Impact of pixel size and shape on physics analysis

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Motivation of this study

- Current situation at the LHC
  - CMS pixel size $100 \times 150\mu\text{m}^2$
  - Atlas pixel size $50 \times 400\mu\text{m}^2 \xrightarrow{\text{IBL}} 50 \times 250\mu\text{m}^2$.
- Usually studies show impact parameter resolution of pixel detectors

$$\sigma(\text{pix}) \Rightarrow \sigma(\text{impact})$$

- Physics analysis on the other hand start with an abstract object 'track' which in some intransparent way is related to the above quantity.
- But what we want is

$$\sigma(\text{pix}) \Rightarrow \sigma(\text{impact}) \Rightarrow \text{Physics result}$$

- Investigate the outcome on sample physics analysis $B_s^0 \to \mu^+\mu^-$.
- Get basic behavior from simple models

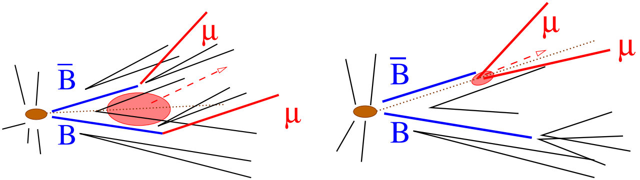
  $\Rightarrow$ Do not get lost with to many parameters...

$B_s^0 \to \mu^+\mu^-$

- Experiments at LHC looking for the decay $B_s^0 \to \mu^+\mu^-$.
- Clear signal topology: Two muons originating from the same vertex.
  - $\Rightarrow$ Nice candidate for this study.
- This decay is heavily suppressed in SM[1]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9}$$

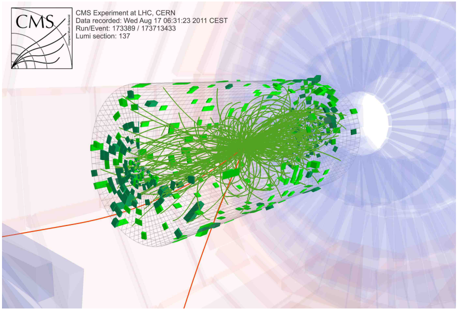
$\Rightarrow$ New physics can possibly be found.



[1] arXiv:1208.0934v1

Event

- In reality, huge amount of tracks.
- Crucial to know whether two tracks actually meet, not to drown in background

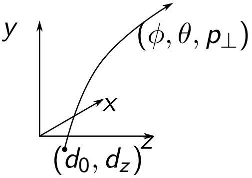


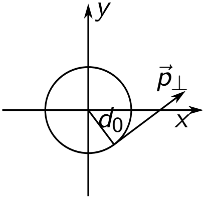
Track model

- Need 5 parameters to describe a track (homogeneous magnetic field)

$$\begin{aligned} (d_0, d_z) &\quad \text{impact parameters} \\ (\phi, \theta, p_\perp) &\quad \text{momentum direction \& curvature} \end{aligned}$$

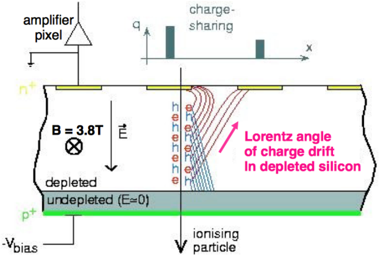
- Ability to see wether two tracks are from the same vertex is described by the impact parameters.
  - resolution of impact parameters given mostly by pixel detector.

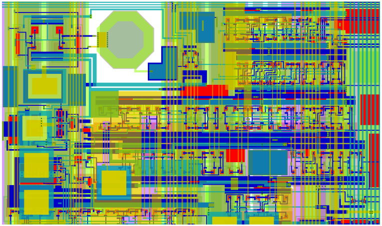




Pixel size

- Position resolution of the pixel detector given by
  1. Pixel dimensions.
  2. Charge sharing of pixels.
- Constraints:
  - Enough electrons have to be collected to trigger pixel readout electronics.
  - Transistors have to fit in the given shape.



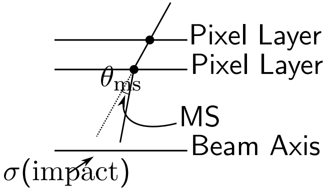


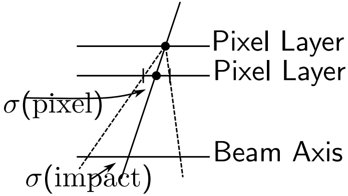
CMS PUC

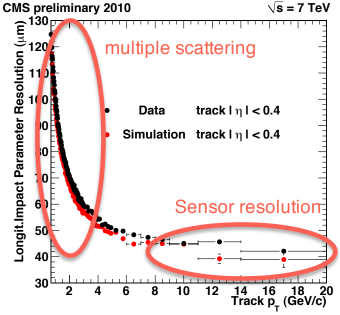
Impact parameter resolution

- Impact parameter resolution:

$$\left.\begin{array}{r}\text{Multiple scattering} \;\Leftrightarrow A/p_{\perp}\\ \text{Sensor resolution} \;\Leftrightarrow B\end{array}\right\} \Longrightarrow \sigma^2 = (A/p_{\perp})^2 + B^2$$







