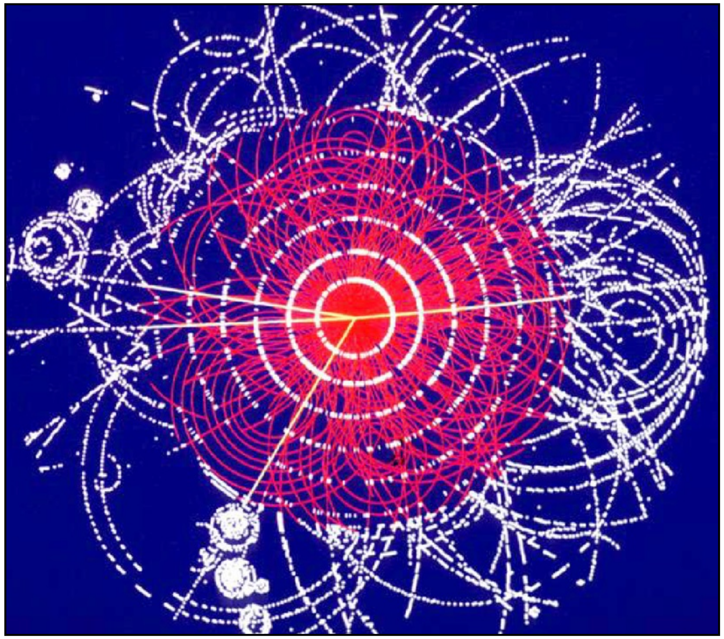
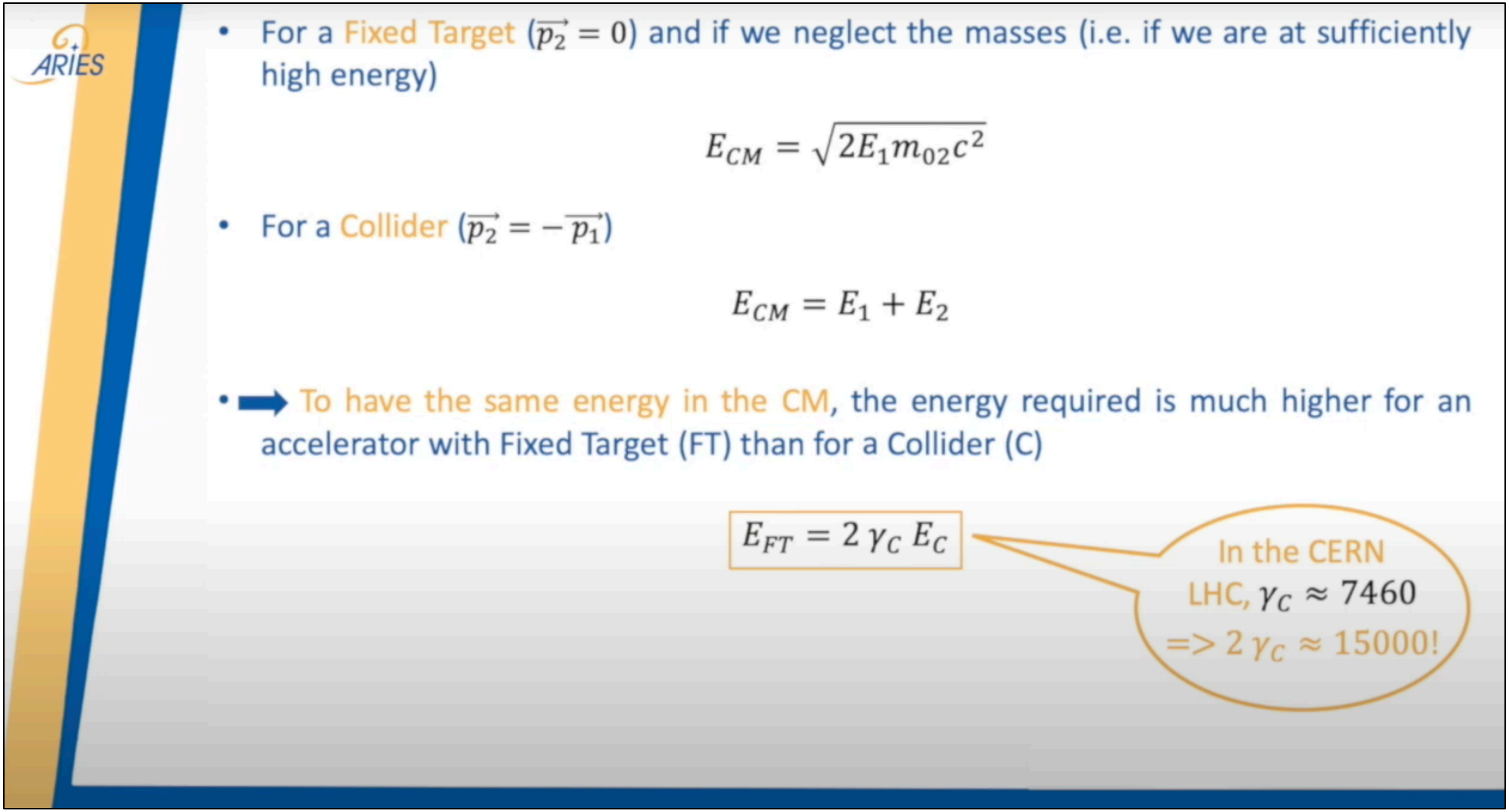
Introduction on Colliders, Luminosity and Pile-Up

(for dedicated session on colliders tomorrow afternoon)

E. Métral and L. Rinolfi



Reminder from the 1st day:
Collider CM energy



- For a Fixed Target ($\vec{p_2} = 0$) and if we neglect the masses (i.e. if we are at sufficiently high energy)

$$E_{CM} = \sqrt{2E_1 m_{02} c^2}$$

- For a Collider ($\vec{p_2} = -\vec{p_1}$)

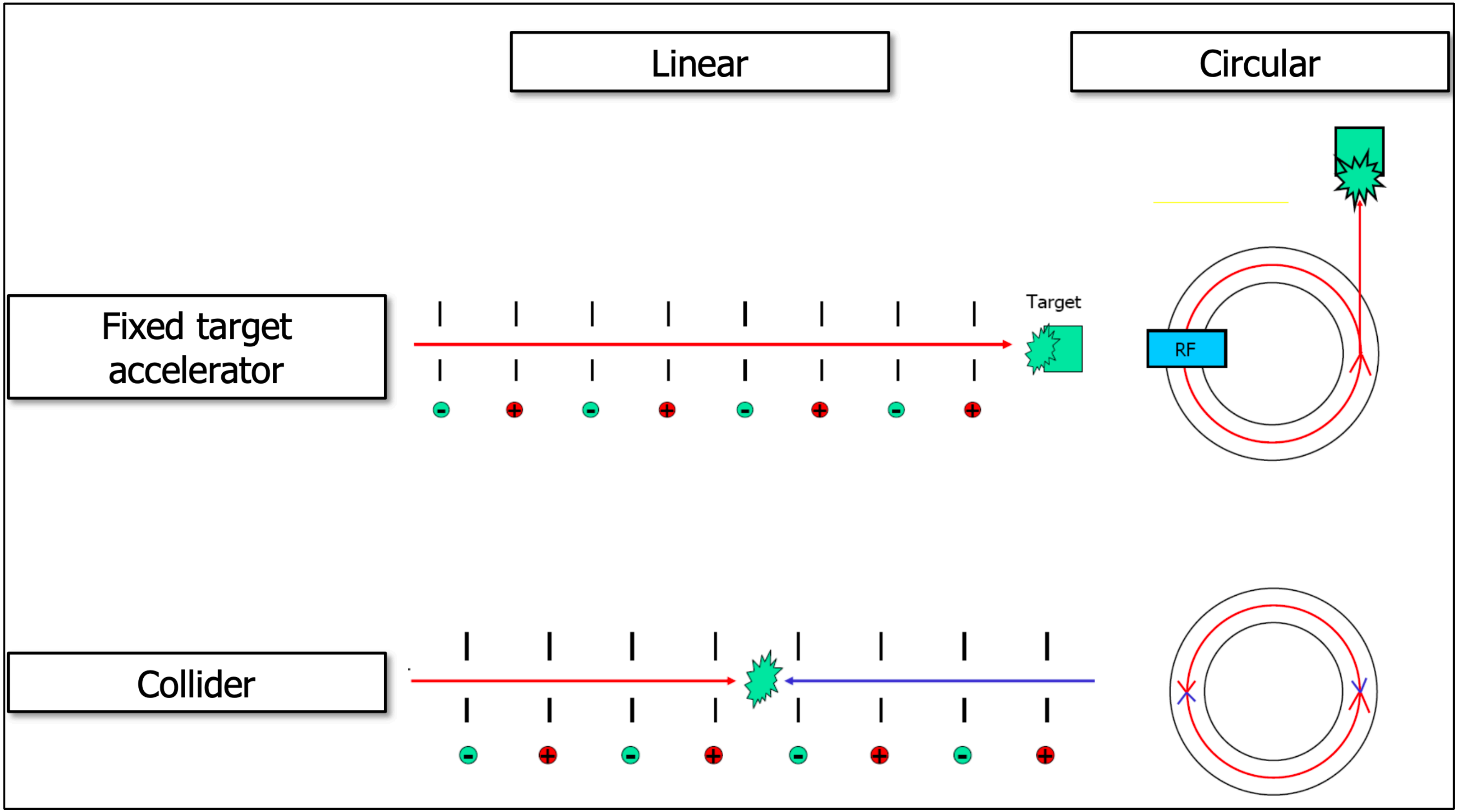
$$E_{CM} = E_1 + E_2$$

- ➡ To have the same energy in the CM, the energy required is much higher for an accelerator with Fixed Target (FT) than for a Collider (C)

$$\boxed{E_{FT} = 2\,\gamma_C\,E_C}$$

In the CERN LHC, $\gamma_C \approx 7460$ => $2\,\gamma_C \approx 15000$!

Reminder from the 1st day:
Collider shape



Linear

Circular

Fixed target accelerator

Collider

Why colliders?

Why colliders? => Particle discoveries and precision measurements

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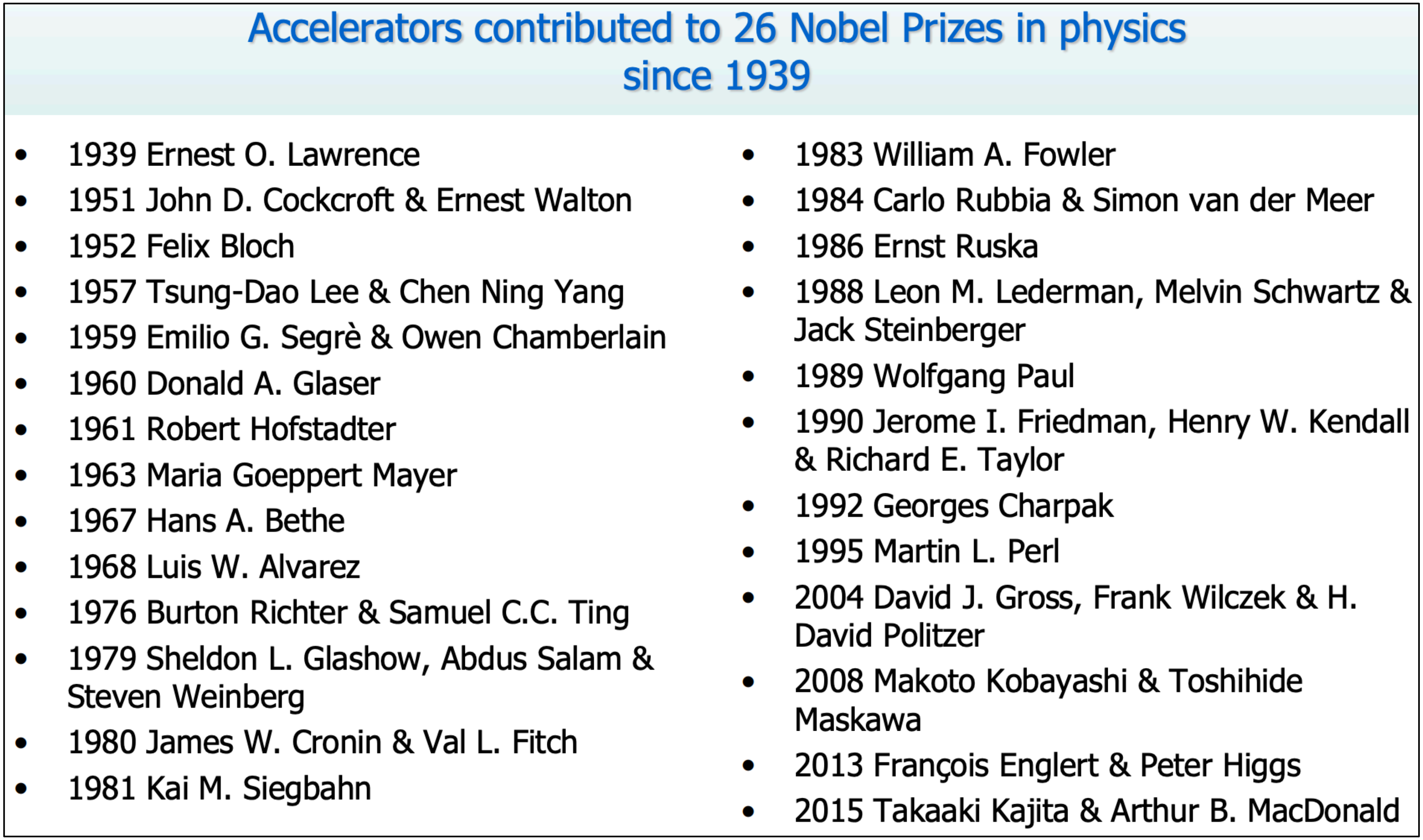

Accelerators contributed to 26 Nobel Prizes in physics since 1939

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- 2015 Takaaki Kajita & Arthur B. MacDonald

Courtesy of P. Lebrun (JUAS-2021, will also give a seminar for JUAS-2023 Course 2 on 13/02/2023)

Why colliders? => Particle discoveries and precision measurements

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Higgs boson in the CERN LHC (2012)

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A historical day : 4th July 2012

=> Announcement of the discovery of a new particle (“Higgs-like” boson)

performance of
accelerators – experiments – Grid computing

Observation of a new particle consistent with a Higgs Boson (but which one…?)

