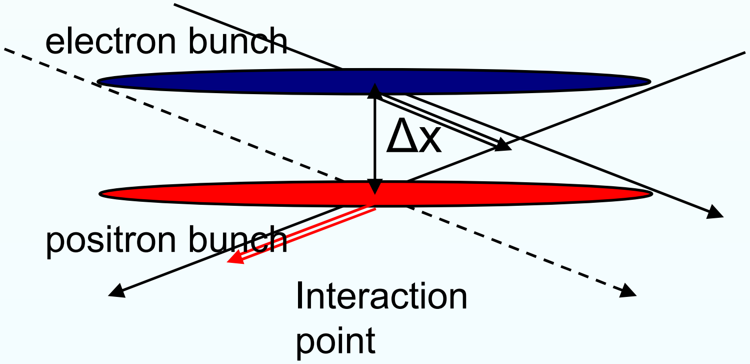
$$\begin{aligned}\sigma_{x,projected} &\approx \sqrt{\sigma_x^2+\phi_c^2\sigma_z^2}\\ &\approx \phi_c\sigma_z\\ &= 20\text{mr}\times 100\mu\text{m}\approx 2\mu\text{m}\end{aligned}$$

→ factor 10 reduction in Lumi





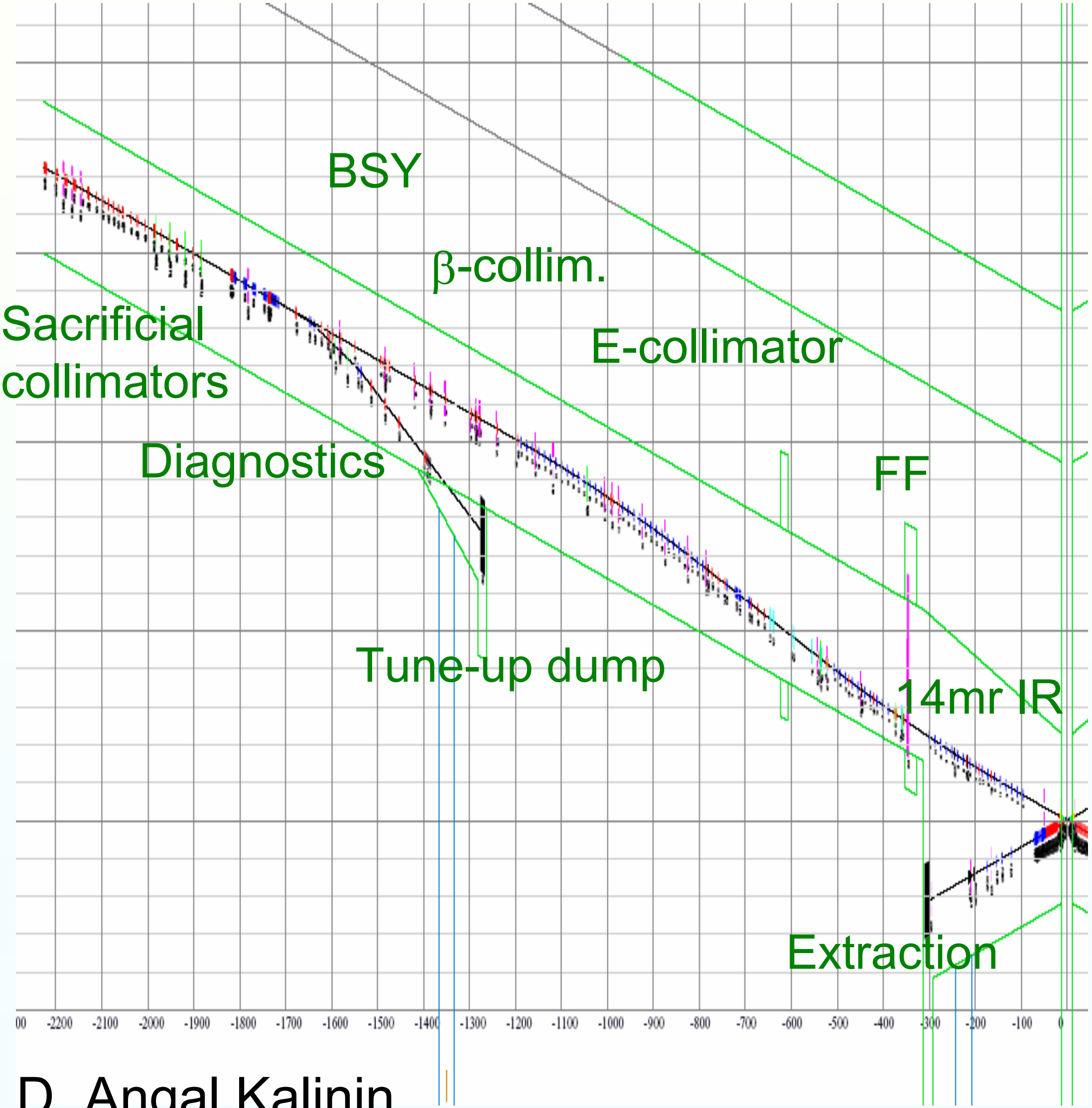
need one or two multi-cell cavities ~15m from IP

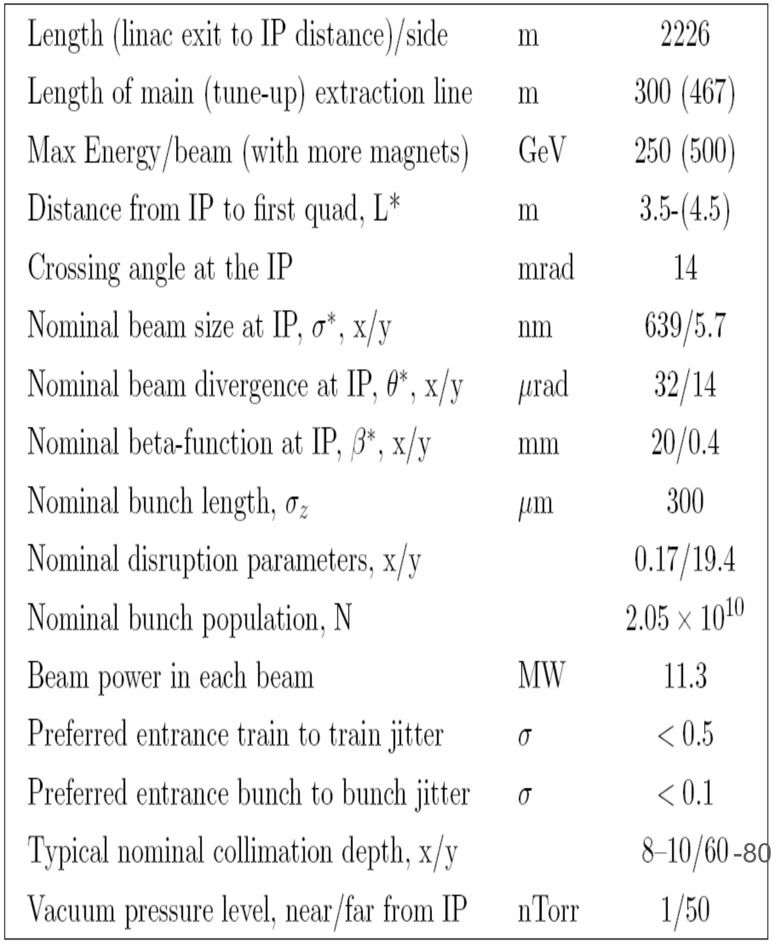


Burt et al.

Crossing angle	Phase error (degrees)	
	1.3GHz	3.9GHz
2mrad	0.222	0.665
10mrad	0.044	0.133
20mrad	0.022	0.066

BDS : RDR configuration



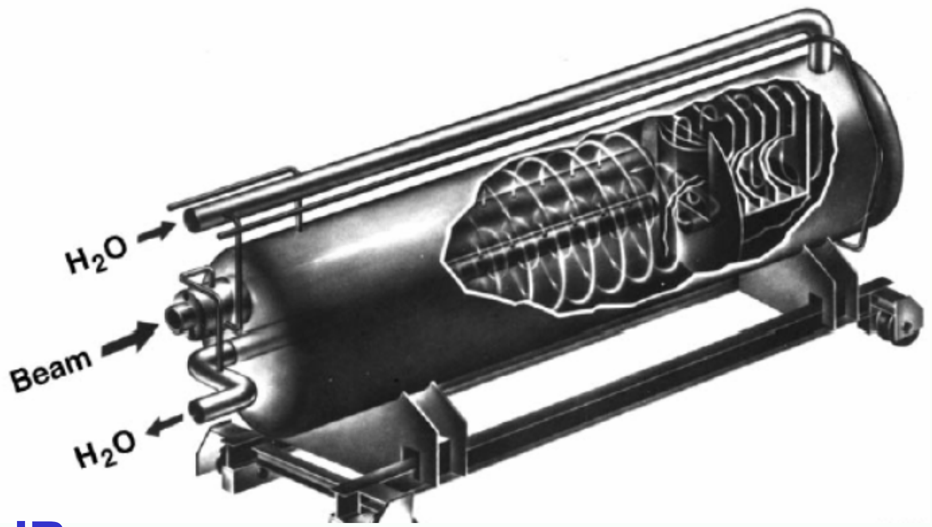


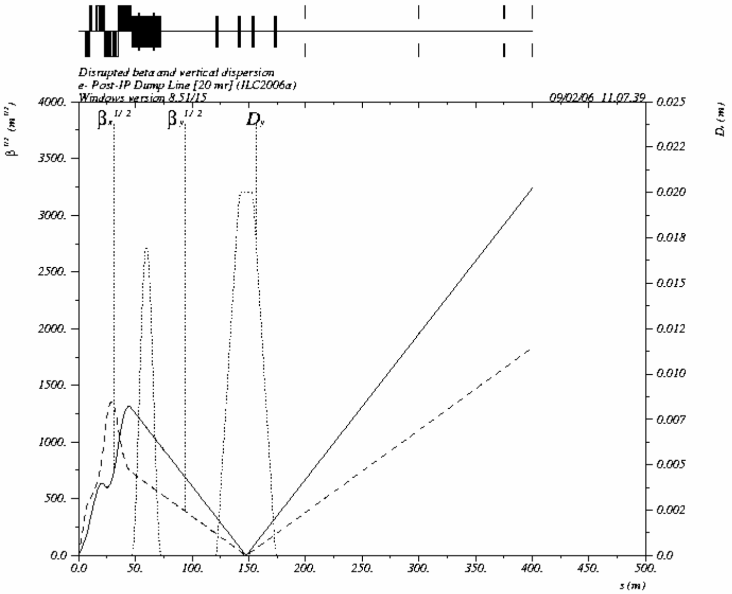
Length (linac exit to IP distance)/side	m	2226
Length of main (tune-up) extraction line	m	300 (467)
Max Energy/beam (with more magnets)	GeV	250 (500)
Distance from IP to first quad, L^*	m	3.5-(4.5)
Crossing angle at the IP	mrad	14
Nominal beam size at IP, σ^*, x/y	nm	639/5.7
Nominal beam divergence at IP, θ^*, x/y	μrad	32/14
Nominal beta-function at IP, β^*, x/y	mm	20/0.4
Nominal bunch length, σ_z	μm	300
Nominal disruption parameters, x/y		0.17/19.4
Nominal bunch population, N		2.05×10^{10}
Beam power in each beam	MW	11.3
Preferred entrance train to train jitter	σ	< 0.5
Preferred entrance bunch to bunch jitter	σ	< 0.1
Typical nominal collimation depth, x/y		8–10/60 -80
Vacuum pressure level, near/far from IP	nTorr	1/50

D. Angal Kalinin

Beam dump for 18MW beam

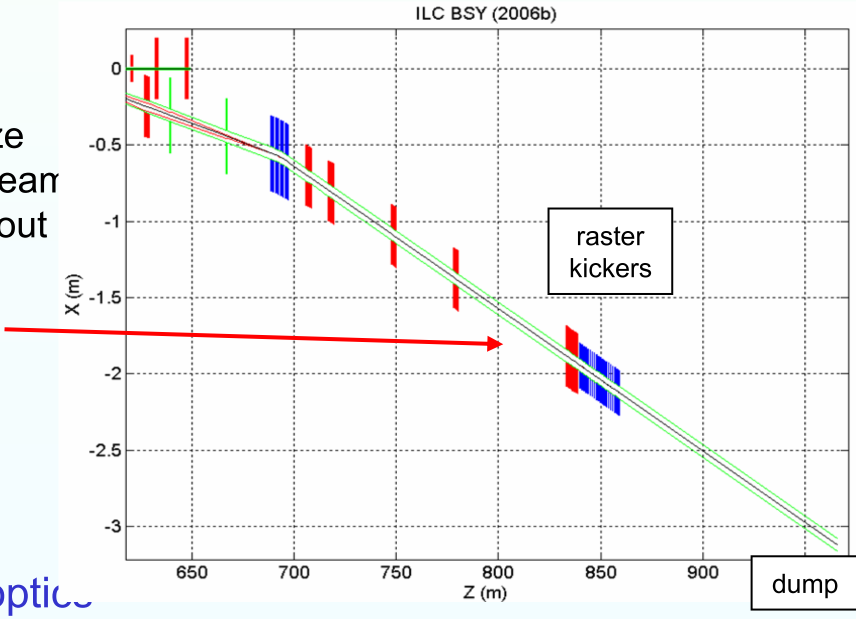
- Water vortex
- Window, 1mm thin, ~30cm diameter hemisphere
- Raster beam with dipole coils to avoid water boiling
- Deal with H, O, catalytic recombination
- Gas dump also being studied
- 3MW beamstrahlung dumps near IR





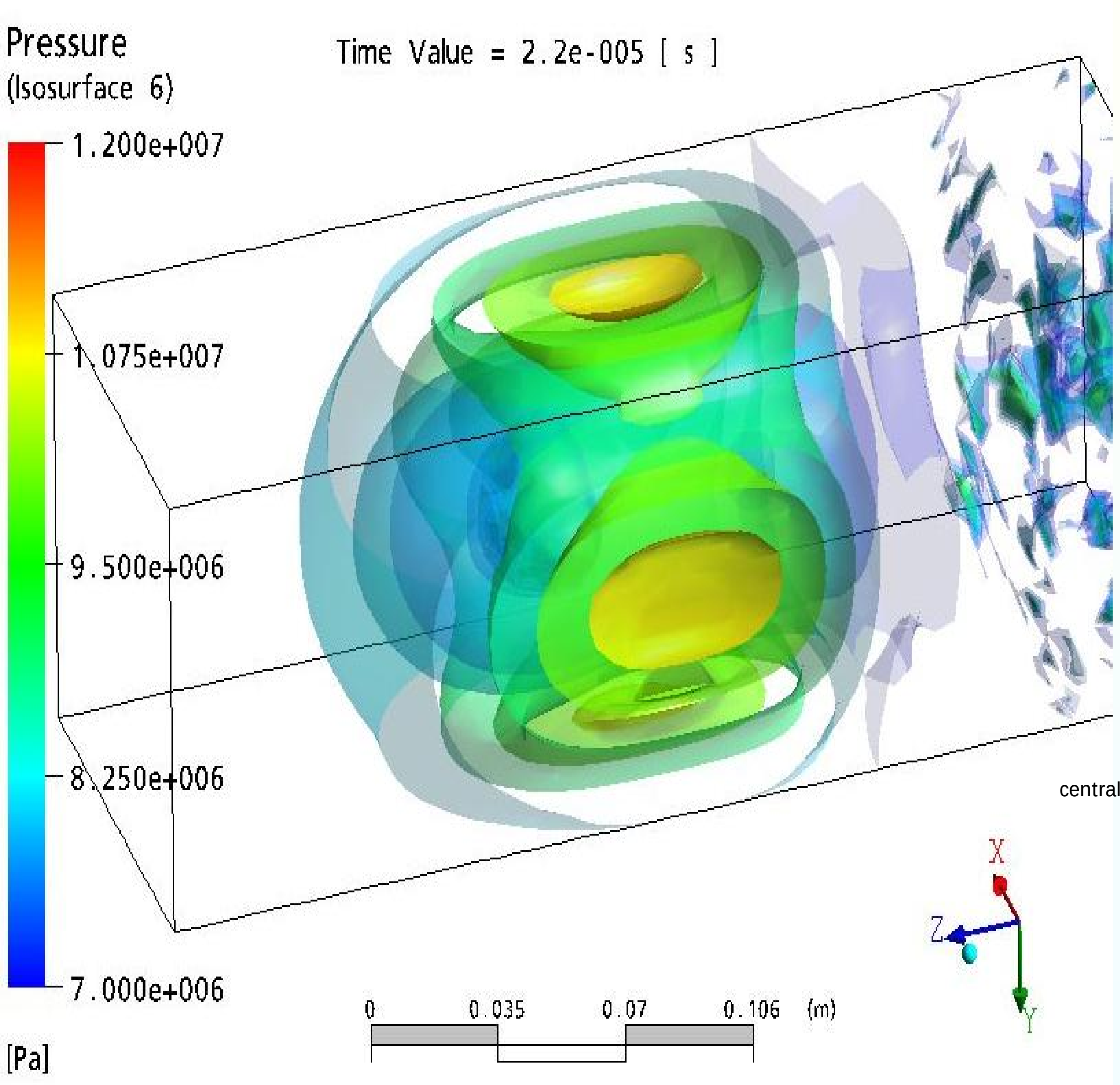
undisrupted or disrupted beam size does not destroy beam dump window without rastering.

Rastering to avoid boiling of water



20mr extraction optic

Beam Dump Pressure Wave Predictions



centralheatsource070125.mpg

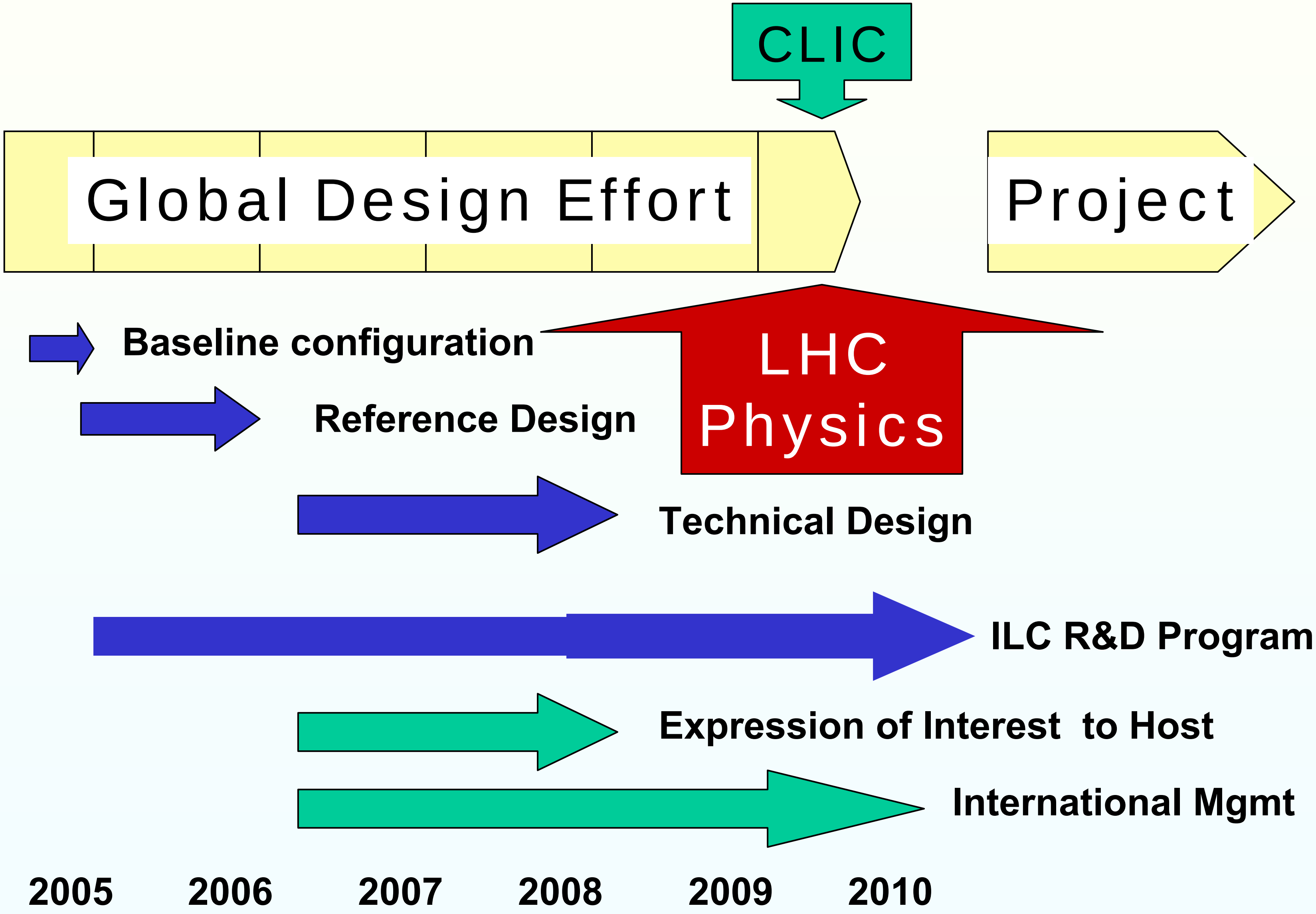
T. Davenne et al.

