Beam-beam effects on the luminosity measurement at FCC

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With inputs from Nicola Baccheta, Helmut Burkhard, Mogens Dam, Dima El Khechen, Patrick Janot, Mike Koratzinos, Daniel Schulte

- Last presentation on these aspects to this WG : talk from Yorgos, https://indico.cern.ch/event/709474/contributions/2918547/attachments/1611999/2560083/EM_Deflection_mdi_060318.pdf
- All numbers shown here refer to FCC at the Z peak.

Introduction and recap

- Determine the luminosity from the rate of Bhabha events, measured in two forward calorimeters centered around the outgoing beam-pipes.

  z (start) = 1074 mm
  sensitive region : 55 mm < R < 115 mm
  shower containment : measurement within 64 – 86 mrad

  corresponding σ(Bhabha) = 14 nb

- Precision measurements programme (esp. Z) requires precise normalisation

- To match the anticipated theoretical precision, the goal is to reach an experimental uncertainty of 10-4 (absolute), and 5 10-5 (relative, line-shape scan)
  - Ambitious !
  - Beam-beam (-like) effects lead to a bias, 15-20 x larger than the target precision …

Recent review: Mogens's talk at the January FCC-ee workshop,
https://indico.cern.ch/event/766859/contributions/3250135/attachments/1775746/2887087/LumiJanuaryWorkshop.pdf

Beam-beam effects and Bhabha events

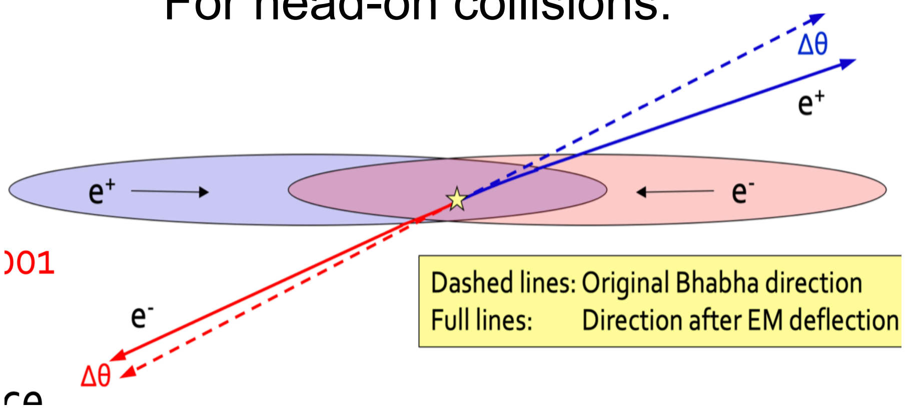
- Prior to interacting : the initial state e- and e+ feel the EM field of the opposite bunch
  - Angular deflection (LEP emittance scans, “pinch effect”) + beamstrahlung

- After the interaction : the final state e- and e+ (outgoing, towards the LumiCal) also feel this field are are focused.

The # of e+/- that end up in the acceptance of the LumiCal is reduced.
Leads to a bias in the luminosity measurement.

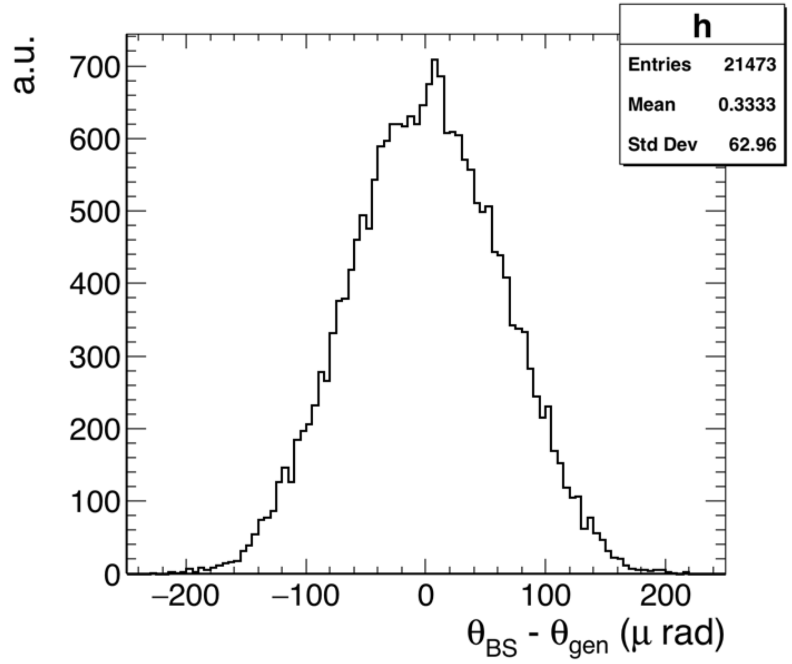
First considered in the context of ILC

For head-on collisions:

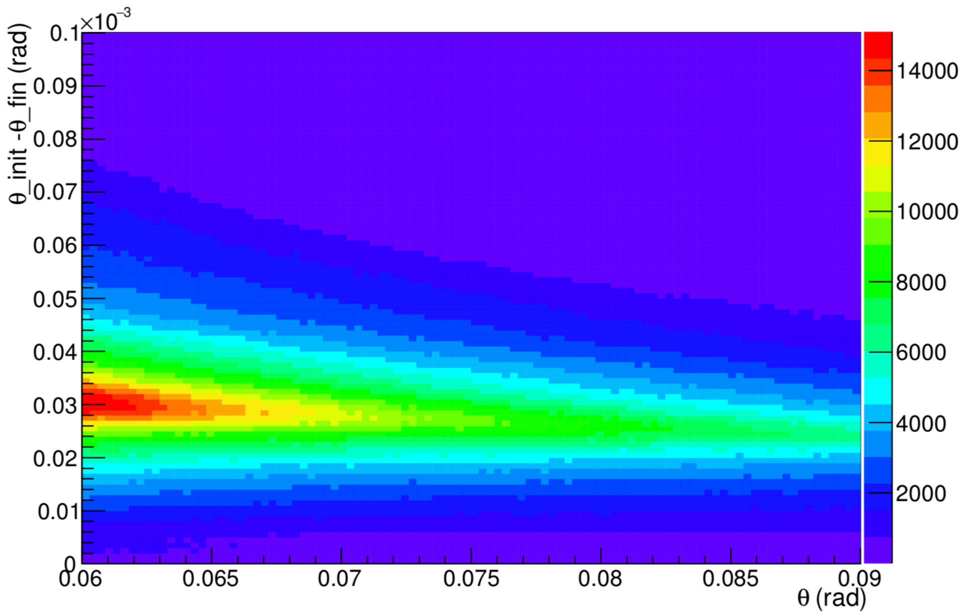


Here : studied numerically using
- (primarily) Guinea-Pig : events generated by BHWIDE
- also independent calculation based on standard formula for the fields

Beam-beam effects and Bhabhas, Guinea-Pig



- Initial state : smearing of θ, but with a negligible effect on the average polar angle : < Δθ > = 0.3 ± 0.4 μrad
  - No bias on the luminosity



- Focusing of the final state : Angular deflection : 30 μrad at θ = 60 mrad.

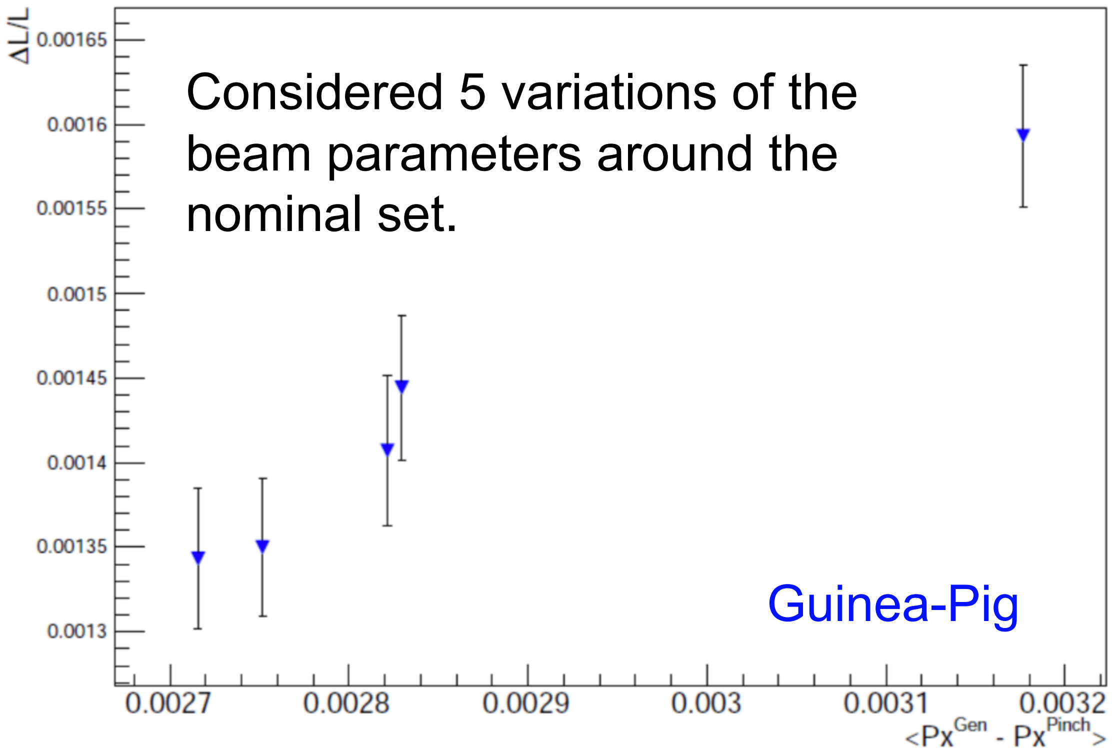
Large ! Bias on the luminosity : typically 0.15 %
15x larger than the target precision

