CMS Experiment at the LHC, CERN

Data recorded: 2010-Jul-09 02:25:58.839811 GMT(04:25:58 CEST)

Run / Event: 139779 / 4994190

CERN Accelerator School

Vysoke-Tatry, Slovakia 2019

Luminosity and (future) colliders

Hermann Schmickler (CERN, ATS-DO)

With many slides taken from:

G.Papotti (CERN): CAS 2016, Budapest
W.Herr (CERN): CAS 2018, Constanta
M.Benedikt(CERN): CAS@ESI 2018

(But also with a few slides by myself)

Outline

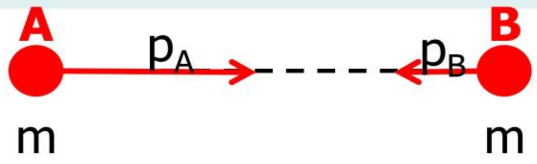
- Why colliding beams?
- What do physicists do with the data?
- Lepton or Hadron Collider?
- Figures of merits: Energy and luminosity

  →Details on luminosity
- Not too much:

  → Detector Occupancy in hadron collisions
- The possible future at CERN:

  HL-LHC
  FCC
  CLIC

Fixed-target vs head-on beam collisions



- Relativistic invariant $(\Sigma m)^2 c^4 = (\Sigma E)^2 - (\Sigma p)^2 c^2$
- In the laboratory frame $4m^2c^4 = (E_A + E_B)^2 - (\overrightarrow{p_A} + \overrightarrow{p_B})^2 c^2$
- Let E^* be the total energy available in the collision
- In the center-of-mass frame $\overrightarrow{p^*} = \overrightarrow{p_A} * + \overrightarrow{p_B} * \equiv 0$

$$4m^2c^4 = {E^*}^2$$

$$\boxed{{E^*}^2 = (E_A + E_B)^2 - (\overrightarrow{p_A} + \overrightarrow{p_B})^2 c^2}$$

- Fixed-target $p_B = 0\,;\; E_B = mc^2$

$${E^*}^2 = {E_A}^2 - {p_A}^2 c^2 + m^2c^4 + 2E_A mc^2$$

$${E^*}^2 = 2m^2c^4 + 2E_A mc^2 \approx 2E_A mc^2$$

$$\boxed{E^* \approx \sqrt{2E_A mc^2}}$$

- Head-on collision $\boxed{E^* = E_A + E_B}$

Past/Existing High Energy Frontier Colliders

Only referring to the highest energy

Lepton colliders:

- LEP (Large Electron Positron Colliders)
  - Z_0 factory at 90GeV electron-positron cms energy
  - W^+W^- factory at 160GeV
  - Maximum 209 GeV cms energy for higgs search
    (bad luck: e+e- → Z^0H needs about 250 GeV)
  - Closed in the year 2000

- SLC (Standford Linear Collider)
  - Z_0 factory at 90GeV electron-positron cms energy
  - Single linac for e+ and e-, two return arcs for collision
  - Closed in summer 1998

Hadron colliders

- LHC (Large Hadron Collider):
  - Proton-proton with 13TeV
  - Ion-ion operation

Considered Future High Energy Frontier Colliders

Circular colliders:

- FCC (Future Circular Collider)
  - FCC-hh: 100TeV proton-proton cms energy, ion operation possible
  - FCC-ee: Potential intermediate step 90-350 GeV lepton collider
  - FCC-he: Lepton-hadron option
- CEPC / SppC (Circular Electron-positron Collider/Super Proton-proton Collider)
  - CepC : e^+e^- 240GeV cms
  - SppC : pp 70TeV cms

Linear colliders

- ILC (International Linear Collider): e^+e^-, 500 GeV cms energy, Japan considers hosting project
- CLIC (Compact Linear Collider): e^+e^-, 380GeV-3TeV cms energy, CERN hosts collaboration

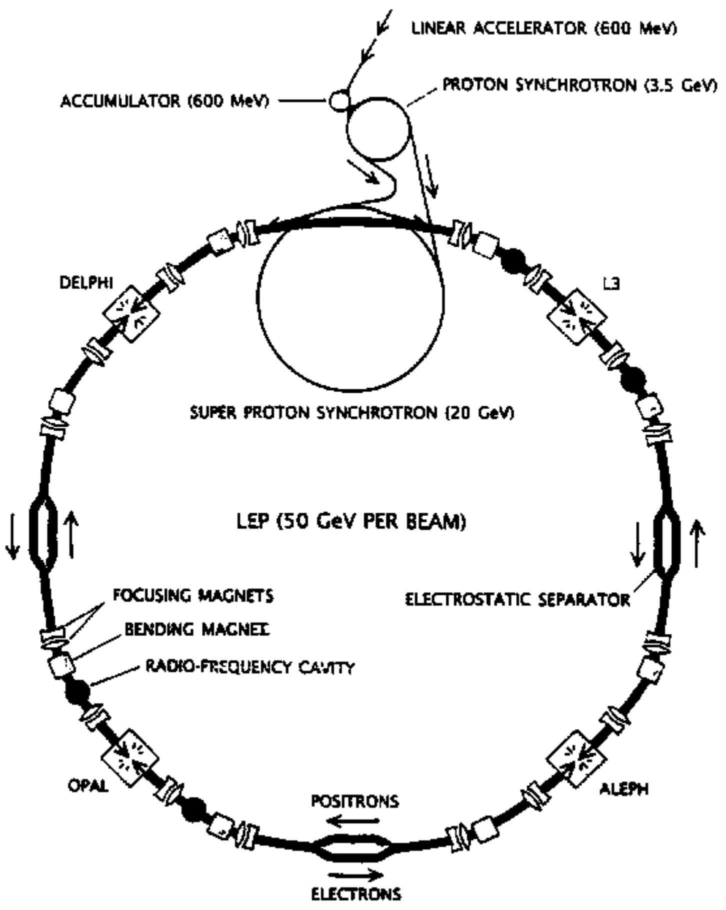
Others

- Muon collider, has been supported mainly in the US but effort has stopped
- Plasma wakefield acceleration in linear collider…not yet ready
- Photon-photon collider
- LHeC

LEP (at CERN)

27km circumference
Electron-positron collider
4 experiments: ALEPH, DELPHI, L3, OPAL
CMS energy: 90GeV (LEP I) - 209GeV (LEP II)
Peak Luminosity: $10^{32} cm^{-2} s^{-1}$
Operation: 1989-2000

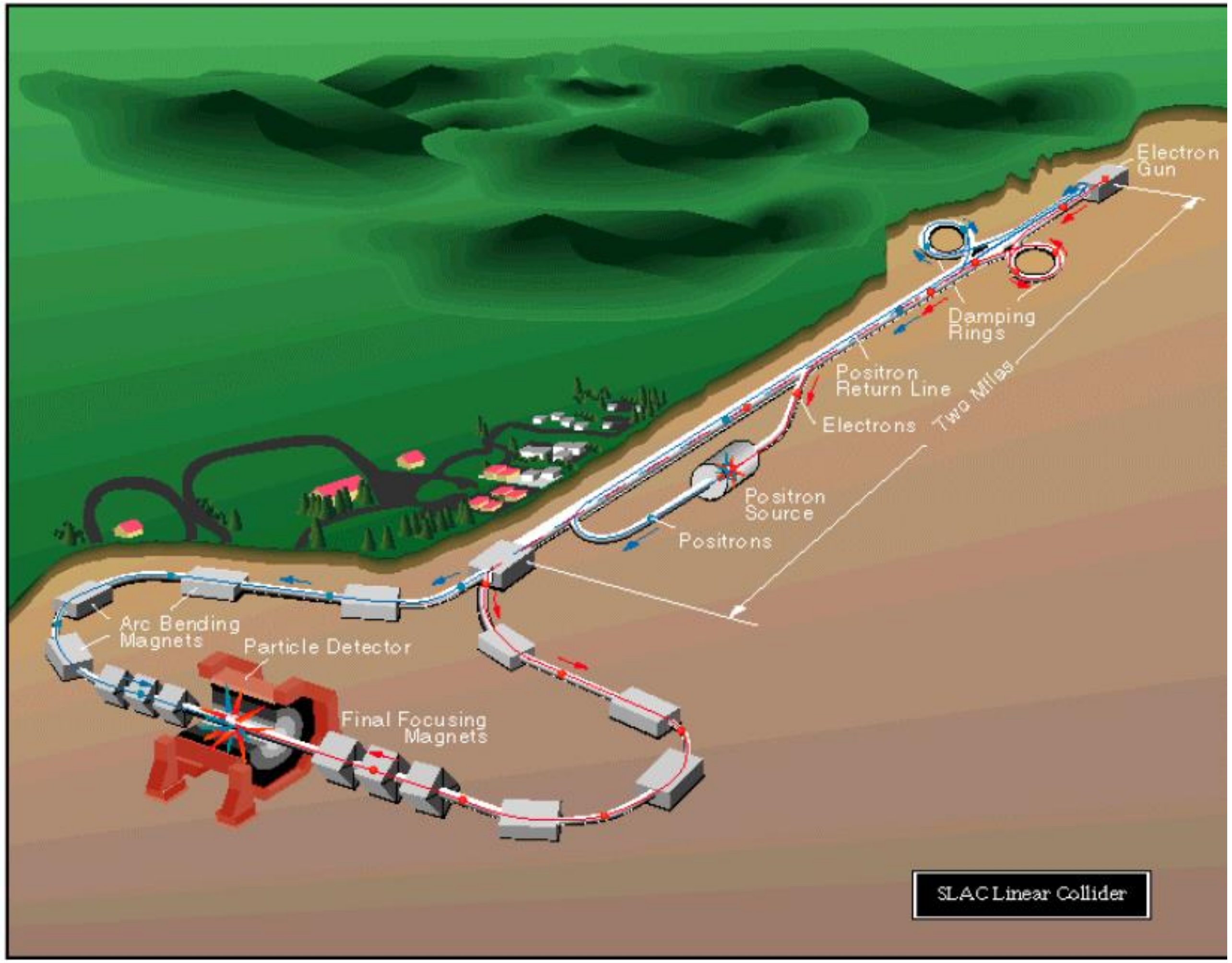
Highest particle speed in any accelerator



SLC (at SLAC)

Electron-positron linear collider
2 experiments: first MARK II, then SLD
CMS energy: 92GeV
Peak Luminosity: $2x10^{30}cm^{-2}s^{-1}$
Operation: 1989-1998

The only linear collider sofar



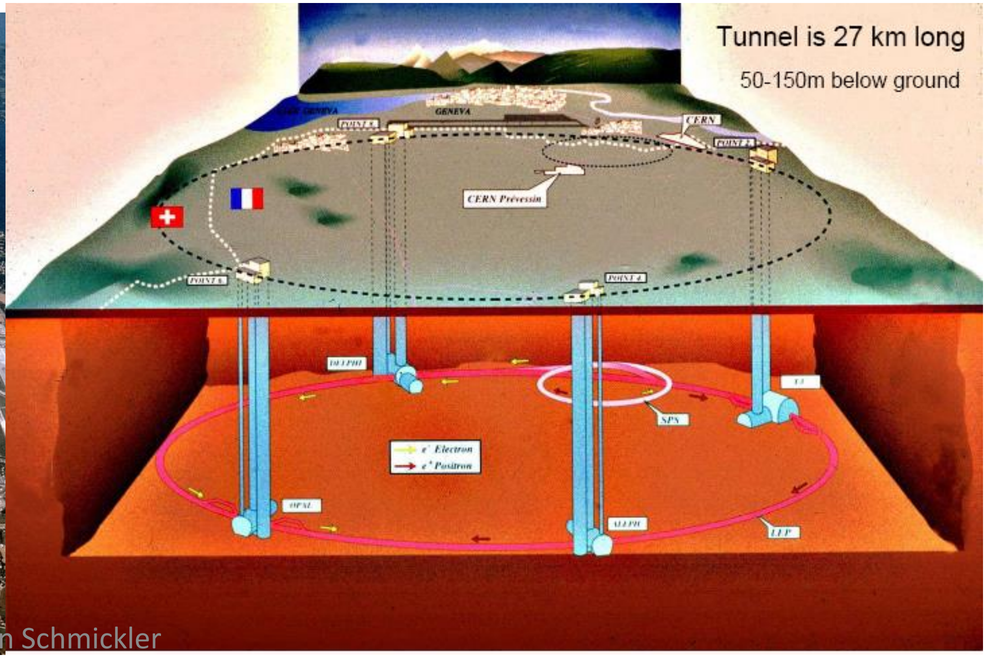
The LHC (at CERN)

27km circumference (well, the LEP tunnel)

4 main experiments

Nominal CMS energy: 14TeV
Peak Luminosity: $10^{34}cm^{-2}s^{-1}$
Operation: 2009-today

