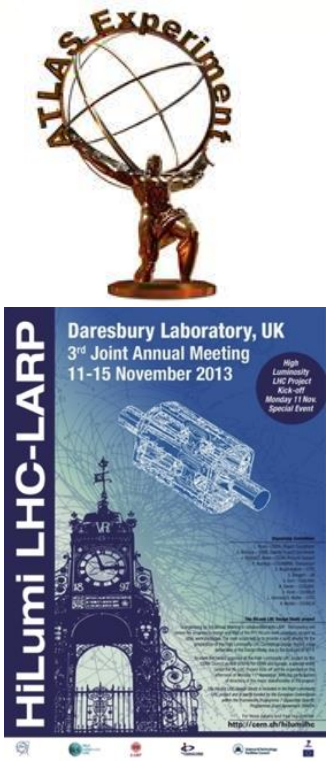
Pile-Up and its density at HL-LHC: a common view from the machine and the experiments



A. Ball, B. Di Girolamo, S. Fartoukh, L. Rossi

3rd HiLumi LHC-LARP Joint Annual Meeting

11 -15 November 2013, Daresbury Laboratory, UK

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Outline

- A brief reminder of the baseline and the crab-kissing scenarios for pile-up and its line density
- Importance of pile-up and its line density
- The first examples of impact on the experiments
- The to-do list

The baseline and the crab-kissing

- **A baseline scenario and a Plan B**
  - Main differences: Hardware (with and w/o crab-cavities) and optics
  - Similarities: performance reach and pile-up (μ_{tot}, $\partial\mu/\partial z$,...)
- **Variability with bunch length and bunch profile (Gaussian, rectangular,...)**
  - Can we gain something in PU line-density?.. **NO**
  - Can we gain something in PU time-density?..**YES**
- **The "crab-kissing" concept: a new approach for reducing, shaping and leveling the PU line-density**

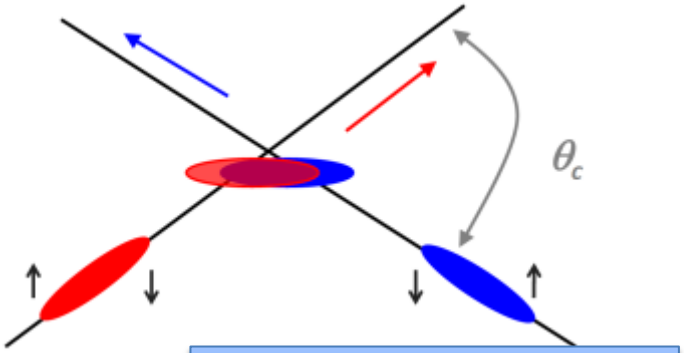
The baseline scenario and the Plan B (1/3)

- **Baseline= HL-LHC baseline with crab-cavities (CC)**

→ **``Round'' optics** (β^*=15 cm in H and V)

→ **``Large'' X-angle** (590 μrad) with the lumi-loss factor compensated by the CCs

→ **Lumi leveling @ 5E34 with β^* with full crabbing** (i.e. at max CC voltage)



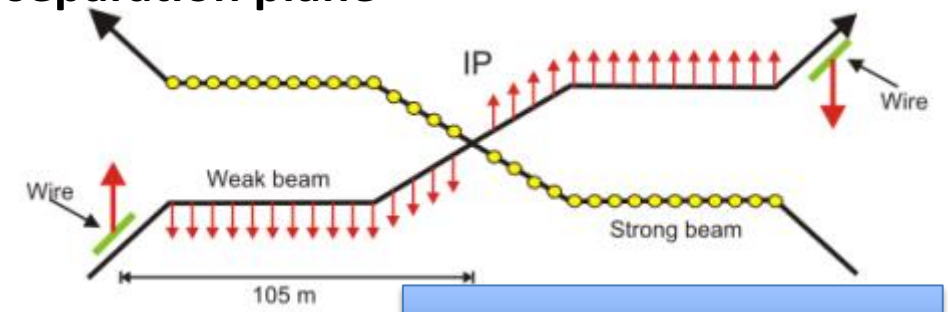
R. Calaga, F. Zimmermann, et al.

- **Plan B (..very recent) = back-up with beam-beam wire compensators (no CC)**

→ **Flat optics:** "large" β^*(50 cm) in X-plane and "small" β^* (10 cm) in || plane

→ **"Minimal" X-angle** (285 μrad) in the plane of larger β^* (thank to the bb wires)

→ **Lumi leveling with β^* in the parallel separation plane**



J.P. Koutchouk, F. Zimmermann, et al.

<u>The goal is the same:</u>
Preserve the performance despite of the crossing-angle, while maximizing the luminous region to keep the z-density of Pile-up "reasonable" at 5E34, i.e. μ_{tot} =140 (→200) @ 25 ns.

The baseline scenario and the Plan B (2/3)

→ Both can be optimized in bunch length to give

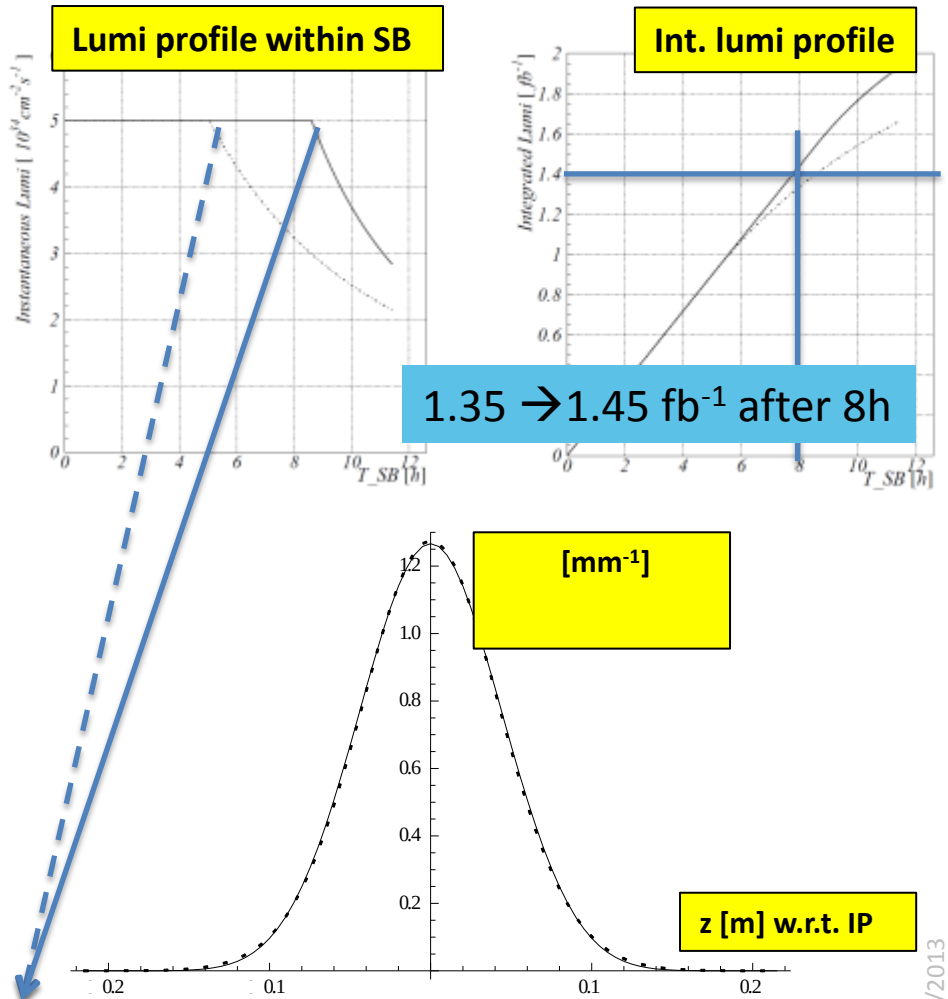
- **Similar performance** of **~ 250 fb^{-1}/y**

(for 25 ns, 2.2E11 p/bunch, $\gamma\varepsilon$=2.5 μm)

- **Same luminous region** of **4.4 cm r.m.s.** and **same peak z-density of pile-up**

→ **$(\partial\mu/\partial z)_{max}$ = 1.27 PU/mm @ $<\mu_{tot}>$=140**

with Gaussian bunch profiles in both cases and σ_z = 7.5/10 cm (r.m.s.) for Plan A/B



Up to **1.27 PU/mm @ $<\mu_{tot}>$=140** and smallest β^*

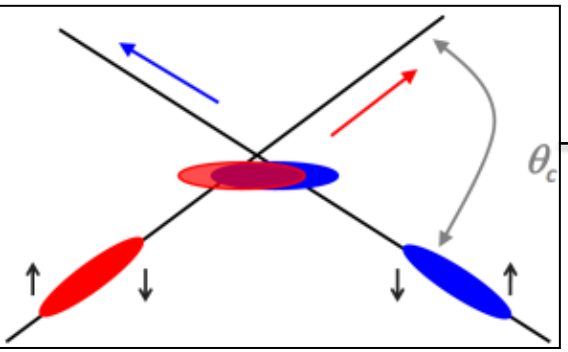
Sensitivity to bunch length & bunch shape (3/3)

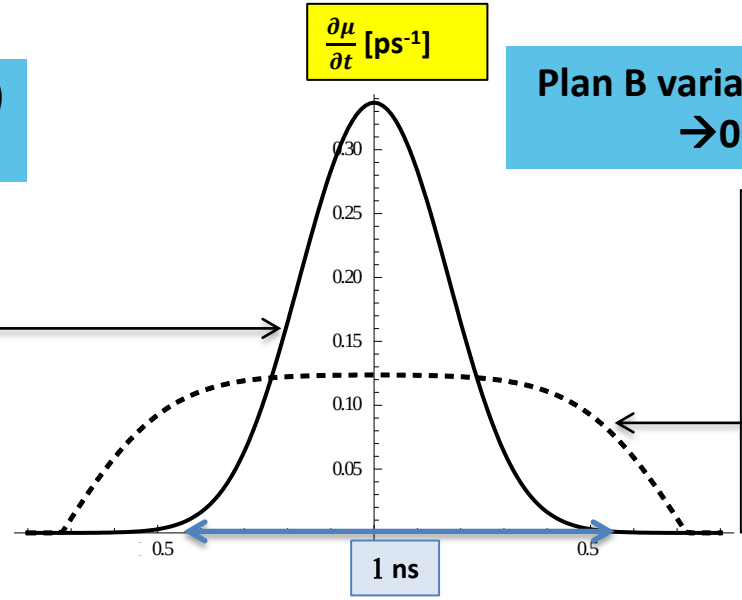
→ Peak **time density** of vertices: **net gain with B**

