Beam backgrounds in the central detector for FCC-ee and their implication on physics analyses

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Outline

- Experimental environment
- Sources of beam induced background
- Simulation of backgrounds in the detectors
  - and effect on reconstructed quantities

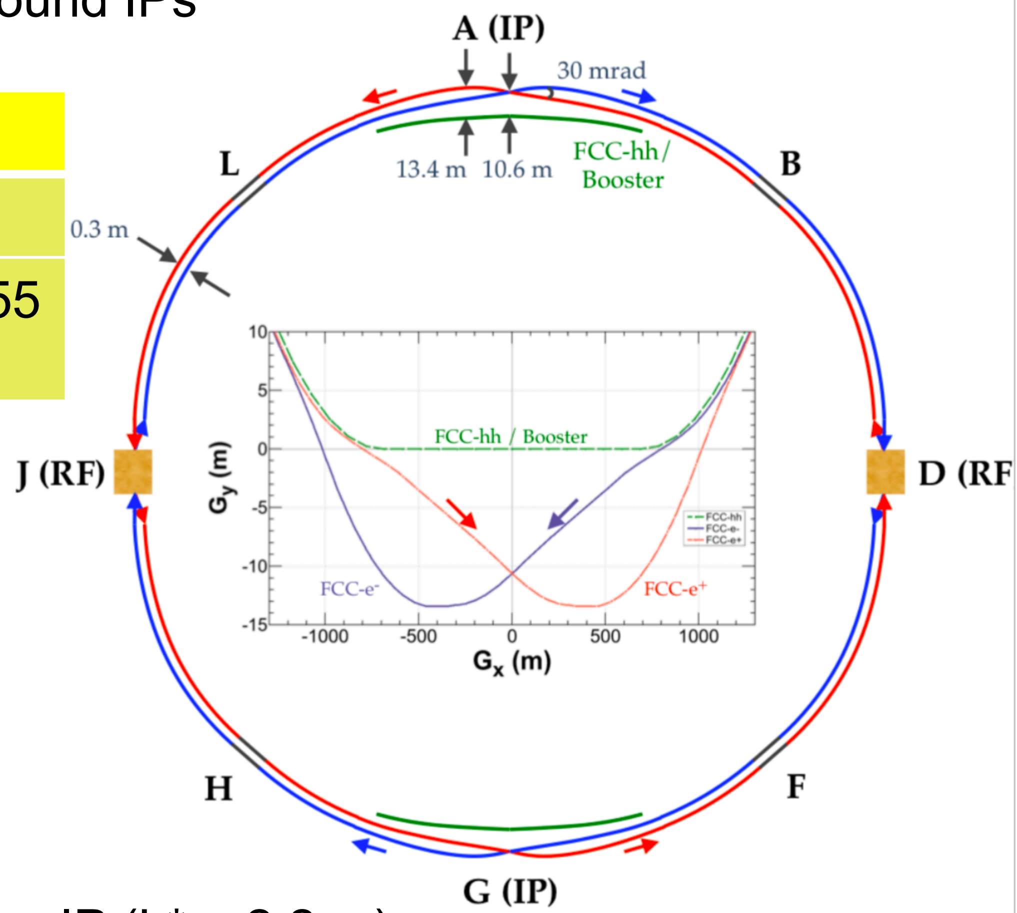
References :

- FCC-ee CDR : CERN-ACC-2018-0057, Geneva, December 2018. Published in Eur. Phys. J. ST., Volume 228, Issue 2, pp 261–623
- CLD detector: LCD-Note-2019-001 [soon public]
- FCC week 2019 : https://indico.cern.ch/event/727555/

Introduction

FCC-ee : e^+e^- collider in a 100 km tunnel
Follows footprint of FCC-hh except around IPs

	Z	WW	ZH	tt
Nb/beam	16640	2000	393	48
L per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55



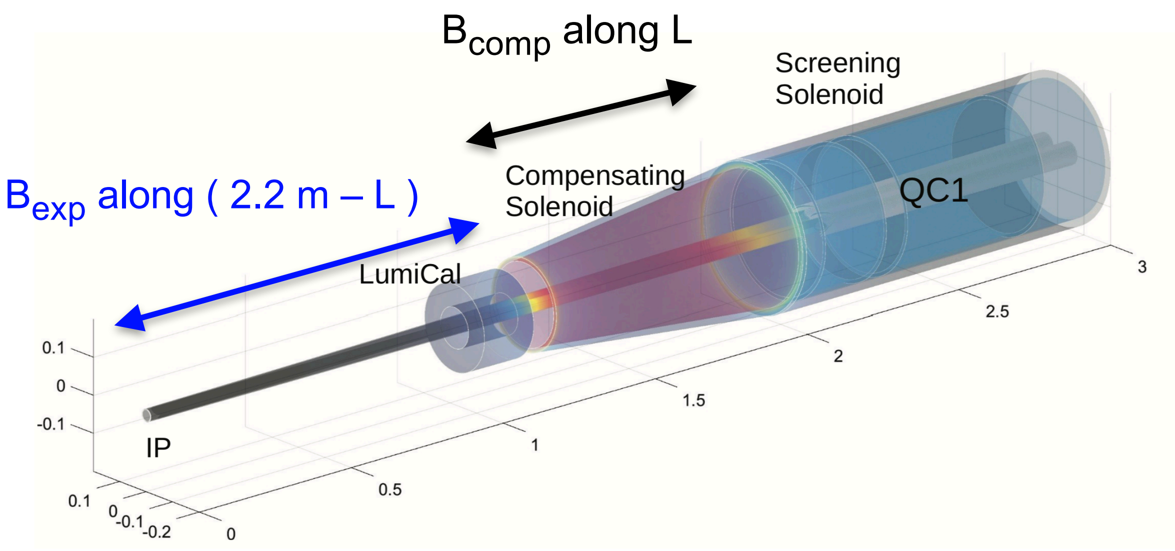
Current design : 2 IPs

- Double ring collider
- Large crossing angle θc = 30 mrad
- Crab-waist optics
- Last focusing quadrupole very close to the IP (L* = 2.2 m)

Asymmetric IR and optics to limit the synchrotron radiation sent towards the IP.

Some experimental constraints

- Large angle (15 mrad) between the beam direction and the mag. field of the detector: Need to "undo" the effect of B_{exp} on the beam to prevent emittance blow-up (budget ε_y ~ 1 nm) → compensating solenoid in front of last quad.



Space constraints : comp. sol. length L is limited < 1 m

integral of B.L = 0 :

$B_{comp} \approx B_{exp} \times (2.2\ m – L) / L$

B_{comp} can not be too high, sets a limit on B_{exp} !