CMS-PAS-TRK-10-005

Analysis

Two Monte Carlo simulations have been produced

1. Signal MC, each event containing one $B_s^0 \to \mu^+\mu^-$.
   $\rightarrow \approx 1 \times 10^7$ Events $\gtrapprox 6.4\,\mathrm{ab}^{-1}$
2. Background MC, Minimum Bias events containing b quarks and two μ with $p_\perp > 2.5$ GeV.
   $\rightarrow \approx 1.7 \times 10^{10}$ Events $\gtrapprox 170\,\mathrm{nb}^{-1}$

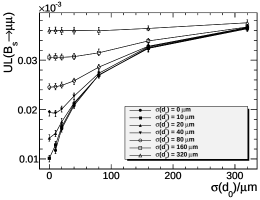
Analysis consists of

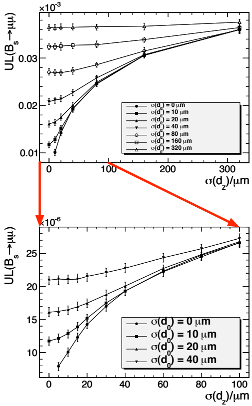
- Construct candidates by combining two muons.
- Apply preselection cuts
- Randomize kinematic variables according to assumed resolution scenario.
- Find cut on distance of closest approach (doca) of the two muon tracks s.t. $\varepsilon_{\mathrm{sig}} = 0.9$.
  $\Rightarrow$ With perfect resolution doca is enough to separate signal from background.
- Compute expected upper limit.

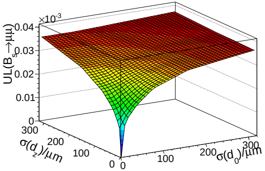
$p_\perp(\mu)$	> 2.5 GeV
$\lvert\eta(\mu)\rvert$	< 2.5
$d_{3,\mathrm{truth}}$	$> 25\ \mu$m.

Scenario $A = 0$

- Understand qualitatively the impact of the asymptotic term affected most by the pixel resolution
- 'saturation' of upper limit result starts at $\sigma(d_0) \approx \sigma(d_z)$



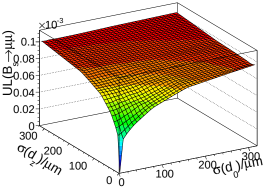




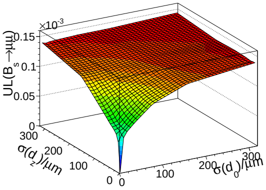
Eta dependence

- Improvement in UL depends on the η region. Qualitatively we have for $\sigma(d_z) \cdot \sigma(d_0) = \mathrm{const}$:
  - $|\eta| < 0.6 \Rightarrow$ analysis gains more improving $\sigma(d_z)$
  - $|\eta| > 1.2 \Rightarrow$ analysis gains more improving $\sigma(d_0)$

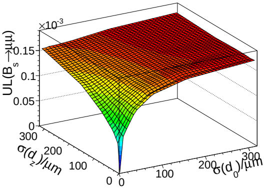
|η| < 0.6



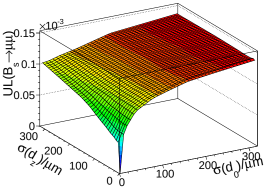
0.6 < |η| < 1.2



1.2 < |η| < 1.8



1.8 < |η| < 2.5

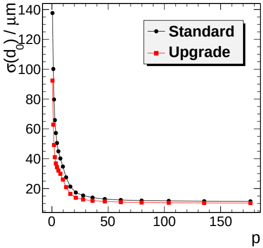


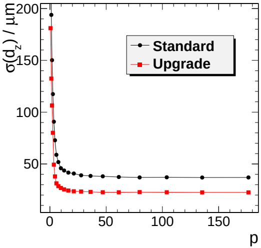
CMS like pixel detector

Compare two models with the preselection tightened to $p_\perp > 3$ GeV and $|\eta| < 1.4$:

- Current design
- Upgrade design

	Current	Upgrade	Change
doca	139 μm	75 μm	-46%
$N_{\rm bkg}$	60 ± 8	39 ± 6	-35%
$N_{\rm sig}$	$(1.369 \pm 0.006) \times 10^{-3}$	$(1.369 \pm 0.006) \times 10^{-3}$	-
UL	$(3.4 \pm 0.2) \times 10^{-5}$	$(2.8 + 0.2) \times 10^{-5}$	-18%





