Backgrounds in the FCC-ee detector and consequences for the trigger and DAQ

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with inputs from Mike Sullivan, Nicola Bacchetta and Helmut Burkhardt

FCC Week, Rome, April 13, 2016

Trigger / DAQ for FCC-ee ?

High precision measurements require :

- a very high luminosity - e.g. at the Z peak, could reach about 2 10^{36} $cm^{-2}s^{-1}$
- highly granular detectors
  - e.g. using ILC detectors as an example :
    - VTX : 1000 M channels (CMS phase-1: 80M, LHCb upgrade: 40M)
    - ECAL : 100 M channels (CMS : 100 000)

$\rightarrow$ Large data through-put to disk (trigger rate times "event size")
- Rate of Z events at the Z peak, 2 10^{36} $cm^{-2}s^{-1}$, close to 100 kHz

$\rightarrow$ Large data volume through the event builder
- L1 trigger rate times the size of a L1-Accepted event
- or crossing rate times the size of a zero-bias event if no hardware trigger
  - but crossing rate can reach 270 MHz at the Z pole (Δt = 4 ns)

For the ILC : most of the data volume is coming from backgrounds !

Background sources

• machine-induced background, e.g. synchrotron radiation upstream of the IP, beam-gas interactions

• Background processes at the IP, e.g. :
  - Especially pair-production background, γγ to e+e-
    low PT particles, enter (many times) in the vertex detector.
    Or can make showers in material in the fwd region (e.g. Lumi monitor), leading to secondaries that can backscatter into the main detector
      - at ILC : most of the data volume is coming from pair-production bckgd
        largely induced by the large amount of beamstrahlung
  - similarly, γγ to hadrons
  - radiative Bhabha events, etc

This talk: first full simulation studies of backgrounds in the detector at FCC-ee
  - pair production background : at the Z peak (c.w. scheme, highest rates)
  - synchrotron radiation : at the top energy (most challenging)

FCC-ee IR and detector model in GEANT4

FCC-ee IR and detector model in GEANT4

- Using the CLIC software
    - description of the geometry based on DD4HEP
    - many thanks to Andre Sailer & Nikiforos Nikiforou (CERN/CLICdp) for their help

- FCC-ee interaction region following proposal shown by Mike Sullivan
    - symmetric L* (sym. quadrupoles on the incoming / outcoming line)
    - starting point. Variants / improvements / other options will be implemented

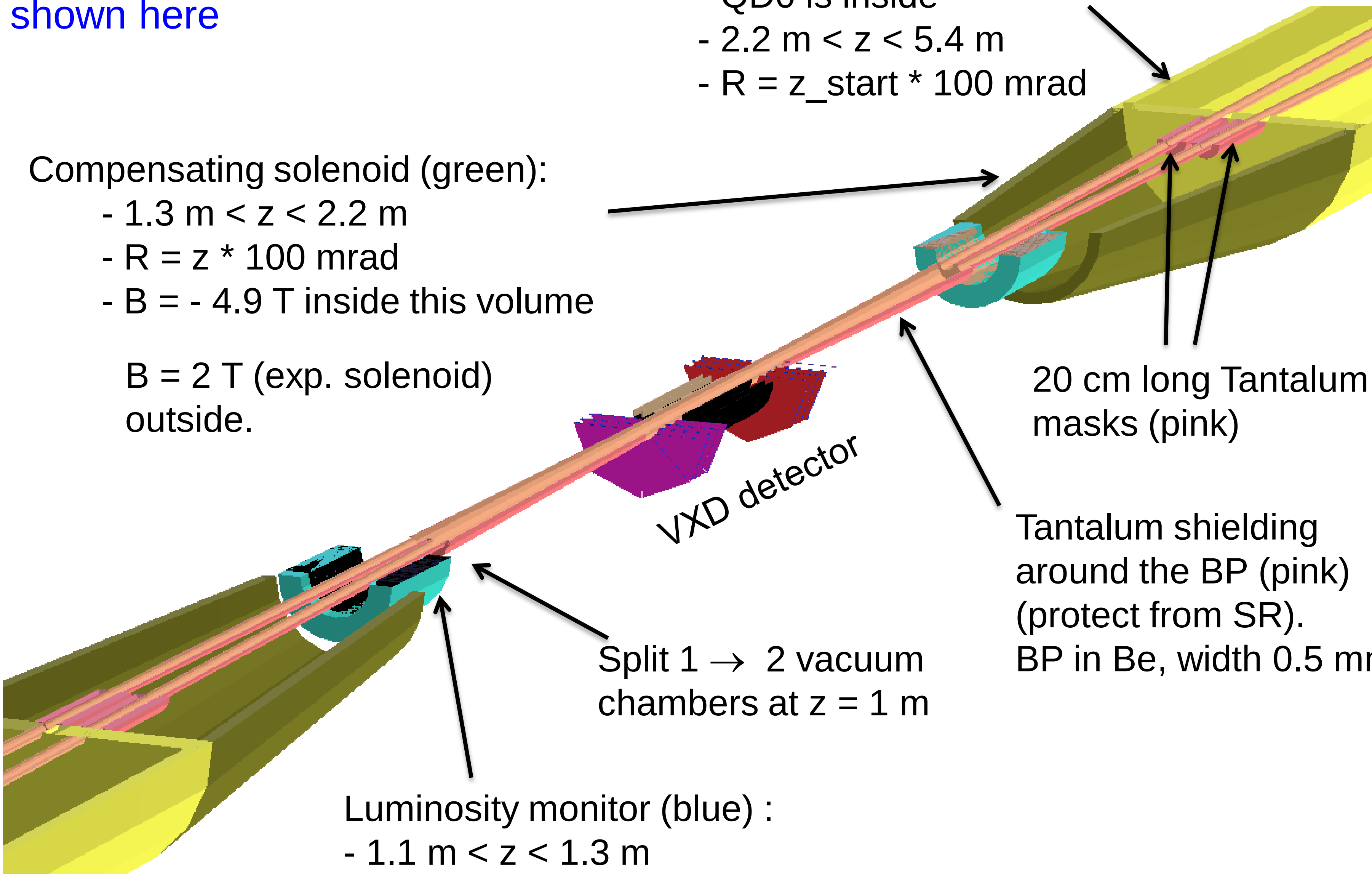
- add “on top” the CLIC detector
    - see e.g. CLIC CDR, or talk of N. Nikiforou, June 2015 detector workshop
    - start from CLIC_o2_v04 : model with full-silicon tracker
    - with minimal modifications to comply with the IR. Mainly :
        - minimal changes to the tracker to adapt to the beam-pipe
        - LumiCal closer to the IP. No BeamCal.
        - B = 2 T
        - calorimeters and muon detectors unchanged from CLIC model
            - for background studies : inner detector is what matters

Implemented for the simulations shown here

"envelope" for the shielding solenoid (yellow) :
- QD0 is inside
- 2.2 m < z < 5.4 m
- R = z_start * 100 mrad

Compensating solenoid (green):
- 1.3 m < z < 2.2 m
- R = z * 100 mrad
- B = - 4.9 T inside this volume

B = 2 T (exp. solenoid) outside.



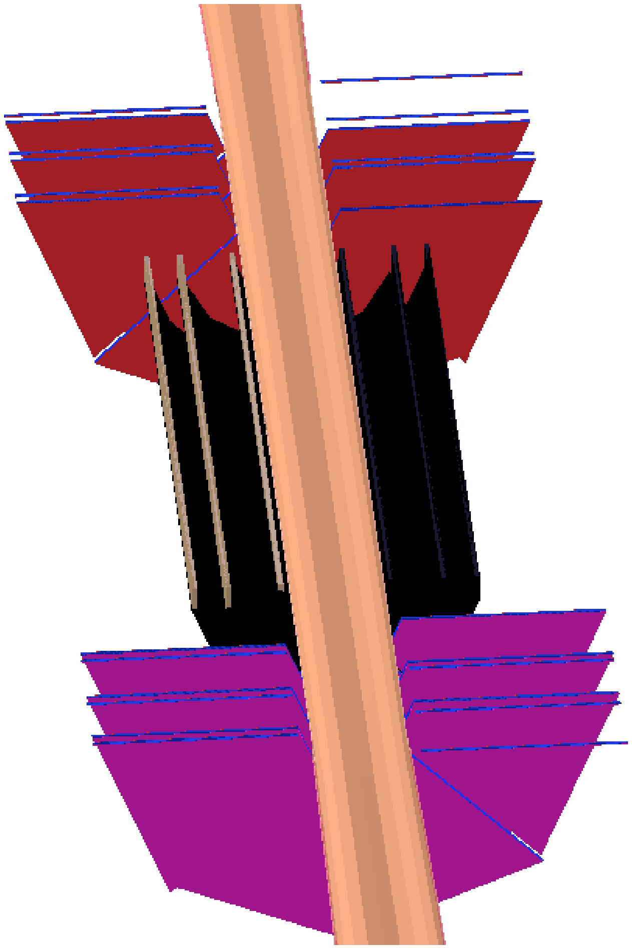
20 cm long Tantalum masks (pink)

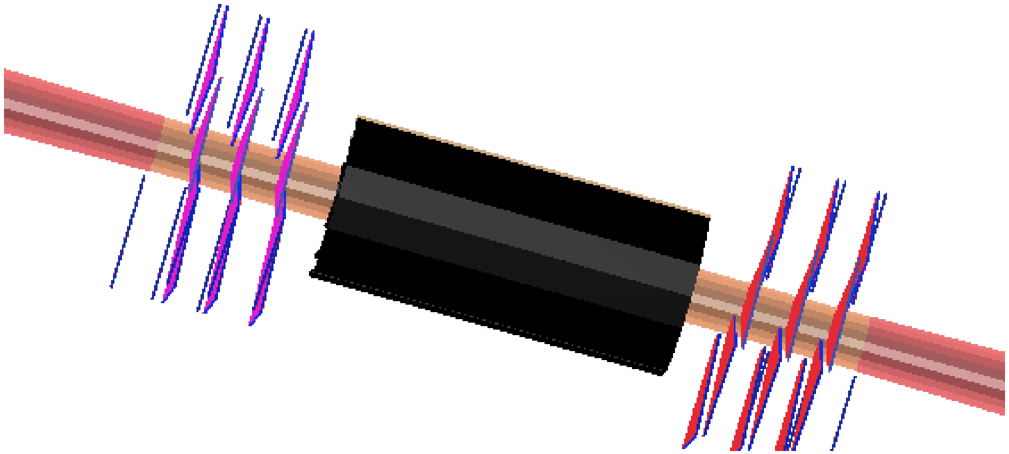
Tantalum shielding around the BP (pink) (protect from SR). BP in Be, width 0.5 mm

Split 1 → 2 vacuum chambers at z = 1 m

Luminosity monitor (blue) :
- 1.1 m < z < 1.3 m
- Si/W calorimeter, 5.6 < R < 9.3 cm
- centered around the outgoing beam