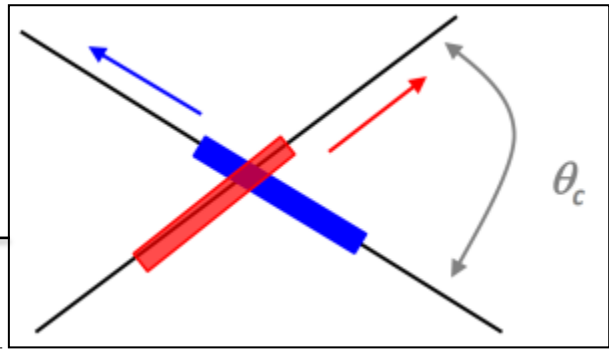
- For longer r.m.s. bunch length
- Even more for rectangular bunches and Plan B (with non-zero Piwinsky angle)

Plan A @ σ_z =7.5 cm (Gaussian)
→ 0.34 PU/ps @ $<\mu_{tot}>$=140

Plan B variant @ σ_z =12.5 cm (Rectangular)
→0.12 PU/ps @ $<\mu_{tot}>$=140







In the best case, still 1.2 pile-up every 10 ps

(and loosing ~10% of integrated performance via the geometric loss factor)

Is it really usable??

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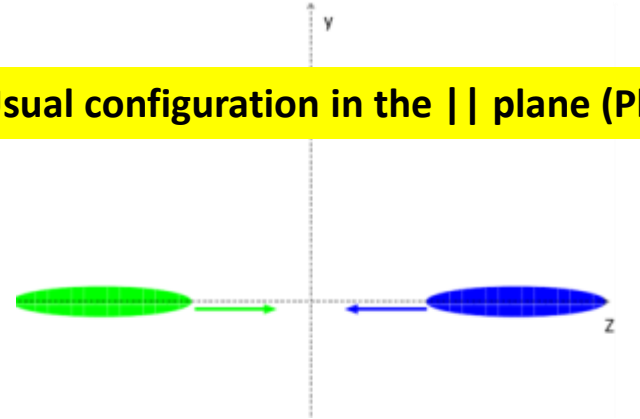
The ``crab-kissing'' (CK) scheme (1/5)

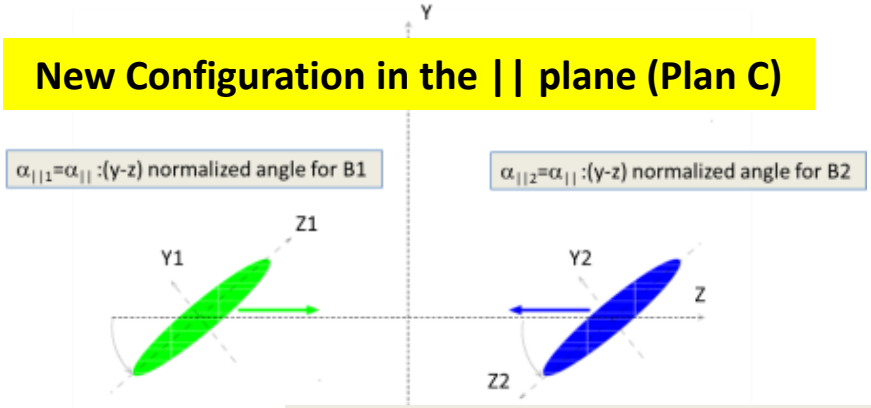
→ Transposing to the **line density** the nice behavior which is observed for the **time density vs. bunch length and bunch shape ...**

- **Crab-cavities in the || plane** **(in anti-phase for beam1/2, and flat optics for efficiency)**

Usual configuration in the || plane (Plan A/B)



New Configuration in the || plane (Plan C)



Typical "Time Piwinsky angle" of **100-150 μrad**

- **.. A tool for** **shrinking the collision time**, hence leveling the lumi, and much more !

a) Gaussian Bunch profile (no 800 MHz) → lumi leveling at "mitigable" z-density

b) Rectangular Bunch profile (800 MHz) → lumi leveling at strongly reduced z-density

c) Reduced BB tune shift in ALL cases (not discussed)

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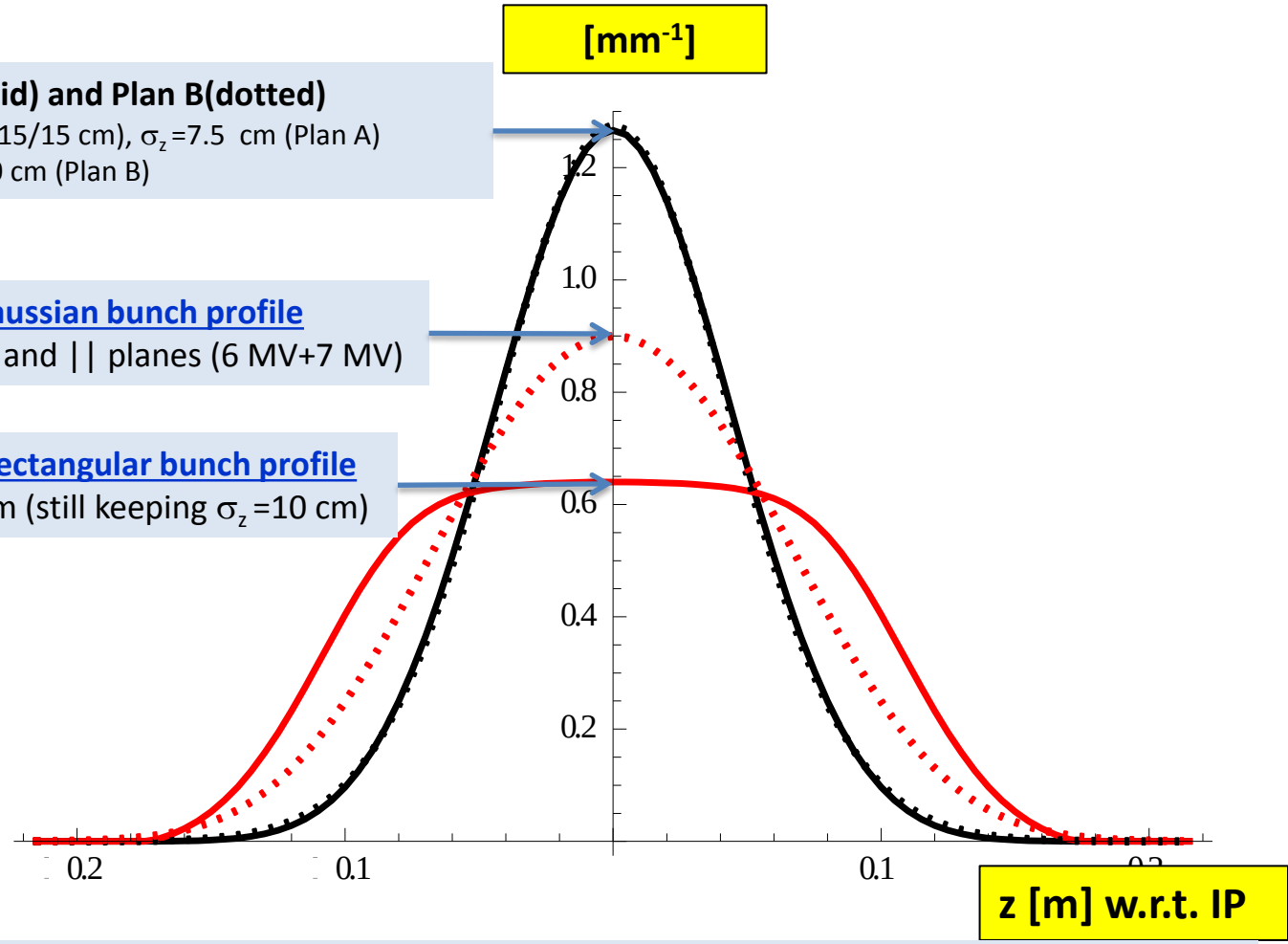
The ``crab-kissing'' (CK) scheme (2/5)

HL-LHC w/o CK scheme: Plan A (solid) and Plan B(dotted)
- 12.5 MV crabs in X-plane, round optics (15/15 cm), σ_z=7.5 cm (Plan A)
- or bb wire, flat optics (50/10 cm), σ_z=10 cm (Plan B)

"HL-LHC+" with CK scheme and **Gaussian bunch profile**
..adding crab-cavities to Plan B in X and || planes (6 MV+7 MV)

"HL-LHC++" with CK scheme and **rectangular bunch profile**
... adding a new 800 MHz RF system (still keeping σ_z=10 cm)