Highest particle energy in any accelerator

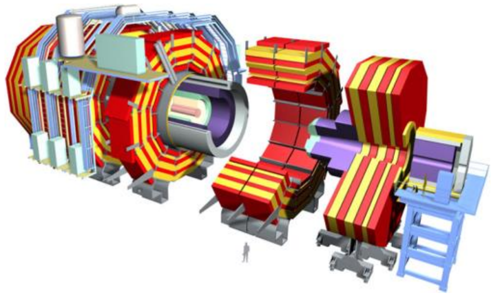


Other Colliders

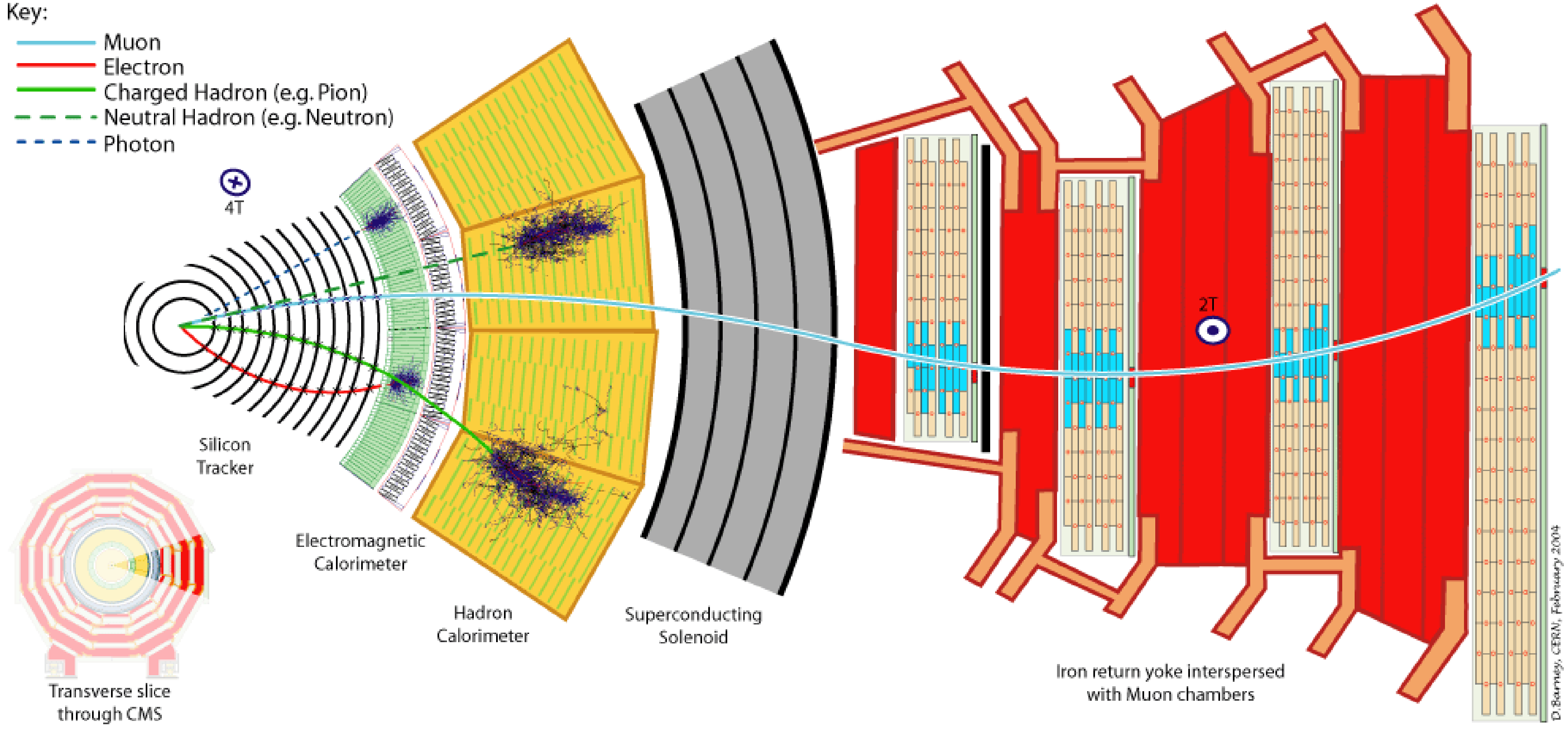
What do physicists with the data? …short outline in a nutshell

- The primary interaction is not visible.
- Physicists measure identity and energy/momentum of secondary particles, which emerge from the primary interaction
- Physicists make model assumptions about the primary interaction and compare observables like the angular distribution of the secondaries with the model. If it fits in all aspects, they declare the model the "truth". (historic example: Rutherford scattering)
- Quantitative measurements like the mass of a new particle are possible, if all secondary particles are measured and the invariant mass is computed.
- It is very useful to know the total energy of the original collision, which is only the case for collisions of elementary particles (leptons)
- Most of the processes have "background" signals with similar signature. Very careful simulations of this background must accompany every measurement.

Particle identification: a CMS slice



or “what the experiments do with the collisions”



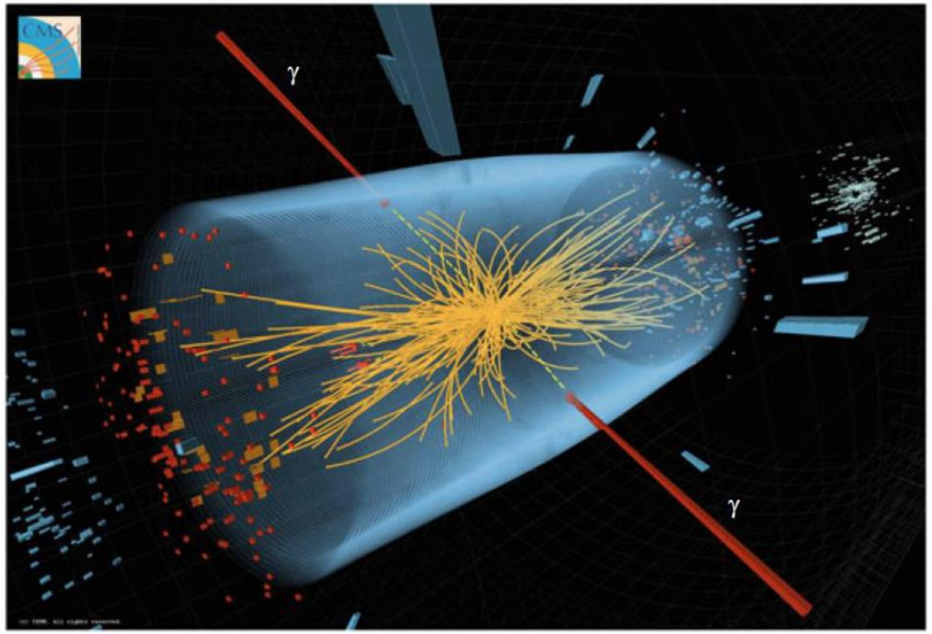
Joint Universities Accelerator School

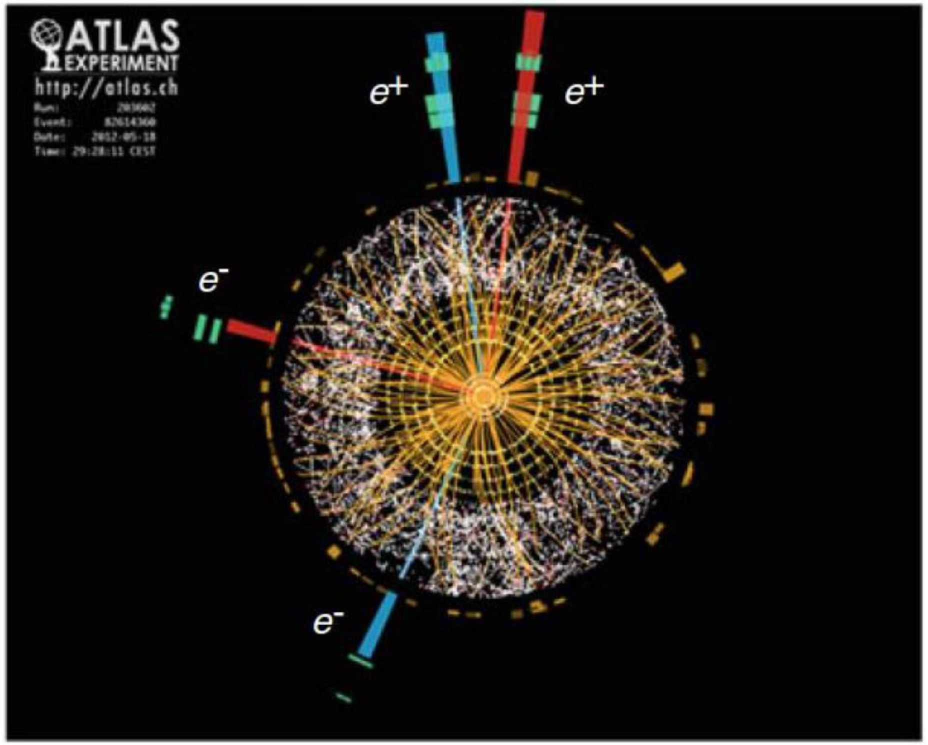
European Scientific Institute

Discovery of the 125 GeV Higgs boson (2012)
The decays of the Higgs boson, observed in the CMS and ATLAS detectors

$\mathrm{H} \rightarrow \gamma\gamma$

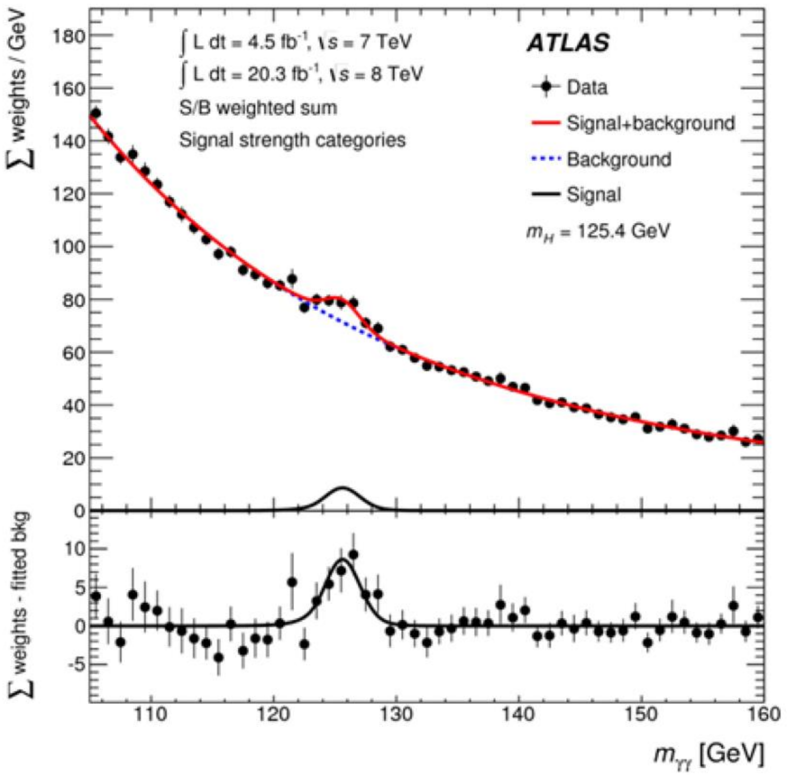
$\mathrm{H} \rightarrow \mathrm{ZZ} \rightarrow 4l$



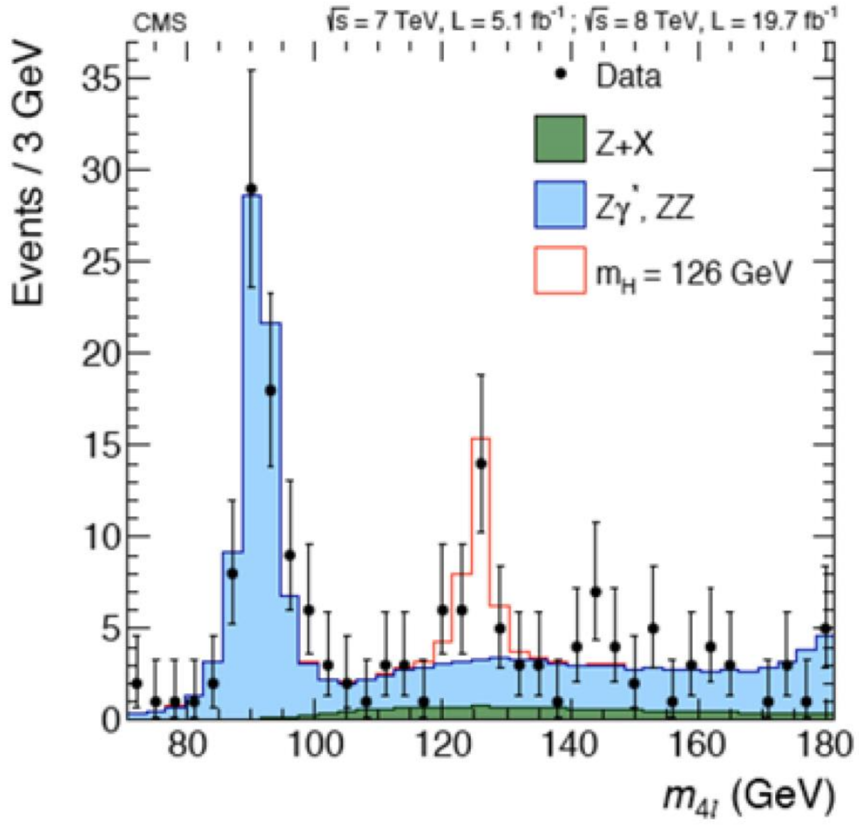


Discovery of the 125 GeV Higgs boson (2012)
The decays of the Higgs boson, observed in the CMS and ATLAS detectors

$\mathrm{H} \rightarrow \gamma\gamma$

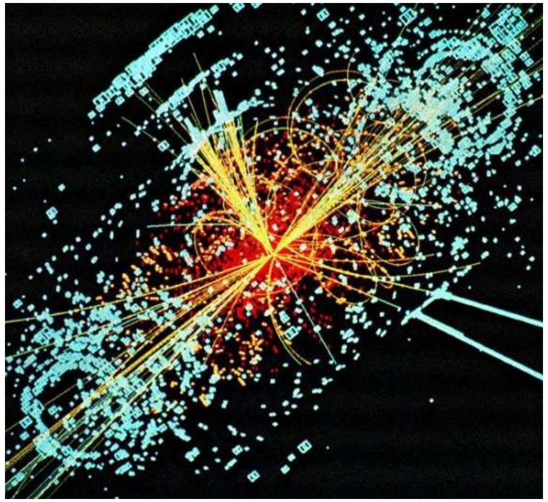


$\mathrm{H} \rightarrow \mathrm{ZZ} \rightarrow 4l$



Collider figures of merit:

1. **c.m.s. energy**: higher energy means particles with higher masses can be produced
2. **Luminosity**: A number characterizing a collider to produce a certain number of events of a given process →



- **The cross section of a process:**

cross-section σ_{ev} expresses the likelihood of the process

- σ_{ev} represents the “area” over which the process occurs
- units: $[m^2]$
  - in nuclear and high energy physics: 1 barn ($1\ b = 10^{-24}\ cm^2$)

definition: Luminosity (L)

$$R = \frac{dN_{ev}}{dt} = L(t)\sigma_{ev}$$

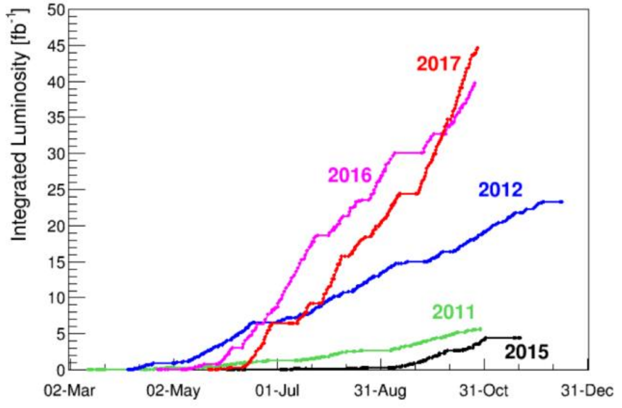
- luminosity L relates cross-section σ and event rate R = dN_{ev}/dt at time t:
  - quantifies performance of collider
  - relativistic invariant and independent of physical reaction

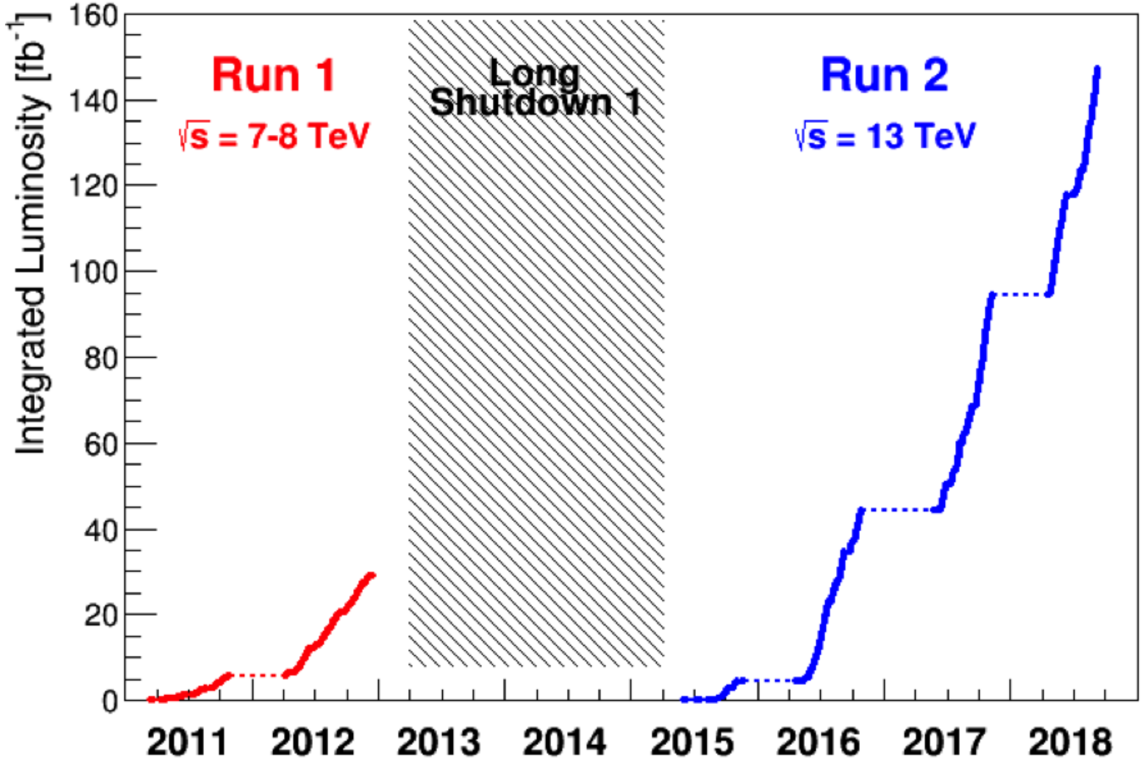
$$N_{ev} = \sigma_{ev} \int L(t)\,dt$$

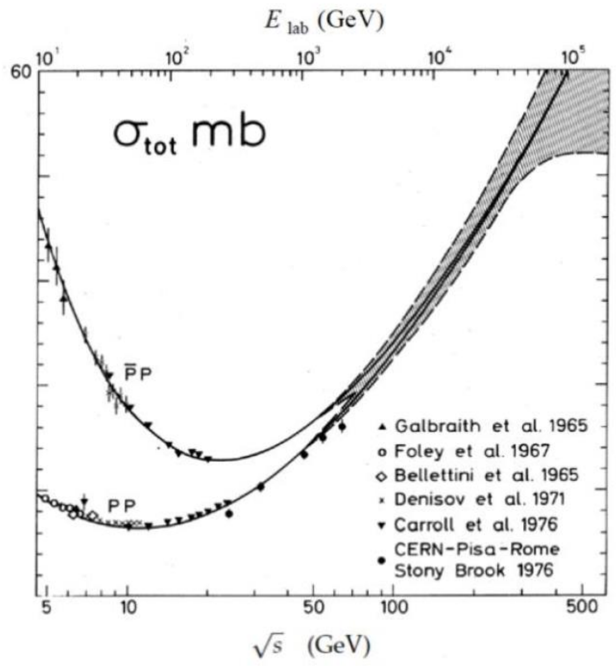
- accelerator operation aims at maximizing the total number of events N_{ev} for the experiments
  - σ_{ev} is fixed by Nature
  - aim at maximizing $\int L(t)dt$

- Luminosity unit : [m^{-2} s^{-1}]
- The integrated luminosity $\int Ldt$ is frequently expressed in $pb^{-1} = 10^{36}$ cm^{-2} or $fb^{-1} = 10^{39}$ cm^{-2}

Example: LHC







Total integrated luminosity LHC Run 2: 150 fb^{-1}
Total cross section pp collisions: 100 mb
→ Ncollisions = 150 * 10^{12} mb^{-1} * 100 mb = 15 * 10^{15} events !!!
→ Only a small fraction gets recorded….still Pbytes of data

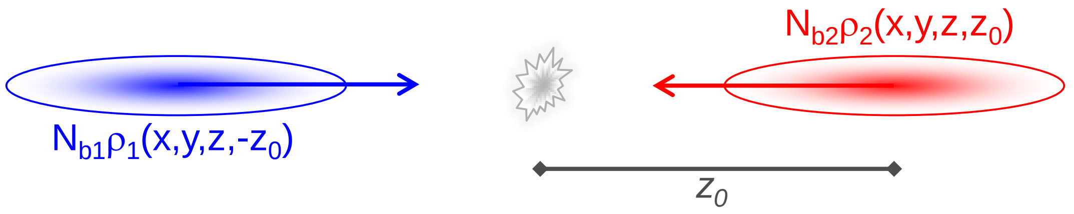
Details on luminosity

- luminosity
  - derivation from machine parameters
  - head-on and offset collisions
  - reduction factors
    - crossing angles and crab cavities, hourglass
  - luminosity lifetime, contributions
  - luminosity scans and luminosity levelling
- integrated luminosity and ideal run time

L from machine parameters -1-

- intuitively: more L if there are more protons and more tightly packed

$$L \propto N_{b1} N_{b2} \Omega_{x,y}$$



$$L \propto N_{b1} N_{b2} K \int_{x,y,z,z_0} \rho_1(x,y,z,-z_0)\rho_2(x,y,z,z_0)\, dx\, dy\, dz\, dz_0$$

- K = 2 *c*: kinematic factor (see *W. Herr, "Kinematics of Particle Beams I - Relativity"*)
- N_{b1}, N_{b2}: bunch population
- $\rho_{1,2}$: density distribution of the particles (normalized to 1)
- x,y: transverse coordinates
- z: longitudinal coordinate
- z_0: "time variable", $z_0 = c\, t$
- $\Omega_{x,y}$: overlap integral

L from machine parameters -2-

- for a circular machine can reuse the beams f times per second (storage ring)
- for n_b colliding bunch pairs per beam
- for uncorrelated densities in all planes: $\rho(x,y,z,t) = \rho_x(x)\rho_y(y)\rho_z(z-vt)$

$$L = 2 f n_b N_{b1} N_{b2} \int_{x,y,z,z_0} \rho_{1x}(x)\rho_{1y}(y)\rho_{1z}(z-z_0)\rho_{2x}(x)\rho_{2y}(y)\rho_{2z}(z+z_0)\,dx\,dy\,dz\,dz_0$$

- for Gaussian bunches: $\rho_u(u) = \frac{1}{\sigma_u\sqrt{2\pi}} \exp\left\{-\frac{(u-u_0)^2}{2\sigma_u^2}\right\};$ $u = x, y$ $\qquad \int_{-\infty}^{+\infty} e^{-at^2} = \sqrt{\frac{\pi}{a}}$
- for equal beams in x or y: $\sigma_{1x} = \sigma_{2x}$, $\sigma_{1y} = \sigma_{2y}$
- can derive a closed expression: $L = \frac{n_b N_{b1} N_{b2} f}{4\pi\sigma_x\sigma_y}$

- f: revolution frequency
- n_b: number of colliding bunch pairs at that Interaction Point (IP)
- N_{b1}, N_{b2}: bunch population
- $\sigma_{x,y}$: transverse beam size at the collision point

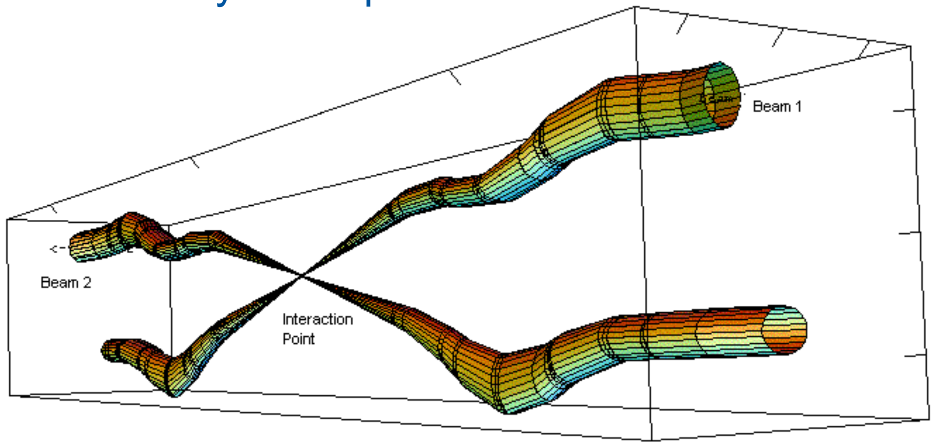
LHC
$n_b = 2808$
$N_{b1}, N_{b2} = 1.15\ 10^{11}$ ppb
$f = 11.25$ kHz
$\sigma_x, \sigma_y = 16.6\ \mu m$
$L = 1.2\ 10^{34}\ cm^{-2}s^{-1}$

need for small β*

- expand physical beam size $\sigma_{x,y}$:
  - * means “at the IP”

$$\sigma_x^* = \sigma_y^* = \sqrt{\frac{\beta^* \varepsilon}{\gamma_r}} \;\Rightarrow\; \boxed{L = \frac{n_b N_{b1} N_{b2} f \gamma_r}{4 \pi \beta^* \varepsilon}}$$

- try and conserve low ε from injectors
  - explicit dependence on energy (γ_r)
- intensity N_b pays more than ε and β^*
- design low β^* insertions
  - limits by triplet aperture, protection by collimators
  - in LHC nominal cycle: “squeeze”



Relative beam sizes around IP1 (Atlas) in collision

J. Jowett

LHC
$\beta^* = 18 \rightarrow 0.55$ m
$\varepsilon = 3.75$ μm
$\gamma_r = 7463$
$\sigma_{x,y} = 16.6$ μm

Luminosity reduction factors (F_i)

$L = L_{max} * F_1 * F_2 * F_3 \ldots.$

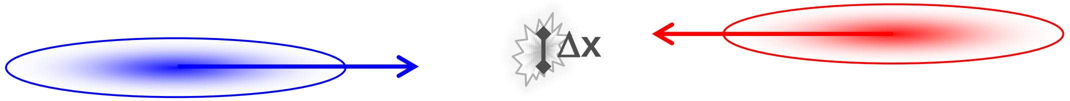
transverse offsets

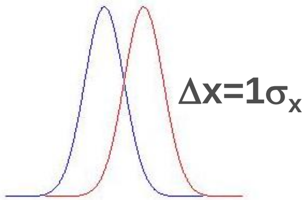
crossing angles and crab cavities

hourglass effect

transverse offsets -1-

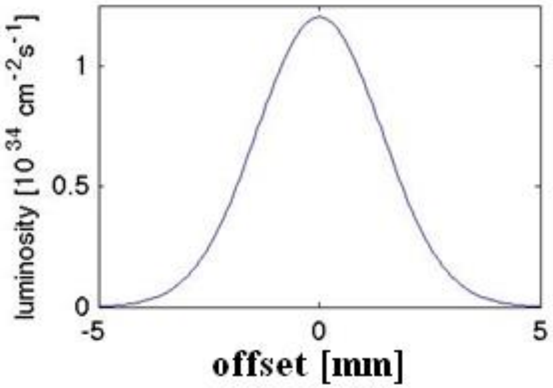
- in case the beams do not overlap in the transverse plane (e.g. in x)

