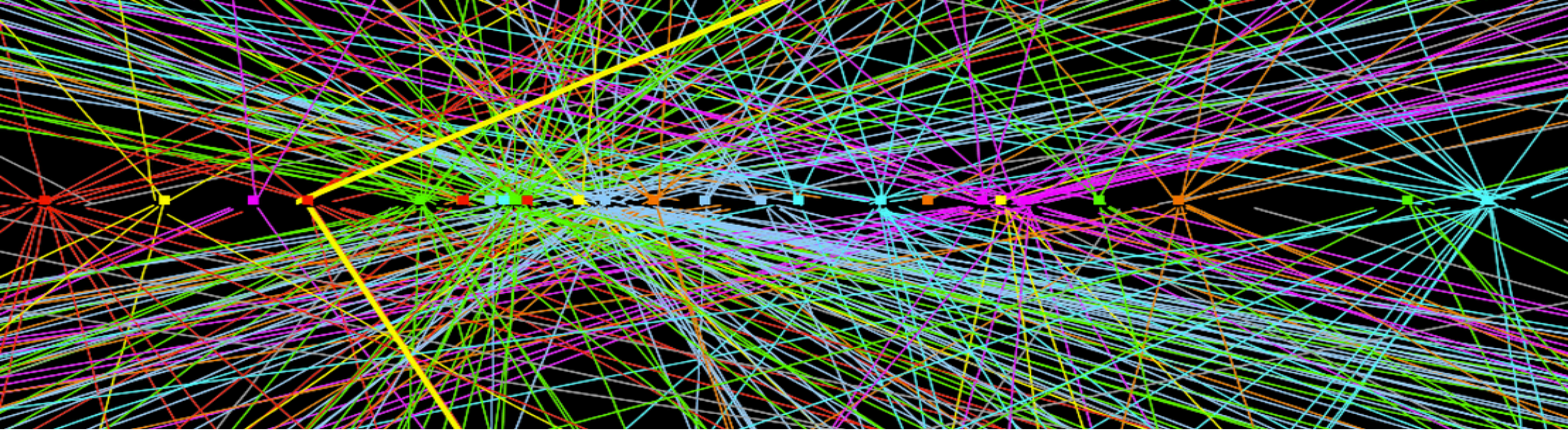
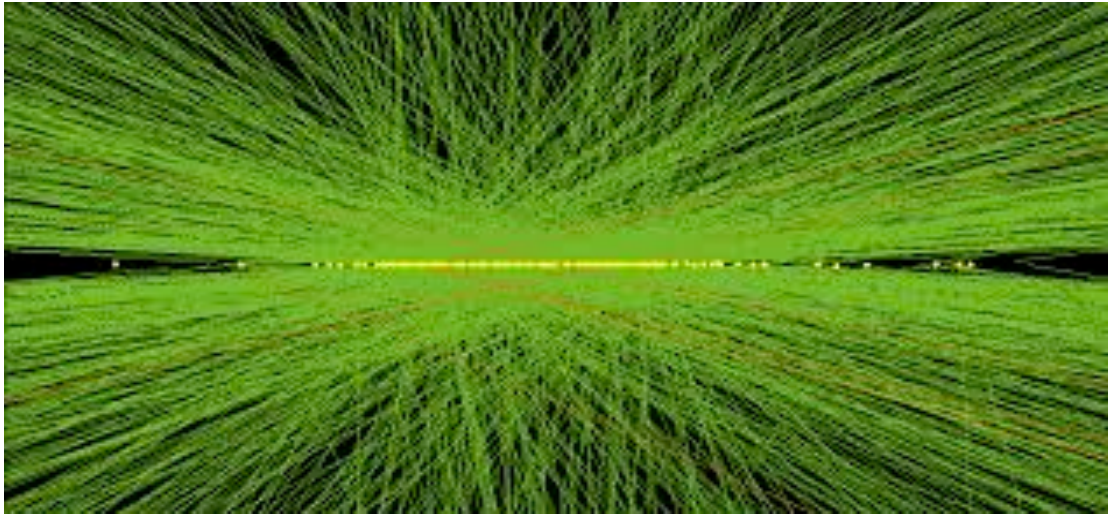


4D Tracking R&D

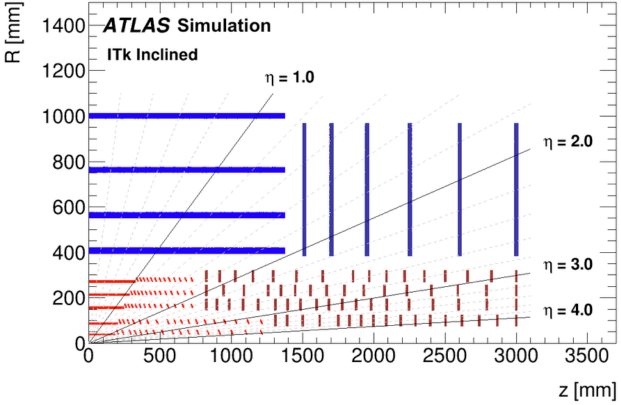
Ariel Schwartzman

23-Sep-2020

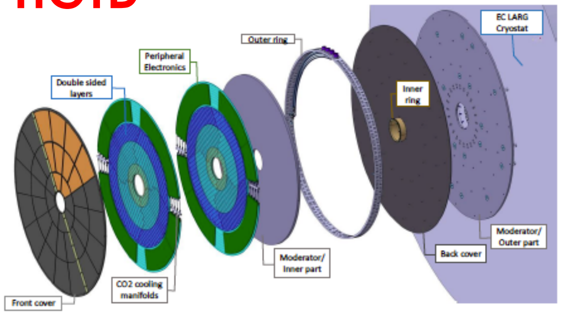
Introduction



ITk inner system

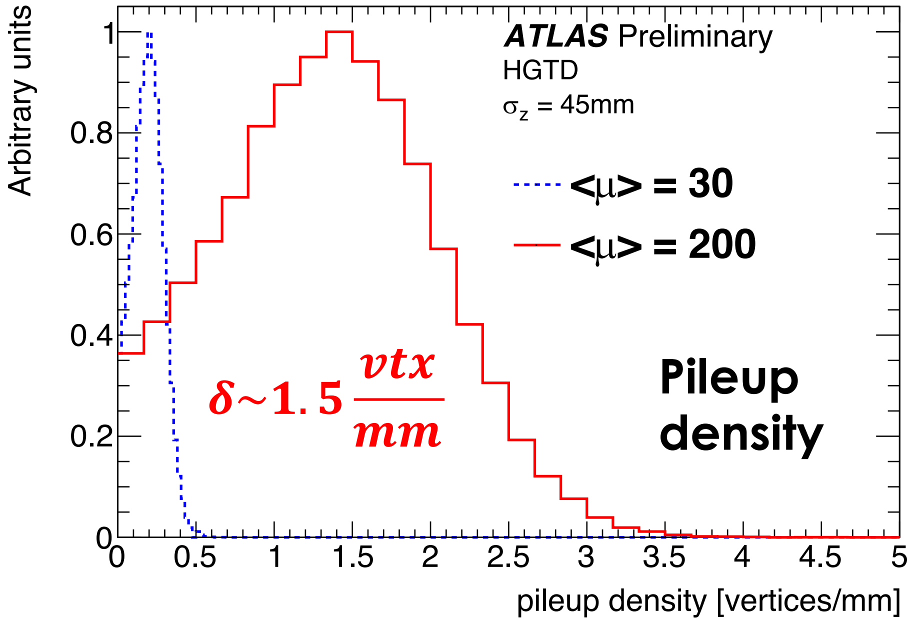


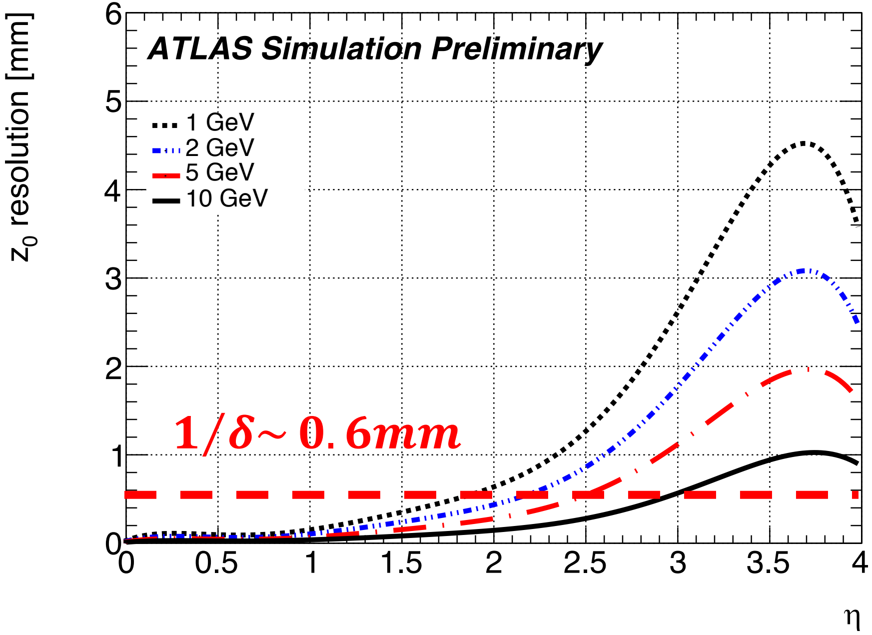
HGTD



- **High luminosity hadron colliders requires new type of detectors to cope with increased radiation level, data rates, and pileup**
  - HL-LHC: Timing layers
  - Future colliders / LS4 HL-LHC upgrade: Integrated space-time (4D) tracking detectors

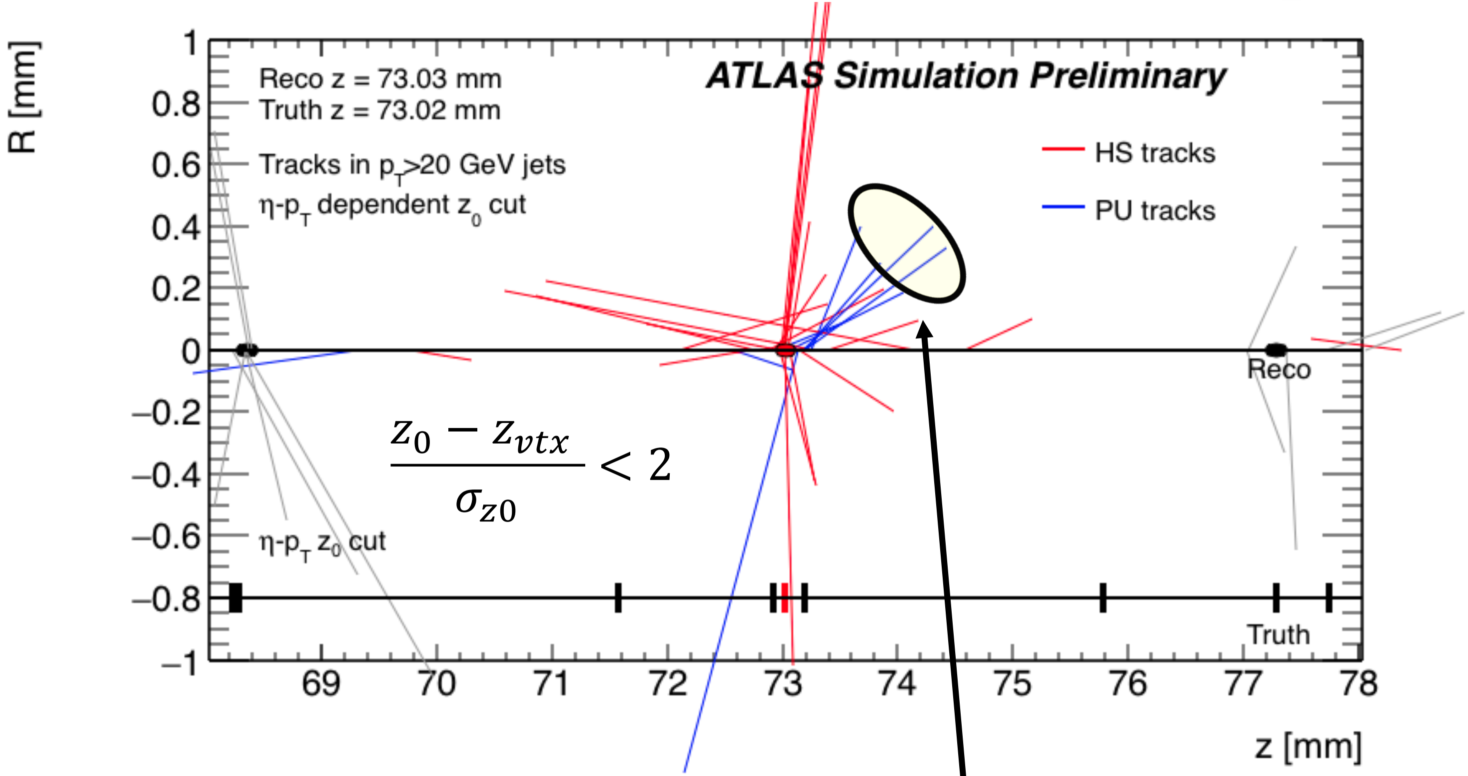
The Pileup Challenge





- Pileup vertex density >~ longitudinal impact parameter resolution
  - **The association of tracks to vertices becomes ambiguous**

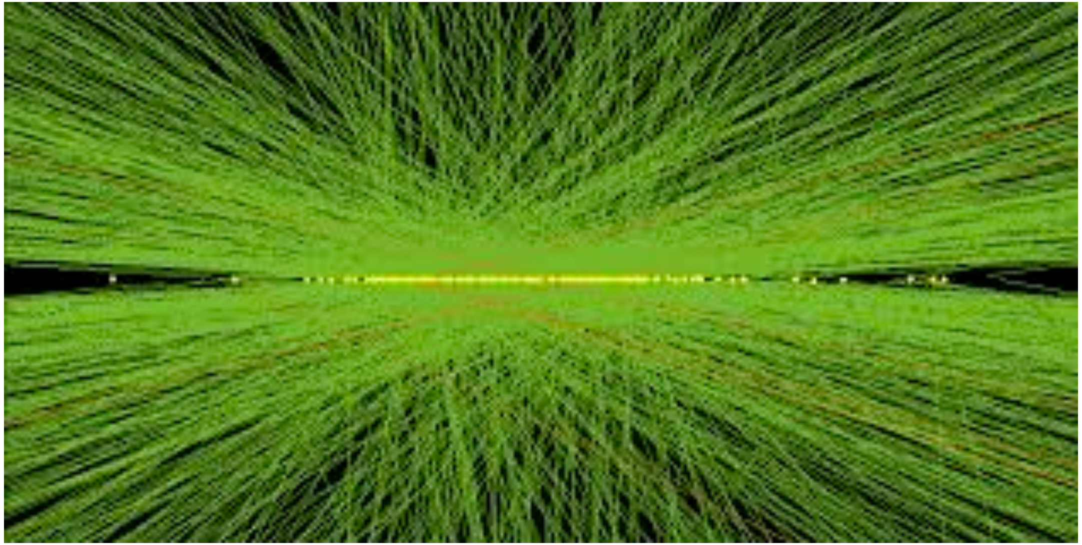
The ITk Challenge

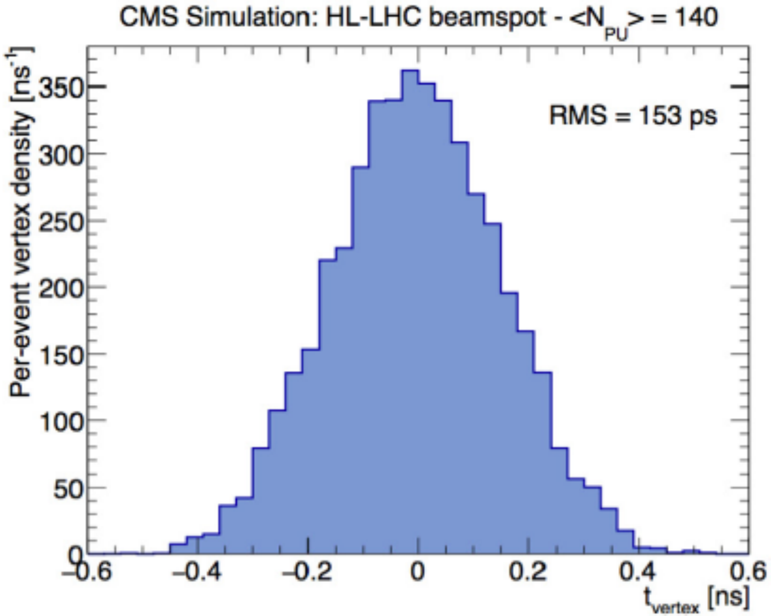


$$\frac{z_0 - z_{vtx}}{\sigma_{z0}} < 2$$

Pile-up jet misidentified as hard-scatter jet when using only using (x,y,z) tracking

