# Injection Background with Crystals

R. de Sangro
for the BEAST-INFN group

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# BEAST - Crystals Subsystem

Collaboration between

- U.Victoria (A. Beaulieu, M. Roney)
- Laboratori Nazionali di Frascati (R. de Sangro, G. Finocchiaro, A. Russo)
- Università & INFN Perugia (C. Cecchi, E. Manoni, A. Rossi, G. Scolieri)
- INFN - Roma 3 (P. Branchini, A. Passeri, A. Budano, D. Tagnani)

# Goals

- Analyse the time structure of the injection background
  - This is needed to devise a vetoing scheme that is capable of reducing the background data in the online stream while at the same time keep the dead time at an acceptable few % level
  - Belle scheme would not work at the foreseen trickle injection rate of 100 Hz, as the dead time would rise to as much as 30%
- Evaluate the dose accumulated during injection, with respect to the dose during beam coasting
  - Dose during coasting is needed to validate the MC predictions with real data
  - The dose during injection, for which no simulation exists, is needed to obtain a rescaling factor to apply to the MC predictions to get a more realistic value for the total dose (injection+coasting) on the calorimeter crystals
- NB: all the absolute values of energy/dose measurements made with the crystals during BEAST phase-1 will not match the ones in the final detector due to the absence of the surrounding material and radiation shields, and they should only be used to validate the MC

Injection Background Time Structure

From Belle II TDR



#### 9.4.4 Dead time during injection

SuperKEKB will operate with continuous injection (Ch. 2). For a brief interval after each injection pulse, the beam is excited and produces more background in the detector. Belle's DAQ copes with this by blocking triggers for about 4 ms after an injection pulse. However, at a 100-Hz injection in SuperKEKB, such a veto time would correspond to 40% dead time. To reduce this, the following veto scheme is proposed. The DAQ is blocked for 4 ms $\pm$ 0.5 $\mu s$ *for the injected bunch only*, as it is the most copious source of background. For the other bunches, the DAQ is blocked for a much shorter time of about 150 $\mu s$.
We have studied the feasibility of this scheme in Belle using a special run without the injection veto. A signal from the backward end-cap calorimeter was used to study the energy deposition during injection.

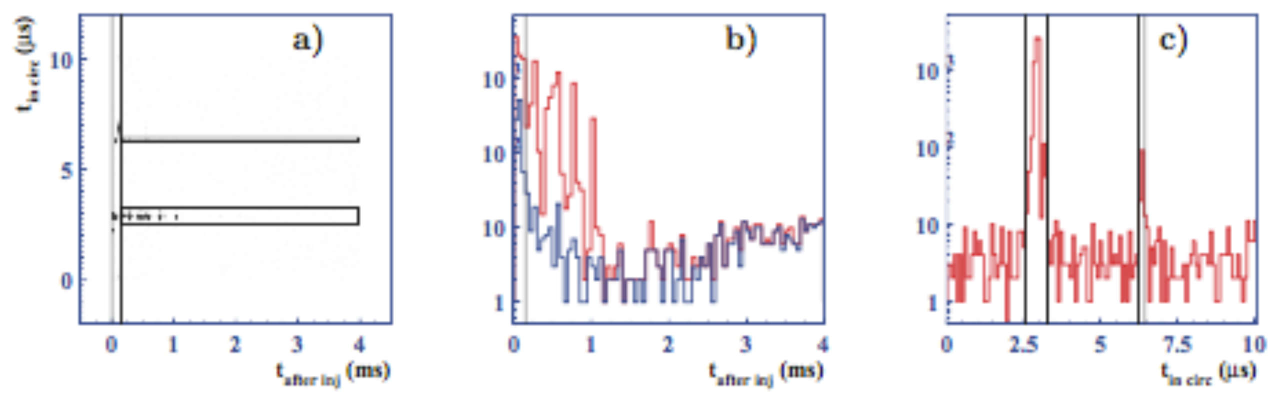



*Figure 9.11: Trigger time distributions for LER injection. a) Scatter plot of time within a revolution period vs. time after injection. b) Time-after-injection distribution (red: all events; blue: excluding the two horizontal bands in (a)). c) Time-in-revolution distribution for* $t_{\rm after\ inj} <$ 150 $\mu s$.

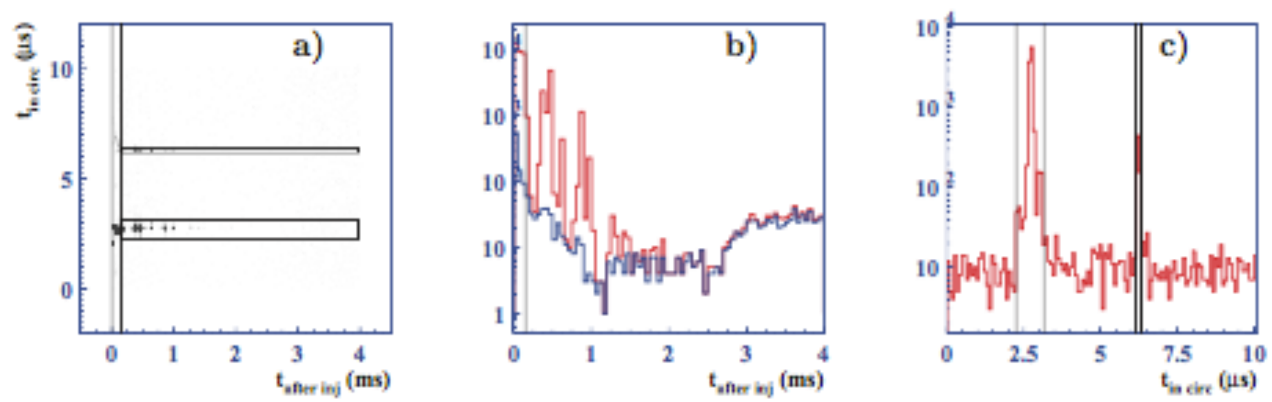
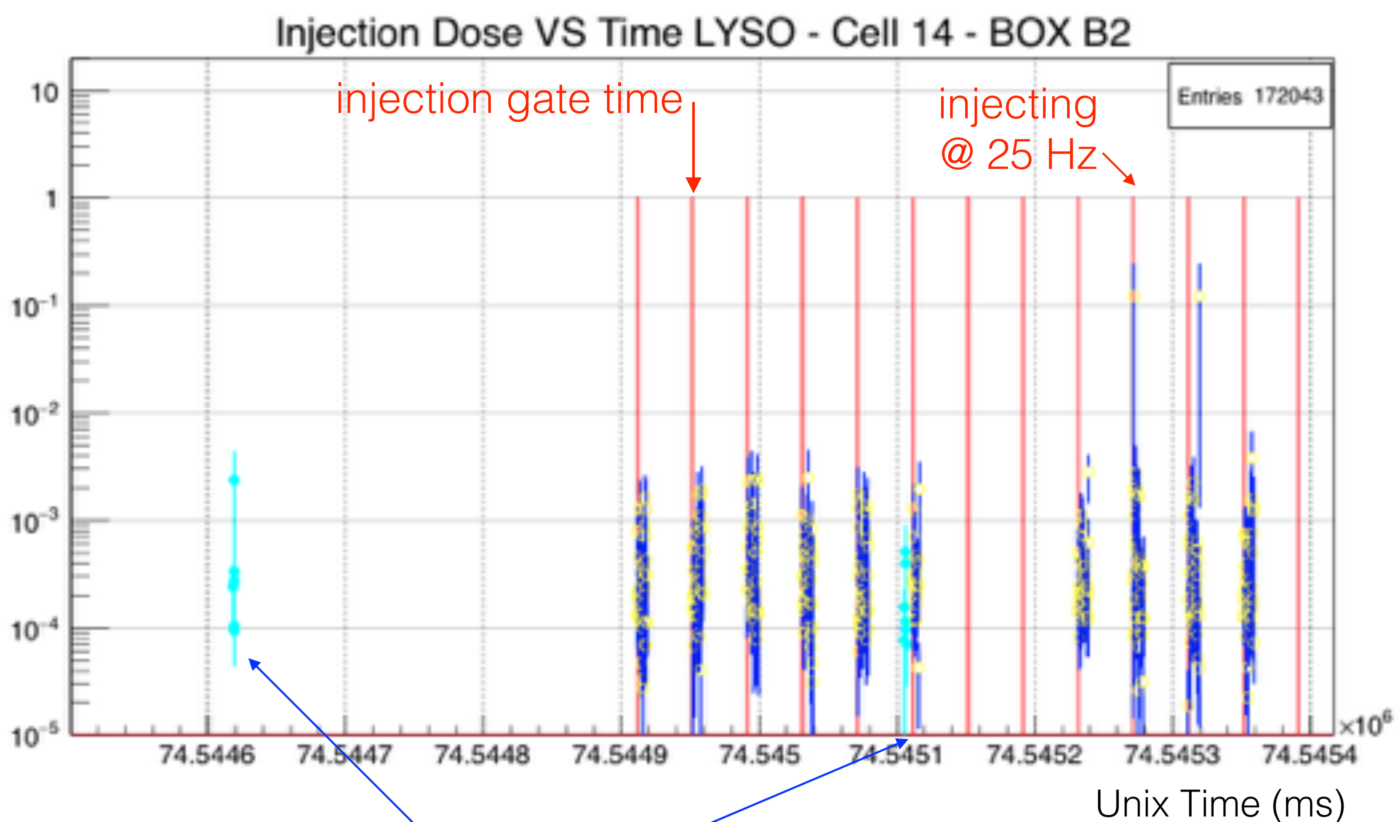



