A Triplet Track Trigger for FCC-hh & its impact on measuring the Higgs self-coupling

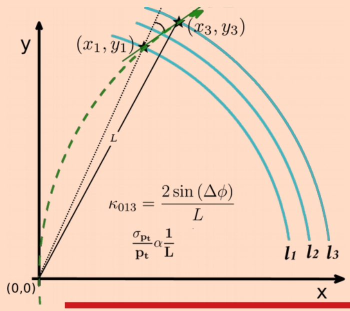
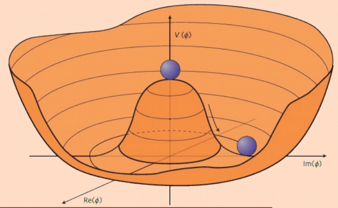


image: Higgs



$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

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FUTURE CIRCULAR COLLIDER

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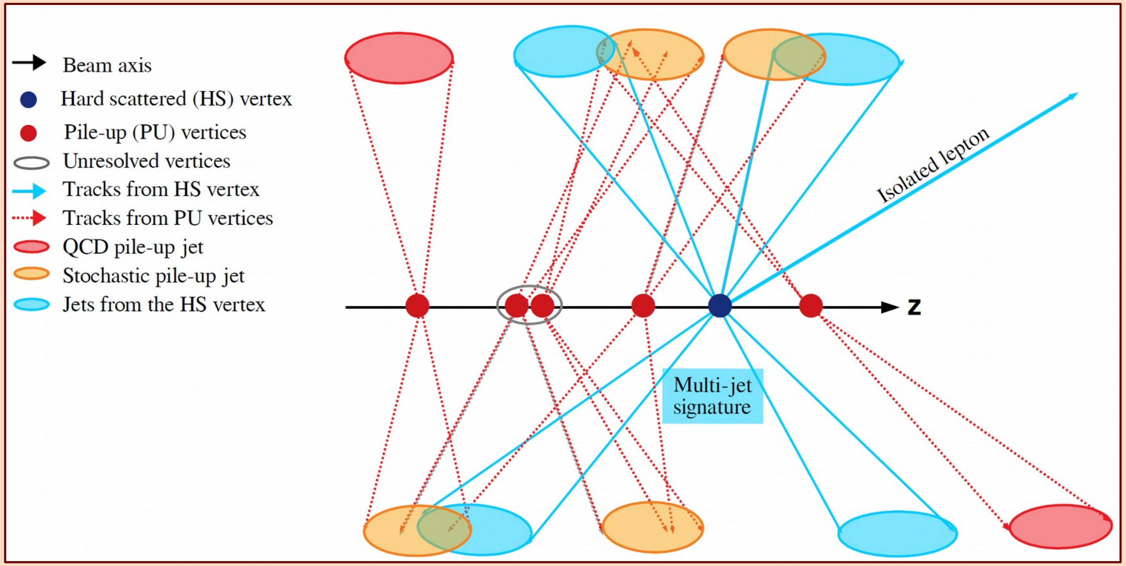
HighR

Pile-up: one of the main challenges at FCC-hh

- Pile-up: number of simultaneous p-p collisions in a single bunch crossing, $\mu \propto L \cdot \sigma$
  ($L \sim 30 \times 10^{34}$ cm^{-2} s^{-1}, $\sqrt{s}$ = 100 TeV, <μ> ~ 1000)
- Pile-up influences the reconstructed objects and kinematics of the Hard Scattering collision

10.11588/heidok.00029043

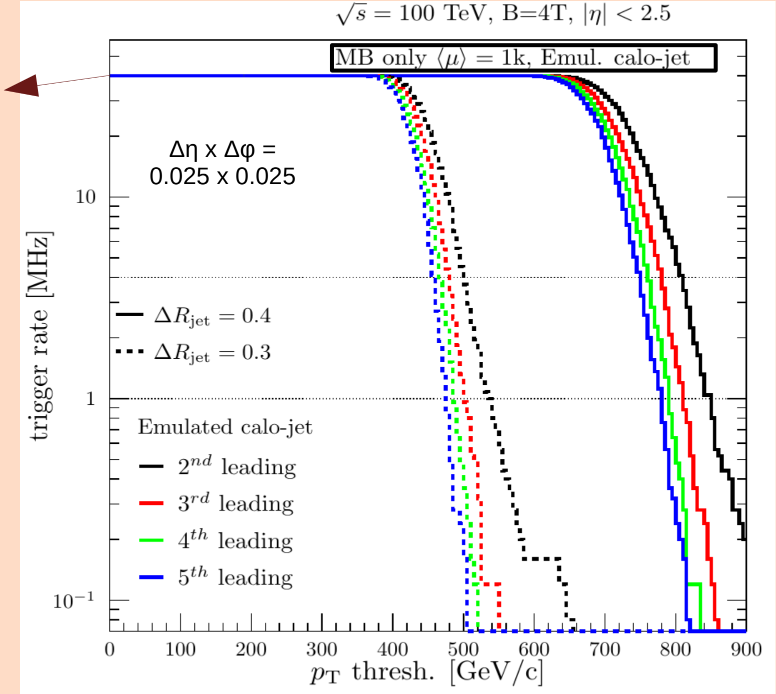


- Limited bandwidth, very high detector occupancies, latency requirements, etc.
  → **Pile-up suppression!!**

Triggers at high rate collider experiments

- Calorimeter triggers ⟶ **energy** distribution and rough **particle id**
  (**1st trigger level:** fast object reconstruction in hardware to select events of interest)

pile-up @ 40MHz



10.11588/heidok.00029043

Unfortunately, enormous amount of **pile-up** forces to **set trigger thresholds** of calo-based triggers significantly high to meet the technical and computational limitations

- More information from **tracking detectors (precise vertex)** or picosecond timing detectors (time coincidence) is essential to excellent pile-up suppression

Triggers at high rate collider experiments

- Highest selectivity is required at earliest possible state to fully explore FCC potential
- Muon triggers → **muon** identification and **momentum**
  (also used at **1st trigger level.** However, not all channels can profit from muon triggers)
- Track triggers → **momentum**, **origin** and **separation of charged particles** using hit combinations
  (typically used at **higher trigger level;** involves software based complex reconstruction algorithms)
- Reconstructing tracks within required latency of trigger systems is difficult
  (more so in very high pile-up environment)

Is it possible to provide tracking information at 40 MHz to resolve pileup?

Triplet Track Trigger (TTT) concept

- **Three closely stacked pixel** tracking layers at **large radii** (0.5 - 1m)
- Charged particle in uniform B:
  → **circle in x-y** (3 points to determine circle params.)
  → **straight line in s-z** (slope: z0 vertex)
- **Beamline constraint** for precise track parameter measurements
- Compromise b/w **high track purity** (close stacking) & **high track parameter resolution** (large TTT gap-size)

Large area pixel detectors!

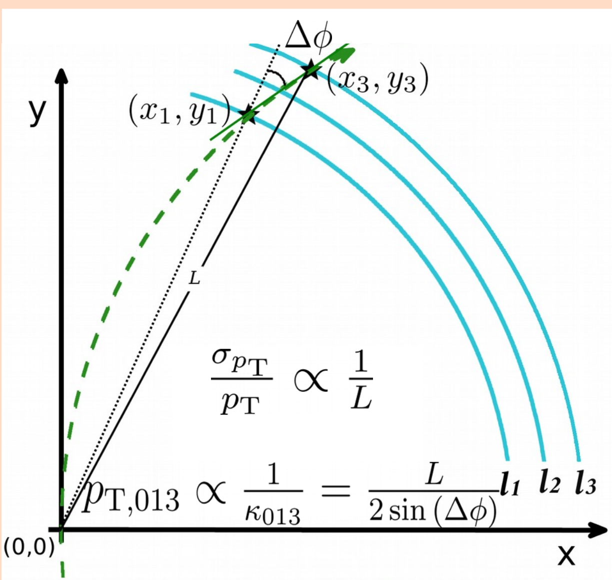
→ **Monolithic Active Pixel Sensors (MAPS)**

► Commercial production

► radiation hard (e.g. HV-MAPS)

arXiv:2002.07253[physics.ins-det]

10.11588/heidok.00029043

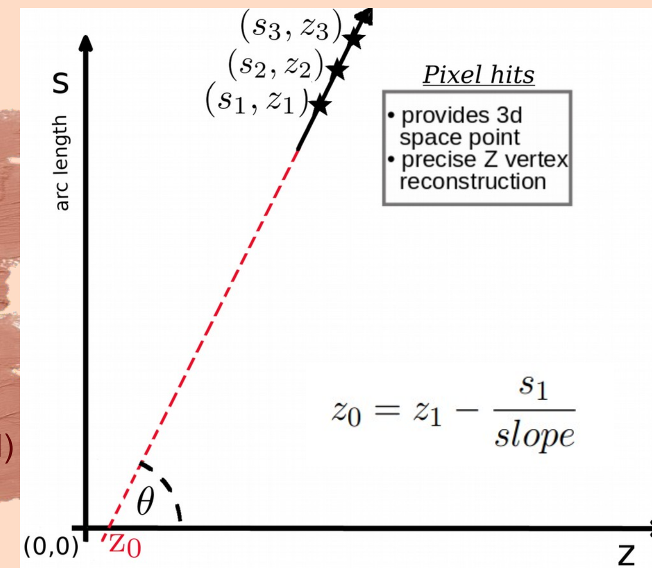


pT reconstruction with beamline constraint

→ **Simple** and **very fast** algorithm!

