Time the Physics

- a brief introduction and a focus on LHC efforts

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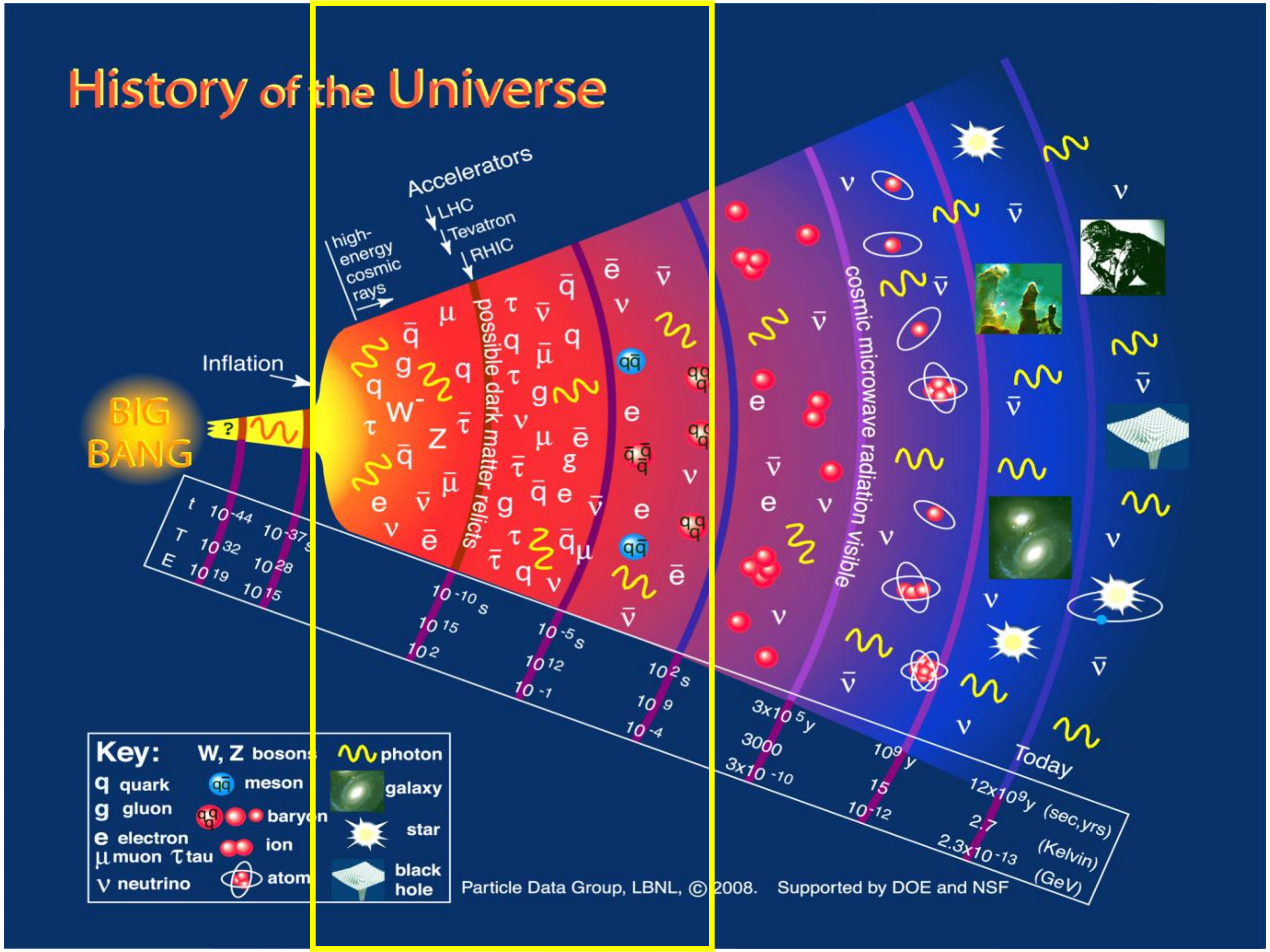
Frontier at smallest scale

Trace back to the "ORIGIN"

Hope to describe material world over 60 orders of magnitudes in a uniform way



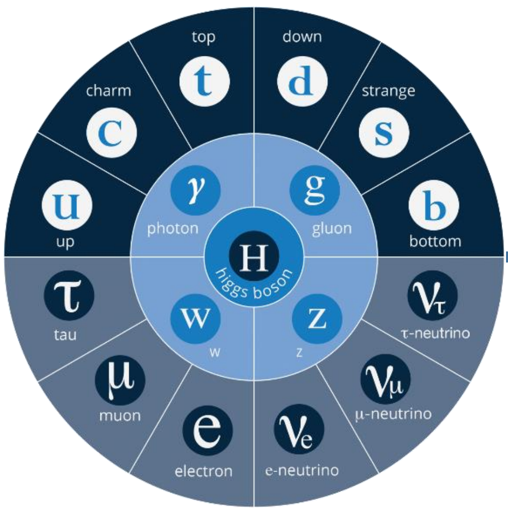
Typical range covered by particle physics research

Frontiers at smallest scale

The "Standard Model" is very successful (verified up to 1ppm precision),

yet evidence of dark matter, ν mass, matter-antimatter asymmetry drives us to seek for more underlying truth

→ **Rely on Ultra-Precision apparatus to reveal**



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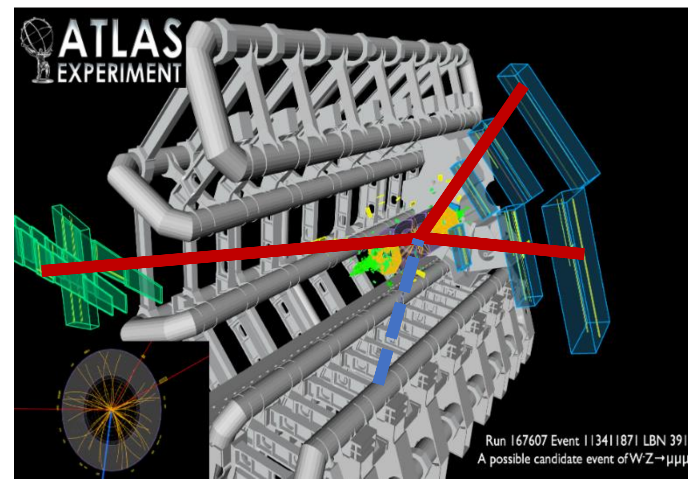
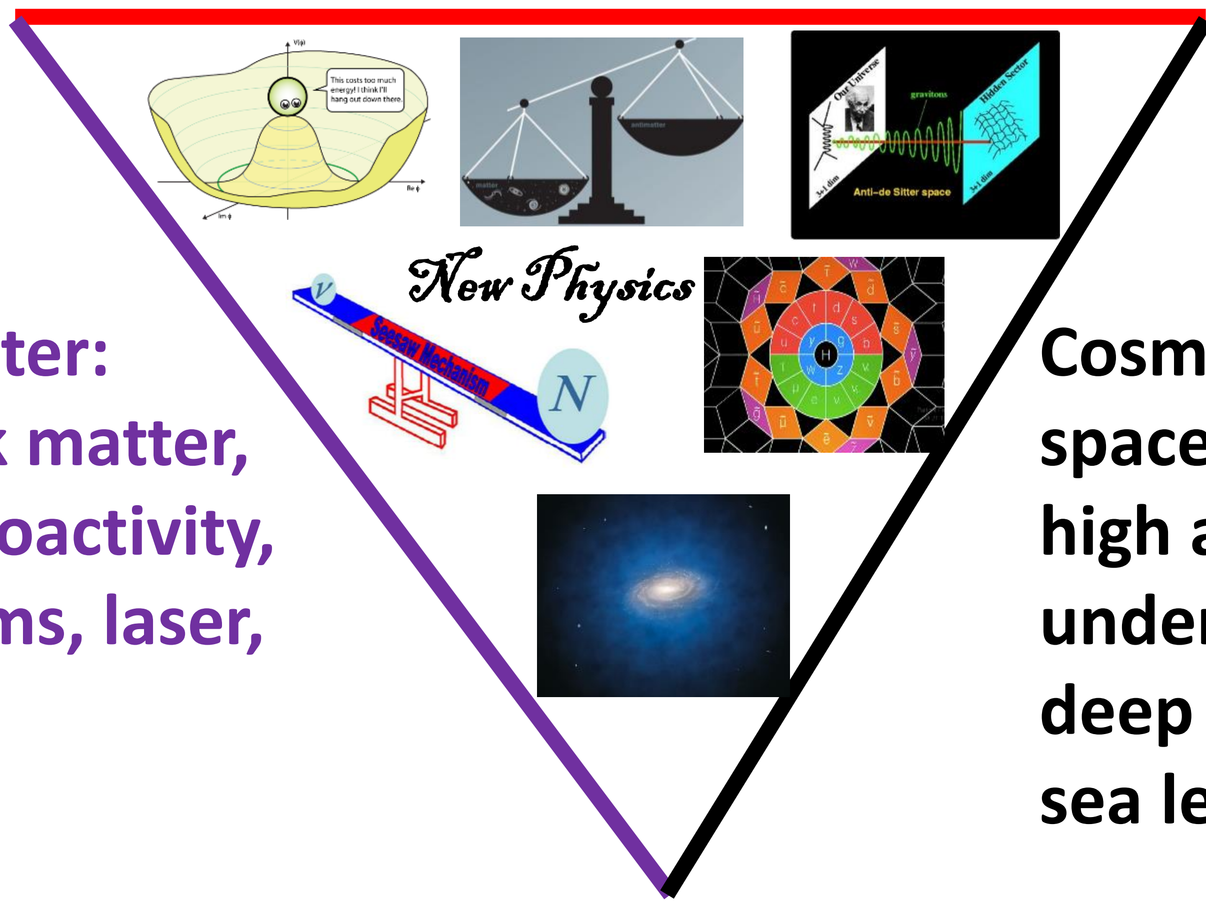
New?

SUSY,
GUT, String,
Extra dim.
ν See-saw……



The multifold means

Collider/Accelerator/Reactor



Matter:
bulk matter,
radioactivity,
atoms, laser,
……

Cosmic Ray:
space, balloon,
high altitude,
underground,
deep sea,
sea level

Signals yet to show up

Illustration of current limits related to new phenomena, info. partly from PDG2020

Heavy "X" not found yet up to 5 TeV

SM parameters consistent up to 1ppm

WIMP interacts with nucleon weaker than 10^{-46} cm^{-2}

Axion-like particles couple to photons lower limit down to 10^{-15} GeV^{-1}

ν mass upper limit down to ~ 0.1 eV; mass splitting precision down to 0.01 eV; half-life $0\nu\beta\beta$ decay rarer than 10^{26} year

EDM down to 10^{-30} e cm; MDM to 10^{-9}; LFV to 10^{-13}; LNV to 10^{-11}; FCNC to 10^{-10}; Proton half-life > 10^{34} yrs

At the corner or still a long way to go?

Quest to improve the precision

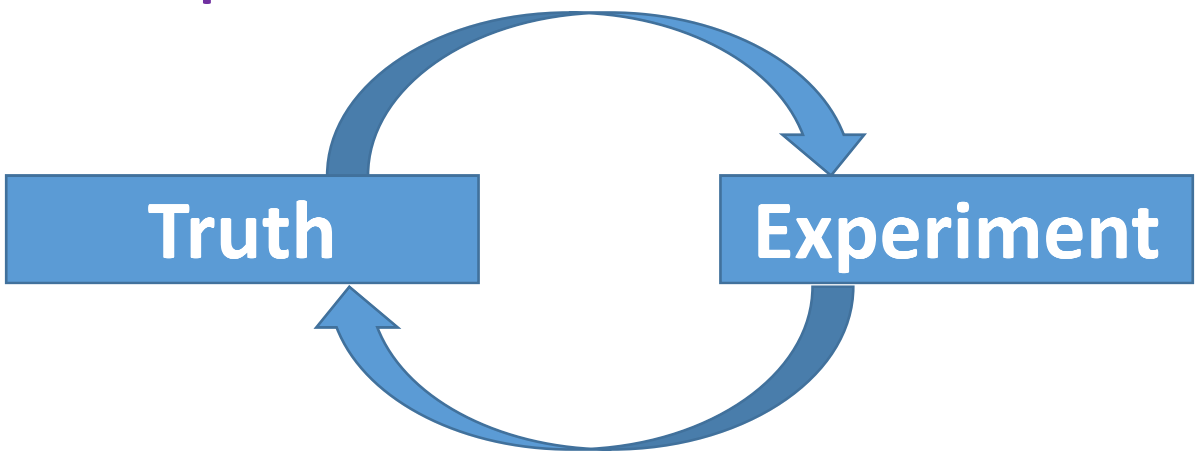
Only a conceptual discussion

Need ultra-sensitive detection with novel technologies if applicable, capturing 5D information (**x**, t, E/p)

Need ultra-precise theory calculations

Create phenomena

Leave detectable traces



Reconstruct the truth

Remove impurity/noises and perfect the detection of signal traces

Need ultra-intelligent data processing and machine learning

Need ultra-careful design and realization of experiments and capable electronic and DAQ systems

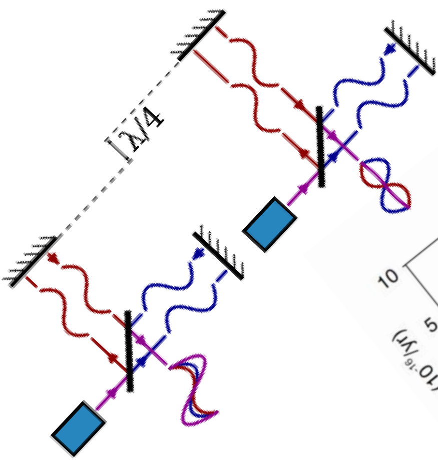
About precision time measurement

A key approach is to make the detection more sensitive and capable

Among 5D, time measurement is an indispensable one

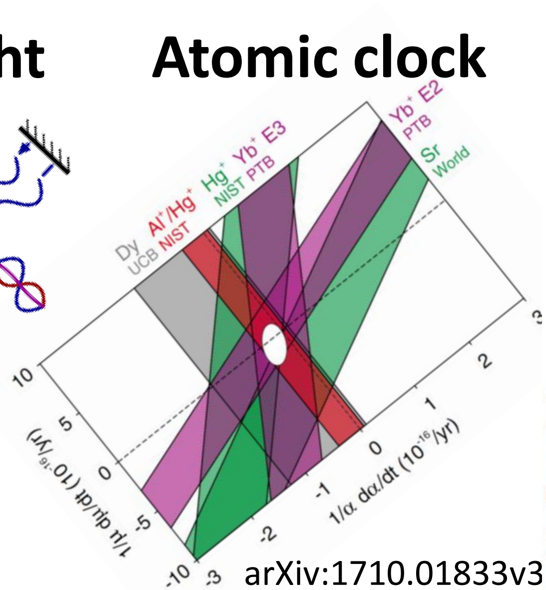
Several examples

Speed of light



Interferometer – high and precise frequency laser

Atomic clock

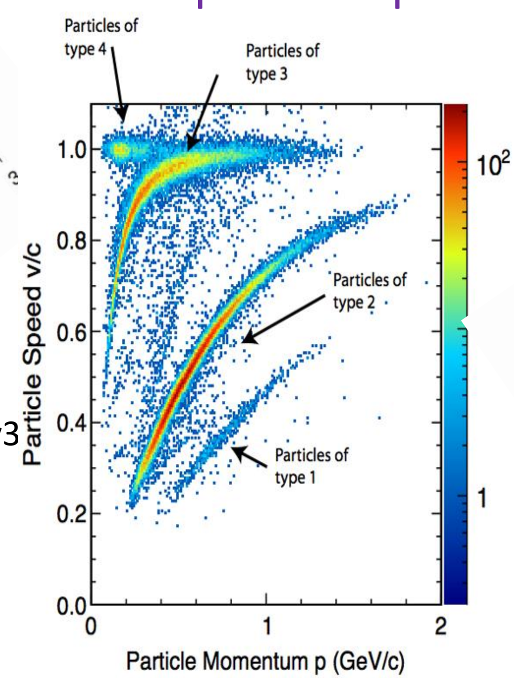


arXiv:1710.01833v3

Definition of time unit, precise to explore constants

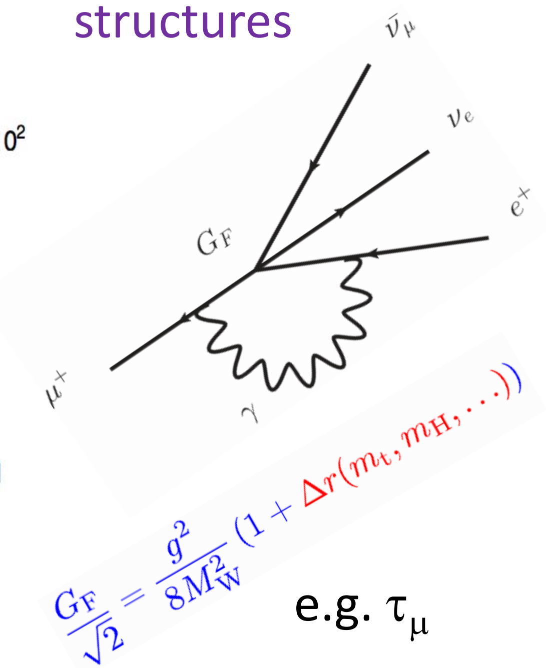
Time of flight

Reveal particle species



Lifetime

Reveal fundamental structures

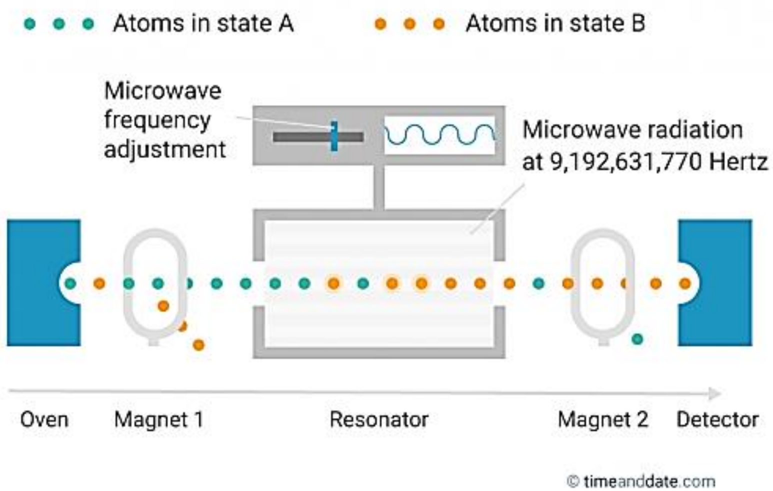


e.g. τ_μ

Example: atomic clock meets dark matter

Atomic clock

simplified example of Cs-133



Quantum transition, atom manipulation, resonation, ultra-high frequency (triumph of modern atomic and electronic science)

➔ The most accurate time standard

➔ Range from 10^{-13} to 10^{-18} precision

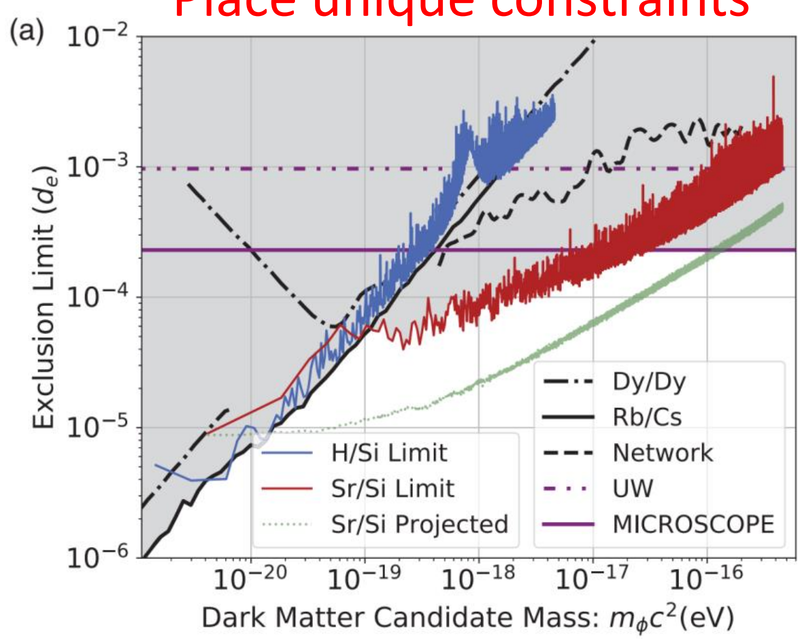
Dark matter

Could be ultralight field which interacts with normal matter

⇒ altering constants (e.g. α)

⇒ therefore affect atomic clock time measurements

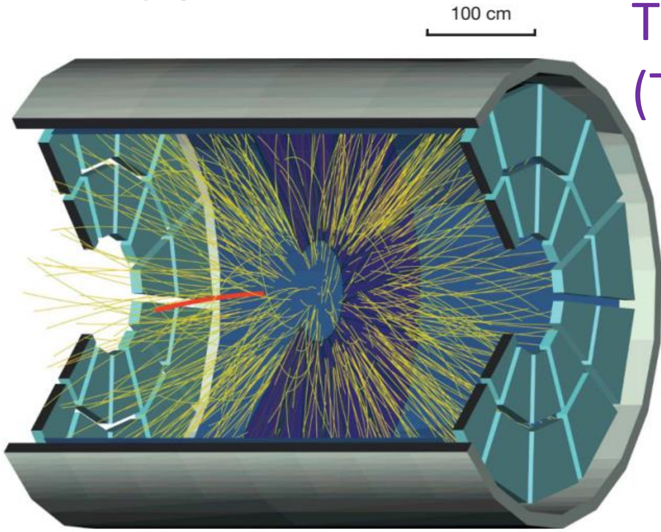
Place unique constraints



PRL 125,201302 (2020)

