LHC Accelerator, Higgs Factory, and a Long-Term Strategy for High Energy Physics

Frank Zimmermann

ANL Physics Division Colloquium,
Chicago, 11 April 2013

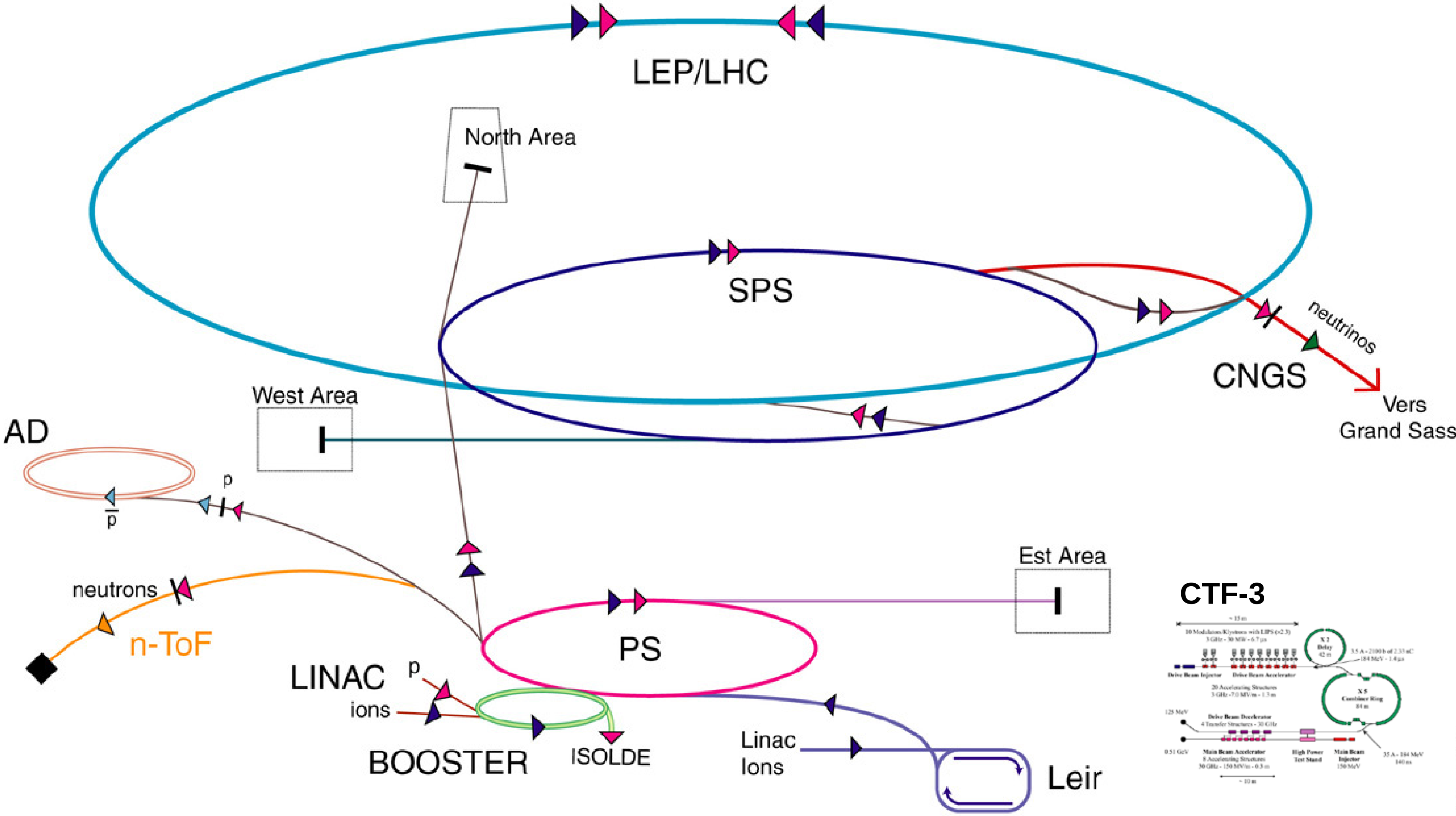
outline

- the Large Hadron Collider - LHC
- LHC performance so far
- plan for next 10 years
- LHC high-luminosity upgrade “HL-LHC”
- beyond LHC
  - higher-energy *pp* collider (“VHE-LHC,” “HE-LHC”) & circular e^+e^- Higgs factory (“TLEP,” “LEP3”) sharing the same infrastructure
  - a long-term strategy for high-energy physics

sequence of CERN accelerators

- PS - Proton Synchrotron (1959-)
  "first strong-focusing proton ring"
- ISR - Intersecting Storage Rings (1971-1985)
  "first hadron collider"
- SPS - Super Proton Synchrotron (1976-)
  "first proton-antiproton collider"
- LEP - Large Electron-Positron storage ring (1989-2001)
  "highest energy e^+e^- collider"
- LHC - Large Hadron Collider (2008-)
  "highest energy *pp* & *AA* collider"
- next machine?!?

Accelerator chain of CERN (operating or approved projects)



▶ p (proton)
▶ ion
▶ neutrons

p̄ ▷ (antiproton)
▶|▷ proton/antiproton conversion
▶ neutrinos

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutrons Time of Flight
CNGS Cern Neutrinos Grand Sasso

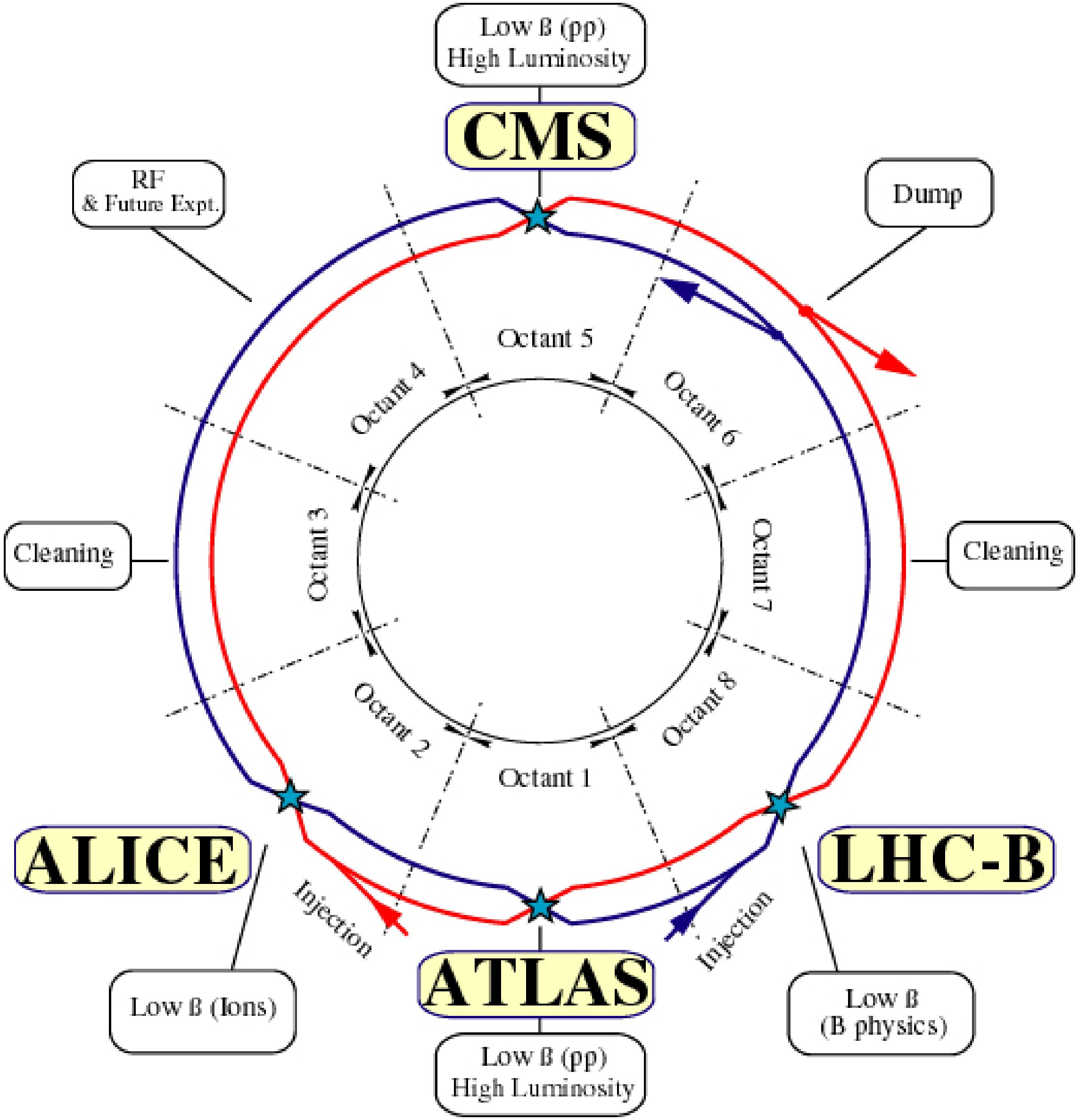
CERN AC _HF205_ V05/09/2001

CERN site view

Large Hadron Collider (LHC):

Superconducting Proton Accelerator & Collider installed in a 27 km circumference underground tunnel (4 m cross section); tunnel was built for LEP collider in 1985

LHC: highest energy *pp*, *AA*, and *pA* collider



design parameters

c.m. energy = 14 TeV (*p*)
luminosity =10^{34} $cm^{-2}s^{-1}$

1.15×10^{11} p/bunch
2808 bunches/beam

360 MJ/beam

$\gamma\varepsilon$=3.75 μm
β^*=0.55 m
θ_c=285 μrad
σ_z=7.55 cm
σ^*=16.6μm

short LHC history

1983 LEP Note 440 - S. Myers and W. Schnell propose
twin-ring *pp* collider in LEP tunnel w 9-T dipoles
1991 CERN Council: LHC approval in principle
1992 EoI, LoI of experiments
1993 SSC termination
1994 CERN Council: LHC approval
1995-98 cooperation w.Japan,India,Russia,Canada,&US
2000 LEP completion
2006 last s.c. dipole delivered
2008 first beam
2010 first collisions at 3.5 TeV beam energy
2015 collisions at ~design energy (plan)

>30 years

1st cyclotron, ~1930
E.O. Lawrence
11-cm diameter
1.1 MeV protons

LHC, 2015
9-km diameter
7 TeV protons

after ~85 years
~10^7 x more energy
~10^5 x larger

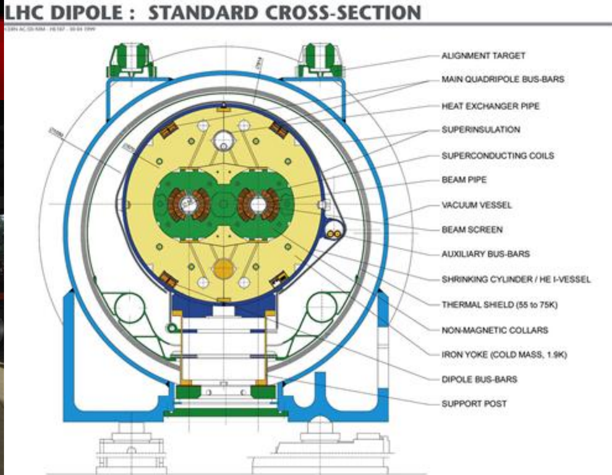
LHC tunnel 2002

L. Rossi

LHC tunnel 2006

L. Rossi

LHC s.c. dipole magnet – 8.33 T



twin magnet concept had been invented by R. Palmer for CBA

luminosity

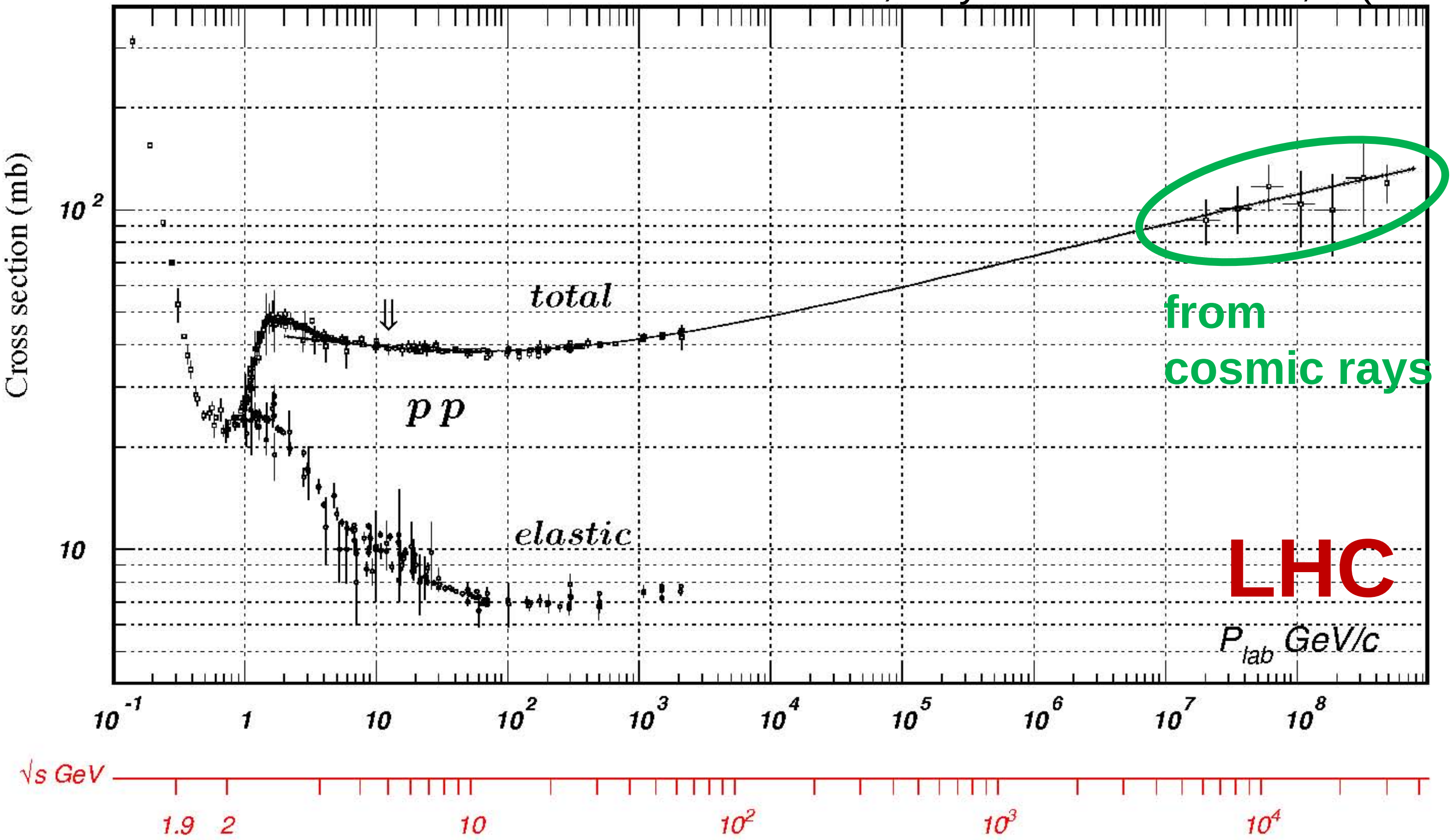
$$R = \sigma L$$

reaction rate

cross section

luminosity

C. Amsler *et al.*, Physics Letters **B667**, 1 (2008)



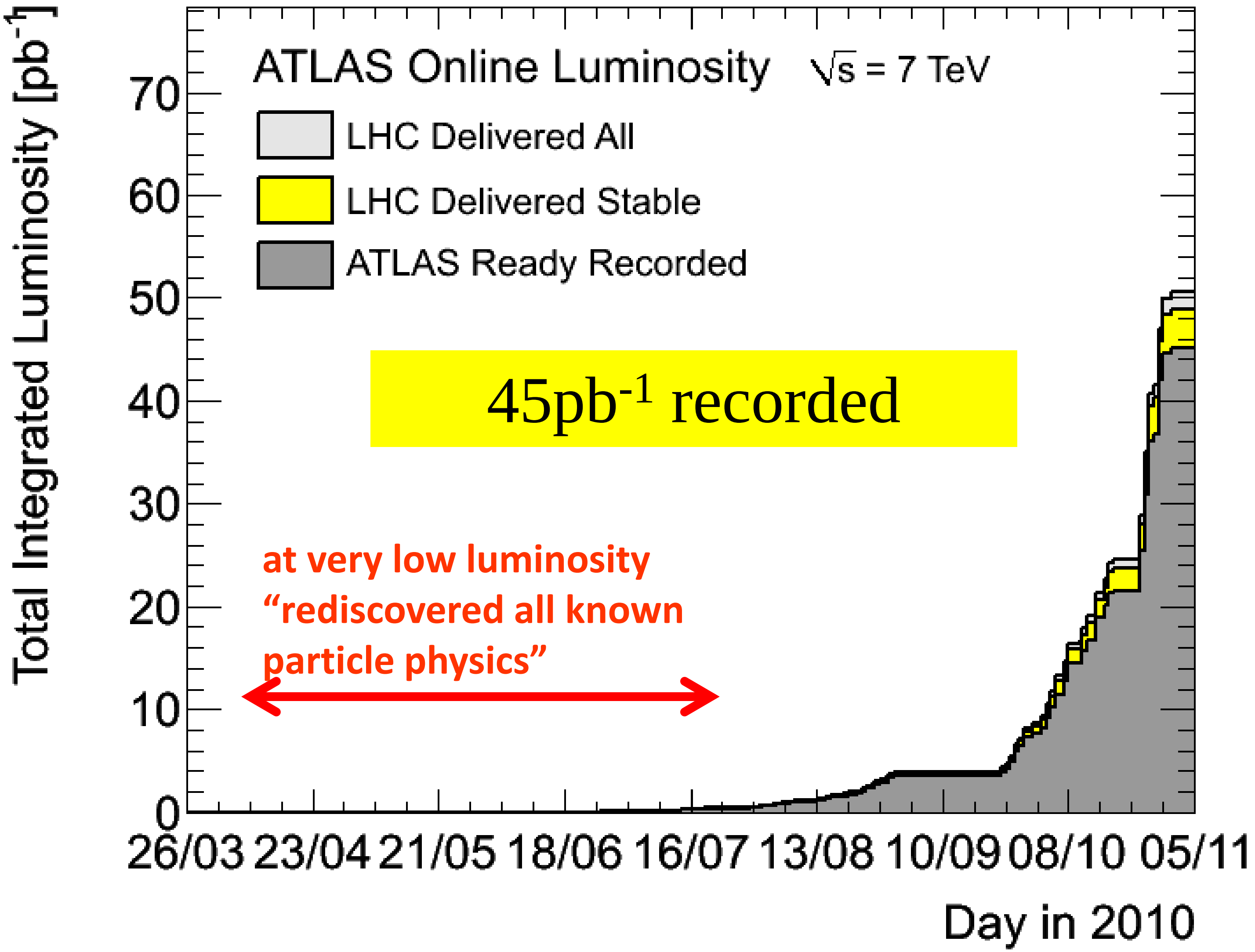
from cosmic rays

LHC

$\sigma_{tot} \sim$ 100 mbarn

$\sim 10^{-25}$ cm^2

integrated LHC luminosity in 2010

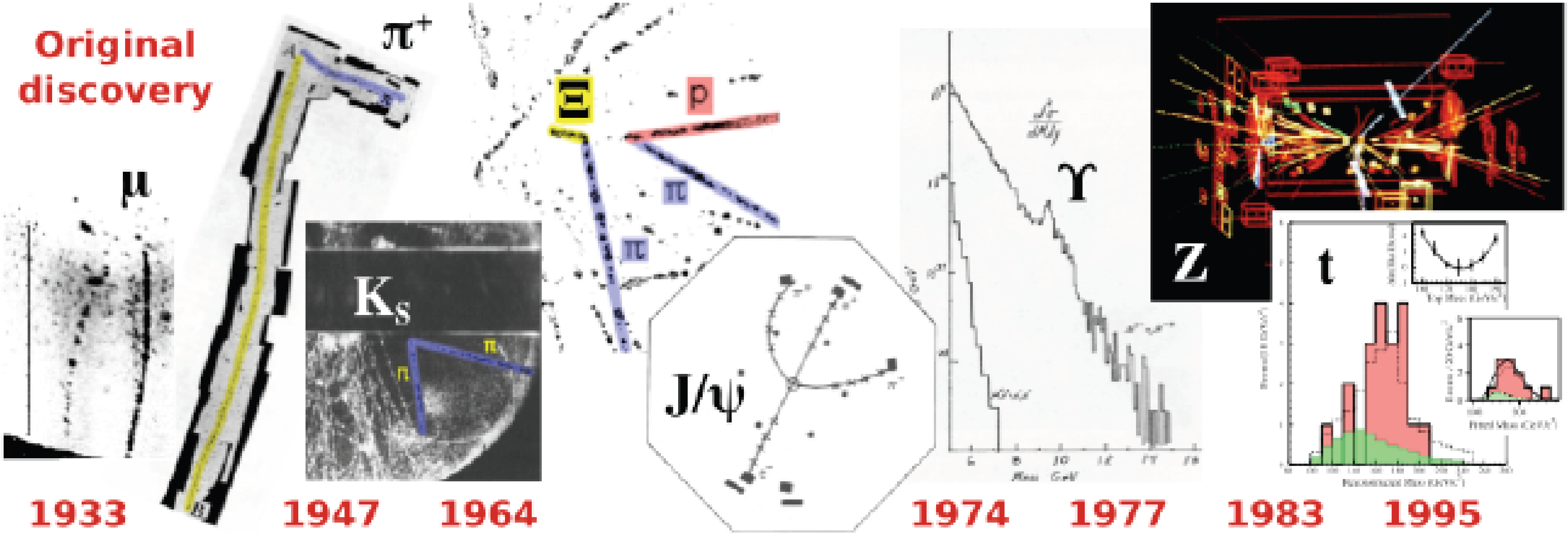


45pb^{-1} recorded

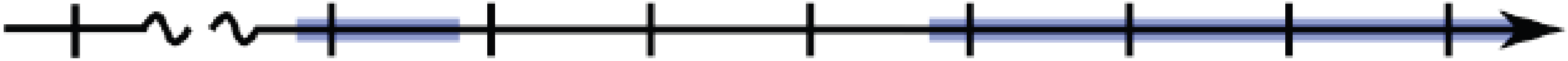
at very low luminosity
“rediscovered all known
particle physics”

Brief History of the Standard Model

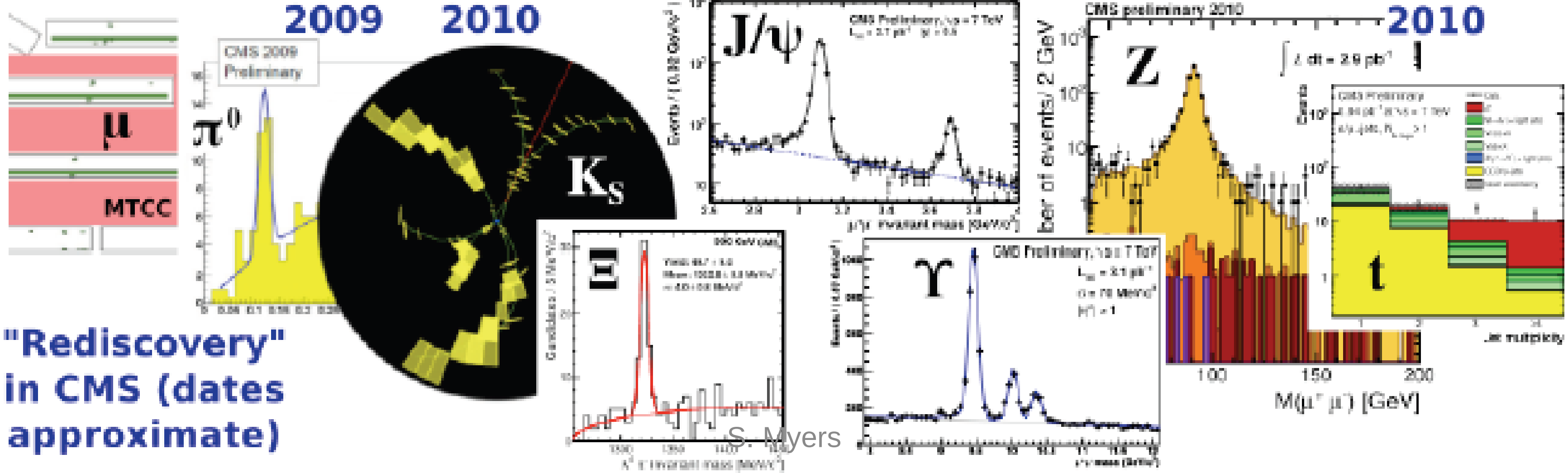
Original discovery



1933 1947 1964 1974 1977 1983 1995

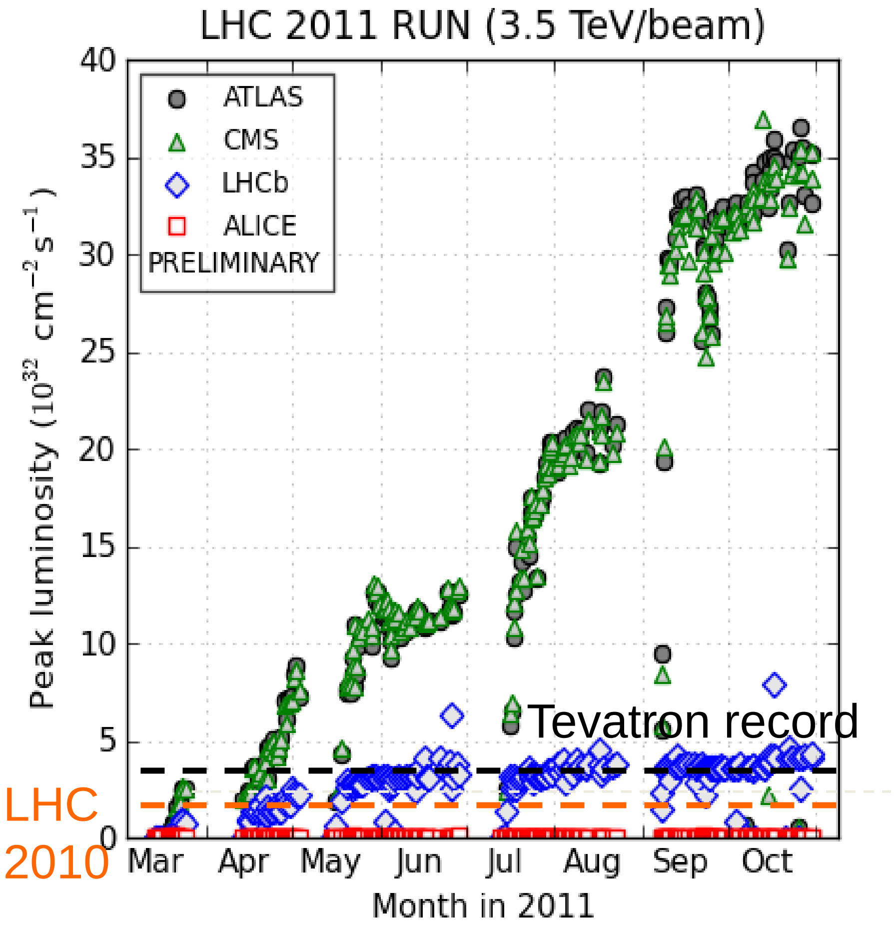


2006 Dec 2009 Jan 2010 Feb Mar Apr May Jun Jul 2010



"Rediscovery" in CMS (dates approximate)

peak *pp* luminosity in 2011 and 2012



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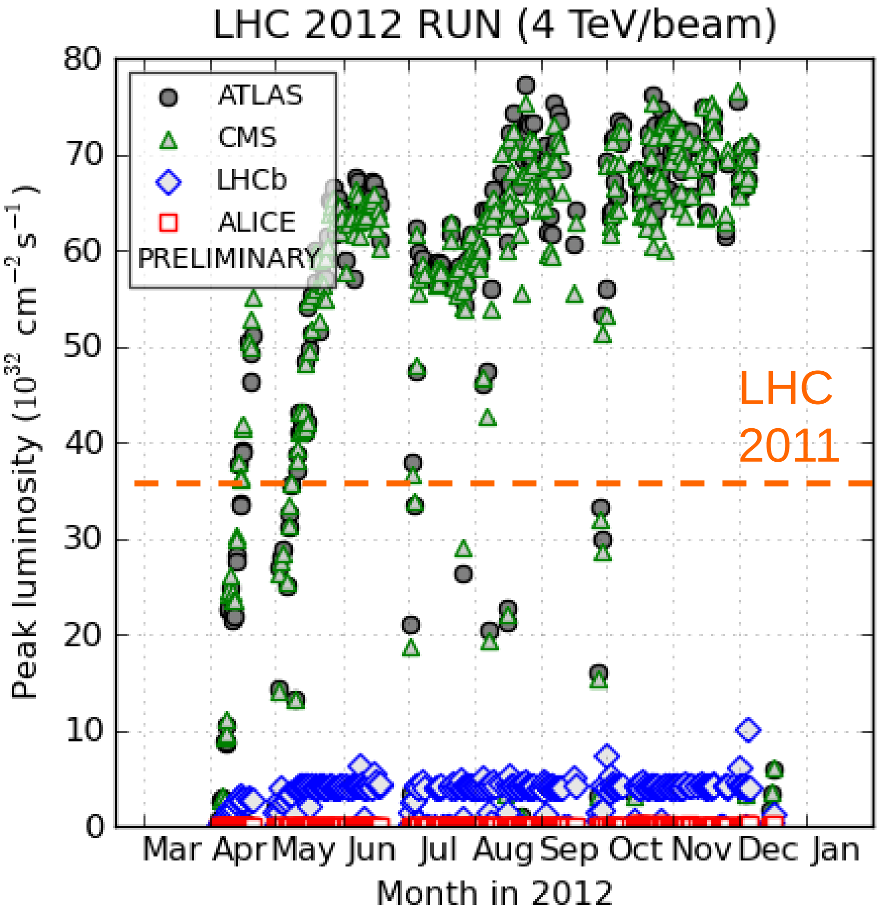

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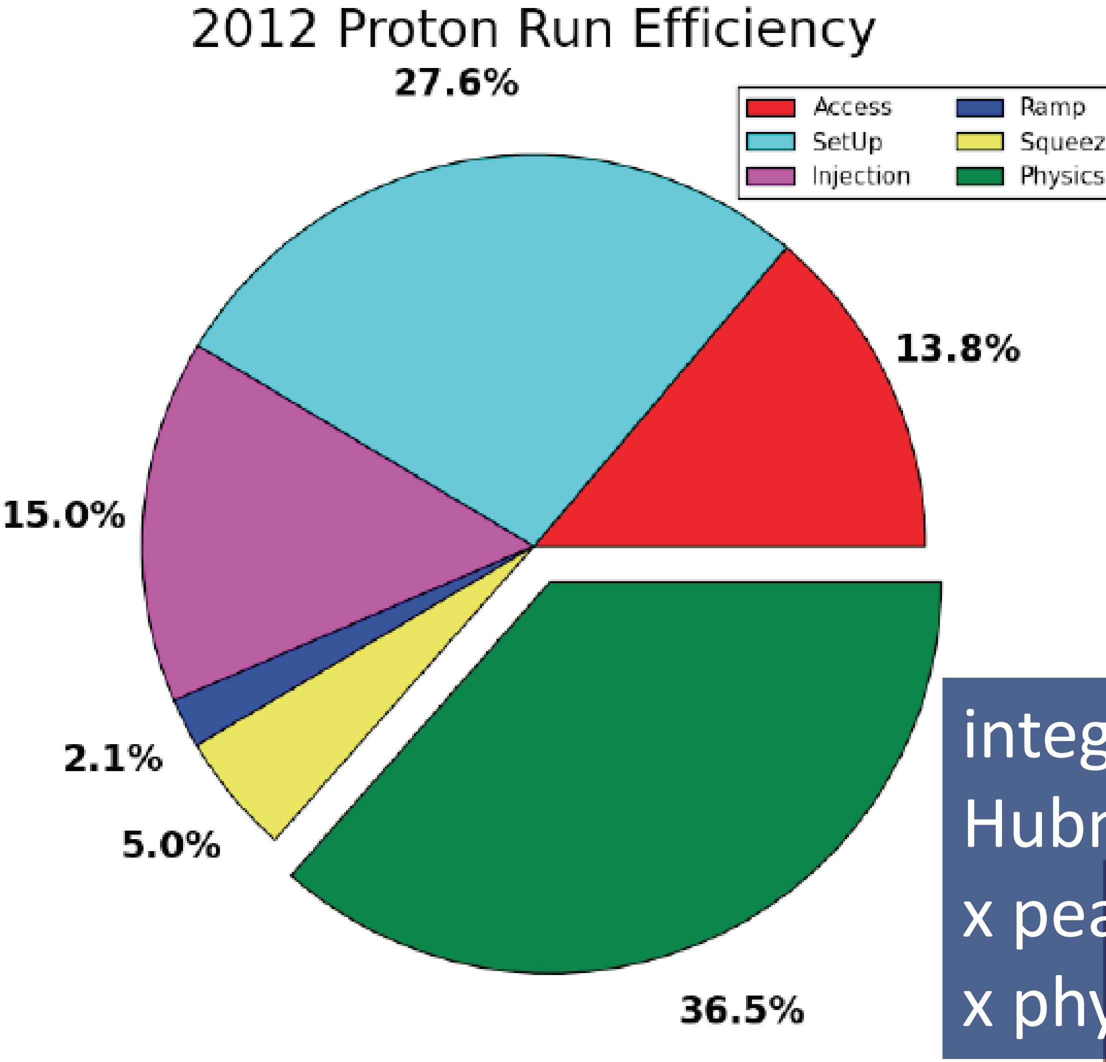
2012 Physics Run: Overall Availability



