A Triplet Track Trigger Case Study for FCC-hh

Enhancing the Measurement of Di-Higgs Production & Higgs Self-Coupling

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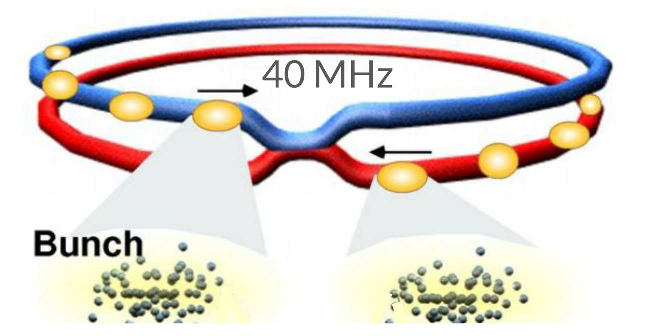
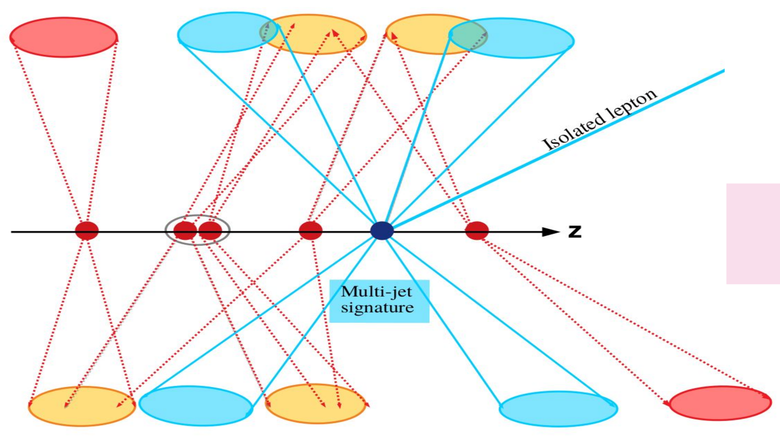
$\sqrt{s}$ = 100 TeV, $\mathcal{L}$ = 30 x 10^{-34} cm^{-2} s^{-1}



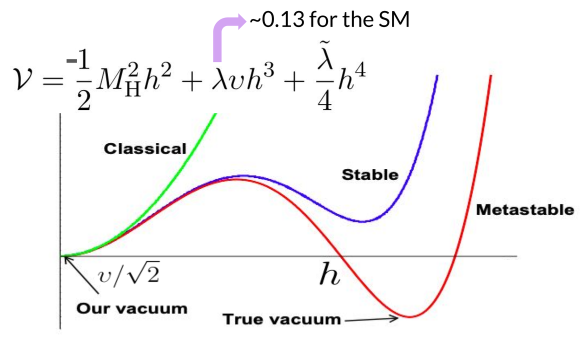
proton-proton collisions in a circular collider [1]



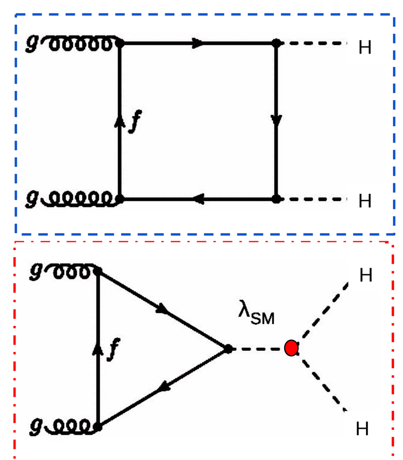
Impact of pileup on jet reconstruction and primary hard interaction vertex reconstruction [4]