Vertex detector





Beam-pipe in central part : cylindrical, R = 2 cm

Barrel: 3 double-layers R = 2.2 cm, 4.4 cm, 5.8 cm
| z max | = 13 cm

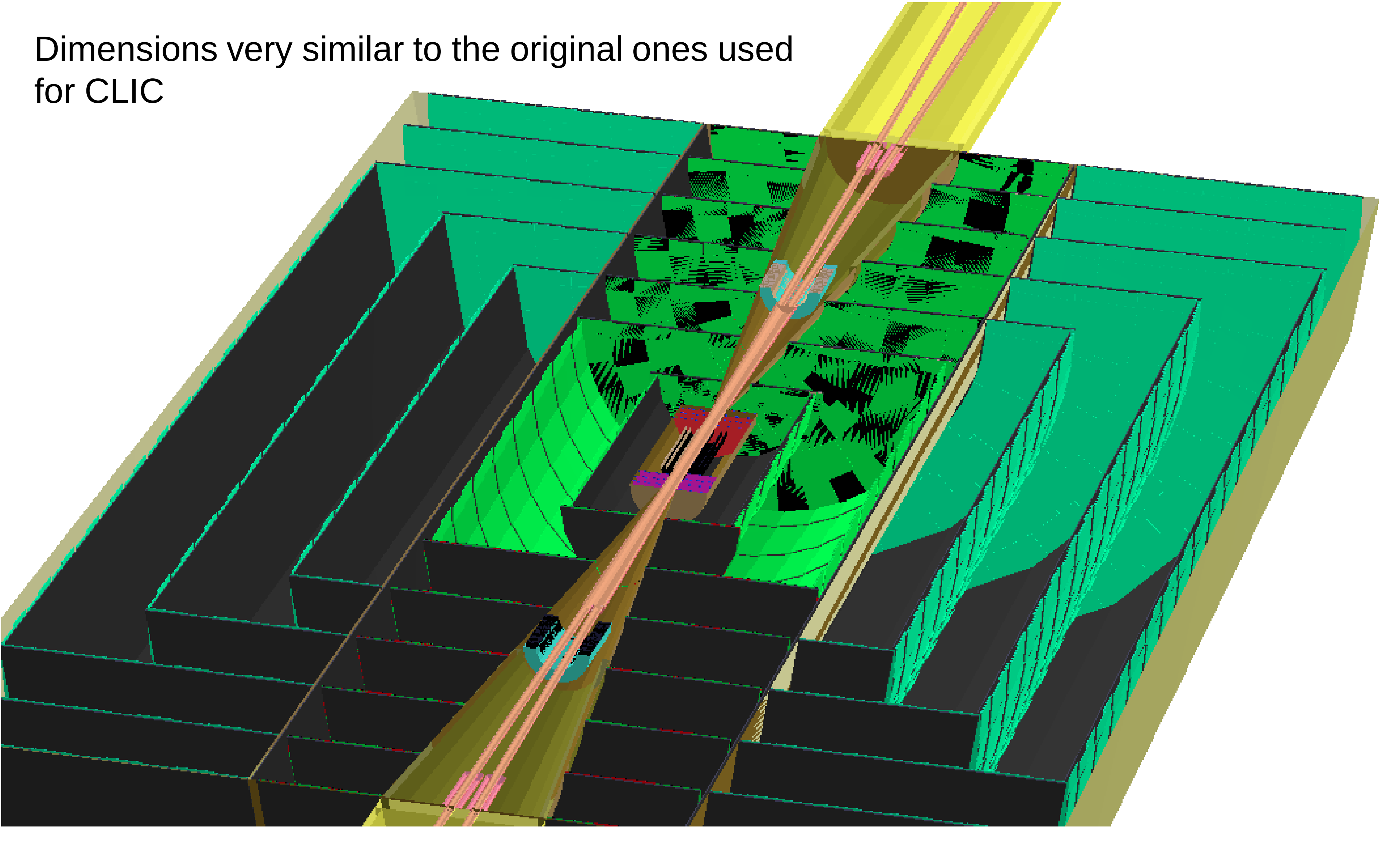
Endcap :3 disks, “spiral” geometry, Rmax = 10.2 cm
| z max | = 22.3 cm
i.e. all endcap disks on the cylindrical BP

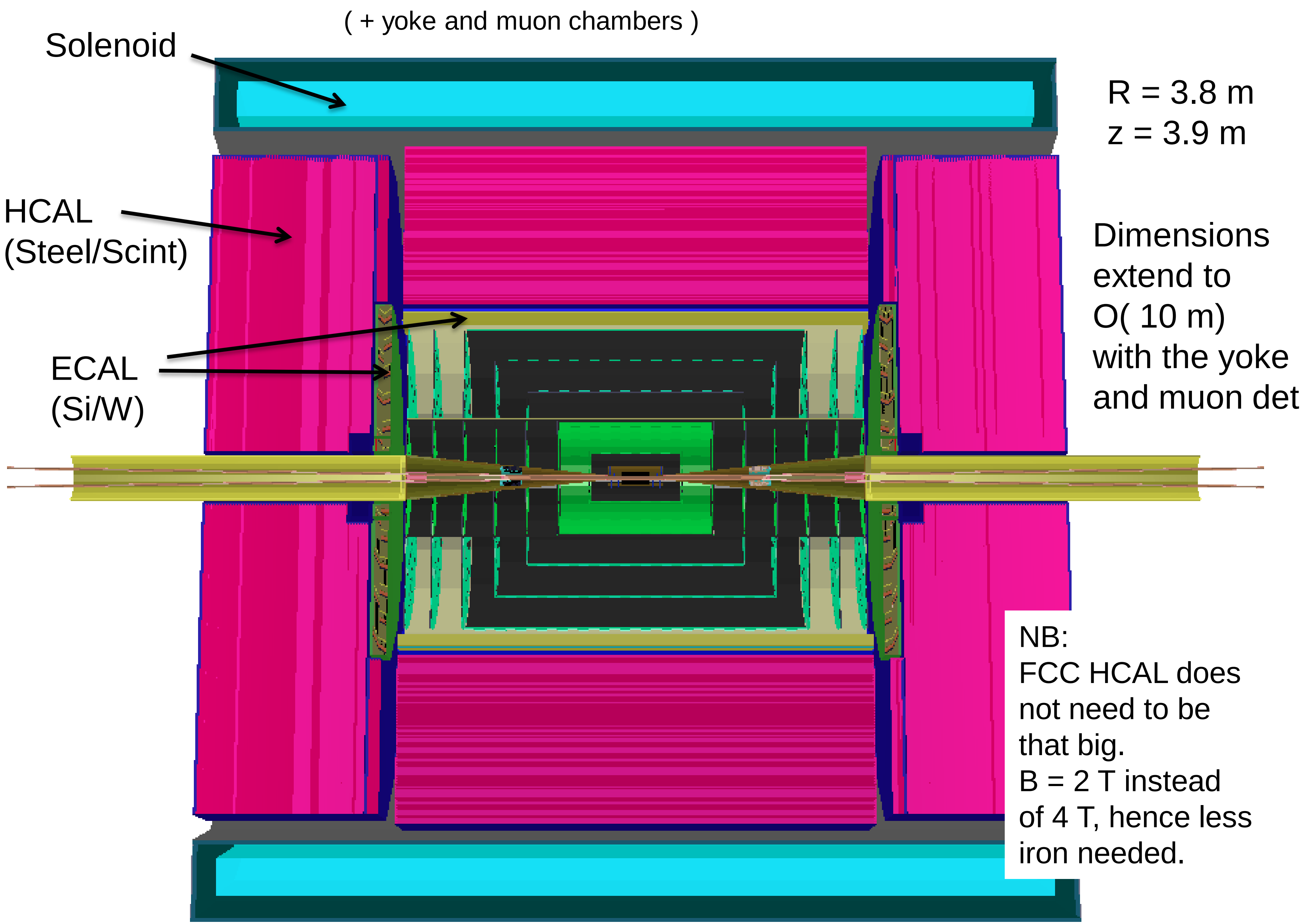
That’s basically the CLIC VXD. Only change is R of innermost layer – and consequently, dimension of the staves.

Adding the CLIC inner and outer tracker

Full silicon tracker, acceptance down to 100 mrad.

Dimensions very similar to the original ones used for CLIC




(+ yoke and muon chambers)
Solenoid
R = 3.8 m
z = 3.9 m
HCAL
(Steel/Scint)
Dimensions extend to O(10 m) with the yoke and muon det.
ECAL
(Si/W)
NB:
FCC HCAL does not need to be that big.
B = 2 T instead of 4 T, hence less iron needed.

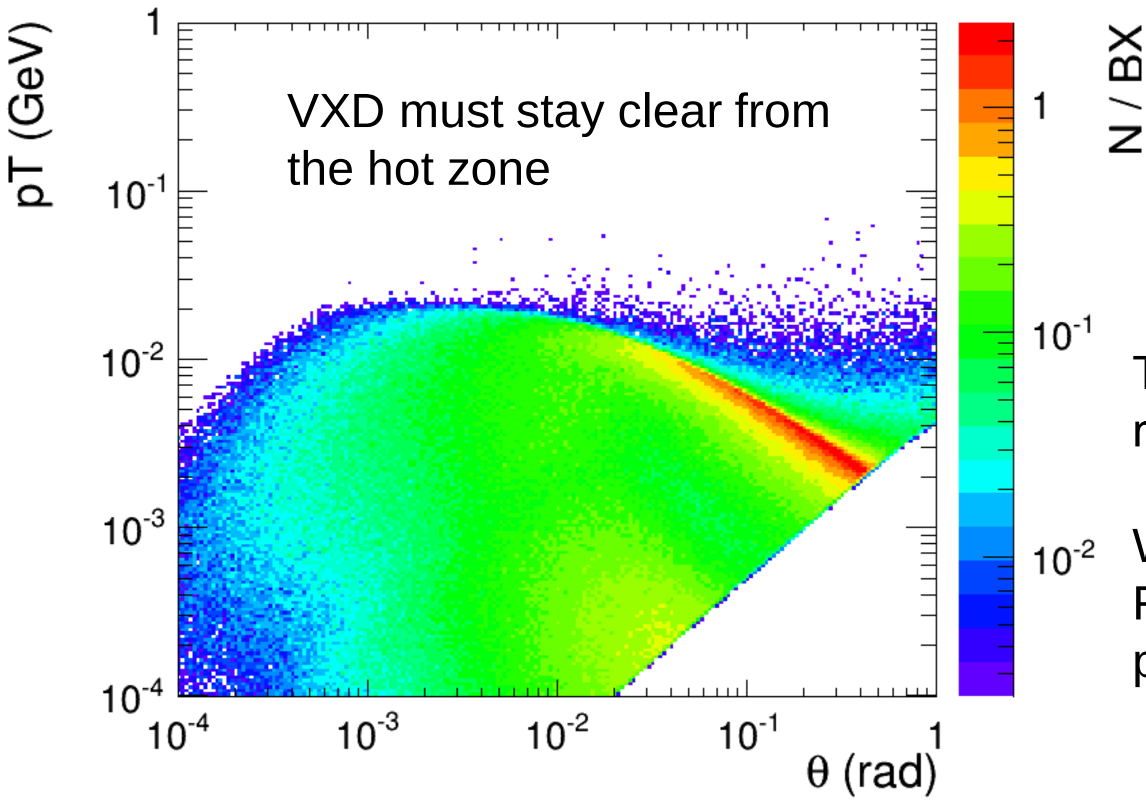
Beamstrahlung and pair-production background

all what is shown here corresponds to the Z peak

Beamstrahlung and pair-production background at the Z peak

Generate events (γγ -> e+ e- including beamstrahlung photons) with Guinea-Pig with the machine parameters of FCC-ee Z c.w (parameters in backup).
Shown here = average over O(700) BXs.

