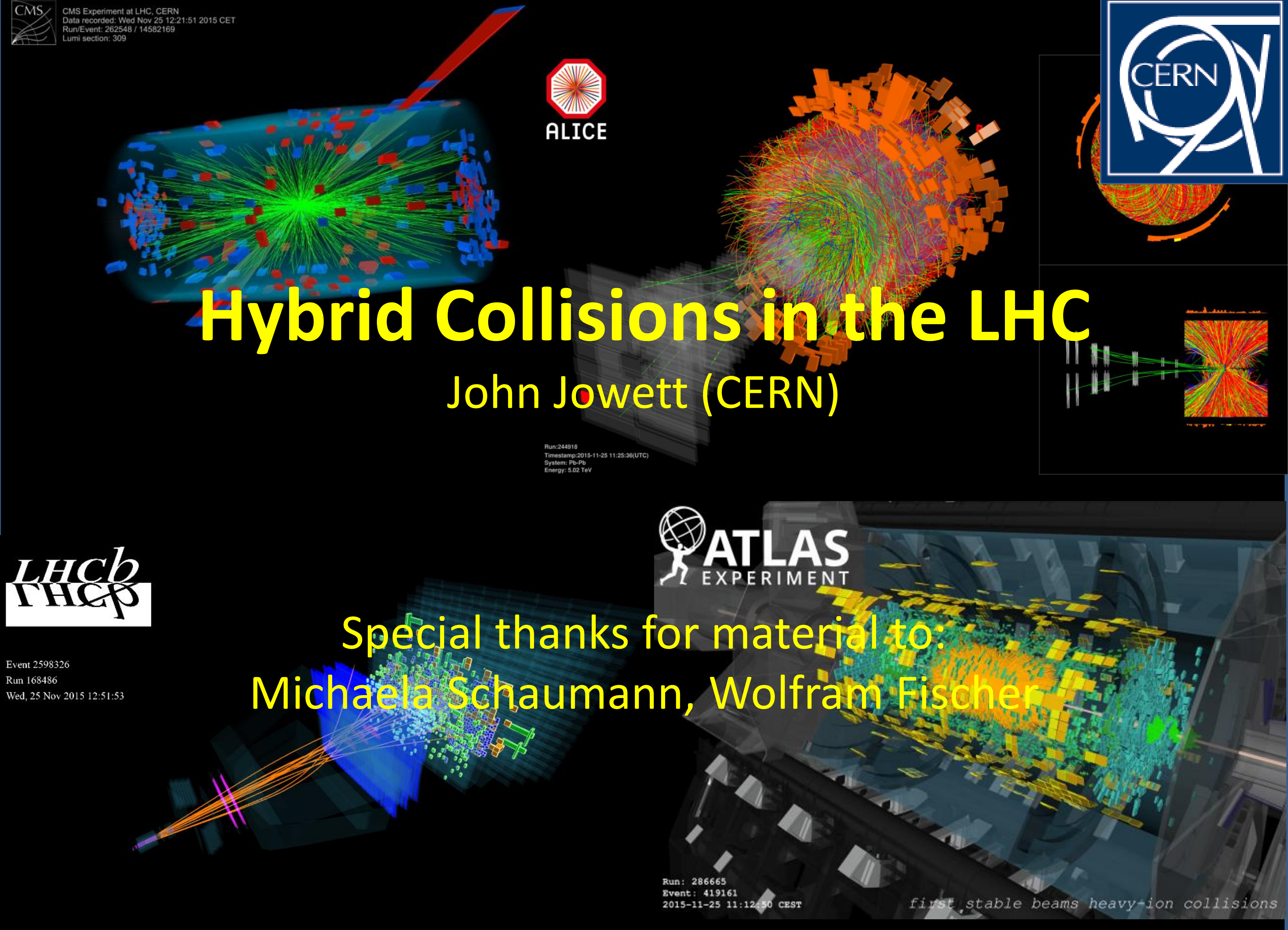


Hybrid Collisions in the LHC

John Jowett (CERN)

Special thanks for material to:
Michaela Schaumann, Wolfram Fischer

Outline

- Some history of hadron colliders
- Introduction to LHC
  - Examples of some optics ideas
- Basic physics and conventions for ion beams
  - Special relativity examples
- Physics of extremely high-energy nuclear collisions
- Acceleration in a synchrotron
- LHC p-Pb collisions
- How p-Pb collisions worked in LHC
- Brief mention of other hybrid collisions

History of hadron colliders in the 20th century

- 1970s:
  - First hadron collider, the ISR at CERN operated
    - Mainly p-p collisions, but also first ppbar, d and α (just a few days)
  - Construction of larger pp collider ISABELLE started
  - 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
- 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 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:
  - Electron-ion collider in USA (the next collider?)
  - Heavy-ion (and p+p) collisions at HL-LHC, SppC and FCC ?

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

- Unimaginably extreme conditions, similar to those that prevailed in the first microseconds of cosmic history, nuclear matter as we know it does not 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.
- Many-body properties of a non-Abelian quantum field theory.
- 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 it 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 the properties of the QGP.
  - Further information is carried by muons and photons.
  - ``Soft'' physics of   particles produced with low transverse momenta is well-modelled by relativistic viscous hydrodynamics.
- Proton-nucleus and (rare) proton-proton collisions have been found to exhbit apparent collective effects despite small system size – current hot topic.

- Nuclear collisions *also* allow experimentation with extreme electromagnetic fields.

Hot and dense matter in Pb-Pb collisions at LHC

Exercise: check all these numbers

Quark Gluon Plasma (QGP) created in Pb-Pb collisions.

Nuclear fusion temperature at core of sun $T_{\text{sun}} = 1.6 \times 10^{7}$ K

Temperature of QGP (thermal photon spectrum measured by ALICE, the highest temperature ever measured in a lab):

$T_{\text{ALICE}} = 304$ MeV / $k_B = 3.5 \times 10^{12}$ K=200,000 T_{sun}

Energy density in QGP: $u_{\text{QGP}} \simeq 15$ GeV/fm^3

Total electrical energy generated in Europe in a year: $U_{\text{Ey}} = 3.6 \times 10^{12}$ kWh

Imagine pumping all that energy into as sphere of radius r and calculate the value of r needed to achieve the same energy density

$\frac{U_{\text{Ey}}}{(4/3)\pi r^3} = u_{\text{QGP}} \Rightarrow r = 1.1\ \mu\text{m}$, a speck of very fine dust, mass 140 kg

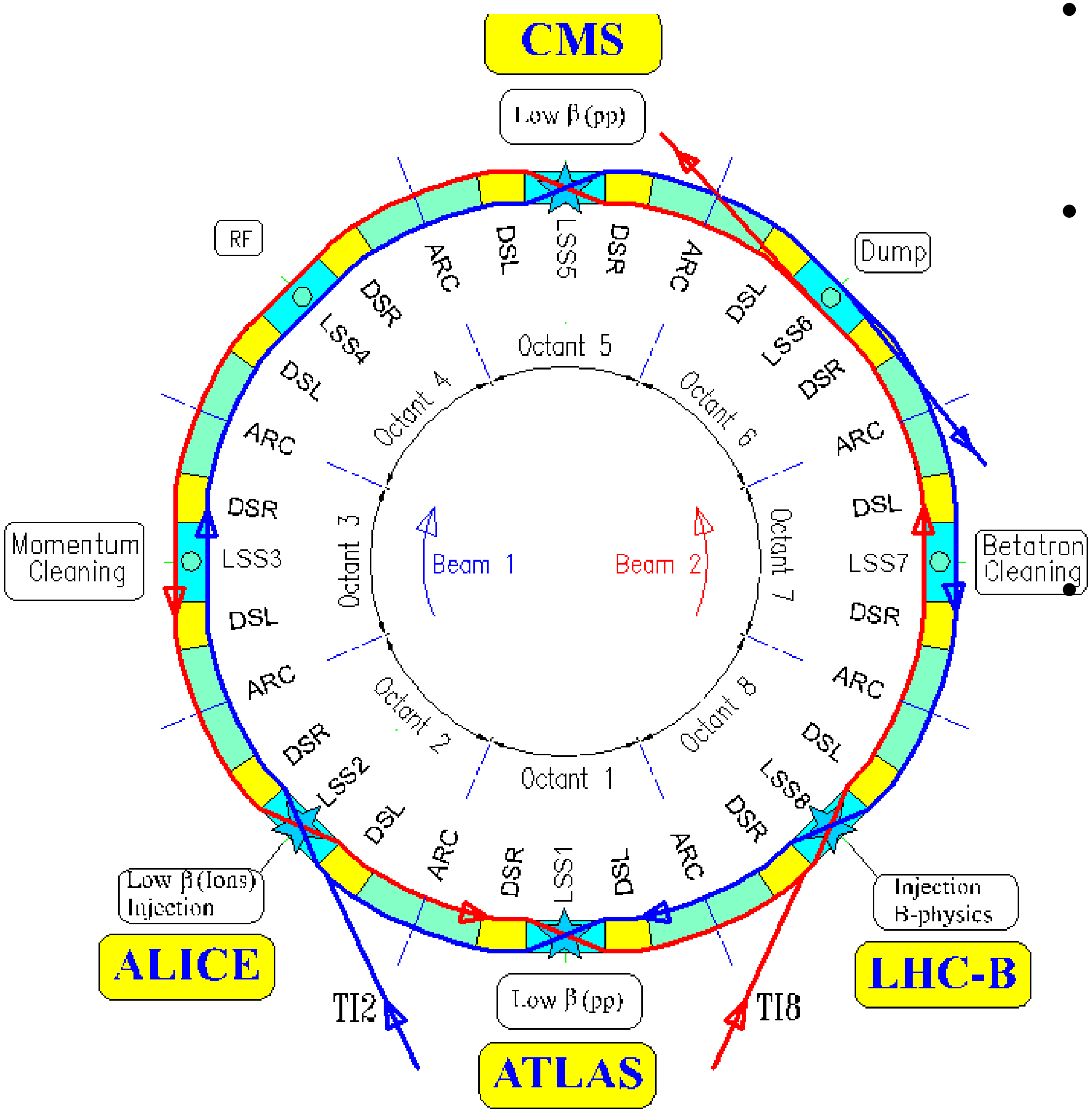
Density = $10^{15} \times$(density of metallic Pb)

World annual electrical energy production ~ 1 mole of LHC Pb-Pb collisions

LHC is an extraordinary concentrator of energy.

INTRODUCTION TO LHC

LHC Layout

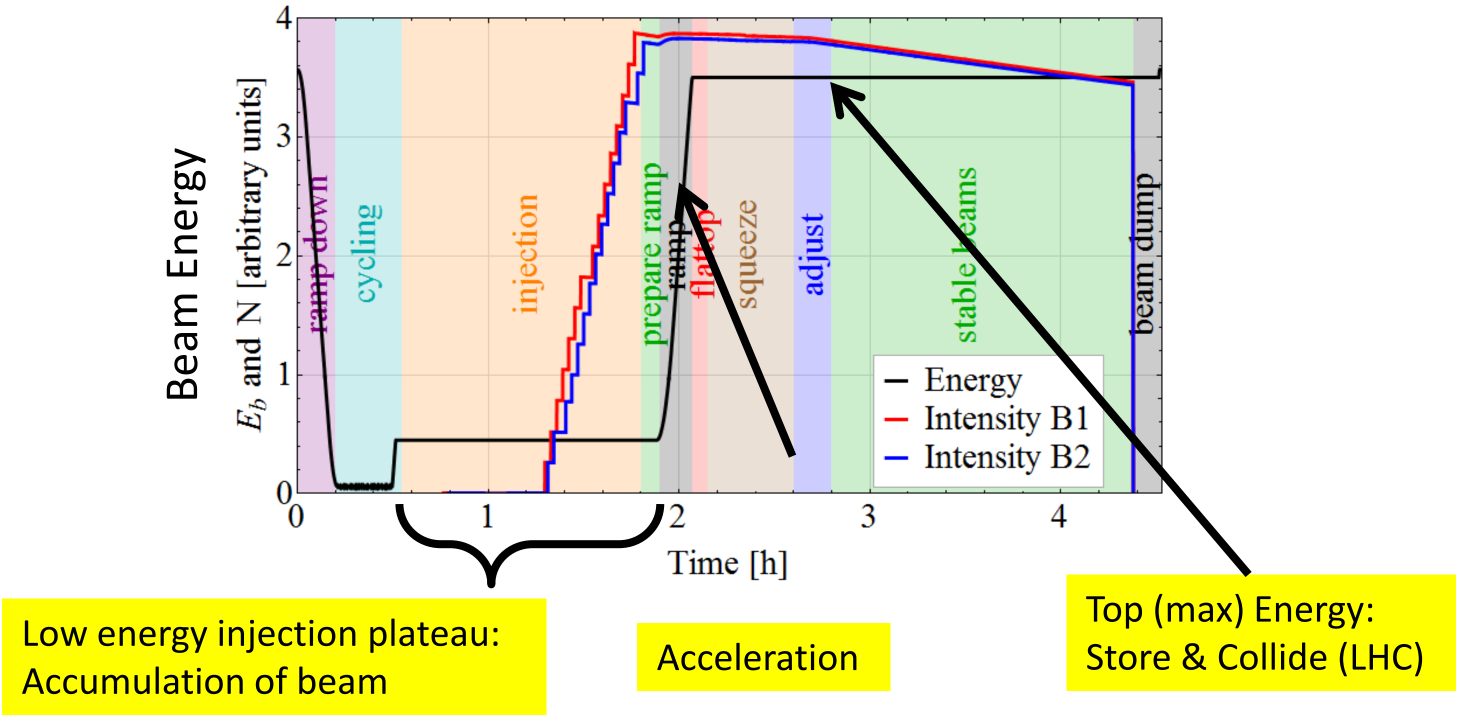


- Beams circulate in independent beam pipes over most of circumference
- Except in:
  - IR1 (ATLAS ± 145 m)
  - IR2 (ALICE ± 117 m)
  - IR5 (CMS ± 145 m)
  - IR8 (LHC-B ± 80 m)

ALICE, ATLAS, CMS may take heavy-ion (and p-A) collisions

s coordinate along each beam's central orbit, clockwise from IP1

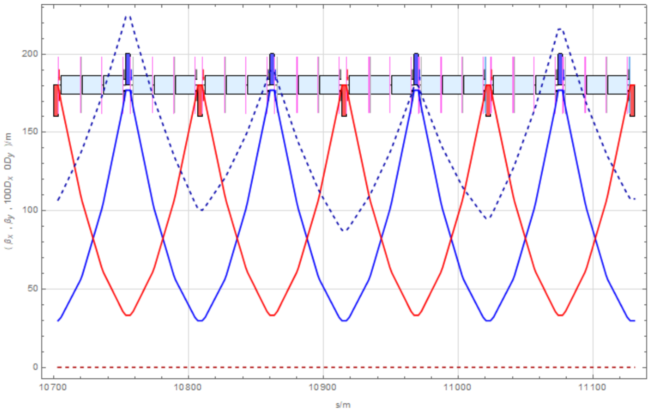
LHC Accelerator Cycle (Fill) schematic



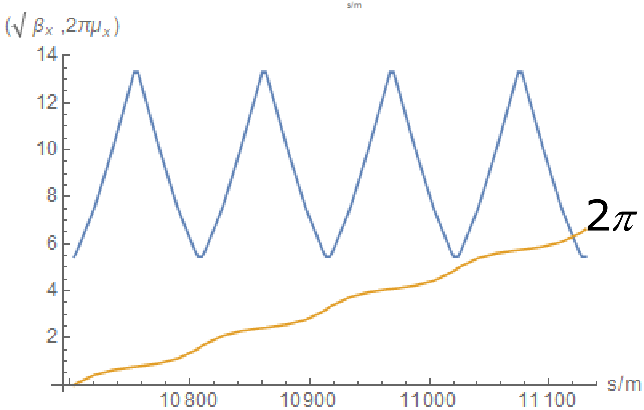
Injector cycles (e.g. PS or SPS) are analogous except that, after the ramp, beams are immediately extracted into a transfer line to the next machine rather than being collided.

