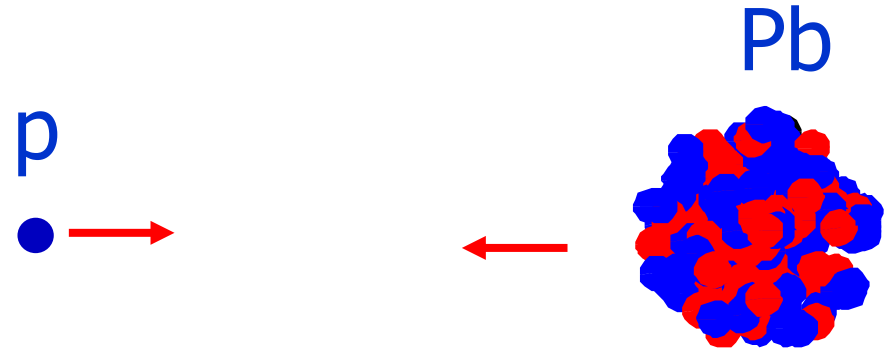

Possible proton-lead run of the LHC in 2012

John Jowett (CERN)

Thanks to

R. Alemany-Fernandez, P. Baudrenghien, C. Carli, E. Carlo-Giraldo, S. Hancock, R. Jones, D. Manglunki, J. Wenninger, and many others in ABP, BI, OP, RF groups.

The physics potential of proton-nucleus collisions at the TeV scale

Carlos A. Salgado
Universidade de Santiago de Compostela

Quark Matter 2011 - Annecy

Partly based on: *Proton-nucleus collisions at the LHC: scientific opportunities and requirements*
arXiv:1105.3919

carlos.salgado@usc.es http://cern.ch/csalgado

Link to plenary talk

Summary

- ***Proton-nucleus essential for benchmarking***
  - Hard processes
  - Bulk particle production
- ***Nuclear PDFs badly constrained at small-x***
  - pA only possibility to reduce uncertainties
  - Very standard technology but data needed
- ***Saturation of partonic densities***
  - pA provide excellent opportunities
  - (only chance before ep/eA collider)
- ***More opportunities***
  - High-multiplicity events
  - Ultraperipheral collisions
  - Measurements of astrophysical interest

CERN-PH-TH/2011-119
LHC-Project-Report-1181

Proton-Nucleus Collisions at the LHC: Scientific Opportunities and Requirements

http://arxiv.org/abs/arXiv:1105.3919

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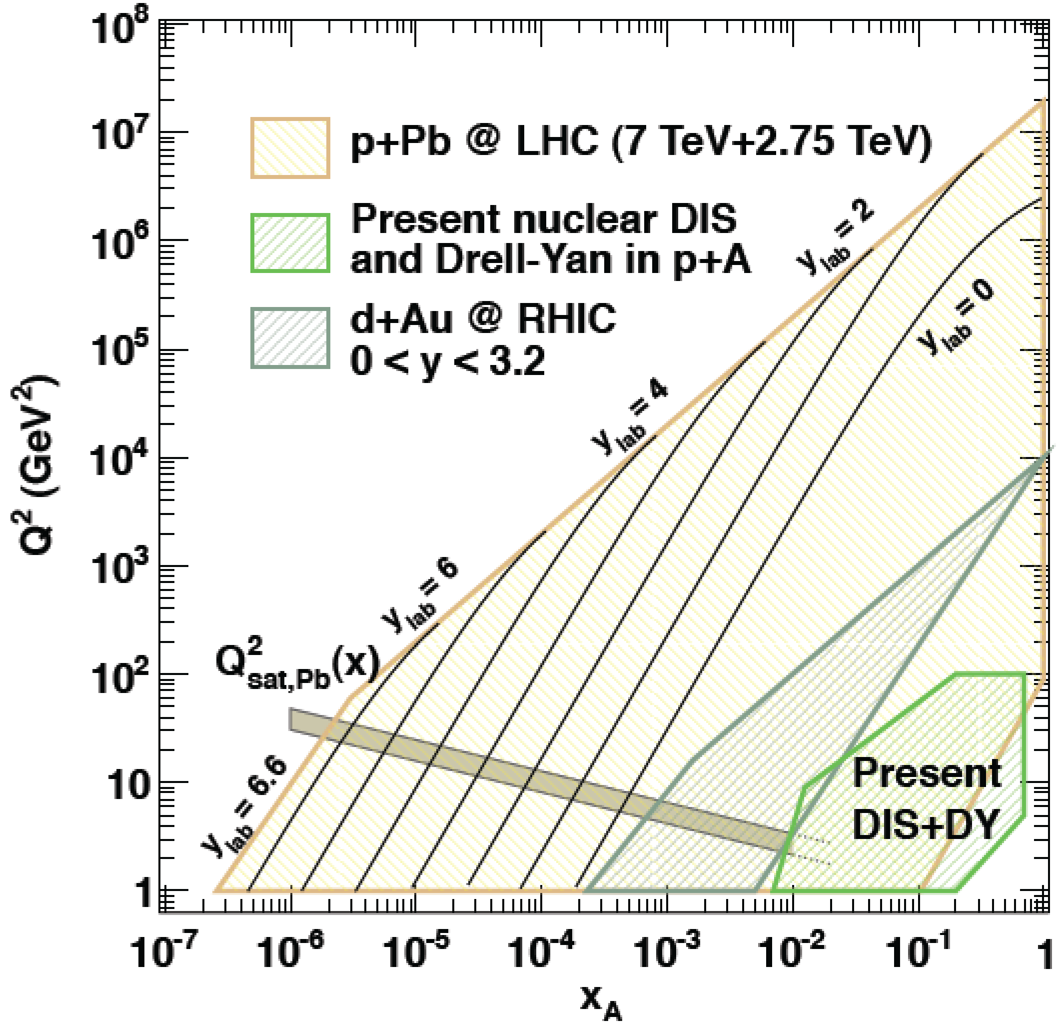
Abstract

Proton-nucleus (p+A) collisions have long been recognized as a crucial component of the physics programme with nuclear beams at high energies, in particular for their reference role to interpret and understand nucleus-nucleus data as well as for their potential to elucidate the partonic structure of matter at low parton fractional momenta (small-x). Here, we summarize the main motivations that make a proton-nucleus run a decisive ingredient for a successful heavy-ion programme at the Large Hadron Collider (LHC) and we present unique scientific opportunities arising from these collisions. We also review the status of ongoing discussions about operation plans for the p+A mode at the LHC.