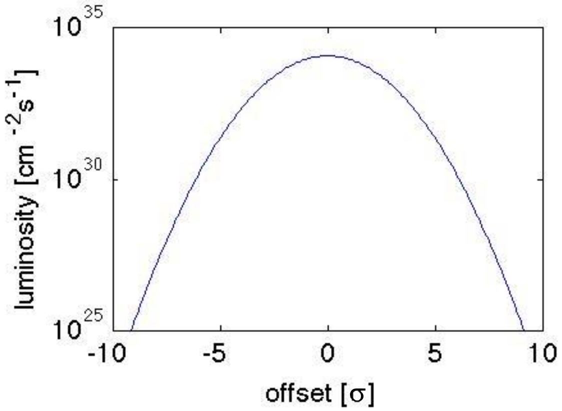




- more generally

$$L = \frac{n_b N_{b1} N_{b2} f}{4\pi\sigma_x\sigma_y} \underbrace{\exp\left\{-\frac{\Delta x^2}{4\sigma_x^2} - \frac{\Delta y^2}{4\sigma_y^2}\right\}}_{F}$$





Δx	F
0	1
1 σ	0.779
2 σ	0.368
3 σ	0.105
4 σ	0.018
5 σ	0.002

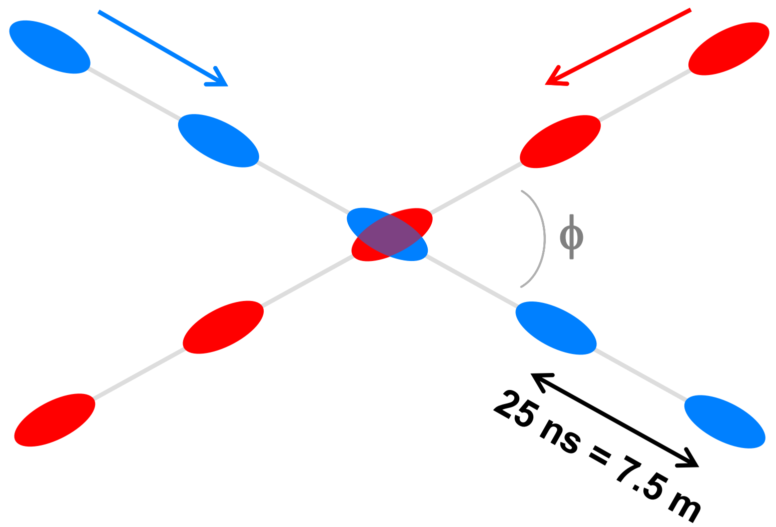
For experts: transverse offsets -2-

- more general expression including different beam sizes:
  - $\sigma_{1x} \neq \sigma_{2x}$, $\sigma_{1y} \neq \sigma_{2y}$

$$L = \frac{n_b N_{b1} N_{b2} f}{2\pi\sqrt{(\sigma_{x,1}^2 + \sigma_{x,2}^2)(\sigma_{y,1}^2 + \sigma_{y,2}^2)}} \exp\left\{ -\frac{(\Delta x)^2}{2(\sigma_{x,1}^2 + \sigma_{x,2}^2)} - \frac{(\Delta y)^2}{2(\sigma_{y,1}^2 + \sigma_{y,2}^2)} \right\}$$

crossing angles

- to avoid parasitic collisions when there are many bunches
  - otherwise collisions elsewhere than in interaction point only
    - e.g.: CMS experiment is 21 m long, common vacuum pipe is 120 m long



- luminosity is reduced as the particles no longer traverse the entire length of the counter-rotating bunch

$$L = \frac{n_b N_{b1} N_{b2} f}{4\pi\sigma_x\sigma_y} \underbrace{\frac{1}{\sqrt{1+\left(\frac{\sigma_z}{\sigma_x}\tan\frac{\phi}{2}\right)^2}}}_{F}$$

$\frac{\sigma_z}{\sigma_x}\tan\frac{\phi}{2}$ is called the Piwinski angle

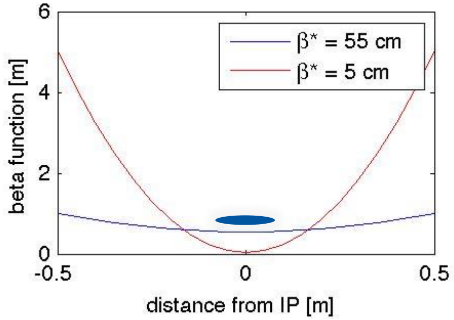
valid for small ϕ and $\sigma_z \gg \sigma_x, \sigma_y$

LHC
ϕ = 285 μrad
σ_z = 7.5 cm
F = 0.84

hourglass effect

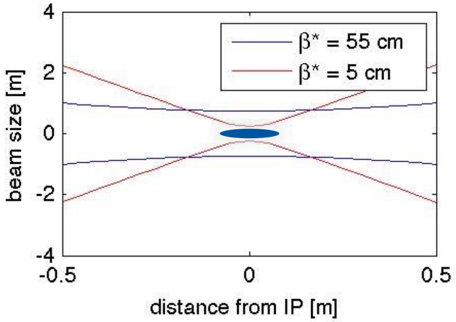
- β depends on longitudinal position z
  - see *W.Hillert, “Transverse Beam Dynamics”*

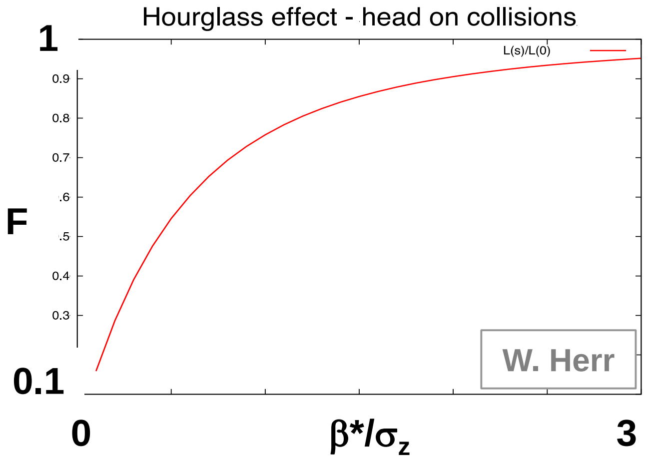
$$\beta(z) \approx \beta^*\left(1+\left(\frac{z}{\beta^*}\right)^2\right)$$



- then beam size $\sigma_{x,y}$ depends on z
  - if $\beta^* >> \sigma_z$, effect is negligible
  - if $\beta^* \sim \sigma_z$, bunch samples bigger β than β^*

$$\sigma_{x,y}(z) \approx \sigma^*_{x,y}\sqrt{1+\left(\frac{z}{\beta^*_{x,y}}\right)^2}$$



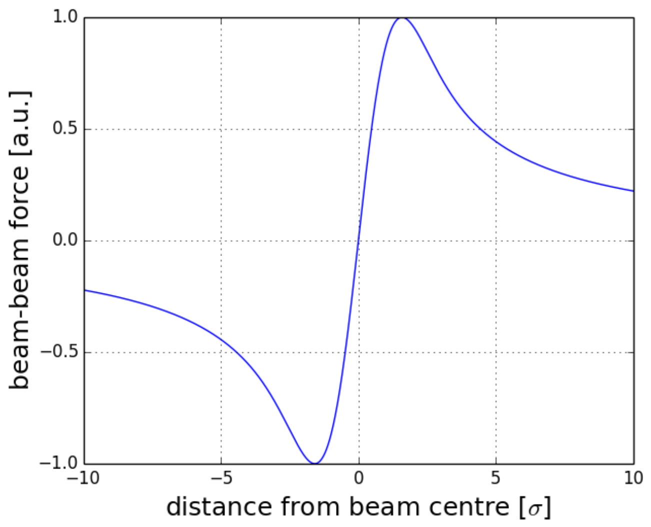


- L reduction is non-negligible for long bunches and small β

LHC	HL-LHC
$\beta^*/\sigma_z > 7$	$\beta^*/\sigma_z \sim 2$
F ~ 1	F ~ 0.90

beam-beam force

$$F(r) \propto \frac{N_b}{\sigma}\frac{1}{r}\left[1 - e^{\frac{-r^2}{2\sigma^2}}\right]$$



- important for high brilliance beams
  - i.e. high luminosity …
- gives an amplitude dependent tune shift
  - for small amplitude, linear tune shift
- the slope of the force at zero amplitude is called the *beam-beam parameter*

$$F \propto -\xi r \qquad \text{with} \qquad \xi = \frac{\beta^*}{4\pi}\frac{\partial(\Delta r')}{\partial r} = \frac{N_b r_0 \beta^*}{4\pi\gamma_r \sigma^2}$$

- indicates the strength of the beam-beam force
  - but does not describe changes to the optical functions, non-linear part…

$$\Delta Q_{bb} \propto \pm\xi$$

LHC
$\sigma_{x,y}$ = 16.6 μm
β* = 0.55 m
N = 1.15 × 10^{11} ppb
ξ = 0.0037

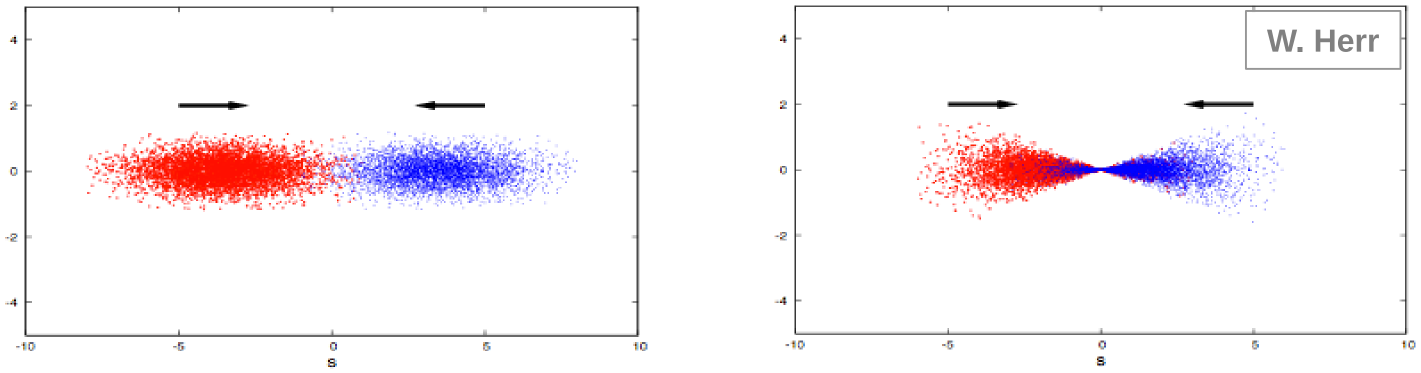
linear colliders:
additional reduction/enhancement factors

disruption, pinch effect

beamstrahlung

disruption effects -1-

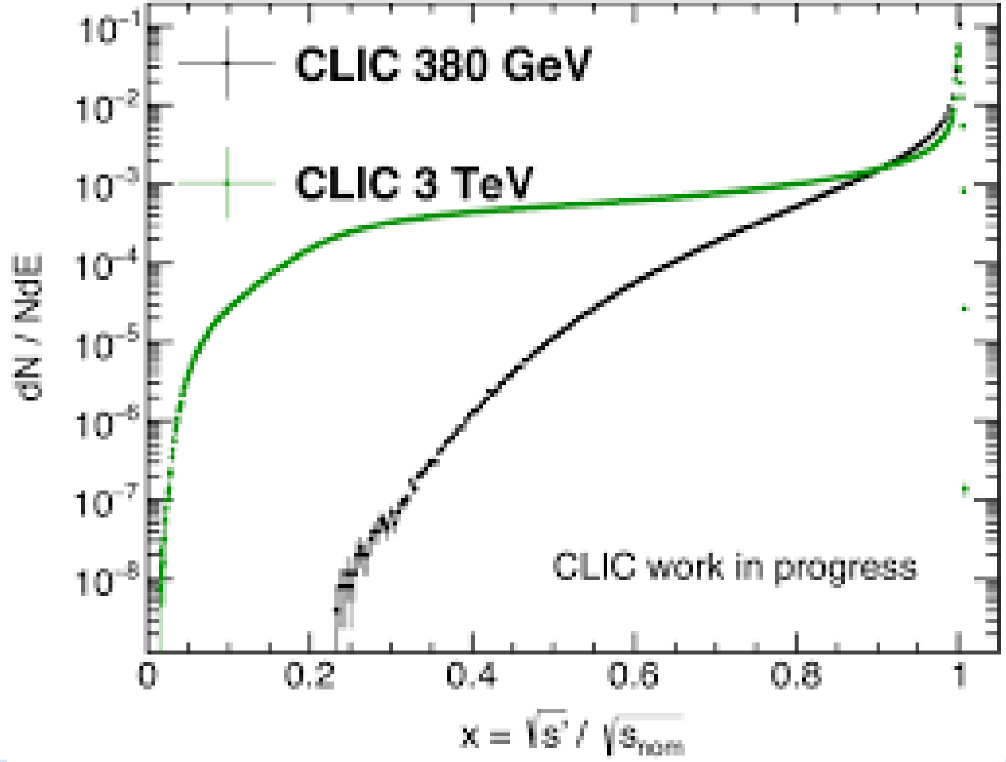
- strong field by one beam bends the opposing particle trajectories
- quantified by disruption parameter $D_{x,y} = \dfrac{2 r_e N_b \sigma_z}{\gamma_r \sigma_{x,y} \left(\sigma_x + \sigma_y \right)}$ $\qquad$ $D_{x,y}$ normally > 1
- nominal beam size is reduced by the disruptive field (*pinch effect*)
  - additional focusing for the opposing beam