Needs to be corrected for. The precision on the correction factor should be about 7% to ensure a residual systematic below 10^{-4}.
Correction can be calculated in principle… but depends on beam parameters, that we may not know very precisely. Desirable to determine it experimentally.

The kick gives the luminosity correction !

We see a strong correlation between the luminosity bias and the kick.

Expected : ΔL is due to the "EM focusing" of the final state Bhabhas. The kick is very much the same effect, but applied to the initial state instead of to the final state.



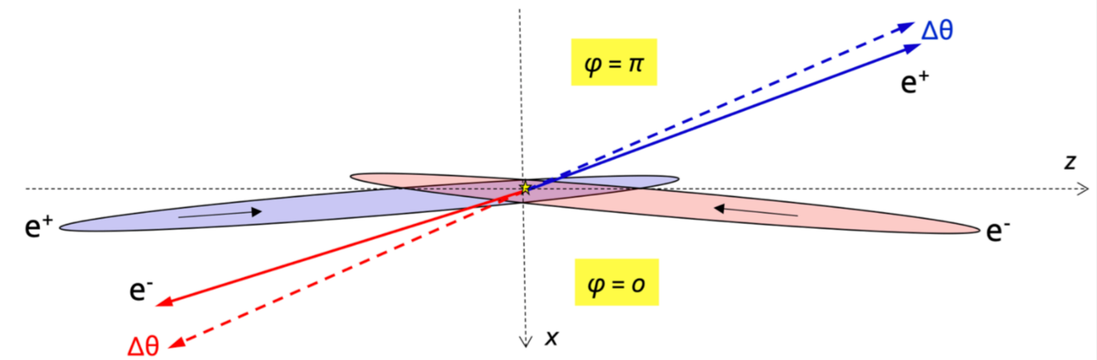
The kick can be measured to the per-cent level – see talk by Patrick.

Hence a similar precision on the bias – well within the 7% needed to reach the goal of 10^{-4}.

The next slides show that an independent determination of this correction factor can also be made, relying solely on Bhabha events in the Lumical.

Azimuthal dependence of the focusing

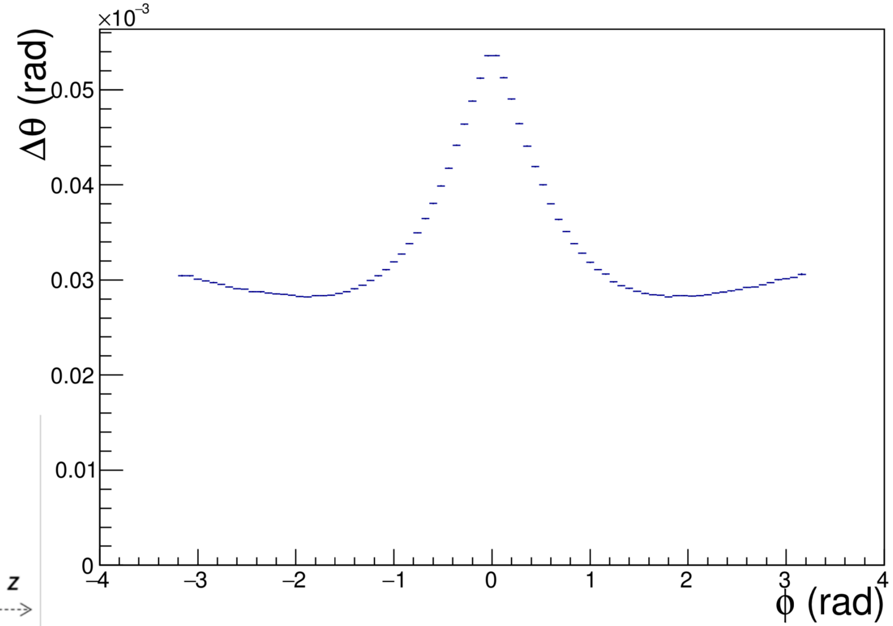
Strong φ dependence of the
EM focusing of the final state $e^{\pm}$
Consequence of the crossing angle.