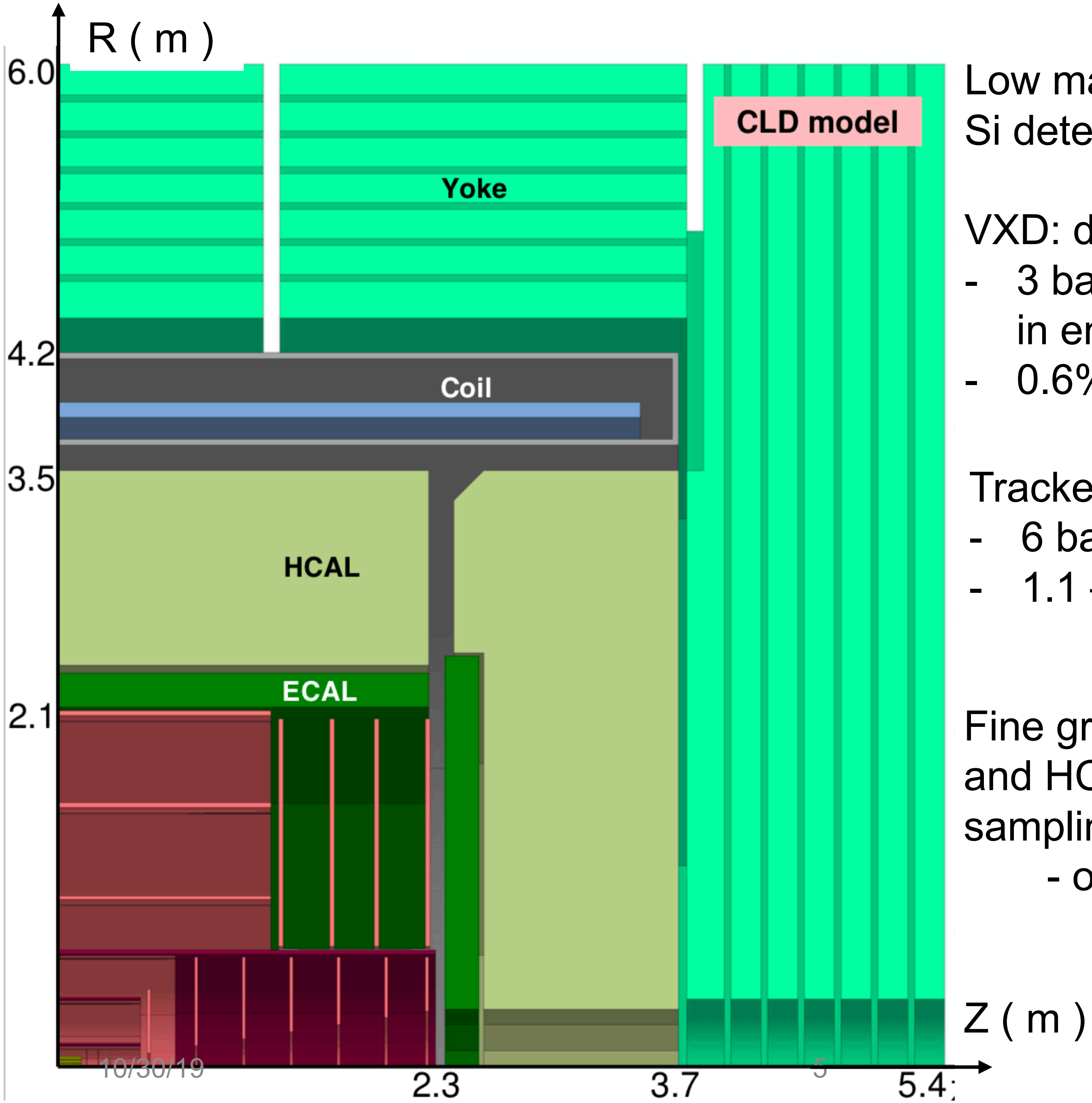
B_{exp} = 2 T

- Synchrotron radiation and higher order EM modes in the transition from one single to two beam pipes constrain the beam pipe radius

Baseline : R_{inner} (BP) = 1.5 cm

Constrains the position of the innermost layer of the vertex detector

Detector concept #1 : CLD detector – based on the CLIC detector



Low mass vertex and tracker, both Si detectors

VXD: double-layers of pixels
- 3 barrel (Rin = 17.5 mm), 3 disks in endcap)
- 0.6% X0 per double-layer

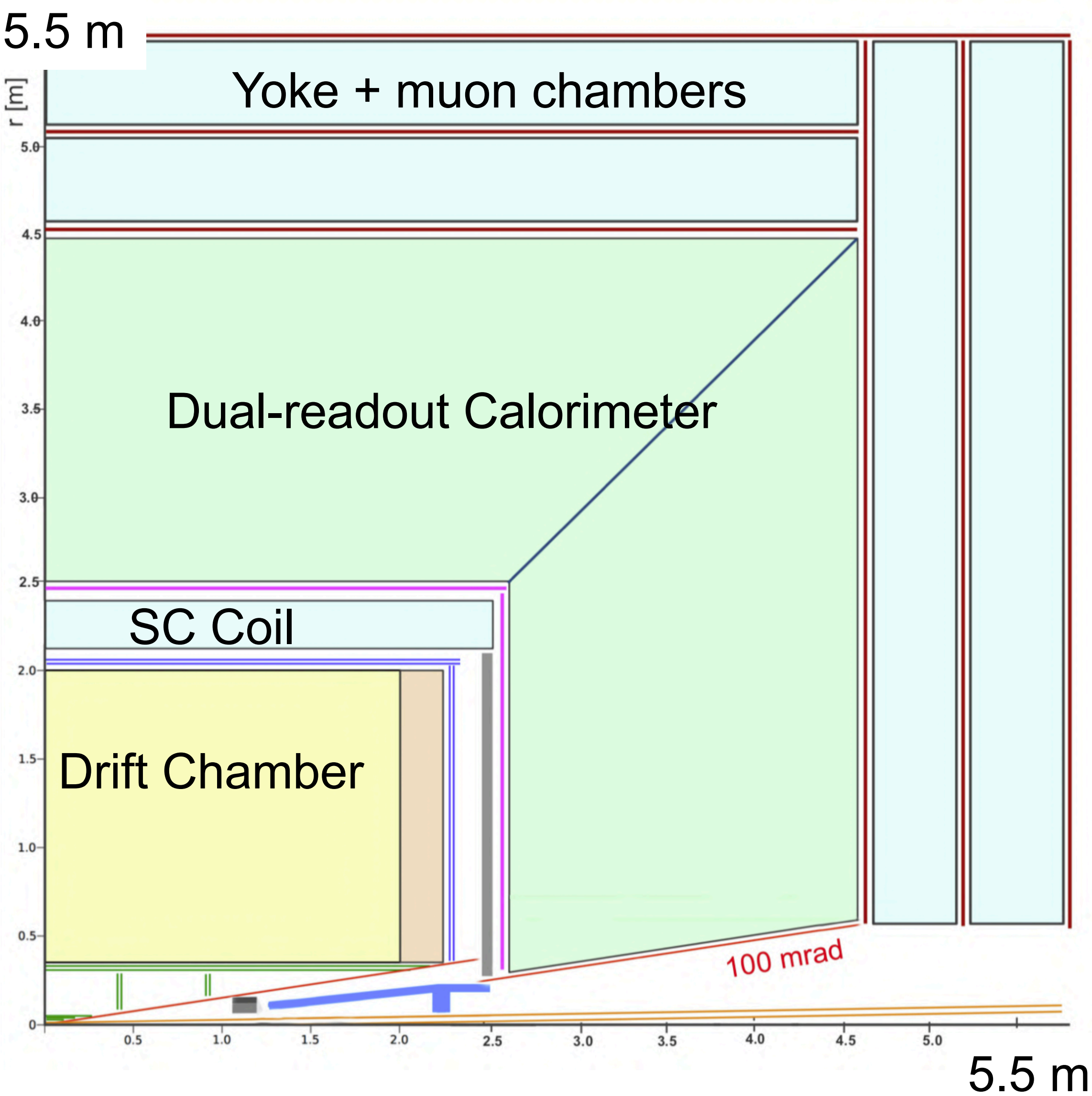
Tracker: pixels and micro-strips
- 6 barrel layers, 11 endcap disks
- 1.1 – 1.6% X0 per layer

Fine granularity ECAL (tungsten-Si) and HCAL (scintillator-Steel) sampling calorimeters

- optimised for particle flow reco

Detector concept #2 : the IDEA detector

" International Detector for
Electron-positron Accelerators "



- VXD : MAPS sensors
- Ultra-light drift chamber with PID
  - 1.6% X0
- Dual readout calorimeter
- Si disks between DCH and DR

Drift chamber :

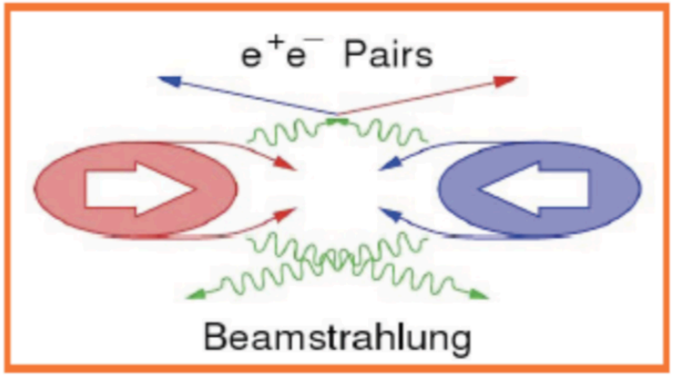
L = 400 cm, R = 35-200
Gas: 90% He - 10% iC_4H_{10}
Drift length: 1 cm → drift time: 350 ns

