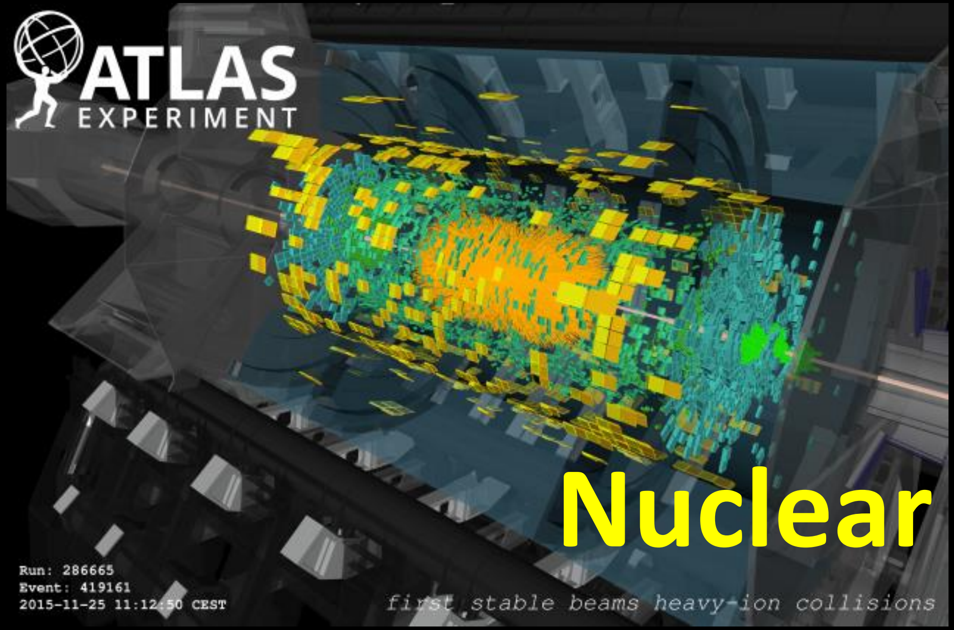
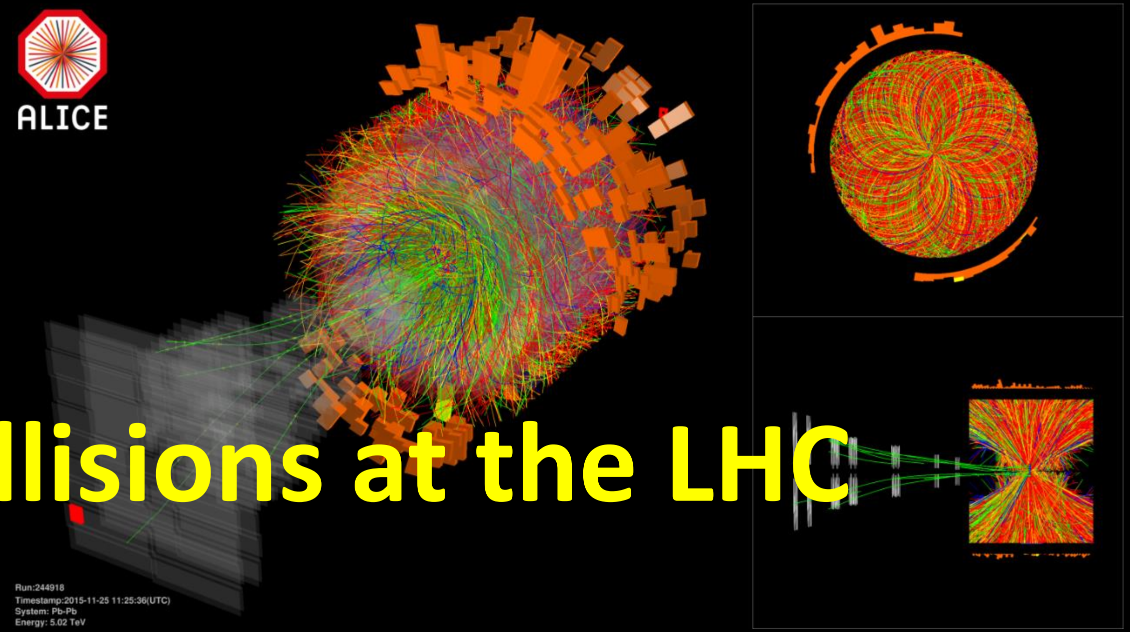
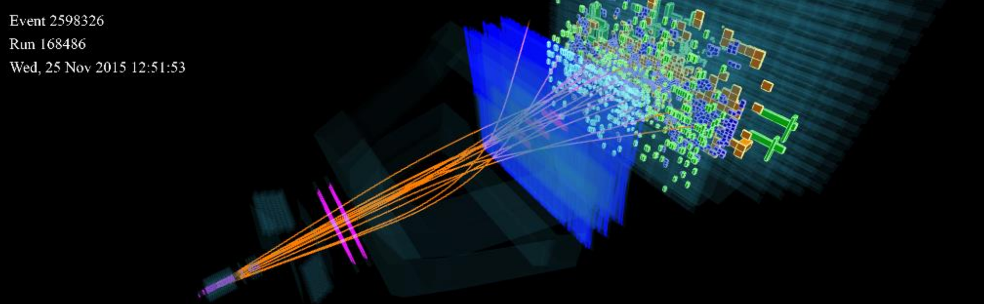
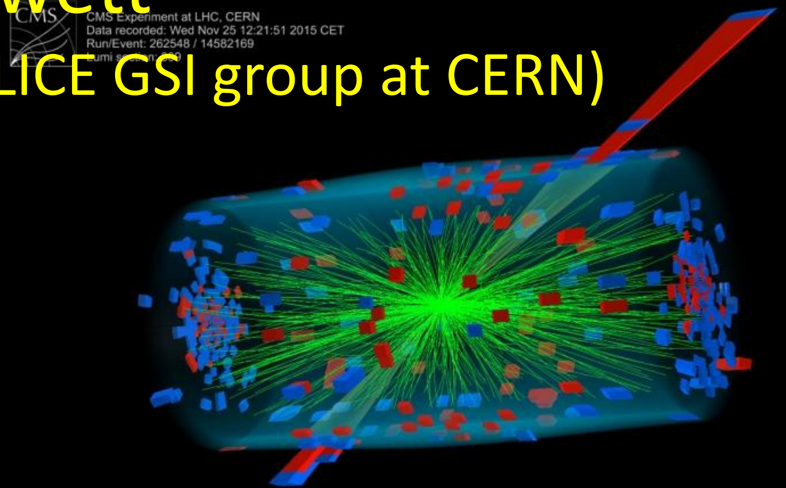
Nuclear Collisions at the LHC

John Jowett
(Formerly CERN, recently ALICE GSI group at CERN)









Outline

- (Yet another) short history of hadron colliders
- Physics of extremely high-energy nuclear collisions
- Basic physics and conventions for nuclear (fully stripped ion) beams
- Evolution of the LHC heavy-ion programme, beam physics and performance limits
  - LHC Pb-Pb collisions
  - LHC p-Pb collisions
  - Xe-Xe collisions
- Outlook for the future

History of hadron colliders in the 20th century

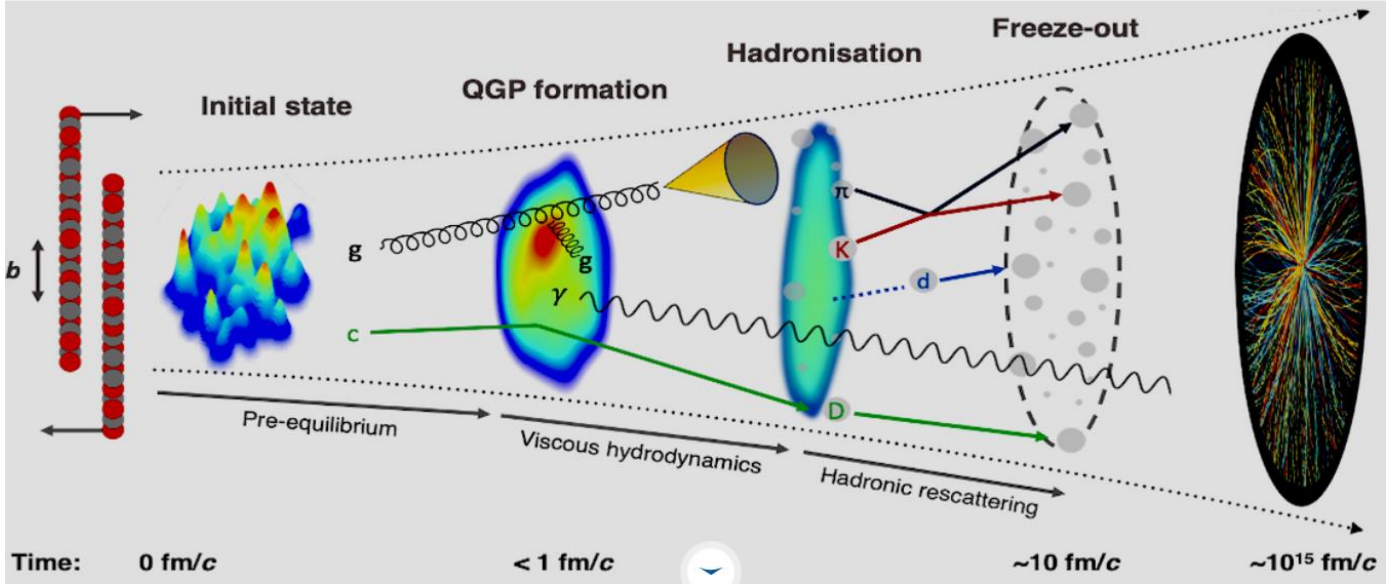
- 1970s:
  - First hadron collider, the ISR at CERN operated
    - Mainly p-p collisions (~30 GeV/beam), but also first ppbar, d and α (just a few days)
  - Construction of higher energy (~200 GeV/beam) pp collider ISABELLE started in USA.
  - But growing conviction that linear e+e- colliders were the future …
- 1980s:
  - Two ppbar colliders, SppS and Tevatron, major discoveries
  - ISABELLE abandoned
  - LHC pp collider feasibility study (1983-4) for late 1990s …
  - UNK pp collider construction (21 km tunnel completed)
  - SSC pp collider, 80 km tunnel construction started in USA
- 1990s:
  - UNK abandoned
  - first ep collider HERA operated
  - SSC abandoned
  - RHIC construction in ISABELLE tunnel
  - LHC pp collider approved, including mention of Pb+Pb for ALICE, CMS experiments

History of hadron colliders in the 21st century

- 2000:
  - RHIC collider at Brookhaven, in ISABELLE tunnel, collides first heavy ions Au+Au, then polarized p-p, many other species, outpouring of discoveries in heavy-ion physics
- 2009-11:
  - LHC first p-p and Pb-Pb collisions …
  - Tevatron closed down
  - Higgs discovery in 2012 in p-p collisions at LHC
- Now:
  - All (both) hadron colliders in the world have substantial heavy-ion programmes
  - All hadron collider experiments in the world study heavy-ion collisions, transition to precision physics
- Future:
  - HL-LHC, including upgrade to ALICE 3 in 2030s
  - Electron-ion collider in USA (seminar later)
  - NICA, a lower-energy heavy-ion collider in Russia
  - Possibly pp and heavy-ion collisions at SppC or FCC-hh (see other seminars)

“Heavy-ion” physics – what is it about? (1)

- Nuclear collisions to study the energy frontier of nuclear physics
- Unimaginably extreme conditions, similar to those that prevailed in the first microseconds of cosmic history, nuclear matter as we know it does not yet exist.
- Above a temperature of T_c=160/k_B MeV, quarks and gluons inside the nucleons (i.e., protons or neutrons) are deconfined, forming the Quark-Gluon Plasma (QGP).

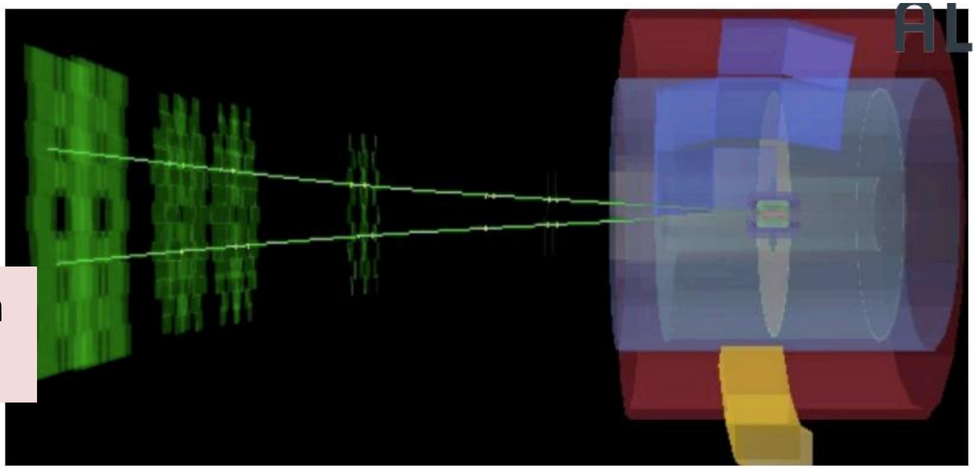


- This occupies a volume that is nevertheless large enough to be considered thermalised bulk matter with meaningful thermodynamic and hydrodynamic properties such as temperature, flow and viscosity.
- Indeed, Quantum Chromodynamics (QCD) is the only sector of the Standard Model of particle physics whose thermodynamical behaviour can be directly studied in the laboratory.

“Heavy-ion” physics – what is it about? (2)

- The LHC experiments have confirmed the discovery at RHIC that this new state of matter is the most nearly perfect liquid, with the lowest viscosity, found in Nature.
- As the QGP expands and cools, it condenses back into a hadron gas.
  - From the distributions of hadrons emerging from this ``freeze-out'' stage, the experiments can infer many of the properties of the QGP.
  - Further information is carried by muons and photons, Z and W bosons.
  - ``Soft'' physics of particles produced with low transverse momenta Is well-modelled by relativistic viscous hydrodynamics.
- Proton-nucleus and (rare) high-multiplicity proton-proton collisions have been found to exhibit apparent collective effects despite small system size – current hot topic.

- Nuclear collisions *also* allow experimentation with extreme electromagnetic fields when nuclei do not touch (“Ultraperipheral collisions” - later).
  - LHC is also a photon-photon collider (so also the “cleanest” events at the LHC)
  - Potential access to “Beyond the Standard Model” physics
  - Photonuclear physics

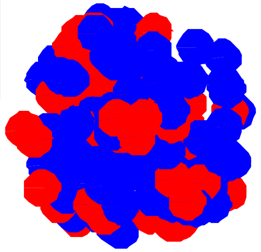


Two tracks in the muon arm
Rapidity of J/Ψ: $2.5 < y < 4$

Change of the operational paradigm for hadron colliders

- A major challenge at LHC:
  - Commission new configurations and provide stable physics operation within typical time frame of one month
  - Simply cannot spend years building up to design luminosity - was done in a few weeks of beam time (of course taking advantage of what was done for protons)
  - Experiments require multiple changes of beam conditions (intensity ramp-up, solenoid reversal, beam reversal, low/high/levelled luminosity, special beam energies, Van der Meer scans, …
  - Different from traditional collider operating paradigm of steady, incremental improvement to operating conditions with maximum energy and luminosity
- This can be achieved with LHC because of (my opinion):
  - Reliability and reproducibility of all systems, especially magnets
  - Thorough understanding of beam physics
  - Efficient, stable, operating procedures and software
  - Careful planning and execution of efficient rapid-commissioning plans

- In this seminar we view the LHC heavy-ion programme as a case-study in extending the capabilities of an accelerator/collider far beyond what was originally foreseen, and for limited cost, thus providing major added-value to the initial investment in construction.



Mass of ions/nuclei

General ion of charge Qe and mass m and nucleon number ("mass number") A.

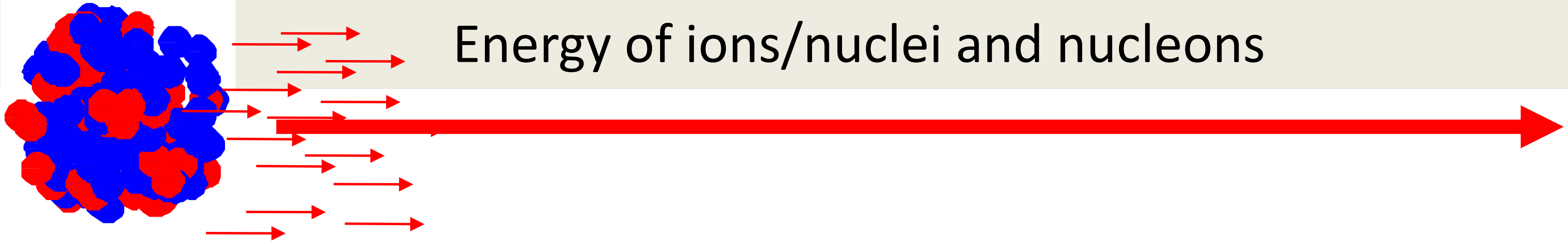
Mainly collide fully-stripped ions, bare nuclei, where $Q = Z$,
e.g., in LHC we use ${}^{208}\mathrm{Pb}^{82+}$ with $Z = 82, A = 208$,

$$\begin{aligned} m &= 207.976652071\,\mathrm{u} - 82 m_e \\ &= (193.729 - 82 \times 0.000511)\,\mathrm{GeV}/c^2 \\ &= 193.687\ \mathrm{GeV}/c^2 \end{aligned}$$

N.B. $208 m_p = 195.161\ \mathrm{GeV}/c^2$ is a poor approximation!

For this species the binding energy of the 82 electrons < 1 MeV.

Energy of ions/nuclei and nucleons



Nucleus of charge Ze and mass m and nucleon number ("mass number") A.

Energy and momentum related as square of 4-momentum vector, $P = (E/c, \mathbf{p})$

mass is basic Lorentz-invariant

$$\mathrm{P}^2 = E^2/c^2 - p^2 = m^2c^2$$

Traditionally, in low-energy ion accelerators, the kinetic energy per nucleon is quoted in parameter lists:

$$E_{Kn} = \frac{\sqrt{\mathrm{p}^2c^2 + m^2c^4} - mc^2}{A} \approx \frac{E}{A}$$ at high energy,

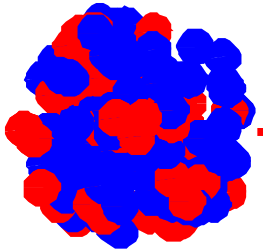
but this quantity does not appear in any equation of motion!

Avoid confusion by never using any kind of "energy per nucleon" in calculations, just quote it at the end. At LHC, we use the conventional, more precise, notations:

$$E \approx pc = \underbrace{7.0Z\ \text{TeV}}_{\text{Energy per charge, relation to proton energy}} = \underbrace{2.76A\ \text{TeV}}_{\text{Energy per nucleon}} = \underbrace{574.\ \text{TeV}}_{\text{Simply the energy of the particle, for all calculations}}$$

Luminosity with nuclei and nucleons

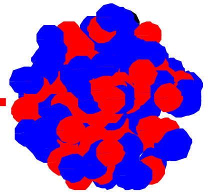
- Luminosities quoted for lead nuclei may seem low compared to pp or e^+e^-
- But comparisons are more meaningful on the basis of nucleon pair luminosities



$$L = 5.0 \times 10^{27} \text{ (Pb)(Pb) cm}^{-2}\text{s}^{-1}$$
$$= 2.2 \times 10^{32} \text{ (nucleon)(nucleon) cm}^{-2}\text{s}^{-1}$$

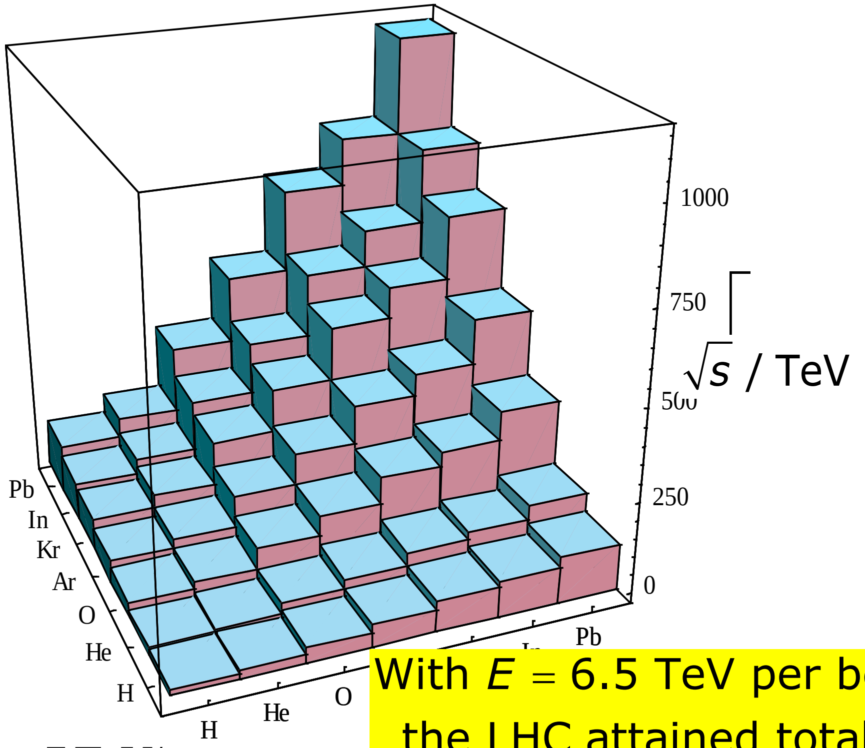
In general case of two different colliding species, the nucleon-nucleon luminosity is defined as

$$L_{NN} = A_1 A_2 L$$

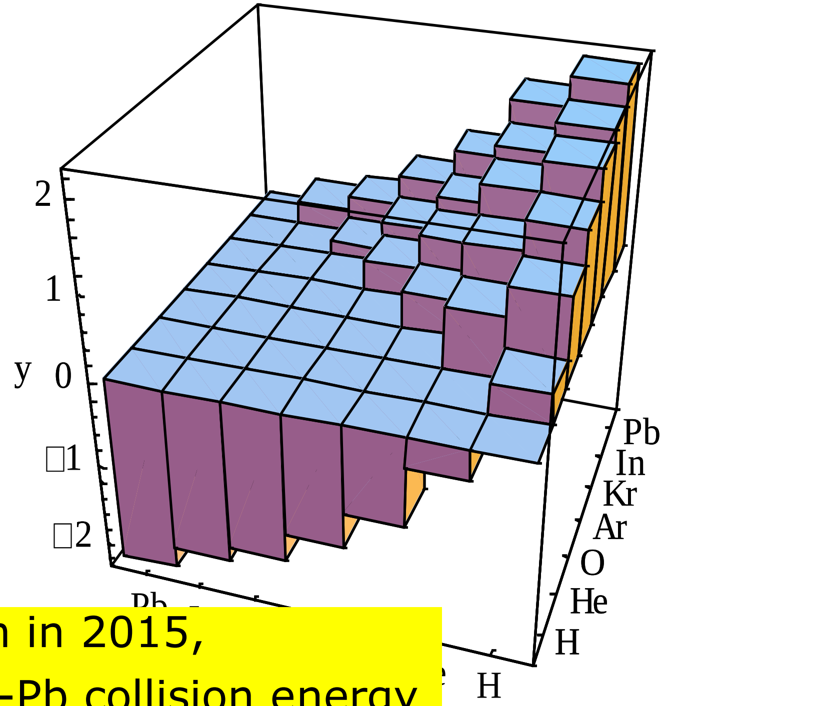


Centre-of-mass energy and velocity/rapidity in collisions of nuclei of charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p

$$\sqrt{s} = (P_1 + P_2)^2 \approx 2c\, p_p \sqrt{Z_1 Z_2}, \qquad \frac{\mathbf{v}_{\mathrm{CM}}}{c} = \frac{(\mathbf{p}_1 + \mathbf{p}_2)}{c(E_1 + E_2)} \approx \frac{Z_1 - Z_2}{Z_1 + Z_2}, \qquad y = \operatorname{arctanh}\frac{\mathbf{v}_{\mathrm{CM}}}{c} = \frac{1}{2}\log\frac{Z_1}{Z_2}$$



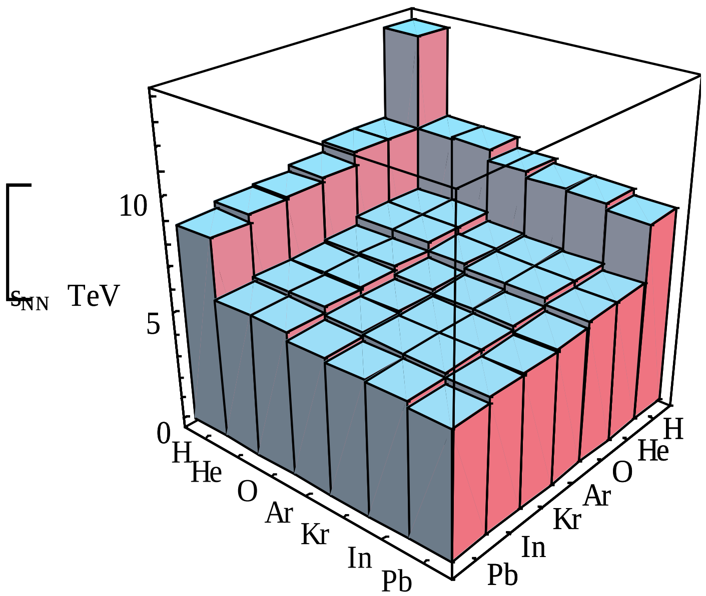
$p_p = 7\ \mathrm{TeV}/c$

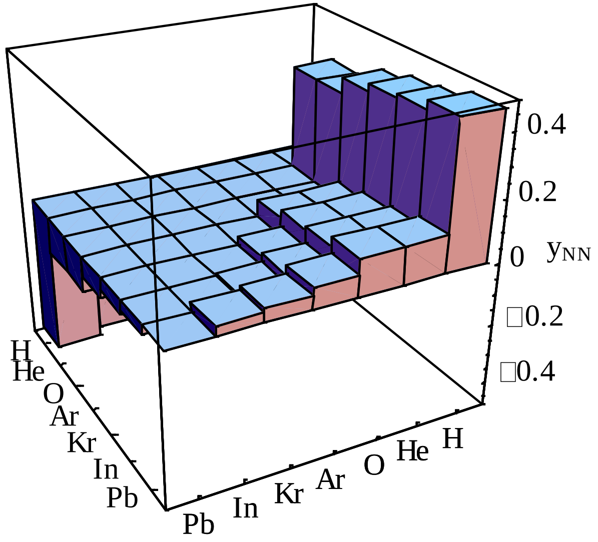


With $E = 6.5$ TeV per beam in 2015,
the LHC attained total Pb-Pb collision energy
$\sqrt{s} > 1000\ \mathrm{TeV} = 1\ \mathrm{PeV}$
in fm^3 volumes.