Historic Milestone but only the beginning

Global Implications for the future

2013 Nobel prize in physics awarded to F. Englert and P. Higgs for their theoretical work on Higgs boson (1964)

Peter Higgs

Short history of colliders

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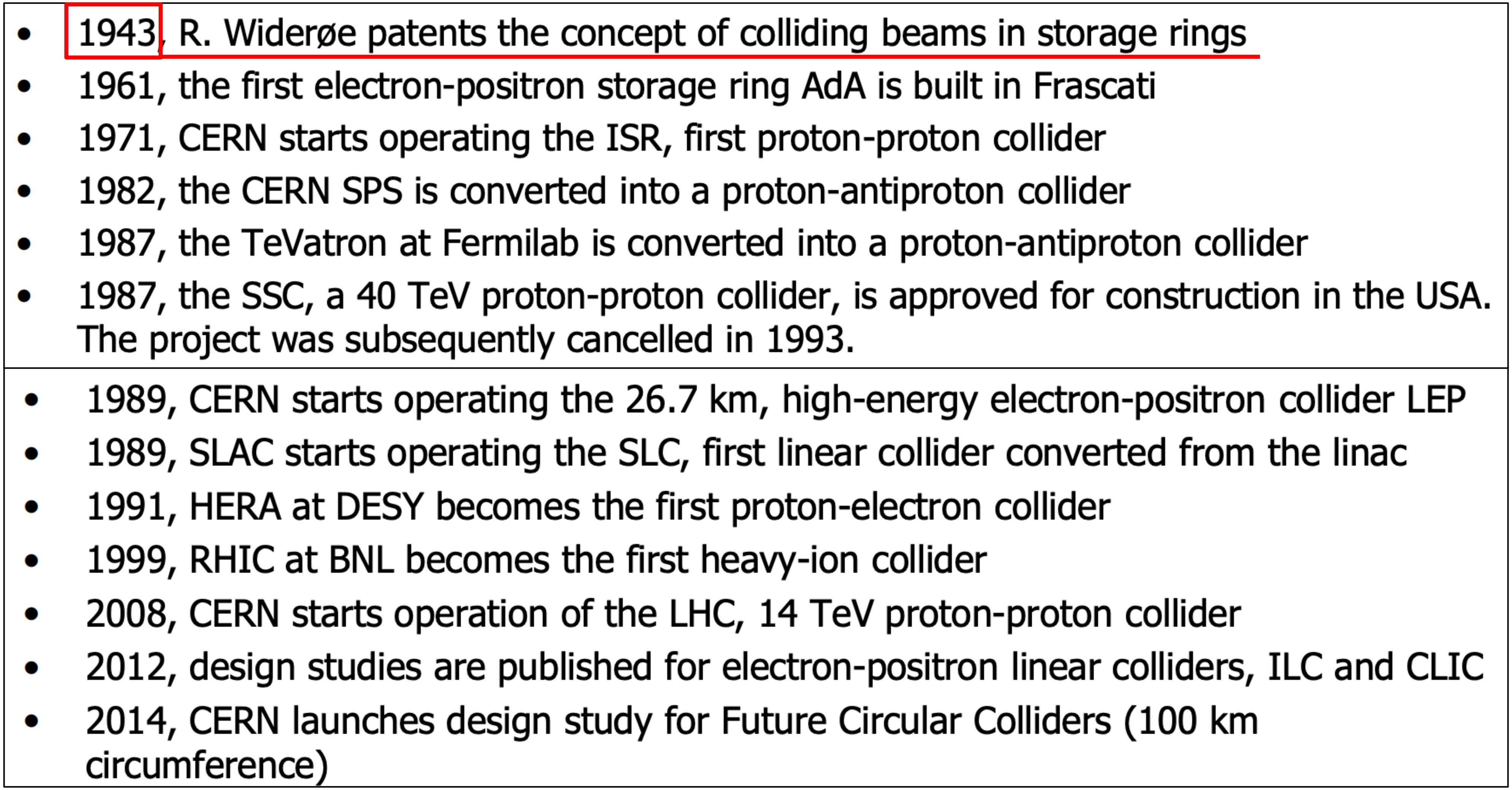

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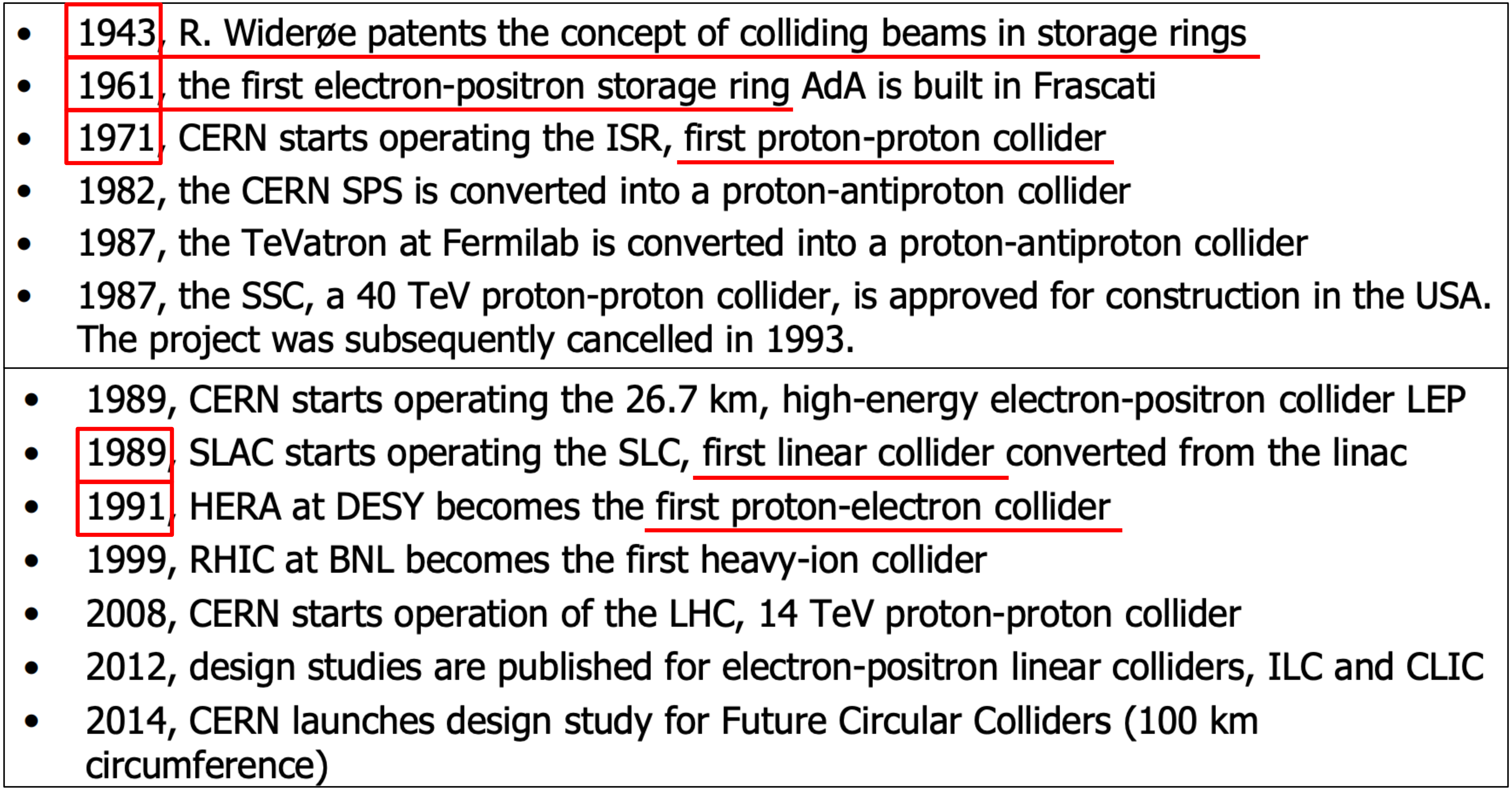

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Hadrons vs. Leptons in circular colliders

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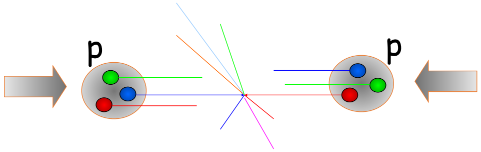

6 quarks

hadron collider => frontier of physics

- discovery machine
- collisions of quarks
- not all nucleon energy available in collision
- huge background

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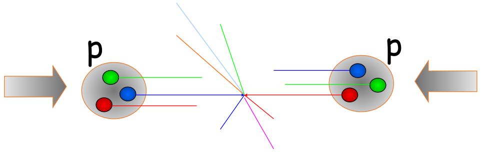

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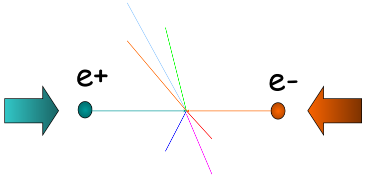
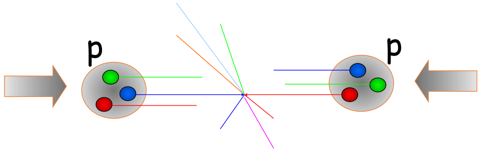


2 leptons

lepton collider => precision physics

- study machine
- elementary particles collisions
- well defined CM energy
- polarization possible

Hadrons vs. Leptons in circular colliders



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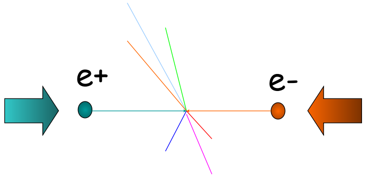
Limited by the dipole field available and the ring size

$$p[\mathrm{GeV/c}] \simeq 0.3 B[\mathrm{T}] \rho[\mathrm{m}]$$

Go to higher magnetic fields (=> Superconducting) or/and large circumferences (=> ten's km)



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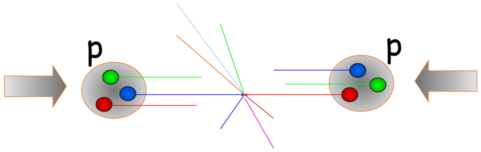

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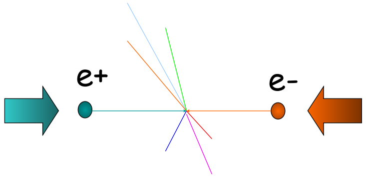

2 leptons

Limited by energy lost from synchrotron radiation

$$U_{lost} \propto \frac{E^4}{\rho E_0^4}$$

↓

lepton collider => precision physics

- –study machine
- –elementary particles collisions
- –well defined CM energy
- –polarization possible

Go to linear colliders or heavier leptons

Luminosity: figure of merit of a collider

The number of events N_{exp} is the product of the cross-section of interest σ_{exp} and the time integral over the instantaneous luminosity $L(t)$

$$\boxed{N_{exp} = \sigma_{exp} \times \int L(t)dt}$$

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$\uparrow$

Nature

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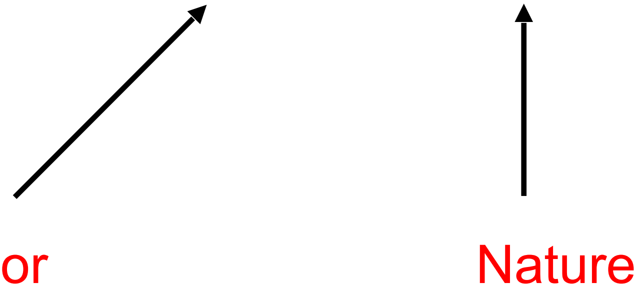

Detector

Nature

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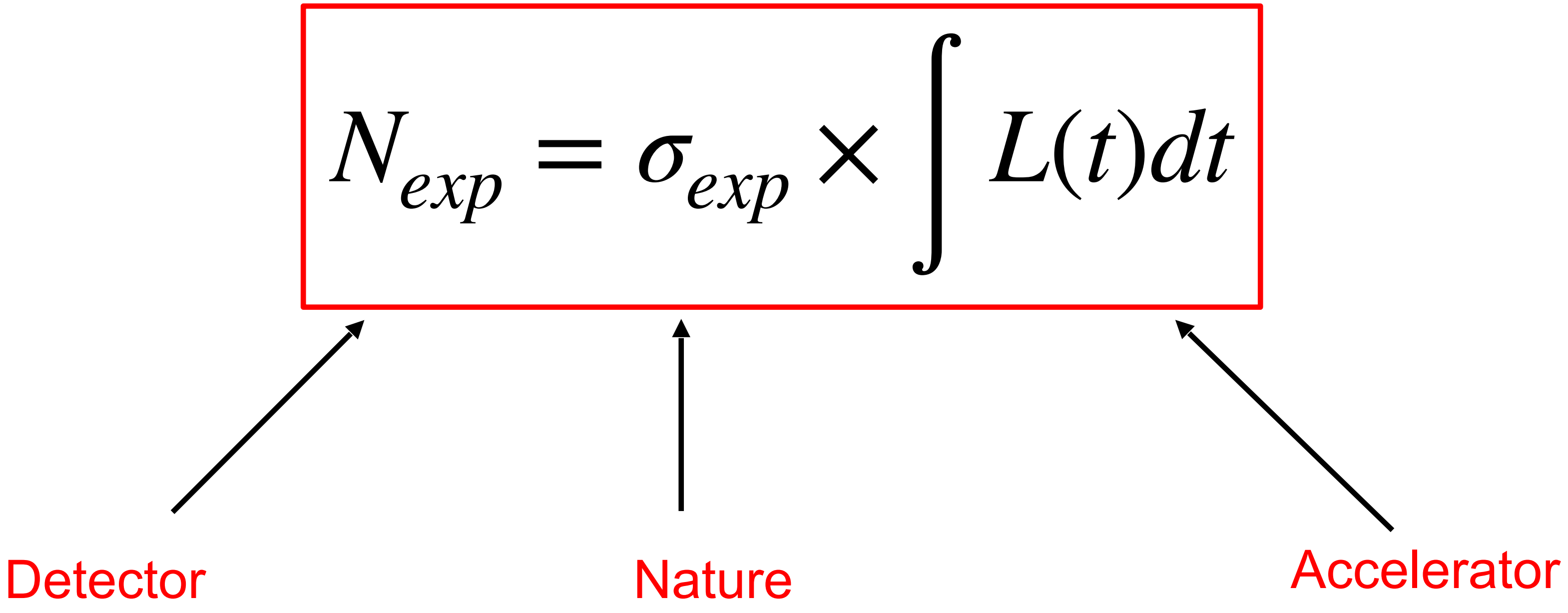
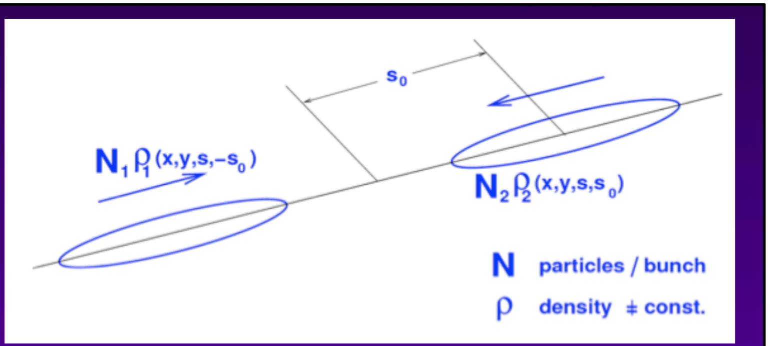