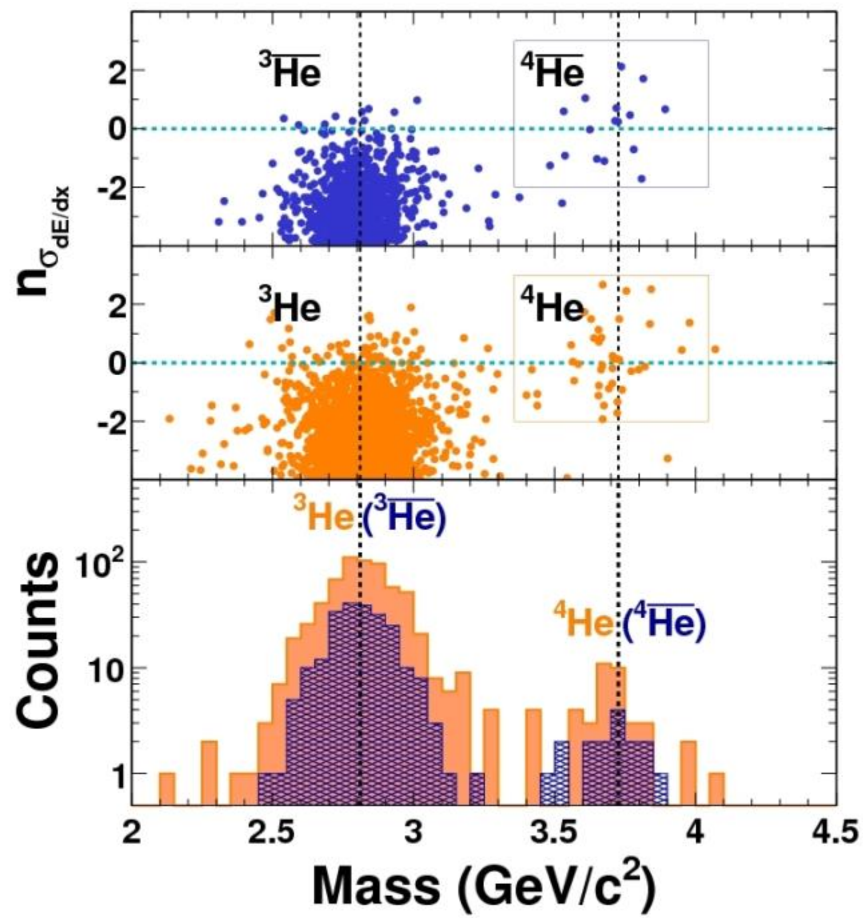
Example: time-of-flight for antimatter

RHIC STAR



Nature 473, 353–356(2011)

First observed anti-α through a combination of Time Projection Chambers and Time-of-flight (TOF) with multi-gap resistive plate chamber



Tracker gives **Z, p**

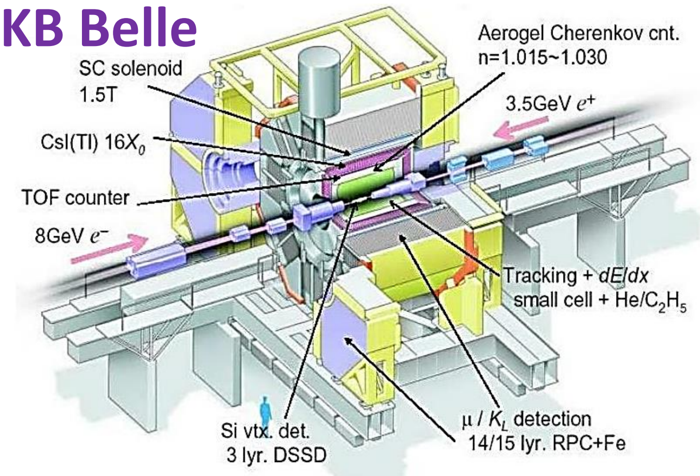
TOF provides another key ingredient for determining mass:

$$m = p\sqrt{\frac{c^2t^2}{L^2} - 1}$$

Timing resolution O(100) ps

Example: time-of-flight for spectroscopy

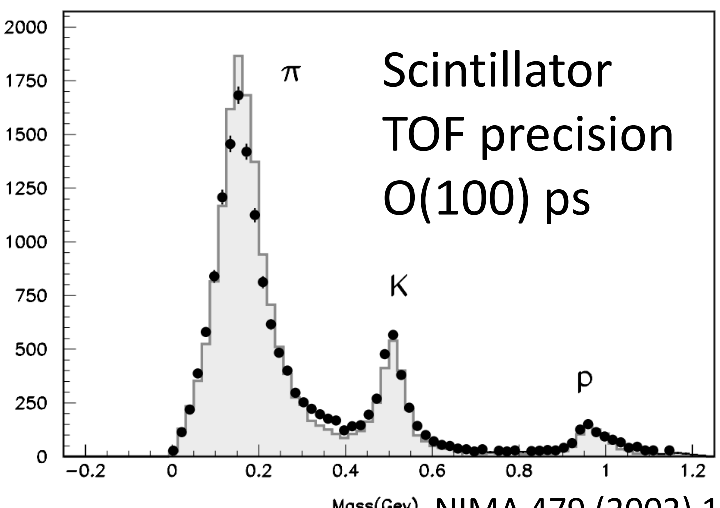
KEKB Belle



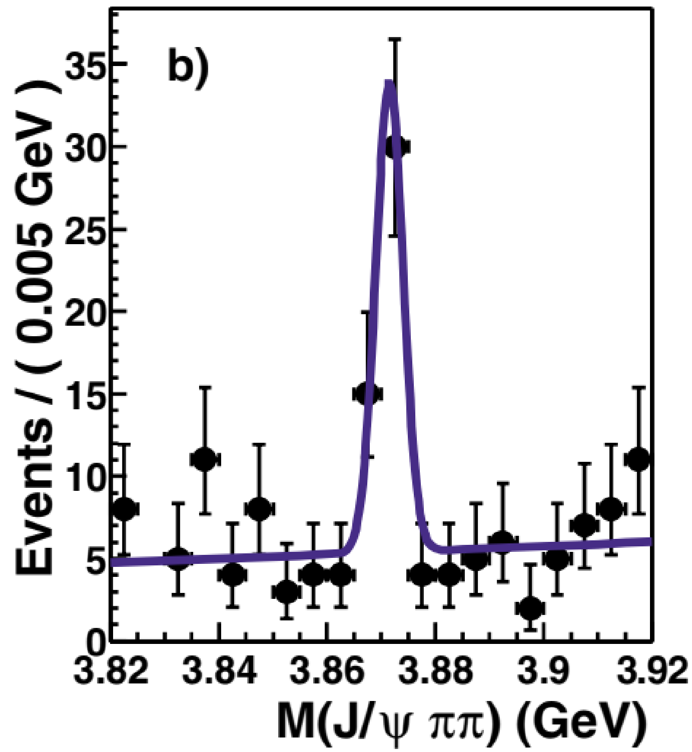
First observed X(3872), a potential candidate for tetraquark, through a typically complicate decay of B mesons

$$B^\pm \to K^\pm \pi^+ \pi^- J/\psi \quad X$$

"Freedom" of QCD cannot be enjoyed without good pID combing TOF and others



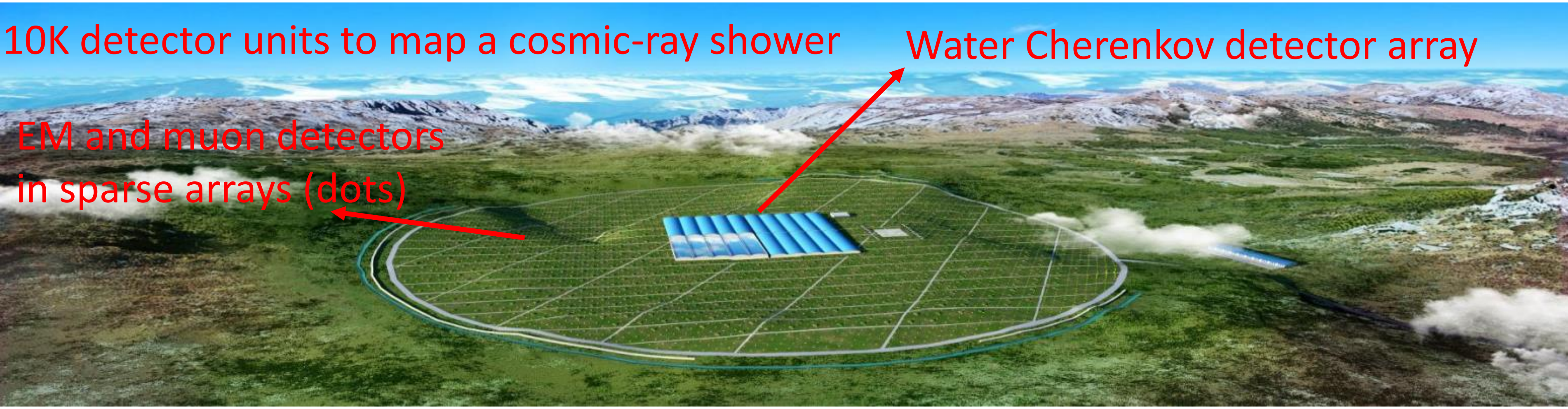
NIMA 479 (2002) 117–232

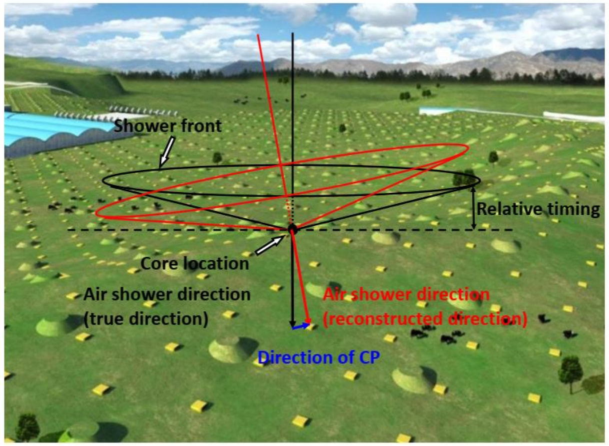


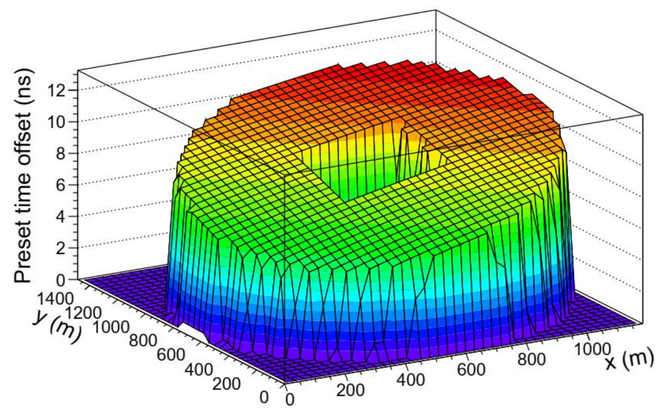
PRL 91, 262001 (2003)

Example: arrival time for cosmic rays

LHASSO A most powerful air-shower array for gamma cosmology and high-energy cosmic ray detection in Sichuan, China. Start to operate now







PoS(ICRC2017)455

Time the shower fronts → pointing of the primaries

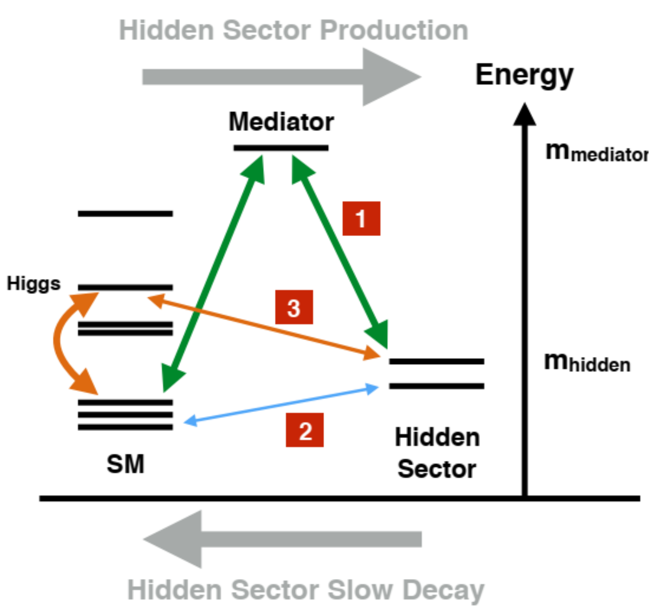
Novel technology to synchronize the large array with sub-ns error

Could improve angle resolution by 50% and more applications

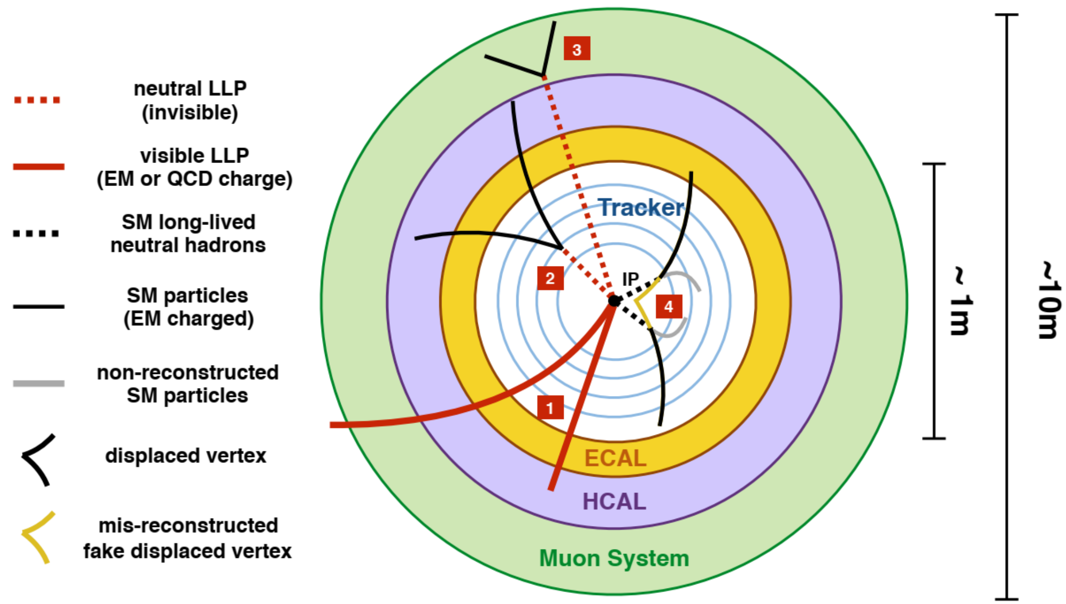
Example: "lifetime" frontiers

Nice illustration in arXiv:1702.02524

A term coined recently, in view of **null search results** especially at the LHC, and the motivation of **dark-sector theories**



Small coupling (hidden) with the SM leads to long lifetime, displaced vertex decays …



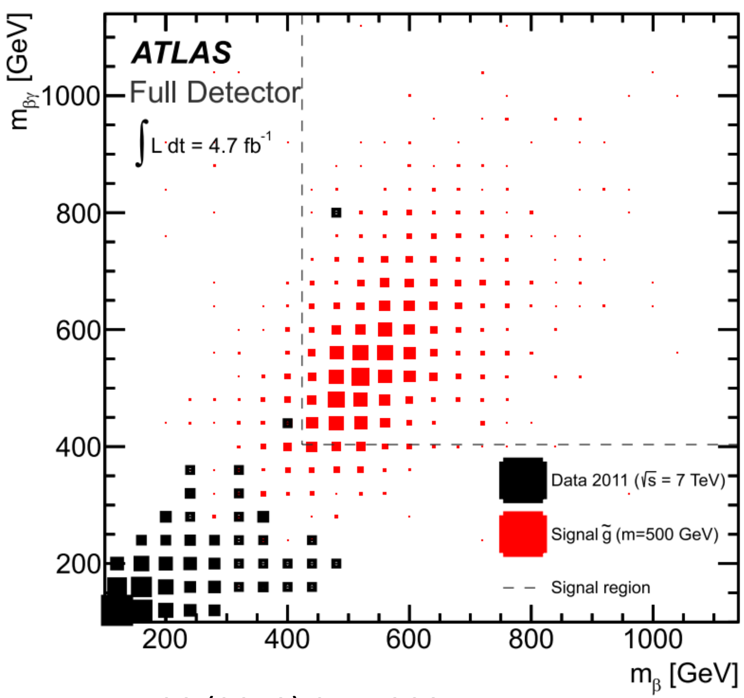
Rich possibilities to search for this signal, relying on great scrutiny of detectors

heavily rely on displaced vertex reconstruction, with **time-of-flight measurement** to be more decisive

Example: "lifetime" frontiers

Existing TeV detectors can provide ns TOF information, a key ingredient for long-lived search

