# Calorimeter performance studies using Monte Carlo simulations for future collider detectors

**S.Chekanov (ANL)**

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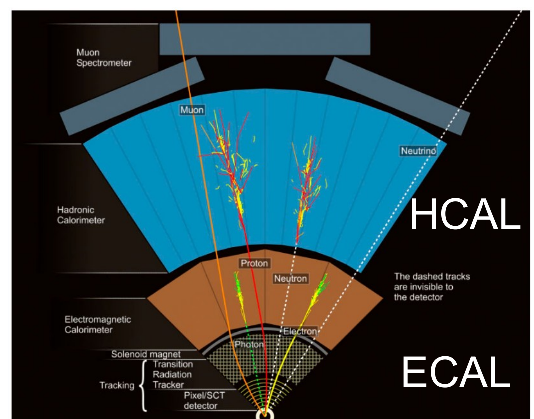
**Based on Snowmass21 LoIs:**

EF/SNOWMASS21-EF0-IF6-007.pdf,
IF/SNOWMASS21-IF6-EF9-002.pdf
EF/SNOWMASS21-EF8-IF6-008.pdf
Contributed paper: JINST 15 (2020) P09021



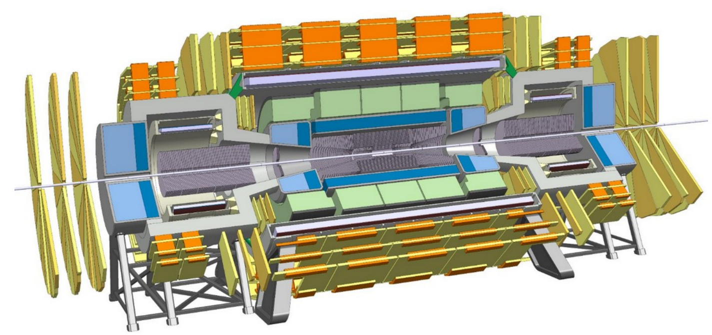
# Calorimeter requirements driven by physics at 100 TeV

- **Good containment up to pT(jet)~30 TeV: 12 $\lambda_I$ for ECAL+HCAL**
  - contributes to jet energy resolution, leakage biases, etc.
- **Small constant term for HCAL energy resolution: b < 3%**
  - dominates jet resolution for pT>5 TeV
  - important for heavy particles decaying to jets etc.

$$\frac{\sigma(p_T)}{p_T} = a/\sqrt{p_T} \oplus b$$

- **Longitudinal segmentation → open question** ?
- **Good transverse segmentation for resolving boosted particles:** ?
  - HCAL studies presented in this talk
- **Precise timing information** ?

*See: The Hadron Collider: "Future Circular Collider Conceptual Design Report" , Volume 3. Eur. Phys. J. Spec. Top. (2019) 228, 755*

