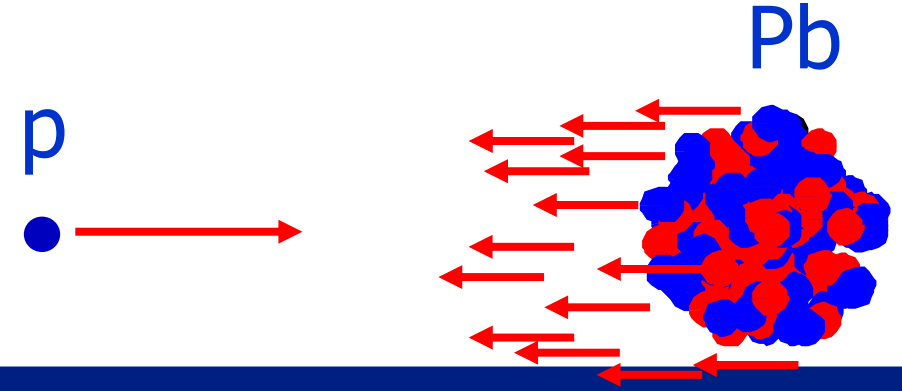



# Proton-nucleus collisions in the LHC: the first physics run

**John Jowett**

**Thanks to many other LHC people, especially:**

**Reyes Alemany, Philippe Baudrenghien, Steve Hancock, Django Manglunki, Michaela Schaumann, Reine Versteegen, Jorg Wenninger**

# Plan of talk

- Brief recapitulation
  - How we got here
  - Why p-Pb is special
- The p-Pb feasibility test
  - What we did, what we learned
  - What we didn't do and still don't know
- The 2012 p-Pb run
  - Choices to be made
- pA in the LHC heavy-ion programme up to 2021 (LS3)

# Nucleus-nucleus programme status

- In ~8 weeks total Pb-Pb operation in 2010-11, the LHC has attained
  - Twice design Pb-Pb luminosity at half-design energy (scaling with $E^2$).
  - ~16% of the integrated luminosity goal (1 $nb^{-1}$) for the present phase of Pb-Pb.
- Pb-Pb in 2012 might give ~250 $\mu b^{-1}$
- Decision to go for p-Pb instead
  - Otherwise no p-Pb before 2016 or 2017
  - But this is a new, more complex and almost unprecedented mode of collider operation

# pA operation of LHC: milestones

- LHC Design Report (2004) – no mention
- pA workshop in 2005
  - "not part of LHC baseline", "a possible future upgrade", … feasibility (RHIC D-Au) ?
- LHC Performance workshop, Chamonix 2011
  - Request from ALICE for 2012
  - Feasibility test agreed for 2011, some resources allocated
- pA workshop and feasibility test in 2011
- This workshop and 2012 physics run
  - So now we are implementing **the first LHC upgrade**

# Relation between Beam Momenta

- LHC accelerates protons through the momentum range

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

  - $p_p$ 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

$$p_{\mathrm{Pb}} = Z p_{\mathrm{p}}$$

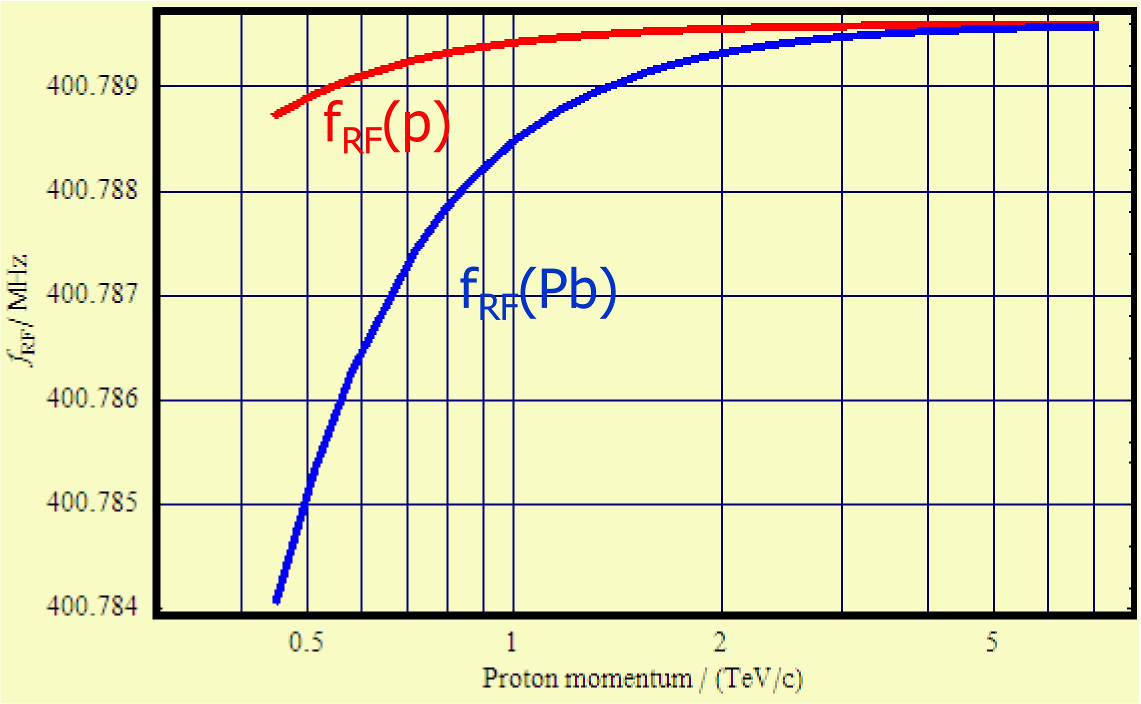
where $Z = 82,\ A = 208$ for fully stripped Pb in LHC

# RF Frequency for p and Pb in LHC

RF frequency $$f_{\mathrm{RF}} = \frac{h_{\mathrm{RF}}}{T\left(p_{\mathrm{p}}, m, Q\right)}$$

where the harmonic number $h_{\mathrm{RF}} \in \mathbb{Z}$, $h_{\mathrm{RF}} = 35640$ 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.

# Distorting the Closed Orbit

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

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

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

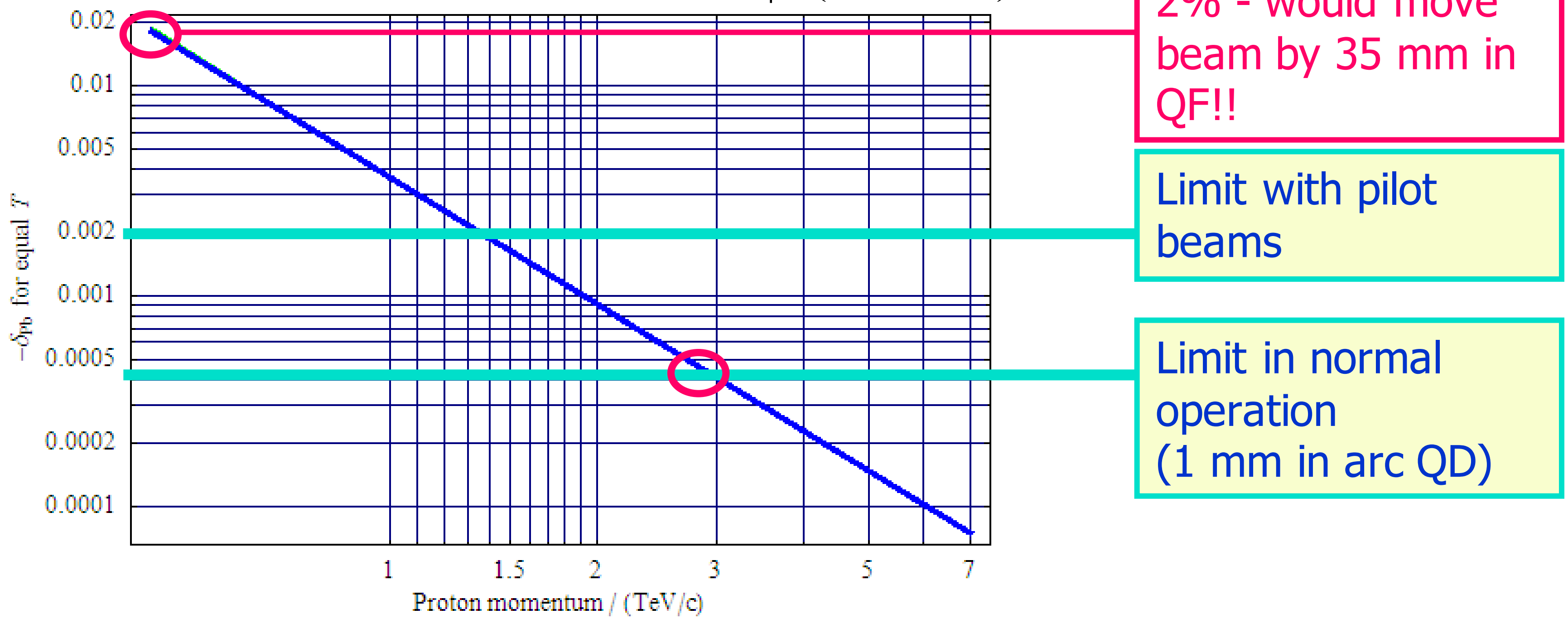
the phase-slip factor $\eta = \dfrac{1}{\gamma_T{}^2} - \dfrac{1}{\gamma^2}$, $\gamma = \sqrt{1+\left(\dfrac{Qp_{\mathrm{p}}}{mc}\right)^2}$, $\gamma_T = 55.8$ for LHC optics.

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

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

# Momentum offset required through ramp

Minimise aperture needed by $\delta_p = -\delta_{Pb} = \frac{c^2 \gamma_T^2}{4 p_p^2} \left( \frac{m_{Pb}^2}{Z^2} - m_p^2 \right)$.



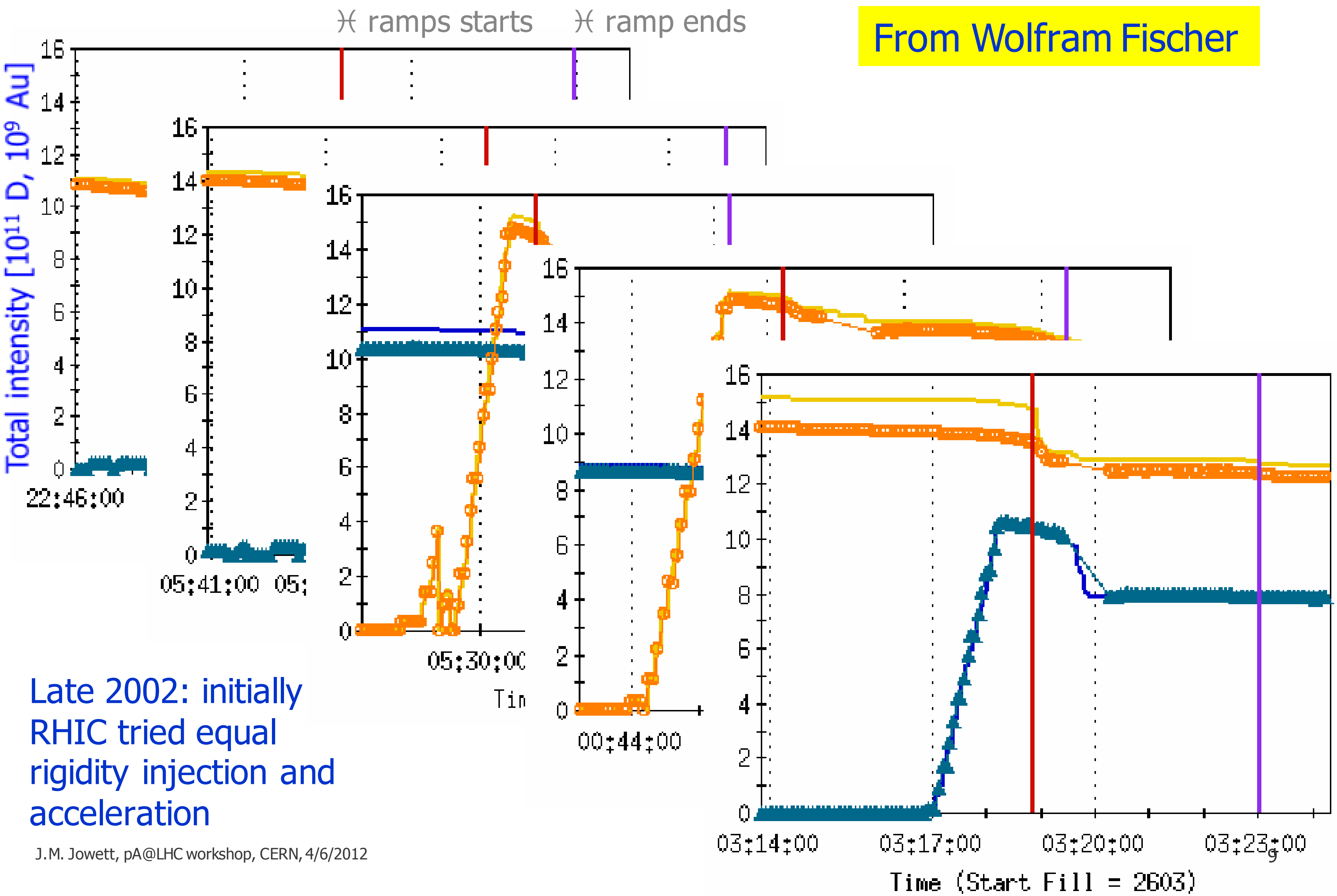

Revolution frequencies must be equal for collisions at top energy.

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

**RF frequencies must be unequal for injection, ramp!**

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

From Wolfram Fischer

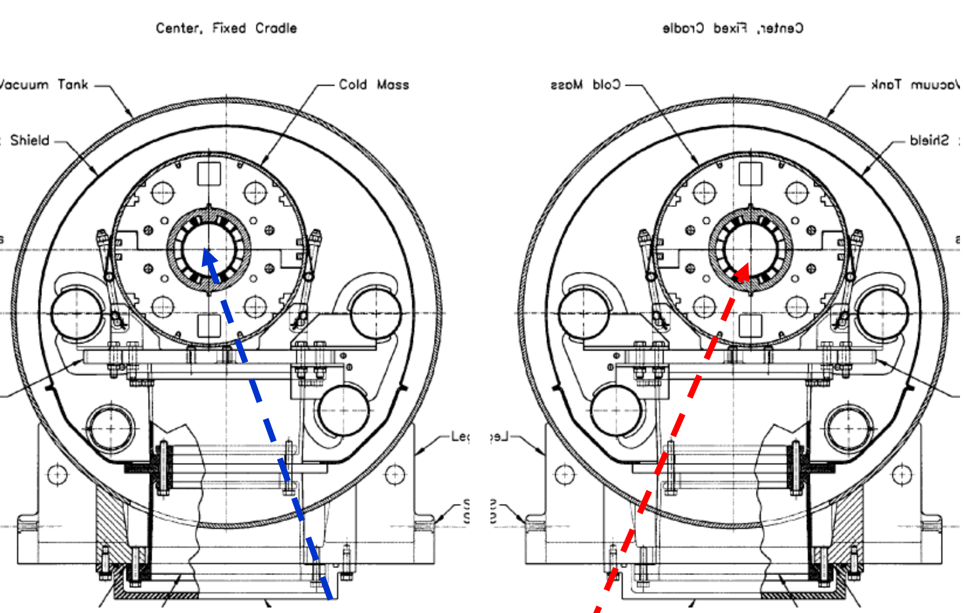


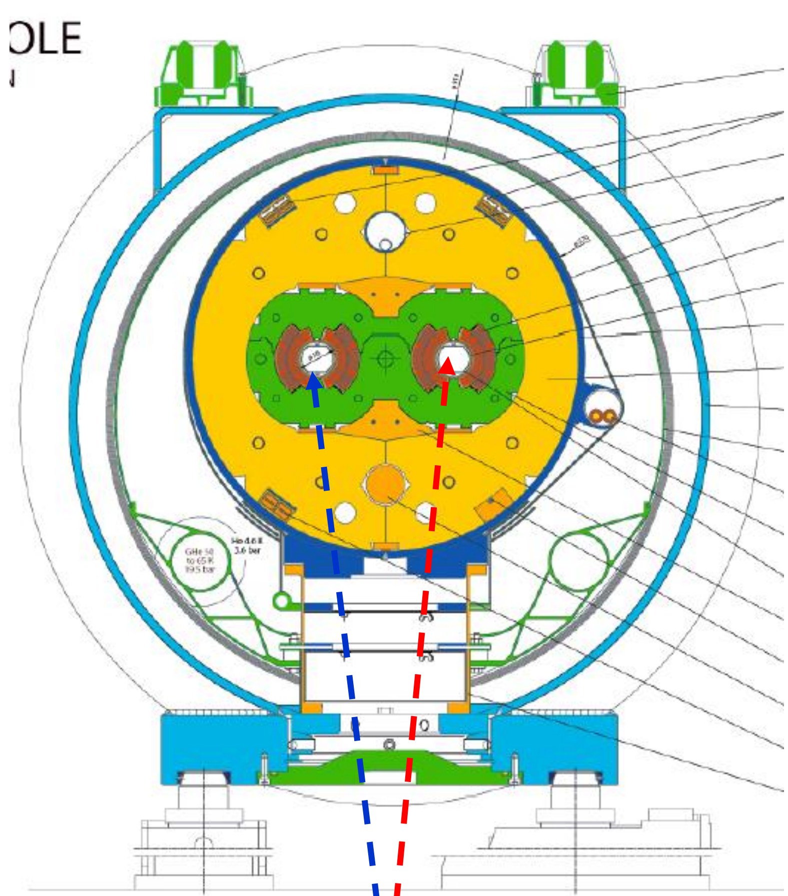

Late 2002: initially RHIC tried equal rigidity injection and acceleration

# Unequal-frequency beam dynamics

- More detail in last year's workshop
  - Moving long-range beam-beam kicks during injection and ramp
- Broken symmetry ⇒ new modes
  - Symmetry restored at high energy
- Present understanding:
  - "Overlap knock-out" resonances shown not to be a problem for LHC
  - Diffusion mechanisms were likely source of problems for RHIC but are weaker in LHC
  - Theoretical work continuing