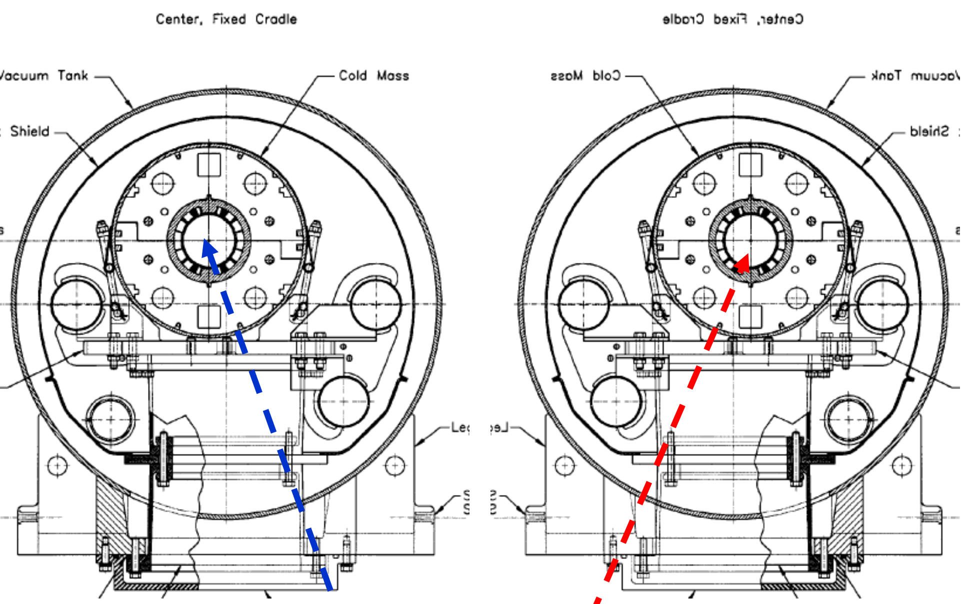
Kinematical reach in nuclear collisions

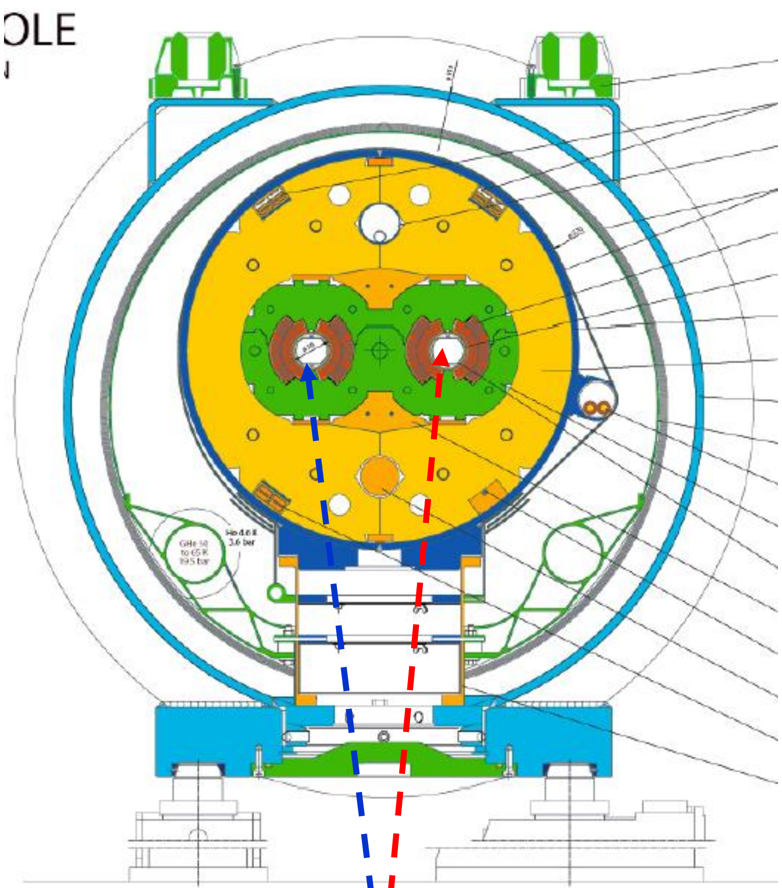


Before Jan 2011: Vox clamantis in deserto

- Not part of "LHC Baseline" … no resources.
- CERN Workshop in 2005
  - Physics case, experiments' performance, …
  - Reviewed RHIC experience with d-Au in 2002-3 (T. Satogata)
  - Schemes for LHC injector operation (C. Carli)
  - LHC operation, beam dynamics concern identified (JMJ)
  - Executive summary of accelerator part (in 2011 report)
- LHC Project Report 928 (= paper at EPAC 2006)
- Key systems groups kept aware meanwhile
  - Eyes open for any showstoppers
- Requested by ALICE for 2012
  - First Pb-Pb run successful. If not 2012 then would be much later otherwise because of shutdown schedule.
  - Discussion at Chamonix workshop, Jan 2011.
  - ATLAS and CMS heavy-ion groups
  - Some resources now available:
    - OP, RF, BI, … collaborating on implementation and operation
    - Fellow to work on beam dynamics in ABP will arrive in October

Critical difference between RHIC and LHC





RHIC: Independent bending field for the two beams

LHC: Identical bending field in both apertures of two-in-one dipole

Relation between Beam Momenta

- LHC accelerates protons through the momentum range

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

  - Use this as reference, measure of magnetic field in main bending magnets
- The two-in-one magnet design of the LHC (unlike RHIC) fixes the relation between momenta of beams in the two rings

$$\frac{p_{\mathrm{Pb}}}{Q} = p_{\mathrm{p}}$$

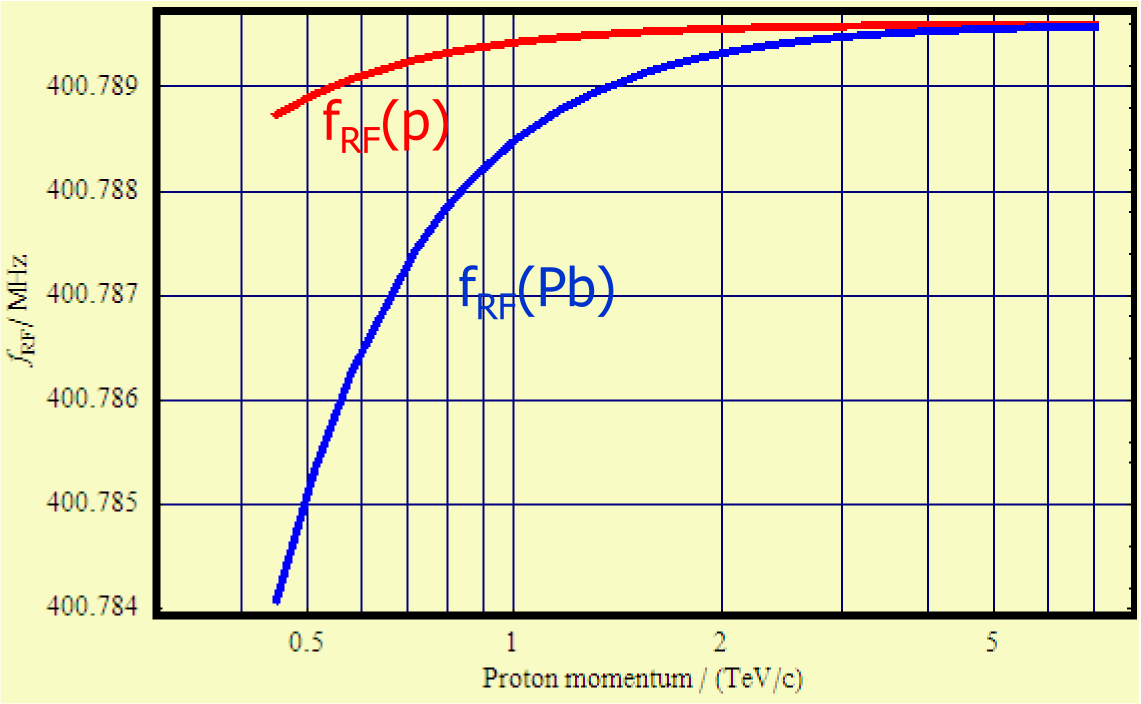
where $Q = Z = 82,\ A = 208$ for fully stripped Pb in LHC

RF Frequency for p and Pb

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.

Which is Beam 1 and which is Beam 2 ?

- Initial preference for ALICE spectrometer asymmetry:

  Beam 1=p, Beam 2=Pb

- Assume this for definiteness in rest of this talk.

- But switching of the beams between the two rings **is important and requested**
  - Clearly equally feasible, just some setup time
  - Important, eg, to access other regions in (x,Q^2)

