FCC: Machines and experiments

Marco Zanetti, Nicola Bacchetta

Machines

Civil Engineering: 93 km racetrack

CERN | FCC hh ee he | ARUP

Alignment | Shaft Tools

Choose alignment option

93km quasi-circular ▼

Tunnel depth at centre: 286mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .3

Slope Angle y-y(%): 0

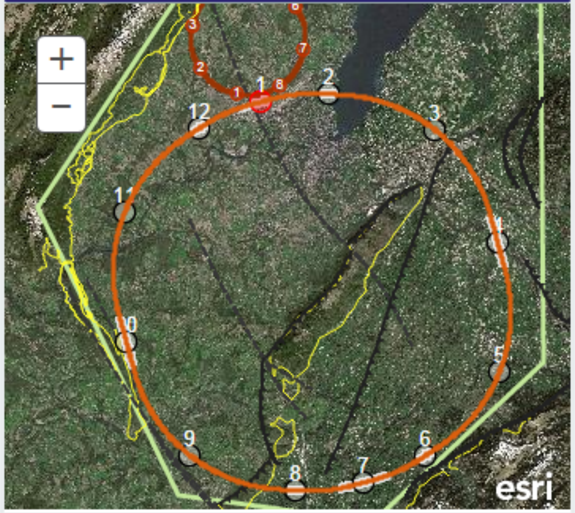
CALCULATE

Alignment centre

X: 2498923 Y: 1106695

LHC Intersection	IP 1	IP 2
Angle	1°	-1°
Depth	542m	542m

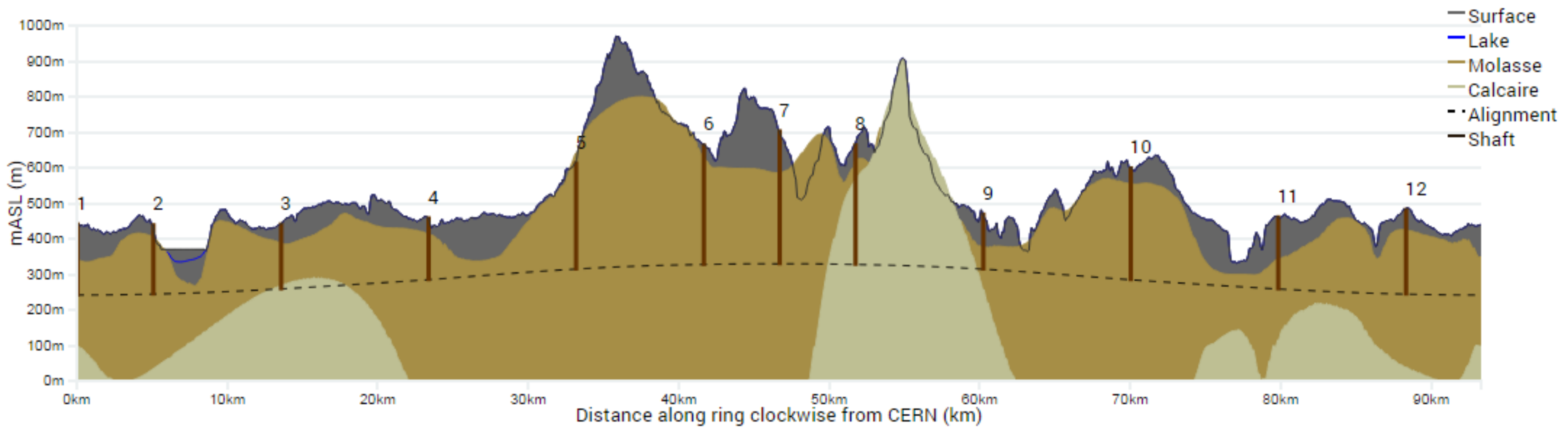
Alignment Location



Geology Intersected by Shafts | Shaft Depths

Shaft	Shaft Depth (m) Actual	Min	Mean	Max	Geology (m) Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	175	184	194	53	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	366	44	56	237
9	155	131	145	167	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	204	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2052	247

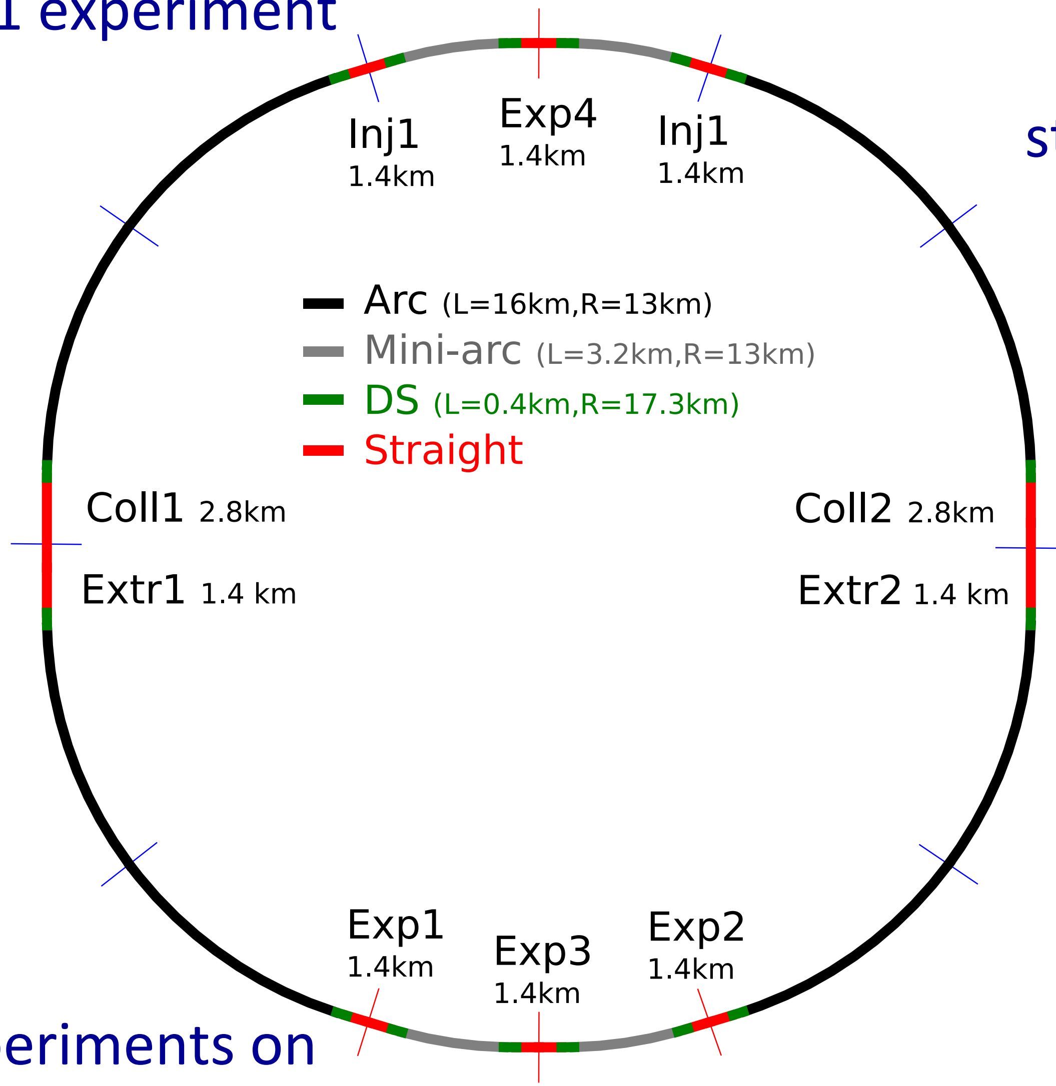
Alignment Profile



Tunnel layout

Meyrin: 1 experiment

RF on every straight section for ee option



Cluster of experiments on the other side

FCC-hh in a nutshell

- The High Energy Physics frontier
- The only way (currently conceivable) to exceed the scale probed by LHC is to build a “LHC++”
  - Larger radius, higher field
- Practical approach: scale the LHC technology to higher energies
- Luminosity performances to scale as well from HL-LHC
- That’s why CERN is currently considered the only lab where this can be achieved

FCC-hh parameters

	LHC (Design)	HL-LHC	HE-LHC	FCC-hh
Main parameters and geometrical aspects				
c.m. Energy [TeV]	14		33	100
Circumference *C* [km]	26.7		26.7	100 (83)
Dipole field [T]	8.33		20	16 (20)
Physics performance and beam parameters				
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	5.0	5.0	5.0
Optimum run time [h]	15.2	10.2	5.8	12.1 (10.7)
Optimum average integrated lumi / day [fb^{-1}]	0.47	2.8	1.4	2.2 (2.1)
Assumed turnaround time [h]				5
Overall operation cycle [h]				17.4 (16.3)
Peak no. of inelastic events / crossing at - 25 ns spacing - 5 ns spacing	27	135 (lev.)	147	171 34
Beam parameters				
Number of bunches *n* at - 25 ns - 5 ns	2808		2808	10600 (8900) 53000 (44500)
Bunch population $N[10^{11}]$ - 25 ns - 5 ns	1.15	2.2	1	1.0 0.2

FCC-hh challenges

MAGNETIC FIELD

- Unprecedented dipole field required => R&D, money
- Final focus (already challenging at LHC)

SYNCHROTRON RADIATION

- High heat load => shielding for SC magnets
- hard SR photons => issues with vacuum

BEAM ENERGY

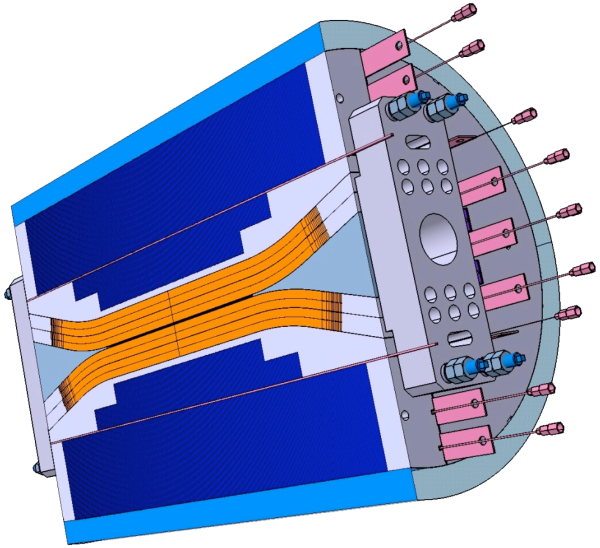
- Machine protection
- Dump system

EXPERIMENTS

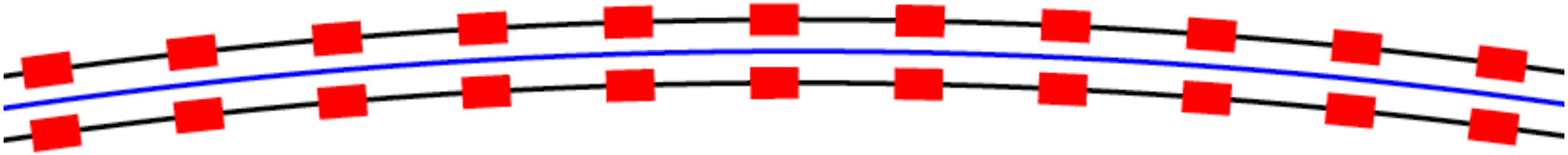
- High pileup=> high energy flow => high dose
- Magnet system for momentum resolution
- DAQ&Trigger

High Field Magnets

- World-wide effort aiming at producing prototypes capable of reaching 15 Tesla
- Materials:
  - Nb3Sn alloy
  - High temperature ceramic superconductors
- Short prototypes already built, tested up to ~13T