Centre-of-mass energy and velocity/rapidity for nucleon pairs in collisions of ions of charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p

$$\sqrt{s_{NN}} \approx 2c\, p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}, \qquad \frac{v_{\mathrm{CMNN}}}{c} \approx \frac{Z_1/A_1 - Z_2/A_2}{Z_1/A_1 + Z_2/A_2}, \qquad y_{NN} = \frac{1}{2}\log\frac{Z_1 A_2}{A_1 Z_2}$$

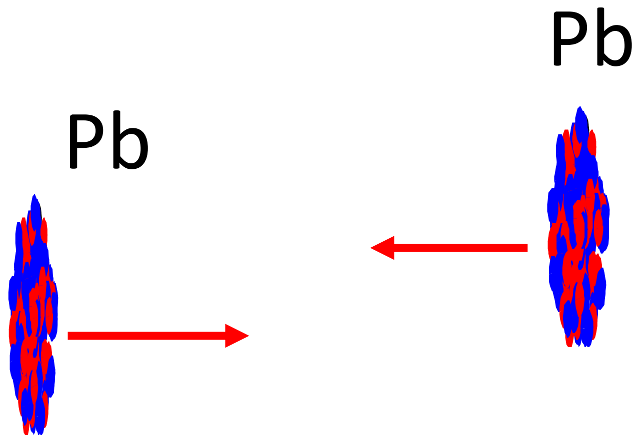




$p_p = 7\ \mathrm{TeV}/c$

Exercise: derive all formulas on this and previous slide.

Sign change w.r.t. CM of whole system.



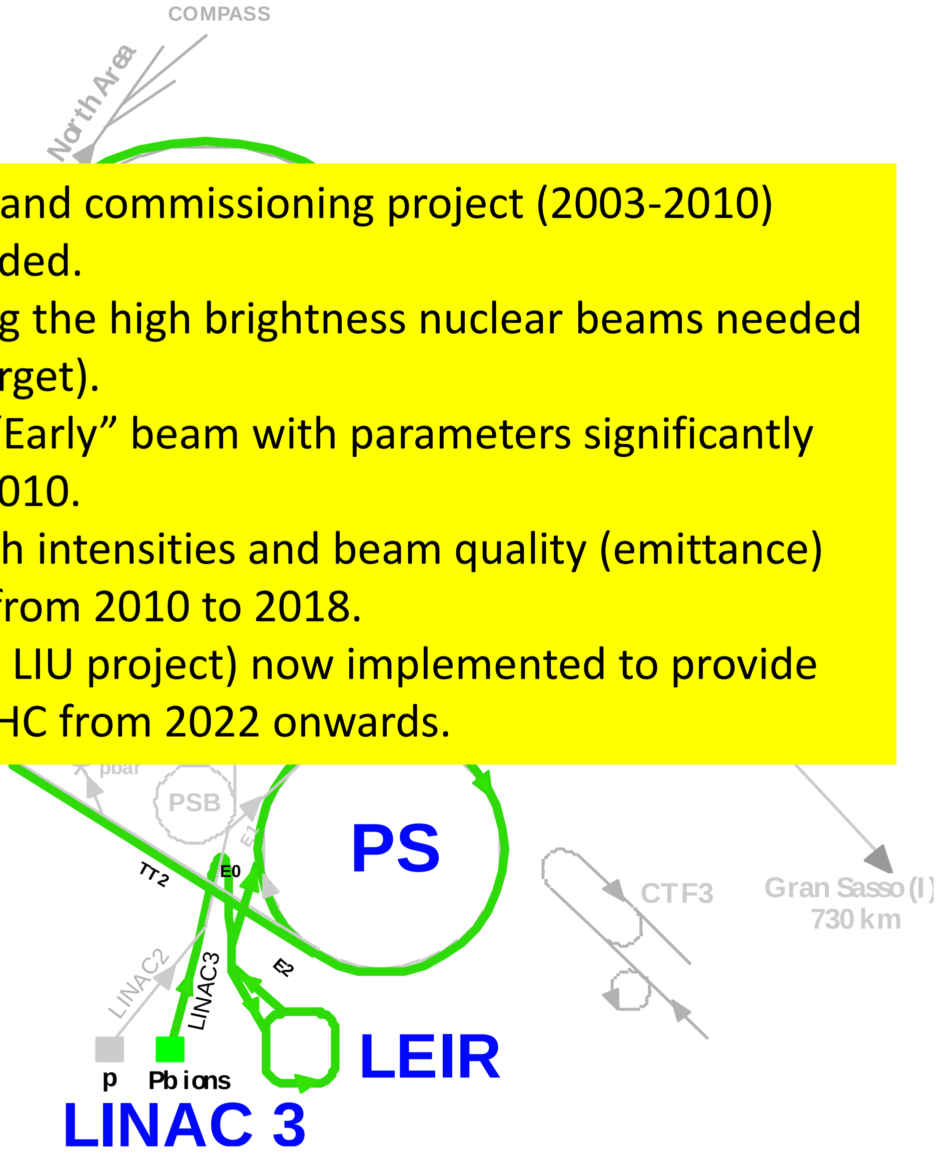
LEAD-LEAD COLLISIONS AT LHC

“Future collider” for many years still

LHC Ion Injector Chain

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

I-LHC construction and commissioning project (2003-2010) successfully concluded.
Vital role in creating the high brightness nuclear beams needed by LHC (vs. fixed target).
Already delivered “Early” beam with parameters significantly beyond design in 2010.
Performance, bunch intensities and beam quality (emittance) steadily improved from 2010 to 2018.
New upgrades (the LIU project) now implemented to provide more bunches to LHC from 2022 onwards.



LHC Design Parameters for Pb-Pb (~2001)

Parameter	Units	Early Beam	Nominal
Energy per nucleon	TeV	2.76	2.76
Initial ion-ion Luminosity L_0	$cm^{-2}\ s^{-1}$	$\sim 5 \times 10^{25}$	1×10^{27}
No. bunches, k_b		62	592
Minimum bunch spacing	ns	1350	99.8
β^*	m	1.0	0.5 /0.55
Number of Pb ions/bunch		$\mathbf{7 \times 10^7}$	$\mathbf{7 \times 10^7}$
Transv. norm. RMS emittance	μm	1.5	1.5
Longitudinal emittance	eV s/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	h	14, 7.5, 5.5	8, 4.5, 3

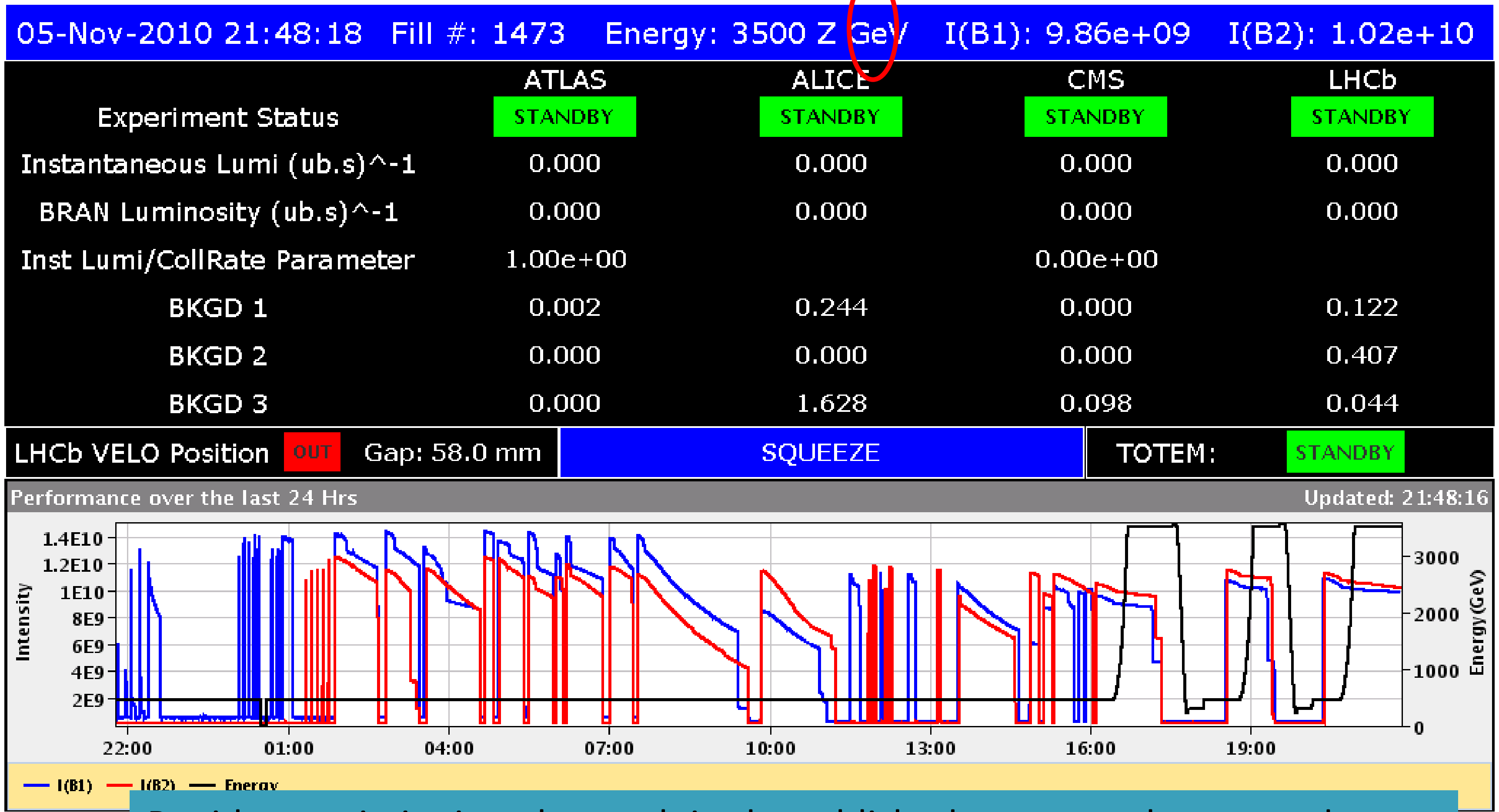
At full energy, luminosity lifetime is determined mainly by collisions ("burn-off" from ultraperipheral electromagnetic interactions) $\sigma \approx 520$ barn

Design performance now far exceeded.

- Exercise: starting from the Lorentz force equation and introducing suitable rescalings of the time variable, demonstrate the *equal rigidity principle*, that particles of different electric charge Z, but equal *p/Z* can circulate on the same orbits in a static magnetic field depending only on position.

- In practice, this tells us that, if we have commissioned the closed orbit and optics of a collider ring for one (non-radiating) species, it should work for another species of the same rigidity *except for any electric or time-varying magnetic fields. Typically an adjustment of the RF frequency and injection timing is sufficient for the latter.*

Heavy Ion Set-up: first 24 h, Thu-Fri 4-5 Nov 2010



Rapid commissioning plan exploited established proton cycle to speed through initial phase of magnetic setup (injection, ramp, squeeze) . Collision crossing angles and collimation conditions different.

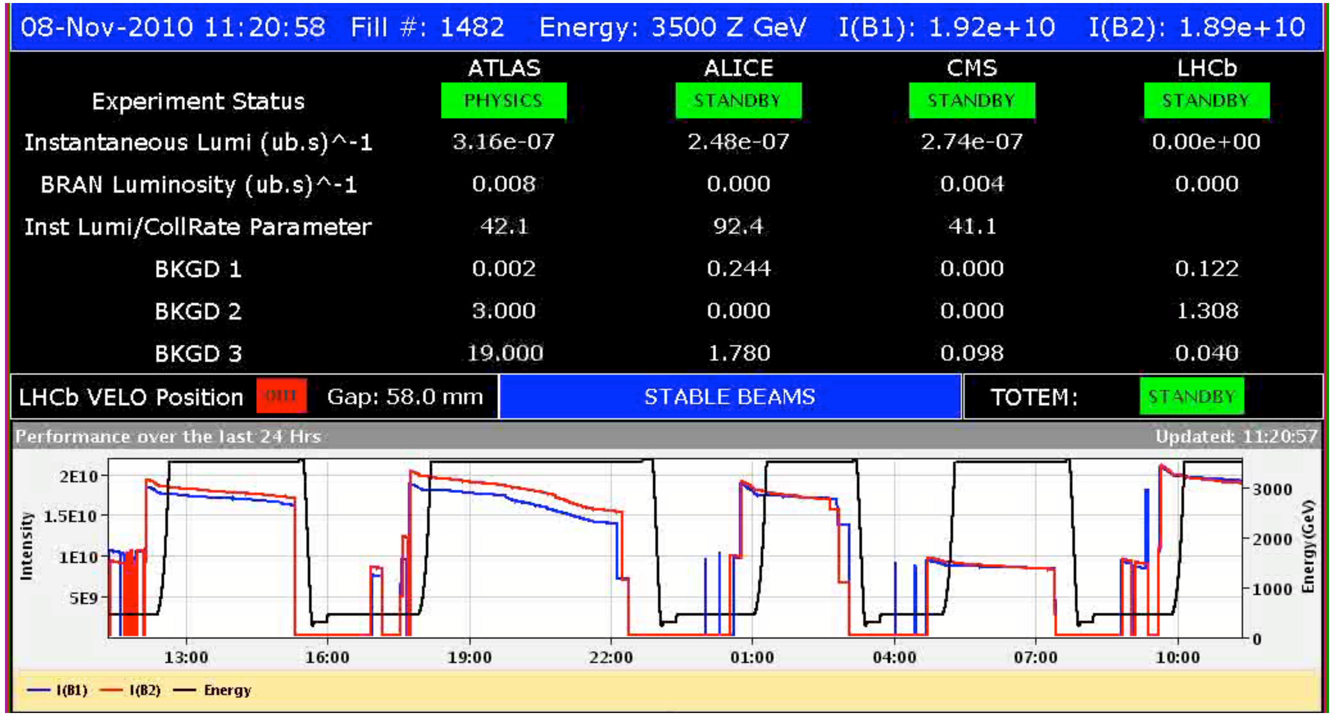
Beam 1
Circ.
& Captu

& Capture

Collimation Checks

Squeeze

Monday morning: First Stable Beams for Pb-Pb



First stable beam with 2 bunches/beam (1 colliding)

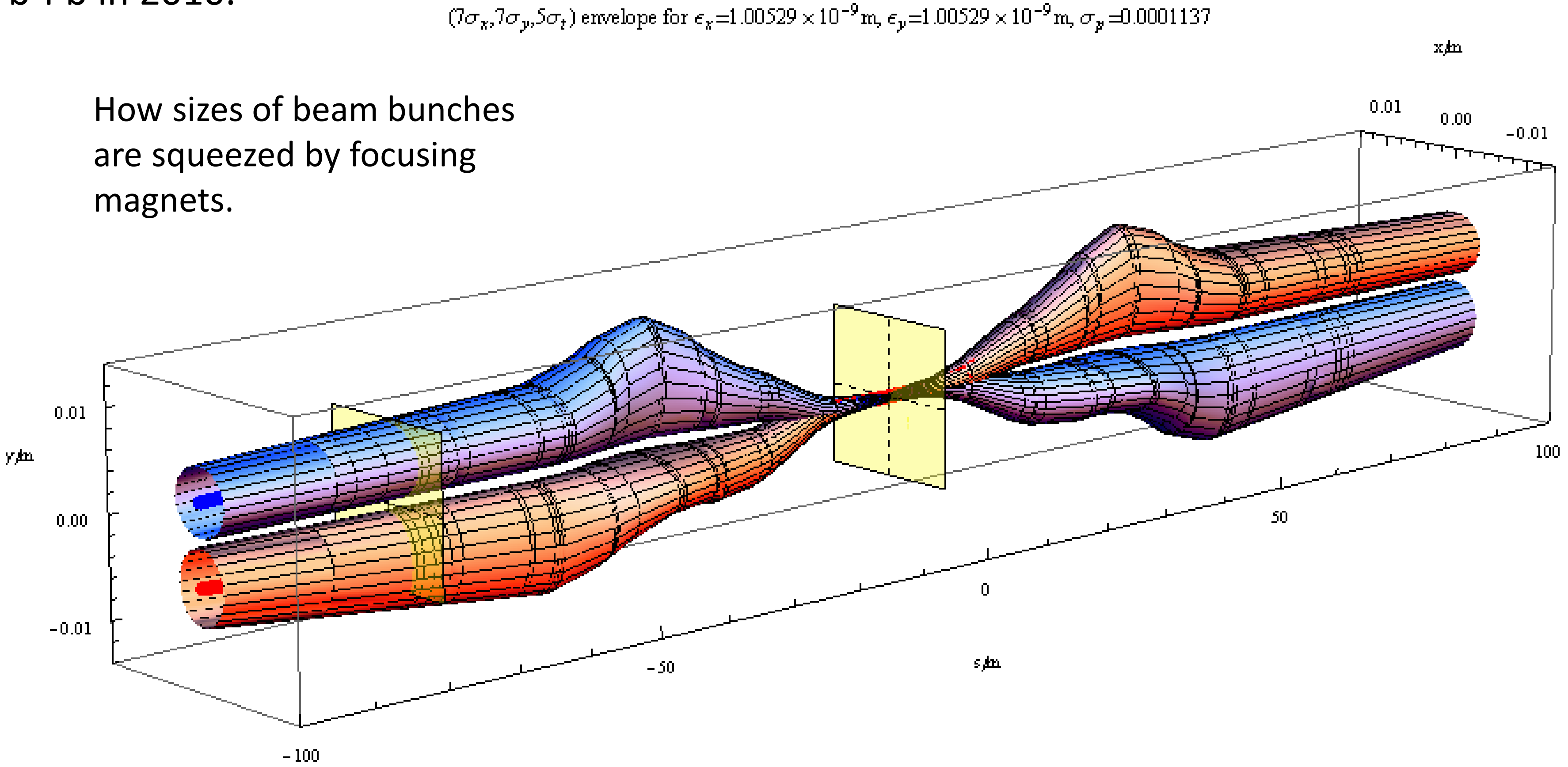
Later same day, 5 bunches/beam, then increased on each fill: 17, 69, 121
Factor 100 in peak luminosity within 6 days.
Many interesting new RF manipulations in LHC in first 2 weeks.
Ion injectors exceeded design intensity/bunch by 70%.

In later Pb-Pb runs, LHC optics commissioning became so efficient that we diverged more and more from the p-p optics.
In 2018, we used a completely new variant of the entire optics cycle.

Beam envelopes around ALICE experiment

Collision conditions for Pb-Pb in 2010.

How sizes of beam bunches are squeezed by focusing magnets.



Zero crossing angle at IP (external crossing angle compensates ALICE spectrometer magnet bump). Beam pipe is about twice transverse size of box.

Where is the new beam physics?

- Optics etc, similar in principle (not in detail) to proton beams
- Charge per bunch is usually ~10% of proton bunches
  - Impedance driven collective effects are generally not a problem
  - Traditional beam-beam effects from collective fields also weak.
  - Space charge in lower energy injectors is an exception
- However charge *per particle* is up to two orders of magnitude higher than protons and most of the interesting beam physics of nuclear beams is due to this:
  - Intra-beam scattering (multiple Coulomb scattering within a bunch), important but well-known
  - Synchrotron radiation damping (twice as fast as protons)
  - New beam-beam effects from ultra-peripheral nuclear collisions
  - More complicated nuclear interactions with beam environment (ie beam losses), particularly collimators

Intra-beam scattering (IBS)

- Multiple small-angle Coulomb scattering of particles within bunch
- Detailed theory covered elsewhere

Intrabeam scattering. The emittance growth rates due to intrabeam scattering can be written as [37]

$$\frac{d}{dt}\begin{pmatrix}\epsilon_x\\ \epsilon_y\\ \epsilon_s\end{pmatrix} = \frac{N_b c}{\gamma\epsilon_x\epsilon_y\epsilon_s}\frac{r_0^2 Z^4}{A^2}\begin{pmatrix}F_x\\ F_y\\ F_s\end{pmatrix}, \qquad (7)$$

where the functions $F_{x,y,s}$ are functions of the lattice parameters and beam sizes averaged over the machine circumference ($F_{x,y,s}$ also have some γ dependence) [37]. Intrabeam scattering is particularly strong for ions with high charge states Z. For heavy ions at the end of the RHIC accelerator chain, the factor $N_b Z^4/A^2$ is typically an order of magnitude larger than that for protons. As with space charge, a low charge state Z is preferred at low energies to minimize intrabeam scattering effects.

Always an important source of emittance growth times ~ few hours in heavy-ion colliders, particularly at injection.

Effect can be modelled with non-linear differential equations (various approaches to calculating the *F* functions) or various types of multi-particle simulation.

In either approach, equations are coupled to evolution of intensity (luminosity burn-off, see later, other losses), radiation damping, etc.

Beam instrumentation

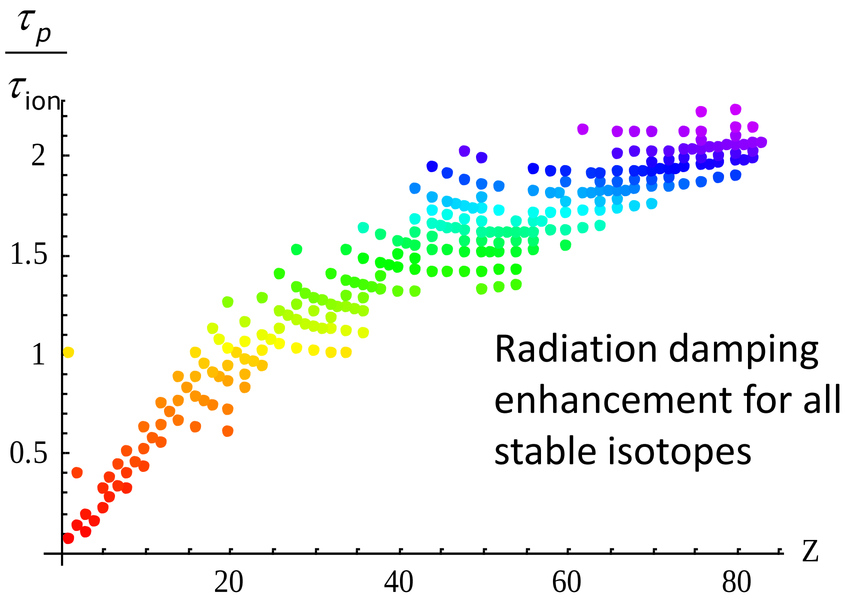
- Low charge/bunch was a major concern before first experience with Pb beams in LHC
- Beam position monitors had intensity threshold –
  - no problem because initial commissioning was done with large fraction of final bunch intensity
- Emittance: harder than protons
  - Wire scanner at low energy and intensity –
    - best absolute calibration
  - BSRT: synchrotron light from nuclei appeared in first ramp (world first!), only bunch-by-bunch measurement typical large spread in emittance set in at injection

Effects of Synchrotron Radiation from Pb nuclei

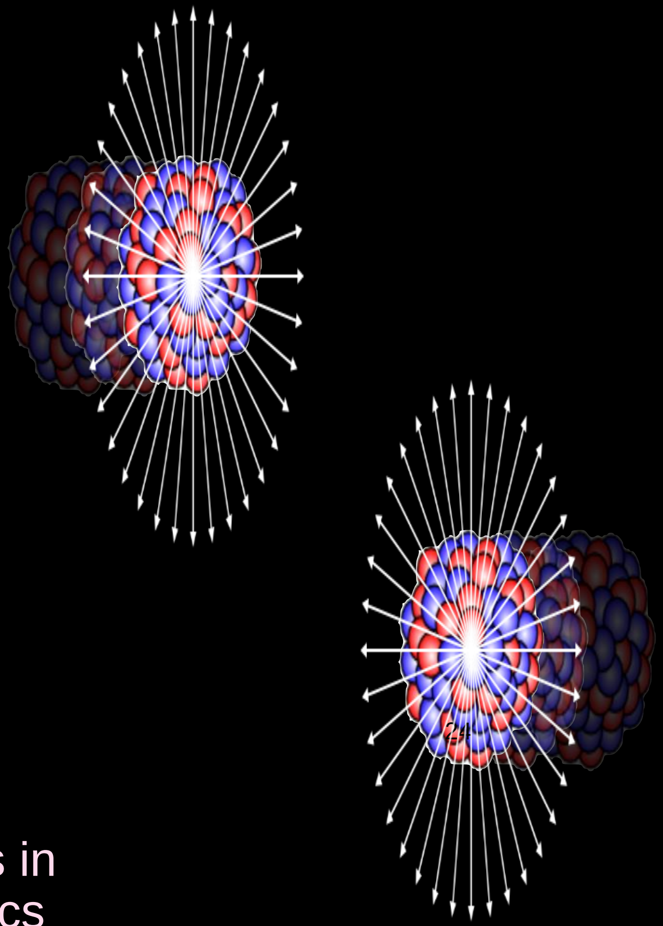
- Nuclear charge radiates *coherently* at relevant wavelengths (~ nm)
- Scaling with respect to protons *in same ring, same magnetic field*
  - Radiation damping for Pb is *twice as fast as for protons*
    - Many very soft photons
    - Critical energy in visible spectrum
- In LHC at 7 Z TeV, transverse emittance damping time of 12.6 h can be fast enough to overcome IBS at full energy and intensity

$$\frac{U_{\rm ion}}{U_{\rm p}} \simeq \frac{Z^6}{A^4} \simeq 162, \qquad \frac{u^c_{\rm ion}}{u^c_{\rm p}} \simeq \frac{Z^3}{A^3} \simeq 0.061,$$

$$\frac{N_{\rm ion}}{N_{\rm p}} \simeq \frac{Z^3}{A} \simeq 2651, \qquad \frac{\tau_{\rm ion}}{\tau_{\rm p}} \simeq \frac{A^4}{Z^5} \simeq 0.5$$



Lead is (almost) best, deuteron is worst.