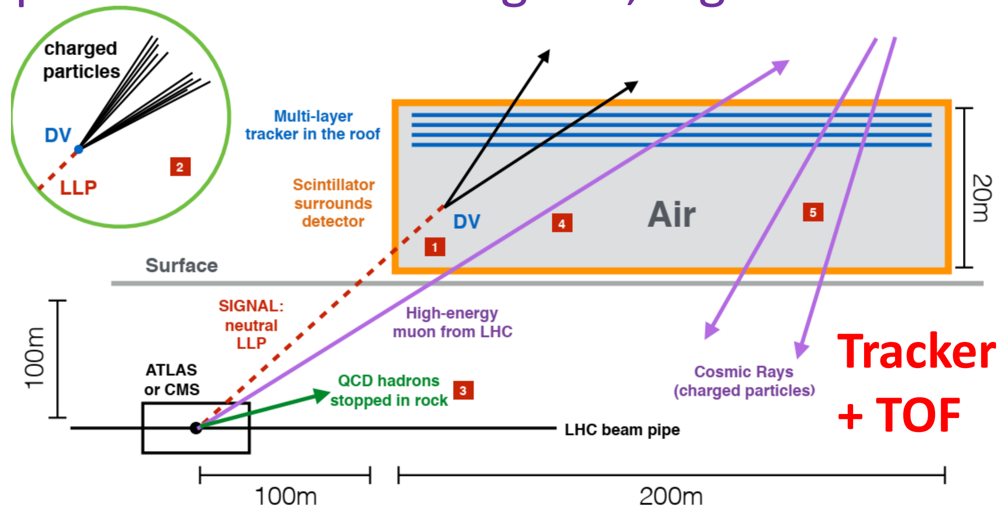
dE/dx

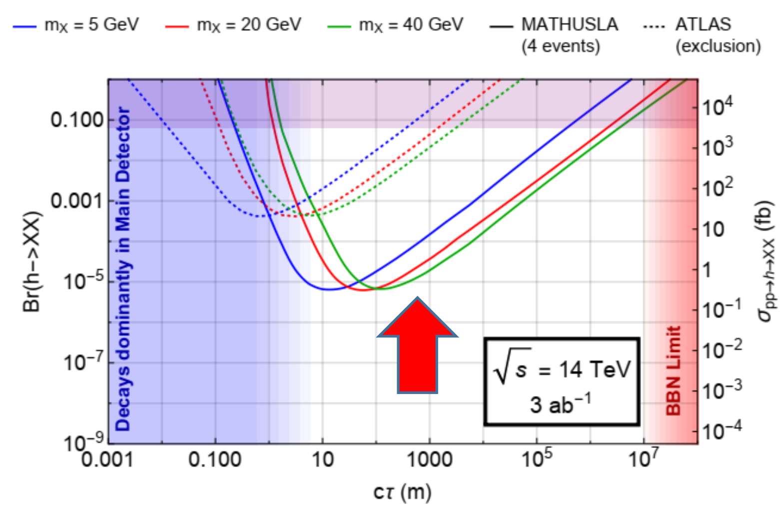


PLB 720 (2013) 277–308

TOF

New experiments being proposed to probe different cτ regions, e.g. MATHUSLA

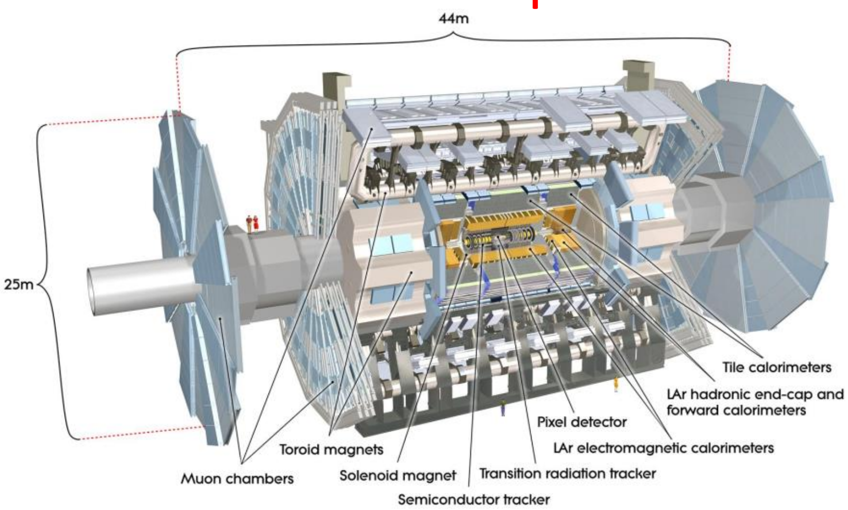


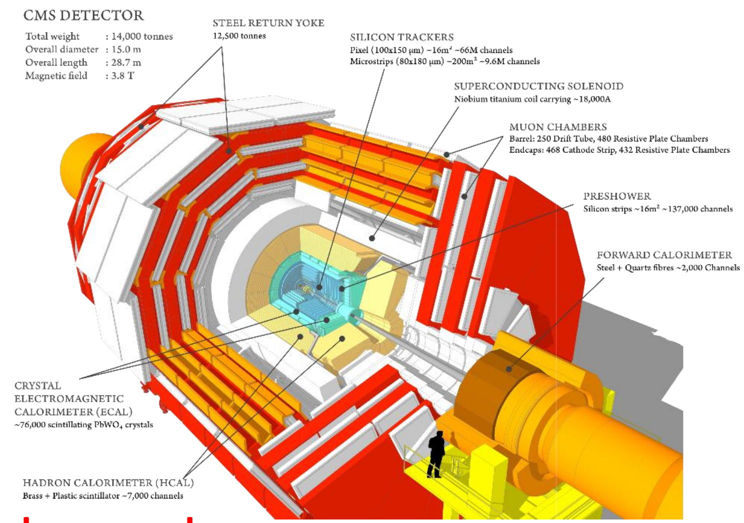


arXiv:1606.06298v3

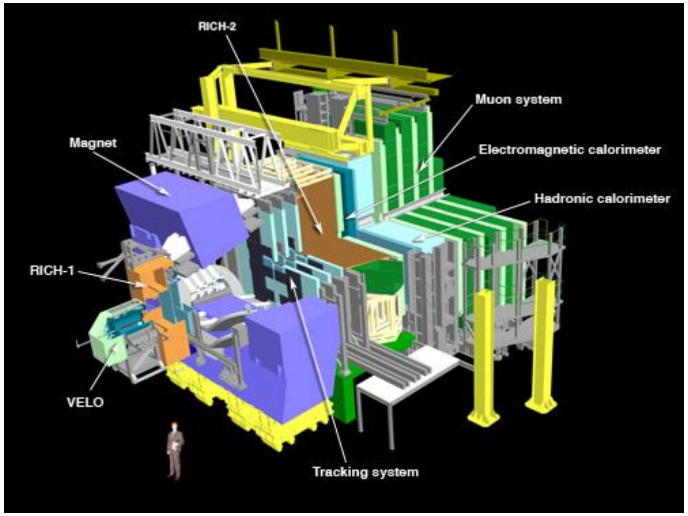
TeV frontiers at the LHC

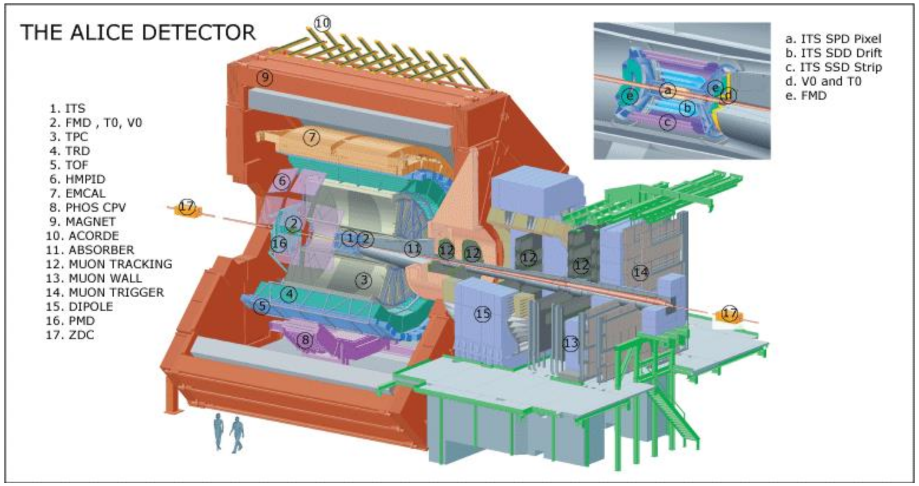
Electroweak and TeV phenomena (e.g. Higgs)





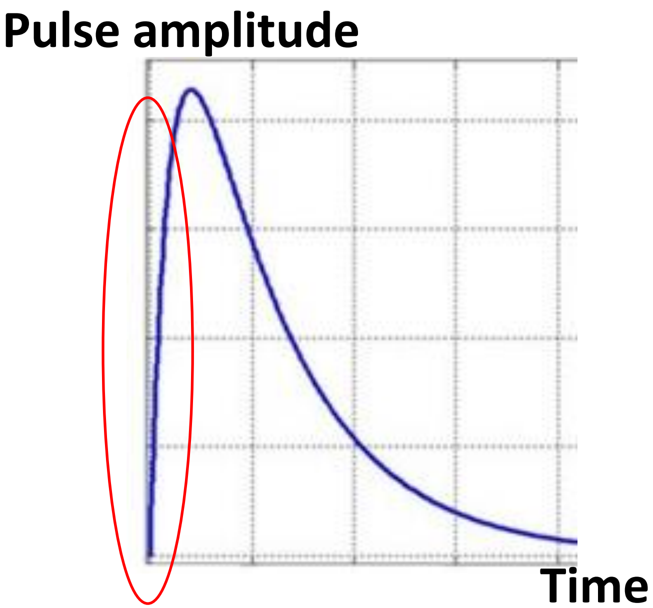
CP violation, hadron physics, quark-gluon plasma





Time measurement at TeV Detectors

Measured as the arrival time, relying on detection and electronics capabilities

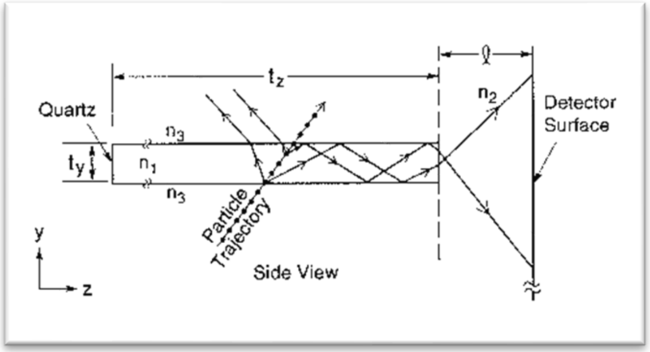


Usual detector units (e.g. calorimeter, muon detectors) at the LHC register time at **ns precision**

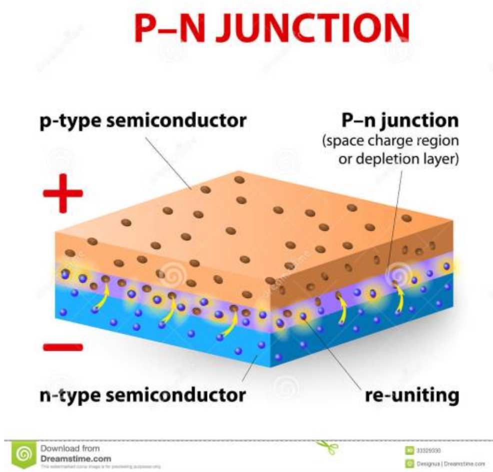
ALICE has a TOF based on MRPC, providing <100 ps time resolution

LHCb, ATLAS and CMS plan to deploy timing detector with
10-30 ps precision before irradiation per particle for high luminosity LHC

LHCb with DIRC

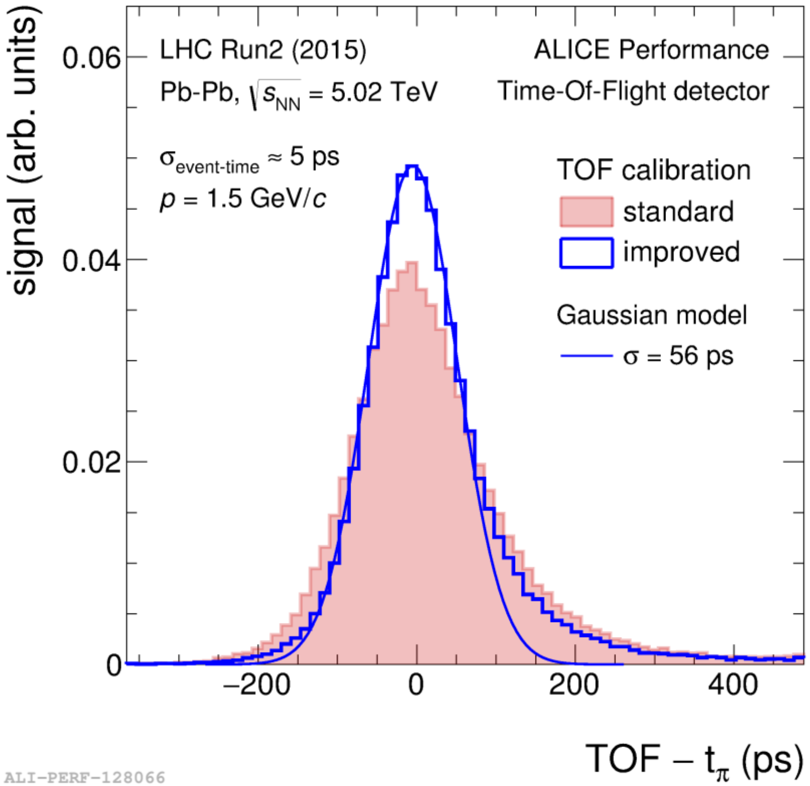


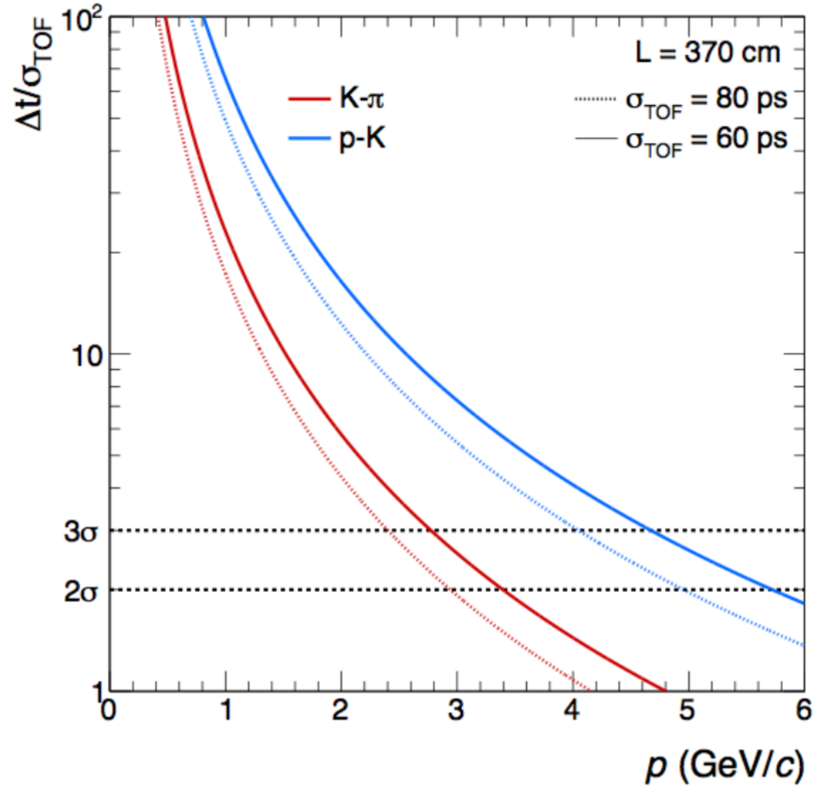
ATLAS/CMS with silicon semiconductor



ALICE TOF performance

arXiv:1809.00574v1

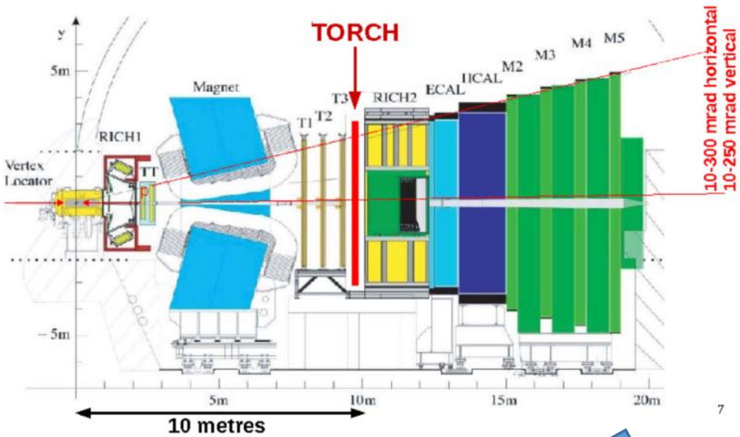


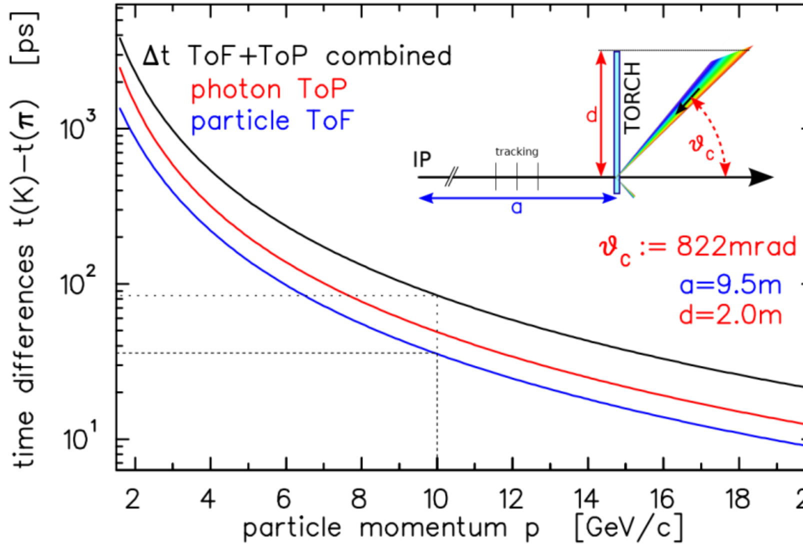


With improved calibration, the TOF time resolution can be as good as 60 ps

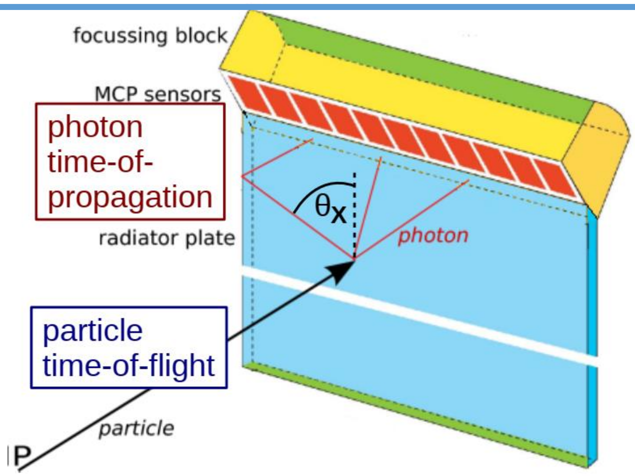
LHCb plans to light a TORCH

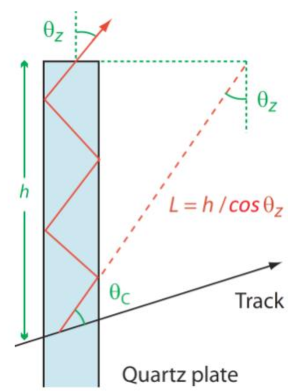
TORCH (Quartz + Mirror + MCP-PMT)

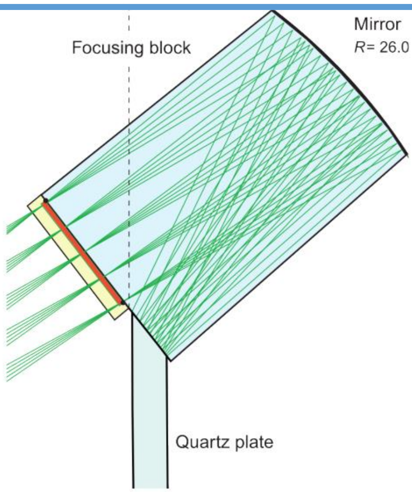




π-K separation and potentials beyond



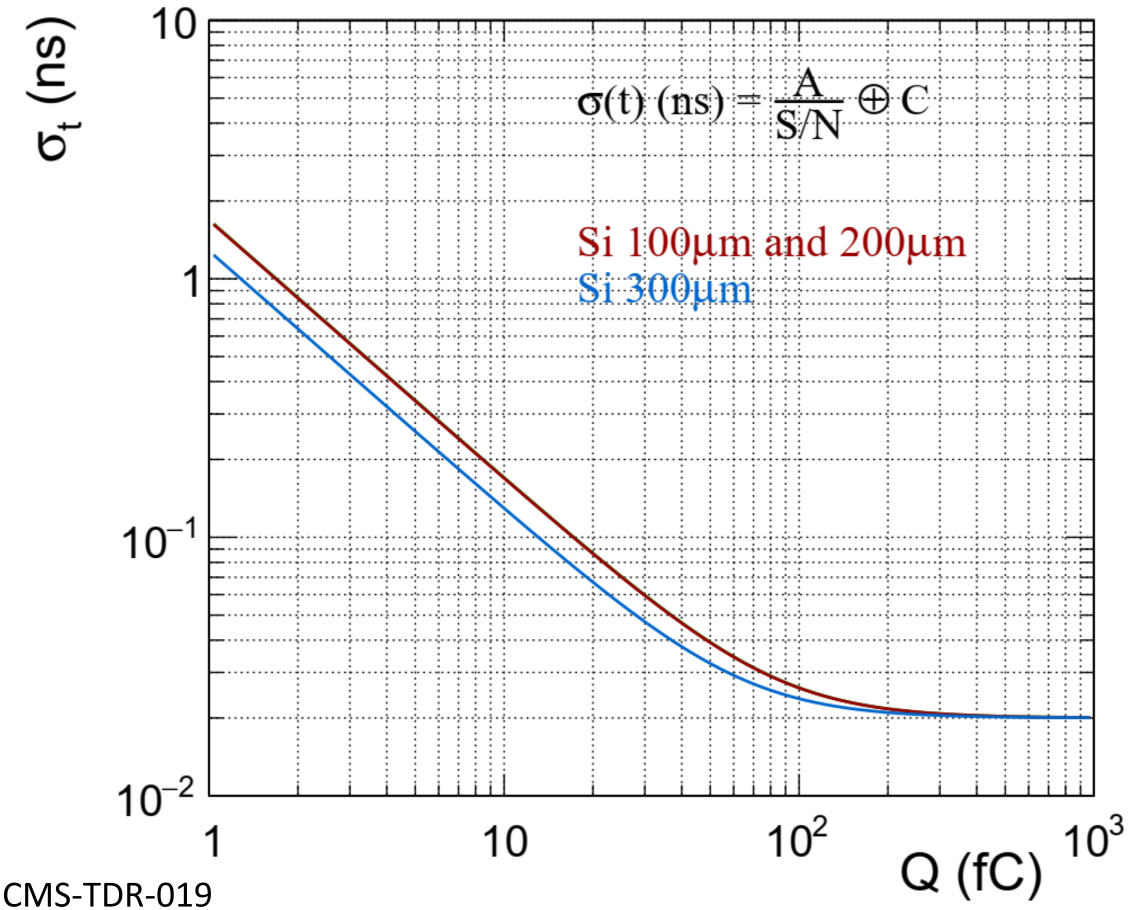




2016 JINST 11 C05020

CMS "Timing" Calorimeter

To use a sampling calorimeter with silicon in the forward region (1.5<|η|<3) to endure high dose and provide timing info.



