The Circular Road to a Higgs Factory and Beyond

Katsunobu Oide, KEK

Frank Zimmermann, CERN

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thanks to R. Aleksan, R. Assmann, A. Blondel, Y. Cai, O. Dominguez, J. Ellis, B. Holzer, P. Janot, M. Koratzinos, S. Myers, K. Ohmi, J. Osborne, L. Rossi, J. Seeman, V. Telnov, R. Tomas, U. Wienands, K. Yokoya, M. Zanetti, +…

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circular *pp* Higgs factories

LHC: 1st circular Higgs factory!
E_{CM}=8-14 TeV, $\widehat{L}\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

1 M Higgs produced so far – more to come!
15 H bosons / min – and more to come

HL-LHC: planned (~2022-2035):
E_{CM}=14 TeV, $L\sim 5\mathrm{x}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (leveled)

10x more Higgs

HE-LHC: proposed in LHC tunnel (2038-?)
E_{CM}=33 TeV, $L \geq 5\mathrm{x}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

6x higher cross section for *H* self coupling

or

VHE-LHC: proposed in new 80-100 km tunnel (2040?)
E_{CM}=84-104 TeV, $L \geq 5\mathrm{x}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

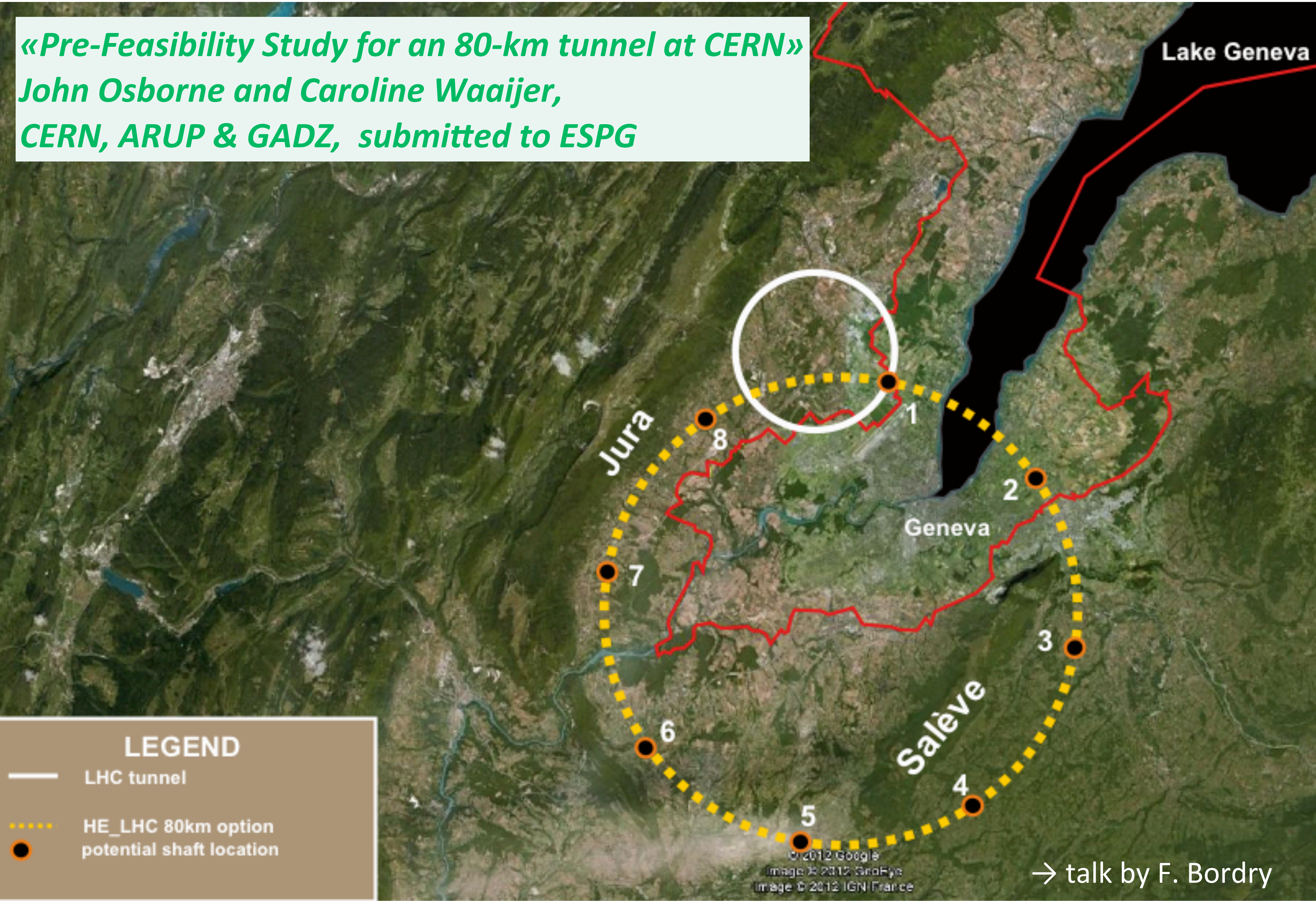
42x higher cross section for *H* self coupling

THE ultimate Higgs factory!

→ talk by F. Bordry

80-100 km tunnel for VHE-LHC, Geneva region

«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG



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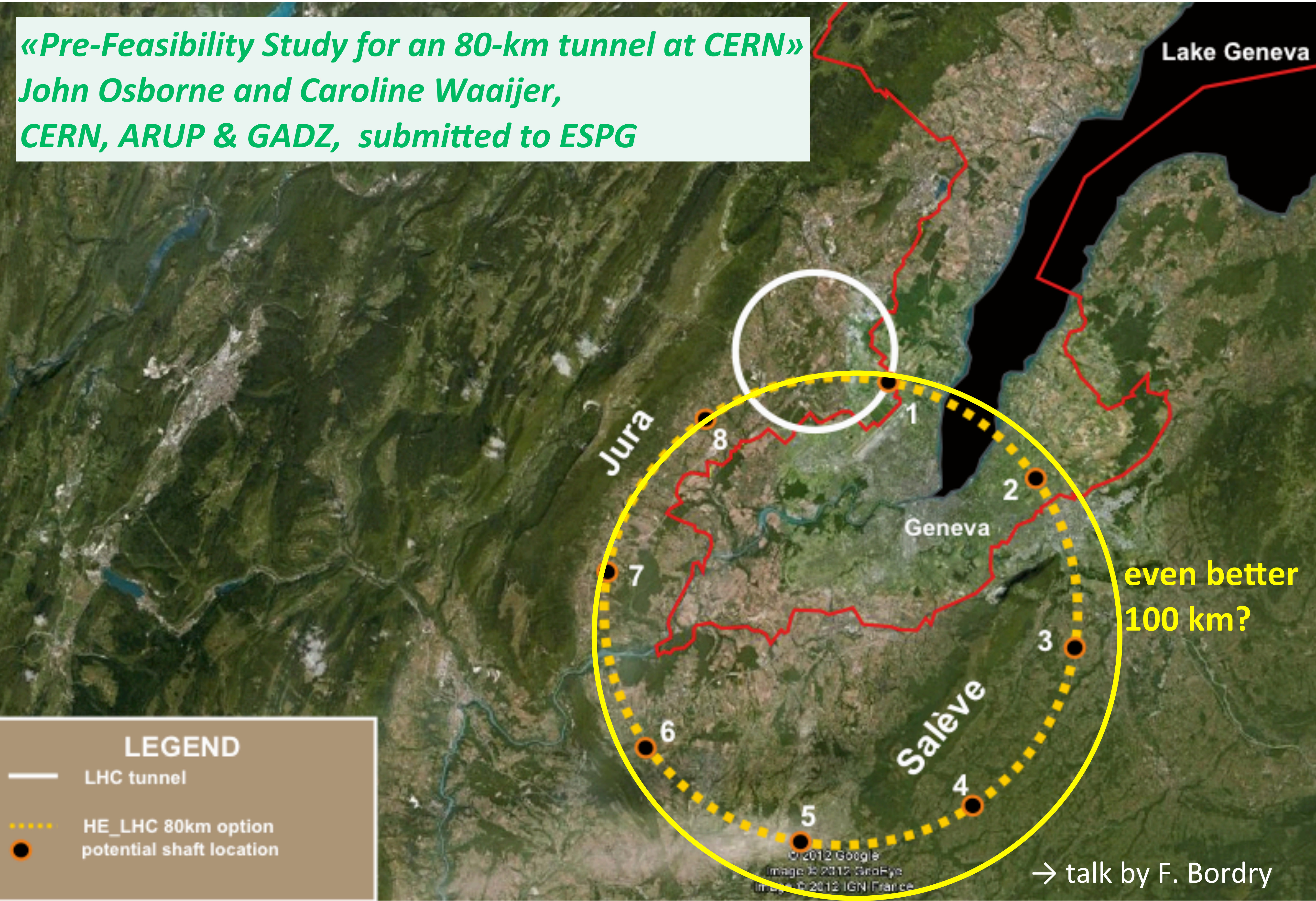


80 km ring in KEK area
12.7 km
KEK
City Office
Makabe Branch
市役所真壁庁舎
真壁城跡
公園
丸山
足尾山
きのこ山
Mt Tsukuba
筑波山
Tsutsujigaoka
つつじヶ丘
Miyawaki
宮脇
Mt Fuji
富士山
Ishioka
フラワー
パーク
サミットGC
東筑波CC
セゴビアGC
インチヨタ
つくばねCC
クリーンパーク
GC筑波コース
つくば
わんわん
ランド
筑波国際CC
不動峠
筑波東急GC
千代田GC
City Office
Chiyoda Branch
市役所千代田庁舎
千代田石岡
千代田PA
City Office
Niihari Branch
市役所新治庁舎
Toyosato
Hospital
下館GC
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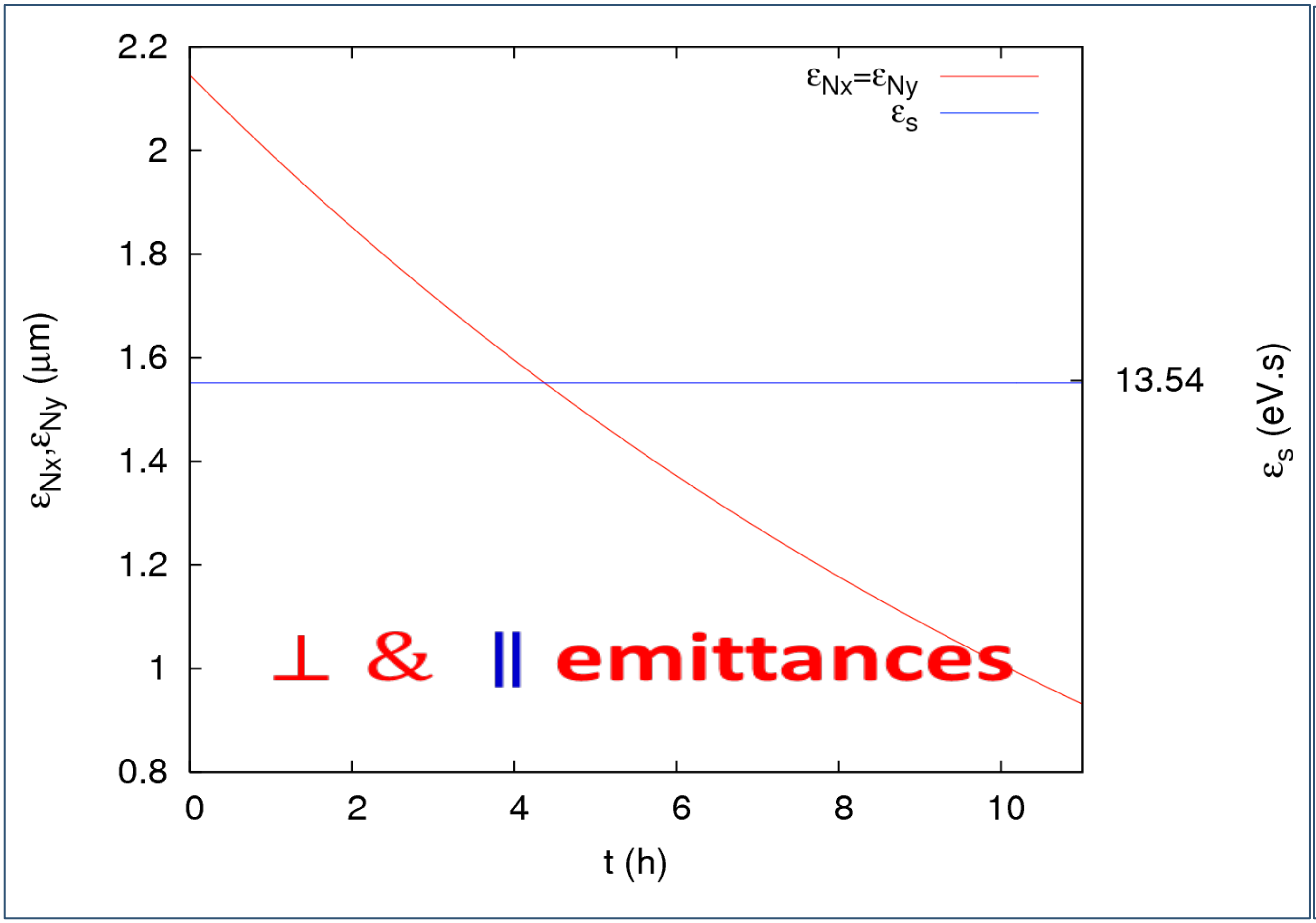
HE-LHC & VHE-LHC parameters

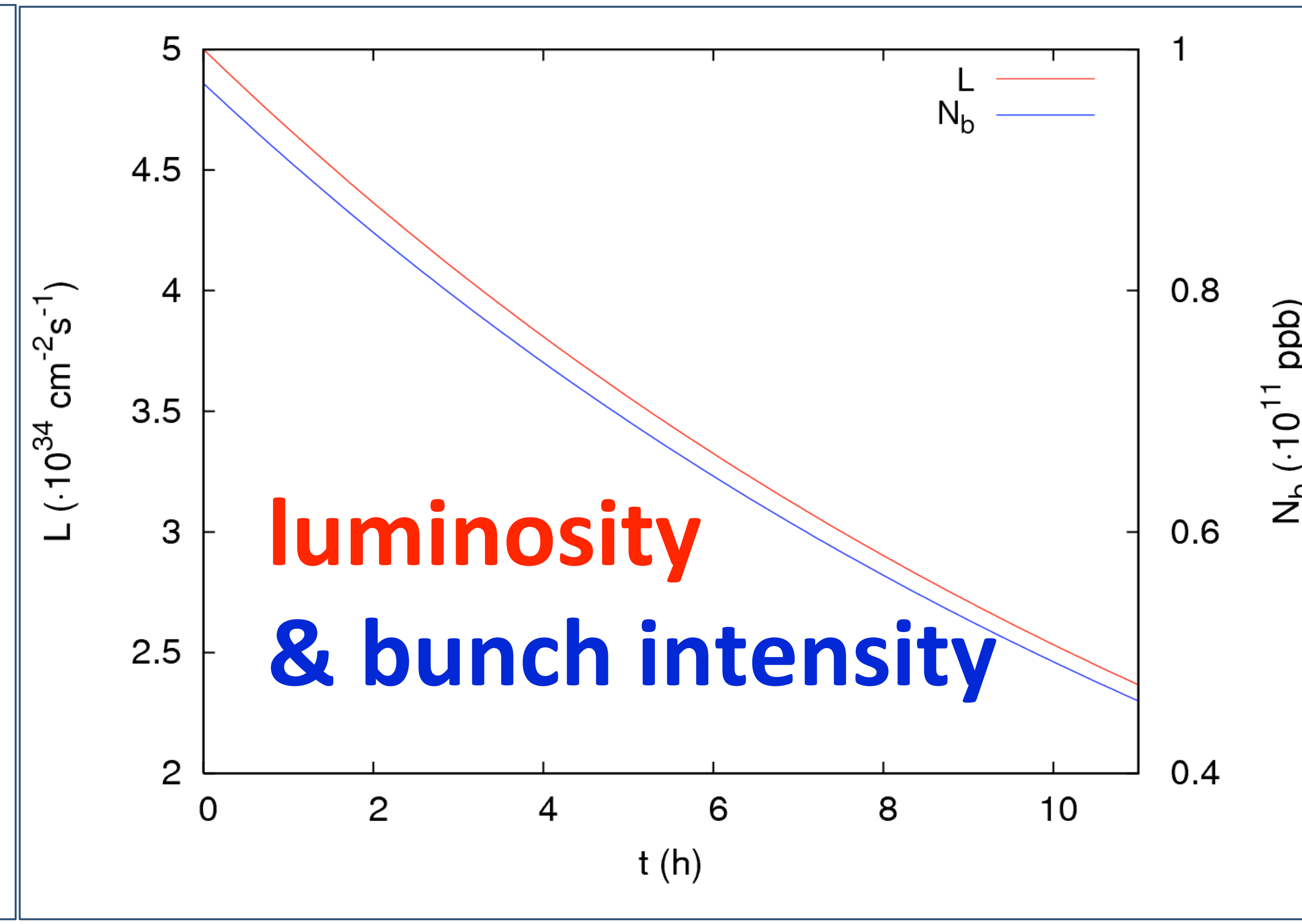
O. Dominguez,
L. Rossi, F. Zimmermann

parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14	14	**33**	**100**
circumference [km]	26.7	26.7	**26.7**	**80 (or 100)**
dipole field [T]	8.33	8.33	**20**	**20 (or 16)**
beam current [A]	0.58	1.12	**0.48**	**0.49**
rms IP spot size [μm]	16/7	7.1 (min)	5.2	6.7
stored beam energy [MJ]	362	694	701	**6610**
SR power per ring [kW]	3.6	7.3	96.2	2900
arc SR heat load [W/m/apert.]	0.17	0.33	**4.35**	**43.4**
energy loss per turn [keV]	6.7	6.7	**201**	**5857**
critical photon energy [eV]	44	44	575	5474
longit. SR emit. damping time [h]	12.9	12.9	**1.03**	**0.32**
peak events / crossing	27	135 (lev.)	**147**	**171**
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	**≥5.0**	**≥5.0**
beam lifetime due to burn off [h]	45	15.4	5.7	14.8
optimum av. luminosity / day [fb^{-1}]	**0.5**	**2.8**	**1.4**	**2.1**

VHE-LHC: time evolution over 11 h in physics with *p* burn off & controlled blow up

O. Dominguez

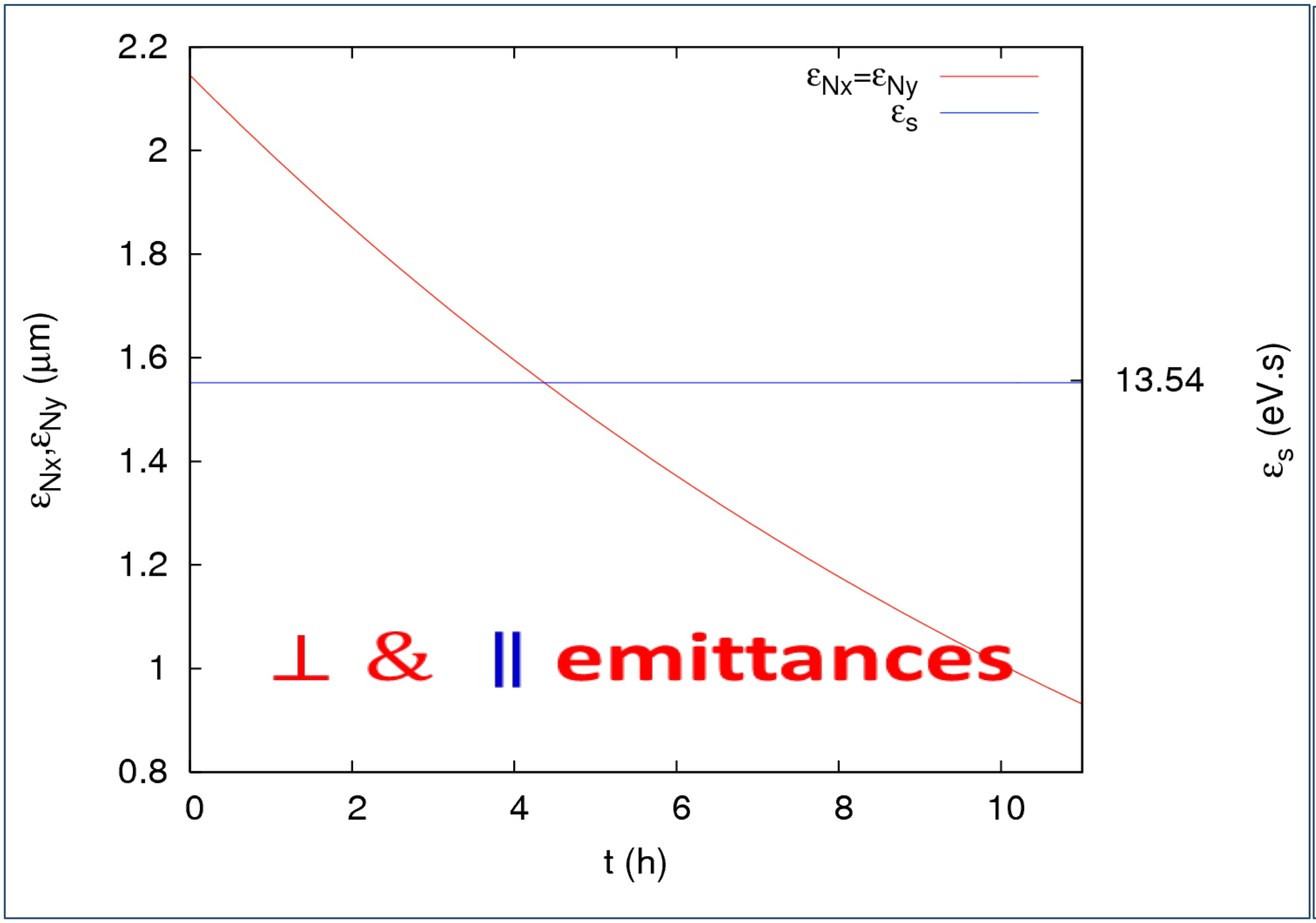


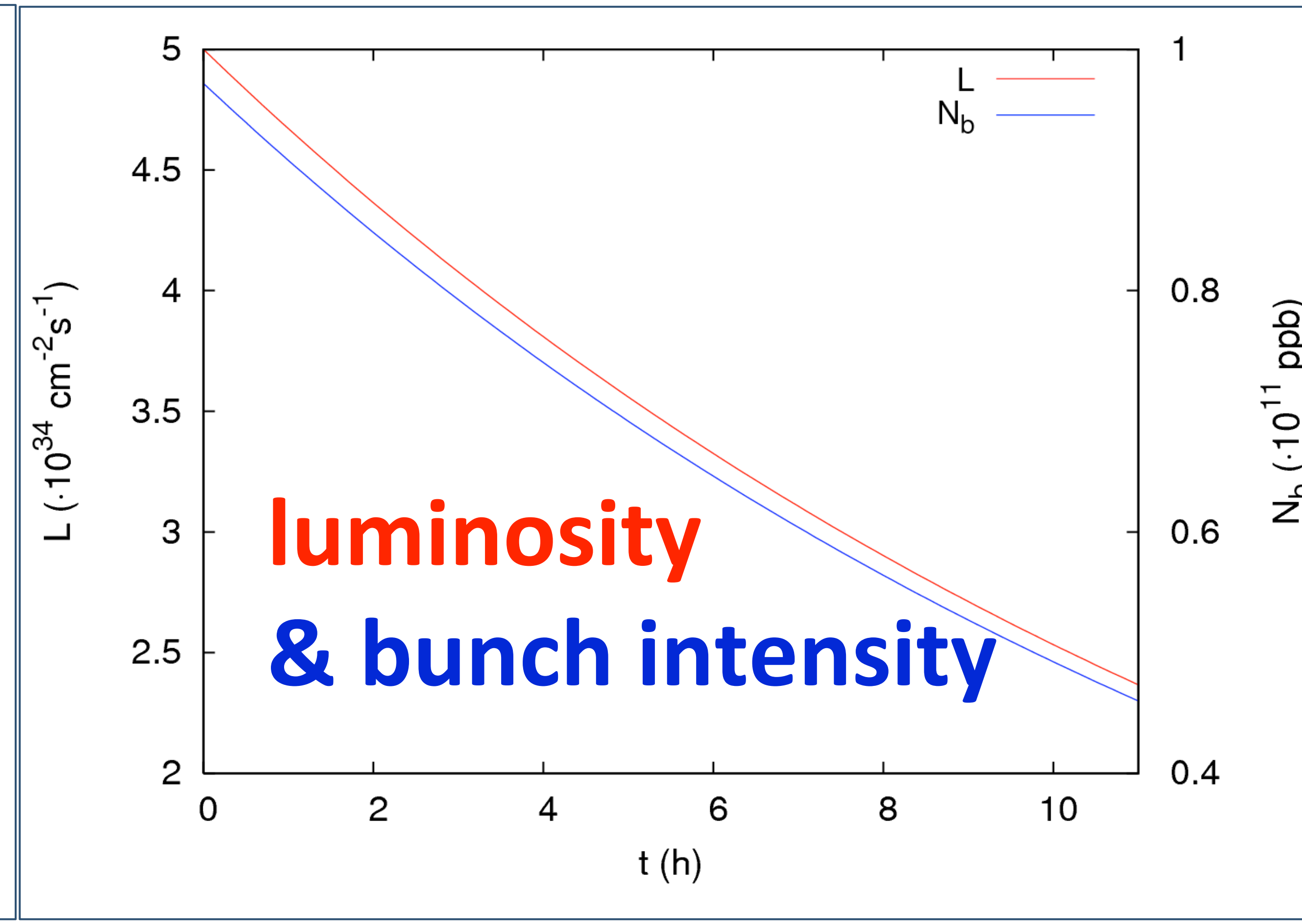


SR damping counteracted by transverse + longit. noise injection (constant tune shift & bunch length)

VHE-LHC: time evolution over 11 h in physics with *p* burn off & controlled blow up

O. Dominguez





SR damping counteracted by transverse + longit. noise injection (constant tune shift & bunch length)

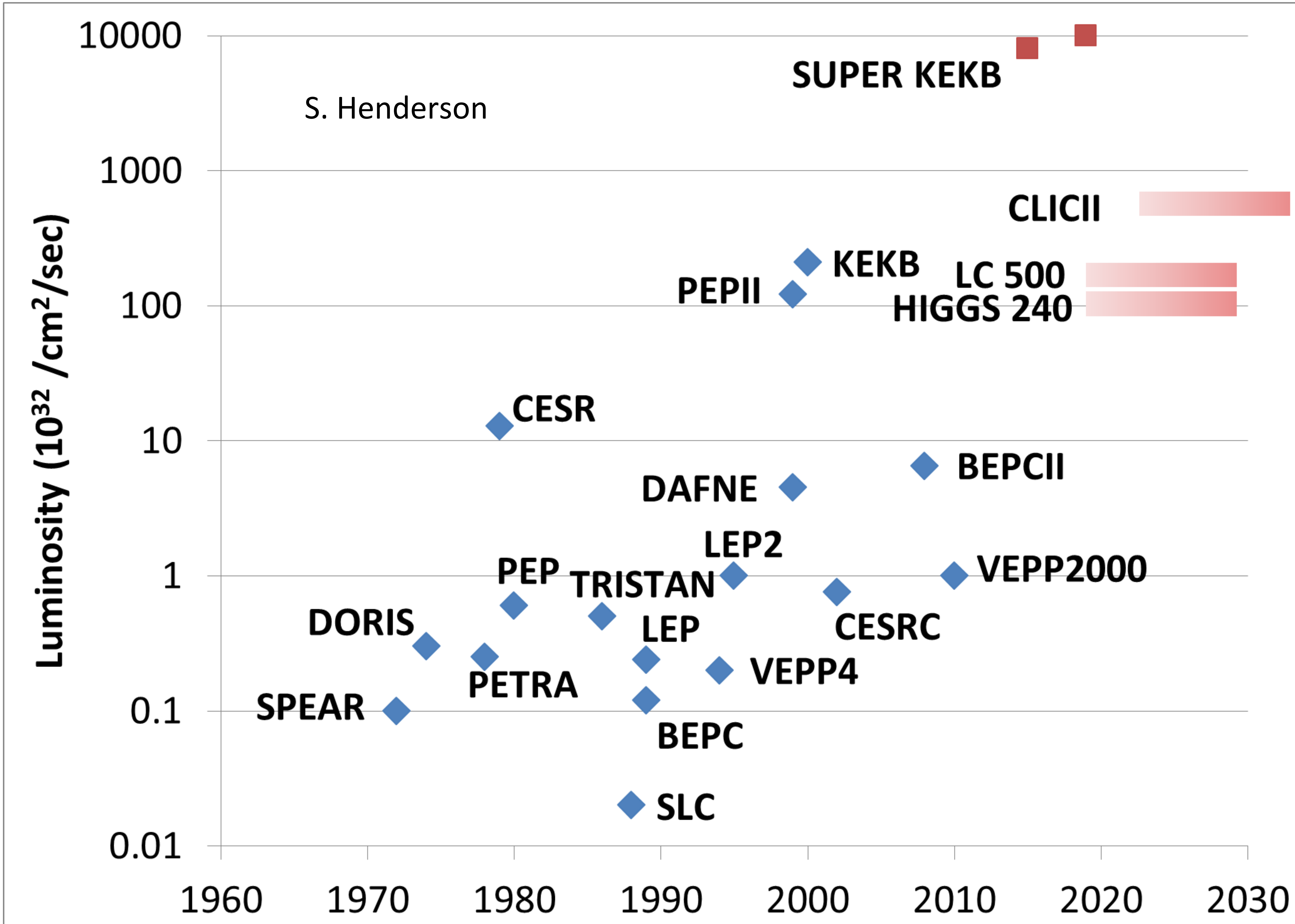
HE-LHC &VHE-LHC luminosities could greatly improve for bunch spacings < 25 ns, e.g. by factor 5 for 5 ns, making better use of strong radiation damping!

are 5 ns spacing & 2.5x10^{35}cm^{-2}s^{-1} acceptable for detectors?

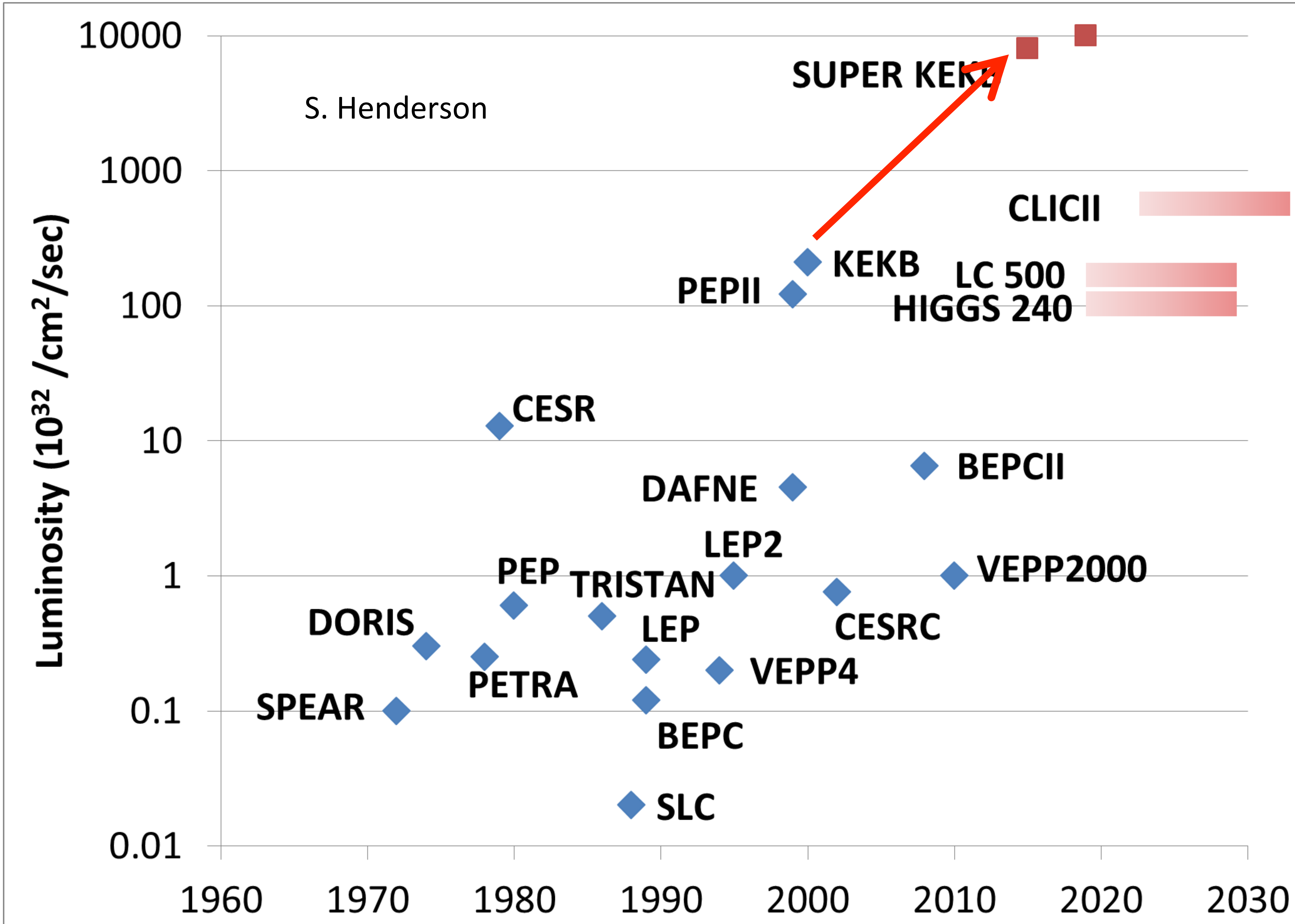
circular e^+e^- Higgs factories

- **2012 - LHC discovered Higgs boson at 126 GeV**
- cross section for ***H*** **production in** e^+e^- **collisions** maximum at **~15% higher beam energy than LEP2**
- **circular collider ("TLEP")** in **new 80-100 tunnel: 300x LEP2 luminosity at 4 IPs** (precision *H* studies); **recipe: smaller** β^* **(esp. *y*), lower emittance (*x* & *y*), top-up injection**
- operation **up to** $t\bar{t}$ **threshold**; **very high luminosity at *Z* pole & *WW* threshold** (+ **polarized beams!**)
- in **same tunnel**: ***pp*** **collider up to 100-TeV c.m.,** and *ep* collider; **TLEP will enhance VHE-LHC physics case**

luminosity - past&planned e^+e^- colliders



luminosity - past&planned e^+e^- colliders



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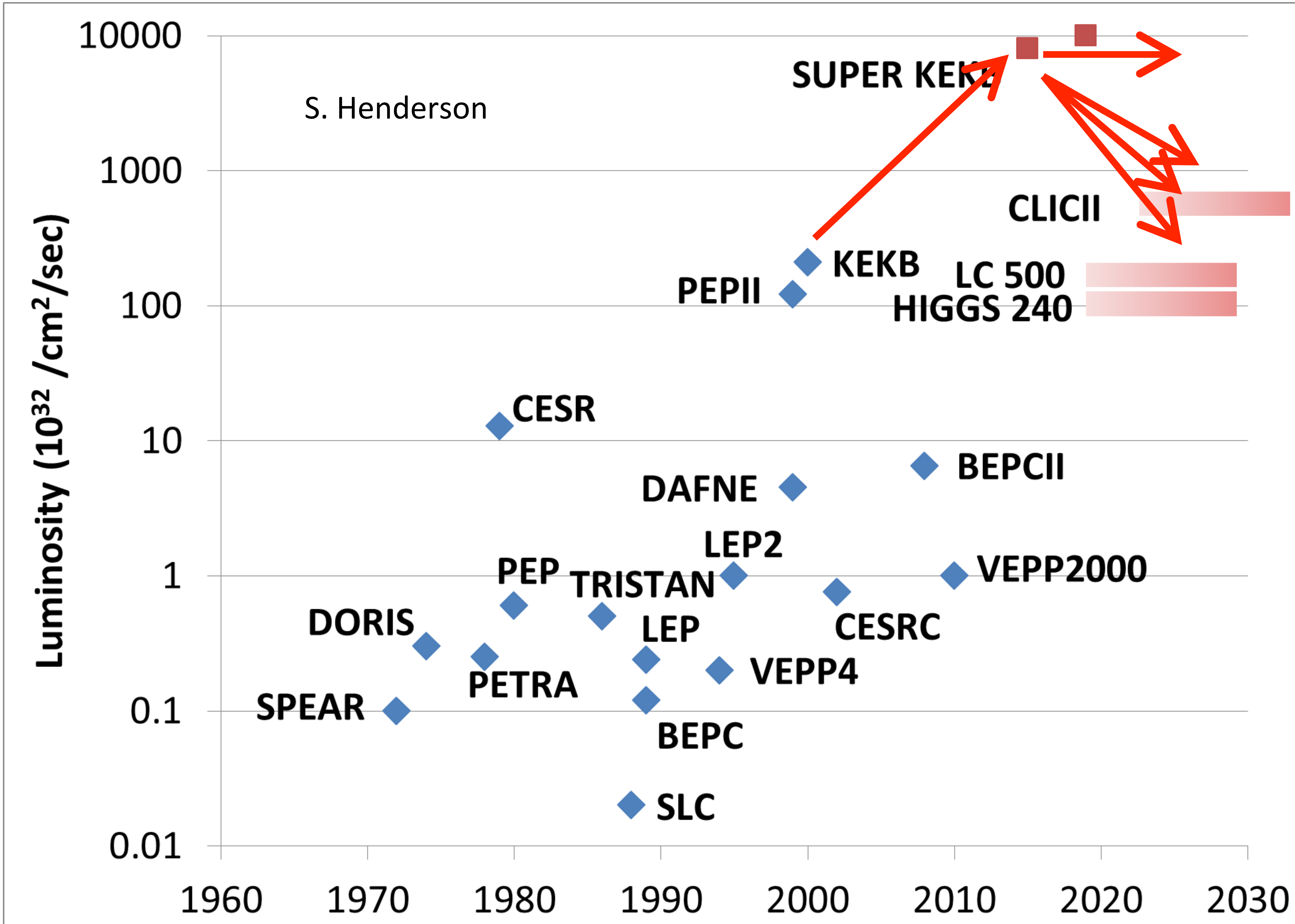