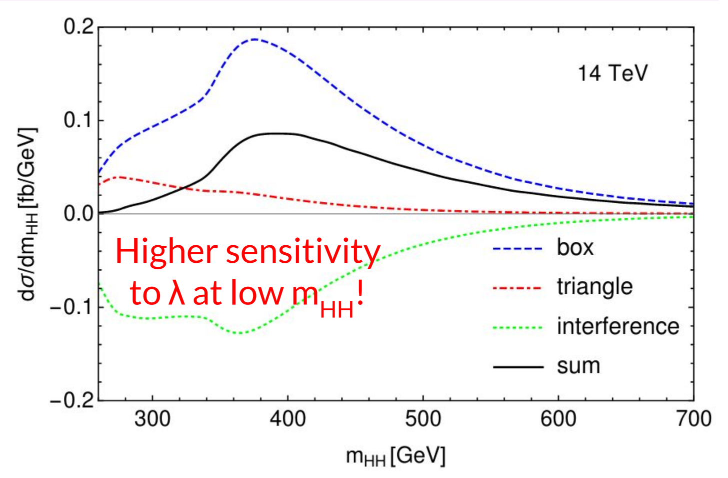
Physics Motivation

Does our Universe lie in a local or a global minimum?



Possible Higgs potentials as a function of the Higgs field [2]

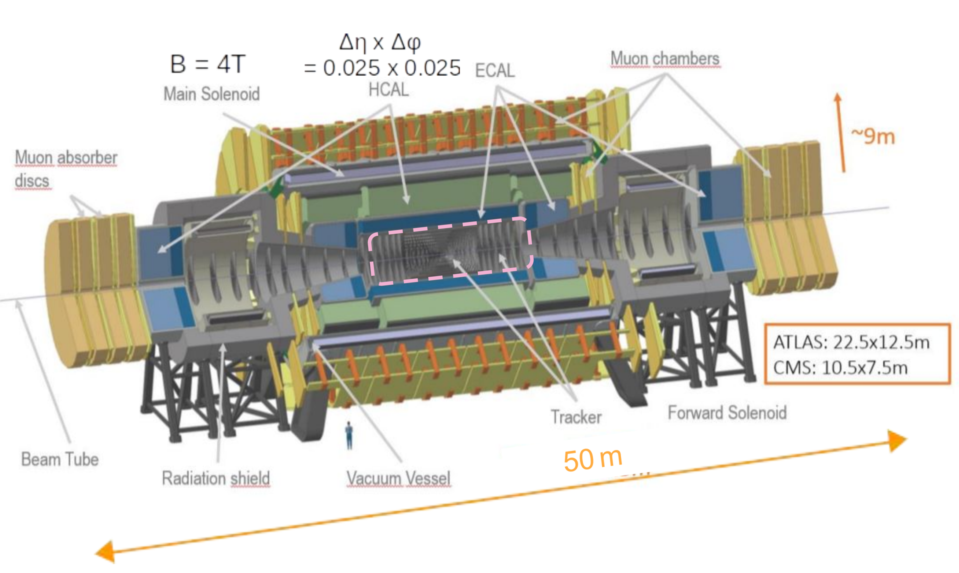




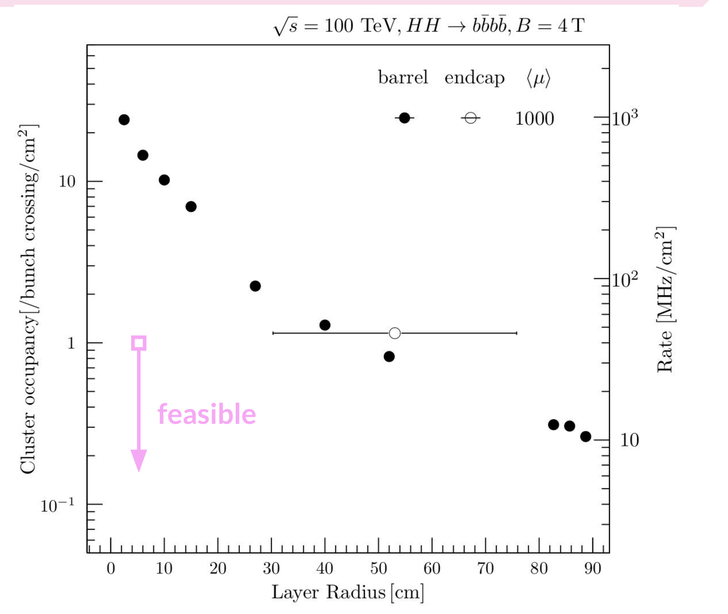
Di-Higgs production via gluon-gluon fusion and the contributions from the triangle and the box component with destructive interference effects [3]

