Accelerator (collider) conditions in the near future

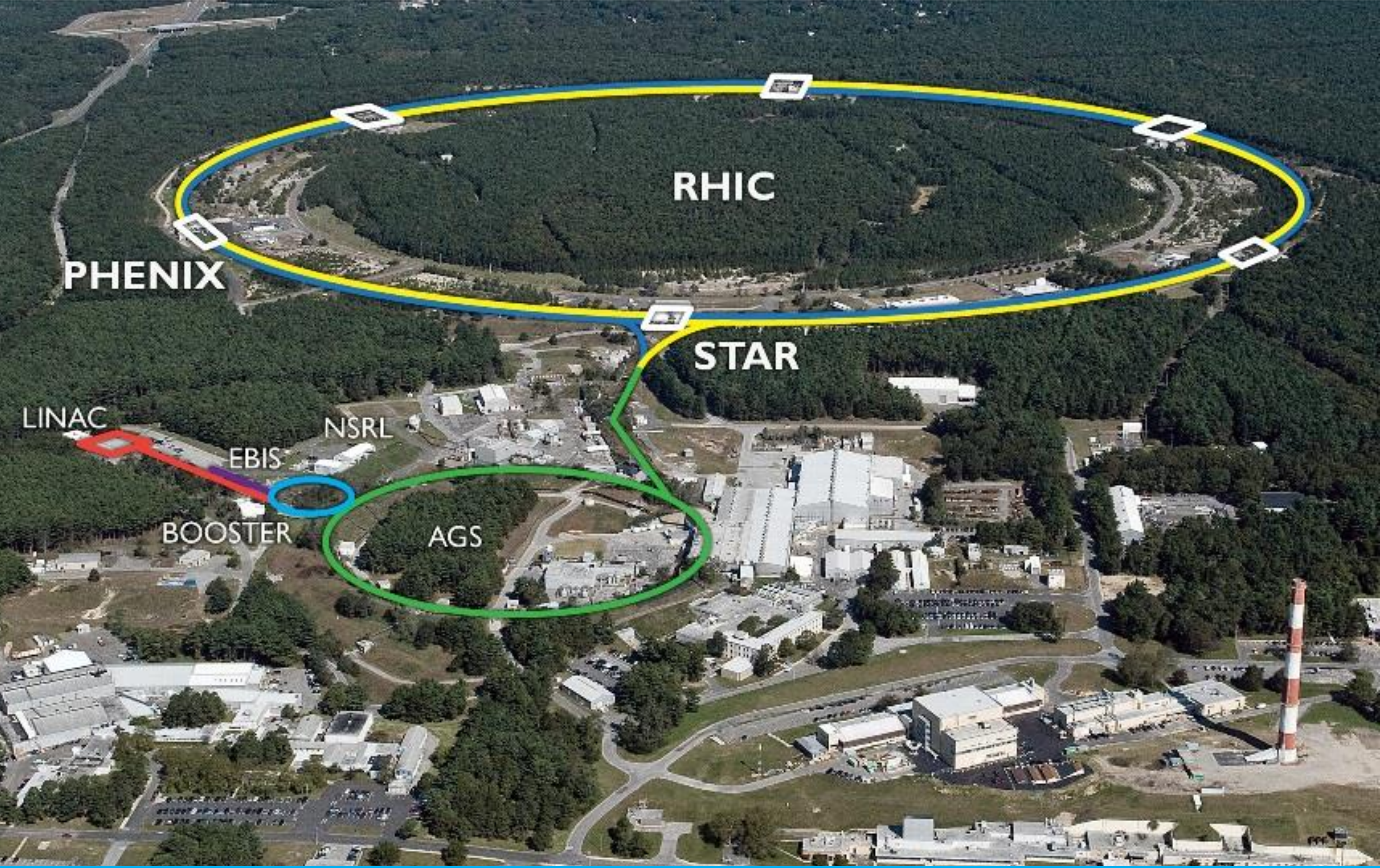
John Jowett

Special thanks to Wolfram Fischer for material on RHIC.

Thanks to Michaela Schaumann, Reyes Alemany-Fernandez and many other colleagues at CERN.

Plan of talk

- RHIC (heavy-ion program only)
  - RHIC achievements to date
  - Plans for the coming years
- LHC (heavy-ion programme only)
  - Where we are: Run 1 and Run 2 so far
  - Plan for p-Pb in 2016
  - Brief look at near future beyond LS2



RHIC

Slides from W. Fischer

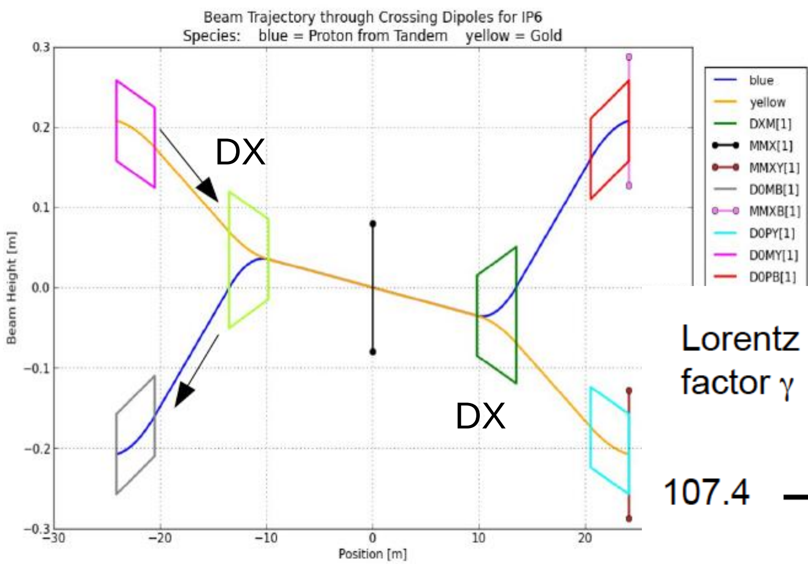
Run-15 p↑+Au/Al at 100 GeV

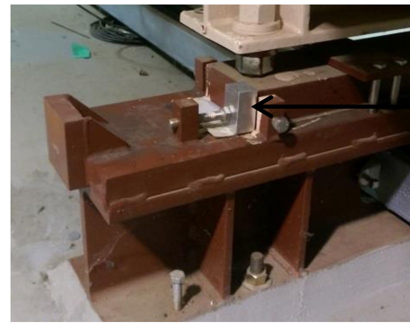
DX and ramp

Run Coordinator: Chuyu Liu

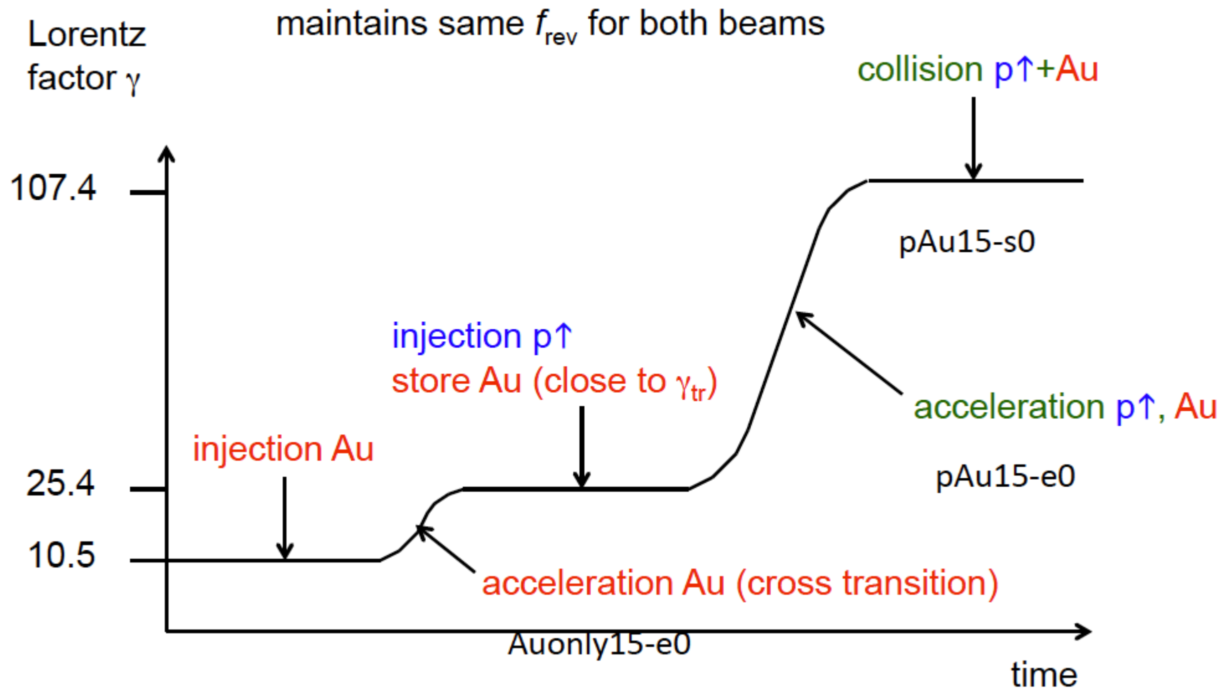
First operating mode that required moving DX magnets

~2 cm, IR2/4 before run start, all other IRs during run after p↑+p↑





spacer block for DX move



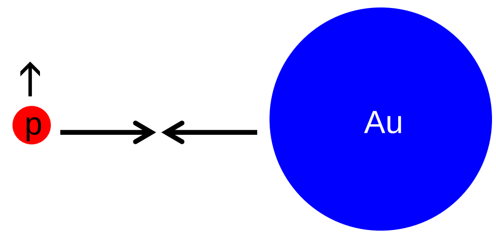
protons injected after Au beam accelerated to intermediate energy

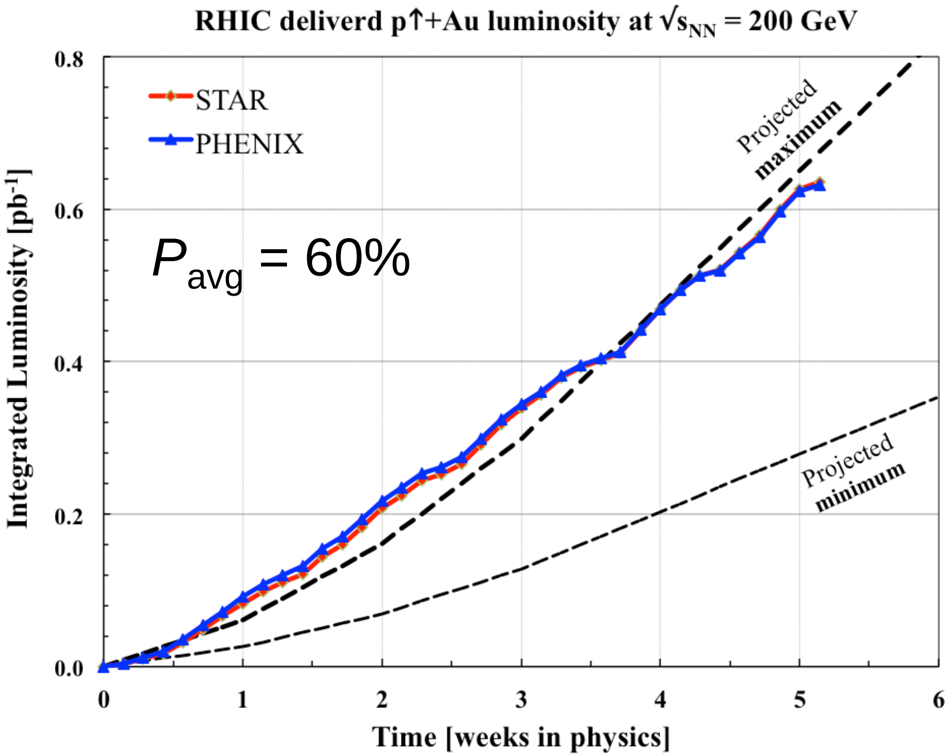
requires ramping AGS cold snake between injections

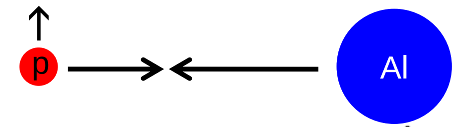
Run-15 p↑+Au/Al 100 GeV luminosity and polarization

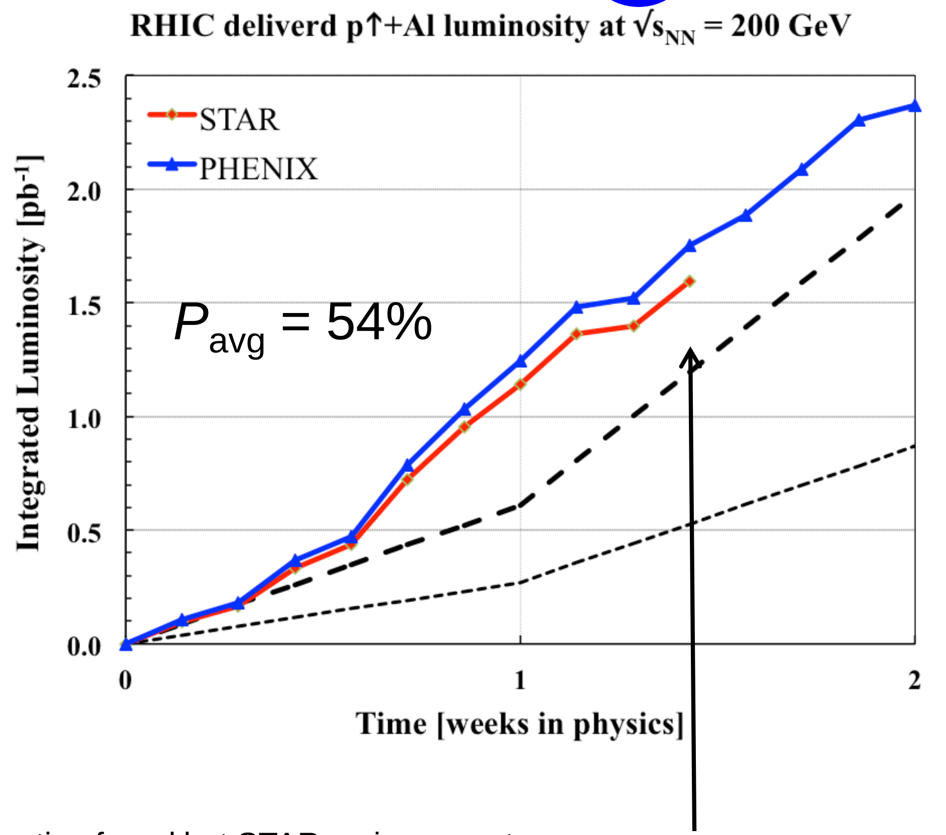
Run Coordinator: Chuyu Liu

2 new (asymmetric) operating modes – met or exceeded luminosity goals





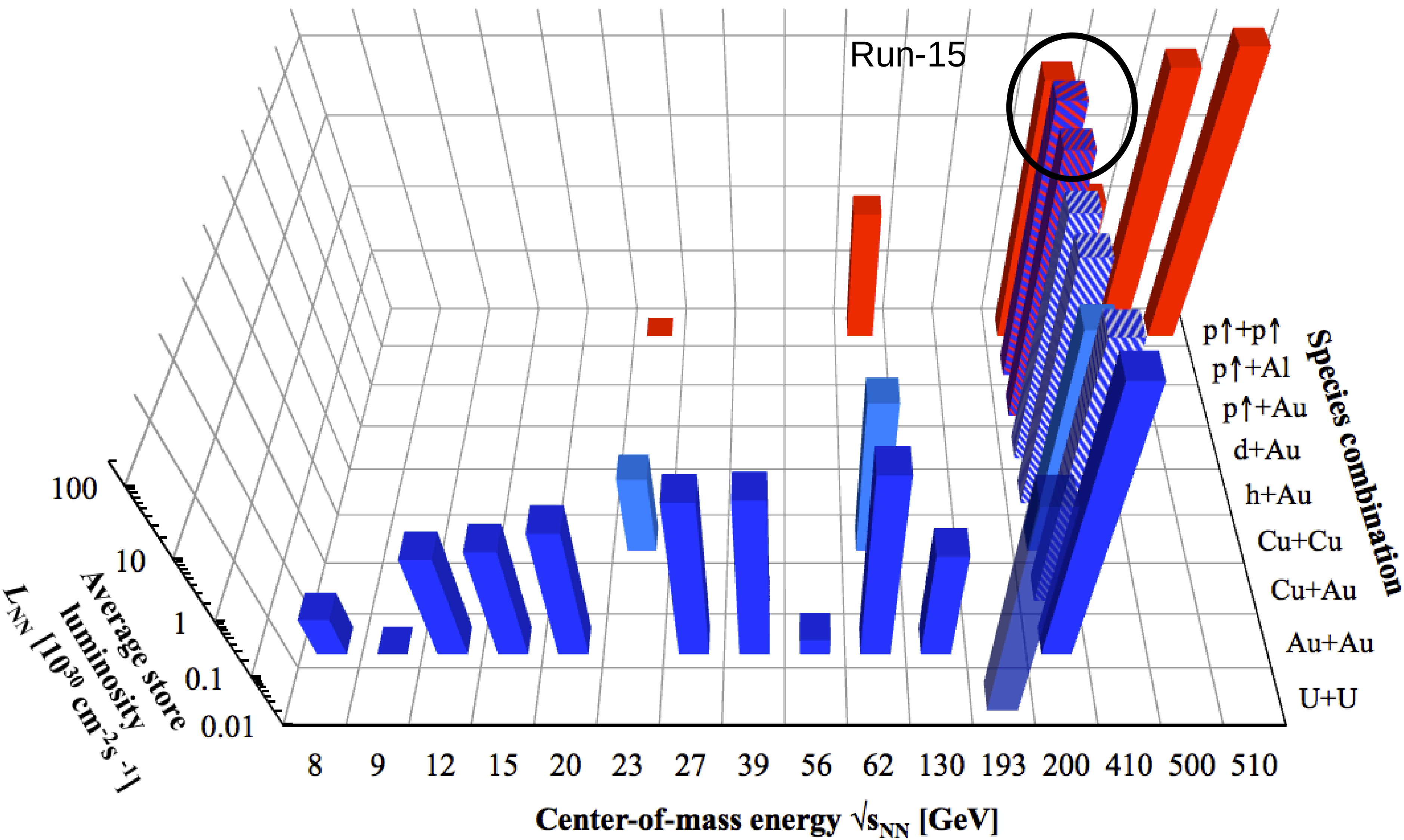




Inspection found hot STAR main magnet transformer that needed replacement insufficient time for completion before run end