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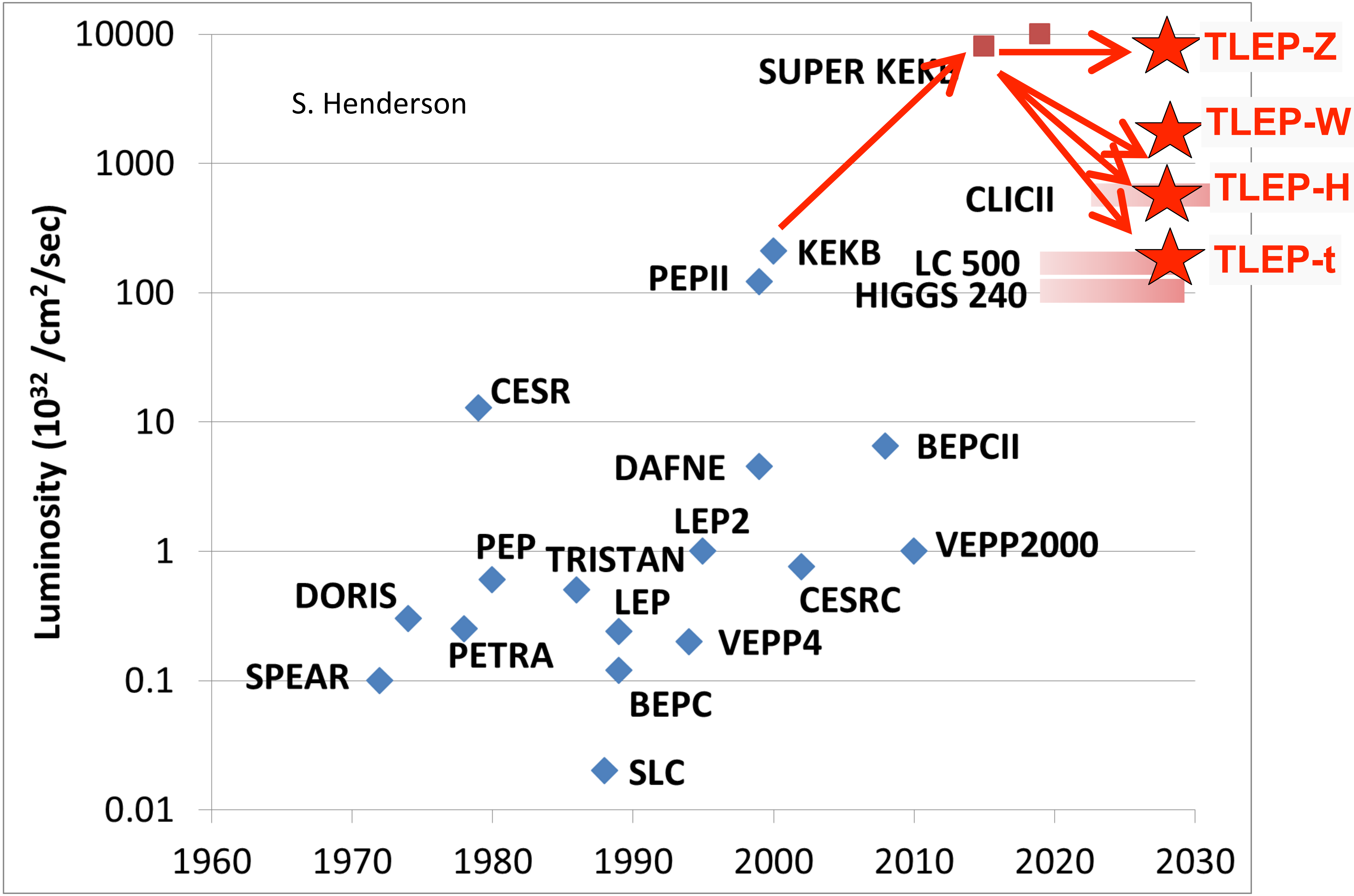

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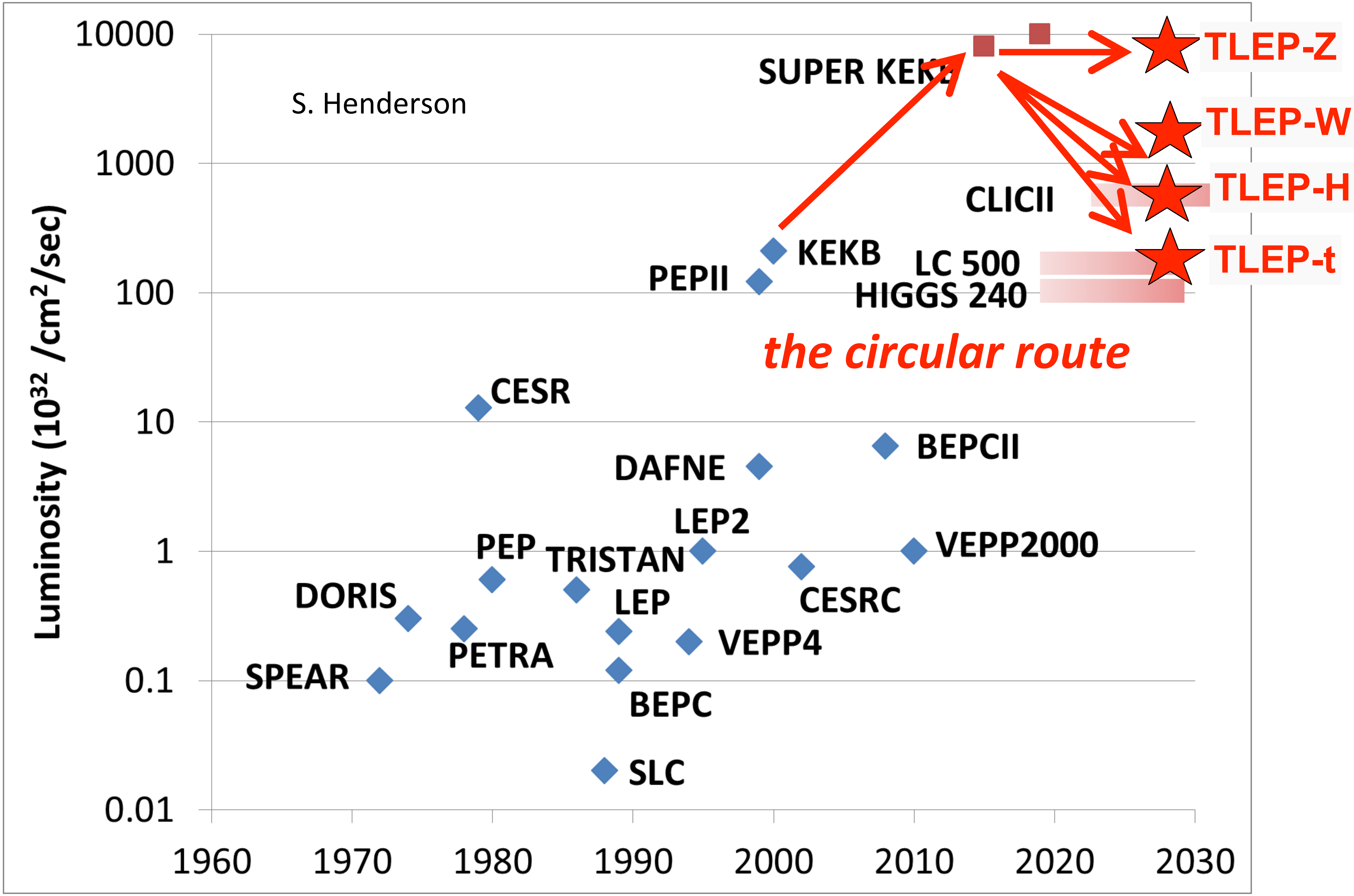


TLEP beam lifetime: two processes

1. radiative Bhabha scattering ($\sigma \approx 0.215$ barn)

LEP2: $\tau_{\mathbf{beam,LEP2}}$ **~ 6 h**

TLEP **with L~5x10^{34} cm^{-2}s^{-1} at 4 IPs**:

$\tau_{\mathbf{beam,TLEP}}$~21 minutes, unavoidable

2. beamstrahlung (synchr. rad. during the collision)

mitigated by:

(1) large momentum acceptance η

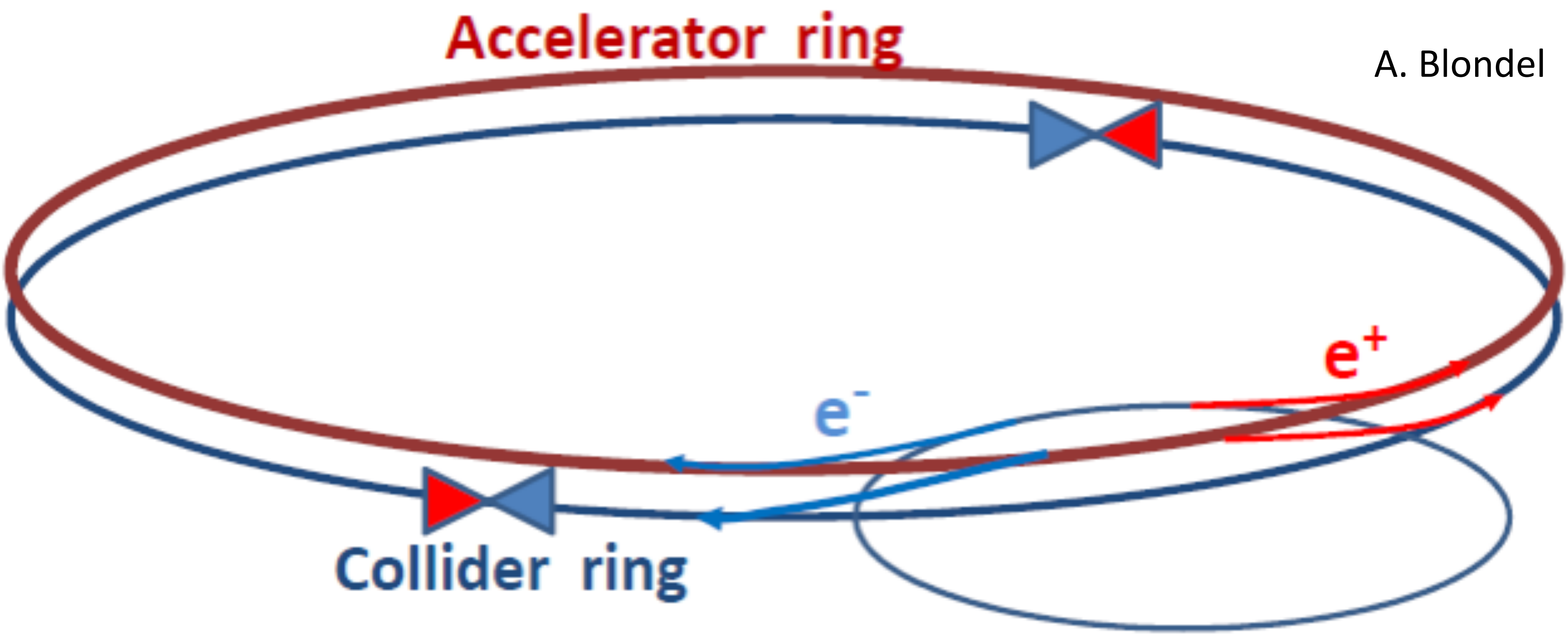
(2) flat beams [i.e. small ε_y & large β_x^*]

(3) fast replenishing

(M. Koratzinos, V.Telnov, K. Yokoya, M. Zanetti,...)

TLEP - circular e^+e^- collider to study the «Higgs boson» X(126)

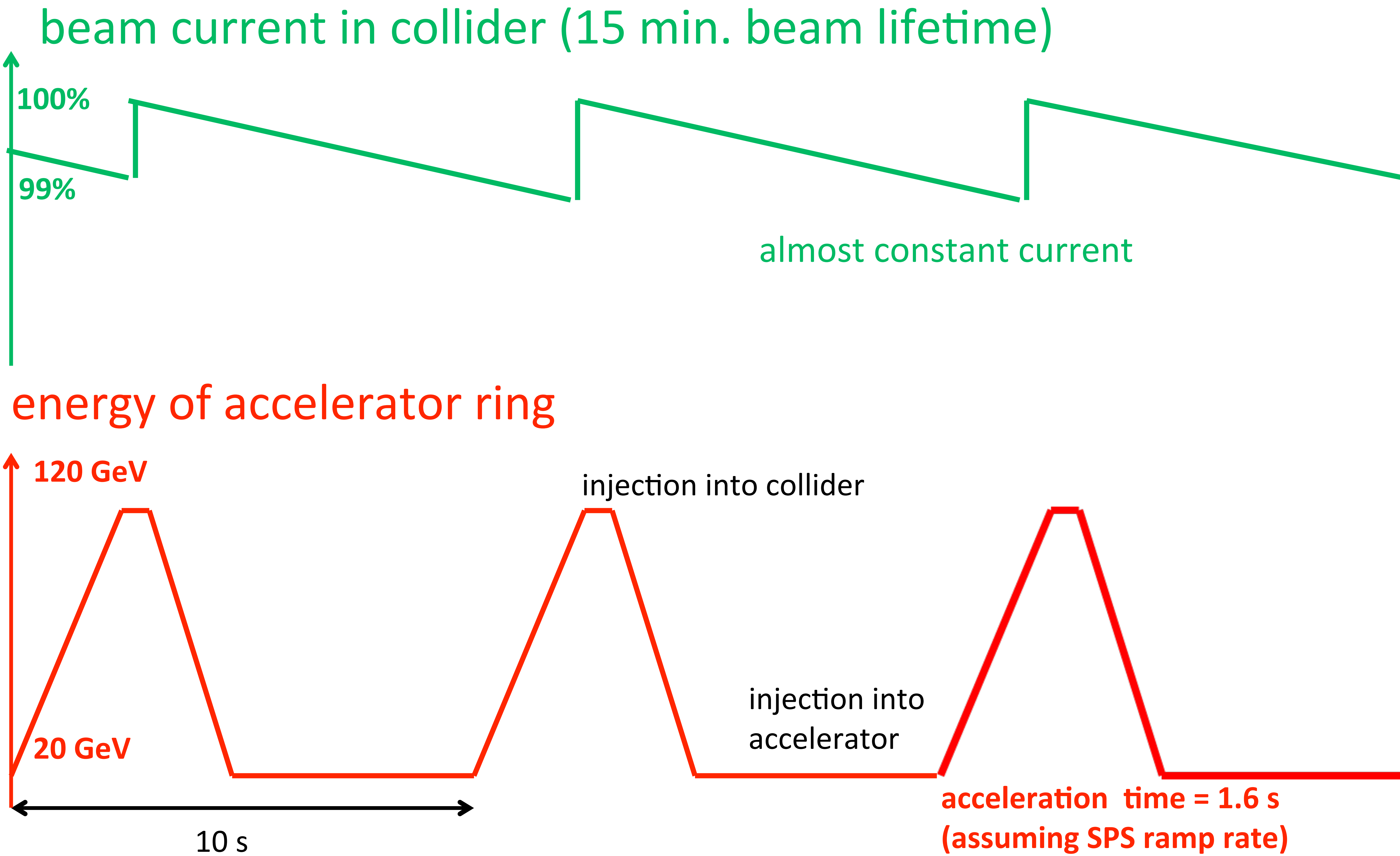
a relatively young concept (2011)



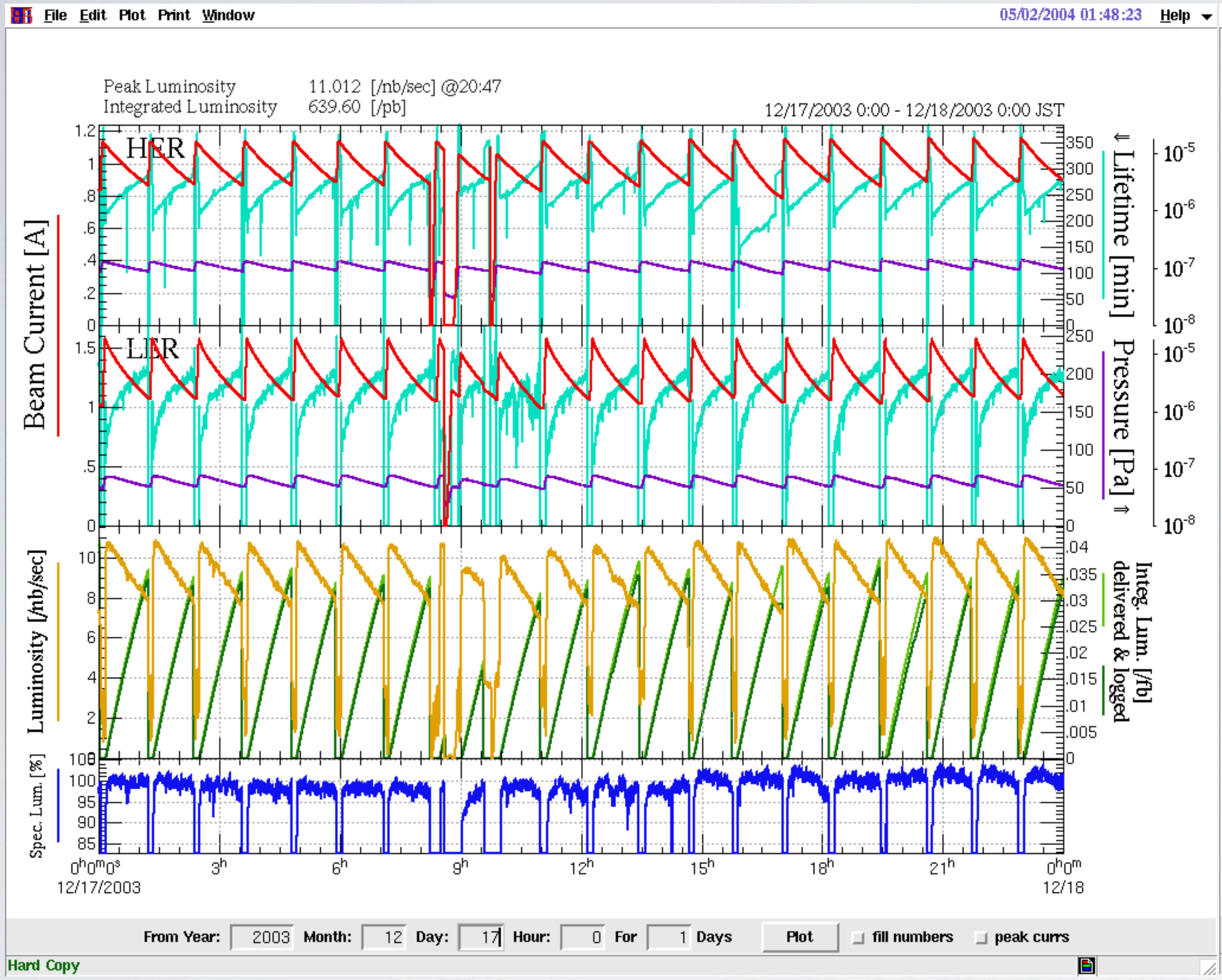
short beam lifetime ($\sim\tau_{LEP2}/40$) due to high luminosity

supported by top-up injection (used at KEKB, PEP-II, SLS,…)

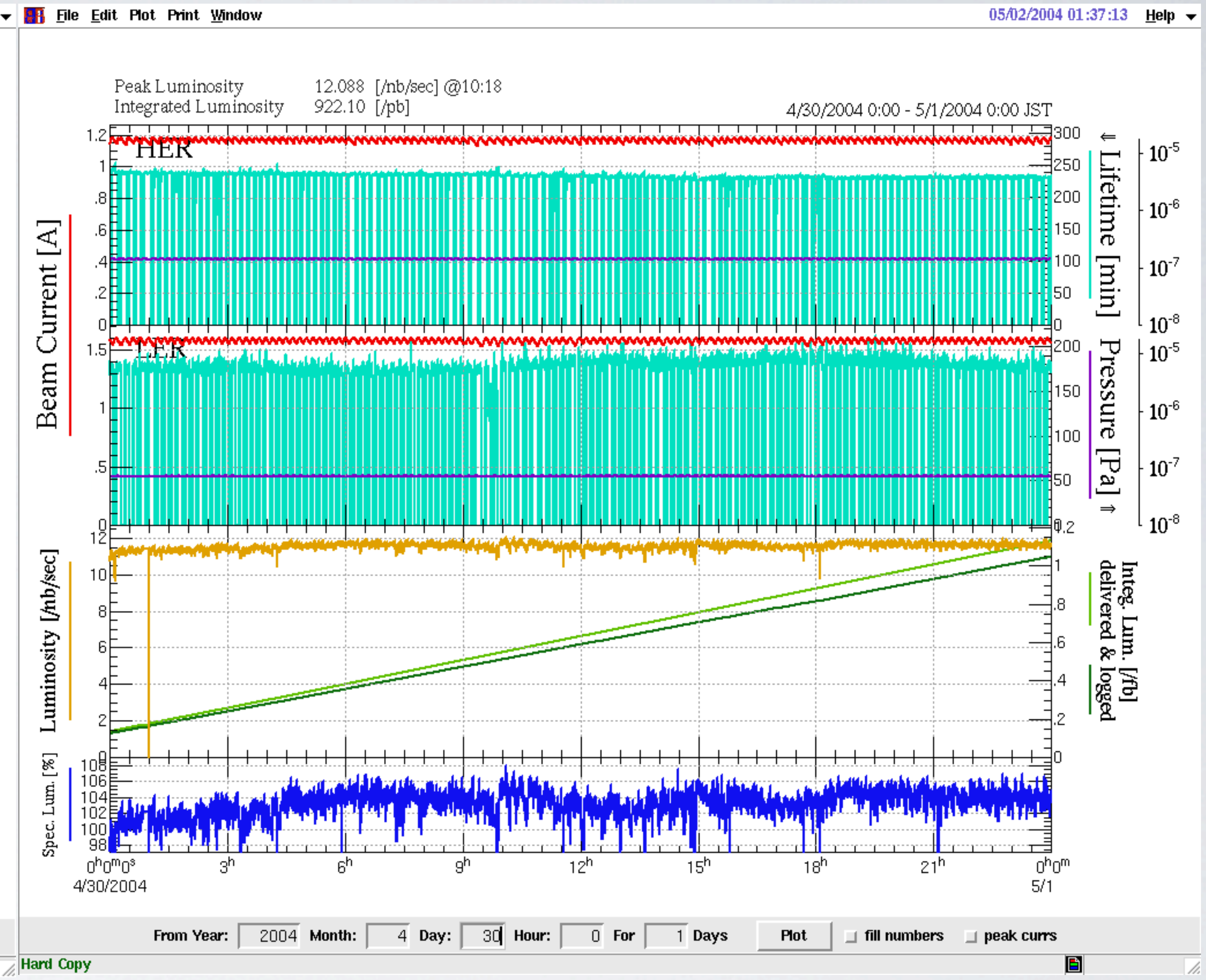
top-up injection: schematic cycle



Top-up at KEKB (2004)



a day before top-up

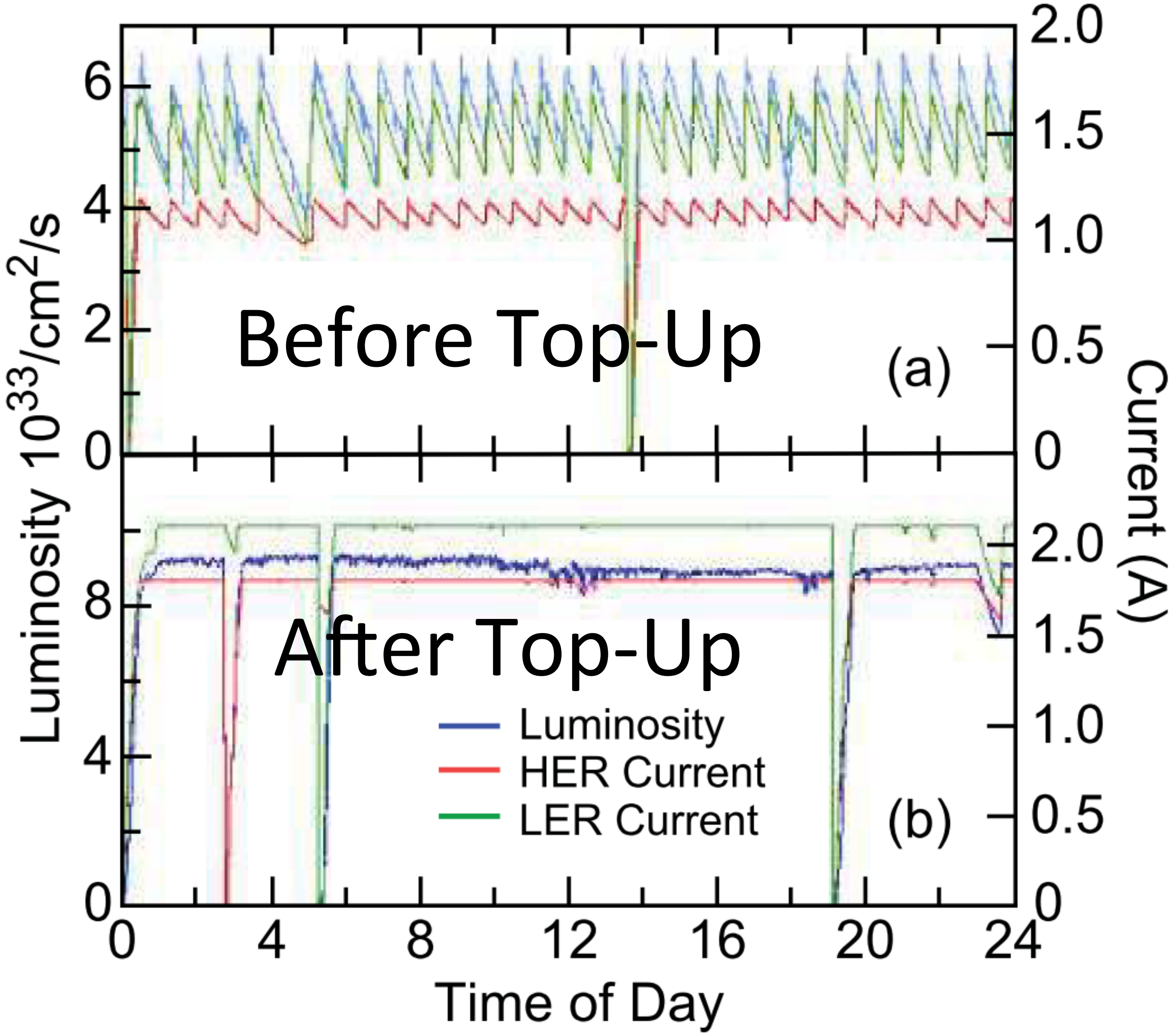


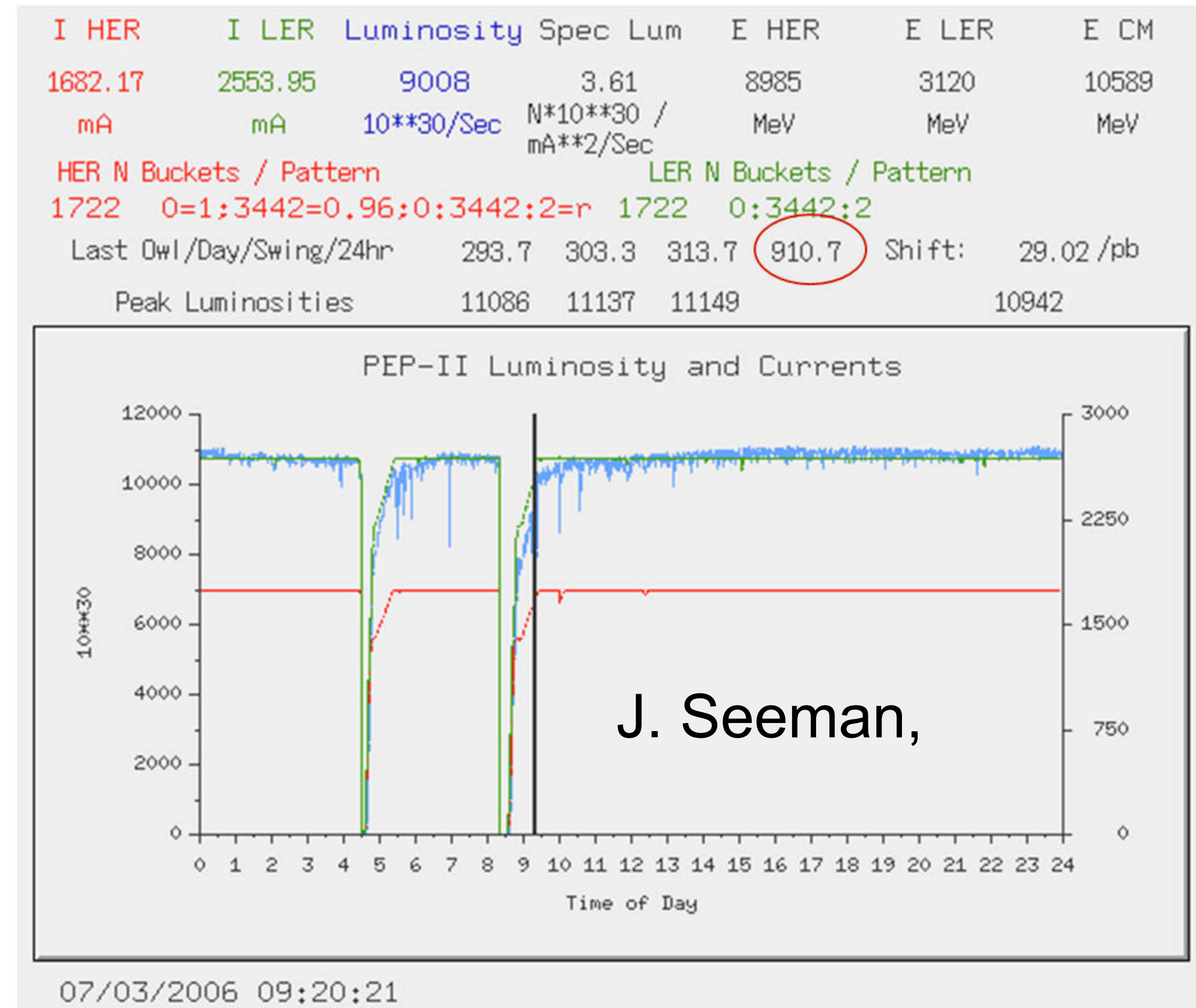
a day after top-up

- Top-up improved the integrated luminosity from 640 pb/day to 920 pb/day in 2004 (eventually reached 1480 pb/day in 2009).
- Machine becomes more stable and less aborts, as the stored beam current is nearly constant.
- Thus the luminosity tuning became easier.

top-up performance at PEP-II/BaBar

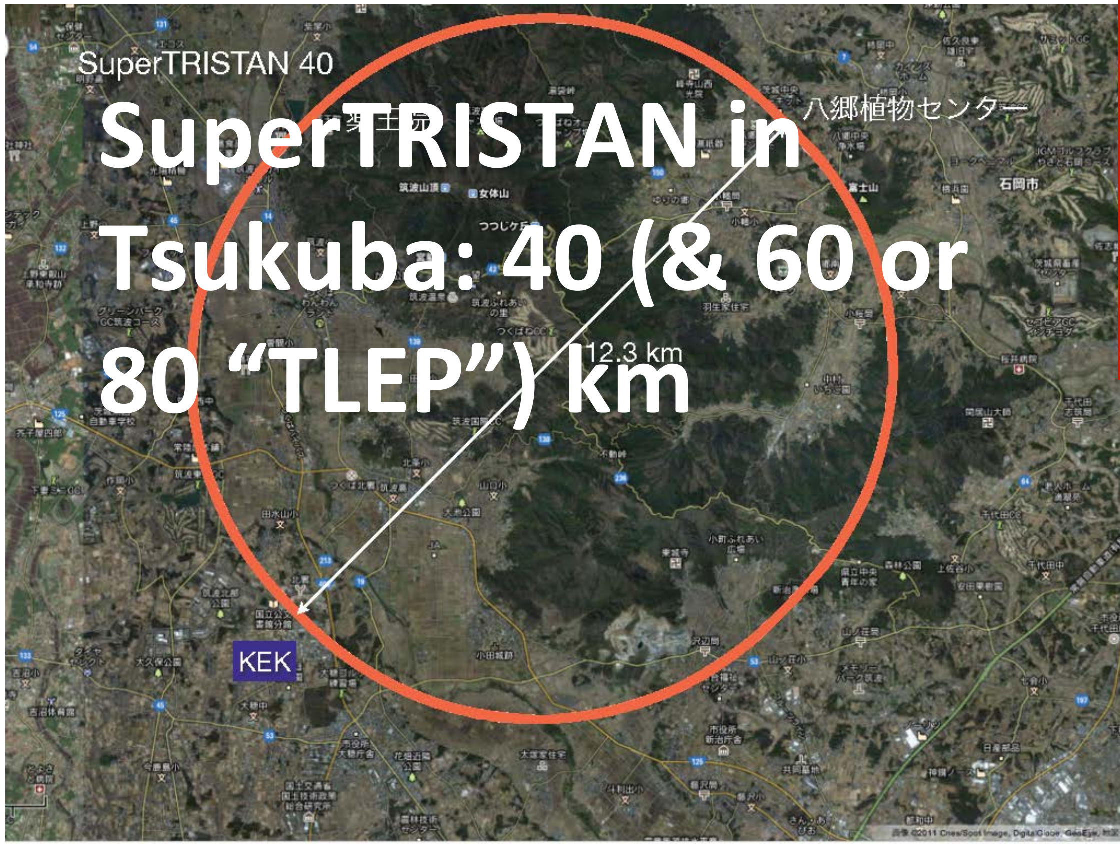
J. Seeman



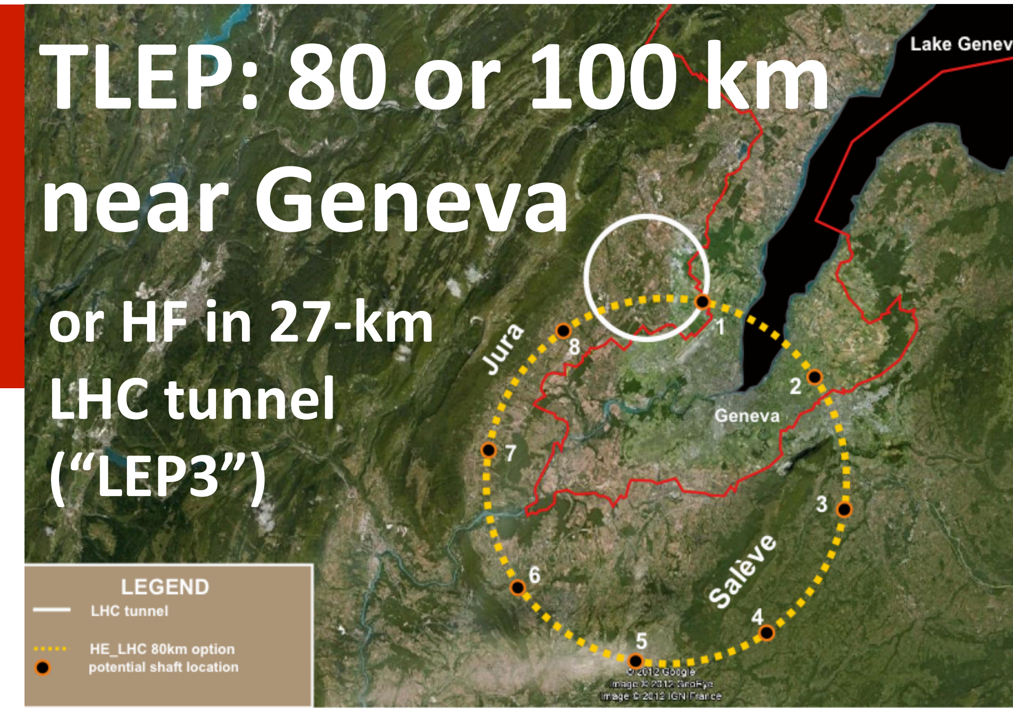


average luminosity ≈ peak luminosity

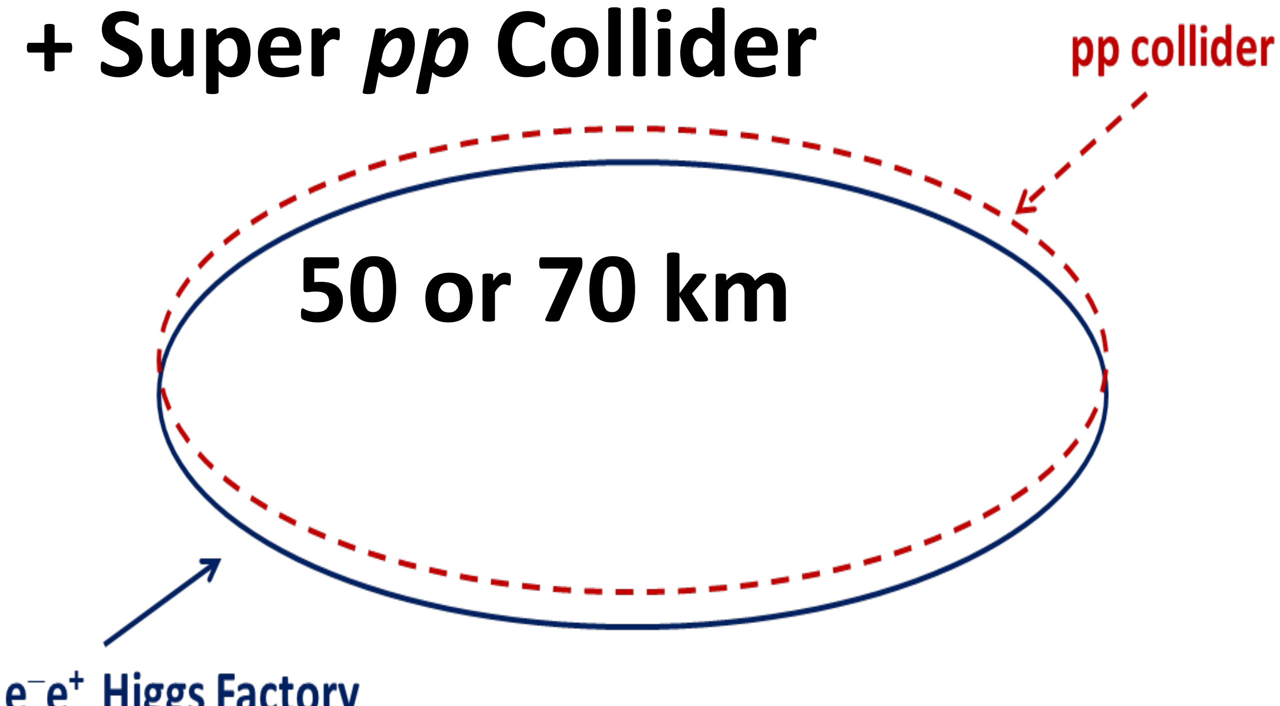
proposed circular e^+e^- Higgs factories



