Inaugural US Muon Collider Accelerator School

indico.uchicago.edu/e/mucschool2025

U.S. Particle Accelerator School

Education in Beam Physics and Accelerator Technology

THE UNIVERSITY OF CHICAGO

Colliders – Lecture VS1:

Introduction: Accelerators Technologies and History Luminosity

Vladimir Shiltsev, Northern Illinois University

part of the "Colliders" class by V.Shiltsev, J.Eldred and B. Simmons

Muon Collider School · Aug. 04 – Aug 07, 2025 · U. Chicago

Day 1: General

Lecture 1 Colliders - V.Shiltsev (NIU)

Lecture 2 Beam Optics – J.Eldred (FNAL)

Lecture 3 Beam Dynamics – V.Shiltsev

Homework: ~1 hrs in groups + 2 hrs together
- V.Shiltsev, J.Eldred, B.Simmons (NIU)

This School is "Just About Concepts"

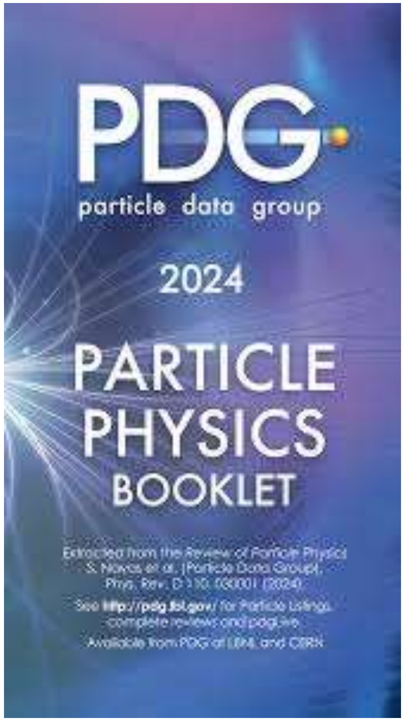
…by no means even a comprehensive intro

US PAS : US Particle Accelerator School
https://uspas.fnal.gov/

CAS: CERN Accelerator School
https://cas.web.cern.ch/

Even better: sign up for undergrad/grad programs in accelerators (>10 in the US Univ.)

This lecture



31. Accelerator Physics of Colliders

Revised July 2023 by V. Shiltsev (FNAL) and F. Zimmermann (CERN).

This article provides background for the High-Energy Collider Parameter Tables that follow and some additional information; see in-depth review and a comprehensive list of references in [1]; citations below are limited to widely used textbooks and open access seminal papers and reviews.

31.1 Energy and Luminosity

Collisions of two beams of particles accelerated to high energies $E_{1,2}$ provide access to center-of-mass energies (c.m.e.) $E_{\rm cme} \approx 2\sqrt{E_1 E_2}$, assuming a typically small or zero crossing angle. Most of the 31 colliders that have ever reached the operational stage (seven are operational now) used equal masses and energies of colliding particles, with c.m.e. equal to twice the beam energy $E_{\rm cme} = 2E_{\rm b}$. Other machines collide beams of unequal energies, such as electron-proton or electron-ion colliders, or asymmetric B-factories, that produce new short-lived particles, whose decays are more easily detected and analyzed with a Lorentz boost.

In an accelerator, charged particles gain energy from an electric field, which usually varies in time at a high frequency ranging from 100s of kHz to 10s of GHz. With proper phasing to the RF field over distance l, the energy gain of a particle with charge Ze is proportional to the average accelerating gradient G, i.e. $\Delta E_{\rm b} = ZeGl$. In principle, the highest beam accelerating gradients achieved to date in operational machines or beam test facilities ($G \approx 100$ MV/m in 12 GHz normal-conducting RF cavities and 31.5 MV/m in 1.3 GHz superconducting ones) allow accessing high energies over reasonably long linear accelerators (linacs), but cost considerations often call for minimization of RF acceleration via repeated use of the same RF system which, in that case, would boost the energy in small portions $\Delta E_{\rm b} = ZeV_{\rm RF}$ per turn every time a particle passes through the total cavity voltage $V_{\rm RF}$. Such an arrangement can be realized either in the form of storage-ring circular colliders or also through novel schemes based on, e.g., recirculating linear accelerators (RLAs) with or without energy recovery. Circular colliders are by far the most common; here, the momentum and energy of ultra-relativistic particles are determined by the bending radius inside the dipole magnets, ρ, and by the average magnetic field B of these magnets:

$$p = ZeB\rho \quad \text{or} \quad E_{\rm b}\,[\text{GeV}] = 0.3Z(B\rho)\,[\text{Tm}]\,. \tag{31.1}$$

Acceleration: Increase of Energy

Energy gain is ***F*[force] x *L*[distance]**

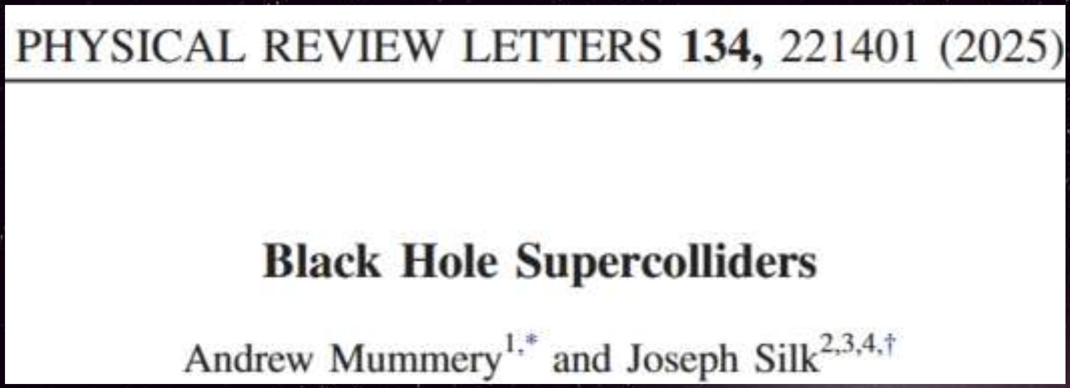
Forces: **Strong/nuclear** [local]

Electromagnetic [used widely]

Weak [??]

Gravitational [see next slide]

Acceleration by the Fields of Gravity


PHYSICAL REVIEW LETTERS **134**, 221401 (2025)

Black Hole Supercolliders

Andrew Mummery[1,*] and Joseph Silk[2,3,4,†]

…collisions between particles free falling from infinity and a disk of material plunging off the retrograde innermost stable circular orbit of a near-extremal Kerr black hole… → result in rest-frame **energies at the level of 1 to 100's of TeV** (or more).

ENERGY: Ideas / Breakthroughts

#1 Electrostatic *E* [10keV – 10 MeV]

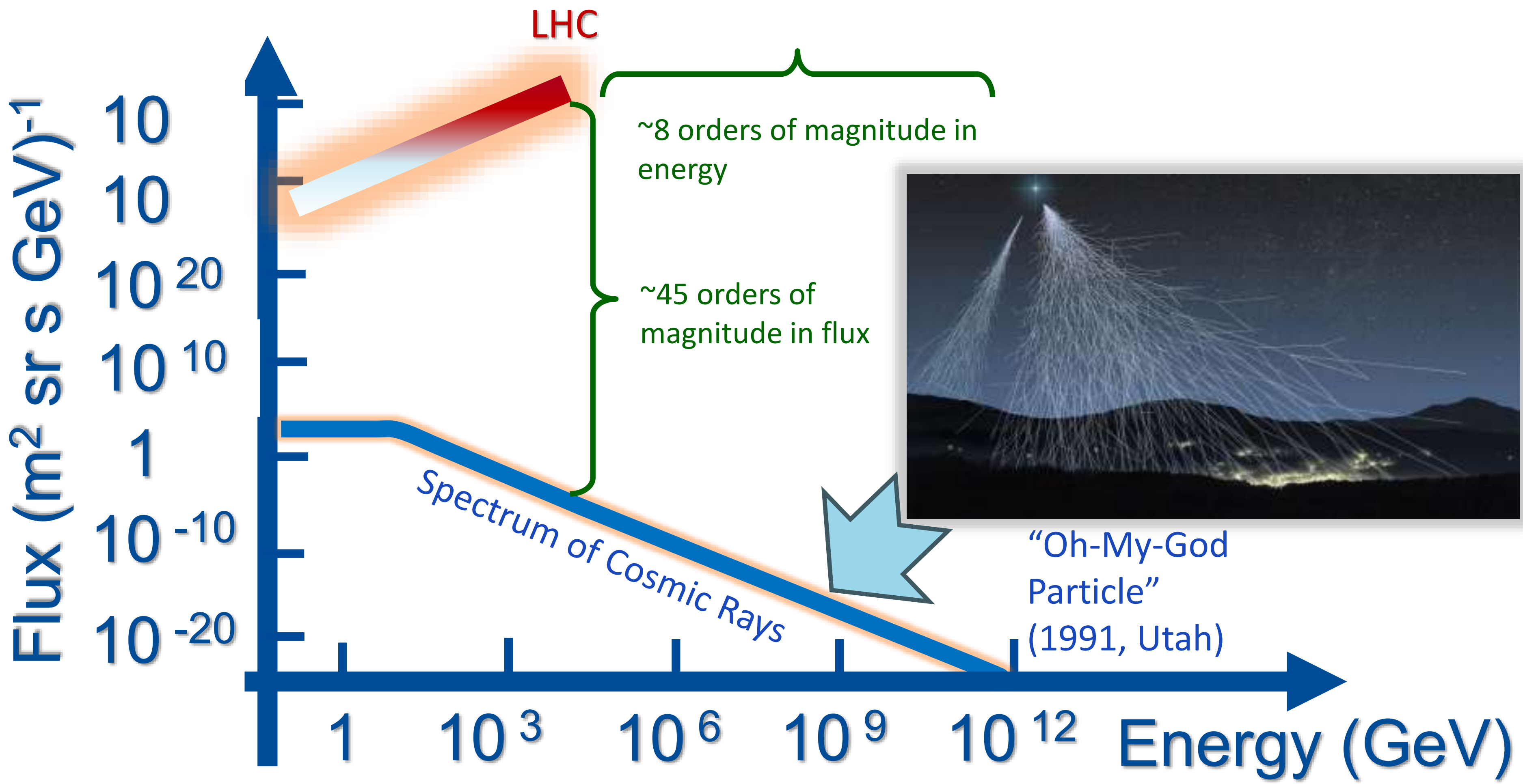
#2 Resonant/RF *E* [0.1 GeV – 1 TeV]

#3 Colliders E_{cm} [1 GeV- 14 TeV]

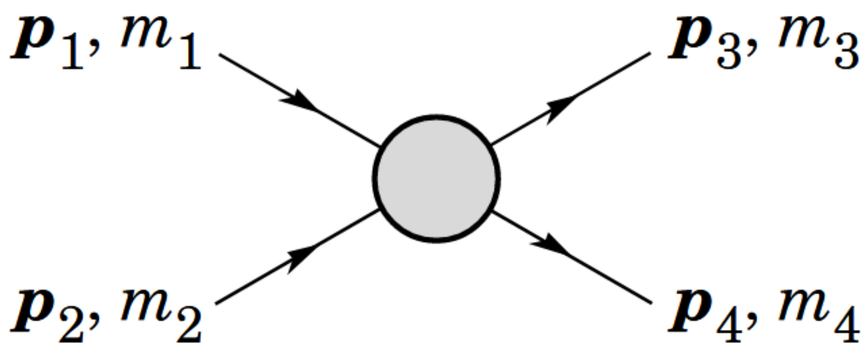
#4 Heavy leptons E_{pcm} [10 - 100 TeV]

#5 Plasma Wakes *E* [0.1- 1 PeV]

ACCELERATORS vs COSMOS



Lorentz-Invariant Mandelstam Variables



$$
\begin{aligned}
s &= (p_1 + p_2)^2 = (p_3 + p_4)^2 \\
&= m_1^2 + 2E_1E_2 - 2\boldsymbol{p}_1 \cdot \boldsymbol{p}_2 + m_2^2 \\
t &= (p_1 - p_3)^2 = (p_2 - p_4)^2 \\
&= m_1^2 - 2E_1E_3 + 2\boldsymbol{p}_1 \cdot \boldsymbol{p}_3 + m_3^2 \\
u &= (p_1 - p_4)^2 = (p_2 - p_3)^2 \\
&= m_1^2 - 2E_1E_4 + 2\boldsymbol{p}_1 \cdot \boldsymbol{p}_4 + m_4^2
\end{aligned}
$$

$s = E^2_{cme}$

Kinematics of collisions

Two particles ($E_{1,2}$, $m_{1,2}$) collide at angle θ_c

$$E_{cme} = \left(2E_1E_2 + (m_1^2 + m_2^2)c^4 + \right.$$

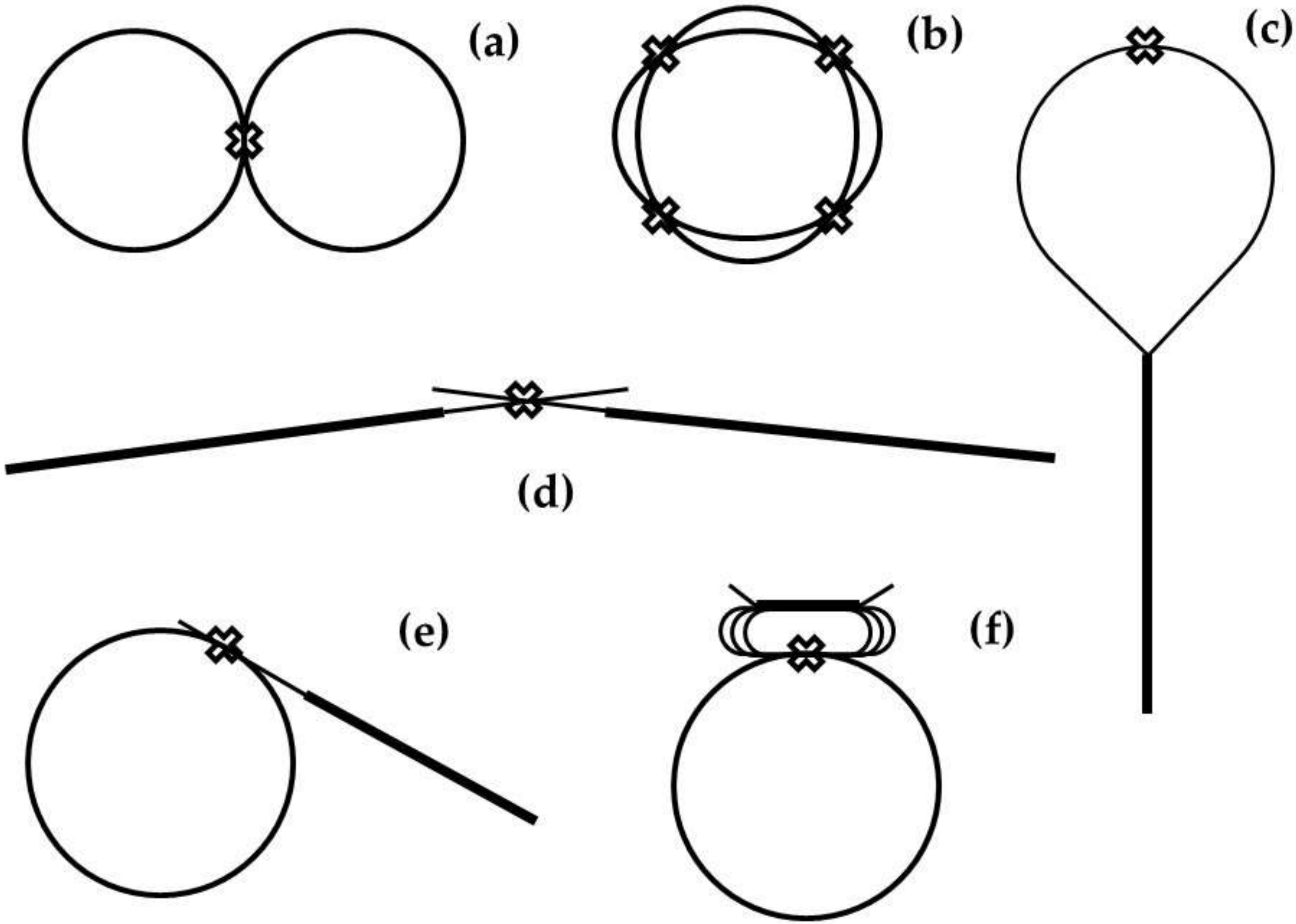
$$\left. +2\cos\theta_c \sqrt{E_1^2 - m_1^2c^4}\sqrt{E_2^2 - m_2^2c^4} \right)^{1/2}$$

One particle stationary ($E_2 = m_2 c^2$) $\quad E_{cme} \approx \sqrt{2Emc^2}$

Both particles move ($E_{1,2} >> m_{1,2}\, c^2$) $\quad E_{cme} \approx 2\sqrt{E_1E_2}$

Gain for (E= 6500 GeV, m=0.936 GeV) is ~120 times (0.11 vs 13 TeV)

Types of colliding beam facilities



Colliders Landscape

61 years since 1st collisions

- Spring 1964 AdA and VEP-1

31 operated since

- (see RMP review)

7 in operation now

- see next slides

2 under construction

- NICA (2025) and EIC (2032)

At least 2 more types needed

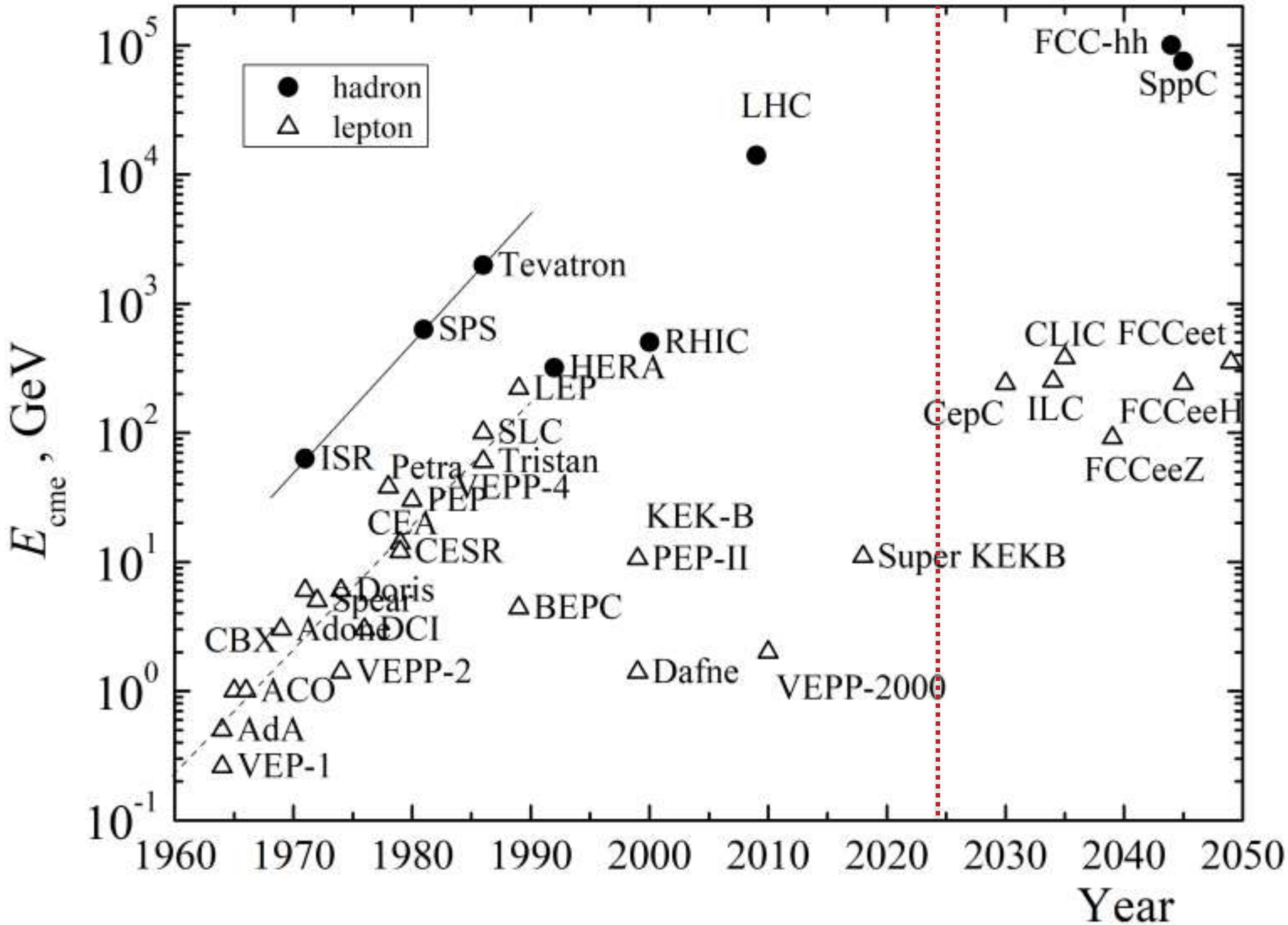
- Higgs/Electroweak factories
- Frontier E >> LHC

V. Shiltsev and F. Zimmermann: Modern and future colliders

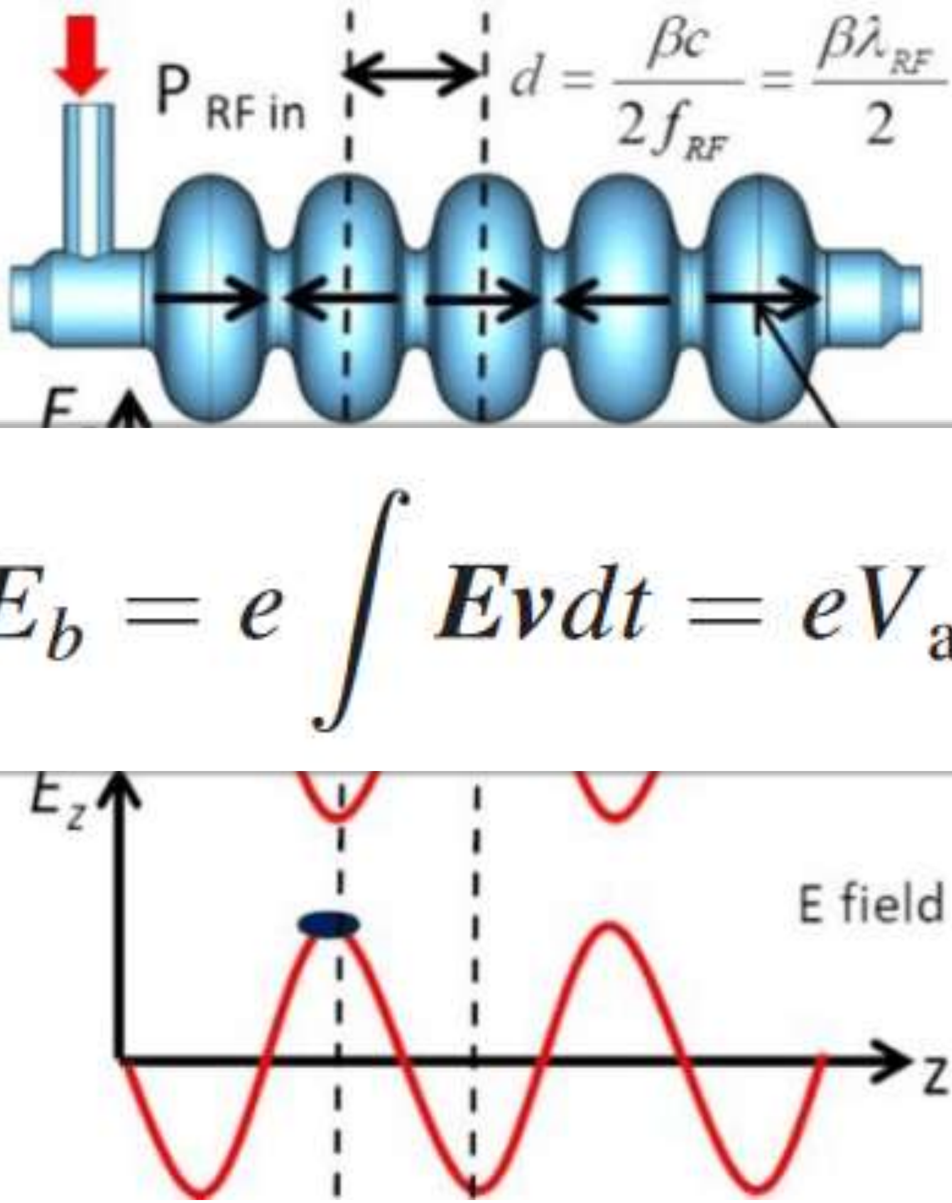
	Species	E_b, GeV	C, m	$\mathcal{L}_{peak}^{max}$	Years
AdA	e^+e^-	0.25	4.1	10^{25}	1964
VEP-1	e^-e^-	0.16	2.7	5×10^{27}	1964-68
CBX	e^-e^-	0.5	11.8	2×10^{28}	1965-68
VEPP-2	e^+e^-	0.67	11.5	4×10^{28}	1966-70
ACO	e^+e^-	0.54	22	10^{29}	1967-72
ADONE	e^+e^-	1.5	105	6×10^{29}	1969-93
CEA	e^+e^-	3.0	226	0.8×10^{28}	1971-73
ISR	pp	31.4	943	1.4×10^{32}	1971-80
SPEAR	e^+e^-	4.2	234	1.2×10^{31}	1972-90
DORIS	e^+e^-	5.6	289	3.3×10^{31}	1973-93
VEPP-2M	e^+e^-	0.7	18	5×10^{30}	1974-2000
VEPP-3	e^+e^-	1.55	74	2×10^{27}	1974-75
DCI	e^+e^-	1.8	94.6	2×10^{30}	1977-84
PETRA	e^+e^-	23.4	2304	2.4×10^{31}	1978-86
CESR	e^+e^-	6	768	1.3×10^{33}	1979-2008
PEP	e^+e^-	15	2200	6×10^{31}	1980-90
S$p\bar{p}$S	$p\bar{p}$	455	6911	6×10^{30}	1981-90
TRISTAN	e^+e^-	32	3018	4×10^{31}	1987-95
Tevatron	$p\bar{p}$	980	6283	4.3×10^{32}	1987-2011
SLC	e^+e^-	50	2920	2.5×10^{30}	1989-98
LEP	e^+e^-	104.6	26659	10^{32}	1989-2000
HERA	ep	30+920	6336	7.5×10^{31}	1992-2007
PEP-II	e^+e^-	3.1+9	2200	1.2×10^{34}	1999-2008
KEKB	e^+e^-	3.5+8.0	3016	2.1×10^{34}	1999-2010
VEPP-4M	e^+e^-	6	366	2×10^{31}	1979-
BEPC-I/II	e^+e^-	2.3	238	10^{33}	1989-
DAΦNE	e^+e^-	0.51	98	4.5×10^{32}	1997-
RHIC	p, i	255	3834	2.5×10^{32}	2000-
LHC	p, i	6500	26659	2.1×10^{34}	2009-
VEPP2000	e^+e^-	1.0	24	4×10^{31}	2010-
S-KEKB	e^+e^-	7+4	3016	8×10^{35} *	2018-

Colliders: Energy

FIG. 2. Center of mass energy reach of particle colliders vs their start of operation. Solid and dashed lines indicate a ten-fold increase per decade for hadron (circles) and lepton (triangles) colliders (adapted from [37]).



Only Electric Field Boosts Energy



$$\omega_{\mathrm{rf}} = 2\pi f_{\mathrm{rf}}$$

$$\Delta E_b = e \int \boldsymbol{E} v dt = eV_{\mathrm{acc}} \cos\left(\omega_{\mathrm{rf}} t + \phi\right)$$

How much power is needed

$$P_{\mathrm{rf}} = P_b + P_{\mathrm{loss}} = I_b \Delta E_b + \frac{V_{\mathrm{acc}}^2}{2R_s}$$

Where "*shunt impedance*": $R_s = Q(R/Q)$

"Quality factor"

~10^4 for Copper 300K

10^(9-10) for SC Nb cavities

"R/Q" cavity geometry factor

~100 for "open" elliptic cavities

196 Ohm for "pillbox" cvavity

RF Cavities

Resonant cavity, eg "pill-box":

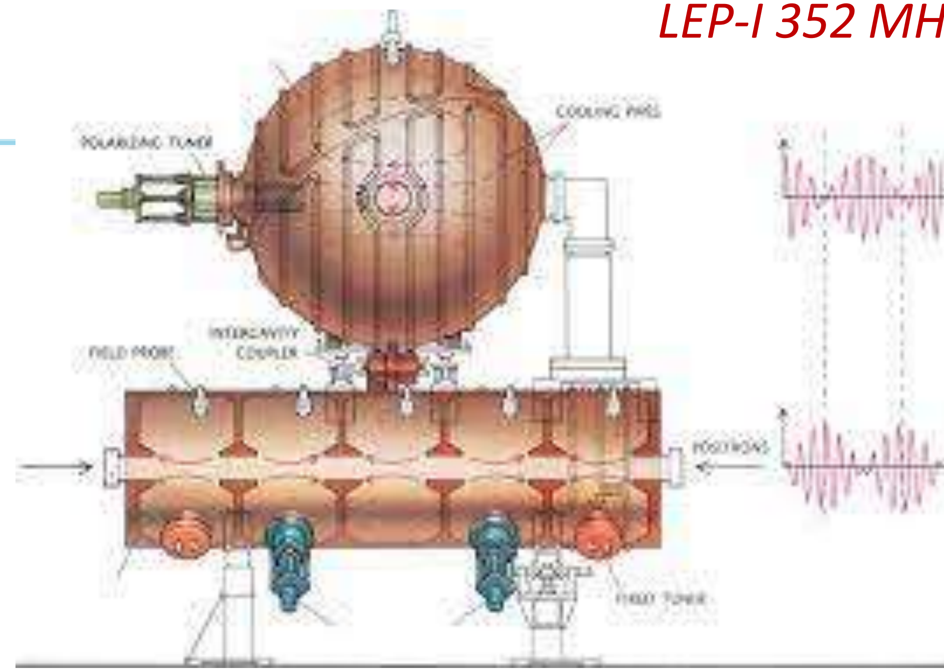
$$\omega_c = \frac{2.405\, c}{R_c}$$

R=10cm at f_{RF}=1.14 GHz

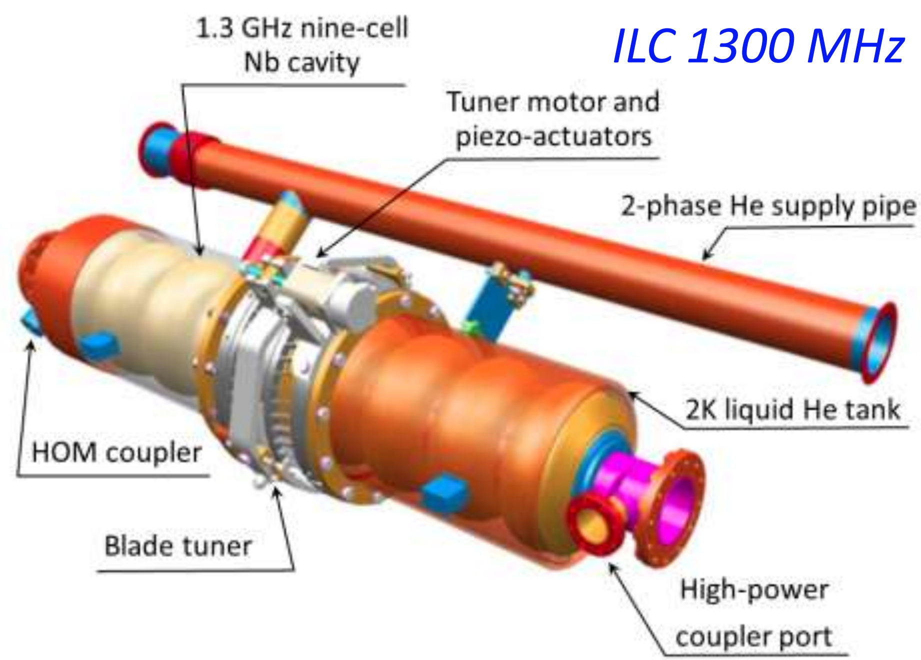
Max gradient/voltage per cavity:

- *Is determined by RF power and shunt impedance*
- *Is limited by breakdown or dark current radiation or loss of superconductivity*
  - depends on frequency, CW or pulse duration, geometry, material, temperature, etc
- *Max ~100 MV/m in normal-conducting cavities at 12 GHz*
- *Max ~31.5 MV/m SRF cavities 1.3GHz*

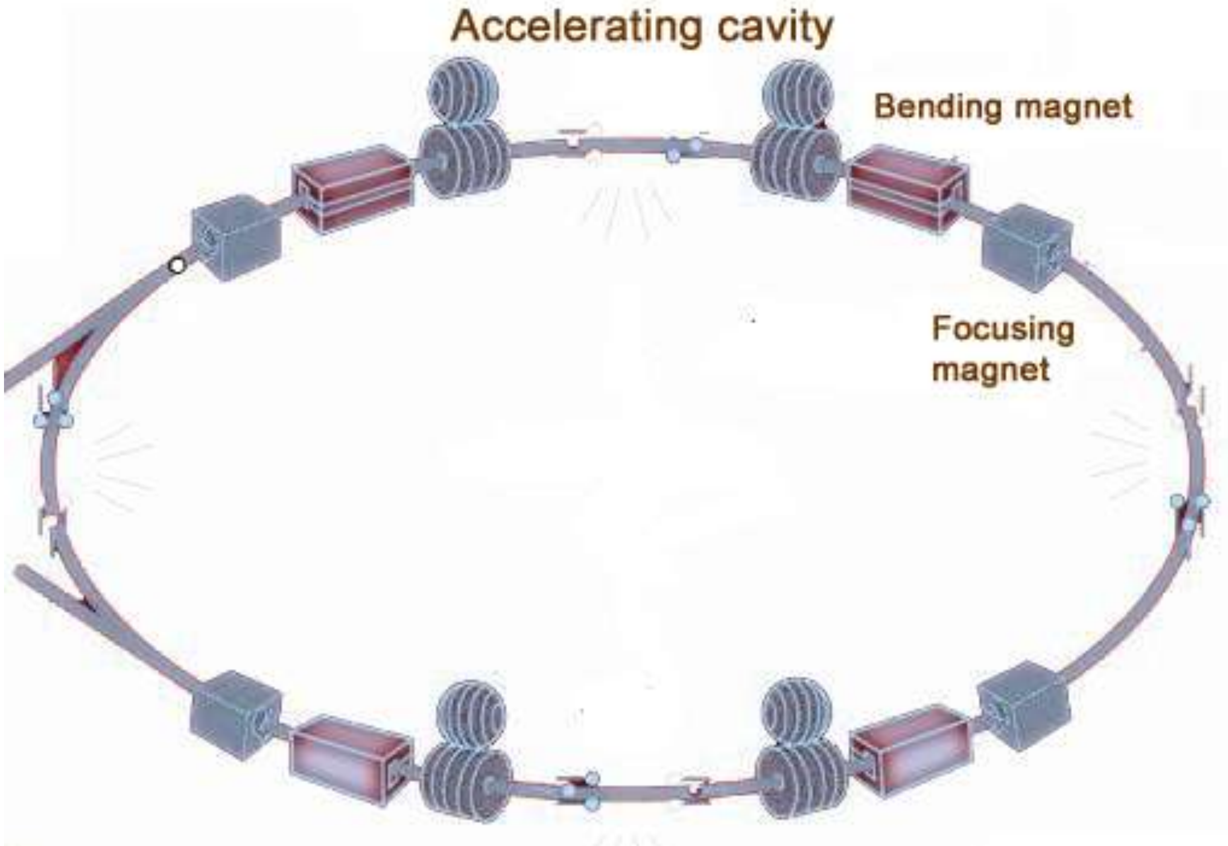
LEP-I 352 MHz

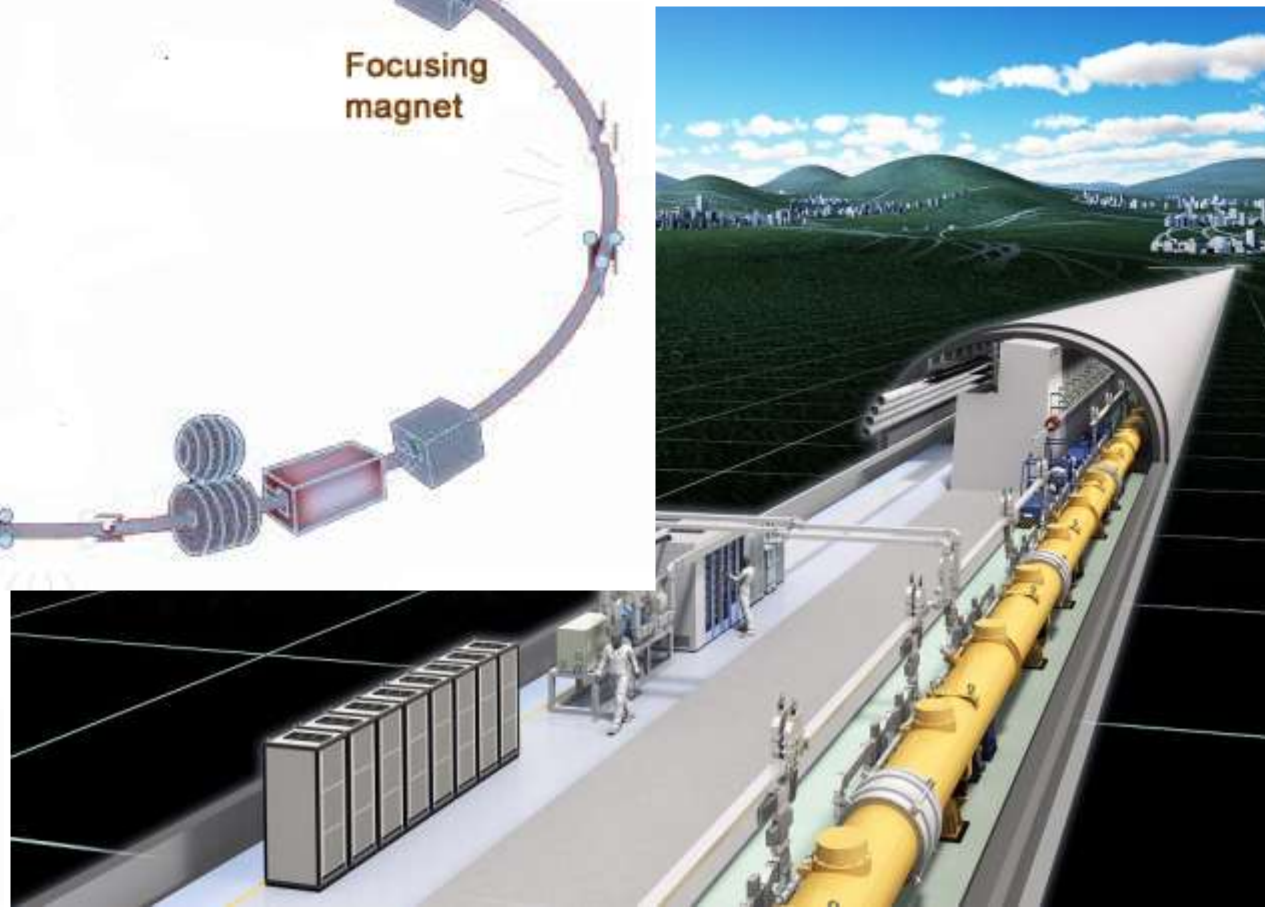


ILC 1300 MHz



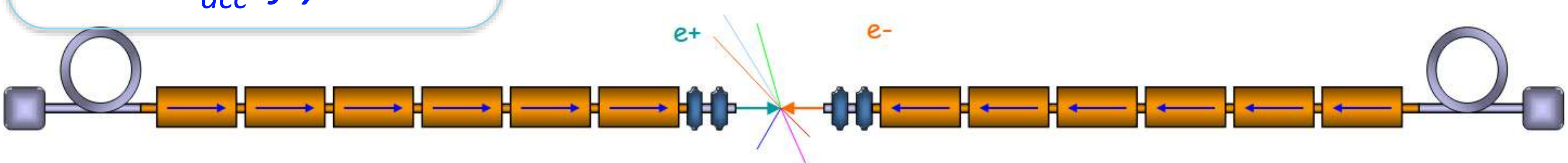
Rings vs Linacs





$$I_b \Delta E_b + \frac{V_{acc}^2}{2R_s}$$

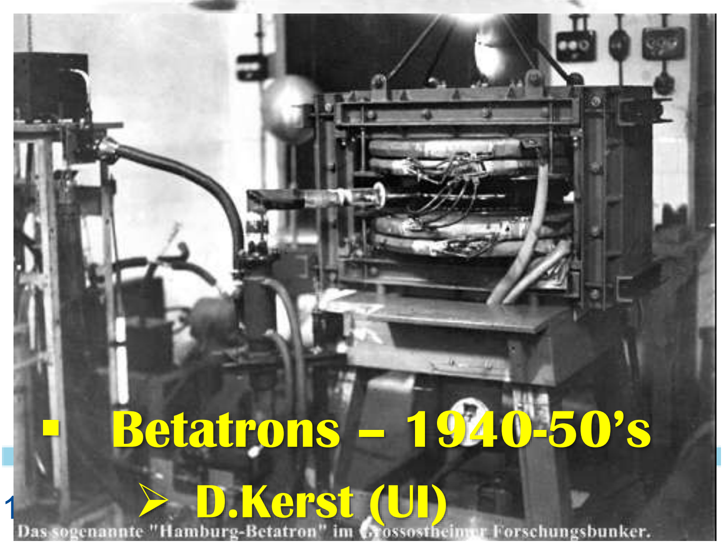
lower V_{acc} if you can



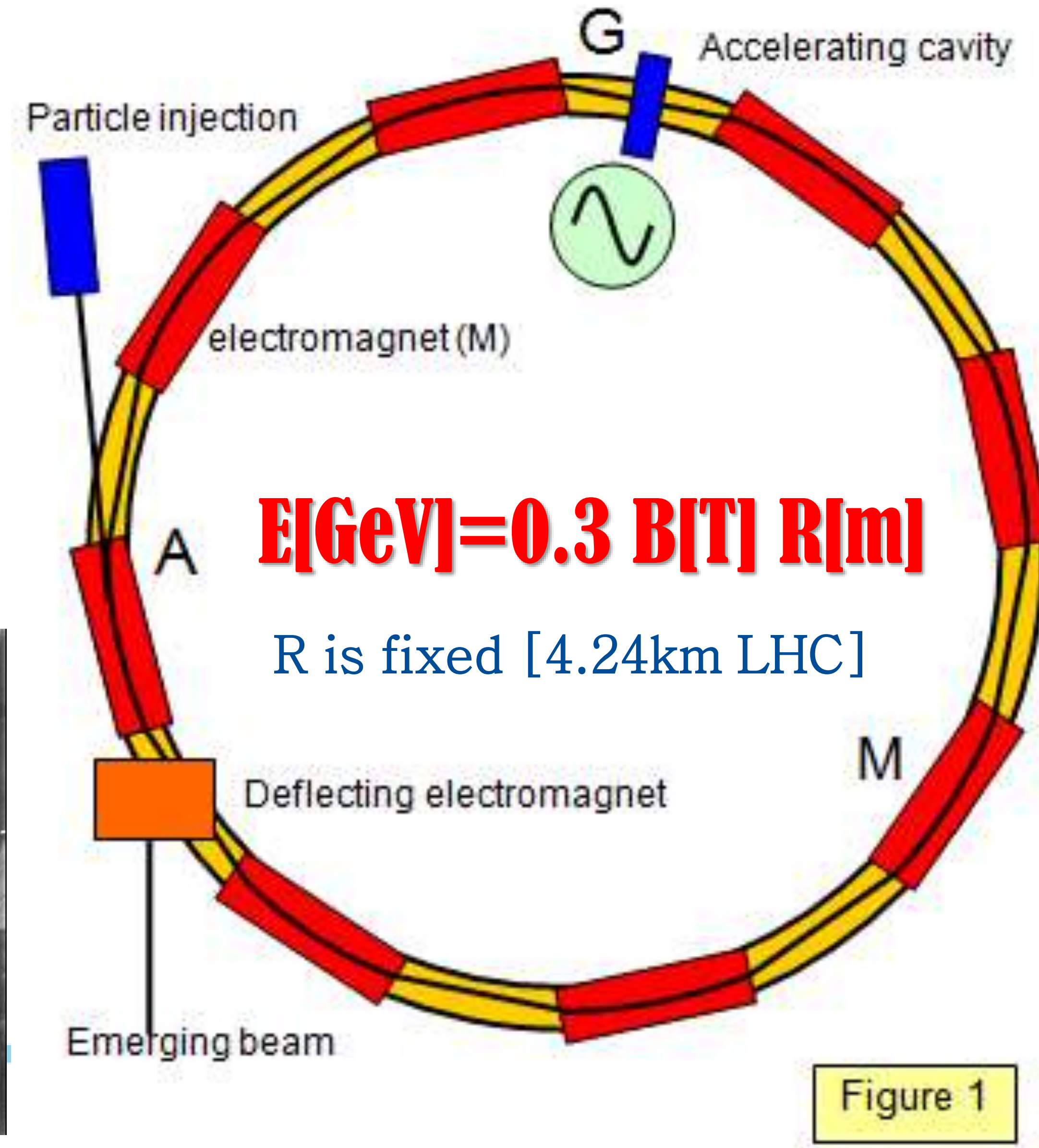
Types of Circular Accelerators

- **Cyclotrons – 1930-40's**
  - **E.O.Lawrence (UCB)**

- **Betatrons – 1940-50's**
  - **D.Kerst (UI)**



Synchrotrons (Tevatron, LHC, MuColl)



$$E[GeV]=0.3\ B[T]\ R[m]$$

R is fixed [4.24km LHC]

Highest Energy = Highest Field SC Magnets

4.5T

Tevatron,
6 m, 76 mm
774 dipoles

4.5 K He, NbTi
+ warm iron
small He-plant

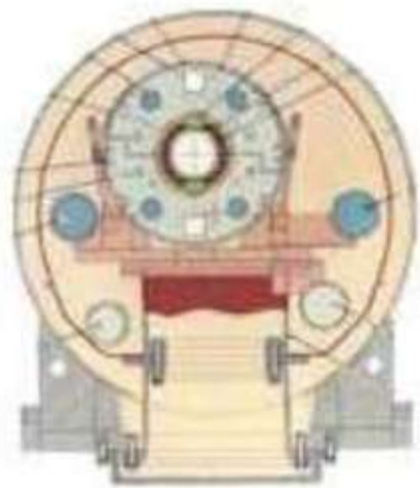
5.3T

HERA,
9 m, 75 mm
416 dipoles

NbTi cable
cold iron
Al collar

3.5T

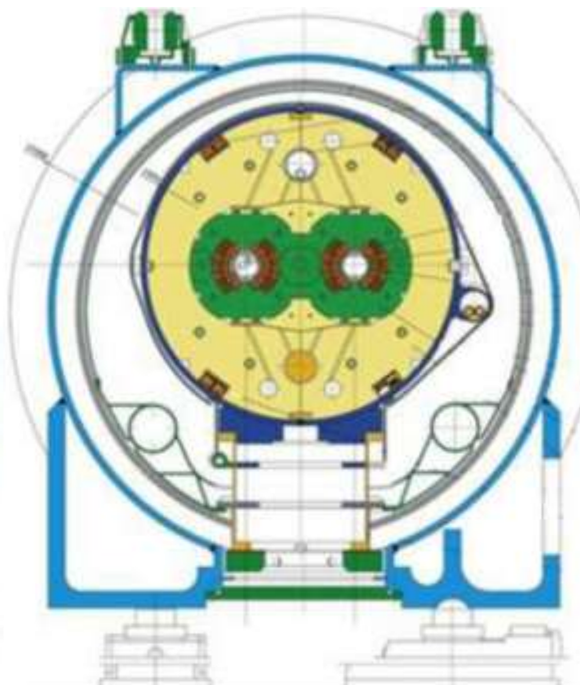
RHIC,
9 m, 80 mm
264 dipoles



NbTi cable
simple &
cheap

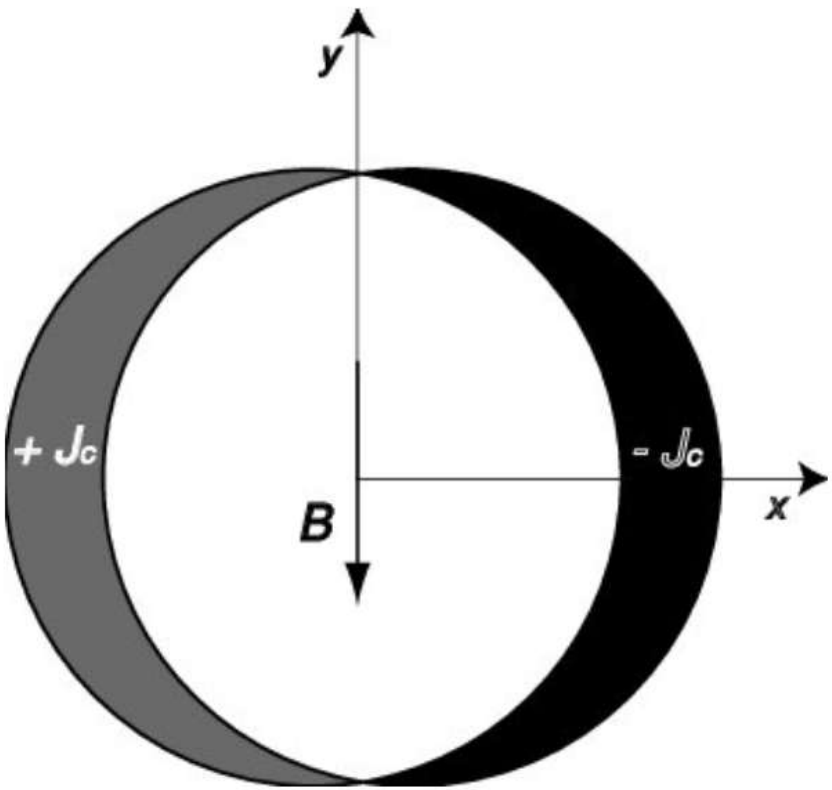
8.3T

LHC,
15 m, 56 mm
1276 dipoles



NbTi cable
2K He
two bores

Key for Magnets: Current Density



Generation of a pure dipole by a *cos θ* current distribution

Scaling: B_{max}~ *J/Aperture*

(assume all *A* is filled by conductor)

J~j(current density) x A^2

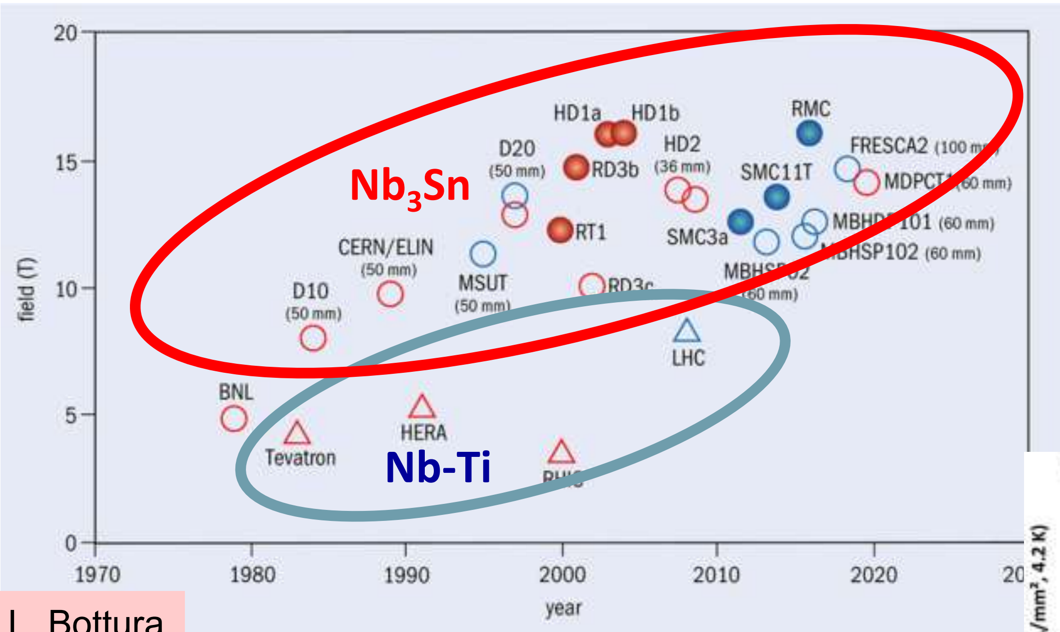
B_{max}~j x A

but Cost ~*A^2* (cost of needed conductor) x length ~ *A^2/B* ~ ***~A/j***

Therefore, high(est) current density is needed to maxizmize B-field and minimize Cost

- For room temperature copper *j~(*1-10) A/mm^2
- For superconductors → kA/mm^2

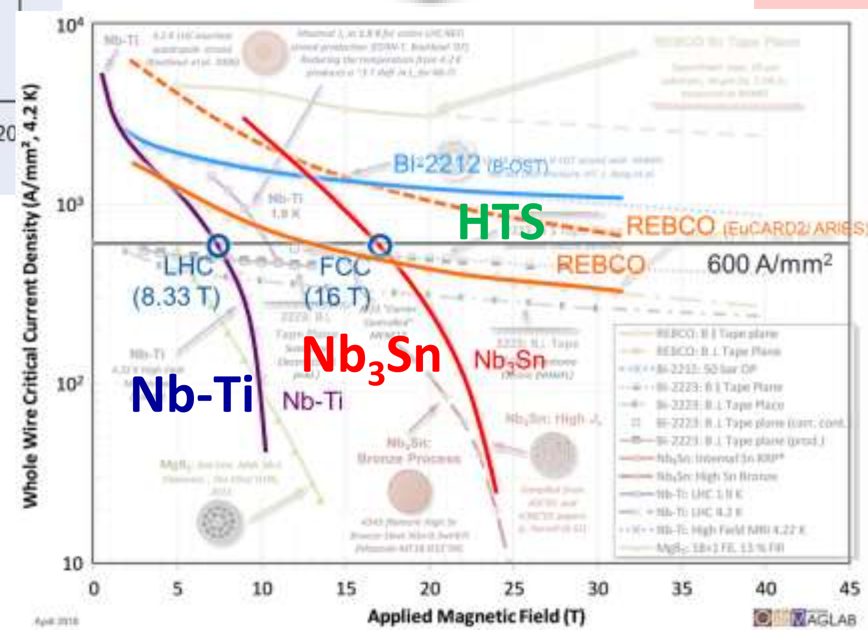
SC Magnets: Fields and Current Densities



L. Bottura

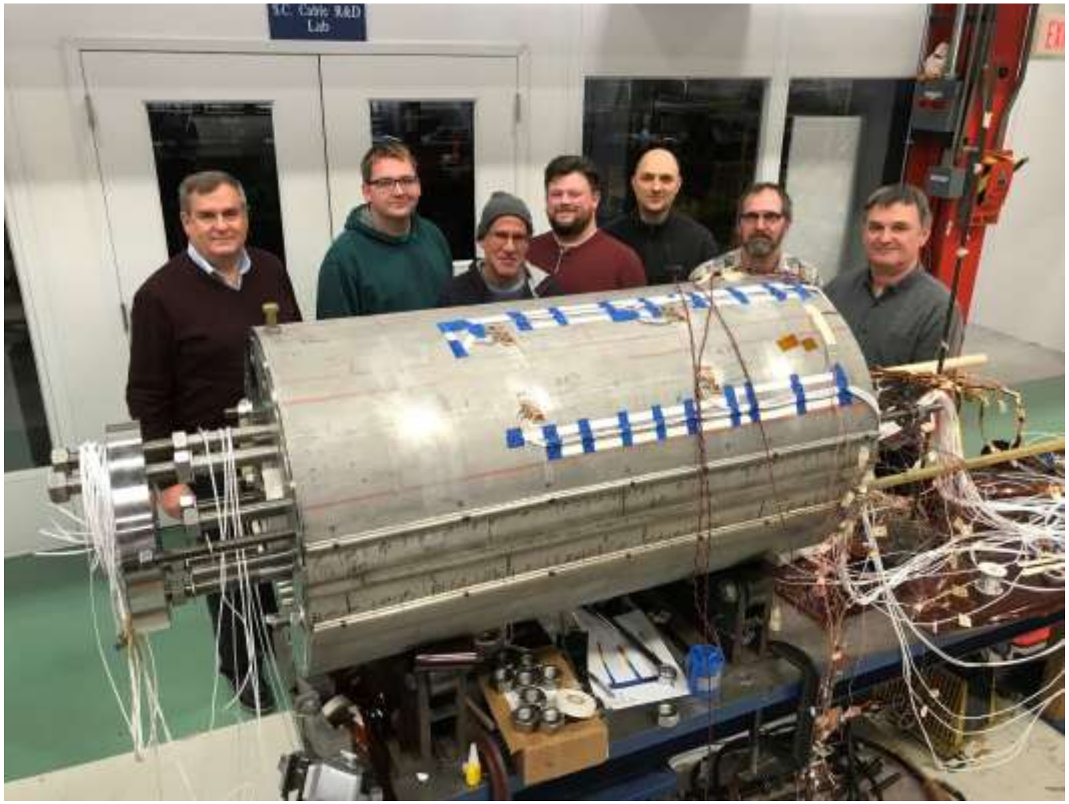
Superconducting wire critical current density versus magnetic field: three main materials Nb-Ti, Nb_3Sn, HTS

P. Lee

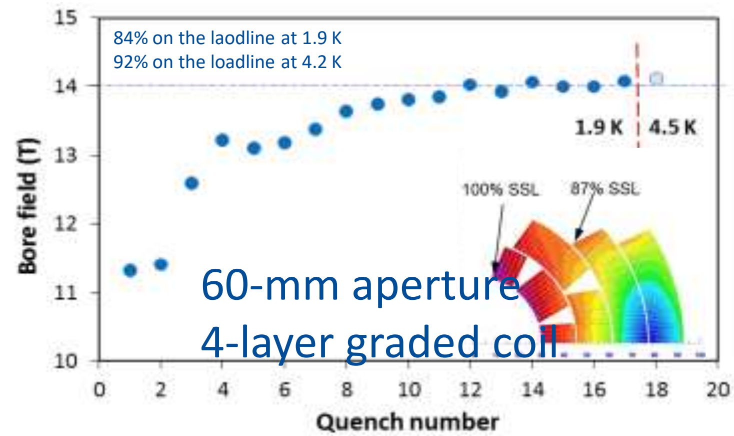


Record fields attained with dipole magnets of various configurations and dimensions, and either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature.

SC Accelerator Magnets: Current Record 14.5T

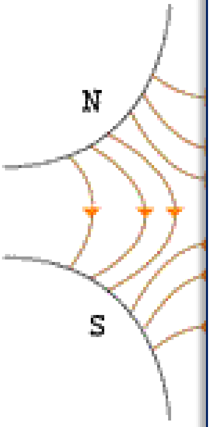


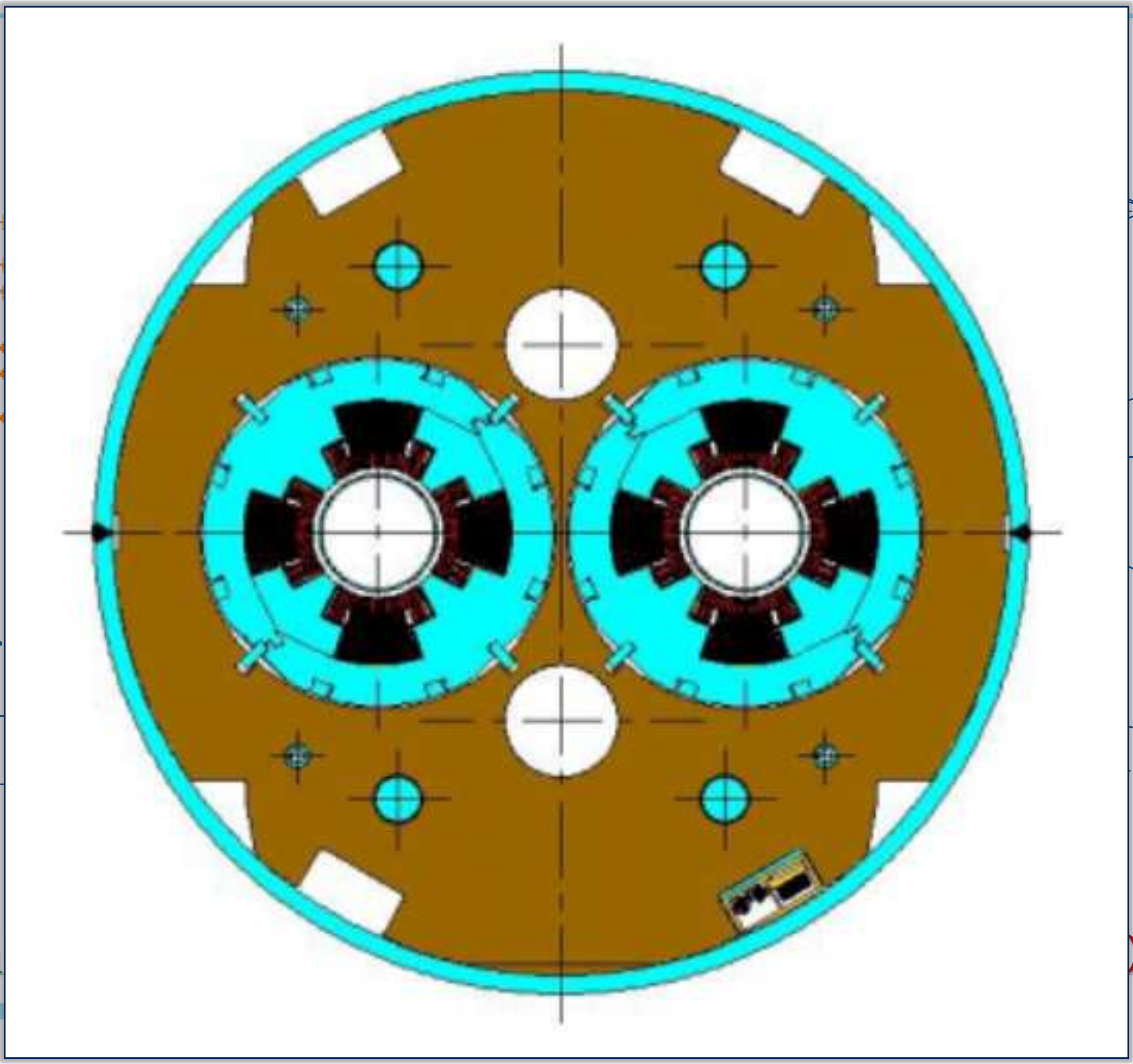
cos*θ* dipole



- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in June 2020 with additional pre-stress reached 14.5 T

Focusing Beams with Quadrupole Magnets

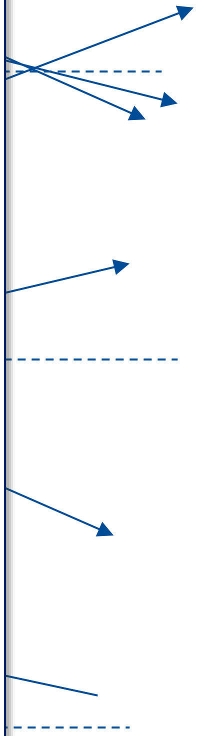




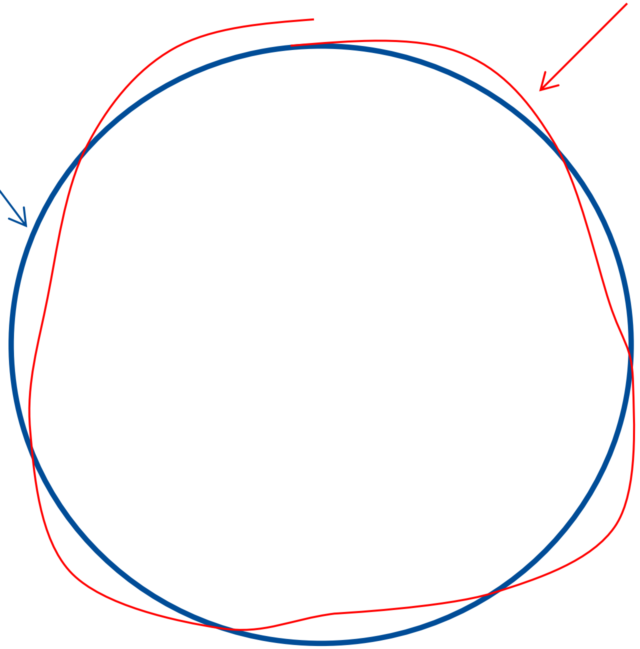
Luckily.