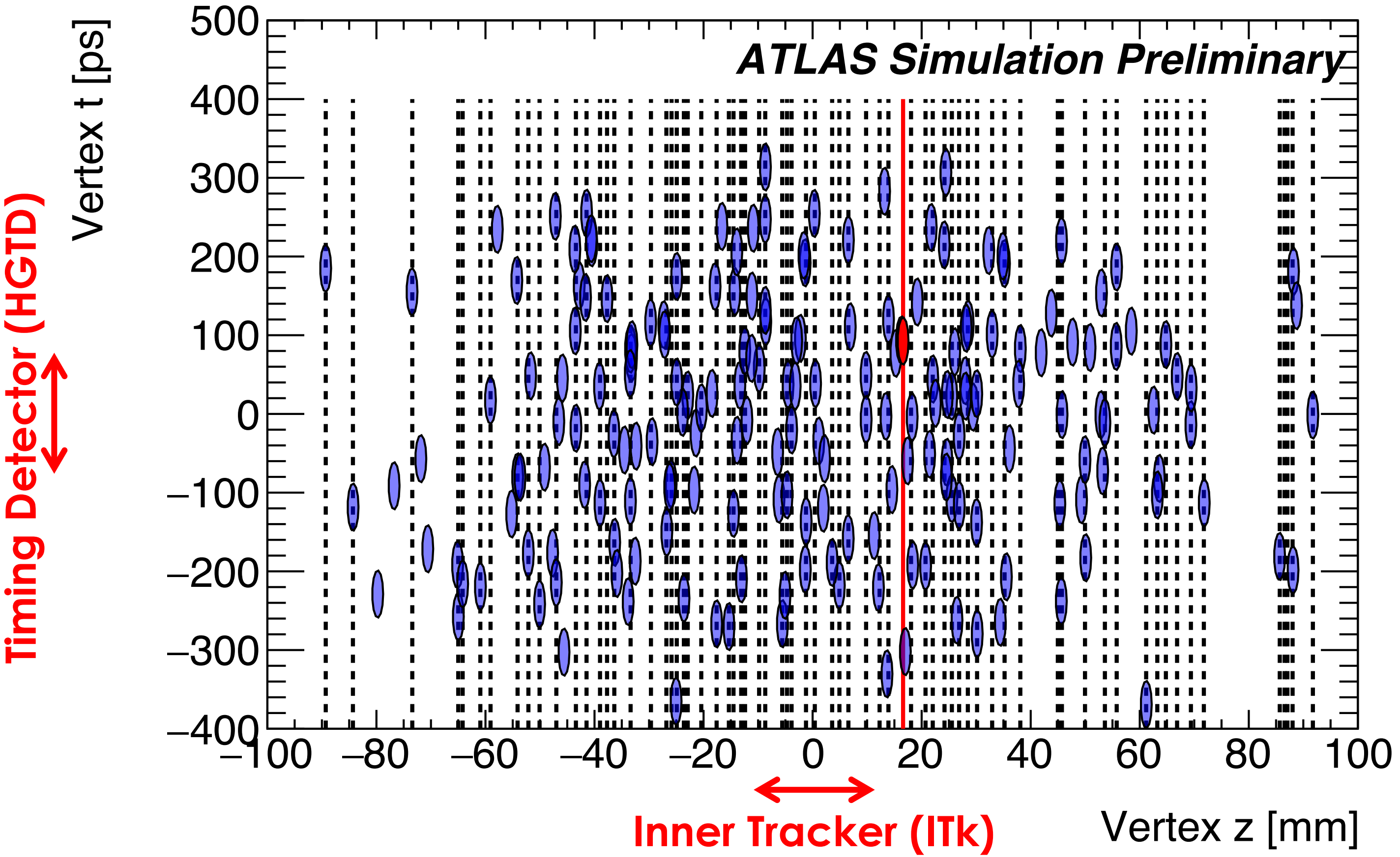
Why timing?



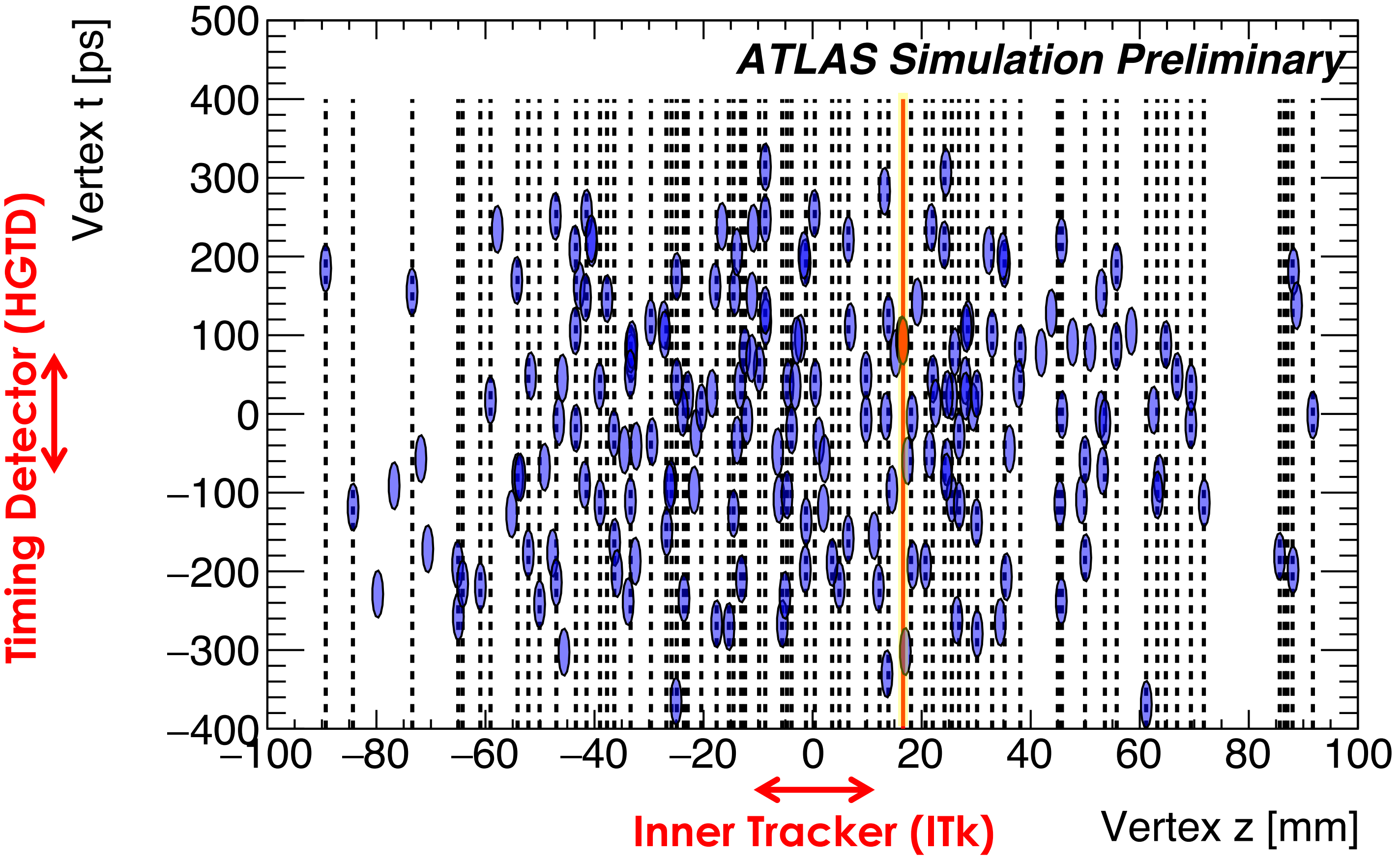


Nominal HL-LHC Luminous region σ_t = 180ps

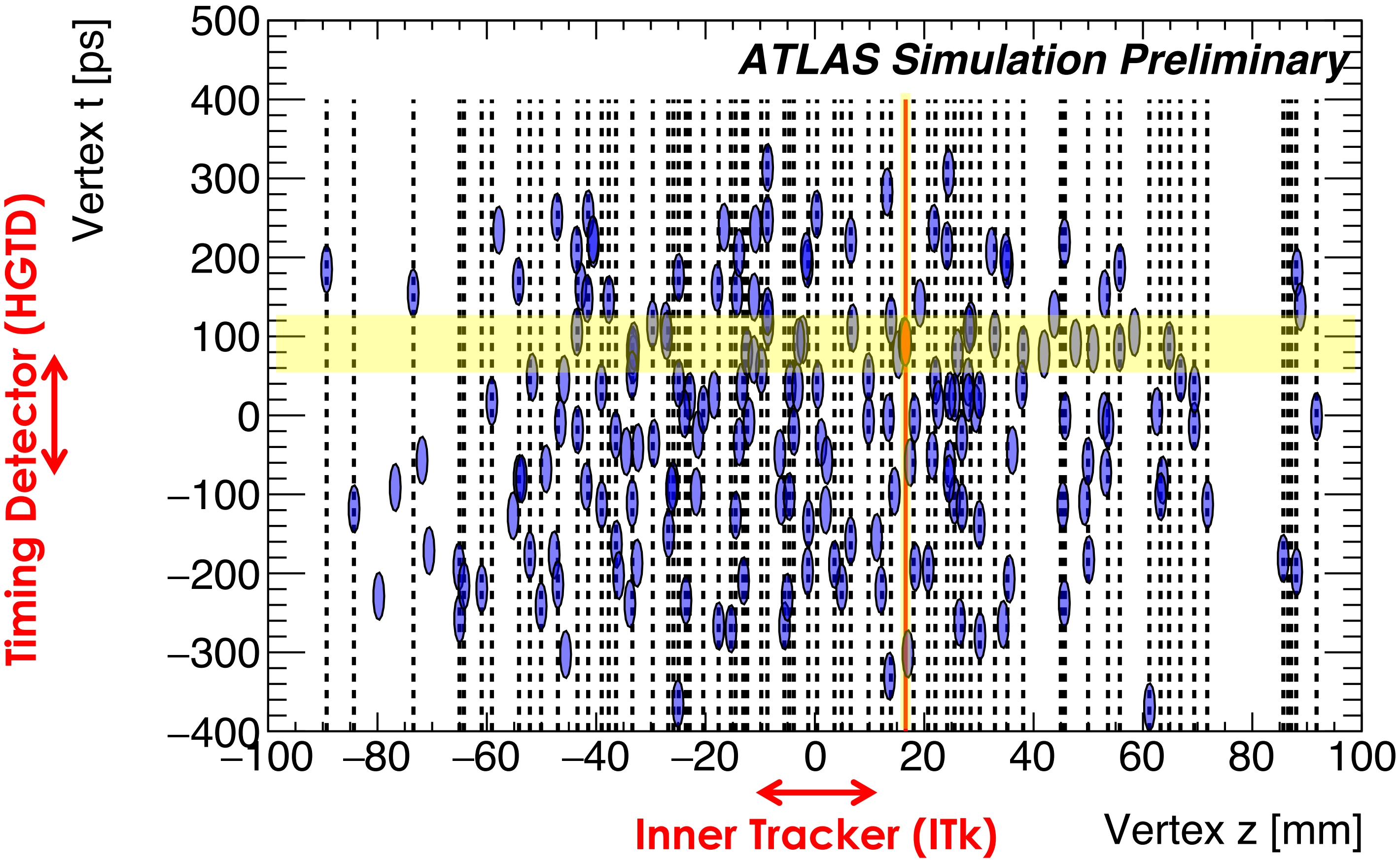
HGTD(30ps) → 30/180 = **6x pile-up rejection**



Exploit the time spread of collisions to reduce pileup contamination

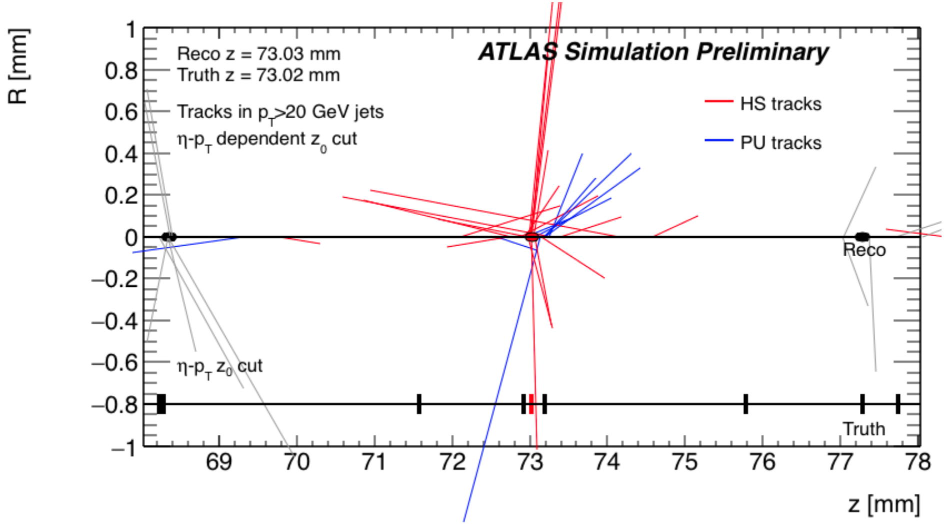


Exploit the time spread of collisions to reduce pileup contamination

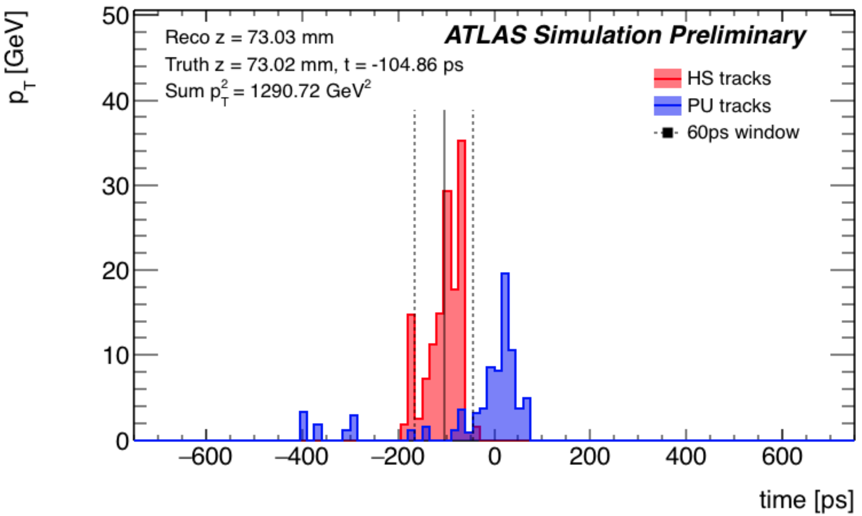


Exploit the time spread of collisions to reduce pileup contamination

Why timing?