Distorting the Closed Orbit

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

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

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

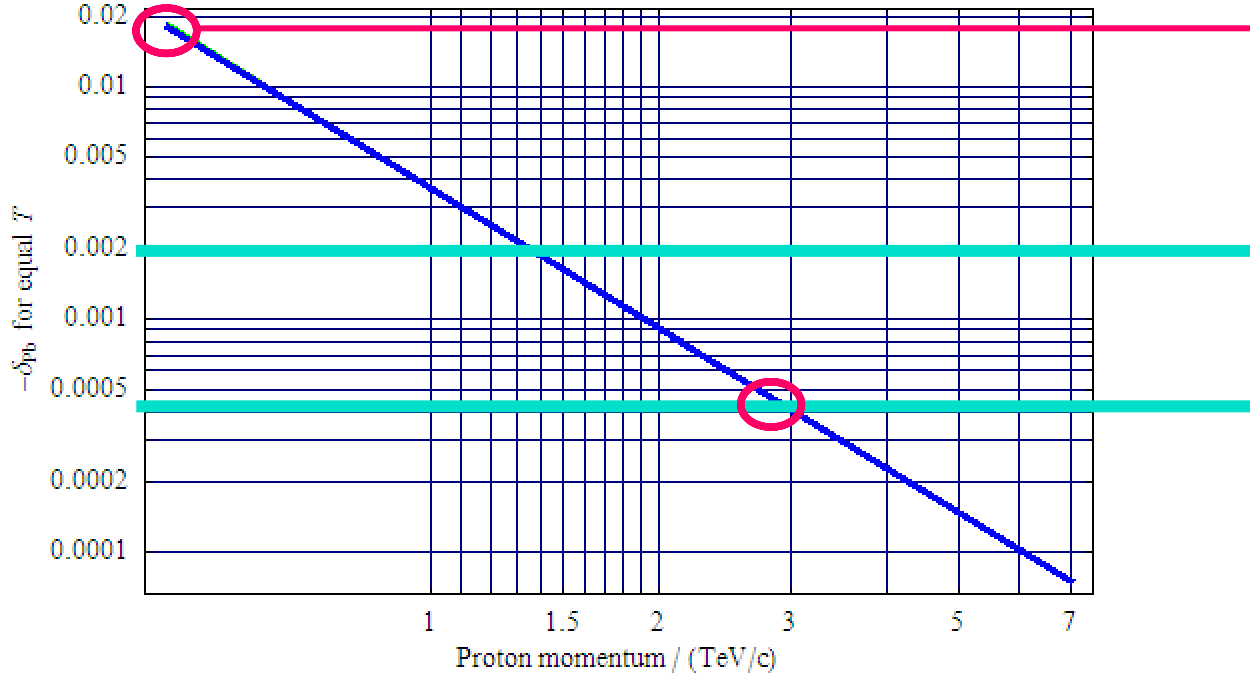
the phase-slip factor $\eta = \dfrac{1}{{\gamma_T}^2} - \dfrac{1}{\gamma^2}$, $\gamma = \sqrt{1 + \left(\dfrac{Qp_\mathrm{p}}{mc}\right)^2}$, $\gamma_T = 55.8$ for LHC optics.

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

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

Momentum offset required through ramp

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



2% - would move beam by 35 mm in QF!!

Limit with pilot beams

Limit in normal operation (1 mm in arc QD)

Revolution frequencies must be equal for collisions at top energy.

Lower limit on energy of p-Pb collisions, *E*=2.7 Z TeV.

RF frequencies must be unequal for injection, ramp!

Moving long-range beam-beam encounters may be a problem (cf RHIC).

Two-beam dynamics with unequal revolution frequencies

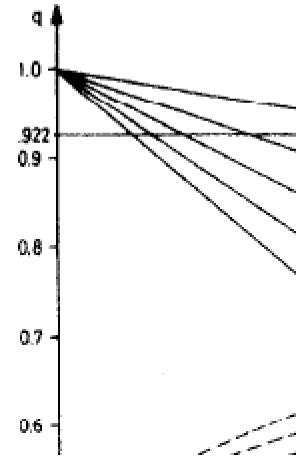
IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

OVERLAP KNOCK-OUT RESONANCES WITH COLLIDING BUNCHED BEAMS IN THE CERN ISR

Stephen Myers*

Summary

A bunched beam can subject a 'perturbed beam' to overlap knock-out (OKO) resonances when the frequencies contained within the longitudinal spectrum of the bunches are equal to any of the transverse betatron frequencies of the perturbed beam. Usually with proton machines this condition can only be attained when the revolution frequencies of the two beams are different. With electron machines and their associated high synchrotron frequency, the betatron frequencies of the per-



Several references on work at ISR (Myers, Hereward, Gourber, et al)

Suggestion from S. Myers at LMC 50 to look at cancellation between IPs.

Overlap knock-out resonances ?

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

Hamiltonian is no longer periodic in s.

Excites modulational resonances

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

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.

We are nevertheless looking at calculations of driving terms, compensation between IRs, etc.

Moving long-range beam-beam at injection

- Outline of method in development …

- Consider Beam 2 (Pb) – the weaker beam at injection, clearly most difficult case
  - Lowest rigidity, longest time
- Evaluate long-range beam-beam effects at every point in every common straight section (IR)
  - Build *continuous* functions of *s* for every IR
    - NB *s* is different for the two beams, path length shift effects are taken care of correctly (no direct correspondence of points in MAD optics)

Method (continued)

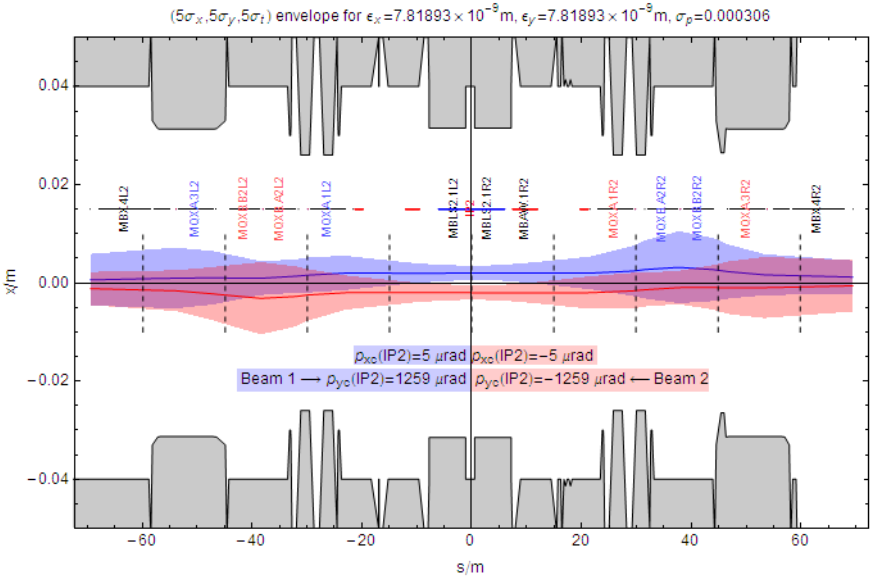
- Calculate combination of beam-beam kicks on a particle on a given turn as the encounters move
  - Add them up with proper betatron phases
    - Partial compensations
  - Take out static component (closed-orbit) from long-term averaging and look at fluctuations around it
  - RMS fluctuation gives emittance growth rate

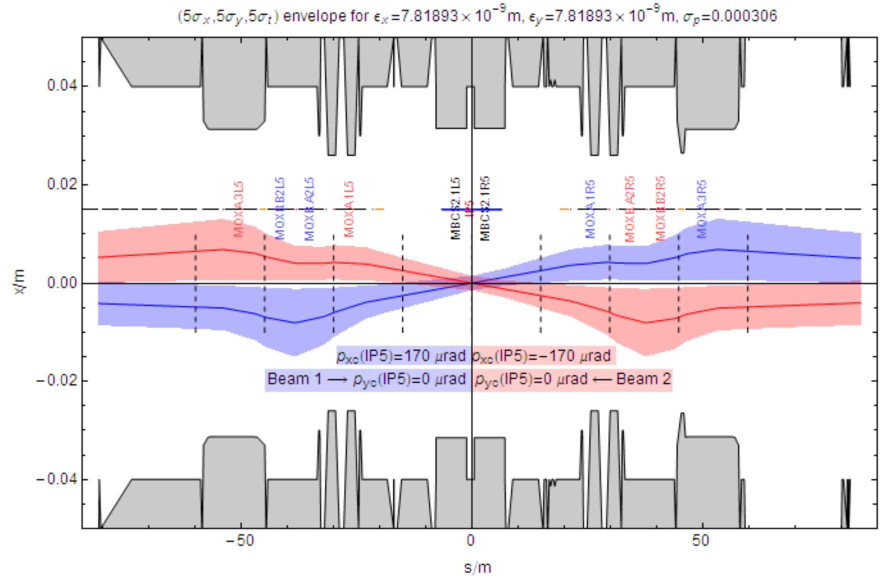
$$\frac{d\varepsilon_{x,yn}}{dt} = \frac{1}{2} f_0 \sqrt{\gamma^2 - 1}\left[\beta_{x,y}(s)\left(\Delta p_{x,y}(s)\right)^2\right]$$