CMS-TDR-019

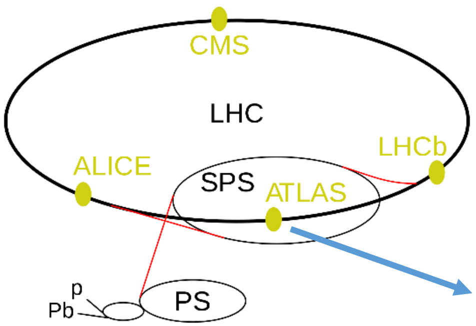
Time the showers to a great precision, ~ 25 ps for 50 fC deposition

Next

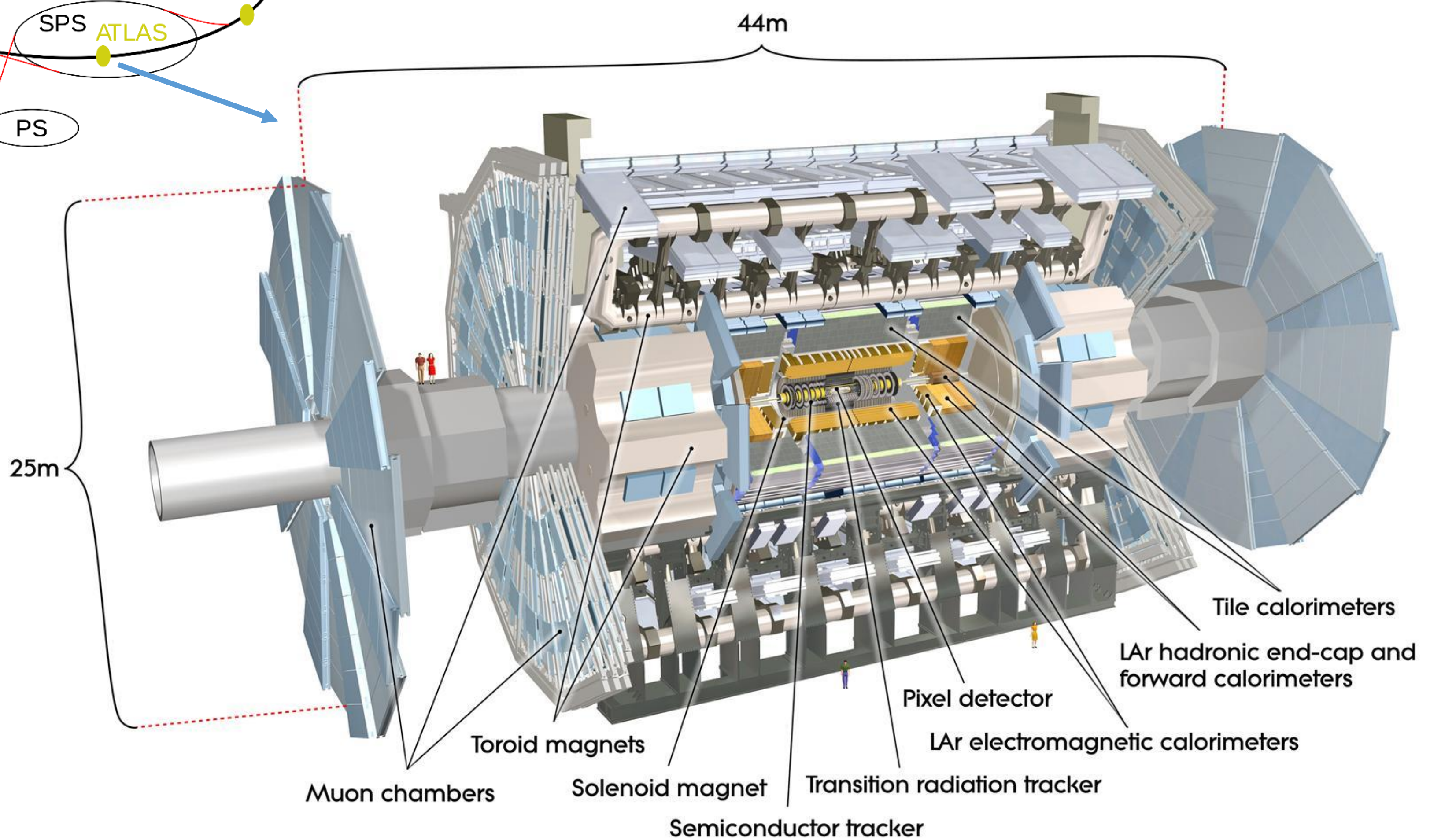
Using the ATLAS timing detector project as an example

to demonstrate the step-by-step considerations for designing those novel detectors

ATLAS Detector

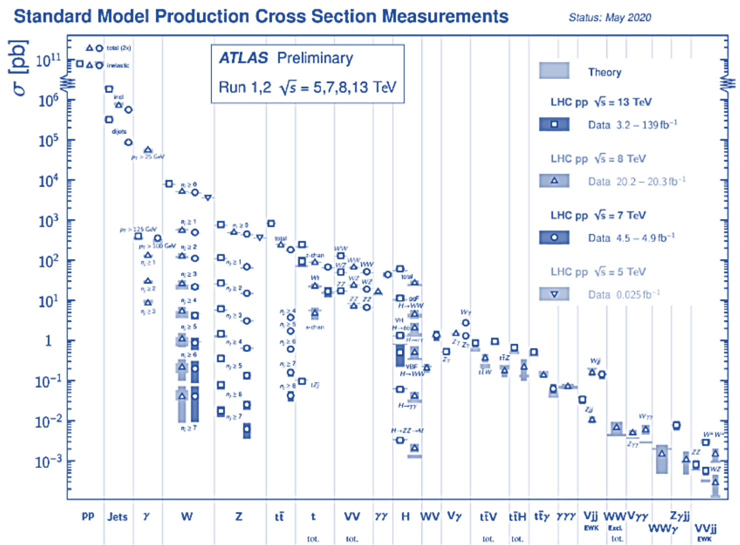


Designed for a thorough investigation of
Higgs boson physics and **new physics** at TeV scale

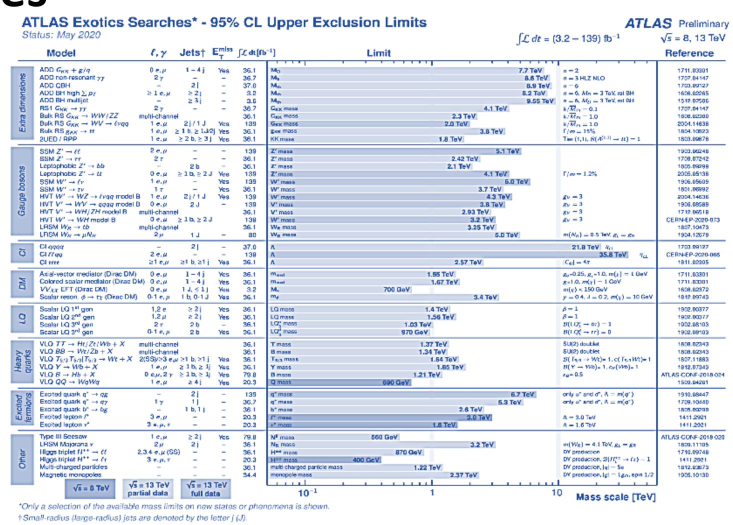


Now: 140 fb^{-1} 13 TeV pp collisions

Measurements



Searches



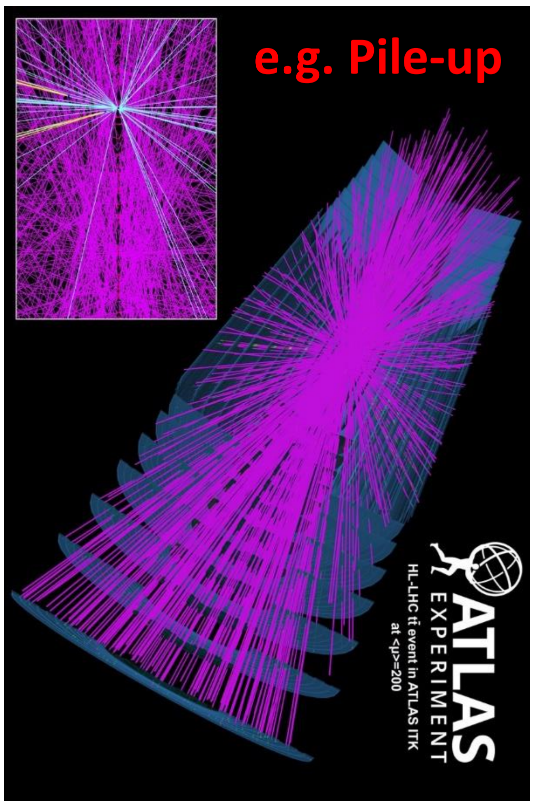
1000+ phase spaces or channels investigated

Standard Model more precisely **verified**, yet **no new physics** found

Ultimate sensitivity to help reveal the nature of Higgs boson and existence of new physics at **High-luminosity LHC,** with about **3 ab^{-1}** 14 TeV pp collisions

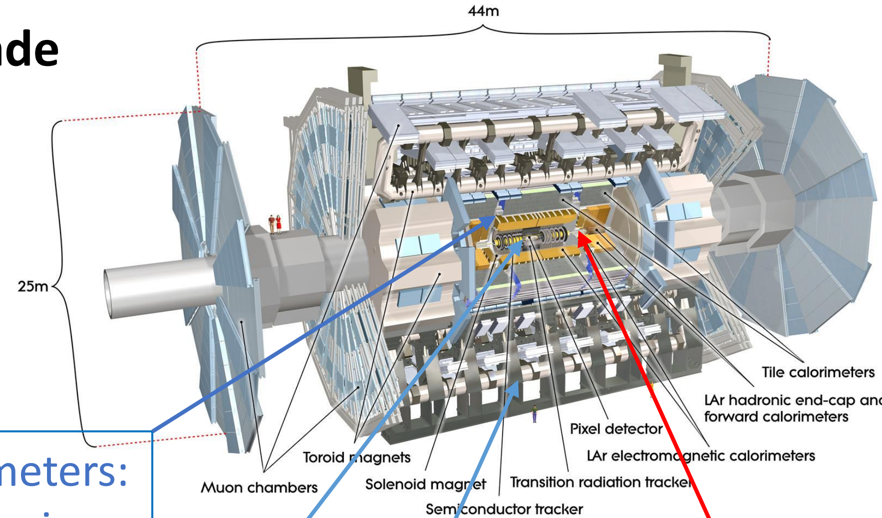
Future: HL-LHC up to $3ab^{-1}$ pp collisions

Unprecedented opportunities,
Unprecedented challenges



Phase-II Upgrade (2025 – 2027)

Sustainability
Improvement
Novelty



LAr, Tile Calorimeters:
Readout electronics

New Inner Detector (ITk):
Full silicon detectors

TDAQ System:
Trigger and DAQ Upgrade

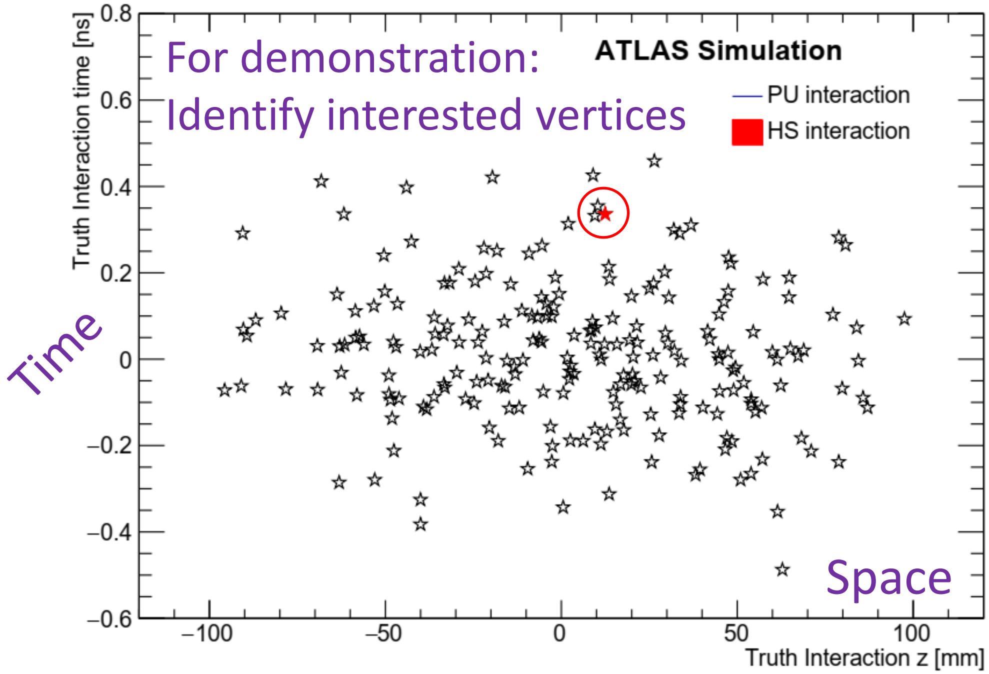
Muon system:
Readout electronics; partial upgrade of precision and trigger chambers

High Granularity Timing Detector (HGTD):
Track timing in forward region
(ATLAS-TDR-031)

More info.

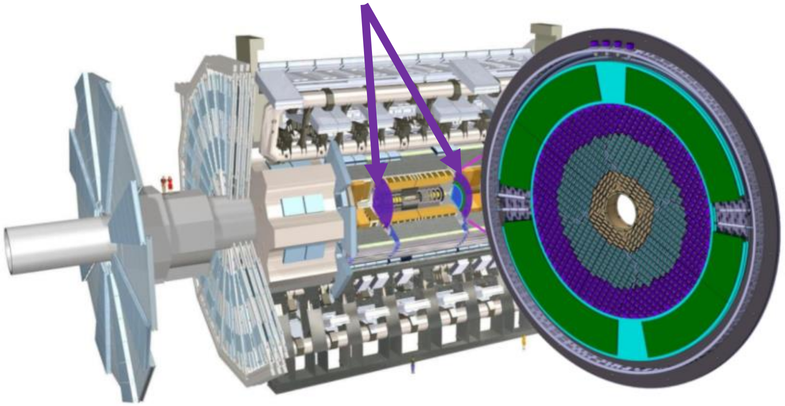
Motivation for HGTD

Precise timing O(10) ps will introduce a new dimension for physics at ATLAS



- Improve on the pileup suppression
- Would enhance lifetime/pID measurement

Minimum-bias scintillator ending service then → **Opportunity to install a novel detector**



- Forward region only (no plans nor resources for a full coverage)
- Tight spatial constraints
- Radiation hardness and O(10) ps timing requires → advanced detector technologies
- Also a luminosity detector

HGTD in a nutshell

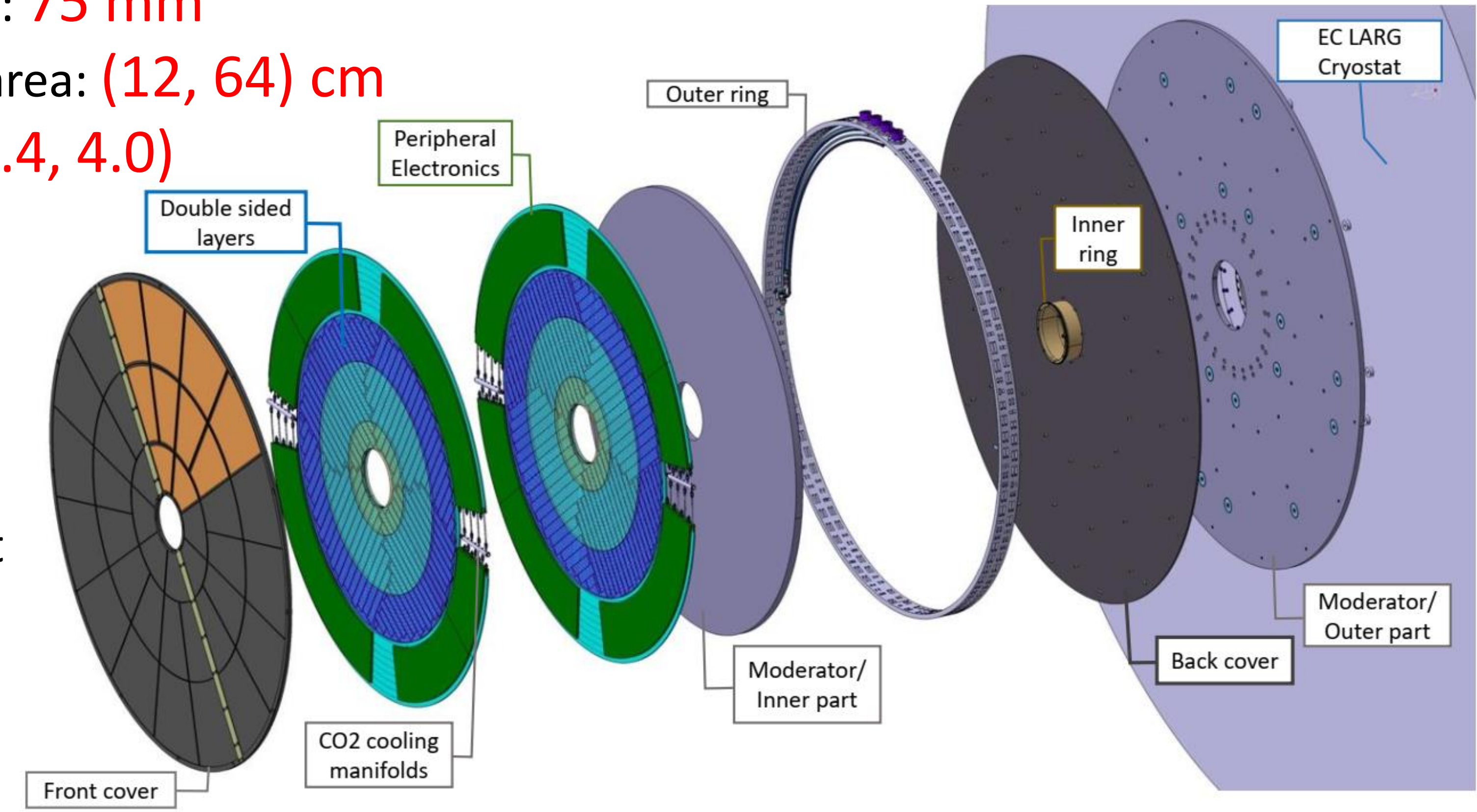
Overall thickness: 75 mm

Radial sensitive area: (12, 64) cm

|η| coverage: (2.4, 4.0)

2 double-sided layers,

4 measurement planes



> 3600000 Low Gain Avalanche Detector (LGAD) units, each 1.3 mm x 1.3 mm x 50 μm (active), grouping into > 8000 modules, containing > 16000 ASIC FEBs ……

Time resolution:

per-hit **35 – 70 ps**

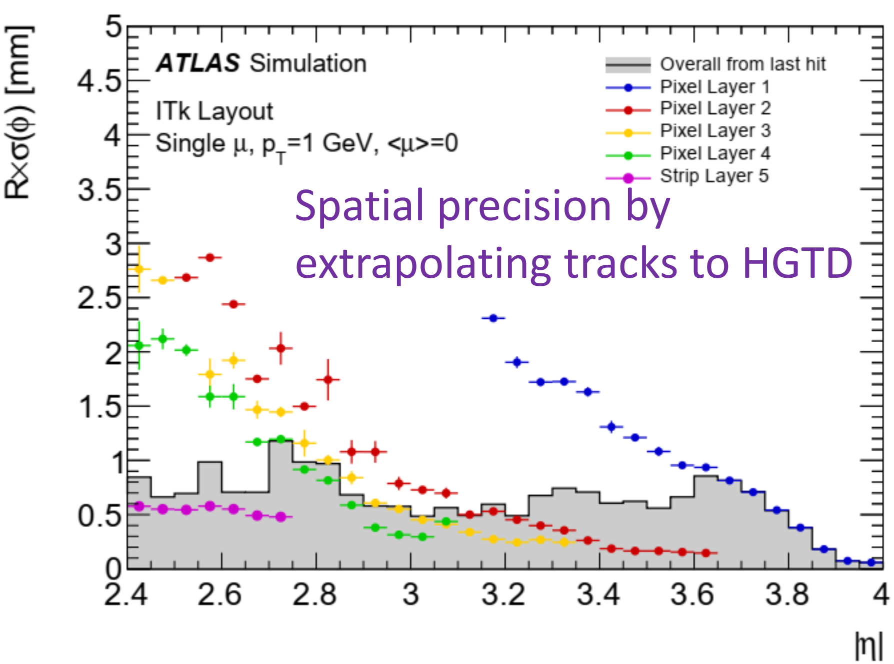
per-track **30 – 50 ps**

Radiation-level dependent

About O(1) mm and O(10) ps

1.3 mm – unit sensor size

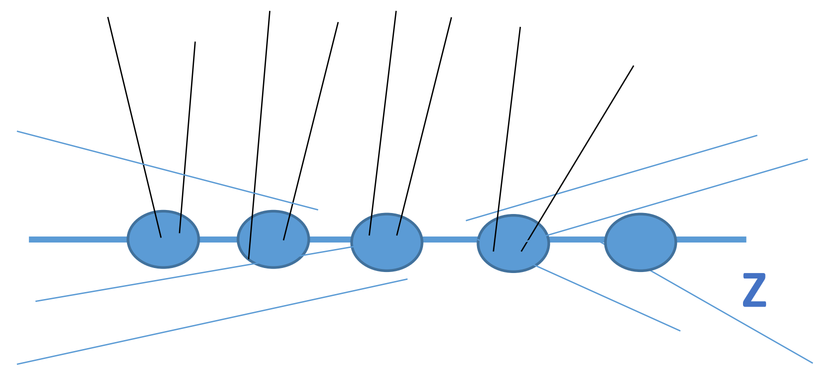
- About the spatial precision of track extrapolation from silicon trackers
- Balanced also between occupancy, double hits, dead areas, capacitance, and increasing channel numbers