On average : ~ 4000 pairs created per BX
carry an energy of ~ 1 TeV (400 x less that at ILC500)
largely dominated by the Landau-Lifschitz process (γ*γ* -> ee **)**



< pT > = 3 MeV
< E > ~ 500 MeV
< θ > = 80 mrad

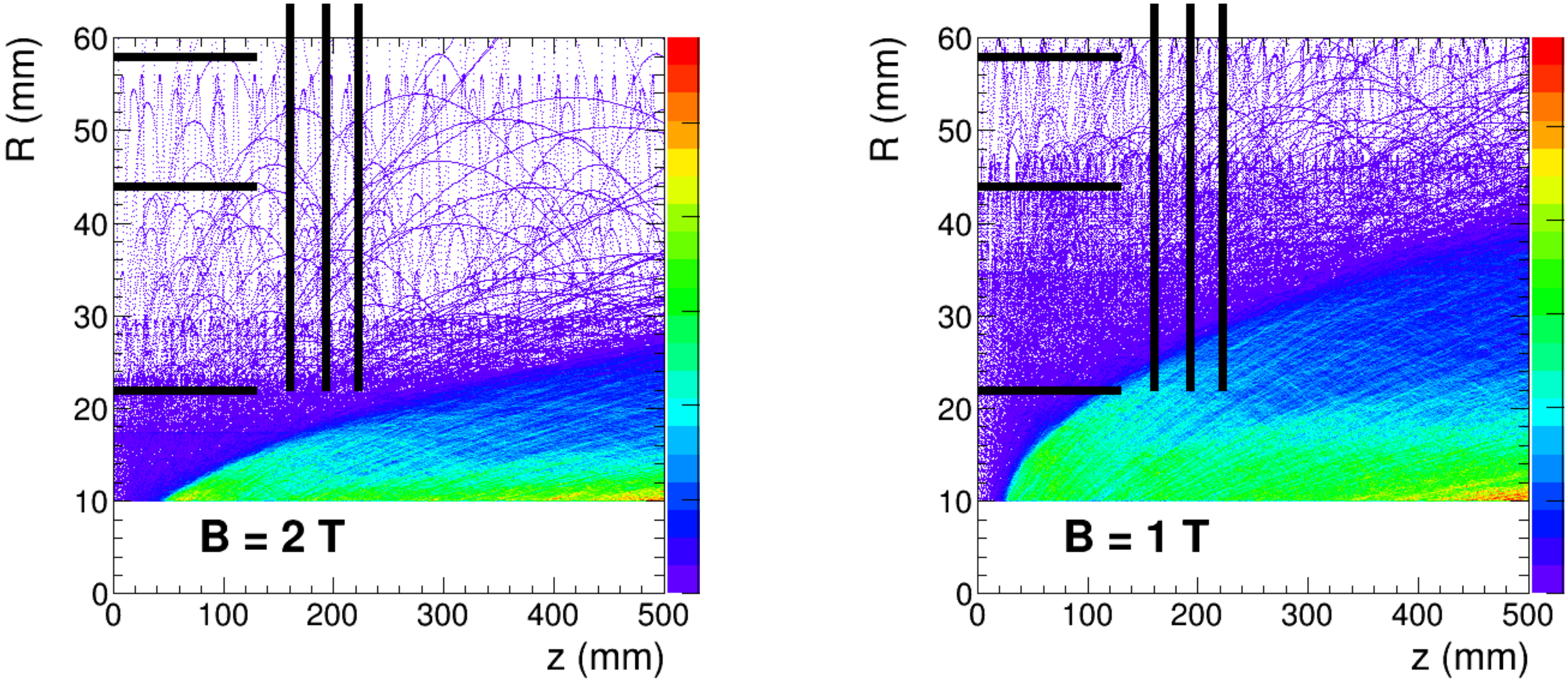
To reach a given R, the particle must bend with 2ρ > R.

With B = 2 T and a beam-pipe at R = 20 mm : particles with pT > 6 MeV can cross the BP.

E.Perez

Trajectories of e+/- pairs in the 2T field

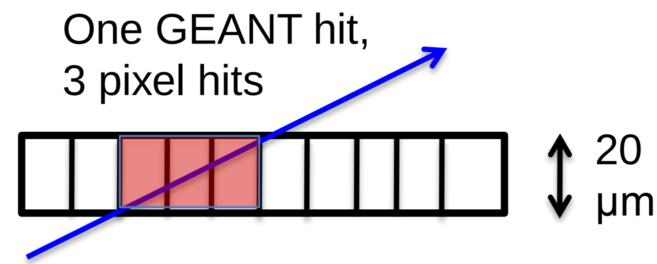
Helicoidal trajectories of the e+/- pairs in the field of the experiment :



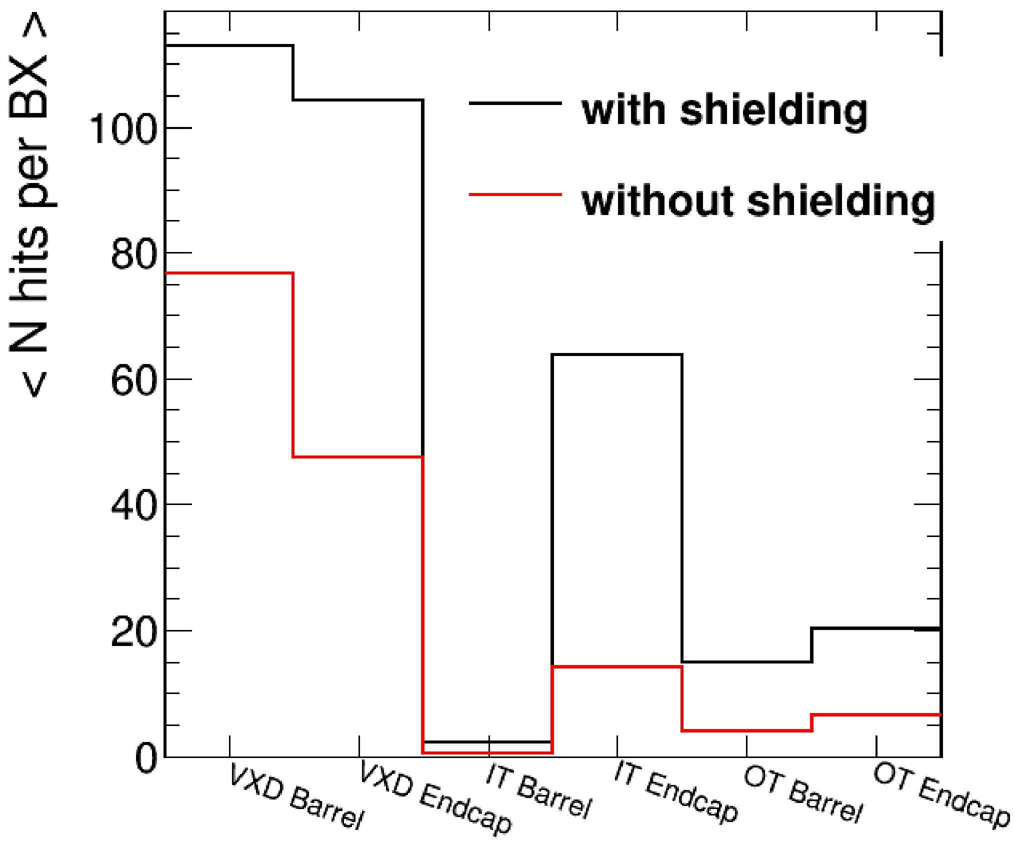
With the nominal value of B = 2 T and innermost layer of VXD at 2.2 cm :
VXD avoids the hot region

Tracker hits in the vertex detector and tracker

GEANT hits: deposited energy > 1 keV
(a MIP crossing 20 µm of Si would deposit 8 keV)
Proportional to the number of pixels that are hit
(typical cluster size in VXD O(3))



VXD Pixel size: 25 µm x 25 µm

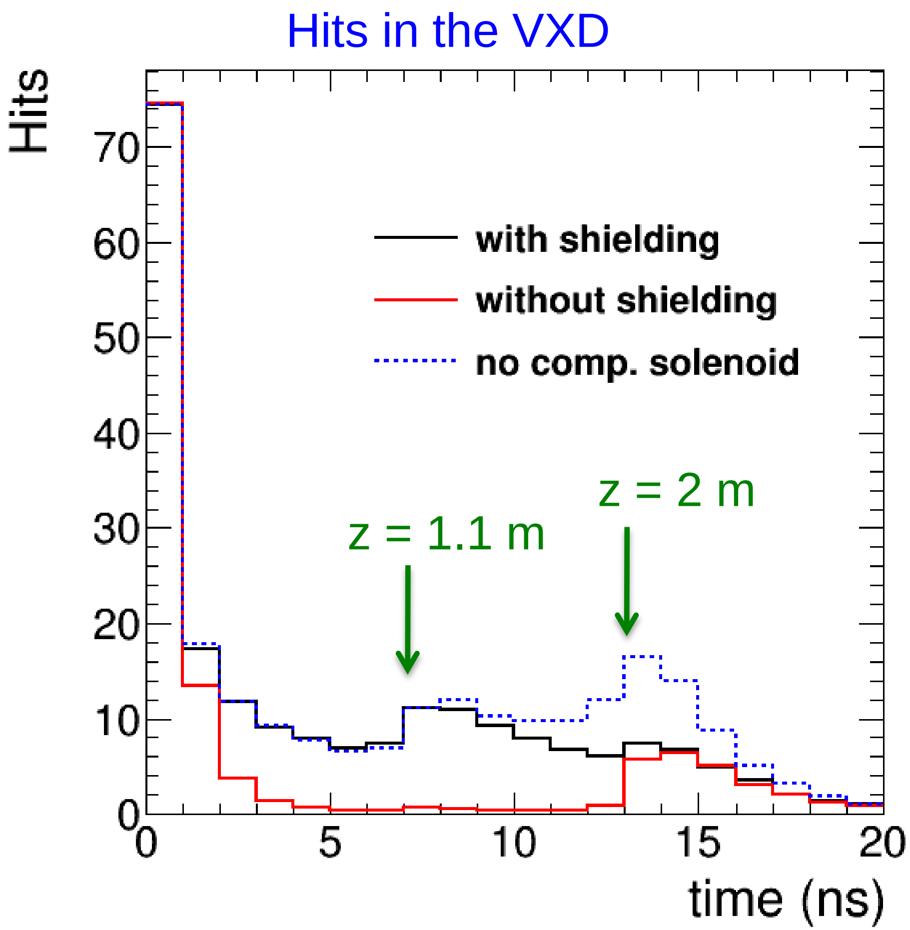


- On average : 320 hits / BX
  - O(220) hits in the VXD,
  - O(65) in Inner Tracker,
  - O (35) in Outer Tracker

- The beam-pipe shielding increases the hit multiplicity by a factor of two :

  0.5 mm of Ta is enough X0 for electrons of < p > = 500 MeV to make a shower :
  - X0 of Ta = 0.4 cm
  - e- crossing the BP at z = 1 m goes through 25 mm = 6 X0 !

