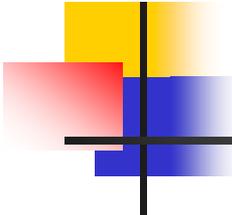


# Методы изучения микромира. Ускорители.

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В.И. Тельнов

Новосибирский Государственный университет



# План

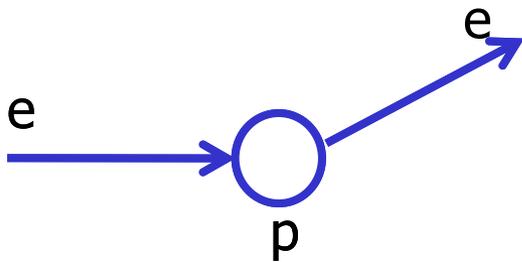
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- Методы изучения микромира;
- Типы, основные принципы, и характеристики современных и планируемых ускорителей;
- протон-протонные, протон-антипротонные накопители;
- электрон-позитронные накопители;
- линейные  $e^+e^-$ ,  $\gamma e$ ,  $\gamma\gamma$  коллайдеры;
- мюонные коллайдеры;
- новые методы ускорения;
- выведенные пучки;
- космические частицы.

# Для чего нужны ускорители?

Фундаментальная физика

Изучение структуры частиц



$$\Delta x \sim \frac{\hbar}{q} \sim \frac{\hbar}{p} \sim \frac{\hbar c}{E} \quad q^2 = (p' - p)^2$$

$$\Delta x \sim \frac{2 \cdot 10^{-14}}{E[\text{ГэВ}]}, \text{ см}$$

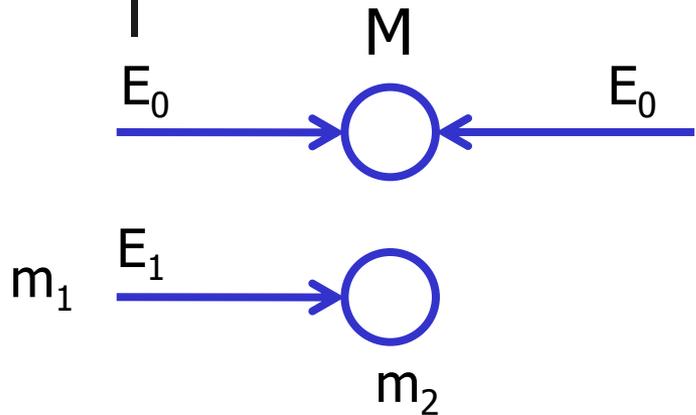
в системе ц.м.

Например, на ер-коллайдере HERA (Гамбург, закрыт в )

$e \xrightarrow{27.5 \text{ ГэВ}} \leftarrow 920 \text{ ГэВ} \text{ p}$  (эквивал. 160x160 ГэВ)  $\Delta x \leq 10^{-16} \text{ см}$

Если измерять с хорошей точностью, то  $\Delta x \leq 10^{-17} \text{ см}$

## Рождение новых частиц



$M = 2E_0$  -встречные пучки (одинаковая энергия)

$M^2 \sim 4E_1 E_2$  встречные пучки (разная энергия)

Неподвижная мишень:

$$M^2 = (E_1 + m_2)^2 - p^2 = 2E_1 m_2 + m_1^2 + m_2^2 \approx 2E_1 m_2$$

Чтобы родить частицу с той же массой (с=1)

$$E_1 \sim E_0 \frac{2E_0}{m_2}$$

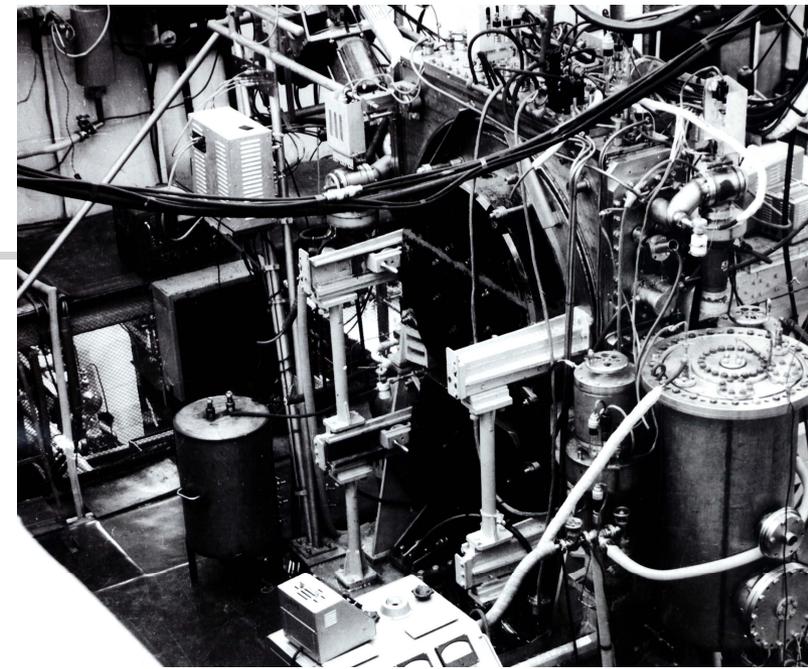
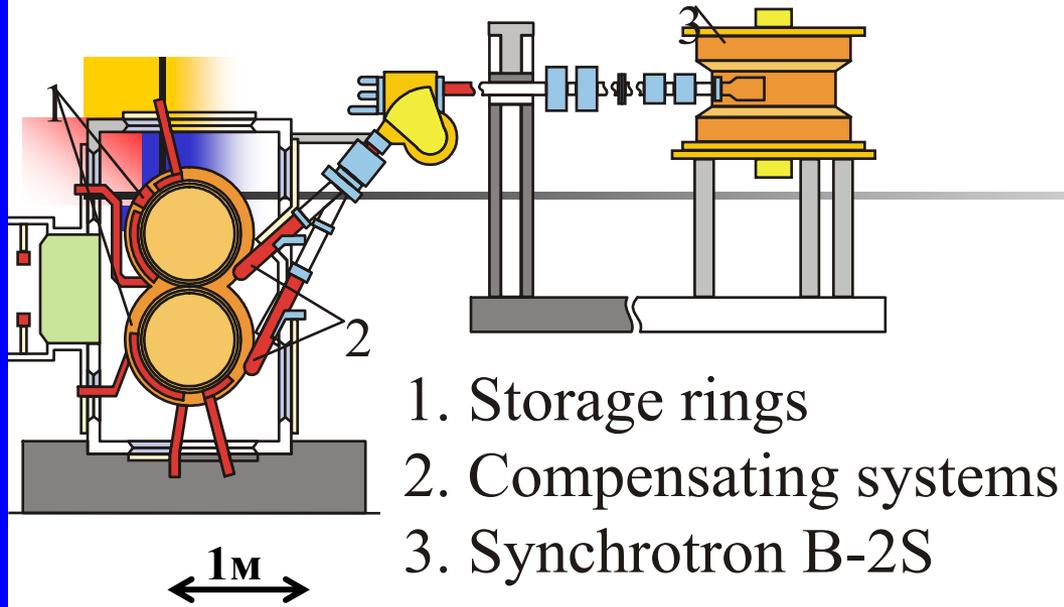
Встречные пучки дают очень большой выигрыш при  $E \gg m$ .

Встречные электрон-позитронные пучки 1x1 ГэВ эквивалентны  $4 \times 10^3$  ГэВ позитроны на неподвижных электронах.

Первые встречные пучки:  $e^-e^-$  ВЭП-1, Stanford, ~1965

$e^+e^-$  ВЭПП-2, 1966

# Electron-electron collider VEP-1

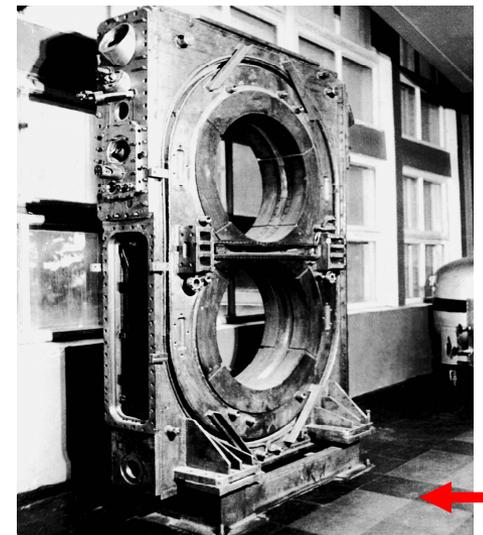


$2E = 90 \text{ MeV} - 320 \text{ MeV}$ , Exps 1965-1967 :

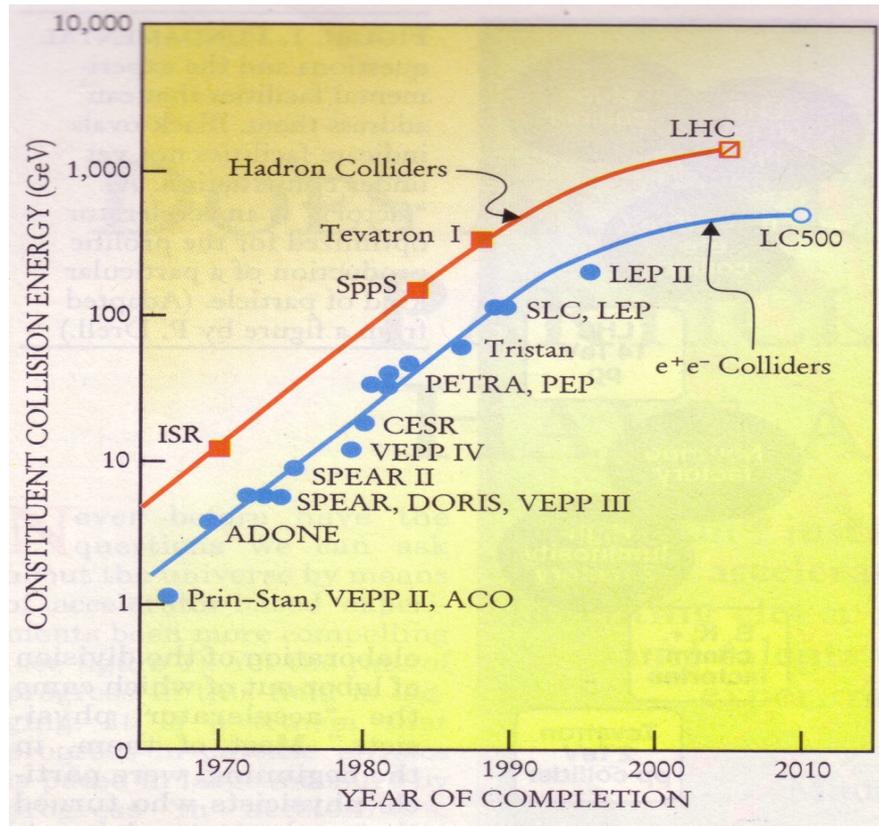
– electron-electron elastic scattering  
(in parallel to Princeton-Stanford Rings);

First electron-electron colliding beam experiments – 1965

VEP-1  
to-day as a monument



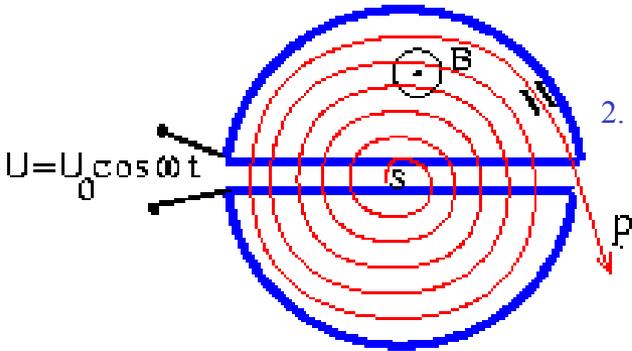
# Диаграмма Ливингстона



$E_{\text{цм}} = 2E_0$  для электронов;

$E_{\text{цм}} \sim (1/6) 2E_0$  для точечных объектов (кварков и глюонов) в протоне.

# Типы ускорителей



## 1. Электростатические

(Ван-Де-Граф, 1931), до  $\sim 10$  МэВ

## 2. Циклотрон (Лоуренс, 1931)

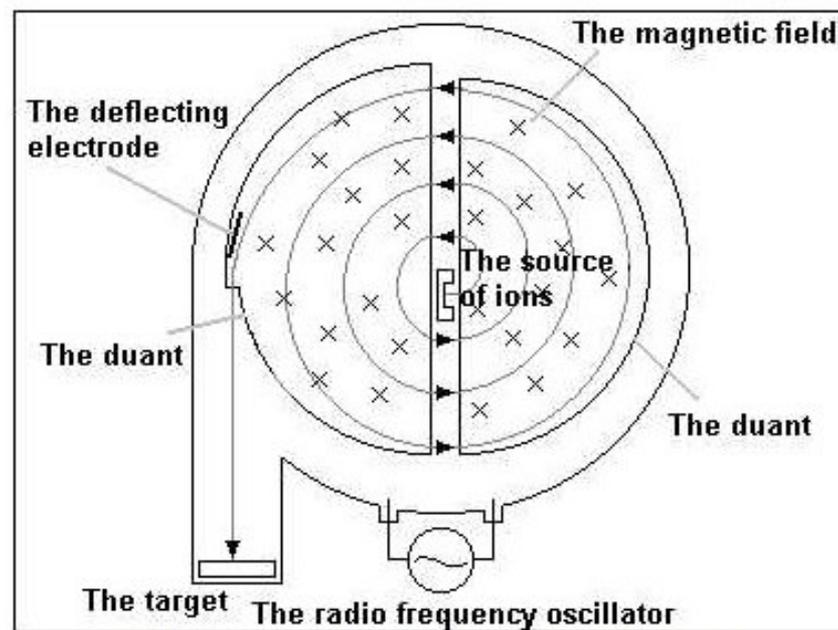
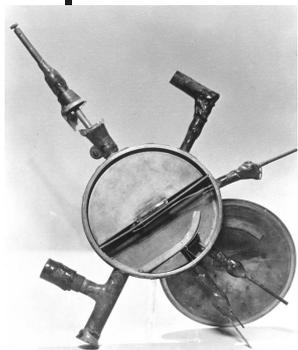
Для нерелятивистских частиц (протонов и ионов низкой энергии).

$$\frac{mv^2}{R} = \frac{eBv}{c} \Rightarrow T = \frac{2\pi R}{v} = \frac{2\pi mc}{eB}$$

$T$  не зависит от энергии при  $B = \text{const}$ , т.е. при  $\omega_{\text{вч}} = \text{const}$ ,  $B = \text{const}$  будет ускоряться, можно иметь непрерывный ток. Не годится для релятивистских скоростей ( $\gamma mv^2/R = eBv/c$ ).

**Фазотрон.** Как циклотрон,  $B = \text{const}$ , но  $\omega$  меняется с энергией, работает при релятивистских скоростях. Ускоряет короткие сгустки, т.к.  $\omega$  меняется. Дубна, 1949, протоны до 700 МэВ.

## Циклотрон Лоуренса, 1938



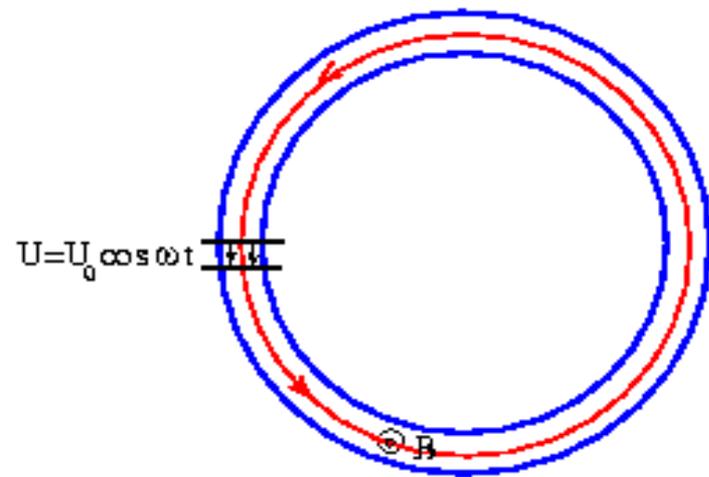
The cyclotron. The positive ions created inside the machine are repeatedly accelerated between the duants - they make bigger and bigger circles perpendicular with the respect to the field direction.

## Типы ускорителей (продолжение)

**Изохронный циклотрон** – циклотрон,  $\omega = \text{const}$ , а поле  $B$  зависит от  $R$ , это компенсирует релятивистские эффекты,

$E_{\text{max}} \sim 1$  ГэВ, может давать непрерывный ток (т.к. все параметры не зависят от времени).

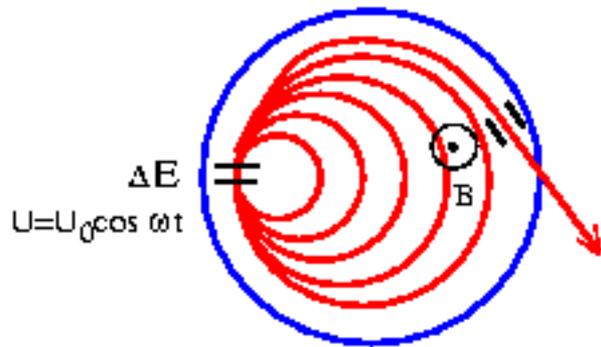
**Синхрофазотрон.** Частицы движутся по дорожке с постоянным радиусом,  $B$  и  $\omega$  меняются с  $E$  (как надо).



Брукхейвен	1958	33 ГэВ	p
ЦЕРН	1960	23	p
Серпухов	1967	76	p
Батавия, FNAL	1972	400 -1000	p-анти-p
ЦЕРН	1976	400-600	p-анти-p
ЦЕРН	2008	14000	pp

## Типы ускорителей (продолжение)

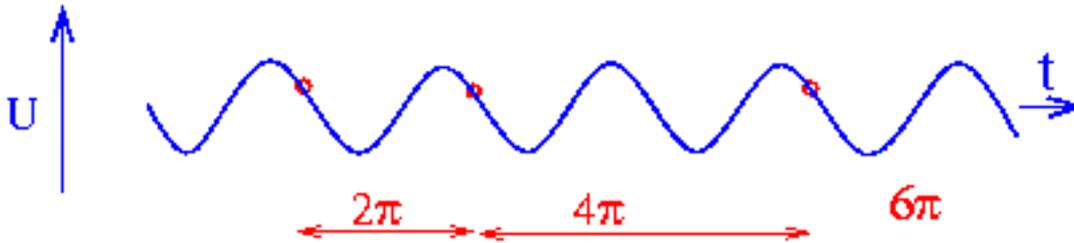
**Микротрон.** Для электронов. За оборот  $\Delta E \sim mc^2$ .



$$T_1 \approx \frac{2\pi(mc^2 + \Delta E)}{eVc} = \mu T_{свч}; \quad \Delta T = \frac{2\pi\Delta E}{eVc} = \nu T_{свч}$$

$$\Delta E \approx mc^2 \nu / (\mu - \nu) = (ecB / 2\pi T_{свч}) \nu \quad E_n = \Delta E (\mu / \nu + n - 1)$$

$$\mu = 2, \nu = 1 \text{ - фундаментальная мода} \Rightarrow \Delta E \approx mc^2$$



Нужно  $\Delta E \sim mc^2$

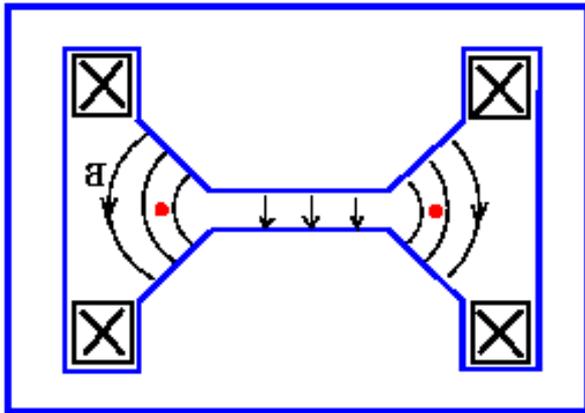
Может работать в непрерывном режиме:  
( $B = \text{const}$ ,  $\omega = \text{const}$ )

## Типы ускорителей (продолжение)

**Синхротрон** - частный случай синхрофазотрона для электронов,  $v/c \rightarrow 1$ .

$\omega_{вч} = \text{const}$ ,  $R = \text{const}$ ,  $V$  пропорционально  $E$ .

$E_{\text{max}}$  для электронов ограничена потерями на синхротронное излучение.



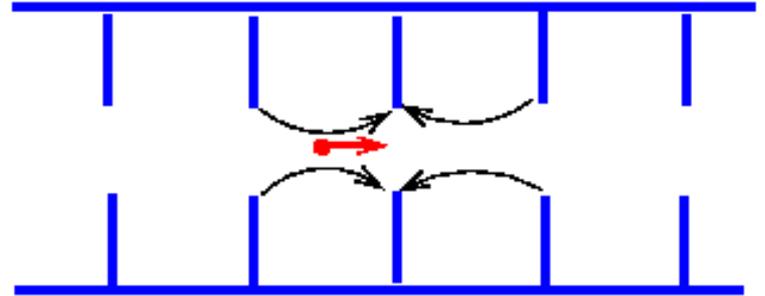
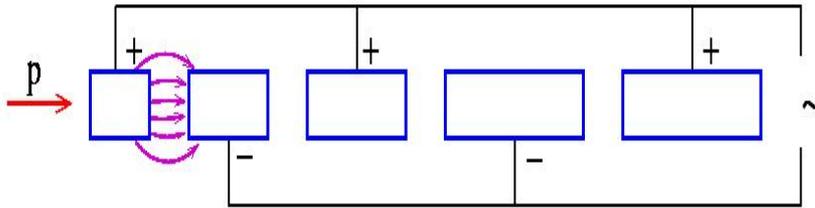
**Бетатрон.** Нарастающее во времени магнитное поле индуцирует электрическое поле  $E$  •

$$E2\pi R = -\frac{1}{c} \frac{\partial \Phi}{\partial t}; \quad \Phi = \bar{B}S; \quad R = \frac{\rho c}{eV}$$

$$R = \text{const} \quad \text{при} \quad V(t) = \frac{1}{2} \bar{B}(t)$$

$E \sim 20\text{-}50$  МэВ для медицины, очень простые!  $E_{\text{max}} \sim 300$  МэВ

# Линейные ускорители

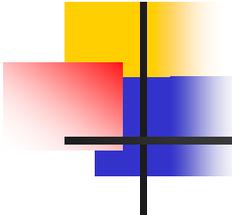


Для протонов (нерелятивистских частиц)  
Внутри трубок поля нет, между  
трубок попадает в ускоряющую фазу

Для электронов (релят. част)  
Диафрагмы делают фазовую  
скорость равной скорости  
электронов ( $\sim c$ ).

**При ускорении вдоль скорости излучение очень мало!**

(При движении в кольцах, ускорение перпендикулярно скорости и  $dE/dt \sim \gamma^2$ ).



# Ускорители на высокую энергию

- Протоны

$$R = \frac{pc}{eB} = 33 \frac{E(\text{ГэВ})}{B(\text{кГс})}, \text{ м}$$

$B \sim 50\text{-}100 \text{ кГс} = 5\text{-}10 \text{ Т}$ ,  $R \sim 5 \text{ км}$  ( $2\pi R = 27 \text{ км}$ , CERN),  
 $2E_{\text{max}} = 14 \text{ ТэВ}$  (LHC- Большой Адронный Коллайдер , начало работы 2009 год). Есть планы в будущем удвоить энергию.  
До 2009 г макс. энергия была у коллайдера Tevatron ( $2E = 2 \text{ ТеВ}$ ), FNAL).

- Электроны-позитроны

излучают за оборот

$$\Delta E = \frac{4\pi e^2 \beta^2 \gamma^4}{R} \propto \frac{E^4}{R}$$

При  $R = 5 \text{ км}$  и  $E = 100 \text{ ГэВ}$ ,  $\Delta E \sim 2 \text{ ГэВ}$ ,  $P/\text{пучок} \sim 20 \text{ МВт}$ ,  
(от сети  $> 200 \text{ МВт}$ ). Это предел (LEP-II, закончил работу в 2000 г.,  $2E = 210 \text{ ГэВ}$ ).

Планируется создание линейных  $e^+e^-$  коллайдеров на энергию 500-3000 ГэВ

# Автофазировка (продольное движение)



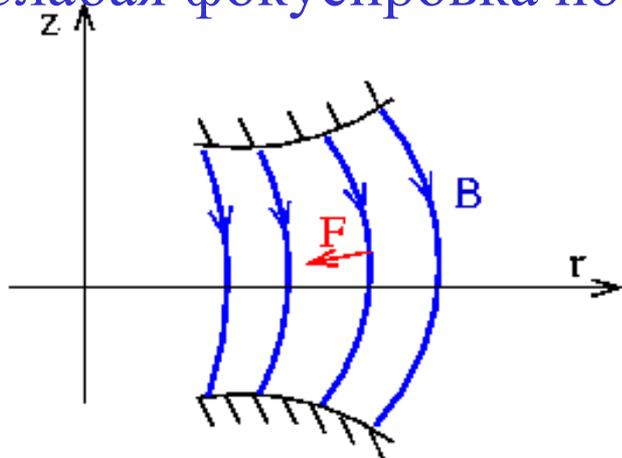
Устойчиво при  $\partial T/\partial E > 0$ , (см. рис)

Устойчиво при  $\partial T/\partial E < 0$ , на левом склоне

Возникают «синхротонные» колебания продольной координаты частицы в пучке и ее энергии относительно равновесной энергии.

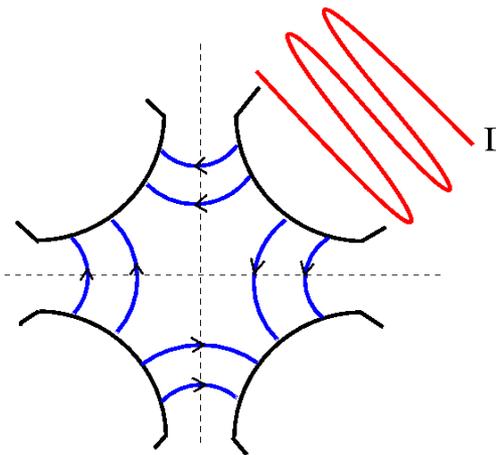
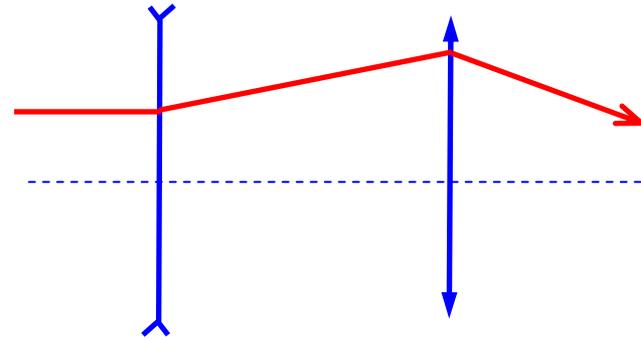
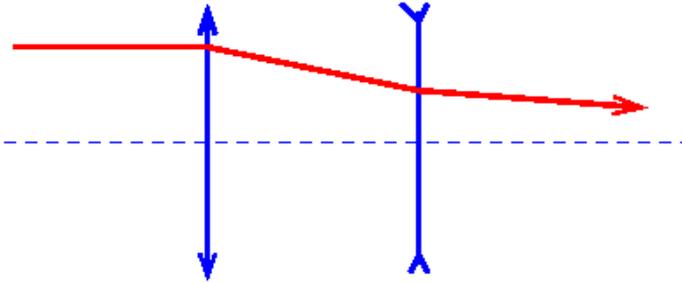
## Поперечная фокусировка

Слабая фокусировка поворотными магнитами



# Сильная фокусировка

Кроме поворотных магнитов в кольце есть специальные квадрупольные линзы, которые по одной координате фокусируют, по другой – дефокусируют. Результат совместного действия (при определенном расстоянии между линзами) – сильная фокусировка.



Слабая: Дубна, 10 ГэВ, 1957 год, вес 36000 тонн!

Сильная: Брукхейвен, 33 ГэВ, 1958, вес 3000 тонн  
(если бы была слабая, то 1 млн.тонн).

**Квадрупольная линза.**

$$B_y = -cx, \quad F_x \sim x$$

$$B_x = -cy, \quad F_y \sim -y$$

# Коллайдеры

$E_1, N_1$

$E_2, N_2$

$$W^2 = 4E_1E_2$$



$N$  соб/сек  $= L\sigma$

$$L = \frac{N_1 N_2}{4\pi\sigma_x \sigma_y} f$$

$\sigma$  – сечение реакции,  $\sigma_x, \sigma_y$  – поперечные размеры пучков.

**Фазовый объем (эмиттанс) пучка**

$\varepsilon_x = \sigma_x \theta_x =$  поперечный размер \* на угловой.

При ускорении от  $E_1$  до  $E_2$   $\varepsilon_2 = \varepsilon_1 E_1 / E_2$ .

В месте встречи

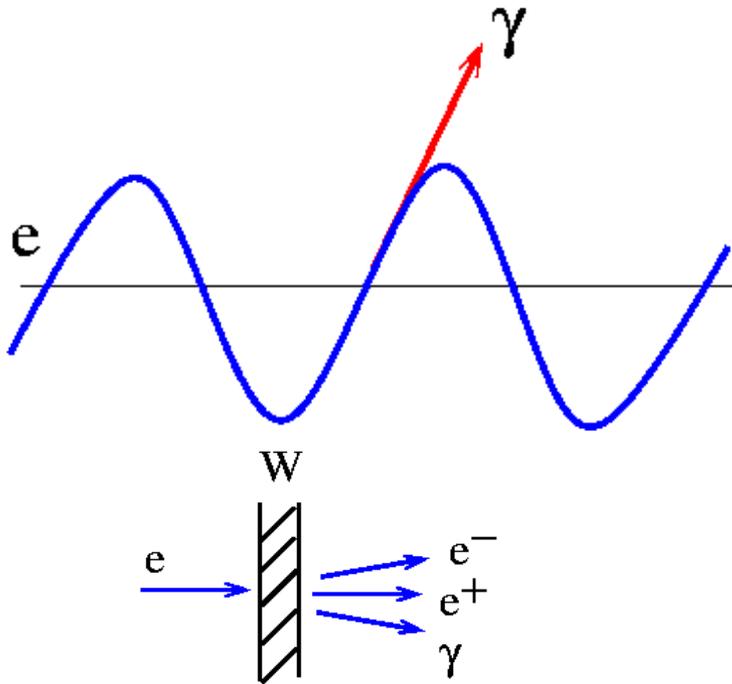
$$\sigma_x = \sigma_{x,o} \sqrt{1 + \frac{z^2}{\beta^2}}; \quad \sigma_{x,o} = \sqrt{\varepsilon\beta}$$

Здесь  $\beta$ - (бэта-функция фок. системы)  $\sim \sigma_z$  (длина пучка).

Для получения высокой светимости нужны пучки с малыми размерами, для этого необходимо получать пучки с малыми эмиттансами

# Охлаждение пучков

## Радиационное затухание на $e^+e^-$ накопителях.



При излучении теряется как поперечный, так и продольный импульсы. Продольный импульс компенсируется СВЧ (ускоряющим резонатором).

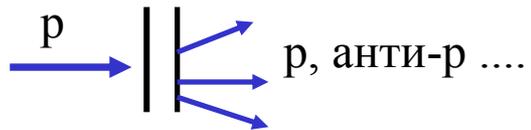
Равновесный размер: за счет флуктуаций числа испущенных фотонов.

## Получение позитронов

тормозное излучение  
рождение пар

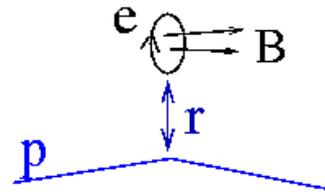
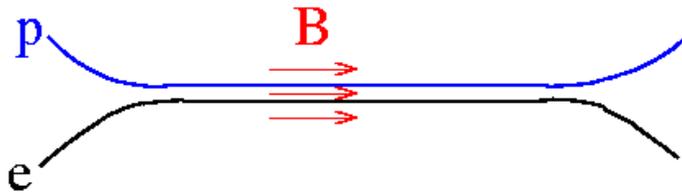
# Получение и охлаждение протонов и антипротонов

Получение анти-протонов



$$p + p = p + p + p + \bar{p}$$

Электронное охлаждение протонов (Г.Будкер, 1966)



Протоны охлаждаются до температуры электронов.

Продольное магнитное поле дает эффект «замагничивания», поскольку Ларморовский радиус электрона меньше характерных прицельных параметров и протон чувствует среднюю координату электрона.

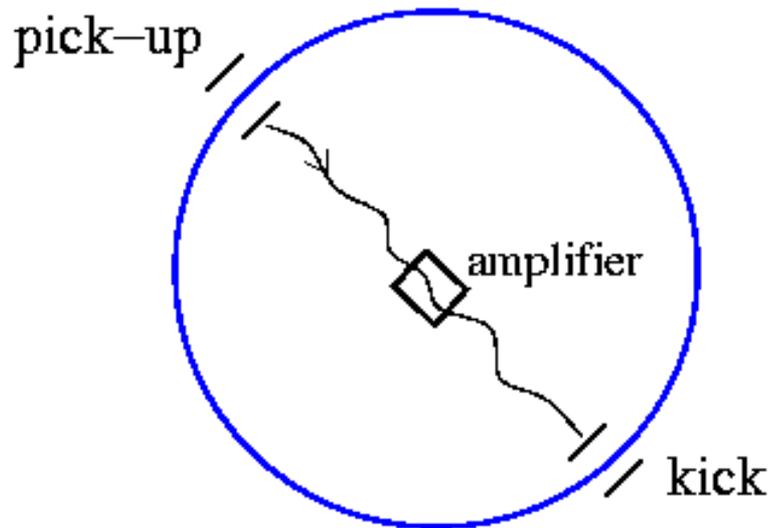
Это существенно понижает эффективную температуру электронов.

Время охлаждения уменьшается с 1 сек до  $10^{-3}$  сек,  $T_p \sim 1$  К!

# Стохастическое охлаждение протонов.

- Метод Ван-Дер-Мейера

Измеряется положение центра тяжести пучка и по хорде посылается сигнал, чтобы ударить по пучку в нужную сторону. Процесс занимает много часов.



Реализован на p-анти-p коллайдере SPS (CERN), где в 1980 г. открыли W и Z-бозоны (Нобелевская премия)

# Пути к высоким энергиям

Ways to high energies:

## 1. Proton colliders.

Now: TEVATRON (FNAL, US),  $2E = 2$  TeV.

Future: LHC(CERN),  $\sim 2007$ ,  $2E = 14$  TeV.

Far future: VLHC,  $2E \sim 100$  TeV

## 2. $e^+e^-$ colliders

### • Storage rings

the last (due to synch. rad.) LEP(CERN),  
 $2E = 200$  GeV,  $2\pi R = 27$  km, synch. rad  
 power about 20 MW, AC power  $\sim 100$  MW.

### • Linear Colliders

SLC(SLAC) (1989-1999),  $2E_0 = 90$  GeV.