- After the Higgs Bosons discovery at the LHC, one of the crucial goals in the particle physics today is to **understand the nature of the Higgs potential precisely.**
- The hadron-hadron Future Circular Collider (**FCC-hh**) with the goal to collide proton-proton beams at a centre of mass energy of **100 TeV** will offer an **extended discovery reach** and **precision measurements** of very rare processes.
- **Di-Higgs production** will offer direct insights into the Higgs potential by allowing **direct measurement of the Higgs self coupling (λ)** in the gluon gluon fusion production mode.

The Challenge



Reference detector for an FCC-hh experiment [5]

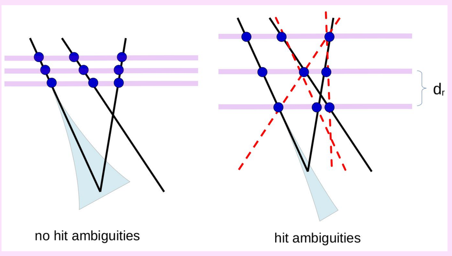


Cluster occupancy per BX, rate as a function of layer radii [6]

- On average **~ 1000 proton proton collisions** per 25 ns bunch crossing event in| z| ≤ 10 cm
  - → **1-2 PB/s** of data is expected from the tracker alone. Full readout at 40 MHz, is extremely challenging.
    - → standard track reconstruction algorithm is **complex and is compromised**.
  - → reconstruction of jets in the calorimeter arising from the hard interaction vertex is also **compromised**.
- **Need for a trigger enabling pileup suppression!**
  - → **Calo-trigger:** blind to origin of particles (trigger threshold >700 GeV/c)
  - → **Track-trigger:** uses momentum and vertex information. However, fast online reconstruction of tracks is computationally very demanding.

The Triplet Track Trigger (TTT) Concept

Three closely stacked highly granular pixel tracking layers at large radii (~ 1 m), in a uniform magnetic field B.



- **Close stacking:**
  - → High track purity
- **Pixels at Large radii:**
  - → precise hit positions and large lever arm for **very good z_0 and momentum resolution.**
  - → radiation expected at r > 40 cm ~$\mathcal{O}(10^{16})$ 1 MeV neq/cm²
  - ⇒ detector technology chosen for HL-LHC can be used, e.g. **Monolithic Active pixel sensors**
- Charged particle track in uniform B (along z):
  - → circle in x-y plane
  - → straight line in s-z

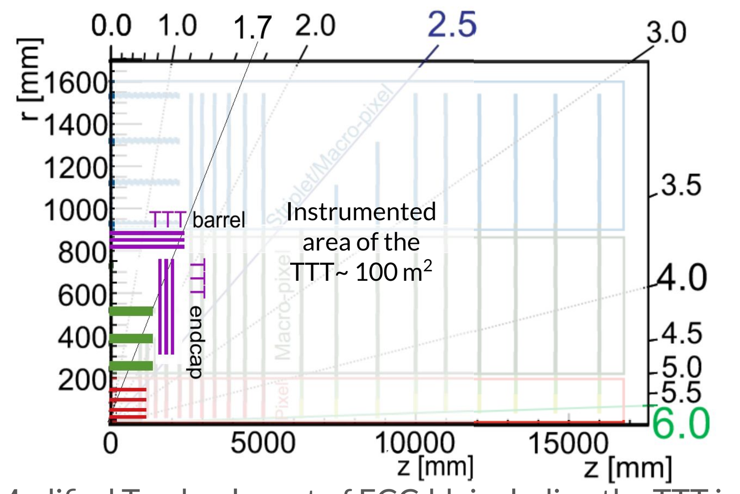
$$\kappa_{123} := \frac{1}{R_{123}} = \frac{2\,(\vec{r}_{23} \times \vec{r}_{12})_z}{|\vec{r}_{23}|\,|\vec{r}_{12}|\,|\vec{r}_{13}|}$$