35-70 ps per hit

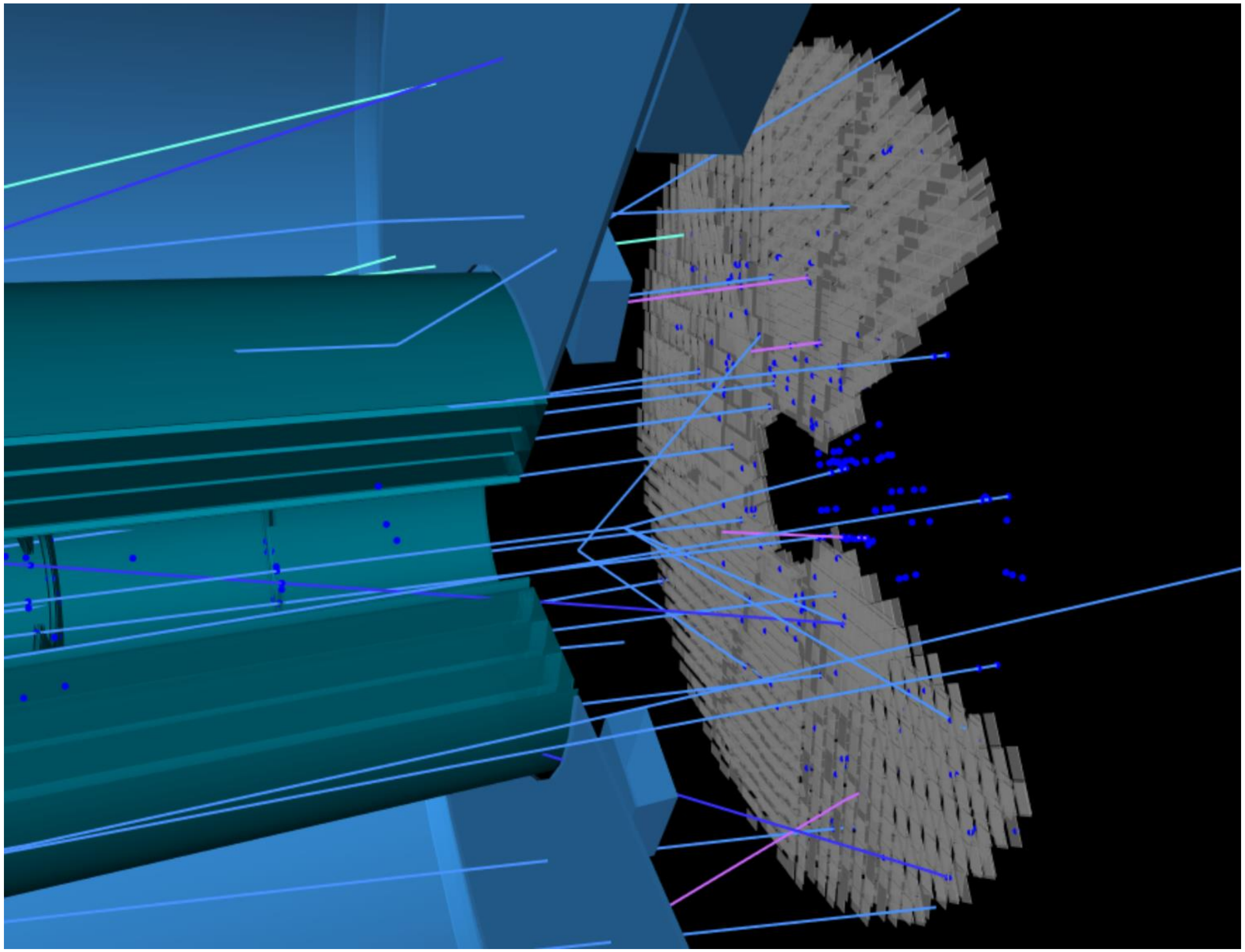
- Already cutting-edge specification
- bottom line: per-hit time resolution ≲ 100 ps to guarantee effectiveness in physics case

Complexity of tracks v.s. vertices, especially in forward region, worsen z_0 resolution



Timing the tracks (blue) can help to solve the mystery

An event display for illustration



Who can reach HGTD for a time measurement?

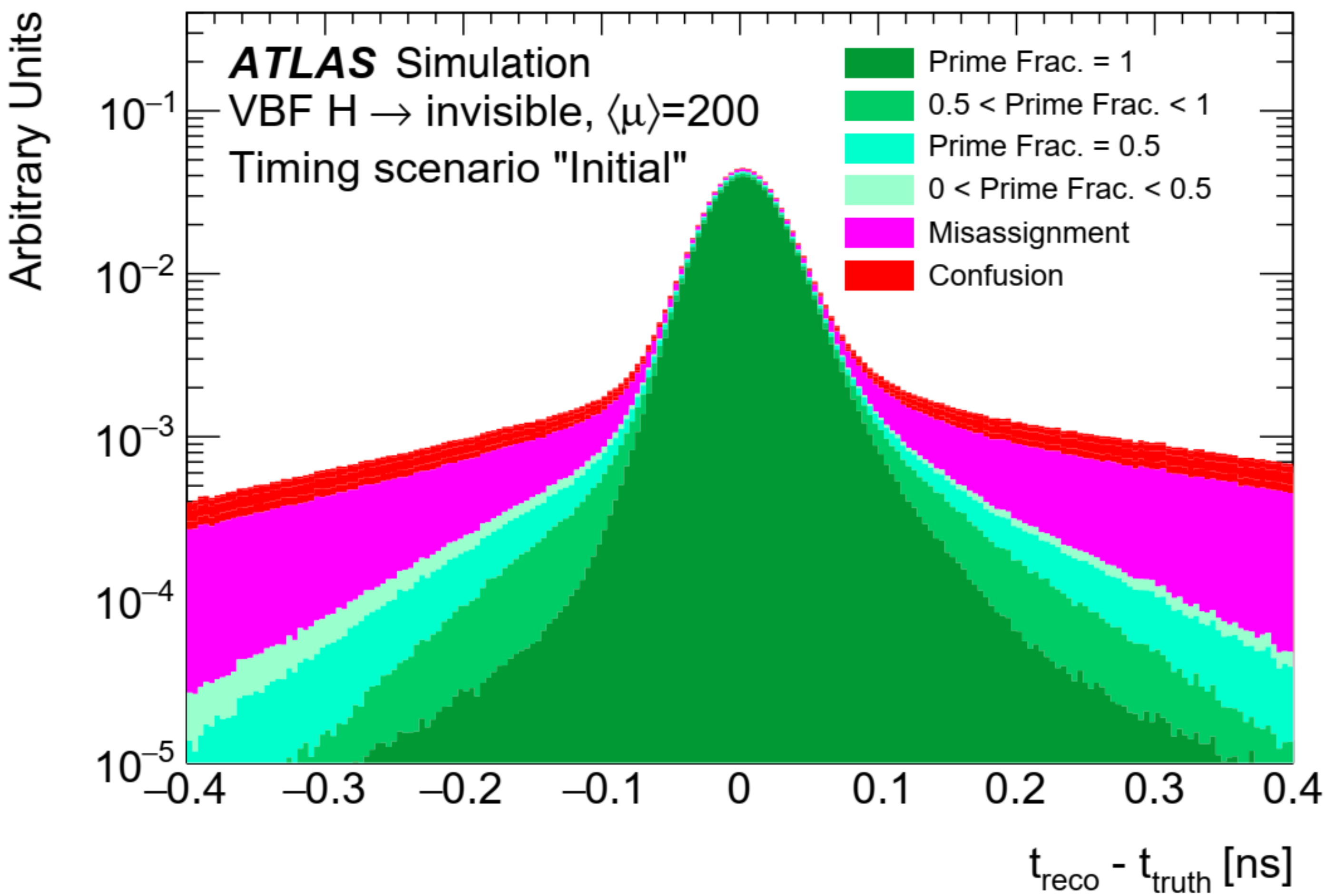
Charged particles from hard scattering produced before touching the detector

Charged long-lived particles

Charged particles from pileup and material interactions (e.g. δ electrons)

Time the charged tracks

A reconstructed inner track can be extrapolated to HGTD (Kalman Filter), extrapolated hits in HGTD provide time measurements

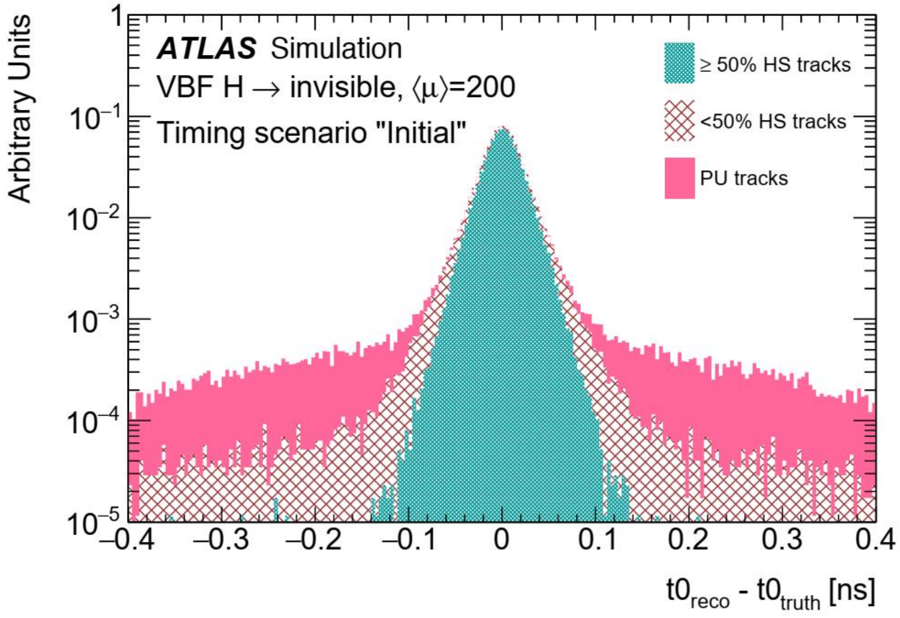


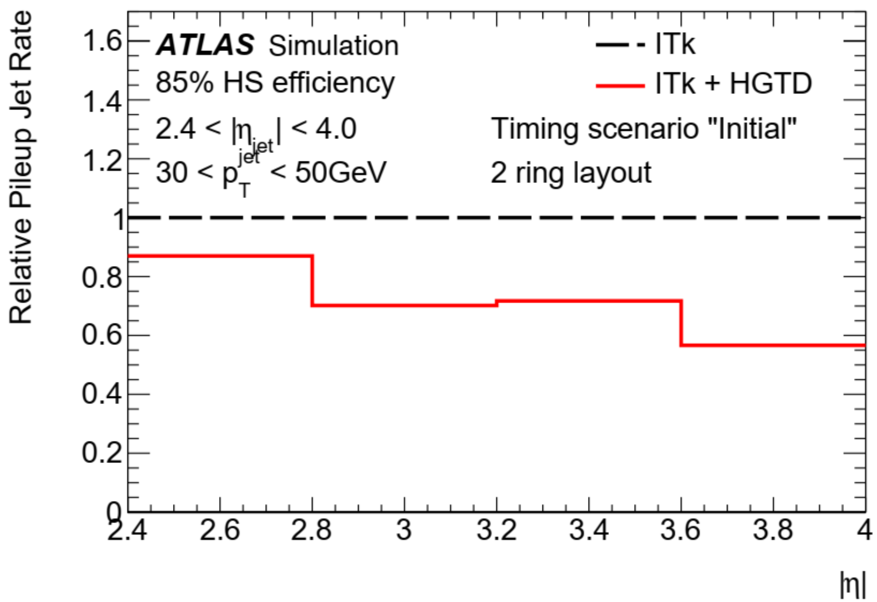
Efficiency and precision strongly depend on the type of the tracks

Performance for interested hard scattering tracks expected to be satisfactory

Demonstration of Physics Potentials

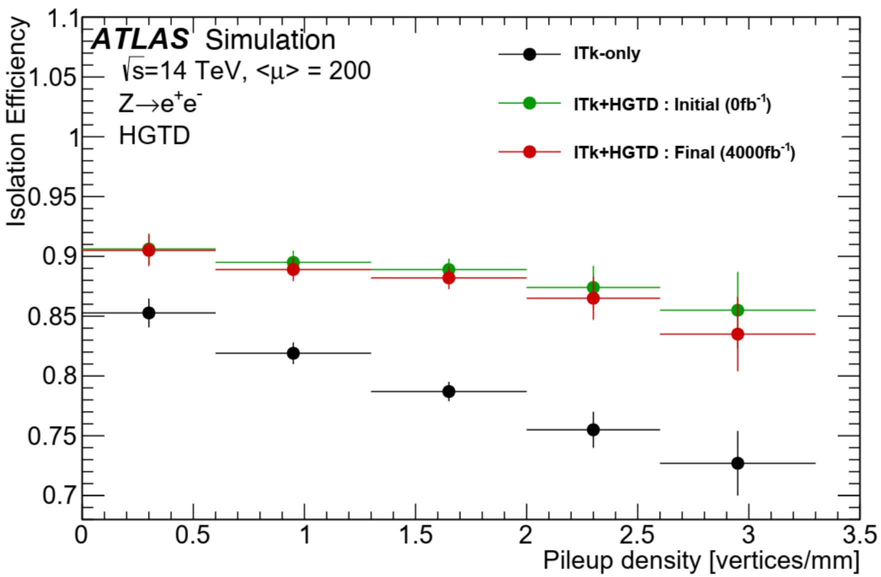
Crucial to have time for vertices, MVA / machine learning in play (for cluster timed tracks and for pick up proper clusters):



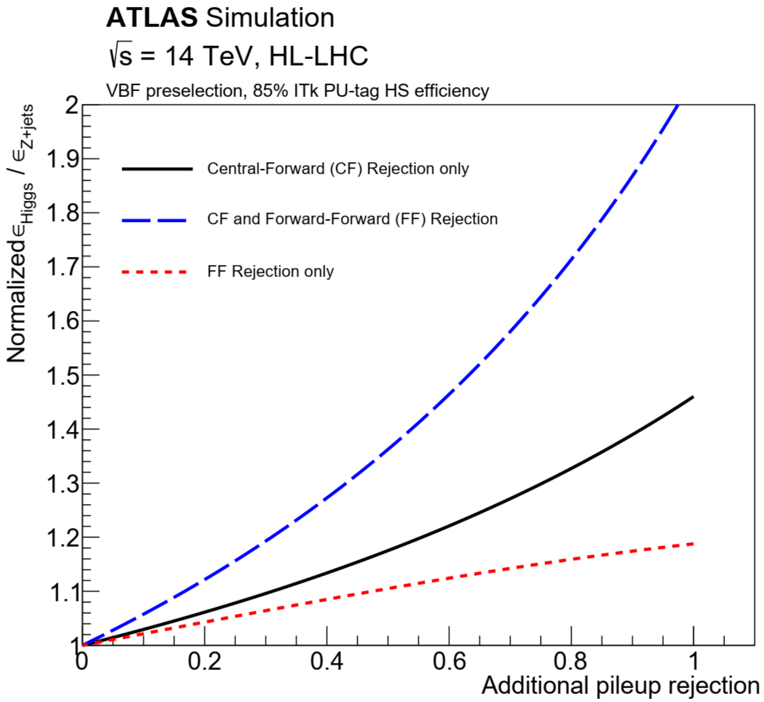


Up to 2 x more power to further suppress pileup contributions in the forward region, on top of the planned full silicon detector

Demonstration of Physics Potentials



Isolation is a standard variable at colliders assisting in pID, time can make isolation more eff. against pileup

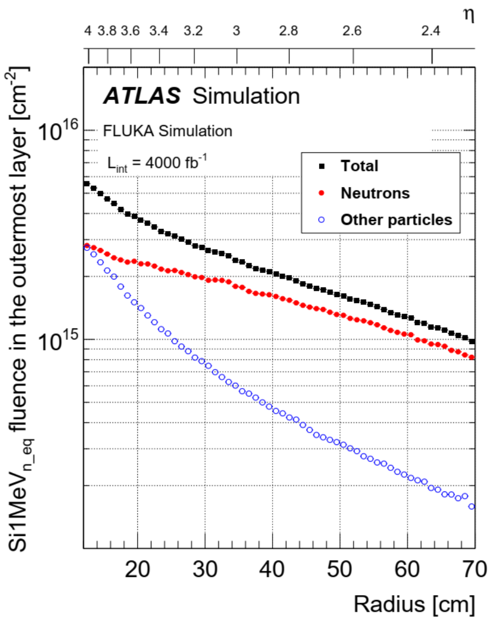


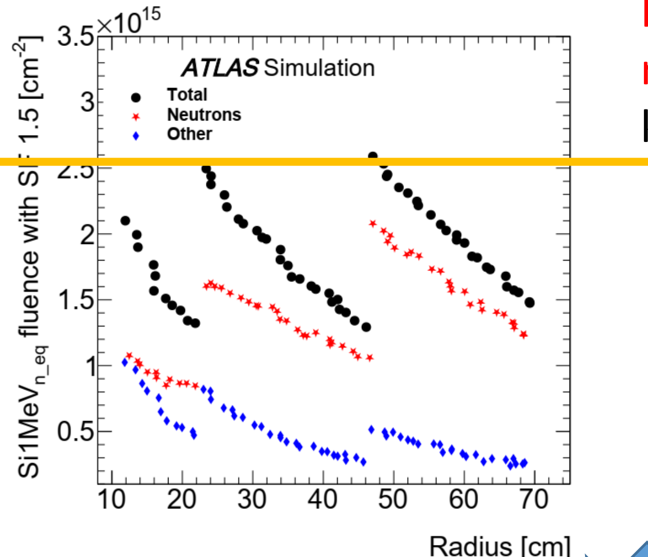
For analyses subject to pileup backgrounds (e.g. VBF H → invisible), sizable improvement of S/N

Although only a limited number of cases were discussed (which focuses on pileup rejection), more opportunities are being further explored – new physics sensitivity, pID, heavy flavor jet tagging, … …

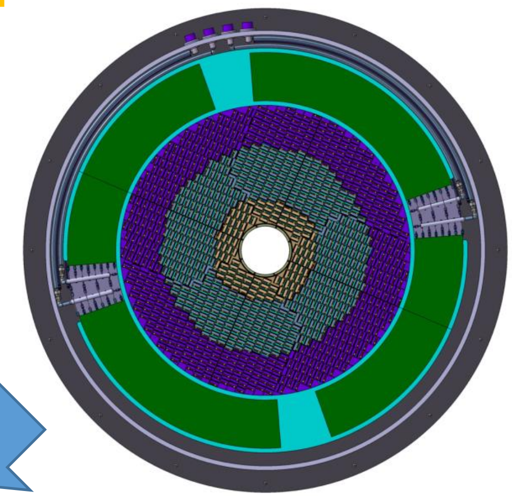
Three-ring and Replacement

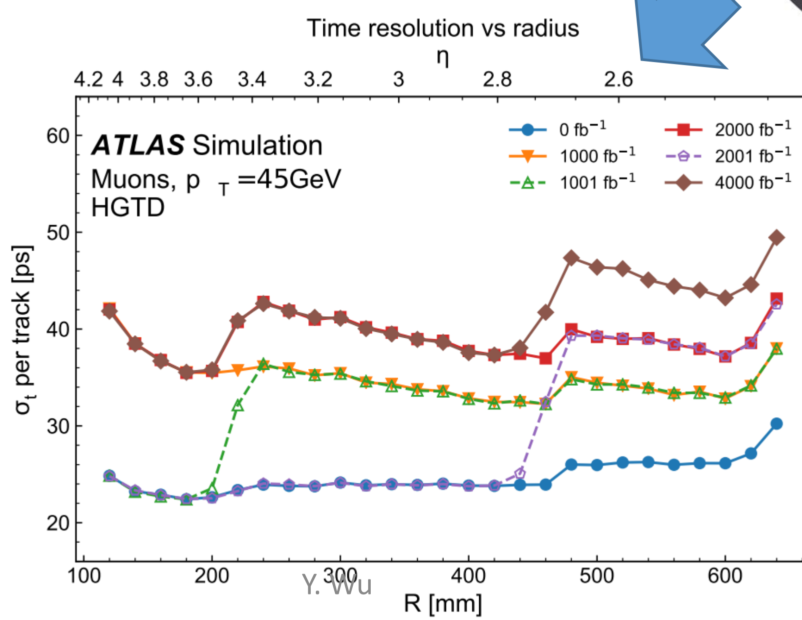
Suffers from high radiation (forward) => worsen performance





Replace inner and middle rings along data taking to keep total dose within safety



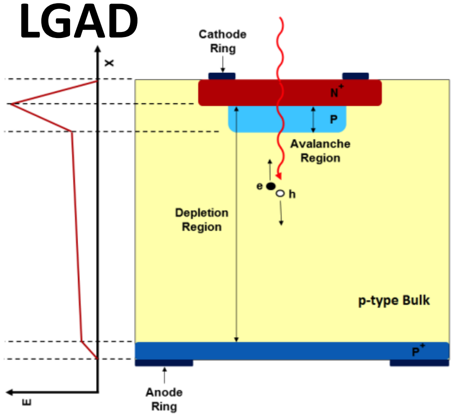


Expected stabilized performance (shown for track σ_t)

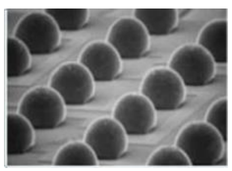
Timing Measurement

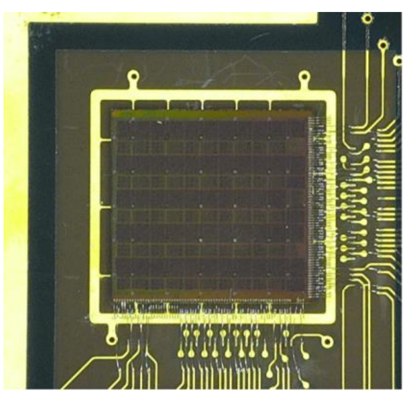
* unirradiated case
** with time-walk correction expected