The next generation of LC:

Collider	Leader	2E (TeV)	Zero Des.Rep.	Techn. Des.Rep.
VLEPP	BINP	0.5 -1	terminated	
NLC	SLAC	0.5-1	1996	
JLC	KEK	0.5-1	1997	
TESLA	DESY	0.5-0.8	1997	2001
CLIC	CERN	0.5-5	2007	
ILC	Japan	0.25-1	2007	2013

## 3. Muon colliders.

$\geq 2040$  ? (Snowmass 2001)

Why LC is necessary?

LHC(pp)  $2E = 14$  TeV 2007  
 LC( $e^+e^-$ )  $2E = 0.5-1$  TeV  $\sim 2012$

- 1.  $E_{eff}(pp) \sim \frac{1}{6} \times 2E_p$   $E_{eff}(e^+e^-) = 2E_e$   
 $p \equiv 3q + gluons$

— difference in energies is not big

- 2. Historically

$pp(p\bar{p})$  discovered  $c, b, t$  quarks,  $W, Z$  - bosons  
 $e^+e^-$  discovered  $c$ -quark,  $\tau$  lepton,  $g$  gluon.

With pp it is easier to reach higher energy

But, main results on  $c, b, W, Z, \tau$  have been obtained and the SM has been tested with a very high precision at  $e^+e^-$  collidres

Because in  $e^+e^-$  collisions

- a) simpler initial state
- b) much lower backgrounds (no strong interactions)
- c) much higher accuracy

LHC - search for signatures of new phenomena

LC - gives physics answer to the new phenomena

# Физическая программа

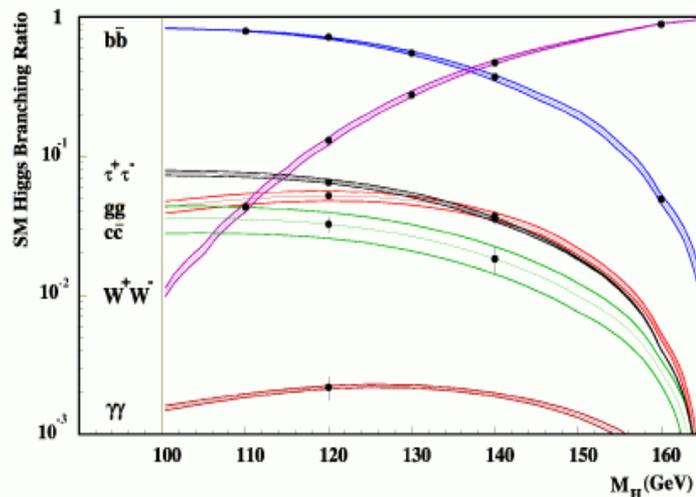
## Outline of LC physics program

Origin of mass, structure of vacuum

Higgs boson,  $M_H \sim 115 - 200$  GeV (LEP data)

$e^+e^- \rightarrow ZH$ ,  $e^+e^- \rightarrow H\nu\bar{\nu}$ ,  $\gamma\gamma \rightarrow H$

Measurement of H-branchings with a high accuracy to test  $\lambda_f \propto m_f$



На LHC в 7.2012 открыли хиггсовский бозон с массой 125 ГэВ!

## Supersymmetry (between fermions and bosons)

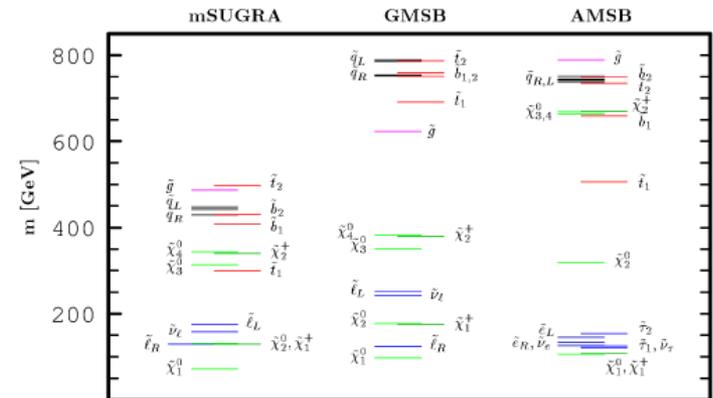
$e(1/2), \mu(1/2), \dots q(1/2), W(s=1)$

$\iff$   
 $\tilde{e}(0), \tilde{\mu}(0), \dots \tilde{q}(1/2), \tilde{W}(1/2)$

Supersymmetry is needed to cancel divergences in theories.

Supersymmetric particles are primary candidates for dark matter in Universe ( $\rho_{dark} \sim 2\rho_{barionic}$ )

Expected mass spectrum of SUSY particles in TeV region

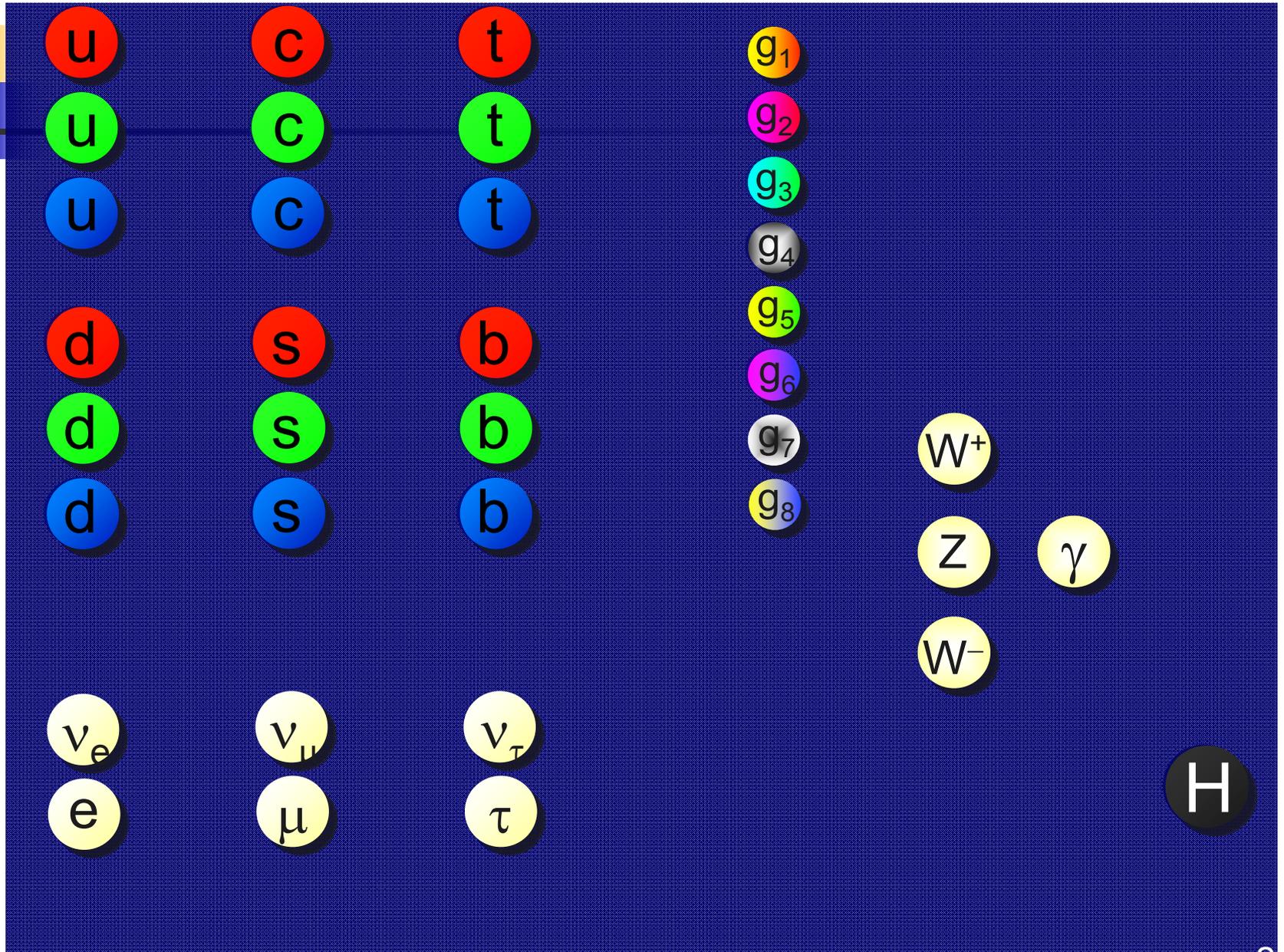


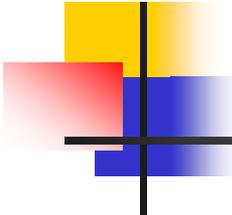
All these particles can be detected and precisely studied at LC

Great physics !

На LHC этого пока не видят

# Стандартная модель





# Линейные коллайдеры

## Достоинства:

(почти) нет излучения при ускорении, энергия по сравнению с кольцевыми накопителями может быть во много раз больше (реально на порядок).

## Проблемы:

Требуется высокий темп ускорения;

Очень малые размеры пучков (0.1 мкм x 0.001 мкм);

Излучение при столкновении пучков.

Разрабатывались три проекта на энергию 500-1000 ГэВ:

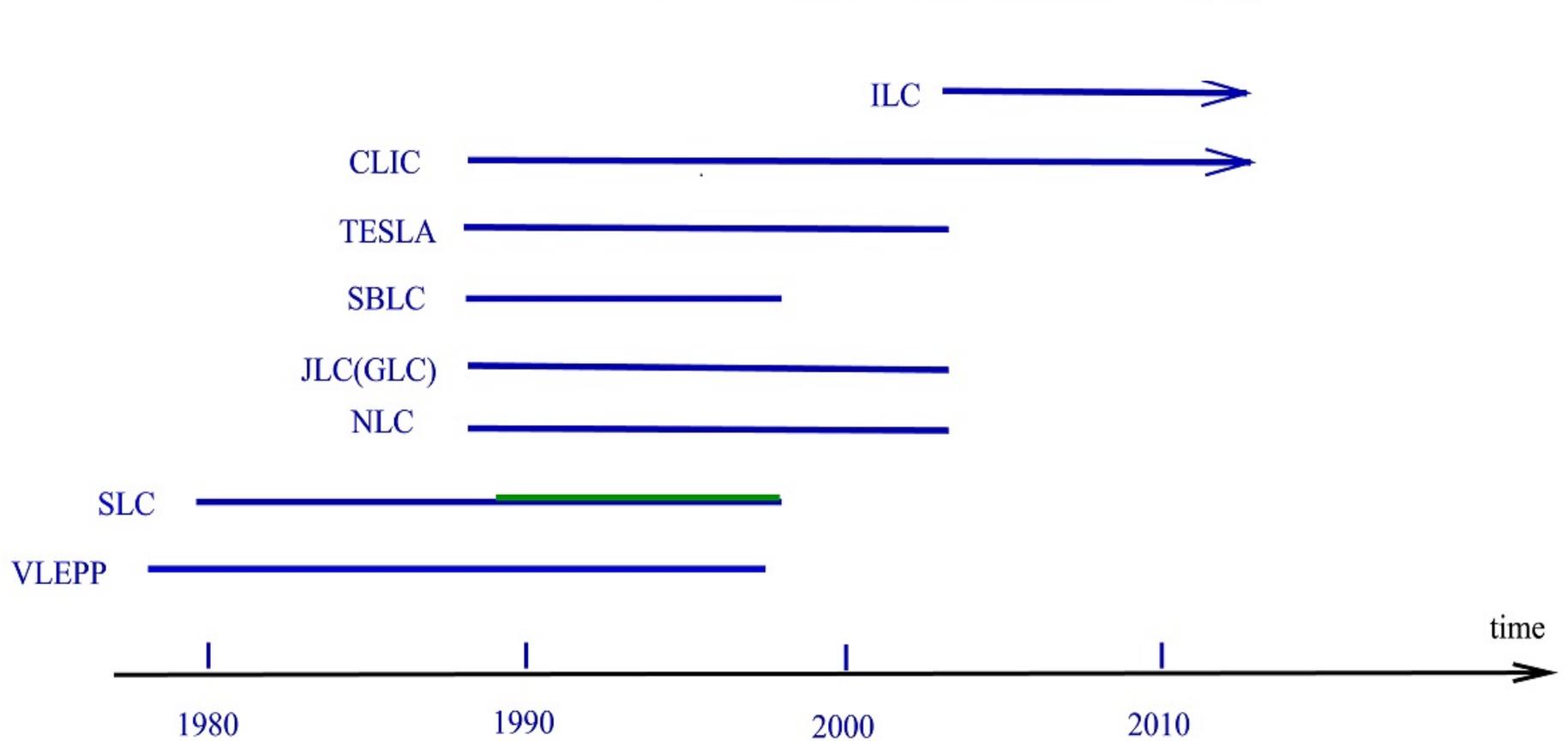
TESLA (Europe), JLC (Japan), NLC(USA)

В 9.2004 было решено строить один международный свехпроводящий коллайдер (как TESLA) на энергию  $2E=0.5-1$  ТэВ, ILC (International Linear Collider). Начало строительства ~201..? Все зависит от результатов с LHC (наличие новой физики). Следующий возможный проект на 3000 ГэВ: CLIC (CERN)

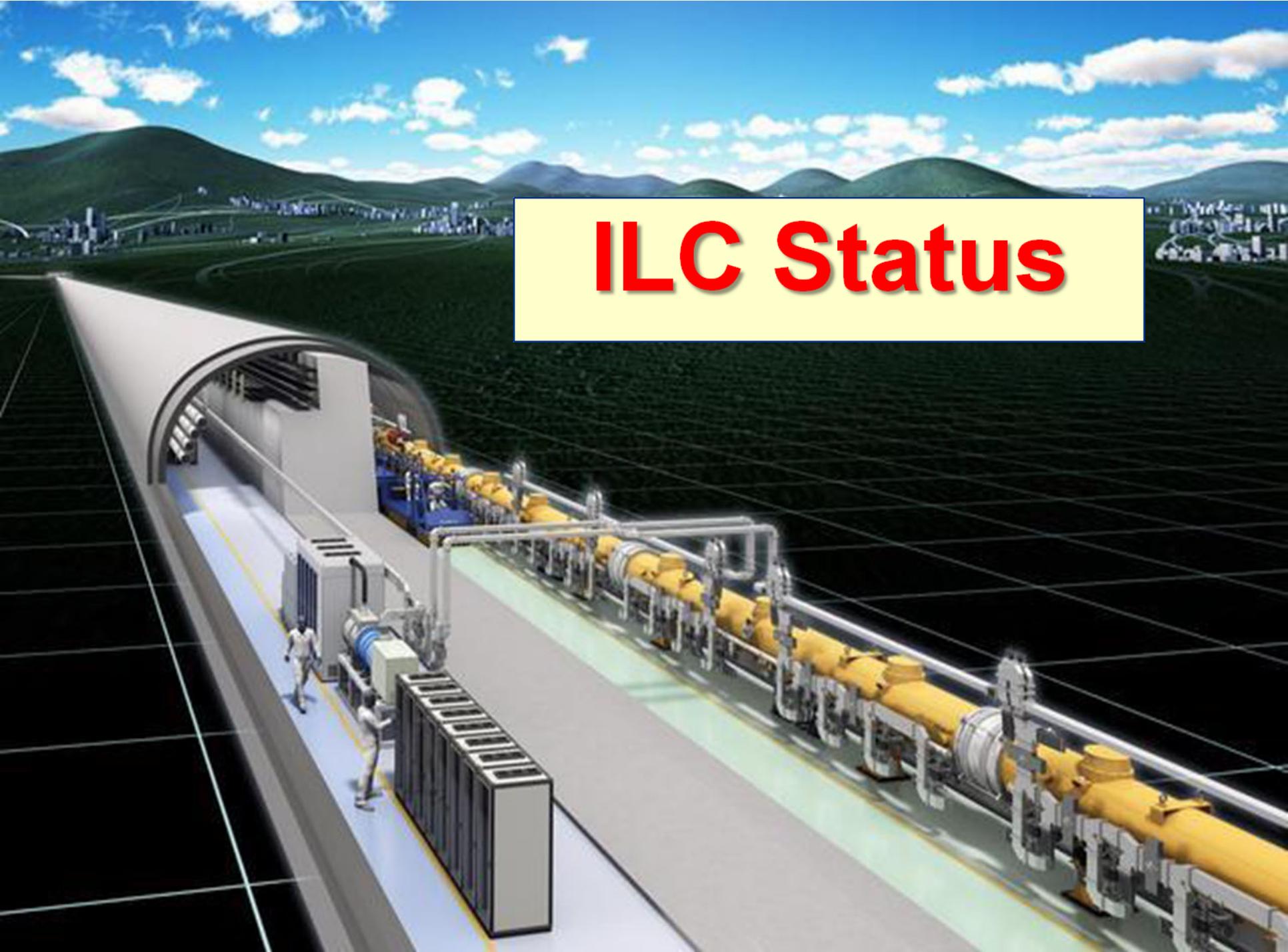


# Linear colliders

## History



# ILC Status



# ILC superconducting cavities, $\nu=1.3$ GHz

1 m

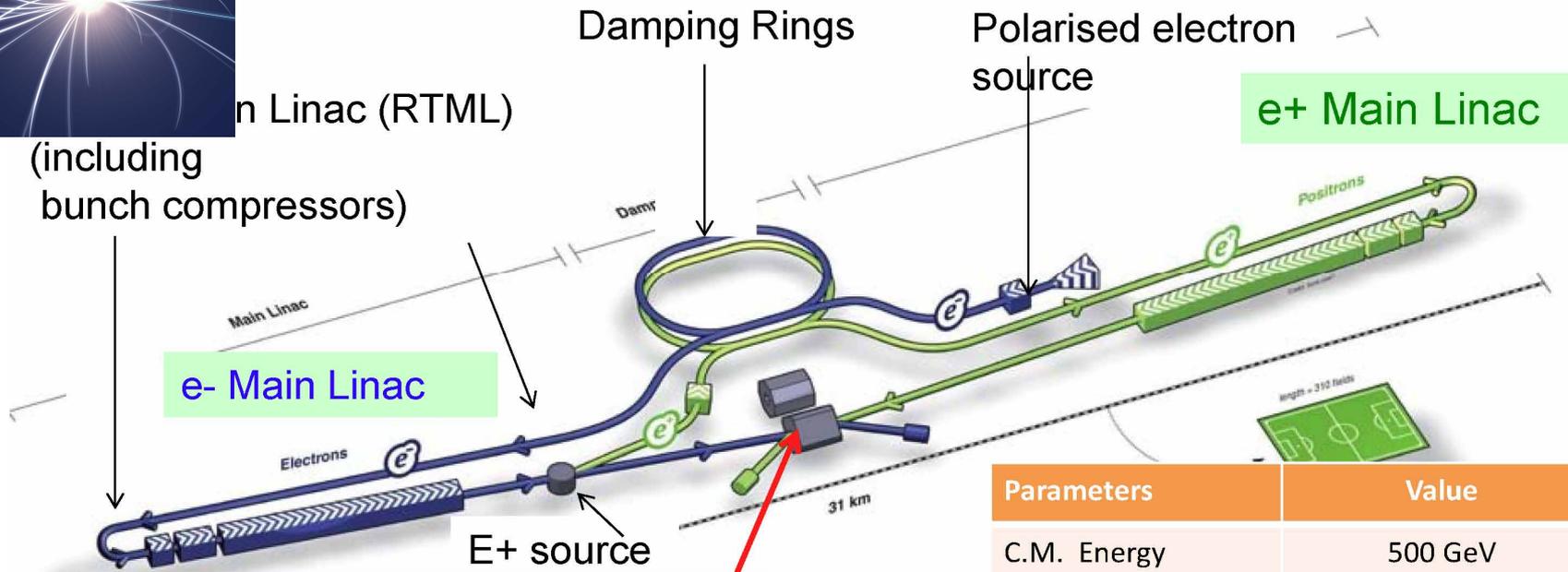


$Q > 10^{10}$  High Gradient (31.5 MV/m  $\rightarrow$  35 MV/m)



ILC TDR  
6.2013

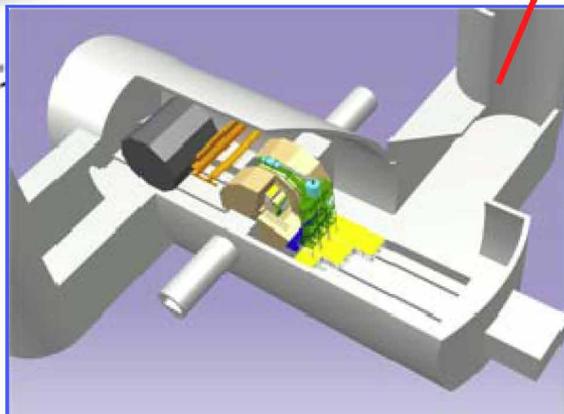
# ILC TDR Layout



e- Main Linac

e+ Main Linac

Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	$1.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% $Q_0 = 1E10$



L=31 km  
2E=500 GeV

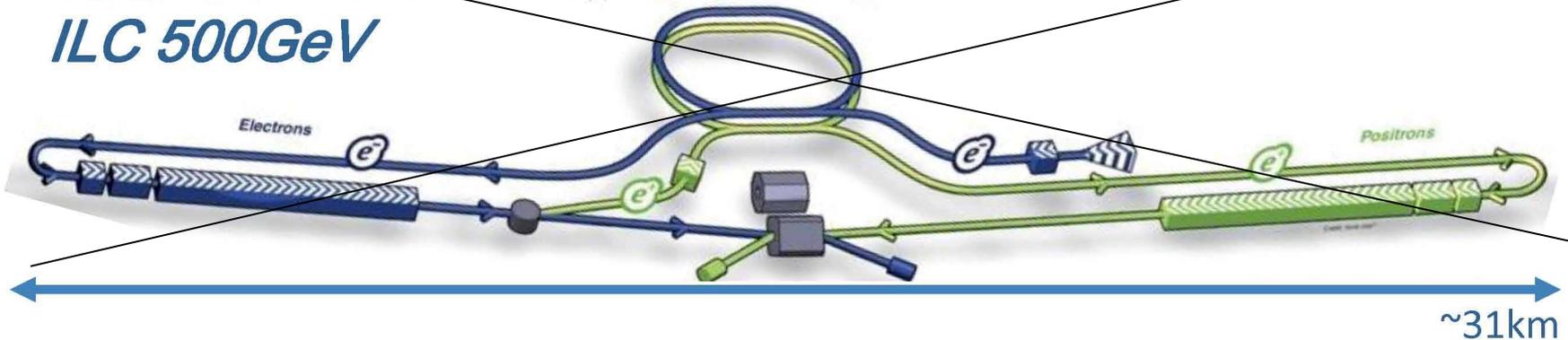
2E=250-500 GeV, upgradable to 1000 GeV

# ILC, since LCWS 2017

At present Japan consider ILC with  $2E=250$  GeV, without any words about possible upgrade (but possible). Thus the cost was reduced by 40% compared to 500 GeV.

## Staging

*ILC 500GeV*



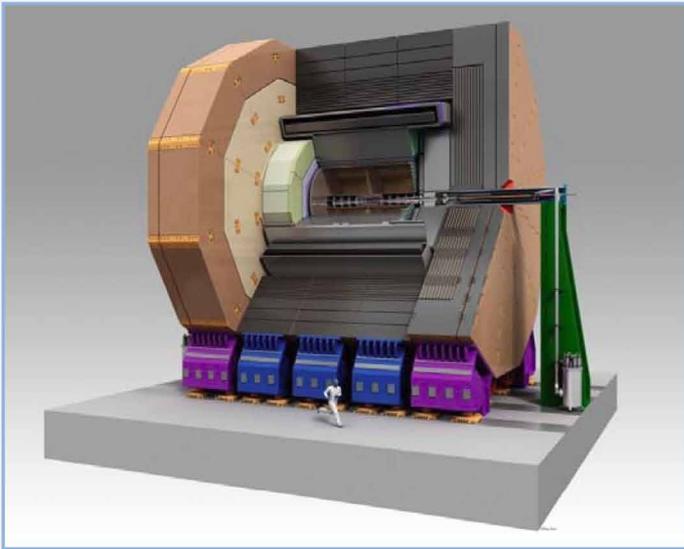
*ILC 250GeV*



This energy is OK for  $e^+e^- \rightarrow ZH$  (no  $tt$ ) and for  $\gamma\gamma \rightarrow H$  as well

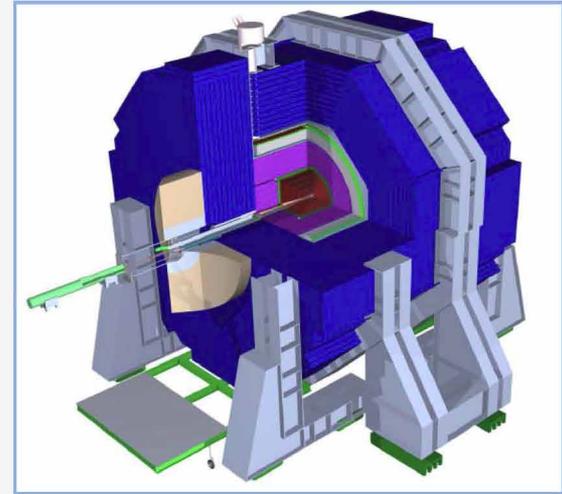
## 2 Detector Concepts: **Detailed Baseline Design**

ILD



- **Large R** with TPC tracker
  - 32 countries,
  - 151 institutions,
  - ~700 members
- **B=3.5T**, TPC + Si trackers
- ECal: **R=1.8m**

SiD

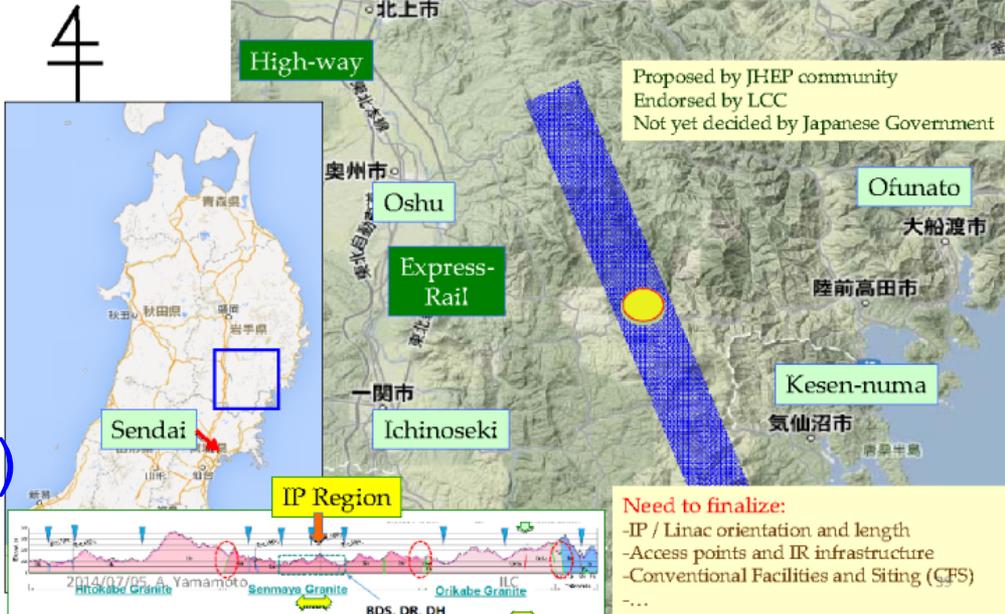


- **High B** with Si strip tracker
  - 18 countries,
  - 77 institutions,
  - ~240 members
- **B=5T**, Si only tracker
- ECal: **R=1.27m**

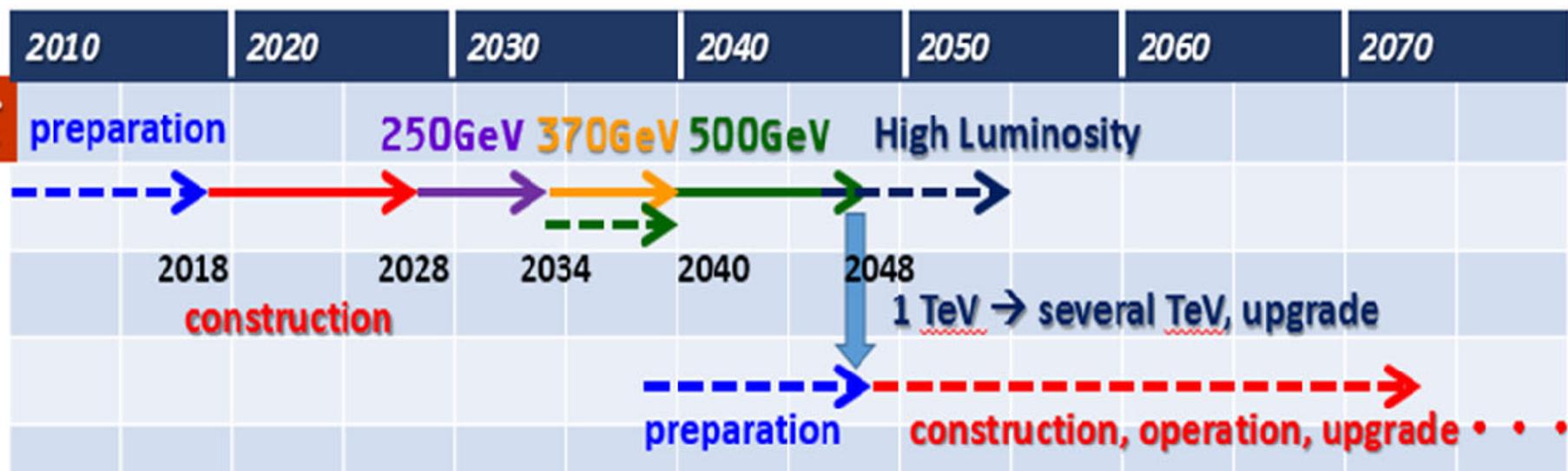


# ILC Site Candidate Location in Japan: Kitakami Area

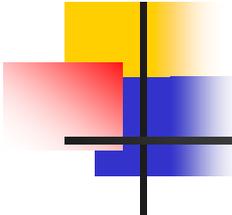
Establish a site-specific Civil Engineering Design - map the (site independent) TDR baseline onto the preferred site - assuming "Kitakami" as a primary candidate



- Japan is interested to host
- decision ~2018-????
- construction ~2019 (~10 years)
- physics ~2030



2.2022 – решение о строительстве не принято (японское правительство ...)