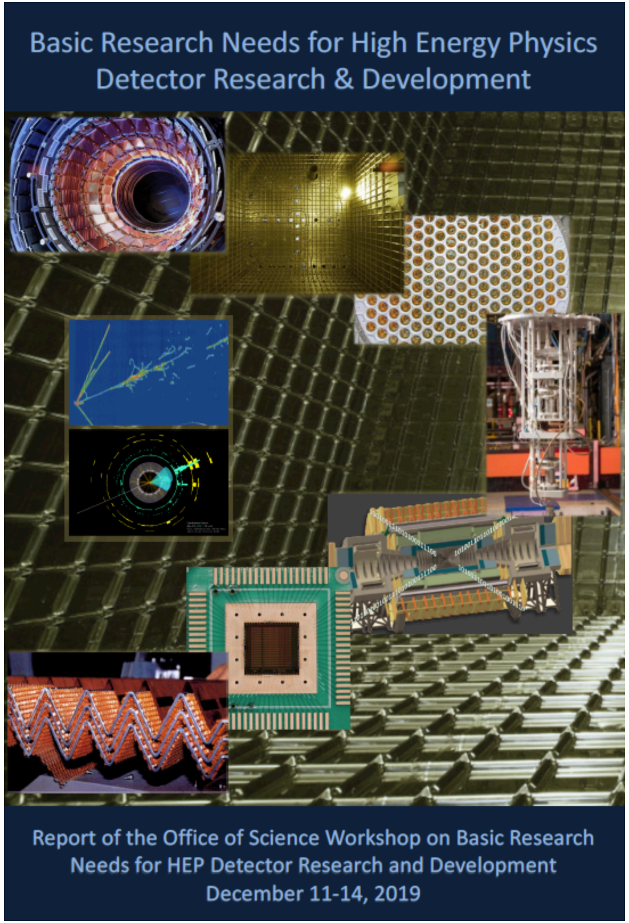


$$\frac{z_0 - z_{vtx}}{\sigma_{z0}} < 2$$



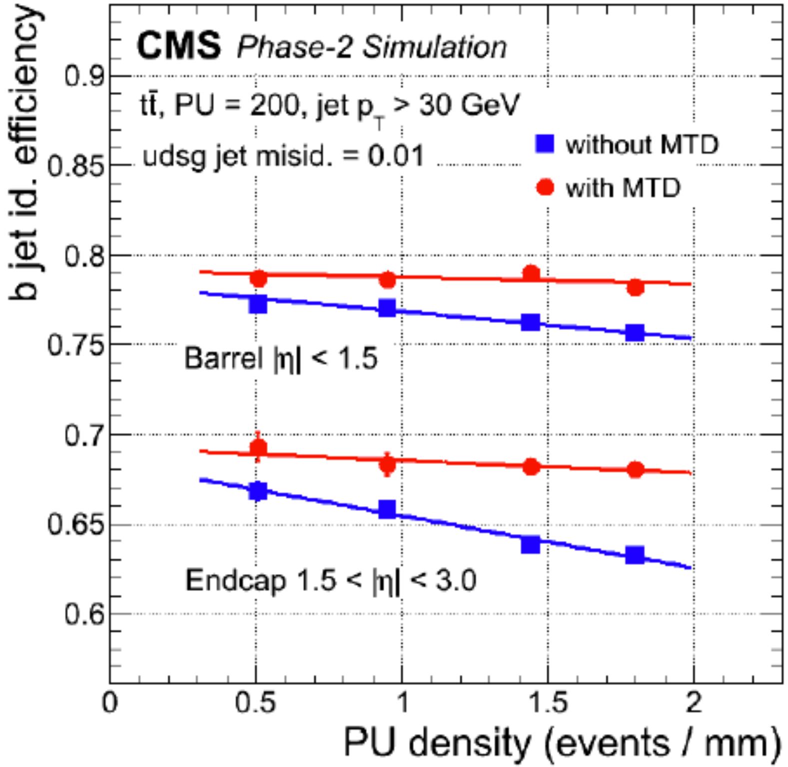
$$\frac{t_0 - t_{vtx}}{\sigma_{t0}} < 2$$

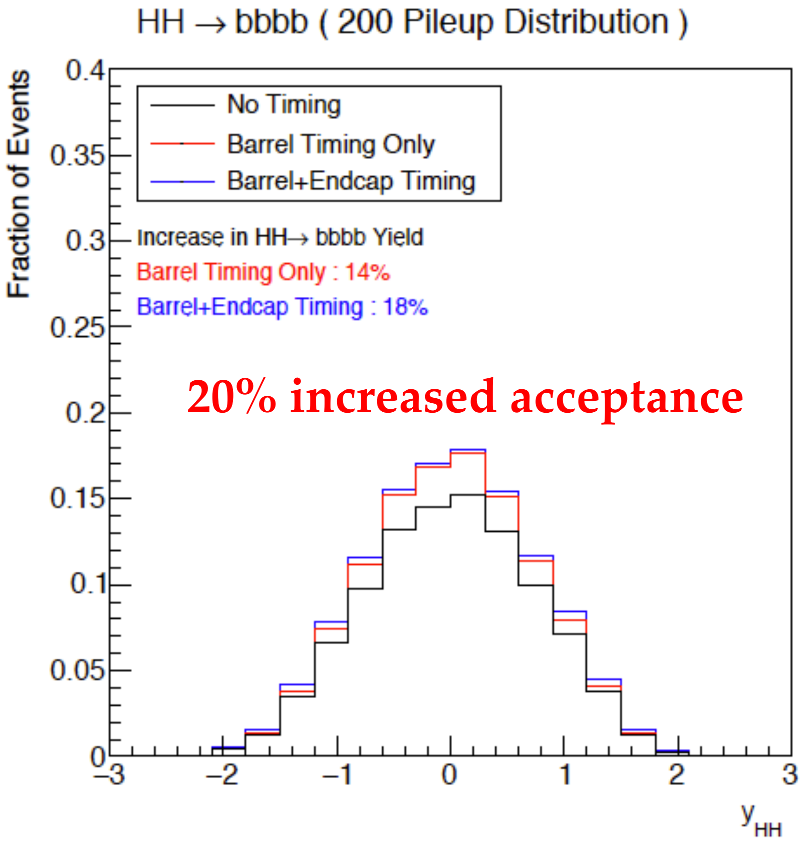
HGTD can resolve pileup from hard-scatter tracks that are within the ITk z_0 resolution



PRD	Thrust
PRD 18: Develop high spatial resolution pixel detectors with precise per-pixel time resolution to resolve individual interactions in high-collision-density environments	Thrust 1: Lepton colliders, requiring timing on the order of 10 ps; pixel pitch on the order of 10 microns Thrust 2: Hadron colliders, requiring timing resolution down to 1 ps to achieve HL-LHC-like pileup, in a high radiation environment (up to fluences in the order of $10^{18} n_{eq}/cm^2$)

Physics impact





ToF Particle ID

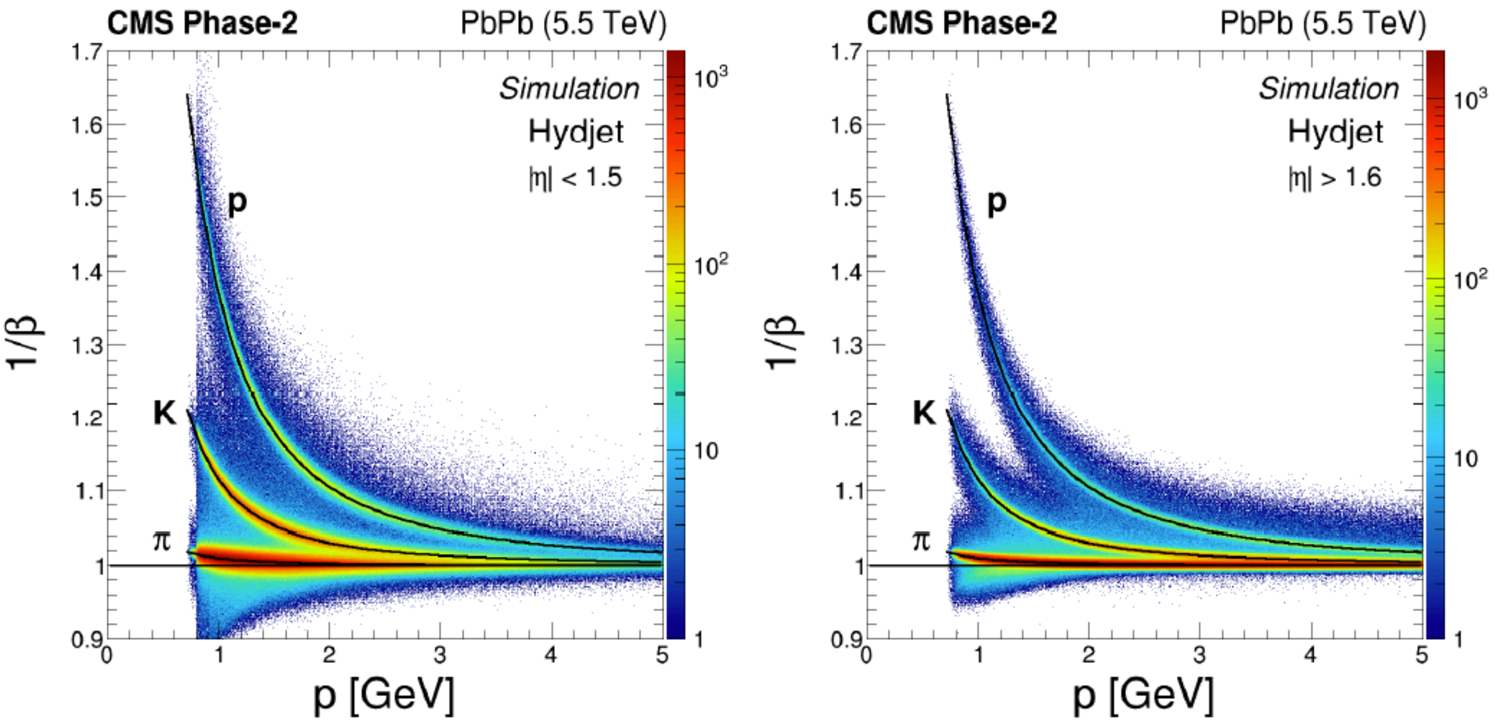


Figure 5.23: The inverse velocity ($1/\beta$) as a function of the particle momentum, p, for BTL ($|\eta| < 1.5$) and ETL ($|\eta| > 1.6$) in HYDJET PbPb simulation at 5.5 TeV.

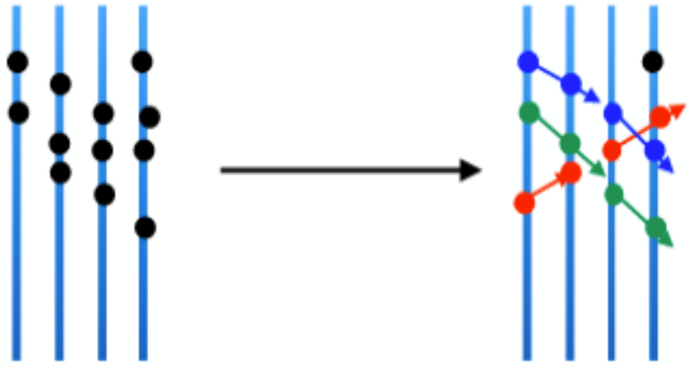
4D Tracking

Add new timing dimension to ITk pixels to address the pileup challenge and enable new reconstruction capabilities

Use pixel hit time in track pattern recognition:

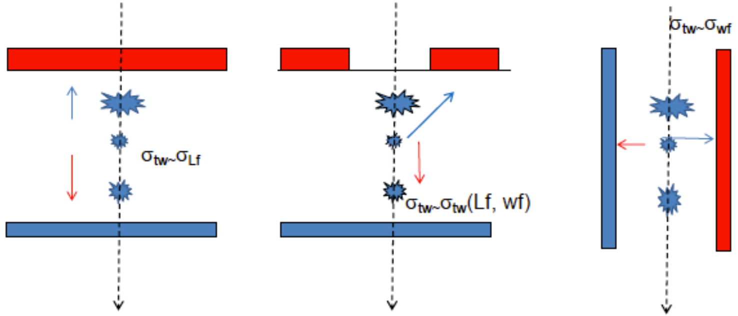
- Reduce combinatorics
  - Improve efficiency and purity
- Speed up tracking reconstruction

4D Vertexing



There are plans to incorporate 4D tracking/vertexing capability in **ACTS**

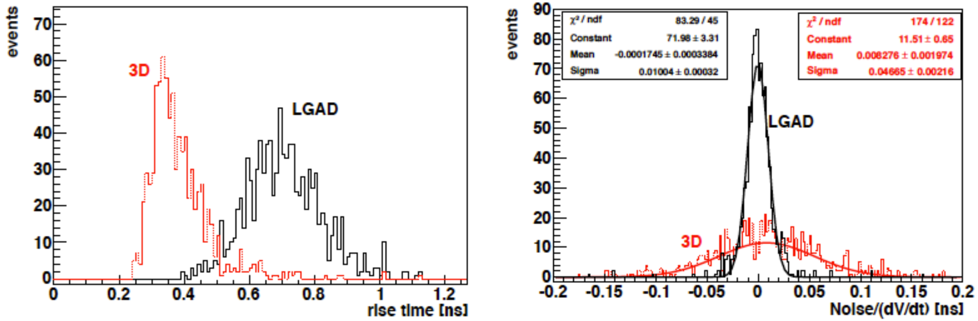
50x50μm 3D pixels



Timing performance of small cell 3D silicon detectors ⋆

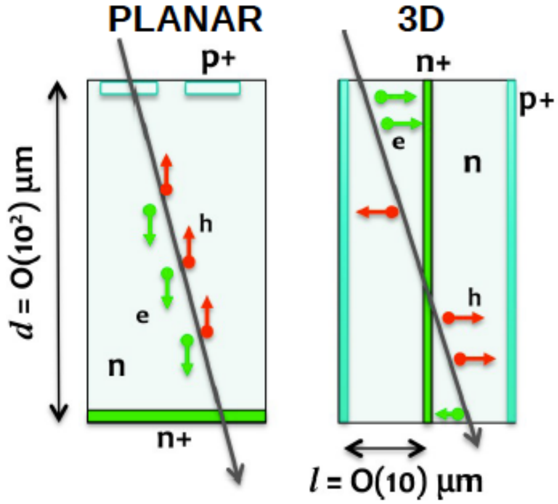
G. Kramberger[a], V. Cindro[a], D. Flores[b], S. Hidalgo[b], B. Hiti[a], M. Manna[b], I. Mandić[a], M. Mikuž[a,c], D. Quirion[b], G. Pellegrini[b], M. Zavrtanik[a]

[a] *Jožef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia*
[b] *Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona 08193, Spain*
[c] *University of Ljubljana, Faculty of Mathematics and Physics, Jadranska 19, SI-1000 Ljubljana, Slovenia*



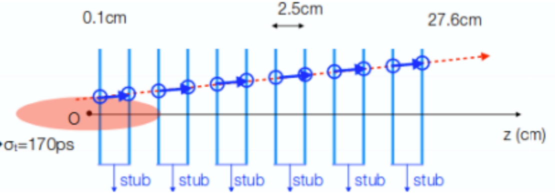
(a) (b)

Fig. 9. (a) Comparison of the rise time in LGAD and 3D detector and (b) measured jitter - σ_j.



Algorithm simulation

Sensor area = 6x6cm²
pixel size = 55x55μm²
thickness = 200 μm
time res σ_t=30 ps



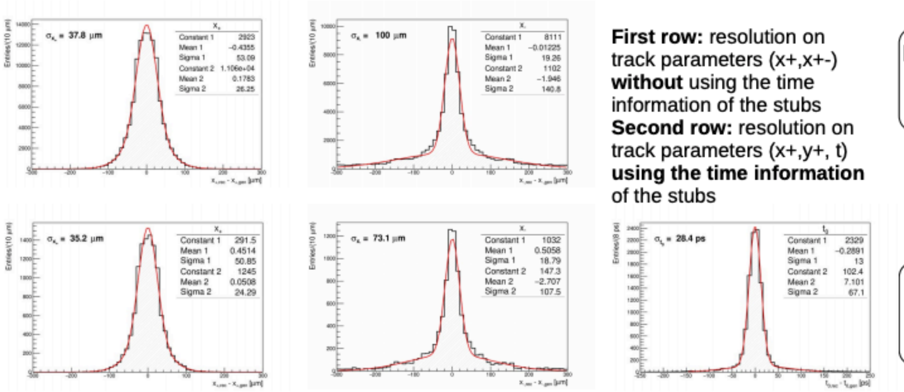
- **LHCb VELO-like detector:**
  - 12 planes in the forward region
  - pile-up ~40
  - ~1200 tracks/event

- **Luminous region:** σ_z=5cm, σ_t=167ps . **90'000 engines** in [-2,2]x[-2,2]cm² reference plane

$\sigma_{x+/y+}$= 37.8 μm
$\sigma_{x-/y-}$= 100.0 μm

Time

$\sigma_{x+/y+}$= 35.2 μm
$\sigma_{x-/y-}$= 73.1 μm
σ_t = 28.4 ps



First row: resolution on track parameters (x+,x+-) **without** using the time information of the stubs
Second row: resolution on track parameters (x+,y+, t) **using the time information** of the stubs