Tracker hits in the vertex detector (pair-production bckgd, Z peak)



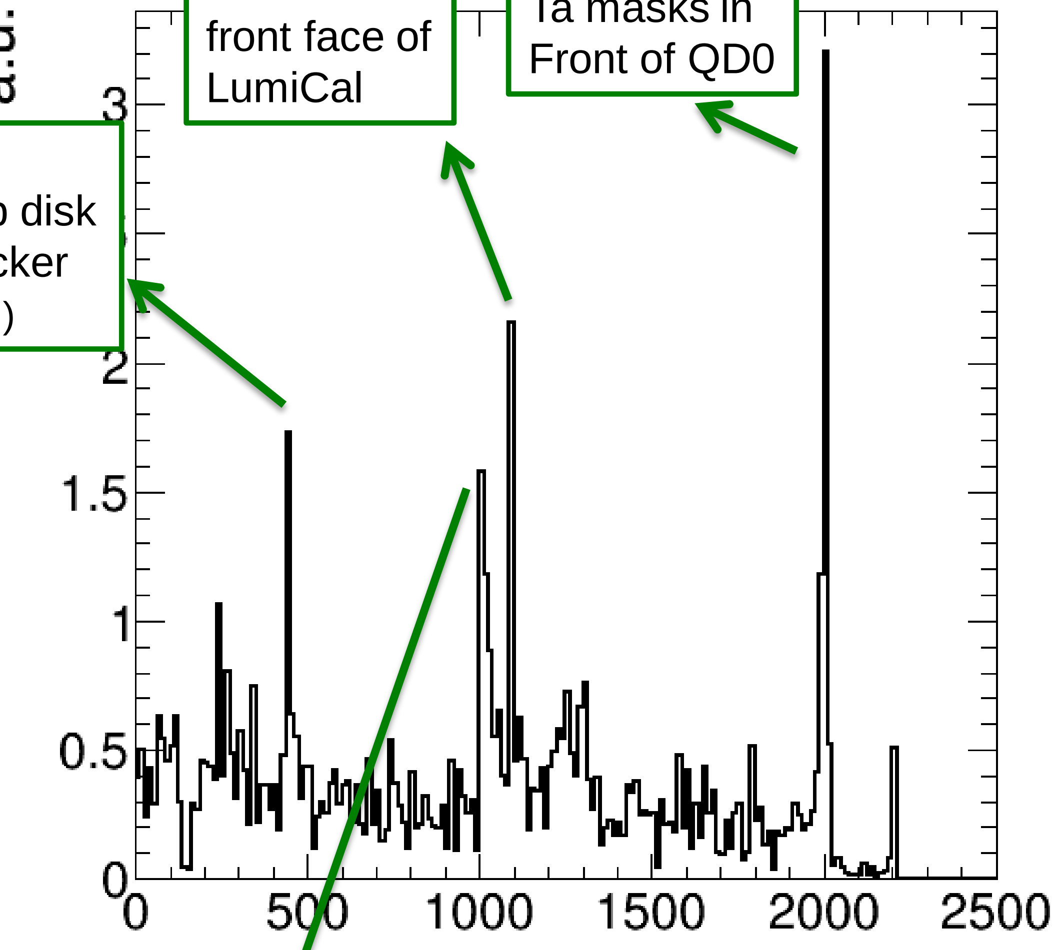
- Evidence for backscattering
  - esp. at z ≈ c t / 2 ≈ 2 m (QD0) and at z ≈ 1.1 m (LumiCal surface)
  - in VXD : 37% of hits are due to backscattering
- Ta shielding leads to more backscattering consistent with the higher fraction of hits in Endcap in previous slide.
- The presence of the compensating solenoid affects the backscattering
  → need a field map for reliable estimates

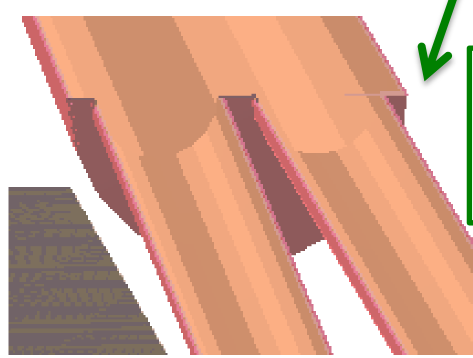
A closer look at the backscattering

For backscattering secondaries that make hits in VXD :

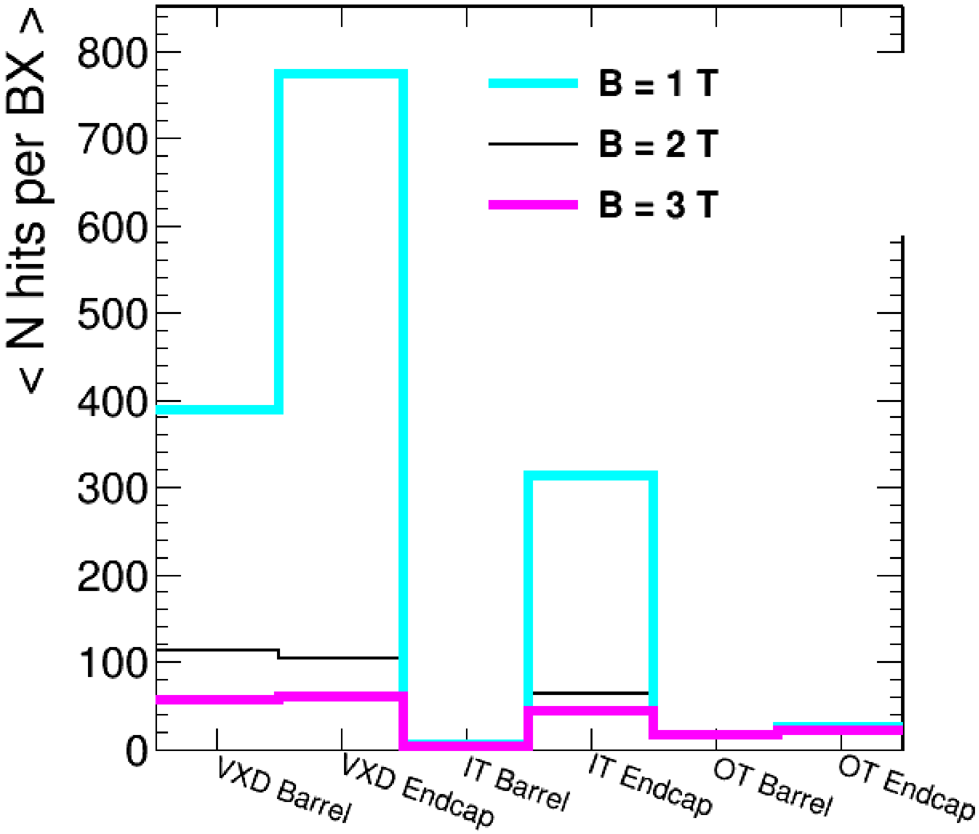
Look at where they come from

(some bias… the full history is not kept …)





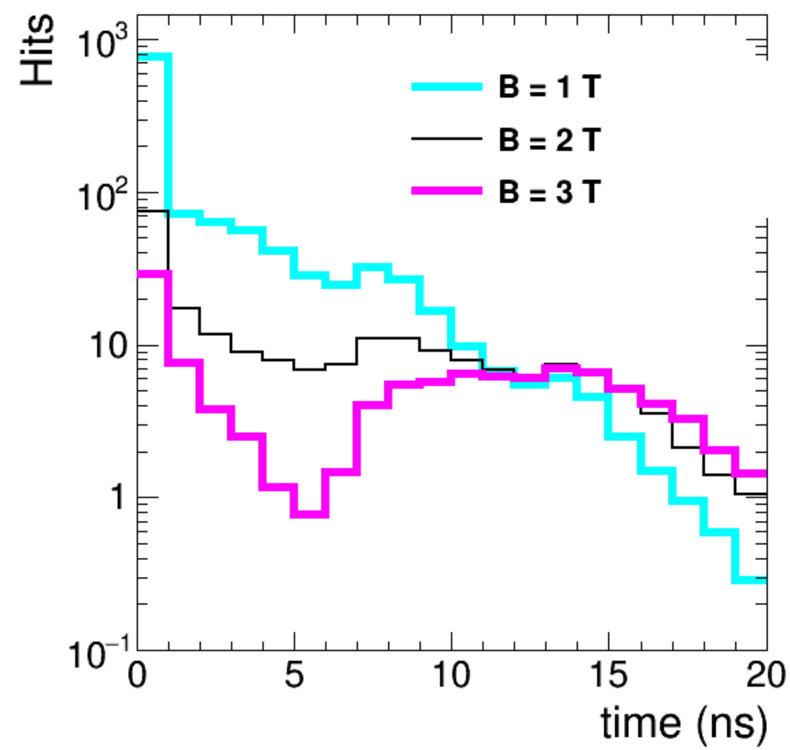
Effect of the magnetic field (exp. solenoid)



The value of the exp. field affects mostly the direct hits. Smaller effect on backscattering.

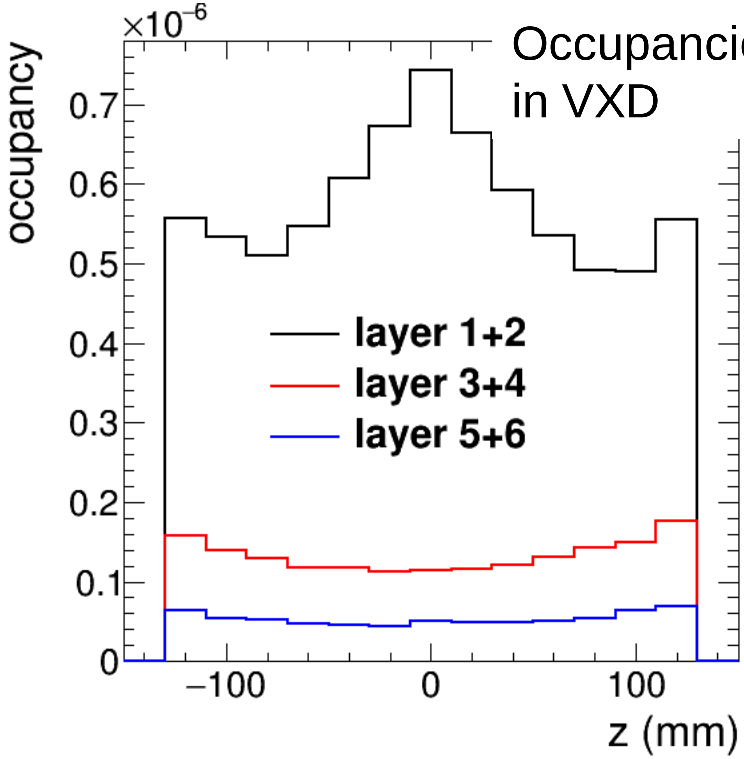
With B = 3 T : number of hits in VXD decreases by a factor of O(2)
- also better tracking performance
- but field of the compensating solenoid would have to be ~ 10 T …

With B = 1 T : number of hits in VXD increases by a factor > 5 !