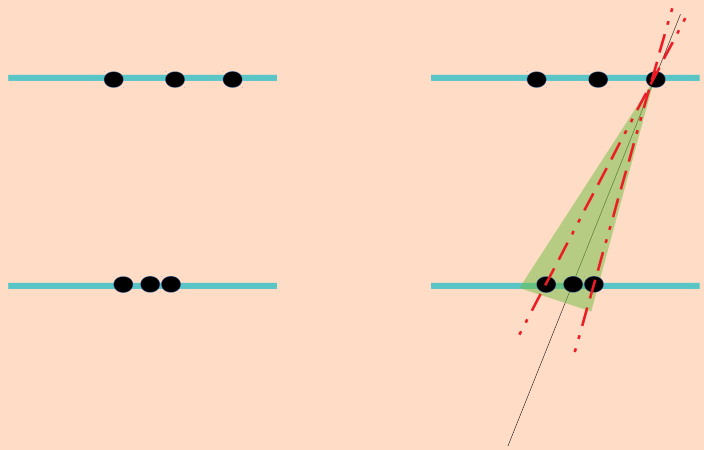
→ Can be implemented in **hardware**

(stratix X firmware being developed)



z0 reconstruction with **sub-mm precision**

What is special about the Triplet design?

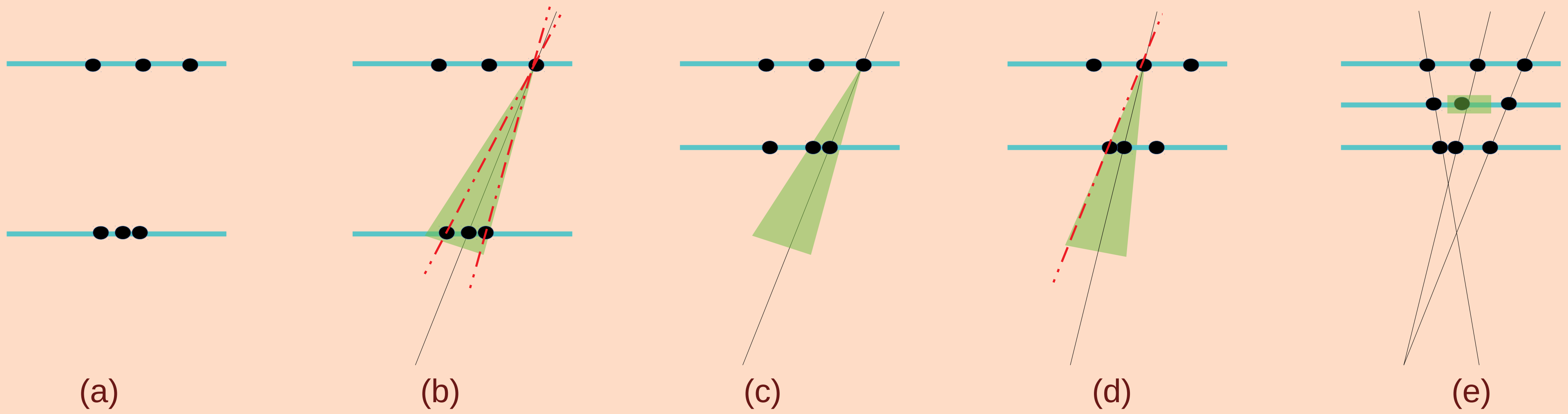


(a) (b)

a) Hits from three tracks on two widely separated detector layers

b) Search window → large number of wrong combinations

What is special about the Triplet design?



a) Hits from three tracks on two widely separated detector layers

b) Search window → large number of wrong combinations

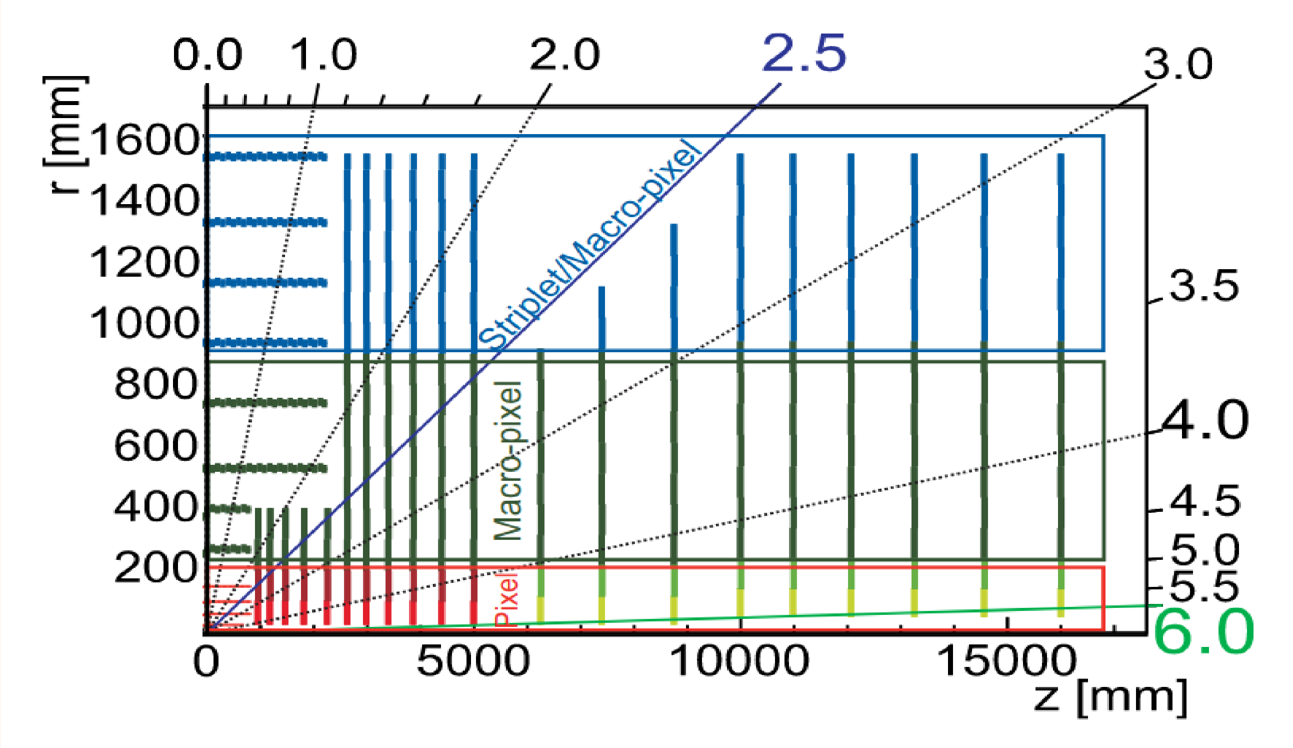
c), d) Close stacking of detector layers reduces candidates (rate of fakes)

e) A 3rd middle layer further reduces fakes (wrong hit combinations) by validation of the selected combination both in x-y and s-z planes.

High track purity!!!