SLAC/LBNL design: 27 km



Chinese Higgs Factory
+ Super *pp* Collider



parameters	TLEP Z	TLEP W	TLEP H	TLEP t	
$E_{\mathrm{c.m.}}$ [GeV]	**91**	**160**	**240**	**350**	
beam current [mA]	**1440**	**154**	**29.8**	**6.7**	
# bunches/beam	7500	3200	167	160	20
#$e-$/bunch [10^{11}]	4.0	1.0	3.7	0.88	7.0
ε_x, ε_y [nm]	29.2, 0.06	3.3,0.017	7.5, 0.015	2, .002	
$\beta^*_{x,y}$ [mm]	500, 1	200, 1	500, 1	1000, 1	
$\sigma^*_{x,y}$[μm]	121, 0.25	26, 0.13	61, 0.12	45,.045	126,.13
$\sigma^{tot}_{z,rms}$ [mm] (w BS)	2.93	1.98	2.11	0.77	1.95
E^{SR}_{loss}/turn [GeV]	0.03	0.3	1.7	7.5	
V_{RF},tot [GV]	2	2	6	12	
$\xi_{x,y}$/IP	0.068	0.086	0.094	0.057	
$\mathscr{L}$ /IP[10^{34}cm^{-2}s^{-1}]	**59**	**16**	**5**	**1.3**	**1.0**
#IPs	**4**	**4**	**4**	**4**	
τ_{beam}[min] (rad.B)	99	38	**24**	**21**	**26**
τ_{beam}[min] (BS,η=2%)	>10^{25}	>10^6	**38**	**14**	**2**

TLEP average power consumption *rough estimate*

system	el. power [MW]
RF (w/o cryogenics)	180
RF for accelerator ring	5
cryogenics	34
cooling	5
ventilation	21
magnet systems	14
general services	20
total	**~274**

large part of power (185 MW) is proportional to beam current & luminosity; e.g. running TLEP-H with $\underline{5\times10^{34}\ cm^{-2}s^{-1}}$ (4 IPs) instead of $2\times10^{35}\ cm^{-2}s^{-1}$ total power would be <u>135 MW</u>

synchroton-radiation: heat load

	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

TLEP has >10 times less SR heat load per meter than PEP-II or SPEAR! (though higher photon energy)

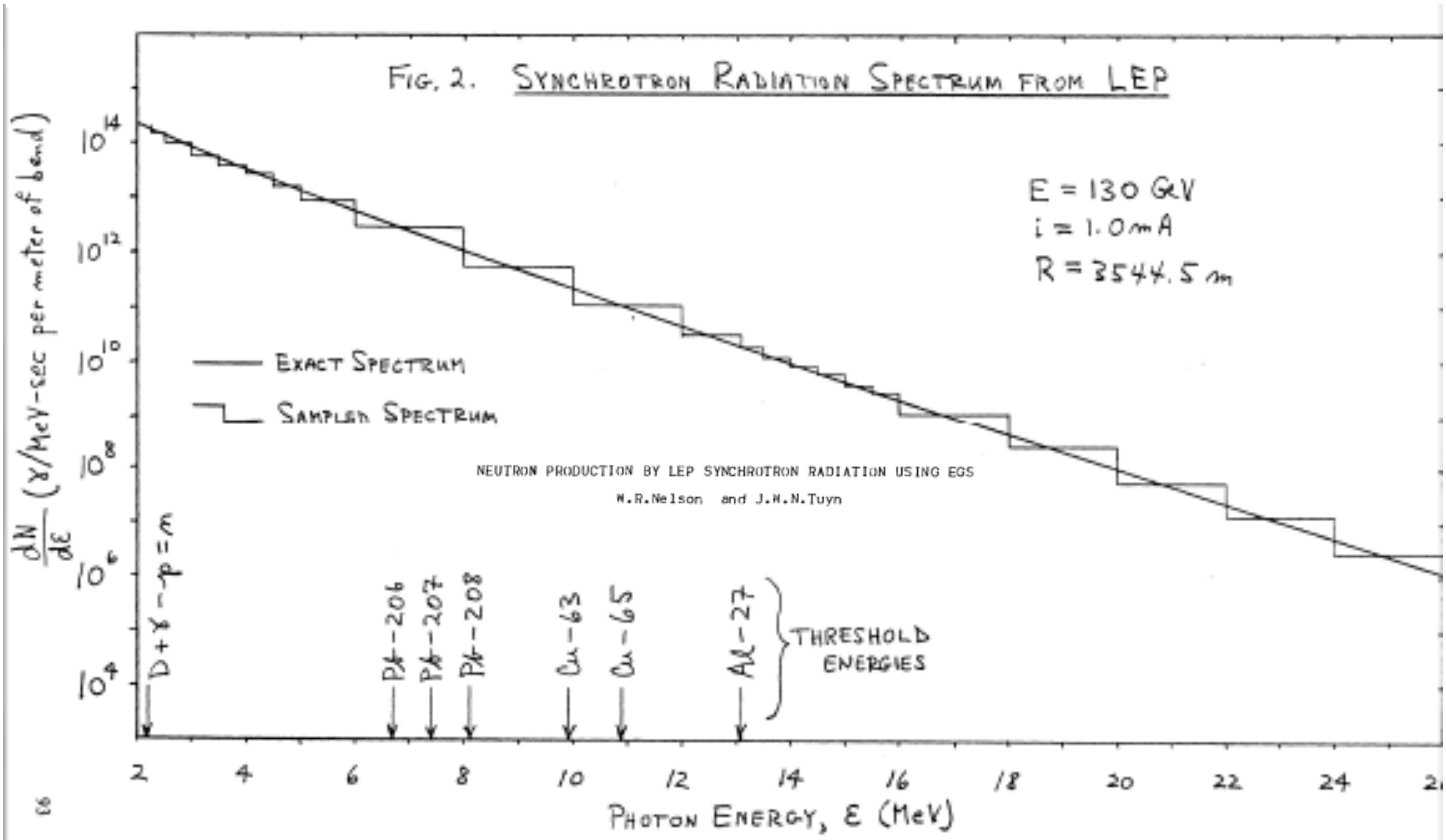
N. Kurita, U. Wienands, SLAC

synchrotron radiation: activation

NEUTRON PRODUCTION BY LEP SYNCHROTRON RADIATION USING EGS

W.R.Nelson and J.H.N.Tuyn

A. Fasso
3rd TLEP3 Day



synchrotron radiation: activation

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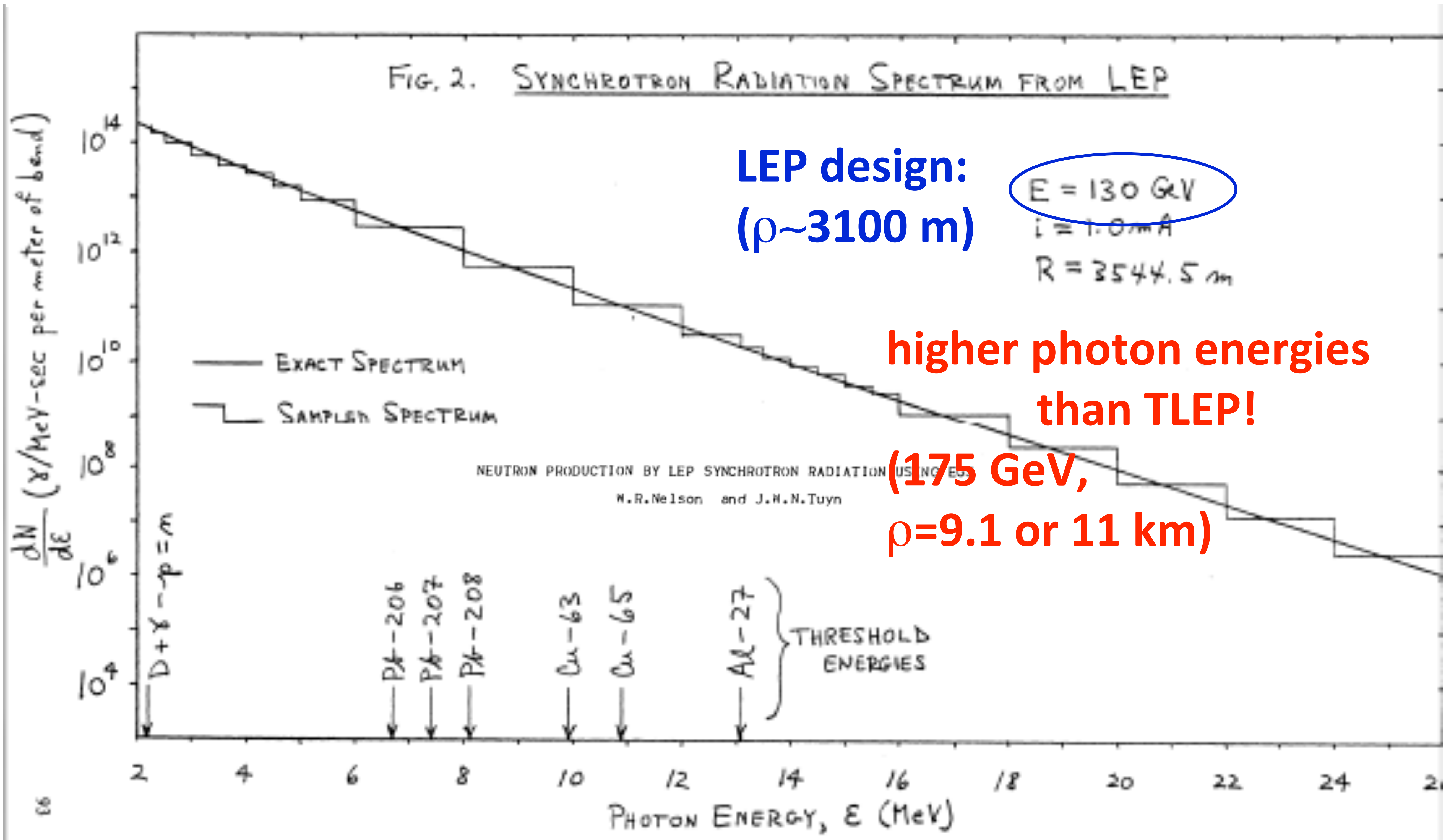
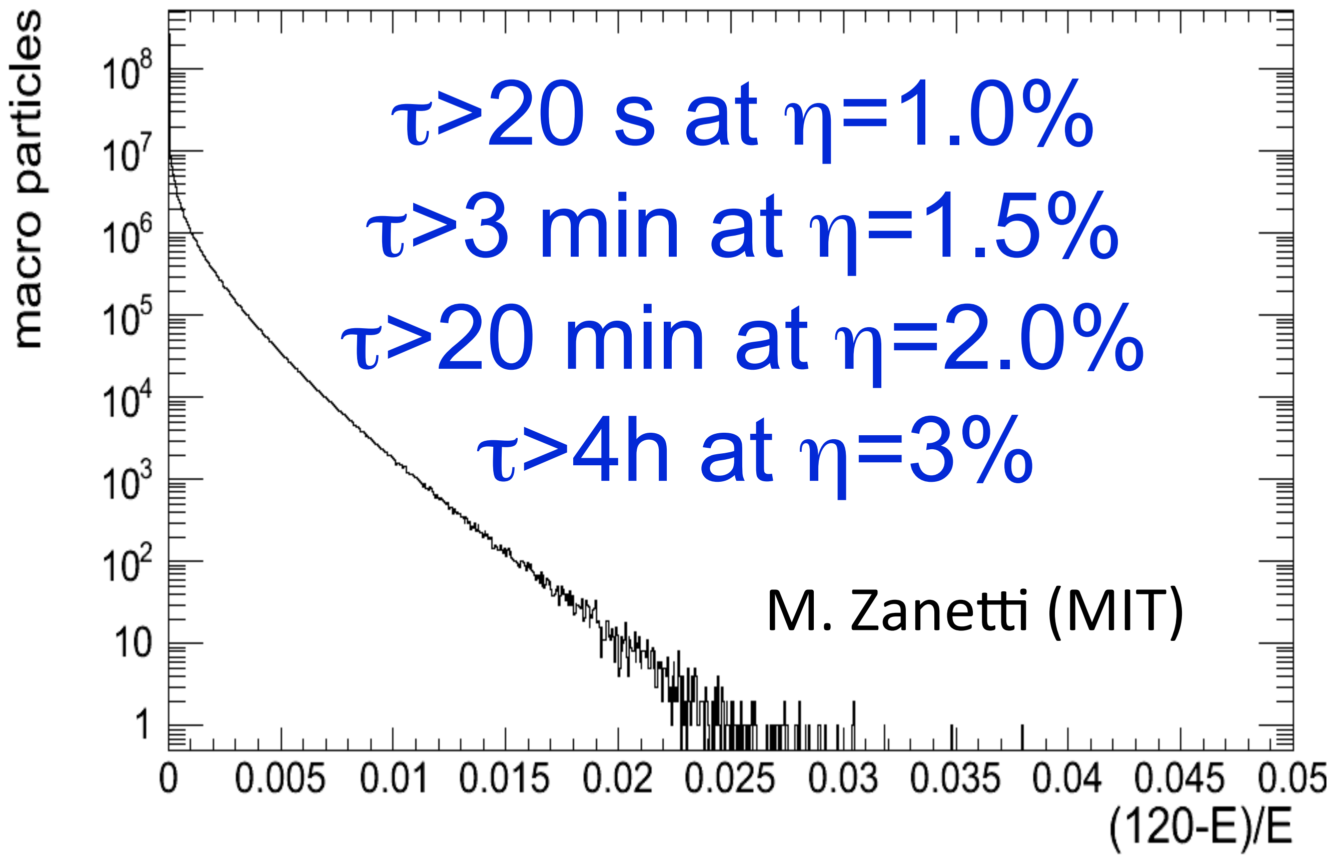


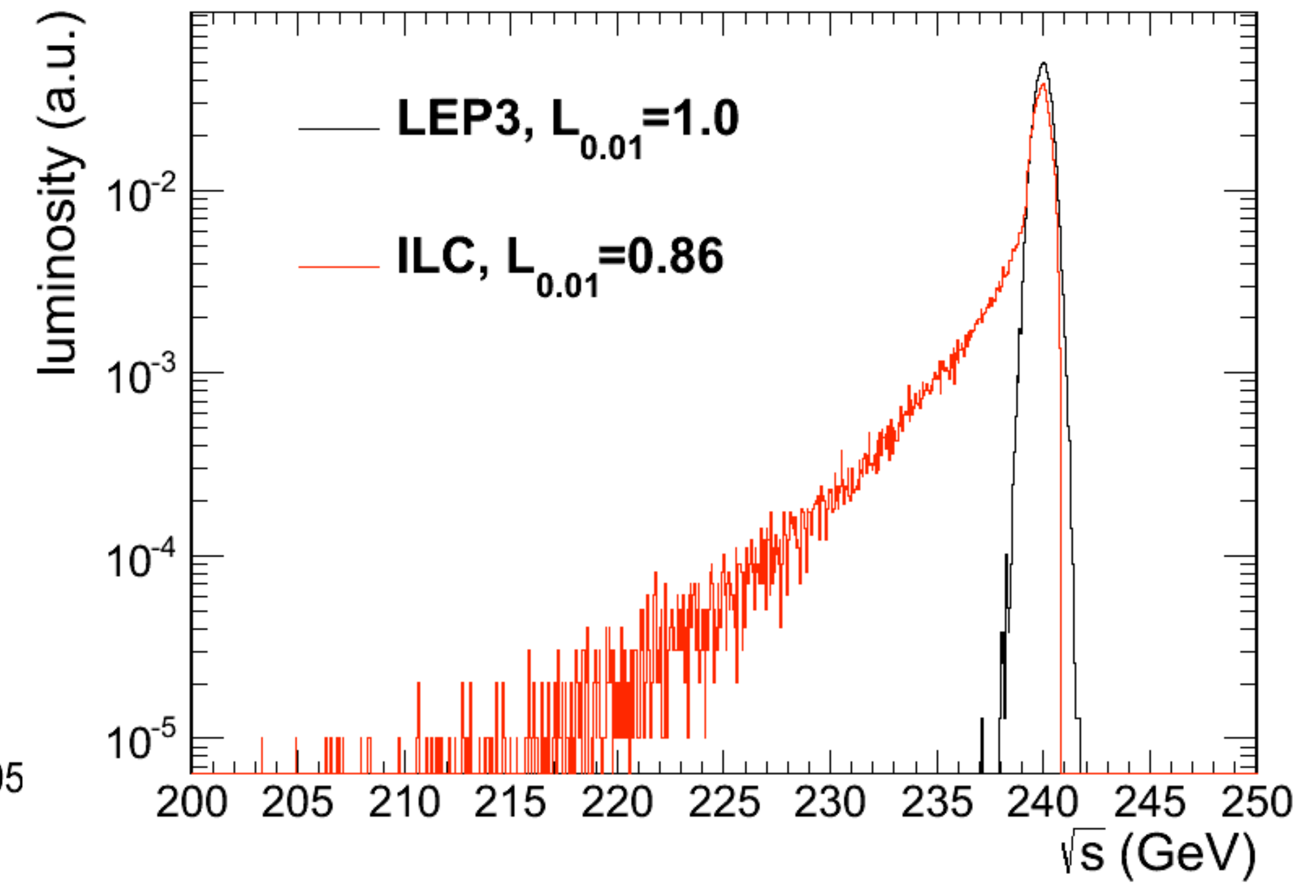
beamstrahlung: lifetime & *L* spectrum

- simulation w 360M macroparticles (Guinea-Pig code)
- τ varies exponentially with momentum acceptance η

TLEP at 240 GeV: post-collision *E* tail → beam lifetime τ

luminosity *energy* spectrum





required acceptance smaller for flatter beams

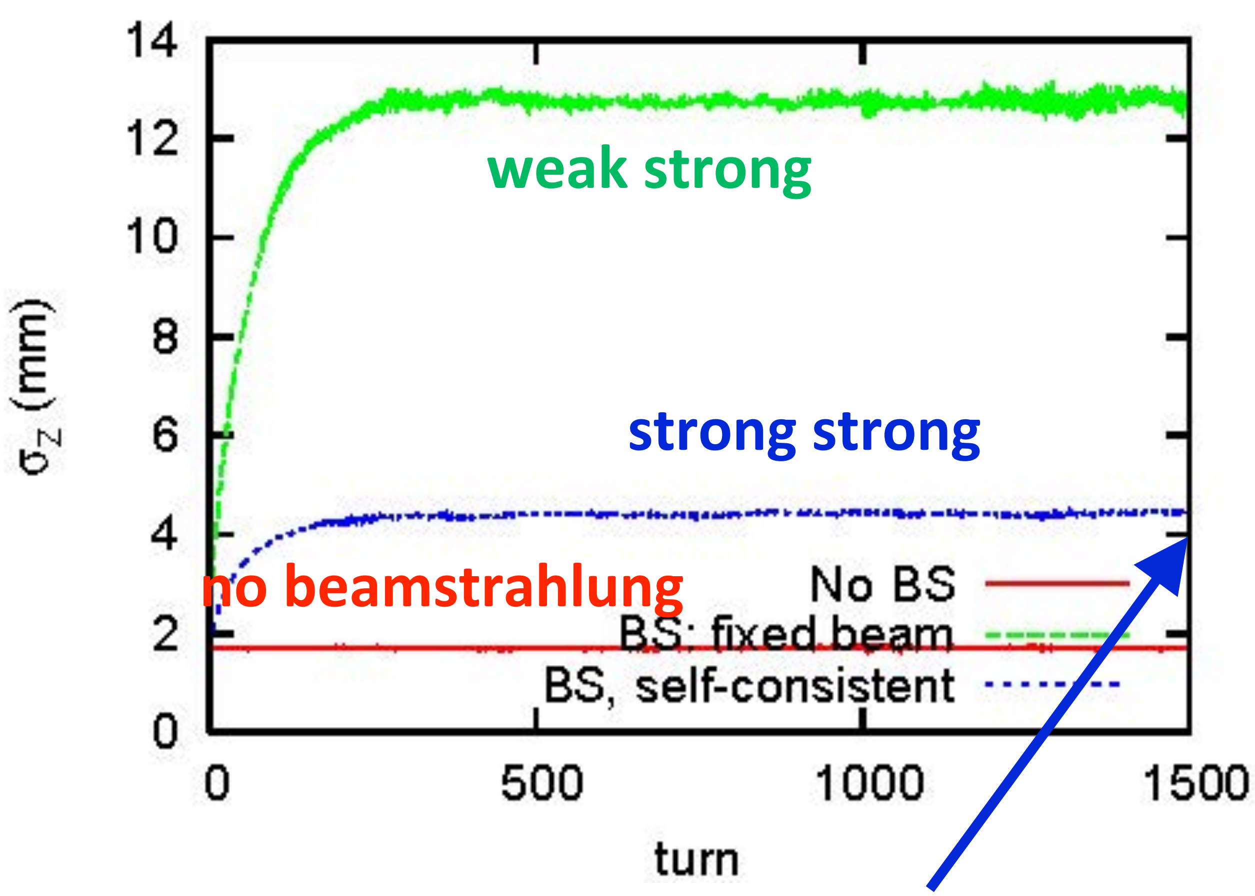
beamstrahlung in circular collider much weaker than for LC

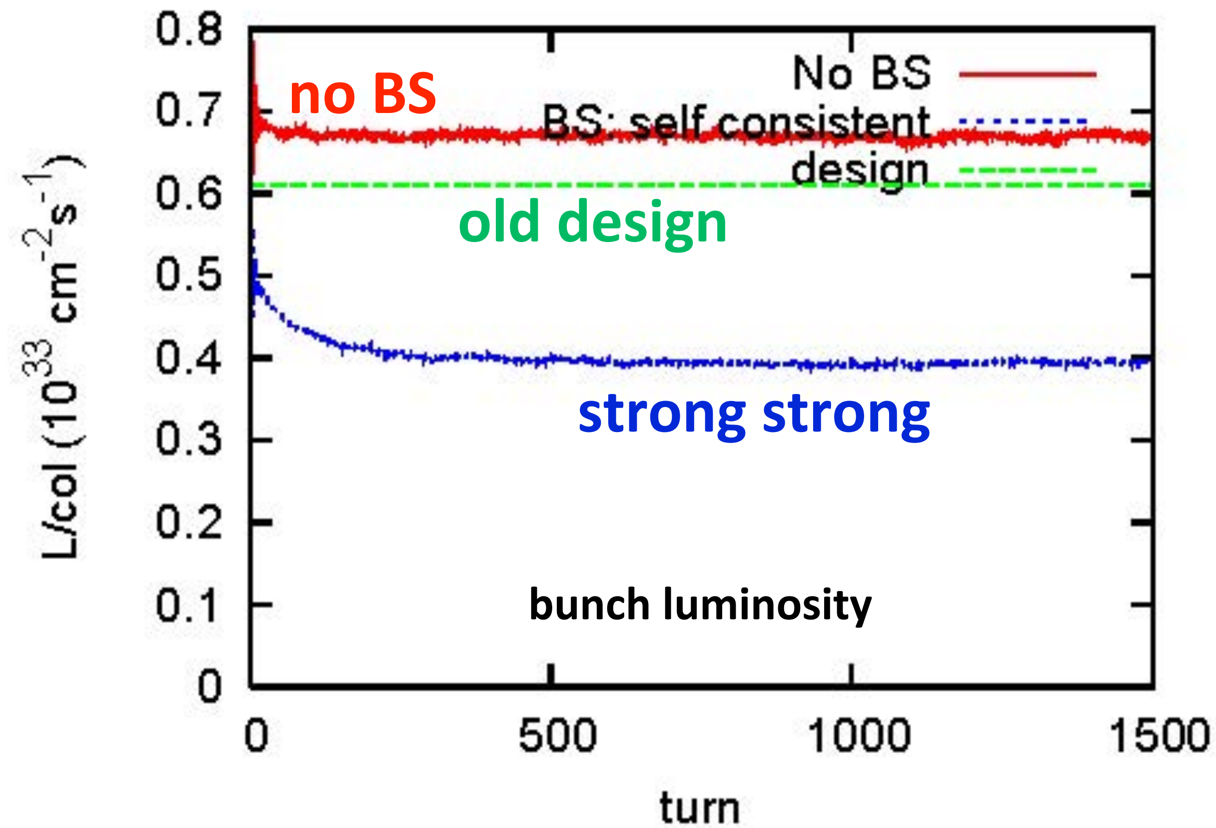
beamstrahlung: equilibrium σ_z

beamstrahlung excites (surviving) $e^{\pm}$ longitudinally, adding to effect of SR quantum excitation

→ **collisions increase σ_z & σ_δ** (K. Yokoya)

1st ever strong-strong beam-beam simulations with BS (K. Ohmi, KEK):





final bunch length from simulation consistent w analytical expectation including BS: σ_z=4.3 mm! (→ updated TLEP parameters)

$$\sigma_{\delta,tot}^2 - \sigma_{\delta,SR}^2 = \left(\frac{\sigma_{\delta,SR}}{\sigma_{\delta,tot}} \Delta\sigma_{\delta,BS,0}\right)^2$$

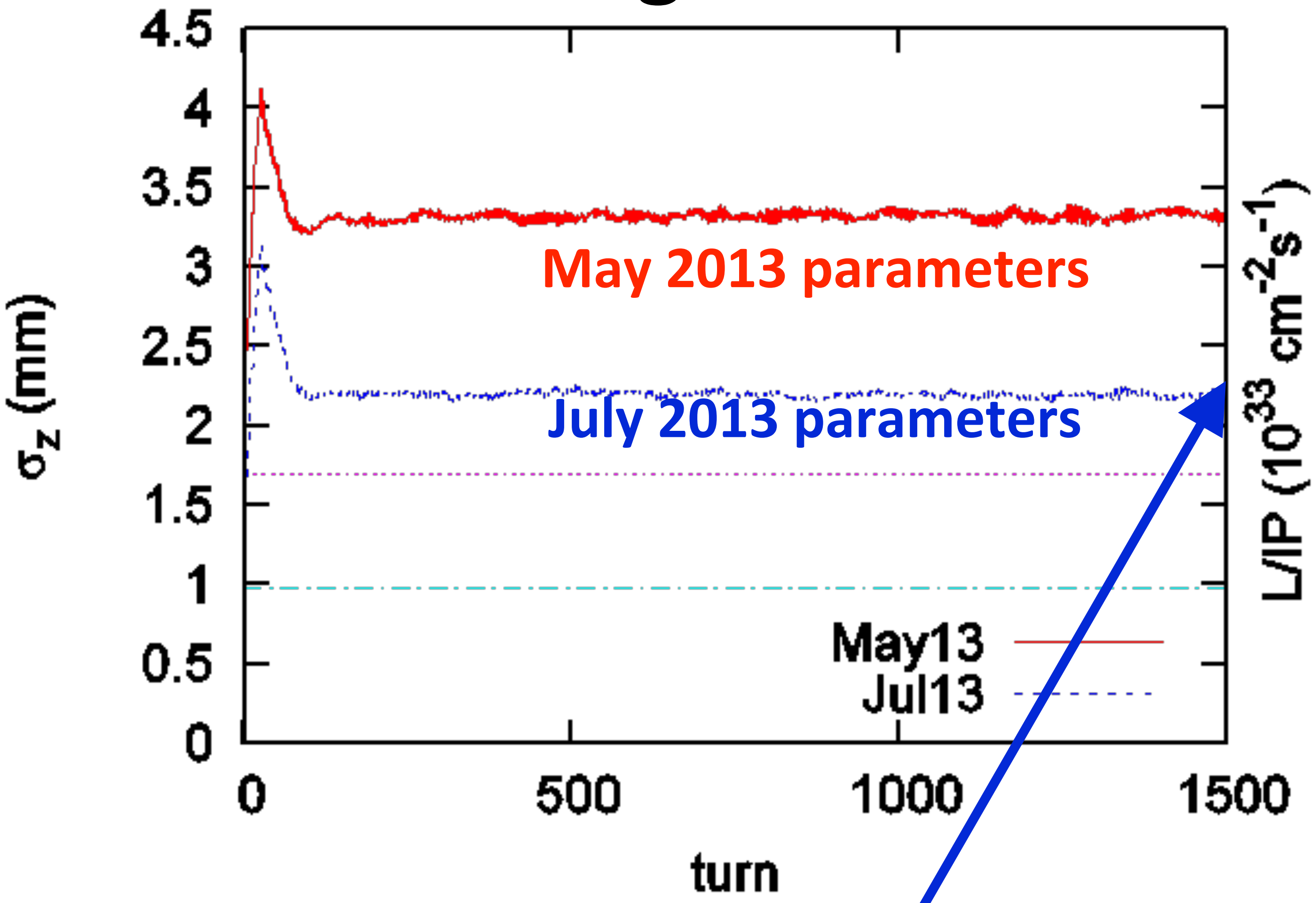
$$\sigma_{z,tot} = \sigma_{\delta,tot}\frac{\sigma_{z,SR}}{\sigma_{\delta,SR}}$$

nonlinear equation

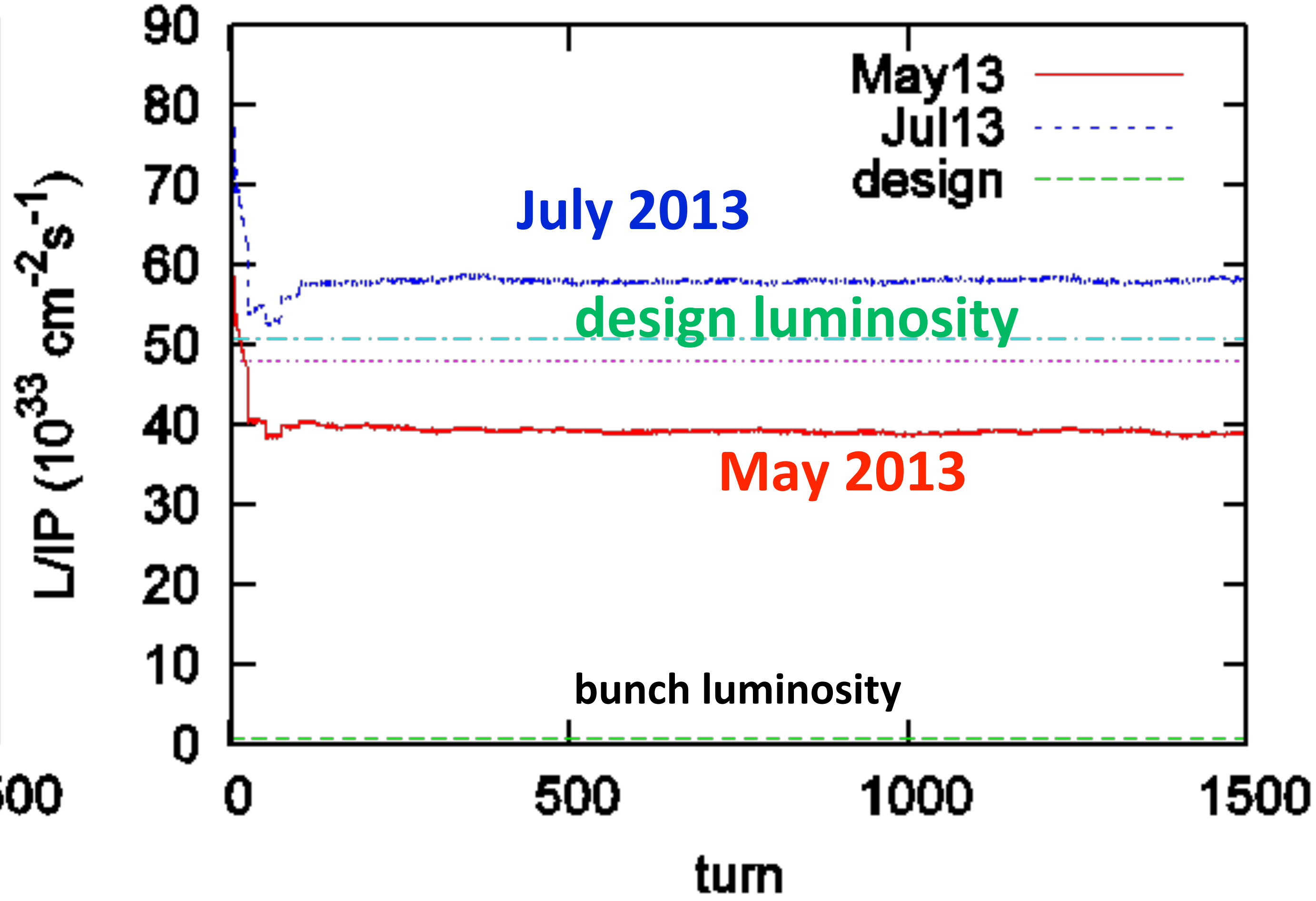
luminosity with beamstrahlung

TLEP-H simulations for latest parameters

rms bunch length



total luminosity / IP

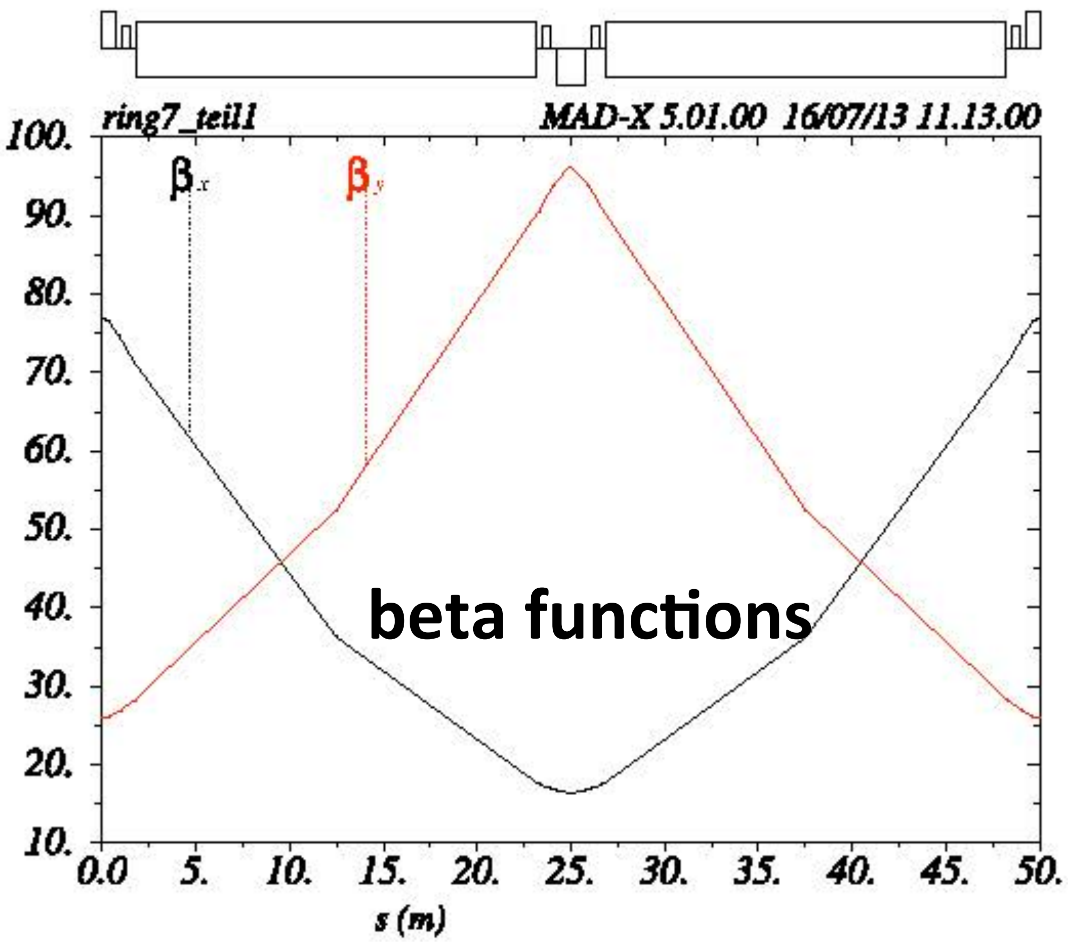


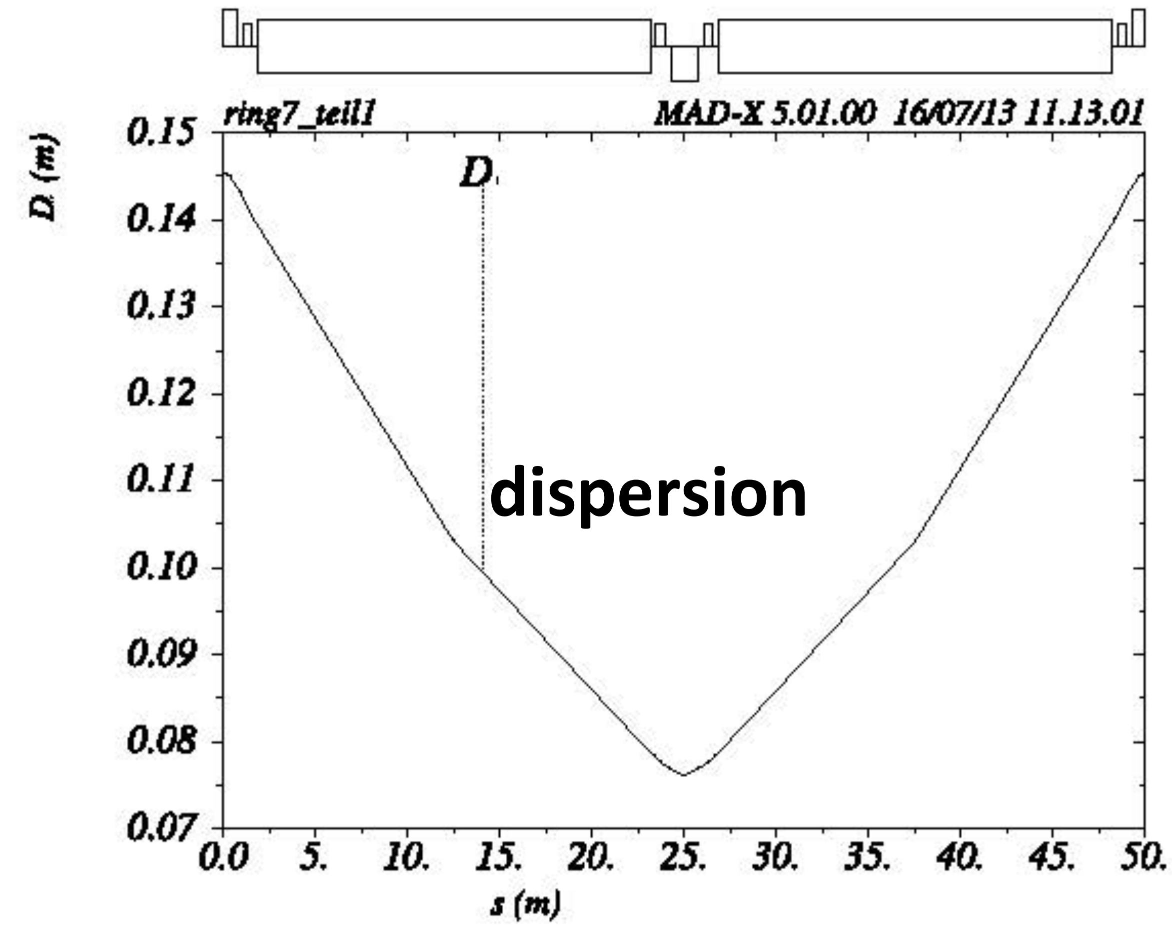
final bunch length from simulation consistent w analytical expectation including BS: σ_z=2.1 mm! (July 2013 parameters)