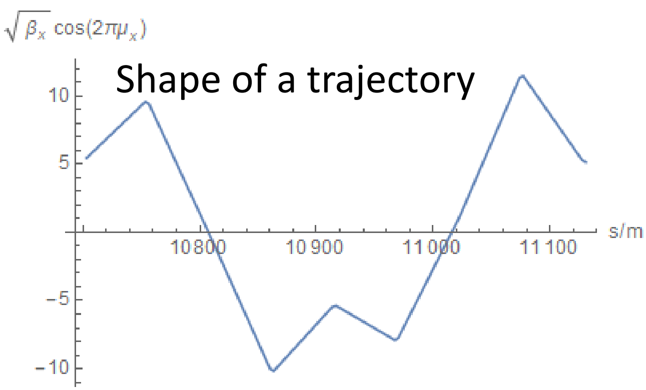
A machine which ramps its magnetic fields in synchronism with a change of the RF frequency like this is called a *synchrotron*.

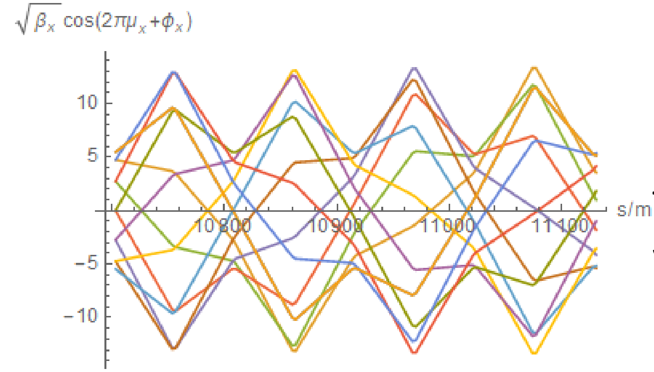
Optical functions and beam envelope, 4 LHC 90° FODO cells



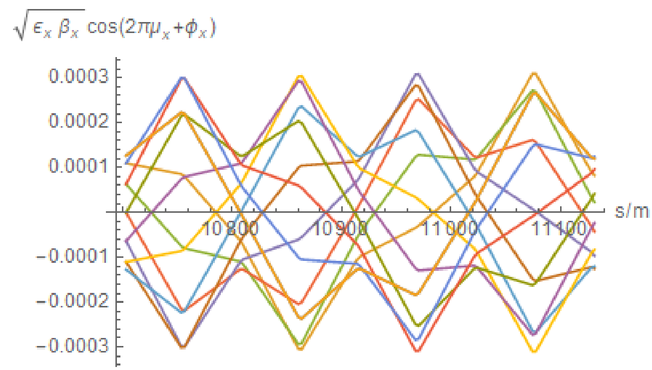
β in m





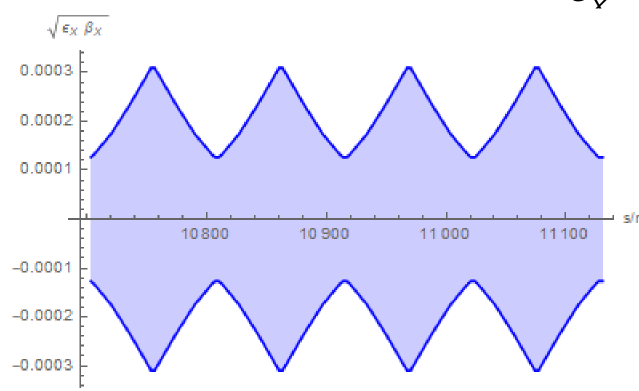


Trajectories with various initial phases



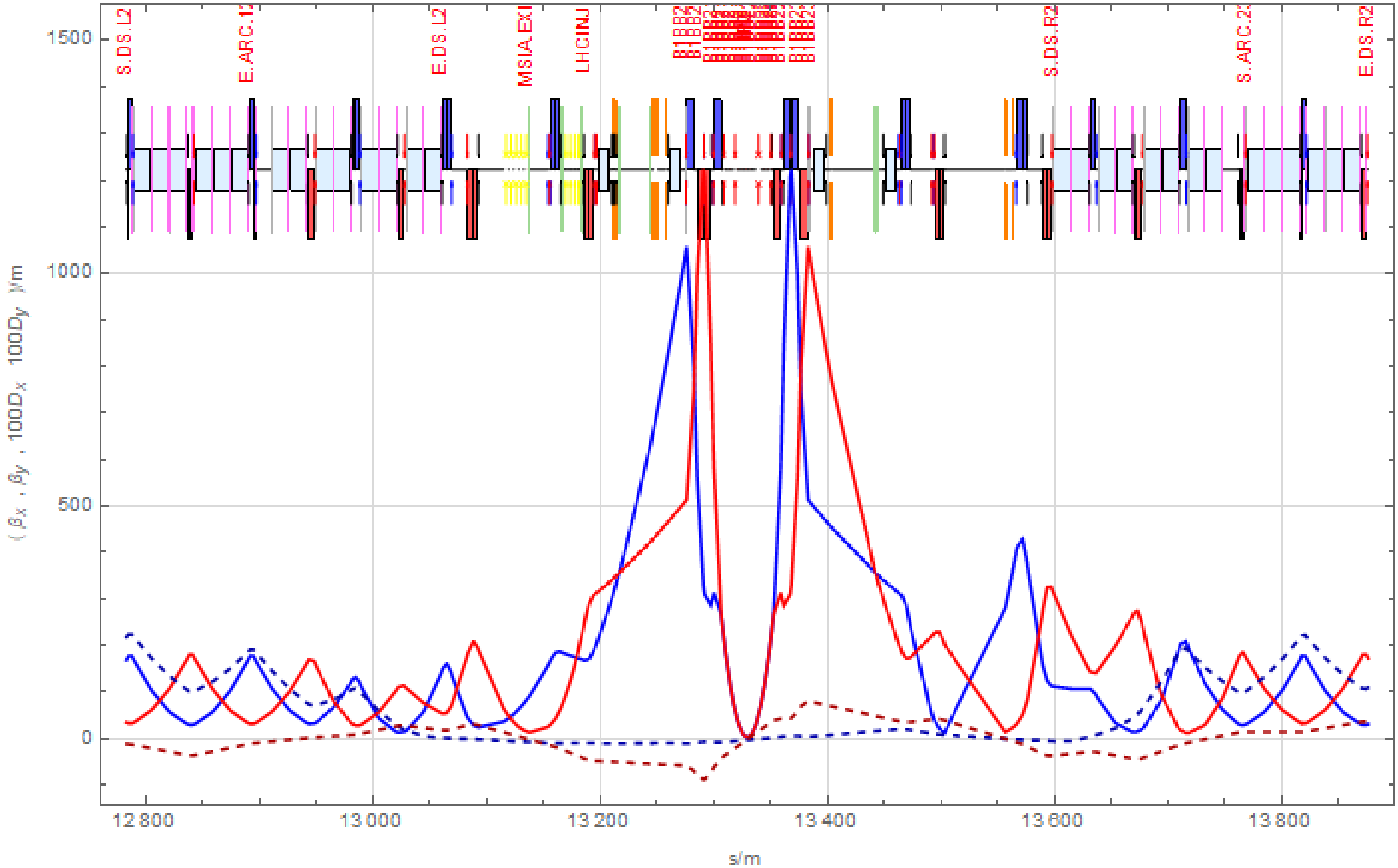
Trajectories with various initial phases, normalised to emittance

$\varepsilon_x = 5.4\times 10^{-10}$ m



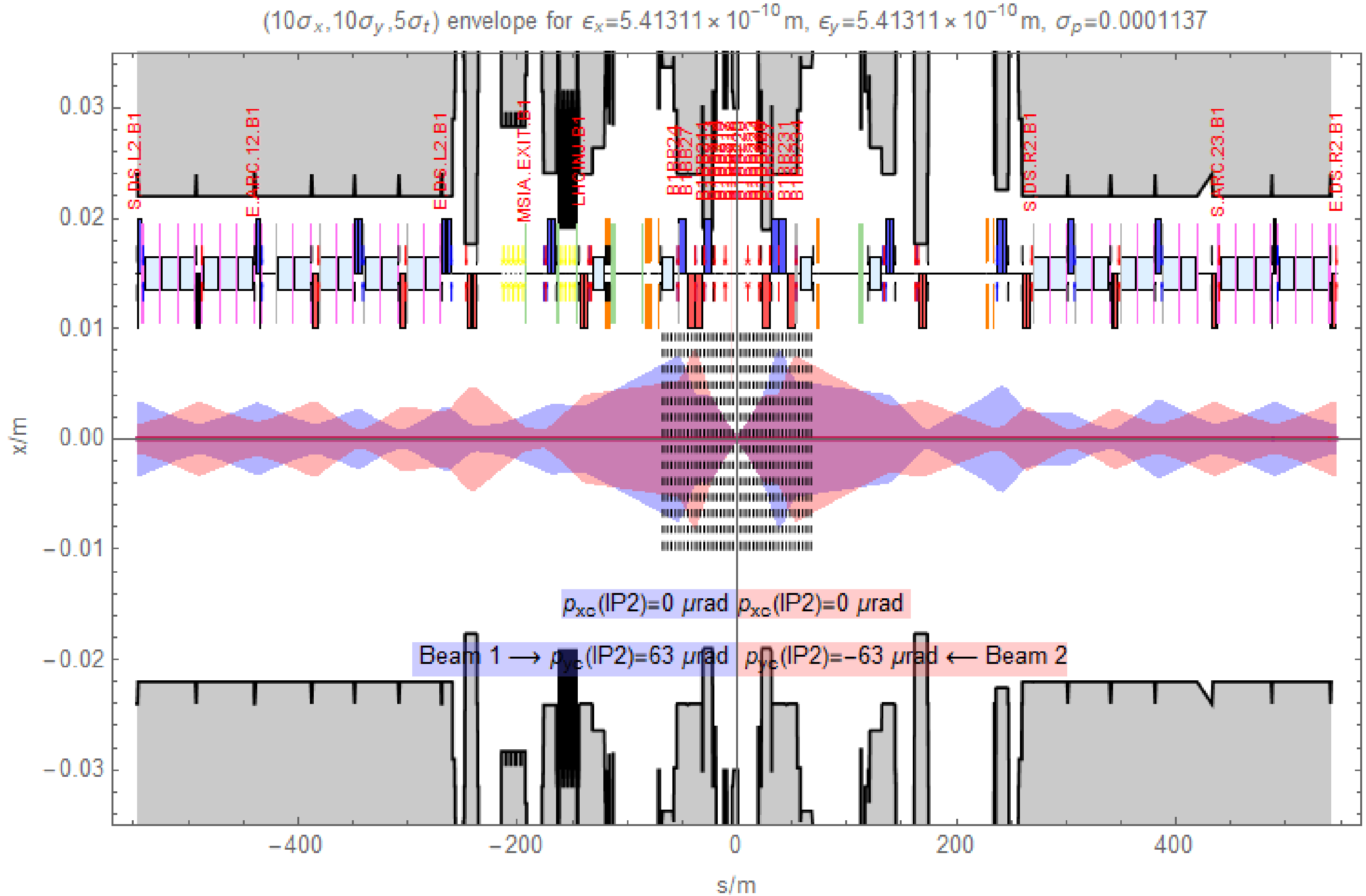
All particles within 1σ (or more) beam envelope.

Optical functions in LHC IR2, 2016



Some common quadrupoles focus/defocus Beam 1/Beam 2.
Optics solutions must be found for each beam with these constraints.

Collision conditions in LHC, IR2 horizontal plane 2016

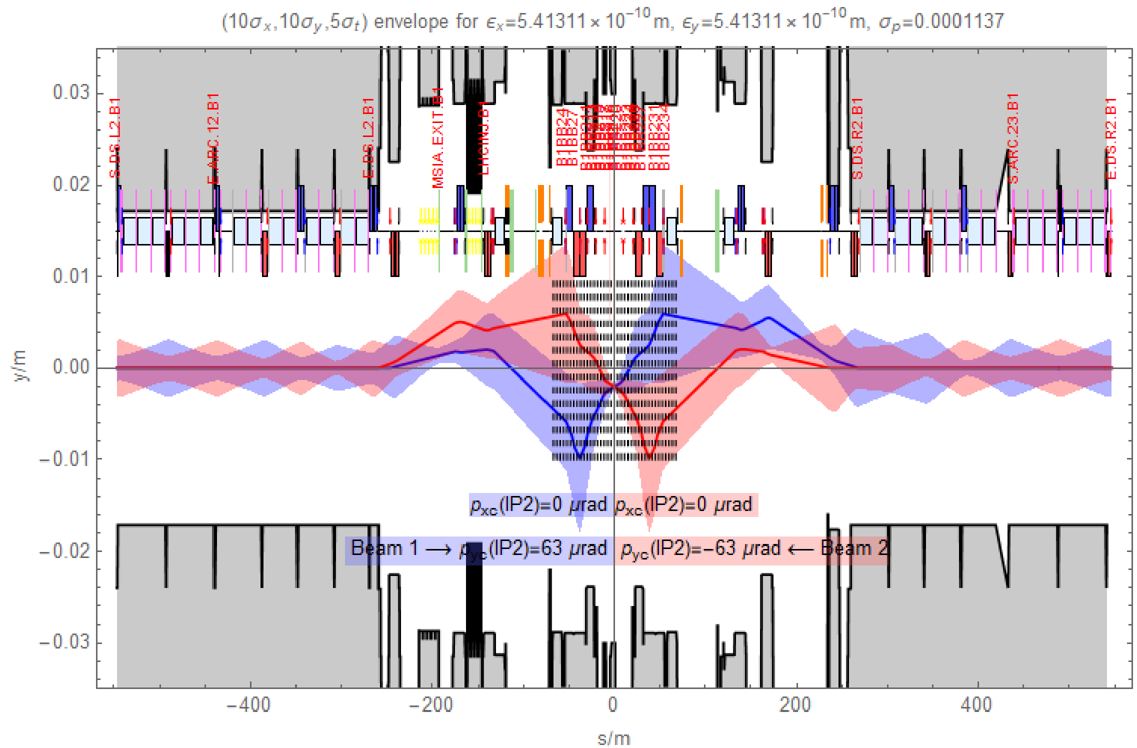


Aim for small β-functions at IP (called β* by convention).

Gives small beams, higher luminosity and collision rate.

Keep beam envelopes sufficiently well within beam pipe (aperture, shown in grey).

Collision conditions in LHC, IR2 vertical plane 2016

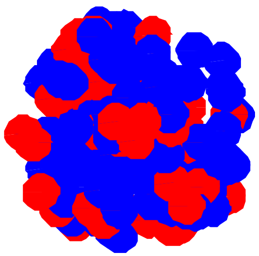


Combination of three orbit bumps (displacement from reference orbit by small dipole magnets called correctors):

1. Compensate magnetic field of ALICE experiment spectrometer magnet
2. Arrange for vertical crossing angle of beams (avoid unwanted encounters)
3. Lower collision point by 2 mm (the experiment sank …)

HEAVY ION BEAMS IN RINGS LIKE LHC

Mass of ions/nuclei



Traditional simple picture of neutral atom:
nucleus containing (Z protons, N neutrons) surrounded by Z electrons.
Nucleon number ("mass number") $A = Z + N$.

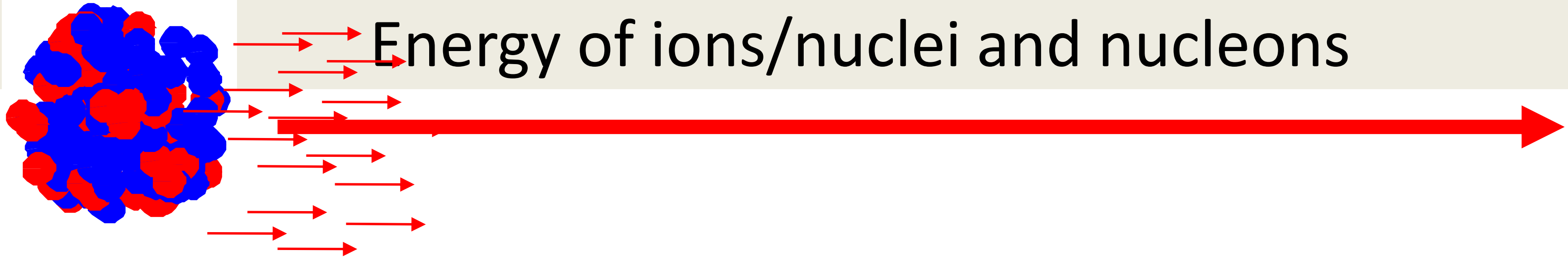
In accelerator equations of motion we consider a general ion of charge Qe and mass m where $Q < Z$. Some electrons have been removed so that ion has a charge and can be accelerated.