SB Time: 73.2 days **Total Time: 200.5 days**

<u>Hubner factor</u>

$H = 11.574 \times L_{Del} / (D \times L_{Peak})$

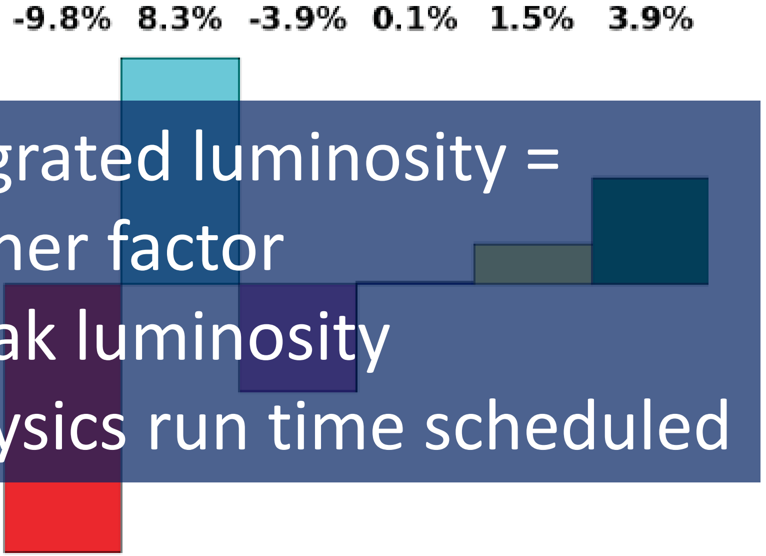
=> $\mathbf{H = 0.175}$

$D = 200.5$ days

$L_{Peak} = 7695\ (\mu b.s)^{-1}$

$L_{Del} = 23.269\ fb^{-1}$

$\mathbf{H_{2011\_LP} = 0.156}$

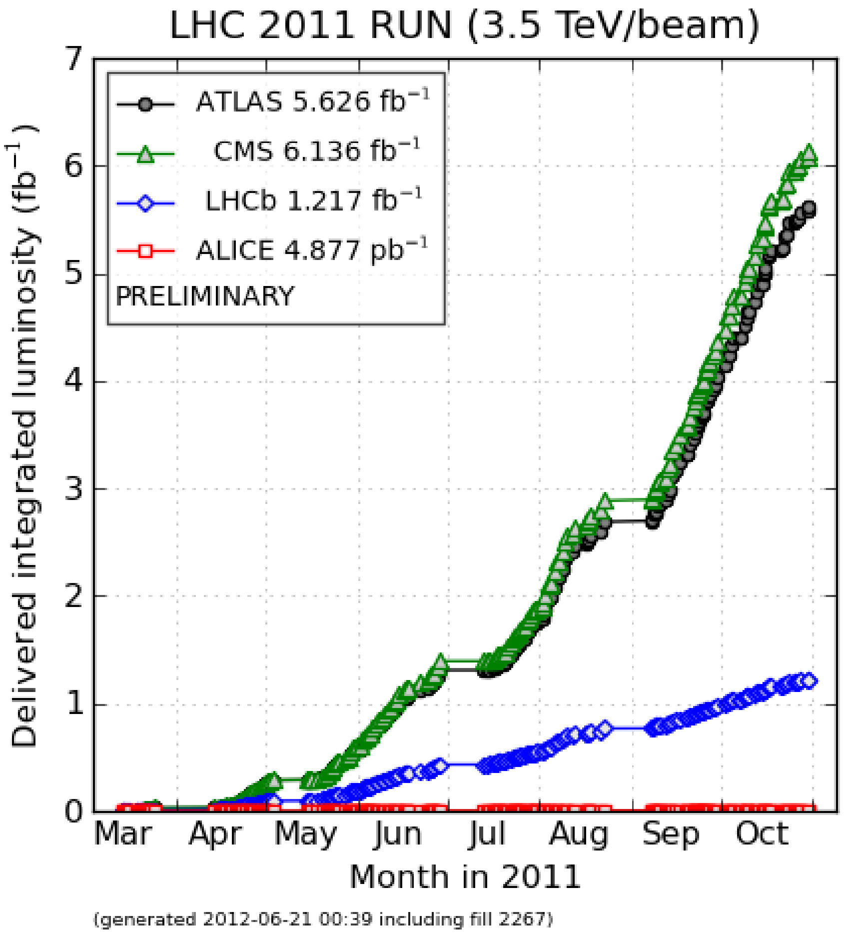


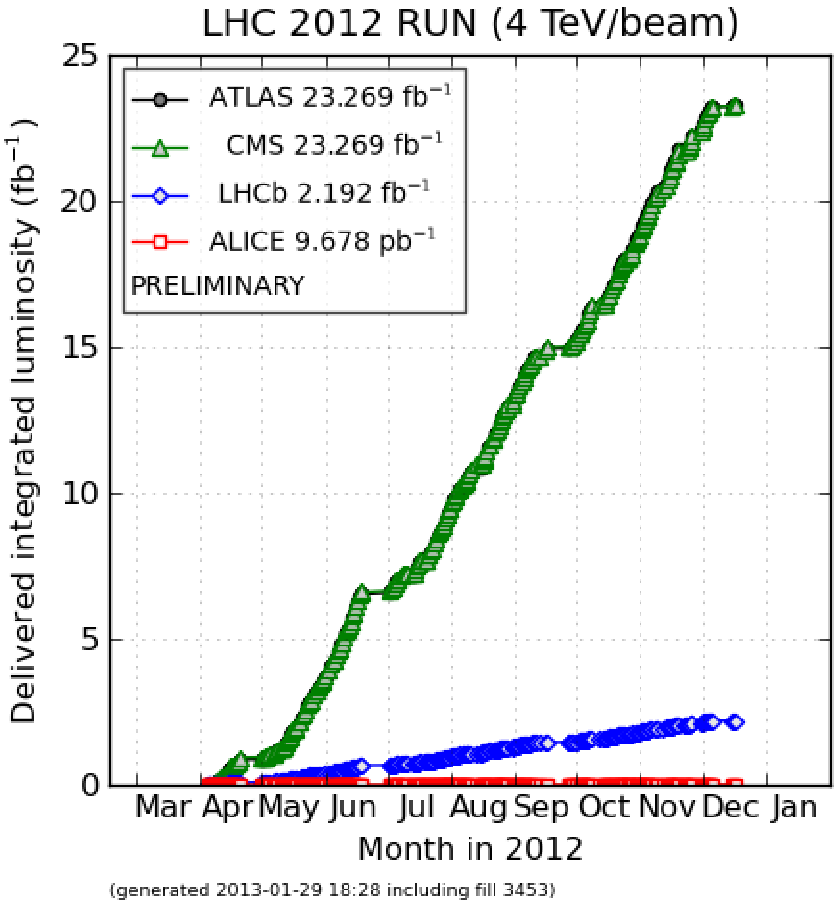
integrated luminosity =
Hubner factor
x peak luminosity
x physics run time scheduled

2012 Availability Compared to 2011 Production Run

Alick Macpherson

integrated *pp* luminosity in 2011 & 2012

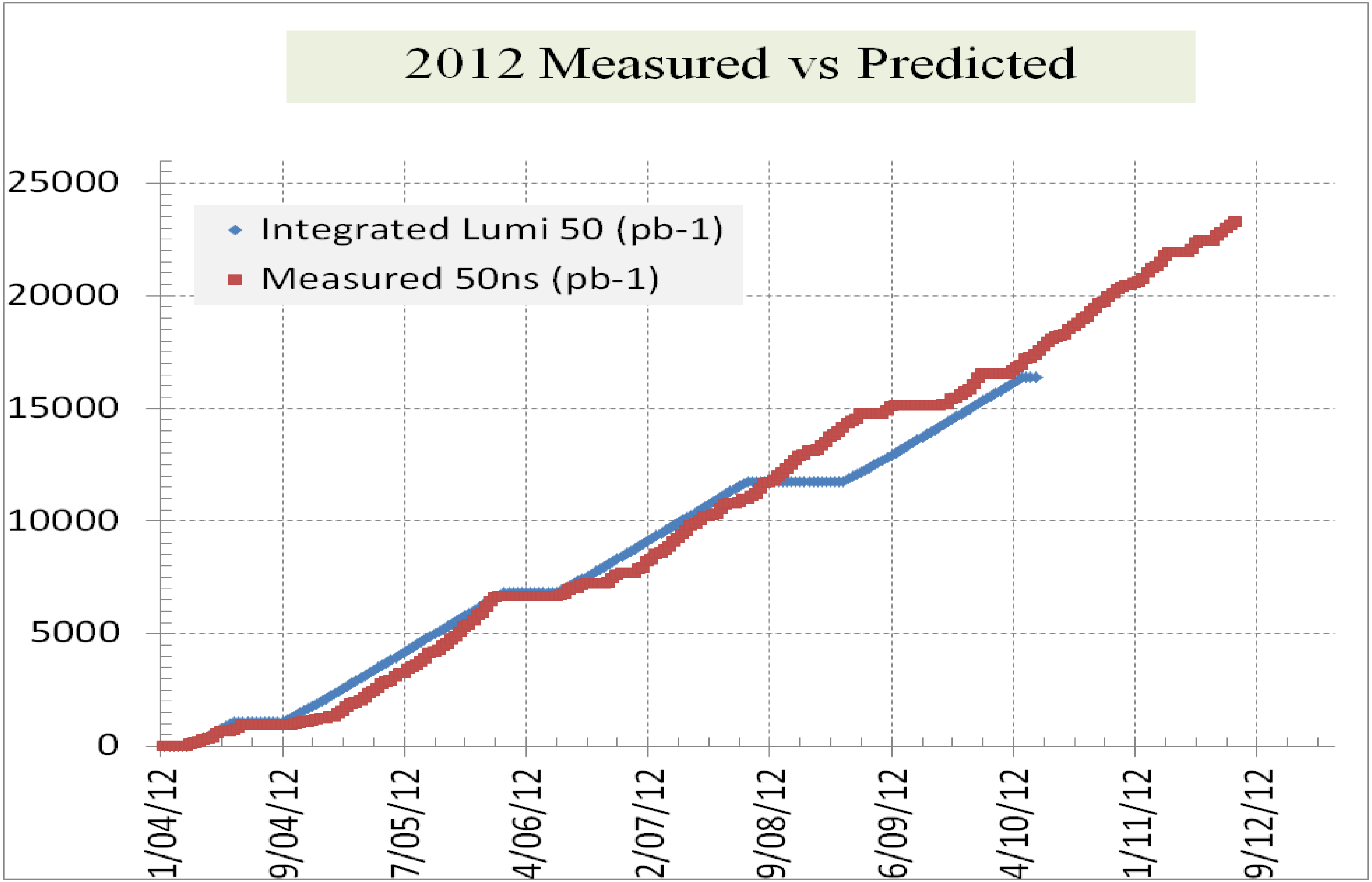




2011: >100 x 2010

2012: ~4x 2011 (for ATLAS & CMS)

2012


2012 Measured vs Predicted
Integrated Lumi 50 (pb-1)
Measured 50ns (pb-1)
25000
20000
15000
10000
5000
0
1/04/12
9/04/12
7/05/12
4/06/12
2/07/12
9/08/12
6/09/12
4/10/12
1/11/12
9/12/12

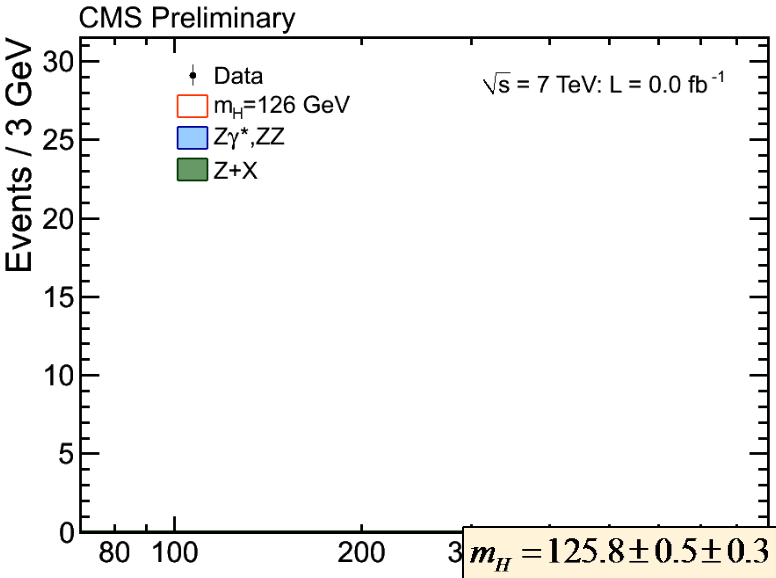
S. Myers

discovery of the "Higgs" boson

A new boson with mass ~ 126 GeV, and with SMS properties

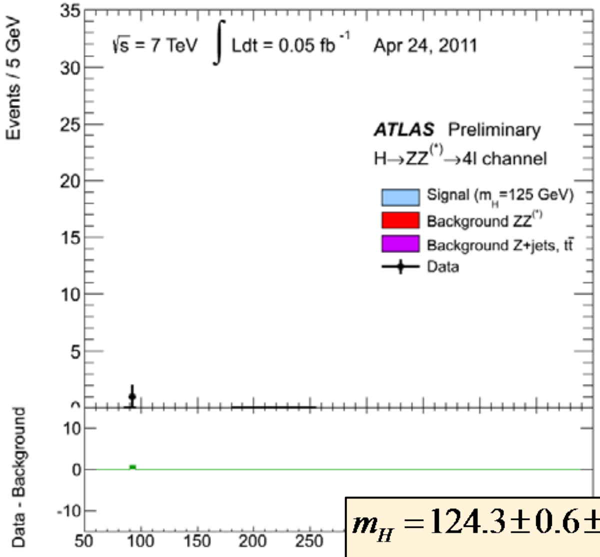
[1,2,3]

- Example : H(126) → ZZ → 4 leptons in CMS and ATLAS



$m_H = 125.8 \pm 0.5 \pm 0.3$ GeV

$\mu = 0.91^{+0.30}_{-0.24}$



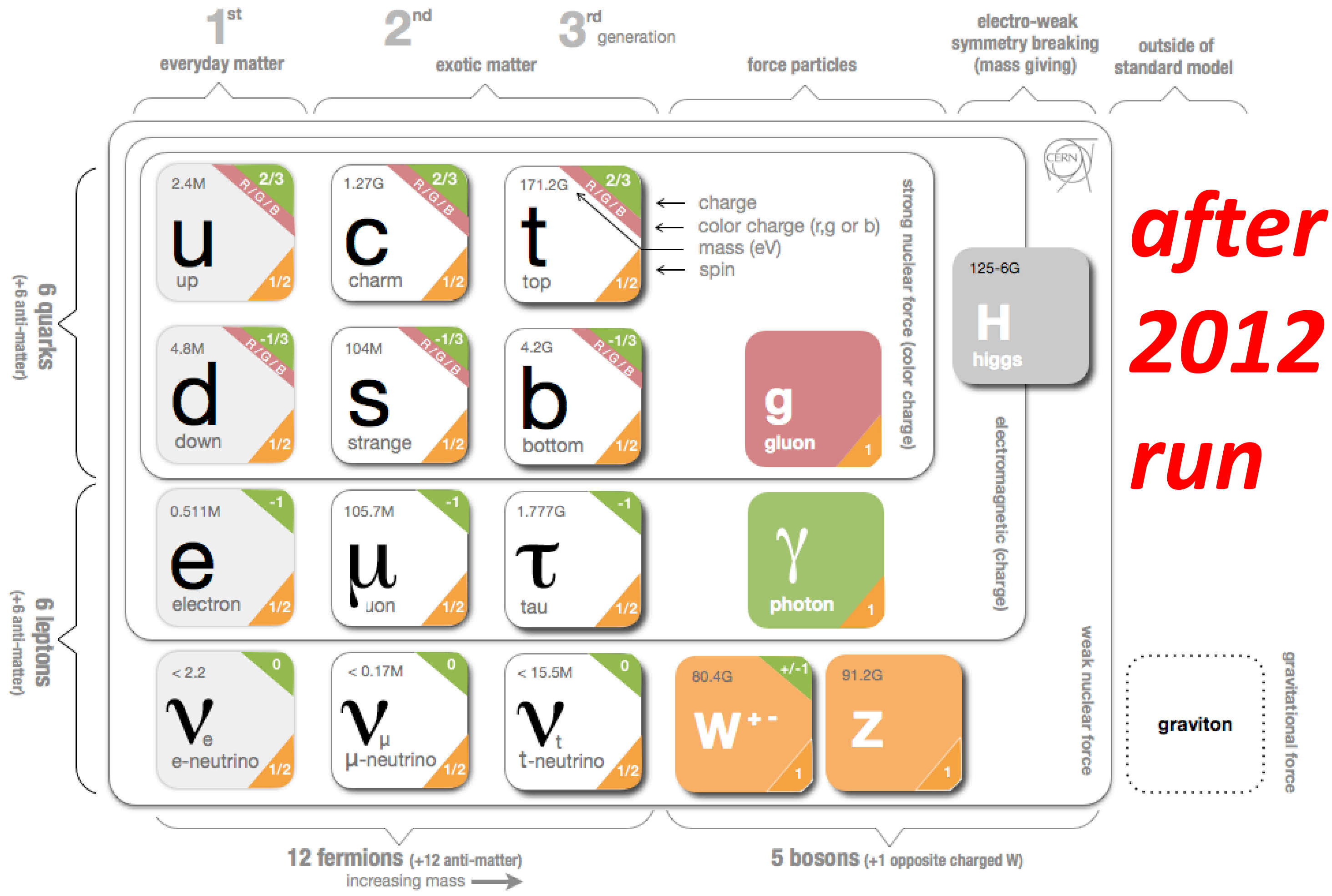
$m_H = 124.3 \pm 0.6 \pm 0.4$ GeV

$\mu = 1.5 \pm 0.4$ (at 125.5 GeV)

- H(126) couples to the Z boson (important for e^+e^- colliders)
- All couplings compatible with those of the Standard Model Scalar
- Scalar hypothesis favoured over pseudo-scalar or spin-2 particle
- m_H known to ~ 400 MeV
- A factor 100 luminosity will bring the statistical uncertainty on μ to a couple %.

[1] G. Gomez-Ceballos, "Study of SMS Production in bosonic decay channels with CMS", talk given at the Rencontres de Moriond (Mar. 2013)
[2] F. Hubaut, "Study of SMS production in bosonic decay channels with ATLAS", talk given at the Rencontres de Moriond (Mar. 2013)
[3] B. Mansoulié, "Combination of SMS results with ATLAS", talk given at the Rencontres de Moriond (Mar. 2013)

The Standard Model

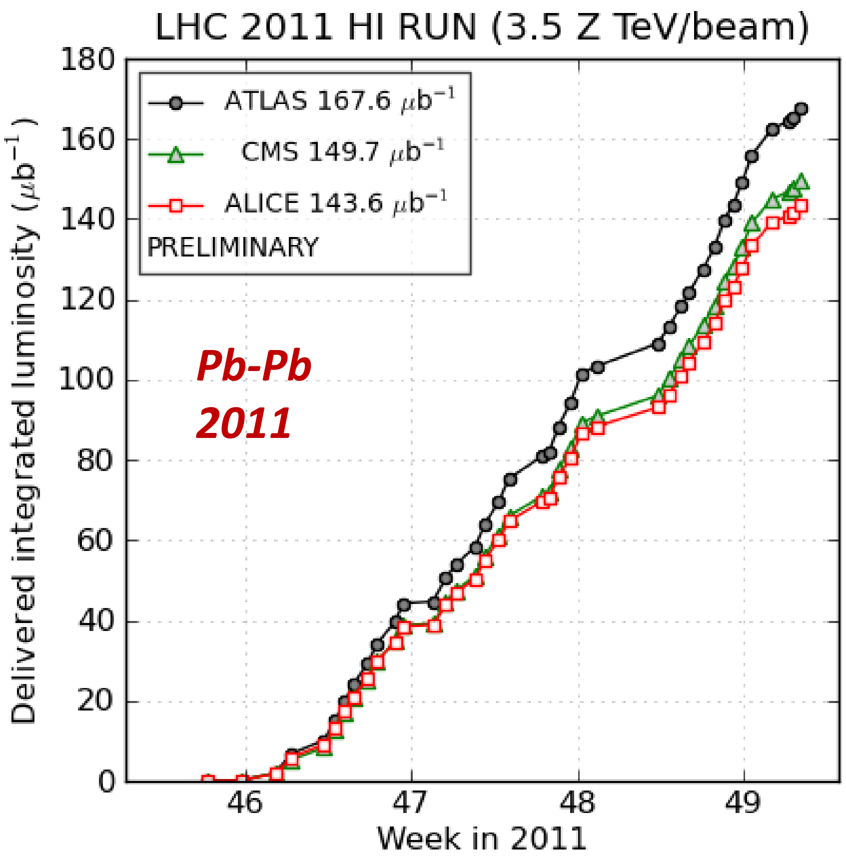


after 2012 LHC run

H: a very special particle, neither matter nor force; spin 0

LHC also runs as ion collider (~4 weeks/yr)

integrated *Pb-Pb* & *p-Pb* luminosity



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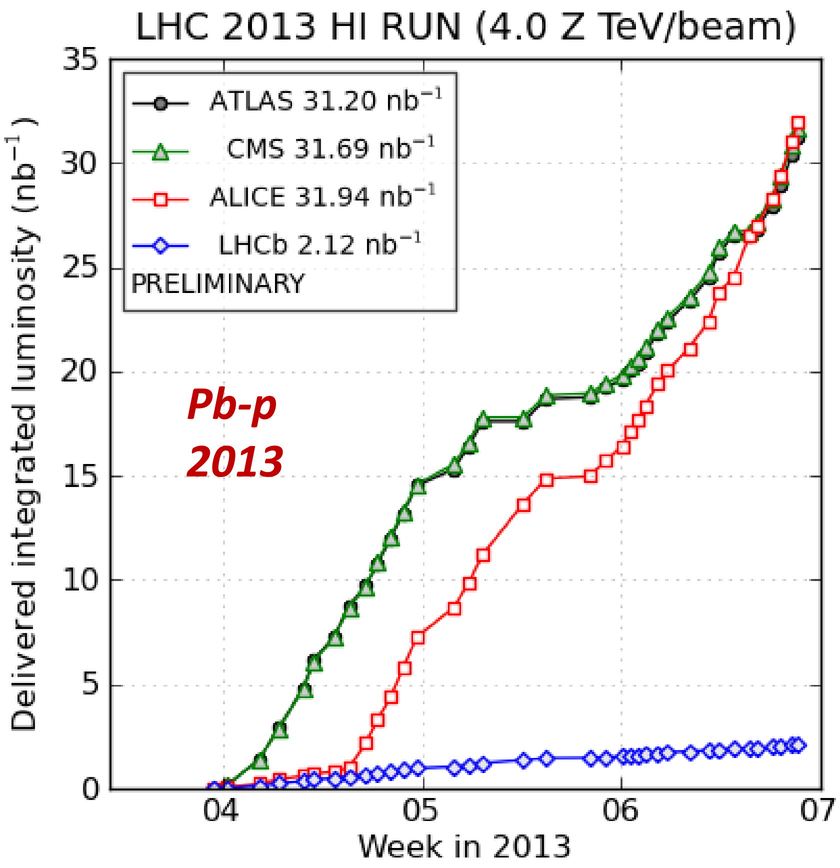
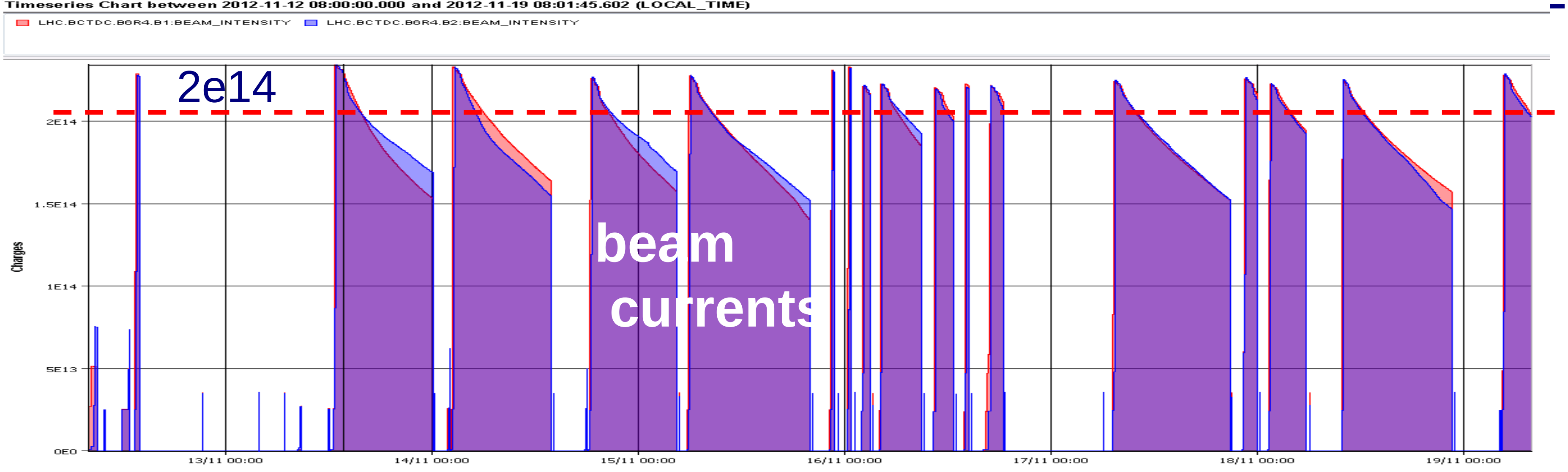


(including fill 3544)

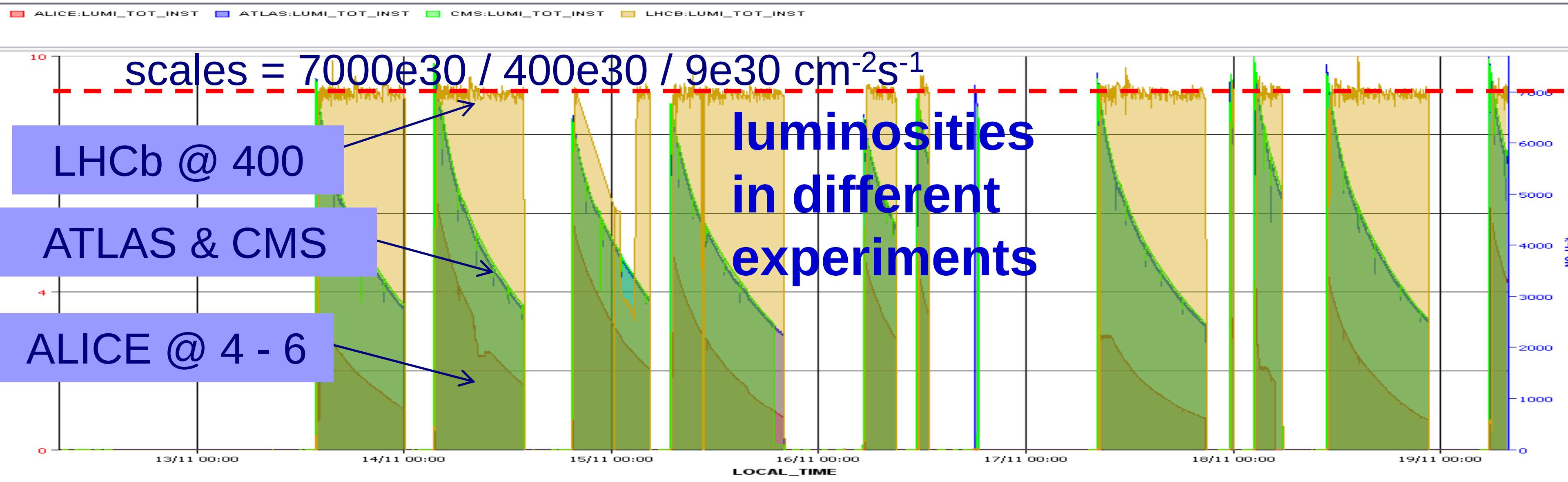
typical LHC week (#46) in 2012



2e14

beam currents

ADT CRYO TOTEM EPC ALICE RF



scales = 7000e30 / 400e30 / 9e30 $cm^{-2}s^{-1}$

LHCb @ 400

ATLAS & CMS

ALICE @ 4 - 6

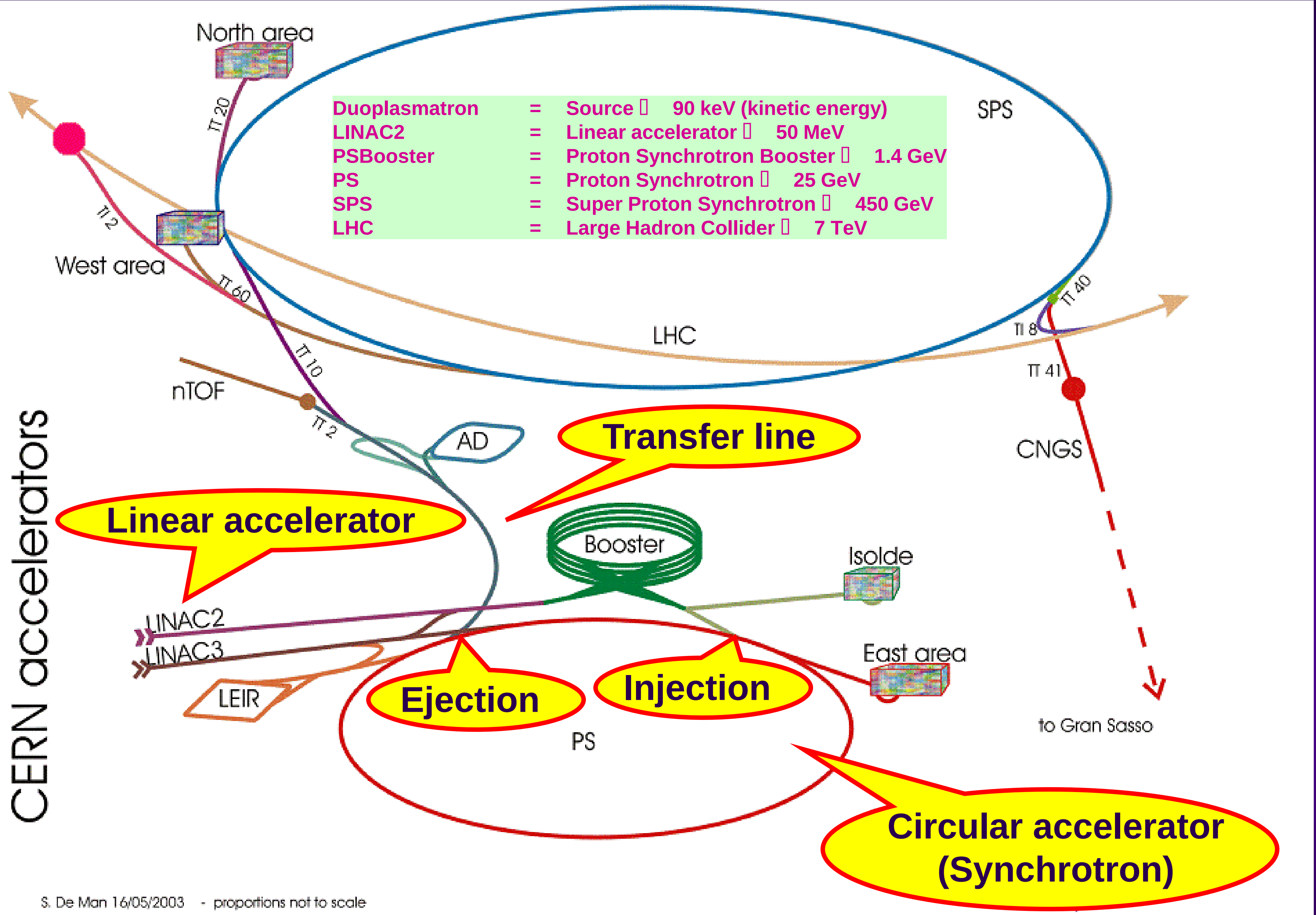
luminosities in different experiments

J. Uythoven, 21.11.2012

LHC actual versus design parameters

	design	June 2012	comment
beam energy	7 TeV	**4 TeV**	>1/2 design
transv. norm. emittance	3.75 μm	**2.4 μm**	0.7x design!
beta*	0.55 m	0.6 m	~ design for 7 TeV
IP beam size	16.7 μm	19 μm	~ design
bunch intensity	$1.15\mathrm{x}10^{11}$	**$1.58\mathrm{x}10^{11}$**	1.4xdesign!
luminosity / bunch	$3.6\mathrm{x}10^{30}$ cm^{-2}s^{-1}	$5.2\mathrm{x}10^{30}$ cm^{-2}s^{-1}	1.5x design
# colliding bunches	2808	1368	~ ½ design
bunch spacing	25 ns	**50 ns**	
beam current	0.582 A	0.390 A	~67% design
rms bunch length	7.55 cm	10 cm	> design
crossing angle	285 μrad	290 μrad	
“Piwinski angle”	0.64	0.79	
luminosity	10^{34} cm^{-2}s^{-1}	$7.1\mathrm{x}10^{33}$ cm^{-2}s^{-1}	~design at 7 TeV

LHC and its injector chain



Duoplasmatron = Source ▯ 90 keV (kinetic energy)
LINAC2 = Linear accelerator ▯ 50 MeV
PSBooster = Proton Synchrotron Booster ▯ 1.4 GeV
PS = Proton Synchrotron ▯ 25 GeV
SPS = Super Proton Synchrotron ▯ 450 GeV
LHC = Large Hadron Collider ▯ 7 TeV

Transfer line

Linear accelerator

Ejection

Injection

Circular accelerator (Synchrotron)

S. De Man 16/05/2003 - proportions not to scale

25 ns vs. 50 ns Spacing in 2012

Operational performance from injectors :

Bunch spacing	From Booster	Protons per bunch (ppb)	Emittance H&V [mm.mrad]
150	Single batch	1.1×10^{11}	1.6
75	Single batch	1.2×10^{11}	2.0
50	Single batch	1.45×10^{11}	3.5
50	Double batch	1.7×10^{11}	2.1
25	Double batch	1.15×10^{11}	2.8

main limits:
SC tune shift in booster & PS ; TMCI & CBI in SPS

$$L_{peak} \approx \frac{f_{rev} k_b N_b^2}{4\pi\sigma_x\sigma_y} R = \frac{f_{rev}\gamma k_b N_b^2}{4\pi\beta^* \varepsilon_n} R$$

at the same total beam current 50 ns gives >2x more luminosity!

in 2011-12 LHC was operating with 50-ns beams

injector improvements in 2012

new SPS optics (H. Bartosik, Y

- γ_t from 22.8 (Q

“Q26

“Q

or 2.85 at

t top energy

ntensity up to ~3x

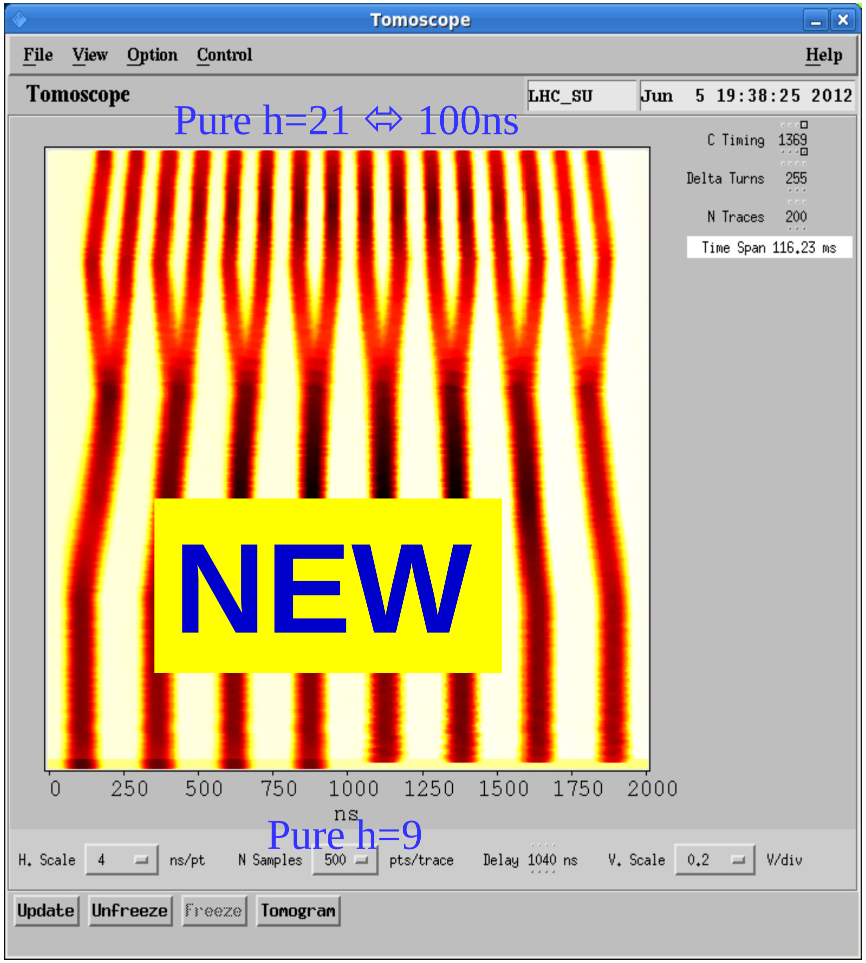
PS b ession (S. Hancock, H. Damerau)

- B intensity for same final intensity
- 3 50% gain in brightness

greatly improved beam parameters by ingenuously changing optics & RF gymnastics without any new hardware!