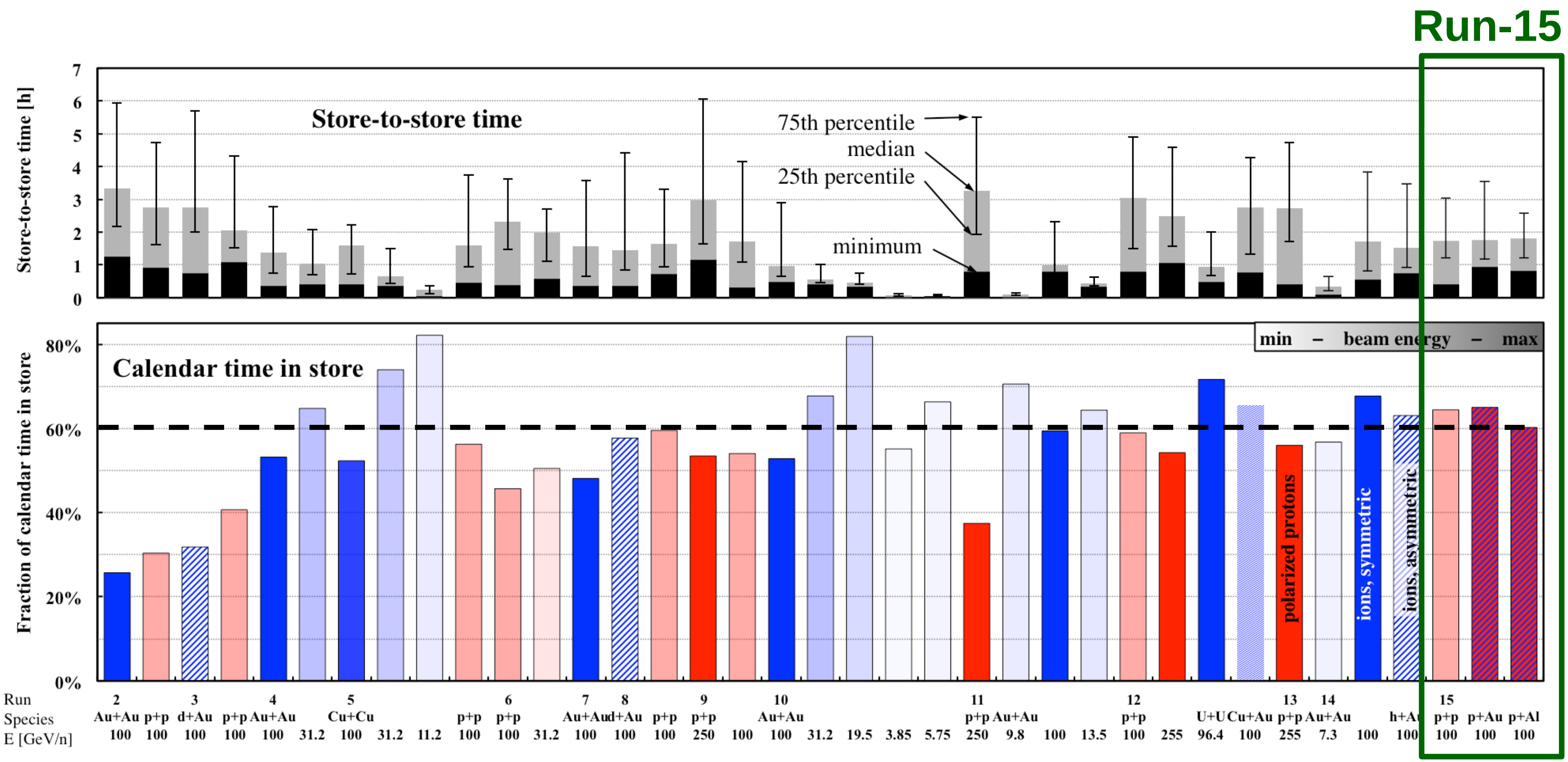
RHIC – all running modes to date

Run-1 to Run-15



Operational efficiency

store-to-store, time in store



Time in store = store time / calendar time

(denominator includes scheduled maintenance, failure, setup, beam experiments)

Time in store goal: 60%

TRANSPARENT: low energy

SOLID: high energy

BLUE: heavy ion runs

RED: polarized proton runs

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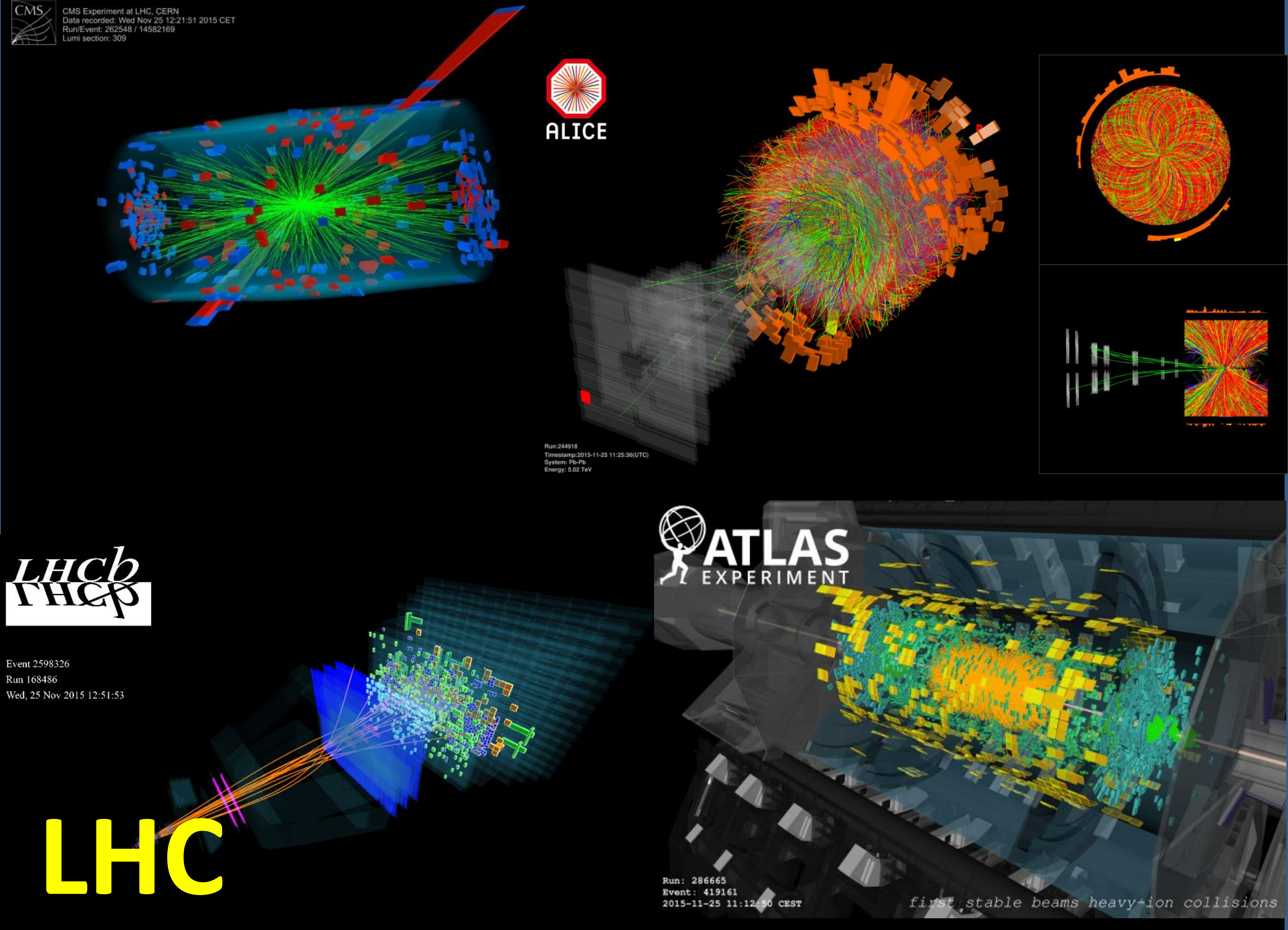
RHIC executed and proposed run plan

Years	Beam Species and energies	Science Goals	New Systems
2014	Au+Au at 15 GeV Au+Au at 200 GeV ^{3}He+Au at 200 GeV	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p↑+p↑ at 200 GeV p↑+Au, p↑+Al at 200 GeV High statistics Au+Au d(p)+Au energy scan	Extract η/s(T) + constrain initial quantum fluctuations Complete heavy flavor studies Sphaleron tests Parton saturation tests	PHENIX MPC-EX STAR FMS preshower Roman Pots Coherent e-cooling test
2017	p↑+p↑ at 510 GeV Ru+Ru vs. Zr+Zr (A=96)	Transverse spin physics Sign change in Sivers function Isobar test of chiral magnetic e	
2018	No Run		Low energy e-cooling install. STAR iTPC upgrade?
2019-20	Au+Au at 5-20 GeV (BES-2)	Search for QCD critical point and onset of deconfinement	Low energy e-cooling iTPC Event plane detector
2021-22	Au+Au at 200 GeV p↑+p↑, p↑+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mech Color screening for different qu Forward spin & initial state physics	
≥ 2023 ?	No Runs		Transition to eRHIC

Now

↓ STAR only

↓ STAR + sPHENIX


CMS Experiment at LHC, CERN
Data recorded: Wed Nov 25 12:21:51 2015 CET
Run/Event: 262548 / 14582169
Lumi section: 309
ALICE
Run:244918
Timestamp:2015-11-25 11:25:36(UTC)
System: Pb-Pb
Energy: 5.02 TeV
LHCb
Event 2598326
Run 168486
Wed, 25 Nov 2015 12:51:53
ATLAS EXPERIMENT
Run: 286665
Event: 419161
2015-11-25 11:12:50 CEST
first stable beams heavy-ion collisions
LHC

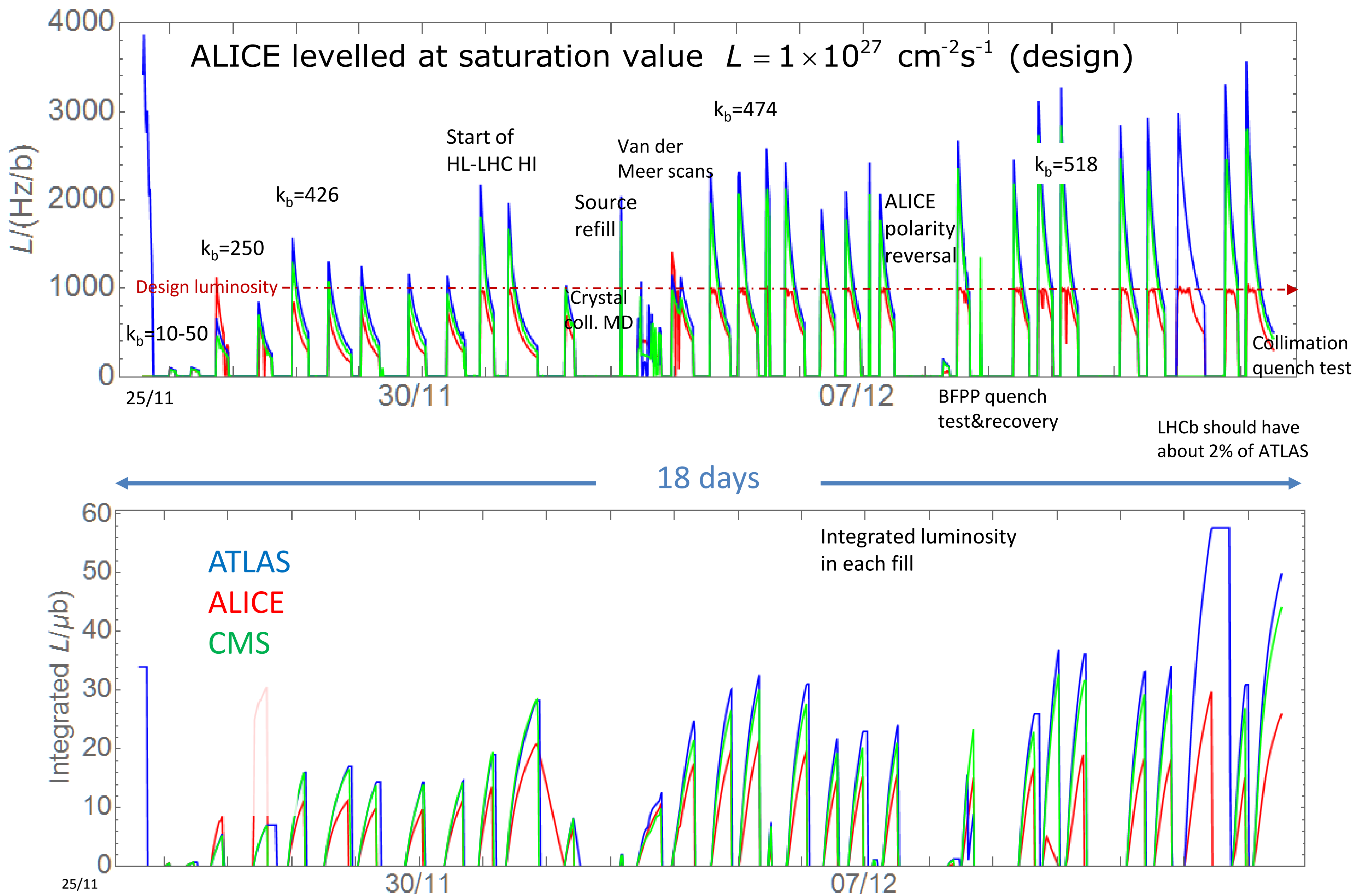
Recently: 3 runs at equivalent energy

- Experiments wanted to compare 3 combinations of colliding species at same centre-of-mass energy per colliding nucleon pair:

$$\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV with } \begin{cases} \text{p-p} & E = 2.51 \quad \text{TeV} & \text{Nov 2015} \\ \text{p-Pb} & E = 4Z \quad \text{TeV} & \text{Jan-Feb 2013} \\ \text{Pb-Pb} & E = 6.37Z \quad \text{TeV} & \text{Nov-Dec 2015} \end{cases}$$

- Two new LHC configurations to be commissioned and put into production within one month run in Nov-Dec 2015
  - Very complicated first 10 days, switching back and forth between p-p and Pb-Pb optics and species
  - Further interruptions for special MDs, ion source refill, van der Meer scans, ALICE polarity reversal, …

Luminosity since start of Stable Beams 10:59 25/11/2015



Integrated nucleon-nucleon luminosity in Run 1 + 2015

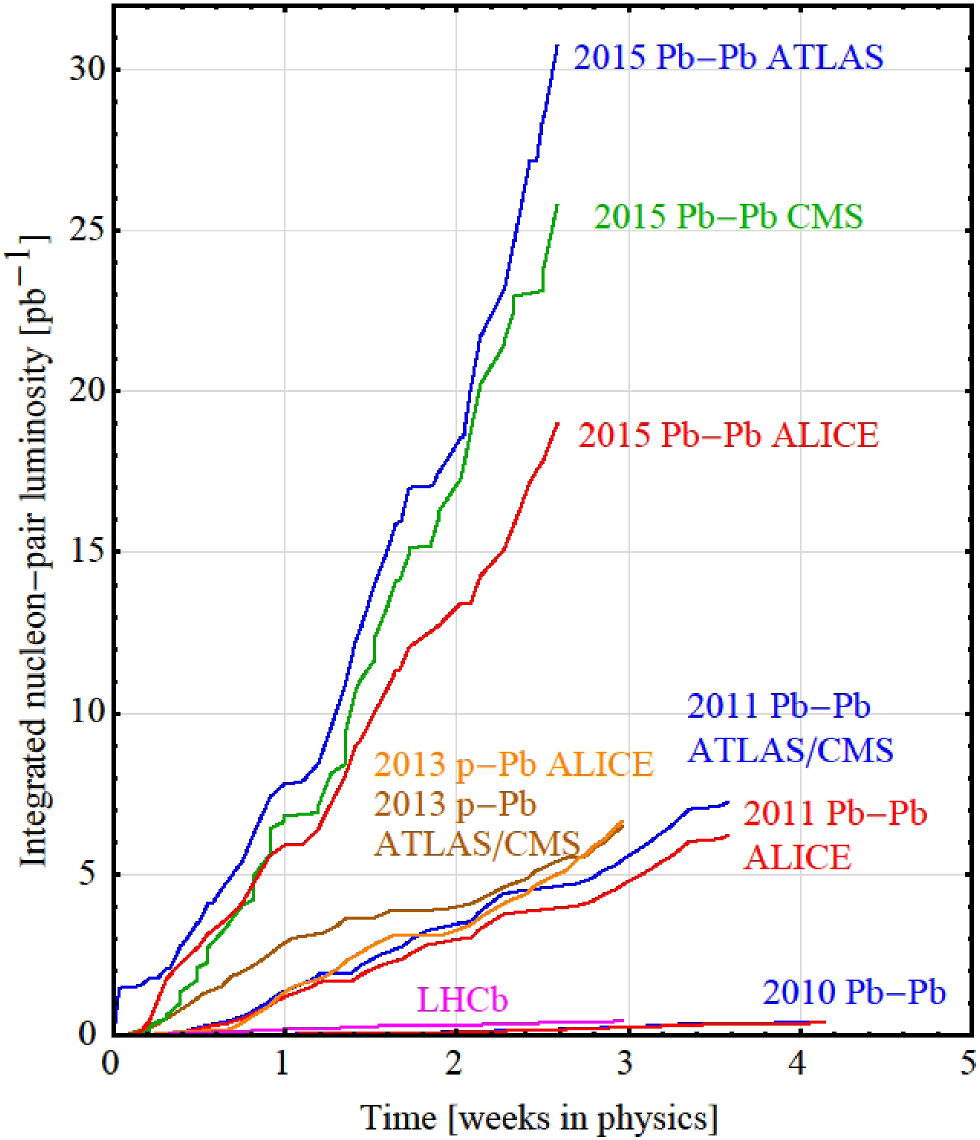
Expect to achieve LHC “first 10-year” baseline Pb-Pb luminosity goal of
1 AA nb^{-1} = 43 NN pb^{-1}
in Run 2 (=2015+2018)

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

$$\sqrt{s_{NN}} = 5.02 \text{ TeV}$$

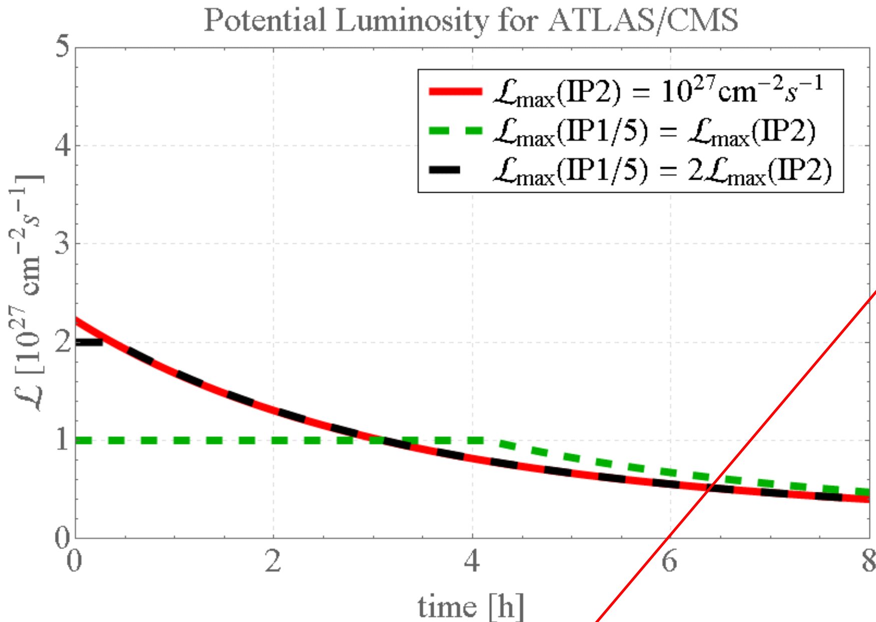
$$\Rightarrow E_b = \begin{cases} 6.37Z \text{ TeV} & \text{in Pb-Pb} \\ 4\ Z \text{ TeV} & \text{in p-Pb} \end{cases}$$

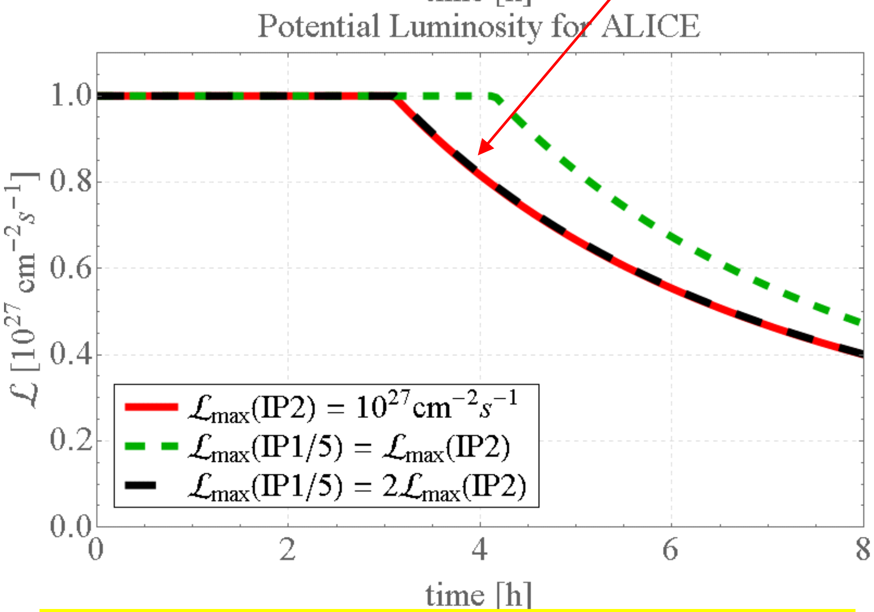
But annual 1-month runs are getting shorter and more complicated … 2015 included p-p reference data and included LHCb.