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

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

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

$$P^2 = E^2/c^2 - p^2 = m^2c^2$$

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,

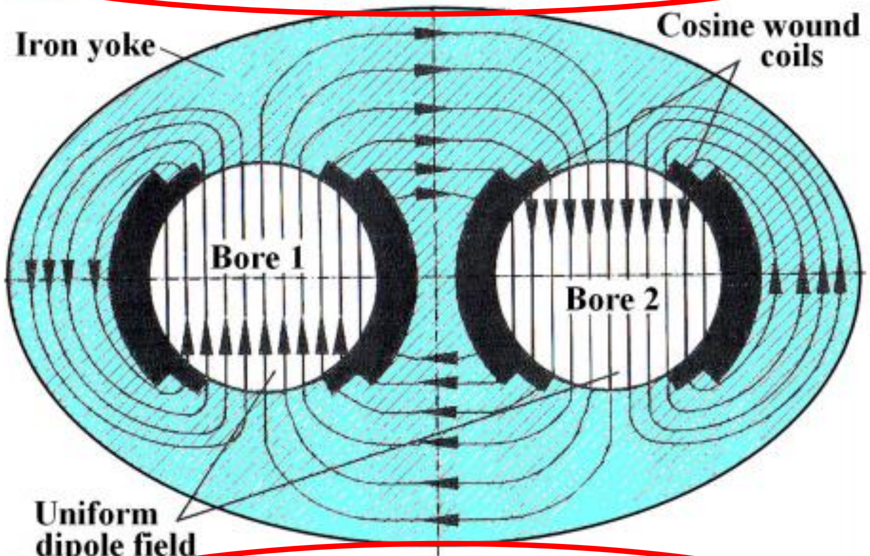
but this quantity does not appear in any equation of motion!

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:

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

Twin-bore magnets

- In 1971, John Blewett proposed the twin-bore superconducting magnet as a cost-saving design for superconducting, proton-proton colliders. The two apertures share 40% of the same flux and only one cryostat is needed Ref [3.1].
- The drawbacks are that asymmetric beam energies and proton-antiproton beams are excluded.



- The twin-bore design is used in the LHC. This choice was driven mainly by the lack of space in the already existing LEP tunnel.

Seemingly a necessary but highly restrictive choice adopted early on (~1984) for the LHC – even the final LHC Design Report of 2004 included only the two possibilities of colliding equal energy beams of p-p or Pb-Pb.

JUAS20_03- P.J. Bryant - Lecture 3
Lattice Design II - Slide5

Relation between Beam Momenta

- LHC accelerates protons through the momentum range

$$0.45 \text{ TeV/c (injection from SPS)} \le p_p \le 7 \text{ TeV/c (collision)}$$

  - 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 on the reference orbit in the two rings (equal *"magnetic rigidity")*

$$\frac{p}{q} = B_y \rho$$

$$\frac{p_1}{Z_1 e} = B_y \rho = \frac{p_2}{Z_2 e} = \frac{p_p}{e}$$

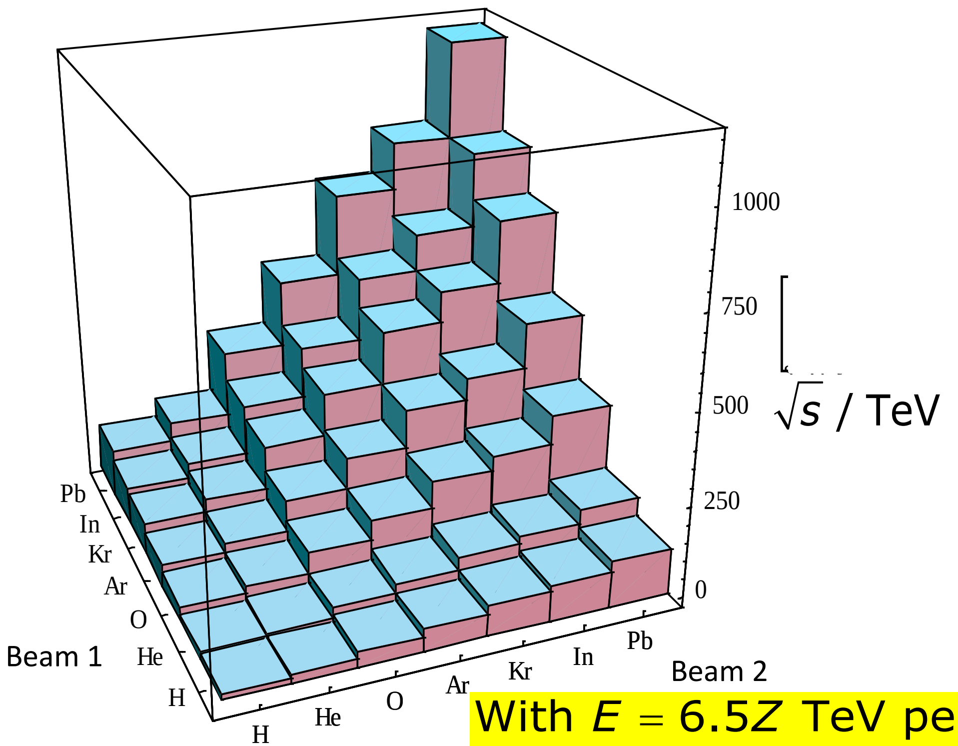
For $Z = 82, A = 208$ fully stripped Pb in LHC

$$p_{\text{Pb}} = 82 p_{\text{p}}$$

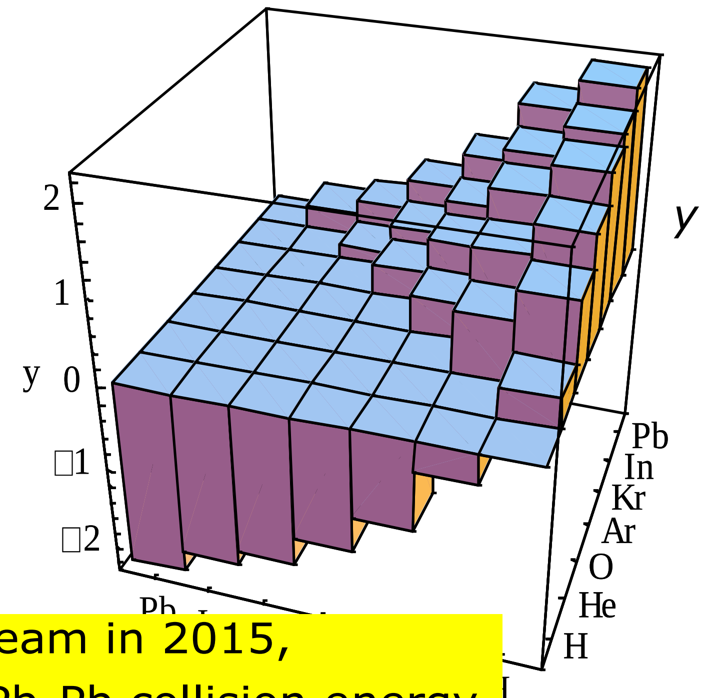
Kinematics of nuclear collisions

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

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



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

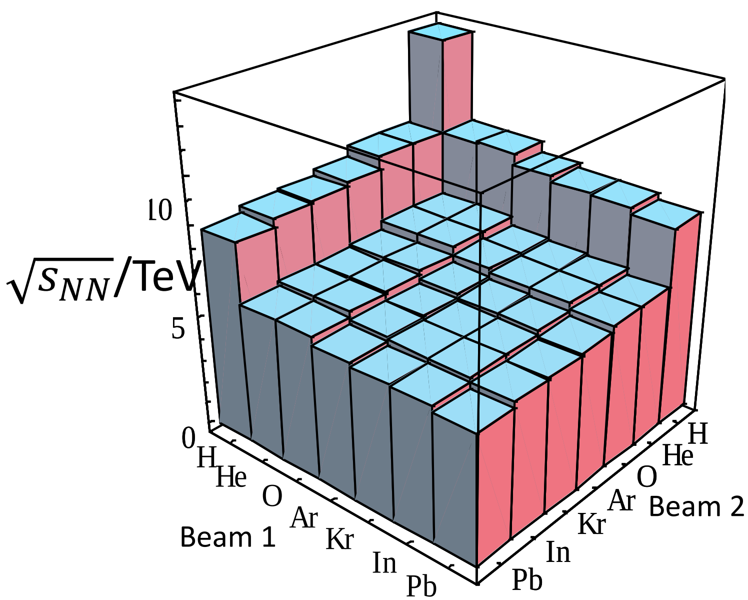


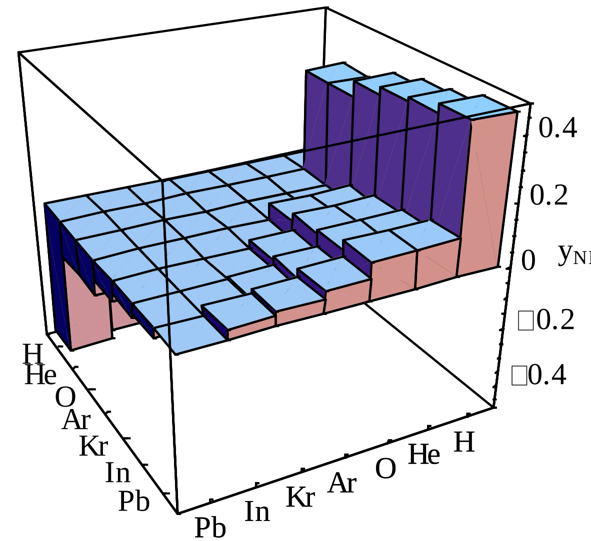
With $E = 6.5Z$ TeV per beam in 2015,
the LHC attained total Pb-Pb collision energy
$\sqrt{s} > 1000$ TeV $= 1$ PeV
in fm^3 volumes.

Average kinematics of colliding nucleon pairs *inside nuclei*

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.

Kinematics of colliding nucleon pairs

	p-p	Pb-Pb	p-Pb	d-Pb
E/TeV	7	574	(7,574)	(7,574)
E_N/TeV	7	2.76	(7,2.76)	(3.5,2.76)
$\sqrt{s}/\mathrm{TeV}$	14	1148	126.8	126.8
$\sqrt{s_{\mathrm{NN}}}/\mathrm{TeV}$	14	5.52	8.79	6.22
y_{CM}	0	0	2.20	2.20
y_{NN}	0	0	-0.46	-0.12

- Maximum values, corresponding to proton equivalent momentum ($\Leftarrow$ magnetic bending field) of 7 TeV/c
- Relations between these numbers are a simple, direct consequence of the two-in-one magnet design.

Luminosity of a hadron collider

$$L = \frac{N^2 k_c f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_c f_0 \gamma}{4\pi\,\varepsilon_n \beta^*} F(\theta_c)$$

Hour glass factor: $F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$

- Parameters in luminosity
  - No. of particles per bunch — N
  - No. of bunches per beam — k_b
  - No. of bunches collliding at IP — k_c
    - ($k_c < k_b$)
  - Relativistic factor — γ
  - Normalised emittance — ε_n
  - Beta function at the IP — β^*
  - Crossing angle factor — F
    - Full crossing angle — θ_c
    - Bunch length — σ_z
    - Transverse beam size at the IP — σ^*

Equal amplitude functions:

$\beta_x^* = \beta_y^* = \beta^*$,

Geometric and normalised emittance:

$$\varepsilon_x^* = \varepsilon_y^* = \varepsilon^* = \frac{\varepsilon_n}{\sqrt{\gamma^2 - 1}}$$

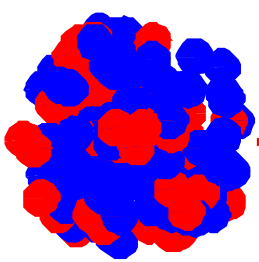
$\Rightarrow$ Round beams at IP:

$$\sigma_x^* = \sigma_y^* = \sigma^* \simeq \sqrt{\frac{\beta^* \varepsilon_n}{\gamma}}$$

(N.B. LHC uses RMS emittances.)

Luminosity with nuclei and nucleons

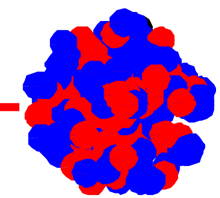
- Luminosities quoted for lead nuclei may seem low compared to pp or e^+e^-
- But comparisons are more meaningful on the basis of nucleon pair luminosities

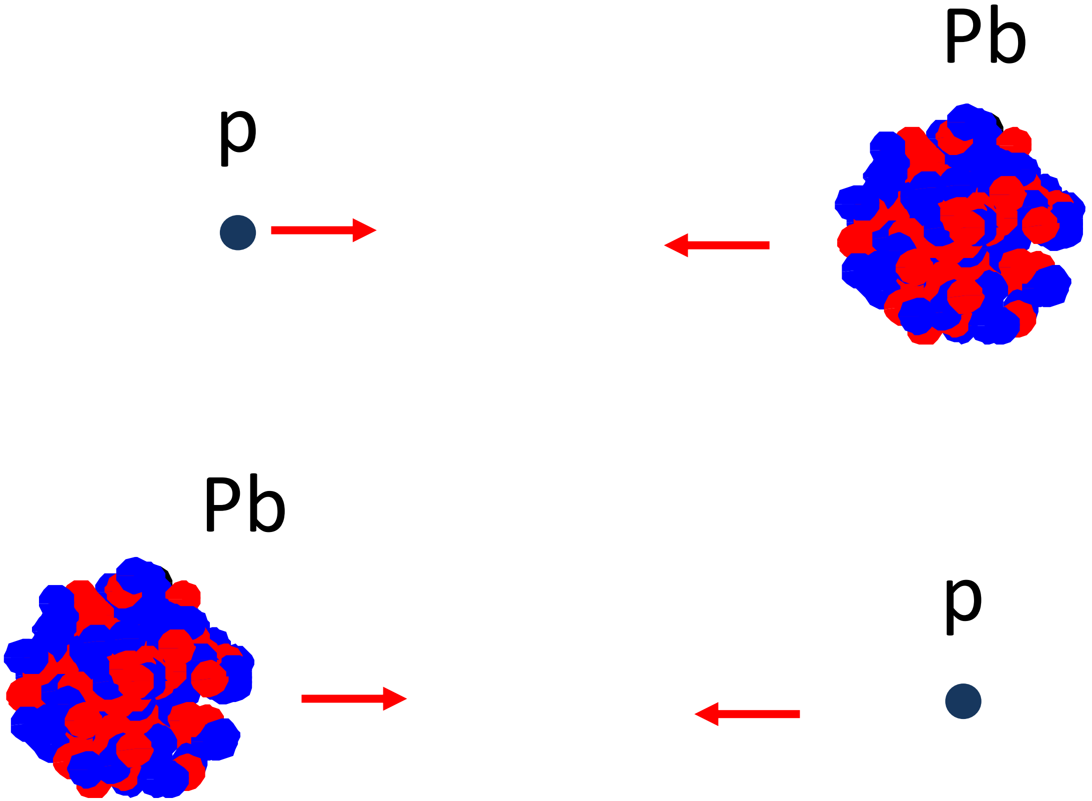


$$L = 5.0 \times 10^{27} \text{ (Pb)(Pb) cm}^{-2}\text{s}^{-1}$$
$$= 2.2 \times 10^{32} \text{ (nucleon)(nucleon) cm}^{-2}\text{s}^{-1}$$

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

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





PROTON-LEAD COLLISIONS IN LHC

First asymmetric collisions at LHC

History of proton-nucleus collisions at LHC (2)