*Figure 9.12: Trigger time distributions for HER injection. a) Scatter plot of time within a revolution period vs. time after injection. b) Time-after-injection distribution (red: all events; blue: excluding the two horizontal bands in (a)). c) Time-in-revolution distribution for* $t_{\rm after\ inj} <$ 150 $\mu s$.

Figures 9.11 and 9.12 show the distributions of the trigger time within one revolution period ($t_{\rm in\ circ}$) and the trigger time after injection ($t_{\rm after\ inj}$). Most of the triggers come within 150

# DAQ - Standard Operation




**Scaler**

- Only available for CsI and LYSO
- Time base set to 0.1 s
- Readout every injection/coast gate
- Published in EPICS @ 1Hz

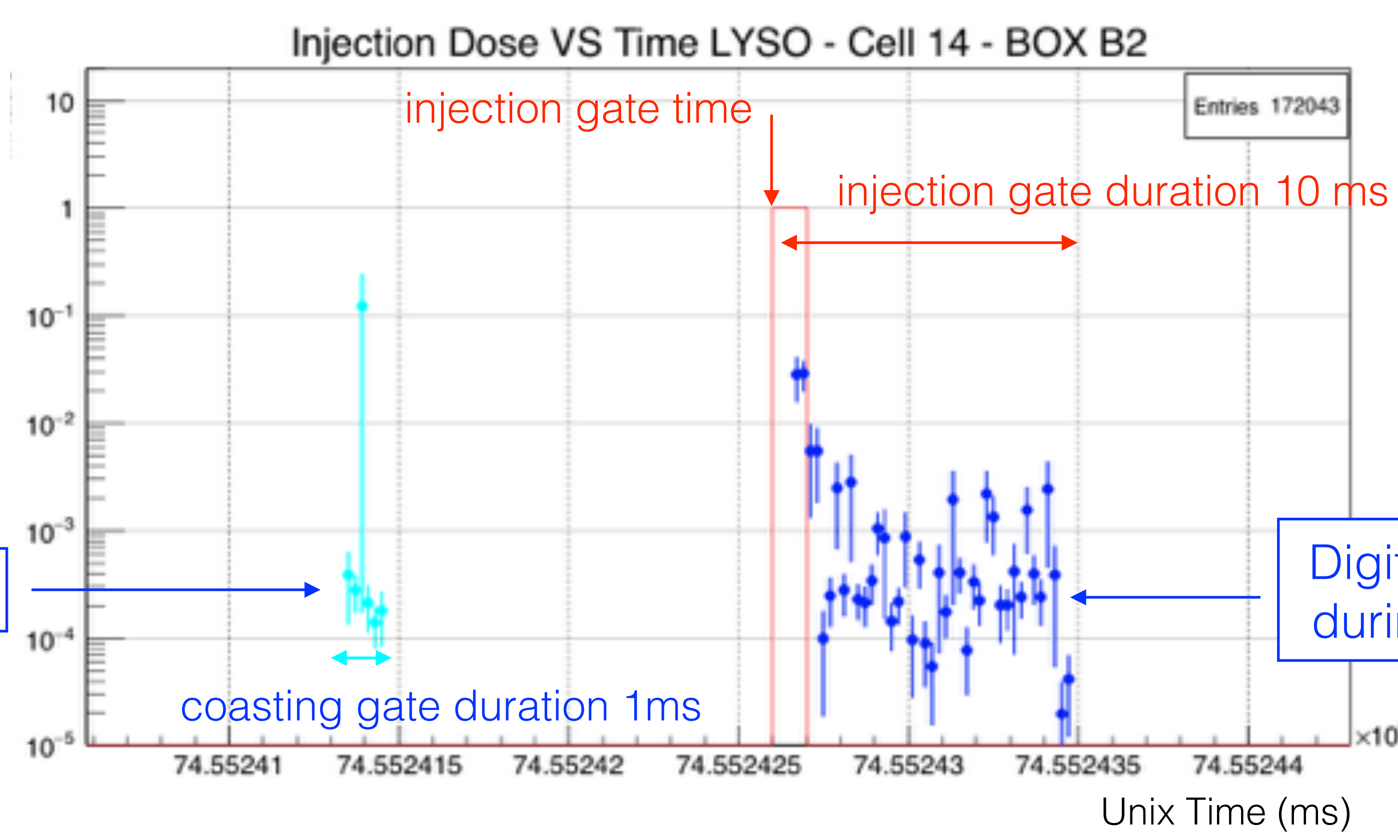
**Digitiser**

- Available for CsI(Tl), CsI and LYSO
- Self triggering on each channel, enabled only during gate
- Record hits' time (2ns/bin) and charge (~pC/ch)

Common Unix Time stamp at each readout operation

coasting gate @ 2 Hz
<u>un-correlated to injection</u>

Digitiser hit rate during coasting




Digitiser hit rate during injection

# DAQ - Injection Study

- For the injection background study the DAQ was modified w.r.t. the standard operation described before
  - The scaler time base changed from 100 ms to 3 μs, and its acquisition has been gated for 5 ms, in synchronism with the injection signal and the acquisition of the digitisers
  - The digitisers' time window changed from 10 to 1 ms to reduce the amount of data to transfer and mitigate the missing hits problem due to the asynchronous acquisition
- With these modifications, the rate of hits as a function of time could be measured with the scalers (3 μs bins) for 5 ms after injection and with the digitisers at 2 ns time bin for the first 1 ms after injection
- Scaler measurements made only for CsI and LYSO.

# Data Set

| LER Inj. Param. | RUN #14 | RUN #3 | RUN #6 | RUN #17 |
|---|---|---|---|---|
| Phase Shift (°) | 1.0 | **31.0** | 1.0 | 1.0 |
| Vert. Steering 1 (mrad) | -0.378 | -0.378 | -0.378 | -0.378 |
| Vert. Steering 2 (mrad) | 0.12 | 0.12 | **0.043** | 0.12 |
| Septum Angle (mrad) | 5.51 | 5.51 | 5.51 | **5.31** |
| Inj. Eff. % | 76 ± 9 | 51 ± 10 | 17 ± 14 | 39 ± 17 |
| Current Ramp (mA) | 0-290 | 330-500 | 260-350 | 0-200 |

| HER Inj. Param. | RUN #10 | RUN #9 | RUN #12 | RUN #13 |
|---|---|---|---|---|
| Phase Shift (°) | 258 | **305** | 258 | 258 |
| Vert. Steering 1 (mrad) | -0.385 | -0.385 | **-0.465** | **-0.435** |
| Vert. Steering 2 (mrad) | 0.08 | 0.08 | 0.08 | 0.08 |
| Septum Angle (mrad) | 2.35 | 2.35 | 2.35 | 2.35 |
| Inj. Eff. % | 93 ± 13 | 72 ± 11 | 74 ± 9 | 75 ± 12 |
| Current Ramp (mA) | 0-150 | 270-450 | 210-300 | 300-400 |

Table 4: Injection parameters setting during the May 25, 2016 study for the LER and HER. In bold faces (red online) the parameter that was changed, in each given run, with respect to the nominal value. "Current Ramp" gives the initial and final beam current in the run. For the injection efficiency we quote the mean value of the distribution of all the measurements taken during the run, with its RMS as the error.

