LHC: The Machine

SLAC Summer Institute 2012

26 July 2012

Frank Zimmermann

CERN, Beams Department

thanks to

Mike Lamont, Steve Myers, Ralph Steinhagen

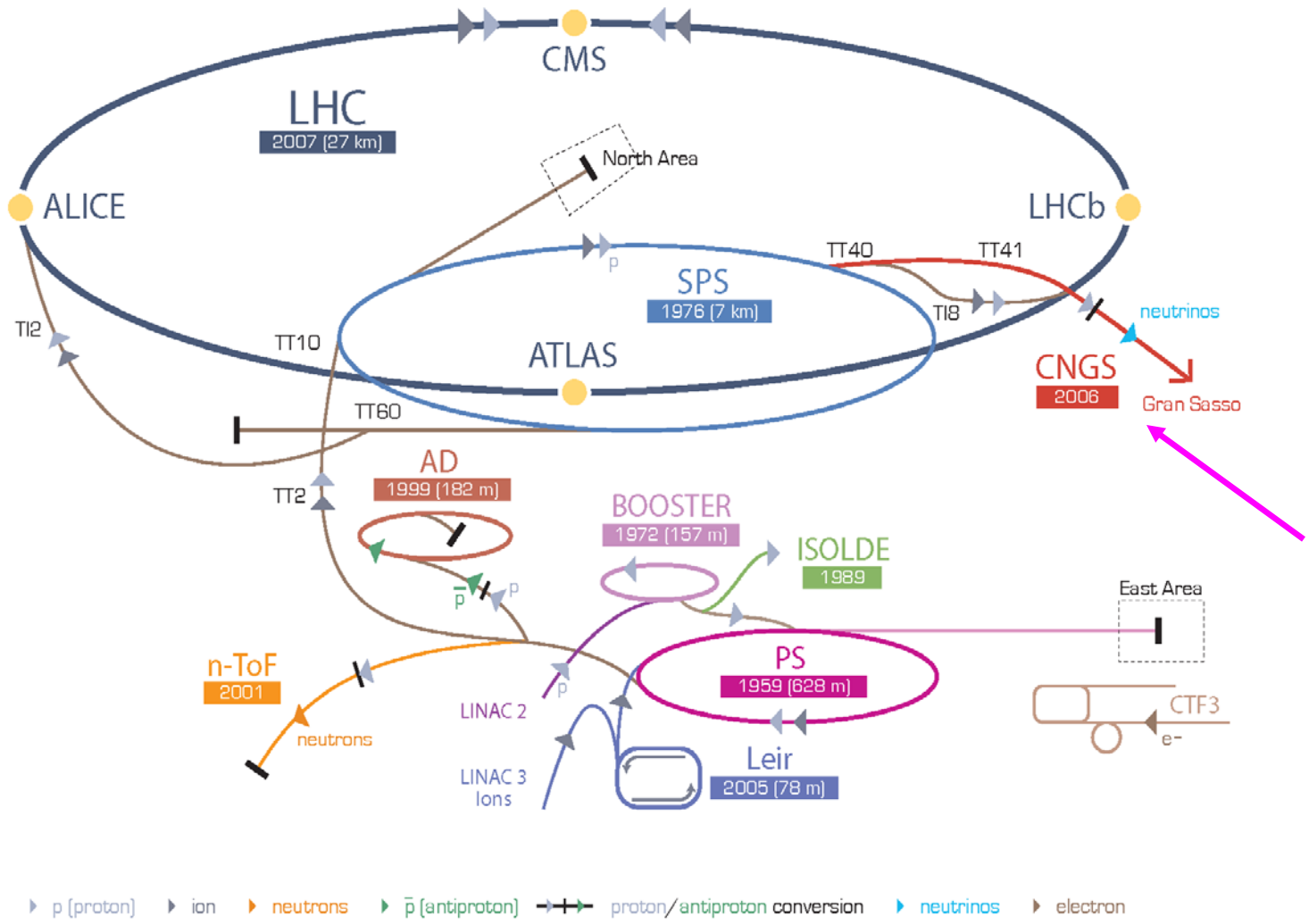
SSI 2012
SLAC SUMMER INSTITUTE

“how well LHC has done and what we can expect next”

- *basics*
- *recent performance*
- *near and long term prospects*

basics

CERN Accelerator Complex



p (proton) ion neutrons p̄ (antiproton) proton/antiproton conversion neutrinos electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

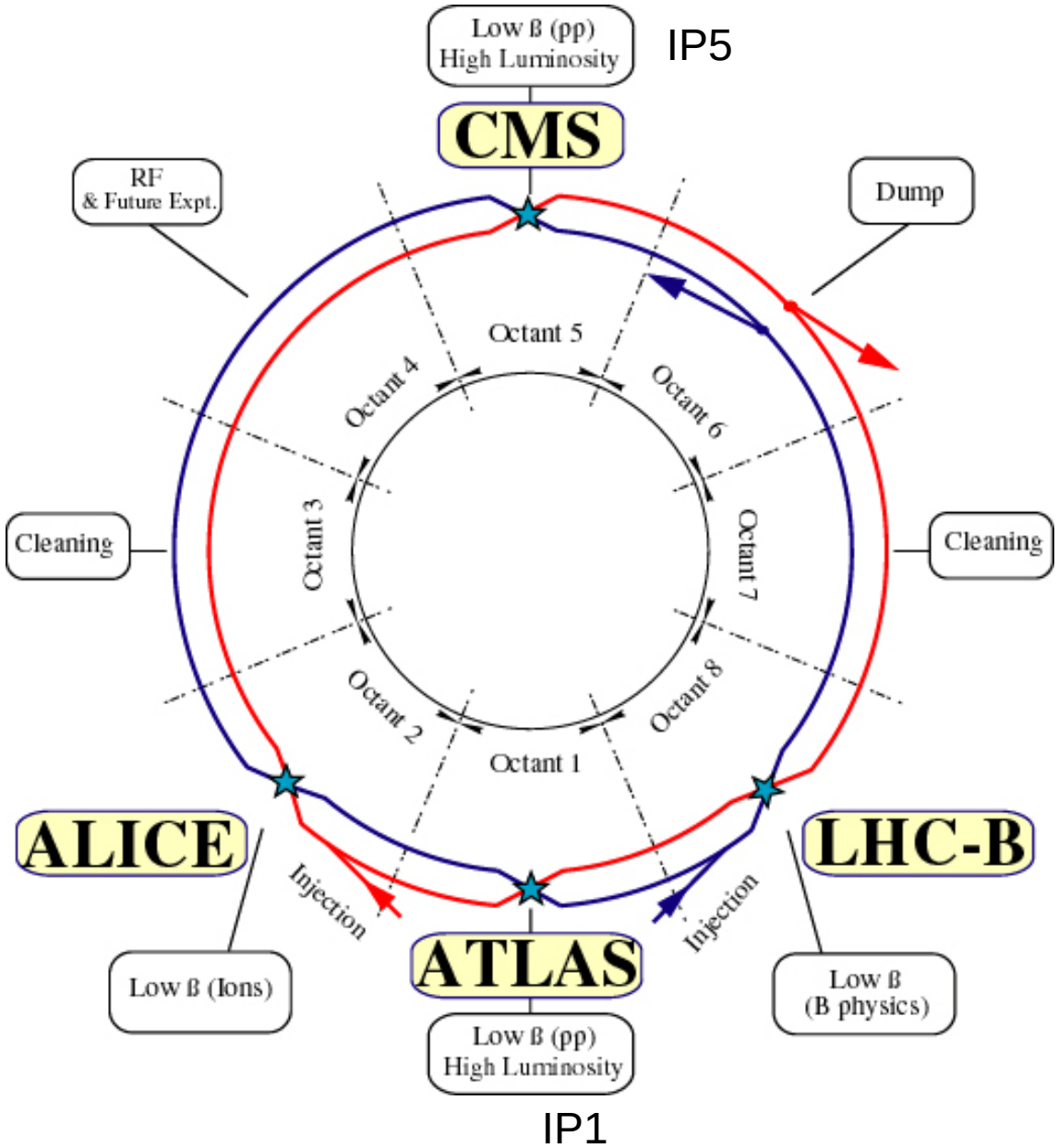
AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

The LHC

Superconducting Proton Accelerator and Collider installed in a 27km circumference underground tunnel (tunnel cross-section diameter 4m) at CERN

Tunnel was built for LEP collider in 1985



LHC design parameters

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

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

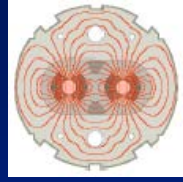
$\gamma\varepsilon=3.75$ μm
$\beta^*=0.55$ m
$\theta_c=285$ μrad
$\sigma_z=7.55$ cm
$\sigma^*=16.6\mu$m (IP1 & 5)

LHC tunnel 2002

L. Rossi

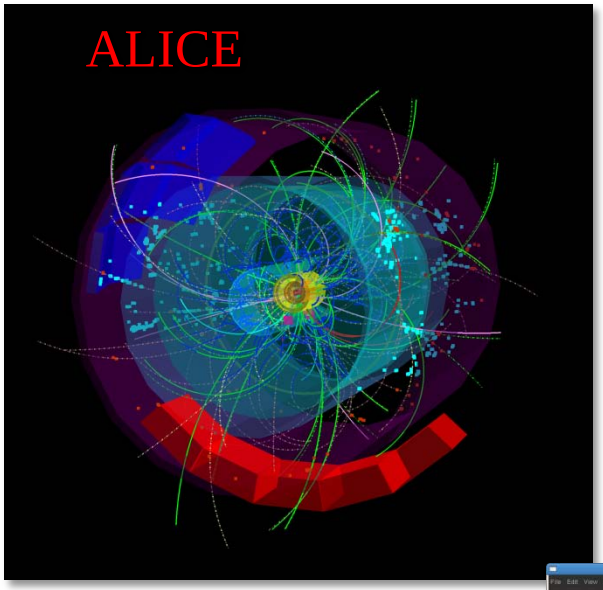

LHC tunnel 2006
L. Rossi

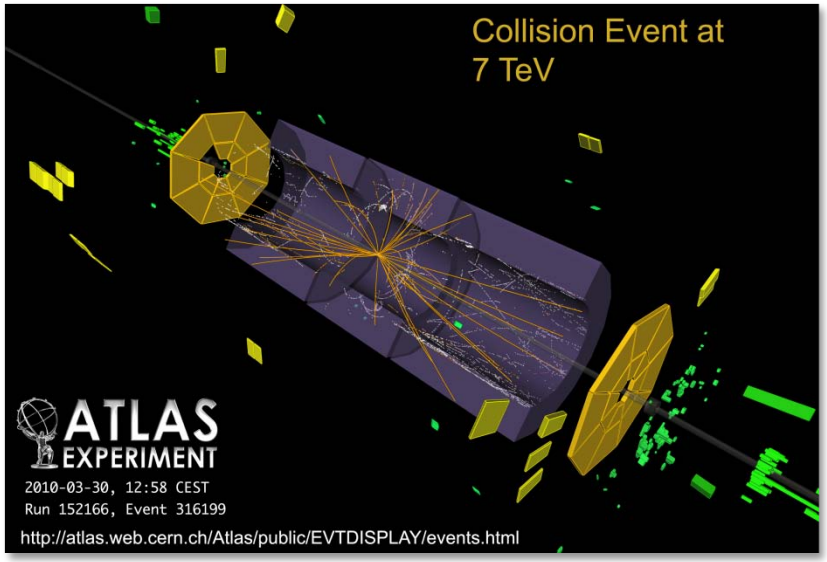
LHC: Some of the Technical Challenges

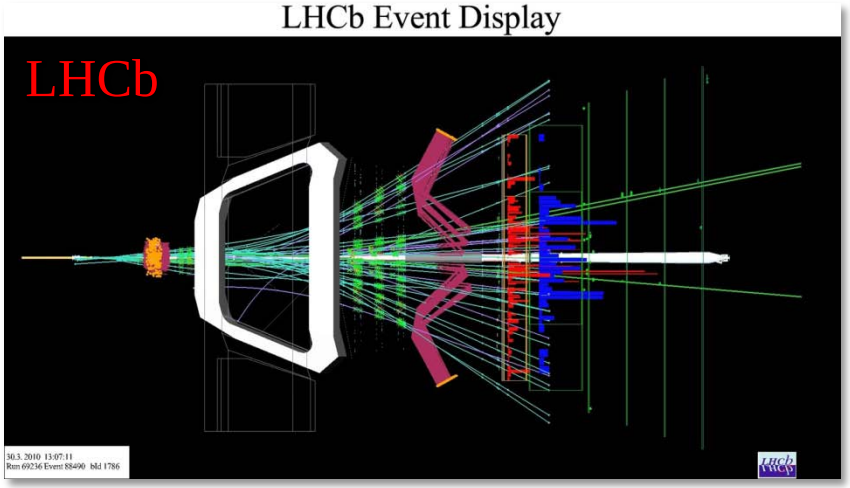


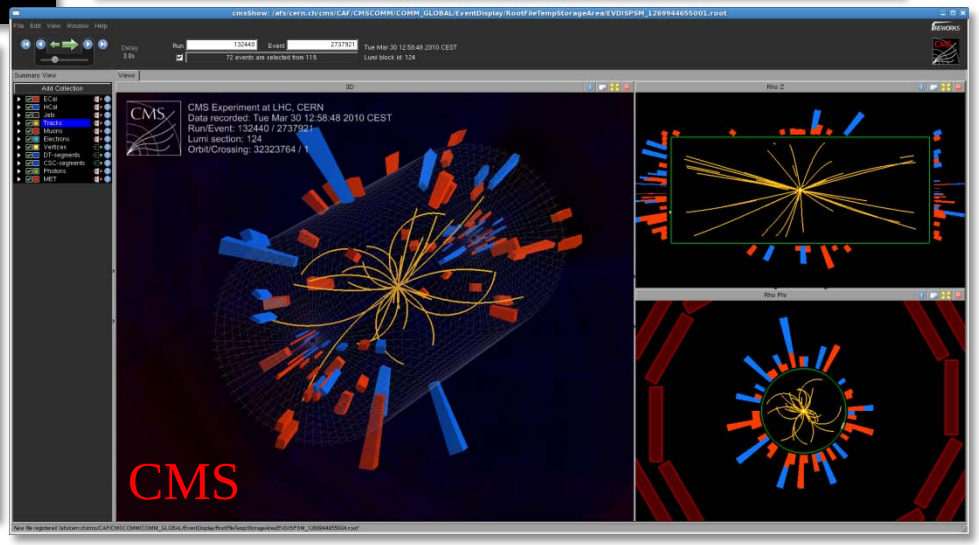
Circumference (km)	26.7	100-150 m underground
Number of Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K)	1.9	Superconducting magnets needed for the high magnetic field Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field 1ppm resolution
Beam Intensity (A)	0.5	2.2 10^{-6} loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current (1MJ melts 2kg Cu)
Magnet Stored Energy (MJoules)/octant	1100	Results from the high magnetic field
Sectors of Powering Circuits	8	1612 different electrical circuits

LHC: First collisions at 7 TeV on 30 March 2010









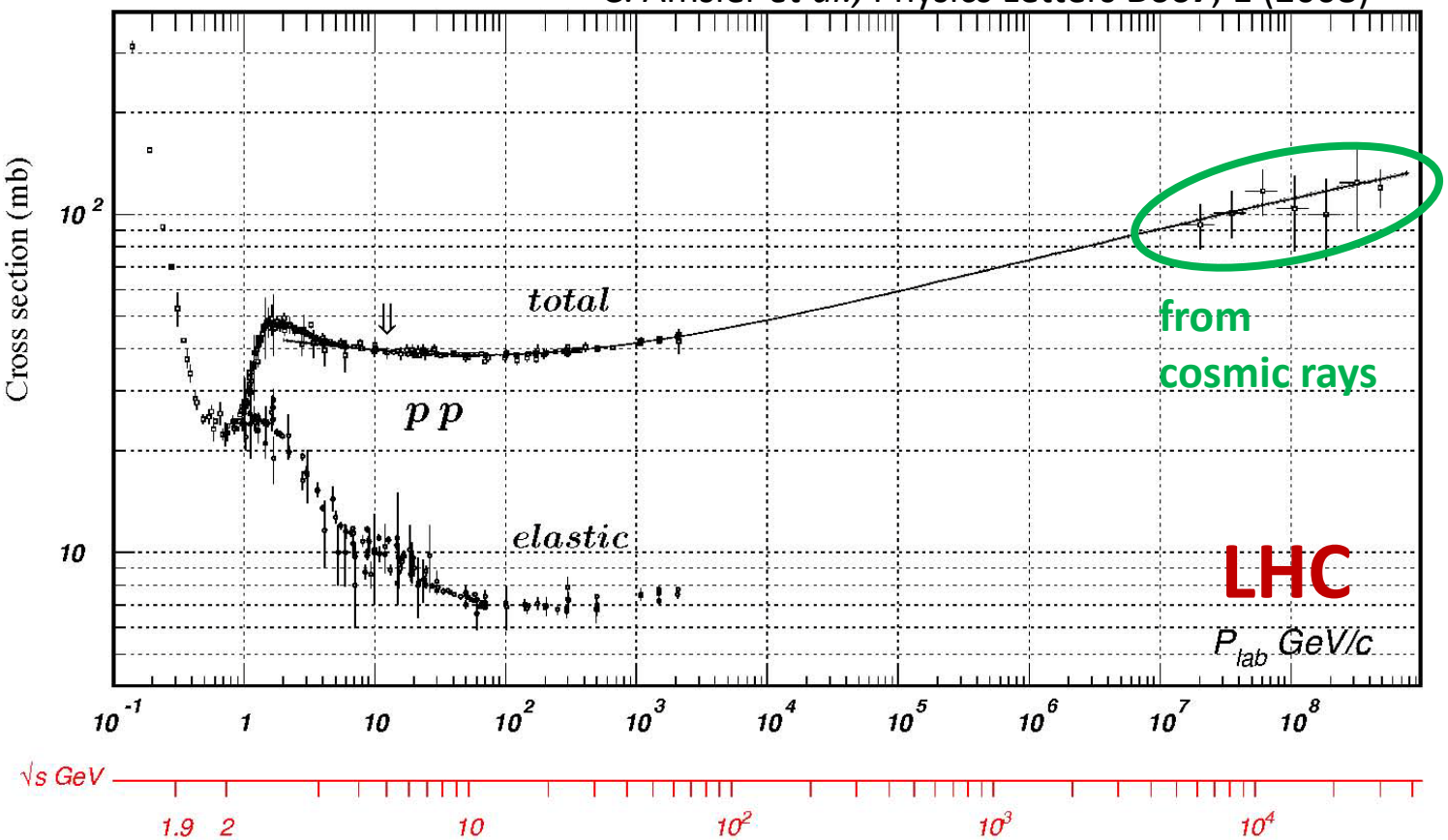
Peak Luminosity for First Run 10^{27} cm^{-2} s^{-1}

luminosity

$$R = \sigma L$$

reaction rate **cross section** **luminosity**

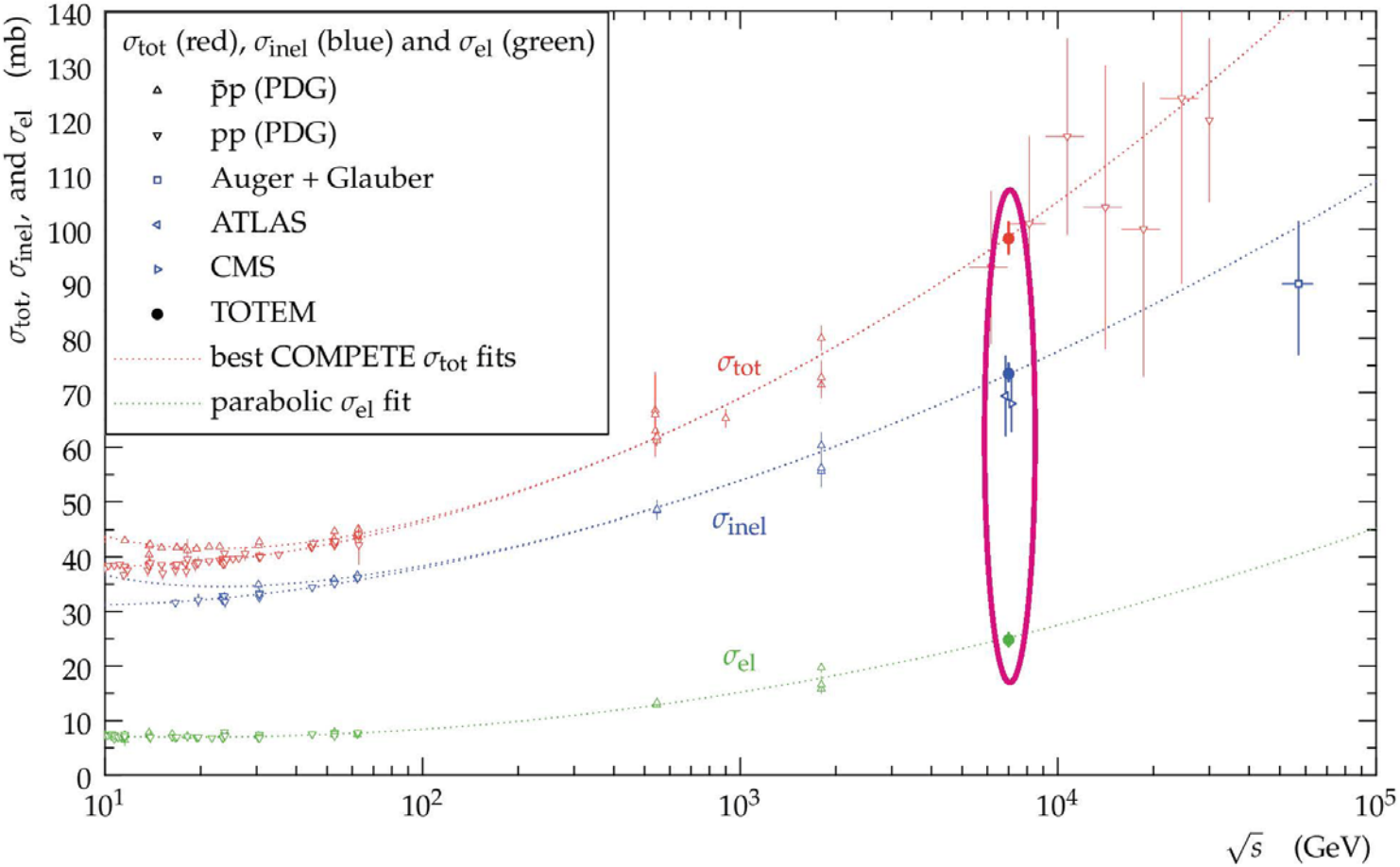
C. Amsler *et al.*, Physics Letters **B667**, 1 (2008)



σ_{tot}~
100 mbarn
~ 10^{-25} cm^2

from cosmic rays

TOTEM measurement at LHC (1 h in 2011)



Elastic Scattering and Total Cross-Section in p+p reactions, arXiv:1204.5689

↓

$\sigma_{inelastic}$~85 mbarn ~8.5x10^{-26} cm^2 at 14 TeV CoM

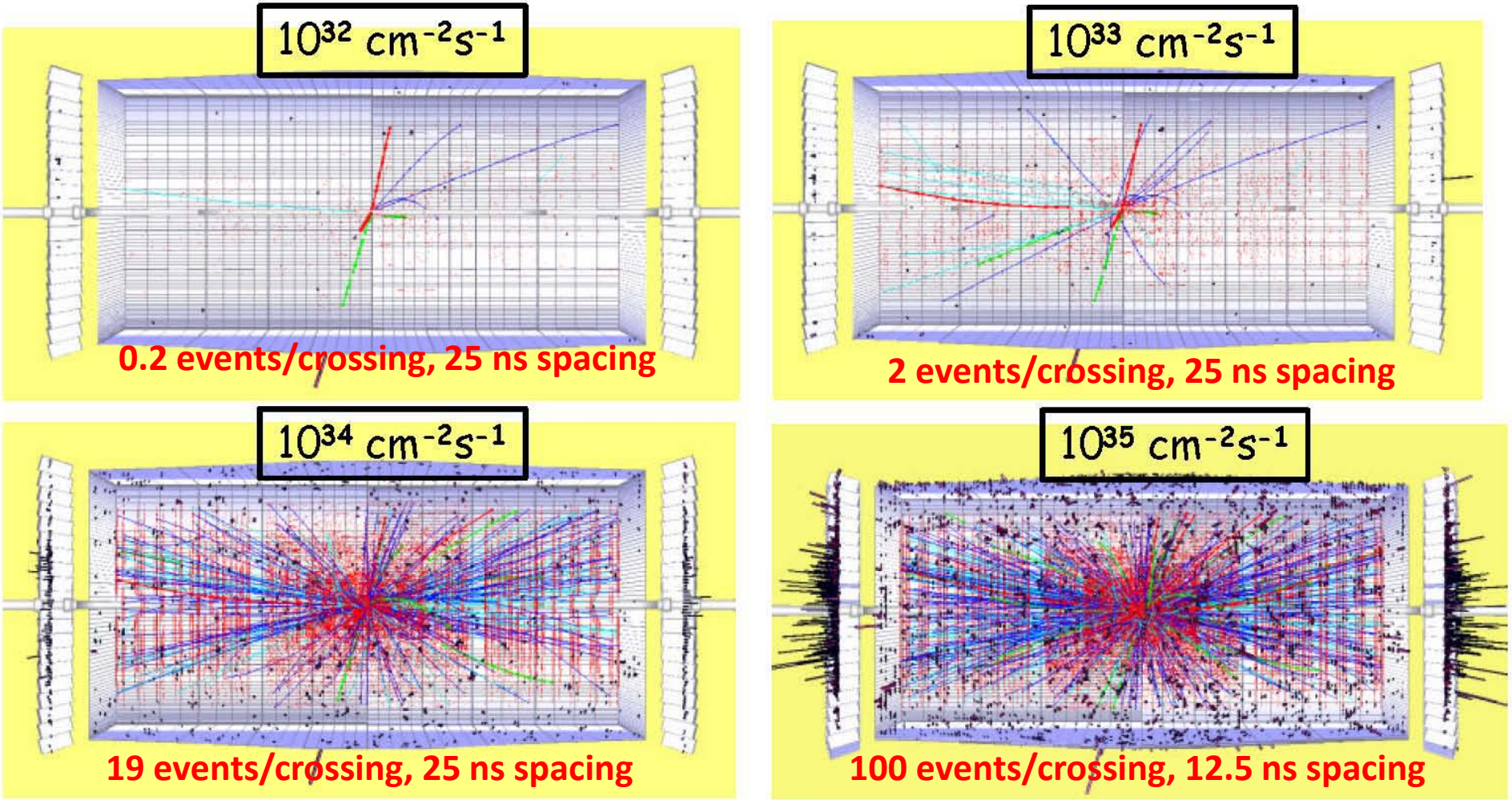
events / crossing ("pile up")

bunch collision rate
= #bunches/beam x revolution frequency

#events per bunch crossing
= cross section x luminosity / bunch collision rate

nominal #events/crossing in the detector
$= 8.5 \times 10^{-26}\ cm^2\ 10^{34}\ cm^{-2} s^{-1} / (32 \times 10^6\ s^{-1})$
= 27

event pile up in detector



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

historical simulation
I. Osborne

maximizing luminosity

luminosity for round beams:

$$L = \frac{f_{rev} n_b N_b^2}{4\pi \sigma_x{}^* \sigma_y{}^*} R(\theta_c, \varepsilon, \beta^*, \sigma_z)$$

$$L = \frac{1}{4\pi} \underbrace{(f_{rev} n_b N_b)}_{\text{maximize total beam current}} \underbrace{\frac{N_b}{\varepsilon_N}}_{\text{maximize brightness (injectors \& beam-beam limit)}} \frac{\gamma}{\beta^*} R(\theta_c, \varepsilon, \beta^*, \sigma_z)$$

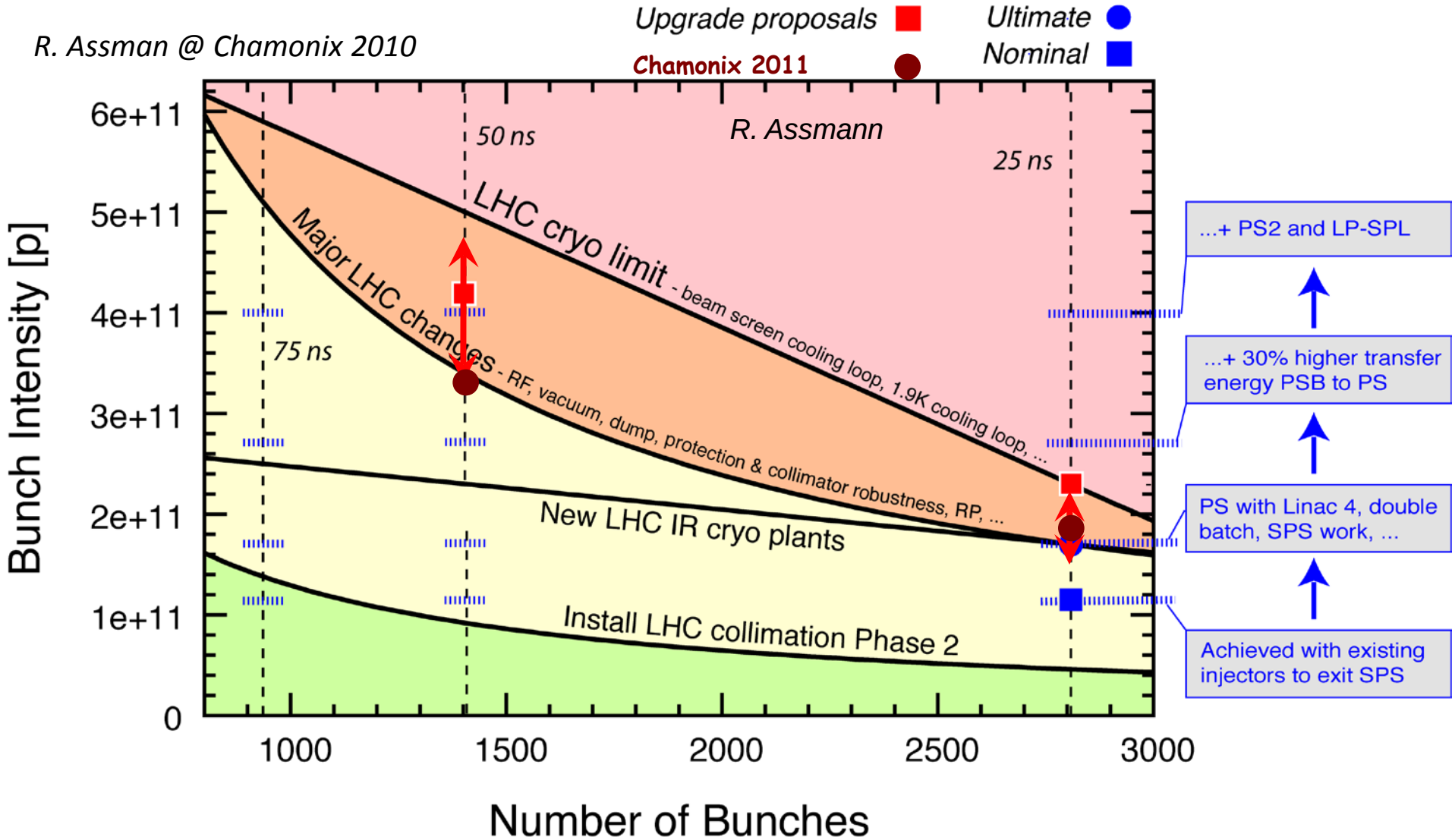
compensate reduction factor *R*

crossing angle

hourglass effect

maximize energy & minimize β*

limits on LHC beam current (7 TeV)

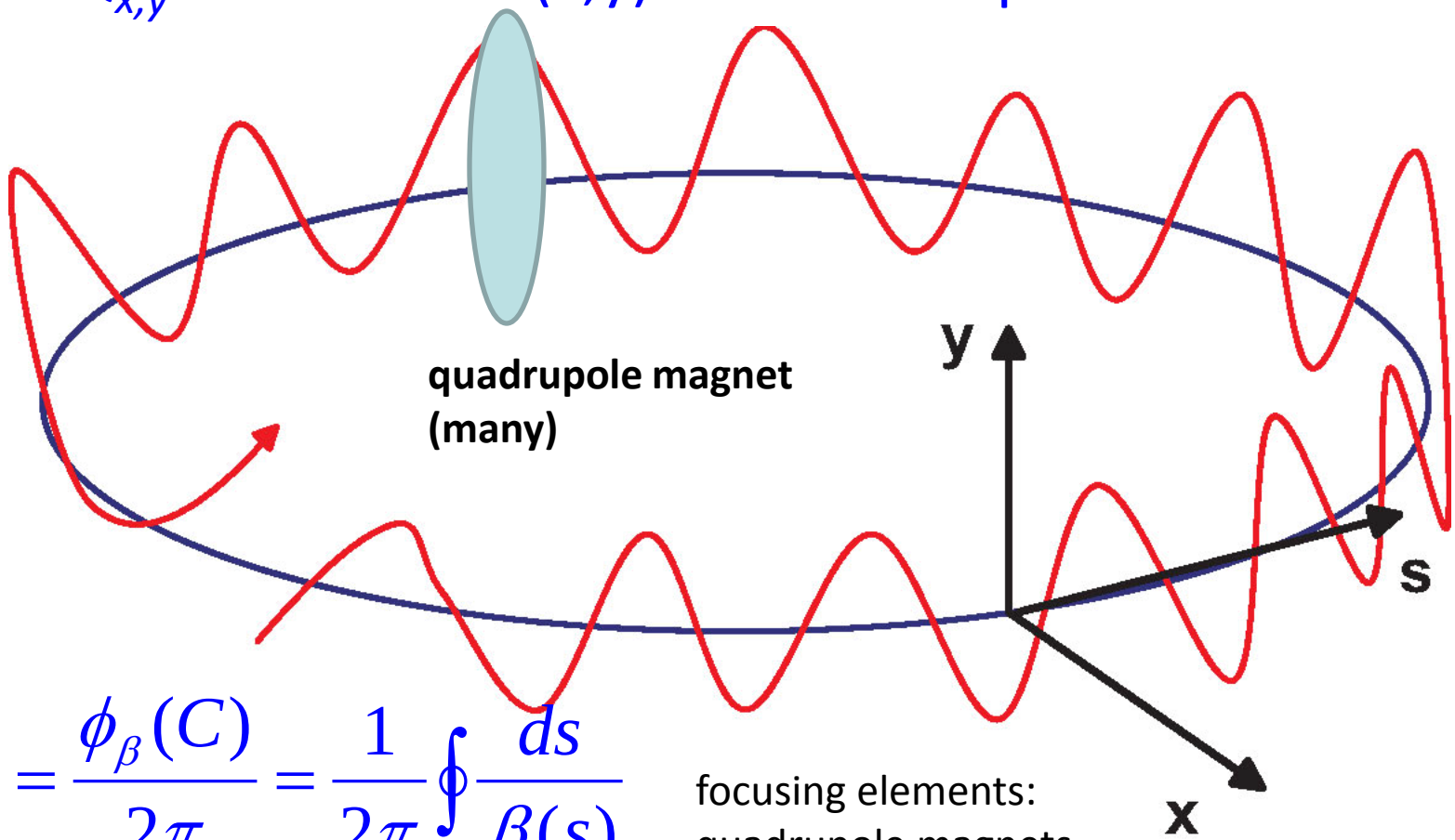


Ideal scenario: no imperfections included!