SR Photons



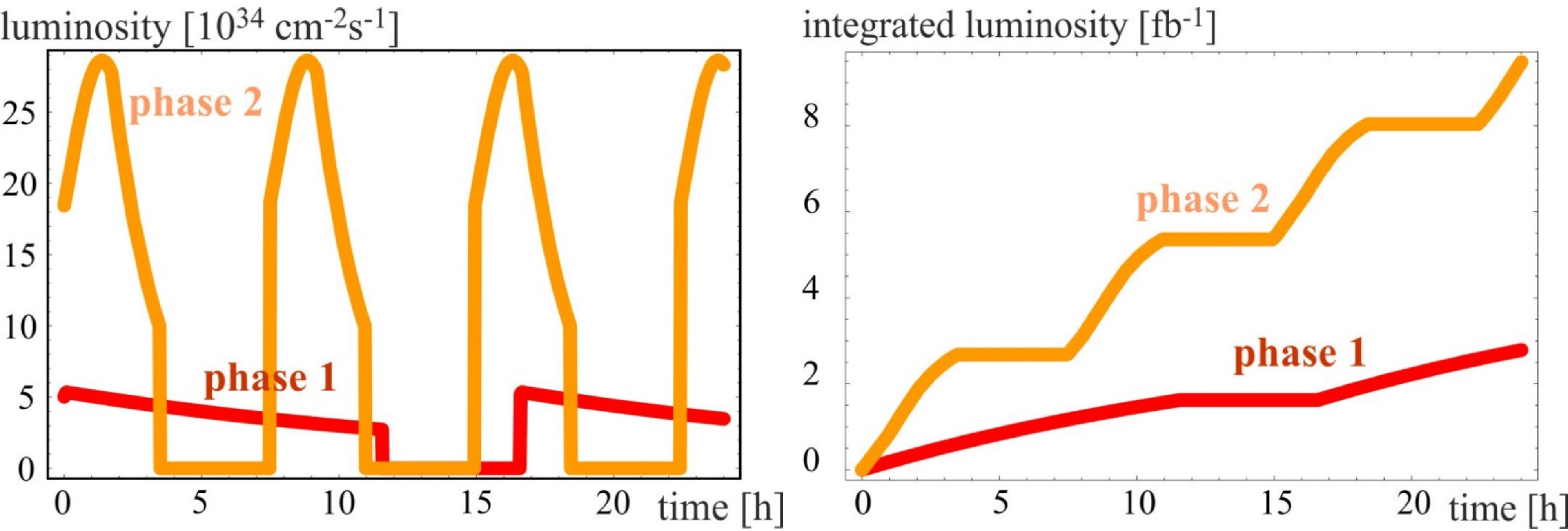
- Photon stops could take most of the heat load and be cooled at a higher temperature
- Photons travel for approx 12-21m at injection and around 14.5m at full energy (20T design)
  - For 13mm beam pipe radius 10mm radius for photon stops requires 1.8m spacing
  - Would need very short magnets or have to integrate the stops into the dipoles
  - Maybe space between beam and magnet aperture can be reduced
- Reflectivity of photons (4keV critical energy) might be OK

Machine protection

- Do not forget Sept 19th 2008 (>1km of the LHC fully damaged)
- Crazy energies involved:
  - Magnetic energy scale as $\sqrt{s}^2$
  - Beam energy: 16 GJ total (A380 @850 km/h

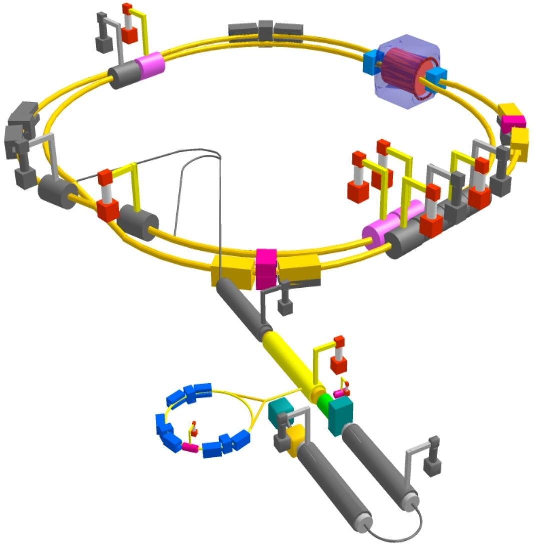
FCC-hh lumi performance

- Two stage approach (pp case):
  - phase 1 (baseline): $L=5\times10^{34}$ $cm^{-2}s^{-1}$(peak), average 250 fb^{-1}/year ➔ same as HL-LHC
  - phase 2 (ultimate): $L=2.5\times10^{35}$ $cm^{-2}s^{-1}$ (peak), average 1000 fb-1/year
- $L=15ab^{-1}$ within 15 years (~6x HL-LHC total luminosity)



FCC-ee in a nutshell

- Can’t get where ILC could go in terms of √s, but unbeatable lumi performance
  - √s<350, all SM physics is there (but di-Higgs production) is there!
- A LEP++ (a.k.a. TLEP), scale LEP technology to reach Higgs scale
  - SuperKEKB as a demonstrator
- General goal: ultimate precision on SM physics:
  - Up to √s=350 GeV, top-antitop production
  - Higgs factory at Z+H threshold √s=250 GeV
  - GigaZ at √s=GeV, repeat LEP1 program in <1 min
- Possibility for several interaction points → multiply L, experimental redundancy
- Challenging but well established technology



FCC-ee challenges

BEAM LIFETIME

- Beam burn-off => 2 rings solution, top-up
- Beamstrahlung => high momentum acceptance

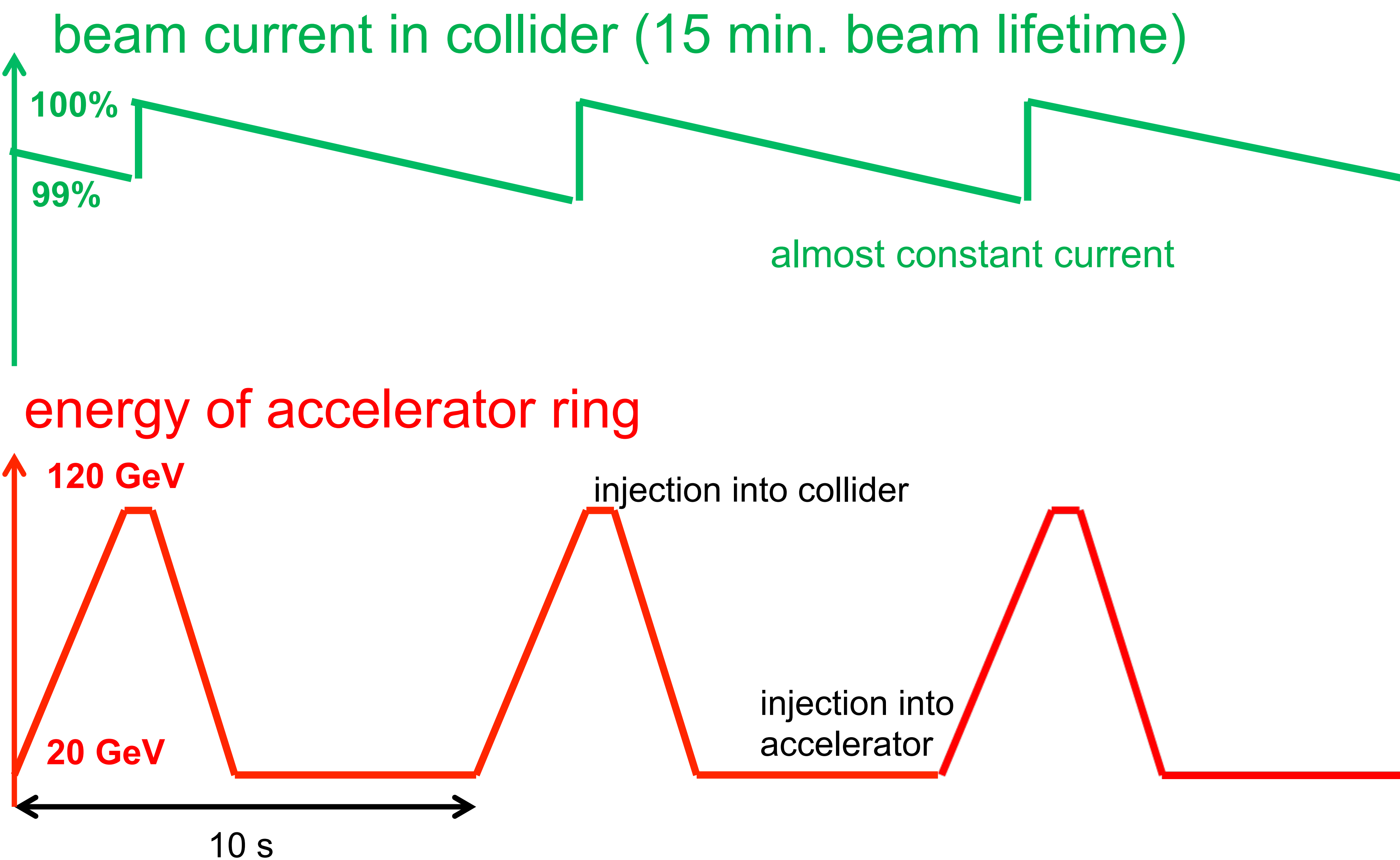
SYNCHROTRON RADIATION

- ~200 MW to recover the energy loss (money!)
- Very hard SR photons => issues with vacuum
- Large heat load => powerful cooling plant

INTEGRATION WITH THE EXPERIMENTS

- SR photons background
- Where does the accelerator beam pipe pass through?

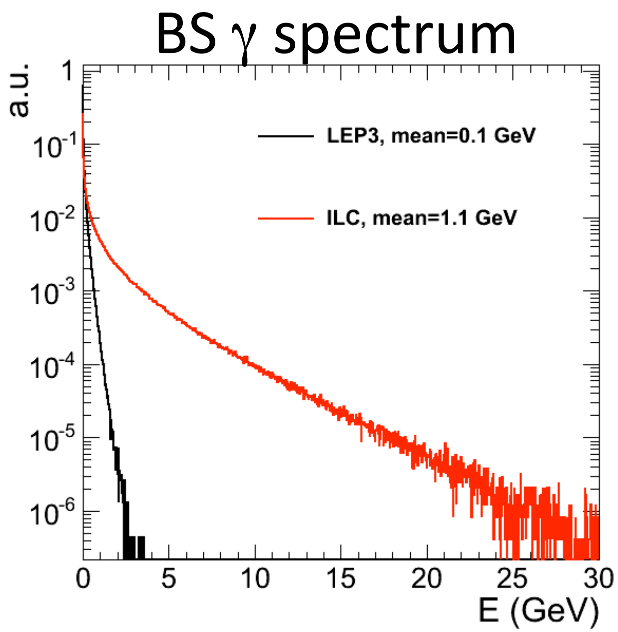
Top-up cycle

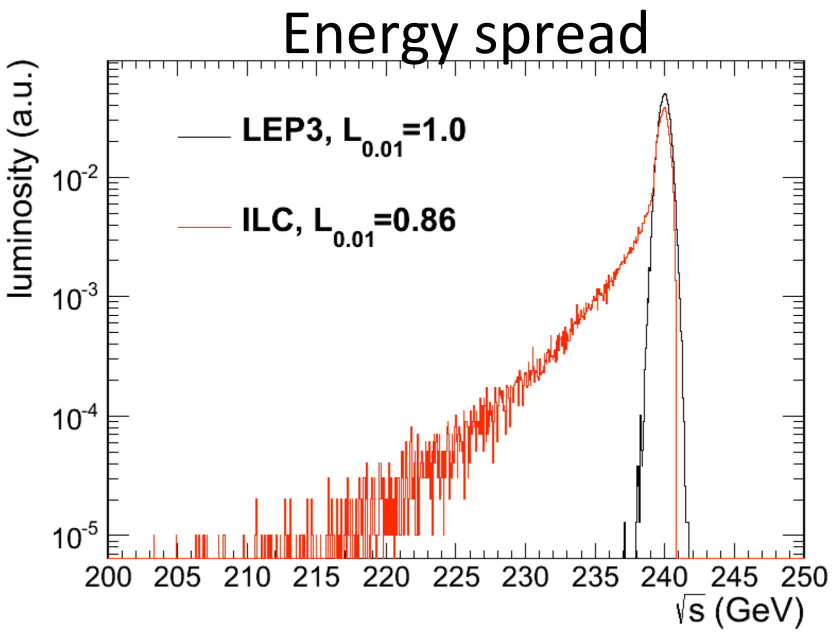

beam current in collider (15 min. beam lifetime)
100%
99%
almost constant current
energy of accelerator ring
120 GeV
injection into collider
injection into
accelerator
20 GeV
10 s