Efficiency = 99%
Purity = 64%

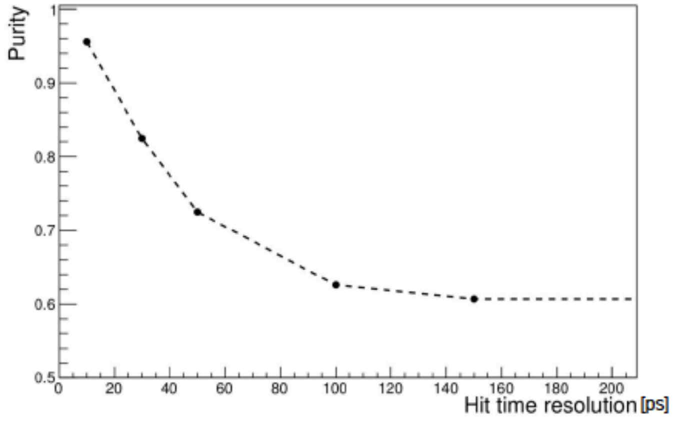
Time

Efficiency= 99%
Purity = 85%

- The **track parameters resolution improves** when including the time information
- The reconstruction **efficiency is stable**
- The tracks **purity improves**

https://indico.cern.ch/event/831165/contributions/3717101/attachments/2023879/3384913/CDT2020_Petruzzo.pdf

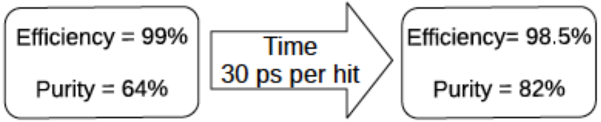
Timing benefits

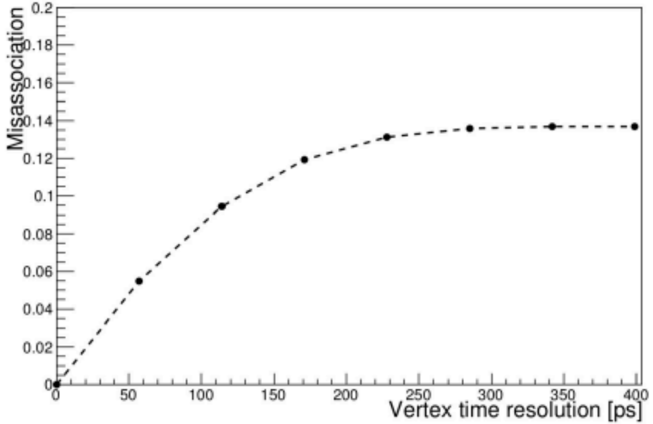


- Inclusion of timing information of the hits allows to evaluate the **time of the track**, to be used to better associate tracks to their primary interaction

- **Track mis-association** >10% (no time information)
- **<1% using precise time** information of the hit in offline reconstruction

- The **track parameters resolution improves** when including the time information
- The reconstruction **efficiency is stable**
- The tracks **purity improves**





4D Tracking R&D @ SLAC

https://www.snowmass21.org/docs/files/summaries/IF/SNOWMASS21-IF3_IF7-131.pdf

Sensors

3D, AC-LGADs, MAPS

Electronics

Smaller sensors, low power, more channels, extremely high radiation environment

Simulation and physics performance

Add timing information to pixel hits
Clustering – Layout studies

- Pixel size and general layout
- Cluster reconstruction in 4D

Track seeding
4D Kalman Filter within ACTS
4D Vertexing

b-tagging
Di-Higgs
Forward PU suppression
Strange-quark jet tagging with ToF

Layout

How to best combine spatial with timing information, optimizing material budget, power, time resolution, radial and eta coverage, …

- Mixture of layers with different balance of spatial and timing resolution for overall 4D tracking for a wide range of applications

12:00 → 12:20 **Introduction** 20m

Speakers: Ariel Schwartzman (SLAC), Caterina Vernieri (SLAC), Dong Su (SLAC)

4-Dimensional track...

12:20 → 12:40 **Sensors** 20m

- 3D silicon sensors
- AC-Coupled Silicon Detectors

Speaker: Christopher Kenney (SLAC)

12:40 → 13:00 **Electronics** 20m

Speaker: Dr Angelo Dragone (SLAC)

13:00 → 13:20 **Layout and simulation** 20m

Speaker: Valentina Cairo (SLAC)

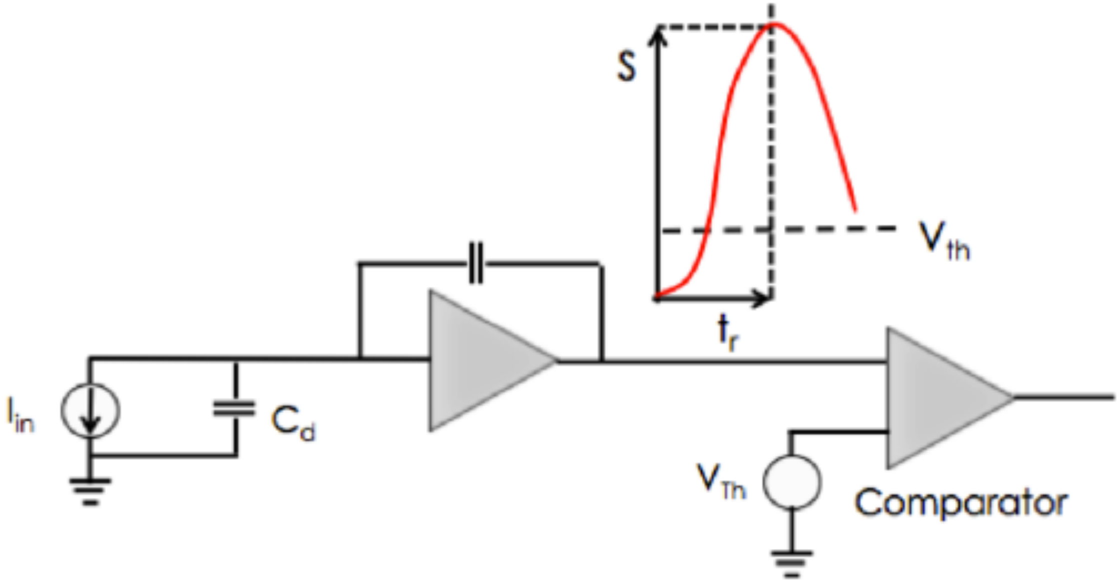
13:20 → 13:40 **Physics performance** 20m

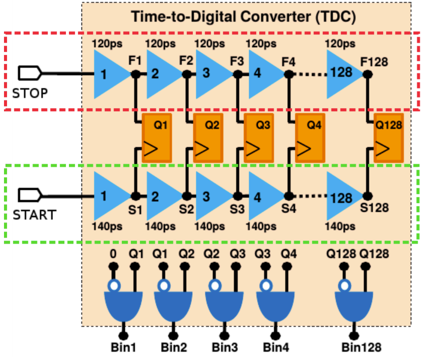
- track reconstruction and performance
- vertexing
- b-tagging
- Long-lived particles
- ToF reconstruction and strange-tagging

Speakers: Caterina Vernieri (SLAC), Valentina Cairo (SLAC)

Backup

Time tagging detectors





Sensor

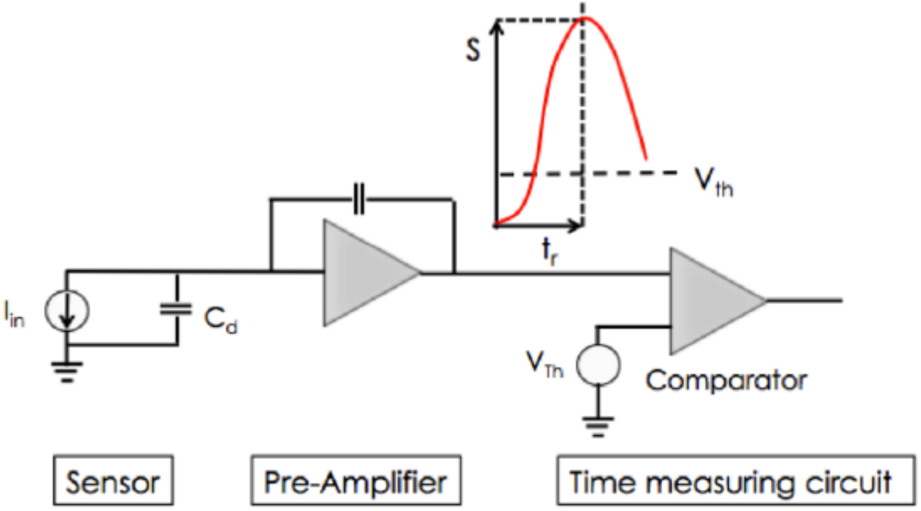
Pre-Amplifier

Time measuring circuit

TDC

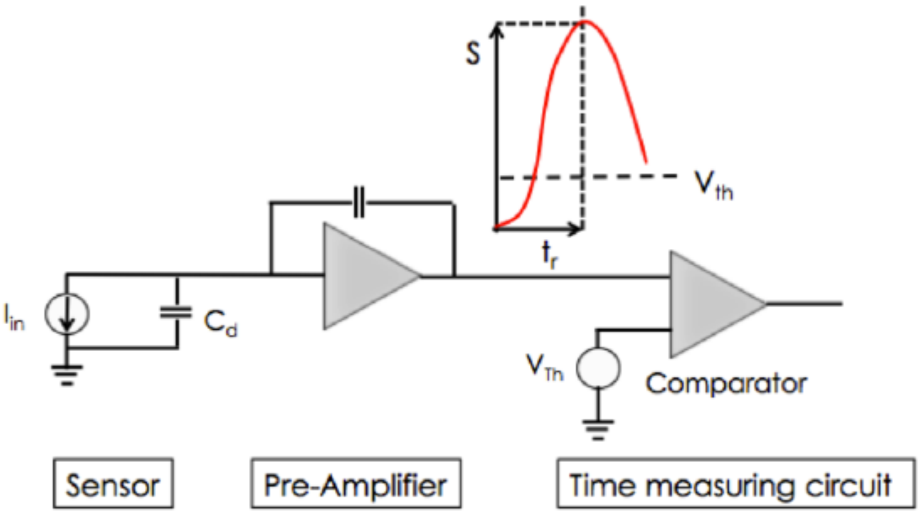
Time tagging detectors

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{time-walk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$



Time tagging detectors

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{time-walk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$



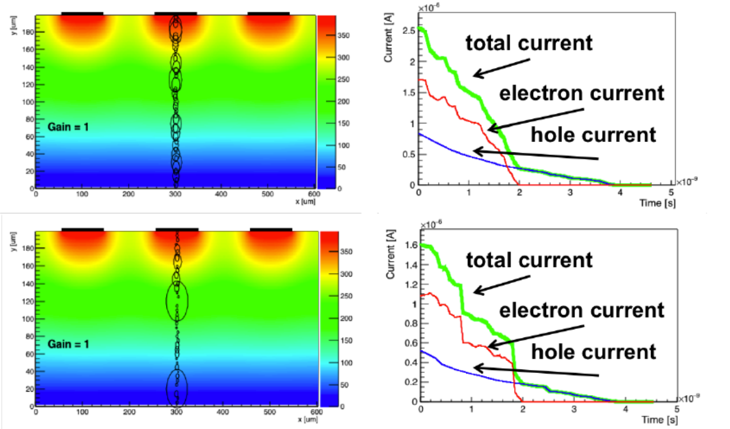
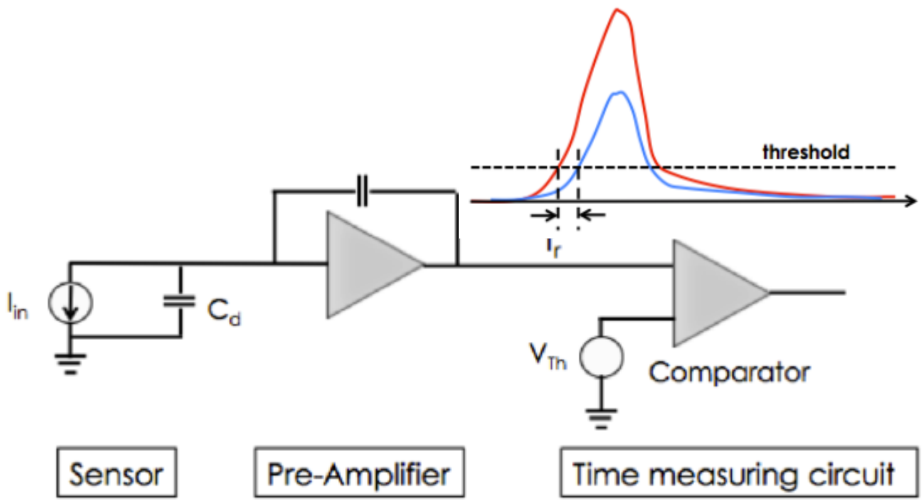


Figure 2. Energy deposits in a silicon detectors and the corresponding current signals. The differences in charge depositions generate current signals that differs significantly on an event-by-event basis. These differences results in a contribution to the overall time resolution that can be the dominant factor.

Fluctuations on the local density of e-h pairs (non-uniform charge deposition)
Physics limit to precision timing with silicon detectors (LGAD, 3D, …)

Time tagging detectors

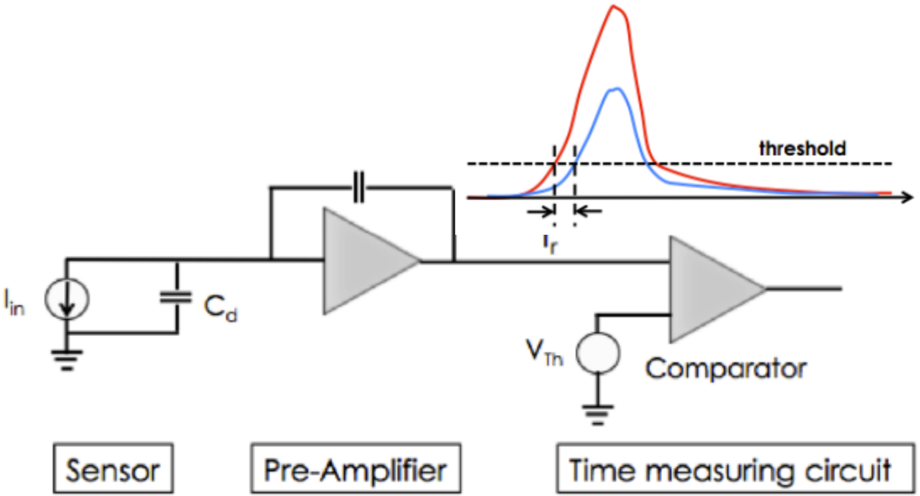
$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{time-walk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$

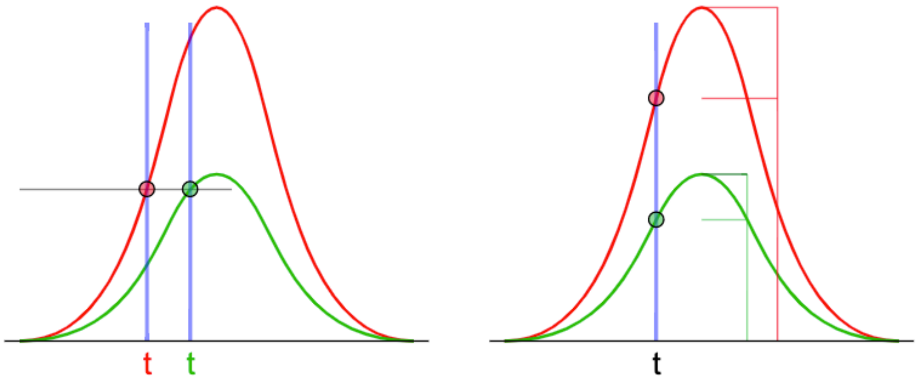


Larger signals cross the discriminant threshold earlier than smaller ones

Time tagging detectors

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{time-walk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$

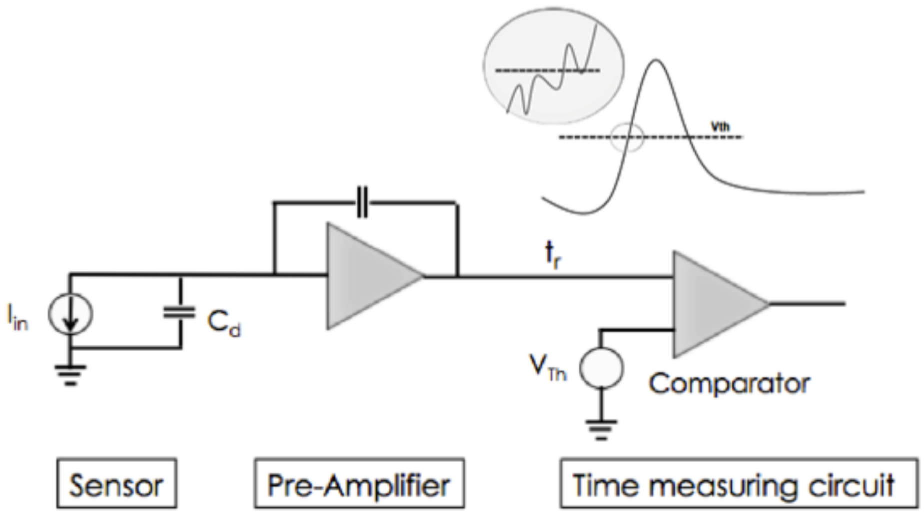




- Constant Fraction Discriminator
- ToT (ATLAS HGTD)
- Multiple Sampling (fit)