2012 pilot p-Pb run not shown (1 fill but major physics output)

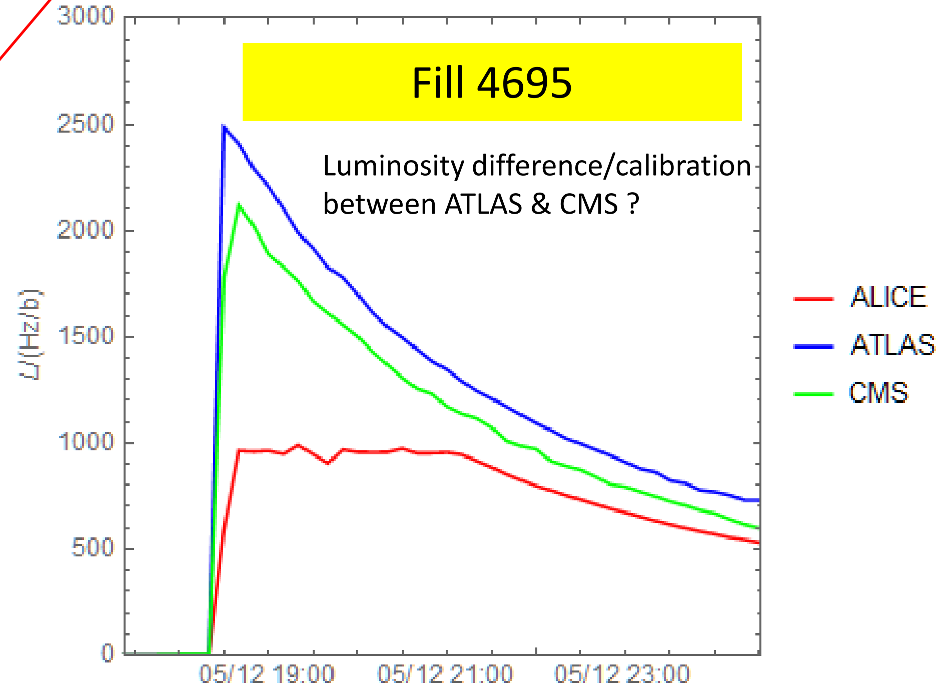
Luminosity evolution: prediction vs reality





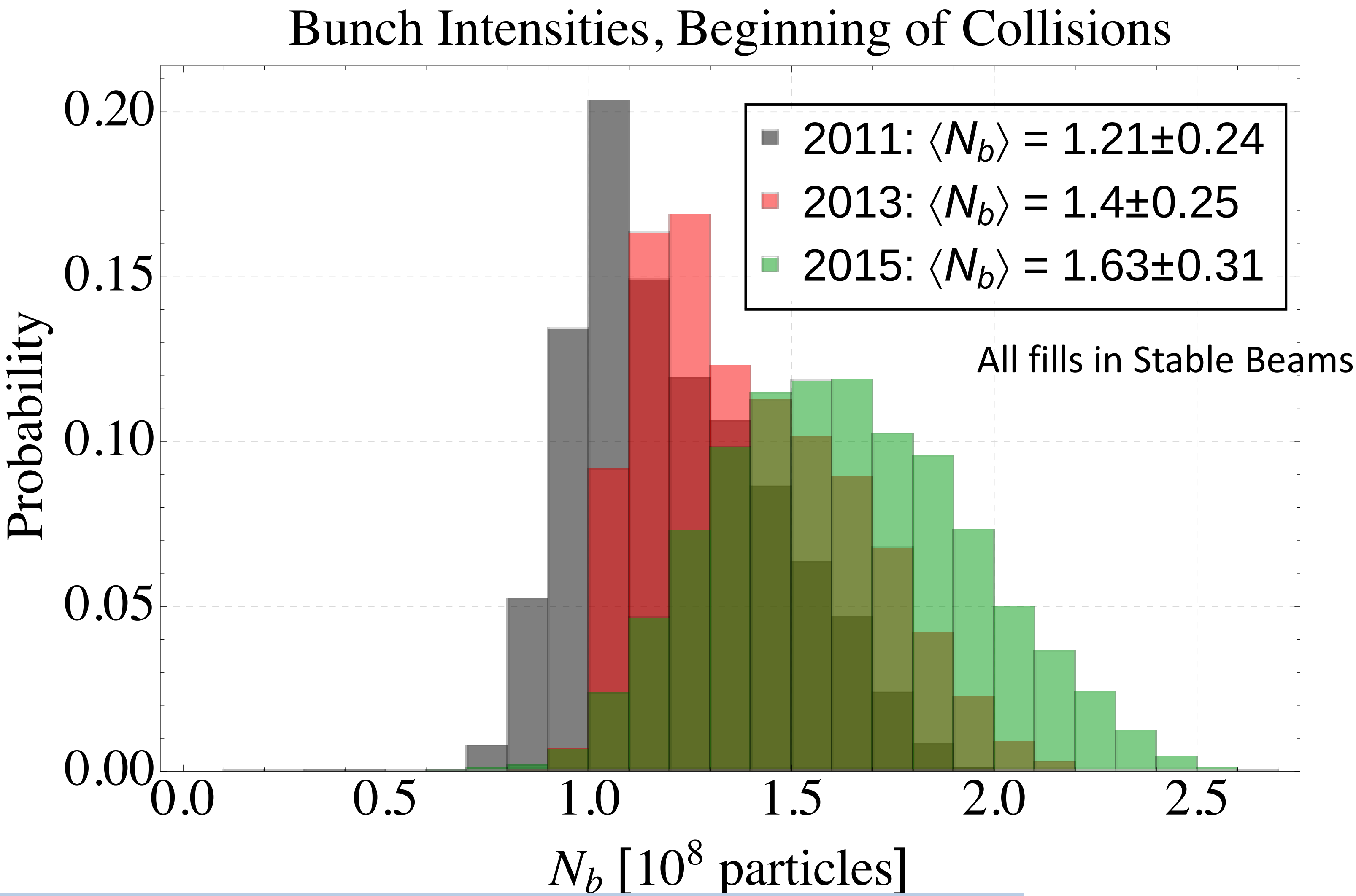
Simulation without LHCb (Michaela Schaumann)

Levelling scenario used is the red line (ALICE only)



CTE simulation (burn-off, radiation damping, IBS, debunching from RF bucket, crossing angles, etc) for individual bunches,
One ingredient of HL-LHC predictions.

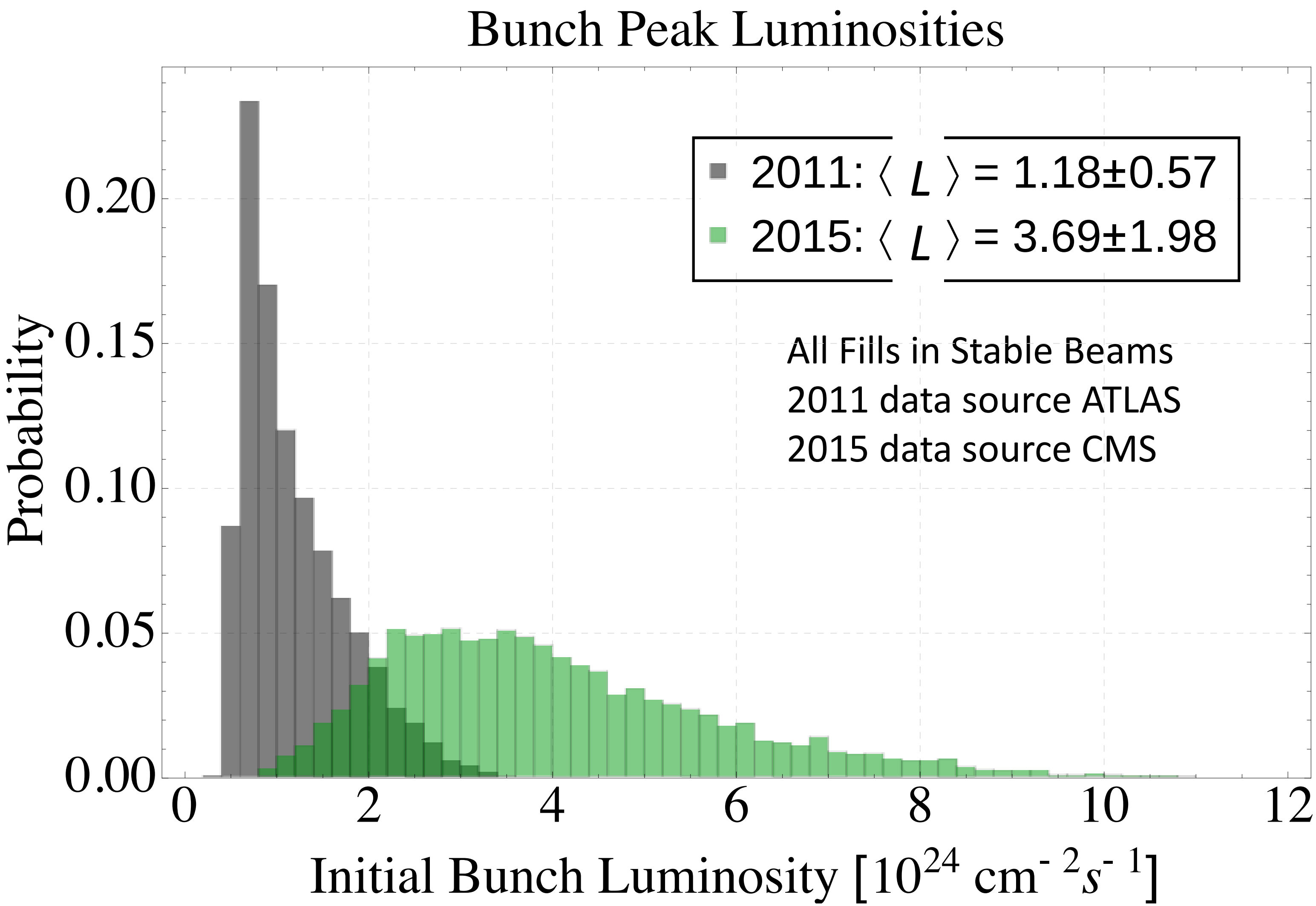
Bunch intensities at the beginning of Stable Beams



Heavy-ion runs are complex – many bunch evolution histories in a single pair of beams. Pb-Pb and, even more so, p-Pb.

Michaela Schaumann

Bunch pair luminosity distribution



Michaela Schaumann

Ultraperipheral processes affecting collider performance

BFPP: $^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + e^{+}$,
$\sigma = 281\ \mathrm{b}, \quad \delta = 0.01235$

EMD1: $^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{207}\mathrm{Pb}^{82+} + n$,
$\sigma = 96\ \mathrm{b}, \quad \delta = -0.00485$

EMD2: $^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{206}\mathrm{Pb}^{82+} + 2n$,
$\sigma = 29\ \mathrm{b}, \quad \delta = -0.00970$

Strong luminosity burn-off of beam intensity.

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

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

Discussed for LHC since Chamonix 2003 … see several references.

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

Electromagnetic Dissociation in Primary Collimator

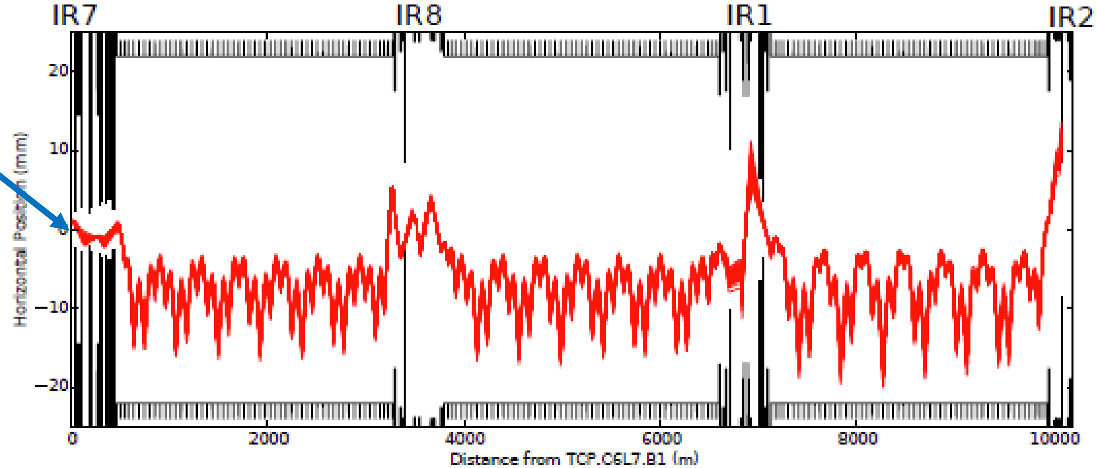
IR2 losses : understanding and mitigations (2015)

- STIER : what ions are causing the TCT loss in IR2 ?

Isotope (A,Z)	TCP jaw	Fraction (%)
(207,82)	**left**	**92.5**
(204,81)	right	3.6
(202,80)	left	2.2
(199,79)	right	0.3

Primary collimator (TCP) in IR7, outer jaw

$$^{208}Pb^{82+} + {}^{12}C \xrightarrow[\gamma]{} {}^{207}Pb^{82+} + n + {}^{12}C$$

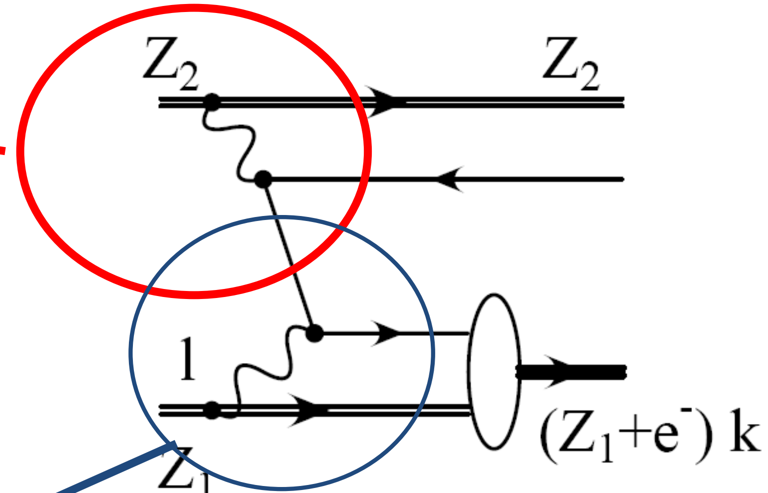


Pascal D. Hermes, CERN, University of Münster

Simulation Tools for Heavy-Ion Collimation

Pascal Hermes

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



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

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

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

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

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

$$Z_1 + Z_2 \to \left(Z_1 + \mathrm{e}^-\right)_{1s_{1/2},\ldots} + \mathrm{e}^+ + Z_2$$

has very strong dependence on ion charges (and energy)

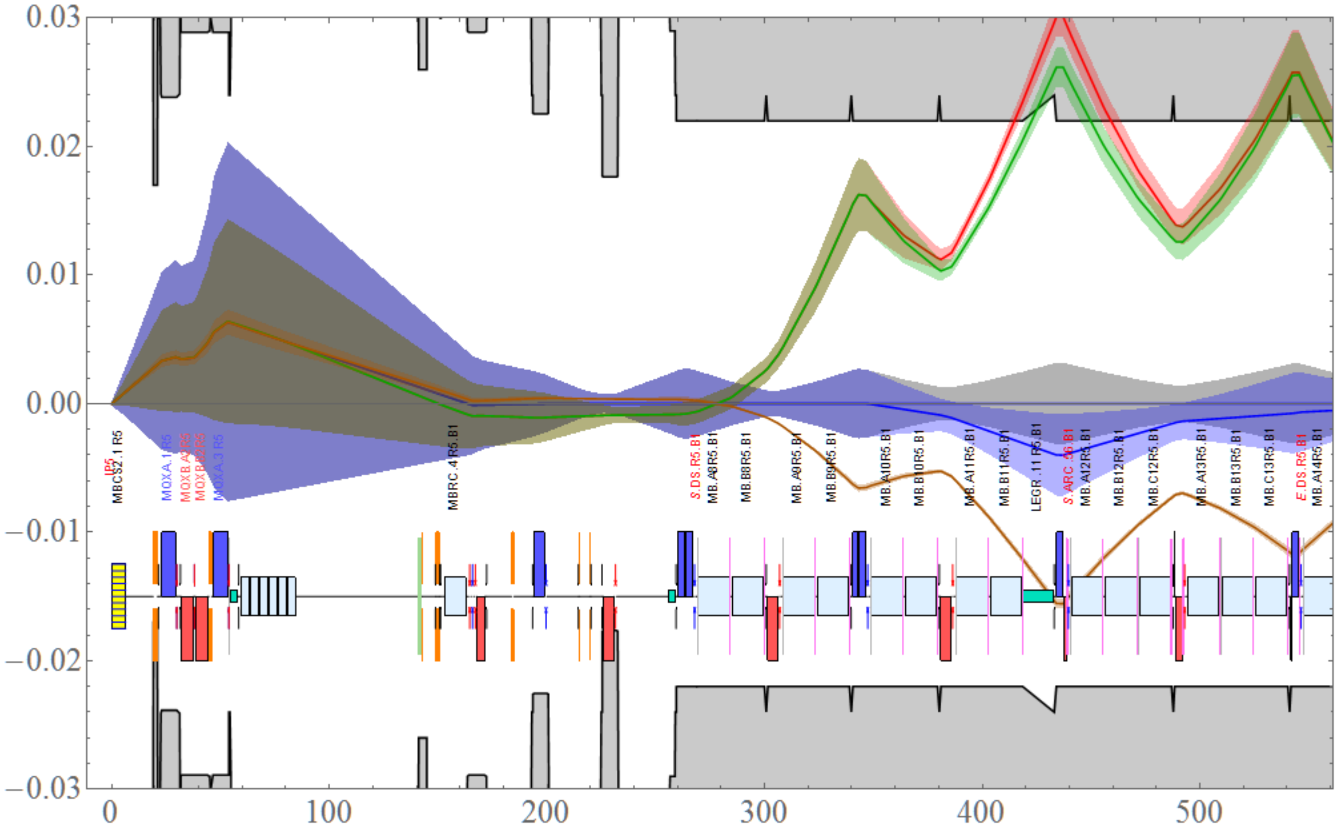
$$\sigma_{\mathrm{PP}} \propto Z_1^{\ 5} Z_2^{\ 2} \left[A \log \gamma_{CM} + B\right]$$

