Higgs Factory Workshops Review

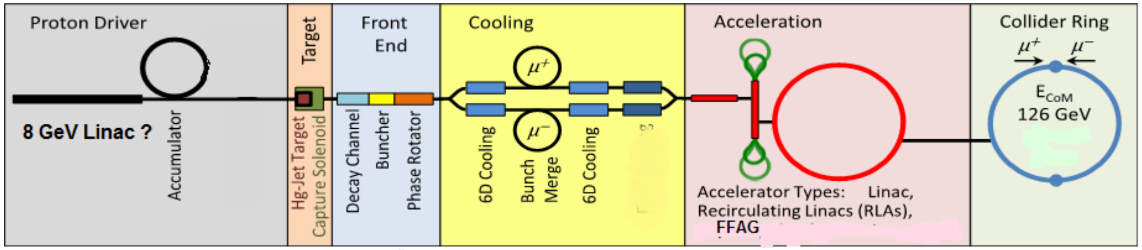
David Neuffer

December 2012

Outline

- **Introduction**
  - Motivation
- ***Higgs Muon Collider mini-workshop***
  - *(November 13, 2012)*
    - *https://indico.fnal.gov/conferenceDisplay.py?confId=6046*
- **Accelerators for a Higgs Factory (linear vs. circular)**
  - *(November 14-16, 2012)*
    - *https://indico.fnal.gov/conferenceDisplay.py?confId=5775*
- ***Higgs 2013* (UCLA)**
  - *(March 21-23, 2013)*
  - *https://hepconf.physics.**ucla**.edu/**higgs**2013/*

Nov. 12 Miniworkshop Schedule




Tuesday 13 November 2012

08:30 - 10:10 Muon Collider Higgs Factory Introduction
Convener: Jean-Pierre Delahaye (SLAC)

08:30 **Welcome** *10'*
Speaker: Pier Oddone (Fermilab)

08:40 **Workshop Goals and Critical Issues** *20'*
Speaker: Mark Palmer (Fermilab)
Material: Slides

09:00 **Physics Motivation** *30'*
Speaker: Estia Eichten (Fermilab)
Material: Slides

09:30 **Scenario Overview and Options** *30'*
Speaker: David Neuffer (Fermilab)
Material: Slides

10:00 **Discussion** *10'*

10:10 - 10:30 Coffee Break

10:30 - 11:30 Proton Source (various options) and Target
Convener: Ronald Lipton (Fermilab)

10:30 **Project X Proton Source** *15'*
Speaker: Keith Gollwitzer (Fermilab)
Material: Slides

10:45 **Superconducting Rapid Cycling Synchrotron as High-Power Proton S**
Speaker: Henryk Piekarz (Fermilab)
Material: Slides

11:00 **Proton Source Options** *15'*
Speaker: Charles Ankenbrandt (Muons, Inc.)
Material: Slides

11:15 **Discussion** *15'*

11:30 - 12:45 Cooling Channel and Acceleration
Convener: Charles Ankenbrandt (Muons, Inc.)

11:30 **Cooling Channel Designs** *20'*
Speaker: Robert B Palmer (Brookhaven National lab)
Material: Slides

11:50 **Helical Cooling Channel Options** *20'*
Speaker: Katsuya Yonehara (Fermilab)
Material: Slides

12:10 **Acceleration Scheme with Project X Linac** *20'*
Speaker: Valeri Lebedev (Fermilab)
Material: Slides


14:00 **Higgs Factory Collider Ring** *15'*
Speaker: Pavel Snopok (IIT/Fermilab)
Material: Slides

14:15 **Updated Higgs Factory Collider Ring Design** *25'*
Speaker: Yuri Alexahin (Fermilab)
Material: Slides

14:40 **Energy Measurement with Polarization** *15'*
Speaker: Rajendran Raja (Fermilab)
Material: Slides

14:55 **Plasma Lens** *15'*
Speaker: Stephen Kahn (Muons Inc)
Material: Slides

15:10 **Discussion** *15'*

15:25 - 16:10 Detector and Background
Convener: Pavel Snopok (IIT/Fermilab)

15:25 **Background Simulation** *20'*
Speaker: Nikolai Terentiev (Carnegie Mellon U, USA)
Material: Slides

15:45 **Detector Considerations** *25'*
Speaker: Ronald Lipton (Fermilab)
Material: Slides

16:10 - 16:30 Coffee Break

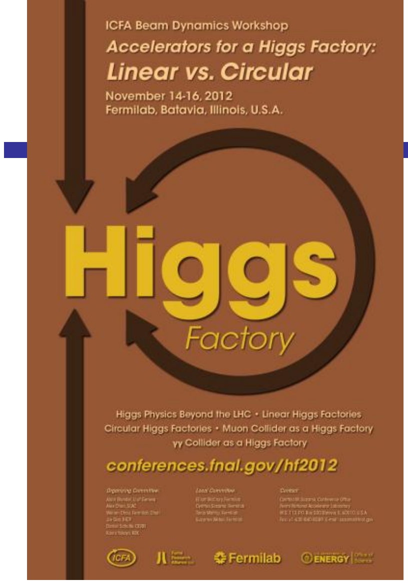
16:30 - 17:00 Detector and Background
Convener: Pavel Snopok (IIT/Fermilab)

16:30 **Polarization and Detector Comments** *15'*
Speaker: Alain Blondel (DPNC Université de Genève)
Material: Slides

16:45 **Discussion** *15'*

17:00 - 17:40 DISCUSSION on Options for a Staged Approach (MASS) - Moderated by J.P. Delahaye *40'*
Speaker: Jean-Pierre Delahaye (SLAC)
Material: Slides Snowmass report

Schedule Nov. 14-16


ICFA Beam Dynamics Workshop
Accelerators for a Higgs Factory:
Linear vs. Circular
November 14-16, 2012
Fermilab, Batavia, Illinois, U.S.A.

Higgs Physics Beyond the LHC • Linear Higgs Factories
Circular Higgs Factories • Muon Collider as a Higgs Factory
γγ Collider as a Higgs Factory

conferences.fnal.gov/hf2012


Wednesday 14 November 2012

08:00 - 09:00 Registration
Location: Wilson Hall - Atrium

09:00 - 12:30 Welcome, Introduction and Physics
Convener: Alain Blondel (University of Geneva)

09:00 **Welcome** *05'*
Speaker: Pier Oddone (Fermilab)

09:05 **Strategy for Higgs Study** *20'*
Speaker: Young-Kee Kim (FNAL)
Material: Slides

09:30 **Higgs at the LHC** *30'*
Speaker: Fabio Cerutti (LBNL - Berkeley)
Material: Slides

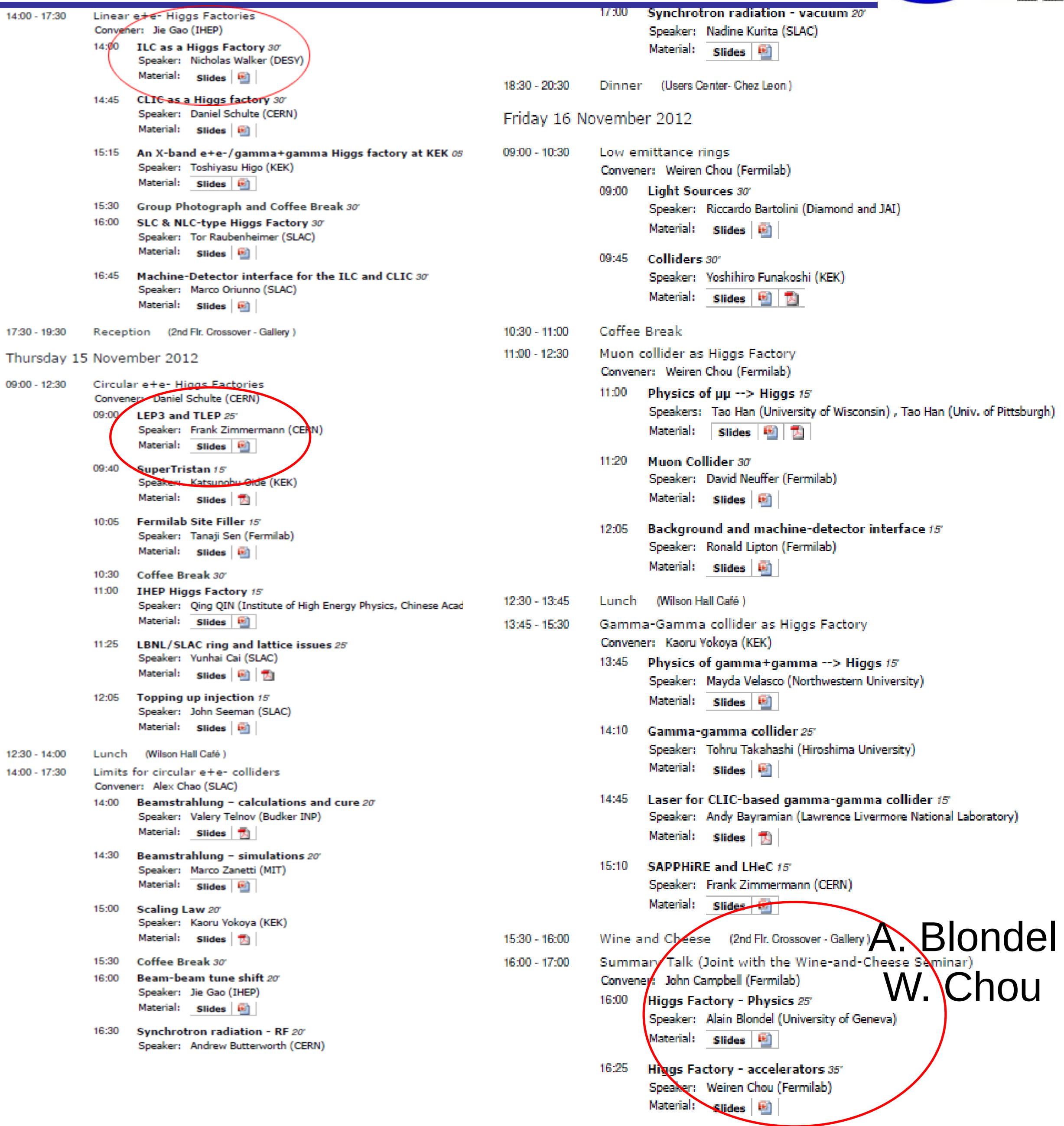
10:10 **Higgs beyond the LHC - theories** *30'*
Speaker: Chris Quigg (Fermilab)
Material: Slides

10:55 Coffee Break *20'*

11:15 **Higgs beyond the LHC - experiment**
Speaker: Patrick JANOT (CERN Geneva, S
Material: Slides

12:00 **Accelerators for a Higgs Factory** *20'*
Speaker: Stuart Henderson (Fermilab)
Material: Slides

12:30 - 14:00 Lunch (Wilson Hall Café)


14:00 - 17:30 Linear e+e- Higgs Factories
Convener: Jie Gao (IHEP)

14:00 **ILC as a Higgs Factory** *30'*
Speaker: Nicholas Walker (DESY)
Material: Slides

14:45 **CLIC as a Higgs factory** *30'*
Speaker: Daniel Schulte (CERN)
Material: Slides

15:15 **An X-band e+e-/gamma+gamma Higgs factory at KEK** *05*
Speaker: Toshiyasu Higo (KEK)
Material: Slides

15:30 Group Photograph and Coffee Break *30'*

16:00 **SLC & NLC-type Higgs Factory** *30'*
Speaker: Tor Raubenheimer (SLAC)
Material: Slides

16:45 **Machine-Detector interface for the ILC and CLIC** *30'*
Speaker: Marco Oriunno (SLAC)
Material: Slides

17:30 - 19:30 Reception (2nd Flr. Crossover - Gallery)

Thursday 15 November 2012

09:00 - 12:30 Circular e+e- Higgs Factories
Convener: Daniel Schulte (CERN)

09:00 **LEP3 and TLEP** *25'*
Speaker: Frank Zimmermann (CERN)
Material: Slides

09:40 **SuperTristan** *15'*
Speaker: Katsunobu Oide (KEK)
Material: Slides

10:05 **Fermilab Site Filler** *15'*
Speaker: Tanaji Sen (Fermilab)
Material: Slides

10:30 Coffee Break *30'*

11:00 **IHEP Higgs Factory** *15'*
Speaker: Qing QIN (Institute of High Energy Physics, Chinese Acad
Material: Slides

11:25 **LBNL/SLAC ring and lattice issues** *25'*
Speaker: Yunhai Cai (SLAC)
Material: Slides

12:05 **Topping up injection** *15'*
Speaker: John Seeman (SLAC)
Material: Slides

12:30 - 14:00 Lunch (Wilson Hall Café)

14:00 - 17:30 Limits for circular e+e- colliders
Convener: Alex Chao (SLAC)

14:00 **Beamstrahlung – calculations and cure** *20'*
Speaker: Valery Telnov (Budker INP)
Material: Slides

14:30 **Beamstrahlung – simulations** *20'*
Speaker: Marco Zanetti (MIT)
Material: Slides

15:00 **Scaling Law** *20'*
Speaker: Kaoru Yokoya (KEK)
Material: Slides

15:30 Coffee Break *30'*

16:00 **Beam-beam tune shift** *20'*
Speaker: Jie Gao (IHEP)
Material: Slides

16:30 **Synchrotron radiation - RF** *20'*
Speaker: Andrew Butterworth (CERN)

17:00 **Synchrotron radiation - vacuum** *20'*
Speaker: Nadine Kurita (SLAC)
Material: Slides

18:30 - 20:30 Dinner (Users Center- Chez Leon)

Friday 16 November 2012

09:00 - 10:30 Low emittance rings
Convener: Weiren Chou (Fermilab)

09:00 **Light Sources** *30'*
Speaker: Riccardo Bartolini (Diamond and JAI)
Material: Slides

09:45 **Colliders** *30'*
Speaker: Yoshihiro Funakoshi (KEK)
Material: Slides

10:30 - 11:00 Coffee Break

11:00 - 12:30 Muon collider as Higgs Factory
Convener: Weiren Chou (Fermilab)

11:00 **Physics of μμ --> Higgs** *15'*
Speakers: Tao Han (University of Wisconsin) , Tao Han (Univ. of Pittsburgh)
Material: Slides

11:20 **Muon Collider** *30'*
Speaker: David Neuffer (Fermilab)
Material: Slides

12:05 **Background and machine-detector interface** *15'*
Speaker: Ronald Lipton (Fermilab)
Material: Slides

12:30 - 13:45 Lunch (Wilson Hall Café)

13:45 - 15:30 Gamma-Gamma collider as Higgs Factory
Convener: Kaoru Yokoya (KEK)

13:45 **Physics of gamma+gamma --> Higgs** *15'*
Speaker: Mayda Velasco (Northwestern University)
Material: Slides

14:10 **Gamma-gamma collider** *25'*
Speaker: Tohru Takahashi (Hiroshima University)
Material: Slides

14:45 **Laser for CLIC-based gamma-gamma collider** *15'*
Speaker: Andy Bayramian (Lawrence Livermore National Laboratory)
Material: Slides

15:10 **SAPPHiRE and LHeC** *15'*
Speaker: Frank Zimmermann (CERN)
Material: Slides

15:30 - 16:00 Wine and Cheese (2nd Flr. Crossover - Gallery)

16:00 - 17:00 Summary Talk (Joint with the Wine-and-Cheese Seminar)
Convener: John Campbell (Fermilab)

16:00 **Higgs Factory - Physics** *25'*
Speaker: Alain Blondel (University of Geneva)
Material: Slides

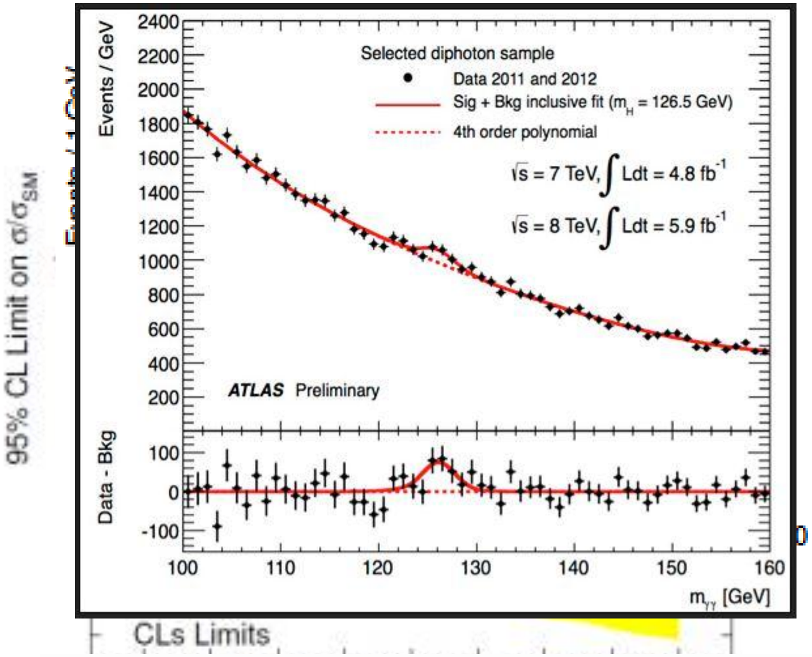
16:25 **Higgs Factory - accelerators** *35'*
Speaker: Weiren Chou (Fermilab)
Material: Slides