K. Ohmi, 17 July 2013

optics – TLEP arc cell

Y. Cai,
B. Holzer,
H. Burkhardt





from LEP to TLEP

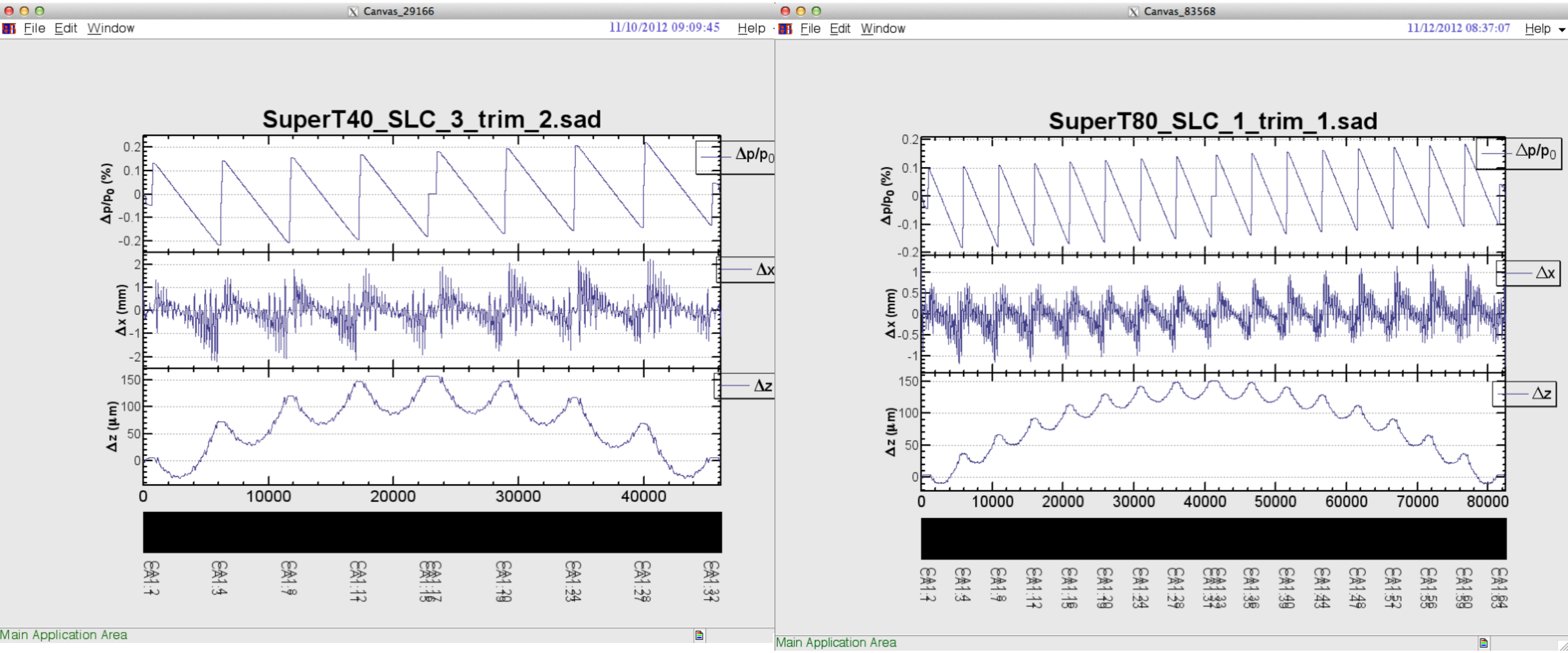
ρ=3100 m, L_{cell}=79 m → ρ=9100 m, L_{cell}=50 m

ε_x=48 nm at 104.5 GeV → ε_x=1.5 nm at 175 GeV

$\varepsilon \propto \gamma^2 \theta^3$: at lower beam energy increase cell length ("θ") x2 or x6!

optics - energy sawtooth

SuperTRISTAN

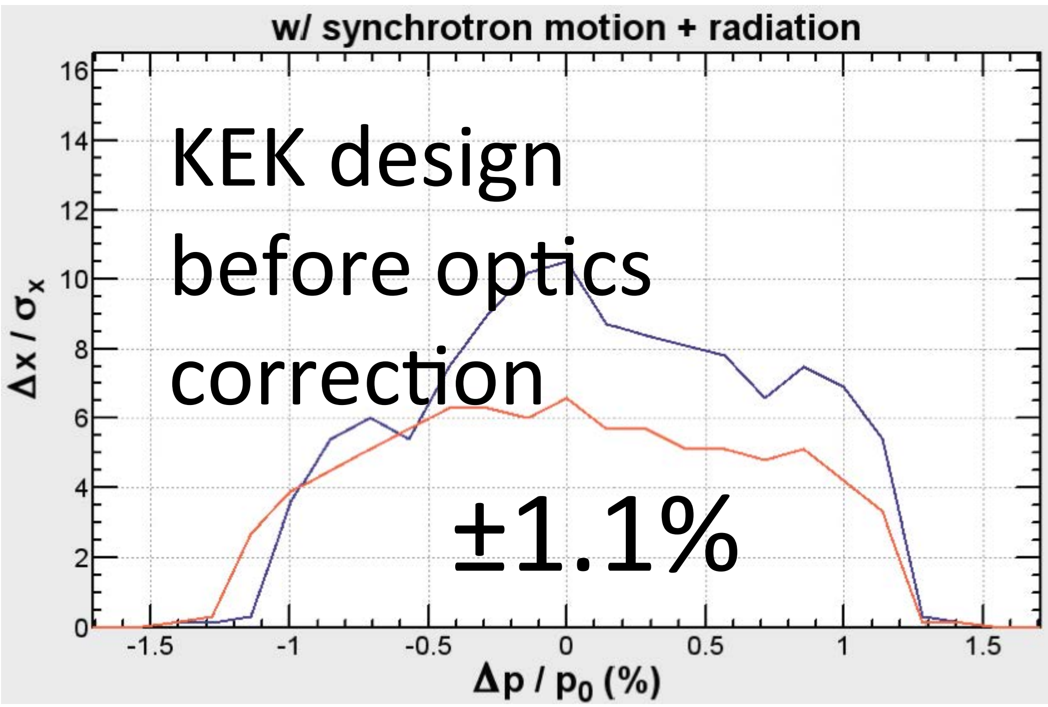


240 GeV, 40 km, 8 segments **350 GeV, 80 km, 16 segments**

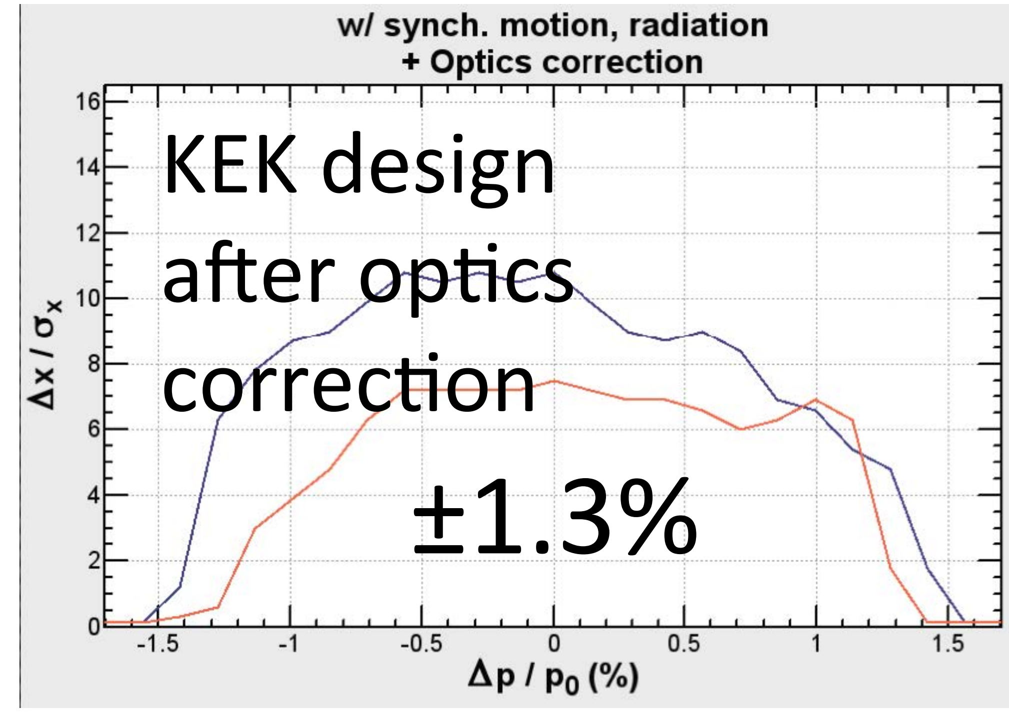
optics correction by shifting sextupoles onto sawtooth orbit

→ separate arcs/rings for e^+ and e^-

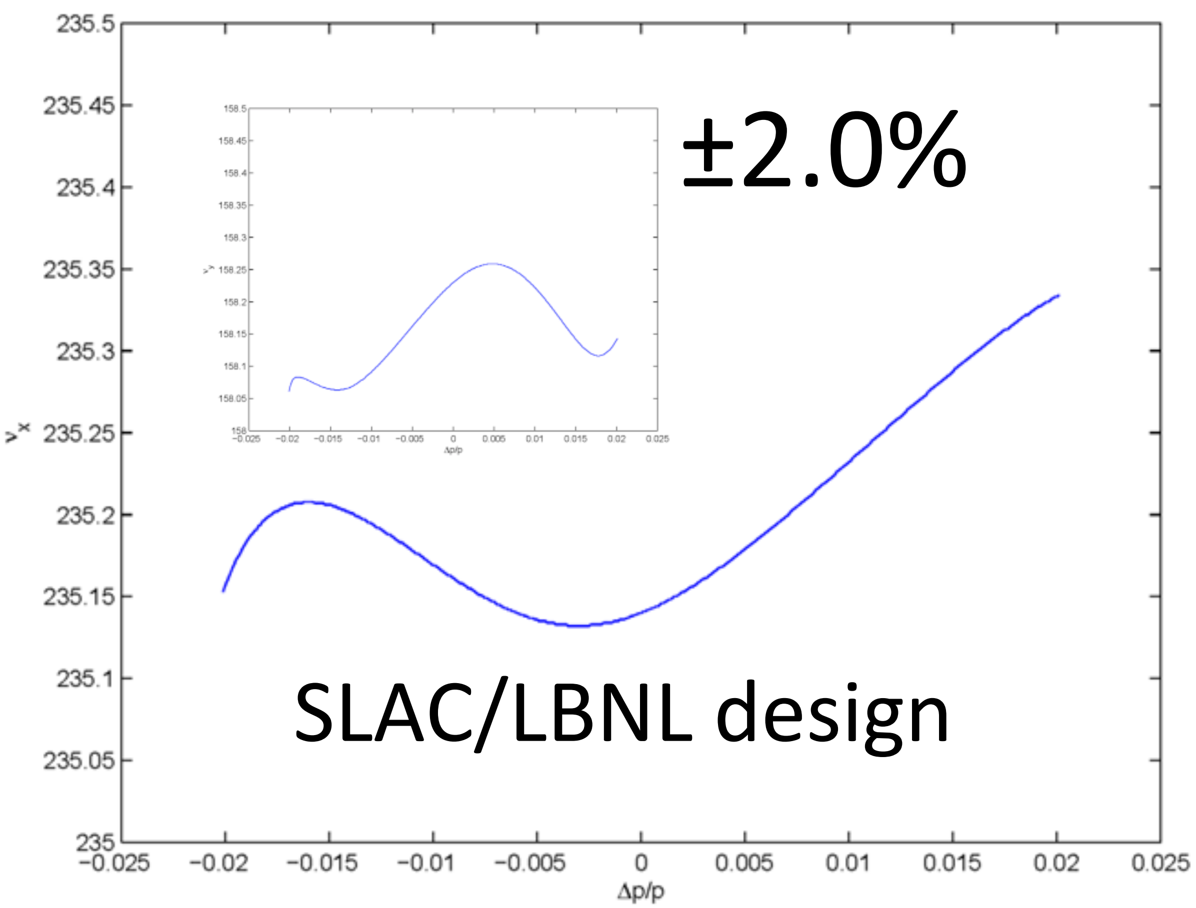
IR optics - momentum acceptance η

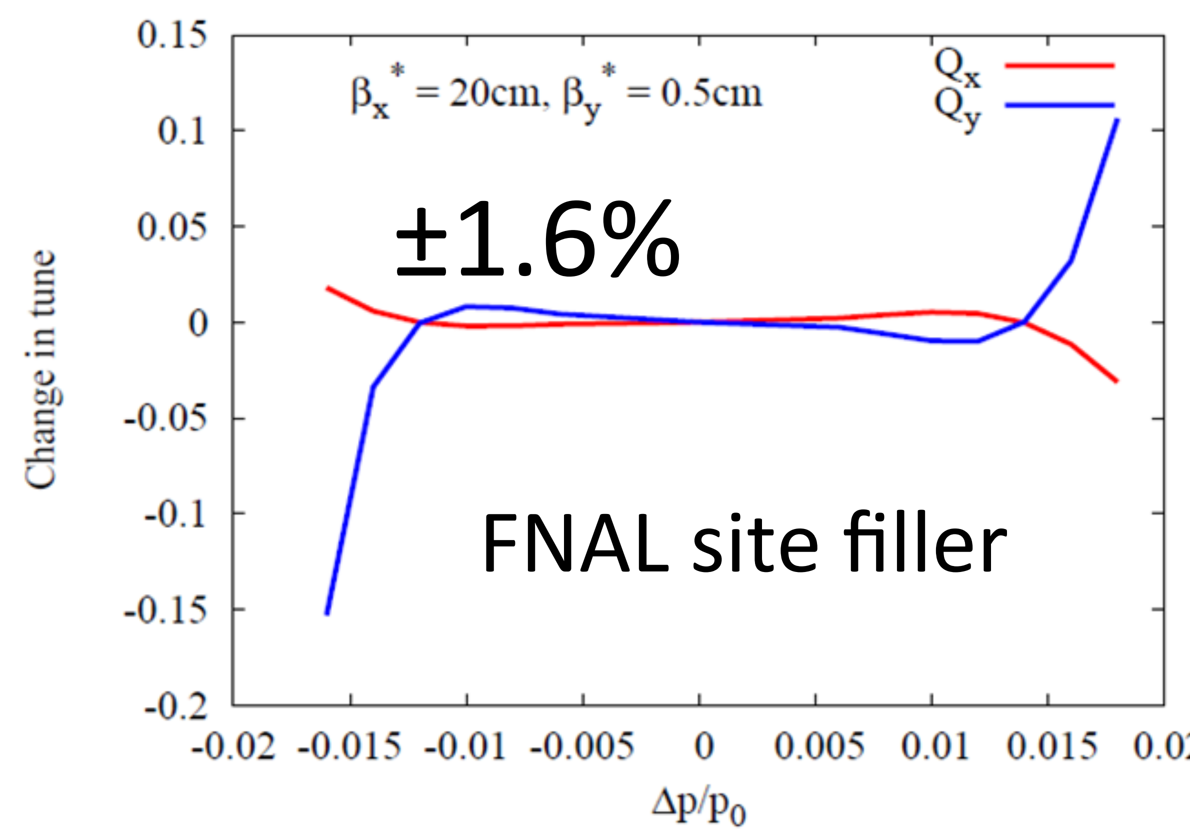


with synchrotron motion & radiation (sawtooth)



K. Oide



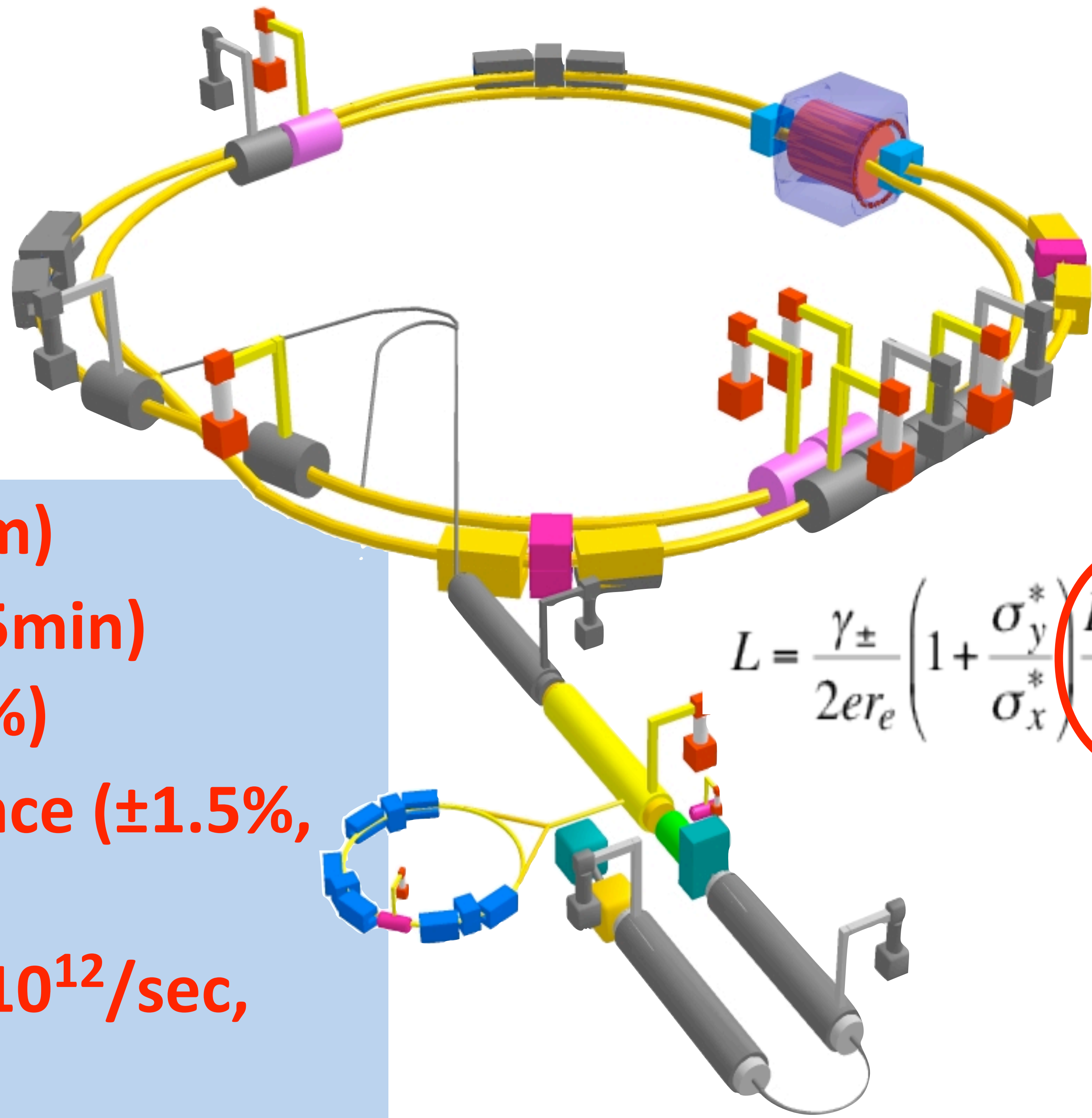


Y. Cai

T. Sen, E. Gianfelice-Wendt, Y. Alexahin

SuperKEKB – a TLEP demonstrator

beam commissioning
will start in early 2015



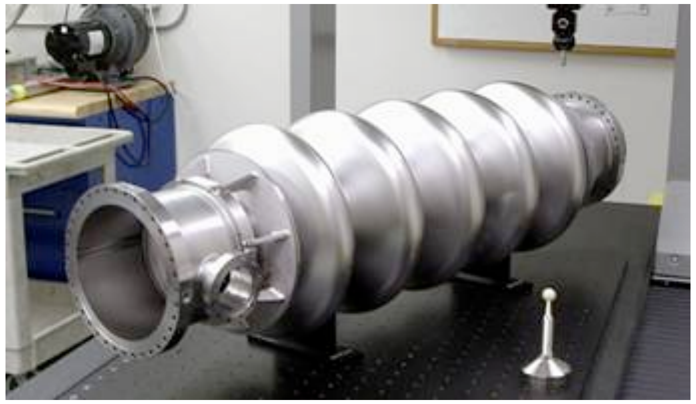
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

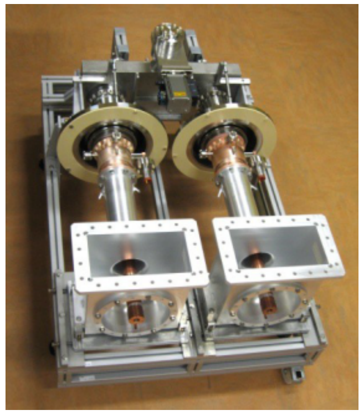
- **β_y*=300 μm (TLEP: 1 mm)**
- **lifetime 5 min (TLEP: ~15min)**
- **$\varepsilon_y/\varepsilon_x$=0.25% ! (TLEP: 0.2%)**
- **off momentum acceptance (±1.5%, TLEP: ±2.0%)**
- ***e^+* production rate ($2.5\text{x}10^{12}$/sec, TLEP < $1\text{x}10^{11}$/sec)**

other TLEP challenges

- **efficient RF system**
  - need 12 GeV/turn at 350 GeV
    - **~600 m of SC RF cavities @ 20 MV/m**
      - **LEP2 had 600 m at 7 MV/m**
  - very high power : up to 200 kW / cavity in collider ring
    - **power couplers similar to ESS** – 700-800 MHz preferred

BNL 5-cell 700 MHz cavity



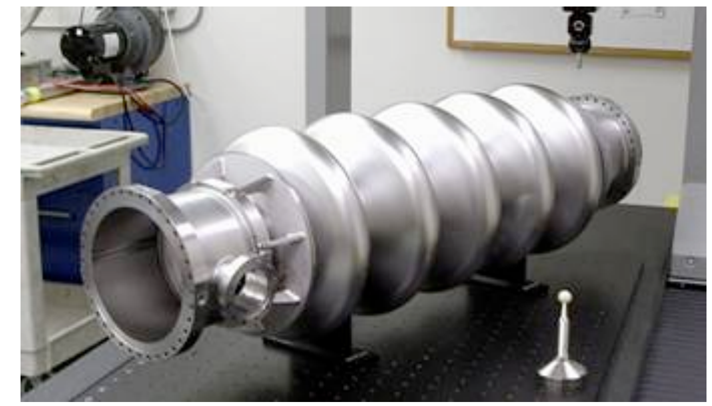


RF Coupler (ESS/SPL)

- **operation at *Z* pole**
  - 7500 bunches : e^+ source, impedance effects, parasitic collisions
    - **two separate rings for e^+ and e^- beams will help here too**

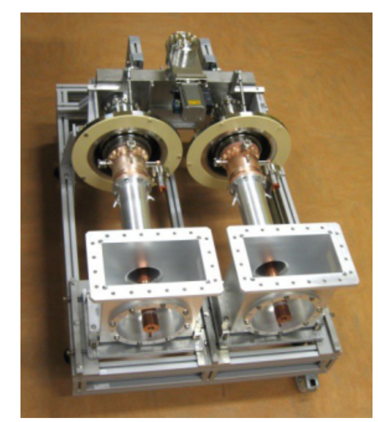
other TLEP challenges

BNL 5-cell 700 MHz cavity



- **efficient RF system**
  - need 12 GeV/turn at 350 GeV
    - **~600 m of SC RF cavities @ 20 MV/m**
      - **LEP2 had 600 m at 7 MV/m**
  - very high power : up to 200 kW / cavity in collider ring
    - **power couplers similar to ESS** –

      700-800 MHz preferred



RF Coupler (ESS/SPL)

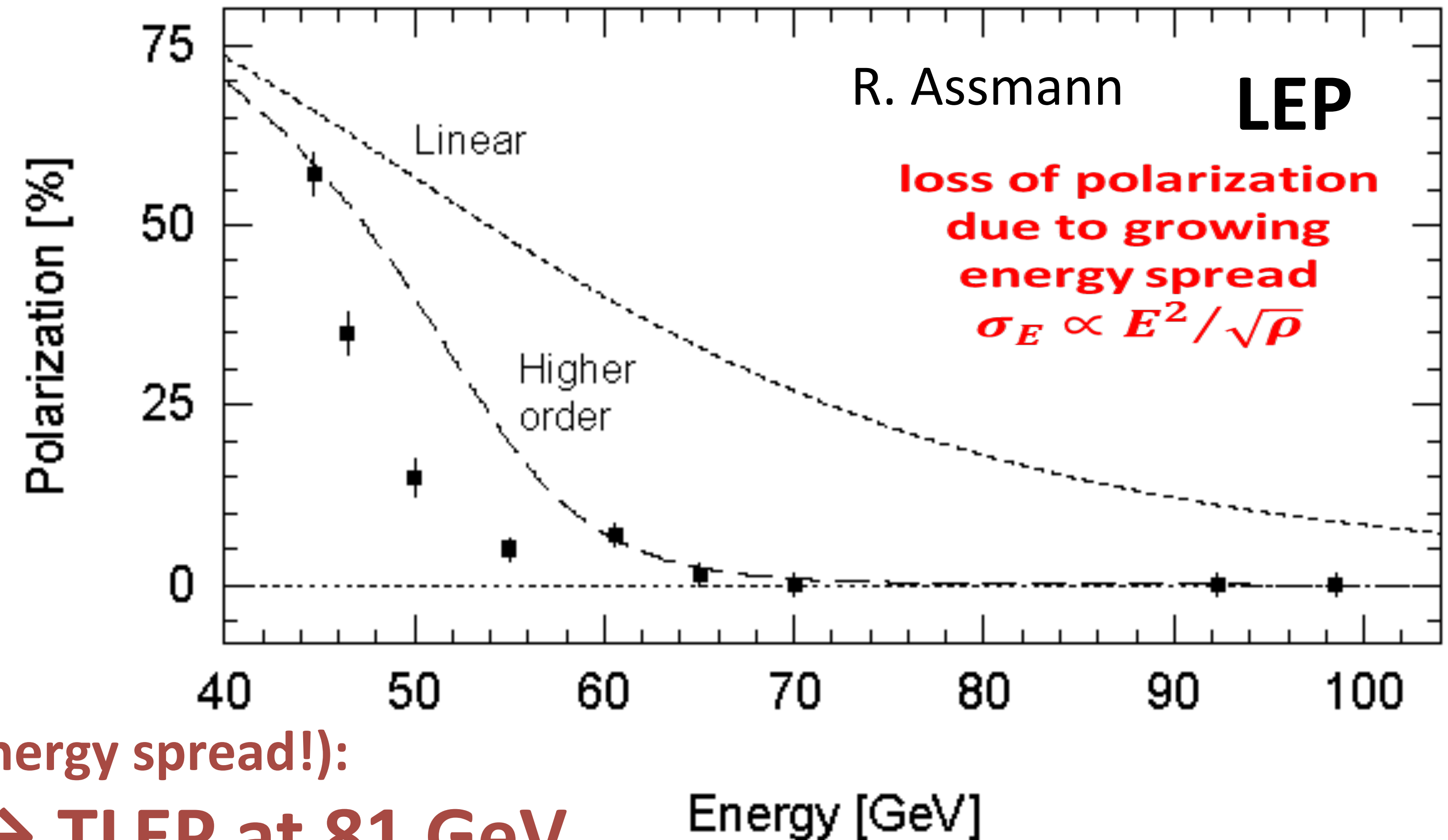
- **operation at *Z* pole**
  - 7500 bunches : e^+ source, impedance effects, parasitic collisions
    - **two separate rings for e^+ and e^- beams will help here too**

polarization

LEP

observations

+ model predictions



polarization scaling (energy spread!):

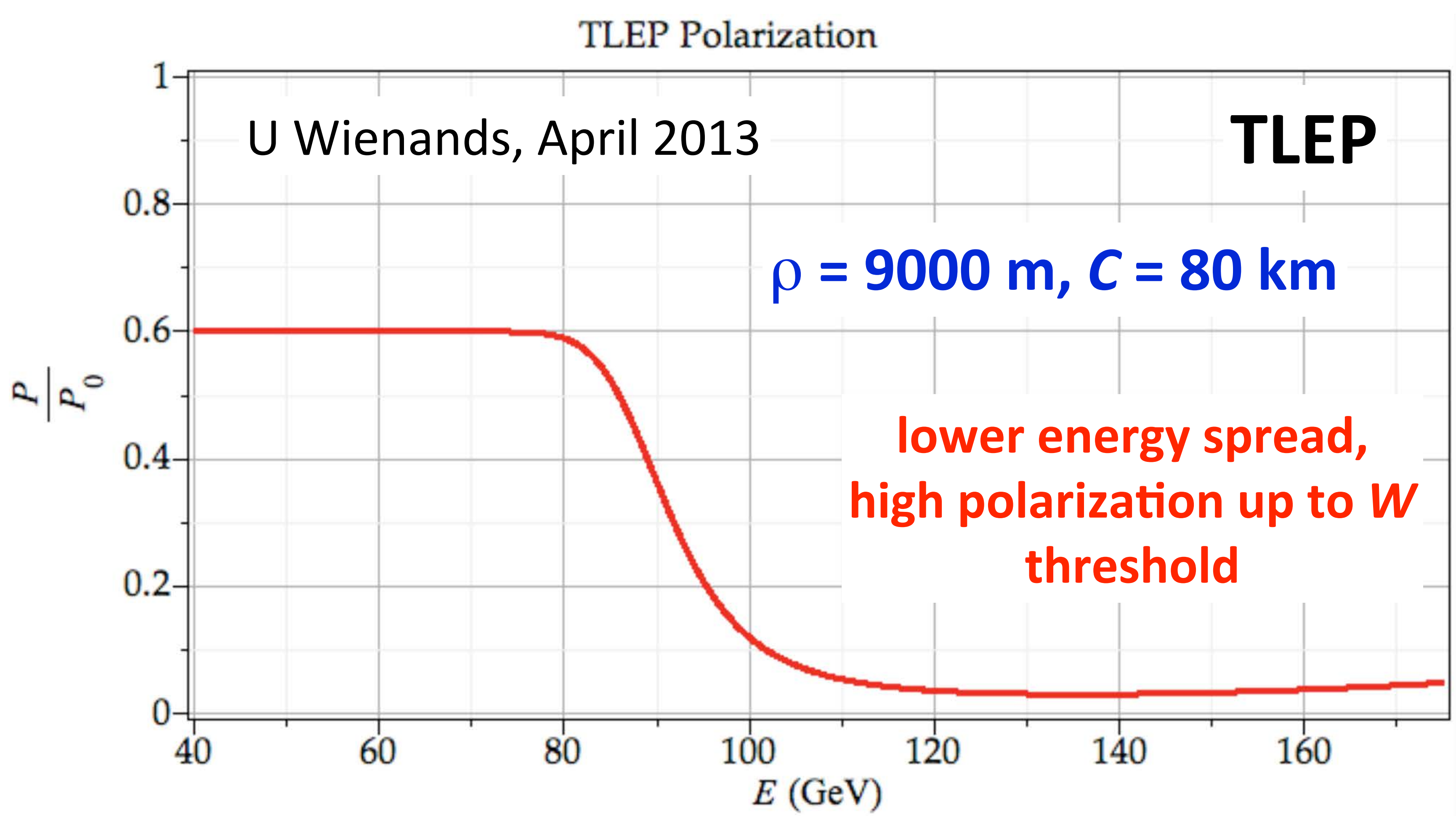
LEP at 61 GeV → TLEP at 81 GeV

TLEP

optimized scenario

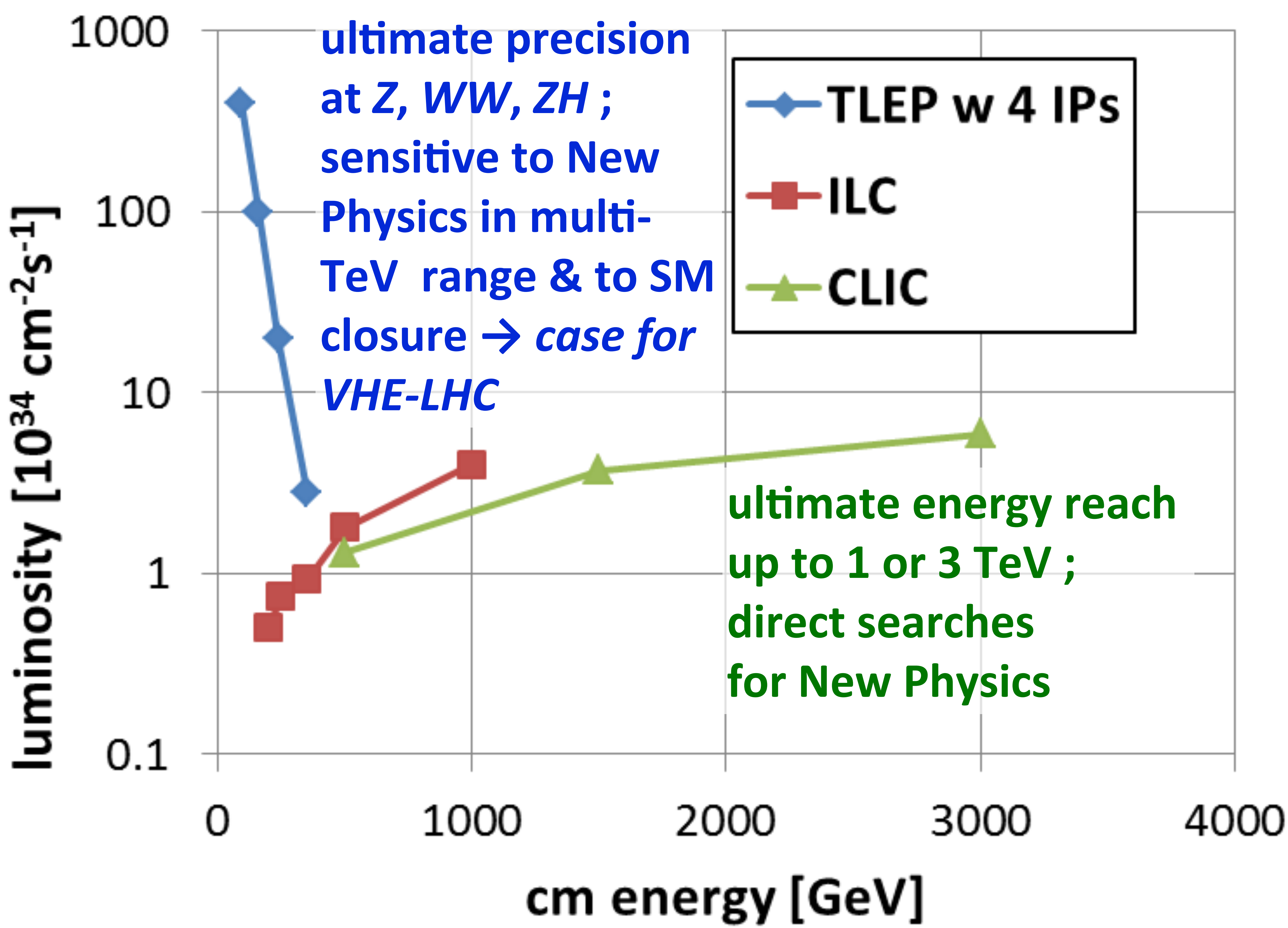
➔ **[100 keV beam energy calibration] by resonant depolarization (using pilot bunches) around *Z* peak and *W* pair threshold:**

Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV



A. Blondel

e^+e^- Higgs factories: luminosity



vertical rms IP spot sizes in nm

in regular font: achieved

in italics: design values

LEP2	3500
KEKB	940
SLC	500
TLEP-H	***120***
ATF2, FFTB	60 (*35*), 60(40)
SuperKEKB	***50***
ILC	*5 – 8*
CLIC	*1 – 2*

β_y^*: **5 cm→ 1 mm**

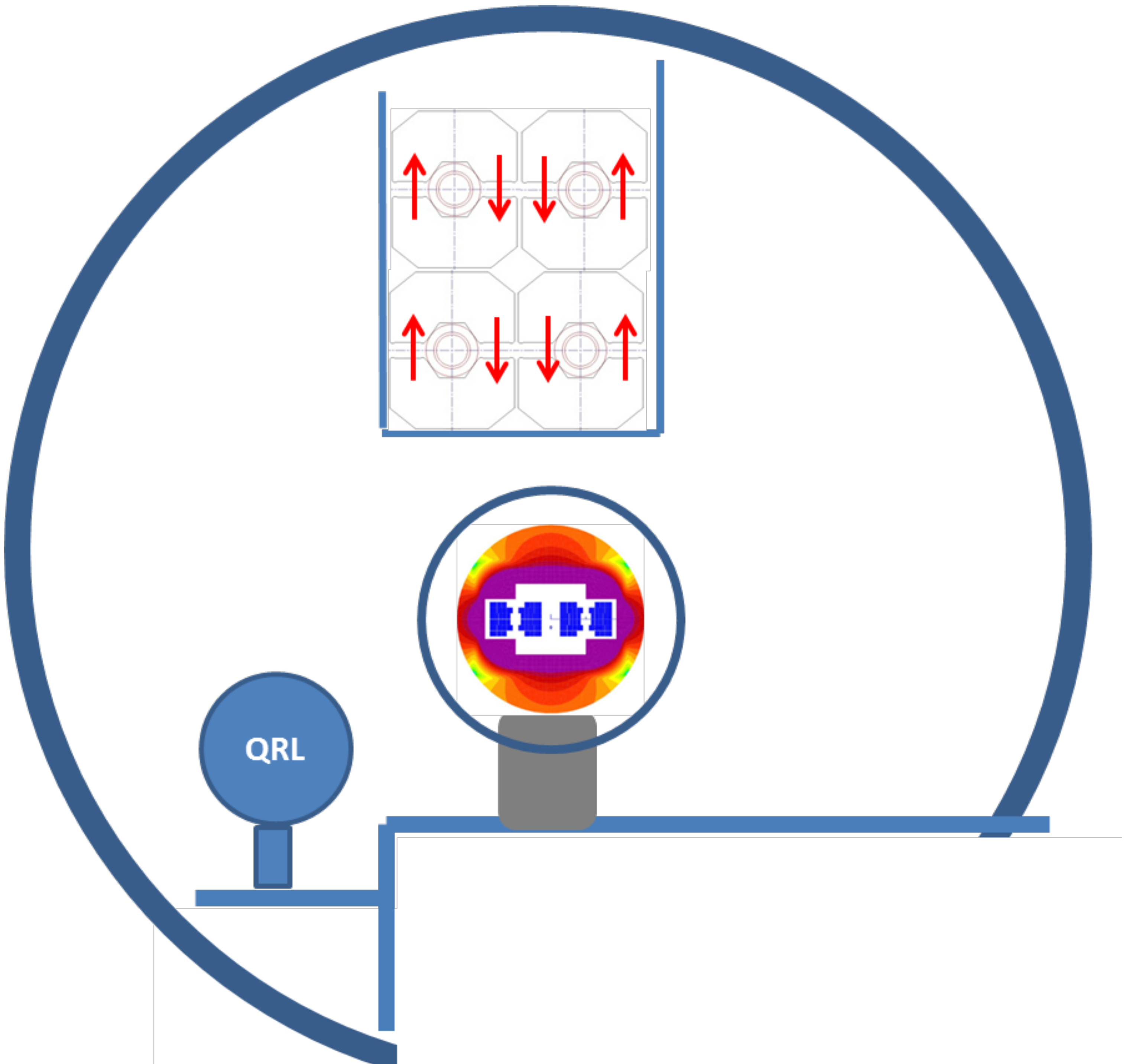
TLEP will learn from ATF2 & SuperKEKB

VHE-LHC + TLEP

L. Rossi

VHE-LHC + TLEP

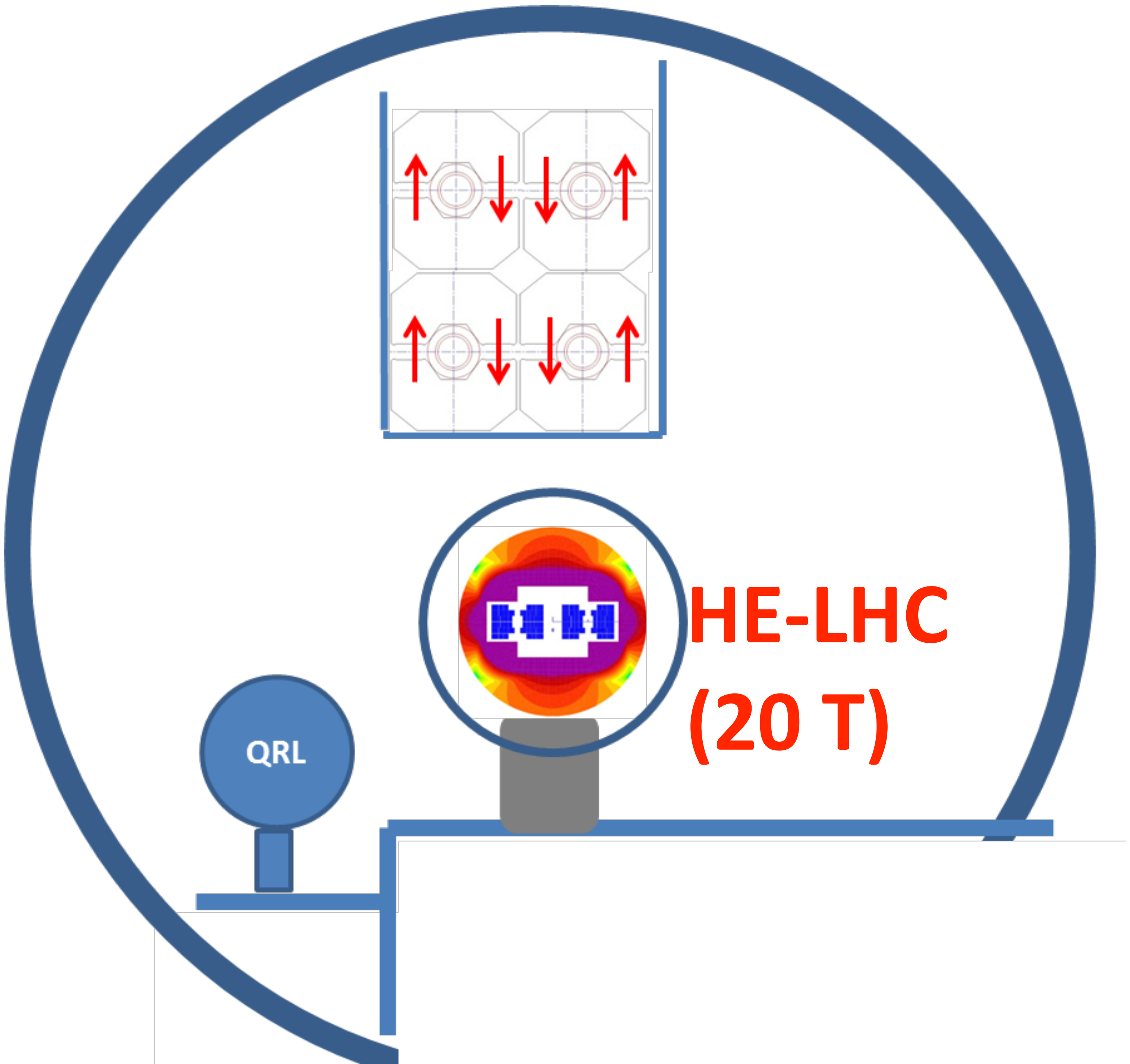
L. Rossi



multipurpose tunnel

VHE-LHC + TLEP

L. Rossi



multipurpose tunnel

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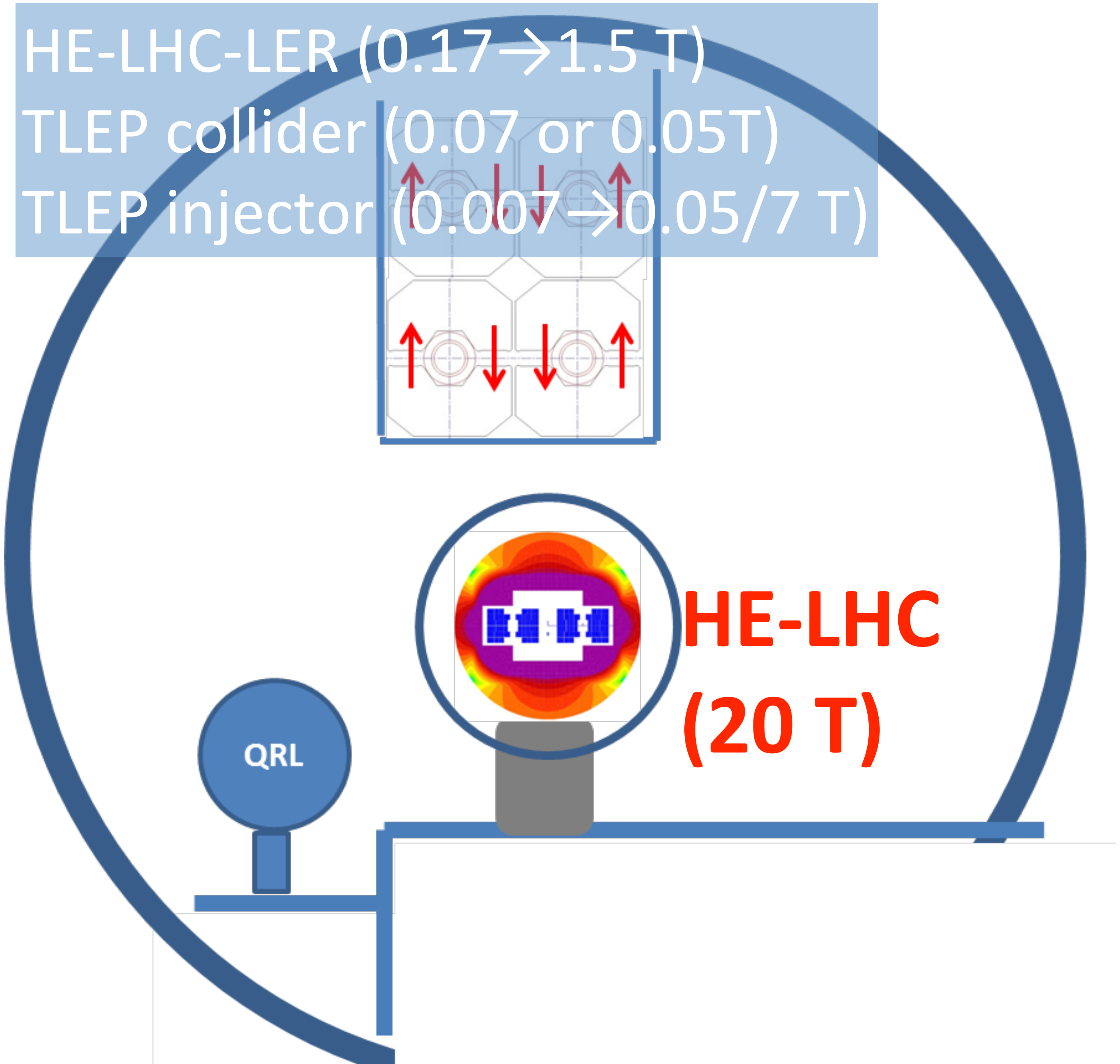
L. Rossi



multipurpose
tunnel

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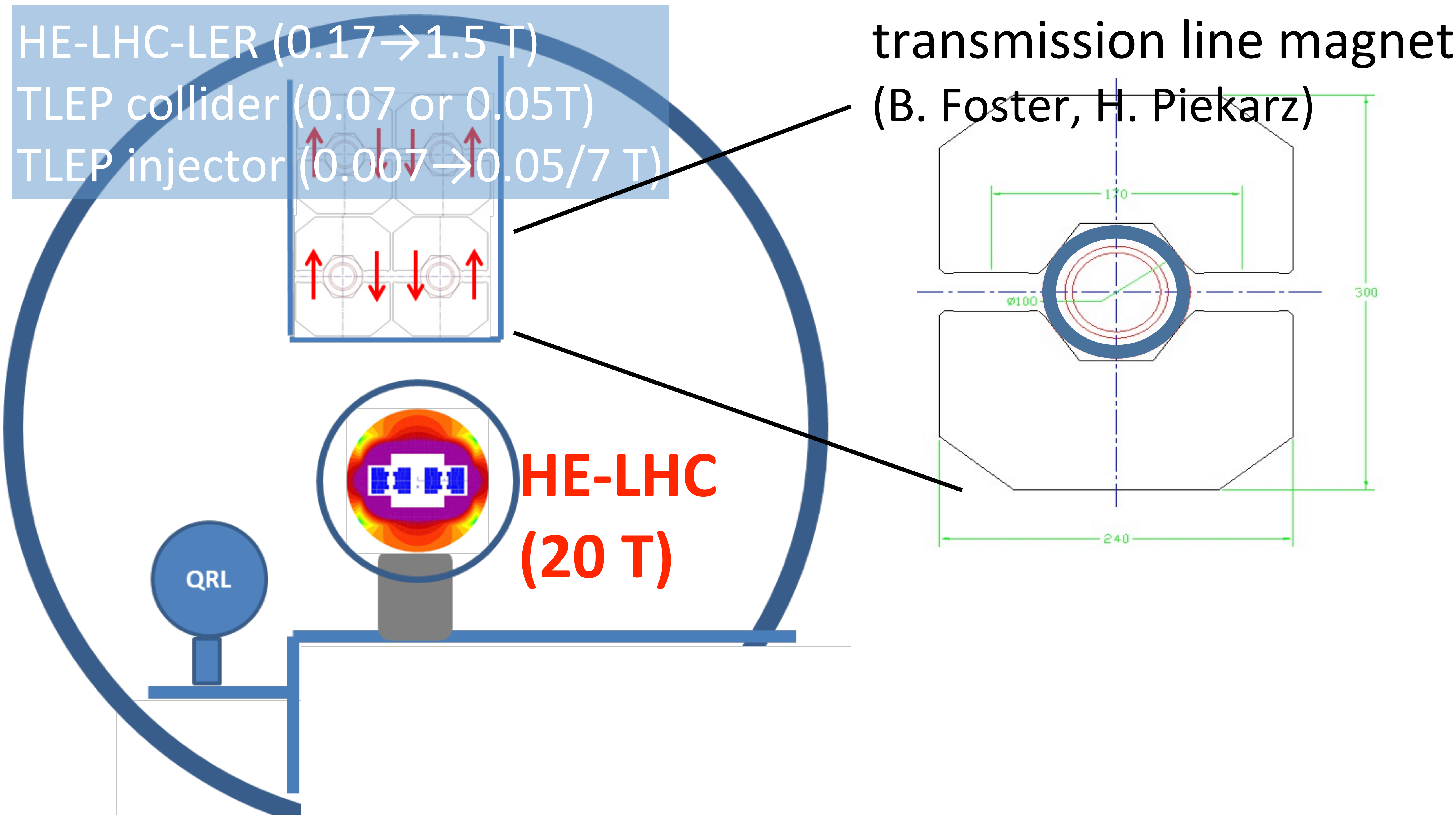

multipurpose
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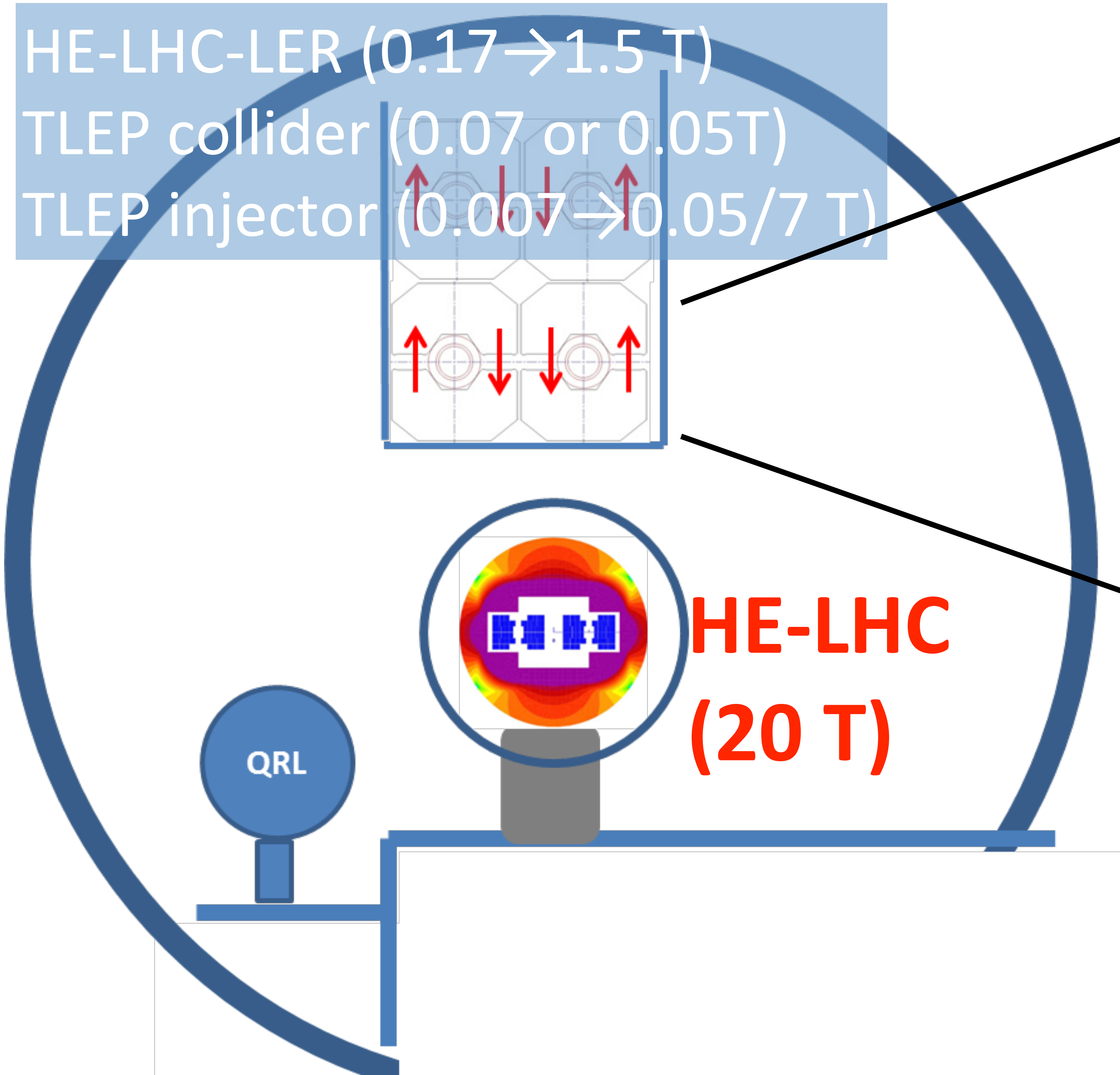
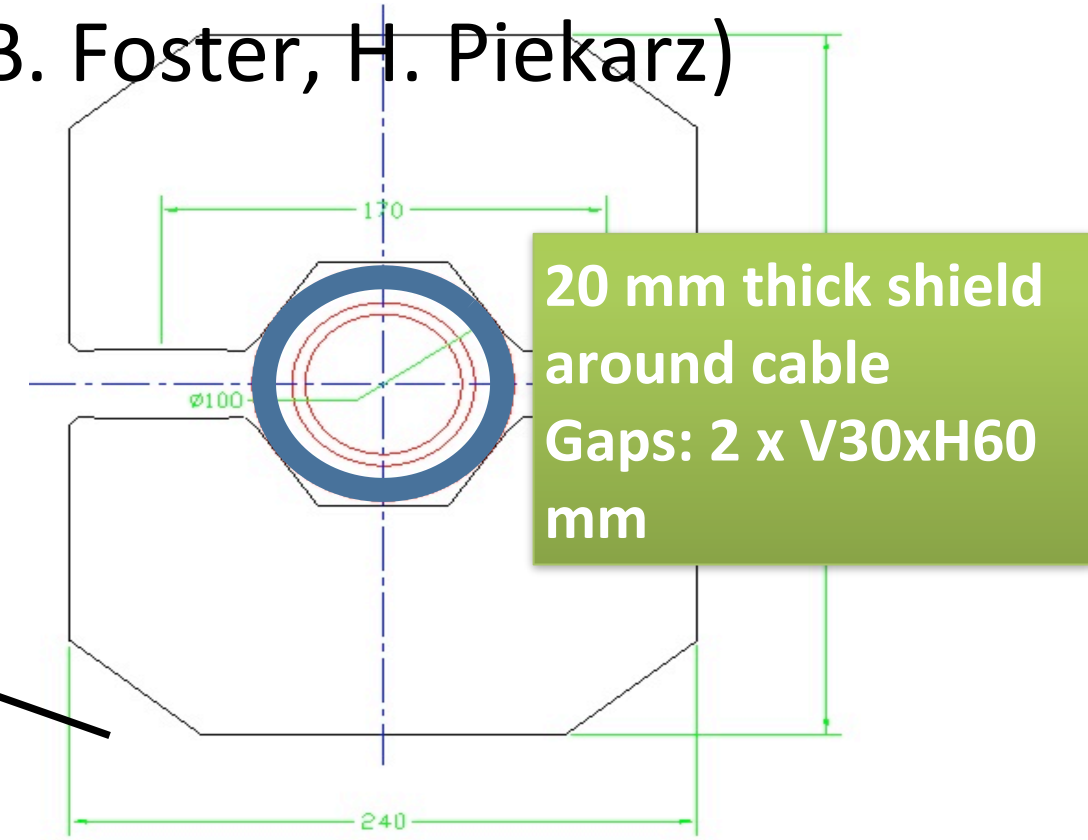


transmission line magnet
(B. Foster, H. Piekarz)



multipurpose tunnel

VHE-LHC + TLEP

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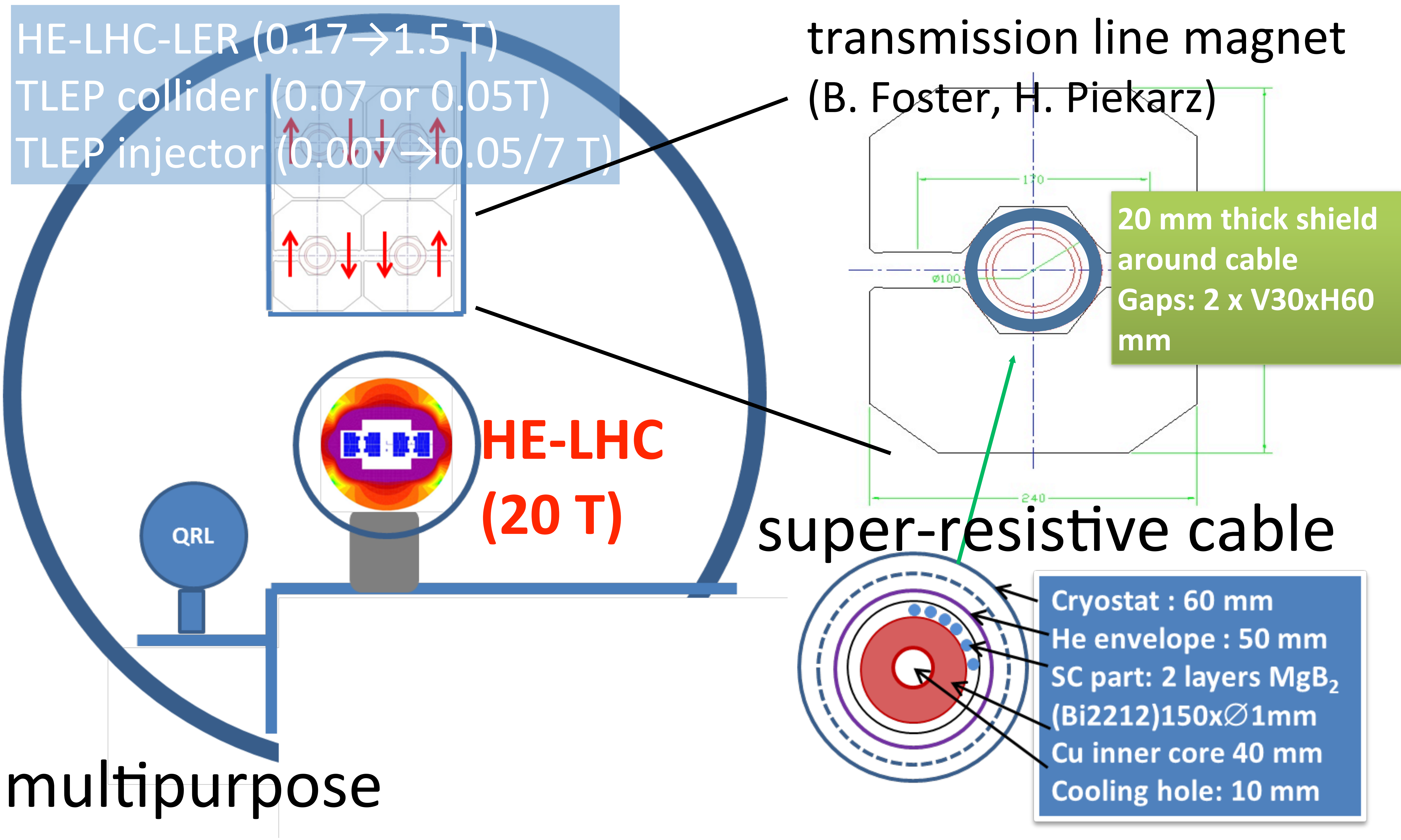

VHE-LHC + TLEP

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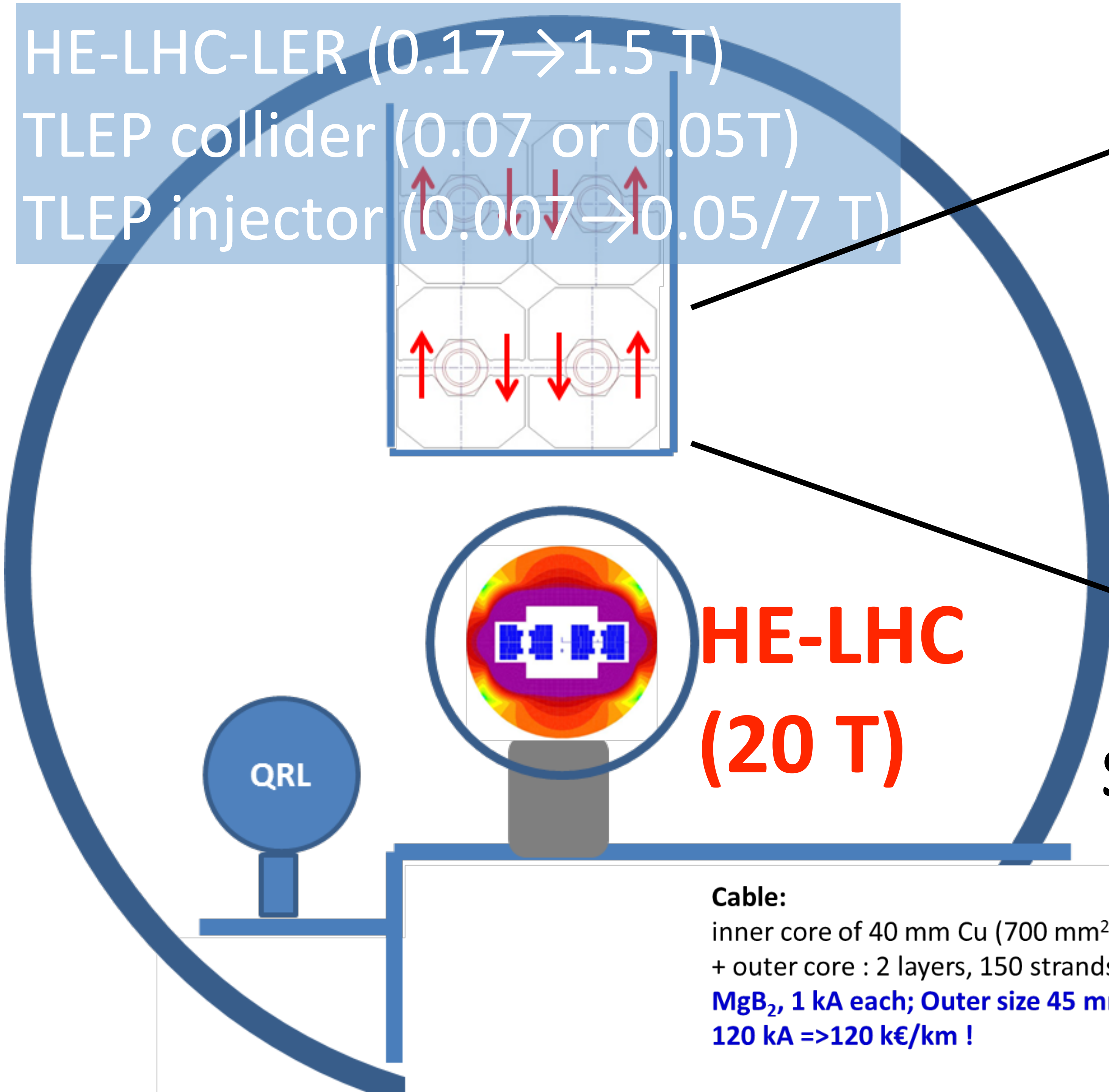

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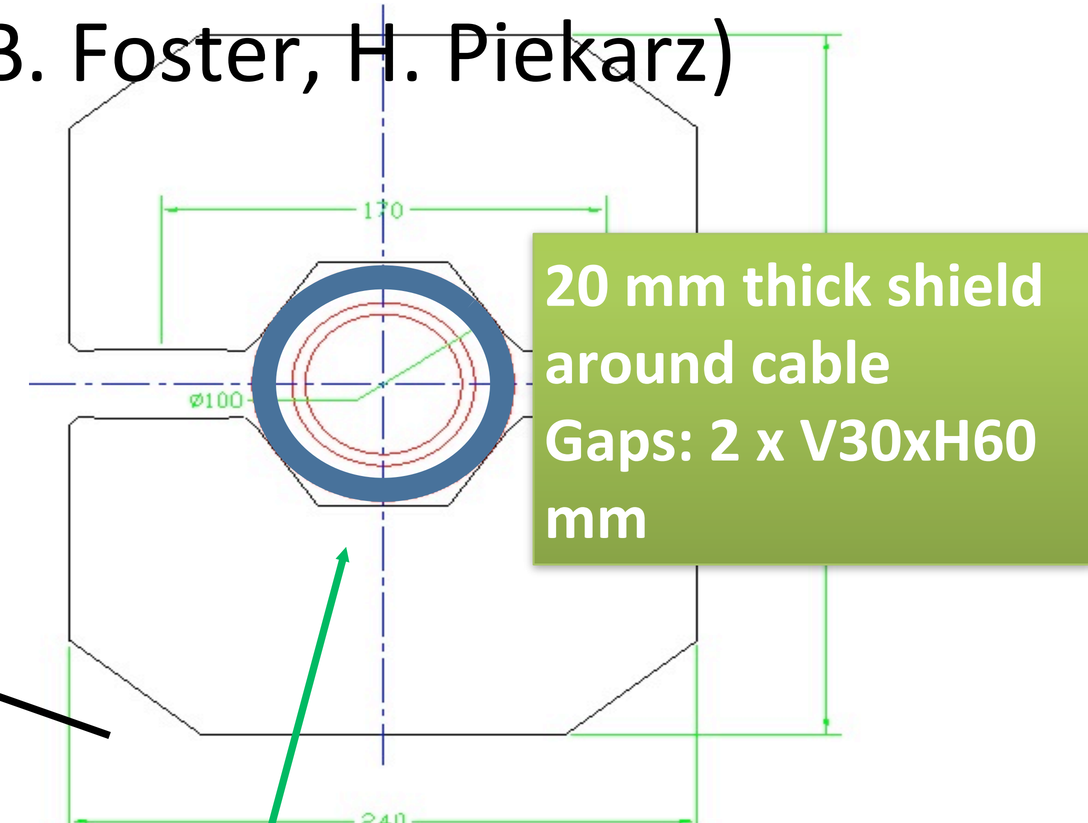
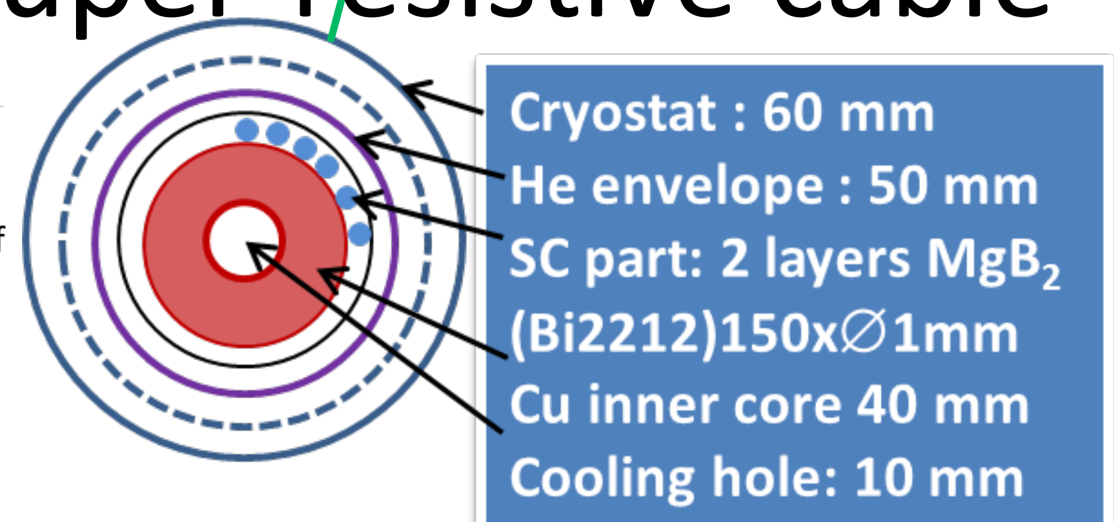


super-resistive cable



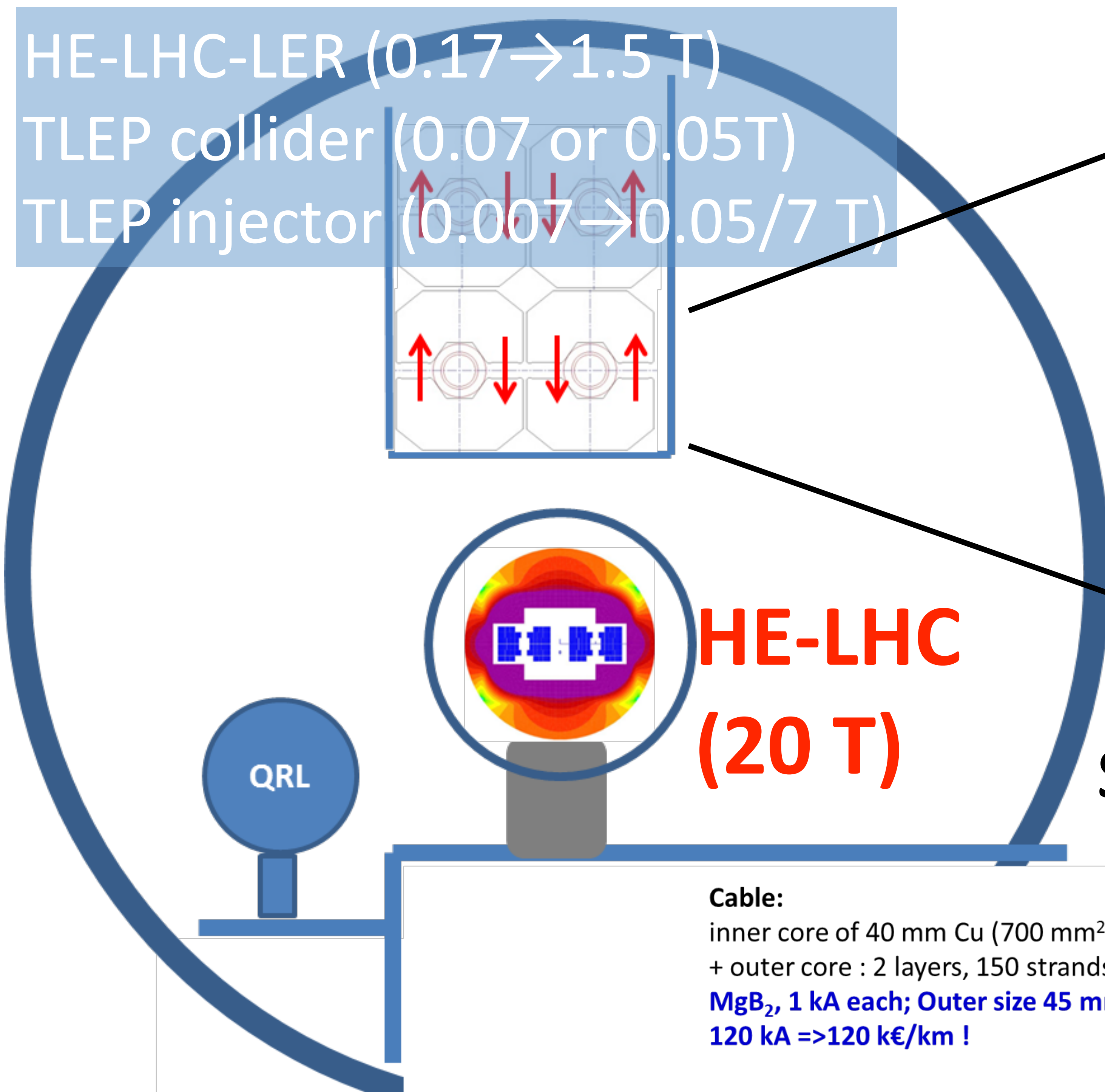
Cable:
inner core of 40 mm Cu (700 mm^2)
+ outer core : 2 layers, 150 strands of
MgB_2, 1 kA each; Outer size 45 mm.
120 kA =>120 k€/km !