Beamstrahlung

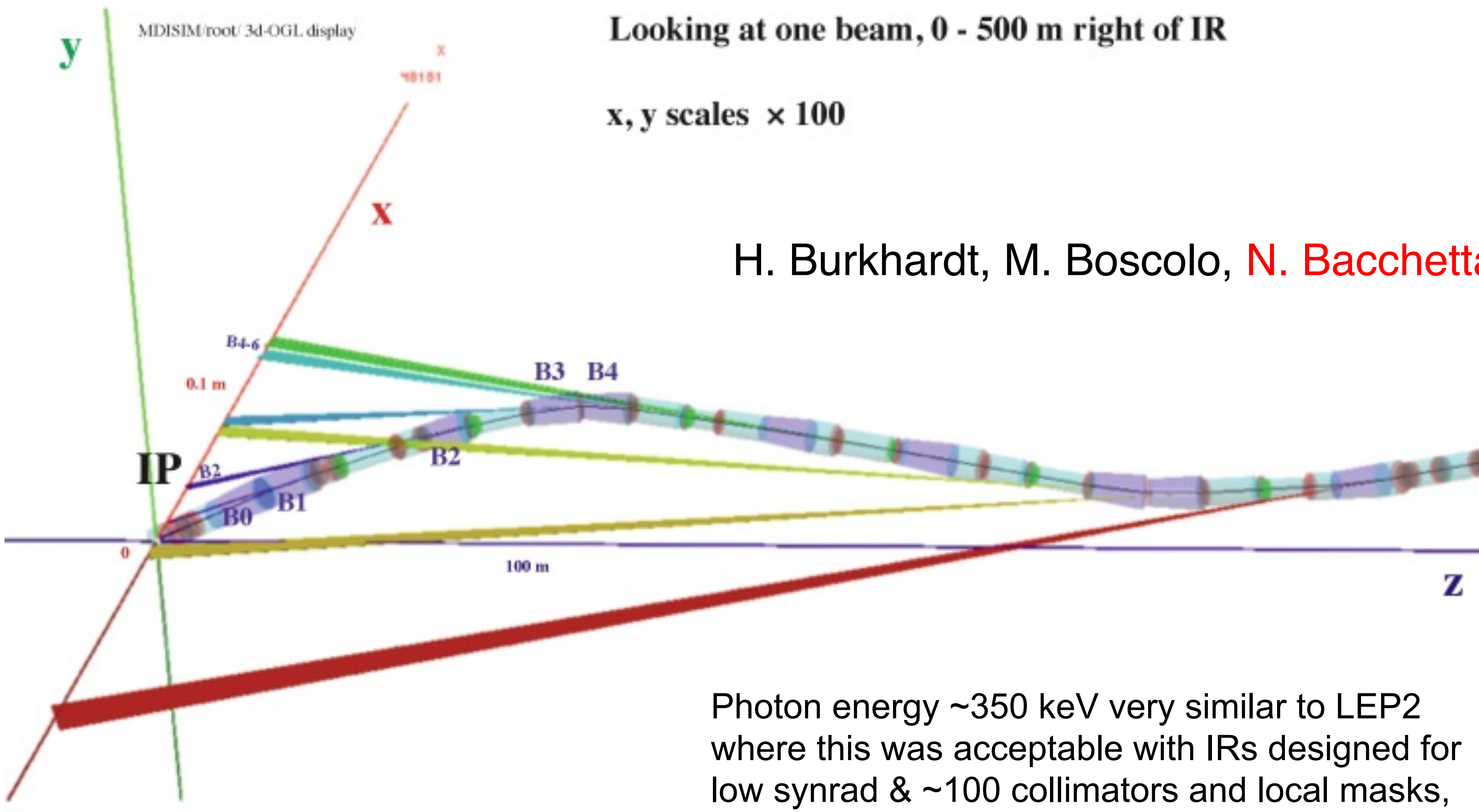
- Strong EM forces between the beams when they cross
- A fraction of the electrons loose enough energy to be kicked out of the orbit
- High momentum acceptance required (beyond what achieved in the past)
- Limited BS however grants other good features

M.Z.





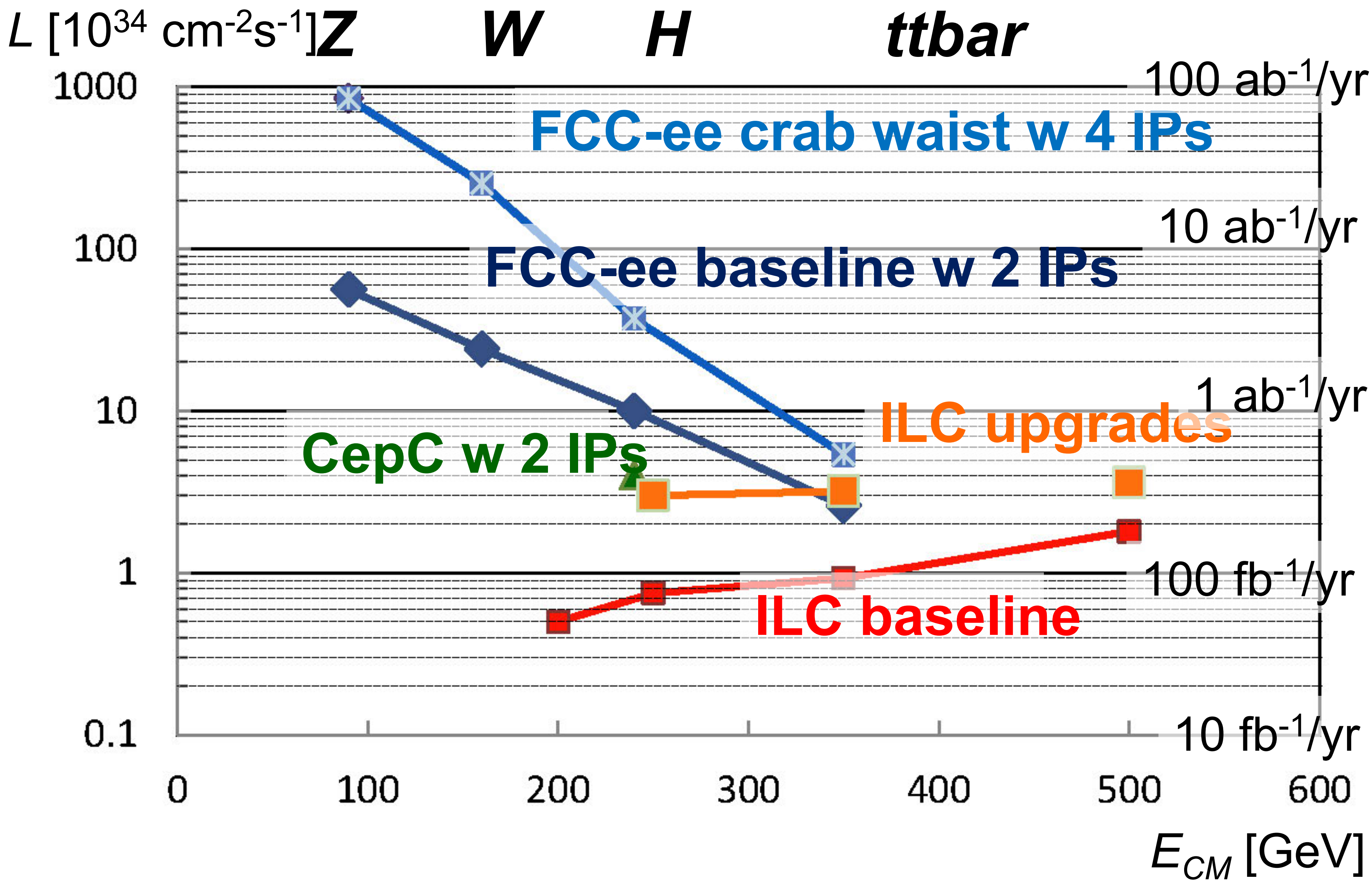
Background di macchina



H. Burkhardt, M. Boscolo, N. Bacchetta

Photon energy ~350 keV very similar to LEP2 where this was acceptable with IRs designed for low synrad & ~100 collimators and local masks,

FCC-ee lumi performance



Experiments

My take

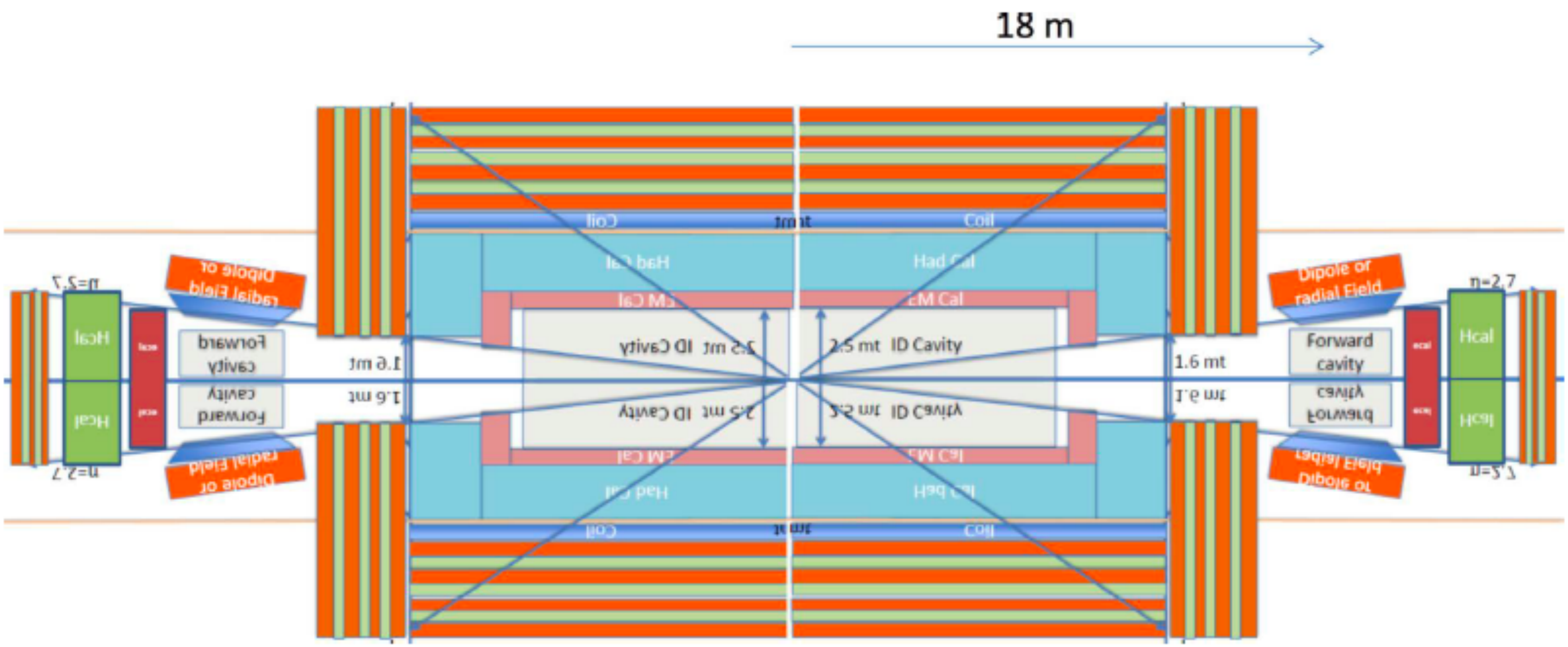
- Real challenge stands on the FCC-hh detectors, FCC-ee can well profit from ILC R&D
- It’s plenty of time before any conceivable date for FCC-hh running
- This is the time when “crazy” ideas on technology solutions and detector R&D should be pursued
  - Plenty of room for detector development studies!
- Currently 3 main approaches are envisaged:
  - Maxi version of a current LHC experiment (e.g. giant CMS)
  - Same size as a LHC experiment, but with improved versions of the devices with visionary performances (resolution, timing, etc.)
  - Something completely different (not well defined yet..)

Driving principles

- Bending power. If tracking resolution is kept the same between 14 and 100 TeV, BL^2 needs to scale by factor 7
  - B up to 6 T
- A lot of physics very boosted longitudinally → tracking up to high pseudorapidity (disambiguate PU)
  - Longer solenoid/tracking systems
  - Add a dipole in the forward region
- HCAL from 10 to 12 λ
  - E.g. bore of big solenoid
- ECAL up to high η as well:
  - Longer detector, high flux resistant
- Everything to be compatible with chose L*
- Here more info can be found

Herman ten Kate and Jeroen van Nugteren

Option 1: Solenoid-Yoke + Dipoles (CMS inspired)



Solenoid: 5-6 m diameter, 5-6 T, 23 m long

+ massive Iron yoke for flux return (shielding) and muon tagging.