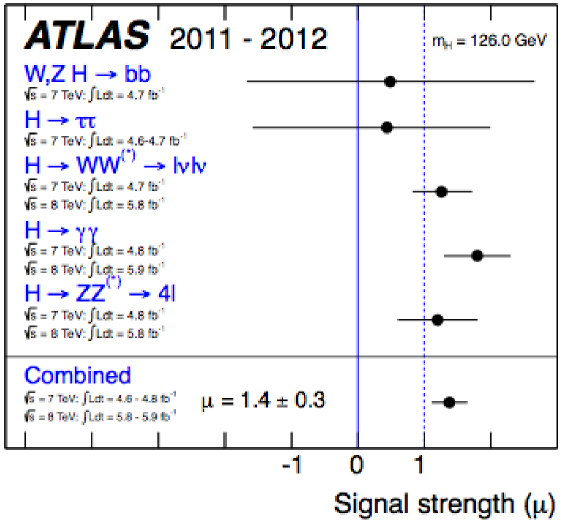
A. Blondel
W. Chou

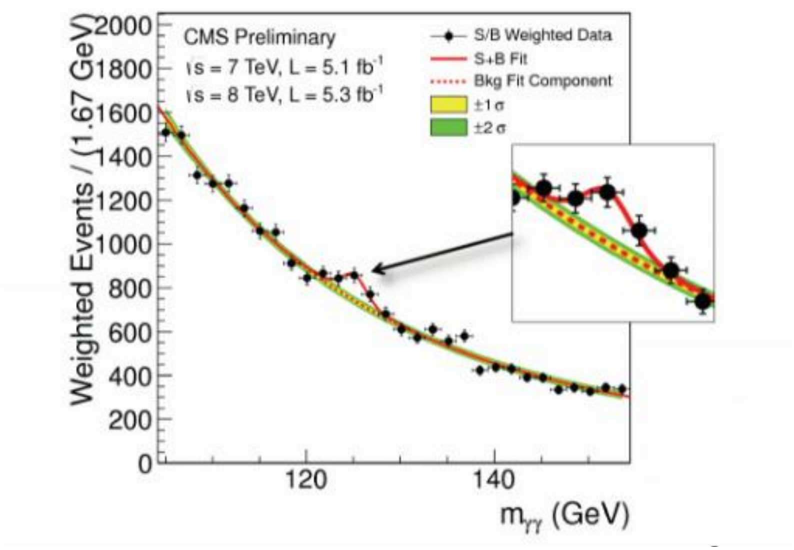
125 GeV Higgs!

Low Mass Higgs ?

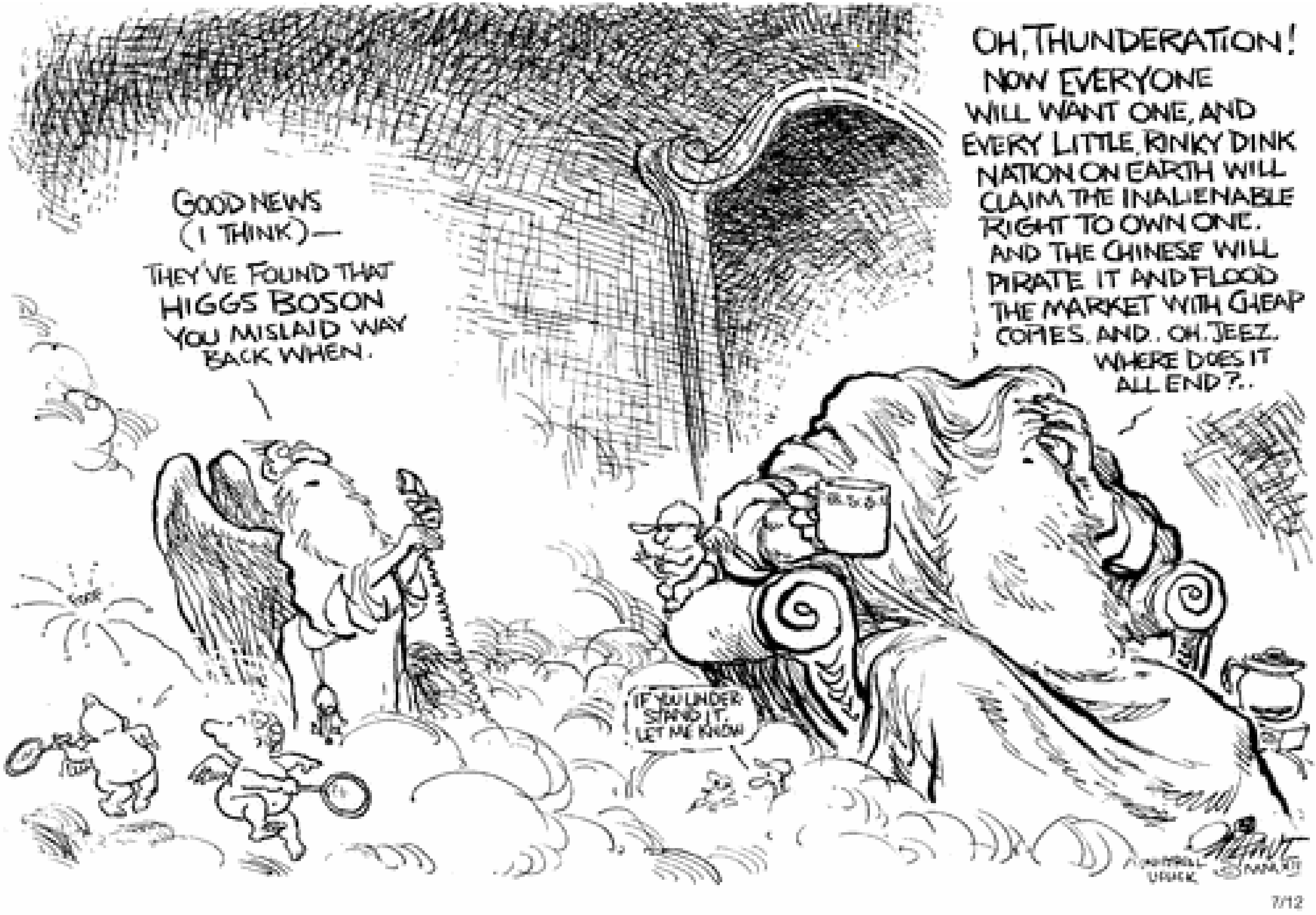
- Observed at ATLAS-CMS
  - ~126GeV
  - ~"5+σ"
- cross-section H→γγ larger than MSM
  - ~<2× in LHC measurement
    - a bit "beyond standard model" ?







Higgs Boson found !



Higgs "Factory" Alternatives

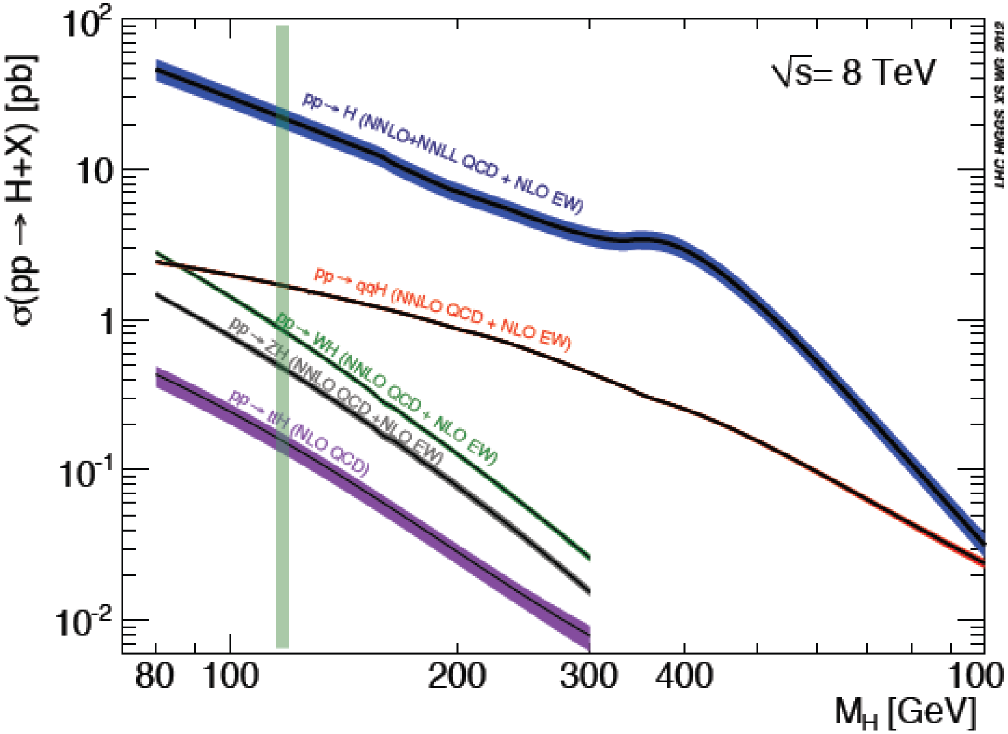
1. LHC → "high luminosity" LHC

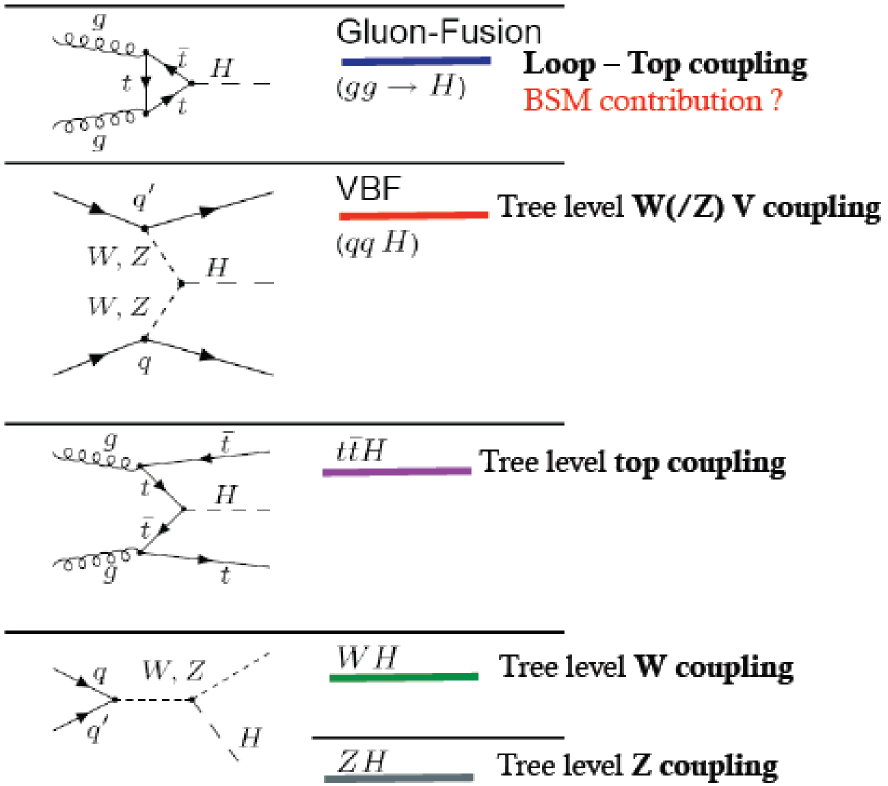
2. Circular e^+e^- Colliders
   - LEP3, TLeP, FNAL site-filler, …

3. Linear e^+e^- Colliders
   - ILC, CLIC, NLC
   - Plasma/laser wakefields/

4. γγ Colliders

5. μ^+-μ^- Colliders
   - only s-channel source





Gluon-Fusion
$(gg \to H)$
Loop – Top coupling
BSM contribution ?

VBF
$(qq\,H)$
Tree level **W(/Z) V coupling**

$t\bar{t}H$
Tree level top coupling

WH
Tree level **W coupling**

ZH
Tree level **Z coupling**

The LHC is a Higgs Factory !

1M Higgs already produced – more than most other Higgs factory projects.

σ_{pp}=100mb (10^{-25}) …10^{15} interactions

15 Higgs bosons / minute – and more to come (gain factor 3 going to 13 TeV)

Difficulties: several production mechanisms to disentangle and significant systematics in the production cross-sections σ_{prod} .

Challenge will be to reduce systematics by measuring related processes.

$$\sigma_{i\to f}^{\ observed} \propto \frac{\sigma_{prod}\ (g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$

extract couplings to anything you can see or produce from

if i=f as in WZ with H→ ZZ → absolute normalization

Conclusions

Approved LHC 300 fb^{-1} at 14 TeV:

- Higgs mass at 100 MeV
- Disentangle Spin 0 vs Spin 2 and main CP component in ZZ*
- **Coupling rel. precision/Exper.**
  - Z, W, b, τ 10-15%
  - t, μ 3-2 σ observation
  - γγ and gg 5-11%

$h(125)$	$\longrightarrow$	$b\bar{b}$	5.78×10^{-1}	W^+W^-	2.16×10^{-1}
		$\tau\bar{\tau}$	6.37×10^{-2}	Z^0Z^0	2.67×10^{-2}
		$c\bar{c}$	2.68×10^{-2}	gg	8.56×10^{-2}
		$s\bar{s}$	4.40×10^{-4}	$\gamma\gamma$	2.30×10^{-3}
		$\mu^+\mu^-$	2.21×10^{-4}	$Z^0\gamma$	1.55×10^{-3}

HL-LHC 3000 fb^{-1} at 14 TeV:

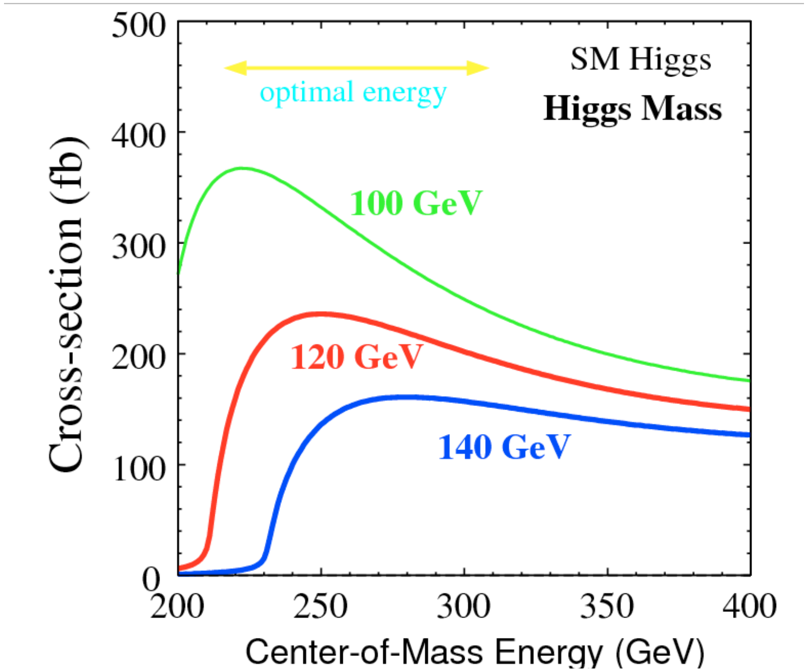
10^8 Higgs produced

- Higgs mass at 50 MeV
- More precise studies of Higgs CP sector
- Couplings rel. precision/Exper.
  - Z, W, b, τ, t, μ 2-10%
  - γγ and gg 2-5%
  - H→HH >3 σ observation (2 Exper.)*Assuming sizeable reduction of theory errors*

LHC experiments entered the Higgs properties measurement era: this is just the beginning !
LHC Upgrade crucial step towards precision tests of the nature of the newly-discovered boson

Higgs from light muons- 240 GeV e^+-e^- Collider

- No direct H production in e^+-e^-
  - No narrow resonance
    - associated production Z +H
- e^+-e^- → ZH
  - ~0.2pb at 250GeV
    - **background is ~10pb**
  - **200/year at L =10^{32} (~LEP)**
  - **20000/year at L =10^{34}**
    - **0.015pb e^+-e^- → ZH→l^+l^-H**
    - **1500 “high-quality” events**
- **Z + H not as cleanly separated from background**
  - **H width cannot be resolved**
- **But do not have to sit on resonance to see H**



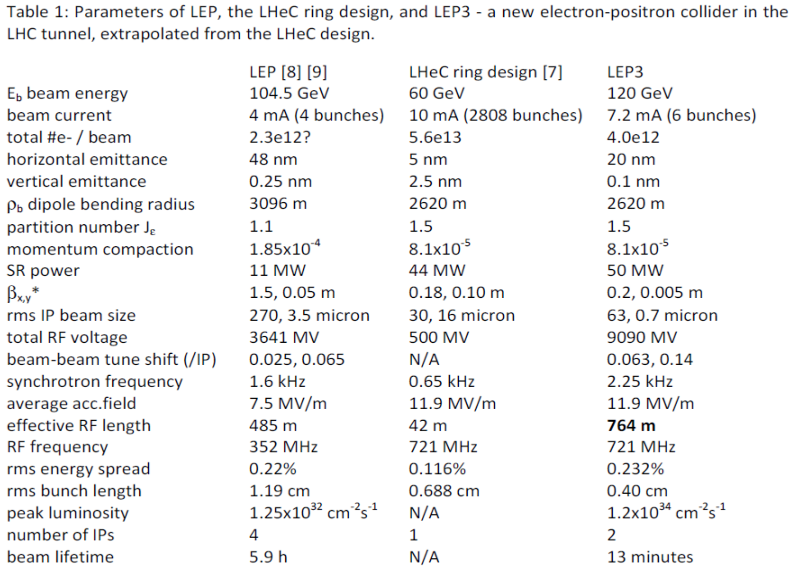


Table 1: Parameters of LEP, the LHeC ring design, and LEP3 - a new electron-positron collider in the LHC tunnel, extrapolated from the LHeC design.