Occupancies and data volume

O(300) hits per BX in VXD + tracker is probably not too much anyway.



Occupancies in VXD

Corresponds to very low occupancies due to the huge number of channels.

E.g. for VXD : with pixels of 25 mum x 25 mum, about 1 billion channels.

Data volume : with 32 bits / channel
(most bits to encode the channel ID)
with cluster size of 3: < 4 kB per BX

- i.e. this background does not add much to the size of a "physics" event (of O(100 kB) that we want to write to disk
  trigger rate of 100 kHz x 100 kB = 10 GB / s ≈ HL-LHC

- Full readout of the events at the BX rate of 270 MHz probably feasible

Trigger architecture : L1 or software only ?

ILC and LHCb upgrade : no L1 hardware trigger
- ILC : because of the bunch structure : can readout everything in the long time (199 ms) between two trains
- LHCb : because they need a very pure selection at the trigger level

	Zero-bias event size	Rate	FE to Event Builder
ATLAS / CMS Phase 2	4 MB	O(500 kHz)	2 TB/ s
LHCb upgrade	100 kB	40 MHz	4 TB / s
FCC ee (Z c.w.)	4 kB (VXD + TRK)	270 MHz	1 TB / s

Assuming that the size of a zero-bias event is indeed of a few kB, the data volume through the event builder should not be a showstopper for a software-only trigger.

Note: 1 TB/s of tracker data could be readout with a few hundreds of cables.
Wire-less readout scheme could allow the readout of the full tracker data with minimal impact on the material budget – active R&D.

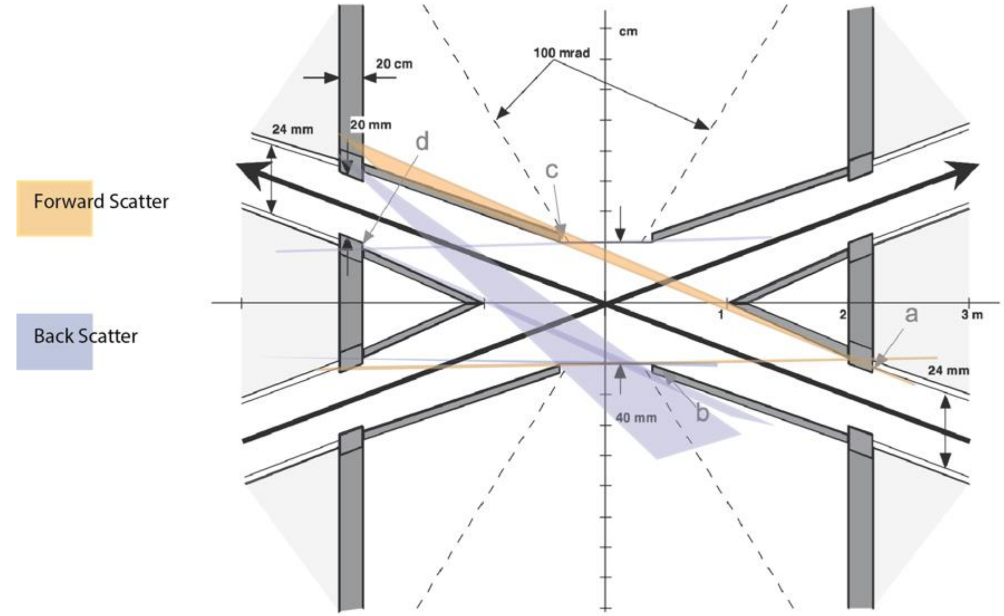
First look at synchrotron radiation in the detector

at the $t\bar{t}$ energy i.e. E(beam) = 175 GeV

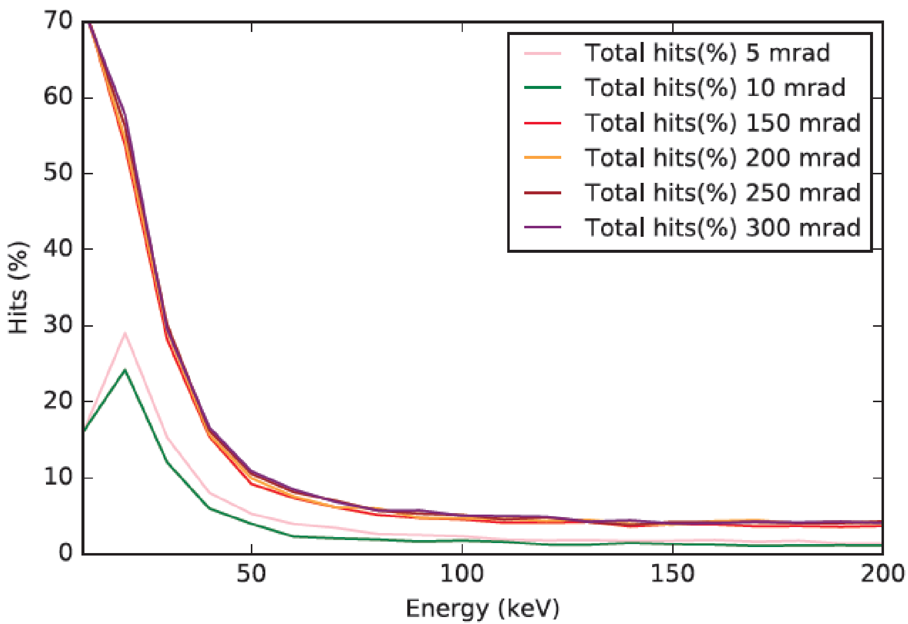
Started recently on this, fresh results…

Synchrotron radiation

- Photons of O(100 keV), hit the beam pipe at a small angle
  - below 10 mrad
  - or O (150 mrad)



- Shoot photons of fixed energy at the center of the BP



Above 50 keV, 10% of the impinging photons make a signal in the VXD.

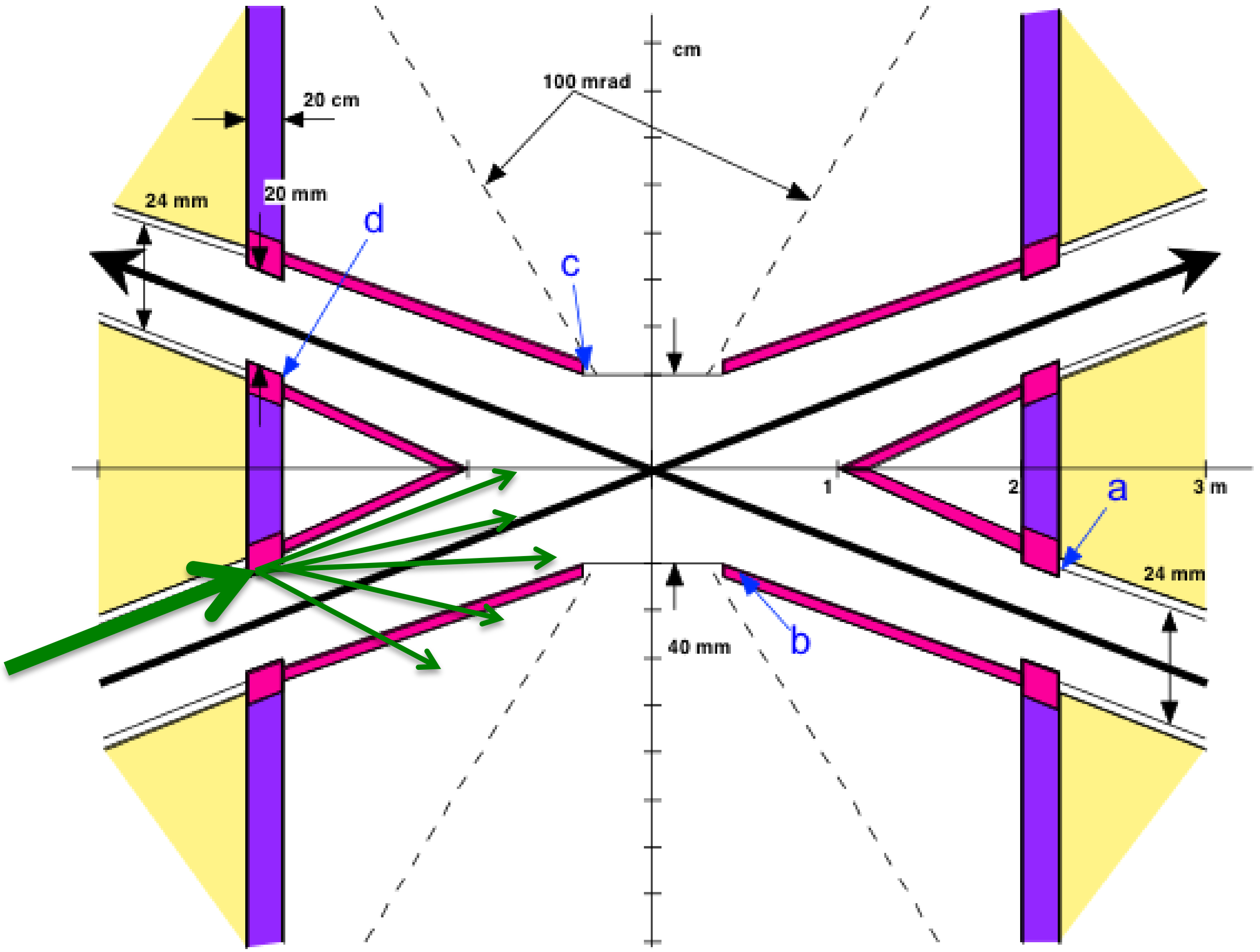
The electrons that make ionisations in the Si are mostly created in the detector itself (not in the BP wall)

Synchrotron radiation

We got a file from Mike Sullivan with the kinematics of photons that forward-scatter on the mask

4.7 10^7 such γ per BX (from bend + final quad) x 2 for the two beams

Fwd scattering expected to be the dominant source of background.