Spatial res: $\sigma_{xy} < 100$ μm, $\sigma_z < 1000$ μm
56448 squared drift cells of 12 - 13.5 mm
112 layers (stereo)

Beam-induced background sources

- Beamstrahlung induced background :
  (incoherent) pair production (IPC) : $\gamma\gamma \rightarrow$ 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



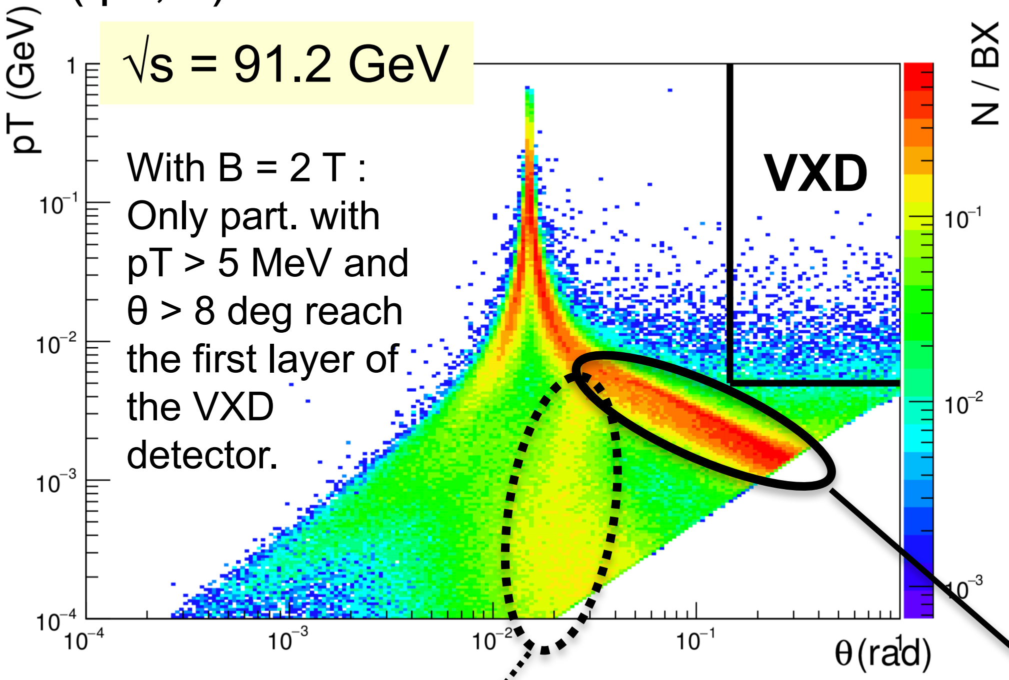
- Synchrotron radiation : only at $\sqrt{s}$ = 365 GeV, but very significant at this energy. But with a careful shielding and design of the IR, background levels in the detector reduced to a sub-leading level – at most 1/5 of IPC.

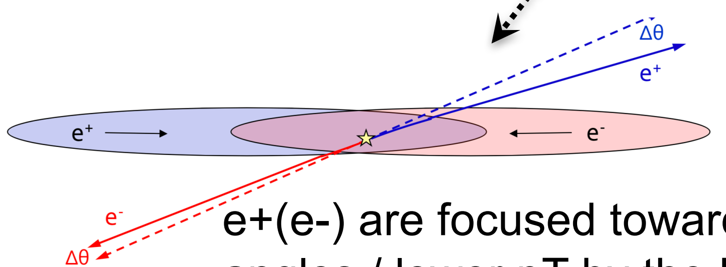
- Other background sources studied : coherent pair production, $\gamma\gamma \rightarrow$ hadrons, beam-gas, radiative Bhabhas: negligible

Incoherent pair production

Events generated with Guinea-Pig

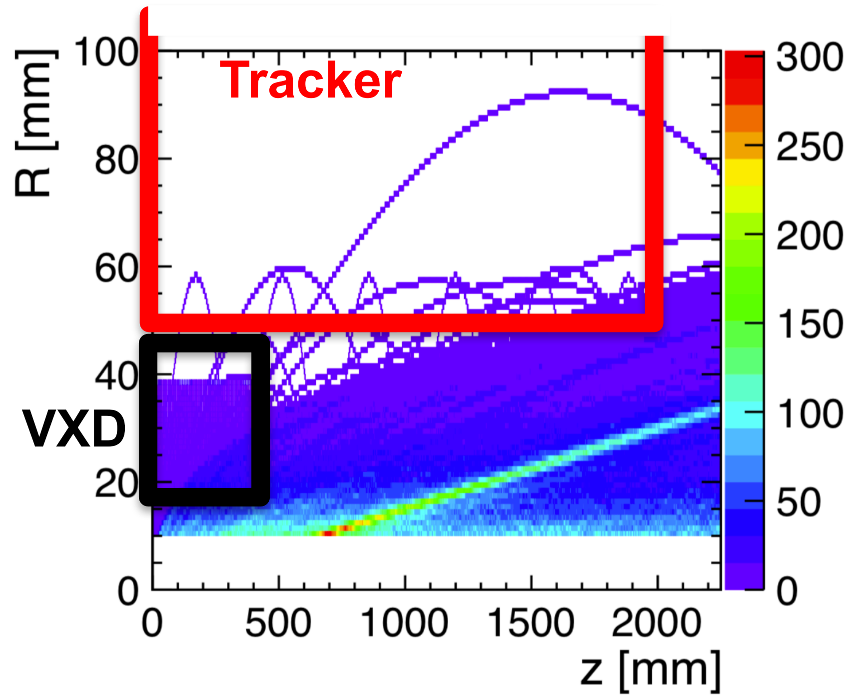
(pT, θ) distribution in detector frame :





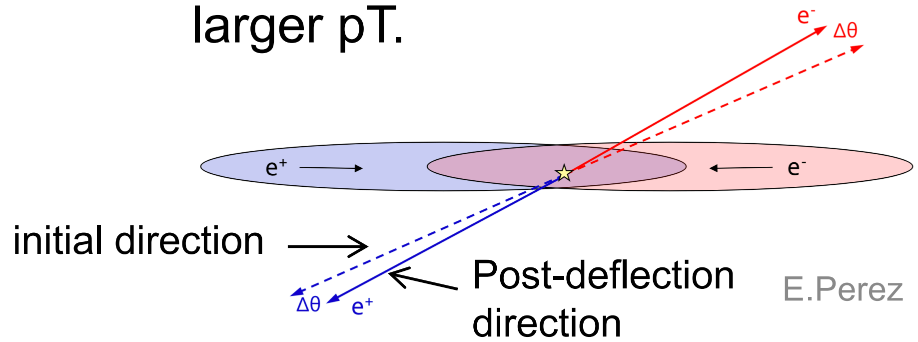
e+(e-) are focused towards smaller angles / lower pT by the EM force created by the e- (e+) bunch. See next talk on luminosity !

Helicoidal trajectories of the pairs in the 2T field of the experiment :