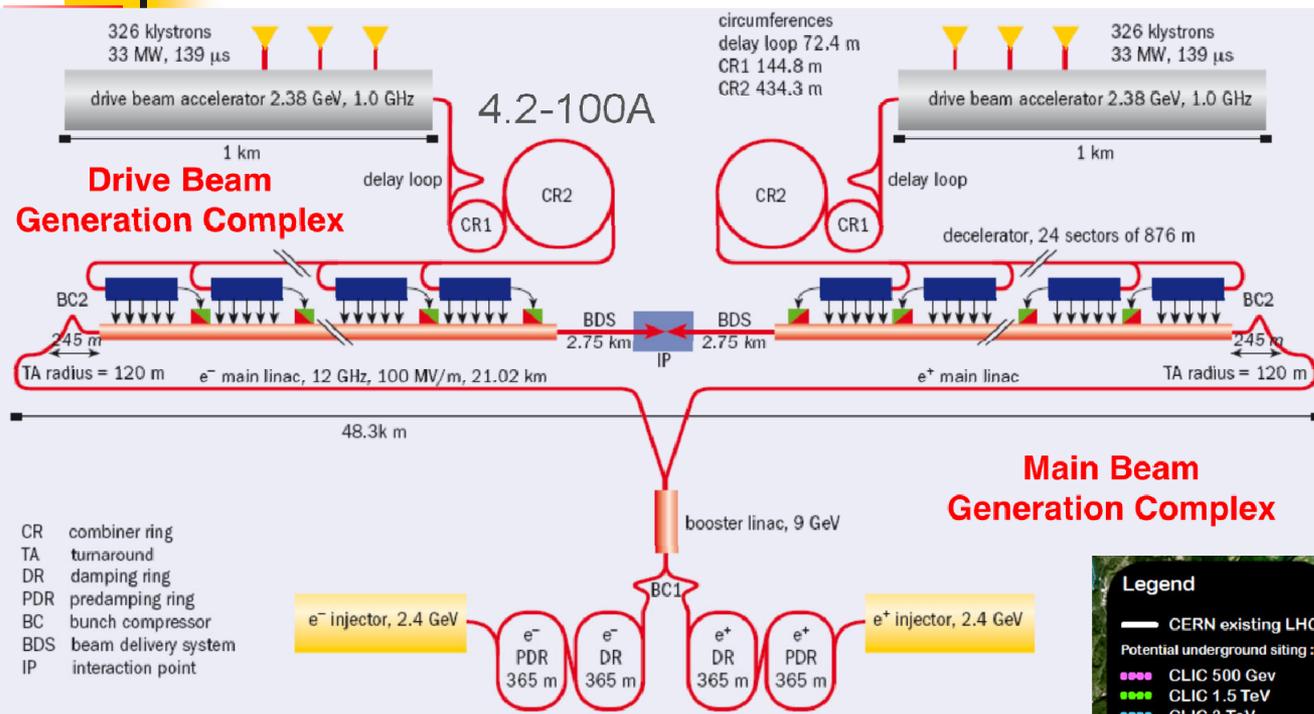


# Known physics, ILC stages

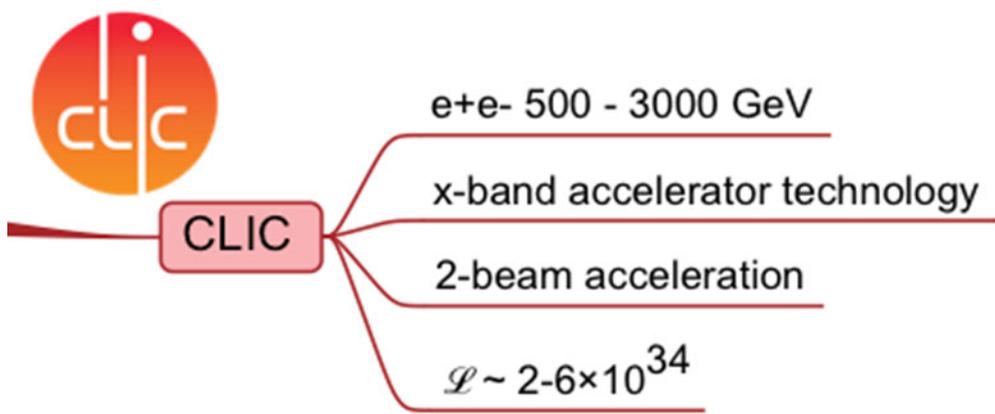
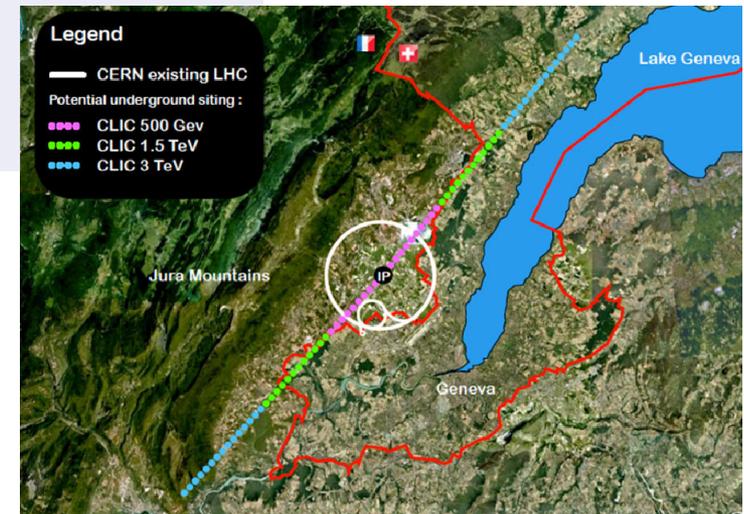
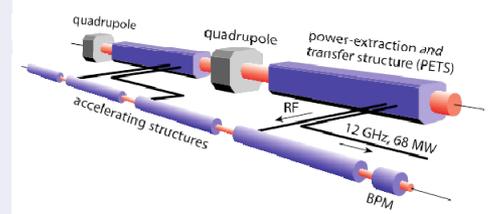
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- $2E=250$  GeV      Higgs boson
- 350              top quark
- 500              ZHH –Higgs self coupling
- 500 and higher    ttH - top Yukawa coupling
- 1000 and higher    Beyond

# Compact Linear Collider (CLIC)



$G_a \sim 100$  MV/m



0.5 TeV: 8,300 MCHF ( $\mathcal{L} \sim 1.4 \times 10^{34}$ )



# CLIC accelerating structure



Outside

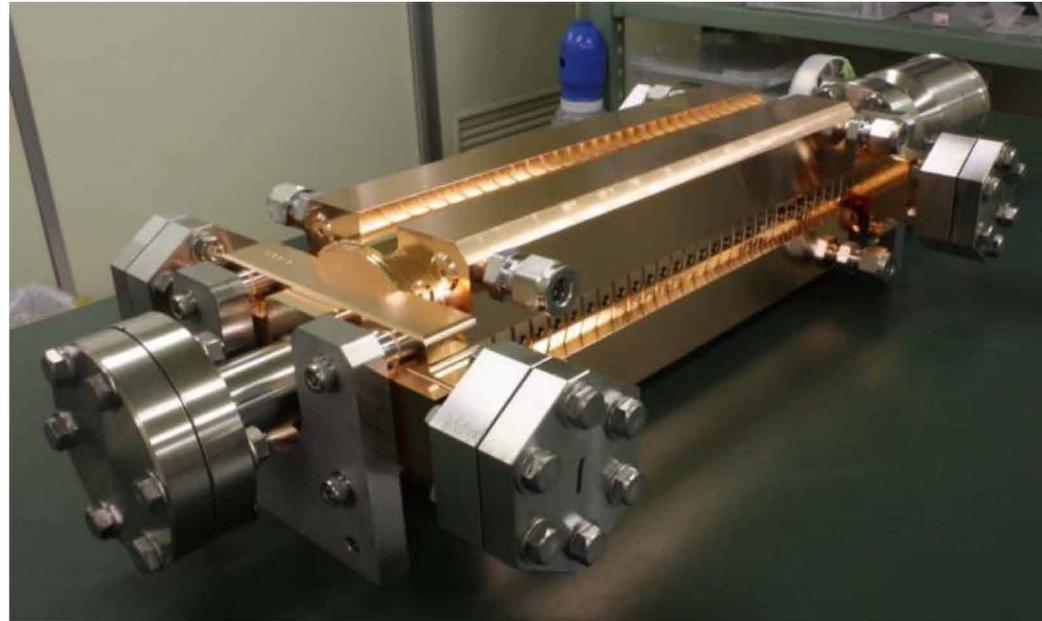
11.994 GHz X-band

100 MV/m

Input power  $\approx 50$  MW

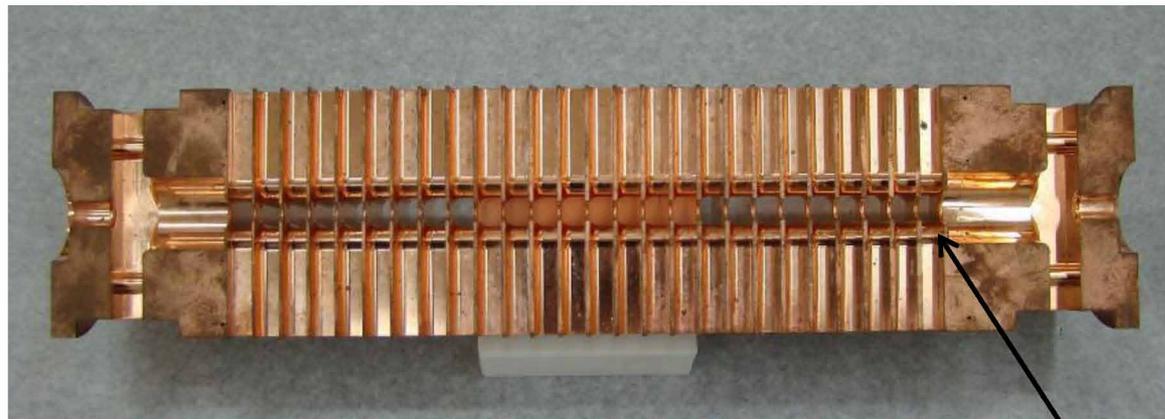
Pulse length  $\approx 200$  ns

Repetition rate 50 Hz



HOM damping waveguide

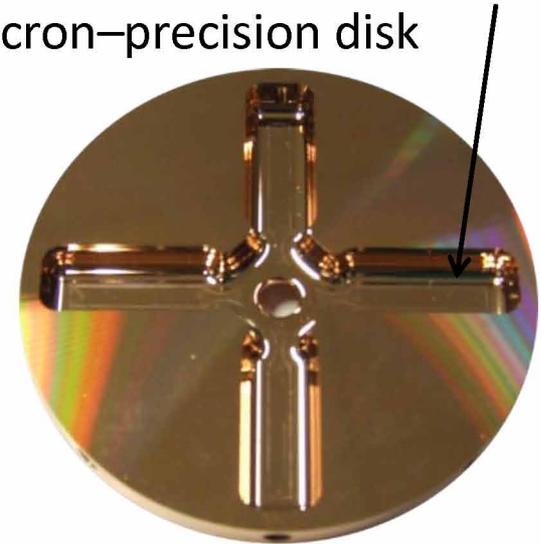
Inside



25 cm

CLIC Project Review, 1 March 2016

Micron-precision disk

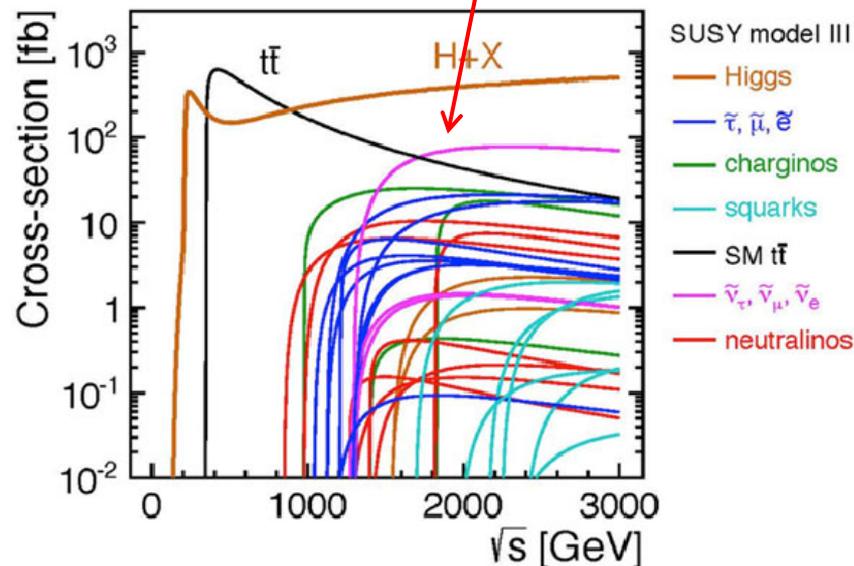
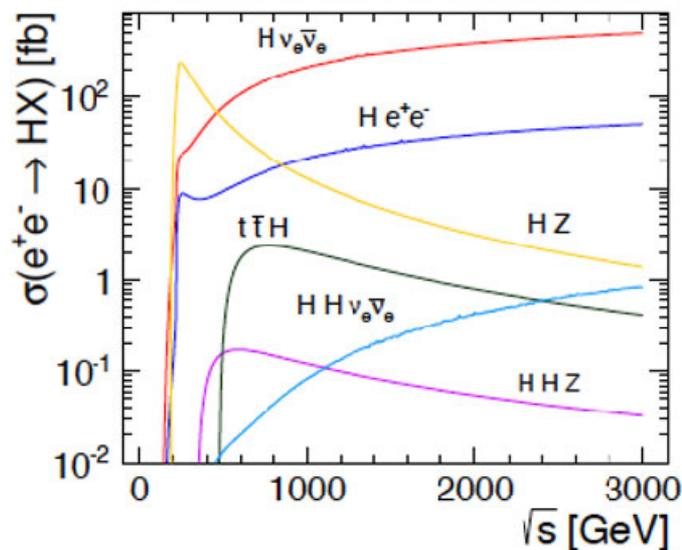


6 mm diameter beam aperture

Walter Wuensch, CERN

# CLIC projects

As usually, rich new physics is expected



The feasibility of the CLIC scheme has been established.

CLIC proposes a staged approach to reach 3 TeV:

Stages with 500fb<sup>-1</sup> at <500 GeV, 1500fb<sup>-1</sup> at 1-2 TeV, 2000 fb<sup>-1</sup> at 3 TeV;

L = 2.3 × 10<sup>34</sup> cm<sup>-2</sup> s<sup>-1</sup> at 500 GeV

Decision: 2018-2019 ??????

Preparation stage: ~5 years

Construction could start in 2024-25; commissioning in ~2033.

2.2022 – решения о строительстве пока нет

# ILC and CLIC parameters

upgrade to  $(3-4)10^{34}$   
is foreseen

	unit	ILC			CLIC		
$2E_0$	GeV	250	500	1000	250	500	3000
$L_{\text{tot}}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	0.75	1.8	4.9	1.37	2.3	5.9
$L_{\text{geom}}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	0.37	0.75	2.61	0.82	1.42	4.29
No. Higgs/yr( $10^7$ s)	1000	23	49	–	34	44	446
Length	km	21	31	48	13.2	13.2	48.3
$P$ (wall)	MW	128	162	301	225	272	589
Pol. $e^-$ /Pol. $e^+$	%	80/30	80/30	80/30	80/0	80/0	80/0
Accel. gradient	MV/m	31.5	31.5	31.5/45	40	80	100
$N$ per bunch	$10^{10}$	2	2	1.74	0.34	0.68	0.372
Bunches per pulse		1312	1312	2450	842	354	312
Bunch distance	ns	554	554	366	0.5	0.5	0.5
Rep. rate	Hz	5	5	4	50	50	50
Norm. emit. $\epsilon_{x,n}$	mm-mrad	10	10	10	0.66	2.4	0.66
Norm. emit. $\epsilon_{y,n}$	mm-mrad	0.035	0.035	0.03	0.025	0.025	0.02
$\beta_x$ at IP	mm	13	11	11	8	8	4
$\beta_y$ at IP	mm	0.41	0.48	0.23	0.1	0.1	0.07
$\sigma_x$ at IP	nm	729	474	335	150	200	40
$\sigma_y$ at IP	nm	7.66	5.9	2.7	3.2	2.3	1
$\sigma_z$ at IP	mm	0.3	0.3	0.225	0.072	0.072	0.044
Ener. loss. $\delta E/E$	%	0.95	4.5	10.5	1.5	7	28

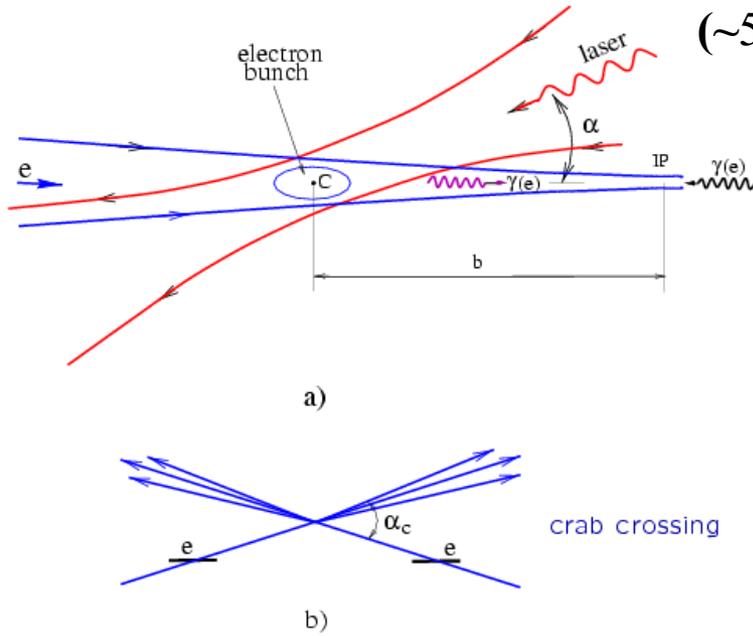
# Фотонный коллайдер

Scheme of  $\gamma\gamma$ ,  $\gamma e$  collider

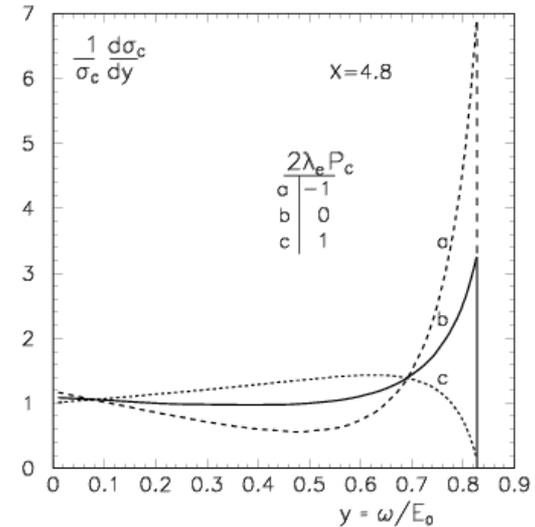
(Т.В.И., 1981)

Electron to Photon  
Conversion

( $\sim 5\text{J}$ ,  $\tau=1\text{ ps}$ ,  $\lambda=1\mu\text{m}$ )



Spectrum of the Compton scattered photons



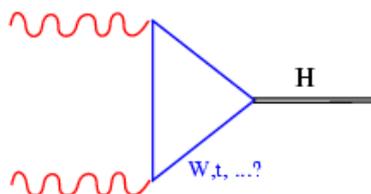
$$\omega_m = \frac{x}{x+1} E_0; \quad x \approx \frac{4E_0\omega_0}{m^2c^4} \approx 15.3 \left[ \frac{E_0}{\text{TeV}} \right] \left[ \frac{\omega_0}{\text{eV}} \right]$$

$E_0 = 250\text{ GeV}$ ,  $\omega_0 = 1.17\text{ eV}$  ( $\lambda = 1.06\ \mu\text{m}$ )  $\Rightarrow x = 4.5$  and  $\omega_m = 0.82E_0 = 205\text{ GeV}$

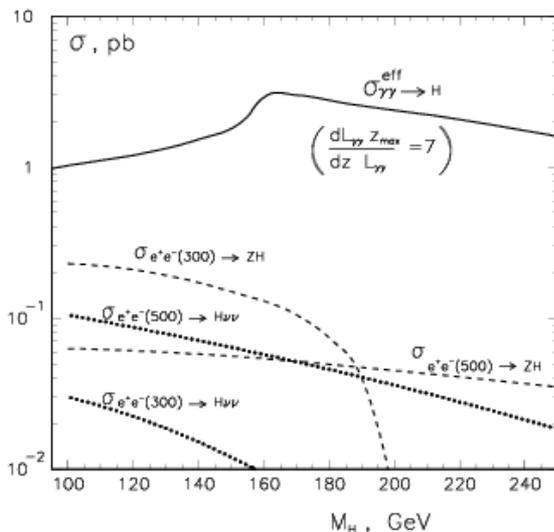
$\lambda_e$  – electron longitudinal polarization  
 $P_c$  – helicity of laser photons

# Физическая программа фотонных коллайдеров

## Higgs boson



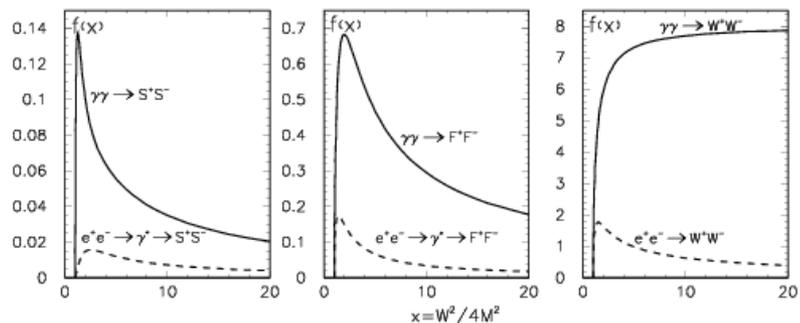
Cross sections of the Higgs boson production in  $\gamma\gamma$  and  $e^+e^-$  collisions



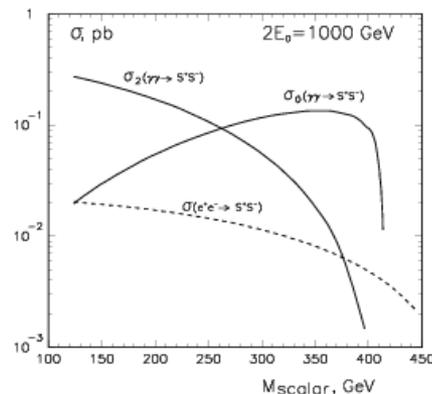
$$\dot{N}_{\gamma\gamma \rightarrow h} = L_{\gamma\gamma} \times \frac{dL_{\gamma\gamma} M_h}{dW_{\gamma\gamma} L_{\gamma\gamma}} \frac{4\pi^2 \Gamma_{\gamma\gamma} (1 + \lambda_1 \lambda_2)}{M_h^3} \equiv L_{\gamma\gamma} \times \sigma^{eff}$$

## Charged pair production in $e^+e^-$ and $\gamma\gamma$ collisions.

(S (scalars), F (fermions), W (W-bosons));  
 $\sigma = (\pi\alpha^2/M^2)f(x)$ , beams unpolarized)



## Cross sections for charged scalars, $2E_0 = 1$ TeV

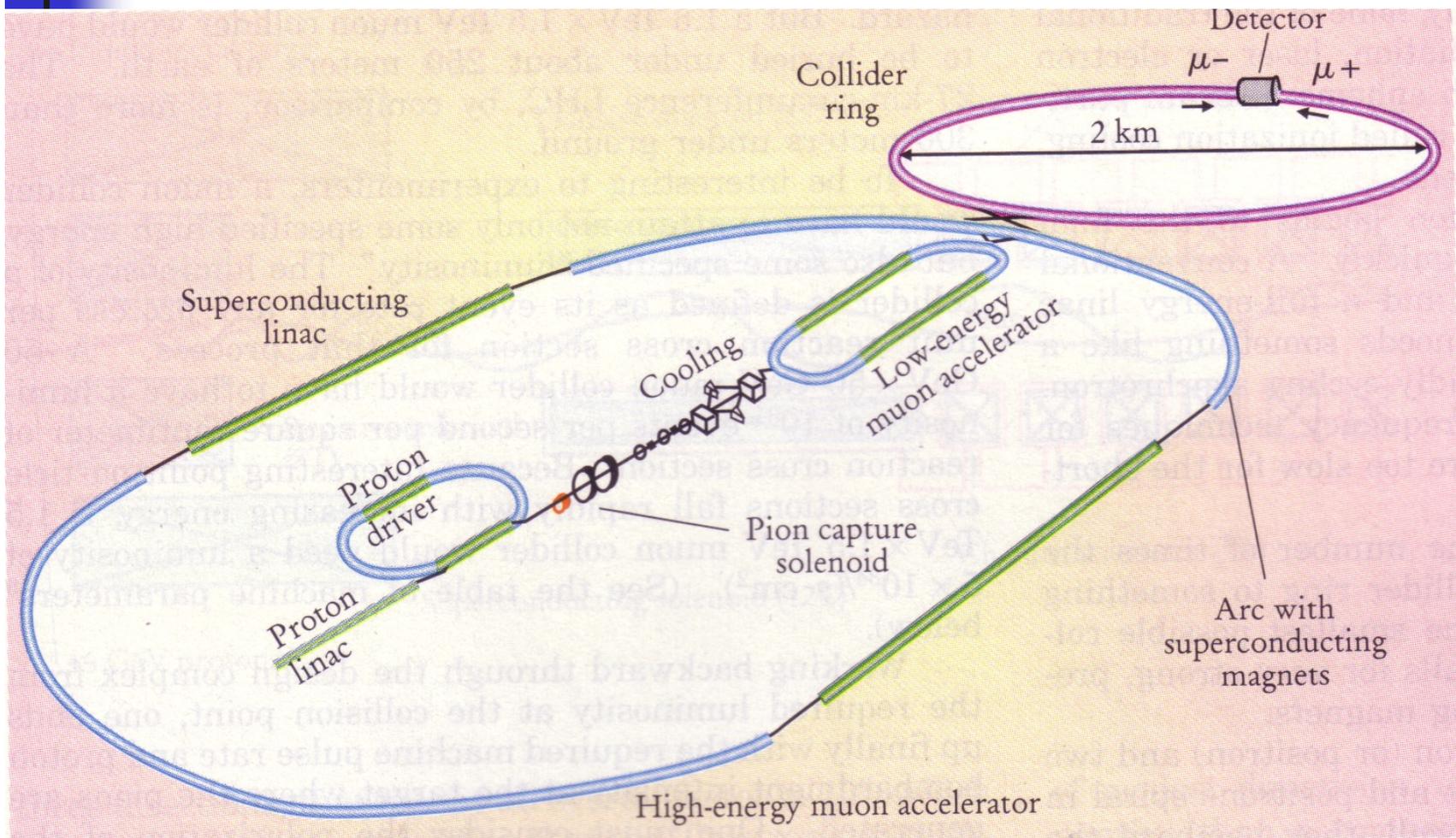


# Физ.программа $\gamma\gamma$ , $\gamma e$ коллайдеров

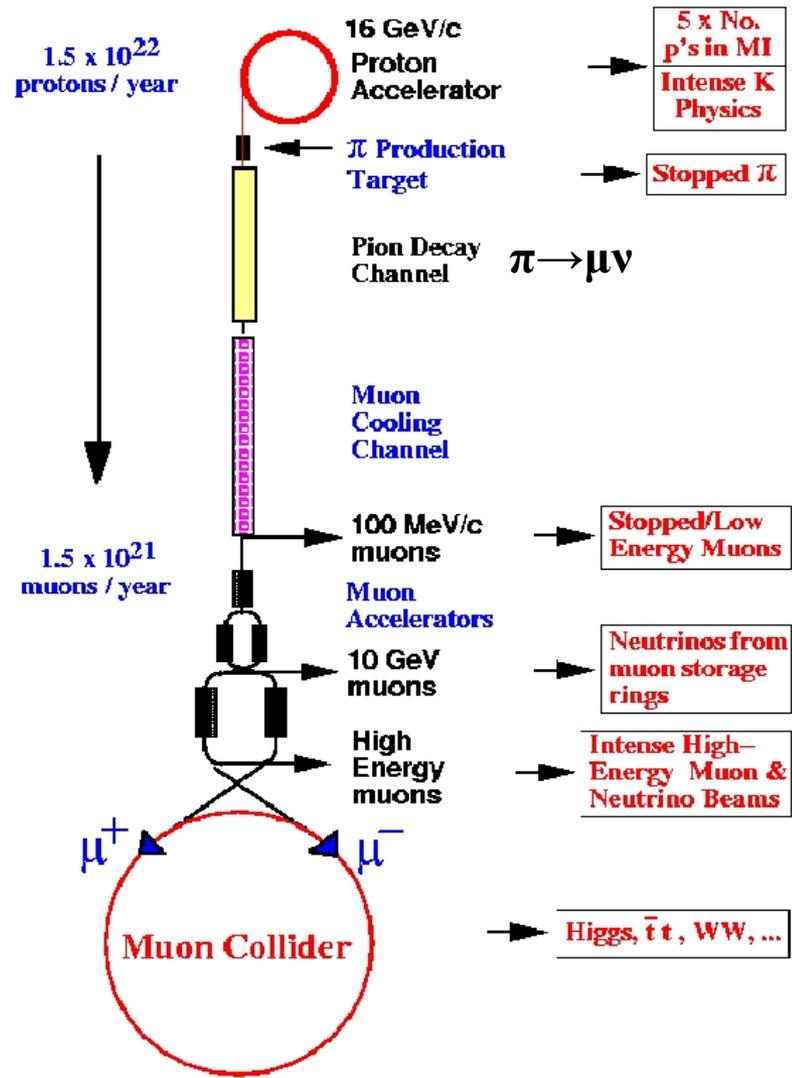
## Gold-plated processes at photon colliders

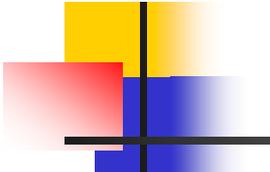
Reaction	Remarks
$\gamma\gamma \rightarrow h_0 \rightarrow \bar{b}b$	<i>SM</i> (or <i>MSSM</i> ) Higgs, $M_{h_0} < 160\text{GeV}$
$\gamma\gamma \rightarrow h_0 \rightarrow WW(WW^*)$	<i>SM</i> Higgs, $140\text{GeV} < M_{h_0} < 190\text{GeV}$
$\gamma\gamma \rightarrow h_0 \rightarrow ZZ(ZZ^*)$	<i>SM</i> Higgs, $180\text{GeV} < M_{h_0} < 350\text{GeV}$
$\gamma\gamma \rightarrow H, A \rightarrow \bar{b}b$	<i>MSSM</i> heavy Higgs, for intermediate $\tan\beta$
$\gamma\gamma \rightarrow \bar{f}f, \bar{\chi}_i^+ \chi_i^-, H^+ H^-$	large cross sections, possible observ. of FCNC
$\gamma\gamma \rightarrow S[\bar{t}t]$	$\bar{t}t$ stoponium
$\gamma e \rightarrow \bar{e}^- \bar{\chi}_1^0$	$M_{\bar{e}^-} < 0.9 \times 2E_0 - M_{\bar{\chi}_1^0}$
$\gamma\gamma \rightarrow W^+ W^-$	anomalous <i>W</i> interact., extra dimen.
$\gamma e^- \rightarrow W^- \nu_e$	anomalous <i>W</i> couplings
$\gamma\gamma \rightarrow WW + WW(ZZ)$	strong <i>WW</i> scatt., quartic anom. <i>W</i> , <i>Z</i> coupl.
$\gamma\gamma \rightarrow \bar{t}t$	anomalous top quark interactions
$\gamma e^- \rightarrow \bar{t}b \nu_e$	anomalous <i>Wtb</i> coupling
$\gamma\gamma \rightarrow \text{hadrons}$	total $\gamma\gamma$ cross section
$\gamma e^- \rightarrow e^- X$ and $\nu_e X$	structure functions (pol. and unpol.)
$\gamma g \rightarrow \bar{q}q, \bar{c}c$	gluon distribution in the photon
$\gamma\gamma \rightarrow J/\psi J/\psi$	QCD Pomeron

# Мюонный коллайдер



# Мюонный коллайдер(прод.)





# Мюонные коллайдеры, программа, проблемы

Мюоны в 200 раз тяжелее электронов, поэтому мало излучают при столкновении пучков. Они нестабильны, но, если их быстро охладить и разогнать, то за время жизни (увеличенной в гамма раз) они успеют столкнуться в кольцевом накопителе около 1000 раз.

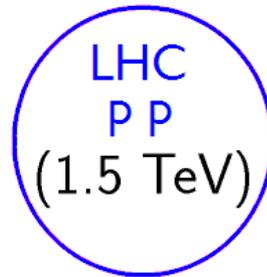
Хигсовский бозон будет рождаться как очень узкий резонанс (на  $e^+e^-$  сечение резонансного рождения в 40000 раз меньше, за счет константы связи  $\sim m^2$ ).

Основная проблема – охлаждение мюонов. Можно охладить за счет ионизационных потерь (излучение и ядерное взаимодействие малы и не мешают).

Мюонные коллайдеры появятся не скоро (хотя работа ведется активно), но есть промежуточная физическая программа: изучение распада мюона с нарушением лептонного числа; нейтринные пучки очень высокой интенсивности.

# Сравнение размеров коллайдеров

Мюонный коллайдер имеет меньший размер (при тех же энергиях)



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ILC  $e^+e^-$  (.5 TeV)

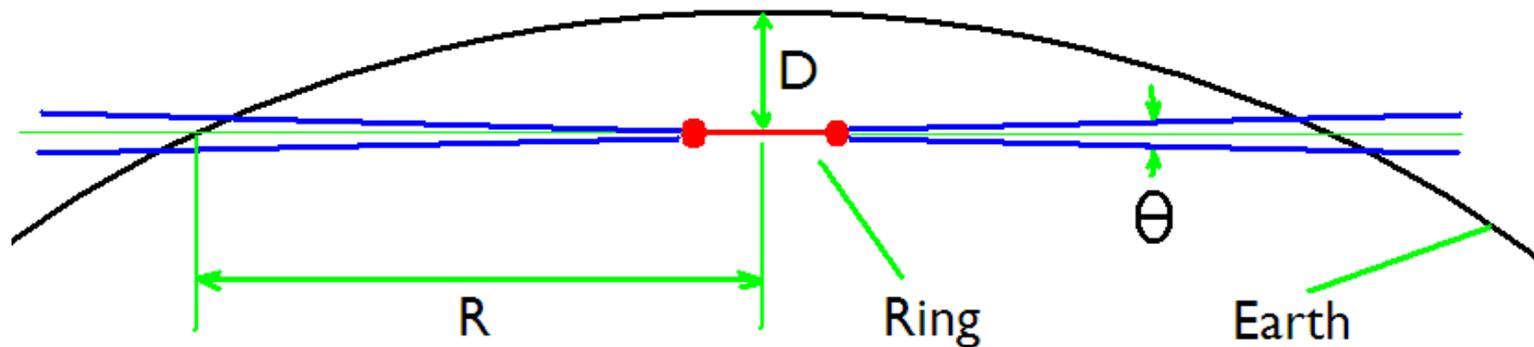
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CLIC  $e^+e^-$  (3TeV)



10 km

Одна из «забавных» проблем мюонного коллайдера – это фон, который создают нейтрино на поверхности Земли. Закапывание глубоко под землю не помогает.



# Higgs factory colliders

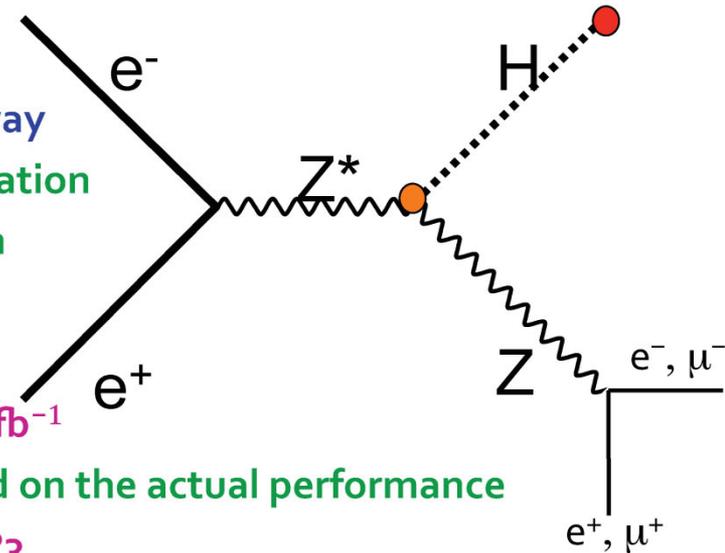
- Linear e+e- collider:
  - ILC
  - CLIC
  - X-band klystron based
- Circular e+e- collider:
  - LEP3
  - TLEP
  - SuperTRISTAN
  - Fermilab site-filler
  - China Higgs Factory (CHF)
  - SLAC/LBNL big ring
- Muon collider
  - Low luminosity
  - High luminosity
- $\gamma\gamma$  collider:
  - ILC-based
  - CLIC-based
  - Recircul. linac-based SAPPHiRE + HERA, Tevatron rings
  - SLC-type

# e+e-: Higgs measurement at 2E<sub>0</sub>=240 GeV

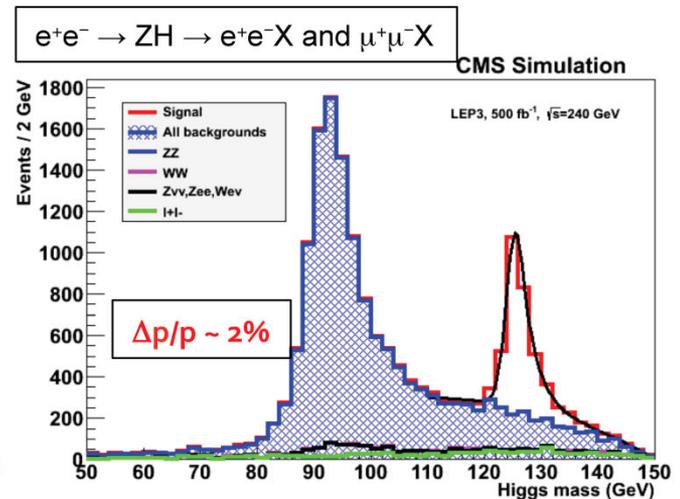
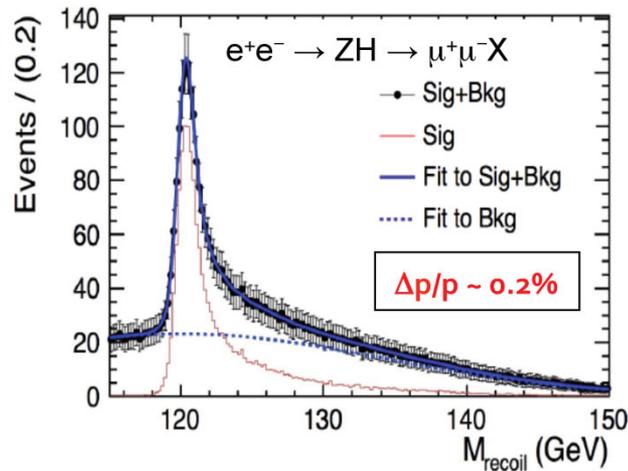
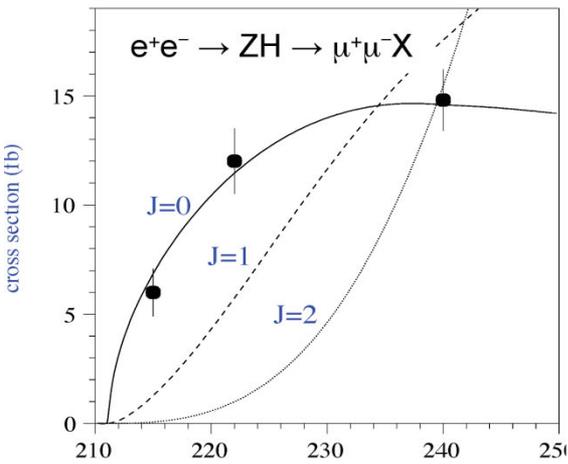
□ With e<sup>+</sup>e<sup>-</sup> → ZH → e<sup>+</sup>e<sup>-</sup>X and μ<sup>+</sup>μ<sup>-</sup>X events

◆ Measure HZ cross section in a model independent way

- Find m<sub>H</sub> peak from the leptons and E,p conservation
- Determine spin with three-point threshold scan
  - 10 fb<sup>-1</sup> / point suffice
- Determine σ<sub>HZ</sub> and g<sub>HZZ</sub> coupling at 240 GeV
  - 3% (1.5%) precision on σ<sub>HZ</sub> (g<sub>HZZ</sub>) with 250 fb<sup>-1</sup>
- Good tracker needed, but details mildly depend on the actual performance
  - Plots below with ILDC@ILC and CMS@LEP3



[9,10,11]



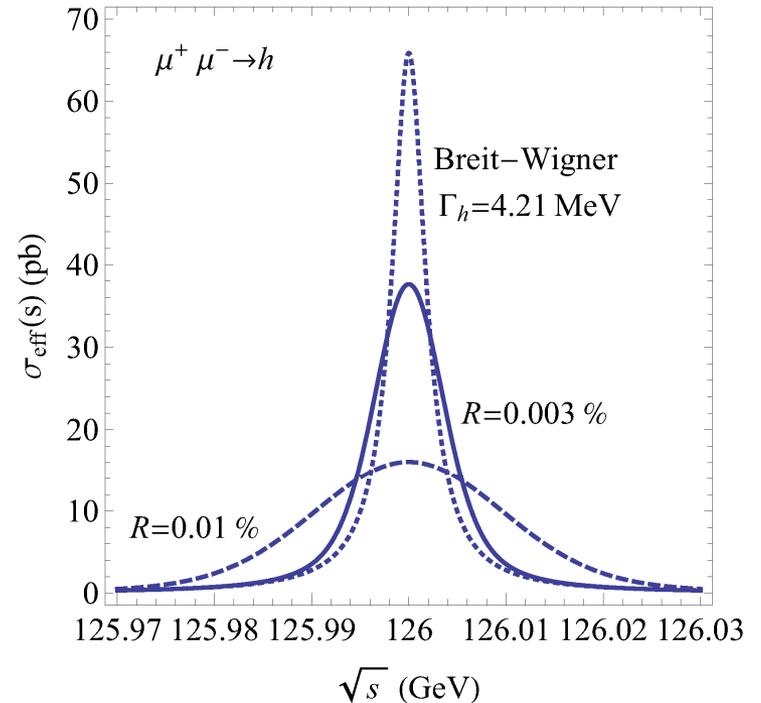
# Higgs physics at muon collider

Resonance H production:

$$\sigma(\mu^+\mu^-\rightarrow H)\approx 40000 \quad \sigma(e^+e^-\rightarrow H)\approx 70 \text{ pb}$$

- The Higgs width is about 4 MeV, the muon collider with  $\delta E/E=0.003\%$  can measure the **Higgs width directly** with an accuracy 5% (comparable that in  $e+e^-$ ).
- The **Higgs mass** can be measured with an accuracy 0.1 MeV, 100 times better than in  $e+e^-$ .
- Coupling  $H\rightarrow\mu^+\mu^+$  can be measured with 1.5% accuracy.