"Long pixels"

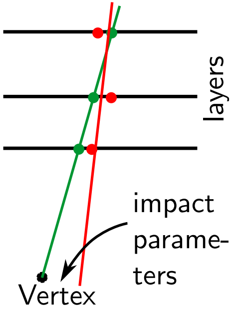
Convolute a long z-pixel size into the CMS like detector

- Intrinsic sensor resolution given by asymptotic term B.
  - $\Rightarrow$ Consider straight tracks.
- What happens to $\sigma(\mathrm{impact}_z)$ when we enlarge $\sigma(\mathrm{pix}_z)$.
- Consider two models with
  1. $\sigma(\mathrm{pix}_{xy}) = 15\ \mu\mathrm{m}$, $\sigma(\mathrm{pix}_z) = 20\ \mu\mathrm{m}$.
  2. $\sigma(\mathrm{pix}_{xy}) = 15\ \mu\mathrm{m}$, $\sigma(\mathrm{pix}_z) = 70\ \mu\mathrm{m}$.

Estimating B

- $p_\perp \to \infty \Rightarrow$ tracks are straight lines
- Compute impact parameter resolution by
  - Generate track with associated hits
  - Randomize hits using assumed resolution
  - Fit track and compute impact parameter
- Assume average pixel resolution:

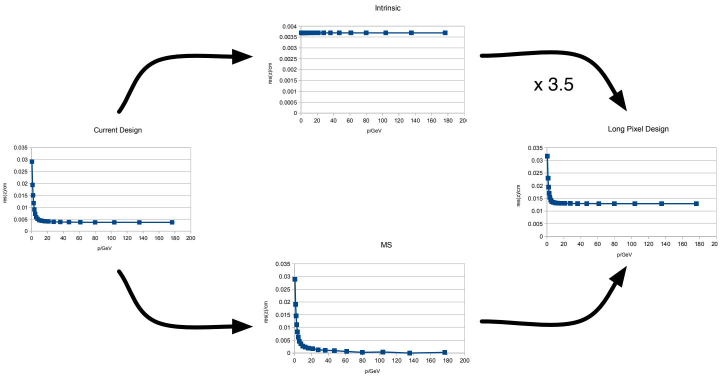
$$\sigma(\mathrm{pix}_{xy}), \sigma(\mathrm{pix}_z) = 15\ \mu\mathrm{m}, 20\ \mu\mathrm{m}$$
$$\Rightarrow \sigma(d_z) \approx 37.5\mu\mathrm{m}$$
$$\sigma(\mathrm{pix}_{xy}), \sigma(\mathrm{pix}_z) = 15\ \mu\mathrm{m}, 70\ \mu\mathrm{m}$$
$$\Rightarrow \sigma(d_z) \approx 130\mu\mathrm{m}$$



- Factor 3.5 remains. This motivates the choice to enlarge the B term by the same factor.

"Long pixel" resolution

- Separate resolution into A-term and B-term.
- Scale B-term by 3.5
- Convolute the two again.



"Long pixel results"

- Full Model

	Current	Long	Change
doca	139 μm	240 μm	+73%
N_{bkg}	60 ± 8	83 ± 9	+38%
N_{sig}	$(1.369 \pm 0.006) \times 10^{-3}$	$(1.369 \pm 0.006) \times 10^{-3}$	-
UL	$(3.4 \pm 0.2) \times 10^{-5}$	$3.9^{+0.1}_{-0.2} \times 10^{-5}$	+15%

- Asymptotic Model

	Current	Long	Change
doca	66 μm	214 μm	+224%
N_{bkg}	36 ± 6	81 ± 9	+125%
N_{sig}	$(1.369 \pm 0.006) \times 10^{-3}$	$(1.369 \pm 0.006) \times 10^{-3}$	-
UL	$(2.7 \pm 0.2) \times 10^{-5}$	$(3.9 \pm 0.2) \times 10^{-5}$	+32%

Summary

- Simple asymptotic model:
  - ⇒ Detector performance $\sim \sigma(d_0)^2 + \sigma(d_z)^2$. Optimal result we need to enhance resolution in a balanced way.
  - ⇒ Optimal choice clearly depends on other detector parameters as well. Might be worth for detectors to investigate this more carefully.
- Reducing the resolution penalty from multiple scattering greatly enhances a detector like CMS.
  - ⇒ However in 'real' analysis, higher $p_\perp$ cuts are applied which should reduce this effect.
- Enlarging the z-pixel size of a CMS like detector by a factor 3.5 does increase the upper limit by a significant amount.
  - ⇒ Again, 'real' analysis expected to lie in between the two states results as $p_\perp$ cut higher and so less effected of multiple scattering.

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THANK YOU FOR YOUR ATTENTION