Note: Some assumptions and conditions apply…

Q & β*: schematic of betatron oscillation in storage ring

tune $Q_{x,y}$= number of (x,y) oscillations per turn



$$Q = \frac{\phi_\beta(C)}{2\pi} = \frac{1}{2\pi}\oint_C \frac{ds}{\beta(s)}$$

focusing elements:
quadrupole magnets

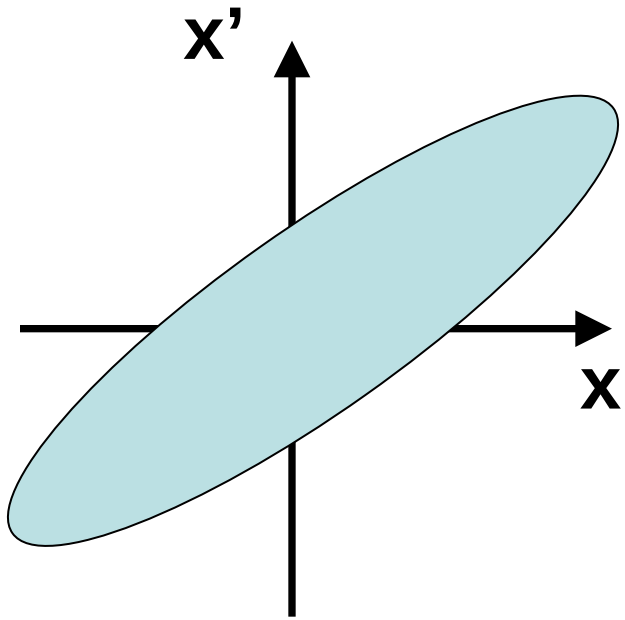
$$\sigma(s) = \sqrt{\frac{\beta(s)\varepsilon_N}{\gamma}}$$

beam size
at point *s*

$$\sigma^* = \sqrt{\frac{\beta^*\varepsilon_N}{\gamma}}$$

beam size
at collision
point

emittance ε

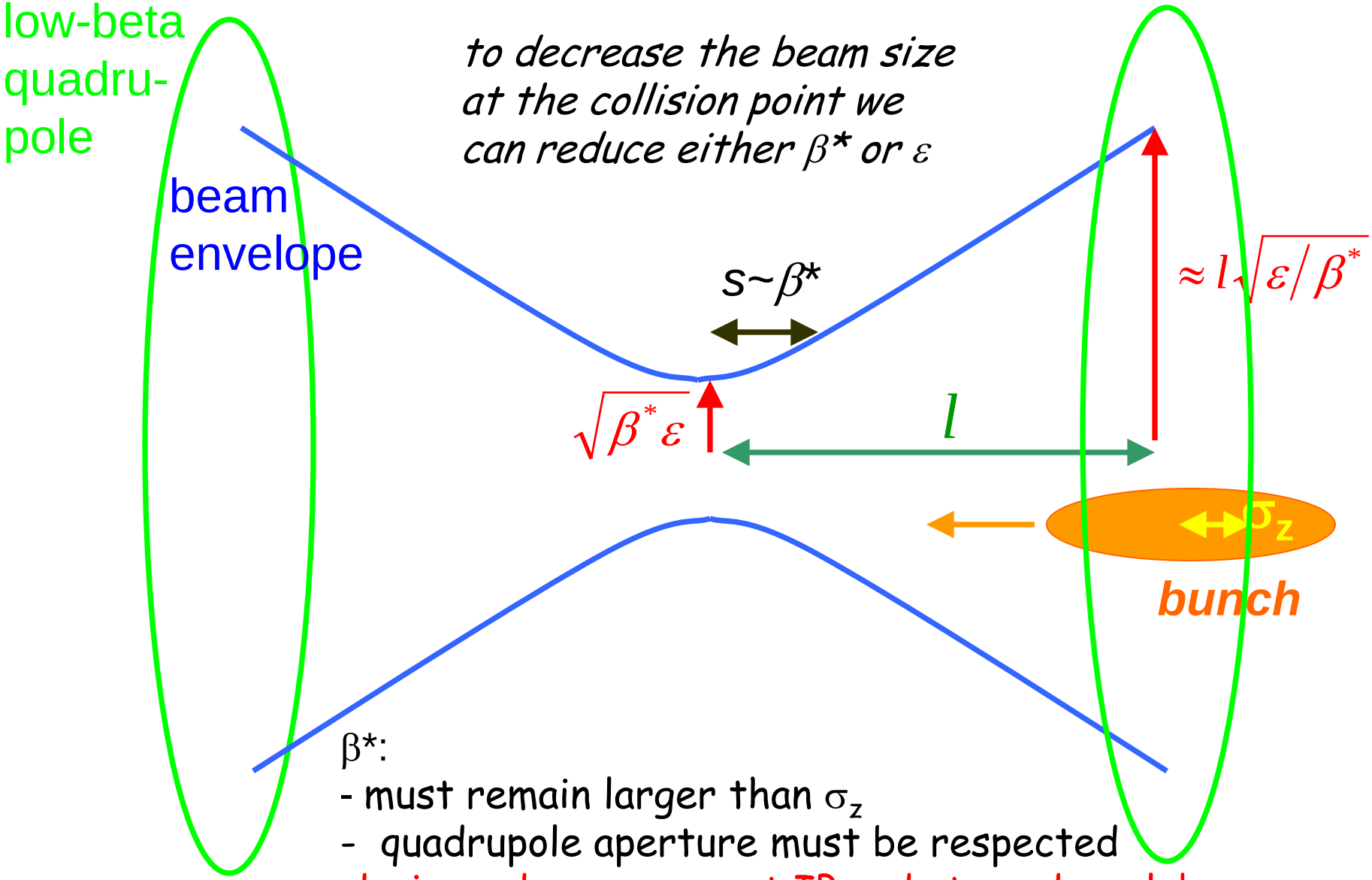


"area in phase space" occupied by the beam = π x ε

rms emittance $\varepsilon_{rms} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$

for Gaussian distribution
ε_{rms} contains 39% of the beam

limits on β*



β*:
- must remain larger than σ_z
- quadrupole aperture must be respected

reducing ε decreases σ at IP and at quadrupole!

limits on beam "brightness"

$$B \equiv \frac{N_b}{\varepsilon_N}$$

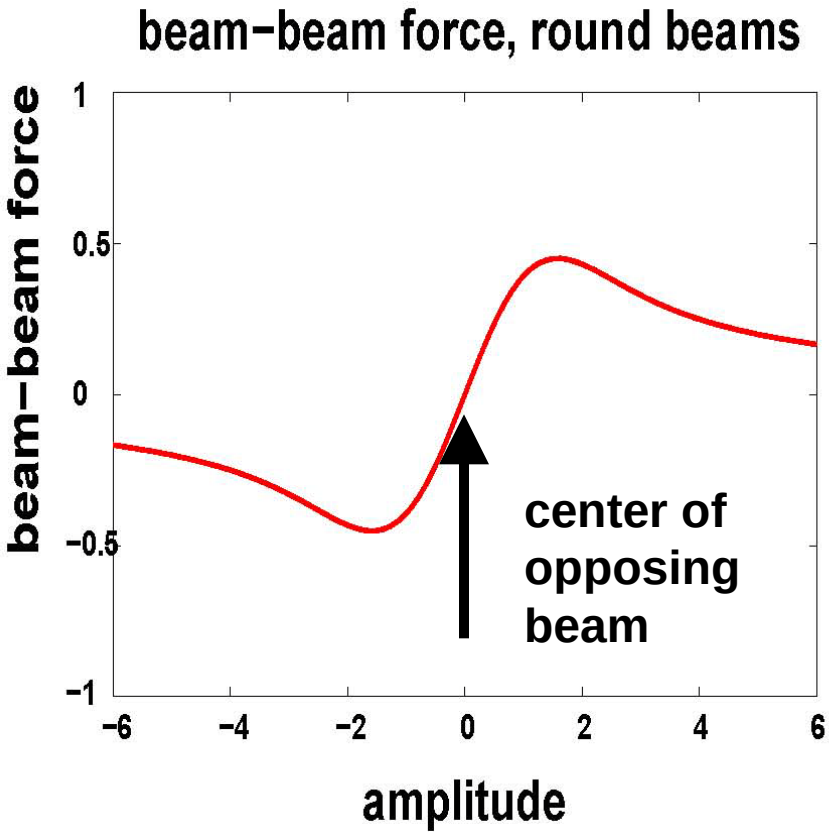
$$\Delta Q_{x.y;\text{beam-beam}} \propto \frac{N_b}{\varepsilon_N}$$

head-on beam-beam limit in the LHC
→ not as severe as expected

$$\Delta Q_{x.y;\text{space charge}} \propto \frac{N_b}{\varepsilon_N} \frac{1}{\beta^2 \gamma^2}$$

space charge tune shift in the injectors
→ present limitation; will be removed by LHC Injector Upgrade in ~2018

(nonlinear) beam-beam force



W. Herr

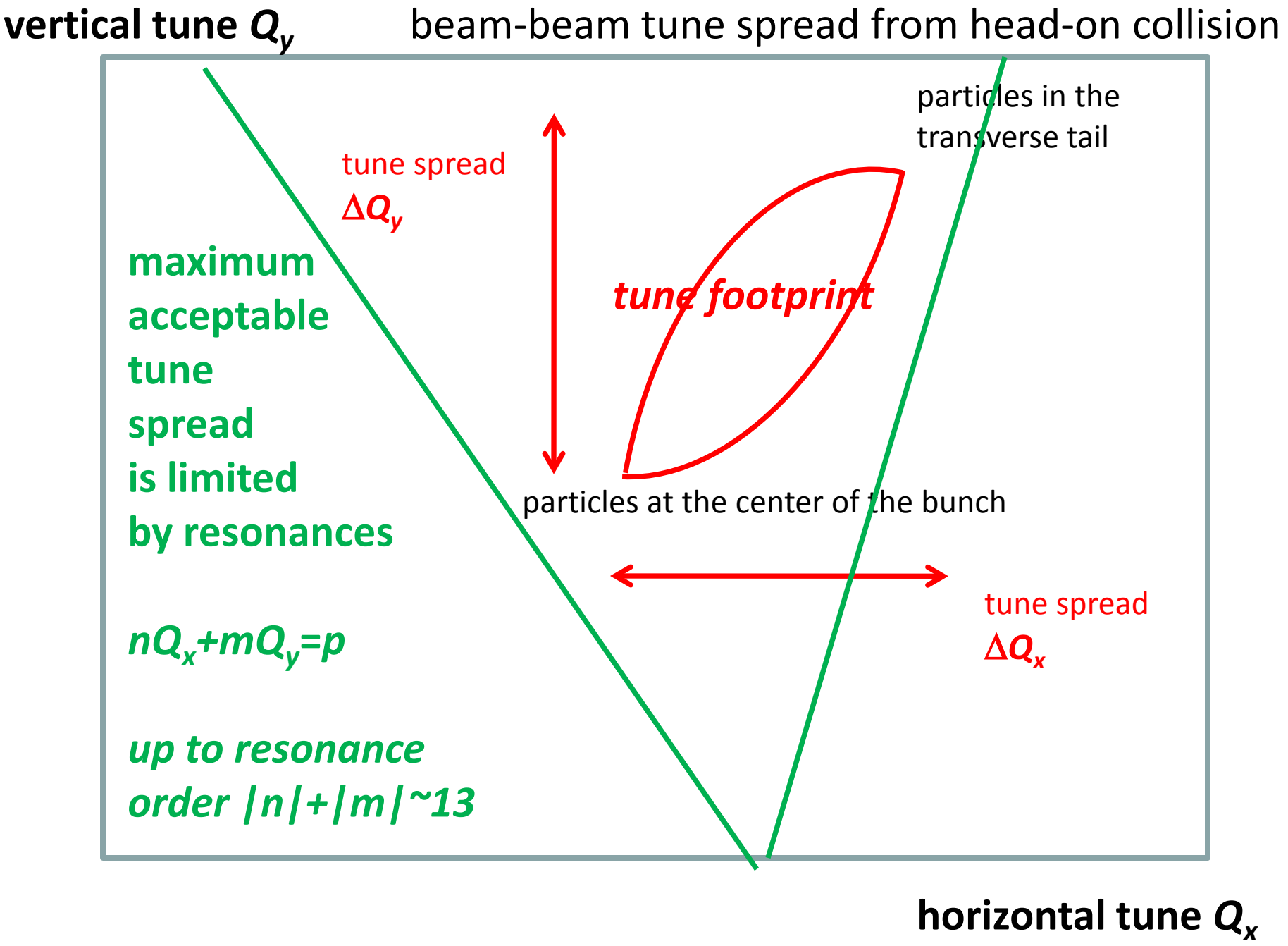
- Force varies strongly with amplitude
- Exponential function:
- Contains many high order multipoles

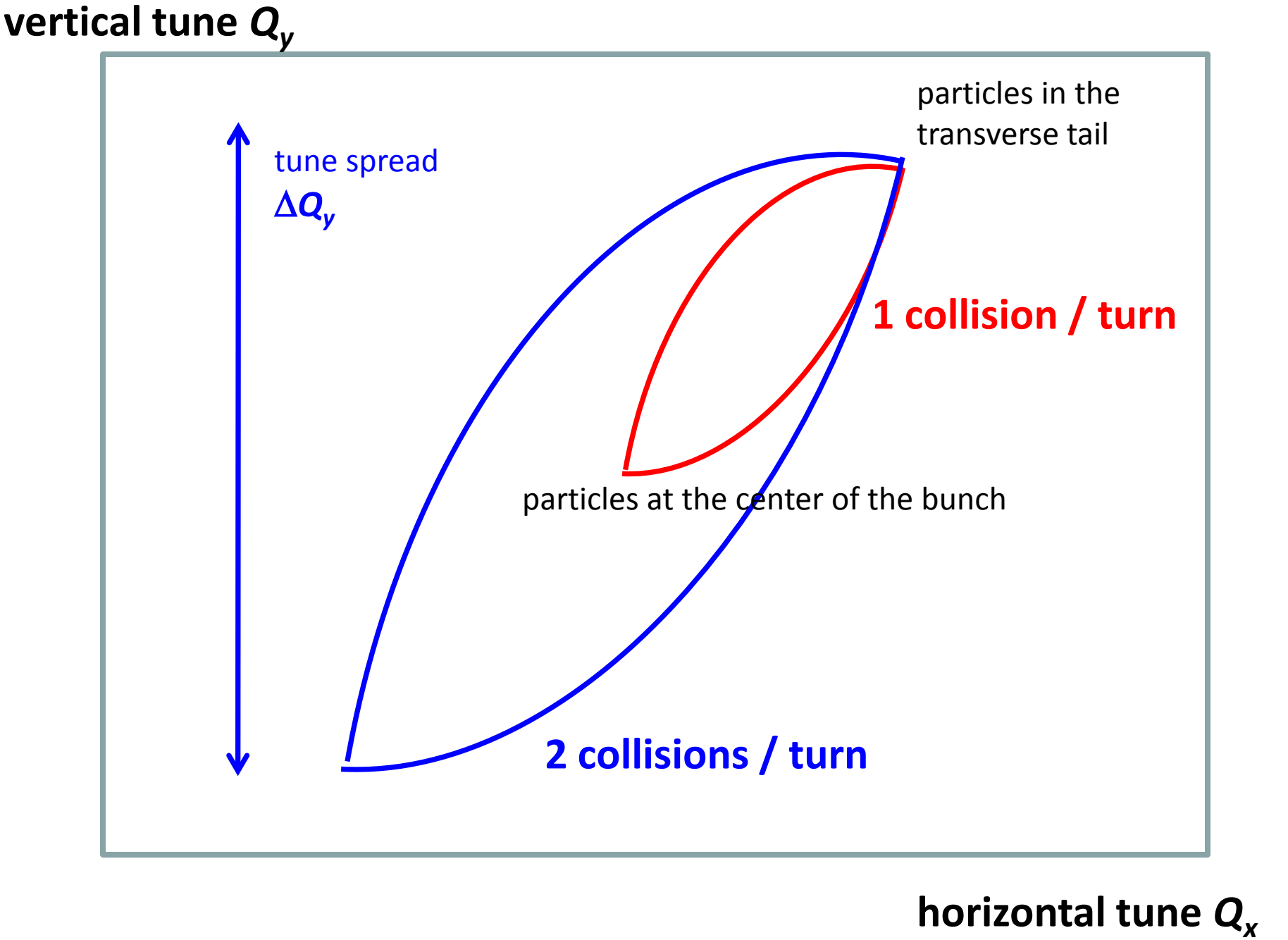
at small amplitude similar to effect of defocusing quadrupole

for pure head-on collision

$$\Delta Q_{x.y;\max} = \xi_{x,y} = \frac{2N_b r_0 \beta^*}{4\pi\gamma\left(2\sigma^{*2}\right)} = \frac{N_b}{\varepsilon_N}\frac{r_0}{4\pi}$$

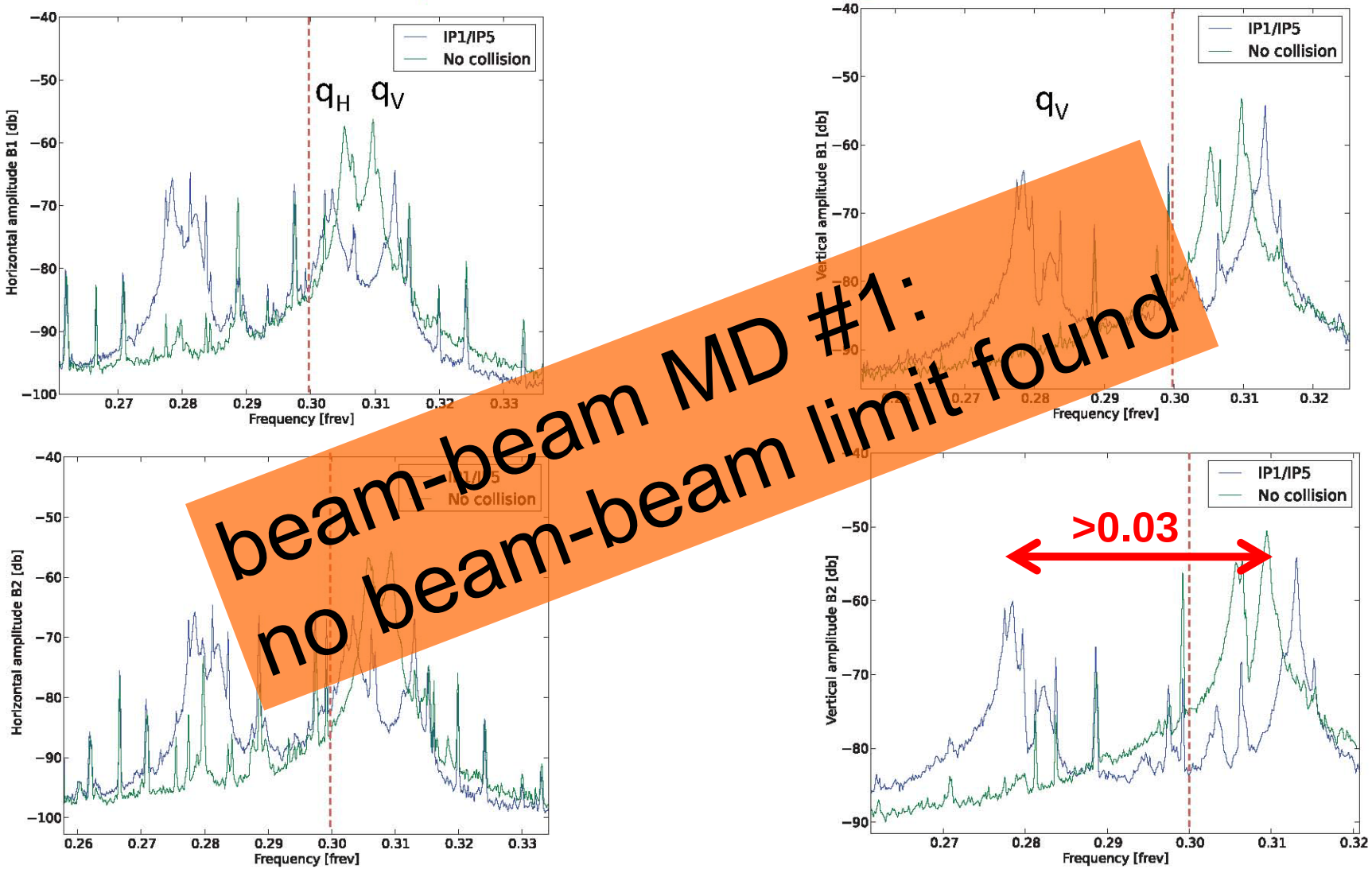
for single collision (nominal LHC ~0.0033)


vertical tune Q_y
beam-beam tune spread from head-on collision
particles in the transverse tail
tune spread ΔQ_y
maximum acceptable tune spread is limited by resonances
tune footprint
particles at the center of the bunch
$nQ_x+mQ_y=p$
tune spread ΔQ_x
up to resonance order $|n|+|m|\sim 13$
horizontal tune Q_x


vertical tune Q_y
particles in the transverse tail
tune spread
ΔQ_y
1 collision / turn
particles at the center of the bunch
2 collisions / turn
horizontal tune Q_x

T. Pieloni, W. Herr et al, May 2011

tune spectra colliding IP1 & IP5

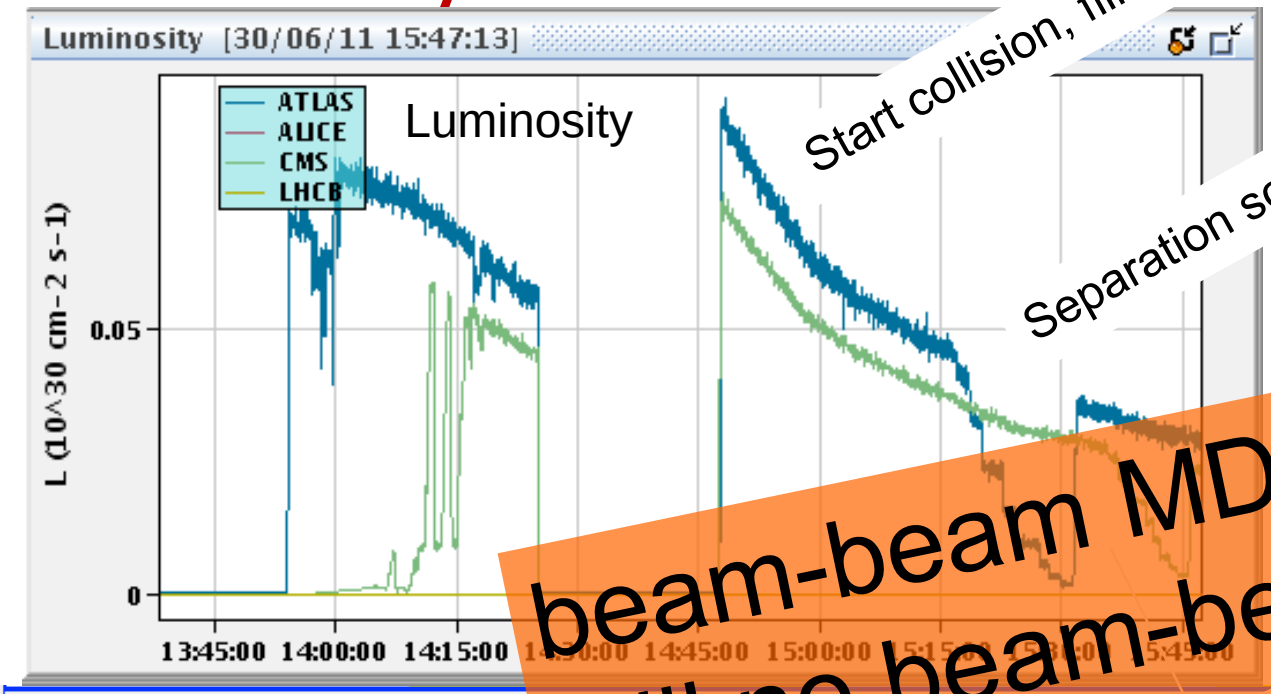


beam-beam MD #1:
no beam-beam limit found

beam parameters investigated **beyond nominal LHC (N_b = 1.8-1.95x10^{11}, ε =1.2-1.4 μm);** no significant beam losses nor emittance effects observed with linear head-on parameter of ξ_{bb}**~ 0.017 /IP** and ξ_{bb}**=0.034 (total)** ***– more than 3x above LHC design*****!**

luminosity and lifetime

W. Herr et al, June 2011



twice nominal bunch intensity, half nominal emittance!

beam-beam MD #2: still no beam-beam limit found

geometric reduction factor

formula for combined effect of crossing angle and hourglass

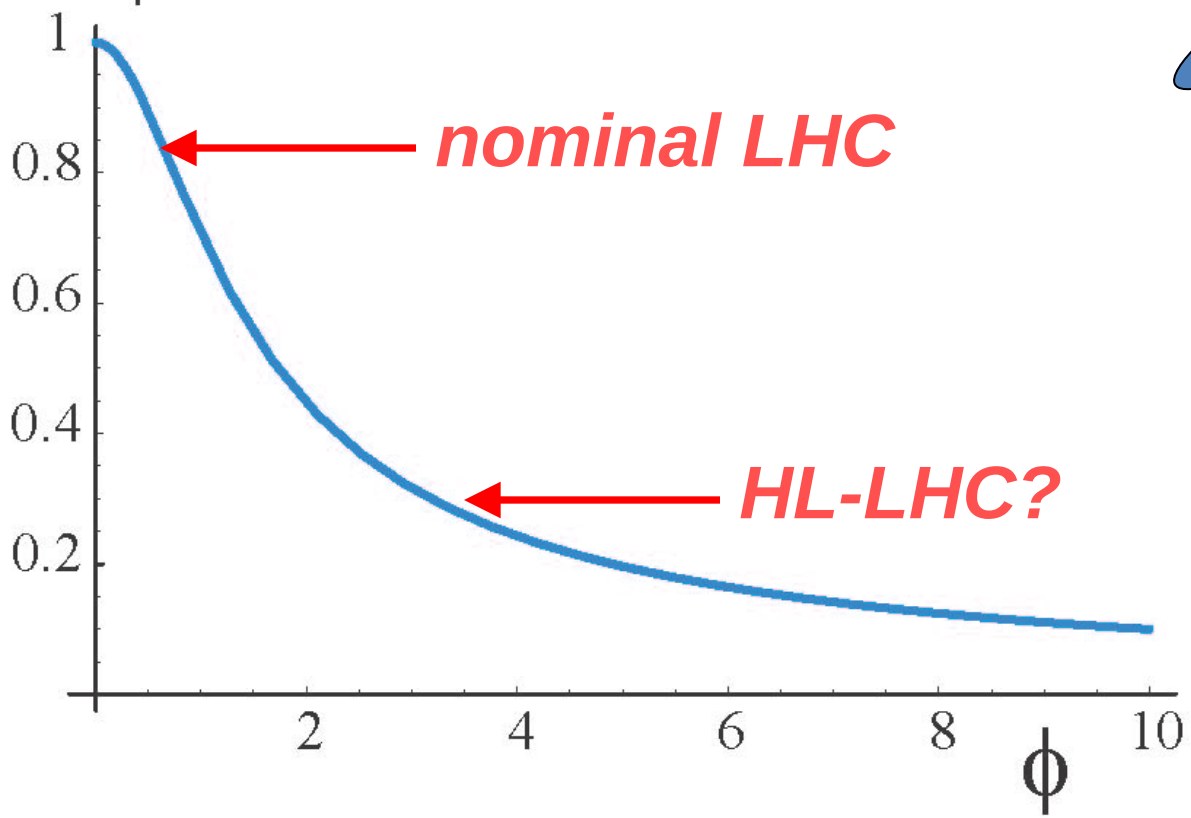
$$R = \frac{\cos(\theta_c/2)}{\sqrt{\pi}\sigma_z} \int_{-\infty}^{\infty} \frac{e^{-As^2}}{1 + \left(\frac{s}{\beta^*}\right)^2} ds$$

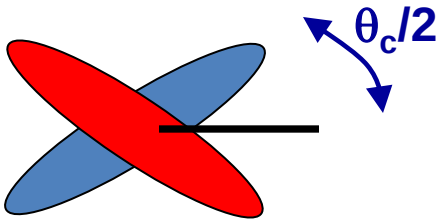
$$A = \frac{\sin^2(\theta_c/2)}{\sigma_x^2 \left(1 + \frac{s^2}{\beta^{*2}}\right)} + \frac{\cos^2(\theta_c/2)}{\sigma_z^2}$$

crossing angle

$$R_\phi = \frac{1}{\sqrt{1+\phi^2}}; \quad \phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$ *"Piwinski angle"*

R_ϕ luminosity reduction factor



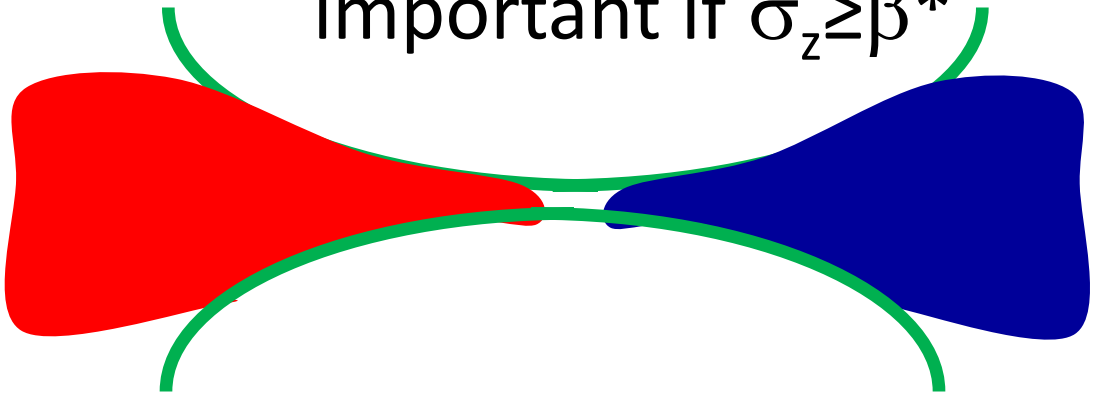


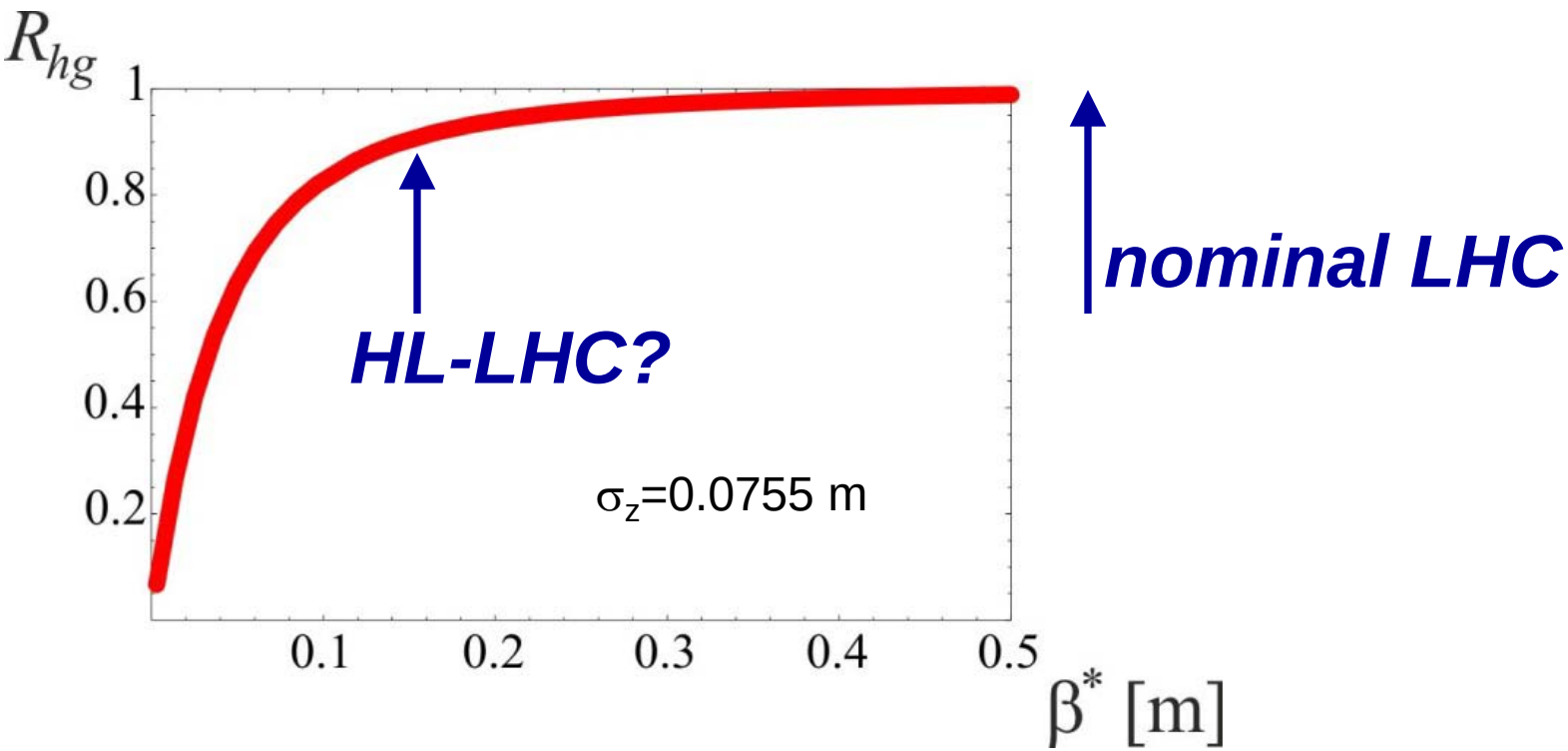
effective beam size $\sigma \rightarrow \sigma / R_\phi$