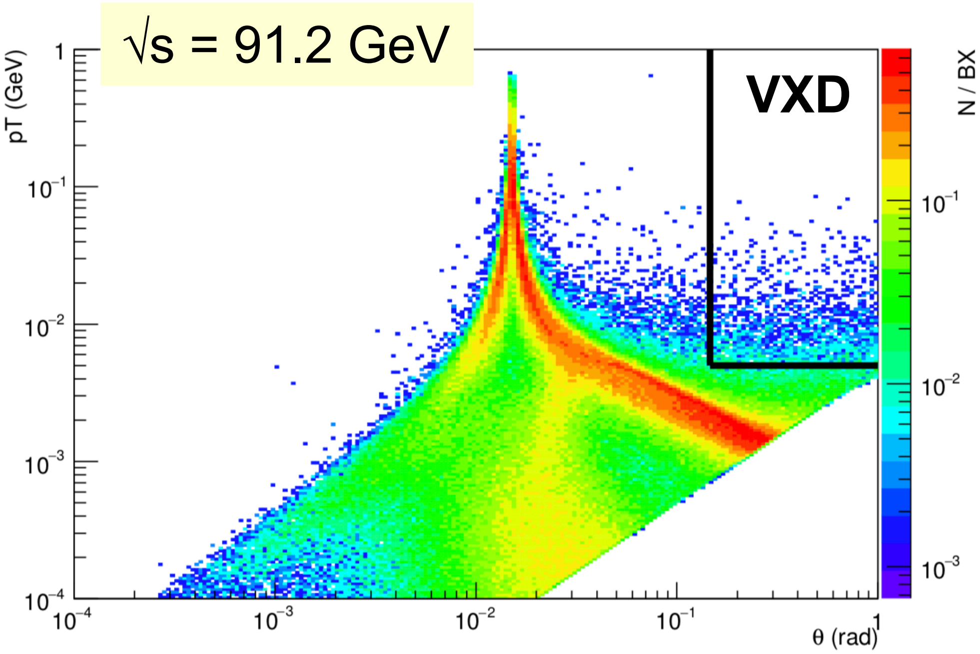


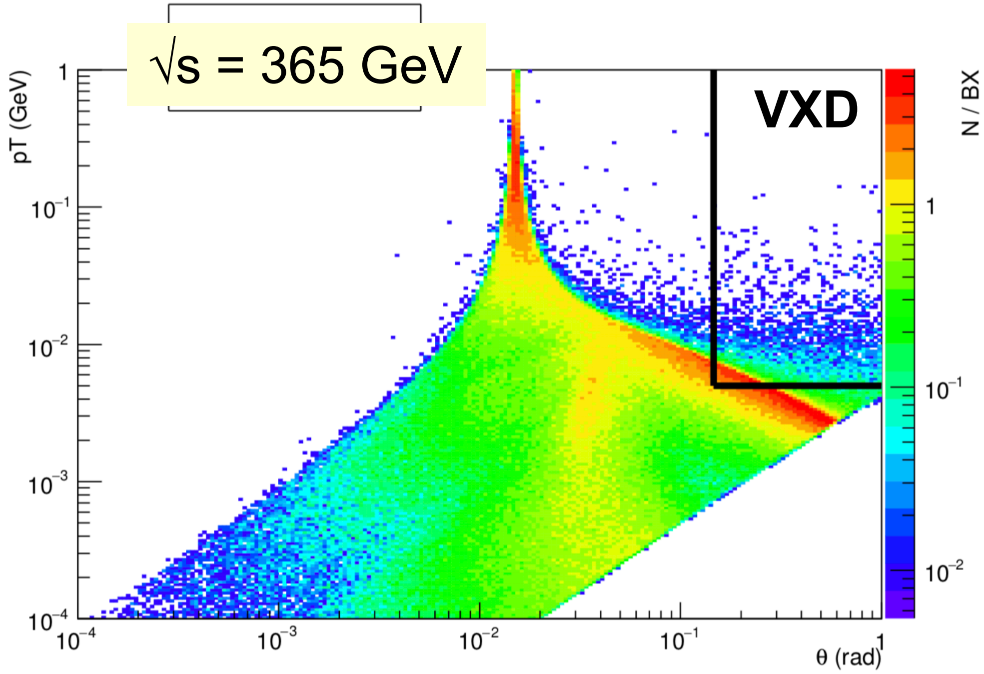
Red region = potentially dangerous.

e^+/ e^- are deflected towards larger angles and shifted to larger pT.



Pair production background





Per BX :

$e^{\pm}$ **pairs**		
$\sqrt{s}$ [GeV]	91.2	365
Total particles	~ 800	~ 6200
Total E (GeV)	~ 500	~ 9250
$p_T \geq 5\ MeV$ and $\theta \geq 8°$	~ 6	~ 292

Large # of particles created, that carry up to 9 TeV.
But few particles reach the detector, even at the highest energy.

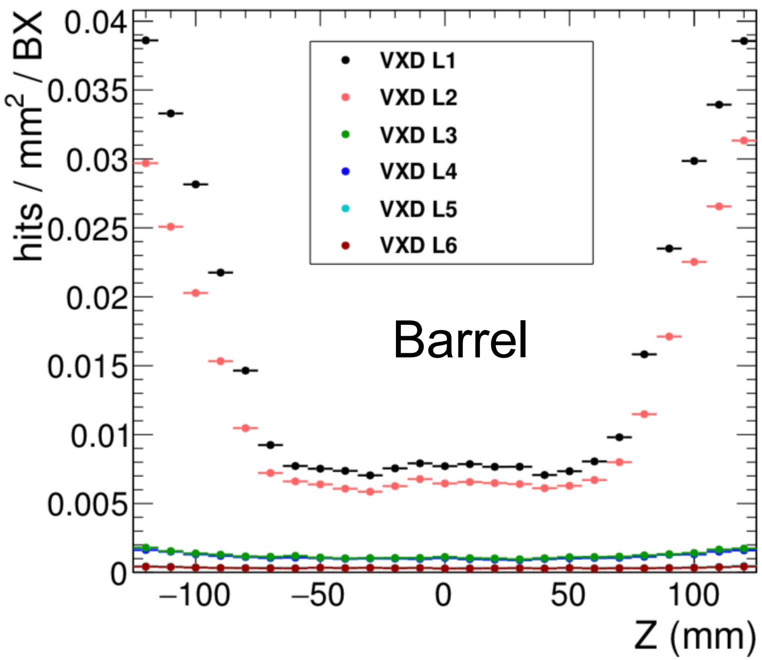
Pair production background

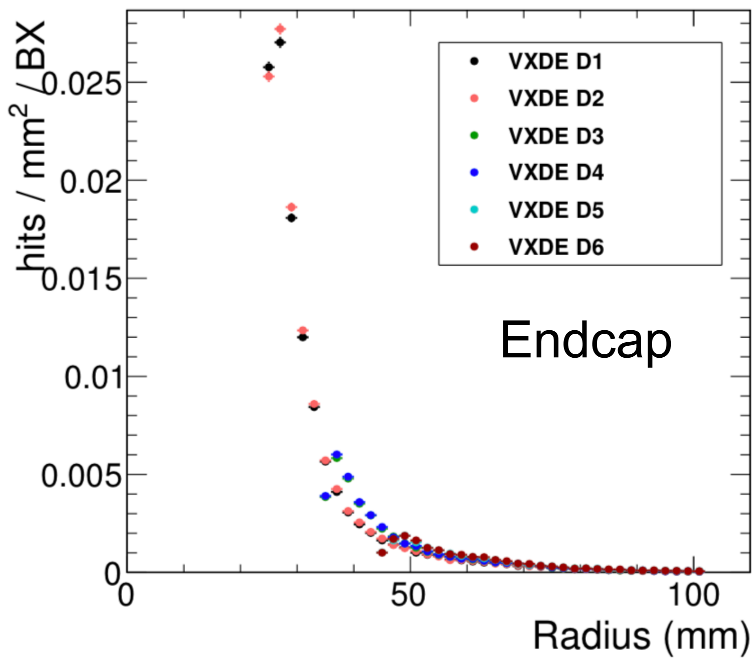
A fraction of of the created pairs can enter directly the main detector volume.
But others, emitted at lower angle, may create backscattering.

Full GEANT-based Monte-Carlo simulation:

- CLD or IDEA detector model
- Detailed interaction region (LumiCal, compensating & screening solenoids, split of the beam pipe, etc)
- Realistic magnetic field map
- DD4HEP for the geometry

Example: hit densities (IPC) in the CLD vertex detector, at √s = 365 GeV :





Background occupancies (IPC + SR) in the VXD / Si tracker

Derived from the hit densities using :
- Pixel (strip) size of 25 μm x 25 μm (50 μm x 1 mm)
- "cluster size" (charge sharing) of 3
- Safety factor of 5

√s [GeV]	**365 [1 BX]**	**91.2 [1 BX]**	**91.2 [1 μs = 50 BX]**
VXD	$\sim 4\ 10^{-4}$	$\sim 8\ 10^{-6}$	$\sim 4\ 10^{-4}$
Tracker	$\sim 3\ 10^{-4}$	$\sim 2\ 10^{-5}$	$\sim 1\ 10^{-3}$

Bunch spacing : Δt = 3396 ns at √s = 365 GeV, but only ~ 20 ns at √s = 91.2 GeV.
At 91.2 GeV : the readout electronics of the Si sensors will integrate many BXs !
- e.g. assuming a readout of 1 μs : 50 BX