FCC-hh reference tracker layout

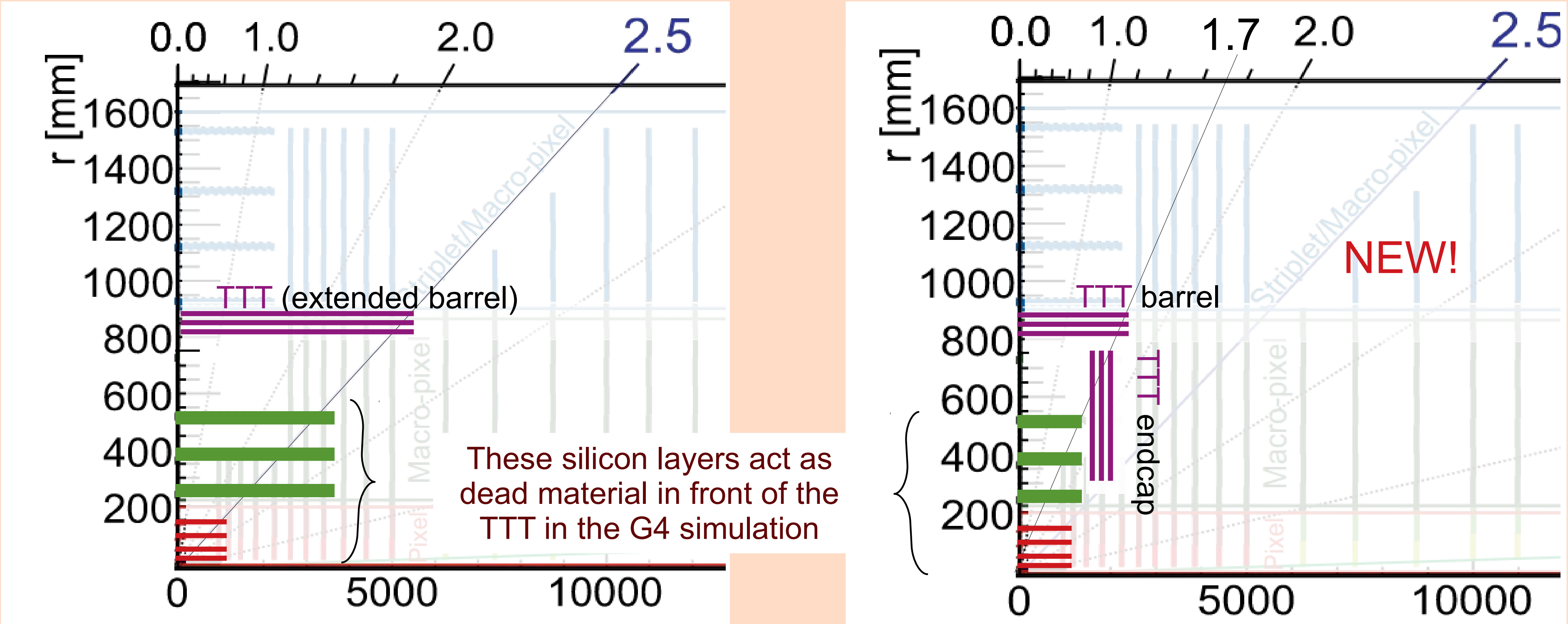
10.1140/epjst/e2019-900087-0



Tracker layout based on ‘flat geometry’ for the FCC-hh reference detector

Modified FCC-hh tracker layout with TTT (|η| < 2.5)

Thesis T.K: 10.11588/heidok.00029043

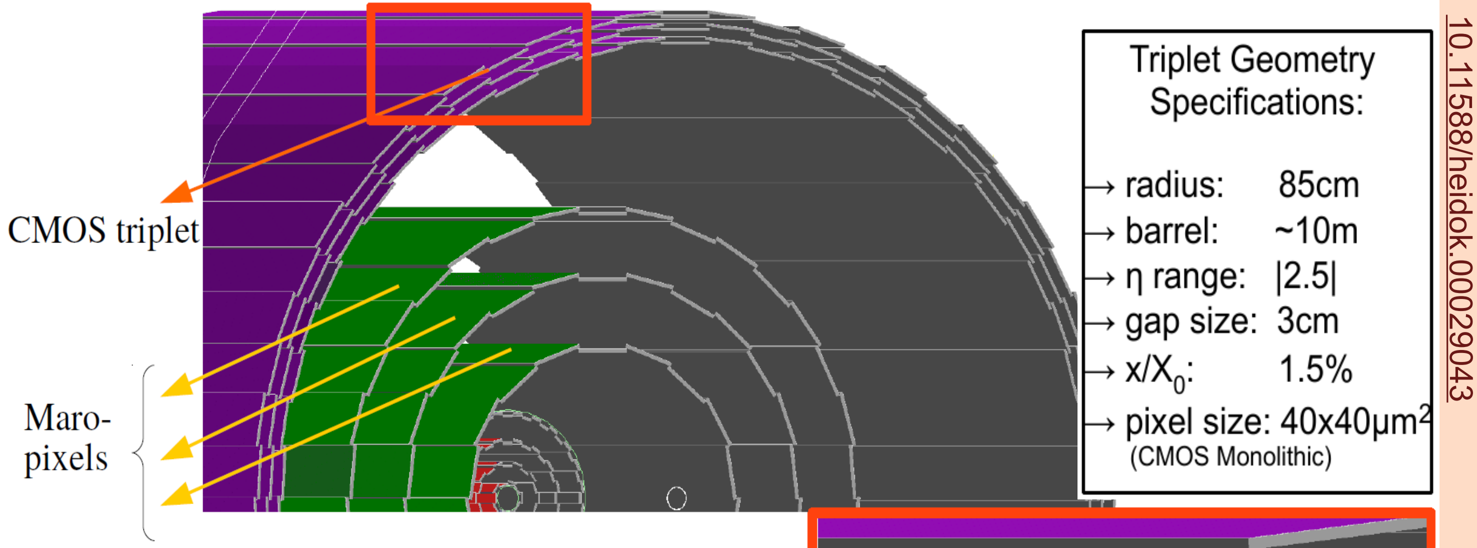


(a) Extended barrel geometry

(b) Barrel Endcap geometry

Full Geant4 simulation of the modified FCC tracker

- Both, the extended TTT barrel geometry & the TTT barrel encap geometry were simulated using Geant4. Below is a G4 geometry implementation of the extended barrel tracker for FCC-hh



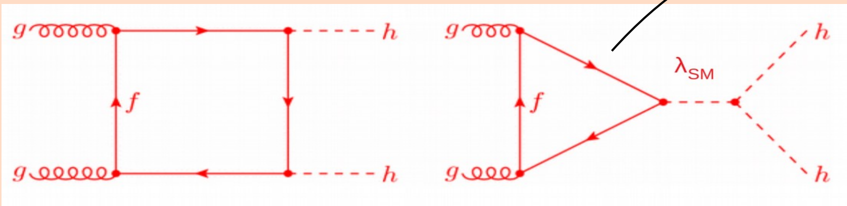
TTT Extended barrel covering |η|<2.5,
Radial gap-size optimized to 3cm

Zoomed view

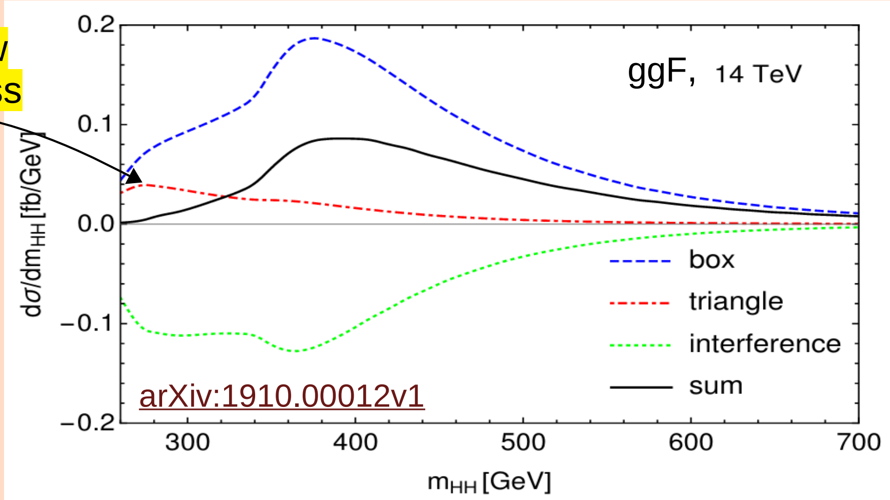
HH → 4b (showcase)

- Di-Higgs production will allow for direct measurement of the Higgs self coupling (λ)
- Dominant HH Production mode:

Peaks at low invariant mass



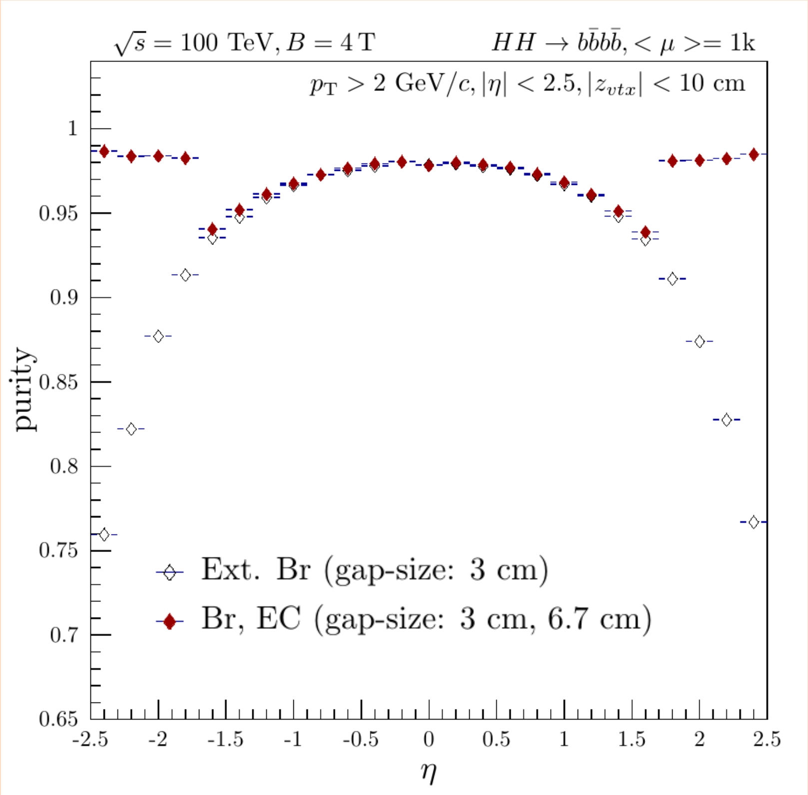
gluon gluon fusion (ggf)



Higher sensitivity to λ at low m_{HH}!

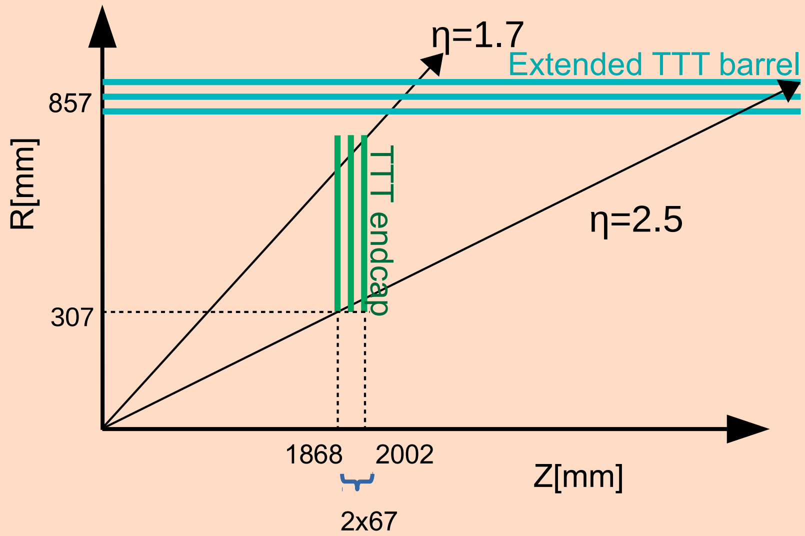
- **Signal: HH→4b**, no leptons/photons for trigger, only jets! Suffers from a huge QCD **background: pp→4b QCD**
- A very difficult channel to trigger
- Perfect showcase for a track trigger

TTT track purity

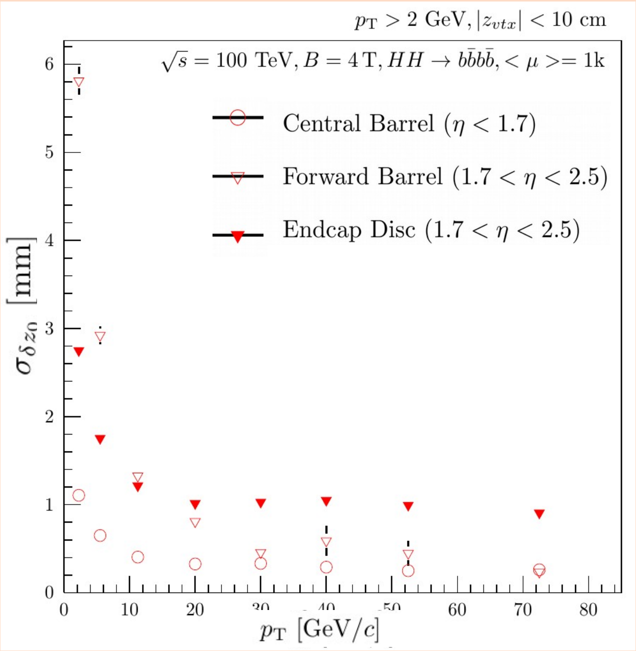


Track purity vs η for extended barrel TTT and TTT with endcap.

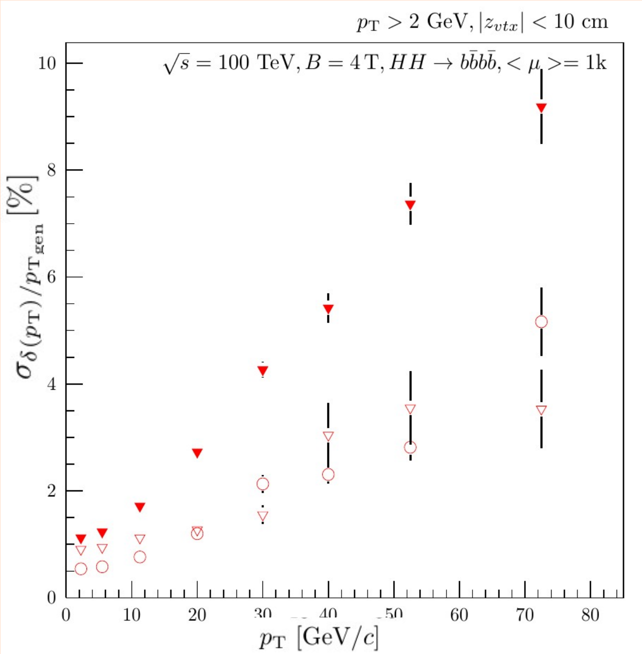
- Excellent track purity **> 95%** with only **three pixel** tracking layers
- Track purity decreases at large η for an extended barrel geometry (multiple Coulomb scattering)
- TTT endcap has better purity than TTT extended barrel