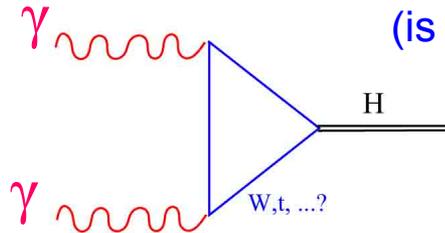
The number of Higgs boson is about 2500/year at expected  $L\sim 10^{31}$  (small L due to transverse-longitudinal emittance exchange for obtaining a high monochromaticity).



# Higgs at photon colliders

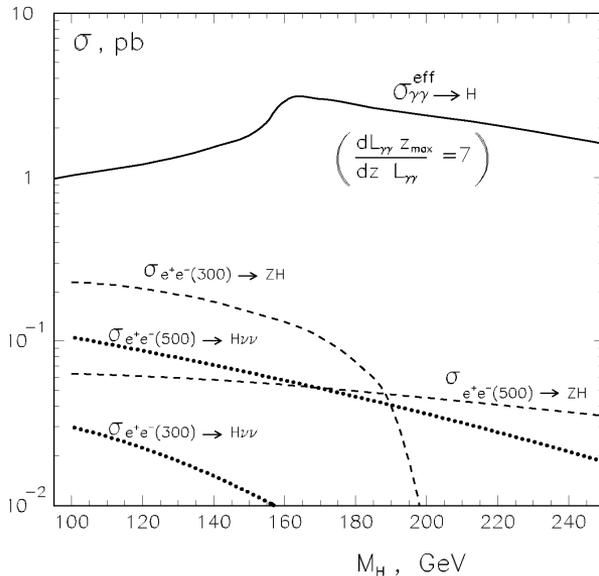
## Higgs boson

(is considered for PLC since 1980<sup>th</sup>)



Very sensitive to heavy charge particles in the loop.

Cross sections of the Higgs boson in  $\gamma\gamma$  and  $e^+e^-$  collisions



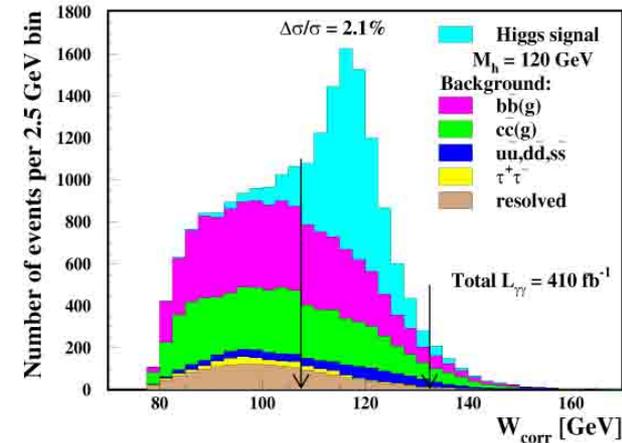
T.V.I., 1999

$$\dot{N}_{\gamma\gamma \rightarrow H} = L_{\gamma\gamma} \times \frac{dL_{\gamma\gamma} M_H}{dW_{\gamma\gamma} L_{\gamma\gamma}} \frac{4\pi^2 \Gamma_{\gamma\gamma} (1 + \lambda_1 \lambda_2)}{M_H^3}$$

At ILC

$$\frac{N(\gamma\gamma \rightarrow H)}{N(e^+e^- \rightarrow H + X)} \sim 1 - 10$$

For  $M_H = 115 - 250$  GeV



At nominal luminosities the number of Higgs in  $\gamma\gamma$  will be similar to that in  $e^+e^-$

# TLEP (Triple LEP) – e+e- кольцевой → FCC-ee

Beyond HE-LHC : new tunnels in Geneve area,  $2\pi R=100$  km

e+e- (2E=350-400 GeV), pp (2E=100 TeV)

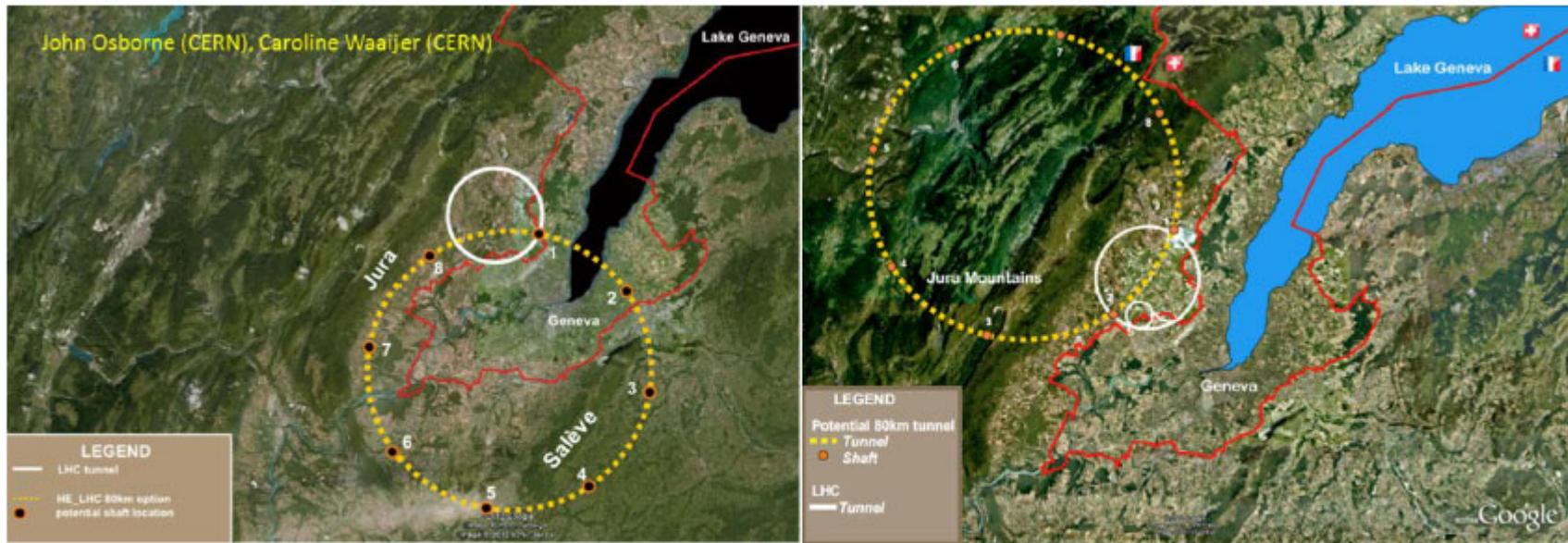
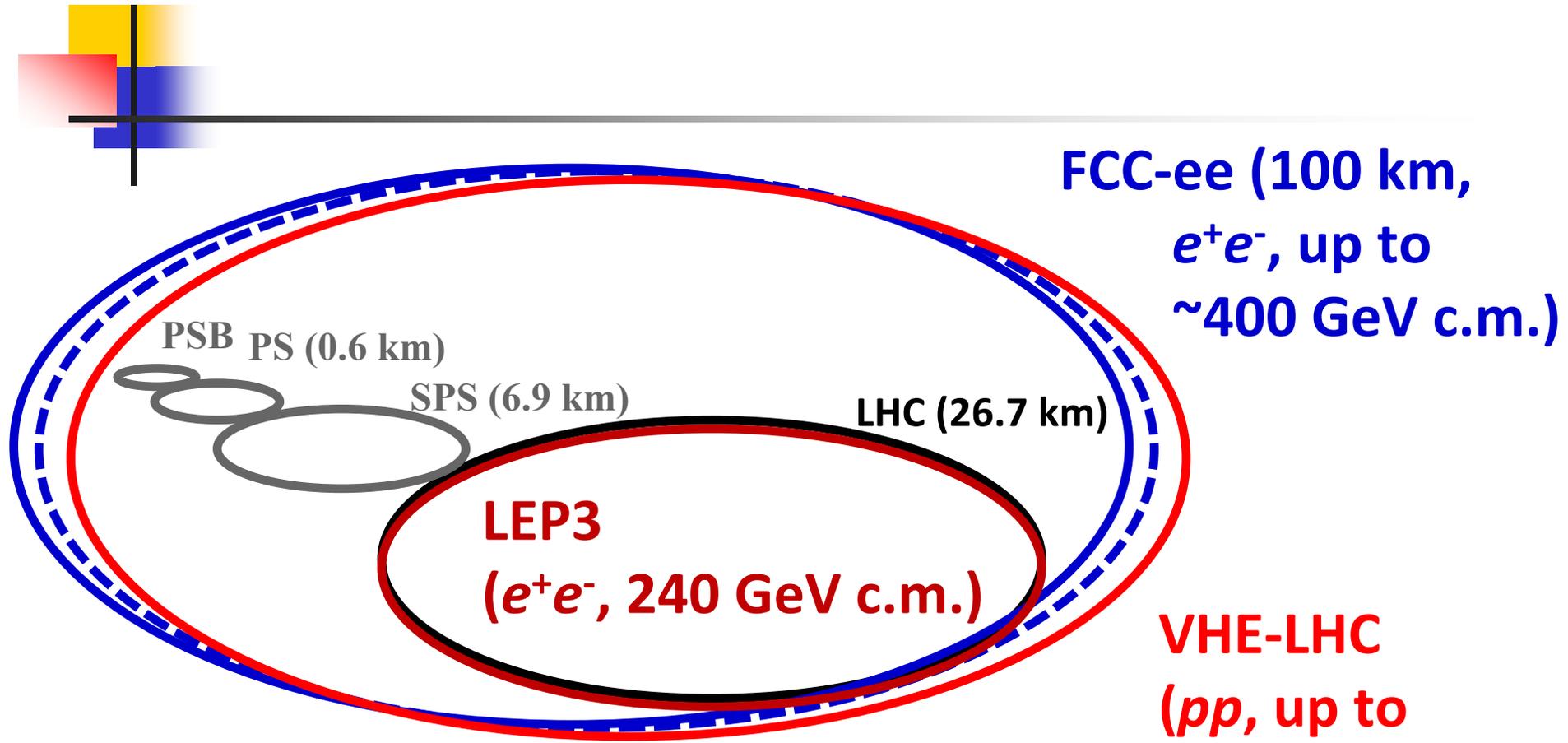


Figure 9. Two possible location, upon geological study, of the 80 km ring for a Super HE-LHC (option at left is strongly preferred)

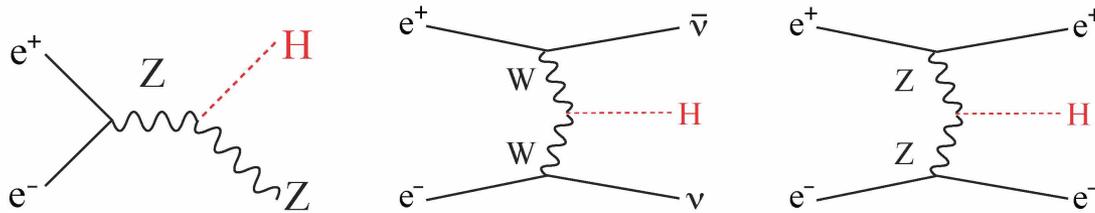
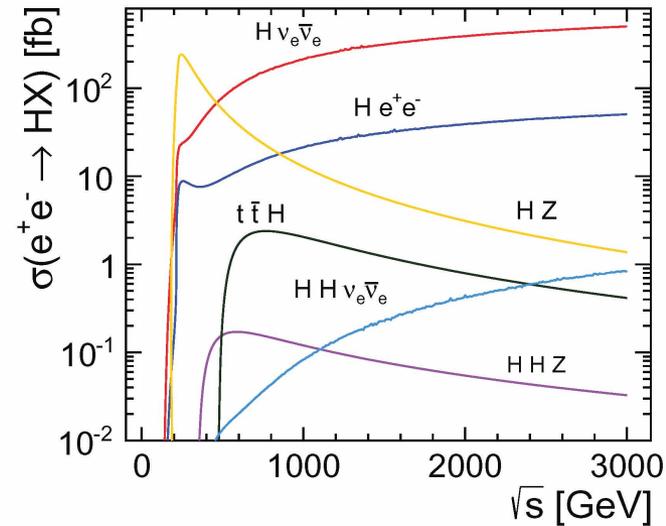
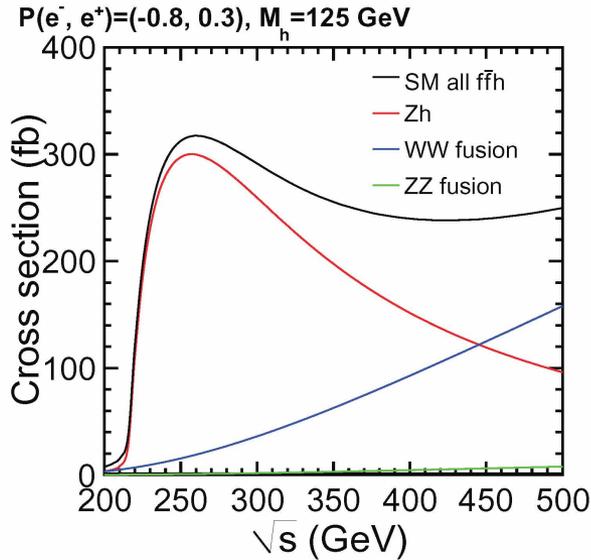
# Circular Higgs factories at CERN & beyond



also:  $e^\pm$  (200 GeV) –  $p$  (7 & 50 TeV) collisions

*a long-term strategy for HEP!*

# Higgs physics in e+e- collisions



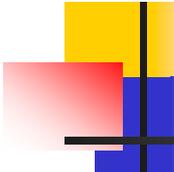
Tagging Z in  $e^+e^- \rightarrow ZH$  one can measure all  $\text{Br}(H)$ , even invisible decays width.

One can measure the Higgs total width:

$$\Gamma(H) \sim \sigma(e^+e^- \rightarrow ZH) / \text{Br}(H \rightarrow ZZ) \quad \text{and} \quad \Gamma(H) \sim \sigma(WW \rightarrow H) / \text{Br}(H \rightarrow WW)$$

At linear colliders  $L \sim 10^{34}$ ,  $N_H \sim 20000/\text{year}$  or  $10^5$  for life of the experiment;

At circular collider with  $C \sim 100 \text{ km}$  and several IP one can have  $N_H \sim 10^6$ .



# Circular Higgs $e+e-$ -factories

## Beginning:

1. A.Blondel and F.Zimmermann, A High Luminosity  $e+e-$  Collider in the LHC tunnel to study the Higgs Boson, arXiv:1112.2518 (Dec. 2011)
2. K.Oide, Super-Tristan, talk at KEK, Feb.2012 (crab-waist scheme)
3. V.Telnov, Restriction on the energy and luminosity of  $e+e-$  storage rings due to beamstrahlung, arXiv:1203.6563 (March 2012), PRL 110,114801 (2013).
4. A. Blondel...V.Telnov..., LEP3: A High Luminosity  $e+e-$  Collider to study the Higgs Boson, arXiv:1208.0504 (Aug.2012) (Triple-LEP (TLEP) with  $C=80$  km is discussed)

HF2012-First Higgs factory workshop (November, 2012, FNAL) – already 7-8 proposals of Circular  $e+e-$  Higgs factories around the world on the energy  $2E=230(H)-370(tt)$  GeV.



**Many  $e^+e^-$  circular Higgs factories are being studied around the world**

# Circular $e^+e^-$ Collider as a Higgs Factory

- 16 km (Fermilab site-filler) USA
- 21 km (Protvino) Russia (free tunnel)
- 27 km (LEP3)
- 40 km (SuperTRISTAN-40)- Japan
- 50 km (CHF-1)- China
- 70 km (CHF-2)- China
- 80 km (TLEP, SuperTRISTAN-80)- Swiss, Japan
- 233 km (VLLC)- USA

At present: two projects are very seriously considered

FCC-ee, FCC-hh (CERN)  $C=100\text{km}$ ,  $2E_{e^+e^-}=90\text{-}400\text{ GeV}$ ,  $2E_{pp}=100\text{ TeV}$

CEPC, SppC (China)  $C\sim 54\rightarrow 100\text{km}$ ,  $2E_{e^+e^-}=240\text{ GeV}$ ,  $2E_{pp}=70\rightarrow 100\text{ TeV}$

FCC (ee, hh) – Future Circular Collider

CEPC – Circular Electron Positron Collider

SppC – Super proton proton Collider

# Main arguments for circular e<sup>+</sup>e<sup>-</sup> colliders

During last 25 years linear colliders were considered as best candidates for the next collider for precision study below 1-3 TeV, why ring e<sup>+</sup>e<sup>-</sup> colliders again?

## Advantages

- 1) No new physics is found up to now by LHC for exception of low mass Higgs boson. The energy  $2E=230$  GeV needed for study H in e<sup>+</sup>e<sup>-</sup> collision can be reached by circular e<sup>+</sup>e<sup>-</sup> colliders.
- 2) Ring colliders are easier and luminosity can be higher than at linear colliders at  $2E=230$  GeV (and much higher at Z), can provide higher accuracy needed for observation of new physics (in Higgs and Z decays). Top threshold  $2E=350$  GeV can be reached.
- 3) Ring tunnels (C~100 km) can be used further for highest energy pp (or muon) colliders. It is a very attractive long-term strategy.

**Disadvantage:** Presence of new physics in the region  $2E=350-3000$  is still not excluded, this region can be covered only by linear colliders

# Beam lifetime due to beamstrahlung

The electron loses the beam after emission of beamstrahlung photon with an energy greater than the threshold energy  $E_{\text{th}} = \eta E_0$ , where a *ring energy acceptance*  $\eta \sim 0.01-0.02$ .

The beam lifetime due to beamstrahlung (V. Telnov)

$$\tau \approx 6 \cdot \frac{2\pi R}{c} \frac{\sqrt{6\pi} r_e \gamma u^{3/2} e^{1.225u}}{\alpha^2 \eta \sigma_z}$$

$$u = \eta \frac{\alpha \sigma_x \sigma_z}{3\gamma r_e^2 N}, \quad \alpha = e^2 / \hbar c$$

The requirement of the lifetime 30 min imposes  
a new restriction on the beam parameters

$$\frac{N}{\sigma_x \sigma_z} < 0.1 \eta \frac{\alpha}{3\gamma r_e^2}$$

# FCC project (CERN)

FCC-hh hadron collider with  
100TeV proton cms energy

**~16 T  $\Rightarrow$  100 TeV  $pp$  in 100 km**

**~20 T  $\Rightarrow$  100 TeV  $pp$  in 80 km**

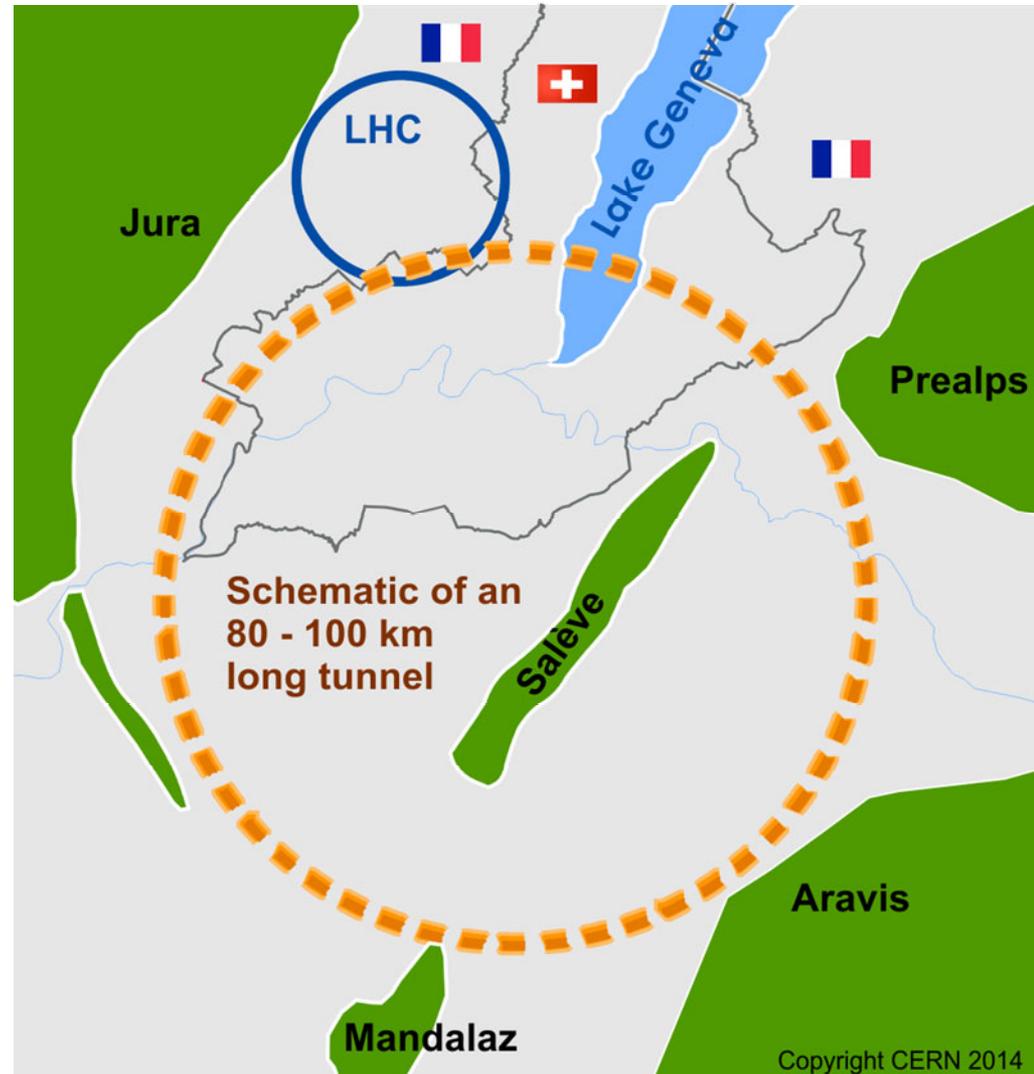
FCC-ee a lepton collider as a  
potential intermediate step

FCC-eh lepton hadron option

International collaboration

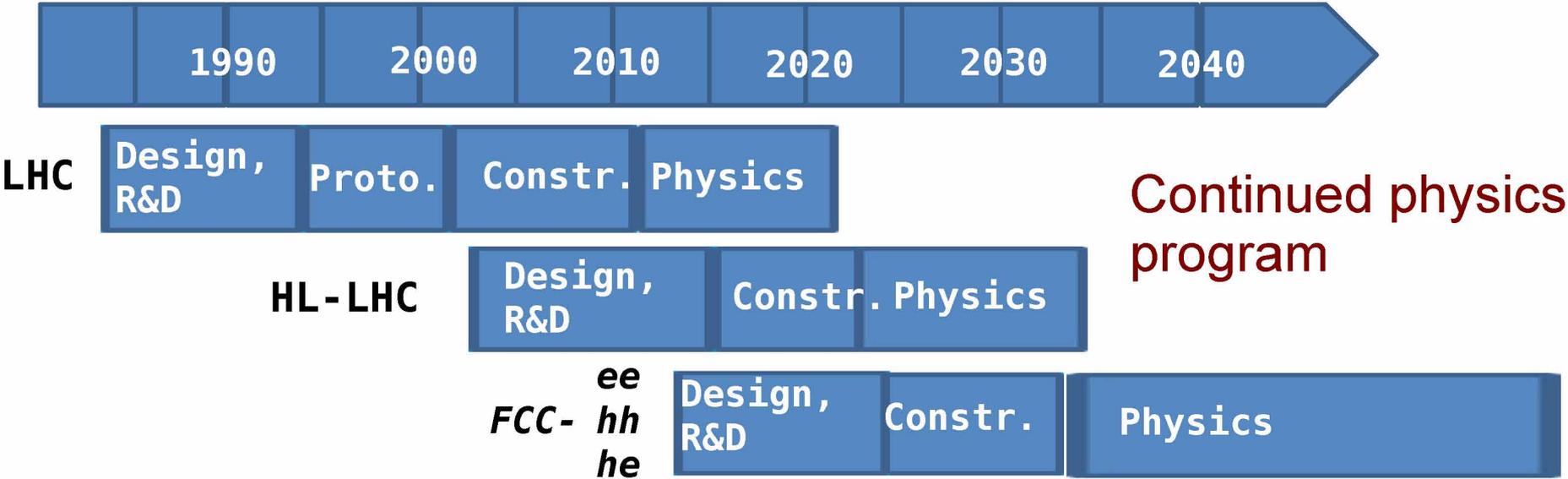
Site studies for Geneva area

CDR for EU strategy update  
in 2018



# tentative time line and milestones

F. Zimmermann, IPAC14





# FCC-hh baseline parameters



parameter	LHC	HL-LHC	FCC-hh
c.m. energy [TeV]	14		100
dipole magnet field [T]	8.33		16 (20)
circumference [km]	26.7		100 (83)
luminosity [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	1	5	5 [ $\rightarrow 20?$ ]
bunch spacing [ns]	25		25 {5}
<b>events / bunch crossing</b>	<b>27</b>	<b>135</b>	<b>170 {34}</b>
bunch population [ $10^{11}$ ]	1.15	2.2	1 {0.2}
norm. transverse emitt. [ $\mu\text{m}$ ]	3.75	2.5	2.2 {0.44}
IP beta-function [m]	0.55	0.15	1.1
IP beam size [ $\mu\text{m}$ ]	16.7	7.1	6.8 {3}
synchrotron rad. [W/m/aperture]	0.17	0.33	28 (44)
critical energy [keV]	0.044		4.3 (5.5)
<b>total syn.rad. power [MW]</b>	<b>0.0072</b>	<b>0.0146</b>	<b>4.8 (5.8)</b>
<b>longitudinal damping time [h]</b>	<b>12.9</b>		<b>0.54 (0.32)</b>



# Hadron collider FCC-hh parameters

- **Energy** **100 TeV c.m.**
  - **Circumference** ~ 100 km (baseline) [80 km option]
  - **Dipole field (50 TeV)** ~ 16 T (baseline) [20 T option]
  - **Dipole field (3 TeV inject.)** ~ 1 T (baseline) [1.2 T option]
  
  - **Bunch spacing** 25 ns [5 ns option]
  - **Bunch population (25 ns)**  $1 \times 10^{11}$  p
  - **Emittance normalised**  $2.15 \times 10^{-6}$  m, normal.
  - **#bunches** 10500
  - **Stored beam energy** 8.2 GJ/beam
  
  - **# Interaction Points** 2 main experiments
  - $\beta^*$  1.1 m [baseline]
  - **Luminosity**  **$5 \times 10^{34}$  cm<sup>-2</sup>s<sup>-1</sup>** [baseline]
  
  - **Synchrotron radiation arc** ~30 W/m/aperture (fill. fact. ~78% in arc)
- Available from SPS/LHC today  
→ 3 TeV injector  
baseline for FCC-hh





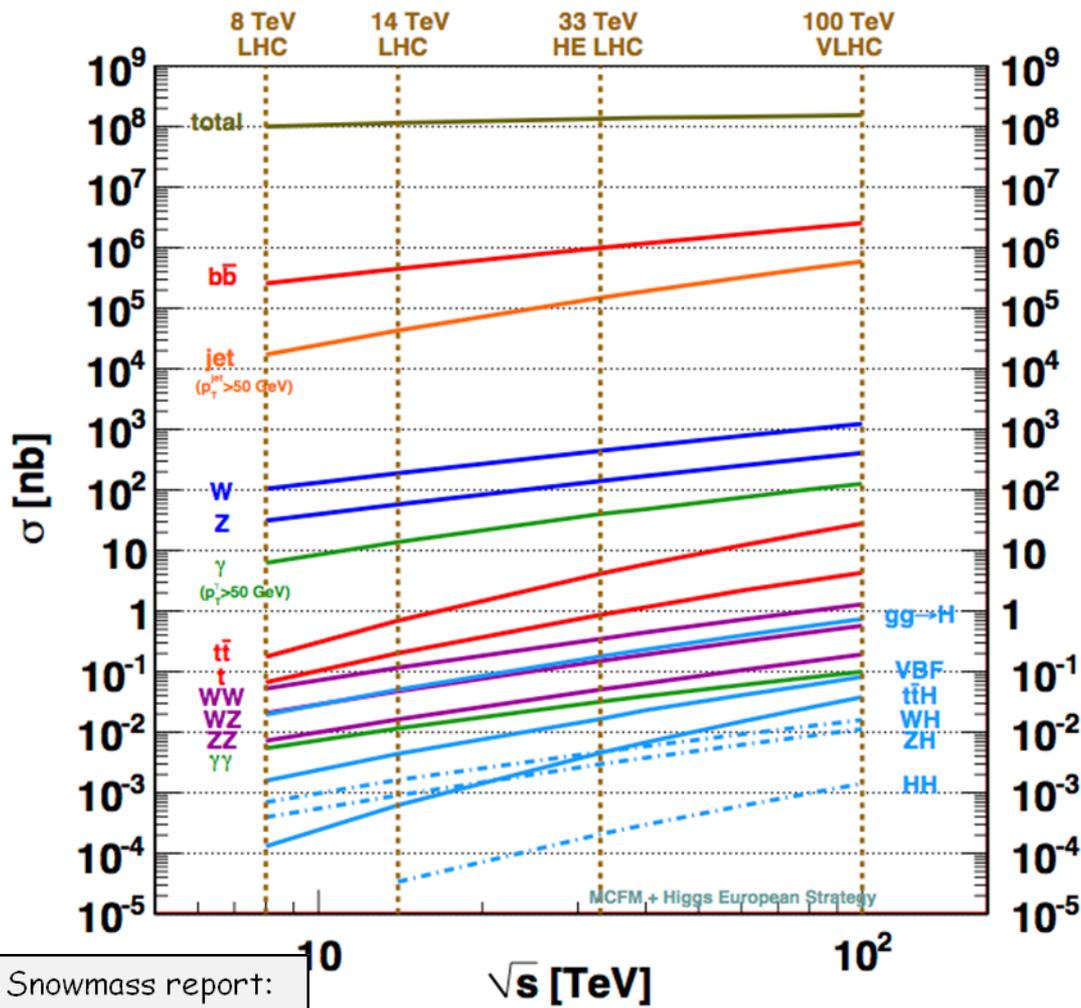
**2 tons of TNT**

energy per proton beam

*LHC*: 0.4 GJ → *FCC-hh*: 8 GJ (20x more !)

- kinetic energy of Airbus A380 at 720 km/h
- can melt 12 tons of copper, or drill a 300-m long hole

# Cross sections vs $\sqrt{s}$



Snowmass report:  
arXiv:1310.5189

Process	$\sigma$ (100 TeV)/ $\sigma$ (14 TeV)
Total pp	1.25
W	$\sim 7$
Z	$\sim 7$
WW	$\sim 10$
ZZ	$\sim 10$
$t\bar{t}$	$\sim 30$
H	$\sim 15$ ( $t\bar{t}H \sim 60$ )
HH	$\sim 40$
stop ( $m=1$ TeV)	$\sim 10^3$

→ With 10000/fb at  $\sqrt{s}=100$  TeV expect:  $10^{12}$  top,  $10^{10}$  Higgs bosons,  $10^8$   $m=1$  TeV stop pairs, ...