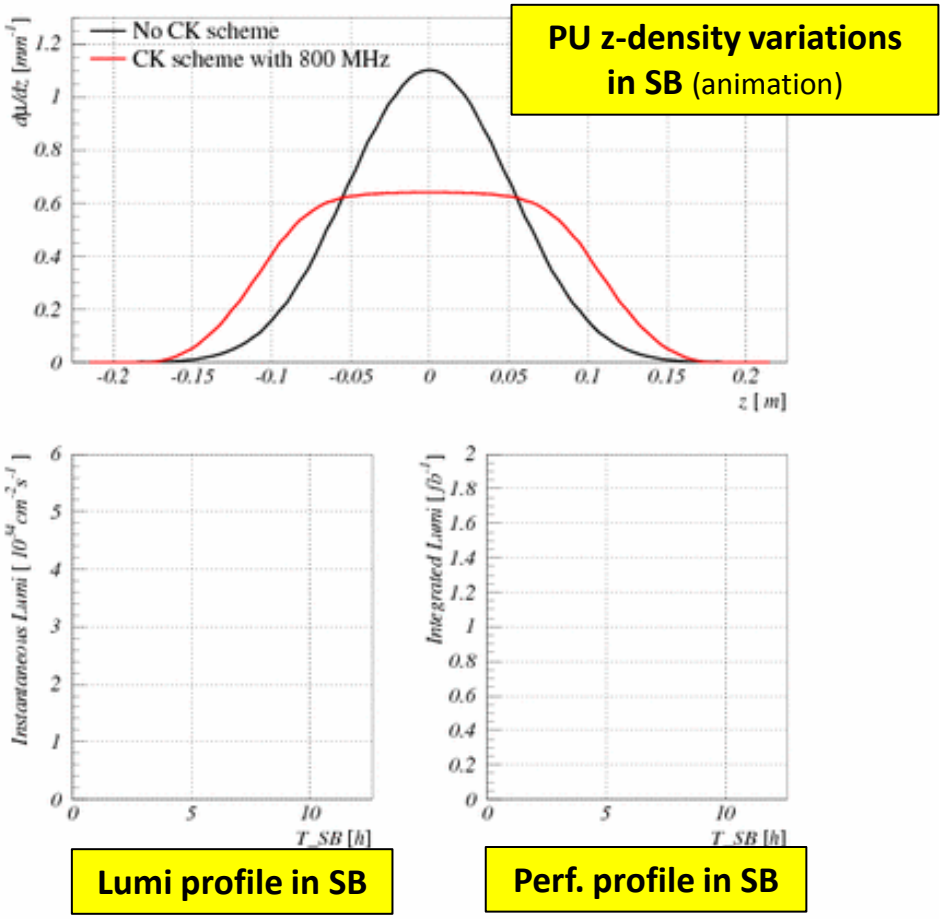
→ A net gain by a factor √2 at each step
.... at nearly constant integrated performance (see next slide)

The ``crab-kissing'' (CK) scheme (3/5)

→ The **density shape** is changing in stable beam

→ **…** but the **peak density** is halved and **stays constant** with the CK scheme.

→ The **integrated lumi**:very similar delivered performance at 50% PU density



CK Conclusions & Outlooks (1/2)

- Strongly relying on high current from the injectors **(2.2E11/b @25 ns),** various scheme can be built **with or w/o crab-cavities to deliver a yearly lumi of ~250 fb^{-1}.** ***But all these scenarios assume new hardware never tested so far in a pp collider.***

- Without crab-cavities, however, the detector will have to leave in an high pile-up environment, ***μ_{tot} =140 @25 ns (→ 200 for the worst collisions) and peak line-density of ~ 1.3 PU/mm (→ 1.8 PU/mm).***

- *Not discussed but to be kept in mind*: **any reduction of current or increase of the bunch spacing (50 ns..)** will immediately translate into an **increase of the peak z-density, if one tries to stick to the target performance.**

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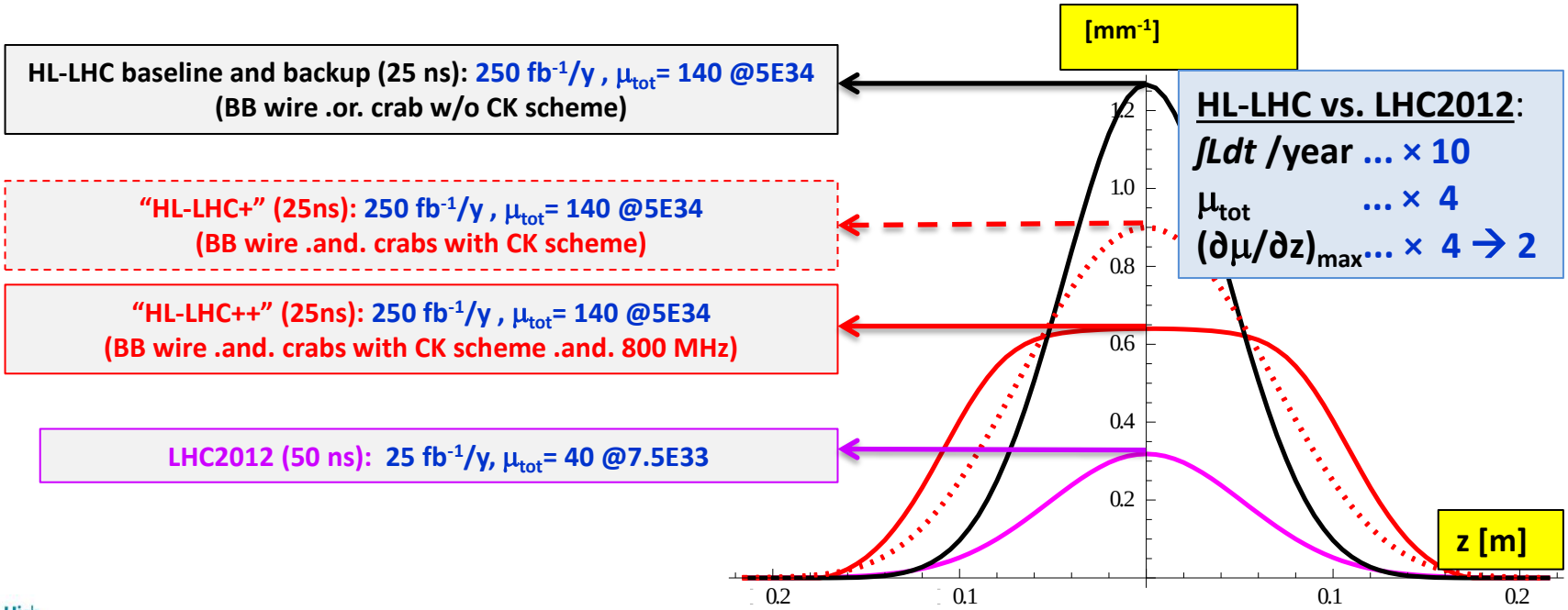
CK Conclusions & Outlooks (2/2)

- **Crab-cavities in specific configuration (CK scheme) remains the key**

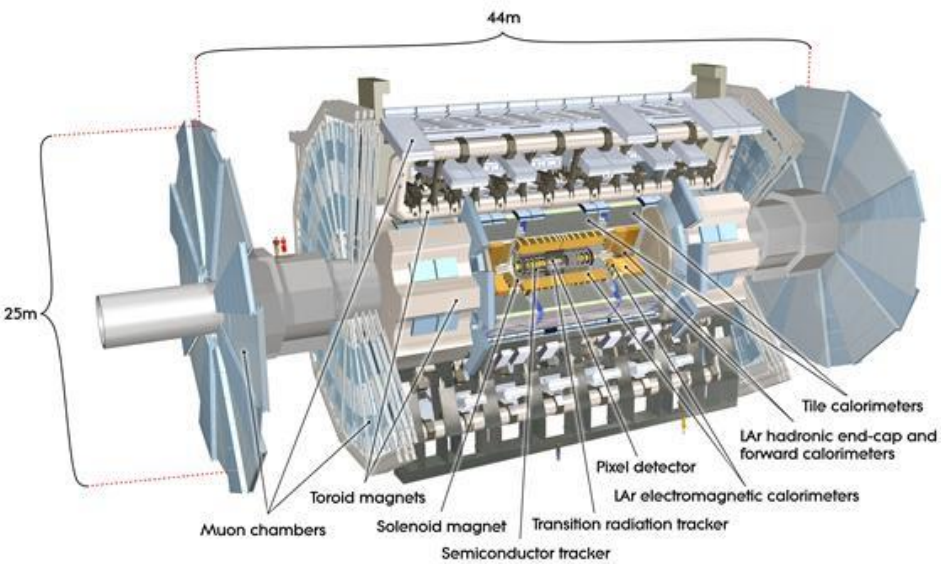
- To reduce the peak PU line density at constant performance,

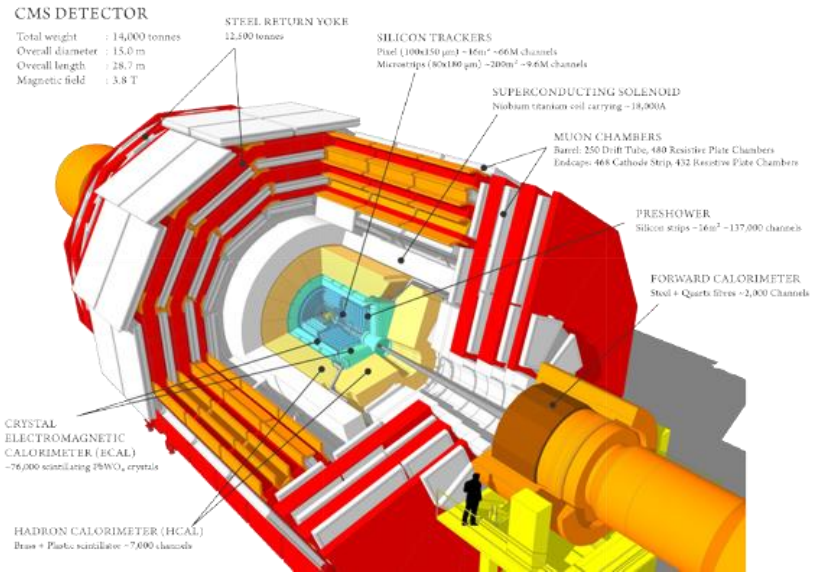
- Or to boost the performance at constant PU line density,

- Or (in the worst case of beam current lower than targeted) to mitigate the performance loss at constant PU line density.