…pai

cell"



Betatron Oscillations, Tune



- As particles go around a ring, they will undergo a number of betatron oscillations *v* (sometimes *Q*) given by

$$\nu = \frac{1}{2\pi} \oint \frac{ds}{\beta(s)}$$

- This is referred to as the **"tune"**

- We can generally think of the tune in two parts:

Integer : magnet/aperture optimization → **64.31** ← **Fraction: Beam Stability**

see Jeff's lecture

Particle Equations of Motion (1)

$$x'' + K_x x = 0, \quad \text{with} \quad K_x \equiv \frac{e}{p}\frac{\partial B_y}{\partial x} + \frac{1}{\rho^2},$$

$$y'' + K_y y = 0, \quad \text{with} \quad K_y \equiv -\frac{e}{p}\frac{\partial B_y}{\partial x},$$

$$z' = -x/\rho,$$

Solution:

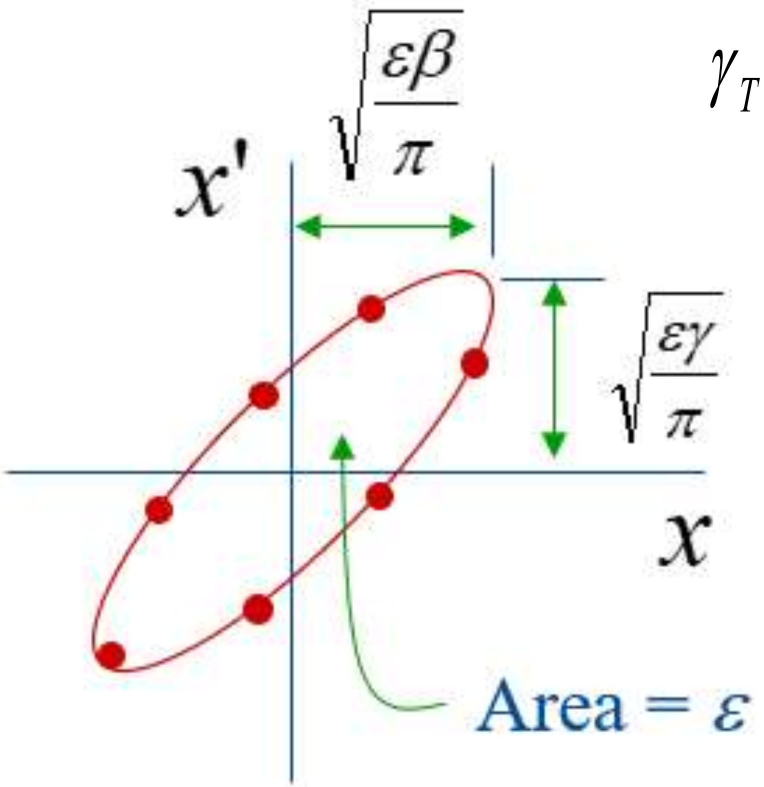
$$x(s) = \sqrt{2J_x\beta_x}\cos\psi_x, \qquad d\psi_x/ds = 1/\beta_x$$

$$x'(s) = -\sqrt{\frac{2J_x}{\beta_x}}[\alpha\cos\psi_x + \sin\psi_x],$$

So, tune: $Q_x = \frac{1}{2\pi}\oint d\psi_x = \frac{1}{2\pi}\oint \frac{ds}{\beta_x(s)}$

see Jeff's lecture

Key beam parameter: Emittance



$$\gamma_T x^2 + 2\alpha_T x x' + \beta_T x'^2 = \frac{\varepsilon}{\pi}$$

β,γ, α - Twiss parameters

For an ensamble of particles:

- Product *size x angle* *X_rms x X'_rms* is called emittance
- *Normalized emittance* = *emittance* x *gamma* is an adiabatic invariant
- Luminosity (tbd) ~ 1/ε

As a particle returns to the same point on subsequent revolutions, it will map out an ellipse in phase space – more in Jeff's lecture

Most Important Equations

normalized emittance

$$\varepsilon_{n\ (x,y)} = \gamma \cdot \sigma_{x,y} \sigma'_{x,y}$$

$$\sigma_{x,y} = \sqrt{\frac{\varepsilon_n \cdot \beta_{x,y}}{\gamma}}$$

rms beam size

$$\sigma'_{x,y} = \sqrt{\frac{\varepsilon_n}{\gamma \cdot \beta_{x,y}}} = \frac{\sigma_{x,y}}{\beta_{x,y}}$$

rms beam angular spread

10^{-6}

Particle Equations of Motion (2)

Beta-functions are defined by

$$2\beta_x\beta_x'' - \beta_x'^2 + 4\beta_x^2 K_x = 4$$

Eg symmetric solution in free space (*K*=0):

$$\beta_x(s) = \beta_x^* + \frac{s^2}{\beta_x^*}$$

Also, note that nonlinear fields on beam orbit add complexity:

$$B_y + iB_x = \sum_{n=1}^{\infty}(B_n + iA_n)(x + iy)^{n-1}$$

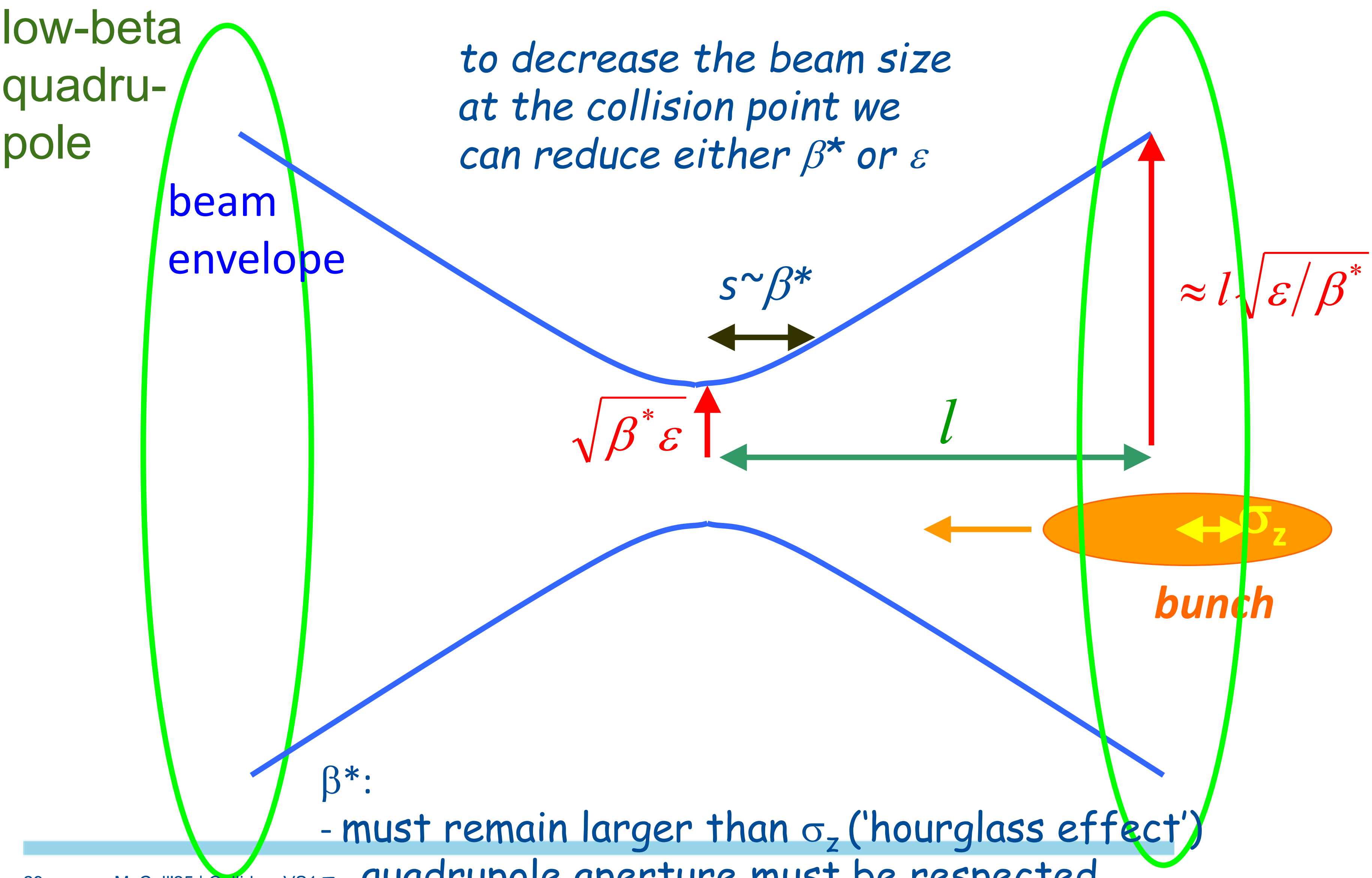
n=1 dipole
n=2 quadrupole
n=3 octupole
n=4,5,6…

especially at resonant frequencies

$kQ_x + lQ_y = m$, where k, l, and m are integers

More in Jeff's lecture

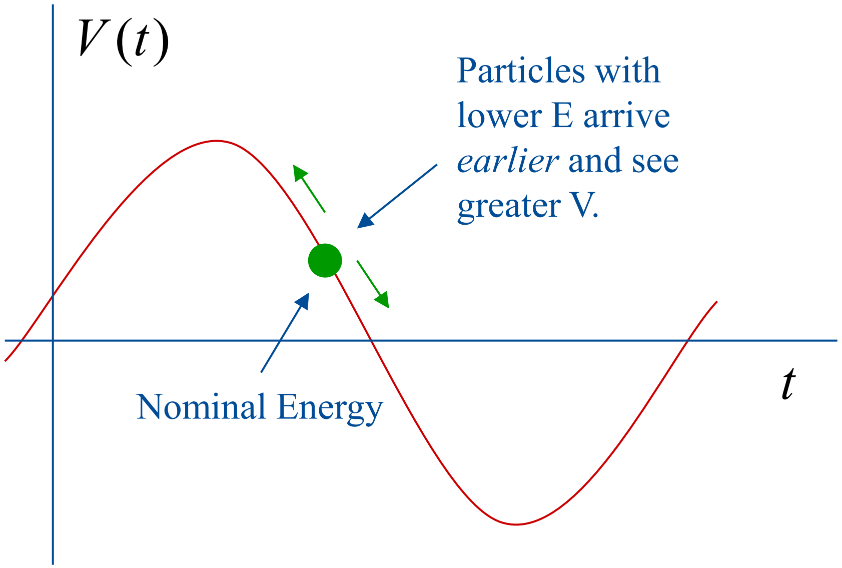
Collider Spot Size



β*:
- must remain larger than σ_z ('hourglass effect')
- quadrupole aperture must be respected

Longitudinal Motion: Phase Stability

Particles are typically accelerated by radiofrequency ("RF") structures. Stability depends on particle arrival time relative to the RF phase. Note: the speed is fixed = speed of light , so time of arrival depends only on the energy (in the bunch – energy deviation wrt "reference central particle")



see Jeff's lecture

Example: LHC

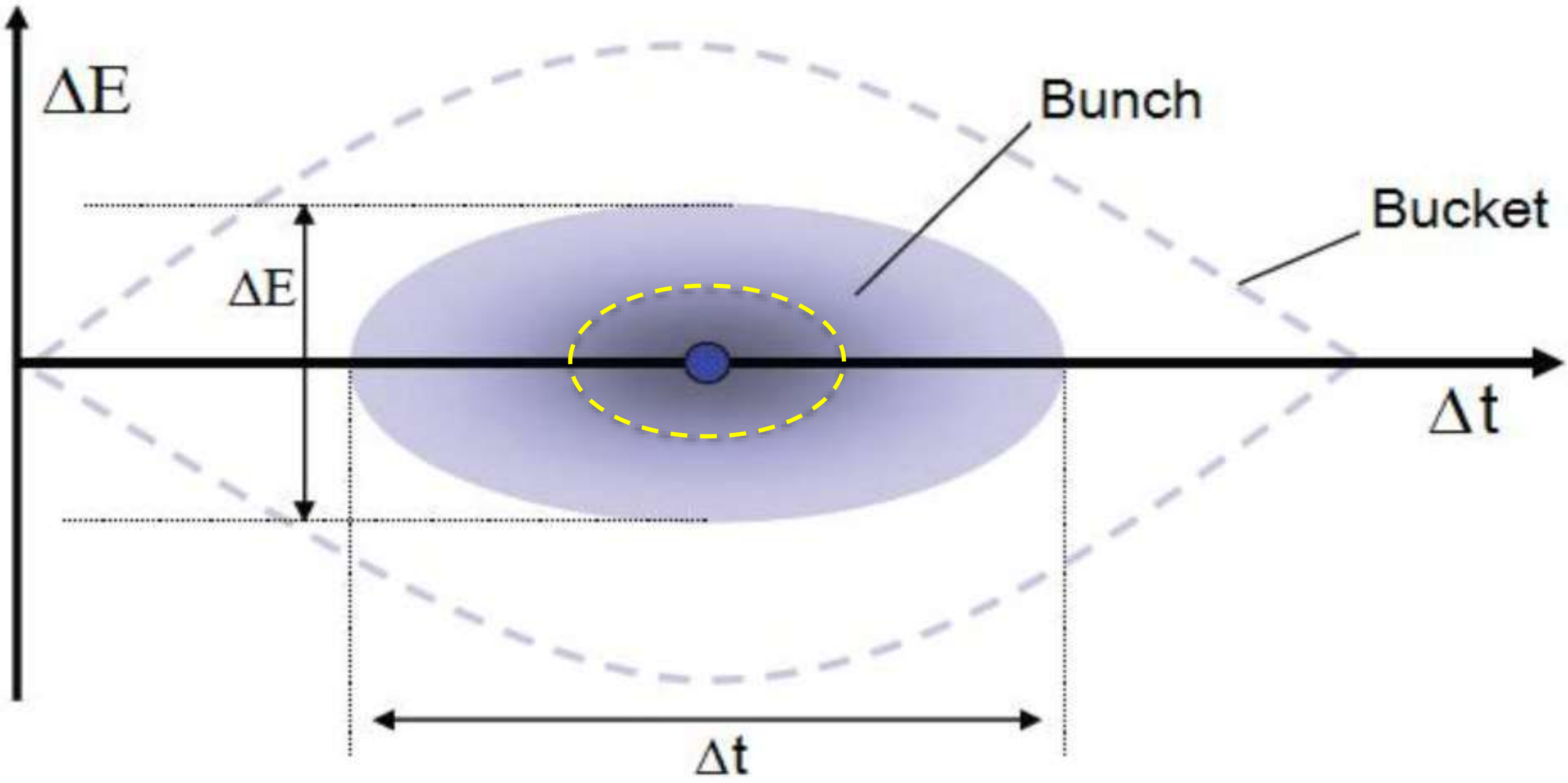
RF Frequency 400 MHz
(35640 times revolution frequency)

- RF Voltage = 8 cavities x 2 MV = 16 MV / turn (max)

In collisions dE/dn= 0 V/turn (synchronouse phase ~0)

Slow energy-position oscillations (23 Hz or ~500 turns)

rms energy spread 1.3e-4 (1GeV) rms bunch length ~ 8cm



Scales of Time-scales/Frequencies

Longitudinal oscillations are the slowest of all the periodic processes that take place in the accelerators. For example, in the LHC, the frequency of synchrotron oscillations at the top energy of 7 TeV is about $f_s = 23$ Hz, the revolution frequency is $f_{\mathrm{rev}} = 11.3$ kHz, the frequency of betatron oscillations is about $Q_{x,y} f_{\mathrm{rev}} = 680$ kHz, and the rf frequency is $f_{\mathrm{rf}} = 400.8$ MHz ($h = 35\,640$).

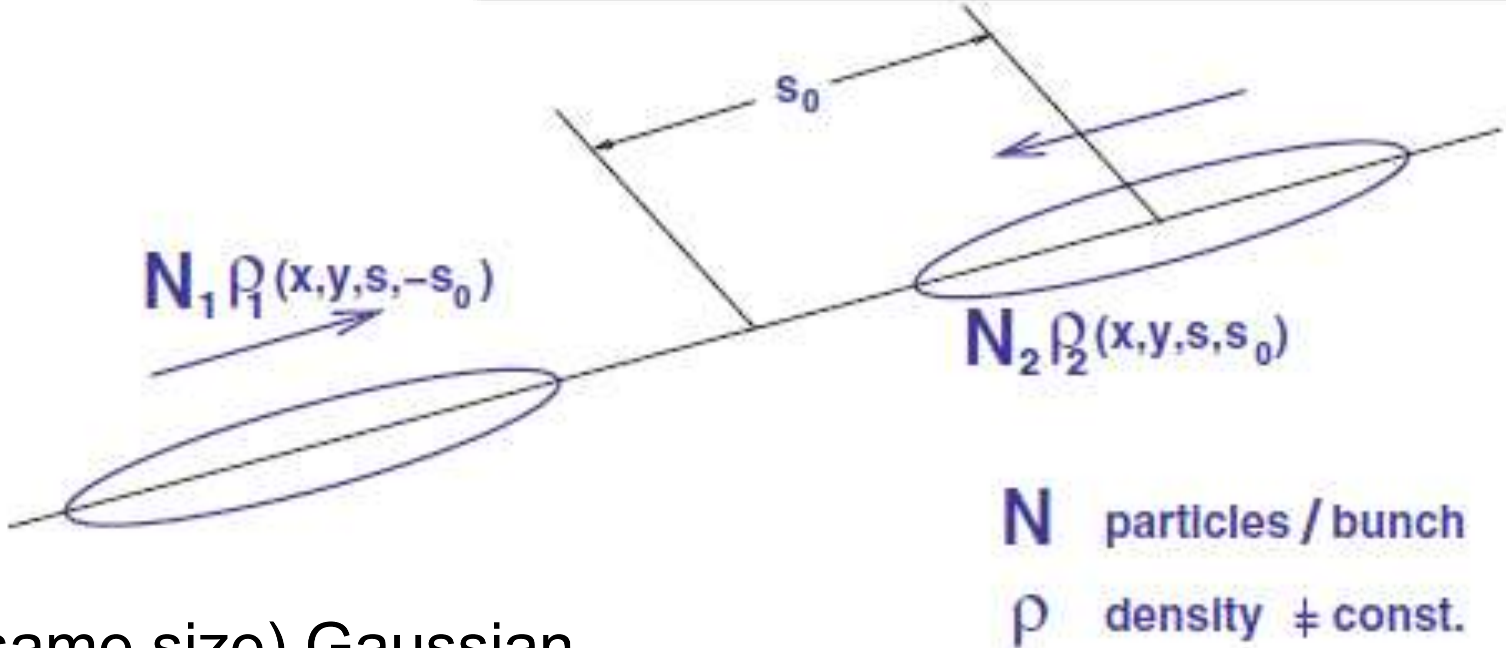
…even slower might be operational processes :

- injection/extraction (1/sec… 1/min… 1/hr … 1/day)
- beam cooling (sometimes - hours)
- luminosity decay (min… days)

BREAK (!...?)

Luminosity

$$N_{\mathrm{exp}} = \sigma_{\mathrm{exp}} \cdot \int \mathcal{L}(t)\,dt.$$



For (same size) Gaussian bunches:

$$\mathcal{L} = f_{\mathrm{coll}} \frac{N_1 N_2}{4\pi \sigma_x^* \sigma_y^*}$$

Luminosity: Unequal Bunches

$$\rho_{iz}(z) = \frac{1}{\sigma_z\sqrt{2\pi}} \exp\left(-\frac{z^2}{2\sigma_z^2}\right) \quad \text{where} \quad i = 1, 2, \quad z = x, y$$

$$\rho_s\,(s \pm s_0) = \frac{1}{\sigma_s\sqrt{2\pi}} \exp\left(-\frac{(s \pm s_0)^2}{2\sigma_s^2}\right)$$

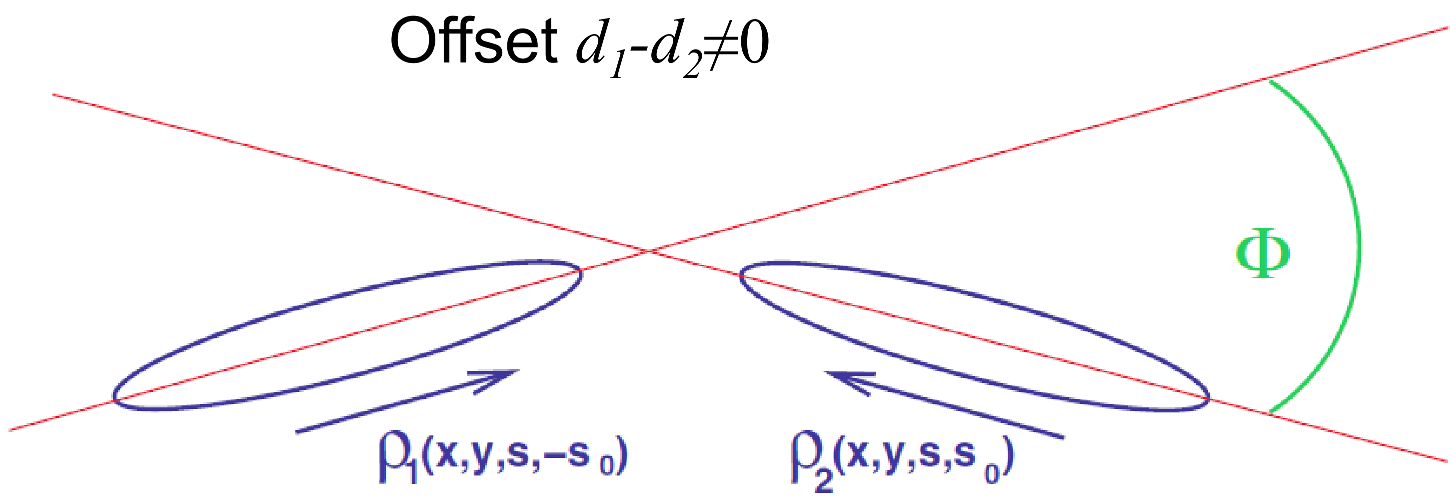
$$K = \sqrt{(\vec{v}_1 - \vec{v}_2)^2 - (\vec{v}_1 \times \vec{v}_2)^2/c^2}$$

$$\mathcal{L} \propto K N_1 N_2 \cdot \int\int\int\int_{-\infty}^{+\infty} \rho_1\,(x, y, s, -s_0)\,\rho_2\,(x, y, s, s_0)\,\mathrm{d}x\mathrm{d}y\mathrm{d}s\mathrm{d}s_0$$

yields:

$$\mathcal{L} = \frac{N_1 N_2 f_c}{2\pi\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}\sqrt{\sigma_{2y}^2 + \sigma_{2y}^2}}$$

Correction for Crossing Angle and Offset



$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi \sigma_x \sigma_y} \cdot W \cdot e^{\frac{B^2}{A}} \cdot S$$

≈ 1

where:

$$A = \frac{\sin^2 \frac{\phi}{2}}{\sigma_x^2} + \frac{\cos^2 \frac{\phi}{2}}{\sigma_s^2}$$

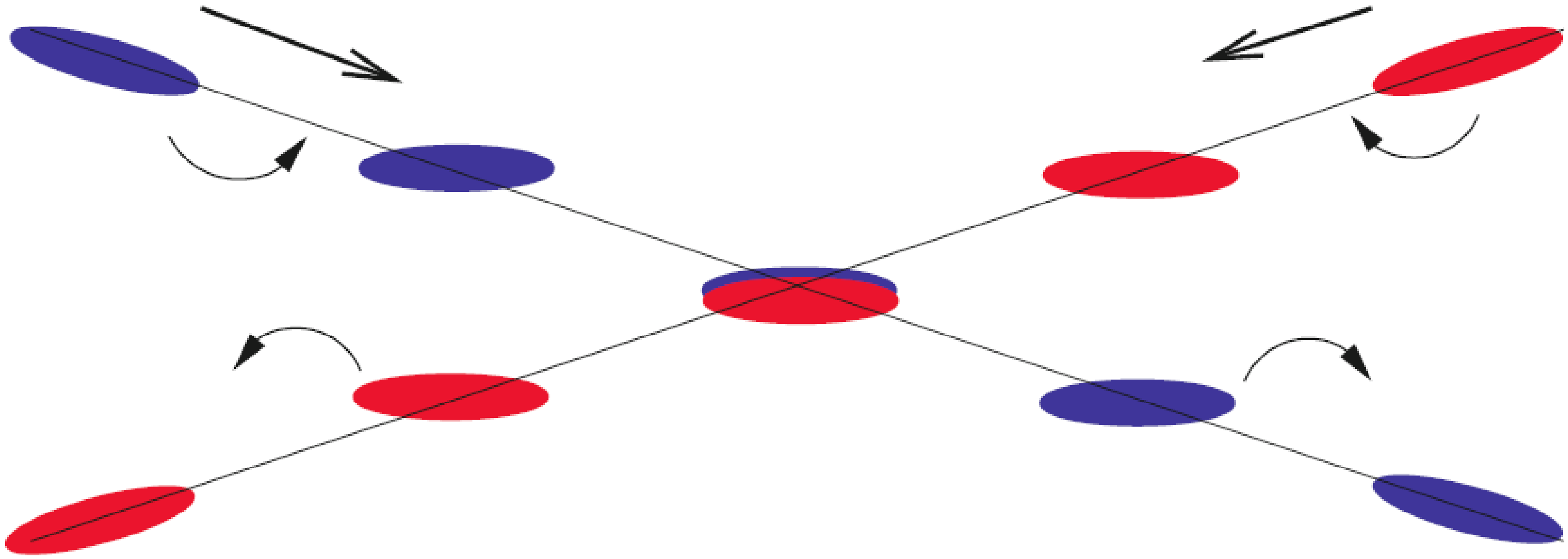
$$B = \frac{(d_2 - d_1)\sin(\phi/2)}{2\sigma_x^2}$$

$$W = e^{-\frac{1}{4\sigma_x^2}(d_2-d_1)^2}$$

$$S = \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2}\right)^2}} \approx \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2}\right)^2}}$$

“Crab Crossing” Collisions

Head-tail rotation by RF dipole deflectors (eg HL-LHC)



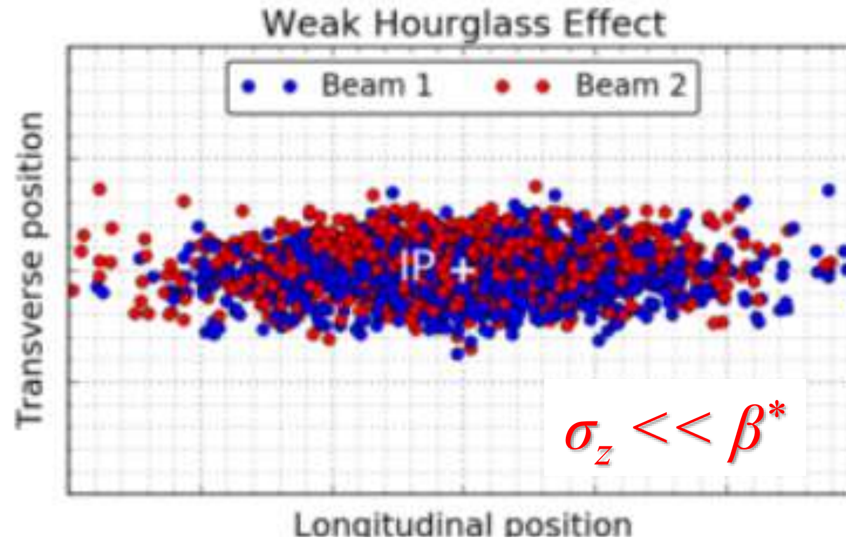
Note: either the crossing angle or amplitude of the crabbing affect instantaneous luminosity → can be used for “luminosity leveling”

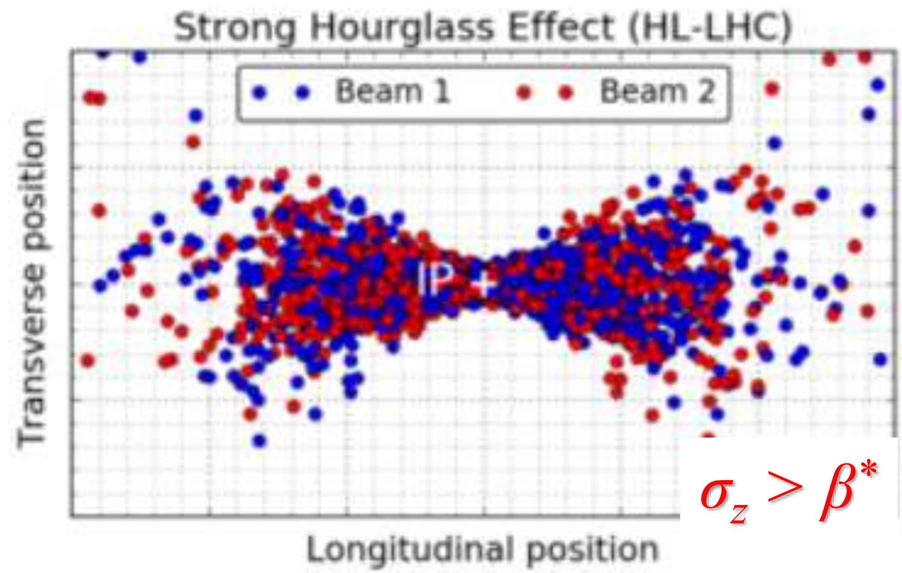
Hour-Glass Effect

$$\beta(s) = \beta^* \left(1 + \left(\frac{s}{\beta^*}\right)^2\right)$$

Same for beam size

$$\sqrt{\beta \, \varepsilon}$$





$$\frac{\mathcal{L}(\sigma_s)}{\mathcal{L}(0)} = \int_{-\infty}^{+\infty} \frac{1}{\sqrt{\pi}} \frac{e^{-u^2}}{\sqrt{\left[1 + \left(\frac{u}{u_x}\right)^2\right] \cdot \left[1 + \left(\frac{u}{u_y}\right)^2\right]}} \mathrm{d}u$$

$$u_x = \beta_x^* / \sigma_s$$

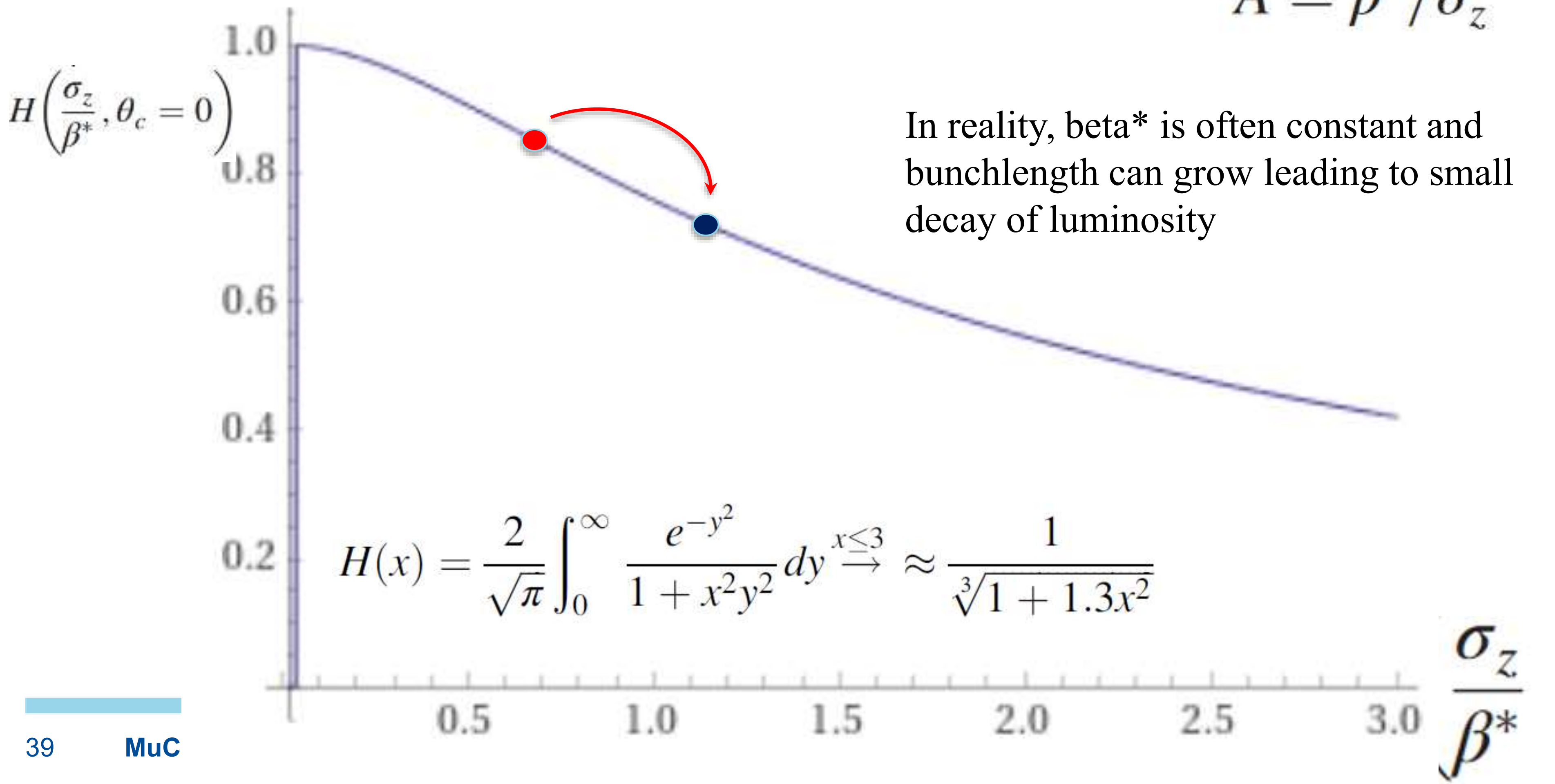
$$u_y = \beta_y^* / \sigma_s$$

Luminosity Reduction Due to Hourglass

For round beams, equal beta's and no crossing angle, *H*-factor

$$\frac{\mathcal{L}(\sigma_s)}{\mathcal{L}(0)} = H\left(\frac{\sigma_z}{\beta^*}, \theta_c = 0\right) = \sqrt{\pi} A \exp(A^2) \mathrm{erfc}(A)$$

$$A = \beta^* / \sigma_z$$



In reality, beta* is often constant and bunchlength can grow leading to small decay of luminosity

$$H(x) = \frac{2}{\sqrt{\pi}} \int_0^\infty \frac{e^{-y^2}}{1 + x^2 y^2} dy \overset{x \leq 3}{\rightarrow} \approx \frac{1}{\sqrt[3]{1 + 1.3x^2}}$$

