Beam-beam effects on the luminosity measurement at FCC

E. Perez, G. Voutsinas (CERN)

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

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 at $\sqrt{s}$ = 91.2 GeV

- 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, much larger than this target precision !

- All numbers shown here refer to FCC at the Z peak.

For a review on luminosity measurement at FCC: see talk by M. Dam, Tuesday

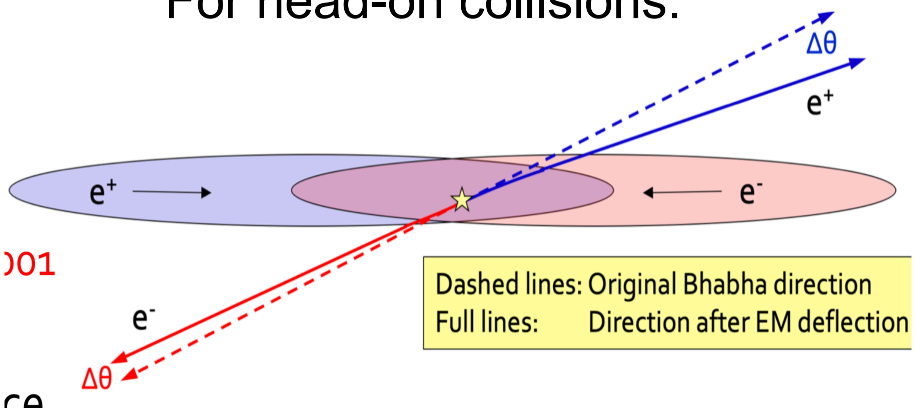
Beam-beam effects and Bhabha events

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

- 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.

For head-on collisions:



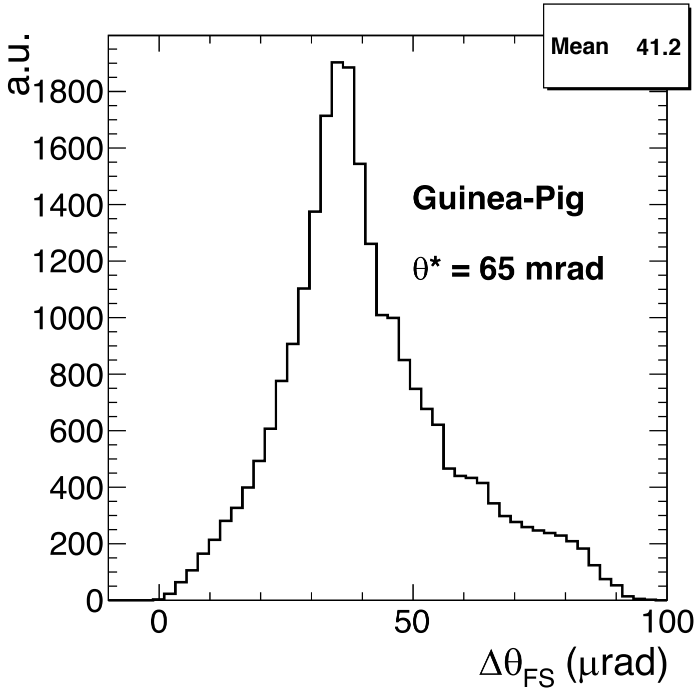
First considered in the context of ILC

[C. Rimbault et al., JINST 2 (2007) P09001]

Here : studied numerically using

- (primarily) Guinea-Pig (D. Schulte) : Bhabha events generated by BHWIDE, or “leading-order Bhabhas” with back-to-back e+/- of E = 45.6 GeV
- also independent calculation that determines average effects from analytical expressions of the EM fields.

Beam-induced focusing of final state Bhabha electrons



At $\theta = \theta_{min}$ = 65 mrad : $< \Delta\theta >$ = 41 μrad
At $\theta = \theta_{max}$ = 85 mrad : $< \Delta\theta >$ = 34 μrad

$$L \propto \int_{\theta_{min}}^{\theta_{max}} \frac{d\theta}{\theta^3}$$

Hence :

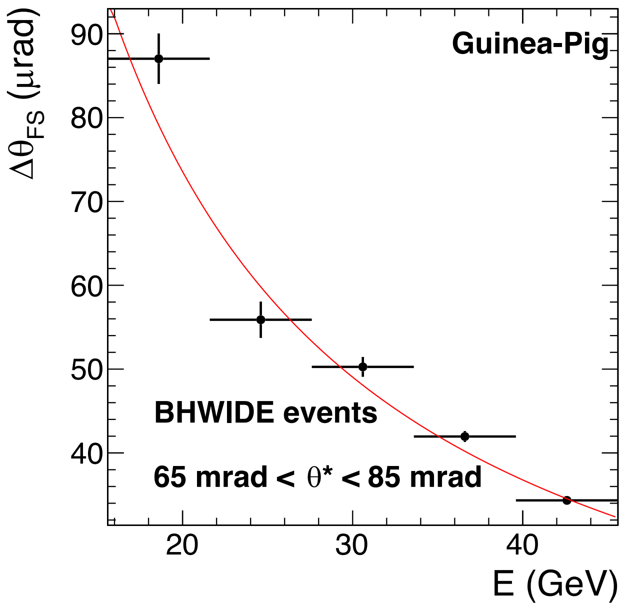
$$\Delta L / L = \frac{-2}{\frac{1}{\theta_{min}^2} - \frac{1}{\theta_{max}^2}} \left(\frac{\Delta\theta(\theta = \theta_{min})}{\theta_{min}^3} - \frac{\Delta\theta(\theta = \theta_{max})}{\theta_{max}^3} \right)$$

i.e. luminosity bias $\Delta L / L$ = - 0.19 %   (19x larger than the targeted precision)