# Critical difference between RHIC and LHC



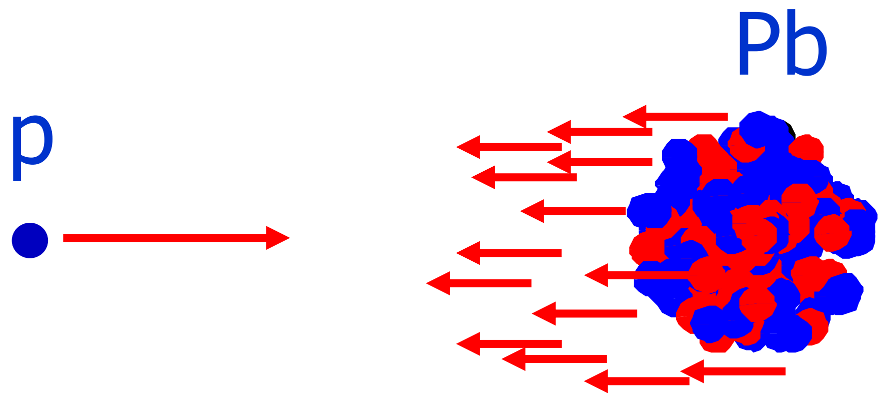



RHIC: Independent bending field for the two beams – they abandoned equal-rigidity and switched to equal-frequency D-Au.

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

# Outline of p-Pb physics cycle (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



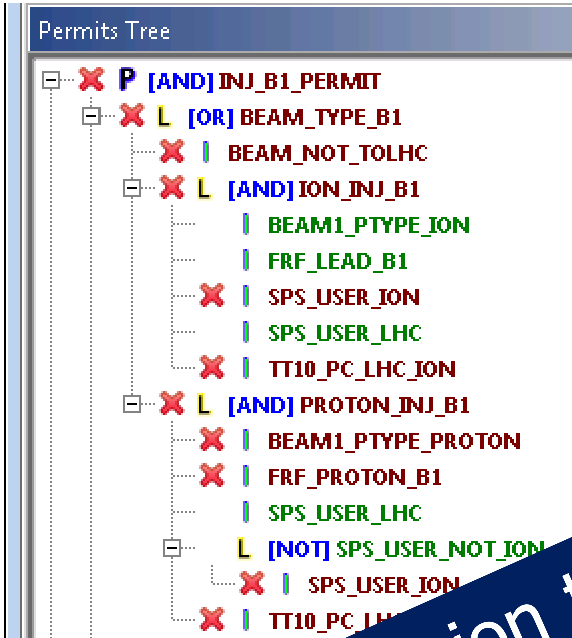

# PROTON-LEAD FEASIBILITY TEST IN 2011

# Re-purposing LHC as proton-nucleus collider

- Systems/procedures developed during 2011 to enable this new mode of operation:
  - Machine Protection ➔ new Software Interlock permit tree to avoid the injection of protons into a ring configured for ions and vice versa
  - RF ➔ New rephasing and cogging procedure, plus FESA properties and sequencer tasks to configure each ring for the right particle type
  - BI ➔ New BPM calibration task to calibrate independently each beam according to the bunch spacing
  - Sequences ➔ New LHC PROTON-NUCLEUS NOMINAL Sequence
  - Timing ➔ New Accelerator Mode = PROTON-NUCLEUS PHYSICS & new telegram line with PARTICLE TYPE "PER" RING
  - Injection schemes ➔ New injection schemes mixing protons and ions
  - Transverse feedbacks already independent

R. Alemany-Fernandez,
P. Baudrenghien, …

# Machine Protection: new SIS permit tree




## Proton/Pb conditions – applied for each ring

LHC: **RF frequency** within 1kHz of proton ... ce.

Monitoring at 0.2 Hz, accura...

LHC : **particle type** in C... n/Pb

SPS: **user nam**... / LHCIONx (x = 1,2,3,4...)

S... **T10 settings** consistent with ...

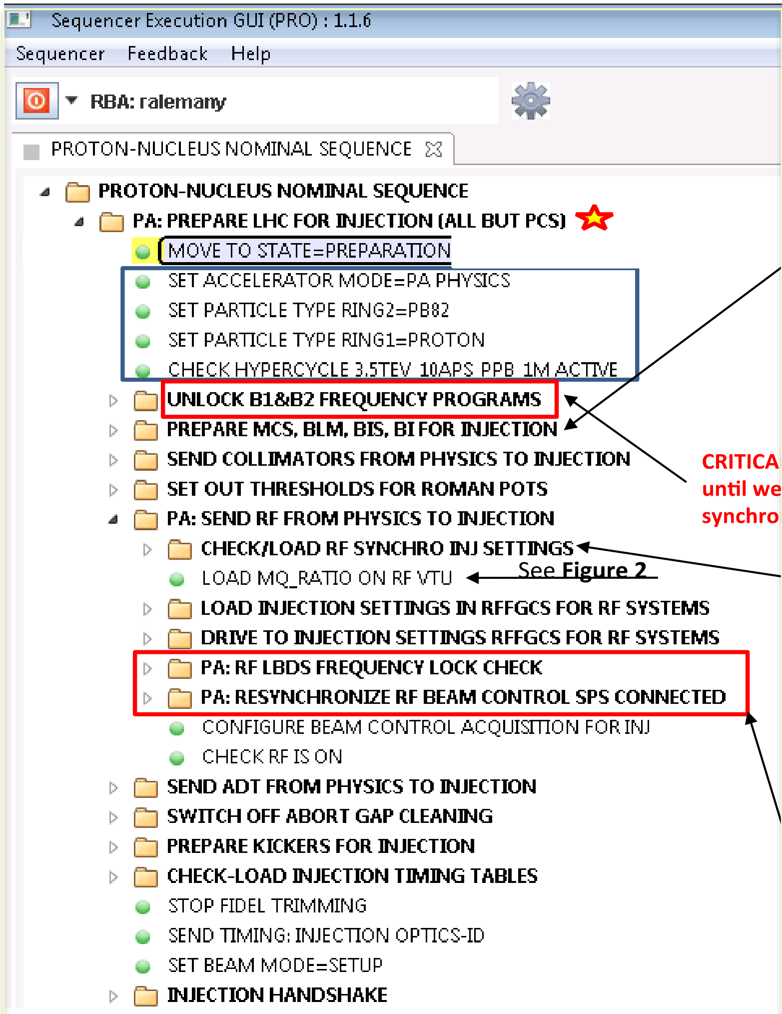
...urrent interlock on 2 dipole and 2 main quadrupole strings.

**Extension to more general cases often introduces useful clarifications in system design.**

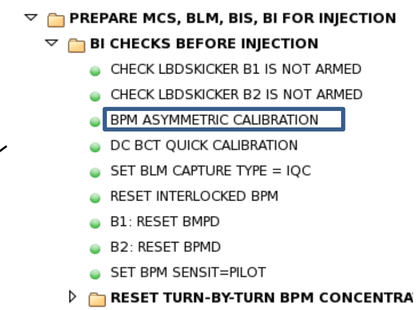
The ... allow injection into a given ring if the settings are consis...ent with ions or with protons. On top of being an efficient machine protection mechanism, it is flexible – no a priori knowledge on which ring is used for which species. It will also work to avoid injecting ions during p-p runs (and vice-versa).

R. Alemany-Fernandez, J. Wenninger

# New LHC PROTON-NUCLEUS NOMINAL Sequence

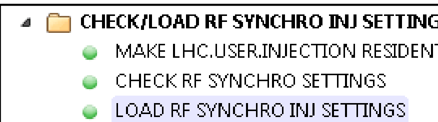



See **Figure 2**




**BPM ASYMMETRIC CALIBRATION**: Allows to use a different bunch spacing for each ring. For the **100 ns proton** beam **select 125 ns bunch spacing**, for the **single bunches** or the **200 ns Pb** trains select **single bunch calibration**.

**CRITICAL: The RF FREQ are unlocked all the time until we lock them after the ramp and the RF synchronization of both beams.**




This action has to be done before the SPS-LHC synchronization sub-sequence, since each time we change the **InjPulseDelay#Ring1/2Bt one has to reset the RF synchro crate.** See **Figure 1** for details

As the pp or PbPb nominal sequences except the RF FREQ is never locked at the end of the sub-sequence

R. Alemany-Fernandez

# p-Pb feasibility test, Part 1, 16h on 31/10/2011

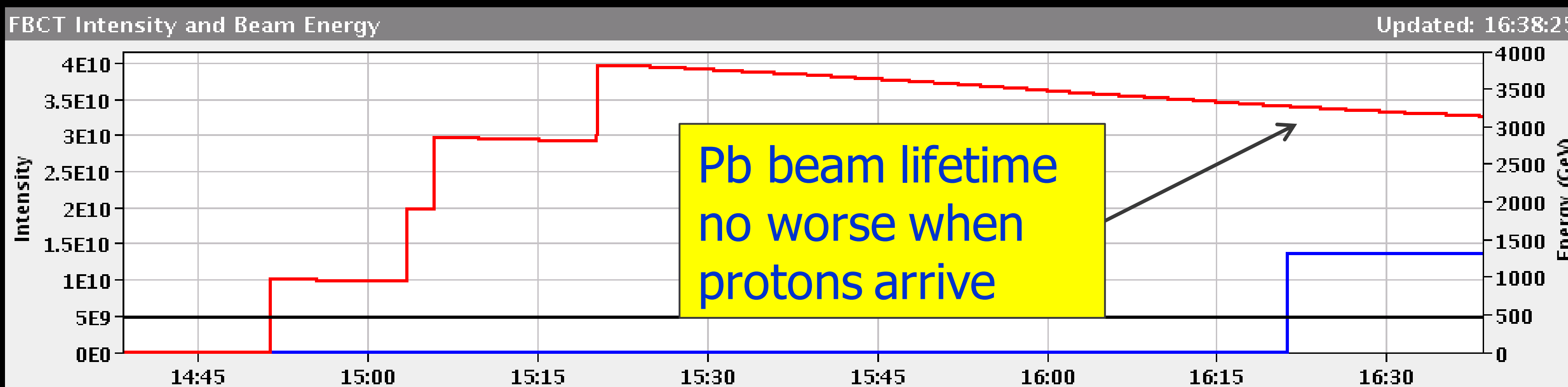
- Several hours setup of first Pb beam of the year (timing, many details…)
- Stored 4 Pb bunches in presence of 304 p bunches (~10% nominal intensity) at injection
  - Lifetime no worse for presence of p bunches
  - Emittance blow-up, does not appear to be worse than for Pb alone
- Dumped and re-injected 4 fresh Pb
  - Still OK
- Ramped 2 Pb and 2 p bunches, good lifetime
- Re-phased RF (cogging) to move bunches 1 encounter point 9 km back to ATLAS, *no losses*

LHC Page1 | Fill: 2269 | E: 450 GeV | 31-10-2011 16:38:25

# MACHINE DEVELOPMENT: INJECTION PROBE BEAM

| BCT TI2: | 0.00e+00 | I(B1): | 1.30e+10 | BCT TI8: | 0.00e+00 | I(B2): | 3.78e+10 |
|---|---|---|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| TED TI2 position: | BEAM | TDI P2 gaps/mm | up: 10.84 | down: 8.57 |
| TED TI8 position: | BEAM | TDI P8 gaps/mm | up: 9.62 | down: 8.92 |




Comments 31-10-2011 15:39:35 :

2011 Proton physics program finished!

Ions circulating in B2

Injection protons in B1

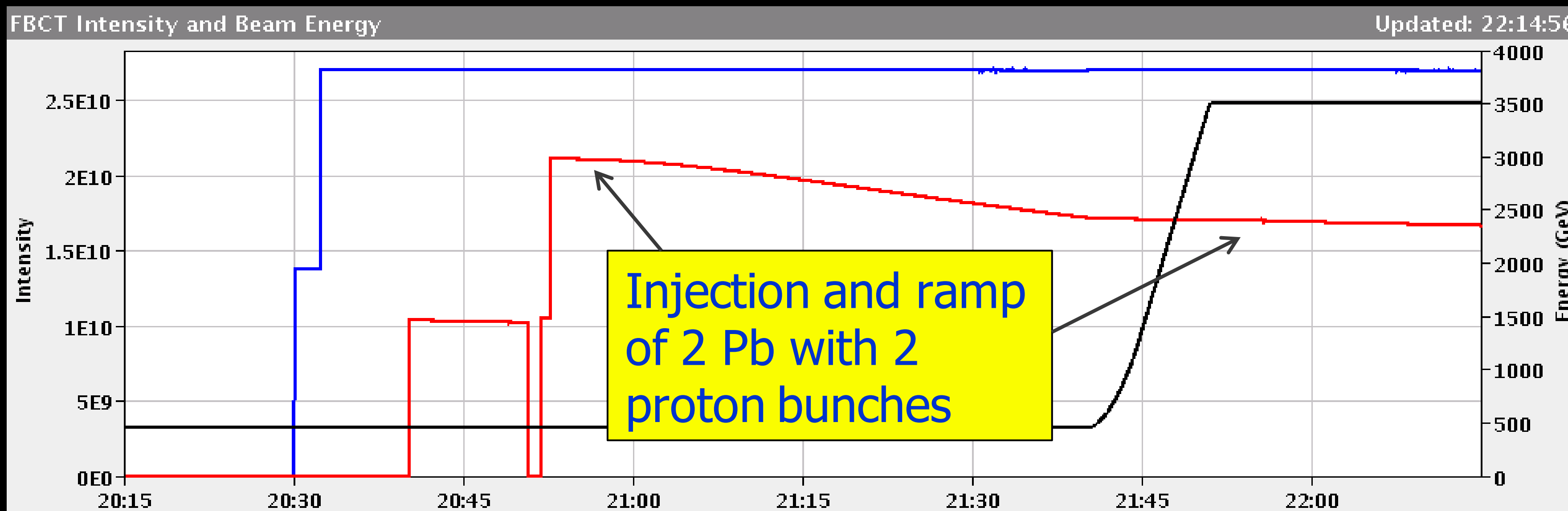
| BIS status and SMP flags | B1 | B2 |
|---|---|---|
| Link Status of Beam Permits | false | false |
| Global Beam Permit | true | true |
| Setup Beam | true | true |
| Beam Presence | true | true |
| Moveable Devices Allowed In | false | false |
| Stable Beams | false | false |

AFS: 100ns_588b_1small_0_0_0_72bpi9inj_pPb | PM Status B1 ENABLED | PM Status B2 ENABLED

LHC Page1 | Fill: 2269 | E: 3500 GeV | 31-10-2011 22:14:56

# MACHINE DEVELOPMENT: FLAT TOP

| Energy: | 3500 GeV | I(B1): | 2.54e+10 | I(B2): | 1.87e+10 |
|---|---|---|---|---|---|




Comments 31-10-2011 21:55:27 :

2011 Proton physics program finished!

Proton and lead ion beams together for the first time at 3.5 Z TeV.