LGAD



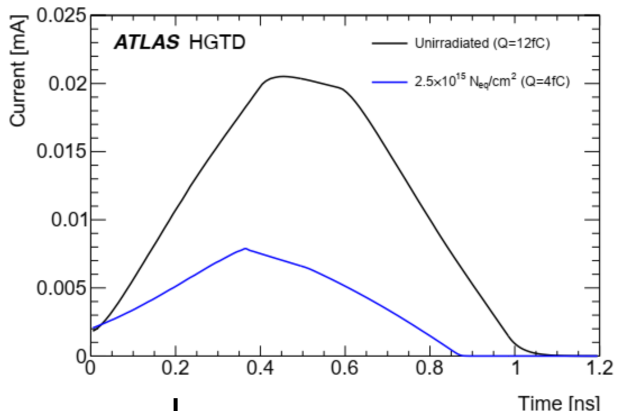
Bump-bonding



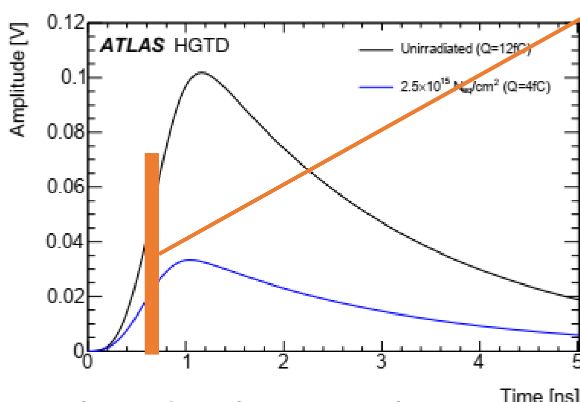


Customized ASIC (ALTIROC)

Simulated current pulse



After preamplification



Simulated voltage pulse

Time of arrival
→ time measurement

Resolution factors:

Sensor:
Landau effects $\lesssim$ 25 ps* → non-uniform e-h generation pattern

$$\sigma^2_{\text{total}} = \sigma^2_{\text{L}} + \sigma^2_{\text{elec}} + \sigma^2_{\text{clock}}$$

Electronics / DAQ:
electronic noise (**jitter**), and amplitude variation (**time-walk****) $\lesssim$ **25 ps**; **clock** distribution $\lesssim$ **15 ps**

LGAD Design

** Pioneered by CNM, Barcelona; further developed with CERN RD50 collaboration*

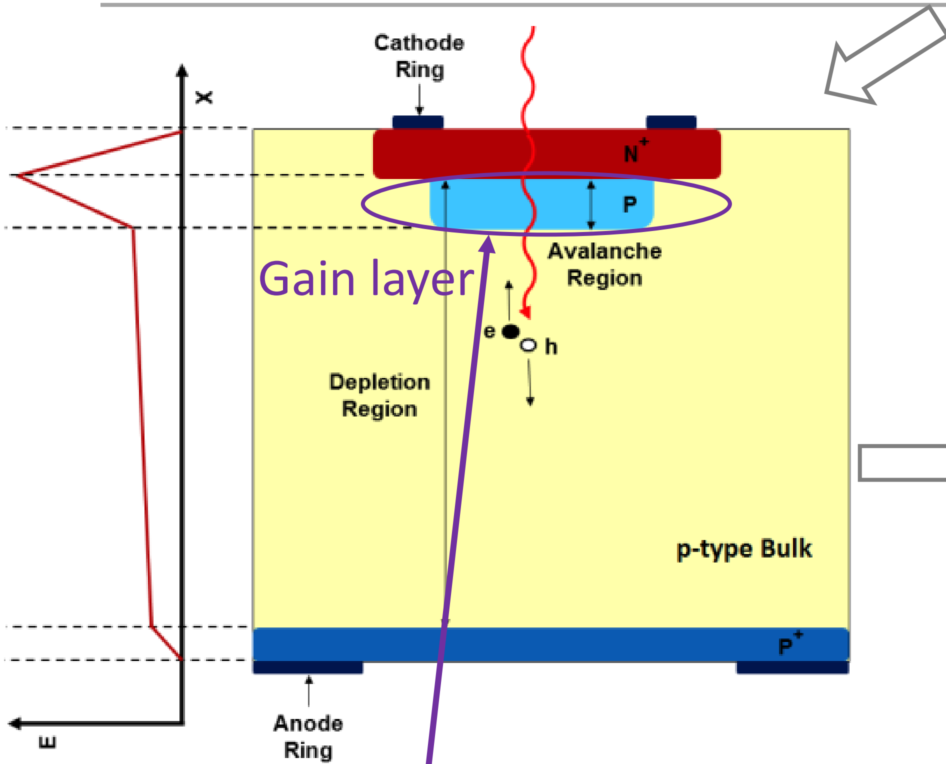
Silicon detector has good virtues for this application (radiation-hard, granularity, mature tech., …)

Keys* to achieve desired resolution

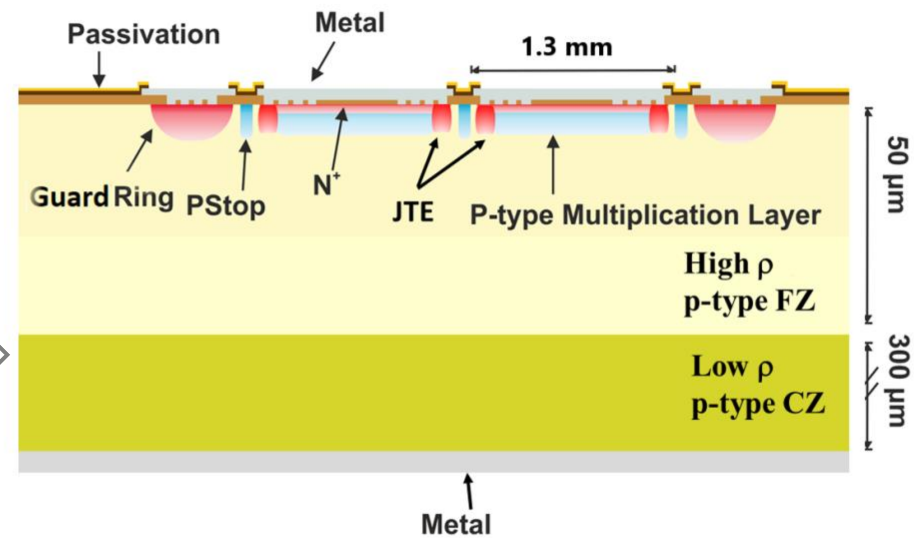
Thin: 50 μm

Gain: x20 (→10 fC)

⇒ Larger dV/dt
Larger S/N
Less Landau non-uniformity



N^+ - (P) - P^- - P^+



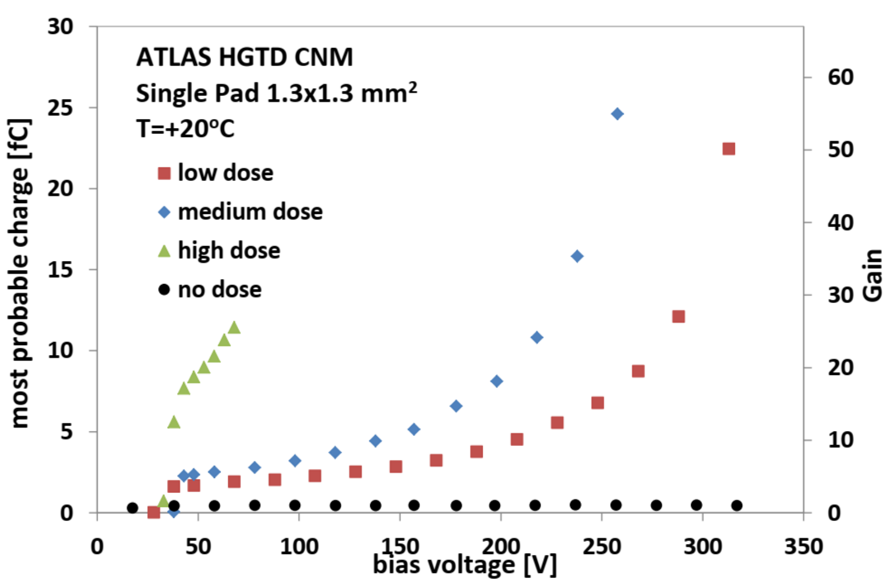
Careful R&D (with JTE, PStop, GR, interpad gap, etc.) to guarantee quality of E-field

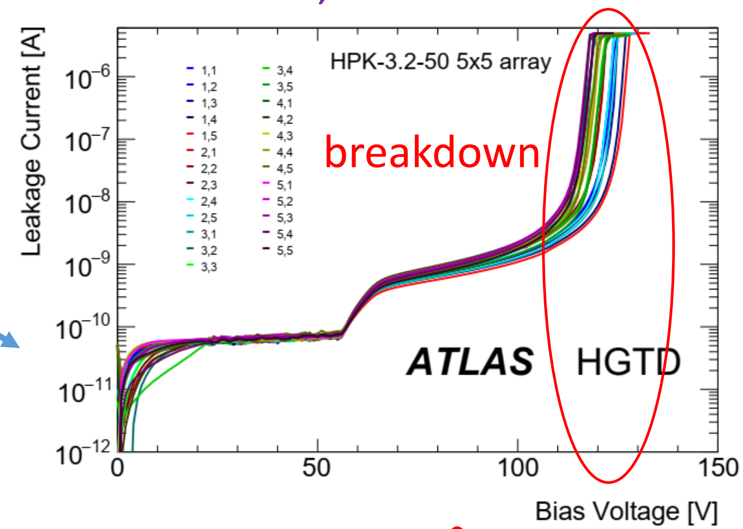
Sensor Performance

Sensor R&D involves multiple manufacturers (varying gain doping etc.) → Electrical measurement (I-V, C-V)
Laser or radioactive source, Test beam

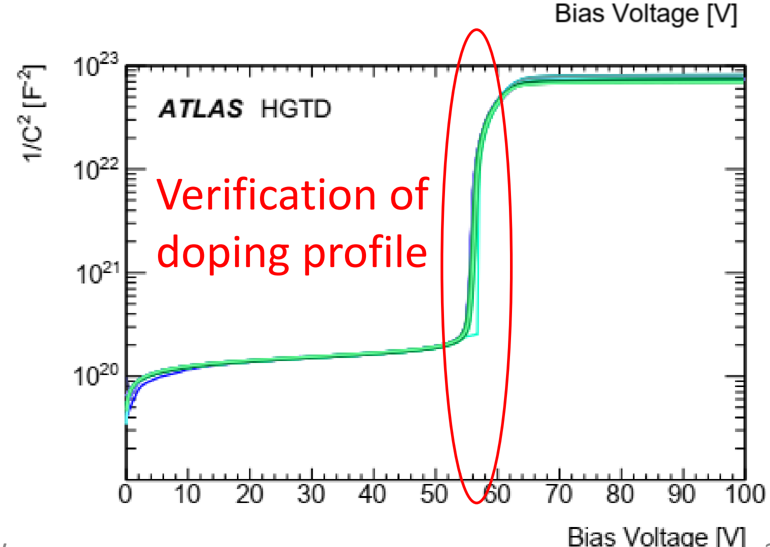
Promising performance shown (unirradiated sensors)

Effectiveness of doping gain layer





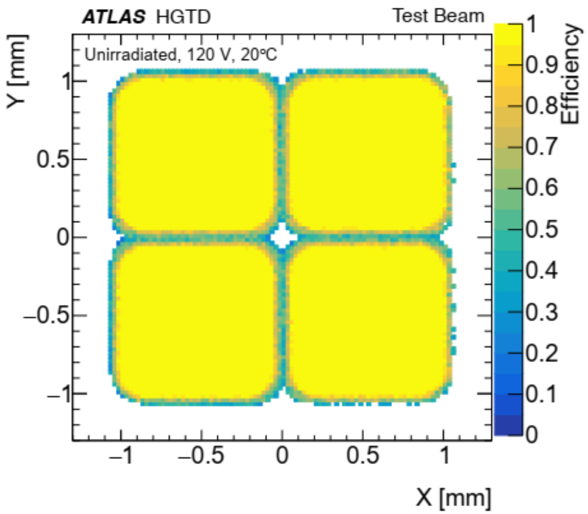
I-V



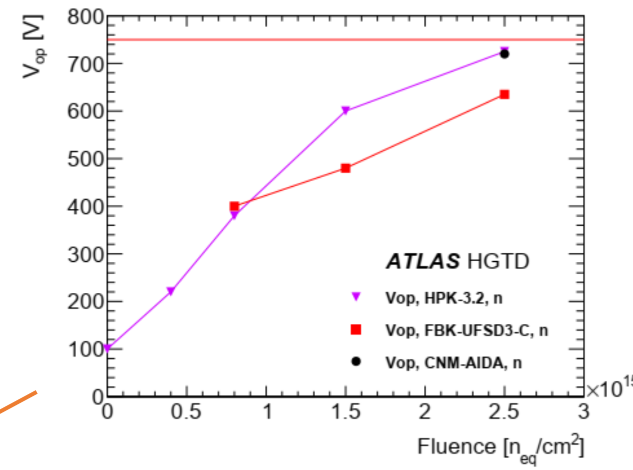
C-V

Sensor Performance

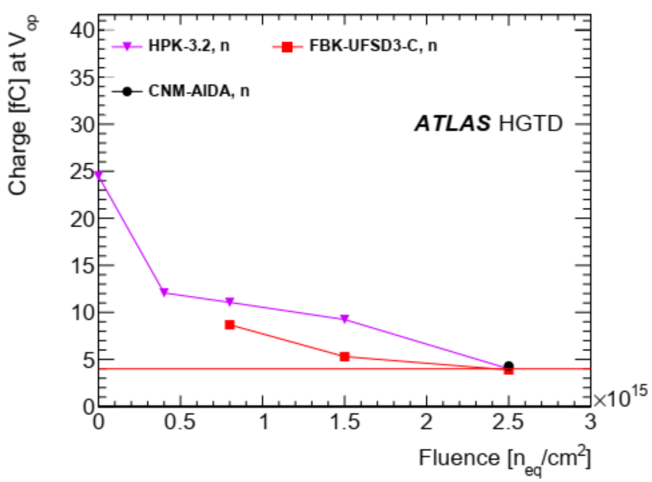
Test beam verified high hit efficiency

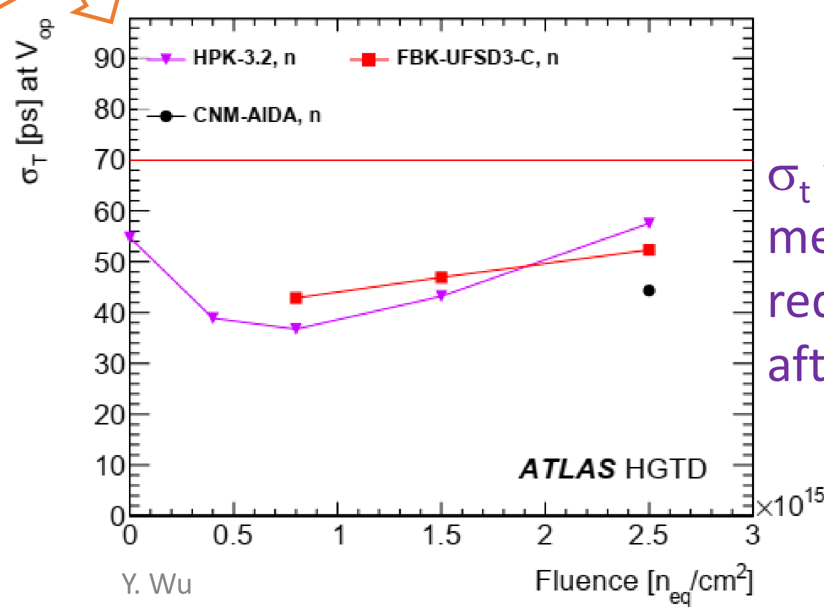


Operation voltage v.s. fluence: 100→ 700 V



Charge collection v.s. fluence

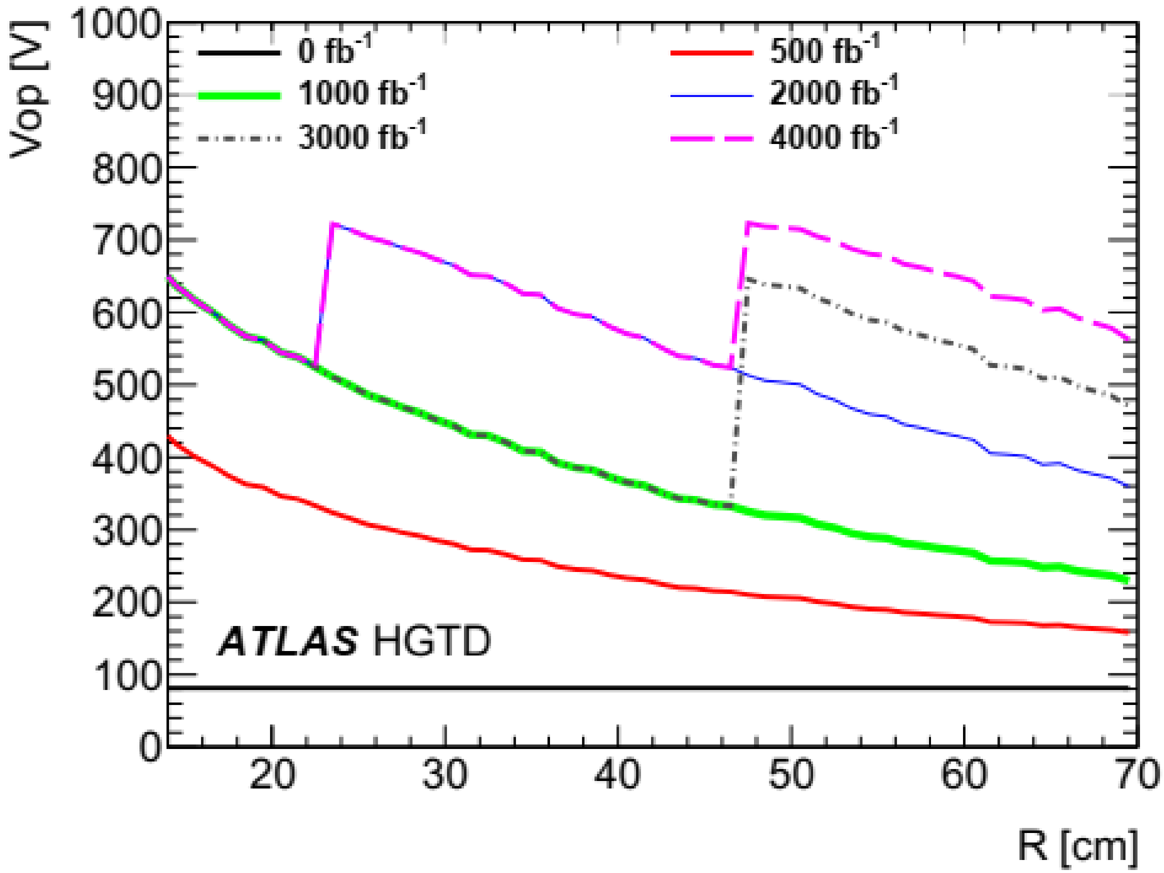




σ_t v.s. fluence: meet the requirement after irradiation

Operation and Plan

Planned operation voltage for LGAD v.s. lumi / R



LGAD manufacturing shown to meet detector specification

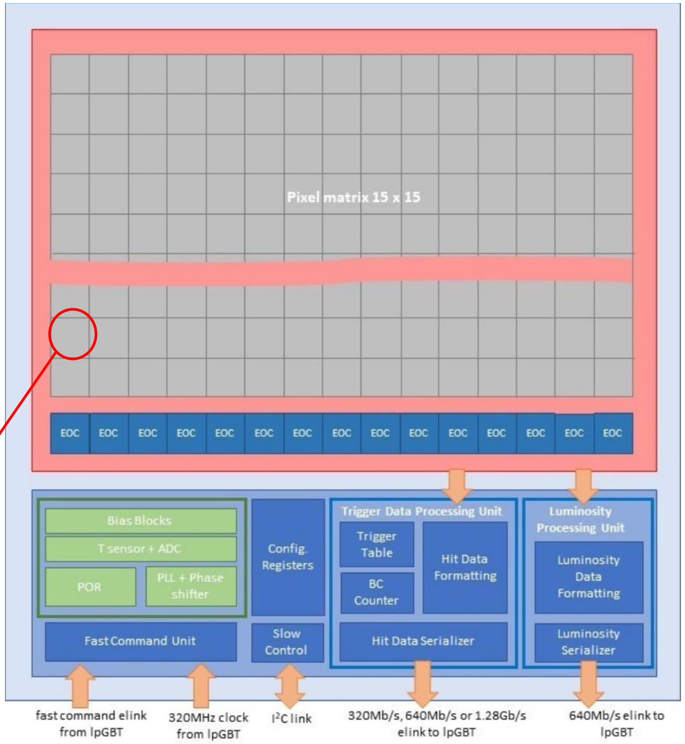
Further optimization ongoing …

Frond-end Electronics

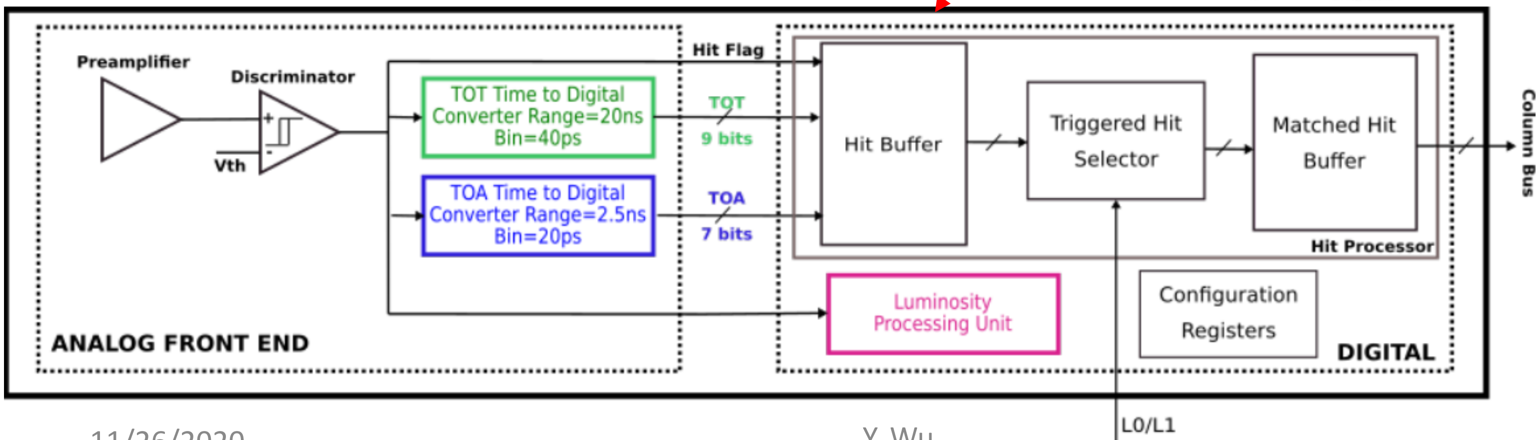
ALTIROC Key characteristics:

- Radiation hardness
- Noise <= 0.5 fC
- Dynamic range: 4-50 fC
- Low min-threshold: 2 fC
- Cross-talk < 5%
- Jitter, time-walk, TDC O(10) ps
- e-link driver bandwidth up to 1.28 Gbit/s

ASIC chip schematic

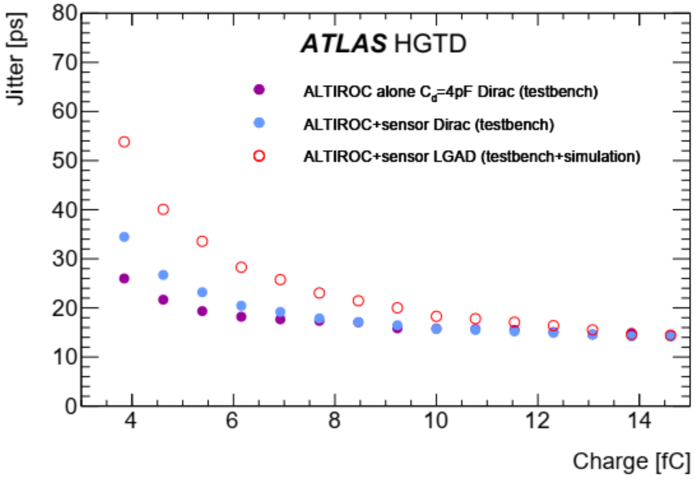


Single channel schematic

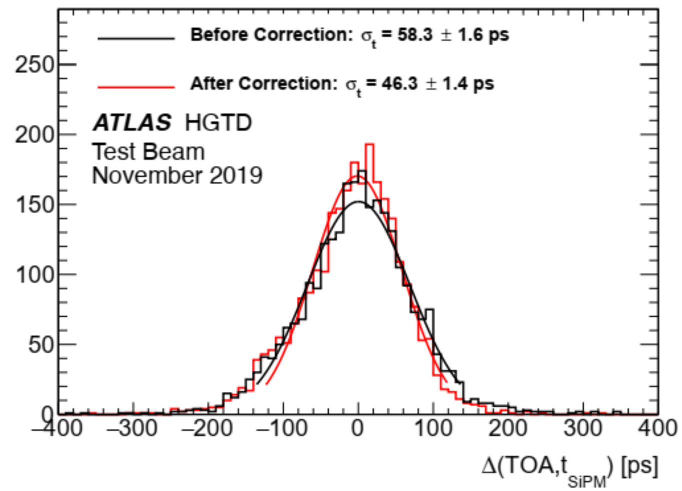


FEE performance

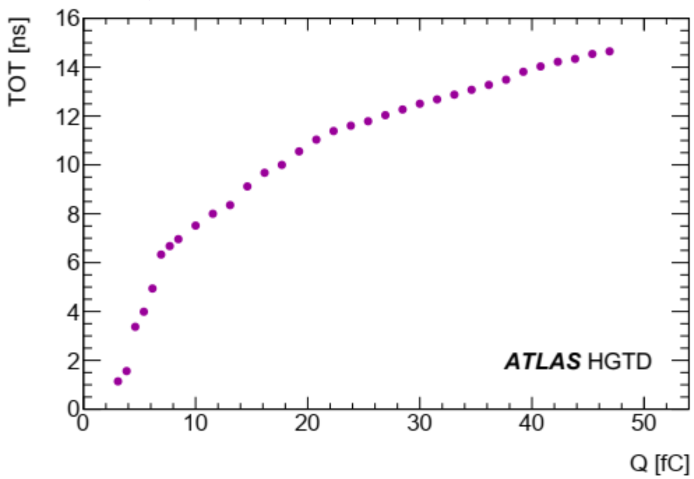
Jitter Estimation: meet the goal



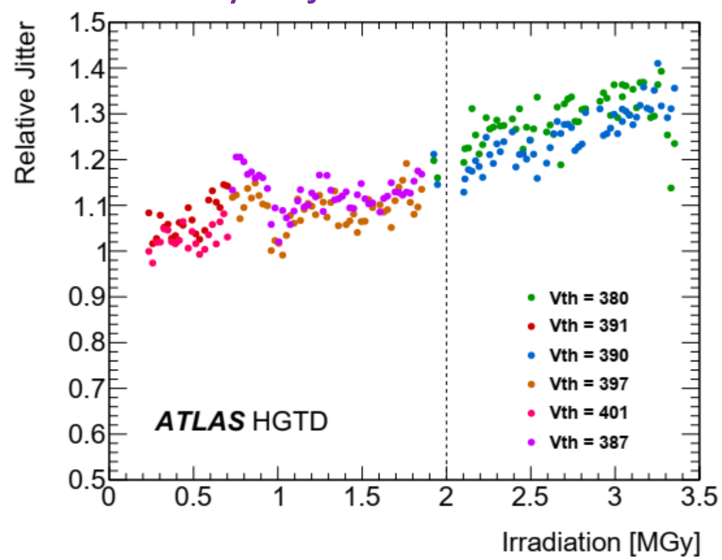
Test-beam LGAD+ALTIROC time resolution



TOT vs Q: used for time-walk correction



Stability of jitter v.s. irradiation

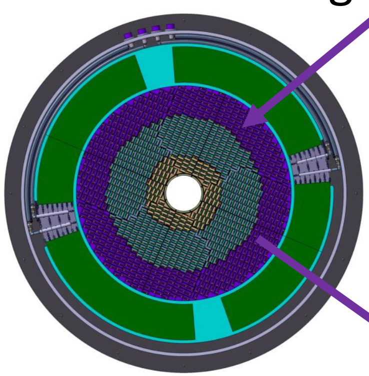


Iteration and completion of ALTIROC ongoing…

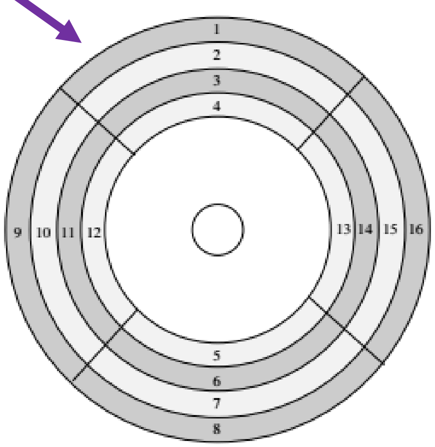
Luminosity Measurement

Precise knowledge of luminosity is a key to many physics studies

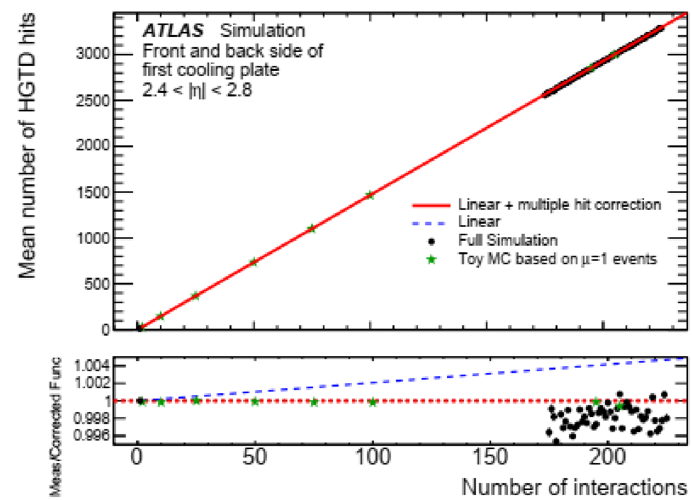
HGTD provides precise bunch-by-bunch luminosity measurement in its outmost ring



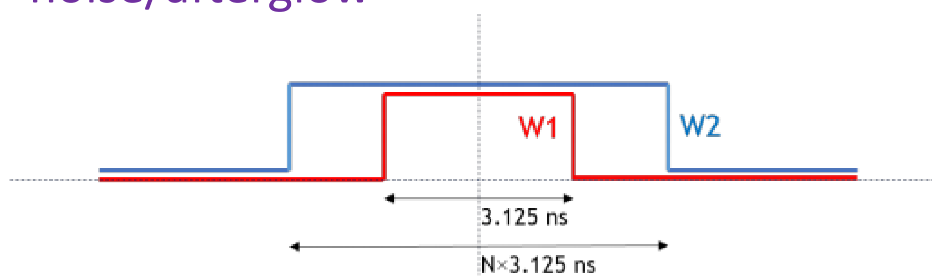
Planned for 16 partitions with independent measurements



High granularity → great linearity between measurements and luminosity

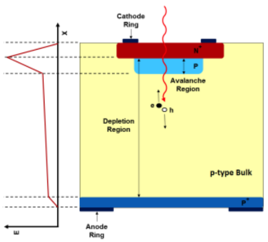


Unique two-timing-window scheme at ASIC level give in-situ measurement of noise/afterglow

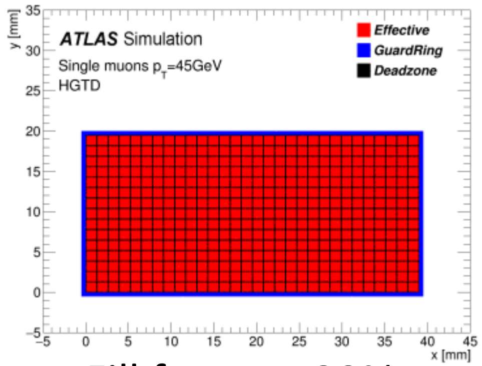


The Flow

Single LGAD Pad

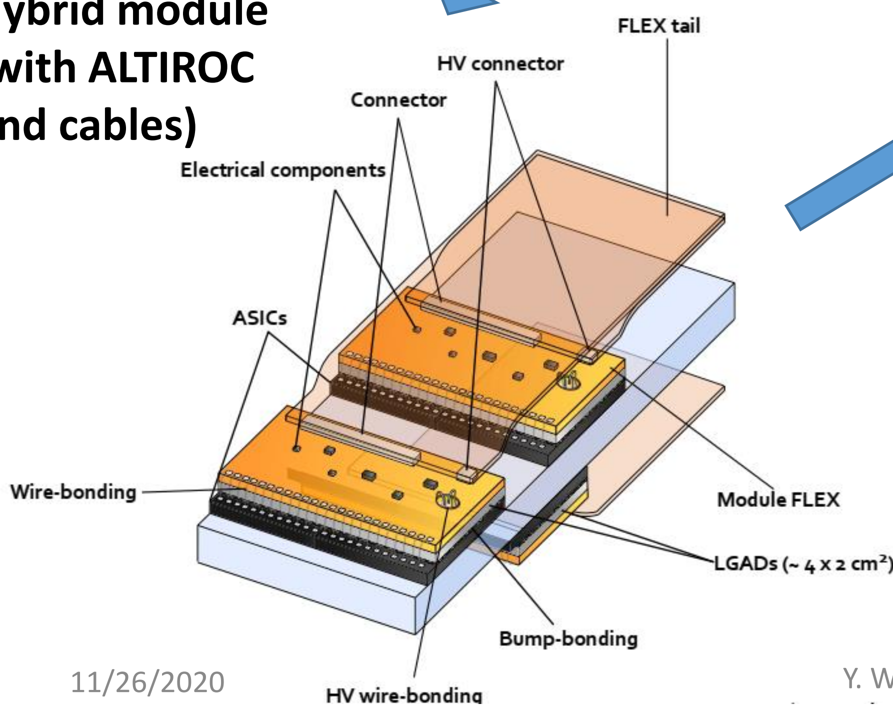


15 x 30 LGAD module



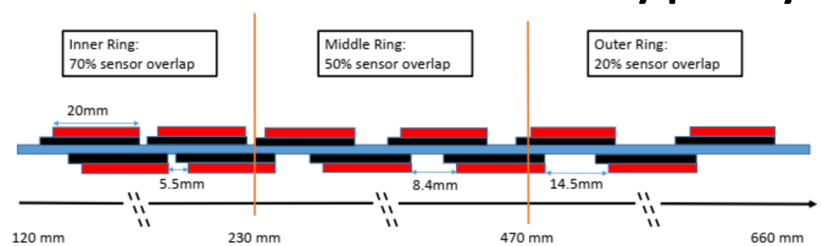
Fill factor ~ 90%

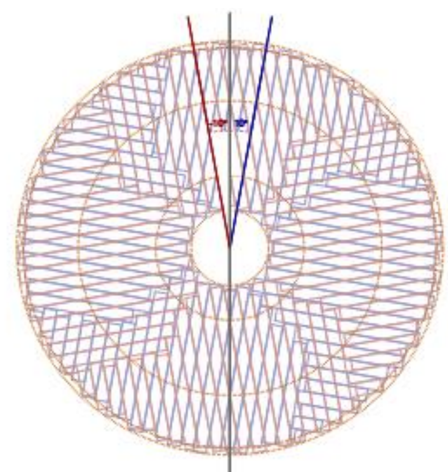
Hybrid module (with ALTIROC and cables)



Position modules on support structure

Front/Back Overlay per layer





Layer 1 and 2: small inclination angle

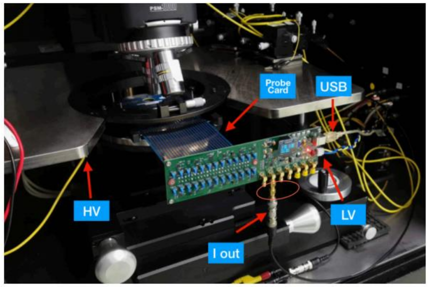
USTC setup for HGTD

More in Xiao's talk at CLHCP2020

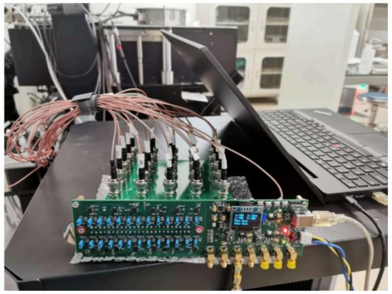
Ongoing R&D for HGTD, expected to install in 2027

USTC started efforts in 2019, building a high-precision silicon detector lab., focusing on sensor R&D and application, and related commitment to ATLAS HGTD

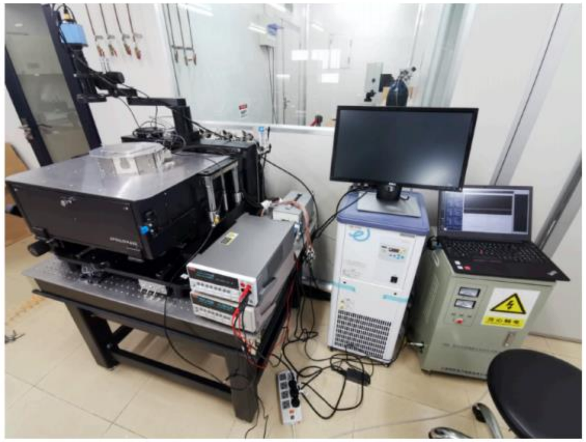
In collaboration with SJTU/TDLI

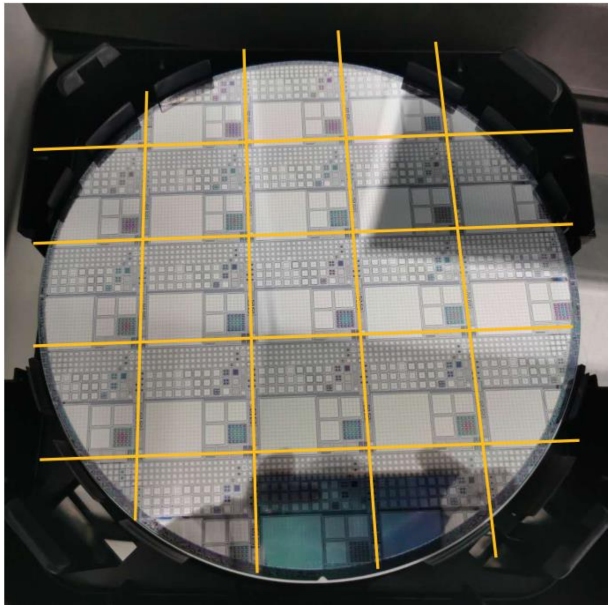


Room T. probe station


Digital switcher


Customized 5x5 probe card


New probe system
(cold, dedicated for HGTD)

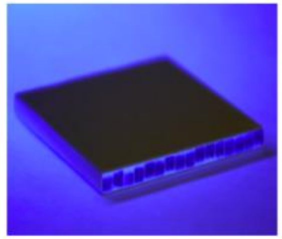


Already managed to successfully design LGAD sensors and meet the specification (fabricated by IME)

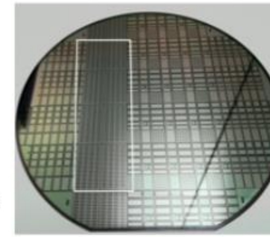
CMS Timing Detector

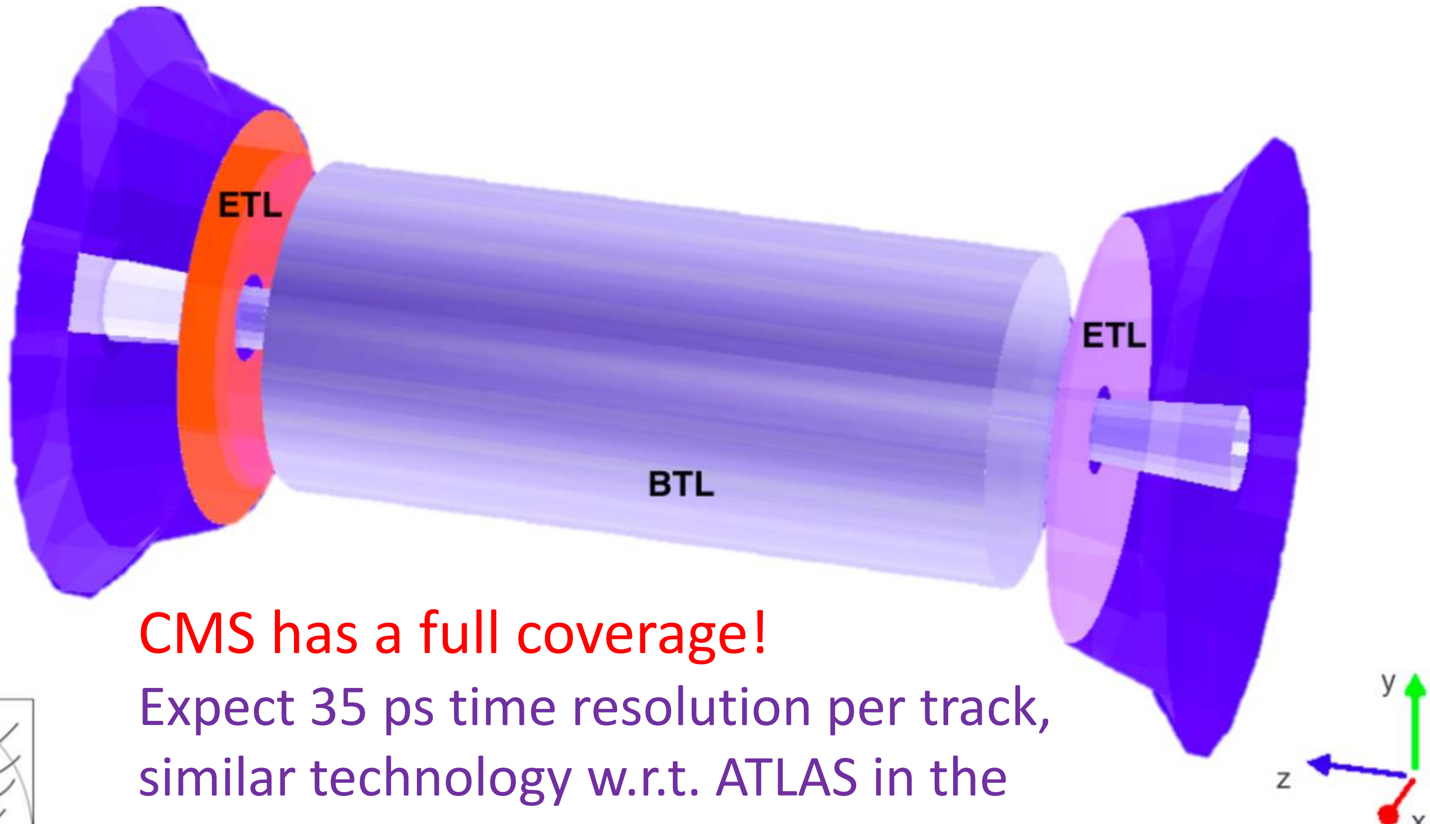
CMS-TDR-020

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}: 2×10^{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 2×10^{15} n_{eq}/cm^2