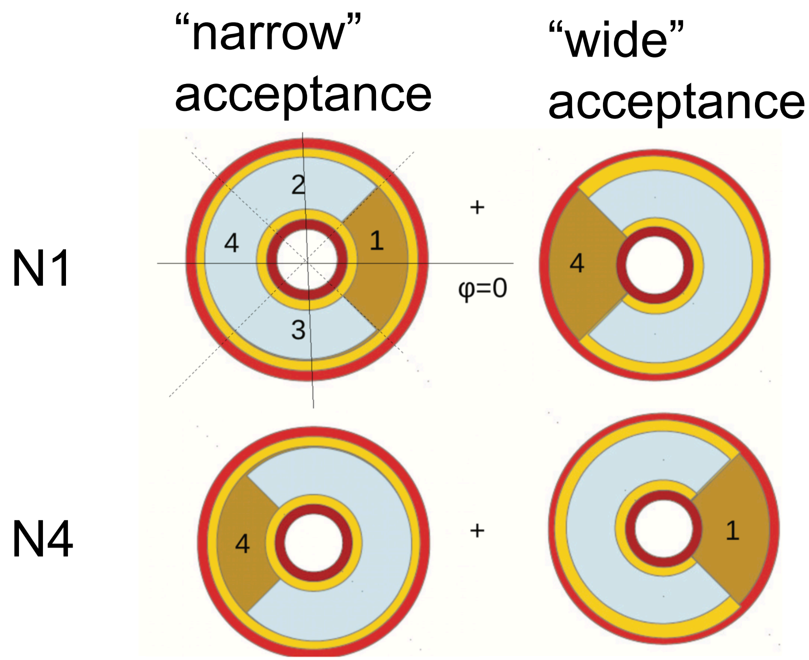


e- at φ = 0 feels a stronger force than the e+
at φ = π, since closer to the opposite bunch

Exploit this φ dependence and build
an asymmetry, from the counted
rates in the LumiCal :

$$A = (N4 - N1) / (N4 + N1) \quad > 0$$

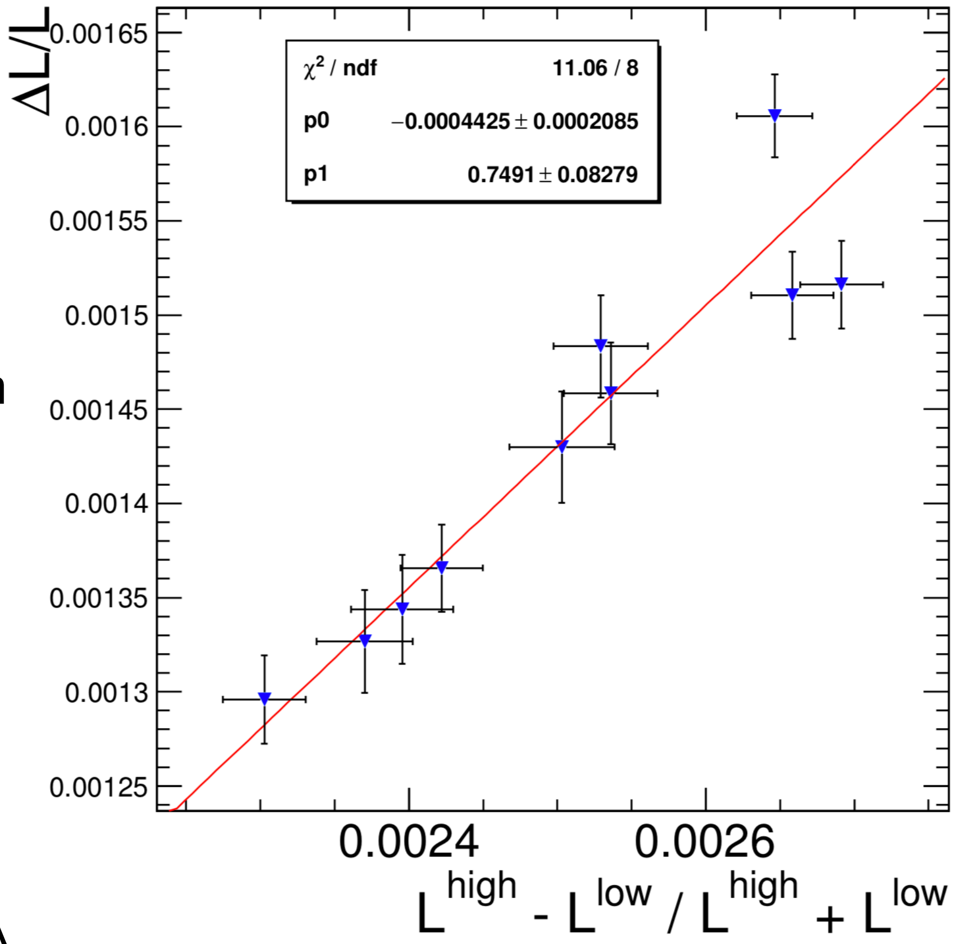




Luminosity Asymmetry and beam parameters

The size of this asymmetry A must reflect the size of the focusing effect
- hence the size of the luminosity bias