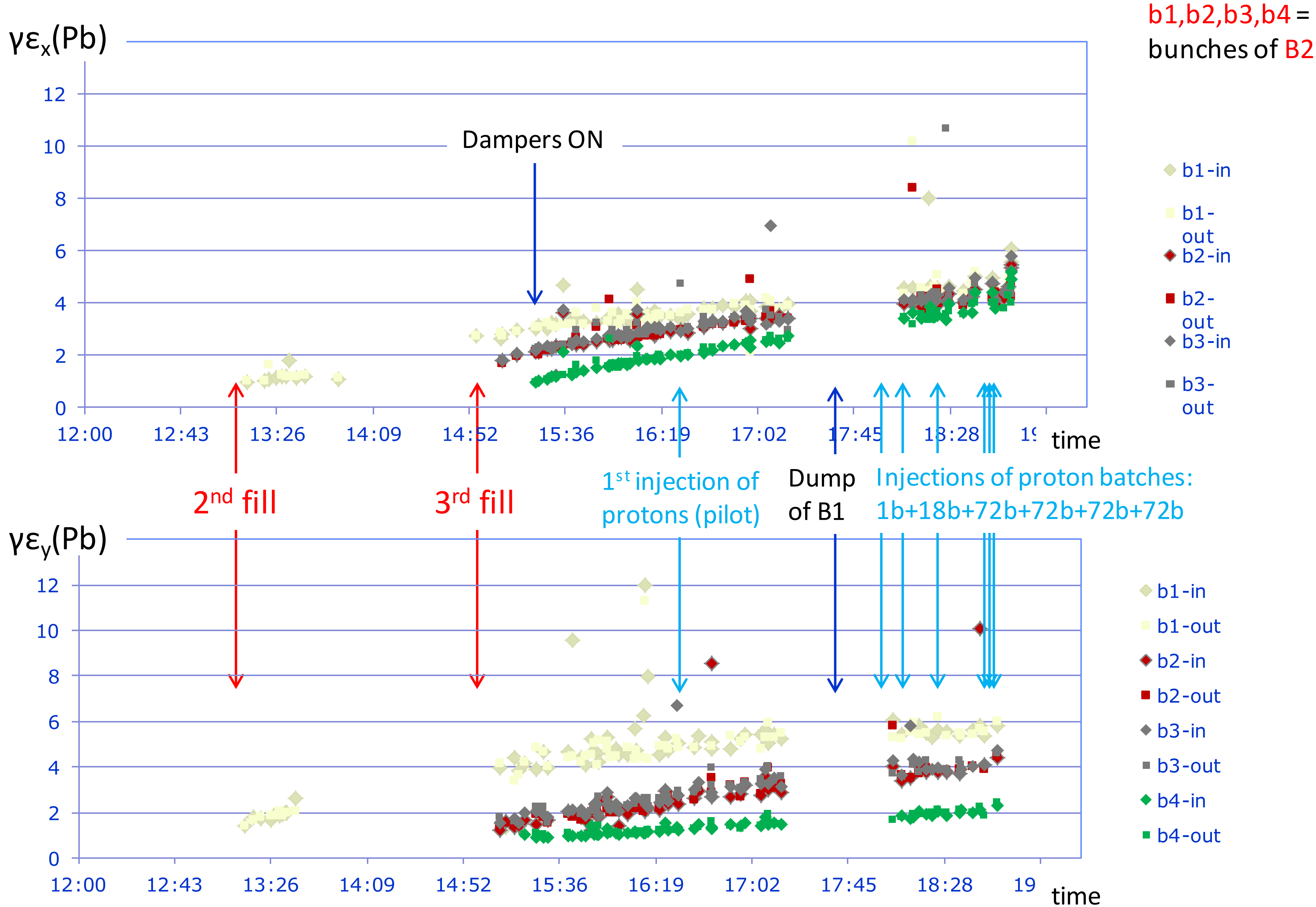
2 bunches each, will try rephasing RF.

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

AFS: pPb_2b_1_1_1_1bpi2inj

PM Status B1: ENABLED | PM Status B2: ENABLED

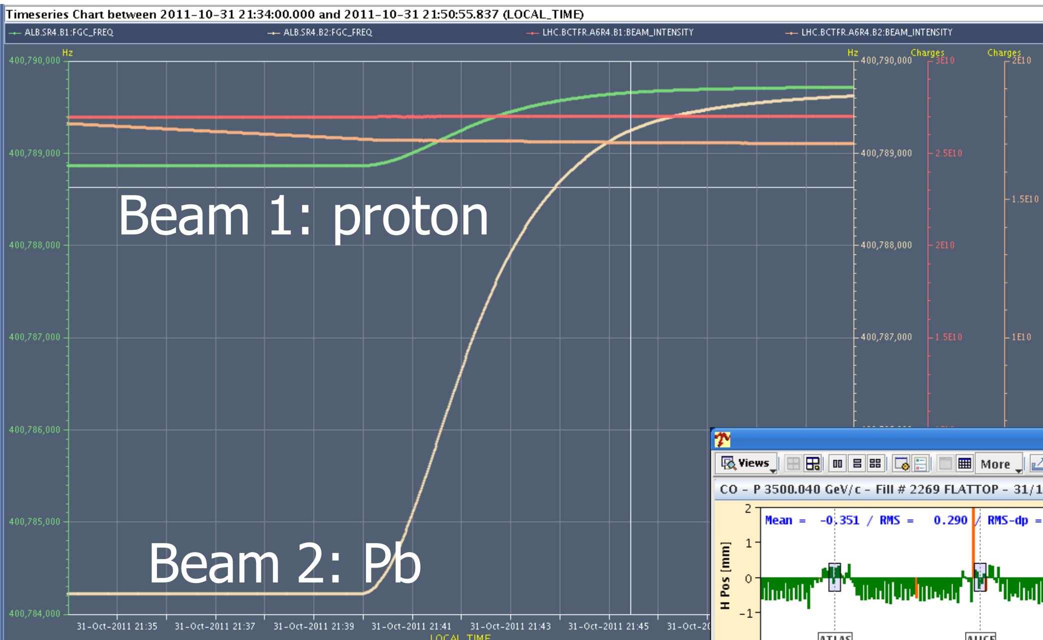
# Wire scans of Pb beam B2, 2nd and 3rd fills



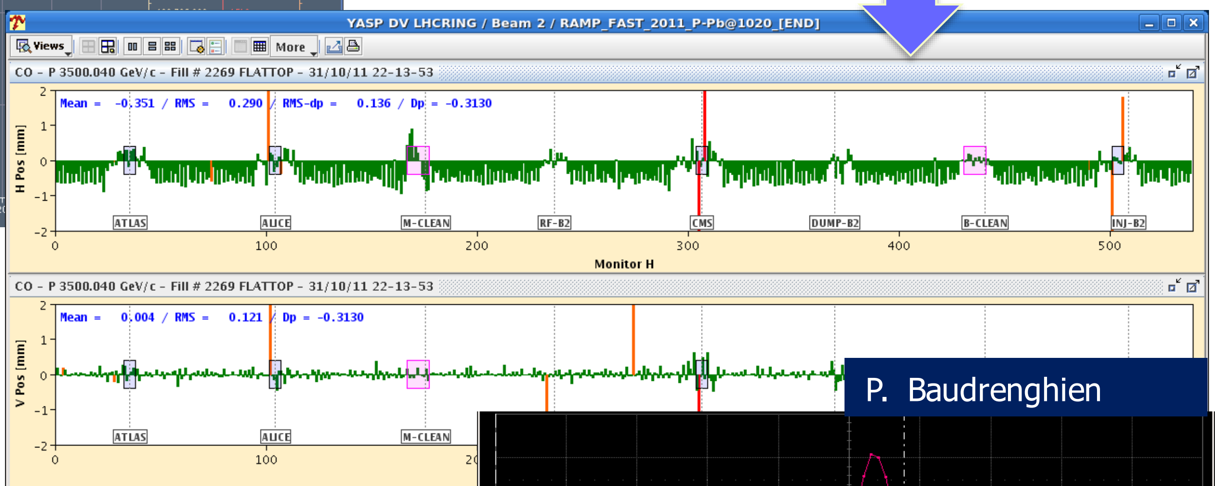



R. Versteegen

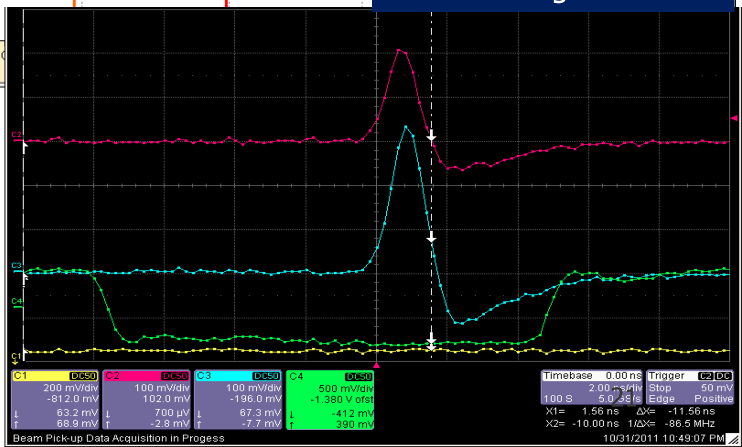
# RF: New rephasing and cogging procedure




At top energy, $f_{RF}$(B1) = 400.789715 MHz and $f_{RF}$(B2) = 400.789639 MHz. Locking RF frequencies together imposes offsets of the central trajectories. We chose to get approximately the mean RF frequency, implying that the momentum offset would be ~ $\pm 3\times10^{-4}$

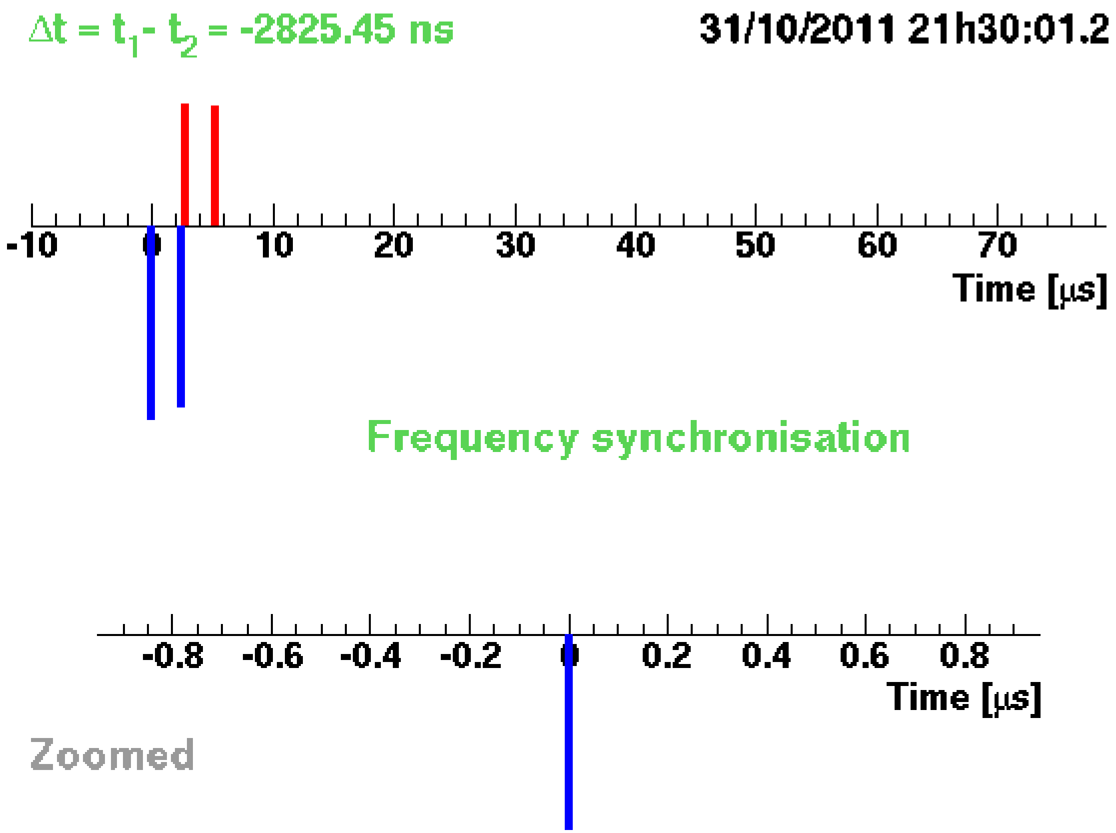



P. Baudrenghien




The final frequency was $f_{RF}$ = 400.789685 MHz.

# Moving the collision point by 9 km

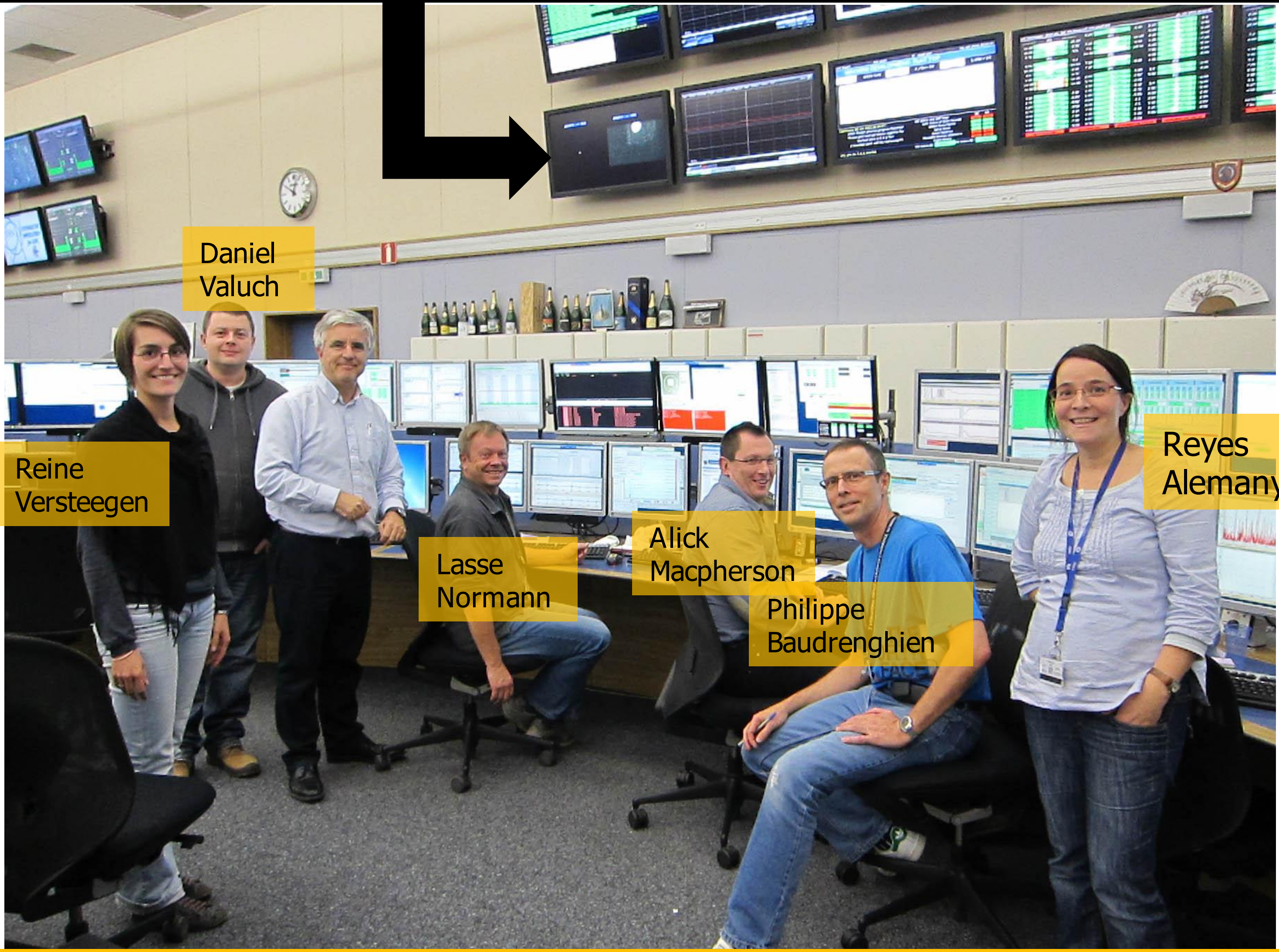



Real-time clock

RF cogging by Philippe Baudrenghien

Video from BPTX data by Thilo Pauly (ATLAS)