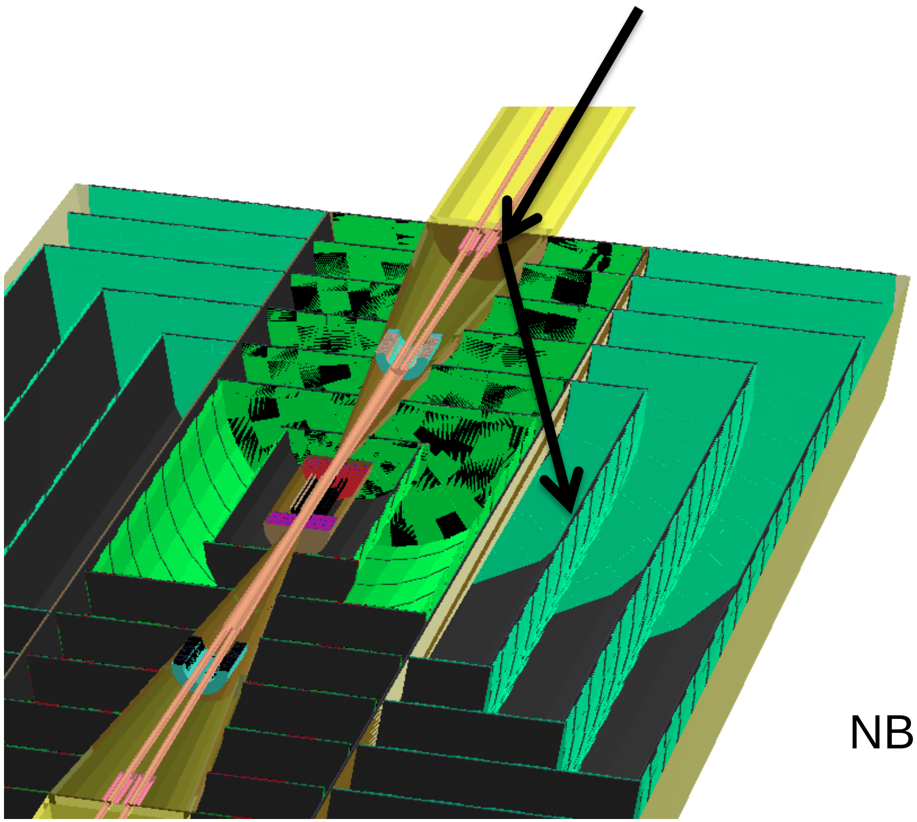
We sent these photons through our full simulation.
- limited statistics simulated so far
- normalised to N(expected)

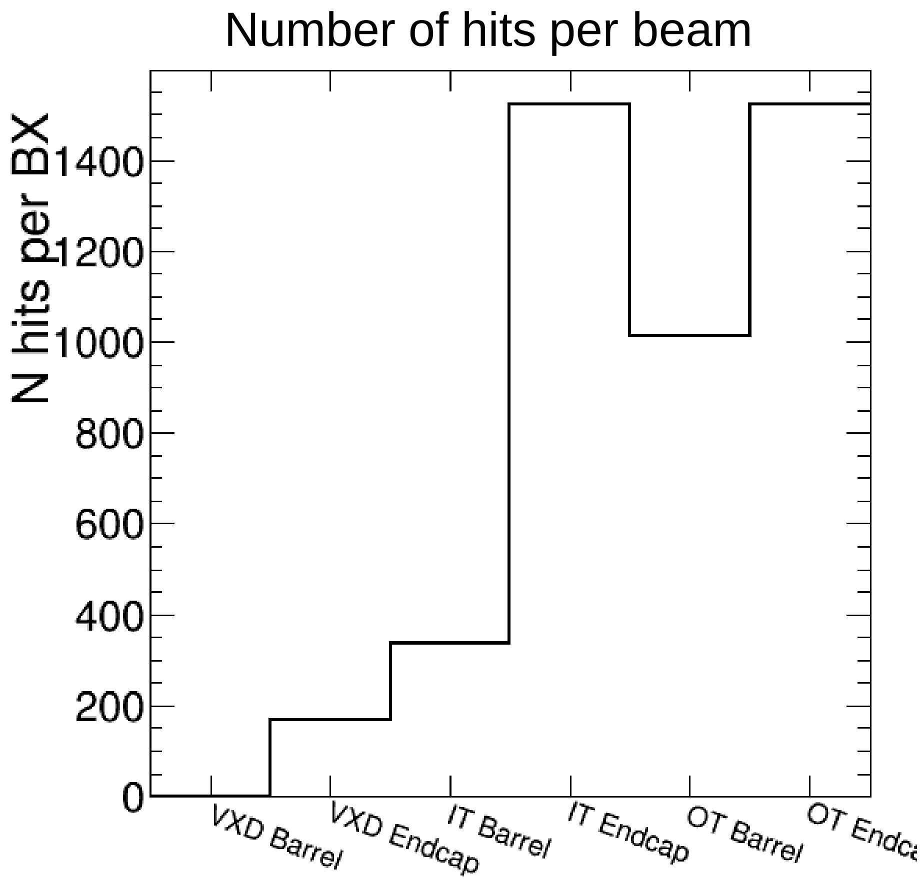
Synchrotron radiation

Number of hits in the VXD + tracker, per BX :

4500 x 2 beams = 9000 hits

(stat uncertainty ≈ 20% on this total)





Most of the hits are in the main tracker, solid angle to reach the VXD is small !

NB: LumiCal may need shielding from behind

Synchrotron radiation: occupancies and data volume

Occupancies :
e.g. 1400 hits in the forward disks of the inner tracker (per beam, i.e. on each side)
7 disks in total, i.e. 200 hits per disk (per z side)
Area of the disks = π ($R^2_{out} - R^2_{in}$) = 7500 cm^2 , strips = 10 cm x 50 μm = 0.05 cm^2
i.e. about 150k strips per disk: 200 hits = average occupancy of O (1 per mil),
to be multiplied by a cluster size of O(3), small.

- need to check the local occupancies, more statistics needed.
- if needed, could be reduced by increasing the Ta shielding behind the LumiCal

Data volume to disk :
e.g. 32 bits per channel. 9000 hits x 3 (cluster size) = 100 kB per BX

- gets comparable to the size of a physics multijet events
- but physics rate at $\sqrt{s}$ = 2mt is < 1 Hz
  - i.e. through-put to disk = 100 kB/s, small

Readout of tracker at full BX rate = 200 kHz (O(80) bunches) :

- 200 kHz x 100 kB = 20 GB / s of data from the FE to the event builder
- not challenging w.r.t O (few TB / s) for HL-LHC

Summary

First simulations of backgrounds in the FCC detector using a realistic FCC-ee interaction region

- pair-production background at the Z peak
    - looks acceptable with the configurations considered here
- starting to investigate the SR at the tt energy
    - more activity in the tracker, but data volume remains acceptable

Backup

Parameters used to steer GuineaPig

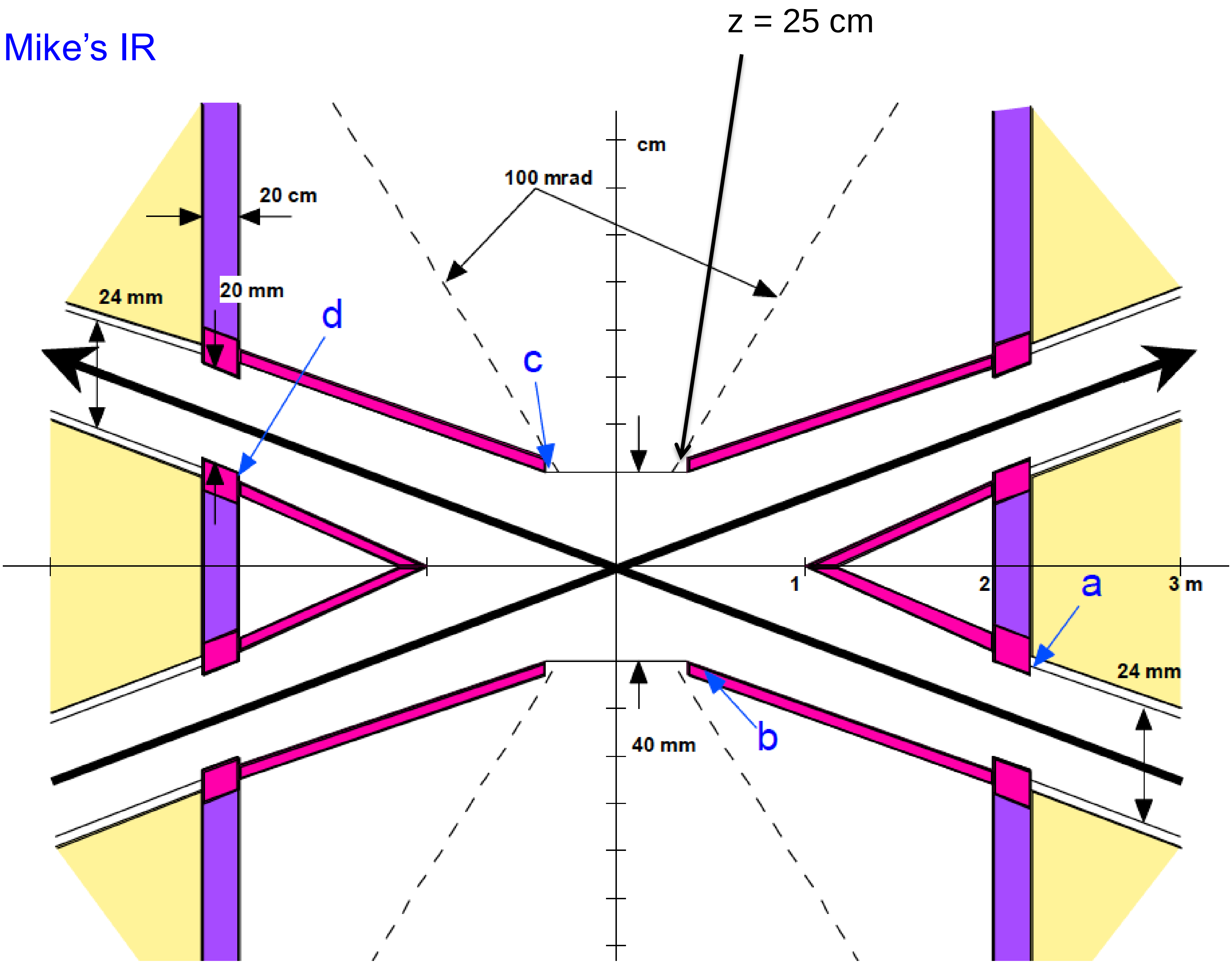
parameter	Z
E_{beam} [GeV]	45
current [mA]	1450
$P_{SR,tot}$ [MW]	100
no. bunches	59581
N_b [10^{11}]	0.5
ε_x [nm]	0.13
ε_y [pm]	1.0
β^*_x [m]	0.5
β^*_y [mm]	1
σ^*_y [nm]	32
σ^*_x [μm]	8

