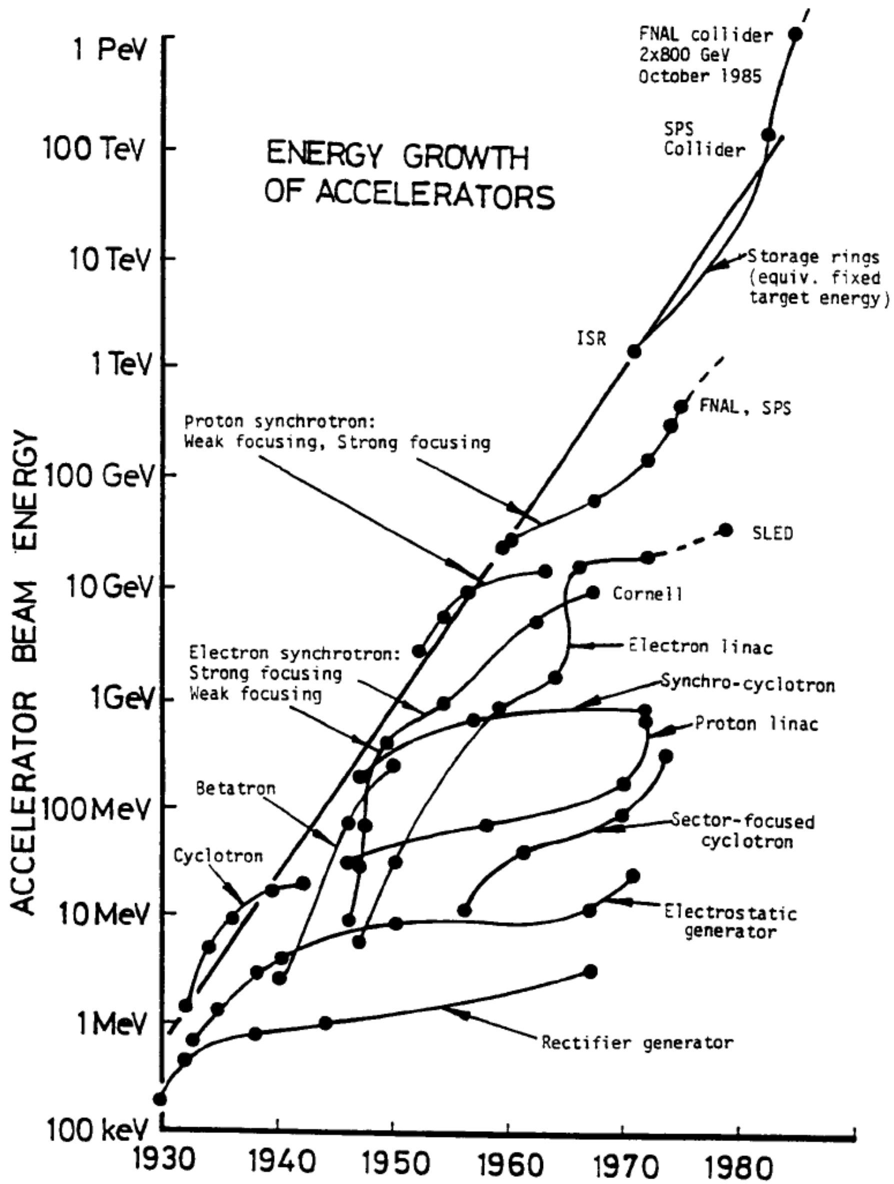
Current and Future Developments in Accelerator Facilities

Jordan Nash, Imperial College London

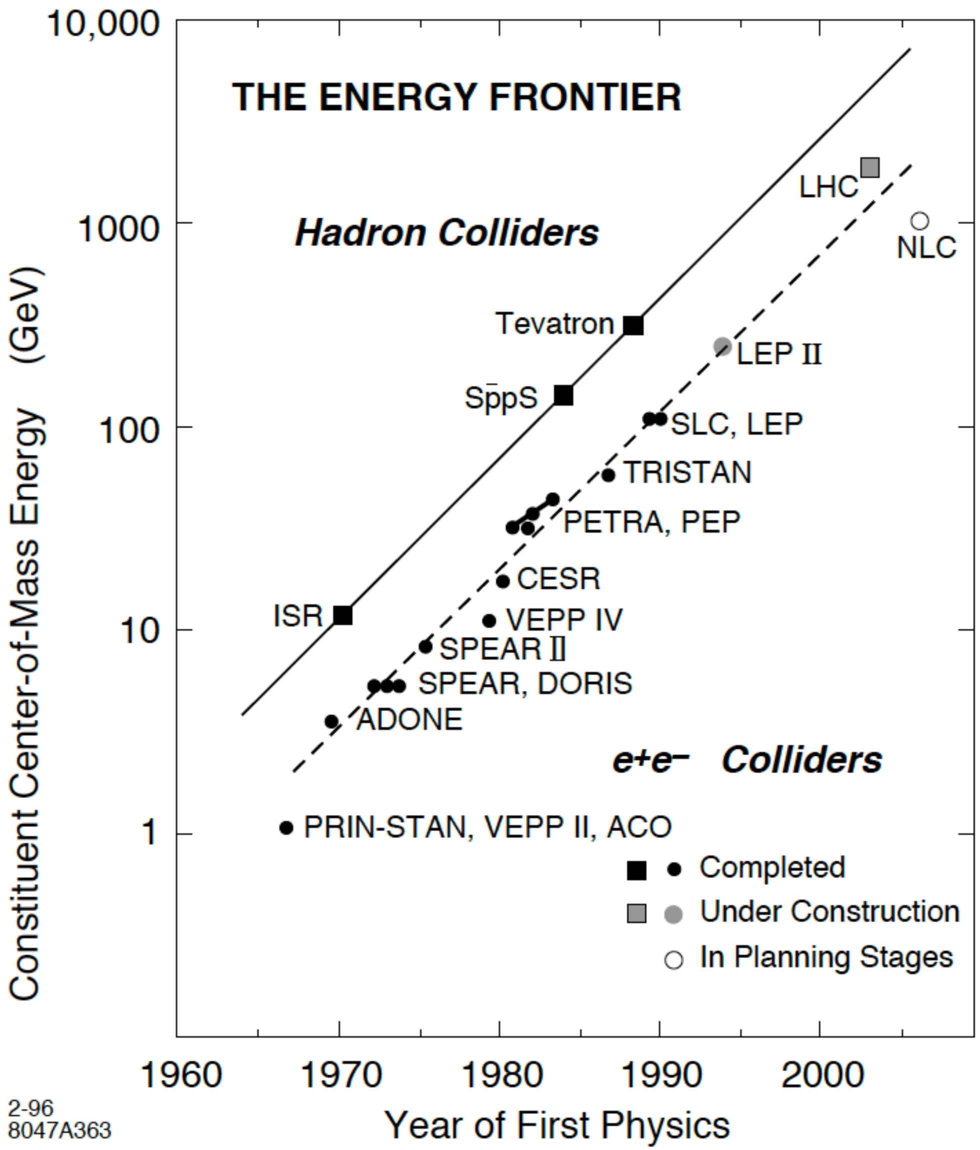


Livingston chart (circa 1985)

Nearly six decades of continued growth in the energy reach of accelerators

Driven by continuous innovation in acceleration techniques

Many new acceleration techniques developed to keep pushing the energy frontier



Livingston Chart - 1996

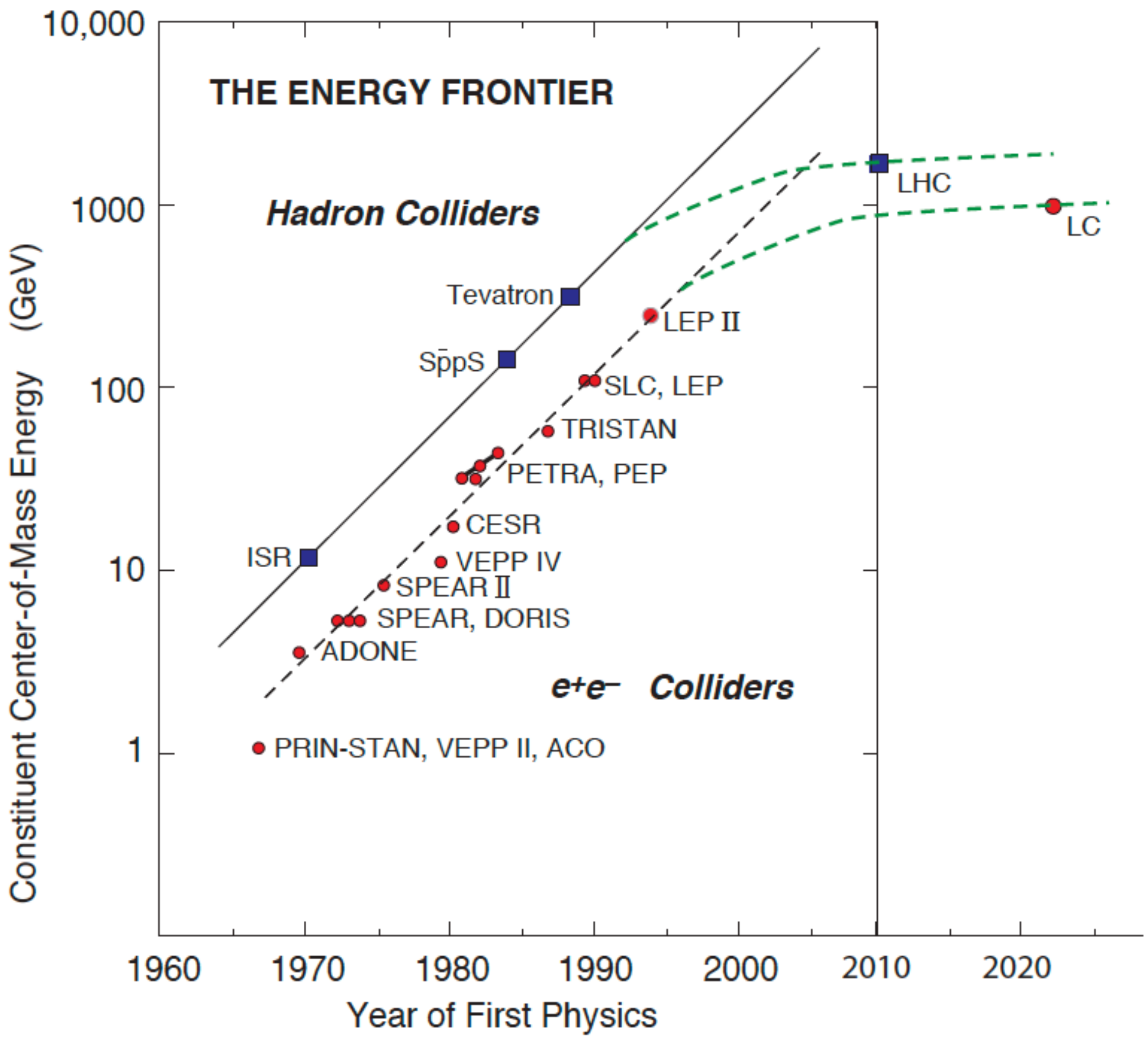
The last machines of the previous century were still on the predicted growth line– strong focusing storage rings

It was already evident that the machines for the 21st century were going to be harder to build (the SSC was meant to fall on the line!)

Two strands:

Energy Frontier with Hadron colliders

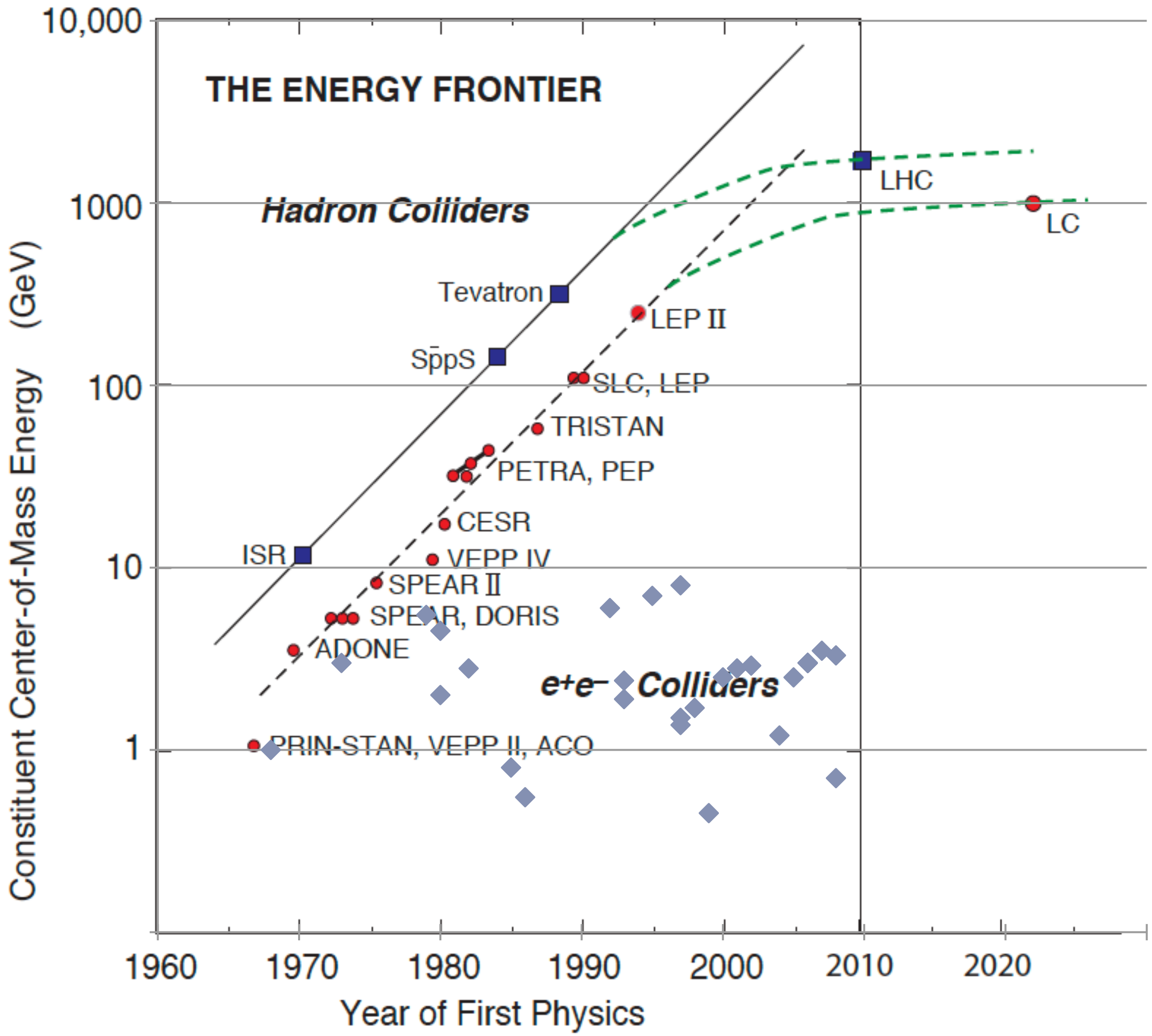
Precision with electron/ positron colliders