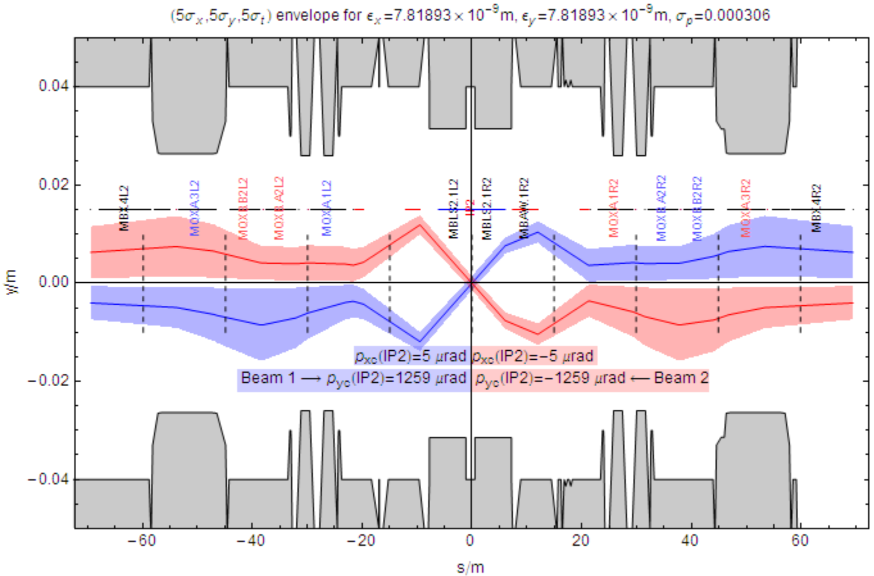
where [..] denotes mean-square deviation

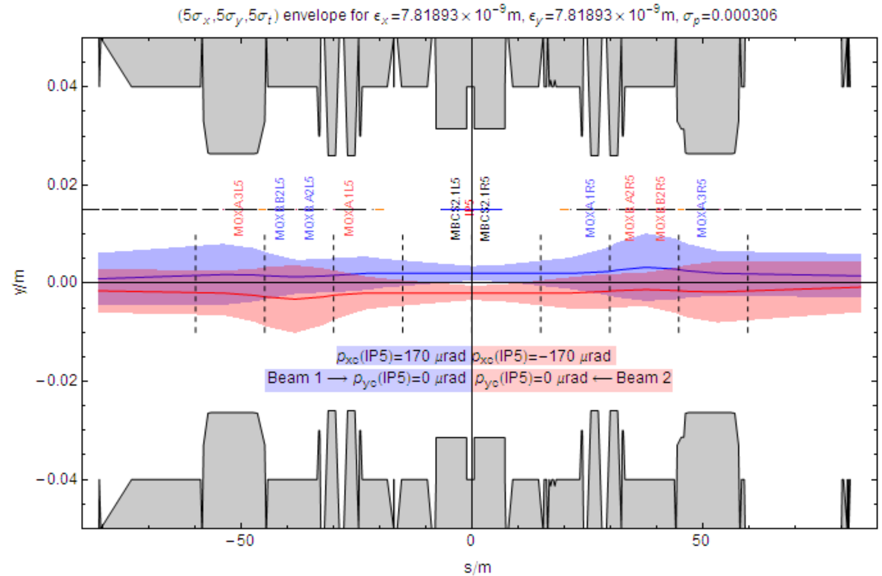
    - Assuming pseudo-random
    - Spectral analysis can confirm
    - Implement detailed collision schedule
- Implementation being debugged for now …