Final Focus

	SLC	FFTB	ATF2	ILC
E_{beam} (GeV)	45.6	46.6	1.3	250
σ_E/E (%)	0.25	0.25	0.1	0.1
N_{e-} ($\times 10^{10}$)	4.2	1	1-2	2
σ_y (nm)	800	60	37	5.7
$\gamma\varepsilon_y$ (m-rad)	1×10^{-5}	3×10^{-6}	3×10^{-8}	4×10^{-8}
Asp. ratio x/y	2.5	16	13	115
σ_z (mm)	~1	~1	~5	0.3

The ILC Plan and Schedule

(B.Barish/CERN/SPC 050913)



CLIC

Global Design Effort

Project

Baseline configuration

LHC Physics

Reference Design

Technical Design

ILC R&D Program

Expression of Interest to Host

International Mgmt

2005 2006 2007 2008 2009 2010

CLIC

Compact

LInea

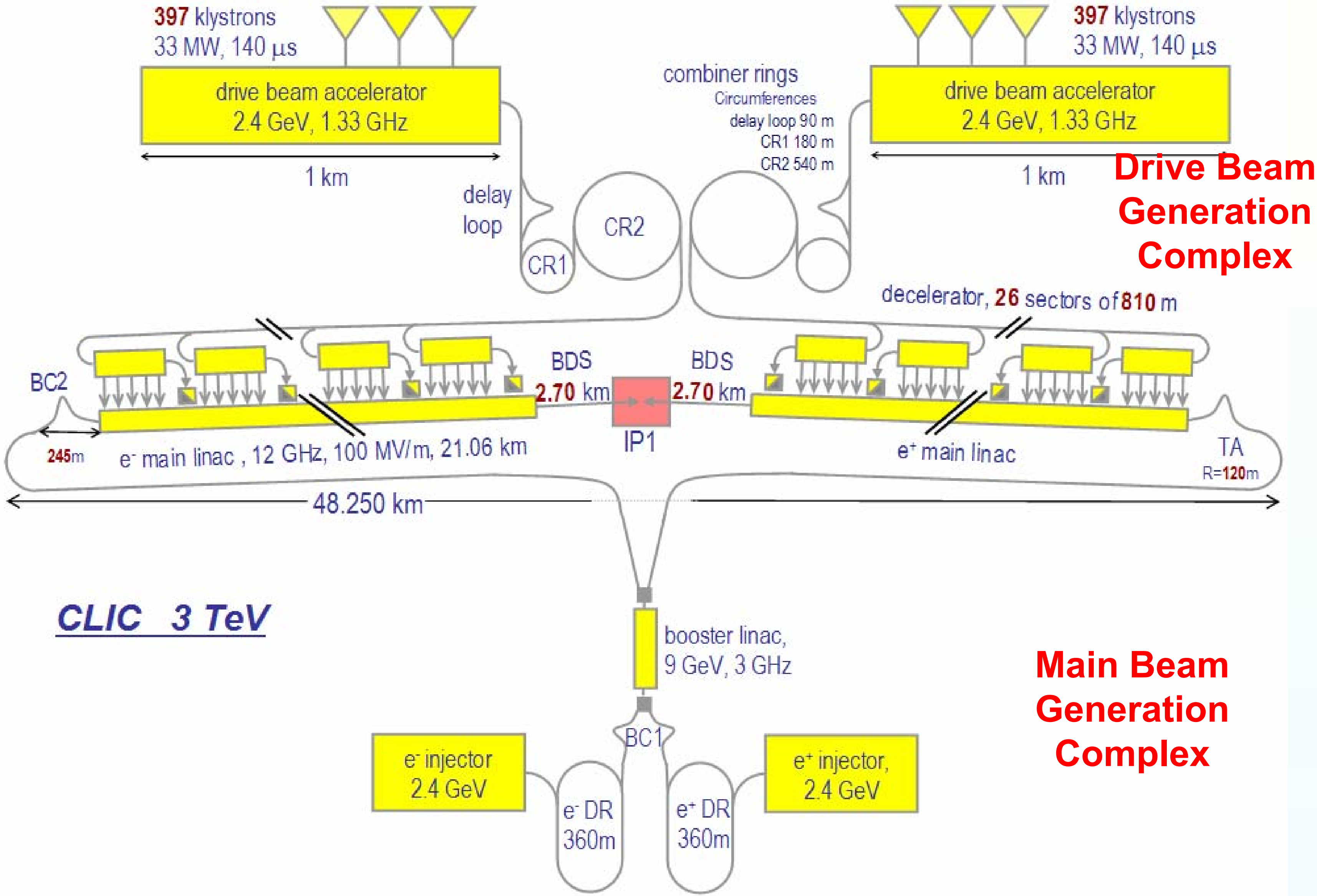
Collider

international linear collider

Reference Design Report

Executive Summary

CLIC – overall layout

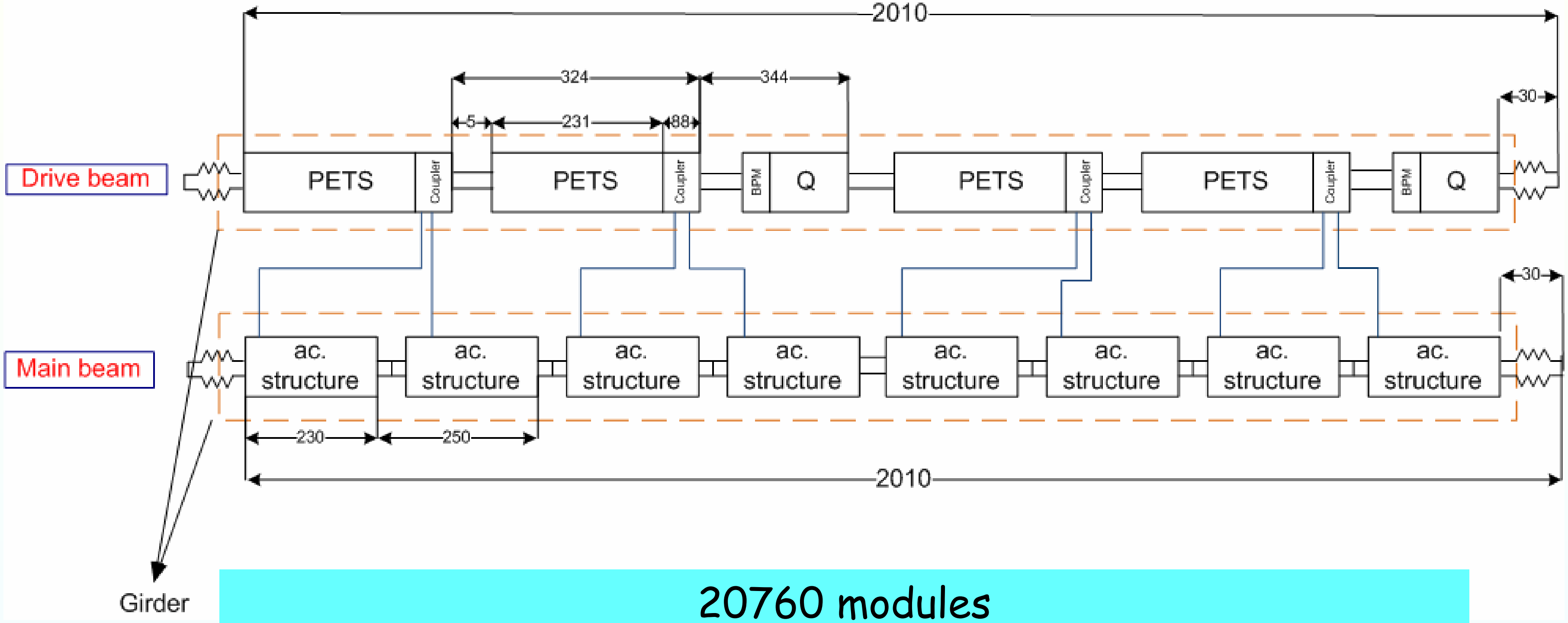


Drive Beam Generation Complex

CLIC 3 TeV

Main Beam Generation Complex

Two Beam Module



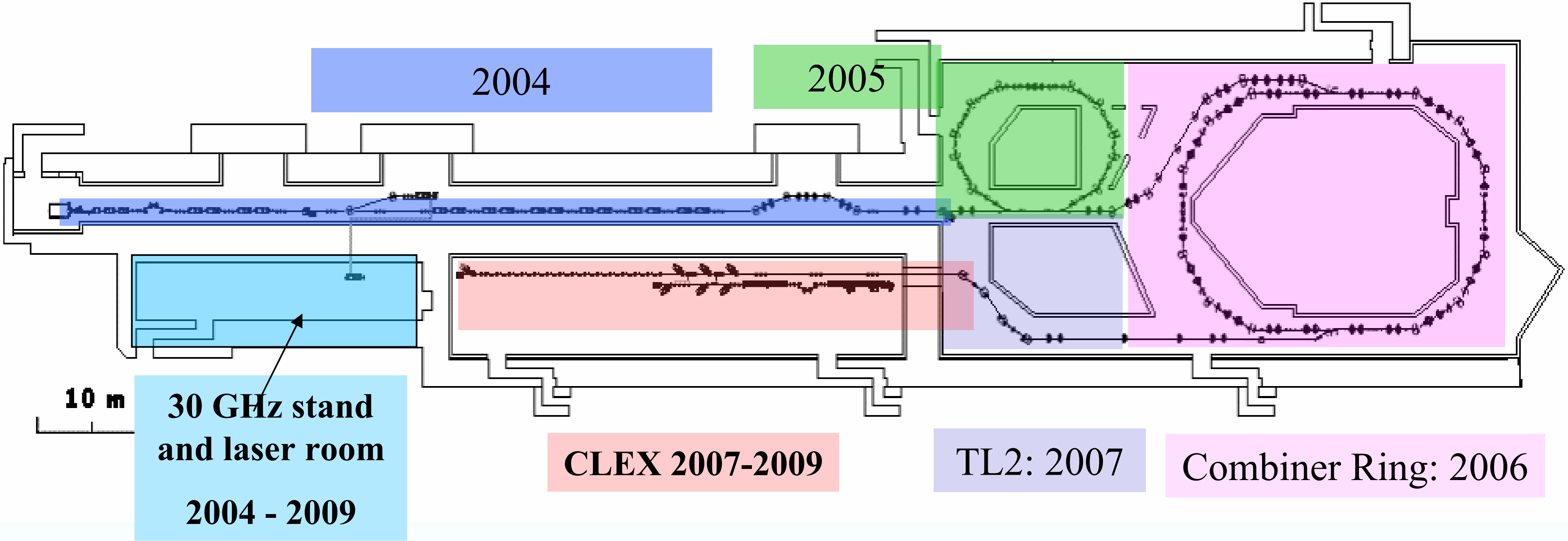
20760 modules

71460 power production structures PETS (drive beam)

143010 accelerating structures (main beam)

After Delahaye

CLIC Test Facility (CTF3)



Key issues

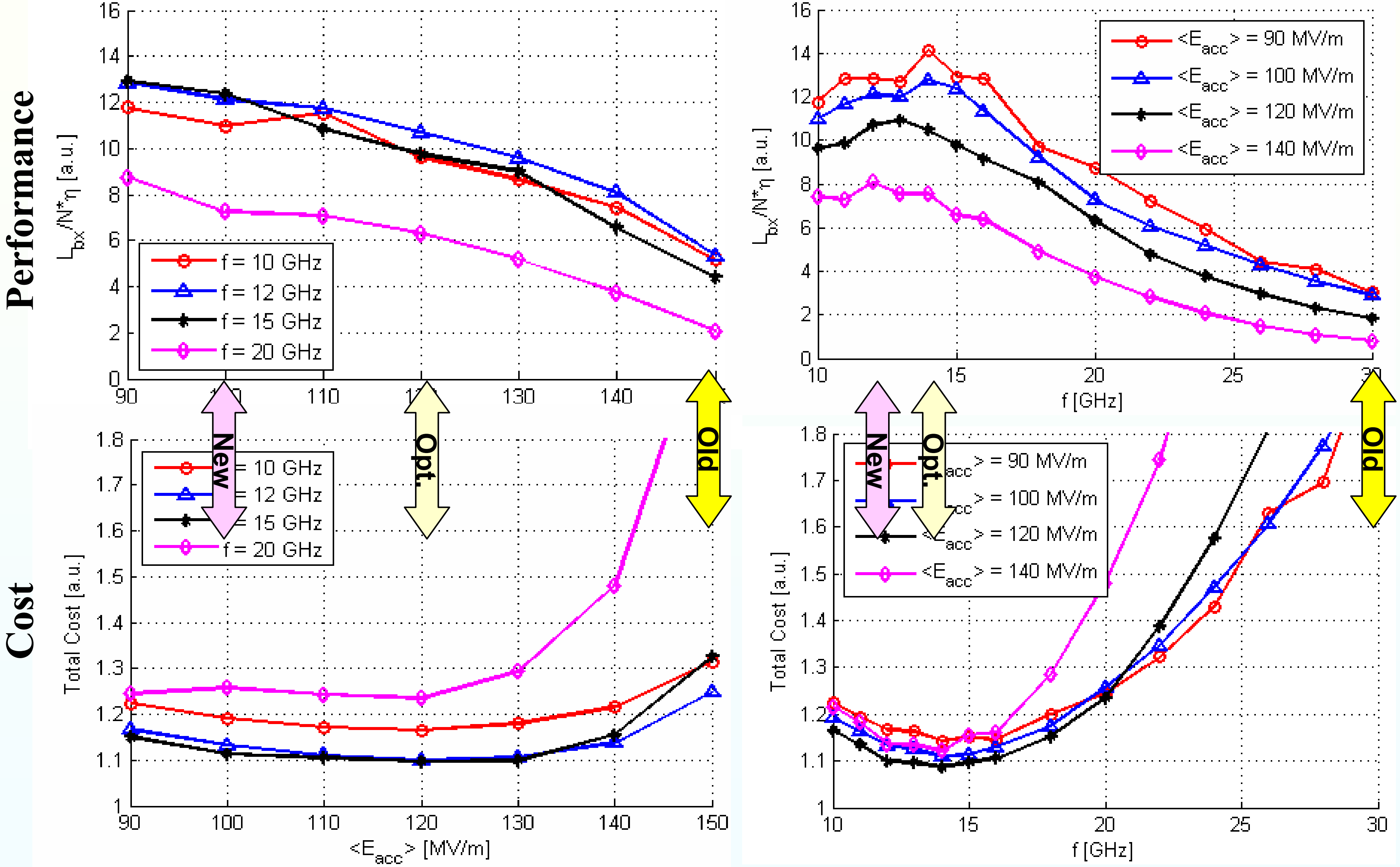
From 2005: Accelerating structures Development& Tests (R2.1)

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)

CLIC performance & cost optimisation

E_{cms} = 3 TeV $L_{(1\%)} = 2.0\ 10^{34}\ cm^{-2}s^{-1}$



After Delahaye

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**

After Delahaye

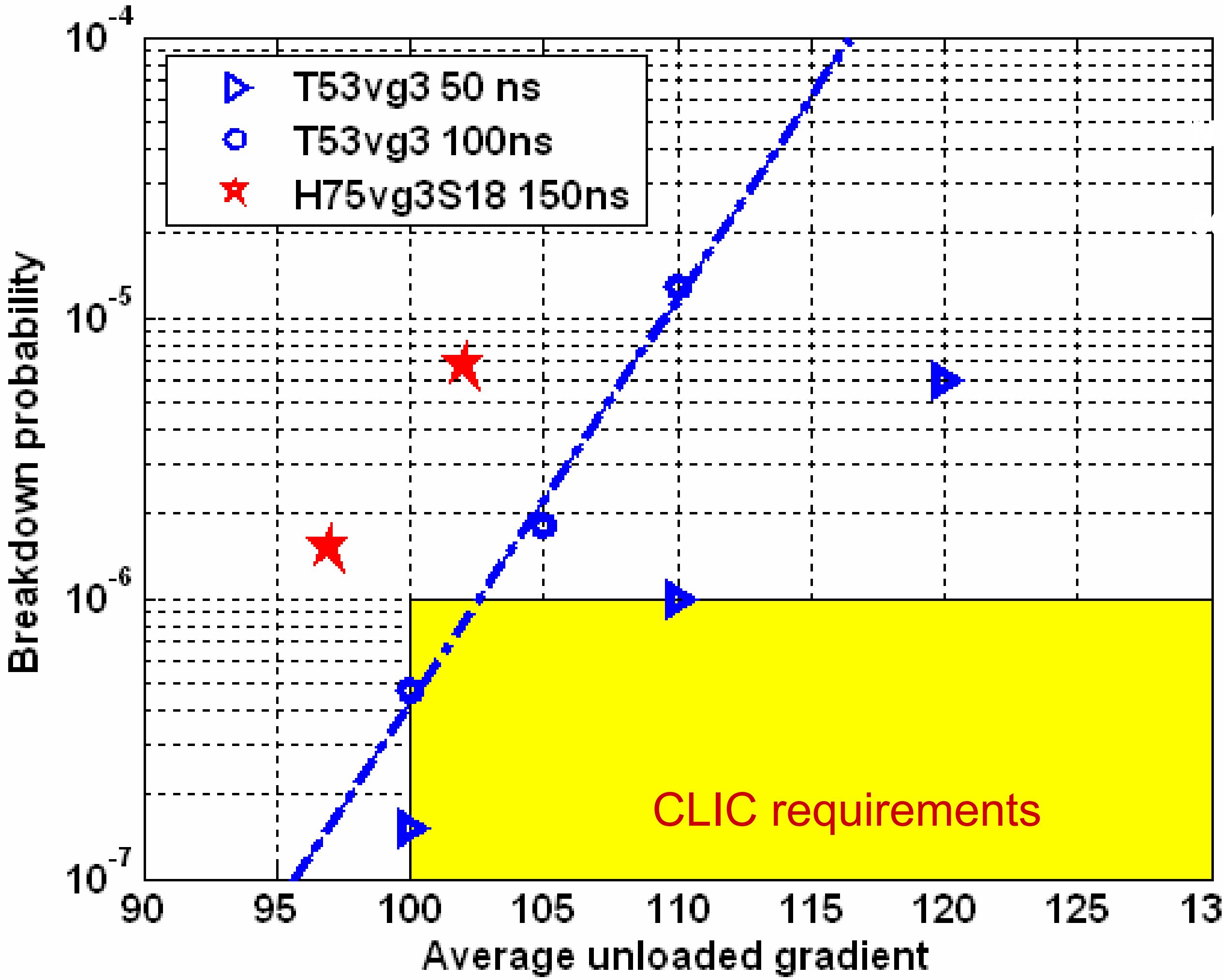
New CLIC main parameters

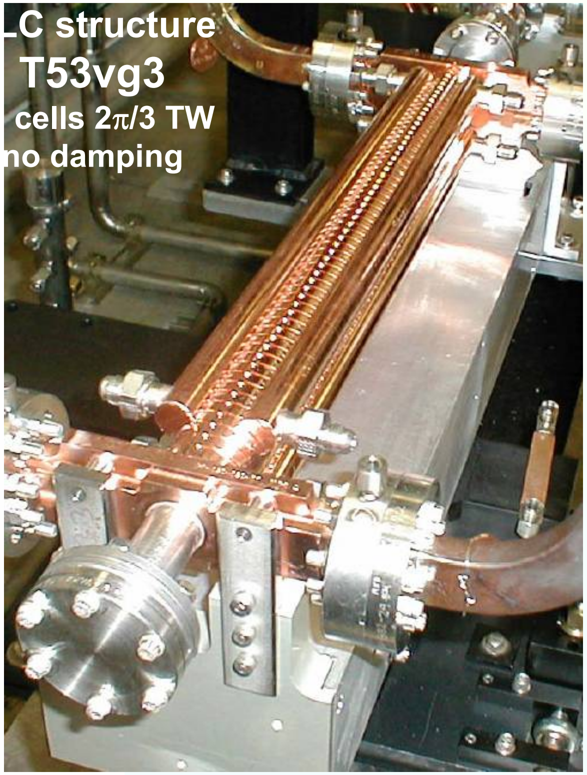
Center-of-mass energy	3 TeV
Peak Luminosity	$7 \cdot 10^{34}$ cm^{-2} s^{-1}
Peak luminosity (in 1% of energy)	$2 \cdot 10^{34}$ cm^{-2} s^{-1}
Repetition rate	50 Hz
Loaded accelerating gradient	100 MV/m
Main linac RF frequency	12 GHz
Overall two-linac length	41.7 km
Bunch charge	$4 \cdot 10^{9}$
Beam pulse length	200 ns
Average current in pulse	1 A
Hor./vert. normalized emittance	660 / 20 nm rad
Hor./vert. IP beam size bef. pinch	53 / ~1 nm
Total site length	48.25 km
Total power consumption	390 MW