Livingston Chart 2010

Progress has slowed in pushing the energy frontier

No longer proceeding along at the rate of development seen over the previous 60 years



Investment in accelerators

There is still a lot of investment by society in accelerators

But much of this is going to the use of accelerators as tools for science – microscopes

Large number of light sources built over the past decade

Limiting factors – Size (~cost)

Design choices LEP/LHC: Radius

Parameter	Symbol	Value
Effective bending radius	ρ	3026.42 m
Revolution frequency	f_{rev}	11245.5 Hz
Length of circumference, $L = c/f_{\text{rev}}$	L	26658.9 m
Geometric radius $(L/2\pi)$	R	4242.9 m
Radio frequency harmonic number	h	31320
Radio frequency of the RF-system, $f_{\text{RF}} = h\, f_{\text{rev}}$	f_{RF}	352 209 188 Hz

Synchrotron radiation loss U_0 per turn (e^+/e^-):

At 104 GeV ~ 3% of beam energy lost per turn

$$U_0 \propto \frac{E^4}{\rho}$$

For e^+/e^- collisions machines designs pushed to large radius

V_{rf} ~ 3.6 GV for 104 GeV. World's largest RF system

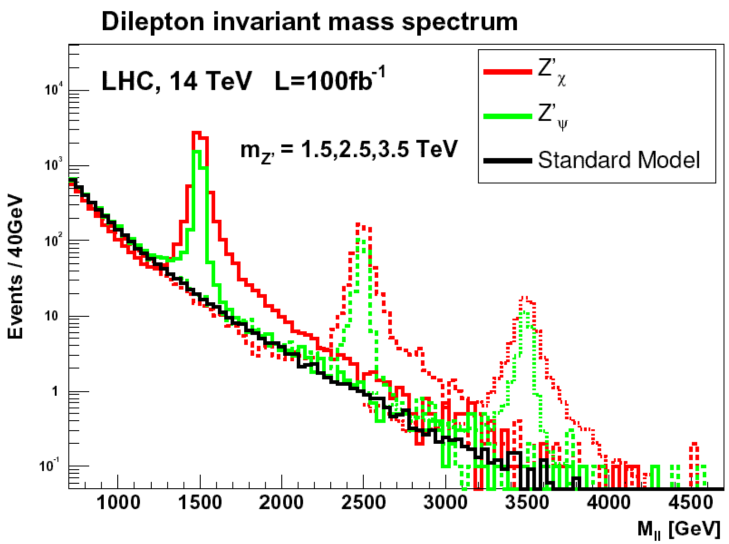
For Proton-Proton collisions in the LHC, the limiting factor is the bending strength of the LHC Dipole magnets

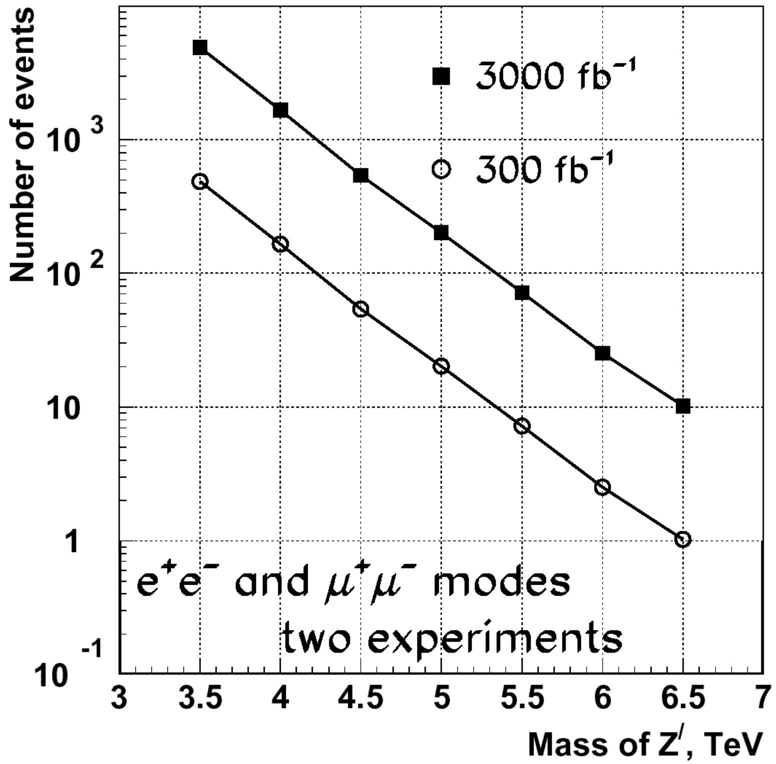
8 T peak field for 7 TeV Beams

Lyn Evans

Pushing the LHC- the SLHC

- Higher LHC luminosity gives extended reach in Energy
  - Cross sections fall with E
  - SLHC gives access to higher E
- Main motivation likely to be precision studies of LHC discoveries
  - Some time before the next machine arrives





Z' mass (TeV)	1	2	3	4	5	6
$\sigma(Z' \to e^+e^-)(fb)$	512	23.9	2.5	0.38	0.08	0.026
$\Gamma_{Z'}$ (GeV)	30.6	62.4	94.2	126.1	158.0	190.0

LHC upgrades

$$L = \frac{N_b^2 n_b f_r \gamma}{4\pi \varepsilon_n \beta^*} F$$

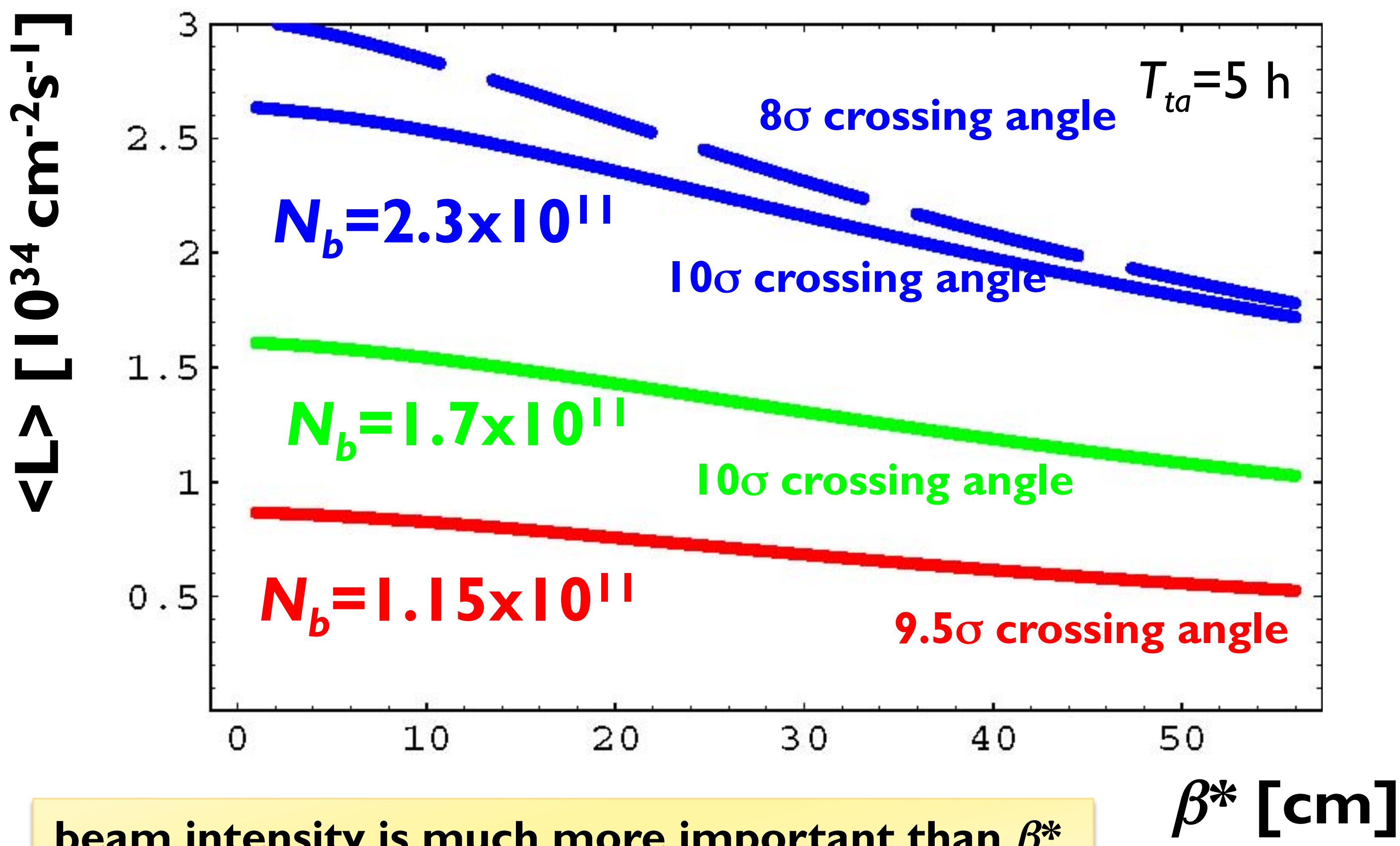
N_b number of particles per bunch
n_b number of bunches
f_r revolution frequency
ε_n normalised emittance
β^* beta value at ip
F reduction factor due to crossing angle

N_b, ε_n → injector chain
β^* → LHC insertion
F → beam separation schemes
n_b → electron cloud effect

- Increasing the beam brightness is probably the most effective way of increasing the luminosity of the LHC
  - Aim is to achieve around a factor of 10 in integrated luminosity collected
- Higher current creates extreme environment for the detector
  - Central trackers need replacment