For electrons: Cu water cooled,
J_{ov} 2.5 A/mm^2

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

VHE-LHC + TLEP

L. Rossi



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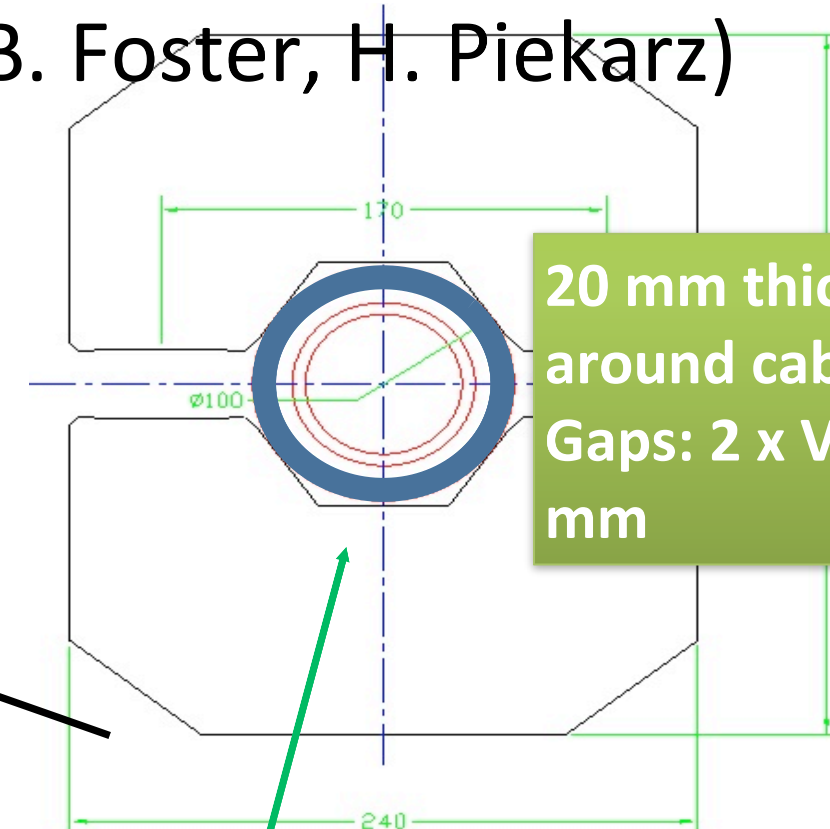
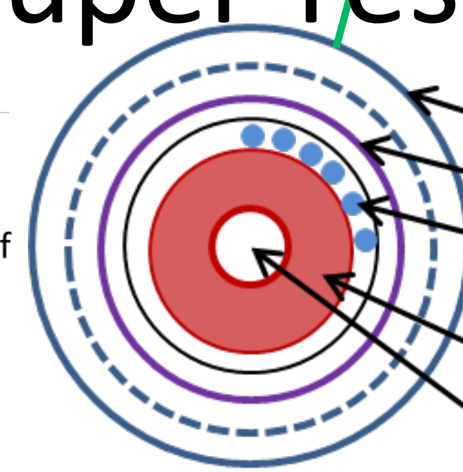


20 mm thick shield around cable Gaps: 2 x V30xH60 mm

super-resistive cable



Cryostat : 60 mm
He envelope : 50 mm
SC part: 2 layers MgB_2 (Bi2212)150x∅1mm
Cu inner core 40 mm
Cooling hole: 10 mm

Cable:
inner core of 40 mm Cu (700 mm^2)
+ outer core : 2 layers, 150 strands of
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120 kA =>120 k€/km !

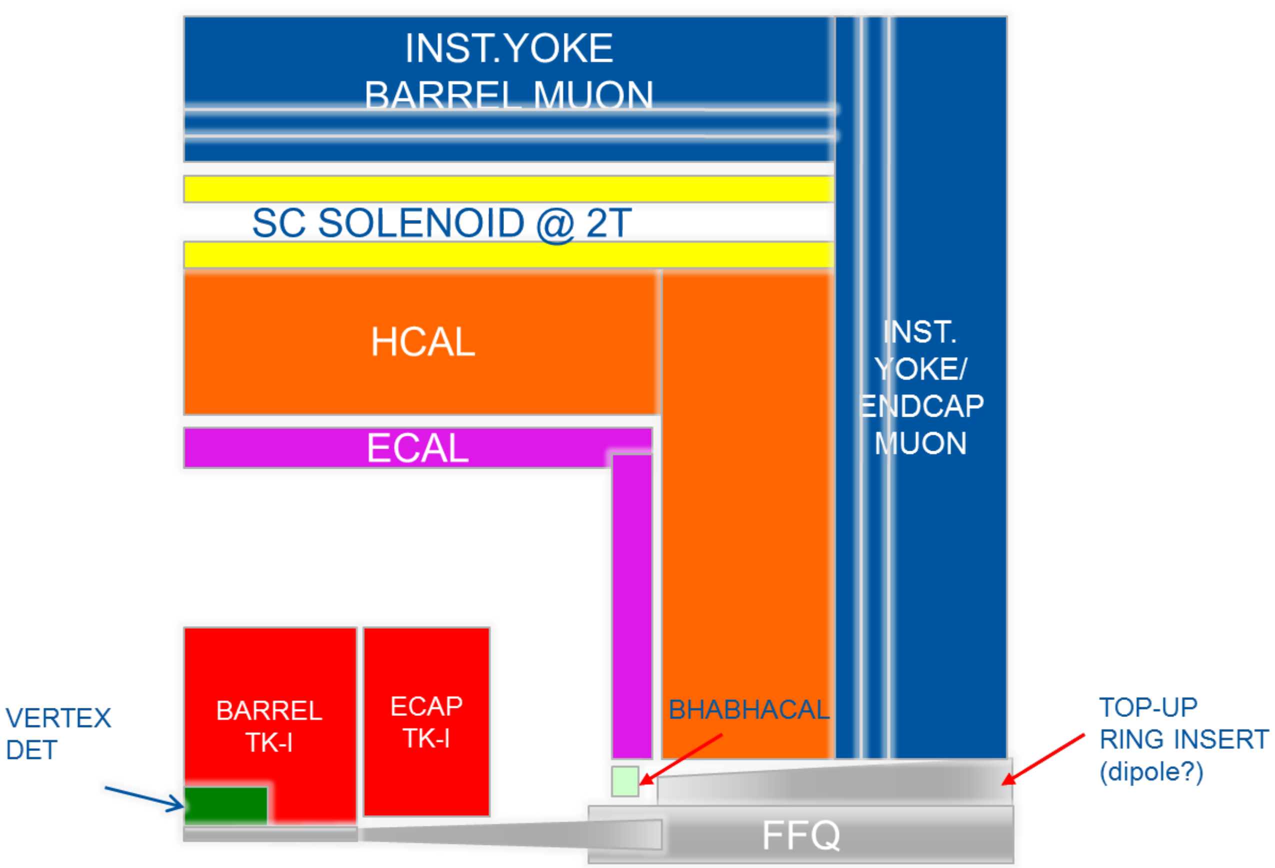
For electrons: Cu water cooled,
J_{ov} 2.5 A/mm^2

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

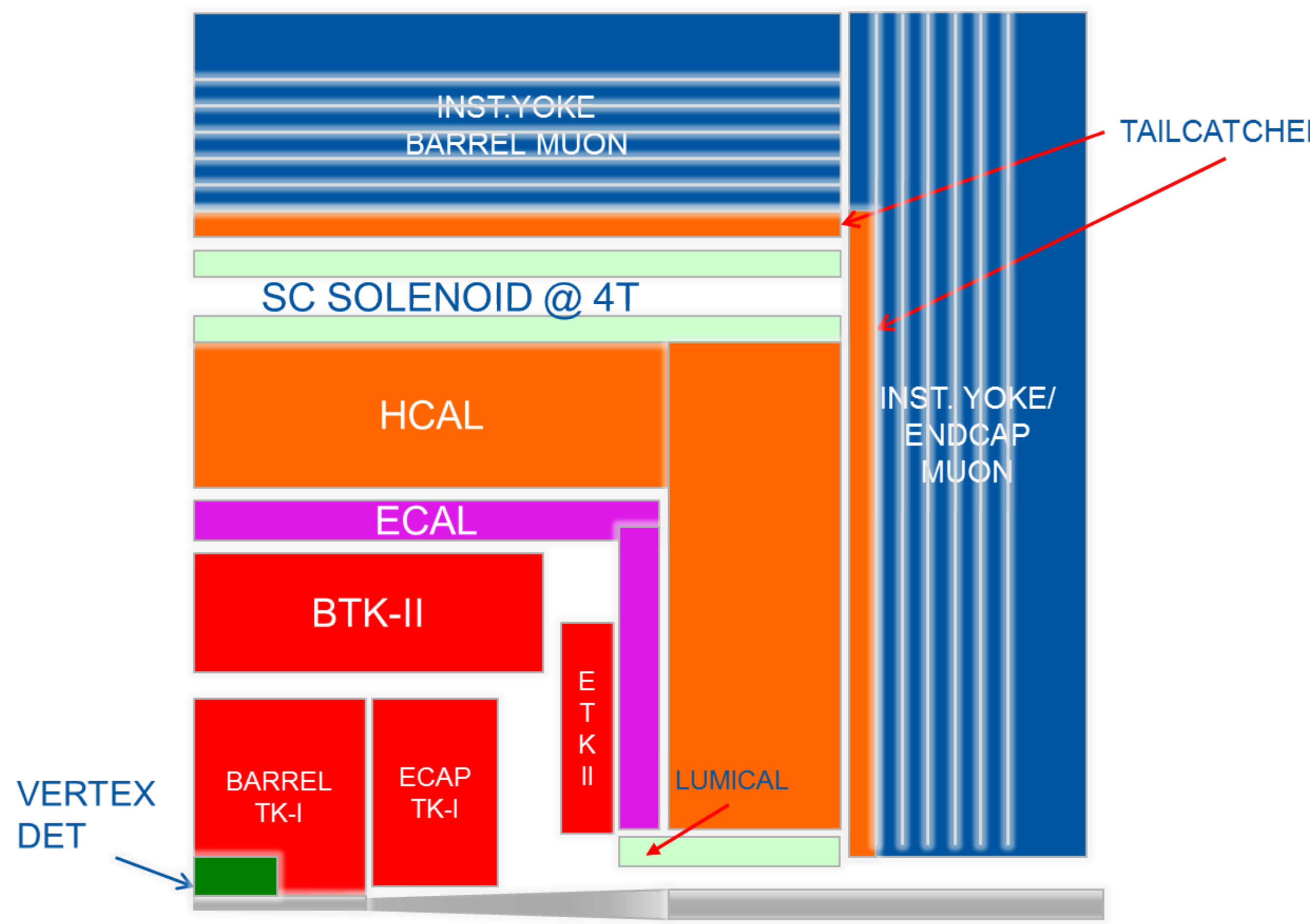
based on *MgB_2* SC
only 12 MEuro/100 km!

common modular detectors for e^+e^- and *pp* collisions!?

GMS-2T (TLEP)



GMS-4T (VHE-LHC)



E. Meschi

possible long-term strategy

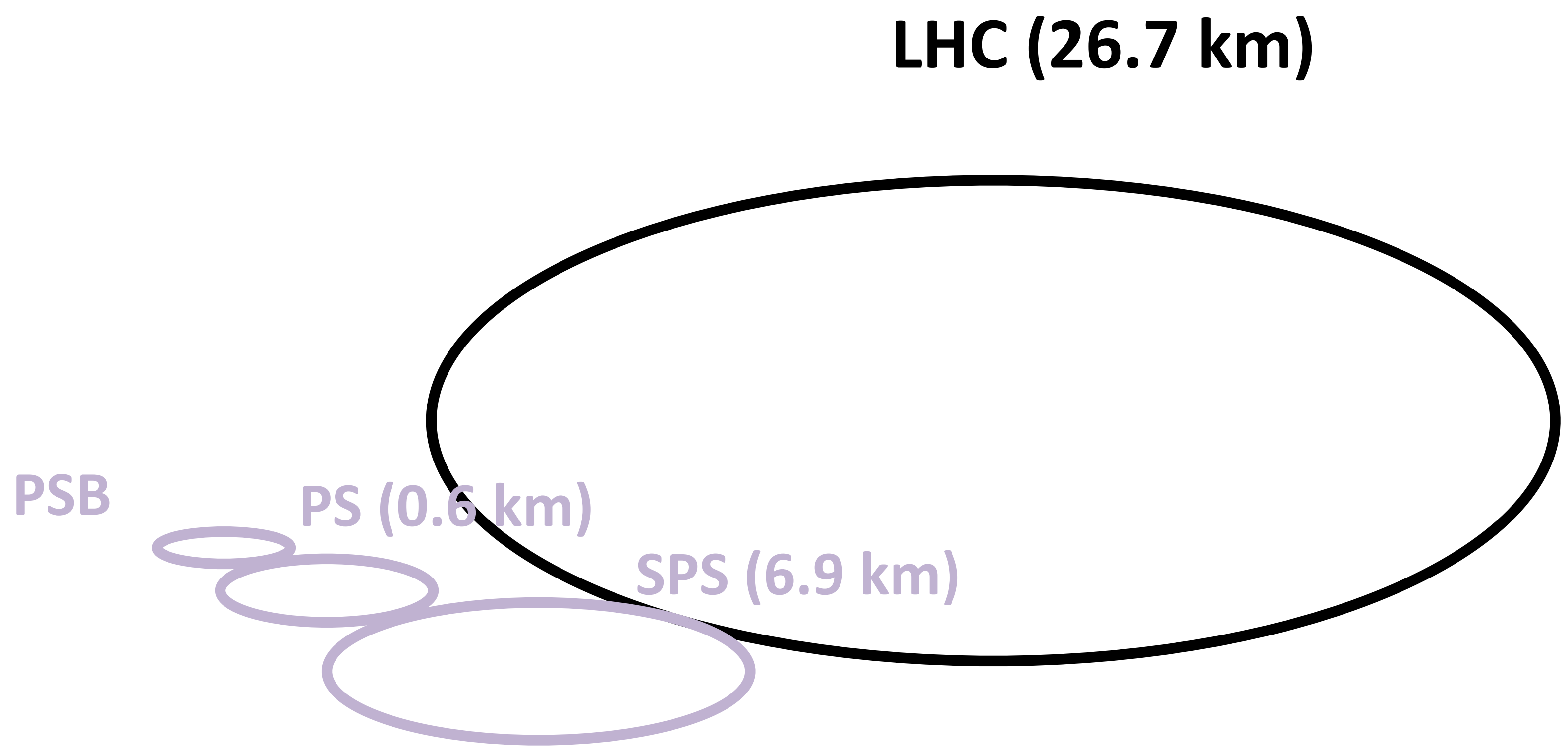
CERN implementation

possible long-term strategy

CERN implementation

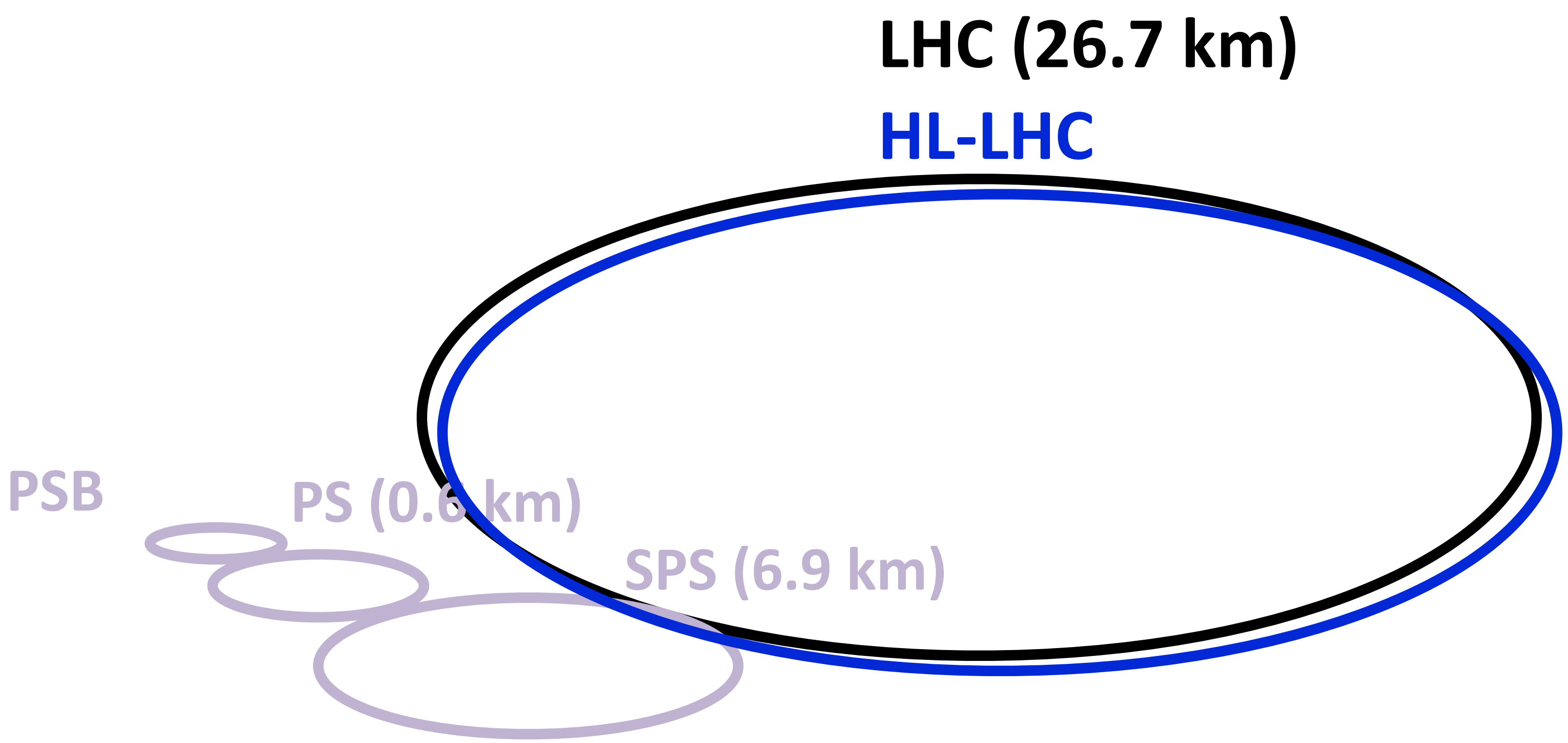
possible long-term strategy

CERN implementation



possible long-term strategy

CERN implementation



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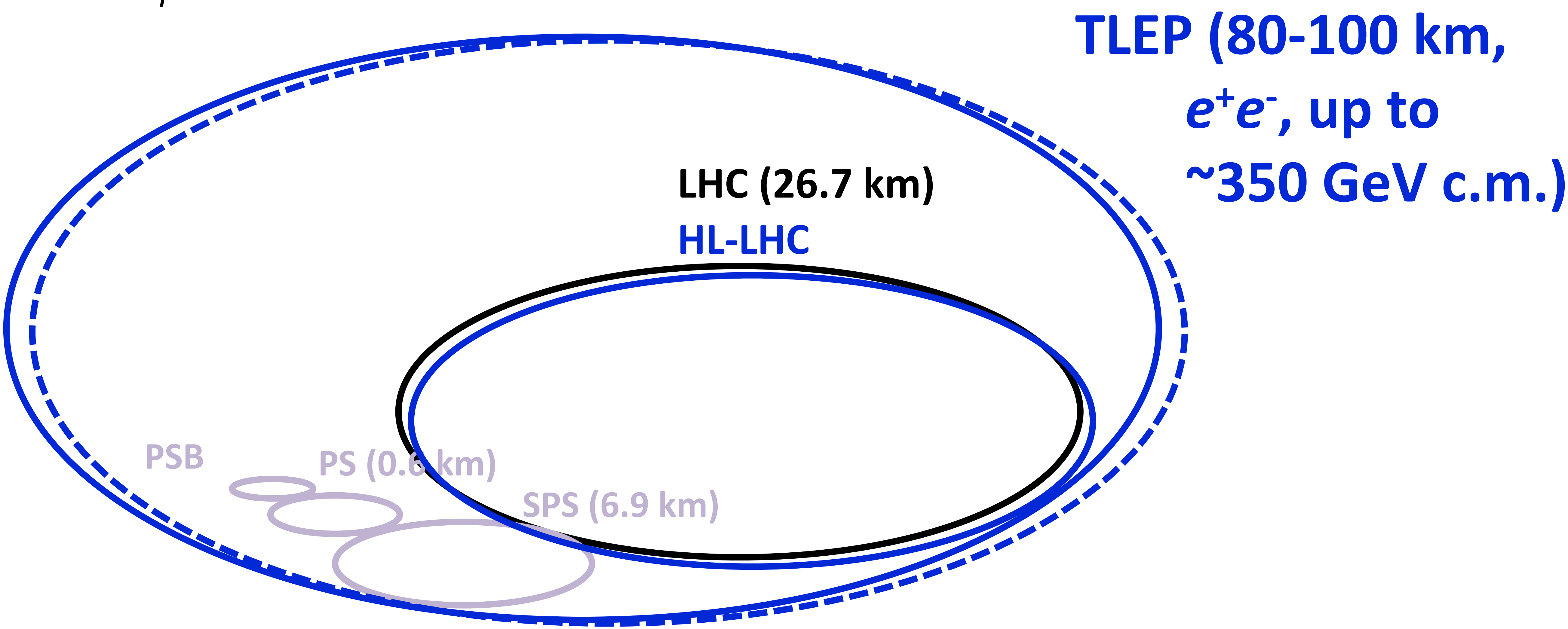

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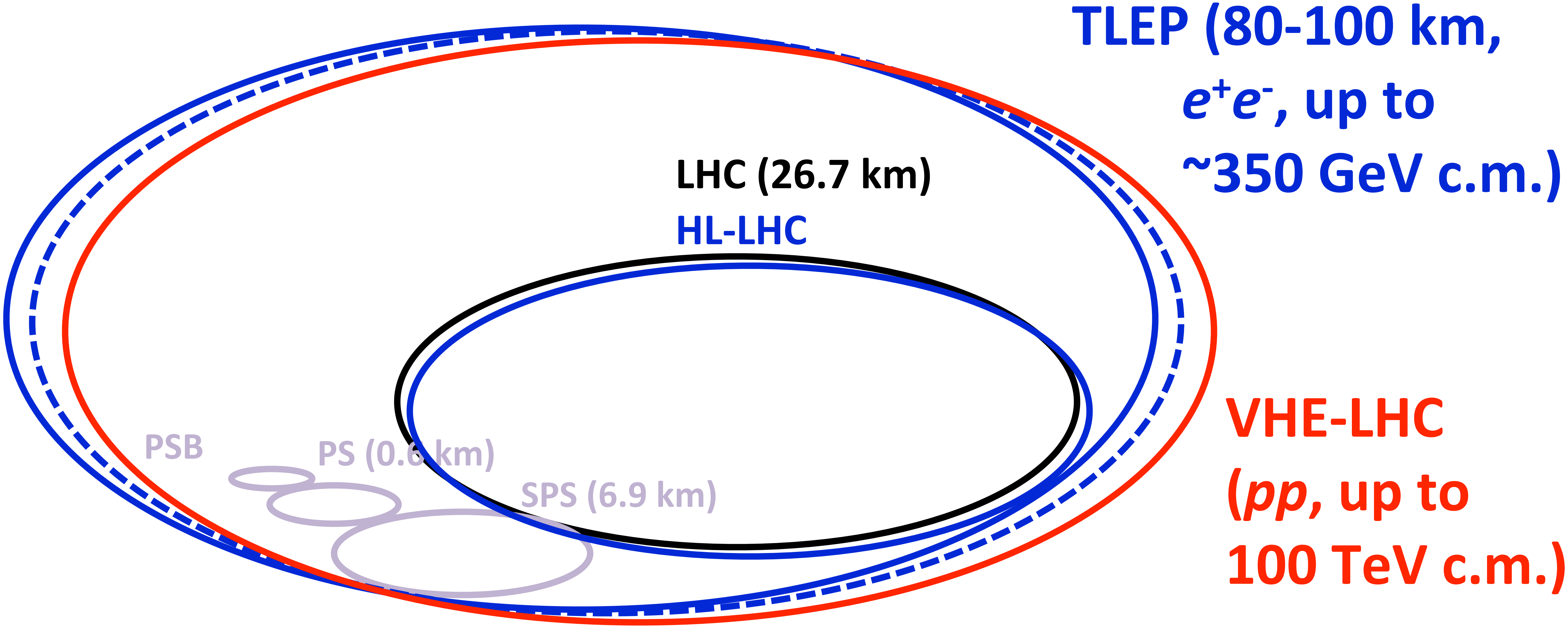
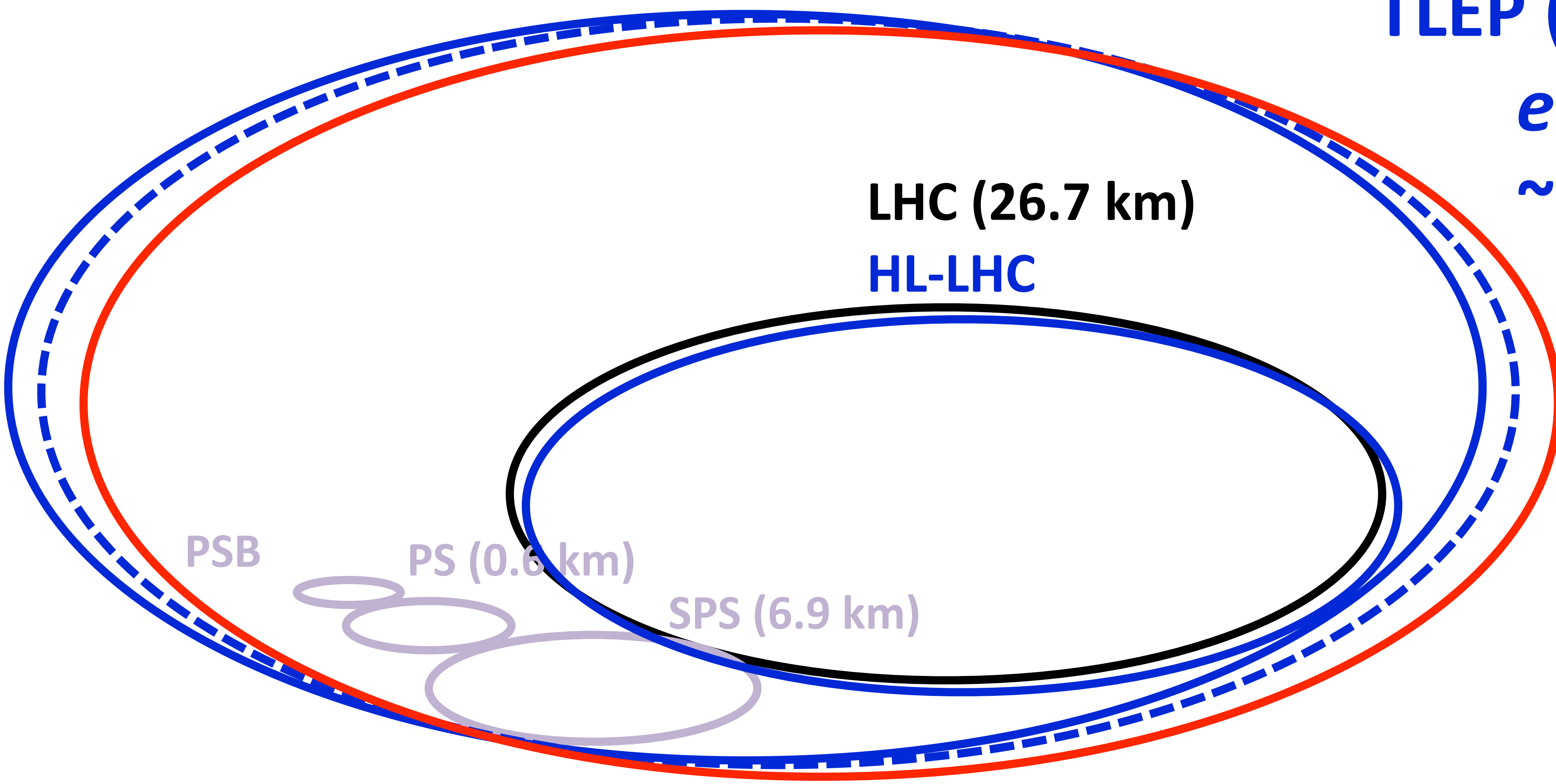


possible long-term strategy

CERN implementation

TLEP (80-100 km, e^+e^-, up to ~350 GeV c.m.)

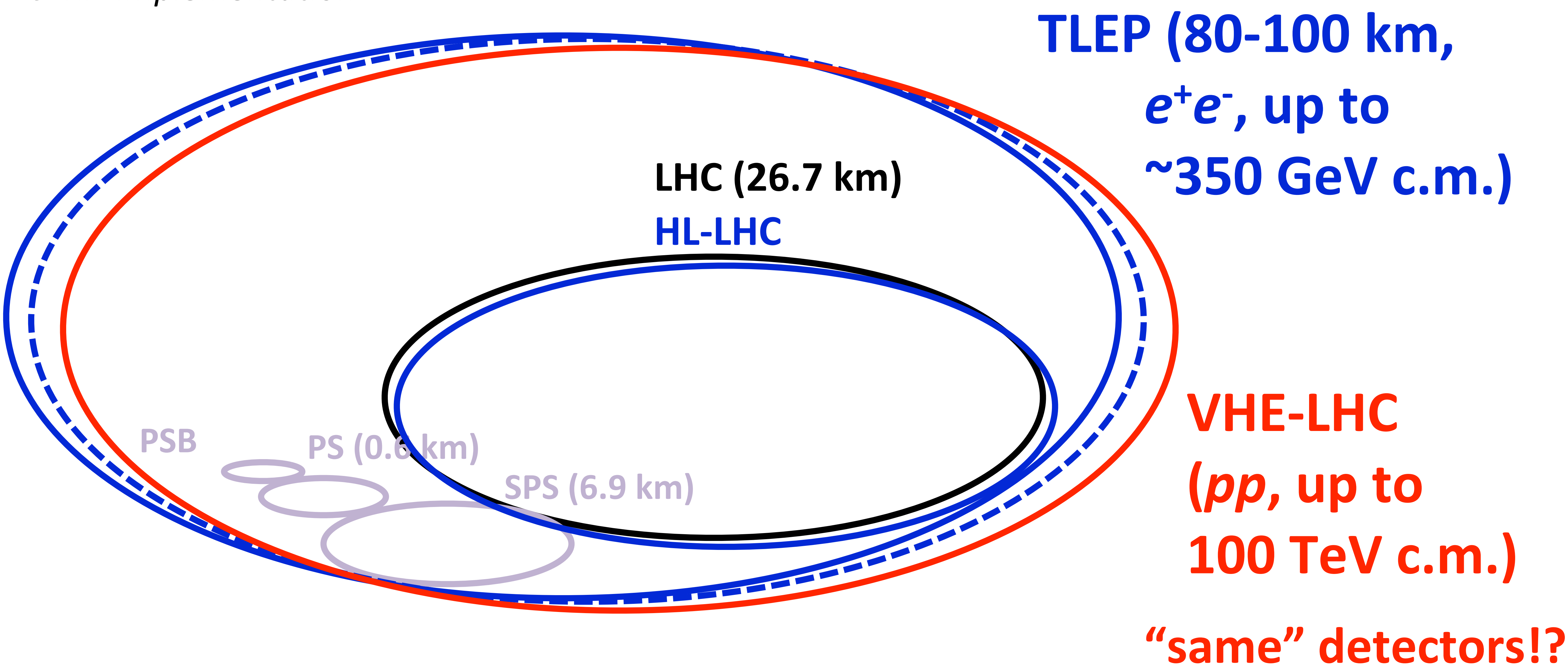


VHE-LHC (*pp*, up to 100 TeV c.m.)

“same” detectors!?

possible long-term strategy

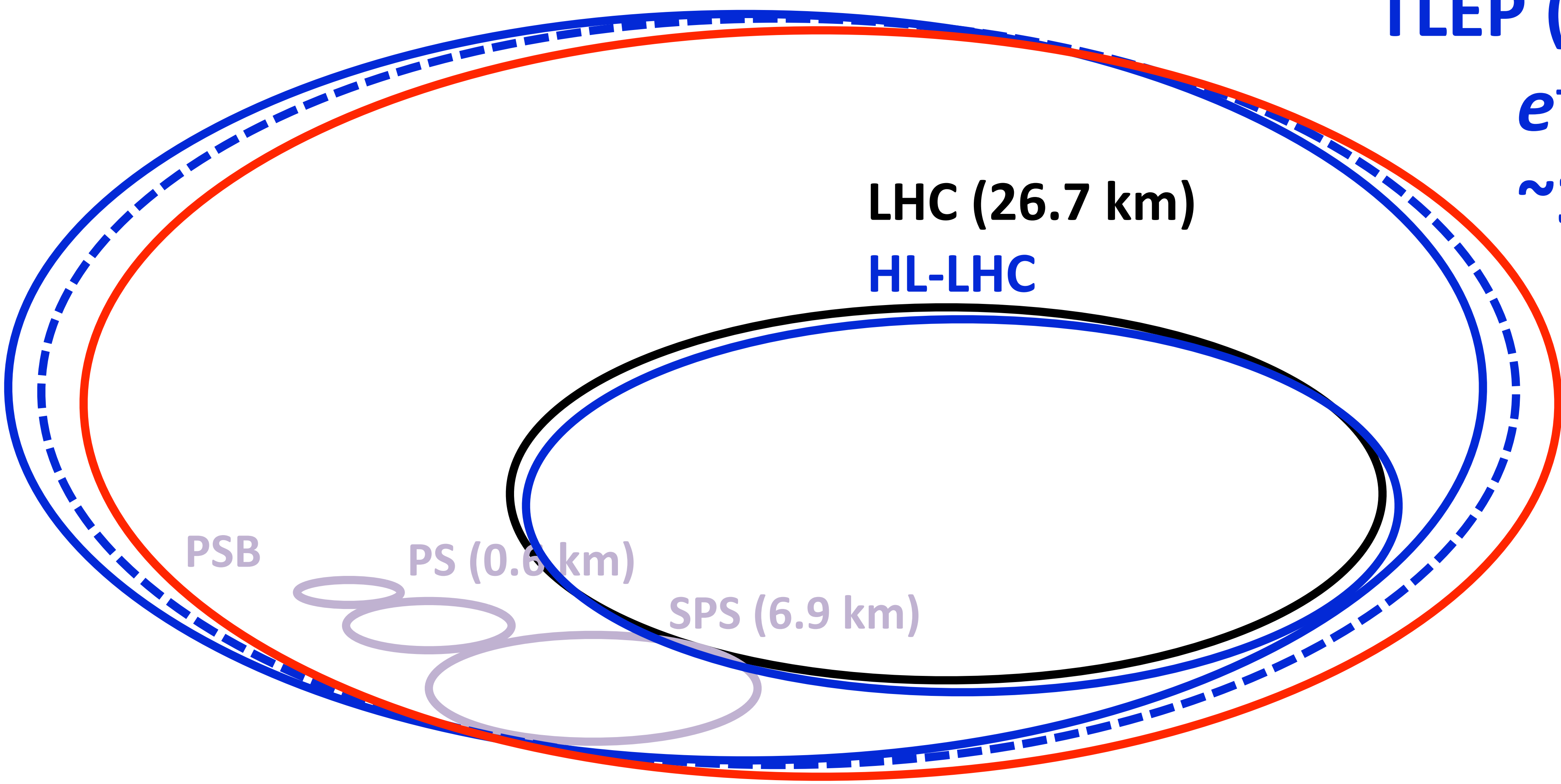
CERN implementation



& $e^{\pm}$ **(120 GeV)–*p* (7 & 50 TeV)** collisions (**[VHE-]TLHeC**)

possible long-term strategy

CERN implementation



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VHE-LHC (*pp*, up to 100 TeV c.m.)