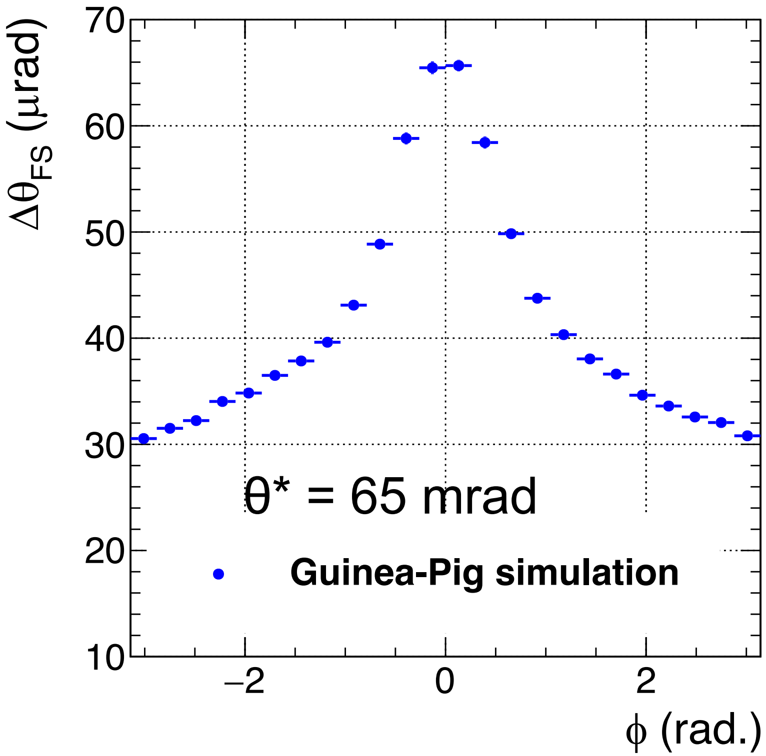
Needs to be corrected for. The precision on the correction factor should be about 6% to ensure a residual systematic below 10^{-4}.
Correction can be calculated in principle… but desirable to determine it experimentally.

Further characterization the beam-induced focusing of Bhabhas

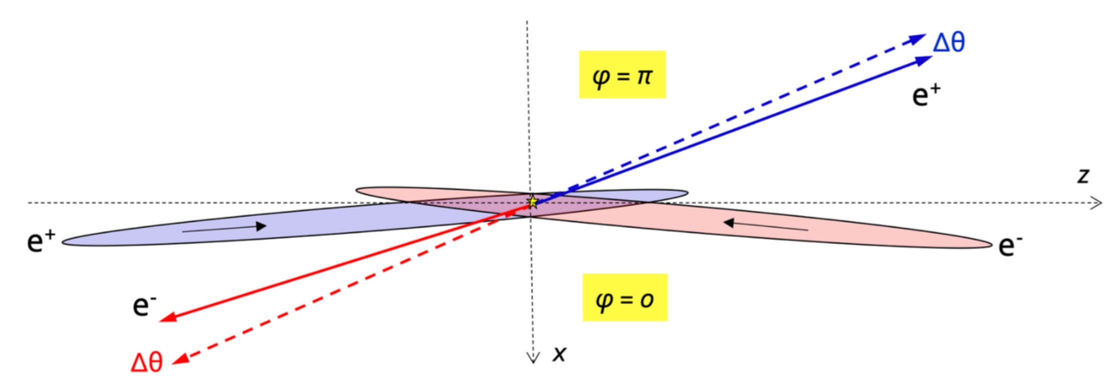
- Decreases with increasing θ, as expected
- Increases with decreasing E as 1 / E, as expected
- Focusing is not only along y (as would be expected for beams flat in y and with no crossing angle)



- Strong phi-dependence :

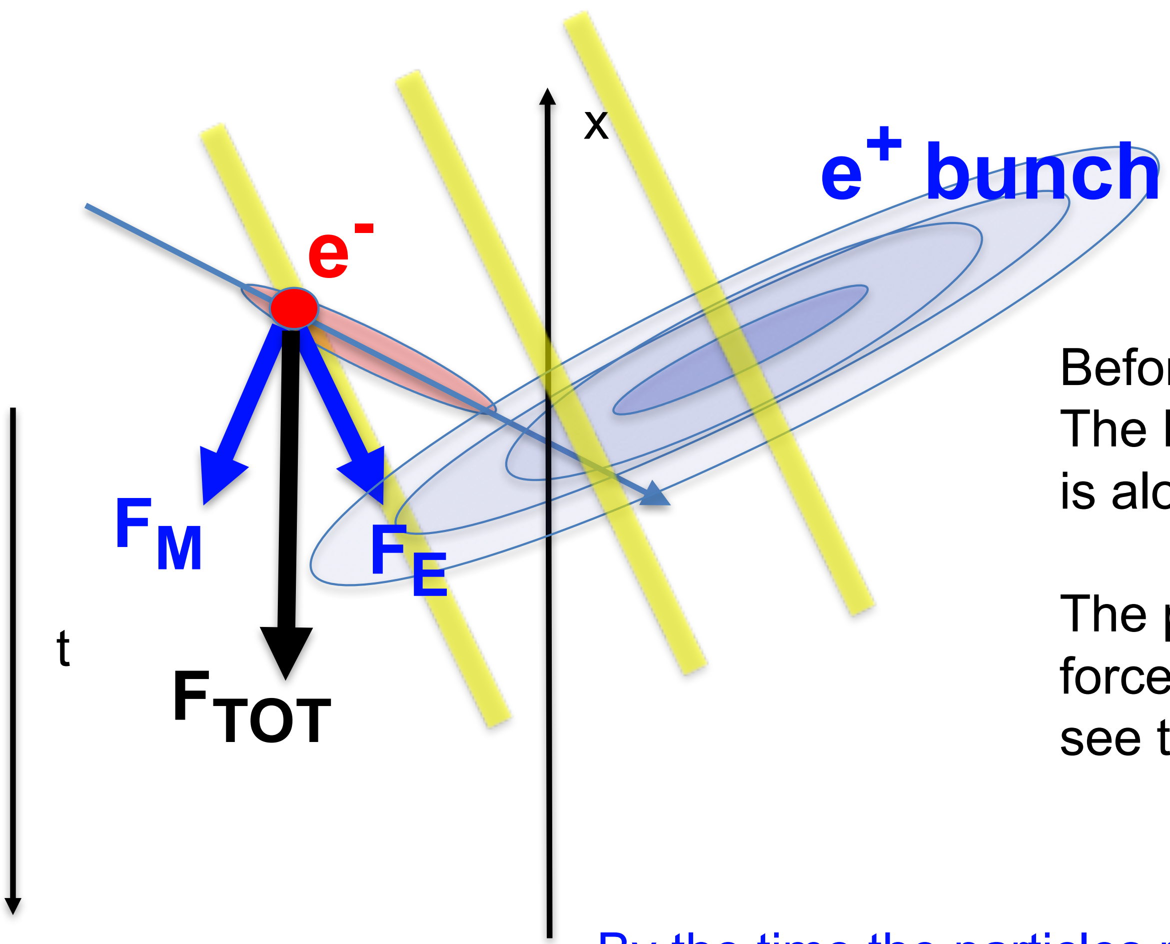


Consequence of the crossing angle :