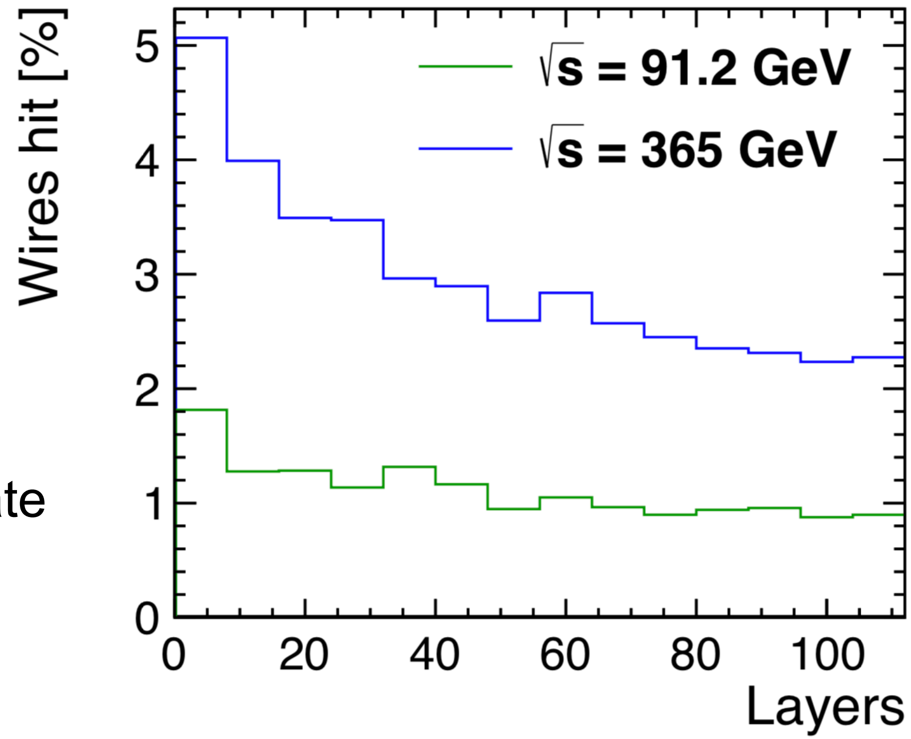
More conservative assumption : using ALICE ITS technology, r/o = 10 μs = 500 BX (3 BX) at 91.2 GeV (365 GeV). The occupancies remain low :
VXD : ~ 0.4% (~ 0.1%).
Tracker : less than 1% (less than 0.1%)

IPC background : occupancies in the Drift Chamber (IDEA)

Only a few of the primary e+/- particles have a pT that is large enough to reach the DCH.

Majority of hits observed are from secondary photons, E < 1 MeV.

Timing information can be used to separate signals from charged particles ("flow" of ionisation clusters) from those from photons (localised cluster) at DAQ level.



→ at 91.2 GeV : enough to integrate bckgd over 100 ns (4 BXs) to get the occupancy.
Average occupancies : ~ 1% at 91.2 GeV, ~ 3% at 365 GeV
[NB : no safety factor is applied here, in contrast to previous slide]

→ Timing offers an additional handle that will reduce the occupancies further, compared to what is shown in the plot.

Impact of background on tracking performance (CLD)

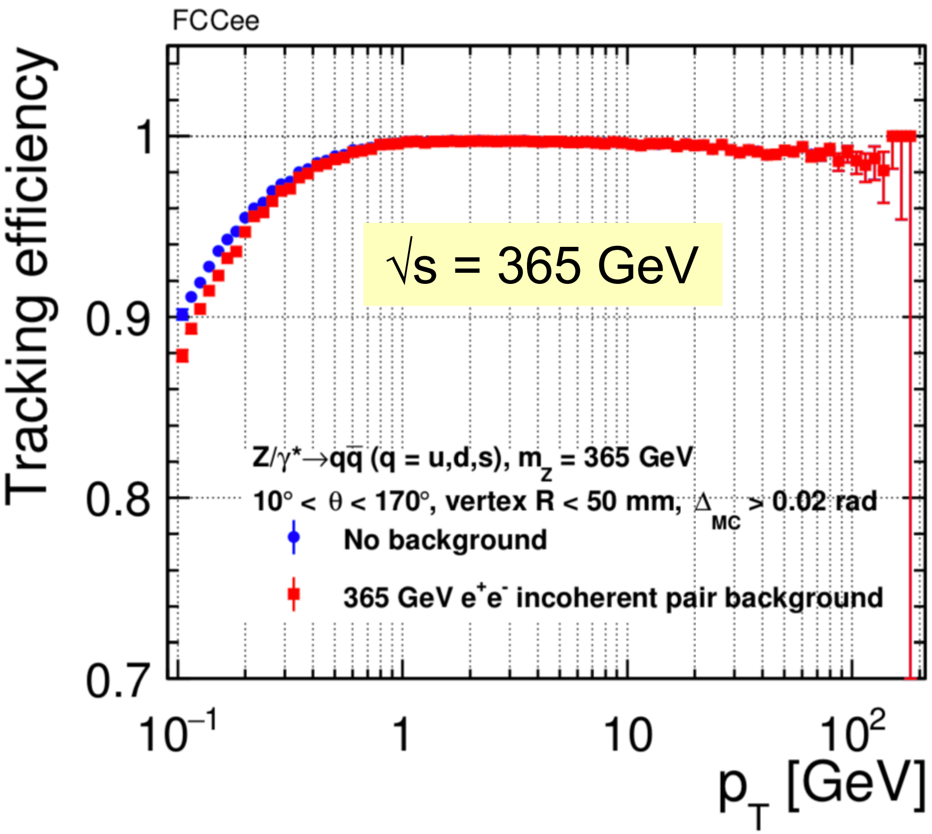
- Full simulation
- Reconstruction framework Marlin
- pattern recognition with conformal tracking
- particle-flow reconstruction with Pandora

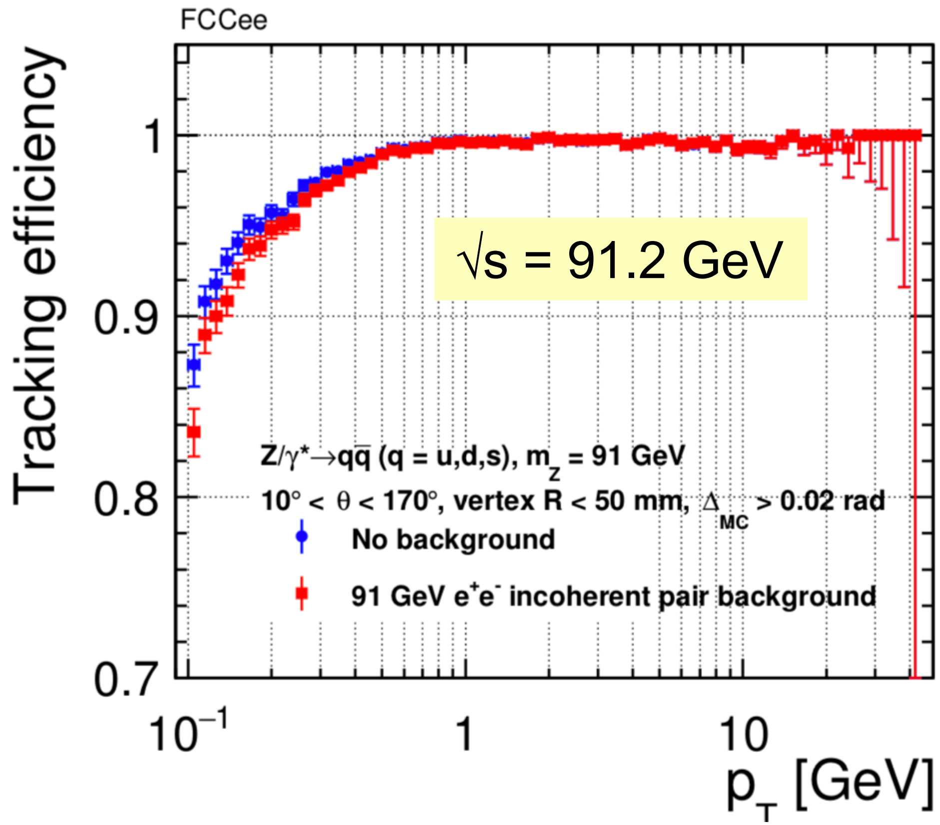
Background events (IPC & SR) overlaid to physics events. The # of overlaid bckgd events corresponds to:

- 1 or 3 BXs for $\sqrt{s}$ = 365 GeV - the latter corresponds to a (conservative) assumption of 10 μs for the readout window of the electronics
    - 3 BXs for tracking studies
    - 1 BX for calorimeter study
- 20 BXs = 400 ns for $\sqrt{s}$ = 91.2 GeV
    - on the lowish side (but not so much)
    - Imposed by current limitation from software/computing

Tracking performance in complex events : qq events (q = u, d, s)

Efficiency = fraction of "reconstructable" MC particles reconstructed as pure tracks, i.e. tracks for which ≥ 75% of the hits belong to the same MC particle

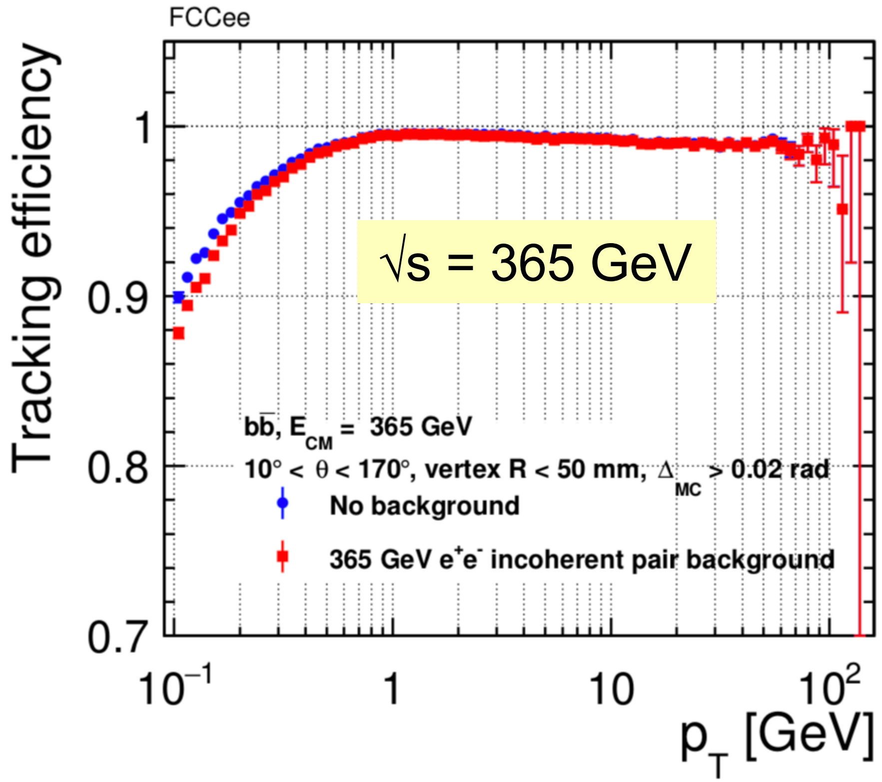


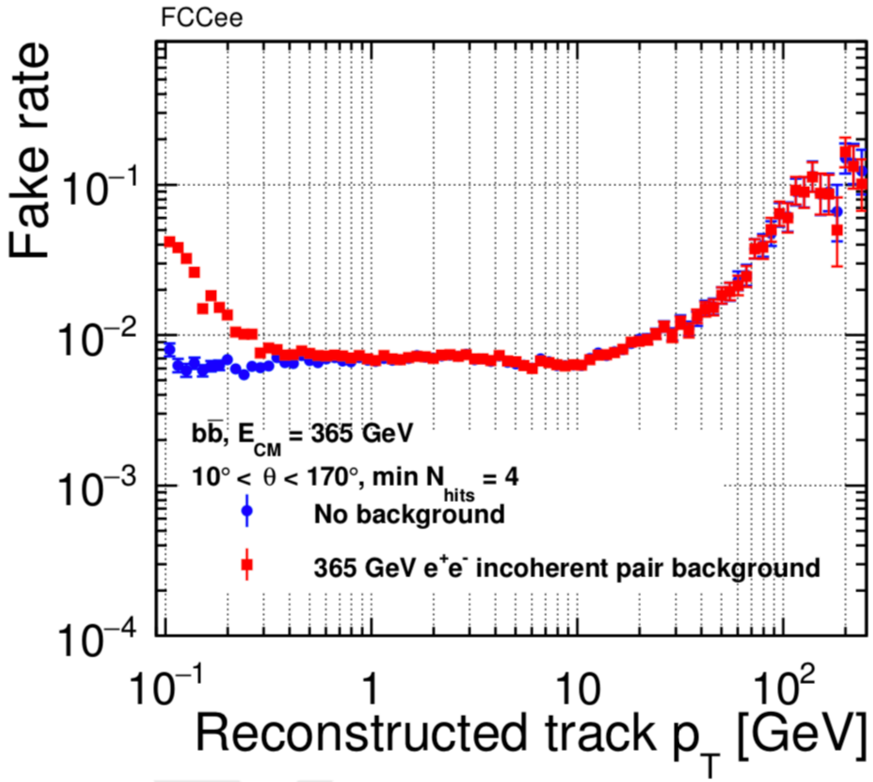


- Tracking is fully efficient from $p_T \approx 500$ MeV
- $>$ 90 % efficiency for low momentum tracks (p_T = 100 - 500 MeV)
- Robustness against beam background both at 91.2 and 365 GeV

Tracking performance in complex events : bb events

Fake rate = fraction of reco'ed tracks for which < 75% of the hits belong to the same Monte-Carlo particle.