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

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

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

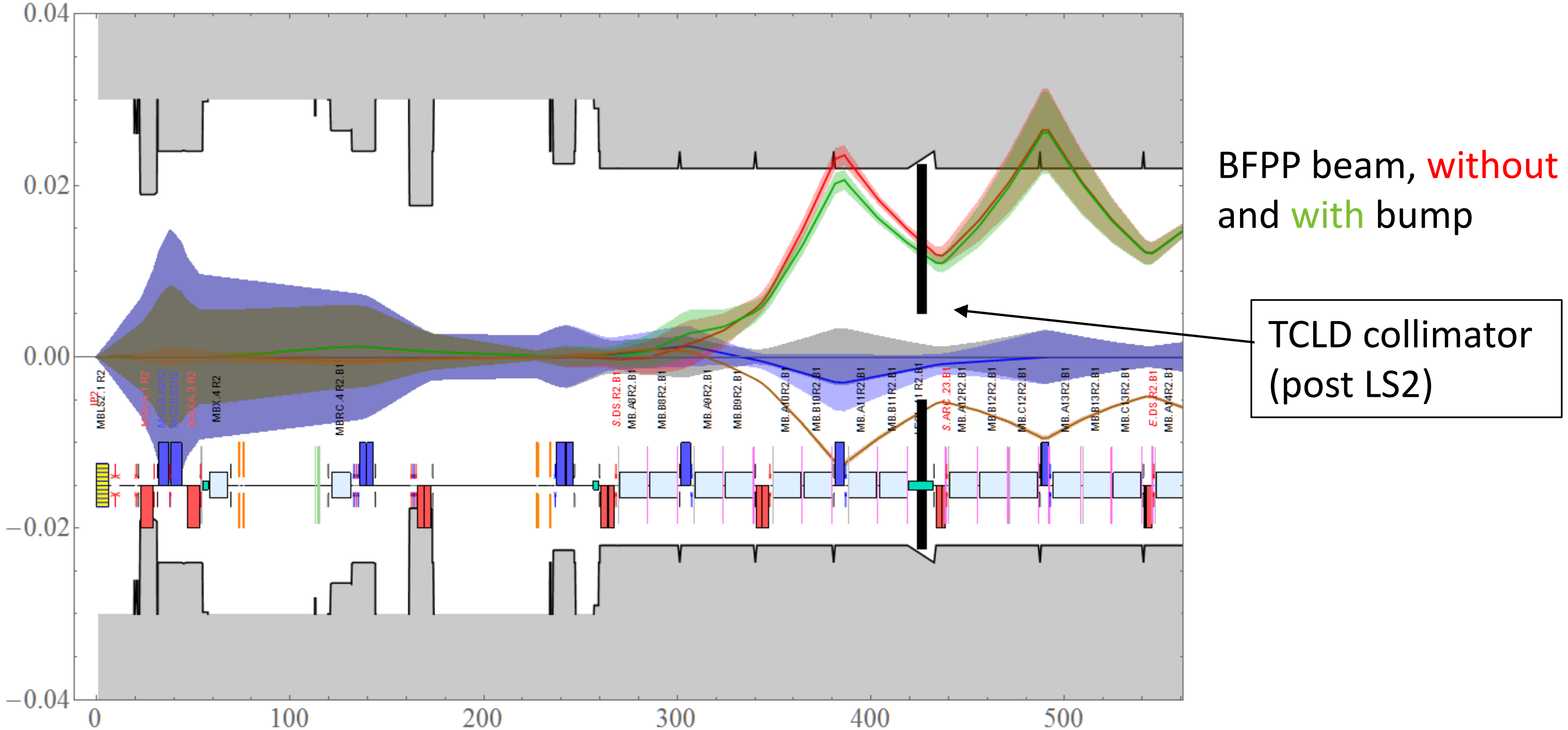
Orbit bumps mitigate BFPP for CMS (or ATLAS)



BFPP beam, without and with bump

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

Orbit bumps alone are not effective for ALICE



- IR2 has different quadrupole polarity and dispersion from IR1/IR5
- Primary BFPP loss location is further upstream from connection cryostat
- Solution is to modify connection cryostat to include a collimator to absorb the BFPP beam –**design is being launched now to be ready for LS2 installation**
- With levelled luminosity in ALICE, quenches were not seen in Run 2

Tests of strategy during 2015 Pb-Pb run

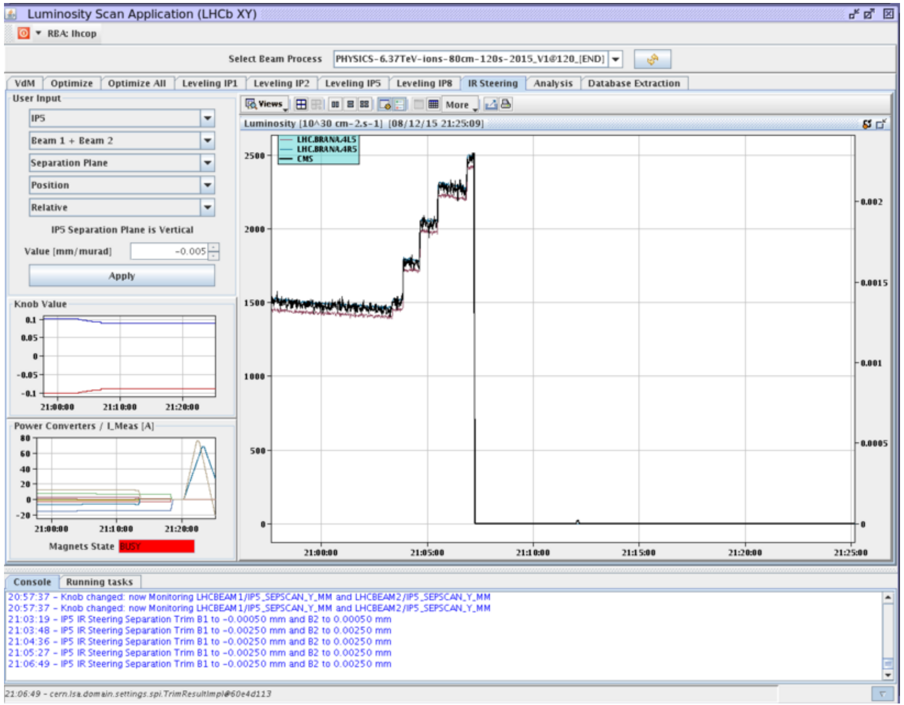
- For safety, mitigation bumps were implemented at 3 mm amplitude in validated physics setup
  - Expected to move losses around ATLAS/CMS into connection cryostat
    - Not quite true on left of IP5 – luminosity losses at start of later fills came close to (raised) BLM dump thresholds
  - Moved losses beyond connection cryostat in IR2
    - Levelled luminosity not expected to be a concern
- MD study around IP5 would attempt to quench by manipulating bump to move losses back into connection cryostat in controlled way
  - Based on latest estimates of steady state quench level, we did not expect a quench … but we tried anyway.
  - An extremely clean measurement of LHC dipole quench limit

BFPP Quench MD – first luminosity quench in LHC

- BLM thresholds in BFPP loss region raised by factor 10 for one fill 8/12/2015 evening.
- Prepared as for physics fill, separated beams to achieve moderate luminosity in IP5 only.
- Changed amplitude of BFPP mitigation bump from -3 mm to +0.5 mm to bring loss point well within body of dipole magnet (it started just outside).
- Put IP5 back into collision in 5 μm steps.
- Unexpectedly quenched at luminosity value (CMS):

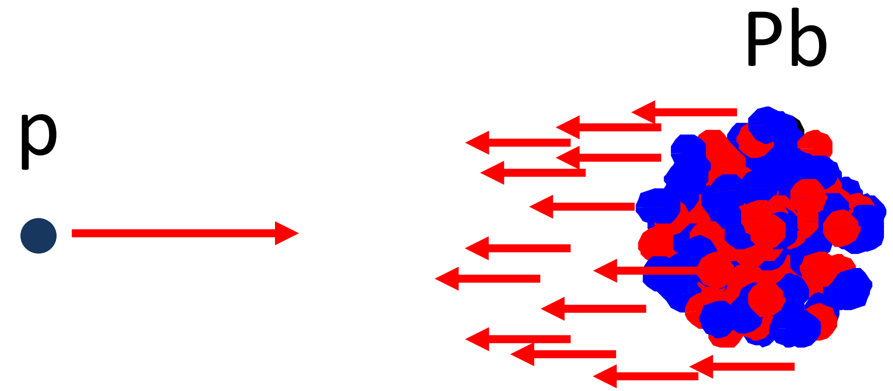
$$L \approx 2.3 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Rightarrow \quad 0.64\ \text{MHz event rate, about 45 W of power in Pb}^{81+}\ \text{beam into magnet}$$



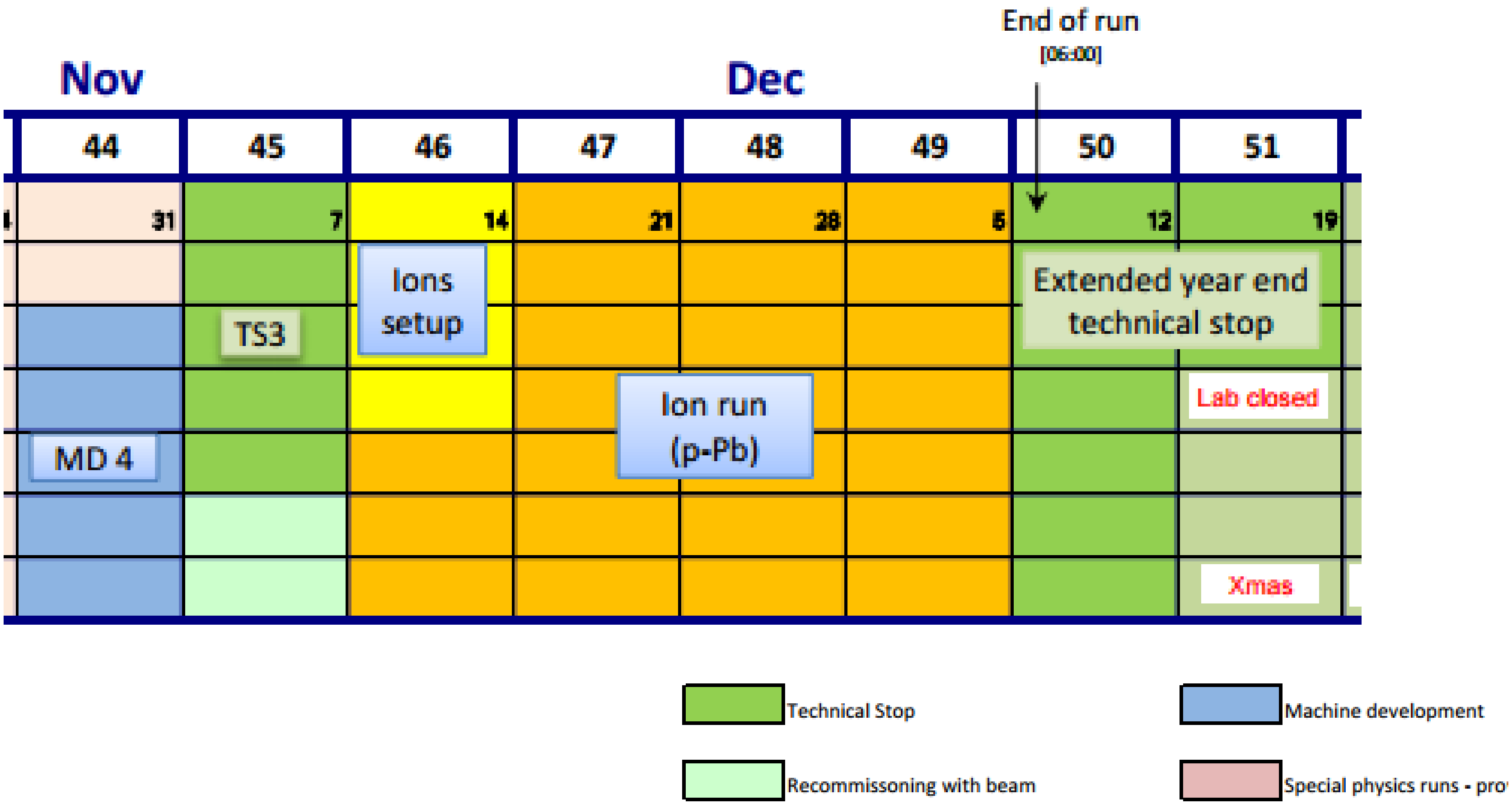
Consequences of the BFPP quench result

- Strong-field QED (!) resolves long-standing (since mid-1990s) uncertainty on steady state quench limit of LHC superconducting magnets and BFPP luminosity limit
  - Factor 2-3 lower than recent expectations from magnet studies
  - Main errors BFPP cross section, luminosity
- Efficacy of BFPP bumps clear – we already needed them in 2015 to avoid luminosity quenches around ATLAS and CMS!
  - FLUKA analysis confirms this is still OK for further increase in luminosity.
  - Radiation effects and heat load may still be issues.
- Closes the case for collimators in the LHC dispersion suppressors around ALICE (where the bump mitigation alone does not work), discussed since Chamonix 2003 …
- The design work for integration of TCLD collimators in the connection cryostats starting now so that they can be installed during LS2.
- Similar collimators with first 11 T dipoles needed for Pb collimation losses in IR7



2016 PROTON-LEAD PLANS

LHC schedule at end of 2016



Reminder of p-Pb run in 2013

- LHCC 13/3/2013 http://indico.cern.ch/event/239117/session/1/contribution/14
- Almost unprecedented mode of collider operation:
  - Injection and ramp with unequal revolution frequencies, resynch and cogging at flat-top (~impossible at RHIC 2003, re-confirmed 2015)
  - Complex filling scheme: p and Pb had to match up, led to 200/225 ns alternating bunch spacing, 338 bunches/beam
  - Off-momentum squeeze ⇒ β*=0.8 m from aperture limit around ALICE (took same for ATLAS/CMS)
  - ALICE levelling briefly at $L \approx 1 \times 10^{29}$ $cm^{-2}s^{-1}$
  - Proton bunch intensity equivalent to 1/β* (but limited by BPMs), integrated luminosity of a fill ~proportional to Pb intensity.
  - Lowest β*=2 m ever for LHCb
  - Beam reversal *and* solenoid polarity reversal
  - Catch-up fills to equalise final integrated luminosity for ALICE
  - p-p reference done in extra time, after final whistle of Run 1

ALICE: 31.94 nb^{-1} ATLAS: 31.2 nb^{-1} CMS: 31.69 nb^{-1} LHCb: 2.12 nb^{-1}

Reminder of 2013 p-Pb run – in view of 2016

Monday	7	January
Tuesday	8	January
Wednesday	9	January
Thursday	10	January
Friday	11	January
Saturday	12	January
Sunday	13	January
Monday	14	January
Tuesday	15	January
Wednesday	16	January
Thursday	17	January
Friday	18	January
Saturday	19	January
Sunday	20	January
Monday	21	January
Tuesday	22	January
Wednesday	23	January
Thursday	24	January
Friday	25	January
Saturday	26	January
Sunday	27	January
Monday	28	January
Tuesday	29	January
Wednesday	30	January
Thursday	31	January
Friday	1	February
Saturday	2	February
Sunday	3	February
Monday	4	February
Tuesday	5	February
Wednesday	6	February
Thursday	7	February
Friday	8	February
Saturday	9	February
Sunday	10	February

→ Restart complex after Christmas stop

>4 days lost to cryo, power failures

→ First injection in the LHC

→ Injection checks and Squeeze commissioning

5 TeV set-up simpler – 3 days

→ Collimation set up, IR2 ape … ions

8 TeV set-up, another 4 days

→ First Stable beams, first injection of trains of p and Pb

→ End of ALICE minimum bias data taking

→ ALICE polarity change

→ Van der Meer scans

→ Pb source refill

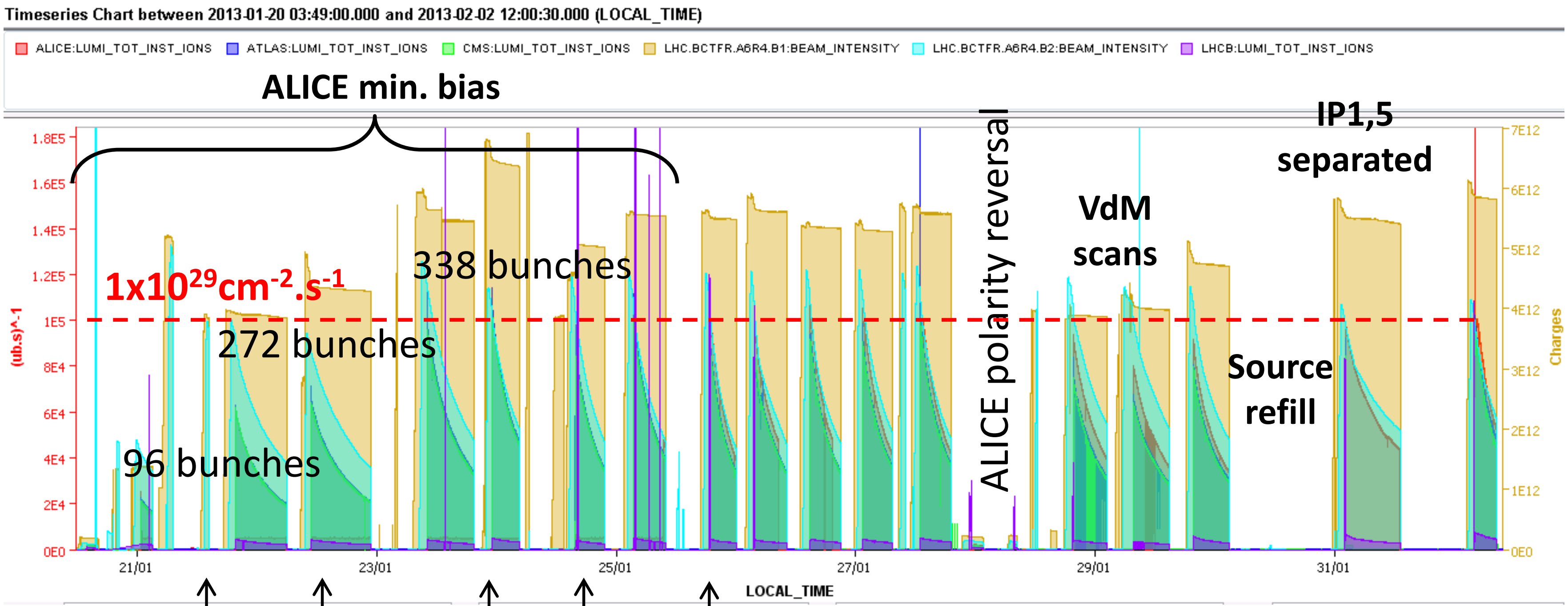
p-Pb

→ Beams reversal

→ Van der Meer scans

Pb-p

2013 Luminosity production in p-Pb mode



Increase of BLM monitor factor (losses during cogging)

Problem of losses during cogging solved

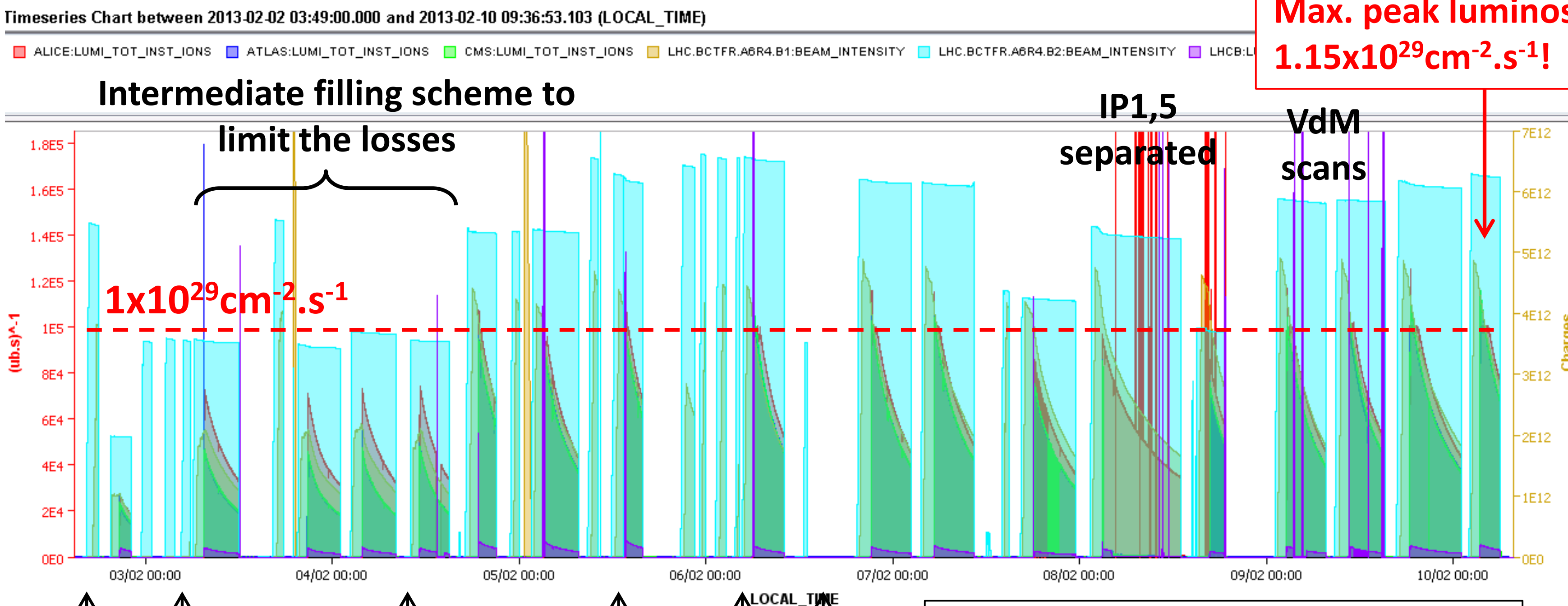
TOTEM Roman Pots moved in

ALFA Roman Pots moved in

Longitudinal blow up ON

2013 Luminosity production in Pb-p mode

Max. peak luminosity $1.15\times10^{29} cm^{-2}.s^{-1}$!