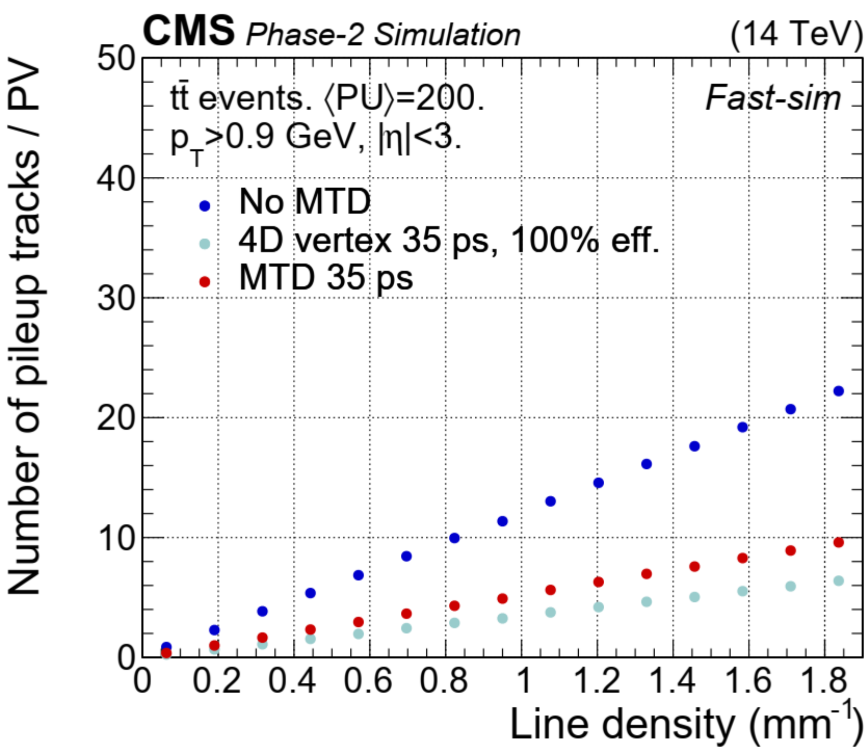




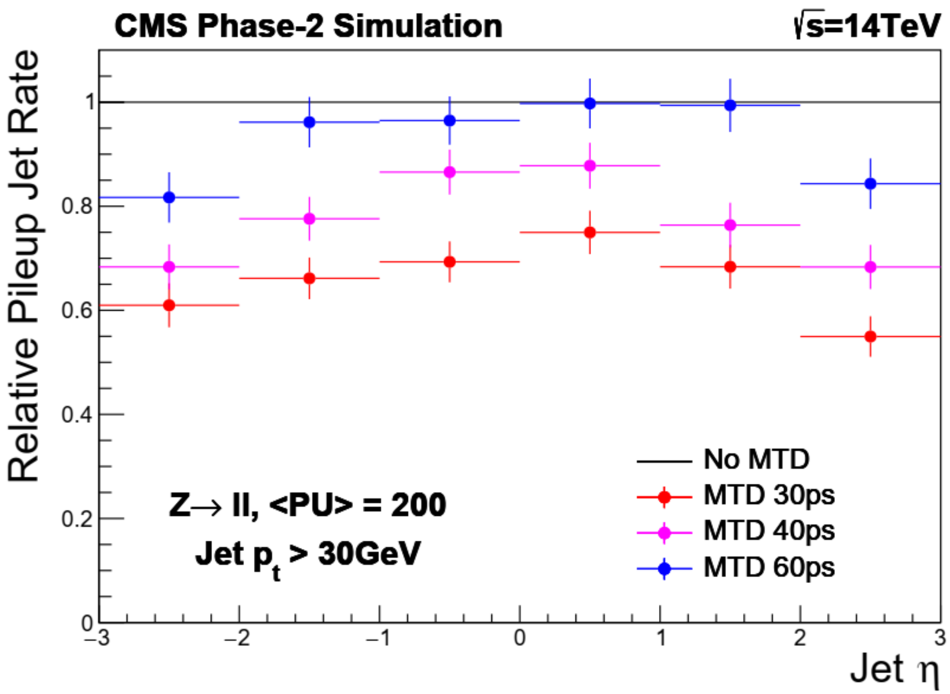
CMS has a full coverage!

Expect 35 ps time resolution per track, similar technology w.r.t. ATLAS in the endcap region

Expected Impact of CMS MTD

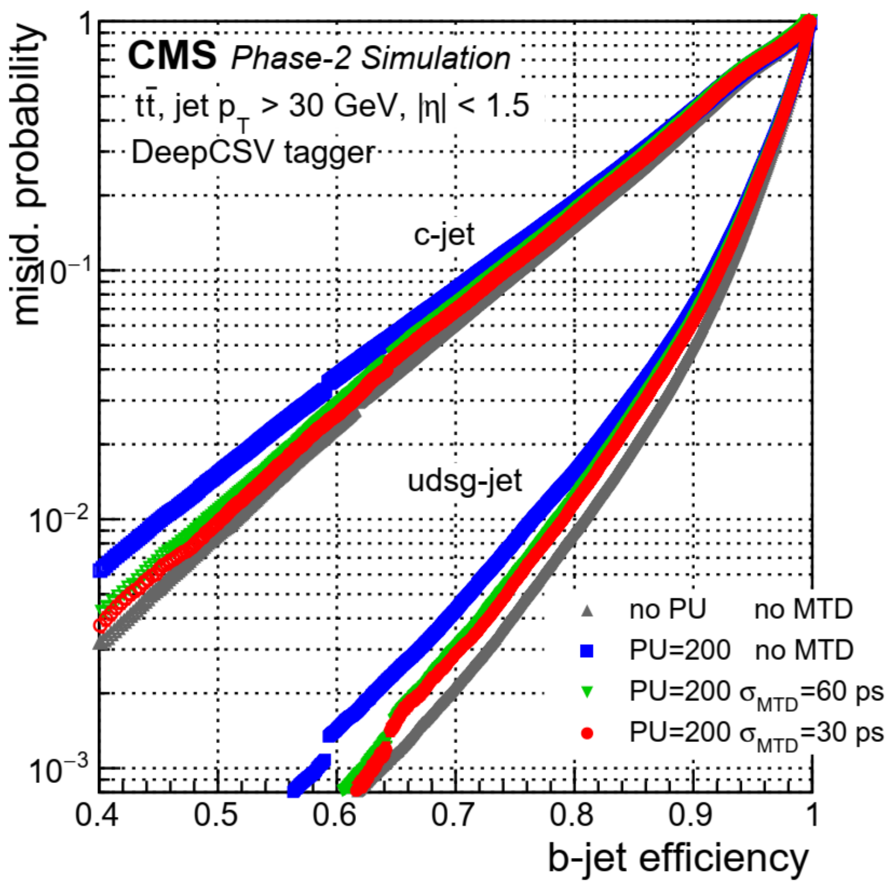


Power of time info. in rejecting pileup tracks

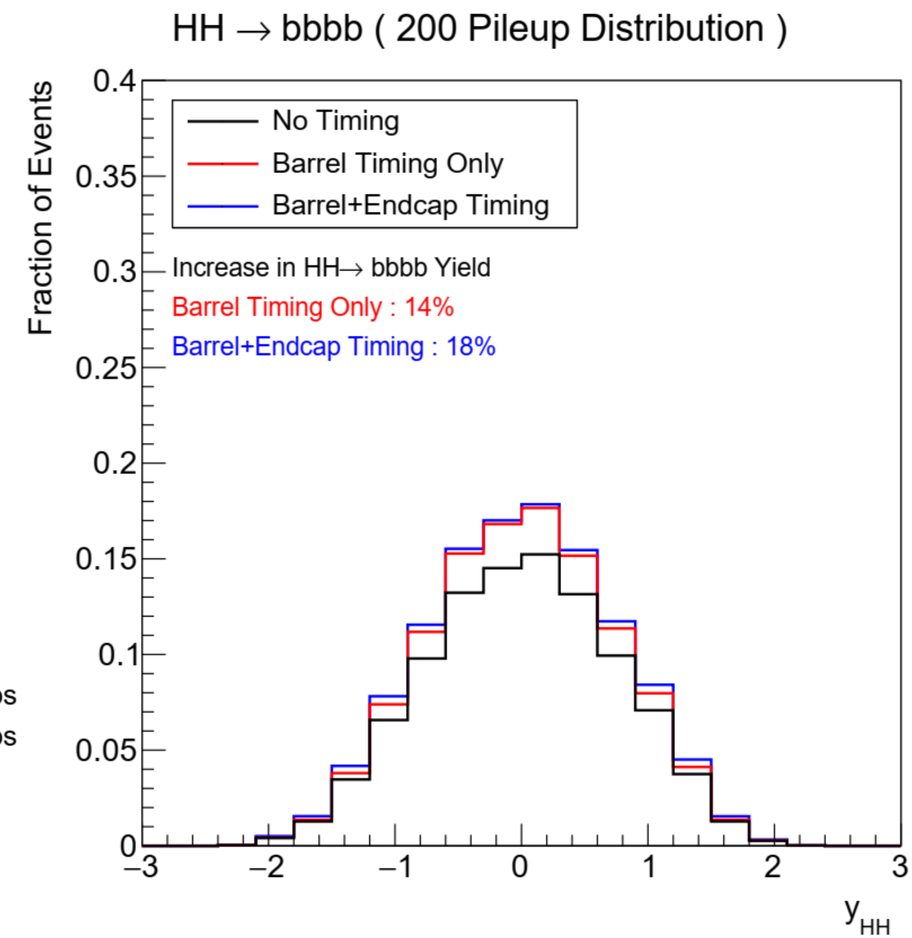


Effect on pileup jet rejection

Expected Impact of CMS MTD

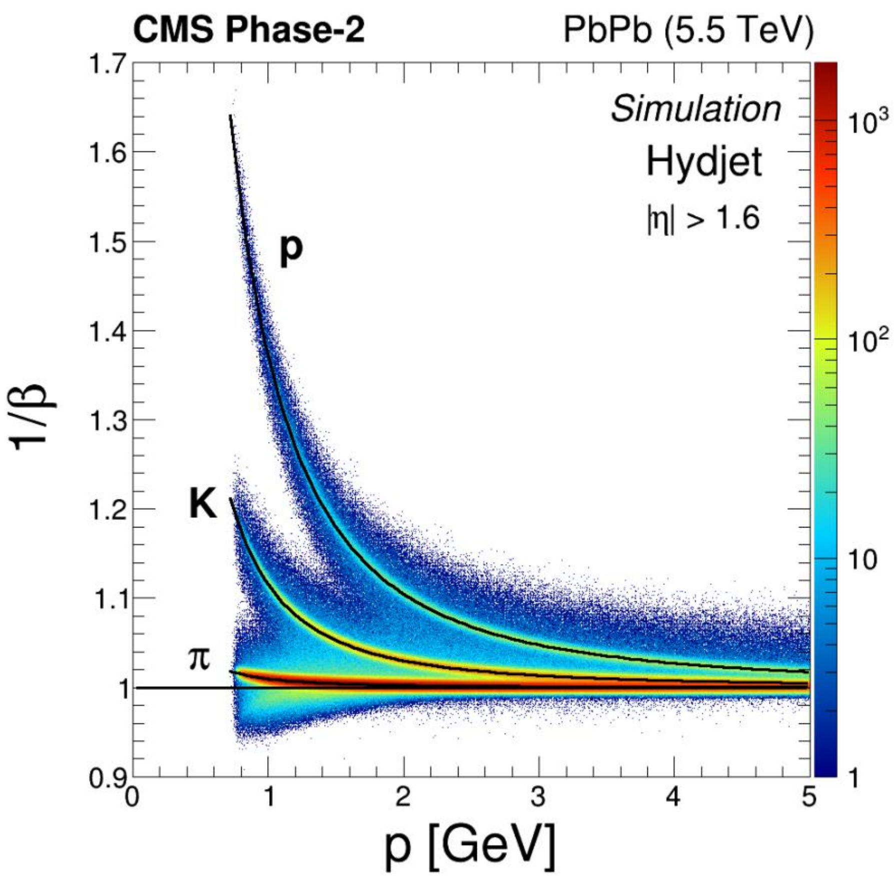


Time and heavy flavor tagging

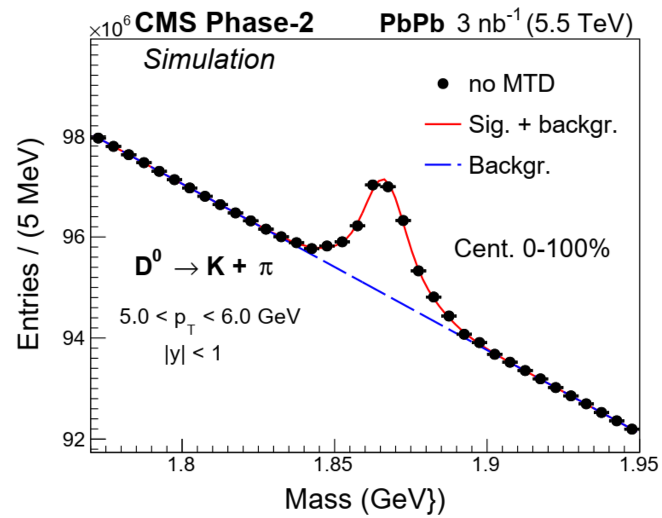


Given a constant mistag rate, time leads to more HH events

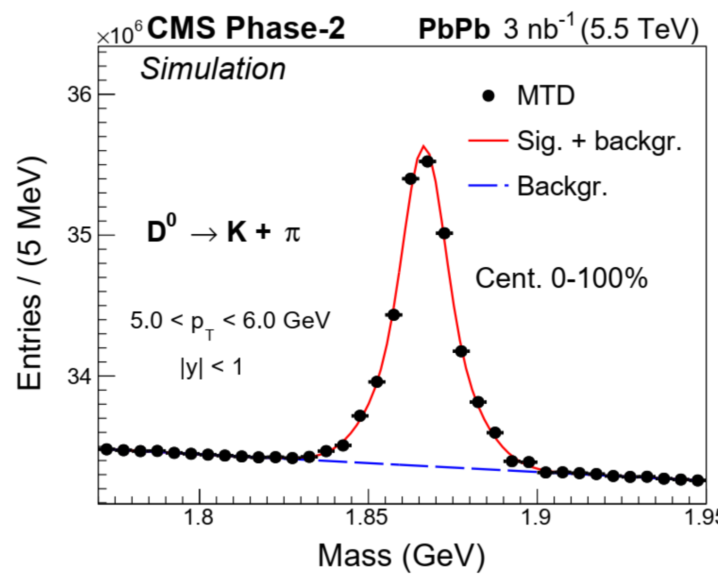
CMS Timing Detector



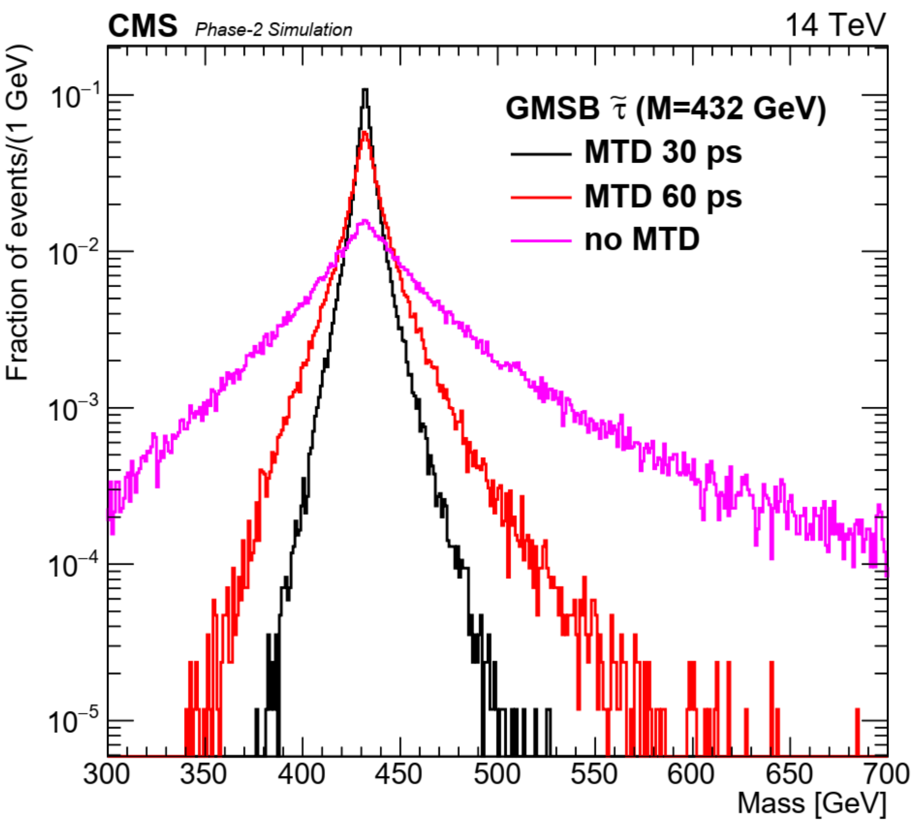
TOF for Particle identification

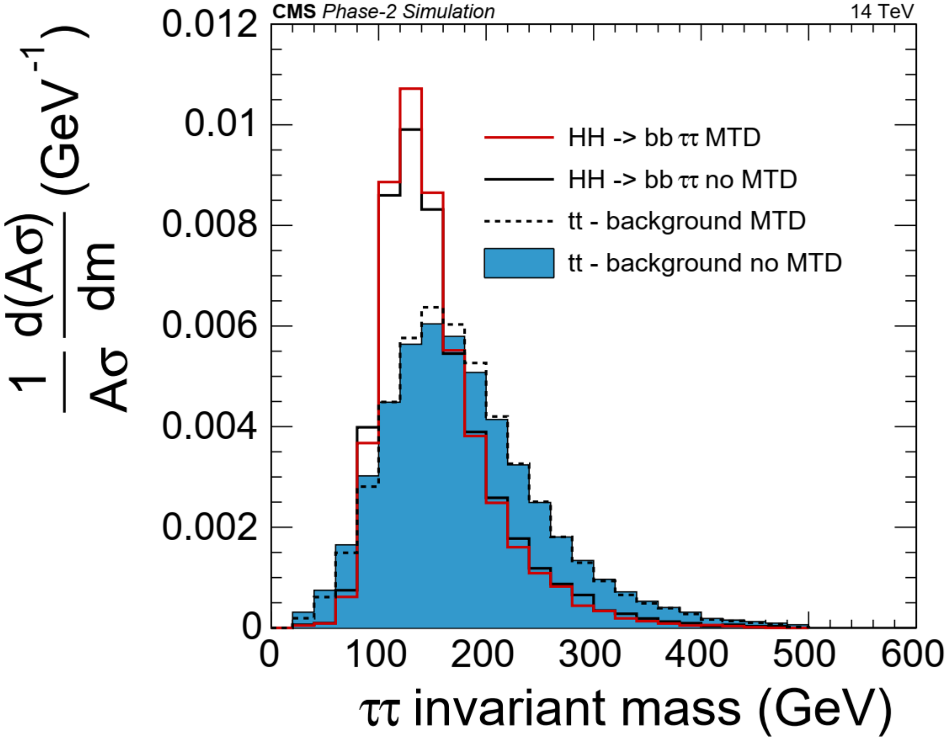


With time



CMS Timing Detector





With TOF, the understanding of long-lived particle mass is much improved

Initial study projects 10% increase to HH detection sensitivity at HL-LHC, but more could be done

Summary

A short discussion was provided on the use of time measurements for particle physics, from general aspects to details in LHC experiments

Precision time measurement could help open a unique window

Atom-level ultra-precision has been utilized for seeking for new phenomena; in terms of particle detection, wide application from ps to ns time resolution can be realized

At TeV frontiers, adventures into using O(10) ps time information in an extreme radiation environment has started

Precision timing can largely assist in identifying known and unknown particles, seeking for even more advanced technologies would be desirable

Be interesting to think even beyond those

Thank you for your attention!