Time tagging detectors

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{time-walk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$



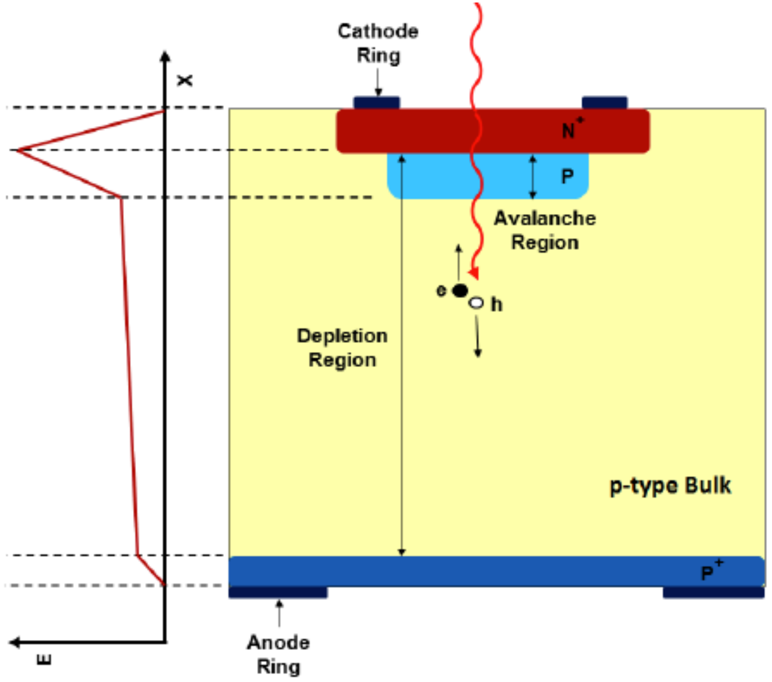
$$\sigma_j = \frac{N}{\frac{dV}{dt}} \propto \frac{t_{rise}}{S/N}$$

Key to precision timing: **Large signal with short rise time and low noise**

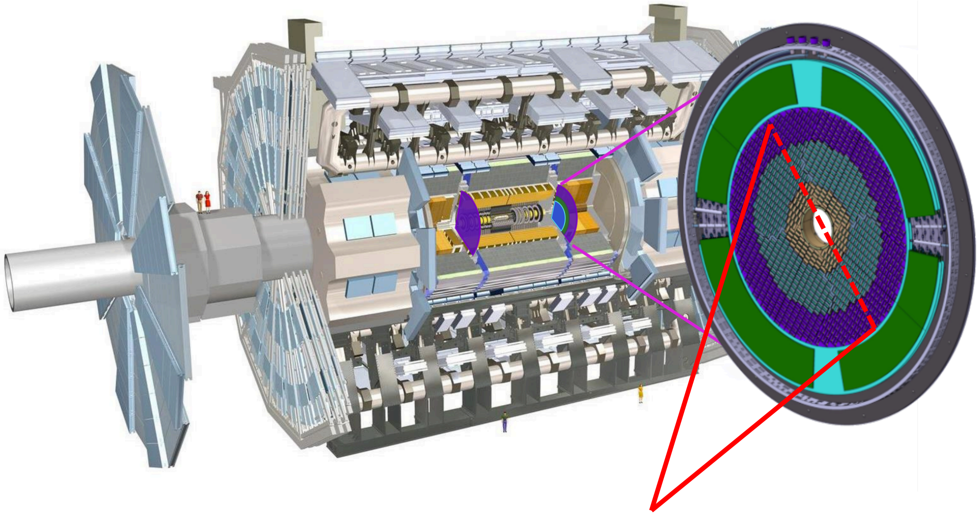
LGAD Silicon Sensors

n-on-p silicon detector with gain from additional highly doped p-layer

- Thin: small t_{rise}
- *Not too thin (low C)*
- Moderate gain: increase signal, limit noise, low power
- *~50µm, Gain~20 seems optimal*
- Radiation hard



ATLAS HGTD



Pseudorapidity coverage: *2.4<|η|<4.0*

Radial extension: *12* cm < R < *64* cm

z position: *3.5* m

Thickness in z: 7.5cm

2 double, 3-ring, planar layers per endcap

Pixel detector with coarse spatial resolution but precision timing

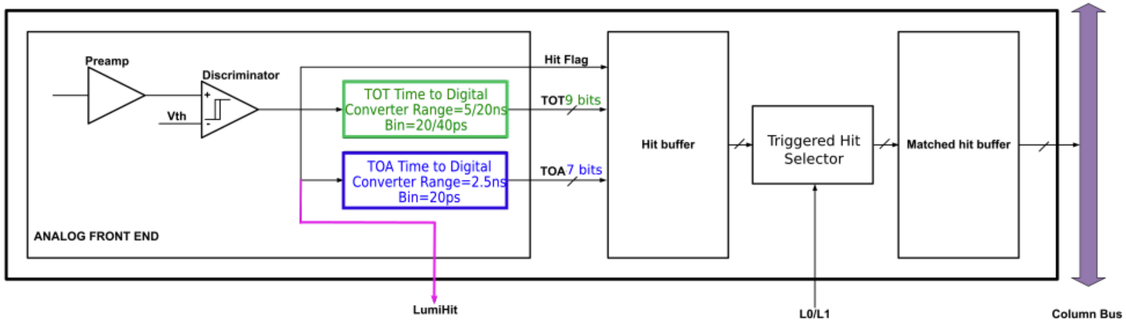
LGAD Si sensors:

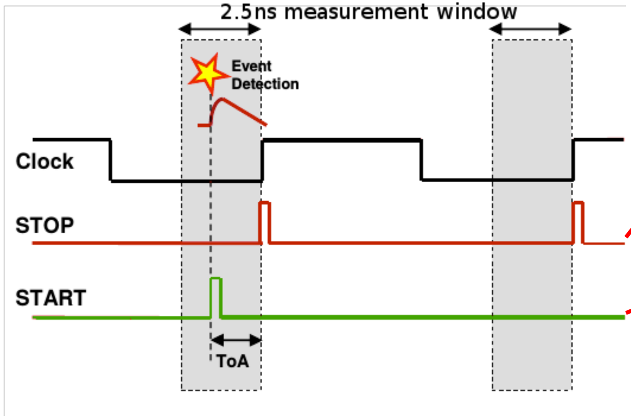
- pad size: 1.3 x 1.3 mm^2
- 3.6M channels
- 6.4 m^2

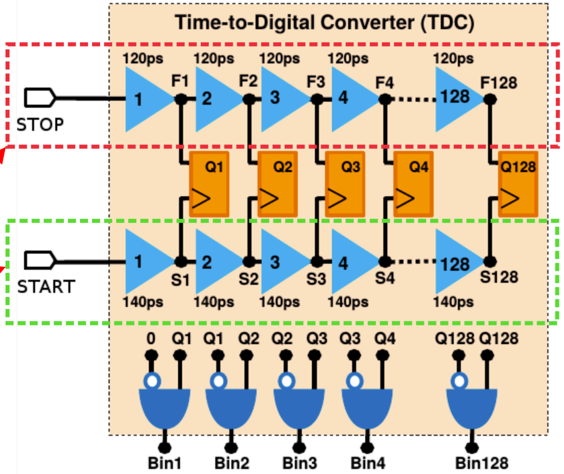
Target time resolution:

- 35-70 ps/hit up to 4000 fb-1
- 30-50 ps/track

TDC (SLAC)



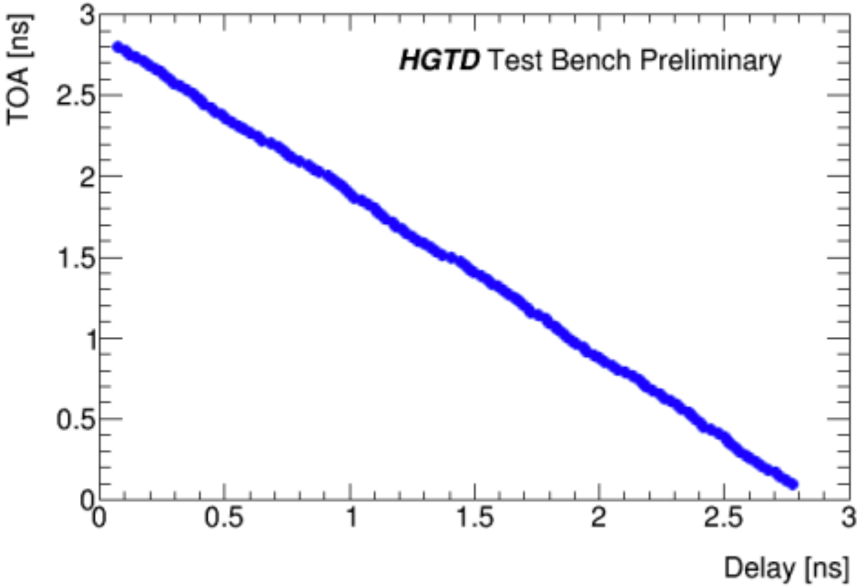


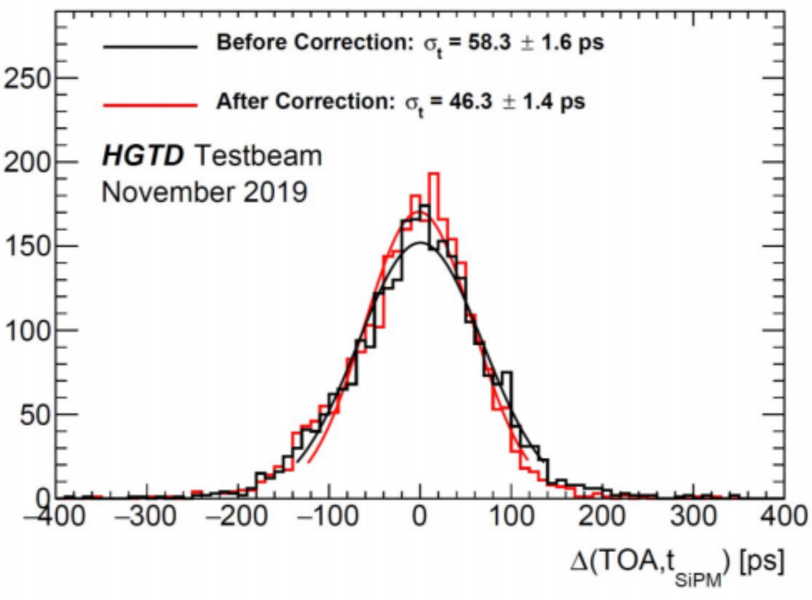


TDC: Vernier configuration with two delay lines

- Time resolution (20ps) = difference in delay of the cells in each line
- TOA given by the number of stages needed for the STOP to surpass the START
- No power consumption if no hit

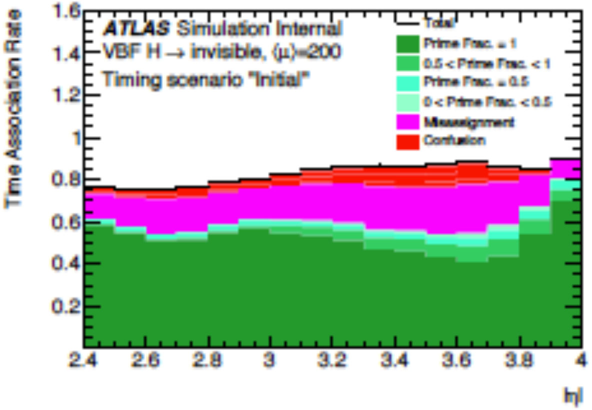
ASIC performance

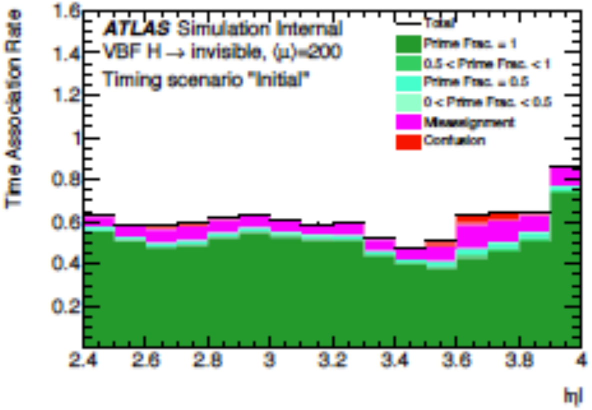


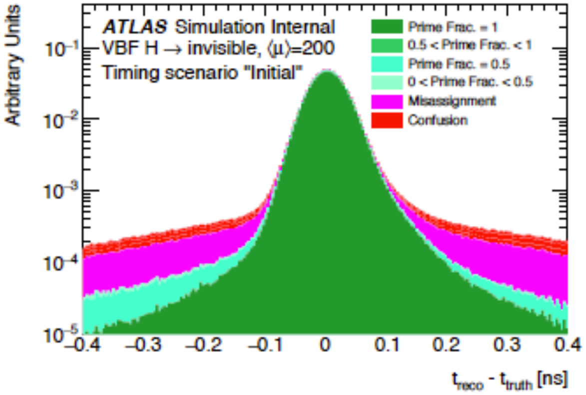


HGTD Performance

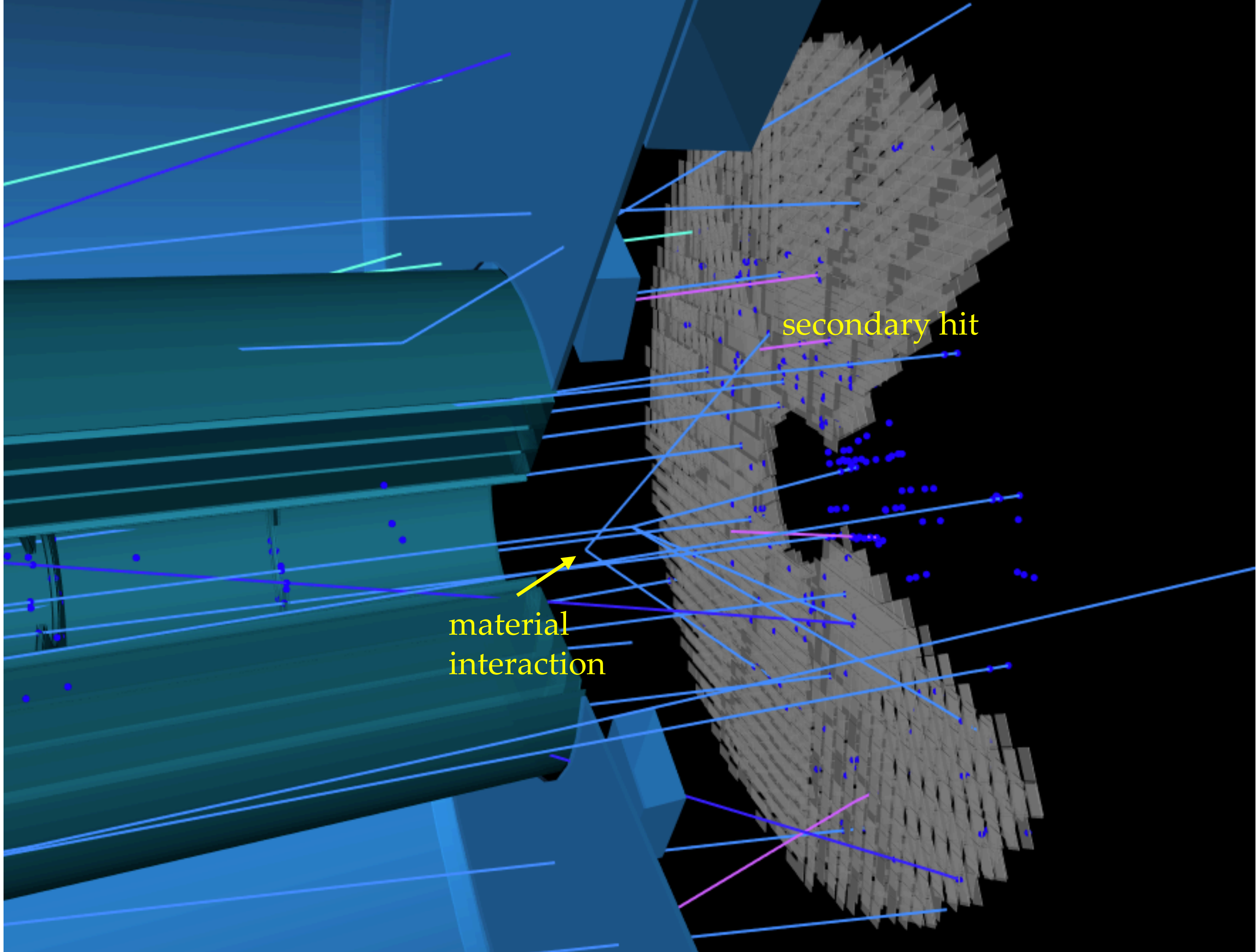
Track-time matching efficiency and time resolution