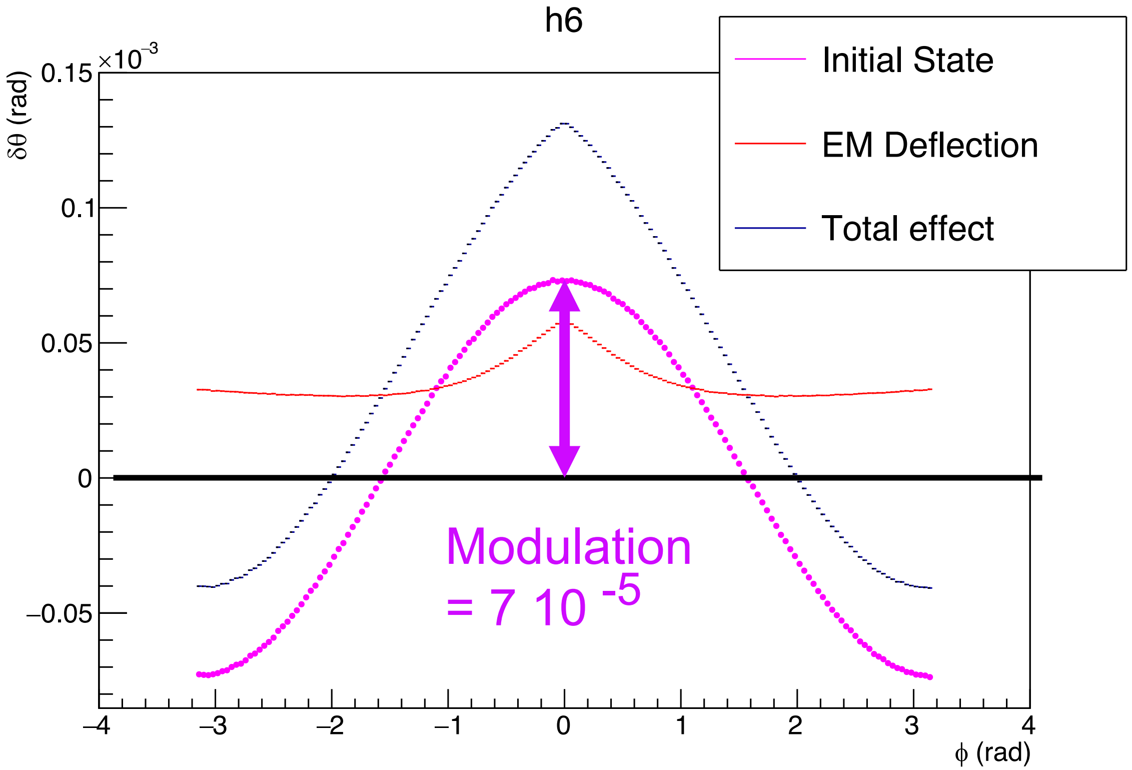
Verification : several variations of the beam parameters around the nominal set, produce a Guinea-Pig sample for each; determine A and ΔL
→ the luminosity bias is indeed proportional to the asymmetry



Hence :
- Use GP simulations to map the bias & A
- An experimental measurement of A then gives the correction factor

But… this asymmetry does not come only from the EM focusing !!

Asymmetry and mis-alignment..



Here comes the kick again…

When $p_x \rightarrow p_x + k_x$:

$p_T \longrightarrow p_T + k_x \cos\varphi$

and $\theta \longrightarrow \theta + k_x / p_z \cos\varphi$

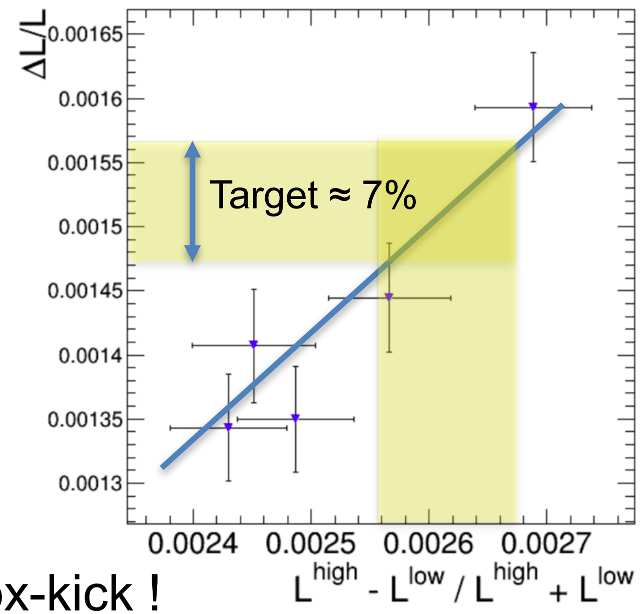
Hence a Δθ due to beam-beam effects in the initial state, that shows a φ modulation with amplitude = 3 MeV / 45 GeV = $7\ 10^{-5}$

This effect dominates the asymmetry. Total asymmetry is about 0.25%, while that due to the sole EM focusing is about 0.03 – 0.04 %.

Problem: a mis-alignment of the Lumical along the x-direction will cause exactly the same effect as a px-kick !

[px-kick of 6 MeV / event ↔ misalignement δx = 55 μm]

Asymmetry : beam-induced versus non beam-induced



The asymmetry A has three sources :

- the EM focusing on the Bhabha $e^{\pm}$ (small…)
- the px-kick
    - introduces a modulation in φ of the Bhabha counting rate
- possible mis-alignements
    - in particular, a misalignment along x produces a phi modulation similar to that induced by the px-kick !

They add up : $A(L) = A_{EM} + A_{Kick} + A_{misalign}$

A_{EM} and A_{Kick} : induced by the beam effects, scale linearly with Npart / bunches.
$A_{misalign}$: independent of N/bunch.

Measuring $A(L)$ in bunches with different Npart can give access to A_{Beam} and $A_{misalign}$ …

First example : assume three types of trains

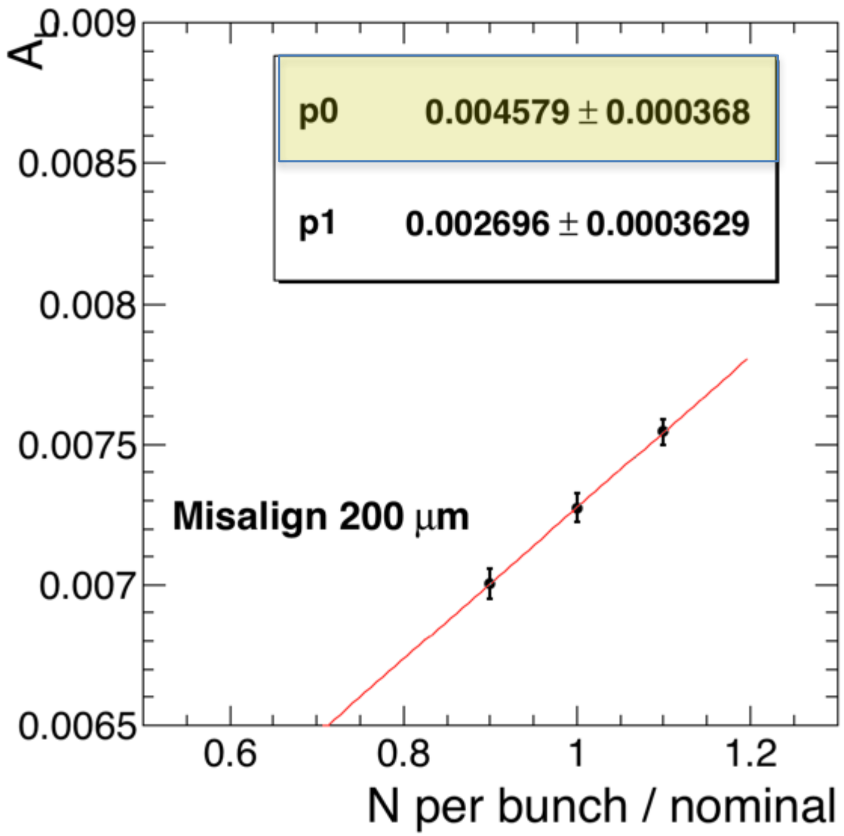
Assume equal sharing of 3 types of trains : N, 10% higher, 10% lower

Consider two sources to A(L) :

- the px-kick, k = 5 MeV : dN / dφ = 1 + a cos(φ) with a \propto k / pT
- a misalignment of one LumiCal by δ = 200 μm, along x :

  dN / dφ = 1 + b cos(φ) with b \propto δ / R_{min}

  (exact expressions used in the calculation)



A_{Kick} = 0.27% $A_{misalign}$ = 0.46%

Measure A(L) in the three types of bunches, from the statistics integrated in 10 minutes.