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

Beam-beam effects on the initial state particles



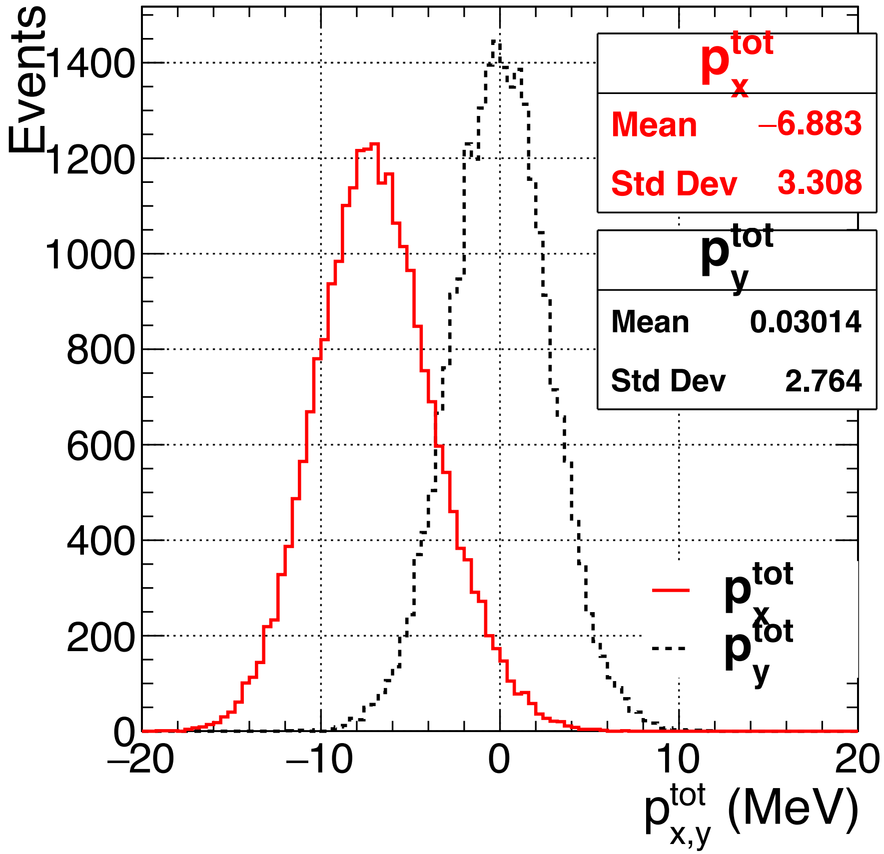
Before it reaches the IP :
The Lorentz force felt by the electron is along the x axis, pointing downwards.

The particle is accelerated by this force along -x, and it gains energy.
see talk by D. Shatilov on Tuesday

By the time the particles reach the IP and may interact, they have acquired a net momentum along (-) x.

≡ the “px-kick”

Beam-beam effects on the initial state particles : the "px-kick"



Total momentum of e^+e^- events as predicted by Guinea-Pig.

(in a frame that moves along x together with the bunches)

Events are boosted along x :
$| < p_{x,\ tot} > | \approx 7$ MeV

Corresponds to an increase of the effective crossing angle by about :

$\Delta\alpha \approx$ kick / $E_{beam} \approx 0.5\%\ \alpha$

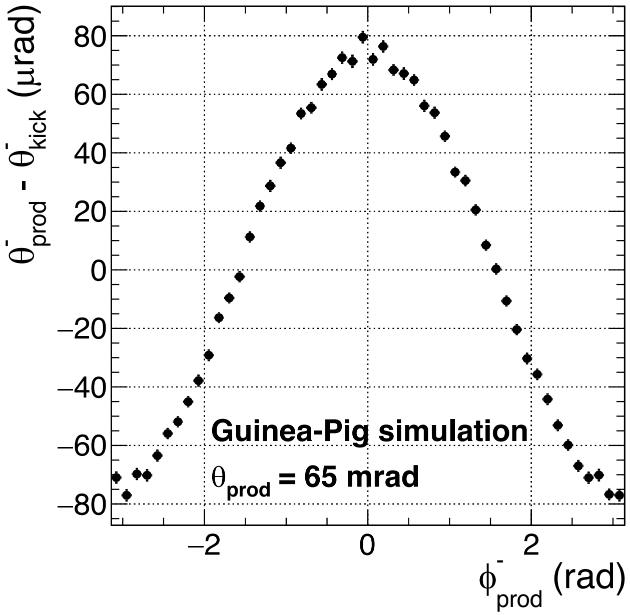
Important to measure $\Delta\alpha$ (i.e. the px-kick) for a precise measurement of the collision energy $\sqrt{s}$!

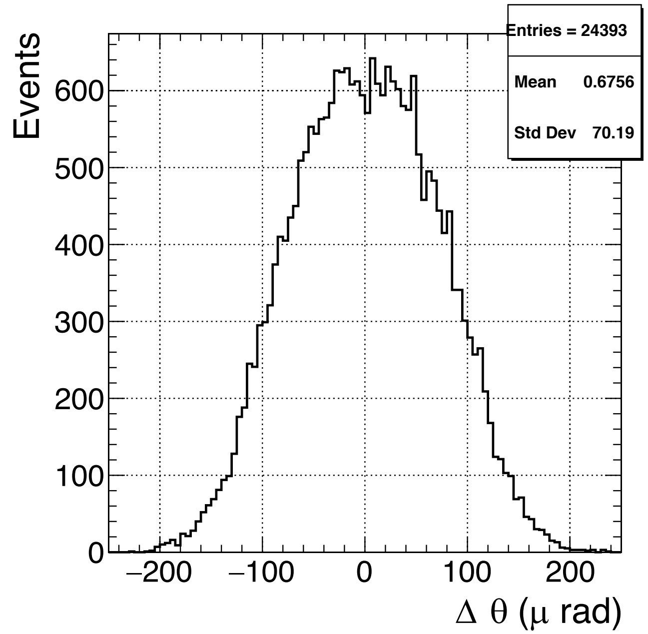
Can be measured very precisely from the constrained kinematics of dimuon events. See talk by P. Janot on Tuesday.
We'll use that in a minute…

Effect of the px-kick on Bhabha e+/- (prior to beam-induced focusing)

The px-kick leads to a modification of the kinematics of the particles that emerge from the interaction.

When $p_x \longrightarrow p_x + k_x$:
$p_T \longrightarrow p_T + k_x \cos \varphi$
and $\theta \longrightarrow \theta + k_x / p_z \cos \varphi$





Average effect is a smearing of the θ distribution of the outcoming $e^{\pm}$, with no net bias.