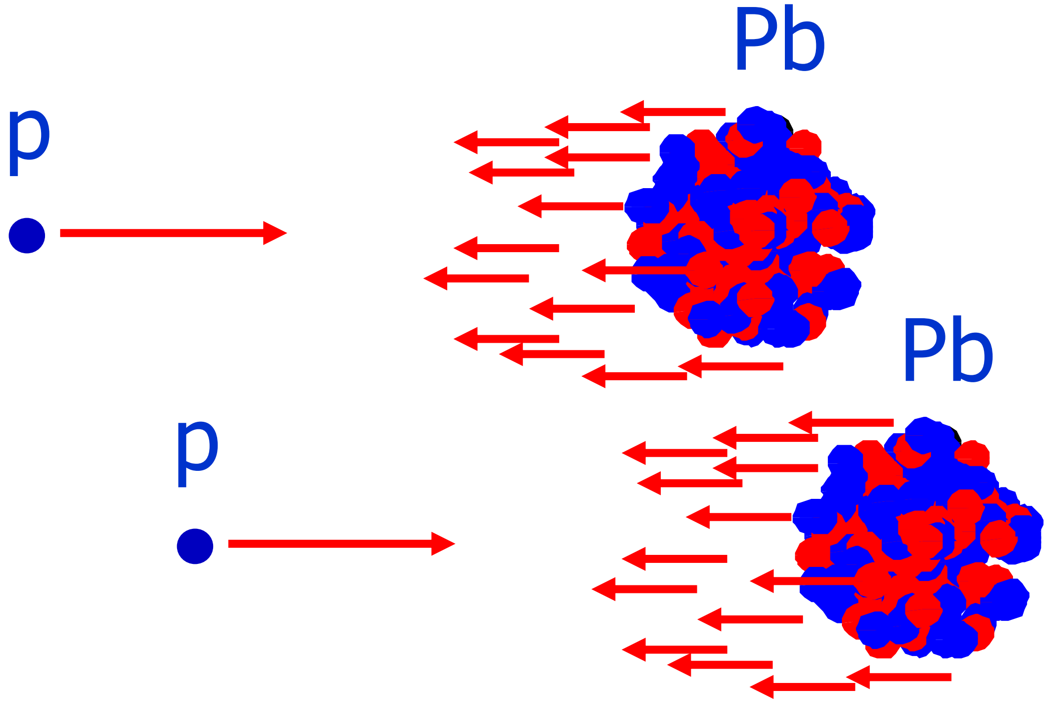
# Hallowe'en 2011: first p and Pb at 3.5 Z TeV




Vital contributors to this 16-hour experiment not in photo:
J. Wenninger, S. Redaelli, M. Schaumann, M. Lamont, D. Jacquet, …

# P-Pb feasibility test, Part 2

- Scheduled for 16-17 Nov 2011, plan was:
  - Ramp many p and some Pb bunches
    - We have NOT demonstrated this
  - Pilot physics fill with moderate no. of bunches
    - Would have clarified potential of detectors
- Cancelled because of leak in PS proton injection septum
  - Continuing with protons = risk of major leak and ~ 1 week of LHC down time (could have happened in p-p!).
- So … we are basing a physics programme with a complex new operating mode on a single MD
  - OK, but please tolerate a certain uncertainty in luminosity predictions!
- Strong motivation to do Part 2 in Aug-Sep 2012!




# 2012 PROTON-NUCLEUS PHYSICS RUN

# Choice of operating energy for p-Pb in 2012

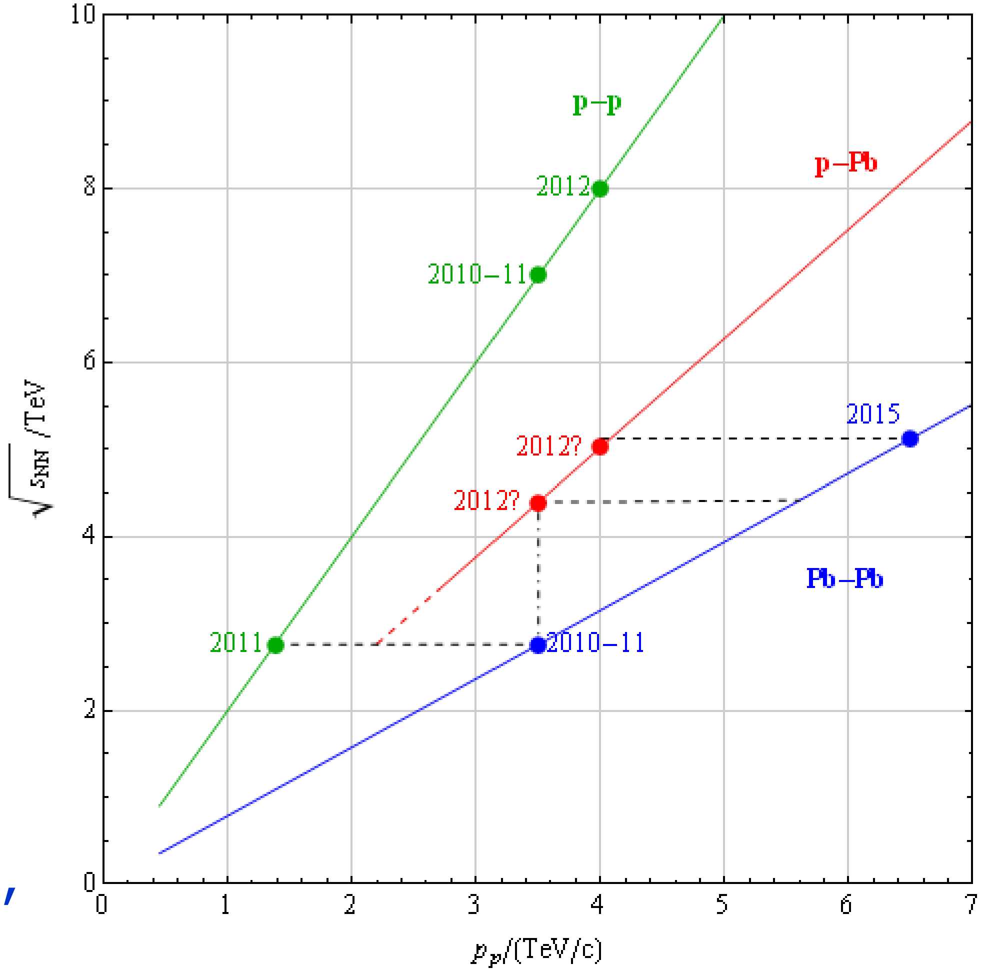
Charges $Z_1, Z_2$ in rings with magnetic field set for protons of momentum $p_p$ : colliding nucleon pairs have:

$$\sqrt{s_{NN}} \approx 2c\, p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}},$$

$$y_{NN} = \frac{1}{2} \log \frac{Z_1 A_2}{A_1 Z_2}$$

2.2 *Z* TeV "ideal" but would cost factor ~6-7 in integrated luminosity and exceeds 1 mm orbit limit in LHC arcs.

4 *Z* TeV, the final choice for 2012, will be "easiest" from accelerator point of view.



# Costs of experimental choices

- Discussions of operating energy will recur. One should bear in mind for future runs:
  - After a p-p run 4 TeV, we estimated that it would have cost *extra* ~2 days commissioning to set up p-Pb at 3.5 TeV
    - "New" ramp and squeeze in all IRs
    - Higher $\beta^*$
    - Larger off-momentum orbits etc
- Reversal from p-Pb to Pb-p: about 1 day
- Two ALICE polarity reversals (if requested) total <1 day

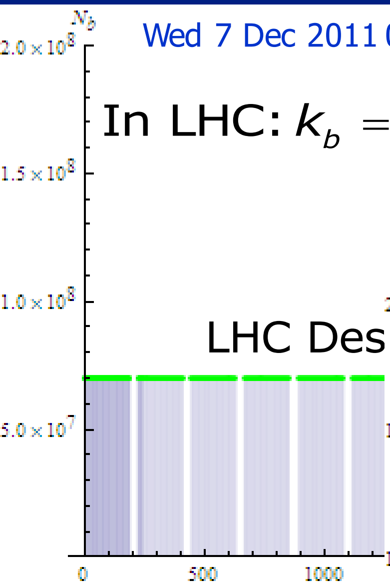
# Injection schemes

- Need filling schemes for p and Pb to produce matching bunch trains in LHC
  - Prepared for 100 ns in 2011
  - Must operate both PS Booster, LEIR, PS to provide identical batches in SPS
- New flexible solution (S. Hancock, D. Manglunki) provides both 100 ns and 200 ns in SPS/LHC
  - Higher $N_b$ with 200 ns (why we used it in 2011, but now the gain in luminosity is less …)
  - See talk by D. Manglunki, Chamonix

# Ion Injector Chain Performance in 2011

Wed 7 Dec 2011 07:44:32

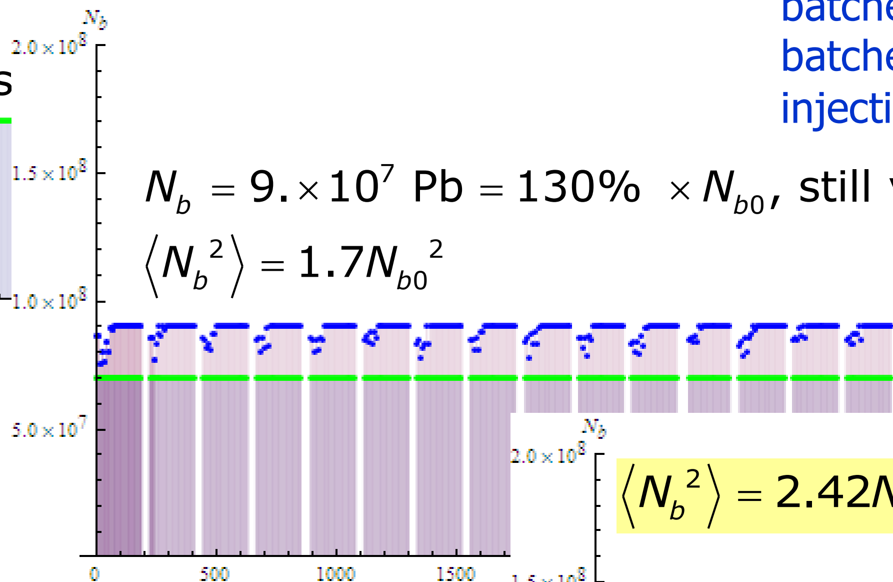
In LHC: $k_b = 385 \approx 0.6 \times 592$ (design)



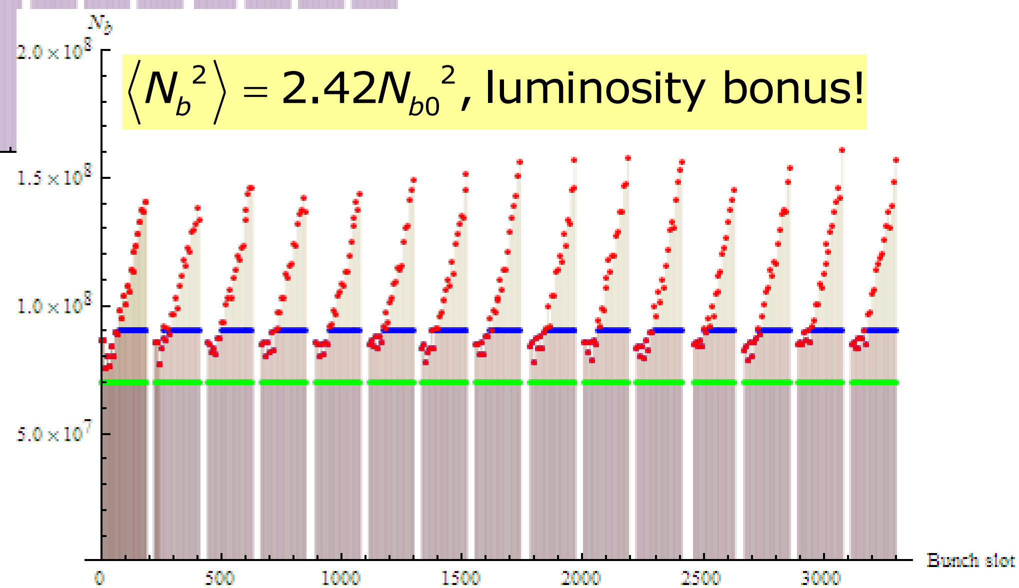

Nominal 100 ns limited to ~design intensity per bunch.
Filling scheme proposed Chamonix 2011: 200 ns created in 2 bunch PS batches, sustained in 24 bunch SPS batches thanks to shortened SPS injection kicker rise time (E. Carlier)

$N_b = 9.\times 10^7$ Pb $= 130\% \times N_{b0}$, still very even!

$\langle N_b^{\;2} \rangle = 1.7 N_{b0}^{\;2}$




$\langle N_b^{\;2} \rangle = 2.42 N_{b0}^{\;2}$, luminosity bonus!




Uneven intensity (and emittance) along batches due to IBS (etc …) on long injection porches in SPS and LHC.

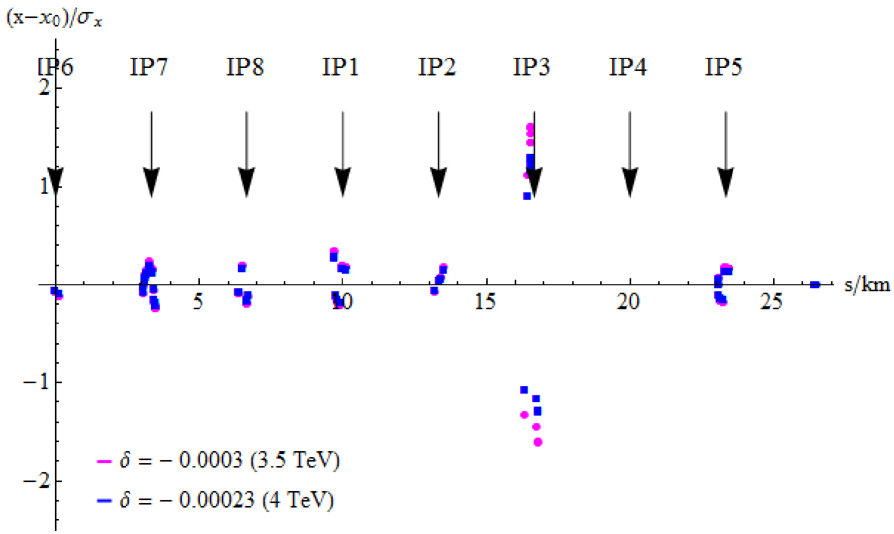
# Optics for p-Pb operation

- Optics become more difficult with smaller β*
  - Need more aperture in triplet quadrupoles
  - Greater sensitivity to perturbations
  - Stronger chromatic effects (e.g., change of betatron oscillation frequency across the energy spread in the beam)
  - For p-Pb, centre of energy distribution of beams have opposite sign shifts: chromatic variation of central optics
- Heavy ion runs generally push optics further by adding lower β* at ALICE to preceding p-p optics
- In 2011 the additional squeeze to β*=(1,1,1,3)m was only just possible because of a still unidentified aperture restriction on the left of IP2.
  - M., Giovannozzi, et al, *IR2 aperture measurements at 3.5 TeV,* CERN-ATS-Note-2012-017 MD, 2012.
- Can we achieve β*=(0.6,0.6,0.6,3)m with p-Pb ??