- **Beamline constraint for precise track parameters**

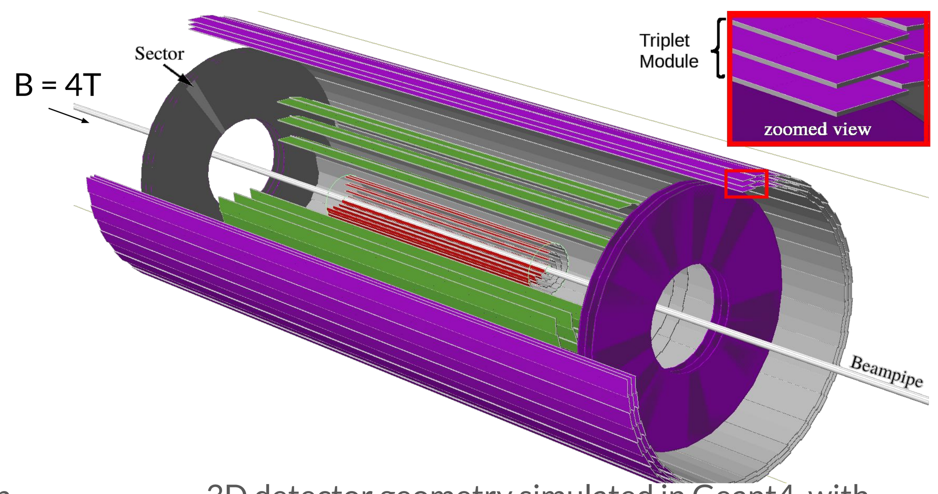
$$\kappa_{013} := \frac{1}{R_{013}} = \frac{2\,(\vec{r}_{13} \times \vec{r}_{01})_z}{|\vec{r}_{01}|\,|\vec{r}_{13}|\,|\vec{r}_{03}|}$$

- Simple track reconstruction algorithm that can be easily implemented in **hardware** (e.g. FPGAs, custom ASICs)
  1. The fast track candidate finding
  2. The curvature consistency check with two independent methods: $|\Delta\kappa| < n \cdot \sigma_\kappa$
  3. Track parameter calculation and Final Cuts

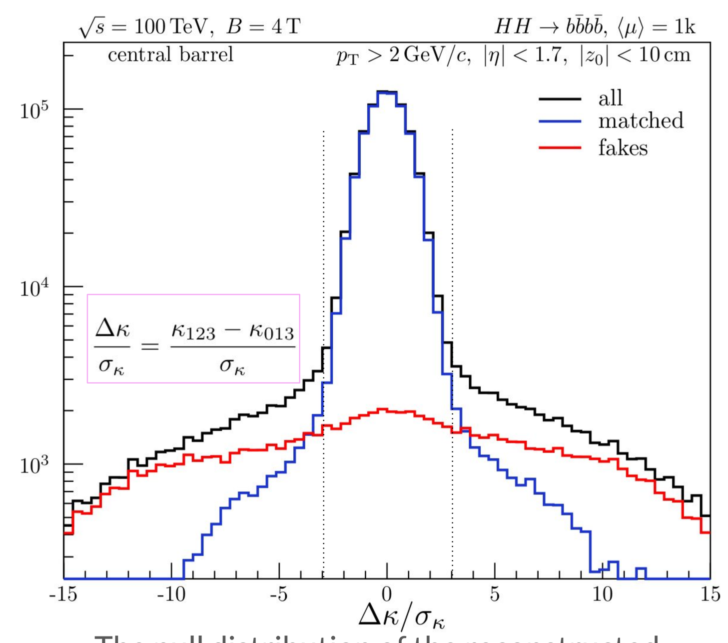
A full Geant4 based simulation of the TTT and the inner pixel layers (as dead silicon layers) has been performed using HH→4b as a showcase.