- r_e: electron classical radius
- N_b: bunch population
- $\sigma_{x,y,z}$: beam size at the collision point
- γ_r: relativistic factor

beamstrahlung

- disruption at the interaction point is a strong bending:
- results in synchrotron radiation (*beamstrahlung*)
  - causes spread of centre-of-mass energy
  - high energy photons increase detector background



- quantified by beamstrahlung parameter Y

$$Y = \gamma \frac{\langle E + B \rangle}{B_C} \approx \frac{5}{6} \frac{r_e^2 \gamma N_b}{\alpha \sigma_z (\sigma_x + \sigma_y)}$$

- with $B_C \equiv \dfrac{m^2 c^3}{e\hbar} \approx 4.4 \times 10^{13}\,\text{Gauss}$

Not too much Luminosity please (in pp)…

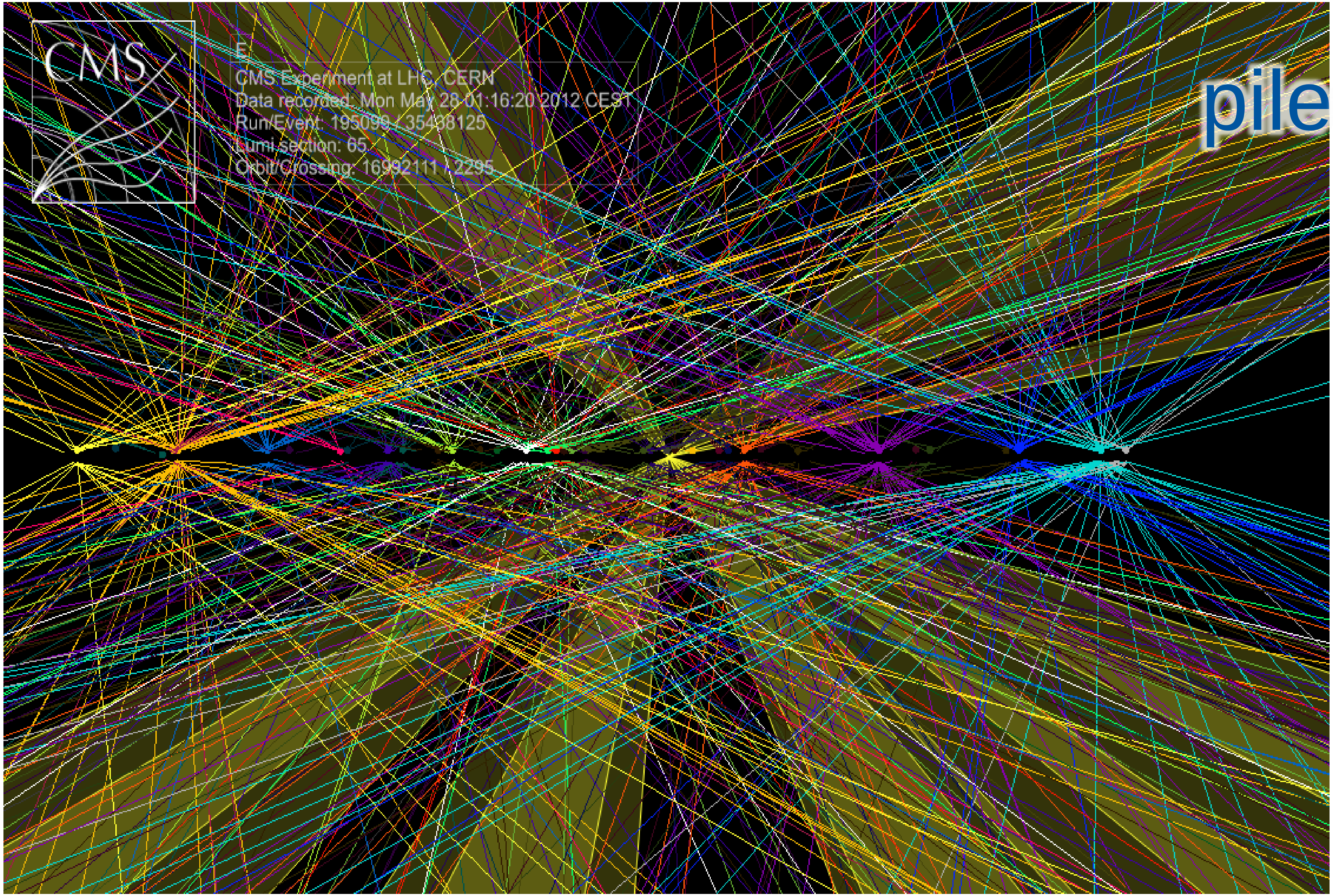
- experiments might need luminosity control
  - if too high can cause high voltage trips then impact efficiency
  - might have event size or bandwidth limitations in read-out
  - too many simultaneous event cause loss of resolution
- ...experiments also care about:
  - time structure of the interactions: *pile up* μ
    - average number of inelastic interactions per bunch crossing

$$\langle R \rangle = \left\langle \frac{dN_{ev}}{dt} \right\rangle = \mu f$$

	design	2010	2011	2012	2015	2016	HL-LHC
μ	21	4	17	37	17	41	140

  - f = bunch repetition frequency
  - spatial distribution of the interactions: *pile-up density*
    - e.g. HL-LHC: accept max pile up density of 1.3 events/mm
  - quality of the interactions (e.g. background)
  - size of luminous region
    - e.g. need constant length (input to MonteCarlo simulations)

pile-up


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295

Luminosity levelling

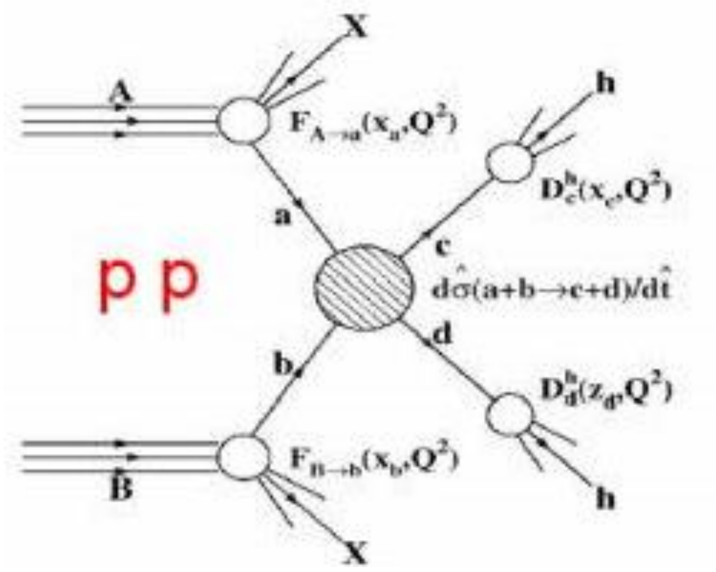
- some experiments need to limit the pile-up
  - thus luminosity per bunch pair
    - e.g. $\mu < 2.1$ at LHCb in 2012

- stay as long as possible at the maximum value that experiment can manage
  - which is lower than what the machine could provide
- maintain the luminosity constant over a period of time (i.e. the fill)

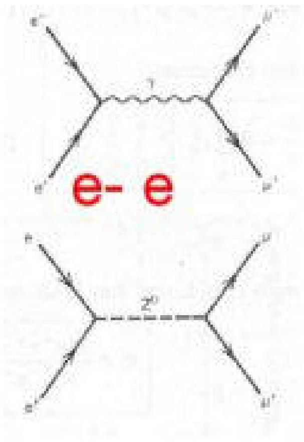
- possible techniques:
  - by transversely offsetting the beams at the IP
  - by changing β^*
  - by decreasing the crossing angle
  - by bunch length variations

The possible future@CERN: Some physics arguments

- Hadron collisions: collision of compound particles
  - Mix of quarks, anti-quarks and gluons: variety of processes
  - Parton energy spread
  - QCD processes large background sources
    total cross section increases with log s;
    "interesting cross sections" decrease with s
  - Hadron collisions $\Rightarrow$ large discovery range

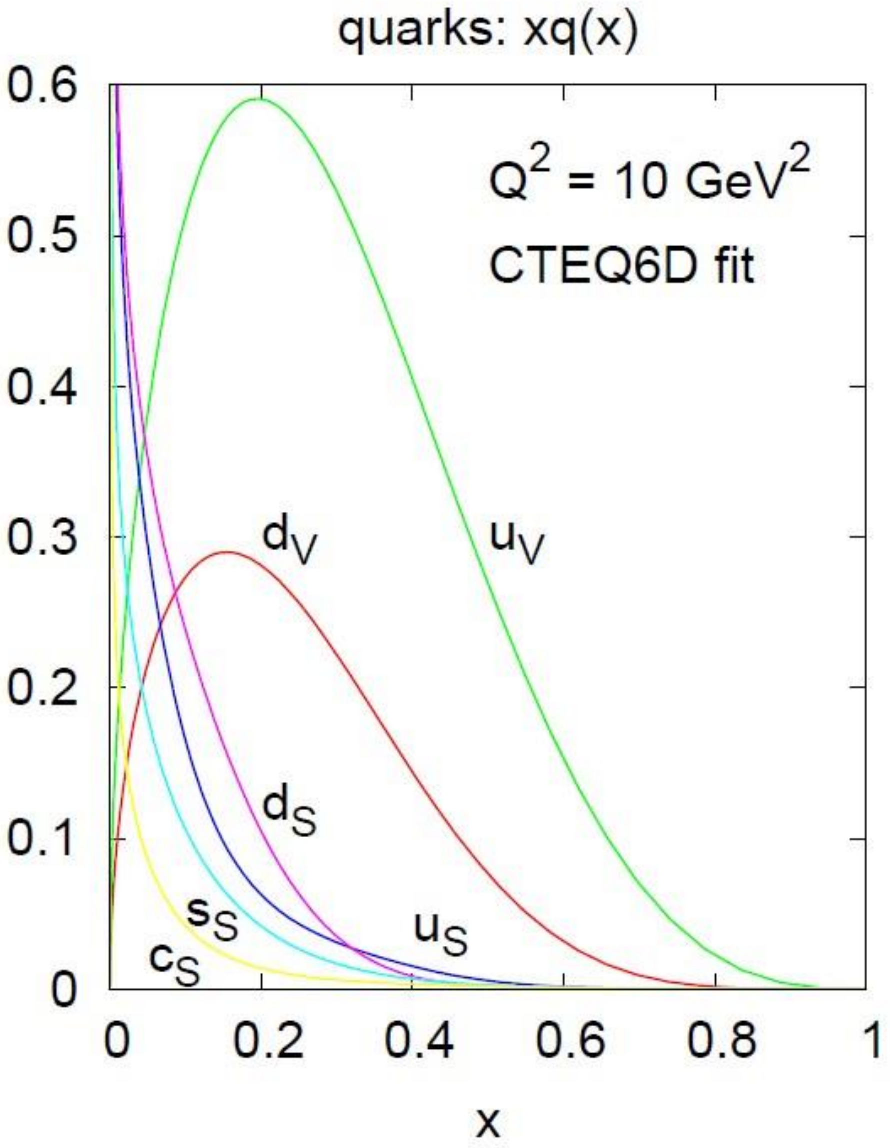


- Lepton collisions: collision of elementary particles
  - Collision process known
  - Well defined energy
  - Other physics background limited
  - All cross sections decrease with s



- Lepton-hadron is also possible

All quarks



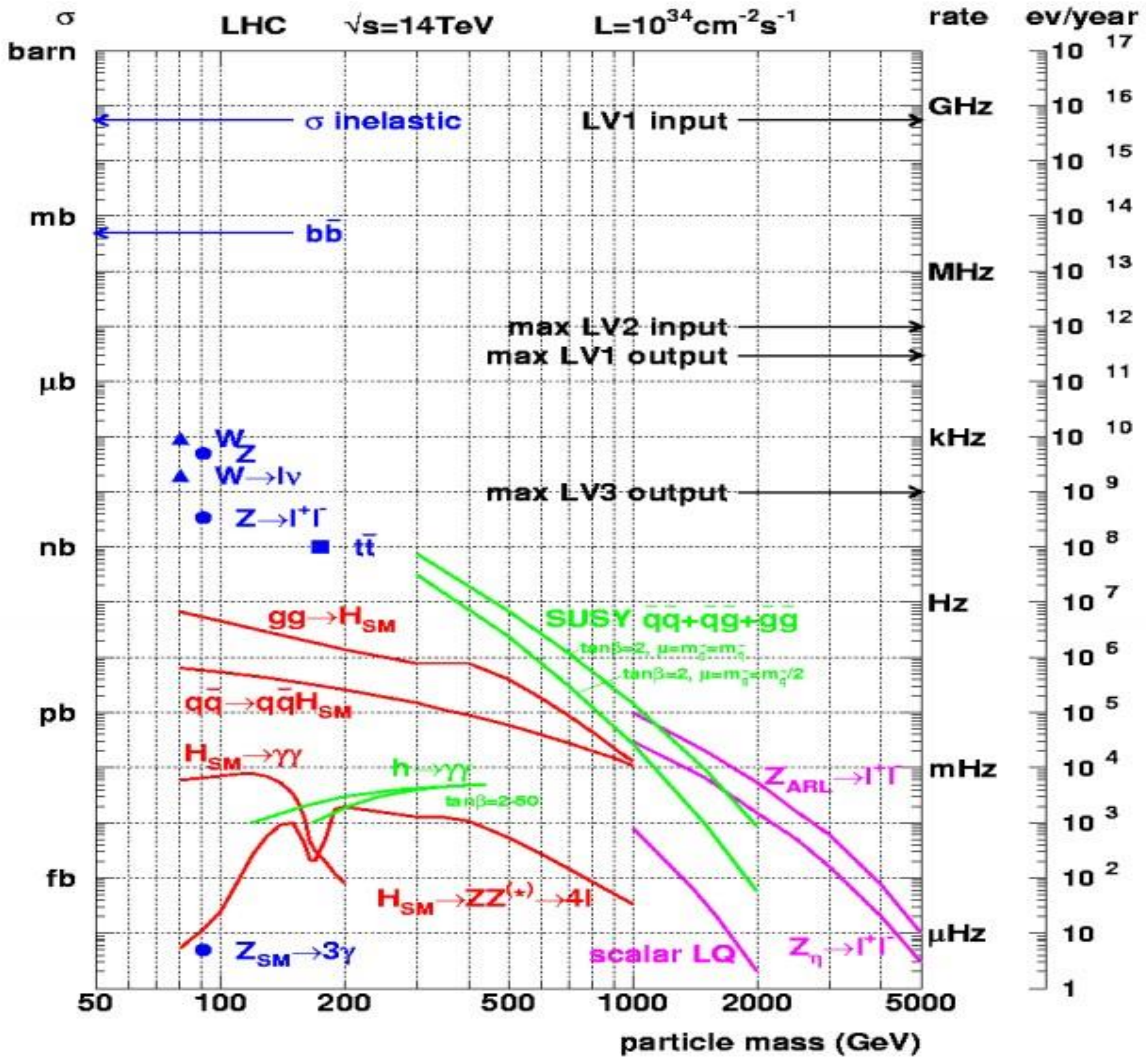
These & other methods $\longrightarrow$ whole set of quarks & antiquarks