	LEP [8] [9]	LHeC ring design [7]	LEP3
E_b beam energy	104.5 GeV	60 GeV	120 GeV
beam current	4 mA (4 bunches)	10 mA (2808 bunches)	7.2 mA (6 bunches)
total #e- / beam	2.3e12?	5.6e13	4.0e12
horizontal emittance	48 nm	5 nm	20 nm
vertical emittance	0.25 nm	2.5 nm	0.1 nm
ρ_b dipole bending radius	3096 m	2620 m	2620 m
partition number J_ε	1.1	1.5	1.5
momentum compaction	1.85×10^{-4}	8.1×10^{-5}	8.1×10^{-5}
SR power	11 MW	44 MW	50 MW
$\beta_{x,y}^*$	1.5, 0.05 m	0.18, 0.10 m	0.2, 0.005 m
rms IP beam size	270, 3.5 micron	30, 16 micron	63, 0.7 micron
total RF voltage	3641 MV	500 MV	9090 MV
beam-beam tune shift (/IP)	0.025, 0.065	N/A	0.063, 0.14
synchrotron frequency	1.6 kHz	0.65 kHz	2.25 kHz
average acc.field	7.5 MV/m	11.9 MV/m	11.9 MV/m
effective RF length	485 m	42 m	**764 m**
RF frequency	352 MHz	721 MHz	721 MHz
rms energy spread	0.22%	0.116%	0.232%
rms bunch length	1.19 cm	0.688 cm	0.40 cm
peak luminosity	1.25×10^{32} $cm^{-2}s^{-1}$	N/A	1.2×10^{34} $cm^{-2}s^{-1}$
number of IPs	4	1	2
beam lifetime	5.9 h	N/A	13 minutes

Circular e^+e^- Collider alternatives

- **LEP +**
  - but LEP tunnel occupied
  - 27km
- **Triple LEP**
  - 81km → 100 TeV pp
  - $L=5*10^{34}$
  - can revisit Z_0 at 10^3 LEP
- **FNAL site filler**
  - 16km
  - or KEK B++

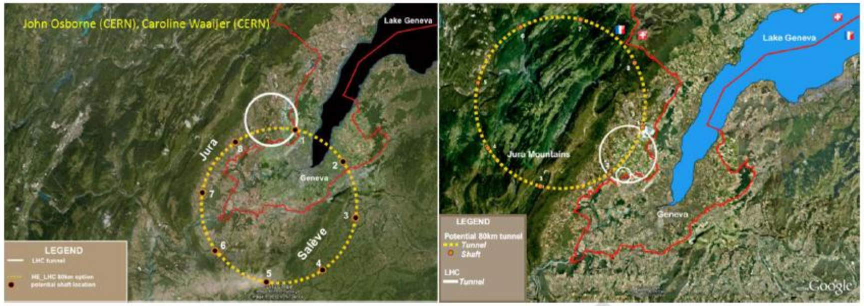
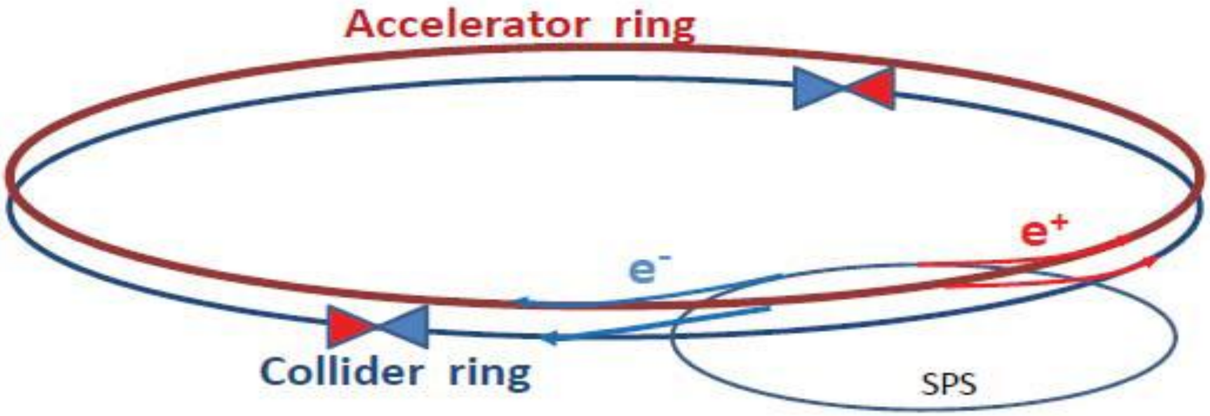
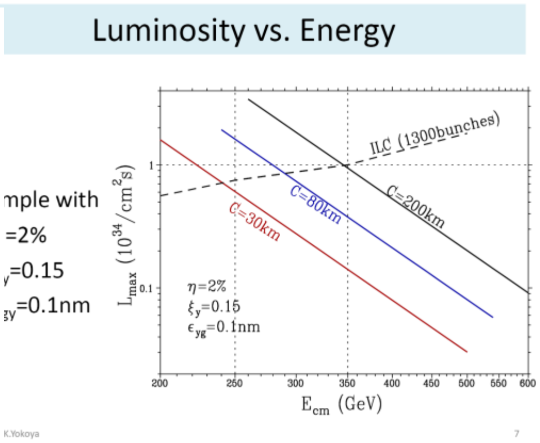


Figure 9. Two possible location, upon geological study, of the 80 km ring for a Super HE-LHC (option at left is strongly preferred)



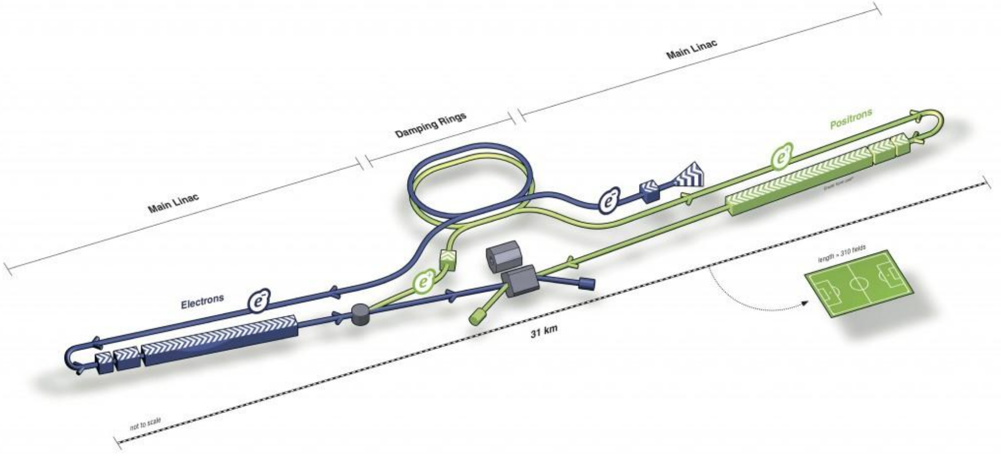


Luminosity vs. Energy

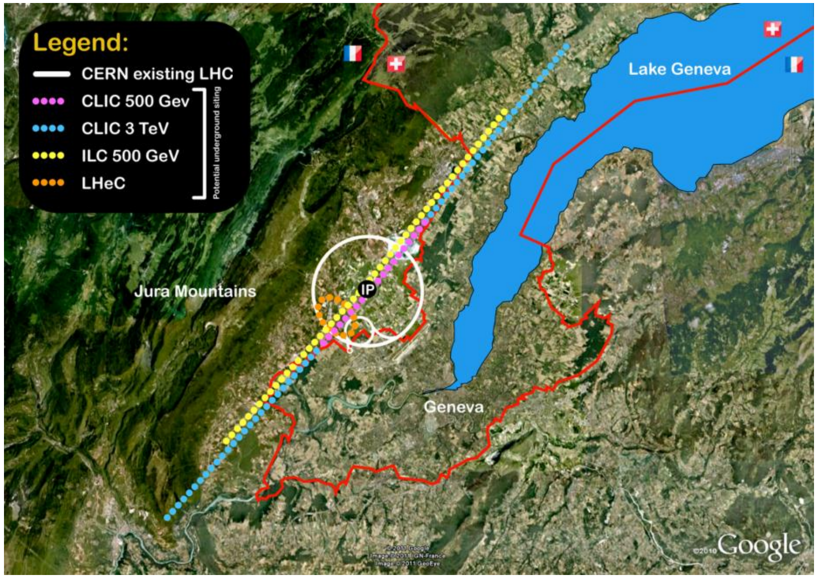
mple with
=2%
$_y$=0.15
$_{gy}$=0.1nm

linear e^+e^- Collider alternatives

- **ILC @250 GeV**

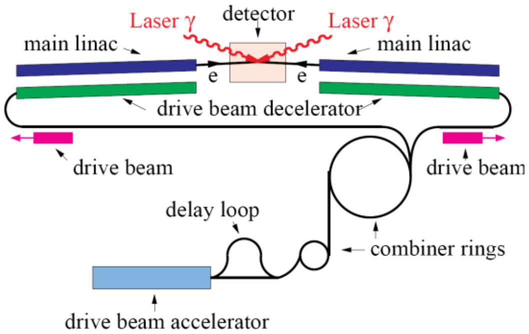


- **CLIC @250**
  - klystron based first stage = NLC
  - upgradeable to 3TeV

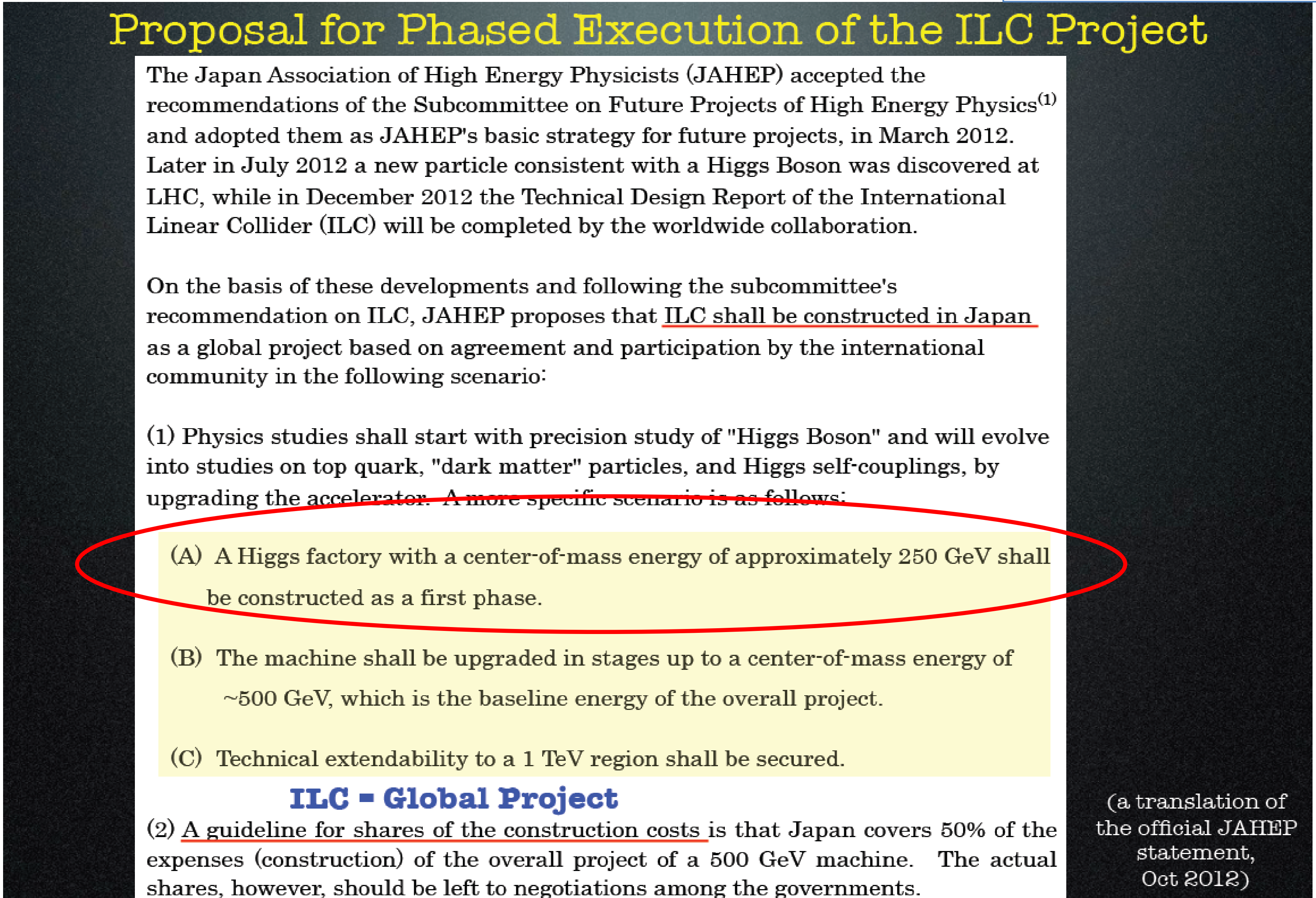


- **SLC +**

- **etc, γ γ**



JAHEP Statement (October 2012)



Proposal for Phased Execution of the ILC Project

The Japan Association of High Energy Physicists (JAHEP) accepted the recommendations of the Subcommittee on Future Projects of High Energy Physics(1) and adopted them as JAHEP's basic strategy for future projects, in March 2012. Later in July 2012 a new particle consistent with a Higgs Boson was discovered at LHC, while in December 2012 the Technical Design Report of the International Linear Collider (ILC) will be completed by the worldwide collaboration.

On the basis of these developments and following the subcommittee's recommendation on ILC, JAHEP proposes that ILC shall be constructed in Japan as a global project based on agreement and participation by the international community in the following scenario:

(1) Physics studies shall start with precision study of "Higgs Boson" and will evolve into studies on top quark, "dark matter" particles, and Higgs self-couplings, by upgrading the accelerator. A more specific scenario is as follows:

(A) A Higgs factory with a center-of-mass energy of approximately 250 GeV shall be constructed as a first phase.

(B) The machine shall be upgraded in stages up to a center-of-mass energy of ~500 GeV, which is the baseline energy of the overall project.

(C) Technical extendability to a 1 TeV region shall be secured.

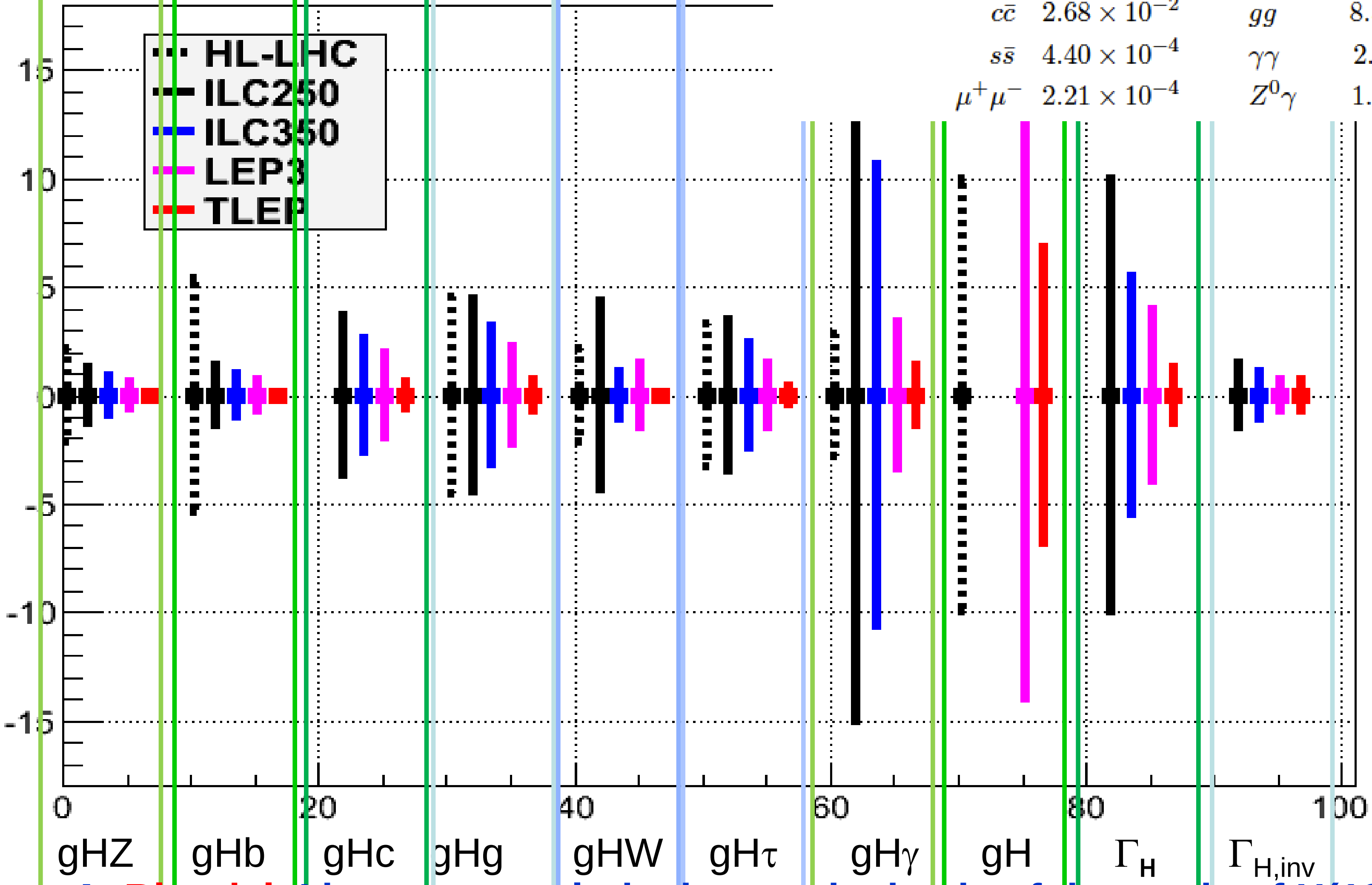
ILC = Global Project

(2) A guideline for shares of the construction costs is that Japan covers 50% of the expenses (construction) of the overall project of a 500 GeV machine. The actual shares, however, should be left to negotiations among the governments.