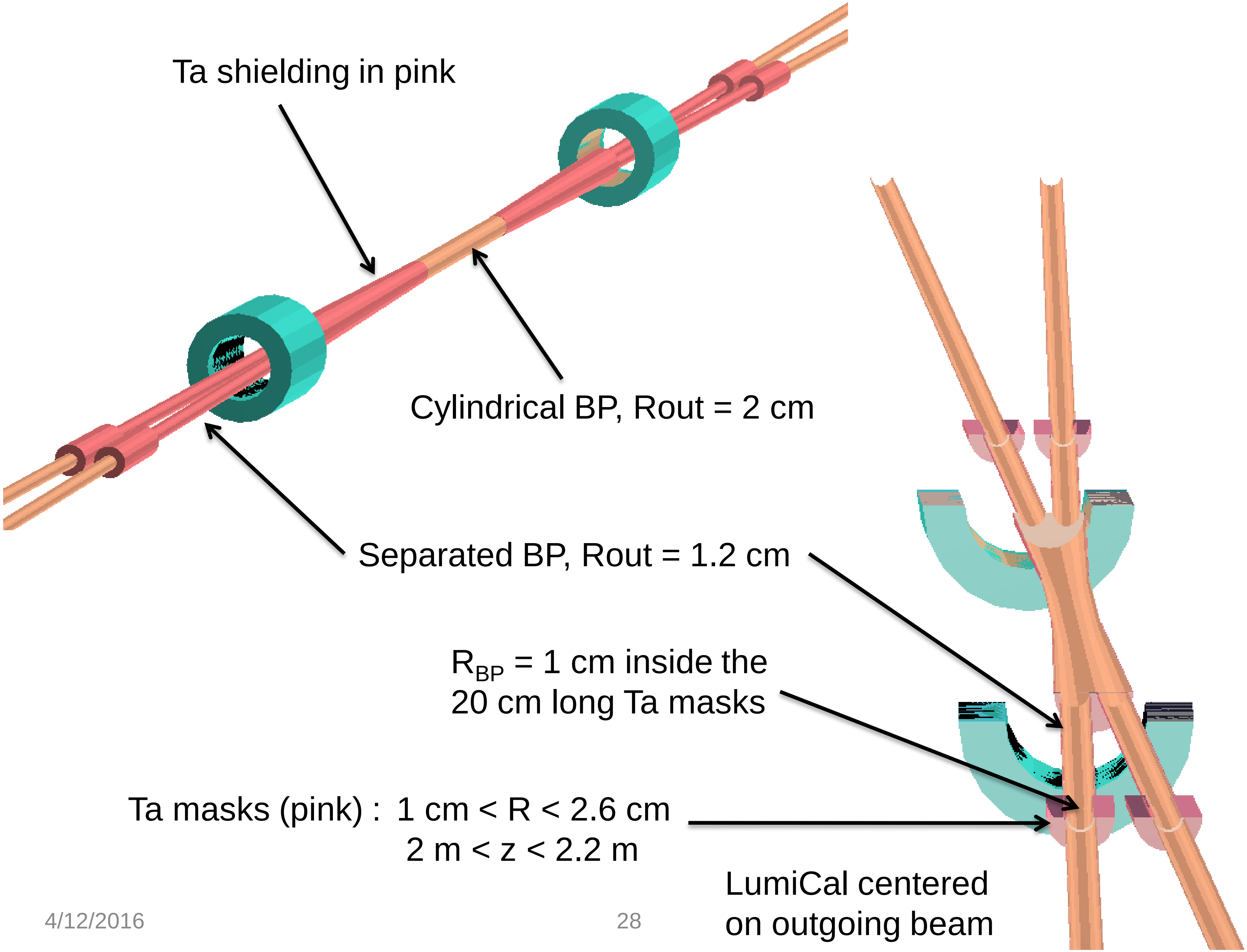
Not the latest ones but close to…

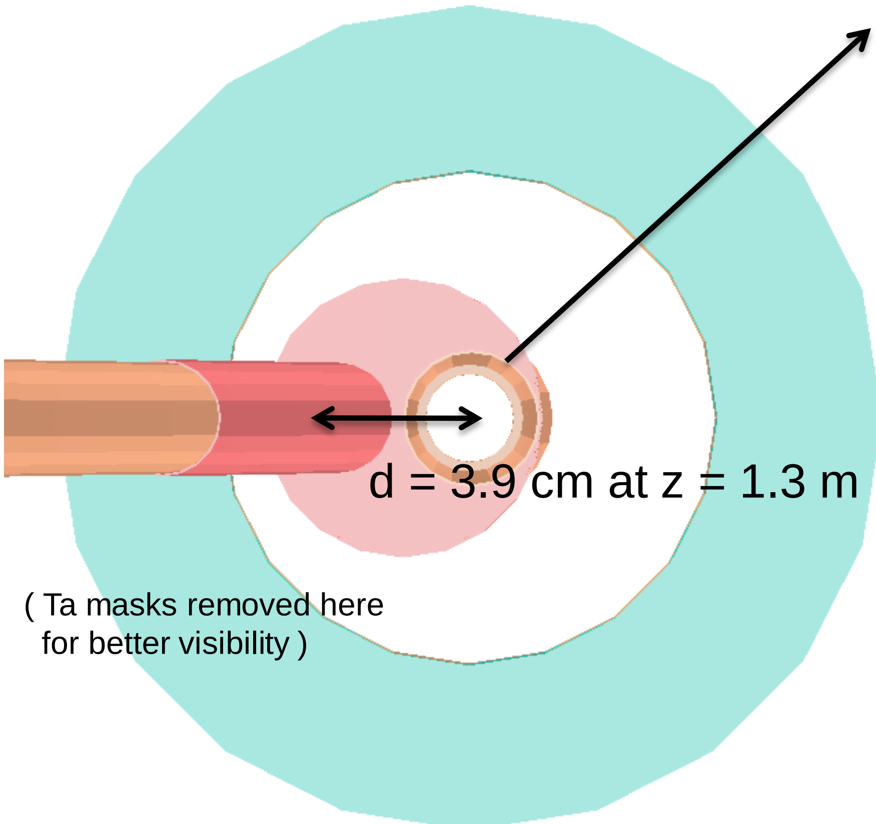
In the latest scheme with 90k bunches :
Nb = 0.33e11
and sigma_x = 9 mum

i.e. number of BS photons O(2) lower.

Mike's IR



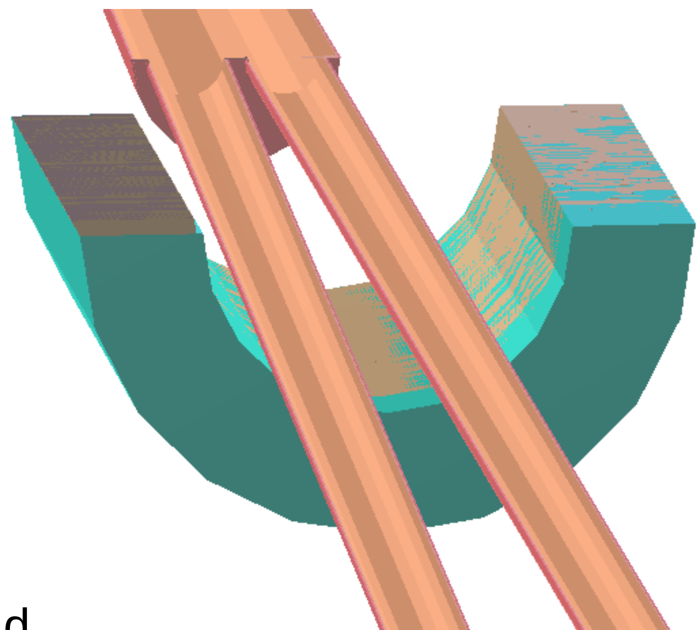

Ta shielding in pink
Cylindrical BP, Rout = 2 cm
Separated BP, Rout = 1.2 cm
R_{BP} = 1 cm inside the
20 cm long Ta masks
Ta masks (pink) : 1 cm < R < 2.6 cm
2 m < z < 2.2 m
LumiCal centered
on outgoing beam



Outgoing beam-pipe :
R_{BP} = 1.2 cm

LumiCal :

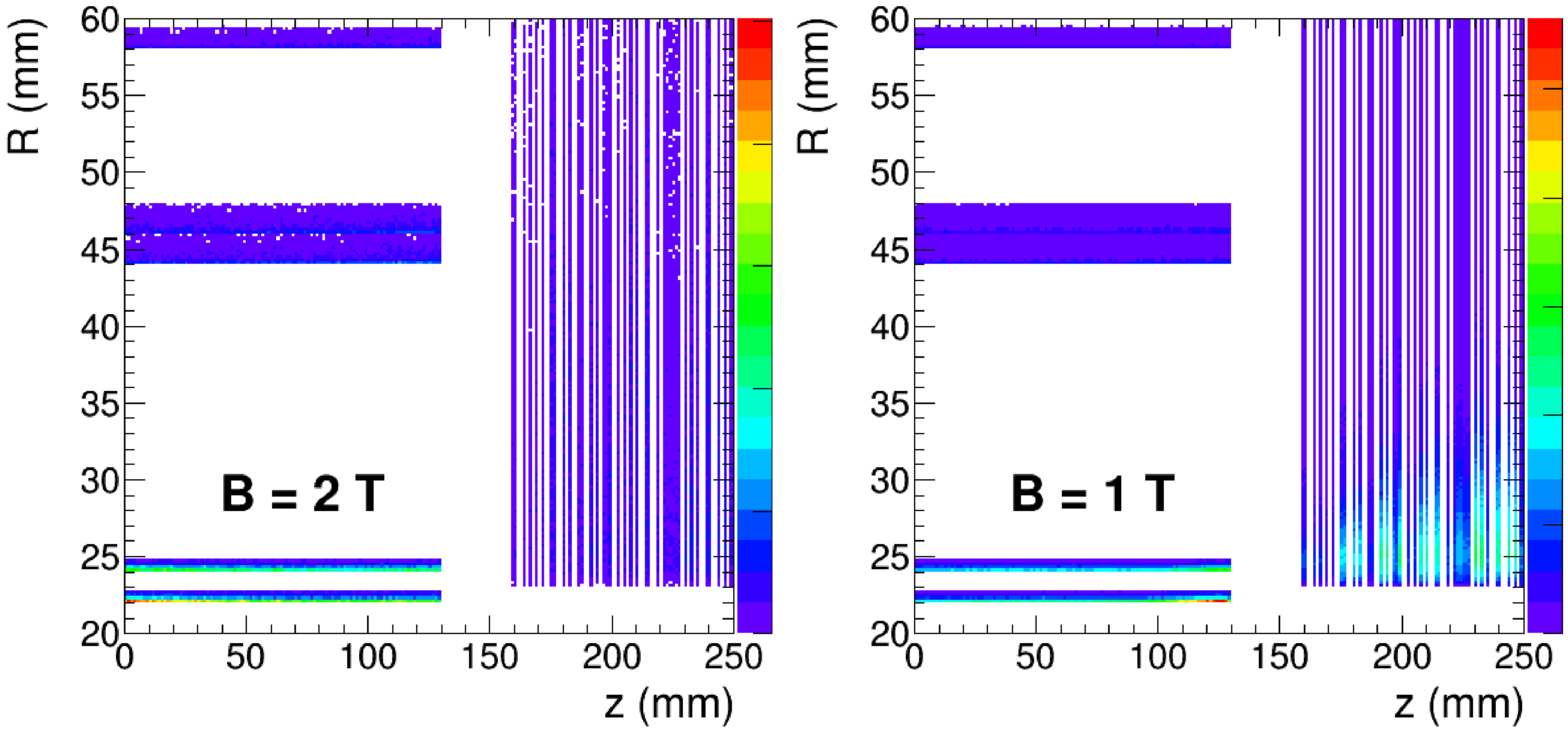
$$Rin = z\_end * 30\ mrad + R_{BP} + tolerance$$
$$= 3.9\ cm + 1.2\ cm + 0.5\ cm$$
$$= 5.6\ cm$$