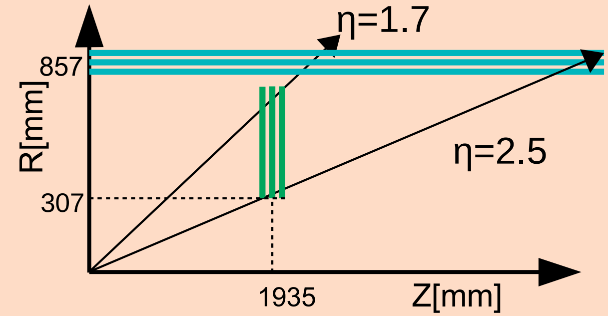
TTT track parameter resolution



(a) z0 resolution vs p_T



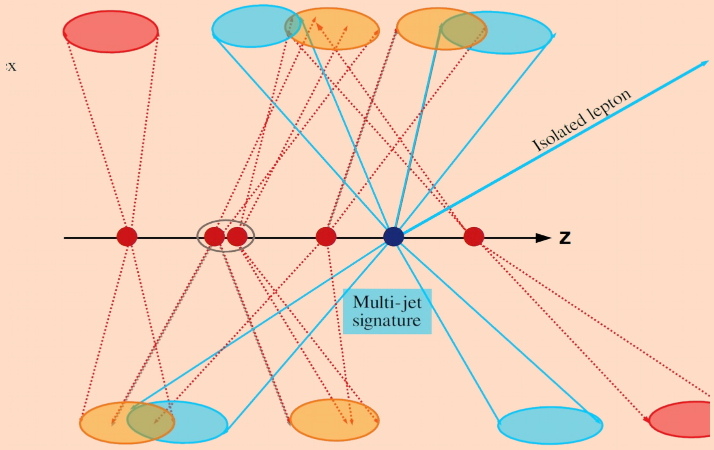
(b) relative p_T resolution vs p_T



Relative p_T resolution of ~5-10% for p_T= 100GeV tracks

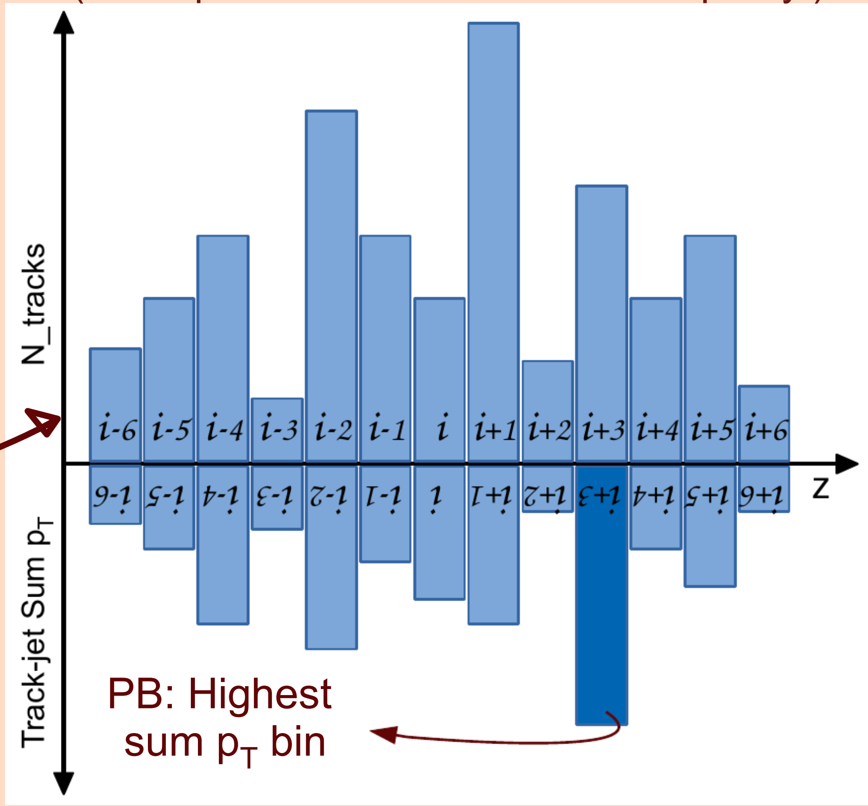
- The z-vertex (z0) is reconstructed with **sub-mm precision** for the central barrel (|η| < 1.7)
- At low momenta, the resolution is affected by multiple scattering (material in front of the TTT)
- At high momenta, the p_T & z0 resolution mainly determined by the length of the lever-arms
  Hence resolution for forward barrel better than the endcap (→ increase the distance b/w endcaps)

How to identify the Hard Scattering vertex?



- Exploit z0 and p_T of the TTT tracks
- Clustering of TTT tracks in all **z-bins in parallel** → **TTT-jets**
- Identify a region around the HS vertex: **primary bin (PB)** with **max-sum p_T** approach
- PB selection efficiency for z-bin = ±1.5mm: ~94% ($|\eta_{acceptance}| < 1.5$), ~82%($|\eta_{acceptance}| < 2.5$)

parallel jet clustering in small z0 regions defined along the beam axis
(overlap b/w bins not shown for simplicity)



sum over the p_T of the first few leading TTT track-jets in small z0 regions

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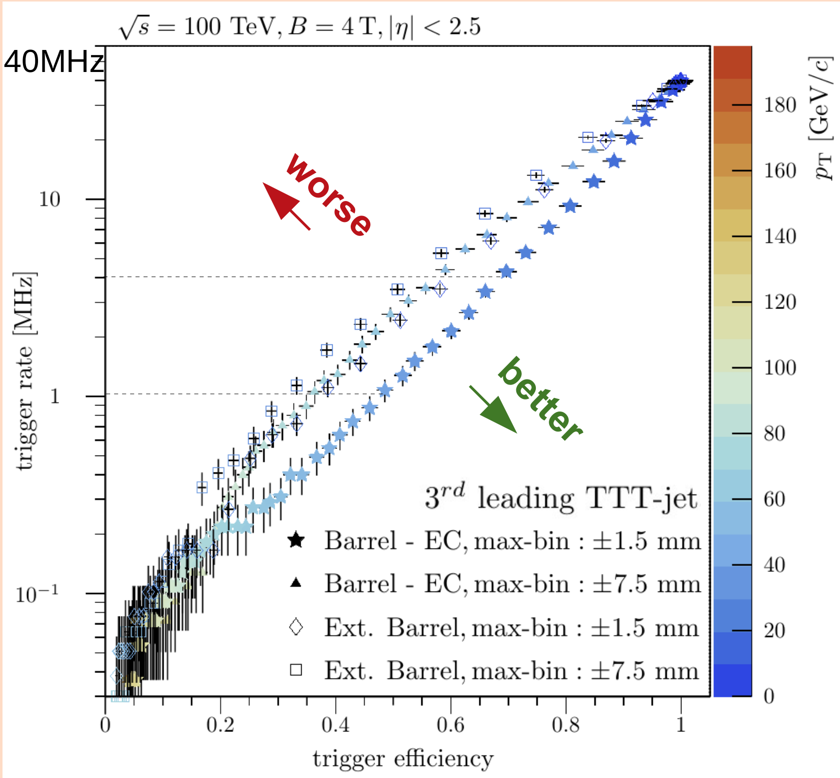
TTT Trigger performance (exploiting z0 information)



Trigger rate vs trigger efficiency
for the 3rd leading jet in the HH→ 4b, <μ>=1k sample.
The corresponding p_T thresholds are shown in the z-axis

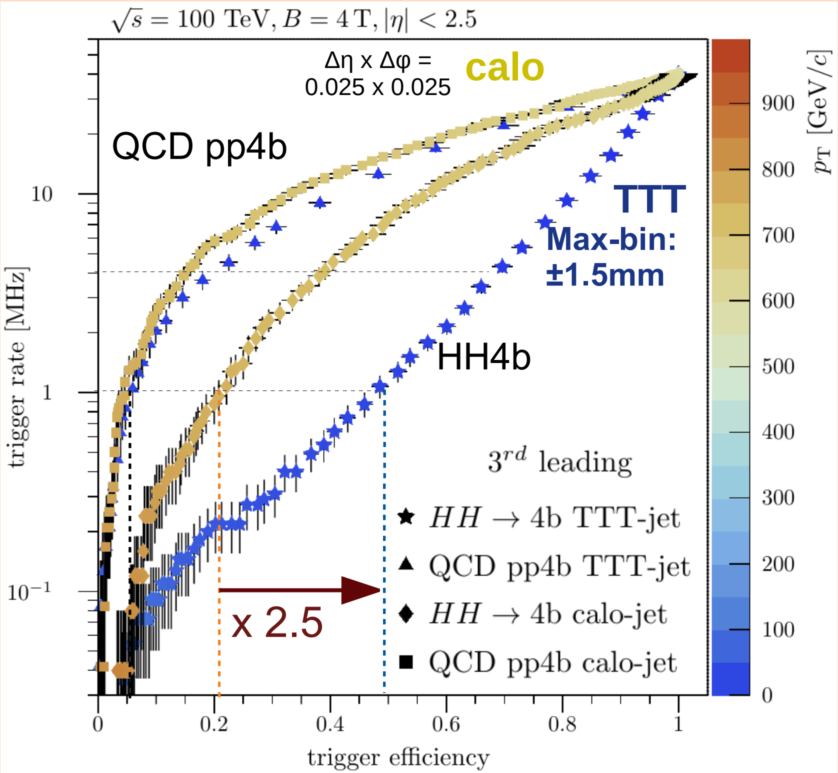
- Events that satisfy the HH→4b selection cuts after fast simulation are considered as signal.
- Triggering on the first few leading TTT-jets from the selected primary bin

Trigger Rate = <u># pile-up events passing a given trigger threshold</u> / #total pile-up events

Trigger Eff. = <u># signal events passing a given trigger threshold</u> / #total signal events

- The best trigger performance: trigger on **3rd leading TTT-jet** with a z-bin size = **±1.5 mm**
- Fine z-binning → Significant pile-up suppression
- TTT endcap outperforms extended TTT barrel **~50% compared to 38%** trigger efficiency at **1MHz**
- Further improvement in selectivity can be achieved by increasing the distance b/w the TTT endcaps

TTT Trigger performance compared to calo-trigger



Trigger rate vs trigger efficiency
for the 3rd leading jet in the HH→ 4b & QCD pp→4b sample with an <μ>=1k.