(a translation of the official JAHEP statement, Oct 2012)

Possible sensitivities

$h(125)$	$\longrightarrow$	$b\bar{b}$	5.78×10^{-1}	W^+W^-	2.16×10^{-1}
		$\tau\bar{\tau}$	6.37×10^{-2}	Z^0Z^0	2.67×10^{-2}
		$c\bar{c}$	2.68×10^{-2}	gg	8.56×10^{-2}
		$s\bar{s}$	4.40×10^{-4}	$\gamma\gamma$	2.30×10^{-3}
		$\mu^+\mu^-$	2.21×10^{-4}	$Z^0\gamma$	1.55×10^{-3}

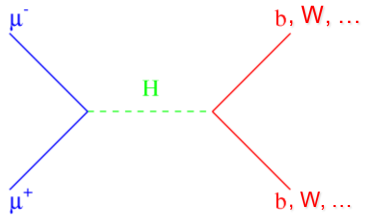


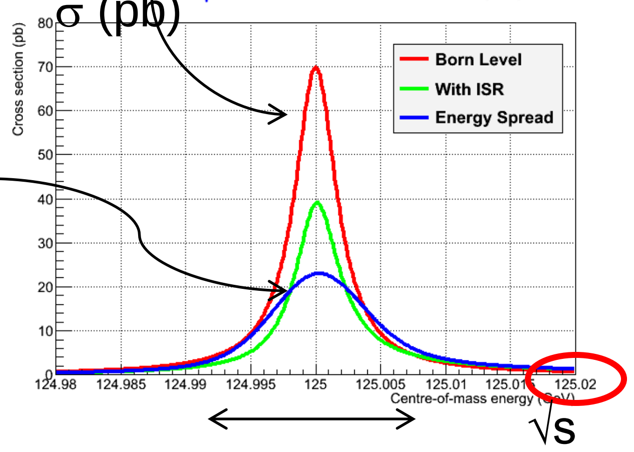
A. Blondel: I have to conclude that on the basis of the study of H(126) alone is concerned, the high energy e+e- collider is not compelling

$\mu^+\mu^-$ Collider vs e^+e^- Collider ?

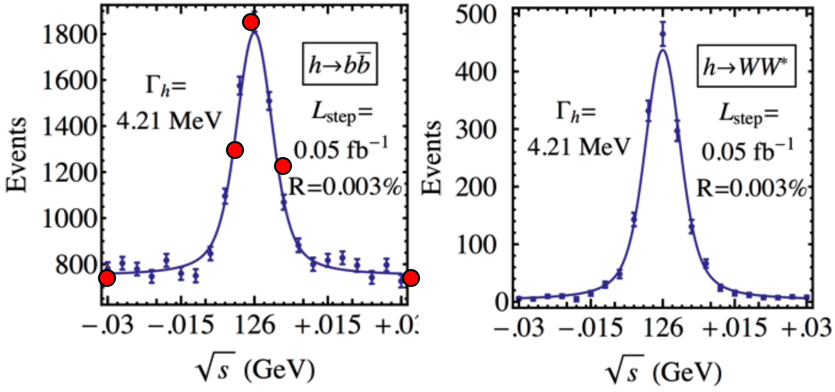
- **A $\mu^+\mu^-$ collider can do things that an e^+e^- collider cannot do** [16,17]
  - Direct coupling to H expected to be larger by a factor m_μ/m_e
    $\sigma(\mu^+\mu^- \to H) \approx 40000 \times \sigma(e^+e^- \to H)$ σ_{peak} = 70 pb at tree level]
  - Beam energy spread $\delta E/E$ may be reduced to 3×10^{-5}
    - 6D Cooling, no beamstrahlung, ~no bremsstrahlung
    - For $\delta E/E$ = 0.003% (δE ~ 3.6 MeV, Γ_H ~ 4 MeV)
      - Corresponding luminosity ~ 10^{31} $cm^{-2}s^{-1}$
        - Expect 2300 Higgs events in 100 pb^{-1}/ year
  - **Polarization, beam energy** and energy spectrum
    - Can be measured with an exquisite precision
      - From the electrons of the muon decays
  - Then measure the lineshape of the Higgs at $\sqrt{s}$ ~ m_H
    - Five-point scan, 50 + 100 + 200 + 100 + 50 pb^{-1}
      - Precision from H→bb and WW :

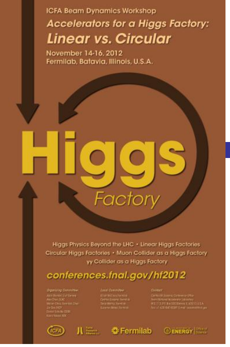
m_H	σ_{Peak}	Γ_H
0.1 MeV	0.6 pb	0.2 MeV
10^{-6}	2.5%	5%





$\sigma(m_H)$, TLEP





What's Next? W. Chou

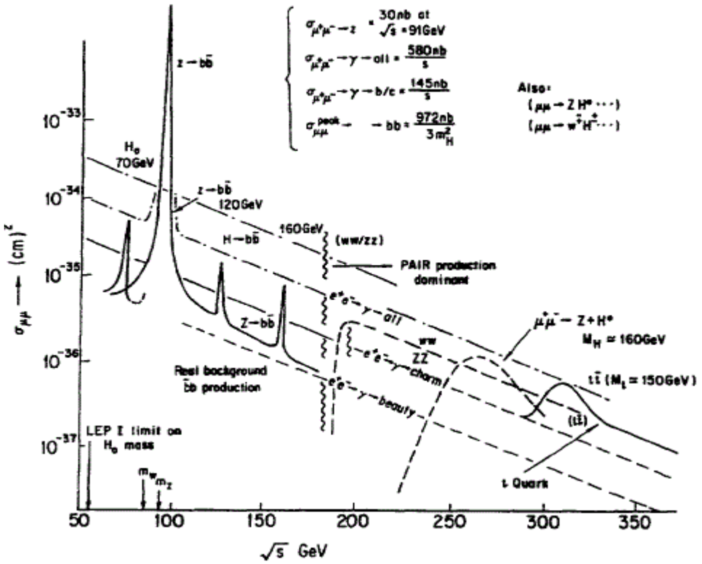
- The Organizing Committee will write a workshop report:
  - Higgs physics: What the LHC can do? What a Higgs factory can do for given energy and luminosity (e+e-, μ+μ-, γγ)?
  - Performance, technology maturity and readiness, upgrade potential, and technical challenges requiring further R&D for each type of Higgs factory
  - Comparison tables
  - An Executive Summary
- Target readers:
  - Joint ICFA – Lab Directors meeting (February 21-22, 2013 at TRIUMF)
  - US Snowmass 2013 conference (July 29 – August 6, 2013 at Univ. of Minnesota)
  - European Strategy Updates meeting (January 21-22, 2013)
  - HEP roadmap study in Asia (Japan and China)
  - World HEP and accelerator communities (report to be published in the *ICFA Beam Dynamics Newsletter* no. 60, April 2013)
- Target date for completing the report:
  - January 15, 2013
- The organizing committee recommends these studies should continue. It also believes this workshop provides a good platform for the international community to get together for discussions of a future Higgs factory and should also continue. The next workshop will be about one year from now. The place and dates are yet to be decided. Stay tuned!

$\mu\mu$ → H Higgs Factory

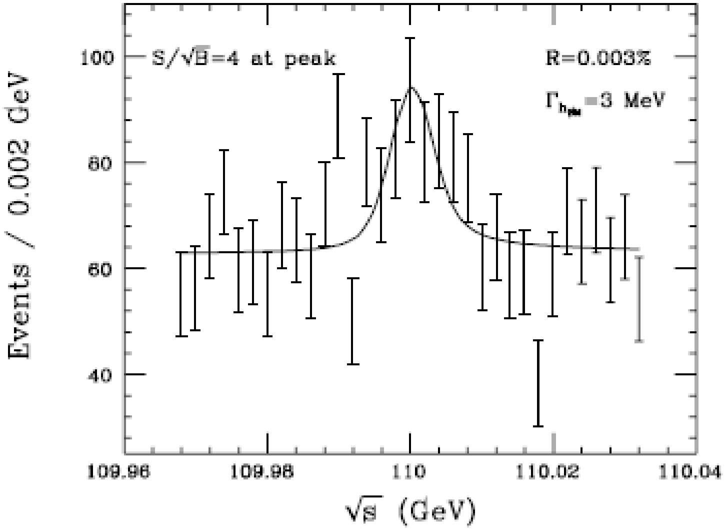
Barger, Berger, Gunion, Han, *Physics Reports* 286, 1-51 (1997)

- Higgs Factory = s-channel resonance production
  - $\mu^+\mu^- \rightarrow H$
- Cross section expected to be ~40pb
  - $\sigma \propto m_\mu^2 = 43000\ m_e^2$
  - width ~4MeV
- at $L=10^{31}$, $t=10^7$s
- →4000 H
- Could scan over peak to get M_H, δE

  $H \rightarrow b\bar{b}$ or W^+W^{-*} mostly



δE = 0.003% =4 MeV



~10^{36}/pt

$h(125) \longrightarrow$	$b\bar{b}$	5.78×10^{-1}	W^+W^-	2.16×10^{-1}		
	$\tau\bar{\tau}$	6.37×10^{-2}	Z^0Z^0	2.67×10^{-2}		
	$c\bar{c}$	2.68×10^{-2}	gg	8.56×10^{-2}		
	$s\bar{s}$	4.40×10^{-4}	$\gamma\gamma$	2.30×10^{-3}		
	$\mu^+\mu^-$	2.21×10^{-4}	$Z^0\gamma$	1.55×10^{-3}	e^+e^-	5.15×10^{-9}

$\mu^+\mu^-$ Collider Parameters

- **0.1~ →0.4 →3 + TeV Collisions**
- **Parameters from 2003 STAB (+ Snowmass 2001)**
  - C. Ankenbrandt et al., *Physical Review STAB* 2, 081001 (1999), M. Alsharo'a et al., *Physical Review STAB* 6, 081001 (2003).

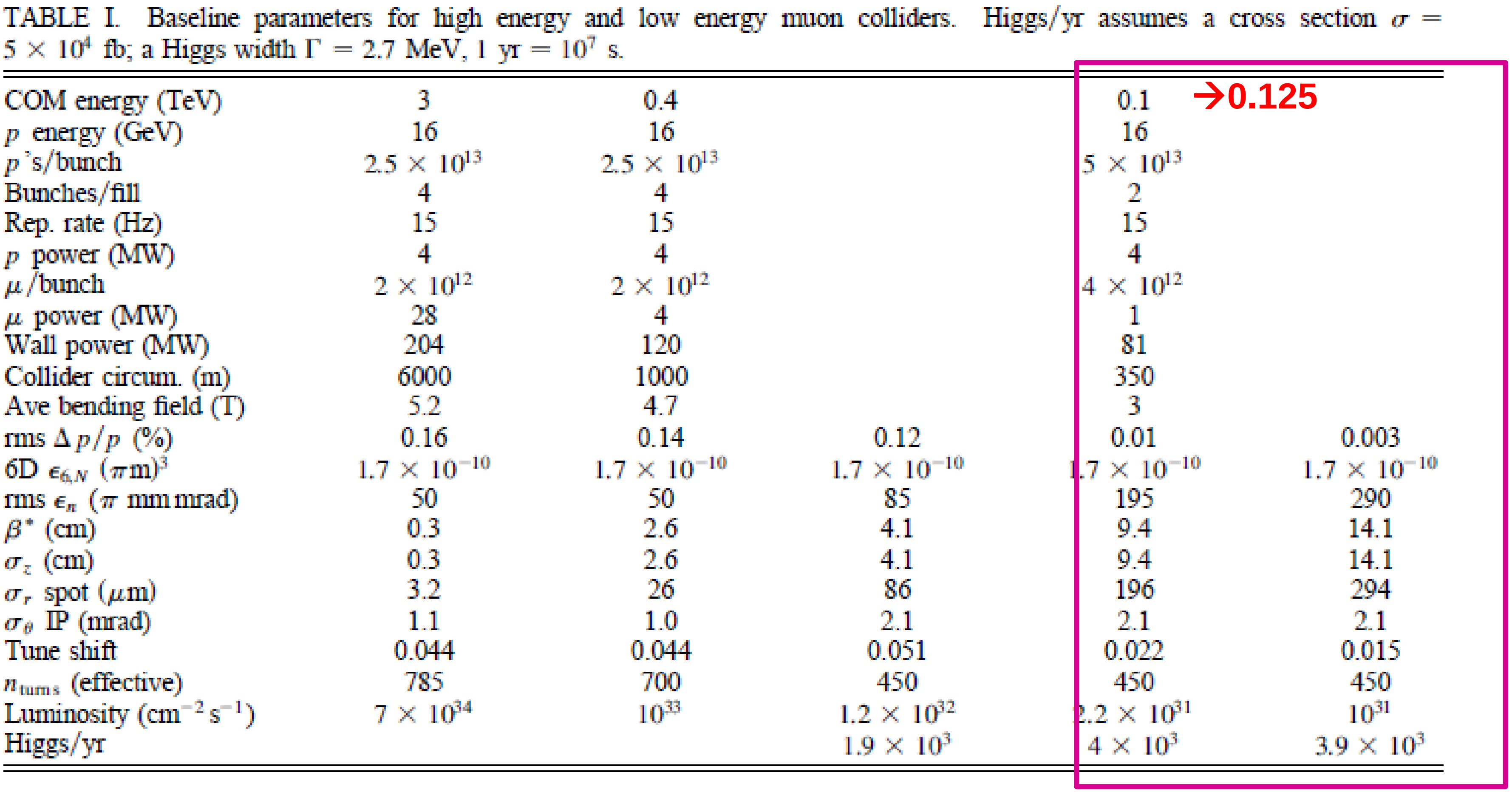


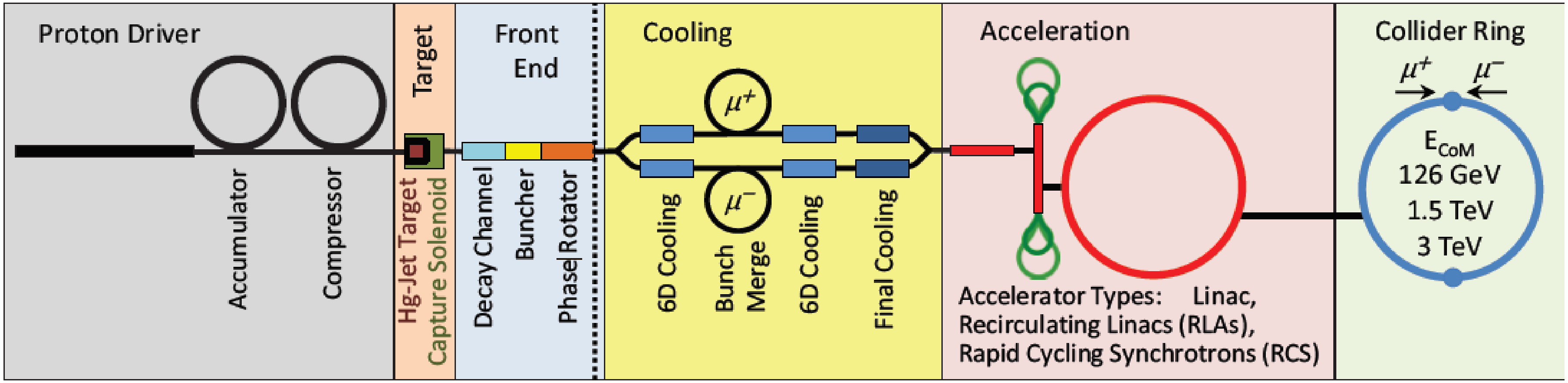
TABLE I. Baseline parameters for high energy and low energy muon colliders. Higgs/yr assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV, 1 yr $= 10^7$ s.