Rout such that it touches the 100 mrad cone at z_start = 1.1 m
i.e. Rout = z_start * (100 mrad – 15 mrad)
= 9.35 cm

i.e. LCal acceptance : 51 mrad < θ < 85 mrad

Effect of the magnetic field : hit maps in VXD

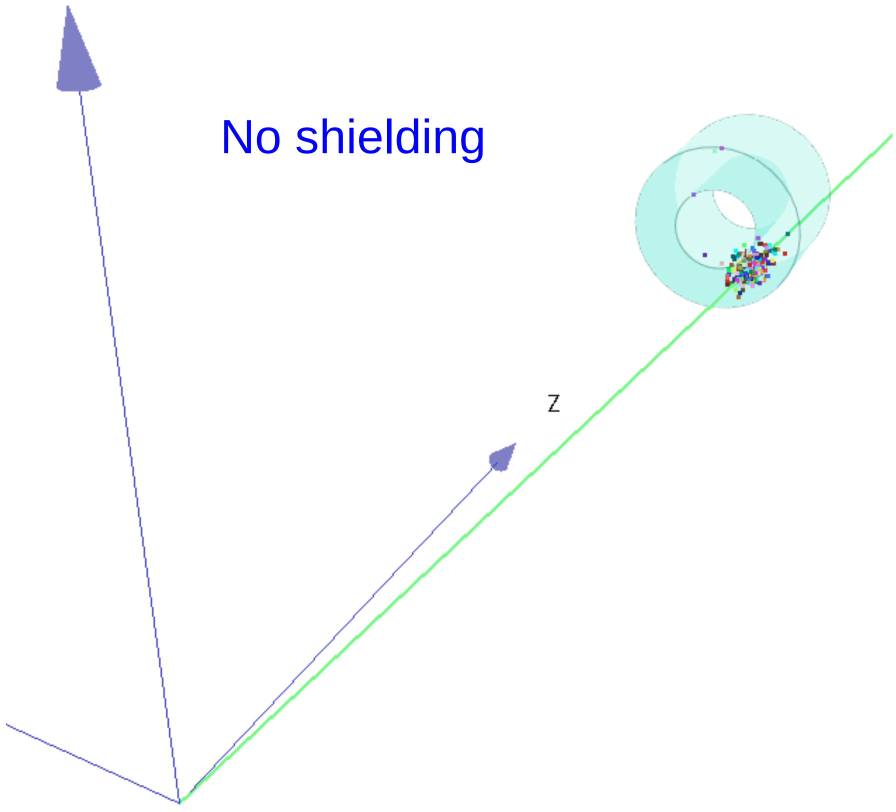


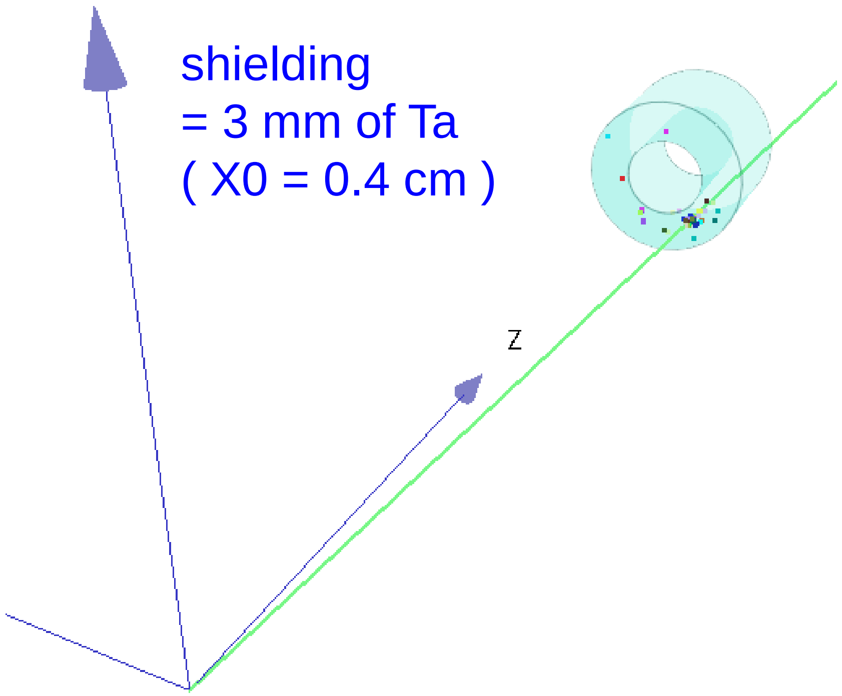
At lower B : as expected, hits in the barrel VXD mostly on the edges (cf slide 12)

Effect of the Ta beam-pipe shielding on “Bhabha” events

Shoot an electron of E = 45 GeV at θ = 70 mrad.

With a 3 mm shielding : it traverse 42 mm of Ta which is 10 X0 !



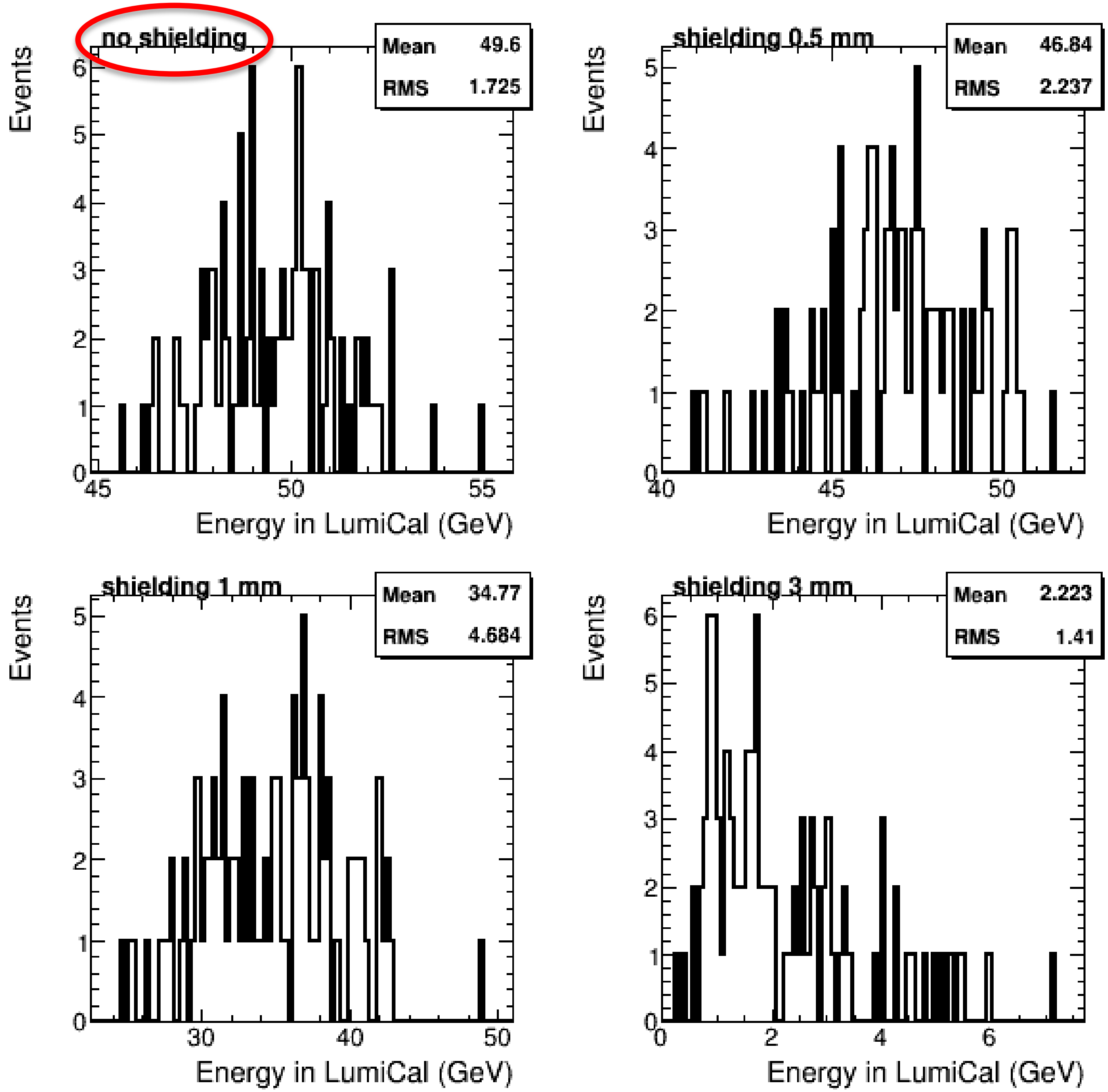


100 “pseudo-Bhabha” events,

i.e. 45 GeV electrons
θ = 70 mrad

With a 3 mm shielding:
No lumi meas !

0.5 mm shielding :
Resolution degraded, but OKish



Data throughput to disk

Luminosity expected at the Z-peak : could reach 2 10^{36} cm^{-2} s^{-1} (crab-waist scheme)
σ(ee -> had at Z peak) ≈ 30 nb
Hence a rate of O(100 kHz) of physics events to write to disk (+ Bhabha).
Feasible ? Depends on the event size.

	Trigger rate	Event size	Throughput to disk
ATLAS / CMS Phase 2	5 kHz	4 MB (PU = 140)	20 GB / s
LHCb upgrade	20 kHz - ?	100 kB	1 GB / s

Event size at of a multi-jet event in the TESLA detector, from the TESLA TDR (*) :

- Data due to the signal event only ≈ 200 kBytes
- However, adding the background, this increased to 5 MB !

100 kHz x 200 kB	=	20 GB / s	would be OK
but 100 kHz x 5 MB	=	500 GB / s	would be a lot !

(*) 15 yrs old… the more recent ILC TDR does not give the event size of a “signal” event, since ~ all the data volume comes from background; and give the volume of a bunch train, which is what is relevant.