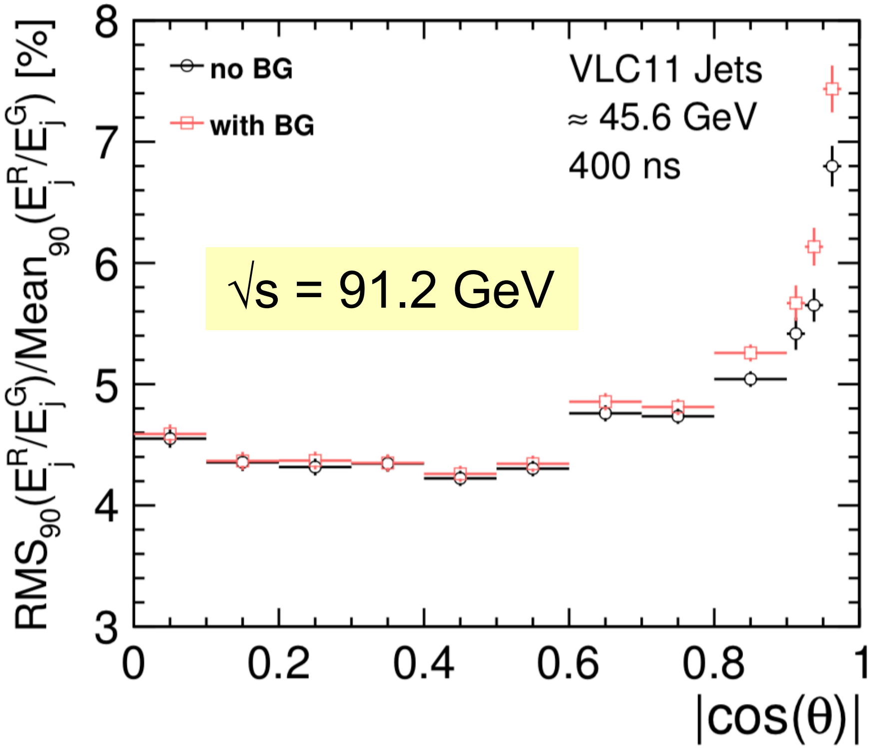


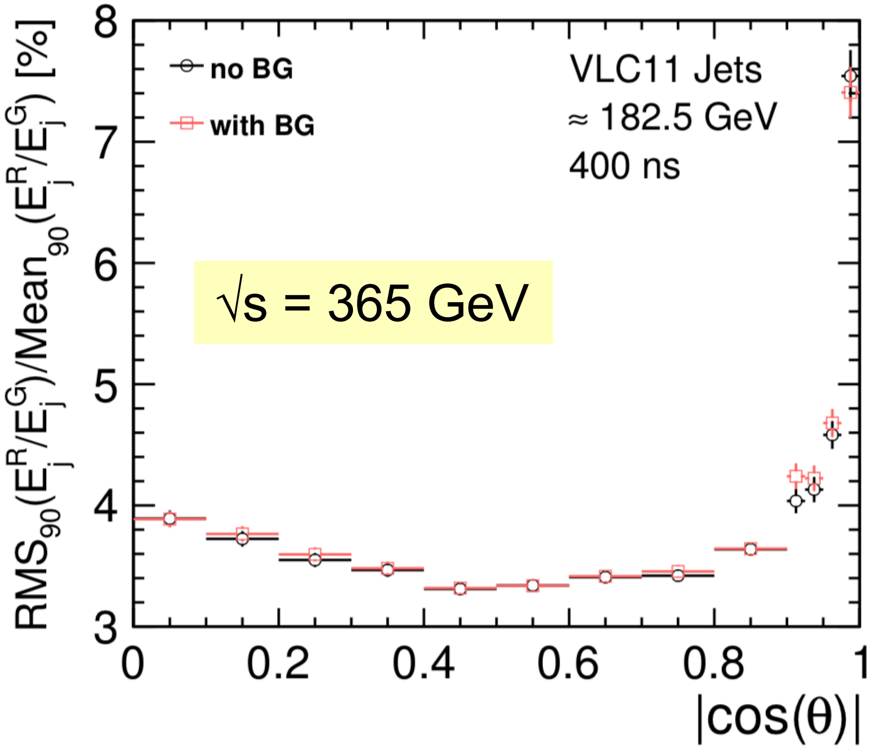
- Very high efficiency maintained, with % level fake rate except at low and high pT
- Effect of background visible only at low pT
  - Esp. increases the fake rate

Effect on jet energy resolution in qq events (q = u, d, s)

Jet reconstruction:

- the Valencia VLC algorithm, ΔR = 1.1, in two-jets exclusive mode
- Input = the reco'ed Particle Flow Objects in the event, or the stable MC particles
- Reco'ed jets are matched to MC jets and energies are compared





Impact of bckgd is negligible, except in fw region at 91.2 GeV

NB : these results are obtained without applying any additional timing or pT cuts - applying such cuts might suppress the effect of the background in the forward region.

Conclusion and next steps

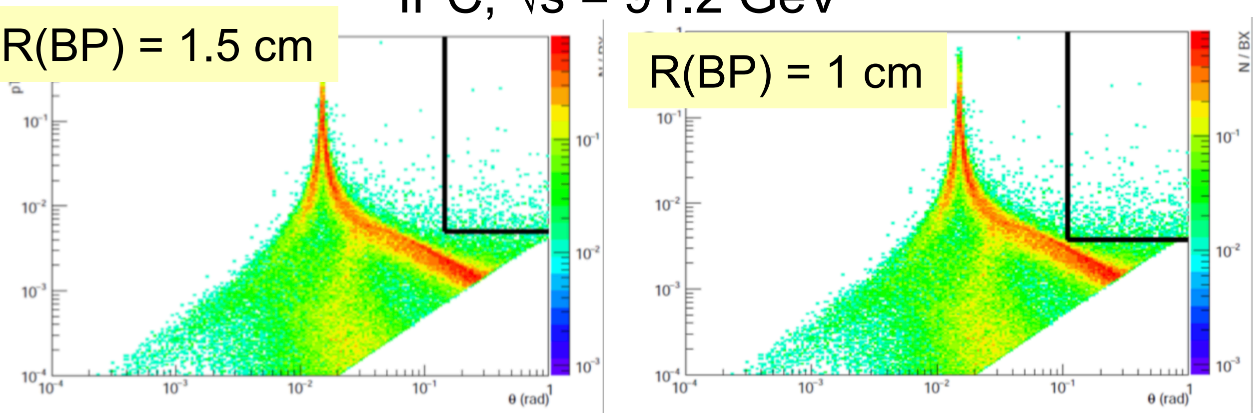
- Effect of beam background (dominated by IPC) on the detector has been studied in full simulation. In general, negligible.

- Very little effect on performances seen in the CLD studies :
  - Small tracking efficiency loss (< 1%) at pT < 300 MeV
  - Increased fake rate for the same pT range (remains < 4%)
  - Slight degradation of jet energy resolution at 91 GeV, in the forward region

- Beyond the baseline model: studies on-going to assess whether a smaller beam-pipe is possible (R = 1 cm instead of 1.5 cm)
  - First layer of VXD closer to beam line : would improve considerably b- and c-tagging performances

  - IPC background remains acceptable (max. occupancy x2)
  - Studies on-going for SR background

IPC, $\sqrt{s}$ = 91.2 GeV



Backup

FCC-ee collider parameters

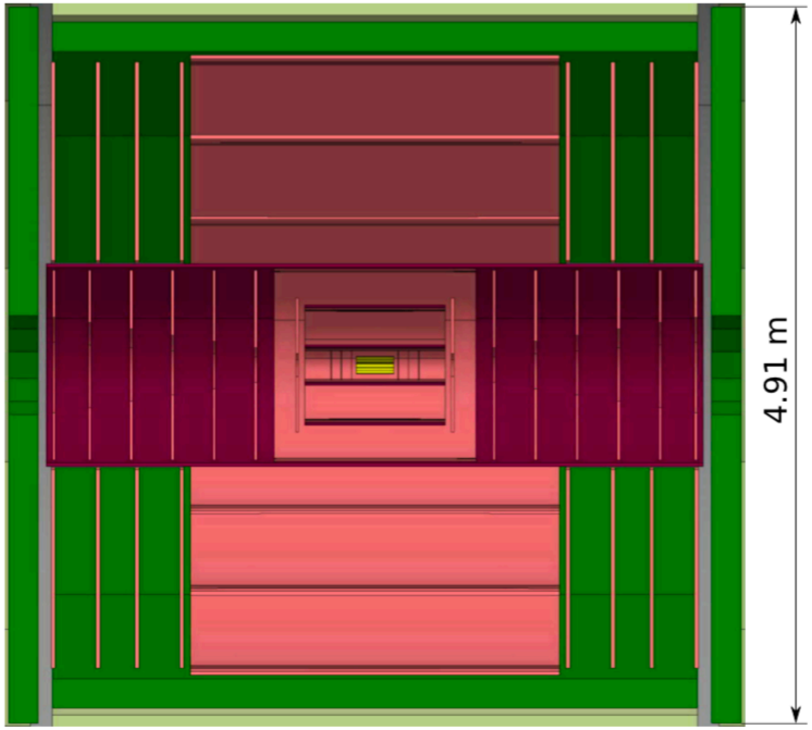
parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

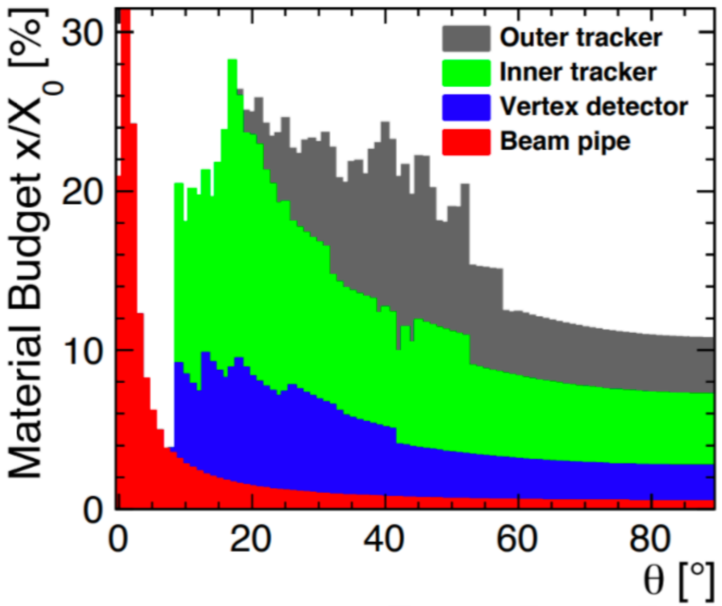
Vertex detector

- Silicon pixels: 25x25μm^2
- Single-point resolution: 3 μm
- 3 double layers in barrel: r = 17, 37, 57 mm
- 3 double endcap disks per side: z = 160, 230, 300 mm
- Material budget: 0.6% X_0 per double layer