hourglass effect

$\beta(s)=\beta^*+s^2/\beta^*$

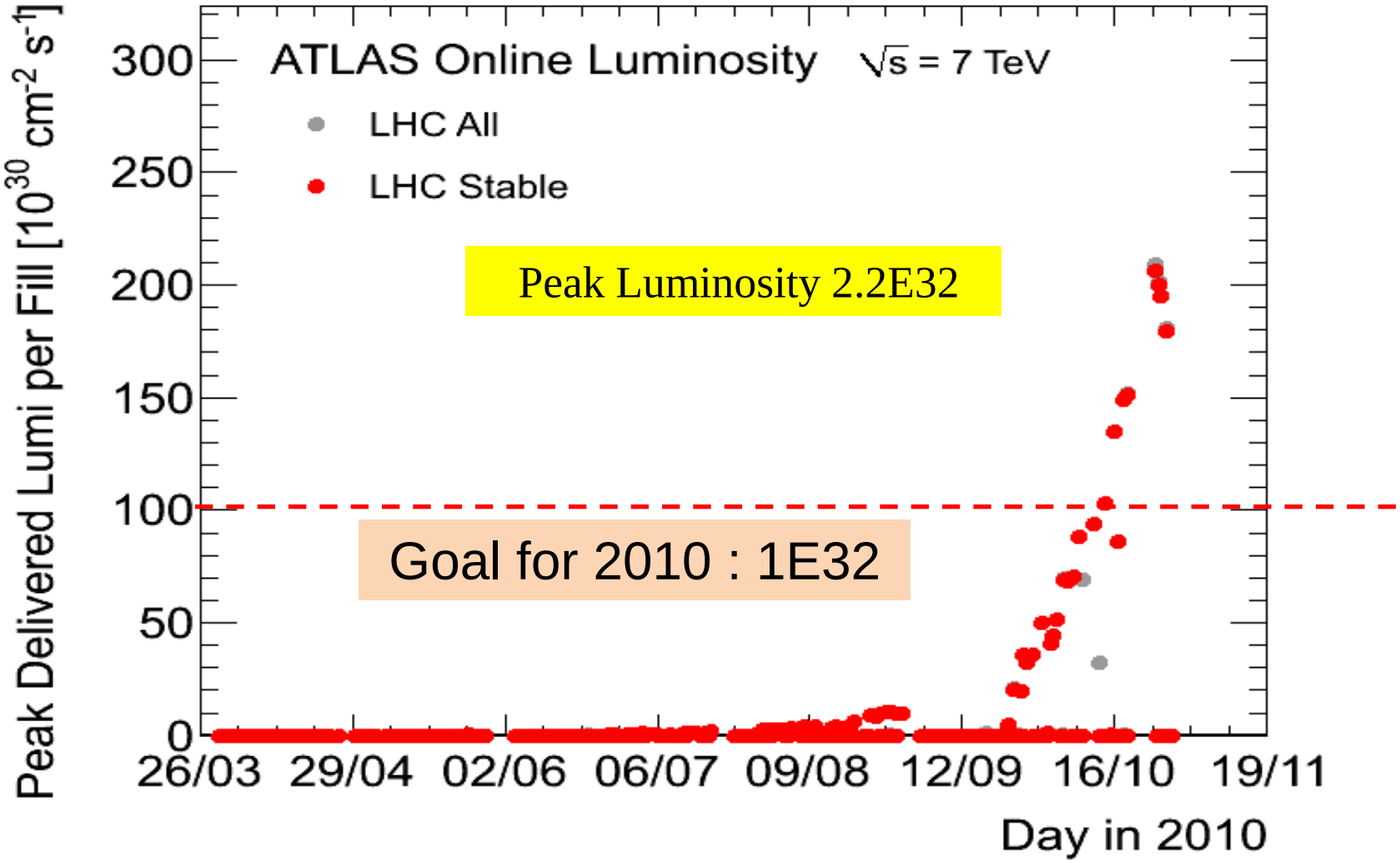
important if $\sigma_z \geq \beta^*$



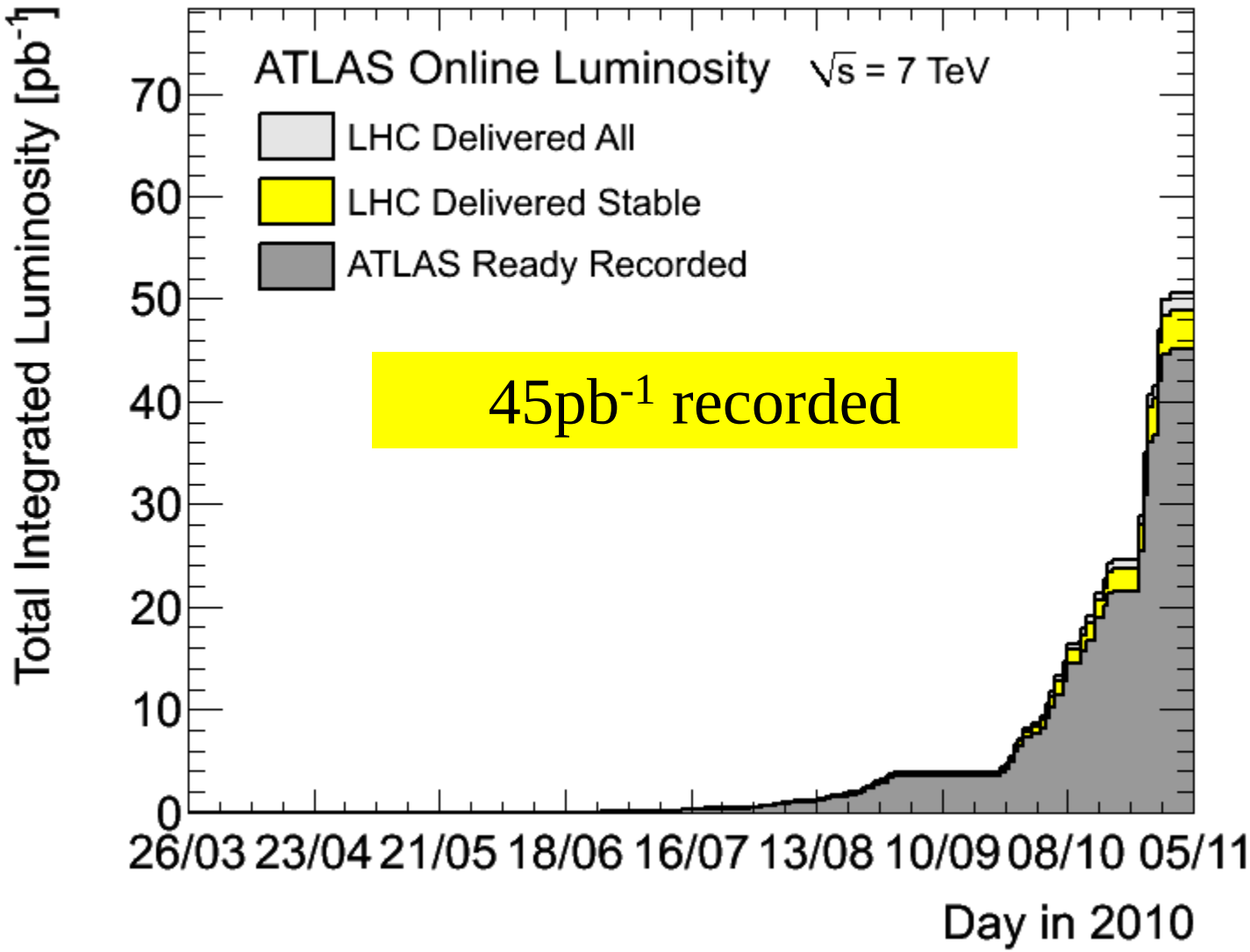


performance 2010-2012

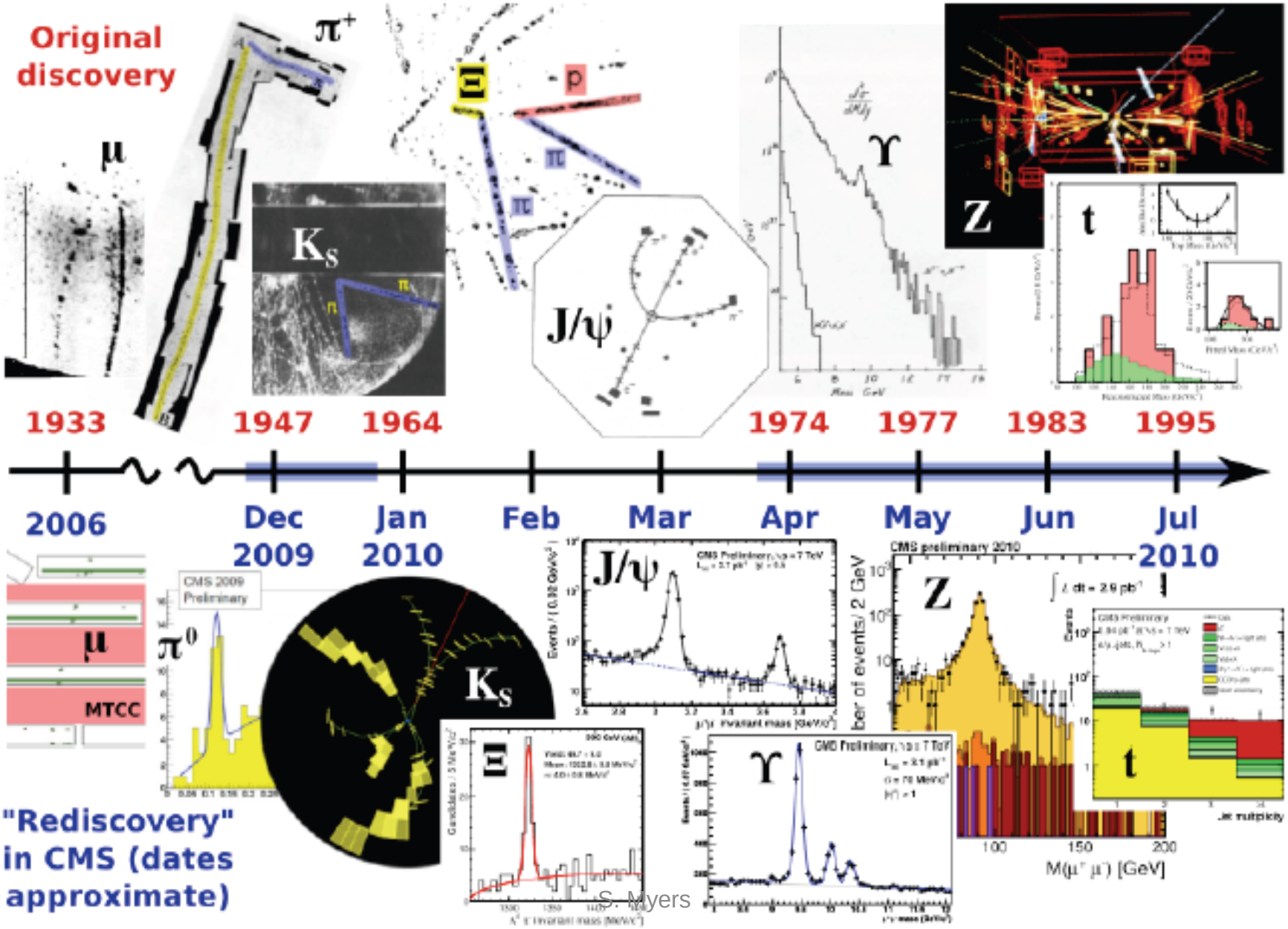
Peak Luminosity 2010



Integrated Luminosity in 2010

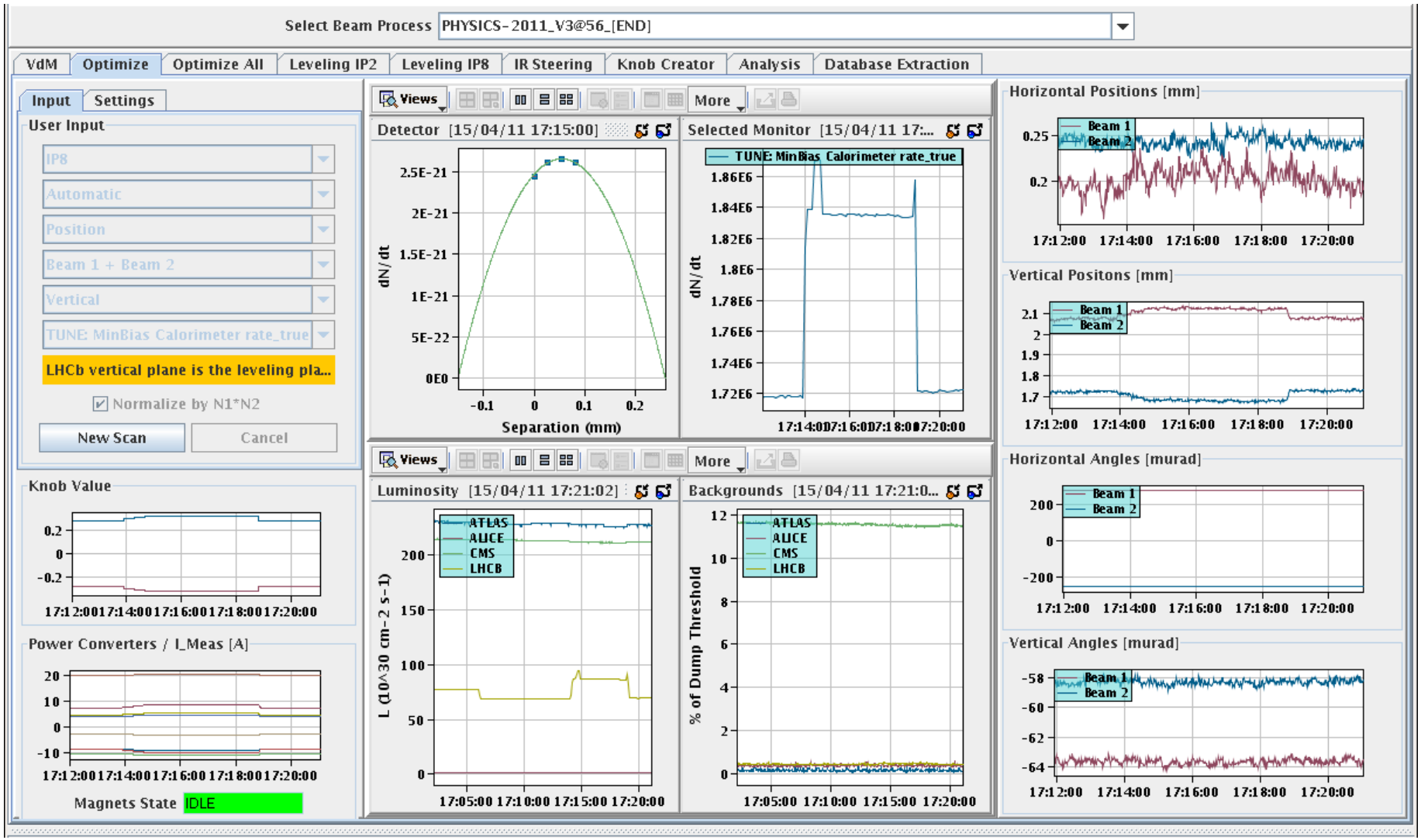


Brief History of the Standard Model



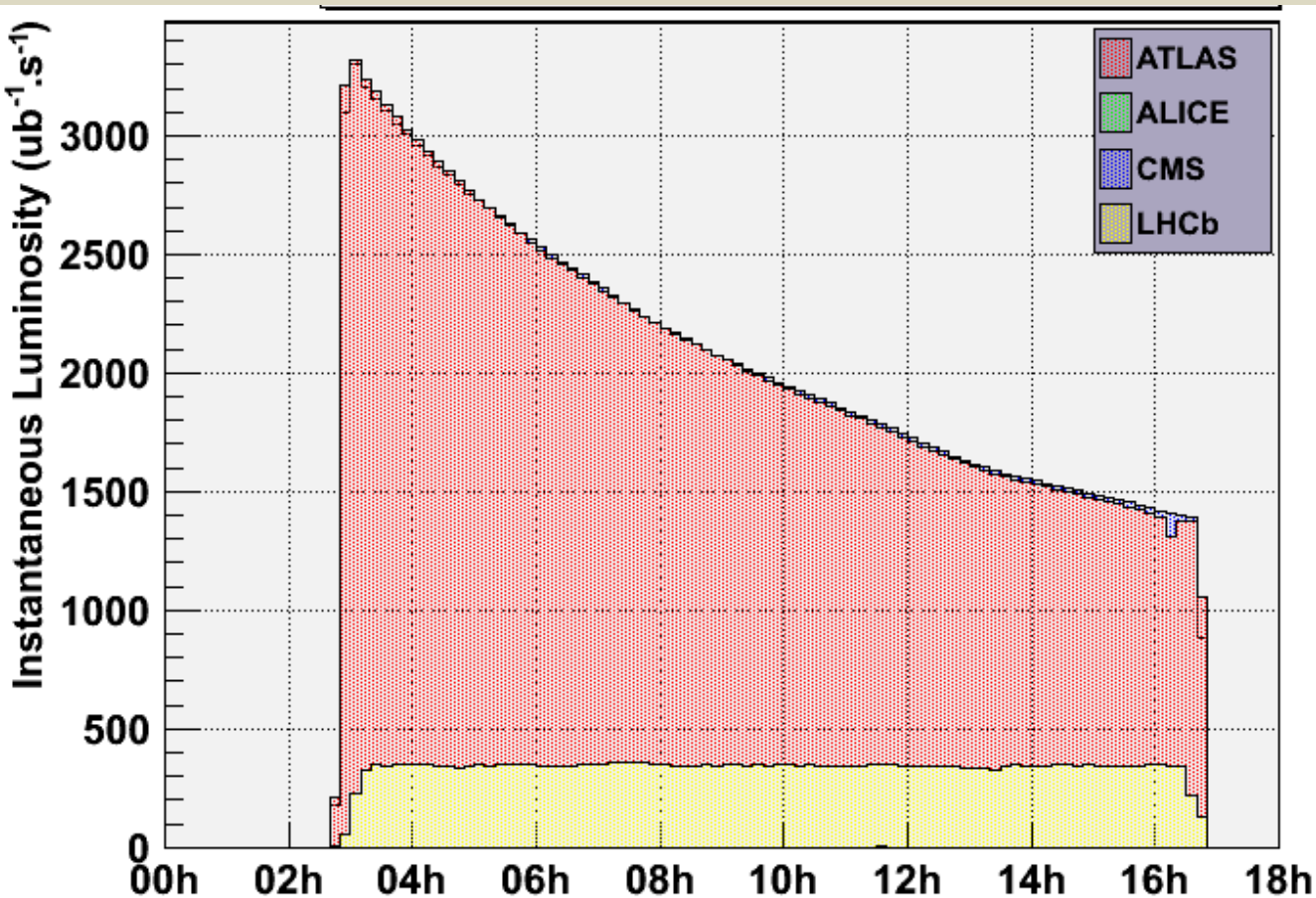
S. Myers

“Luminosity leveling” first tested 15 April 2011



Luminosity Leveling via beam Separation

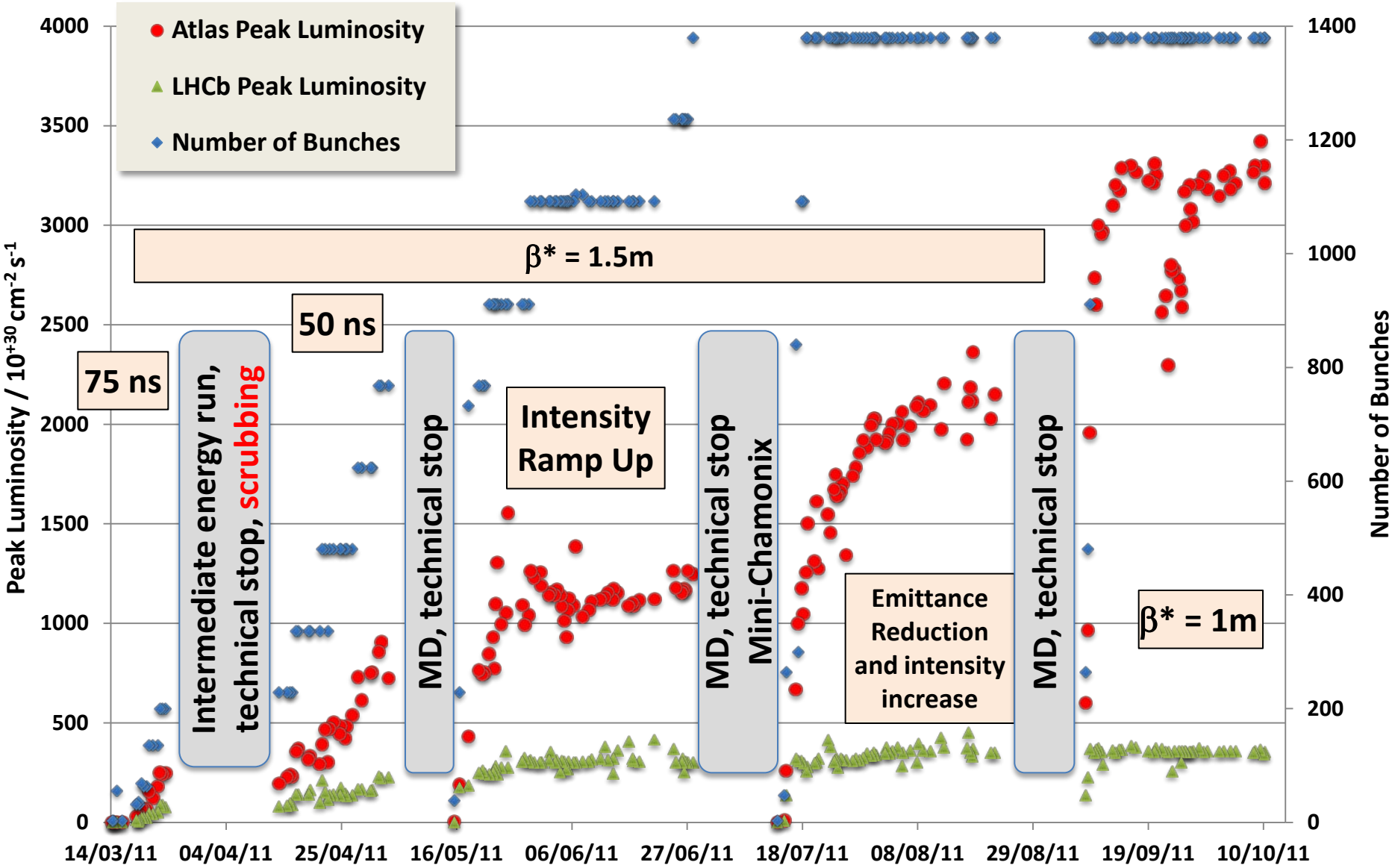
Introduced <u>luminosity leveling</u> for LHCb → can run at optimal μ and L_{max}



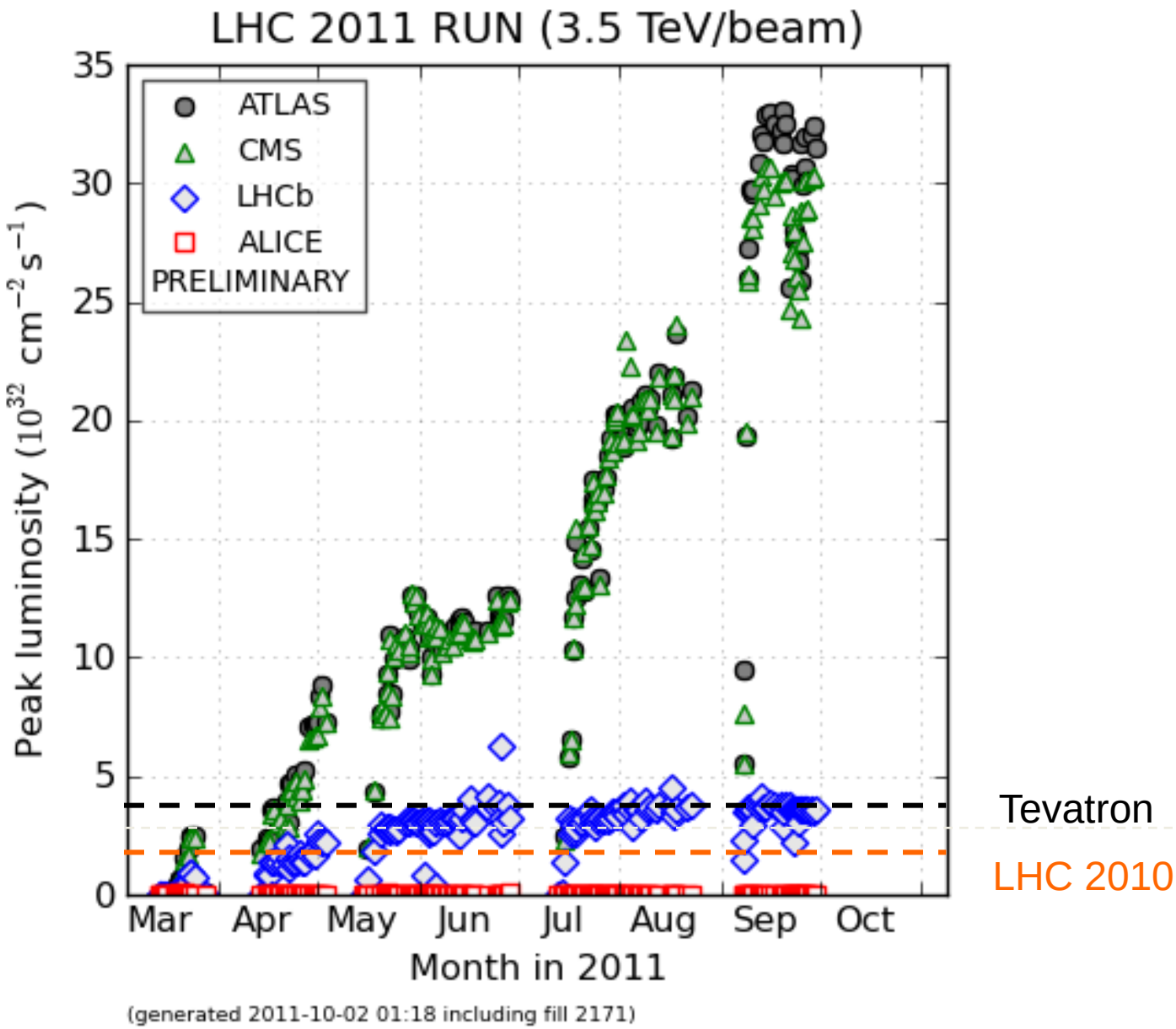
→ Since end of May running at constant L ~ 3-3.5·10^{32} $cm^{-2}s^{-1}$ with μ ~ 1.5

→ LHCb wants maximum time in physics and not an increase in peak performance

History of 2011 Peak Luminosity



LHC peak luminosity in 2011



LHC Instantaneous Luminosity: September 2011

14-Sep-2011 02:39:18 | Fill #: 2105 | Energy: 3500 GeV | I(B1): 1.88e+14 | I(B2): 1.88e+14

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Lumi (ub.s)^-1	3299.941	0.000	3194.219	66.763
BRAN Luminosity (ub.s)^-1	4064.439	8.672	5687.963	73.411
Fill Luminosity (nb)^-1	0.0	0.0	0.0	0.2
BKGD 1	0.461	0.933	4.409	0.376
BKGD 2	96.861	0.000	12.909	8.319
BKGD 3	20.438	7.419	5.839	0.333

LHCb VELO Position: OUT | Gap: 58.0 mm | STABLE BEAMS | TOTEM: STANDBY

R. Assmann, 19.09.2011

Record Lumi > 3.3e33 cm^{-2} s^{-1}

Comments 30-09-2011 21:04:44 :

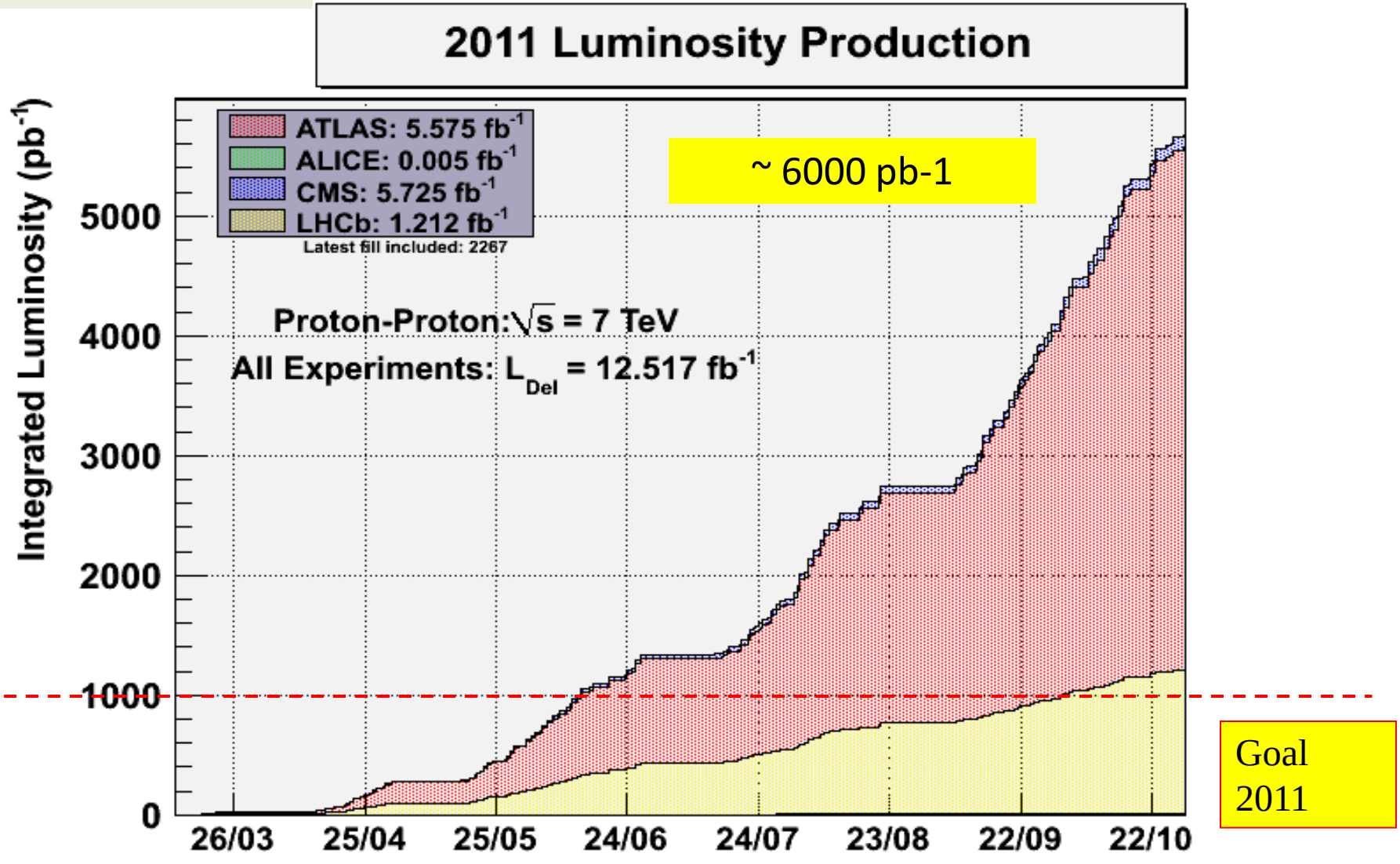
So long Tevatron. We'll miss you.
Thanks for everything.

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	false	false
Setup Beam	true	true
Beam Presence	false	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: Single_2b+12small_13_1_1_1bpi14inj | PM Status B1: ENABLED | PM Status B2: ENABLED

J. Uythoven, 03.10.2011

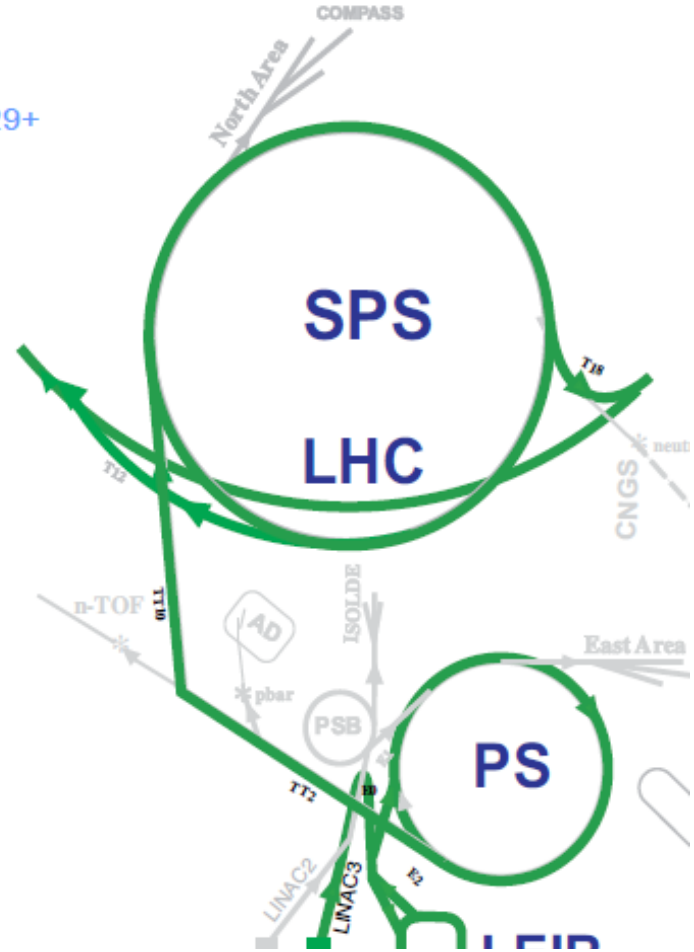
Protons


2011 Luminosity Production
ATLAS: 5.575 fb-1
ALICE: 0.005 fb-1
CMS: 5.725 fb-1
LHCb: 1.212 fb-1
Latest fill included: 2267
~ 6000 pb-1
Proton-Proton: √s = 7 TeV
All Experiments: L Del = 12.517 fb-1
Integrated Luminosity (pb-1)
5000
4000
3000
2000
1000
0
26/03
25/04
25/05
24/06
24/07
23/08
22/09
22/10
Goal
2011

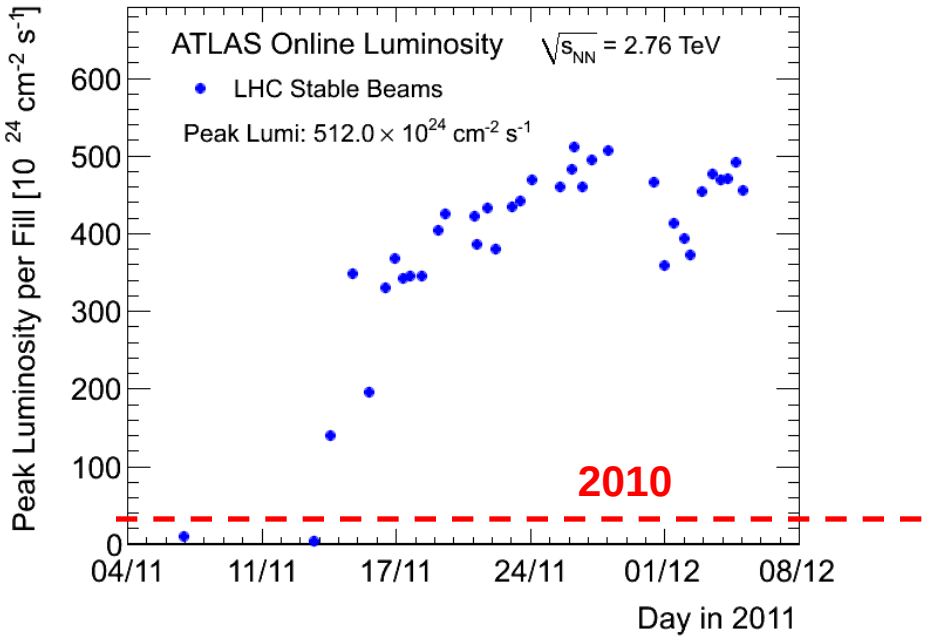
Heavy Ion Operation

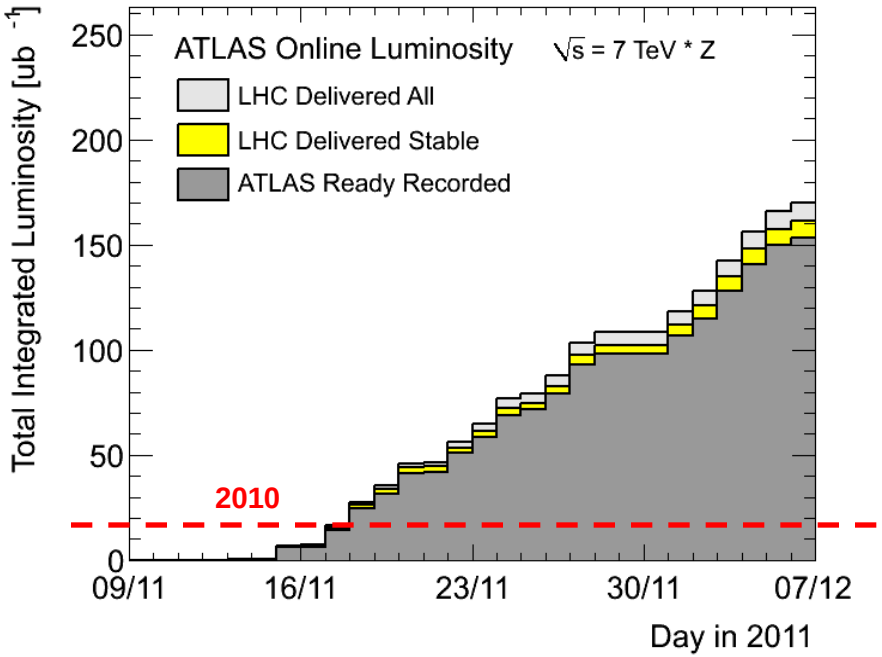
Lead ion injector chain

- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool Linac 3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)



Peak & Integrated Pb-Pb luminosity in 2011





356 bunches

In 2010:

Peak ~18E24; Integrated ~18ub-1
Max 137 bunches, larger β*, smaller bunch intensities

2012 – canonical (long) year

	Days
Machine check-out	2
Commissioning with beam	21
Machine development	22
Technical stops	20
Scrubbing (25 ns)	3
Technical stop recovery	6
Initial intensity ramp-up	~21
Proton running	~126
Special runs	~8
Ion setup	4
Ion run	24

~150 days

Mike Lamont

2012 Run Configuration

- beam energy – 4 TeV
  - assuming low number of quenches
  - extra luminosity
    & higher cross sections
- bunch spacing 50 ns kept
- tight collimator settings
  - operationally proven
- ATLAS and CMS - $\beta^* = 60$ cm
- ALICE and LHCb - $\beta^* = 3$ m
  - natural satellites versus main bunches in ALICE
  - tilted crossing and offset luminosity leveling in LHCb

Real Challenge
2 high luminosity experiments (ATLAS, CMS)
1 mid-luminosity (LHCb)
x20 lower
1 low-luminosity (ALICE)
x10,000 lower!
also TOTEM and ALFA

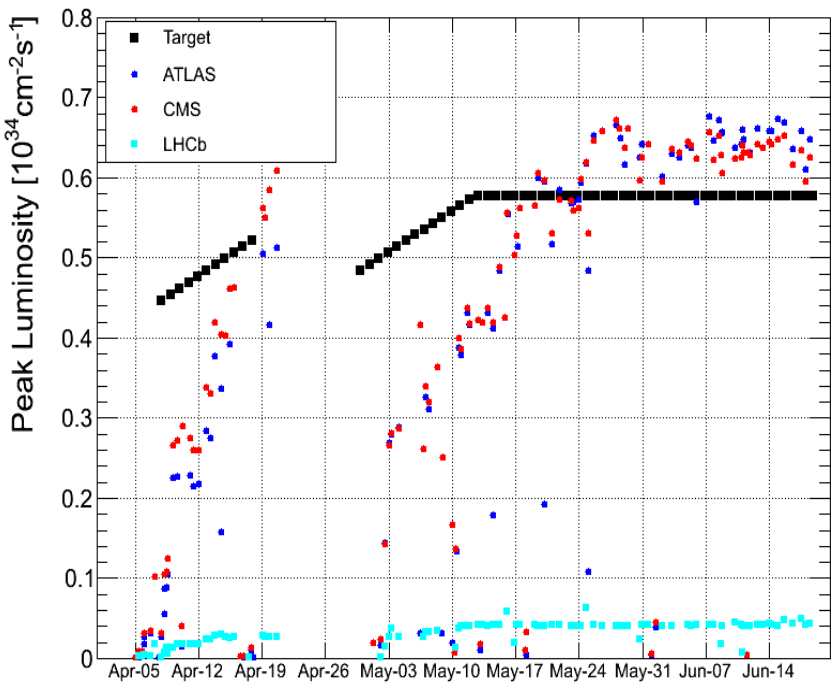
S. Myers, IPAC12, New Orleans; R. Steinhagen, ICHEP 2012

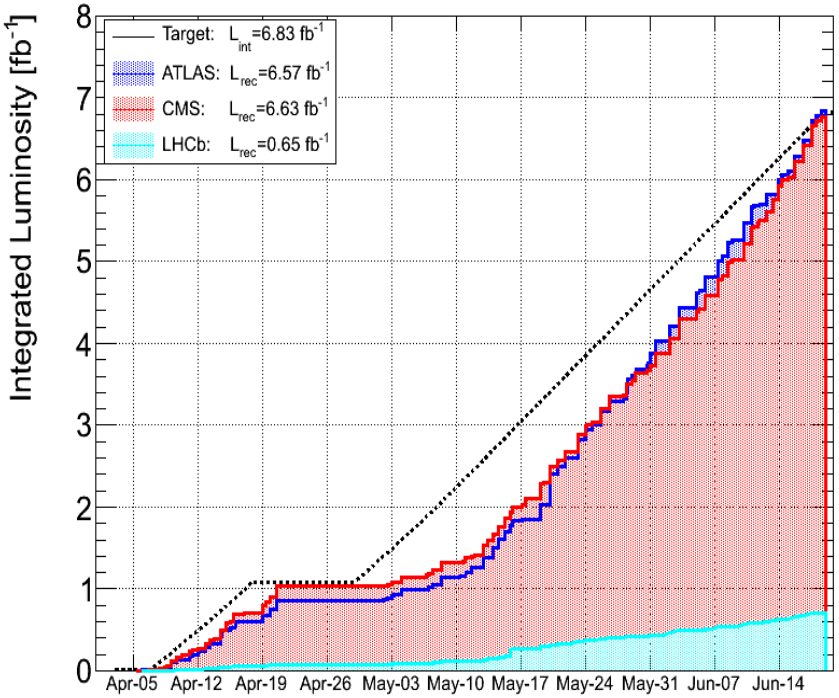
2012 Achieved vs. Target Luminosity

Estimates from Moriond (Mike Lamont & Steve Myers)

Assumptions:

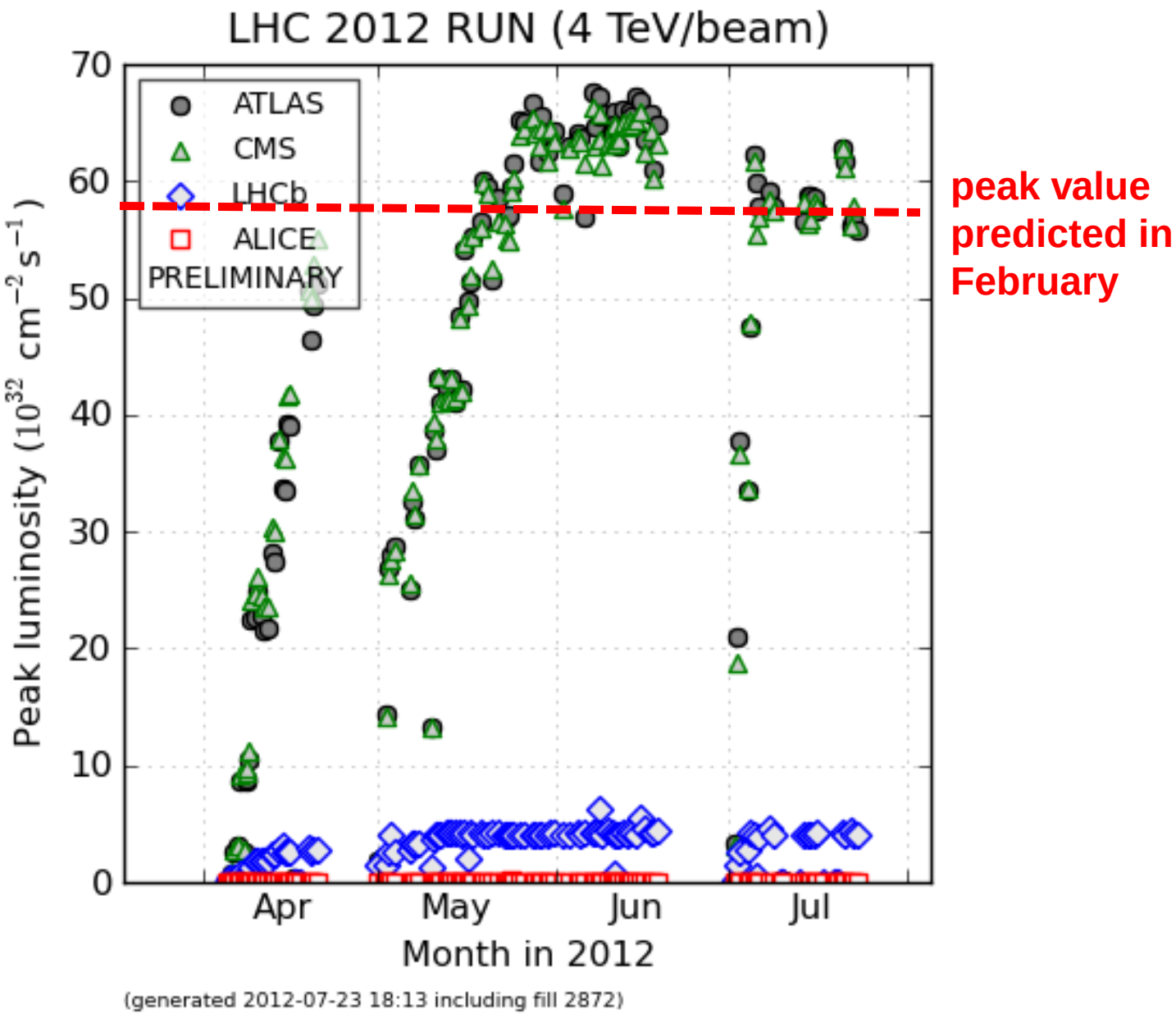
- 4 TeV, 50 ns, 1380 bunches, 1.6e11, 2.5 um, pile-up ~ 35
- 150 days of proton physics (assuming similar efficiencies to 2011)



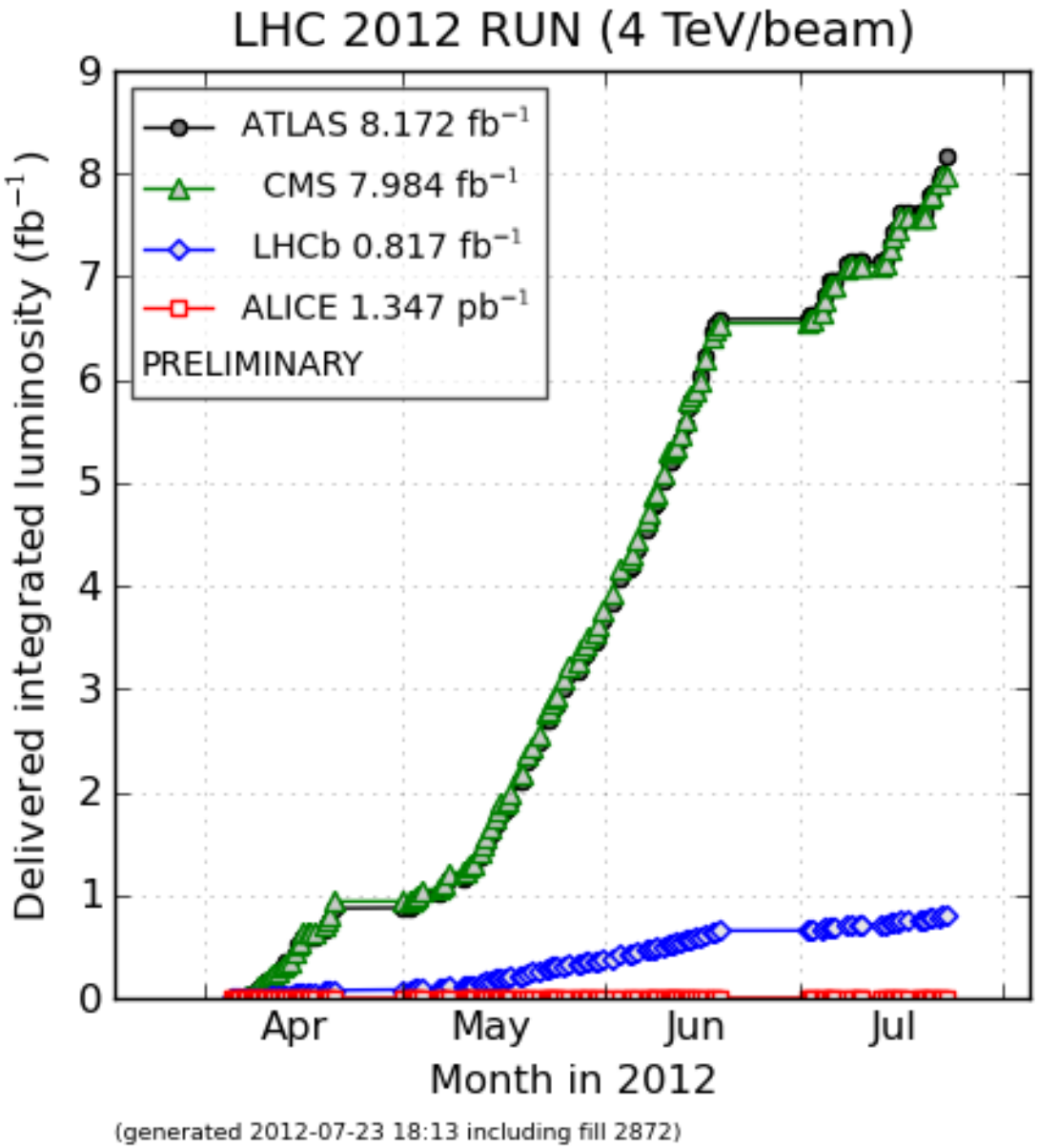


R. Steinhagen, ICHEP 2012

Achieved Peak Luminosity in 2012



Integrated Luminosity in 2012 so far



2012 integrated luminosities:

ALICE: 1.64 pb^{-1}

ATLAS: 8.49 fb^{-1}

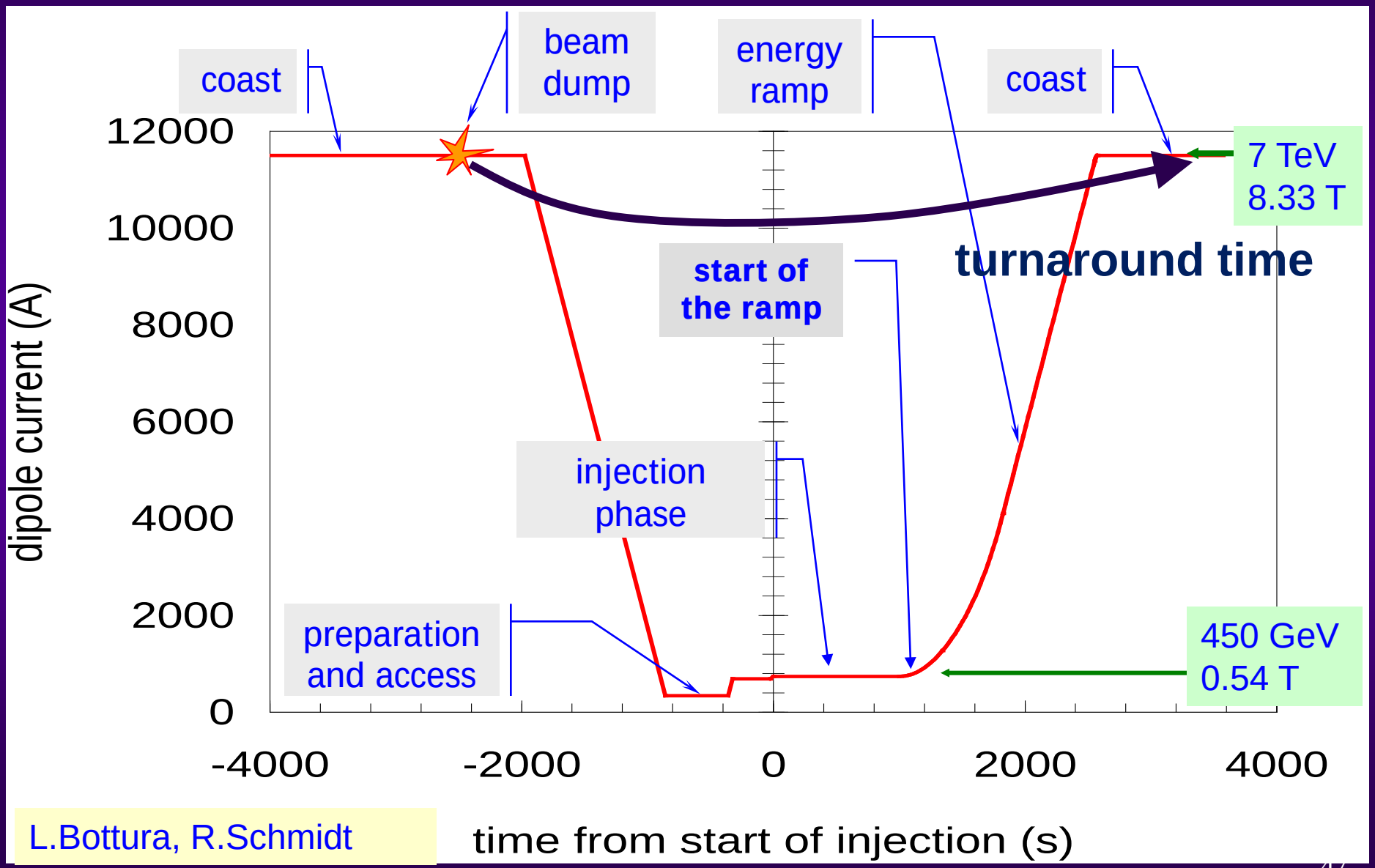
CMS: 8.47 fb^{-1}

LHCb: 855 pb^{-1}

LHC actual versus design parameters

	design	June 2012	comment
Beam energy	7 TeV	**4 TeV**	>1/2 design
transv. norm. emittance	3.75 μm	**2.6 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	1.15×10^{11}	**1.48×10^{11}**	1.3xdesign!
luminosity / bunch	3.6×10^{30} cm^{-2}s^{-1}	1.1×10^{30} cm^{-2}s^{-1}	only factor 3 away (x4 from energy!)
# bunches	2808	1380	~ ½ design
bunch spacing	25 ns	**50 ns**	
beam current	0.582 A	0.369 A	~60% design
rms bunch length	7.55 cm	≥9 cm	
crossing angle	285 μrad	290 μrad	
"Piwinski angle"	0.64	≥0.69	
luminosity	10^{34} cm^{-2}s^{-1}	6.8×10^{33} cm^{-2}s^{-1}	~design at 7 TeV

LHC magnetic cycle

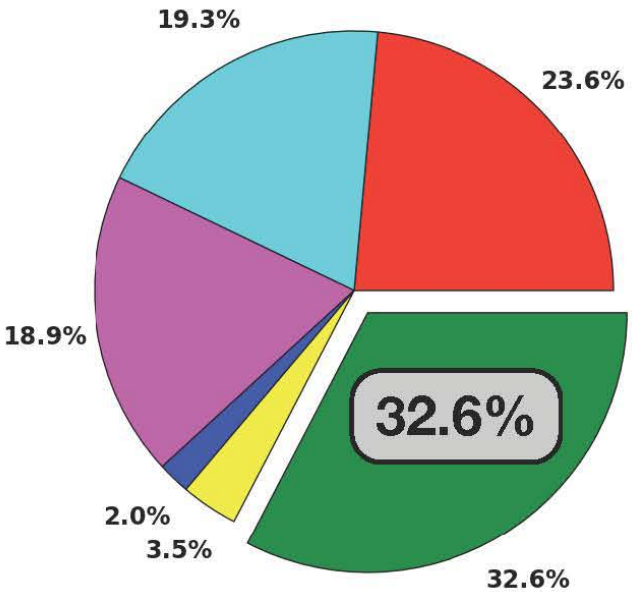


L.Bottura, R.Schmidt

Performance Comparison 2011-2012

2011

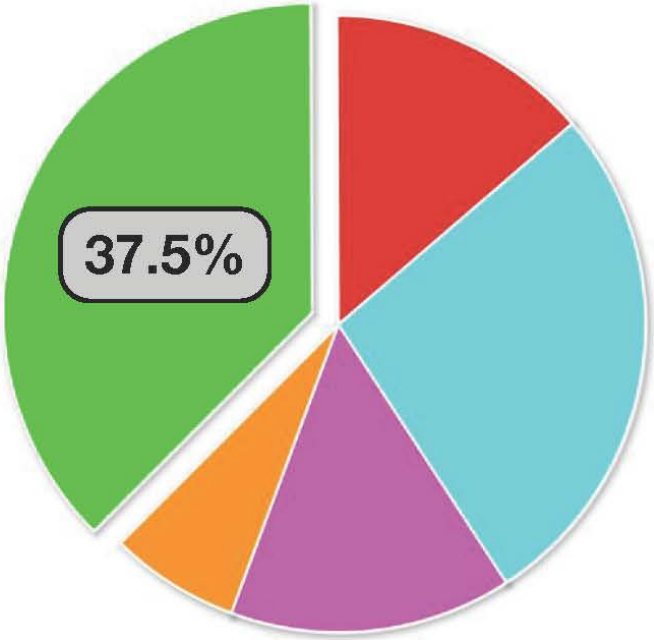
2011 Proton Run: Luminosity Production



SB Time: 26.6 days Total Time: 81.4 days

2012

Mode: Proton Physics
Number of Fills: 236
Time in SB: 23 days 21 hrs 55 mins



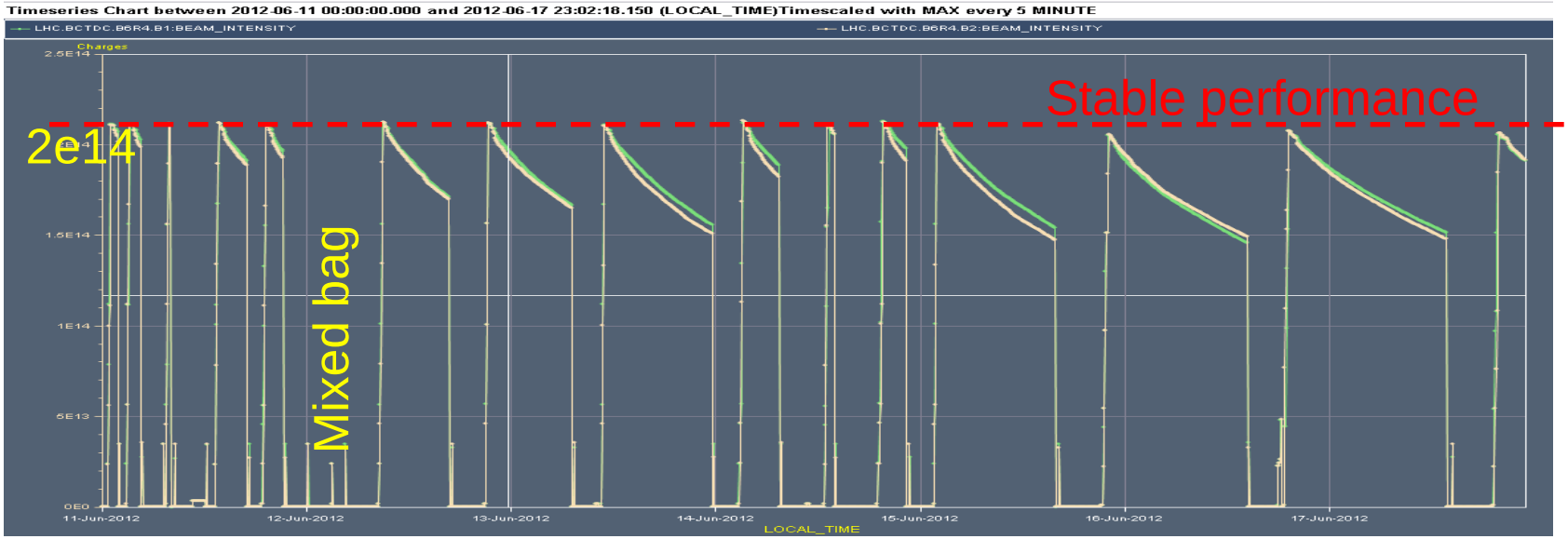
Percentage of time in NO BEAM and SETUP is ~same

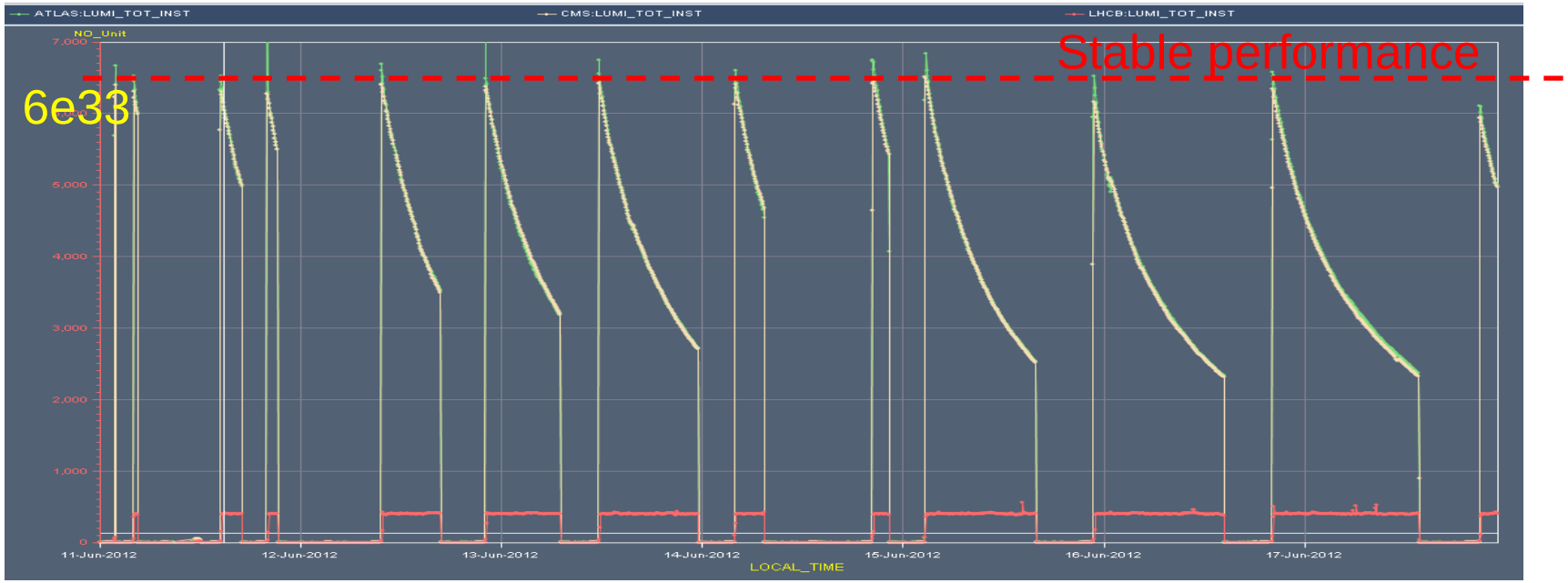
NB	Ramp
SetUp	FTSQAD
Inj	SB

- Access – No beam : 13.75%
- Machine setup : 27.03%
- Beam in : 14.84%
- Ramp + squeeze : 6.87%
- Stable beams: 37.5%

A. Mcpherson, June 2012

Intensities & Lumi over one week in June





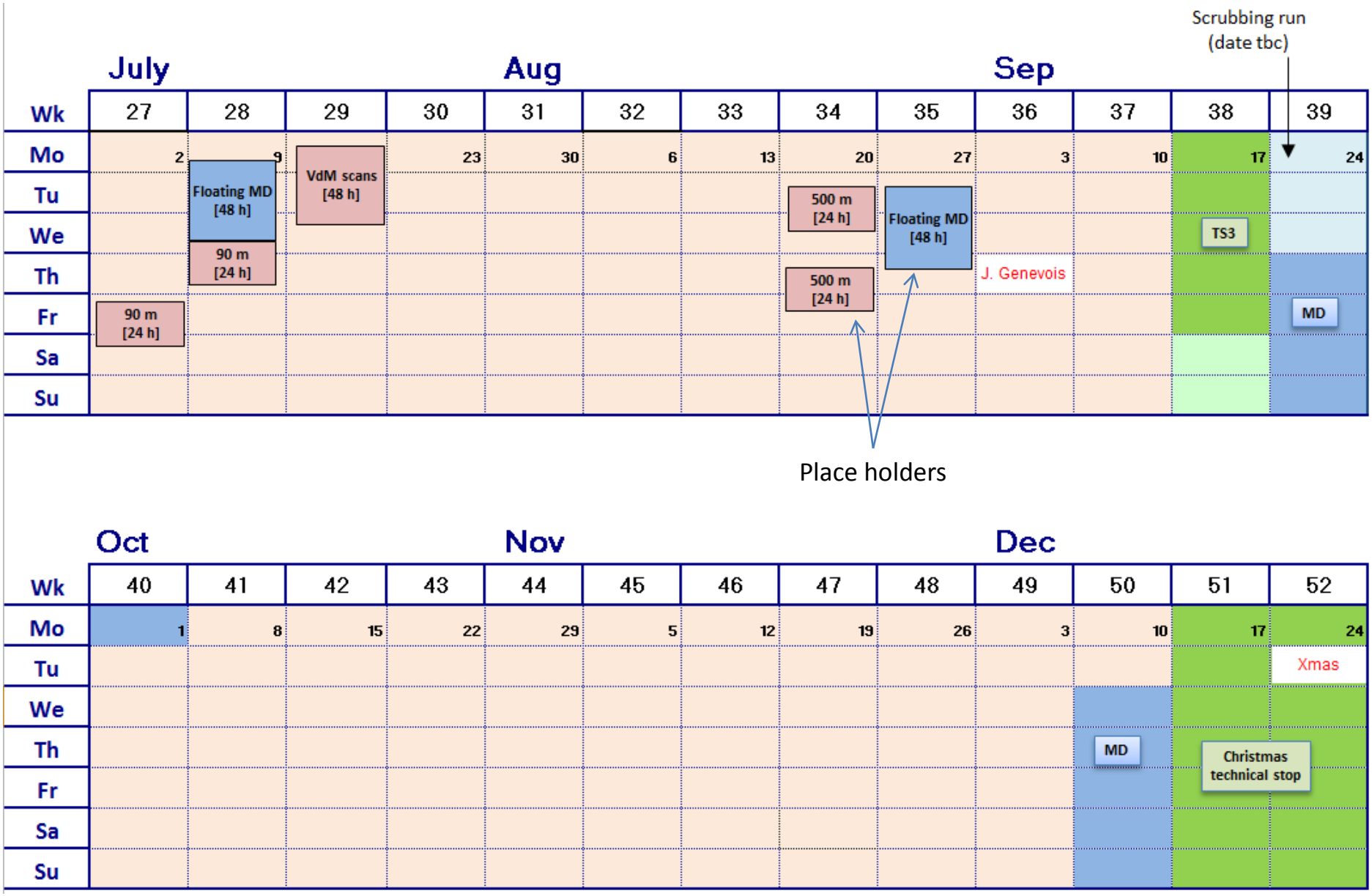
M. Lamont, 18 June 2012

Overview of fills in the week of 11-18 June

Fill	Duration	Ibeam	Lpeak [e30 cm-2s-1]	Lint [pb-1]	Dump
2723	2:26	2.03E+14	6406	46.06	Trip of ROD.A81B1, SEU?
2724	1:13	2.03E+14	6329	25.905	Electrical perturbation
2725	7:04	2.05E+14	6520	115.5	Trip of S81
2726	8:58	2.05E+14	6499	142.5	Elecitrical perturbation, FMCM
2728	11:41	2.06E+14	6525	171.5	**Operator dump**
2729	3:28	2.06E+14	6502	67.7	BLM self trigger
2732	1:52	2.06E+14	6592.5	40	QPS trigger RQX.R1, SEU?
2733	12:34	2.06E+14	6674	183	Triplet RQX.L2 tripped.
2734	15:33	2.01E+14	6257.5	203.5	**Operator dump**
2736	17:29	2.02E+14	6465.5	233	**Operator dump**
2737	3:36	1.99E+14	6021	66.1	RF Trip 2B2
Tot	51.1%			1301	

51% of time in stable beams; total **1.3 fb^{-1}** in one week

LHC 2012 Q3/Q4 – updated schedule



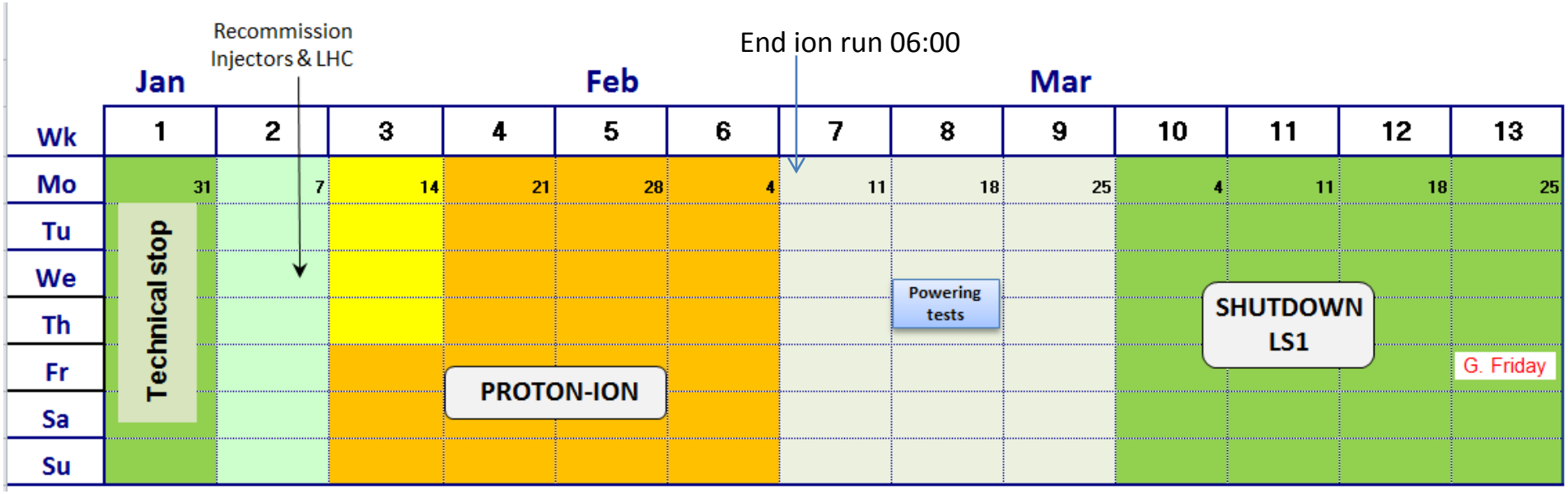
LHC 2012 schedule - details

- TS3 moved to W38 17th September
- Lost TS4 (effectively moved to Xmas)
- End of proton run – 06:00 Monday 17th December

Mode	Days left
MD	12
Technical stop	5
Recovery from TS	2
Scrubbing - 25 ns	3
Proton running	~131
Special runs	~5
Ion setup	4
Ion run	24

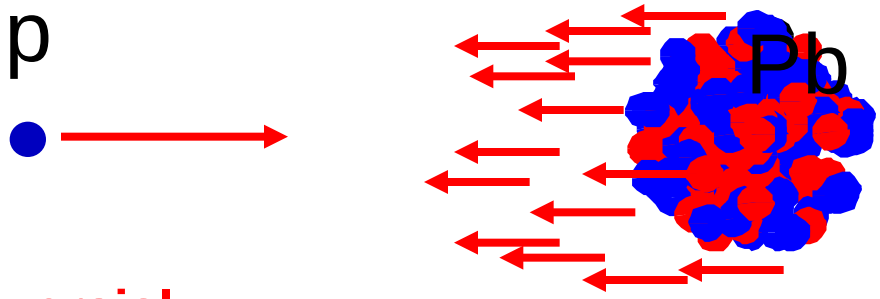
we could get additional ~20/fb from now until 17 December

2013 schedule



- Minimum interventions before and during Xmas stop
- Need both protons and lead (i.e. ion source, LINAC3, LEIR in addition…)
- Non-LHC physics is not foreseen – flat line complex when beam not needed
- Should foresee doing maximum p-A preparation before Christmas (pilot run, aperture measurements, test squeeze…)

p-Pb lead collisions in 2013



Feasibility controversial

Beams of unequal revolution frequencies, moving long-range beam-beam encounters at injection and in ramp

RHIC abandoned equal rigidity acceleration

LHC 1st feasibility test on31 October 2011:

Established new RF rephasing and cogging procedure

Stored 4 Pb bunches in presence of 304 p bunches (~10% nominal intensity) at injection; lifetime and emittance growth no worse for presence of p bunches

Ramped 2 Pb and 2 p bunches, good lifetime, cogging by 9 km w/o losses

LHC 2nd feasibility test planned for September 2012:

Ramp many p and some Pb bunches

Pilot physics fill with moderate no. of bunches

Indeed our work inspired an unknown artist working for the CERN Bulletin to create this moving depiction of an LHC proton discussing behavioural competenc(i)es with his supervisor.

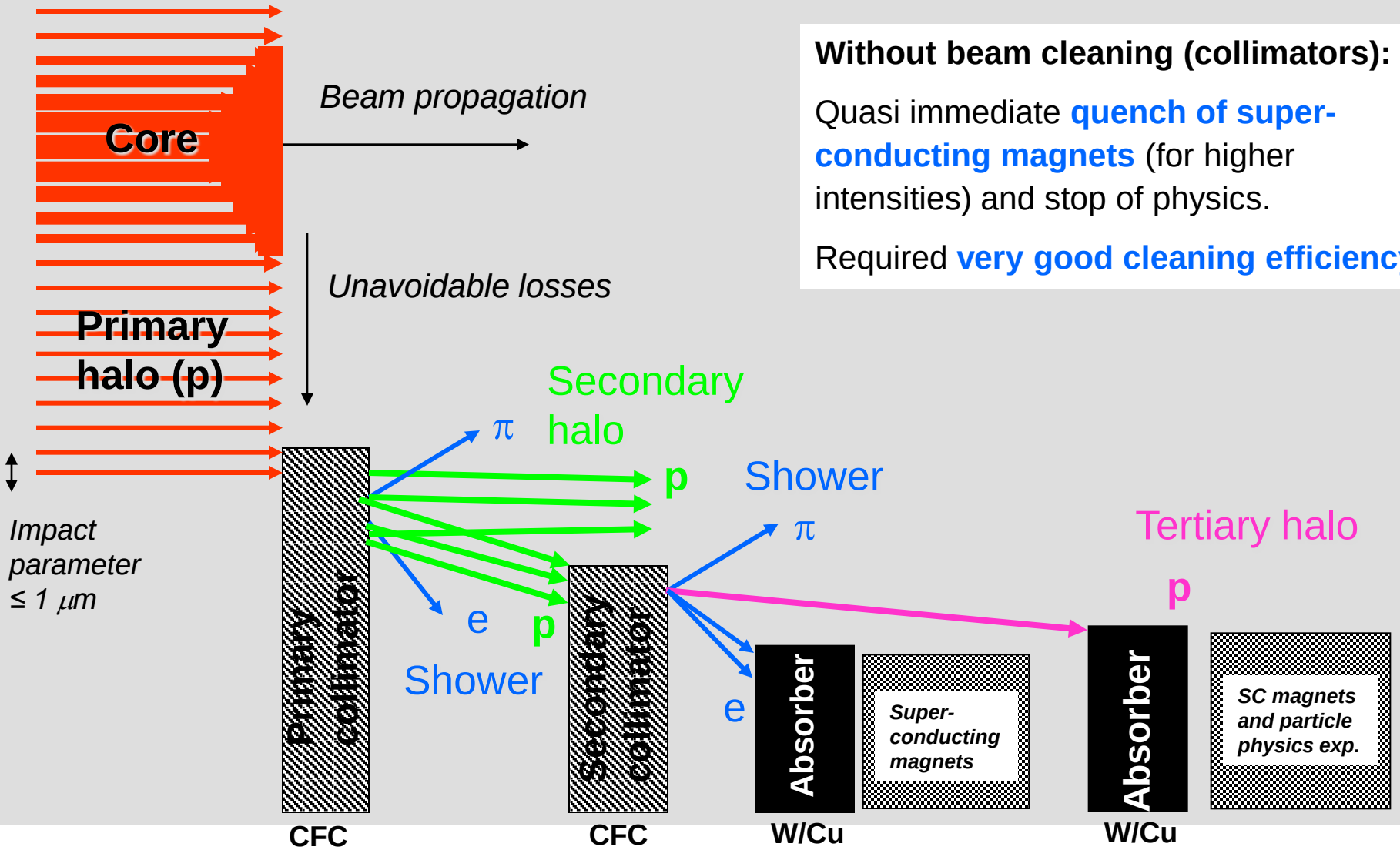
Now the proton's nightmare is coming true.

LHC beam dynamics

2011/12 Lessons for the Future

- Head-on beam-beam effect not a limitation
- Long range beam-beam to be taken seriously
  - Need sufficient separation (otherwise bad lifetime & beam loss) of 10 -12 σ separation as expected
- Established β* reach (aperture, collimation, optics)
- *Lumi*-leveling via offset tested – works fine in LHCb! Alternative *Lumi*-leveling with β* tested during last MDs
- High-intensity operation close to beam instability limits
  - **Transverse instabilities for small IP beam offsets while going into collisions,** impedances (kicker, collimator heating)
  - **Electron cloud effects**, especially for 25 ns bunch spacing
  - Longitudinal instabilities controlled by longitudinal blow up
- Availability issues (SEUs, vacuum, **UFOs**, cryogenics, …) – vigorous follow-up and consolidation

LHC – multistage cleaning



Without beam cleaning (collimators):

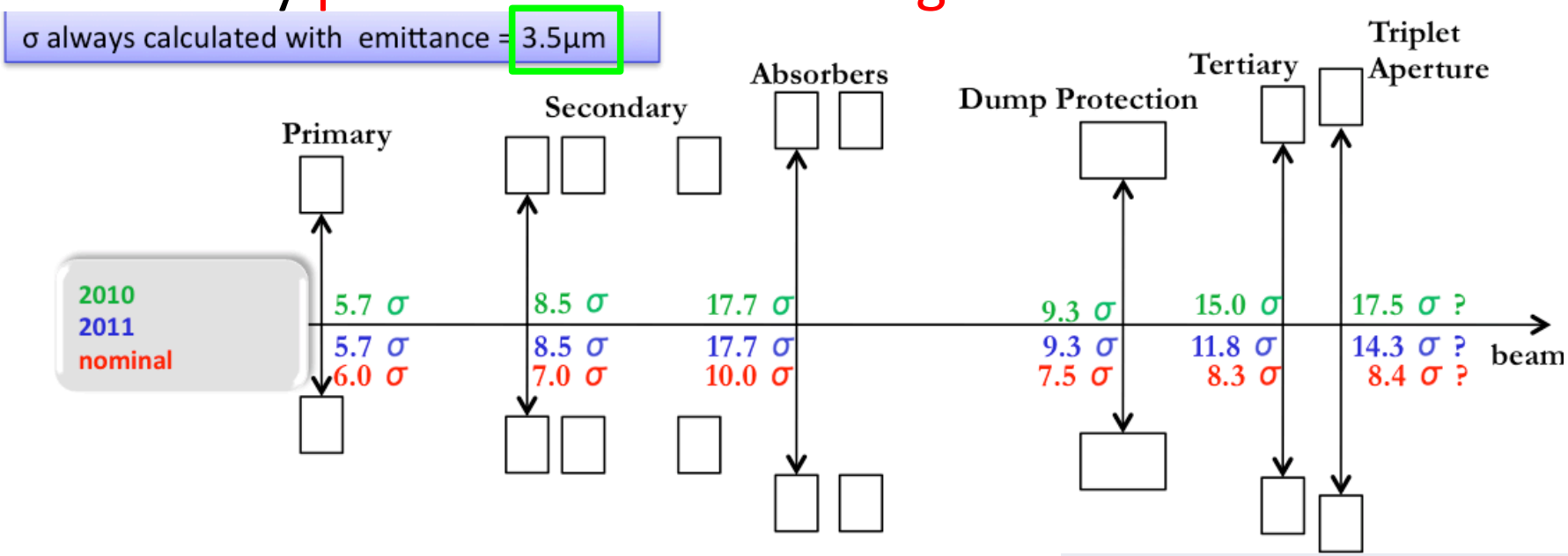
Quasi immediate **quench of super-conducting magnets** (for higher intensities) and stop of physics.

Required **very good cleaning efficiency**

R. Assmann

Collimator Settings in 2012

Collimation hierarchy has to be respected to achieve satisfactory protection and cleaning



aperture plus tight settings
allow us to squeeze to 0.6 m

2012 tight settings:	σ
TCP 7	4.3
TCSG 7	6.3
TCLA 7	8.3
TCSG 6	7.1
TCDQ 6	7.6
TCT	9.0
Aperture	10.5

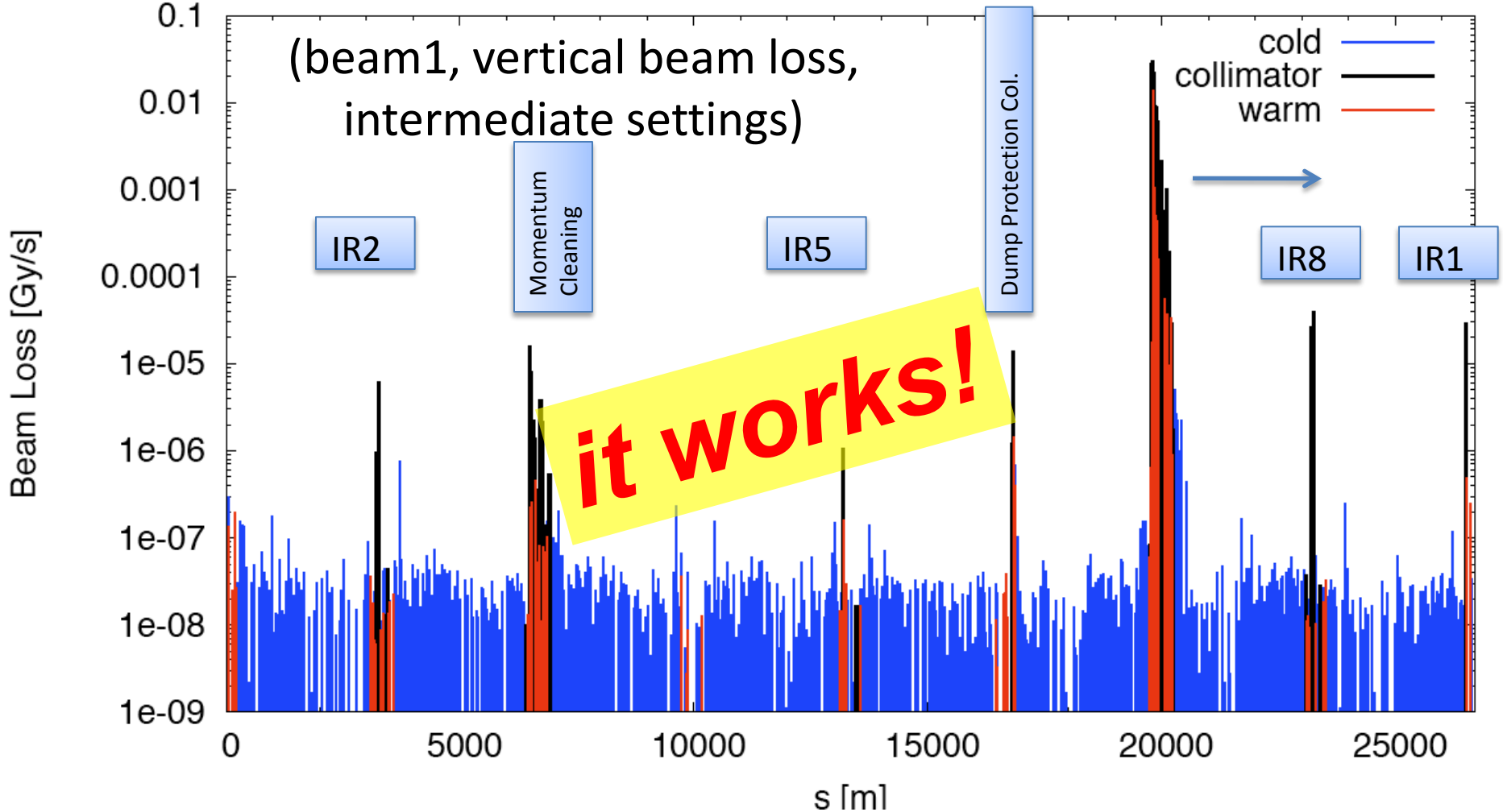
Roderik Bruce

How tight?

Nose of George Washington on US quarter

Tight settings (2012): ~2.2 mm gap at primary collimator

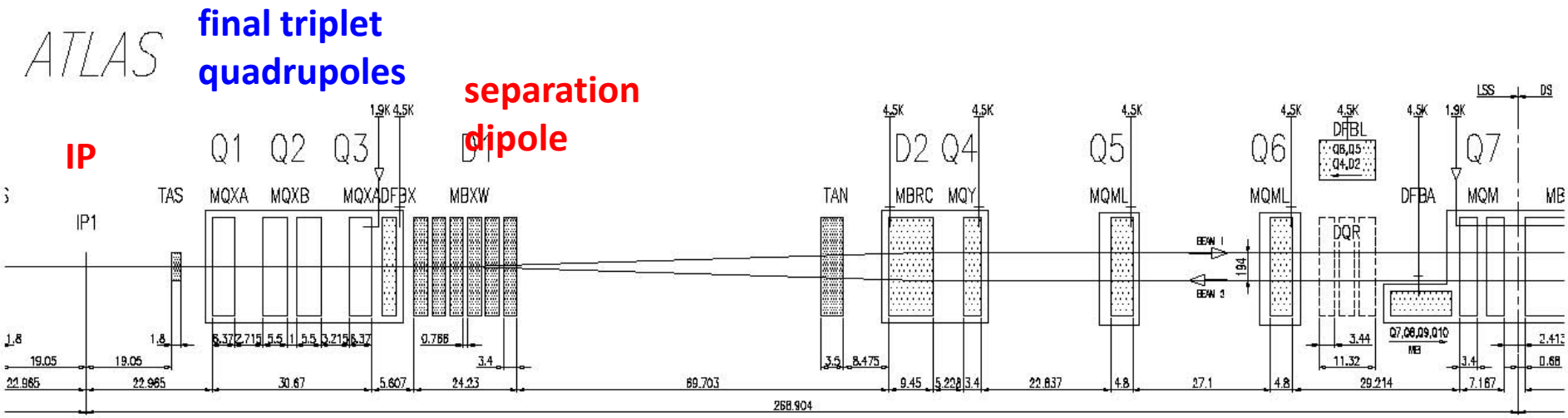
LHC – measured cleaning at 3.5 TeV



Almost all protons losses in warm regions and not in cold SC arcs.

R. Assmann

LHC interaction-region layout



~59 m

nominal bunch spacing= 7.5 m

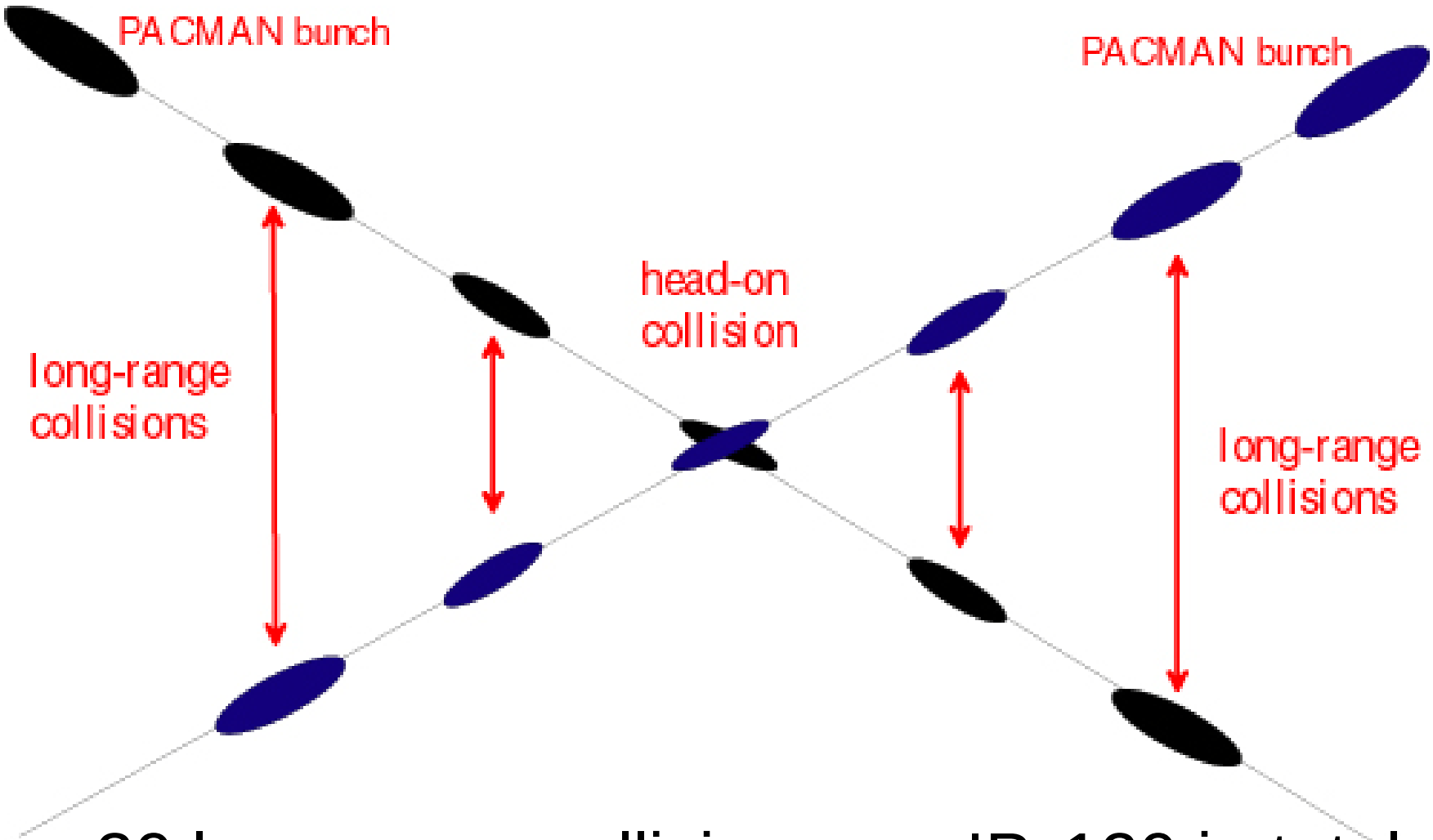
nominal collision spacing = 3.75 m

→ *about 2x15 collisions between IP and separation dipole!*

tune shift would increase 30 times!