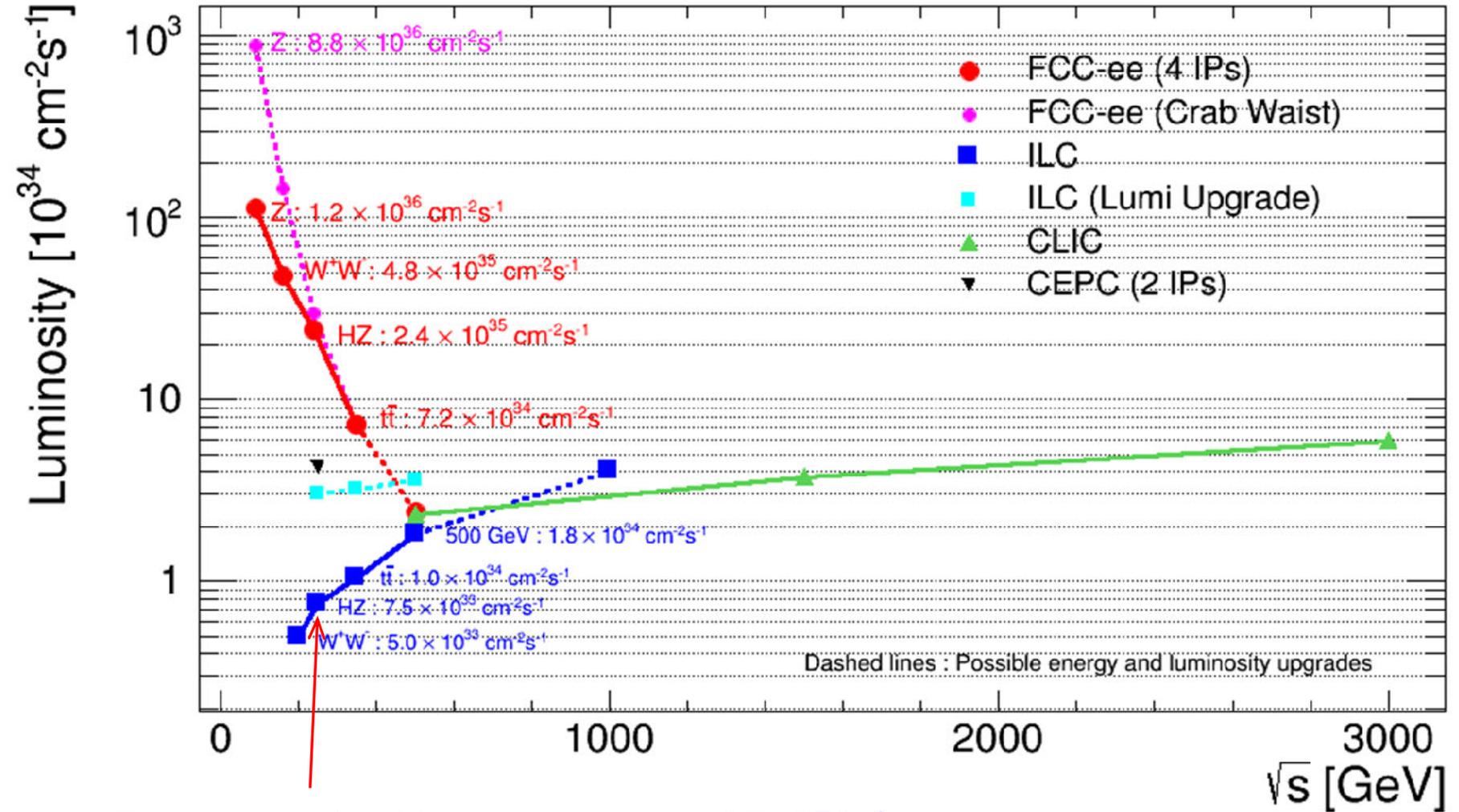


# FCC-ee baseline parameters



parameter	LEP2	FCC-ee				
		Z	Z (c.w.)	W	H	t
$E_{\text{beam}}$ [GeV]	104	<b>45</b>	<b>45</b>	<b>80</b>	<b>120</b>	<b>175</b>
circumference [km]	26.7	<b>100</b>	<b>100</b>	<b>100</b>	<b>100</b>	<b>100</b>
current [mA]	3.0	1450	1431	152	30	6.6
$P_{\text{SR,tot}}$ [MW]	22	<b>100</b>	<b>100</b>	<b>100</b>	<b>100</b>	<b>100</b>
no. bunches	4	16700	29791	4490	1360	98
$N_b$ [ $10^{11}$ ]	4.2	1.8	1.0	0.7	0.46	1.4
$\epsilon_x$ [nm]	22	<b>29</b>	<b>0.14</b>	<b>3.3</b>	<b>0.94</b>	<b>2</b>
$\epsilon_y$ [pm]	250	<b>60</b>	<b>1</b>	<b>1</b>	<b>2</b>	<b>2</b>
$\beta_x^*$ [m]	1.2	0.5	0.5	0.5	0.5	1.0
$\beta_y^*$ [mm]	50	<b>1</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>1</b>
$\sigma_y^*$ [nm]	3500	250	32	84	44	45
$\sigma_{z,\text{SR}}$ [mm]	<b>11.5</b>	<b>1.64</b>	<b>2.7</b>	<b>1.01</b>	<b>0.81</b>	<b>1.16</b>
$\sigma_{z,\text{tot}}$ [mm] (w beamstr.)	<b>11.5</b>	<b>2.56</b>	<b>5.9</b>	<b>1.49</b>	<b>1.17</b>	<b>1.49</b>
hourglass factor $F_{hg}$	0.99	0.64	0.94	0.79	0.80	0.73
$L/IP$ [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	0.01	<b>28</b>	<b>212</b>	<b>12</b>	<b>6</b>	<b>1.7</b>
$\tau_{\text{beam}}$ [min]	434	<b>298</b>	<b>39</b>	<b>73</b>	<b>29</b>	<b>21</b>

$10^5 Z$  per sec

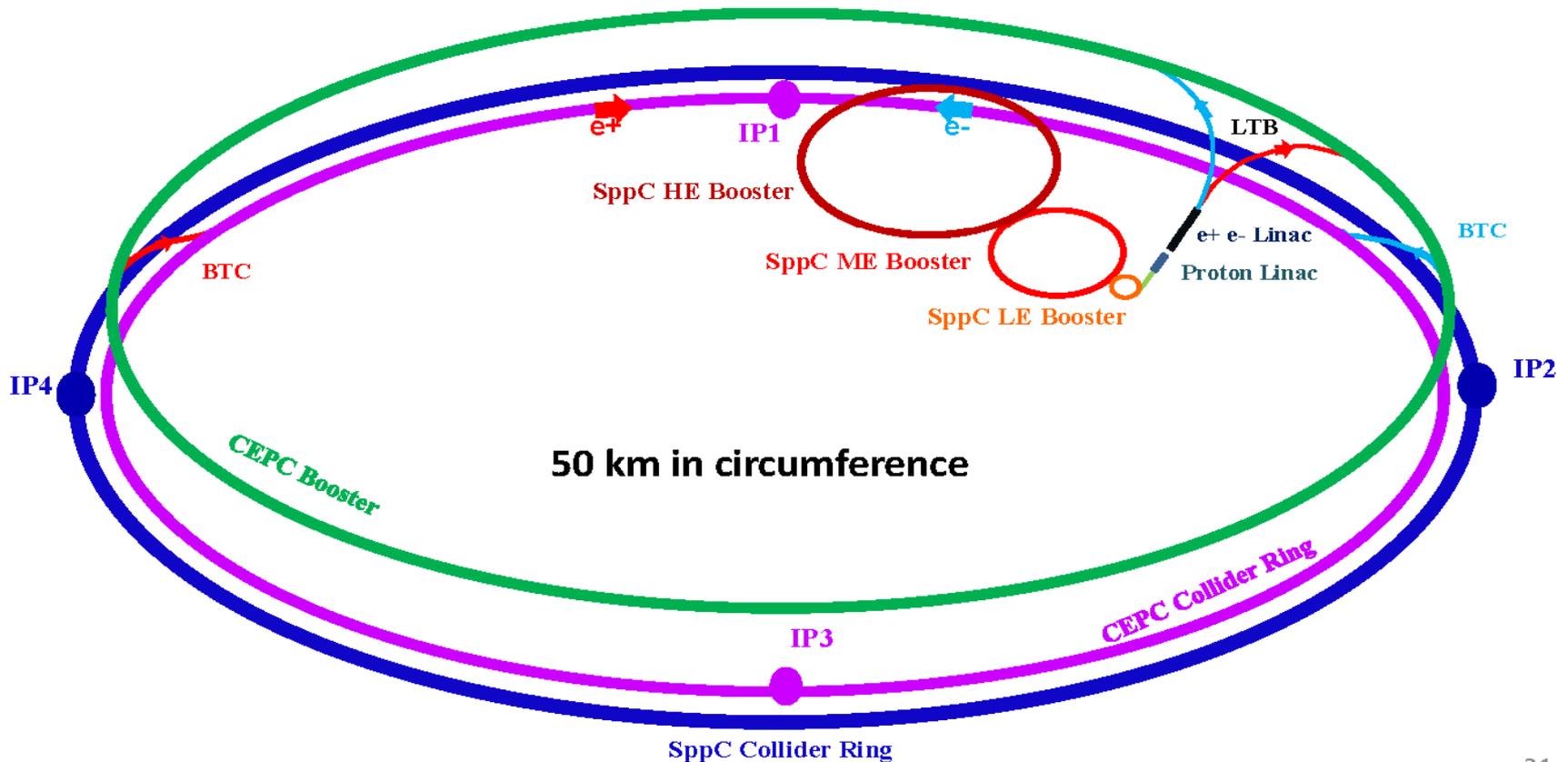


The luminosity at the Higgs energy  $2E=250$  GeV at FCC-ee is higher than at the ILC by one order of magnitude

# CEPC-SppC

Китай

**CEPC** is an 240 GeV Circular Electron Positron Collider, proposed to carry out high precision study on Higgs bosons, which can be upgraded to a 70 TeV or higher pp collider **SppC**, to study the new physics beyond the Standard Model.



Проект непрерывно изменяется в сторону FCC (100 км, 100 ТэВ)

# CepC/SppC study (CAS-IHEP), CepC CDR end of 2014, $e^+e^-$ collisions ~2028; $pp$ collisions ~2042



Qinhuangdao (秦皇岛)

CepC, SppC

高能所

秦皇岛市

抚宁县

50 km

easy access

300 km from Beijing

3 h by car

1 h by train

70 km

*“Chinese Toscana”*

Image © 2013 DigitalGlobe  
Data SIO, NOAA, U.S. Navy, NGA, GEBCO  
© 2013 Mapabc.com  
Image © 2013 TerraMetrics

Google earth

# CEPC-SppC Project Timeline (dream)



## CEPC



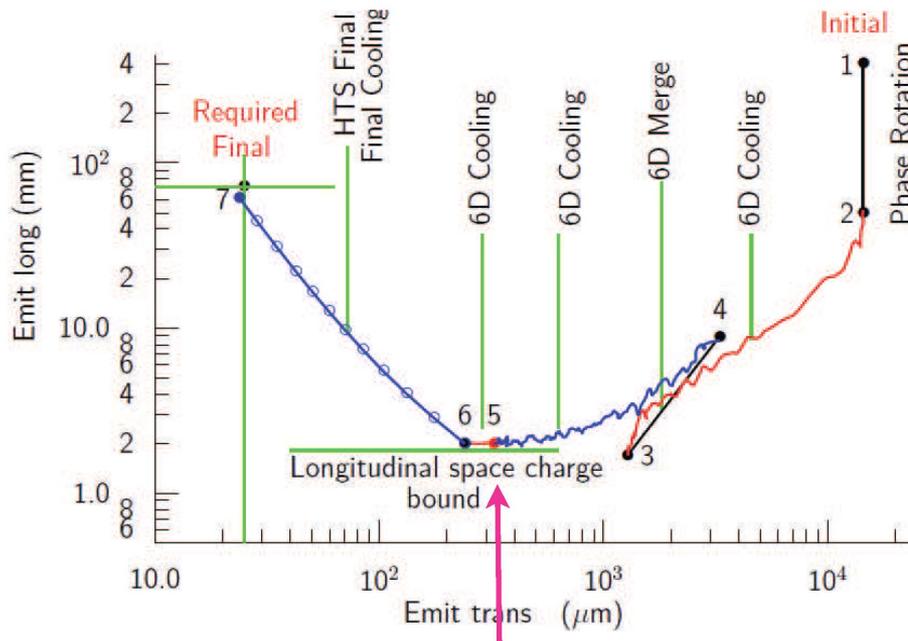
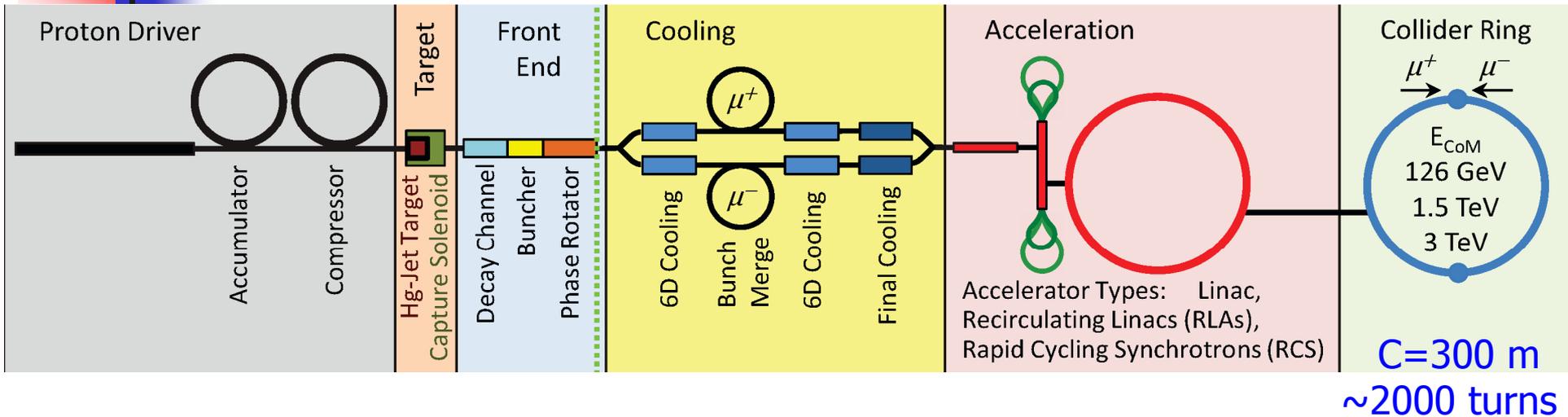
1<sup>st</sup> Milestone: pre-CDR (by the end of 2014) → R&D funding request to Chinese government in 2015 (China's 13<sup>th</sup> Five-Year Plan 2016-2020)

## SppC



(2.2022) Решение о строительстве пока не принято

# Muon collider as a Higgs factory



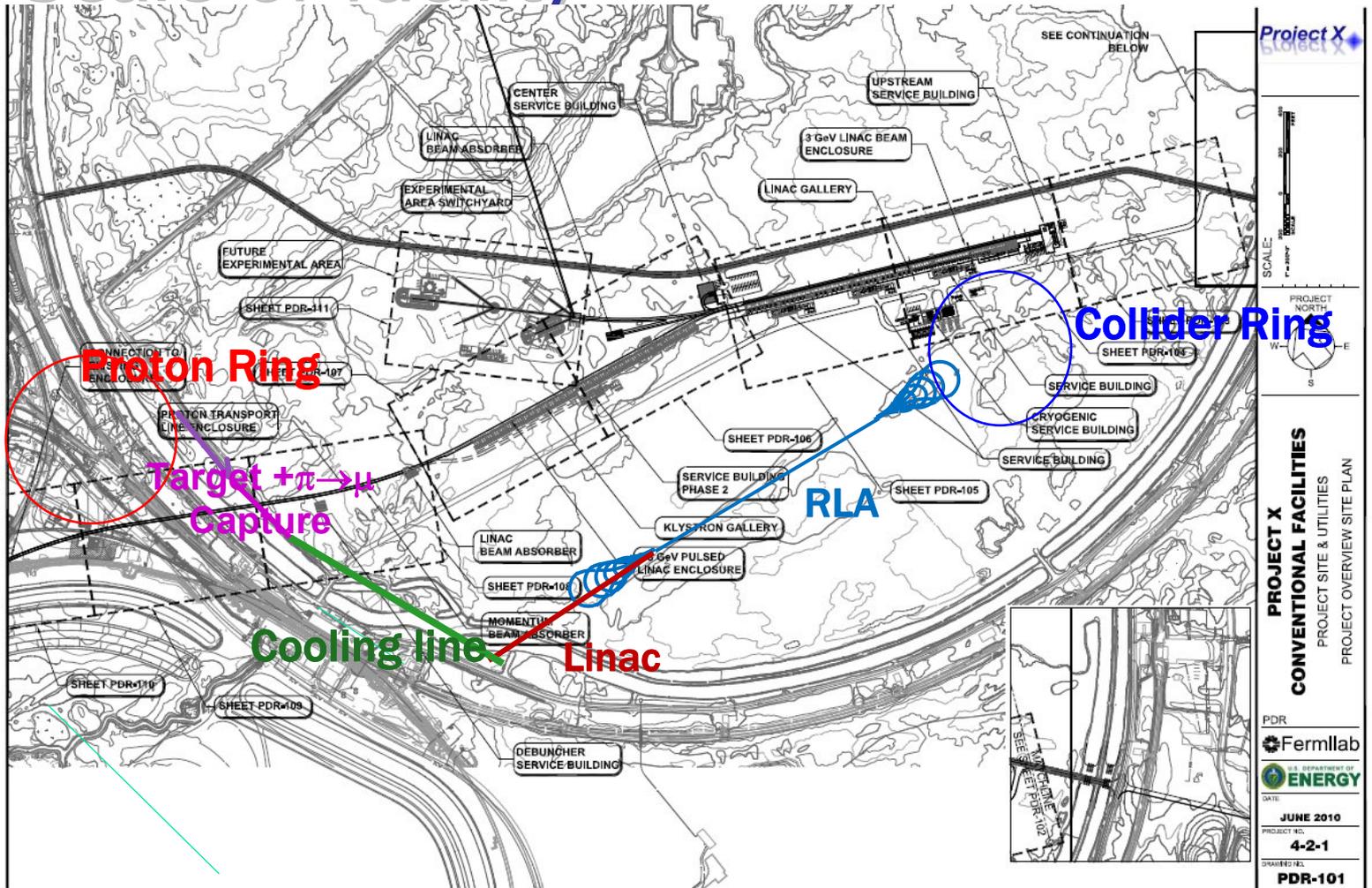
6D ionization cooling

# Parameters of 126 GeV $\mu^+\mu^-$ Higgs factory

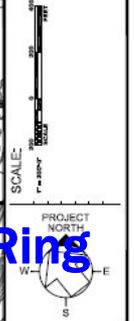
	unit	Low L	High L
$2E_0$	GeV	126	126
Luminosity per IP	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	0.001	0.01
Number of IPs		2	2
No. Higgs/yr( $10^7$ s) per IP	1000	5	50
Circumference	km	0.3	0.3
$P$ (wall)	MW	100	125
Pol. $\mu^-$ and $\mu^+$	%	10	10-20
$N$ per bunch	$10^{10}$	200	500
Bunches per beam		1	1
Norm. emit. $\epsilon_{x,n}$	mm-mrad	400	200
Norm. emit. $\epsilon_{y,n}$	mm-mrad	400	200
$\beta_x$ at IP	mm	60	40
$\beta_y$ at IP	mm	60	40
$\sigma_x$ at IP	$\mu\text{m}$	200	120
$\sigma_y$ at IP	$\mu\text{m}$	200	120
$\sigma_z$ at IP	mm	60	40
$\sigma_E/E$	%	0.003	0.003

The luminosity is 2-3 orders of magnitude smaller than at e+e- colliders, but the Higgs production cross section is 200 times larger

# Scale of facility



Project X  
Collect X



**PROJECT X**  
**CONVENTIONAL FACILITIES**  
PROJECT SITE & UTILITIES  
PROJECT OVERVIEW SITE PLAN

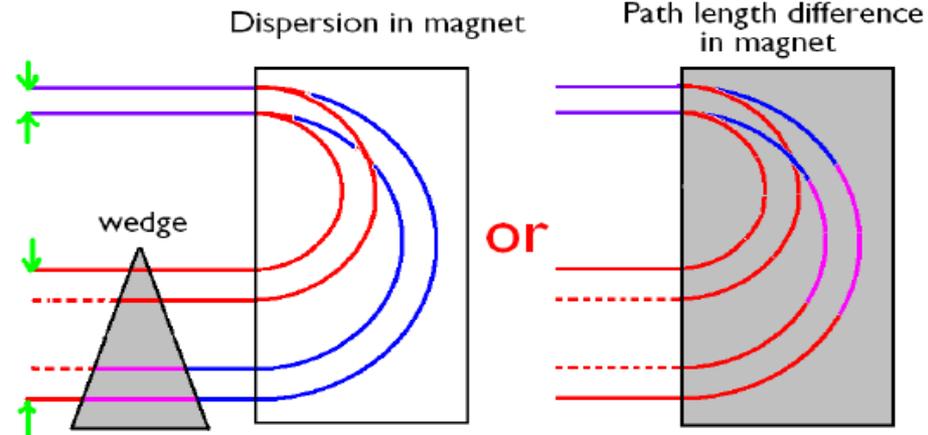
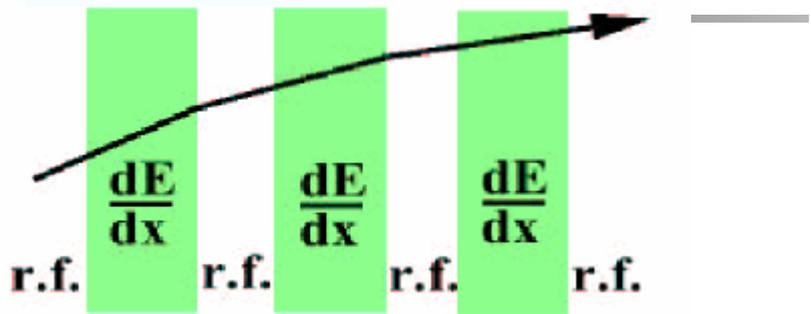
PDR  
Fermilab  
U.S. DEPARTMENT OF ENERGY  
DATE: JUNE 2010  
PROJECT NO.: 4-2-1  
DRAWN BY: PDR-101

FNAL

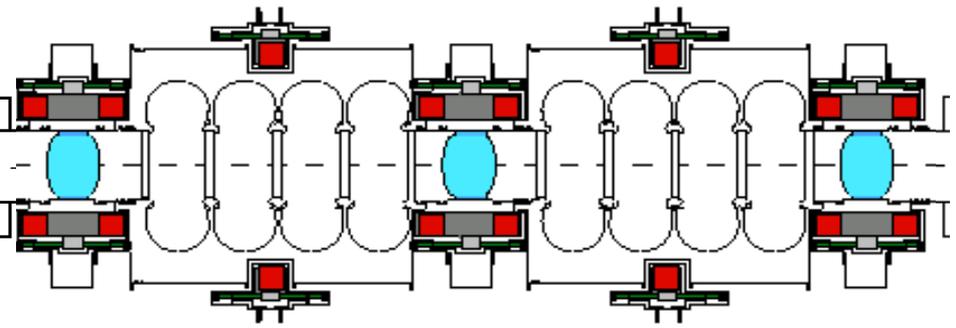
# COOLING -- Principle is straightforward...

## Longitudinal:

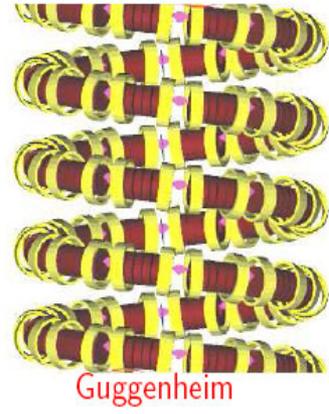
### Transverse:



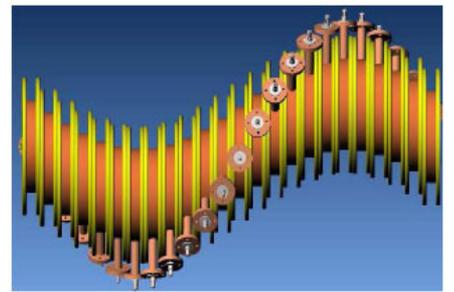
Practical realization is not!



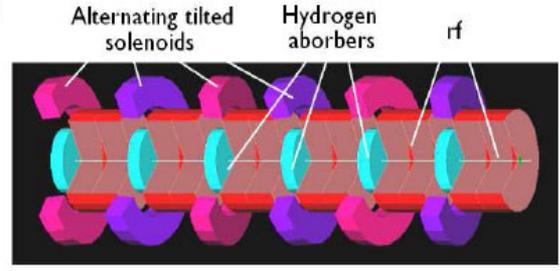
MICE cooling channel (4D cooling)



Guggenheim

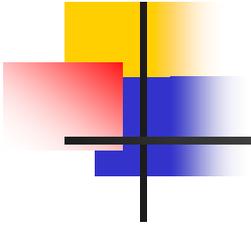


Helical Cooling Channel



Snake

6D candidate cooling lattices



New, 2021 !

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Twin  $e^+e^-$  LC with energy recovery  
(ERLC)

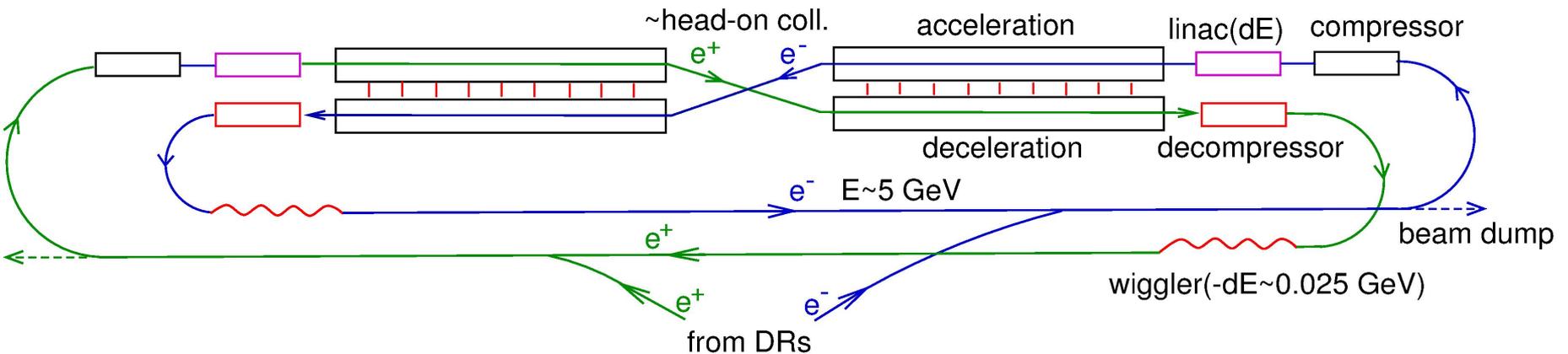
# The proposed LC scheme

V.Telnov, LCWS21

arXiv:2105.11015

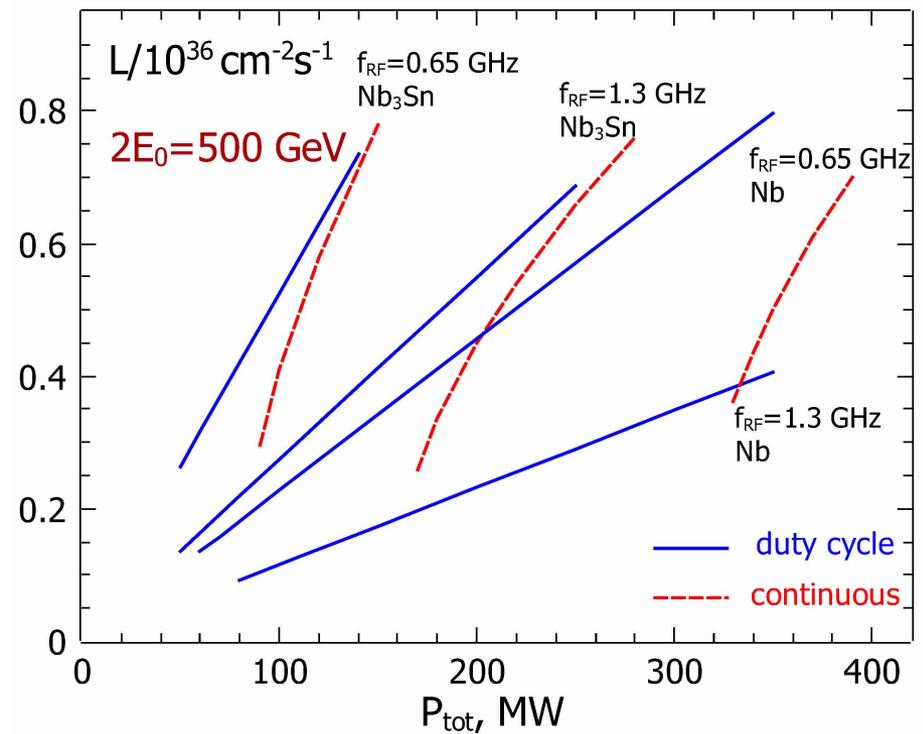
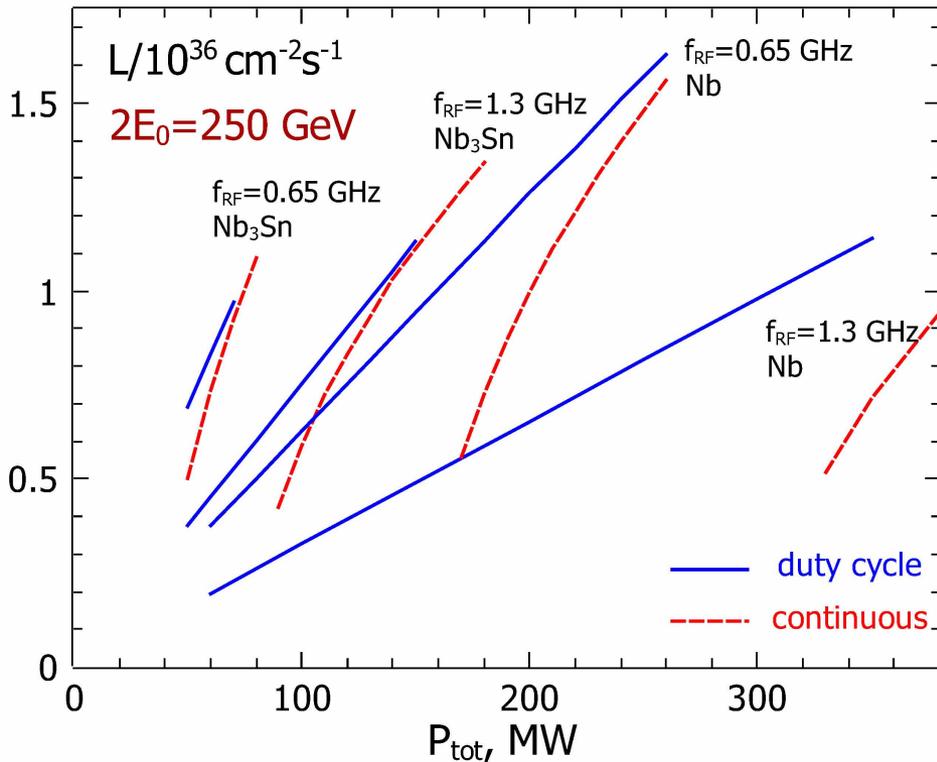
JINST 16 (2021) 12, P12025

## Twin LC with the energy recovery



- 1) LC consists of two parallel SC linac connected with each other with rf-couplers, so that the fields are equal at any time. One line is for acceleration, the other for deceleration.
- 2) Damping is provided by wigglers (no damping rings) at the “return” energy about  $E \sim 5$  GeV. The energy loss per turn  $dE/E \sim 1/200$ . Damping is needed to reduce the energy spread arising from collision of beams.
- 3) In the presence of a return path,  $e^+$  and  $e^-$  are always correctly focused by their own FF.
- 4) The duration of one cycle (several seconds) is determined by the refrigeration system (rise of temperature on  $\sim 0.1$  K at 1.8 K).

# Possible luminosities vs power



## 2E=250 GeV

**Table 2.** Parameters of  $e^+e^-$  linear colliders ERLC and ILC,  $2E_0 = 250$  GeV.

	unit	ERLC pulsed Nb 1.8 K 1.3 GHz	ERLC pulsed Nb 1.8 K 0.65 GHz	ERLC contin. Nb <sub>3</sub> Sn 4.5 K 1.3 GHz	ERLC contin. Nb <sub>3</sub> Sn 4.5 K 0.65 GHz	ILC Nb 1.8 K 1.3 GHz
Energy $2E_0$	GeV	250	250	250	250	250
Luminosity $\mathcal{L}_{\text{tot}}$	$10^{36} \text{ cm}^{-2} \text{ s}^{-1}$	0.39	0.75	<u>0.83</u>	<u>1.6</u>	0.0135
$P$ (wall) (collider)	MW	120	120	120	120	129(tot.)
Duty cycle, $DC$		0.19	0.37	1	1	n/a
Accel. gradient, $G$	MV/m	20	20	20	20	31.5
Cavity quality, $Q$	$10^{10}$	3	12	3	12	1
Length $L_{\text{act}}/L_{\text{tot}}$	km	12.5/30	12.5/30	12.5/30	12.5/30	8/20
$N$ per bunch	$10^9$	1.13	2.26	0.46	1.77	20
Bunch distance	m	0.23	0.46	0.23	0.46	166
Rep. rate, $f$	Hz	$2.47 \cdot 10^8$	$2.37 \cdot 10^8$	$1.3 \cdot 10^9$	$6.5 \cdot 10^8$	6560
$\epsilon_{x,n}/\epsilon_{y,n}$	$10^{-6}$ m	10/0.035	10/0.035	10/0.035	10/0.035	5/0.035
$\beta_x^*/\beta_y$ at IP	cm	2.7/0.031	10.8/0.031	0.46/0.031	6.8/0.031	1.3/0.04
$\sigma_x$ at IP	$\mu\text{m}$	1.05	2.1	0.43	1.66	0.52
$\sigma_y$ at IP	nm	6.2	6.2	6.2	6.2	7.7
$\sigma_z$ at IP	cm	0.03	0.03	0.03	0.03	0.03
$(\sigma_E/E_0)_{\text{BS}}$ at IP	%	0.2	0.2	0.2	0.2	$\sim 1$

goal

CERN next exits  
GET IN LANE

China next right

HE-LHC  
construction  
2028+??  
physics 2038+??

FCC-pp  
(FCC-ee)  
construction 2028+??  
physics 2038+??

CLIC  
construction 2028+??  
physics 2038+??

SppS  
construction 2028+??  
physics 2038+??

LHC  
for the next 20 years

pp  
2028+?  
physics 2038+?

Muon Collider  
construction 2030+?  
physics 2040+?

ILC in Japan  
construction 2018?  
physics 2028?