Provisional values

After Delahaye

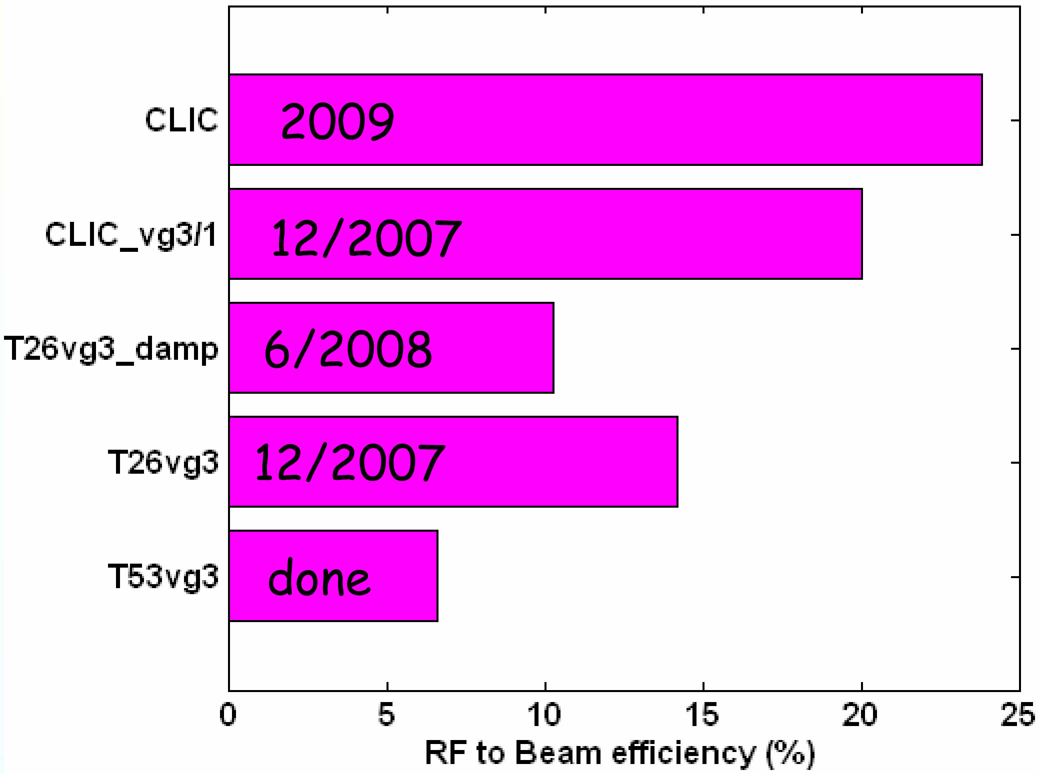
Recent High-Power test results @ SLAC (11.4 GHz)





LC structure
T53vg3
cells 2π/3 TW
no damping

RF to Beam Efficiency milestones



P = 65 MW; 297 ns ⇔ nb = 311

P = 70 MW; 295 ns ⇔ nb = 359

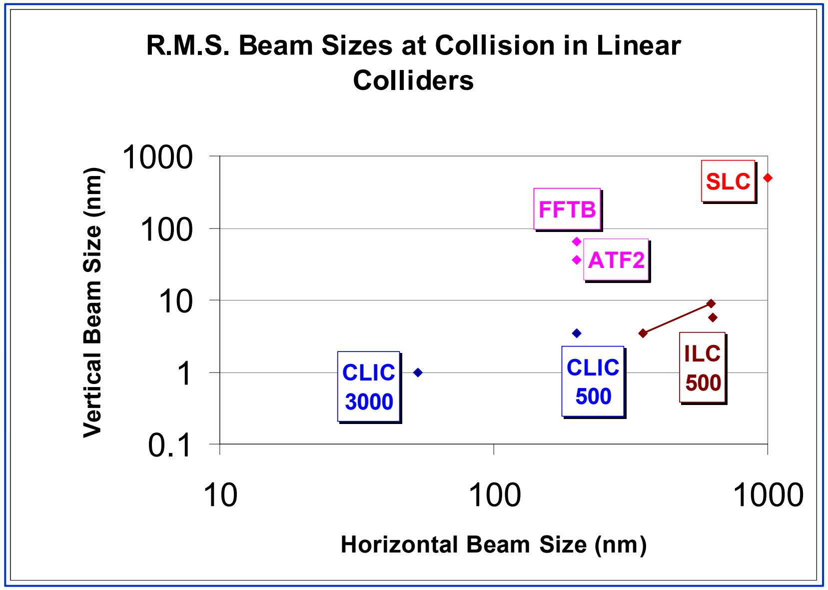
P = 111 MW; 102 ns ⇔ nb = 66

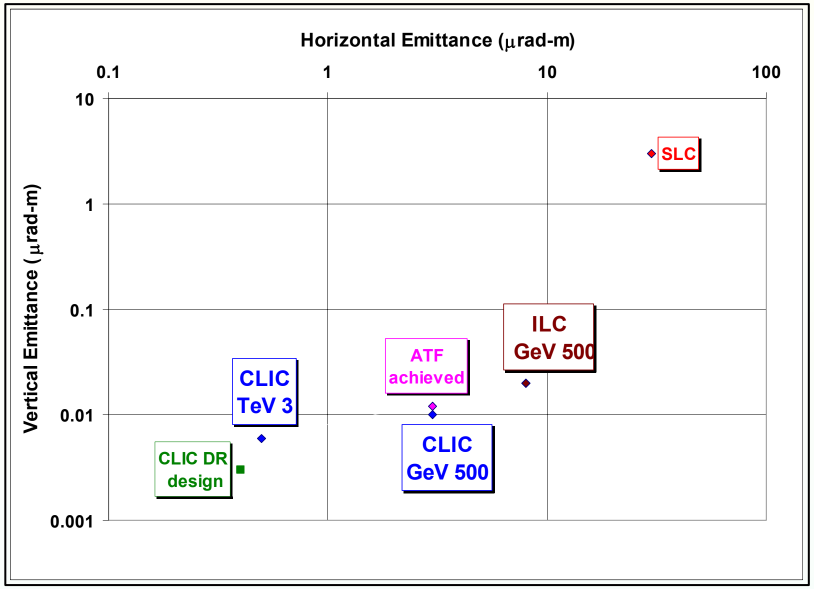
P = 102 MW; 113 ns ⇔ nb = 93

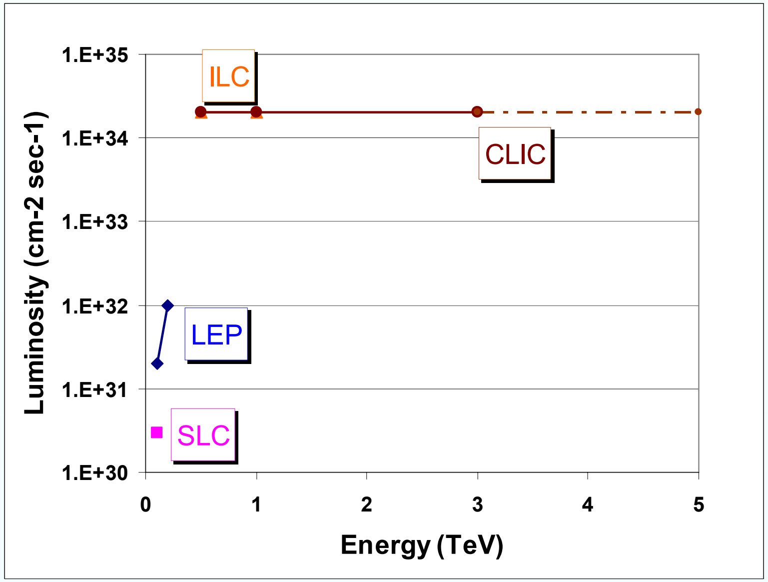
P = 134 MW; 104 ns ⇔ nb = 27

100 MV/m loaded, 10^{-6} break down rate, qb=$4*10^9$,
8 rf period bunch spacing, P*pl/C = 18 Wue

Performances of Lepton Colliders







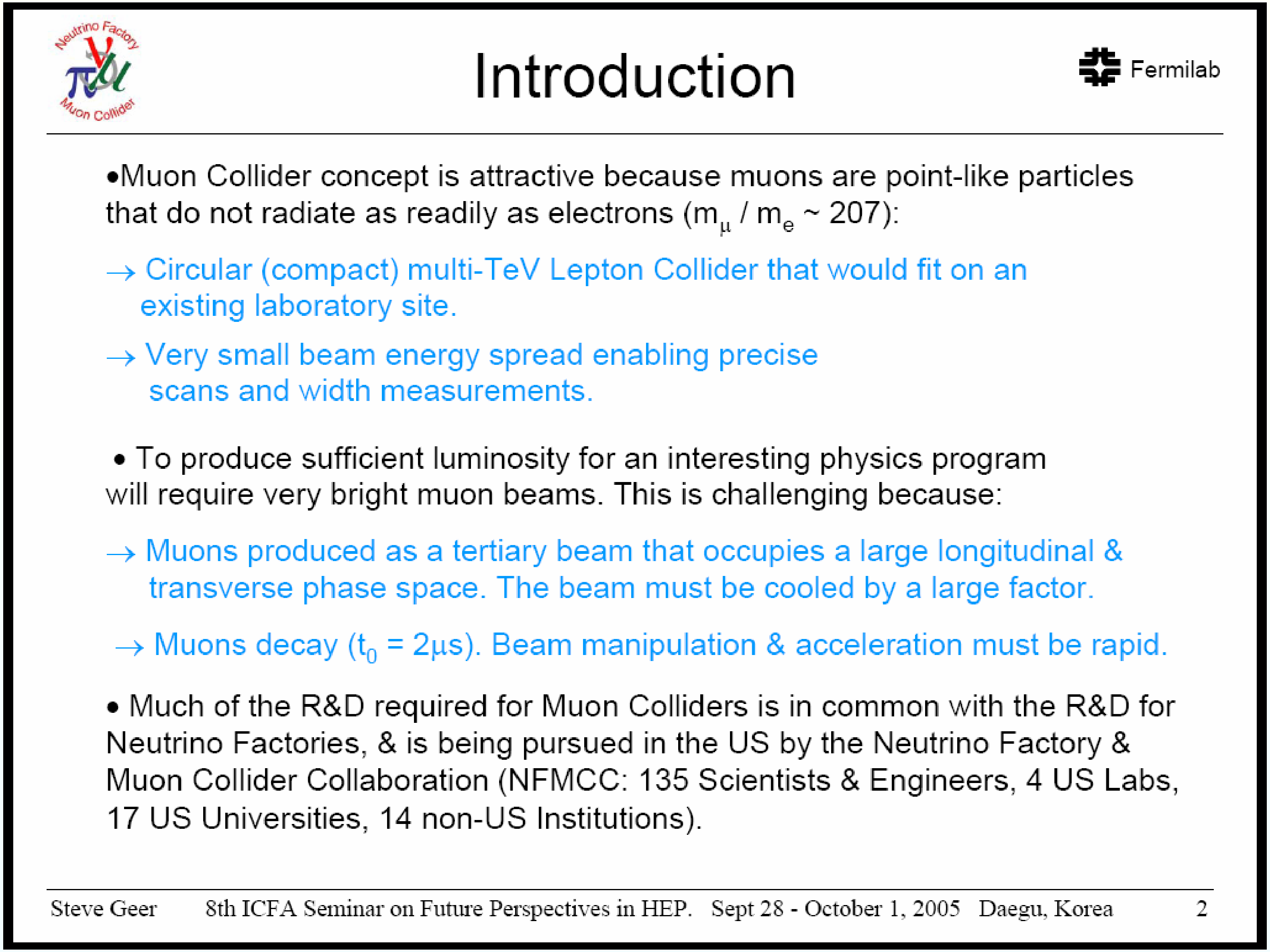
After Delahaye

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

(from Steve Geer)



Fermilab

Introduction

- Muon Collider concept is attractive because muons are point-like particles that do not radiate as readily as electrons ($m_\mu / m_e \sim 207$):

  → Circular (compact) multi-TeV Lepton Collider that would fit on an existing laboratory site.

  → Very small beam energy spread enabling precise scans and width measurements.

- To produce sufficient luminosity for an interesting physics program will require very bright muon beams. This is challenging because:

  → Muons produced as a tertiary beam that occupies a large longitudinal & transverse phase space. The beam must be cooled by a large factor.

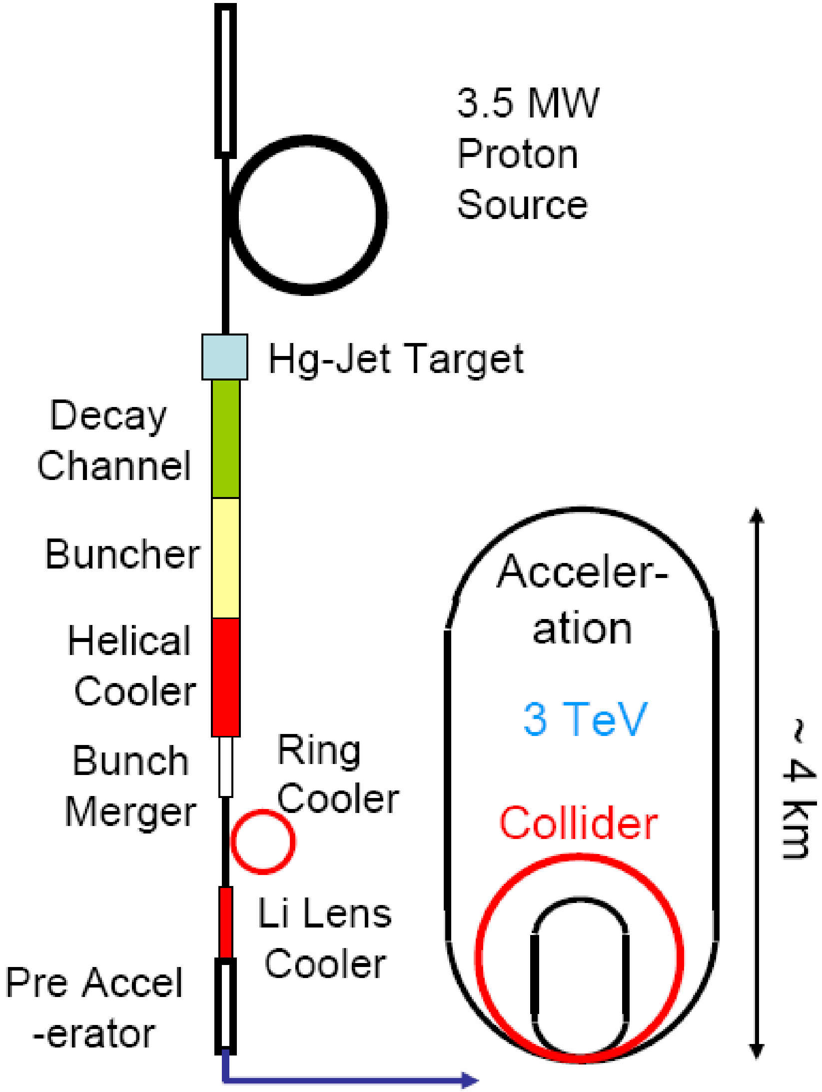
  → Muons decay ($t_0 = 2\mu s$). Beam manipulation & acceleration must be rapid.

- Much of the R&D required for Muon Colliders is in common with the R&D for Neutrino Factories, & is being pursued in the US by the Neutrino Factory & Muon Collider Collaboration (NFMCC: 135 Scientists & Engineers, 4 US Labs, 17 US Universities, 14 non-US Institutions).

Steve Geer 8th ICFA Seminar on Future Perspectives in HEP. Sept 28 - October 1, 2005 Daegu, Korea 2

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 → up to 1.5 TeV
- Storage Ring
  - store for ~1000 turns
  - One IP



Steve Geer

Parameters

Energy	0.1 TeV	3 TeV
Proton Srce Power	4 MW	3.5 MW
Rate	15 Hz	30 Hz
Muons / bunch	4×10^{12}	2×10^{12}
Bunches	1 × 1	2 × 2
Circumference	0.35 km	6 km
Effective turns	450	900
$\beta_\perp$	9.4 mm	3 mm
$\varepsilon_\perp$ (mm radians)	0.195	0.05
$\varepsilon_{//}$	5 mm	72 mm
$\Delta\nu$	0.022	0.044
$\Delta p/p$	0.01 %	0.16 %
Luminosity ($cm^{-2}\ s^{-1}$)	2.2×10^{34}	7×10^{34}

Requires 1×10^{21} μ^+ / year

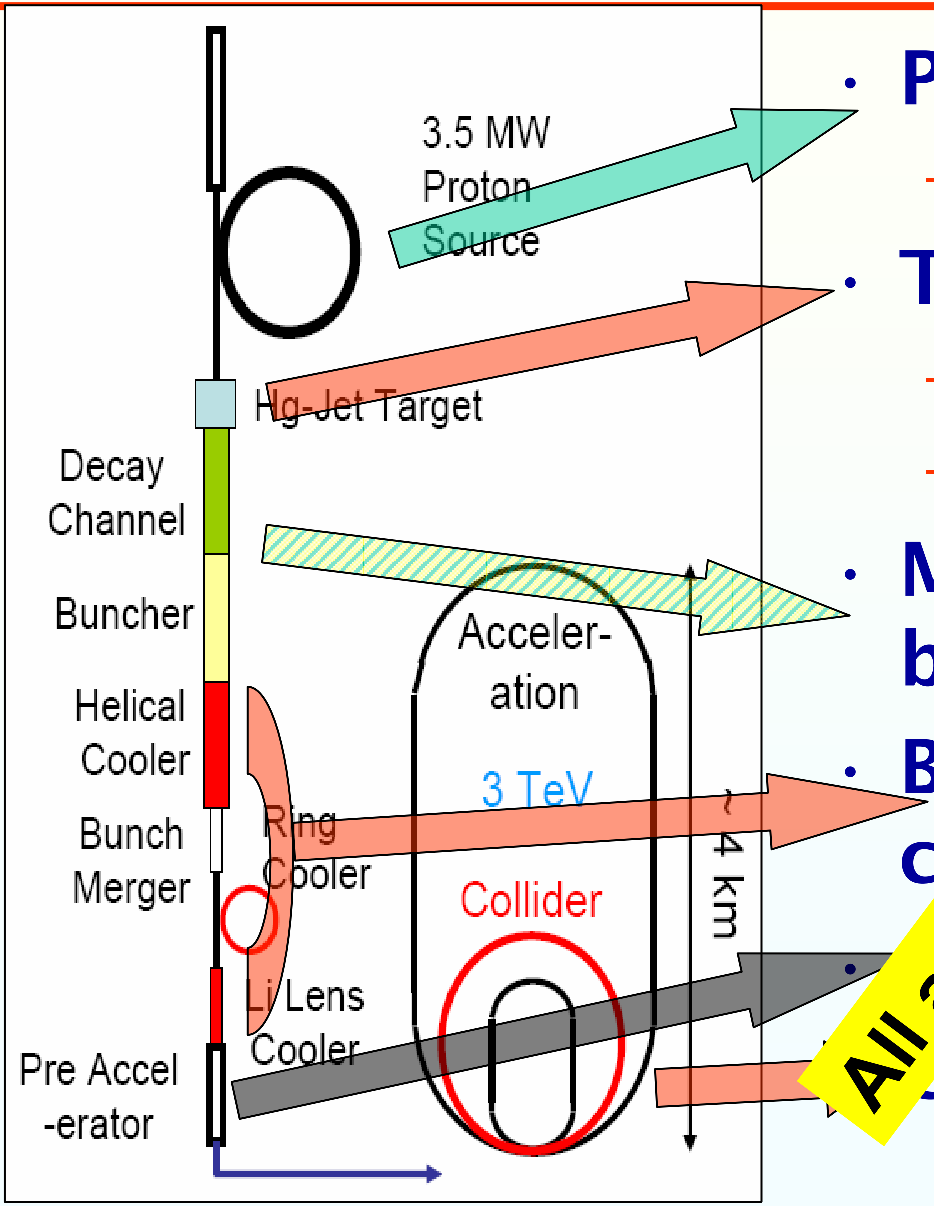
Similar to (a little more than) number of muons expected from Neutrino Factory front-end

Collider energy limited by "neutrino radiation" – high energy muon decays in straight sections produce a collimated beam of neutrinos that interact in the Earth to produce a radiation field at their exit point.