Luminosity Summary : Key Factors

Want it higher
either smaller rings = higher B or high rep linear collider (= power)

High *E* helps
This factor comes from adiabatic reduction of the rms beam size for the same emittance

Higher intensity drives *L* *note that N(bunch) comes squared while # of bunches linear; sometimes N is limited by beam-beam, often $n_b N$ is limited → try to put all charge in one bunch*

$$\mathcal{L} = f_0 \gamma n_b \frac{N^2}{4\pi\varepsilon_n \beta^*} H\left(\frac{\sigma_z}{\beta^*}, \theta_c\right)$$

Smallest *emittance*
that's where most of beam physics goes to – cooling to stop heating, noises, dyna-mics in injectors, etc etc etc

Minimize *beta*
need stronger focusing = larger aperture and stronger LB quads

Keep *H* under control
keep bunch length and beta more or less matched, be aware of the crossing angle (sometimes need it → crabs)*

Colliders: Luminosity

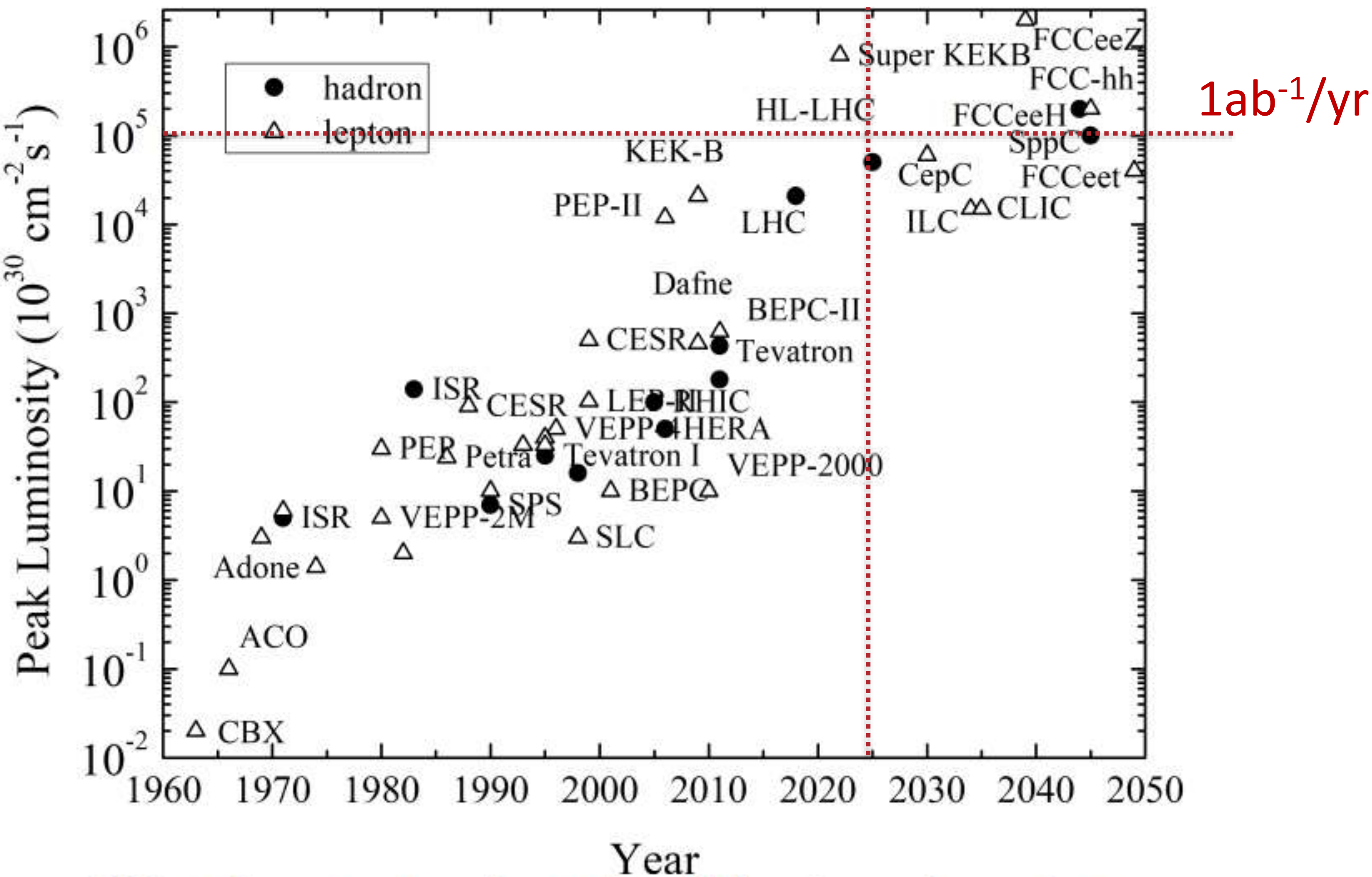
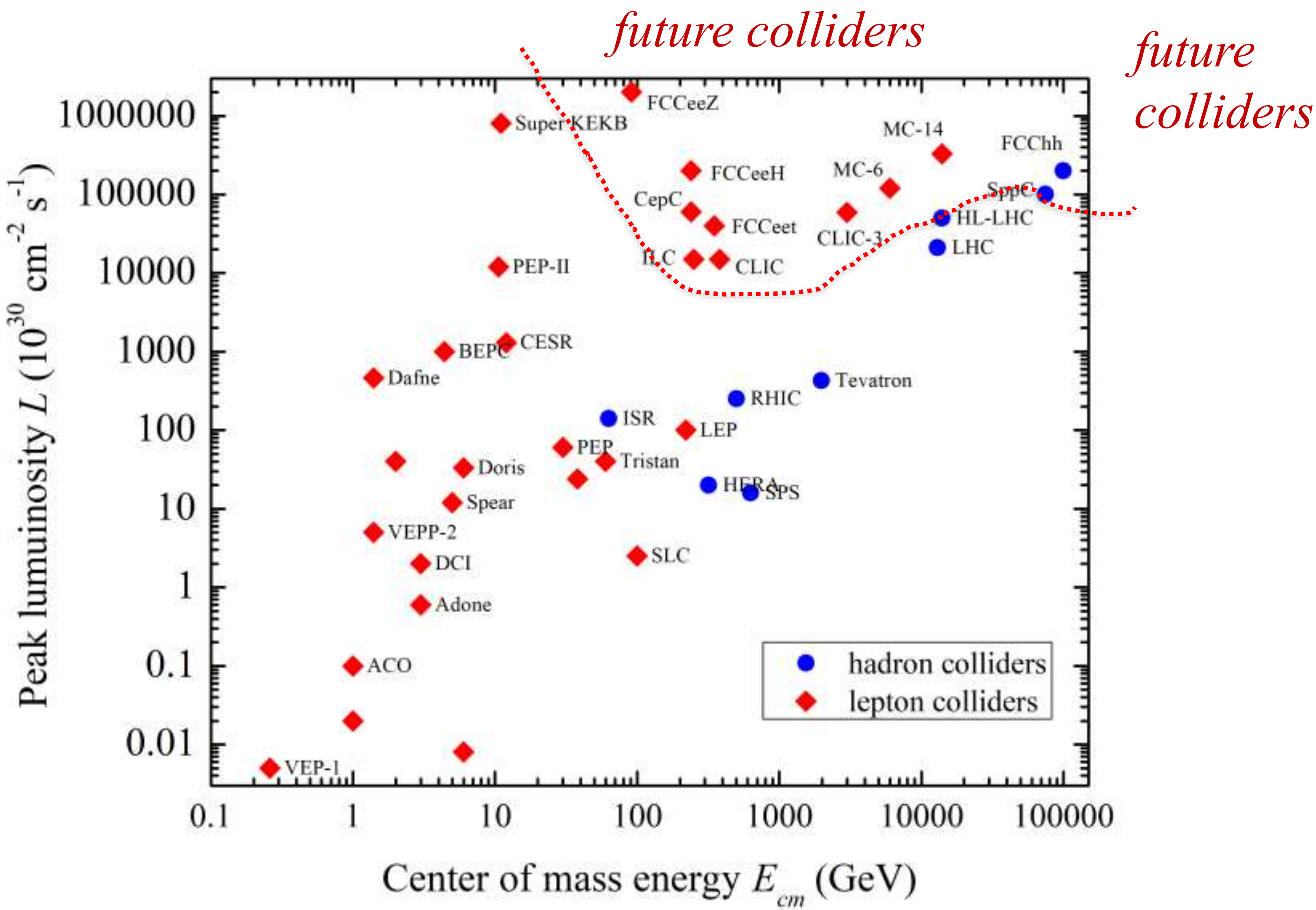


FIG. 3. Luminosities of particle colliders (triangles are lepton colliders and full circles are hadron colliders, adapted from [37]). Values are per collision point.

Colliders: Need More Luminosity vs Energy



Luminosity evolution

$$L = \gamma f_B \frac{N_1 N_2}{4\pi\beta^* \varepsilon} H(\sigma_s / \beta^*)$$

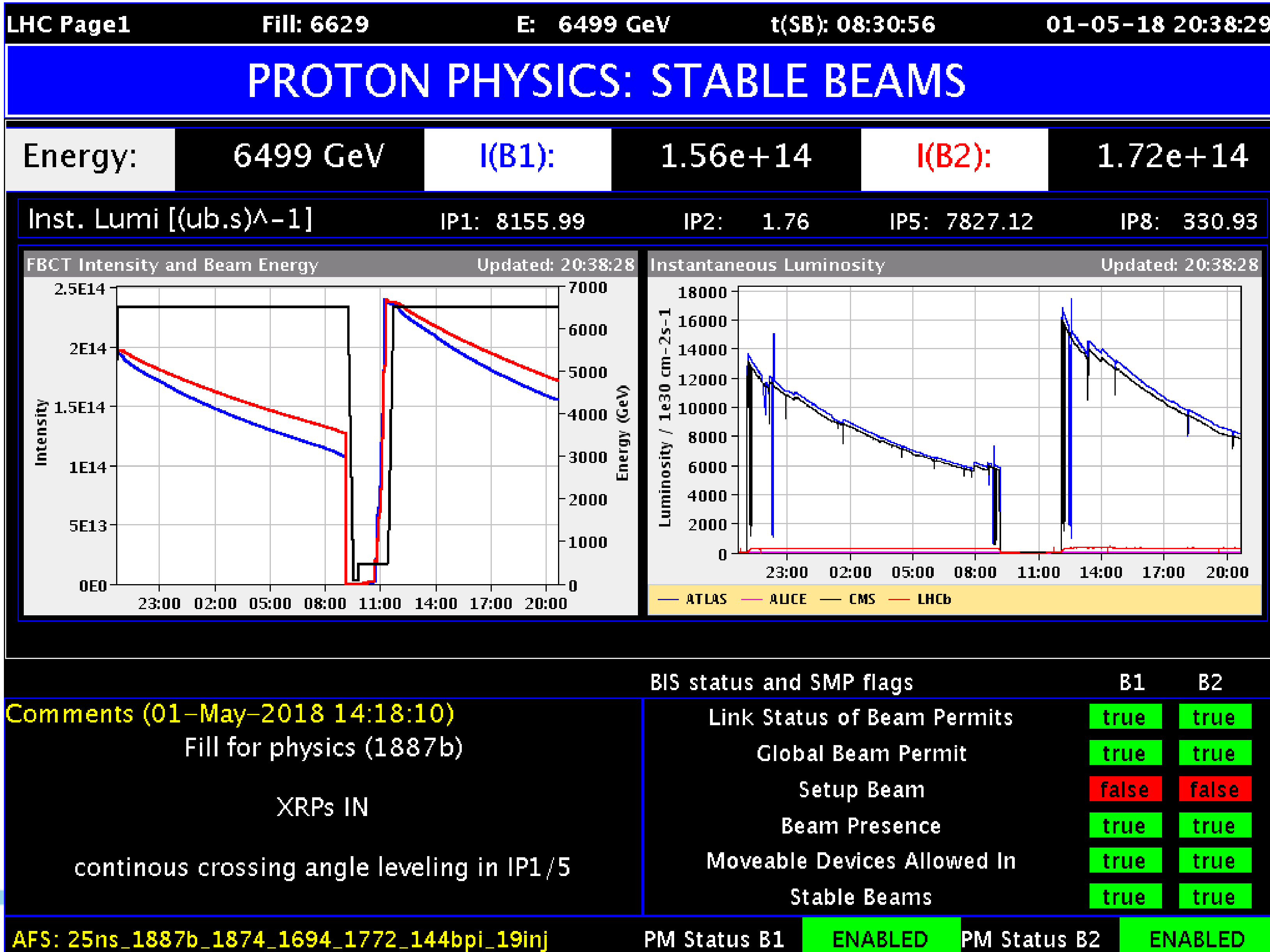
- Factors change in time

$$L(t) = C \frac{N_1(t) N_2(t)}{\varepsilon(t)} H(t)$$

- Therefore, the lifetime

$$\tau_L^{-1} = \frac{dL(t)}{L(t)dt} = \tau_{N1}^{-1} + \tau_{N2}^{-1} - \tau_{\varepsilon}^{-1} + \tau_H^{-1}$$

LHC Lumi Lifetime (~7 hrs) and Integral



Colliders : Most Important Topics/Effects

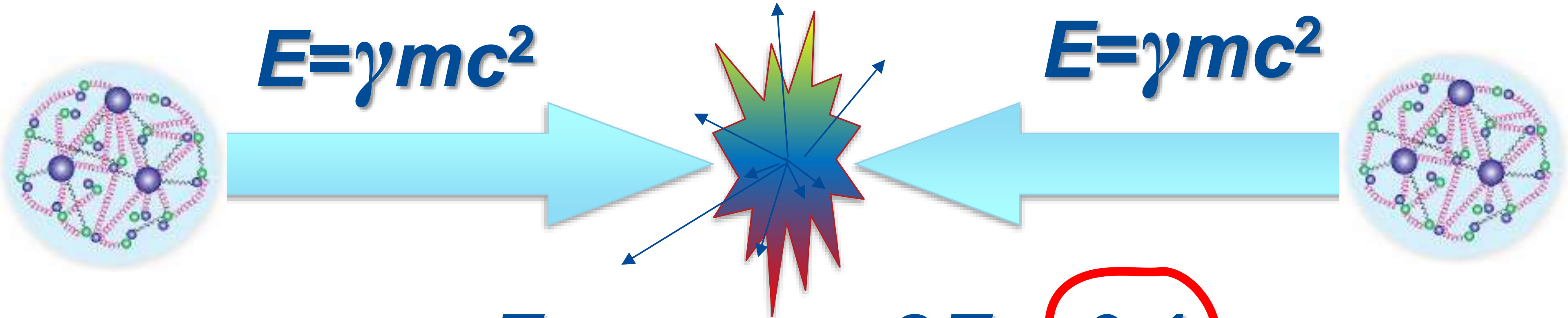
- **Engineering** of magnets, RF, PSs, vacuum, sources, targets, diagnostics, collimators, etc
  - Exciting science: new acceleration techniques/plasma
- **Beam physics**
  - One particle: beam optics, long-term stability, resonances, losses, noises, diffusion/emittance growth, etc
  - One beam: instabilities, synchrotron radiation, beam-induced radiation deposition, intrabeam scattering, cooling, space-charge effects and compensation
  - Two-beams: beam-beam effects and compensation, beamstrahlung, machine-detector interface, etc
- Assuming particle physics interest → choice of accelerator scheme depends on
  - Readiness, cost and power consumption vs *E, L* reach → **MuColl**

BREAK (!...?)

Muon Colliders

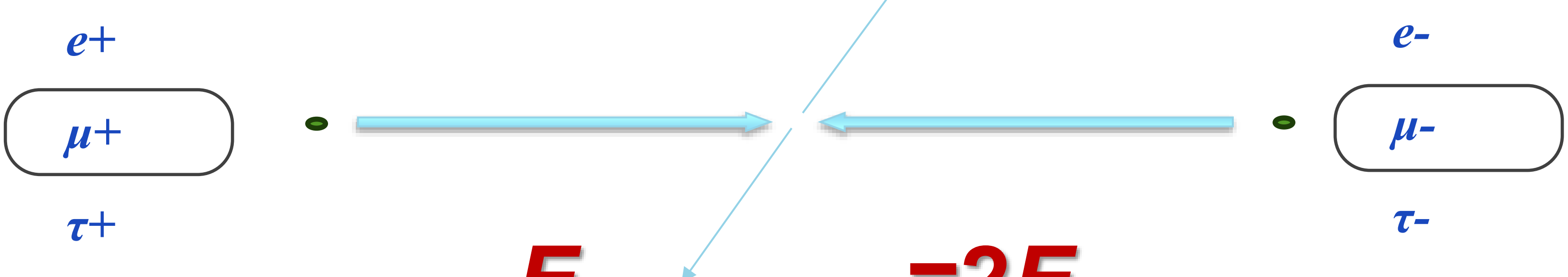
Colliding Leptons vs Hadrons

Protons



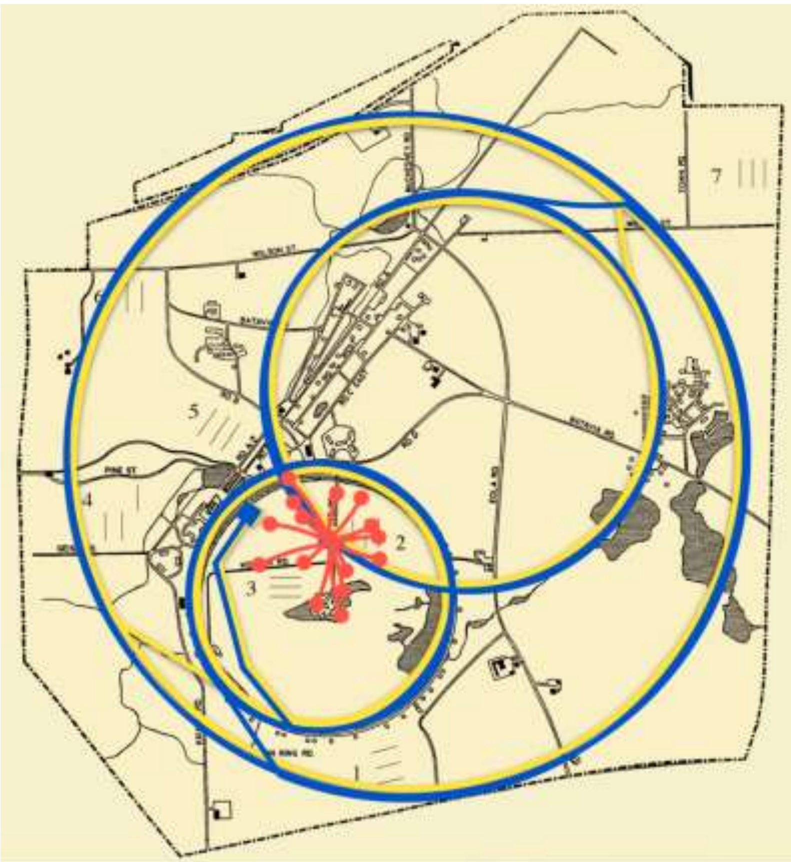
$$E_{CM\ partons} \approx 2E \times 0.1$$

Leptons



$$E_{CM\ leptons} = 2E$$

Muon Colliders in the US



Fermilab site: about 3 x 4 miles, 6,800 acres

circular | **compact** | **low(er)cost**

low(est) power consumption

Muons decay quickly 2.2μs × γ

→ Fast production, cooling (size reduction) & acceleration

Muon Collider eg at FNAL μ+μ-

Circumference ~10 km, E_{cm} =3…10 TeV

NC+SC magnets and SRF

Cost ~12-18 B$ (ITF'21) 17 ±4 BCHF (IMCC'25)

**no labor, escalation, or contingency*

20 yrs of R&D

Muon Colliders: Main Challenges

- Muons are not stable particles
  - Muon lifetime at rest (mc^2=0.105 GeV) is 2.2 microseconds
  - Muon lifetime at 5 TeV (collider $\gamma \approx 50000$) is 100 milliseconds
  - Muon can be made available only as secondary or tertrially particle products of reactions like
    - *p*(beam)+*p*(target)→ K,π → μ
    - e+e- → μ+μ-
    - γ + Ze → μ+μ-
- That usually results in large emittance (large angular spread) muon beams and requires deep cooling for **high Luminosity**
- Therefore, major challenges for High Luminosity MC are:
  - Muon production
  - Fast muon cooling
  - Fast muon acceleration
  - Neutrino flux hazard

Muon Collider Parameter Table

under development by the *International Muon Collider Collaboration*

International MUON Collider Collaboration

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Reasonably conservative

- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- But might need some operational margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

Tentative target parameters, scaled from MAP parameters

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Snowmass process to give feedback on this

Average Luminosity of Muon Collider

NB: each muon makes ~300B[T] turns in a ring with average field B

$$\langle \mathcal{L} \rangle = f_0 \gamma^2 \frac{c\tau_0}{2C} \frac{n_\mathrm{b} N^2}{4\pi \varepsilon_\mathrm{n} \beta^*} \mathcal{F} = B P_\mathrm{b} \frac{N r_0}{4\pi \varepsilon_\mathrm{n}} \frac{\gamma}{\beta^*} \left(\frac{c\tau_0 \mathcal{F}}{8\pi e} \right)$$

scales with B, the total beam power P_b, and the beam brightness (the third factor above is the beam-beam ξ)

The beta-function at the two IPs scales as $\beta^* \sim 1/\gamma$ within certain range of energies, giving overall scaling Lumi ~ γ^2 with other limiting parameters fixed. The main challenges to luminosity achievement with decaying particles are related to production and fast cooling and acceleration of $O(10^{12})$ muons per bunch without emittance degradation.

(Explanatory to Previous slide)

$$\Delta \int \mathcal{L} \approx \sum_{i=0}^{\infty} \frac{\left(N_0 e^{-i\Delta t/\gamma\tau}\right)^2}{4\pi\sigma_x\sigma_y} \leftarrow \sum_{i=0}^{\infty} \left(N_0 e^{-i\Delta t/\gamma\tau}\right)^2 \propto N_0^2 B$$

$$\Delta \int \mathcal{L} \propto \frac{BN_0^2}{4\pi\epsilon\beta/\gamma}$$

$$\beta \approx \sigma_z \qquad \frac{\sigma_E}{E} = \text{const}$$

$$\beta \propto \frac{1}{\gamma} \qquad \sigma_E\sigma_z = \text{const}$$

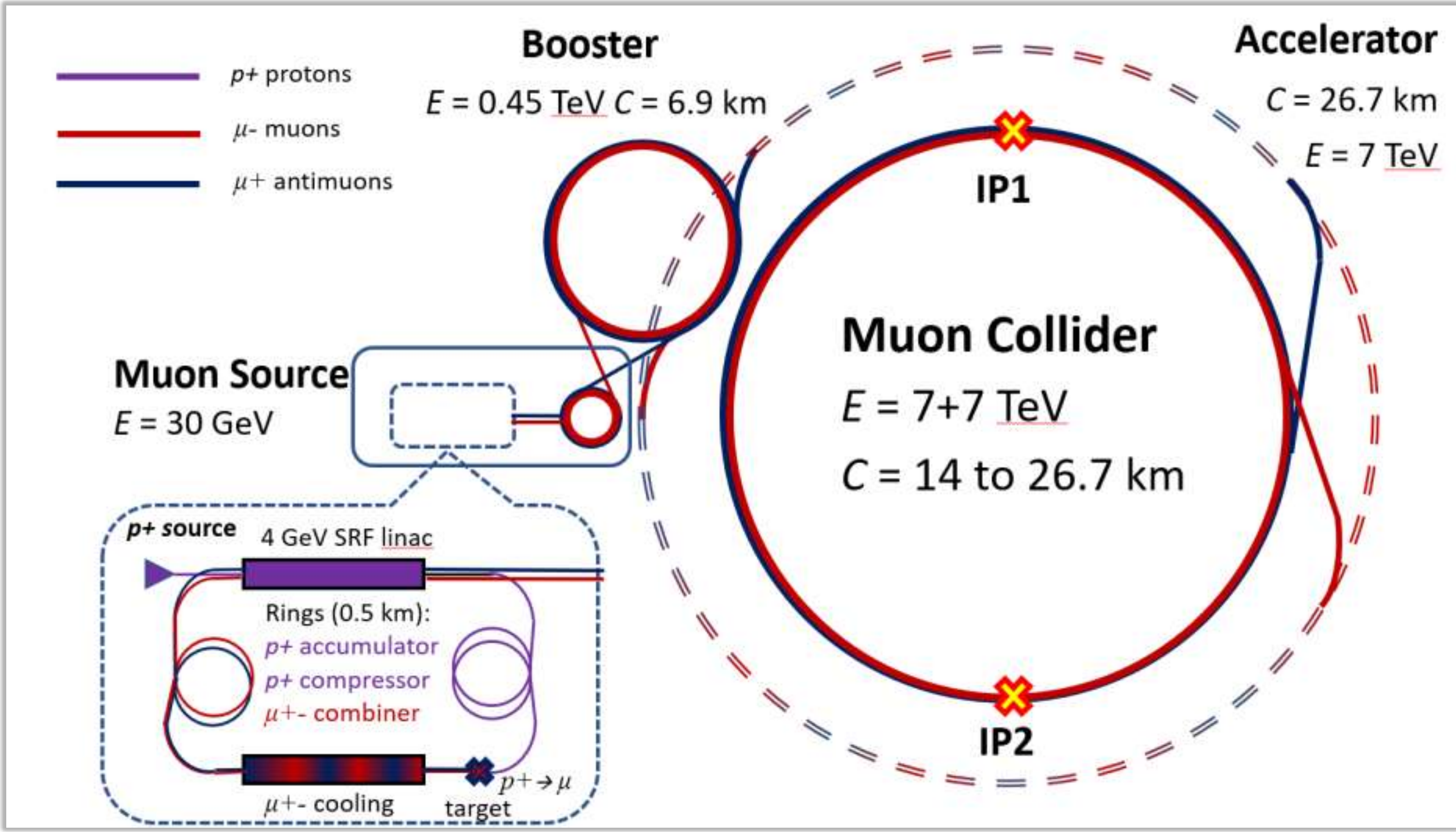
$$\sigma_z \propto \frac{1}{\gamma}$$

Note: this might be limited by technology

$$\Delta \int \mathcal{L} \propto B\frac{N_0^2\gamma^2}{\epsilon}$$

$$\mathcal{L} \propto B\frac{N_0}{\epsilon}\gamma P_{beam}$$

O(14 TeV) Muon Collider Sub-Systems (approx. to scale)



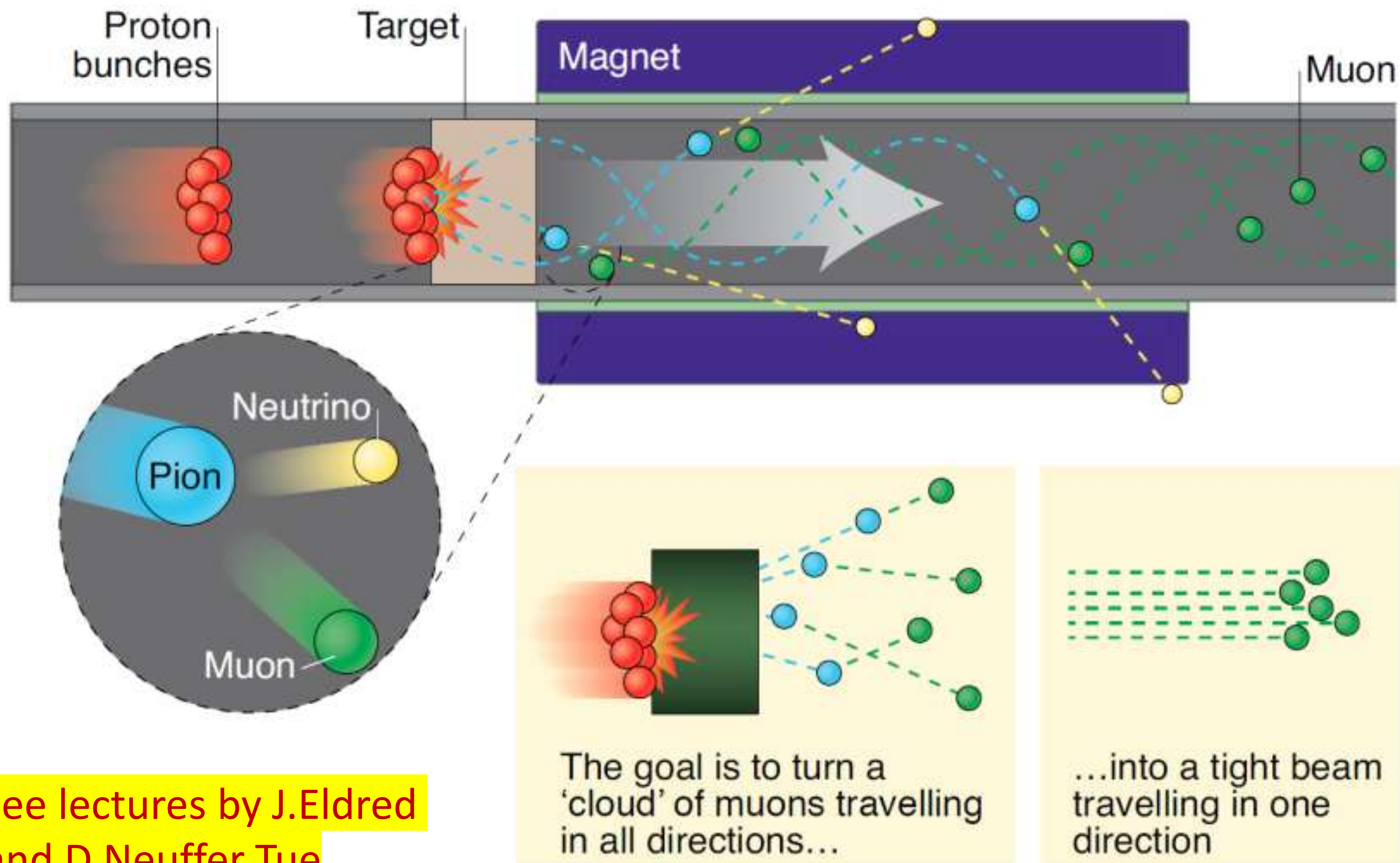
Muon Collider Subsystems

- (i) a high power proton driver (SRF 4 GeV 2-4 MW *H-* linac);
- (ii) pre-target accumulation and compressor rings, in which high-intensity 1-3 ns long proton bunches are formed;
- (iii) a liquid mercury target for converting the proton beam into a tertiary muon beam with energy of about 200 MeV;
- (iv) a multi-stage ionization cooling section that reduces the transverse and longitudinal emittances and, thereby, creates a low emittance beam;
- (v) a multistage acceleration (initial and main) system --- the latter employing a series recirculating rapid cycling synchrotrons (RCS) to accelerate muons in a modest number of turns up to 3-7 TeV using high gradient superconducting RF cavities;
- (vi) about 8.5 km diameter collider ring located some 100 m underground, where counter-propagating muon beams are stored and collide over the roughly 1000--2000 turns corresponding to the muon lifetime.