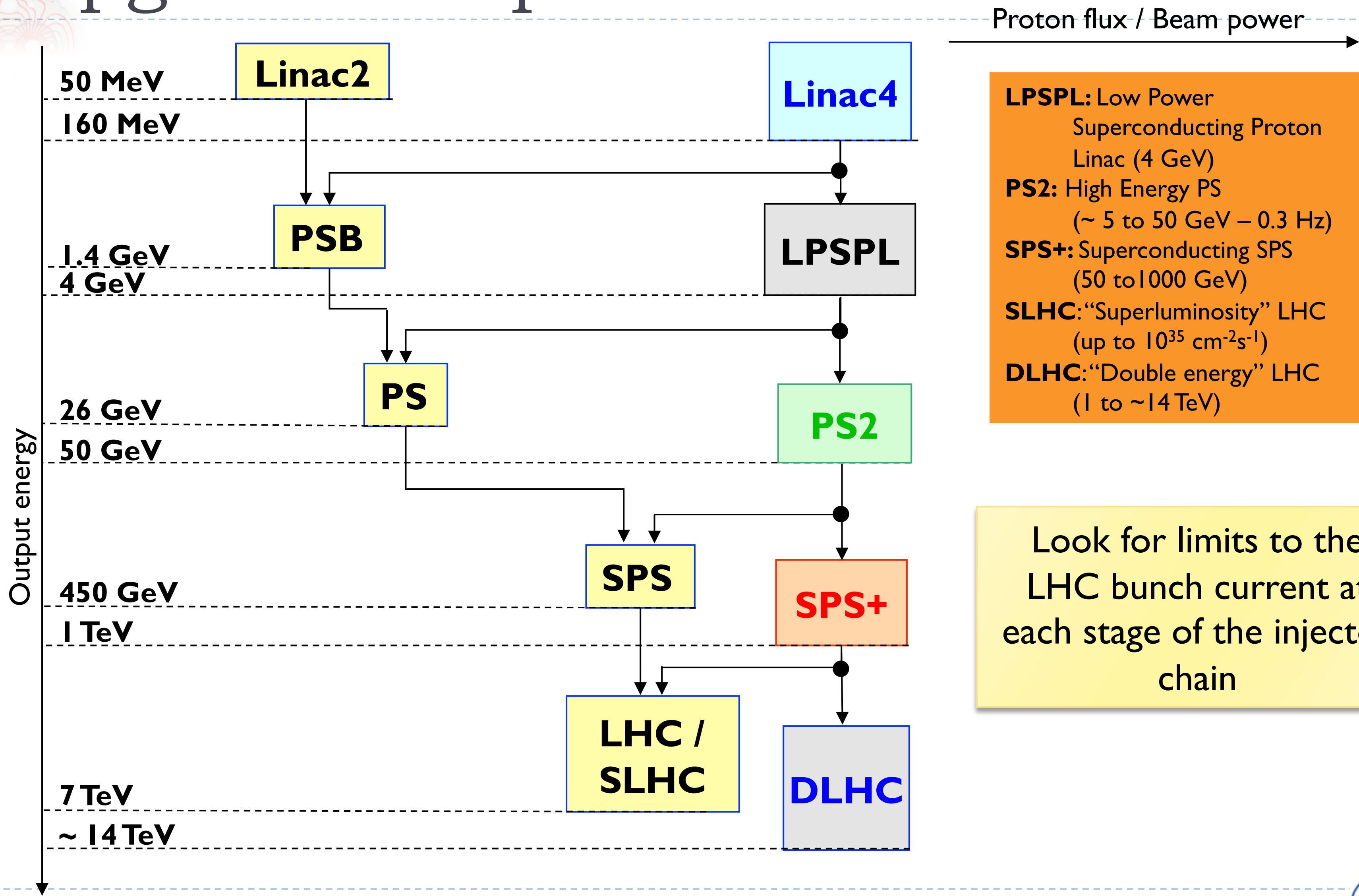
Lyn Evans

F. Zimmerman : Example SLHC scenarios



beam intensity is much more important than β*

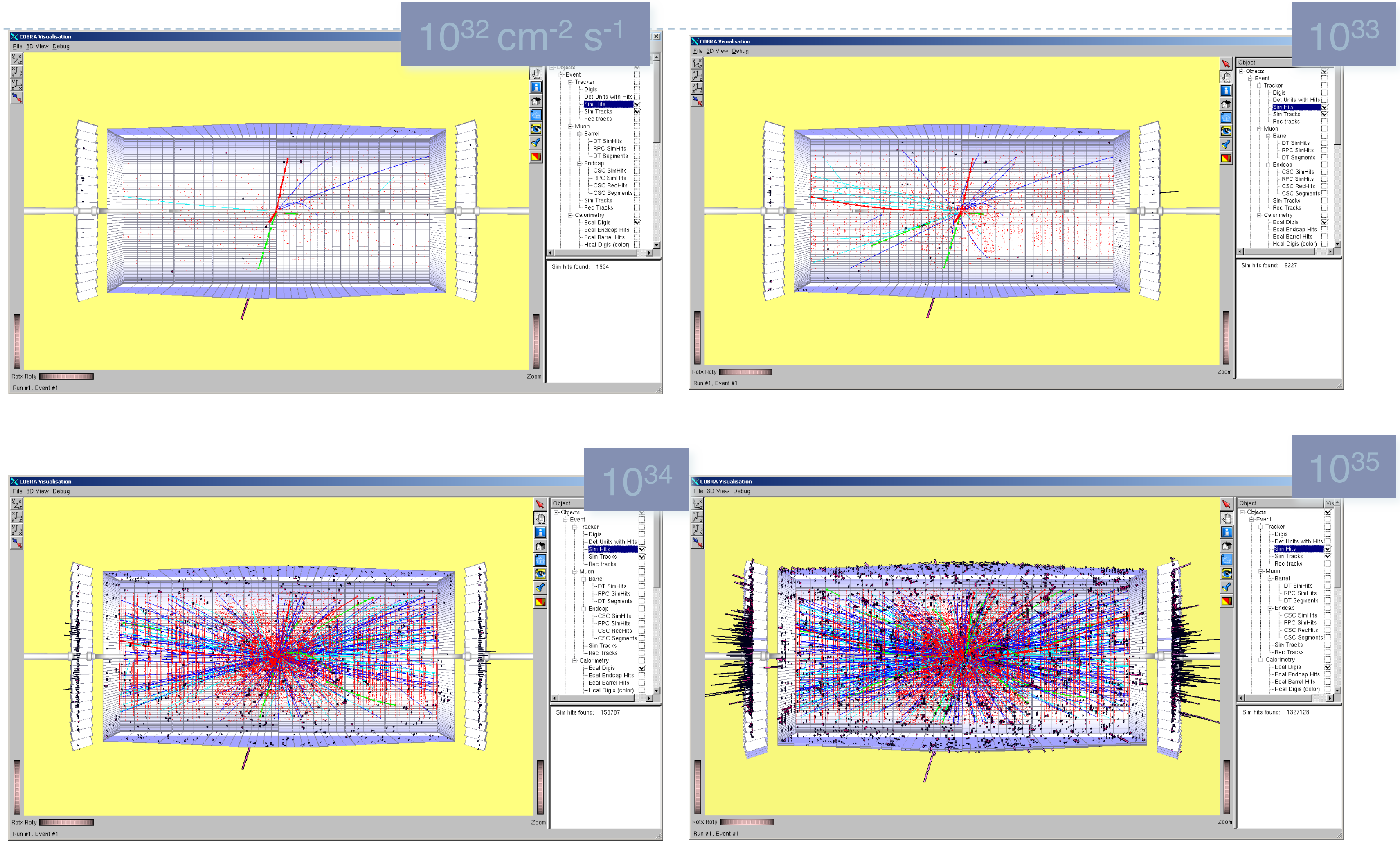
Upgrade components



LPSPL: Low Power Superconducting Proton Linac (4 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: "Superluminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: "Double energy" LHC (1 to ~14 TeV)

Look for limits to the LHC bunch current at each stage of the injector chain

Detector Challenges from LHC to SLHC



Tracking is the key component which will require upgrading for SLHC

I. Osborne

Precision measurements of new discoveries

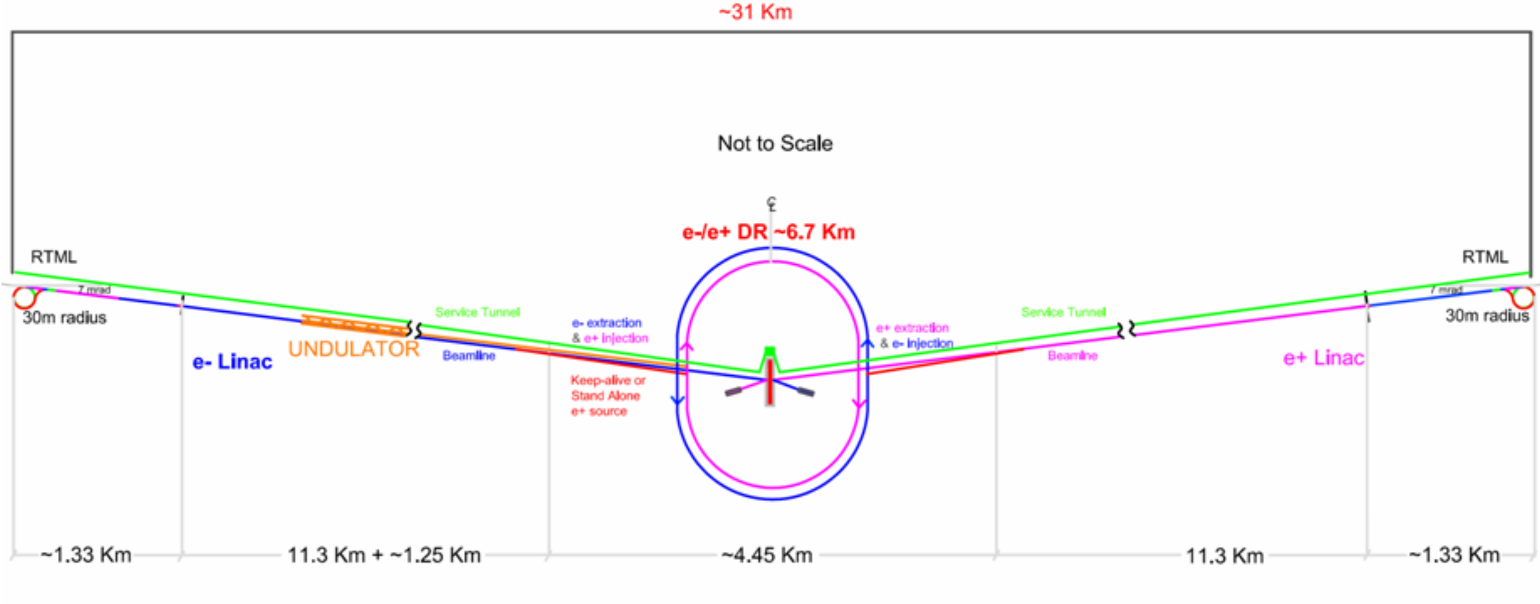
- Lepton colliders offer us a much cleaner environment for studying whatever physics we discover at the LHC
- How to overcome the limit of synchrotron radiation?
- Linear colliders offer a solution

$$L = \frac{N_b^2 n_b f_r \gamma}{4\pi \varepsilon_n \beta^*} F$$

- Accelerate electrons in a linear accelerator
  - No problem of synchrotron radiation loss
  - But lose the high rate of collisions that a storage ring offers
    - Have to do many rapid shots of the accelerator
- Compensate for the reduction in collision rate by decreasing the beam size dramatically
  - Beam cross sections of order nm at the collision points

The ILC -

- The International Linear Collider is a very advanced design for a Linear Collider which can operate at 500 GeV (upgradeable to 1 TeV(
- Based on superconducting RF acceleration
- A Technical Design Report is being prepared
  - Ready to build a machine when LHC discoveries arrive

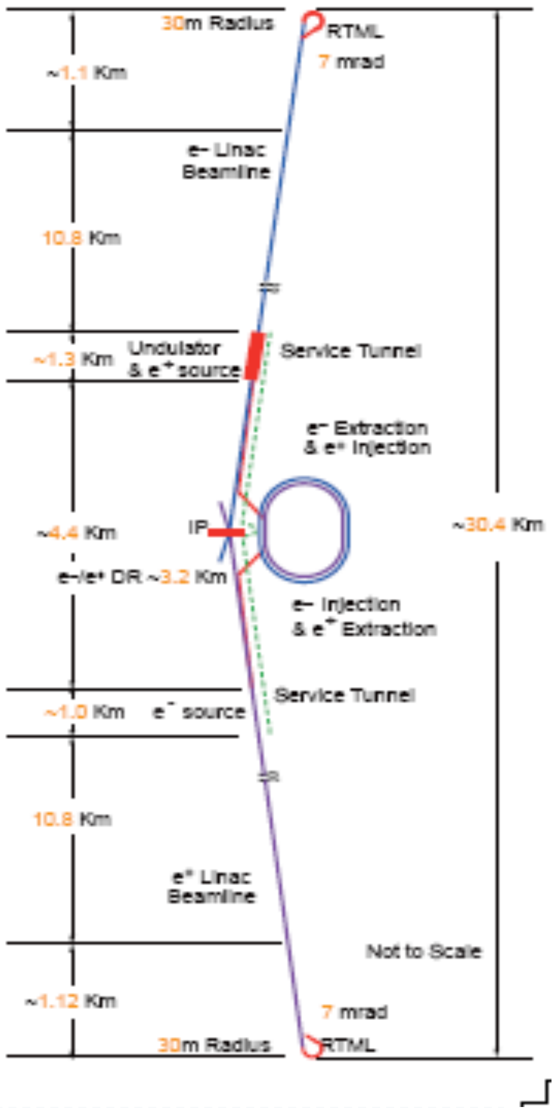


Schematic Layout of the 500 GeV Machine

ILC Design parameters

Max. Center-of-mass energy	500	GeV
Peak Luminosity	$\sim 2 \times 10^{34}$	$1/cm^2 s$
Beam Current	9.0	mA
Repetition rate	5	Hz
Average accelerating gradient	31.5	MV/m
Beam pulse length	0.95	ms
Total Site Length	31	km
Total AC Power Consumption	~230	MW

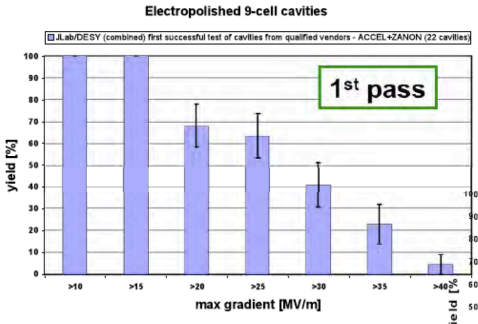
- Machine is 31 km long
- Low repetition rate, but very small beam sizes
- Need to be able to produce a very large number of superconducting RF cavities to accelerate the beams
  - Focus on moving this process into industry
- Careful studies of how to reduce the cost
  - Move to 1 tunnel, smaller damping rings

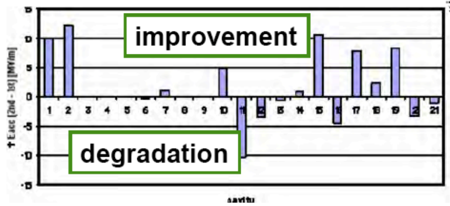


The ILC SCRF Cavity

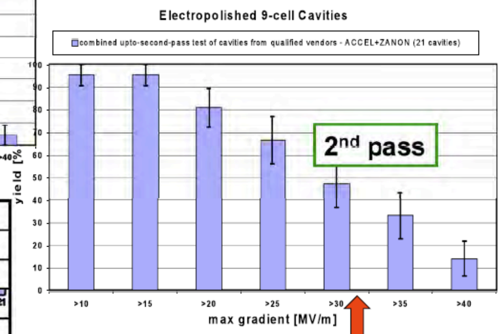
Figure 1.2-1: A TESLA nine-cell 1.3 GHz superconducting niobium cavity.