Lower emittance beams (more cooling) would enable use of fewer muons → higher energy colliders become plausible.

Steve Geer

Challenges for the Muon Collider

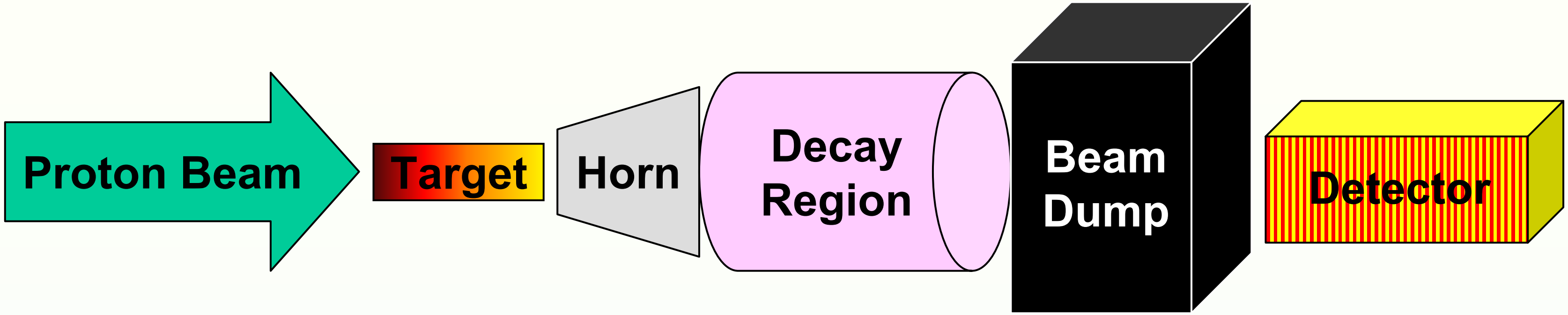


- **Proton Driver**
  - ~4MW, 1ns bun s
- **Target**
  - ~4MW, 1ns unches
  - “open” g etry
- **Muon C ection and bunch g**
- **Bun cooling & co ression**
- **celeration)**
- **Collider**

All are needed for a Neutrino Factory

Neutrino Factory

Conventional Neutrino Beams



- Main components
  - Proton Beam
    - Energy, Intensity, frequency
  - Target
  - Horn (focussing)
  - Decay Region
  - Beam Dump
  - Detector

Note

For any (class of) experiment

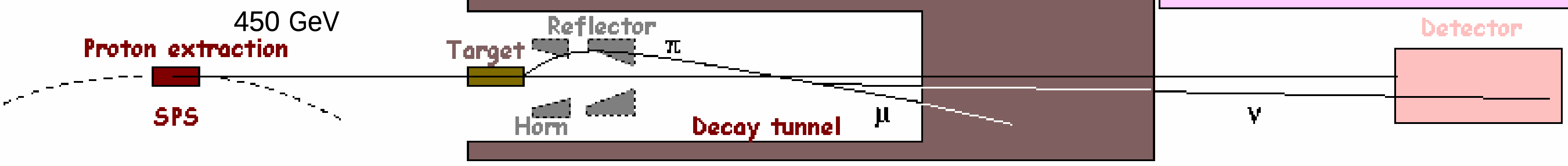
$N_{ev} \propto P \times M \quad (\times E_\nu)$

P: Beam Power
M: Target Mass
E_ν: Neutrino Energy

Example of a Neutrino Beam

West Area Neutrino Facility at CERN SPS

Why Change?



CHORUS, NOMAD

Wide Band Beam

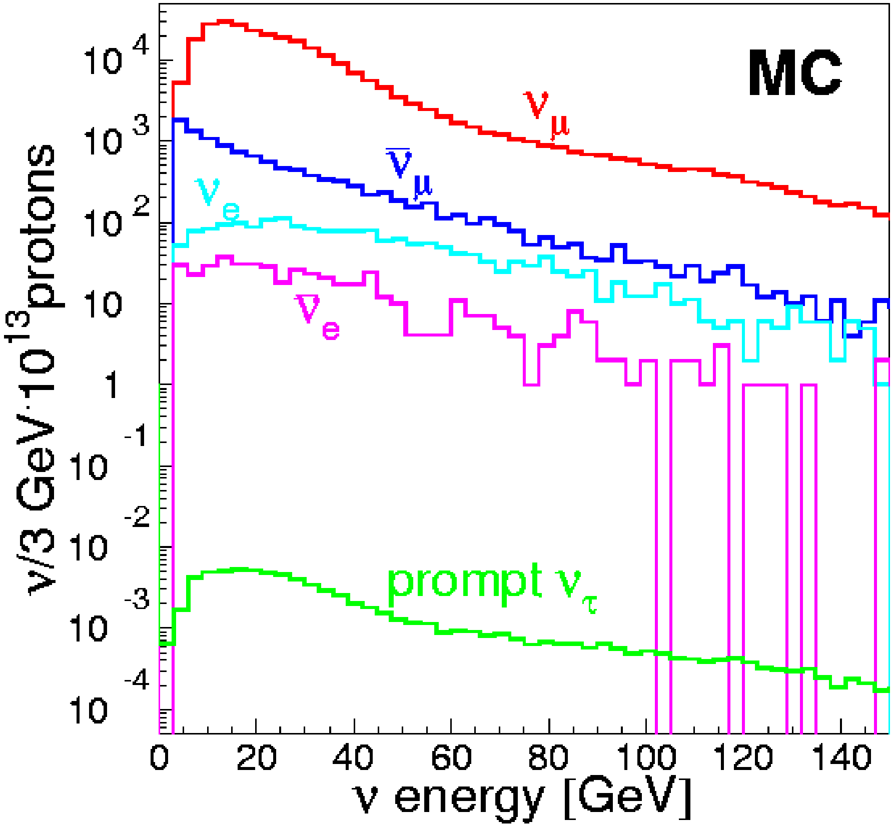
- 5.06×10^{19} POTs (1994-1997)
- $\langle E\nu_\mu \rangle \sim 27$ GeV
- $\langle L \rangle \sim 0.6$ km

  $\langle L \rangle / \langle E \rangle \sim 2 \times 10^{-2}$ km/GeV

  $\rightarrow \Delta m^2 > 1$ eV^2

- Prompt ν_τ : negligible

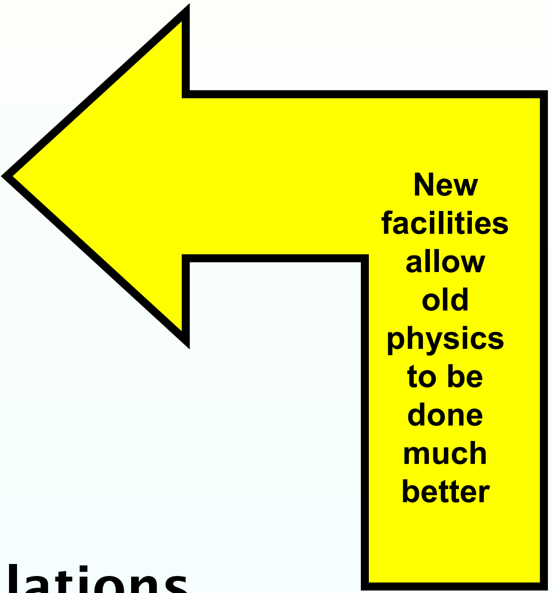
$\sim 10^{12}$ neutrinos



J Panman, Neutrino 2004

… because Neutrino Physics has changed!!!

- 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 facilities allow old physics to be done much better

Neutrino Mixing

Atmospheric **3G** **solar** **Majorana**

$$U_{MNS}=$$

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

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

$$\left|\Delta m^2_{32}\right| = 2.4(1^{+0.21}_{-0.26})\times10^{-3}\,\mathrm{eV}^2$$

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

$$\Delta m^2_{21} = 7.92(1\pm0.09)\times10^{-5}\,\mathrm{eV}^2$$

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

$$\sin^2\theta_{13} < 3.2\times10^{-2}$$

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

δ,α,β unknown

masses $<$ O(1eV)

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 Δm^2_{12} , Δm^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 θ_{12} , θ_{23} , θ_{13}

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

2 Majorana phases α,β

Measuring the Parameters

$$P\left(\nu_\mu \Rightarrow \nu_e\right) = 4c_{13}^2 s_{12}^2\left(c_{12}^2 c_{23}^2\right)\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

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

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

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

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

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

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

$a = 2\sqrt{2}\, G_F n_e E_\nu = 7.6\ 10^{-5}\ \rho\ E$

Where is the electron density ; ρ is the density (g/cm³) ;   E is the neutrino energy (GeV)

$c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$

(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)**

The need for long baselines

$$P_{Oscillation} \approx \left(\text{Sines \& Cosines}\right)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

$$\Rightarrow \tfrac{1}{4}\lambda = \frac{2\pi E}{\Delta m_{ij}^2}$$

$$\approx \frac{0.8E}{\Delta m_{ij}^2} \qquad [E \text{ in GeV}; \Delta m_{ij}^2 \text{ in eV}^2; L \text{ in km}]$$

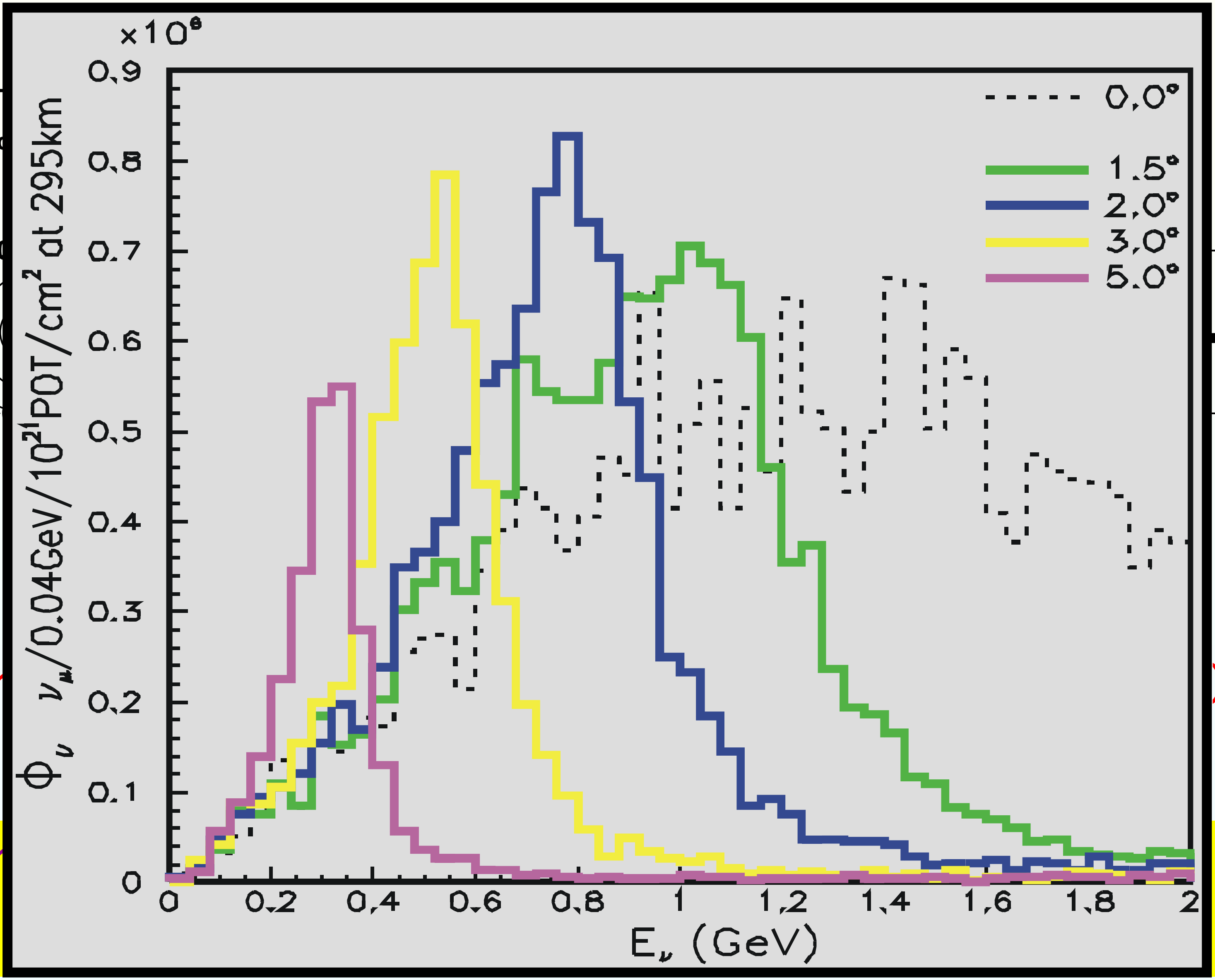
$$\tfrac{1}{4}\lambda_{12} \approx 11\times 10^3\, E \text{ km}$$

$$\tfrac{1}{4}\lambda_{23} \approx 0.3\times 10^3\, E \text{ km}$$

Means more intense neutrino beams!

Well matched to the dimensions of the earth!

The "Off Axis" trick



- **Lor**)
  –
- **Lor**
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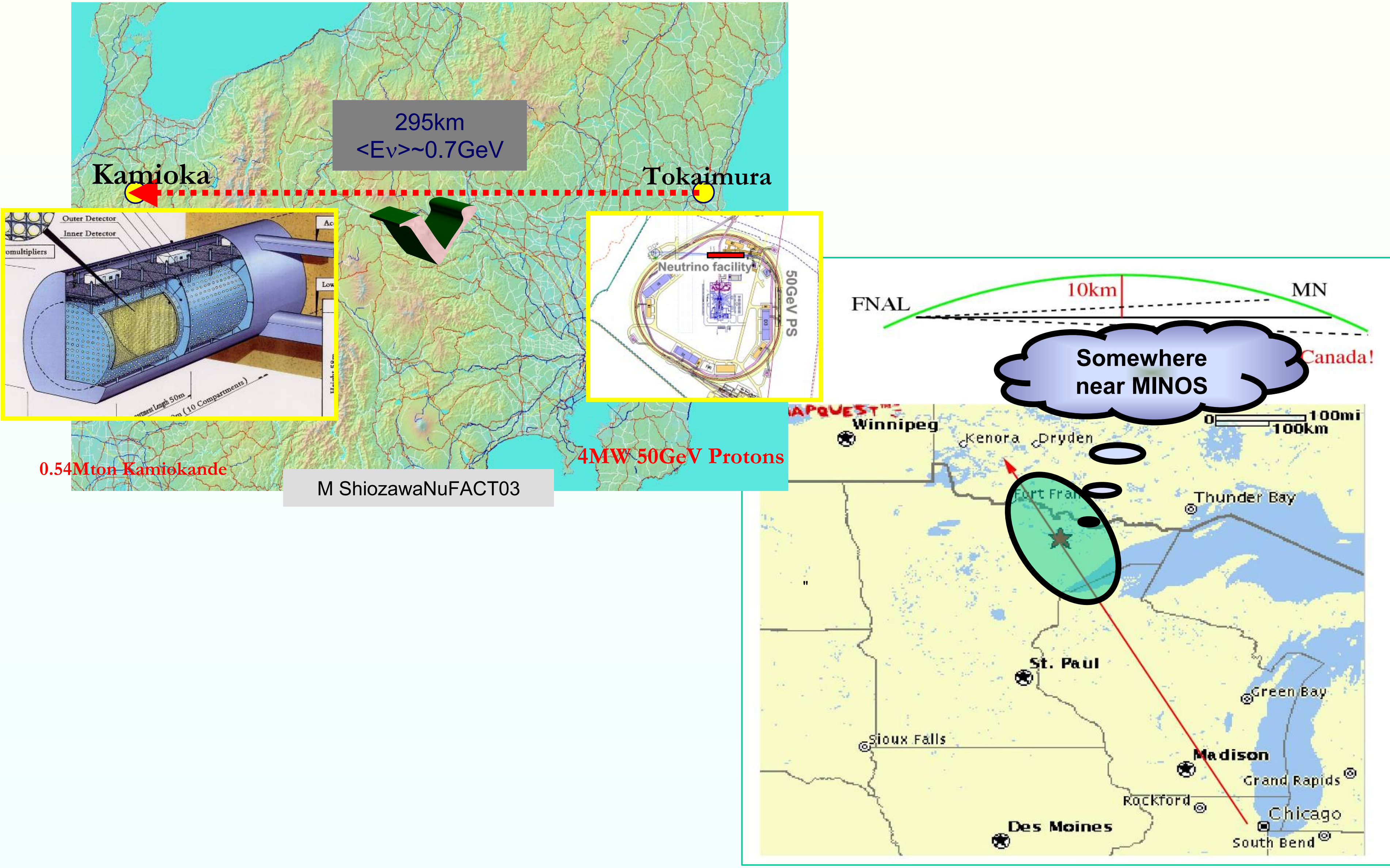
D. Beavis et al., "Long Baseline Neutrino Oscillation Experiment, E889, Physics Design Report," BNL-52459. (1995)

T2K & Nova?



295km
<Eν>~0.7GeV

0.54Mton Kamiokande

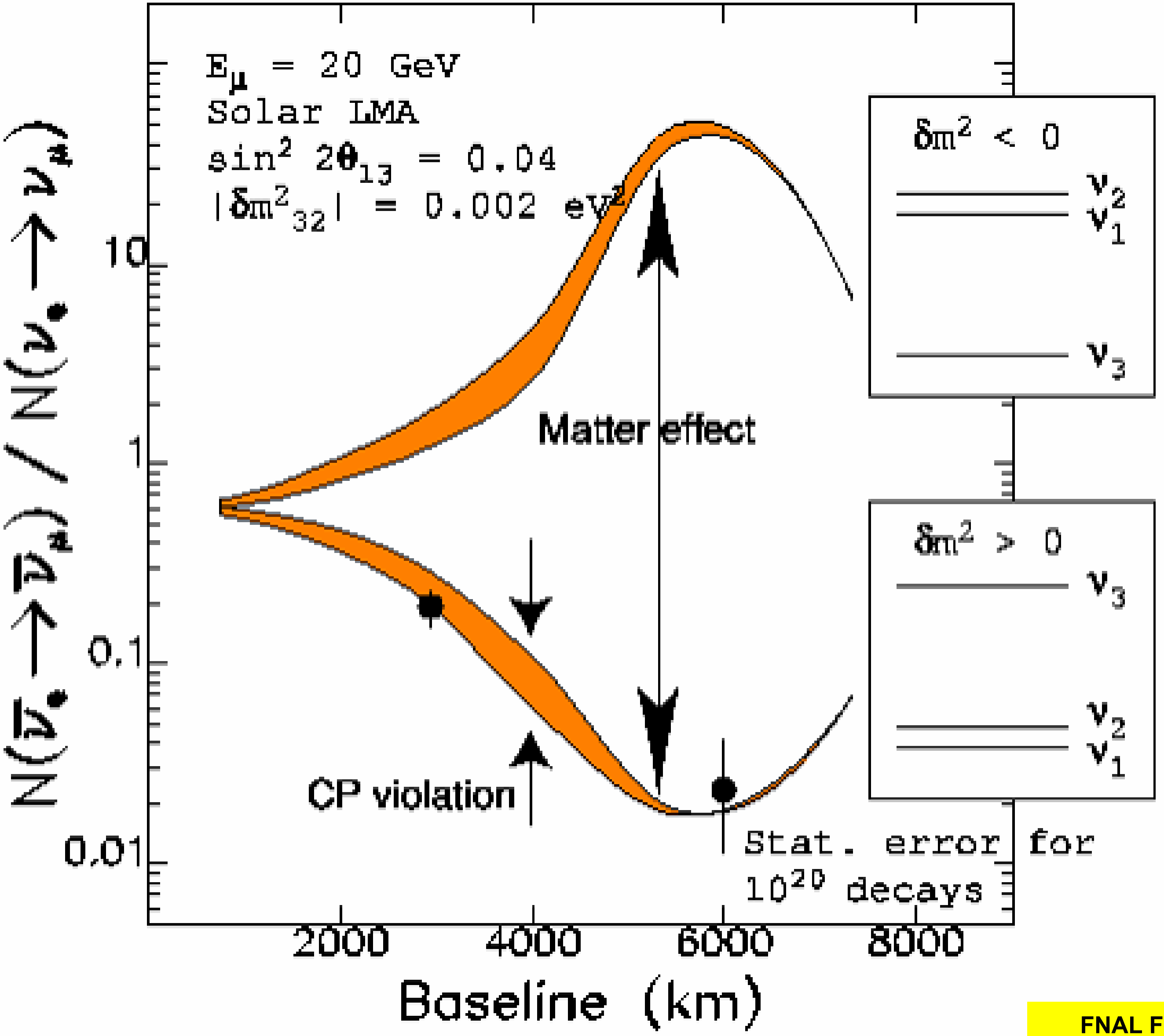
4MW 50GeV Protons

M ShiozawaNuFACT03

Somewhere near MINOS

Canada!