Stripped nuclei have
very strong EM fields
(B=O(10^{15}) T!)

Z=82 packed into a subatomic volume traveling ultra relativistic speeds (highly Lorentz contracted)!

Classical fields can be understood as a source of nearly-real high energy photons! (Fermi-Weizsacker-Williams)

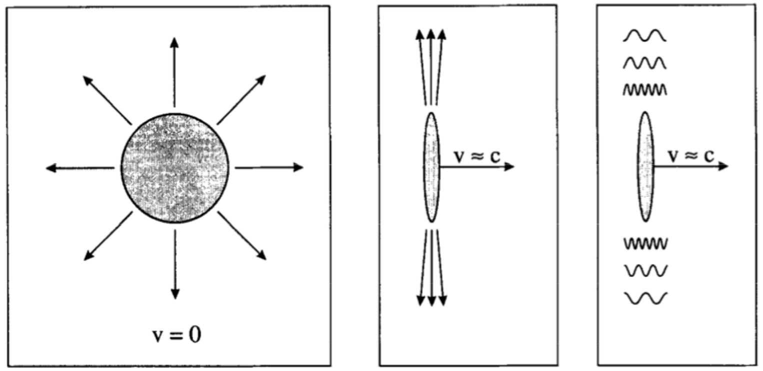
A powerful QCD laboratory is also a powerful QED laboratory!

[Similar diagrams in accelerator physics usually show the field around a macroscopic particle bunch.]

Slide from Peter Steinberg

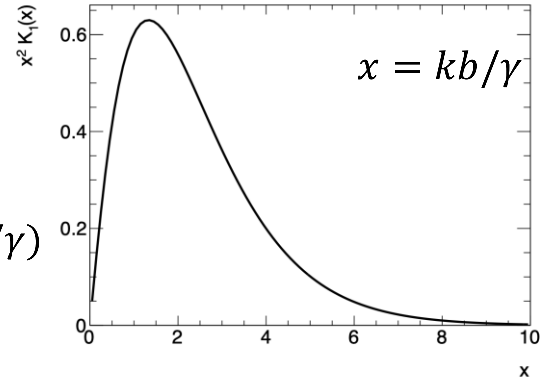
Equivalent Photon Approximation

Fermi, Landau, von Weiszacker, Williams
See also Jackson's Classical Electrodynamics



For a point charge:

$$n(k,b) = \frac{d^3N_\gamma}{d^2b\,dk} \propto \frac{\alpha Z^2}{kb^2} f(kb/\gamma)$$



maximum energy **$E_{\gamma,max}$~γ(ħc/R)**	**80 GeV in Pb+Pb@LHC** **3 GeV in Au+Au@RHIC**
typical p_T (& virtuality) **p_{Tmax} ~ ħc/R**	**O(30) MeV @ RHIC & LHC**
Coherent strengths (rates) scale as **Z^2**: nuclei >> protons	Flux of photons on other nucleus ~ **Z^2**, flux of photons on photons ~ **Z^4 (45M!)**

Slide from Peter Steinberg

Photon-photon processes at the collision point

BFPP: $^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + ^{208}Pb^{81+} + e^{+}$,

$\sigma = 281\ \mathrm{b}, \quad \delta = 0.01235$

EMD1: $^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + ^{207}Pb^{82+} + n$,

$\sigma = 96\ \mathrm{b}, \quad \delta = -0.00485$

EMD2: $^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + ^{206}Pb^{82+} + 2n$,

$\sigma = 29\ \mathrm{b}, \quad \delta = -0.00970$

Each of these makes a secondary beam, with rigidity change, emerging from the IP that may quench bending magnets.

$$\delta = \frac{1 + \Delta m / m_{\mathrm{Pb}}}{1 + \Delta Q / Q} - 1$$

Strong luminosity burn-off of beam intensity.

Discussed for LHC since 2001 … see several references.

Hadronic cross section is 8 b (so luminosity debris contains much less power).

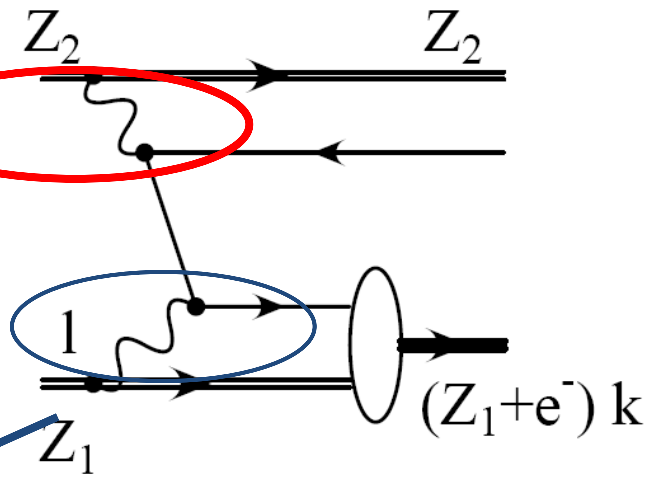
Pb-Pb BFPP cross-section (heuristic)

Pair production $\propto Z_1^{\,2} Z_2^{\,2}$

Radial wave function of $1s_{1/2}$ state of hydrogen-like atom in its rest frame

$$R_{10}(r) = \left(\frac{Z_1}{a_0}\right)^{3/2} 2\exp\left(-\frac{Z_1 r}{a_0}\right)$$

$$\Rightarrow \quad \Psi(0) \sim Z_1^{\,3/2} \quad \Rightarrow \quad |\Psi(0)|^2 \sim Z_1^{\,3}$$



G. Baur et al, Phys. Rept. 364 (2002) 359

Cross section for Bound-Free Pair Production (BFPP) (various authors)

$$Z_1 + Z_2 \rightarrow (Z_1 + e^-)_{1s_{1/2},\ldots} + e^+ + Z_2$$

has very strong dependence on ion charges (and energy)

$$\sigma_{PP} \propto Z_1^{\,5} Z_2^{\,2} \left[A \log \gamma_{CM} + B\right]$$

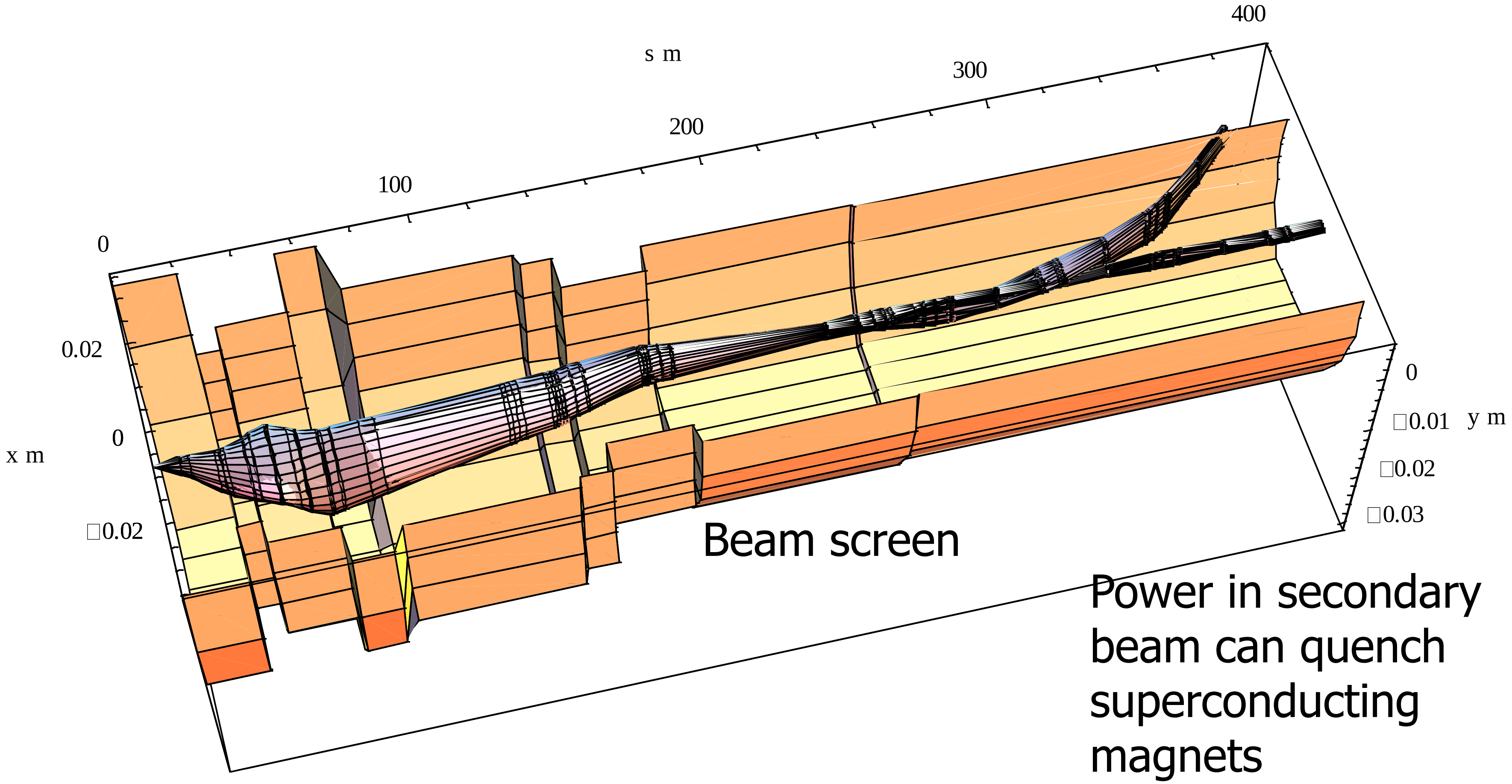
$$\propto Z^7 \left[A \log \gamma_{CM} + B\right] \quad \text{for } Z_1 = Z_2$$

$$\approx \begin{cases} 0.2 \text{ b for Cu-Cu RHIC} \\ 114 \text{ b for Au-Au RHIC} \\ 281 \text{ b for Pb-Pb LHC} \end{cases}$$

Total cross-section $\sim Z_2^{\,2} Z_1^{\,5}$

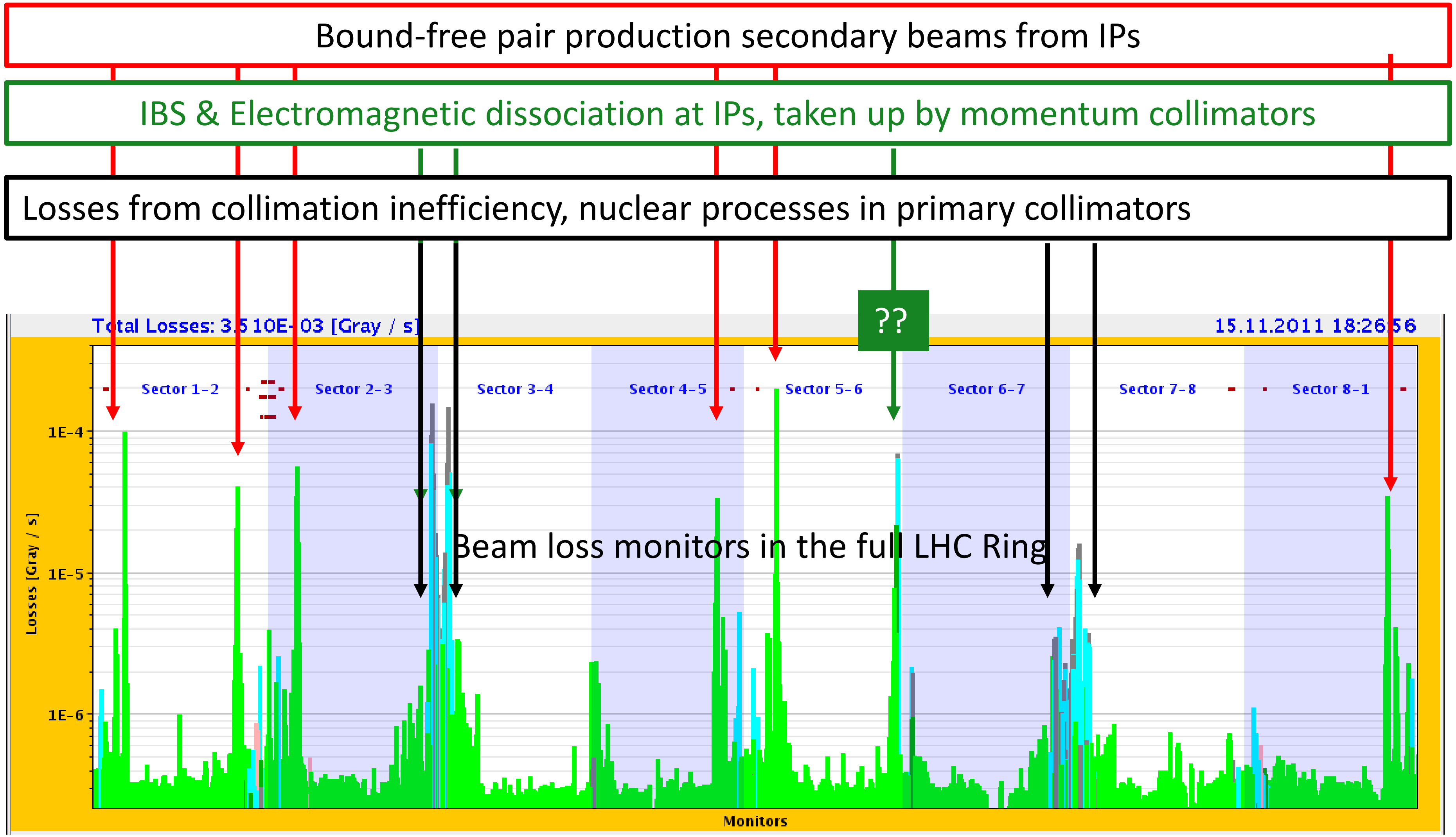
Main and BFPP secondary beams

5σ beam envelopes, emerging to right of IP2

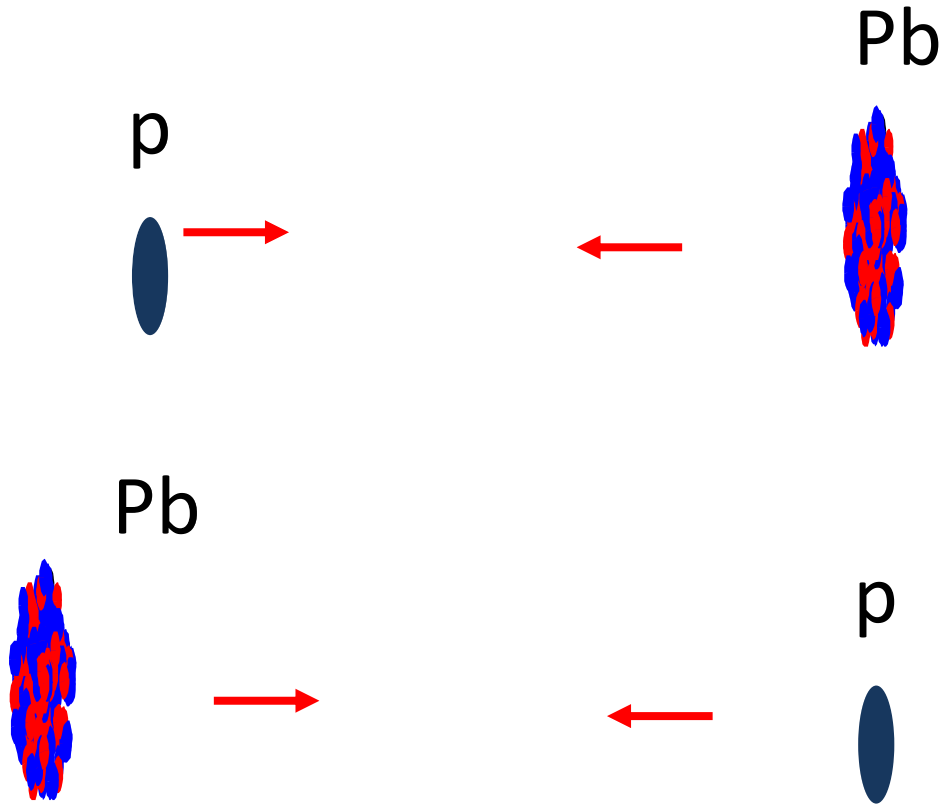


Power in secondary beam can quench superconducting magnets

Steady-state losses during Pb-Pb Collisions in 2011



No time to discuss major topic of heavy-ion collimation in this talk. Important limit of total beam intensity for Run 3 onwards, now relying on new crystal collimation system.



PROTON-LEAD COLLISIONS IN LHC

First asymmetric collisions at LHC

History of proton-nucleus collisions at LHC

The first (almost free) “upgrade” of the LHC

- **2005**: physics interest and operation scheme first outlined at TH workshop in CERN
- **2006**: First paper at European Particle Accelerator Conference, in Edinburgh
- **Early 2011**: LHC Chamonix workshop – go-ahead given for feasibility tests on LHC
- **2011**: Preparation of LHC systems during 2011
- **31 Oct. 2011**: successful feasibility test
- **Early 2012**: after high Pb-Pb luminosity in Nov 2011, experiments really want p-Pb comparison data
- **13 Sep. 2012**: Successful pilot collision run (one night) yields new physics - the largest jump in collision energy, factor 25 (of given collision type), in history of particle accelerators
- **Jan.–Feb. 2013**: first full physics run
- **Nov. 2016**: second run, multiple collision conditions including higher energy, almost 9 times “design” luminosity

Relation between Beam Momenta

- LHC accelerates **protons** through the momentum range

$$0.45 \text{ TeV (injection from SPS)} \leq p_p \leq 7 \text{ TeV (collision)}$$

  - p_p is measure of magnetic field in main bending magnets
- The two-in-one magnet design of the LHC fixes the relation between momenta of beams in the two rings (equal *"magnetic rigidity")*

$$p_{\text{Pb}} = Z\, p_{\text{p}}$$

$$\text{where } Z = 82,\ A = 208 \text{ for fully stripped Pb in LHC}$$

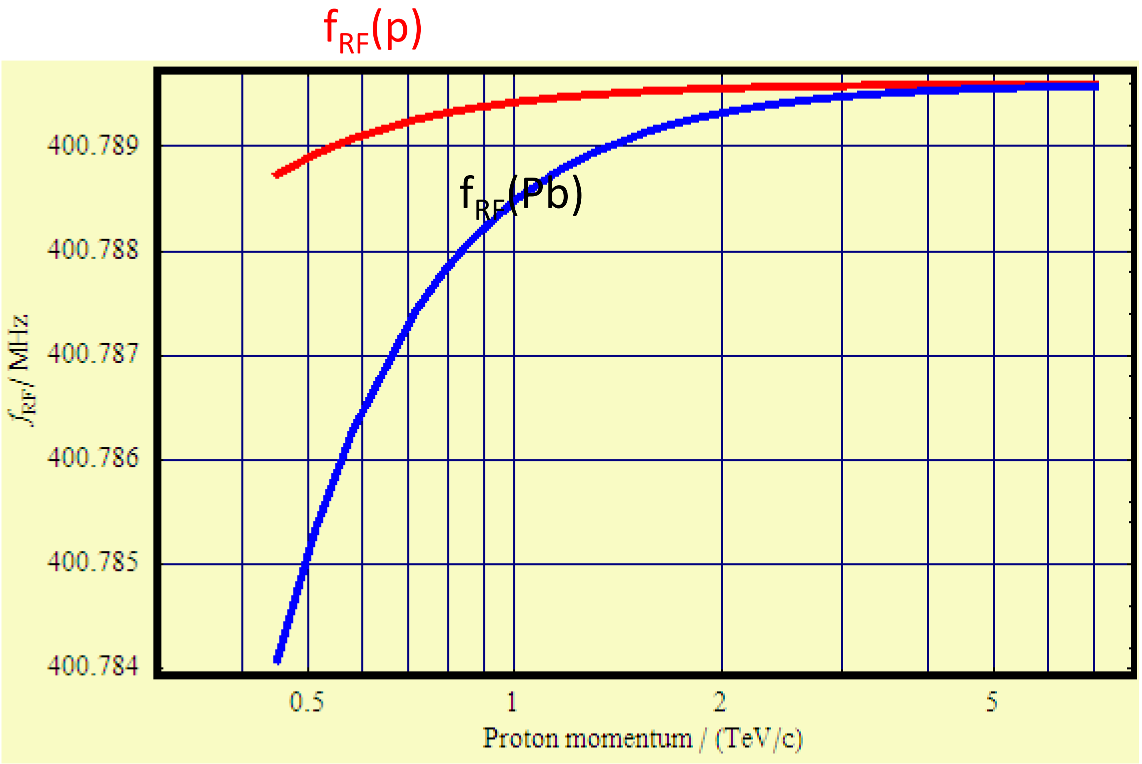
RF Frequency for p and Pb in LHC (see Longitudinal Dynamics …)

Revolution time of a general particle, mass m, charge Q, is

$$T(p_p, m, Q) = \frac{C}{c}\sqrt{1+\left(\frac{mc}{Qp_p}\right)^2} \quad \text{and RF frequency} \quad f_{RF} = \frac{h_{RF}}{T(p_p, m, Q)}$$

where the harmonic number $h_{RF} = 35640$ in LHC

RF frequencies needed to keep p or Pb on stable *central* orbit of constant length *C* are different at low energy.



No problem in terms of hardware as LHC has independent RF systems in each ring.