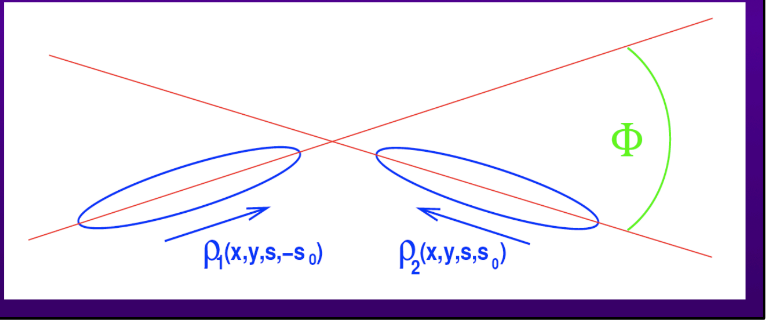
$$\boxed{N_{exp} = \sigma_{exp} \times \int L(t)dt}$$

Luminosity for the SIMPLEST case

- **Collision without crossing angle**



- **Collision with crossing angle (general case)**



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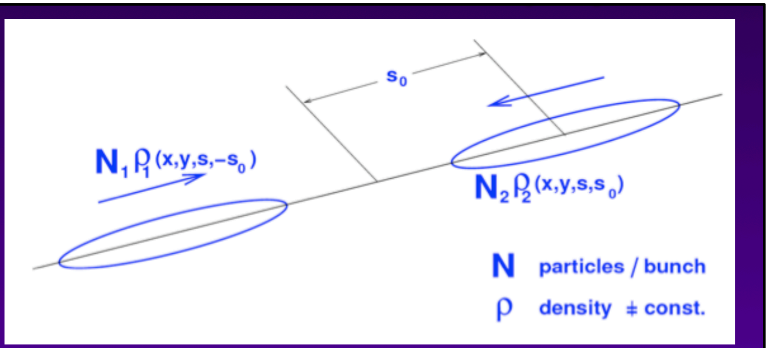

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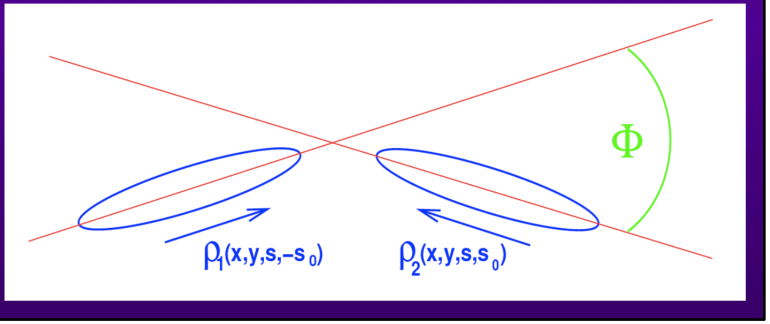

◆ Luminosity in the absence of crossing angle (and transverse beam offset and hourglass effect => See later)

$$\boxed{M f_{rev} = f_{coll}}$$

Number of bunches

$$\boxed{L = M \, N_1 \, N_2 \, f_{rev} \, 2 \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \rho_1 (x , y , s , - s_0) \, \rho_2 (x , y , s , s_0) \, dx \, dy \, ds \, ds_0}$$

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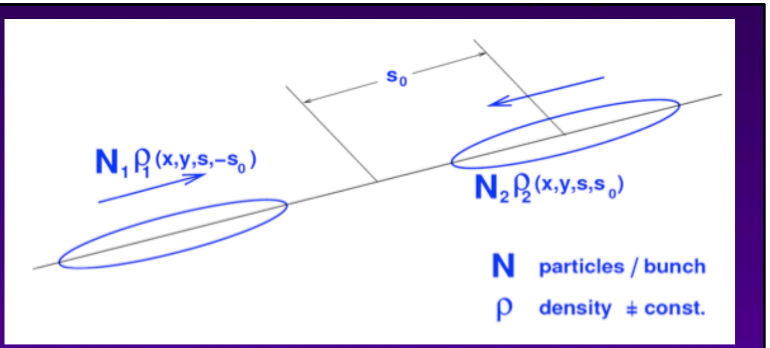

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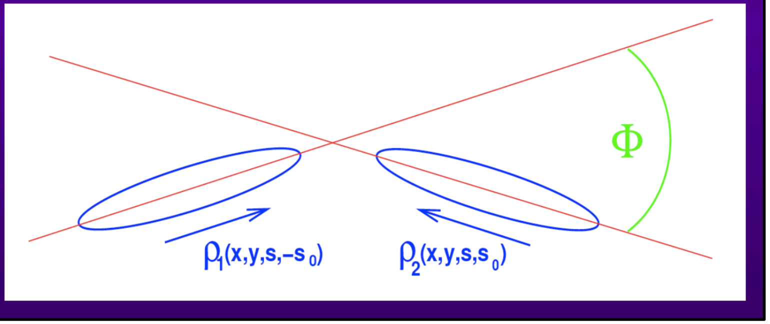

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$$\boxed{M f_{rev} = f_{coll}}$$

Number of bunches

$= M_{KLF}/c$

$$\boxed{L = \underbrace{M}_{\text{Number of bunches}} N_1 N_2 f_{rev}\, \underbrace{2}_{= M_{KLF}/c} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \rho_1(x,y,s,-s_0)\,\rho_2(x,y,s,s_0)\,dx\,dy\,ds\,ds_0}$$

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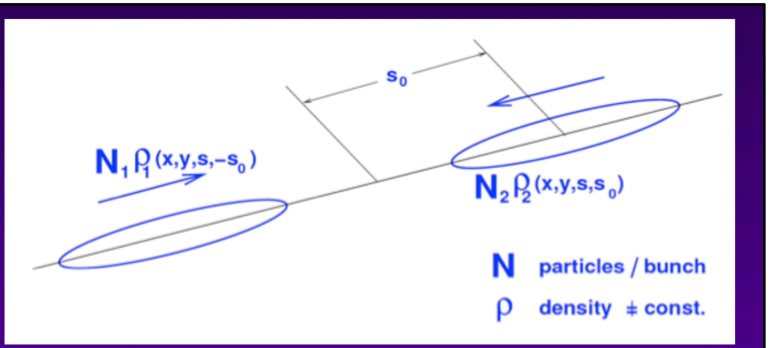

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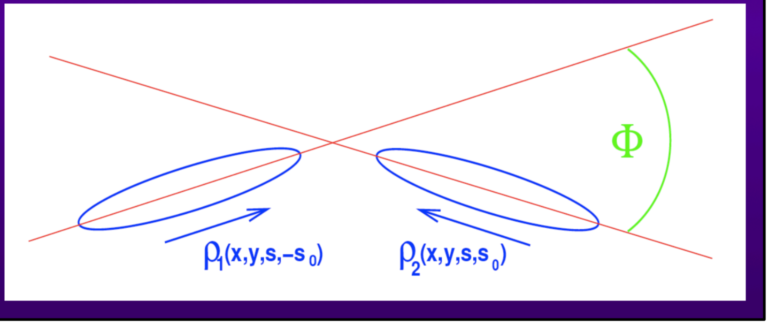

Møller kinematic luminosity factor

$$M_{\mathrm{KLF}} = \sqrt{(\vec{v_1} - \vec{v_2})^2 - \frac{(\vec{v_1} \times \vec{v_2})^2}{c^2}}$$

$$\frac{M_{\mathrm{KLF}}}{c} = \sqrt{\beta_1^2 + \beta_2^2 + 2\beta_1\beta_2 \cos\Phi - \beta_1^2\beta_2^2 \sin^2\Phi}$$

If $\beta_1 = \beta_2 = 1$: $\frac{M_{\mathrm{KLF}}}{c} = 2\cos^2\frac{\Phi}{2}$

◆ Luminosity in the absence of crossing angle (and transverse beam offset and hourglass effect => See later)

$$M f_{rev} = f_{coll}$$

$$L = \overset{\text{Number of bunches}}{M}\, N_1\, N_2\, f_{rev}\, \overset{= M_{KLF}/c}{\boxed{2}} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \rho_1(x,y,s,-s_0)\,\rho_2(x,y,s,s_0)\,dx\,dy\,ds\,ds_0$$

Luminosity for the **SIMPLEST case**

- With several assumptions
  - 1) Uncorrelated densities in all planes
  - 2) Gaussian distributions in all dimensions
  - 3) Same longitudinal dimension for both beams (rms beam size σ_s)
  - 4) Same transverse dimensions for both beams (rms beam sizes σ_x and σ_y)
  - 5) No modifications during the bunch crossing

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the simplest formula for the **peak luminosity** is obtained

$$L = \frac{M\, N_1\, N_2\, f_{rev}}{4\, \pi\, \sigma_x\, \sigma_y}$$

Let's call it L_0

Luminosity for the SIMPLEST case

- Assuming now a round beam ($\sigma_x = \sigma_y = \sigma$), but flat optics can also be used, and the same bunch intensities ($N_1 = N_2 = N_b$), this leads to

$$\boxed{L_0 = \frac{M\, N_b^2\, f_{rev}\, \beta\, \gamma}{4\, \pi\, \beta^*\, \varepsilon_n}}$$

using $\varepsilon_n = \beta\, \gamma\, \varepsilon = \beta\, \gamma\, \frac{\sigma^2}{\beta^*}$

Normalized transverse beam emittance

β-function at the collision point

Luminosity for the GENERAL case

- In the general case: $\boxed{L = L_0 \times F \text{ with } 0 \leq F \leq 1}$

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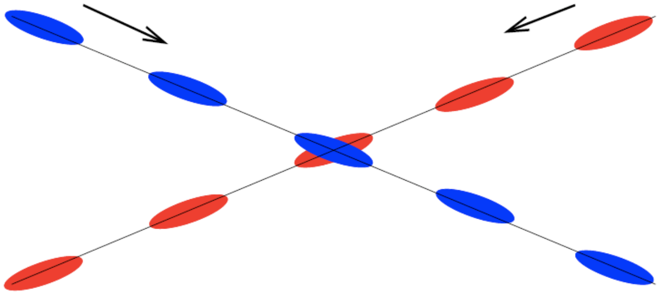
  - **Crossing angle**



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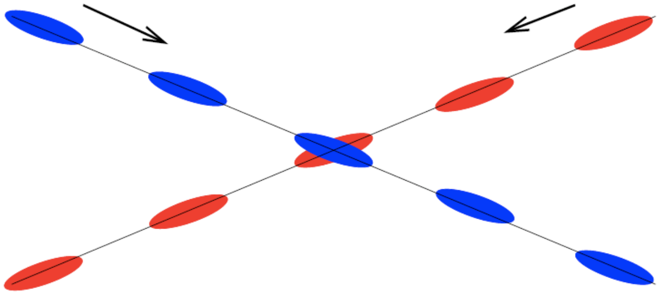

$$F_{CA} = \frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_x} \tan \frac{\Phi}{2} \right)^2}}$$

tan Φ / 2 ~ Φ / 2

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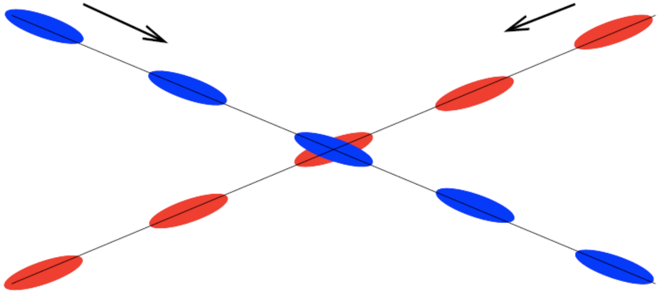

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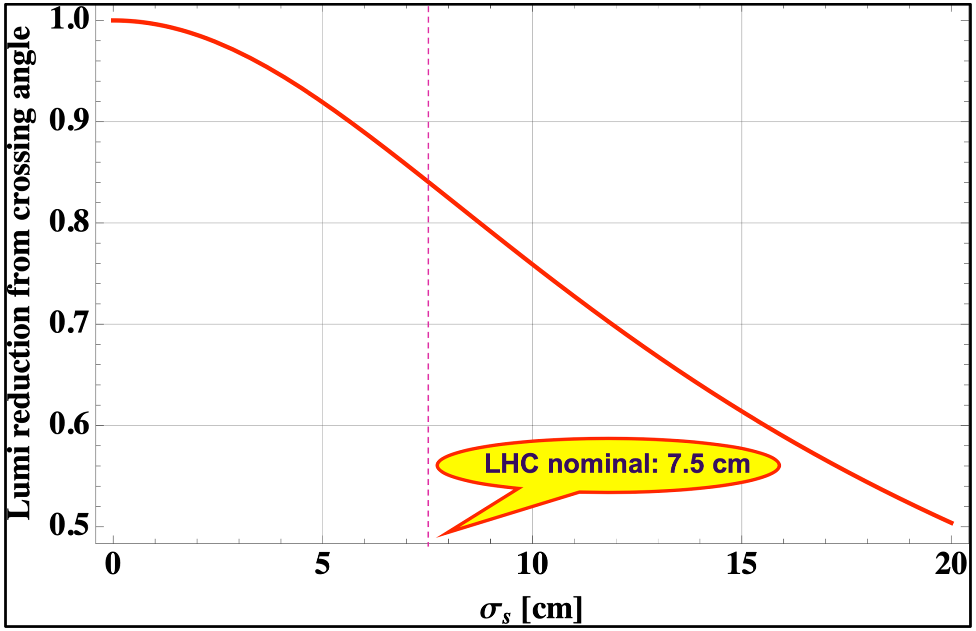