CP-violation



FNAL Feasibality Study 1

The Neutrino Factory

CPV: > 10^{20} muon decays

Conventional ν beams

- **π,μ & K decay**
- **Some flavour selectivity**
- **Contamination**

Reactor ν beams

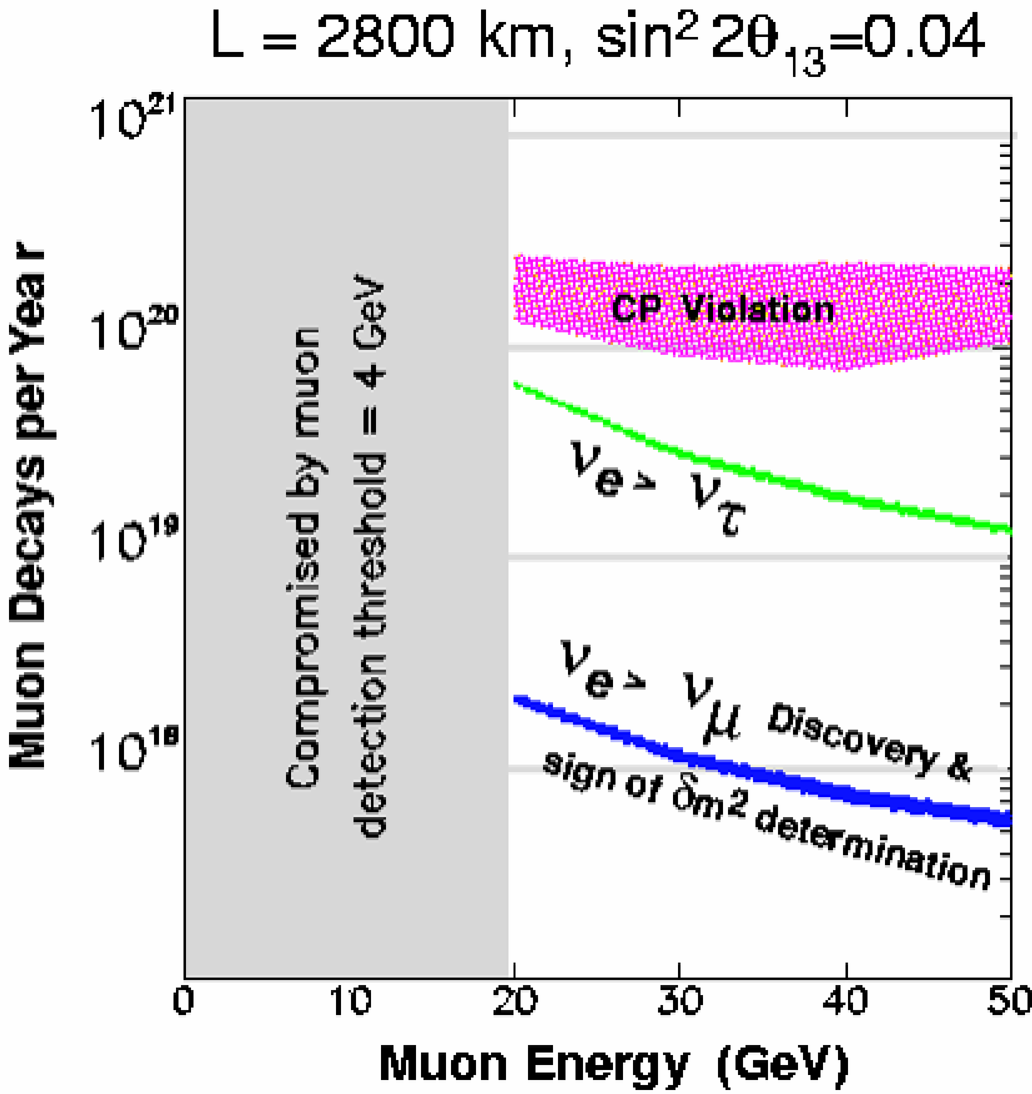
- **Pure ν_e**
- **Huge Fluxes**
- **Very low energy (MeV)**

Super Conventional ν beams

- **π, (& some μ) decay**
- **Flavour selectivity (ν_μ)**
- **Low Contamination at E<200MeV**

The Neutrino Factory

- **β beams**

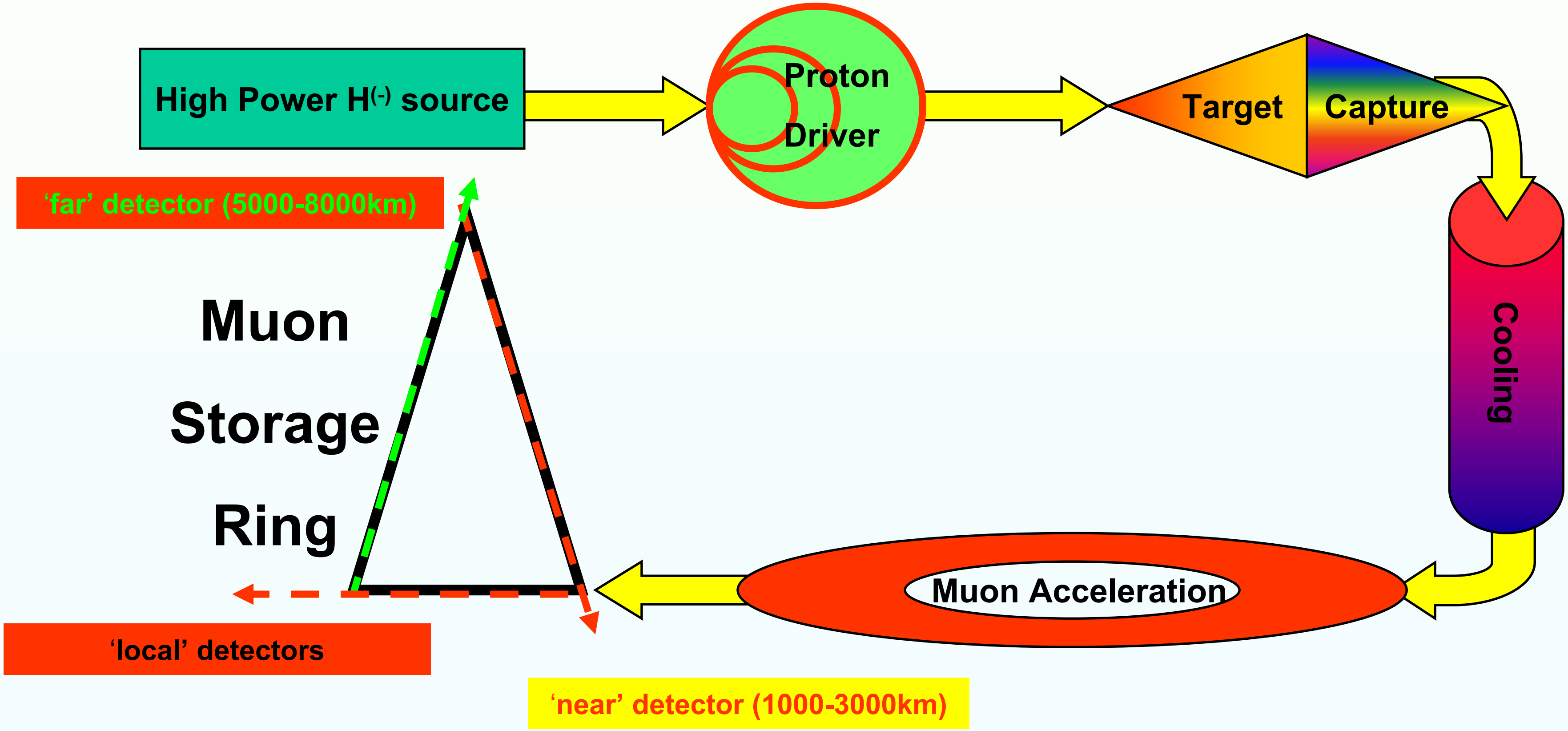


FNAL Feasibality Study 1

A Neutrino Factory is …

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

Principal Components



High Power $H^{(-)}$ source

Proton Driver

Target

Capture

Cooling

Muon Acceleration

Muon Storage Ring

‘far’ detector (5000-8000km)

‘local’ detectors

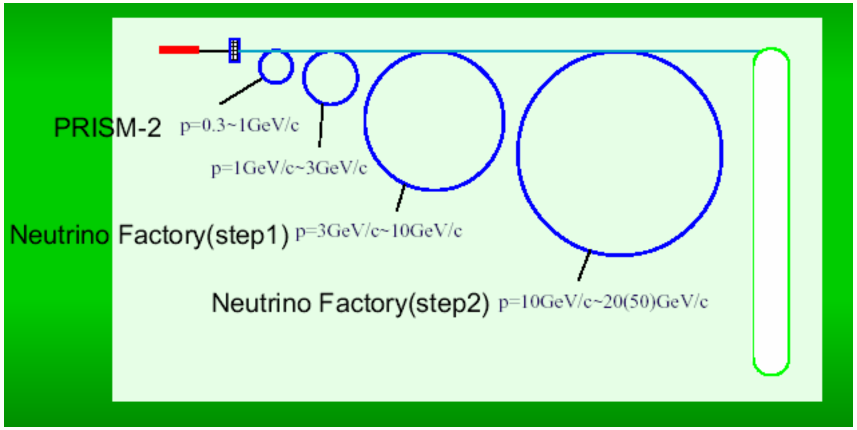
‘near’ detector (1000-3000km)

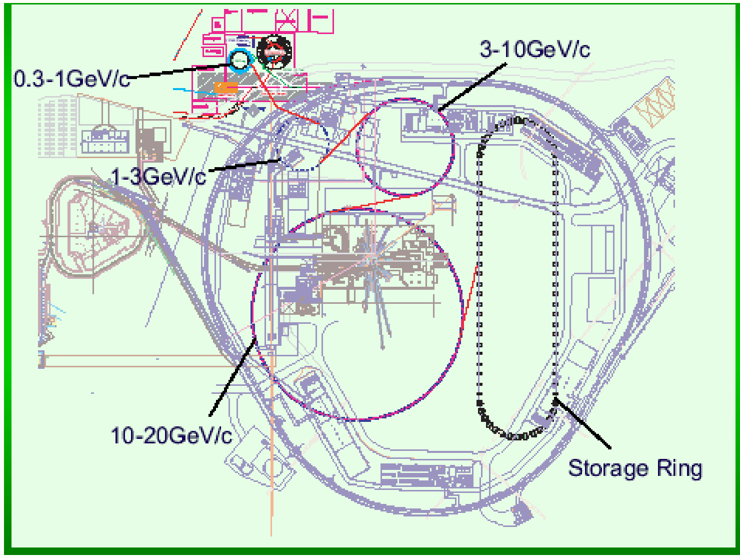
Neutrino Factory Challenges

- **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?

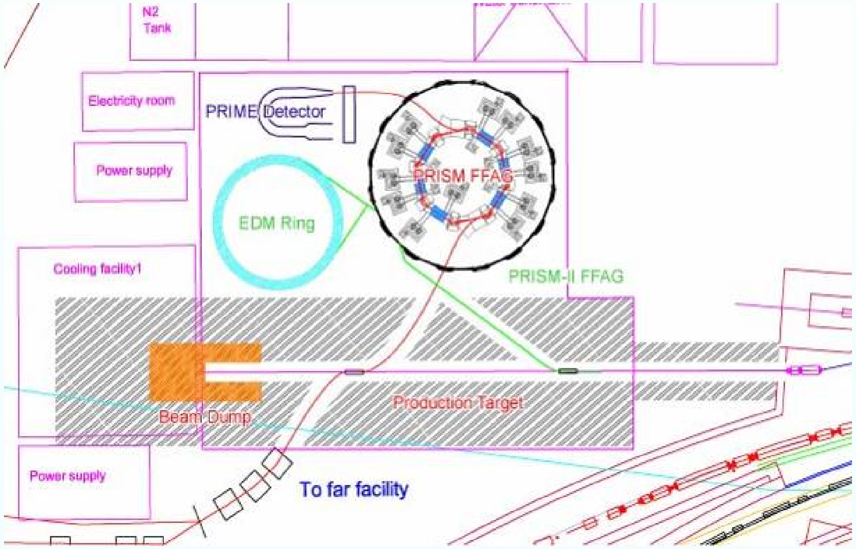
- **Other uses of high power protons & muons?**

The FFAG model





- **High Power Proton Driver**
  - **Muon g-2**
- **Muon Factory (PRISM)**
  - **Muon LFV**
- **Muon Factory-II (PRISM-II)**
  - **Muon EDM**
- **Neutrino Factory**
  - **Based on 1 MW proton beam**
- **Neutrino Factory-II**
  - **Based on 4.4 MW proton beam**



After Y Kuno

Key Challenges

Targets

- ~ same power as SNS targets
  - Open
  - Small
  - Environmental protection?

Muon Cooling

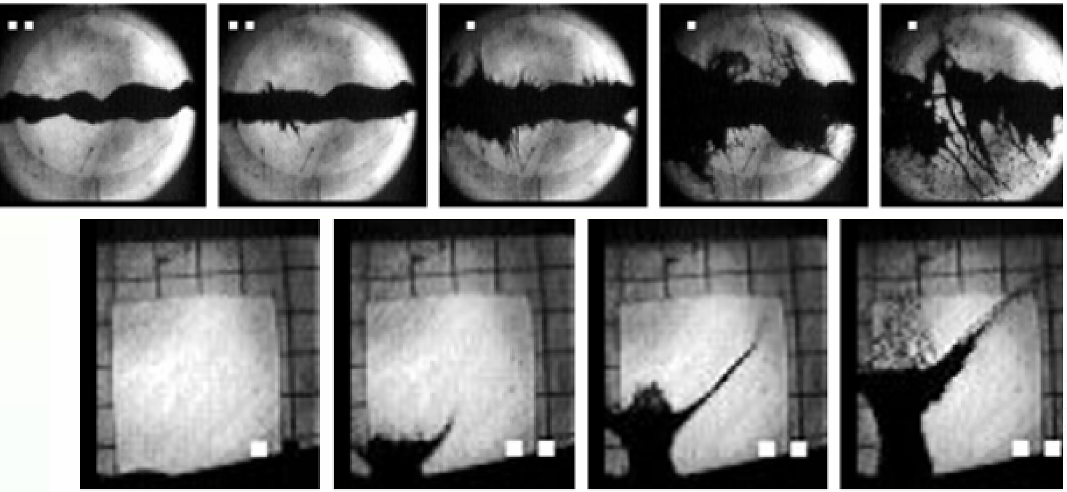
- Certainly needed for a muon collider
- Almost certainly needed for a neutrino factory
  - (combined FFAG/cooling or ring-coolers?)

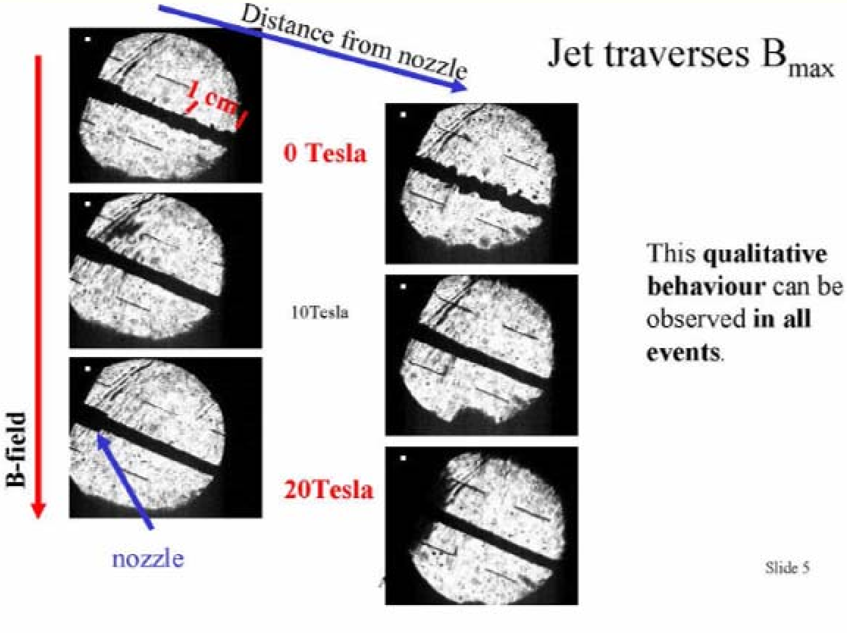
Target R&D

- **Requirements**
  - Pulsed Beam
  - Small Beams
  - Short High-Z Material
  - Embedded Targets
  - High Beam Power
- **Tests**
  - Stress = $E\alpha\Delta T$
  - Need tough materials to withstand stress
  - Materials with small α (CTE) to reduce stress
  - Beam test (short and longer term) are mandatory

- **Options**
  - Solid
    - Radiation cooled
    - Liquid cooled
    - Continuous
    - pellets
  - Liquid
    - Mercury?

Target Studies

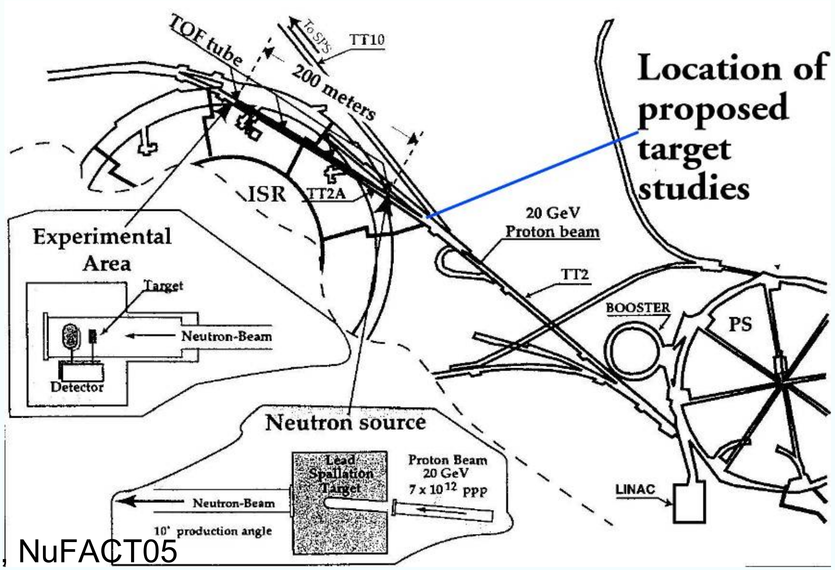




Jet traverses B_{max}

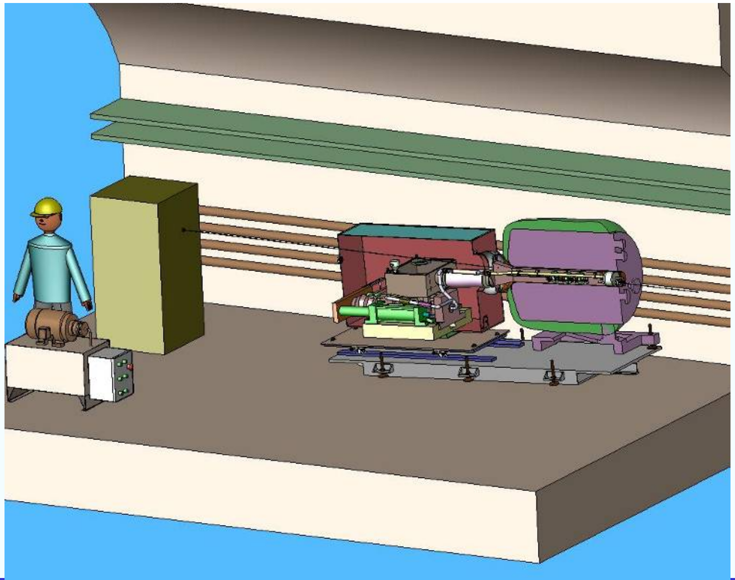
This qualitative **behaviour** can be observed **in all events**.