CepC in China  
construction 2018?  
physics 2028?

# Новые методы ускорения

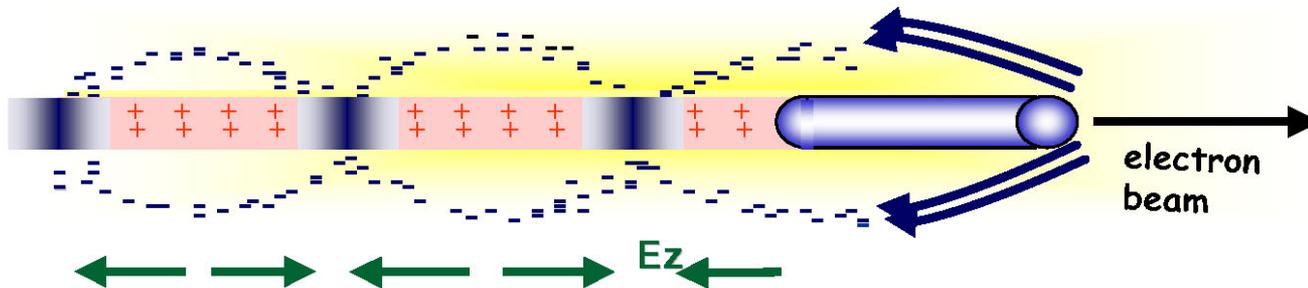
## Ускорение в плазме

короткий сгусток заряженных частиц (например электронов) двигаясь в плазме расталкивает в стороны электроны плазмы, создавая в плазме продольные электрические поля. Второй пучок, следующий за первым на определенном расстоянии будет находиться в ускоряющем поле, забирая энергию поля. Меняя лидирующий пучок можно разогнать второй пучок до высоких энергий с очень высоким темпом ускорения, порядка 0.1-1 ГэВ/см и выше.

В качестве лидирующего пучка используют также лазерный пучок, но здесь есть проблема с дифракционной расходимостью.

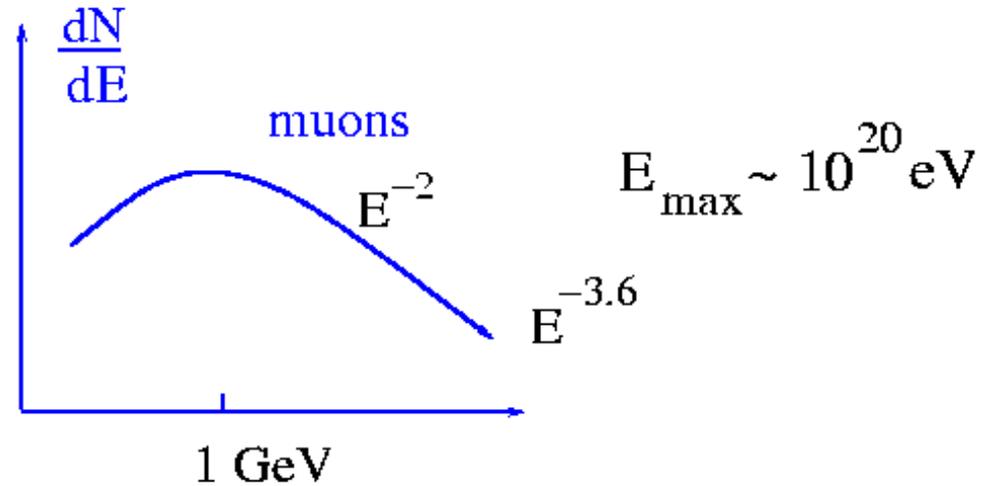
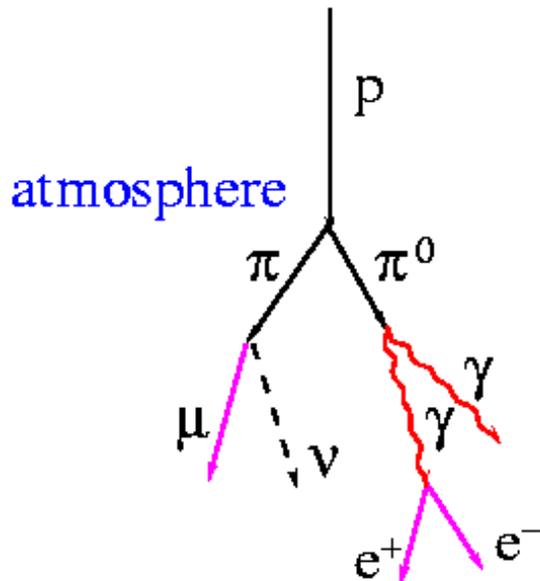
Пока это находится на стадии разработок. Возможные области применения . . .

- Space charge of **drive beam** displaces plasma electrons



- **Plasma ions** exert restoring force => **Space charge oscillations**
- Wake Phase Velocity = Beam Velocity (like wake on a boat)
- Wake amplitude  $\propto N_b / \sigma_z^2$

# Космические частицы

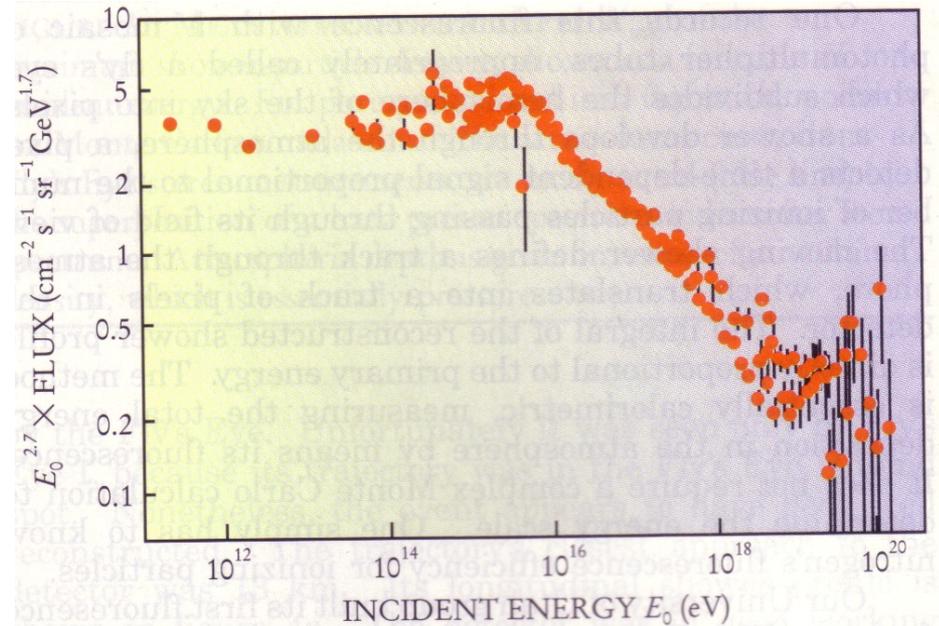
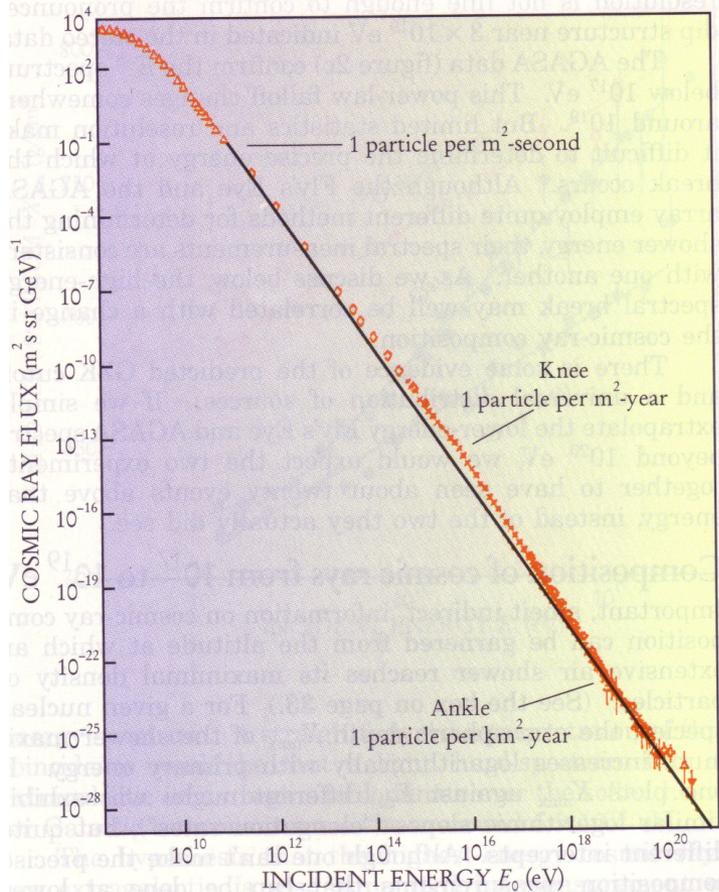


Вне атмосферы:  $p, \alpha, \text{ядра} = 93:6:1$

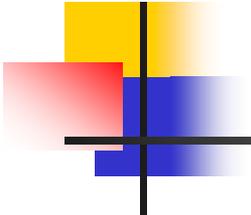
На уровне моря: в основном мюоны со средней энергией 2 ГэВ,  
 $\mu:p = 100:3$  при 1 ГэВ,  $100:0.3$  при 10 ГэВ,  
также есть  $<10\%$   $e, n$ .

Поток: мюонов  $\sim 0.025$  шт./сек/см<sup>2</sup>, нейтрино солнечных  $5 \times 10^{10}$ ,  
нейтрино реликтовых  $10^{12}$  шт./сек/см<sup>2</sup> (еще не зарегистрированы).

# Космические частицы сверхвысокой энергии



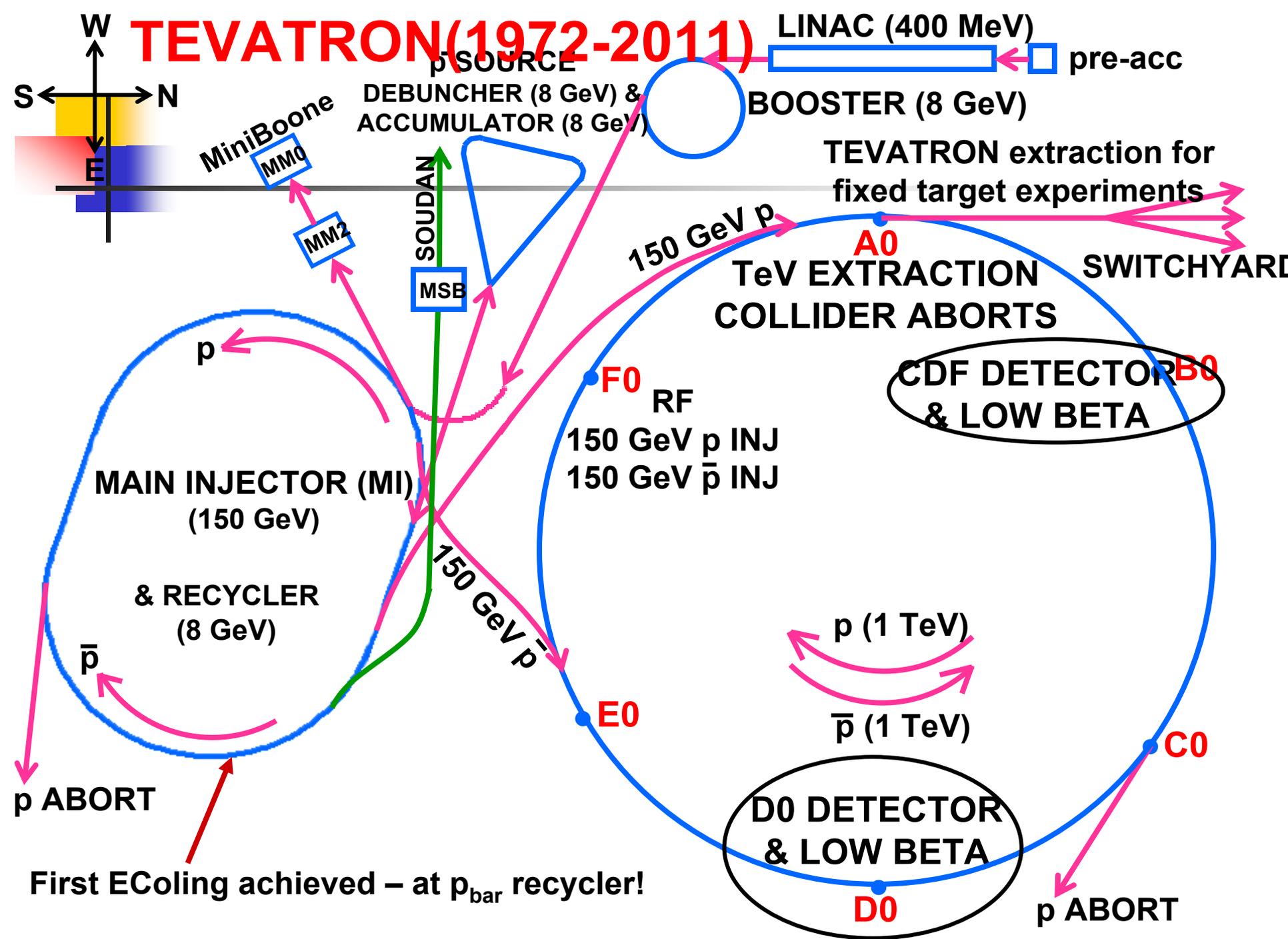
При  $5 \cdot 10^{19}$  eV должен быть завал спектра за счет взаимодействия протонов (ядер) с реликтовыми фотонами (рождение пионов) .



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# Современные и будущие ускорители (примеры)

# TEVATRON (1972-2011)



# HERA @ DESY

(1991-2006)

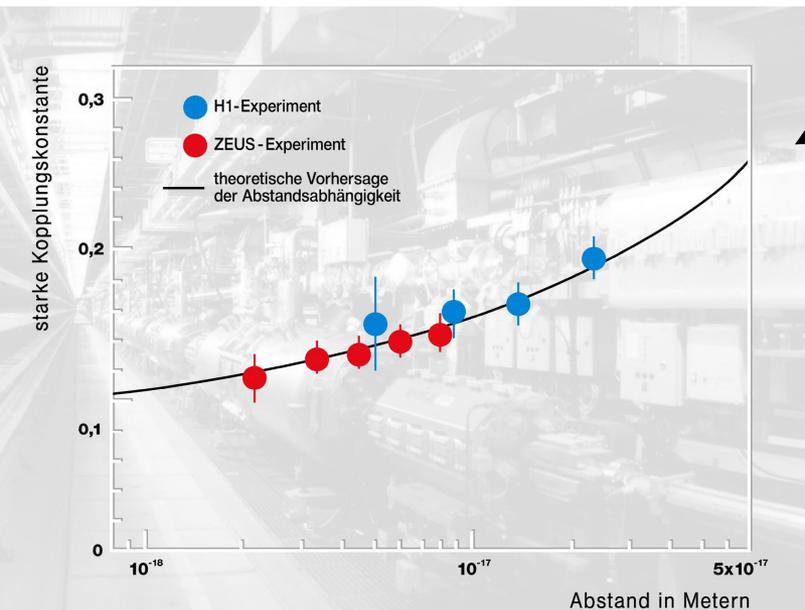
$p \{1 \text{ TeV}\} - e^- (e^+) \{30 \text{ GeV}\}$   
collider



im Baubereich der Pro- und der Hamburger Wissenschafts-

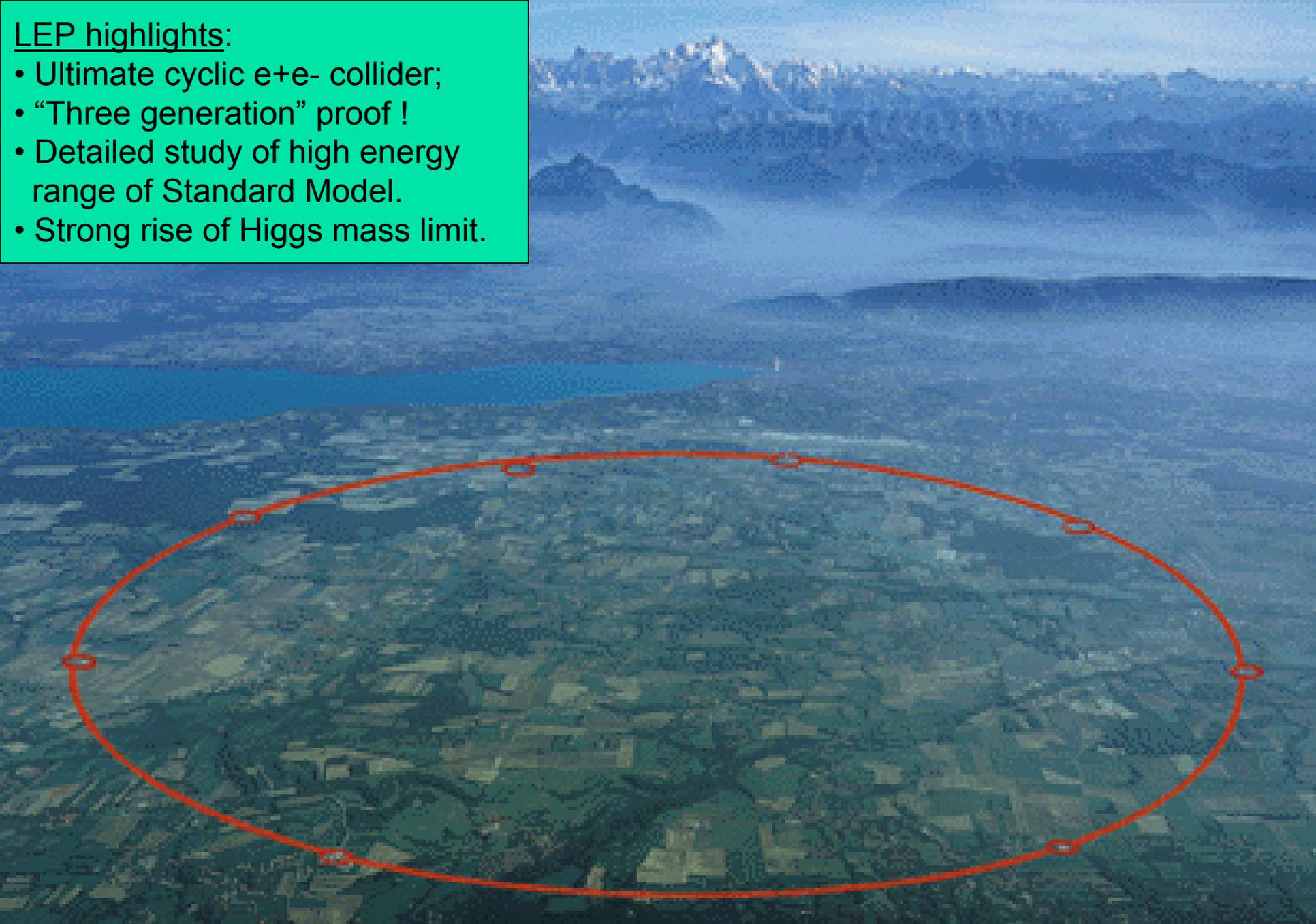
The most important achievements:

- The first big super-conducting accelerator ( $p$ ).
- The first  $e^-(e^+) - p$  collider.
- Detailed study of parton distribution functions in very wide  $q^2$  range.

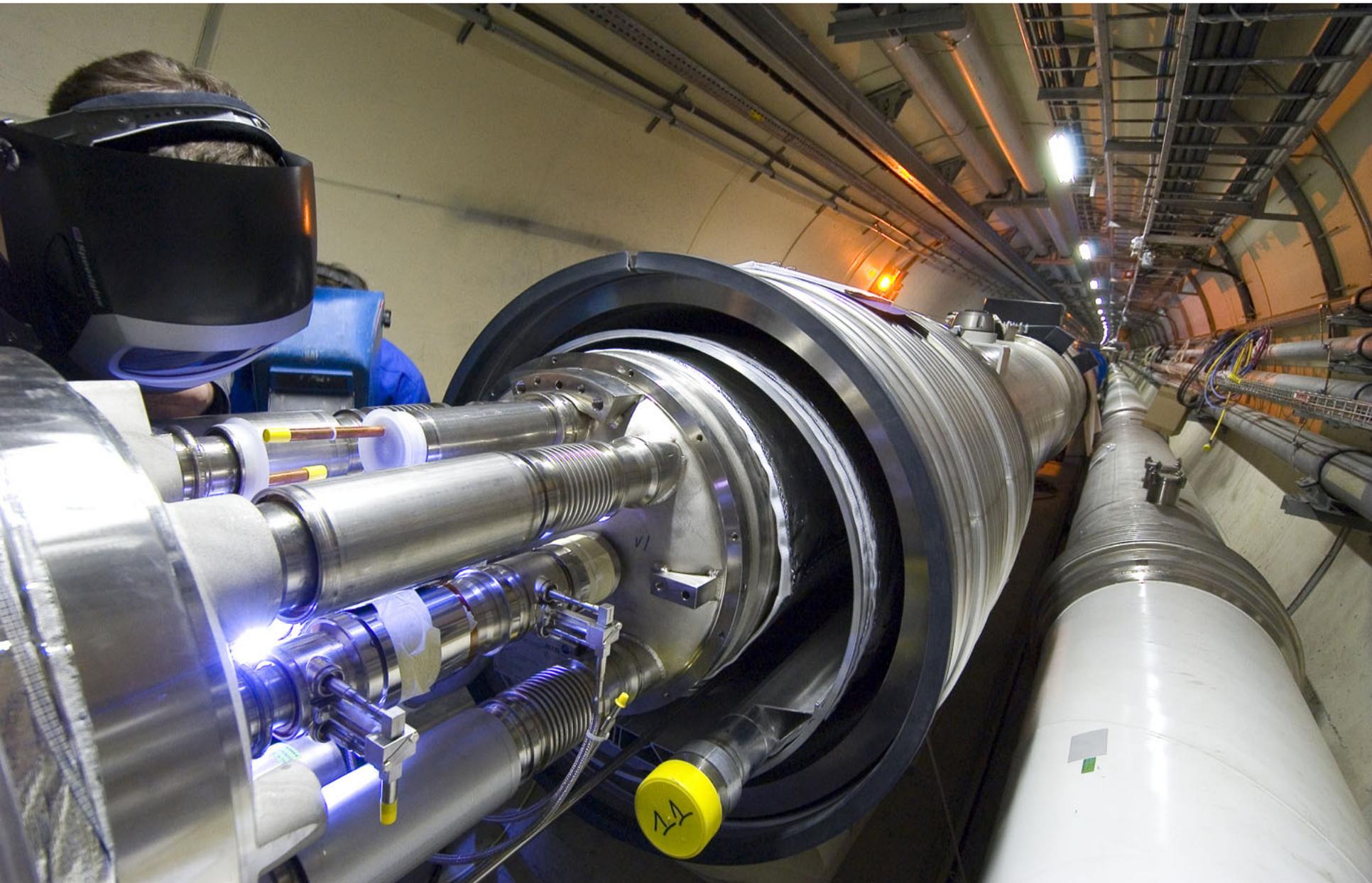


## LEP highlights:

- Ultimate cyclic  $e^+e^-$  collider;
- “Three generation” proof !
- Detailed study of high energy range of Standard Model.
- Strong rise of Higgs mass limit.



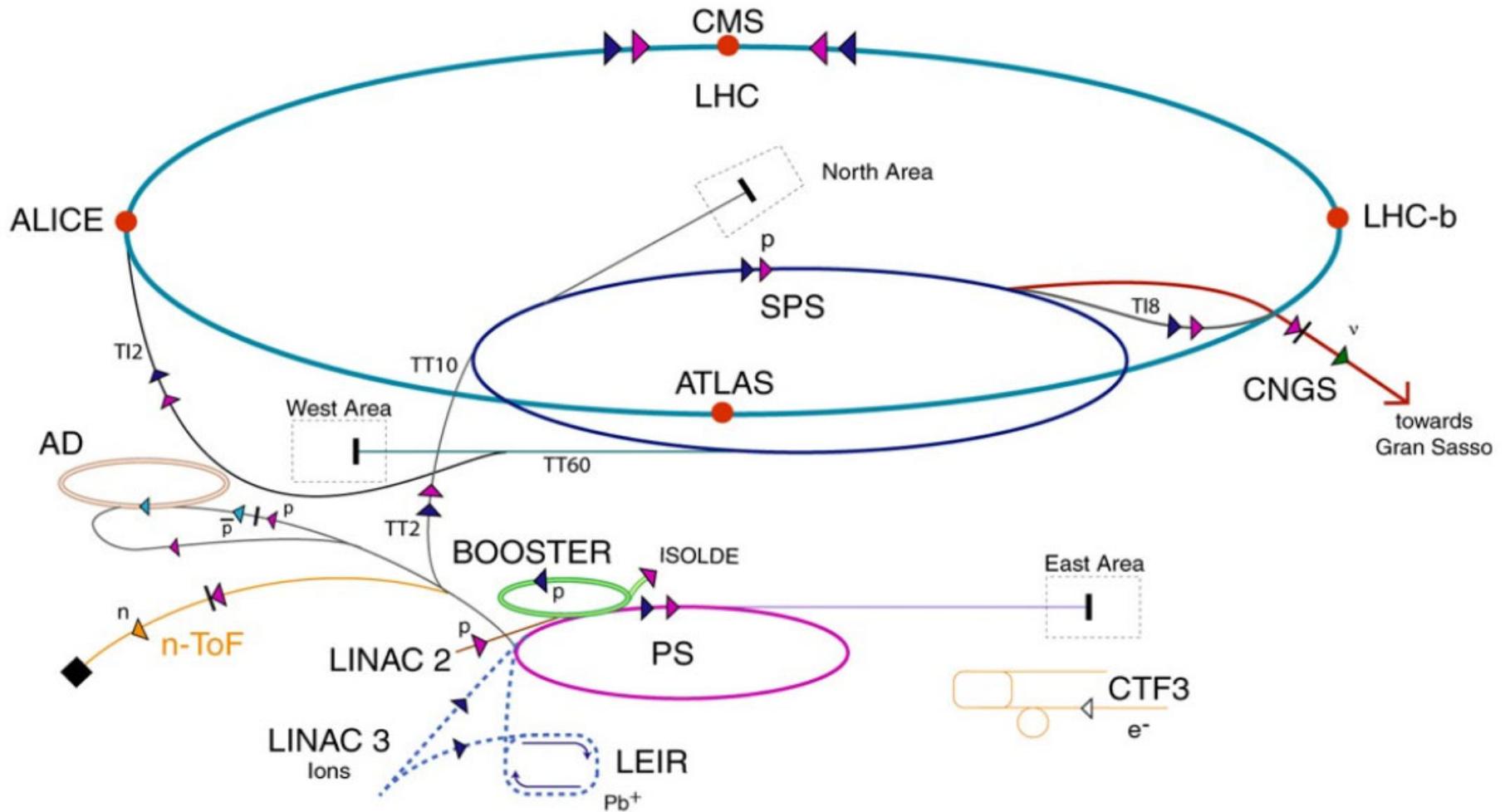
CERN from the AIR (LEP  $\rightarrow$  LHC !)



Assembly welding of LHC magnets in the tunnel

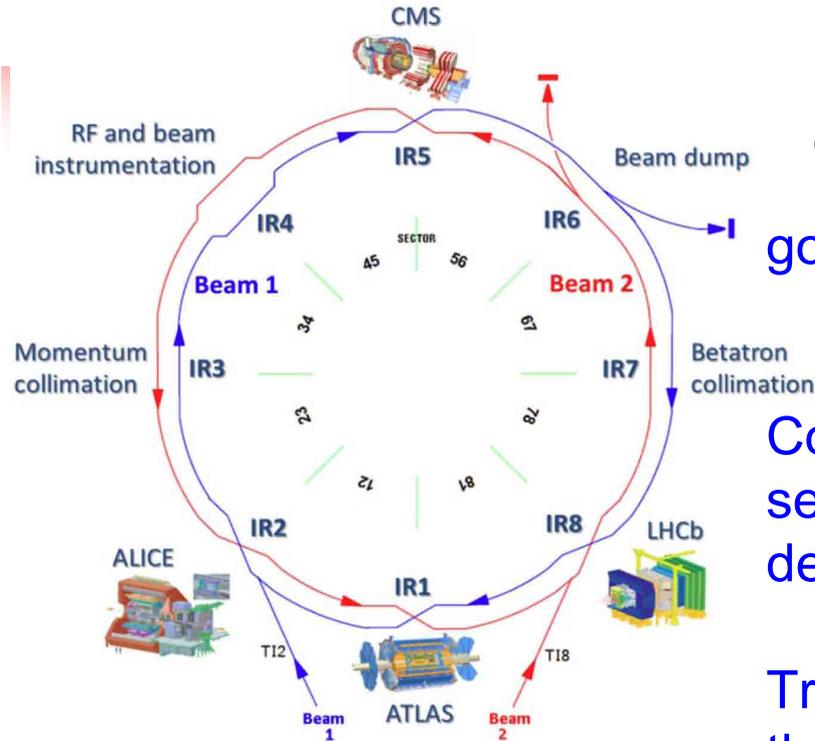
Начало работы 2009 г.

# CERN Accelerator Complex (not to scale)



- |            |               |                              |                                |
|------------|---------------|------------------------------|--------------------------------|
| ▶ protons  | ▶ antiprotons | AD Antiproton Decelerator    | LHC Large Hadron Collider      |
| ▶ ions     | ▶ electrons   | PS Proton Synchrotron        | n-ToF Neutron Time of Flight   |
| ▶ neutrons | ▶ neutrinos   | SPS Super Proton Synchrotron | CNGS CERN Neutrinos Gran Sasso |
|            |               |                              | CTF3 CLIC Test Facility 3      |

# LHC



Present: long shutdown 2  
2019-2020 → 2021

goals –upgrade of the LHC injectors  
- preparation for E=7 TeV

Cooldown started in Oct.2020  
several short circuit etc, requiring warm-up,  
delay > 4 month

Training to 7 TeV takes time,  
there is risk, 6.8 as target is discussed

The start of Run 3      March 2022

# LHC

## Run 2 summary

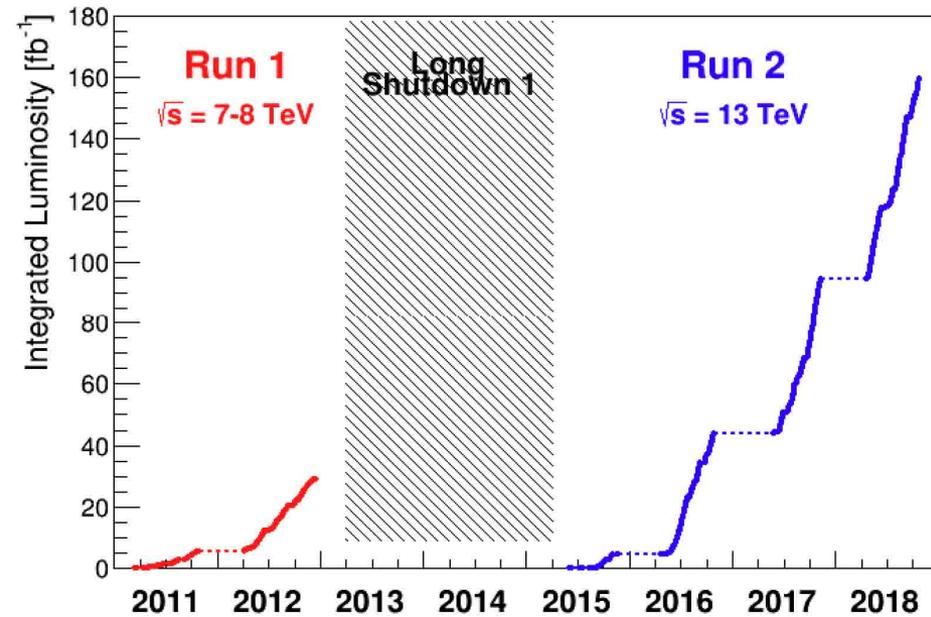
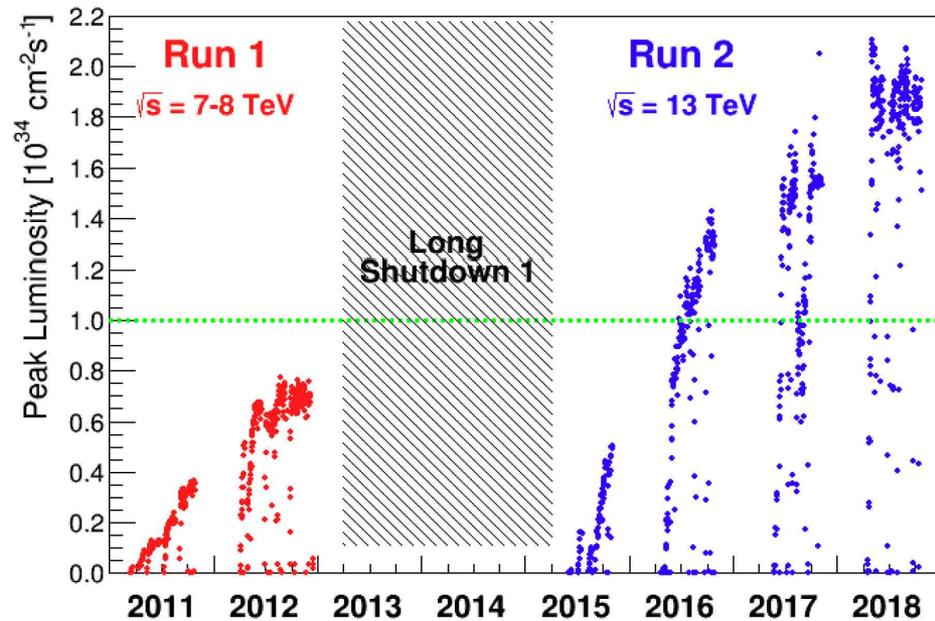
performance in 2011-2018

$$L_{\max} \sim 2 \times 10^{34} \text{ (design } 1 \times 10^{34}\text{)}$$

Total integrated luminosity

30 fb<sup>-1</sup> Run 1, E=3.5-4 TeV

160 fb<sup>-1</sup> Run 2, E=6.5 TeV



more stability,  $\beta^* = 25 \text{ cm}$ , optimized crossing angle

# LHC

## Run 3 -plans

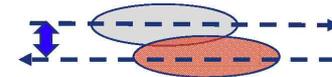
$$N=1.15 \times 10^{11} \rightarrow N=2 \times 10^{11}$$

$$\varepsilon = 3.5 \mu\text{m} \rightarrow \varepsilon = 2.1 \mu\text{m}$$

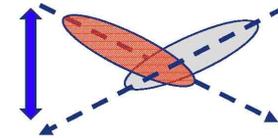
$$L_{\text{peak}}(10^{34}) \sim 2 \rightarrow 4.5$$

The luminosity is too high (pile up), will be levelled **dynamically**:

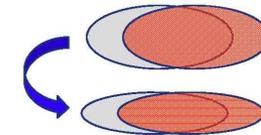
1) offset (2011)



2) crossing angle (2017)