- Additional degree of freedom: adjust length of closed orbits to compensate different speeds of species.
  - Done by adjusting RF frequency

$$T(p_{\mathrm{p}}, m, Q) = \frac{C}{c}\sqrt{1+\left(\frac{mc}{Qp_{\mathrm{p}}}\right)^2}\,(1+\eta\delta)$$

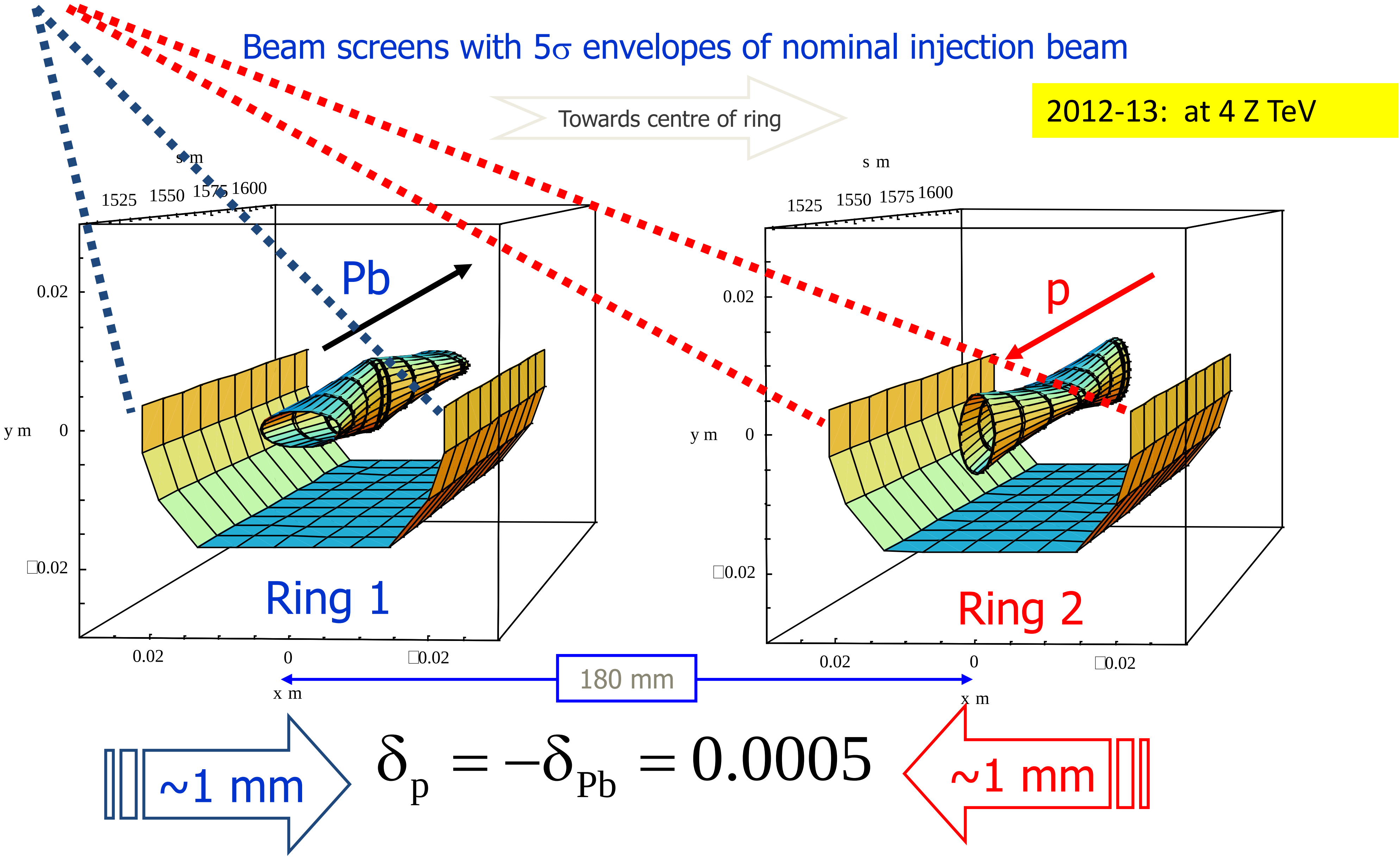
where $\delta = \frac{(p - Qp_{\mathrm{p}})}{Qp_{\mathrm{p}}}$ is a fractional momentum deviation and

the phase-slip factor $\eta = \frac{1}{{\gamma_T}^2} - \frac{1}{\gamma^2}$, $\gamma = \sqrt{1+\left(\frac{Qp_{\mathrm{p}}}{mc}\right)^2}$, $\gamma_T = 55.8$ for LHC optics.

Moves beam on to off-momentum orbit, longer for $\delta > 0$.

Horizontal offset given by dispersion: $\Delta x = D_x(s)\,\delta$.

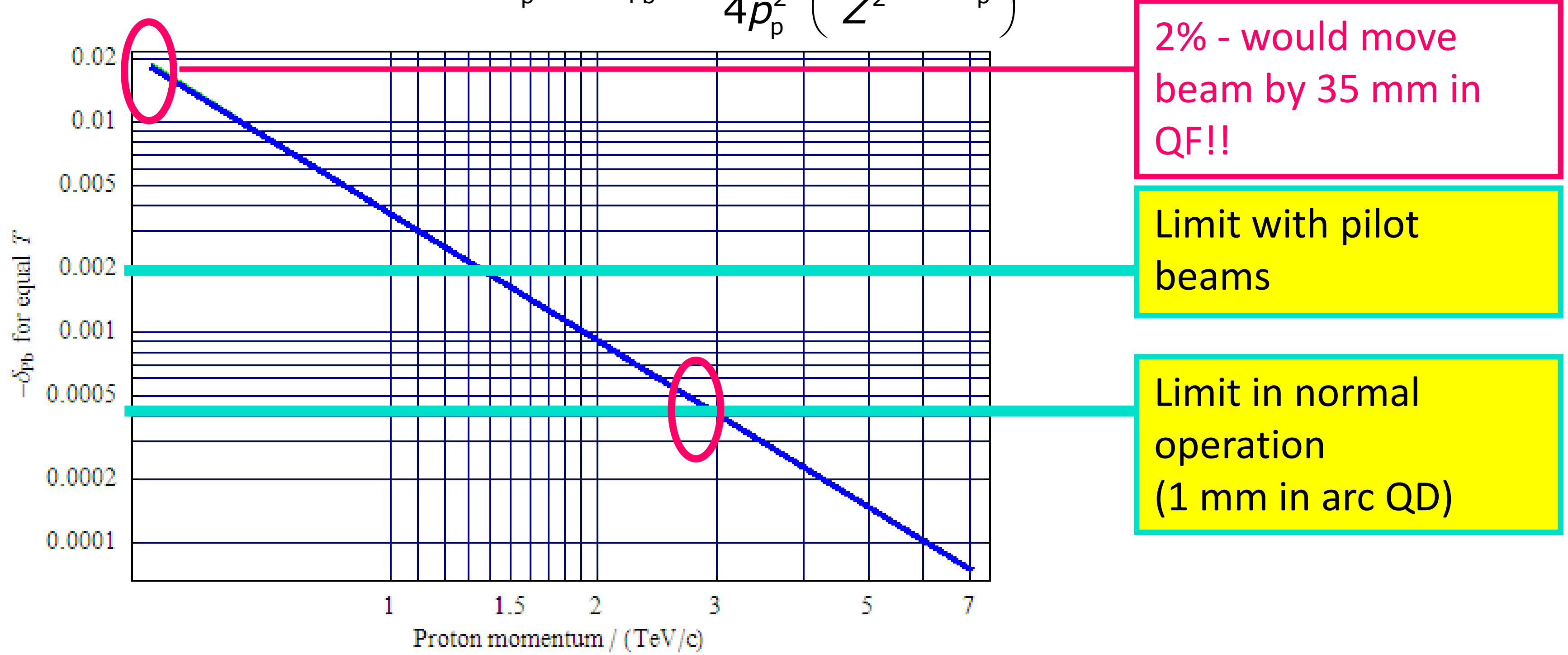
A FODO cell in the arc between ATLAS and ALICE



$$\delta_p = -\delta_{Pb} = 0.0005$$

Momentum offset required through ramp

Minimise aperture needed by $\delta_{\rm p} = -\delta_{\rm Pb} = \dfrac{c^2 {\gamma_T}^2}{4 p_{\rm p}^2}\left(\dfrac{m_{\rm Pb}^2}{Z^2} - m_{\rm p}^2\right).$

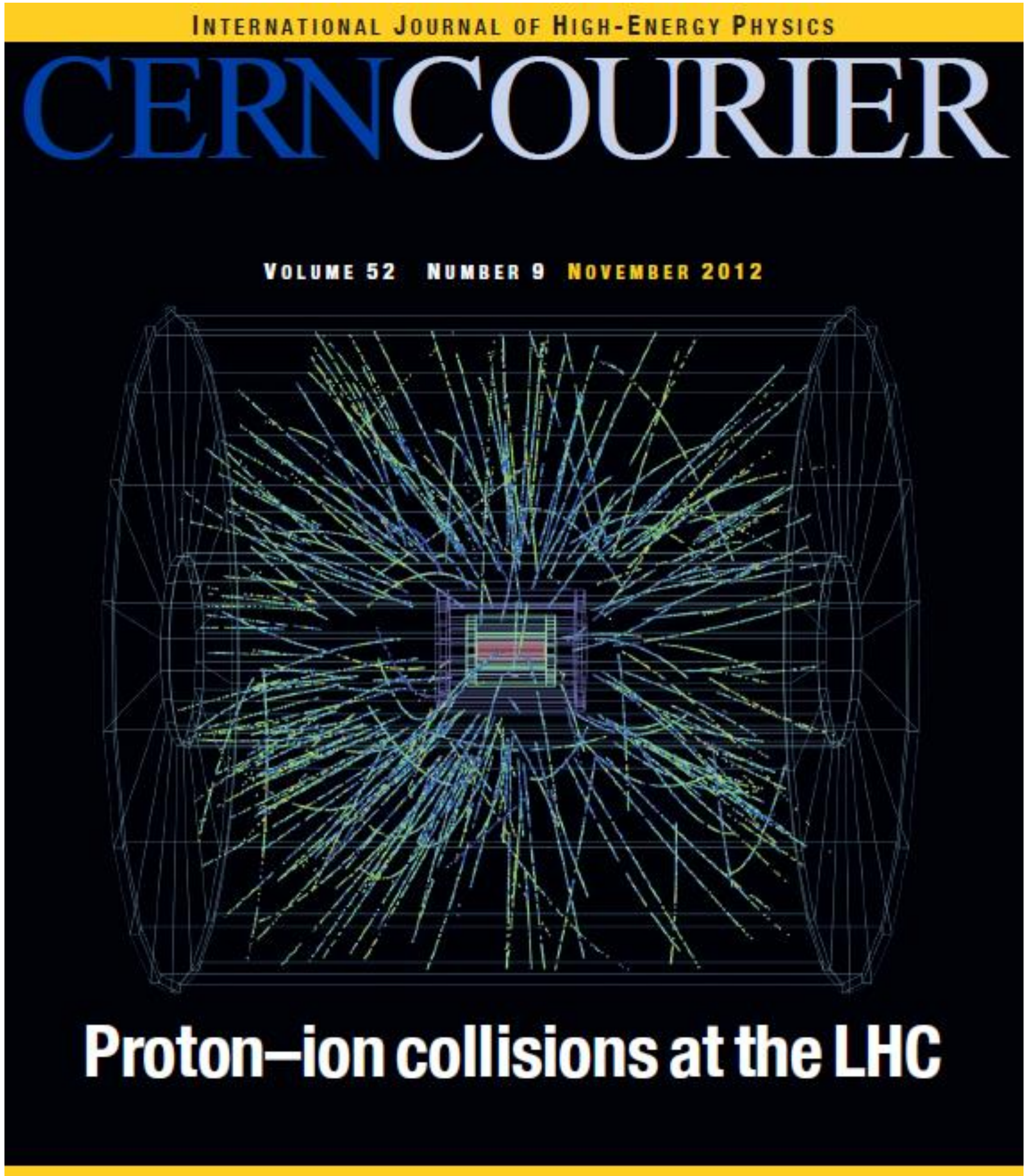


Revolution frequencies must be equal for collisions at top energy.

Lower limit on beam energy for p-Pb collisions, E=2.7 Z TeV.

RF (and revolution) frequencies must be unequal for injection, ramp!

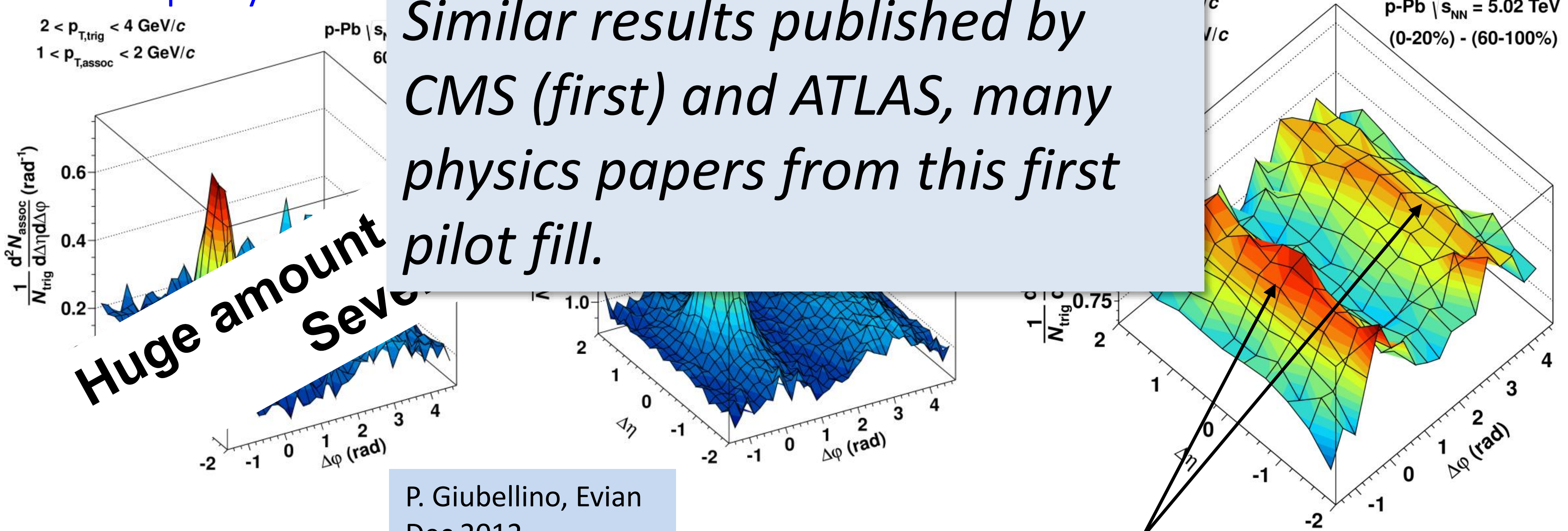
Concerns about instabilities driven by modulated beam-beam effects that were major problem at RHIC – see backup slides.


INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
CERNCOURIER
VOLUME 52 NUMBER 9 NOVEMBER 2012
Proton–ion collisions at the LHC

First 4 h of physics: Correlations in p-Pb: the unexpected "ridge"

- A double-ridge structure appears, with remarkable properties:
  - Can be expressed in terms of $v_{2,3}$, Fourier coefficients of single particle az... distribution, with $V_{2,3}$ increasing with p_T and v_2 also with multiplicity
  - **Same yield near and away side for all classes of p_T and multiplicity: common underlying process**
  - Width independent of yield
  - No suppression of away side observed (its observation at ... RHIC is considered a sign of saturation effects)
  - In agreement with viscous hydro calculations ?!

Low multiplicity event c...



...ing a new window in the field

... 4 h of collisions

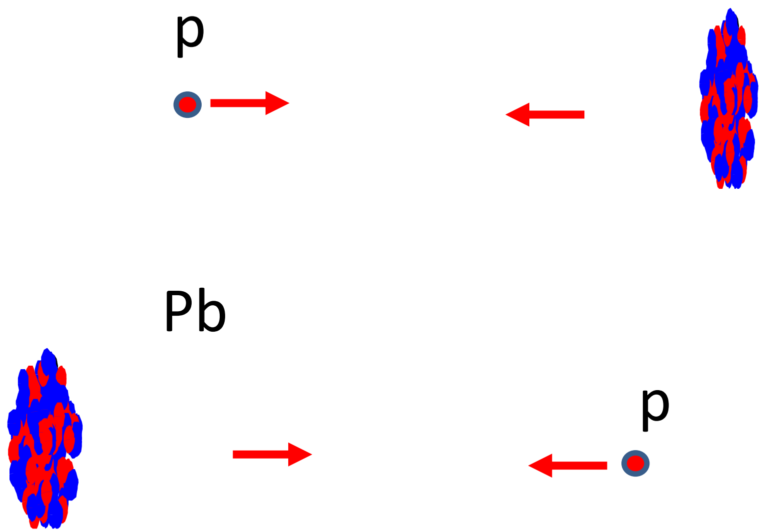
Huge amount ...

Seve...

Similar results published by CMS (first) and ATLAS, many physics papers from this first pilot fill.

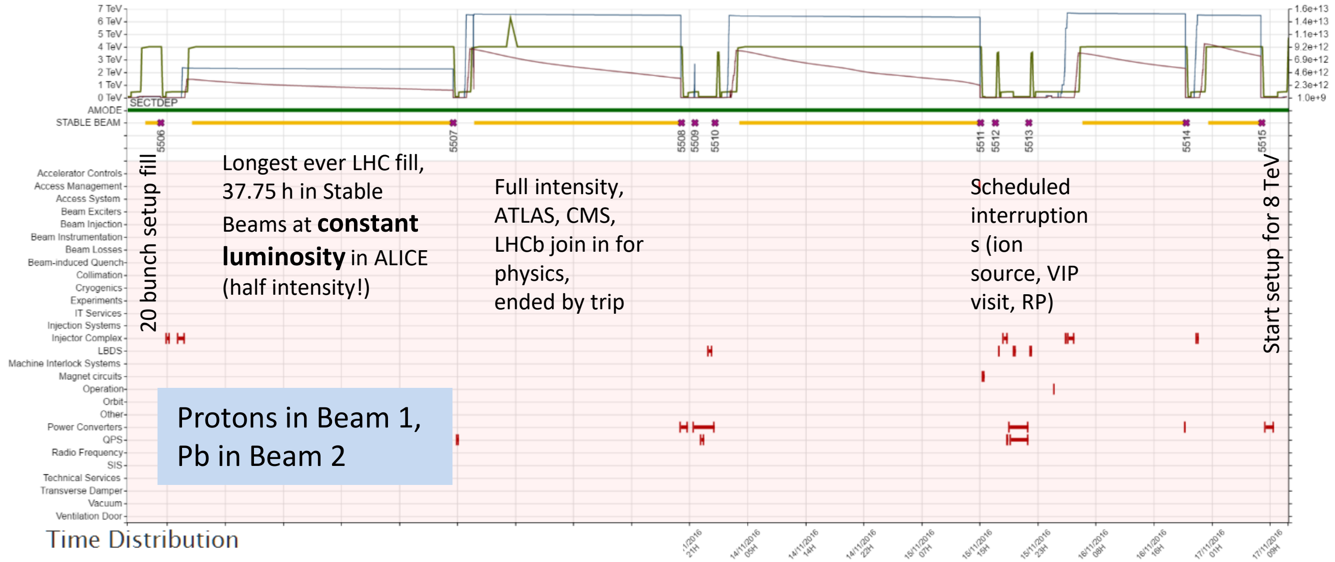
P. Giubellino, Evian Dec 2012

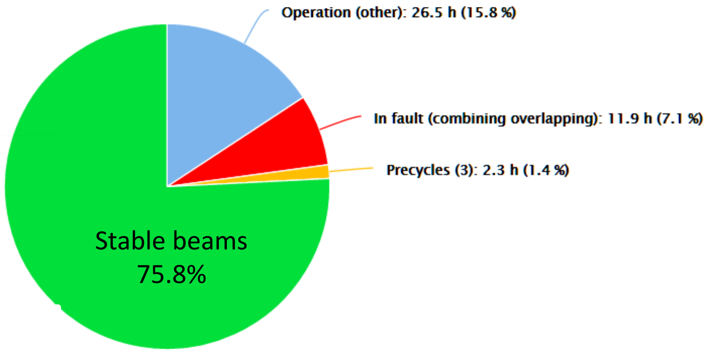
Double-ridge structure



2016

Part 1: 1 week at 5 TeV, levelled luminosity for ALICE



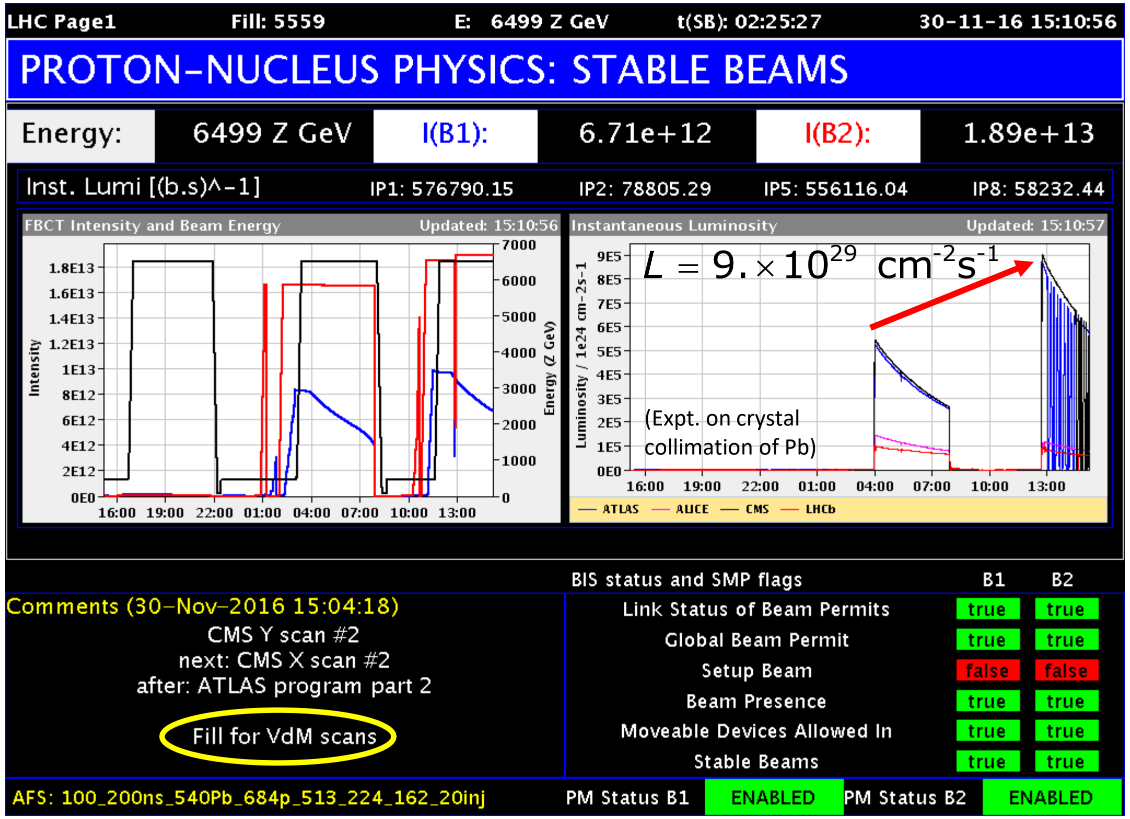


Fills could have been much longer still. Lifetime good enough to give bonus minimum-bias programmes to ATLAS, CMS as well as ALICE.

LHCb colliding p-He (gas).

Special conditions admittedly, but astonishing availability!

Part 2: Record Pb-p luminosity in ATLAS/CMS at 8.16 TeV



Peak luminosity a factor ~6 beyond original "design" value
(J. Phys. G 39 (2012) 015010)

Could have gone higher still by further increase of p intensity but limited at present by Pb beam luminosity debris in magnets of Sector 12.

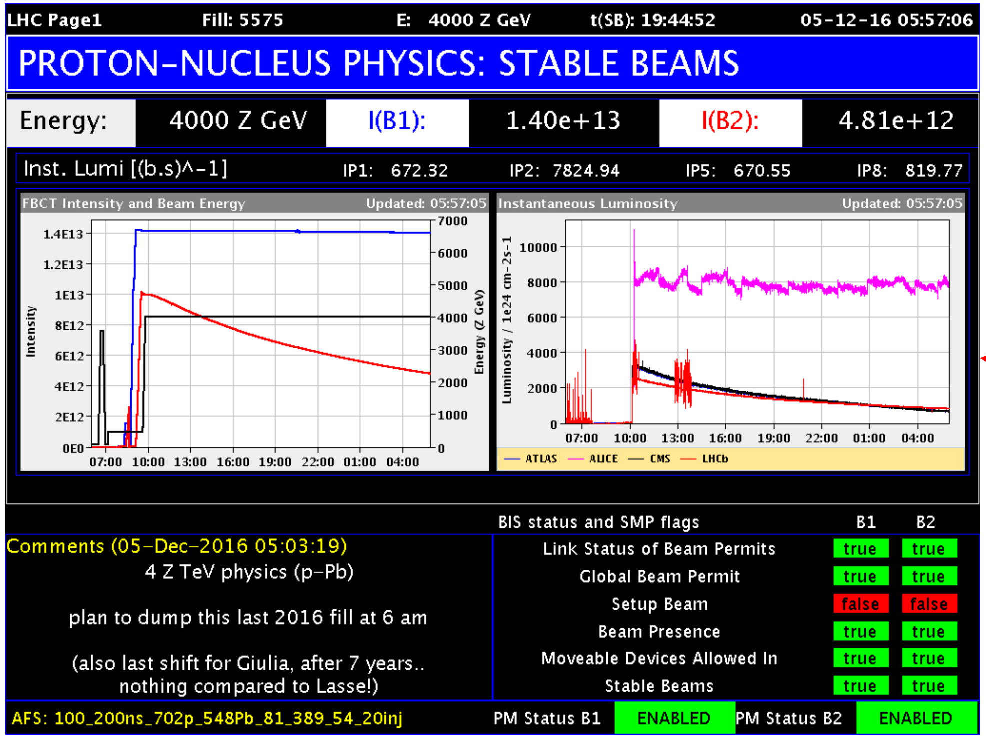
Common BPMs and moving encounters had constrained charge of p and Pb bunches to be similar.