Injection efficiency values are the average of all measurements stored in EPICS during the run. Errors are the RMS

Beam backgrounds depend on beam current, so care is taken to compare data from different runs with similar beam current ranges

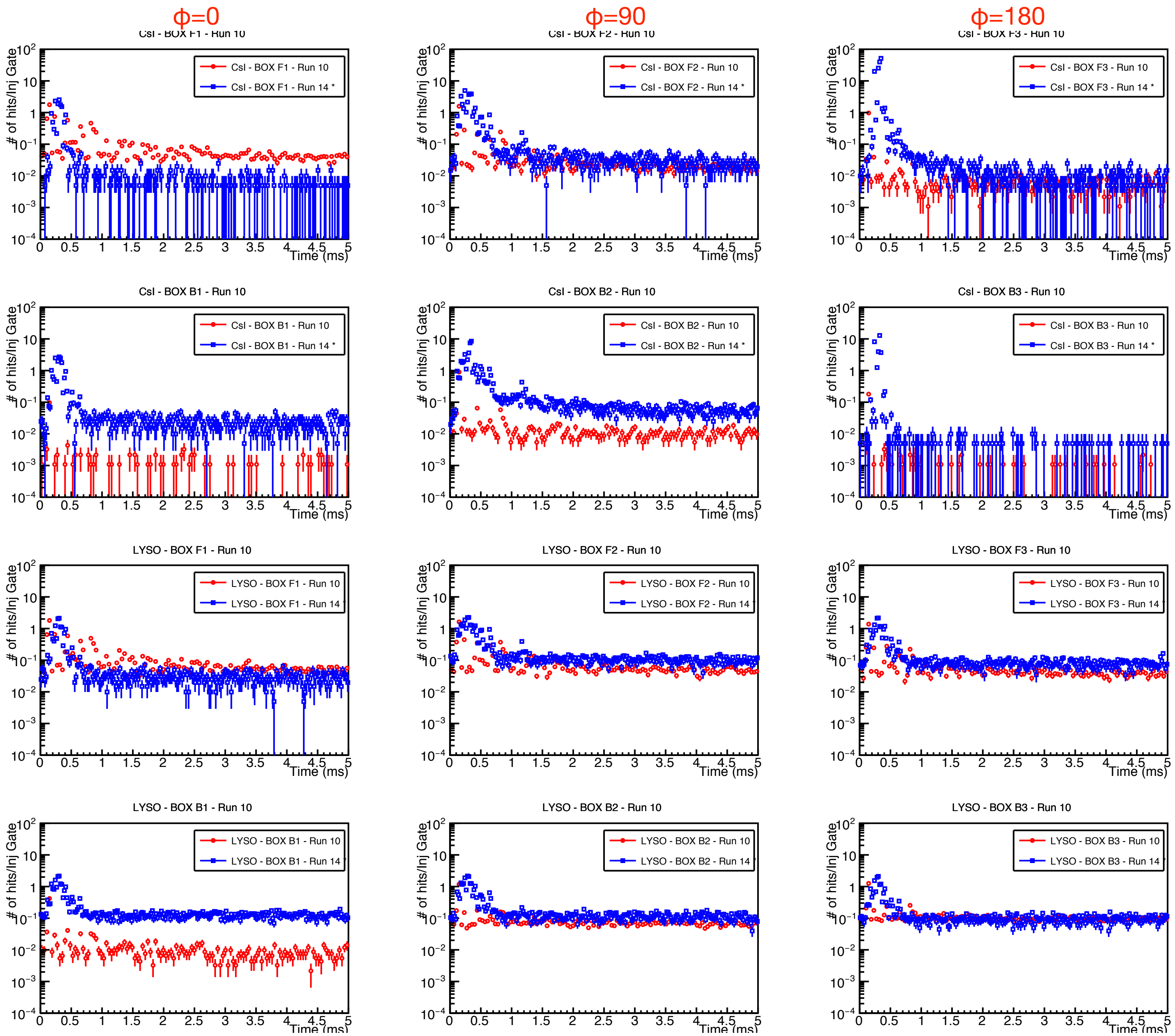
Each run lasted typically a few minutes accumulating ~few thousand injection gates

- This program was severely limited by time constraints
- However, we have plenty of injection data. If we can fetch from EPICS the history of these injection parameters we could find and analyse more data with:
    - Wider range of values for each parameter
    - Wider range of beam currents
    - Different values of injection efficiency

# Time Structure

- We are interested in the time evolution of the background hits correlated with the arrival of an injection gate
- Digitiser
  - We have a measurement of the injection gate made with the digitiser itself with 2 ns precision.
  - We can thus compute and plot the time difference of each hit from the gate time (time after injection, $T_{inj}$) for all the hits that have $T_{inj}$ within the gate width (~1 ms)
- Scaler
  - For each injection gate we have ~1500+ scaler readings spaced 3 μs apart in time. We compute the scaler time difference with the injection gate using the common Unix Time stamp known with μs precision as a reference.
- To have sufficient statistics in the extremely fine time bins we must sum more contiguous injection gates, being careful that the beam conditions affecting the backgrounds (i.e. current) do not change too much over the time spanned by the sum
  - Typically 2-300 gates are sufficient
- To compare different data, we normalise all plots to the number of gates over which we sum