Slide 5

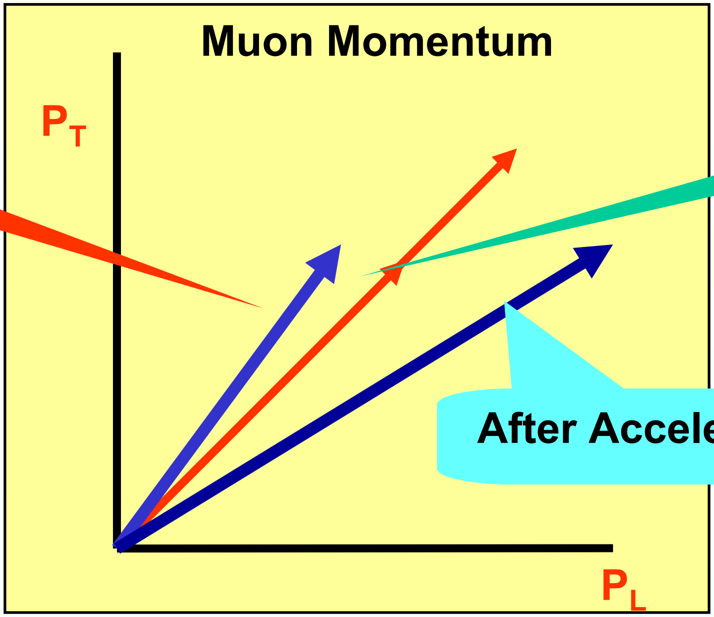


Location of proposed target studies

Kirk, NuFACT05



Ionization Cooling



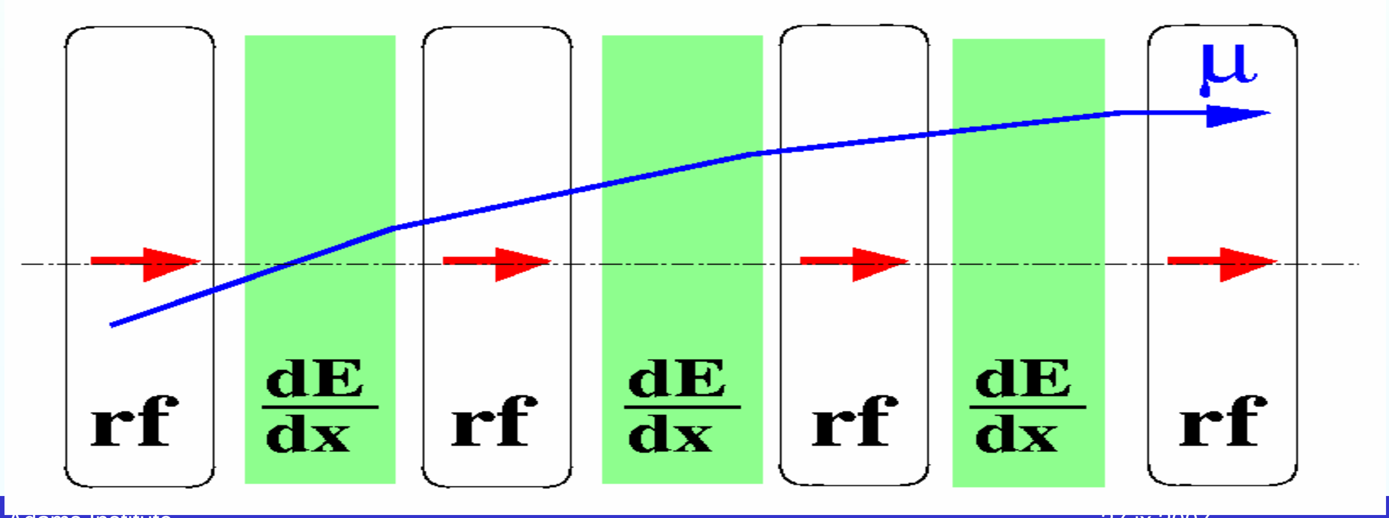
After Multiple Scattering

$$\frac{d\varepsilon_n}{ds} = \frac{\beta_\perp}{\beta^3 m_\mu c^2 X_0 E_\mu}\frac{dE_\mu}{ds}$$

After ionisation energy loss

$$\frac{d\varepsilon_n}{ds} = -\frac{\varepsilon_n}{\beta^2 E_\mu}\frac{dE_\mu}{ds}$$

After Acceleration

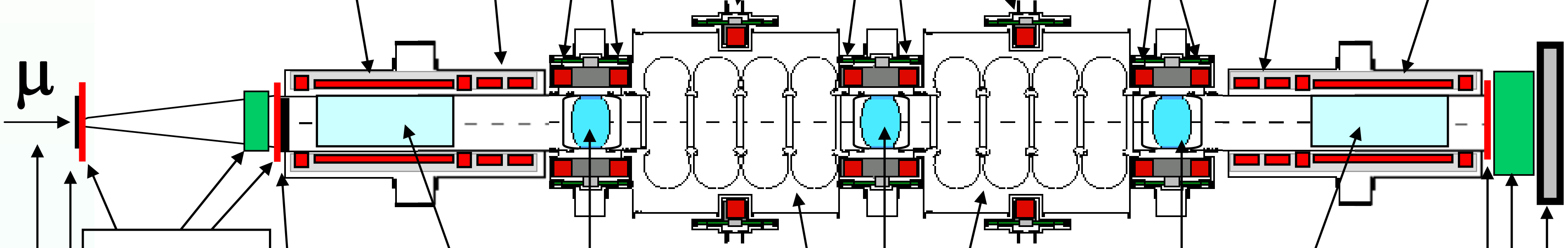


10% cooling of 200 MeV/c muons requires ~ 20 MV of RF

single particle measurements =>

measurement precision can be as good as $\Delta(\varepsilon_{out}/\varepsilon_{in}) = 10^{-3}$

never done before either….



Coupling Coils 1&2

Spectrometer solenoid 1

Matching coils 1&2

Focus coils 1

Focus coils 2

Focus coils 3

Matching coils 1&2

Spectrometer solenoid 2

Beam PID
TOF 0
Cherenkov
TOF 1

RF cavities 1

RF cavities 2

Downstream particle ID:
TOF 2
Cherenkov
Calorimeter

Diffusers 1&2

Liquid Hydrogen absorbers 1,2,3

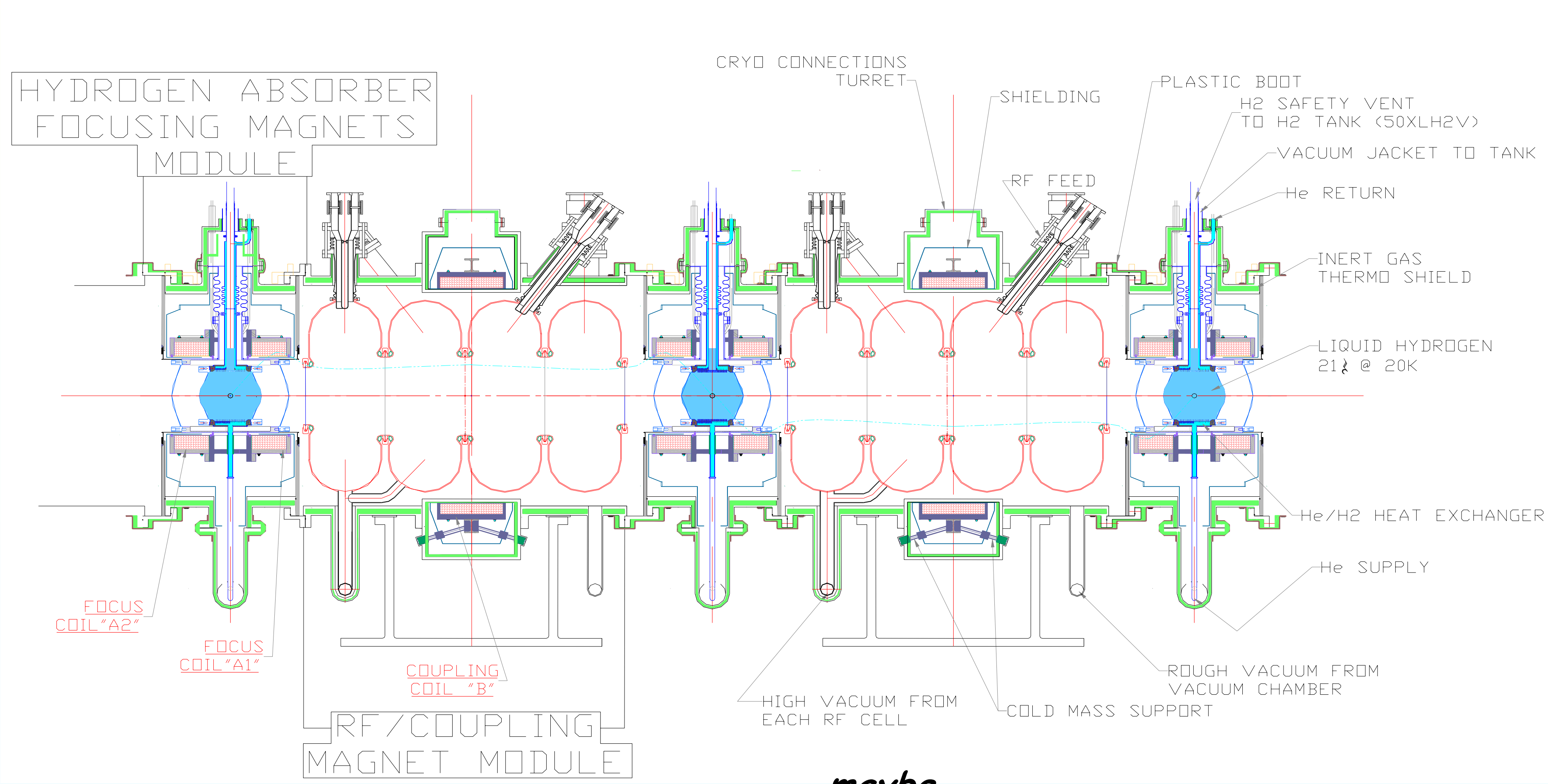
Incoming muon beam

Trackers 1 & 2
measurement of emittance in and out

Blondel

… after engineering …

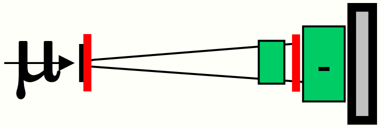
reality (simplified)



….maybe…

Blondel

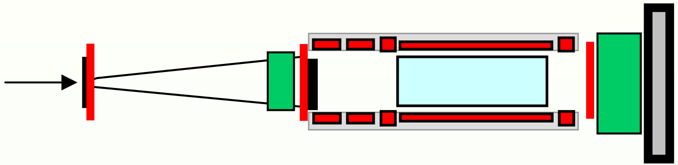
A Phased Approach



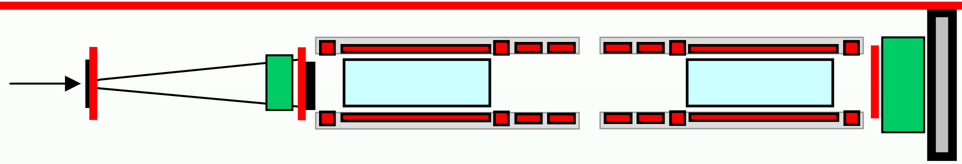
STEP I: spring 2007

PHASE I

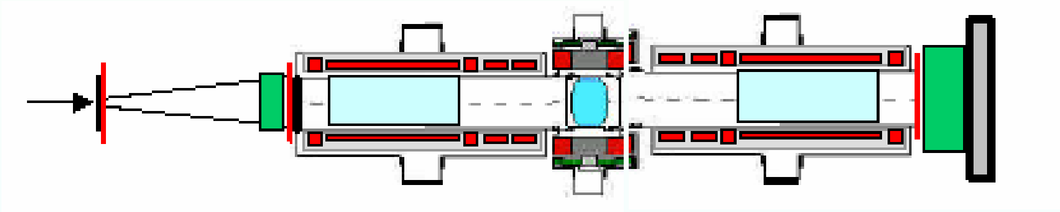
approved



STEP II: fall 2007



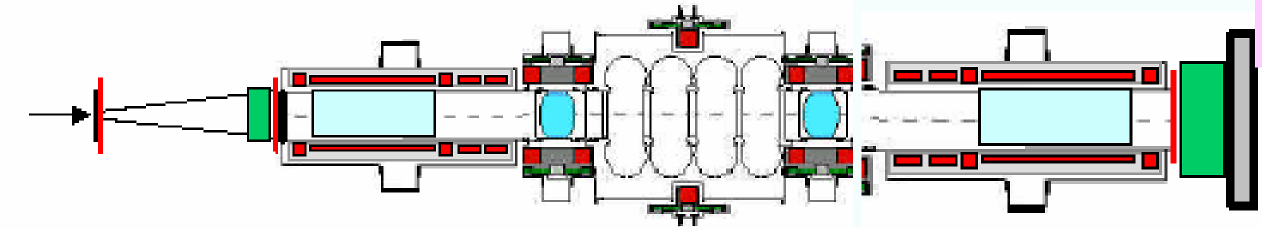
STEP III: 2008



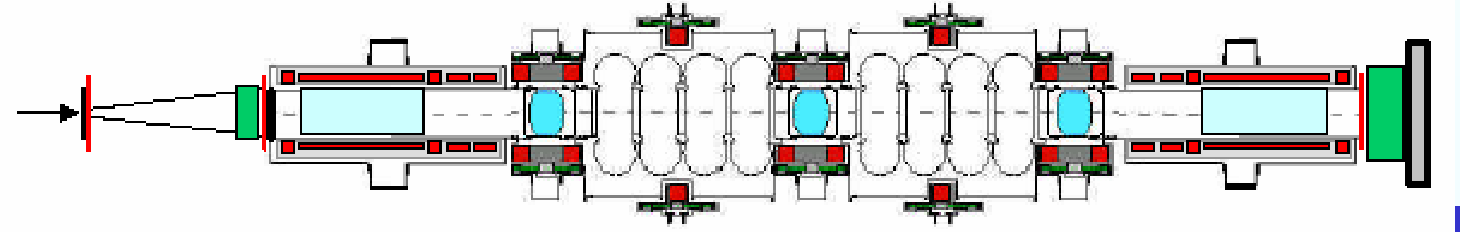
STEP IV: 2008

PHASE II

in preparation



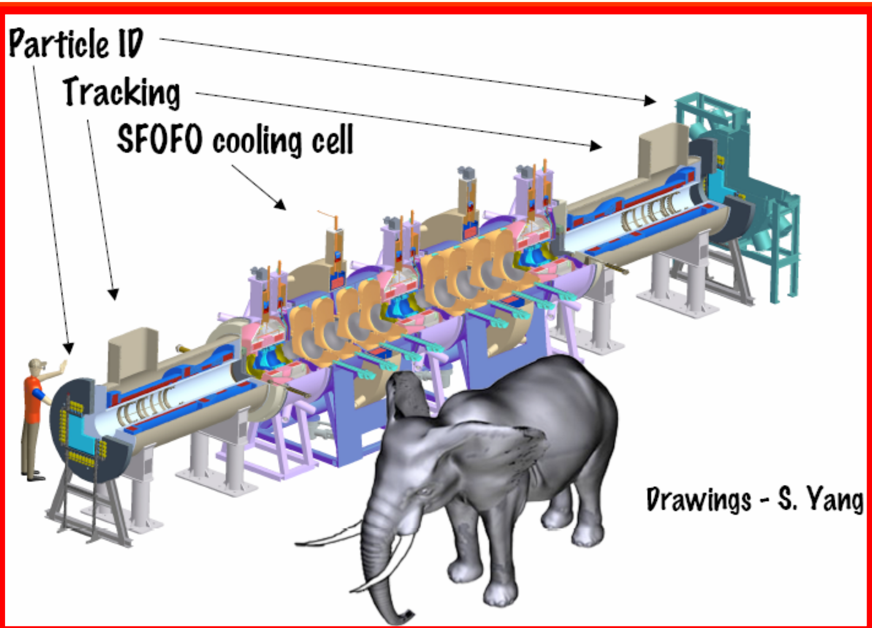
STEP V: fall 2008?

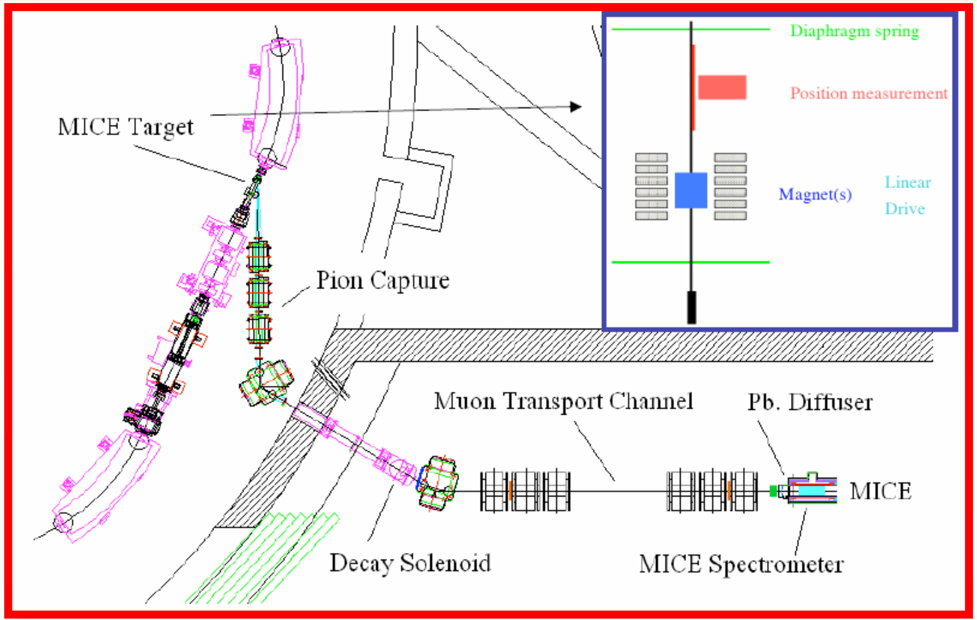


STEP VI:

2009?

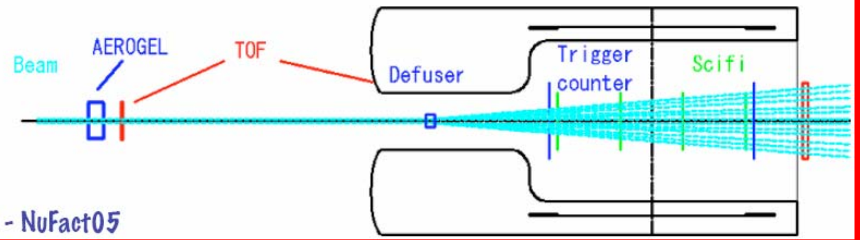
MICE



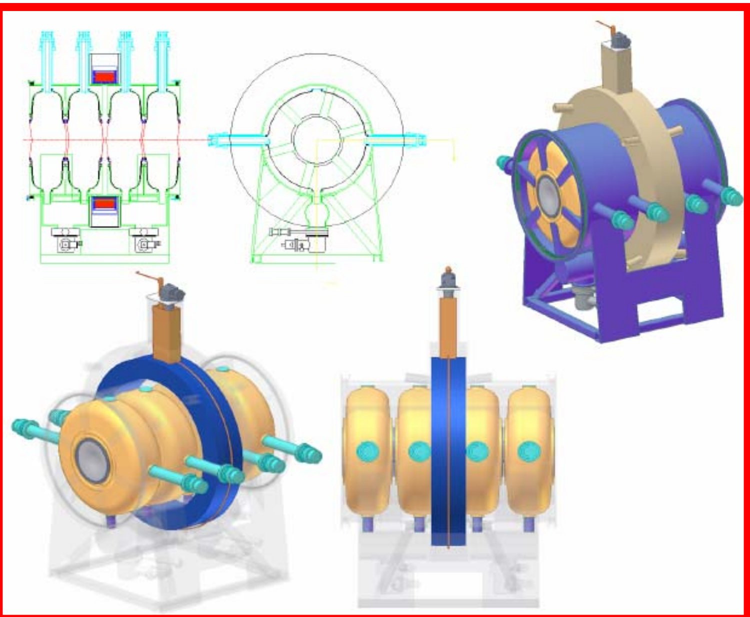


- First part completed June 2 at KEK π2 beamline
- Data taken for
  - TOF calibration
  - Aerogel Cerenkov performance
  - Beam survey
  - DAQ test
- Ready to test tracker prototype

Super JACEE



Y. Torun - NuFact05



Neutrino Factory Challenges

Not all match efficiently

- **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 (ring, linear, …)?
  - RF and acceleration
    - RLA's or FFAG's?
  - Muon Storage Ring
    - Racetrack, triangular or bow-tie
    - Conventional or FFAG?