PS Batch Compression v. normal Triple Splitting

only bunch splitting →
batch compressing & bunch splitting



Tomoscope LHC_SU Jun 5 19:38:25 2012

C Timing 1369
Delta Turns 255
N Traces 200
Time Span 116.23 ms

H. Scale 4 ns/pt
N Samples 500 pts/trace
Delay 1040 ns
V. Scale 0.2 V/div

Pure h=21 ⇔ 100ns

NEW

Pure h=9

Double batch 4+4b, h=9 → 10 → 20 → 21, 16b

Tomoscope LHC_MD Mar 14 15:33:04 2012

C Timing 1369
Delta Turns 123
N Traces 200
Time Span 56.07 ms

H. Scale 4 ns/pt
N Samples 500 pts/trace
Delay 540 ns
V. Scale 0.5 V/div

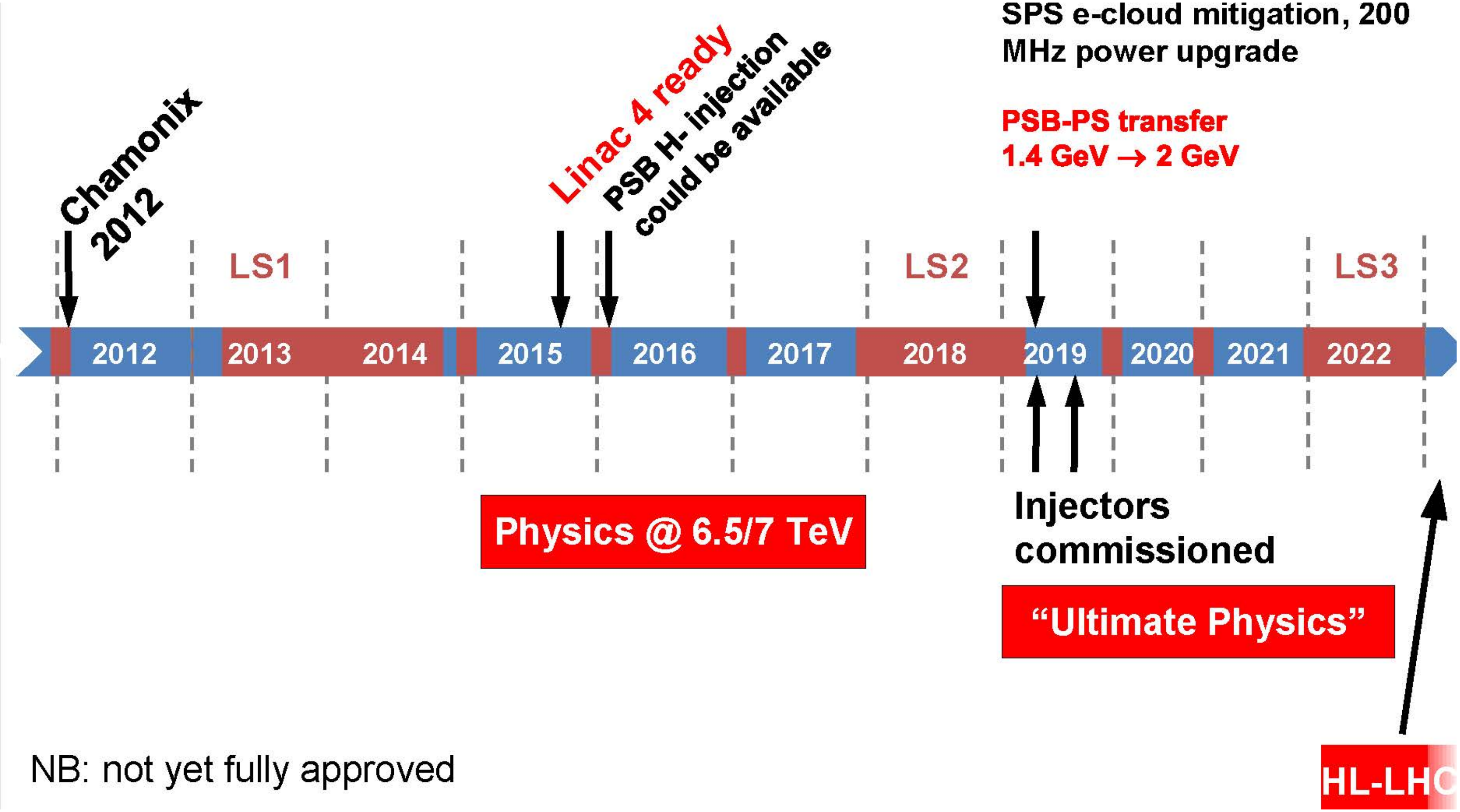
Pure h=21 ⇔ 100ns

OLD

Pure h=7

Double batch 4+2b, h=7 → 7+14+21 → 21, 18b

LHC time line – next ten years



NB: not yet fully approved

Ralph Steinhagen, ICHEP2012

2015:

25-ns bunch spacing (strong request from ATLAS & CMS for pile up)

~design energy (after IC consolidation)

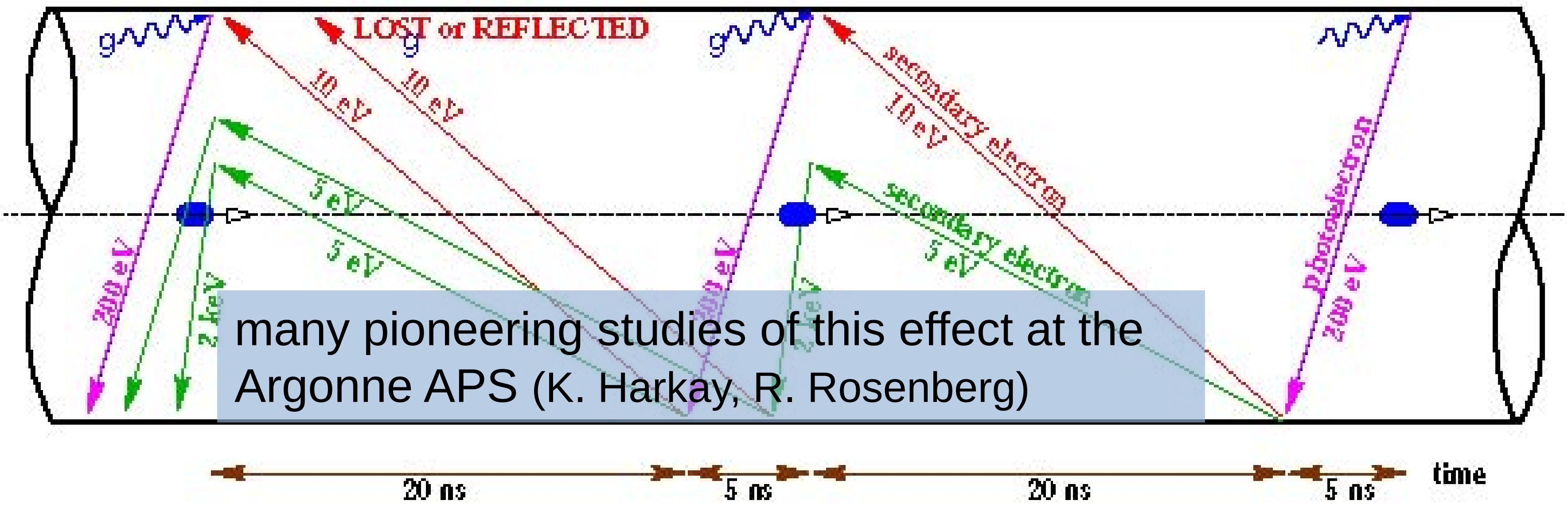
two uncertainties:

- electron cloud
- UFOs

both get more difficult at 25 ns & at higher energy

electron cloud

[F. Ruggiero]



many pioneering studies of this effect at the Argonne APS (K. Harkay, R. Rosenberg)

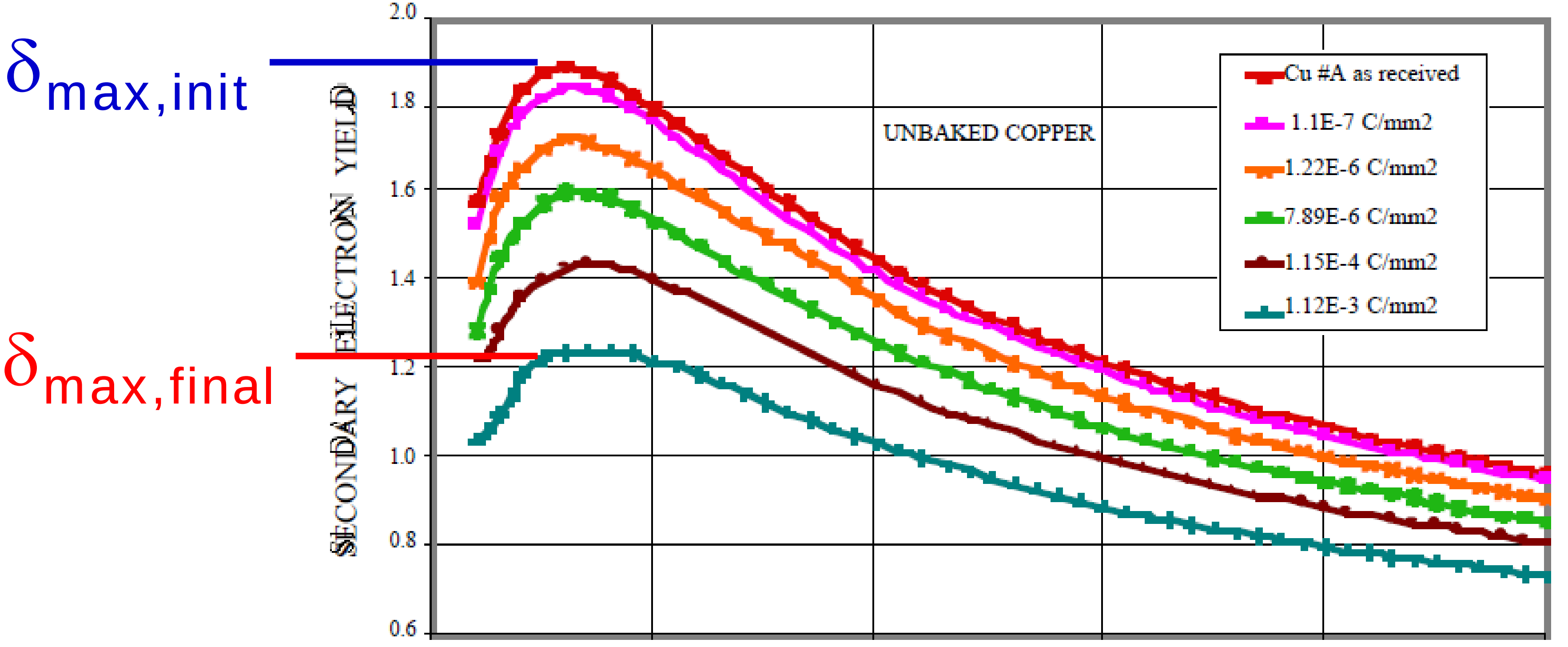
schematic of e- cloud build up in LHC beam pipe, due to **photoemission** and **secondary emission**

harmful consequences:

heat load (→ SC magnet quenches), instabilities, emittance growth, poor beam lifetime

effect much worse for 25 ns than for 50 ns

SEY conditioning by e^- bombardment

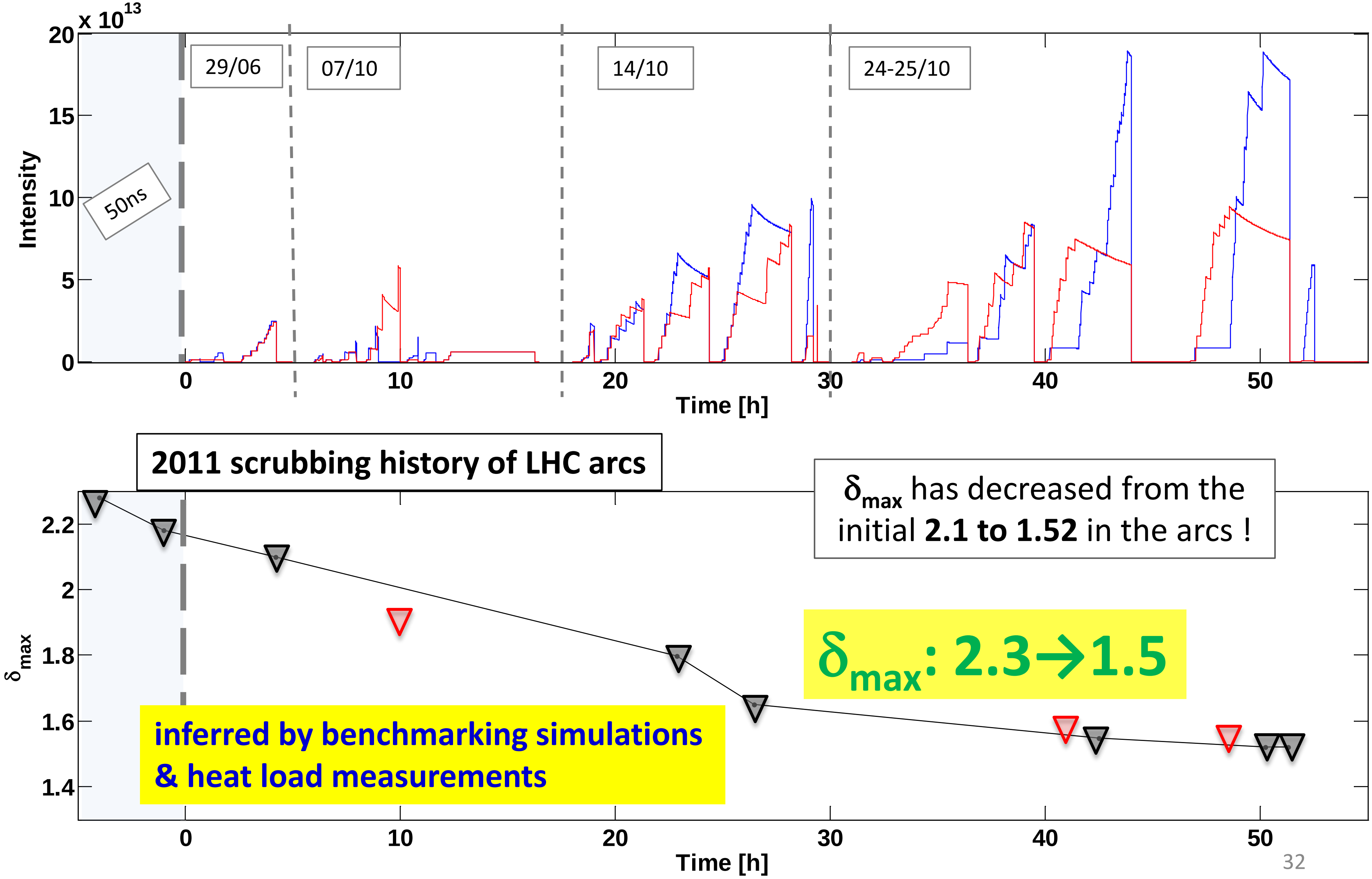


main strategy for LHC arcs: “scrubbing” at injection energy

THE SECONDARY ELECTRON YIELD OF TECHNICAL MATERIALS AND ITS VARIATION WITH SURFACE TREATMENTS V. Baglin, J. Bojko, O. Gröbner, B. Henrist, N. Hilleret, C. Scheuerlein and M. Taborelli
https://cds.cern.ch/record/466534?ln=it

G. Rumolo, G. Iadarola

arc SEY evolution during 25-ns scrubbing in **2011**:



2011 scrubbing history of LHC arcs

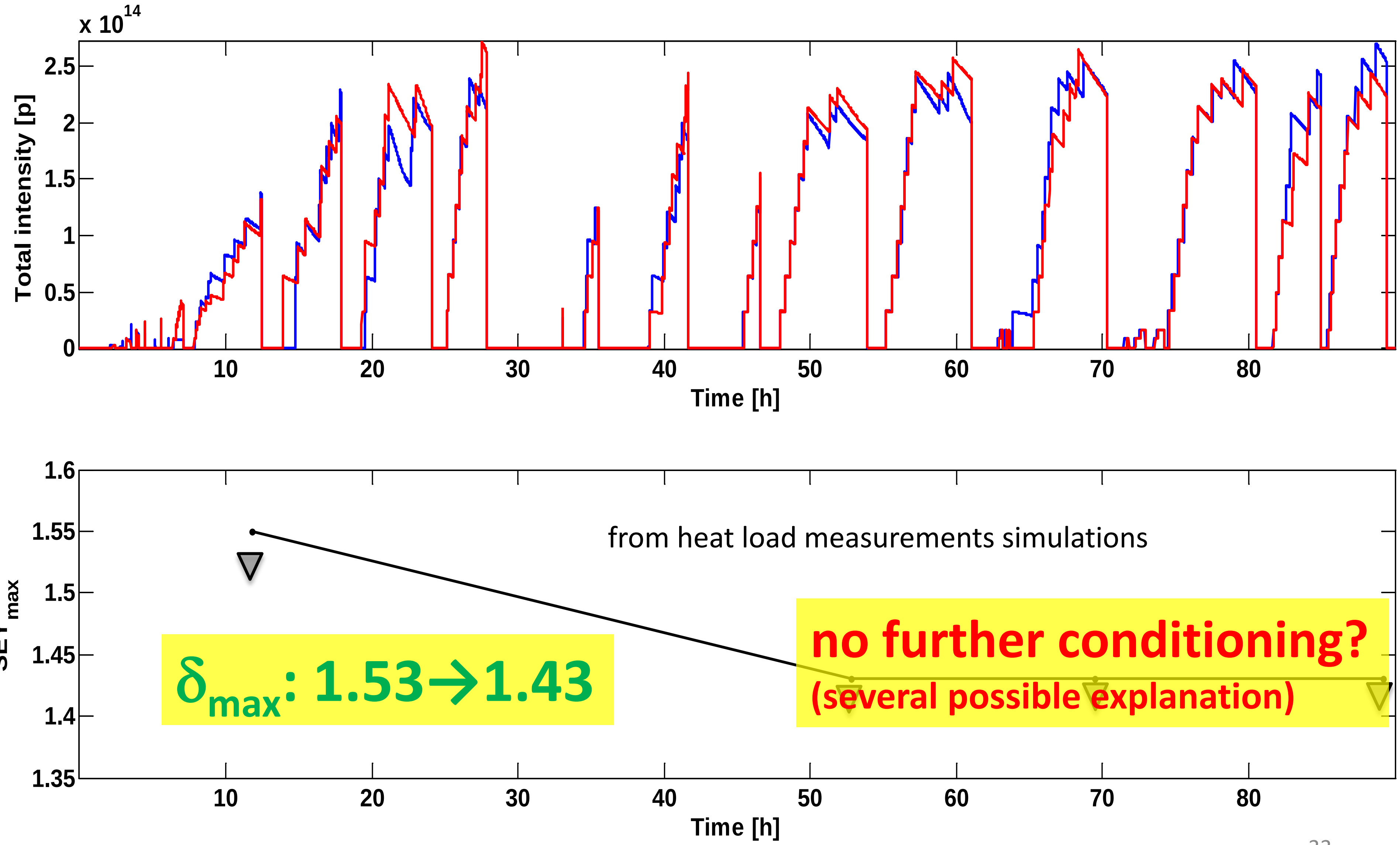
δ_{max} has decreased from the initial **2.1 to 1.52** in the arcs !

δ_{max}: 2.3→1.5

inferred by benchmarking simulations & heat load measurements

G. Rumolo, G. Iadarola

arc SEY evolution during 25-ns scrubbing in **2012**:



from heat load measurements simulations

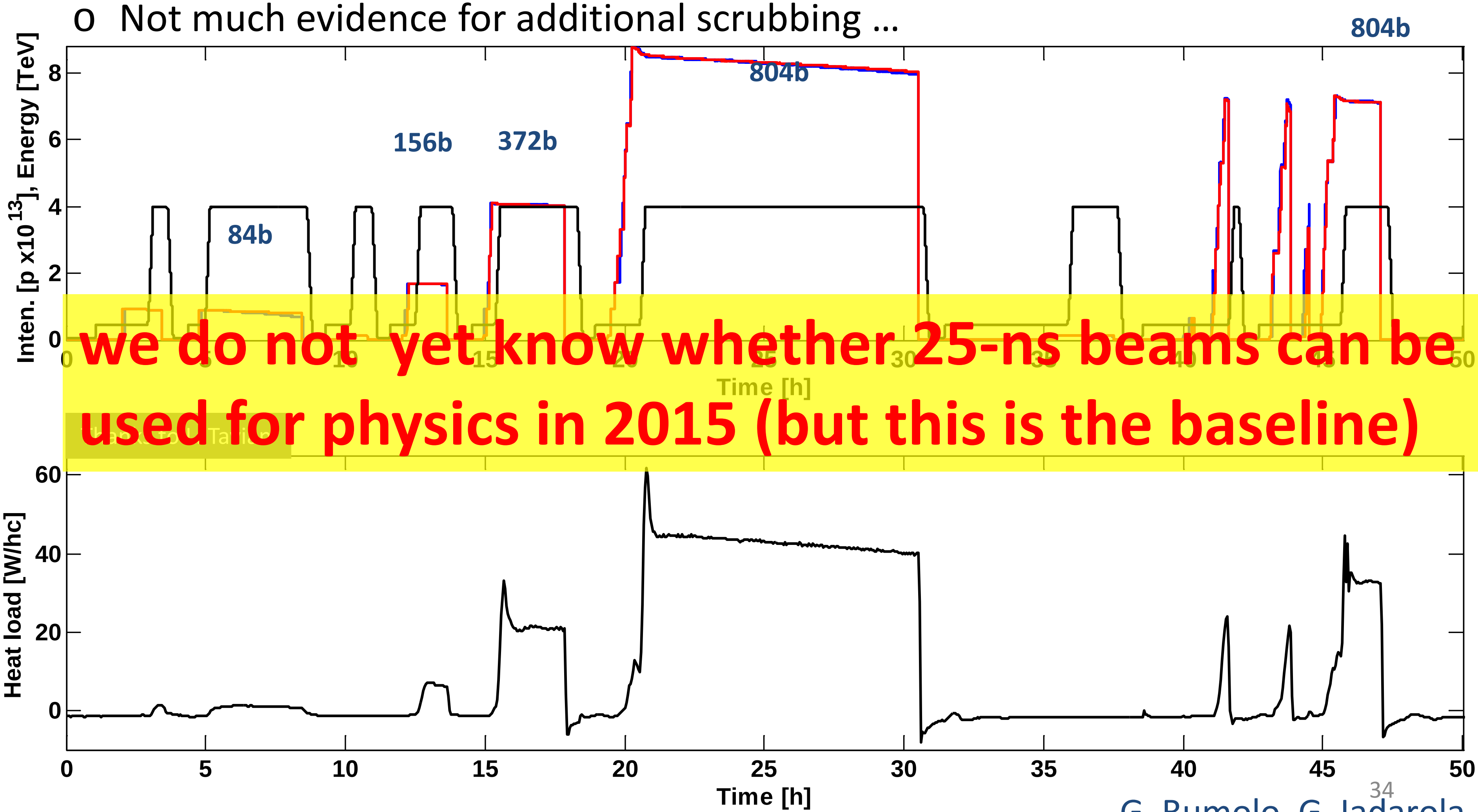
δ_{max}: 1.53→1.43

no further conditioning?

(several possible explanation)

arc heat load during trial energy ramp (12/2012)

- Enhanced heat load due to photoelectrons : 804 bunches at 4 TeV produce the same heat load as 2748 bunches at 450 GeV
- Violent transient during the ramp (limiting #bunches)
- Not much evidence for additional scrubbing …



we do not yet know whether 25-ns beams can be used for physics in 2015 (but this is the baseline)

G. Rumolo, G. Iadarola

LHC UFOs

T. Baer

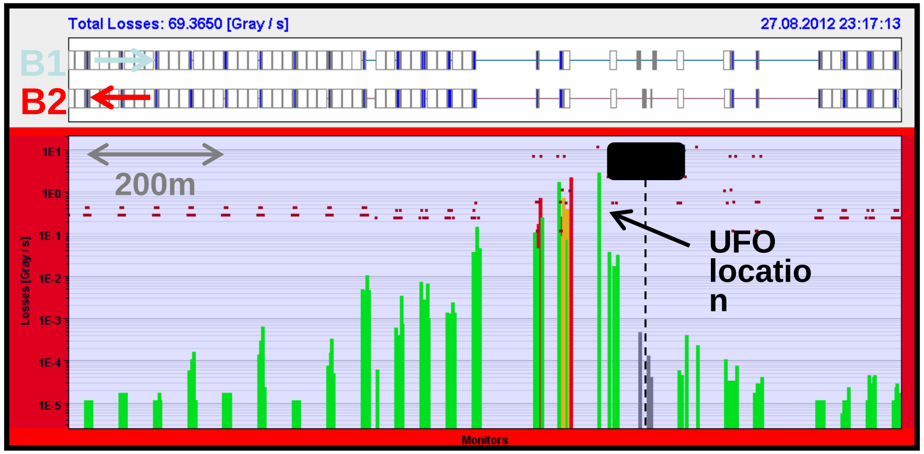
In 2012: **21 beam dumps** due to (***U***n)identified ***F***alling ***O***bjects.

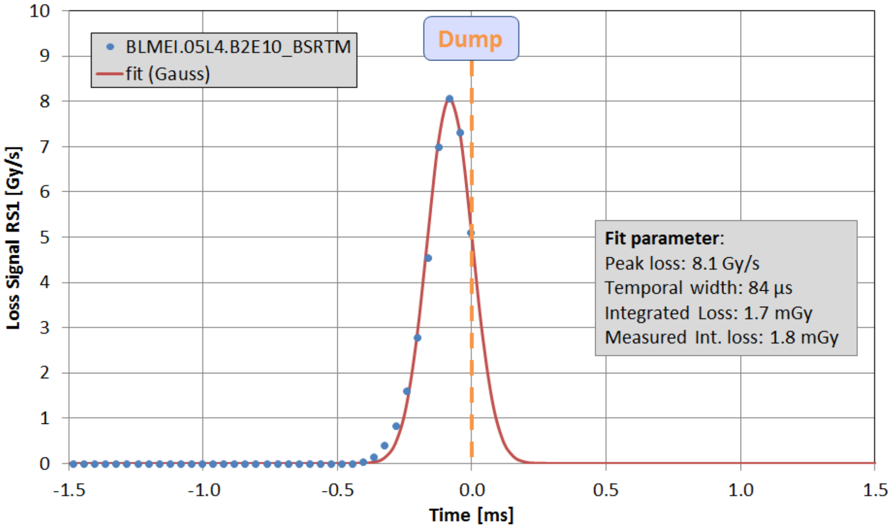
- *2011: 18 dumps, 2010: 18 dumps.*
- ***15 dumps at 4TeV****, 3 during ramp, 3 at 450GeV.*
- *8 dumps by MKI UFOs,*
  4 by UFOs around collimators during movement (TCL.5L5.B2, TCSG.4L6.B2)
  4 by ALICE Ufinos.

≈ 17,000 candidate UFOs

below BLM thresholds found in 2012

2011: about 16,000 candidate UFOs.