COM energy (TeV)	3	0.4		0.1	
p energy (GeV)	16	16		16	
p's/bunch	2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill	4	4		2	
Rep. rate (Hz)	15	15		15	
p power (MW)	4	4		4	
μ/bunch	2×10^{12}	2×10^{12}		4×10^{12}	
μ power (MW)	28	4		1	
Wall power (MW)	204	120		81	
Collider circum. (m)	6000	1000		350	
Ave bending field (T)	5.2	4.7		3	
rms $\Delta p/p$ (%)	0.16	0.14	0.12	0.01	0.003
6D $\epsilon_{6,N}$ $(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
rms ϵ_n (π mm mrad)	50	50	85	195	290
β^* (cm)	0.3	2.6	4.1	9.4	14.1
σ_z (cm)	0.3	2.6	4.1	9.4	14.1
σ_r spot (μm)	3.2	26	86	196	294
σ_θ IP (mrad)	1.1	1.0	2.1	2.1	2.1
Tune shift	0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)	785	700	450	450	450
Luminosity ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/yr			1.9×10^3	4×10^3	3.9×10^3

→0.125

μ^+-μ^- Higgs Collider Design

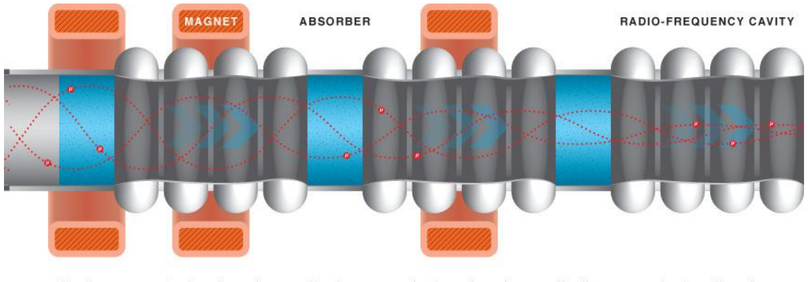
- **Based on “3 TeV” μ^+-μ^- Collider design**
  - scaling back cooling system; acceleration, collider ring
  - 126 GeV precision Higgs measurements could be done as initial part of HE μ^+-μ^- Collider program …
    - follow-up to LHC/LC programs ?
  - 4 MW proton driver, solenoid target and capture, ionization cooling system, acceleration and collider ring
- **plus polarization precession for energy measurement at 10^{-6}**
  - ~10—20% polarization precession
- **Is there a “fast-track” path to the μ^+-μ^- Higgs ?**



Cooling Constraints

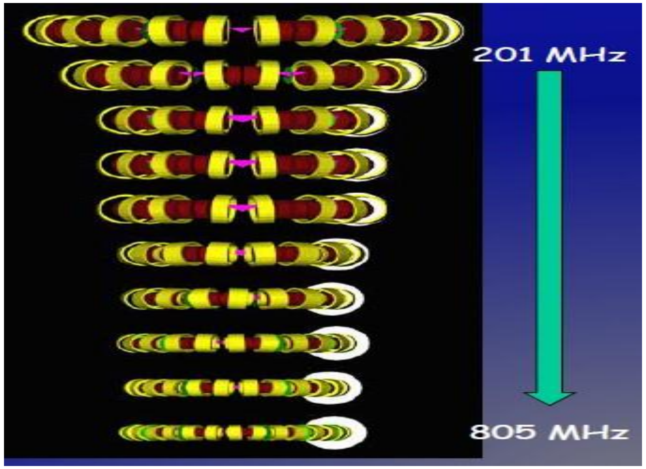
- Cooling method is ionization cooling
  - energy loss in material
    - compensated by rf
  - opposed by d $\langle\theta_{rms}^2\rangle/ds$, d$\langle\delta E^2\rangle/ds$
- Cooling couples x, y, z

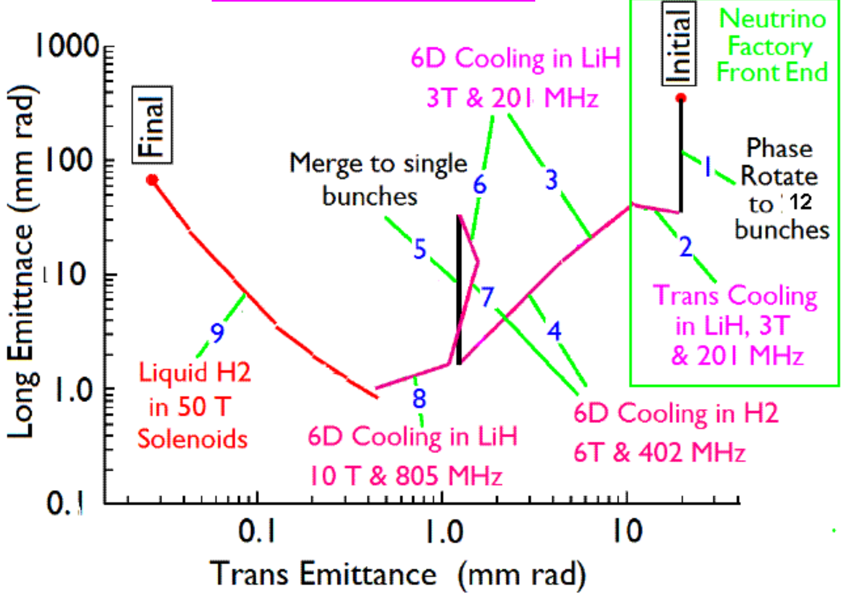
$$\boxed{2g_\perp + g_L \cong 2}$$

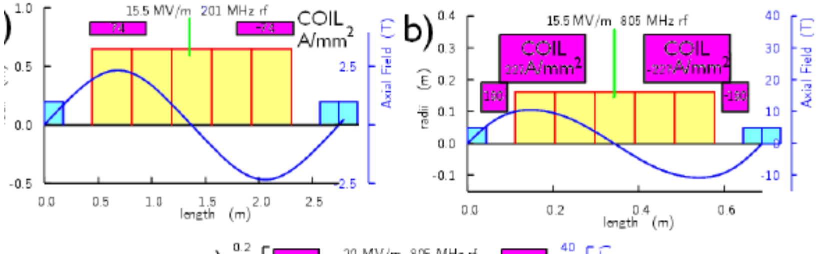


$$\frac{d\varepsilon_{\perp,N}}{ds} = -g_\perp \frac{\frac{dP_\mu}{ds}}{P_\mu}\varepsilon_{\perp,N} + \beta_\perp \frac{\beta\gamma}{2}\frac{d\left\langle\theta_{rms}^2\right\rangle}{ds}$$

$$\frac{d\varepsilon_{L,N}}{ds} = -g_L \frac{\frac{dP_\mu}{ds}}{P_\mu}\varepsilon_{L,N} + \frac{\beta_L}{2}\frac{d\left\langle E_{rms}^2\right\rangle}{ds}$$







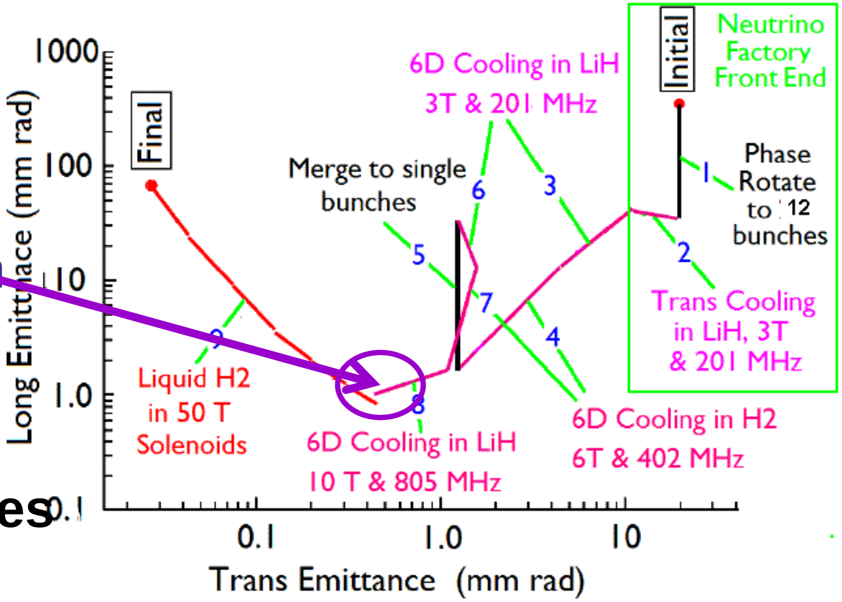
Natural 6-D muon cooling limits

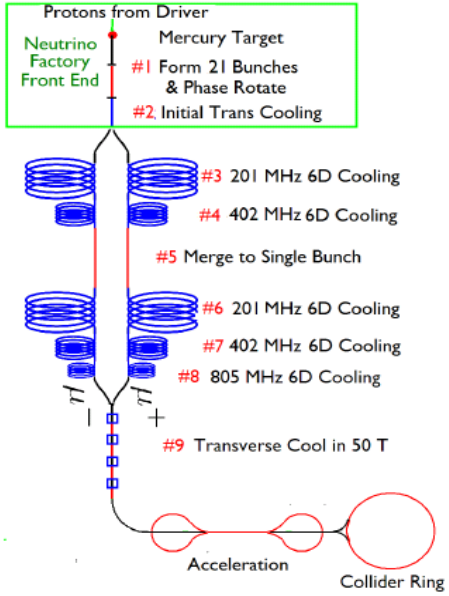
- Ionization cooling couples x, y, z

- At moderate B, E_{RF}, $\lambda_{RF,}$ optimal 6-D cooling is:
  - ϵ_T = ~0.0003m,ϵ_L = ~0.0015m
  - σ_E= 3MeV→ σ_z=0.05m

- Cooling to much smaller ϵ_T requires “extensions”
  - reverse ϵ exchange
  - high B-fields, extreme rf, small E_μ

- Initial derated values
  - ϵ_T = 0.0004m, ϵ_L = 0.002m

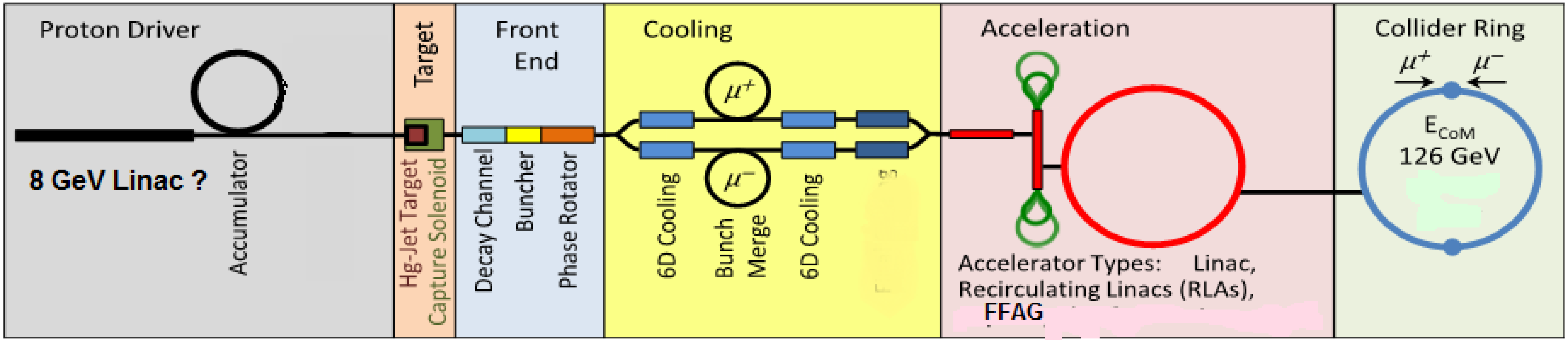




126 GeV μ^+-μ^- Collider

- **8 GeV, 4MW Proton Source**
  - 15 Hz, 4 bunches 5×10^{13}/bunch
- **π→μ collection, bunching, cooling**
- $\varepsilon_{\perp,N}$ =400 π mm-mrad, $\varepsilon_{\parallel,N}$= 2 π mm
  - 10^{12} μ/ bunch
- **Accelerate, Collider ring**
  - δE = 4 MeV, C=300m
  - Detector
  - monitor polarization precession
  - for energy measurement
    - δE_{error} → 0.1 MeV

Parameter	Symbol	Value
Collision Beam Energy	$E_{\mu+}, E_{\mu-}$	63GeV
Luminosity	L_0	10^{31}
Number of μ bunches	n_B	1
$\mu^{+/-}$/ bunch	N_μ	10^{12}
Transverse emittance	$\varepsilon_{t,N}$	0.0004m
Longitudinal emittance	ε_{LN}	0.002m
Energy spread	δE	4MeV
Collision β*	β*	0.05 m
Beam size at collision	$\sigma_{x,y}$	0.02cm
Beam size (arcs)	$\sigma_{x,y}$	1.0cm
Beam size IR quad	σ_{max}	5.4cm
Storage turns	N_t	1000
Proton Beam Power	P_p	4 MW
Bunch frequency	F_p	60 Hz
Protons per bunch	N_p	5×10^{13}
Proton beam energy	E_p	8 GeV

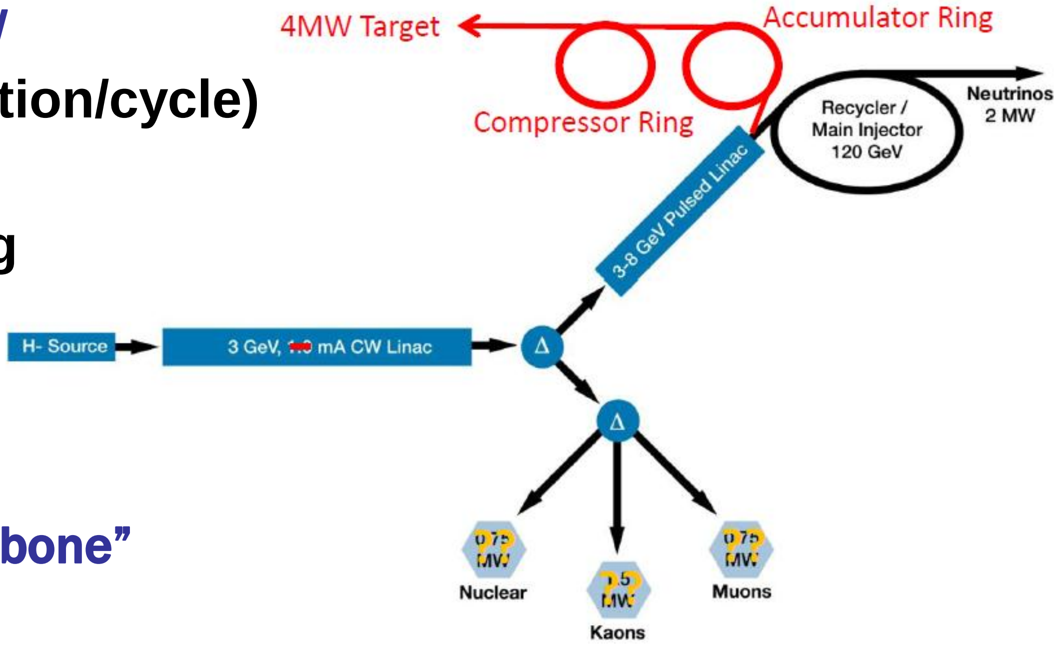


Proton Source: Project X Upgrade to 4MW

- Upgrade cw Linac to 5ma
  - 15 MW peak power
  - run at 10% duty cycle
- Increase pulsed linac duty cycle to ~10%
  - 8GeV × 5ma × 10% = 4MW
- Run at 15 Hz (6.7ms injection/cycle)
  - matches NF/MC scenarios
- Chop at 50% for bunching
  - source/RFQ →10ma
- Need Accumulator,

Compressor to bunch beam

  - + bunch combiner “trombone”