Equivalent to a misalignment of the luminometer system with respect to the IP along the x direction, by $\delta x = (\text{kick} / \sqrt{s}) \times z_{\text{LumiCal}} = 80\ \mu\text{m}$. Negligible effect on L !

Hence the luminosity bias is only due to the "final state" effects.

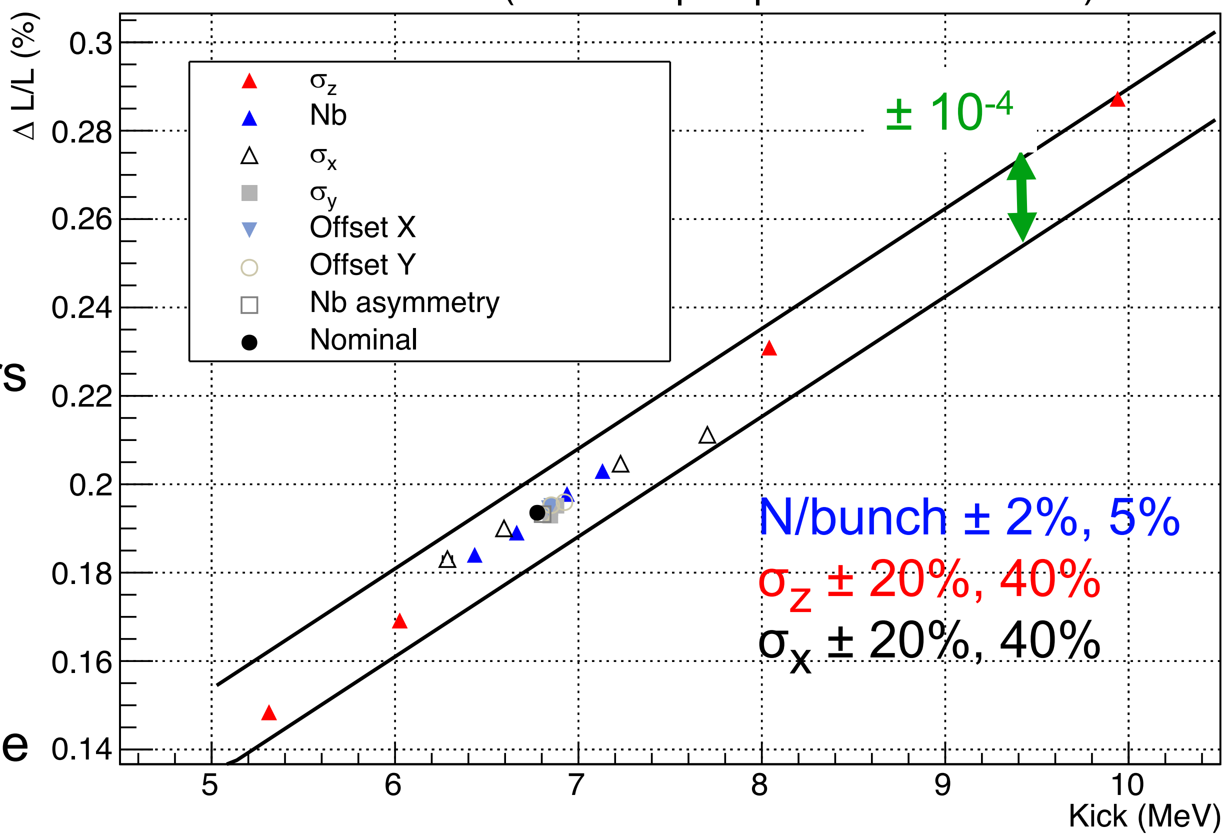
The px-kick gives the luminosity correction !

Very strong correlation between the luminosity bias and the kick.

Plot : Guinea-Pig with several variations of the beam parameters around the nominal settings.

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.

(NB: it is | ΔL | / L that is shown)



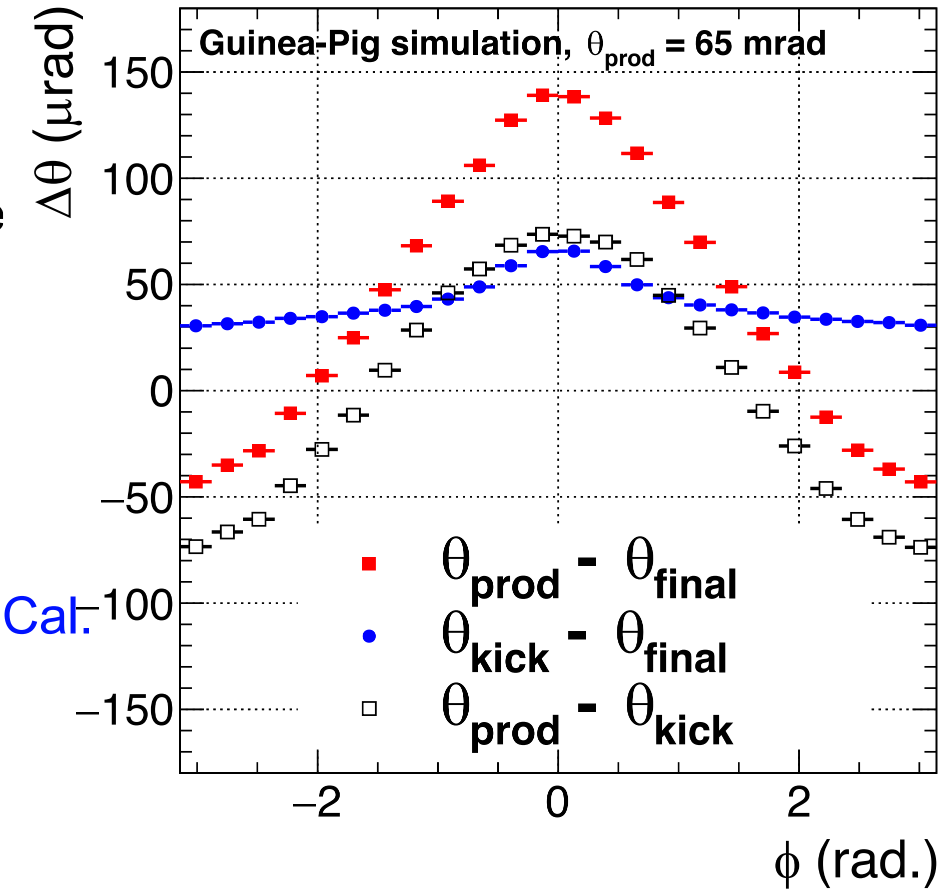
Hence: the per-cent level measurement of the px-kick, as can be obtained from dimuon events, provides a determination of the bias within the target precision.