# Orbit at collimators, 3.5 TeV vs. 4 TeV

**Additional collimator set-up will be required in squeeze**

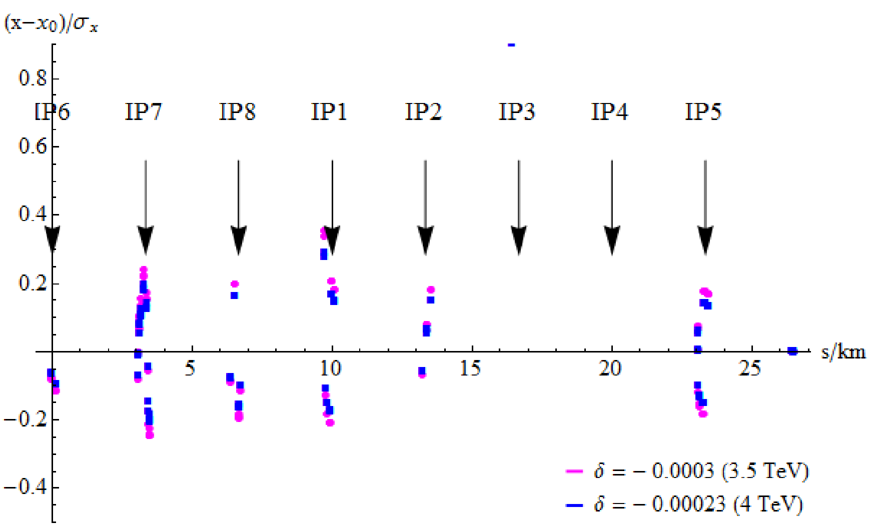
Horizontal plane



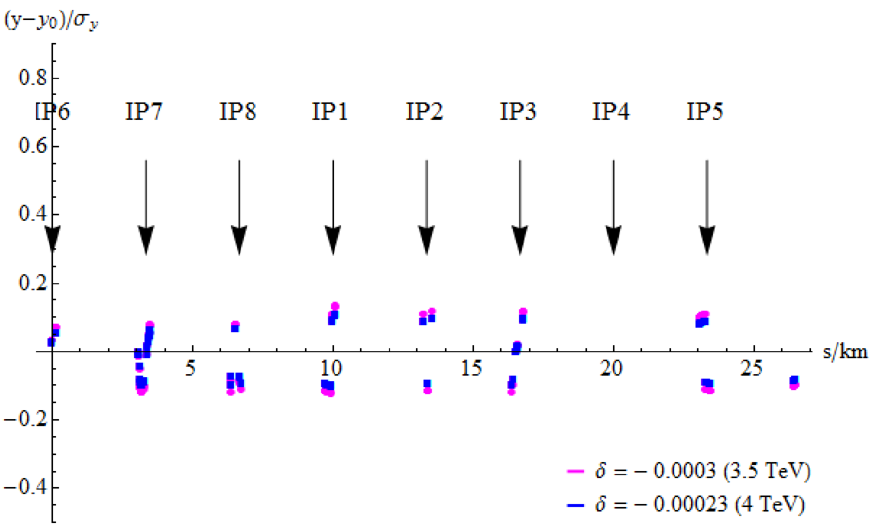

x = orbit with δ offset,

$x_0$ = orbit with zero offset

Horizontal plane, zoomed in




Vertical plane

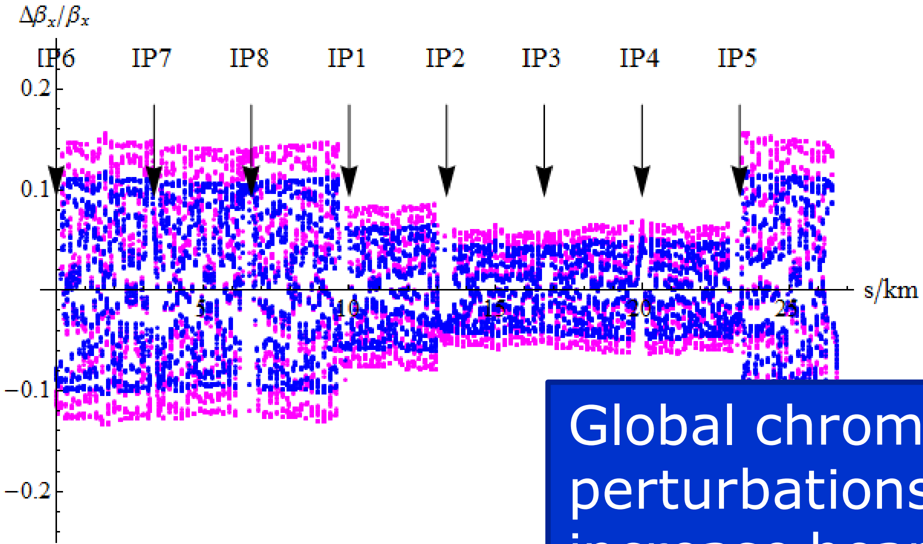



R. Versteegen

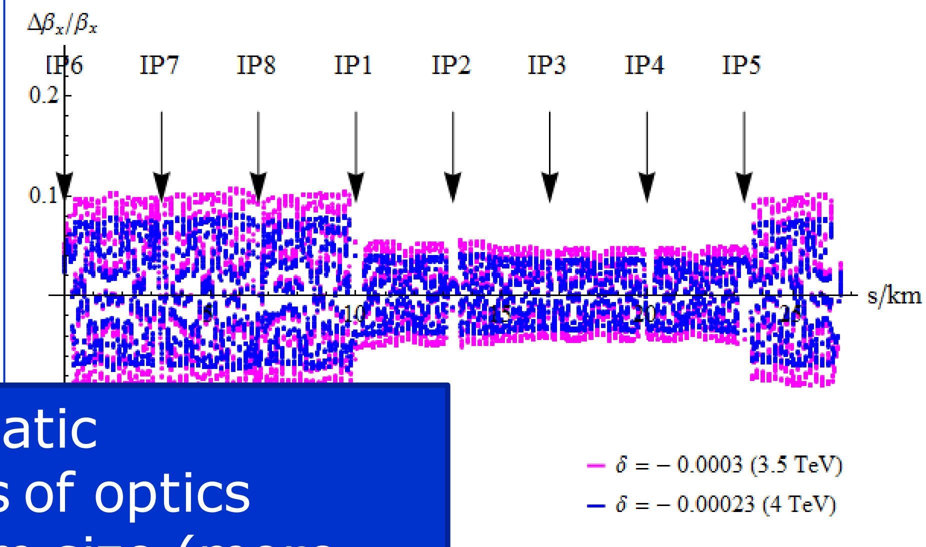
# Δβ/β for β* = (0.6, 0.6, 0.6, 3.0), 3.5 TeV vs. 4 TeV

$$\frac{\Delta\beta}{\beta} = \frac{\beta(\delta) - \beta(\delta = 0)}{\beta(\delta = 0)}$$

B1, Horizontal plane

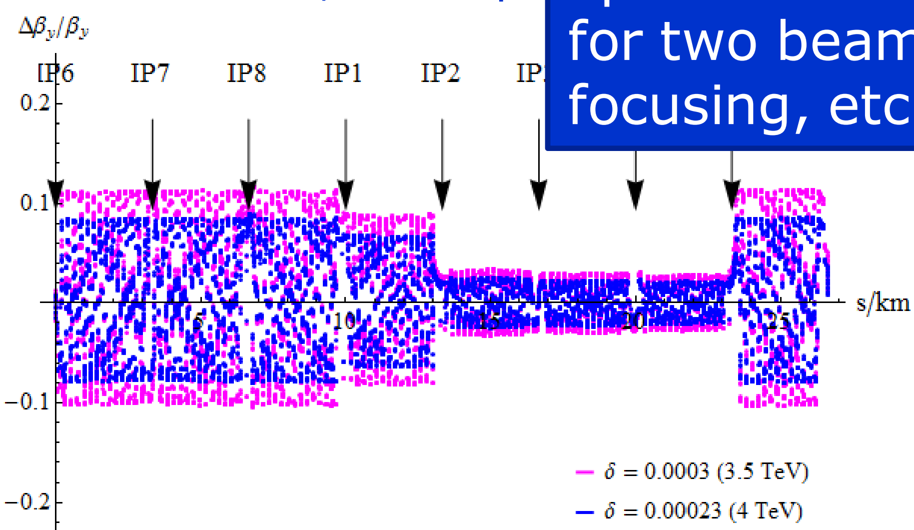



B2, Horizontal plane

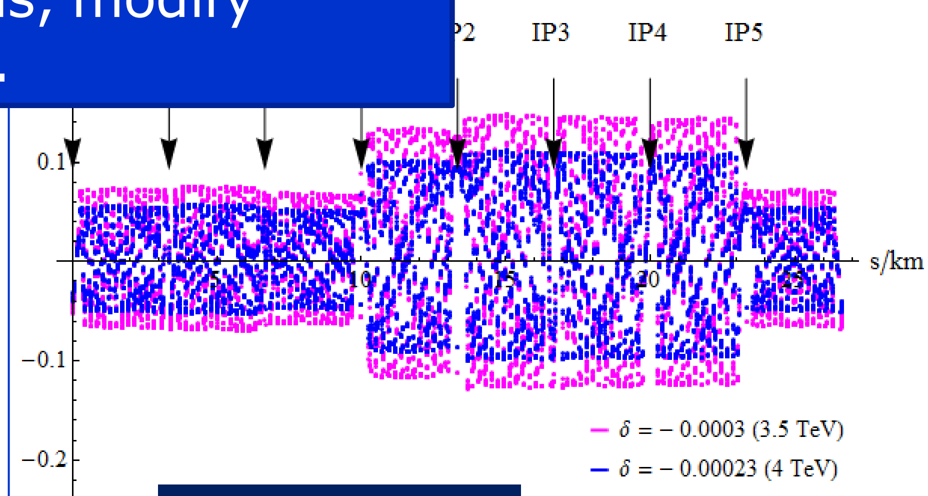



Global chromatic perturbations of optics increase beam size (more aperture needed) differently for two beams, modify focusing, etc.

B1, Vertical pla…

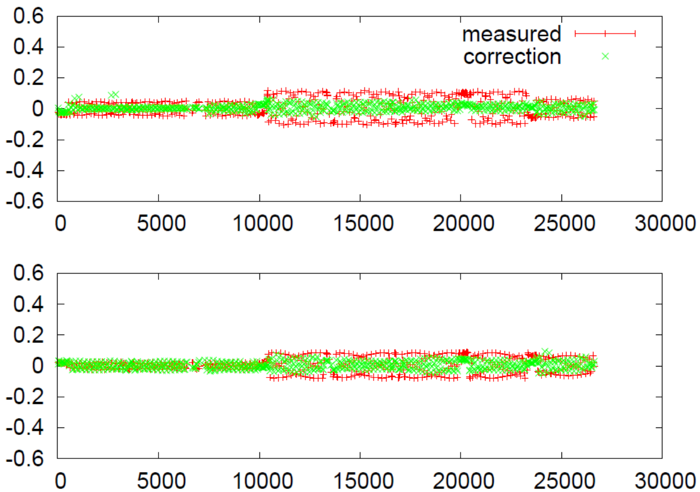



…cal plane

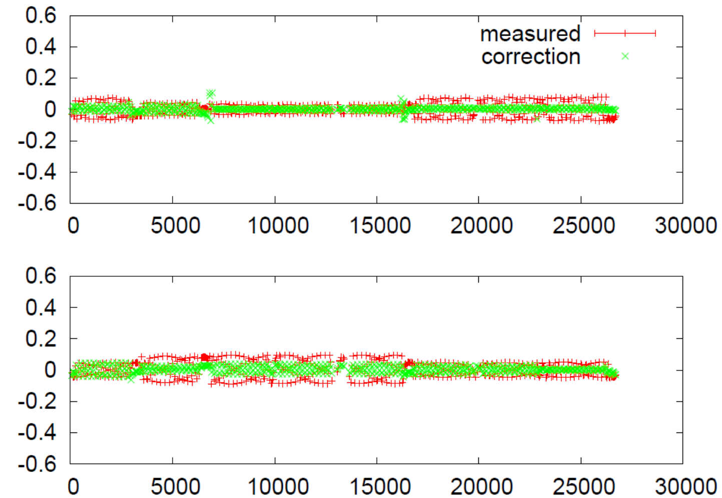



R. Versteegen

# Corrections of β-beating




Beam 1 (p)




Beam 2 (Pb)

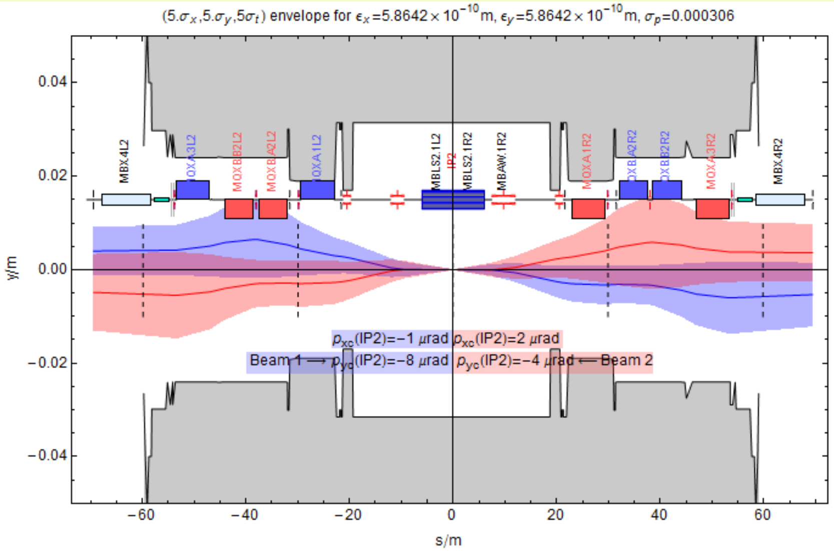
Corrections schemes using trim quadrupoles under study, will probably be incorporated in optics from start.

R. Versteegen

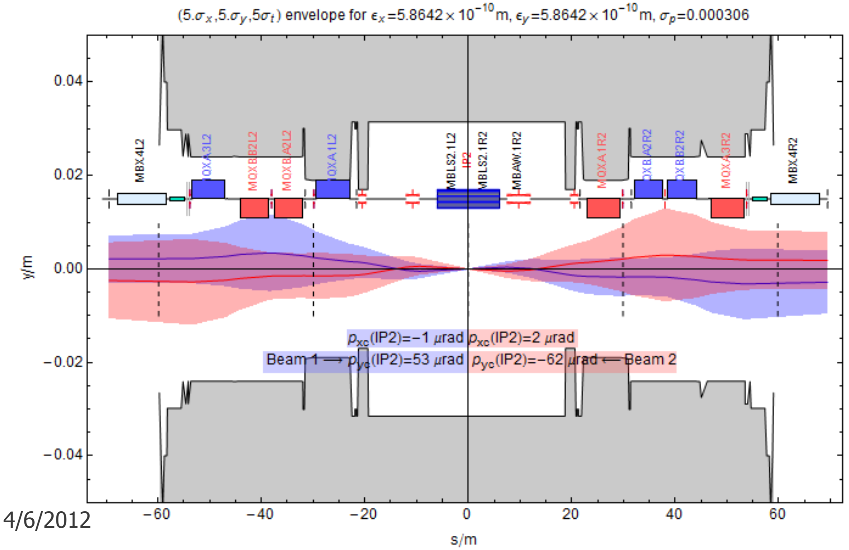
# Vertical envelopes in IR2,

**β*=0.6m, 4. TeV , (γε)$_p$=2.5μm**, (γε)$_{Pb}$=1.5μm, bunch spacing=200ns

**0 μrad**

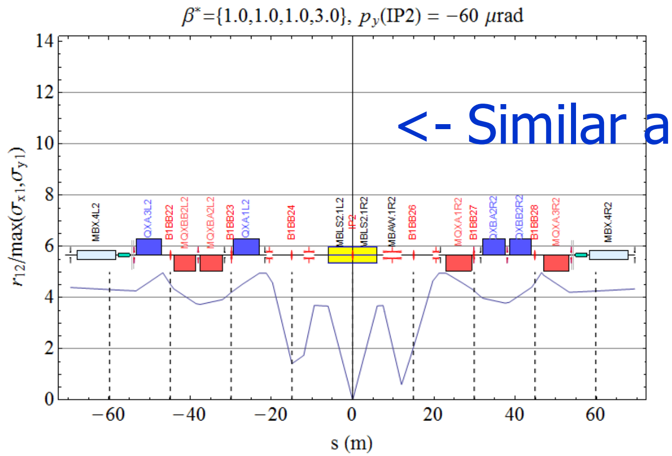


**-60 μrad**

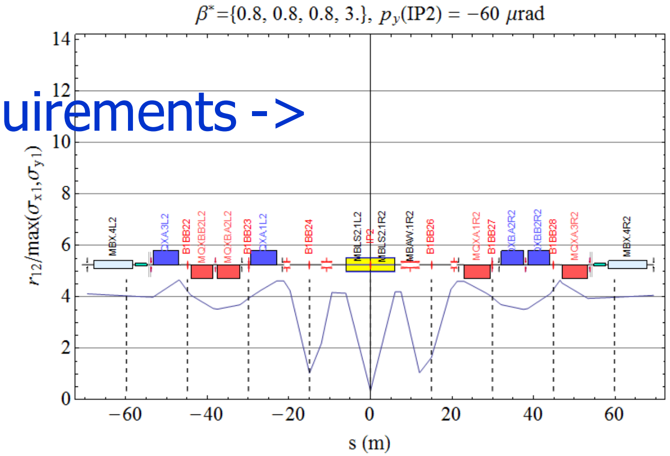


Crossing angle limited by need to avoid shadowing of spectator neutrons at ZDCs.