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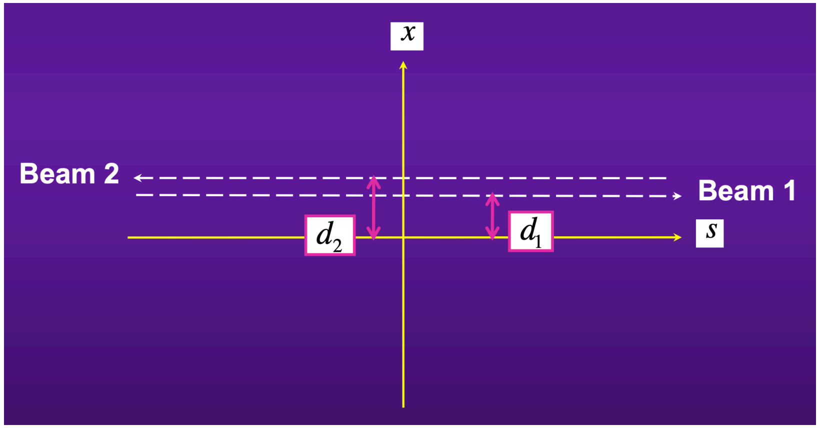

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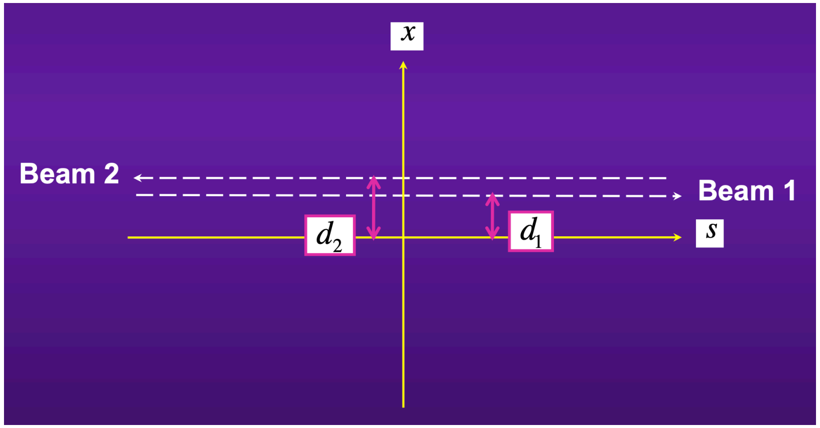

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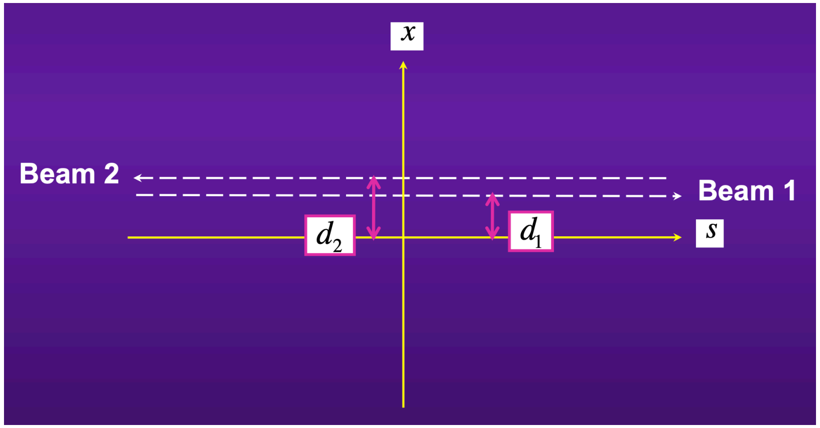

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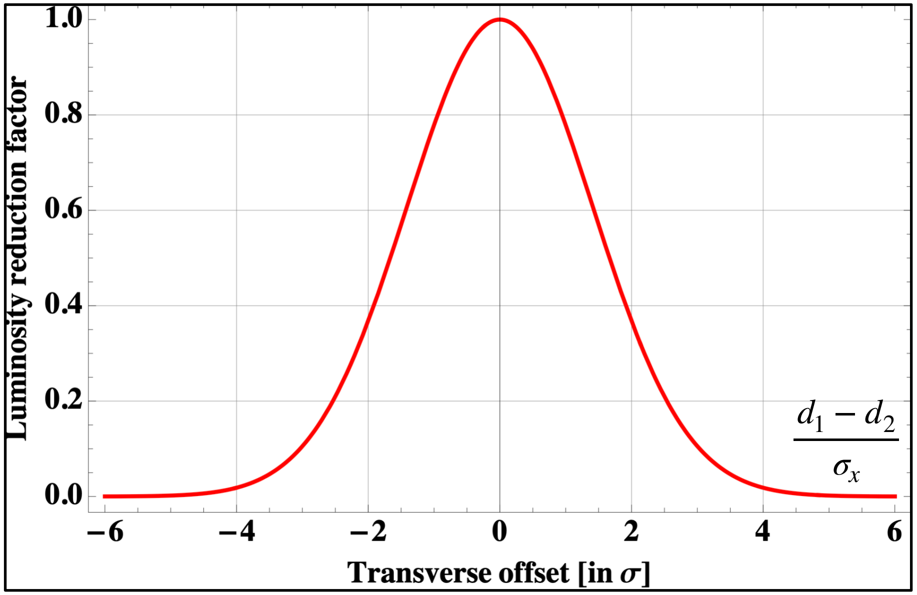

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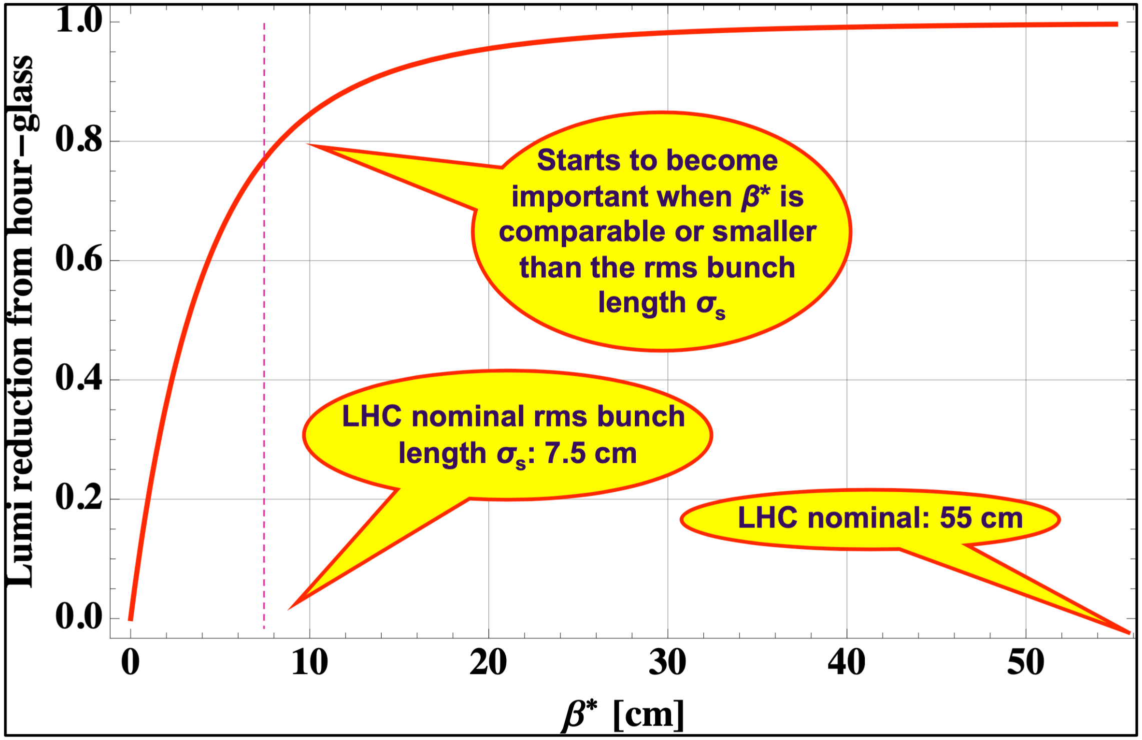

Starts to become important when β^* is comparable or smaller than the rms bunch length σ_s

LHC nominal rms bunch length σ_s: 7.5 cm

LHC nominal: 55 cm

Luminosity **units**

- The unit of the cross-section (σ_{exp}) is the **barn**:

$$1 \text{ barn} = 10^{-28}\ \text{m}^2 = 10^{-24}\ \text{cm}^2$$

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$$1\ \mu\text{b}^{-1} = 10^{34}\ \text{m}^{-2} = 10^{30}\ \text{cm}^{-2}$$

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- Thus if a detector has accumulated 100 fb^{-1} of integrated luminosity, one expects to find 100 events per femtobarn of cross-section within these data

INTEGRATED LUMINOSITY AND MAXIMIZATION (1/4)

- **Integrated luminosity** $$L_{\text{int}} = \int_0^T L(t)\,dt$$

- **Real figure of merit** $$L_{\text{int}}\,\sigma_{exp} = \text{number of events}$$

- **Let's assume some luminosity lifetime behaviour => Exponential decay (due to intensity decay, emittance growth, etc.)**

$$L(t) = L_{peak}\, e^{-\frac{t}{\tau_l}}$$

Luminosity lifetime

- **What is the best run time t_r?**

INTEGRATED LUMINOSITY AND MAXIMIZATION (2/4)

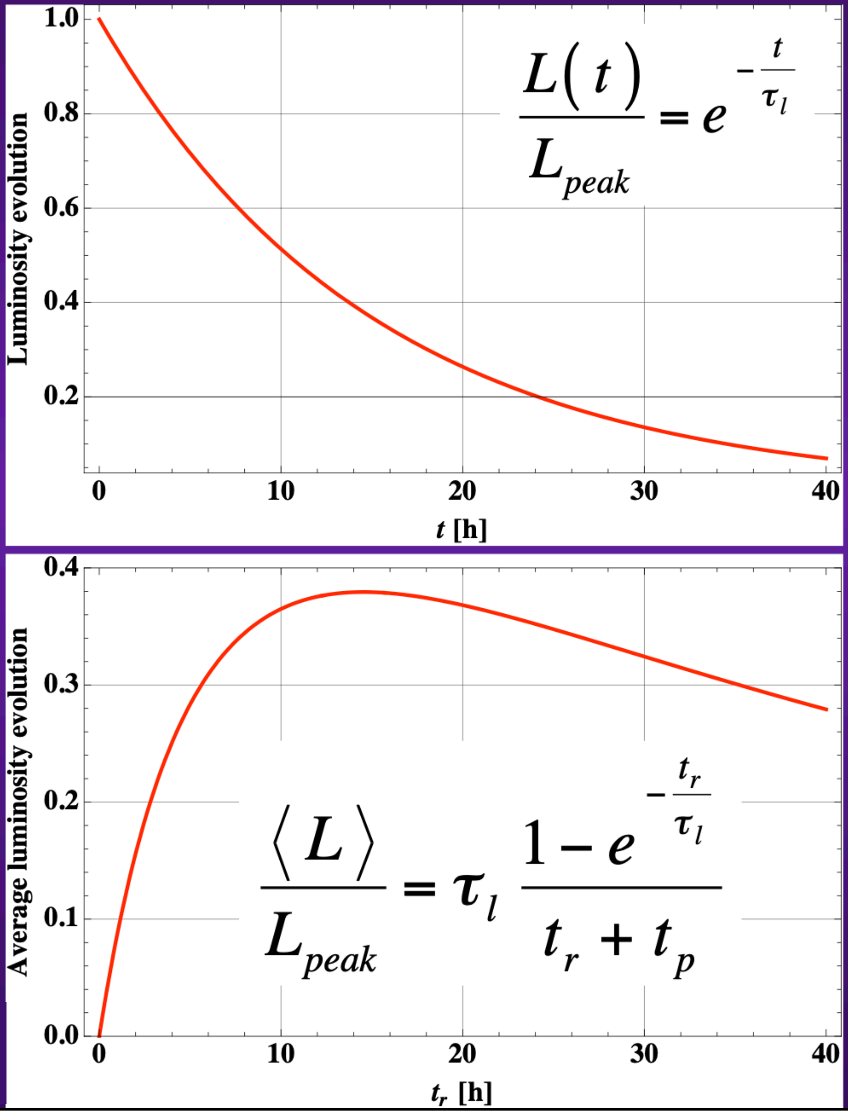
- Let's call t_p the preparation time (time needed to put the beams in collision after the end of the previous physics fill) => Optimization of t_r and t_p gives the maximum luminosity

$$\langle L \rangle = \frac{1}{t_r + t_p} \int_0^{t_r + t_p} L(t)\, dt$$

=>

$$\langle L \rangle = L_{peak}\, \tau_l \, \frac{1 - e^{-\frac{t_r}{\tau_l}}}{t_r + t_p}$$

INTEGRATED LUMINOSITY AND MAXIMIZATION (3/4)



$$\frac{L(t)}{L_{peak}} = e^{-\frac{t}{\tau_l}}$$

$$\frac{\langle L \rangle}{L_{peak}} = \tau_l \, \frac{1 - e^{-\frac{t_r}{\tau_l}}}{t_r + t_p}$$

$\tau_l = 15\ \mathrm{h}$

$t_p = 10\ \mathrm{h}$

INTEGRATED LUMINOSITY AND MAXIMIZATION (4/4)

- The average luminosity is maximum when

$$t_r \approx \tau_l \ln\left(1 + \sqrt{2\,\frac{t_p}{\tau_l}} + \frac{t_p}{\tau_l}\right)$$

Gives ~ 15.5 h…

Pile-up

- **Pile-Up (PU) = Number of events / crossing for a given luminosity**

$$\boxed{\mathrm{PU} = \frac{L\sigma_{exp}}{Mf_{rev}}}$$

  - **This is a limit coming from the experiments' detectors => Better to have larger number of bunches (for the same beam intensity)**