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

Correction in-situ using LumiCal measurements only

Idea: exploit the strong φ-dependence of the beam-induced effects

- both in the initial and in the final state
- φ-dependence primarily due to the crossing angle



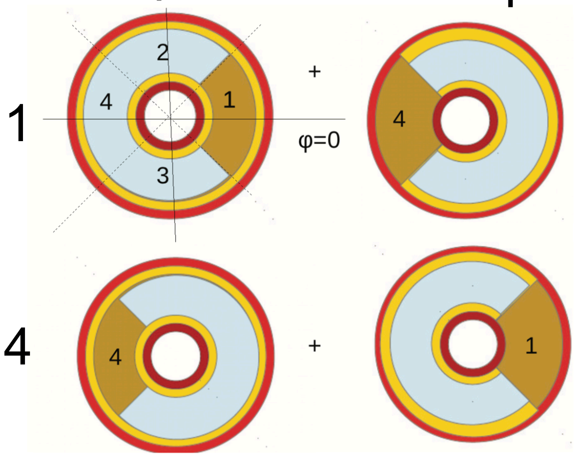
Particles at φ = 0 are focused while particles at φ = π are deflected towards larger angles. Will be reflected in the counting rates in LumiCal.

"narrow" acceptance

"wide" acceptance

N1

N4



$N1 = (e^-_{N, \varphi=0} \ \& \ e^+_{W, \varphi=\pi}) \ || \ (e^+_{N, \varphi=0} \ \& \ e^+_{W, \varphi=\pi})$

$N4 = (e^-_{N, \varphi=\pi} \ \& \ e^+_{W, \varphi=0}) \ || \ (e^+_{N, \varphi=\pi} \ \& \ e^+_{W, \varphi=0})$

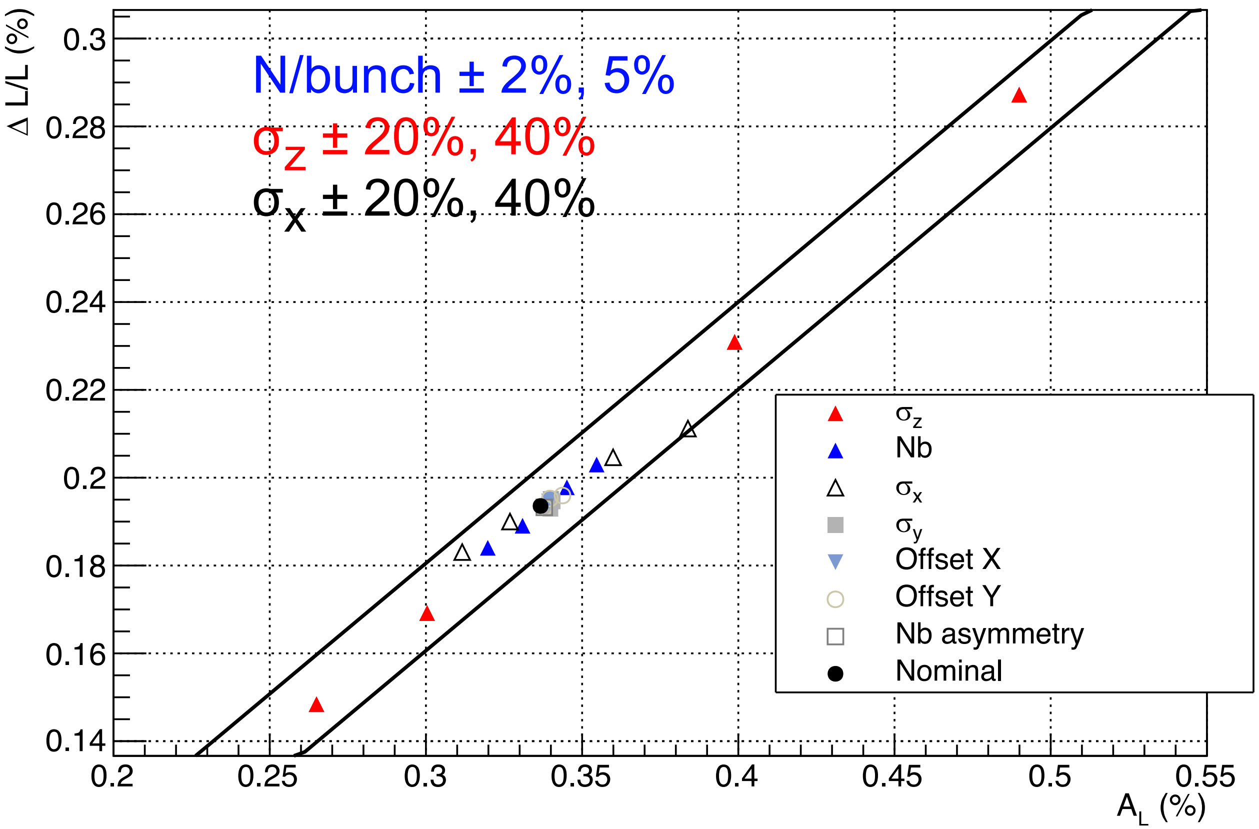
$A_L = (N4 - N1) / (N2 + N3) \quad > 0$

Luminosity Asymmetry and beam parameters

The size of this asymmetry A_L reflects the size of the beam-induced effects, hence the size of ΔL / L

Verification : several variations of the beam parameters around the nominal set, Guinea-Pig simulation for each; determine A_L and ΔL

→ the luminosity bias is indeed proportional to A_L



Hence :

- Use GP simulations to map the bias & the asymmetry
- An experimental measurement of A_L then gives the correction factor

A_L measured with a stat. uncertainty of 6 % within < 1 min of data-taking.
But… this asymmetry may not come only from beam-induced effects !!