# Time Structure - LER vs HER




CsI: FWD, BWD

LYSO: FWD, BWD

Scaler Data

Blue = LER run #14

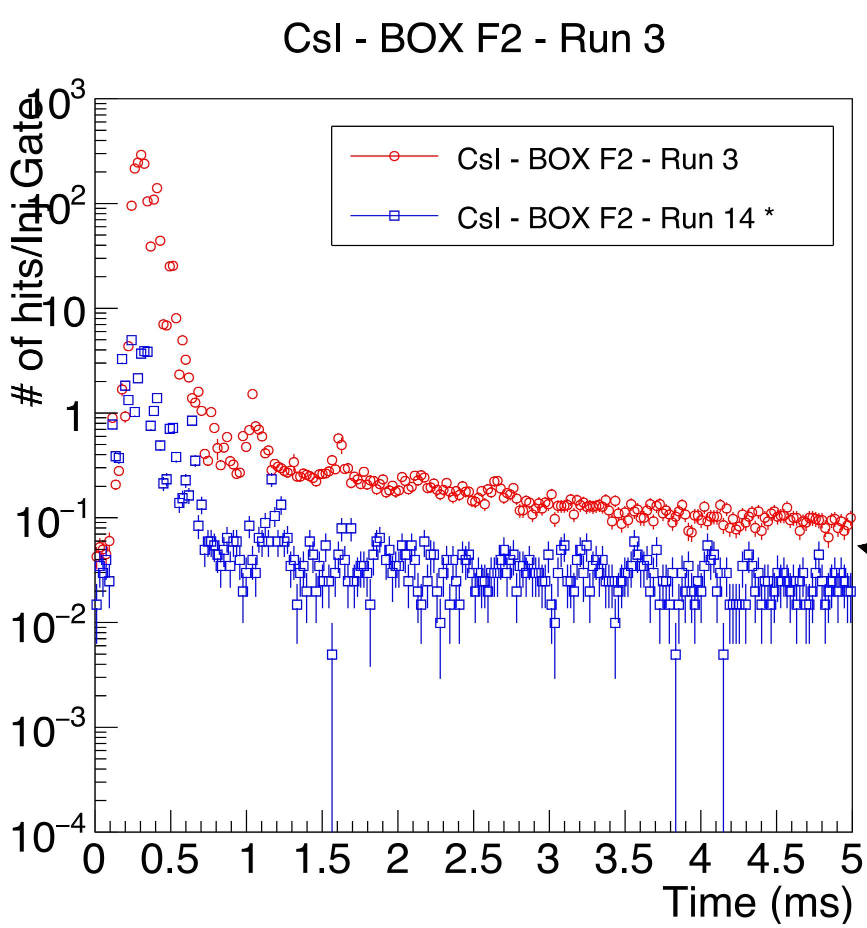
Red = HER run #10

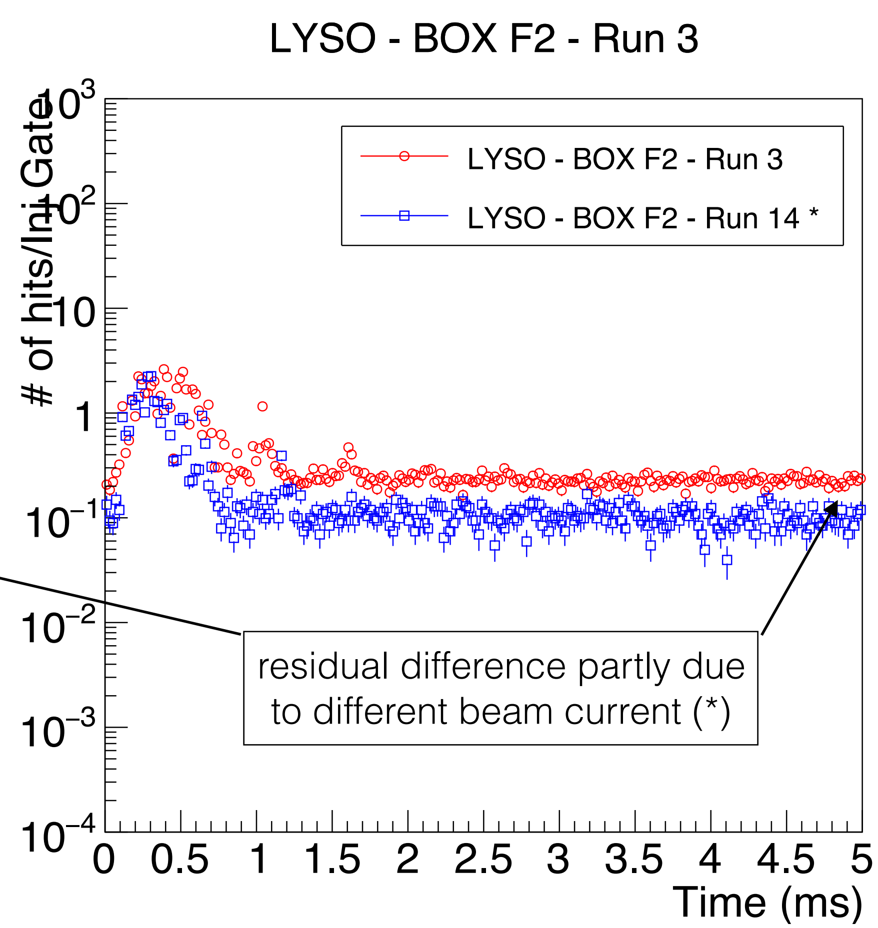
$I_{beam}$ 140 mA

NB: Comparing two reference runs

- LER injection backgrounds are overall higher than HER
- Hit rate peaks at $T_{inj}$ <1ms, ~2-3 order of magnitude higher than for $T_{inj}$ >1ms

# Time Structure - Injection Phase




**LER**

Scaler Data

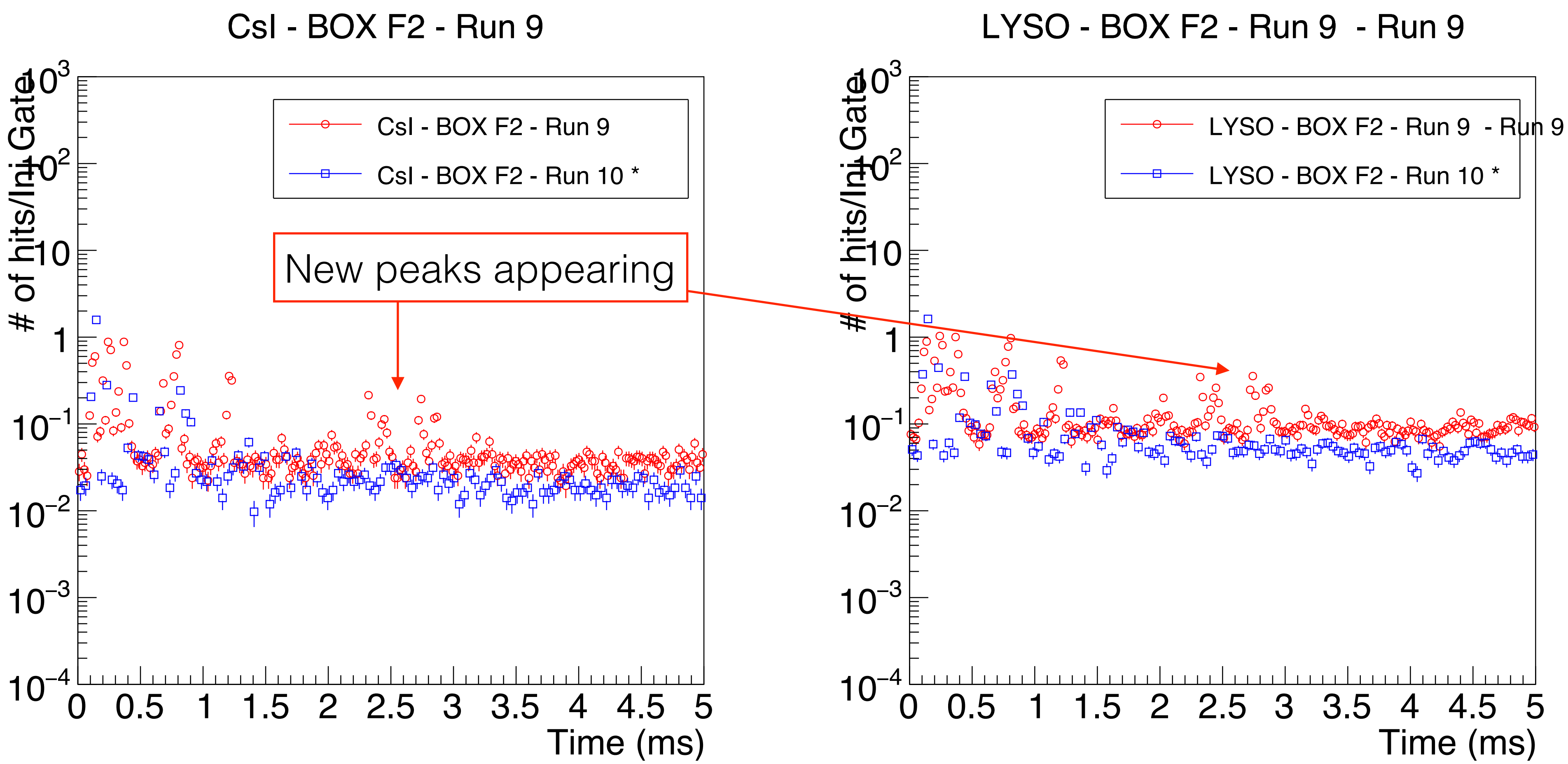
Blue = run #14, reference
Red = run #3

Injection phase angle = 31°

- Changing the injection phase from 1° to 31° produces higher backgrounds, as expected
- Slower decay after injection recorded by CsI

(*) In this case the average beam currents for the two runs were slightly different, I=330 mA for run #3 and I=285 for run #3