- **In case the pile-up is too big, luminosity leveling techniques could be used to remain at the limit => Playing with the different parameters which can reduce the luminosity (transverse beam offset, β^*, etc.)**

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PU = 19 from
LHC Design Report
(ATLAS and CMS)

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- Small transverse offset
- Short bunches

6 major challenges for future high-energy colliders

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6. Cost

APPENDIX

16 collider options at Snowmass 2021 (US Particle Physics Community Planning Exercise)

9:00 AM → 9:10 AM **Introduction: goals, format, etc**

9:10 AM → 9:25 AM **FCCee** ¶
Speaker: Katsunobu Oide (KEK)

9:25 AM → 9:40 AM **CepC** ¶
Speaker: Yu Chenghui

9:40 AM → 9:55 AM **ILC**
Speaker: Shinichiro MICHIZONO (KEK)

9:55 AM → 10:10 AM **CLIC**
Speaker: Steinar Stapnes (FNAL)

10:10 AM → 10:25 AM **EIC**
Speaker: Christoph Montag (BNL)

10:25 AM → 10:40 AM **LHeC**
Speaker: Oliver Bruning (CERN)

10:40 AM → 10:55 AM **HE-LHC**
Speaker: Frank Zimmermann (CERN)

10:55 AM → 11:10 AM **SppC**
Speaker: Jingyu Tang (Institute of High Energy Physics)

11:10 AM → 11:25 AM **FCChh**
Speaker: Michael Benedikt

9:00 AM → 9:10 AM **Introduction: gioals, format, etc**

9:10 AM → 9:30 AM **Cold NC-Linear Collider**
Speaker: Emilio Nanni (SLAC National Accelerator Laboratory)

9:30 AM → 9:50 AM **ERL based FCCee**
Speaker: Thomas Roser (BNL)

9:50 AM → 10:10 AM **Gamma-Gamma Higgs factories**
Speaker: Frank Zimmermann (CERN)

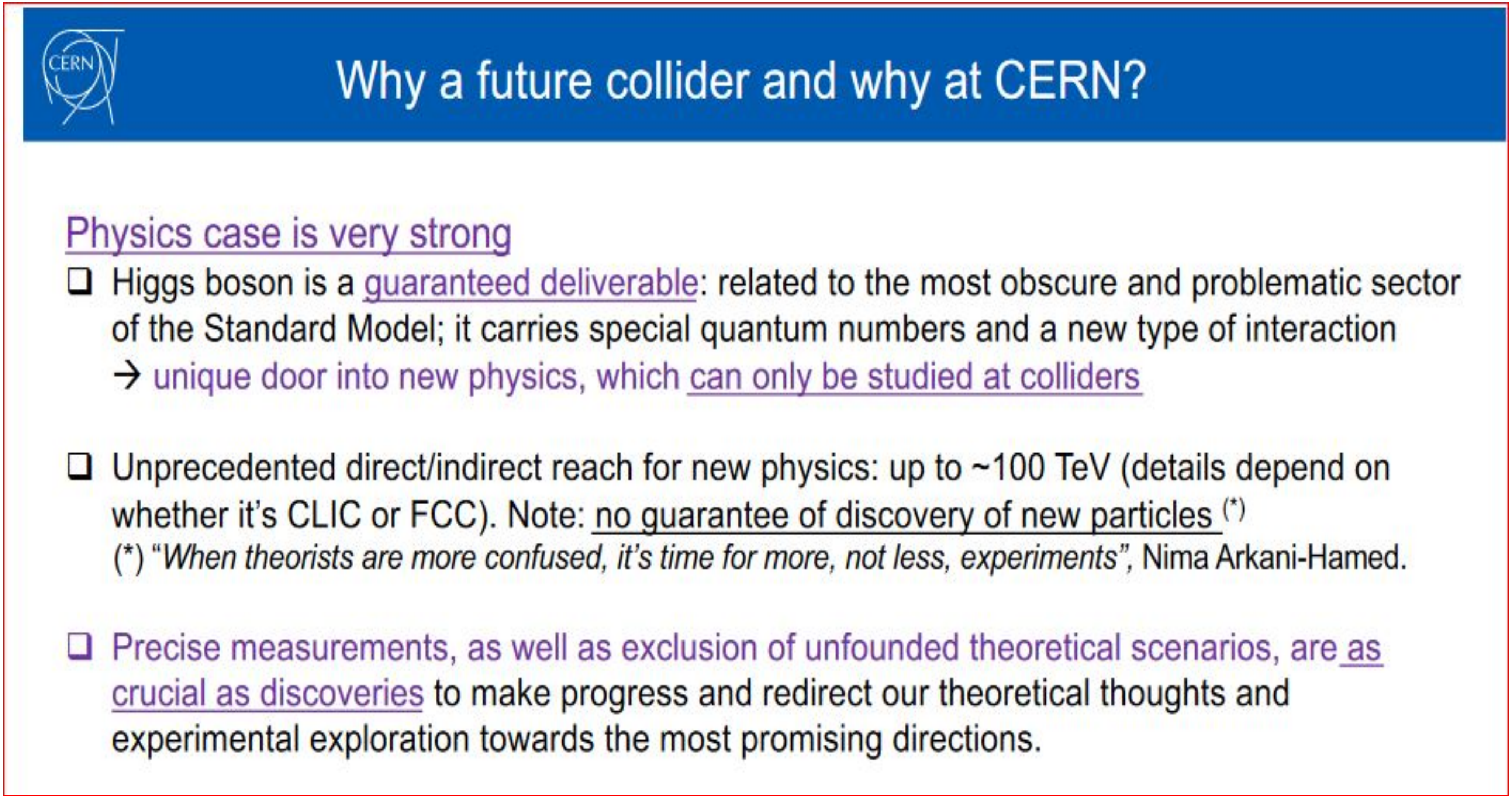
10:10 AM → 10:30 AM **Plasma-Laser WFA 1 TeV +**
Speaker: Carl Schroeder (Lawrence Berkeley National Laboratory)

10:30 AM → 10:50 AM **Plasma-Beam WFA 1 TeV +**
Speaker: Spencer Gessner

10:50 AM → 11:10 AM **Structure-beam WFA 1 Tev +**
Speaker: John Power (Argonne National Lab)

11:10 AM → 11:30 AM **Muon Coliders: Higgs Factory and 3-14 TeV**
Speaker: Daniel Schulte (CERN)

11:30 AM → 12:10 PM **Discussion/ Q&A**



Why a future collider and why at CERN?

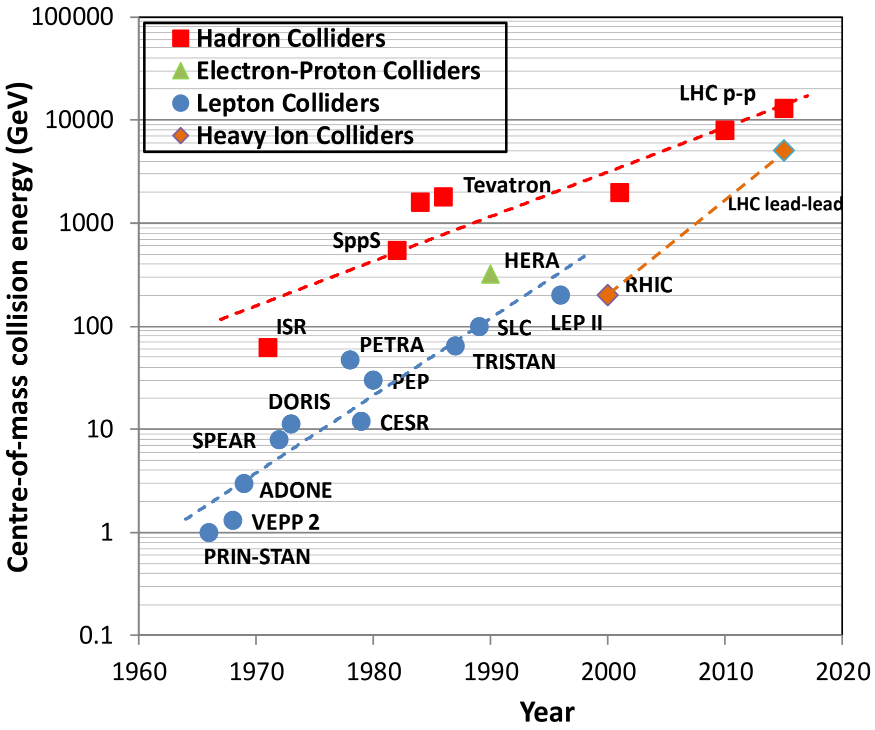
Physics case is very strong

- ☐ Higgs boson is a guaranteed deliverable: related to the most obscure and problematic sector of the Standard Model; it carries special quantum numbers and a new type of interaction
→ unique door into new physics, which can only be studied at colliders

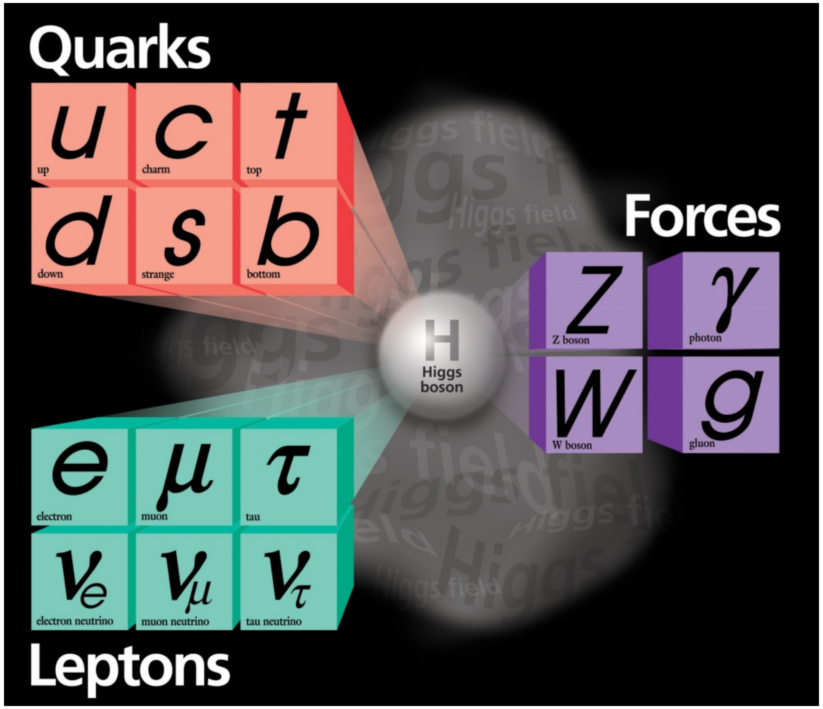
- ☐ Unprecedented direct/indirect reach for new physics: up to ~100 TeV (details depend on whether it's CLIC or FCC). Note: no guarantee of discovery of new particles (*)
(*) "*When theorists are more confused, it's time for more, not less, experiments*", Nima Arkani-Hamed.

- ☐ Precise measurements, as well as exclusion of unfounded theoretical scenarios, are as crucial as discoveries to make progress and redirect our theoretical thoughts and experimental exploration towards the most promising directions.

Fabiola Gianotti (CERN Director General, 14/01/2020)

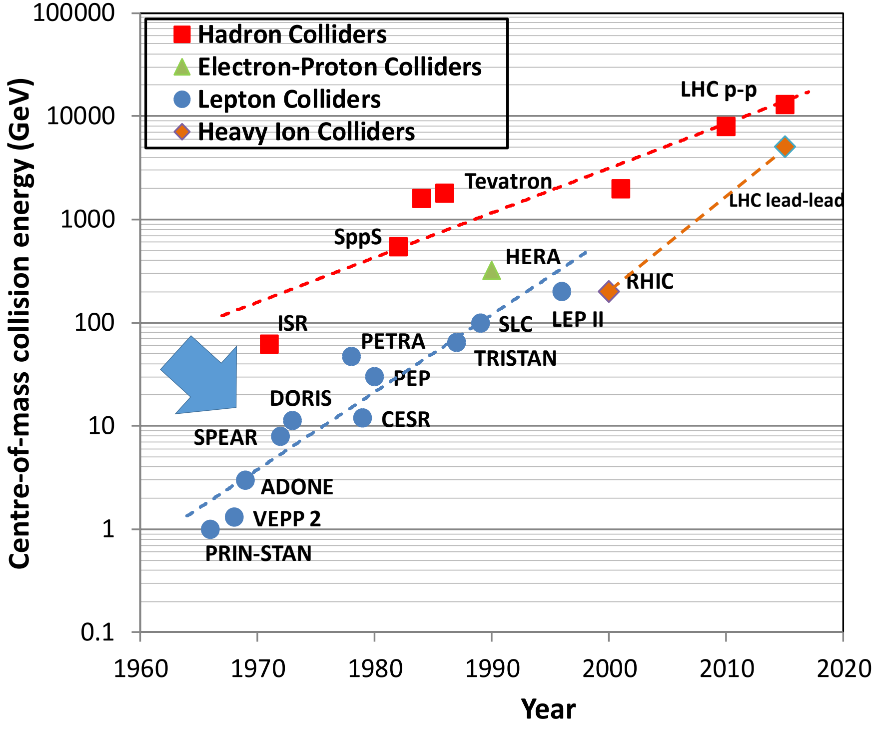


Standard Model
Particles and forces



Courtesy of F. Zimmermann (with A. Ballarino and F. Gianotti)