Asymmetry : beam-induced versus non beam-induced

The asymmetry $A_L = A_{EM} + A_{Kick} + A_{misalign}$ has three sources :

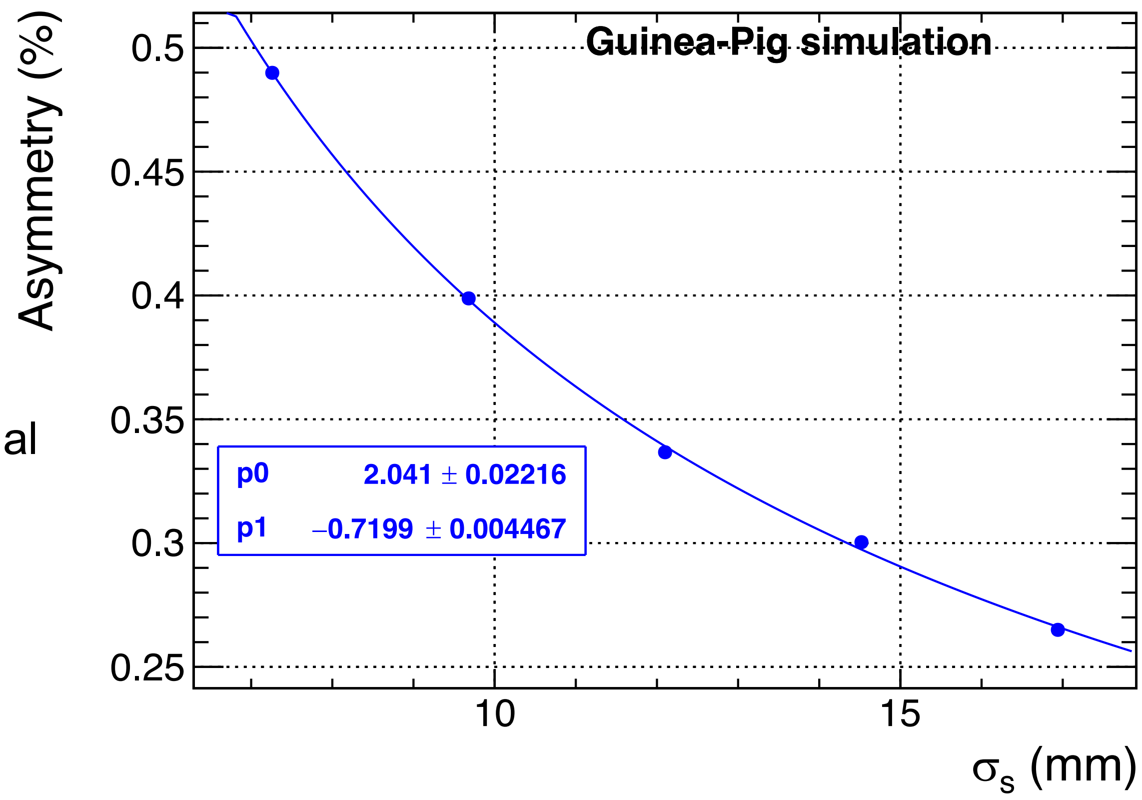
- the EM focusing on the final state Bhabha $e^{\pm}$ (small contribution to A_L)
- the px-kick : introduces a modulation in φ of the Bhabha counting rate
- possible mis-alignements: in particular, a misalignment along x produces a φ modulation identical to that induced by the px-kick !

$A_{EM} + A_{Kick} = A_{beam}$ 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} & $A_{misalign}$: slope & intercept of a linear fit.

$N \neq N_{nominal}$ implies $\sigma_s \neq \sigma_{s,nominal}$

But A_L dependence on σ_s can be parameterised by a power-law :
$A_L \; \alpha \; 1 / \sigma^a$ with $a \approx 0.72$



Measurement of AL during the ramp-up

Filling period of the machine, at the beginning of each fill : naturally offers collisions with bunches with N < Nnominal. N/bunch is gradually increased, starting from 50% of Nnominal, e.g. adding 10% of the nominal N per step

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

[Idea proposed by P. Janot to measure the increase of the crossing angle due to the beam-beam effects]

Illustration: assume a misalignment of the luminometer system w.r.t. the IP along the x direction by 100 μm

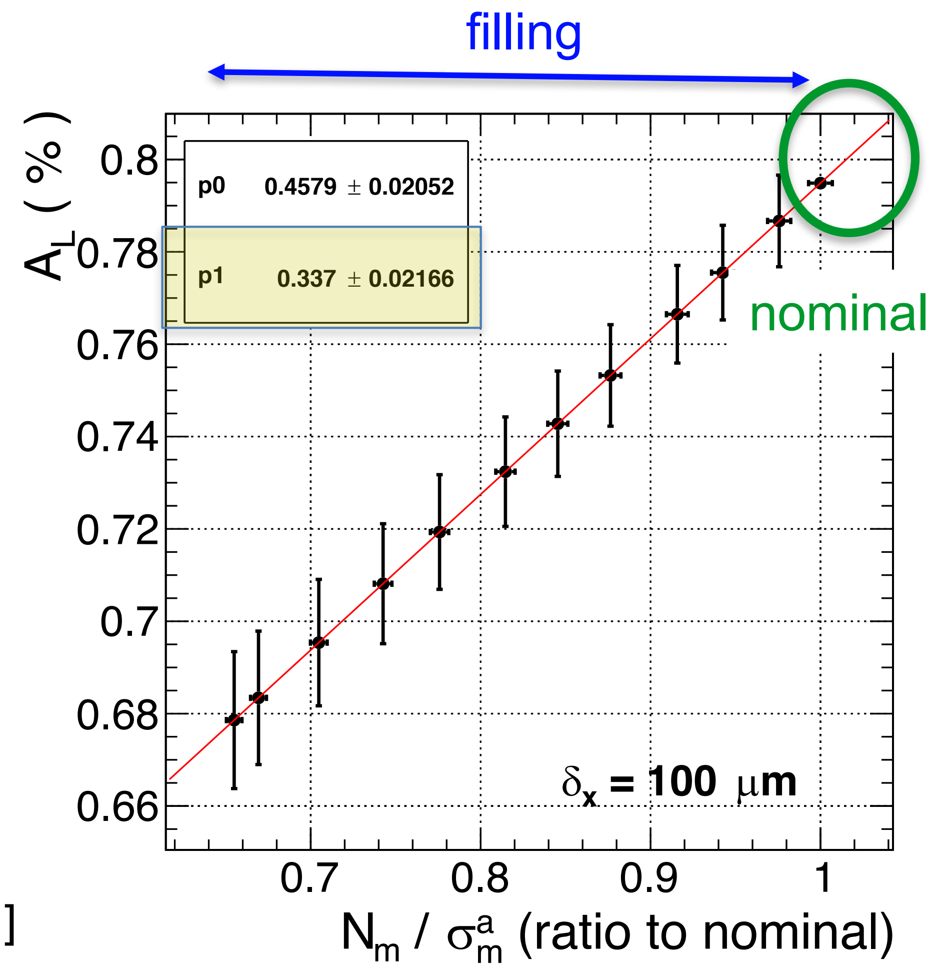
$$A_{misalign} = 0.45\%$$
$$A_{beam} = 0.34\ \%$$