# Time Structure - Injection Phase




**HER**

Scaler Data

Blue = run #10, reference

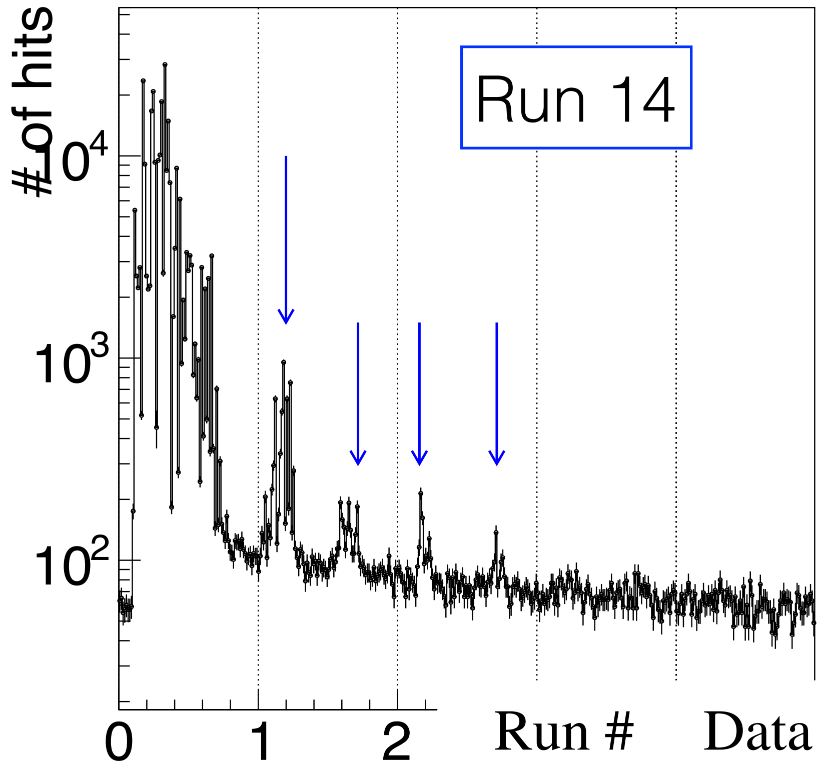
Red = run #9

Injection phase angle = 31°

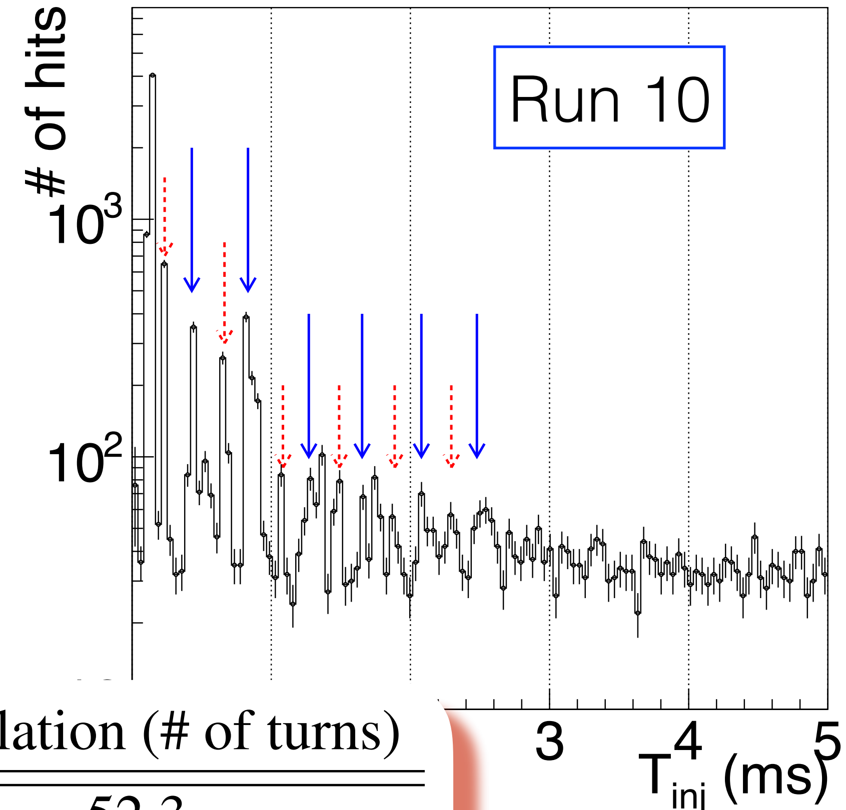
- Changing the injection phase from 258° to 305° does not produce much higher backgrounds, as it was the case for the LER. The observed difference can indeed be accounted for by the factor of ~2 in the beam currents (*).
- However: several peaks, spaced by ~450-500 us, appear at Tinj~2.5 ms which were not there

(*) In this case the average beam currents for the two runs were different by a factor ~2, I=310 mA for run #9 and I=140 for run #3

# Synchrotron Oscillations



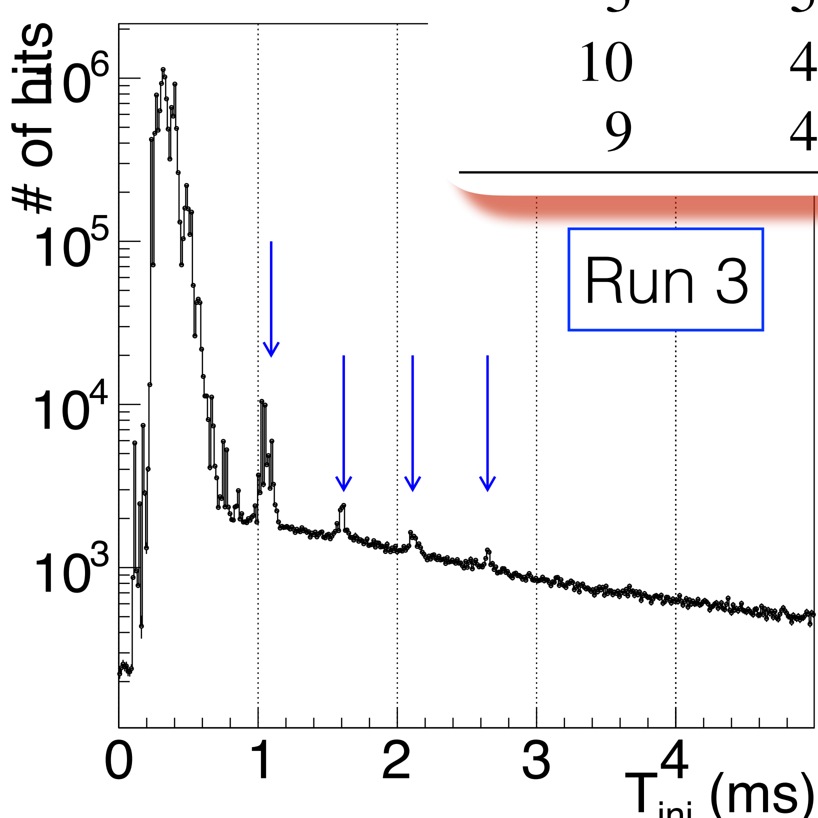

Nominal:
HER 40.7
LER 50.5



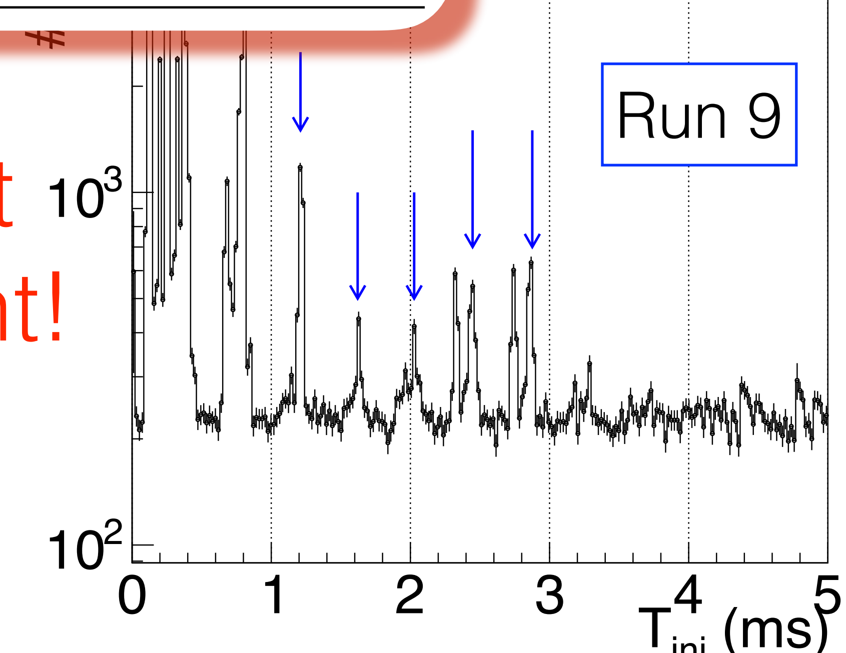

LER

HER

| Run # | Data (# of turns) | Simulation (# of turns) |
|---|---|---|
| 14 | 52.5±0.5 | 52.3 |
| 3 | 53.1±1.4 | 53.3 |
| 10 | 40.6±0.7 | 40.6 |
| 9 | 41.7±1.0 | 42.4 |




Excellent
Agreement!