SPEAR:
- charm quark
- tau lepton



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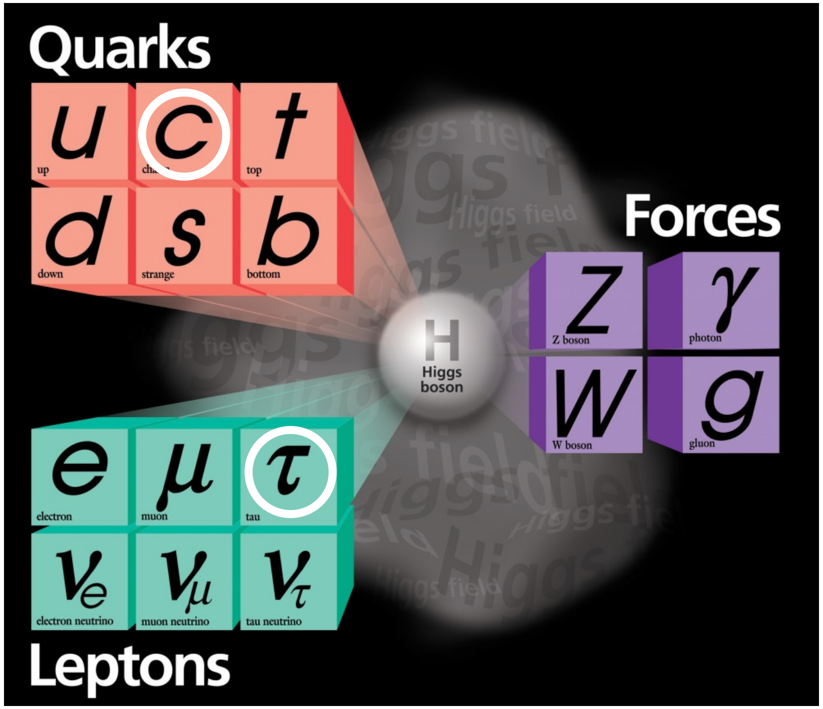

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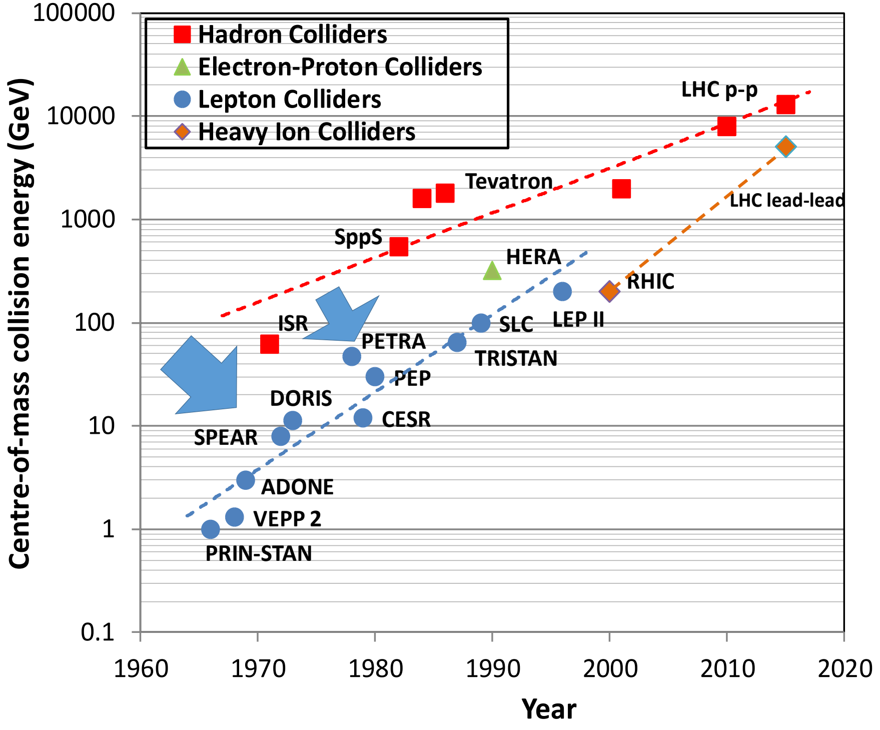

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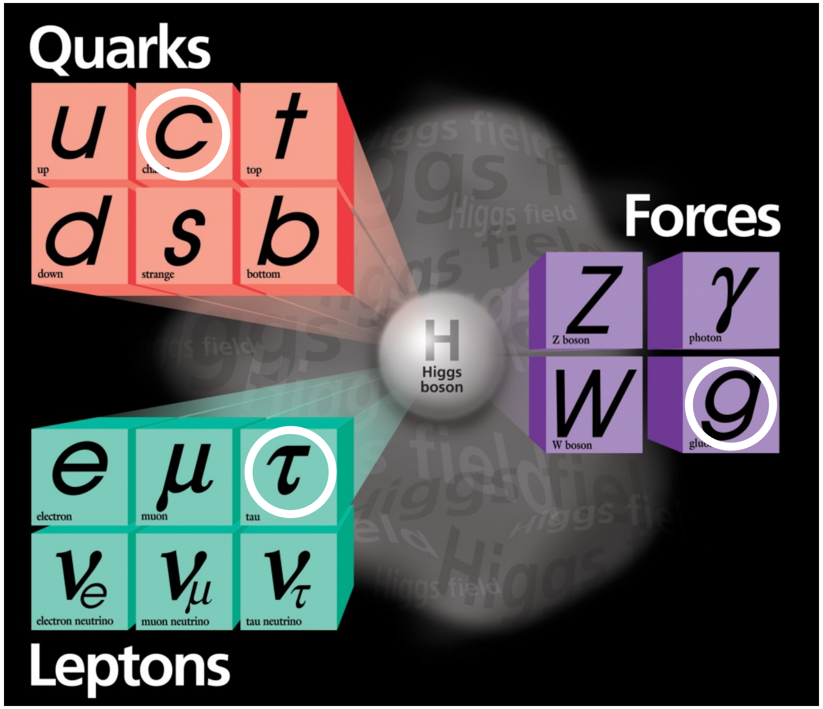

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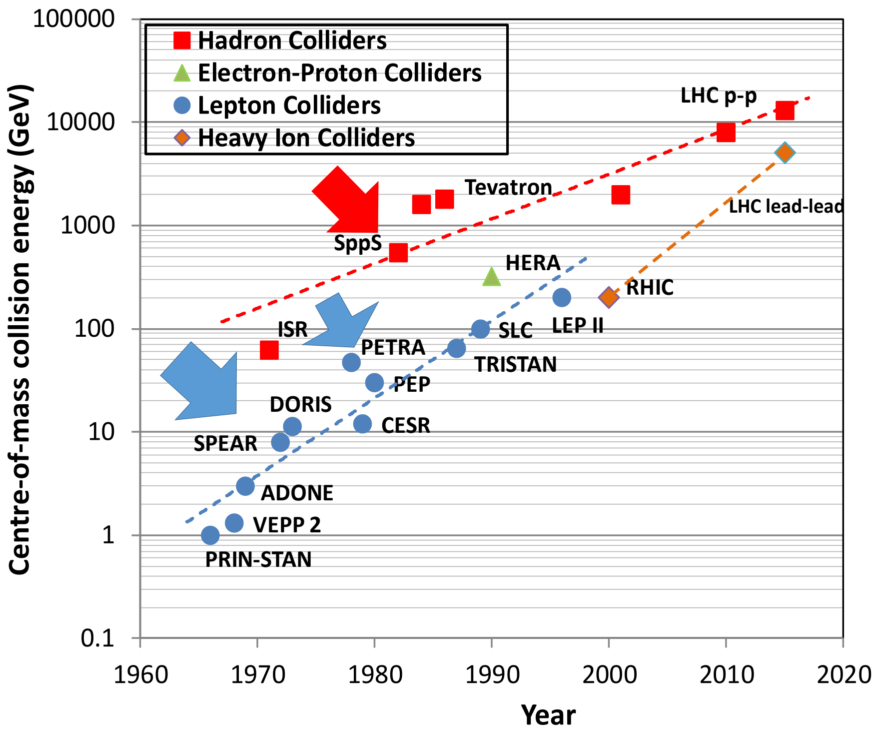

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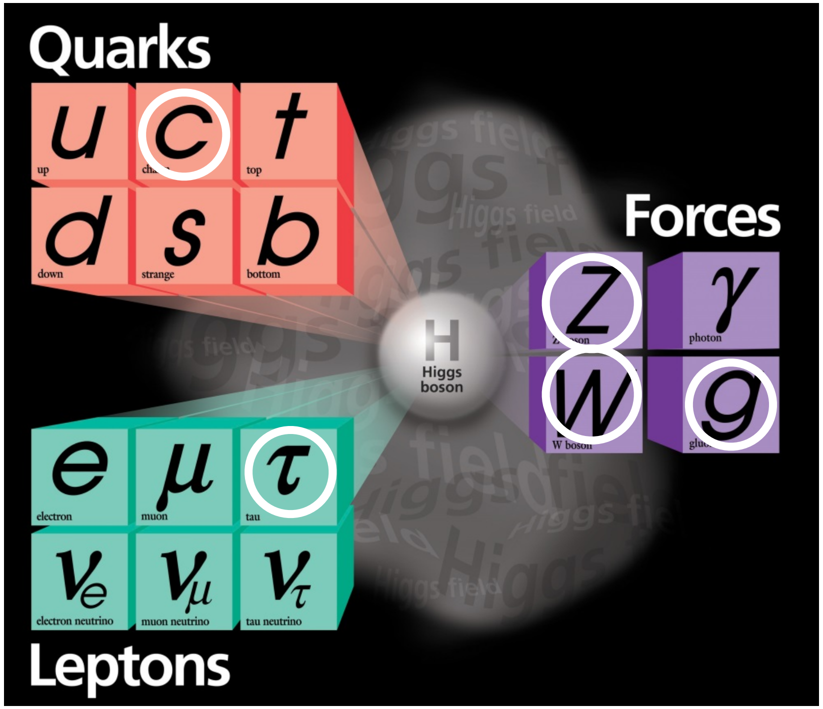

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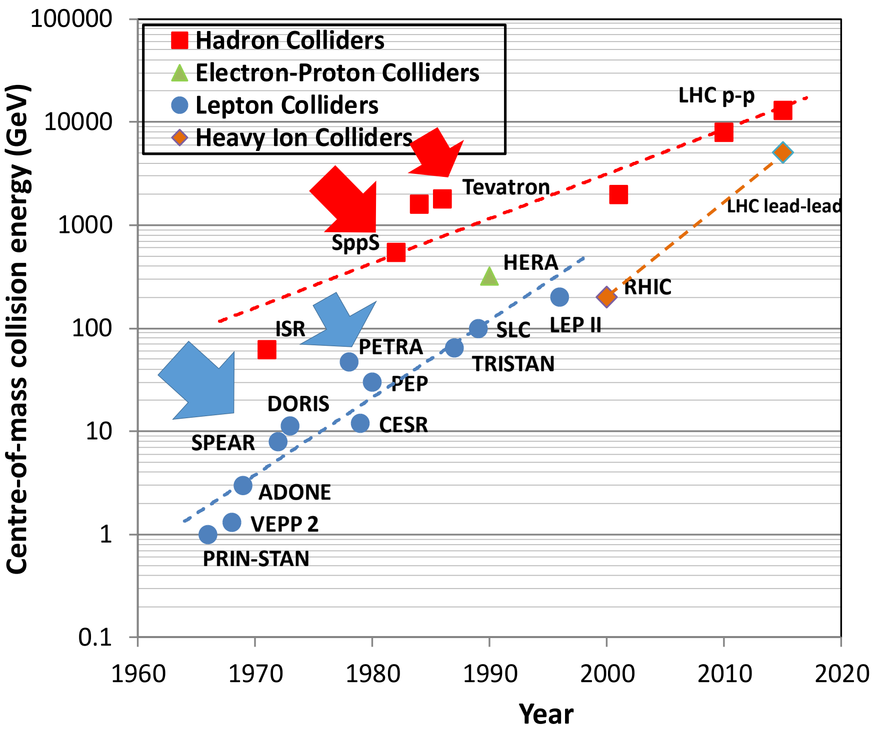

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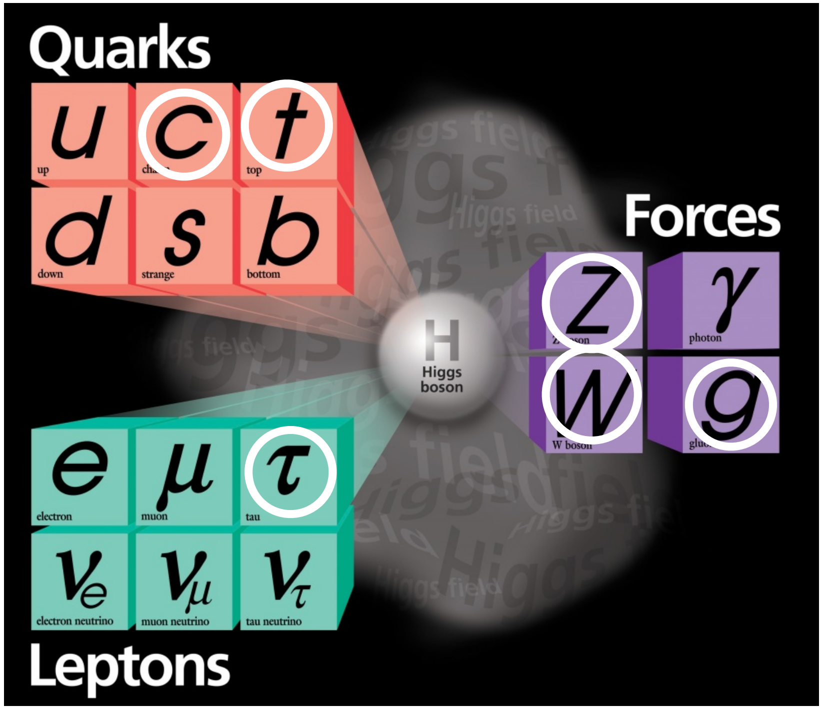

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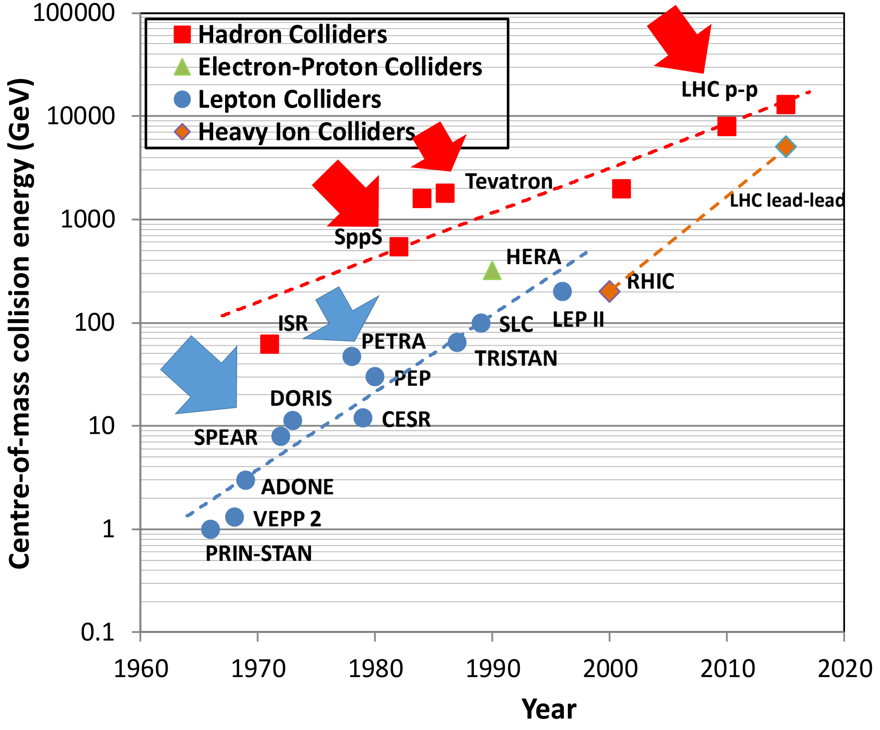