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& ***e***$^{\pm}$ **(120 GeV)–*p* (7 & 50 TeV)** collisions (**[VHE-]TLHeC**)

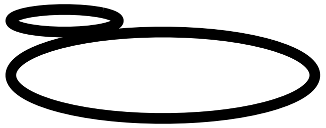
≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

possible long-term strategy

KEK implementation

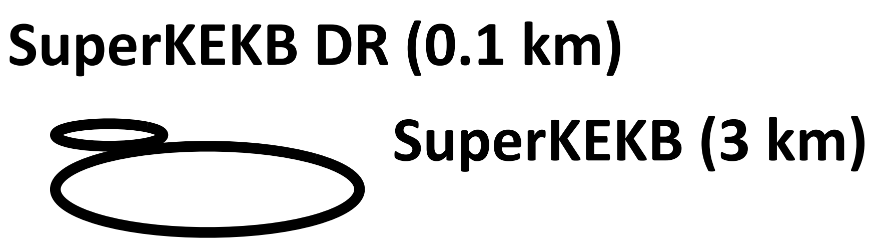
possible long-term strategy

KEK implementation



possible long-term strategy

KEK implementation



possible long-term strategy

KEK implementation

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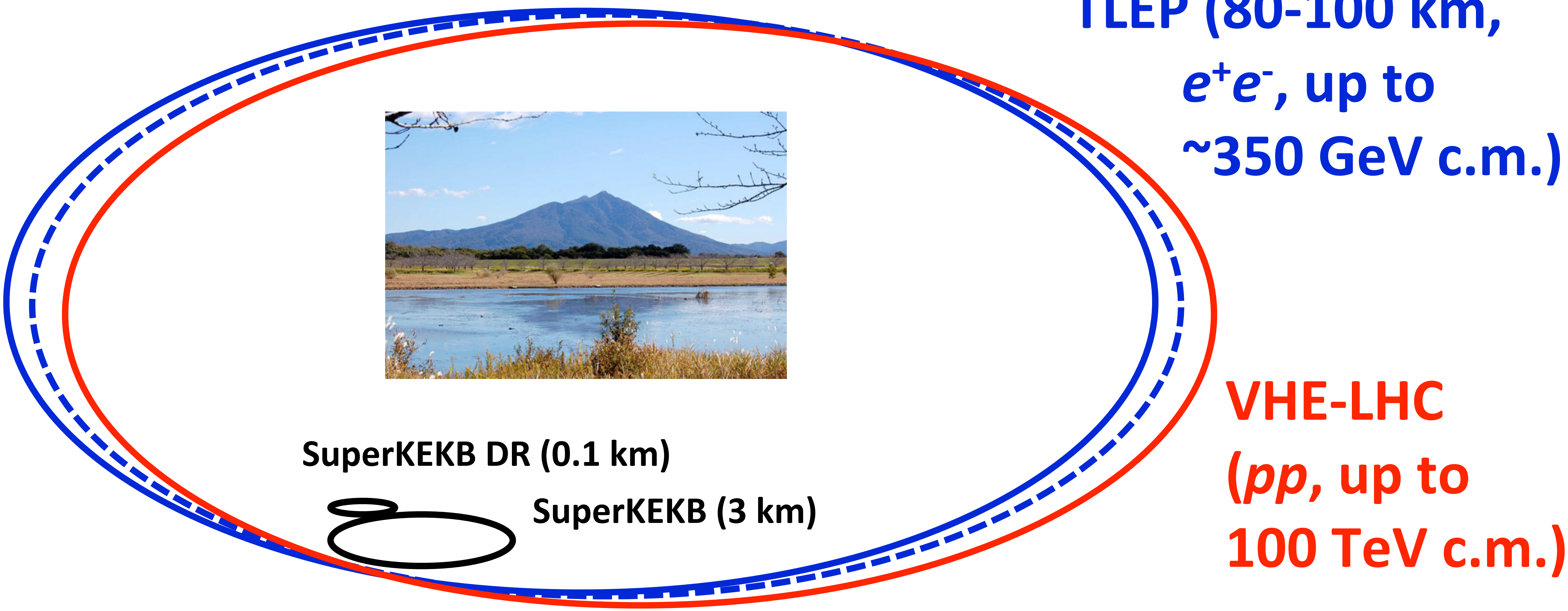
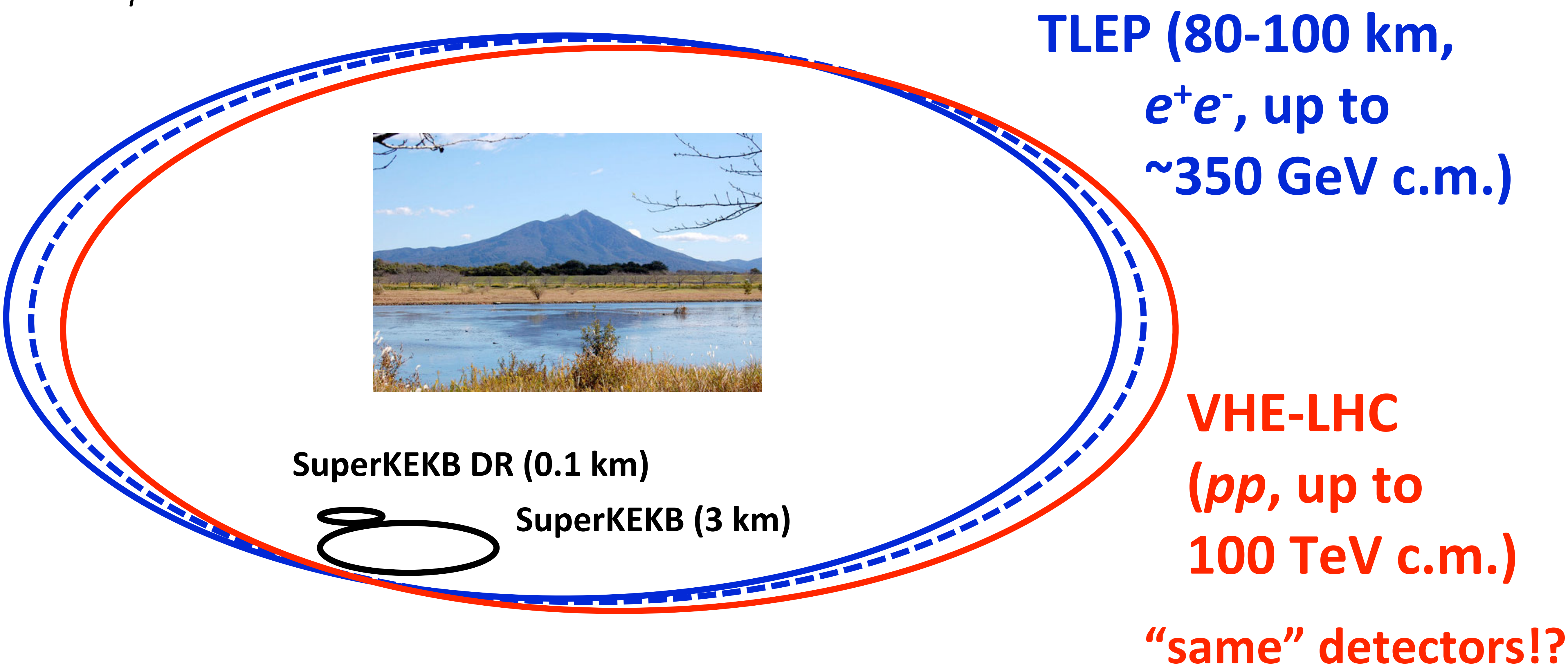
possible long-term strategy

KEK implementation



possible long-term strategy

KEK implementation



possible long-term strategy

KEK implementation

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VHE-LHC (*pp*, up to 100 TeV c.m.)

"same" detectors!?

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possible long-term strategy

KEK implementation

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"same" detectors!?

& ***e*$^{\pm}$ (120 GeV)–*p* (50 TeV)** collisions (**VHE-TLHeC**)

≥50 years of *e*$^+$*e*$^-$, *pp*, *ep/A* physics at highest energies

TLEP cost breakdown – extremely rough (GEuro)

	TLEP
Bare tunnel (with shafts & 8 caverns)	3.1 (1)
Services & additional infrastructure (electricity, cooling, ventilation, service cavern, RP, surface structure, access roads)	1.0 (2)
RF system	0.7 (3)
Cryo system	0.2 (4)
Vacuum system & RP	0.5(5)
Magnet system for collider & injector ring	0.8(6)
Pre-injector complex SPS reinforcements	0.5
Total	**6.8**

(1): J. Osborne, Amrup study

(2): very rough guess, conservative escalated extrapolation from LEP

(3): O. Brunner, Note, May 2013; B. Rimmer, SRF cost /GeV/Watt for CEBAF upgrade, 2010

(4): 2x LHeC cryo plant cost [Friedrich Haug, 4th TLEP workshop]

(5): factor 2.5 higher than KEK estimate for 80 km ring

(6): 24,000 magnets for collider & injector; cost per magnet 30 kCHF (LHeC study); 10% added; no cost saving from mass production assumed

Note: detector costs not included

TLEP cost breakdown – extremely rough (GEuro)

preliminary – not endorsed by anybody

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possible long-term time line

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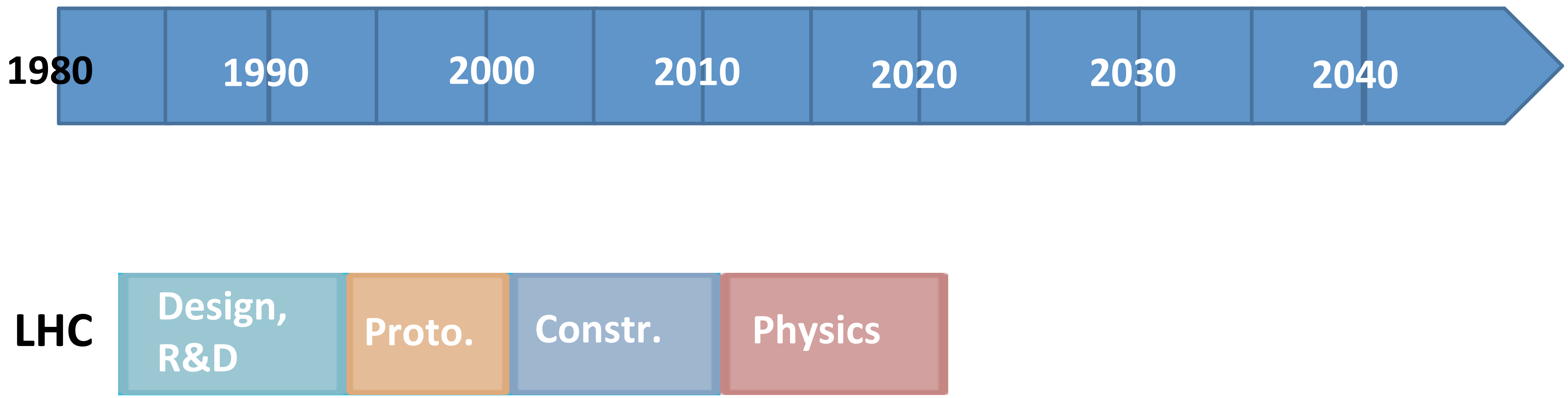

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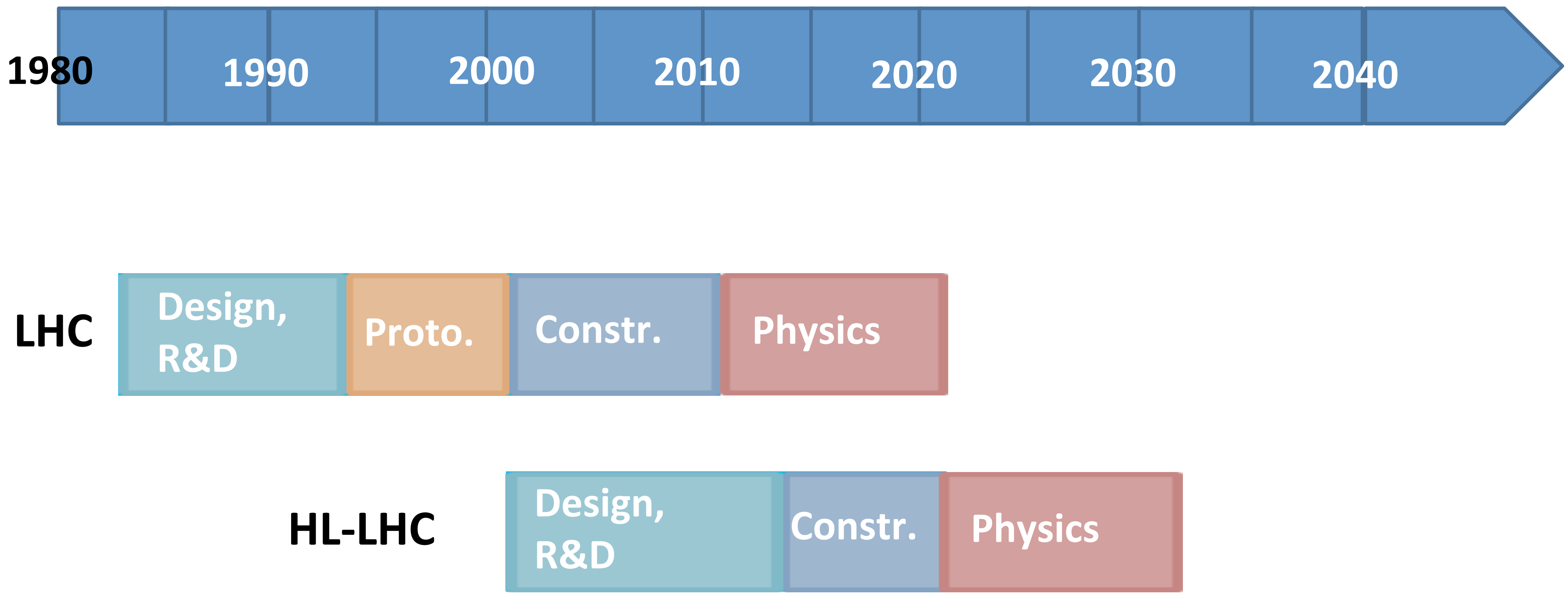

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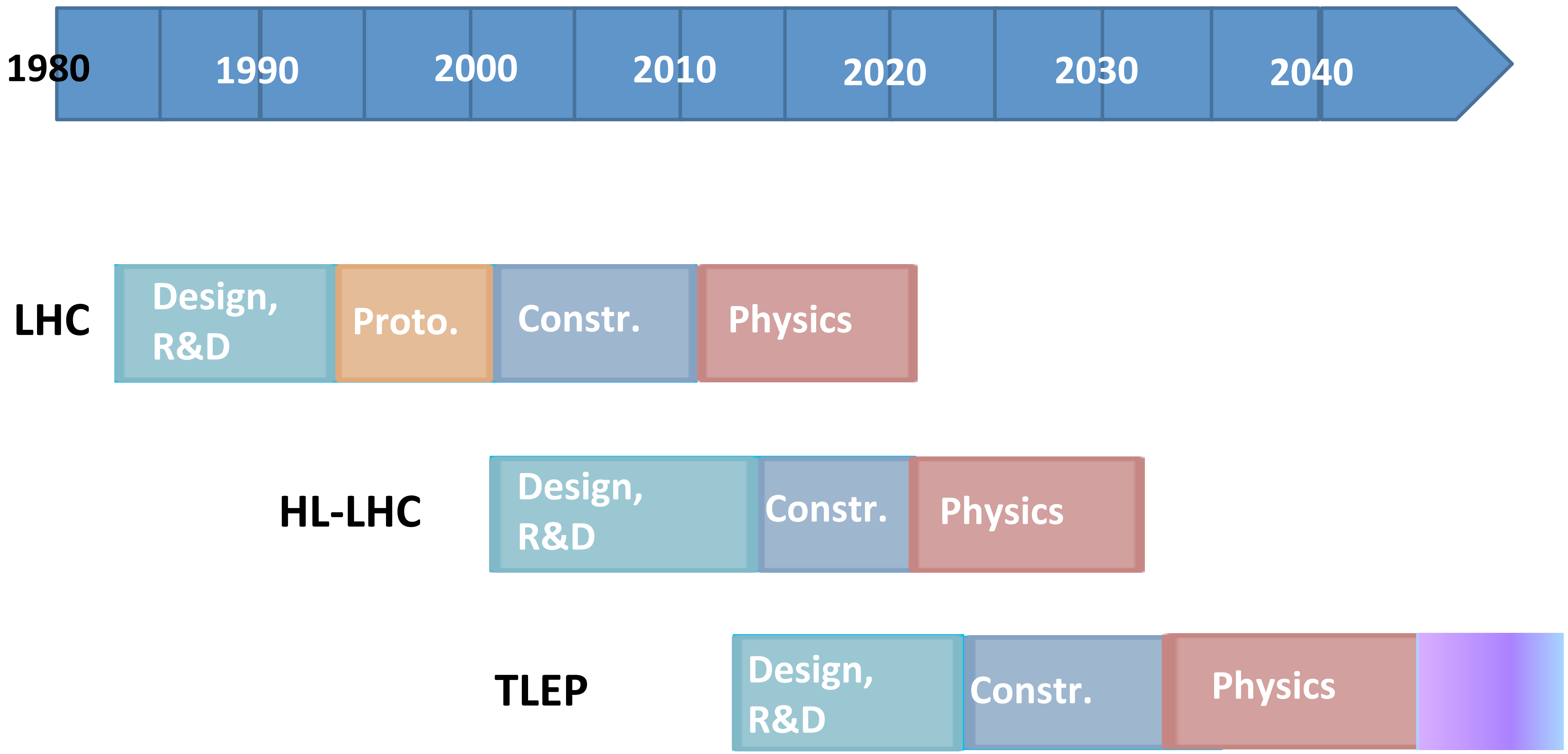

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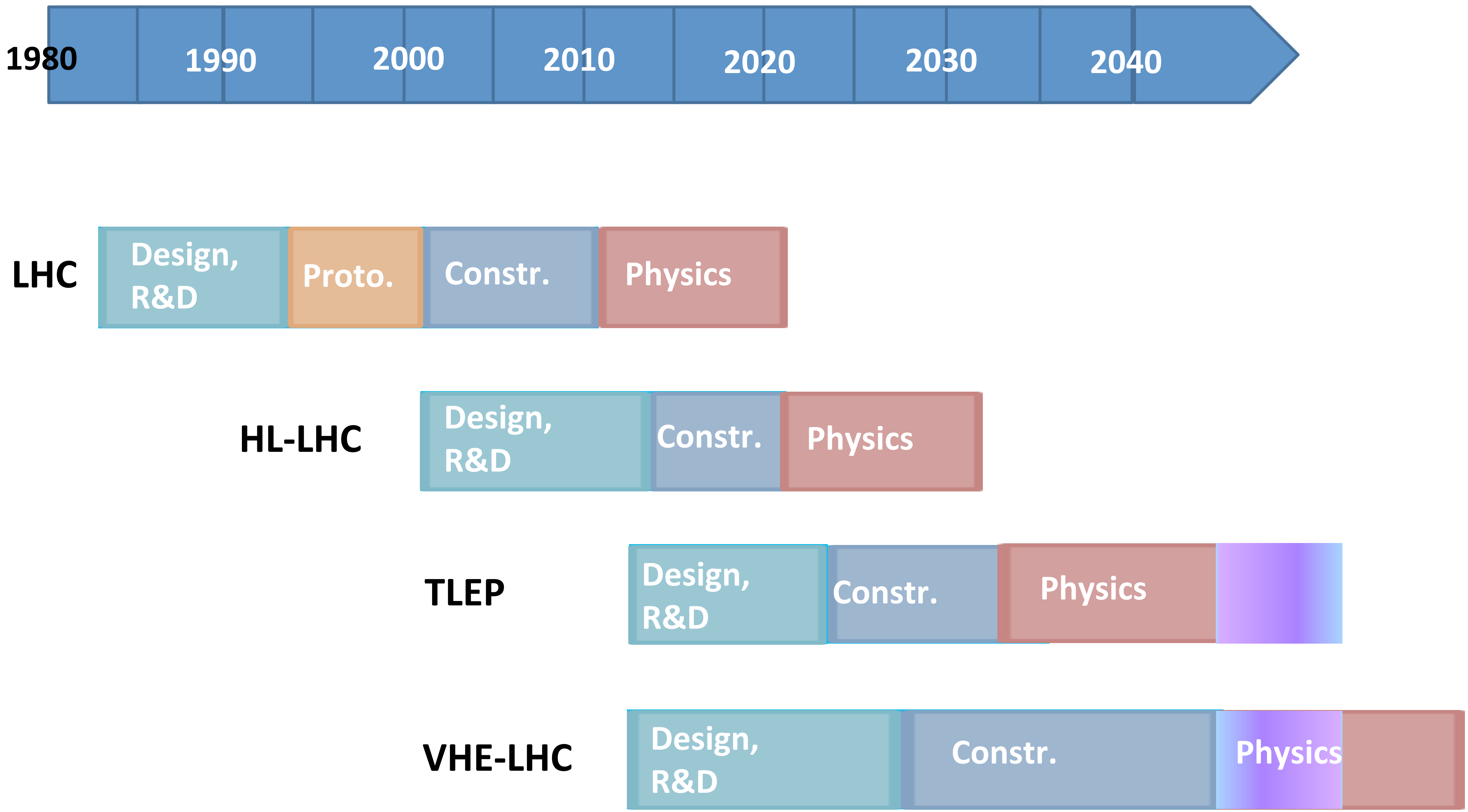
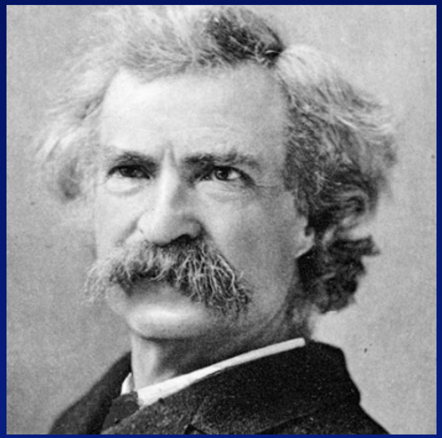


circular e^+e^- Higgs factory - conclusions

- **highest e^+e^- luminosity for *H* production**
- **extreme luminosity at *Z* pole & *W* threshold**
- **energy reach up to $t\bar{t}$ threshold** (& beyond?)
- based on **well-known technology**
- supported by **progress over last 20 years: LEP(2), (Super)*B* factories, light sources, LHC**
- **first step in a long-term vision for HEP**, e.g. **many synergies with VHE-LHC** (*pp* collisions at 100 TeV): tunnel, accelerator, experiments, physics,...

is future circular or linear or both?

“A circle is a round straight line with a hole in the middle.”



Mark Twain,
in "English as She Is Taught",
Century Magazine, May 1887

spare slides

Higgs factory performances

Precision on couplings, cross sections, mass, width, Summary of the ICFA HF2012 workshop (FNAL, Nov. 2012) arxiv1302:3318

Table 2.1: Expected performance on the Higgs boson couplings from the LHC and e^+e^- colliders, as compiled from the Higgs Factory 2012 workshop. Many studies are quite recent and still ongoing.

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}) 1.4 TeV (1.5 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} 5 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hνν	7.5×10^4 ZH 4.7×10^5 Hνν	4×10^5 ZH	2×10^6 ZH 3.5×10^4 Hνν
m_H (MeV)	100	50	35	35	100	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	ongoing	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	ongoing	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	ongoing	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	< 3%	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%	~22% (~11% at 3 TeV)	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	< 30%	< 10%	--	--	10%	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%	2%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	1%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	5%	3%	--	30%

(*) The total luminosity is the sum of the integrated luminosity at four IPs.

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N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hvv	7.5×10^4 ZH 4.7×10^5 Hvv	4×10^5 ZH	2×10^6 ZH 3.5×10^4 Hvv
m_H (MeV)	100	50	35	35	100	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	ongoing	4%	1.3%
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$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	< 3%	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%	~22% (~11% at 3 TeV)	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	< 30%	< 10%	--	--	10%	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%	2%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	1%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	5%	3%	--	30%

(*) The total luminosity is the sum of the integrated luminosity at four IPs.

Higgs factory performances

Precision on couplings, cross sections, mass, width, Summary of the ICFA HF2012 workshop (FNAL, Nov. 2012) arxiv1302:3318

Table 2.1: Expected performance on the Higgs boson couplings from the LHC and e^+e^- colliders, as compiled from the Higgs Factory 2012 workshop. Many studies are quite recent and still ongoing.

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}) 1.4 TeV (1.5 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} 5 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 $H\nu\nu$	7.5×10^4 ZH 4.7×10^5 $H\nu\nu$	4×10^5 ZH	2×10^6 ZH 3.5×10^4 $H\nu\nu$
m_H (MeV)	100	50	35	35	100	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	ongoing	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	ongoing	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	ongoing	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	< 3%	2.2%	0.7%
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$\Delta g_{HZZ} / g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	~1%	0.65%	0.2%
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N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hνν	7.5×10^4 ZH 4.7×10^5 Hνν	4×10^5 ZH	2×10^6 ZH 3.5×10^4 Hνν
m_H (MeV)	100	50	35	35	100	26	7
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Circular Higgs Factory really goes to precision at few permil level.

Higgs factory performances

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m_H (MeV)	100	50	35	35	100	26	7
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$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	5%	3%	--	30%

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see talk by A. Blondel

Performance Comparison

Need sub-percent precision for sensitivity to multi-TeV New Physics

– Compare (LHC), HL-LHC, ILC, TLEP

±1%

HF2012

- **TLEP reaches the needed sub-percent accuracy**

J. Ellis et al.

P. Janot

Performance Comparison

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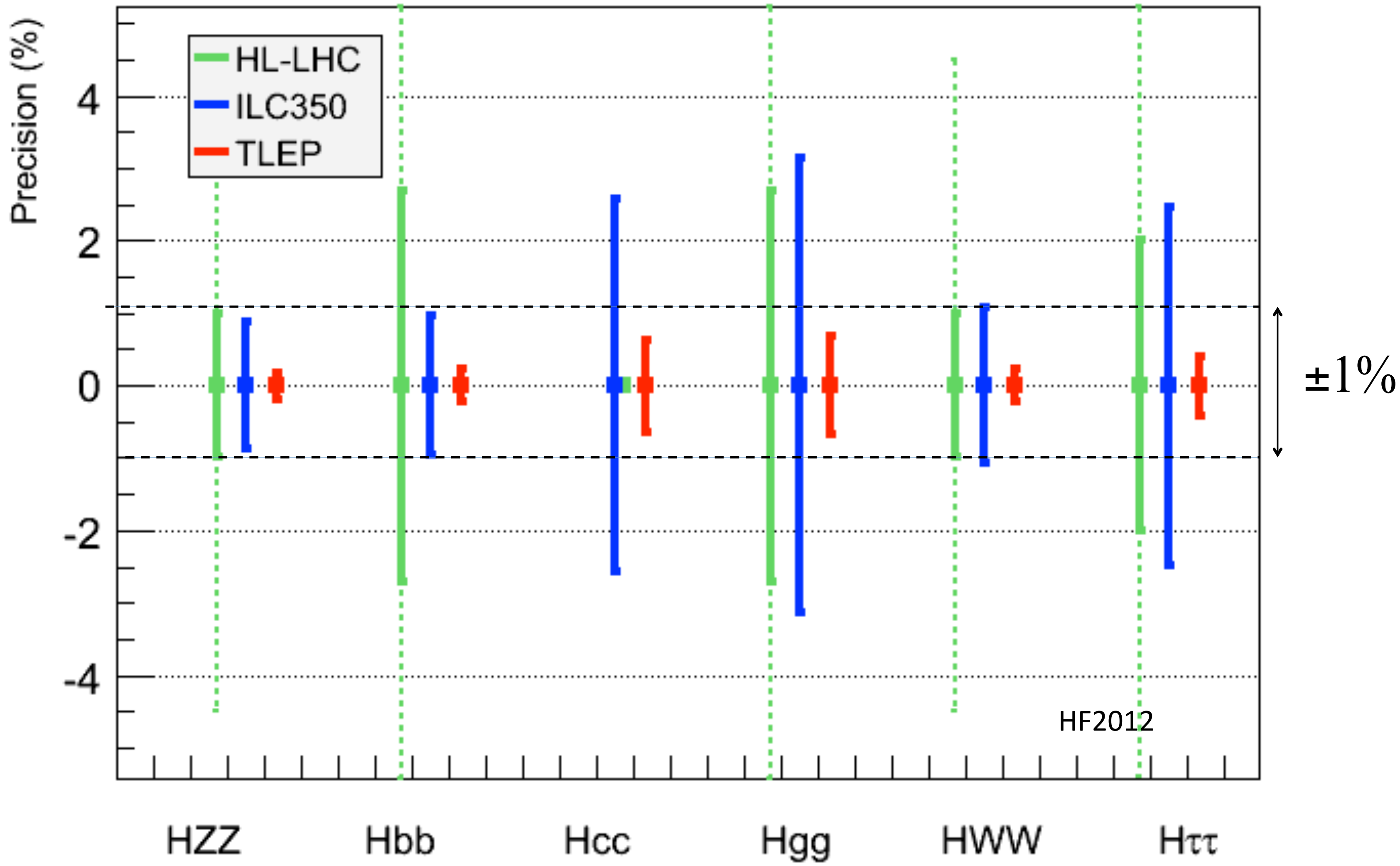

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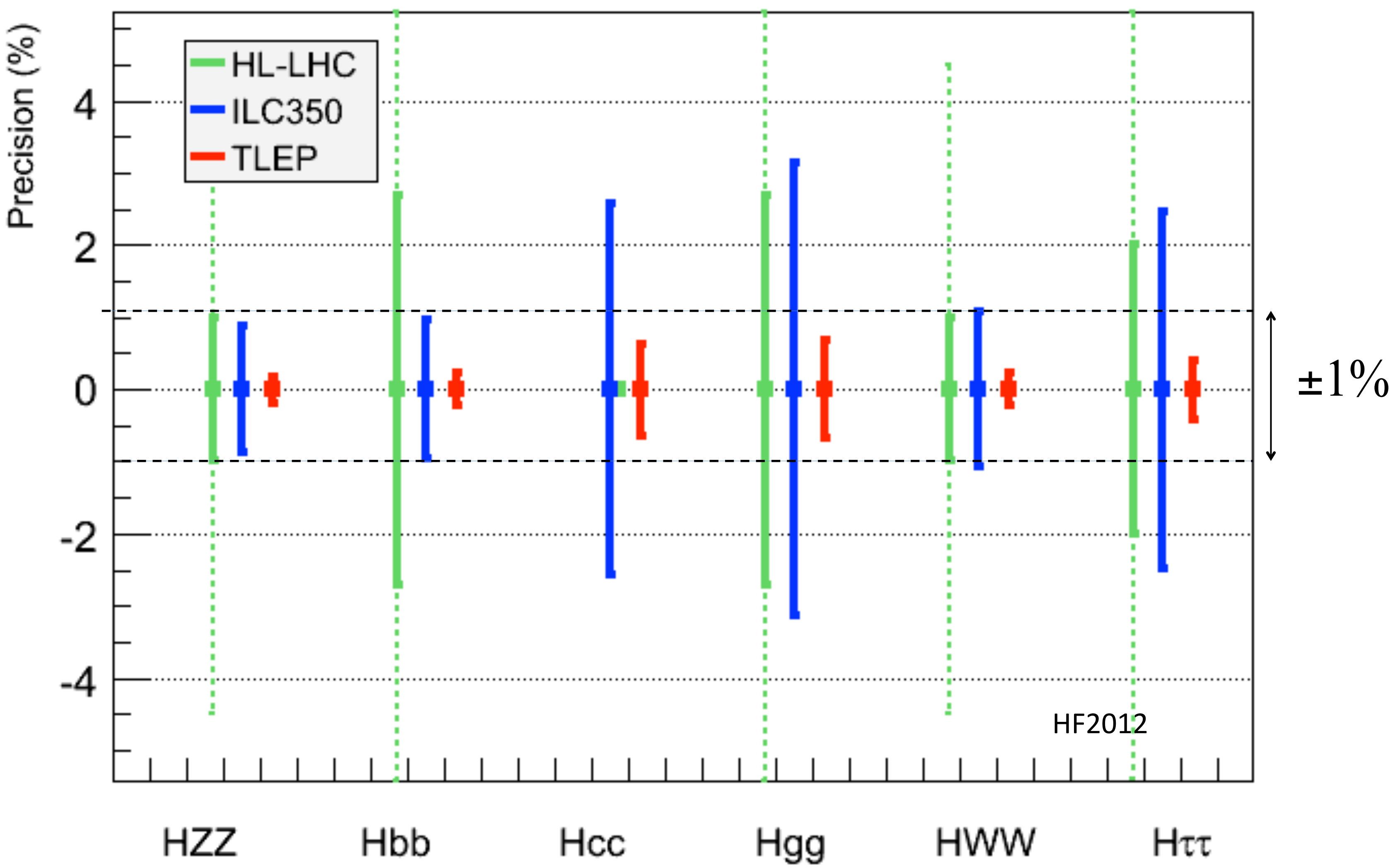

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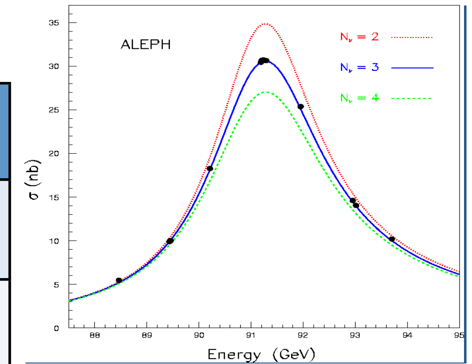
see talk by A. Blondel

TLEP TeraZ, Oku-W & Mega-Top

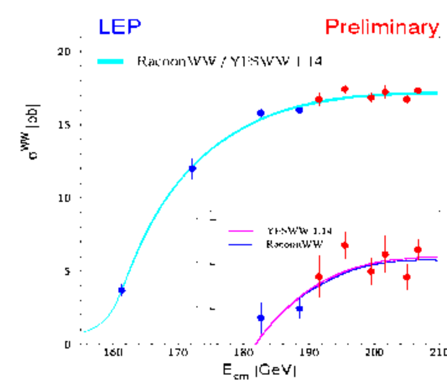
- Precision tests of EWSB

	LEP	ILC	TLEP
$\sqrt{s} \sim m_Z$	Mega-Z	Giga-Z	Tera-Z
#Z / year Polarization Precision vs LEP1 Error on m_Z, Γ_Z	2×10^7 Yes (T) 1 2 MeV	Few 10^9 Easy 1/5 to 1/10 –	10^{12} (>10^{11} b,c,τ) Yes (T,L) ~1/100 < 0.1 MeV
$\sqrt{s} \sim 2m_W$			
#W pairs / year Polarization Error on m_W	Few dozens No 220 MeV	2×10^5 Easy 7 MeV	2.5×10^7 Yes (T) 0.5 MeV
$\sqrt{s}$ = 240 GeV			Oku-W
# W pairs / 5 years Error on m_W	4×10^4 33 MeV	4×10^6 3 MeV	2×10^8 0.5 MeV
$\sqrt{s} \sim 350$ GeV			Mega-Top
# top pairs / 5 years Error on m_{top} Error on λ_t	– – –	100,000 30 MeV 40%	500,000 13 MeV 15%

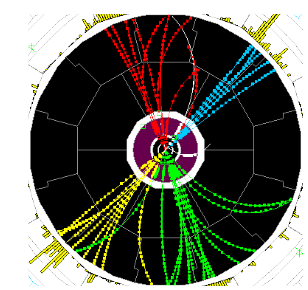
Asymmetries, Lineshape



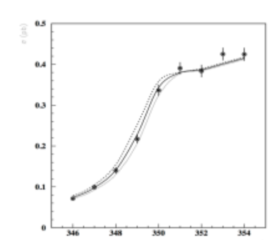
WW threshold scan

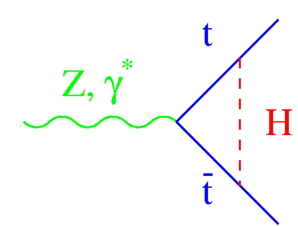


WW production



$t\bar{t}$ threshold scan





TLEP : Repeat the LEP1 physics programme every 15 min

Transverse polarization up to the WW threshold

➢ Exquisite beam energy determination (10 keV)