- 2005 First workshop on need and proposal for a way to provide them at LHC
- 2006 First paper at European Particle Accelerator Conference, in Edinburgh
- 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
- Early 2012, after high Pb-Pb luminosity in Nov 2011, experiments *really* want p-Pb comparison data
- 13/9/2012 Successful pilot collision run (one night)
- Jan-Feb 2013 first full physics run
- Nov 2016 second run, multiple collision conditions including higher energy, almost 9 times "design" luminosity proposed in 2005

The Revolution Period Problem

- Synchrotrons and storage rings are based on the existence of a *closed orbit,* length *C,* that an ion of the right momentum, mass *m*, charge *Z*, will follow.
- The forces on beam are *periodic* if arc-length *s* along the closed orbit is used as independent "time" variable (basis of single-particle dynamics)
- The frequencies of small oscillations around the closed orbit (in units of revolution period) are called the *tunes.*
- Revolution period on the closed orbit depends on ion mass (speed):

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

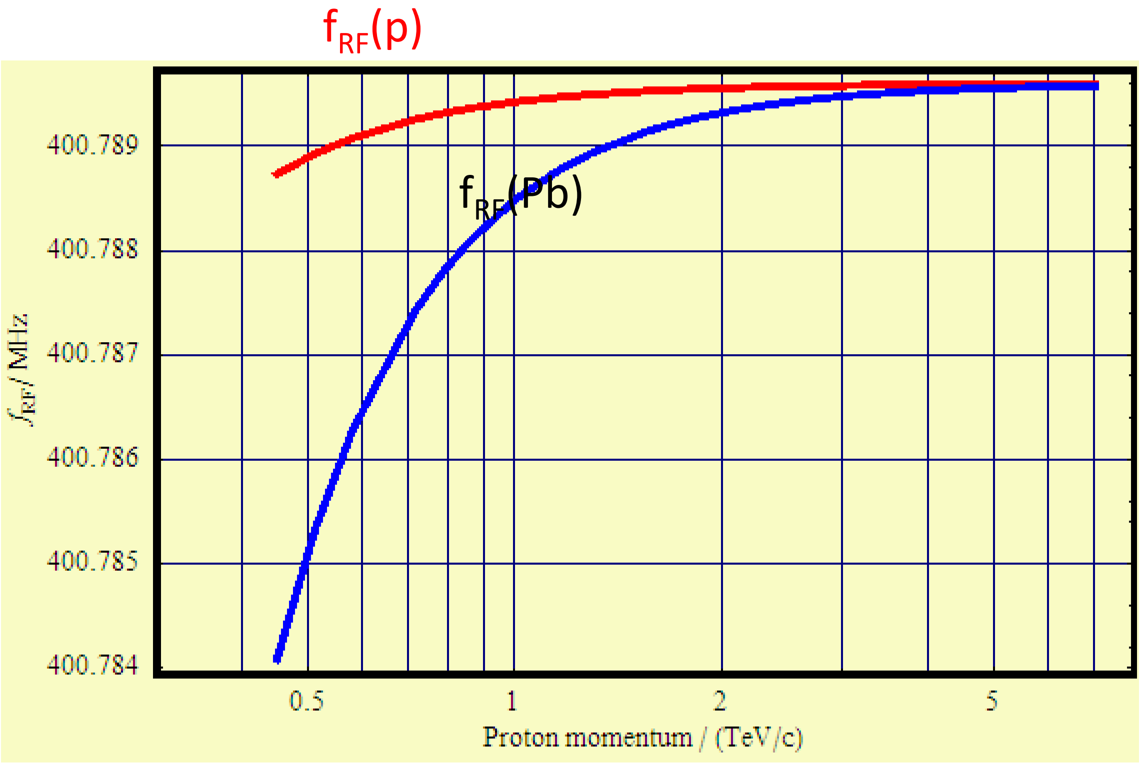
RF Frequency for p and Pb in LHC

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

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

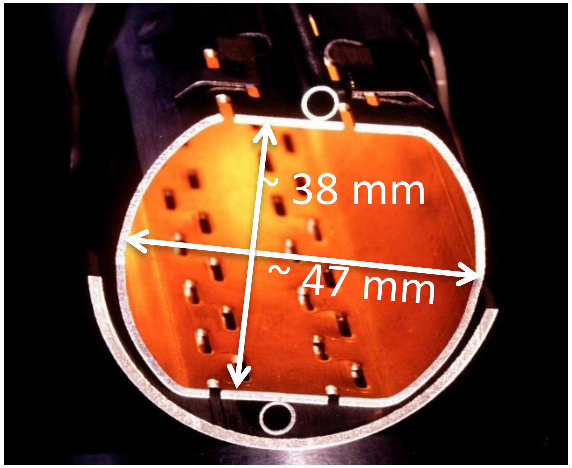
where the harmonic number $h_{\mathrm{RF}}=35640$ in LHC

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 to to move slower Pb in, faster p out from centre of ring:



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

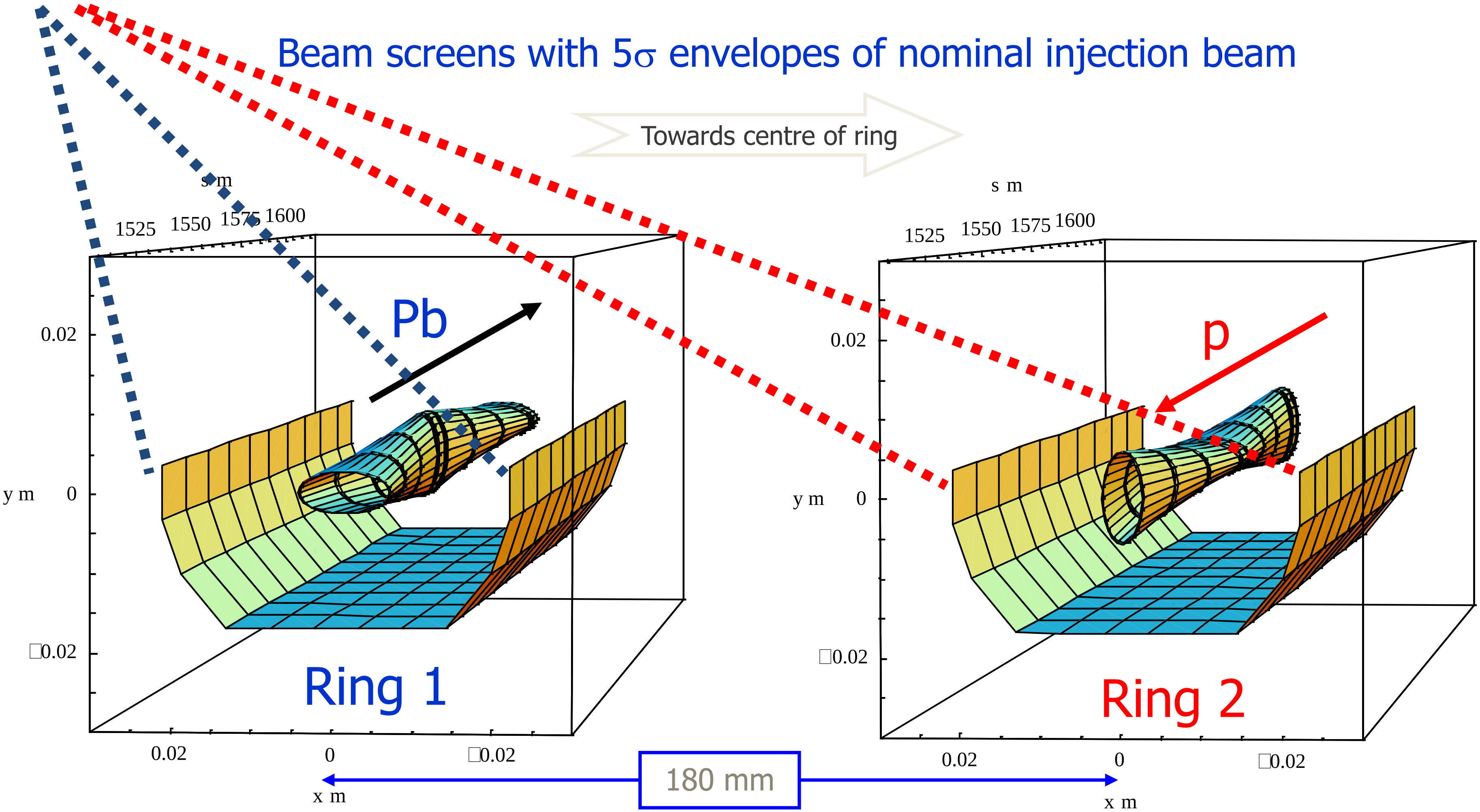
where $\delta = \dfrac{(p - Zp_{\mathrm{p}})}{Zp_{\mathrm{p}}}$ is a fractional momentum deviation and

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

Moves beam on to off-momentum orbit, longer for $\delta > 0$.
Horizontal offset given by dispersion function peak in horizontally focussing quadrupoles in the arcs: $\Delta x = D_x(\mathrm{QF})\delta$.

A FODO cell in the arc between ATLAS and ALICE

Beam screens with 5σ envelopes of nominal injection beam



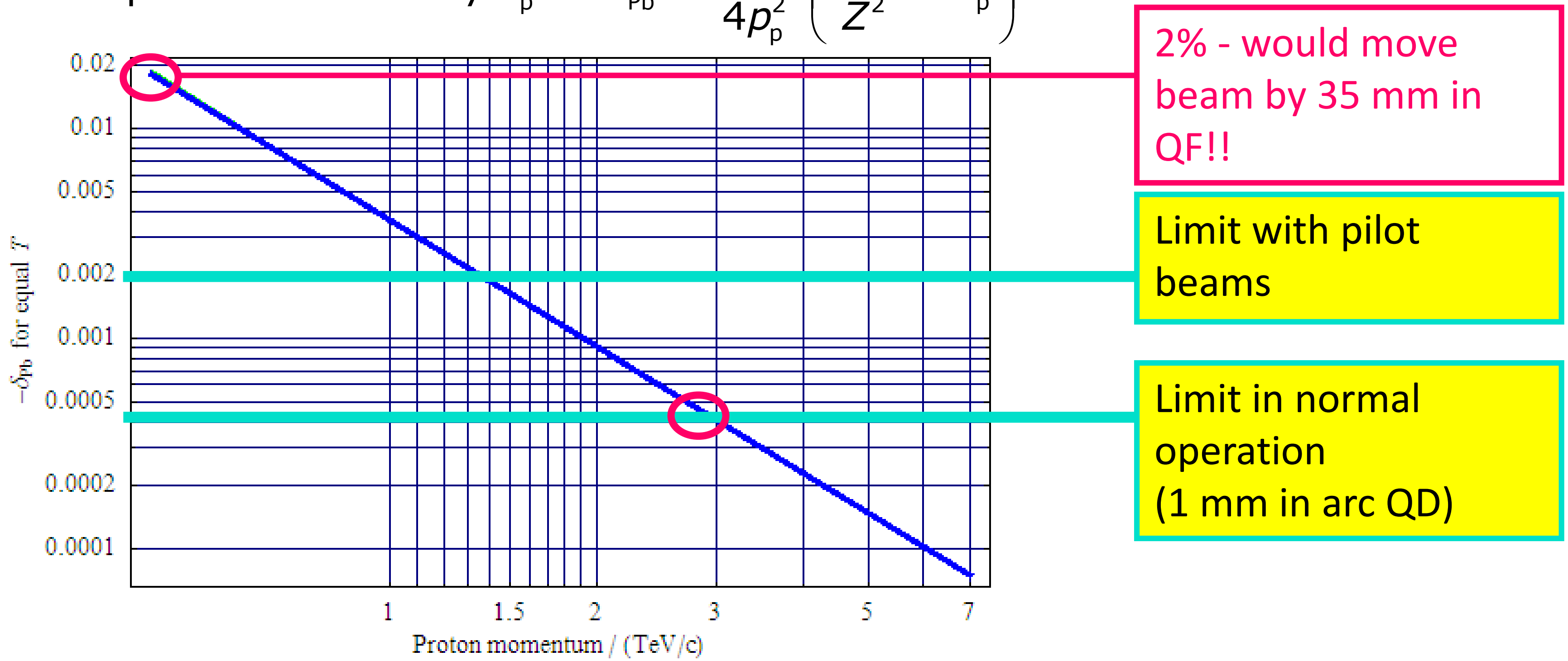
~1 mm

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

~1 mm

Momentum offset required through ramp

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

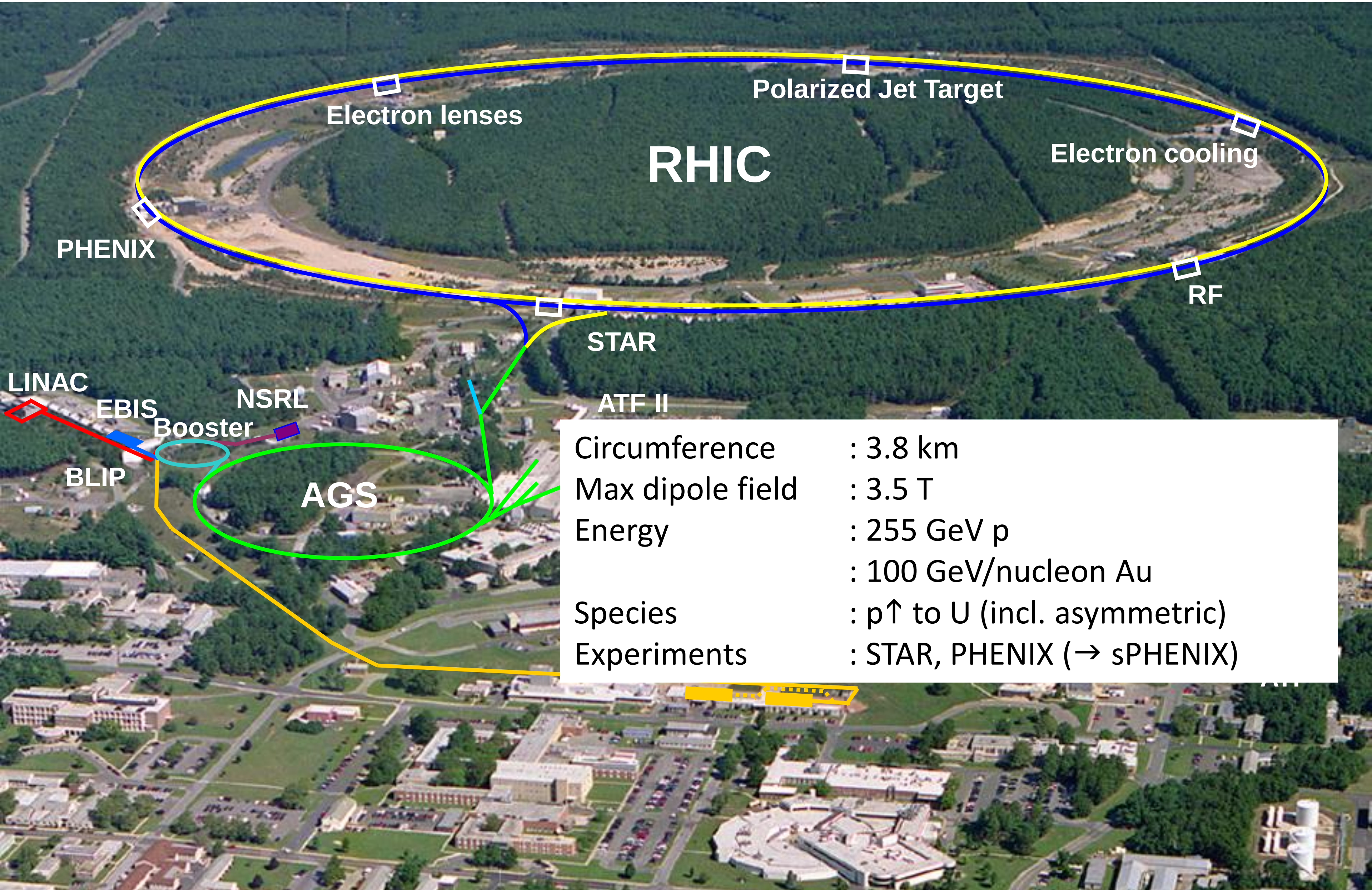


Revolution frequencies must be equal for collisions at top energy.

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

RF frequencies must be unequal for injection, ramp with equal rigidity but necessarily unequal revolution frequencies!