3)  $\beta^*$ (at the IP)



In Run 3 levelled  $L=2 \times 10^{34}$  up to 12 hours

In 2022

2022-2024

Total 2022-2024

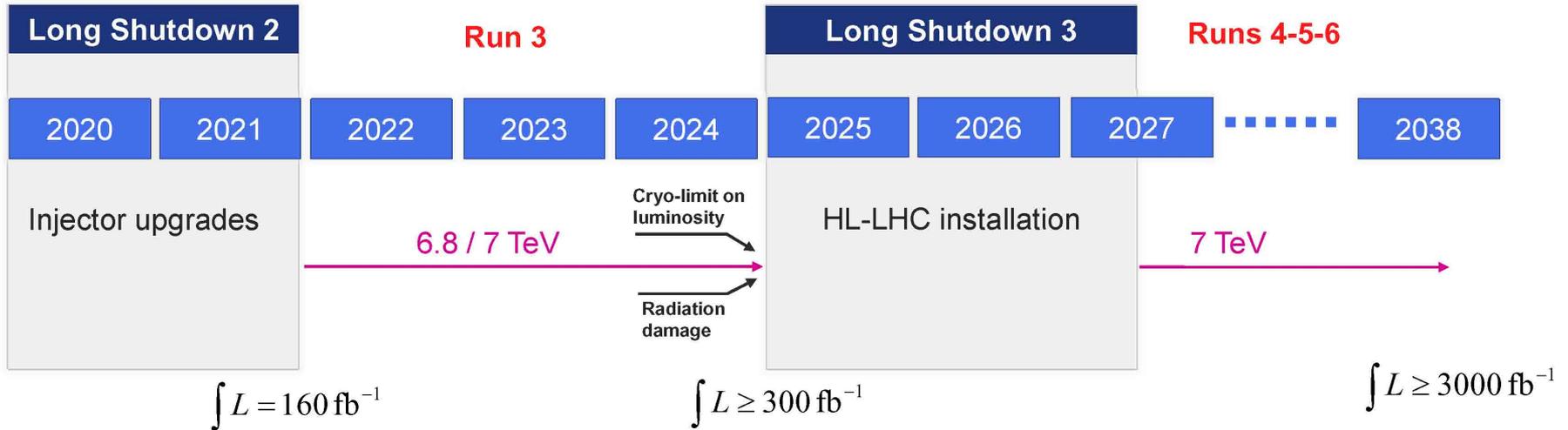
$\int L dt \sim 30-40 \text{ fb}^{-1}$  (reduced length 2022 run)

70-80  $\text{fb}^{-1}/\text{year}$

160-200  $\text{fb}^{-1}$  –doubled (Run-1+Run-2)

# HL-LHC

## Long term plan

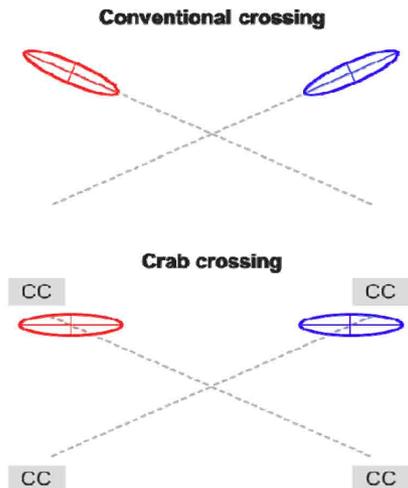


Goal:  $\sim 250 \text{ fb}^{-1}/\text{year}$  in ATLAS and CMS  
 $3000 \text{ fb}^{-1}$   $\sim 2038-2040$

$$N_H \sim 2 \times 10^8$$

Methods:

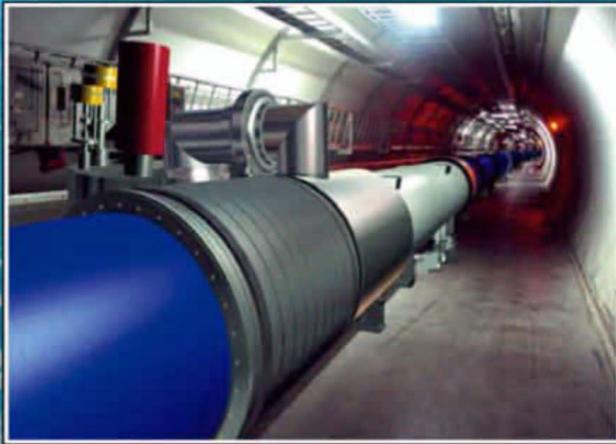
$N, \beta^*, \epsilon$  + crab crossing



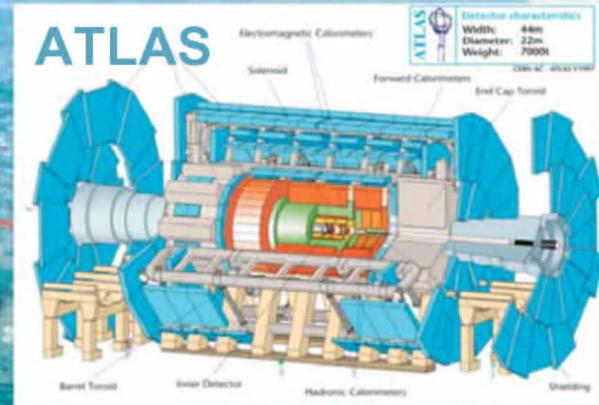
pp, B-Physics,  
CP Violation



LHC : 27 km long  
100m underground

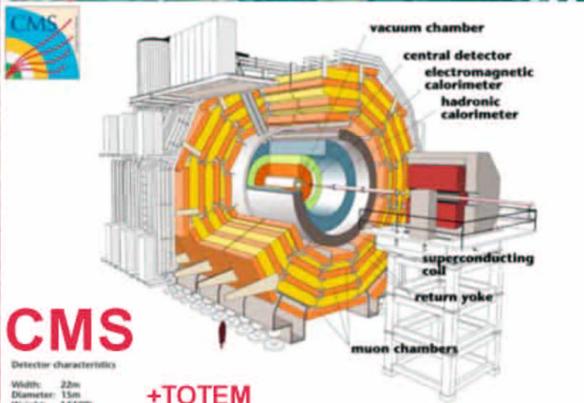


ATLAS



General Purpose,  
pp, heavy ions

Heavy ions, pp



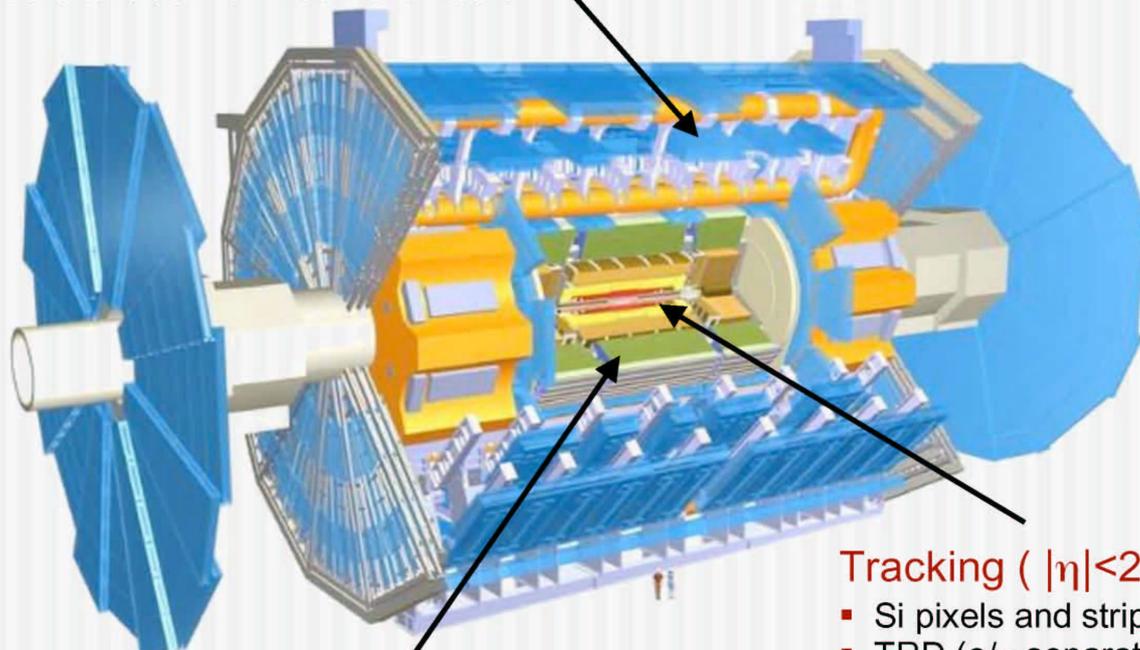


# ATLAS

- Introduction
- Status of
- Machine
- Detectors**
- Startup of
- Machine
- Detectors
- First Physics
- Phys. Reach

## Muon Spectrometer ( $|\eta| < 2.7$ )

- air-core toroids with muon chambers



## Tracking ( $|\eta| < 2.5, B=2T$ )

- Si pixels and strips
- TRD (e/π separation)

## Calorimetry ( $|\eta| < 5$ )

- EM : Pb-LAr
- HAD : Fe/scintillator (central), Cu/W-Lar (fwd)

Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 tons

Gomes  
Tartarelli  
Gonzalez  
Teuscher  
Dubbart  
Haller  
Gossens



# CMS

- Introduction
- Status of Machine
- Detectors**
- Startup of Machine
- Detectors
- First Physics
- Phys. Reach

Cavallari  
Colaleo  
Klein  
Hernandez  
Varela

**Superconducting Coil, 4 Tesla**

**CALORIMETERS**

**ECAL**

76k scintillating PbWO4 crystals

**HCAL**

Plastic scintillator/brass sandwich

**IRON YOKE**

**TRACKER**

Pixels  
Silicon Microstrips  
210 m<sup>2</sup> of silicon sensors  
9.6M channels

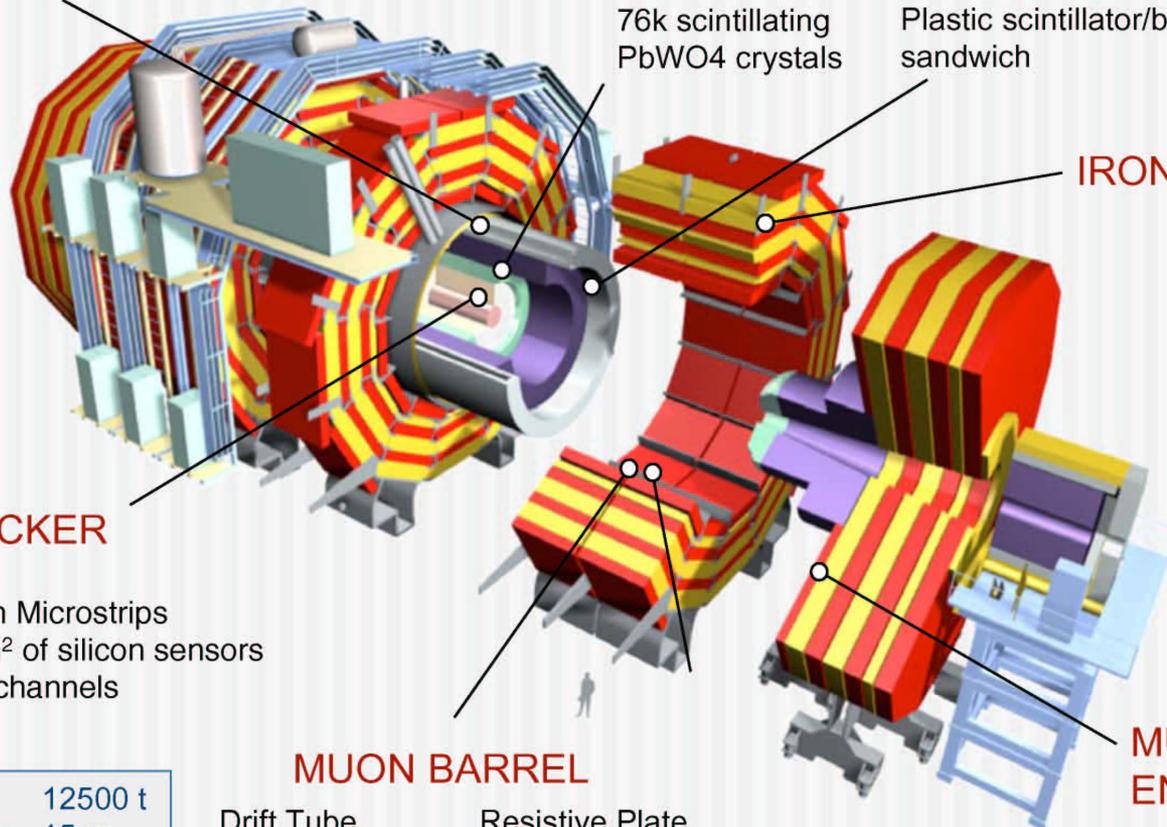
**MUON BARREL**

Drift Tube Chambers (**DT**)      Resistive Plate Chambers (**RPC**)

**MUON ENDCAPS**

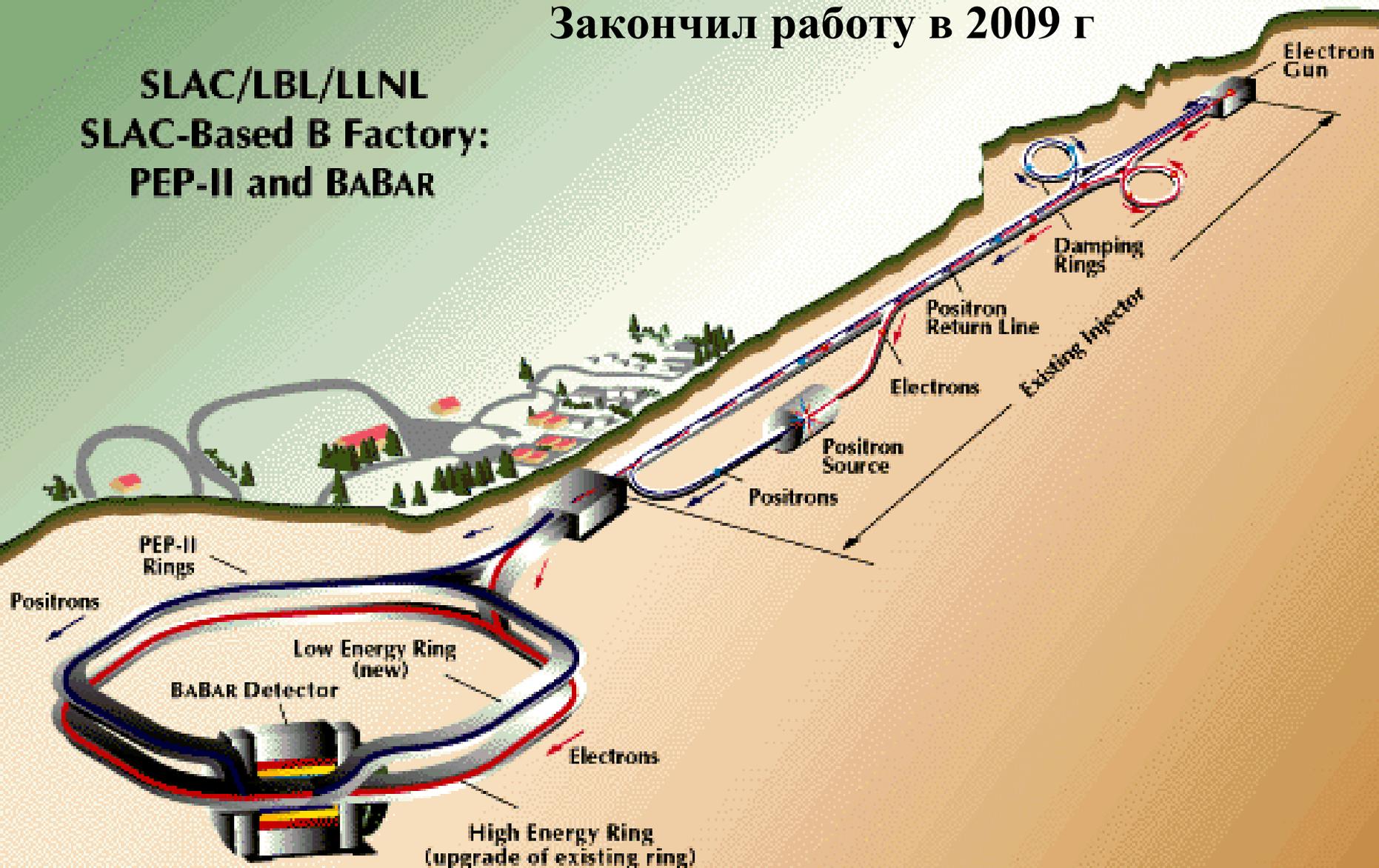
Cathode Strip Chambers (**CSC**)  
Resistive Plate Chambers (**RPC**)

Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

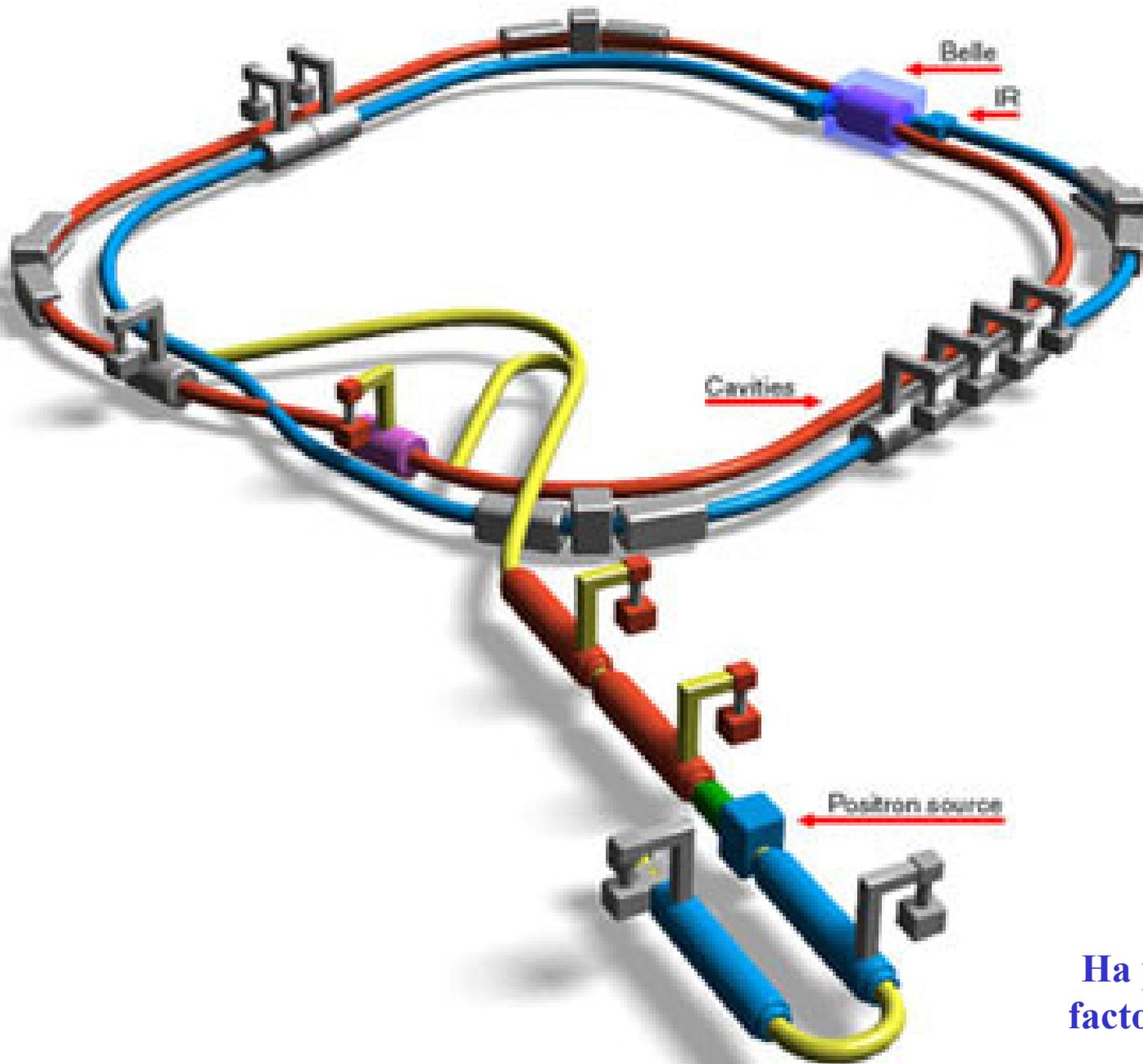


Закончил работу в 2009 г

SLAC/LBL/LLNL  
SLAC-Based B Factory:  
PEP-II and BABAR



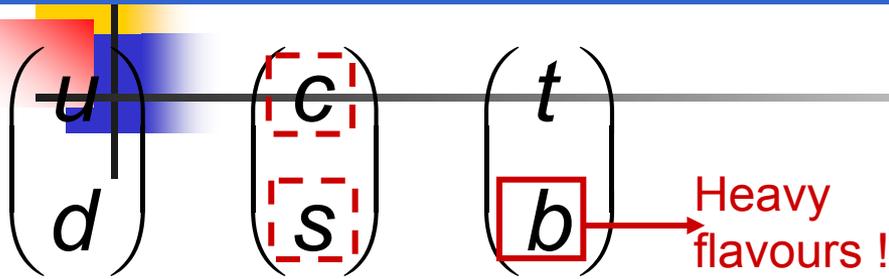
Both Rings Housed in Current PEP Tunnel



# KEK-B Factory

На реконструкции:  
factory → superfactory

# Framework : the CKM matrix

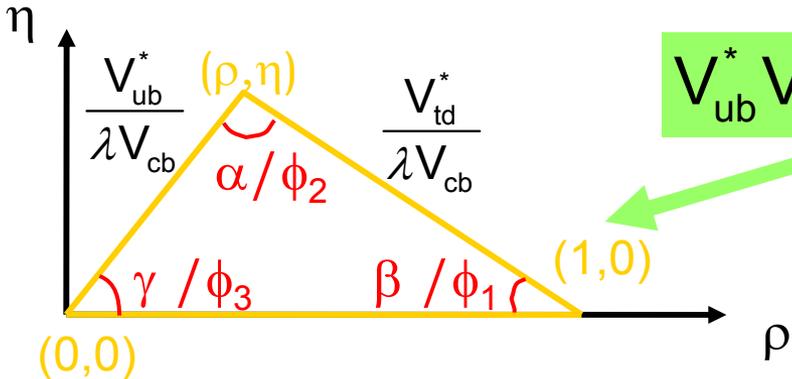


$$\lambda = \sin(\theta_c) = 0.2256 \pm 0.0014$$

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2 & \lambda & A \lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A \lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A \lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

CP violation

The unitarity triangle :

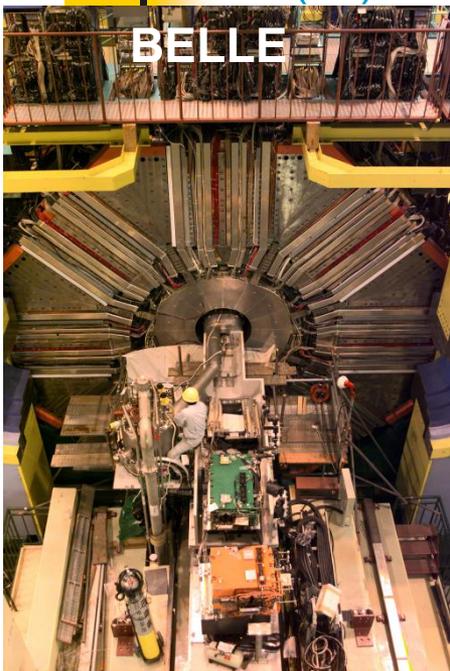


$$V_{ub}^* V_{ud} + V_{tb}^* V_{td} + V_{cb}^* V_{cd} = 0$$

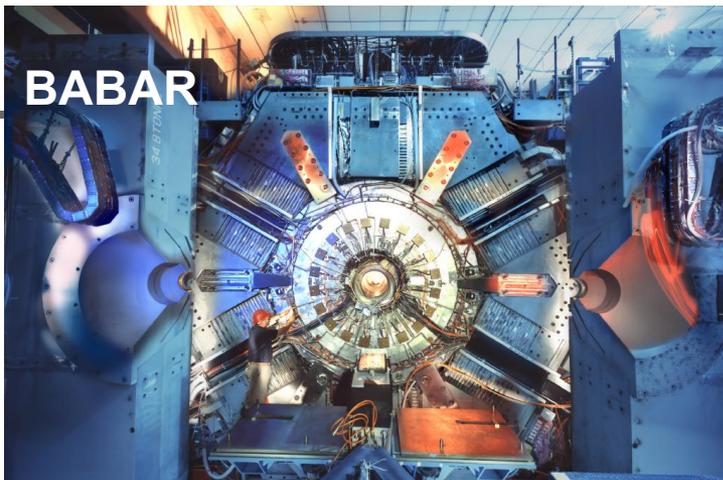
# Some of the experiments

$$e^+e^- \rightarrow Y(4s)$$

BELLE

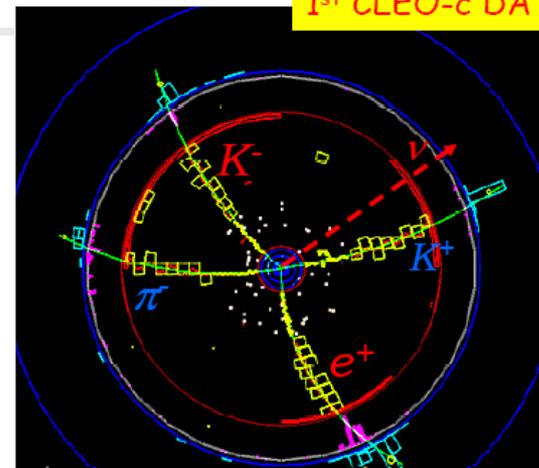


BABAR



$$e^+e^- \rightarrow \psi''(3770)$$

1<sup>st</sup> CLEO-c DATA



$\bar{D}^0 \rightarrow K\pi$

$D^0 \rightarrow K e \nu$

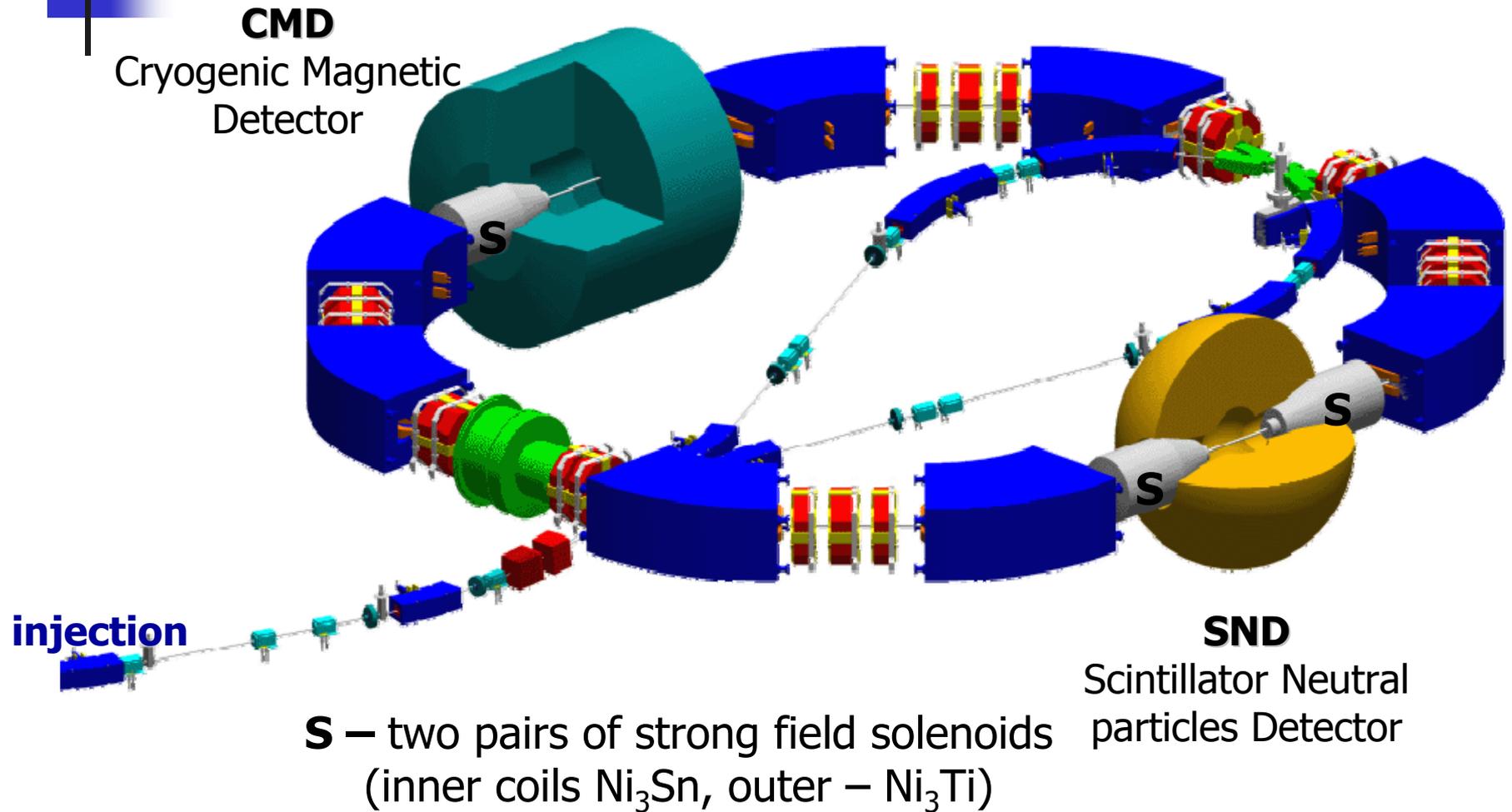
$p\bar{p}$

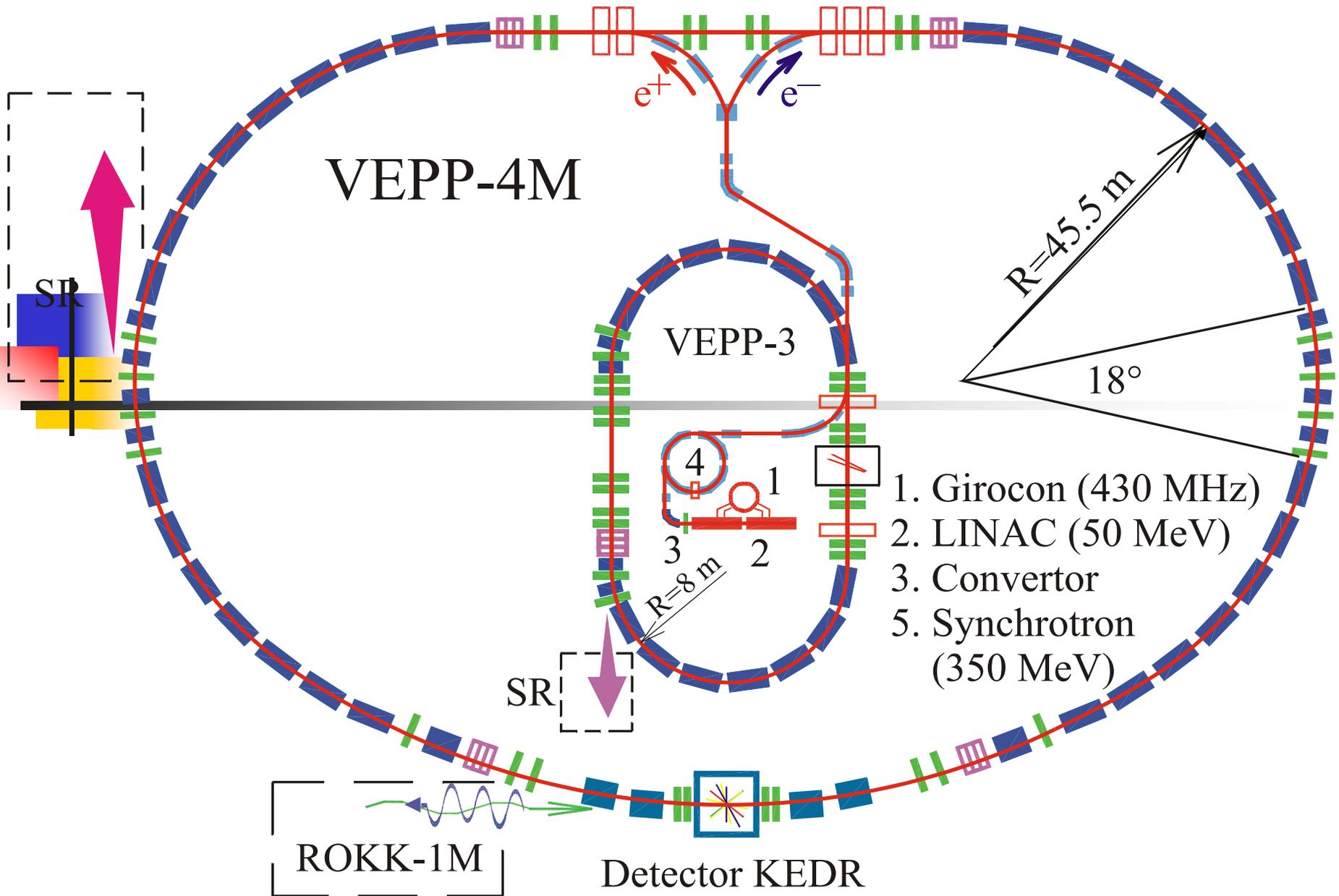
$\sqrt{s} = 1.96 \text{ TeV}$



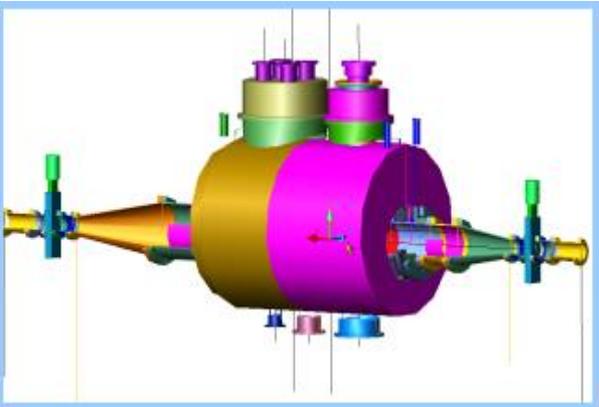
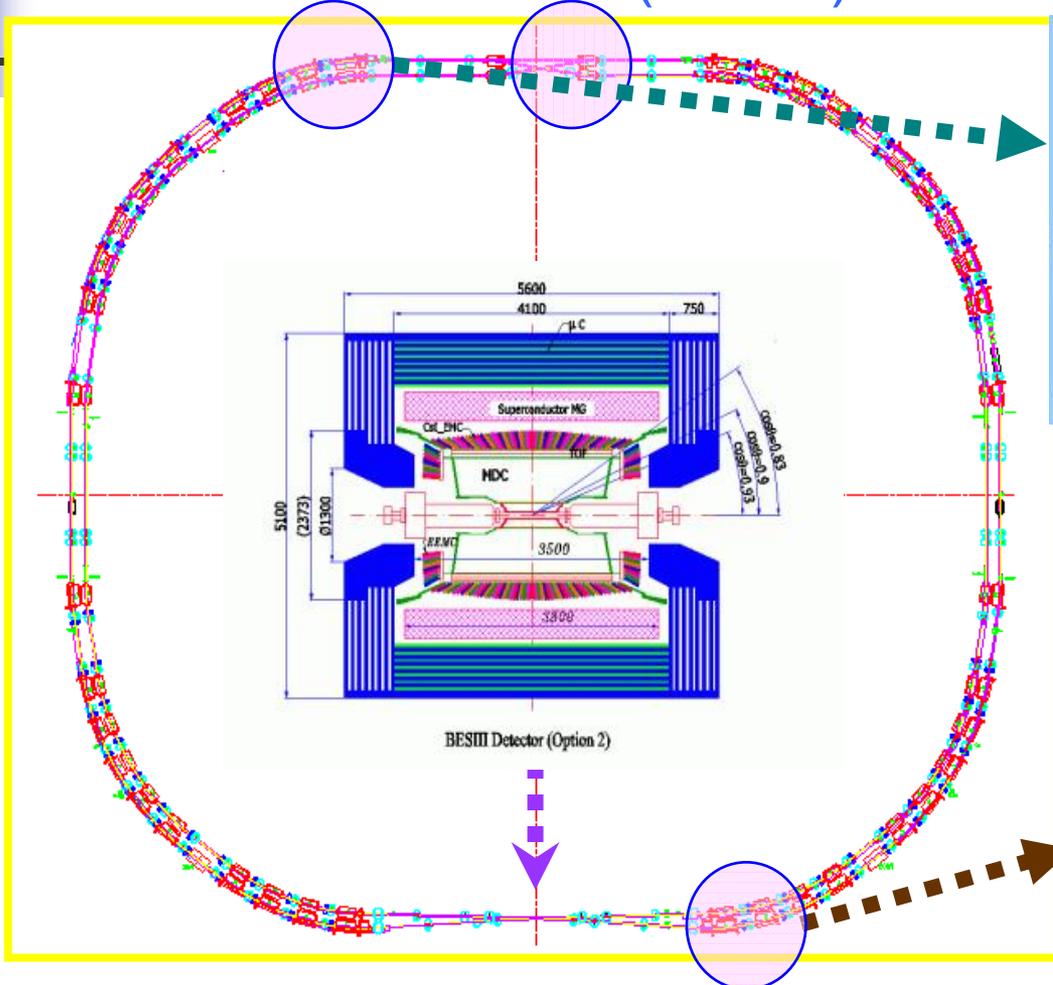
# Nearest future: round beams **VEPP-2000 Collider**