- ~ 70 parts electron-beam welded at high vacuum
  - mostly stamped 3mm thick sheet metal
- pure niobium and niobium/titanium alloy
  - niobium cost similar to silver
- weight ~ 35 kg (less than 10% cryomodule mass)
- 6 flanges





Yield at 35 MV/m:
22 % at 1st pass
33 % at up to 2nd pass



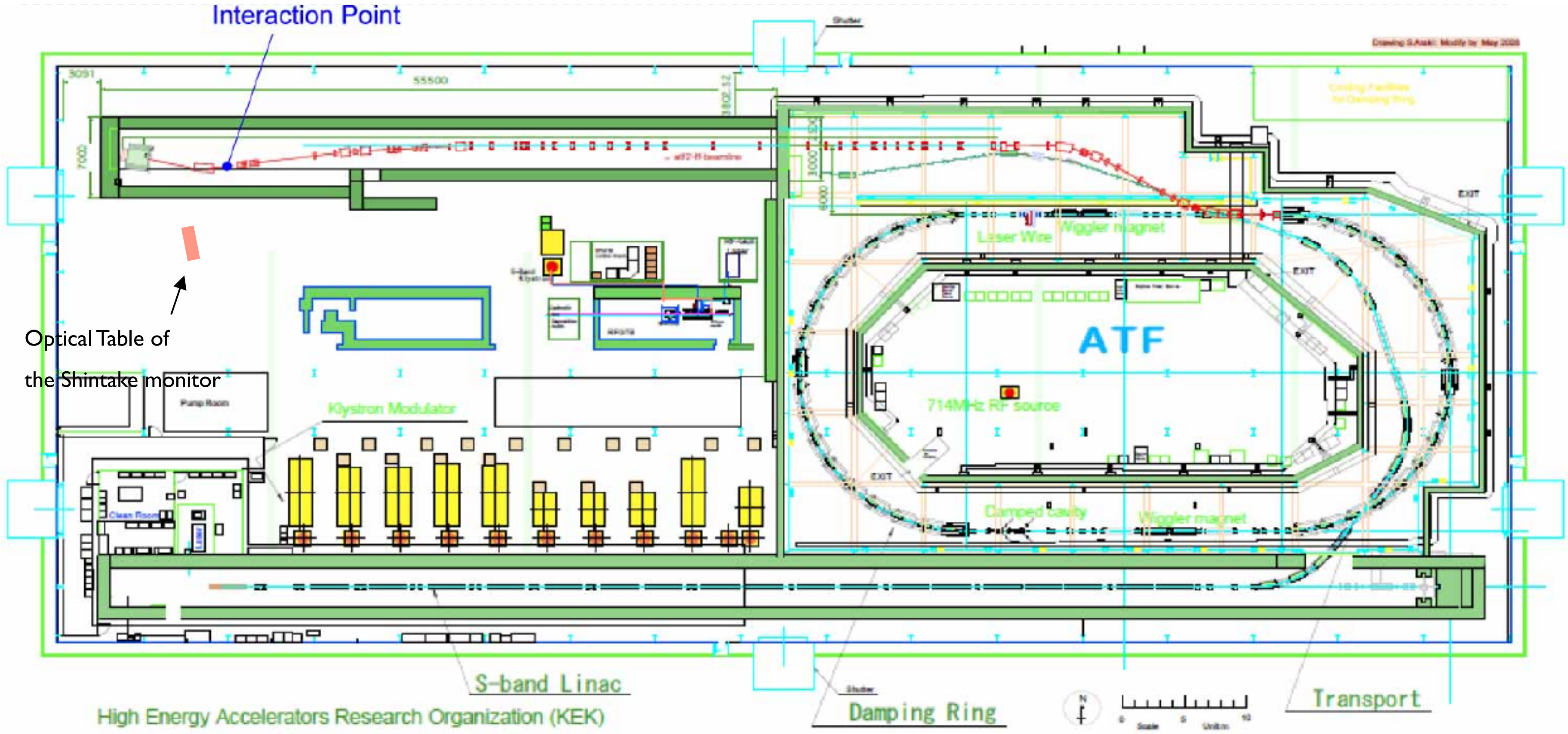
ILC Operation at <31.5 MV/m>

- Achieve high gradient (35MV/m); develop multiple vendors; make cost effective, etc

- Focus is on high gradient; production yields; cryogenic losses; radiation; system performance

B. Foster/B. Barish

Key R&D – Beam Delivery



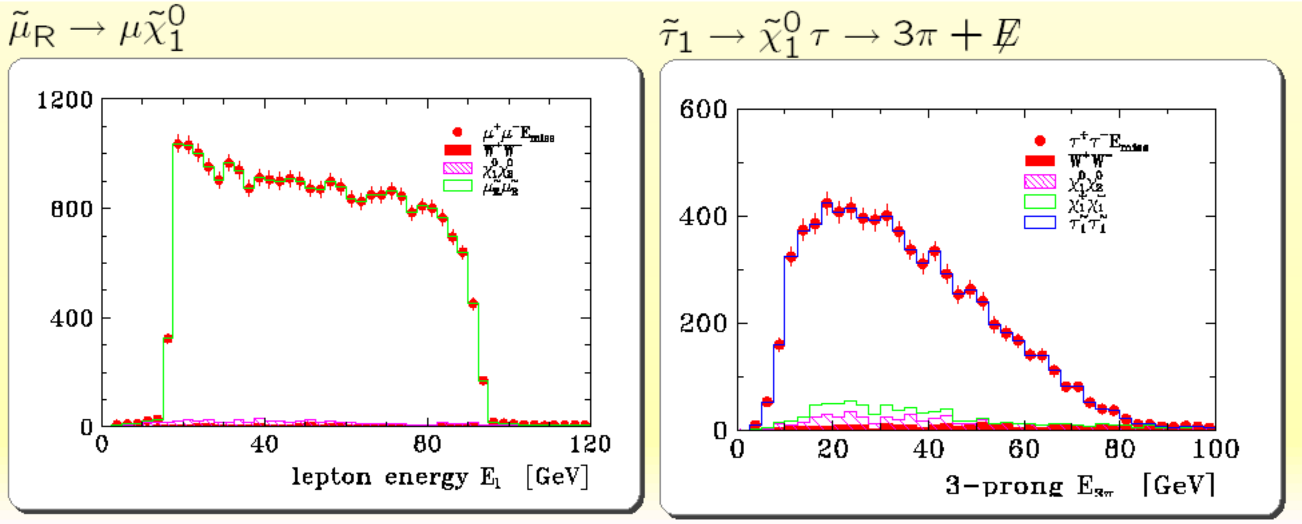
ATF2 Goals

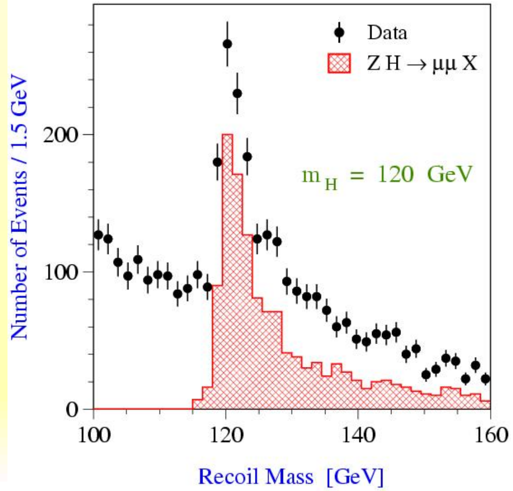
- **<u>Test fast kicker magnet</u>**
- **Focus the electron beam to 35 nm in vertical**
- **Stabilize the vertical beam position with 2 nm resolution**

ATF/ATF2 Layout

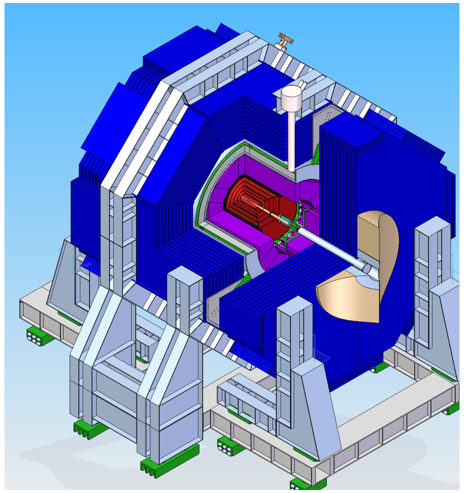
B. Foster

Physics with the ILC





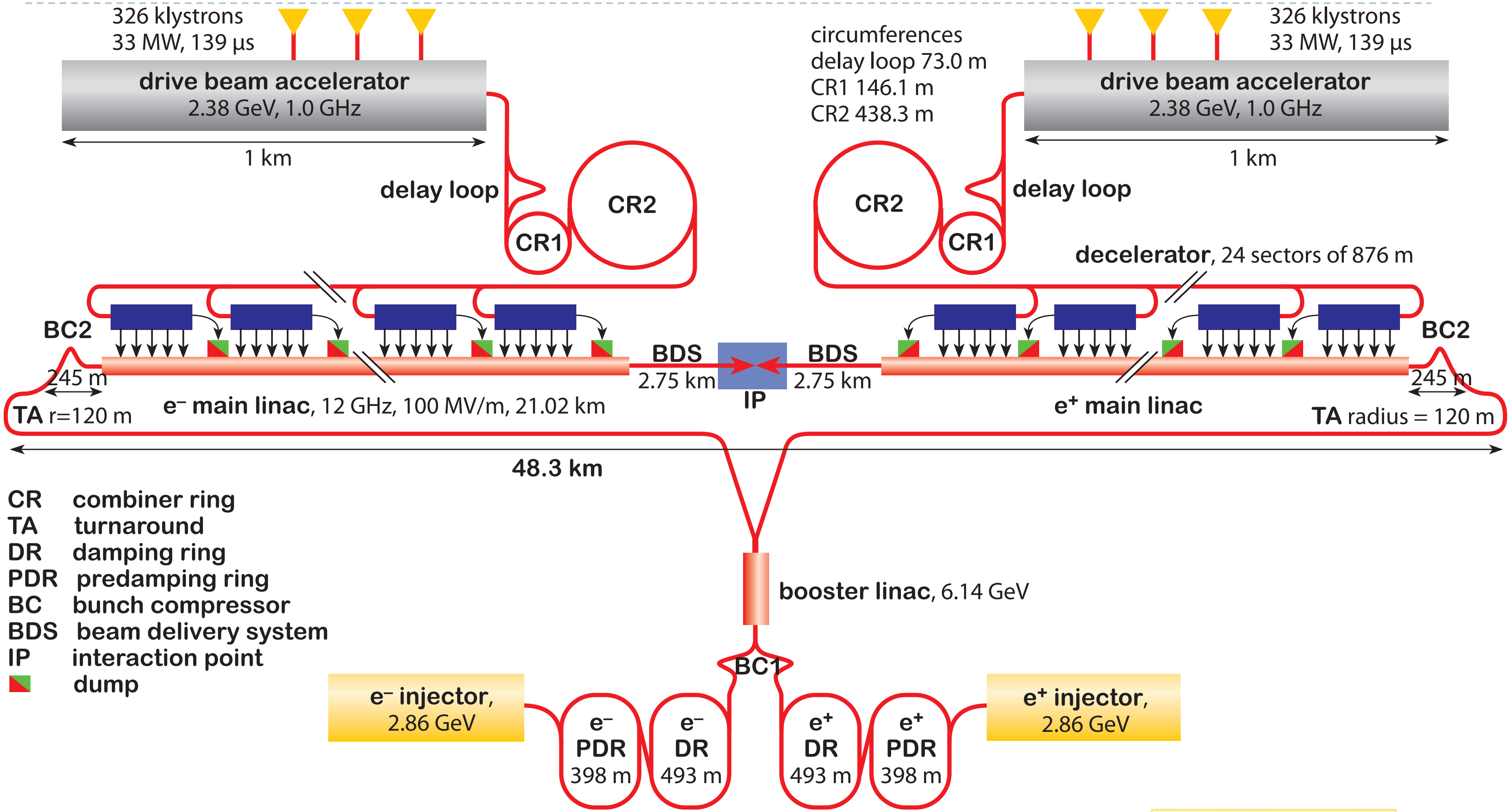
- Lepton colliders offer the ability to make detailed studies of whatever is discovered by the LHC
- Detector concepts and simulations well advanced



Pushing the electron linear collider concept to higher energies

- To move beyond the ILC energy range of about a TeV a higher accelerator gradient is needed
- One concept is the Compact Linear Collider (CLIC)
- Uses a two beam acceleration technique
  - A drive beam is used to create very high accelerating gradients in a second accelerator
  - Achieve 100 MV/m acceleration
  - Aim is potentially a machine that could achieve ~3TeV CM collisions
- This is a very complicated machine and pushes a lot of accelerator technologies
  - A lot of accelerator R/D required to prove the concepts

Reminder: The CLIC Layout



CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump

D. Schulte

CLIC Main Parameters

http://cdsweb.cern.ch/record/1132079?ln=fr http://clic-meeting.web.cern.ch/clic-meeting/clictable2007.html

High gradient to reduce cost

- Break down of structures at high fields and long pulses
  - Pushes to short pulses
  - and small iris radii (high wakefields)

High luminosity

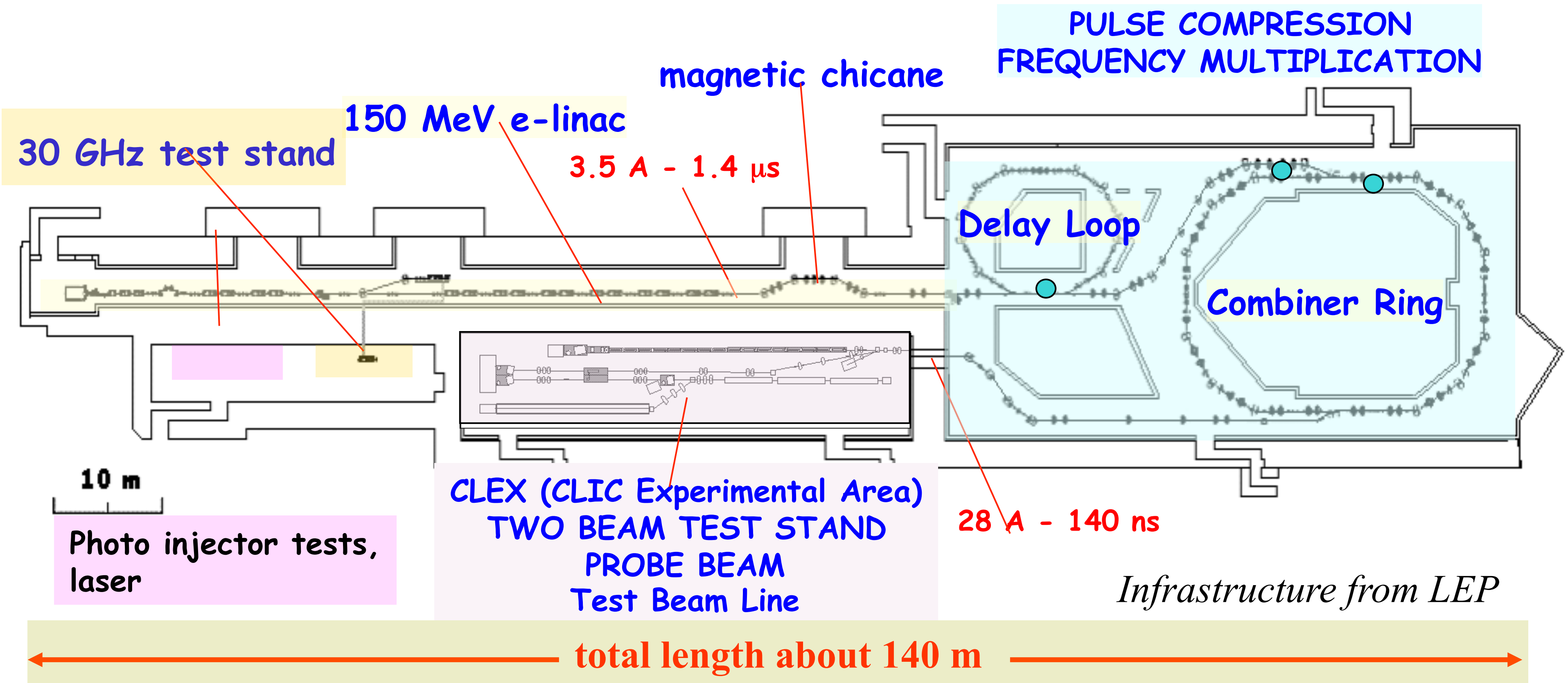
- Improve wall plug to RF efficiency
- Push RF to beam efficiency
  - Push single bunch charge to beam dynamics limit
  - Reduce bunch distance to beam dynamics limit
- Push specific luminosity -> High beam quality
  - Beam-based alignment and tuning
  - Excellent pre-alignment
  - Component stabilisation