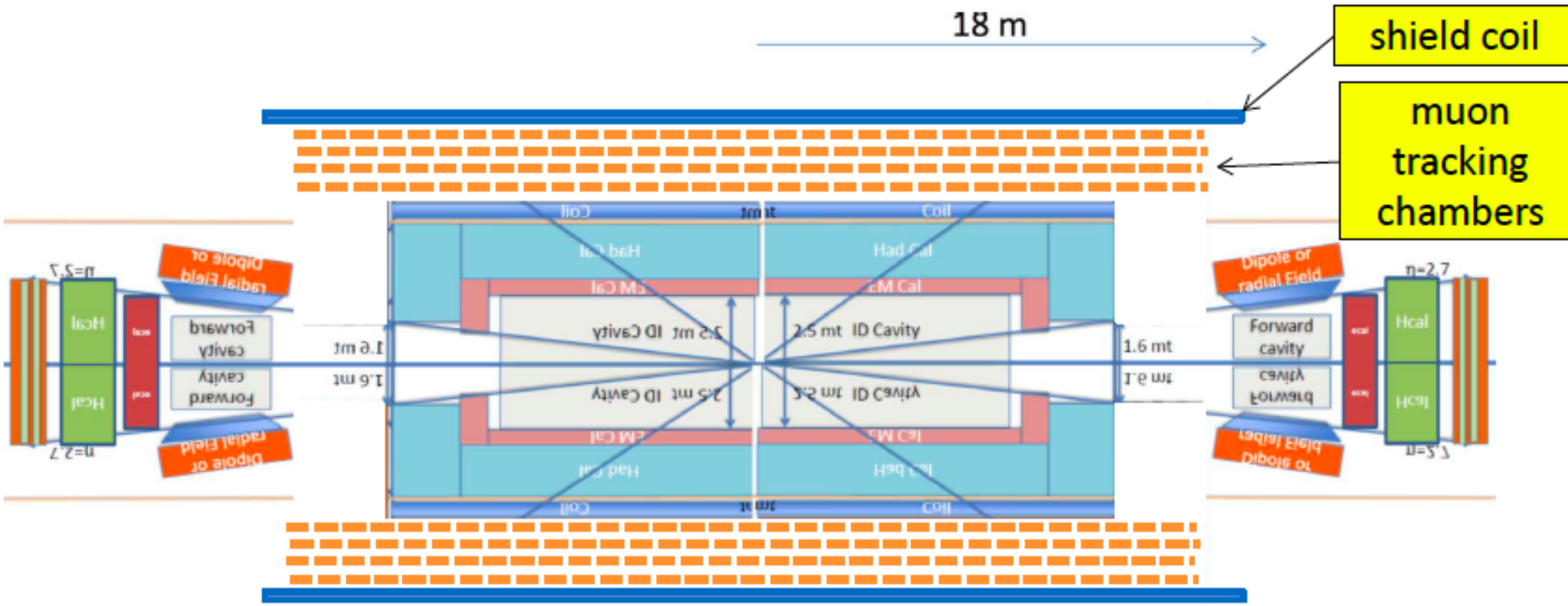
Dipoles: 10 Tm with return yoke placed at 18 m.

Practically no coupling between dipoles and solenoid.

They can be designed independently at first.

Herman ten Kate and Jeroen van Nugteren

Option 2: Twin Solenoid + Dipoles

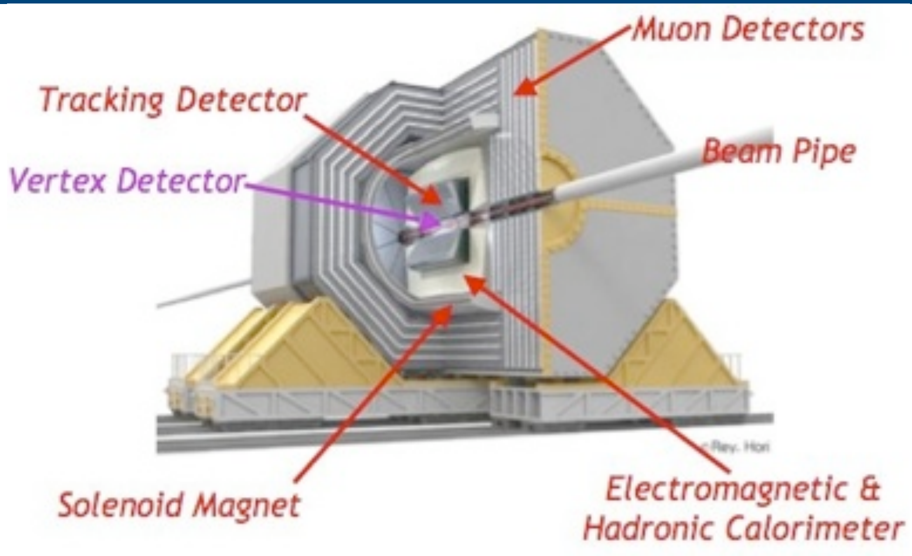


Twin Solenoid: the original 6 T, 12 m x 23 m solenoid + now with a shielding coil {concept proposed for the 4th detector @ILC, also an option for the LHeC in the case of large solenoid; and this technique is in all modern MRI magnets!}.

Gain?

- + **Muon tracking space:** nice new space with 3 T for muon tracking in 4 layers.
- + **Very light:** 2 coils + structures, ≈ 5 kt, only ≈4% of the option with iron yoke!
- + **Smaller:** outer diameter is less than with iron .

Experiments at FCC-ee



- Much less demanding as the FCC-hh case
  - Possibly with a few exceptions (DAQ&Trigger @Z, TPC, extreme vertexing for c-tagging, etc.)
- A lot of R&D studies for the ILC detector: same design can be used for circular machine as well (0^{th} order)
- Power pulsing not possible (too high collision rate):
  - Either more cooling (higher material budget)
  - Or less channels
- Most likely much less sophisticated can do as well
  - Current physics results based on CMS full simulation

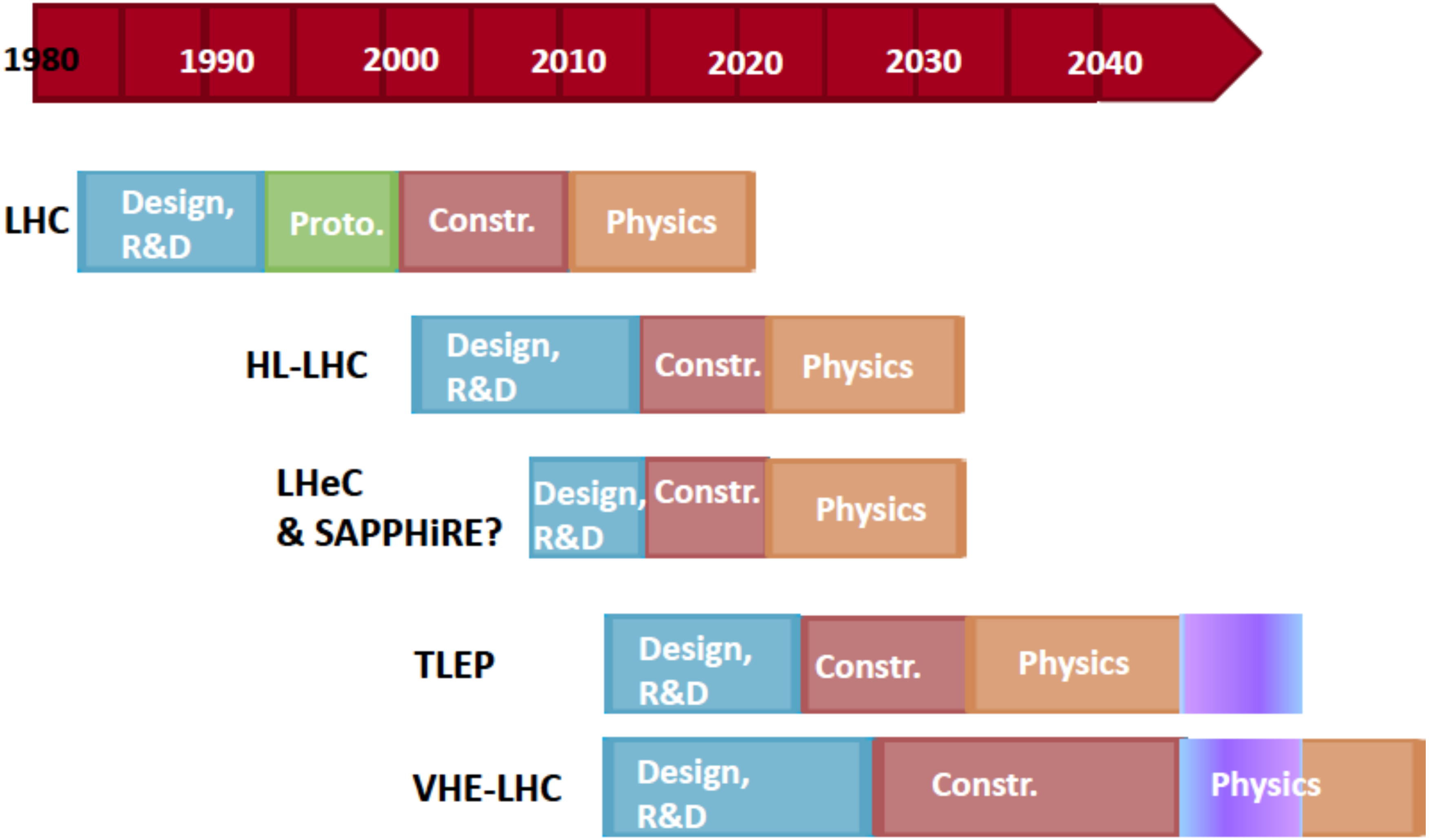
Conclusions

If what you have done yesterday still looks big to you, you haven't done much today.

Mikhail Gorbachev

BACKUP

(very) Tentative (CERN-centric) timeline



80-km Tunnel Cost Estimate

- Costs
  - Only the **minimum civil requirements** (tunnel, shafts and caverns) are included
  - 5.5% for external expert assistance (underground works only)
- Excluded from costing
  - Other services like cooling/ventilation/ electricity etc
  - service caverns
  - beam dumps
  - radiological protection
  - Surface structures
  - Access roads
  - In-house engineering etc etc
- **Cost uncertainty = 50%**
- Next stage should include costing based on technical drawings

CE works	Costs [BCHF]
Underground	
Main tunnel (5.6m)	
Bypass tunnel & inclined tunnel access	
Dewatering tunnel	
Small caverns	
Detector caverns	
Shafts (9m)	
Shafts (18m)	
Consultancy (5.5%)	
TOTAL	~3.1?(unofficial)

AMBERG ENGINEERING

(→raw tunnel cost could be 4.5 BCHF)

Luminosity is the key

Synchrotron Radiation constrains Lumi and Energy

$$nN\nu = P_{SR}\frac{R}{E^4}$$

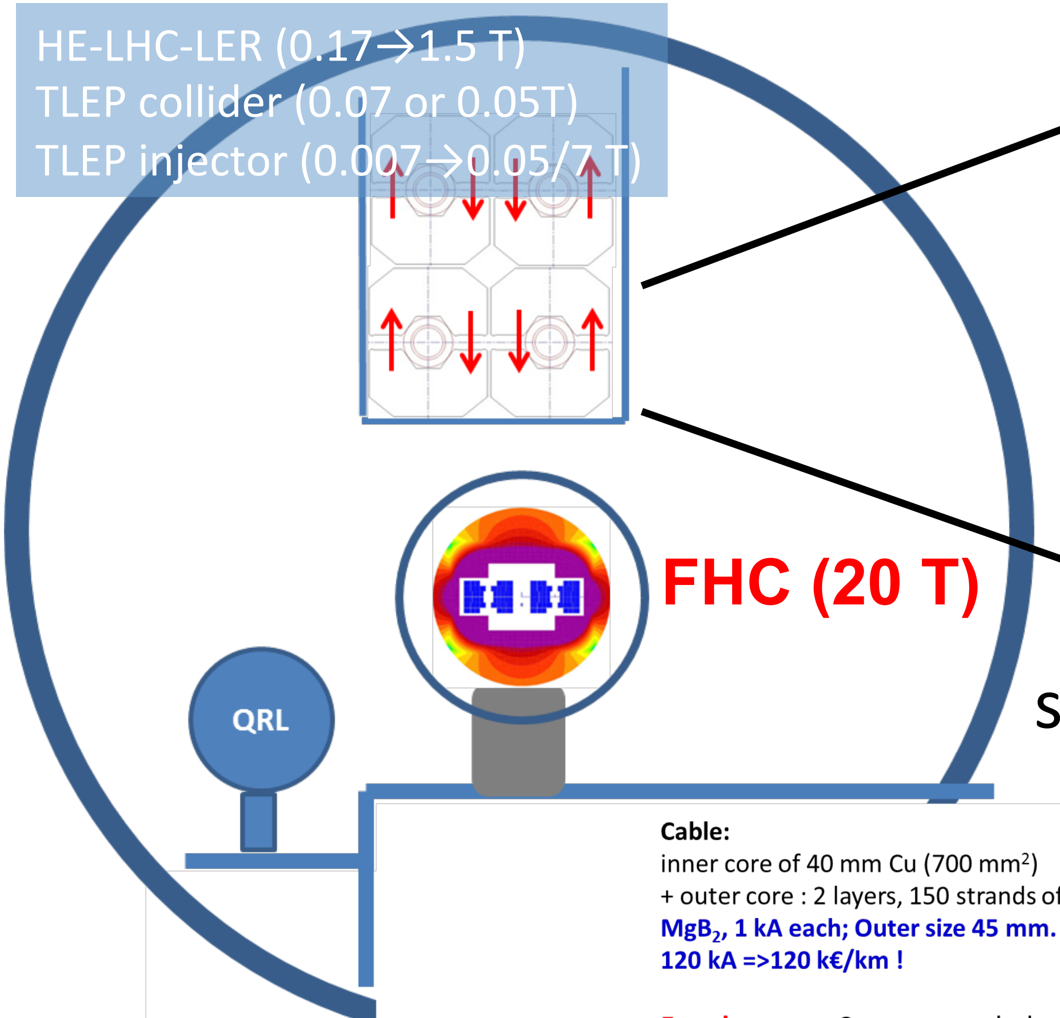
$$L = \frac{nN^2\upsilon}{4\pi\sigma_x\sigma_y} = nN\upsilon\frac{N}{\varepsilon_x}\frac{1}{4\pi\sqrt{\beta_x\beta_y}}\sqrt{\frac{\varepsilon_x}{\varepsilon_y}}$$