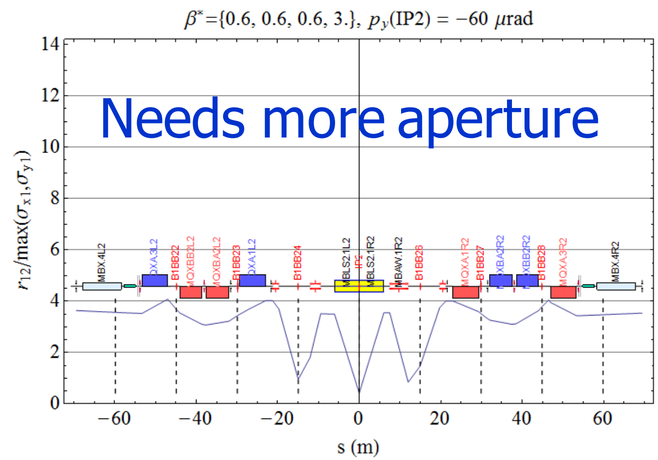
# Beam separation around ALICE




<- Similar aperture requirements ->




Pb-Pb in 2011 (showing 100 ns encounters although we had 200 ns)




Needs more aperture

Increase of angle to -80 μrad does not help much.

May limit us to β*=0.8 m ?

Aperture measurements needed, probably not before setup for p-Pb run.

p-Pb in 2011 (showing 100 ns encounters although we may choose 200 ns)

R. Versteegen (forthcoming note)

# Target p-Pb performance in 2012 (ATLAS/CMS)

| **Main choice:** | **Units** | **200 ns** | | **100 ns** | |
|---|---|---|---|---|---|
| Beam energy/( Z TeV) | *Z* TeV | 3.5 | 4 | 3.5 | 4 |
| Colliding bunches | | 356 | 356 | 550 | 550 |
| $\beta^*$ | m | 0.7 | 0.6 | 0.7 | 0.6 |
| Emittance protons | μm | 3.75 | 3.75 | 3.75 | 3.75 |
| Emittance Pb | μm | 1.5 | 1.5 | 1.5 | 1.5 |
| **Pb/bunch** | $10^8$ | 1.2 | 1.2 | 0.8 | 0.8 |
| p/bunch | $10^{10}$ | 1.15 | 1.15 | 1.15 | 1.15 |
| Initial Luminosity $L_0$ | $10^{28}$ cm$^{-2}$ s$^{-1}$ | **6.2** | **8.3** | **6.4** | **8.5** |
| Operating days | | **22** | **24** | **22** | **24** |
| Difficulty (subjective) | | **0.9** | **1** | **0.9** | **1** |
| Integrated luminosity | nb$^{-1}$ | **15.4** | **22.4** | **15.9** | **23.1** |
| Nucleon-nucleon | pb$^{-1}$ | **3.2** | **4.7** | **3.3** | **4.8** |

Integrated luminosity by scaling from 2011 (c.f. ~7 pb$^{-1}$ NN in Pb-Pb)

Average Pb bunch intensities from best 2011 experience.

Proton bunch intensities conservative, another factor 10 **???**

Proton emittance conservative, another factor 1.37 **?**

Untested moving encounter effects, possible reduction factor 0.1 **??**

# LHCb joins in …

- Up till now the heavy-ion filling schemes provided no collisions at IP8

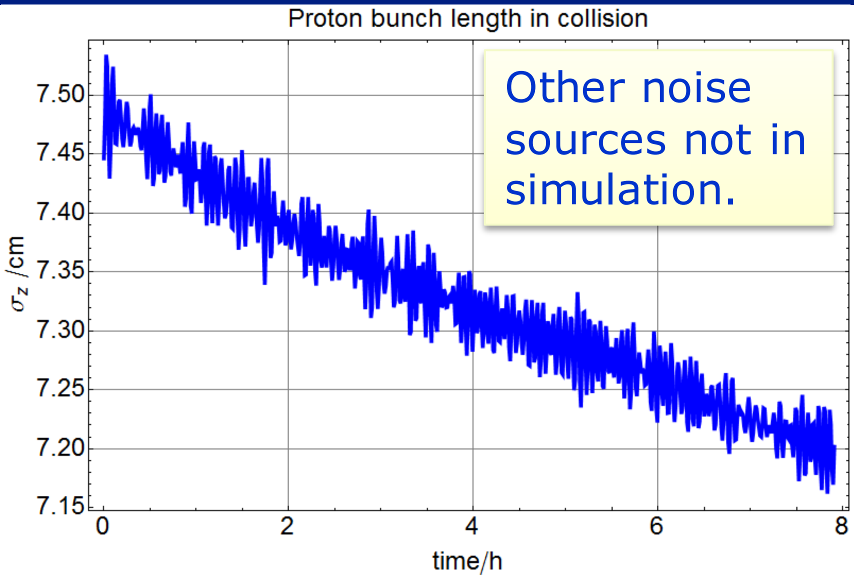
$$s_{IP8} = \frac{1039}{1188} C = \frac{7}{8} C - 6\lambda_{RF}$$

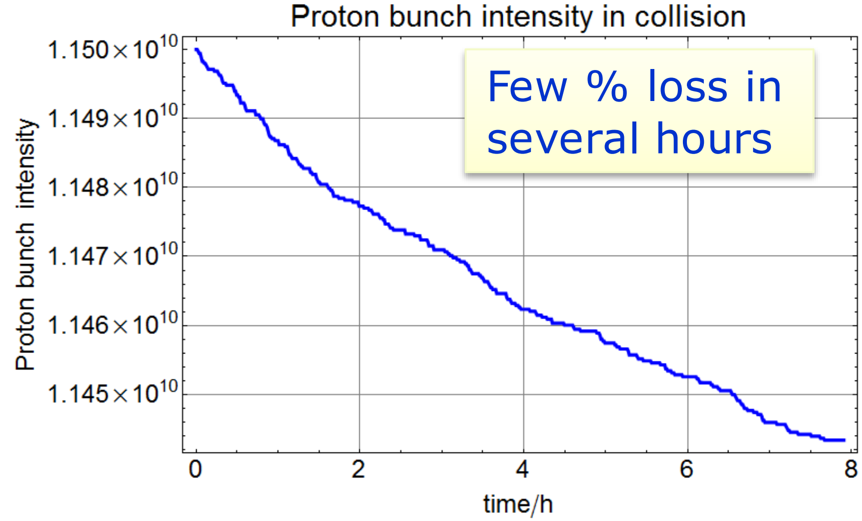
- Discussions in LPC 3/2/2012
- LHCb optics will be kept at $\beta^{*}=3$ m
  - Factor 4-5 down in luminosity
- Filling schemes must be adapted to provide collisions at IP8
  - Shift 1 or more batches ?
  - Reduce luminosity for others – how much ?
  - Another factor ~5-12 down for LHCb
  - Details to be worked out
  - Possible max. luminosity in ALICE ?
- Further motivation for early MD/pilot physics fill

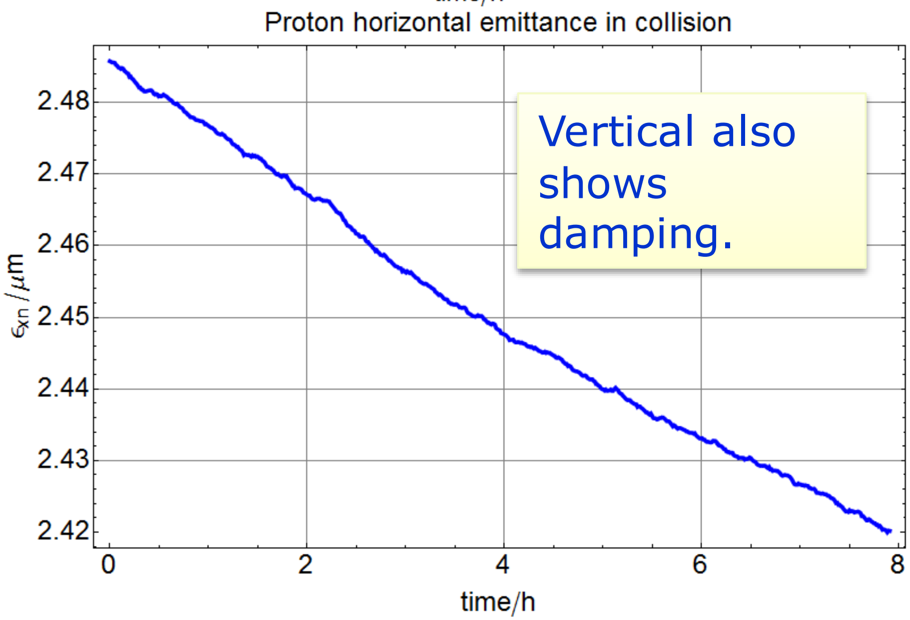
# More predictions for p-Pb (no detail)

- Bound-free pair production rate will be reduced to a few % of the Pb-Pb rate, one side of IP
- Similar scaling for electromagnetic dissociation
  - Same equivalent photon spectrum of proton
- Luminosity lifetime better than Pb-Pb
  - Dominated by IBS of Pb beam or, maybe, beam-beam
- Luminosity losses in dispersion suppressors around experiments and in IR3 much reduced
  - Less irradiation, R2E, etc.

# Proton beam evolution in collision (preliminary)



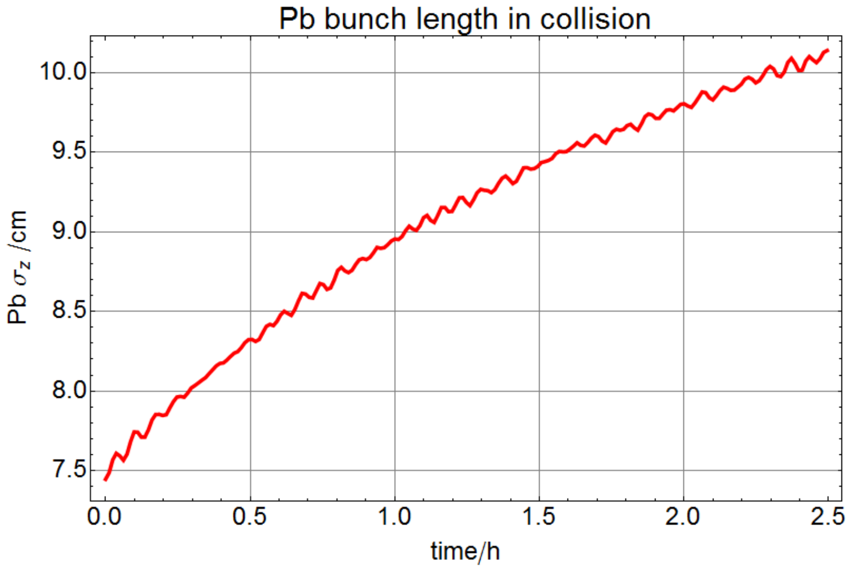



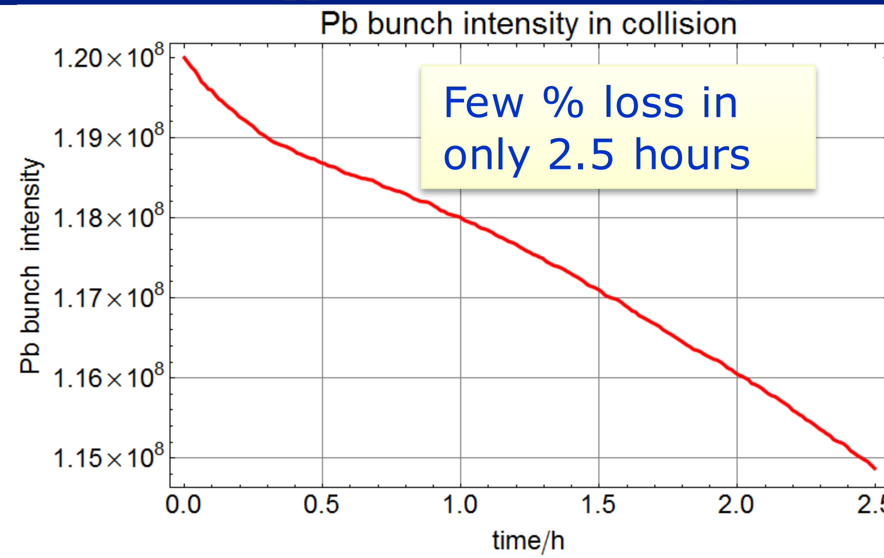

Low intensity (10% of nominal) proton bunches have very weak IBS so shrink slowly due to synchrotron radiation damping.

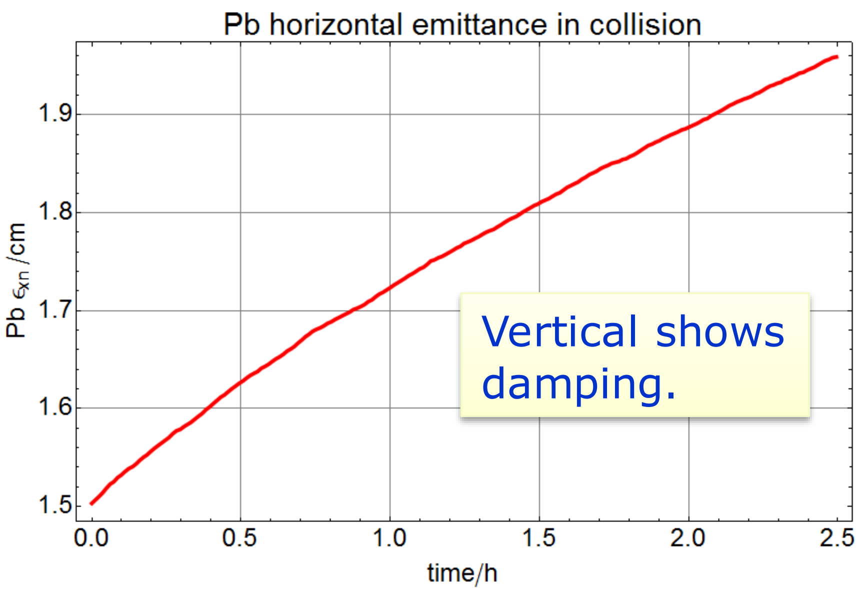
Intensity loss from luminosity (cross section with Pb ~2 barn) is also small.

M. Schaumann

# Pb beam evolution in collision (preliminary)




High intensity (150% of nominal) Pb bunches have strong IBS growth (as in 2011) despite having twice the synchrotron radiation damping of protons.

Fractional intensity loss from luminosity (cross section on Pb ~2 barn) is more significant, but much less than in Pb-Pb.
Losses also from IBS debunching.

M. Schaumann

# Luminosity evolution (preliminary)

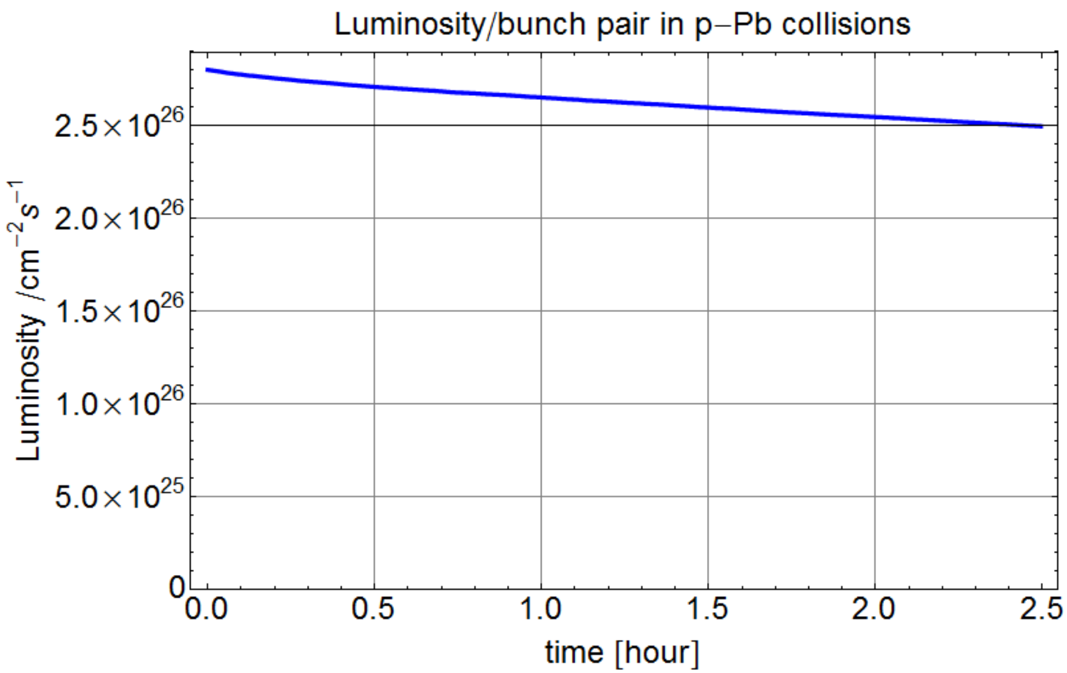
Luminosity made by the bunches shown on previous two slides.