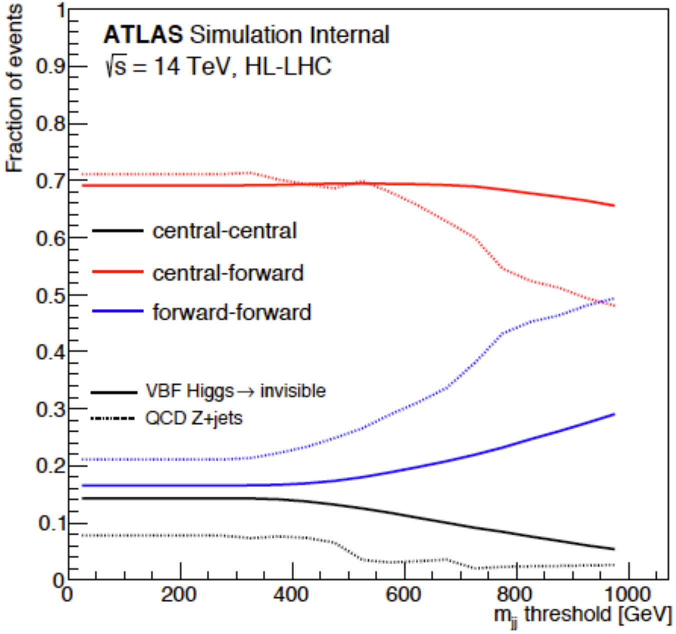


Tracks extrapolated to HGTD surface + iterative algorithm to assign HGTD hits to tracks: **performance limited by material interactions inside ITk volume, services, and PP1**


secondary hit
material
interaction

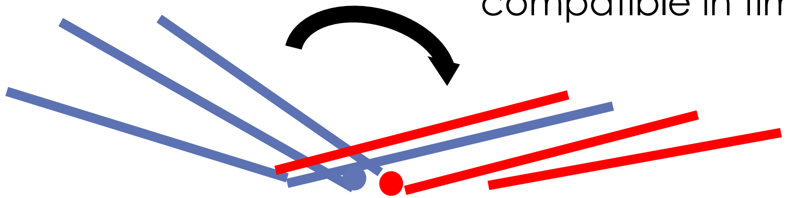
Vertex t_0

Two type of topologies, depending on the number of forward jets: CF, FF



FF is straightforward, but it is not the largest contribution

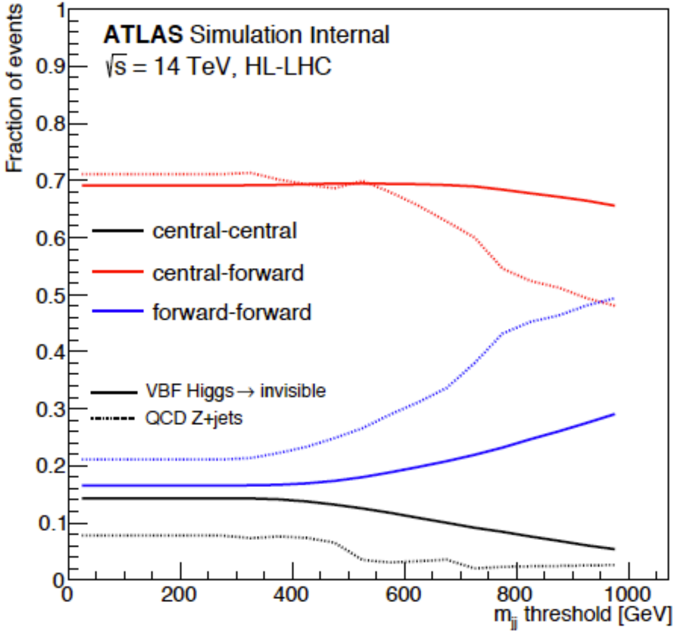
Are the two jets compatible in time?



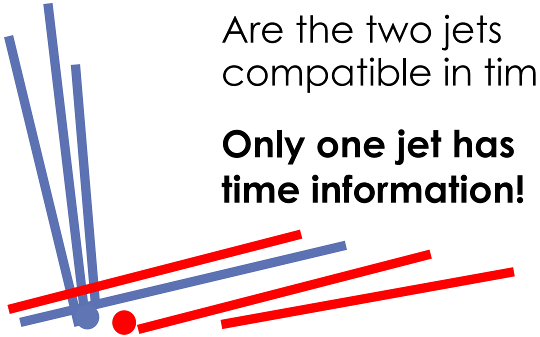
No need to know the time of the primary vertex (t_0)

Vertex t_0

Two type of topologies, depending on the number of forward jets: CF, FF



CF is the largest contribution, and the most difficult



Are the two jets compatible in time?

Only one jet has time information!

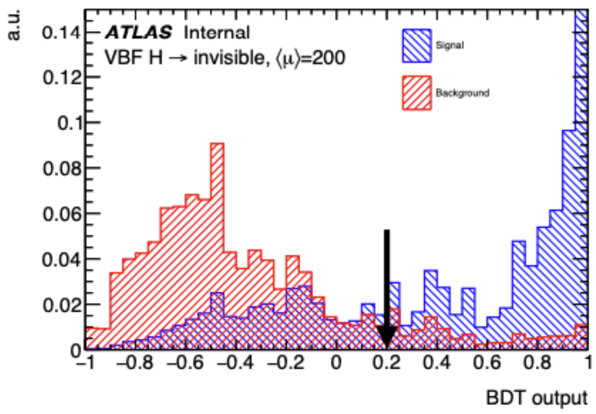
Requires the knowledge of the vertex t_0

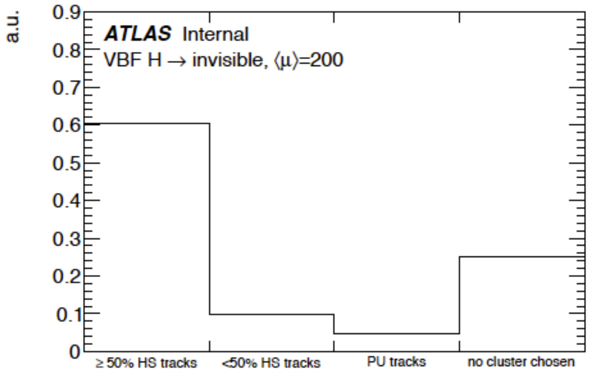
Vertex t_0

- **The challenge:**

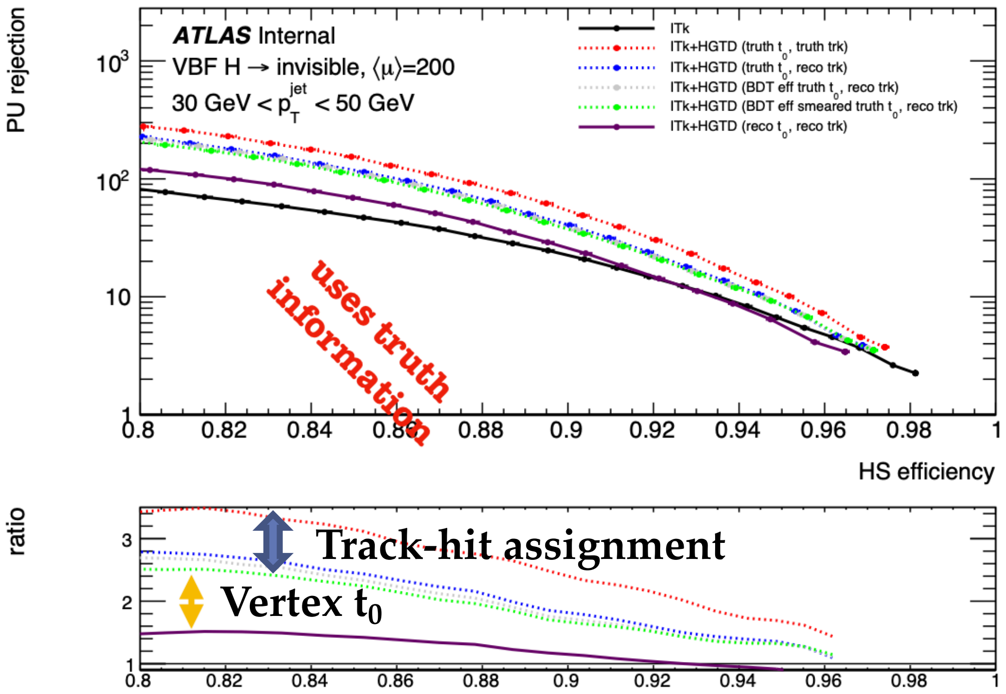
1. The primary vertex needs to have enough tracks within the HGTD acceptance.
    - Physics process dependent
    - Track-hit efficiency ~ 50%

2. When the HS does have enough tracks within acceptance, how do we pick the correct vertex time?



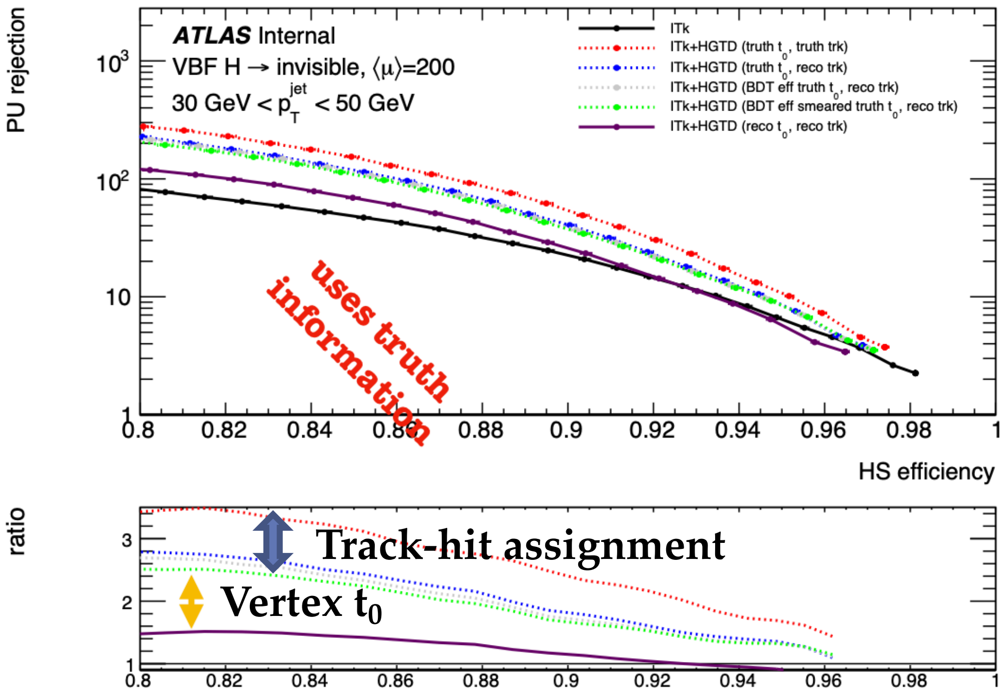


What limits HGTD performance?



- **Key challenges**
  - Track-hit assignment efficiency (~50%), and mistag rate (~10%) -- **material**
  - Vertex t_0 determination
    - **Eta coverage**
    - Algorithm performance

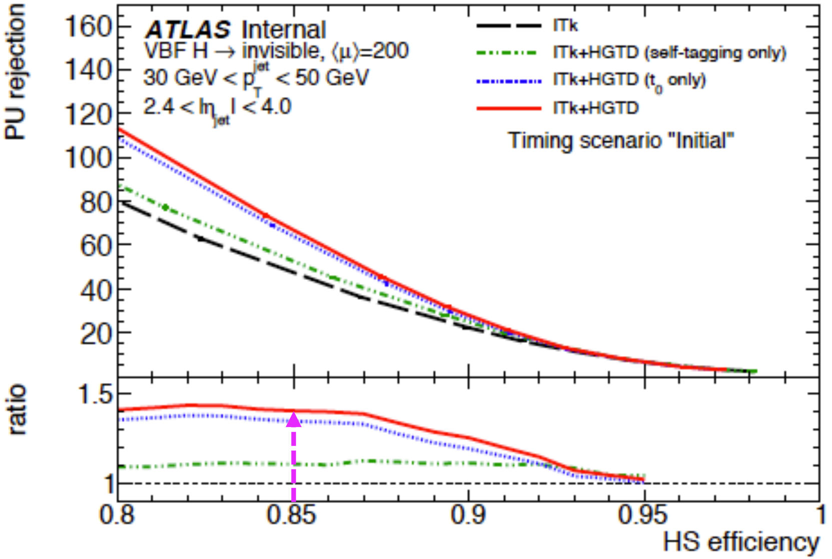
What limits HGTD performance?



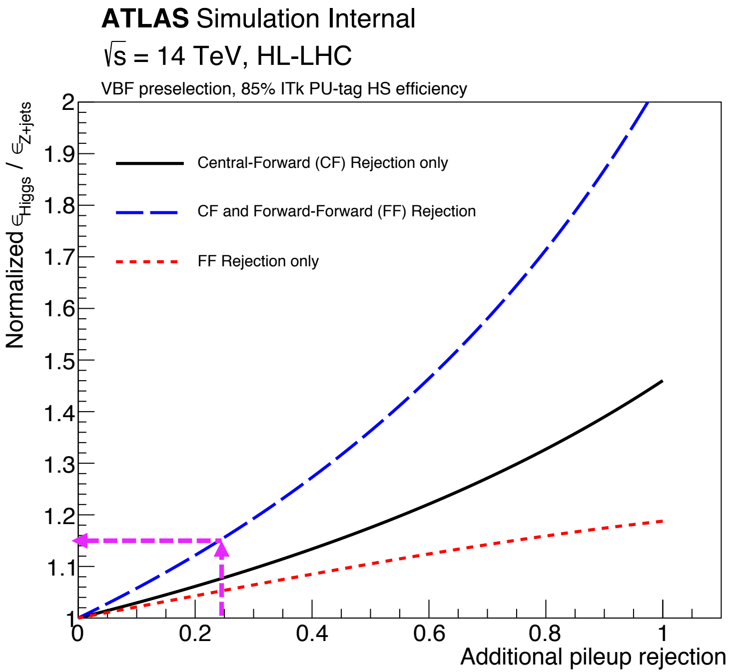
- **Key challenges**
  - Track-hit assignment efficiency (~50%), and mistag rate (~10%) -- **material**
  - Vertex t_0 determination
    - **Eta coverage**
    - Algorithm performance

A barrel timing detector would directly improve HGTD and forward physics performance!