NB: also strange and charm quarks

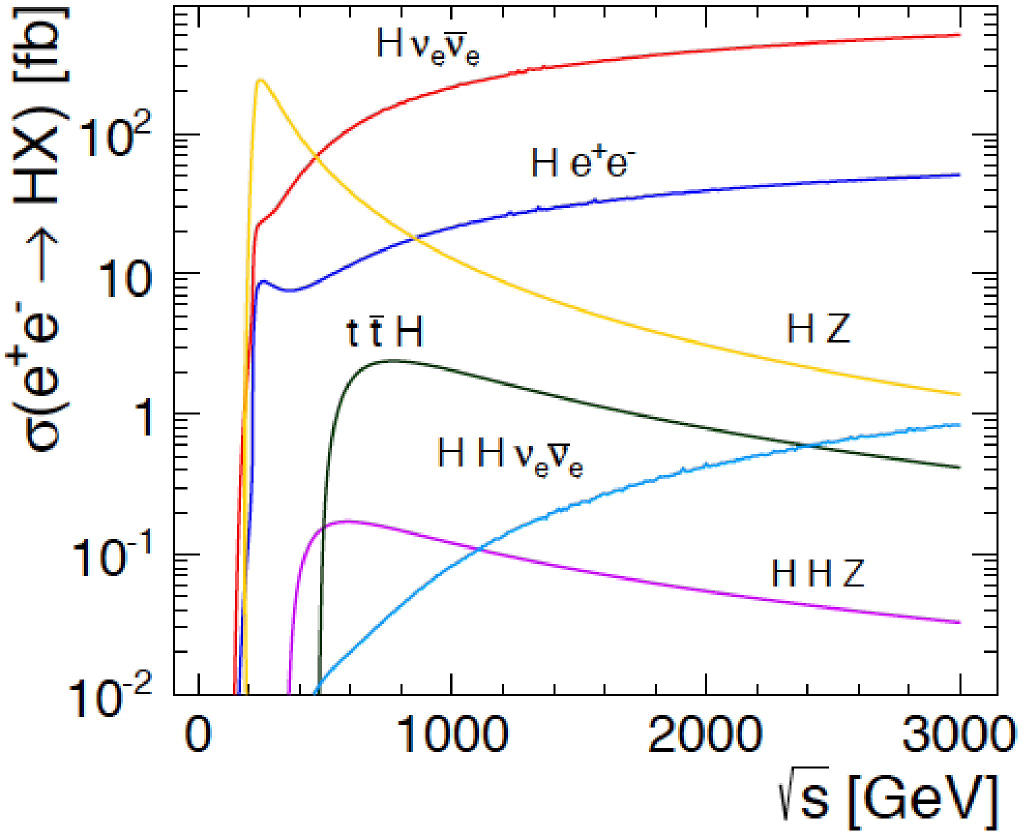
- valence quarks ($u_V = u - \bar{u}$) are *hard*
  $x \to 1 : xq_V(x) \sim (1-x)^3$
  quark counting rules
  $x \to 0 : xq_V(x) \sim x^{0.5}$
  Regge theory
- sea quarks ($u_S = 2\bar{u}, \ldots$) fairly *soft* (low-momentum)
  $x \to 1 : xq_S(x) \sim (1-x)^7$
  $x \to 0 : xq_S(x) \sim x^{-0.2}$

The LHC: signals much smaller than “bkg”

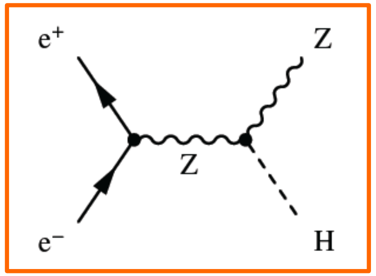
- General event properties
- Heavy flavor physics
- Standard Model physics
  - QCD jets
  - EWK physics
  - Top quark
- Higgs physics
- Searches for SUSY
- Searches for ‘exotica’

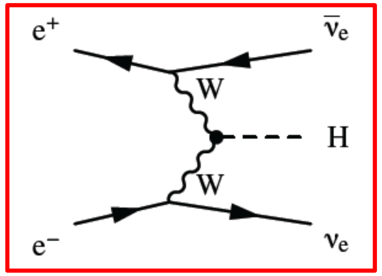


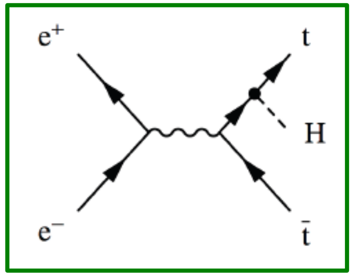
Higgs Physics in e+e- Collisions

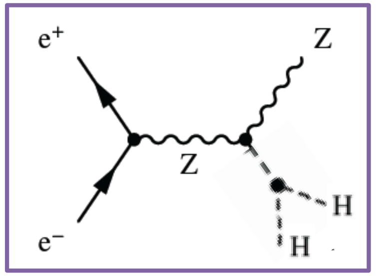


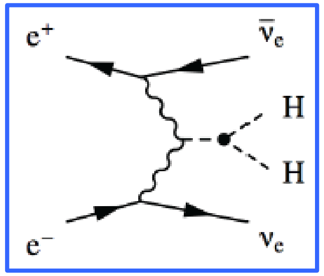
- **Precision Higgs measurements**
- Model-independent
  - Higgs couplings
  - Higgs mass
- Large energy span of linear colliders allows to collect a maximum of information:
  - ILC: 500 GeV (1 TeV)
  - CLIC: ~350 GeV – 3 TeV











Future seen from the accelerators: Lepton Collider Options

Three main approaches

- Big LEP-type collider ring
  - FCC-ee (or/and CepC in China)
  - Later a proton collider in the same tunnel

- Linear collider
  - CLIC (or ILC in Japan)

- Muon collider (presently all efforts stopped)

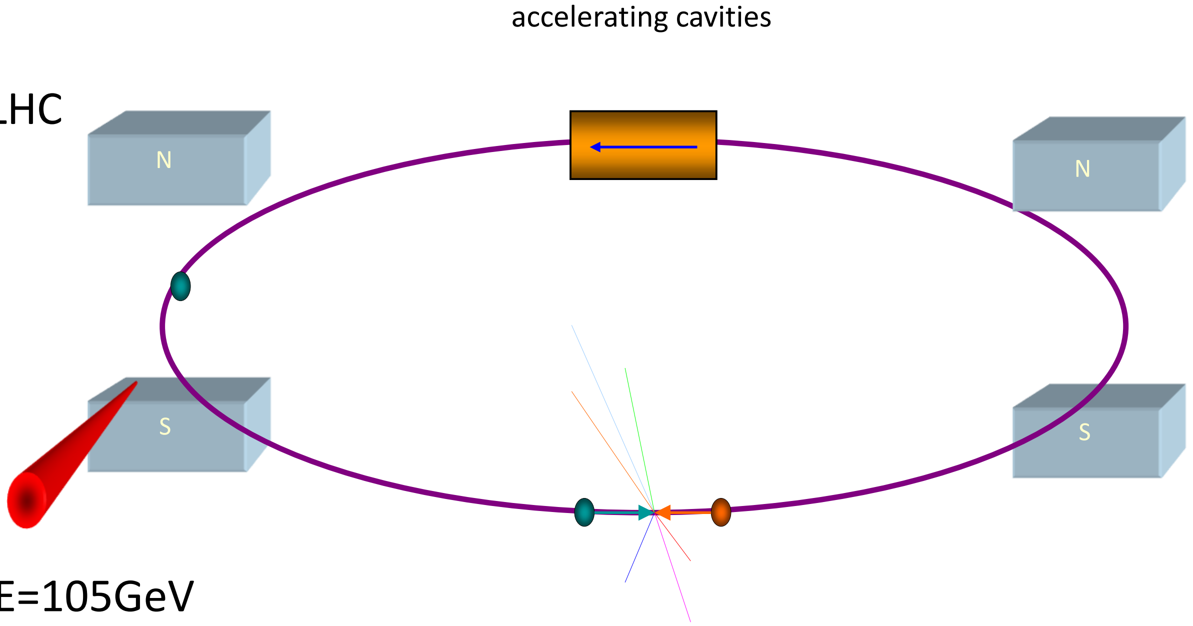
e+ e- Ring Collider Energy Limitation

Beam can be used many times

Lepton beam energy is below LHC
-> magnets are not a problem

But synchrotron radiation is:

$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$



At LEP2 lost 2.75GeV/turn for E=105GeV

Pay for installed voltage (ΔE) and size (R),
so scale as:

$$R \propto E^2$$

$$\Rightarrow \Delta E \propto E^4 / E^2$$

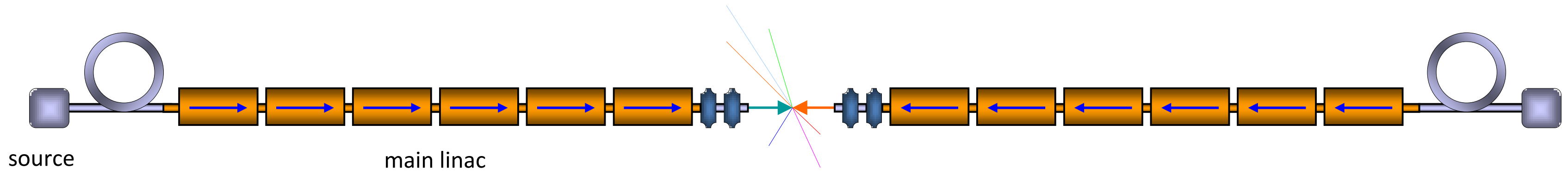
$$\Rightarrow \Delta E \propto E^2$$

$$\Rightarrow \Delta E \propto R$$

$$C_R = a_R E^2 + b_R$$

-> use heavier particles, e.g. muons
-> or linear collider
(-> or try to push a bit harder on cost)

Linear Collider Energy Limitation



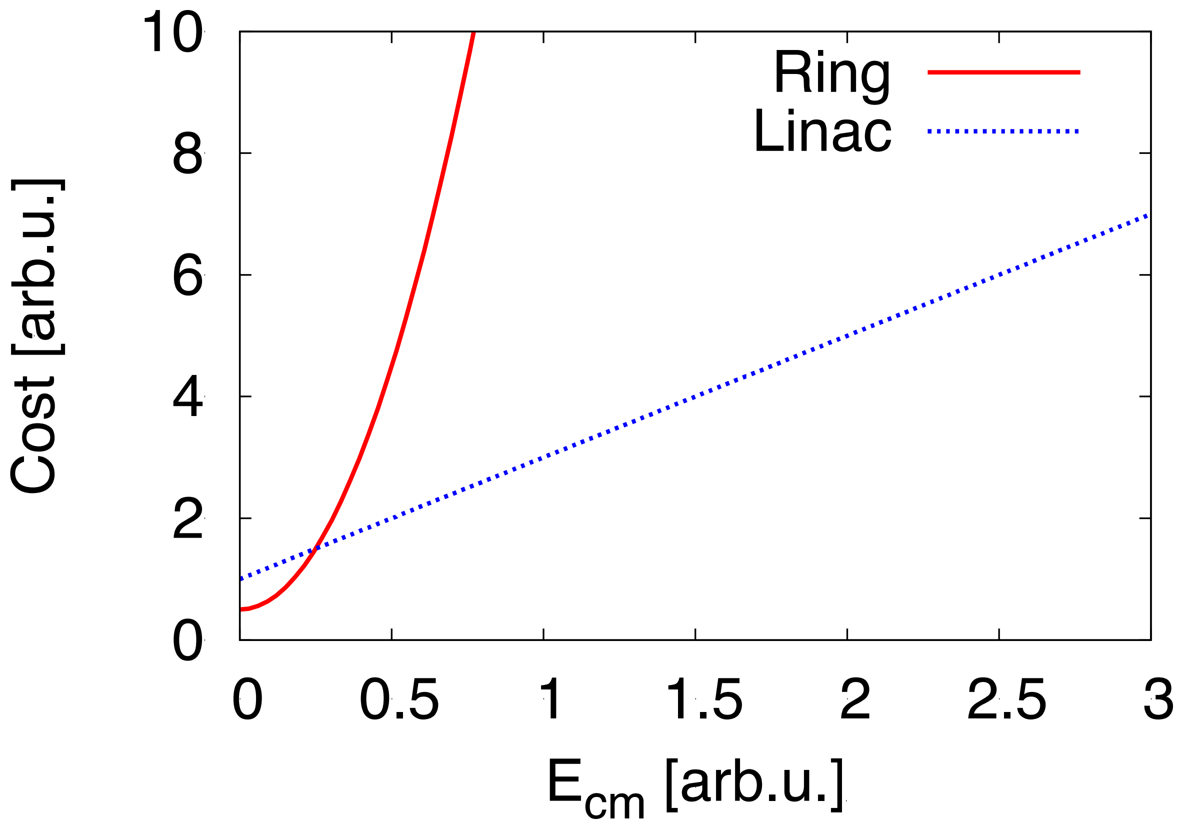
Hardly any synchrotron radiation

Beam can only be used only once
-> strong beam-beam effects

$$C_L = a_L E + b_L$$

Acceleration gradient is an important issue

Simplified Cost Scaling Comparison



Linac:

$$C_L = a_L E + b_L$$

Ring:

$$C_R = a_R E^2 + b_R$$

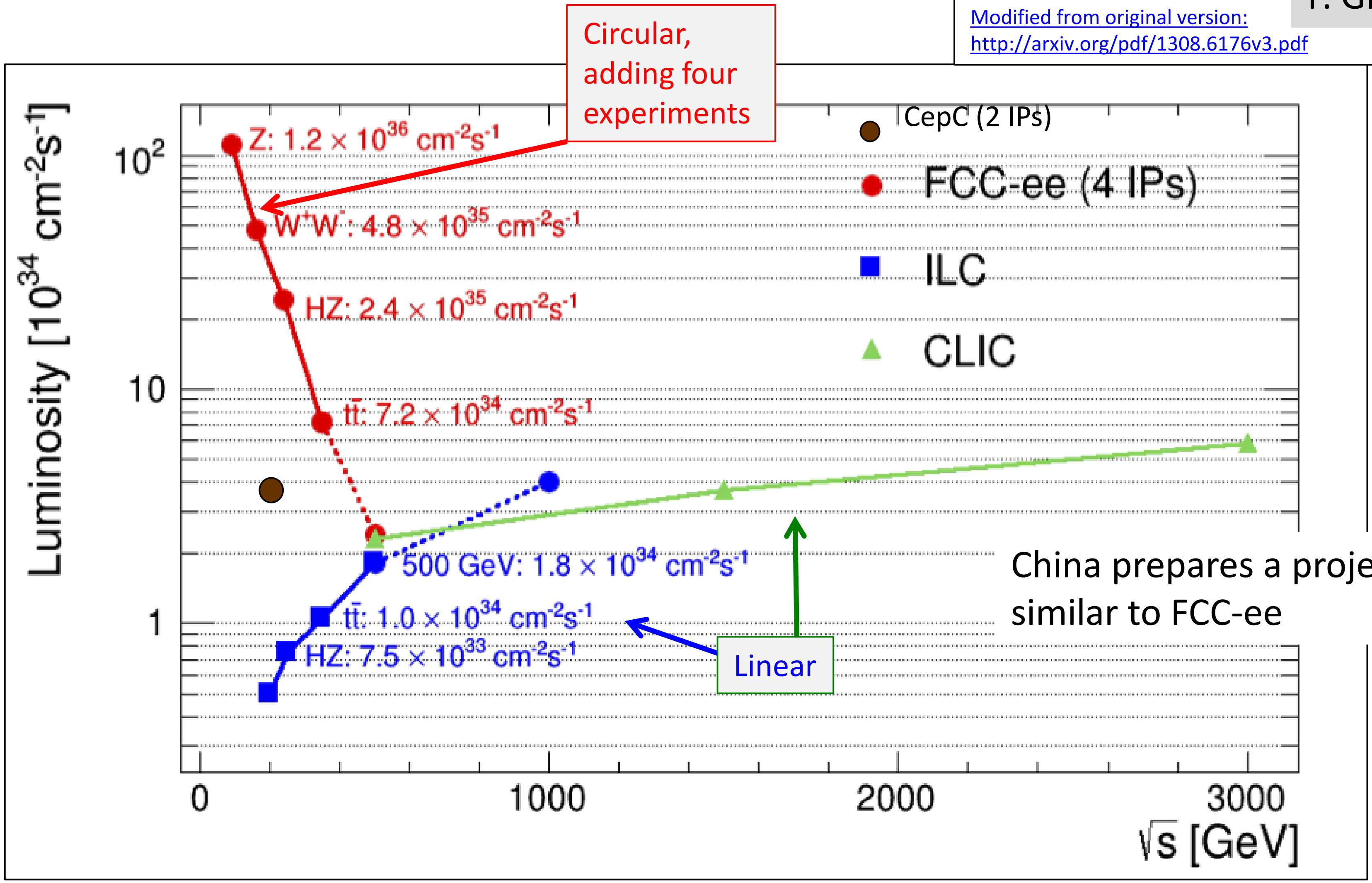
Power consumption behaves similar to cost for constant luminosity

There will always be an energy where linear colliders are better

Circular vs. Linear Colliders

F. Gianotti

Modified from original version:
http://arxiv.org/pdf/1308.6176v3.pdf



China prepares a project similar to FCC-ee

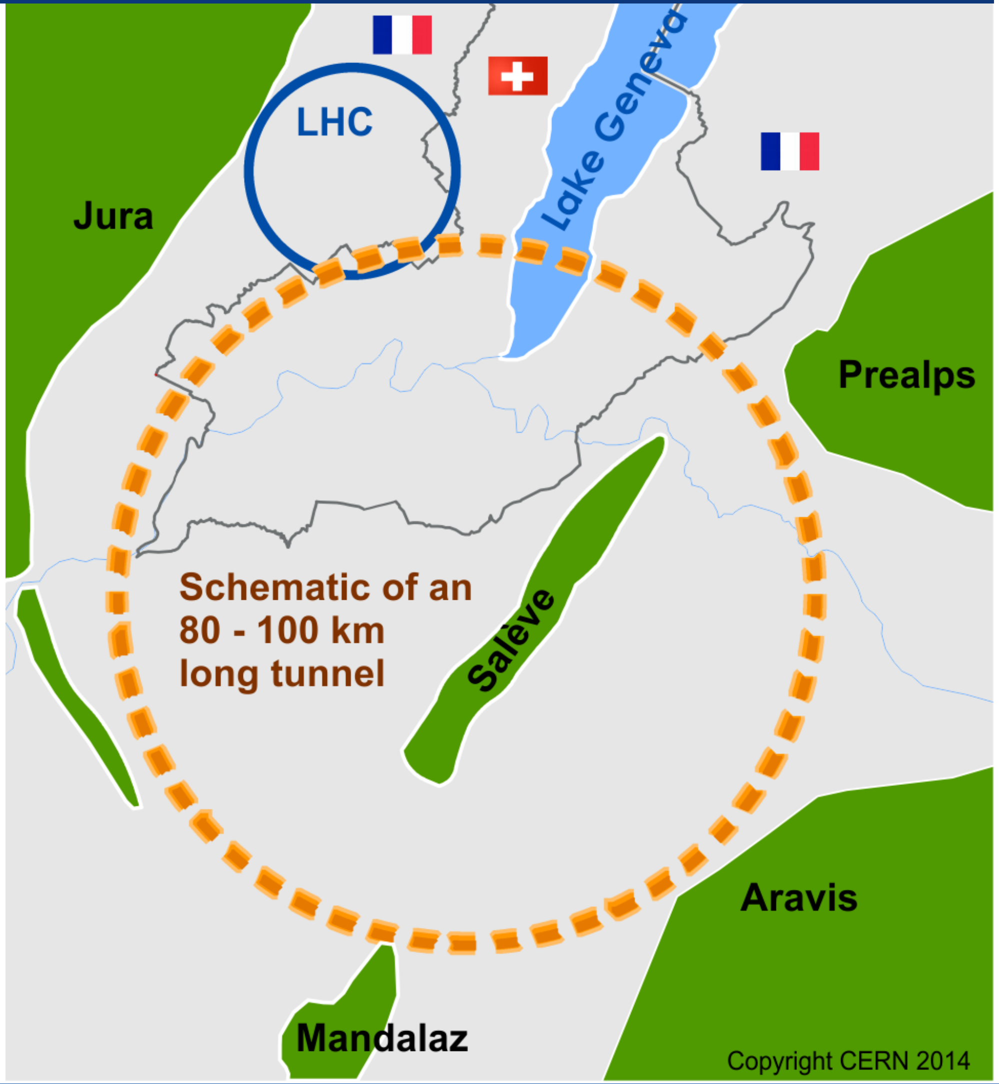
Future Circular Collider Study
Goal: CDR for European Strategy Update 2018/19

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology



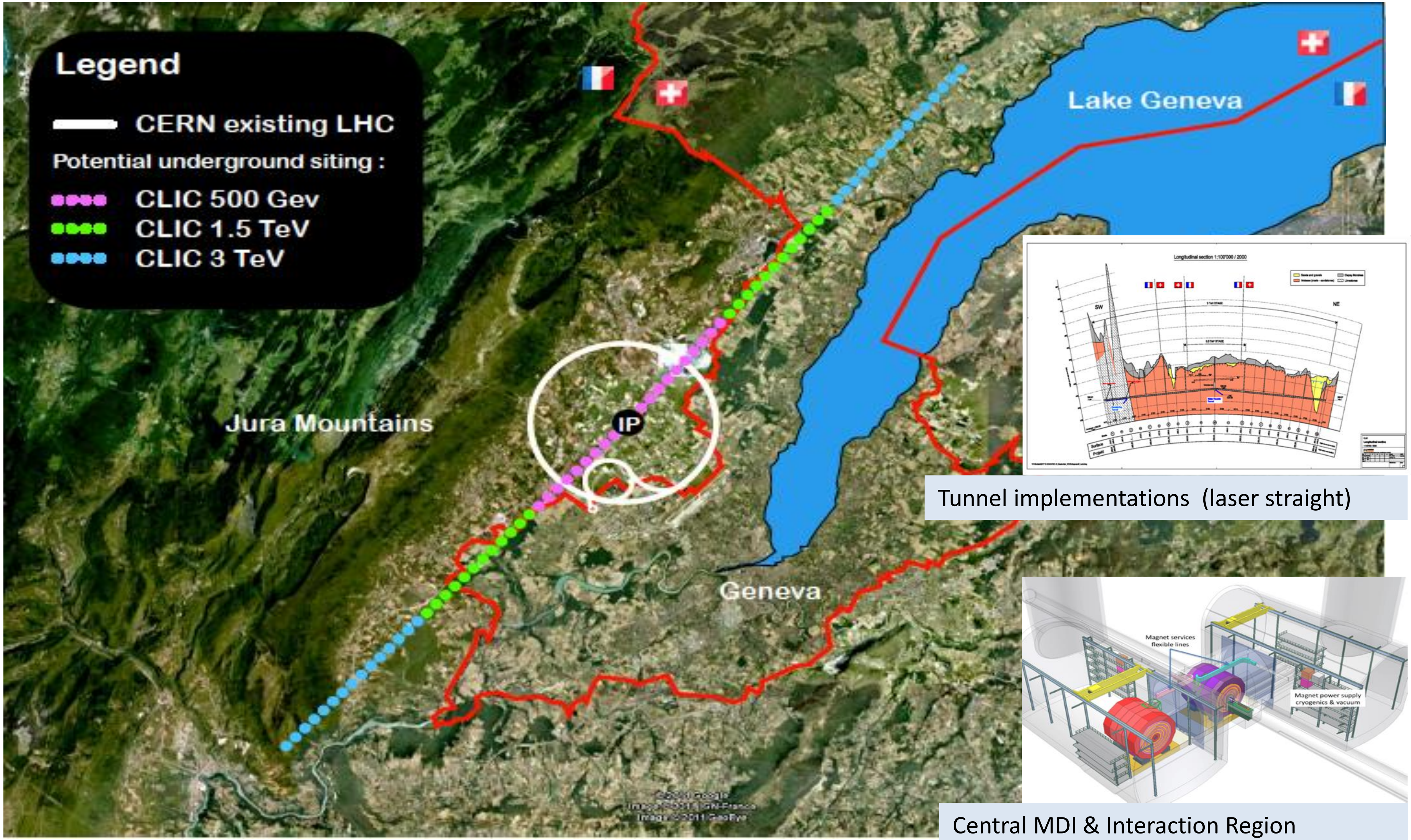
CepC/SppC study (CAS-IHEP) 100 km (new baseline!) , e^+e^- collisions ~2028; *pp* collisions ~2042

easy access
300 km east
from Beijing
3 h by car
1 h by train

Yifang Wang

"Chinese Toscana"

CLIC near CERN



Tunnel implementations (laser straight)