**** From the point of beam physics, complexity of a Muon Collider is closer to that of the Tevatron (higher) than to that of the LHC (lower)***

Muon Production: 1-4 MW proton driver needed

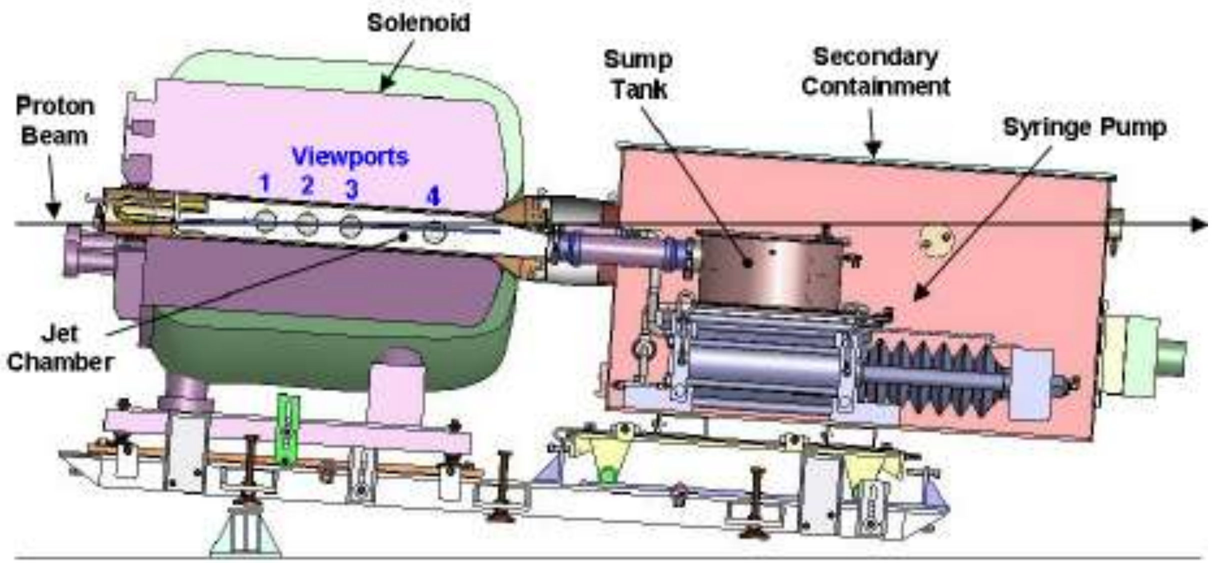
Protons → Target → Pions → Muons



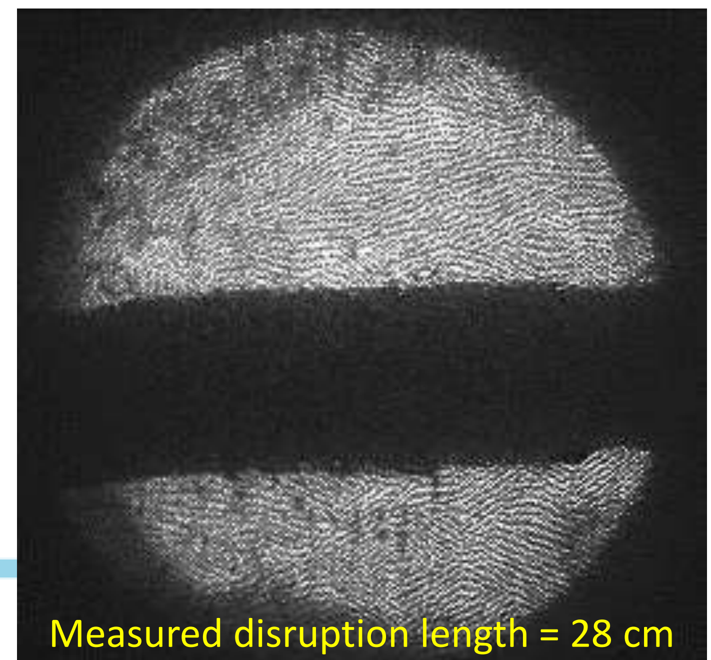
see lectures by J.Eldred and D.Neuffer Tue

MERIT Experiment – Demo of 4-8 MW Proton Targetry

- At CERN PS
- 1e13 protons 24 GeV (115kJ/pulse)
- Liquid Mercury target 20 m/s
- 15 T Solenoid



see R.Zwaska lecture Wed

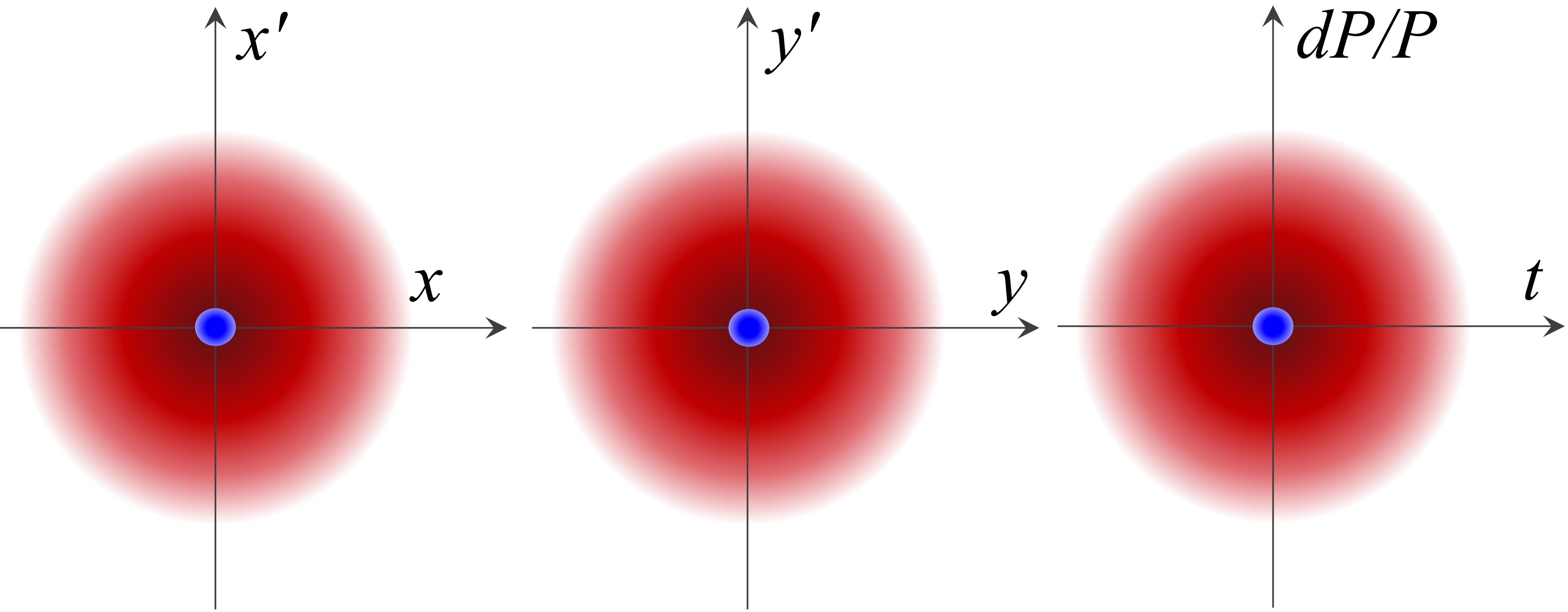


The Need for Muon Cooling

$$\mathcal{L} = f_{\text{coll}} \frac{N_1 N_2}{4\pi \sigma_x^* \sigma_y^*}$$

Muon Phase Space After Target

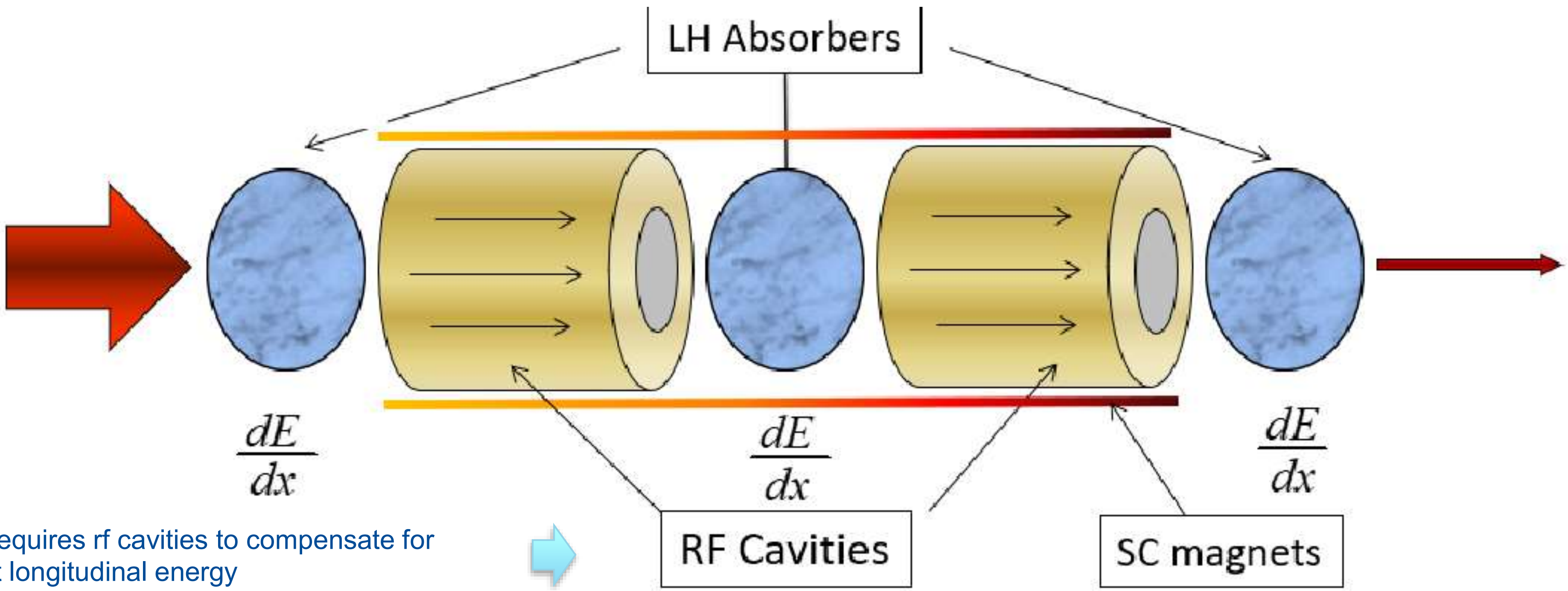
vs What's Needed for Collider



Need "6D-Cooling"

Fast Cooling of Muon Beams

- The desired 6D emittance for a MC is 5-6 orders of magnitude less from the emittance of the beam at the target
- How that can be done before muons decay? → ionization cooling: ionization loss ***along momentum*** followed by RF acceleration (***restore energy***) along longitudinal axis only (like in the Synchr Rad damping)



- Requires rf cavities to compensate for lost longitudinal energy
- Use strong B-fields to confine beams

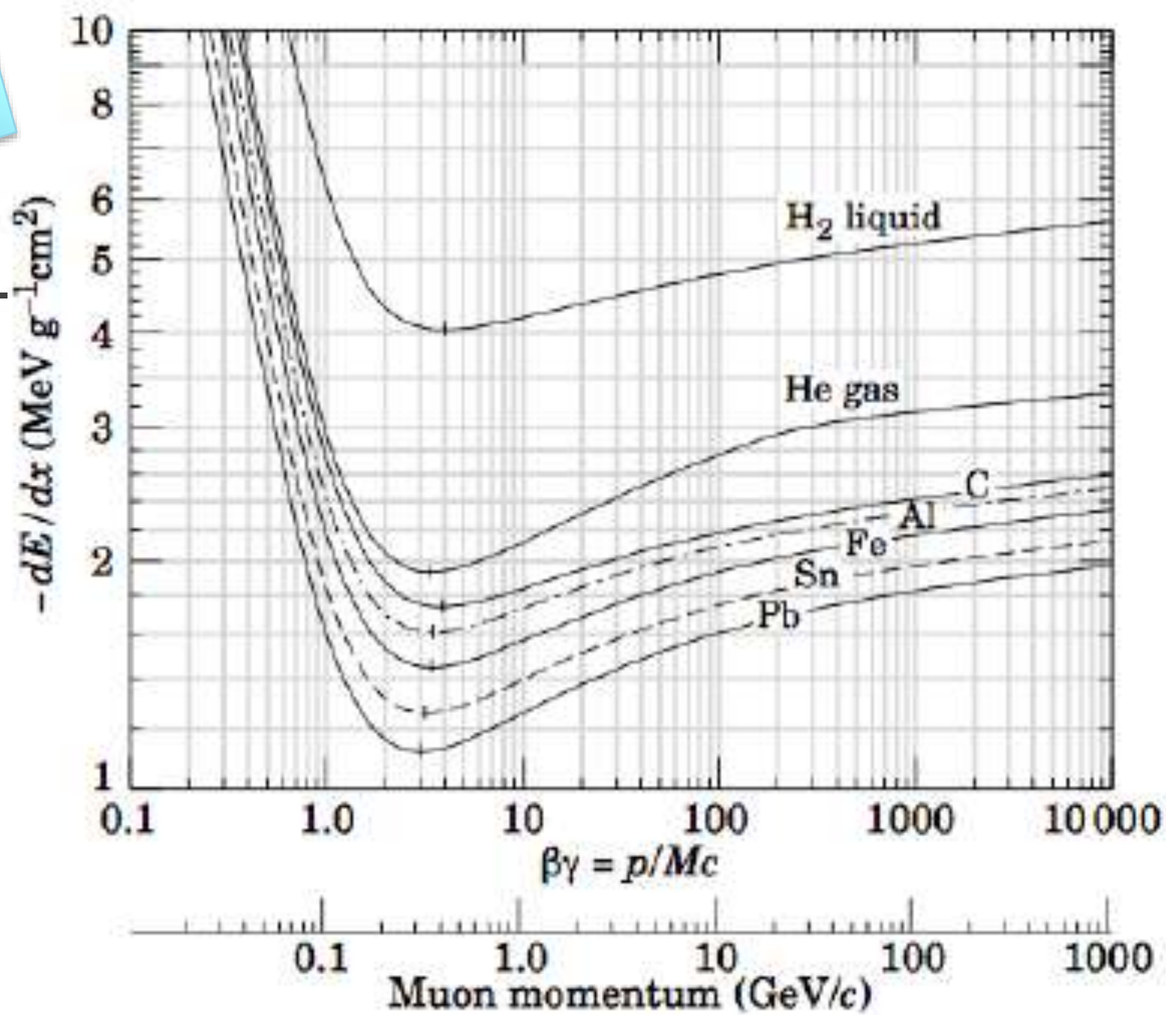
$$\frac{d\epsilon_N}{ds} \approx \underbrace{-\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu}}_{\text{Cooling}} + \underbrace{\frac{\beta_\perp(0.014GeV)^2}{2\beta^3 E_\mu m_\mu X_0}}_{\text{Heating}}$$

see K.Yonehara lecture Tue

Equation:

$$\frac{d\epsilon_n}{ds} = -\frac{dE_\mu}{ds}\frac{\epsilon_n}{E_\mu} + \frac{\beta_\perp (0.014)^2}{2\ E_\mu m_\mu\ L_R}$$

- (1st) Cooling term ~ (dE/ds) – larger the better
- (2nd) Heating/ scattering term ~ beta-function at the absorber and *1/radiation length* of the material (a low-Z preferred, *Liquid Hydrogen, Li, LiH, Be*)
- Energy of muons



Longitudinal DoF: rms E spread

cooling term

fluctuations of ionization energy losses

$$\frac{d(\Delta E)^2}{ds} = -2\,\frac{d\left(\frac{dE_\mu}{ds}\right)}{dE_\mu} < (\Delta E_\mu)^2 > + \frac{d(\Delta E_\mu)^2_{straggling}}{ds}$$

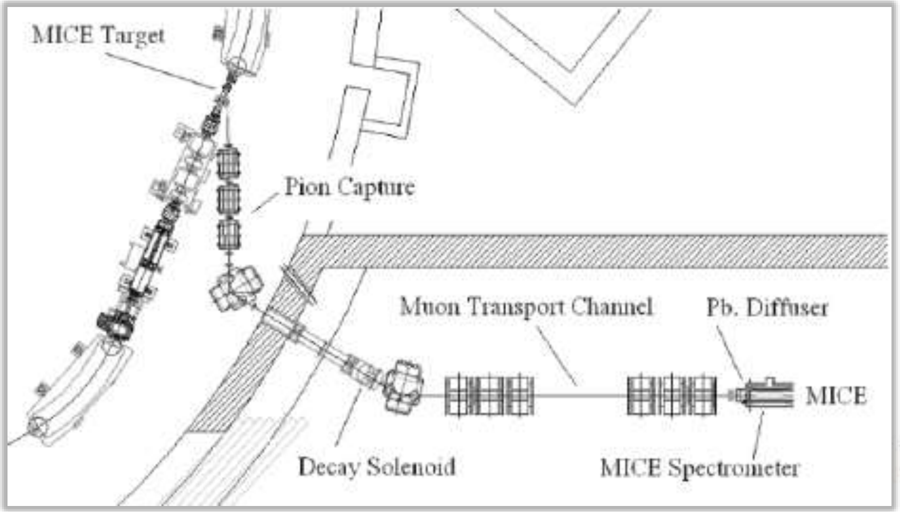
- Cooling requires that d(dEμ/ds)/dEμ > 0. But at energies below about 200 MeV, the energy loss function for muons, dEμ/ds, is decreasing with energy and there is thus heating of the beam. Above 400 MeV the energy loss function increases gently, thus giving some cooling, though not sufficient for fast cooling application (see previous slide).
- The “struggling” term

$$\frac{d(\Delta E_\mu)^2_{straggling}}{ds} = 4\pi\,(r_e m_e c^2)^2\,N_o\,\frac{Z}{A}\,\rho\gamma^2\left(1-\frac{\beta^2}{2}\right)$$

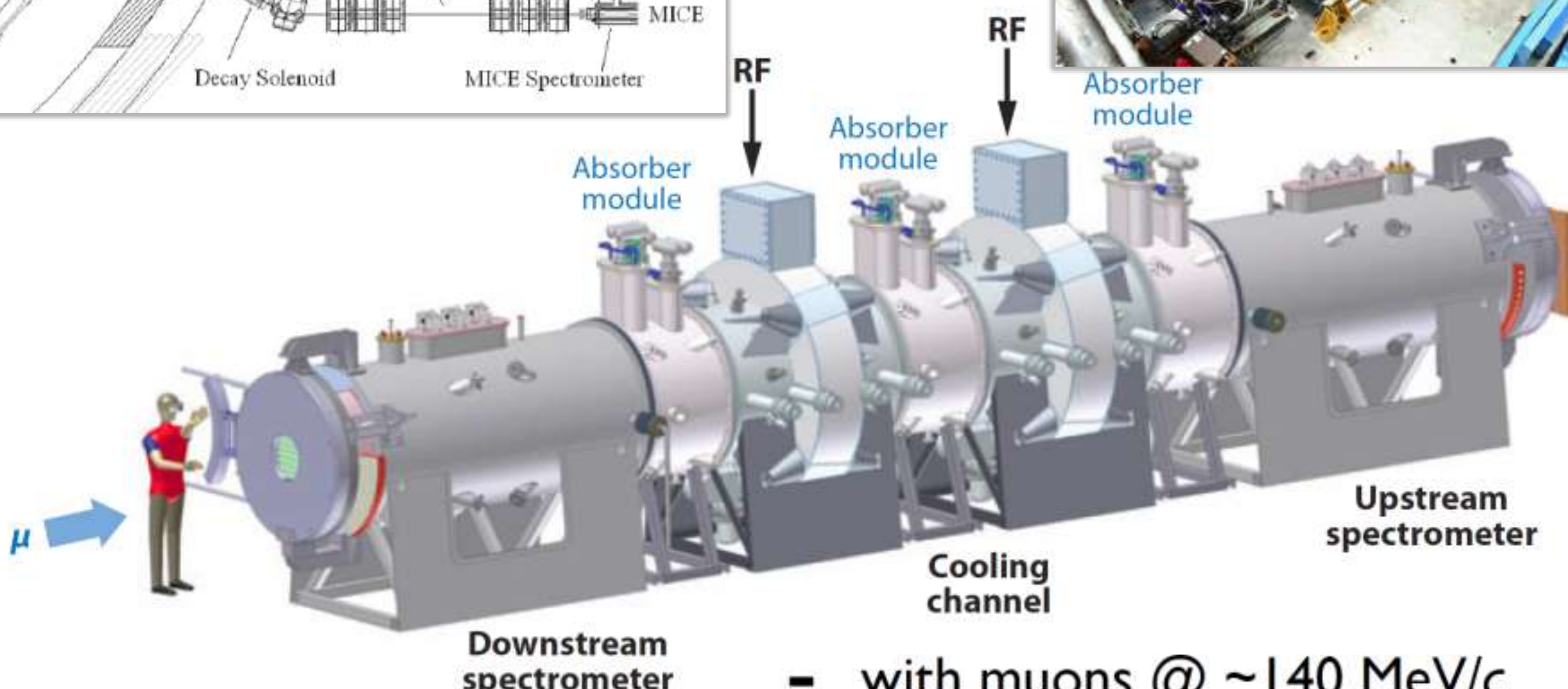
increases as γ^2, and the cooling system size scales as γ → cooling at low energies is desired.

- Energy spread can also be reduced by artificially increasing d(dEμ/ds)/dEμ by placing a transverse variation in absorber density or thickness at a location where position is energy dependent, i.e. where there is dispersion (= emittance exchange long→ transverse)

MICE: Muon Ionization Cooling Experiment = 1 "cell"



ISIS 800 MeV proton synchrotron @ RAL (UK)



- with muons @ ~140 MeV/c
- each muon individually measured

Muon 4D Cooling: MICE Results (2024)

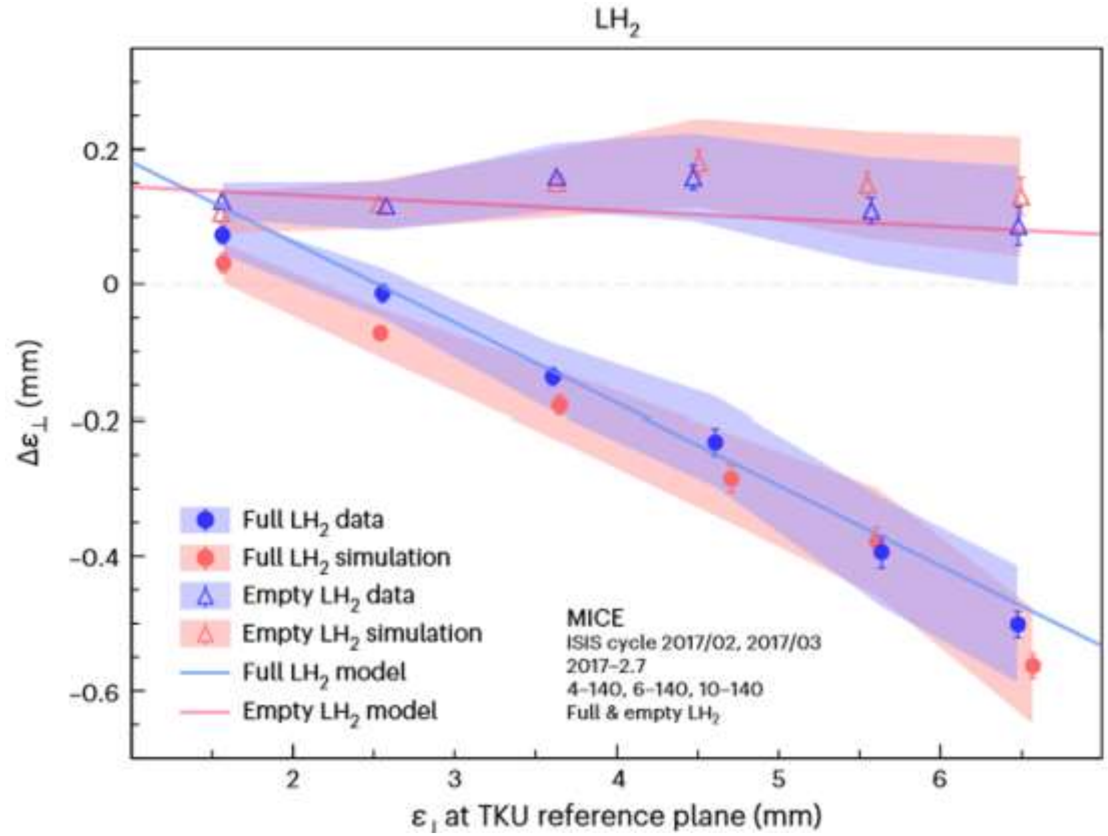
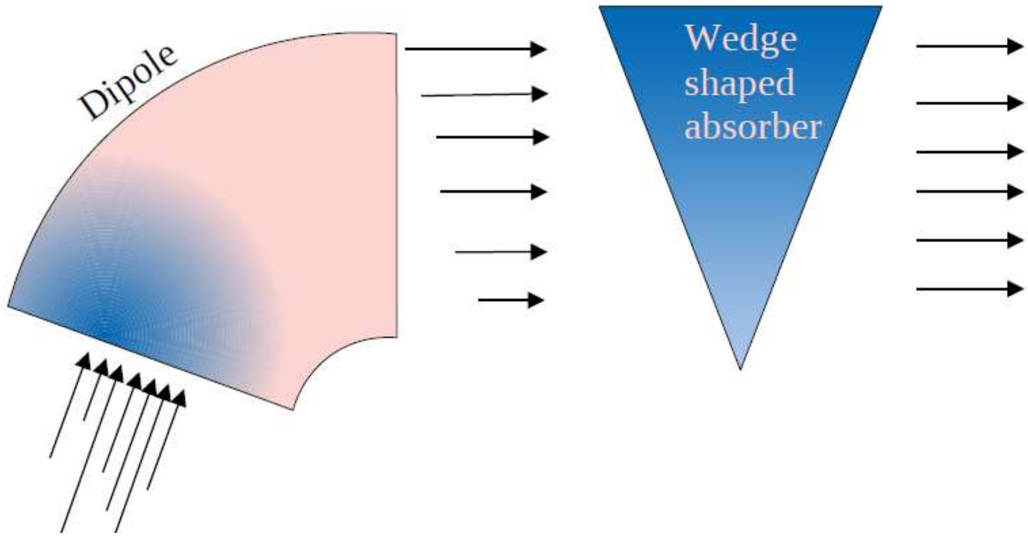


Fig. 3 | Transverse emittance change measured by MICE. Emittance change between the TKU and TKD reference planes, Δε⊥, as a function of emittance at TKU for 140 MeV/c beams crossing the LH2 MICE absorbers. Results for the empty cases, namely, No absorber and Empty LH2, are also shown. The measured effect is shown in blue, whereas the simulation is shown in red. The corresponding semitransparent bands represent the estimated total standard error. The error bars indicate the statistical error and for some of the points, they are smaller than the markers. The solid lines represent the approximate theoretical model defined by equation (10) (Methods for the absorber (light blue) and empty (light pink) cases. The dashed grey horizontal lines indicate a scenario where no emittance change occurs.

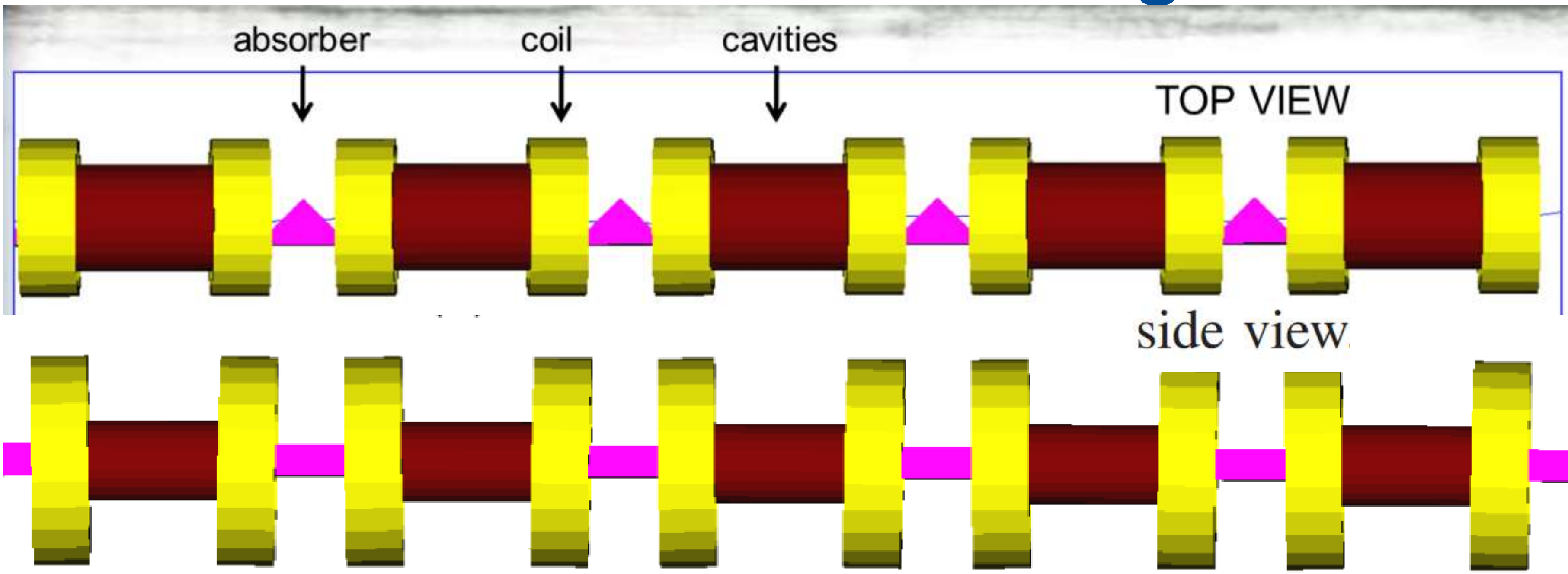
https://doi.org/10.1038/s41567-024-02547-4

6D Ionization Cooling



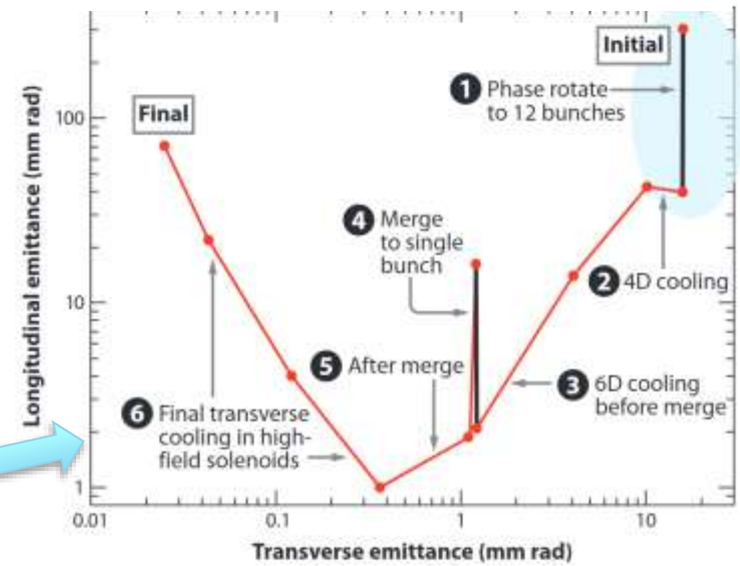
- Initial beam is narrow with some momentum spread
  - Low transverse emittance and high longitudinal emittance
- Beam follows curved trajectory in dipole
  - Higher momentum particles have higher radius trajectory
  - Beam leaves wider with energy-position correlation
- Beam goes through wedge shaped absorber
  - Beam leaves wider without energy-position correlation
  - High transverse emittance and low longitudinal emittance
- (Do transverse 4D cooling… and repeat the cycle)

Rectilinear Ionization Cooling Channel



6D emittance reduction by 5 orders of magnitude (between point 2 to 5).