Measurements

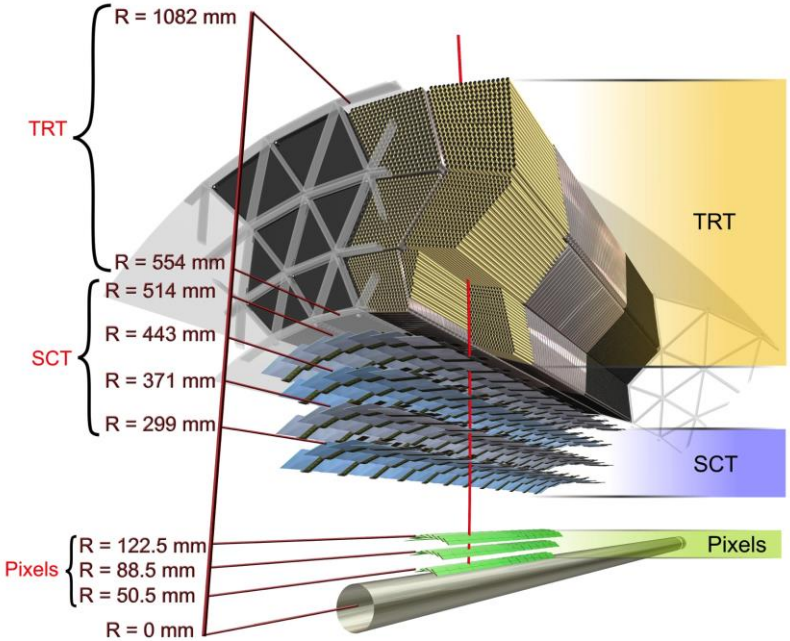




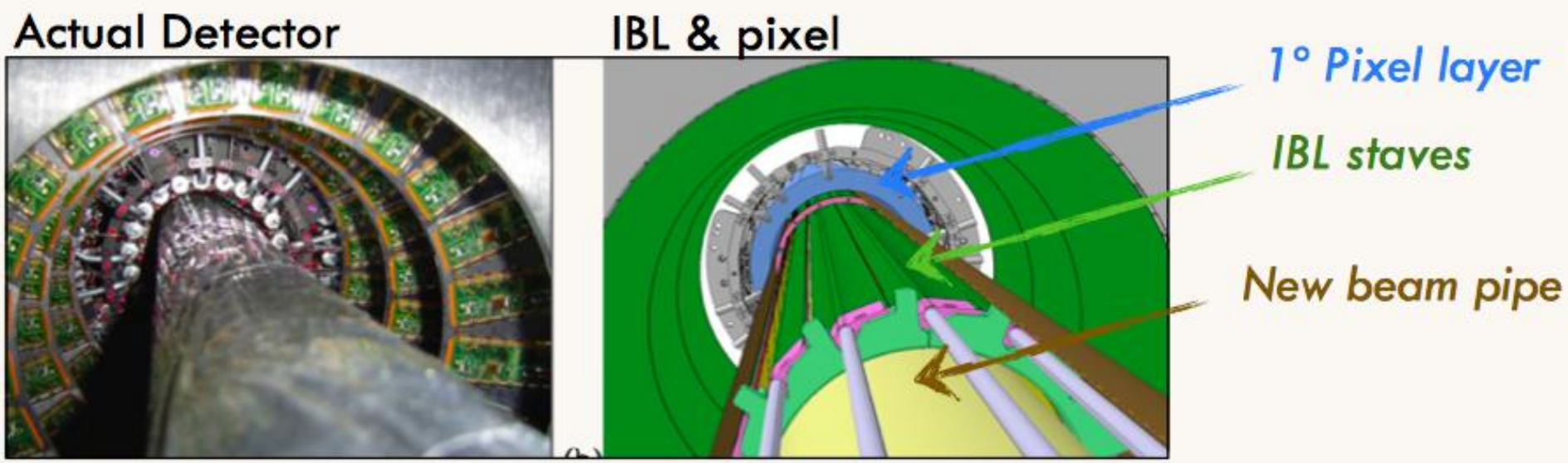
How important is the pile-up line density

- Let's focus for a moment on the inner tracker
  - That is not the end of the story in complex detectors, but it is the "first affected" by pile-up and its line density
- In addition let's also mention what is the impact of the distance between IP and the first sensitive layer (and possible impacts of the TAS aperture)

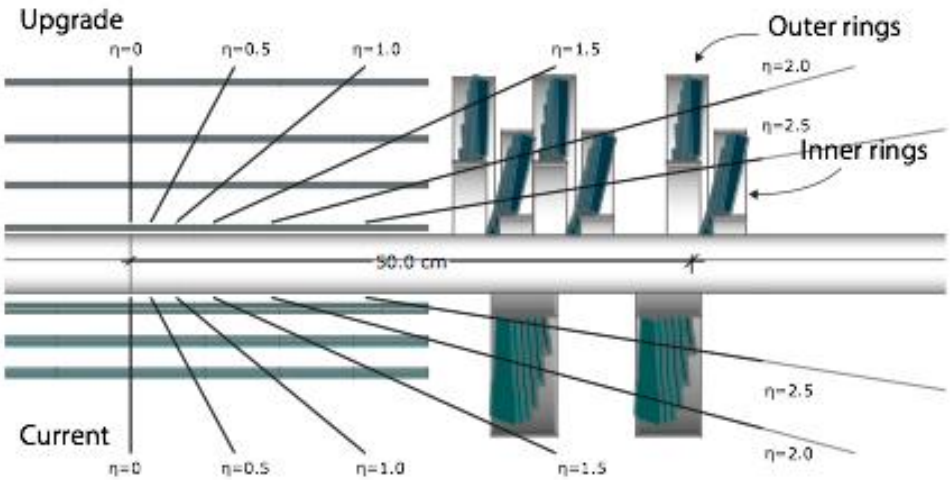
ATLAS current Inner detector and its evolution

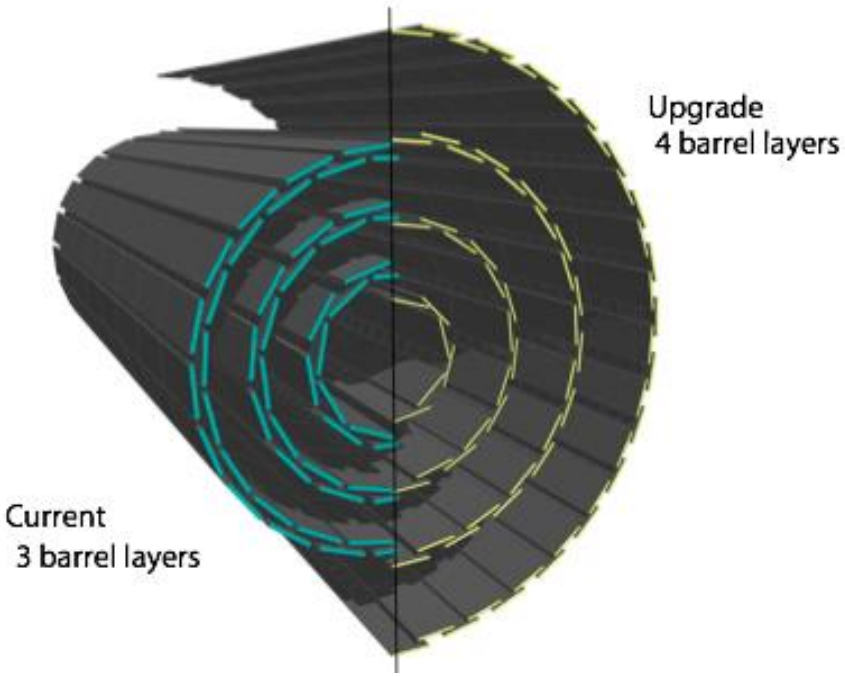


- Adding an innermost layer at 3.3 cm from IP
- Current innermost layer at 5 cm



CMS Pixel Detector: current and future

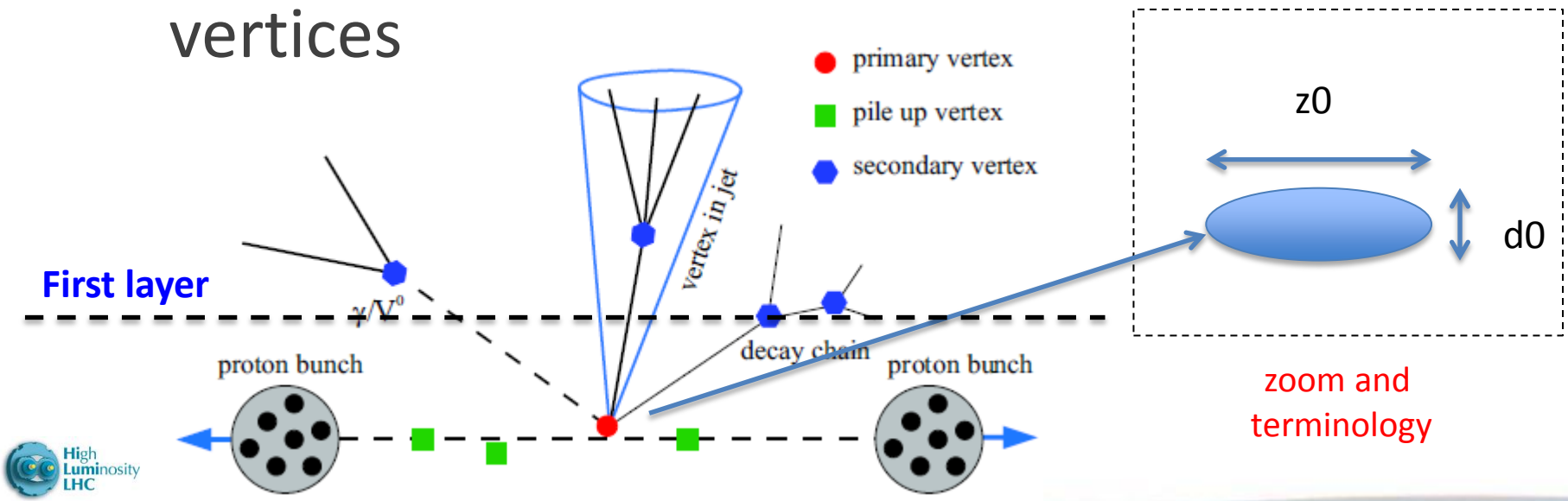




- Innermost layer: from 4.4 to 3.0 cm from IP
- Second layer: from 7.3 to 6.8 cm
- Third layer unchanged and adding fourth layer at 16 cm