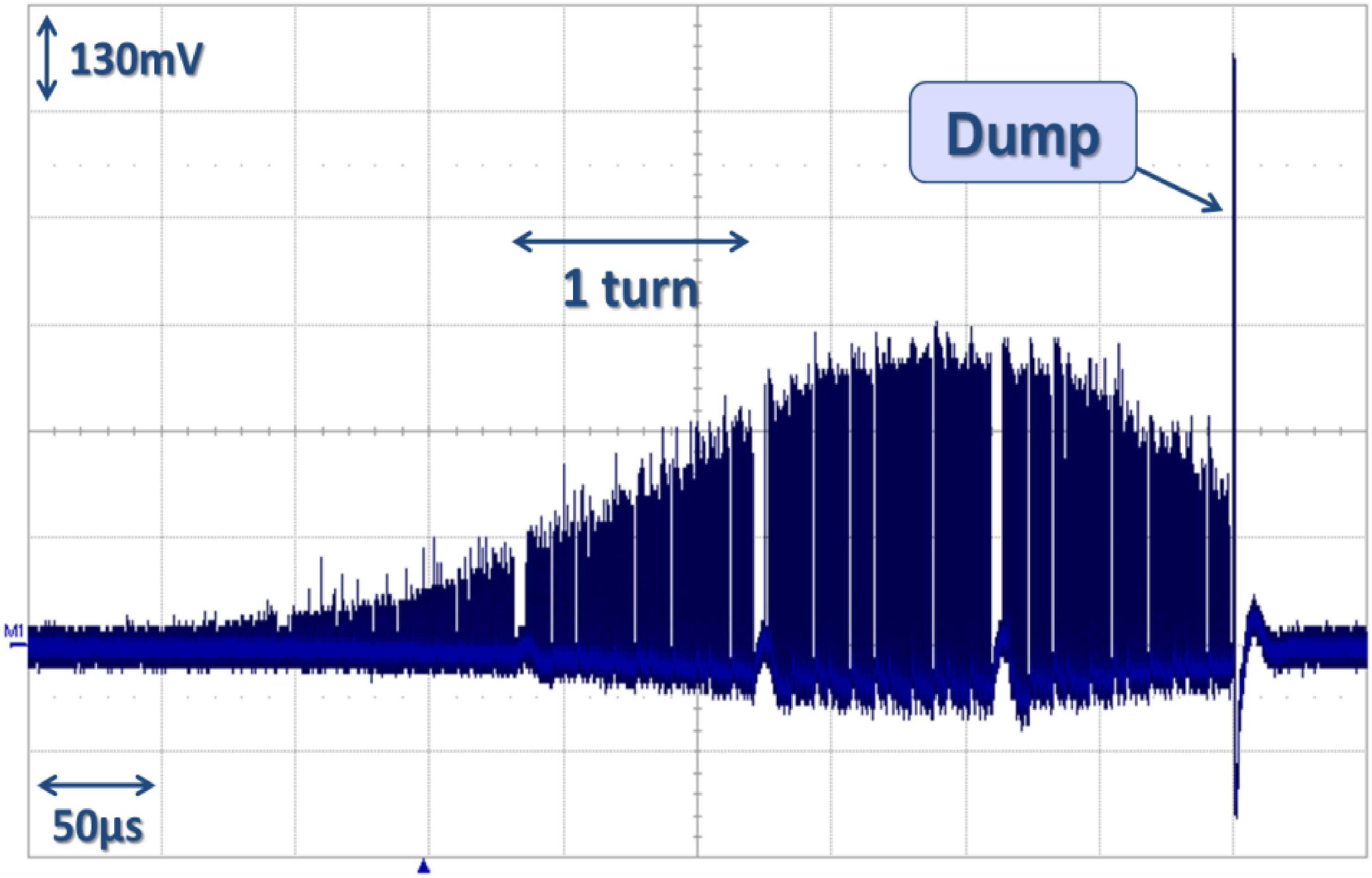




Fit parameter:
Peak loss: 8.1 Gy/s
Temporal width: 84 µs
Integrated Loss: 1.7 mGy
Measured Int. loss: 1.8 mGy

Spatial and temporal loss profile of UFO at BSRT.B2 on 27.08.2012 at 4TeV.

finer temporal resolution UFO event using new diamond detectors

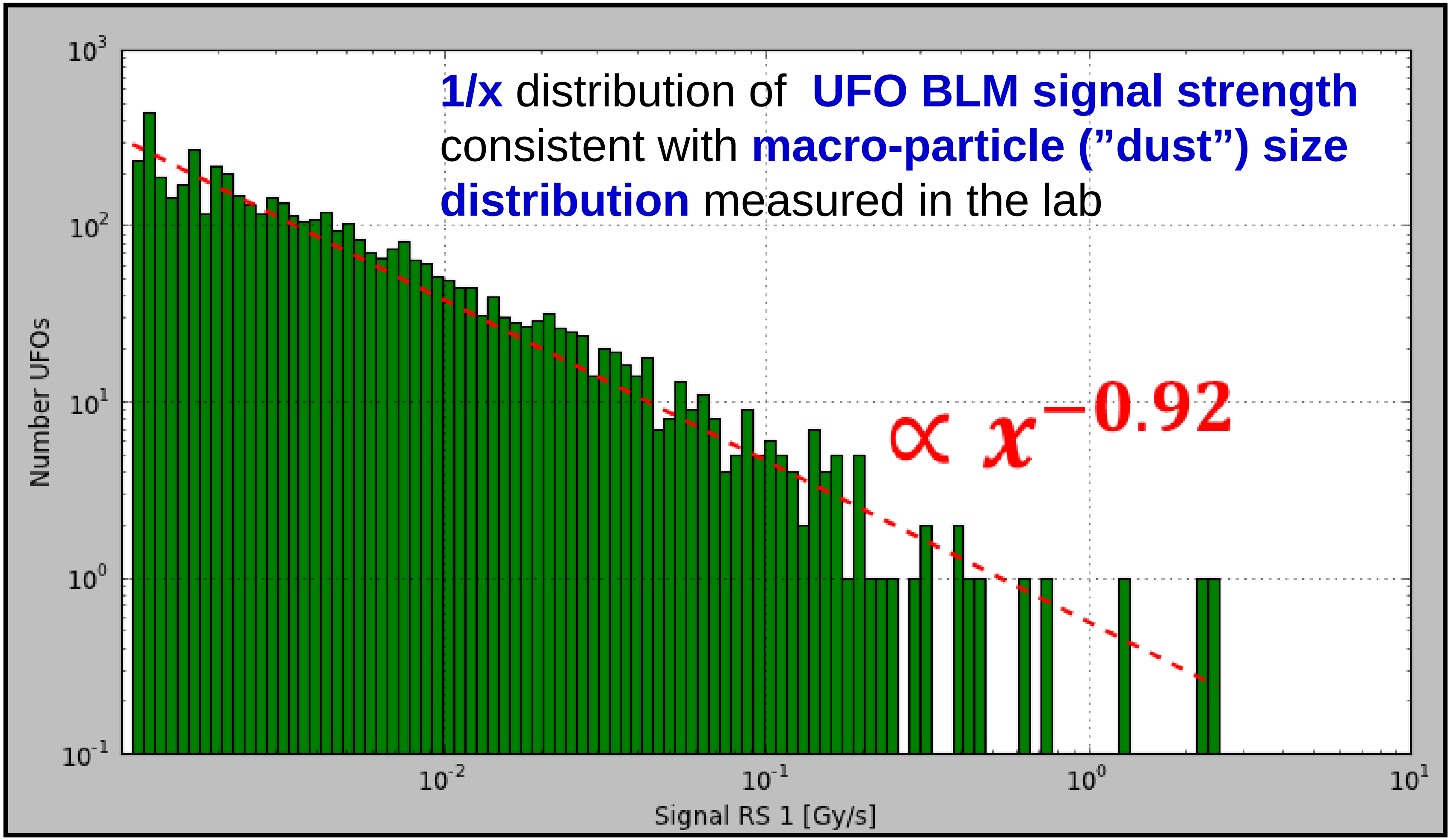


Diamond BLM in IR7

T. Baer

UFO strength

distribution of signal strength



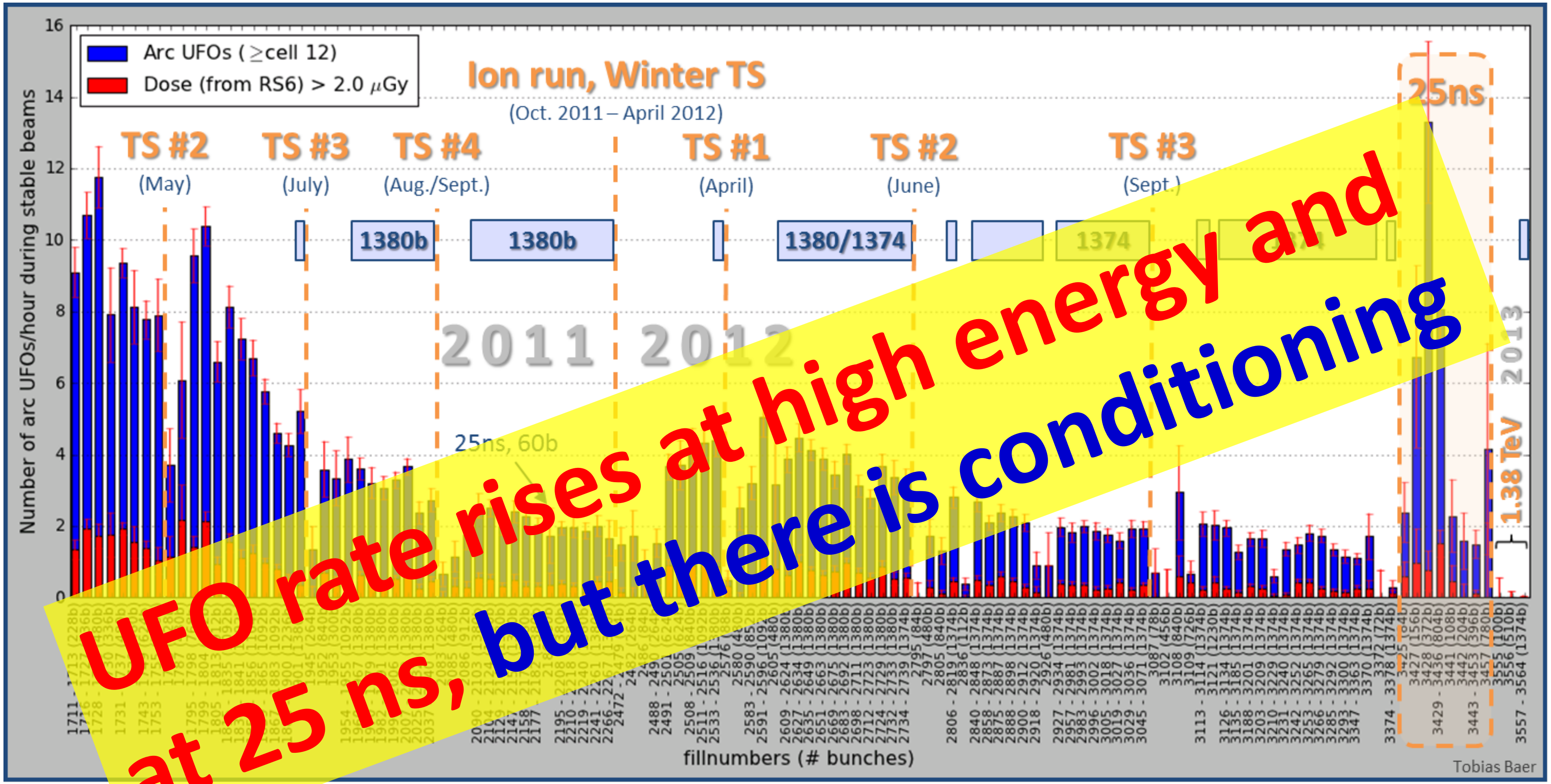
1/x distribution of **UFO BLM signal strength** consistent with **macro-particle (”dust”) size distribution** measured in the lab

$\propto x^{-0.92}$

T. Baer

arc UFO rate

T. Baer

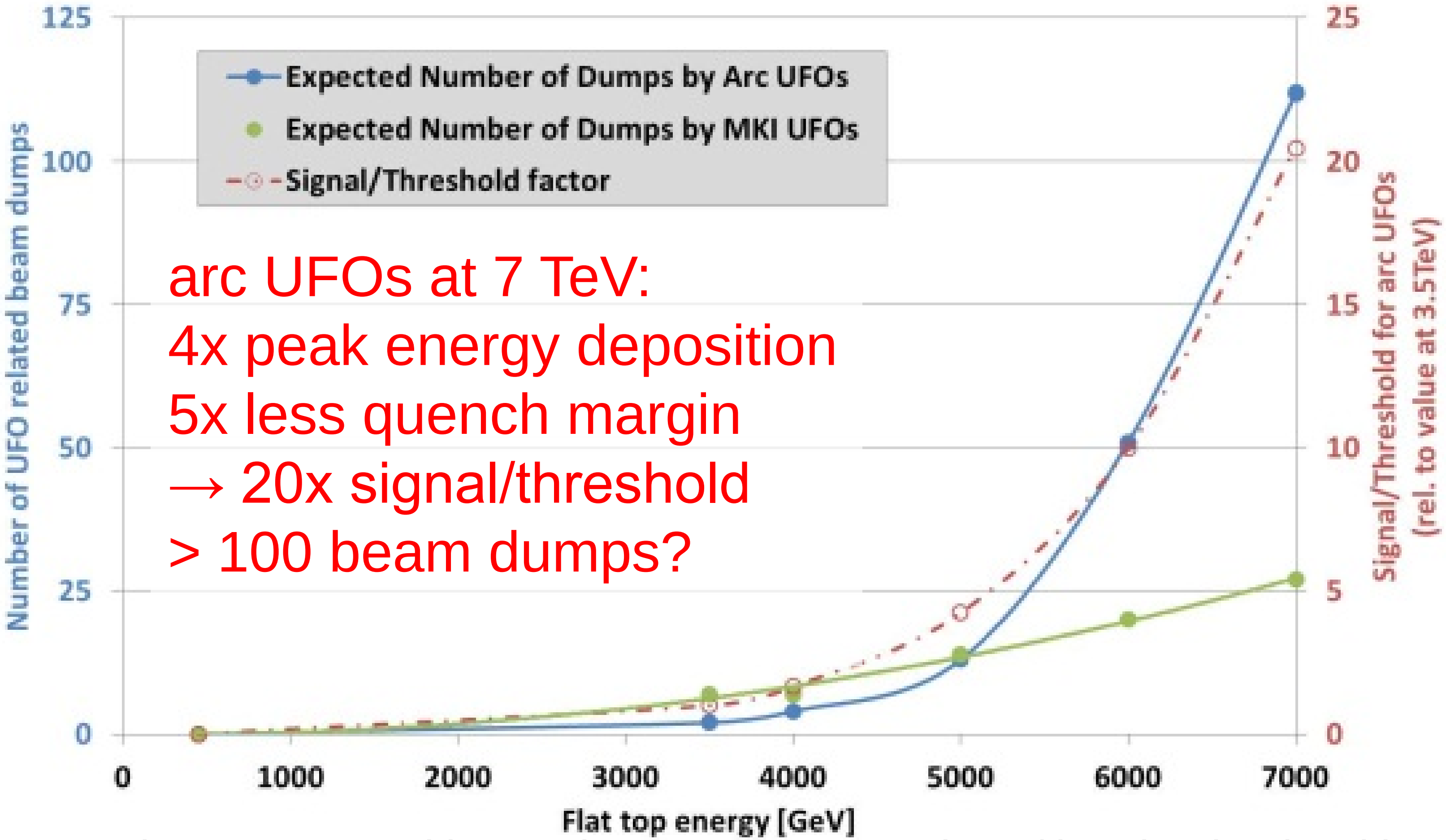


UFO rate rises at high energy and at 25 ns, but there is conditioning

*Clear **conditioning effect** in 2011 and 2012. UFO rate **≈2.5 times higher** in beginning of 2012 than in Oct. 2011. About **10 times increased** UFO rate with **25ns. No UFO in 17.5h with 1374b at 1.38TeV** (special lower-energy run).*

UFO - Extrapolation to 7 TeV

T. Baer



arc UFOs at 7 TeV:
4x peak energy deposition
5x less quench margin
→ 20x signal/threshold
> 100 beam dumps?

Expected # UFO-related beam dumps & arc BLM signal/threshold ratio with energy

plan for 2015:raise BLM thresholds (2013 “quench test”),
& improve BLM locations

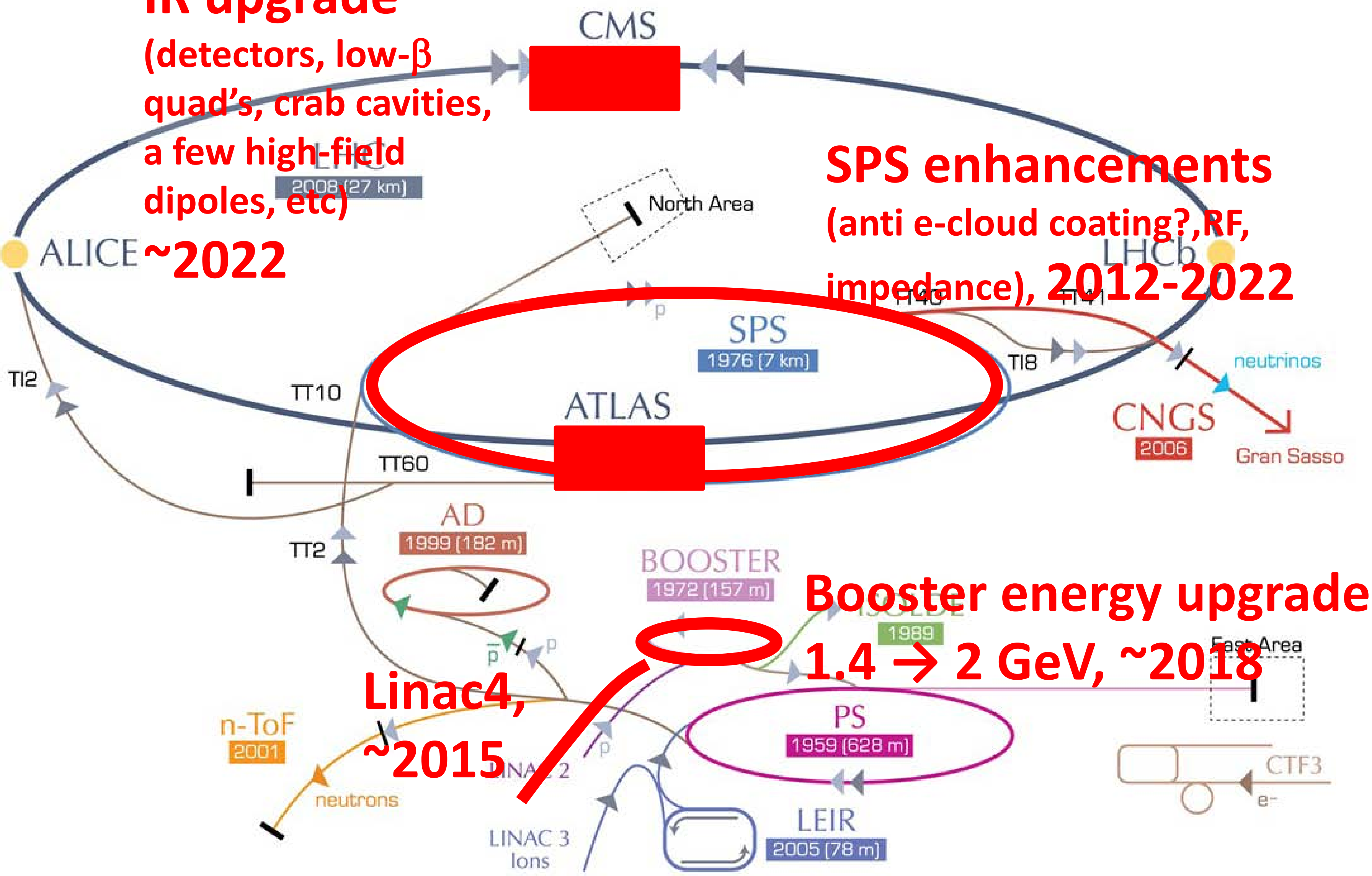
LHC luminosity forecast

~30/fb at 3.5 & 4 TeV	**2012 DONE**
~300/fb at 6.5-7 TeV	**2020 goal**
~3000/fb at 7 TeV	**2035 goal**

question: how do we get 3000/fb by 2035?

*answer: with **HL-LHC***

HL-LHC – LHC modifications



IR upgrade

(detectors, low-β quad's, crab cavities, a few high-field dipoles, etc)

~2022

SPS enhancements

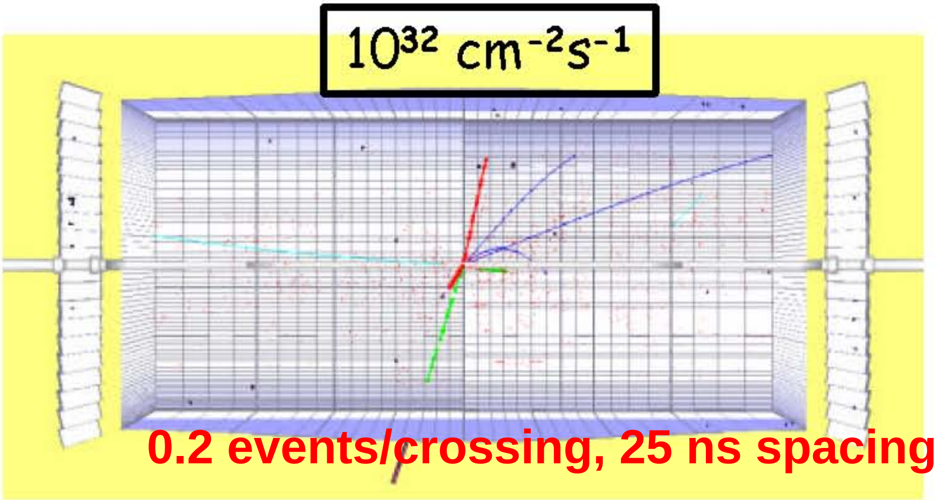
(anti e-cloud coating?,RF, impedance), 2012-2022

Booster energy upgrade

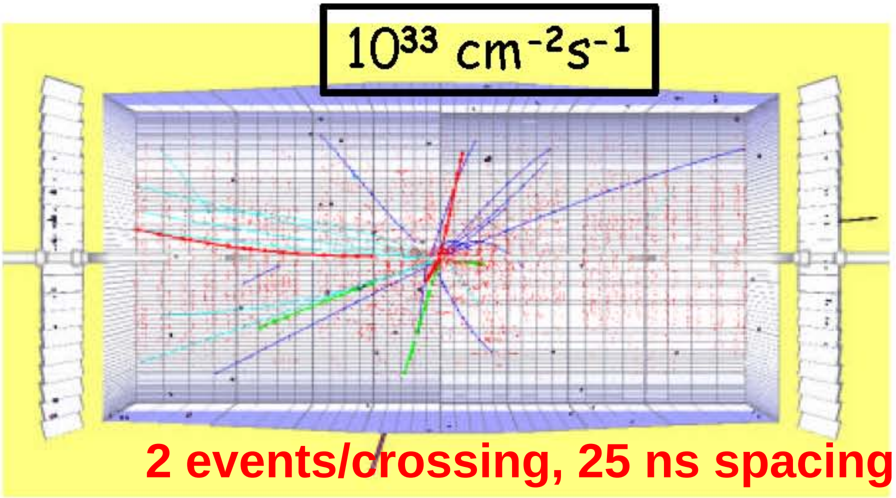
1.4 → 2 GeV, ~2018

Linac4, ~2015

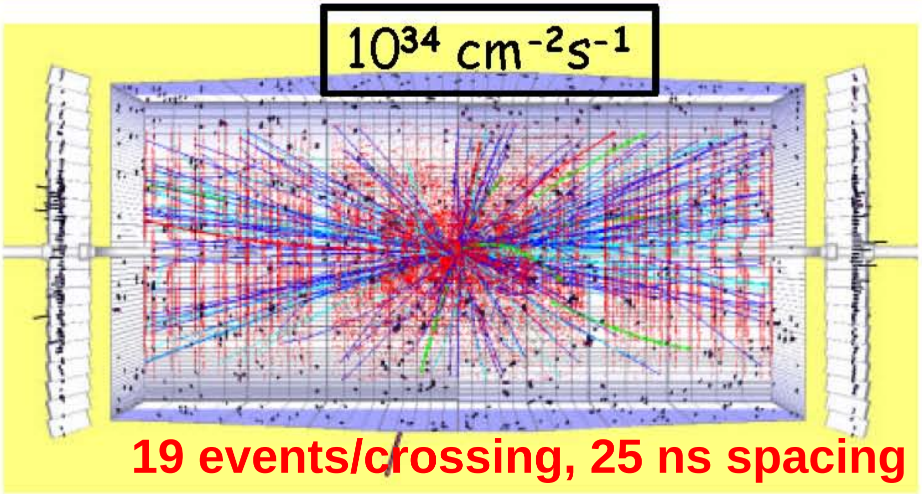
high luminosity → event pile up↑


$10^{32}\ \mathrm{cm^{-2}s^{-1}}$

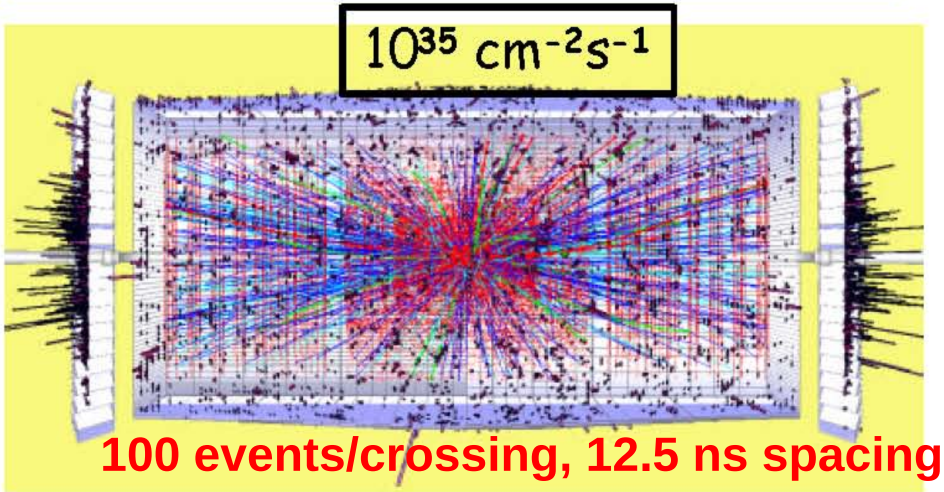
0.2 events/crossing, 25 ns spacing


$10^{33}\ \mathrm{cm^{-2}s^{-1}}$

2 events/crossing, 25 ns spacing


$10^{34}\ \mathrm{cm^{-2}s^{-1}}$

19 events/crossing, 25 ns spacing


$10^{35}\ \mathrm{cm^{-2}s^{-1}}$

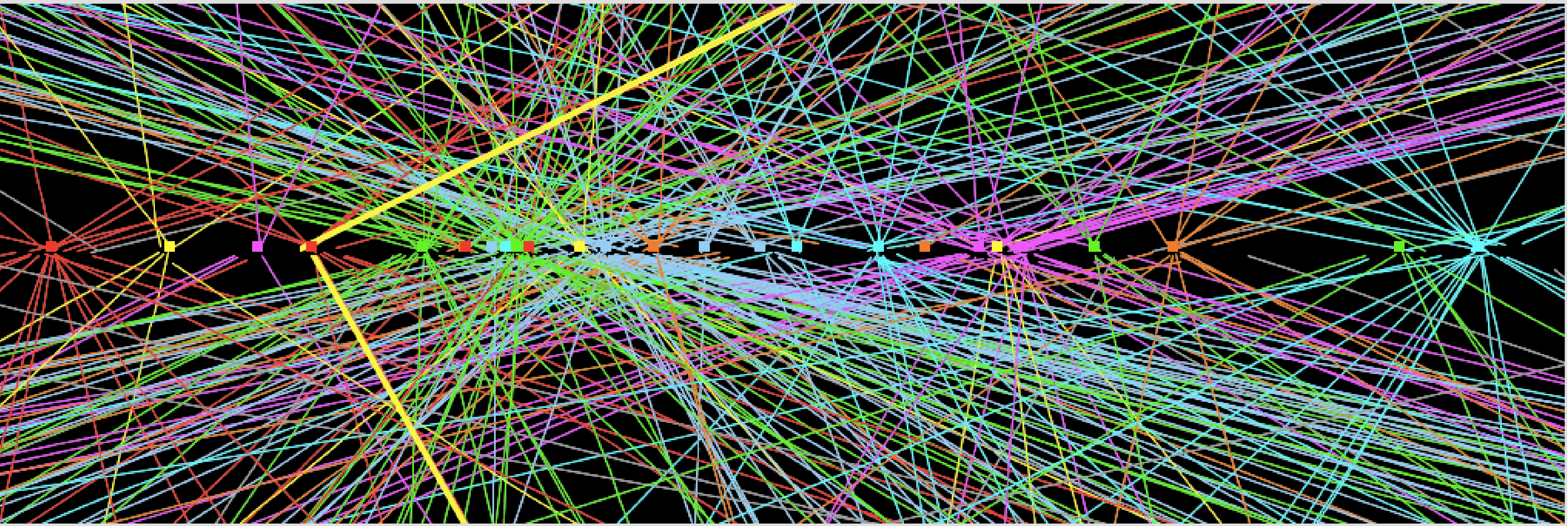
100 events/crossing, 12.5 ns spacing

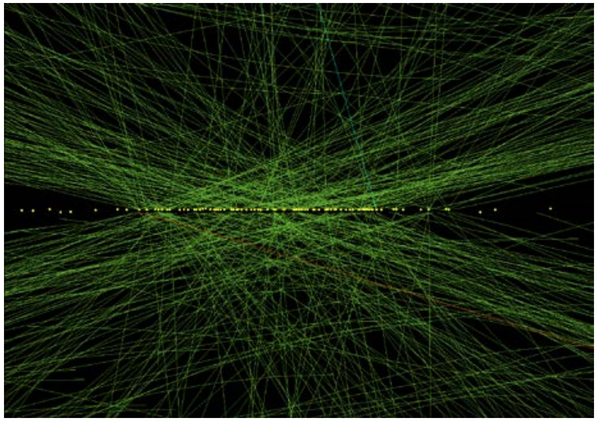
$p_t > 1$ GeV/c cut, i.e. all soft tracks removed

I. Osborne

historical simulation

Z→ μμ event from 2012 data with 25 reconstructed vertices (ATLAS)





78 reconstructed vertices in event from high-pileup run (CMS)

actual data

HL-LHC requires leveling for ATLAS & CMS

High-Luminosity LHC (HL-LHC)

luminosity goals:

leveled peak luminosity: $L = 5\text{x}10^{34}\ \text{cm}^{-2}\,\text{s}^{-1}$
(upgraded detector pile up limit ~140)

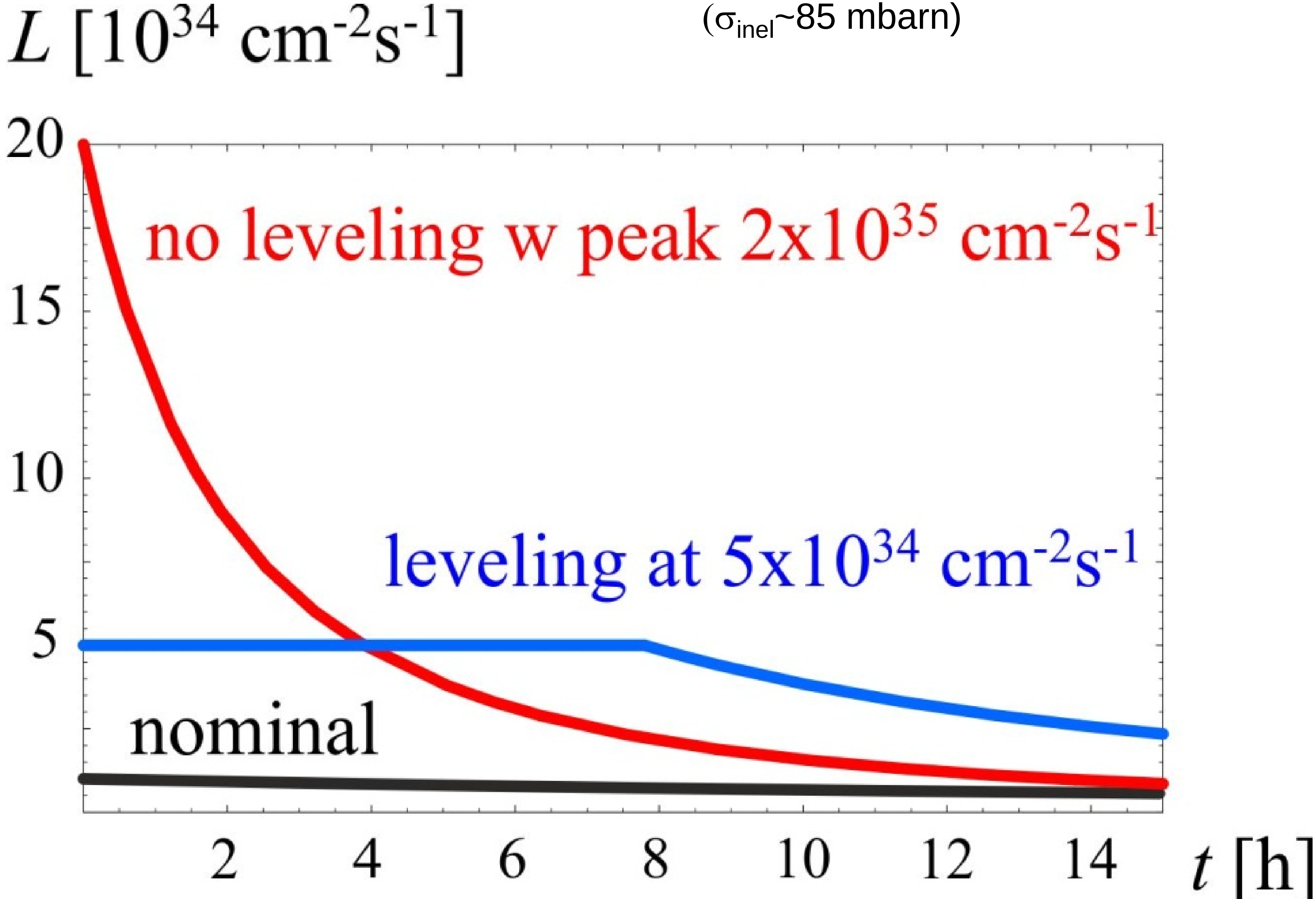
“virtual peak luminosity”: $L \geq 20\text{x}10^{34}\ \text{cm}^{-2}\,\text{s}^{-1}$

integrated luminosity: 200 - 300 fb^{-1} / yr

total integrated luminosity: ca. 3000 fb^{-1} by ~2035

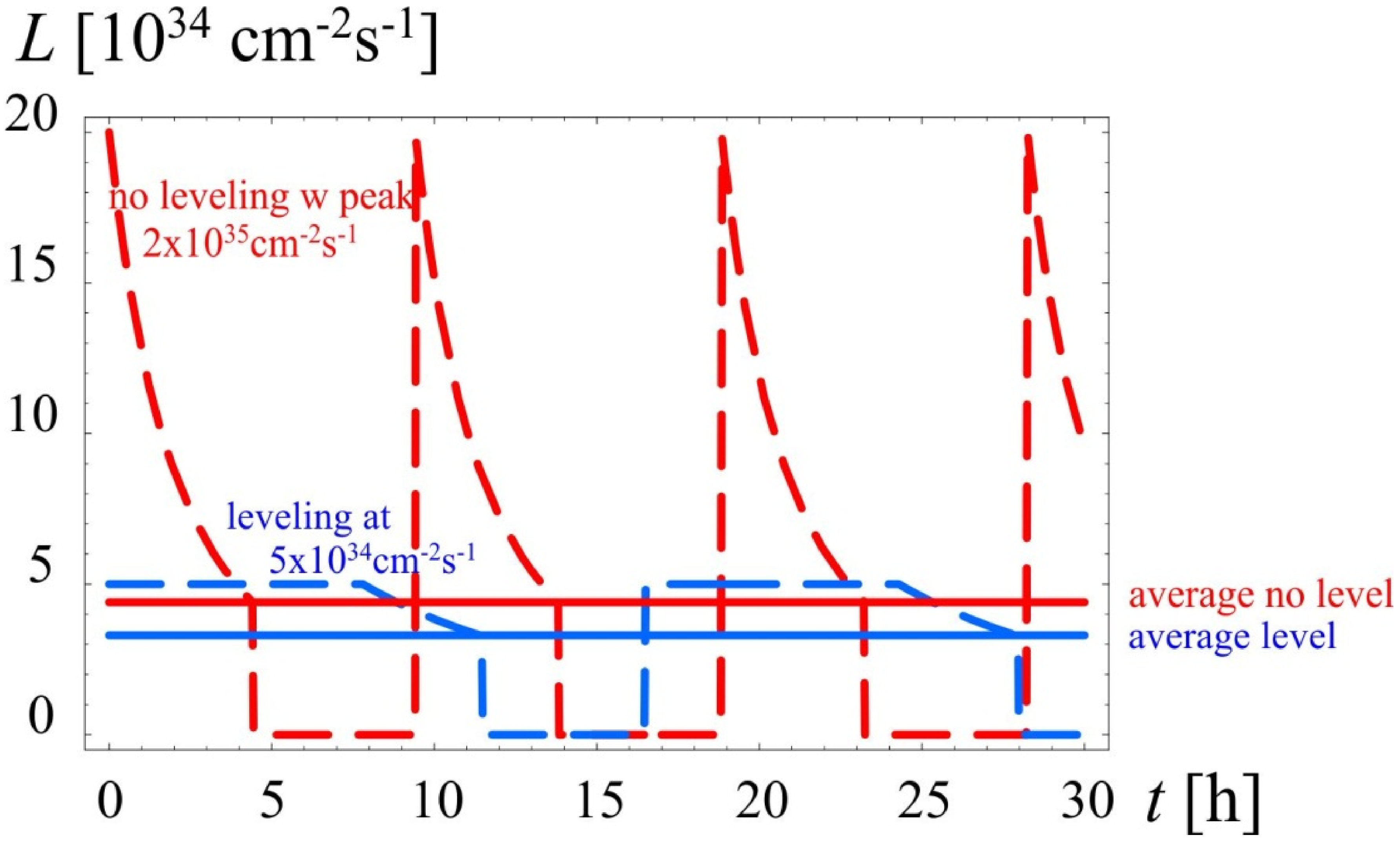
luminosity leveling at the HL-LHC

example: maximum pile up 140
(σ_{inel}~85 mbarn)