Tracker detector

- Silicon pixel and microstrips detector
- Inner Tracker:
  - 3 barrel layers, 7 disks per side
- Outer Tracker:
  - 3 barrel layers, 4 disks per side
- Single-point resolution:
  - 7 μm x 90 μm
  - except 1st IT disk: 5 μm x 5 μm
- Material: 1.1-1.6% X_0 per layer



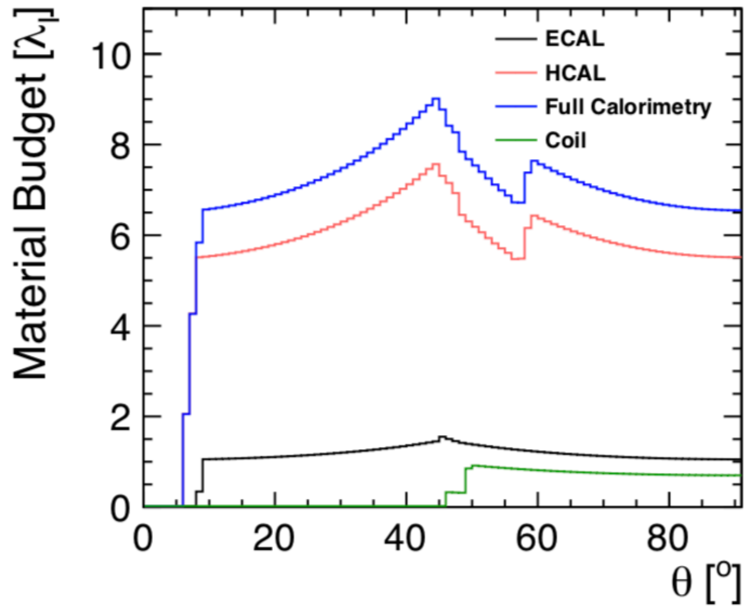


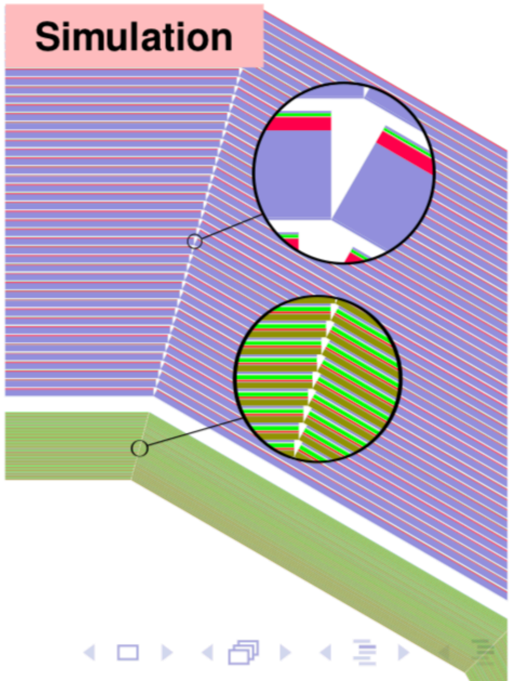
Electromagnetic Calorimeter

- Si-W sampling calorimeter
- cell size 5x5 mm^2
- 40 layers (1.9 mm thick W plates)
- Depth: 22 X_0, 1 λ_I, 20 cm

Hadronic Calorimeter

- Scintillator-steel sampling calorimeter
- cell size 30x30 mm^2
- 44 layers (19 mm thick steel plates)
- Depth: 5.5 λ_I, 117 cm (inspired by ILD)

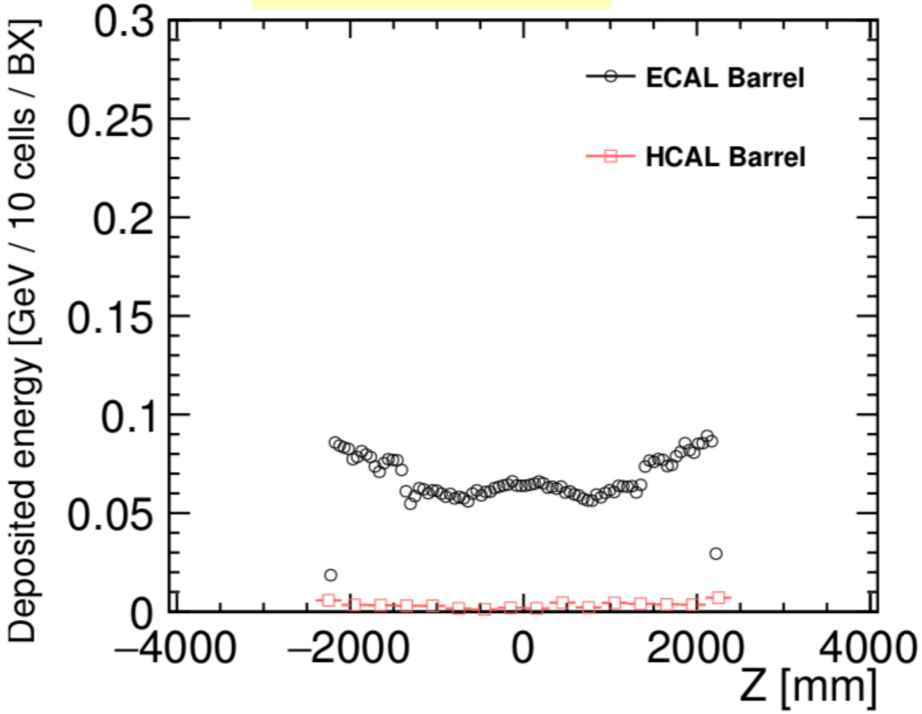


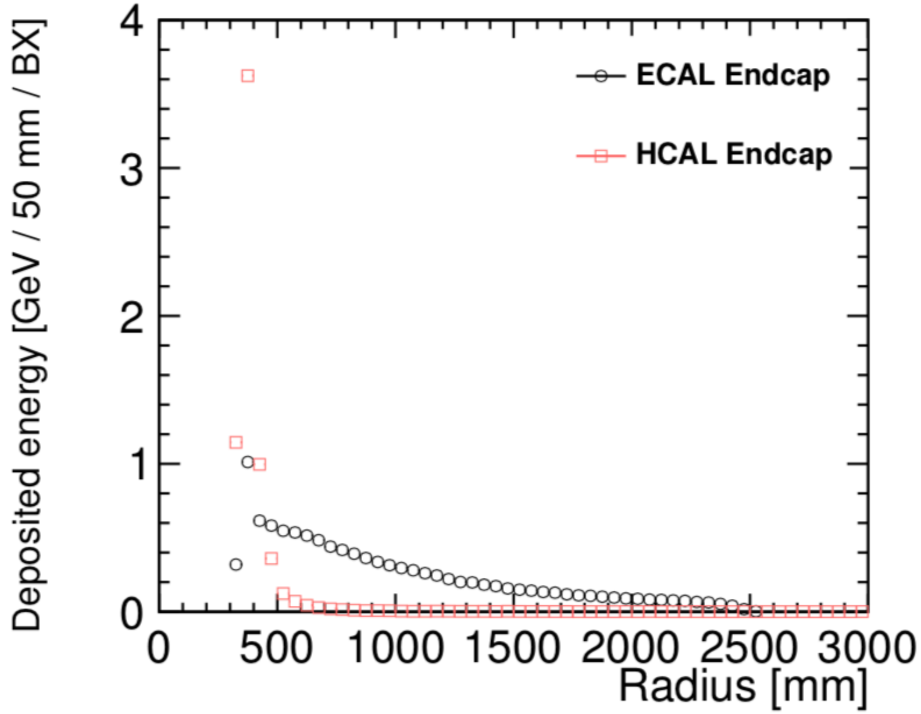


Background impact on calorimeter quantities

Total deposited energy (calibrated) per BX, due to incoherent pair production :

√s = 365 GeV





- Largest deposit in the fwd region (endcap), close to the beam-pipe
- Energies at √s = 91.2 GeV are smaller by O(10) – but need to be multiplied by the number of BXs during which the readout integrates signal