HGTD Physics Impact



Pileup jet suppression

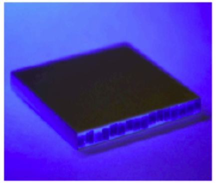


VBF H→invsible

CMS MTD

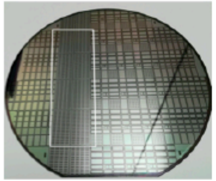
BTL: LYSO bars + SiPM readout:

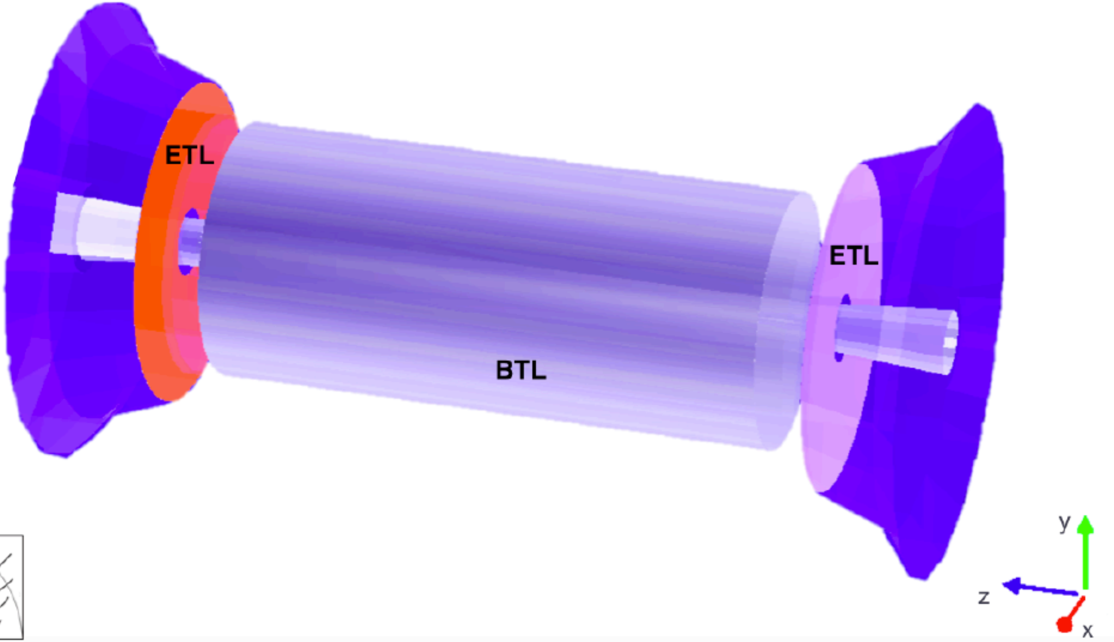
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2 \times 10^{14}\ n_{eq}/cm^2$



ETL: Si with internal gain (LGAD):

- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2 \times 10^{15}\ n_{eq}/cm^2$



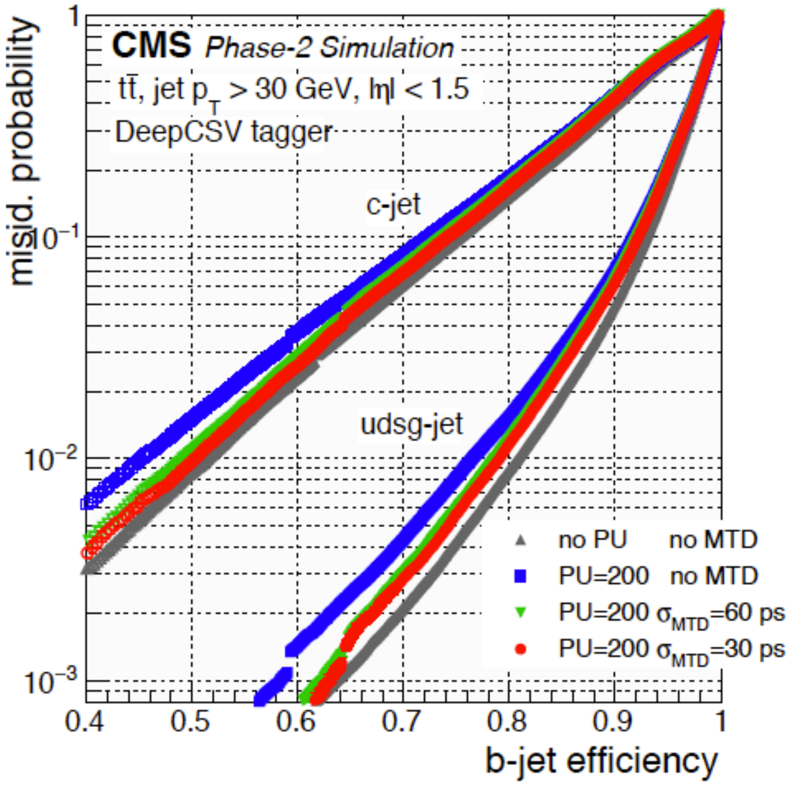


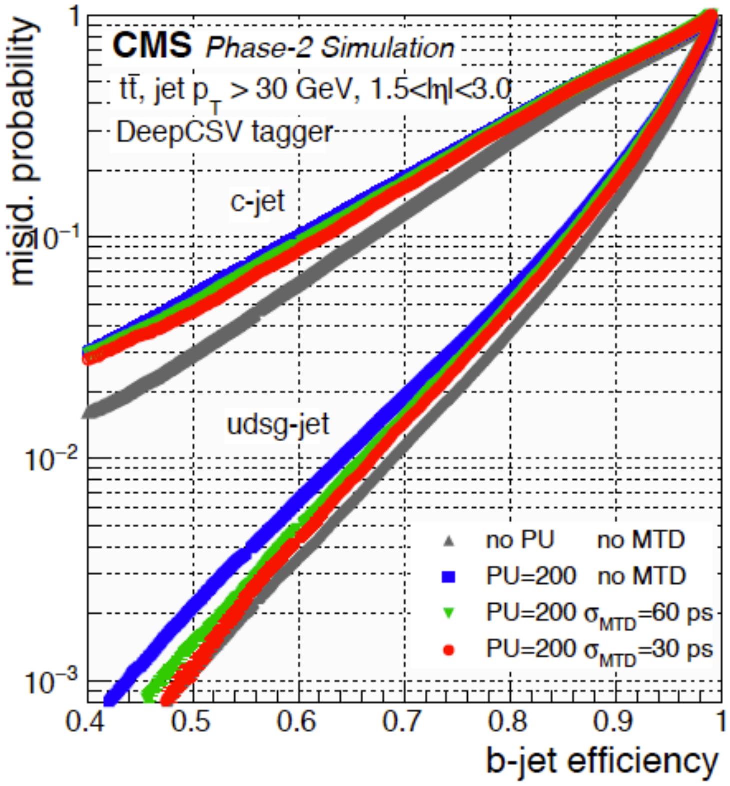
CMS Physics Impact

Table 1.1: Expected scientific impact of the MIP Timing Detector, taken from Ref. [8].

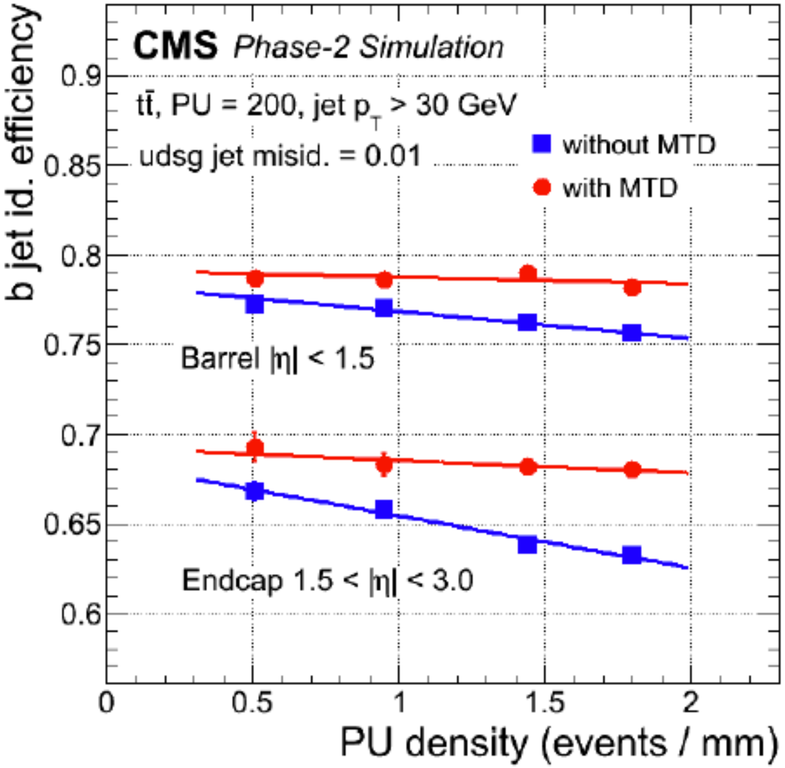
Signal	Physics measurement	MTD impact
$H \to \gamma\gamma$ and $H \to 4$ leptons	+15–25% (statistical) precision on the cross section $\to$ Improve coupling measurements	Isolation and Vertex identification
$VBF \to H \to \tau\tau$	+30% (statistical) precision on cross section $\to$ Improve coupling measurements	Isolation VBF tagging, p_T^{miss}
HH	+20% gain in signal yield $\to$ Consolidate searches	Isolation b-tagging
EWK SUSY	+40% background reduction $\to$ 150 GeV increase in mass reach	MET b-tagging
Long-lived particles (LLP)	Peaking mass reconstruction $\to$ Unique discovery potential	β_{LLP} from timing of displaced vertices

b-tagging

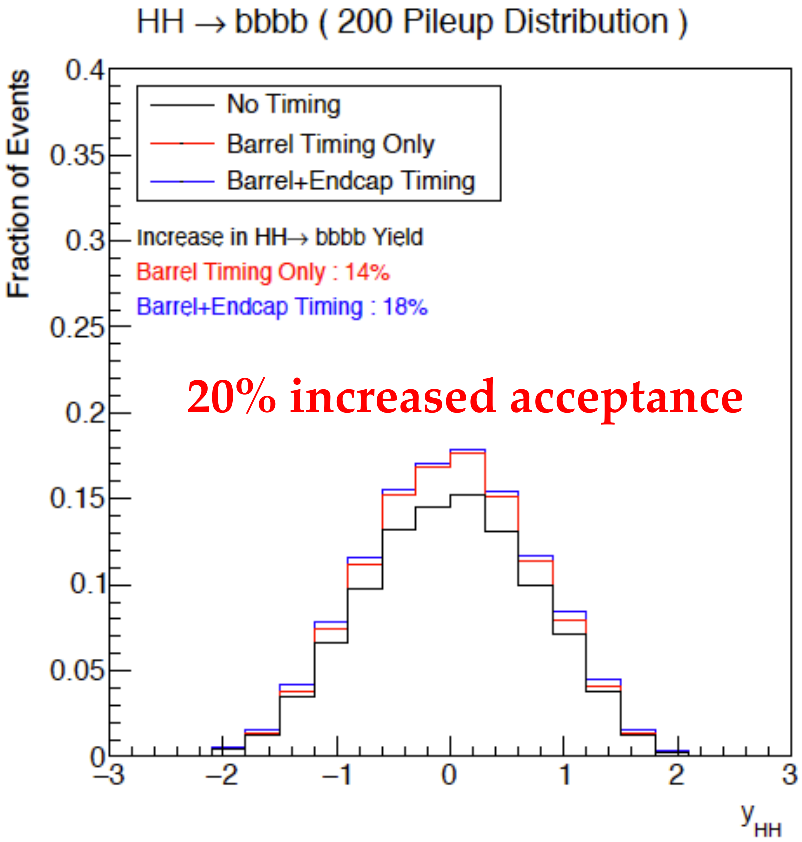

CMS Phase-2 Simulation
tt̄, jet p_T > 30 GeV, |η| < 1.5
DeepCSV tagger
c-jet
udsg-jet
no PU no MTD
PU=200 no MTD
PU=200 σ_MTD=60 ps
PU=200 σ_MTD=30 ps
misid. probability
b-jet efficiency


CMS Phase-2 Simulation
tt̄, jet p_T > 30 GeV, 1.5<|η|<3.0
DeepCSV tagger
c-jet
udsg-jet
no PU no MTD
PU=200 no MTD
PU=200 σ_MTD=60 ps
PU=200 σ_MTD=30 ps
misid. probability
b-jet efficiency

HH→bbbb

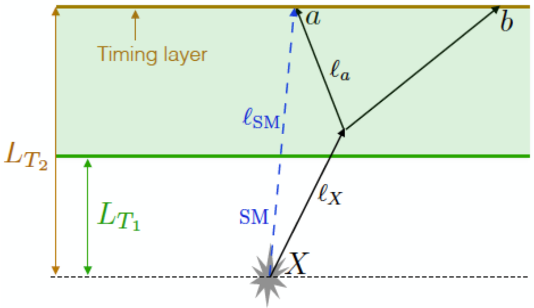


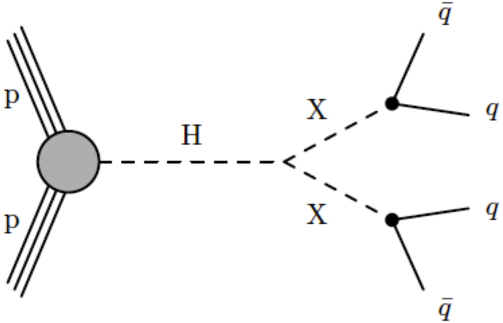
CMS Phase-2 Simulation
tt̄, PU = 200, jet p_T > 30 GeV
udsg jet misid. = 0.01
without MTD
with MTD
Barrel |η| < 1.5
Endcap 1.5 < |η| < 3.0
b jet id. efficiency
PU density (events / mm)
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0
0.5
1
1.5
2

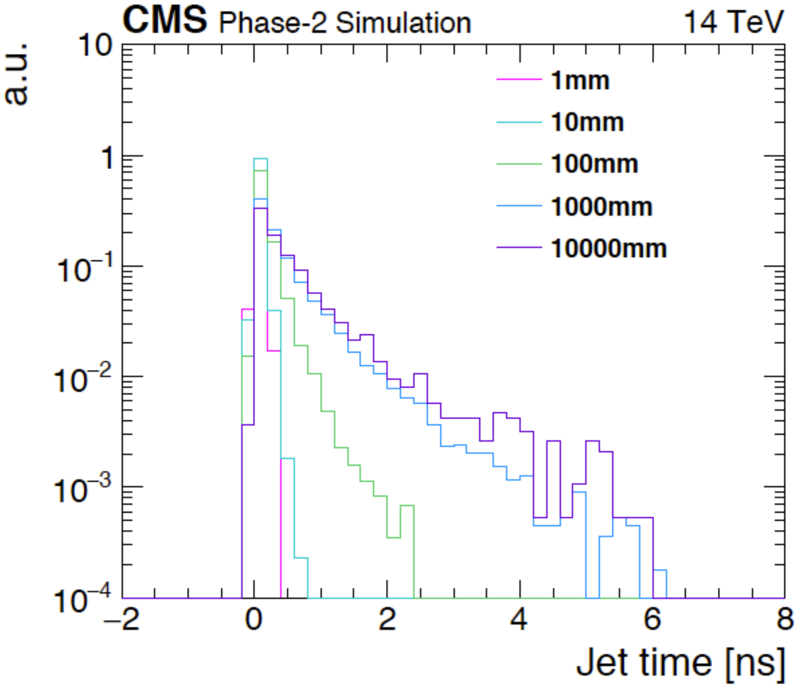


HH → bbbb (200 Pileup Distribution)
No Timing
Barrel Timing Only
Barrel+Endcap Timing
Increase in HH→ bbbb Yield
Barrel Timing Only : 14%
Barrel+Endcap Timing : 18%
20% increased acceptance
Fraction of Events
y_{HH}
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
−3
−2
−1
0
1
2
3