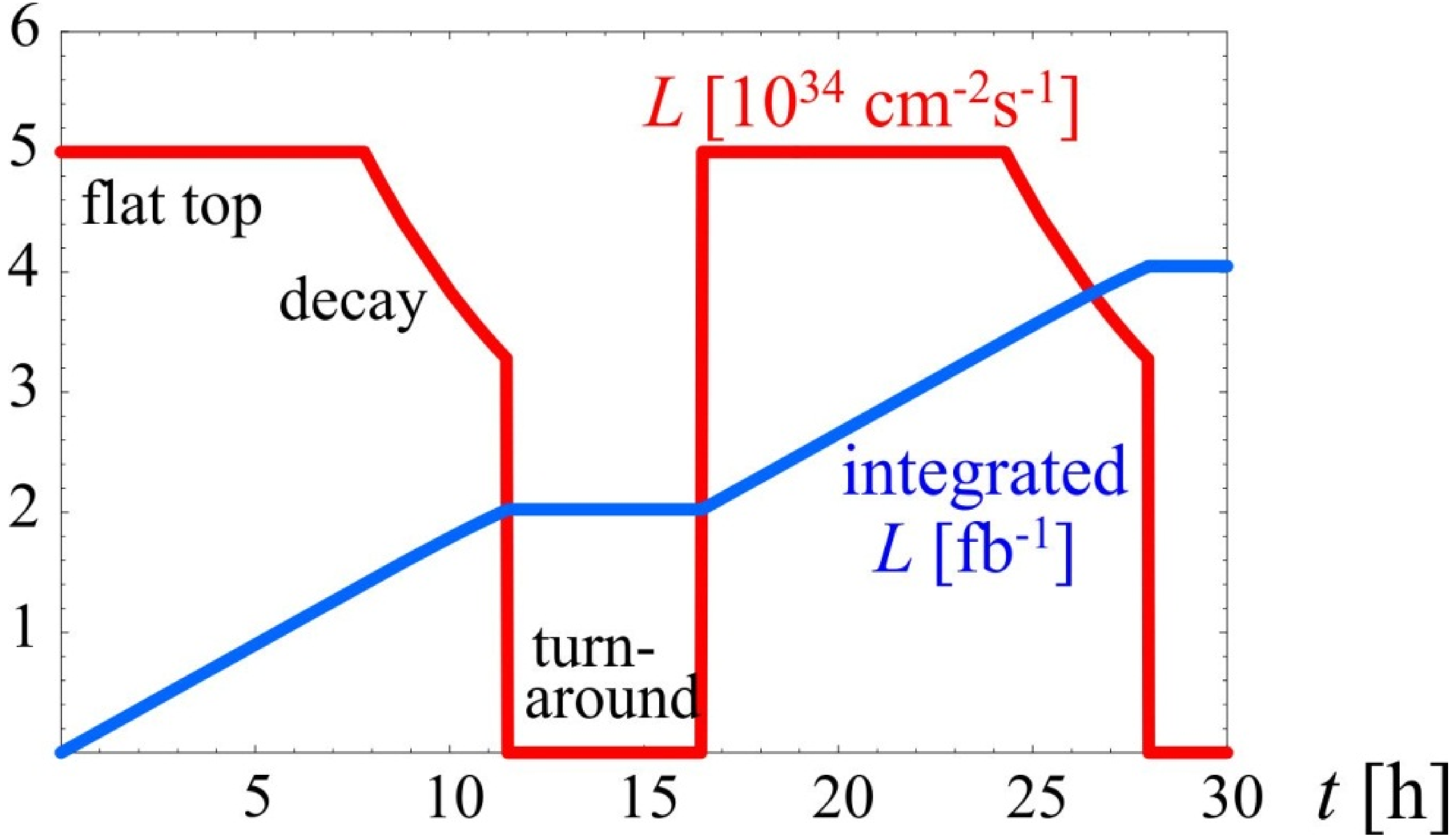
luminosity leveling at the HL-LHC

example: maximum pile up 140



luminosity & integrated luminosity during 30 h at the HL-LHC

example: maximum pile up 140



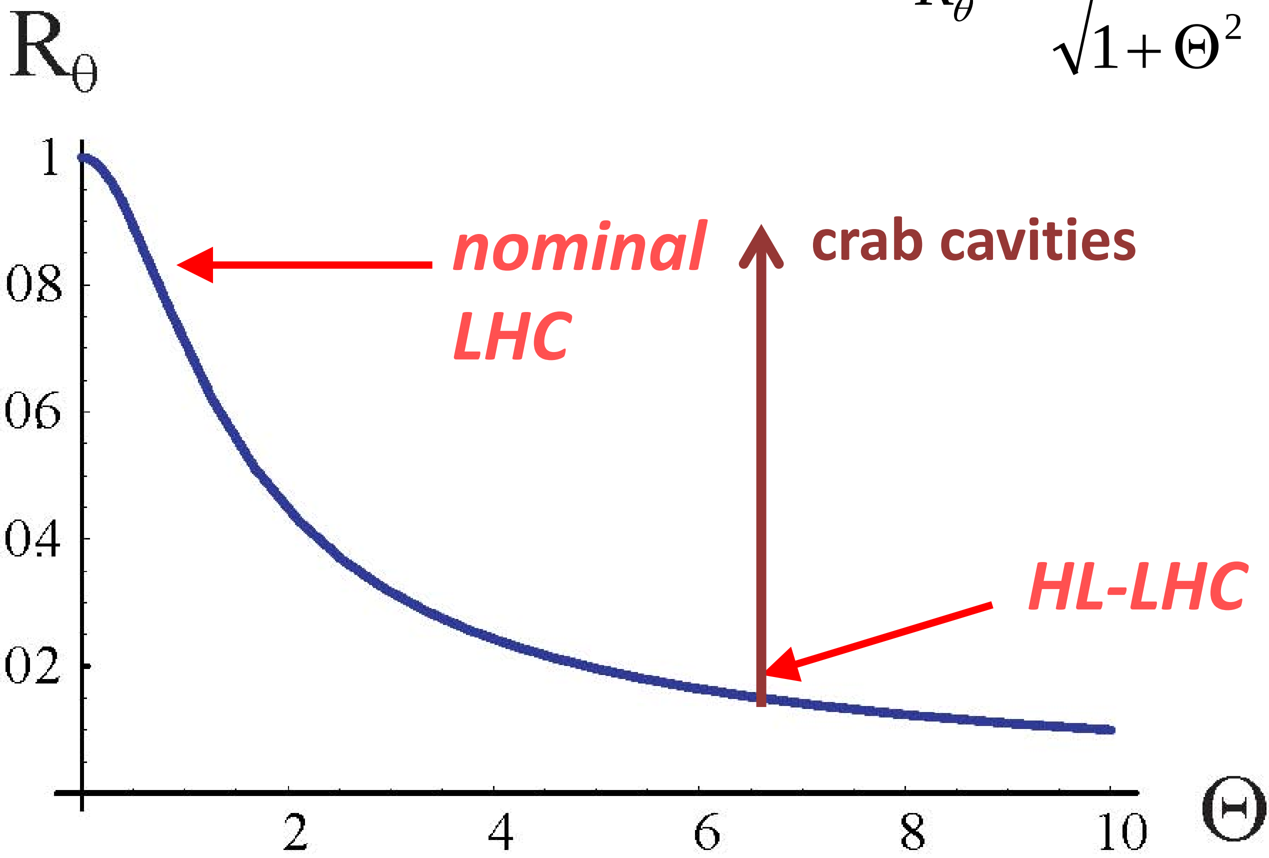
luminosity reduction due to crossing angle

more pronounced at smaller β^*

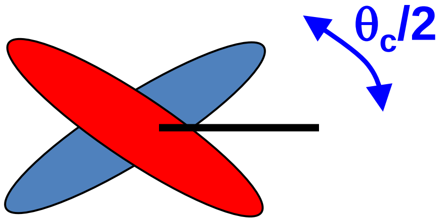
"Piwinski angle"

luminosity reduction factor

$$R_\theta = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$



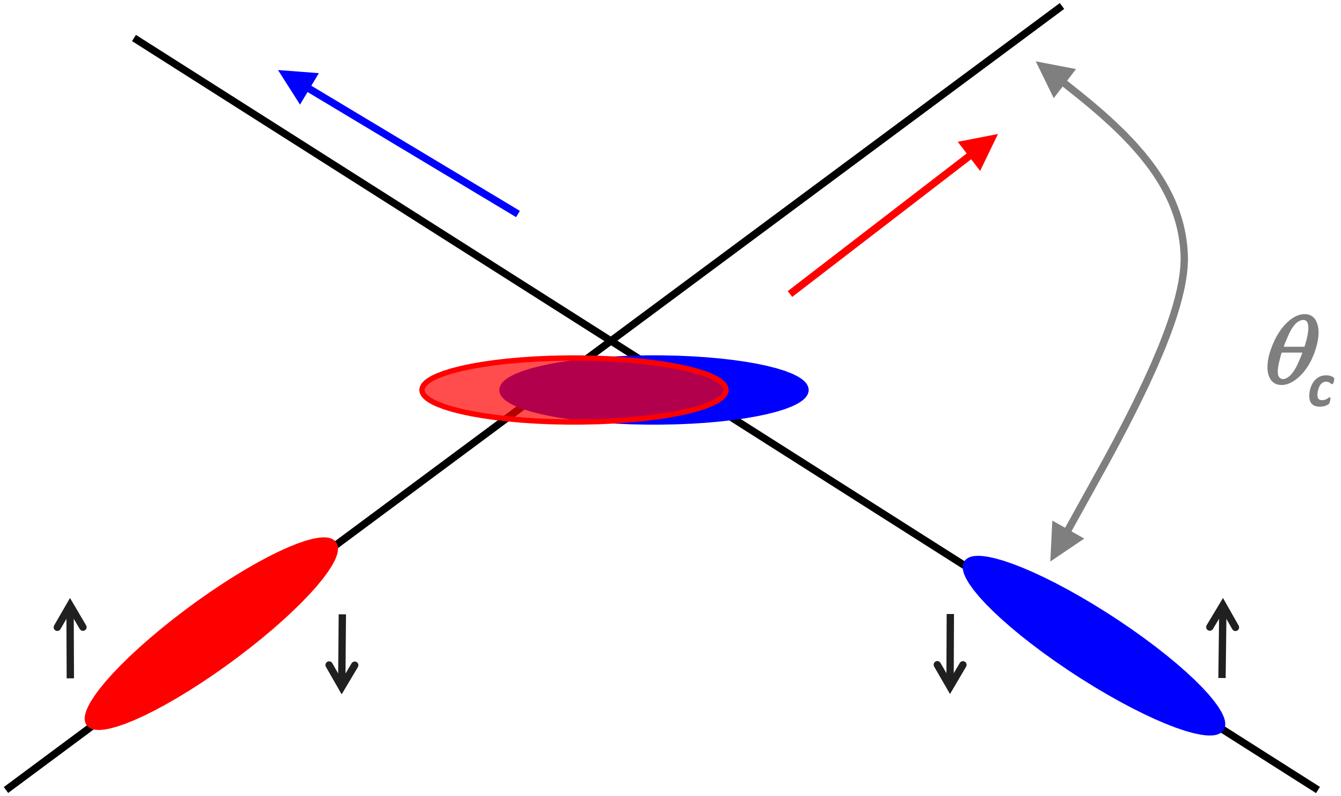
$\Theta \sim 1/\beta^*$



eff. beam size:

$\sigma^*_{x,\mathrm{eff}} \approx \sigma_x^*/R_\theta$

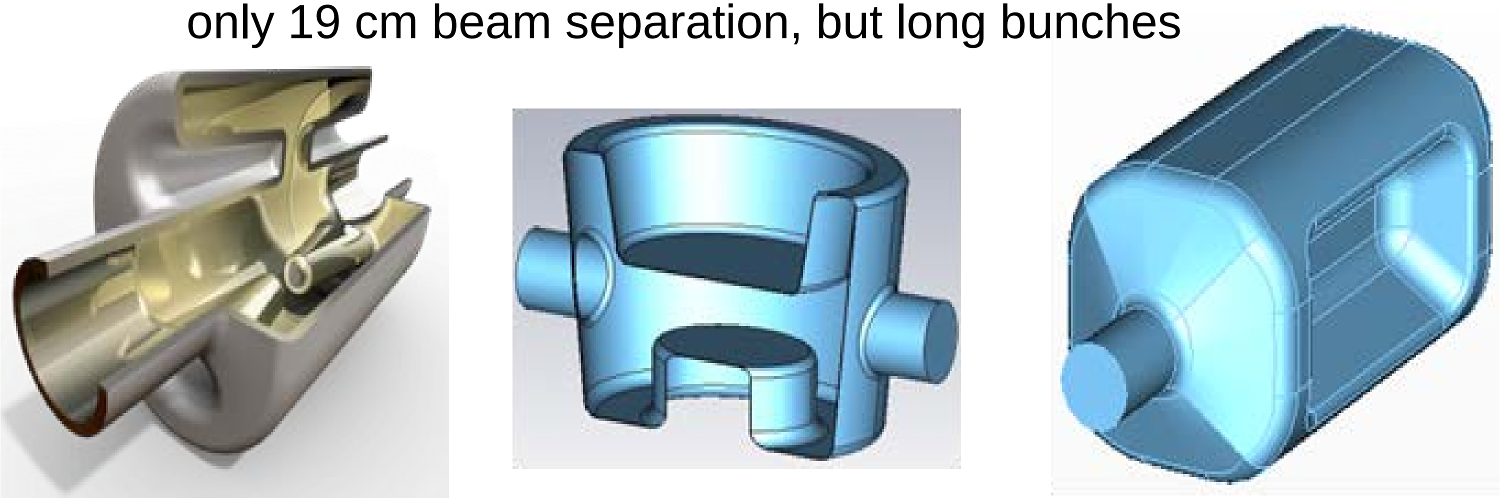
schematic of crab crossing



- RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" for luminosity and tune shift
- bunch centroids still cross at an angle (easy separation)
- 1st proposed in 1988, used in operation at KEKB since 2007

HL-LHC needs compact crab cavities

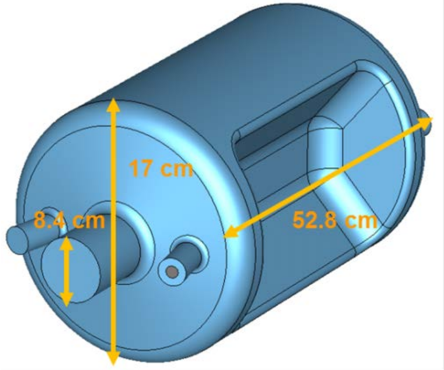
only 19 cm beam separation, but long bunches



Final down-selected compact cavity designs for the LHC upgrade: 4-rod cavity design by Cockcroft I. & JLAB (left), λ/4 TEM cavity by BNL (centre), and double-ridge λ/2 TEM cavity by SLAC & ODU (right).

Prototype compact Nb-Ti crab cavities for the LHC: 4-rod cavity (left) and double-ridge cavity (right).

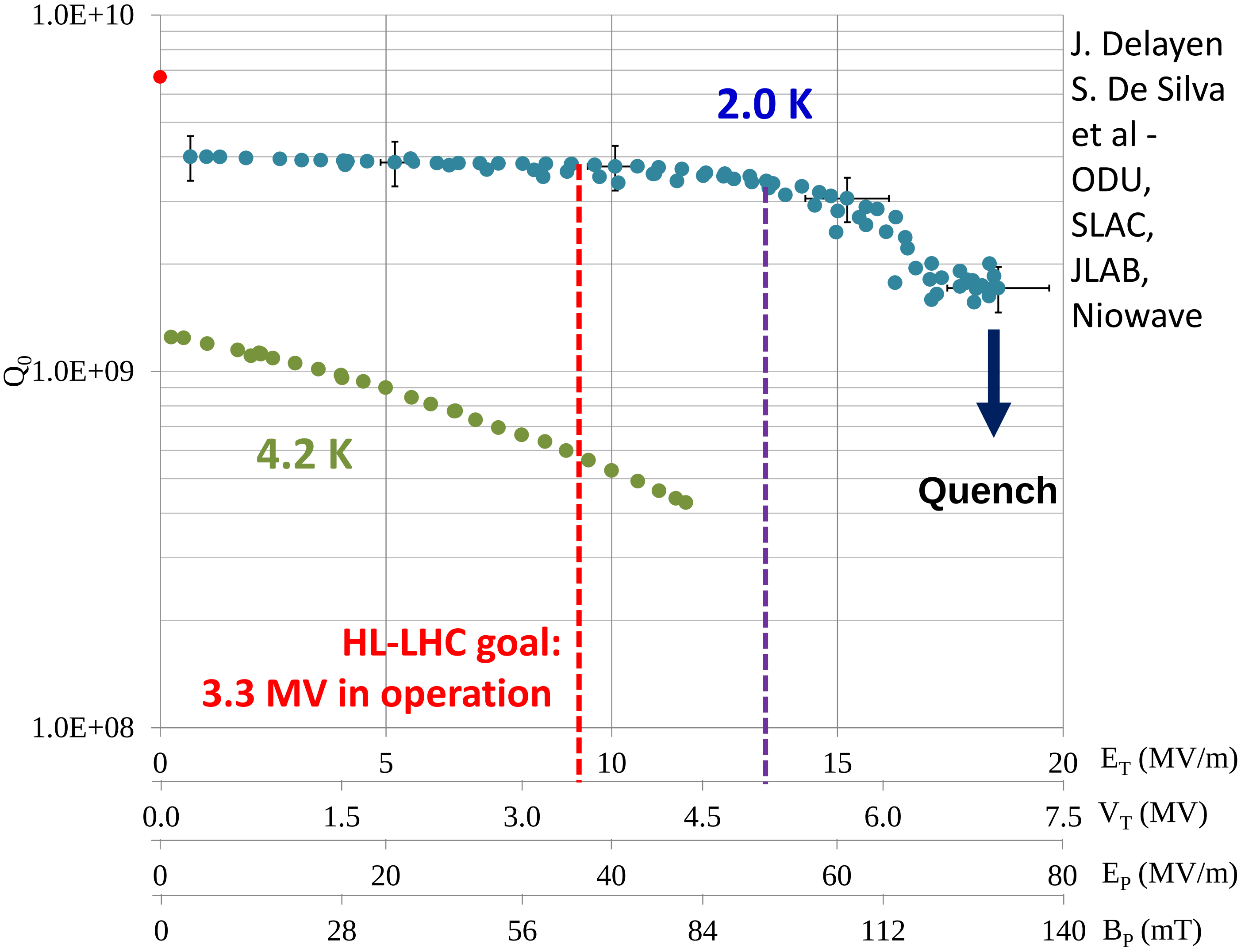
breaking news – PoP double-ridge cavity achieved 7 MV deflecting voltage cw



- Expected

  $Q_0 = 6.7\times10^9$
  - At R_S = 22 nΩ
  - And R_{res} = 20 nΩ
- Achieved

  $Q_0 = 4.0\times10^9$
- Achieved fields
  - E_T = 18.6 MV/m
  - V_T = 7.0 MV
  - E_P = 75 MV/m
  - B_P = 131 mT



J. Delayen
S. De Silva
et al -
ODU,
SLAC,
JLAB,
Niowave

better than required!

J. Delayen, LARP CM20

Recommendations from European Strategy Group, January 2013

Recommendation #1:

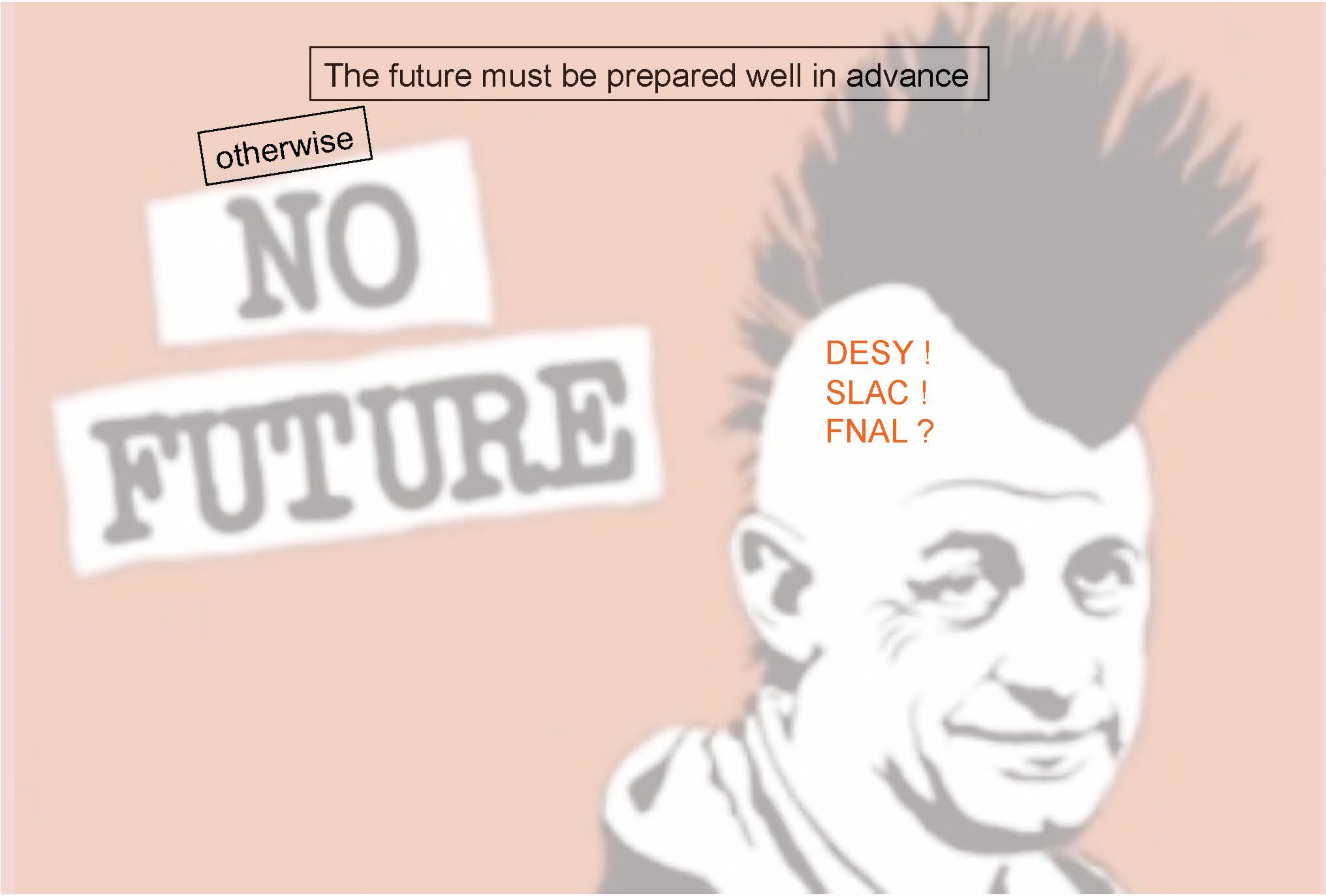
… Europe's top priority should be the exploitation of the **full potential of the LHC, including the high-luminosity upgrade** of the machine and detectors with a view to collecting **ten times more data than the initial design** …

Recommendation #2:

Europe needs to be in a position to **propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update [2017/18]** when physics results from the LHC running at 14 TeV will be available

Recommendation #3:

There is a strong scientific case for an **electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded**



The future must be prepared well in advance

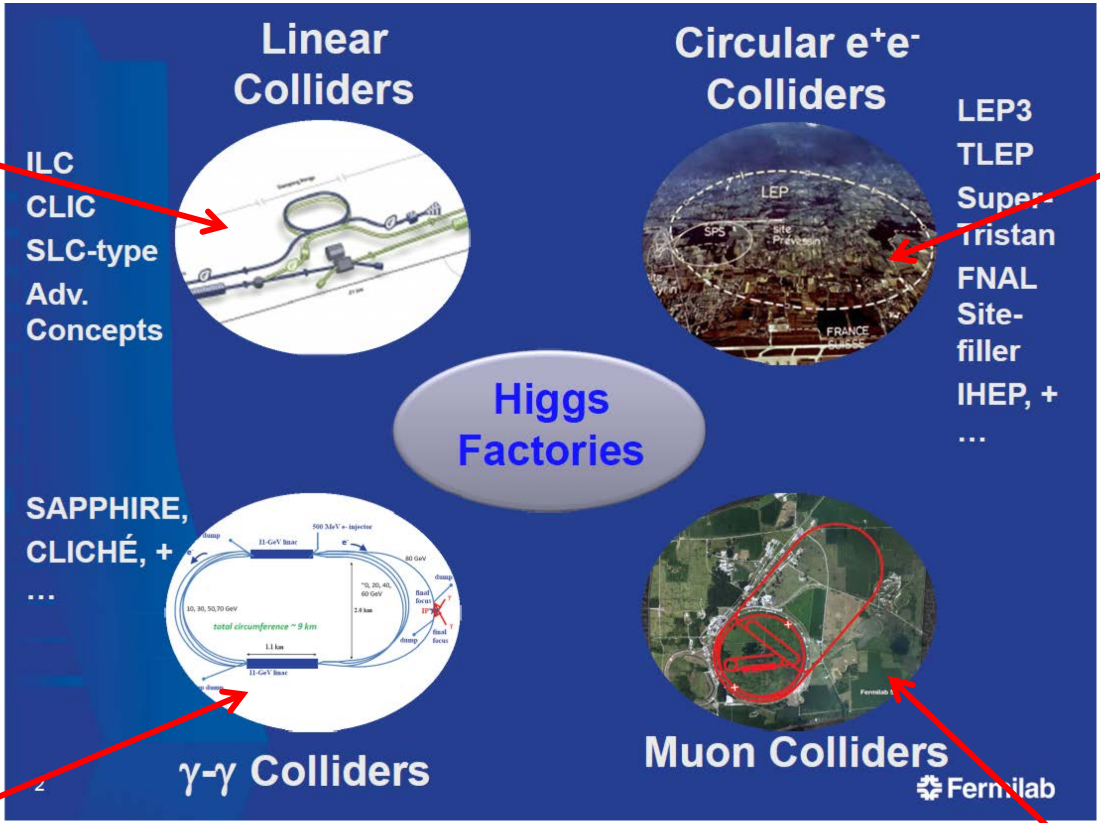
otherwise

DESY !
SLAC !
FNAL ?

Source: Francois Le Diberder, Clermont Ferrand, March 2013

Paths towards the future : Precision Higgs Factories

- **Several options for Higgs factories are being studied**



Linear Colliders

ILC
CLIC
SLC-type
Adv. Concepts

Circular e^+e^- Colliders

LEP3
TLEP
Super-Tristan
FNAL Site-filler
IHEP, +
…

Higgs Factories

SAPPHIRE,
CLICHÉ, +
…

γ-γ Colliders

Muon Colliders

Studied for decades

This talk

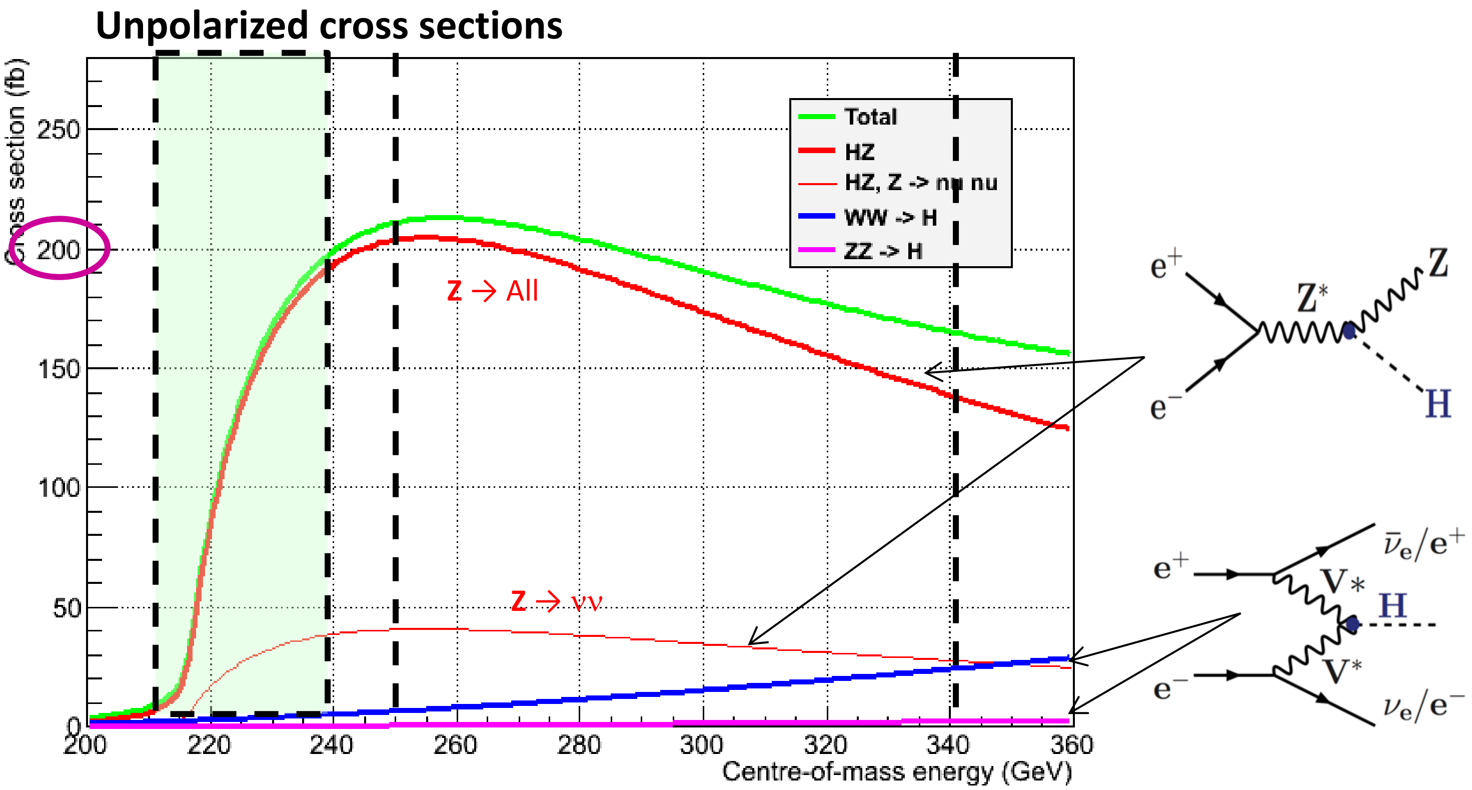
Smaller Physics Potential

Not encouraged by European Strategy

e^+e^- colliders have largest potential as Precision Higgs Factories

Higgs production in e^+e^- collisions

Need 100's fb^{-1}


Unpolarized cross sections

- Scan of *HZ* threshold : √s = 210-240 GeV — Spin
- Maximum of *HZ* cross section : √s = 240-250 GeV — Mass, BRs, Width, Decays
- Just below the *tt* threshold : √s ~ 340-350 GeV — Width, CP

circular e^+e^- Higgs factories: LEP3 & TLEP

option 1: installation in the LHC tunnel “LEP3”

+ inexpensive (<0.1xLC)

+ tunnel exists

+ reusing ATLAS and CMS detectors

+ reusing LHC cryoplants

\- interference with LHC and HL-LHC

option 2: in new 80 or 100-km tunnel “TLEP”

+ higher energy reach, 5-10x higher luminosity

+ decoupled from LHC/HL-LHC operation & construction

+ tunnel can later serve for VHE-LHC (factor 3 in energy from tunnel alone)

\- more expensive (?)

LEP3, TLEP

key parameters

	LEP3	TLEP
circumference	26.7 km	80 km
max beam energy	120 GeV	175 GeV
max no. of IPs	4	4
luminosity at 350 GeV c.m.	-	$0.7\mathrm{x}10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
luminosity at 240 GeV c.m.	10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$5\mathrm{x}10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
luminosity at 160 GeV c.m.	$5\mathrm{x}10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$2.5\mathrm{x}10^{35}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
luminosity at 90 GeV c.m.	$2\mathrm{x}10^{35}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	10^{36} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$

at the Z pole repeating LEP physics programme in a few minutes…!

history repeating itself…?