Moving the first measurement closer and closer

- The precise Pixel tracking allows to:
  - Have a better extrapolation to the primary vertices
  - Have a better measurement of the secondary vertices



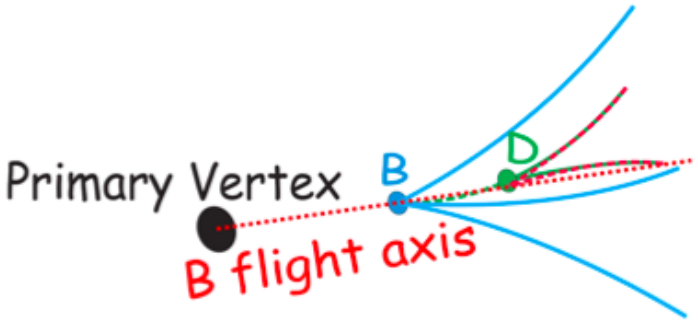
Primary vertex measurements

5.2 Primary vertices in pile-up environment

G. Piacquadio's thesis

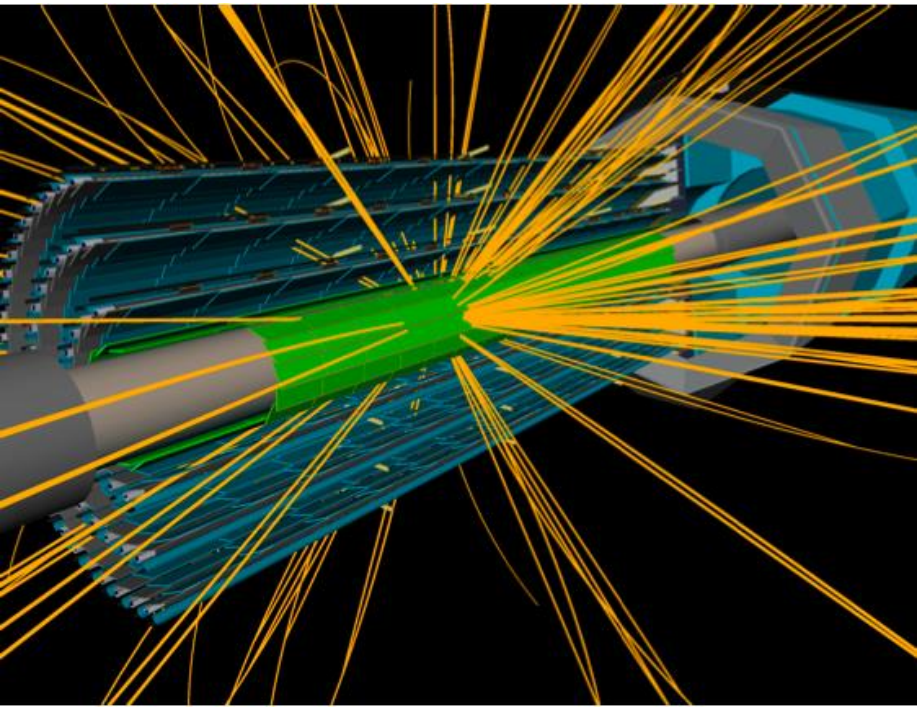
The longitudinal size of the interaction region of several tenths of centimetres is of crucial importance to create the conditions to distinguish the high p_T event of interest from additional physics events produced by the interaction of additional proton-proton pairs during a single bunch crossing, which are usually defined as *pile-up* (or minimum bias) events.

- The **primary vertex determination** is crucial to fully reconstruct the event. Necessary even though not sufficient: loosing it makes everything extremely worse with unusable events, i.e. unusable luminosity
- It is an "indirect" measurement based on track extrapolation

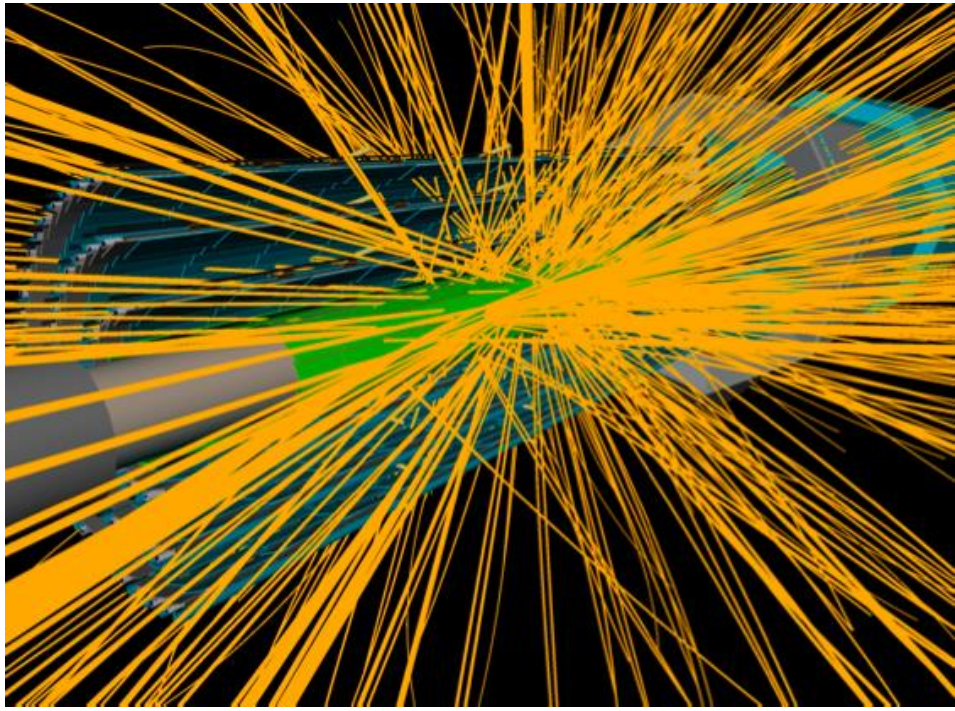


Ideal situation

Real situations



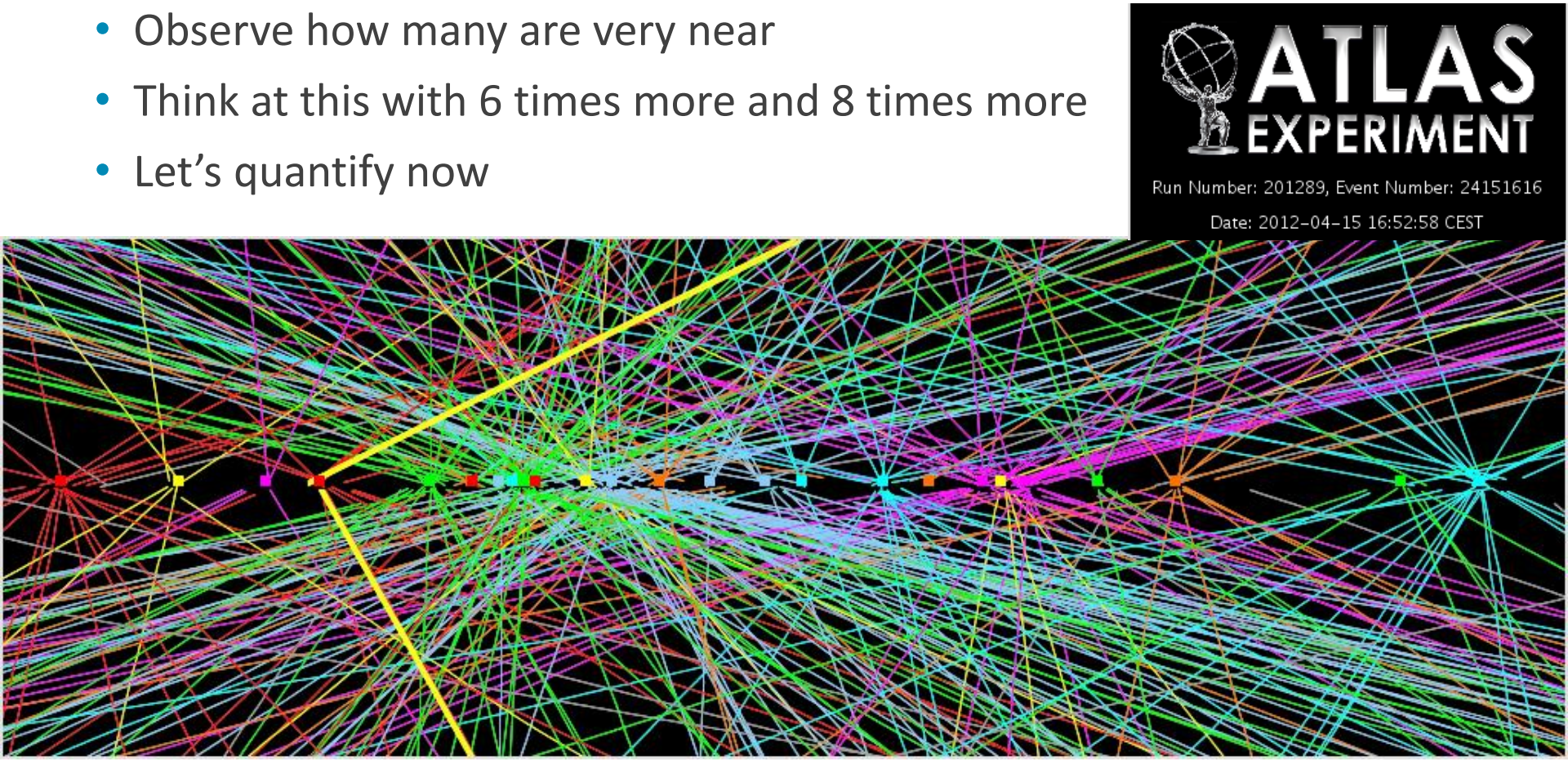
No pile-up: 2 jets of 500 GeV



Same at $2 \cdot 10^{34}$ $cm^{-2}s^{-1}$

More explictly Z -> μμ with 25 pile-up events

- It is worth looking at few details
- Observe how many are very near
- Think at this with 6 times more and 8 times more
- Let's quantify now