Layout for 2013 RDR

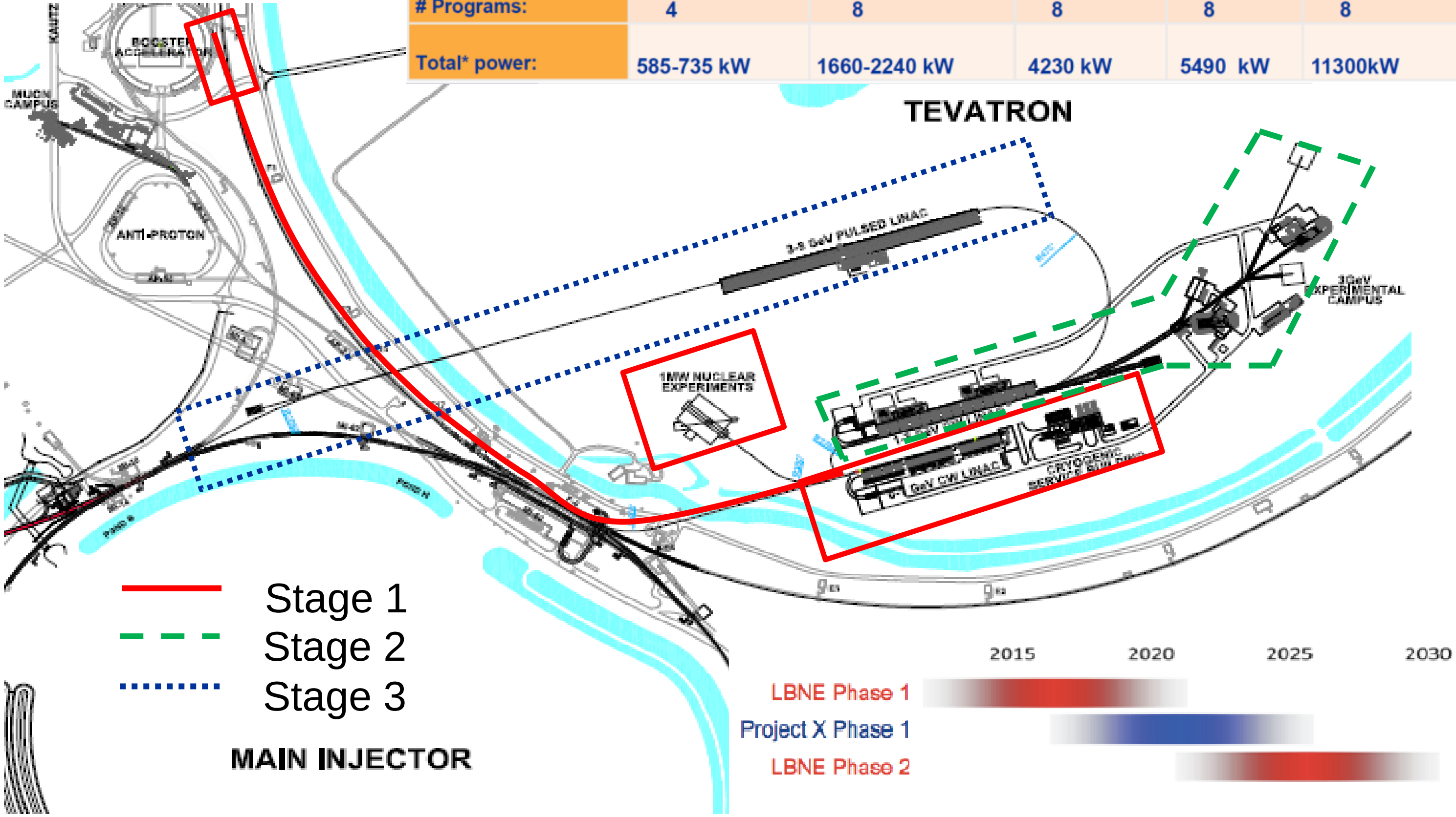
Fermilab Project X Plan

Currently focused on CD-0 for Stage 1

Multiple steps; each less < 1G$

Phase 3 = 8 GeV Linac

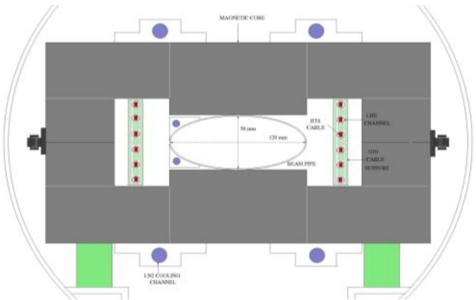
Program:	Onset of NOvA operation in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, EDM programs (MI>80 GeV)	Stage-2: Upgrade to 3 GeV CW Linac (MI>80 GeV)	Stage-3: Project X RDR (MI>60GeV)	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2300 kW	2300-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-40 kW* + 0-90 kW**	0-40 kW*	85 kW	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	85 kW	1000 kW
1-3 GeV Muon program	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1100 kW	1100 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
# Programs:	4	8	8	8	8
Total* power:	585-735 kW	1660-2240 kW	4230 kW	5490 kW	11300kW

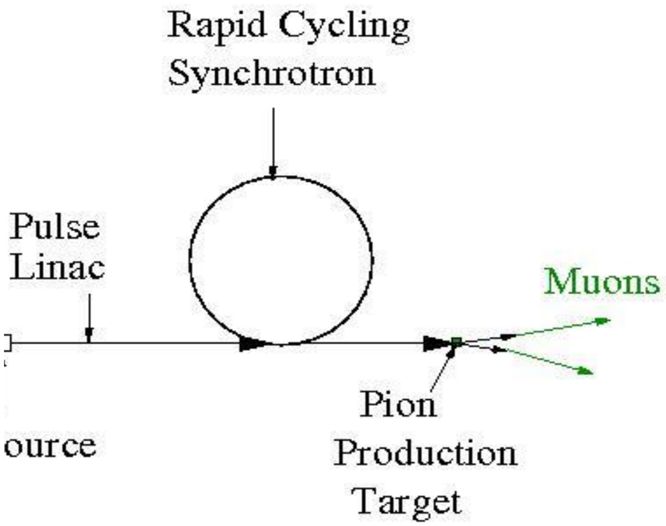


28-Nov-2012

Proton Driver Options

- **H. Piekarz**
  - SCRSC

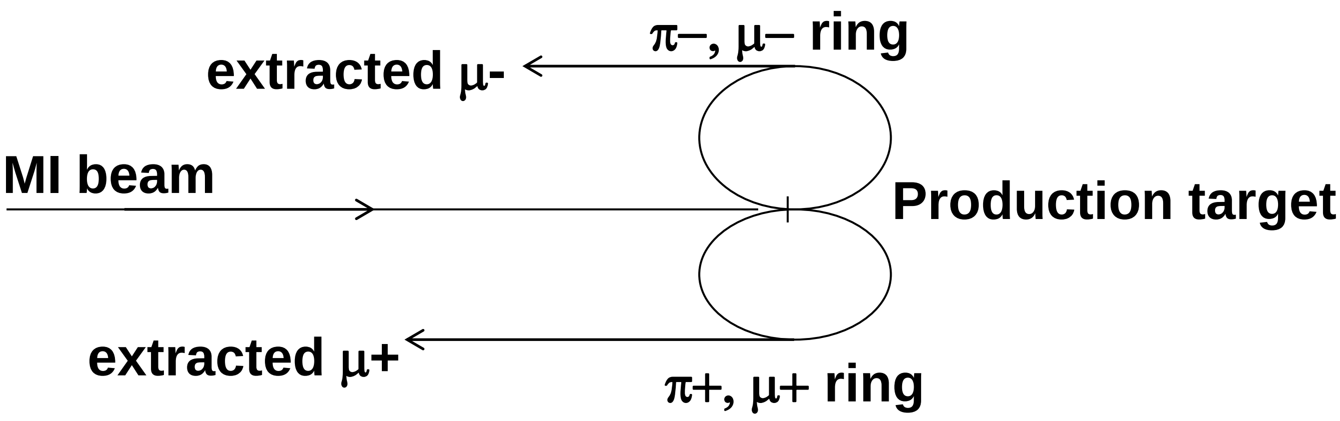




- **C Ankenbrandt**
  - 2-ring circus
  - MI / project X
  - 3MW stage 2

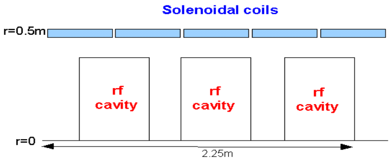
Proton source consists of:

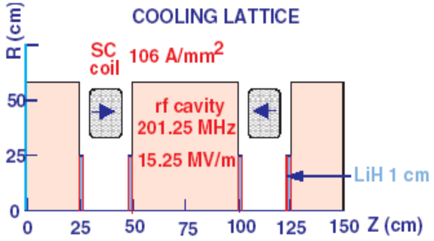
H^- Source	50 keV
Pulse Linear Accelerator	1 GeV
Rapid Cycling Synchrotron	8 GeV, 60 Hz
Pion/Muon production target	2-3 MW

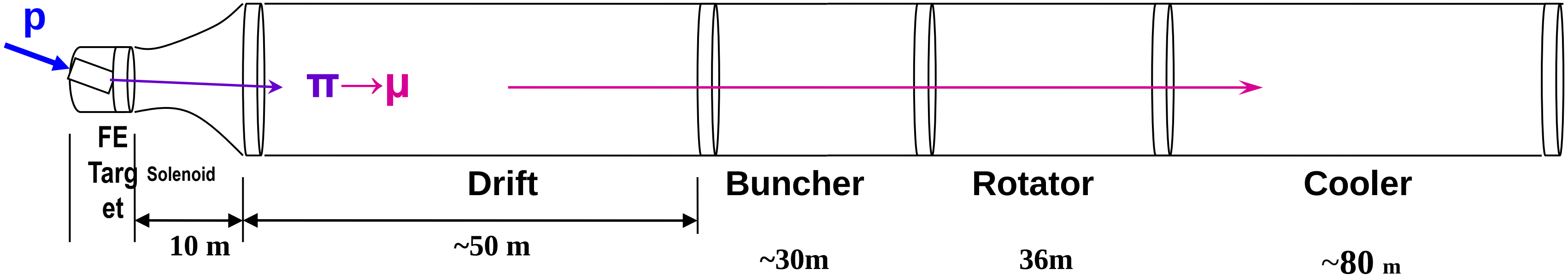


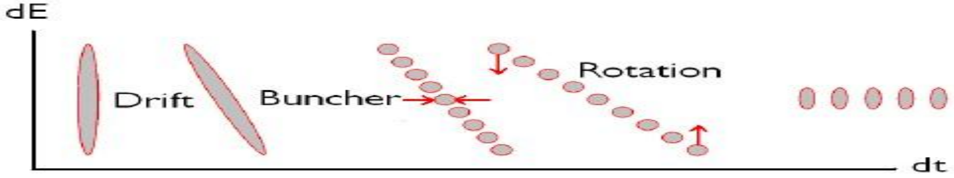
High-frequency Buncher and φ-E Rotator

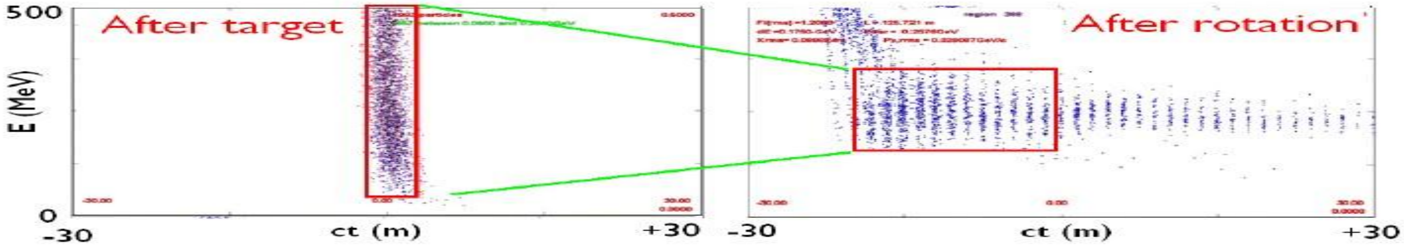
- **Drift (π→μ), "Adiabatically" bunch beam first** (weak 320 to 240 MHz rf)
- **Φ-E rotate bunches – align bunches to ~equal energies**
  - 240to 202 MHz, 15MV/m
- **Cool beam** 201.25MHz
- **Captures both μ$^+$ and μ$^-$**
  - born from same proton bunch





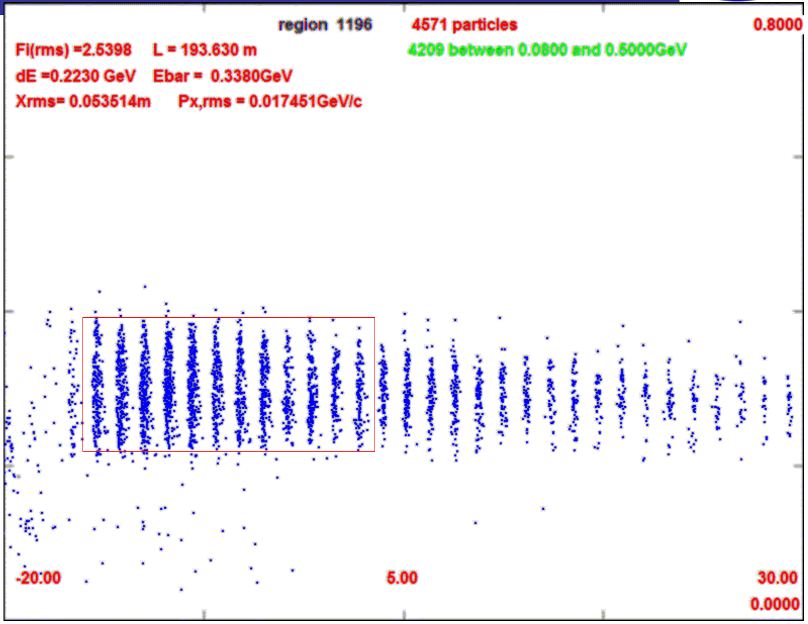






μ Capture / Buncher /Φ-E Rotation

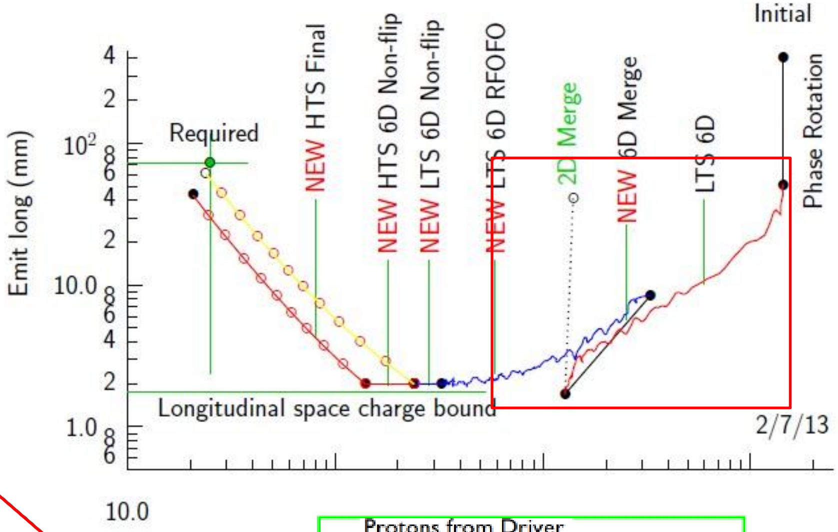
- **Advantages**
  - high rf frequency (200 MHz)
  - captures both signs
  - high-efficiency capture
- **Obtains ~0.1 μ/p_8**
  - *Choose best 12 bunches*
    - ~0.01 μ/p_8 per bunch
- **Disadvantages**
  - requires initial protons in a few short, intense bunches
  - train of μ bunches (not single)
    - requires later recombiner
  - low polarization
    - 10—20%

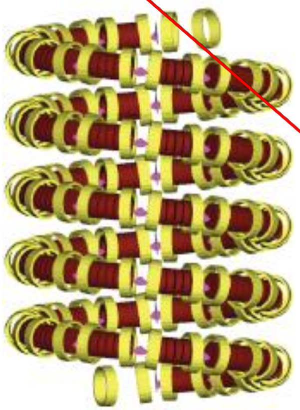


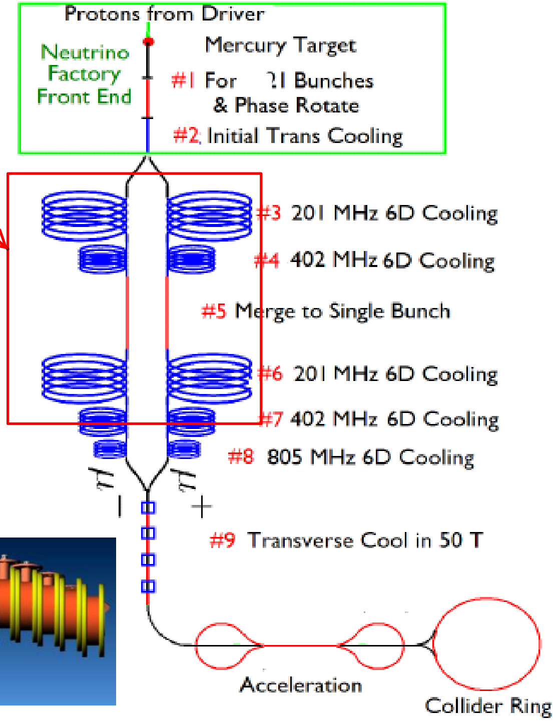
- **Alternatives/variations should be explored**
  - 200 MHz →325 ?
    - 162.5 MHz ?
  - shorter ?
  - improve initial cooling

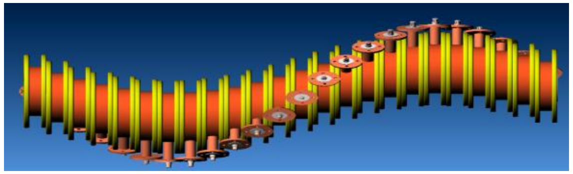
Cooling Scenario for 126 GeV Higgs

- Use much of baseline cooling scenarios
  - need initial 200/400 Mhz cooling sections
  - need bunch merge
  - and initial recooler
- Do not need final cooling (high field section)
  - final transverse cooling sections for luminosity upgrade
  - high-field cooling not needed (B < ~12T)
- HCC “Complete Cooling Channel” ?