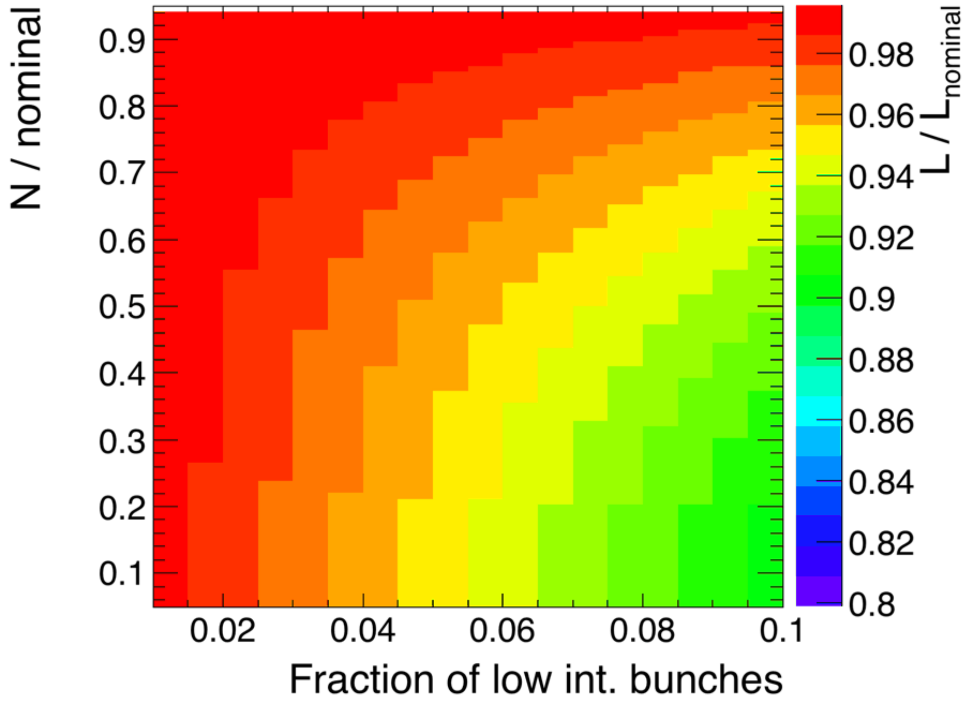
Intercept determined with a relative uncertainty = 13% of A_{Kick}

Within 40 min, one gets the intercept with an uncertainty < 7% of A_{Kick}

(15 min enough for δ = 10 μm)

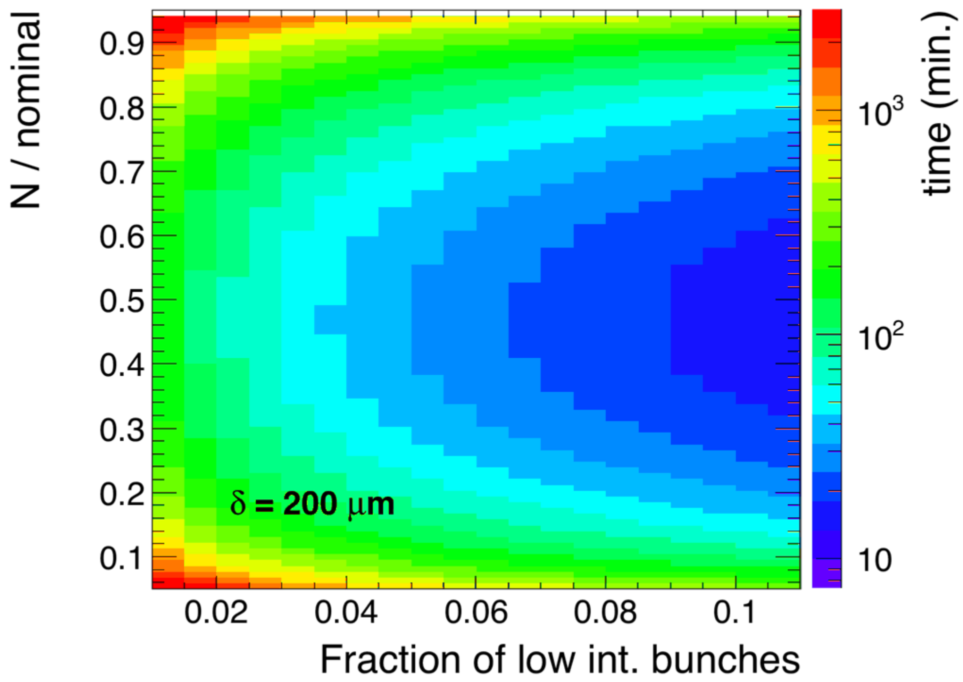
Second example, two measurement points

Assume that a fraction of the bunches are filled with a lower intensity than the nominal one.