Slower decay than in Pb-Pb or even p-p fills.

We can hope for long fills which will increase the ratio of average to peak luminosity!

Good, since set-up will be longer than usual.

N.B. this is the worse case for luminosity decay, the higher intensity Pb bunches from the 200 ns filling scheme.



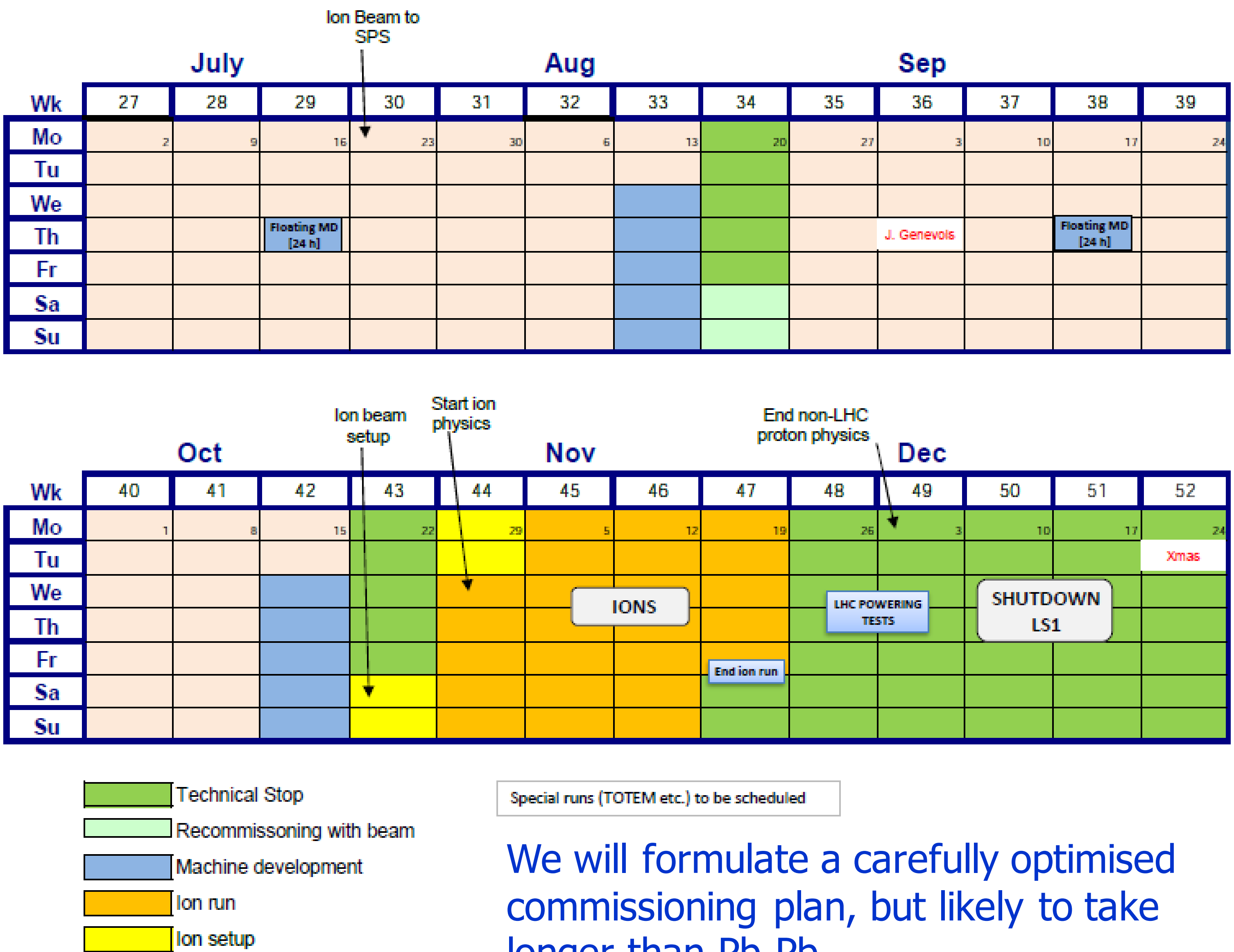

**Caveats:**

Unequal beam sizes may give beam-beam problems (but tune-shifts are still small).

This is still the conservative proton bunch intensity.

Not all physics in this simulation.

# Schedule for late 2012



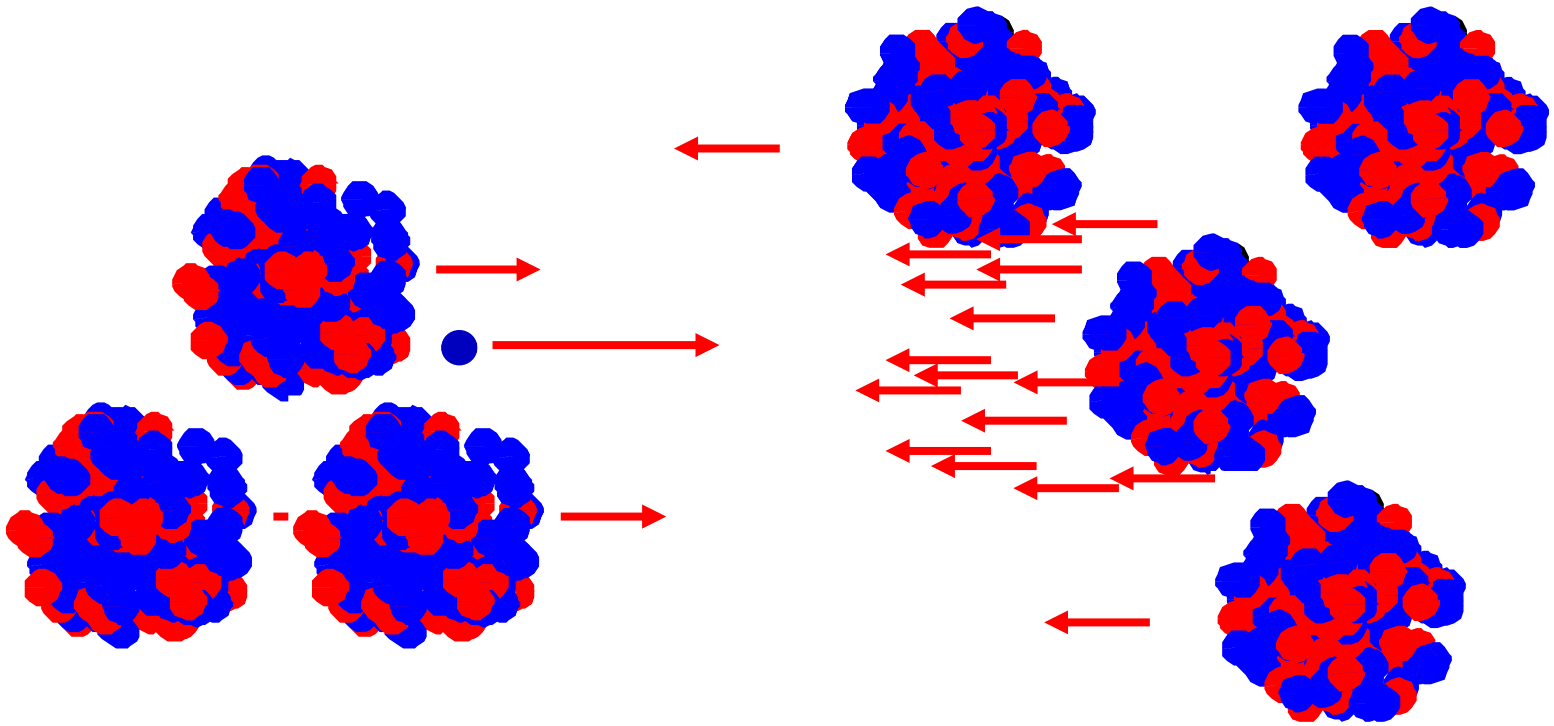

We will formulate a carefully optimised commissioning plan, but likely to take longer than Pb-Pb.

# Fitting in some p-p at $\sqrt{s_{NN}}$=2.76 TeV ?

- After last of 4 fills at this energy in March 2011:

Fill # 1658
Date: 19:16 – 27/3/2011
ATLAS : $L_{Fill}$:94.55 $nb^{-1}$ $L_{Int}$:322.68 $nb^{-1}$
ALICE : $L_{Fill}$:14.69 $nb^{-1}$ $L_{Int}$:52.87 $nb^{-1}$
CMS : $L_{Fill}$:100.66 $nb^{-1}$ $L_{Int}$:345.12 $nb^{-1}$
LHCb : $L_{Fill}$:17.74 $nb^{-1}$ $L_{Int}$:538.12 $nb^{-1}$

- This is $< 7\ pb^{-1}$ we had from Pb-Pb ⇒ strong interest but:
  - Time is short, risk is high
  - Uncertainties about p-Pb performance and setup time
- [My rough, unofficial guesstimate: ~1 $pb^{-1}$ in a few days]
- In any case, very careful planning of strategy will be necessary.
- Could we consider a conditional strategy?
  - Eg: if we have <so much> p-Pb integrated luminosity by <a certain date> then stop p-Pb and re-commission low energy p-p (?)



# LHC HEAVY-ION PROGRAMME UP TO 2022 (LS3)

# Status of this plan

- An implementation of the (long ago) approved physics programme consistent with plans for the CERN accelerator complex in coming decade
  - Takes account of p-p operation, shutdowns, SPS HI programme, etc.
  - March 2011: Agreed among ATS Director, ALICE management, S. Maury, JMJ
  - Presented to 2011 IEFC workshop
  - Presented to LHC Machine Committee 20/4/2011
  - Presented at EPS-HEP 2011 Conference, Grenoble, July 2011
  - Presented again at LHC Chamonix Workshop, Feb 2012
- Some flexibility still available
- Next slide presents an update incorporating new knowledge from the 2011 Pb-Pb run

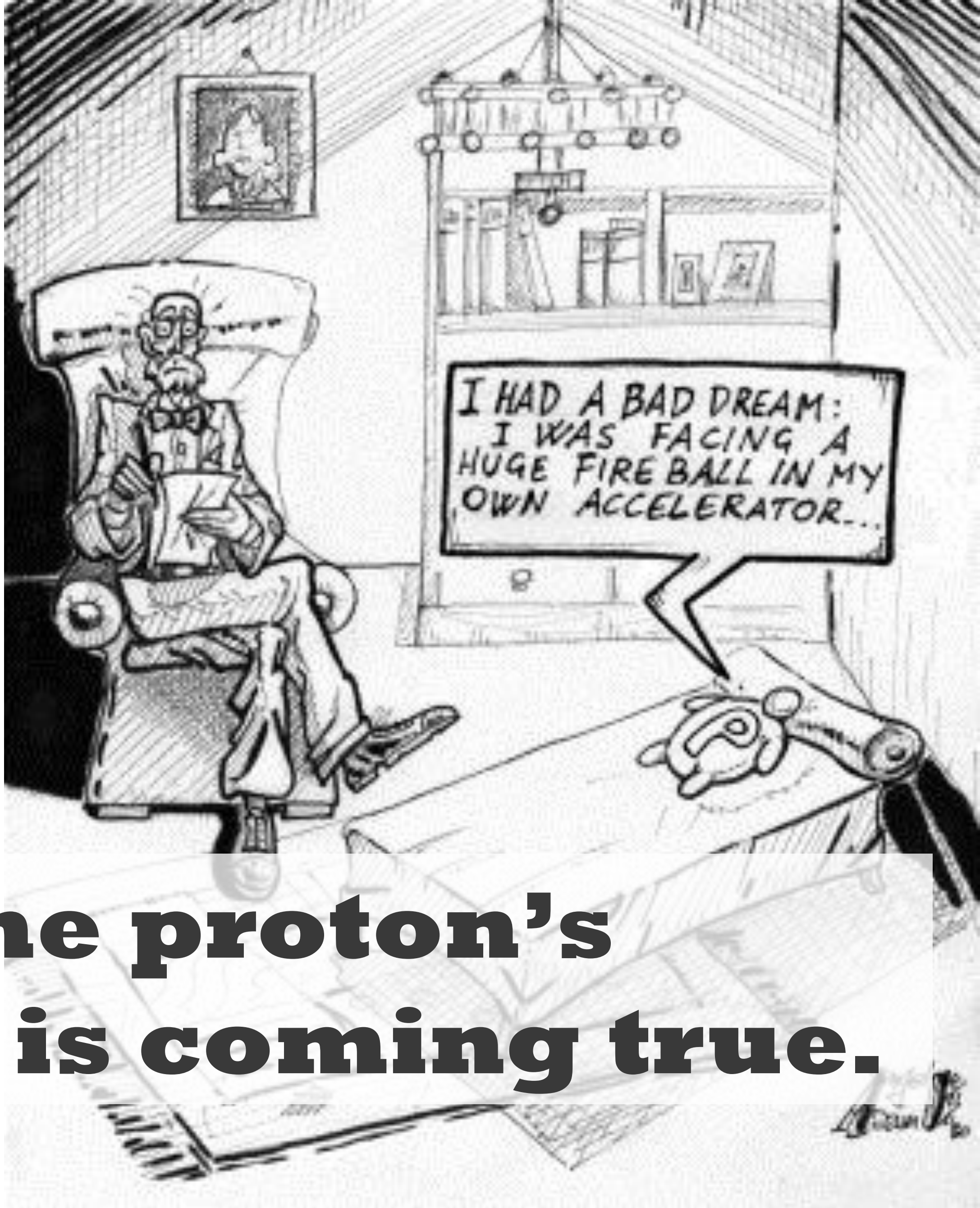
# LHC Heavy-Ion Programme to 2021

| | | |
|---|---|---|
| **2013-14** | | Long shutdown LS1, increase *E* |
| **2015-16** | **Pb-Pb** | Design luminosity, ~ 250 $\mu b^{-1}$/year,<br>Luminosity levelling? |
| **2017** | **p-Pb *or* Pb-Pb** | P-Pb to enhance 2015-16 data. Energy?<br>Pb-Pb if $\mu b^{-1}$ still needed |
| **2018** | | LS2: ? install DS collimators to protect magnets<br>? ALICE upgrade for 6 × design luminosity |
| **2019** | **Pb-Pb** | Beyond design luminosity … as far as we can.<br>Reduce bunch spacing? |
| **2020** | **p-Pb** | |
| **2021** | **Ar-Ar** | Intensity to be seen from injector commissioning for SPS fixed target.<br>Demanding collimation requirements? |
| **2022** | | LS3, upgrades ?? Stochastic cooling ?? |
| **>2022** | | Talks on Thursday |

# Summary

- Feasibility of p-Pb is partially established
- We are ready for a p-Pb physics run in 2012
  - Luminosity achievable remains uncertain
- Important further steps:
  - RF re-phasing MD with p-p (faster procedure)
  - Part 2 of feasibility test (multi-bunch ramp + pilot physics) in Aug-Sep
  - Clarification of LHCb potential/priority
  - Aperture measurements in IR2 during setup to determine final optics

*Our work inspired an unknown artist working for the CERN Bulletin to create this moving depiction of the angst of an LHC proton*