Increase in p intensity to ~3×10^{10}/bunch enabled by new synchronous orbit mode of beam position monitors (R. Alemany, J. Wenninger, beam instrumentation group …)

Pb intensity to ~2.1×10^{8}/bunch

25% increase in ATLAS/CMS from filling scheme

Last LHC fill of 2016 - back to p-Pb at 5 TeV

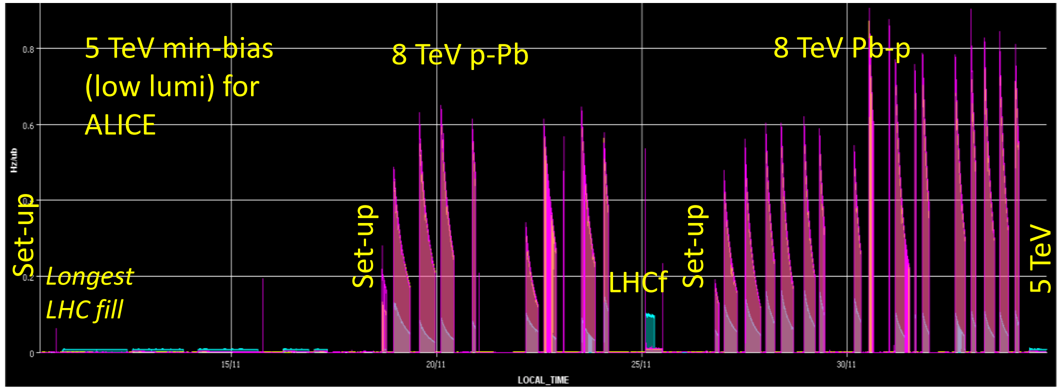


Fast switch back to original conditions to top-off ALICE minimum-bias data-taking.

Levelled 19h50 in Stable Beams, dumped at 06:02 Monday 5 Dec.

Complex run made possible by extraordinary quality of LHC construction and operation, excellent performance of ALL the injectors together.

Luminosity during the whole run



Proton-nucleus programme status

Feasibility and first p-Pb run at 4 Z TeV in 2012/13.

Complex 2016 run plan determined after Chamonix 2016:

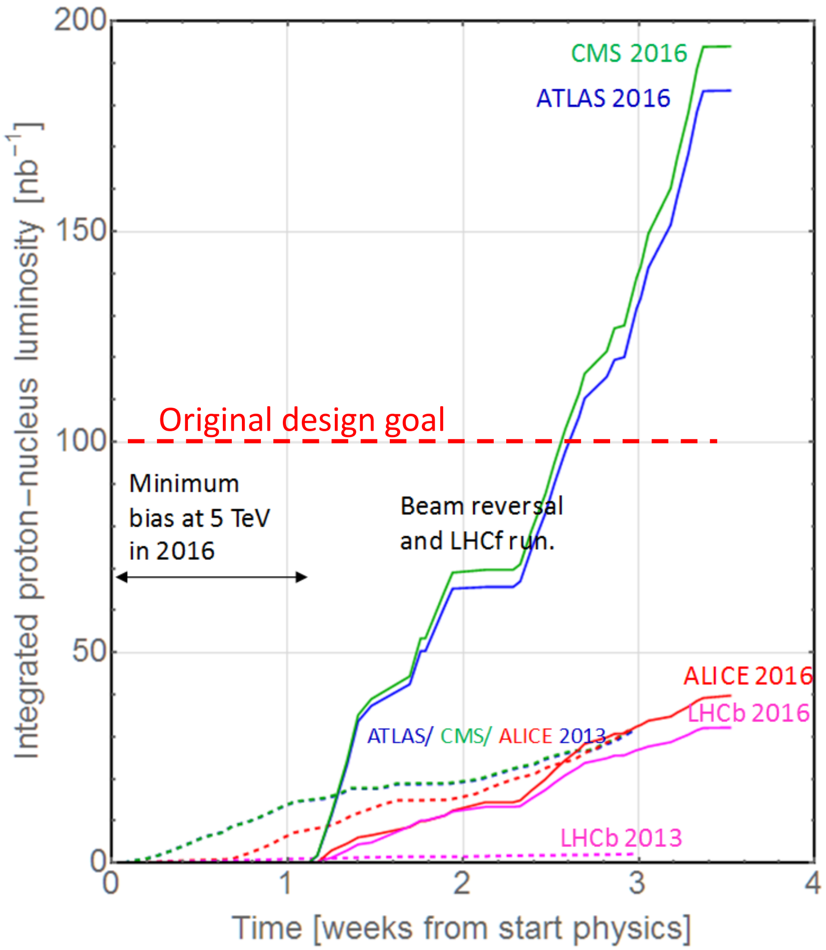
Minimum bias run at 4 Z TeV mainly for ALICE

High luminosity run for all experiments (+LHCf) at 6.5 Z TeV, with beam reversal p-Pb and Pb-p.

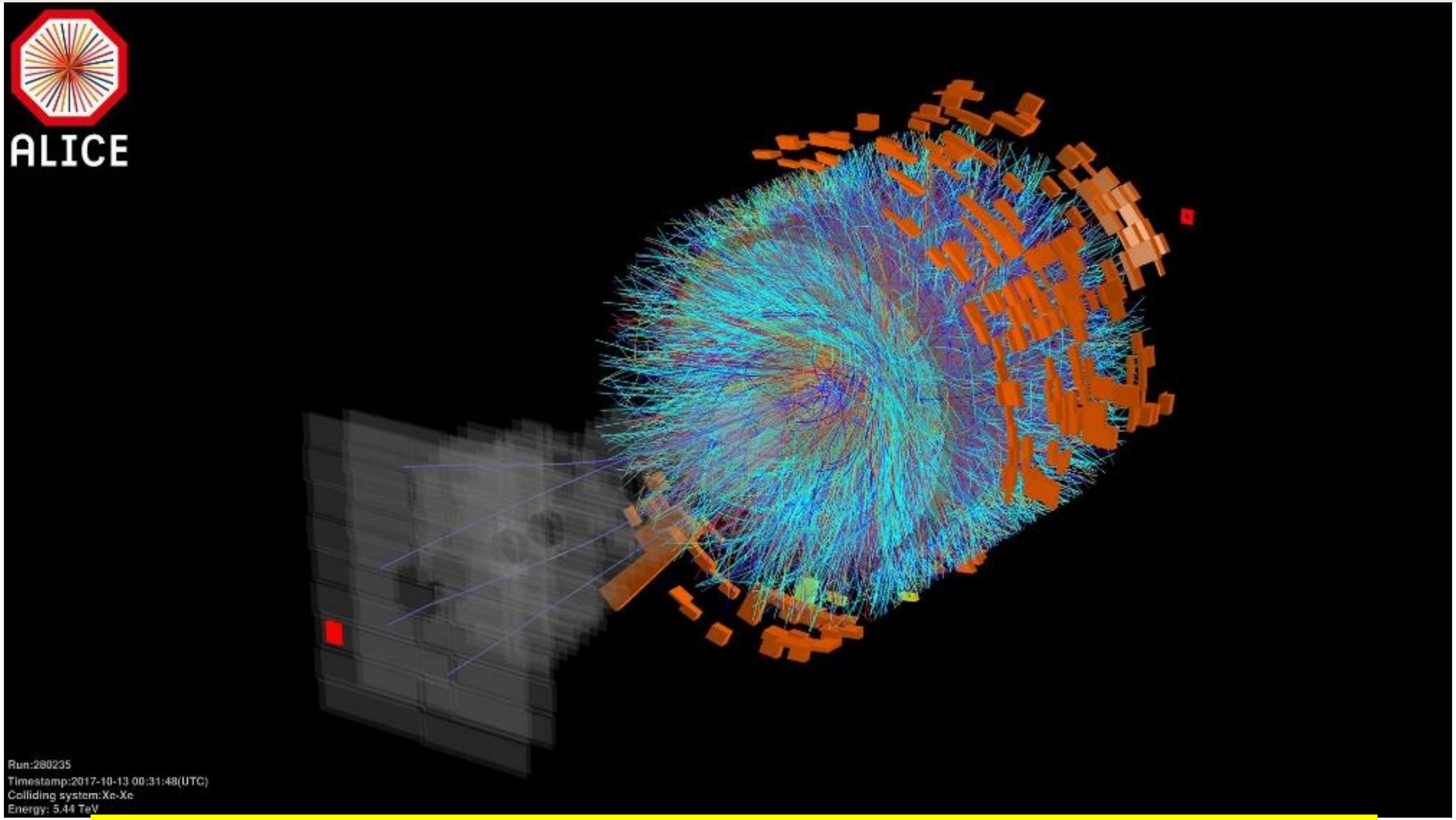
Ie, 2 new optics and 3 setups with full qualifications in 1 month.

Asymmetric beams, unequal frequency ramp, cogging for collisions off-momentum, etc.

Many filling schemes used for luminosity sharing.



Xe-Xe collisions in LHC, 13 October 2017



Short opportunistic run with new ions. Modelled on 2012 p-Pb: 8 h set-up, 8 h collisions.
Low luminosity again but something completely new …
Also used to test collimation and crystal collimation with new beams.

Results from Xe-Xe run of LHC at Quark Matter conference, May 2018

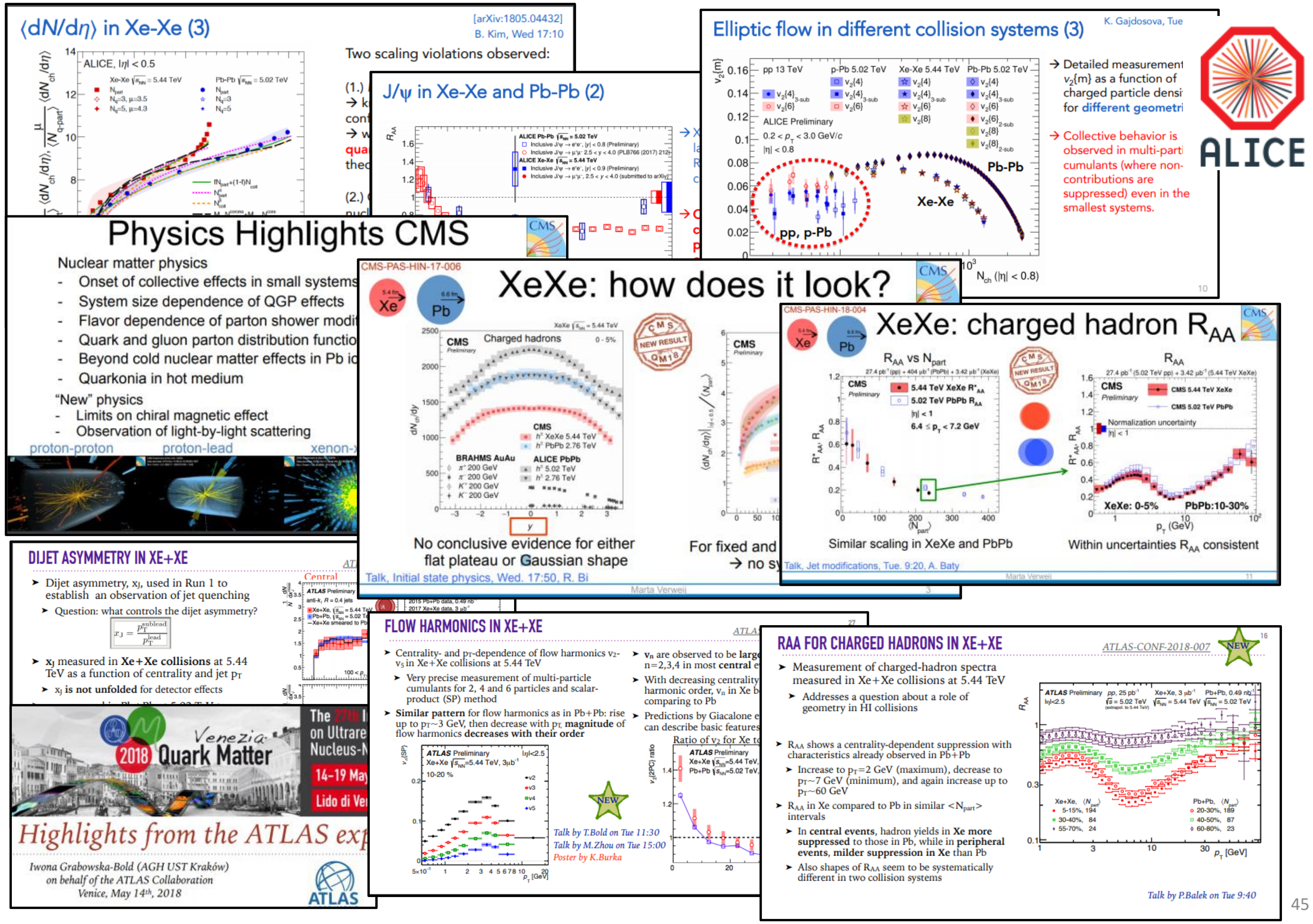
Rich physics harvest from 16 h (6.5 h Stable Beams) Xe-Xe run of LHC on 12/10/2017.

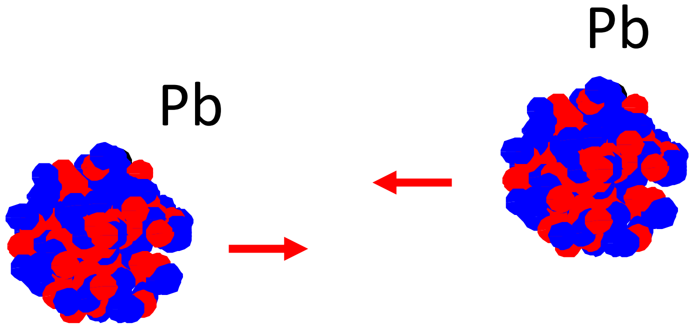
Results reported by all LHC experiments, clarifying the transitions between Pb-Pb, p-Pb and p-p.

Illustrates "beyond-design" potential of LHC.

Input to HL/HE-LHC Physics Workshop case for possible future runs with lighter nuclei.

Papers using the Xe-Xe data continued to be published now in 2022.

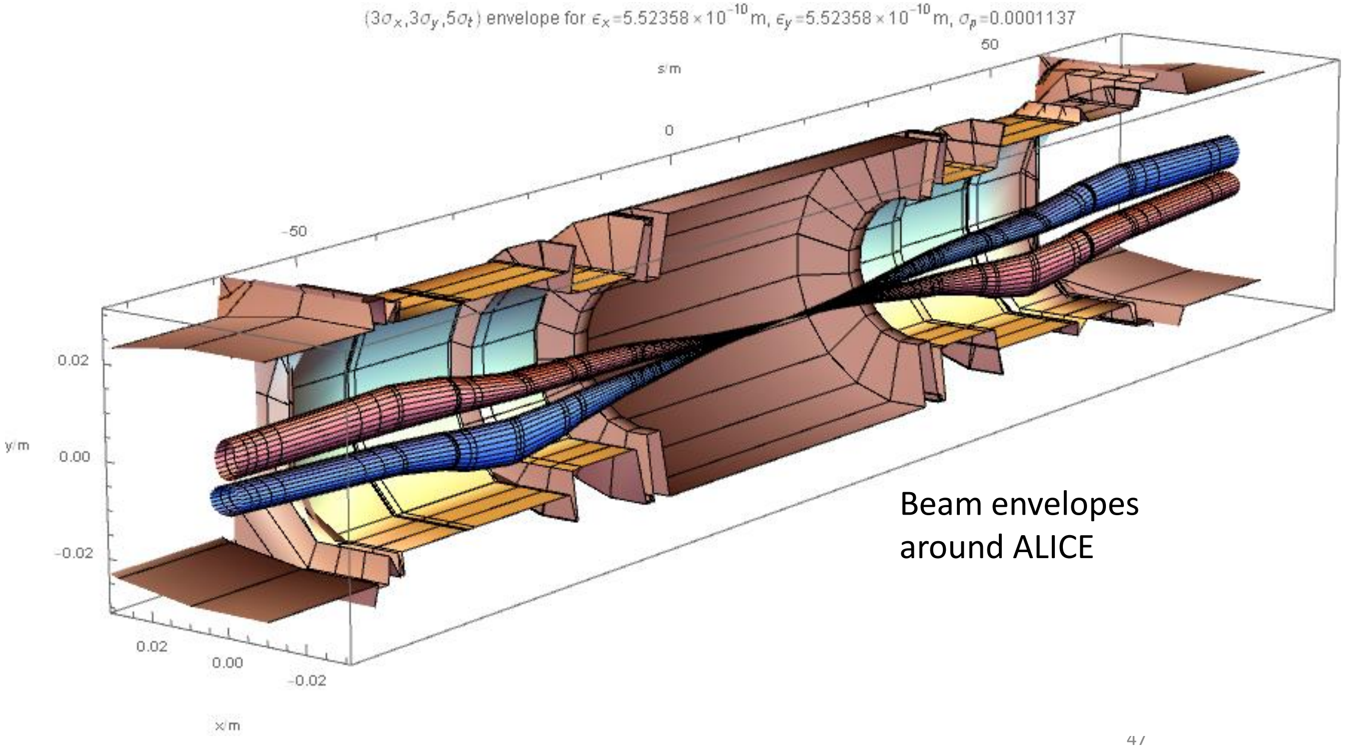




2018

Pb-Pb in 2018: new optics with smallest ever β* in both ALICE and LHCb

- Optics design by S. Fartoukh, new combined ramp & squeeze
- Gradual divergence from identical to pp optics in 2010 to a completely new cycle in 2018
- Initial problem with beam size in ALICE now ~completely understood
- Fixed for reversed-polarity part of run
- Some lessons for optics correction procedure in future

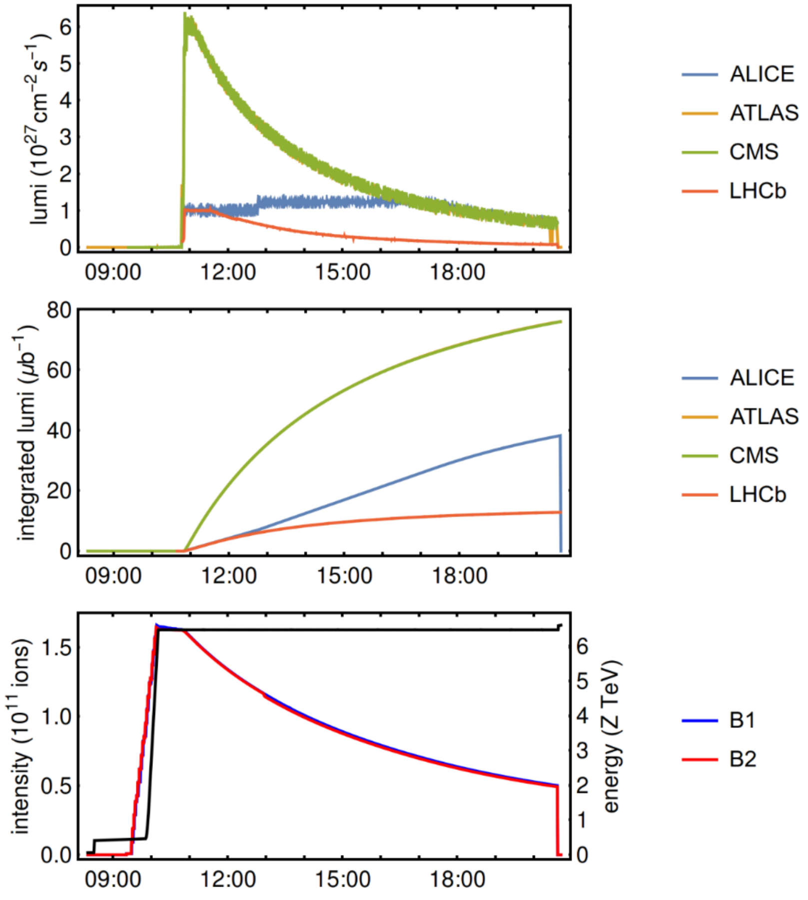


Beam envelopes around ALICE

A high peak luminosity Pb-Pb fill in 2018 with 100 ns

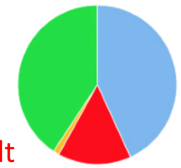
- Leveling in ATLAS and CMS gradually increased to 6×10^{27} cm^{-2}s^{-1}
- ALICE leveled at design luminosity 1×10^{27} cm^{-2}s^{-1}

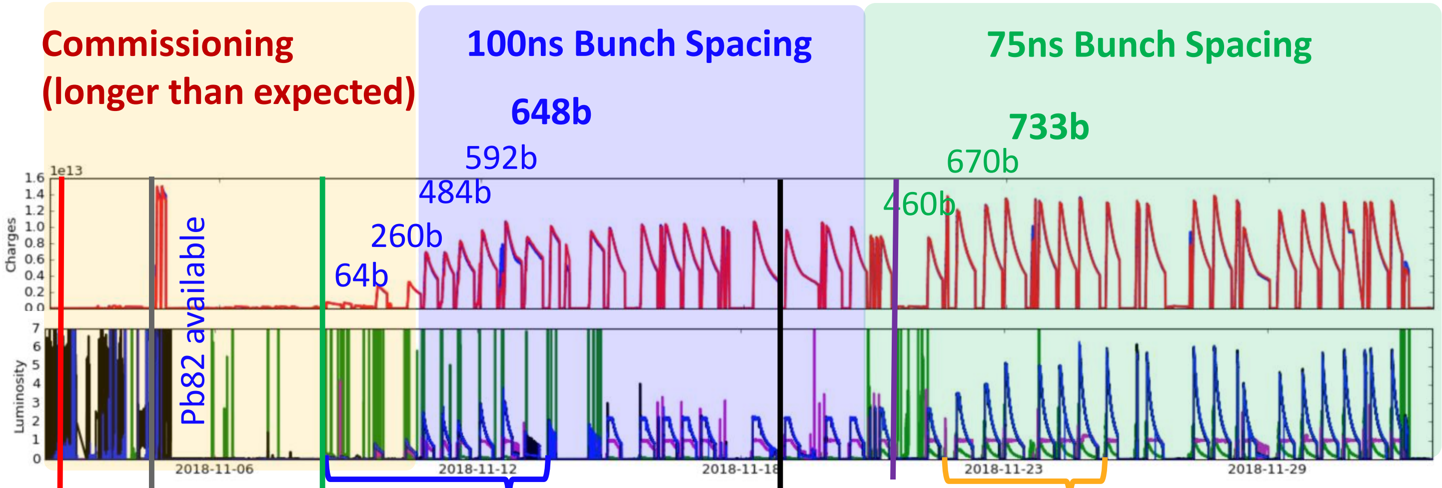
- After correction of local coupling, ALICE level times increased to ~ 8 h.



Evolution of 2018 Pb-Pb run – the last HI operation of LHC (until short test in 2022)

Availability
85%





Ion source fault
no ions
available

1st Pb-Pb
Stable
Beams

Intensity ramp-up
100ns beams

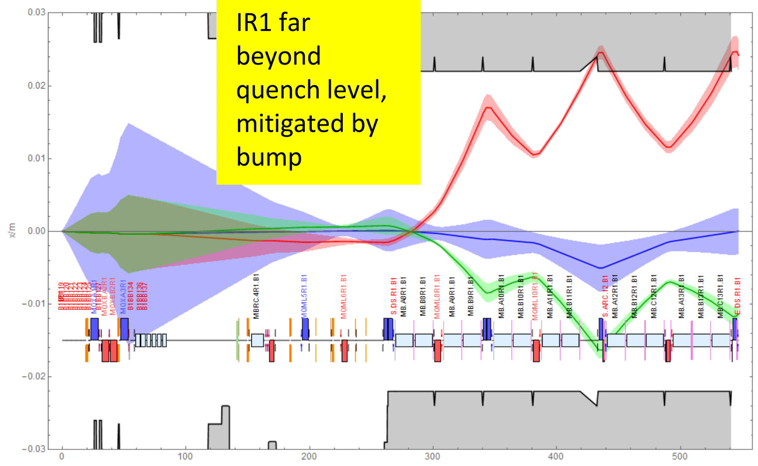
Ion source refill

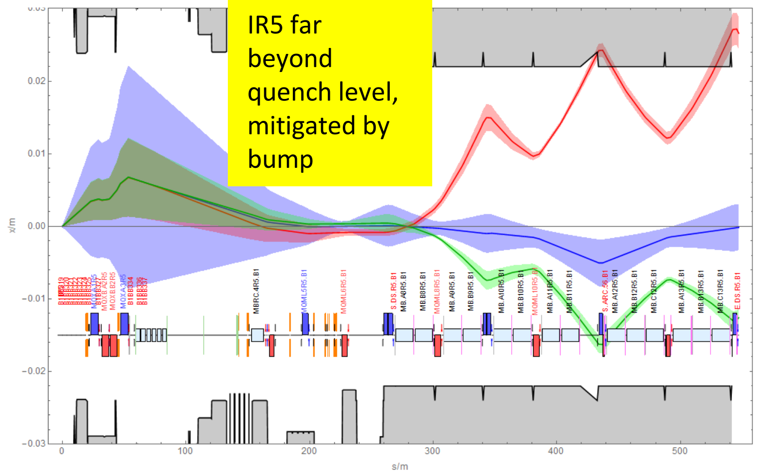
New Record Peak
luminosity in every fill
up to $6.4\times10^{27}cm^{-2}s^{-1}$

Repetition of luminosity calibration
for special physics run (protons)

ALICE
polarity
switch & fix
of IR2
coupling

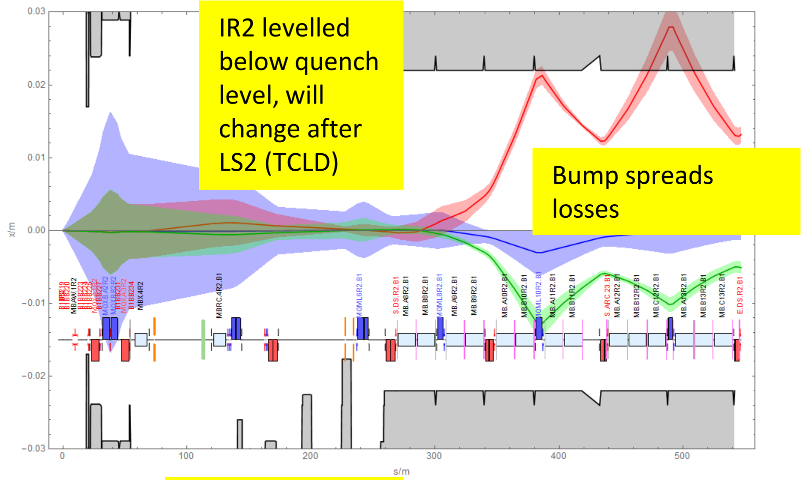
Significant BFPP beams in all IPs (horizontal envelopes)

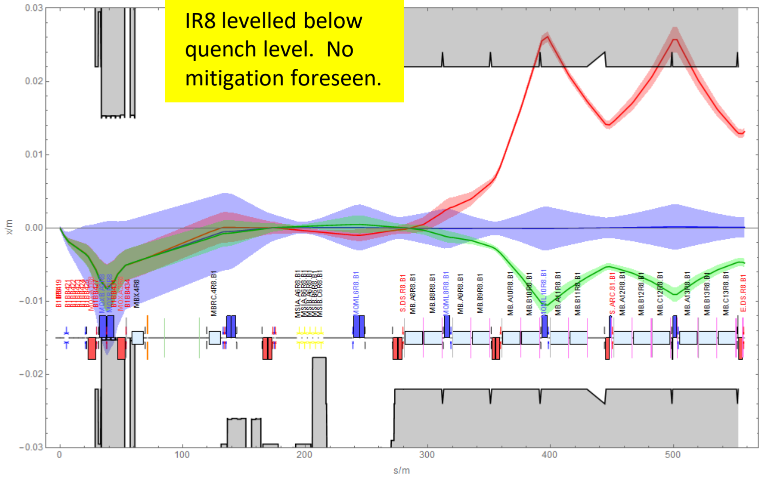




Bumps were adjusted empirically, good agreement with calculation, except left of IP5, location of 2015 BFPP quench test.