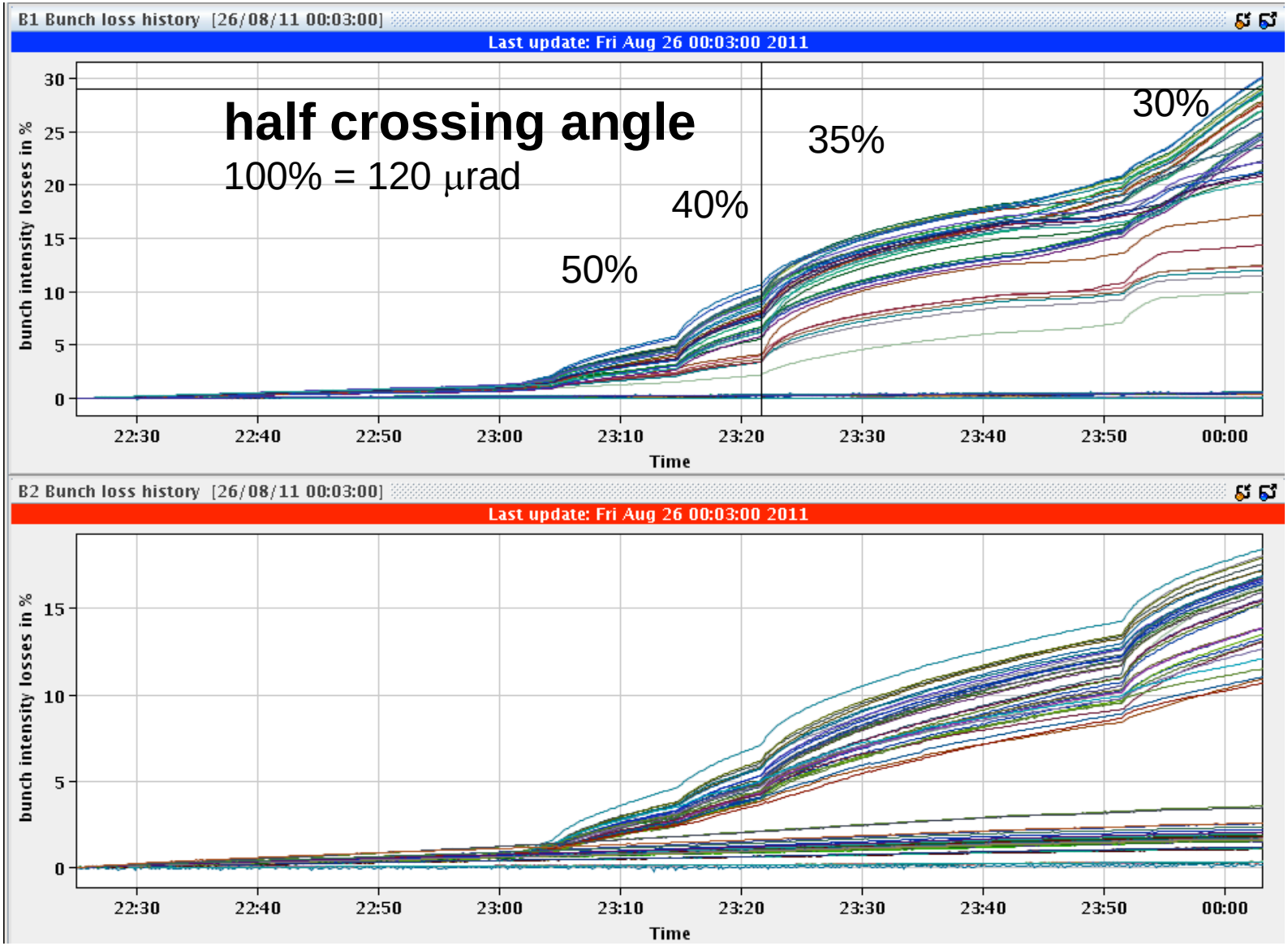
solution: crossing angle

LHC: long-range beam-beam



30 long-range collisions per IP, 120 in total

LR-BB: Losses per Bunch, August 2011



HD 1-2-5
Strong LR

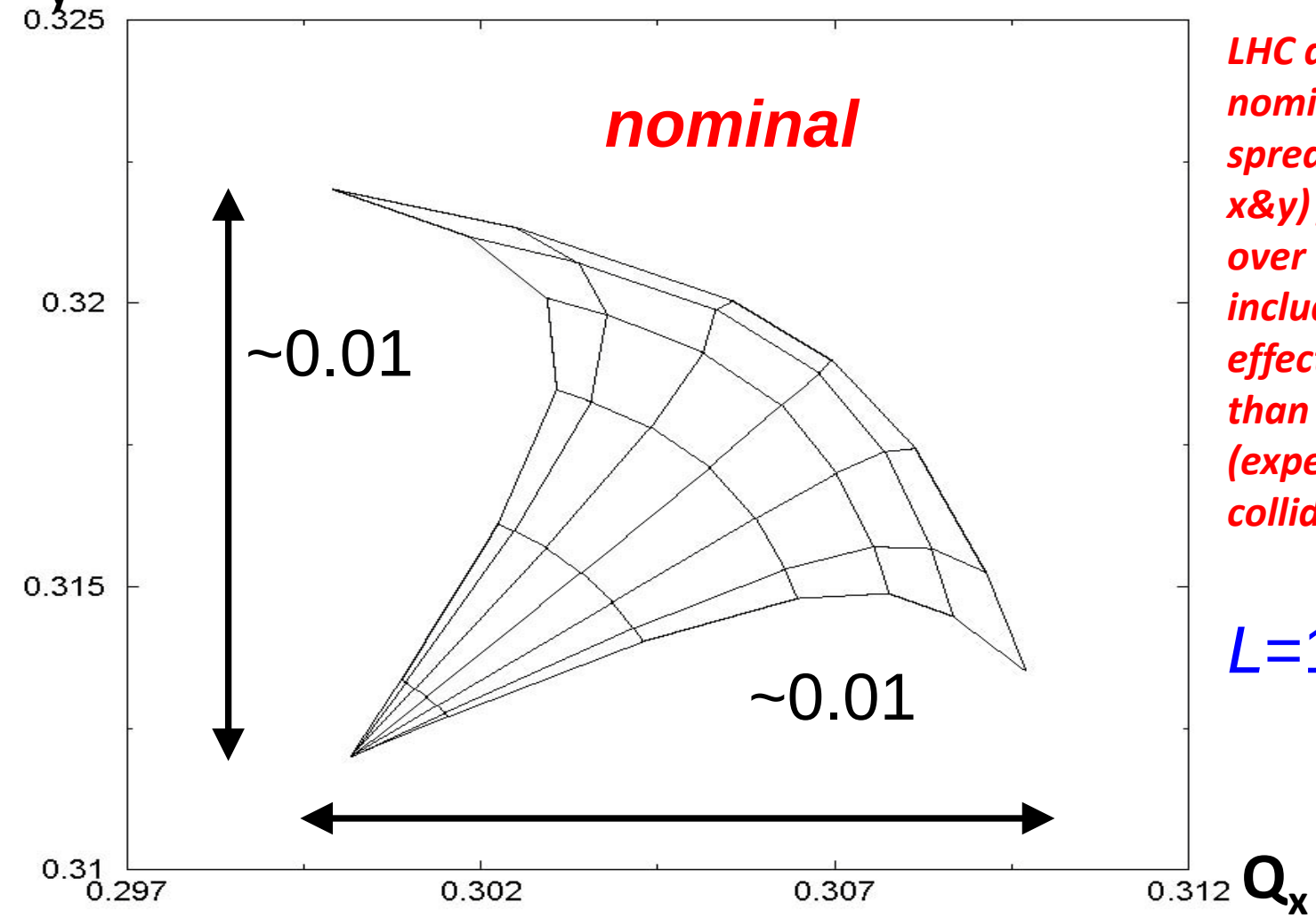
HD 8
Tiny LR

HD 1-5
Strong LR

HD 2-8
Small LR

W. Herr et al

LHC beam-beam tune footprint



LHC design criterion: nominal total tune spread (up to 6σ in x&y) from all IPs and over all bunches, including long-range effects, should be less than 0.01 (experience at SPS collider)

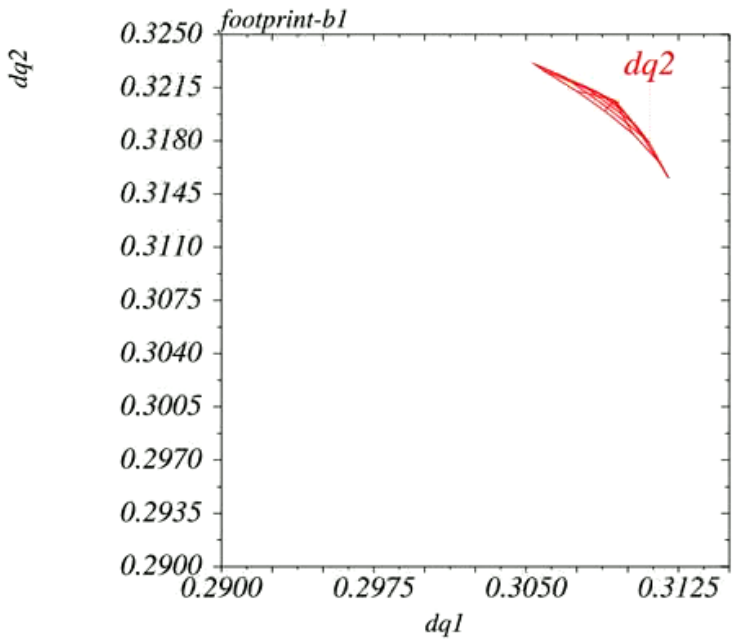
$L=10^{34}$ cm^{-2}s^{-1}

nominal tune footprint up to 6σ with

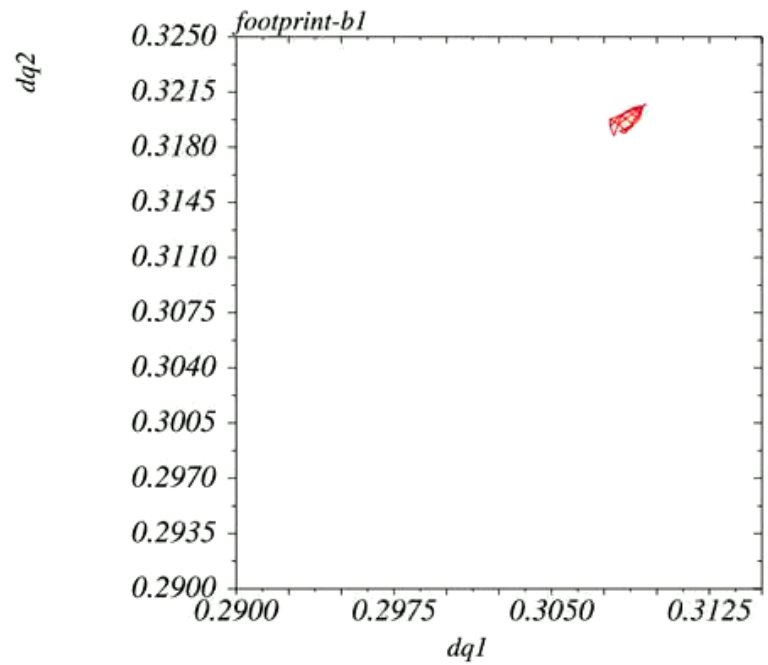
4 IPs & nom. intensity $N_b=1.15\times10^{11}$

tune footprint when bringing LHC beams into collisions

w/o octupole magnets



w actual octupole magnet settings

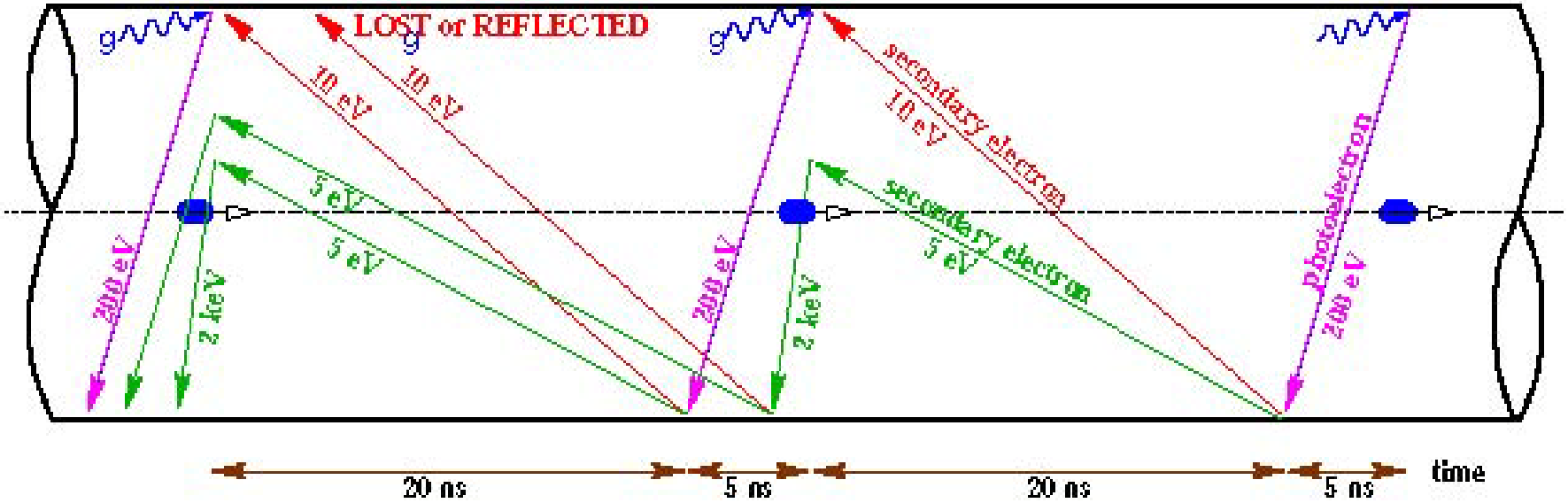


shrinking footprint and octupole settings related to instabilities

Stephane Fartoukh, 3 July 2012

electron cloud

[F. Ruggiero]



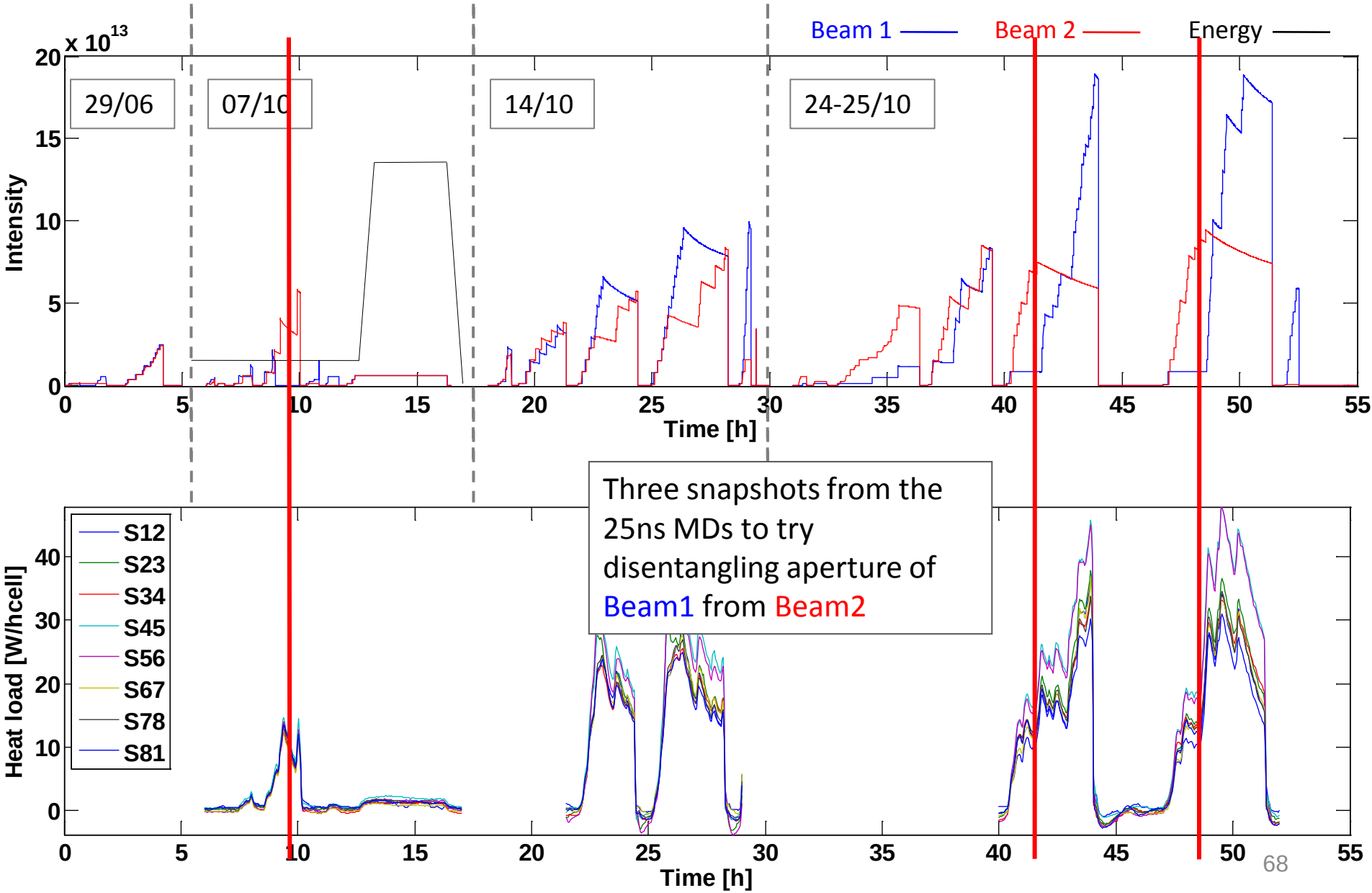
schematic of e- cloud build up in LHC beam pipe, due to **photoemission** and **secondary emission**

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

also synchrotron radiation & beam image currents add to heat load

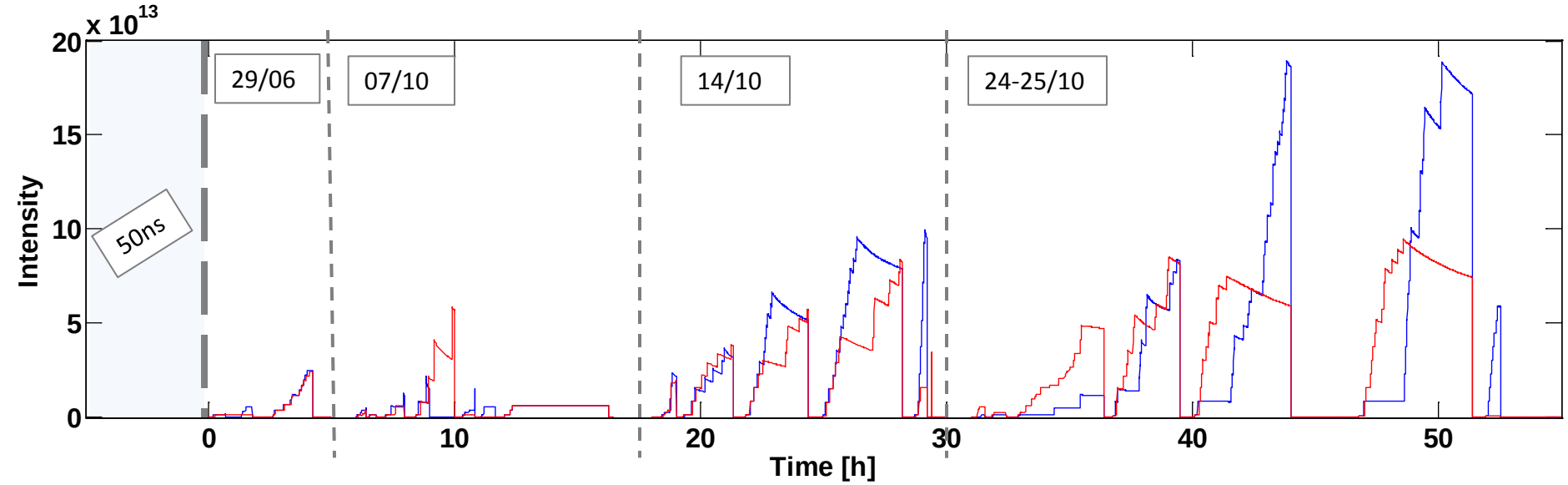
Electron cloud: δ_{max} in the arcs: results (25ns)

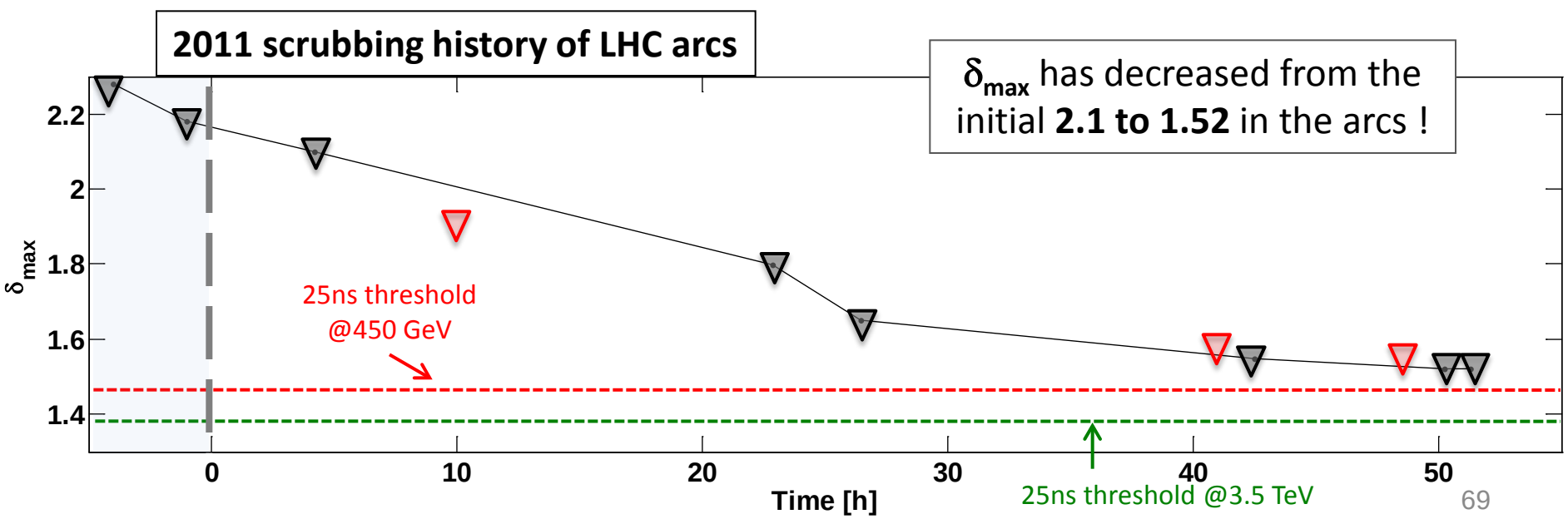
G. Rumolo



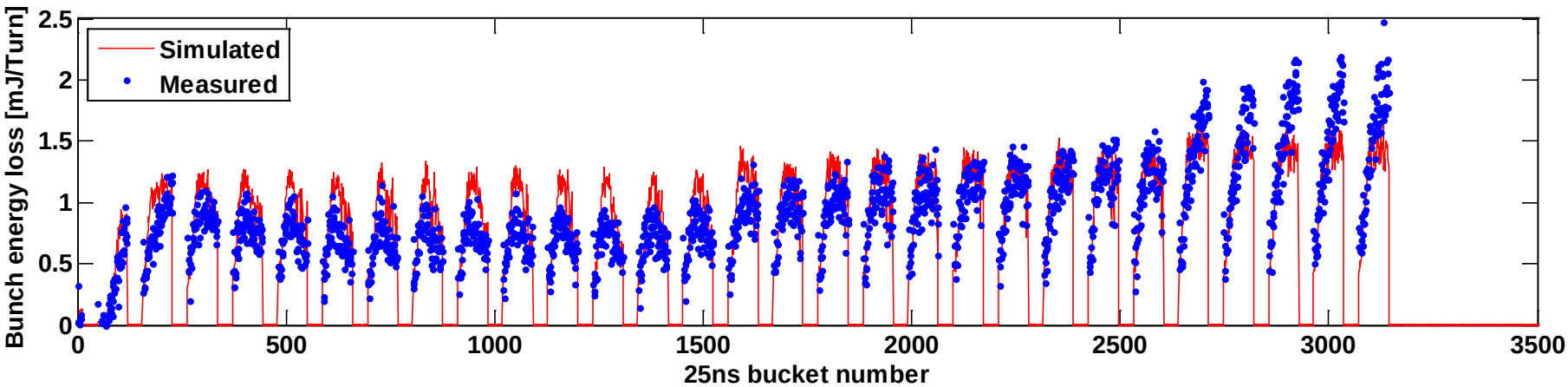
G. Rumolo

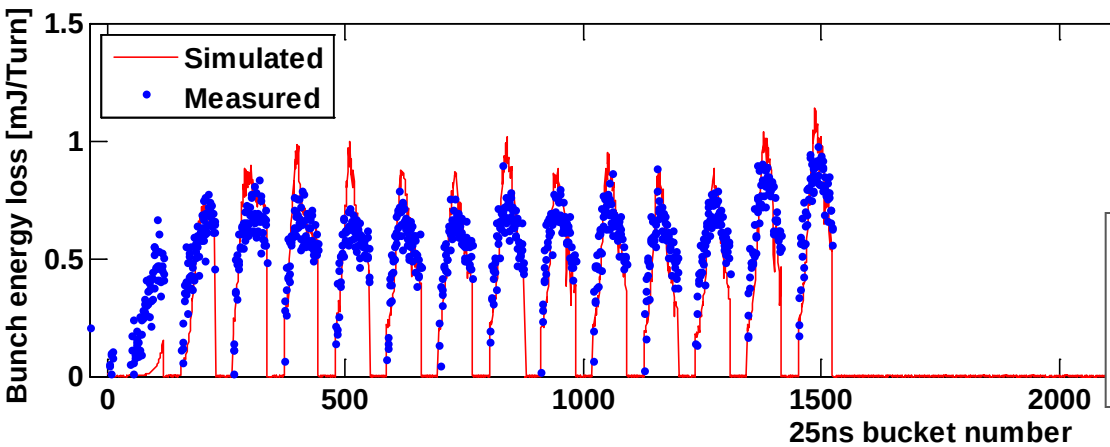
Electron cloud: δ_{max} in the arcs: results





Electron-cloud beam observable: energy loss





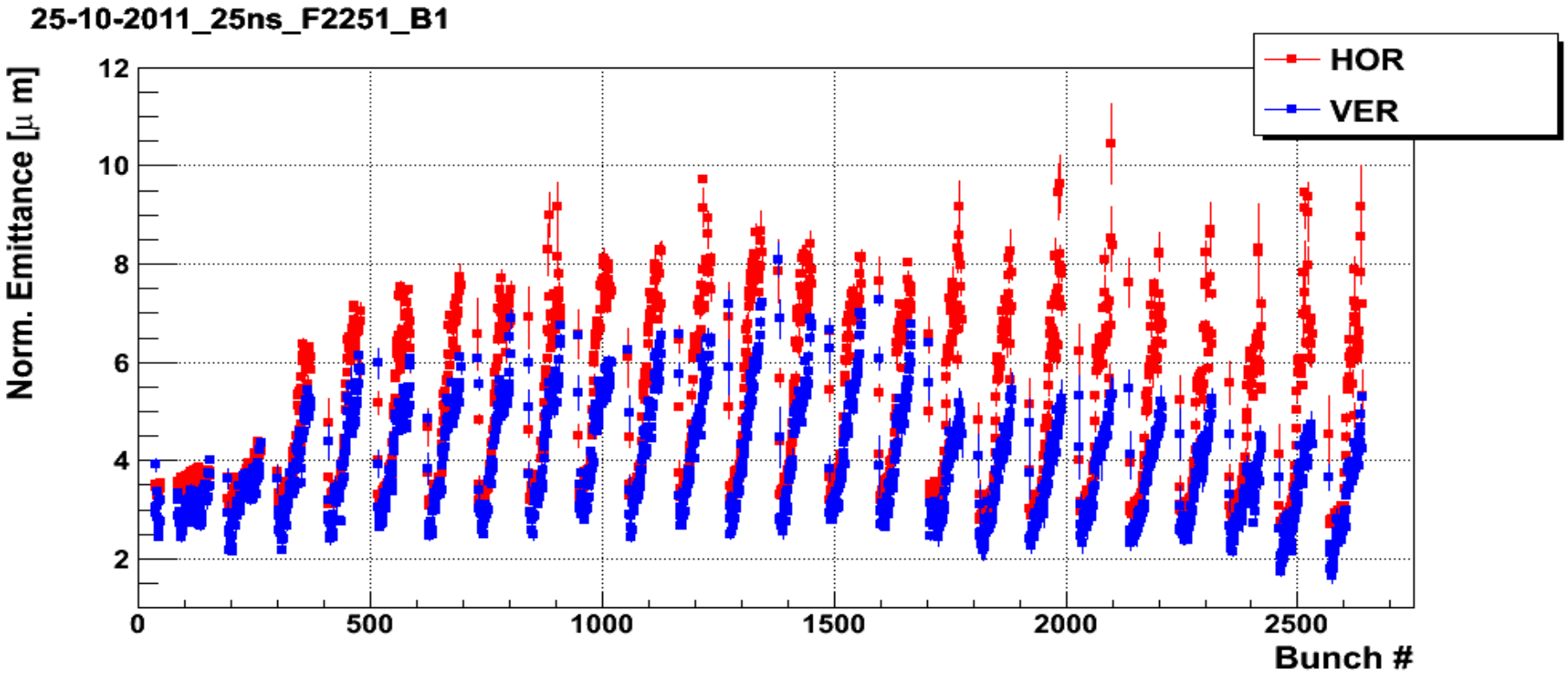
Measurements ◆ → the energy loss per bunch is obtained from the stable phase shift

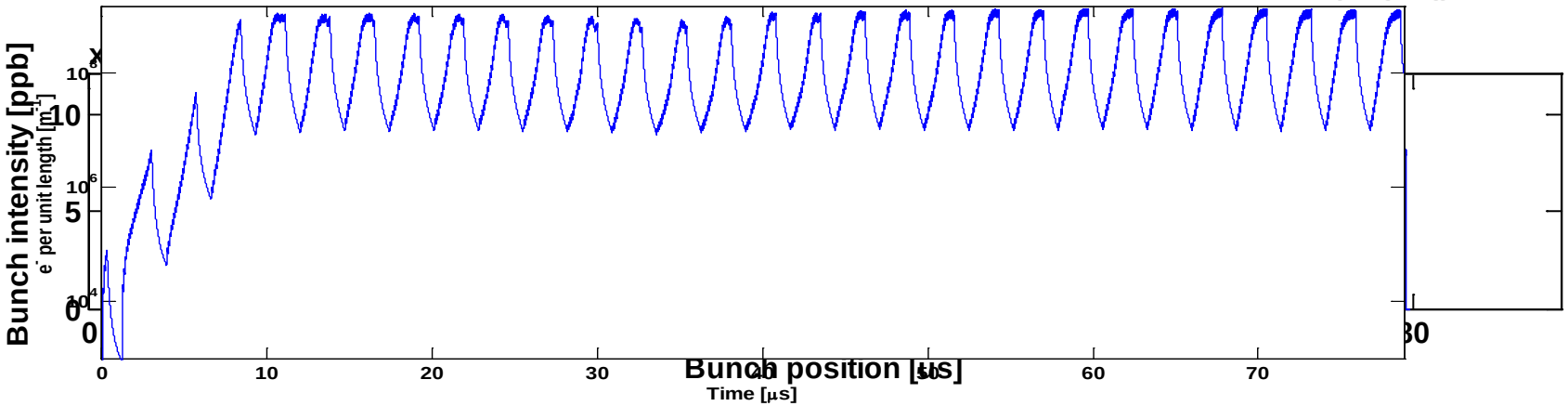
Simulations – → We use as test case the last fill on 25 October

G. Rumolo, O. Boine-Frankenheim, F. Petrov, J. Esteban, E. Shaposhnikova, G. Iadarola

Electron-cloud beam observable: emittance growth

G. Rumolo





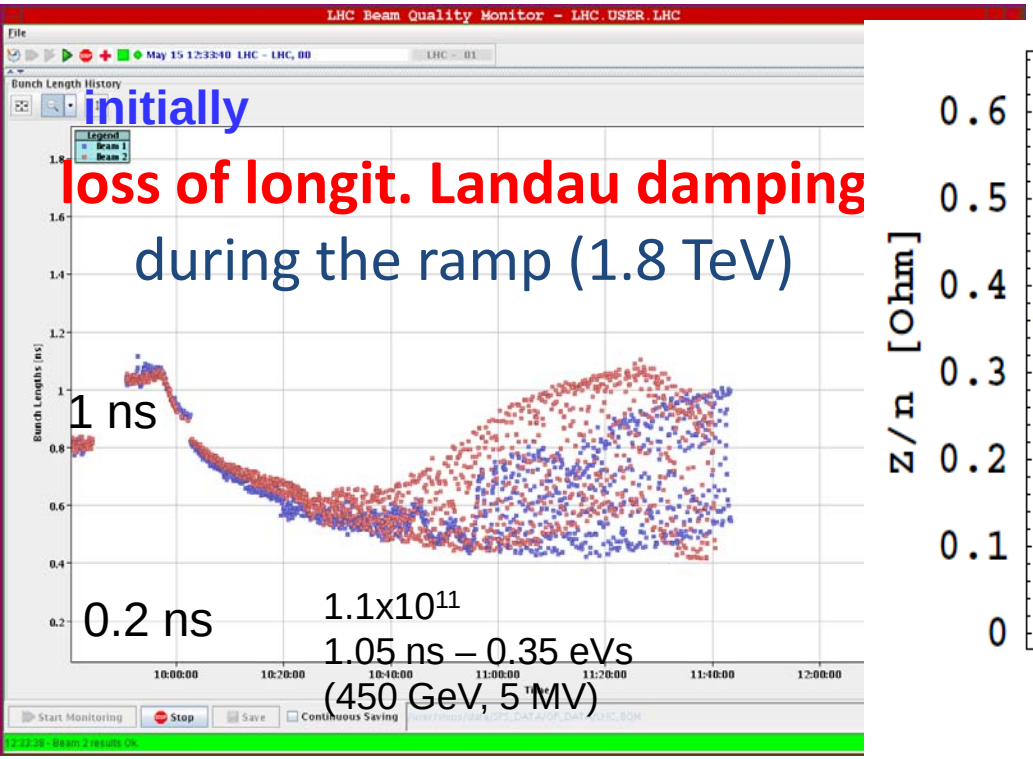
fully self-consistent simulation of e-cloud effects: build-up & beam dynamics

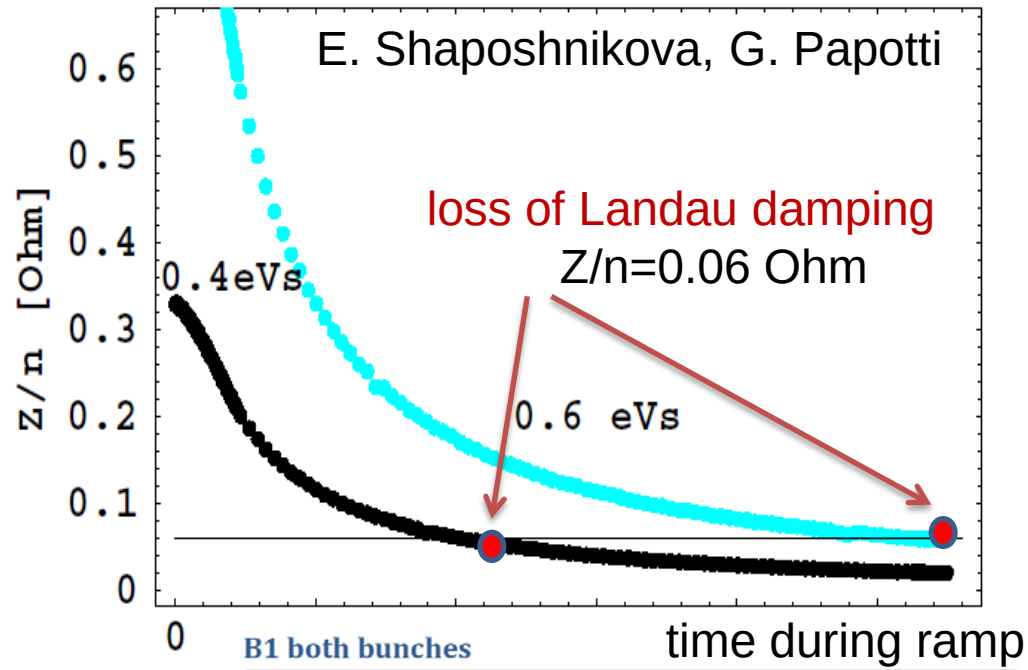
turn 0

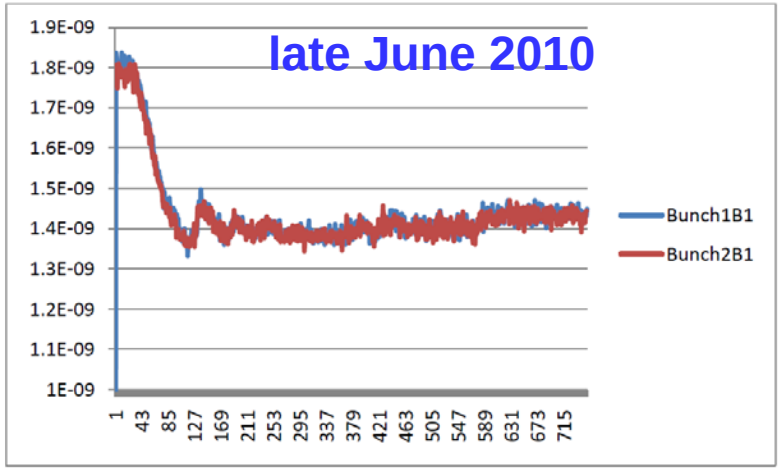
turn 1000

CERN SPS at injection (26 GeV): 3 trains of 72 bunches each passing 1000 turns around the entire ring, simulated with WARP-POSINST code using 9,600 CPUs on Franklin supercomputer (NERSC, U.S.A.)
J.-L. Vay, et al, IPAC12 Proc., (2012) TUEPPB006