Assume :

- One measurement during 2 min at each filling step
- One longer measurement at the nominal intensity (e.g. 2 hours)

Linear fit: the slope A_{beam} can be measured with an uncertainty of 6%

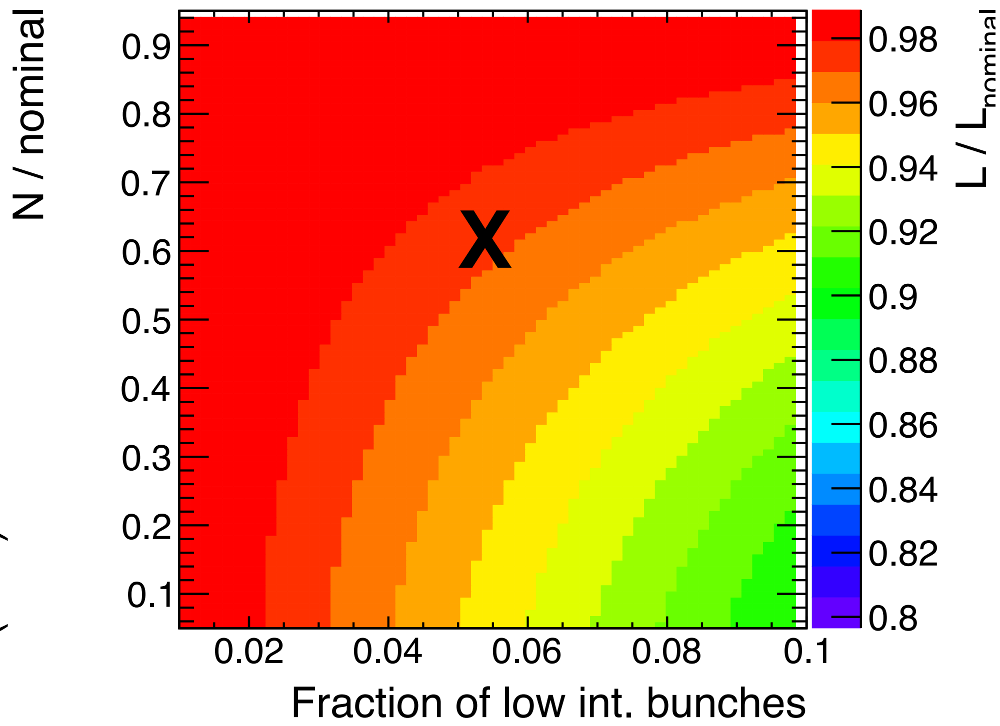
[with 10 μm : < 1 min at each filling step + nominal]



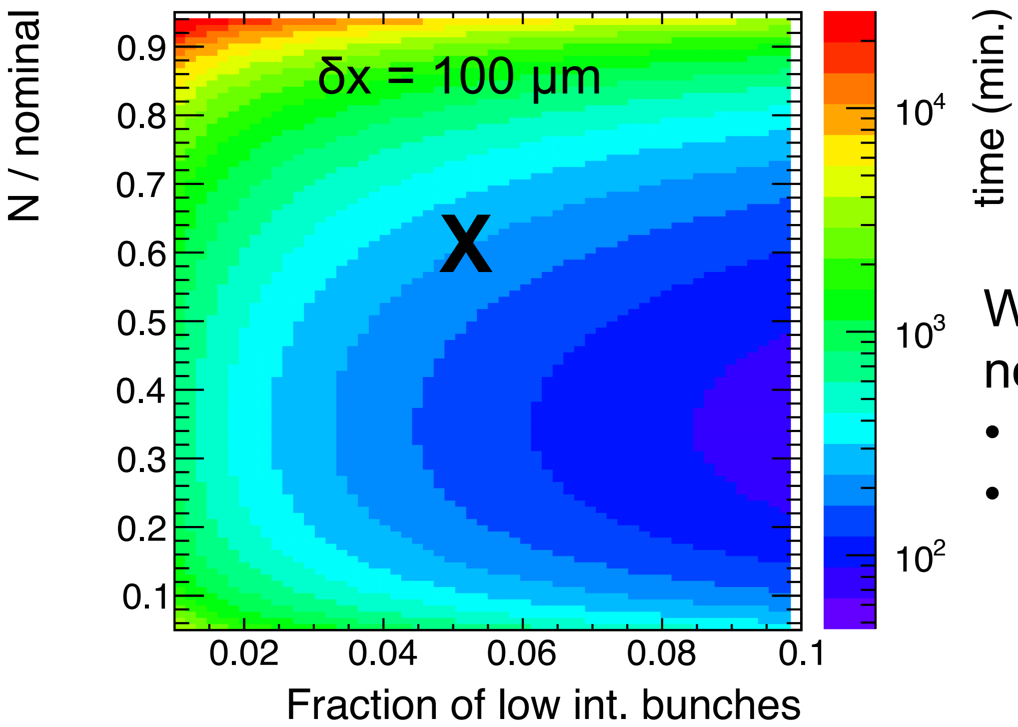
Measurement of A_L using pilot (colliding) bunches

Assume that a fraction of the bunches are filled with a lower intensity than the nominal one. Two measurement points: Nominal & pilot.

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 5% of the bunches at 60% of the nominal intensity:

- 2.5 % lumi loss
- would need 120 min to get the slope with the required precision of 6%

E.Perez

Conclusions

We think it is possible to control the luminosity bias due to the EM focusing of the Bhabha electrons. Two methods can be exploited :

- use the measurement of the px-kick using dimuon events in the central detector
- in-situ measurement using a φ-asymmetry in the Lumical :
  - mis-alignment effects can be disentangled from beam-beam effects even under conservative assumptions for the mis-alignment

Both should be used, providing nice consistency cross-checks between several observables that are related to beam-induced effects.