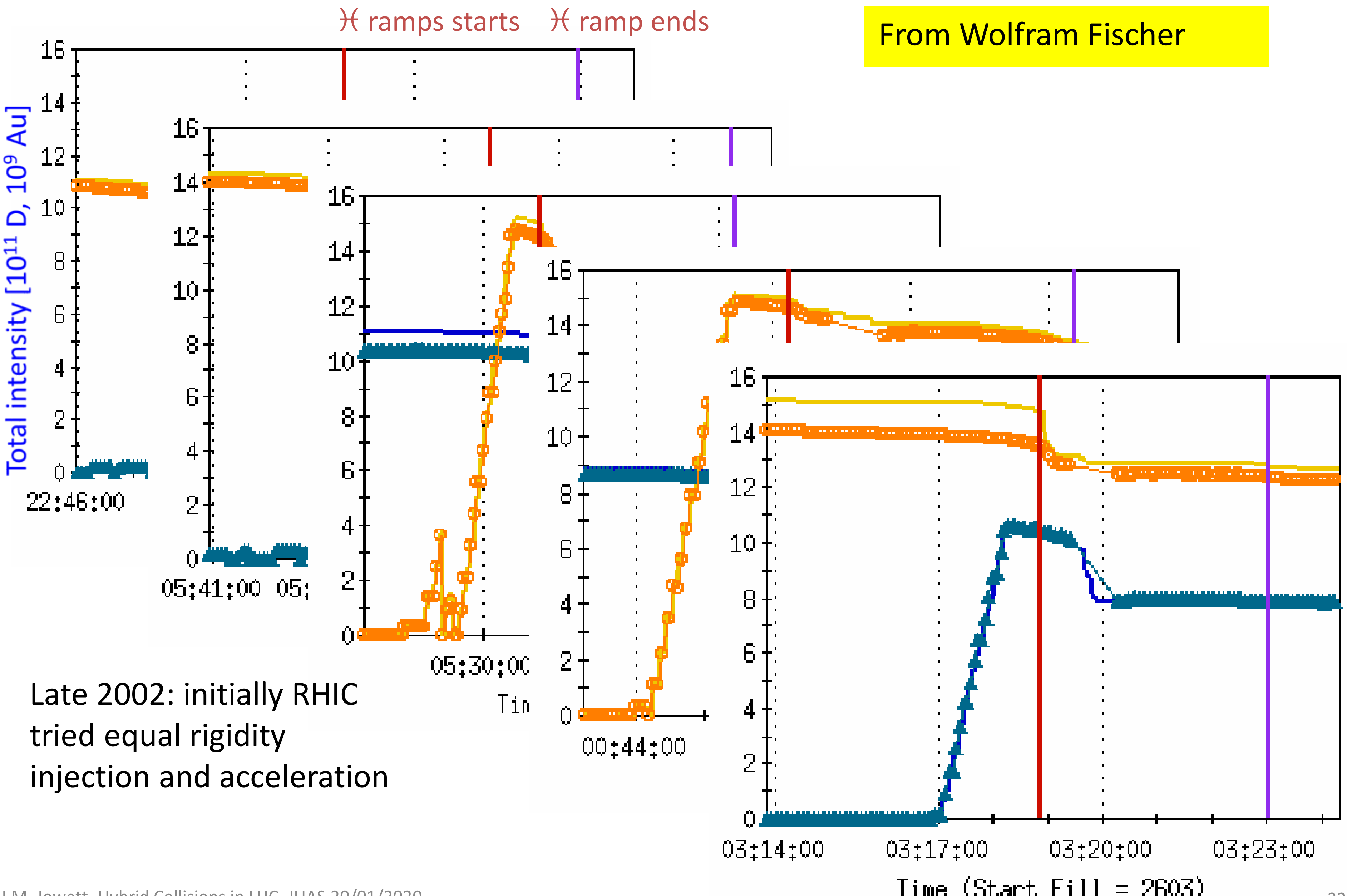
Relativistic Heavy Ion Collider at Brookhaven National Lab



Circumference	: 3.8 km
Max dipole field	: 3.5 T
Energy	: 255 GeV p
	: 100 GeV/nucleon Au
Species	: p↑ to U (incl. asymmetric)
Experiments	: STAR, PHENIX (→ sPHENIX)

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

- RHIC found that this led to intensity limit or emittance blos-up
  - attributed to kicks and tune-modulation from moving long-range beam-beam encounters.

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

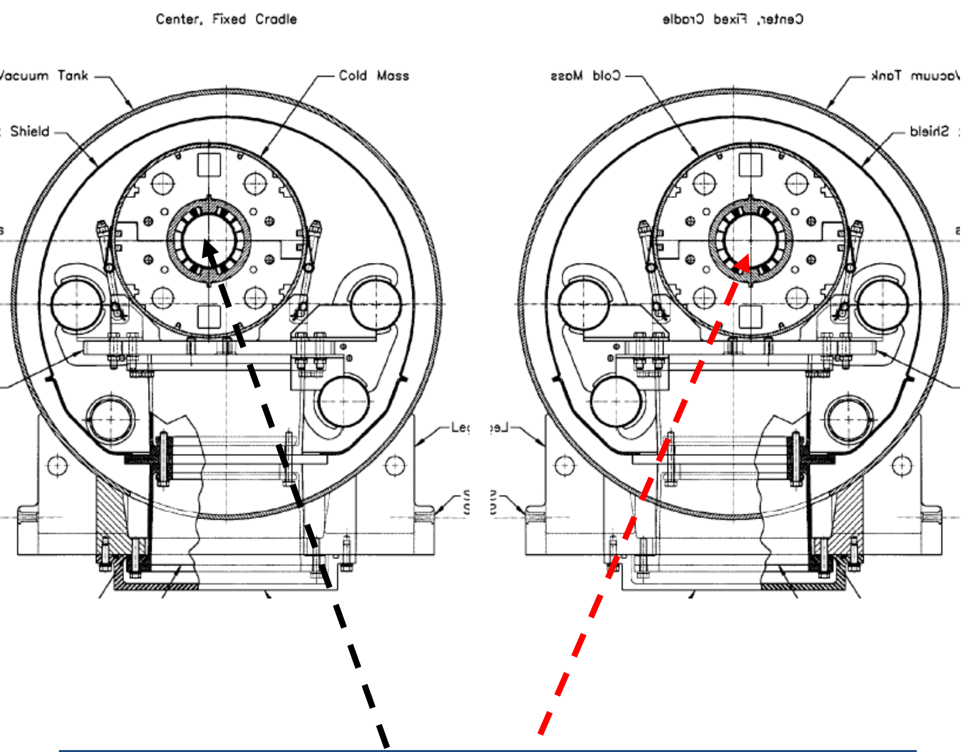
Fields of one beam acting on the other are no longer periodic in *s*.

Excites modulational resonances (called "overlap knock-out" at the ISR):

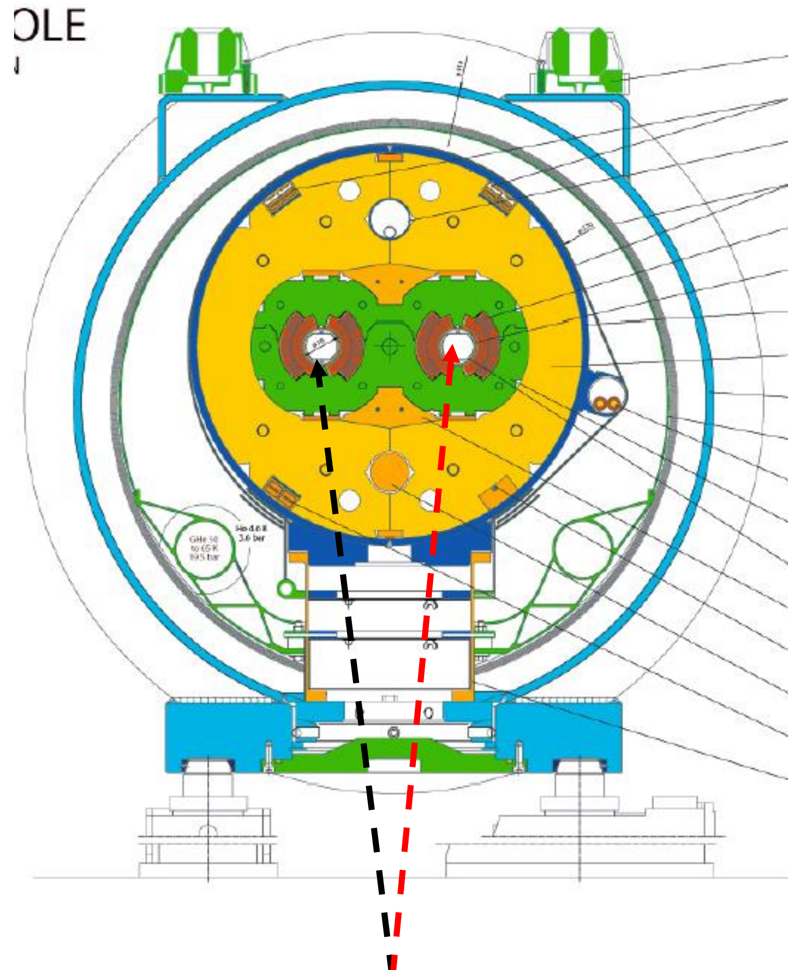
$$m_x \nu_x + m_y \nu_y = p + k \underbrace{\frac{c\left(T_{\mathrm{Pb}} - T_{\mathrm{p}}\right)}{S_b}}_{0.01};\ m_x, m_y, p, k \in \mathbb{Z}$$

  - Solution for d-Au at RHIC was to adjust magnetic field separately in the two rings
  - Instabilities were not well-understood at the time.

Critical difference between RHIC and LHC



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 in LHC (Pb-p similar)

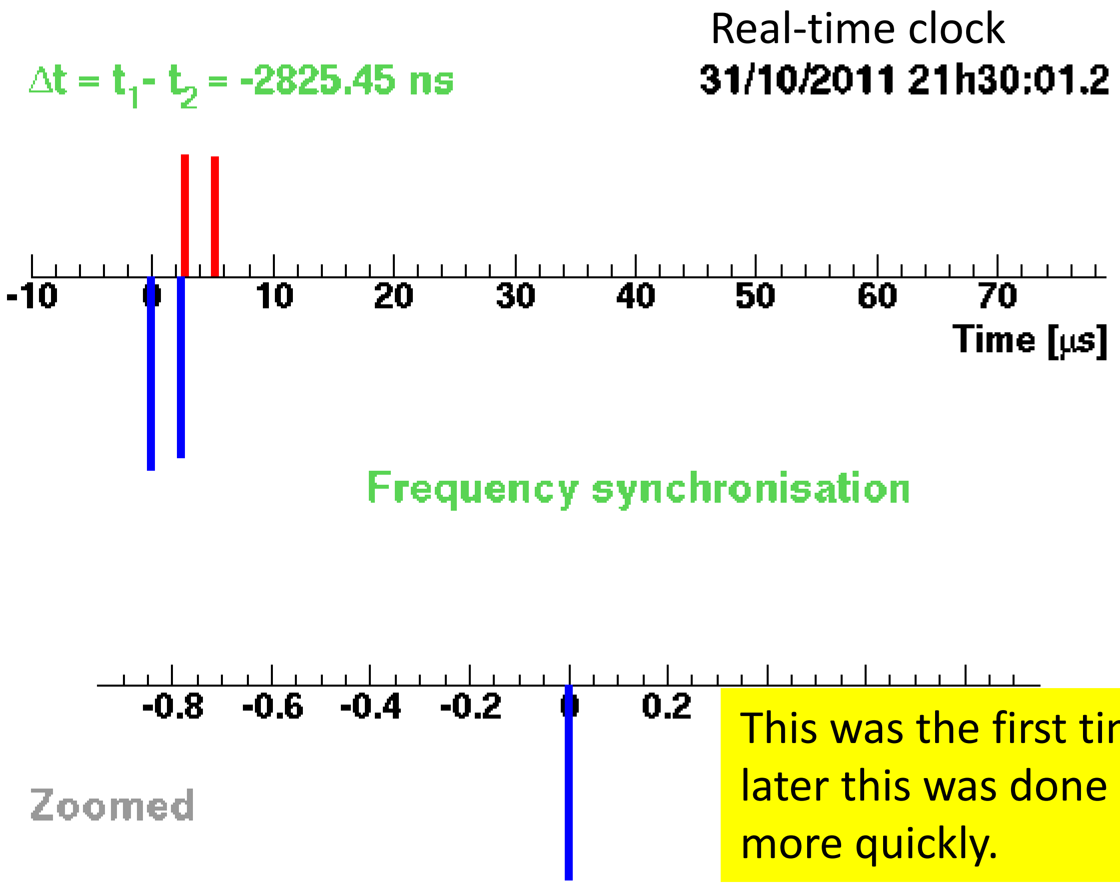
- Inject p beam in Ring 1, f_{RF1} for p
- Inject Pb beam in Ring 2, f_{RF2} for Pb
- Ramp both beams on central orbits
  - Orbit feedback decouples RF frequencies
- Bring f_{RF} together to lock, beams are slightly off central orbits
- RF re-phasing to position collision point
- Squeeze
- Change ALICE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

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

Ramping, then moving the collision point by 9 km

At top energy:

- **Equalize revolution frequencies** for collisions: move beams to off-momentum orbit.
- **Cogging**: RF re-phasing to re-establish synchronization of bunch arrival times in IP.



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

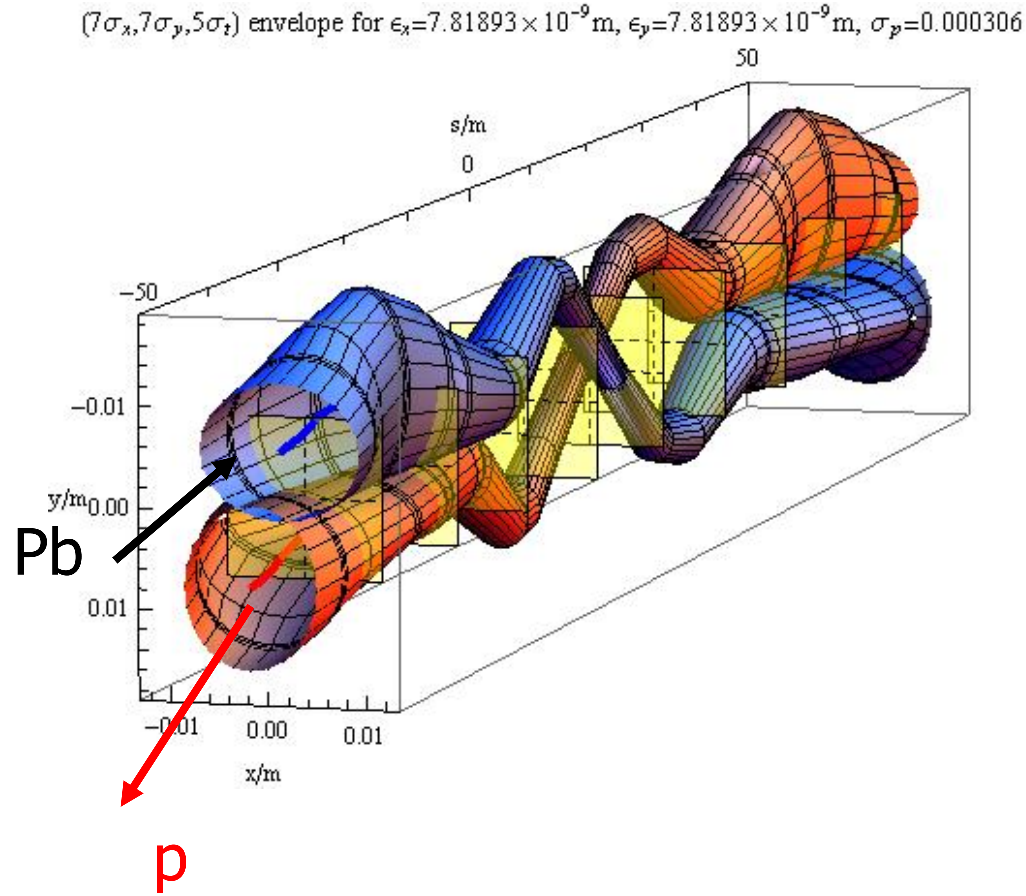
RF cogging by Philippe Baudrenghien.