- TTT has a significantly higher selectivity to the signal events compared to the calo-trigger (**x 2.5 at 1MHz**)
- The calorimeter would have to trigger at **~800GeV** to bring down the pile-up rate to 1MHz
- TTT exploits the z0 information to suppress pile-up at much lower trigger thresholds **~50GeV** (3rd leading)
- TTT enhances HH→4b signal over QCD background

Impact on HH→4b signal significance

- Simple **cut-based** analysis was performed for different κ_λ values of HH→4b considering pp→ 4b QCD background, $\sqrt{s}$ = 100TeV, $\int L dt$ = 30ab^{-1}, ε(b-tag) = 80%, jet energy smearing = 50% (assuming negligible systematic uncertainty & excellent offline pile-up suppression)
- Assuming full detector readout, i.e. 100% trigger efficiency for signal and background events yields S/√B ≈ 21 for κ_λ = 1 (SM sample)
- The very **good (bad) selectivity** of the **TTT (calo-trigger)** further increases (reduces) the signal significance by a factor of **1.6 (0.6)** obtained from the cut-based analysis
- The significantly low trigger thresholds of the TTT allows to probe λ at much lower p_T (→ reduces systematic uncertainties)

HH→4b Analysis cuts:

at least four $\Delta R_{\mathrm{jet}} = 0.4$ anti-k_t jets,
the leading jet $p_{\mathrm{T}} \geq 55\,\mathrm{GeV/c}$,
sub-leading jet $p_{\mathrm{T}} \geq 40\,\mathrm{GeV/c}$,
3^{rd} leading jet $p_{\mathrm{T}} \geq 35\,\mathrm{GeV/c}$,
and the 4^{th} leading jet $p_{\mathrm{T}} \geq 20\,\mathrm{GeV/c}$.
$N_{\mathrm{b-tags}} \geq 4 \quad |M^{\mathrm{cand.}}_{\mathrm{H}_{1(2)}} - 125| \leq 30$

Impact on signal significance of HH→4b

	Trigger Efficiency		S/√B
	S	B	
HH→4b analysis cuts	100%	100%	21
Calo	**20%**	**10%**	**13**
TTT	**50%**	**10%**	**33**

Summary

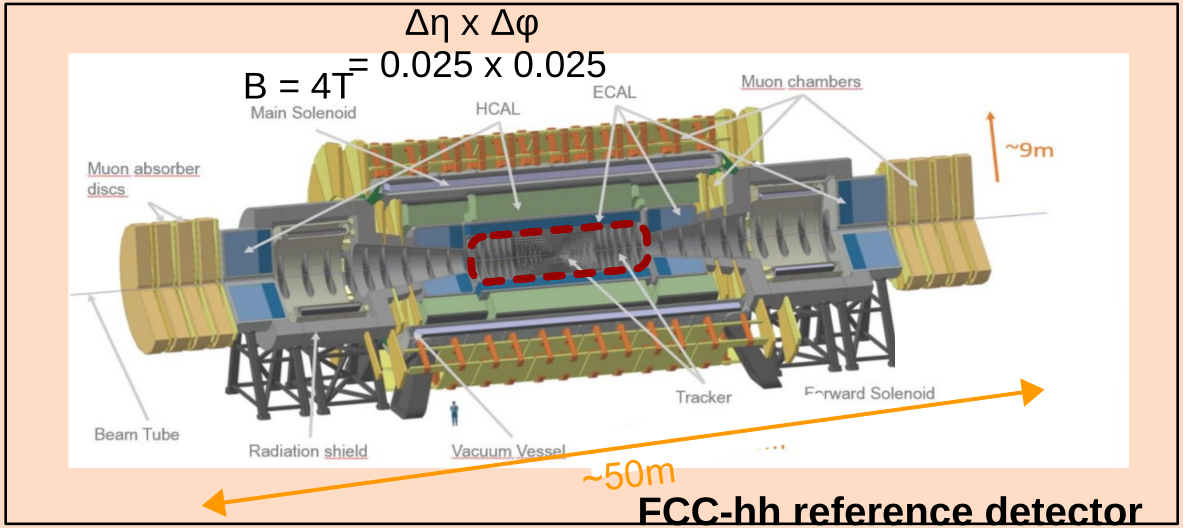
- The TTT is based on a simple detector design and fast reconstruction algorithm
- It can reconstruct tracks at **40MHz** with good momentum resolution ~O(100GeV)
- TTT exploits the good z0 resolution to facilitate **excellent pile-up suppression** at trigger level
- By forming track-jets, the TTT is an ideal tool to trigger on multi-jets signatures (low p_T physics at 100GeV scale)
- TTT can help to improve the signal sensitivity to the **trilinear Higgs self-coupling (λ)** in the HH→4b channel

A **Triplet Track Trigger** based on MAPS is an interesting design option for triggering in the challenging environment of the FCC-hh

Thank you!

Backup

Calorimeter Emulation for FCC-hh scenario



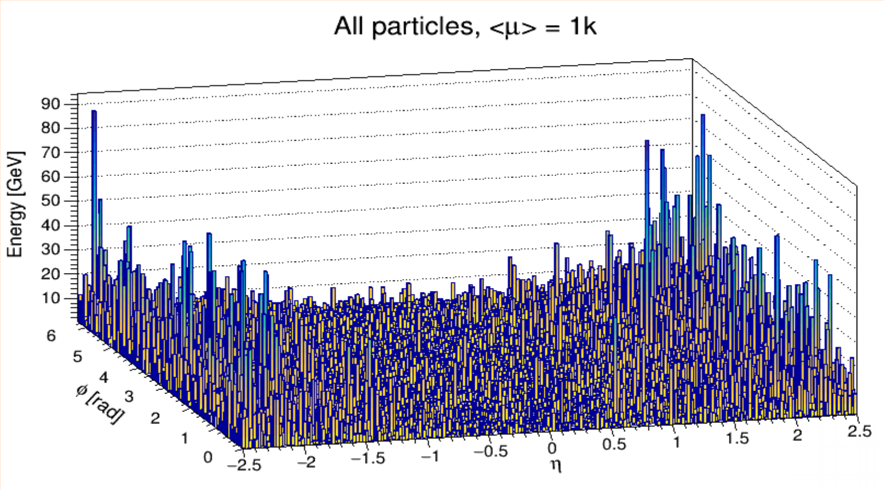
- Radius : 2m, Cell granularity: **Δη x Δφ = 0.025 x 0.025** for eta range **-2.5 to 2.5** → 2D Hist
- Example case: signal **HH → 4b** (dominant background pp → 4b QCD events) , **<μ> = 1000**
- total energy deposited in each cell

  → smeared with **50% energy resolution.***

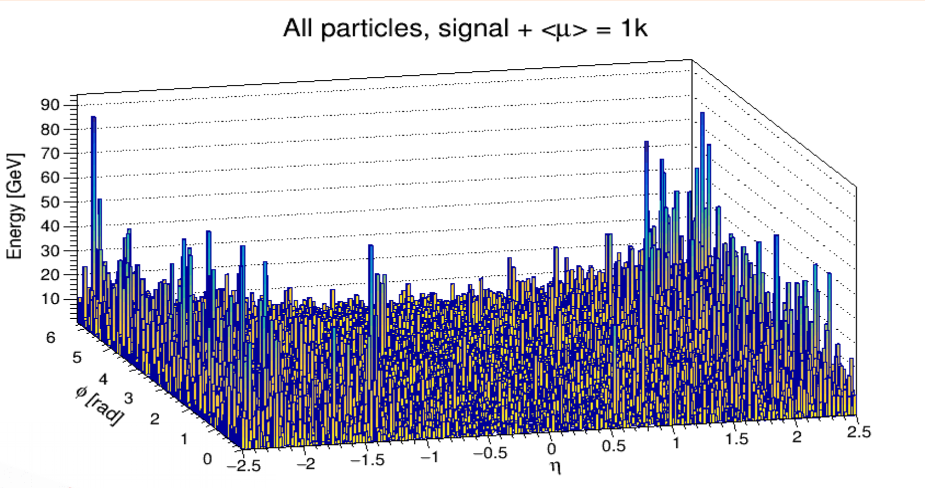
* $\sigma_E/E \sim a*1/\sqrt{E} + c$. Constant term c = 3% also added in addition to the stochastic term a = 50%

Energy deposits in the calorimeter cells

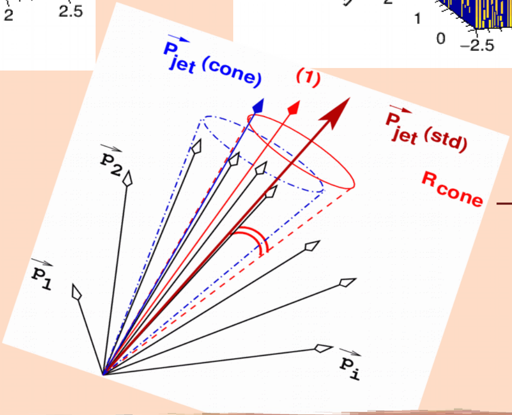
Pile-up only



Signal + Pile-up



Energy deposits → Jet clustering algorithm
(e.g. anti-kt R=0.4)