		CLIC	CLIC	ILC
E_{cms}	[TeV]	0.5	3.0	0.5
f_{rep}	[Hz]	50	50	5
f_{RF}	[GHz]	12	12	1.3
G_{RF}	[MV/m]	80	100	31.5
n_b		354	312	2625
Δt	[ns]	0.5	0.5	369
N	$[10^9]$	6.8	3.7	20
σ_x	[nm]	202	40	655
σ_y	[nm]	2.26	1	5.7
ϵ_x	[μm]	2.4	0.66	10
ϵ_y	[nm]	25	20	40
$\mathcal{L}_{total}$	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	2.3	5.9	2.0
$\mathcal{L}_{0.01}$	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1.4	2.0	1.45

D. Schulte

Two-Beam Acceleration R/D:
CLIC Test Facility (CTF3)

- Demonstrate Drive Beam generation
  (fully loaded acceleration, beam intensity and bunch frequency multiplication x8)
- Demonstrate RF Power Production and test Power Structures
- Demonstrate Two Beam Acceleration and test Accelerating Structures

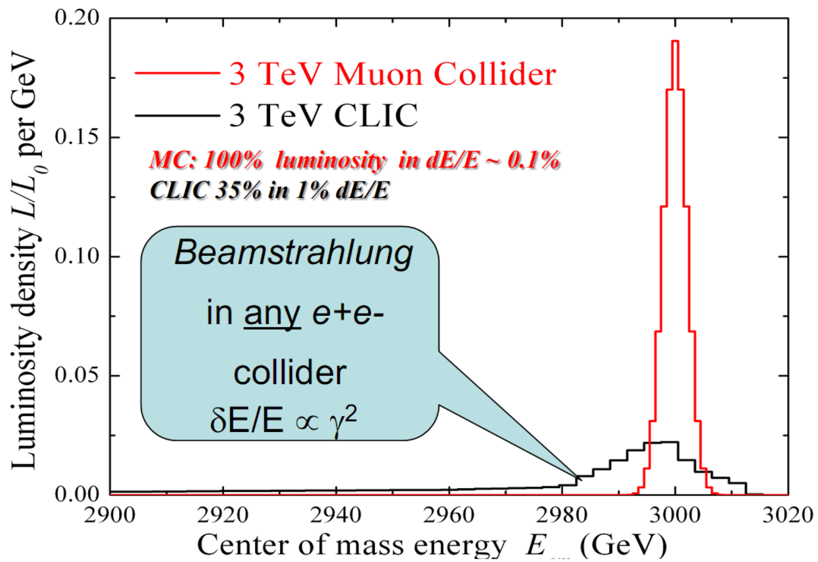


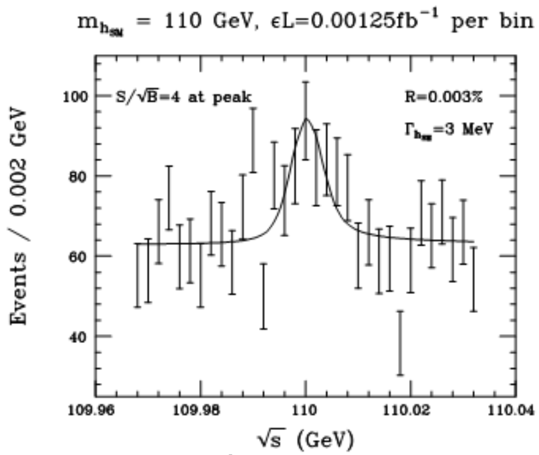
Why not use Muons?

K. Long

Muon mass: 106 Mev/c^2
Electron mass: 0.511 MeV/c^2

- Consequences:
  - Negligible synchrotron radiation at Muon Collider:
    - Rate $\propto m^4$:
      $\Rightarrow$ Muon Collider reduction factor: 5×10^{-10}
    - Compact, *circular*, accelerator
    - Small energy spread
  - Strong coupling to Higgs:
    - Production rate $\propto m^2$:
      $\Rightarrow$ Muon Collider enhancement factor: 5×10^4
    - Large data set allows branching ratios to be measured





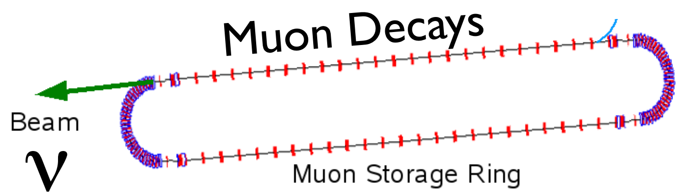
100 pb^{-1}

Using Muons in accelerators

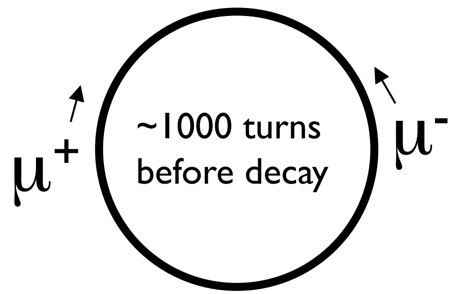
There is the little problem (opportunity) that the muon lifetime is finite (2.2 microseconds)!
Intensity Frontier and Energy Frontier

S. Geer

NEUTRINO FACTORIES in which muons decaying in the straight section of a storage ring create a neutrino beam with unique properties for precision neutrino oscillation measurements.



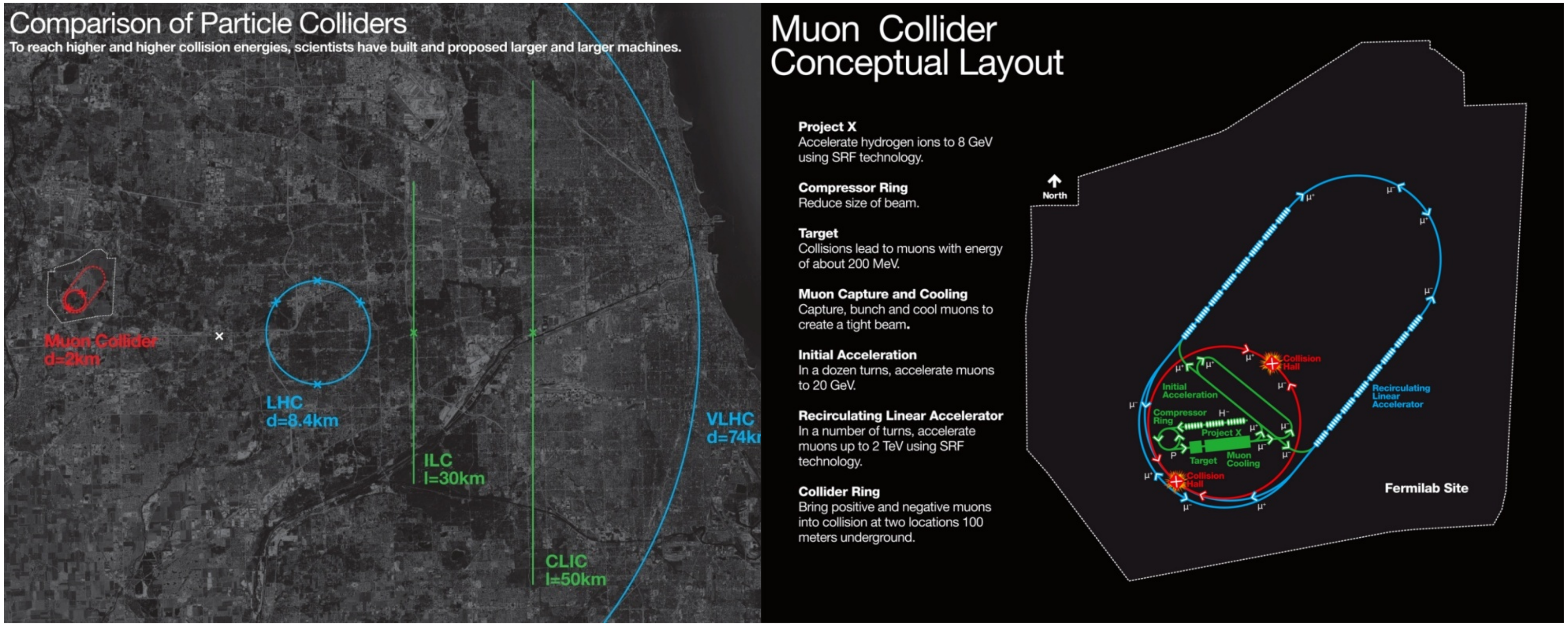
MUON COLLIDERS in which positive & negative muons collide in a storage ring to produce lepton-antilepton collisions up to multi-TeV energies.



Muon colliders are relatively compact

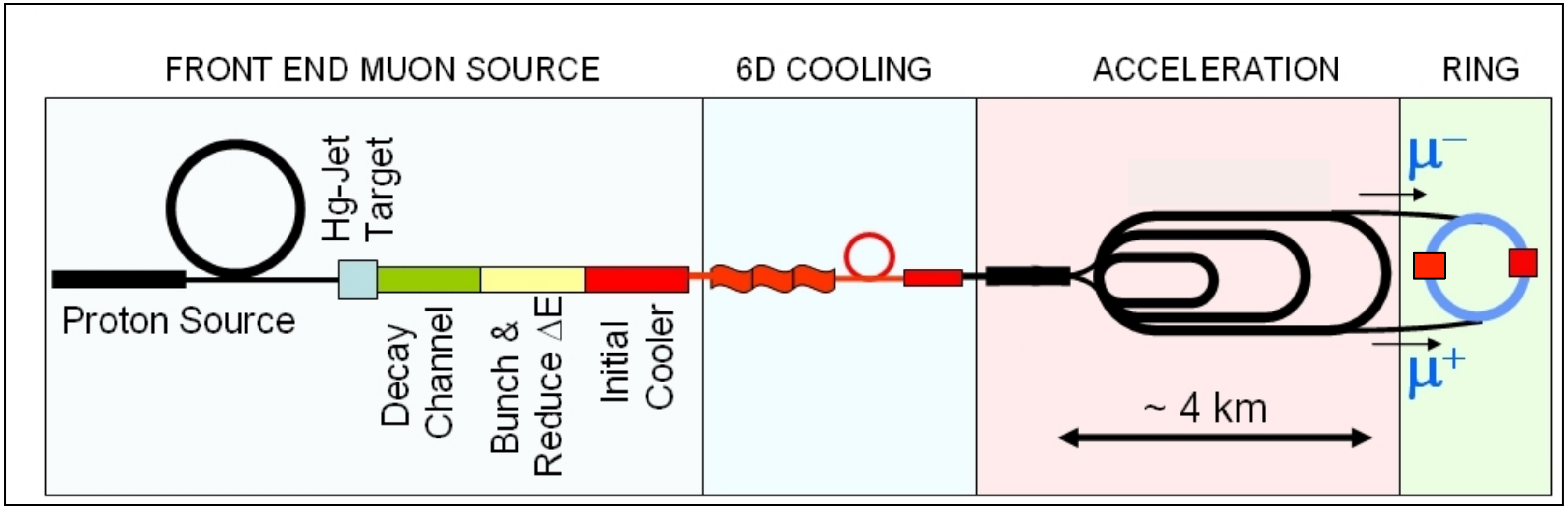
S. Geer

- A 4 TeV muon collider would fit on the Fermilab site:



Ultimate energy limit may come from neutrino radiation issues!

Key accelerator R/D for using Muons

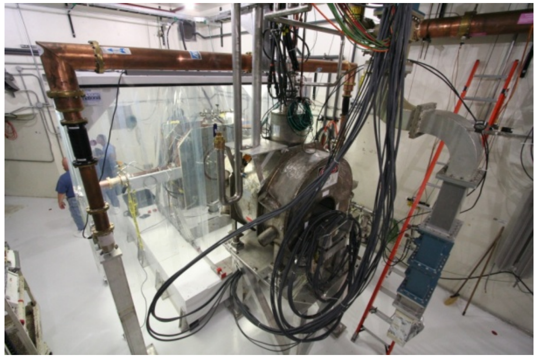


High Power Proton Source

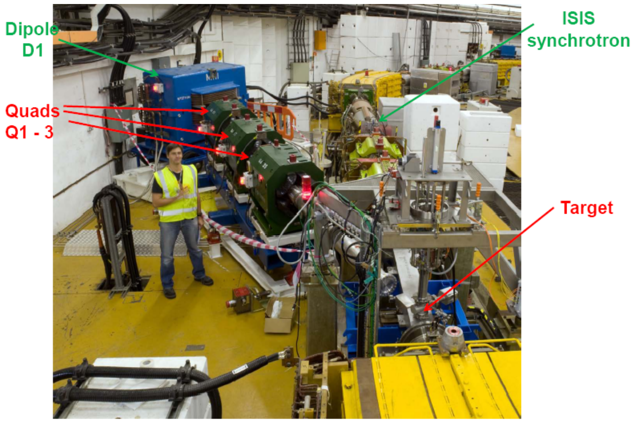
Muon Cooling
10^{21} muons per year that fit within the acceptance of an accelerator

$\sqrt{s}$ = 3 TeV
Circumference = 4.5km
$L = 3{\times}10^{34}$ cm^{-2}s^{-1} μ/ bunch = $2{\times}10^{12}$
$\sigma(p)/p$ = 0.1%
$\varepsilon_{\perp N}$ = 25 μm
β^* = 5mm
Rep Rate = 12Hz

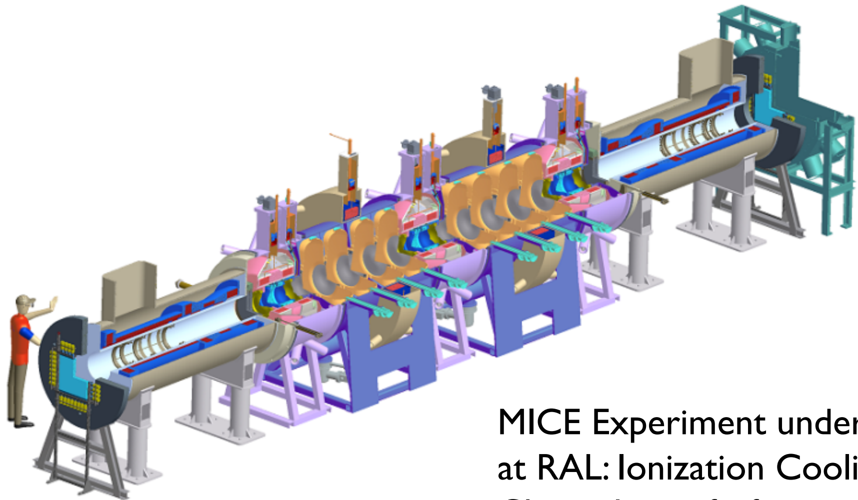
Cooling R/D


MUCOOL Test Area built at FNAL for ionization cooling component testing:
5T magnet, RF power at 805MHz & 201MHz, LH2 handling capability, 400MeV beam from linac.