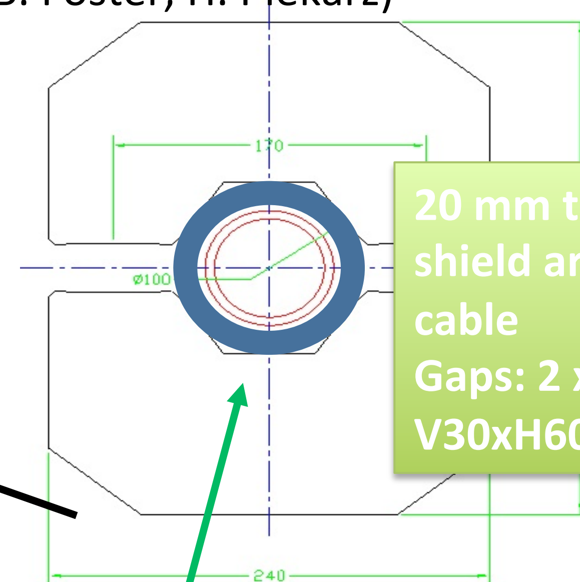
Beam-beam limit

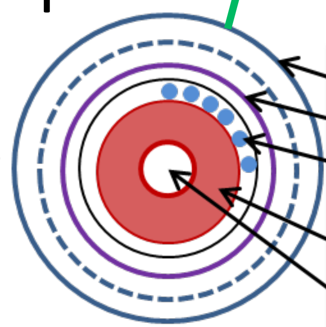
Beamstrahlung limit on lifetime $\frac{N}{\sigma_z\sigma_x}$

Do not forget lifetime and time integration!

FHC and TLEP together?







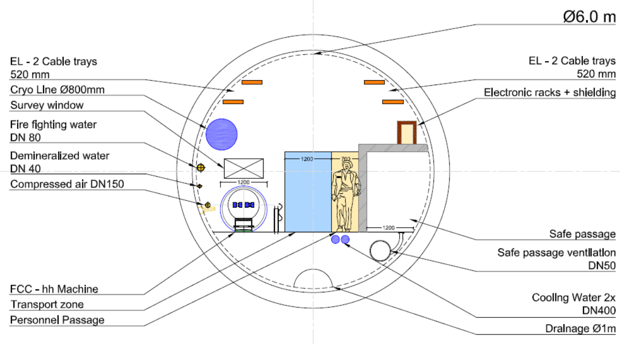
Cable:
inner core of 40 mm Cu (700 mm²)
+ outer core : 2 layers, 150 strands of **MgB_2, 1 kA each; Outer size 45 mm.**
120 kA =>120 k€/km !

For electrons: Cu water cooled, J_{ov} 2.5 A/mm²

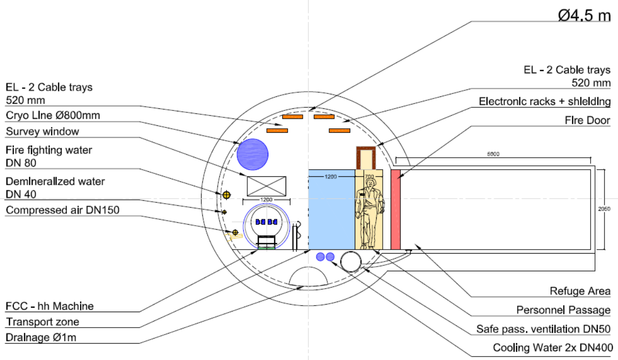
For protons: 800 A/strands
120 kA (for >2.1 T); central copper acts as stabilizer

based on *MgB_2* SC
only 12 MEuro/100 km!

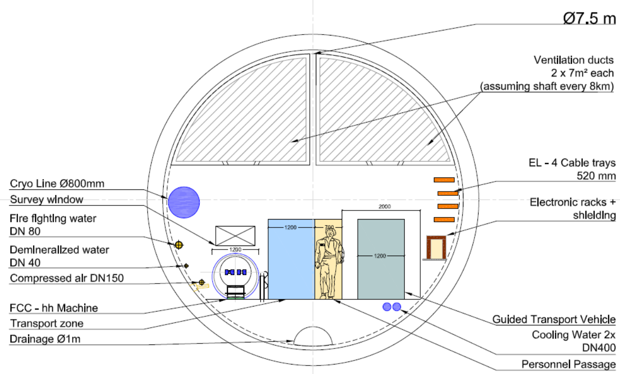
Tunnel Cross section studies



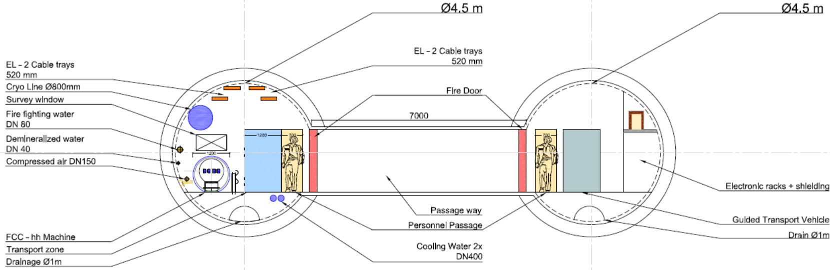
6m tunnel : Escape Passageway



4.5m tunnel : Rescue stub tunnels



7.5m tunnel : Transversal Ventilation



2x 4.5m double tunnel solution

FCC-hh parameters

	LHC (Design)	HL-LHC	HE-LHC	FCC-hh
Main parameters and geometrical aspects				
c.m. Energy [TeV]	14		33	100
Circumference C [km]	26.7		26.7	100 (83)
Dipole field [T]	8.33		20	16 (20)
Arc filling factor	0.79		0.79	0.79
Straight sections	8		8	12
Average straight section length [m]	528		528	1400
Number of IPs				2 + 2
Injection energy [TeV]	0.45		> 1.0	3.3
Physics performance and beam parameters				
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0	5.0
Optimum run time [h]	15.2	10.2	5.8	12.1 (10.7)
Optimum average integrated lumi / day [fb^{-1}]	0.47	2.8	1.4	2.2 (2.1)
Assumed turnaround time [h]				5
Overall operation cycle [h]				17.4 (16.3)
Peak no. of inelastic events / crossing at - 25 ns spacing - 5 ns spacing	27	135 (lev.)	147	171 34
Total / inelastic cross section σ_{proton} [mbarn]	111 / 85		129 / 93	153 / 108
Luminous region RMS length [cm]				5.7 (5.3)
Beam lifetime due to burn off [h]	45	15.4	5.7	19.1 (15.9)
Beam parameters				
Number of bunches n at - 25 ns - 5 ns	2808		2808	10600 (8900) 53000 (44500)
Bunch population N[10^{11}] - 25 ns - 5 ns	1.15	2.2	1	1.0 0.2
Nominal transverse normalized emittance [μm] - 25 ns - 5 ns	3.75	2.5	1.38	2.2 0.44
Number of IPs contributing to ΔQ	3	2	2	2
Maximum total b-b tune shift ΔQ	0.01	0.015	0.01	0.01
Beam current [A]	0.584	1.12	0.478	0.5
RMS bunch length [cm]	7.55		7.55	8 (7.55)
IP beta function [m]	0.55	0.15 (min)	0.35	1.1
RMS IP spot size [μm] - 25 ns - 5 ns	16.7	7.1 (min)	5.2	6.8 3
Full crossing angle [μrad] - 25 ns - 5 ns	285	590	185	74 n/a
Other beam and machine parameters				
Stored energy per beam [GJ]	0.392	0.694	0.701	8.4 (7.0)
SR power per ring [MW]	0.0036	0.0073	0.0962	2.4 (2.9)
Arc SR heat load [W/m/aperture]	0.17	0.33	4.35	28.4 (44.3)
Energy loss per turn [MeV]	0.0067		0.201	4.6 (5.86)
Critical photon energy [keV]	0.044		0.575	4.3 (5.5)
Longitudinal emittance damping time [h]	12.9		1.0	0.54 (0.32)
Horizontal emittance damping time [h]	25.8		2.0	1.08 (0.64)
Initial longitudinal IBS ε rise time [h]* - 25 ns - 5 ns	57	23.3	40	1132 (396) 226 (303)
Initial horizontal IBS ε rise time [h]* - 25 ns - 5 ns	103	10.4	20	943 (157) 189 (29)
Dipole coil aperture [mm]	56		40	40
Beam half aperture [cm]	~2		1.3	1.3
Mechanical aperture clearance at any energy at any element				>12

FCC-ee parameters

	LEP1	LEP2	Z	W	H	tt
Circumference [km]	26.7		100			
Bending radius [km]	3.1		11			
Beam energy [GeV]	45.4	104	45.5	80	120	175
Beam current [mA]	2.6	3.04	1450	152	30	6.6
Bunches / beam	12	4	16700	4490	1360	98
Bunch population [10^{11}]	1.8	4.2	1.8	0.7	0.46	1.4
Transverse emittance ε - Horizontal [nm] - Vertical [pm]	 20 400	 22 250	 29.2 60	 3.3 7	 0.94 1.9	 2 2
Momentum comp. [10^{-5}]	18.6	14	18	2	0.5	0.5
Betatron function at IP β^* - Horizontal [m] - Vertical [mm]	 2 50	 1.2 50	 0.5 1	 0.5 1	 0.5 1	 1 1
Beam size at IP σ^* [μm] - Horizontal - Vertical	 224 4.5	 182 3.2	 121 0.25	 26 0.13	 22 0.044	 45 0.045
Energy spread [%] - Synchrotron radiation - Total (including BS)	 0.07 0.07	 0.16 0.16	 0.04 0.06	 0.07 0.09	 0.10 0.14	 0.14 0.19
Bunch length [mm] - Synchrotron radiation - Total	 8.6 8.6	 11.5 11.5	 1.64 2.56	 1.01 1.49	 0.81 1.17	 1.16 1.49
Energy loss / turn [GeV]	0.12(1)	3.34	0.03	0.33	1.67	7.55
SR power / beam [MW]	0.3(1)	11	50			
Total RF voltage [GV]	0.24	3.5	2.5	4	5.5	11
RF frequency [MHz]	352		800			
Longitudinal damping time τ_E [turns]	371	31	1320	243	72	23
Energy acceptance RF [%]	1.7	0.8	2.7	7.2	11.2	7.1
Synchrotron tune Q_s	0.065	0.083	0.65	0.21	0.096	0.10
Polarization time τ_p [min]	252	4	11200	672	89	13
Hourglass factor H	1	1	0.64	0.77	0.83	0.78
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	0.002	0.012	28.0	12.0	6.0	1.8
Beam-beam parameter - Horizontal - Vertical	 0.044 0.044	 0.040 0.060	 0.031 0.030	 0.060 0.059	 0.093 0.093	 0.092 0.092
Luminosity lifetime [min](2)	1250	310	213	52	21	15

Synchrotron radiation

- 2x50 MW supplied to the beams need to be cooled away, heat load non negligible
- Previous machines (e.g. PEP-II and SPEAR) coped with much higher heat load per meter
- Need to manage higher max photon energy though