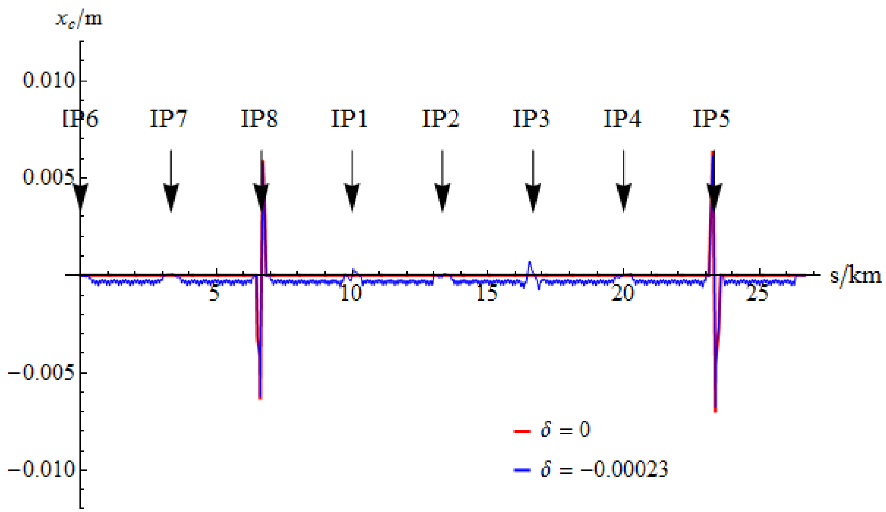



**Now the proton's nightmare is coming true.**

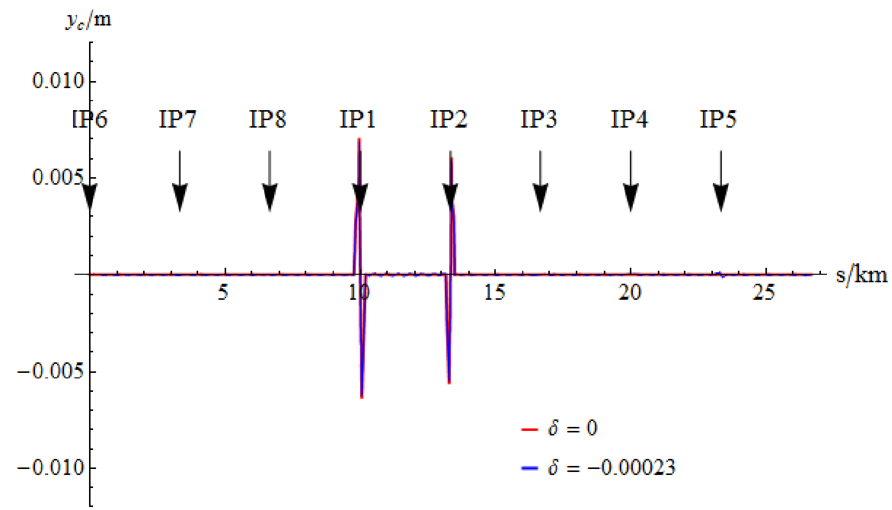
# BACKUP SLIDES

# Central orbits for β* = (0.6, 0.6, 0.6, 3.0)

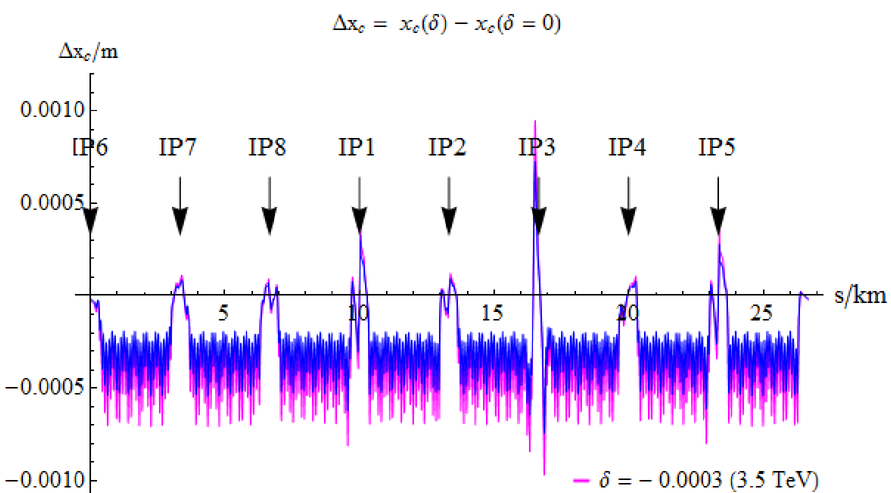
## Horizontal central trajectory at 4 TeV



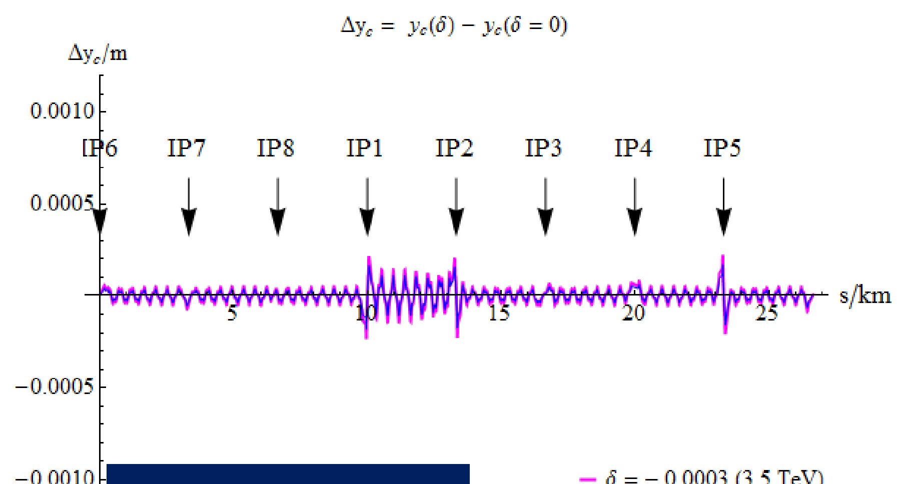

## Vertical central trajectory at 4 TeV




## Shift of the horizontal central trajectory, 3.5 TeV vs. 4 TeV

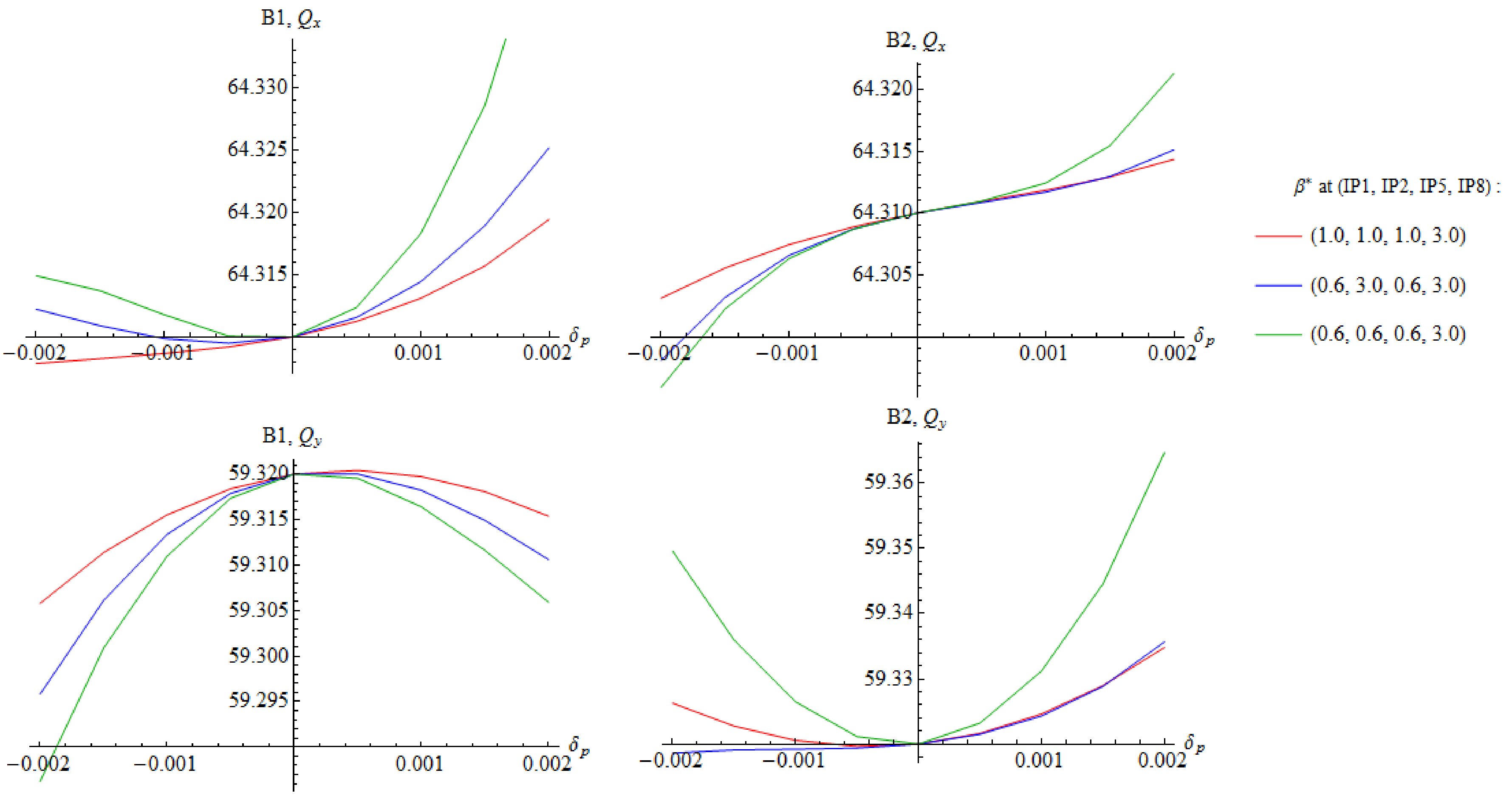



## Shift of the vertical central trajectory , 3.5 TeV vs. 4 TeV




R. Versteegen

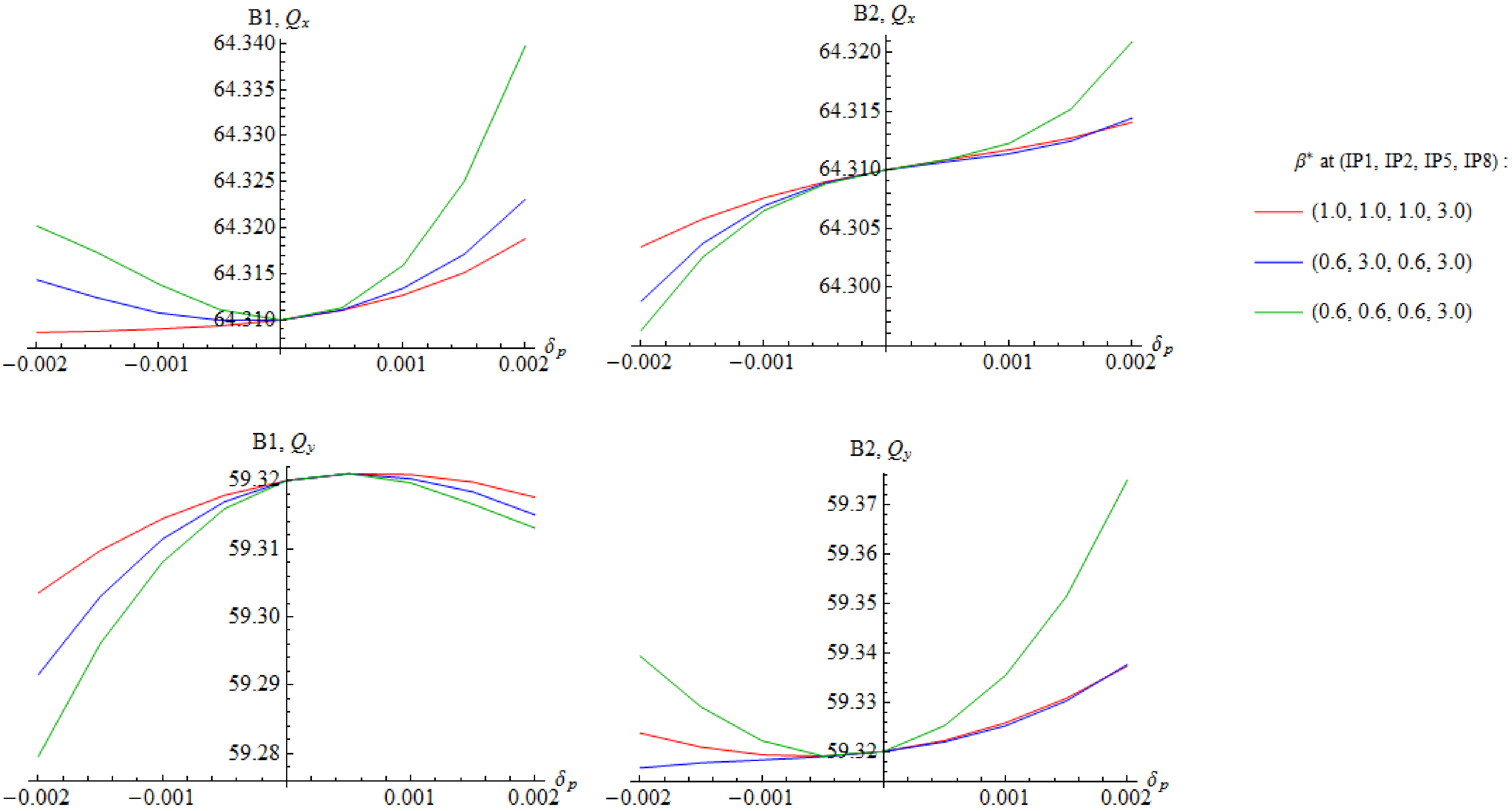
# Tune vs energy offset at 4 TeV, chromaticity matching on momentum





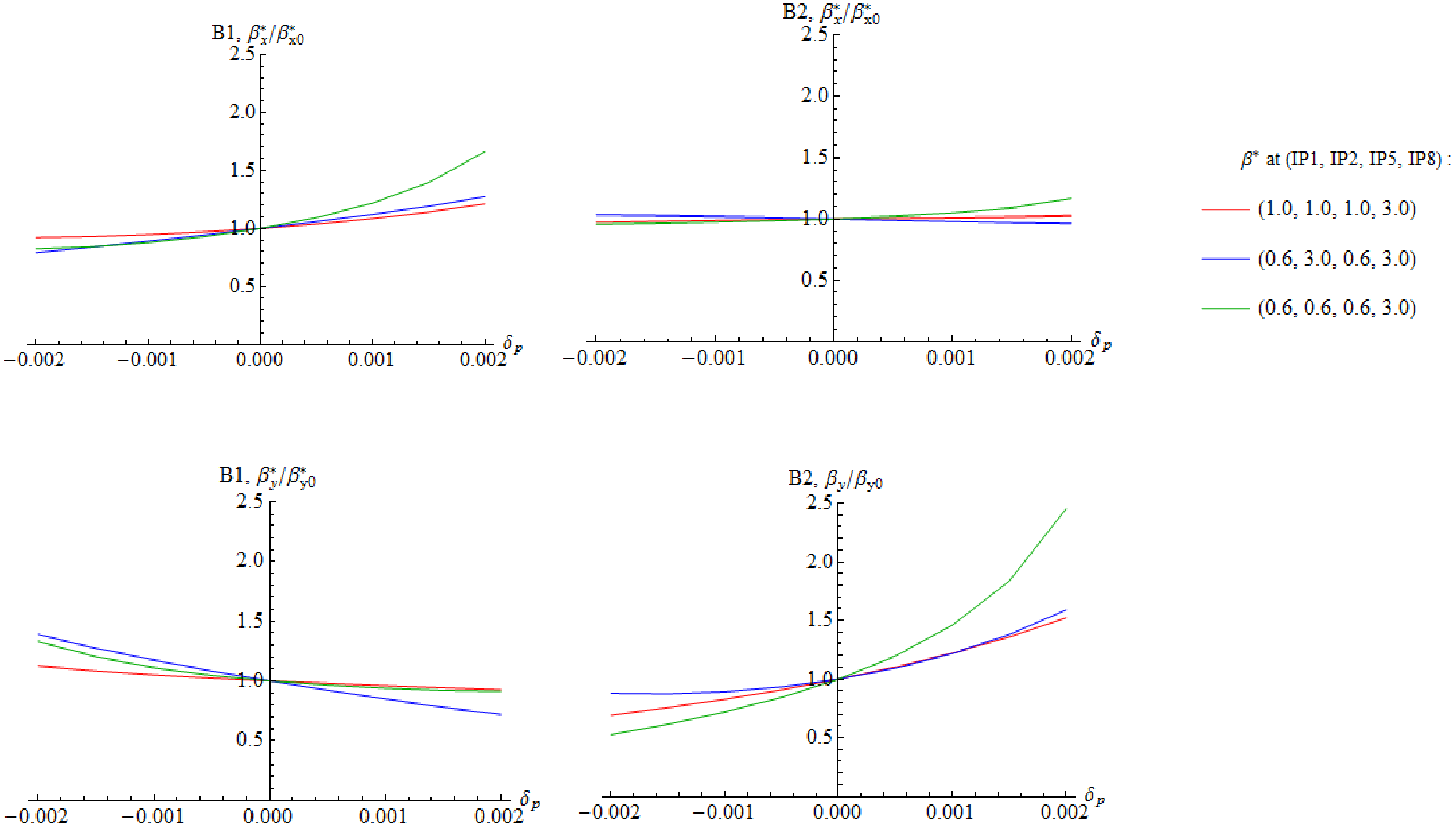

R. Versteegen

# Tune vs energy offset at 4 TeV for a matching off momentum for each beam separately




R. Versteegen

# β* vs energy offset at IP2, at 4 TeV, chromaticity matched off-momentum






R. Versteegen