Increase of BLM monitor factor (losses end of ramp + squeeze)

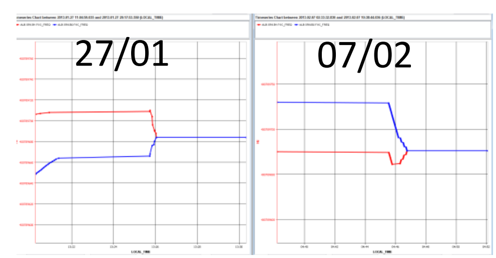
Common frequency trimmed by -10Hz

Increase bandwidth of orbit feedback

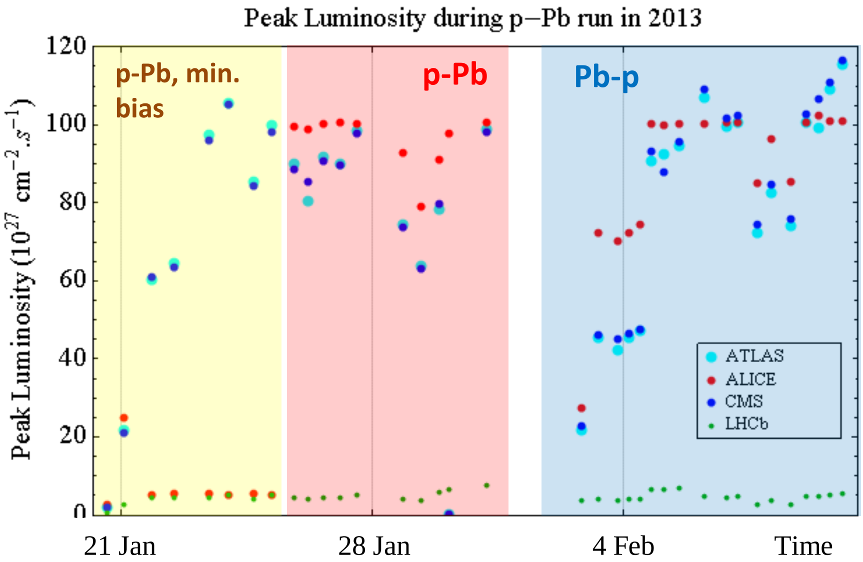
Increase of BLM monitor factor (losses during the squeeze),

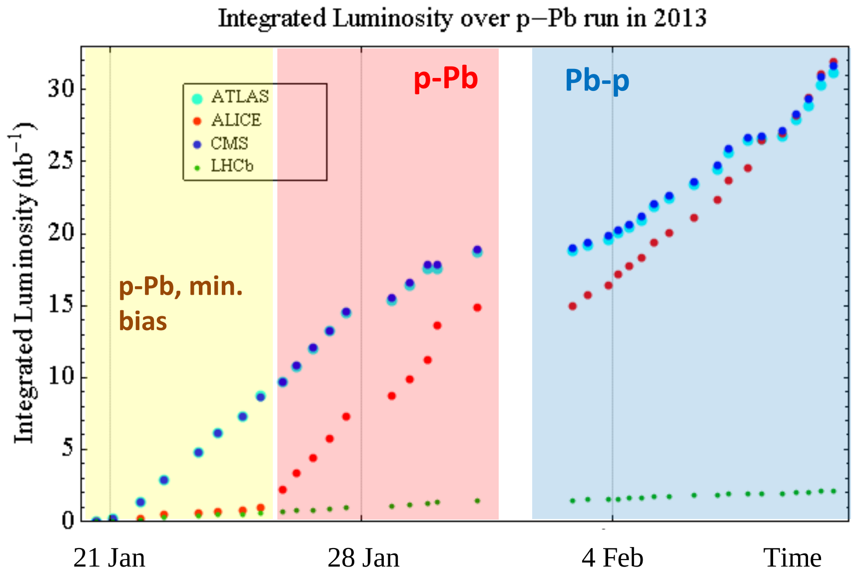
Increase of BLM monitor factor (losses at the start of the ramp), rematch injection energy to the SPS

reduction of longitudinal blow-up at injection



RF frequencies





- Full instantaneous luminosity 1×10^{29} $cm^{-2}.s^{-1}$ already reached with the first fill with full filling scheme
- Levelling in ALICE at 1×10^{29} $cm^{-2}.s^{-1}$ in almost all standard fills
- Two fills were done with IP1 and 5 separated, allowing ALICE to catch up after initial minimum-bias
- Van der Meer scans done in both configurations
- Final integrated luminosity above experiments' request of 30 nb^{-1}
- The run ended with record peak luminosity of 1.15×10^{29} $cm^{-2}.s^{-1}$, record turn around of 2.37 h

ALICE: 31.94 nb^{-1} ATLAS: 31.2 nb^{-1} CMS: 31.69 nb^{-1} LHCb: 2.12 nb^{-1}

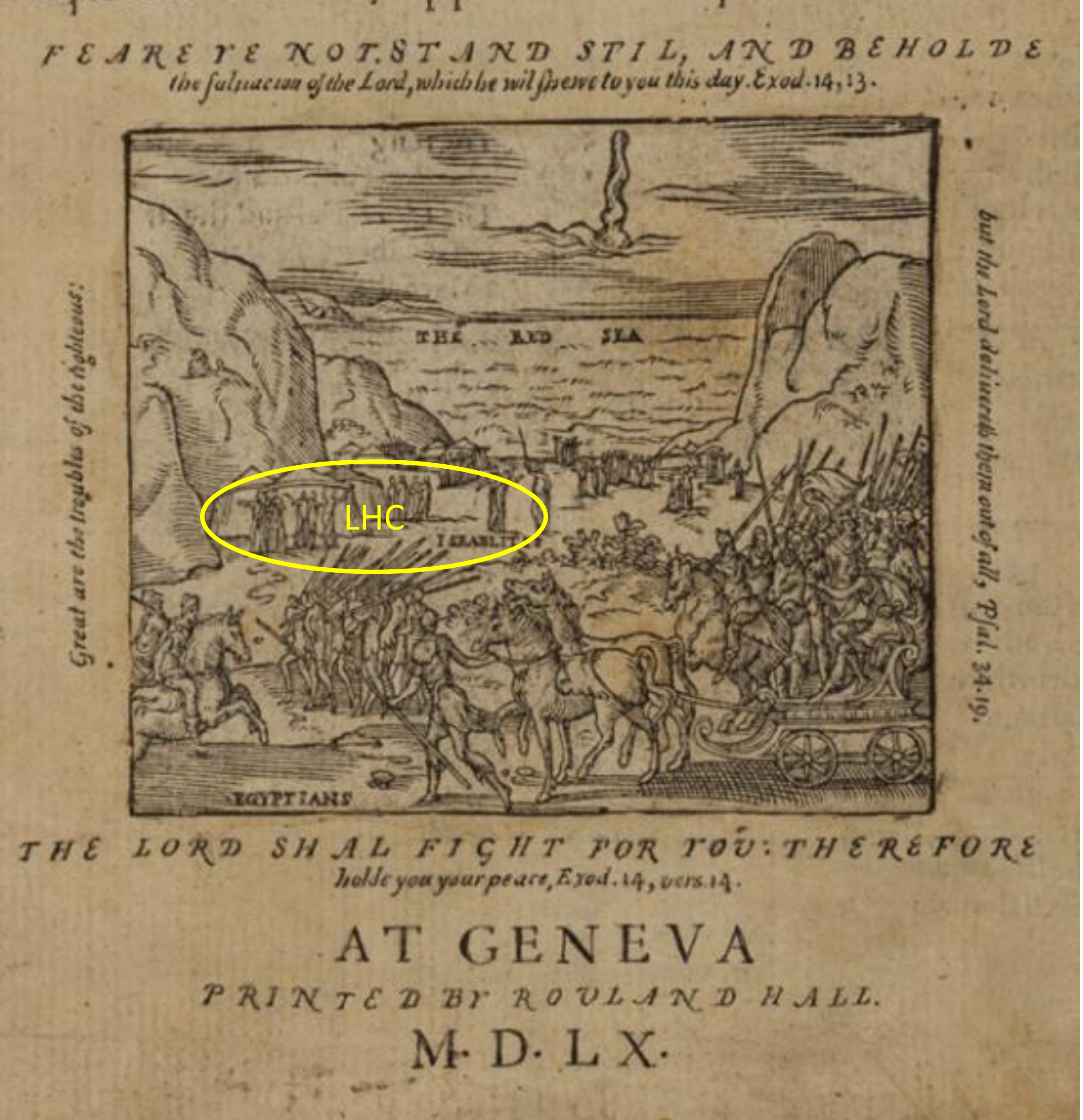
Experiments' requests for 2016

- Experiments initially gave clear but incompatible requests for species (Pb-Pb, p-Pb, Ar-Ar, …) and energy for p-Pb case:

$E = 4\ Z$ TeV (where $Z = 1$ & 82) $\Rightarrow \sqrt{s_{NN}} =$ 5.02 TeV (ALICE, low L)

$E = 6.5\ Z$ TeV $\Rightarrow \sqrt{s_{NN}} =$ 8.16 TeV (ATLAS, CMS, LHCb, high L)

- Following LHC Chamonix workshop and LPC meetings: proposal for a p-Pb run at *both* energies, designed to:
  - Meet major/most physics goals of all experiments
  - Shortcut need for a full p-Pb setup at either energy as was done in 2013
  - Maintain overall set-up time and complexity at or below level of 2013



FEARE YE NOT, STAND STIL, AND BEHOLDE
the saluacion of the Lord, which he wil shewe to you this day. Exod. 14, 13.

Great are the troubles of the righteous:

but the Lord deliuereth them out of all, Psal. 34.19.

THE LORD SHAL FIGHT FOR YOU: THEREFORE
holde you your peace, Exod. 14, vers. 14.

AT GENEVA
PRINTED BY ROULAND HALL.
M. D. L X.

Proposal inspired by
1 Kings 3:16-28

Proposal for 2016 pA run - Part 1

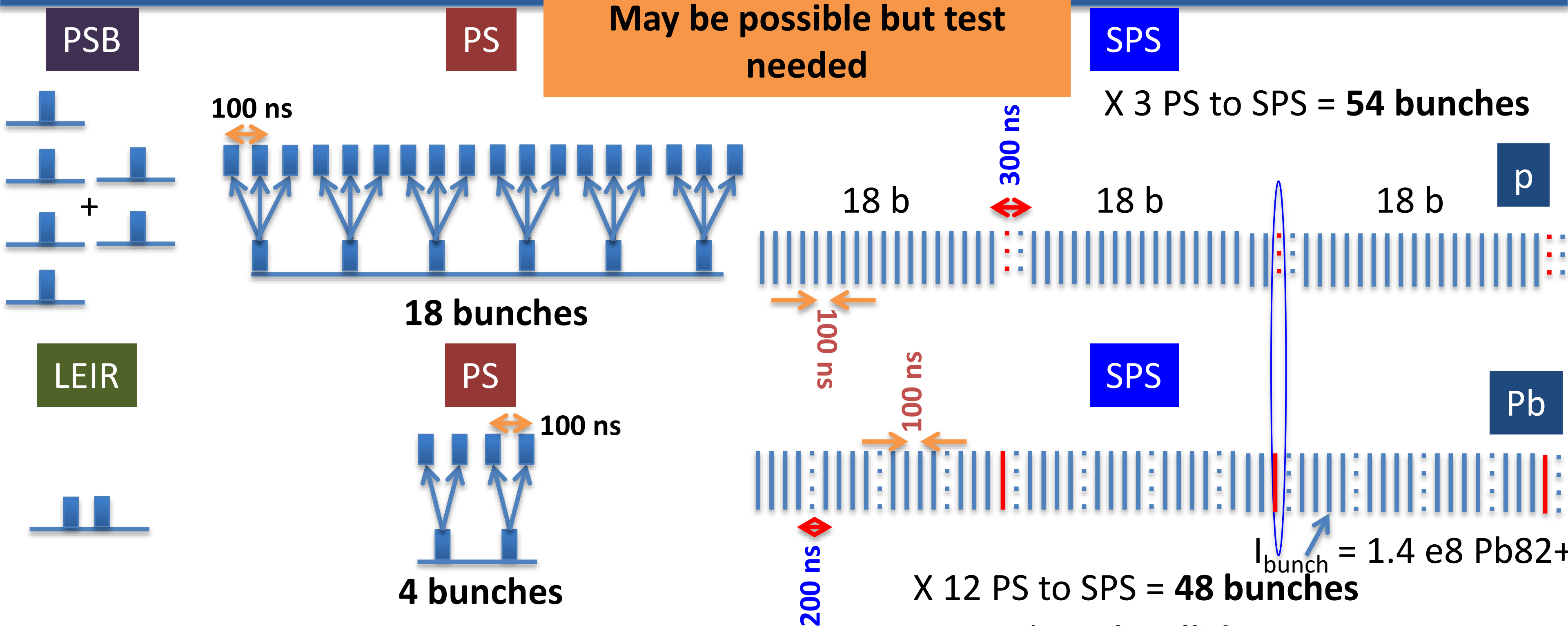
- Run at 5.02 TeV (mainly(for ALICE
  - Full filling scheme > 400 bunches for low μ in ALICE
  - Level ALICE at 10^{28} cm^{-2} s^{-1}
    $\Rightarrow$ very long luminosity lifetime and very long fills
    $\Rightarrow$ Large fraction of time in Stable Beams (cf catch-up fills in 2013)
    $\Rightarrow$ Can fulfil ALICE requirement in a few days
  - Minimise set-up time by using moderately-squeezed optics β^*~2 or 3 m in ALICE only
    - Relatively easy squeeze to set-up and correct
    - Fewer concerns about IR2 aperture (IP2 vertical shift, chromatic squeeze)
    - Will not need correction of off-momentum optics (known from 2013)
    - Fast turn-around, just a few times
    - Still have RF frequency locking/cogging
    - No reversal of beams (p-Pb only, no Pb-p) required
    - Loss maps etc still required
- Possibly collide some bunches in the other experiments at much smaller luminosity ~10^{27} cm^{-2} s^{-1} (unsqueezed)

Proposal for 2016 pA run – Part 2 at 8.16 TeV

- Original idea was to minimise set-up time by re-using p-p optics unchanged
  - High luminosity for ATLAS and CMS with β^*= 0.4 m
    - Rapid burn-off, short fills
  - No ALICE squeeze β^*=10 m $\Rightarrow$ only few 10^{28} cm^{-2}
  - LHCb has β^*=3 m $\Rightarrow$ factor >10 down
- But LHCb requests ~ 20 nb^{-1} , ALICE also
  - Consider adding squeeze to
    β^*~3 m for ALICE, β^*~1.5-2 m for LHCb
  - Time cost for one or both is similar ~ 2 shifts
  - May need to increase β^*= 0.6 m for ATLAS/CMS ?
    - Will not dramatically reduce integrated luminosity
- Beam reversal p-Pb to Pb-p requested by LHCb/ALICE
  - quite expensive in time 1.5-2 days
- One day for short LHCf run

pPb injection patterns: potential for 2016

May be possible but test needed



- **Faster Pb & p+ filling**
- **Less Pb bunch intensity; degrade less on the SPS flat bottom**
- **3 Pb bunches per SPS batch do not collide**

N.B.: 100 ns bunch separation needs beam-be
encounters studies. No problems observed in 2
beam-beam effects could be stronger in pPb.

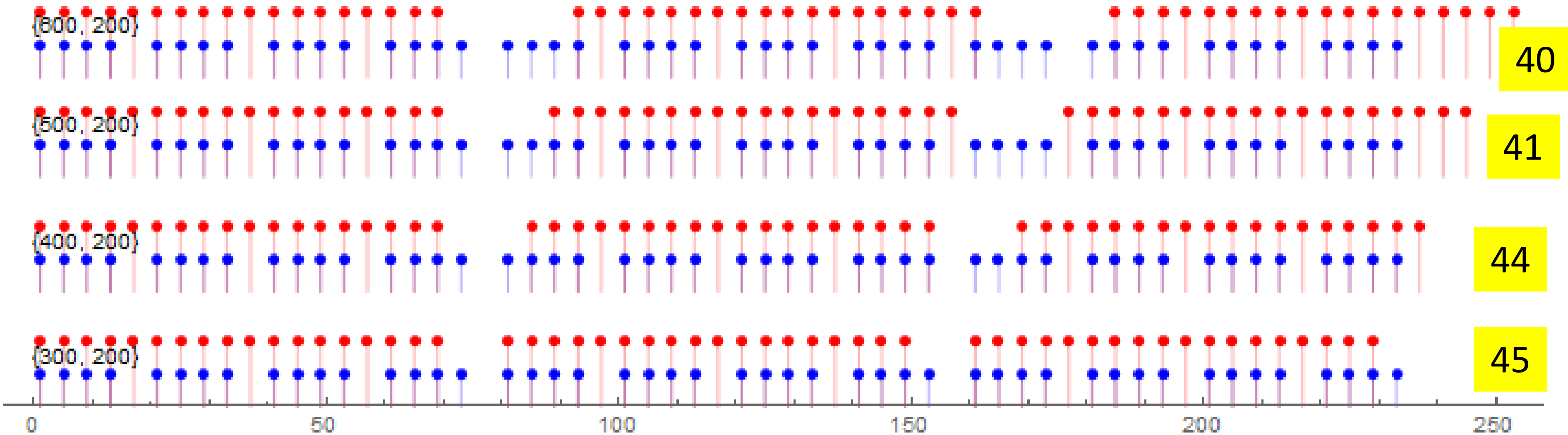
Consider this possibility for now. Some freedom to adjust kicker gaps, may even reduce some.

R. Alemany, Chamonix 2016

PS bunch compression
SPS injection kickers

SPS train variants

Minimum SPS kicker rise times of {225 ns (p), 150 ns (Pb)} do not give useful schemes.



SPS trains cannot be stacked up against each other in the normal way in the LHC.

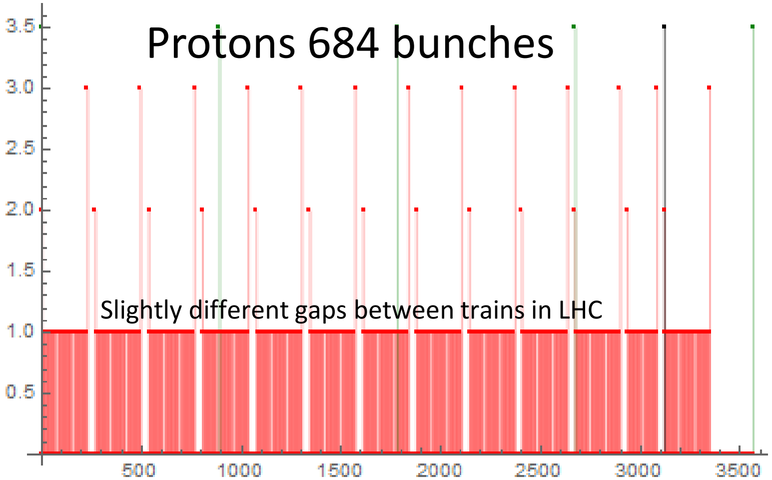
Collisions have to be optimised, and luminosity shared, using longer gaps and special selections of injection buckets in LHC.