Length ~ 900 m

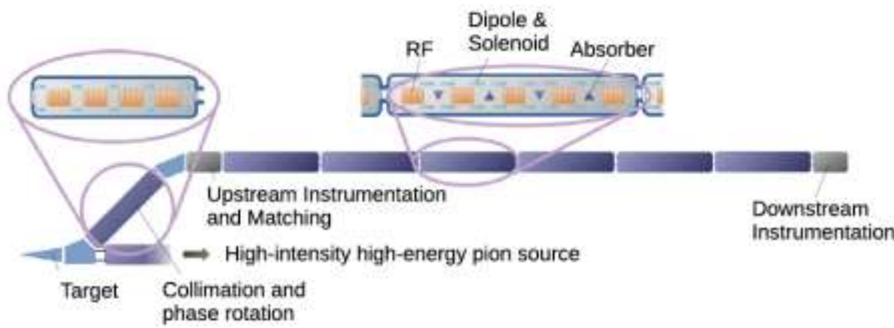


Final cooling section design requires ~30 T solenoids (point 5 to 6)

Full Ionization Cooling & Demonstrator

- **MC ionization cooling** channel consists of ~800 muon cooling cells
- The cooling of muons requires very compact assembly of normal conducting RF cavities, superconducting solenoids, and either liquid hydrogen or LiH absorbers
- **Large bore solenoids:** from 2 T (D=1 m) to 20+ T (D=0.05 m)
- **RF cavities** (300-800 MHz) must operate in multi-Tesla fields
- **Wedge-shaped absorbers** must and large muon beam intensities

https://doi.org/10.1140/epjc/s10052-023-11889-x



Schematic of the muon cooling demonstrator

	Muon mom. MeV/c	Total length, m	Total # of cells	Total RF voltage, MV	B_max, T	6D emm. reduction	Beam loss, %
Full scale MC	200	~980	~820	~15,000	2-14	x 1/10^5	~70%
Demonstrator	200	48	24	~260	0.5-7	x 1/2	4-6%

The Muon Ionization Cooling Demonstrator Experiment:

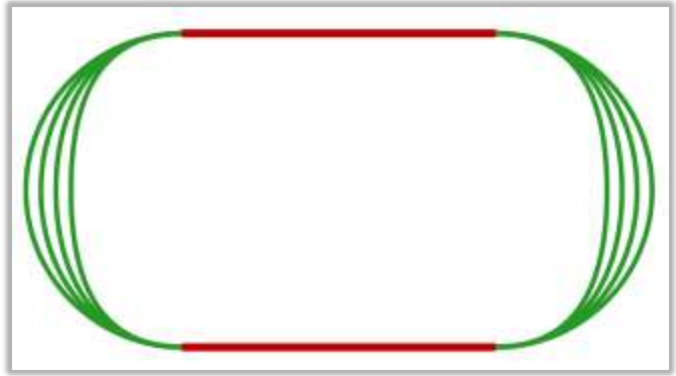
■ Timeline: 2029-2034 ■ Location: Fermilab or CERN ■ Cost: 300 ? M$

see D.Stratakis lecture Wed

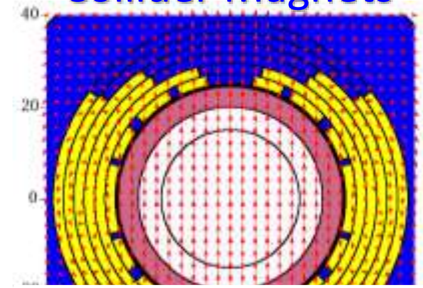
Acceleration and Collider Ring ~75% of the MC Cost

Options (high→ low cost):

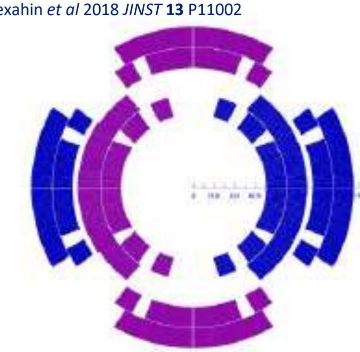
- Linac (very costly!)
- Recirculating linear accelerator (RLA)
- Fixed field alternating gradient (FFA)
- Pulsed synchrotrons



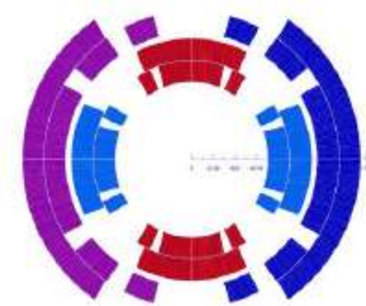
~14T Large Aperture Collider Magnets



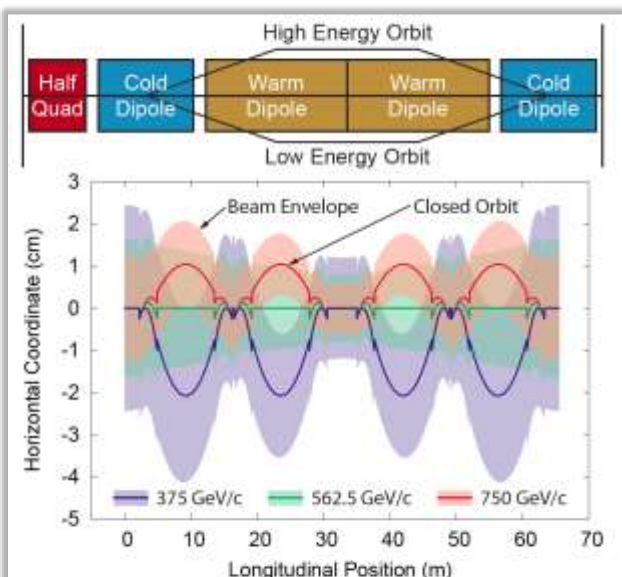
Alexahin *et al* 2018 *JINST* **13** P11002

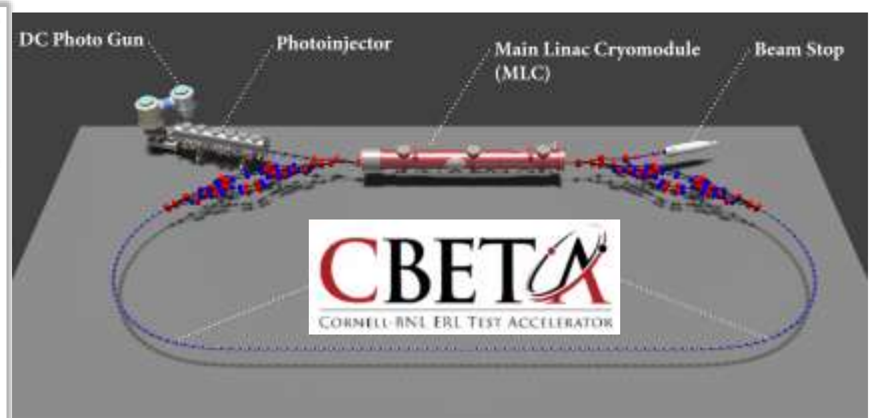


Dipole/Quad



Quad/Dipole

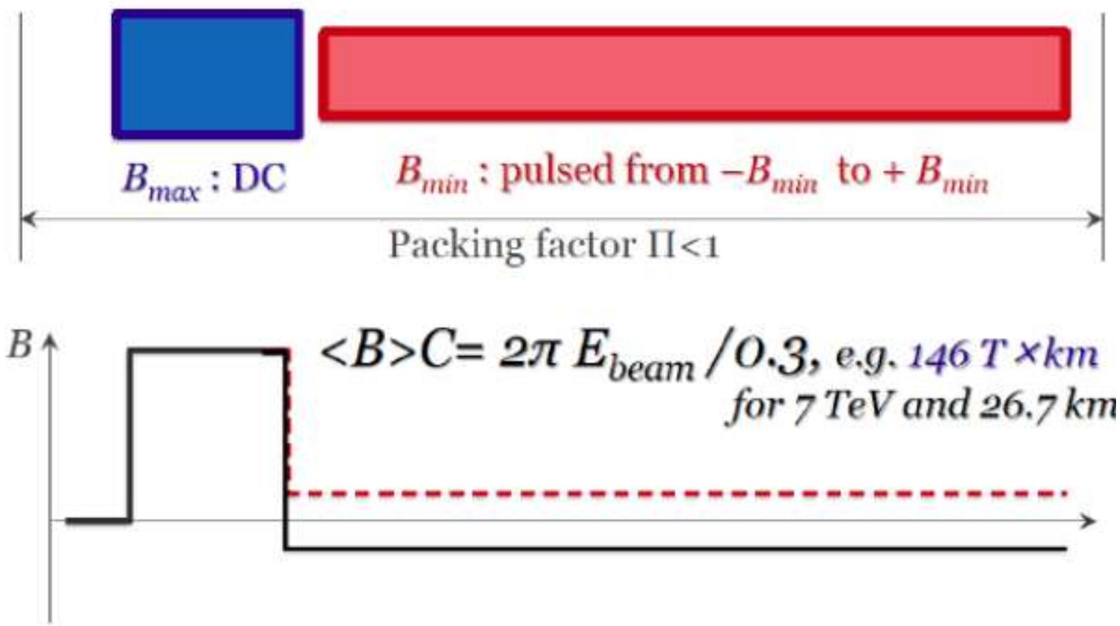




CBETA FFA at Cornell/BNL arXiv1706.04245

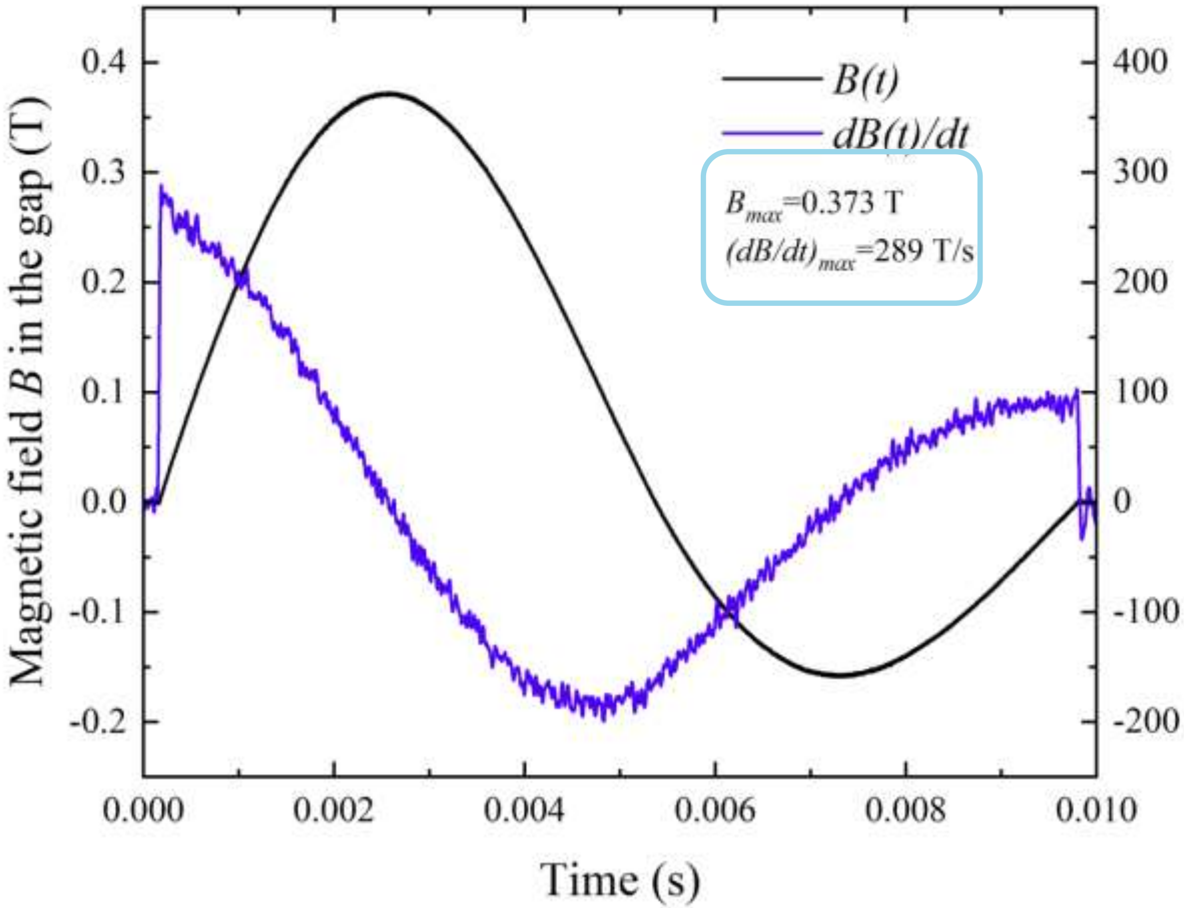
The Idea of Pulsed Muon RCS

- Rapid cycling synchrotron (RCS)
  - Potentially larger acceleration range at affordable cost
  - Could use combination of static superconducting and ramping normal-conducting or HTS magnets
  - But have to deal with energy in fast pulsing magnets

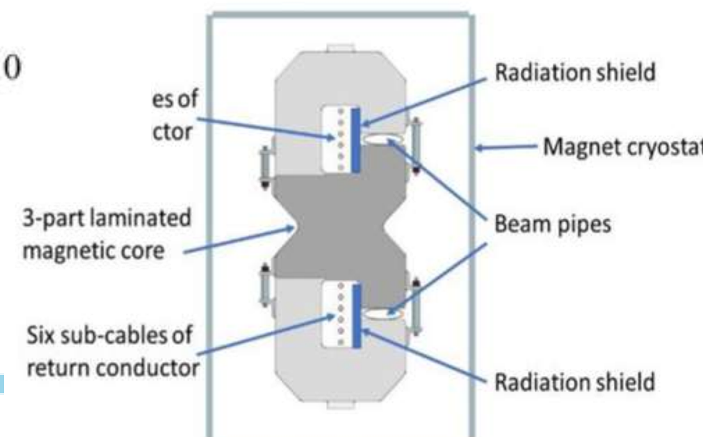


- Of course, circumference of the RCS will be larger than that of collider as AVERAGE max B-field in RCS < AVERAGE (static) B-field collider ring

Need pulsed magnets dB/dt ~1000T/s

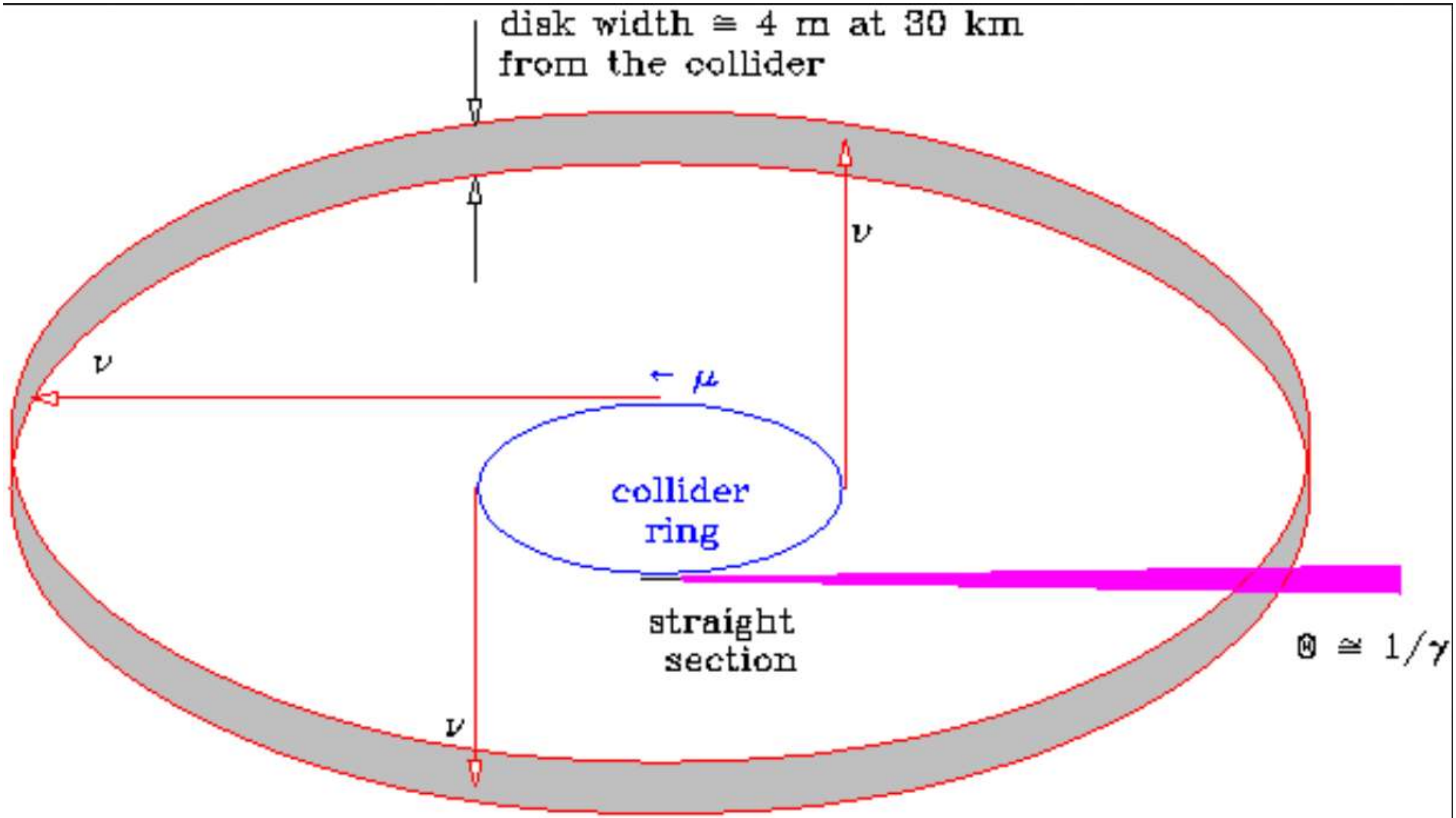


Fermilab, 2021



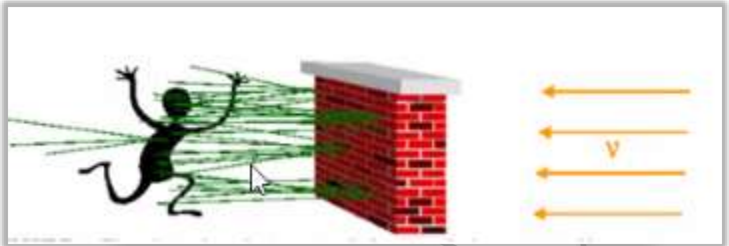
Approach to an economical magnet is to use HTS tape: very low AC losses in superconductor

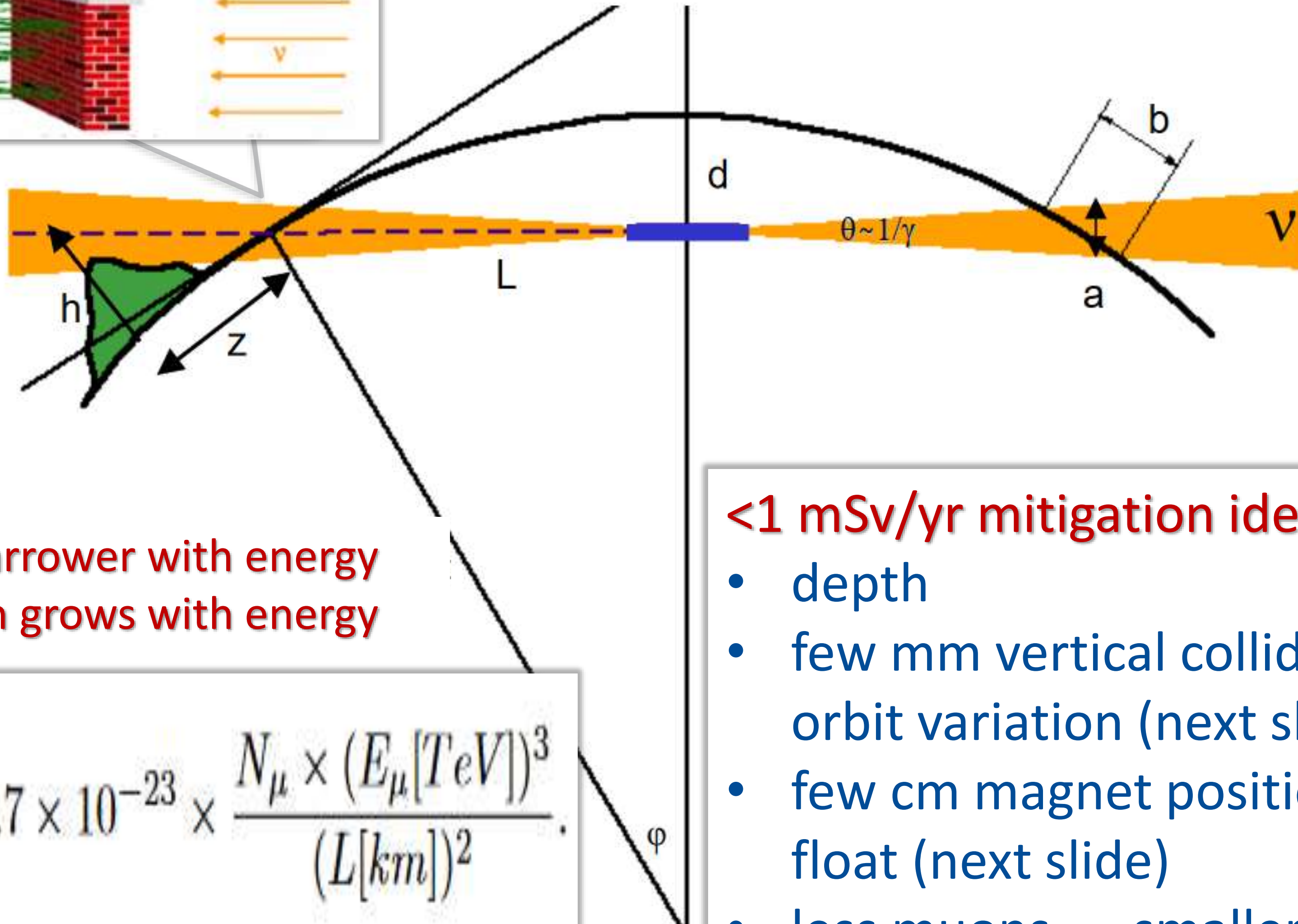
Neutrino Flux (Muons decay to $e+\nu\,\bar{\nu}$)



Collider Ring design - see lecture of E.Gianfelice-Wendt on Wed

Neutrino Radiation Dose & Control





Cone gets narrower with energy
Cross section grows with energy

$$D^{ave}[Sv] = 3.7 \times 10^{-23} \times \frac{N_\mu \times (E_\mu[TeV])^3}{(L[km])^2}.$$

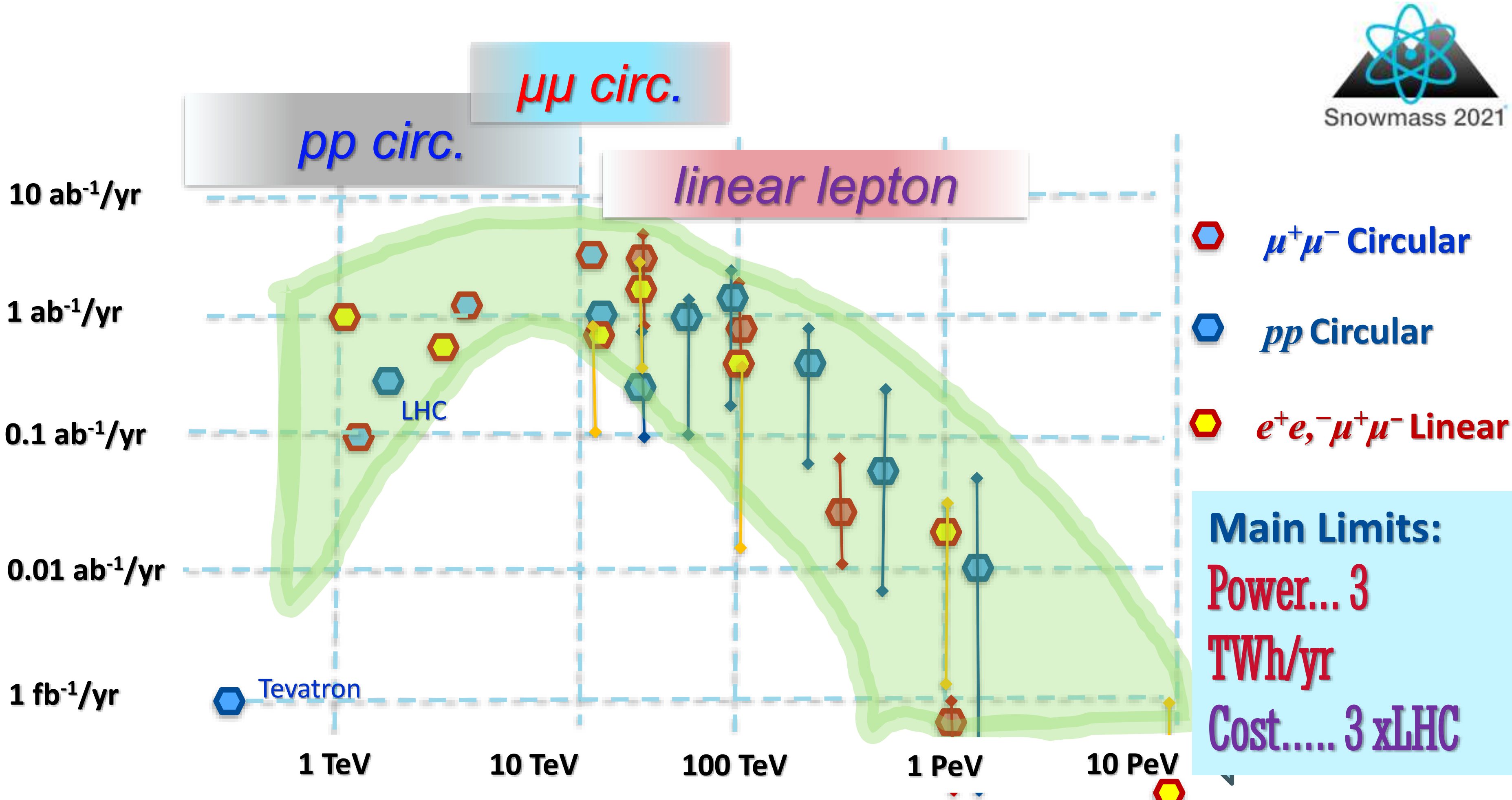
<1 mSv/yr mitigation ideas:

- depth
- few mm vertical collider orbit variation (next slide)
- few cm magnet positions float (next slide)
- less muons… =smaller emittance to keep ***L***

On Required R&D: μ-Coll Costs and Risks

	Approx. % of the Total Cost	Approx. Luminosity Risk Factor
Proton Driver & Targetry	15 - 20 %	10^{1-2}
Muon Cooling	10 - 15 %	10^{3-4}
Acceleration	30 - 60 %	10^{1-2}
Collider	25 - 40 %	10^{0-1}
TOTAL	**12 - 18 B$** ***ITF?**	$\mathbf{10^{5-9}}$

Ultimate Colliders *Luminosity* vs *Energy*



Main Limits:
Power… 3 TWh/yr
Cost….. 3 xLHC

V.Shiltsev, "Ultimate Colliders" (Oxford Encyclopedia, 2023);

DOI: 10.1093/acrefore/9780190871994.013

Thanks for Your Attention !

Questions !?

Literature

- V.Shiltsev, F.Zimmermann, Modern and Future Colliders (Rev.Mod.Phys., 2021)

https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.93.015006

- V.Lebedev, V.Shiltsev, Tevatron Book

https://indico.cern.ch/event/774280/attachments/1758668/2915590/2014_Book_AcceleratorPhysicsAtTheTevatro.pdf

W.Herr, CAS school
https://cds.cern.ch/record/941319/files/p379.pdf

Proc. 2013 ICFA mini-workshop on "Beam-Beam Effects in Hadron Colliders"
https://indico.cern.ch/event/189544/

Comprehensive *JUAS-book* (2371 pages – all topics!)
https://doi.org/10.23730/CYRSP-2024-003.

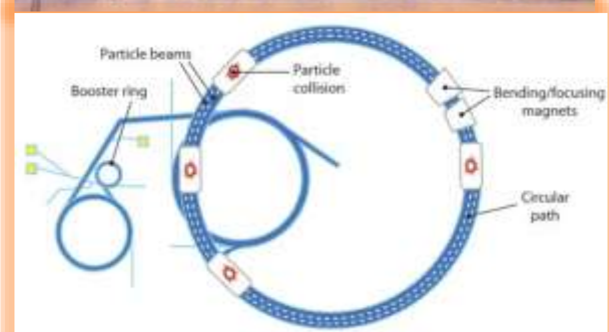
ENERGY: Brute Force Approaches

Particle Energy Increase

ΔE = *Electric Field Gradient* x *Length*

#1 Increase *length* = linac

(linear accelerator)



#2 Accelerate in a ring ($N_{turns}\,\Delta E$)

increase *circumference* as $E=0.3BR$

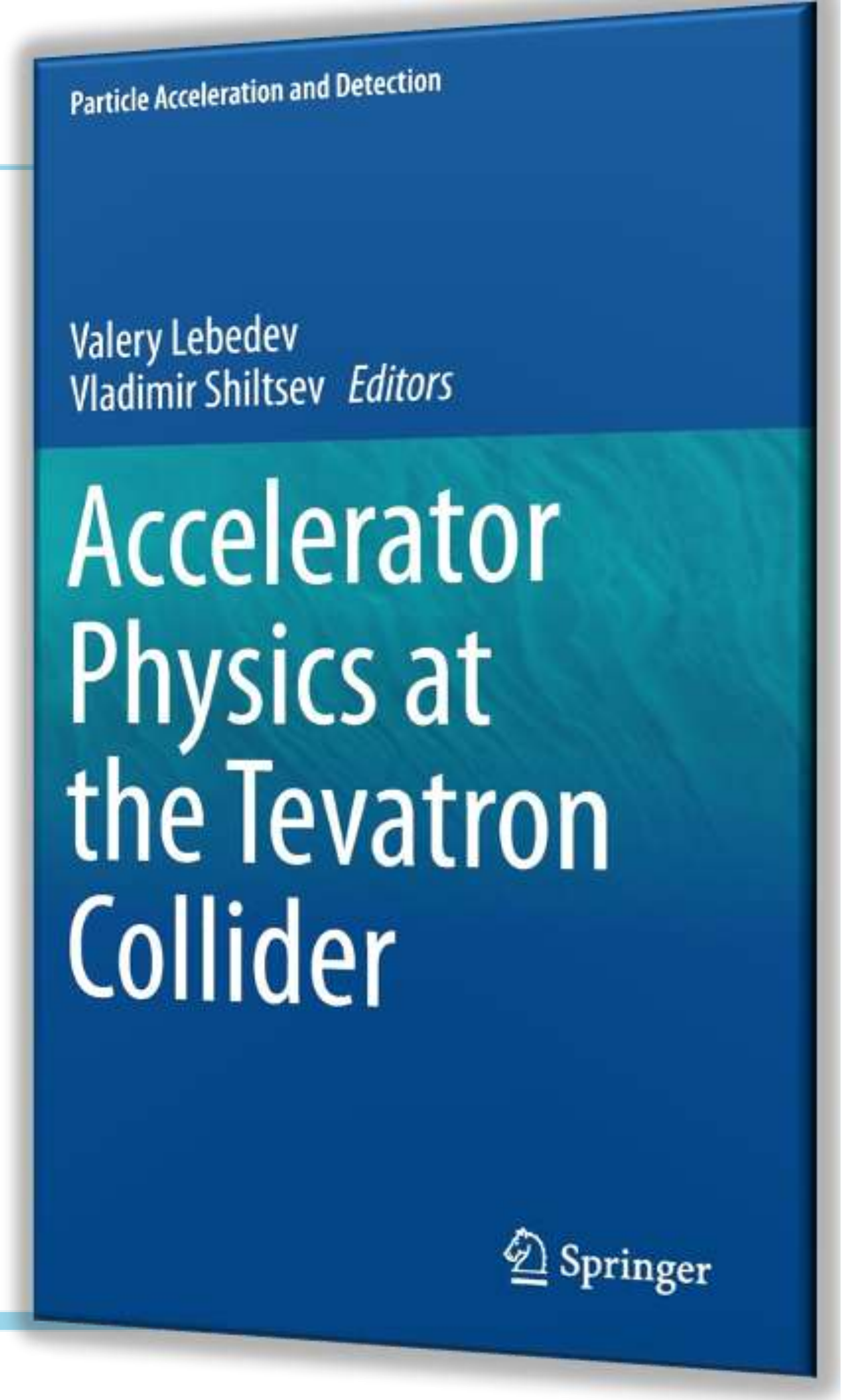
(synchrotrons)

CCC=CERN Control Center

Over 100,000 signals are generated by the cryogenics, machine protection and beam monitoring systems.