ALICE - Separation schemes - CMS

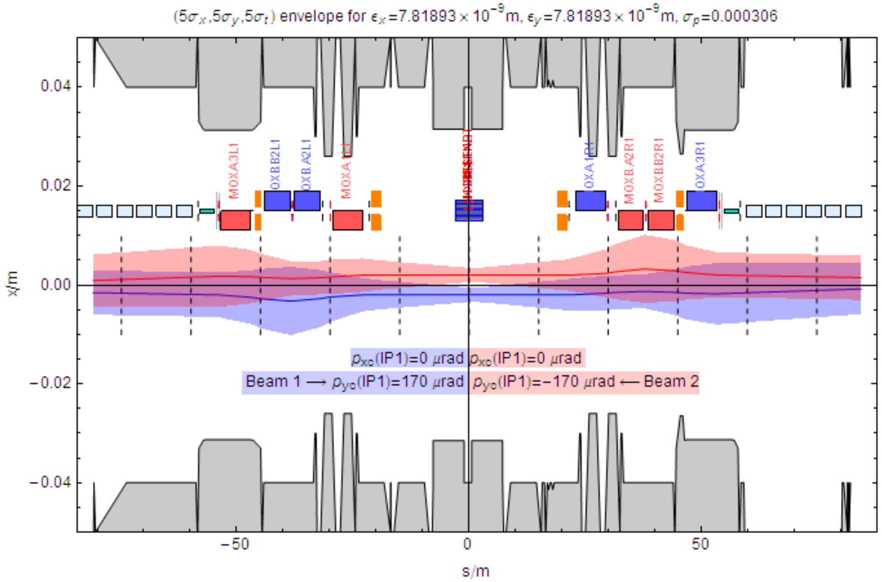


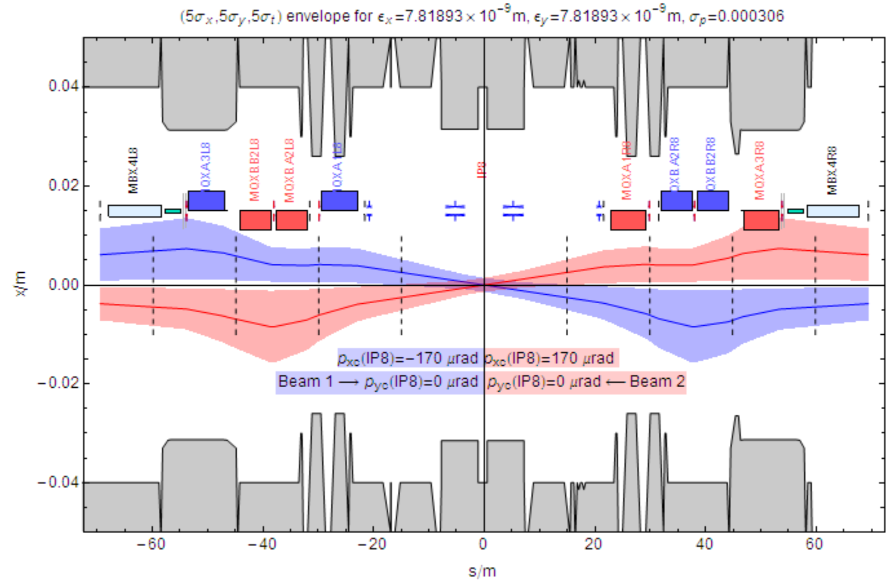


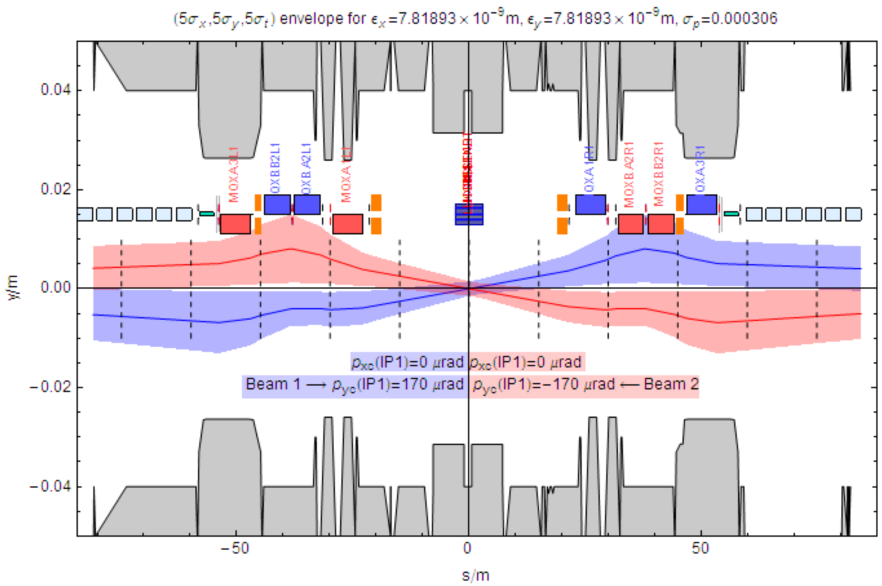


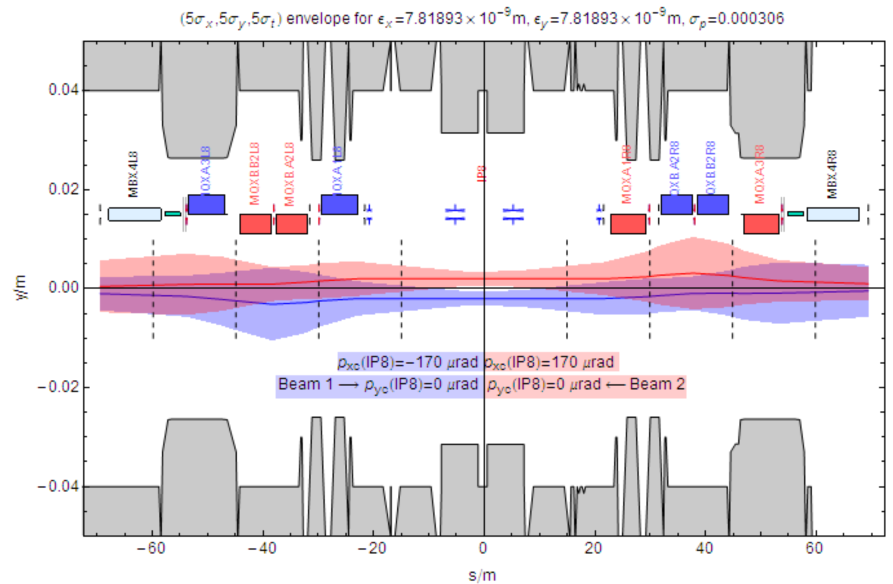


ATLAS - Separation schemes - LHCb

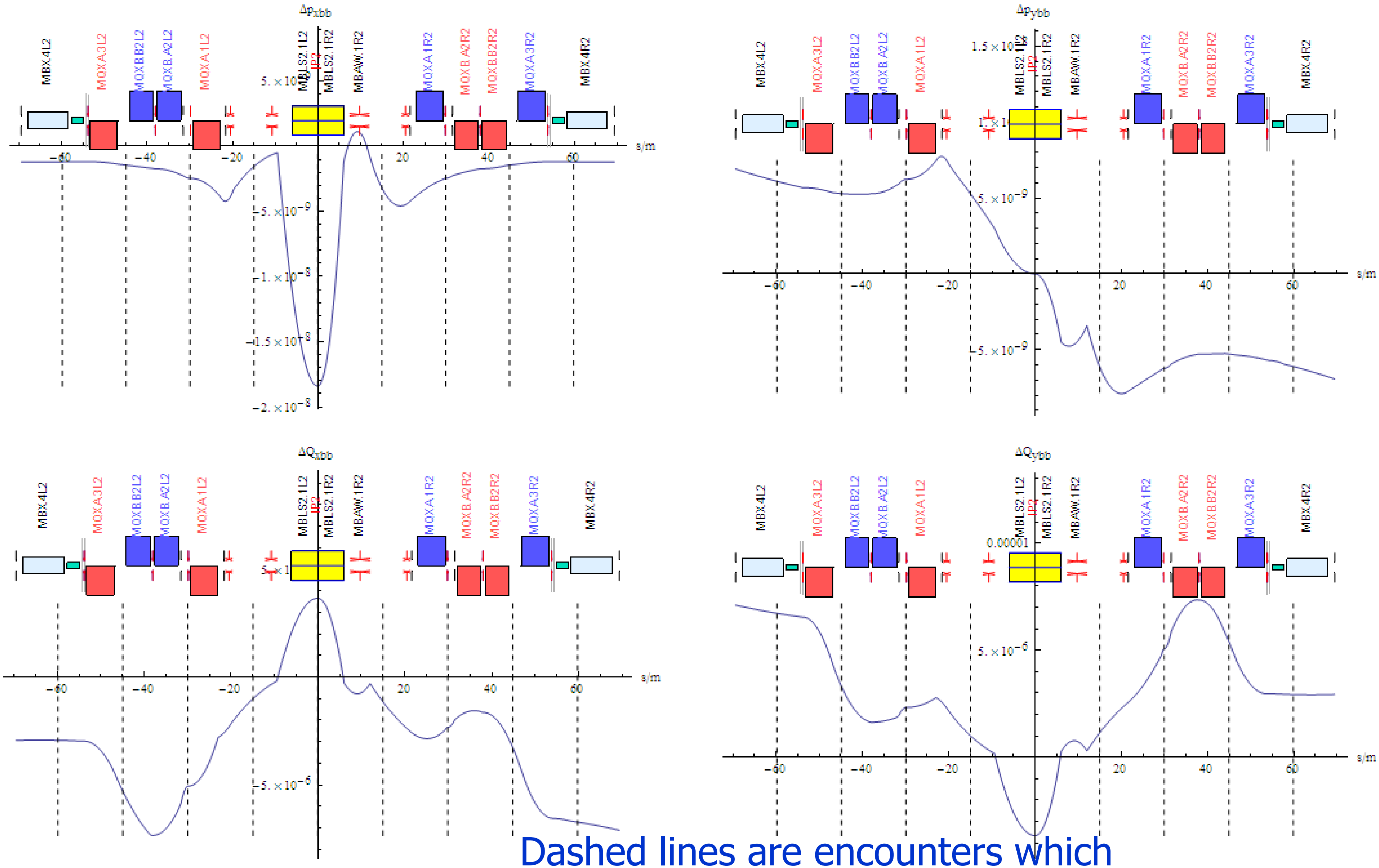






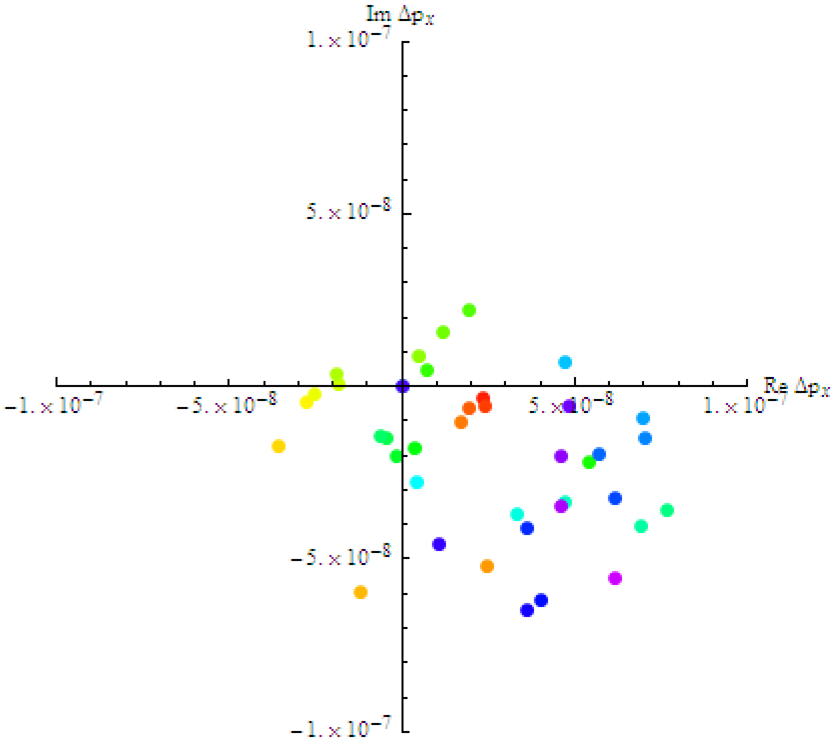


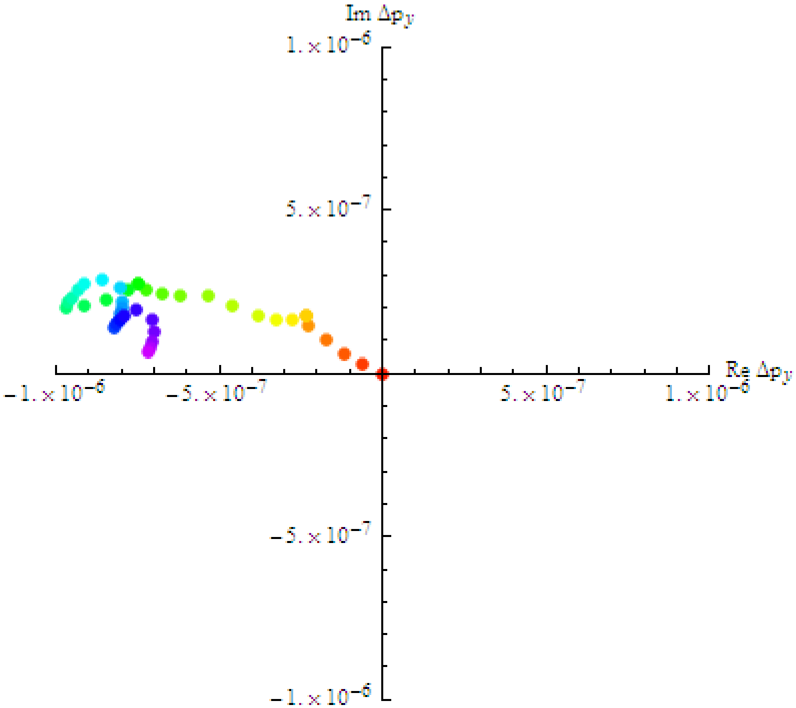
Example: beam-beam for Pb around ALICE



Dashed lines are encounters which will move along IR on next turn …

Distribution of normalised kicks in 1 turn





Mitigation by adjusting phases between IPs, increasing separation ?

Transverse Feedback

- 4 independent systems, 1 per plane and per ring
- High bandwidth to act on individual bunches
- Located in IP4, so no concerns about timing of p-Pb bunch passages.
- Potentially very important for p-Pb:
  - Damping any coherent oscillations driven by the coherent dipole kicks from moving beam-beam encounters at injection and during ramp

Accessible energies and CM rapidities

Possible range of collision energies Minimum p-Pb energy for equal revolution frequency.

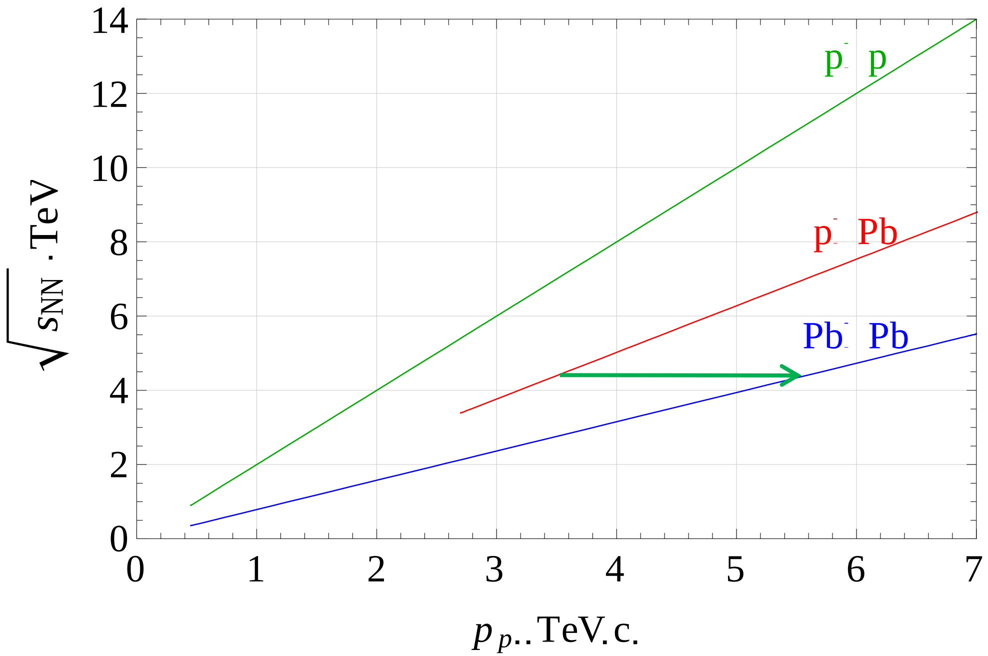
Relations between these numbers are a simple consequence of the two-in-one magnet design

	p-p	Pb-Pb	p-Pb
E/TeV	0.45-7	287-574	(2.7-7,287-574)
E_N/TeV	0.45-7	1.38-2.76	(2.7-7, 1.38-2.76)
$\sqrt{s}/\mathrm{TeV}$	7-14	73.8-1148	48.9-126.8
$\sqrt{s_{\mathrm{NN}}}/\mathrm{TeV}$	7-14	0.355-5.52	3.39-8.79
y_{CM}	0	0	-2.20
y_{NN}	0	0	+0.46

Charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p

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

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



Injection

- Nominal Pb beam has 592 bunches, 100 ns minimum bunch spacing
- p-Pb collisions in LHC will be done with a special proton filling scheme, designed to match the Pb beam
  - Other p-p schemes are different
  - Schemes worked out in 2005 by K. Schindl and C. Carli
  - This beam is now being prepared in the injectors (S. Hancock et al in PS)
    - Feasibility test may not be with final version

Potential Performance (if it works ...)

Assume Pb ion bunch with nominal intensity $N_{\mathrm{Pb}} = 7 \times 10^7$,
proton bunch with 10% nominal intensity $N_p = 1.15 \times 10^{10}$,
nominal emittances (equal geometric beam sizes).

With Pb ion nominal bunch structure in both beams, $\beta^* = 0.5$ m,
peak $L = 1.5 \times 10^{29}$ cm^{-2}s^{-1}, in p+Pb collisions at $7\,Z$ TeV.