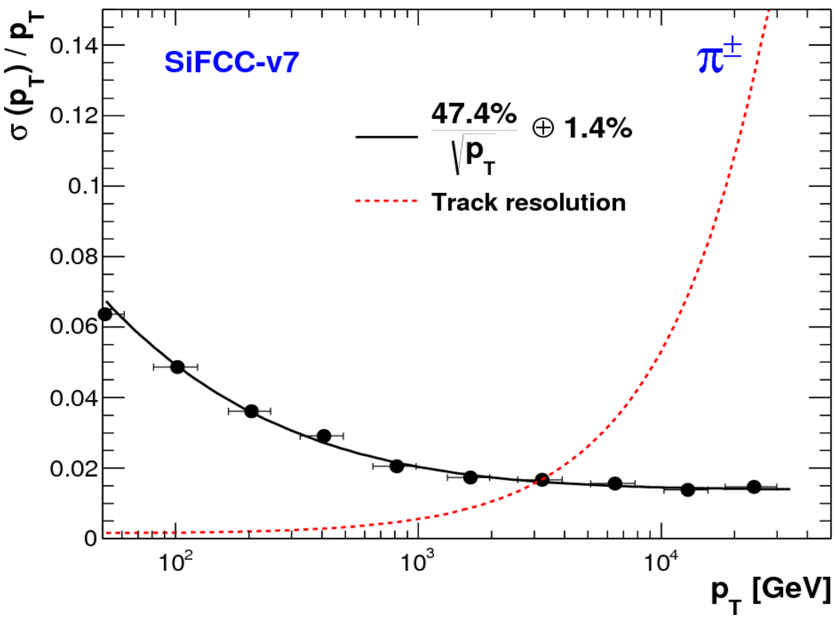


# Energy measurements at multi-TeV scale

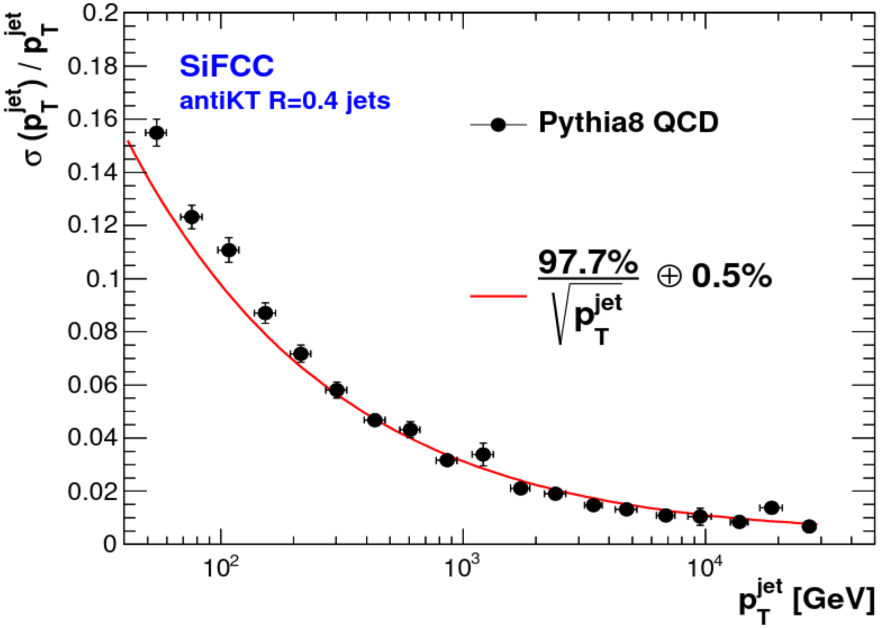
*JINST 12 (2017) P06009*

- **Energy resolution. Geant4 simulations using FCC-hh ($ECAL$:35 X0, HCAL~ 11.5$\lambda_I$ - see backup)**