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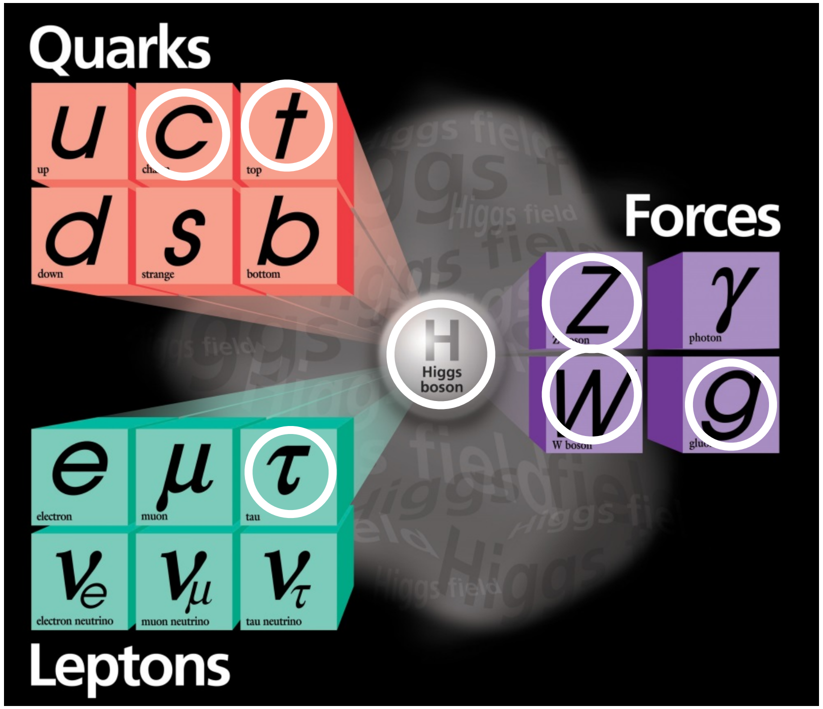

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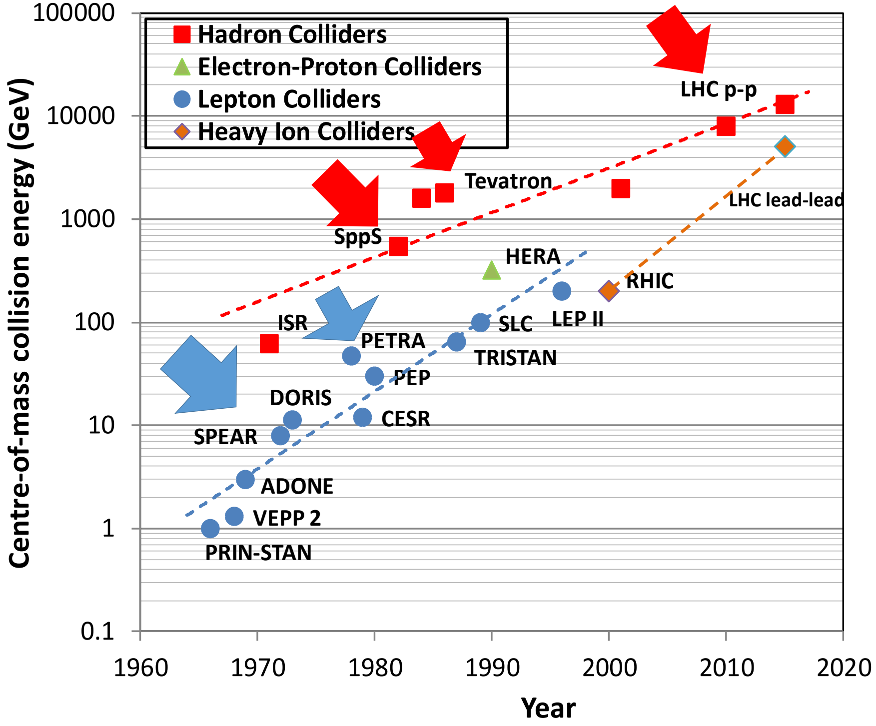

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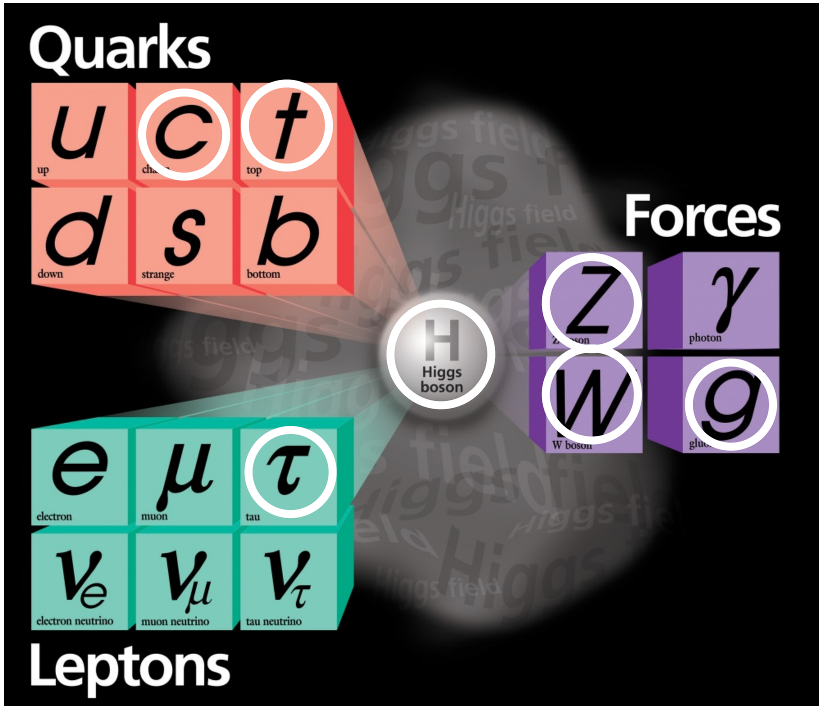
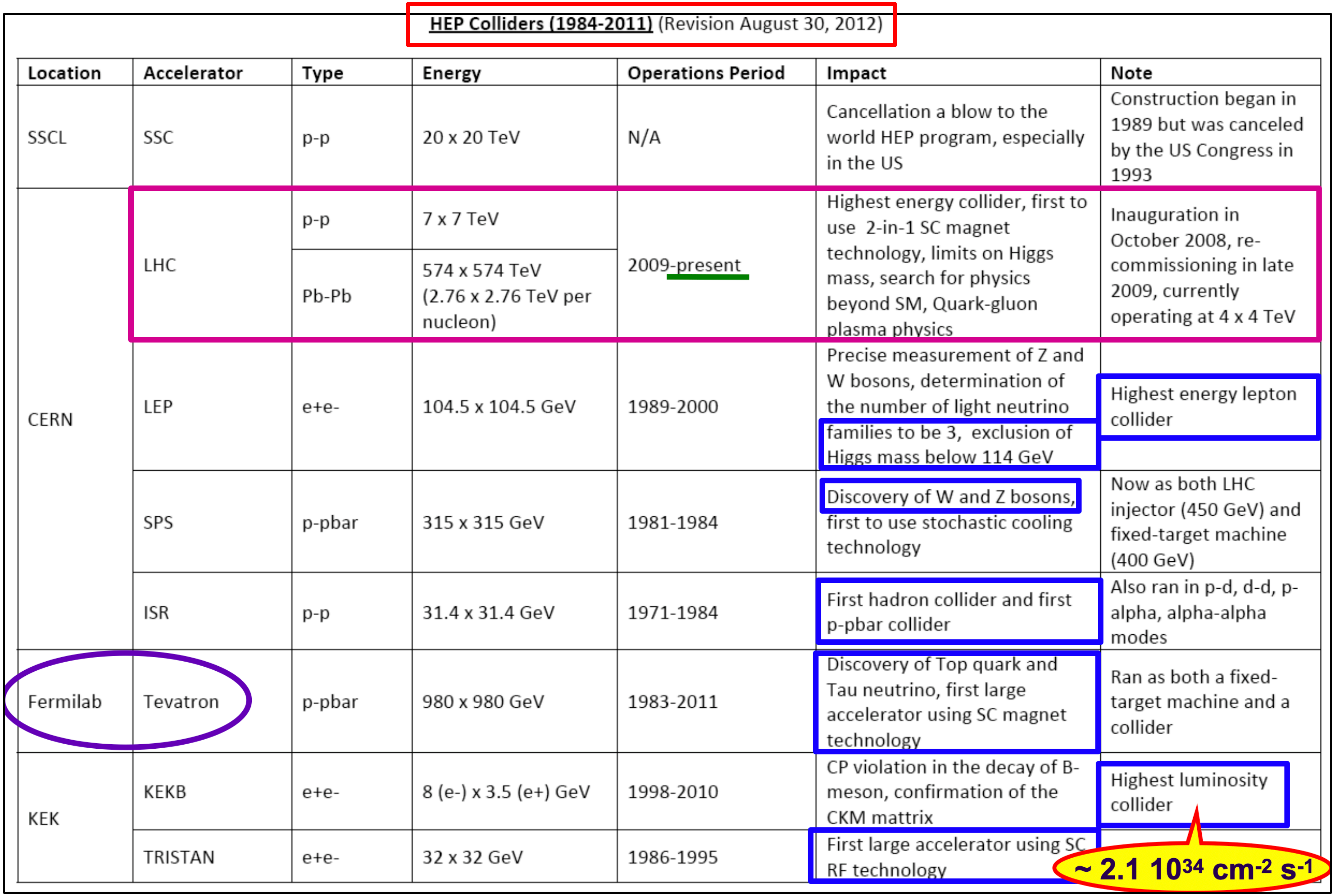


Colliders are powerful instruments in HEP for particle discoveries and precision measurements

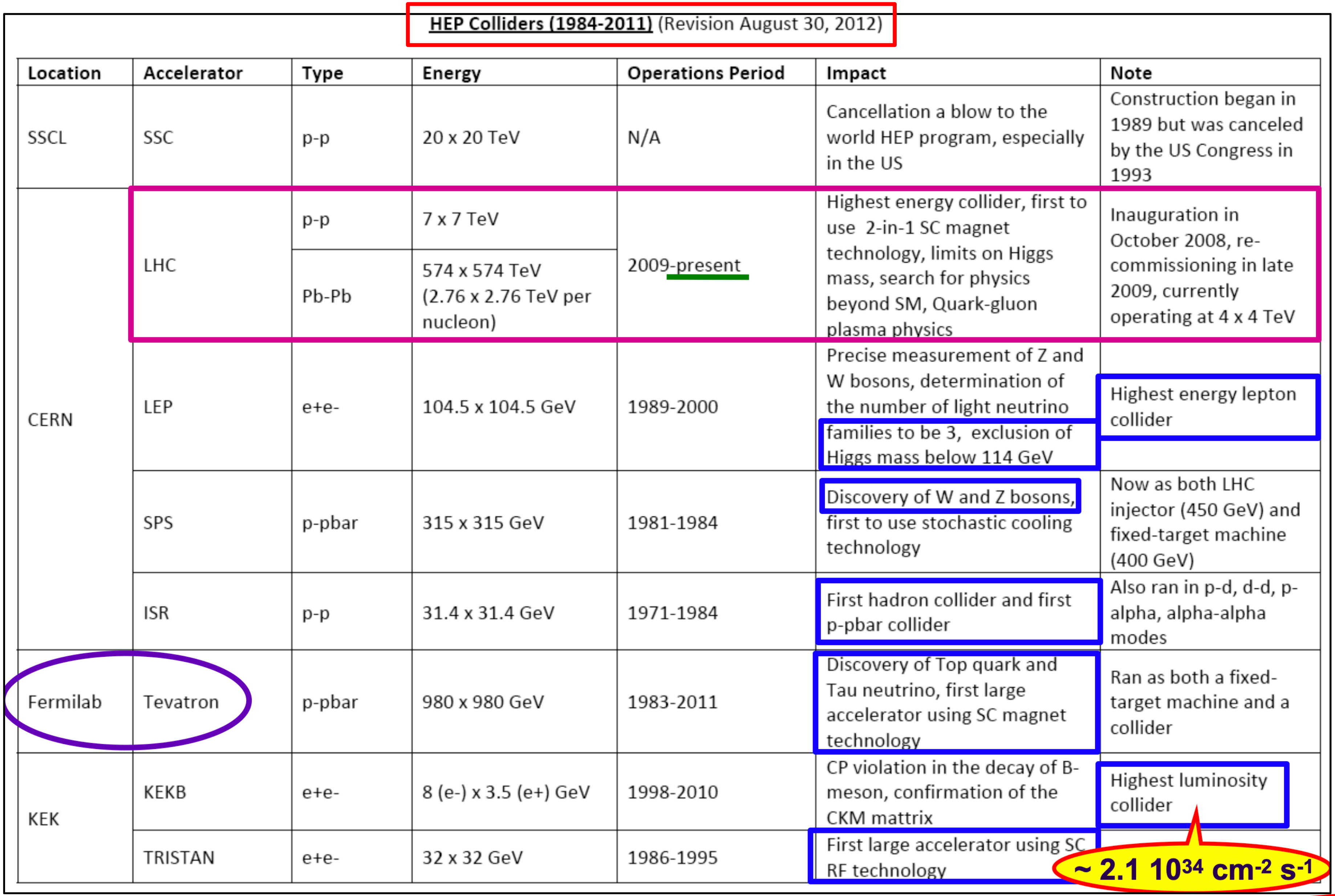
Courtesy of F. Zimmermann (with A. Ballarino and F. Gianotti)