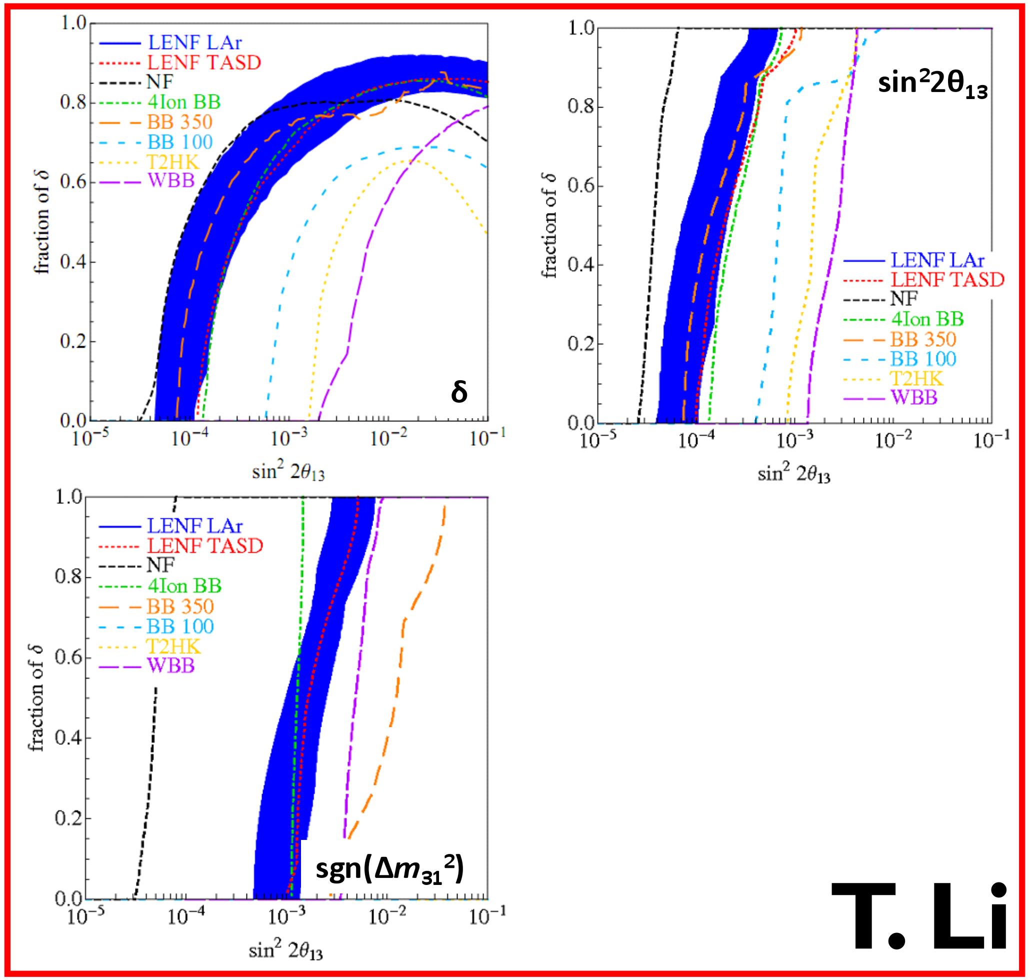


MICE – upstream beamline

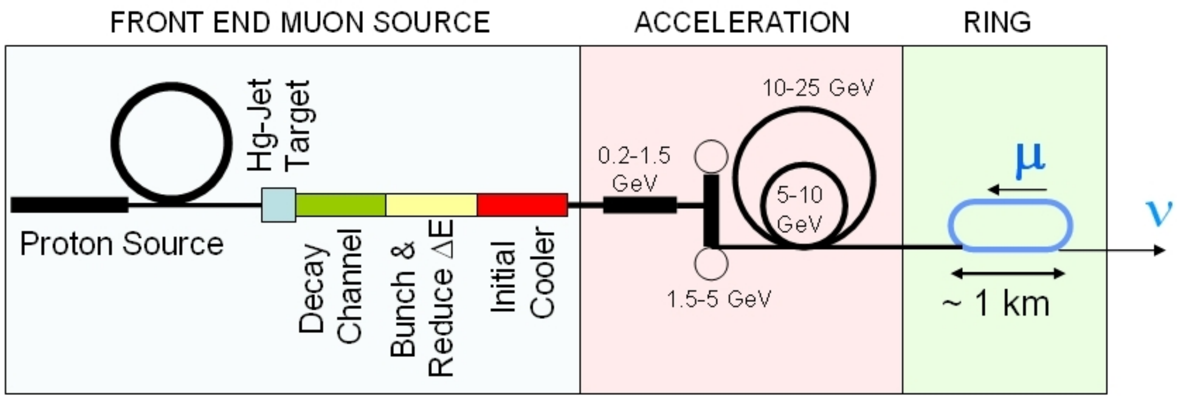


MICE Experiment under way at RAL: Ionization Cooling Channel proof-of-principle

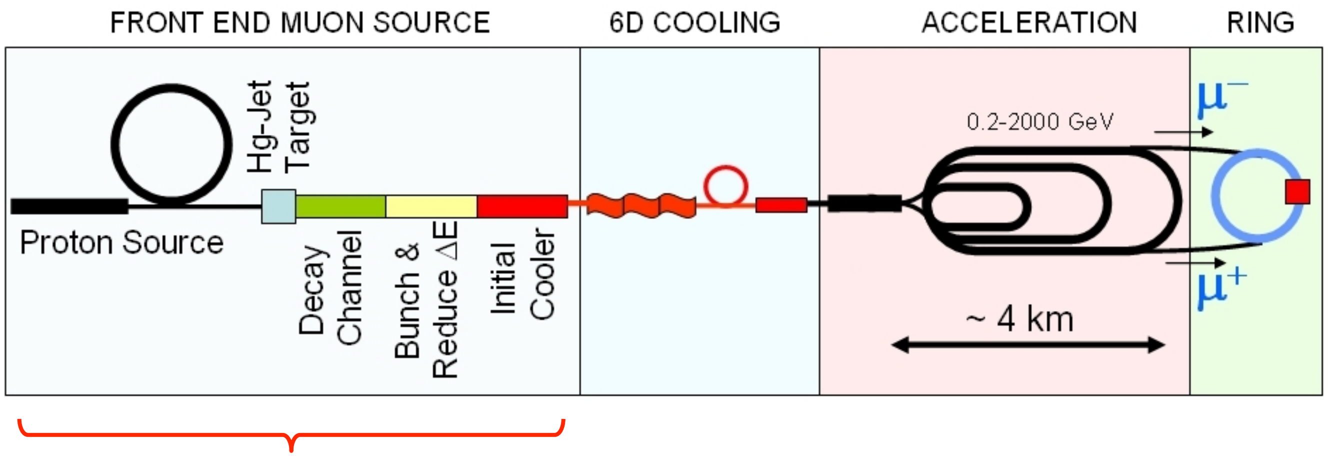
Neutrino Factories – A way to look at CP Violation in the neutrino sector



Overlap in R/D Neutrino Factories



NEUTRINO FACTORY



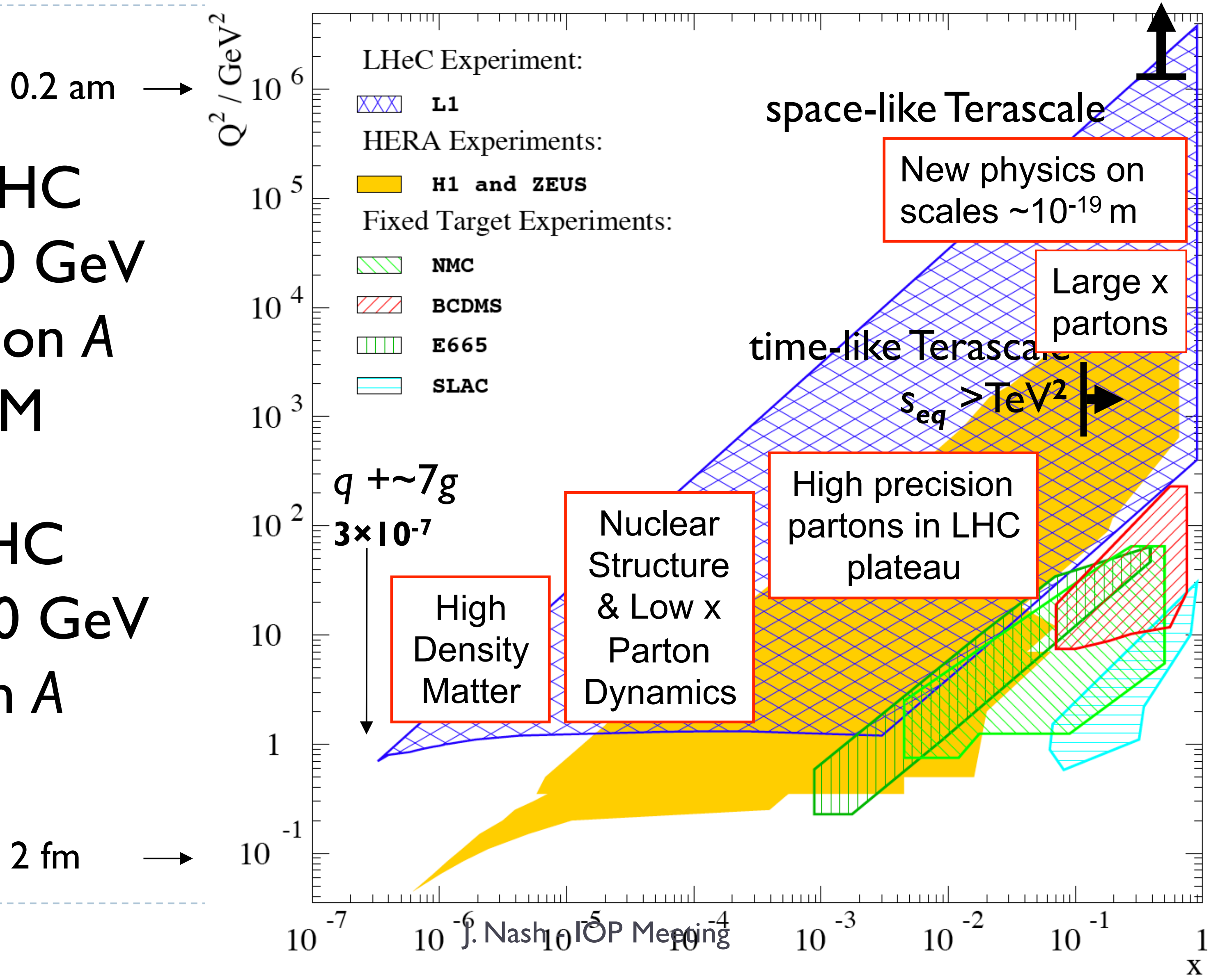
MUON COLLIDER

In present MC baseline design, Front End is same as for NF

J. Dainton

Electron-Proton collisions @ LH*e*C

- e-ring ⊗ LHC
  50 ⊗ 7000 GeV
  e ⊗ *p* or ion *A*
  1.4 TeV CM
- e-linac ⊗ LHC
  140 ⊗ 7000 GeV
  e ⊗ *p* or ion *A*
  2 TeV CM