Central MDI & Interaction Region

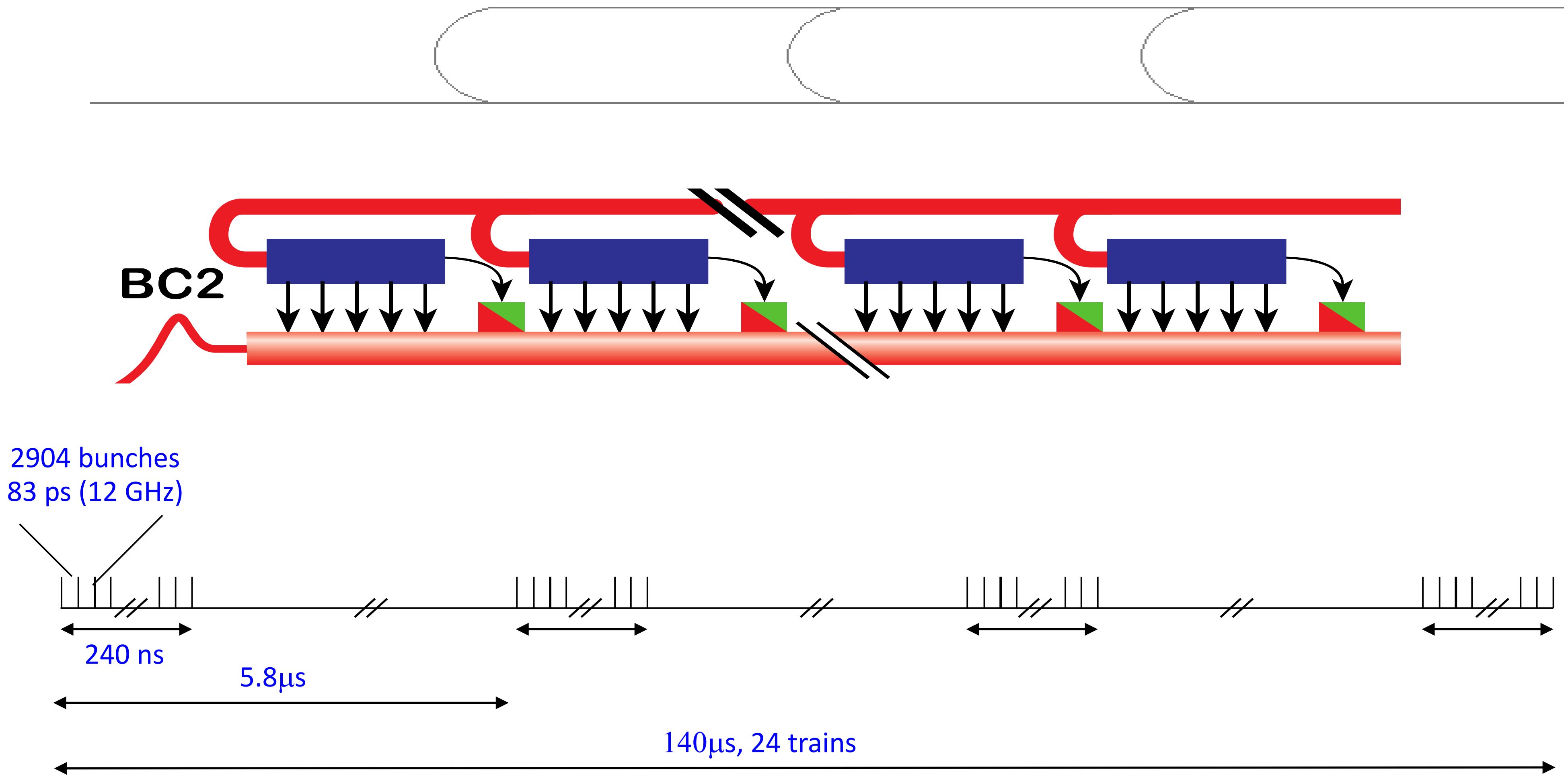
hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.27	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.2)	1 (0.2)	2.5	(2.2) 1.15
bunch spacing [ns]	25 (5)	25 (5)	25 (5)	25
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.45	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	16	(5) 1
peak #events/bunch crossing	170	1020 (204)	460 (92)	(135) 27
stored energy/beam [GJ]	8.4		1.4	(0.7) 0.36
synchrotron rad. [W/m/beam]	30		4.1	(0.35) 0.18

The main technology challenges

- FCC – hh
  - SC dipole magnets with 16T or 20T field strength
  - machine protection and beam collimation
- FCC-e^+e^-
  - 100 MW synchrotron radiation power
  - @350 GeV cms energy > 10GV energy loss/turn
  - huge RF plants based on SC-RF
- CLIC
  - 100 MV/m gradient for acceleration
  - Uses drive-beam of 100 A! (electrons) to power main linac
  - vertical beam size at IP = 1nm for high luminosity (10^{34})
  - very high demand on alignment of RF (wakefields) and on quadrupole mechanical stability (in order to maintain small emittance)

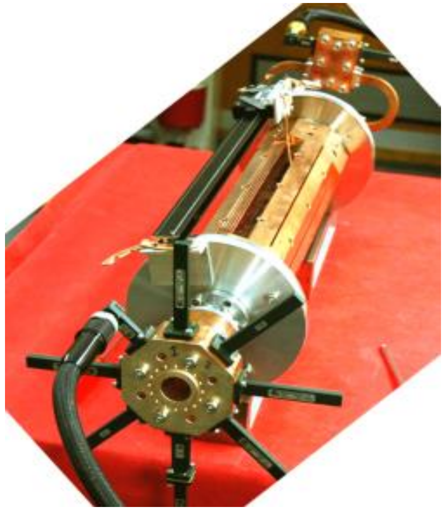
Drive beam time structure

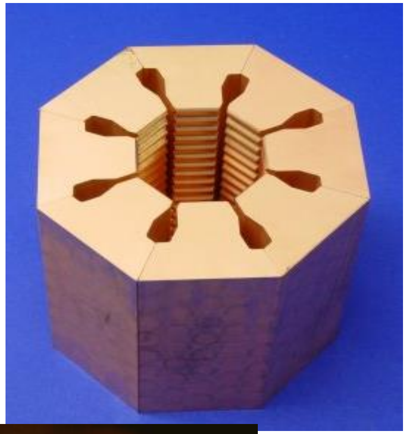


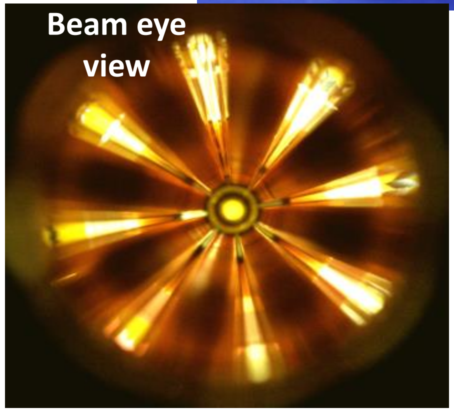
Bunch charge: 8.4 nC, Current in train: 100 A

Power extraction structure PETS

- must extract efficiently >100 MW power from high current drive beam
- passive microwave device in which bunches of the drive beam interact with the impedance of the periodically loaded waveguide and generate RF power
- periodically corrugated structure with low impedance (big a/λ)
- ON/OFF mechanism







The power produced by the bunched (ω_0) beam in a constant impedance structure:

Design input parameters

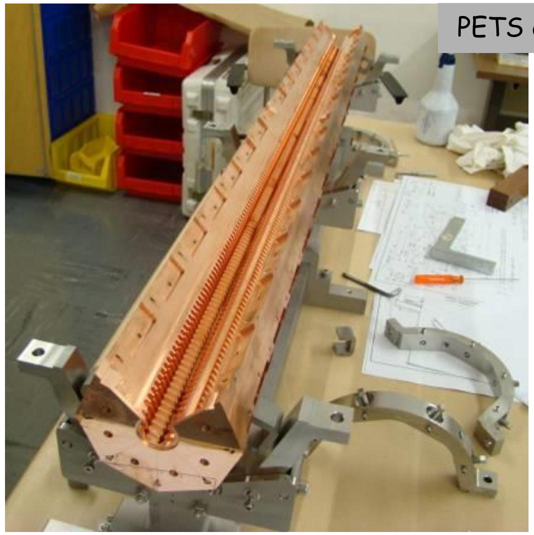
PETS design

$$P = I^2 L^2 F_b^2 w_0 \frac{R/Q}{4 v_g}$$

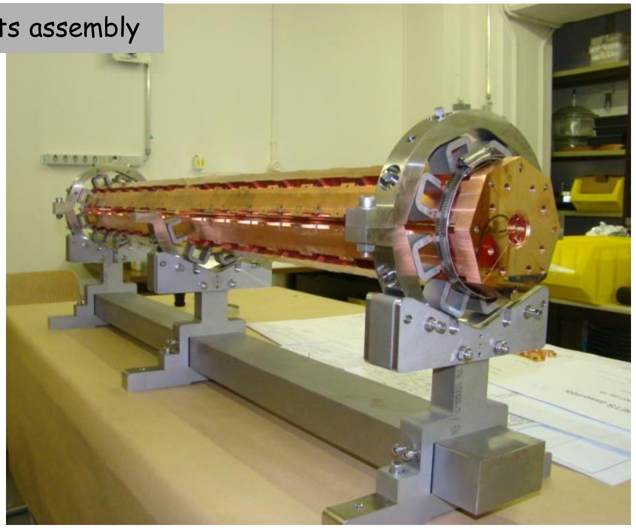
P – RF power, determined by the accelerating structure needs and the module layout.
I – Drive beam current
L – Active length of the PETS
F_b – single bunch form factor (≈ 1)

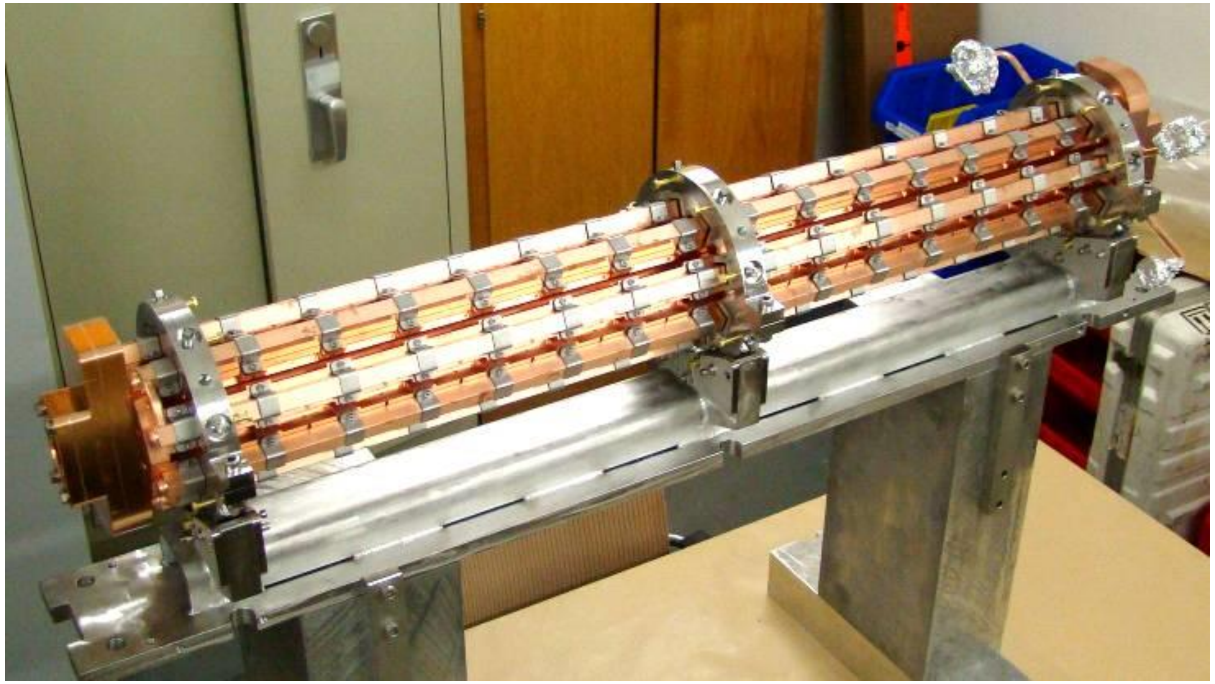
12 GHz PETS assembly

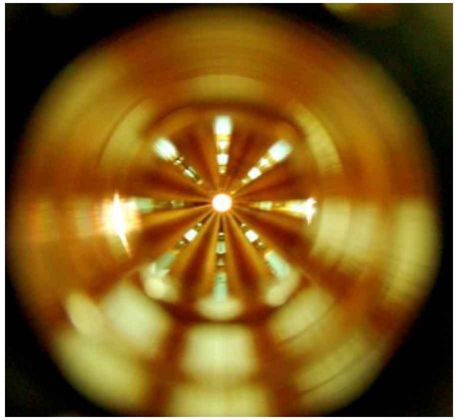
8 bars, as received from VDL



PETS octants assembly







I. Syratchev

Summary

- Interesting time ahead of us in high energy physics
  → LHC still “usefull” until about the year 2035
  → LHC will get a luminosity upgrade around the year 2025
  (5-10 times integrated luminosity/year)
- HE-LHC (LHC tunnel filled with FCC magnets) is also an actively discussed option
- Expect publication of “European strategy update” within the next month: Guidance for all laboratories for the next 5 years
- Presently active R&D on all three options:
  - CLIC, FCC (leptons) and FCC (hadrons)
- All options require a lot of resources and collaboration across the whole world

- Backup Slides

Past/present circular colliders

Machine	Years in operation	Beam type	Beam energy [GeV]	Luminosity [$cm^{-2}\ s^{-1}$]
ISR	1971-'84	p p	31	$>2\times10^{31}$
LEP I	1989-'95	e+ e-	45	3×10^{30}
LEP II	1995-2000	e+ e-	90-104	10^{32}
KEKB	1999-2010	e+ e-	8 x 3.5	2×10^{34}
SppS	1981-'84	p anti-p	315 (400)	6×10^{30}
TEVATRON	1983-2011	p anti-p	980	2×10^{32}
LHC	2008-?	p p (Pb)	7000	10^{34}
HL-LHC	~2026-2037	p p (Pb)	7000	5×10^{34}
FCC-hh	2040+	p p (Pb)	50000	$2\text{-}3\times10^{35}$
FCC-ee	2040+	e+ e-	45-175	$\sim10^{36}$