Chamber misalignment.





Nucleus-nucleus programme status after 2018

LHC "first 10-year" baseline Pb-Pb luminosity goal was 1 nb^{-1} of Pb-Pb luminosity (only) in Runs 1+2.

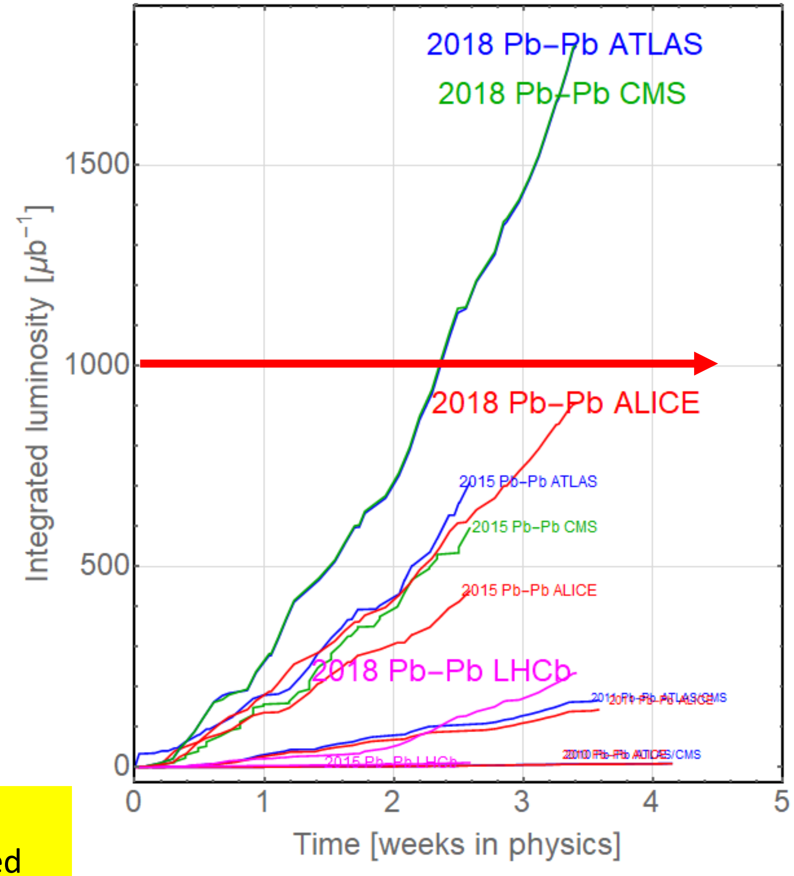
Goal of the first p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs but it already provided reference data at 2015 energy.

Equivalent energy runs

$$\sqrt{s_{NN}} = 5.02 \text{ TeV} \quad (\sqrt{s}=1.045 \text{ PeV in Pb-Pb})$$

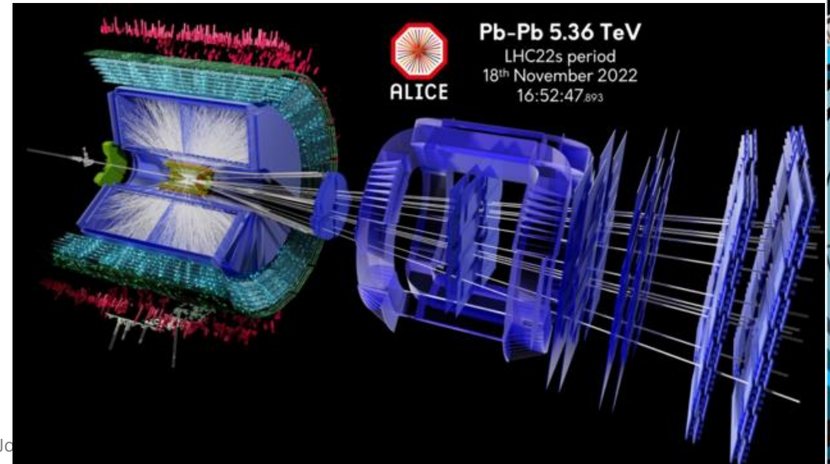
$$\Rightarrow E_b = \begin{cases} 6.37Z \text{ TeV} & \text{in Pb-Pb (2015,2018)} \\ 4\ Z \text{ TeV} & \text{in p-Pb (2013,part 2016)} \\ 2.51 \text{ TeV} & \text{in p-p (2015)} \end{cases}$$

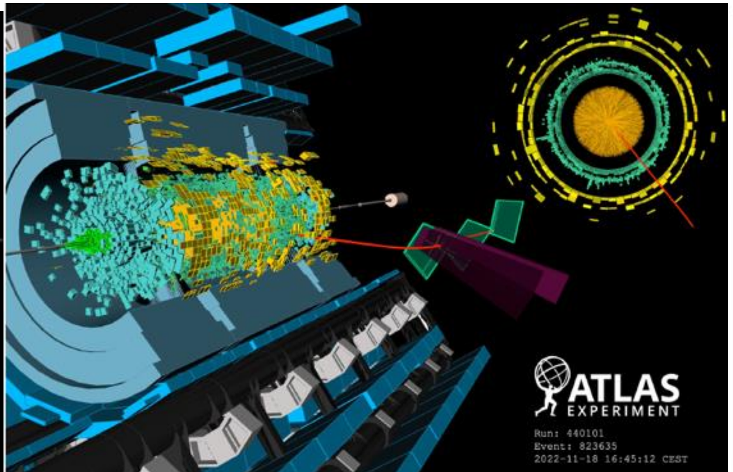
ALICE integrated luminosity in 2018 was equivalent to spending 10.4 days, 100% of the time, at constant levelled saturation luminosity.

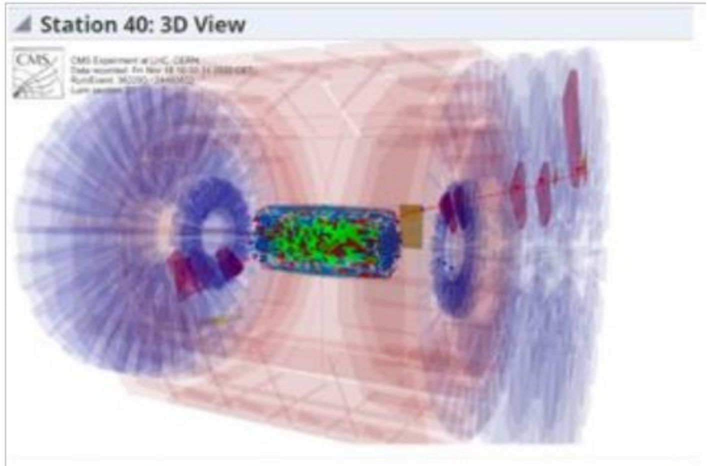


Outlook for future nuclear collisions at LHC

- Rich physics output from Run 2 still emerging.
- All “HL-LHC” upgrades have now been implemented for heavy ions
  - New collimators around IP2 will remove the BFPP limit and allow the upgraded “ALICE2” detector to take the same high luminosity as ATLAS and CMS
  - New crystal collimation system
  - More bunches (LIU project, slip-stacking in SPS, …) will provide higher total beam intensity (shorter bunch spacing) and luminosity
- Plans for a short run with O-O and p-O collisions in 2024
- Proposal for a new ALICE3 detector in Run 5 will open up new physics possibilities, perhaps with lighter nuclei

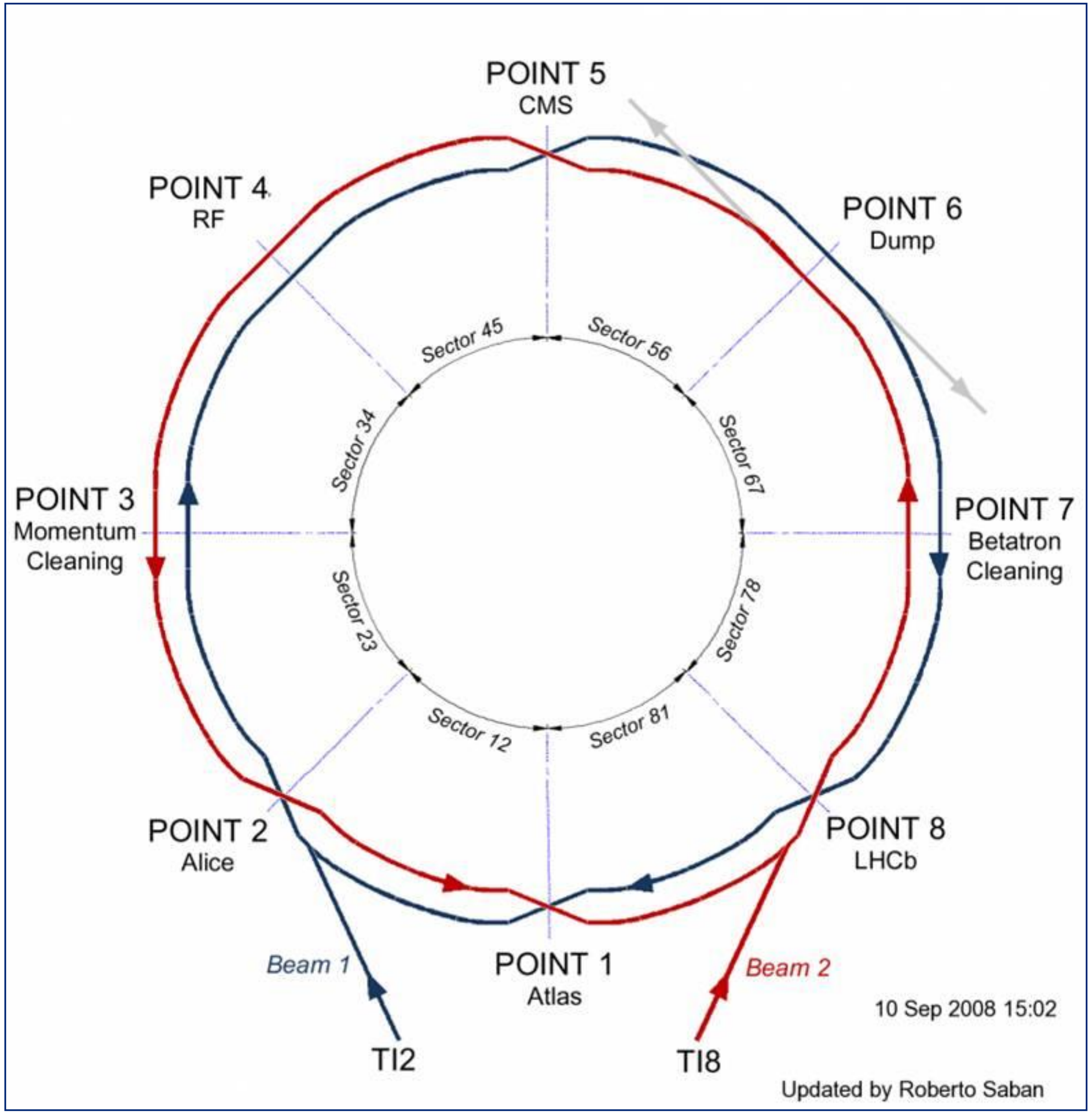






BACKUP SLIDES

LHC orientation - schematic



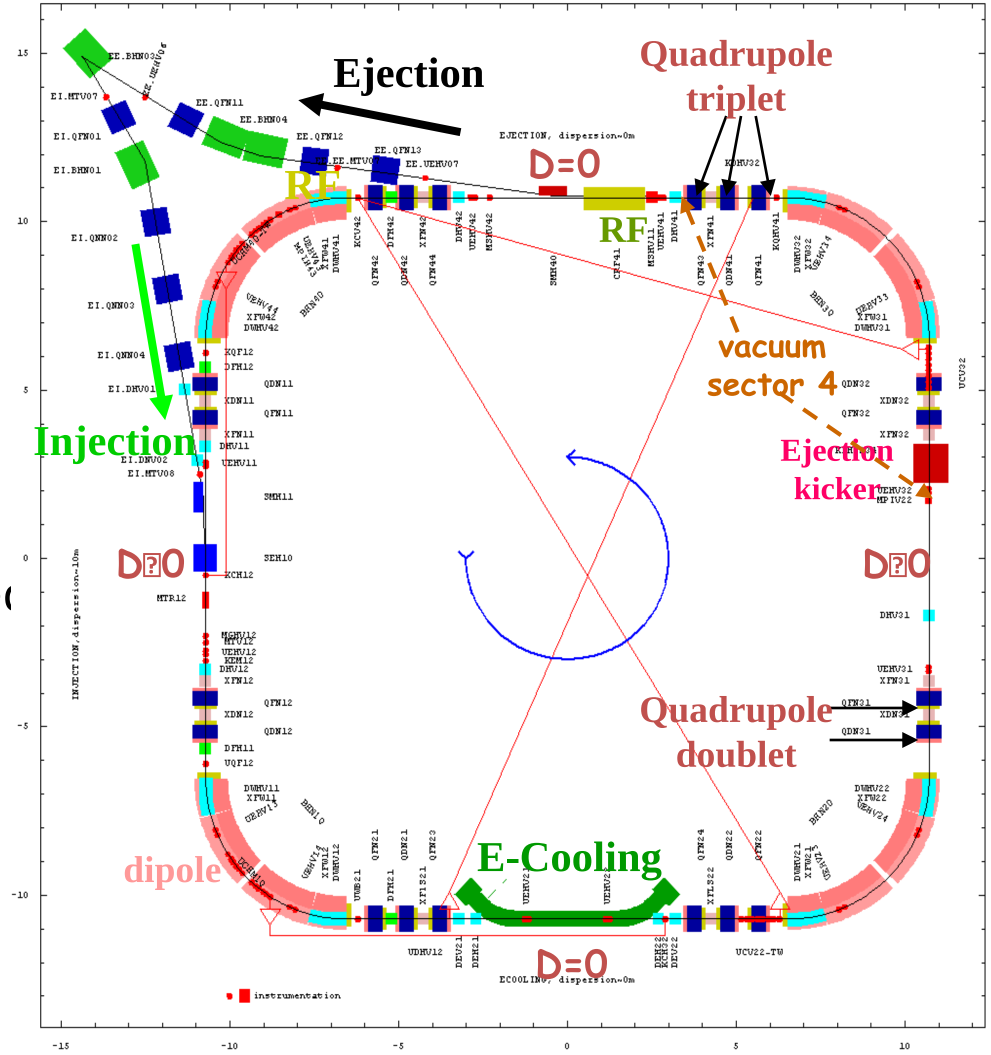
Four large and highly capable heavy-ion physics experiments:
ALICE, CMS, ATLAS
LHCb since 2012

Each beam has its own reference orbit in the twin-aperture magnets of the arcs, common in interaction regions.

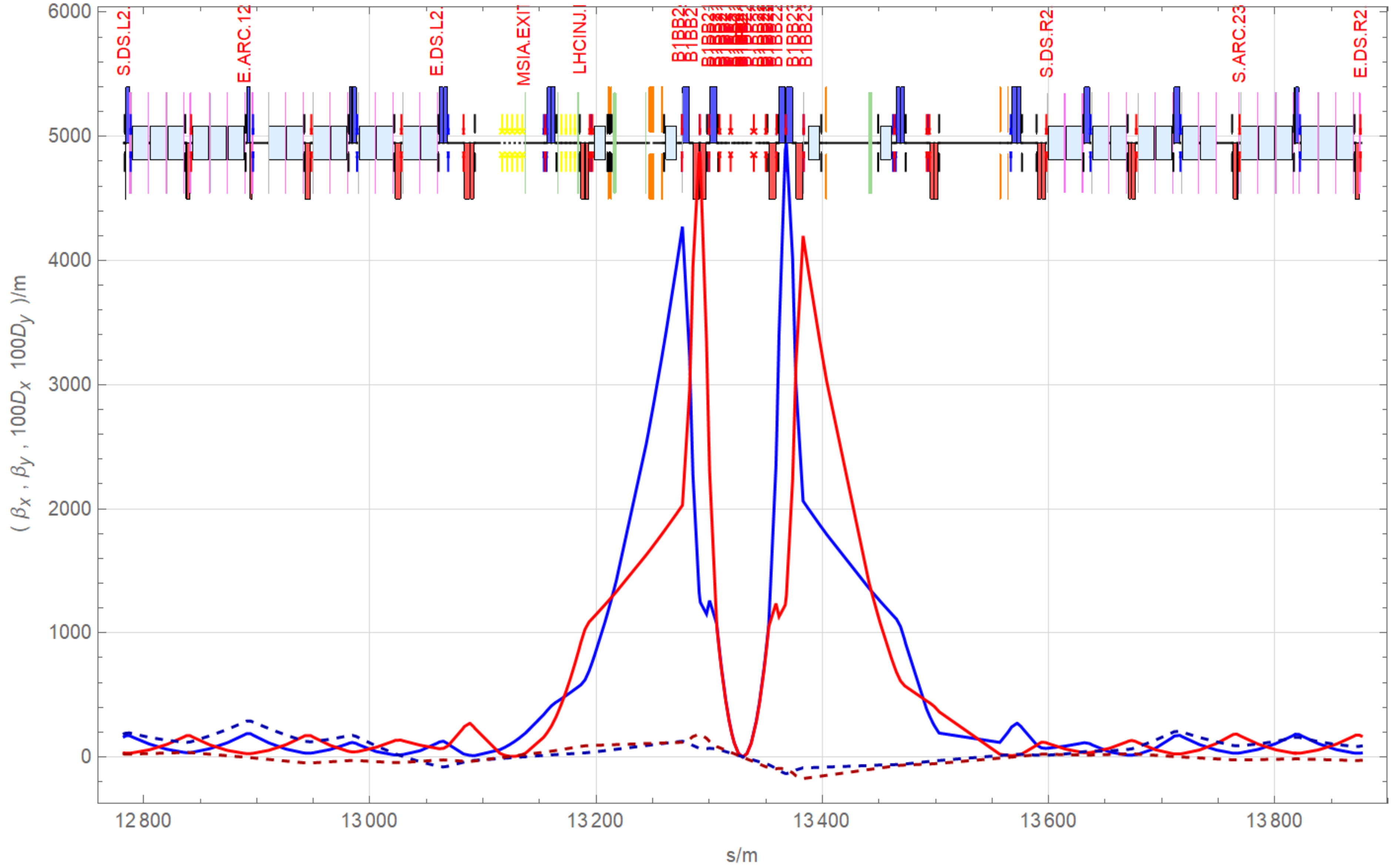
$s_1(\text{IP1}) = s_2(\text{IP1}) = 0$ (ATLAS) for both beams by convention

Inner and outer arc lengths are slightly different so
$s_1(\text{IP2}) = 3332.436$ m
$s_2(\text{IP2}) = 3332.284$ m

- Prepares beams for LHC using electron cooling
- circumference 25p m (1/8 PS)
- Multiturn injection into horizontal+vertical+longitudinal phase planes
- Fast Electron Cooling : Electron current from 0.5 to 0.6 A with variable density
- Dynamic vacuum (NEG, Au-coated collimators, scrubbing)

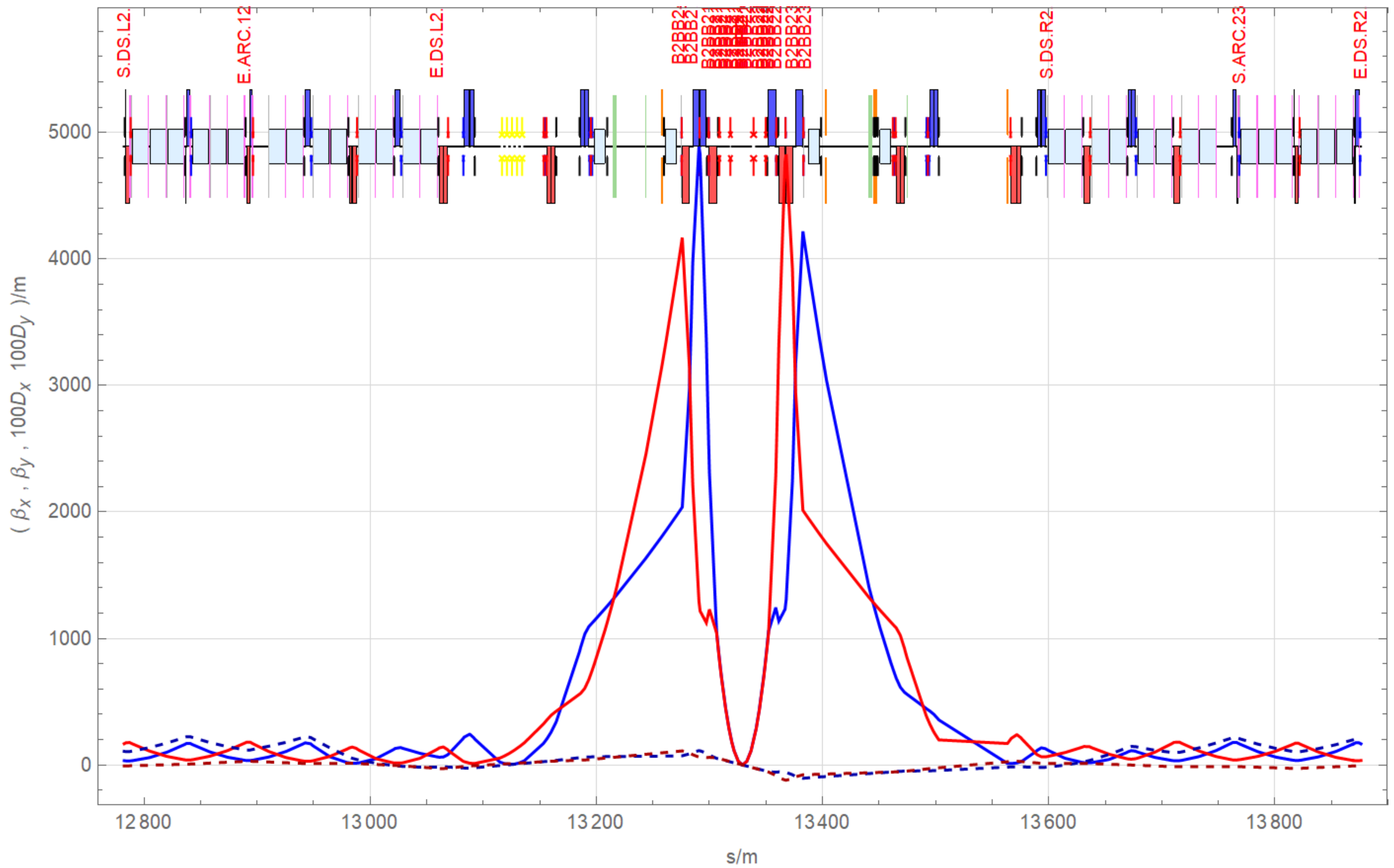


Optical functions for Beam 1 in LHC IR2, 2018



Optics solutions must be found for each beam with these constraints.