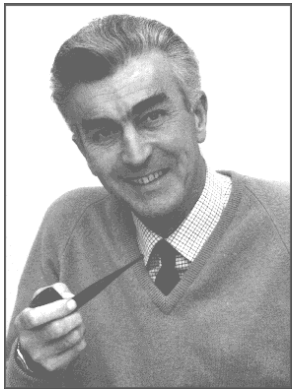
When **Lady Margaret Thatcher** visited CERN in the 1980s, she asked the then CERN Director-General **Herwig Schopper** ***how big the next tunnel after LEP would be.*** Dr. Schopper‘s answer was ***there would be no bigger tunnel at CERN***. Lady Thatcher replied that she had obtained ***exactly the same answer from* Sir John Adams *when the SPS was built ~10 years earlier***, and therefore she didn‘t believe him.

maybe the Iron Lady was right!

Herwig Schopper, private communication, 2013

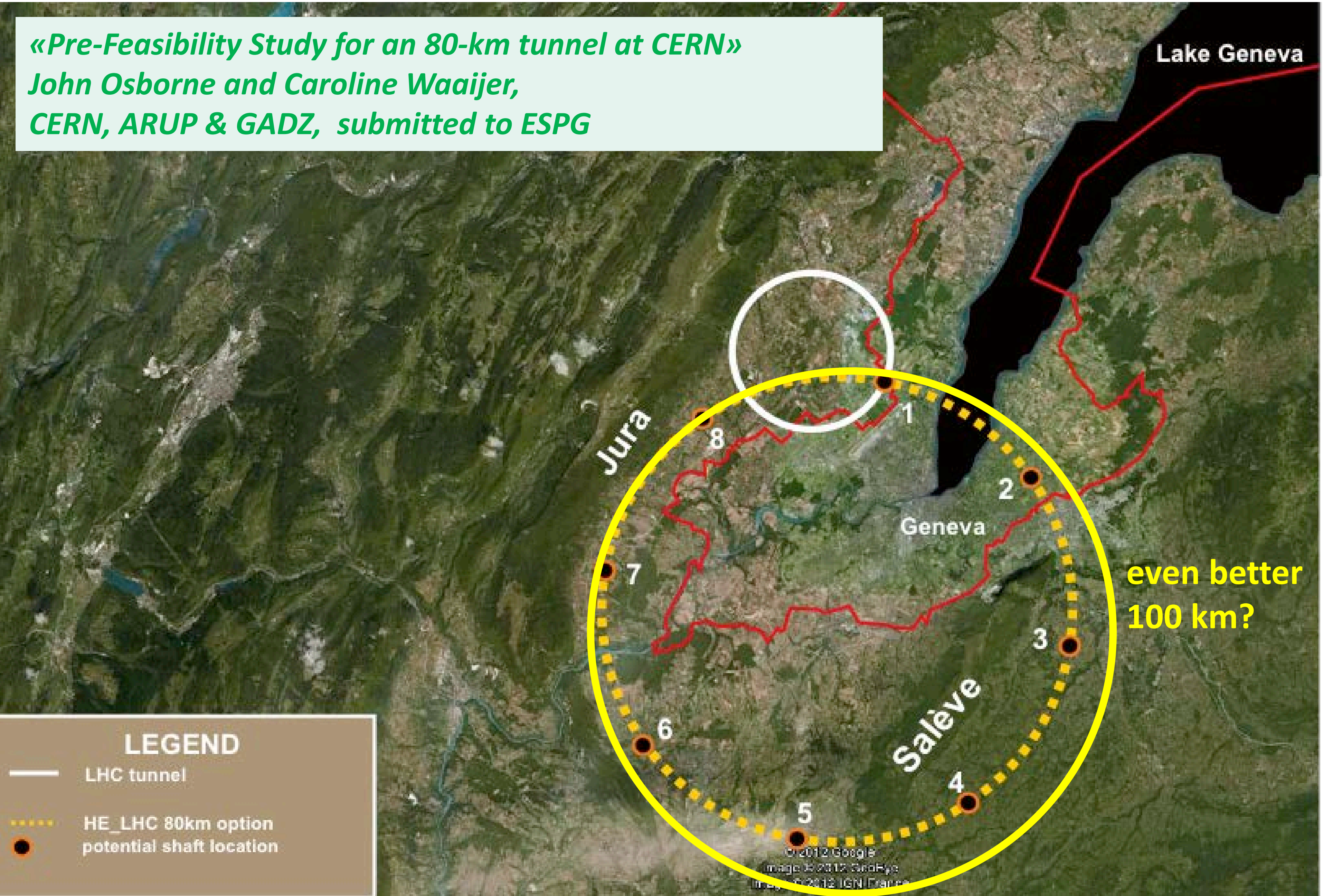
Margaret Thatcher,
British PM 1979-90

Herwig Schopper
CERN DG 1981-88
built LEP



John Adams
CERN DG 1960-61 & 1971-75
built PS & SPS

80-km tunnel in Geneva area – “best” option



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

even better
100 km?

80-km Tunnel Cost Estimate (preliminary)

- 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

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	

AMBERG ENGINEERING

- **Cost uncertainty = 50% (→ cost of bare tunnel up to 4.5 BCHF)**
- Next stage should include costing based on technical drawings

luminosity formulae & constraints

$$L = \frac{f_{rev} n_b N_b^2}{4\pi \sigma_x \sigma_y} = (f_{rev} n_b N_b)\left(\frac{N_b}{\varepsilon_x}\right)\frac{1}{4\pi}\frac{1}{\sqrt{\beta_x \beta_y}}\frac{1}{\sqrt{\varepsilon_y/\varepsilon_x}}$$

$$(f_{rev} n_b N_b) = \frac{P_{SR}\,\rho}{8.8575 \times 10^{-5}\,\frac{\mathrm{m}}{\mathrm{GeV}^{-3}} E^4}$$

SR radiation power limit

$$\frac{N_b}{\varepsilon_x} = \frac{\xi_x 2\pi\gamma(1+\kappa_\sigma)}{r_e}$$

beam-beam limit

$$\frac{N_b}{\sigma_x \sigma_z}\frac{30\,\gamma r_e^2}{\delta_{acc}\,\alpha} < 1$$

>30 min beamstrahlung lifetime (Telnov) → N_b, β_x

→minimize $\kappa_\varepsilon = \varepsilon_y/\varepsilon_x$, $\beta_y \sim \beta_x(\varepsilon_y/\varepsilon_x)$ and respect $\beta_y \approx \sigma_z$

LEP3/TLEP parameters -1

soon at SuperKEKB:
$\beta_x^*=0.03$ m, $\beta_y^*=0.03$ cm

	LEP2	LHeC	LEP3	TLEP-Z	TLEP-H	TLEP-t
beam energy E_b [GeV]	104.5	60	120	45.5	120	175
circumference [km]	26.7	26.7	26.7	80	80	80
beam current [mA]	4	100	7.2	1180	24.3	5.4
#bunches/beam	4	2808	4	2625	80	12
#e–/beam [10^{12}]	2.3	56	4.0	2000	40.5	9.0
horizontal emittance [nm]	48	5	25	30.8	9.4	20
vertical emittance [nm]	0.25	2.5	0.10	0.15	0.05	0.1
bending radius [km]	3.1	2.6	2.6	9.0	9.0	9.0
partition number J_ε	1.1	1.5	1.5	1.0	1.0	1.0
momentum comp. α_c [10^{-5}]	18.5	8.1	8.1	9.0	1.0	1.0
SR power/beam [MW]	11	44	50	50	50	50
β^*_x [m]	1.5	0.18	0.2	0.2	0.2	0.2
β^*_y [cm]	5	10	0.1	0.1	0.1	0.1
σ^*_x [μm]	270	30	71	78	43	63
σ^*_y [μm]	3.5	16	0.32	0.39	0.22	0.32
hourglass F_{hg}	0.98	0.99	0.59	0.71	0.75	0.65
ΔE^{SR}_{loss}/turn [GeV]	3.41	0.44	6.99	0.04	2.1	9.3

SuperKEKB:$\varepsilon_y/\varepsilon_x$=0.25%

even with 1/5 SR power (10 MW) still > L_{ILC}!

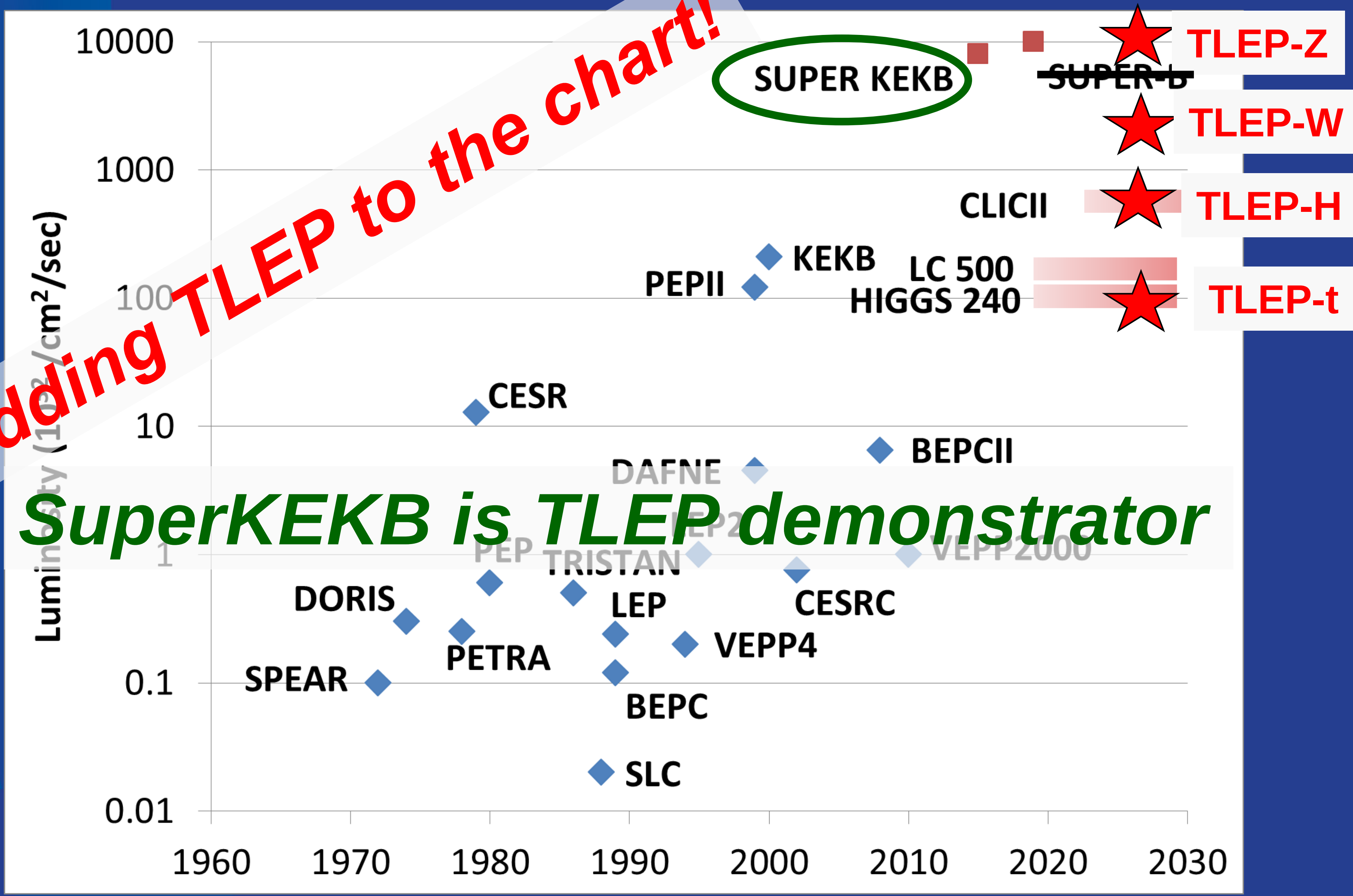
LEP3/TLEP parameters -2

LEP2 was not beam-beam limited

	LEP2	LHeC	LEP3	TLEP-Z	TLEP-H	TLEP-t
$V_{RF,tot}$ [GV]	3.64	0.5	12.0	2.0	6.0	12.0
$\delta_{max,RF}$ [%]	0.77	0.66	5.7	4.0	9.4	4.9
ξ_x/IP	0.025	N/A	0.09	0.12	0.10	0.05
ξ_y/IP	0.065	N/A	0.08	0.12	0.10	0.05
f_s [kHz]	1.6	0.65	2.19	1.29	0.44	0.43
E_{acc} [MV/m]	7.5	11.9	20	20	20	20
eff. RF length [m]	485	42	600	100	300	600
f_{RF} [MHz]	352	721	700	700	700	700
δ^{SR}_{rms} [%]	0.22	0.12	0.23	0.06	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.69	0.31	0.19	0.17	0.25
L/IP[$10^{32}cm^{-2}s^{-1}$]	1.25	N/A	94	10335	490	65
number of IPs	4	1	2	2	2	2
Rad.Bhabha b.lifetime [min]	360	N/A	18	37	16	27
Υ_{BS} [10^{-4}]	0.2	0.05	9	4	15	15
n_γ/collision	0.08	0.16	0.60	0.41	0.50	0.51
$\Delta\delta^{BS}$/collision [MeV]	0.1	0.02	31	3.6	42	61
$\Delta\delta^{BS}_{rms}$/collision [MeV]	0.3	0.07	44	6.2	65	95

LEP data for 94.5 - 101 GeV consistently suggest a beam-beam limit of ~0.115 (R.Assmann, K. C.)

Stuart’s Livingston Chart: Luminosity (/IP)



adding TLEP to the chart!

SuperKEKB is TLEP demonstrator

Stuart Henderson, Higgs Factory Workshop, Nov. 14, 2012

beam lifetime

LEP2:

- beam lifetime ~ 6 h
- due to radiative Bhahba scattering (σ~0.215 b)

TLEP:

- with L~5x10^{34} cm^{-2}s^{-1} at each of four IPs:

  $\tau_{\text{beam,TLEP}}$~16 minutes from rad. Bhabha

  SuperKEKB: τ~6 minutes!

- **additional lifetime limit due to beamstrahlung**

  (1) large momentum acceptance ($\delta_{\text{max,RF}}\geq$3%),

  (2) flatter beams [smaller ε_y & larger β_x^*,
  maintaining the same L & ΔQ_{bb} constant], or

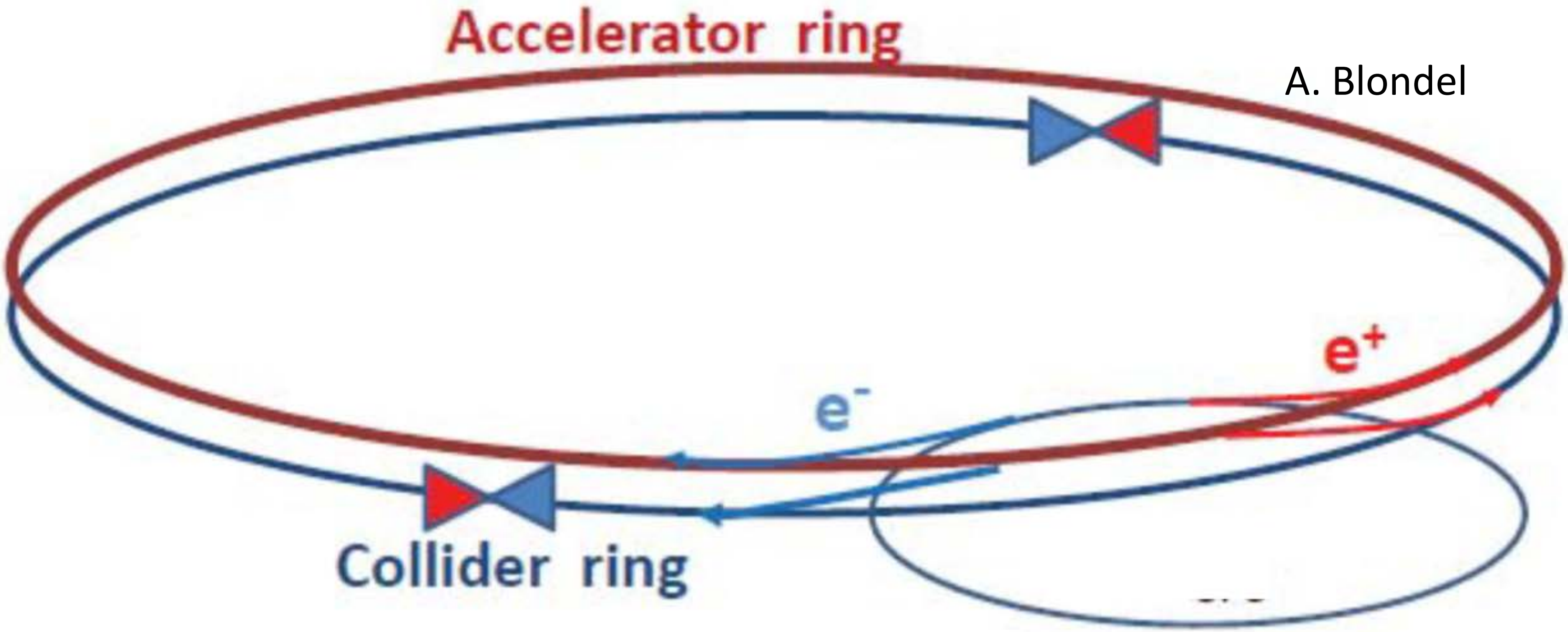
  (3) fast replenishing

  (Valery Telnov, Kaoru Yokoya, Marco Zanetti)

circular HFs – top-up injection

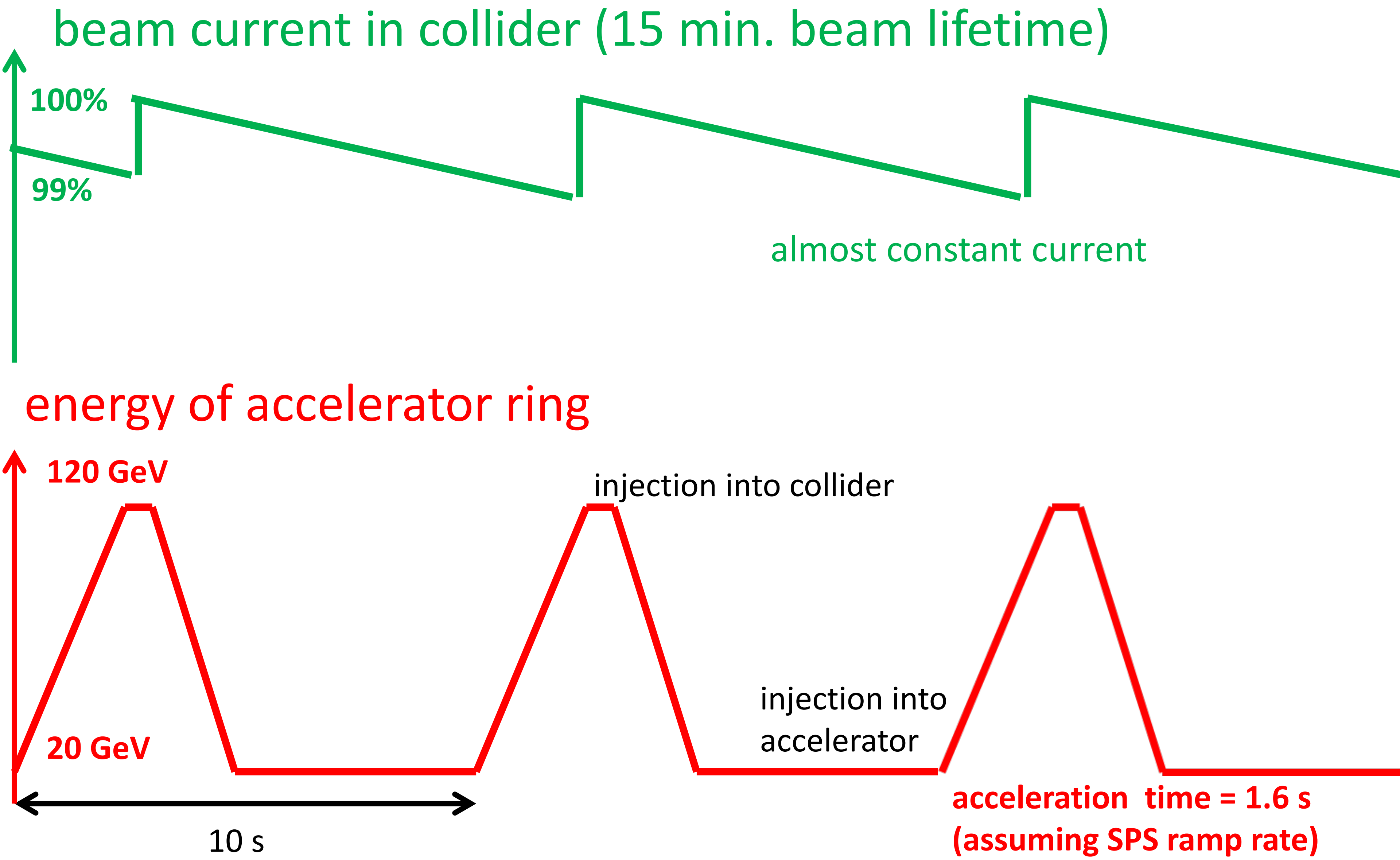
double ring with top-up injection

supports short lifetime & high luminosity



top-up experience: PEP-II, KEKB, light sources

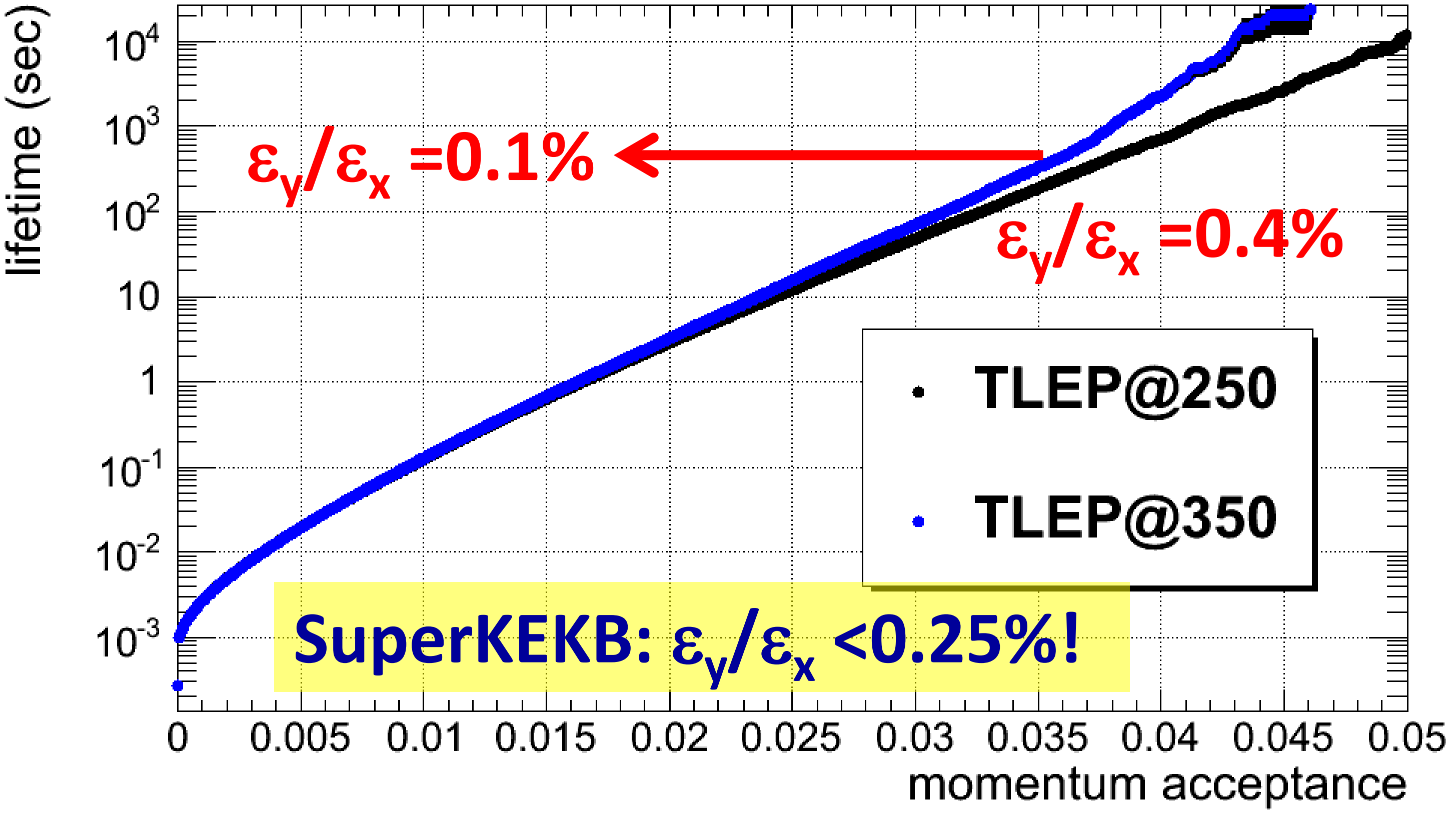
top-up injection: schematic cycle



beamstrahlung lifetime

- simulation w 360M macroparticles
- τ varies exponentially w energy acceptance η
- post-collision *E* tail → lifetime τ

beam lifetime versus acceptance δ_{max} for 4 IPs:



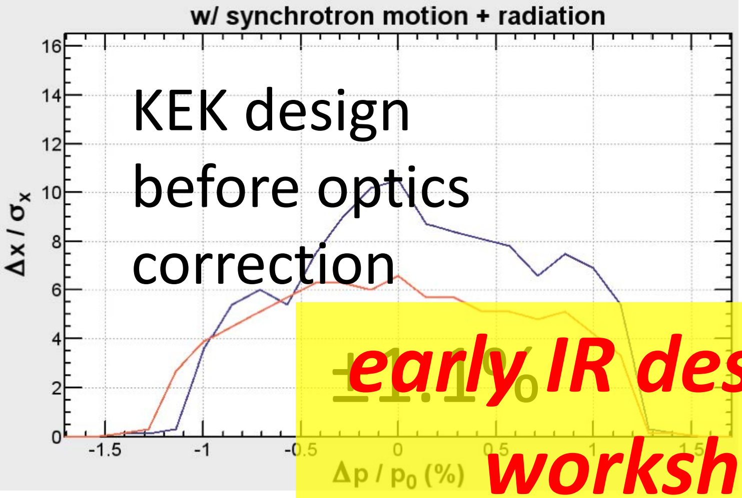
$\varepsilon_y/\varepsilon_x = 0.1\%$

$\varepsilon_y/\varepsilon_x = 0.4\%$

SuperKEKB: $\varepsilon_y/\varepsilon_x < 0.25\%$!

M. Zanetti

circular HFs - momentum acceptance

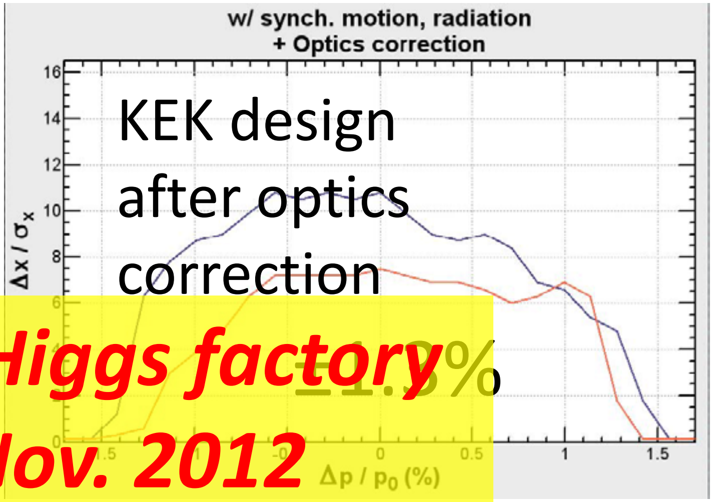


KEK design before optics correction

±1.1%

with synchrotron motion & radiation (sawtooth)

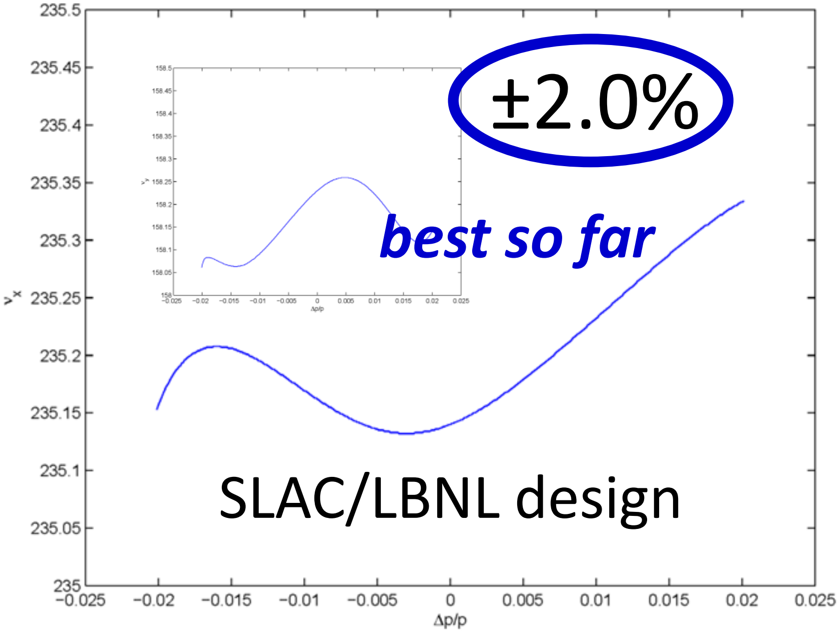
K. Oide



KEK design after optics correction

±1.3%

early IR designs, ICFA Higgs factory workshop, FNAL, Nov. 2012

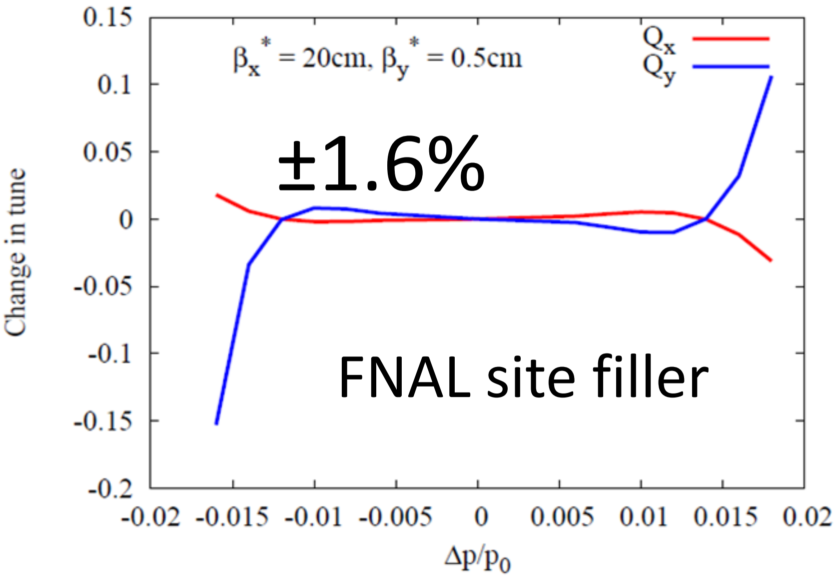


±2.0%

best so far

SLAC/LBNL design

Y. Cai



±1.6%

FNAL site filler

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

circular collider & SR experience

…

CESR

BEPC

LEP

Tevatron

LEP2

HERA

DAFNE

PEP-II

KEKB

BEPC-II

LHC

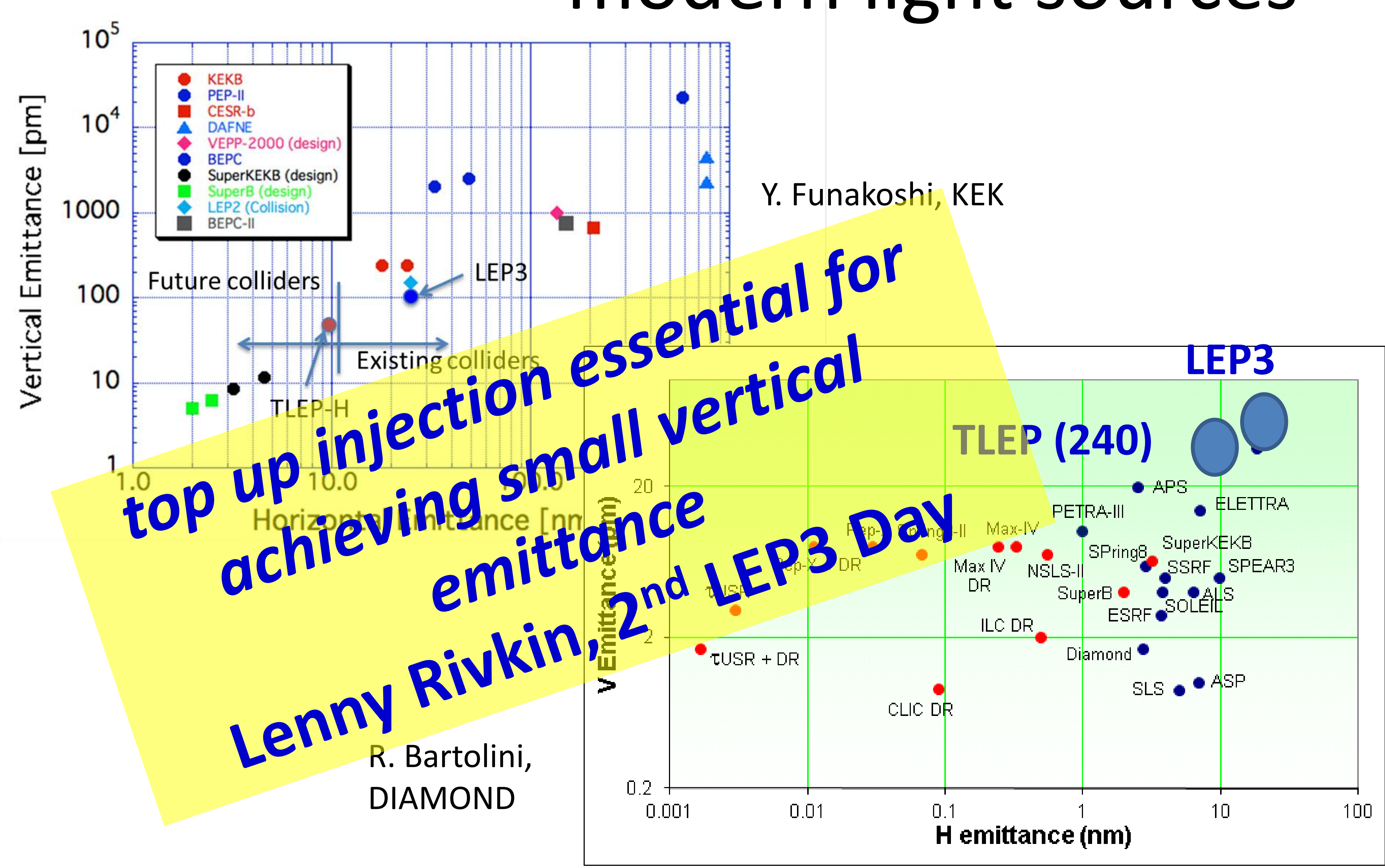
SuperKEKB (soon)