Further Reading on Accelerator Physics

- An Introduction to Particle Physics High Energy Accelerators, D. Edwards and M. Syphers (John Wileyand Sons, Inc, 1993)
- Accelerator Physics, S.Y. Lee (World Scientific, 1999)
- Hand Book of Accelerator Physics and Engineering – Eds. A. Chao and M. Tinger , World Scientific (1999)
- CAS CERN Accelerator, Accelerator Physics Courses http://cas.web.cern.ch/
- Accelerator Physics at the Tevatron Collider - by V.Lebedev and V.Shiltsev, Springer (2014)



Luminosity and Burn-Up

The relationship of the beam to the rate of observed physics processes is given by the "Luminosity"

$$R = L\sigma$$

Rate → R; "Luminosity" → L; Cross-section ("physics") → σ

Standard unit for Luminosity is $cm^{-2}s^{-1}$

Example: total *p-p* inelastic+elastic cross section at 13 TeV cme is ~*110* mbarn (58 inel+ 12 ssd+40 el not seen)→ ~60 interactions per crossing x 40,000,000 collision/sec= 2.4e9 protons leave each beam every second

Beam lifetime due to such "Burn up" *T=N/(dN/dt)=*
2.8e14 protons/(2.4e9/s) =32 hours


❑ 26 658.883 m
❑ 6.5 TeV x 2

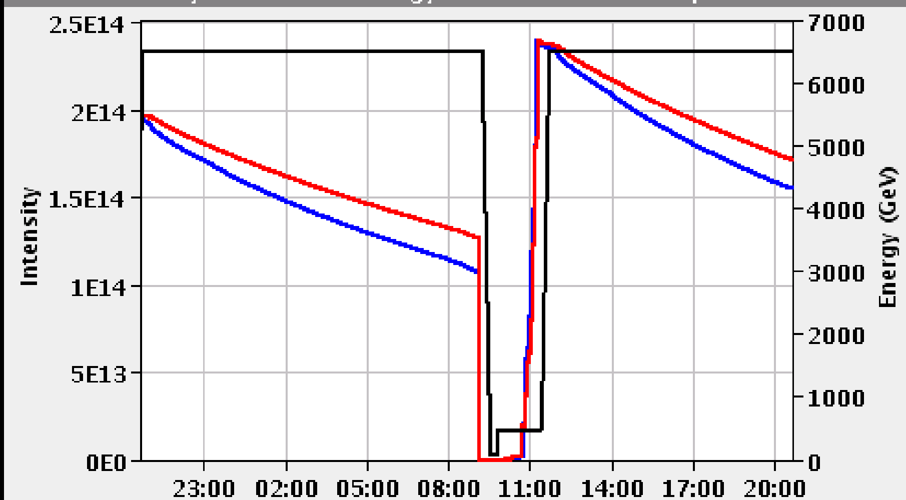
LHC Page1	Fill: 6629	E: 6499 GeV	t(SB): 08:30:56	01-05-18 20:38:29

PROTON PHYSICS: STABLE BEAMS

Energy:	6499 GeV	I(B1):	1.56e+14	I(B2):	1.72e+14

Inst. Lumi [(ub.s)^-1]	IP1: 8155.99	IP2: 1.76	IP5: 7827.12	IP8: 330.93

FBCT Intensity and Beam Energy Updated: 20:38:28



Instantaneous Luminosity Updated: 20:38:28

Comments (01-May-2018 14:18:10)

Fill for physics (1887b)

XRPs IN

continous crossing angle leveling in IP1/5

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 25ns_1887b_1874_1694_1772_144bpi_19inj

PM Status B1	ENABLED	PM Status B2	ENABLED

Numerical Example: LHC (γ »1, $\beta = v/c \approx 1$)

$$\varepsilon_{n\,(x,y)} = \gamma \cdot \sigma_{x,y} \sigma'_{x,y}$$

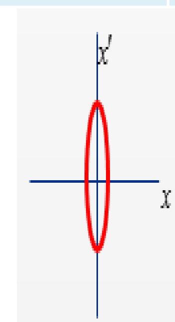
$$\sigma_{x,y} = \sqrt{\frac{\varepsilon_n \cdot \beta_{x,y}}{\gamma}}$$

$$\sigma'_{x,y} = \sqrt{\frac{\varepsilon_n}{\gamma \cdot \beta_{x,y}}} = \frac{\sigma_{x,y}}{\beta_{x,y}}$$

ε_n = 1.8 mm·mrad ($10^{-6} m$)

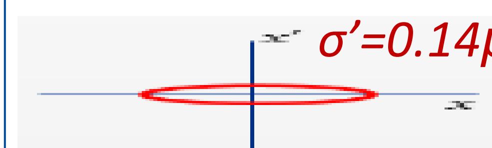
$$\gamma = 6930$$

β*	Sigma*
25 cm	8 um



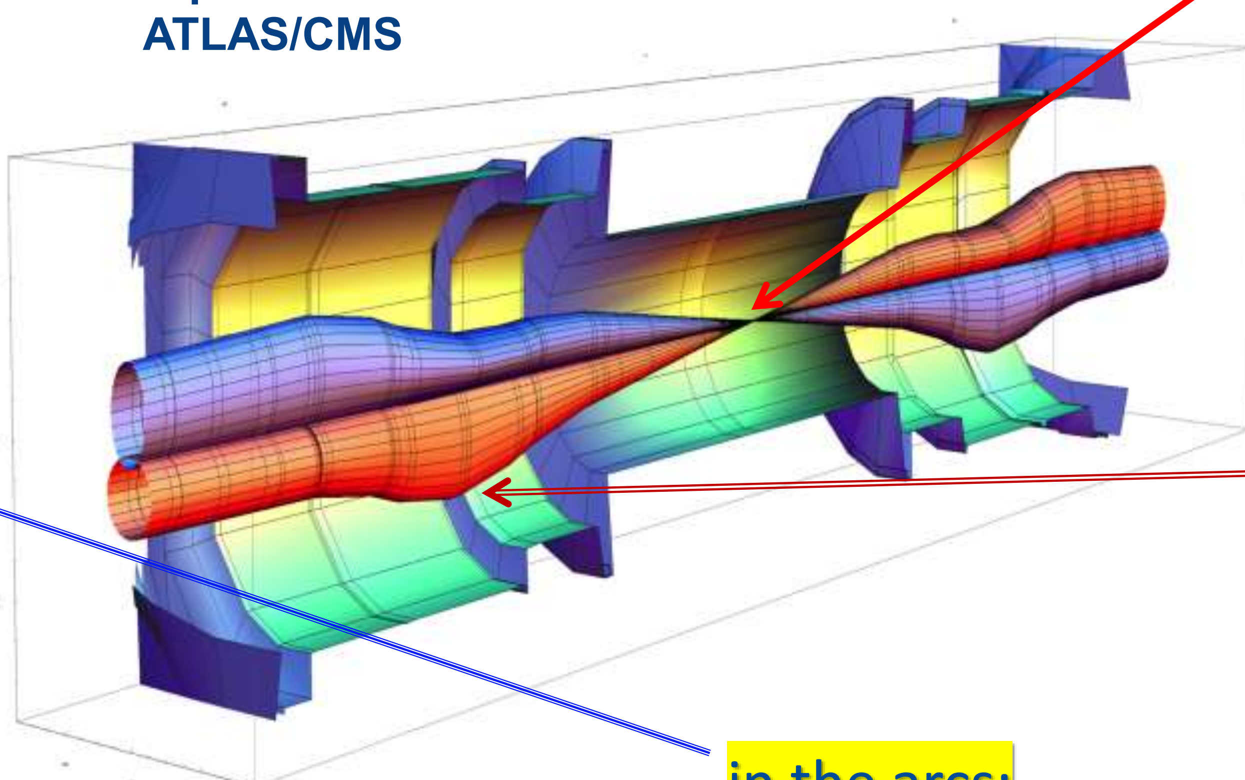
σ′=32μrad

$\beta_{triplet}$	Sigma triplet
~5 km	1.1 mm



σ′=0.14μrad

Squeeze in ATLAS/CMS



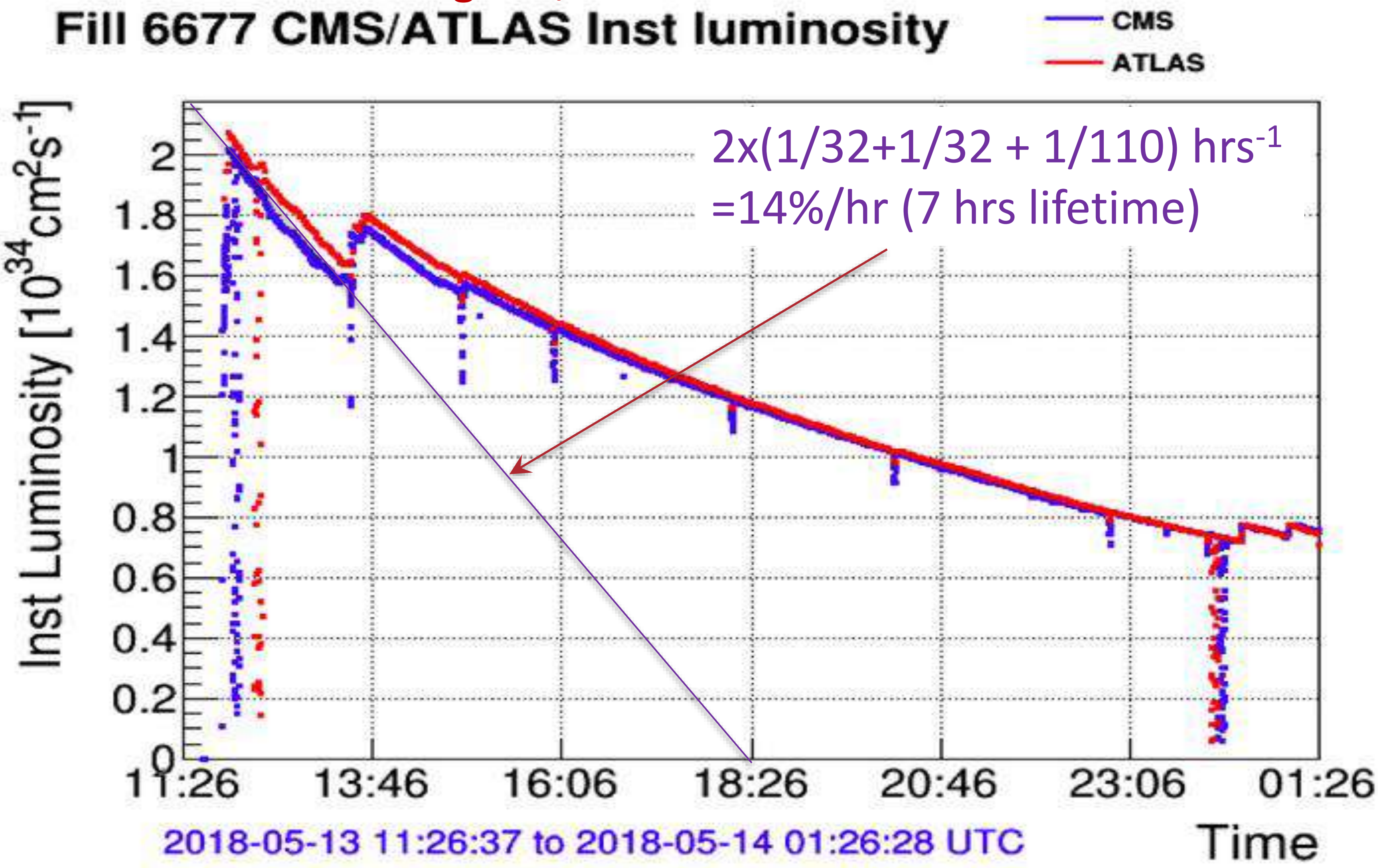
in the arcs:
β~200m, σ≈0.23mm

Image courtesy John Jowett

Luminosity Lifetime and Integral

Take into account two IPs (ATLAS, CMS and 3% LHCb) 1/32+1/32 hrs^{-1}

Take into account beam gas 1/110hrs^{-1} and that *Lumi~N^2* → x2



(Very) Brief History of Colliders

- Notable machines and most notable effects/discoveries/breakthroughs
- Note that we later will consider in detail:
  - LEP, KEK-B and Super-KEKB (lecture VS6)
  - Tevatron (lecture VS7)
  - LHC and HL-LHC (lecture VS8)
  - RHIC and EIC (lecture VS9)
  - SLC and linear colliders (lecture VS12)

Collider Patent R.Wideroe Sept. 8, 1943

Erteilt auf Grund des Ersten Überleitungsgesetzes vom 8. Juli 1949
(WiGBl. S. 175)

BUNDESREPUBLIK DEUTSCHLAND

AUSGEGEBEN AM
11. MAI 1953

DEUTSCHES PATENTAMT

PATENTSCHRIFT

Nr. 876 279

KLASSE 21g GRUPPE 36

W 687 VIIIc / 21g

Dr.-Ing. Rolf Wideröe, Oslo
ist als Erfinder genannt worden

Aktiengesellschaft Brown, Boveri & Cie, Baden (Schweiz)

Anordnung zur Herbeiführung von Kernreaktionen

Patentiert im Gebiet der Bundesrepublik Deutschland vom 8. September 1943 an
Patentanmeldung bekanntgemacht am 18. September 1952
Patenterteilung bekanntgemacht am 26. März 1953

Kernreaktionen können dadurch herbeigeführt werden, daß geladene Teilchen von hoher Geschwindigkeit und Energie, in Elektronenvolt gemessen, auf die zu untersuchenden Kerne geschossen werden. Wenn die geladenen Teilchen in einen gewissen Mindestabstand von den Kernen gelangen, werden die Kernreaktionen eingeleitet. Da aber neben den zu untersuchenden Kernen noch die gesamten Elektronen der Atomhülle vorhanden sind und auch der Wirkungsquerschnitt des Kernes sehr klein ist, wird der größte Teil der geladenen Teilchen von den Hüllenelektronen abgebremst, während nur ein sehr kleiner Teil die gewünschten Kernreaktionen herbeiführt.

Erfindungsgemäß wird der Wirkungsgrad der Kernreaktionen dadurch wesentlich erhöht, daß die Reaktion in einem Vakuumgefäß (Reaktionsröhre) durchgeführt wird, in welchem die geladenen Teilchen hoher Geschwindigkeit gegen einen Strahl von den zu untersuchenden und sich entgegengesetzt bewegenden Kernen auf einer sehr langen Strecke laufen müssen. Dies kann in der Weise durchgeführt werden, daß die geladenen Teilchen zum mehrmaligen Umlauf in einer Kreisröhre gezwungen werden, wobei die zu untersuchenden Kerne auf derselben Kreisbahn, aber in entgegengesetzter Richtung umlaufen. Da die geladenen Teilchen dabei nicht von bei der Reaktion unwirksamen Elektronen abgebremst werden und andererseits auf einer sehr langen Wegstrecke gegen die Kerne sich bewegen können, wird die Wahrscheinlichkeit für das Eintreten der Kernreaktionen wesentlich größer und der Wirkungsgrad der Reaktion sehr stark erhöht.

Um die bei der Kreisbewegung entstehenden Zentrifugalkräfte aufzuheben, müssen die umlaufenden Teilchen von nach innen gerichteten Ablenkkräften gesteuert werden, während eine Diffusion der Teile mittels stabilisierender, von allen Seiten auf den Bahnkreis gerichteter Kräfte verhindert wird. Falls die gegen-

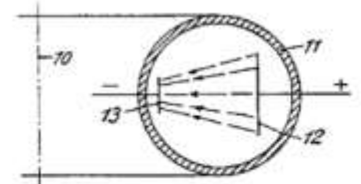


Abb. 1

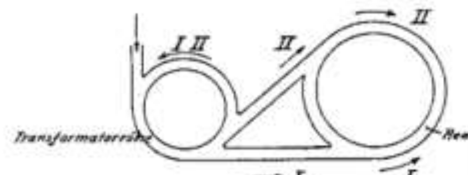


Abb. 2

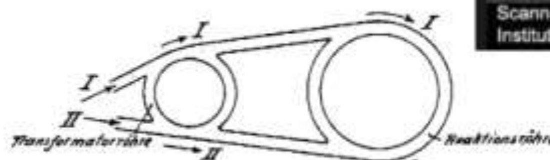


Abb. 3

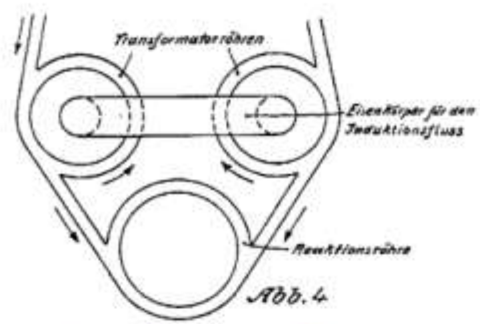
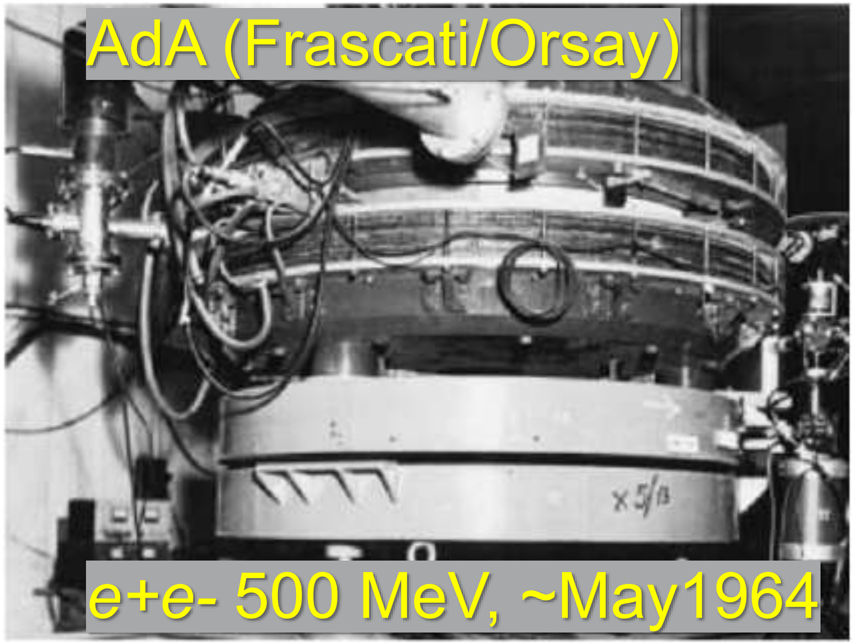


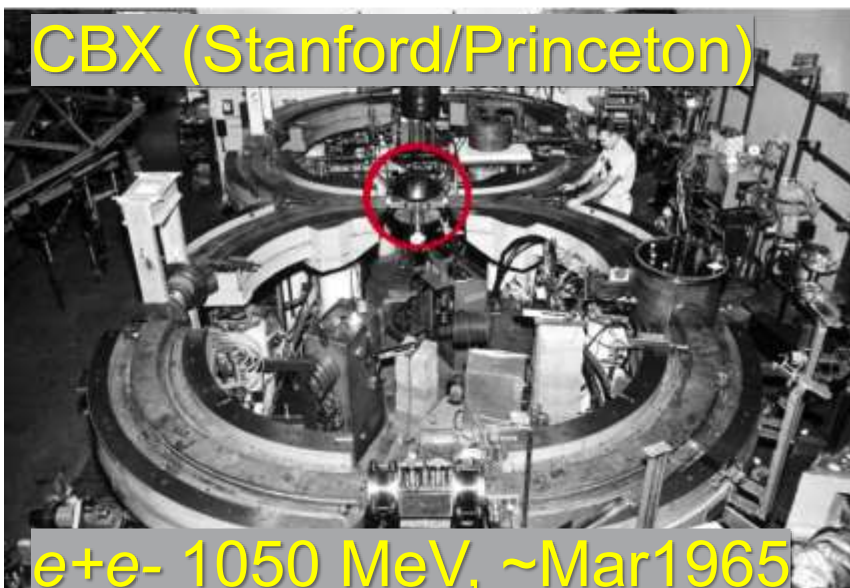
Abb. 4

182

During rough war times, a patent was the only way to communicate the notion !

First Colliders



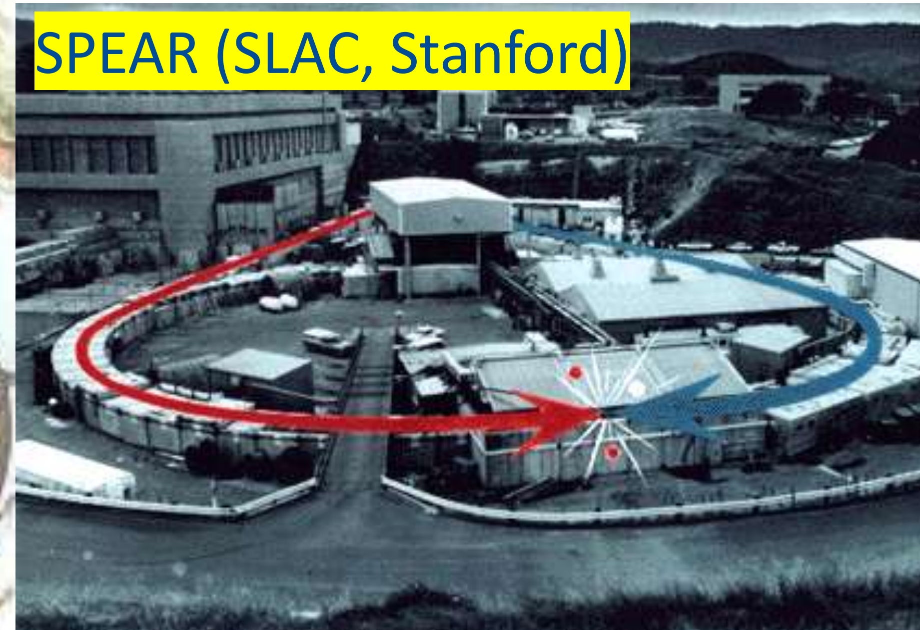


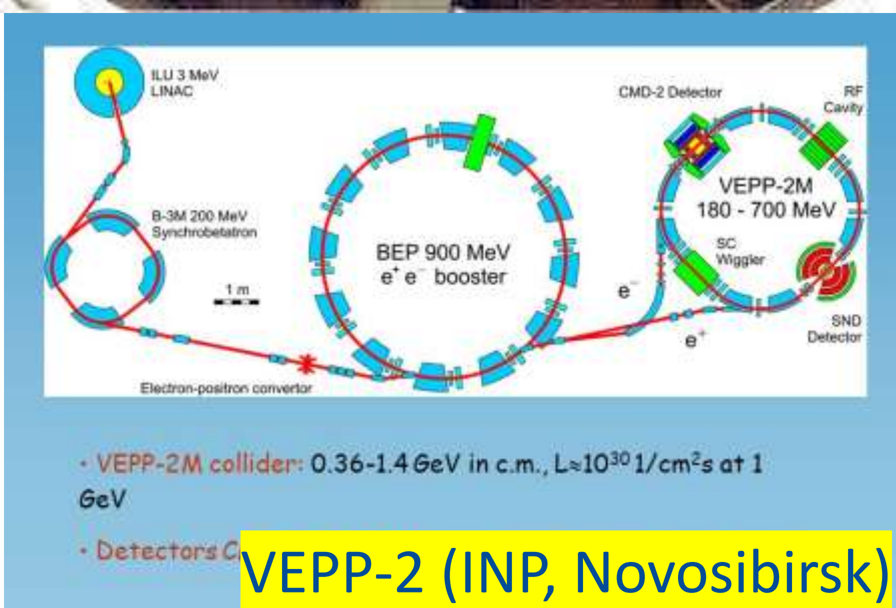
The First "Trio" of Colliders

- Technological challenges addressed:
  - development of nano-second-fast injector kickers
  - attainment of an ultrahigh vacuum of about a micropascal or better
  - reliable luminosity monitoring and other beam diagnostics
- Beam physics advances:
  - Touschek effect (low energy beam losses due to particle scattering inside beam leading to e+e- gettinbg out of RF buckets)
  - luminosity degradation due to beam-beam effects at $\xi_{x;y} \sim 0.02–0.04$
  - complex beam dynamics at non-linear high-order resonances
  - coherent instabilities due to resistive vacuum pipe walls

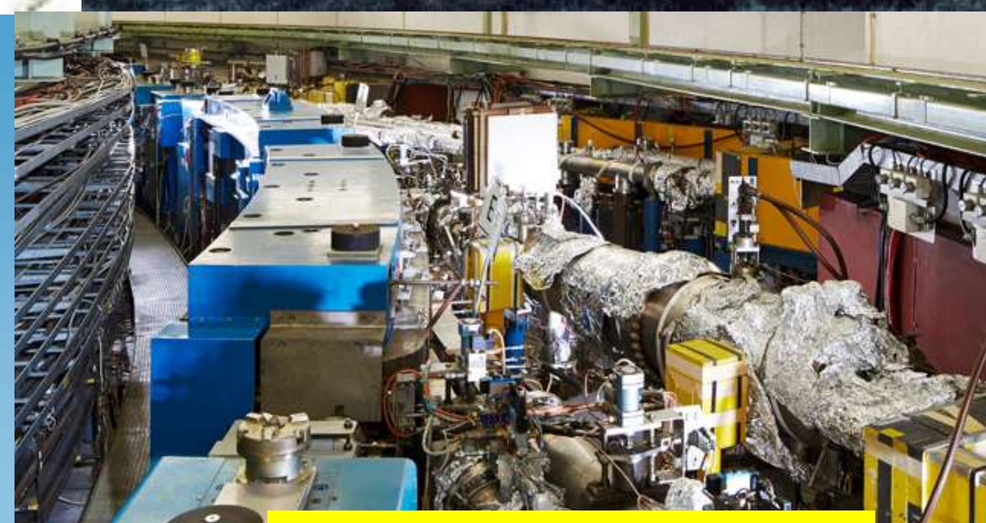
1970s-80s “small” e+e- (*C*=20…200 m)


ADONE (INFN, Frascati)


SPEAR (SLAC, Stanford)



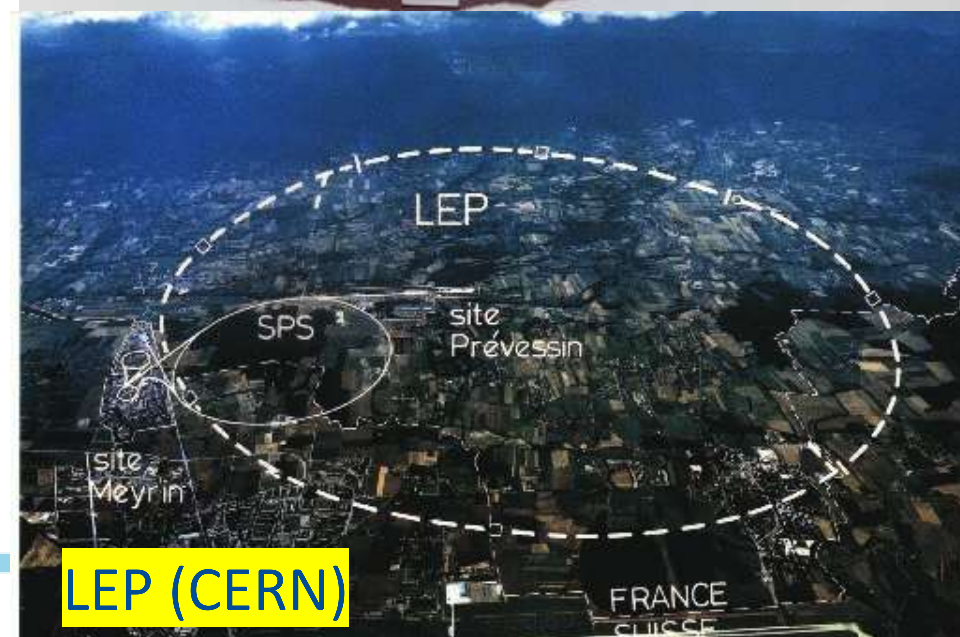
VEPP-2 (INP, Novosibirsk)


DORIS (DESY, Hamburg)

1970s-80s “small” e+e-

- Technological challenges addressed:
  - longitudinal phase feedback system developed and installed (ADONE)
  - 7.5 T SC wiggler to decrease the damping time (VEPP-2M)
- Beam physics advances:
  - Luminosity scaling in SR dominated beams $\mathcal{L} \propto \gamma^4$ (ADONE)
  - Sokolov-Ternov effect: the buildup of electron spin polarization through synchrotroton radiation (VEPP-2 and ACO)
  - CEA: first time a low-beta insertion optics with a small $\beta_y \approx 2.5$ cm
  - SPEAR: Transverse horizontal and vertical head-tail instabilities were observed and suppressed a positive chromaticity Q’>0
  - DCI: first four-beam compensation attempt (limited success)
  - $dE/E{\sim}10^{-5}$ resolution via resonant depolarization method (VEPP-2M)
  - Multibunch, e.g. 480 bunches in each ring in DORIS

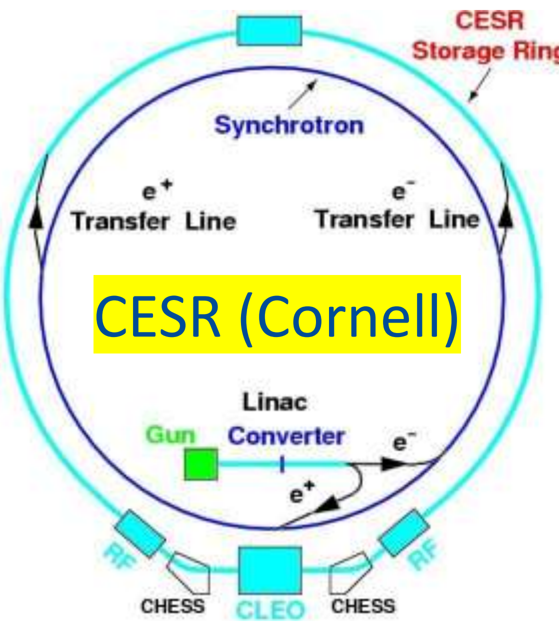
1980s-90s "large" e+e- (*C*=2…27 km)