Longitudinal polarization at the Z pole

➢ Measure $\sin^2\theta_W$ to 2.10^{-6} from A_{LR}

P. Janot

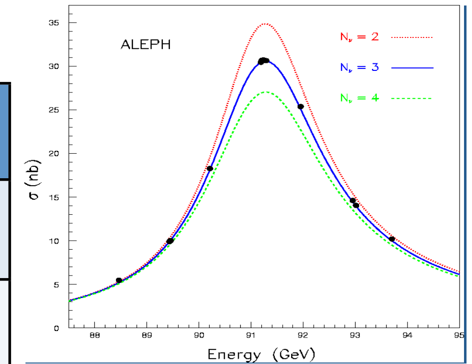
see talk by A. Blondel

TLEP TeraZ, Oku-W & Mega-Top

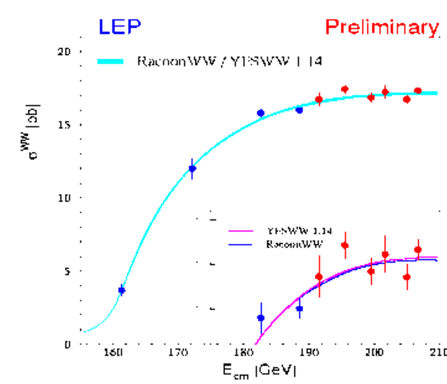
- Precision tests of EWSB

	LEP	ILC	TLEP
$\sqrt{s} \sim m_Z$	Mega-Z	Giga-Z	Tera-Z
#Z / year Polarization **Precision vs LEP1** **Error on m_Z, Γ_Z**	$2{\times}10^7$ Yes (T) **1** **2 MeV**	Few 10^9 Easy **1/5 to 1/10** **–**	10^{12} (>10^{11} b,c,τ) Yes (T,L) **~1/100** **< 0.1 MeV**
$\sqrt{s} \sim 2m_W$			
#W pairs / year Polarization **Error on m_W**	Few dozens No **220 MeV**	$2{\times}10^5$ Easy **7 MeV**	$2.5{\times}10^7$ Yes (T) **0.5 MeV**
$\sqrt{s}$ = 240 GeV			Oku-W
# W pairs / 5 years **Error on m_W**	$4{\times}10^4$ **33 MeV**	$4{\times}10^6$ **3 MeV**	$2{\times}10^8$ **0.5 MeV**
$\sqrt{s} \sim 350$ GeV			Mega-Top
# top pairs / 5 years **Error on m_{top}** **Error on λ_t**	– **–** **–**	100,000 **30 MeV** **40%**	500,000 **13 MeV** **15%**

Asymmetries, Lineshape



WW threshold scan



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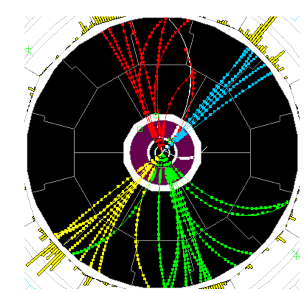

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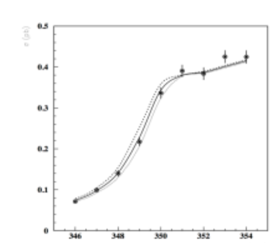

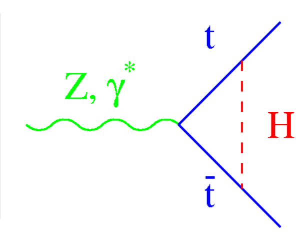

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Longitudinal polarization at the Z pole

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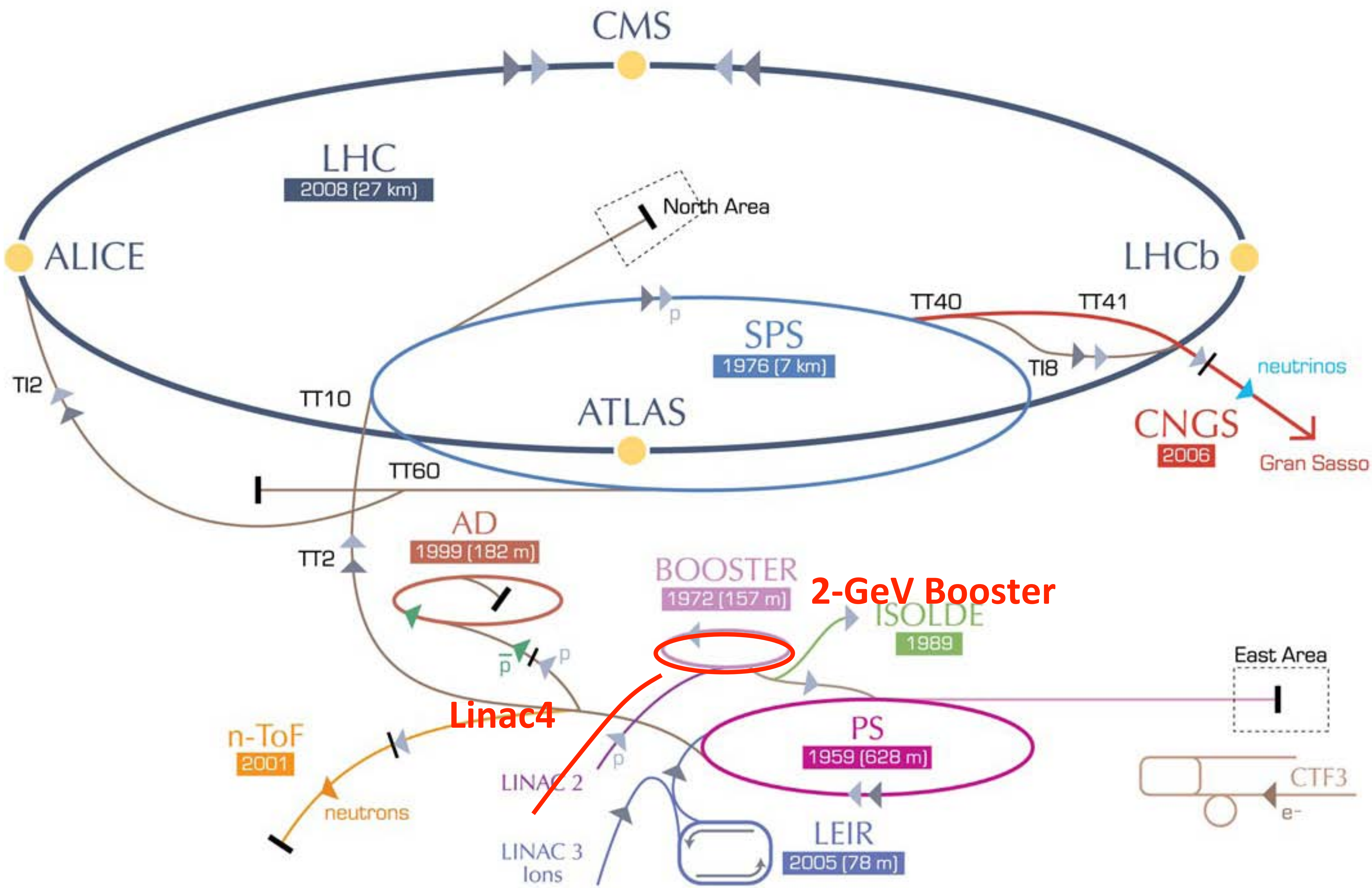
P. Janot

High-Energy LHC



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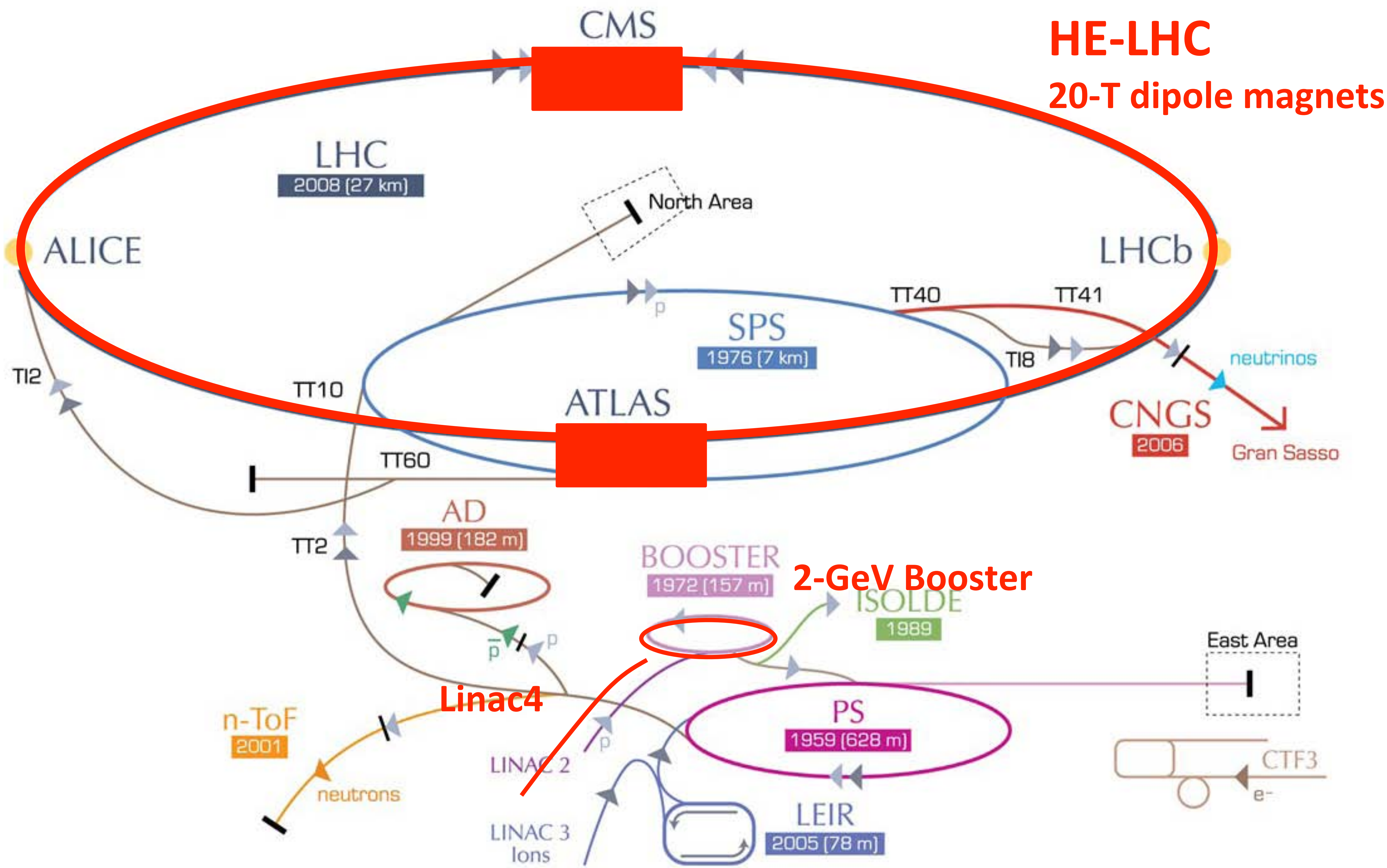

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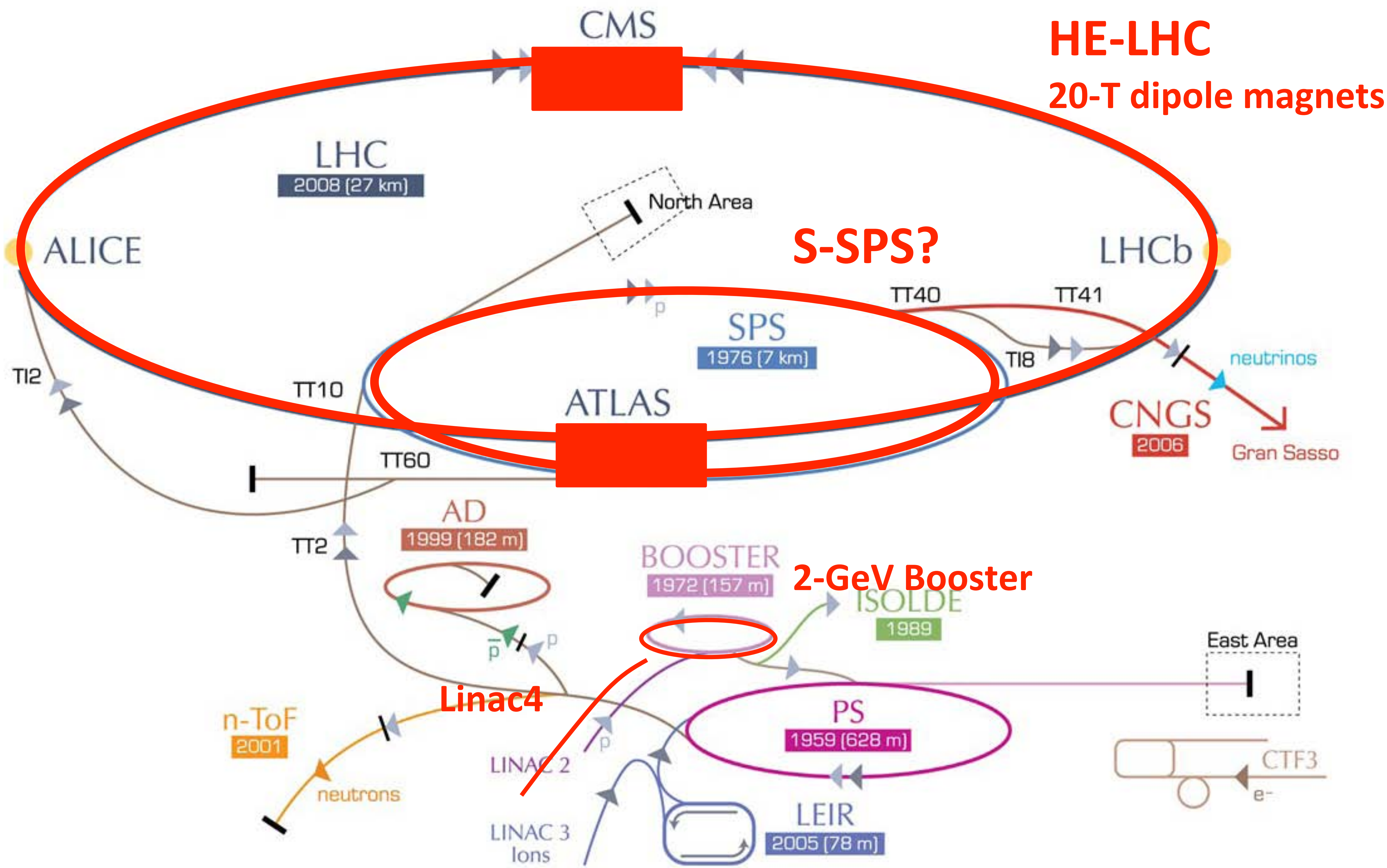

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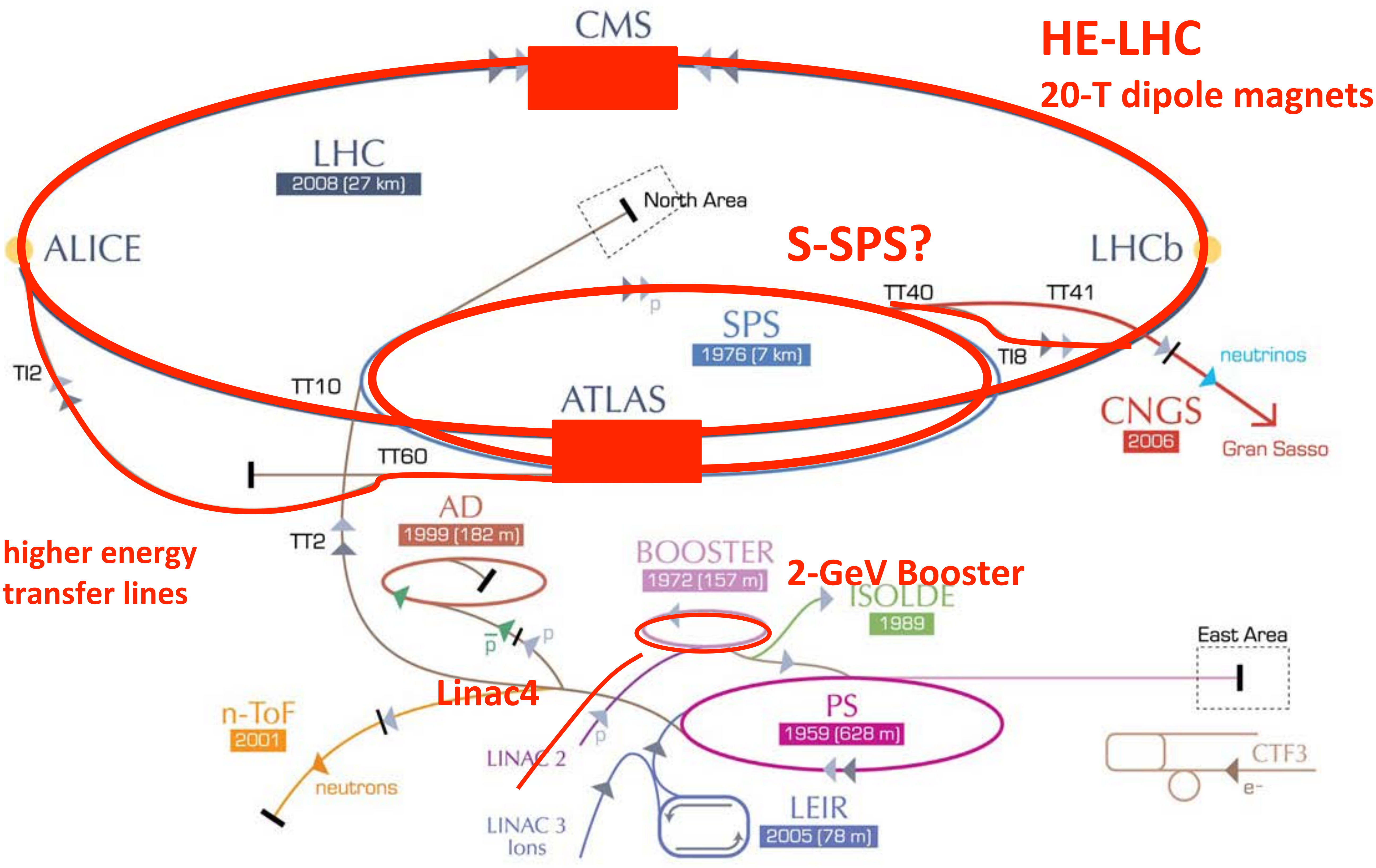
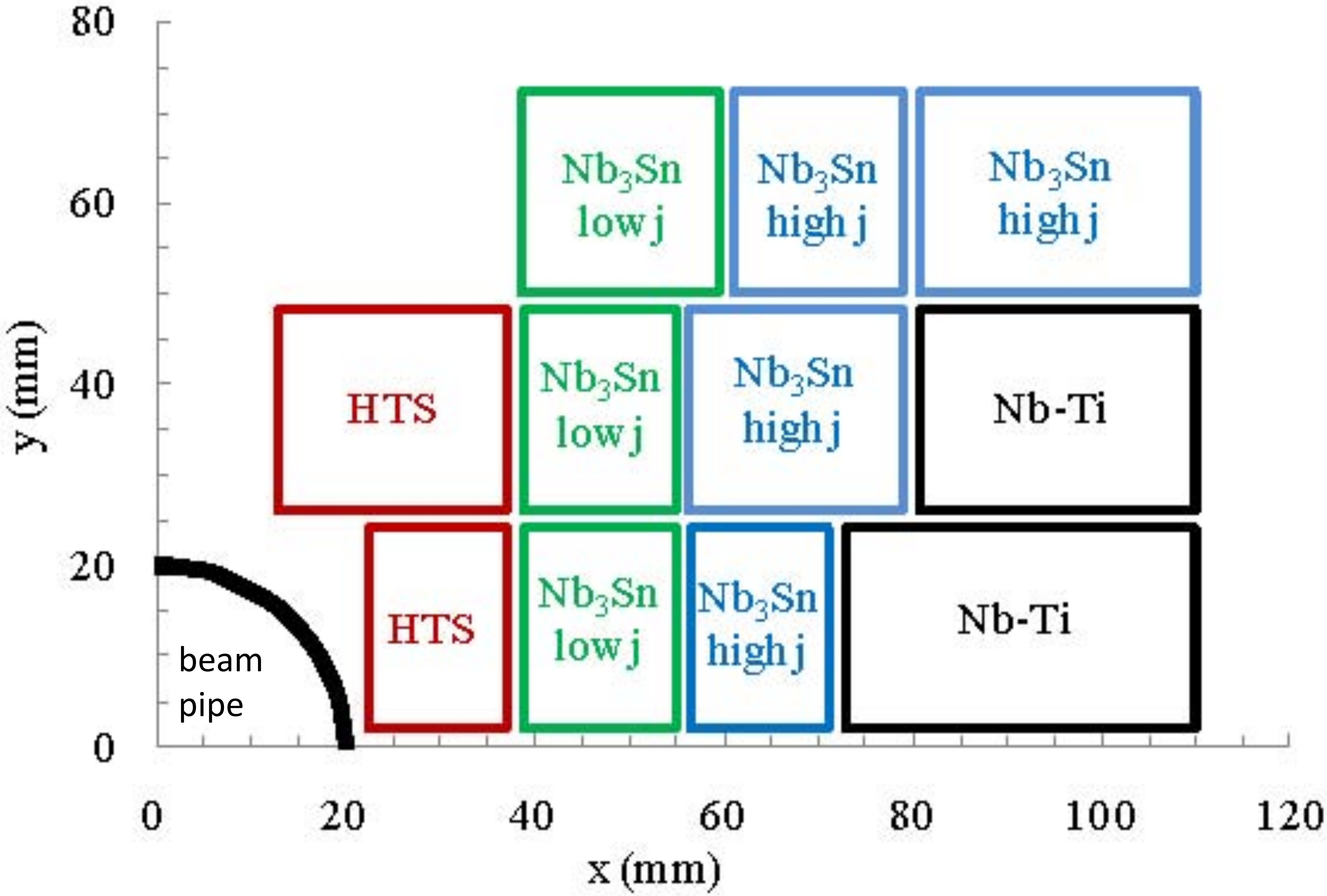


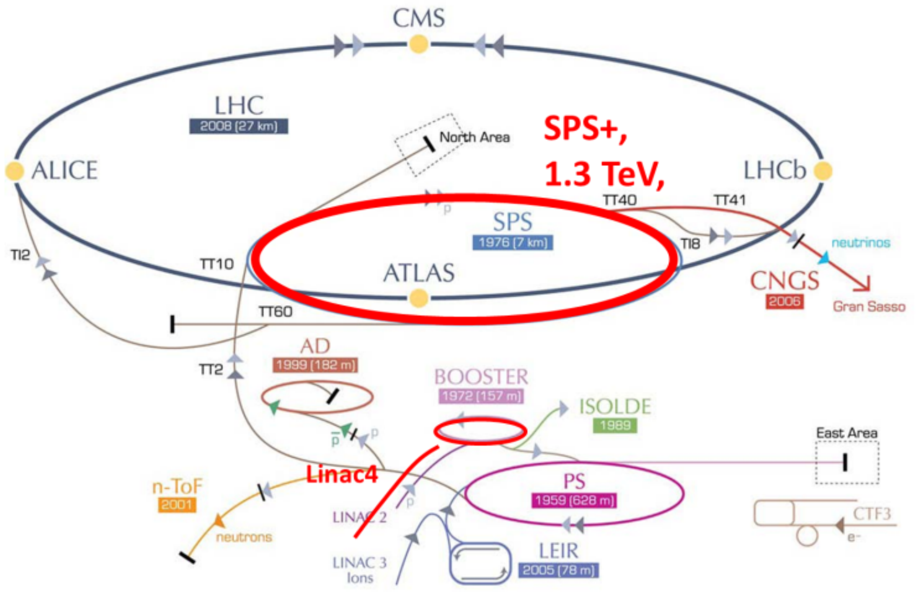
beam
pipe

20-T dipole magnet



E. Todesco, L. Rossi, P.. McIntyre

VHE-LHC


CMS
LHC
2008 (27 km)
North Area
SPS+,
1.3 TeV,
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI2
TT10
ATLAS
TI8
neutrinos
CNGS
2006
Gran Sasso
TT60
TT2
AD
1999 (182 m)
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
Linac4
n-ToF
2001
PS
1959 (628 m)
neutrons
LINAC 2
CTF3
LINAC 3
Ions
LEIR
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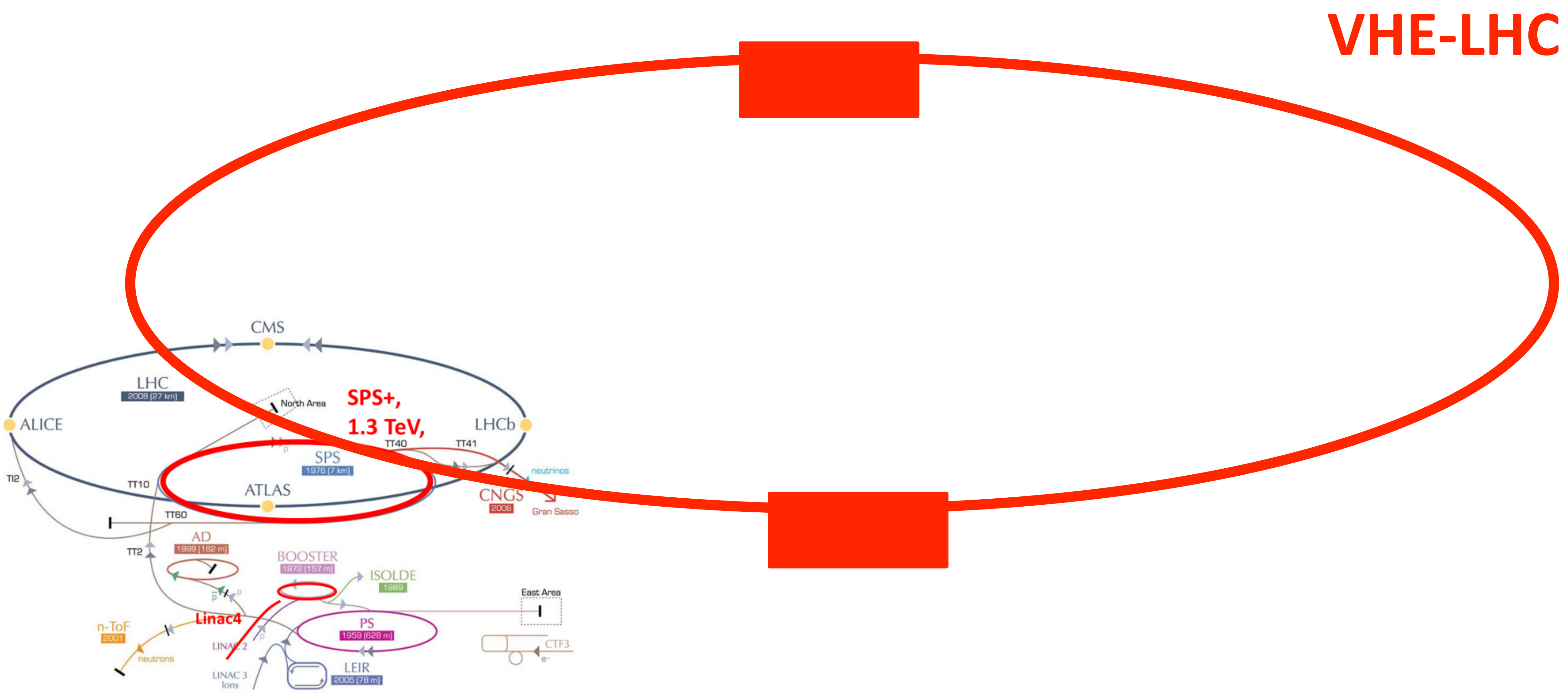
VHE-LHC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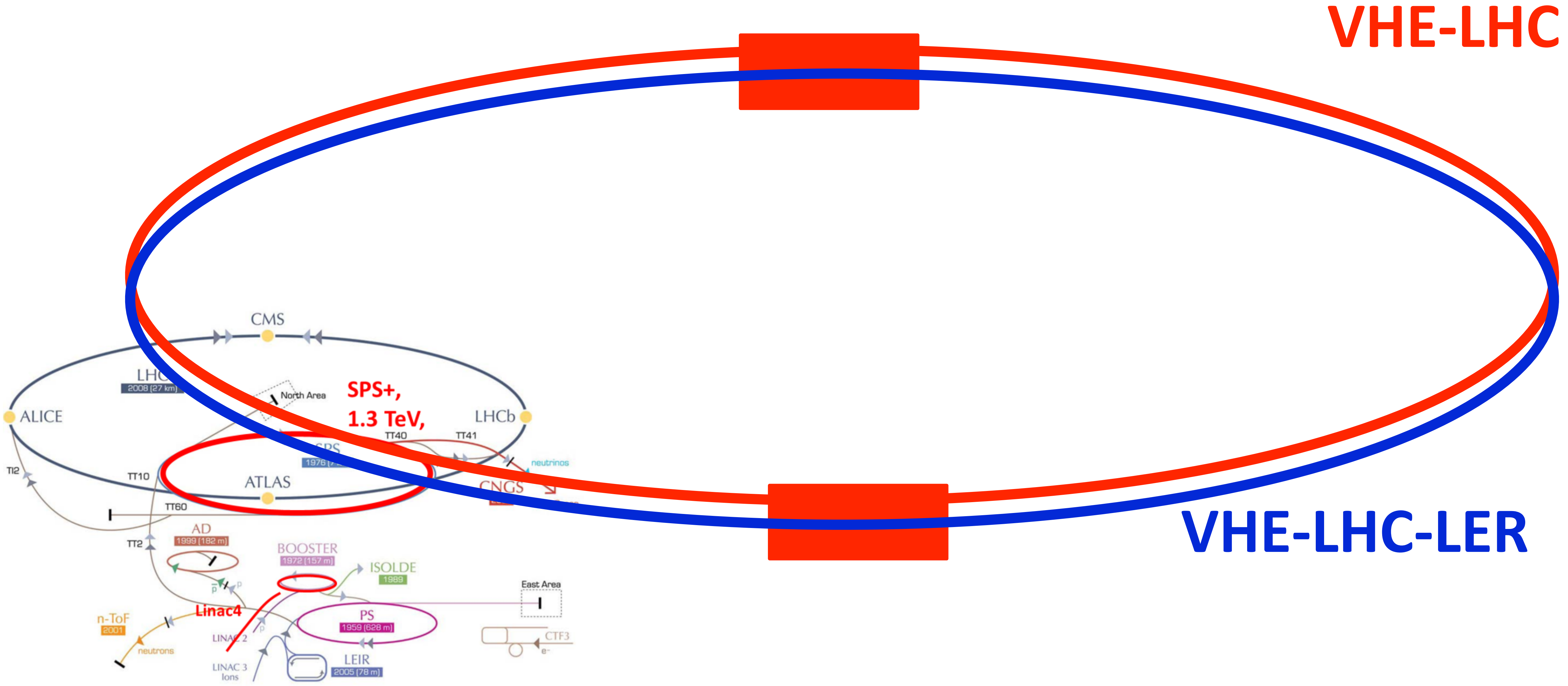
VHE-LHC
VHE-LHC-LER
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LINAC 3
Ions
LEIR
2005 (78 m)
CTF3

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 120 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	***$e^{\pm}$***	*p*	***$e^{\pm}$***	*p*
beam energy [GeV]	**120**	**7000**	**120**	**50000**
bunch spacing [μs]	3	3	3	3
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	24.3	51.0	24.3	51.0
rms bunch length [cm]	0.17	4	0.17	2
rms emittance [nm]	10,2	0.40	10,2	0.06
$\beta_{x,y}$*[cm]	2,1	60,5	0.5,0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	0.05, 0.09	**0.03,0.01**	0.07,0.10	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.8		4.9	
luminosity [10^{34} $cm^{-2}s^{-1}$]	[illegible]		[illegible]	

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 120 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	***$e^{\pm}$***	*p*	***$e^{\pm}$***	*p*
beam energy [GeV]	**120**	**7000**	**120**	**50000**
bunch spacing [μs]	3	3	3	3
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	24.3	51.0	24.3	51.0
rms bunch length [cm]	0.17	4	0.17	2
rms emittance [nm]	10,2	0.40	10,2	0.06
$\beta_{x,y}$*[cm]	2,1	60,5	0.5,0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	0.05, 0.09	**0.03,0.01**	0.07,0.10	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.8		4.9	
luminosity [10^{34} cm^{-2}s^{-1}]	[illegible]		[illegible]	

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 120 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	***e***$^{\pm}$	*p*	***e***$^{\pm}$	*p*
beam energy [GeV]	**120**	**7000**	**120**	**50000**
bunch spacing [μs]	3	3	3	3
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	24.3	51.0	24.3	51.0
rms bunch length [cm]	0.17	4	0.17	2
rms emittance [nm]	10,2	0.40	10,2	0.06
$\beta_{x,y}$*[cm]	2,1	60,5	0.5,0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	0.05, 0.09	**0.03,0.01**	0.07,0.10	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.8		4.9	
luminosity [10^{34} $cm^{-2}s^{-1}$]	[illegible]		[illegible]	

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 120 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	$e^{\pm}$	p	$e^{\pm}$	p
beam energy [GeV]	**120**	**7000**	**120**	**50000**
bunch spacing [μs]	3	3	3	3
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	24.3	51.0	24.3	51.0
rms bunch length [cm]	0.17	4	0.17	2
rms emittance [nm]	10,2	0.40	10,2	0.06
$\beta_{x,y}$* [cm]	2,1	60,5	0.5,0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	0.05, 0.09	**0.03,0.01**	0.07,0.10	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.8		4.9	
luminosity [10^{34} cm^{-2}s^{-1}]	[illegible]		[illegible]	

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 120 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	***$e^{\pm}$***	*p*	***$e^{\pm}$***	*p*
beam energy [GeV]	**120**	**7000**	**120**	**50000**
bunch spacing [μs]	3	3	3	3
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	24.3	51.0	24.3	51.0
rms bunch length [cm]	0.17	4	0.17	2
rms emittance [nm]	10,2	0.40	10,2	0.06
$\beta_{x,y}$*[cm]	2,1	60,5	0.5,0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	0.05, 0.09	**0.03,0.01**	0.07,0.10	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.8		4.9	
luminosity [10^{34} $cm^{-2}s^{-1}$]	[illegible]		[illegible]	

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 120 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	***$e^{\pm}$***	*p*	***$e^{\pm}$***	*p*
beam energy [GeV]	**120**	**7000**	**120**	**50000**
bunch spacing [μs]	3	3	3	3
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	24.3	51.0	24.3	51.0
rms bunch length [cm]	0.17	4	0.17	2
rms emittance [nm]	10,2	0.40	10,2	0.06
$\beta_{x,y}$* [cm]	2,1	60,5	0.5,0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	0.05, 0.09	**0.03,0.01**	0.07,0.10	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.8		4.9	
luminosity [10^{34} cm^{-2}s^{-1}]	[illegible]		[illegible]	

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 120 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	$e^{\pm}$	p	$e^{\pm}$	p
beam energy [GeV]	**120**	**7000**	**120**	**50000**
bunch spacing [μs]	3	3	3	3
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	24.3	51.0	24.3	51.0
rms bunch length [cm]	0.17	4	0.17	2
rms emittance [nm]	10,2	0.40	10,2	0.06
$\beta_{x,y}$* [cm]	2,1	60,5	0.5,0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	0.05, 0.09	**0.03,0.01**	0.07,0.10	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.8		4.9	
luminosity [10^{34} cm^{-2}s^{-1}]				

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 60 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	***$e^{\pm}$***	*p*	***$e^{\pm}$***	*p*
beam energy [GeV]	**60**	**7000**	**60**	**50000**
bunch spacing [μs]	0.2	0.2	0.2	0.2
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	390	51.0	390	51.0
rms bunch length [cm]	0.18	4	0.18	2
rms emittance [nm]	10, 2	0.40	10, 2	0.06
$\beta_{x,y}$*[cm]	2, 1	60, 5	0.5, 0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	**0.10, 0.18**	**0.03,0.01**	**0.14, 0.20**	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.3		3.5	
luminosity [10^{34} $cm^{-2}s^{-1}$]	[illegible]		[illegible]	

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 60 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	***$e^{\pm}$***	*p*	***$e^{\pm}$***	*p*
beam energy [GeV]	**60**	**7000**	**60**	**50000**
bunch spacing [μs]	0.2	0.2	0.2	0.2
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	390	51.0	390	51.0
rms bunch length [cm]	0.18	4	0.18	2
rms emittance [nm]	10, 2	0.40	10, 2	0.06
$\beta_{x,y}$*[cm]	2, 1	60, 5	0.5, 0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	**0.10, 0.18**	**0.03,0.01**	**0.14, 0.20**	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.3		3.5	
luminosity [10^{34} $cm^{-2}s^{-1}$]	[illegible]		[illegible]	

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 60 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	***$e^{\pm}$***	*p*	***$e^{\pm}$***	*p*
beam energy [GeV]	**60**	**7000**	**60**	**50000**
bunch spacing [μs]	0.2	0.2	0.2	0.2
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	390	51.0	390	51.0
rms bunch length [cm]	0.18	4	0.18	2
rms emittance [nm]	10, 2	0.40	10, 2	0.06
$\beta_{x,y}$*[cm]	2, 1	60, 5	0.5, 0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	**0.10, 0.18**	**0.03,0.01**	**0.14, 0.20**	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.3		3.5	
luminosity [10^{34} $cm^{-2}s^{-1}$]	[illegible]		[illegible]	

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 60 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	***$e^{\pm}$***	*p*	***$e^{\pm}$***	*p*
beam energy [GeV]	**60**	**7000**	**60**	**50000**
bunch spacing [μs]	0.2	0.2	0.2	0.2
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	390	51.0	390	51.0
rms bunch length [cm]	0.18	4	0.18	2
rms emittance [nm]	10, 2	0.40	10, 2	0.06
$\beta_{x,y}$*[cm]	2, 1	60, 5	0.5, 0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	**0.10, 0.18**	**0.03,0.01**	**0.14, 0.20**	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.3		3.5	
luminosity [10^{34} cm^{-2}s^{-1}]	[illegible]		[illegible]	

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 60 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	***$e^{\pm}$***	*p*	***$e^{\pm}$***	*p*
beam energy [GeV]	**60**	**7000**	**60**	**50000**
bunch spacing [μs]	0.2	0.2	0.2	0.2
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	390	51.0	390	51.0
rms bunch length [cm]	0.18	4	0.18	2
rms emittance [nm]	10, 2	0.40	10, 2	0.06
$\beta_{x,y}$*[cm]	2, 1	60, 5	0.5, 0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	**~~0.10, 0.18~~**	**0.03,0.01**	**~~0.14, 0.20~~**	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.3		3.5	