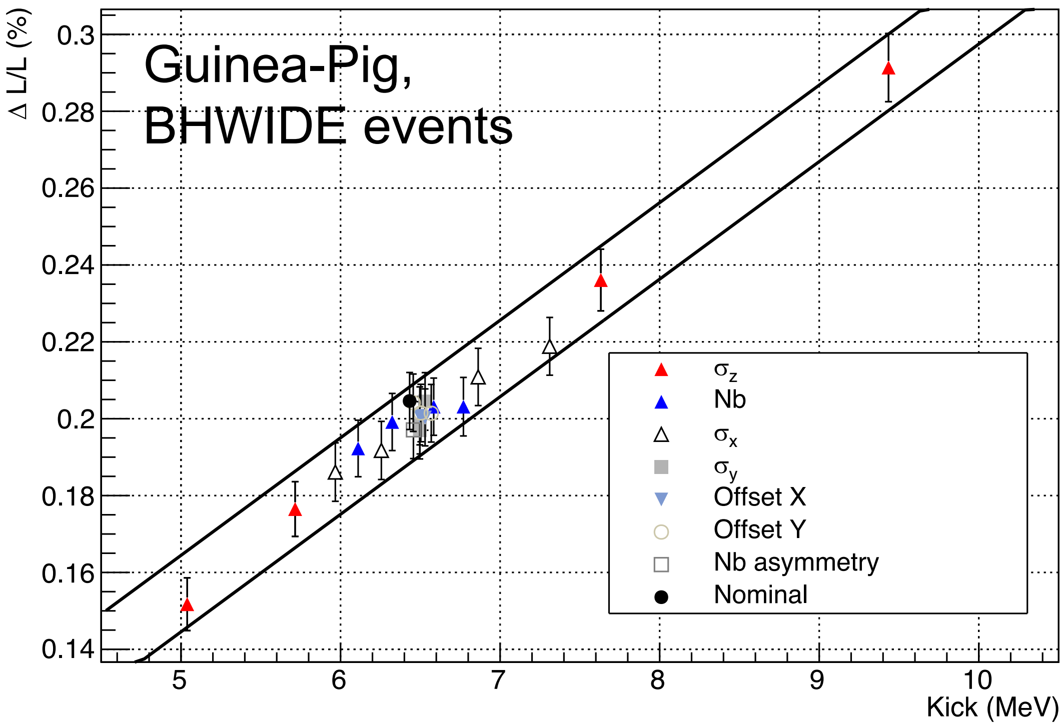
Back-up

Luminosity bias versus the kick : BHWIDE events

- What is shown in the talk corresponds to “leading order” Bhabha events, i.e. pairs of 45 GeV e+/- that are back-to-back.

- In real Bhabha events, a fraction of e- would have a lower E, hence the deflection could be stronger
  - on the other hand, in the case of FSR radiation, a non-deflected photon will be close-by, and the clustering will partly compensate for the deflection
  - a precise analysis requires a simulation that includes clustering

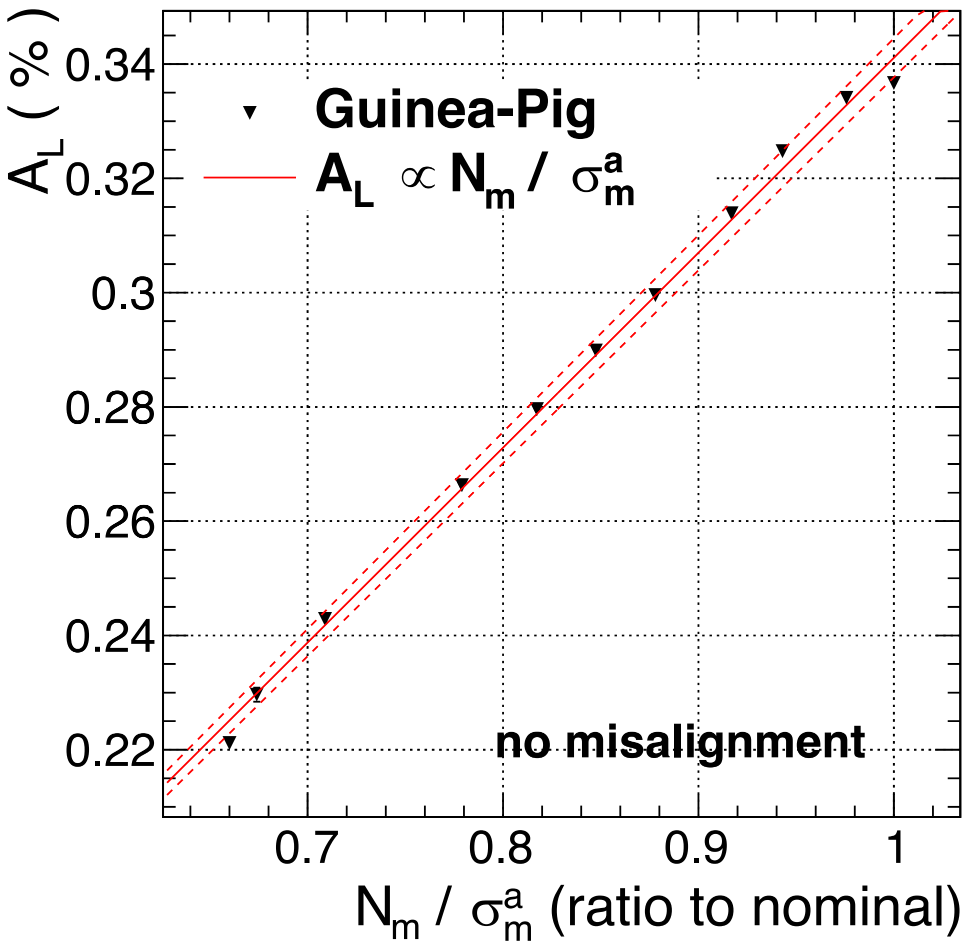
- With the caveat of no clustering, the plot shows what we get from BHWIDE events
  - The linear behaviour remains
  - Actually the bias is very similar to what we got from the “leading-ordre” Bhabhas



Measurement of AL during the ramp-up : Guinea-Pig simulations

GP simulations for each (N, σ_s) corresponding to each step, with σ's for each step taken from D. Shatilov as shown in the table

$N^{+}_{\rm part}$	$N^{-}_{\rm part}$	$\mathcal{L}$	σ^{+}_{δ}	σ^{-}_{δ}
0.50	0.50	0.37	0.68	0.68
0.50	0.55	0.38	0.79	0.61
0.60	0.55	0.44	0.64	0.84
0.60	0.65	0.50	0.87	0.68
0.70	0.65	0.56	0.69	0.93
0.70	0.75	0.62	0.94	0.74
0.80	0.75	0.68	0.76	0.99
0.80	0.85	0.74	1.02	0.80
0.90	0.85	0.81	0.82	1.04
0.90	0.95	0.87	1.09	0.84
1.00	0.95	0.91	0.86	1.12
1.00	1.00	1.00	1.00	1.00



Shows that A_L scales with N / (σ_s) $^{0.72}$

with N = $\sqrt{N_- N_+}$ and $\sigma^2 = 1/2(\sigma^2_- \oplus \sigma^2_+)$

Dependence versus the bunch parameters