LHC – longitudinal instability







main cure: controlled longitudinal blow up on LHC ramp

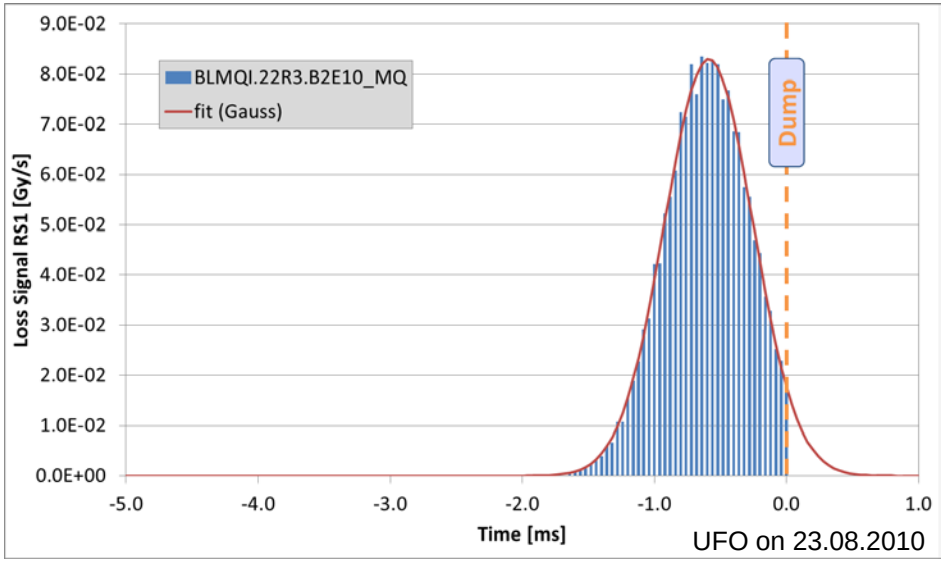
feedback on bunch length measurement modulates noise amplitude to control blow-up rate;
bunch lengths converge correctly to target 1.5 ns (now ~1.25 ns)

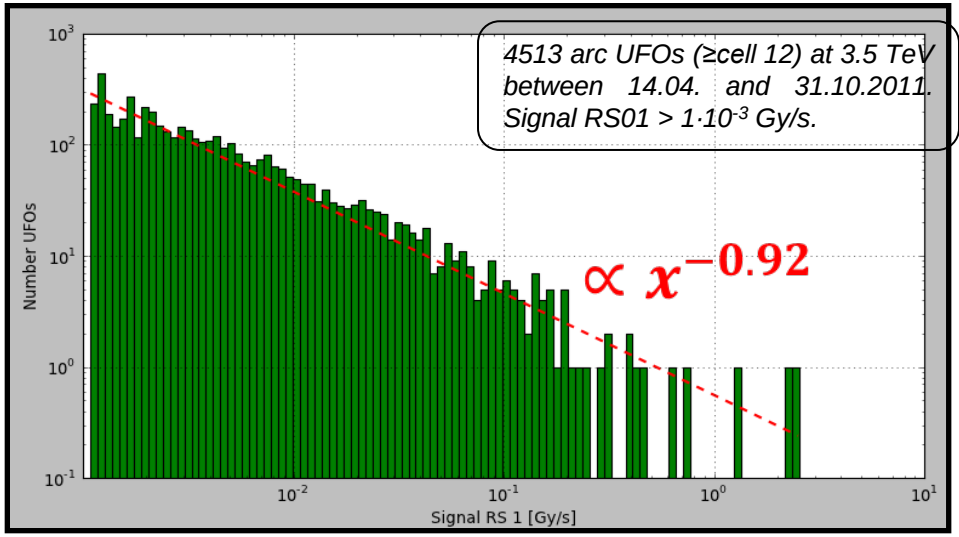
UFOs in the LHC

UFOs in the LHC

T. Baer

- Since July 2010, **35 beam dumps** due to (***U***n)identified ***F***alling ***O***bjects (17 in 2011).
  - *Loss duration: about 10 turns.*
  - *Often unconventional loss locations (e.g. in the arc).*
- In 2011: **16,000 candidate UFOs** below BLM dump thresholds found.
- $\frac{1}{x}$ **distribution** of BLM signal is well explained by **dust particle size distribution** measured in SM12. *(T. Baer et al., Evian Workshop 2011)*





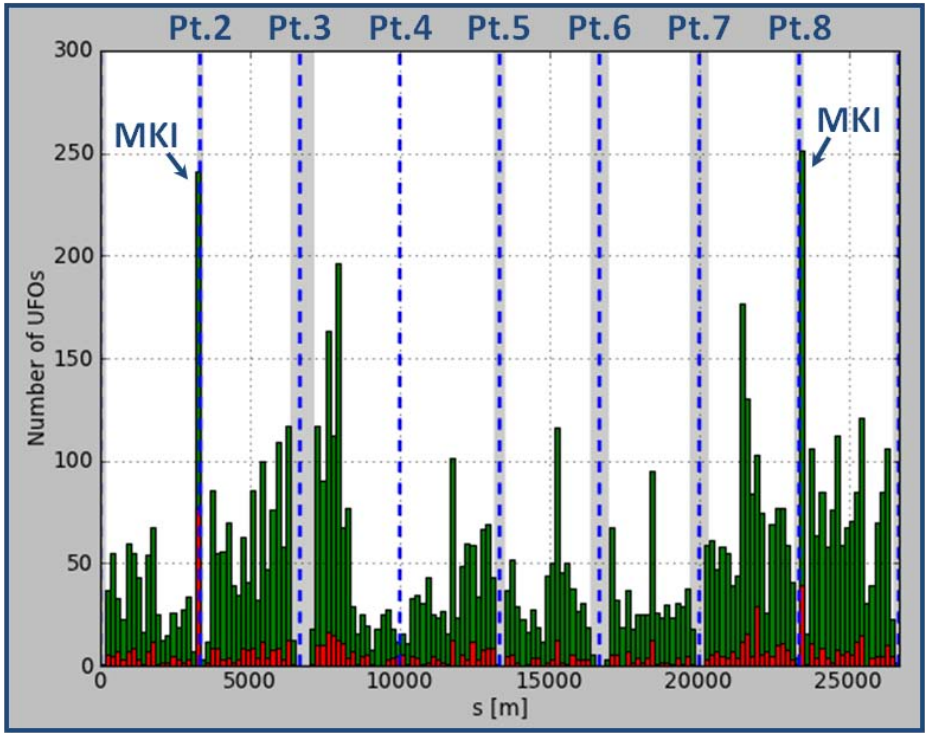
Spatial UFO Distribution

T. Baer

- UFOs occur all around the LHC
- **Many UFOs around injection kickers (MKIs)**
- Some arc cells with significantly increased number of UFOs:

  25R3 B2: 144 UFOs
  19R3 B1: 126 UFOs.
  28R7 B2: 118 UFOs.

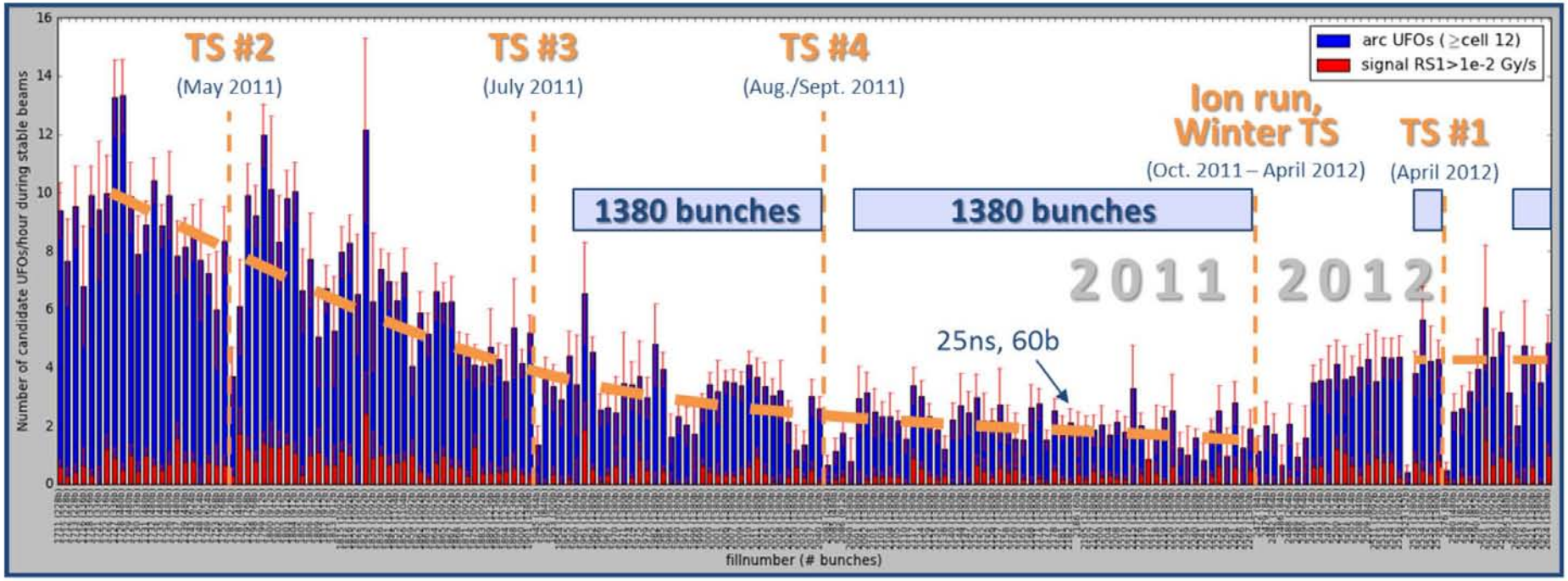
- *No correlation with sector 34 repairs has been identified.*



7784 UFOs at 3.5 TeV between 14.04. and 31.10.2011.
Signal RS04 > $2 \cdot 10^{-4}$ Gy/s.
Red: Signal RS01 > $1 \cdot 10^{-2}$ Gy/s.
Gray areas around IRs are excluded from UFO detection.

UFO rate 2011-2012

T. Baer



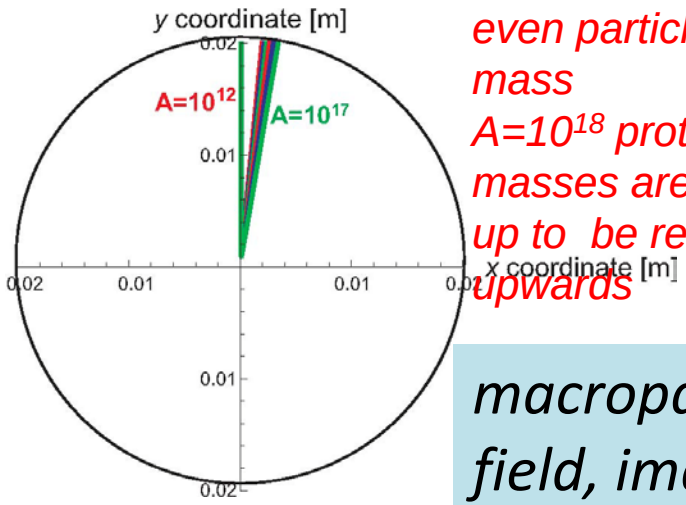
The rate of **5957 arc UFO events** during stable beam operation at top energy (stable beams) for all proton fills with at least one hour of stable beams between April 2011 and May 2012. During 2011, the rate decreased from about 10 events per hour to about 2 events per hour. The rate is reduced during the low intensity fills directly after the technical stops (TS).

UFOs: “dust” particles falling into the LHC beam?

round Al object: $A=10^{14} \rightarrow R \sim 2.5\ \mu m$, $A=10^{16} \rightarrow R \sim 11\ \mu m$

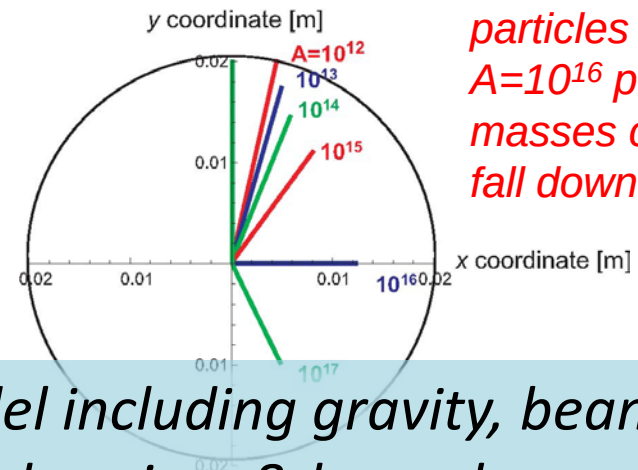
trajectory in x-y space

design beam current, $N_{tot}=3.2\times10^{14}$



even particles of mass $A=10^{18}$ proton masses are charging up to be repelled upwards

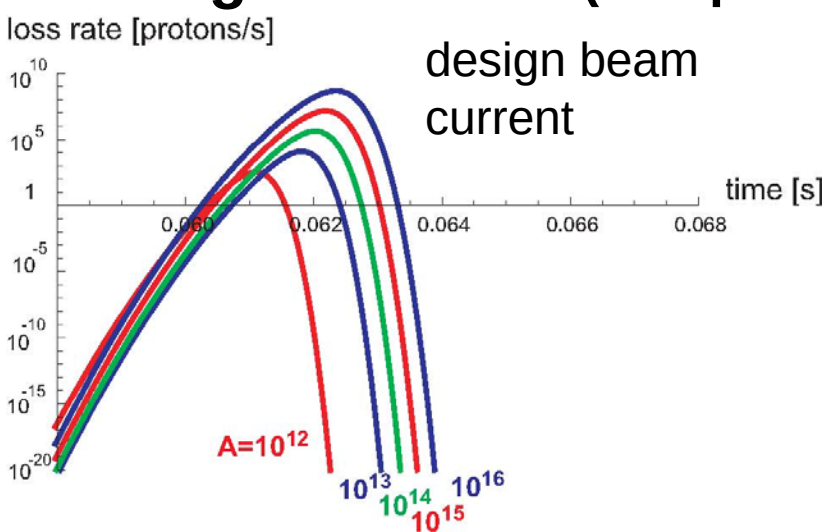
present beam current, $N_{tot}=2.3\times10^{12}$



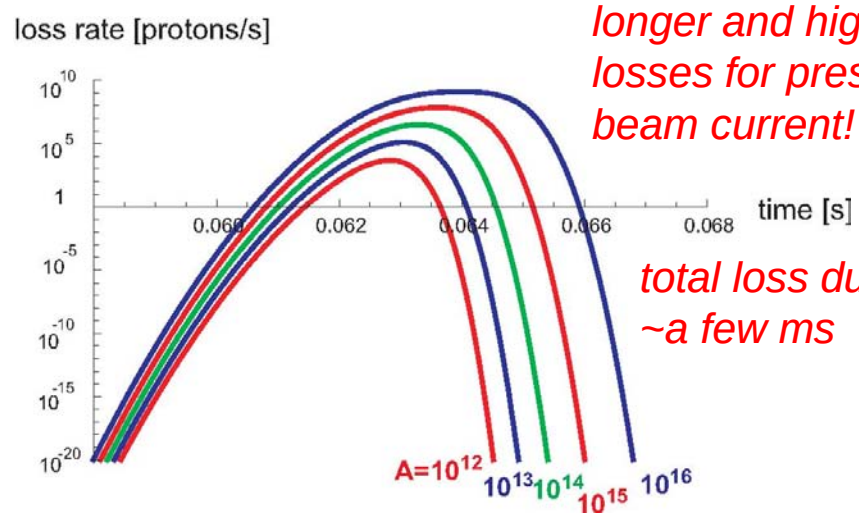
particles heavier than $A=10^{16}$ proton masses continue to fall down

macroparticle model including gravity, beam electric field, image force, charging, & beam loss

resulting loss rates (compare with quench threshold ~a few 10^7 p/s)



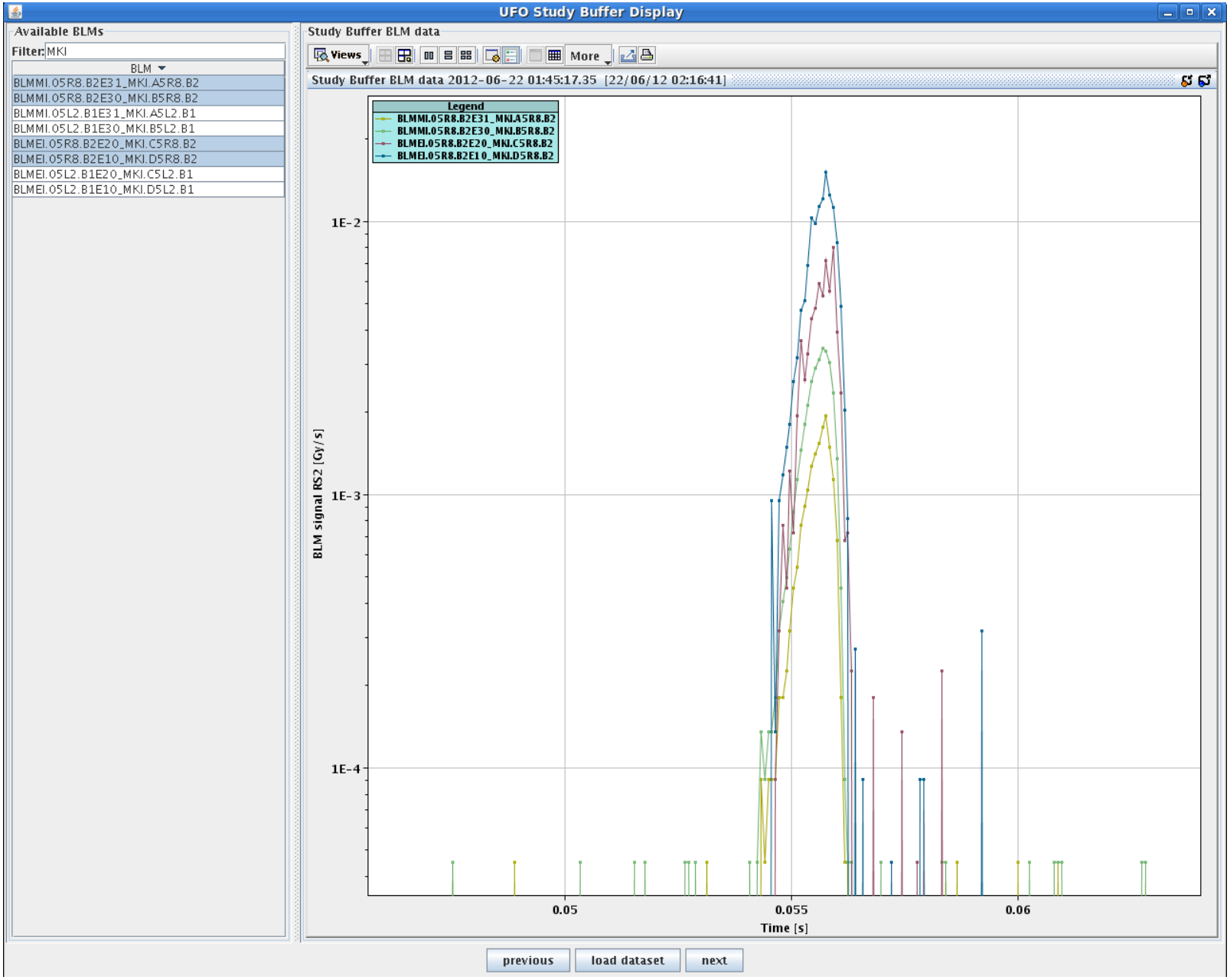
design beam current



longer and higher losses for present beam current!

total loss duratio ~a few ms

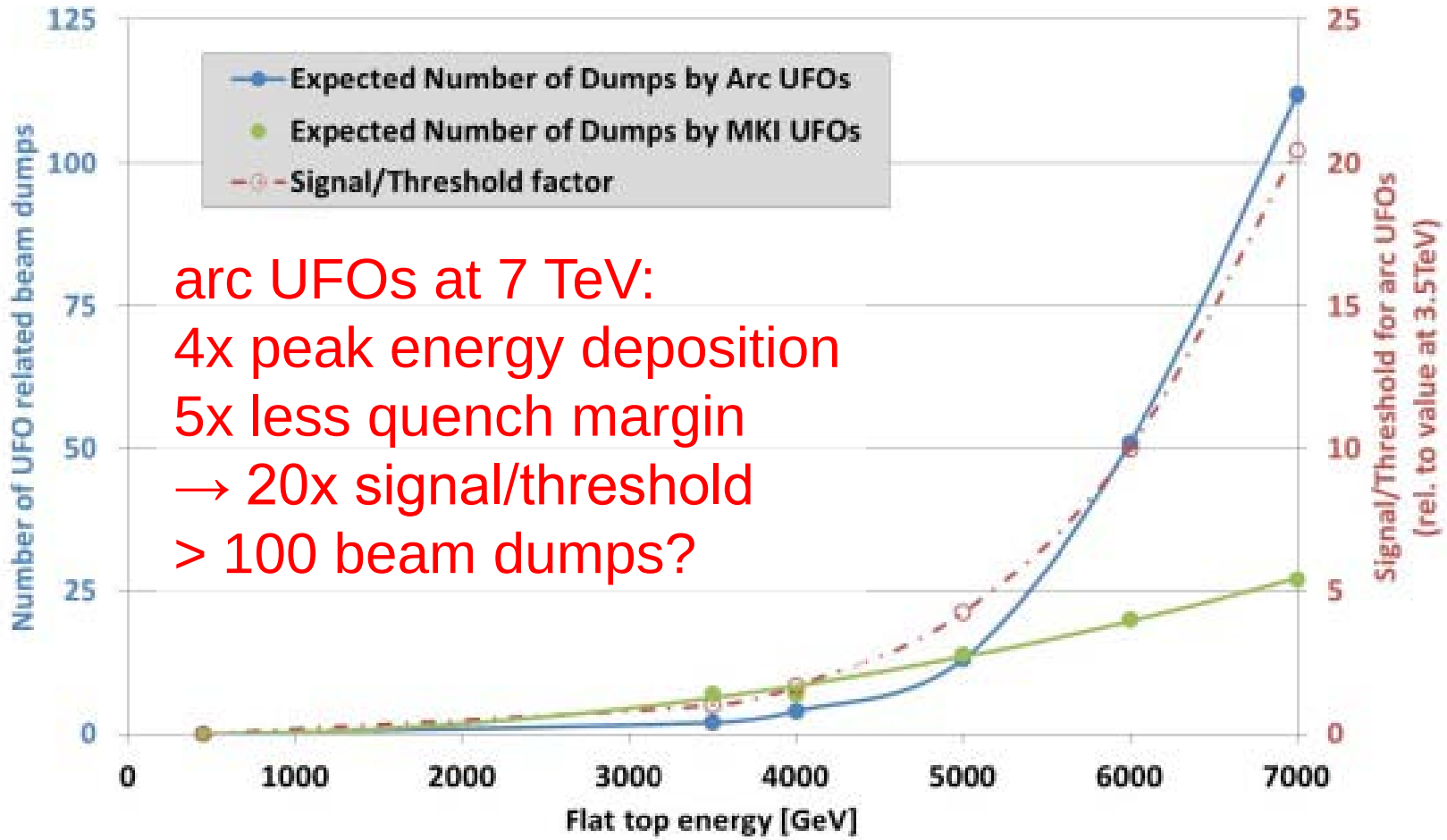
asymmetric UFO shape indeed observed



T. Baer

UFO - Extrapolation to 7 TeV

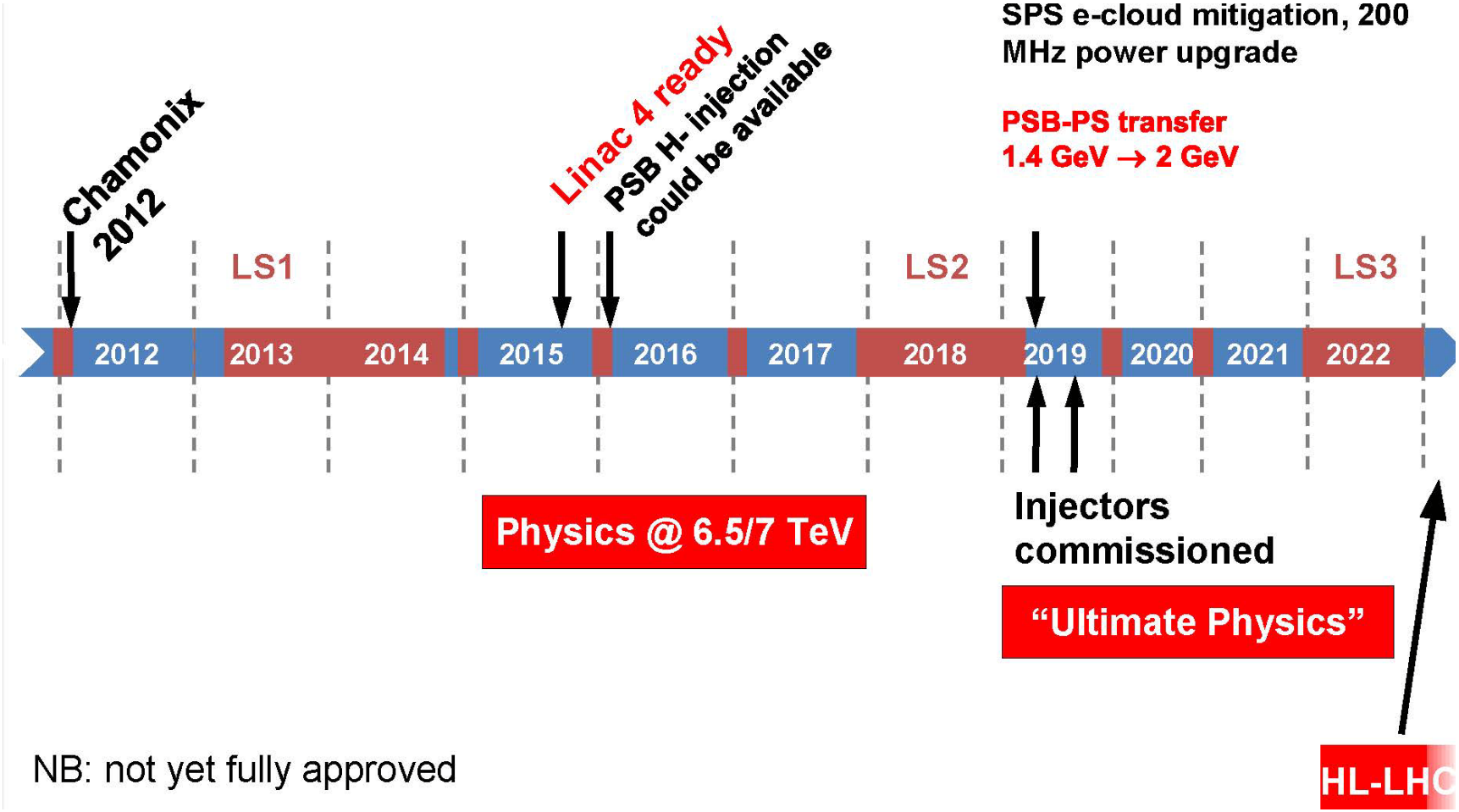
T. Baer



Expected number of UFO related beam dumps and the expected scaling of arc BLM signal/threshold with energy

LHC – next years

LHC time line



NB: not yet fully approved

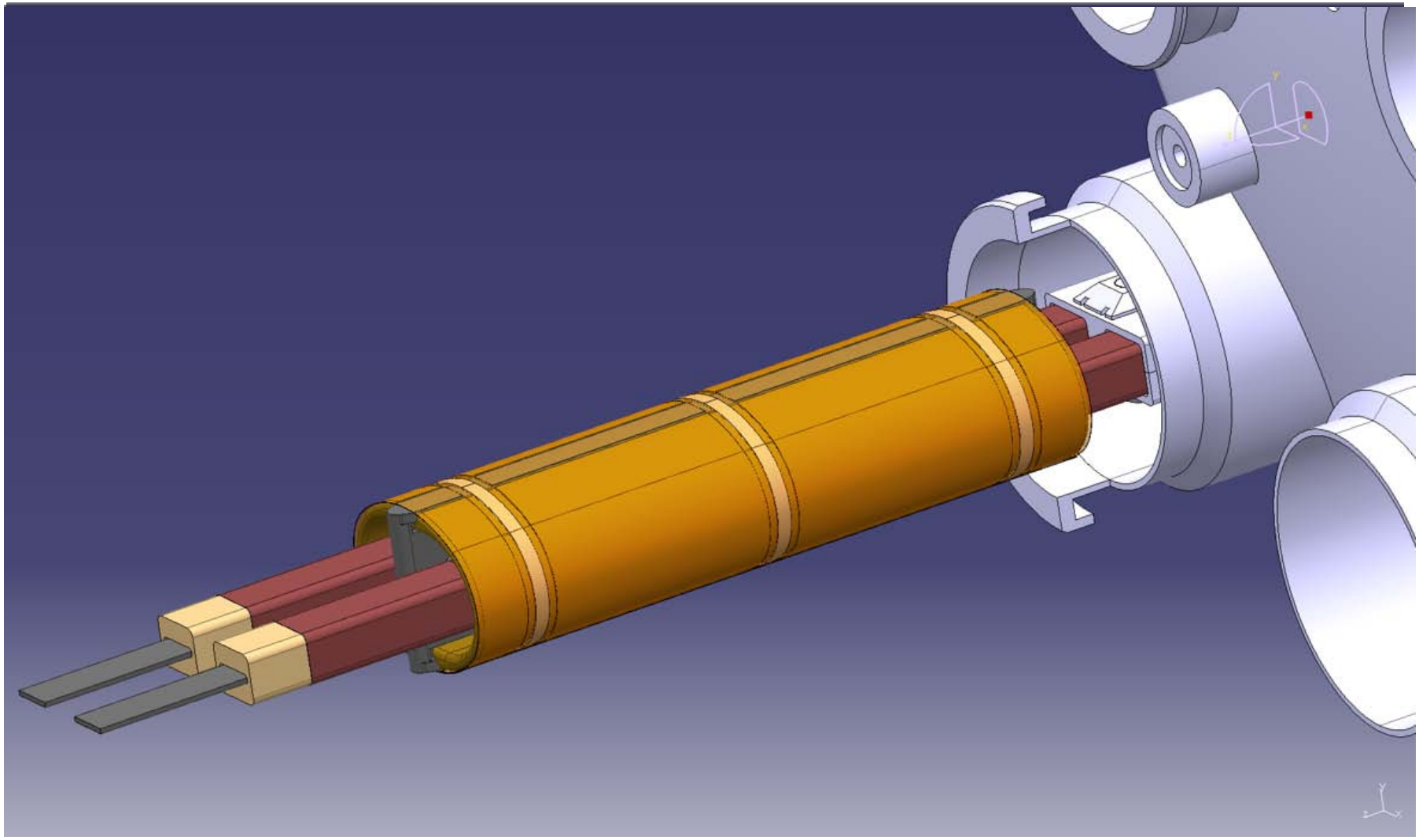
Ralph Steimhagen, CHEP2012

Long Shutdown 1 (LS1): 2013 to end ’14; afterwards operation around 7TeV/beam

LS1 Work

- **repair defect interconnects**
- **consolidate all interconnects with new design**
- complete installation of pressure release valves
- bring all necessary equipment up to the level needed for 7TeV/beam

LHC MB circuit splice consolidation proposal

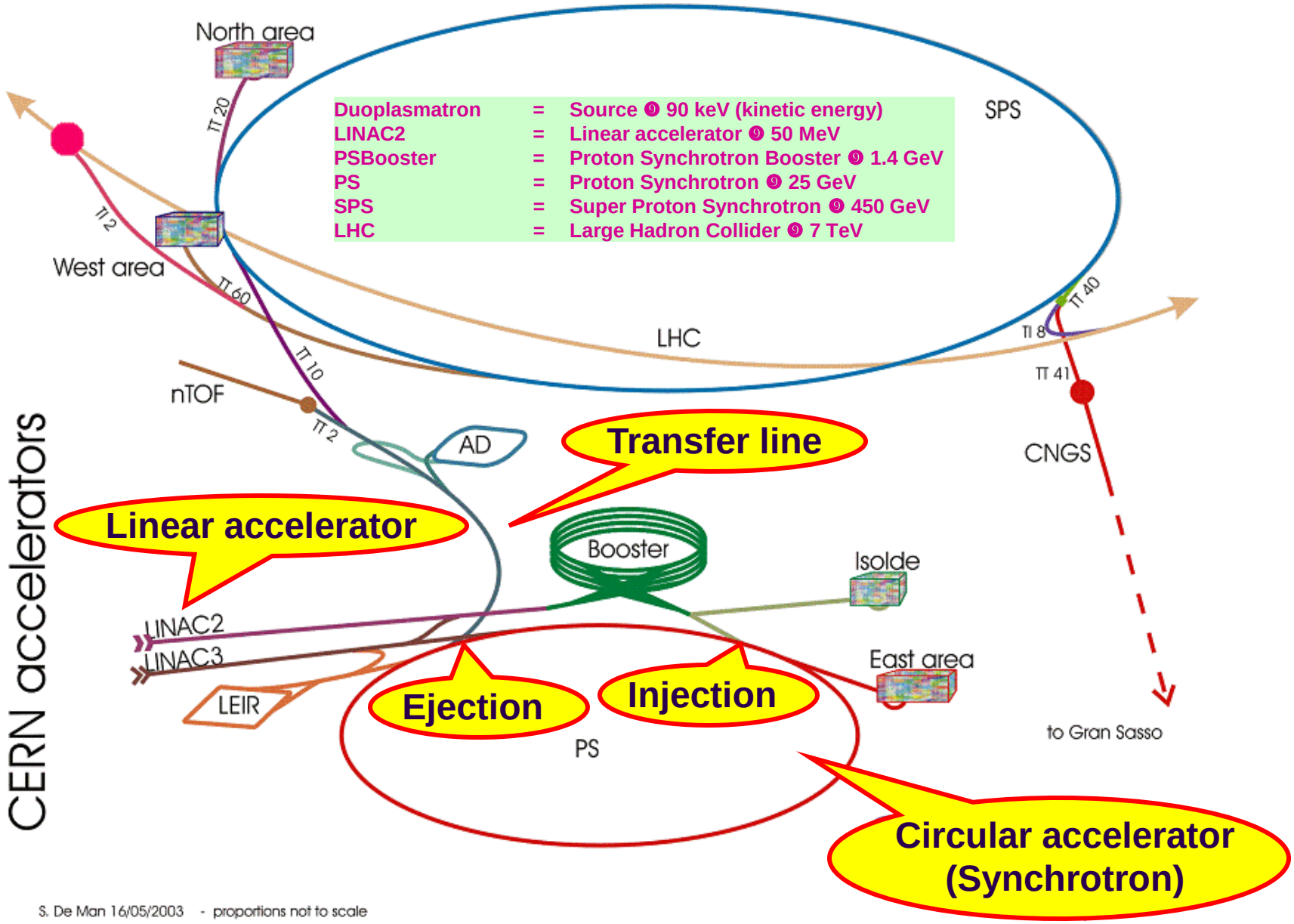


Phase III
Insulation between bus bar and to ground, Lorentz force clamping

Long Shutdown 2 (LS2): 2018; afterwards operation w higher brightness

LS2 Work (mainly)

- **connect new Linac4 to PSB**
  (50→160 GeV)
- **set up H- injection into PSB**
- **increase extraction energy of PSB**
  (1.4→2 GeV)
- SPS anti e-cloud coatings (?)
- PS & SPS RF improvements
- …



LHC and its injector chain

25 ns vs. 50 ns Bunch 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

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

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

intermediate injector improvements
(2012, 2015)

SPS “Q20” optics

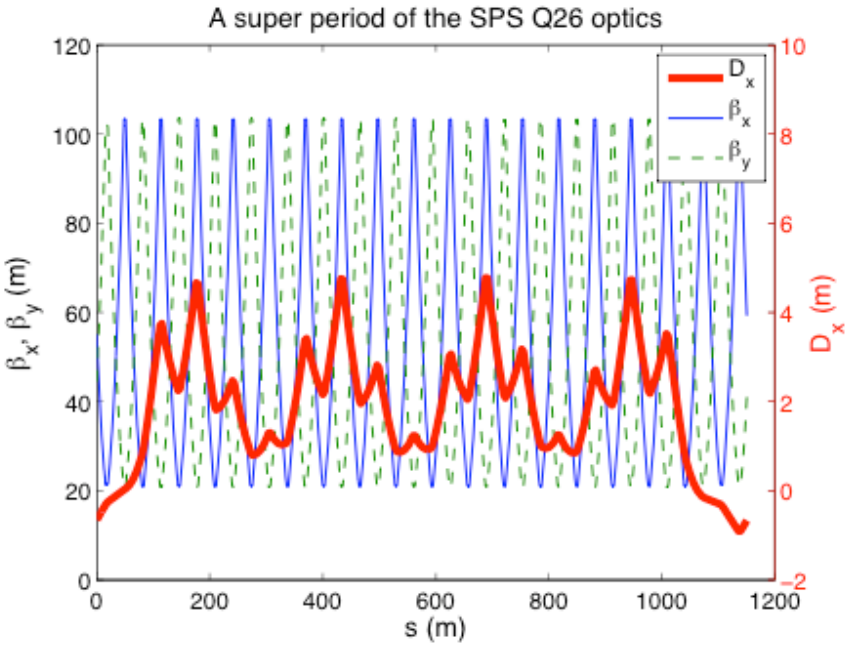
- increases bunch intensity limit up to 3x