Long Lived Particles



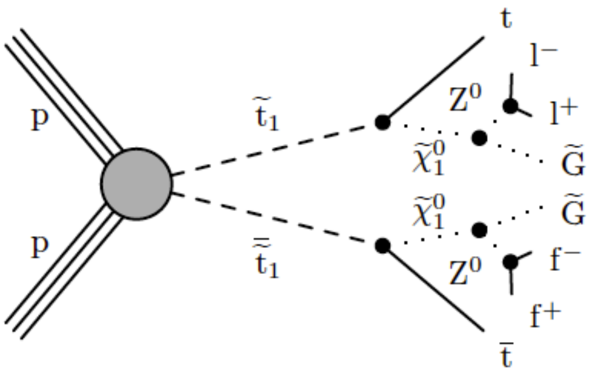


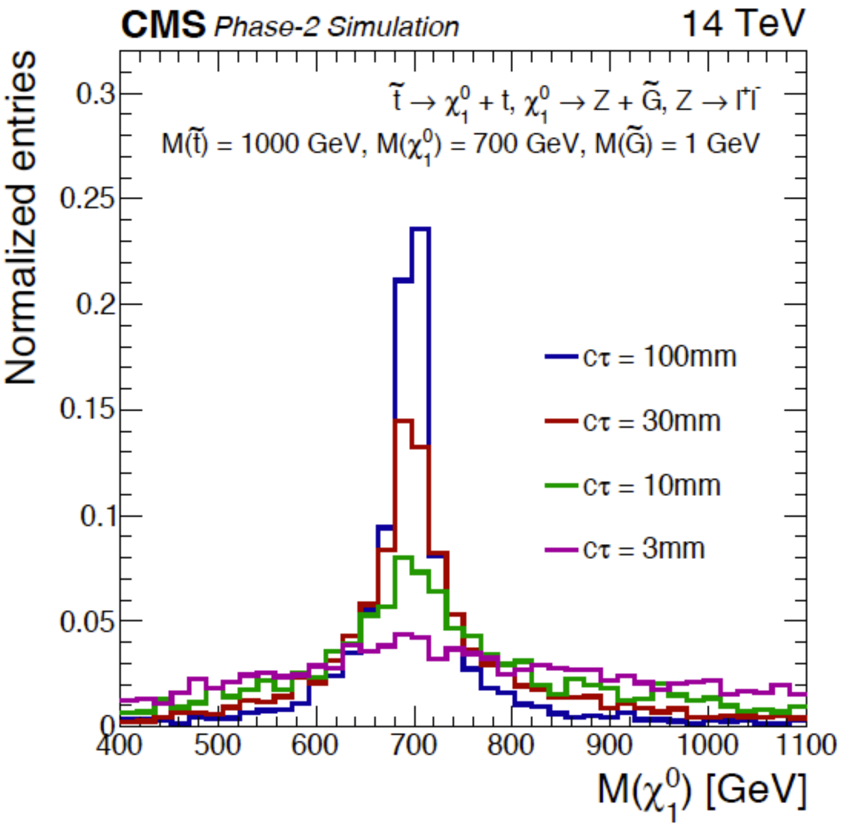


- Need long time readout window
- Better with large radius layer

Long Lived Particles

New capability to determine particle **velocity** (beta) → mass reconstruction





Better with large radius layer

ToF Particle ID

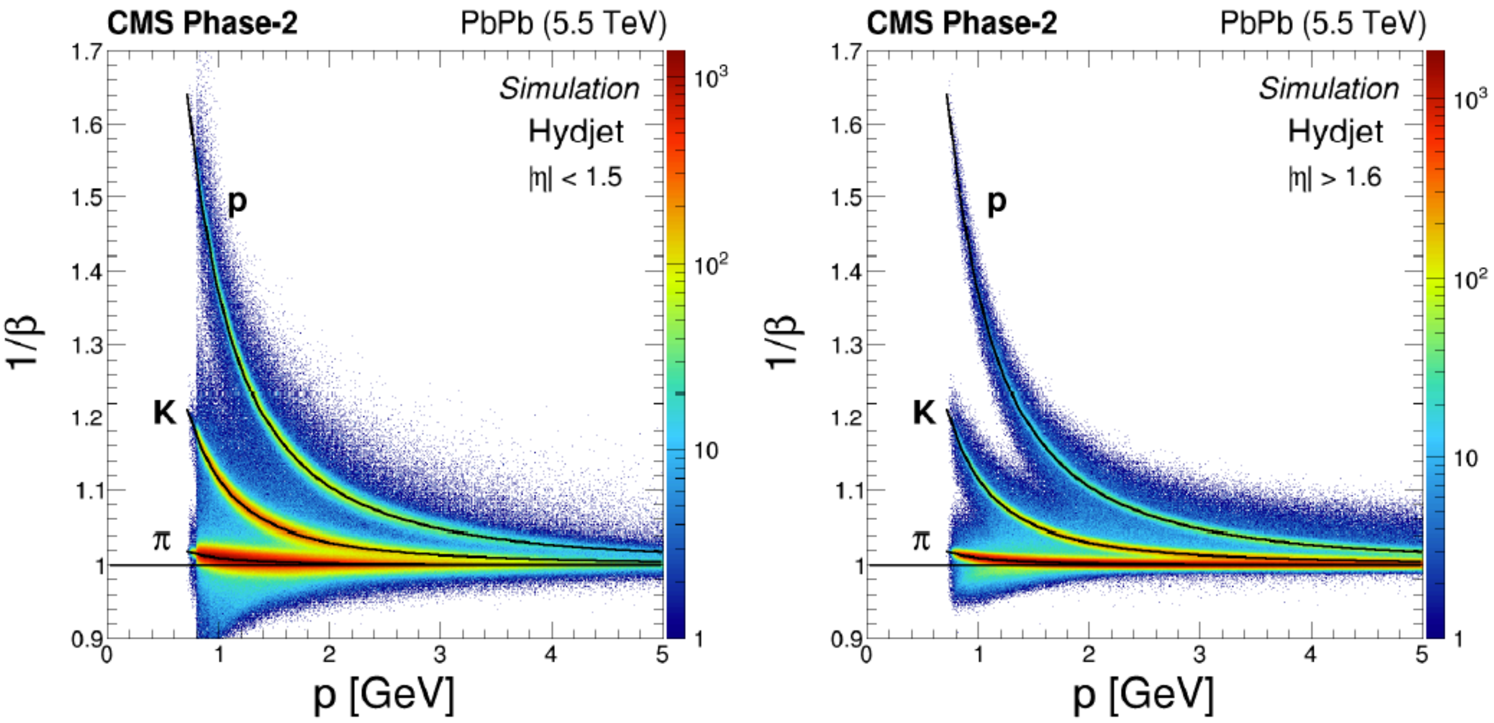
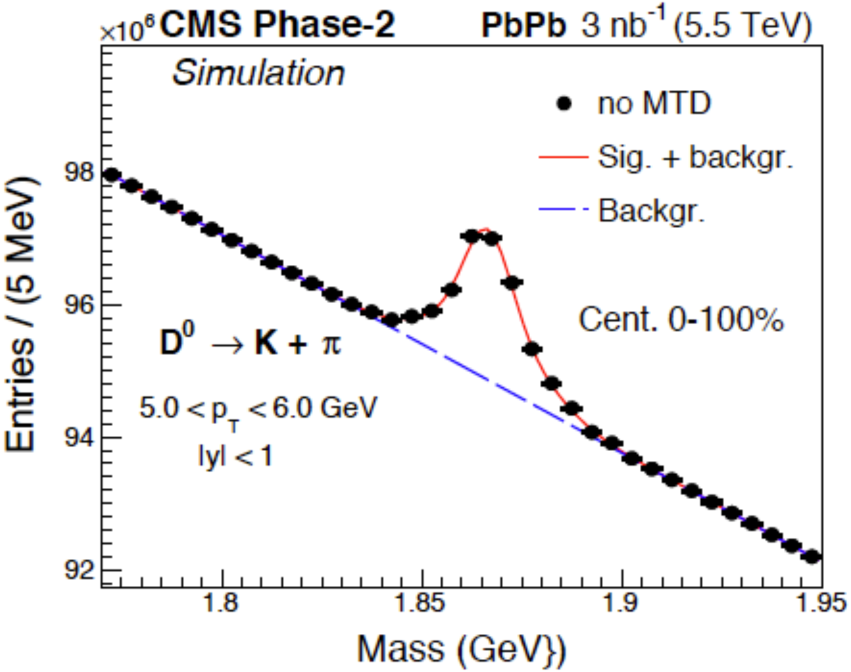
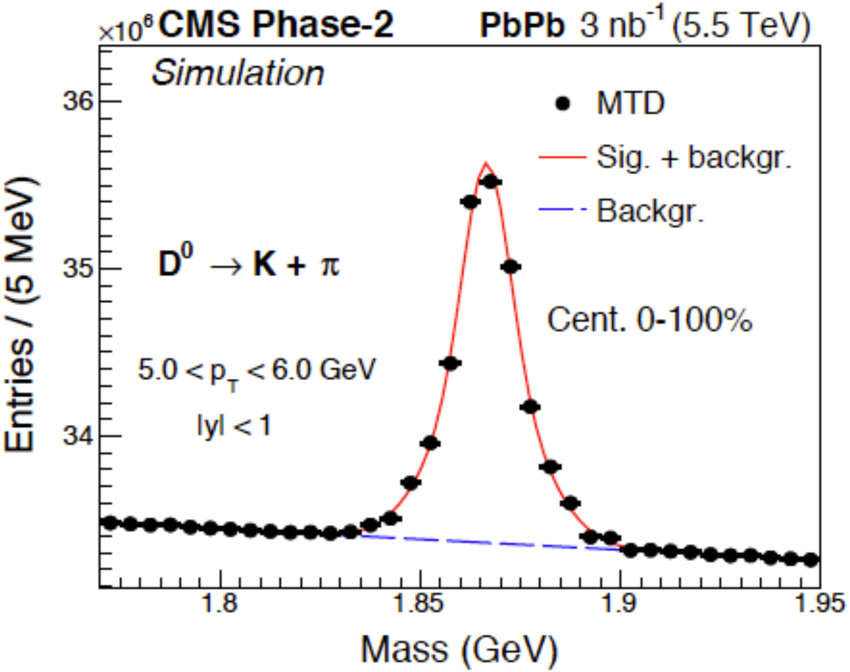


Figure 5.23: The inverse velocity ($1/\beta$) as a function of the particle momentum, p, for BTL ($|\eta| < 1.5$) and ETL ($|\eta| > 1.6$) in HYDJET PbPb simulation at 5.5 TeV.


×10⁶ CMS Phase-2
PbPb 3 nb⁻¹ (5.5 TeV)
Simulation
no MTD
Sig. + backgr.
Backgr.
Cent. 0-100%
D⁰ → K + π
5.0 < p_T < 6.0 GeV
|y| < 1
Entries / (5 MeV)
Mass (GeV})


×10⁶ CMS Phase-2
PbPb 3 nb⁻¹ (5.5 TeV)
Simulation
MTD
Sig. + backgr.
Backgr.
D⁰ → K + π
Cent. 0-100%
5.0 < p_T < 6.0 GeV
|y| < 1
Entries / (5 MeV)
Mass (GeV)

Strange Jet Tagging

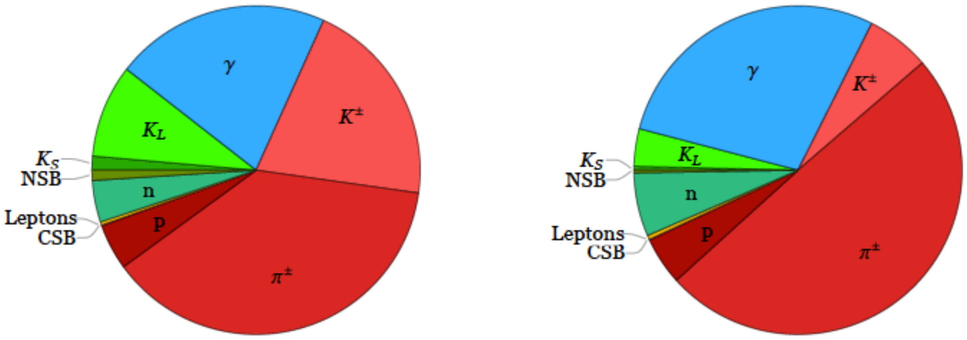
Yuichiro Nakai[1], David Shih[2,3,4] and Scott Thomas[2]

[1] *Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China*

[2] *New High Energy Theory Center, Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08854, USA*

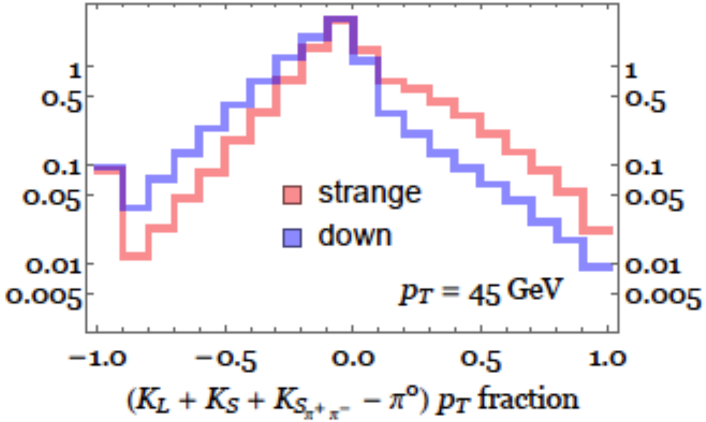
[3] *Theory Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

[4] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA*



Strange $p_T = 45$ GeV

Down $p_T = 45$ GeV



Ideal for Su Dong's
Higgs flavor exploration

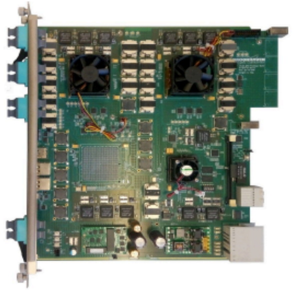
Context

- **TIMEPOST R&D** project
  - **TIME** & **SP**ace real-time **O**perating **T**racker
  - three years project, from 2018, funded by **INFN**
  - development of a **silicon and diamond 3D tracker with timing facilities:**
    - **demonstrated 30 ps** hit resolution at testbeam at PSI[https://pandora.infn.it/public/52d779]
  - **construction of a demonstrator** integrating sensors, electronics, **real-time** processors

https://web.infn.it/timespot/

- **Work Packages and coordinators:** – Principal investigator: A. Lai
  - 3D silicon sensors: development and characterization – G.F. Dalla Betta
  - 3D diamond sensors: development and characterization – S. Sciortino
  - design and test of pixel front-end – V. Liberali
  - design and implementation of fast tracking devices – N. Neri
  - design and implementation of high speed readout boards – A. Gabrielli
  - system integrations and tests – A. Cardini

gFEX board, developed at BNL for ATLAS calorimeter:

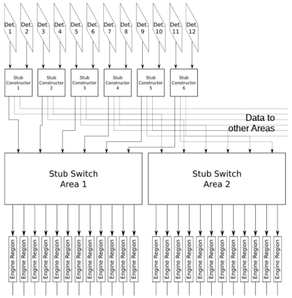


- two **Xilinx Virtex Ultrascale** FPGAs
- high-speed optical transceivers → ~**1.6 Tbps input data rate**
- one Xilinx Zynq FPGA

Switch + Engines + Fan Ins fully implemented

Hardware architecture

- **Independent Stub Constructors:**
  - one for each plane doublet
- **Independent Stub Switches:**
  - one for each Area of Engines
- **Engines** in the 2D tracking plane organized into multiple **independent regions**
- **Absence of "lateral" communication** between modules, make the system **modular and scalable**



LBNL ATLAS Effort

Simulation and strategy

•Start with 20.20.14.3 HGTDExtension release.

•Unfortunately pixel timing is not saved in the current simulated pixel hit.

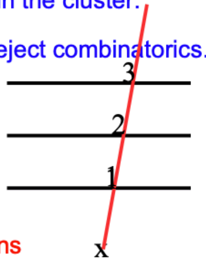
•Modified code to repack both charge and time into PixelSDO_MAP for pixel hits including delta rays after truth smearing with a timing resolution.

•The pixel cluster time is a simple average of pixel timing in the cluster.

•Run standard tracking and study timing performance to reject combinatorics.

•Timing consistency of two pixel hits(1,2) in each seed:

- $\Delta T12 = T2 - T1 - \Delta r12/c$ (ps)
- Pixel T0 = T - r/c (ps)
- Dividing seeds into truth, track seed, fake seed
- Apply a ΔT(3 sigma) cut to measure eff. and rejections



•Rejections: ttbar with pileup mu=0,60,140,200 and timing of 30, 60, 100 ps.

Conclusion

•4D pixel detector with both excellent spatial and timing resolution will open a new era for silicon tracking.

•By requiring timing consistency at hit level some fake seeds can be rejected and make tracking faster.

•Fake seed rejection ranges from 50-30% with timing resolution of 30-100 ps for ITK innermost layers.

•At the track level, additional 30% of pile-up rejection can be achievable with timing for out-time pile-up tracks inside the HS vertex.

•Development of a timing pixel chip is in progress.

LS4 4D Tracking @ SLAC

https://www.snowmass21.org/docs/files/summaries/IF/SNOWMASS21-IF3_IF7-131.pdf

- **Sensors**
  - 3D, AC-LGADs, MAPS?
- **Electronics**
  - Smaller sensors, low power, more channels, extremely high radiation environment
- **Layout**
  - How to best combine spatial with timing information, optimizing material budget, power, time resolution, radial coverage, eta-coverage, …
    - Mixture of layers with different balance of spatial and timing resolution for overall 4D tracking for a wide range of applications

LS4 4D Tracking @ SLAC

- **Simulation, tracking and vertexing performance**
  - Add timing information to pixel hits (+ resolution smearing)
  - Clustering – Layout studies
    - Pixel size and general layout
    - Cluster reconstruction in 4D
  - Track seeding in 4D
  - 4D Kalman Filter within ACTS
  - 4D Vertexing

- Tracking efficiency, purity, impact parameter and time resolution in single muon/pions at mu=0, 200, and jets from Di-Higgs and VBF events
- Vertex time resolution

- **Physics performance**
  - b-tagging
  - Di-Higgs
  - Forward PU suppression (in conjunction with HGTD)
  - strange-quark jet tagging with ToF PID