Acceleration Scenario (Lebedev)

Linac + ~10 Pass Recirculating Linac to 63 GeV

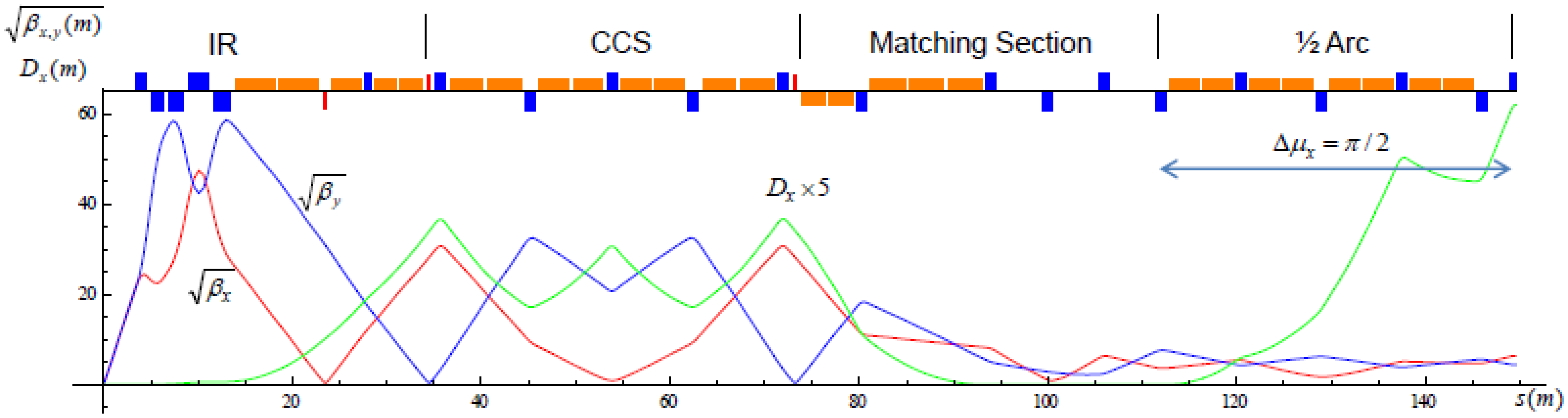
- **5-6 GeV pulsed SRF Linac (650 MHz)**
  - **“Dog-bone” recirculation**

- **same Linac can also be used for 3→8 GeV Project X stage 3**
  - **4MW for protons ?**

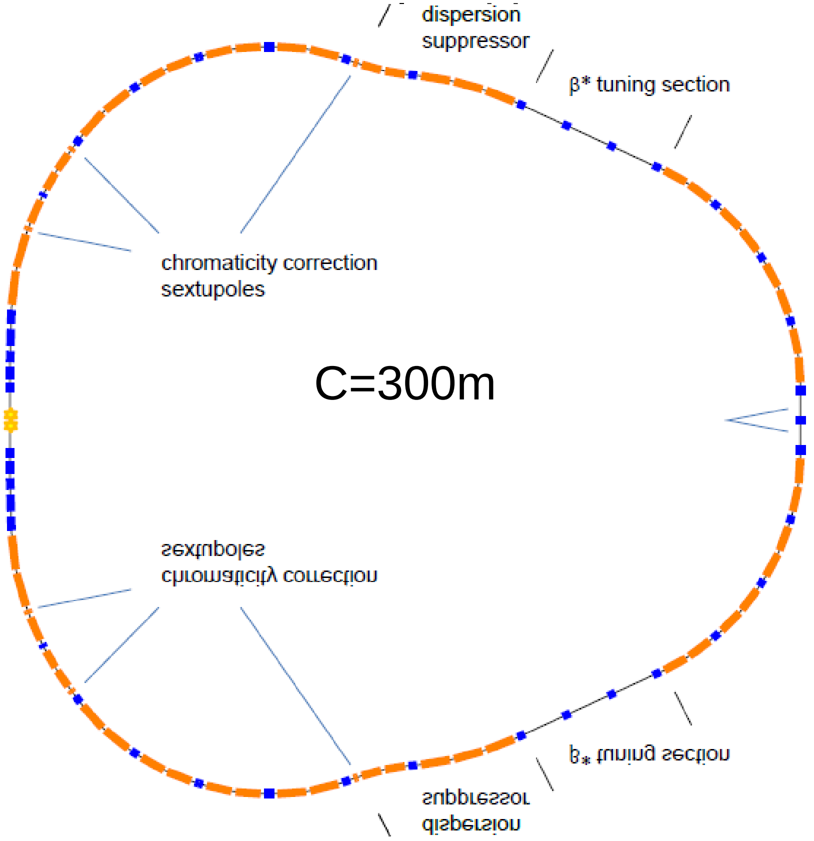
3 GeV Linac
- **650 MHz SRF**

~5 GeV Recirculating Linac
- **650 MHz**
- **~12 turns to 63 GeV**

Updated 63 x 63 GeV Lattice



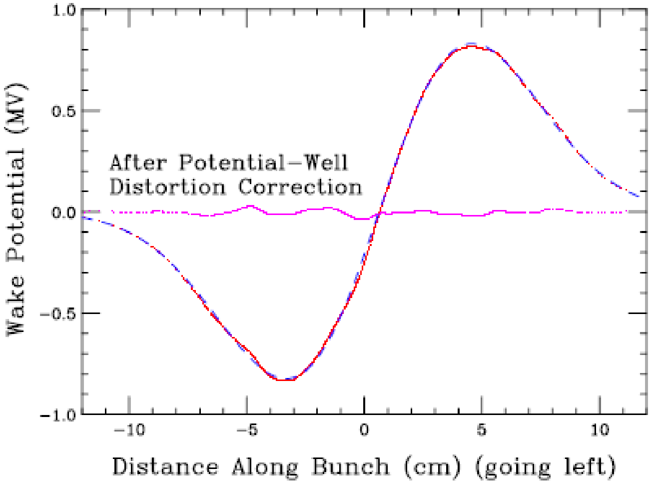
Parameter	Unit	Value
Circumference, C	m	299
β*	cm	2.5 (1.5-10)
Momentum compaction, α_p	-	0.0793
Betatron tunes	-	4.56 / 3.56
Bare lattice chromaticity	-	-124 / -197
Synchrotron tune (100kV, 200MHz)	-	0.002
Number of muons / bunch	10^{12}	1.5 → 2
Normalized emittance, $\varepsilon_{\perp N}$	π·mm·rad	0.3
Long. emittance, $\varepsilon_{\|\|N}$	π·mm·rad	1.0
Beam energy spread	%	0.003
Bunch length, σ_s	cm	5.64
Beam-beam parameter	-	0.0054 → 0.0072
Repetition rate	Hz	10 → 30
Average luminosity	10^{31}/cm^2/s	0.46 → 2.5

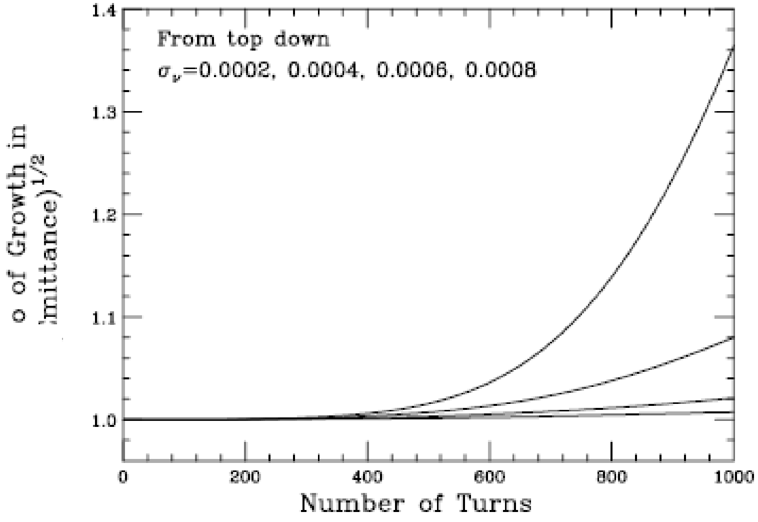


Y. Alexahin

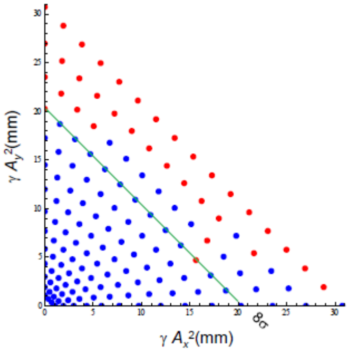
Beam Instability Issues

- Studied in some detail by K.Y Ng
  - PhysRevSTAB 2, 091001 (1999
    - “Beam Instability Issues of the 50x50 GeV Muon Collider Ring”
  - Potential well distortion
    - compensated by rf cavities
  - Longitudinal microwave instability
    - ~isochronous lattice, small lifetime
  - Transverse microwave Instability
    - damped by chromaticity (+ octupoles)
  - Beam Breakup
    - BNS + δν damping





- Dynamic aperture
  - larger than physical
    - Y. Alexahin



Polarization & Energy measurement

Raja and Tollestrup (1998) Phys. Rev. D 58 013005

➢ Electron energy (from decay) depends on polarization

- polarization is ~25% → 10%

$$< E_{lab} > = \frac{7}{20}E_{\mu}(1+\frac{\beta}{7}\hat{P})$$

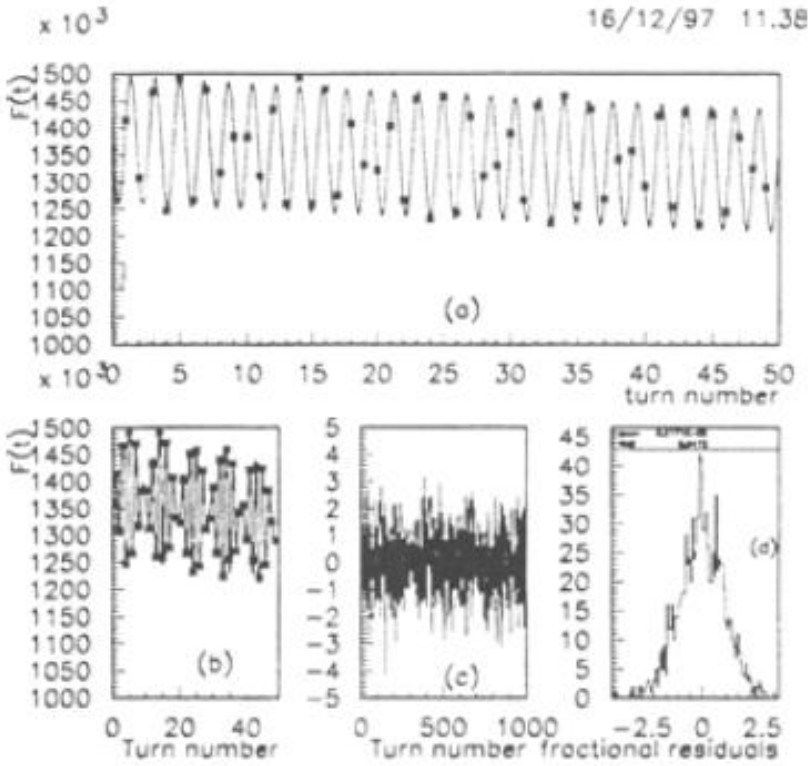
$$E(t) = Ne^{(-\alpha t)}(\frac{7}{20}E_{\mu}(1+\frac{\beta}{7}(\hat{P}cos\omega t+\phi)))$$

$$\omega = 2\pi\gamma\frac{g-2}{2} = \sim 0.7 * 2\pi$$

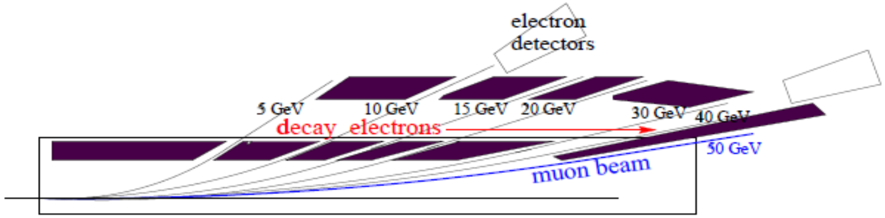
- Measure ω from fluctuations in electron decay energies
  - 10^6 decays/m

$<E_\mu>$ depends on Frequency

- **Frequencies can be measured very precisely**
- E, δE to 0.1 MeV or better (?)
- need only > ~5% polarization ?



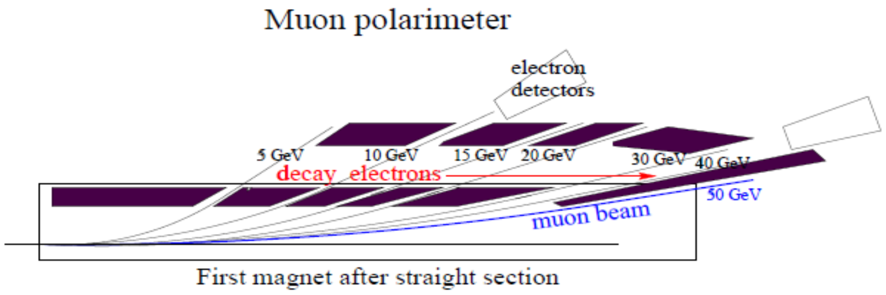
Muon polarimeter

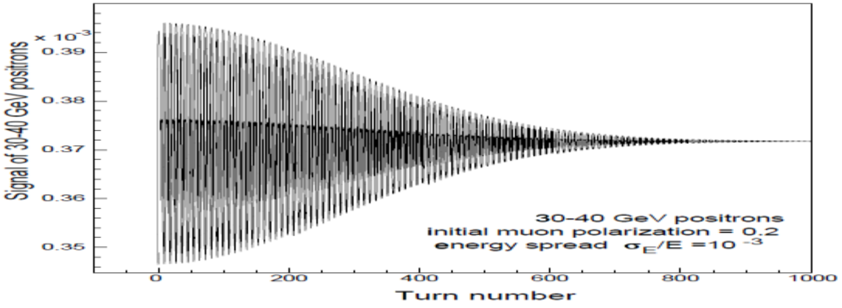


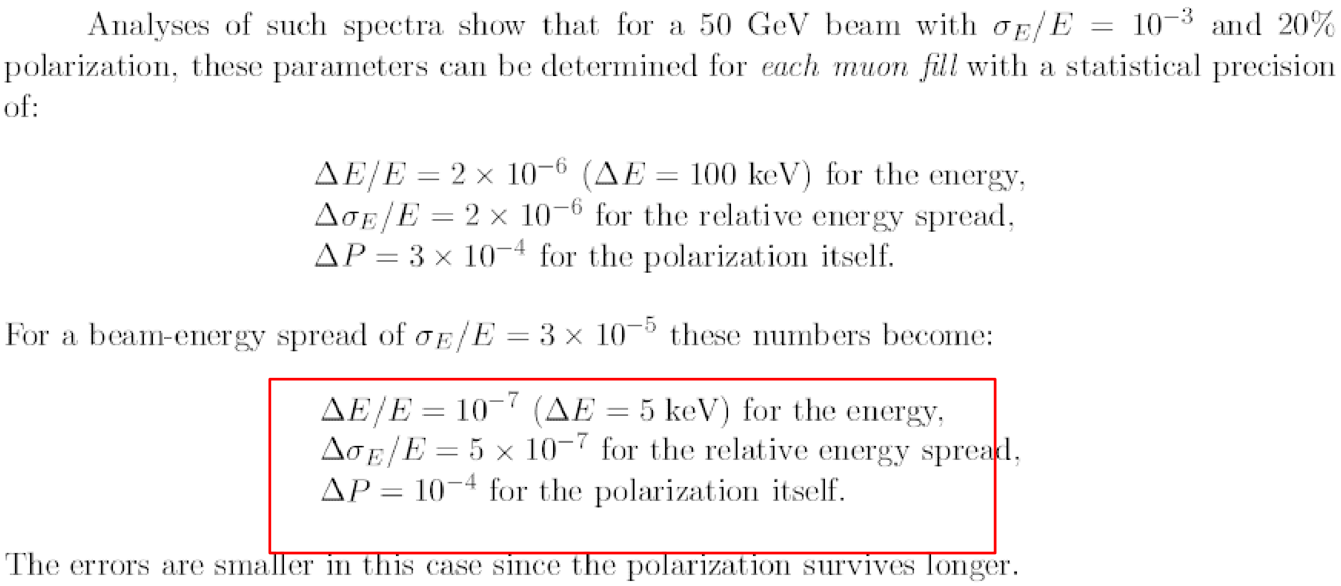
First magnet after straight section

Polarization

- **Because the absolute value of the polarization is not relevant, and only frequencies are involved, the systematic errors are very small (~5-100 keV) on both the beam energy and energy spread.**
  - A. Blondel