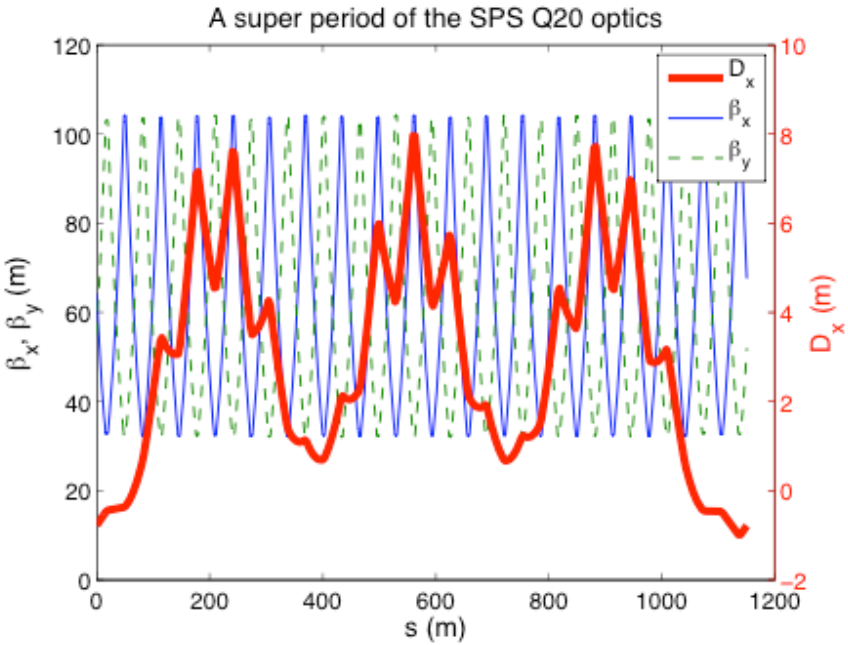
batch compression in the PS

- 30-50% gain in brightness

New SPS optics Q26 → Q20

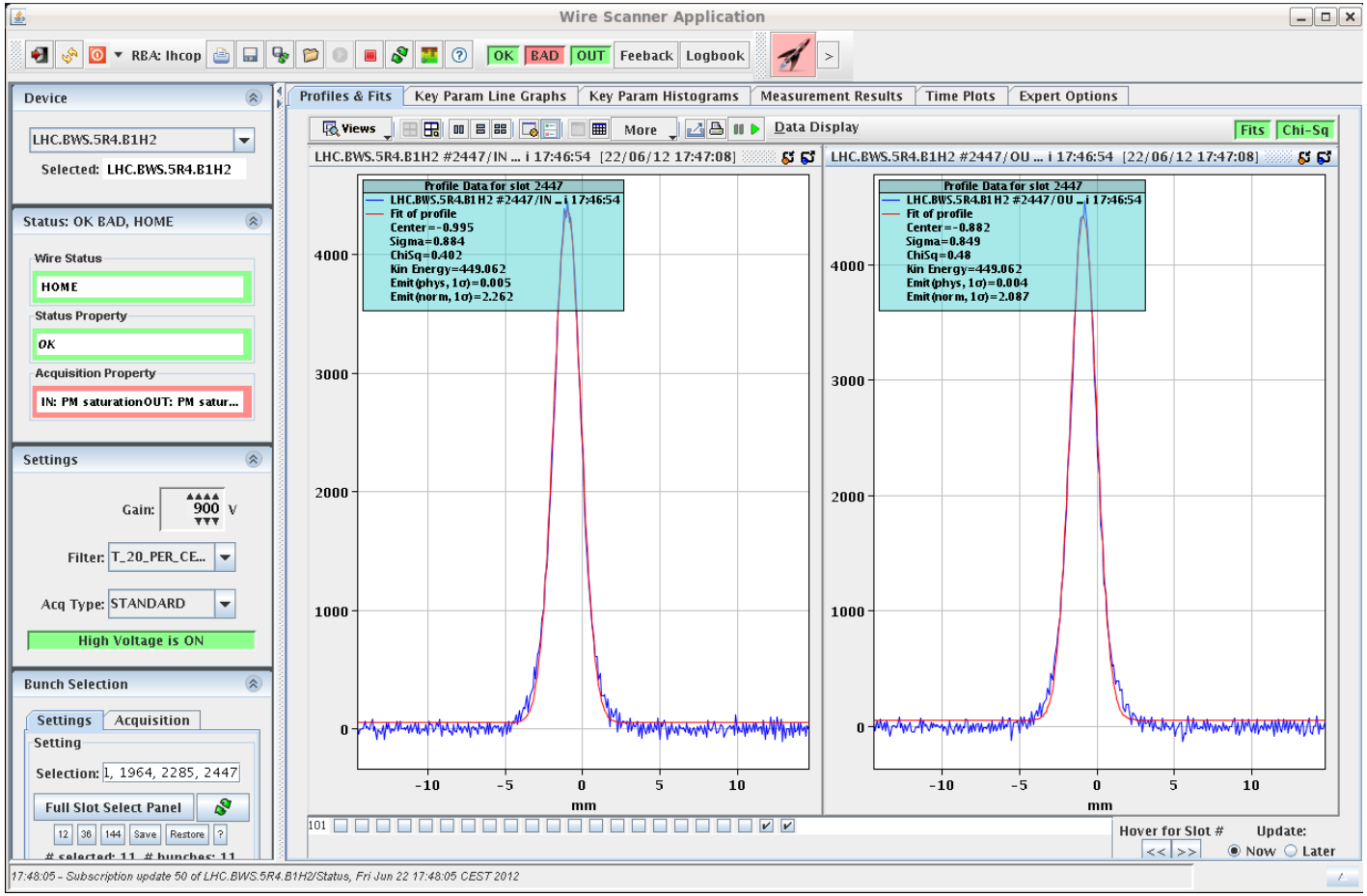
H. Bartosik,
Y. Papaphilippou





- **Low γ_t optics by reducing (integer) tunes**
  - $\eta=(1/\gamma_\tau^2-1/\gamma^2)$ increased by factor 2.85 at injection and 1.6 at top energy by changing γ_t from 22.8 (Q_x~26, nominal optics "Q26 optics") to 18 (Q_x~20 → "Q20 optics")
  - Significantly increased dispersion in the arcs → lower γ_t
  - No increase of maximal β-function values; minima increased from 20m to 30m
- **Dispersion in long straight sections similar to nominal optics**
  - By choosing phase advance of μ~3x2π per arc (instead of μ~4x2π)

SPS Q20 test (June 2012): Emittances of 3e+11 bunch in the LHC



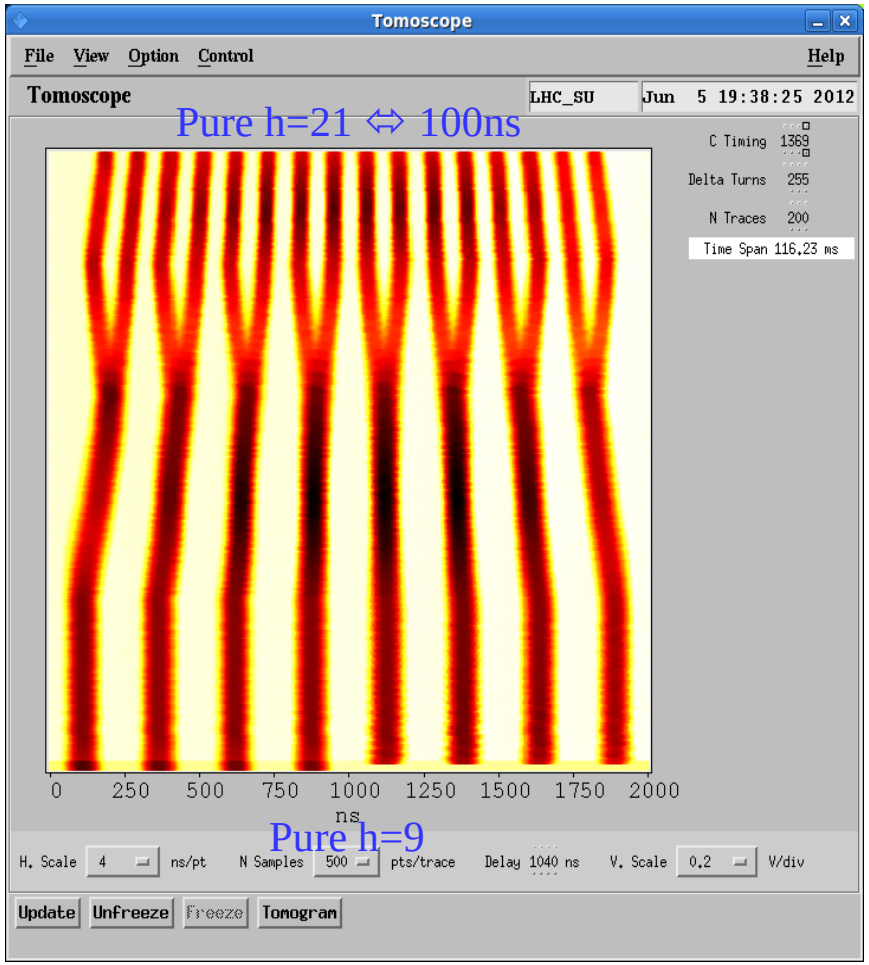
H. Bartosik,
C. Bracco, V. Kain,
Y. Papaphilippou,
et al

ε~2 μm (both planes)

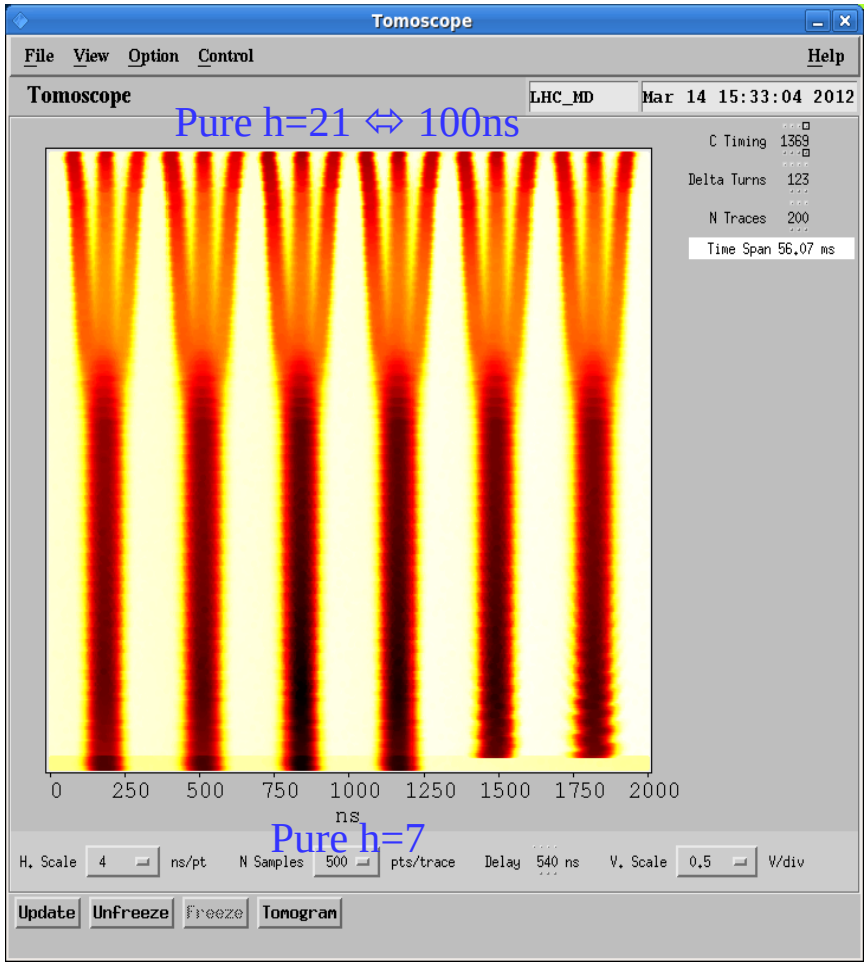
PS Batch Compression v. normal Triple Splitting

Steven Hancock et al

The desired final harmonic is achieved by additive steps (compression) and not just by multiplicative ones (splitting) so less PSB intensity is needed for the same final intensity per bunch.



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

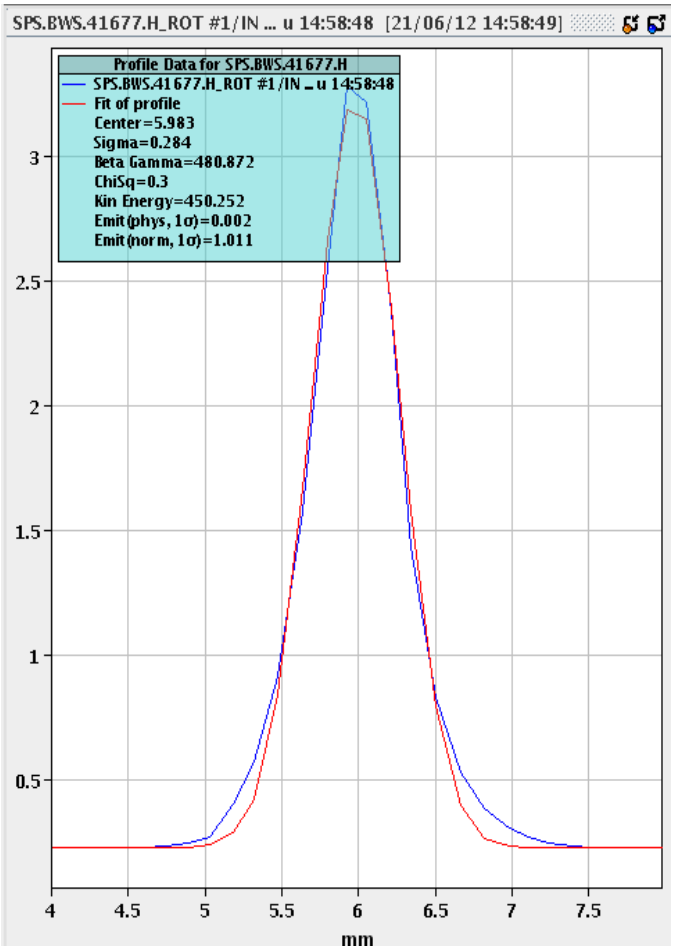


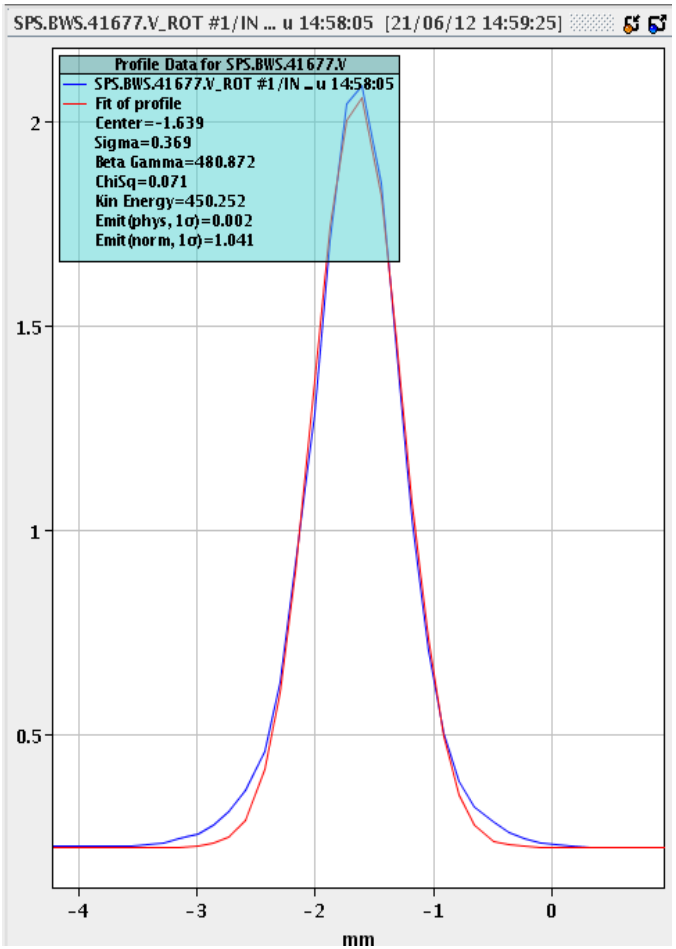
Double batch 4+2b, h=7 → 7+14+21 → 21, 18b

PS Batch Compressed Beam in the SPS

Steven Hancock et al

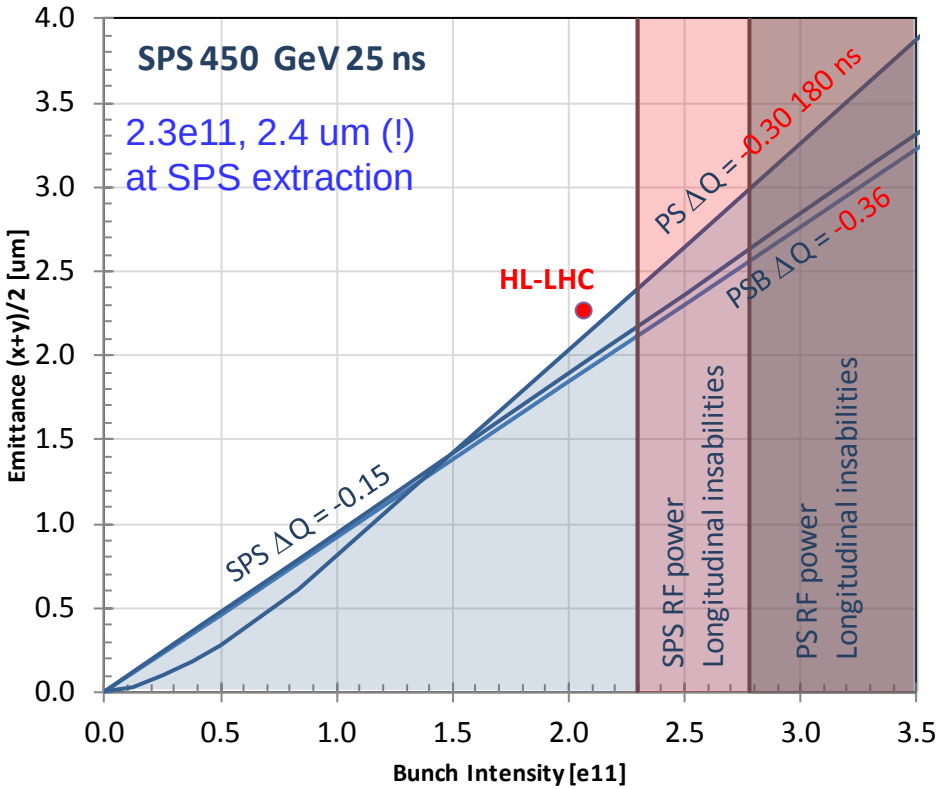
Transverse emittances at SPS exit have been measured at $\varepsilon_H = \varepsilon_V = 1.0\mu m$. Although this was only for 1.2E11ppb and hence represents a 30% gain in brightness rather than the 50% expected on paper, it was nevertheless readily achieved in a single brief parasitic MD.

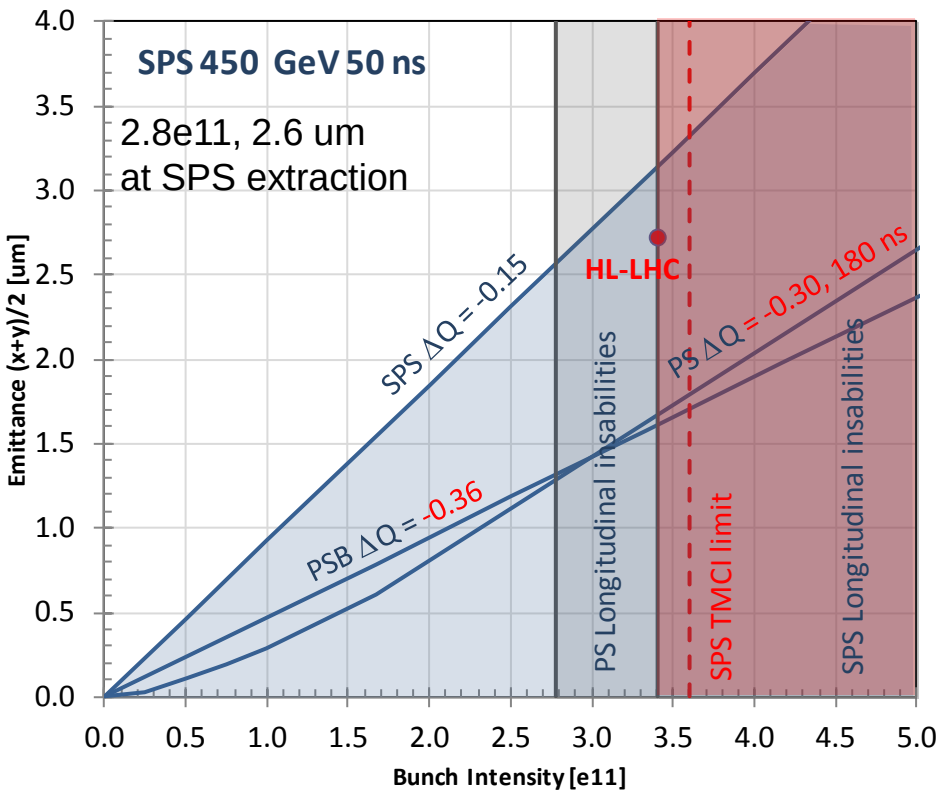




LHC Injectors Upgrade

‘conceivable’ injector improvements after LS2/3 (2018?)



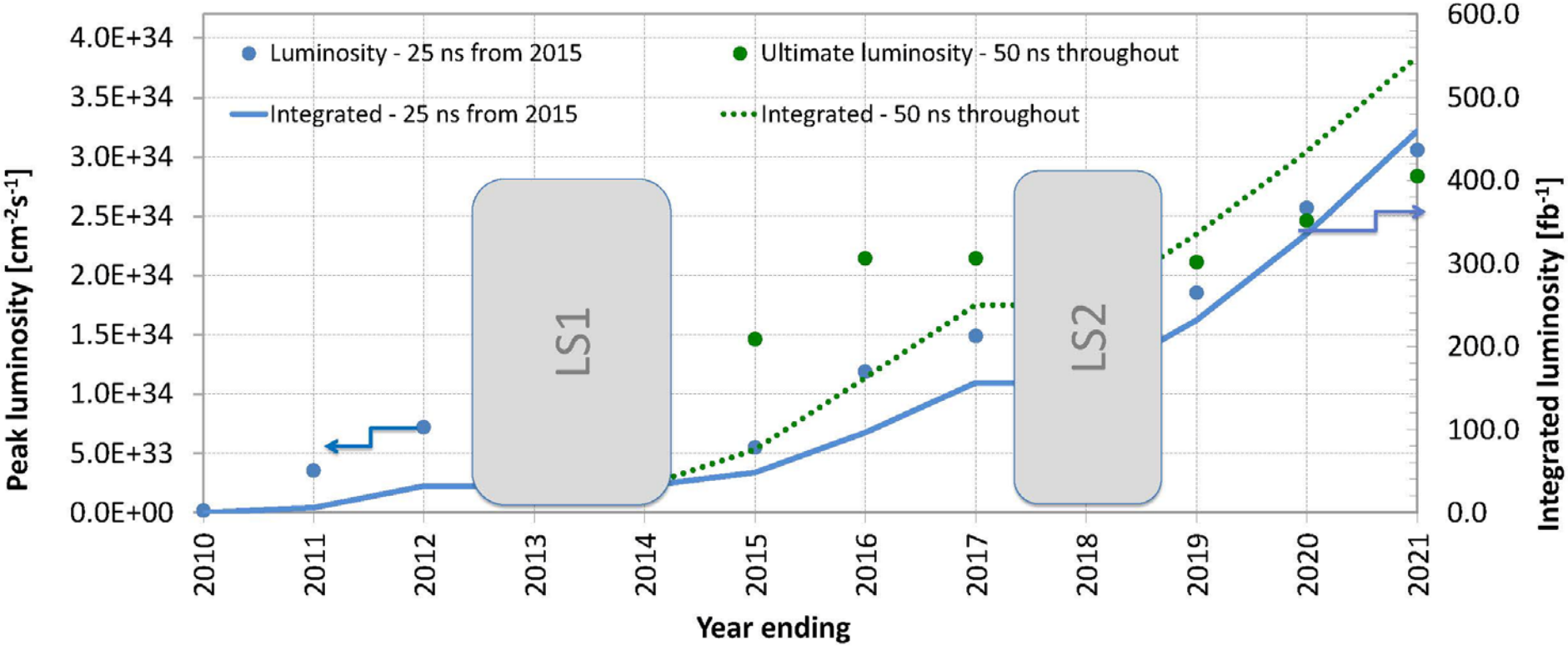


25 ns limited by space charge in PS, PSB. SPS; SPS RF power & SPS longit. instabilities
50 ns limited by PS longitudinal instabilities & SPS space charge, and SPS TMCI

50 ns looks less favorable for the upgraded injectors…

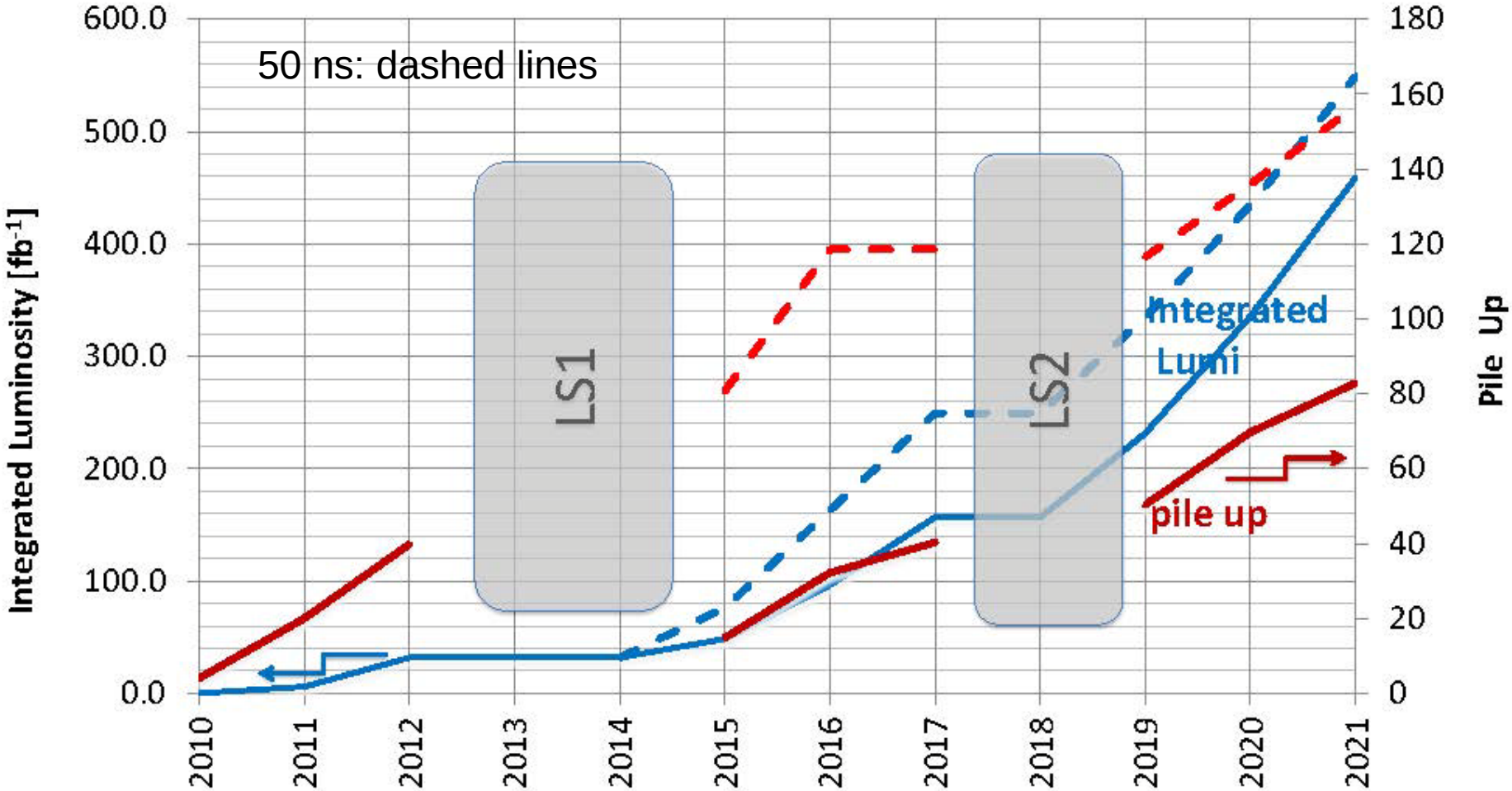
Brennan Goddard, HL-LHC / LIU Joint Workshop (30 March 2012)

(my) forecast to 2021 (25 & 50 ns)



- total integrated luminosity ~500/fb by 2021
- by 2018 ~50% more integrated luminosity with 50 ns
- peak luminosity reaching 2-3x10^{34} $cm^{-2}s^{-1}$
- little gain from LIU for 50 ns spacing ?!

(my) forecast to 2021 (25 & 50 ns)



- pile up high (80-120) in 2015-2017 with 50 ns spacing
  (50-ns pile up >2x more than for 25 ns spacing)

conclusion

switch to 25 ns bunch spacing in 2014/2015

keep 50 ns as backup in case of problems
(electron cloud, total intensity limit,…)

beyond 2021:
LHC upgrades & extensions

High-Luminosity LHC (HL-LHC)

goals:

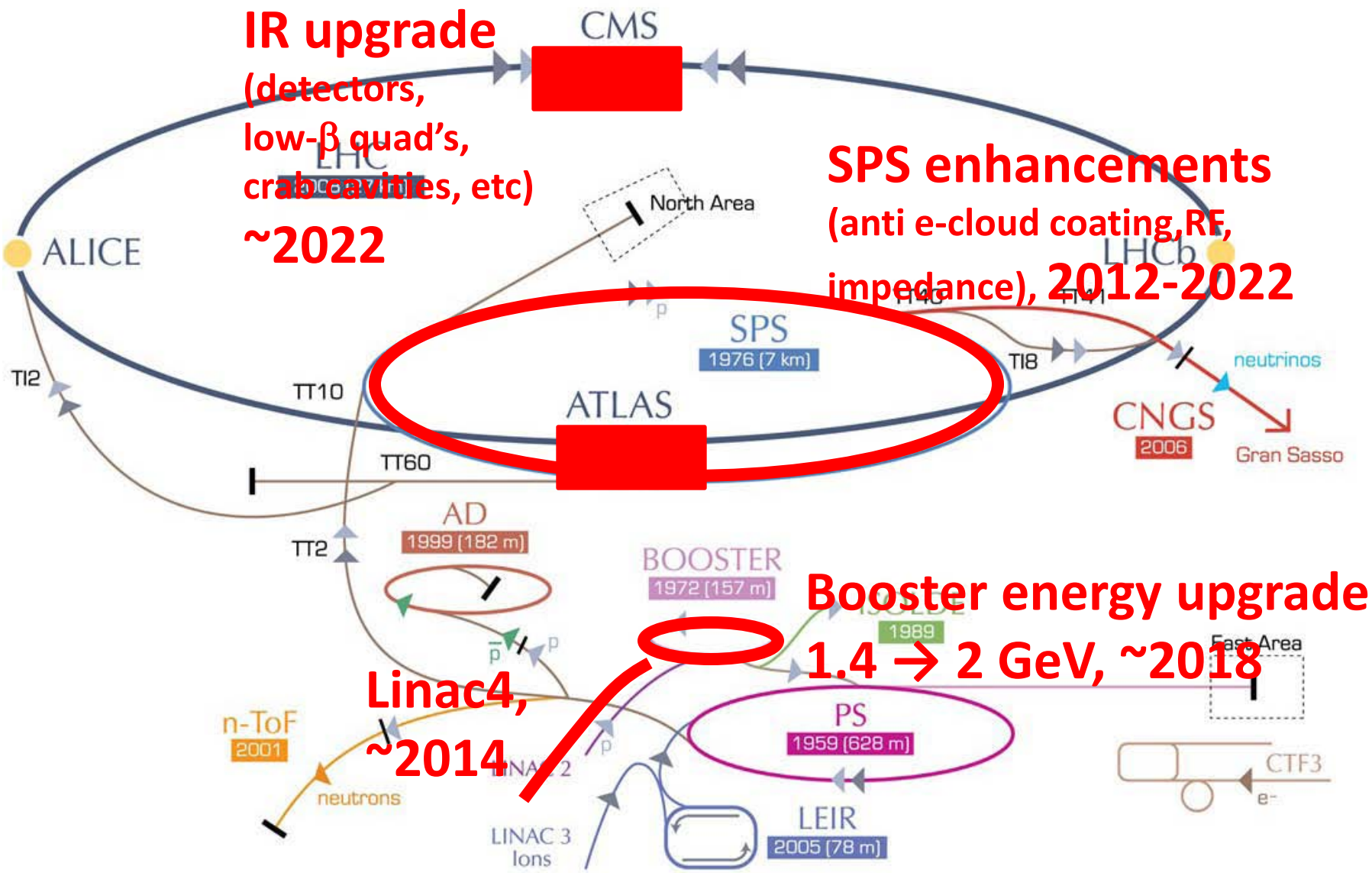
leveled peak luminosity: $L = 5 \times 10^{34}\ cm^{-2}\ s^{-1}$
(detector pile up ~140)

"virtual peak luminosity": $L \geq 20 \times 10^{34}\ cm^{-2}\ s^{-1}$

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

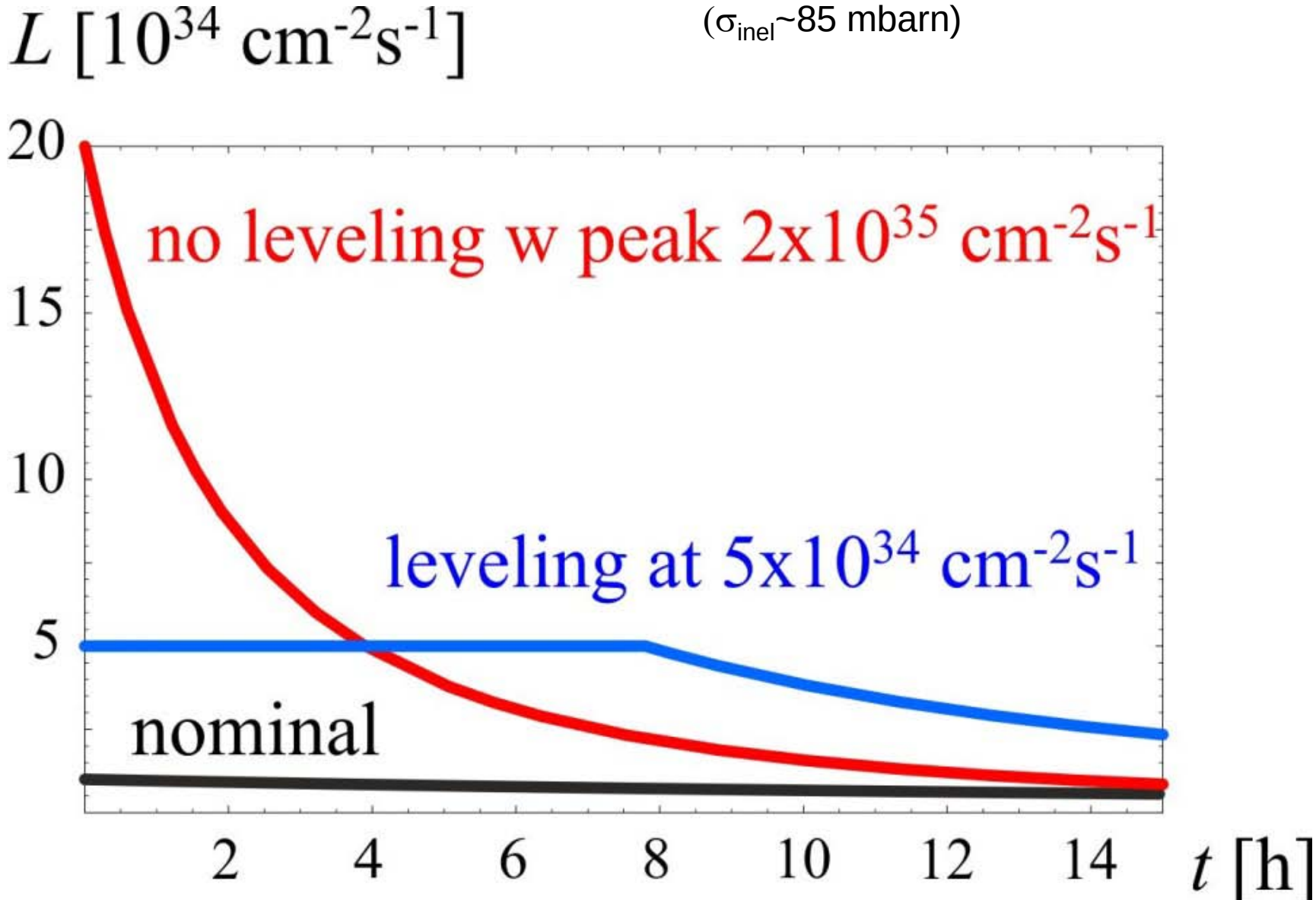
total integrated luminosity: ca. 3000 fb^{-1} by ~2030