	PEPII	SPEAR3	LEP3	TLEP-Z	TLEP-H	TLEP-t
E (GeV)	9	3	120	45.5	120	175
I (A)	3	0.5	0.0072	1.18	0.0243	0.0054
rho (m)	165	7.86	2625	9000	9000	9000
Linear Power (W/cm)	101.8	92.3	30.5	8.8	8.8	8.8

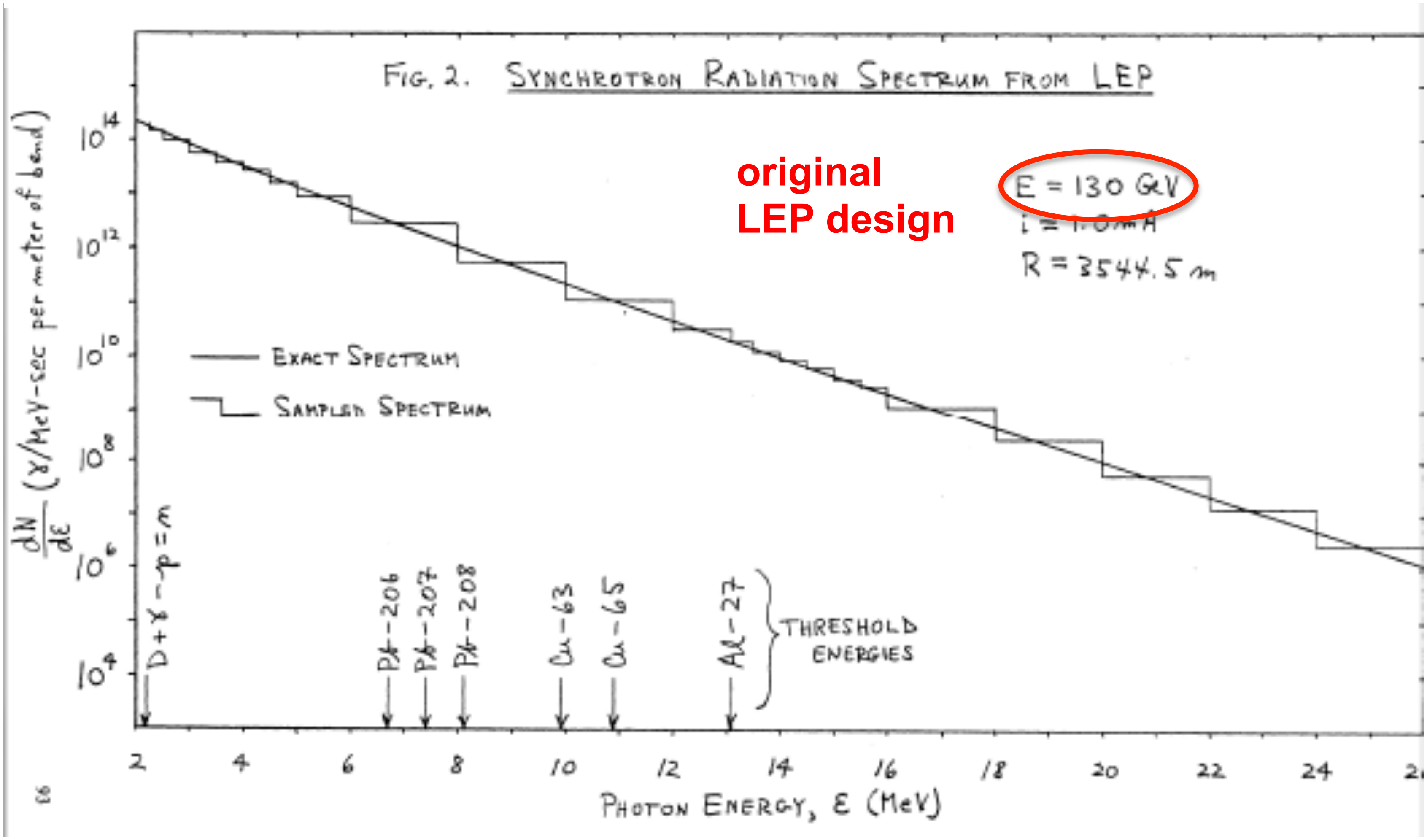
N. Kurita, U. Wienands, SLAC

Synchrotron radiation

NEUTRON PRODUCTION BY LEP SYNCHROTRON RADIATION USING EGS

A. Fasso

N.R.Nelson and J.M.N.Tuyn

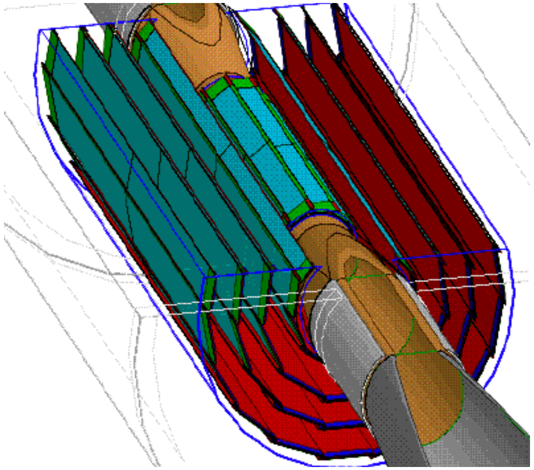


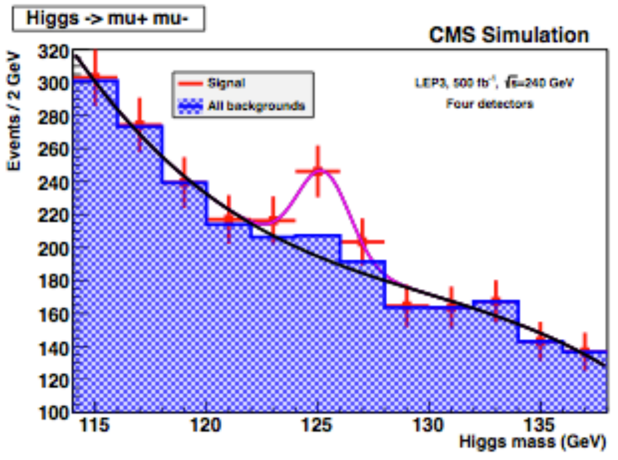
Power consumption

- Fixing energy, beam-beam limit and beamstrahlung conditions: => power is linearly proportional to luminosity
- For TLEP self imposed limit on power to beams ~200MW, assuming 50% wall to beam efficiency
- Complete accounting of power consumers brings the total to beyond 300 MW for TLEP at top energy
  - To be compared with current max CERN site consumption of <200MW
- Still margin thanks to possibility of several IPs
  - Number of IPs affecting BS lifetime

Experiments at FCC-ee

- Vertexing:
  - c-tagging (Higgs)
  - Compatible with 2nd beam pipe?
- Tracking:
  - recoil analysis
  - H->μμ
- Calorimetry
  - Particle flow based, do not need high granularity
- Very forward detectors for e+e-?
  - E.g. for yy collisions tagging
- No issue for triggering, even at the GigaZ rate





Physics performances: Higgs

Accelerator → Physical Quantity ↓	**LHC** 300 fb^{-1} /expt	**HL-LHC** 3000 fb^{-1} /expt	**ILC** 250 GeV 250 fb^{-1} 5 yrs	**Full ILC** 250+350+ 1000 GeV 5yrs each	**CLIC** 350 GeV (500 fb^{-1}) 500 GeV (500 fb^{-1}) 1.4 TeV (2 ab^{-1}) 5 yrs each	**LEP3, 4 IP** 240 GeV 2 ab^{-1} (*) 5 yrs	**TLEP, 4 IP** 240 GeV 10 ab^{-1} 5 yrs (*) 350 GeV 1.4 ab^{-1} 3 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hvv		4×10^5 ZH	2×10^6 ZH
m_H (MeV)	100	50	35	35	~70	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	6%	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	--	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	N/A	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	N/A	2.2%	0.7%
$\Delta g_{Hww} / g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	1%	1.5%	0.25%
$\Delta g_{HZZ} / g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	1%	0.65%	0.2%
$\Delta g_{HHH} / g_{HHH}$	--	< 30% (2 expts)	--	~30%	~20%	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	< 30%	< 10%	--	--	15%	14%	7%
$\Delta g_{H\tau\tau} / g_{H\tau\tau}$	8.5 – 5.1%	5.4 – 2.0%	3.5%	2.5%	3%	1.5%	0.4%
$\Delta g_{Hcc} / g_{Hcc}$	--	--	3.7%	2%	4%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	2%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	15%	3%	--	30%

Higgs Physics

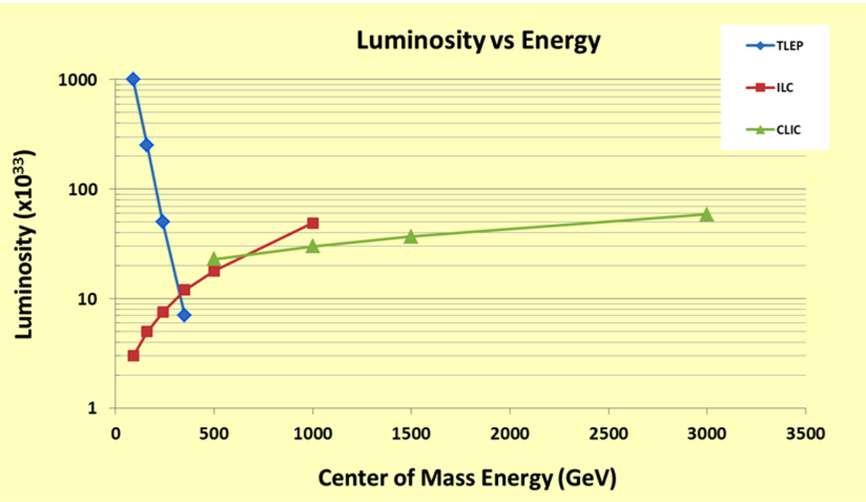
NLO rates **R(E)** = σ(E TeV)/σ(14 TeV)

	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

- More than linear increase for the Higgs production processes
- Factor 40x for di-Higgs production, percent level quartic coupling should be at reach (modulo syst. errors, to be studied)

Physics performances: low √s

- Unprecedented precision on EW observables:
  - $\sigma(m_W)$~0.2 MeV, predict top mass at 100 MeV
- Probe the loop structure, ultimate closure test of SM
- Beam energy assessed by means of resonant depolarization
  - Dedicate one bunch during physics operation, no extrapolation needed



	LEP	ILC	LEP3	TLEP
$\sqrt{s} \sim m_Z$	MegaZ	GigaZ	~TeraZ	TeraZ
Lumi ($cm^{-2}s^{-1}$) #Z / IP / year Polarization vs LEP1	Few 10^{31} 2×10^{7} no 1	Few 10^{33} Few 10^{9} easy ~5-10	Few 10^{35} Few 10^{11} maybe ~50	10^{36} 10^{12} maybe ~100
$\sqrt{s} \sim 2m_W$				
Lumi ($cm^{-2}s^{-1}$) Lumi / IP / year Error on m_W	Few 10^{31} 10 pb^{-1} 220 MeV	Few 10^{33} 50 fb^{-1} 7 MeV	5×10^{34} 500 fb^{-1} 0.7 MeV	2.5×10^{35} 2.5 ab^{-1} 0.4 MeV
$\sqrt{s}$ ~ 200-250 GeV				
Lumi ($cm^{-2}s^{-1}$) Lumi / IP / 5 years Error on m_W	10^{32} 500 pb^{-1} 33 MeV	5×10^{33} 250 fb^{-1} 3 MeV	10^{34} 500 fb^{-1} 1 MeV	5×10^{34} 2.5 ab^{-1} 0.4 MeV

Comparison with ILC

Circular

- Pros:
  - Highest instantaneous lumi
  - High duty cycle
  - Several IPs
  - Well established technology
  - Reduced beamstrahlung
  - Upgradable to ~100 TeV pp
- Cons:
  - High power consumption
  - Limited in $\sqrt{s}$ (for e+e-)
  - No polarization at high $\sqrt{s}$
  - Cost & Timescale

Linear

- Pros
  - Mature project, large community and studies devoted to it
  - Ugradable to O(1)TeV
  - Polarization of the beams
- Cons
  - No “successful” predecessors, big leap in performances
  - Not optimal till $\sqrt{s}$~350 GeV
  - No reach to energy frontier, what if a desert below O(1)TeV?
  - Only 1 experiment
  - Cost, Timescale, Power