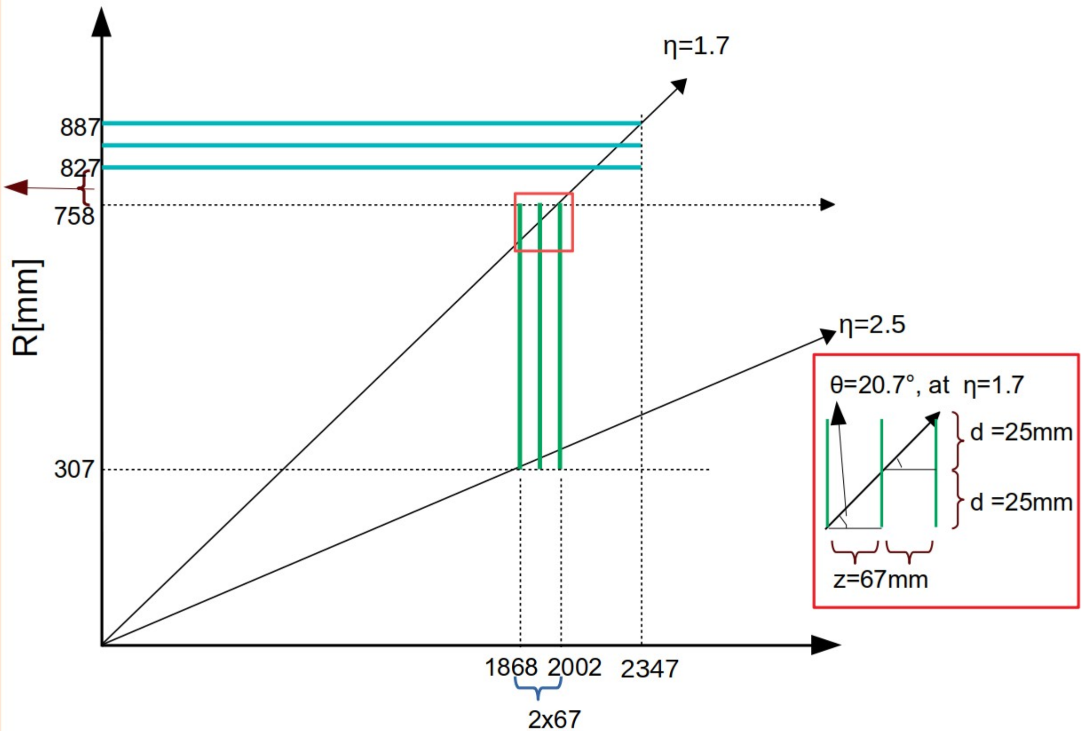
→ trigger on highest p_T jets

Usually come from HS collision
(not in the case of high pile-up)

Calo-trigger has almost no selectivity to signal events!

TTT Endcap Design

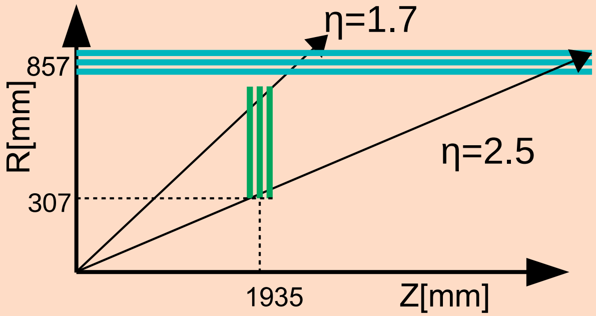
Assumed space for services = 69mm

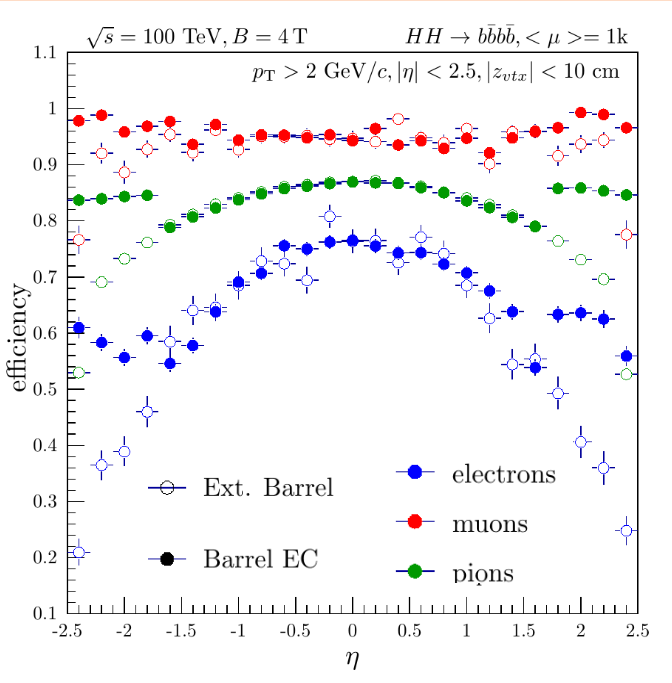


TTT Barrel: |η| < 1.7, Endcap: 1.7 < |η| < 2.5
z gap-size: 6.7cm

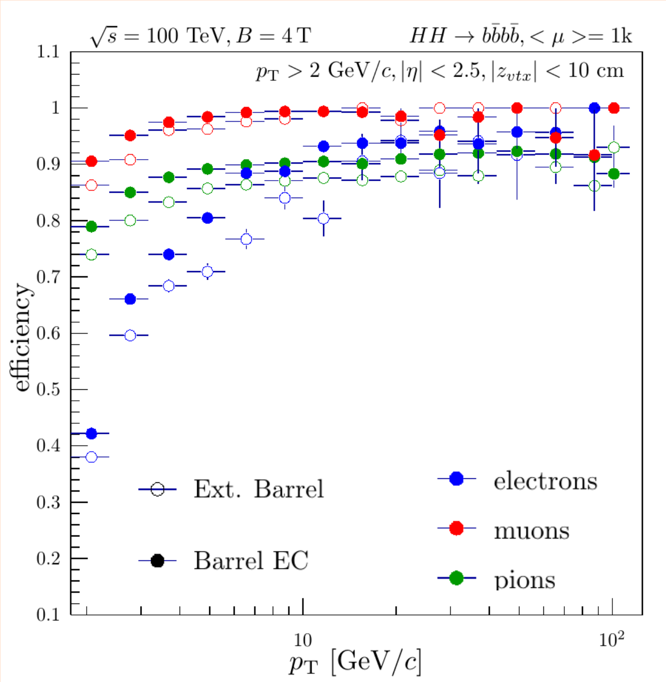
(inner tracking layers (not shown above) also simulated to account for material effects)