Options

2

×

6

×

3

×

2 x 6

×

2

×

3 x 2

~~5184~~ ~~72~~

Some don't work – divide by 2

~~36~~

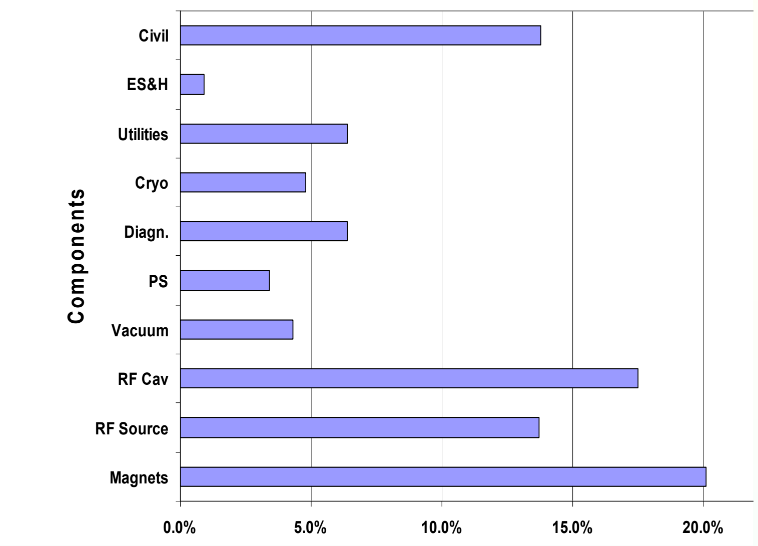
9

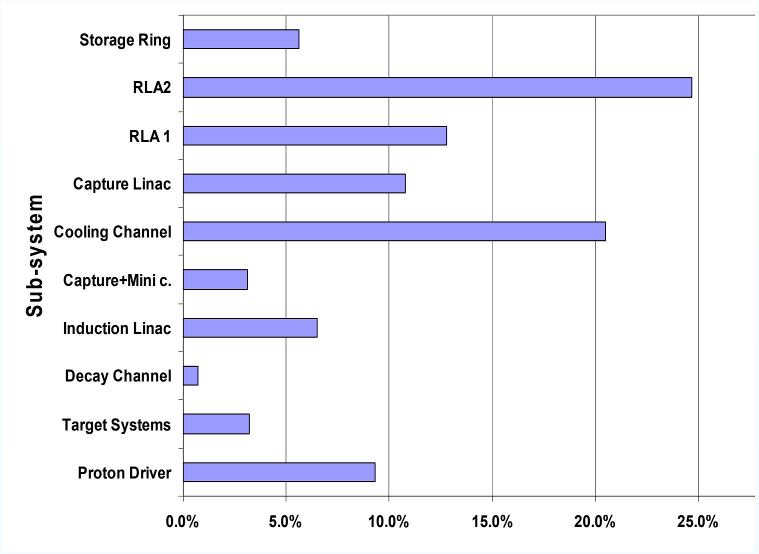
¾ don't make any sense

~ 9 feasible NF designs!!!!

Neutrino Factory R&D

- High Power proton drivers
  - MW power, ns pulses
- RF
  - 30% of the cost?
- Cooling
  - How much? (20% of the cost?)
- RLA or FFAG?
  - Which is cheaper?





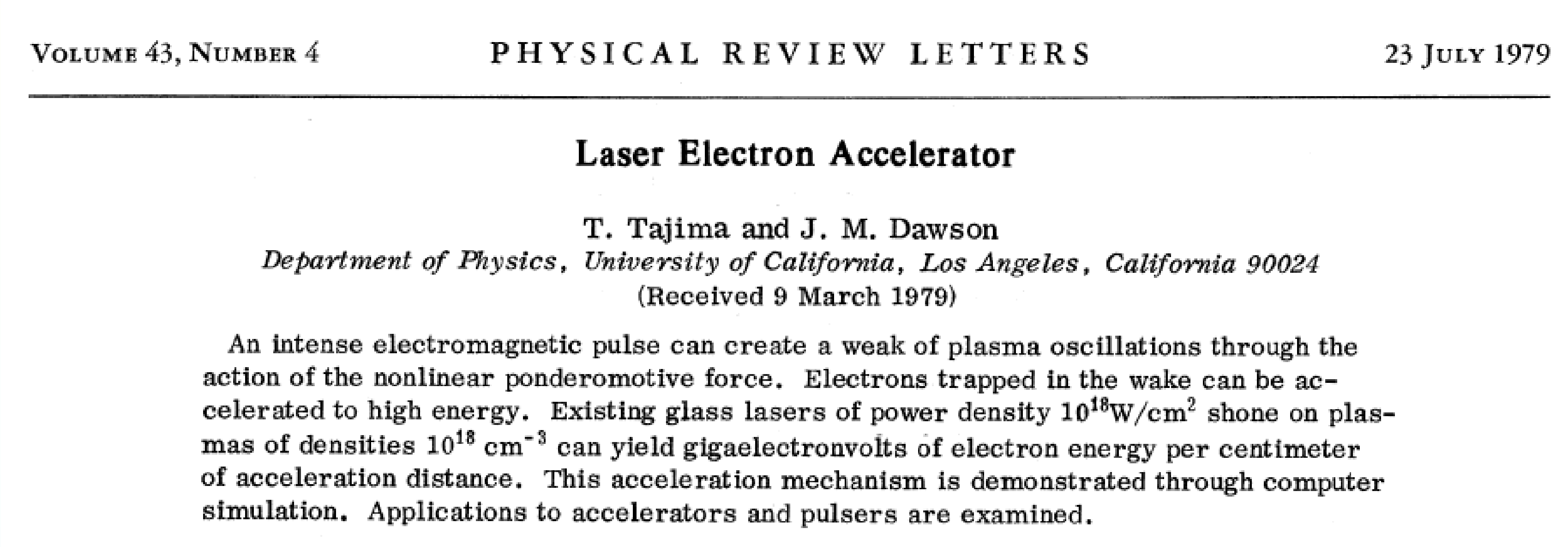
BNL Feasibality Study 2

John Adams Institute
J.A.I.
for Accelerator
Science

Laser-Plasma accelerators

Plasma accelerators driven by TW lasers

Tajima & Dawson *Phys Rev. Lett.* **43** 267 (1979)



Volume 43, Number 4 PHYSICAL REVIEW LETTERS 23 July 1979

Laser Electron Accelerator

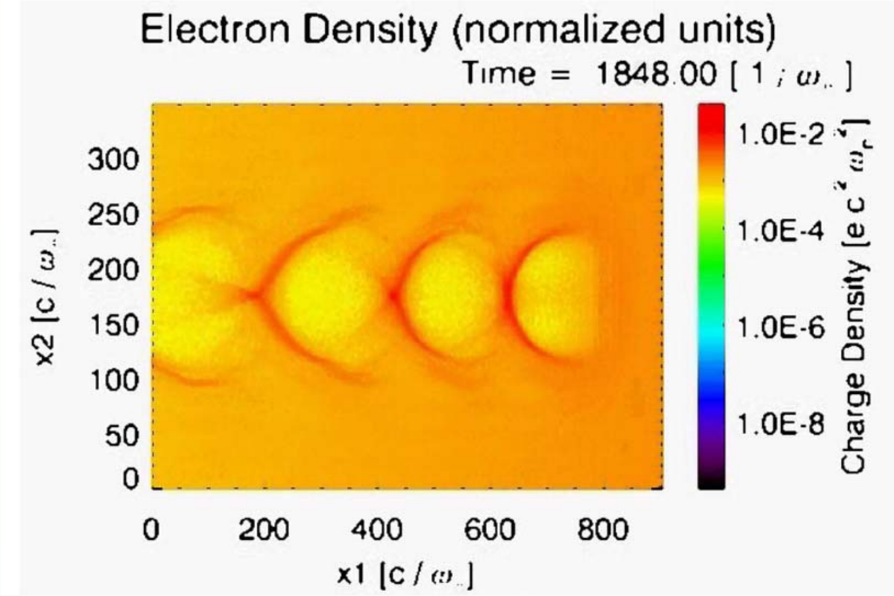
T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024

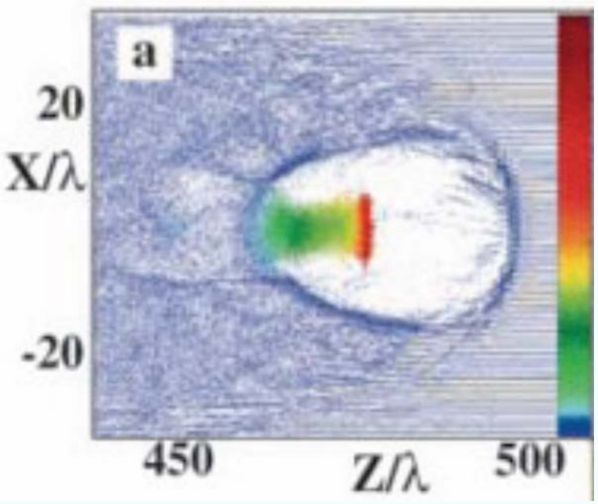
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Hooker, Oxford

Nonlinear plasma waves





- Plasma frequency decreases with intensity.
- Wavefronts of plasma wave become curved.
- At very high intensities reach the “blow-out” or “bubble” regime.

Pukhov *et al.* Appl. Phys. Lett. **74** 355 (2002)

Hooker, Oxford

Generation of quasi-monoenergetic beams

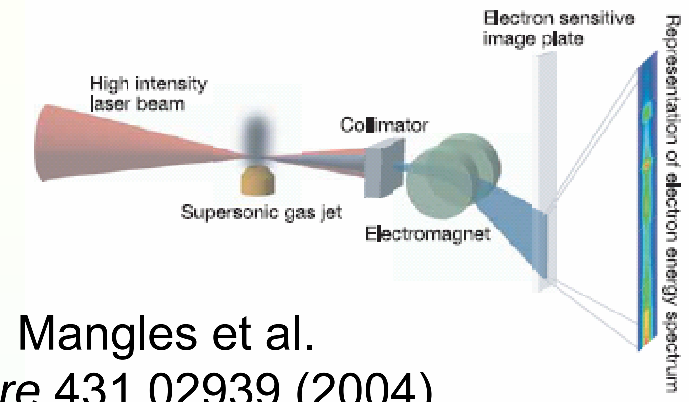
nature

Dream beam

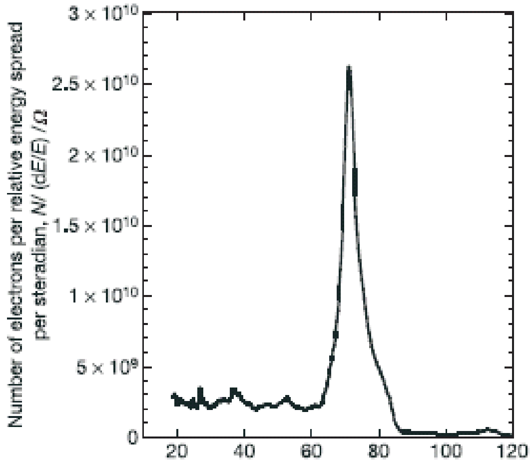
- Three milestone results published in Nature at end of 2004 by:
  - Karl Krushelnick (Imperial College, UK)
  - Victor Malka (LOA, France)
  - Wim Leemans (Lawrence Berkeley, USA)
- These showed evidence of *quasi-monoenergetic* electron beams for the first time.

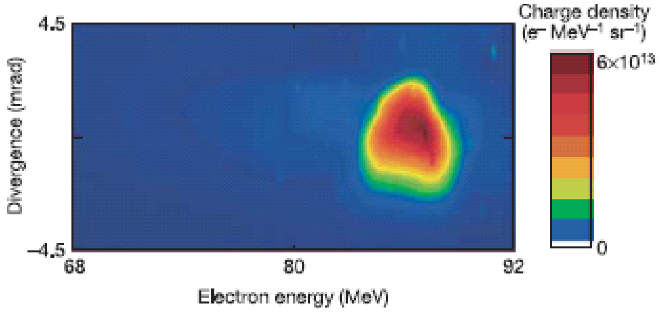
Hooker, Oxford

Generation of quasi-monoenergetic beams

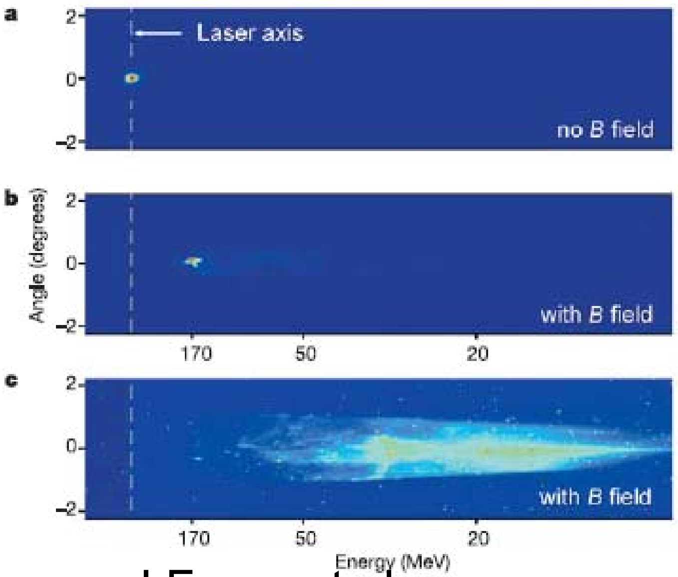


S. D. Mangles et al.
Nature 431 02939 (2004)





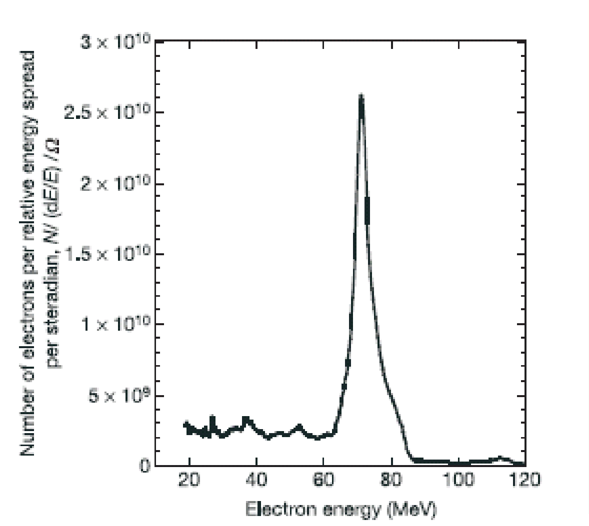
C. G. R. Geddes et al.
Nature 431 02900 (2004)

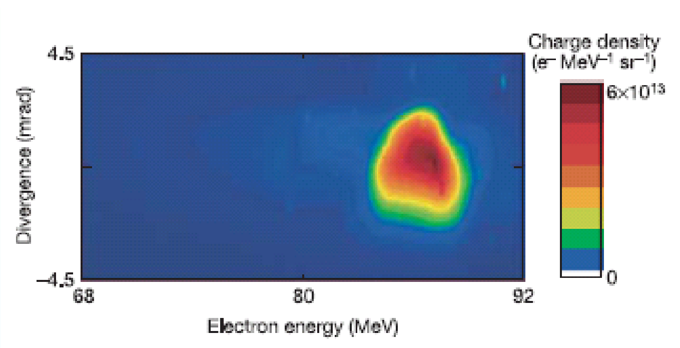


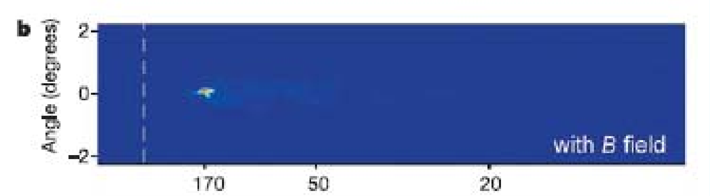
J Faure et al.
Nature 431 02963 (2004)

Hooker, Oxford

Generation of quasi-monoenergetic beams







– Typical output parameters:

- Output energy: 100 - 170 MeV
- Energy spread: 2.5 - 8%
- Bunch charge: 20 - 500 pC
- Normalized emittance: 1-2 π mm mrad

Hooker, Oxford

Conclusions and future prospects

- In the last 5 years laser-driven plasma accelerators have made enormous progress:
  - Demonstration of quasi-mononergetic beams
  - Increase of output energy to 1 GeV
  - Demonstration of controlled injection

Hooker, Oxford

Future Accelerators for other sciences

What is needed and why

X-ray sources

Neutron sources

Nuclear Physics

No time to discuss this

... sorry, because it is important

Future Accelerators for other applications

Accelerators in Medicine

Development of NS-FFAG
EMMA & PAMELA

(After Takeichiro Yokoi)

Introduction ...

- FFAG(Fixed Field Alternating Gradient) Accelerator
  - rapid particle acceleration
  - large beam acceptance
    - wide variety of applications
      - fundamental science (e.g. Neutrino factory)
      - practical applications (e.g. cancer therapy)
- Compared to existing fixed field accelerators, a new approach to FFAG, Non-Scaling FFAG, has advantages such as small beam excursion and flexibility in machine design and operation and variable energy beam extraction
- However, no NS-FFAG has ever been realized up to now.

→ **Real working machine is needed !!**

CONFORM (Construction of a Non-scaling FFAG for Oncology, Research and Medicine) aims to develop the Non-scaling FFAG as a versatile accelerator. (Project HP: www.conform.ac.uk)

Scaling FFAG & Non-Scaling FFAG

Both have large acceptance and ability of fast acceleration
* Acceleration speed of fixed field accelerator is unlimited
(in synchrotron, ramping speed of magnet limits the repetition rate)

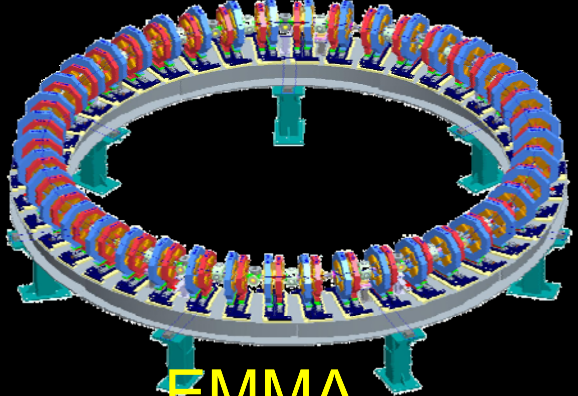
- **Scaling FFAG**
  - Similar orbit shape
  - Large beam excursion
  - Stable betatron tune
  - Combined function($B \propto r^k$)

- **Non-Scaling FFAG**
  - Non-similar orbit shape
  - Small beam excursion
    (small path length variation)
  - Large tune change
  - Linear lattice (quadrupole etc)


Already Constructed

PoP FFAG(KEK)

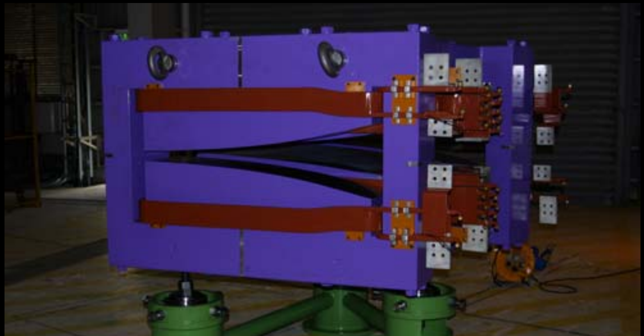
It has never been built


EMMA

How to realize NS-FFAG lattice...

Element of NS-FFAG provides bending and focusing field in a magnet

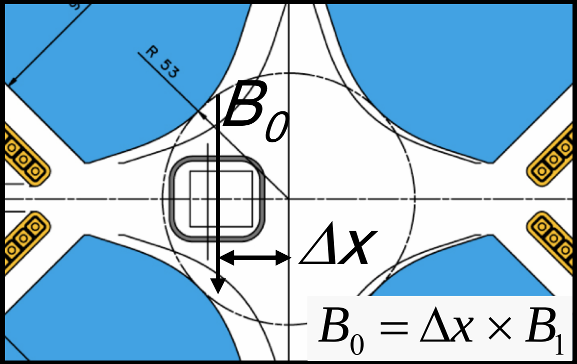
⇒ " Combined function magnet"



Typical combined function magnet(KEK 150MeV FFAG)

In NS-FFAG, focusing force is linear (quadrupole field) ...