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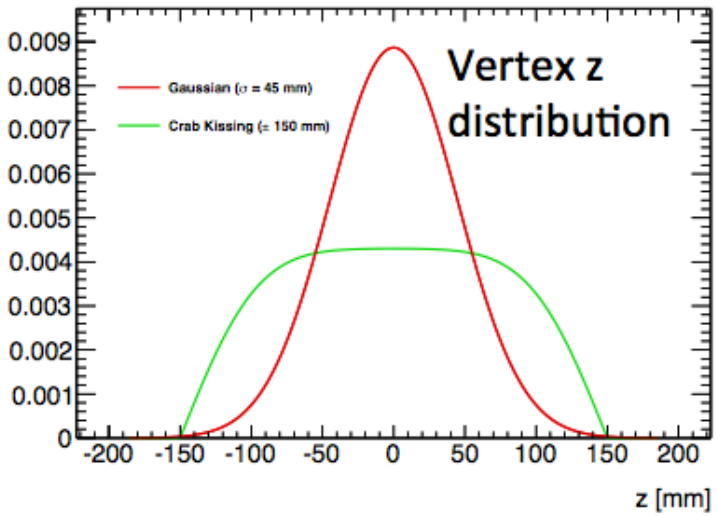
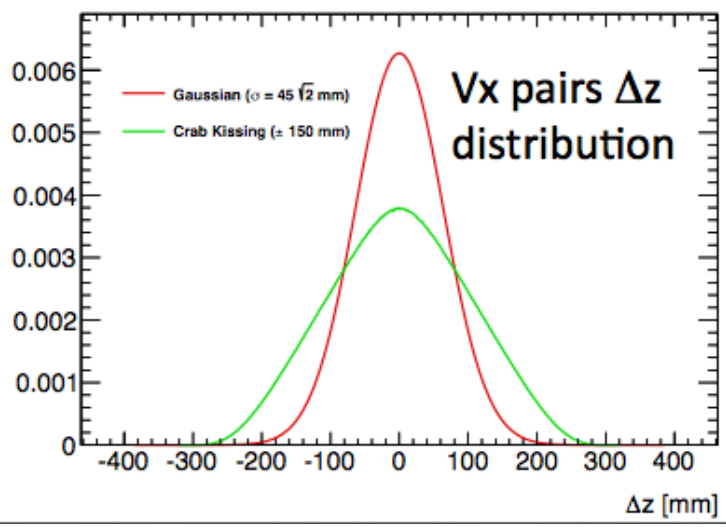
Quality assessment

- We need to look at how many vertices we can reconstruct vs. μ
- Higher pile-up means higher merging: indistiguishable primary vertices affecting heavily the precision of the measurement and increasing the fakes
- Keep in mind that only a part of the vertices is "useful": part of them belong to too low p_T, to diffractive and double diffractive events, etc.
- It is normal that only 70% of the vertices are interesting and reconstructed at zero pile-up. Higher the pile-up lower the efficiency… higher the merging probability

Implementation of the CK scheme in the ATLAS simulation (F. Meloni, S. Pagan Griso)





The density and the distance between pairs of vertices (convolution of density function with itself)

Implementation of the CK scheme in the ATLAS simulation (F. Meloni, S. Pagan Griso)

$$\langle n_{Vx} \rangle = p_0 + \varepsilon \cdot \mu - F(\varepsilon \cdot \mu, p_{mask})$$

- $\mathbf{p_0}$ = beam halo and cavern backgrounds
- ε = vertex reconstruction efficiency
- $\mathbf{p_{mask}}$ = vertex masking probability

$\mathbf{F(\mu, p_{mask})}$ is a function that for each given number of *reconstructible* vertices $\varepsilon\mu$ and p_{mask} returns the number of lost vertices due to masking, taking into account:

- the poissonian distribution of the number of reconstructed vertices
- the probability of two to multiple vertex masking

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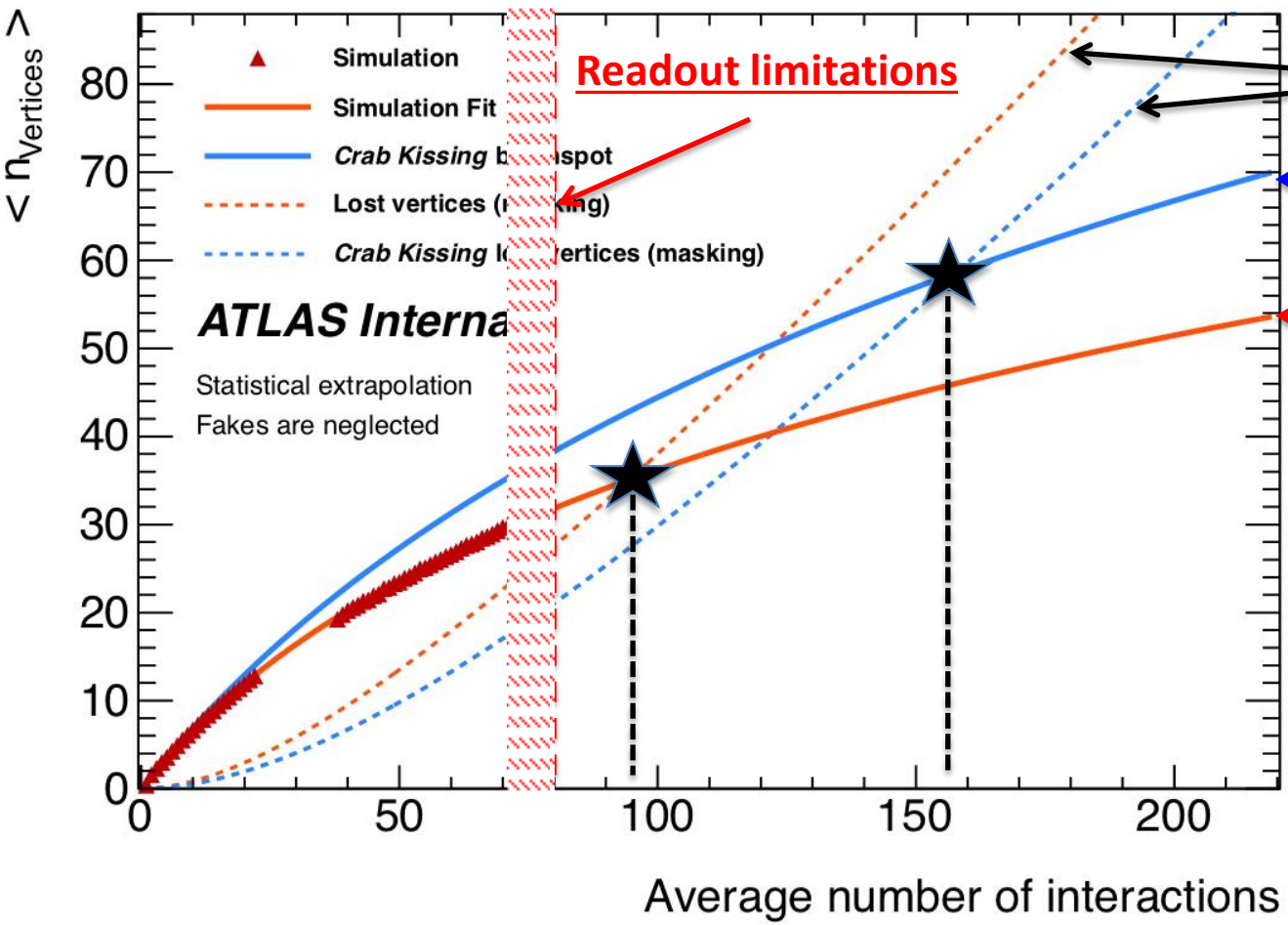
Fresh results comparing CK and baseline



Lost because merged

Crab-kissing

Baseline HL-LHC

Figure of merit: a factor ~1.8 gain with CK. Confirmed by CMS (to be approved)

This is the current ATLAS detector

IBL and future tracker will help… in both cases

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This is not the end of the story: to-do list (part 1)

- The z_0 and d_0 primary vertex resolution need now to be better quantified
- Then we need to look at the benefits of IBL and of the future tracker, but these will improve absolute pile-up capabilities while improving the primary vertices resolution in the same way for baseline and CK
- The impact on the secondary vertices and specifically on b-tagging is then the next step