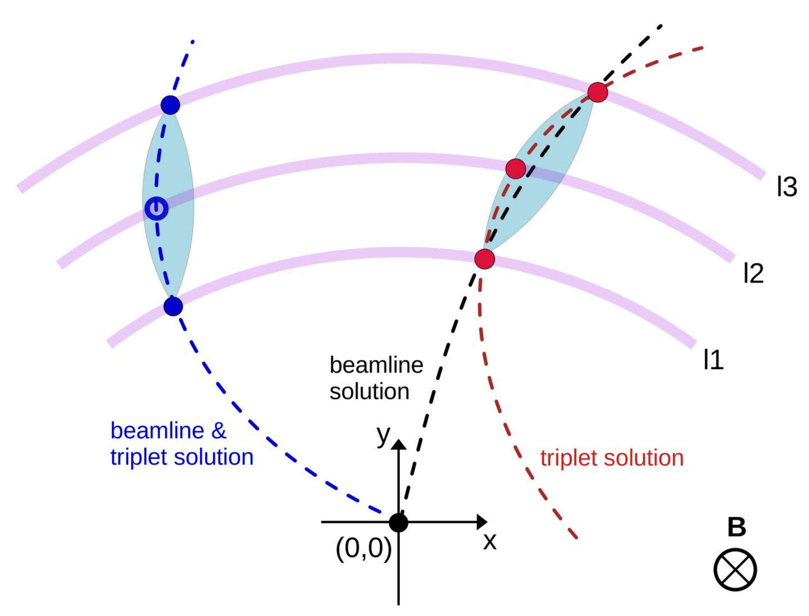
Modified Tracker layout of FCC-hh including the TTT in the barrel and endcap regions covering |η| ≤ 2.5 [6]



3D detector geometry simulated in Geant4, with TTT layers in violet [6]



The pull distribution of the reconstructed curvature for all, matched and fake tracks [6]



Track reconstruction concept in the transverse plane [6]

Tracking Performance:

The TTT tracking performance is evaluated based on the **reconstruction efficiency, purity and the p_T, and z_0 resolution of the TTT tracks.**

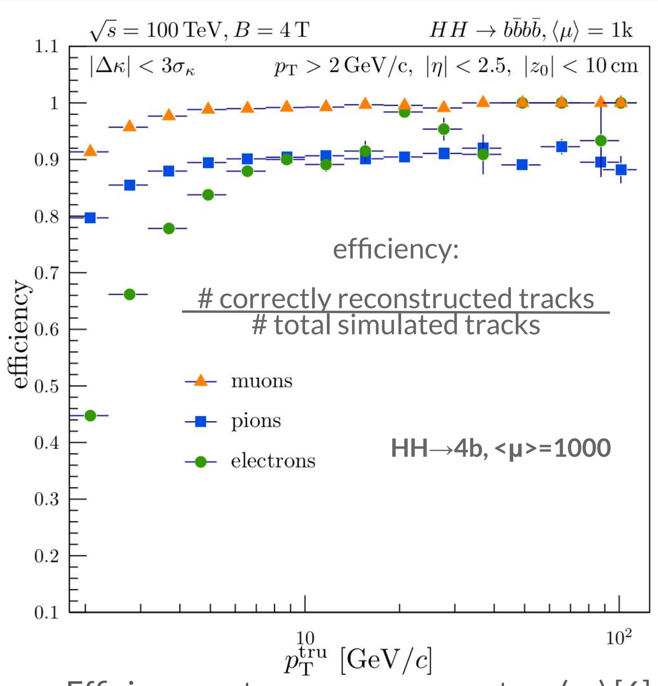
- The reconstruction efficiency for **pions and muons** in the **HH→4b** events with **<μ>=1000** is found to be **~85–90%** and **~100%**, respectively.
- A track **purity of >92%** is obtained using the TTT
- The relative transverse **momentum resolution is better than 6–10%** and **sub-mm z_0** resolution is obtained for a wide p_T range.