Beamstrahlung

- Electrons are lost if they emit a photon with $E>\eta E_0$ (η momentum acceptance)
- Defining:

$$u = \frac{\eta E_0}{E_C} \sim \frac{1}{\gamma}\eta\frac{\sigma_z\sigma_x}{N_b}$$

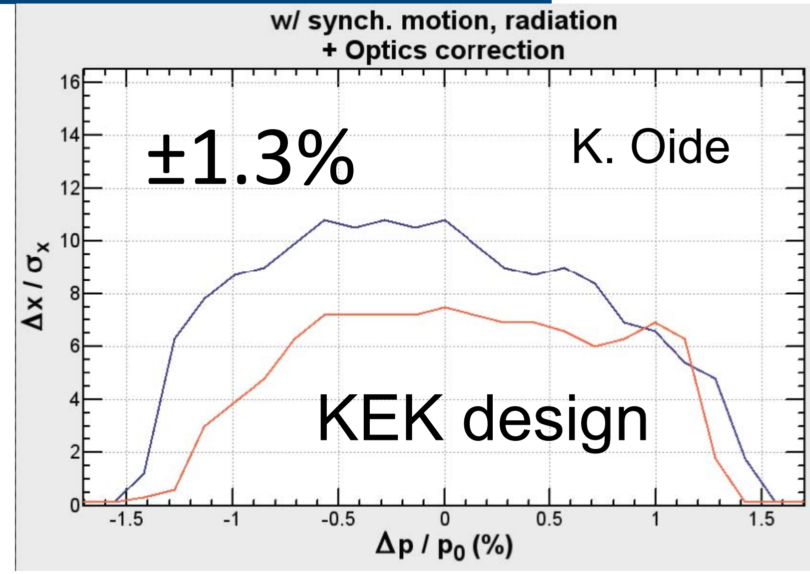
- The number of photons with $E>\eta E_0$ (i.e. impacting lifetime):

$$n \sim \frac{\eta}{\gamma}\frac{e^{-u}}{u^{3/2}}$$

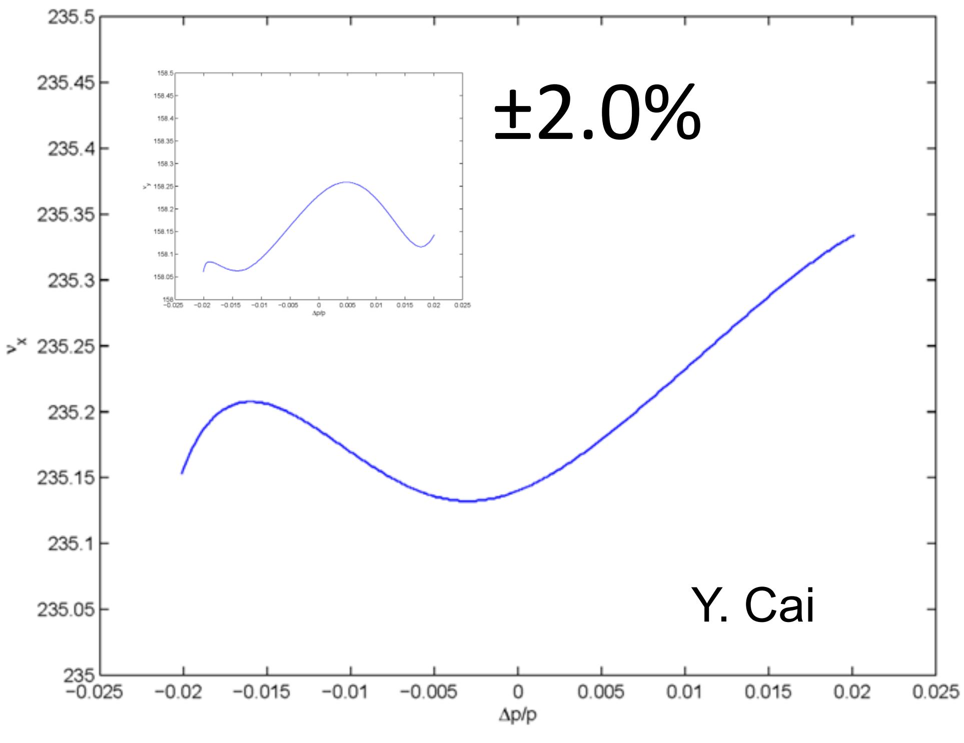
- η can be traded off with $N_b/\sigma_x\sigma_z$
- High lumi and decent lifetime requires either high momentum acceptance or aspect ratio

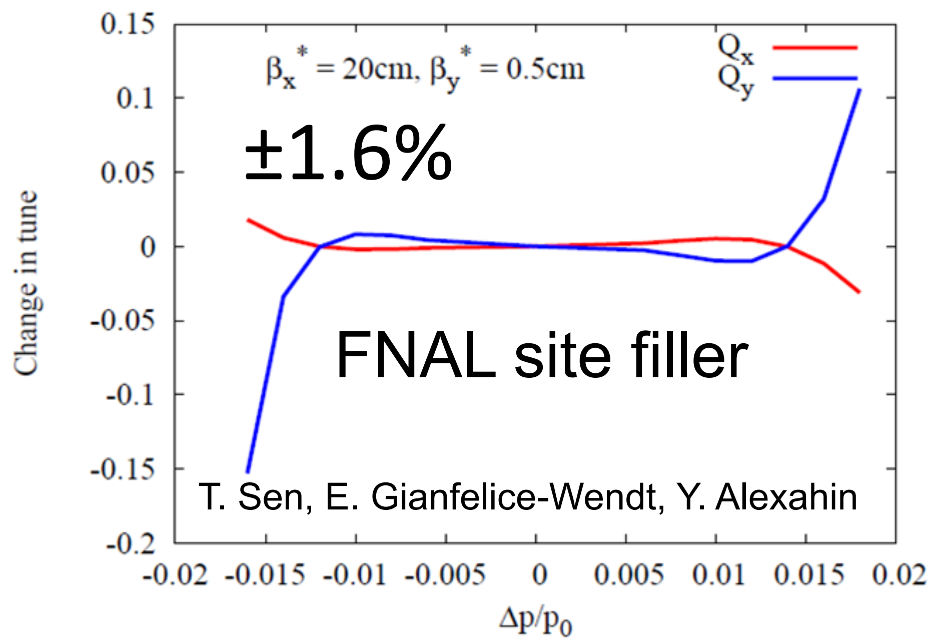
Momentum acceptance

- Very preliminary IR designs aimed at high momentum acceptance
- 2.5-3% feasible?



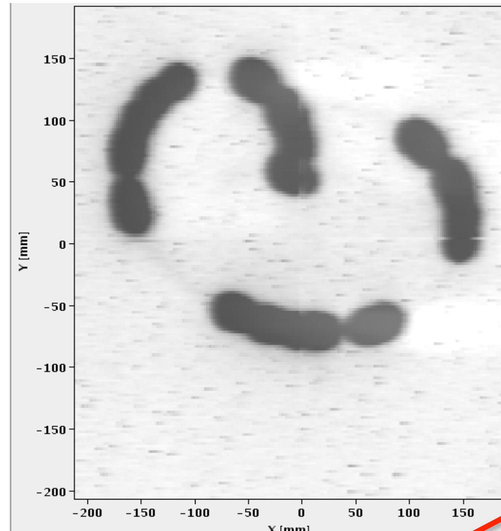
SLAC/LBNL design

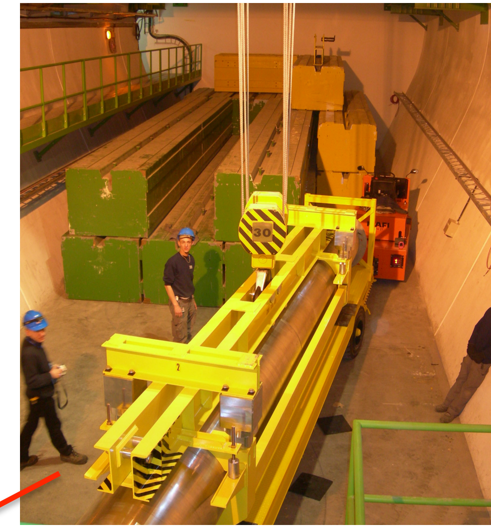


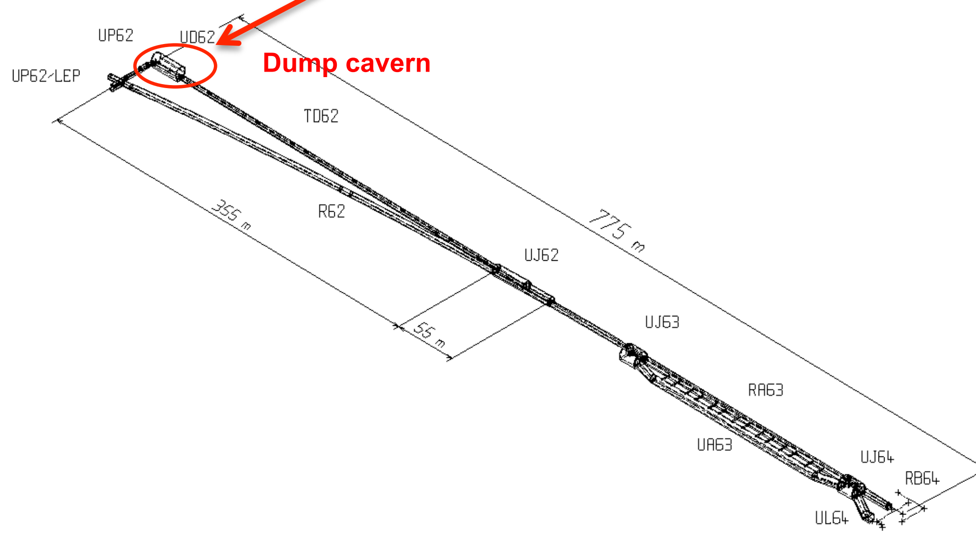


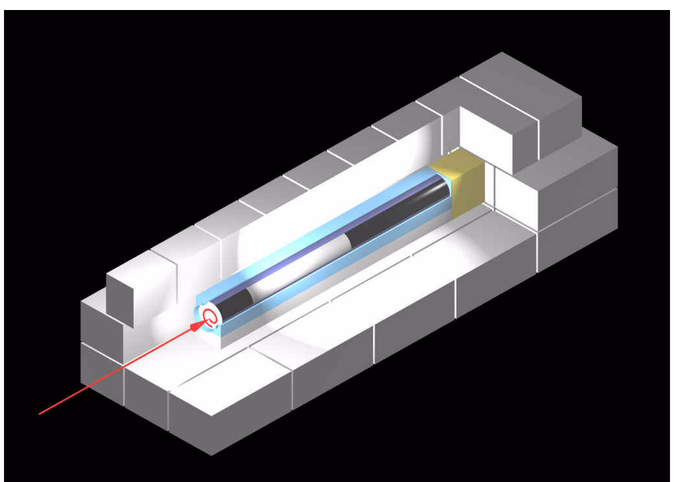
Beam dump system

- Huge energy (2x4.2 GJ, 8.5x LHC) to be extracted and dumped
- Dump block has to deal with ~200kW average power..
- Beam rigidity: 167 T.km => need a looong way to dilute the beam, ~3km!