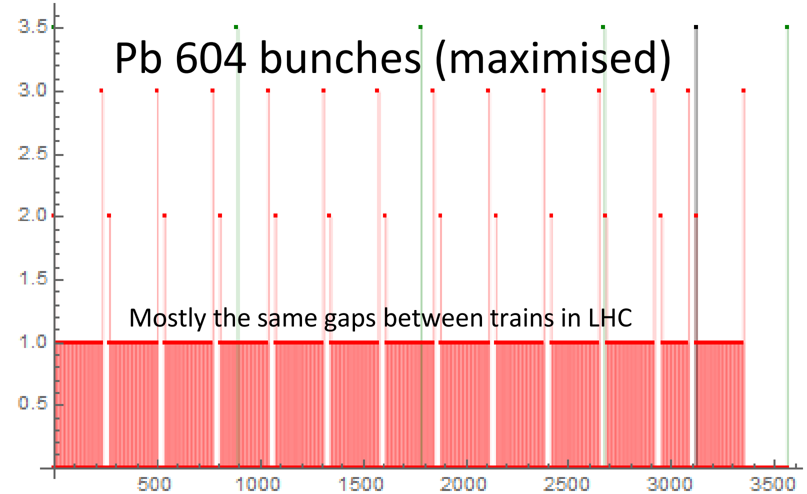
Always some bunches that do not collide at all.

Potential for complicated beam-beam effects and varying beam lifetimes.

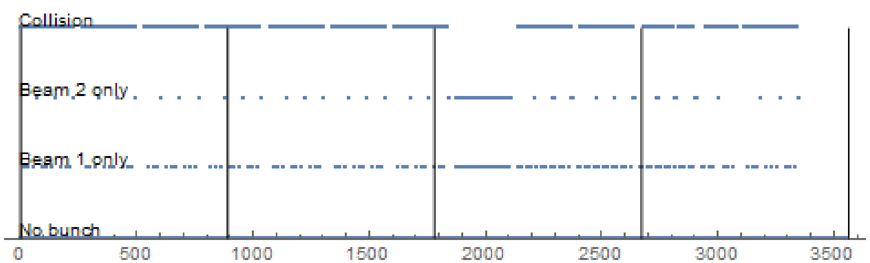
Beware of protection dumps when ANY ONE Pb bunch intensity drops below threshold.

A candidate scheme for 8 TeV

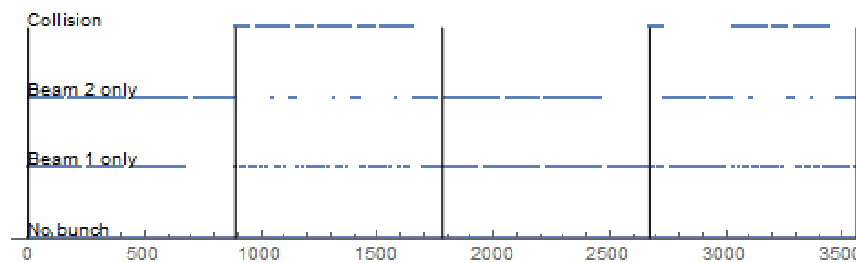




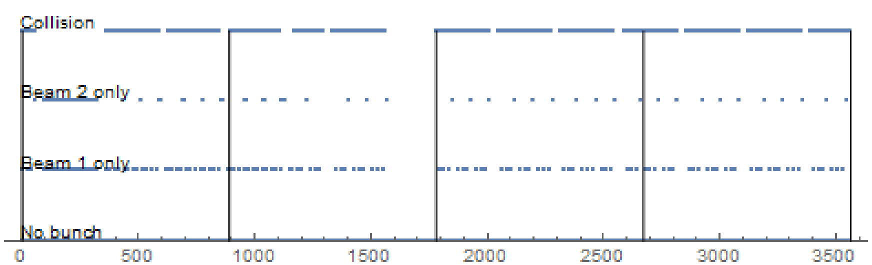
Encounter sequence at IP1



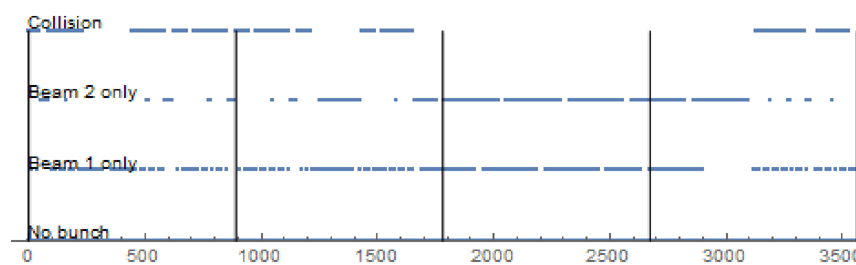
Encounter sequence at IP2



Encounter sequence at IP5



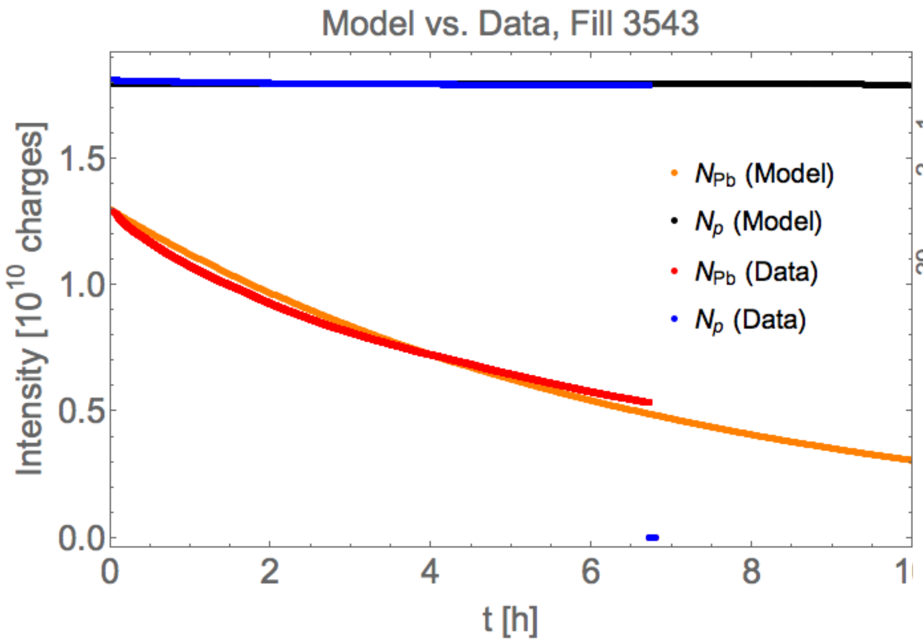
Encounter sequence at IP8

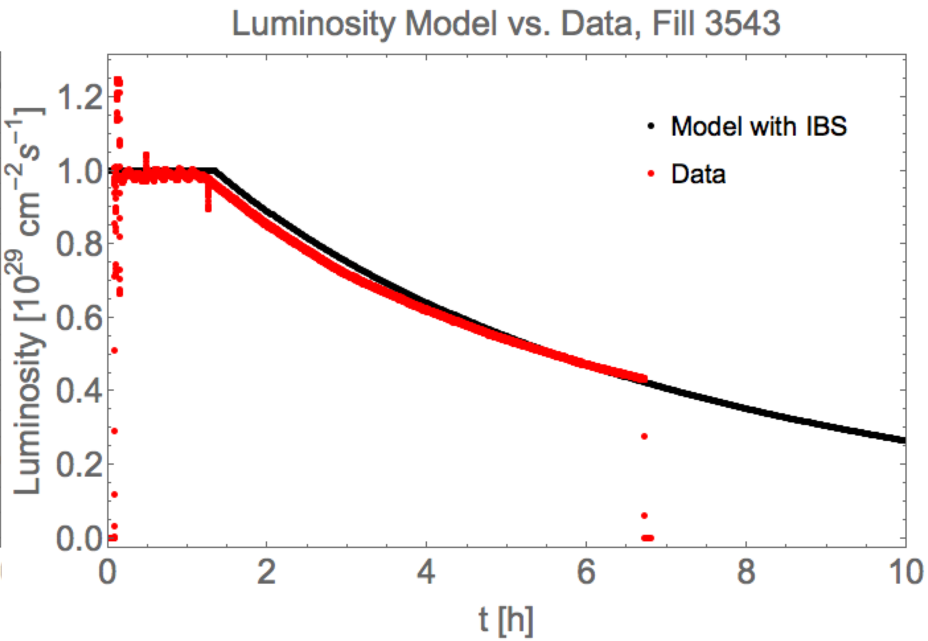


Collision counts: "IP1" → 510, "IP2" → 199, "IP5" → 510, "IP8" → 260

Luminosity and beam lifetime

- Pb beam lifetime "should" be dominated by luminosity burn-off against protons but was higher in 2013 p-Pb run
  – Likely due to colliding unequal beam sizes, extra terms included in ODE model (M. Schaumann, R. Alemany)
  – Proton beam loss ~negligible

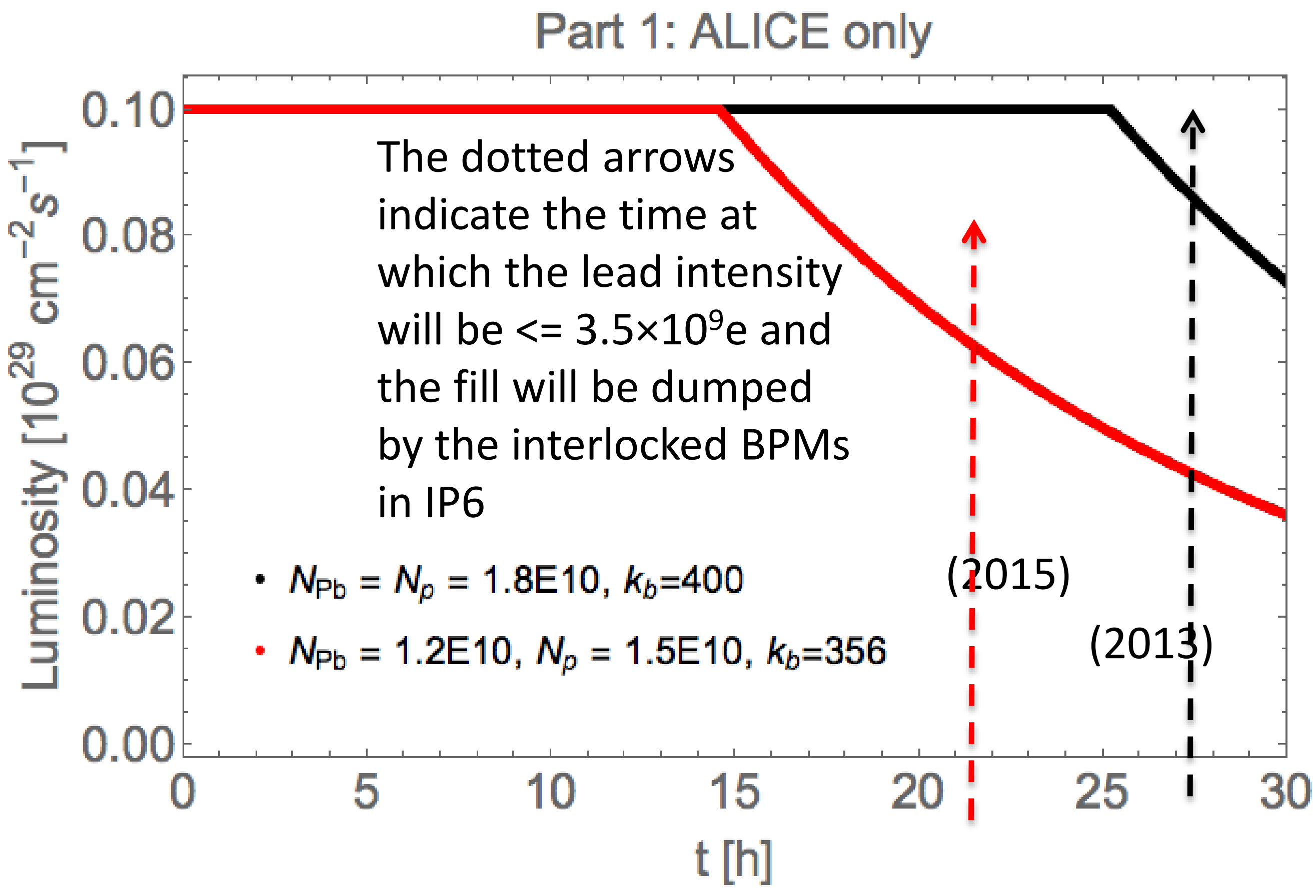




Simple model was basis for some preliminary predictions for 2016 … but needs update!

PART 1 5 TeV: ALICE levelled at 4Z TeV, β* = 3 m and at a constant luminosity of 1×10^{28} cm^{-2}s^{-1}; ignoring possible small luminosity in other experiments.

Possible fill evolution using the model. Two different beam parameters are compared, the ones for one fill in 2013 and the ones corresponding to the 2015 performance. The plot shows a clear strong dependence on the beam parameters, as expected. However, even less favourable parameters as in 2013 give levelling times of 15 hours.



With cross-section of 2 b, one fill like this gives ~2×10^9 events, of which 2×10^8 are taken by ALICE.

Need ~5 good fills like this.

PART 2 8TeV: IP1&5 head-on at 6.5Z TeV and beta* = 0.4 m; and then ALICE with the following three configurations:

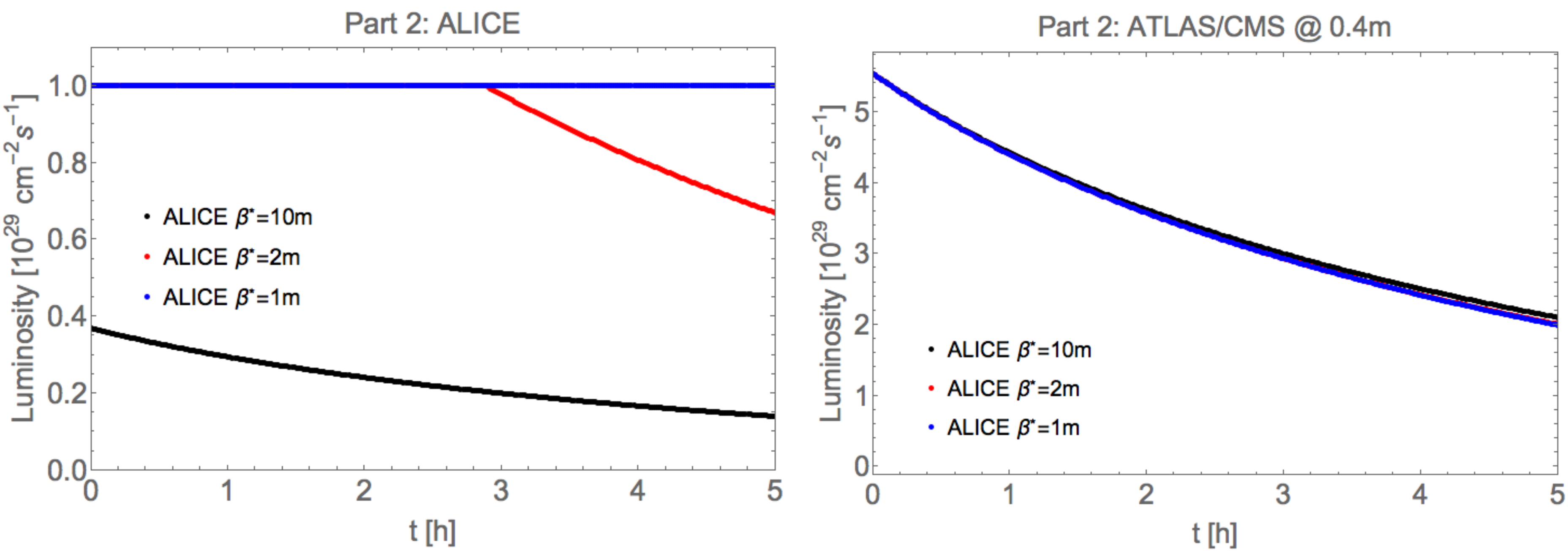
A. ALICE head-on with beta*= 10 m (peak luminosity is 3.7e28 cm-2s-1, no levelling needed);
B. ALICE levelled at constant luminosity of 1e29 cm-2s-1 with beta = 2 m (peak luminosity = 1.8e29 cm-2s-1); N.B. beta*=3 m not considered because it just gives a peak luminosity of 1e29 cm-2s-1.
C. ALICE levelled at constant luminosity of 1e29 cm-2s-1 with beta = 1 m (peak luminosity = 3.7e29 cm-2s-1);

	Lint IP1/5 [nb^{-1}]	Lint IP2 [nb^{-1}]	tlevel [h]
Conf. A	6.2	0.4	0
Conf. B	6.1	1.6	2.8
Conf. C	6.1	1.8	5 (6.4)

Integrated luminosity values after 5h in stable beams and the duration of levelling in ALICE. Peak luminosity in ATLAS/CMS is 5.5e29 cm-2s-1.

Needs to be updated for new bunch numbers, they assumed 400 bunches colliding in ATLAS, CMS, ALICE and no LHCb, so factor 2 optimistic for ALICE.

Luminosity Evolution for Part 2, 8 TeV

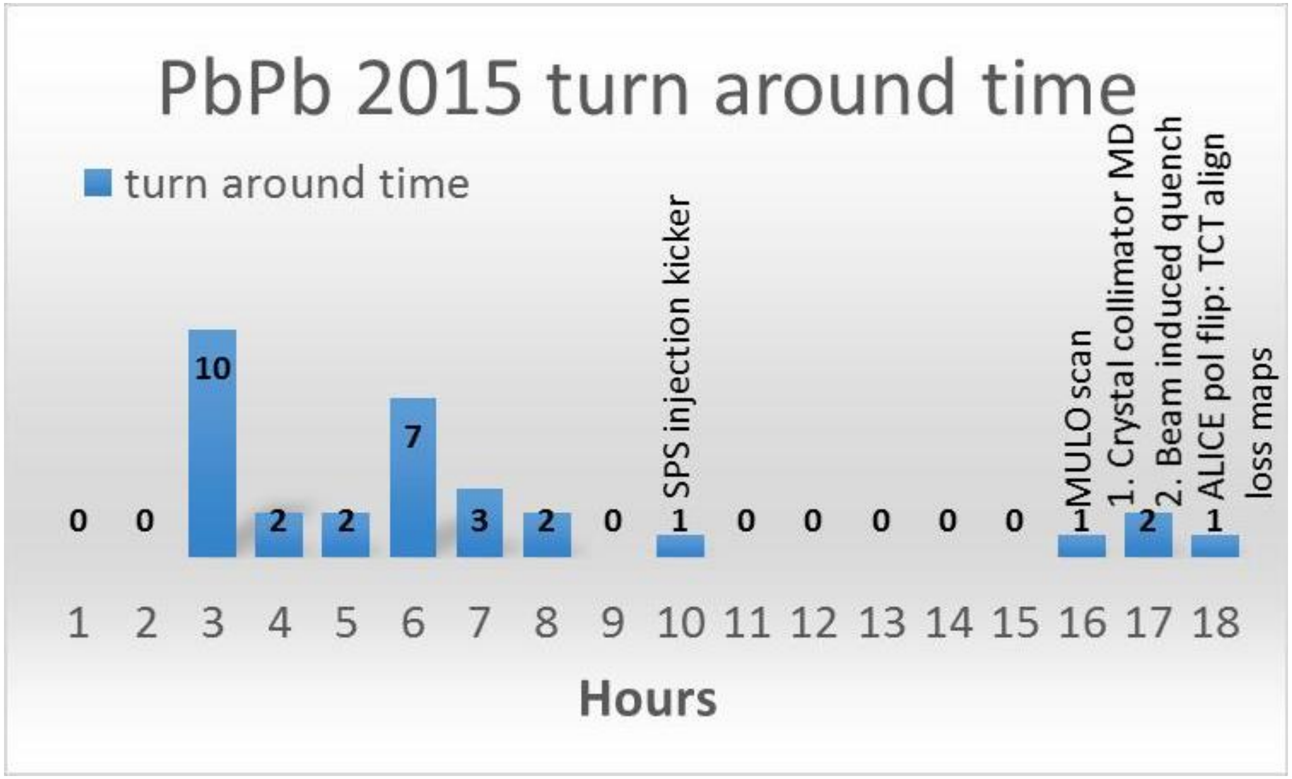


Needs to be updated for new bunch numbers, they assumed 400 bunches colliding in ATLAS, CMS, ALICE and no LHCb.