Video shows the difference in arrival time of the bunches at IP1, taking Beam 1 (blue) as reference.

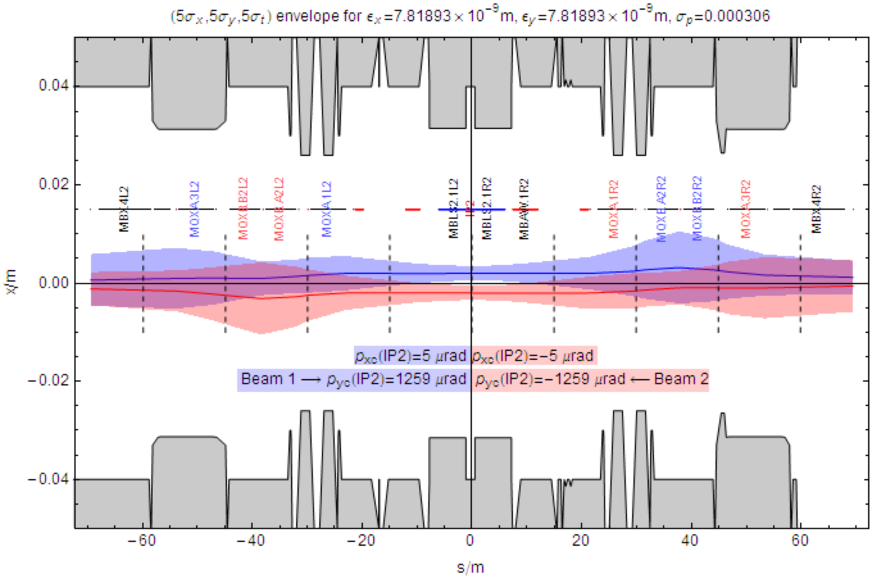
Timing data from BPTX beam position monitor (from Thilo Pauly, ATLAS).

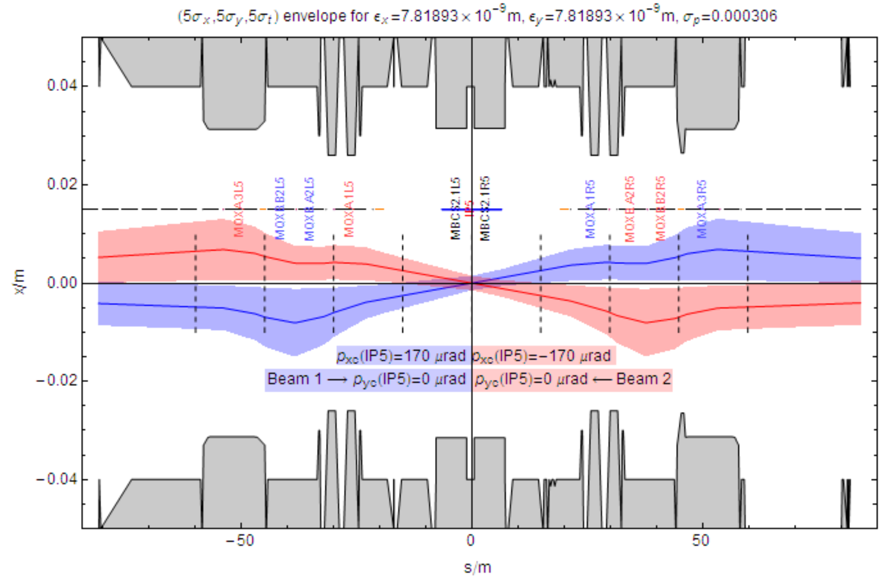
Beam Separation in IR2 (around ALICE)

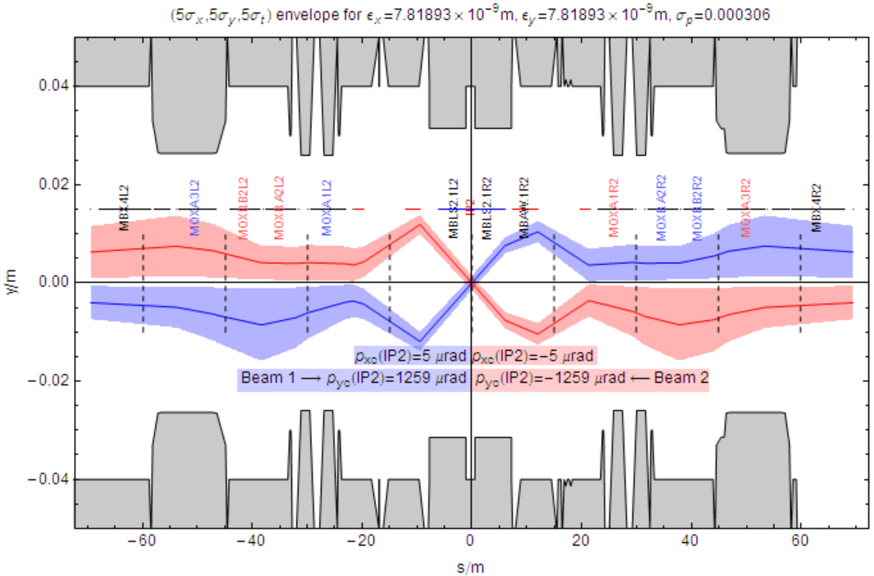
- 5σ envelopes of beams at injection out to first D1 separation magnet
  - Vertical crossing angle bump
  - Horizontal injection separation bump
  - Encounter points have basic spacing of 15 m, but there are gaps in the bunch train.
  - Comb of 5-6 encounter points moves across IR at 0.15 m per turn.

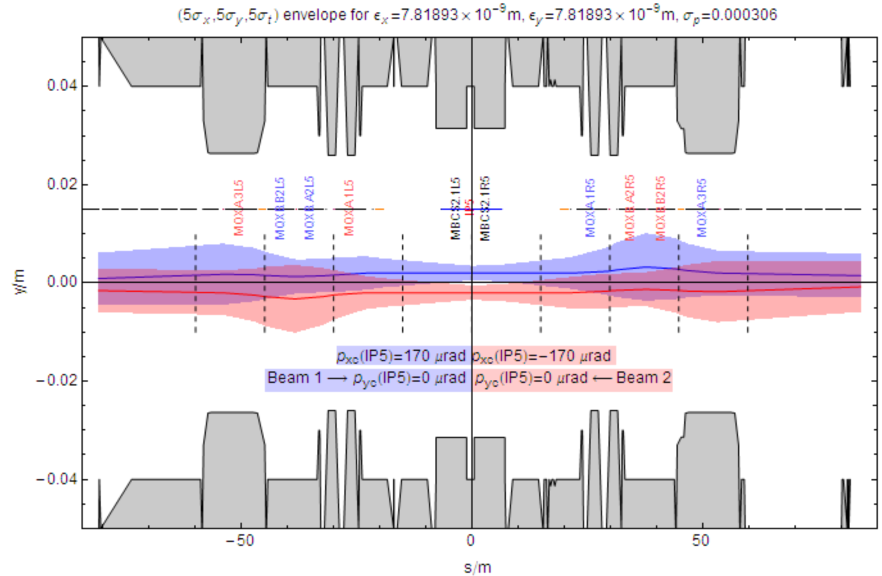


ALICE – Separation at injection - CMS









Long-range beam-beam effects

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

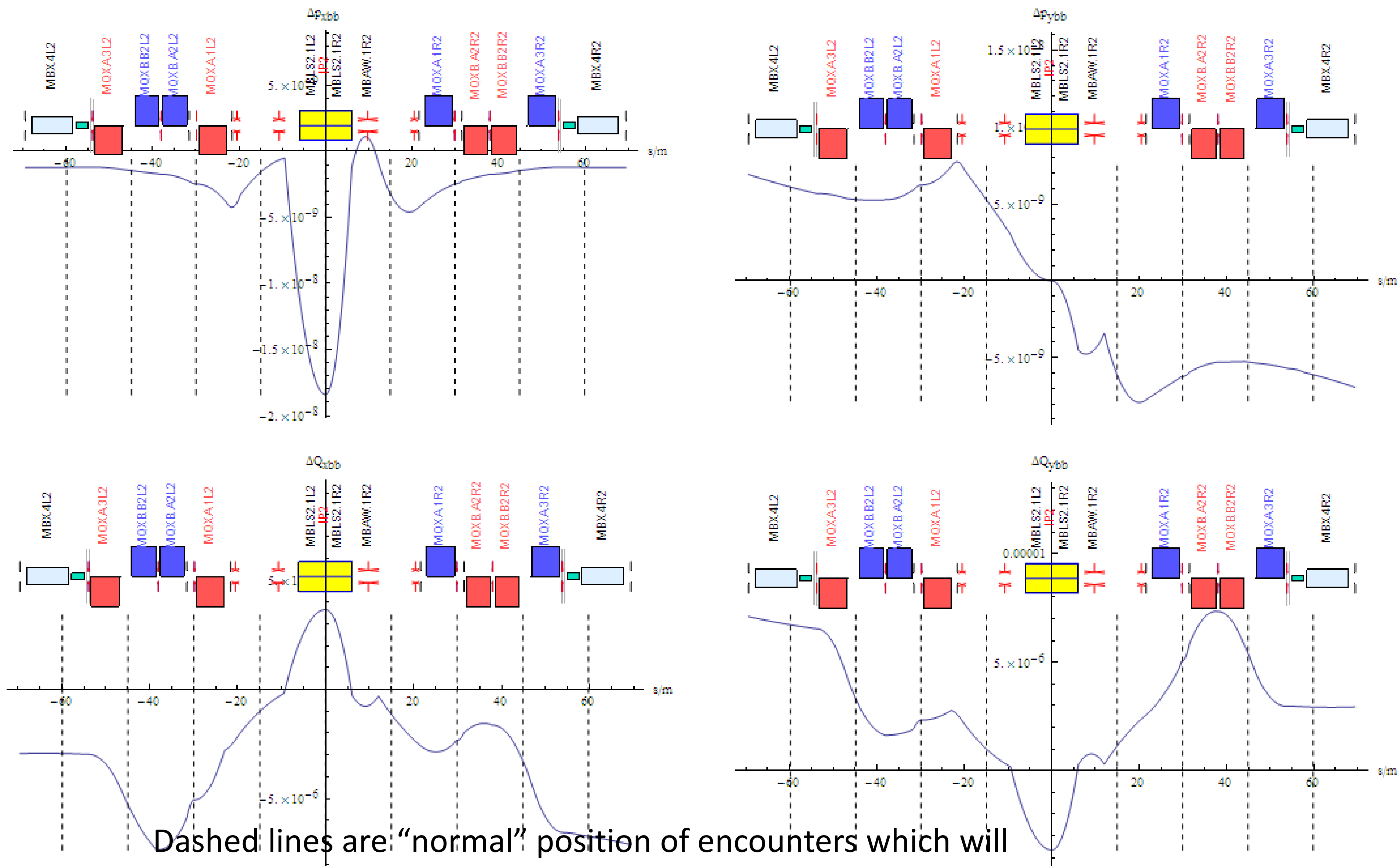
$$(\Delta p_x, \Delta p_y) = \frac{2ZNr_0}{\gamma}\frac{(x, y)}{x^2 + y^2}, \qquad \text{where} \quad r_0 = e^2 / (4\pi\epsilon_0 mc^2)$$

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 ?

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.

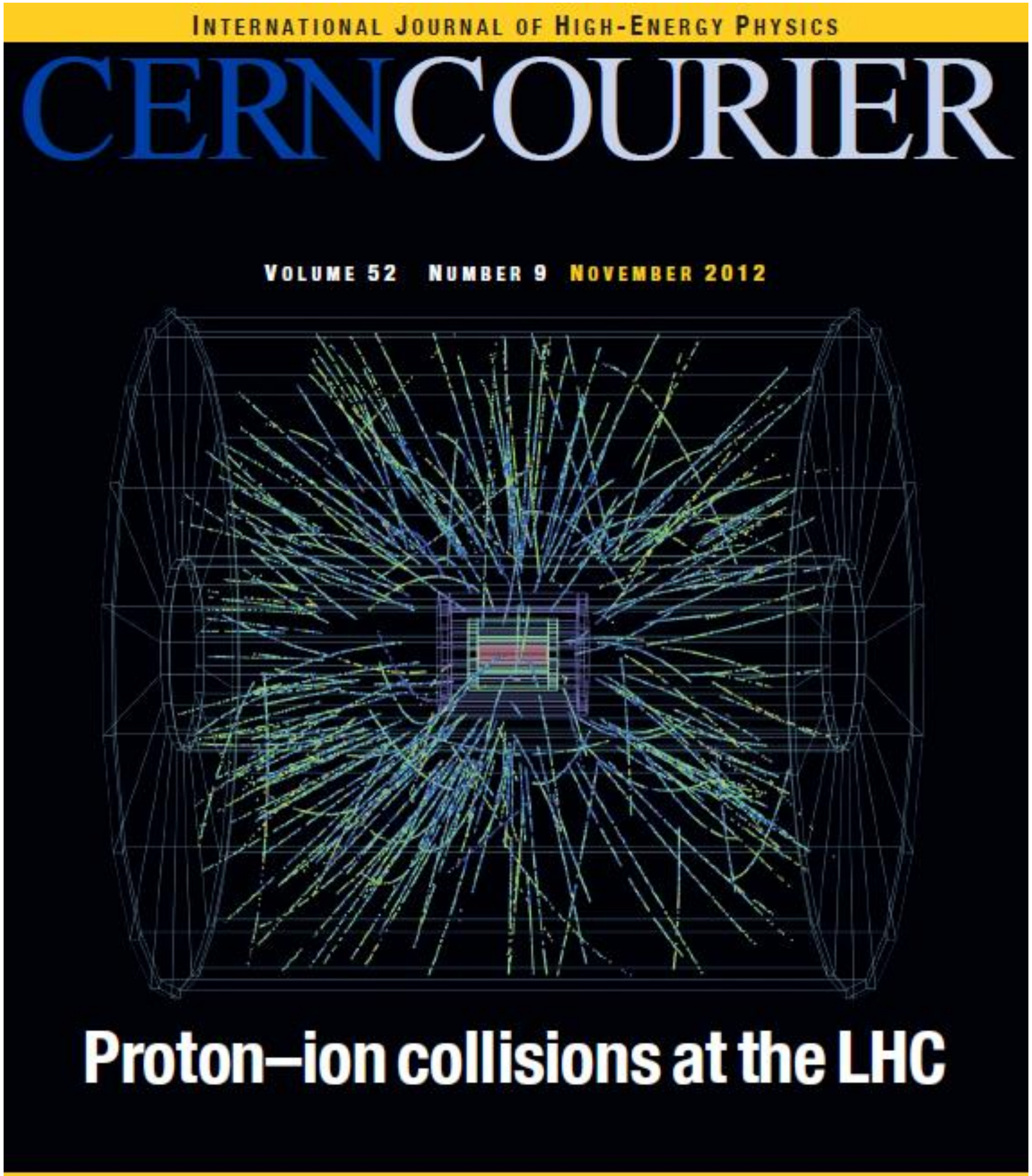
Excites modulational resonances

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

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.

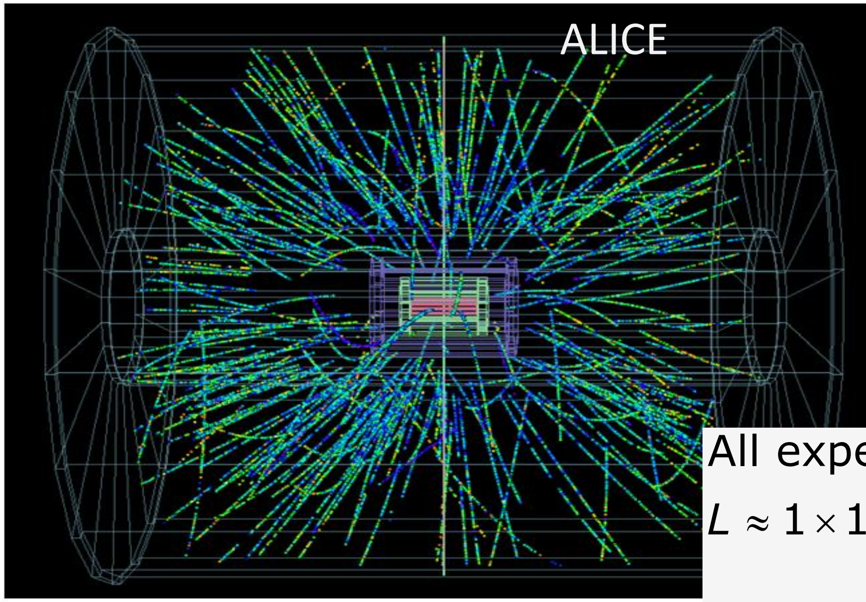
Very unlikely to be a problem (similar in RHIC, W. Fischer).