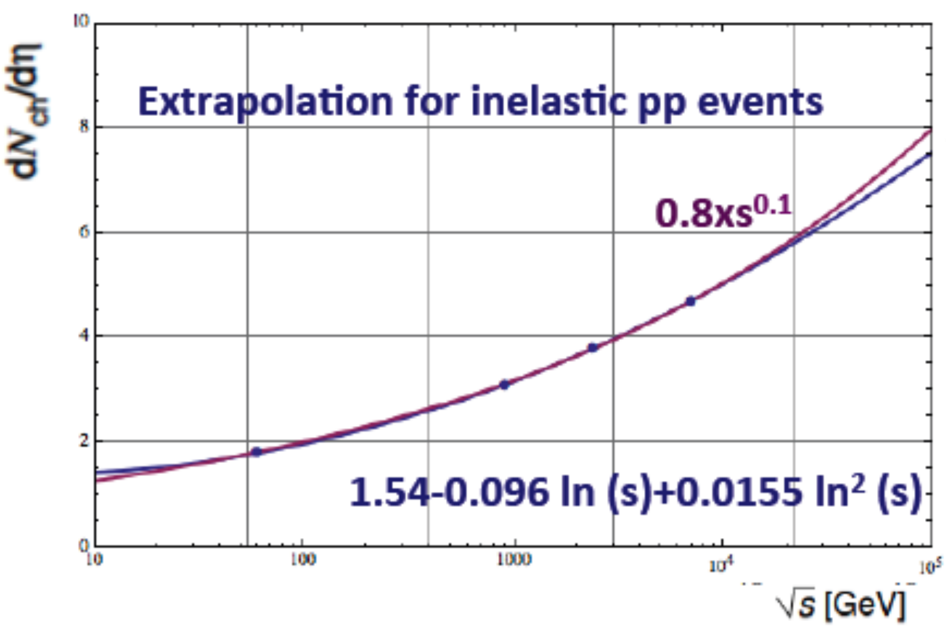


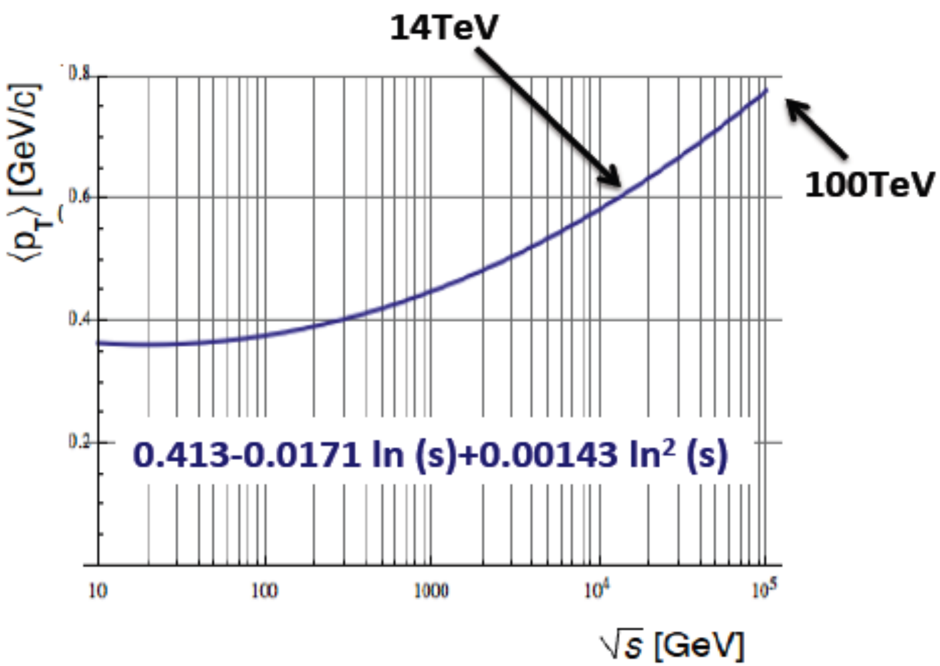




Pileup and Minimum Bias

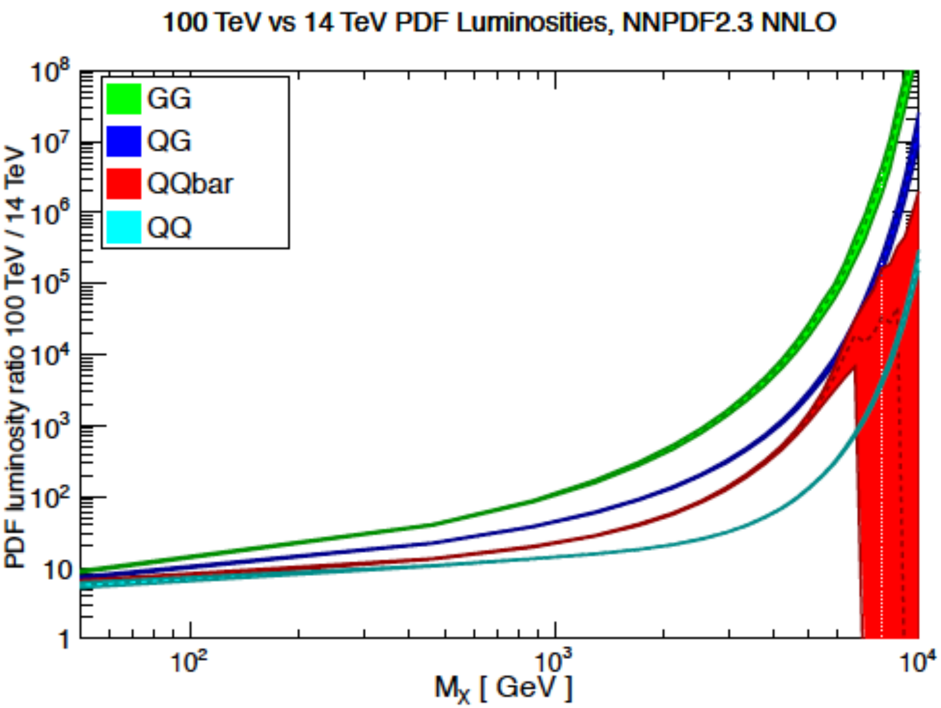
- QCD not much harder than at the LHC!
  - Cross section ~100mb (vs 80 @√s=14 TeV)
  - Multiplicity 1.5x
  - Average transverse momentum 1.3x
- ➔ Pileup will not be more of an issue than at theLHC
- Integrated dose only ~2x HL-LHC

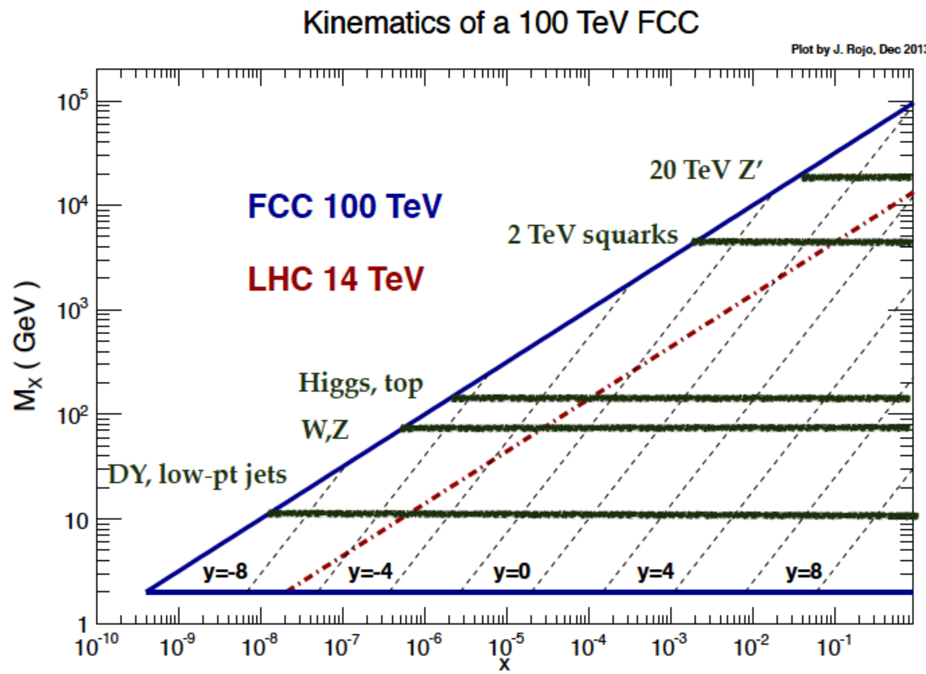




PDF luminosities

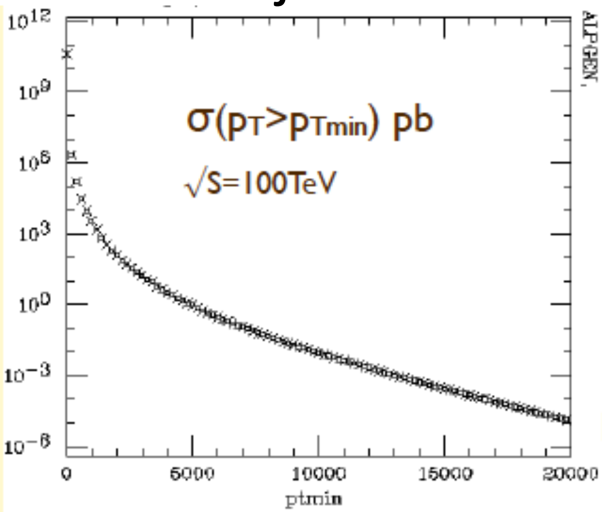
- Luminosities for small x, high M are of course order of magnitude larger than LHC!
- Top is also ~massless at high √s => need to include it in the PDF (~1/2 of the other quarks)



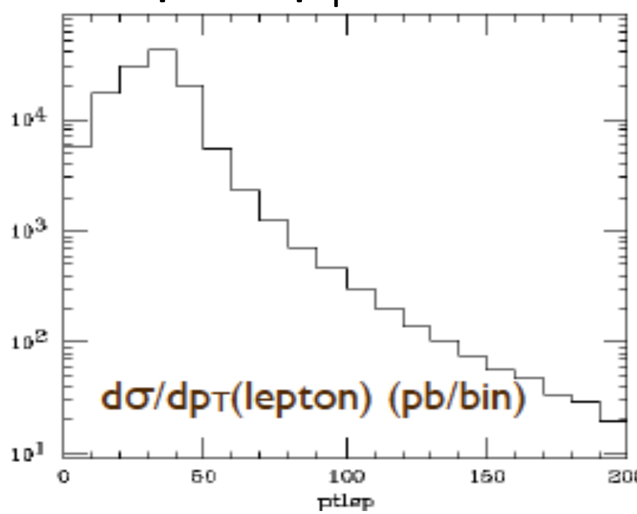


SM cross sections

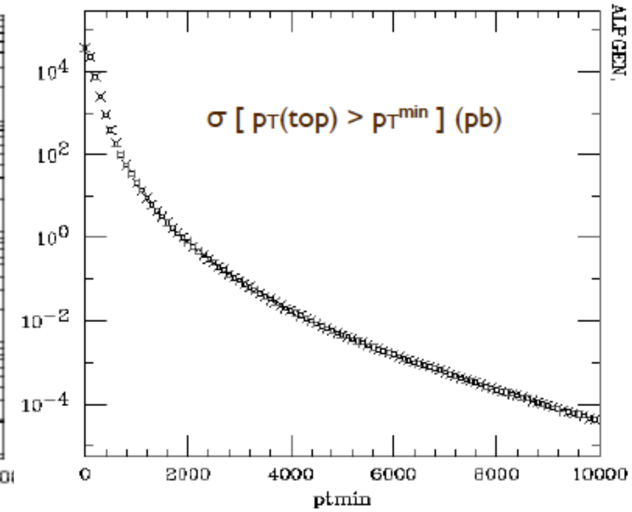
di-jet



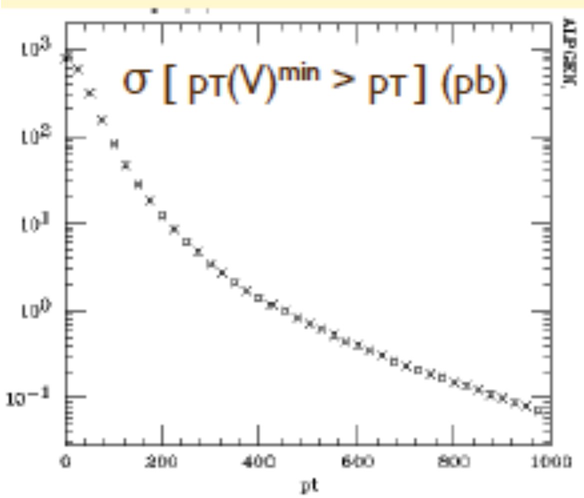
Lepton p_T from W



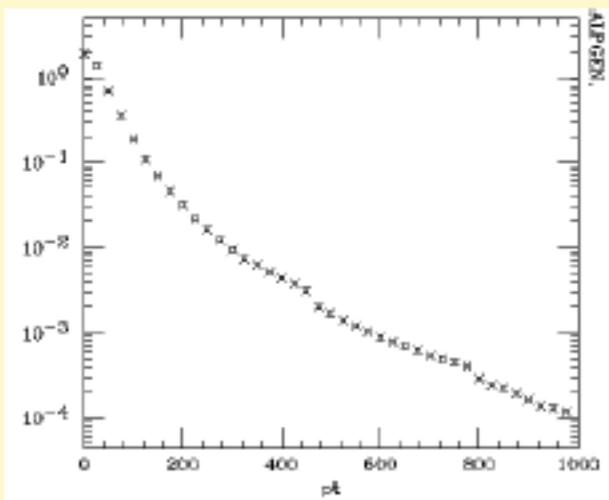
tt



WW σ=770 pb



WWW σ= 2 pb



WWZ σ= 1.6 pb