# Time Structure

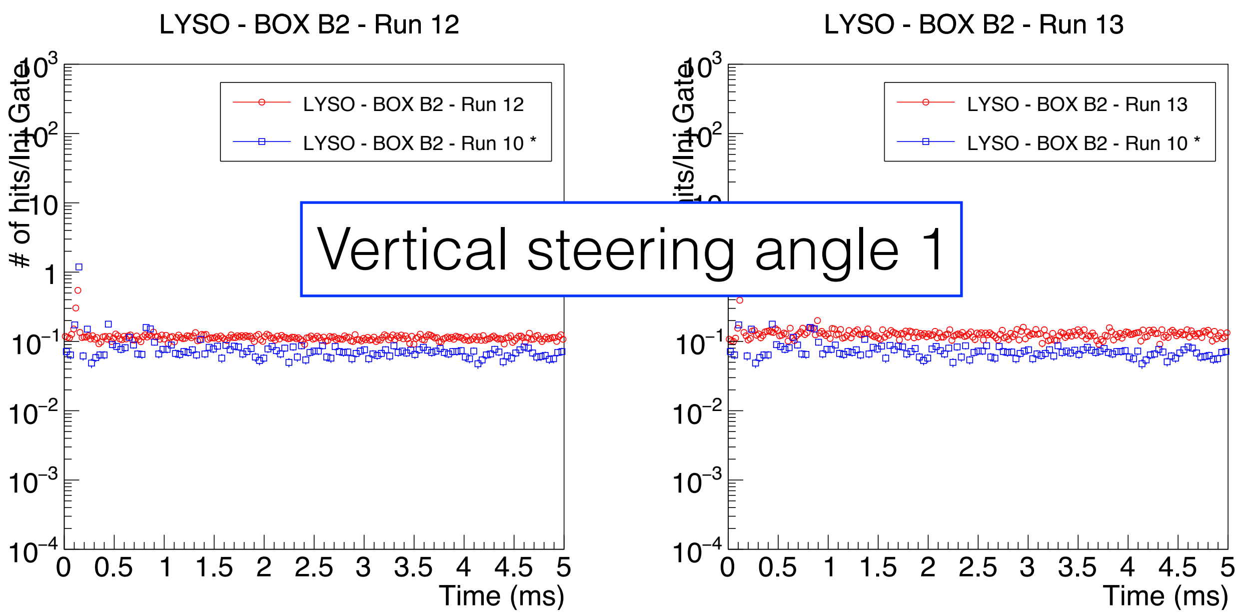



Figure 9: Hit rates recorded by the LYSO crystal in positions B2 for two different values of Vertical Steering Angle 1: -0.465 mrd (red circles, left) and -0.435 mrd (red circles, right), Blue squares: reference value -0.385 mrd in both (colors online).

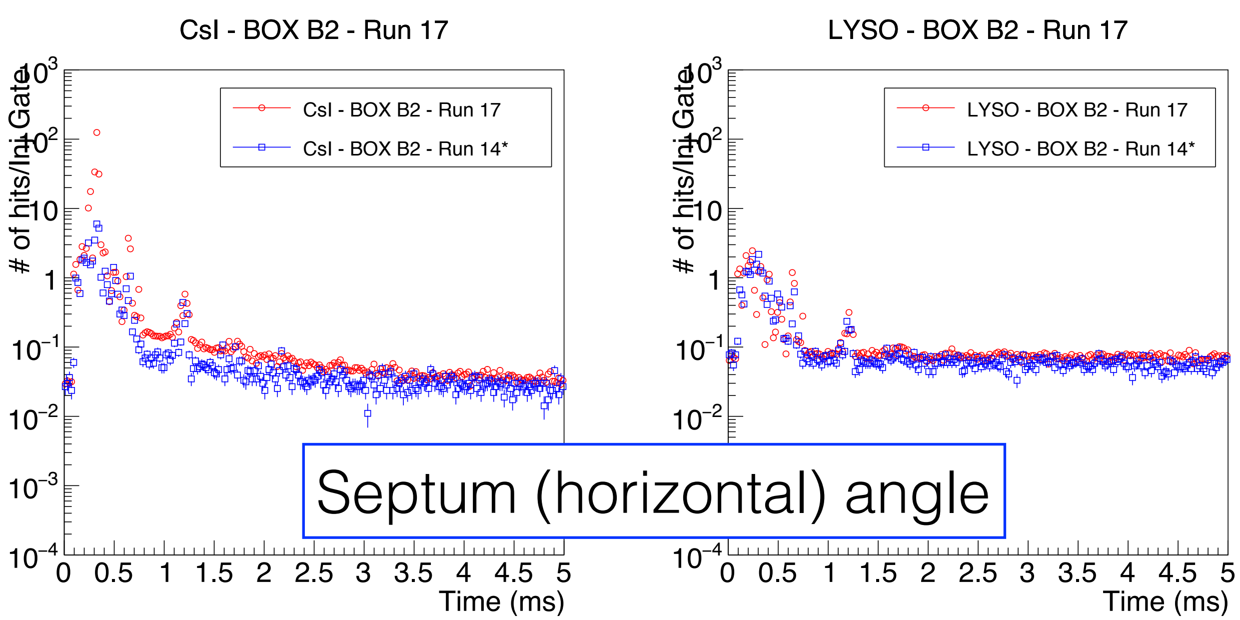



Figure 10: Hit rates recorded by the CsI (left) and LYSO (right) crystal in positions B2 when the spetum angle was changed from 5.51 mrad to 5.31 mrad in run # 17. Blue squares: reference run # 14 in both (colors online).

- Little effects observed when changing the other parameters
- Maybe the range of change was not sufficient?