Status: assembling

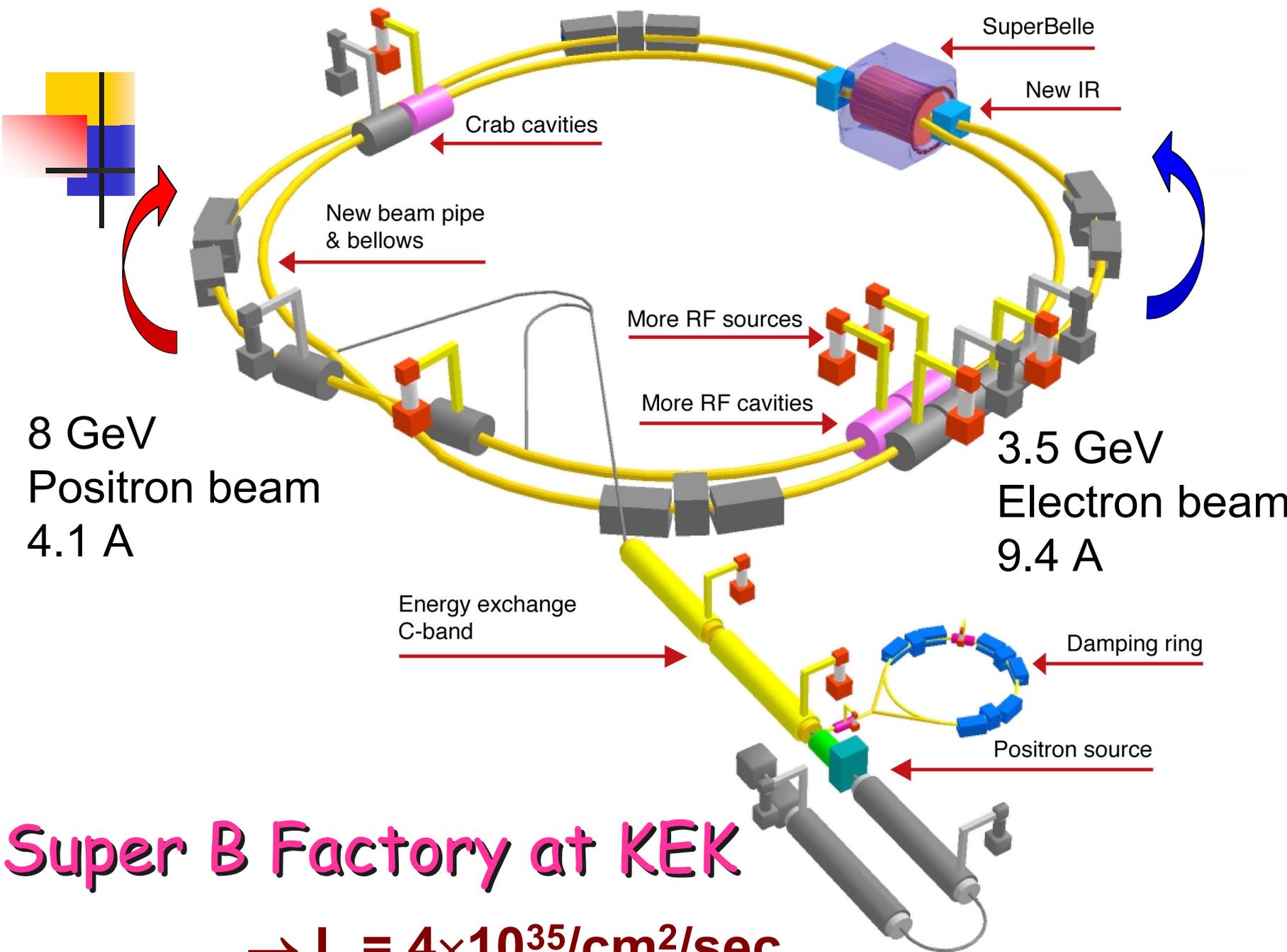




# BEPCII: a high luminosity double-ring collider (Китай)



Работает в настоящее время  $L=10^{33}$  (с,т фабрика)



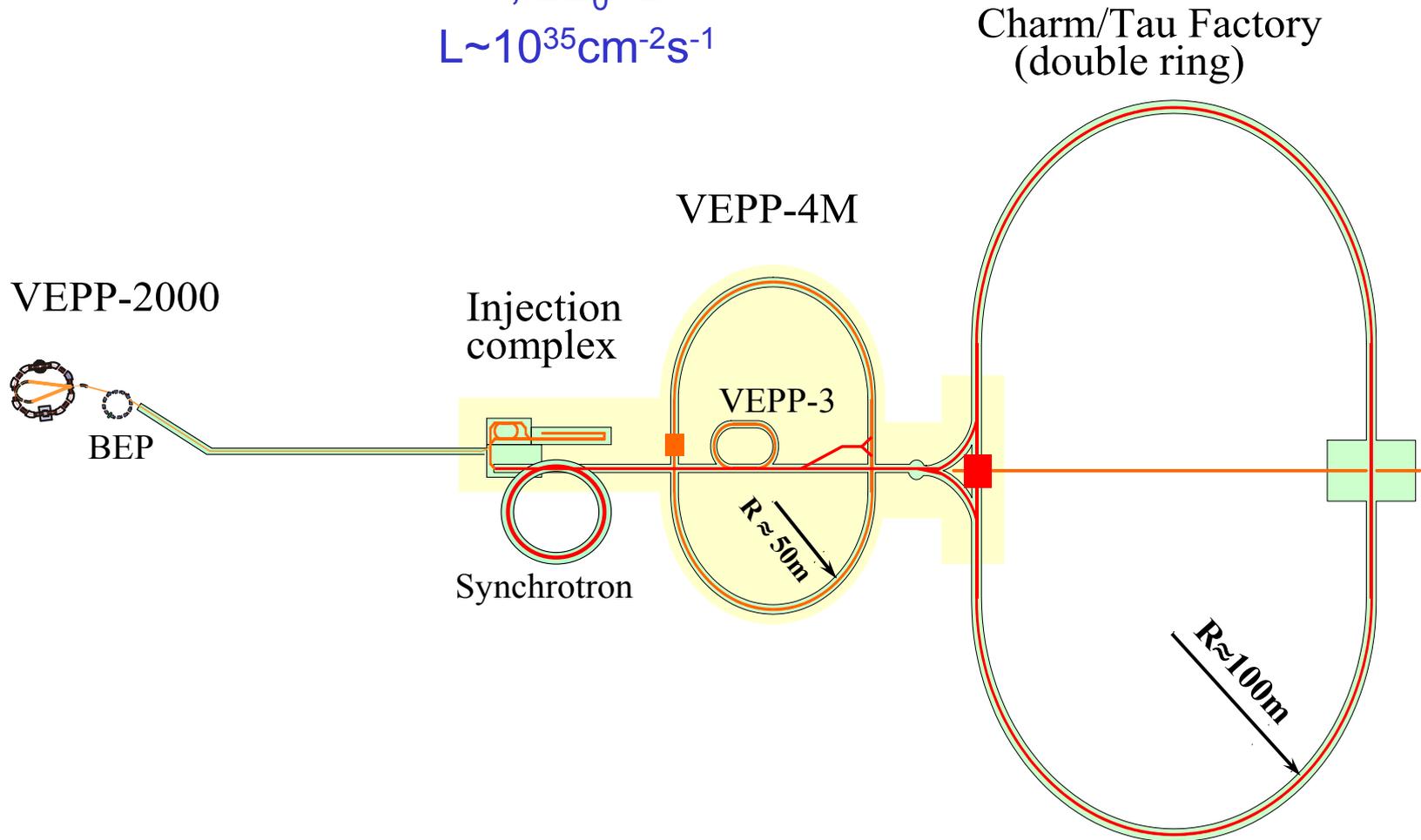
# Super B Factory at KEK

→  $L = 4 \times 10^{35} / \text{cm}^2 / \text{sec}$

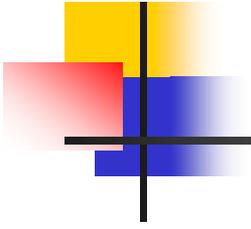
# charm- $\tau$ –factory

$e^+e^-$ ,  $2E_0 \sim 2-5$  GeV

$L \sim 10^{35} \text{cm}^{-2}\text{s}^{-1}$



Charm/Tau Factory, разработана в ИЯФ и планировалось строительство, однако в настоящее время (2.2022) (почти) принято решение строить ее около г. Саров (новый центр физики-математики при ядерном центре)

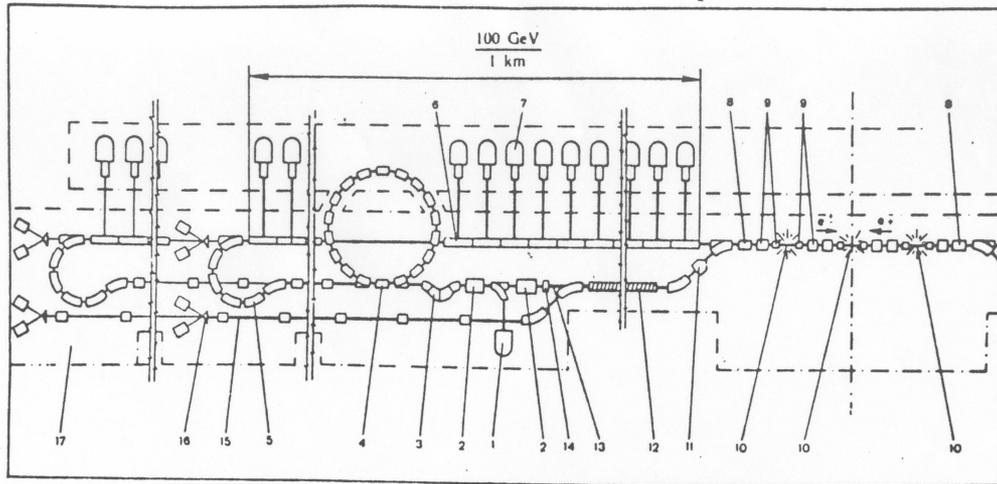


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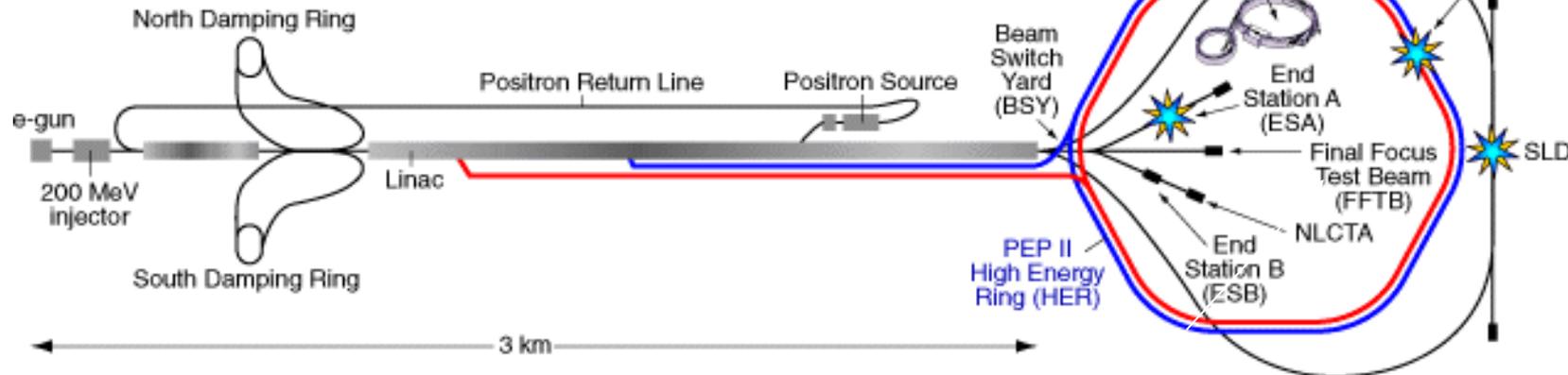
# Линейные коллайдеры

# VLEPP (Novosibirsk)!

(Published proposal 1978)



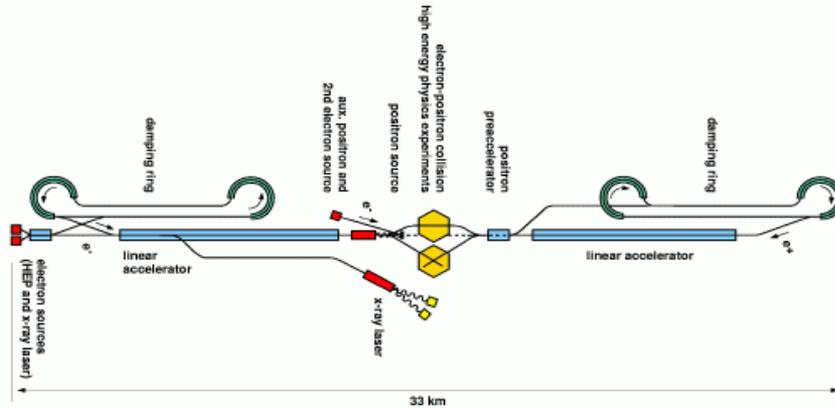
The general lay-out of the VLEPP facility:  
 1—initial injector; 2—intermediate accelerator; 3—debuncher-monochromatizer; 4—storage ring; 5—buncher; 6—accelerating sections; 7—RF-generators; 8—pulse deflector; 9—focusing lenses; 10—collision points; 11—spectrometer; 12—helical undulator; 13—the beam of  $\gamma$ -quanta; 14—conversion target; 15—residual electron (positron) beam; 16—electron (positron) beam experiments; 17—the second stage.



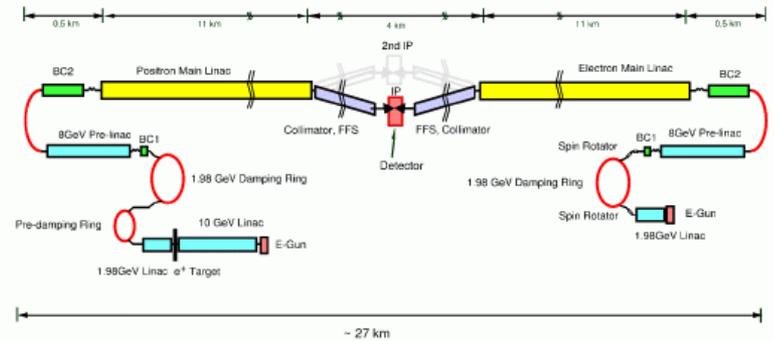
(паб. 1990-2000) **SLC**

# Линейные $e^+e^-$ коллайдеры

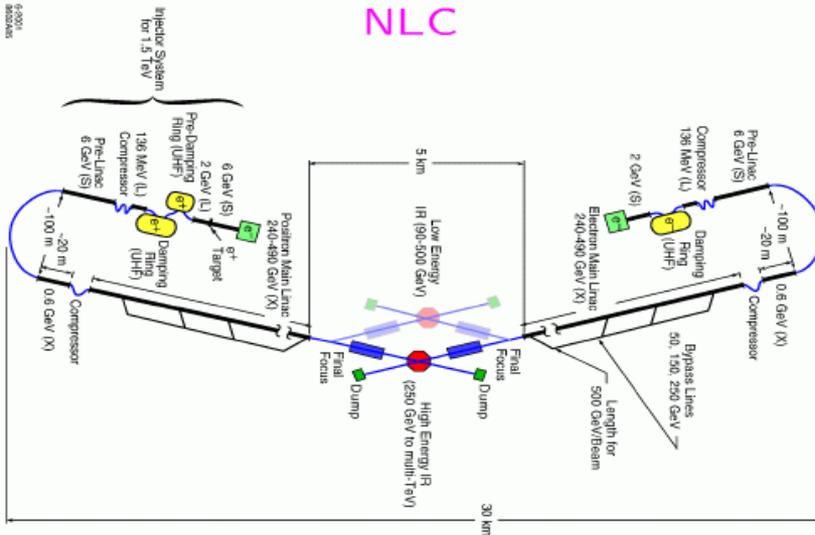
## TESLA



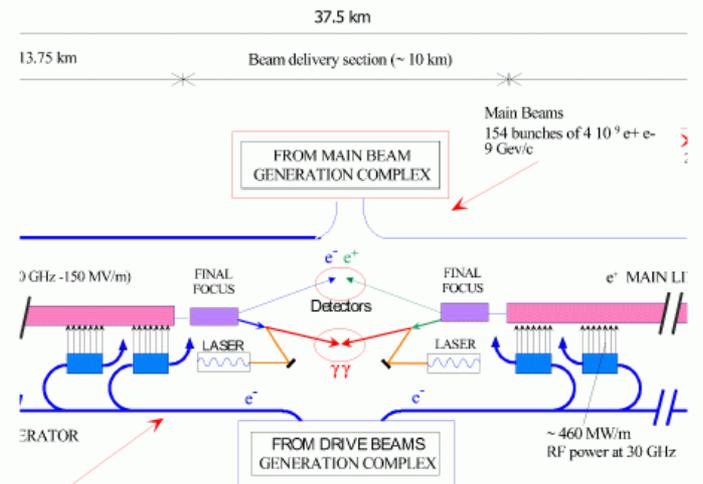
## JLC



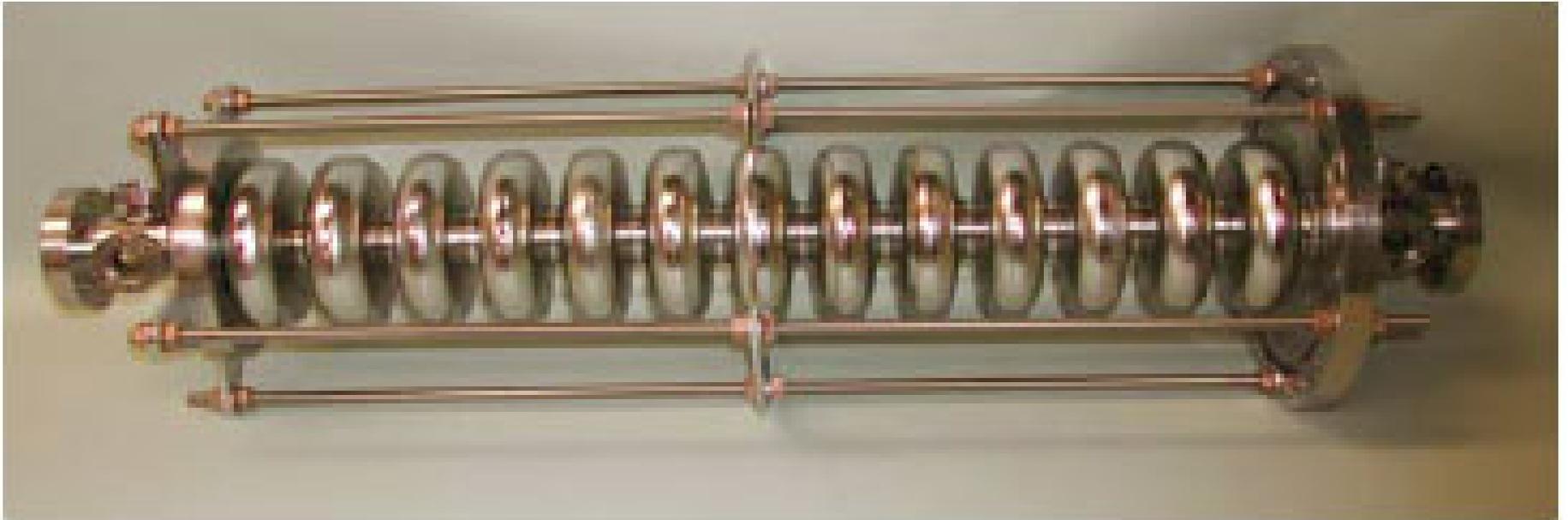
## NLC

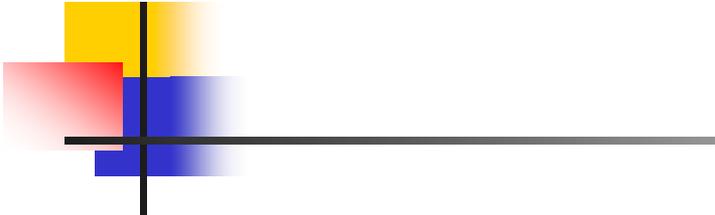


## CLIC



# SC acceleration structure

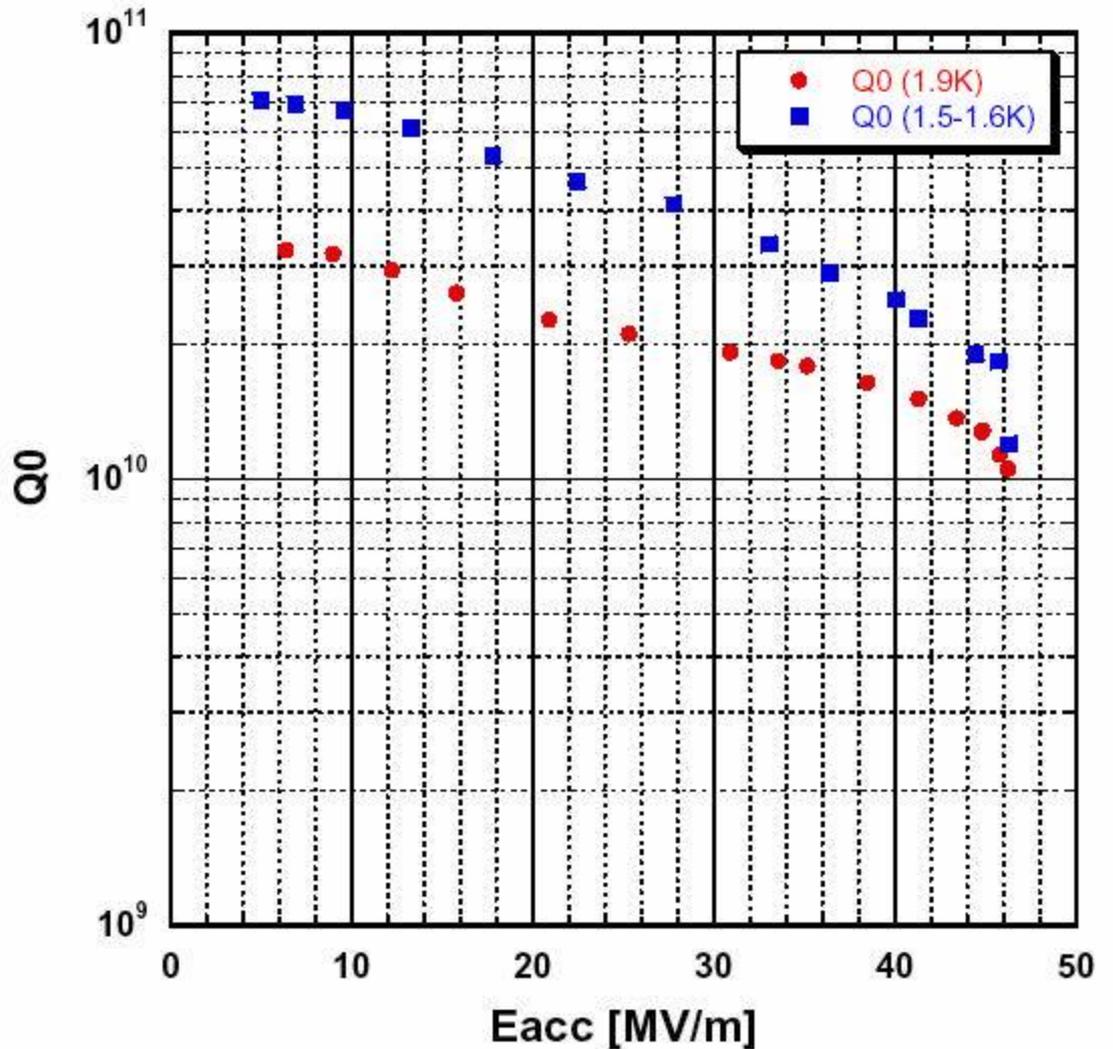


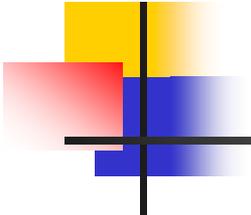


World Record  
 $E_{\text{acc}} = 46.4 \text{ MV/m}$ , **CW**

47 MV/m pulsed

Cornell Reentrant Cavity LR1-2





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В 2004 году принято решение объединить работы по  
лин.коллайдерам и вместо TESLA, NLC, JLC начаты работы  
над

## International Linear Collider (ILC)

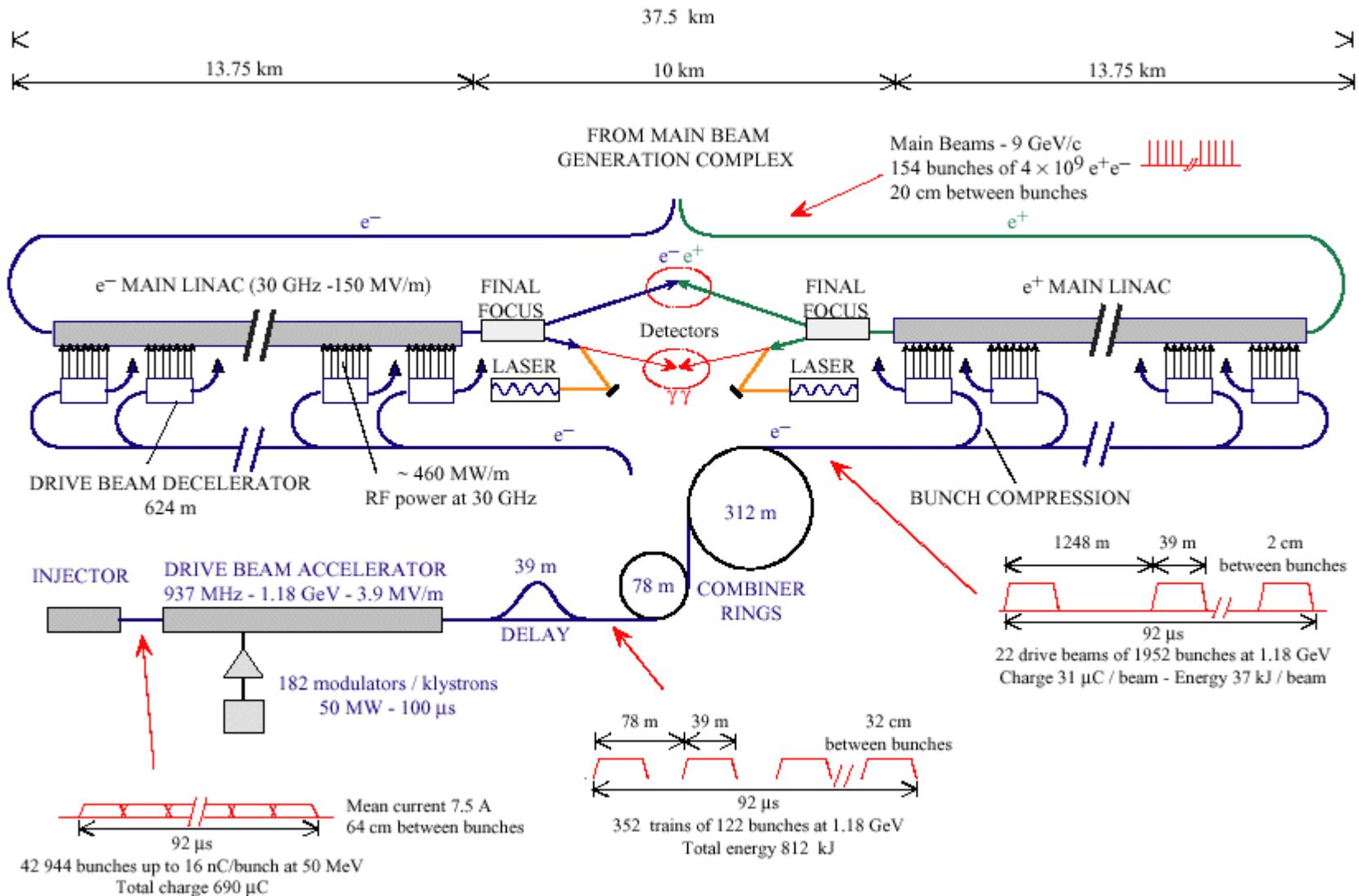
на базе сверхпроводящей технологии (как TESLA)  
на энергию  $2E=500-1000$  ГэВ.

Где и когда еще не решено

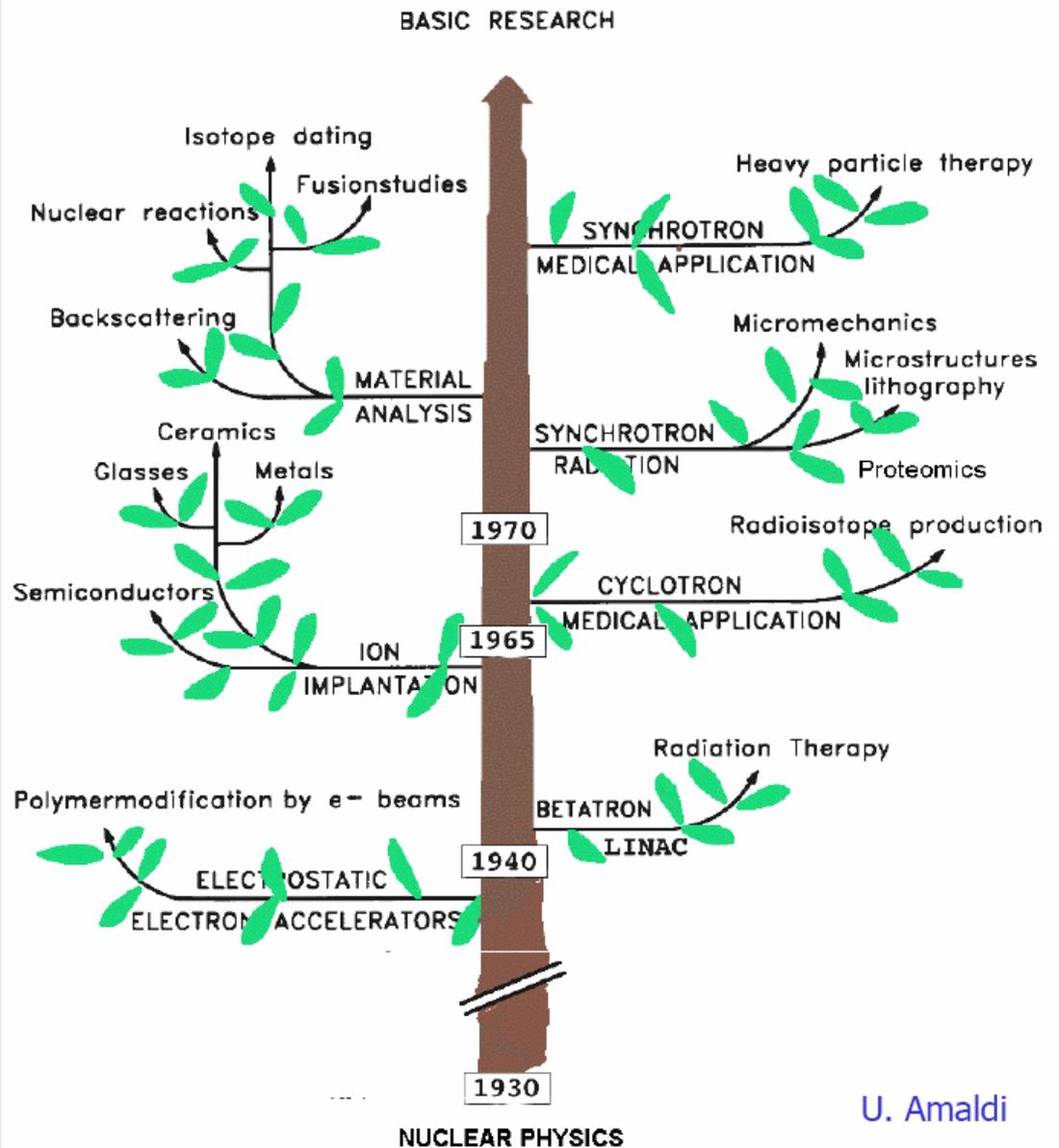


# For higher energies – possibly, CLIC.

## CLIC Complex at 3-5 TeV



# The Time Tree of Accelerators



Будет отдельная лекция о применении ускорителей и детекторов в прикладных задачах