Want to minimize the luminosity loss,
Still allowing a measurement of
A $_{misalign}$ on a time-scale << fill duration.

Low intensity : larger lever-arm… but low statistics !



With 3% of the bunches at 60% of the nominal intensity:

- < 2 % lumi loss
- would need 120 min to get the intercept with the required precision if δx=200 μm (30 min for δx=10 μm)

Or use the filling of the machine !

Patrick had the idea to use the filling of the machine, at the beginning of each fill. N/bunch is gradually increased

- e.g. adding 10% of the nominal N per cycle

The beams do collide during this filling, and the beta* is the nominal one !

[That's what he is exploiting to measure the increase of the crossing angle (and of the energy) due to the beam-beam effects – see his talk earlier at this meeting]

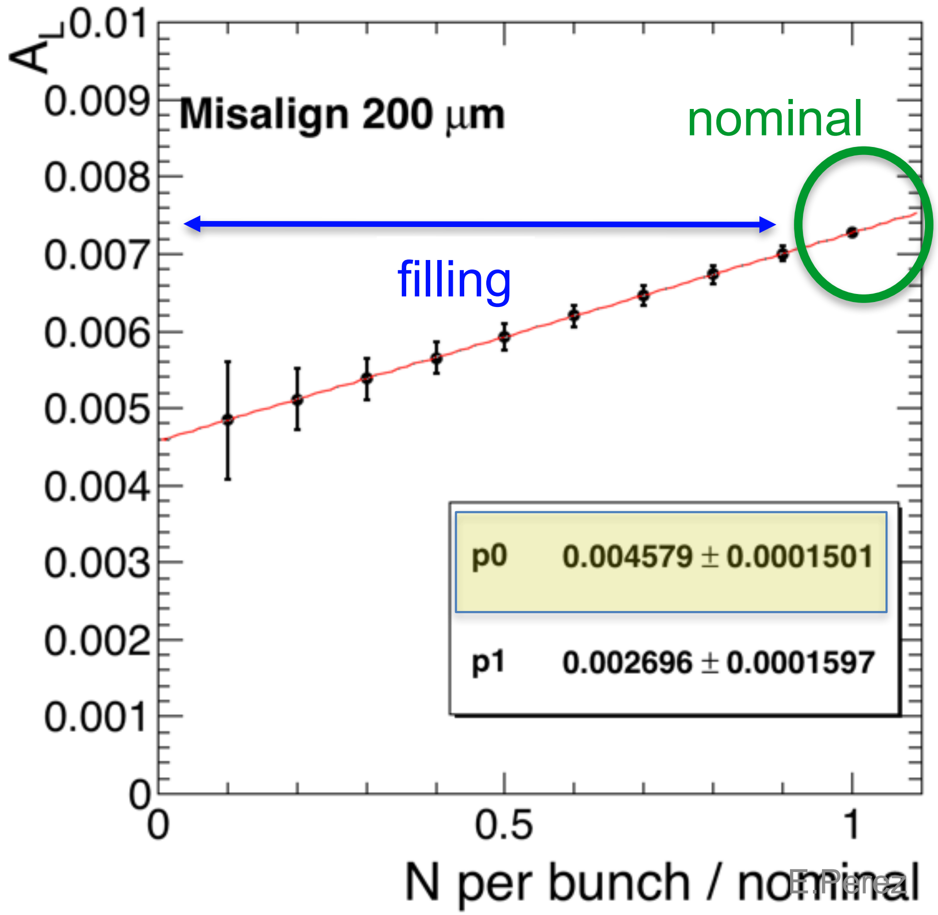
Assume :

- One measurement during 1 min at each filling step (10%, 20%, etc)
- One measurement of 10 min at the nominal intensity

200 µm: Intercept determined with a relative uncertainty < 6% of A_{Kick}

10 µm : 2.7 % of A_{Kick}

All this during ramp + 10 min, no luminosity loss !



Conclusions and to-do's

We think it is possible to control the luminosity bias due to the EM focusing of the Bhabha electrons.

via the measurement of the px-kick

or in-situ measurement using a phi-asymmetry in the Lumical :
- mis-alignment effects can be disentangled from beam-beam effects even under conservative assumptions for the mis-alignment

To-do : consolidation of numerical results
"maps" of $\Delta L/L$ versus A for many more beam-parameters scenarios and with smaller statistical errors
- may require more efficient calculations,
- or a way to model the main effects on $\Delta L/L$ and A from GP input