# Time Structure - Digitiser

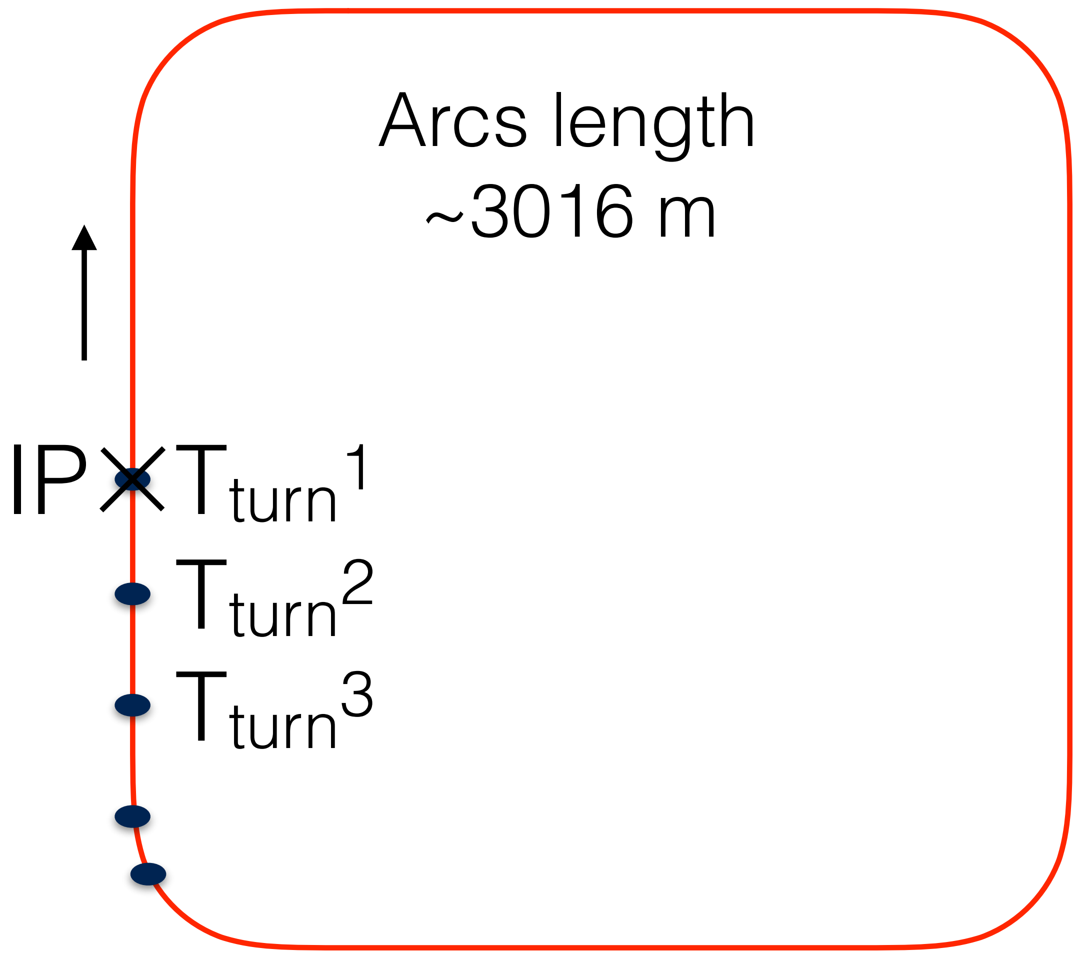
- Time to complete 1 turn = 10.0614 μs

- Each bunch crosses IP at a different time $T_{turn}$ between 0 and 10.0614 μs, which is fixed by its position in the bunch train

- We can obtain this time by using the time after injection $T_{inj}$ which is synchronised with the machine time because it uses the injection gate as a reference, in the following way:

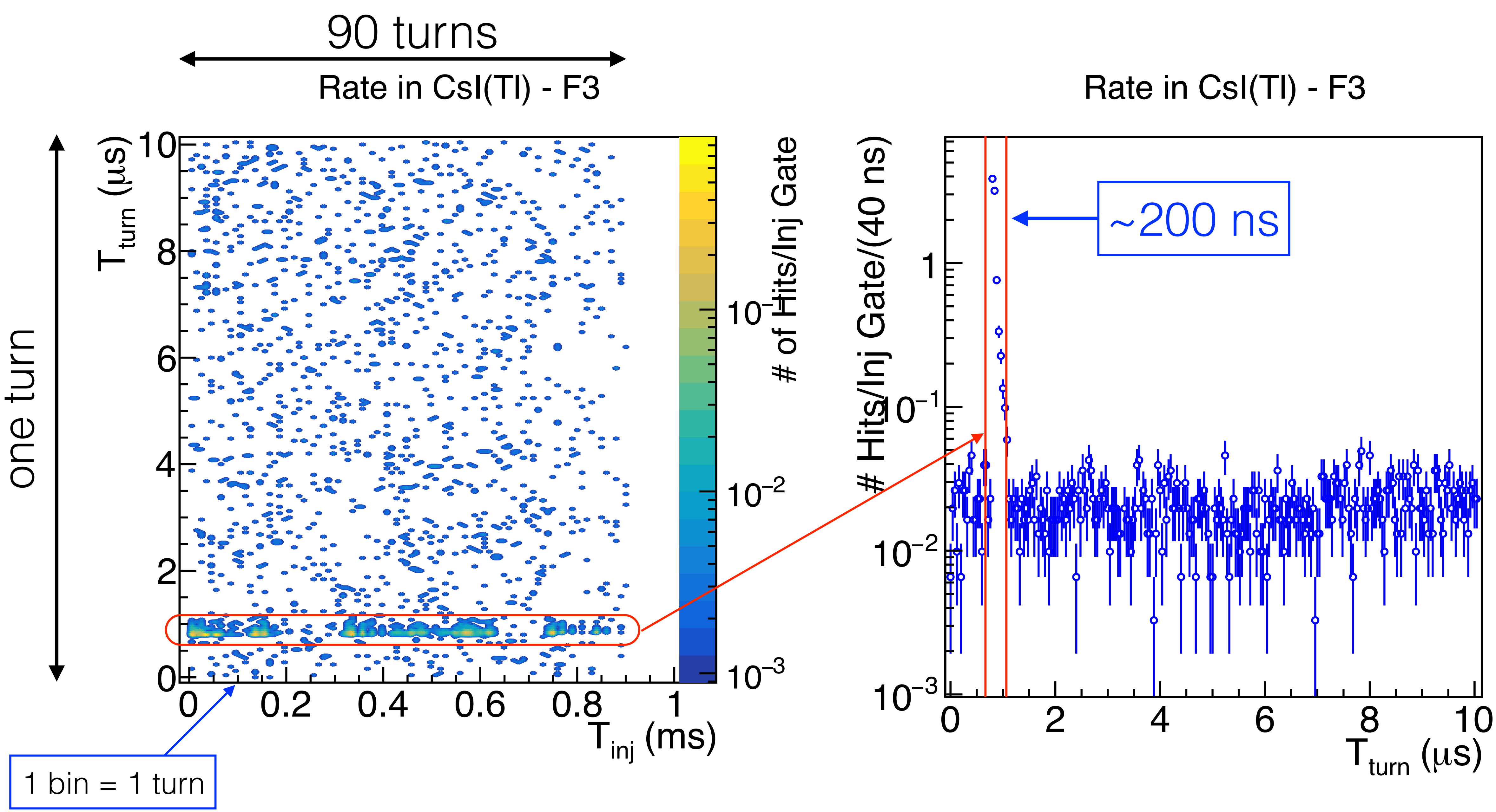
  $T_{turn} = T_{inj}$ (in ns) modulo (100614 ns)

- Of course there is a time offset that can be accounted for, but is not relevant in our case




NB: this measurement cannot be done with the scaler because of the 3 μs time bin width