TTT tracking efficiency





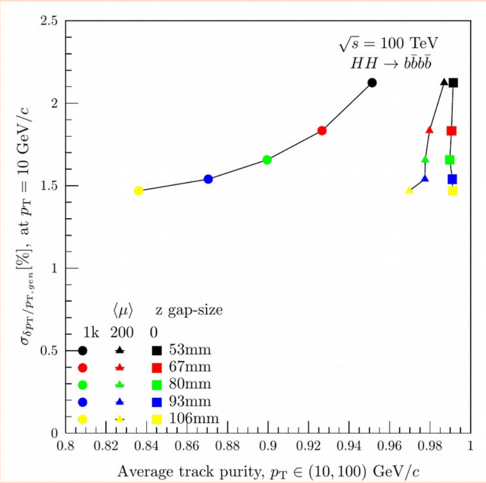
(a) TTT efficiency vs η

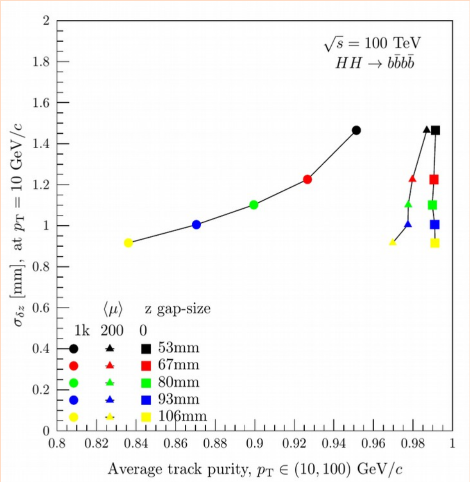


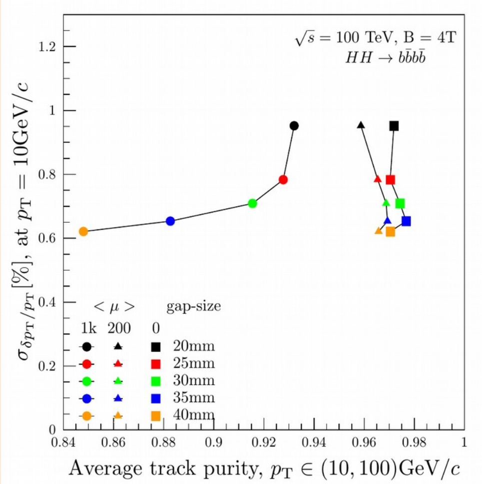
(b)TTT efficiency vs p_T

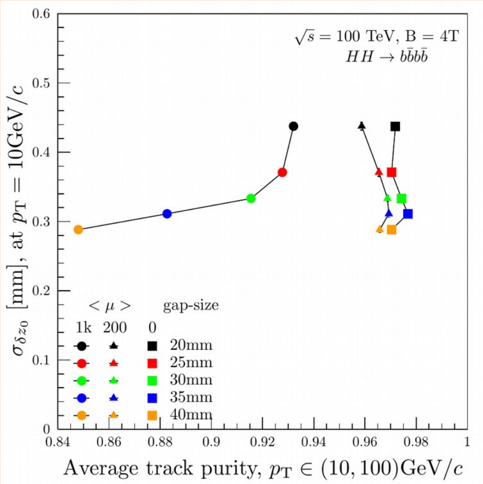
- Muons are reconstructed with very high efficiency except around p_T threshold (finite resolution)
- Inefficiencies for electrons and pions are due to bremsstrahlung and nuclear interactions resp.
- At large η, TTT endcap also ensures better tracking efficiency compared to an extended barrel

Triplet track reconstruction performance





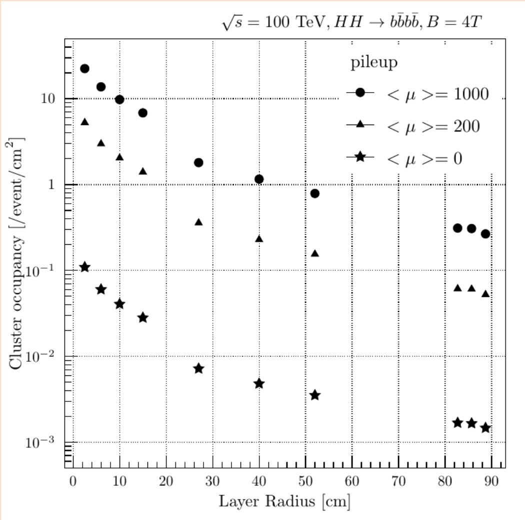




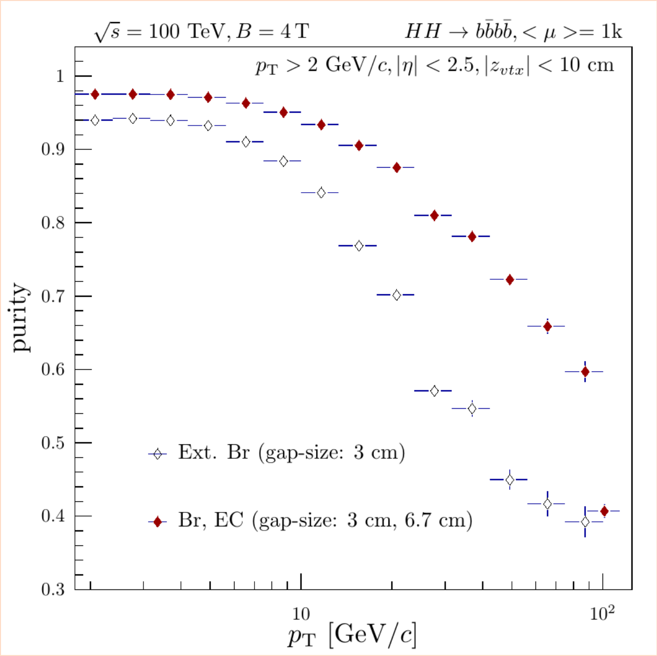
TTT Endcap: 1.7 < |η| < 2.5

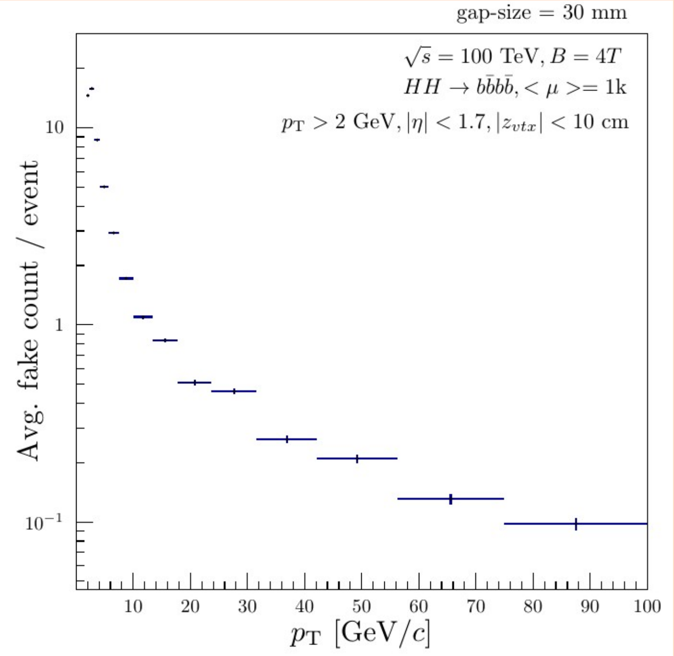
TTT Barrel: |η| < 1.7

- Track parameter resolution improves with increase in TTT gap-size
- Resolution mainly determined by the material in front of the TTT
- Track purity degrades with increasing pile-up
- Optimum gap-size chosen for FCC-hh: 30mm



TTT tracking performance: Track Purity





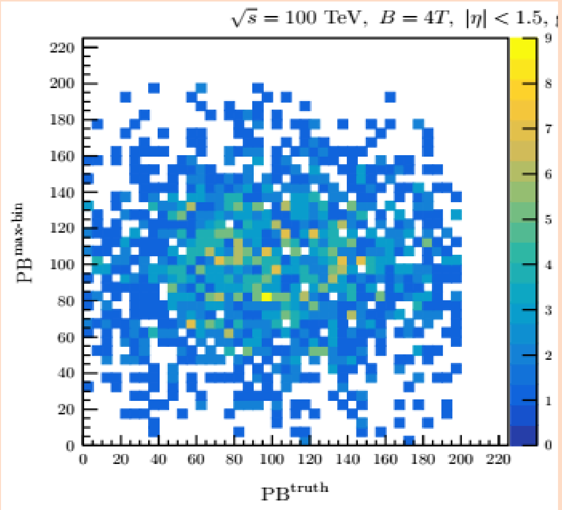
Average # fake tracks/event vs. p_T

Primary Bin selection efficiency

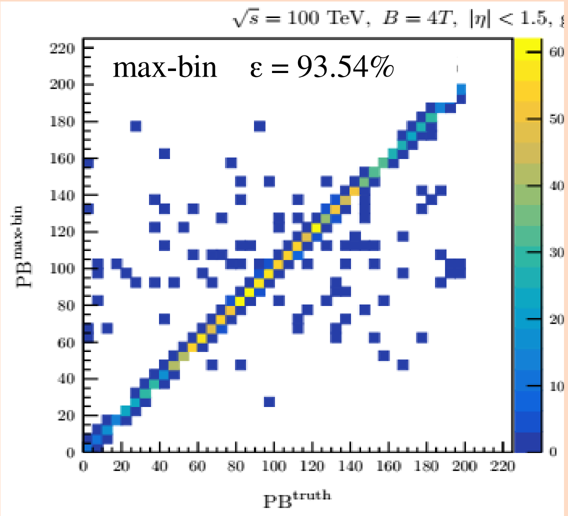
$$\epsilon_{\mathrm{PB}} = \frac{\#\ \text{events with PB matched to PB}^{\text{truth}}\ (\text{sel. \&\& acc.})}{\#\ \text{total events (sel. \&\& acc.)}}$$

$\mathrm{PB}^{\mathrm{truth}}$: z-bin containing the actual primary vertex

Matched PB → Correctly reconstructed → Bin corresponding to the $\mathrm{PB}^{\mathrm{truth}} \pm 1$



pile-up



signal + pileup