At 3.5 Z TeV, $\beta^* = 1.5$ m, peak $L \approx 3 \times 10^{28}$ cm^{-2}s^{-1}.

Luminosity burn-off much less than Pb-Pb:

BFPP flux of $^{208}\mathrm{Pb}^{81+}$ from IP reduced to 1.5% of Pb-Pb value
(BFPP flux of neutral H atoms to ZDC is tiny!)
EMD also less

IBS of Pb beam will likely limit length of fills, simulations will come.

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BFPP flux of $^{208}\mathrm{Pb}^{81+}$ from IP reduced to 1.5% of Pb-Pb value
(BFPP flux of neutral H atoms to ZDC is tiny!)
EMD also less

IBS blow-up stronger for Pb will probably limit length of fills (simulations for integrated luminosity will come soon, earlier work A. Morsch 1997)

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

- Nominal Pb beam (100 ns basic spacing)
- Matching proton beam
  - See injection scheme details (C. Carli)
- Inject p beam in Ring 1, f_{RF} for p
  - Orbit, ramp established in advance
- Inject Pb beam in Ring 2, f_{RF} for Pb
  - Orbit, ramp established in advance
- Ramp both beams on central orbits
  - Orbit feedback decouples RFs
- Rephase RF and bring fRF together to lock
- Squeeze, collide, (almost) as usual Pb-Pb
  - Preliminary off-momentum set-up for 3.5 Z TeV?

Review of LHC systems

- RF (P. Baudrenghien, A. Butterworth)
  - Independent for two rings, OK
  - Decouple radial control
- Transverse Damper (ADT) (D. Valuch, W. Hofle)
  - Independent for two rings, OK
  - Possible variable Q reference should be OK
- Beam instrumentation (R. Jones, E. Giraldo, …)
  - Common BPMs identified as main concern at LMC50 – later slide
  - All other BI independent for two beams
- Orbit and tune feedback – very important
  - Looks OK (J. Wenninger, R. Steinhagen)
    - Q/Q' systems are independent for both beams
    - Orbit feedback does not use common BPMs
    - Need to decouple radial control
    - Check possibility of variable Q reference ?

Collimation

- Settings according to beam, mostly separate
- IR2 vertical tertiary collimators (TCTVs) require special consideration
  - ALICE zero-degree calorimeter (ZDC) shadowing with present location, we have to minimise real crossing angle
  - IR2 modification (see LMC 79) to move (new) TCTVs behind ZDC should be done for 2012 p-Pb run, otherwise may have to request open TCTs L2 (for incoming proton beam, as for Pb beam in 2010-11) – machine protection ?