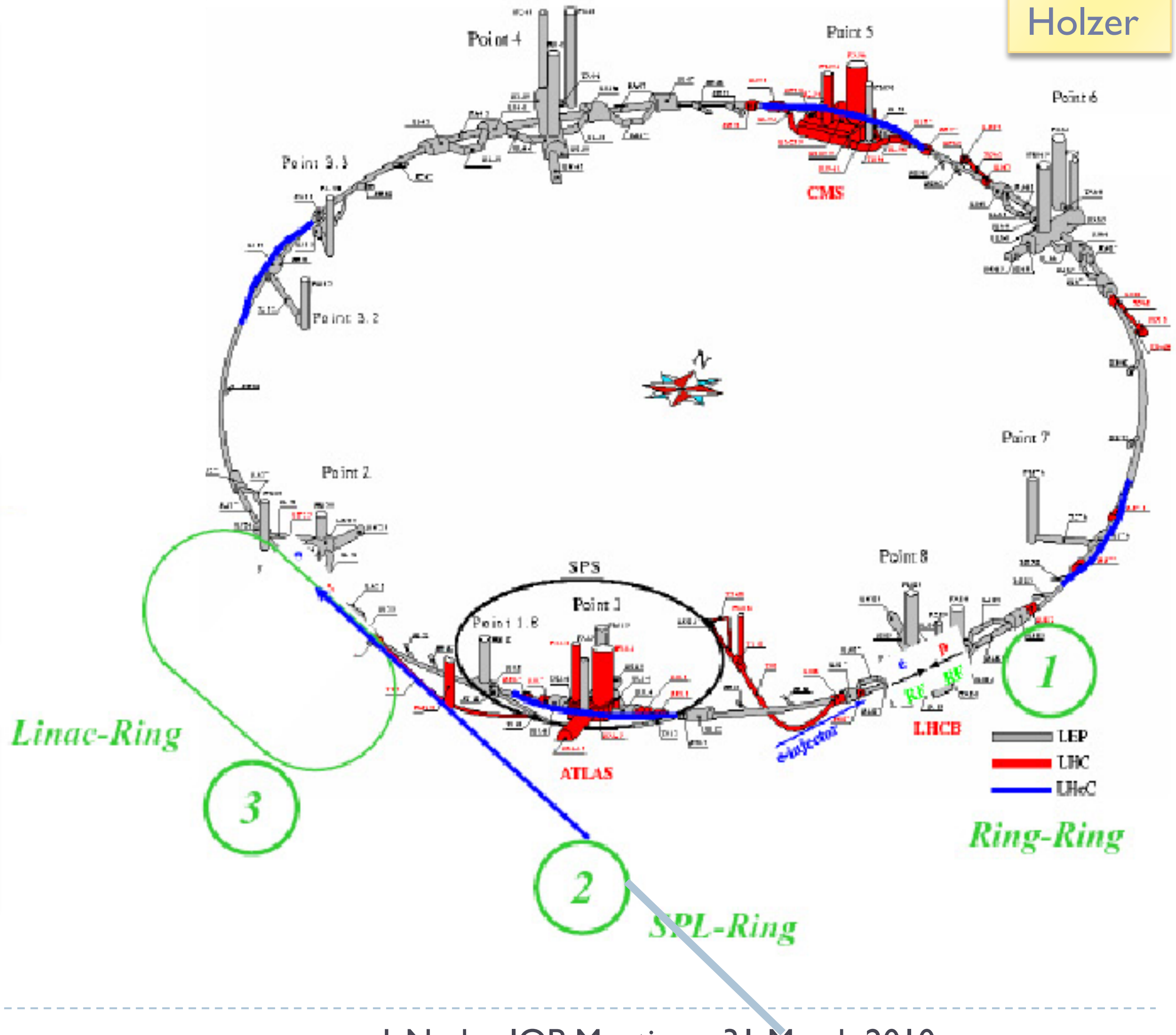
LHeC options

- Ring-Ring 1
  - E_e = 50 GeV
  - 3×10^{33} cm^{-2}s^{-1} acceptance>10°
  - 10^{32} cm^{-2}s^{-1} acceptance>1°

- SPL-Ring 2
  - E_e = 20 GeV
  - 10^{32} cm^{-2}s^{-1}

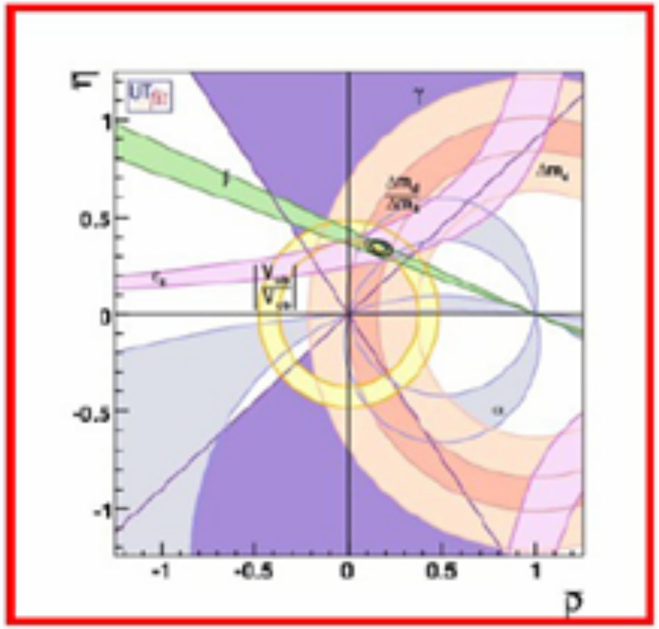
- Linac-Ring 3
  - E_e = 100 GeV
  - 3×10^{32} cm^{-2}s^{-1}

Holzer



Super B – High Luminosity flavour physics

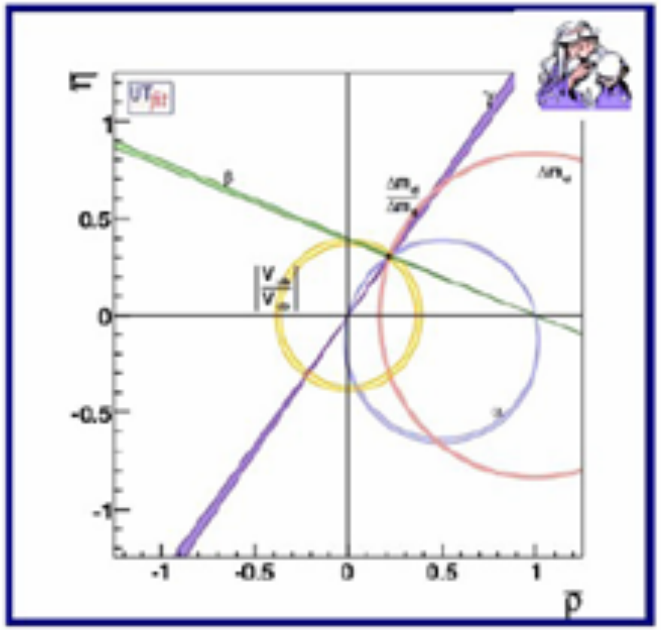
1 ab^{-1}



$\bar{\rho} = 0.163 \pm 0.028$

$\bar{\eta} = 0.344 \pm 0.016$

50 ab^{-1}



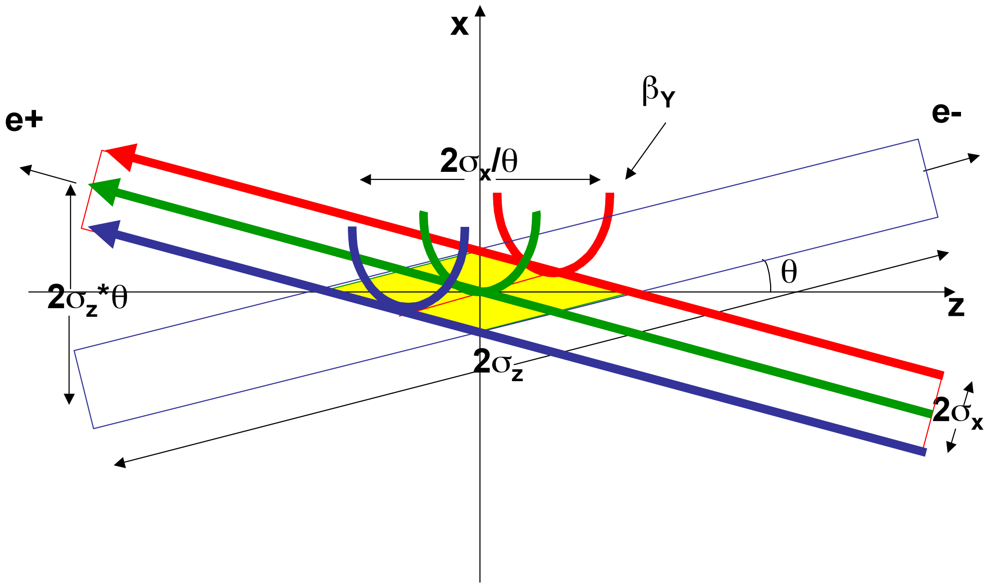
$\bar{\rho} = 0.2226 \pm 0.0028$

$\bar{\eta} = 0.3052 \pm 0.0024$

M. Giorgi

Machine concept : (Crab Waist in 3 Steps)

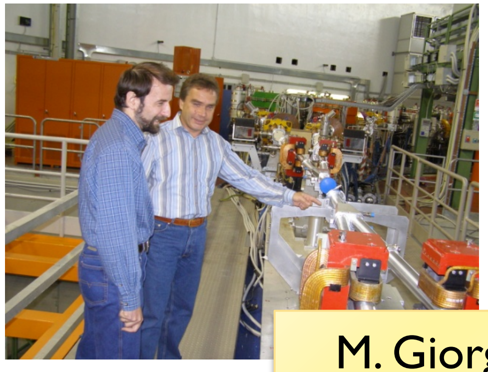
1. Large Piwinski's angle $F = tg(q)s_z/s_x$
2. Vertical beta comparable with overlap area $b_y \approx s_x/q$
3. Crab waist transformation $y = xy'/(2q)$



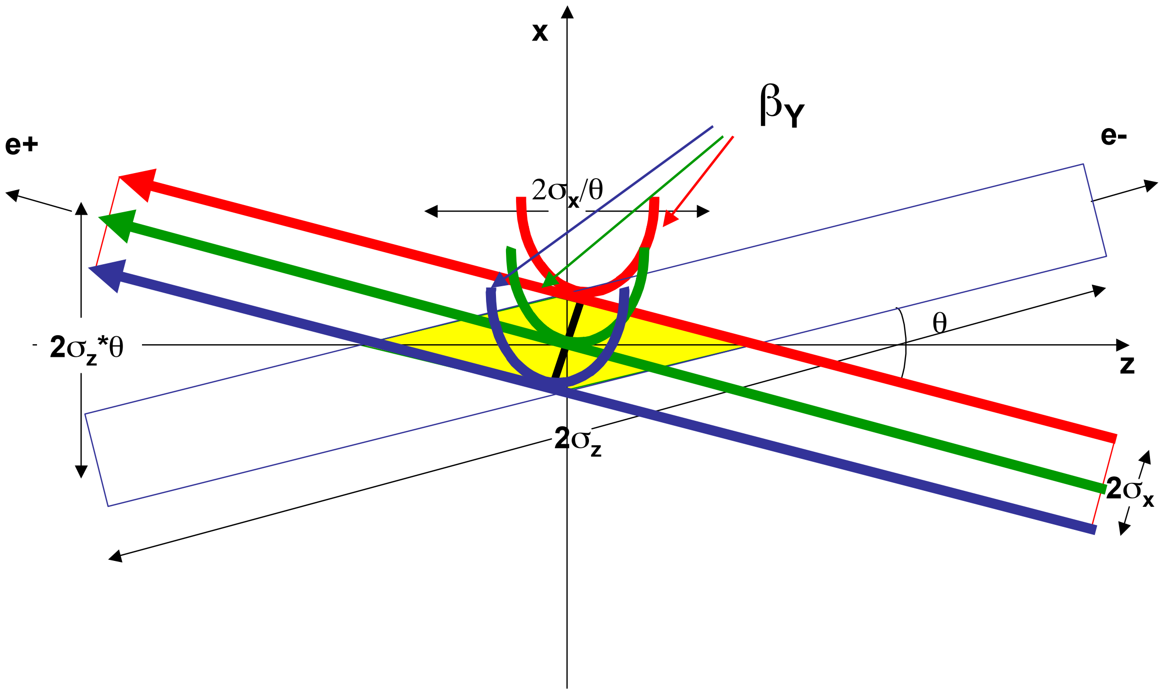
Crabbed waist is realized with a sextupole in phase with the IP in X and at $\pi/2$ in Y

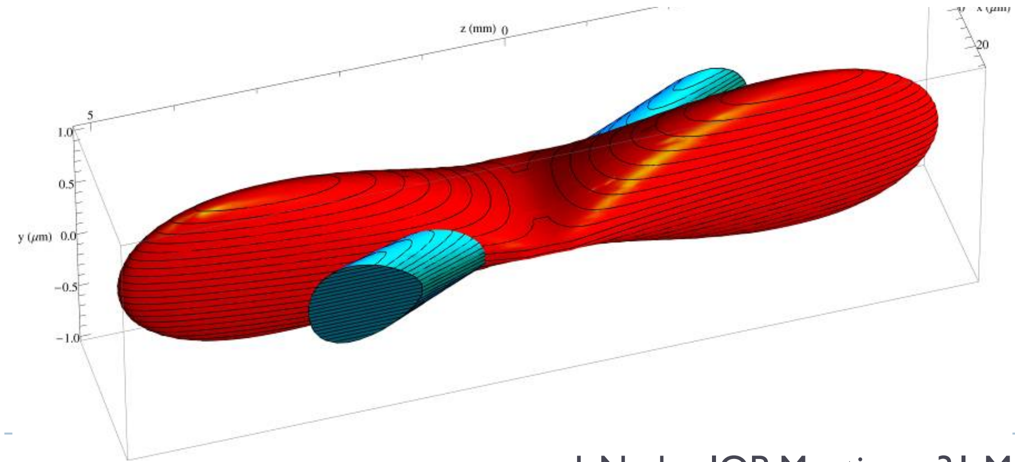
1. *P.Raimondi, 2° SuperB Workshop, March 2006*