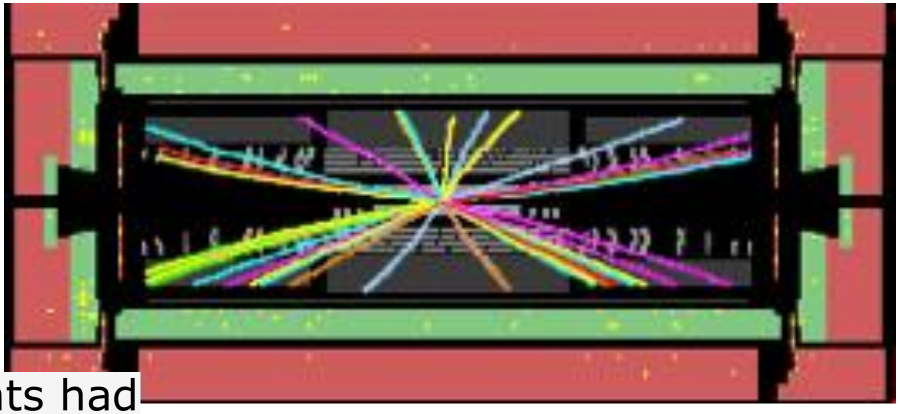
After the first 16 h test (last slide) in October 2011, another 16 h of LHC time was taken in September 2012 to implement the first p-Pb collisions in LHC.

This provided just 4 h of colliding beam time at low luminosity but it was the largest ever jump in collision energy (for a given type of collision), by a factor 25, in the history of particle accelerators.

Collisions in all experiments

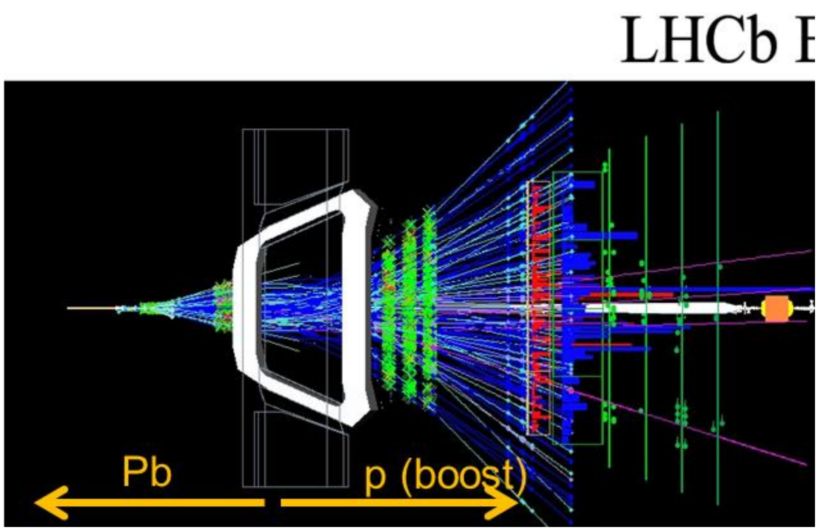


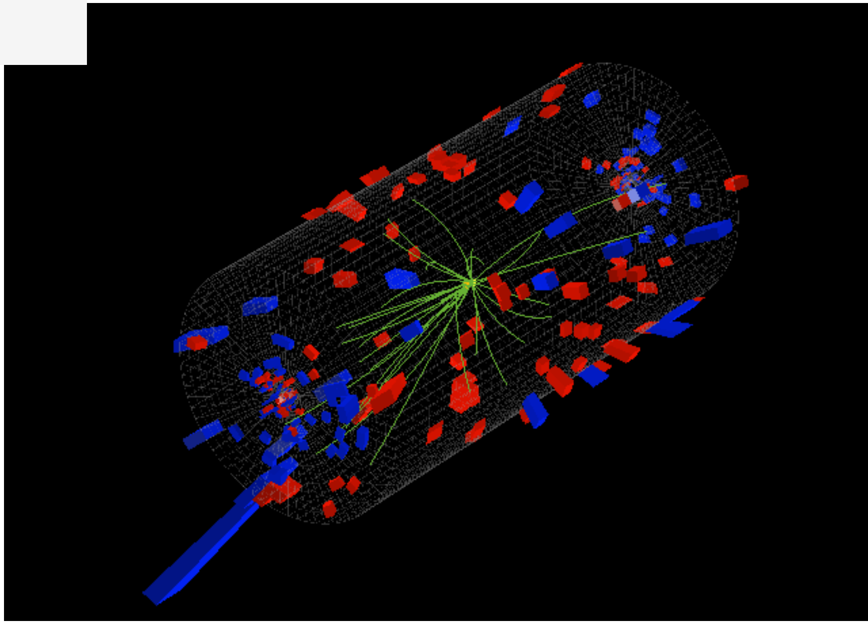
ATLAS



All experiments had

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





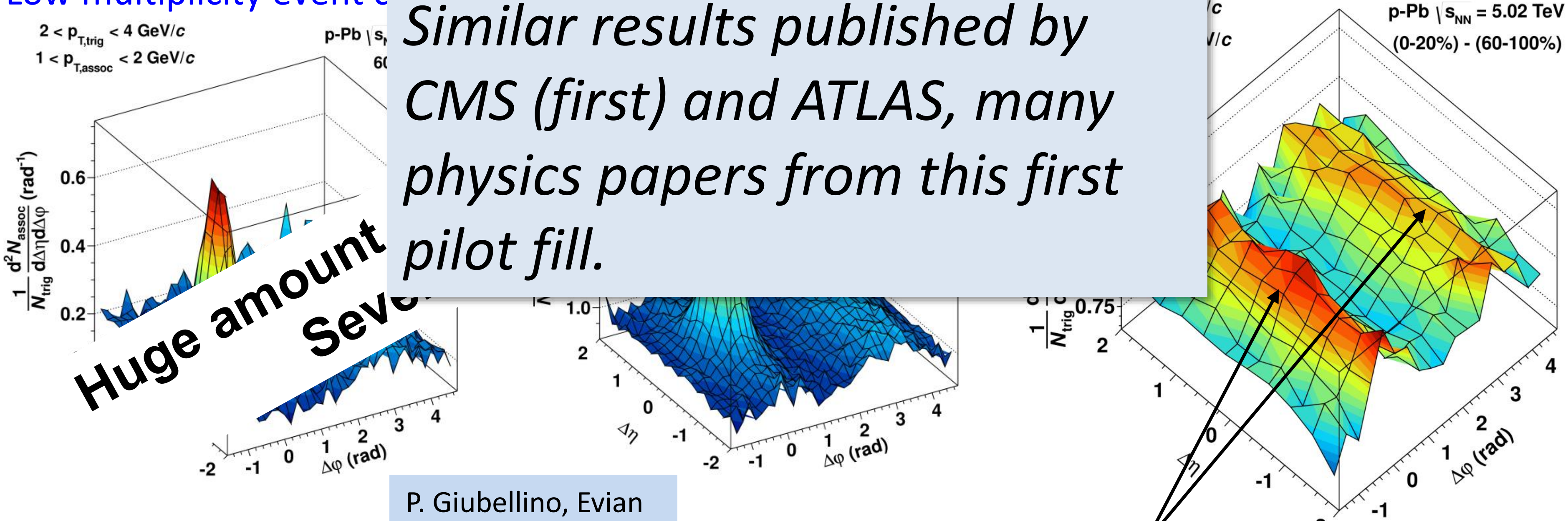
CMS

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 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 a… …t RHIC is considered a sign of saturation effects)
  - In agreement with viscous hydro calculations ?'…

…ing a new window in the field
…4 h of collisions

Low multiplicity event c…



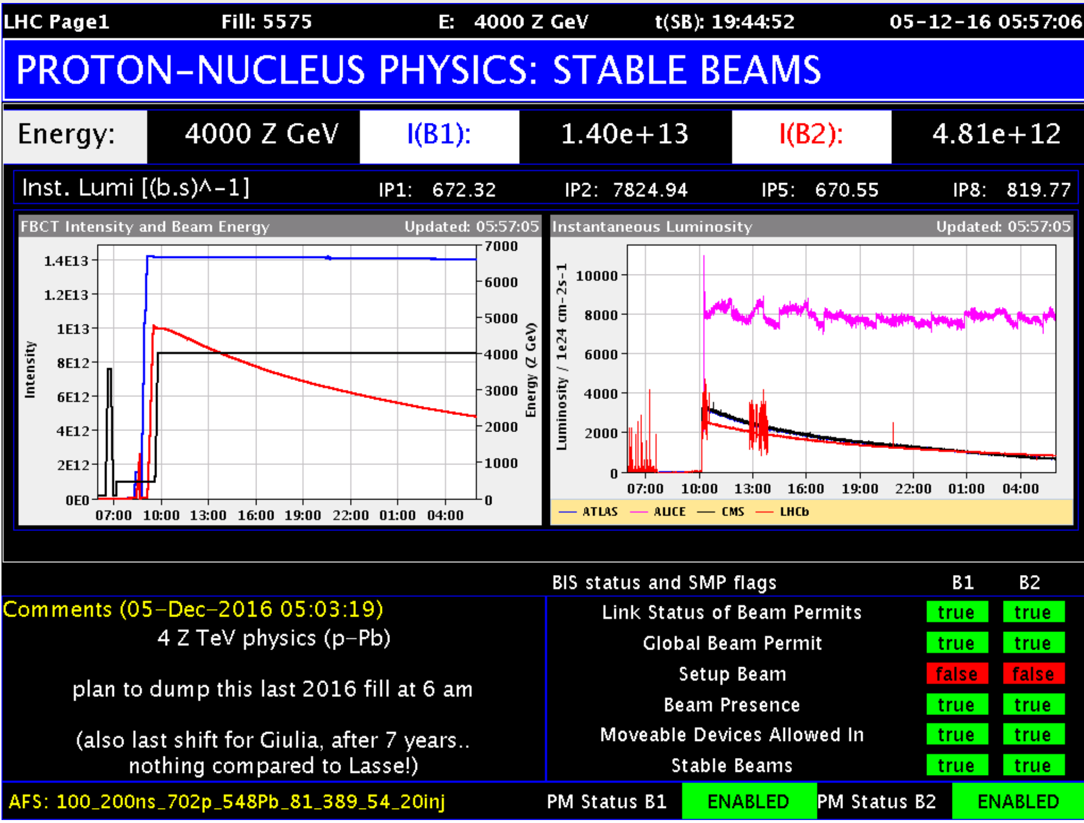
Huge amount …
Seve…

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

P. Giubellino, Evian Dec 2012

Double-ridge structure

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

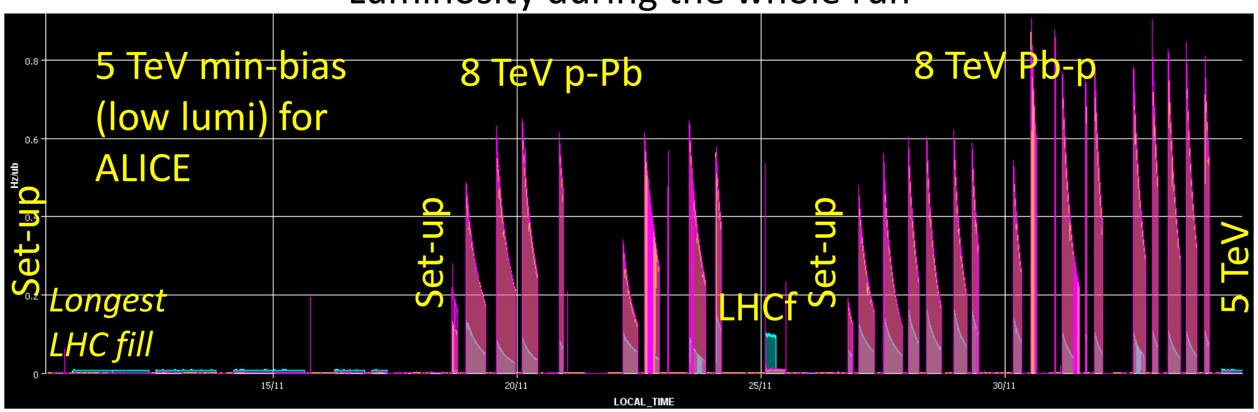


Fast switch back to original conditions to top-off ALICE minimum-bias data-taking.

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 run at 4 Z TeV in 2012/13.

Complex 2016 run plan determined after Chamonix 2016:

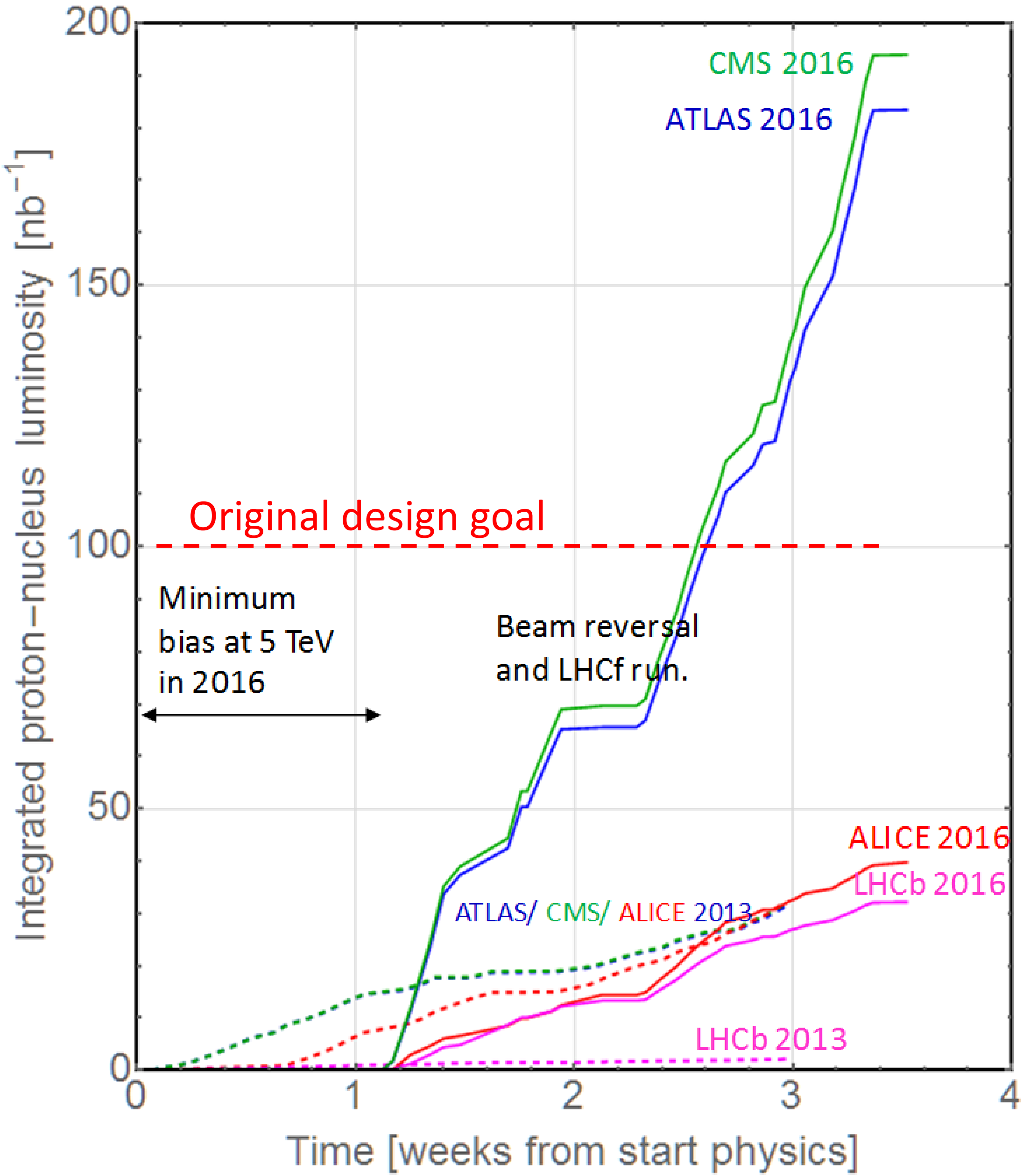
Minimum bias run at 4 Z TeV mainly for ALICE

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.