Analyses of such spectra show that for a 50 GeV beam with $\sigma_E/E = 10^{-3}$ and 20% polarization, these parameters can be determined for *each muon fill* with a statistical precision of:

$$\Delta E/E = 2\times10^{-6}\ (\Delta E = 100\ \text{keV})\ \text{for the energy,}$$
$$\Delta\sigma_E/E = 2\times10^{-6}\ \text{for the relative energy spread,}$$
$$\Delta P = 3\times10^{-4}\ \text{for the polarization itself.}$$

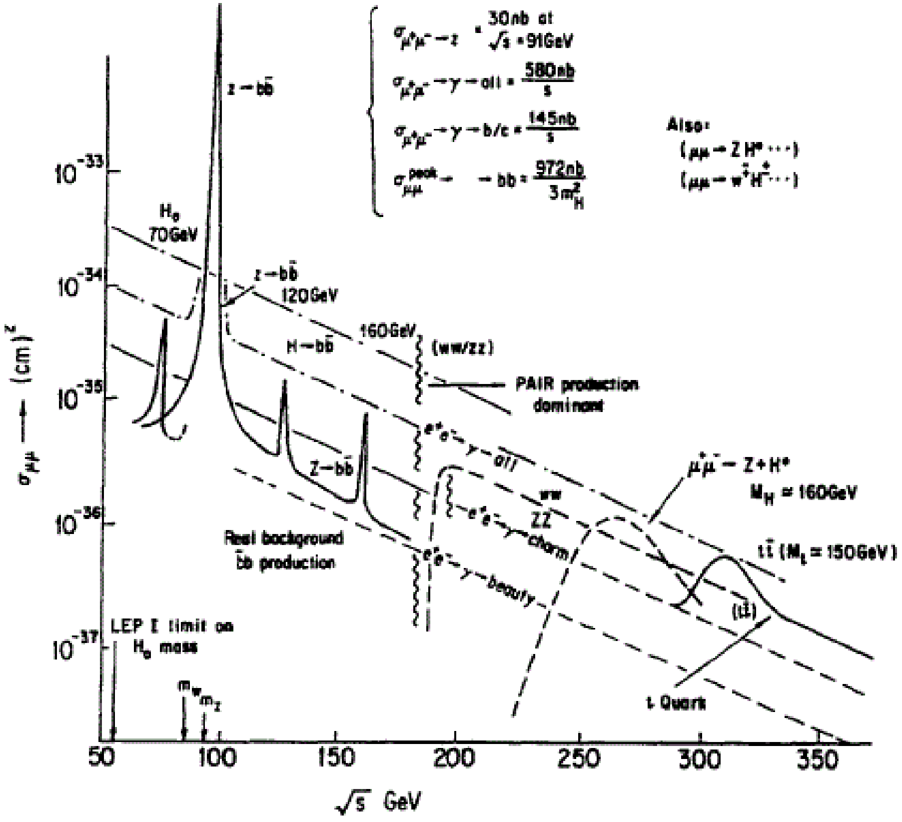
For a beam-energy spread of $\sigma_E/E = 3\times10^{-5}$ these numbers become:

$$\Delta E/E = 10^{-7}\ (\Delta E = 5\ \text{keV})\ \text{for the energy,}$$
$$\Delta\sigma_E/E = 5\times10^{-7}\ \text{for the relative energy spread,}$$
$$\Delta P = 10^{-4}\ \text{for the polarization itself.}$$

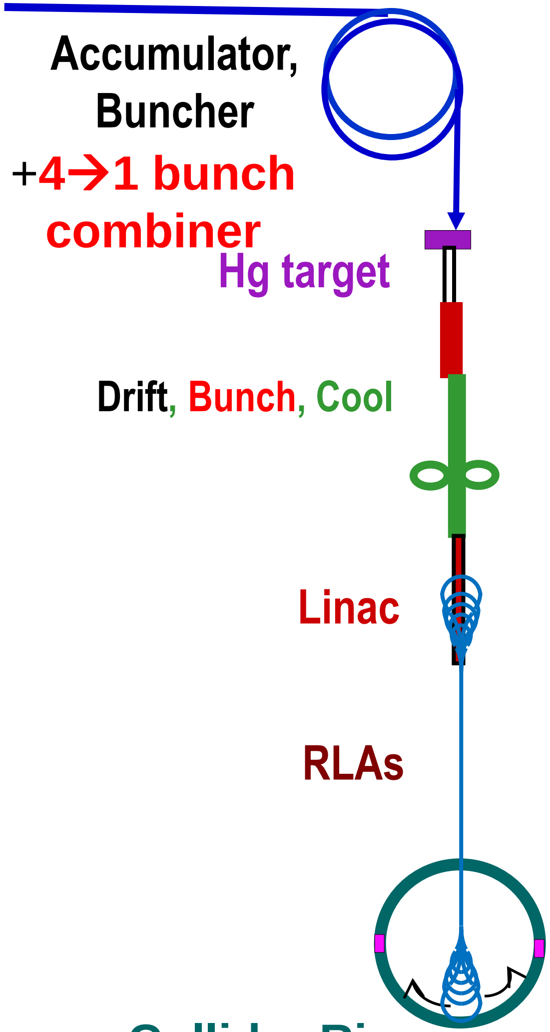
The errors are smaller in this case since the polarization survives longer.

$\mu^+\mu^- \rightarrow$ Z (90 GeV) = "Training Wheels"

- Run on Z until luminosity established
  - easier starting point
  - σ = ~30000 pb
    - 3000 Z/day at $L=10^{30}$
  - Debug L, detectors, background suppression, spin precession, at manageable parameters
  - Useful Physics at Z ?
    - E, ΔE to ~0.1 MeV or less
    - $\mu^+\mu^- \rightarrow Z_0$
  - Then move up to 125 GeV
    - energy sweep to identify H
    - δE ~ 10MeV → 3MeV



Higgs MC Parameters -Upgrade



Proton Linac 8 GeV

Accumulator, Buncher

+4→1 bunch combiner

Hg target

Drift, Bunch, Cool

Linac

RLAs

Collider Ring

$\delta\nu_{BB}$ =0.027

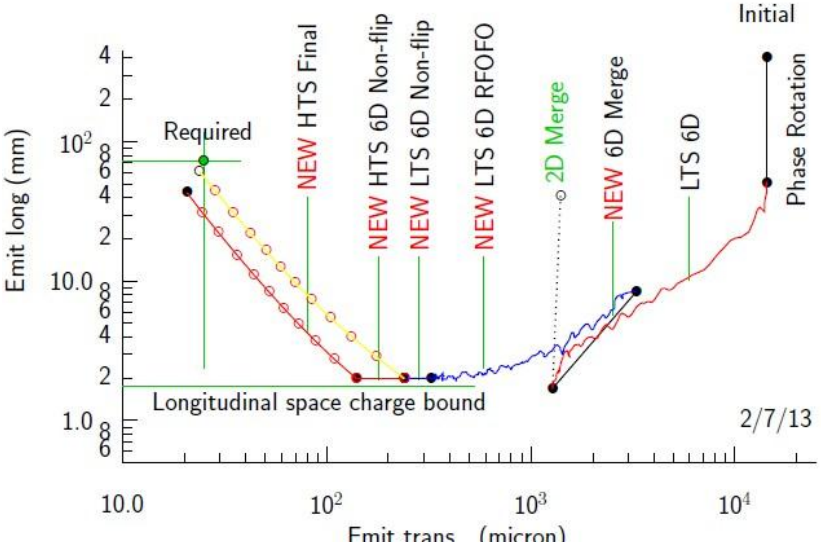
- Reduce transverse emittance to 0.0002m
- More Protons/pulse (15 Hz)

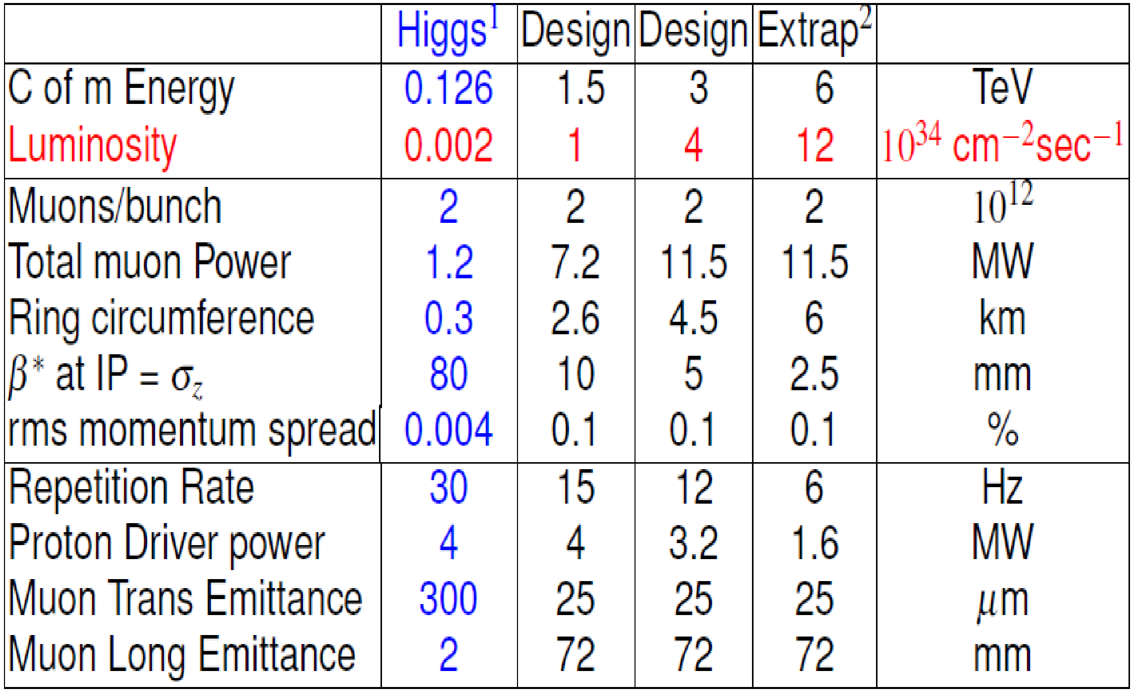
Parameter	Symbol	Value
Proton Beam Power	P_p	4 MW
Bunch frequency	F_p	15 Hz
Protons per bunch	N_p	$4\times5\times10^{13}$
Proton beam energy	E_p	8 GeV
Number of muon bunches	n_B	1
$\mu^{+/-}$/ bunch	N_μ	5×10^{12}
Transverse emittance	$\varepsilon_{t,N}$	0.0002m
Collision β^*	β^*	0.05m
Collision β_{max}	β^*	1000m
Beam size at collision	$\sigma_{x,y}$	200000nm
Beam size (arcs)	$\sigma_{x,y}$	0.3cm
Beam size IR quad	σ_{max}	4cm
Collision Beam Energy	$E_{\mu+},E_{\mu\_}$	62.5(125geV total)
Storage turns	N_t	1300
Luminosity	L_0	10^{32}

50000 H/yr

Upgrade path (E and L)

- **More cooling**
  - low emittance
  - $\varepsilon_{t,N} \rightarrow 0.00003$, $\beta^* \rightarrow 0.3$cm
  - $L \rightarrow 10^{33}$
- **More Protons**
  - 4MW → 8 → ?
  - 15Hz
  - $L \rightarrow 10^{34}$
- **more Acceleration**
  - →4 TeV or more …
  - $L \rightarrow 10^{35}$

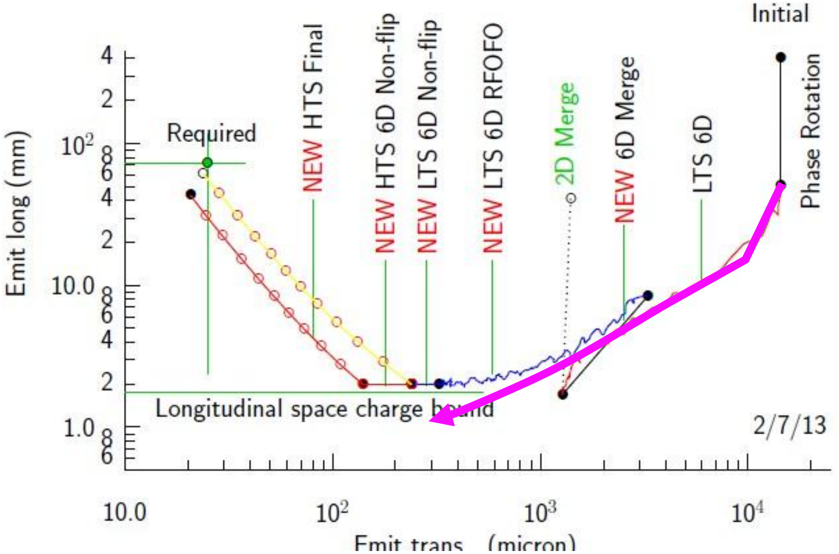


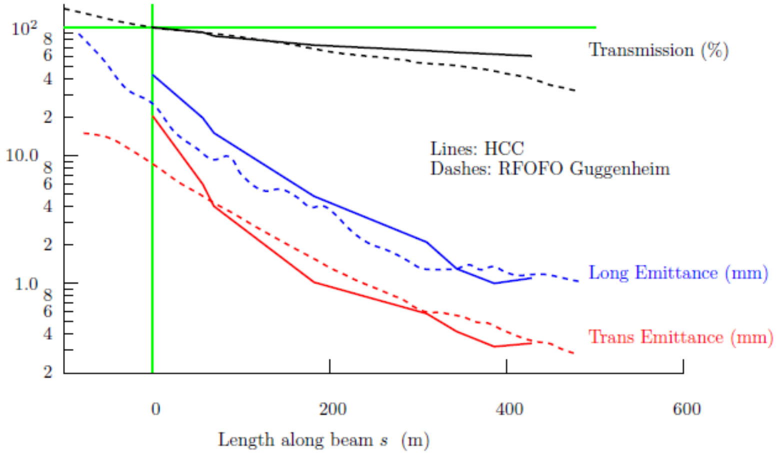


	Higgs[1]	Design	Design	Extrap[2]	
C of m Energy	0.126	1.5	3	6	TeV
Luminosity	0.002	1	4	12	10^{34} cm^{-2}sec^{-1}
Muons/bunch	2	2	2	2	10^{12}
Total muon Power	1.2	7.2	11.5	11.5	MW
Ring circumference	0.3	2.6	4.5	6	km
β^* at IP = σ_z	80	10	5	2.5	mm
rms momentum spread	0.004	0.1	0.1	0.1	%
Repetition Rate	30	15	12	6	Hz
Proton Driver power	4	4	3.2	1.6	MW
Muon Trans Emittance	300	25	25	25	μm
Muon Long Emittance	2	72	72	72	mm

Initial scenario possibilities (Nov. HFWS)

- start with 10^{30} luminosity?
  - measure m_H , δm_H
- Fewer protons?
  - ~1—2MW source
- Less cooling?
  - leave out bunch recombiner
  - ~300-400m path length
- Need to validate cooling , polarization energy measurement





To do for Higgs 2013

- **Ideas?**

(incidentally, the only appearance of a Roman in the history of mathematics)

"NOLI TURBARE CIRCULOS MEOS!"

Archimedes of Syracuse, 287 – 212 BC

thank you for listening!

Professional endorsements

New boson sparks call for 'Higgs factory'

physicsworld.com
BEST SPECIALIST SITE FOR JOURNALISM 2011

Jul 5, 2012 15 comments

Former CERN boss Carlo Rubbia wants a muon collider

CERN's discovery of a new fundamental particle – most likely a Higgs boson – was barely hours old when physicists speaking at this year's Lindau Nobel Laureate Meeting in Germany argued the case for a new facility to measure its properties in detail. Speaking out in favour of a new machine was former CERN boss Carlo Rubbia, who shared the 1984 Nobel Prize for Physics for the discovery of the W and Z bosons. "The technology is there to construct a Higgs factory," he claimed. "You don't need €10bn; it could be done relatively cheaply."

"With a Higgs of 125 GeV we need only a modest machine, perhaps not a large linear collider." Rubbia points out that muons colliding at a combined energy of roughly 125 GeV would suffice – just over half the energy of LEP and requiring a machine with a much smaller radius.

Comments

- **125.9 GeV Higgs is not easy**
  - small cross section, small width
- **Need high-luminosity (> ~10^{30} cm^{-2}s^{-1})**
  - Need high-intensity proton Driver
    - N MW, 5—50 GeV, pulsed mode (10—60 Hz)
  - Need MW target, π→μ collection
  - Need ionization cooling by large factors
    - ε_t: 0.02 → 0.0003 m; ε_L: 0.4 → 0.002 m.
  - acceleration, collider ring, detector
    - spin precession energy measurement
  - can get precision energy and width
- **Not extremely cheap**
  - Most of what we need for high-L high-E μμ Collider