3rd generation light sources

1992	**ESRF**, France (EU)	6 GeV
	ALS, US	1.5-1.9 GeV
1993	**TLS**, Taiwan	1.5 GeV
1994	**ELETTRA**, Italy	2.4 GeV
	PLS, Korea	2 GeV
	MAX II, Sweden	1.5 GeV
1996	**APS**, US	7 GeV
	LNLS, Brazil	1.35 GeV
1997	**Spring-8**, Japan	8 GeV
1998	**BESSY II**, Germany	1.9 GeV
2000	**ANKA**, Germany	2.5 GeV
	SLS, Switzerland	2.4 GeV
2004	**SPEAR3**, US	3 GeV
	CLS, Canada	2.9 GeV
2006:	**SOLEIL**, France	2.8 GeV
	DIAMOND, UK	3 GeV
	ASP, Australia	3 GeV
	MAX III, Sweden	700 MeV
	Indus-II, India	2.5 GeV
2008	**SSRF**, China	3.4 GeV
2009	**PETRA-III**, Germany	6 GeV
2011	**ALBA**, Spain	3 GeV

well understood technology & typically exceeding design performance within a few years

emittances in circular colliders & modern light sources



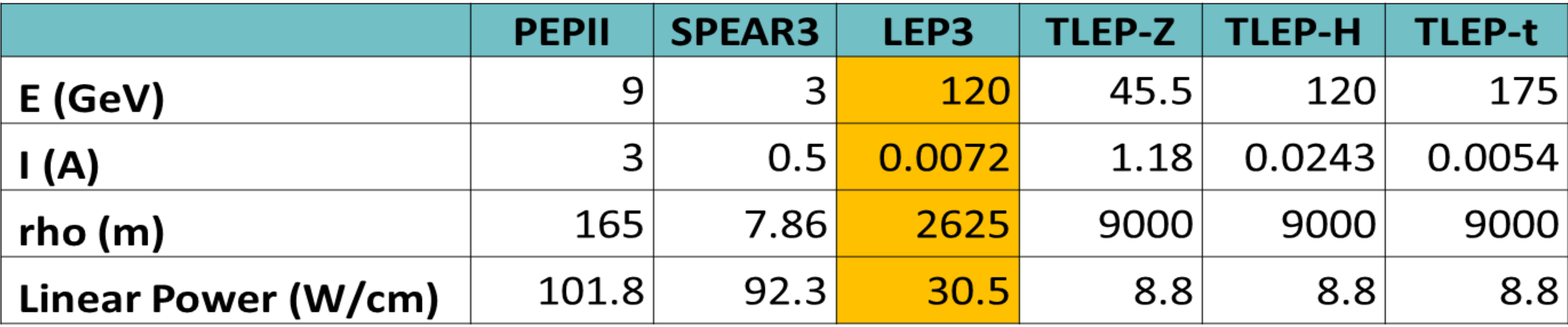
Y. Funakoshi, KEK

R. Bartolini,
DIAMOND

top up injection essential for achieving small vertical emittance

Lenny Rivkin, 2nd LEP3 Day

circular HFs: 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

LEP3 and TLEP have 3-10 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.W.N.Tuyn

A. Fasso
3rd TLEP3 Day

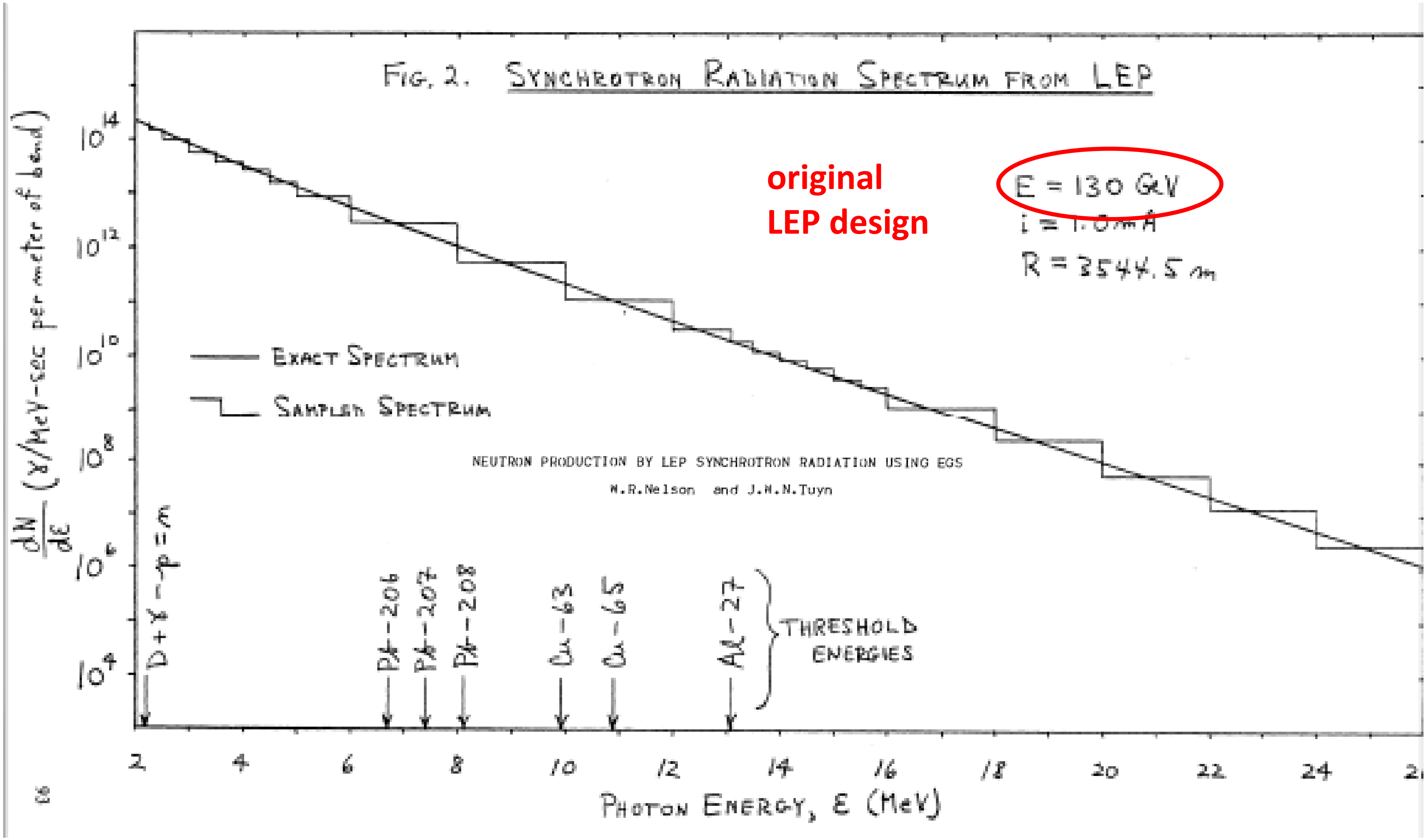


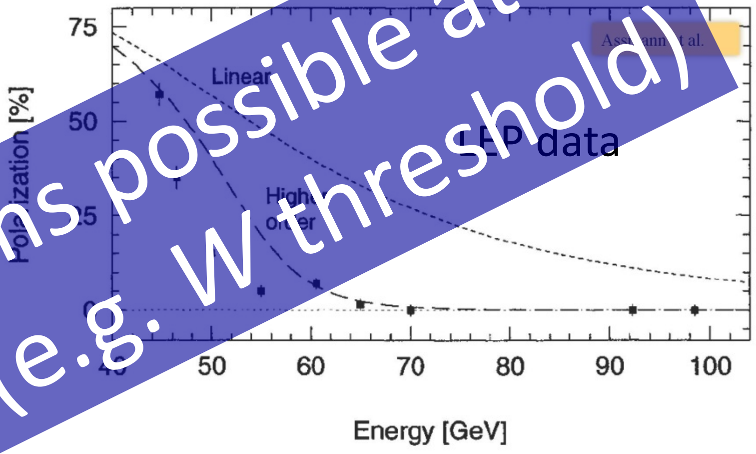
FIG. 2. SYNCHROTRON RADIATION SPECTRUM FROM LEP

original LEP design

polarization

motivation: access to some physics (≥50%) at *Z* pole,
energy calibration (a few %) at *W* threshold

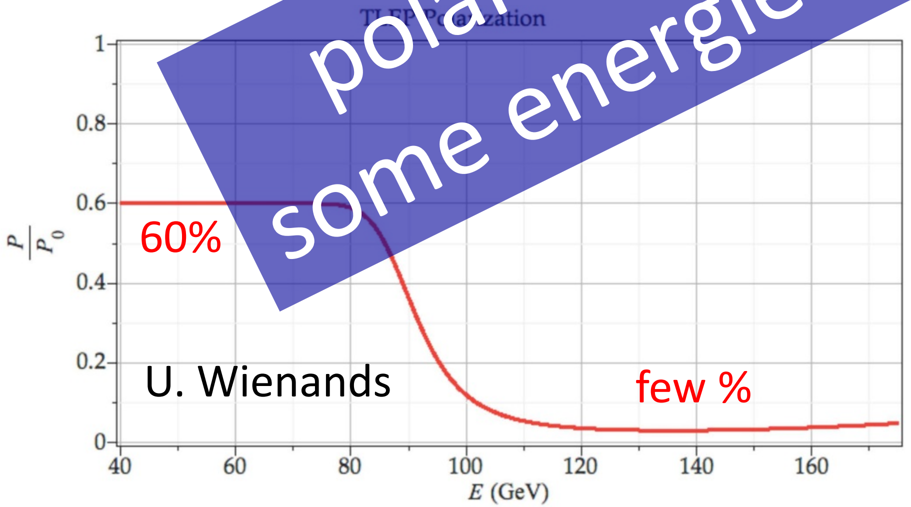
LEP had the highest-energy (self-)polarized electron beams ; energy spread reduces polarization at highest energy



LEP data

polarized beams possible at some energies (e.g. W threshold)

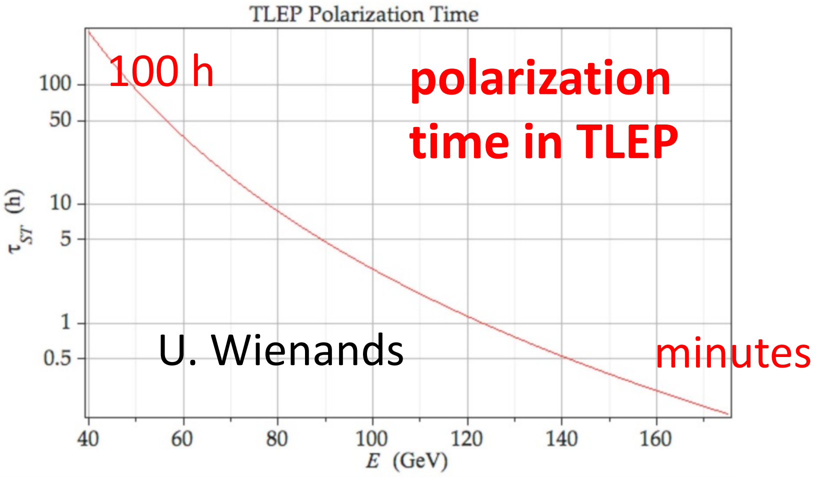
model prediction for TLEP



60%

U. Wienands

few %



100 h

polarization time in TLEP

U. Wienands

minutes

options: snakes & injection of polarized beams at Z pole, polarization wigglers,…

TLEP key components

- tunnel
- SRF system
- cryoplants
- magnets
- injector ring
- detectors

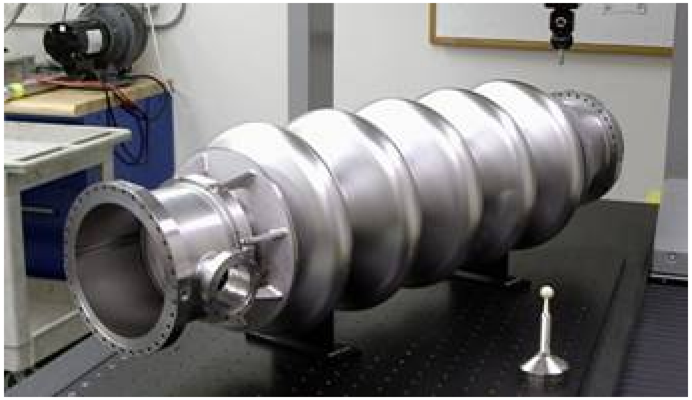
tunnel is main cost

RF is main system

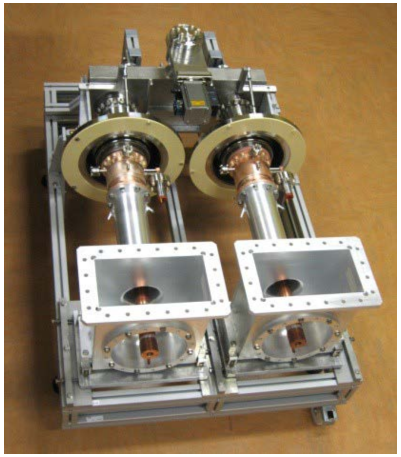
TLEP SC RF system

total collider ring voltage: **12 GV**
cw RF gradient: **20 MV/m** → 600 m eff. RF length (~LEP2)
RF frequency: **700-800 MHz** (BNL eRHIC, ESS, SPL, SNS – high power)
total power throughput to beam: **100 MW**
power / cavity: up to 200 kW
RF efficiency (wall→beam): **50%**

"Super-power" klystrons at 700 MHz with 63-65% efficiency are available from CPI, Toshiba and Thales



BNL 704 MHz 5-cell cavity



High power RF coupler (ESS/SPL)

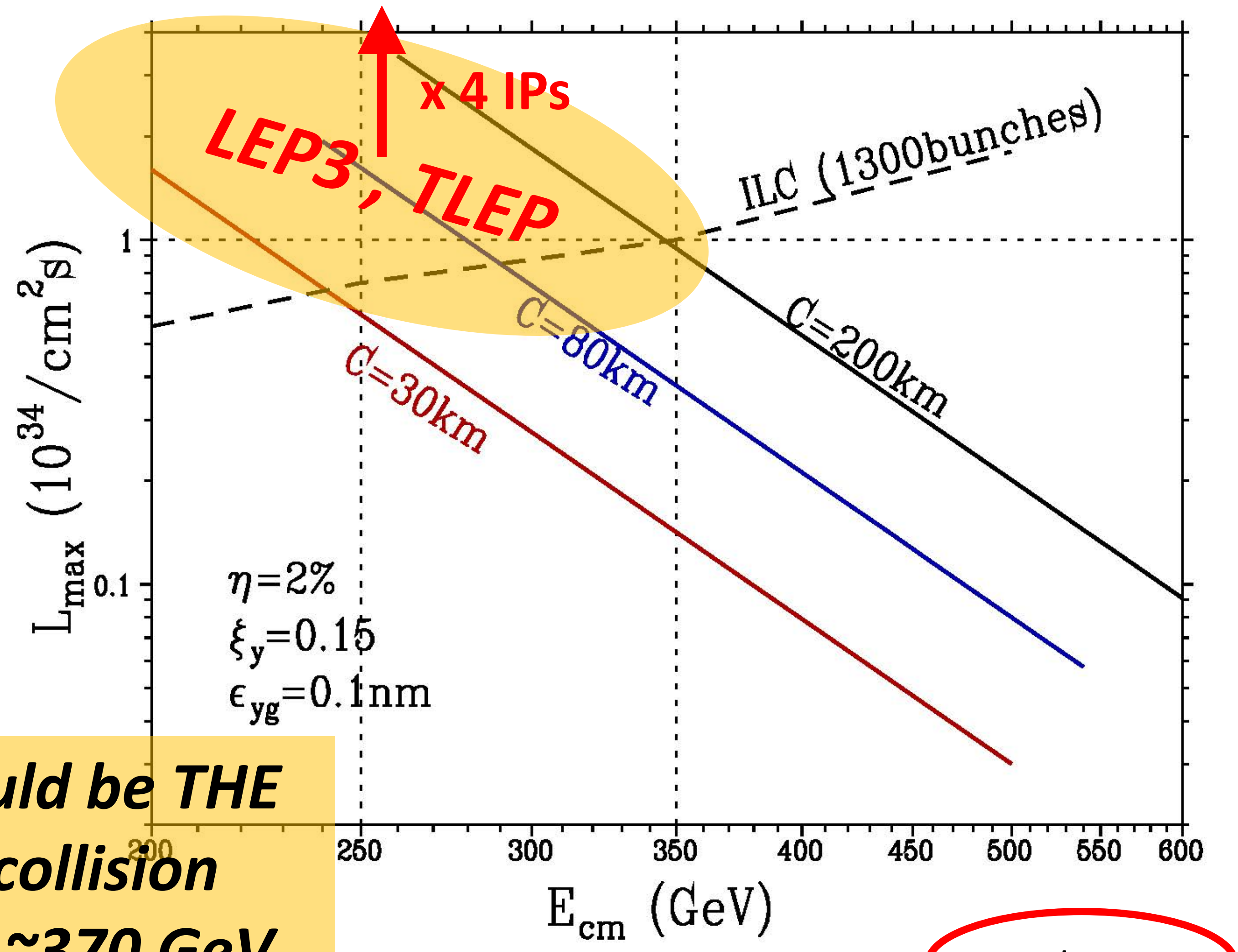
TLEP/LEP3 key issues

- SR handling and **radiation shielding**
- optics effect of **energy sawtooth**
  [separate arcs?! (K. Oide)]
- beam-beam interaction for **large Q_s**
  and significant **hourglass effect**
- **β_y*=1 mm IR with large acceptance**
- **Tera-Z operation** (impedance effects & parasitic collisions)

→ Conceptual Design Study by 2014/15!

circular & linear HF: peak luminosity vs energy

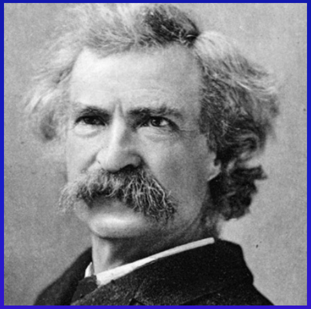
example with
- $\eta=2\%$
- $\xi_y=0.15$
- $\varepsilon_{gy}=0.1\text{nm}$



***LEP3/TLEP* would be THE choice for e^+e^- collision energies up to ~370 GeV**

K. Yokoya, KEK

“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

risk?

extrapolation from past experience

	LEP2→TLEP-H	**SLC→ILC 250**
peak luminosity	x400	x2500
energy	x1.15	x2.5
vertical geom. emittance	x1/5	x1/400
vert. IP beam size	x1/15	x1/150
e^+ production rate	x1/2	x65
commissioning time	<1 year → ?	>10 years →?

vertical rms IP spot sizes in nm

in regular
font:
achieved

in italics:
design
values

LEP2	3500
KEKB	940
SLC	500
LEP3	***320***
TLEP-H	***220***
ATF2, FFTB	73 (35), 77
SuperKEKB	*50*
ILC	*5 – 8*
CLIC	*1 – 2*

β_y^*:
5 cm→
1 mm

LEP3/TLEP will learn from ATF2 & SuperKEKB

#Higgs bosons at √s = 240-250 GeV

	ILC-250	LEP3-240	TLEP-240
Lumi / IP / 5 years	250 fb^{-1}	500 fb^{-1}	2.5 ab^{-1}
# IP	1	2 - 4	2 - 4
Lumi / 5 years	250 fb^{-1}	1 - 2 ab^{-1}	5 - 10 ab^{-1}
Beam Polarization	80%, 30%	–	–
$L_{0.01}$ (beamstrahlung)	86%	100%	100%
#Higgs	70,000	400,000	2,000,000

in a given amount of time, Higgs coupling precisions scale like

➔ 2% for ILC : 1% for LEP3 : 0.3% for TLEP

➔ 1 year of TLEP = 5 years of LEP3 = 15-30 years of ILC (at 240 GeV)

comparing expected performance on Higgs coupling

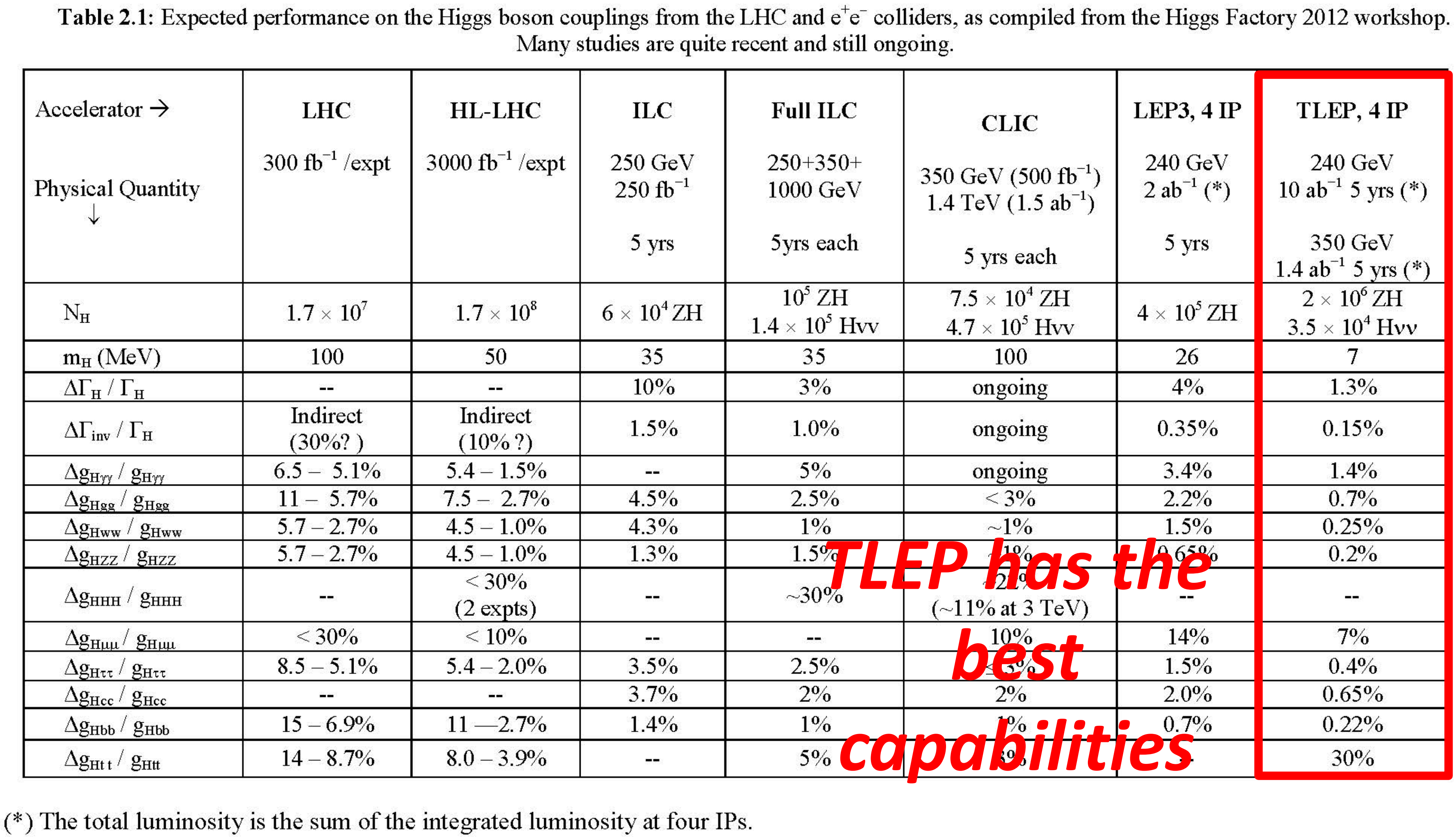


Table 2.1: Expected performance on the Higgs boson couplings from the LHC and e^+e^- colliders, as compiled from the Higgs Factory 2012 workshop. Many studies are quite recent and still ongoing.

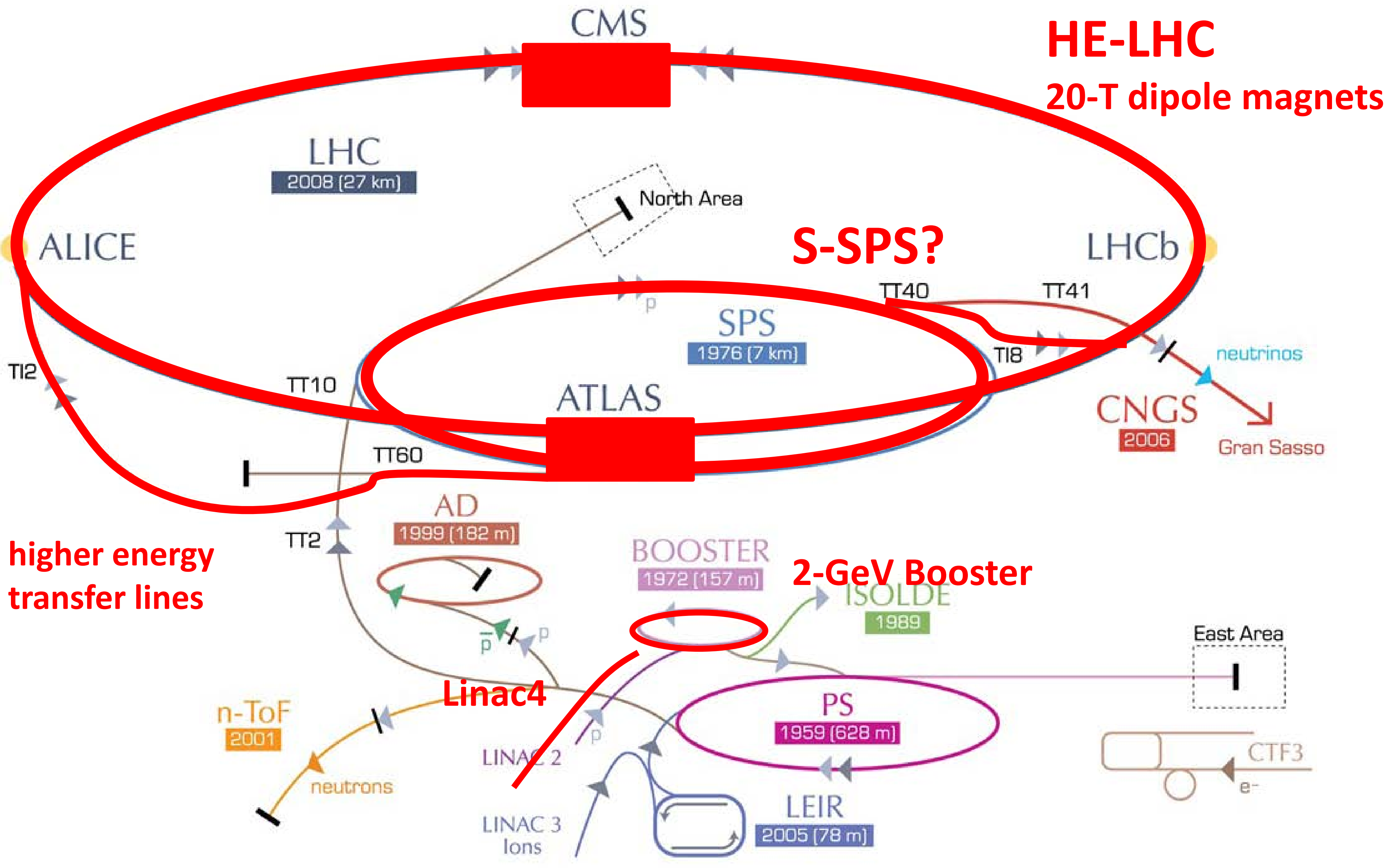
Accelerator → Physical Quantity ↓	LHC $300\ fb^{-1}$ /expt	HL-LHC $3000\ fb^{-1}$ /expt	ILC 250 GeV $250\ fb^{-1}$ 5 yrs	Full ILC 250+350+ 1000 GeV 5yrs each	CLIC 350 GeV ($500\ fb^{-1}$) 1.4 TeV ($1.5\ ab^{-1}$) 5 yrs each	LEP3, 4 IP 240 GeV $2\ ab^{-1}$ (*) 5 yrs	TLEP, 4 IP 240 GeV $10\ ab^{-1}$ 5 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.