BPMs (from Eva Calvo Giraldo, Rhodri Jones)

- BPM sensitivities for B1 and B2 are completely independent (no limit of p intensity from this)
- Strip-line monitors can have two types of issues:
  - Both beams cross exactly at the same time
    - Located so cannot happen with 100 ns once the frequencies are cogged.
    - While frequencies separate, both beams will sometimes cross BPM at same time.
      - Then orbit can have errors 5.5 mm (10% bunch intensity ratio, unlikely),
        or ~1 mm (50% bunch intensity ratio, more likely).
  - False triggers: *see next slide …*

BPMs (continued)

- False triggers:
  - possible for bunch intensities close to the high end of each sensitivity mode range (B2 port of monitor sees B1-induced signals), can trigger acquisitions in the wrong channel, degrading orbit precision.
  - Nevertheless with bunch intensities of 1e10 p/bunch and ~6e9 charge/bunch, there will be no false triggers.
- Common BPMs: disabled on the orbit feedback system most of the time.
  - Only used in squeeze.
- Ghost bunches:
  - Simulations showed that they could lead to an error of up to ~120 μm.
- (More detail in notes from E. Giraldo)

Machine Protection (preliminary!)

- Most protection issues dealt with independently in the two rings, either for p or Pb
    - Eg, either beam becomes unstable, losses
- Injection: must avoid trying to inject wrong beam in wrong ring
  - Since SPS is phase-locked, impossible to pass momentum acceptance of transfer lines
  - Protect SPS and transfer lines with software interlocks – detailed scheme being implemented

System	Status	Date for test	Possible issues
BPM	- BPM sensitivities for B1 and B2 are completely independent. - Two independent RF systems used to trigger BPMs		1 . **Both beams cross exactly at the same time in these monitors** ➔Issue only until cogging is done ➔Solution: disable common BPMs until cogging is done 2. **False triggers**: NO with bunch intensities of 1e10 p/bunch (p+)and ~6e9p/bunch (Pb)
RF	RF settings completely independent for each ring		
RF	Rephasing	28.08.2011 (MD3)	Last test in Oct 2010 showed high beam losses during rephasing
Feedback	Fully decoupled radial loop	- p+p+: 05.09.2011 (Start up after TS) - p+Pb: MD4 Nov	
Interlocks for MP	Protect TL&LHC from wrong particle injection	- 28.08.2011 (MD3) - SIS interlock by Jorg in place - Injection line TT10 settings consistent after TS	
Timing: Particle type & Accelerator Mode	-Two telegram words to define the circulating particle type: Proton, Pb82, Ar18, D, Xe54 - Accelerator Mode: PROTON ION PHYSICS	- In place after the September TS	

From R. Alemany

Feasibility test in 2011

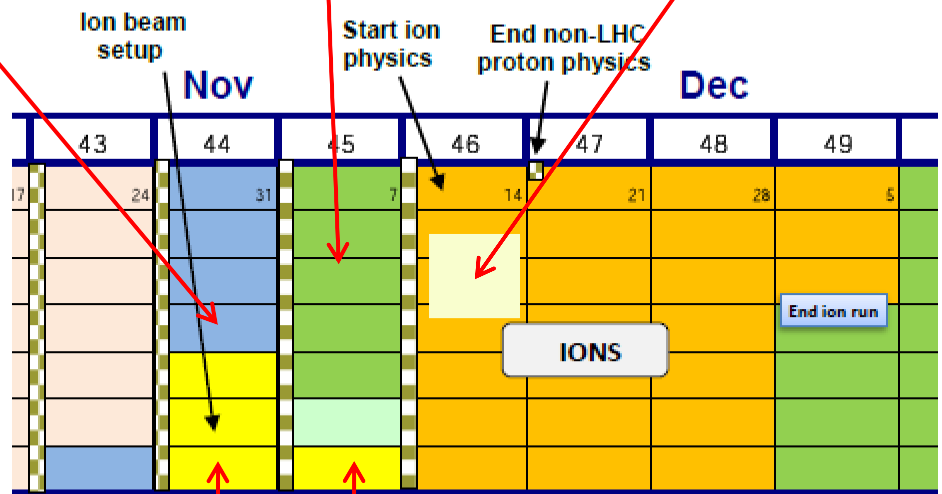
- Goal: clarify main beam dynamics uncertainty
  - Effect of moving long-range encounters, OLKO resonances during injection and ramp
- Proton beam stronger: should be enough to inject and ramp a few Pb bunches with good emittance
- Test first part of operation cycle
  - Inject full proton beam (540 bunches, 10% of Nominal p intensity/bunch)
  - Inject one or a few Pb bunches against it
  - If this works, ramp
  - Dump
    - Possibly do manual re-phasing to make a few collisions unsqueezed
(earlier MD on re-phasing p-p also very relevant)

Schedule in 2011

Set up p beam, Pb injection, test injection of Pb on p (2 shifts designated MD)

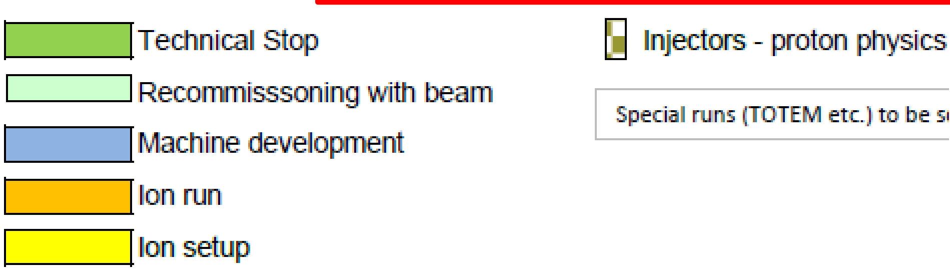
Time to think …

Test ramp of p-Pb, while p still available from injectors



Use of physics time for MD will of course be minimised

Set up Pb beam, ramp, squeeze, crossing angles, collimation in two instalments



Conclusions

- Operational cycle for physics taking shape
- Matching p beam in preparation in injectors
- Check-out of all LHC systems almost complete
  - No showstoppers for p-Pb
- Machine protection, ~OK
- Main uncertainty remains beam dynamics
  - Overlap knock-out resonances very unlikely to be a problem
  - Possible diffusive emittance growth ?
    - Studies advancing …
  - Feasibility test this year crucial
    - Plan carefully, interleaved with Pb-Pb commissioning

BACKUP SLIDES

Transverse Feedback

- 4 independent systems, 1 per plane and per ring
- High bandwidth to act on individual bunches
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  - Damping any coherent oscillations driven by the coherent dipole kicks from moving beam-beam encounters at injection and during ramp

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  - Damping any coherent oscillations driven by the coherent dipole kicks from moving beam-beam encounters at injection and during ramp

Summary of key facts about p-Pb

- Modes of operation of injectors worked out
  - Some concern about 80 MHz cavities in PS
  - Priority protons in Beam 1
- 4 Z TeV gives comparison data for Pb-Pb at full energy
  - Unlikely to be another opportunity to run at this energy
- Important to resolve uncertainties regarding feasibility, Pb intensity limit from unequal revolution frequencies at injection, ramp
  - Modulation of long-range beam-beam, excitation of overlap knock-out resonances, transverse feedback, tune-control …

Testing p-Pb in 2011

- Crucial questions are related to injection and ramping
  - Effects of protons (say 10% of nominal) on one Pb bunch
  - Inject few Pb bunches against some convenient p filling scheme
  - Possible in 2011 (small LLRF upgrade needed to collide, OK in 2012)
  - Detailed planning of MD strategy needs to be done: study and overcome intensity/emittance blow-up

Aside on magnetic compensation

- Compensate using dipole corrector magnets?
  - Even if we could devote all available dipole corrector strength to ramping down (!) the protons before injecting Pb, we could only reduce their energy by ~7.5%, not the ~60% that would fix the problem
- Somebody else can propose a higher energy injector

Nominal Pb-Pb parameters (Design Report)

		Injection	Collision
Beam parameters			
Lead ion energy	[GeV]	36900	574000
Lead ion energy/nucleon	[GeV]	177.4	2759.
Relativistic "gamma" factor		190.5	2963.5
Number of ions per bunch		$7. \times 10^7$	
Number of bunches		592	
Transverse normalized emittance	[μm]	1.4[a]	1.5
Peak RF voltage (400 MHz system)	[MV]	8	16
Synchrotron frequency	[Hz]	63.7	23.0
RF bucket half-height		1.04×10^{-3}	3.56×10^{-4}
Longitudinal emittance (4σ)	[eV s/charge]	0.7	2.5[b]
RF bucket filling factor		0.472	0.316
RMS bunch length[c]	[cm]	9.97	7.94
Circulating beam current	[mA]	6.12	
Stored energy per beam	[MJ]	0.245	3.81
Twiss function $\beta_x = \beta_y = \beta^*$ at IP2	[m]	10.0	0.5
RMS beam size at IP2	μm	280.6	15.9
Geometric luminosity reduction factor F[d]		-	1
Peak luminosity at IP2	[$cm^{-2}sec^{-1}$]	-	$1. \times 10^{27}$