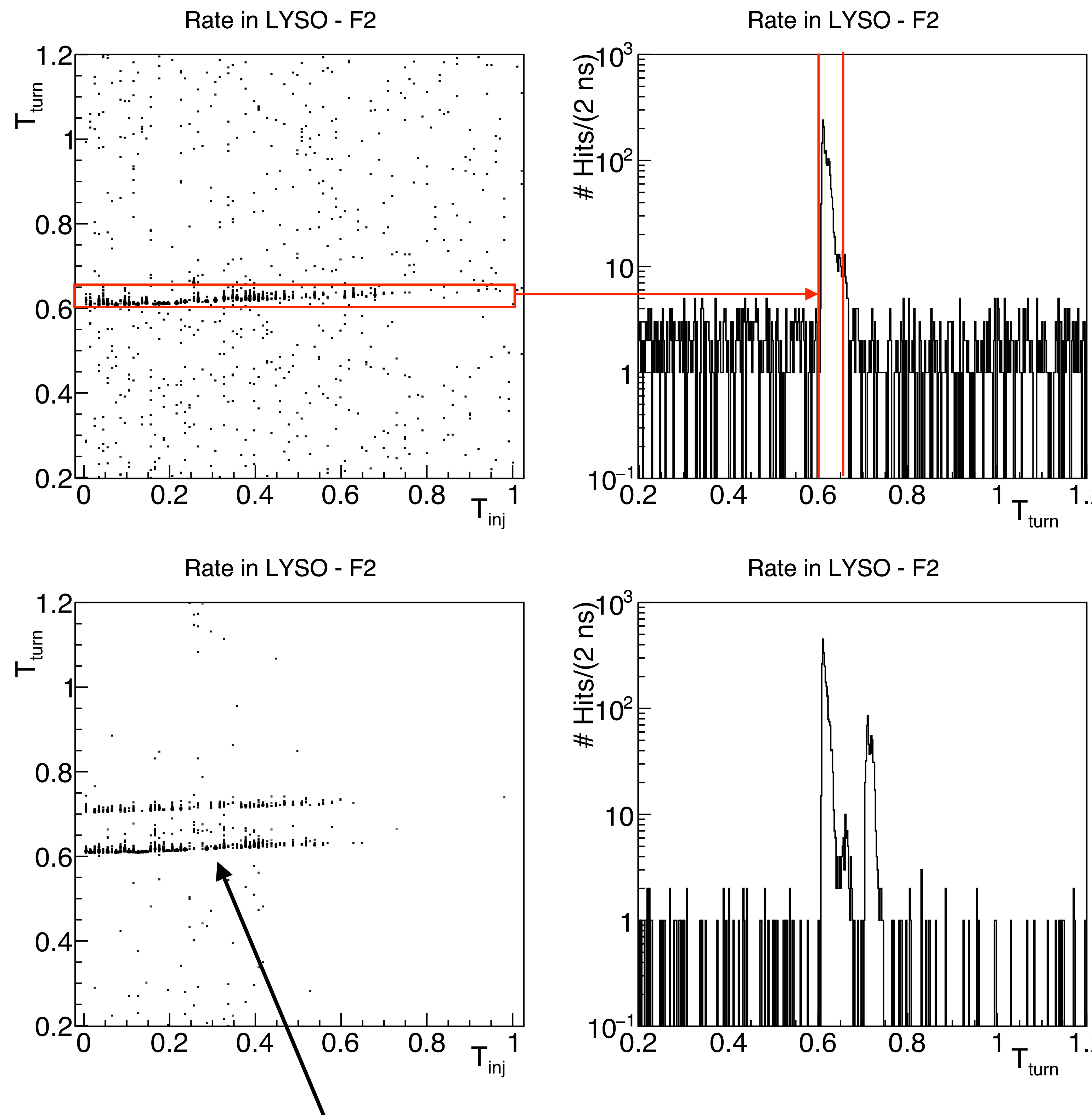
# Time Structure




Equal $T_{turn}$ means same bunch → a few bunches

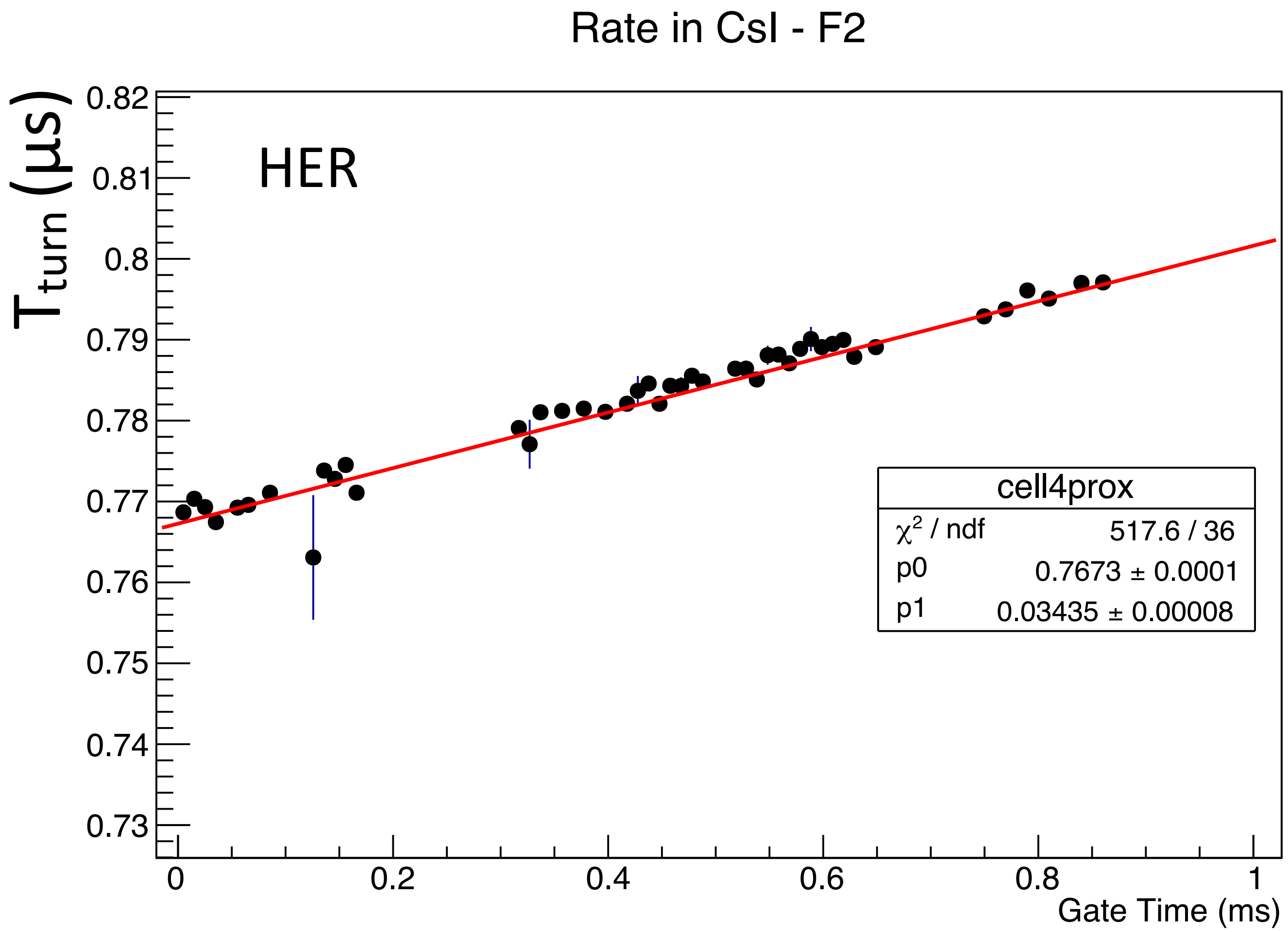
# Time Structure 1-bunch vs 2-bunch Injection

- Clear evidence that crystal hits are strongly correlated in time with the **injected bunch**
  - Measuring injection background!
- The calorimeter acquisition could be vetoed for a full ms, but only for a few 10s of ns around the time of passage of the injected bunch through the IP (red box)
- This could be done separately for each injected bunch




What’s this slope?

# Orbit Revolution Time




$T_{turn}$ = Gate Time mod ($T_{rev}^{nom}$)

Nominal Revolution Time
$T_{rev}^{nom}$ = **10061.4** ns

- The observed slope is due to a small shift in the value of $T_{rev}$ assumed in the modulo operation. This small shift is calculated using the measured slope

$T_c$ (ns/turn) = 1000*p1 (μs/ms) / [1000/10.061 (turn/ms)] = +0.346 ns/turn

$T_{rev} = T_{rev}^{nom} + T_c = 10061.346 \pm 0.003$ (stat) $\pm 0.06$ (syst) ns

# Belle II Note/Paper Status

- Text describing the time structure is complete and has been reviewed by the internal reviewer
  - Editing final text now
- The part discussing the energy and the measurement of the integrated dose during injection will be the subject of a different dedicated note
- NIMA Paper based on this note to be submitted by beginning of June

# Summary

- The dependence of injection background hits in the calorimeter crystals has been studied in details
  - The background is highly correlated in time with the injected bunch (~ ± few 10ns for pure CsI/LYSO, maybe slightly larger for CsI(TI)). Very relevant information to be able to design an effective DAQ veto
  - Despite the high variability of background levels and time development between different positions, injection conditions and crystal types, a common feature is that the background quiets down within 1-1.5 ms after injection
  - The crystal data is very sensitive to beam oscillations in space and provides a very powerful diagnostic tools for SuperKEKB operators
- A measurement of the dose integrated by the crystals during injection and during coasting is the next priority
  - Compare MC predictions to coasting data, and estimate the total dose to be expected during Bell II data taking runs using the injection to coasting dose ratio