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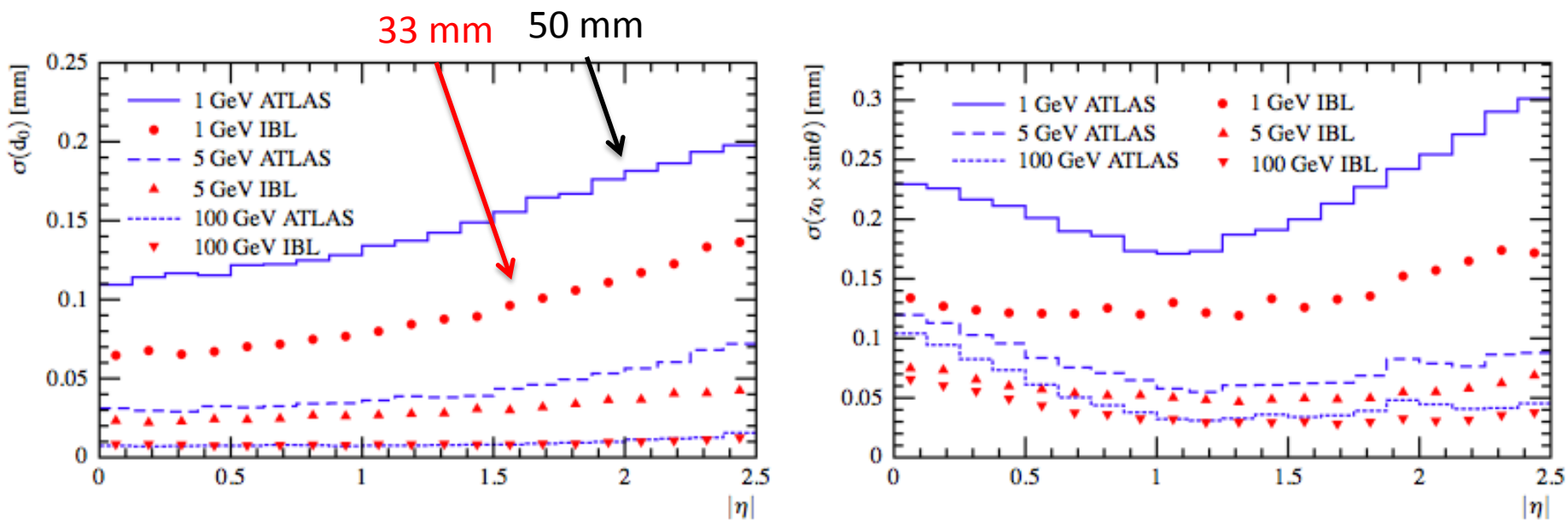
Profiting of the occasion…

- Before switching to calorimeters
  - What is the impact of the aperture?
  - TAS going from 34 to 60 mm: how that impacts on the placement of the first sensitive layer?
- **Today**: TAS aperture 34 mm, inner beam pipe diameter 47 mm (it was 58 mm). That allows to place IBL at 33 mm (33-23.5 mm i.e. just 9.5 mm for aerogel, bake-out heaters, wrapping…)
- **Tomorrow**: can we keep a 47 mm beam pipe with a TAS opened at 60 mm? First results are promising, but any improvement is welcome… (see Helmut's slides at Aix)

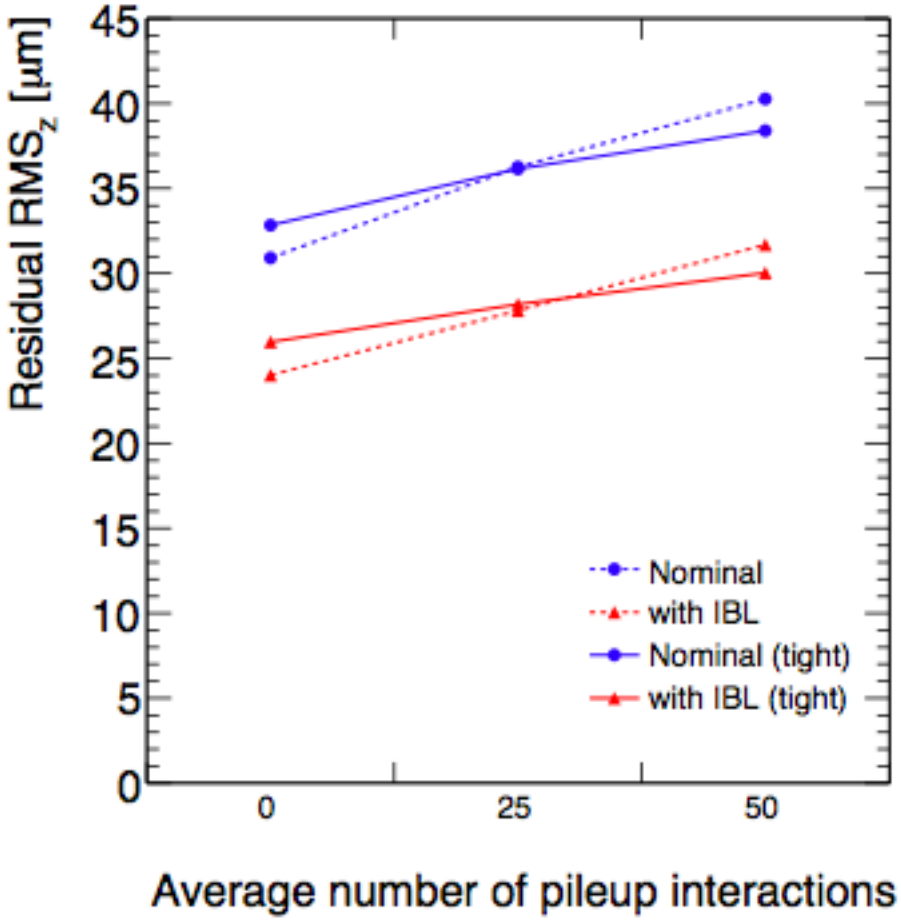
What is the impact of a layer at 33 mm: no pile-up

- Now we know what the primary vertex measurement means and what d_0 and z_0 are



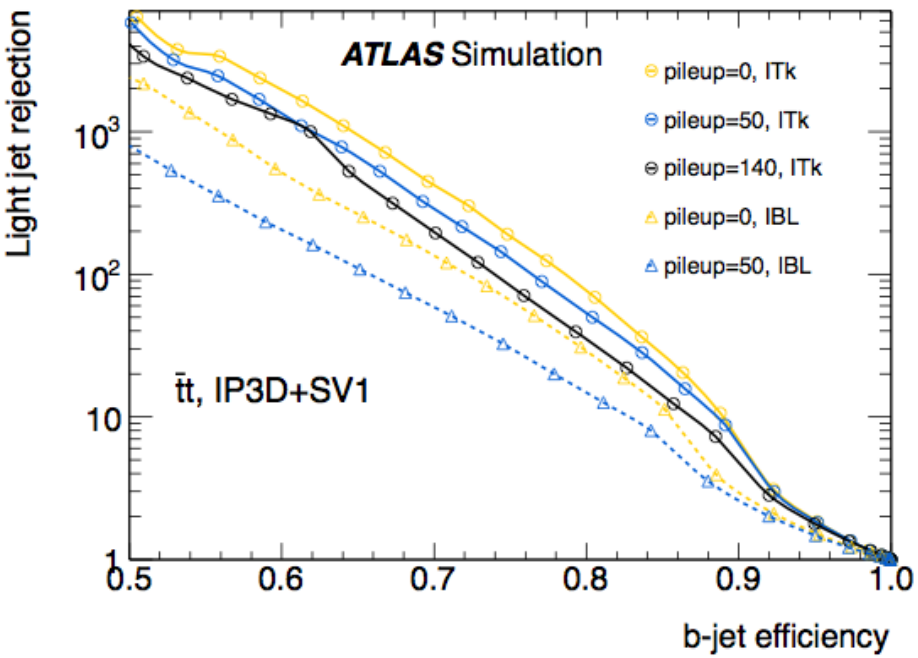
The improvement is p_T dependent, at 1 GeV: ~ a factor 2

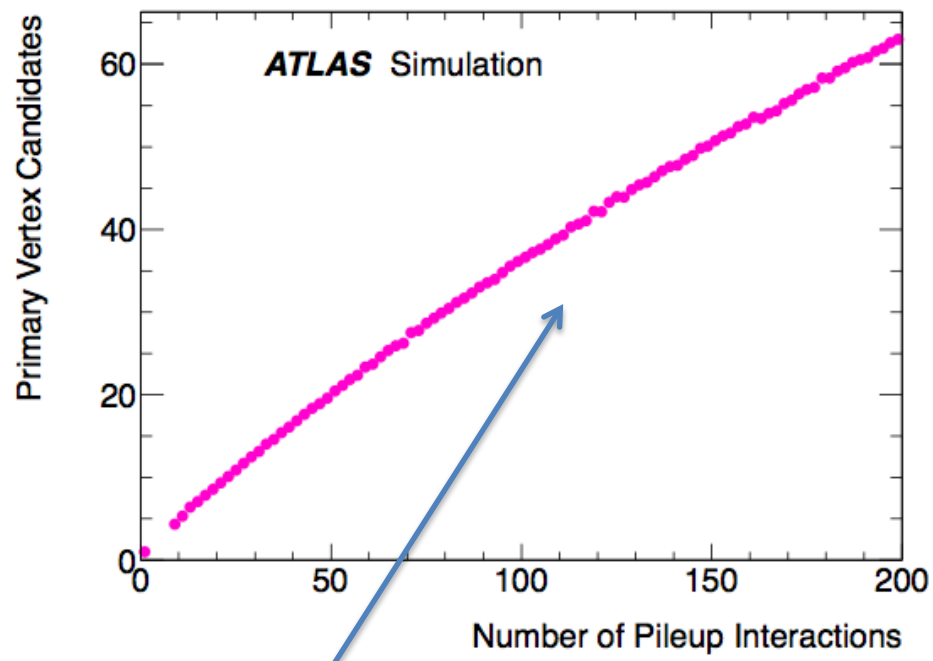
What is the impact of a layer at 33 mm: with pile-up



- The improvement is clear (40%)
- The curves stop at 50 pile-up events
  - We need now to look at high level of PU and its associated density
- These are tt events: primary vertex longitudinal resolution

Preview of the 140 pile-up situation





- If we can gain a factor 2 with CK all will improve
  - This is done using a gaussian beam
  - Please notice that the efficiency is quite low, we need to improve

What about higher than 140 events pile-up: to-do list (part 2)

- This is the tough part
- **Motivation**: is it worth exploring that to reduce the number of years to complete the program? Human-affordable period
- Key to this is the possibility to moderate the density of pile-up