ALICE, LHCb should get 10-20

Turn-around and integrated luminosity

From 2015 Pb-Pb run, the average turn around time we consider for 2016 is 5 hours, giving about 2 fills per day at 8 TeV. Expect 50-100 nb^{-1} in 8 days for ATLAS/CMS, 10-20 nb^{-1} for LHCb, 5-15 nb^{-1} for ALICE.
Some scope for tuning the final outcome with catch-up fills, special filling schemes as we did in 2013.
An increase of β* in ATLAS/CMS could also help.



Agreed outline - Coordinators' slides at LHCC

	M	T	W	T	F	S	S
week1	set up 5	set up 5	set up 5	5 TeV	5 TeV	5 TeV	5 TeV
week2	5 TeV	5 TeV*	set up 8	set up 8	set up 8	set up 8	8 TeV
week3	8 TeV	8 TeV	8 TeV	8 TeV	8 TeV / LHCf run*	LHCf run* reversal	reversal
week4	reversal 8 TeV	8 TeV	8 TeV	8 TeV	8 TeV	8 TeV	MD

operation	days
5 TeV setup	3
8 TeV setup (both directions)	4
direction reversal	2
MD	1
LHCf run	1 (hopefully less than 12hrs)
5 TeV data taking	6
8 TeV data taking	11 days (5.5 for each direction)
Total	28 days (= 4 weeks)

*-source re-fill

Shorthand:
5 TeV = $\sqrt{s_{NN}}$ = 5.02 TeV
8 TeV = $\sqrt{s_{NN}}$ = 8.16 TeV

3

Coordinators' slides at LHCC

Proposed scheme – part-1

- Start with 5 TeV run
  - Less risk (low luminosity running, non-aggressive optics)
  - Hope to complete 5 TeV physics programme in short time
- Stop 5 TeV run when any of these criteria are met:
  - After 1B events delivered to ALICE
  - If by end of day-9 ≥700M events delivered
  - If the above criteria have not been met, continue the run till 700M events are delivered, unless this appears to significantly delay the start of the 8 TeV run
- During 5 TeV run
  - Protons in beam-1 / Moderate squeeze in ALICE (~3m)
  - Very long fills (~20hrs) luminosity leveled to 10^{28} cm^{-2} s^{-1} in ALICE
  - Can try to have very low luminosity collisions in other IPs (luminosity<10^{27} cm^{-2} s^{-1}) but stop this if any problems encountered

Disclaimer: We should leave some flexibility to change some of the cut-off numbers / dates, depending on the actual situation. With the goal of giving the best physics output of all parts of the programme.

LPC Heavy Ion proposal - LHCC May 2016 4

Coordinators' slides at LHCC

Proposed scheme – part-2

- Default strategy for 8 TeV run
  - Moderate squeeze in ALICE (~3m) / LHCb (~2m)
  - ATLAS/CMS pp optics (40cm) or slight de-squeeze
    - To be determined by machine experts after more studies
  - Beam reversal
- If significantly behind expectation drop beam reversal (this would save ~2 days)
  - e.g. if <25/nb delivered to ATLAS/CMC by end of day-19
- Fills optimized to give luminosity to ATLAS/CMS
  - Short fills (~5hrs)
- Expectation (assuming no significant down time):
  - ~70/nb for ATLAS/CMS (~5.5/nb per ~5hr fill with 5hr turn-around time)
  - ~10/nb each for ALICE/LHCb* (less than requested)

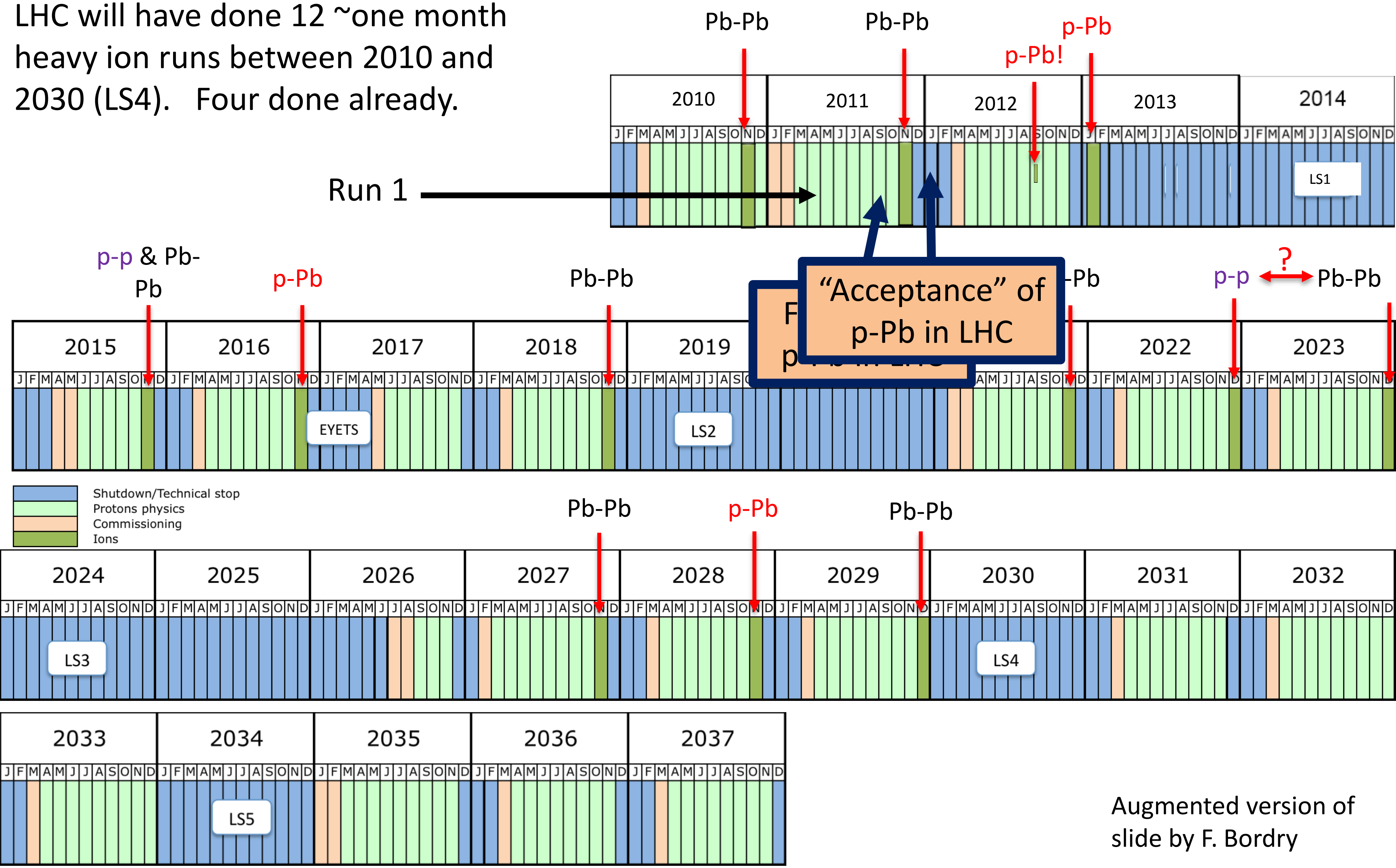
    (* - For LHCb this depends on exact filling schemes, which in turn depend on various kicker magnet rise-times which have not been measured yet).

Disclaimer: We should leave some flexibility to change some of the cut-off numbers / dates, depending on the actual situation. With the goal of giving the best physics output of all parts of the programme.

LPC Heavy Ion proposal - LHCC May 2016 5

LHC heavy-ion runs, past & planned future
+ species choices according to ALICE 2012 LoI (could evolve if required)

LHC will have done 12 ~one month heavy ion runs between 2010 and 2030 (LS4). Four done already.



Augmented version of slide by F. Bordry

Conclusions (1)

- All hadron collisions can be heavy-ion collisions ??
- All the world's hadron colliders are now heavy-ion colliders.
- All the world's hadron-collider experiments are now heavy-ion experiments.
- All the world's theorists …

Conclusions (2)

- RHIC's great efficiency, flexibility and continuing upgrades will bring numerous new physics opportunities in coming years
- LHC has demonstrated the path to HL-LHC Pb-Pb performance level
  - Mainly depends on injector upgrades now
- Diverse experimental requirements have led to a challenging plan for the LHC p-Pb run in 2016
  - Operation at both 5 TeV and 8 TeV
  - Achievable, assuming operational efficiency similar to 2013 and 2015 – overall complexity is similar
  - Otherwise re-prioritisation strategies are beng put in place
- i

BACKUP SLIDES

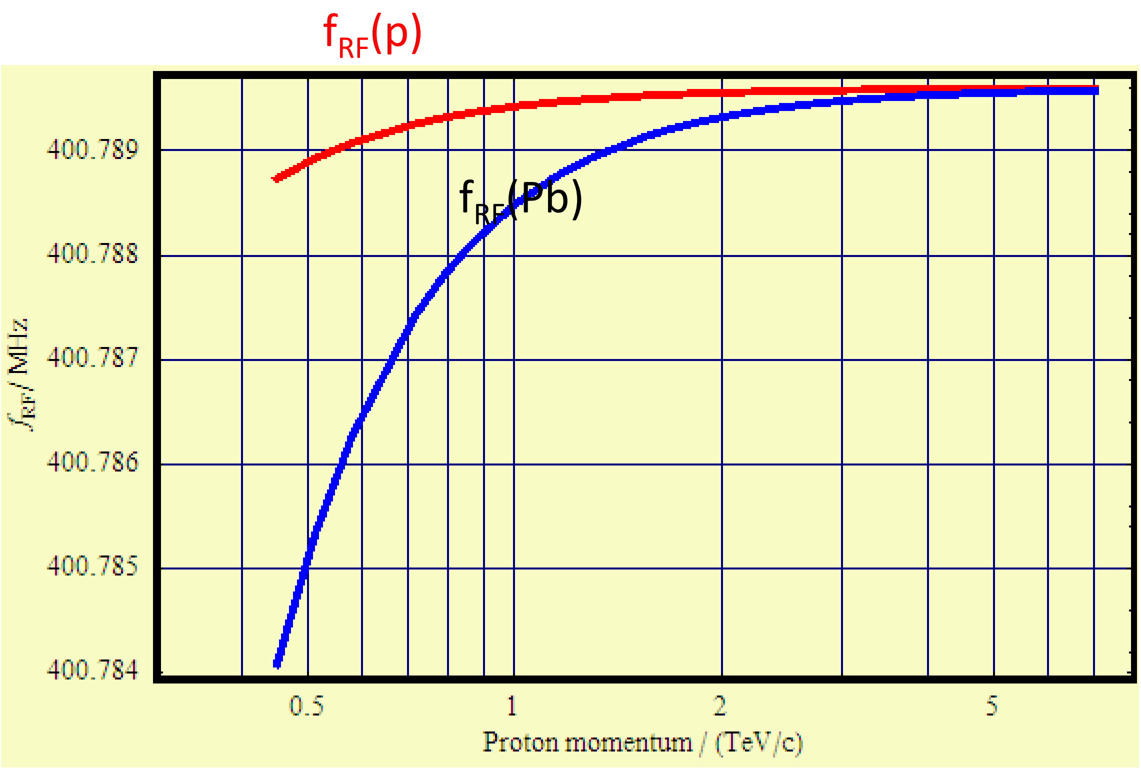
RF Frequency for p and Pb in LHC

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

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

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

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



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

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

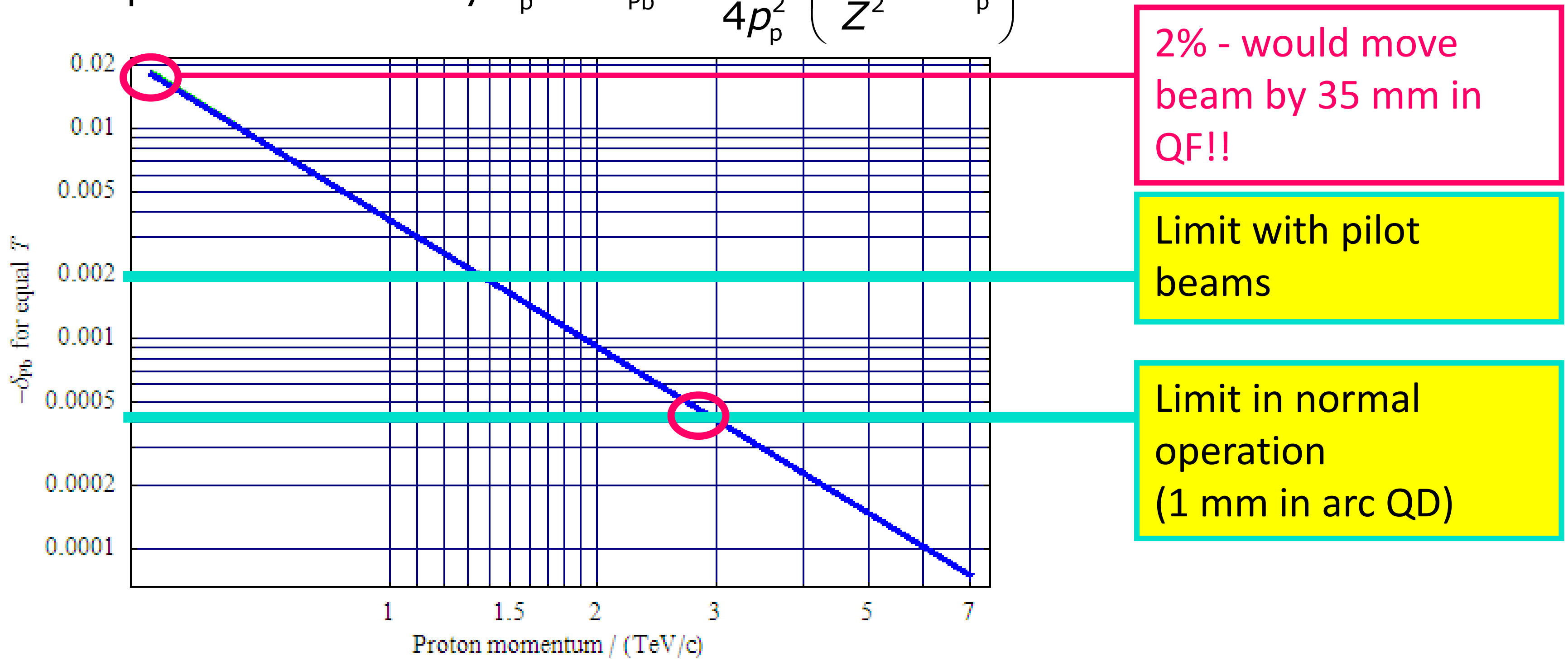
the phase-slip factor $\eta = \dfrac{1}{{\gamma_T}^2} - \dfrac{1}{\gamma^2}$, $\quad \gamma = \sqrt{1+\left(\dfrac{Qp_{\mathrm{p}}}{mc}\right)^2}$, $\quad \gamma_T = 55.8$ for LHC optics.

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

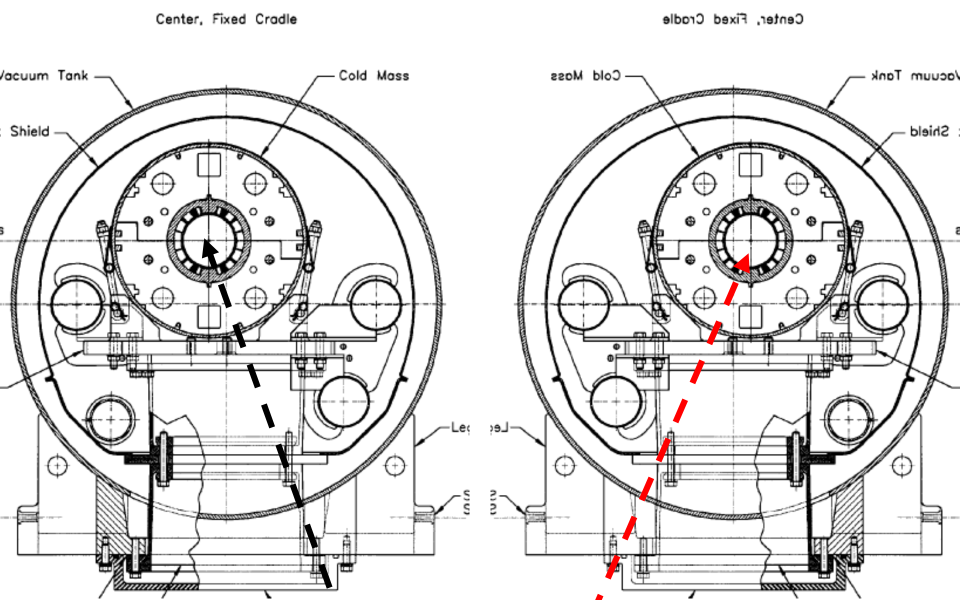


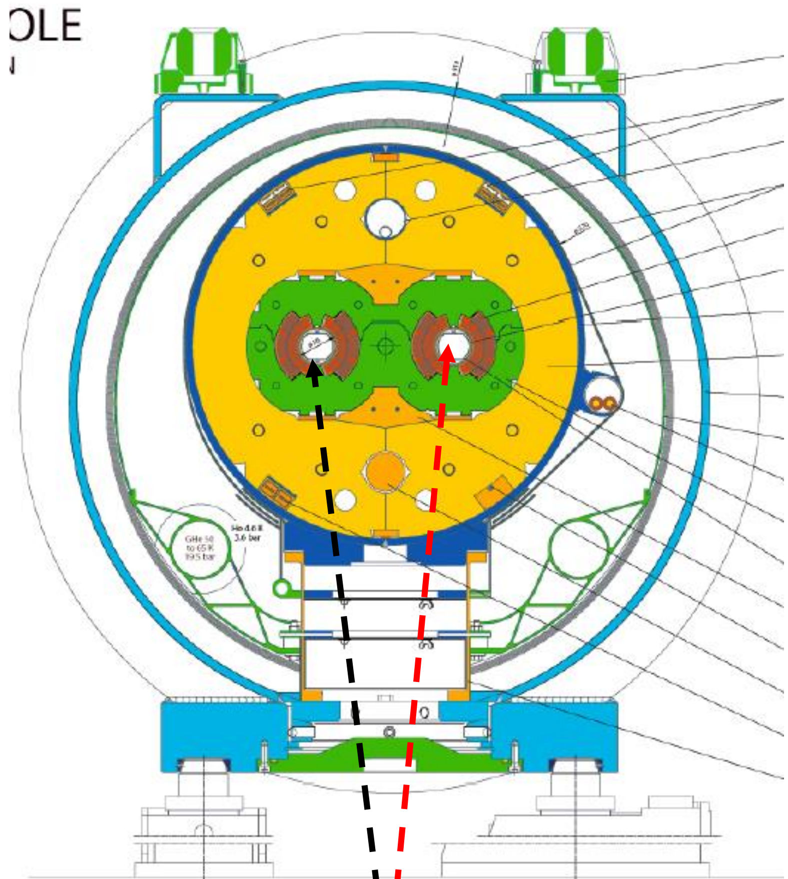
Revolution frequencies must be equal for collisions at top energy.