TLEP has the best capabilities

Report of the ICFA Beam Dynamics Workshop ***"Accelerators for a Higgs Factory: Linear vs. Circular"*** **(HF2012) by** Alain Blondel, Alex Chao, Weiren Chou, Jie Gao, Daniel Schulte and Kaoru Yokoya, FERMILAB-CONF-13-037-APC, IHEP-AC-2013-1, SLAC-PUB-15370, CERN-ATS-2013-032, arXiv:1302.3318 [physics.acc-ph]

High-Energy LHC



HE-LHC

20-T dipole magnets

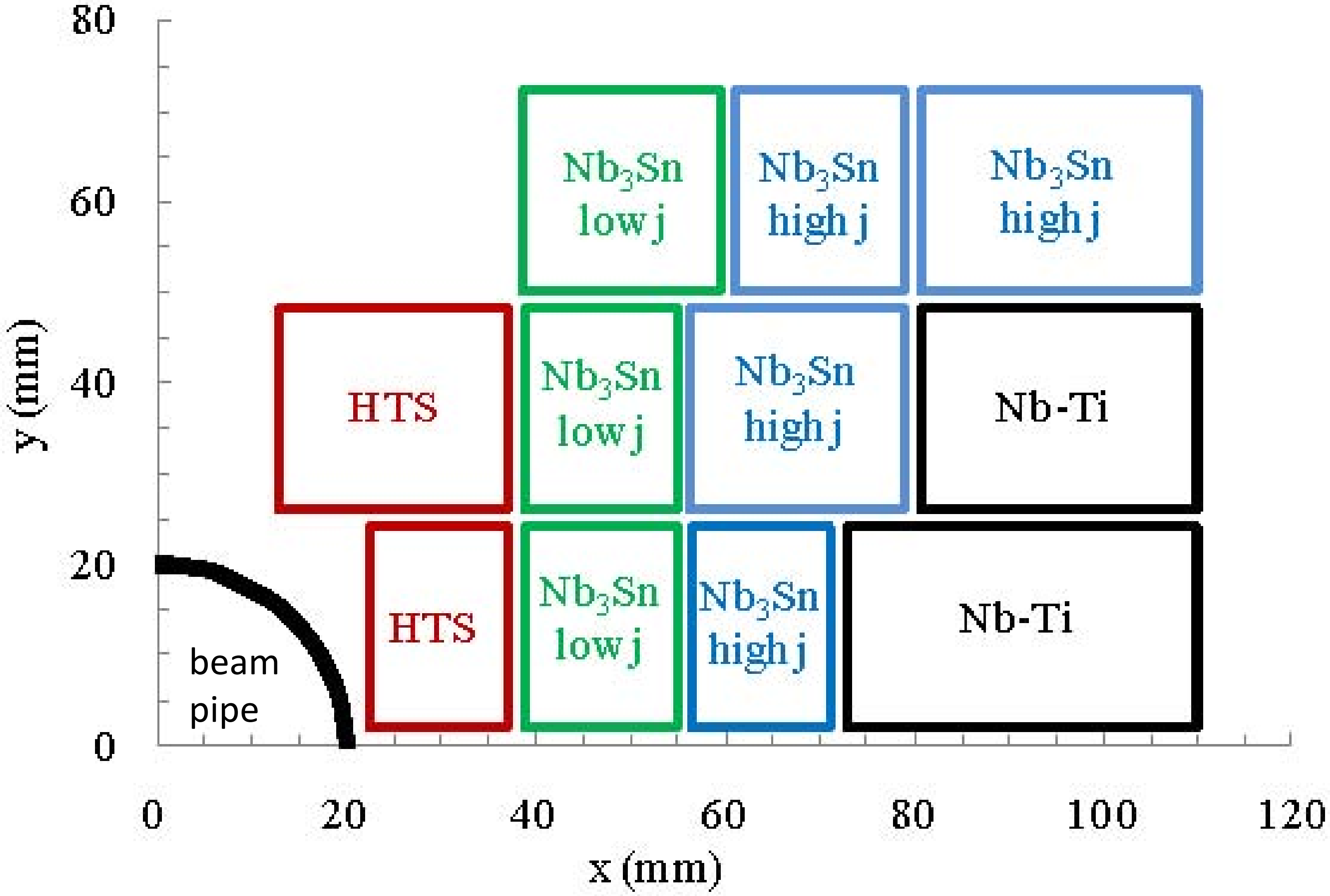
S-SPS?

higher energy transfer lines

2-GeV Booster

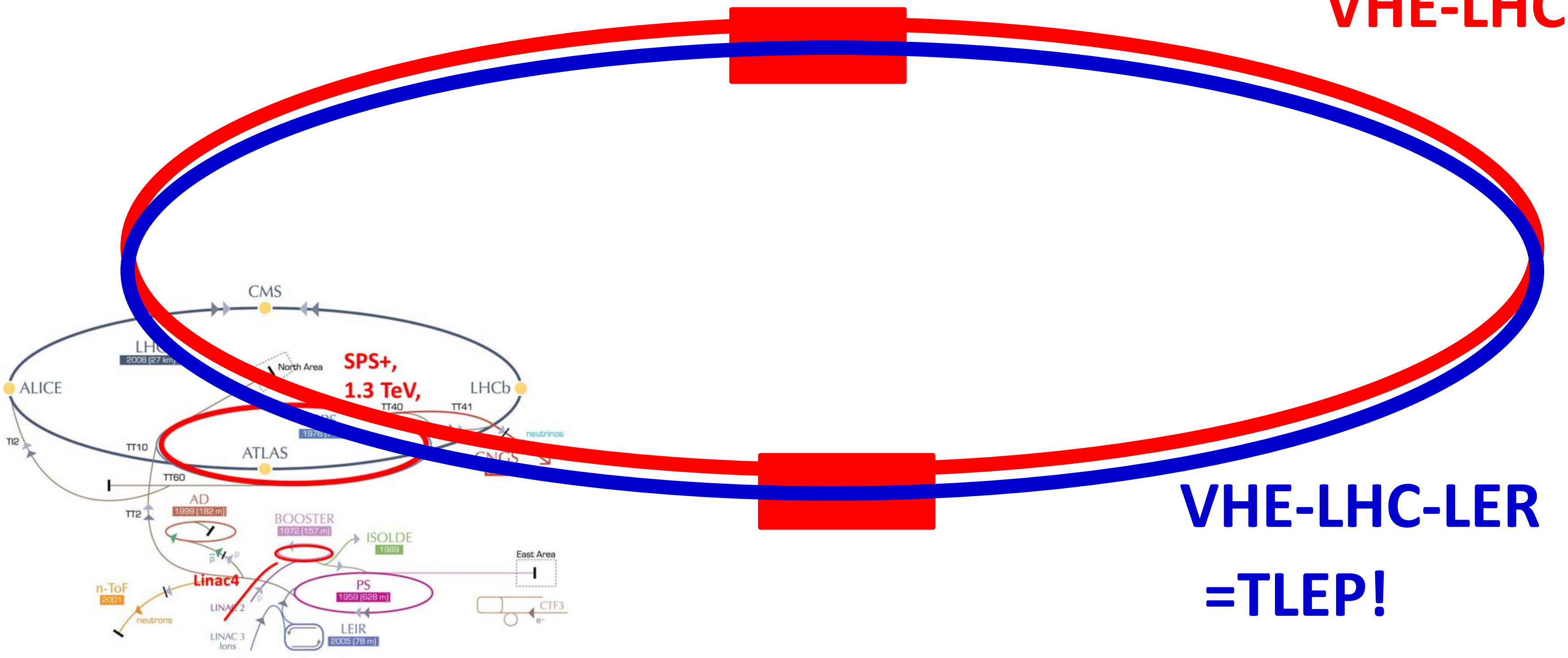
Linac4

20-T dipole magnet



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

VHE-LHC



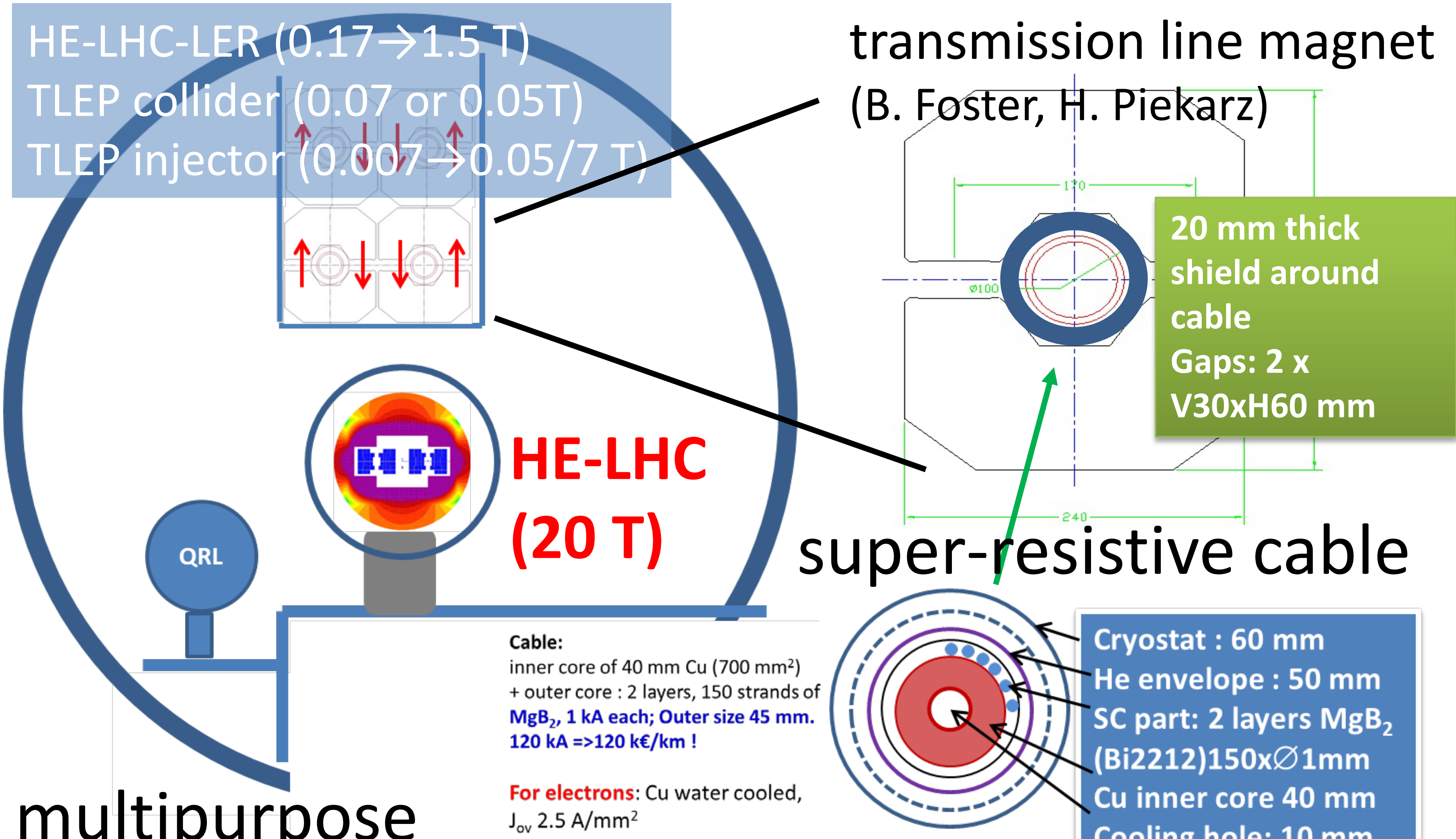
VHE-LHC

VHE-LHC-LER
=TLEP!

(Lucio Rossi)

VHE-LHC + TLEP

L. Rossi



HE-LHC-LER (0.17→1.5 T)
TLEP collider (0.07 or 0.05T)
TLEP injector (0.007→0.05/7 T)

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

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

HE-LHC (20 T)

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
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

multipurpose tunnel

conclusions

- **LHC is running well** & already made important discoveries, Higgs boson being most prominent
- **detailed schedule until 2022**
- **HL-LHC goal:** 100x the present integrated luminosity at design energy by 2035
- focused **R&D** to be ready with **proposal for future machine by 2017/18**
- **TLEP + VHE-LHC** offer large synergies & prepare **≥50 years e^+e^-, *pp*, *ep*/A highest-energy physics**
- **SuperKEKB will be important TLEP demonstrator**

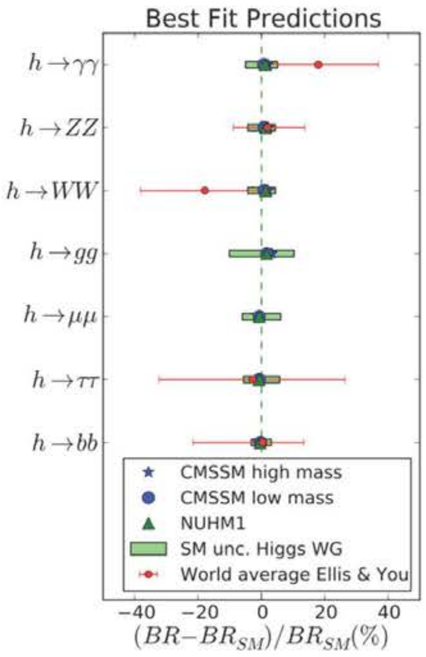
physics situation

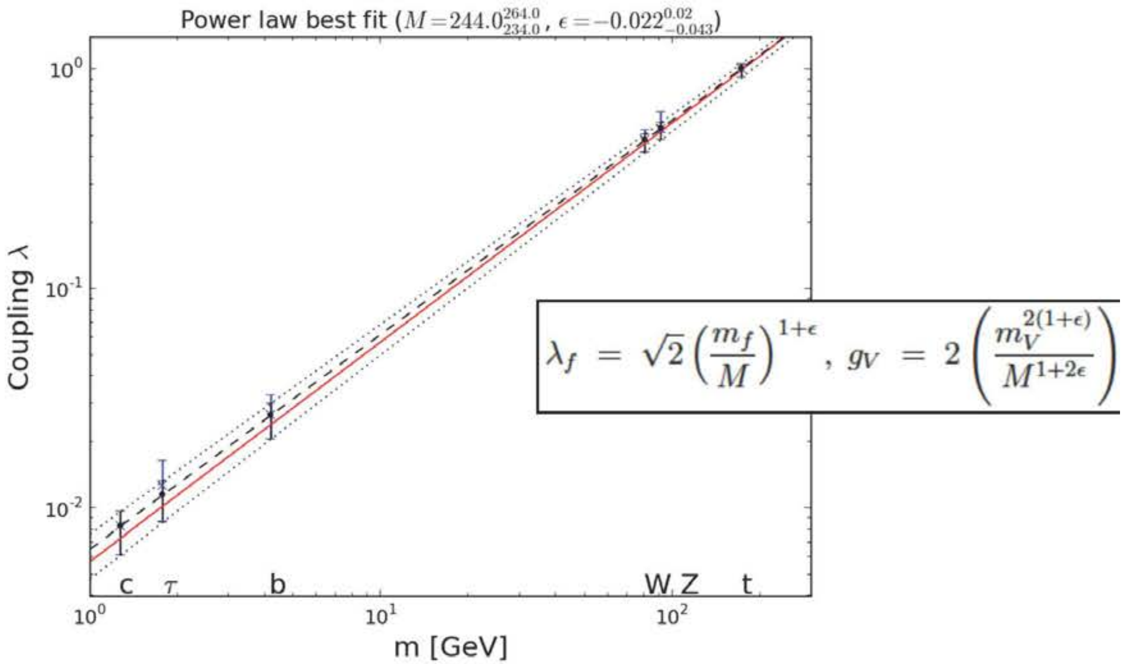
P. Janot,
J. Ellis,
A. Blondel

Today's situation

- A (very) Standard Higgs boson

J. Ellis et al.





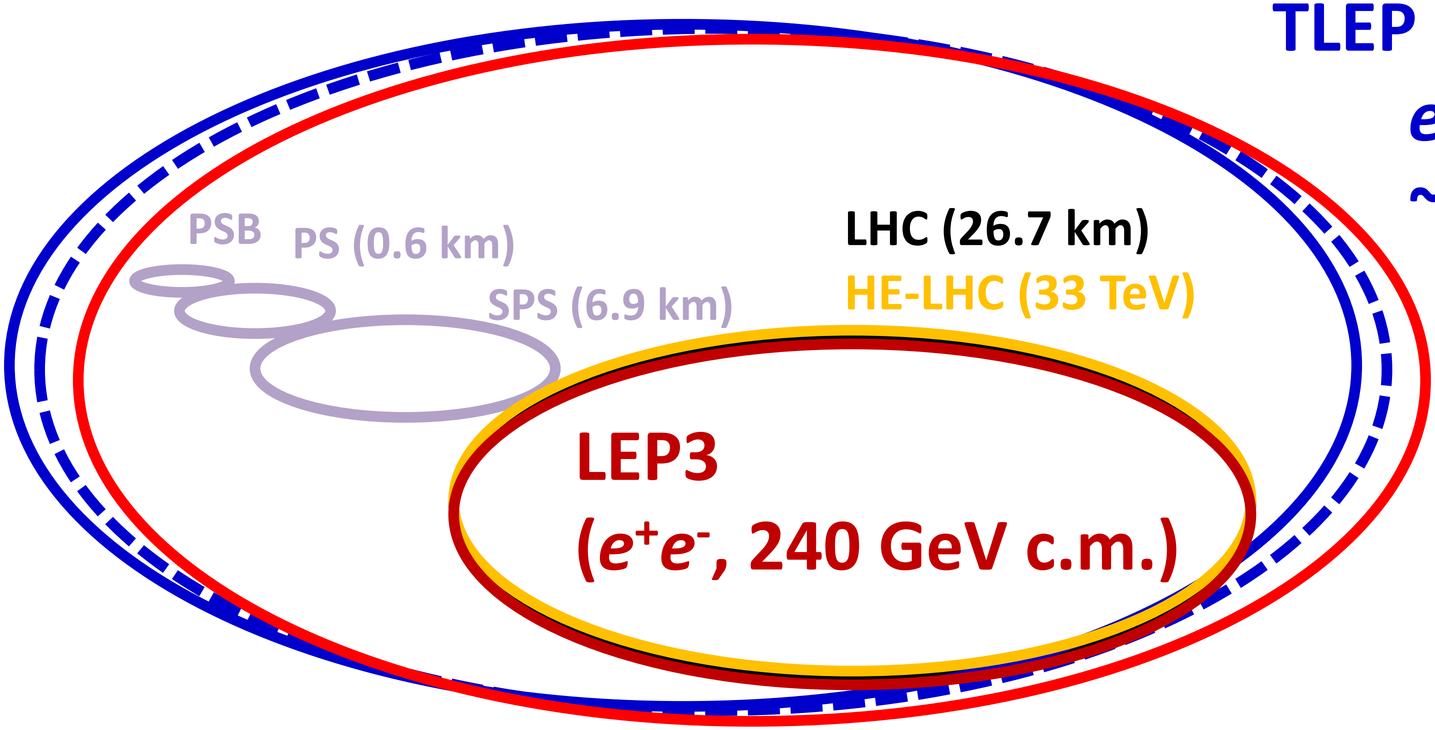
$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \quad g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

- No new physics all the way to several 100's GeV (SUSY) or more
  - Next run at 14 TeV will extend the coverage to ~500 GeV (SUSY) or more
    - ➨ Very strong incentive to look for multi-TeV new Physics
    - ➨ Linear Colliders with √s = o(TeV) do not cover this Physics case

What else, then ?

- ➢ **precision measurements sensitive to multi-TeV New Physics (TLEP)**
- ➢ **direct search for New Physics in the 10-100 TeV range (VHE-LHC)**

possible long-term strategy



PSB

PS (0.6 km)

SPS (6.9 km)

LHC (26.7 km)

HE-LHC (33 TeV)

LEP3
(e^+e^-, 240 GeV c.m.)

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

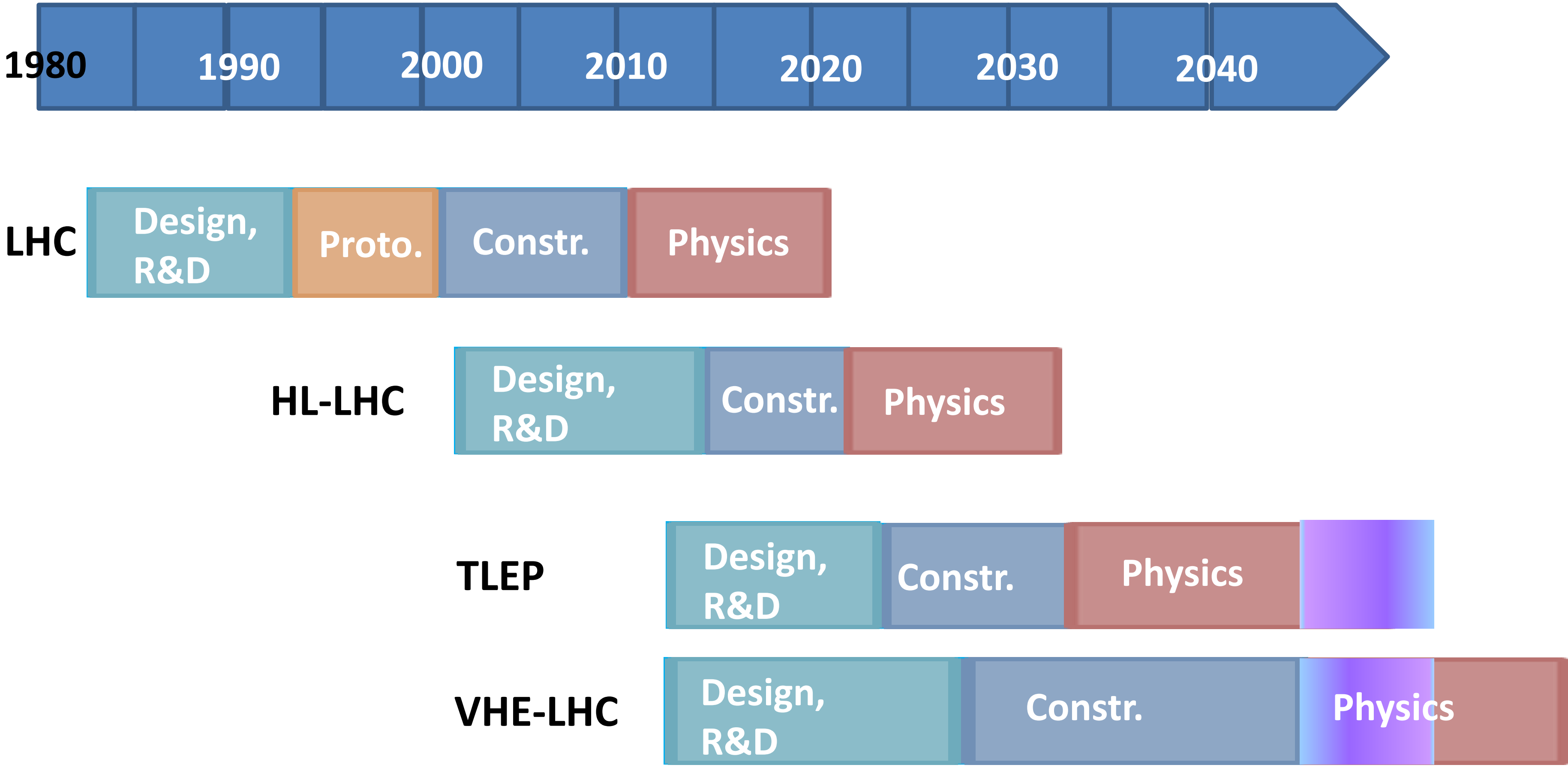
VHE-LHC
(pp, up to
100 TeV c.m.)

"same" detectors!

& **$e^\pm$ (120 GeV) – p (7, 16 & 50 TeV)** collisions **([(V)HE-]TLHeC)**

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

tentative time line



TLEP design study –preliminary structure for discussion

Institutional board

Steering group
web site, mailing lists,
speakers board, etc..

International Advisory board

Accelerator

1. Optics, low beta, alignment and feedbacks
2. Beam beam interaction
3. Magnets and vacuum
4. RF system
5. Injector system
6. Integration w/(SHE)-LHC
7. Interaction region
8. Polarization &E-calib.
9. Elements of costing

Experiments

1. [illegible] properties
2. Precision EW measurements at the Z peak and W threshold
3. Top quark physics
4. Experimental environment
5. Detector design
6. Online and offline computing

Physics

1. Theoretical implications and model building
2. Precision measurements, simulations and monte carlos
3. Combination + complementarity with LHC and other machines ; global fits

launch of international design study:
are you interested in participating and/or like to be informed about progress & events?

http://tlep.web.cern.ch/contribute-to-the-design-study

TLEP/LEP3 events & references

A. Blondel, F. Zimmermann, *"A High Luminosity e^+e^- Collider in the LHC Tunnel to study the Higgs Boson,"* arXiv:1112.2518v1, 24.12.'11

K. Oide, *"SuperTRISTAN - A possibility of ring collider for Higgs factory,"* KEK Seminar, 13 February 2012

1st EuCARD LEP3 workshop, CERN, 18 June 2012

A. Blondel et al, *"LEP3: A High Luminosity e+e- Collider to study the Higgs Boson,"* arXiv:1208.0504, submitted to ESPG Krakow

P. Azzi et al, *"Prospective Studies for LEP3 with the CMS Detector,"* arXiv:1208.1662 (2012), submitted to ESPG Krakow

2nd EuCARD LEP3 workshop, CERN, 23 October 2012

P. Janot, *"A circular e^+e^- collider to study H(125),"* PH Seminar, CERN, 30 October 2012

ICFA Higgs Factory Workshop: Linear vs Circular, FNAL, 14-16 Nov. '12

A. Blondel, F. Zimmermann, *"Future possibilities for precise studies of the X(125) Higgs candidate,"* CERN Colloquium, 22 Nov. 2012

3rd TLEP3 Day, CERN, 10 January 2013

4th TLEP mini-workshop, CERN, 4-5 April 2013

5th TLEP mini-workshop, 25-26 July 2013, Fermilab

https://tlep.web.cern.ch https://cern.ch/accnet

HE-LHC &VHE-LHC events & references

R. Assmann, R. Bailey, O. Brüning, O. Dominguez, G. de Rijk, J.M. Jimenez, S. Myers, L. Rossi, L. Tavian, E. Todesco, F. Zimmermann, “First Thoughts on a Higher-Energy LHC,” CERN-ATS-2010-177

E. Todesco, F. Zimmermann (eds), **“EuCARD-AccNet-EuroLumi Workshop: The High-Energy Large Hadron Collider,”** Proc**. EuCARD-AccNet workshop HE-LHC’10 , Malta, 14-16 October 2010**, arXiv:1111.7188 ; CERN Yellow Report CERN-2011-003

HiLumi LHC WP6 HE-LHC

Joint Snowmass-EuCARD/AccNet-HiLumi meeting `Frontier Capabilities for Hadron Colliders 2013,‘ CERN, 21-11 February 2013

http://hilumilhc.web.cern.ch/HiLumiLHC/activities/HE-LHC/WP16/

https://cern.ch/accnet

Mikhail S. Gorbachev

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

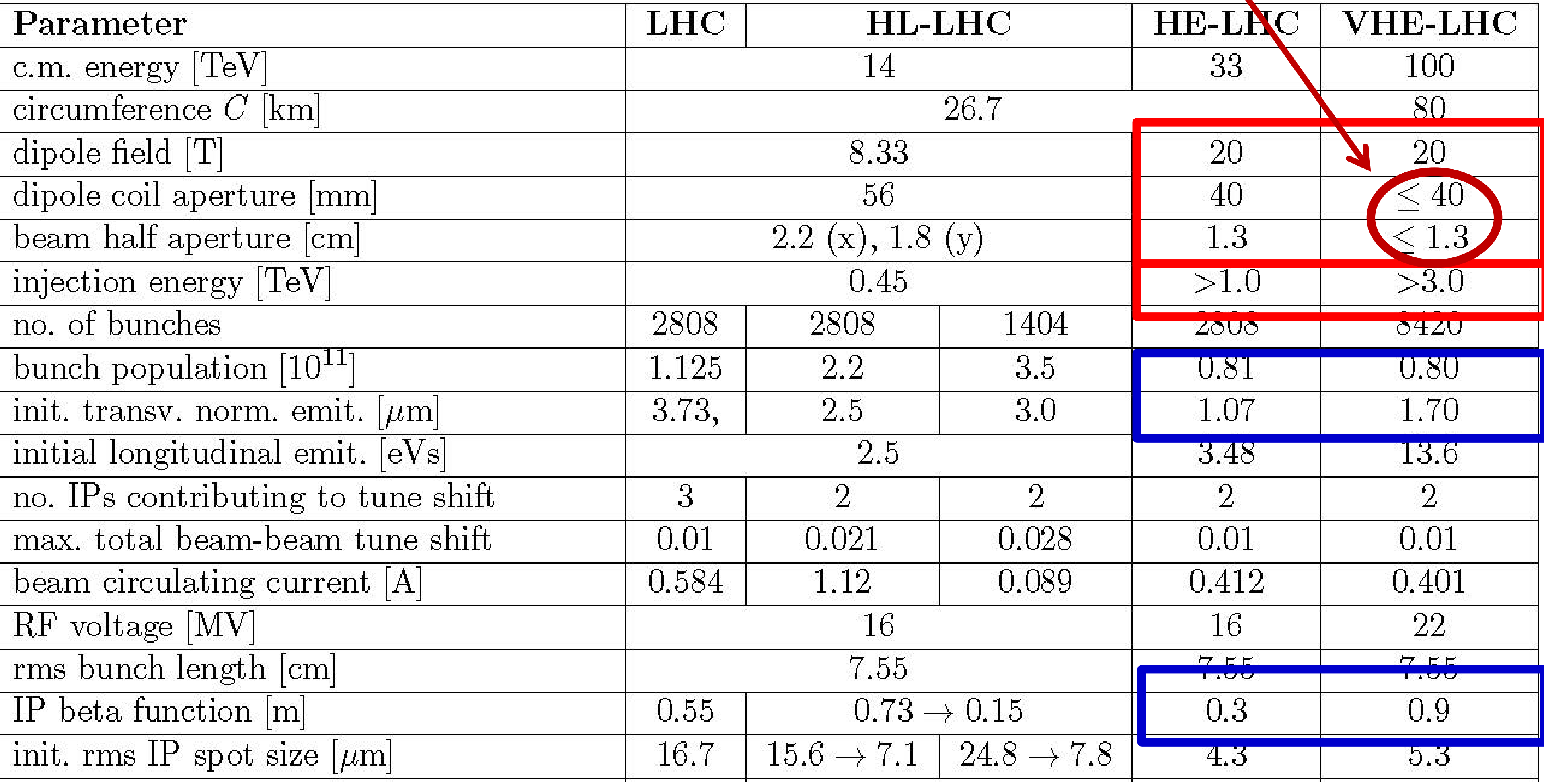
Appendix

- example parameters for HL-LHC, HE-LHC, VHE-LHC, TLHeC, VHE-TLHeC
- Higgs-factory quality table

(V)HE-LHC parameters – 1

preliminary

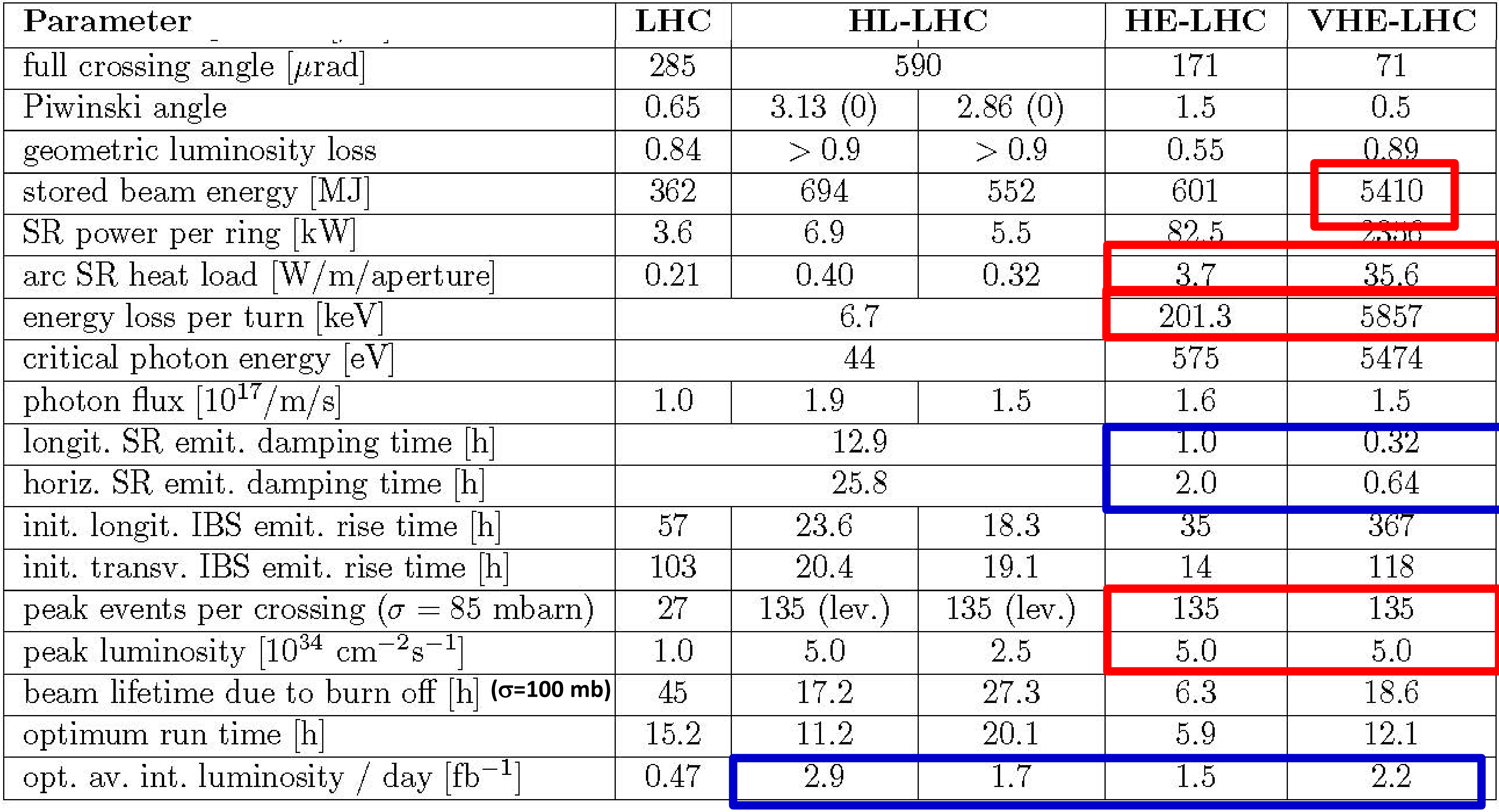
smaller?! (x1/4?)



Parameter	LHC	HL-LHC		HE-LHC	VHE-LHC
c.m. energy [TeV]	14			33	100
circumference C [km]	26.7				80
dipole field [T]	8.33			20	20
dipole coil aperture [mm]	56			40	≤ 40
beam half aperture [cm]	2.2 (x), 1.8 (y)			1.3	≤ 1.3
injection energy [TeV]	0.45			>1.0	>3.0
no. of bunches	2808	2808	1404	2808	8420
bunch population [10^{11}]	1.125	2.2	3.5	0.81	0.80
init. transv. norm. emit. [μm]	3.73,	2.5	3.0	1.07	1.70
initial longitudinal emit. [eVs]	2.5			3.48	13.6
no. IPs contributing to tune shift	3	2	2	2	2
max. total beam-beam tune shift	0.01	0.021	0.028	0.01	0.01
beam circulating current [A]	0.584	1.12	0.089	0.412	0.401
RF voltage [MV]	16			16	22
rms bunch length [cm]	7.55			7.55	7.55
IP beta function [m]	0.55	$0.73 \rightarrow 0.15$		0.3	0.9
init. rms IP spot size [μm]	16.7	$15.6 \rightarrow 7.1$	$24.8 \rightarrow 7.8$	4.3	5.3

O. Dominguez, L. Rossi, F.Z.

(V)HE-LHC parameters – 2 *preliminary*



Parameter	LHC	HL-LHC		HE-LHC	VHE-LHC
full crossing angle [μrad]	285	590		171	71
Piwinski angle	0.65	3.13 (0)	2.86 (0)	1.5	0.5
geometric luminosity loss	0.84	> 0.9	> 0.9	0.55	0.89
stored beam energy [MJ]	362	694	552	601	5410
SR power per ring [kW]	3.6	6.9	5.5	82.5	2356
arc SR heat load [W/m/aperture]	0.21	0.40	0.32	3.7	35.6
energy loss per turn [keV]	6.7			201.3	5857
critical photon energy [eV]	44			575	5474
photon flux [10^{17}/m/s]	1.0	1.9	1.5	1.6	1.5
longit. SR emit. damping time [h]	12.9			1.0	0.32
horiz. SR emit. damping time [h]	25.8			2.0	0.64
init. longit. IBS emit. rise time [h]	57	23.6	18.3	35	367
init. transv. IBS emit. rise time [h]	103	20.4	19.1	14	118
peak events per crossing ($\sigma = 85$ mbarn)	27	135 (lev.)	135 (lev.)	135	135
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	2.5	5.0	5.0
beam lifetime due to burn off [h] **(σ=100 mb)**	45	17.2	27.3	6.3	18.6
optimum run time [h]	15.2	11.2	20.1	5.9	12.1
opt. av. int. luminosity / day [fb^{-1}]	0.47	2.9	1.7	1.5	2.2

numbers for lifetime and average integrated luminosity need to be updated for ~40% higher cross section at 100 TeV

O. Dominguez, L. Rossi, F.Z.

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}]	**0.5**		**1.6**	

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}]	**8.0**		**25.6**	

HF Accelerator Quality (My Opinion)

	Linear C.	Circular C.	LHeC	Muon C.	γ–γ C.
maturity	☺	☺ ☺	☺ ☺	☹	☹
size	☹	☹	☺	☺☺	☺
cost	☹	☺ - 😐	☺	☹	☺
power	😐	😐	😐	😐	😐
#IPs	1	4	1	1	1
com. time	10 yr	2 yr	2 yr	10 yr	5 yr
H factor	0.2 (SLC)	0.5 (1/2 PEP-II)	0.2?	0.1?	0.1?
Higgs/IP/yr	7 k [10 k]	20-100 k	5 k	5 k	10 k
expanda-bility	1-3TeV e^+e^-, γγ C.	100 TeV *pp*	γγ C.	10 TeV μμ	LC later

inspired by S. Henderson, FNAL