HEP Colliders (1984-2011) (Revision August 30, 2012)

Location	Accelerator	Type	Energy	Operations Period	Impact	Note
SSCL	SSC	p-p	20 x 20 TeV	N/A	Cancellation a blow to the world HEP program, especially in the US	Construction began in 1989 but was canceled by the US Congress in 1993
CERN	LHC	p-p	7 x 7 TeV	2009-present	Highest energy collider, first to use 2-in-1 SC magnet technology, limits on Higgs mass, search for physics beyond SM, Quark-gluon plasma physics	Inauguration in October 2008, re-commissioning in late 2009, currently operating at 4 x 4 TeV
		Pb-Pb	574 x 574 TeV (2.76 x 2.76 TeV per nucleon)			
	LEP	e+e-	104.5 x 104.5 GeV	1989-2000	Precise measurement of Z and W bosons, determination of the number of light neutrino families to be 3, exclusion of Higgs mass below 114 GeV	Highest energy lepton collider
	SPS	p-pbar	315 x 315 GeV	1981-1984	Discovery of W and Z bosons, first to use stochastic cooling technology	Now as both LHC injector (450 GeV) and fixed-target machine (400 GeV)
	ISR	p-p	31.4 x 31.4 GeV	1971-1984	First hadron collider and first p-pbar collider	Also ran in p-d, d-d, p-alpha, alpha-alpha modes
Fermilab	Tevatron	p-pbar	980 x 980 GeV	1983-2011	Discovery of Top quark and Tau neutrino, first large accelerator using SC magnet technology	Ran as both a fixed-target machine and a collider
KEK	KEKB	e+e-	8 (e-) x 3.5 (e+) GeV	1998-2010	CP violation in the decay of B-meson, confirmation of the CKM mattrix	Highest luminosity collider
	TRISTAN	e+e-	32 x 32 GeV	1986-1995	First large accelerator using SC RF technology	

~ 2.1 10^{34} cm^{-2} s^{-1}

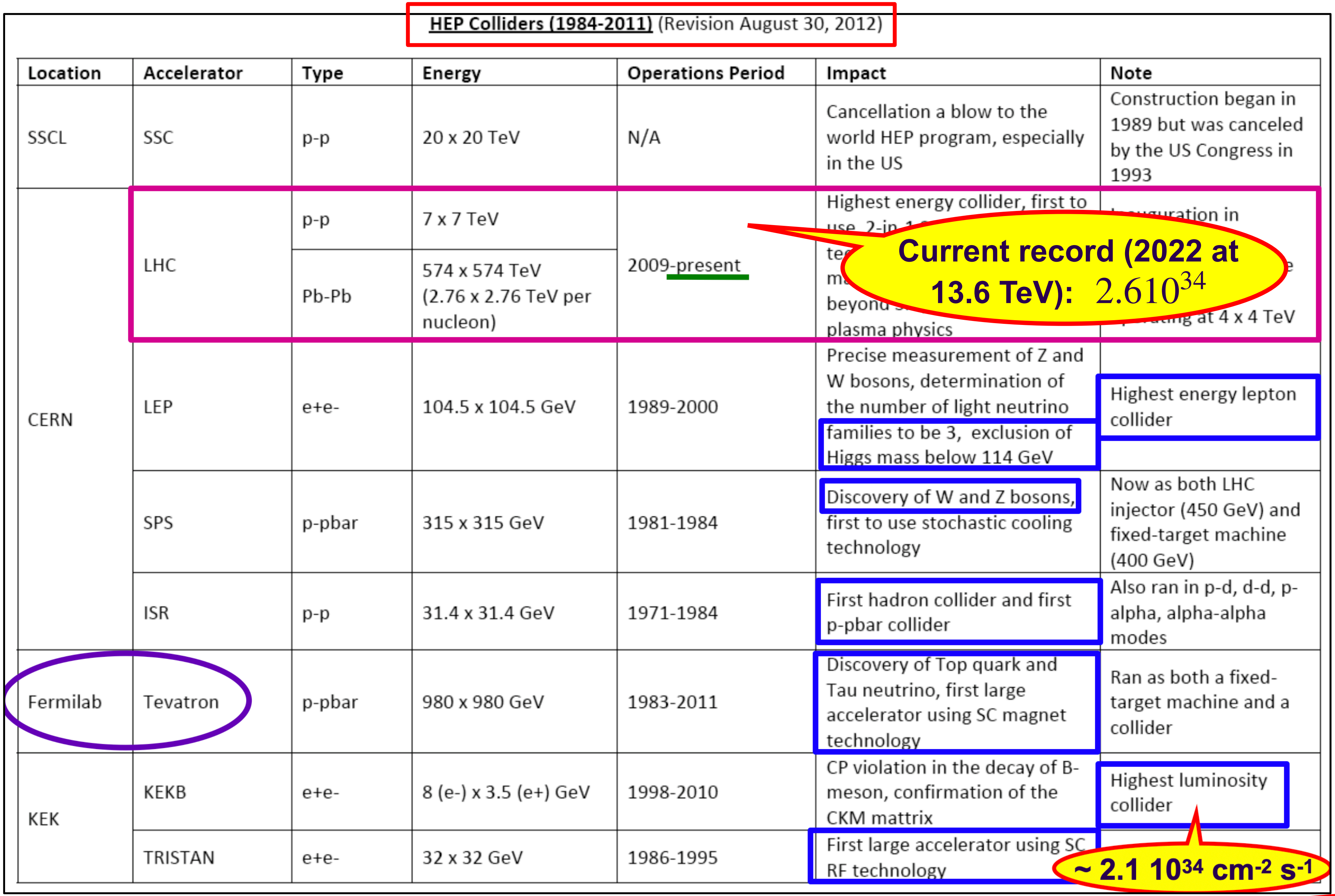


HEP Colliders (1984-2011) (Revision August 30, 2012)

Location	Accelerator	Type	Energy	Operations Period	Impact	Note
SSCL	SSC	p-p	20 x 20 TeV	N/A	Cancellation a blow to the world HEP program, especially in the US	Construction began in 1989 but was canceled by the US Congress in 1993
CERN	LHC	p-p	7 x 7 TeV	2009-present	Highest energy collider, first to use 2-in-1 SC magnet technology, limits on Higgs mass, search for physics beyond SM, Quark-gluon plasma physics	Inauguration in October 2008, re-commissioning in late 2009, currently operating at 4 x 4 TeV
		Pb-Pb	574 x 574 TeV (2.76 x 2.76 TeV per nucleon)			
	LEP	e+e-	104.5 x 104.5 GeV	1989-2000	Precise measurement of Z and W bosons, determination of the number of light neutrino families to be 3, exclusion of Higgs mass below 114 GeV	Highest energy lepton collider
	SPS	p-pbar	315 x 315 GeV	1981-1984	Discovery of W and Z bosons, first to use stochastic cooling technology	Now as both LHC injector (450 GeV) and fixed-target machine (400 GeV)
	ISR	p-p	31.4 x 31.4 GeV	1971-1984	First hadron collider and first p-pbar collider	Also ran in p-d, d-d, p-alpha, alpha-alpha modes
Fermilab	Tevatron	p-pbar	980 x 980 GeV	1983-2011	Discovery of Top quark and Tau neutrino, first large accelerator using SC magnet technology	Ran as both a fixed-target machine and a collider
KEK	KEKB	e+e-	8 (e-) x 3.5 (e+) GeV	1998-2010	CP violation in the decay of B-meson, confirmation of the CKM mattrix	Highest luminosity collider
	TRISTAN	e+e-	32 x 32 GeV	1986-1995	First large accelerator using SC RF technology	

~ 2.1 10^{34} cm^{-2} s^{-1}

In 2022: $4.6 10^{34}$



HEP Colliders (1984-2011) (Revision August 30, 2012)

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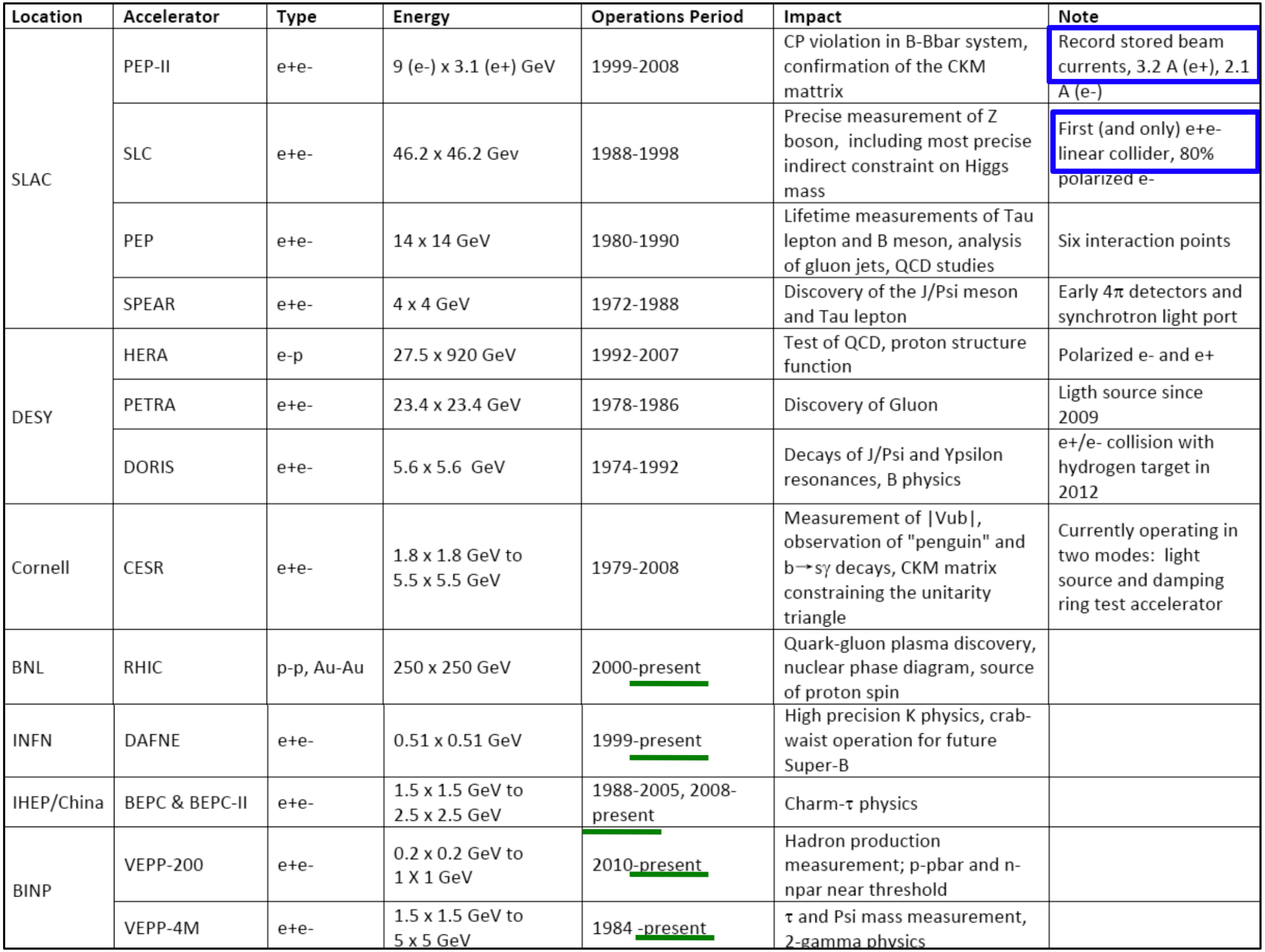
Current record (2022 at 13.6 TeV): 2.610^{34}

~ 2.1 10^{34} cm^{-2} s^{-1}

In 2022: 4.610^{34}



Location	Accelerator	Type	Energy	Operations Period	Impact	Note
SLAC	PEP-II	e+e-	9 (e-) x 3.1 (e+) GeV	1999-2008	CP violation in B-Bbar system, confirmation of the CKM mattrix	Record stored beam currents, 3.2 A (e+), 2.1 A (e-)
	SLC	e+e-	46.2 x 46.2 Gev	1988-1998	Precise measurement of Z boson, including most precise indirect constraint on Higgs mass	First (and only) e+e- linear collider, 80% polarized e-
	PEP	e+e-	14 x 14 GeV	1980-1990	Lifetime measurements of Tau lepton and B meson, analysis of gluon jets, QCD studies	Six interaction points
	SPEAR	e+e-	4 x 4 GeV	1972-1988	Discovery of the J/Psi meson and Tau lepton	Early 4π detectors and synchrotron light port
DESY	HERA	e-p	27.5 x 920 GeV	1992-2007	Test of QCD, proton structure function	Polarized e- and e+
	PETRA	e+e-	23.4 x 23.4 GeV	1978-1986	Discovery of Gluon	Ligth source since 2009
	DORIS	e+e-	5.6 x 5.6 GeV	1974-1992	Decays of J/Psi and Ypsilon resonances, B physics	e+/e- collision with hydrogen target in 2012
Cornell	CESR	e+e-	1.8 x 1.8 GeV to 5.5 x 5.5 GeV	1979-2008	Measurement of |Vub|, observation of "penguin" and b→sγ decays, CKM matrix constraining the unitarity triangle	Currently operating in two modes: light source and damping ring test accelerator
BNL	RHIC	p-p, Au-Au	250 x 250 GeV	2000-present	Quark-gluon plasma discovery, nuclear phase diagram, source of proton spin	
INFN	DAFNE	e+e-	0.51 x 0.51 GeV	1999-present	High precision K physics, crab-waist operation for future Super-B	
IHEP/China	BEPC & BEPC-II	e+e-	1.5 x 1.5 GeV to 2.5 x 2.5 GeV	1988-2005, 2008-present	Charm-τ physics	
BINP	VEPP-200	e+e-	0.2 x 0.2 GeV to 1 X 1 GeV	2010-present	Hadron production measurement; p-pbar and n-npar near threshold	
	VEPP-4M	e+e-	1.5 x 1.5 GeV to 5 x 5 GeV	1984 -present	τ and Psi mass measurement, 2-gamma physics	