Optical functions or Beam 2 in LHC IR2, 2018



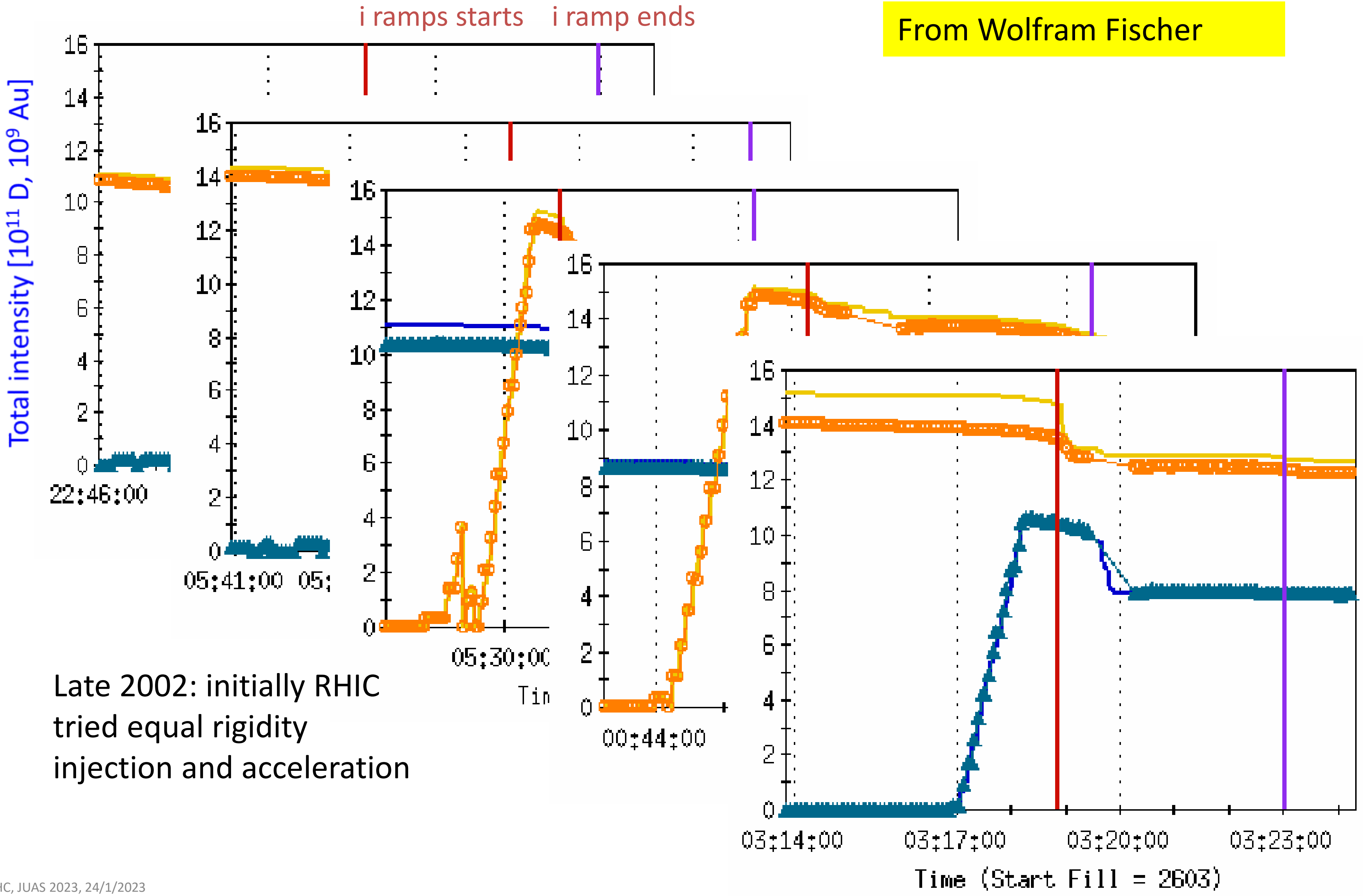
Approximate symmetry with Beam 1 under Left <->Right and x <-> y

History of proton-nucleus collisions at LHC (1)

- Long considered desirable by experiments but never included in baseline design of LHC
- 2003: RHIC finds a way to collide deuterons and gold nuclei but this way is not open to LHC …
- 2005 CERN TH workshop on pA in LHC, operation scheme worked out
  - Predicted that p-Pb in LHC could work (despite RHIC …)
- Early 2011, LHC Chamonix workshop – go-ahead given for feasibility tests on LHC
- Preparation of LHC systems during 2011
- 31/10/2011 successful feasibility test (12 h beam time)
- Early 2012, after high Pb-Pb luminosity in Nov 2011, experiments *really* want p-Pb comparison data
- 13/9/2012 Successful pilot collision run (8 h set-up+8 h collisions) yields new physics - the largest jump in collision energy, factor 25 (of given collision type), in history of particle accelerators
- Jan-Feb 2013 first full physics run
- Nov 2016 second run, multiple collision conditions including higher energy, almost 9 times “design” p-Pb luminosity

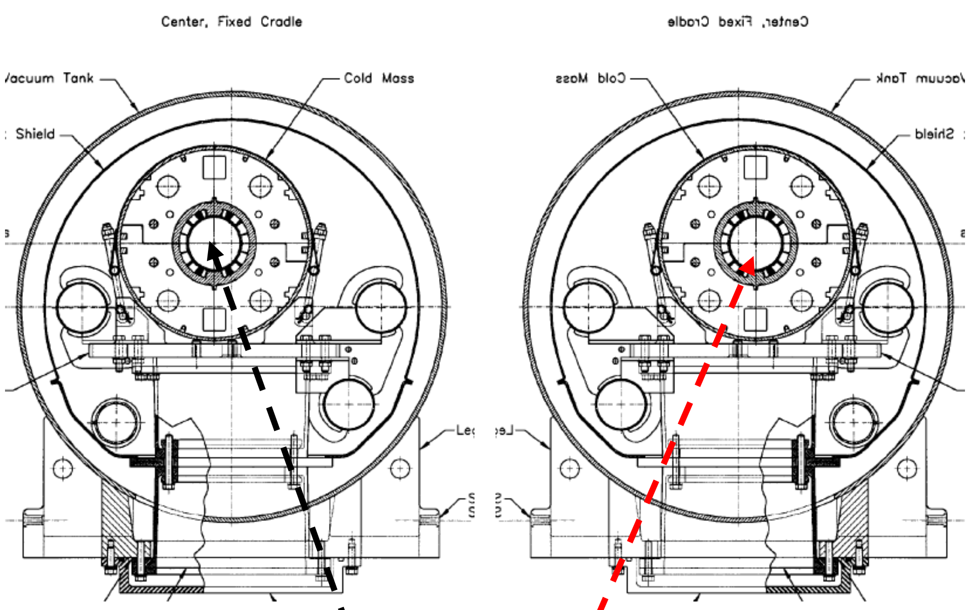
RHIC d-Au injection and ramp $(B\rho)_d = (B\rho)_{Au}$

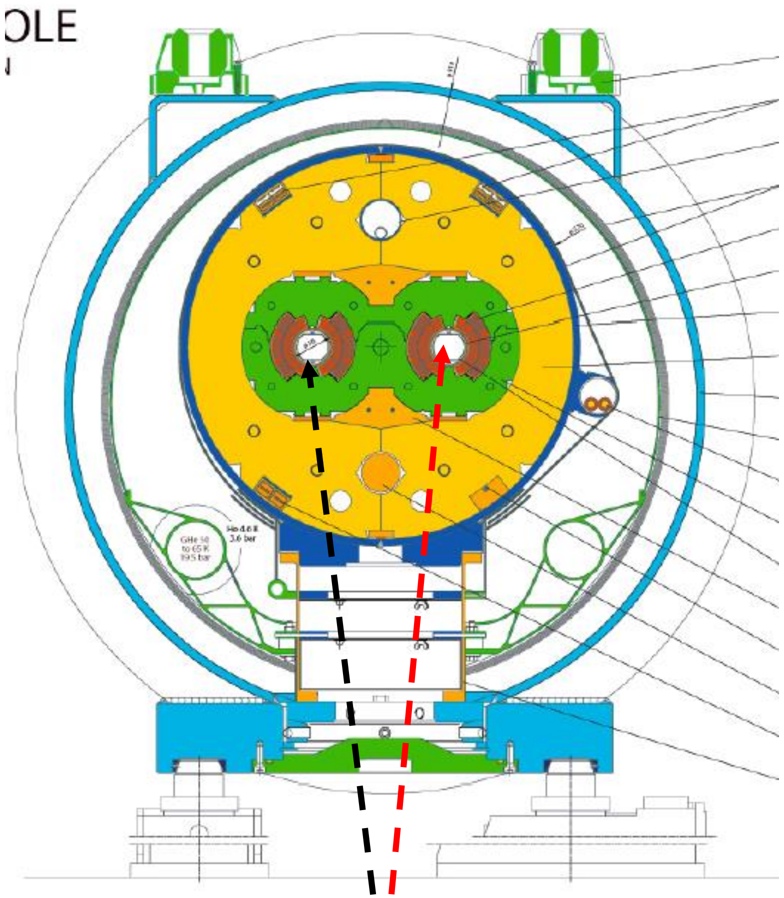
From Wolfram Fischer



Late 2002: initially RHIC tried equal rigidity injection and acceleration

Critical difference between RHIC and LHC for asymmetric beams





RHIC: Independent bending field for the two beams – they abandoned equal-rigidity and switched to equal-frequency d-Au.

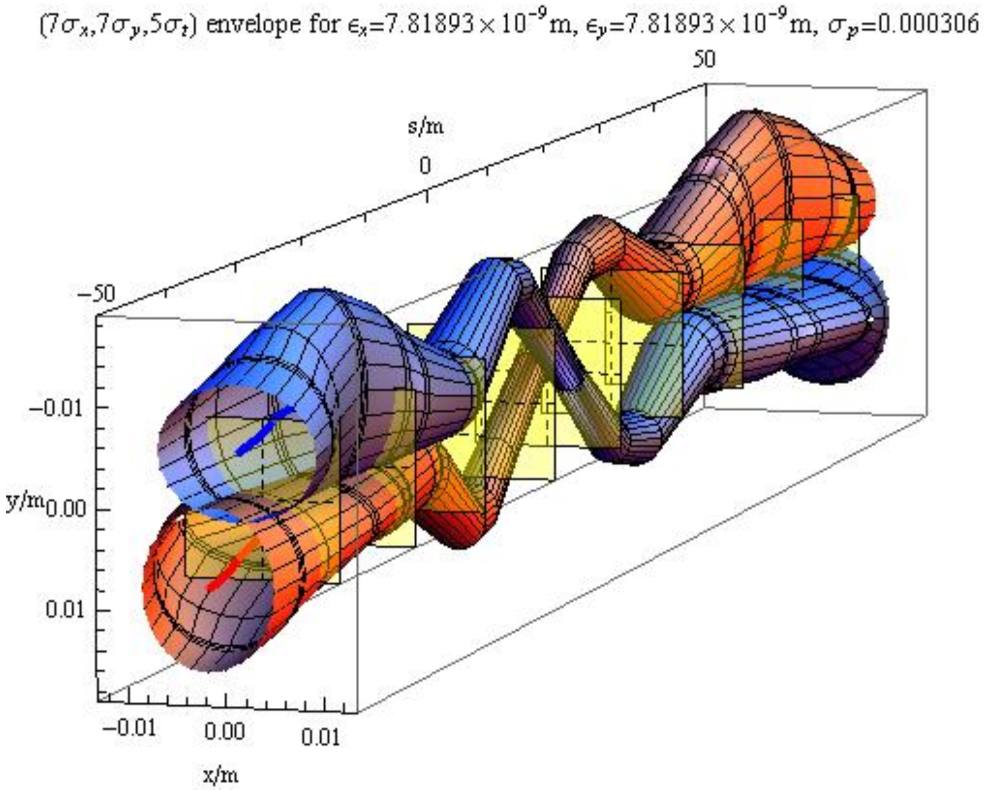
LHC: Identical bending field in both apertures of
two-in-one dipole – no choice

Outline of p-Pb physics cycle (Pb-p similar)

- Inject p beam in Ring 1, f_{RF1} for p
- Inject Pb beam in Ring 2, f_{RF2} for Pb
- Ramp both beams on central orbits
  - Orbit feedback decouples RF frequencies
- Bring f_{RF} together to lock, beams are slightly off central orbits
- RF re-phasing to position collision point correctly
- Squeeze of β-functions at collision points
- Change ALICE crossing angle to collision configuration
- Collide

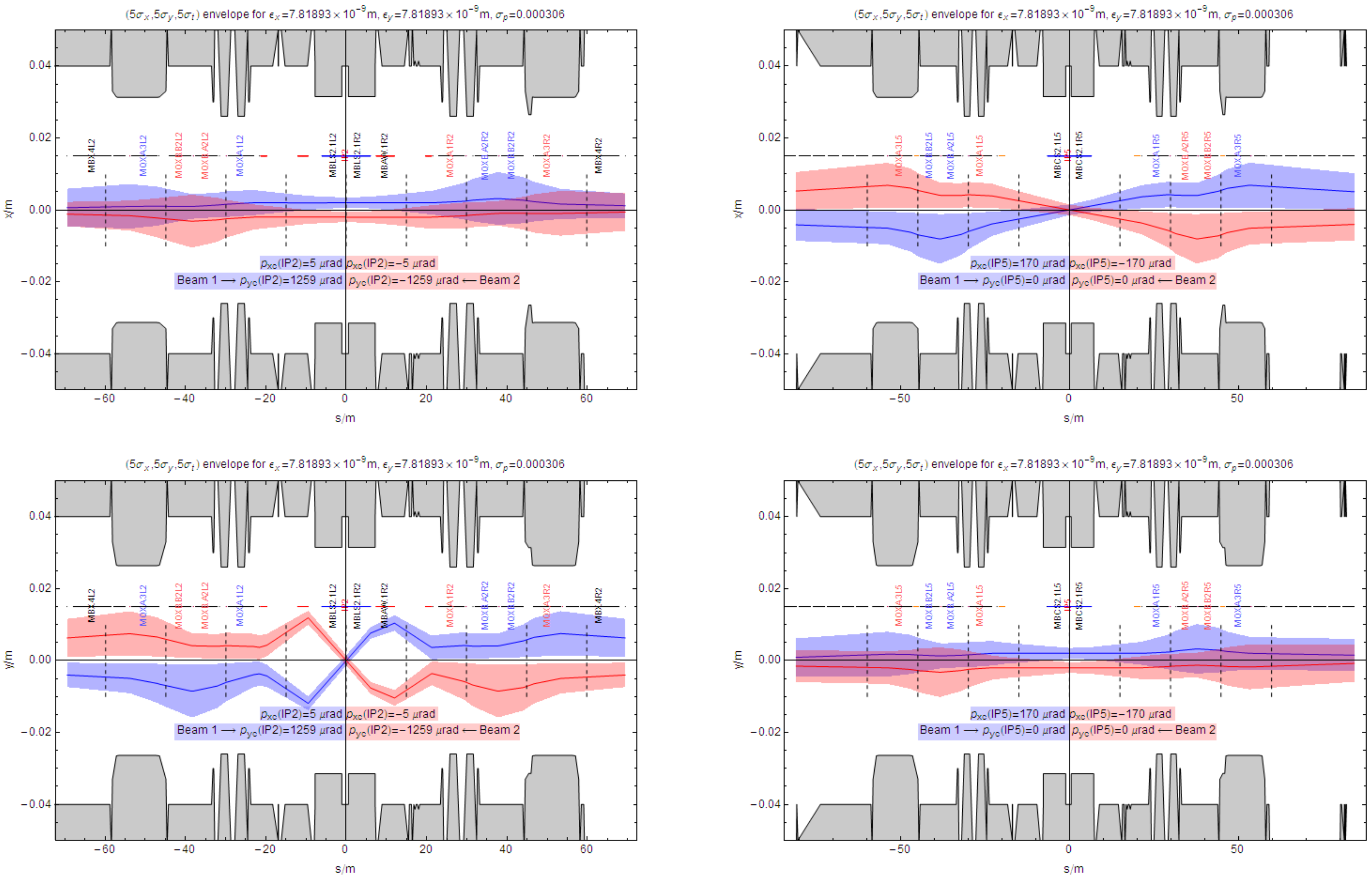
At injection the proton beam makes 8 more revolutions per minute than the Pb beam

Beam envelopes around ALICE at injection



Crossing angle from spectrometer and external bump separates beams vertically everywhere except at IP (also in physics).
Parallel separation also separates beams horizontally at the IP during injection, ramp, squeeze.
Other experiments have different separation schemes …

ALICE – Separation at injection - CMS



For separations $x, y \gg \sigma_{x,y}$, the (angular) beam-beam kick on a particle of charge Ze, due to an opposing beam of total charge Ne is

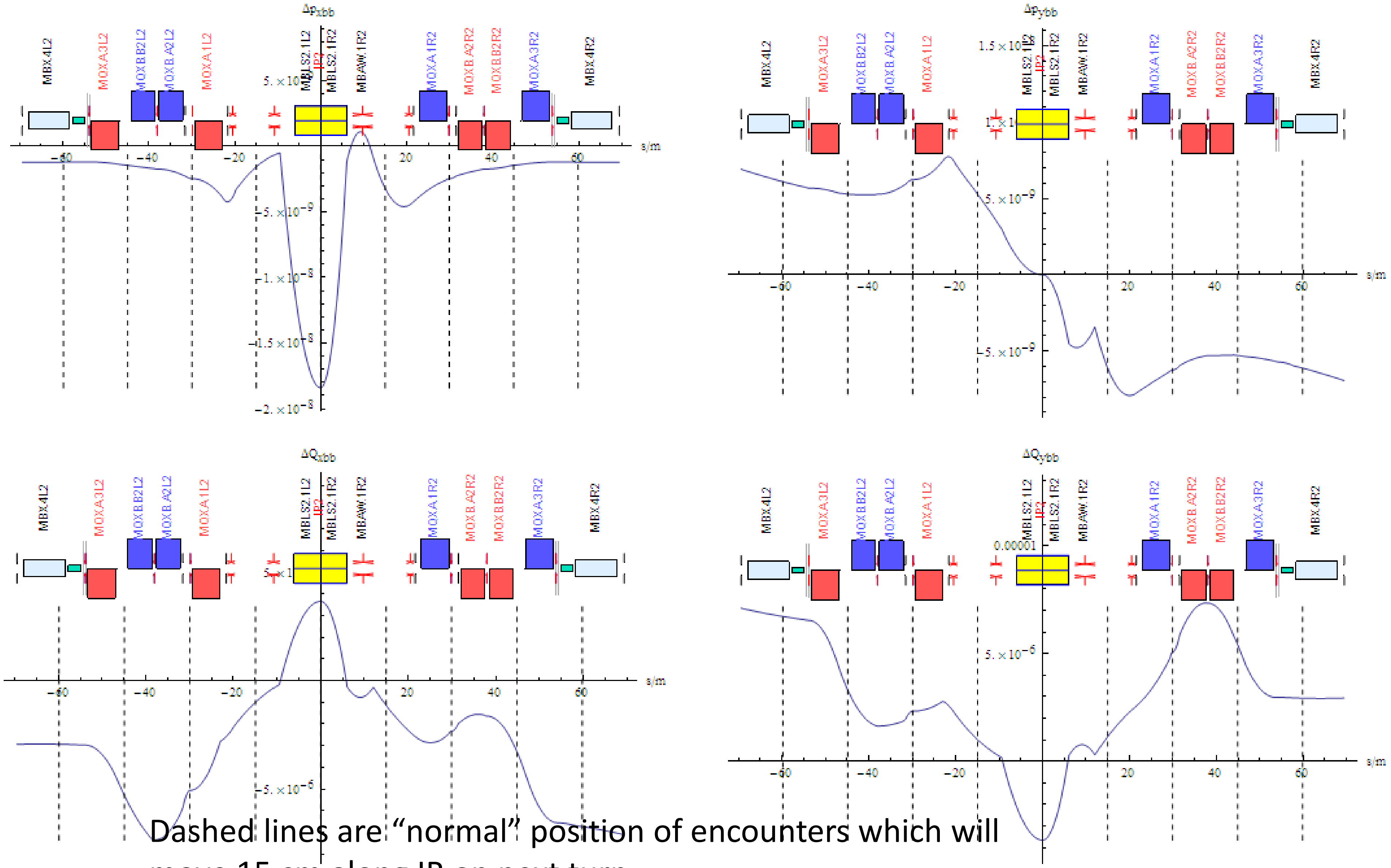
$$(\Delta p_x, \Delta p_y) = \frac{2ZNr_0}{\gamma} \frac{(x, y)}{x^2 + y^2}, \qquad \text{where} \quad r_0 = e^2 / (4\pi\epsilon_0 mc^2)$$

and gives rise to perturbative betatron tune-shifts

$$\Delta Q_{x,y} = -\frac{\beta_{x,y}}{4\pi} \partial_{x,y} \Delta p_{x,y} = \frac{ZNr_0}{2\pi\gamma} \frac{(\beta_x, -\beta_y)(x^2 - y^2)}{(x^2 + y^2)^2}$$

LHC separation configurations were chosen to minimise the tune effects in physics (“footprint”).

Example: beam-beam for Pb around ALICE



Dashed lines are "normal" position of encounters which will move 15 cm along IR on next turn …

"Overlap knock-out" resonances – a new twist on nonlinear dynamics

Encounter points move at speed $V = \frac{v_{\mathrm{p}} - v_{\mathrm{Pb}}}{2} = 1734\ \mathrm{m/s} = 0.15\ \mathrm{m/turn}$

Hamiltonian is no longer periodic in s.

Excites modulational resonances

$$\underbrace{m_x Q_x + m_y Q_y}_{m_{x,y}=1,2,\ldots\ \text{transverse modes}} = p + \underbrace{k}_{\substack{\text{Bunch harmonic,}\\ 891\\ \text{or at most } 3564}} \underbrace{\left(\frac{v_{\mathrm{p}} - v_{\mathrm{Pb}}}{2c}\right)}_{\substack{3.\times 10^{-6}\ \text{at injection,}\\ \text{decreases in ramp}}} \quad ; \quad m_x, m_y, p, k \in \mathbb{Z}$$

Known as "overlap knock-out resonances" at the ISR.

However with LHC tunes, $Q_x \approx 64.3, Q_x \approx 59.3$, only extremely high-order resonance conditions can be satisfied.

Very unlikely to be a problem (not so clear at RHIC).