2. *P.Raimondi, D.Shatilov, M.Zobov, physics/0702033*



M. Giorgi


x
βY
e+
e-
2σx/θ
2σz*θ
θ
z
2σz
2σx


z (mm) 0
x (μm)
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5
1.0
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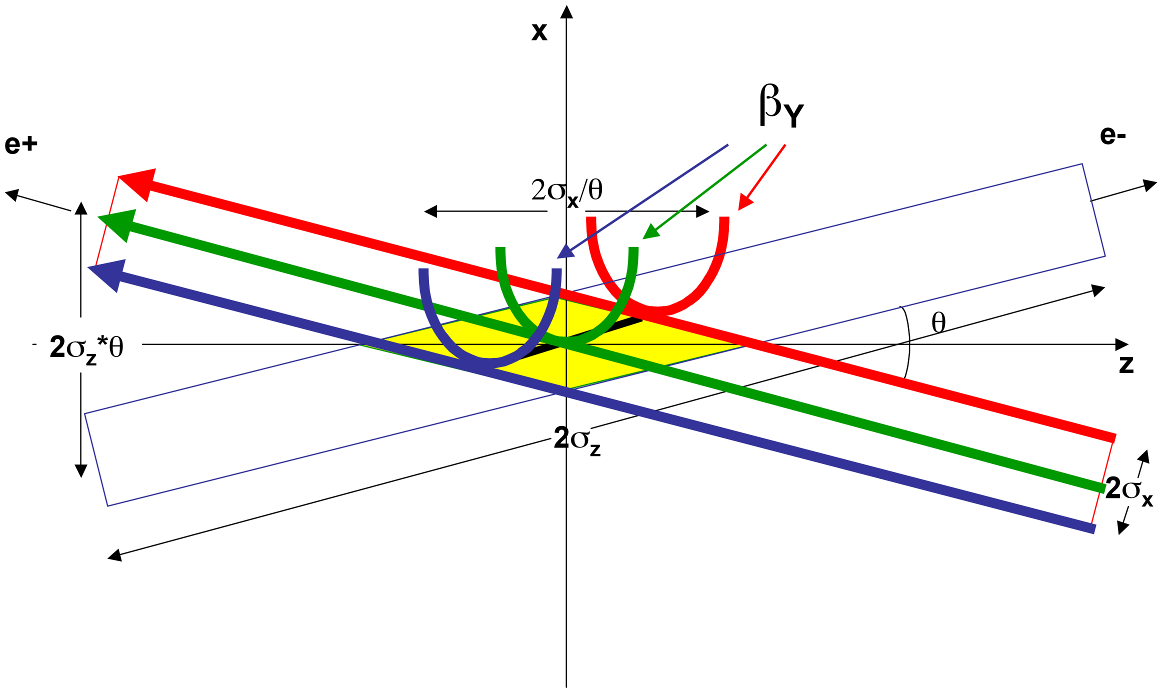
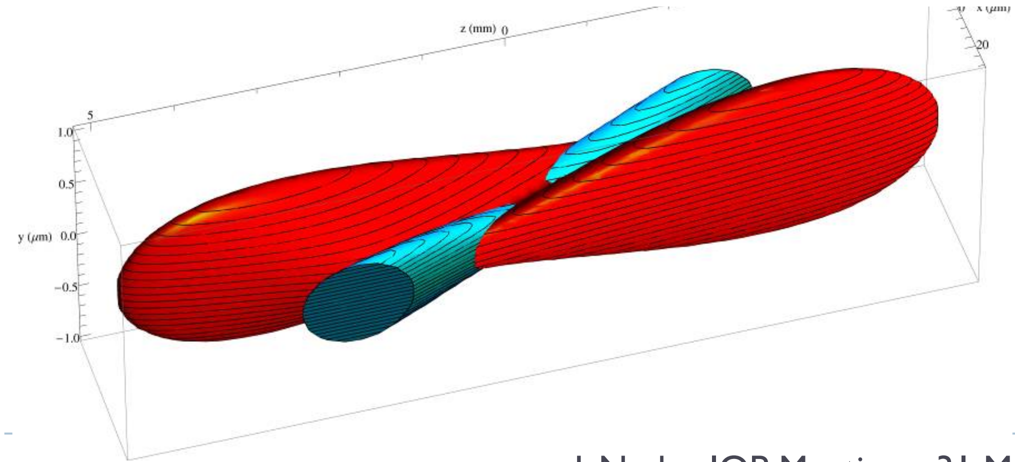
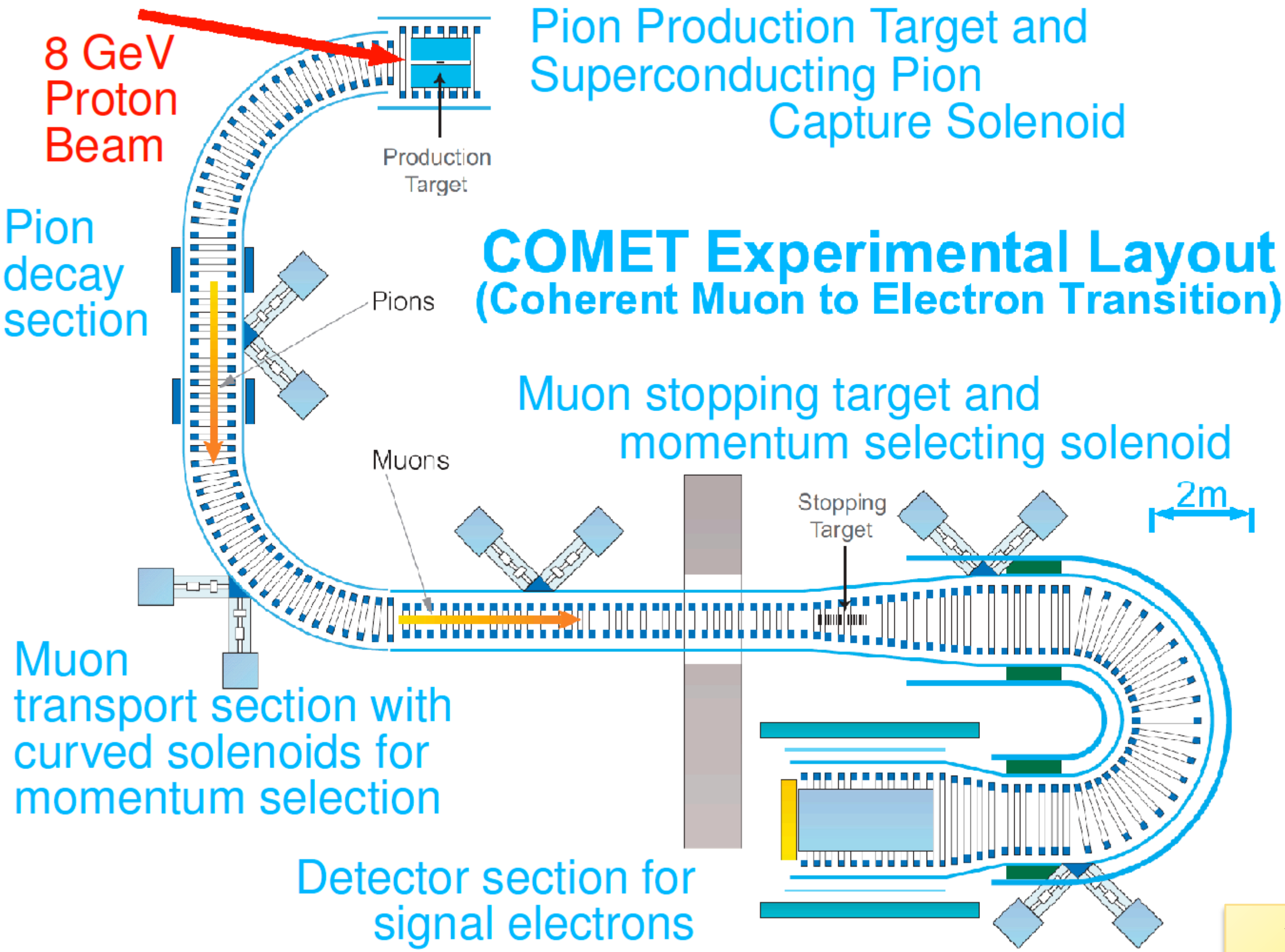
y (μm) 0.0
−0.5
−1.0

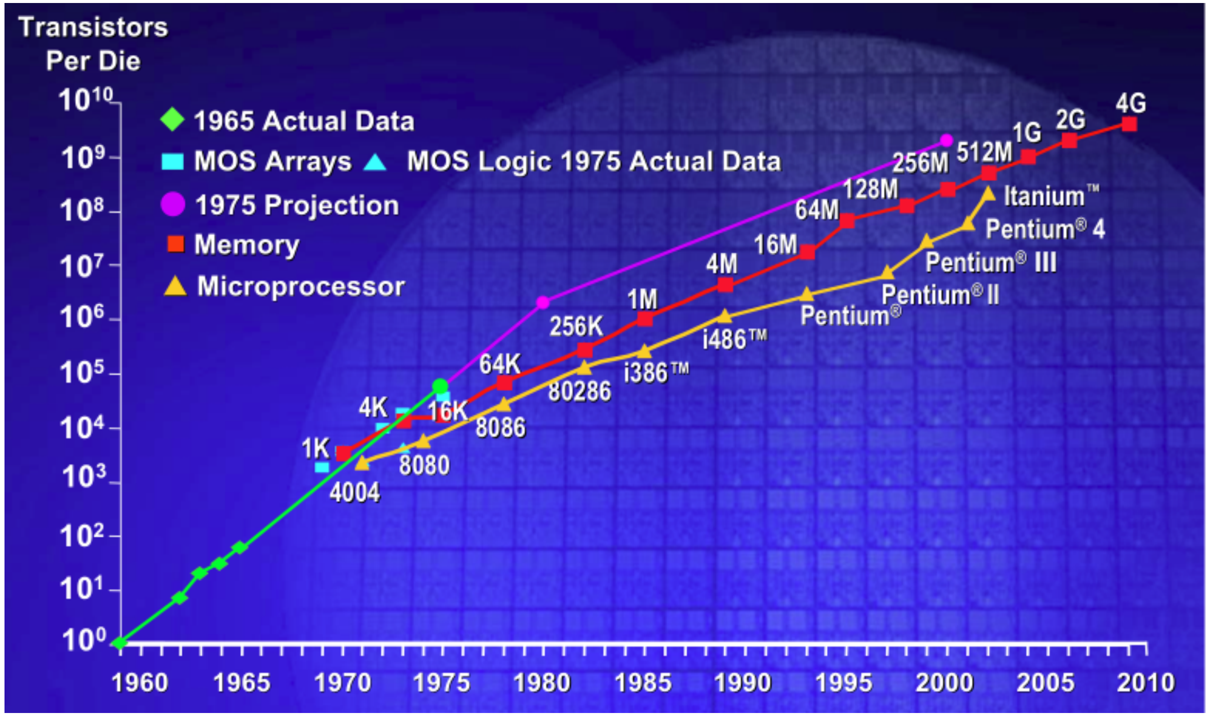

x
β_Y
e+
e-
$2\sigma_x/\theta$
$2\sigma_z*\theta$
θ
z
$2\sigma_z$
$2\sigma_x$


z (mm) 0
x (μm)
20
5
1.0
0.5
y (μm) 0.0
−0.5
−1.0

Smaller scale: muon to electron conversion search - COMET



Y. Uchida

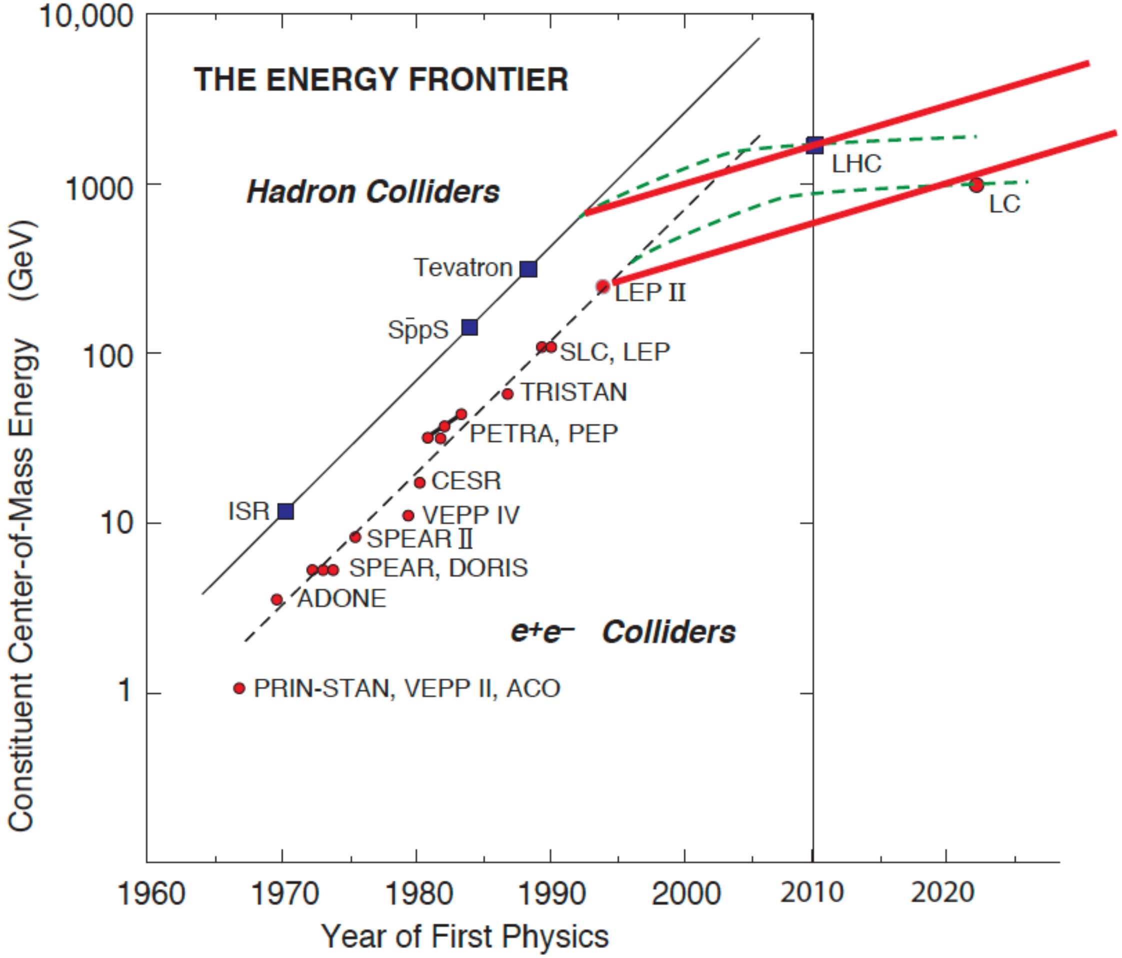


Changes in the rate of progress do happen

There are huge financial incentives to pushing transistor technology

Continued innovation and large investment mean progress continues

There are changes in slope (both positive and negative) which arrive when new concepts are introduced



Is this just a change of slope in rate of progress?

New technologies required to push the frontier

Cost of exploring new solutions is high, hence the rate of change slows

We need to keep pushing hard on accelerator R/D in order to keep pushing back the frontiers we will be able to look at with accelerators