⇒ Shifted quadrupole magnet works as a combined function magnet

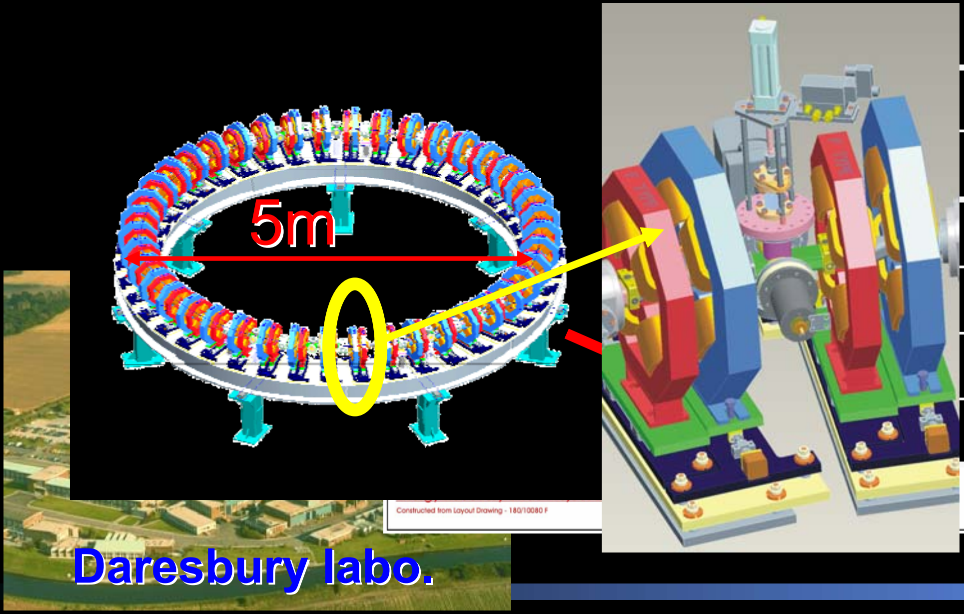


By changing the horizontal position of magnet, bending power and focusing power can be changed independently.

⇒ "Separated function FFAG"

EMMA: Electron Model for Many Applications

- Electron NS-FFAG as a proof of principle is to be built as 3-year project.(host lab: Daresbury lab.)
- It is also a scaled-down model of muon accelerator for neutrino factory.
- Research items are . . .
  - (1) Research of beam dynamics of NS-FFAG
  - (2) Demonstration of NS-FFAG as a practical accelerator
  - (3) Demonstration of fast acceleration with fixed frequency RF



Number of Cell	42 (doublet Q)
Circumference	16.57m
Injection energy	10~20MeV(variable)
Extraction energy	10~20MeV(variable)
RF	1.3GHz
Acceptance	3mm(normalized)

Beam acceleration : EMMA

Resonance is a coherent effect
⇒Fast acceleration can circumvent the problem

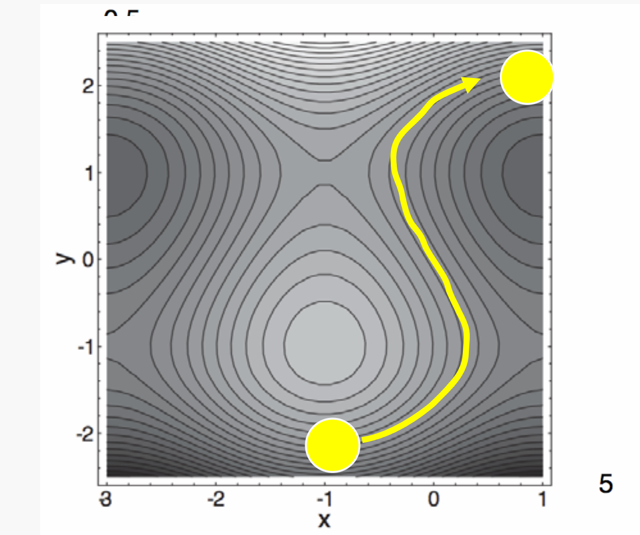
Resonant crossing acceleration

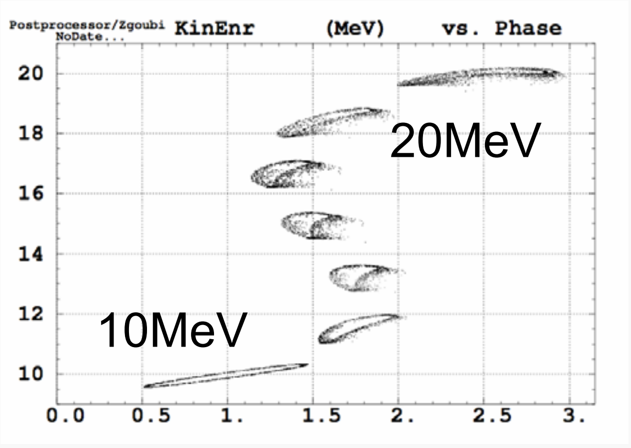
Small variation of path length makes it possible to adopt fixed frequency rf for relativistic particle

Fast asynchronous acceleration

* In EMMA, Acceleration completes within 10turns(~500ns)

EMMA is a unique system to observe transient process of resonance precisely.
⇒ Unique playground for nonlinear dynamics !!



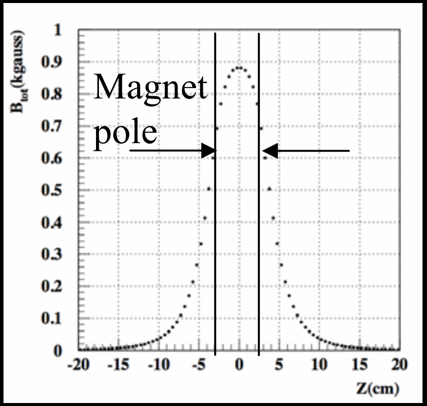


Linear Model, Nonlinear Reality

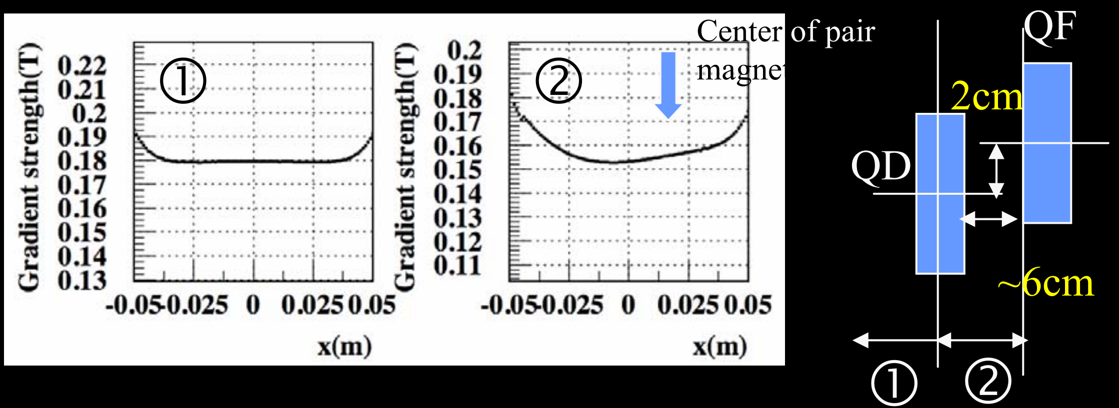
in the actual lattice of EMMA ...

Magnet aperture ~ Magnet length ~ Magnet distance

⇒ Severe nonlinearity arises due to coupling and fringing field



Fringing field is dominant!!



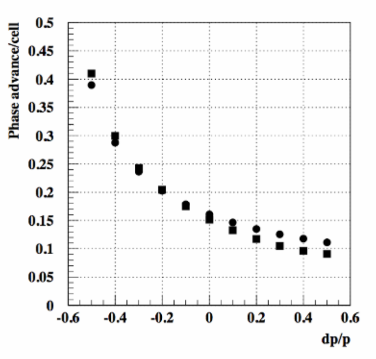
Inter-magnet coupling introduces strong nonlinearity

Tracking study with realistic 3D field is indispensable in machine design

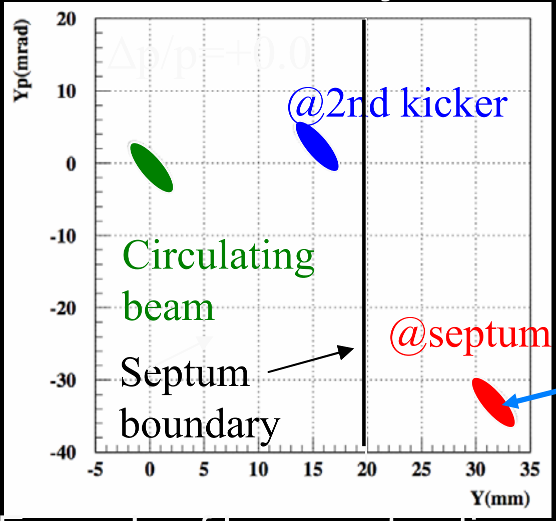
Beam Injection & extraction

Small beam excursion of NS-FFAG makes energy variable beam extraction easier

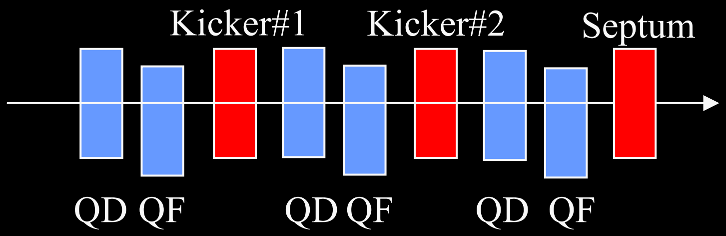
⇐ Unique feature for fixed field accelerator



However, large tune change requires phase adjustment mechanism in injection & extraction⇒ **multi-kicker system**



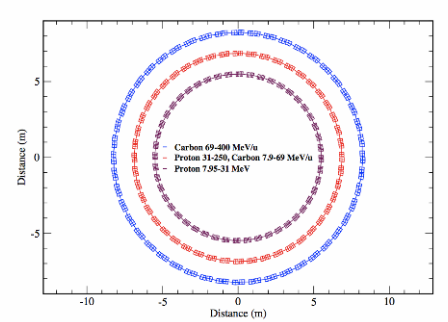
Example of beam extraction (PAMELA)



By changing the field strength and direction, beam position in phase space can be adjusted

PAMELA : Particle Accelerator for MEdicaL Applications

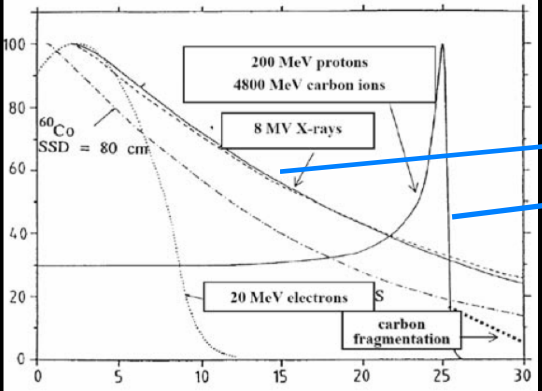
- Particle therapy has advantages in cancer therapy compared to X-ray therapy due to good dose concentration and better biological effectiveness (especially HI therapy).
- As an accelerator for particle therapy, the advantage of FFAG is higher intensity compared to ordinary synchrotron, flexible machine operation compared to cyclotron, and simultaneous(multi-port) beam extraction
- PAMELA aims to design particle therapy accelerator facility for proton and carbon using NS-FFAG
- It also aims to design a smaller machine for biological study as a prototype.

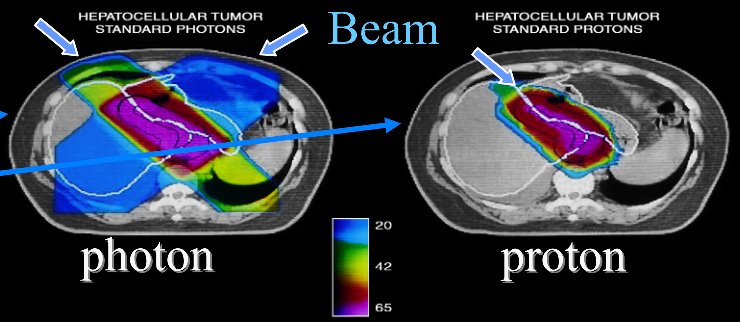


3-ring scheme by E.Keil, A.Sessler, D. Trbojevic

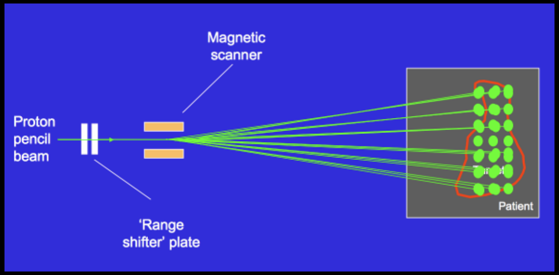
Particle therapy

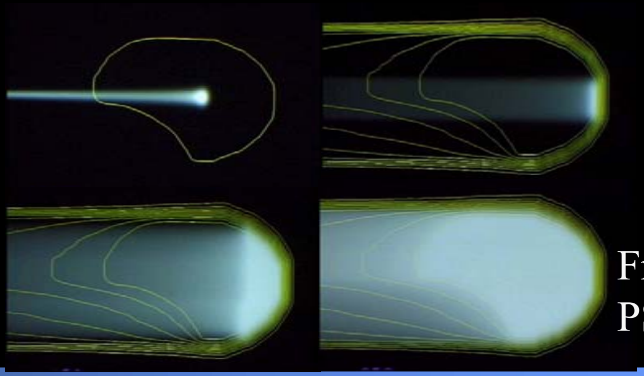
With the help of Bragg peak, proton and heavy ion beam can form sharp-edged irradiation field, and can minimize radiation damage to normal tissues.





Spot scanning can fully exert the advantage of particle therapy and pulsed beam of FFAG matches well to the treatment

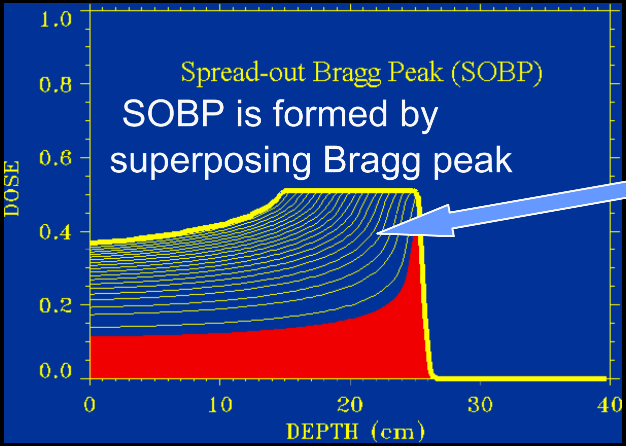




From
PSI website

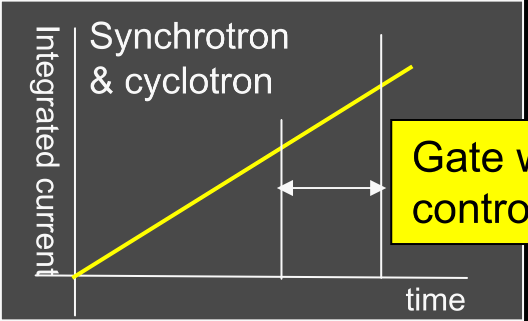
Monitoring and Control

:Key issues for medical applications

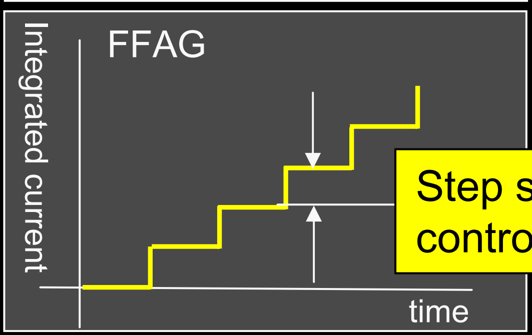


SOBP is formed by superposing Bragg peak

Dose uniformity should be < ~2%
⇒To achieve the uniformity, precise **intensity modulation** is a must



Gate width controls dose



Step size controls dose

Beam of FFAG is quantized.
⇒Active intensity control at the injection level and precise loss control are indispensable.

New approach to medical accelerator control is required in PAMELA
(New postdoc is employed for the issue)

Beam acceleration : PAMELA

Two approaches in NS-FFAG
for non-relativistic beam acceleration……

(1) Harmonic number jump (A. Ruggiero)

- Fixed frequency RF (high Q rf : high gradient)
- Amplitude modulation

⇐ Can high Q cavity accommodate amplitude modulation ?

(2) Frequency modulation

- low Q rf (low gradient)
- no need of amplitude modulation

(adiabatic capture requires AM)

⇐ Can beam be accelerated sufficiently fast?

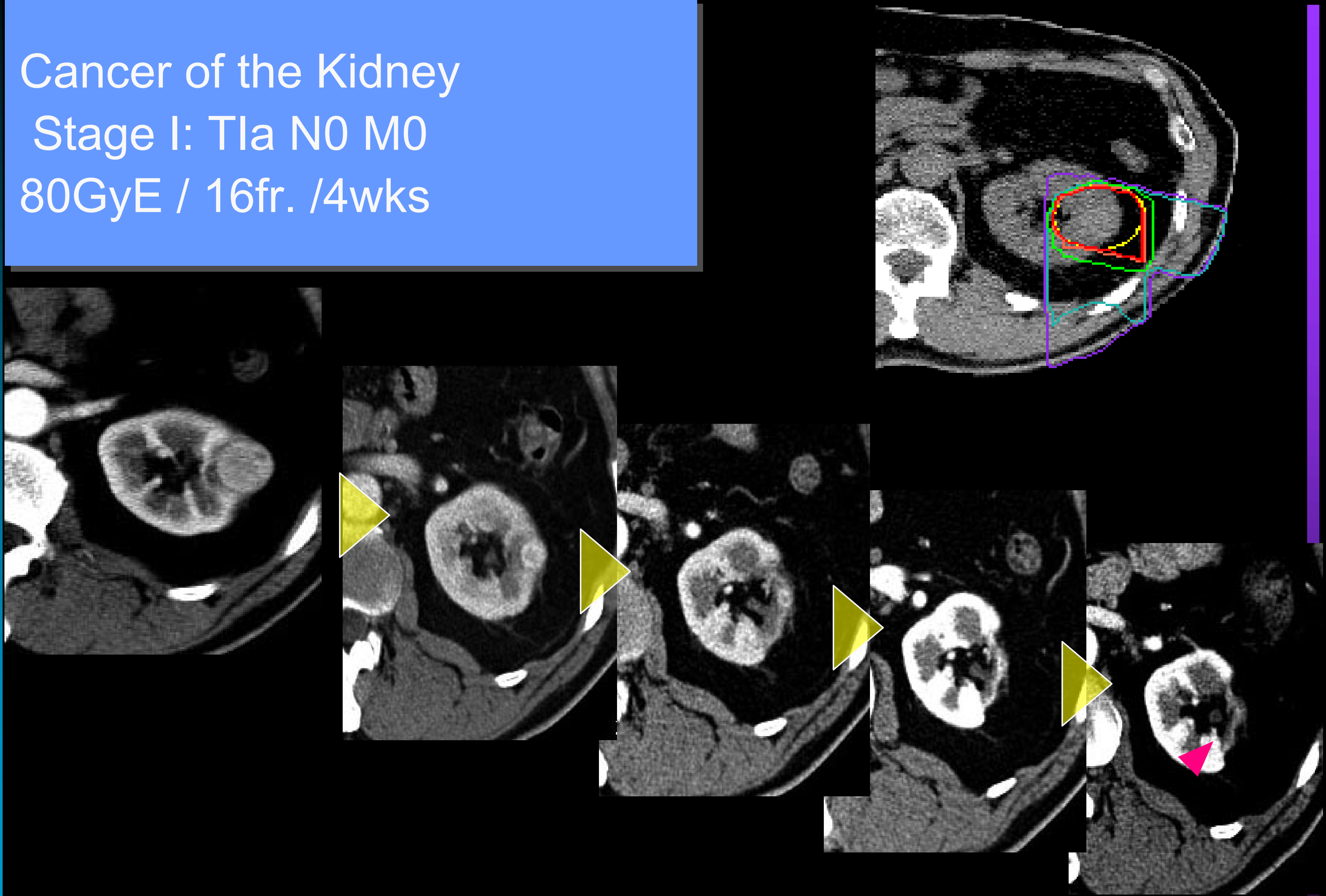
How fast beam should be accelerated in NS-FFAG ?

* Now, preparing for the study

Cancer of the Kidney

Stage I: TIa N0 M0

80GyE / 16fr. /4wks



Summary

- NS-FFAG is a novel accelerator and will open up new fields in accelerator science and its application
- COMFORM is to be engaged in two developments, EMMA(electron) and PAMELA(proton,HI)

Results of EMMA and design of PAMELA will come within 4 years

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!*