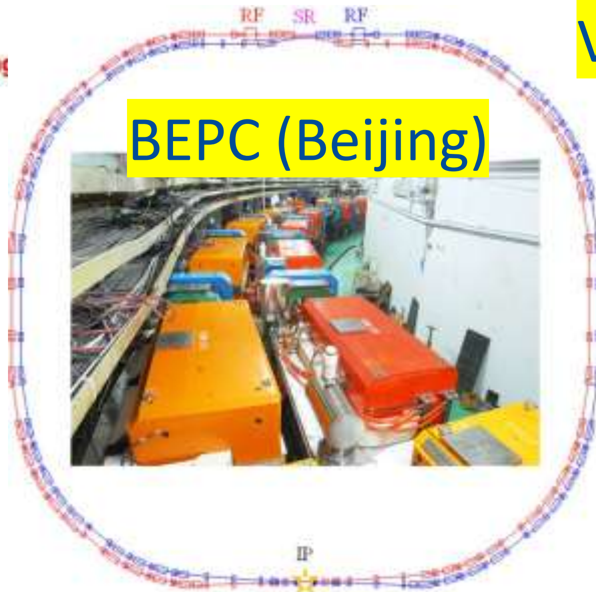
1980s-90s “large” e+e-

- Technological challenges addressed:
  - SLC: first ever (and only) linear collider – many subsystems
  - pioneer SRF technology - TRISTAN: 508 MHz 0.4 GV/turn; LEP 352 MHz SC niobium-on-copper cavities, 3.5 GV/turn
  - High current positron sources, incl. 80% polarized e- (SLC)
- Beam physics advances:
  - LEP: losses via e+/e- scattering off thermal photons in RT beampipe
  - LEP single-bunch current limited by TMCI at injection energy
  - LEP: beam-beam record tune shift $4x\xi_y=0.33$
  - SLC : BNS (Balakin-Novokhatsky-Smirnov) damping of BBI
  - SLC: ~x2 increase of luminosity due to disruption enhancement @IP

2000s-now “factories” e+e- (Φ-, Charm-, B-meson)

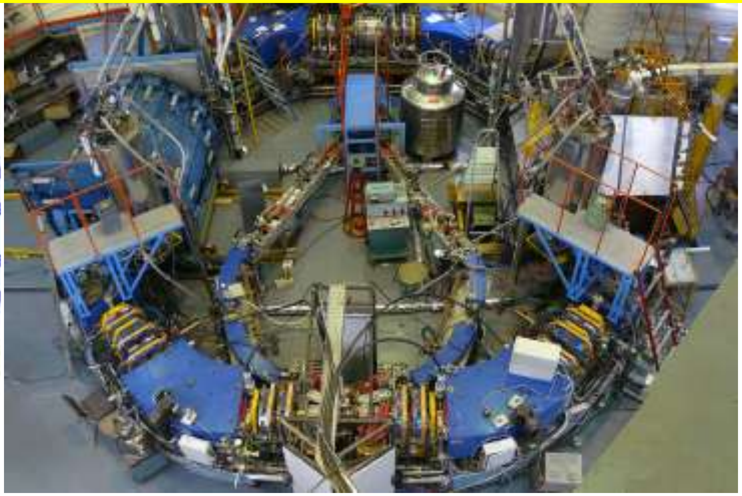


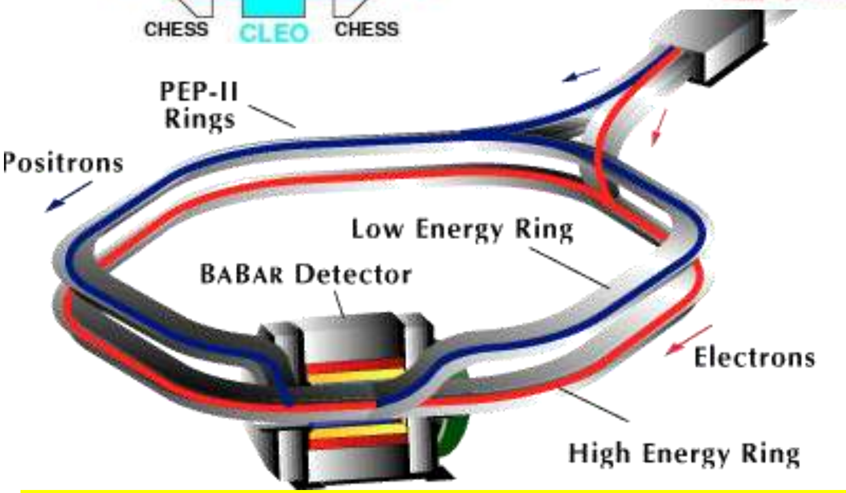
CESR (Cornell)



BEPC (Beijing)

VEPP-2000 (BINP, Novosibirsk)





KEK-B → SuperKEKB (KEK, Japan)

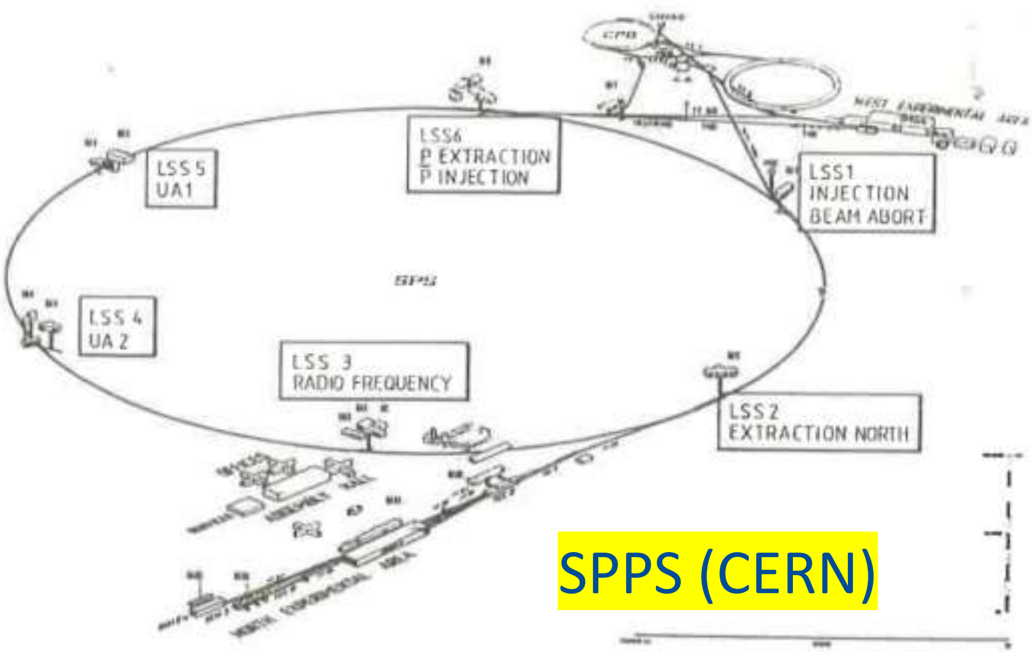
PEP-II (SLAC, Stanford)

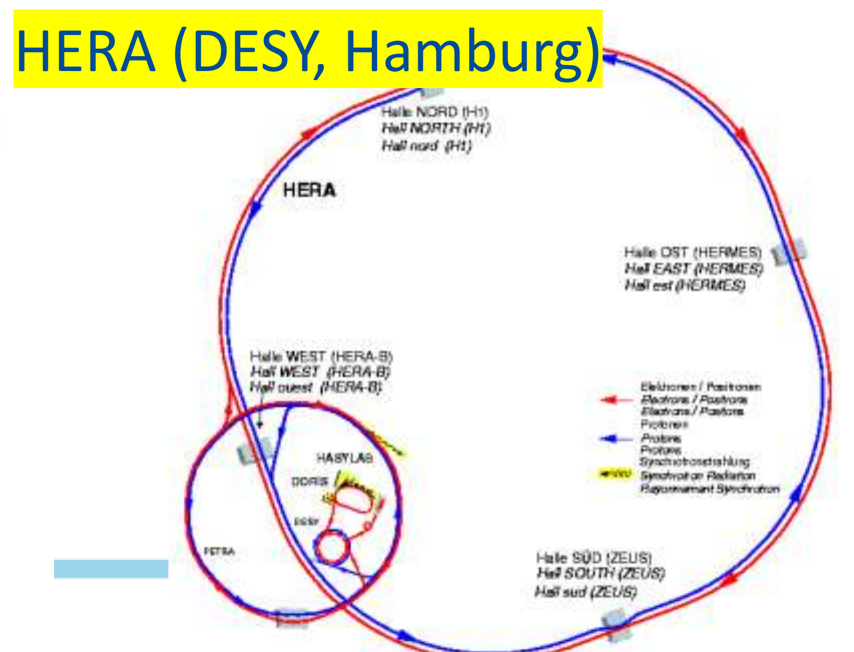
DAΦNE (INFN, Frascati)

2000s-now "factories" e+e-

- Technological challenges addressed:
  - HV electrostatic orbit separation for e+e- (CESR)
  - Efficient SRF for *Ampere*-class currents, HOM damping
  - Asymmetric rings – KEK-B, PEP-II, Super-KEKB
  - Tight detector background control - vacuum and collimation
  - Since PEP-II/KEKB: top-up injection mode of operation
- Beam physics advances:
  - Advanced optics for tight vertical focusing with β_y ~1cm – few mm
  - VEPP2000 : "round beams" concept $\xi \sim 0.25$
  - (less successful) CESR "Moebius ring" collider scheme (x-y flips)
  - DAΦNE : "crab waist" focusing optics, demo "wire b-b compensation"
  - KEK-B: crab crossing (limited success) → nonobeams (Super-KEKB)

1970s-2010s Hadron Colliders (*C*=1…7 km)



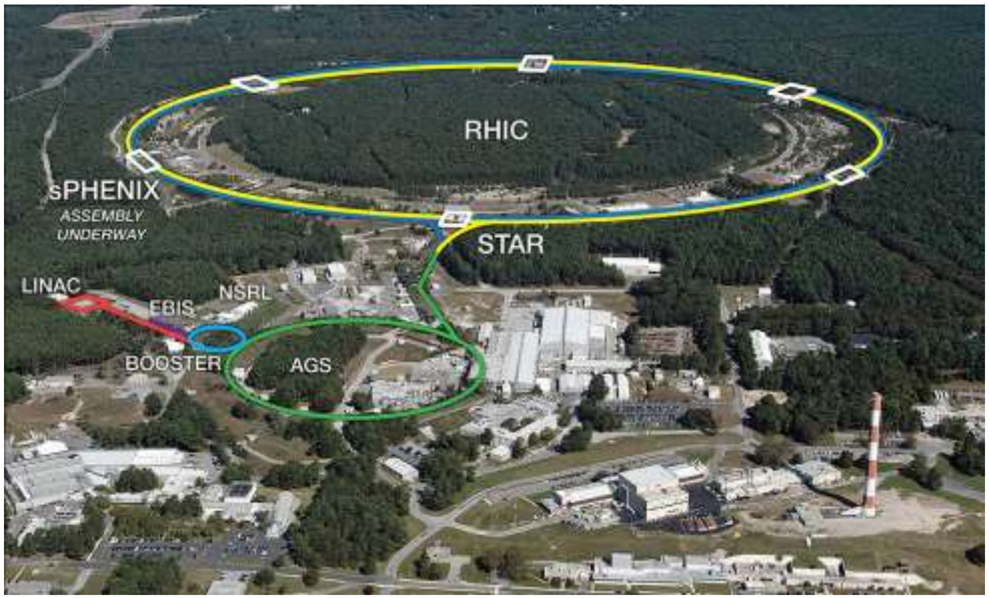


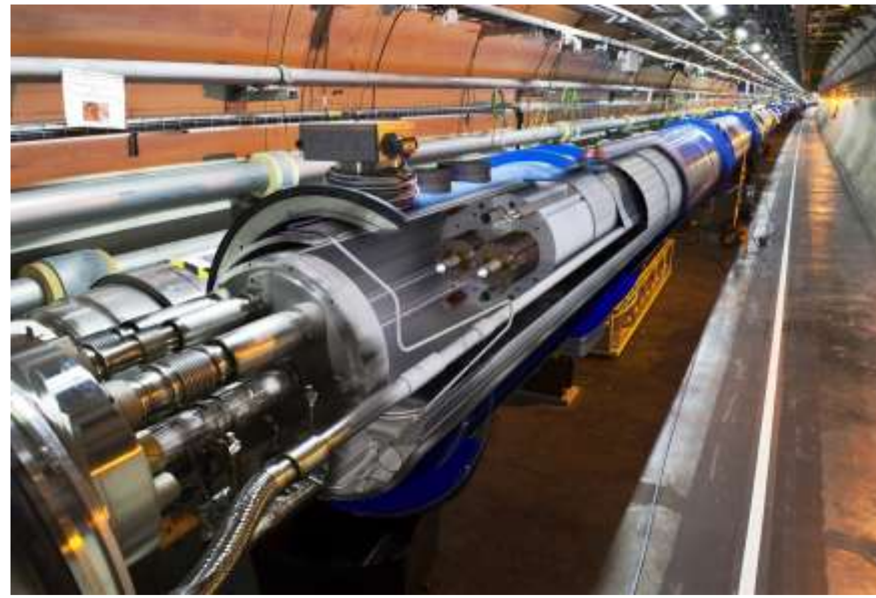
1970s-2000's Hadron Colliders (1)

- Technological challenges addressed:
  - ISR: world's first pp collider (and pp Lumi record holder for >20 yrs)
  - SC NbTi magnets 4-8 T (Tevatron → HERA→ RHIC → LHC)
  - SPPS, &Tevatron: technology of antiproton production & scienc of stochastic (Nobel prize) and electron cooling (up to 4 MeV e-)
  - Tevatron: permanent magnets (3.3 km 8 GeV Recycler)
  - Two-stage collimation systems (HERA, Tevatron)

- Beam physics advances:
  - Longitudinal manipulations : momentum stacking (ISR), slip-stacking and momentum mining (Tevatron)
  - Tevatron: beam-beam record at $\xi_{x;y} \sim 0.025$, first successful demo b-b compensation by electron lenses, hollow e-lens collimation
  - HERA: first e-p collider, transversely polarized e- & spin rotators to l

2000s-now Hadron Colliders (C=4…27 km)





RHIC (BNL, Brookhaven)

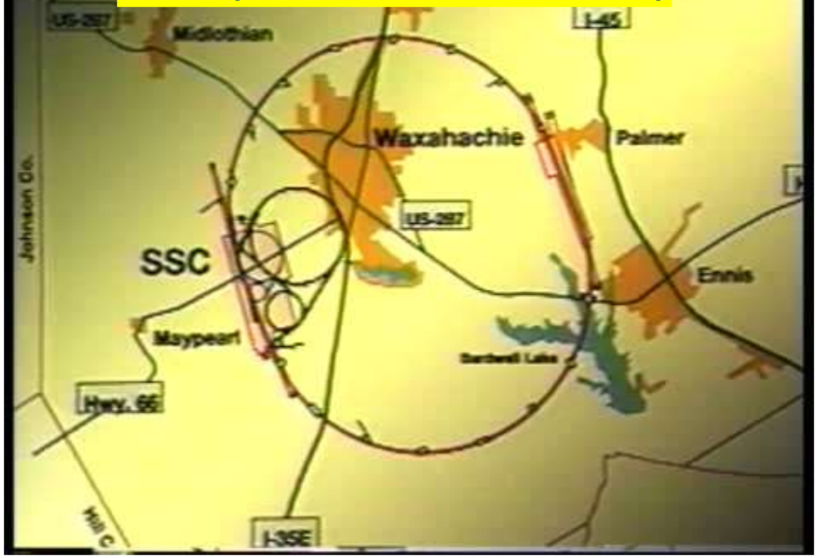
LHC (CERN)

2000s-now Hadron Colliders (2)

- Technological challenges addressed:
  - First use of Nb3Sn SC magnets (HL-LHC)
  - Three (4) stage 99.99% efficient collimation system (LHC)
  - Ions sources and ion-ion, ion-p collisions (RHIC, LHC)
  - Sophisticated polarization control along the chain (55% in RHIC)
- Beam physics advances:
  - RHIC: bunched beam stochastic cooling, bunched beam electron cooling
  - RHIC: head-on beam-beam compensation with electron lenses
  - LHC: sophisticated control of electron-cloud and other instabilities
  - LHC: novel achromatic telescopic squeeze optics to lower beta*
  - LHC: demo wire compensation of long-range beam-beam effects

Super-Colliders That Were Not (1990's)

SSC (Waxahachie, TX)



UNK (IHEP, Protvino)

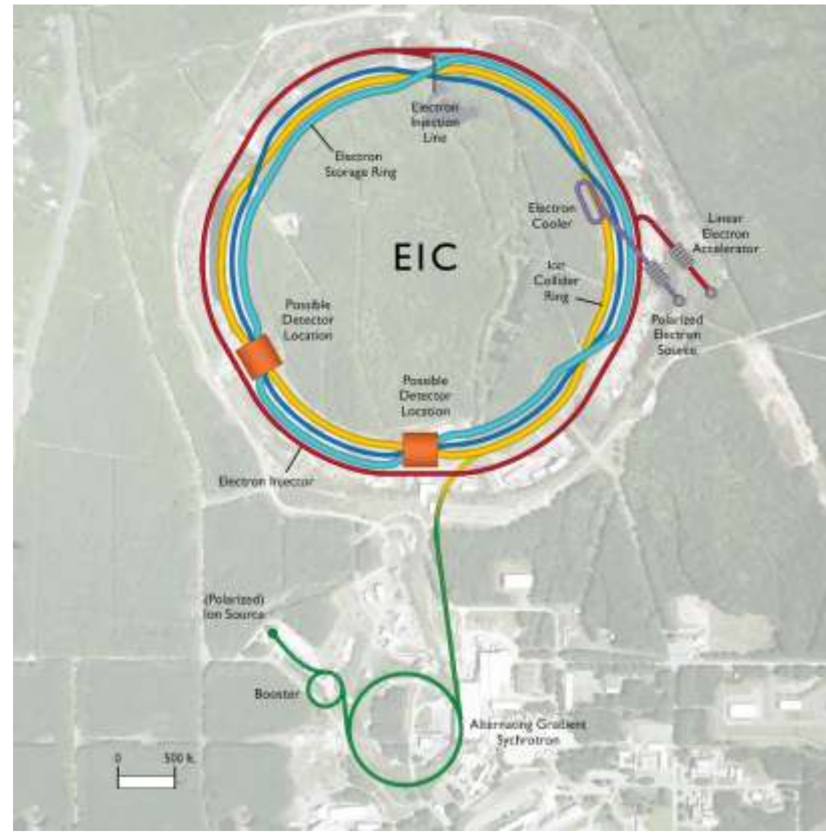
Colliders That Will Be

NICA (JINR, Dubna)

Main Parameters of The NICA Collider

Circumference, m	503,04		
Bunch number per ring	22		
Mean-square bunch size, m	0.6		
Min. beta-function (β*), m	0.6		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch, 1e9	0.275	2.4	2.2
Peak luminosity, $cm^{-2} \cdot s^{-1}$	0.9e25	0.9e27	6.3e27

EIC (BNL, Brookhaven)

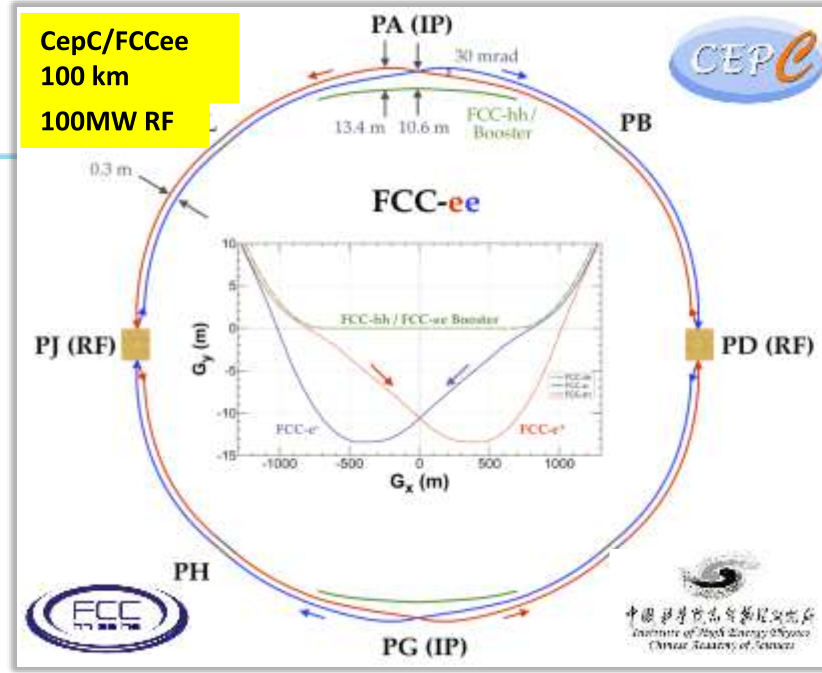


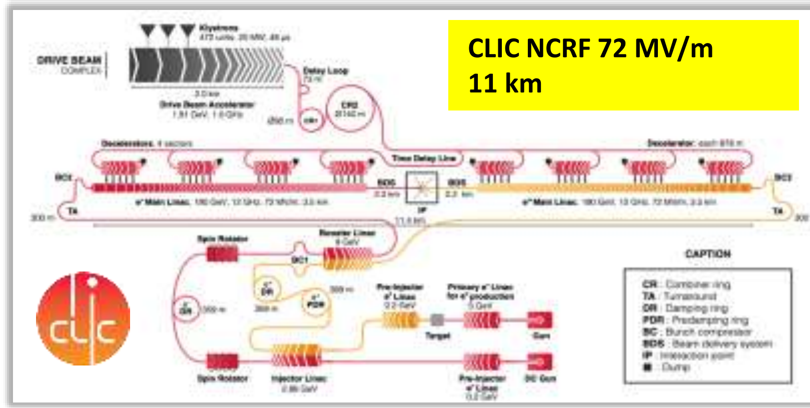
BINP C/Tau-Factory (Novosibirsk)

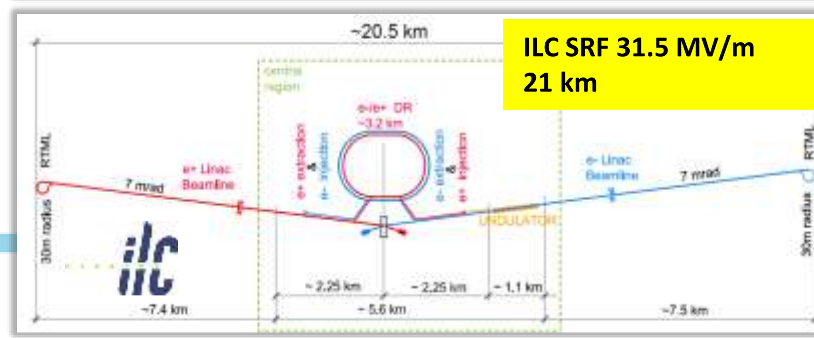
Colliders That Might Be :

Higgs factories proposals

Name	Details
CepC	e+e-, $\sqrt{s} = 0.24$ TeV, L= 3.0 $\times 10^{34}$
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.38$ TeV, L= 1.5 $\times 10^{34}$
ERL ee collider	e+e-, $\sqrt{s} = 0.24$ TeV, L= 73 $\times 10^{34}$
FCC-ee	e+e-, $\sqrt{s} = 0.24$ TeV, L= 17 $\times 10^{34}$
gamma gamma	X-ray FEL-based $\gamma\gamma$ collider
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.25$ TeV, L= 1.4 $\times 10^{34}$
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 0.1 $\times 10^{34}$
MC (Higgs factory)	$\mu\mu$, $\sqrt{s} = 0.13$ TeV, L= 0.01 $\times 10^{34}$

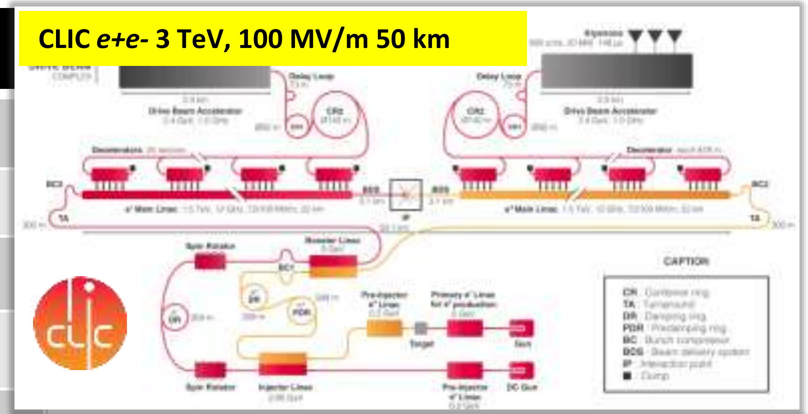


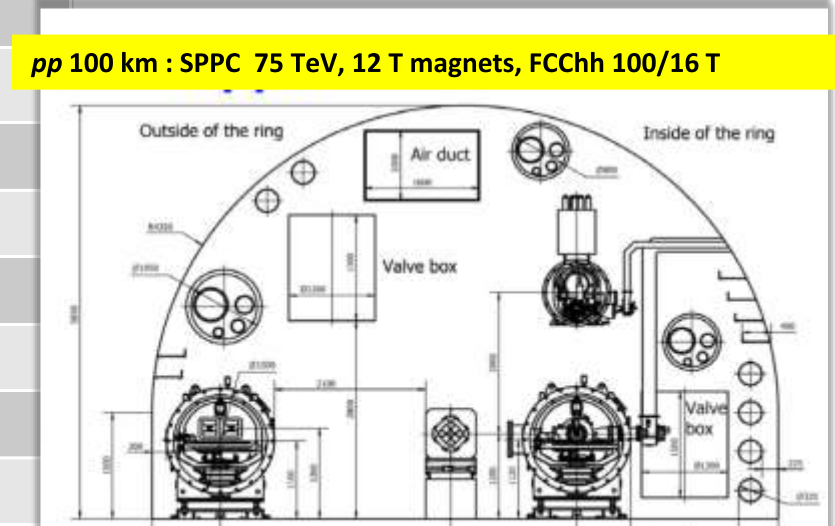


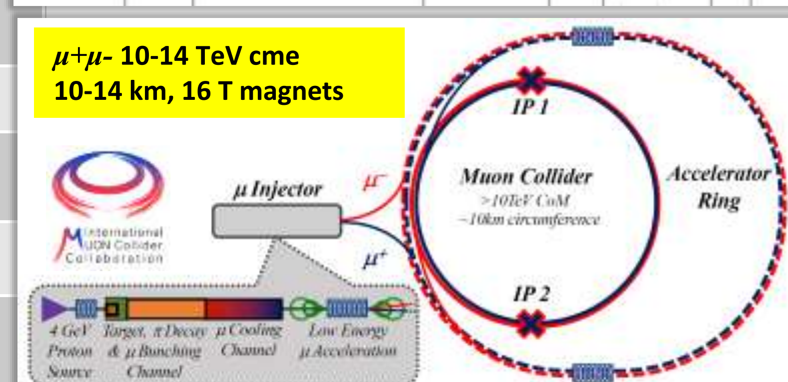


Far-Future High Energy Collider Concepts/Proposals

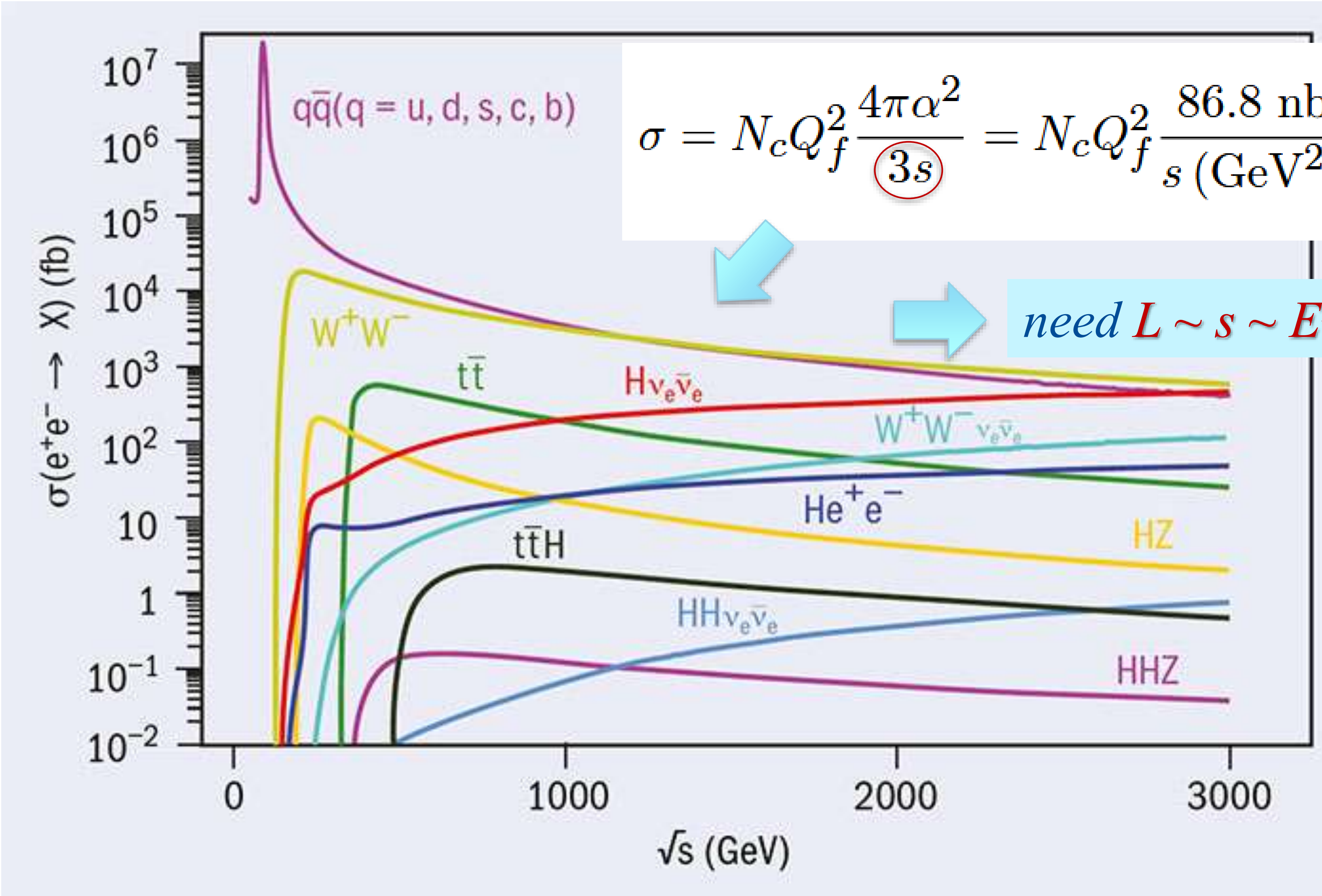
Name	Details
Cryo-Cooled Copper linac	e+e-, $\sqrt{s} = 2$ TeV, L= 4.5 $\times 10^{34}$
High Energy CLIC	e+e-, $\sqrt{s} = 1.5 - 3$ TeV, L= 5.9 $\times 10^{34}$
High Energy ILC	e+e-, $\sqrt{s} = 1 - 3$ TeV
FCC-hh	pp, $\sqrt{s} = 100$ TeV, L= 30 $\times 10^{34}$
SPPC	pp, $\sqrt{s} = 75/150$ TeV, L= 10 $\times 10^{34}$
Collider-in-Sea	pp, $\sqrt{s} = 500$ TeV, L= 50 $\times 10^{34}$
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 1 $\times 10^{34}$
FCC-eh	ep, $\sqrt{s} = 3.5$ TeV, L= 1 $\times 10^{34}$
CEPC-SPPpC-eh	ep, $\sqrt{s} = 6$ TeV, L= 4.5 $\times 10^{33}$
VHE-ep	ep, $\sqrt{s} = 9$ TeV
MC – Proton Driver 1	$\mu\mu$, $\sqrt{s} = 1.5$ TeV, L= 1 $\times 10^{34}$
MC – Proton Driver 2	$\mu\mu$, $\sqrt{s} = 3$ TeV, L= 2 $\times 10^{34}$
MC – Proton Driver 3	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
MC – Positron Driver	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
LWFA-LC (e+e- and $\gamma\gamma$)	Laser driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
PWFA-LC (e+e- and $\gamma\gamma$)	Beam driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
SWFA-LC	Structure wakefields; e+e-, $\sqrt{s} = 1 - 30$ TeV







Luminosity Demand : Leptons



$$\sigma = N_c Q_f^2 \frac{4\pi\alpha^2}{3s} = N_c Q_f^2 \frac{86.8 \text{ nb}}{s\,(\text{GeV}^2)}$$

need $L \sim s \sim E^2$

Hadron Cross Sections – Inclusive vs Parton