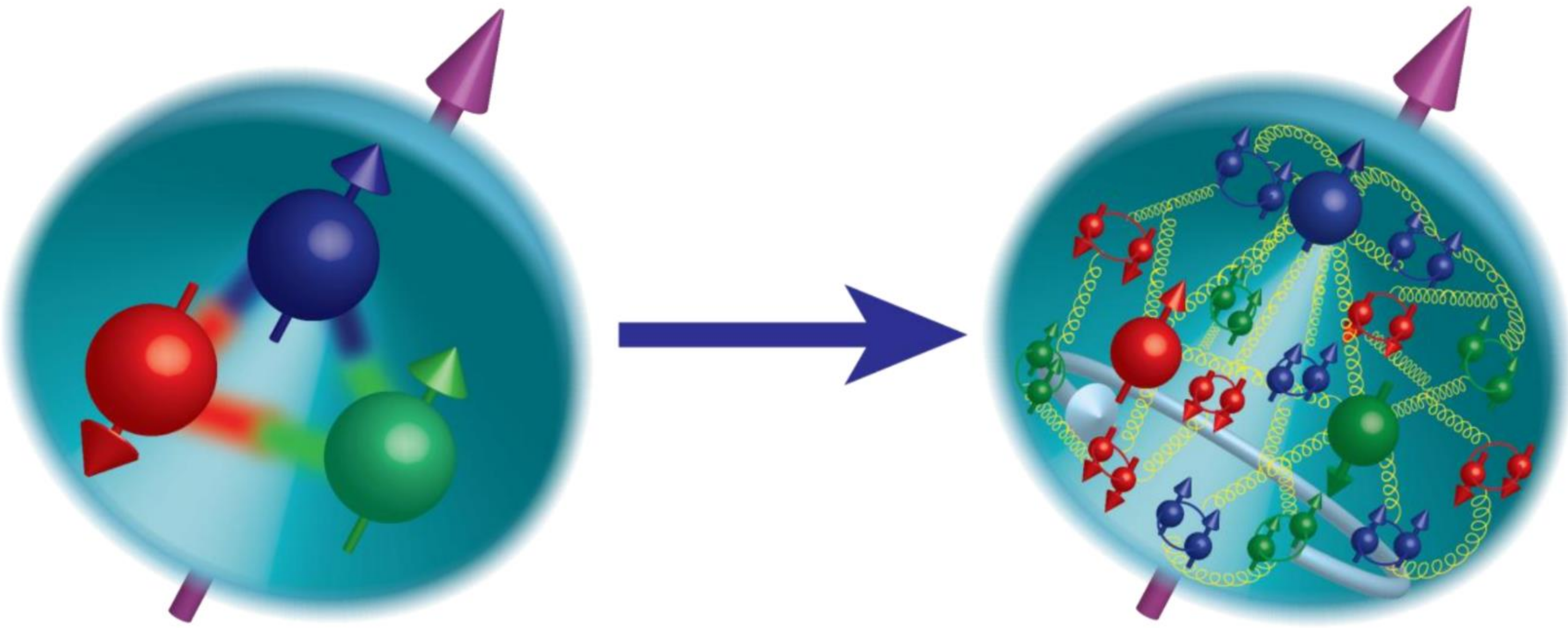
Many filling schemes used for luminosity sharing.



Electron-Ion Collider

- Proposed for construction in USA
  - Potentially the first “Future Collider” to be built in the world
- Two candidate designs:
  - ~~JLEIC at Jefferson Lab~~
    - ~~Uses existing CEBAF electron accelerator, adds hadron and electron rings~~
  - eRHIC at Brookhaven National Lab – just selected by DOE
    - Uses existing RHIC ring and adds electron ring
- Aim to collide e-p and e-A with eN luminosity comparable to LHC and both beams polarized.
  - ~1000 times ep luminosity of HERA
  - Huge range of new accelerator concepts and technology to be deployed.

One Electron-Ion Collider physics topic: structure of proton



21st century: quarks, sea quark-antiquark pairs and gluons;
total spin is composed of that of the elementary spins (colored arrows) and orbital motion (light blue arrow).

1970s picture: proton was composed of three valence quarks, with spins neatly adding up to observed total spin 1⁄2.

Courtesy: Zein-Eddine Meziani

Take-home messages

- Large colliders are most often built to find or measure the properties of elementary particles
  - Always the focus of project management …
- But they can do more … sometimes at low cost.
- Nuclear collisions, including hybrid collisions, at RHIC and LHC have greatly extended a whole new field of physics
- There are other examples of hybrid collisions which may also have important physics cases:
  - Polarized beams, e+e-, ep, eA, pp, pd, ^{3}He, …
- Diversity pays off, not only in accelerator physicists, but in the colliders themselves.
- Talk to, and understand, your physics/user community and consider re-purposing your accelerator.

BACKUP SLIDES

Ion Collider history to 2014

Table 1. Ion combinations in long and short notation*, and center-of-mass energy ranges per nucleon pair $\sqrt{s_{NN}}$ for ISR [1–3], RHIC [5], and LHC [6]. The symbol ↑ in the short notation indicates spin-polarized beams. Planned extensions are given in square brackets.

Species combination		Nucleon pair center-of-mass energy $\sqrt{s_{NN}}$ (GeV)		
		ISR	RHIC	LHC
$^{1}H^{1+} + {}^{1}H^{1+}$				
$^{1}H^{1+} + {}^{1}H^{1+}$				
$^{1}H^{1+} + {}^{1}\bar{H}^{1+}$				
$^{1}H^{1+} + {}^{2}H^{1+}$				
$^{1}H^{1+} + {}^{3}He^{2+}$				
$^{1}H^{1+} + {}^{4}He^{2+}$				
$^{1}H^{1+} + {}^{27}Al^{13+}$				
$^{1}H^{1+} + {}^{197}Au^{79+}$				
$^{1}H^{1+} + {}^{208}Pb^{82+}$				
$^{2}H^{1+} + {}^{2}H^{1+}$				
$^{2}H^{1+} + {}^{197}Au^{79+}$				
$^{3}He^{2+} + {}^{197}Au^{79+}$				
$^{4}He^{2+} + {}^{4}He^{2+}$				
$^{40}Ar^{18+} + {}^{40}Ar^{18+}$	Ar + Ar	—	—	[6300]
$^{63}Cu^{29+} + {}^{63}Cu^{29+}$	Cu + Cu	—	22.4–200	—
$^{63}Cu^{29+} + {}^{197}Au^{79+}$	Cu + Au	—	200	—
$^{197}Au^{79+} + {}^{197}Au^{79+}$	Au + Au	—	[5.0] 7.7–200	—
$^{208}Pb^{82+} + {}^{208}Pb^{82+}$	Pb + Pb	—	—	2760–3153 [5518]
$^{235}U^{92+} + {}^{235}U^{92+}$	U + U	—	192.8	—

*p or $^{1}H^{1+}$ (proton) is the nucleus of the ^{1}H atom (hydrogen); $\bar{p}$ (p-bar or antiproton) is the antiparticle to p (proton); d or $^{2}H^{1+}$ (deuteron) is the nucleus of the ^{2}H atom (deuterium); h or $^{3}He^{2+}$ (helion) is the nucleus of the ^{3}He atom (helium-3); α or $^{4}He^{2+}$ (alpha) is the nucleus of the ^{4}He atom (helium-4).

Since 2014, LHC has also collided

Pb+Pb at 5.02 (very briefly at 5.13) TeV
p+Pb, Pb+p at 8.16 TeV
Xe+Xe at 5.44 TeV

RHIC has also collided
p+Au, p+Al, Zr, Ru, more Au

From W. Fischer, J.M. Jowett, "Ion Colliders"

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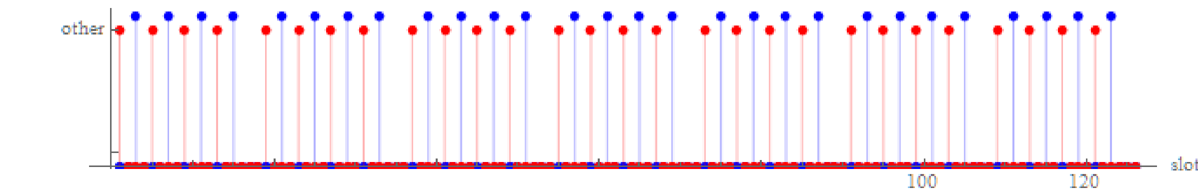
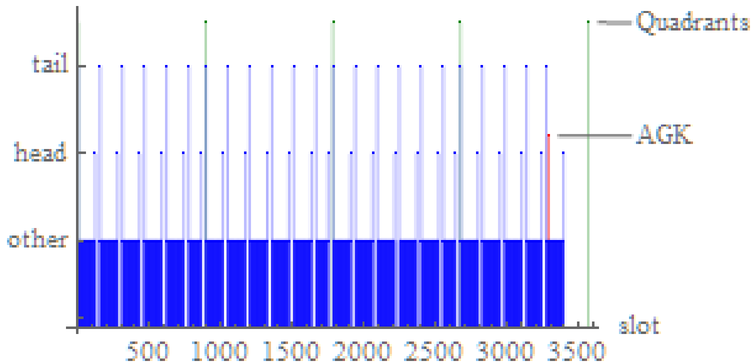
Single-particle dynamics, beam optics

- 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.*

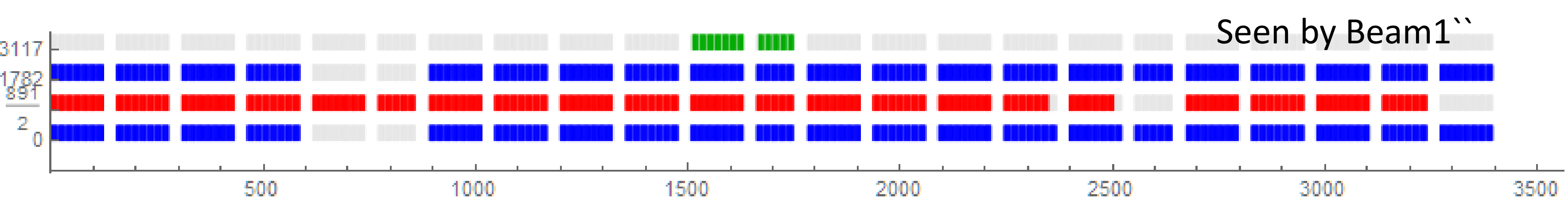
Bunch filling scheme example (future)

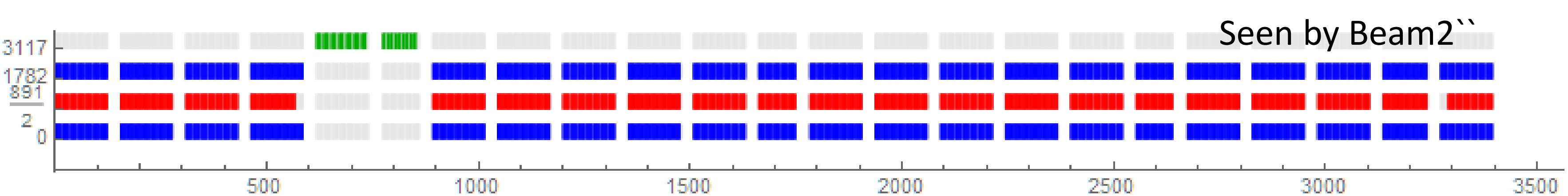


56 bunch SPS train after slip-stacking



Displace two trains in Beam 2 to make collisions in LHCb





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).

Diffusion models

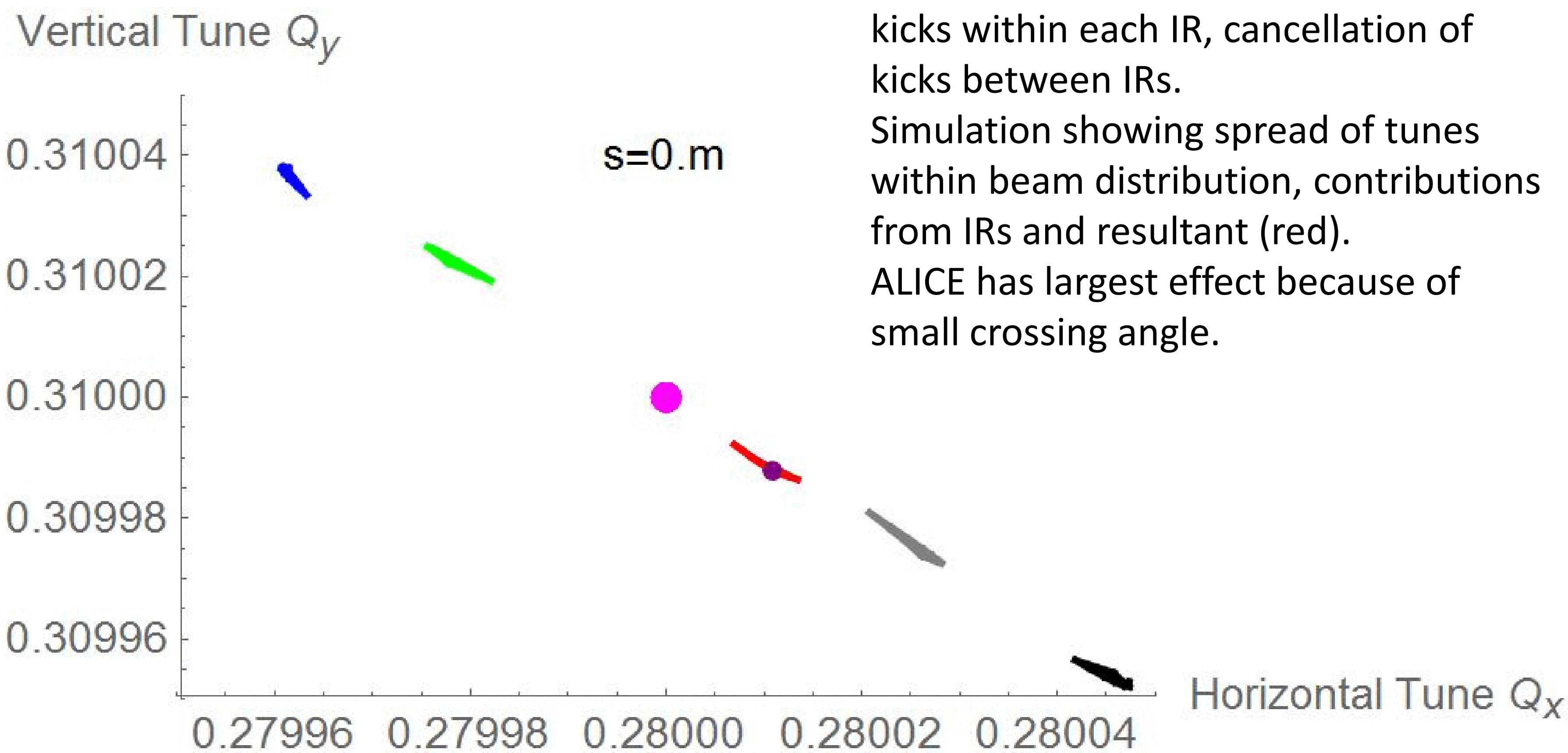
- Naively regarding the kicks as purely random
  - Works fairly well for RHIC data (W. Fischer)

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

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) now providing 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

Pb-Pb in 2018: new optics with smallest ever β* in ALICE, 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