Nominal scheme, lifetime parameters (Design Report)

2 experiments

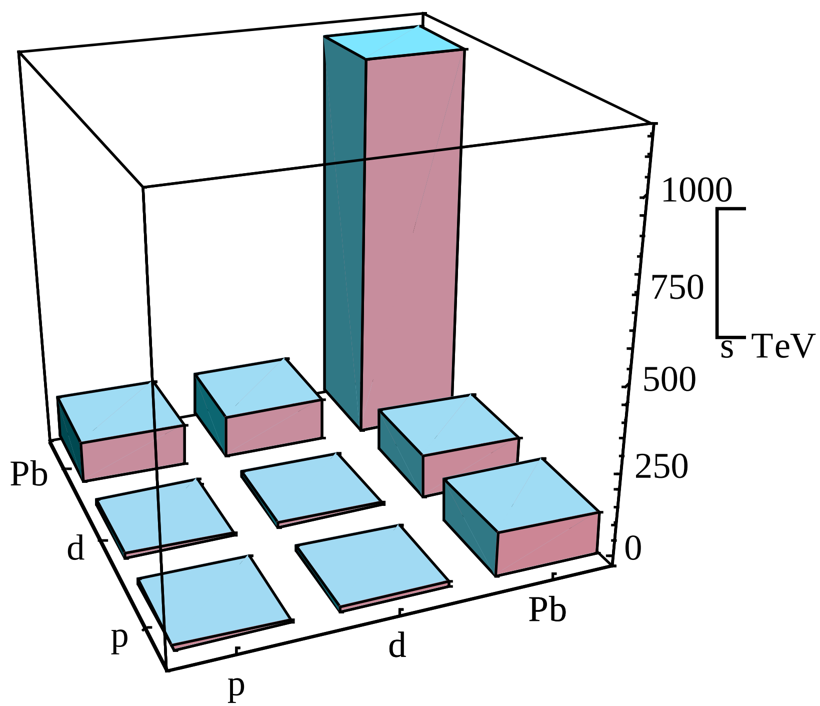
		Injection	Collision
Interaction data			
Total cross section	[mb]	-	514000
Beam current lifetime (due to beam-beam)[a]	[h]	-	11.2
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	$[10^{-4}]$	3.9	1.10
RMS bunch length	[cm]	9.97	7.94
Longitudinal emittance growth time	[hour]	3	7.7
Horizontal emittance growth time[b]	[hour]	6.5	13
Synchrotron Radiation			
Power loss per ion	[W]	3.5×10^{-14}	2.0×10^{-9}
Power loss per metre in main bends	$[\mathrm{Wm}^{-1}]$	8×10^{-8}	0.005
Synchrotron radiation power per ring	[W]	1.4×10^{-3}	83.9
Energy loss per ion per turn	[eV]	19.2	1.12×10^{6}
Critical photon energy	[eV]	7.3×10^{-4}	2.77
Longitudinal emittance damping time	[hour]	23749	6.3
Transverse emittance damping time	[hour]	47498	12.6
Variation of longitudinal damping partition number[c]		230	230
Initial beam and luminosity lifetimes			
Beam current lifetime (due to residual gas scattering)[d]	[hour]	?	?
Beam current lifetime (beam-beam, residual gas)	[hour]	-	< 11.2
Luminosity lifetime[e]	[hour]	-	< 5.6

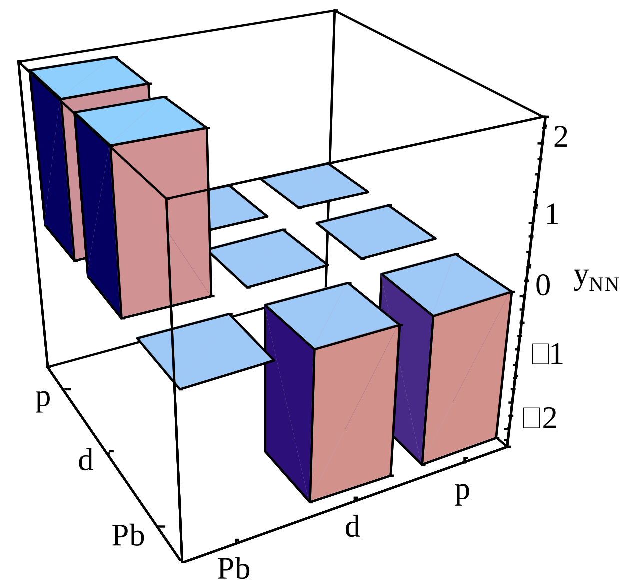
Centre-of-mass in collisions

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

$$\sqrt{s} \approx 2c\, p_p \sqrt{Z_1 Z_2},$$

$$\frac{v_{\mathrm{CM}}}{c} \approx \frac{Z_1 - Z_2}{Z_1 + Z_2}, \quad y = \frac{1}{2} \log \frac{Z_1}{Z_2}$$

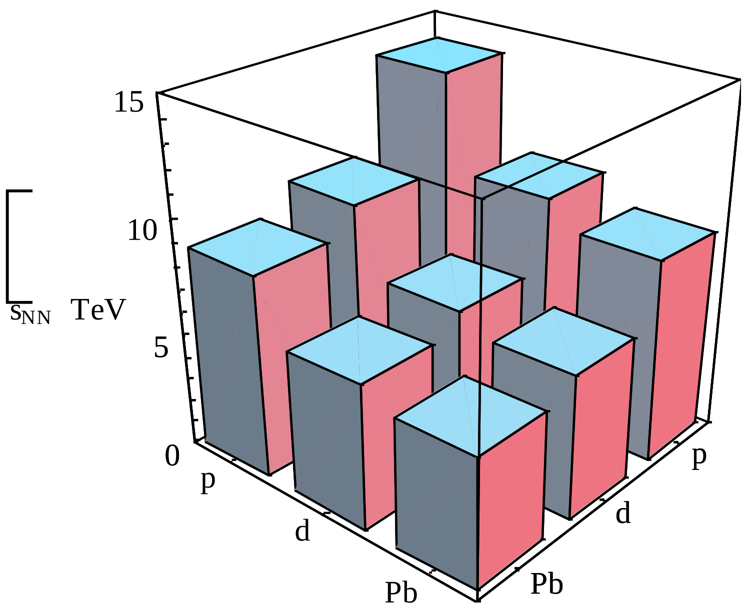


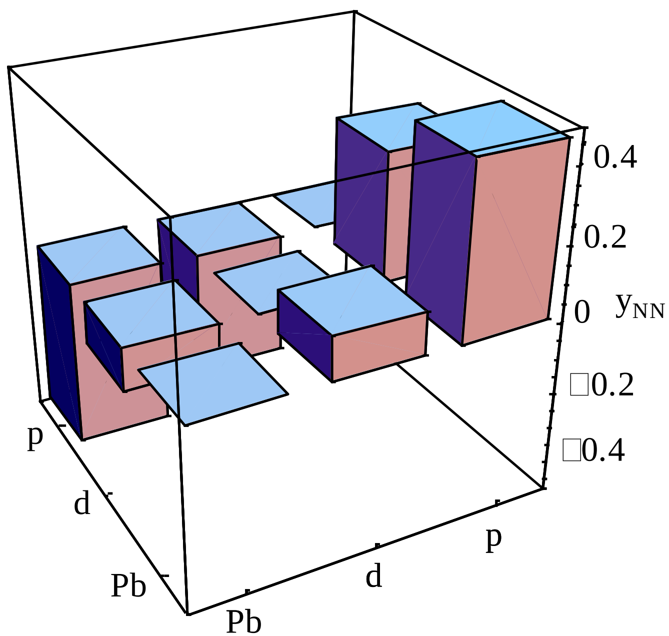


Kinematics of colliding nucleon pairs

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

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





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

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