Diffusion models

- Naively regarding the kicks as purely random
  - Works fairly well for RHIC data (W. Fischer)

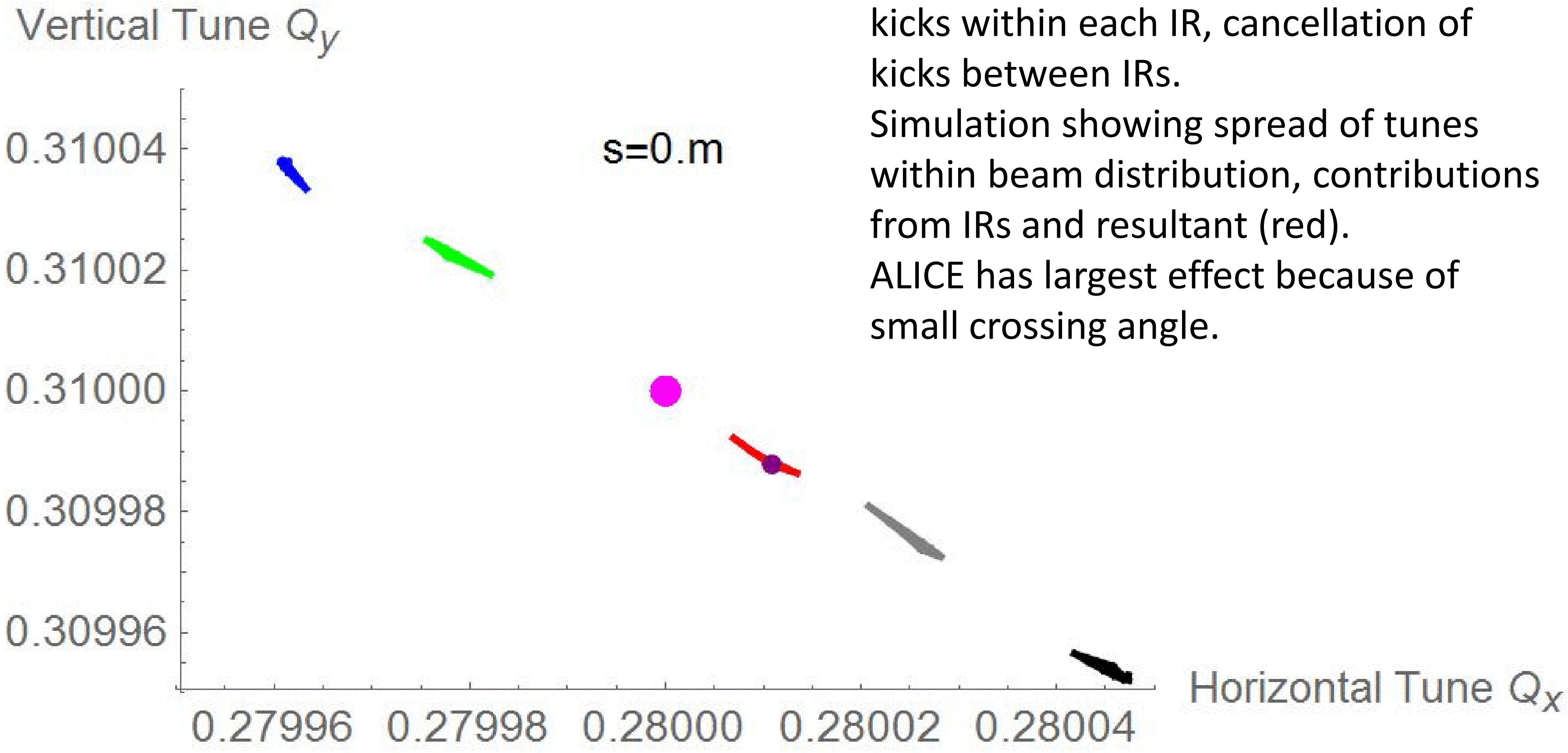
$$\frac{d\varepsilon_{x,yn}}{dt} = \frac{1}{2} f_0 \sqrt{\gamma^2 - 1}\left[\beta_{x,y}(s)\left(\Delta p_{x,y}(s)\right)^2\right]$$

where [..] denotes mean-square deviation

gives an emittance doubling time around 40 min

- Better calculate combination of beam-beam kicks on a particle on a given turn as the encounters move
  - Add them up with proper betatron phases
    - Partial compensations
  - Take out static component (closed-orbit) from long-term averaging and look at fluctuations around it
  - RMS fluctuation gives emittance growth rate
- More elaborate simulation models (Marc Jebramcik) provide further understanding of differences in beam dynamics between RHIC and LHC

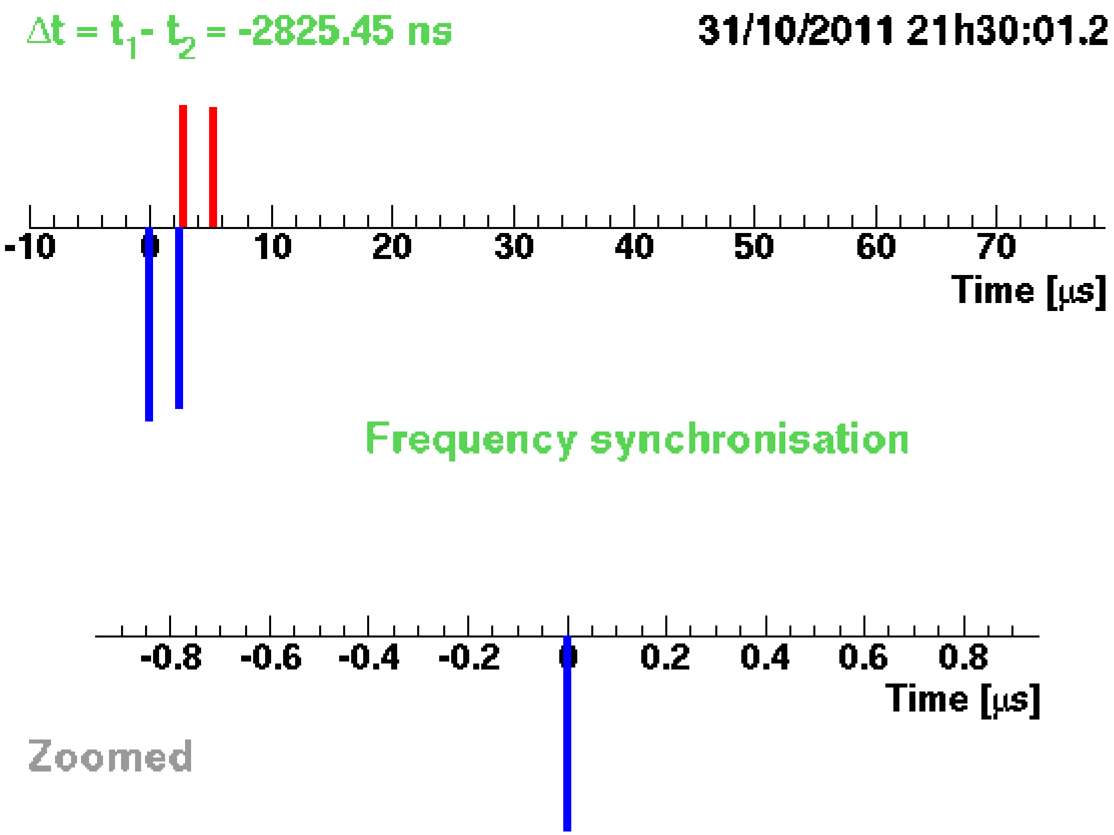
One way to see why p-Pb injection works in LHC



Modulation of beam-beam kicks as encounters slide along IRs due to unequal revolution frequencies.
At LHC, unlike RHIC, effects are less (higher energy, some compensation of kicks within each IR, cancellation of kicks between IRs.
Simulation showing spread of tunes within beam distribution, contributions from IRs and resultant (red).
ALICE has largest effect because of small crossing angle.

M.A. Jebramcik

Ramping, then moving the collision point by 9 km



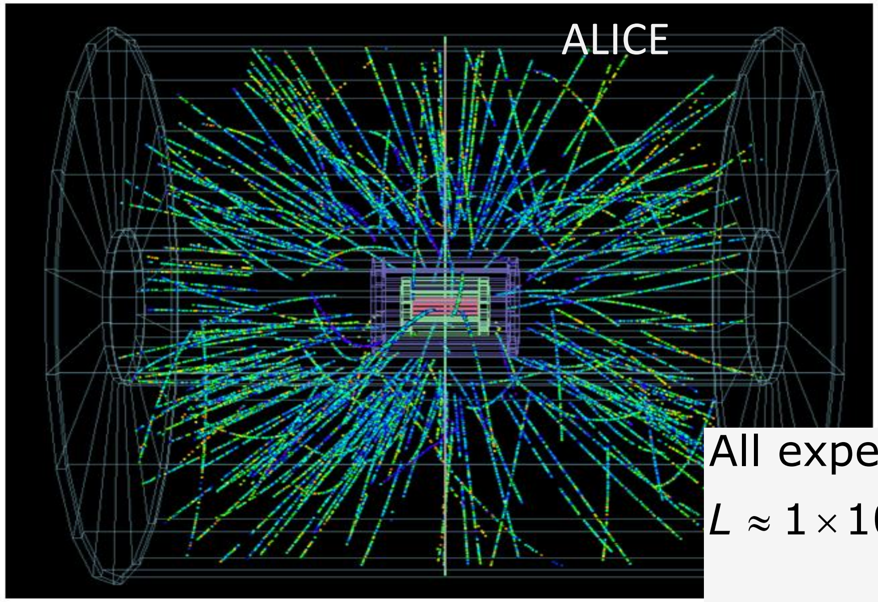
Real-time clock

RF cogging by Philippe Baudrenghien

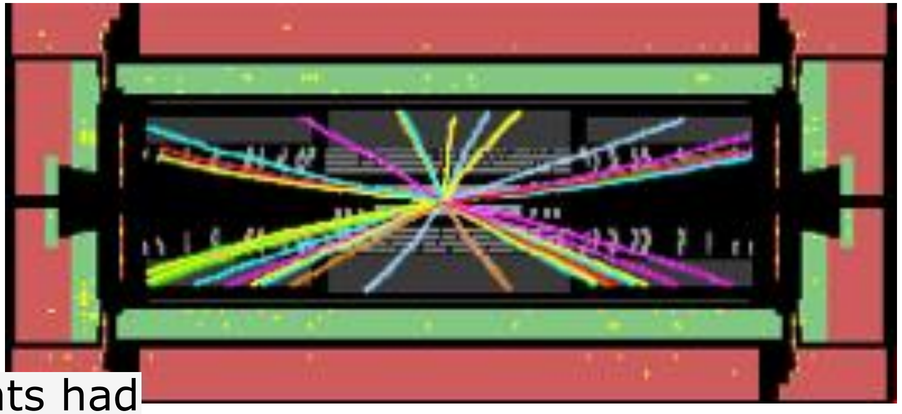
Video from BPTX beam position monitor timing data by Thilo Pauly (ATLAS)

This was the first time, later this was done much more quickly.

Collisions in all experiments



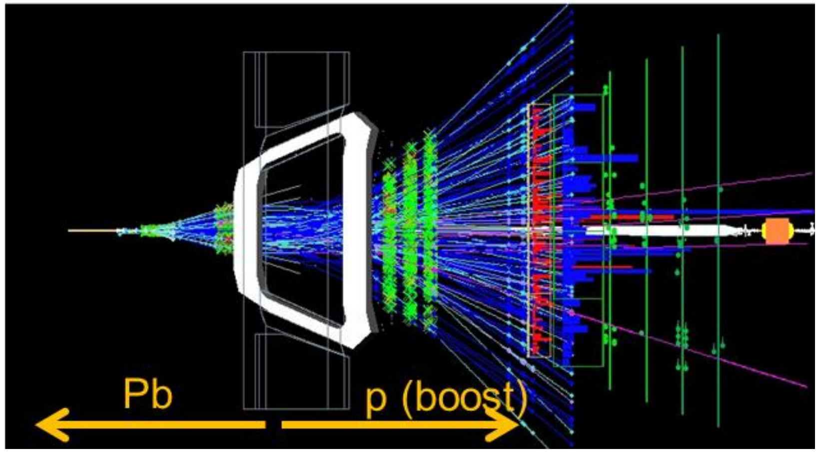
ATLAS

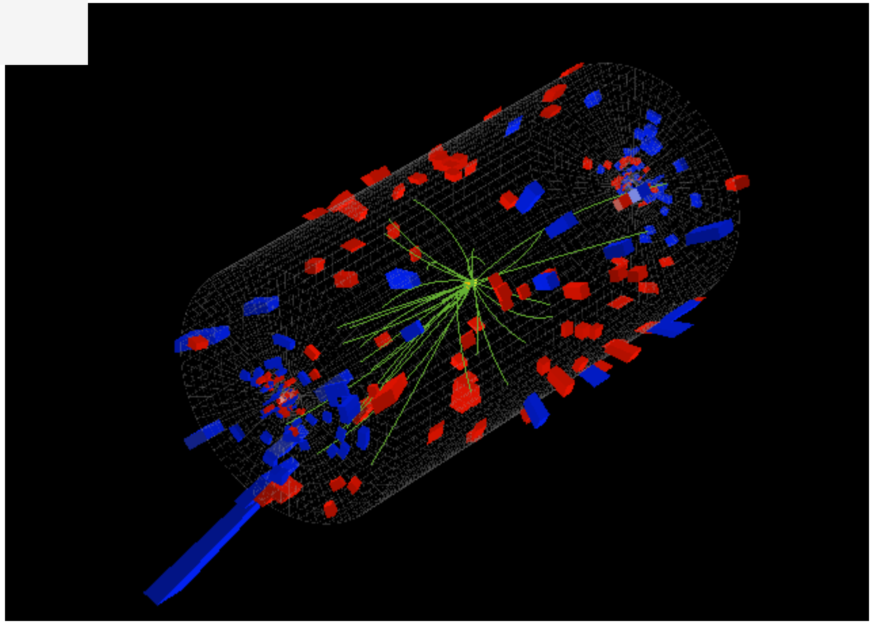


All experiments had

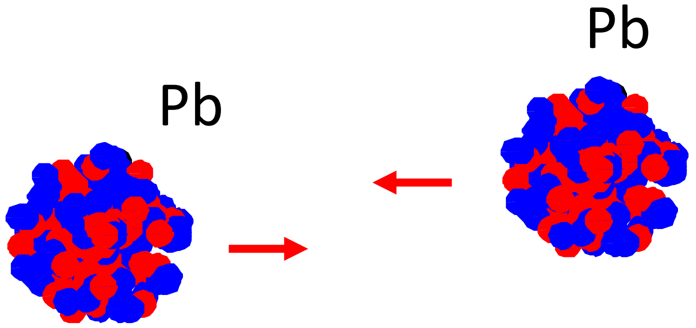
$L \approx 1 \times 10^{26}\ \text{cm}^{-2}\text{s}^{-1}$

LHCb I



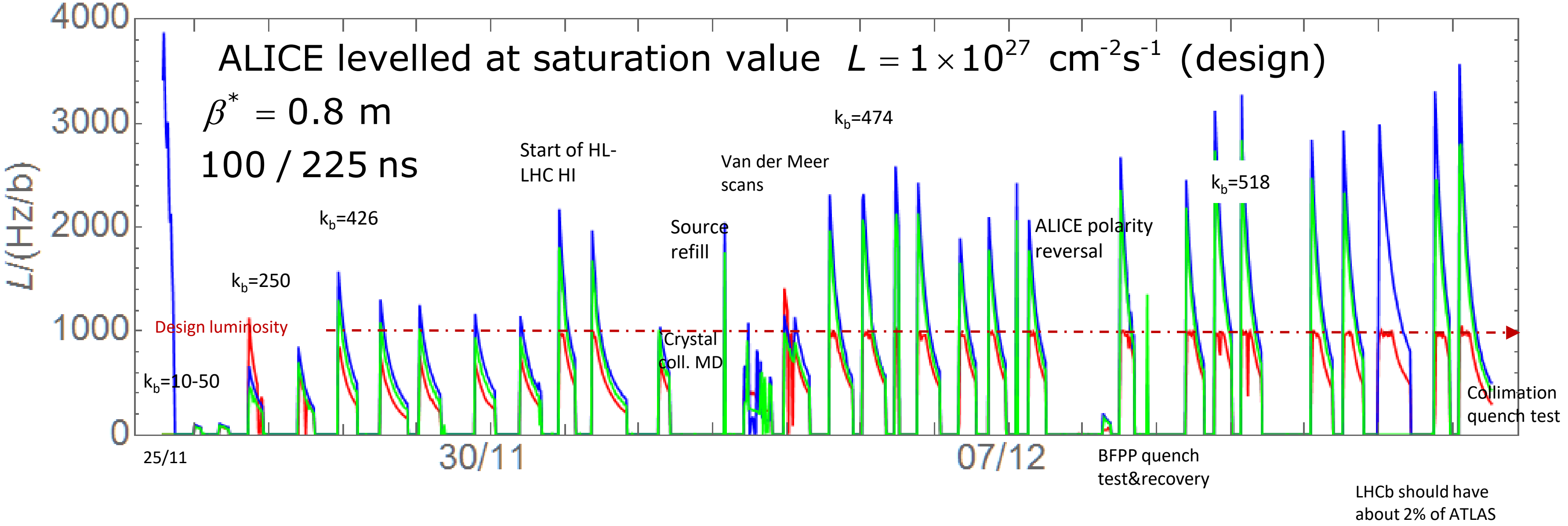


CMS



2015

Pb-Pb peak luminosity at 3×design in 2015



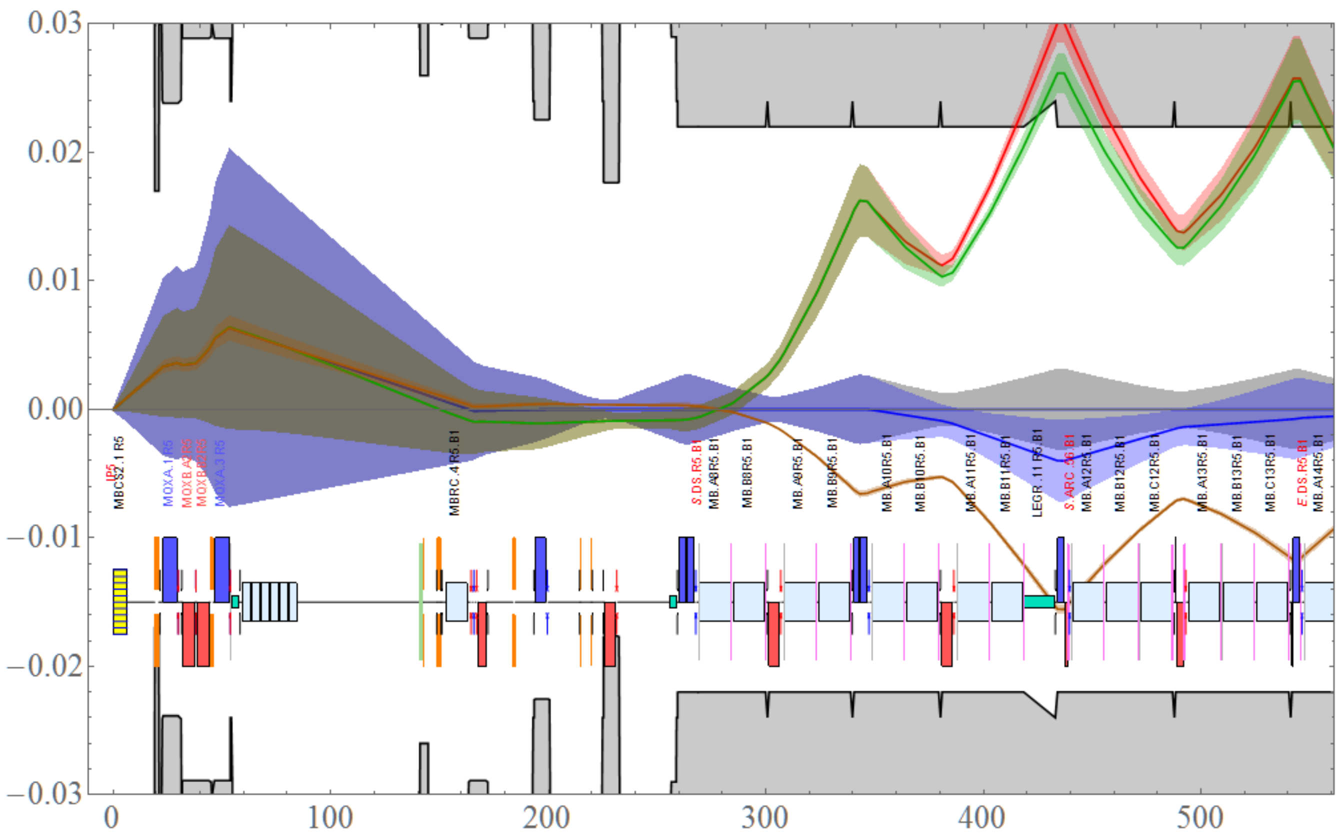
18 days of Pb-Pb since 2011

Heavy-ion runs of LHC are very short but very complex.
Experiments have many requests for changes of conditions.

This run was preceded by a week of equivalent energy p-p collisions to provide reference data.

Completely different from classical operation of Tevatron or LHC p-p.

Orbit bumps are effective mitigation of BFPP for CMS (or ATLAS)



BFPP beam, without and with bump

- Primary loss location close to the connection cryostat - details slightly optics-dependent (If necessary, bumps should avoid quenches at the start of physics
- Extra BLMs were specifically added for heavy-ion operation in loss region
- Variations of bump possible, uses moderate fraction of available corrector strengths
- We applied bumps like these with ~ 3 mm amplitude around CMS and ATLAS from the beginning of the run

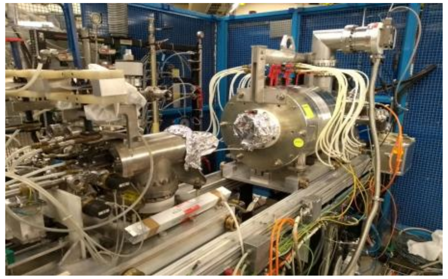
Goals of 2016 p-Pb run surpassed

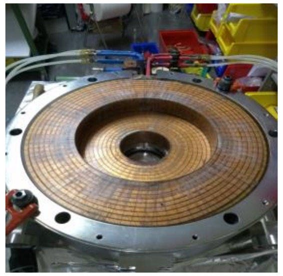
	Experiments	Primary goal	Achieved	Additional achieved
5 TeV p-Pb (Beam energy 4 Z TeV) $\sqrt{s_{NN}}$	ALICE (priority)	700 M min bias events	**780 M**	
	ATLAS, CMS			>0.4 /nb min bias
	LHCb			SMOG p-He etc
8 TeV p-Pb *or* Pb-p (Beam energy 6.5 Z TeV)	ATLAS, CMS	100 /nb	**194,183 /nb**	
8 TeV p-Pb	ALICE, LHCb	10 /nb	**14,13 /nb**	
	LHCf	9-12 h @ 10^{28} $cm^{-2}s^{-1}$	**9.5 h** @ 10^{28} $cm^{-2}s^{-1}$	Min bias ATLAS, CMS, ALICE
8 TeV Pb-p	ALICE, LHCb	10 /nb	**25,19 /nb**	

Note: ALICE and LHCb are asymmetric experiments, with different coverage according to beam direction.

Reminder: first 1 month p-Pb/Pb-p run at 5 TeV in 2013 gave 31/nb to ALICE, ATLAS, CMS and 2/nb to LHCb.

2018 Major Hurdles …



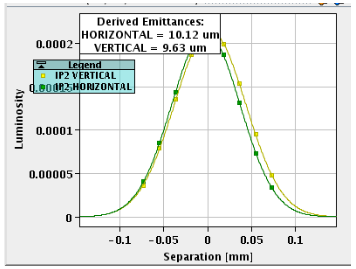


Ion source fault: No ions available after TS3

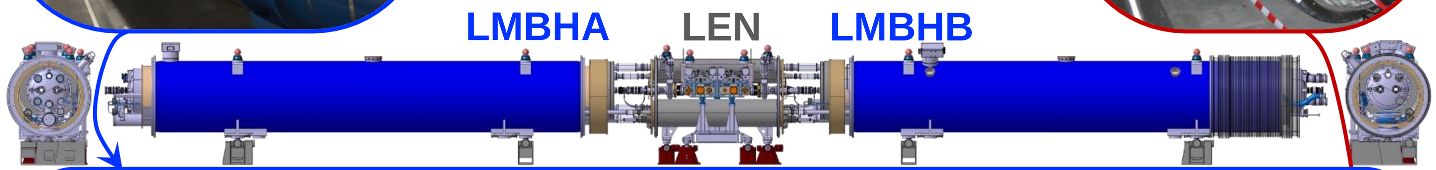
- Many commissioning tasks were advanced with protons.
- Degraded beam quality during the first week of the run.
  - Resulting in lower beam intensity and longer turn around time.
  - Shorter levelling periods and less time in physics.

ALICE luminosity lower than expected:

- *Cause:* beam deformation and reduced overlap at IP introduced by strong local betatron coupling in IR2.
- *Solution:* correction with skew-quadrupoles implemented during ALICE polarity reversal.
  - Luminosity sharing strategies used until solution was found.
    - Filling schemes (number and distribution of bunches).
    - Luminosity levelling target of ATLAS/CMS.



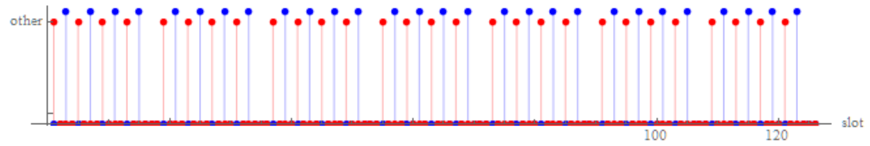
DS collimators



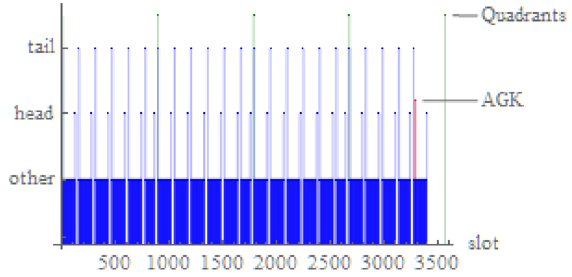
- **IP7**, for both proton and heavy-ion collimation losses
  - Design, fabricate, test, and install during **LS2**, around **IP7**, **two 11 T Dipole Full Assemblies** (replace the MBs MBA-B8L7 and MBB-B8R7)
  - Fabricate and test **one spare 11 T Dipole Full Assembly**
  - Plan **includes 14 magnet models**, and ~~2~~**1 full-length prototype**
)
- **IP2**, for heavy-ion secondary beams
  - Design, fabricate, and install during **LS2**, around **IP2**, **two Connection Cryostat Full Assemblies**, i.e. no 11 T Dipole magnet needed for this
  - Fabricate **one spare Connection Cryostat Full Assembly**
  - A Connection Cryostat Full Assembly contains two new connection cryostats, **LEP**, and one by-pass cryostat, **LEN**

F. Savary

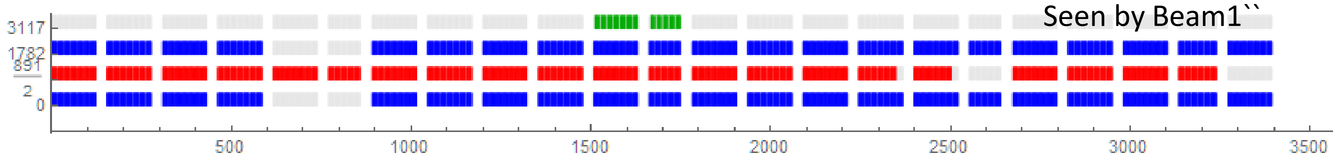
Filling scheme with some collisions in LHCb

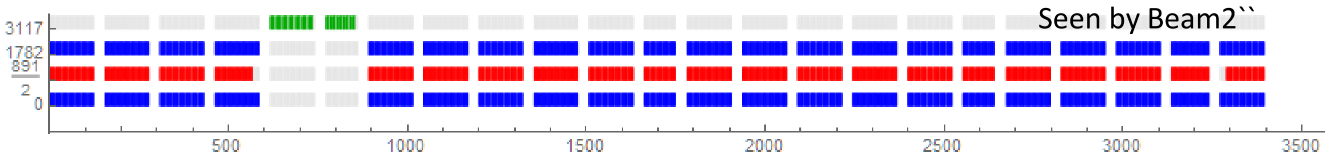


56 bunch SPS train after slip-stacking



Displace two trains in Beam 2 to make collisions in LHCb (assumption while waiting for specification).





23 injections of 56-bunch trains give total of 1232 in each beam.
1136 bunch pairs collide in ATLAS CMS, 1120 in ALICE, 81 in LHCb (longer lifetime).