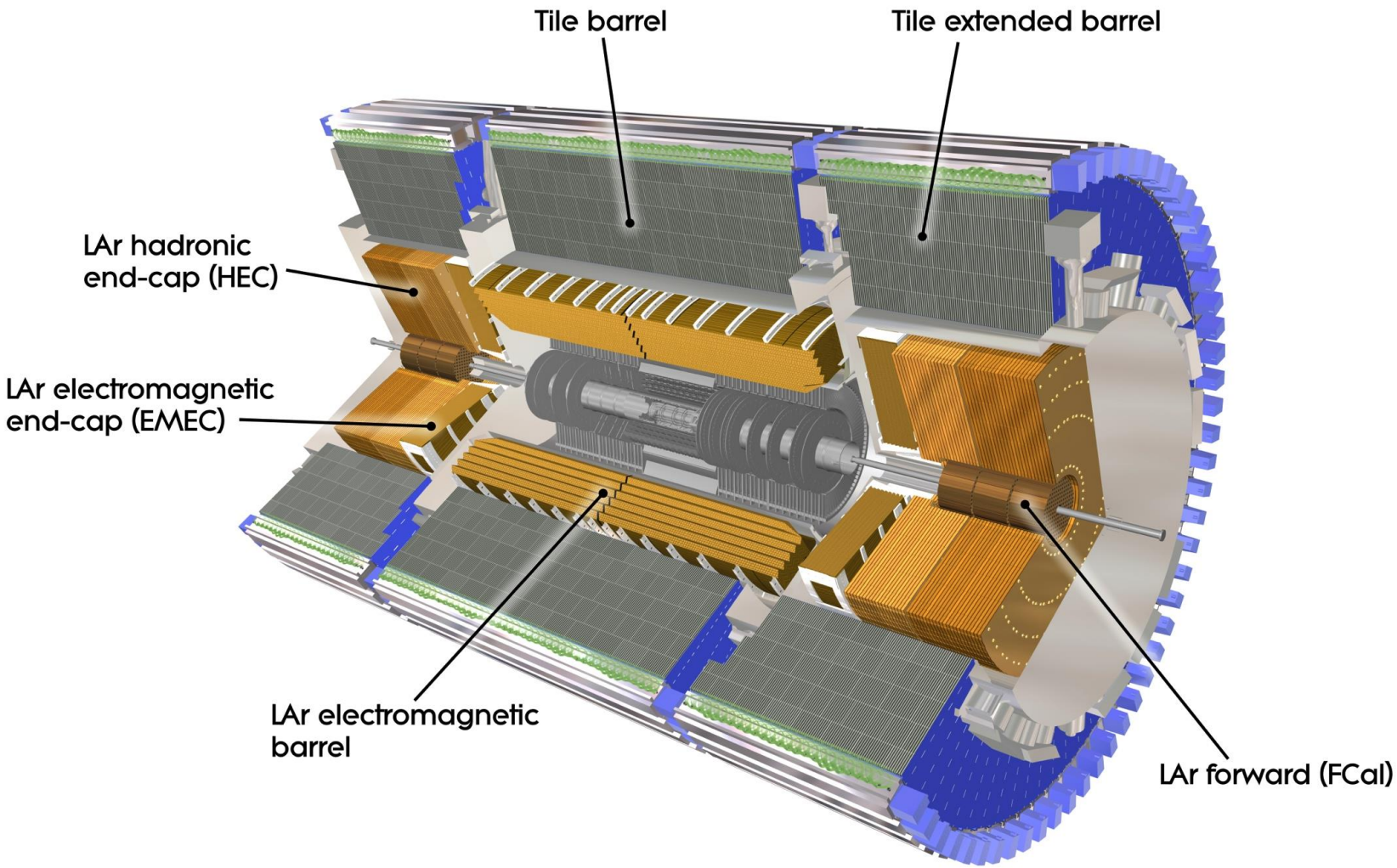
What about higher than 140 events pile-up: to-do list (part 2)

- We do have information at 200 events
  - 5 σ tails, but that is not enough as the tails are a problem, but less frequent
- We need now to look if we can manage in the range 140 (200 max) to 200 (300 max)
- Is it mission impossible for the tracker?
  - We don't know, we need to go from feelings to real plots with robust simulation

Next step: the calorimeters

- Again we have feelings
- We checked our plans of upgrades up to 200 events (the tails)
- What can we do? Only change the electronics, the calorimeters are structural elements in the detectors
- Possible limiting factors: smaller volume (CMS e.m.), LAr ions build up and high HV current with signal distortion and temperature increase (ATLAS e.m.)

Calorimeters in ATLAS



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Calorimeters: limits with pile-up and its density

- Studies have been done so far at 140 average number of pile-up events
- Plots are more complicated and we need to produce now robust plots of comparison baseline-CK
- Few considerations:
  - Mentioned before possible effects of higher pile-up
  - However the line density helps a lot also for the calorimeters especially in the barrel region
    - Lower density better situation with in-time pile-up
    - In the forward region the absolute pile-up is more relevant: the beam spot is seen as a point-like source
      - Higher pile-up will certainly have some bad effects, but we need to quantify. We have measured 2.1 K increase at 6E34 lumi equivalent, possible to handle with cooling (sub-cooled LAr)

To-do list

- Quantify effects for absolute pile-up and for comparison of higher and lower pile-up density
- First results on primary vertex merging
- Continue with secondary vertices and b-tagging aspects. Look at specific channels
- Define the usable luminosity: that is (can be) physics channel dependent, therefore define a figure of merit as the sum of the usable luminosity per channel
- Study the impact of volume effects vs. absolute pile-up
- Look at the impact of in-time pile-up for baseline and CK scheme

The density as an important parameter

- The absolute pile-up and its density are key parameters
- As already mention in Aix-les-Bains: the ball in is detector camp now and we need to answer to the questions on where are our limits
  - Define in this way all together the acceptable parameters for HL-LHC and make the accelerator and the experiments a successful future story
  - But do it on a reasonable time scale

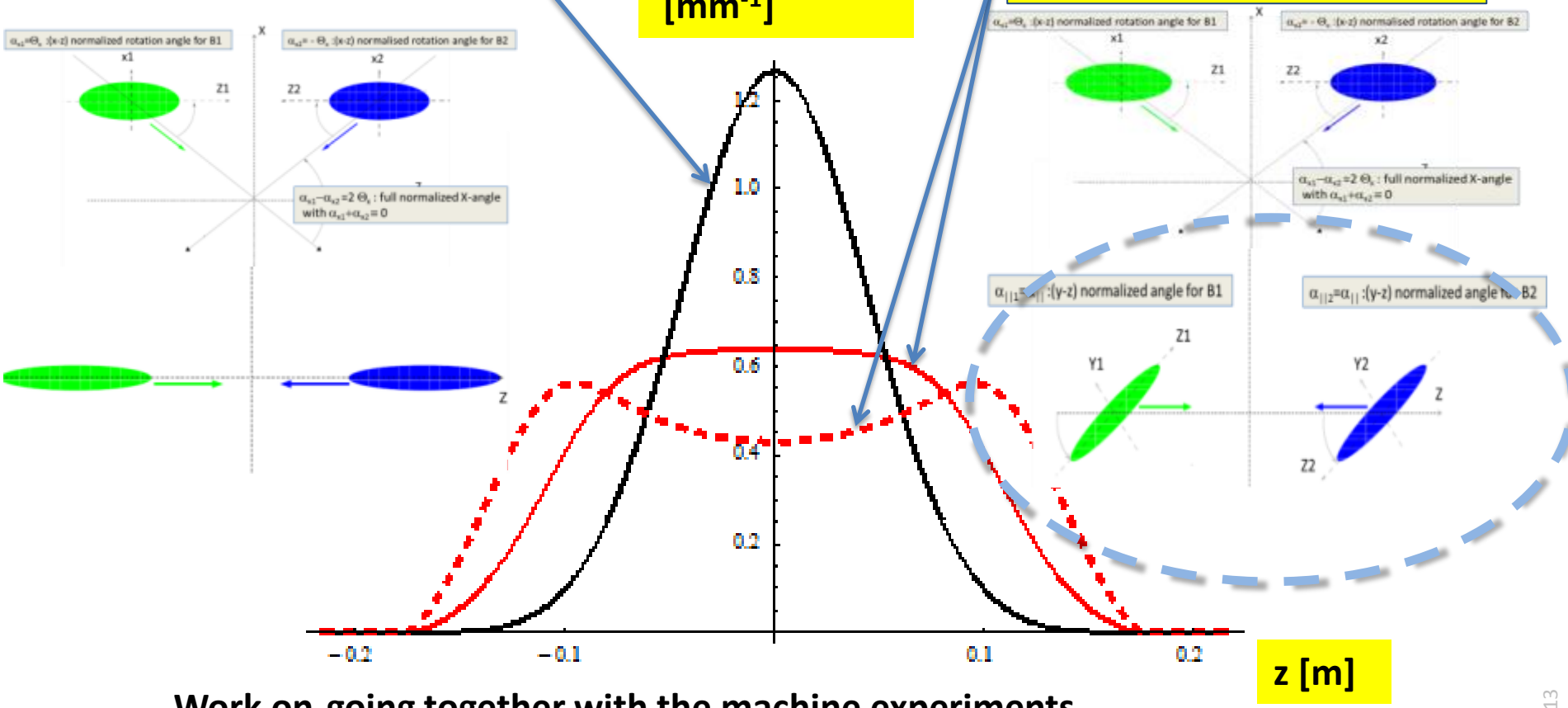
If we don’t go fast

Keep getting options and quite good ones

The **Crab-kissing** (CK) scheme for **pile-up density** shaping and leveling (S. Fartoukh)

Baseline: CC in X-plane "only"

Crab-kissing & variants: CC also in ||-plane



... Work on-going together with the machine experiments (S. Fartoukh, A. Valishev, A. Ball, B. Di Girolamo, *et al.*)

L. Rossi's slide

Conclusions

- The to-do list is long and we are refining the list as well as defining the figures of merit for comparison
- The first look at primary vertices indicate a clear advantage of limiting the pile-up density
- Many studies to be done to understand and quantify what is the usable luminosity
  - The needs for the experiments are to have usable **3 ab^{-1}**
    - Delivered, but not usable lumi means many many years with high selections of events and a lot of pain

High Luminosity LHC

11/14/2013

Thank You