Trigger Performance:

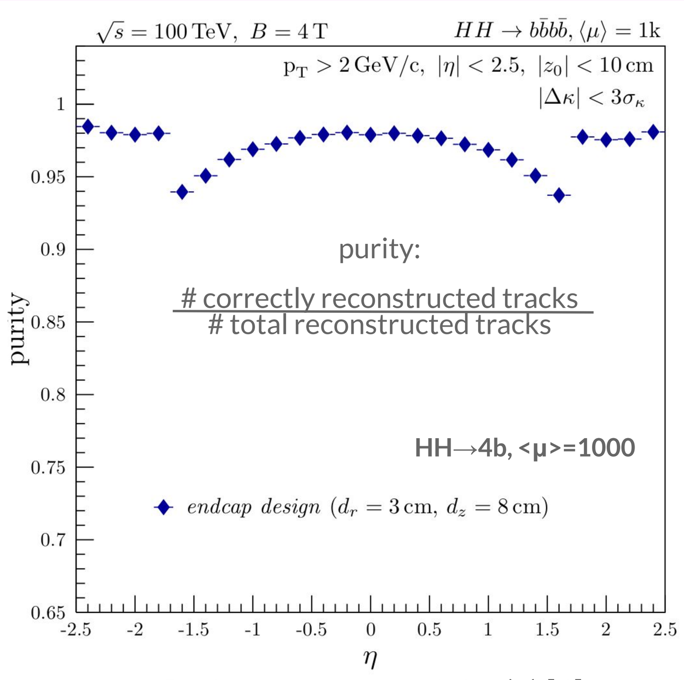
Goal: maximum suppression of pileup (minimum bias events), while keeping high signal efficiency for HH→4b events used as a showcase.

- The luminous region $|z_0|$ < 10 cm is subdivided into 200 overlapping bins and **TTT track-jets** are simultaneously reconstructed in all bins using the **anti-kT jet clustering** algorithm.
- The bin with the highest sum of the jet momenta is then chosen as **hard interaction vertex bin.**
- The best discrimination power was found for the transverse momentum of the **third leading jet** and is used as the basis for the trigger decision.
- Assuming **4 MHz trigger rate** @40 MHz BX frequency, the **TTT** achieves a trigger efficiency of **69%** with a trigger threshold of **33 GeV/c** for **HH→4b events with <μ>=1000 events.**
- In comparison, a **calo-trigger** achieves an efficiency of only **37%** and a very high threshold of **750 GeV/c**
- **TTT** also has **a superior ability** to distinguish **HH→4b** events from the **pp→4b QCD** events.