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

RF frequencies must be unequal for injection, ramp!

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

5 TeV or 8 TeV – which should come first ?

- Reasons for 8 TeV first:
  - 8 TeV configuration somewhat closer to p-p one
    - But LHC is very reproducible, not a great advantage
- Reasons for 5 TeV first:
  - Less risk in 5 TeV – get it in the bag
    - May also have time to learn/debug any p-Pb-specific problems that come up in the easier configuration
  - Ion source refill during Stable Beams
    - Advantage of very long 5 TeV fills, no time lost (unless bad luck!)
    - Refill timed during last physics fill should last for remainder of run

- Conclusion: prefer 5 TeV first

Miscellaneous

- Plan to not lose set-up time in the case that we do not do the reversal (so setup the reversed beam only when necessary)
- Each new mode of running (5 TeV, 8 TeV direction1 and direction 2) will require a short intensity ramp-up for machine protection reasons (1 day for each part where we wont be running at full luminosity)
- Related to the LHCf run
  - Direction of first part should be as wanted by LHCf (e.g. protons in beam-1), as LHCf run foreseen in this part
  - LHCf/ATLAS common trigger rate of 400Hz try to minimize time of LHCf run
- VdM scans
  - No optics change for p-Pb VdM, so can be done in standard physics fills
  - Up to the experiments to decide if they want VdM for neither, one or both directions (but this will take away luminosity from them)

	M	T	W	T	F	S	S
week1	set up 5	set up 5	set up 5	5 TeV	5 TeV	5 TeV	5 TeV
week2	5 TeV	5 TeV*	set up 8	set up 8	set up 8	set up 8	8 TeV
week3	8 TeV	8 TeV	8 TeV	8 TeV	8 TeV / LHCf run*	LHCf run* / reversal	reversal
week4	reversal / 8 TeV	8 TeV	8 TeV	8 TeV	8 TeV	8 TeV	MD

Switch to 8 TeV run if 700M events delivered to ALICE by this point (if not continue the run until 700M events are delivered, unless this appears to significantly delay the start of the 8 TeV run)

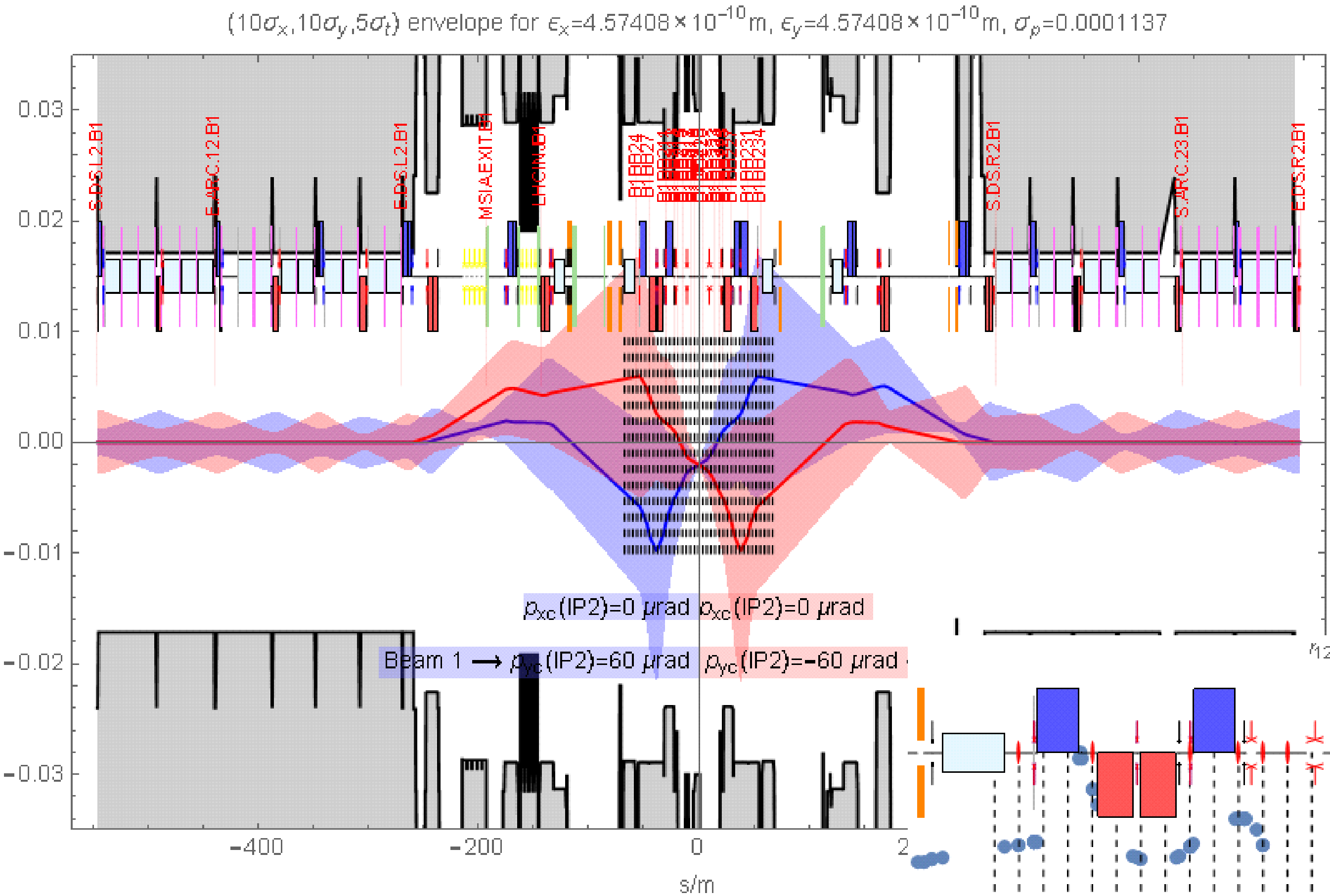
	M	T	W	T	F	S	S
week1	set up 5	set up 5	set up 5	5 TeV	5 TeV	5 TeV	5 TeV
week2	5 TeV	5 TeV*	set up 8	set up 8	set up 8	set up 8	8 TeV
week3	8 TeV	8 TeV	8 TeV	8 TeV	8 TeV / LHCf run*	LHCf run* reversal	reversal
week4	reversal 8 TeV	8 TeV	8 TeV	8 TeV	8 TeV	8 TeV	MD

Drop beam-reversal if <25/nb delivered to ATLAS/CMS by this point

Accelerator aspects of energy choice

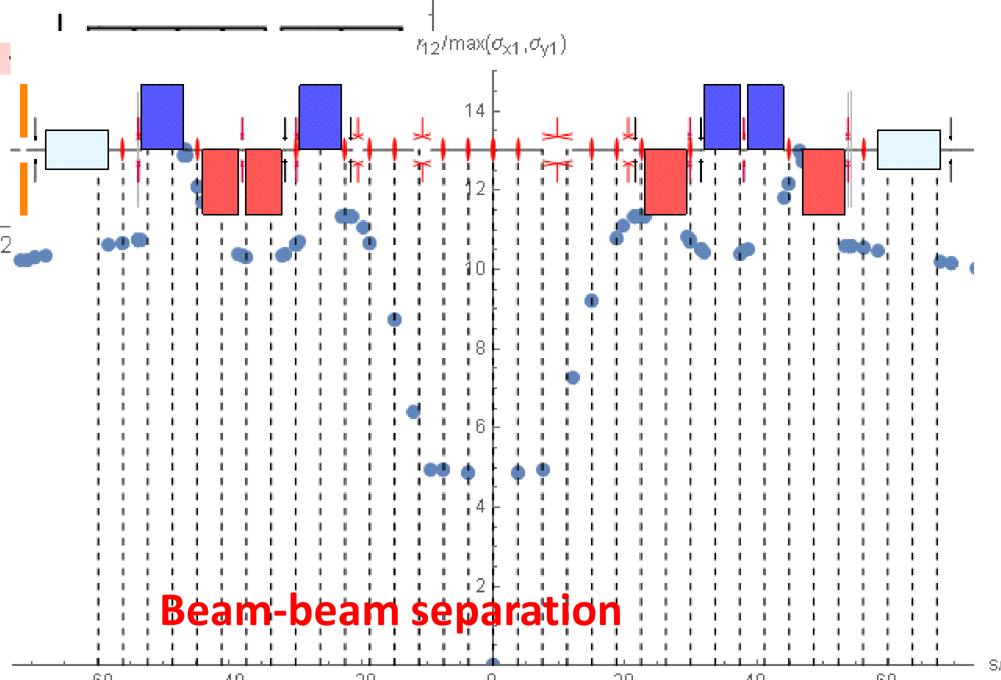
- 5 TeV
  - Full run would be re-run of 2013, more or less, some more bunches, higher luminosity (~77 nb^{-1} RA in Chamonix)
    - May need to increase β*>0.8 m in ALICE (IP displacement + chromatic optics)
    - Levelling ALICE, need to explore potential for more *L* in LHCb
  - Fully squeezed p-Pb and Pb-p optics have different chromatic corrections (not needed above β* ~ 2 m)
- 8 TeV
  - Revolution frequency differences smaller so squeezed p-Pb and Pb-p optics might be identical (to study)
  - Expect less IBS, less effect of unequal beam sizes
  - Higher peak luminosity accessible, rapid burn-off (116 nb^{-1} RA in Chamonix)
  - Levelling ALICE but lower β* potentially accessible
    - New squeeze setup, etc

Spectrometer ON_ALICE=-7/6.37 (start of Pb-Pb run)

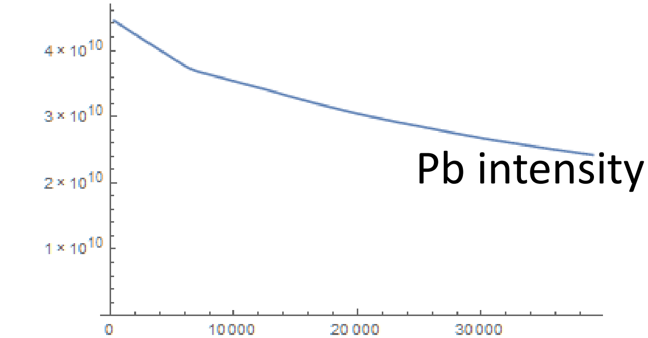


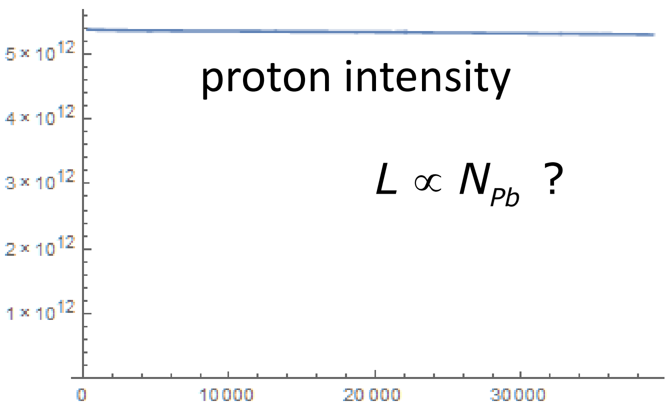
May constrain ALICE β* for rest of Run 2 (important to fix in LS2). To be studied

Spectrometer bump angle -77 μrad, external bump +137 μrad for Beam 1.

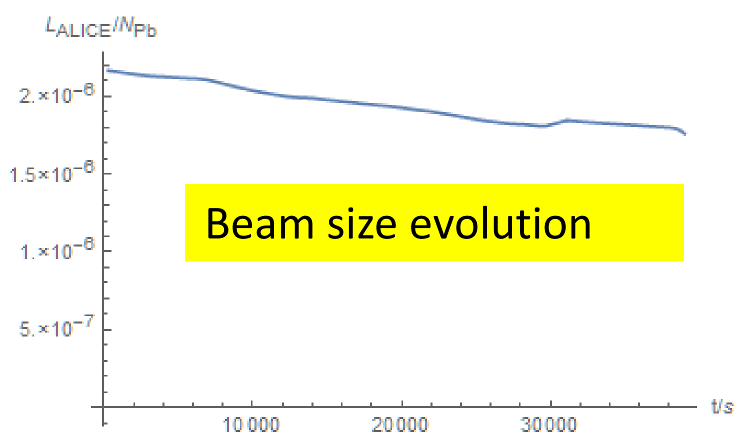


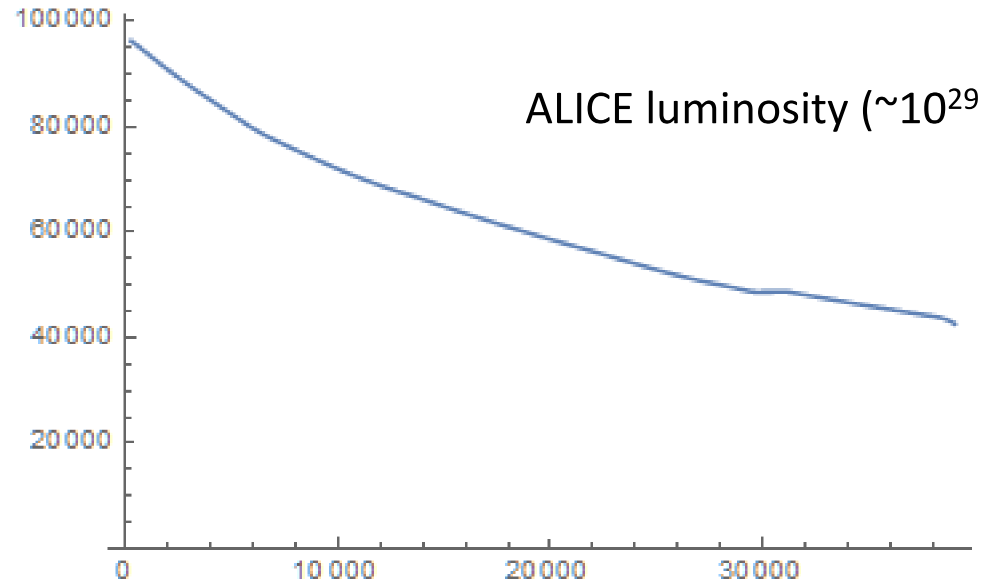
Fill 3509 – only ALICE colliding, 31/1/2013 – 10 h

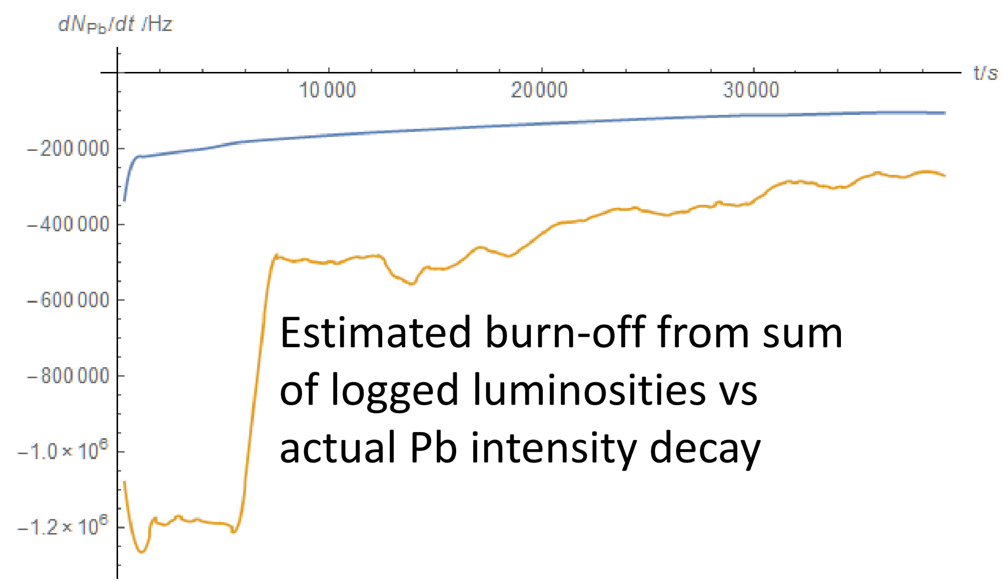




$L \propto N_{Pb}$?

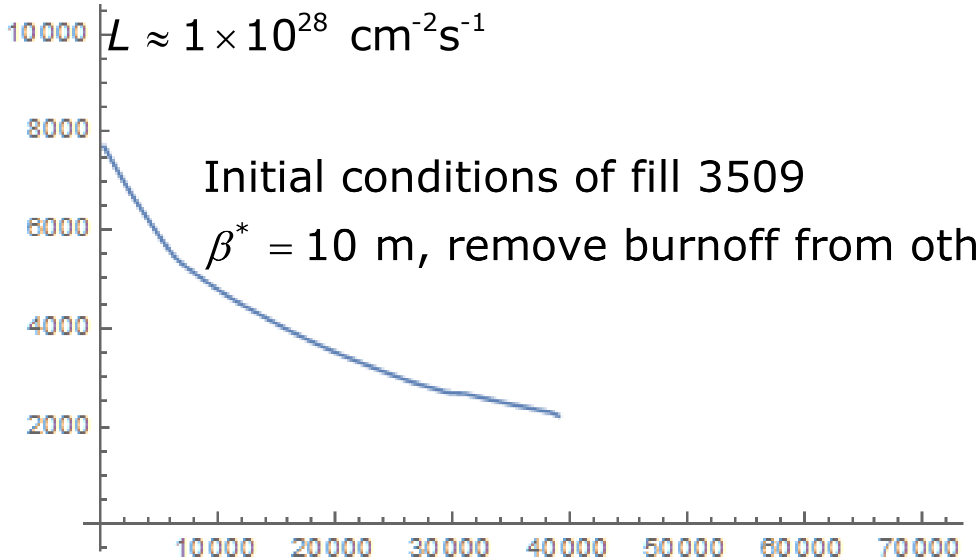






Need to understand 2013 losses better

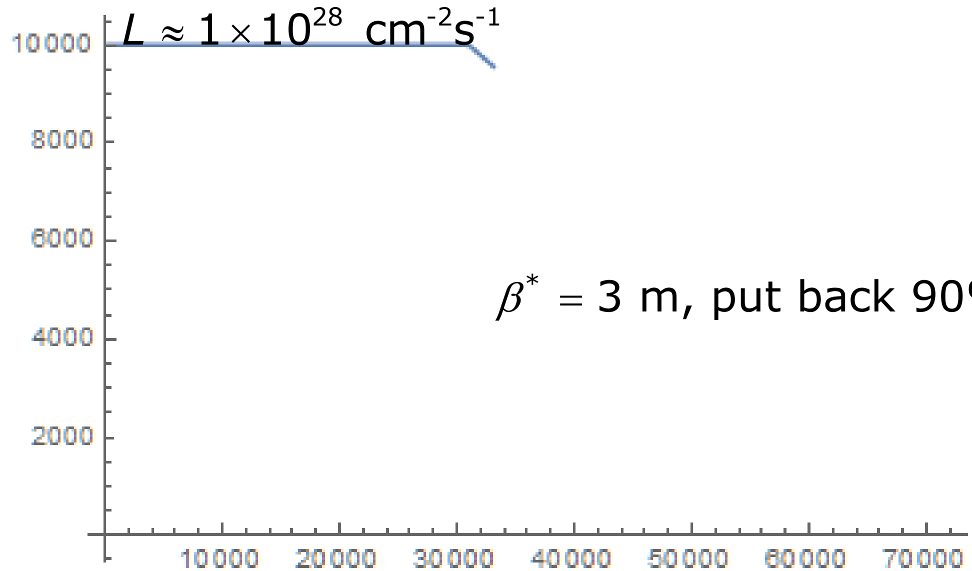
Rough estimate of levelled fill for ALICE alone



Initial conditions of fill 3509

$\beta^* = 10$ m, remove burnoff from other experiments, scale luminosity

24 h



$\beta^* = 3$ m, put back 90% of burnoff, scale luminosity, level

Could be better than this with higher initial Pb and p intensities (and less beam-beam from other experiments?)