HL-LHC – LHC modifications



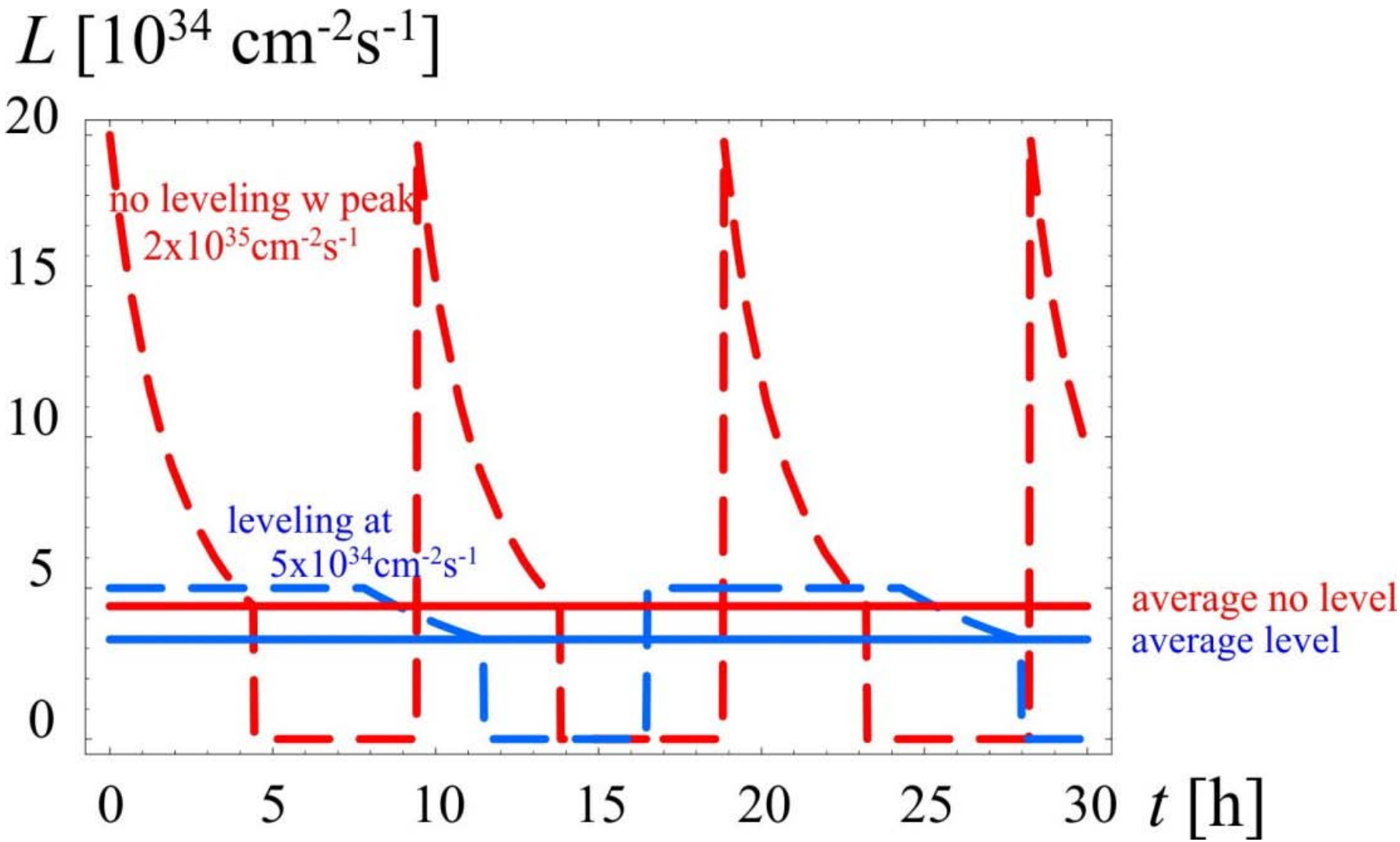
luminosity leveling at the HL-LHC

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



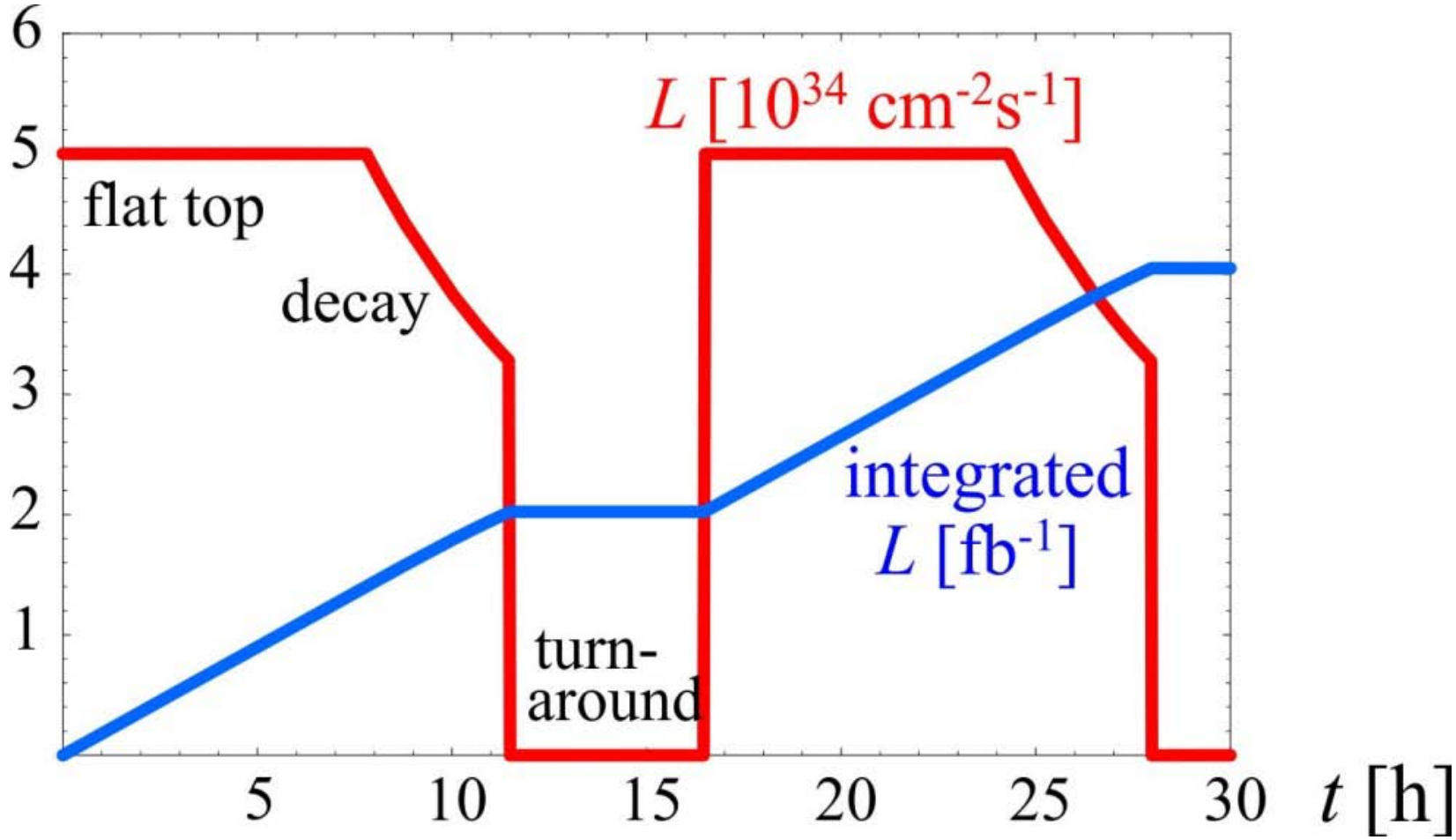
luminosity leveling at the HL-LHC

example: maximum pile up 140



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

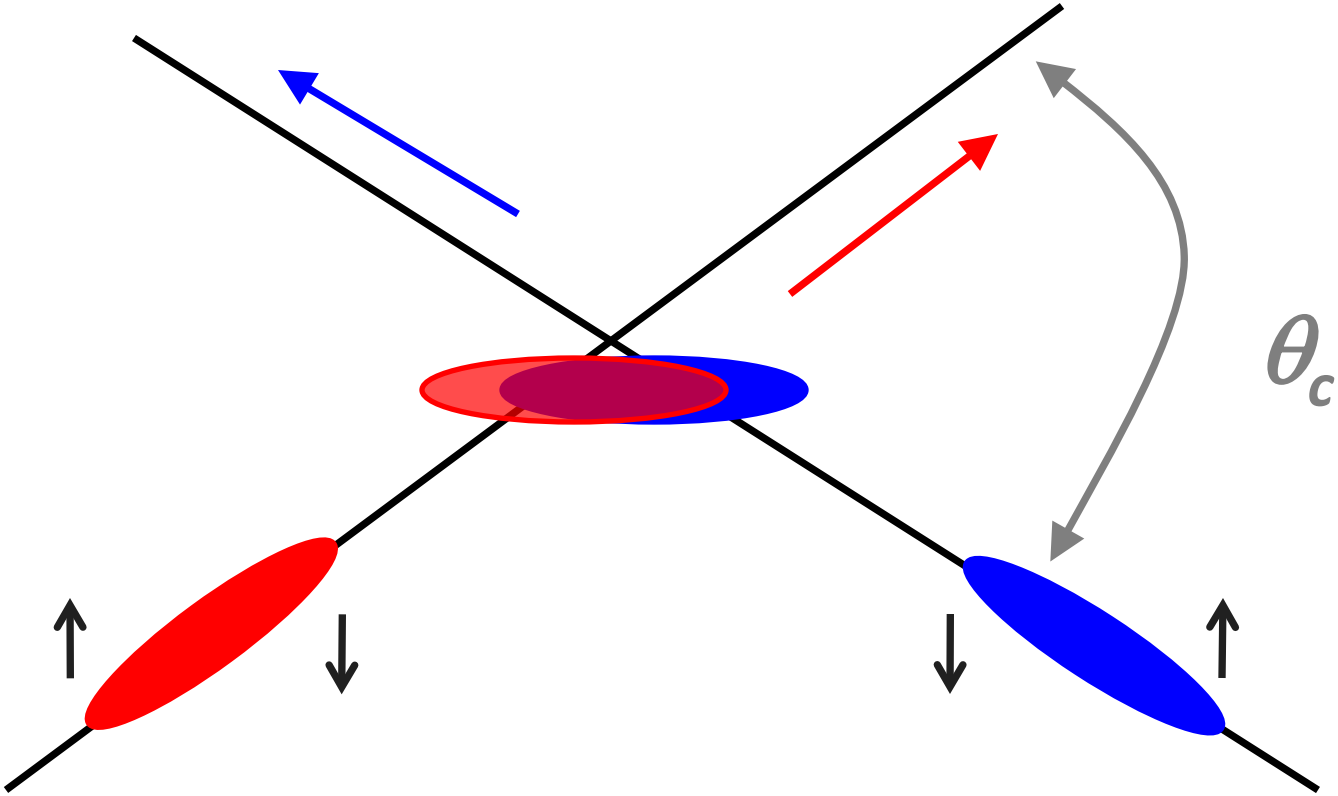
example: maximum pile up 140



HL-LHC parameters

parameter	symbol	nominal	HL-LHC 25 ns	HL-LHC 50 ns
beam energy	E_b [TeV]	7	**7**	**7**
protons per bunch	N_b [10^{11}]	1.15	**2.0**	**3.3**
#bunches per beam	n_b	2808	**1404**	**2808**
beam current	I [A]	0.58	**1.01**	**0.83**
rms bunch length	σ_z [cm]	7.55	**7.55**	**7.55**
beta* at IP1&5	$\beta*$ [m]	0.55	**0.15**	**0.15**
full crossing angle	θ_c [μrad]	285 (9.5σ)	**590 (12.5σ)**	**590 (11.4σ)**
normalized emittance	$\gamma\varepsilon$ [μm]	3.75	**2.5**	**3.0**
IBS ε rise time (z, x)	$\tau_{IBS,z/x}$ [h]	57, 103	**24, 17 (ATS)**	**17, 15 (ATS)**
max. total b-b tune shift	ΔQ_{tot}	0.011	**0.013**	**0.017**
potential pk luminosity	L [10^{34} cm^{-2}s^{-1}]	1	**24**	**25**
actual leveled pk luminosity	L_{lev} [10^{34} cm^{-2}s^{-1}]	1	**5**	**2.5**
max. #events / #ing (pile up)		19	**140**	**140**
effective beam lifetime	τ_{eff} [h]	44.9	**15.6**	**25.7**
level time, run time	t_{level} [h], t_{run} [h]	0, 15.2	**7.8, 11.5**	**17.2, 20.1**
needed availability	A [%]	(50)	**59**	**78**
needed efficiency	E [%]	(38)	**41**	**63**
annual integrated luminosity	L_{int}[fb^{-1}]	(37)	**250**	**200**

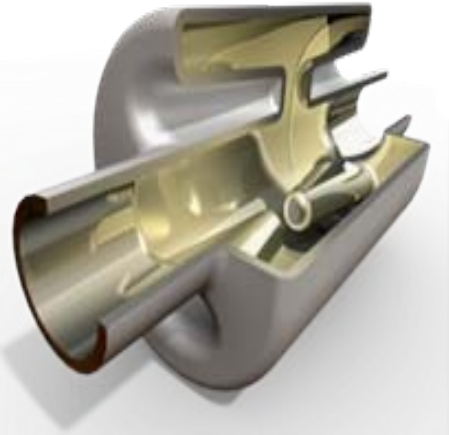
schematic of crab crossing at HL-LHC

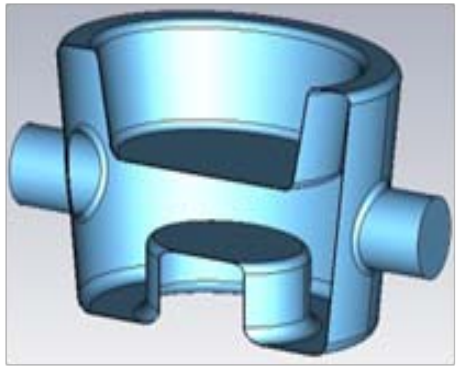


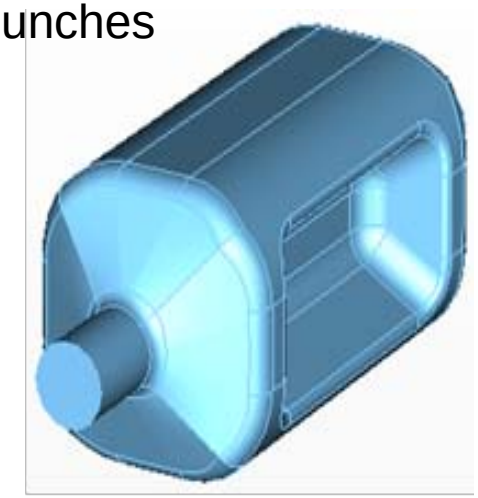
- RF crab cavity deflects head and tail in opposite direction so that collision is effectively “head on” for luminosity and tune shift
- bunch centroids still cross at an angle (easy separation)
- 1st proposed in 1988, in operation at KEKB since 2007

HL-LHC: compact crab cavities

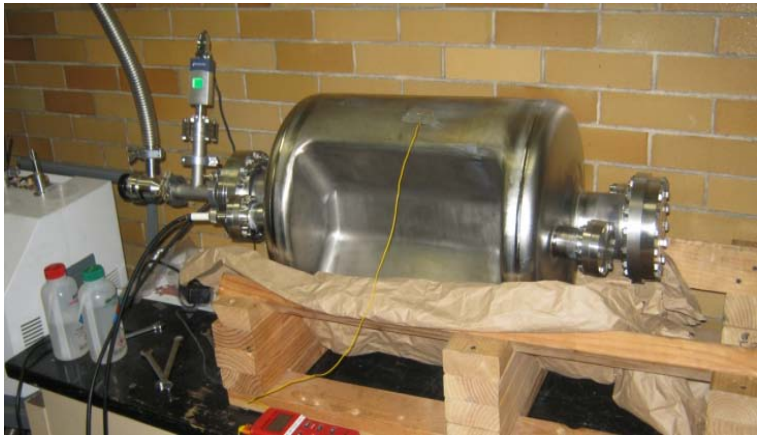
only 19 cm beam separation, but long bunches





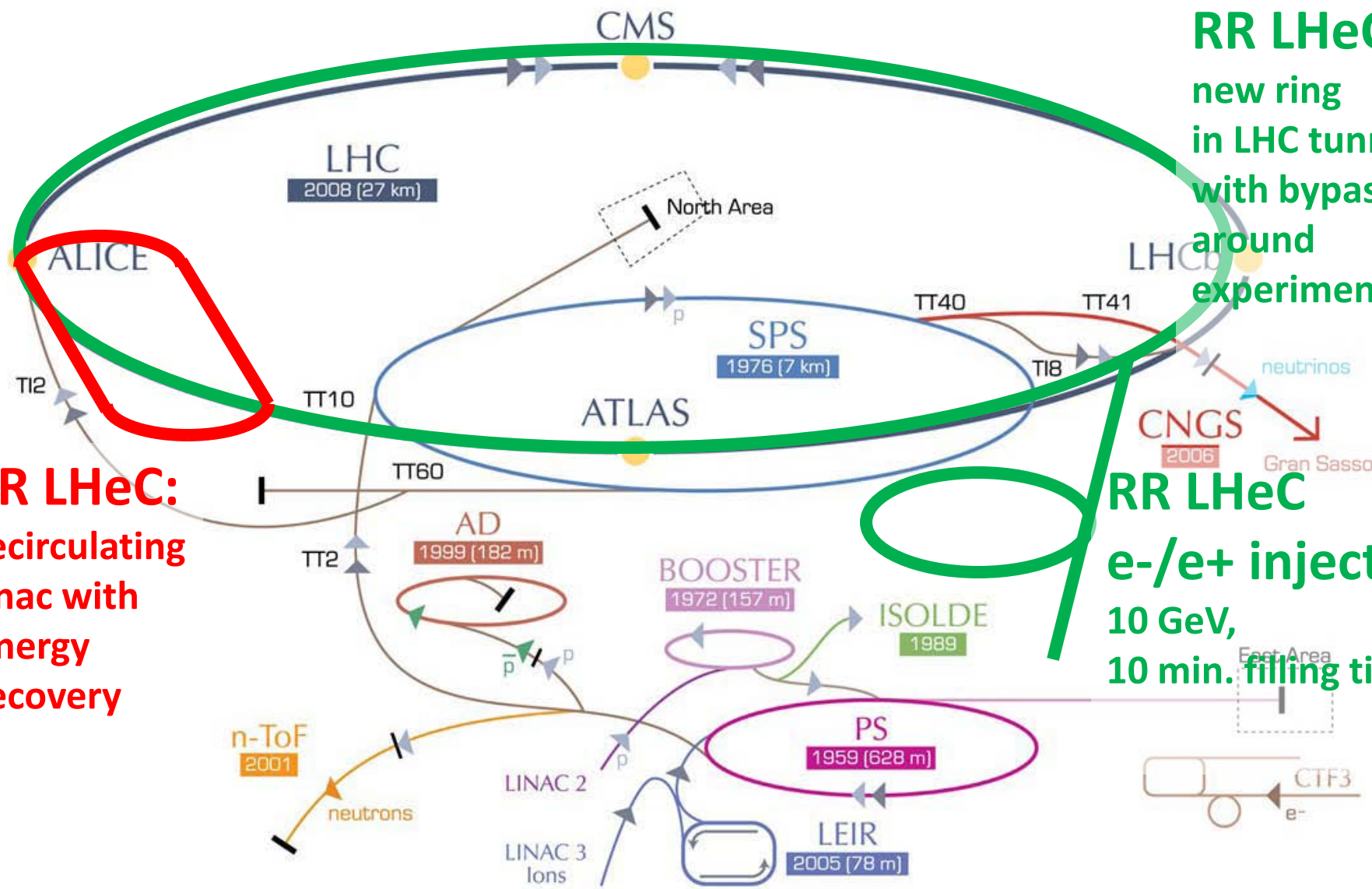


Final down-selected compact cavity designs for the LHC upgrade: 4-rod cavity design by Cockcroft I. & JLAB (left), $\lambda/4$ TEM cavity by BNL (centre), and double-ridge $\lambda/2$ TEM cavity by SLAC & ODU (right).



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

Large Hadron electron Collider



RR LHeC:
new ring
in LHC tunnel,
with bypasses
around
experiments

LR LHeC:
recirculating
linac with
energy
recovery

RR LHeC
e-/e+ injector
10 GeV,
10 min. filling time

LHeC Conceptual Design Report

CERN-OPEN-2012-015
LHeC-Note-2012-001 GEN
Geneva, June 13, 2012

A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group

Submitted to J.Phys. G

The CDR is submitted to the arXiv and to J.Phys.G

http://cern.ch/lhec

LHeC Study Group

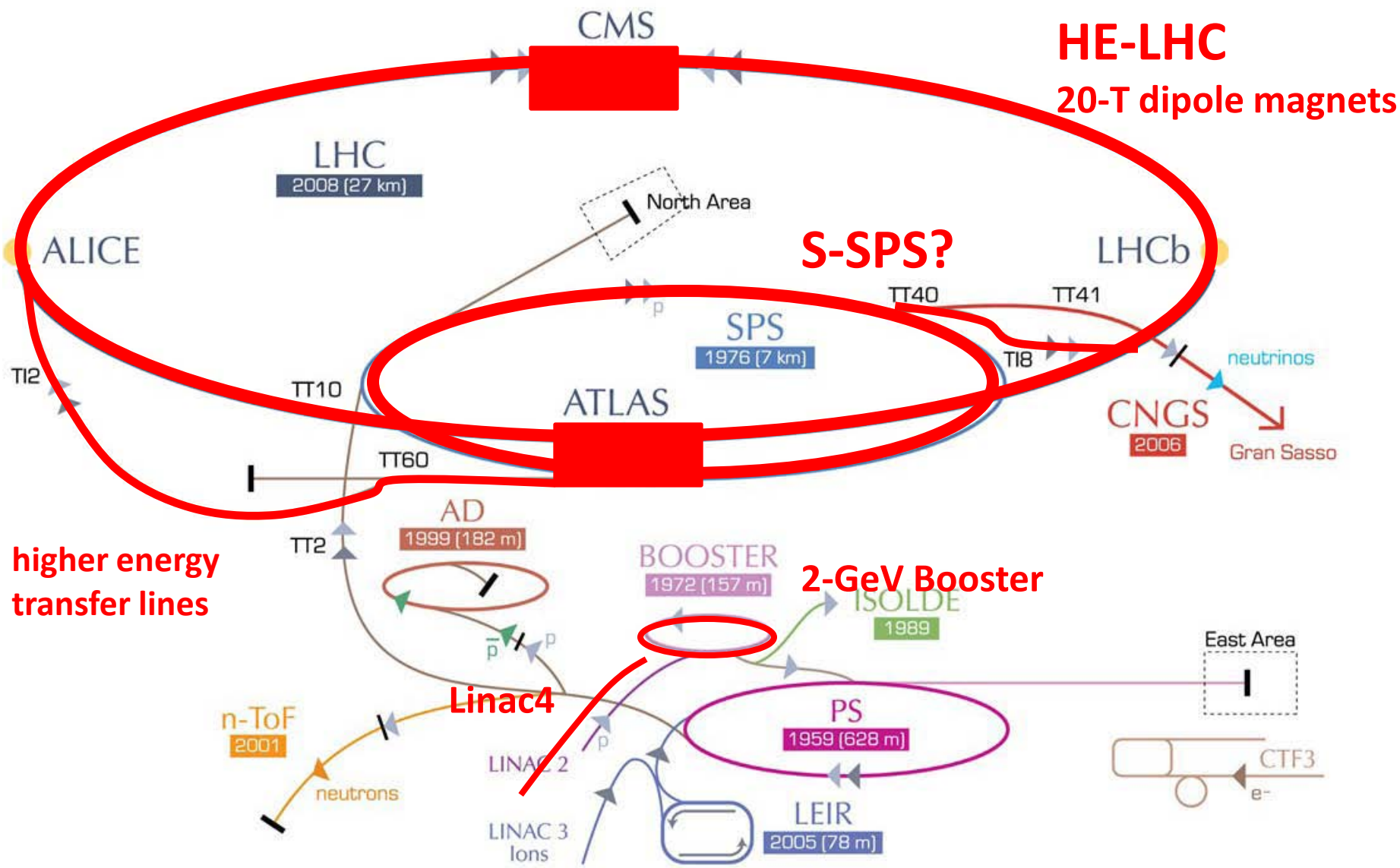
J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], S.Alekhin[17,54], P.Allport[24], V.Andreev[34], R.B.Appleby[14,30], E.Arikan[39], N.Armesto[53,a], G.Azuelos[33,64], M.Bai[37], D.Barber[14,17,24], J.Bartels[18], O.Behnke[17], J.Behr[17], A.S.Belyaev[15,56], I.Ben-Zvi[37], N.Bernard[25], S.Bertolucci[16], S.Bettoni[16], S.Biswal[41], J.Blümlein[17], H.Böttcher[17], A.Bogacz[36], C.Bracco[16], G.Brandt[44], H.Braun[65], S.Brodsky[57,b], O.Brüning[16], E.Bulyak[12], A.Buniatyan[17], H.Burkhardt[16], I.T.Cakir[02], O.Cakir[01], R.Calaga[16], V.Cetinkaya[01], E.Ciapala[16], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[38], J.C.Collins[48], O.Dadoun[42], J.Dainton[24], A.De.Roeck[16], D.d'Enterria[16], A.Dudarev[16], A.Eide[60], R.Enberg[63], E.Eroglu[62], K.J.Eskola[21], L.Favart[08], M.Fitterer[16], S.Forte[32], A.Gaddi[16], P.Gambino[59], H.García Morales[16], T.Gehrmann[69], P.Gladkikh[12], C.Glasman[28], R.Godbole[35], B.Goddard[16], T.Greenshaw[24], A.Guffanti[13], V.Guzey[19,36], C.Gwenlan[44], T.Han[50], Y.Hao[37], F.Haug[16], W.Herr[16], A.Hervé[27], B.J.Holzer[16], M.Ishitsuka[58], M.Jacquet[42], B.Jeanneret[16], J.M.Jimenez[16], J.M.Jowett[16], H.Jung[17], H.Karadeniz[02], D.Kayran[37], A.Kilic[62], K.Kimura[58], M.Klein[24], U.Klein[24], T.Kluge[24], F.Kocak[62], M.Korostelev[24], A.Kosmicki[16], P.Kostka[17], H.Kowalski[17], G.Kramer[18], D.Kuchler[16], M.Kuze[58], T.Lappi[21,c], P.Laycock[24], E.Levichev[40], S.Levonian[17], V.N.Litvinenko[37], A.Lombardi[16], J.Maeda[58], C.Marquet[16], B.Mellado[27], K.H.Mess[16], A.Milanese[16], S.Moch[17], I.I.Morozov[40], Y.Muttoni[16], S.Myers[16], S.Nandi[55], Z.Nergiz[39], P.R.Newman[06], T.Omori[61], J.Osborne[16], E.Paoloni[49], Y.Papaphilippou[16], C.Pascaud[42], H.Paukkunen[53], E.Perez[16], T.Pieloni[23], E.Pilicer[62], B.Pire[45], R.Placakyte[17], A.Polini[07], V.Ptitsyn[37], Y.Pupkov[40], V.Radescu[17], S.Raychaudhuri[35], L.Rinolfi[16], R.Rohini[35], J.Rojo[16,31], S.Russenschuck[16], M.Sahin[03], C.A.Salgado[53,a], K.Sampei[58], R.Sassot[09], E.Sauvan[04], U.Schneekloth[17], T.Schörner-Sadenius[17], D.Schulte[16], A.Senol[22], A.Seryi[44], P.Sievers[16], A.N.Skrinsky[40], W.Smith[27], H.Spiesberger[29], A.M.Stasto[48,d], M.Strikman[48], M.Sullivan[57], S.Sultansoy[03,e], Y.P.Sun[57], B.Surrow[11], L.Szymanowski[66,f], P.Taels[05], I.Tapan[62], T.Tasci[22], E.Tassi[10], H.Ten.Kate[16], J.Terron[28], H.Thiesen[16], L.Thompson[14,30], K.Tokushuku[61], R.Tomás García[16], D.Tommasini[16], D.Trbojevic[37], N.Tsoupas[37], J.Tuckmantel[16], S.Turkoz[01], T.N.Trinh[47], K.Tywoniuk[26], G.Unel[20], J.Urakawa[61], P.VanMechelen[05], A.Variola[52], R.Veness[16], A.Vivoli[16], P.Vobly[40], J.Wagner[66], R.Wallny[68], S.Wallon[43,46,f], G.Watt[16], C.Weiss[36], U.A.Wiedemann[16], U.Wienands[57], F.Willeke[37], B.-W.Xiao[48], V.Yakimenko[37], A.F.Zarnecki[67], Z.Zhang[42], F.Zimmermann[16], R.Zlebcik[51], F.Zomer[42]

193 Experimentalists and Theorists from 69 Institutes

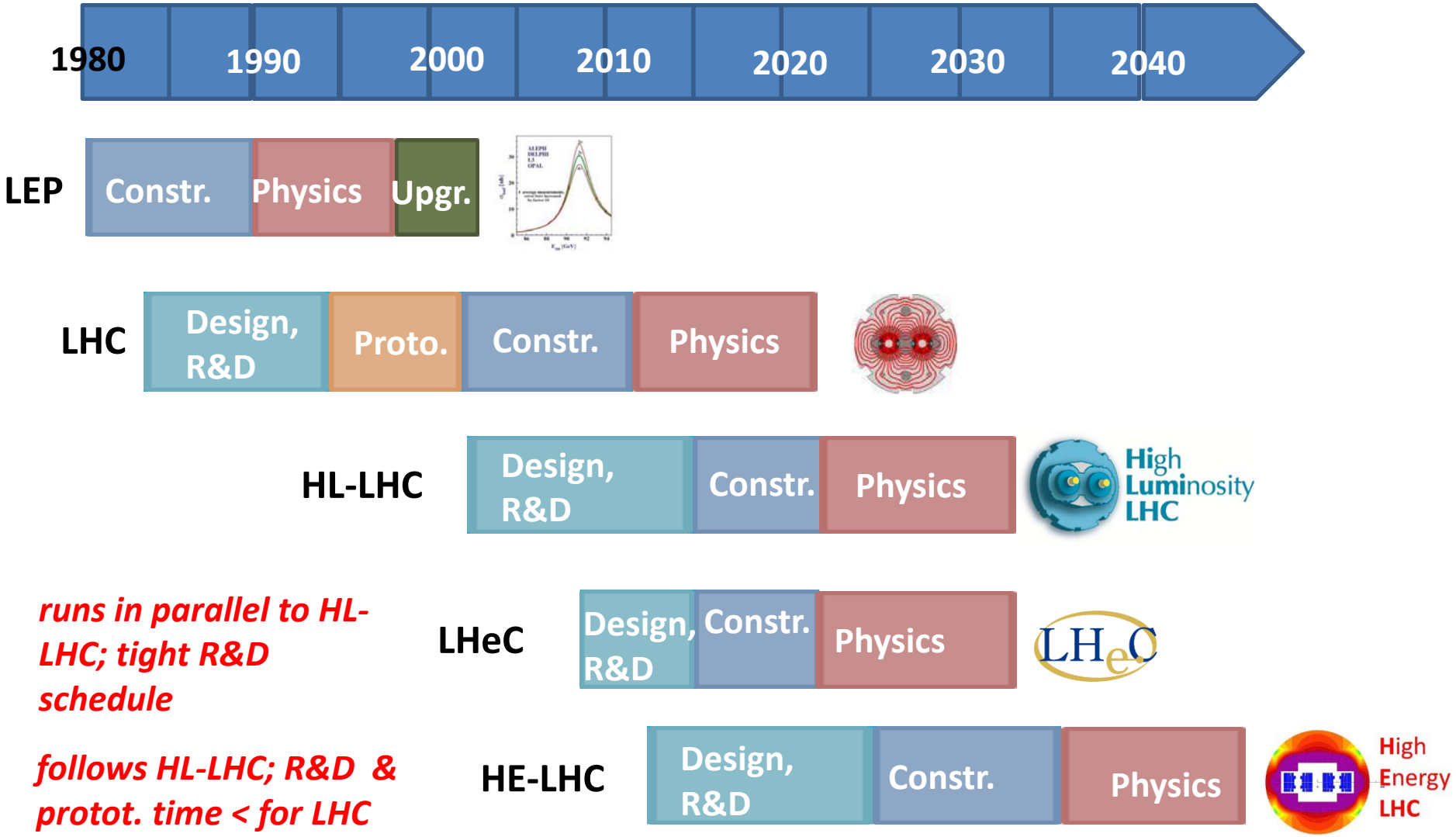
Supported by
CERN, ECFA, NuPECC

M. Klein

High-Energy LHC



time line of CERN HEP projects

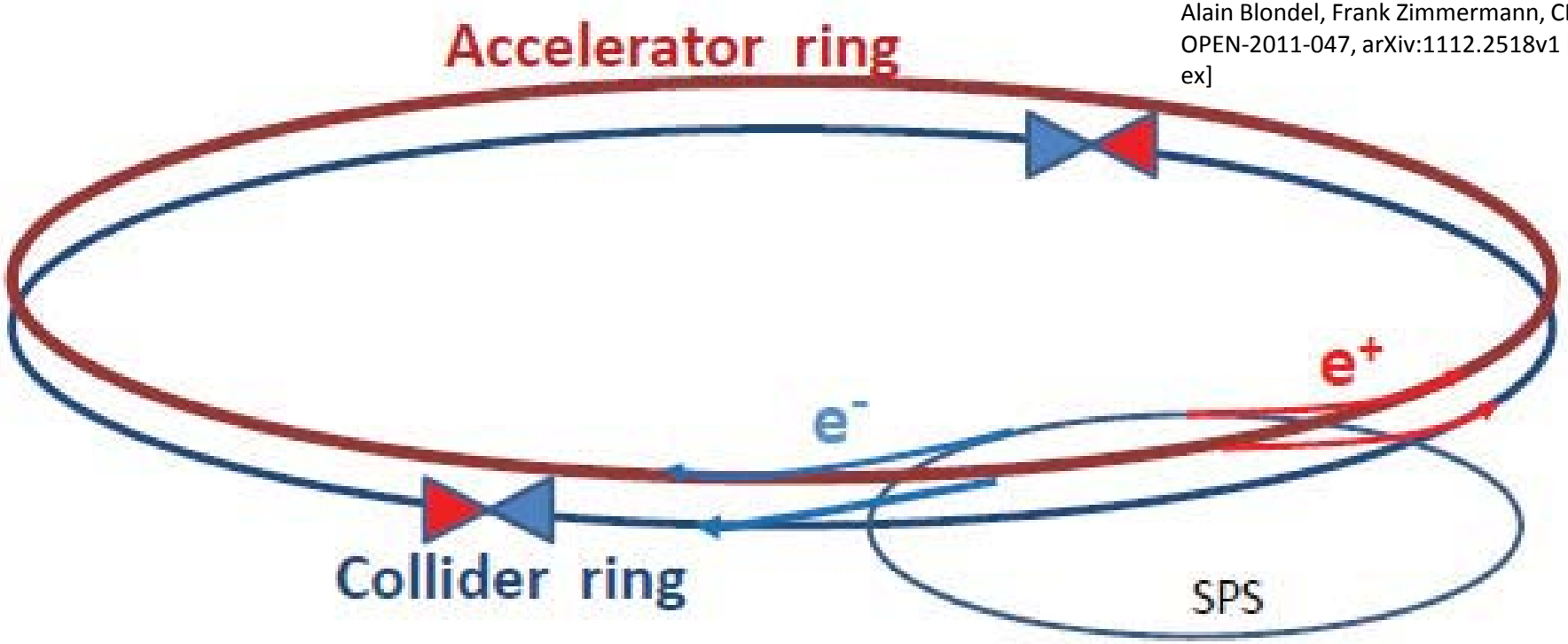


Source: L. Rossi. LMC 2011 (modified)

new proposal

LEP3 Higgs factory in LHC tunnel?

Alain Blondel, Frank Zimmermann, CERN-OPEN-2011-047, arXiv:1112.2518v1 [hep-ex]



A first ring accelerates electrons and positrons up to operating energy (120 GeV) and injects them at a few minutes interval into the low-emittance collider ring, with two high luminosity 10^{34} cm^{-2} s^{-1} interaction points.

two LEP3 scenarios

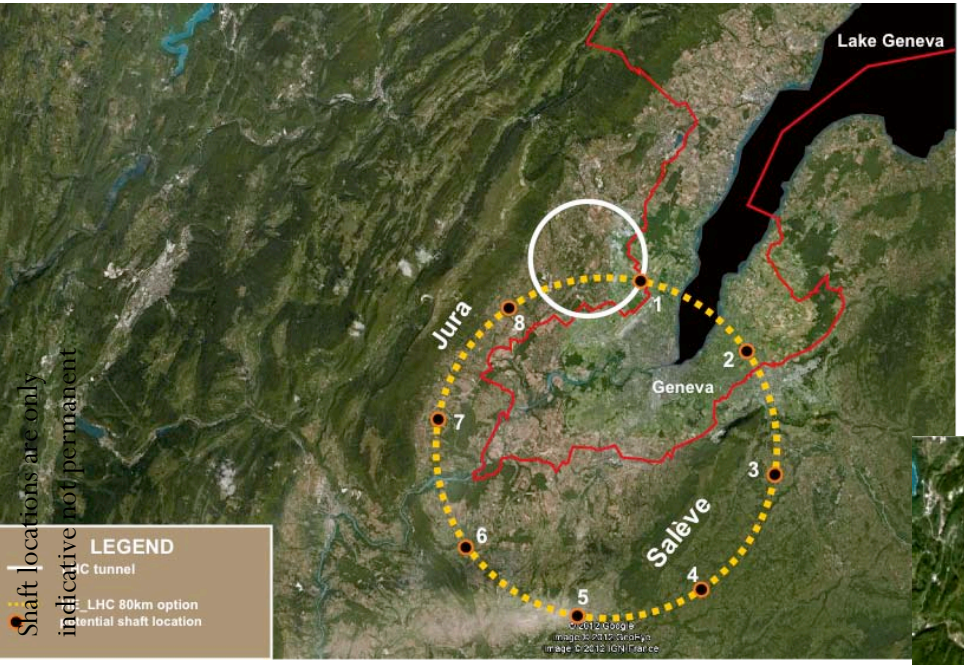
- installation in the LHC tunnel “LEP3”
  - + inexpensive
  - + tunnel exists
  - + reusing ATLAS and CMS detectors
  - + reusing LHC cryoplants
  - - interference with LHC and HL-LHC
- new larger tunnel “DLEP” or “TLEP”
  - + higher energy reach
  - + decoupled from LHC and HL-LHC operation and construction
  - + tunnel can later serve for HE-LHC (factor ~3 in energy from tunnel alone) with LHC remaining as injector; also HE-LHeC
  - - 3-4x more expensive (new tunnel, cryoplants, detectors?)

80-km tunnel for LEP3, LHeC & HE-LHC?

- New Ring of about 80km, connected to the existing LHC
- Two possible alignments considered:
  - 80km tunnel in the plain (option 1)
    - Passing under the Lake of Geneva
    - Passing behind the Salève mountain
    - Partially in limestones
    - Located both in France and Switzerland
    - Shafts every 10km (or inclined /double tunnel if shafts are not possible)
  - 80km tunnel in the Jura Mountain chain (option 2)
    - Vast majority in the Jura limestones
    - Fully located in France
    - Shafts every 10km (or inclined/double tunnel if shafts are not possible)
- The ring should be ‘connected’ to the LHC
- For this study **only** looking at the tunnel & shaft components.

80km tunnel project

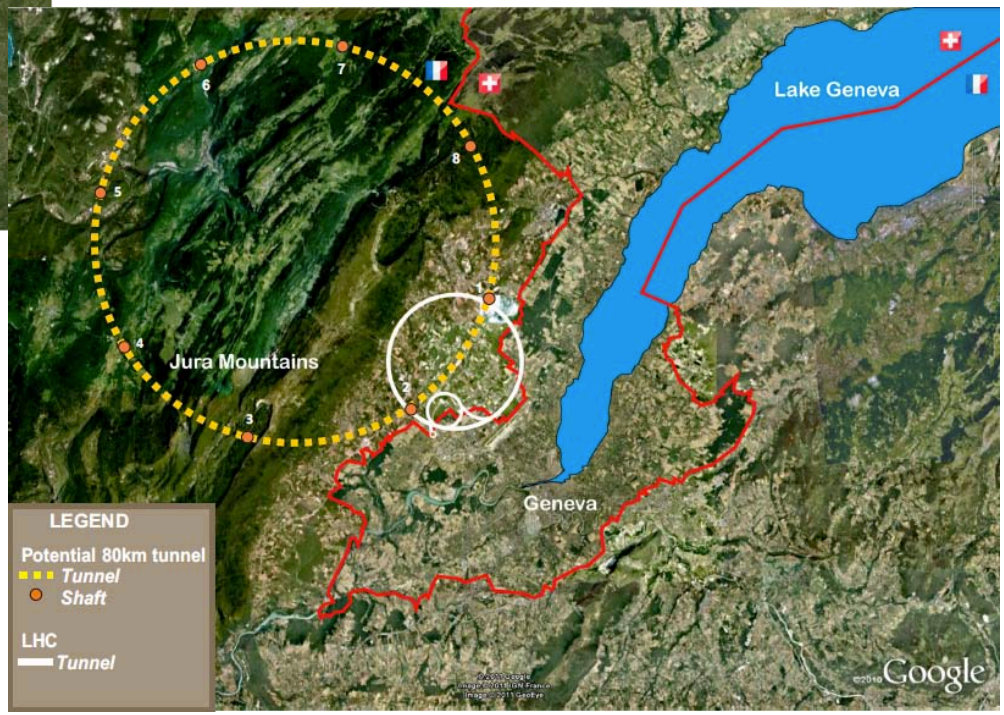
Layouts



Shaft locations are only indicative not permanent

Option 1

Option 2



Shaft locations are only indicative not permanent

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LEP3/DLEP/TLEP parameters -1

	LEP2	LHeC	LEP3	DLEP	TLEP
beam energy E_b [GeV]	104.5	60	**120**	120	**175**
circumference [km]	26.7	26.7	**26.7**	53.4	**80**
beam current [mA]	4	100	7.2	14.4	5.4
#bunches/beam	4	2808	4	60	12
#e-/beam [10^{12}]	2.3	56	4.0	16.0	9.0
horizontal emittance [nm]	48	5	25	10	20
vertical emittance [nm]	0.25	2.5	0.10	0.05	0.1
bending radius [km]	3.1	2.6	2.6	5.2	9.0
partition number J_ε	1.1	1.5	1.5	1.5	1.0
momentum comp. α_c [10^{-5}]	18.5	8.1	8.1	2.0	1.0
SR power/beam [MW]	11	44	50	50	50
β^*_x [m]	1.5	0.18	0.2	0.2	0.2
β^*_y [cm]	5	10	0.1	0.1	0.1
σ^*_x [μm]	270	30	71	45	63
σ^*_y [μm]	3.5	16	0.32	0.22	0.32
hourglass F_{hg}	0.98	0.99	0.67	0.75	0.65
ΔE^{SR}_{loss}/turn [GeV]	3.41	0.44	6.99	3.5	9.3

LEP3/DLEP/TLEP parameters -2

	LEP2	LHeC	LEP3	DLEP	TLEP
$V_{RF,tot}$ [GV]	3.64	0.5	12.0	6.0	12.0
$\delta_{max,RF}$ [%]	0.77	0.66	4.2	4.2	4.9
ξ_x/IP	0.025	N/A	0.09	0.05	0.05
ξ_y/IP	0.065	N/A	0.08	0.05	0.05
f_s [kHz]	1.6	0.65	3.91	0.97	0.43
E_{acc} [MV/m]	7.5	11.9	20	20	20
eff. RF length [m]	485	42	600	300	600
f_{RF} [MHz]	352	721	1300	1300	700
δ^{SR}_{rms} [%]	0.22	0.12	0.23	0.16	0.22
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.69	0.23	0.16	0.25
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	N/A	**107**	144	**65**
number of IPs	4	1	2	2	2
Rad.Bhabha b.lifetime [min]	360	N/A	16	42	54
Υ_{BS} [10^{-4}]	0.2	0.05	10	8	15
n_γ/collision	0.08	0.16	0.60	0.25	0.51
$\Delta\delta^{BS}$/collision [MeV]	0.1	0.02	33	12	61
$\Delta\delta^{BS}_{rms}$/collision [MeV]	0.3	0.07	48	26	95


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thank you!