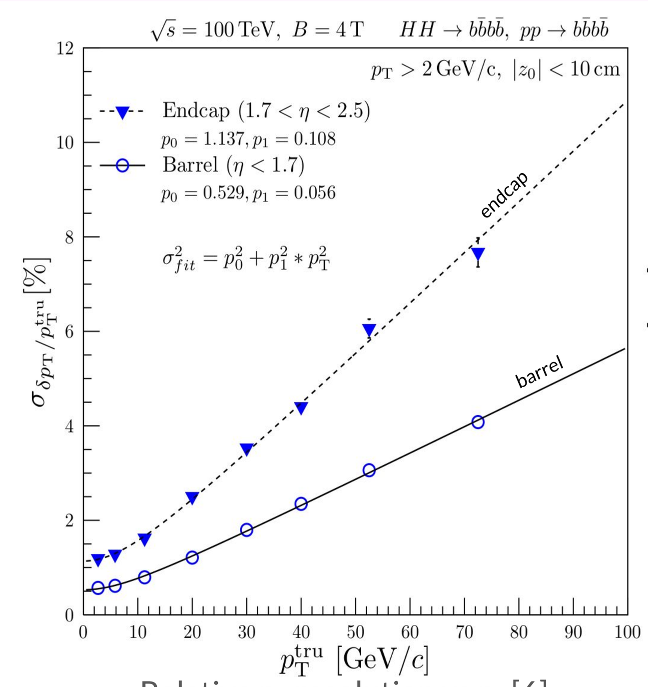
TTT Performance



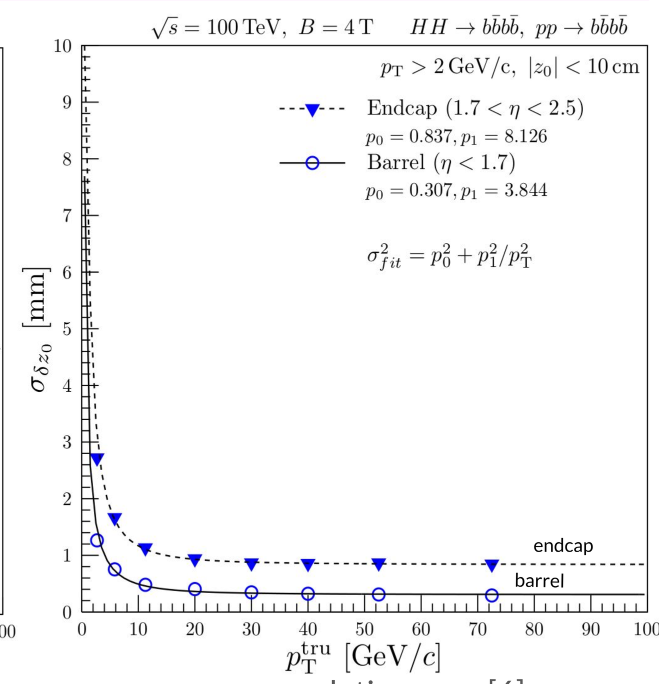
Efficiency vs transverse momentum (p_T) [6]



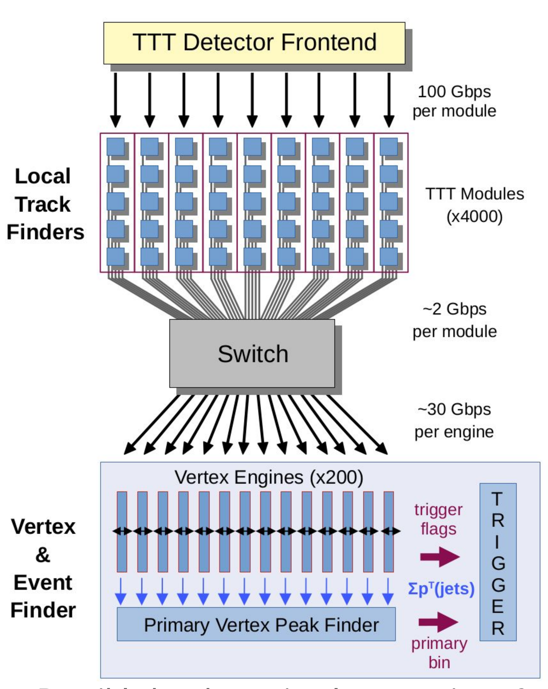
Purity vs pseudorapidity (η) [6]



Relative p_T resolution vs p_T [6]



z_0 resolution vs p_T [6]



Possible hardware implementation of the TTT algorithm [6]

Hardware Implementation

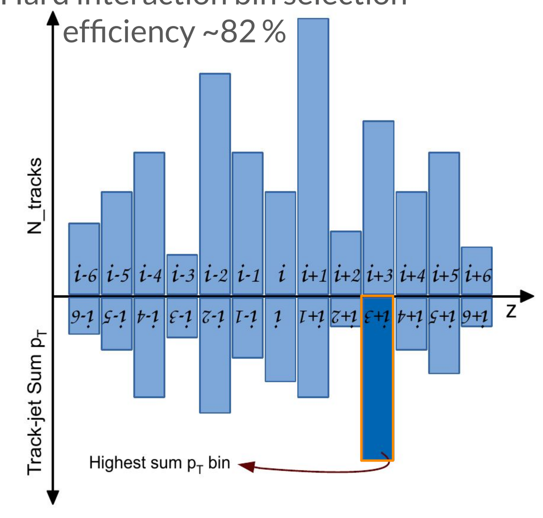
- **Highly parallel** implementation.
- **Local Track Finders** realised in an ASIC → track parameters.
- A **switch** acting as a z_0 selector distributes TTT tracks to vertex engines that run jet clustering.
- Trigger decision is based on the information from the **peak finder and vertex engines.**

Impact on HH → 4b signal measurement & further opportunities

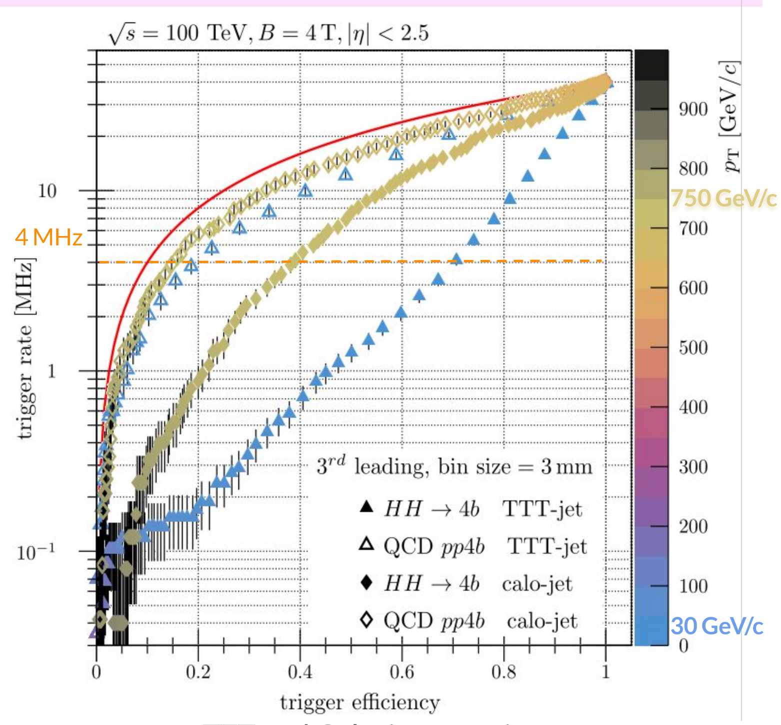
Considering only statistical uncertainties & the dominant pp→4b QCD background, the **expected cross section measurement precision for the HH→4b** channel using $\int\mathcal{L}\,dt$ = 30 ab⁻¹:

- **< 2% at FCC-hh with the TTT** compared to **~66% at HL-LHC**. Furthermore, the **low trigger threshold** would enhance the sensitivity to **λ**.

Other multi-jet Di-Higgs channels, e.g. HH→2b2γ, HH→2b2τ could also significantly benefit from the TTT.



Simplified sketch for primary hard interaction vertex identification [6]



TTT and Calorimeter trigger rate vs trigger efficiency [6]

References:

[1] A. K. Srivastava, "Development of Si Detectors for the CMS LHC Experiments", 2019. [2] I. Melo, "Higgs potential and fundamental physics", 2017. [3] B. D Mico, et al, "Higgs boson potential at colliders: Status and perspectives", 2020. [4] T. Kar, "A Triplet Track Trigger for Future High Rate Collider Experiments", PhD thesis, 2020. [5] A. Abada, et al. "FCC-hh: The Hadron Collider. *Eur. Phys. J. Spec. Top.* 228" CDR, 2019. [6] T. Kar, A. Schöning, "A Triplet Track Trigger for the FCC-hh to improve the measurement of Di-Higgs production and the Higgs self-coupling", 2024.