single-particles




anti-KT 0.5 jets



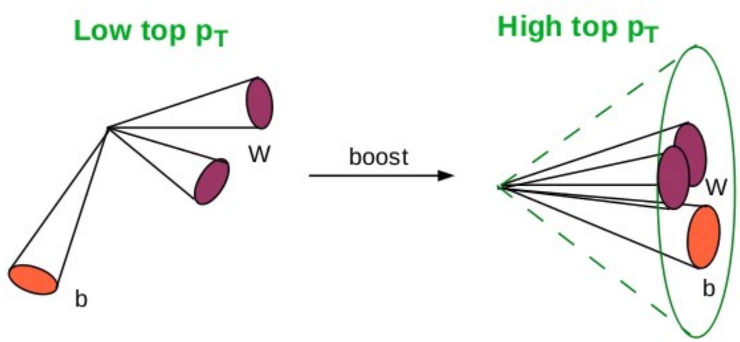

$$\frac{\sigma(p_T)}{p_T} = a/\sqrt{p_T} \oplus b$$

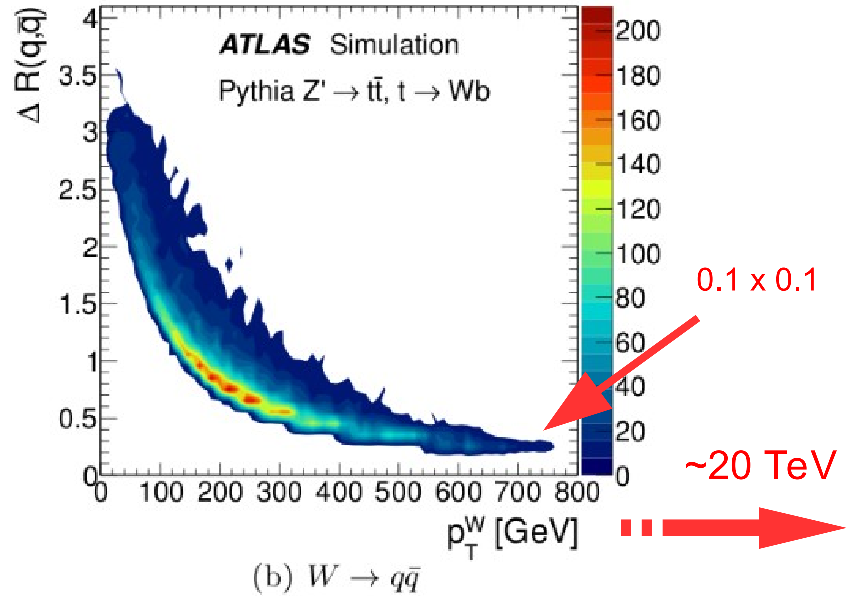
*a – stochastic/sampling term,*
*b- constant term*

- **b < 3% for ~12 $\lambda_I$ ECAL+HCAL is achievable using traditional technologies. What about granularity of cells?**

# Calorimeter cells for HCAL

- ATLAS/CMS: HCAL cell size ~ $\lambda_I$
  - or $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$
  - or ~20 x 20 cm$^2$



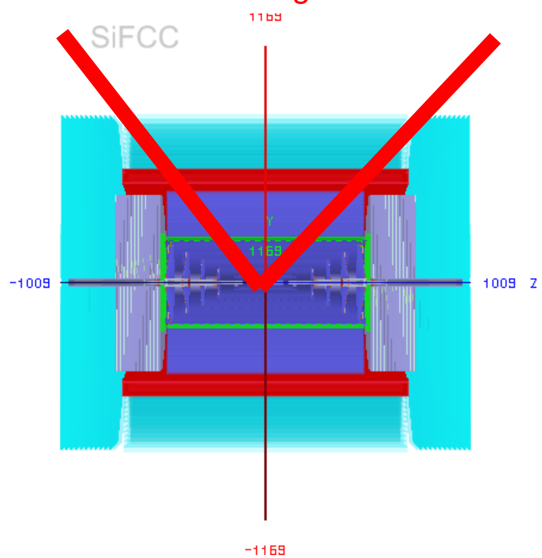




- 100 TeV: Cell sizes should be optimized for substructure of (boosted) jets
- CALICE: Small cell sizes are beneficial for sparse e+e- physics using PFO
- Recent Geant4 study extends this conclusion to ~1 TeV for single particles
  *JINST 12 (2017) P06009* https://arxiv.org/abs/1612.07291

What is most optimal transverse granularity for multi-TeV scale **jets** physics?

- **Requires realistic physics events and Geant4 simulations ( + object reconstruction) with a FCC-hh representative detector geometry**

# Geant4 simulation setup based on SiFCC




SiFCC9 description:

- Derived from SiD/CLIC "all silicon" concept
- |η|<2.5 optimized for 100 TeV collisions
- Compact (~20% smaller than ATLAS)
- Playground for Geant4 simulations

***Notes:***
*- 100 ns cut for hits*
*- No PFA for this study*

**SLIC 5.0.1 with Geant4 10.3p1**
**Inelastic physics list for pi+/p/n (validated<400 GeV):**
**QGSP_BERT 4.0**
QGSP: 12 GeV - 100 TeV
FTFP: 9.5 GeV - 25 GeV
BertiniCascade: 0 eV - 9.9 GeV
**Elastic:** ElasticLHEP/ Gheisha: 0 eV-100 TeV

**raw hits**

**slicPandora: Sampling fractions, hit cuts ..**

**cells**

**PandoraPFA: Topological 3D RecoClusters**

**clusters**

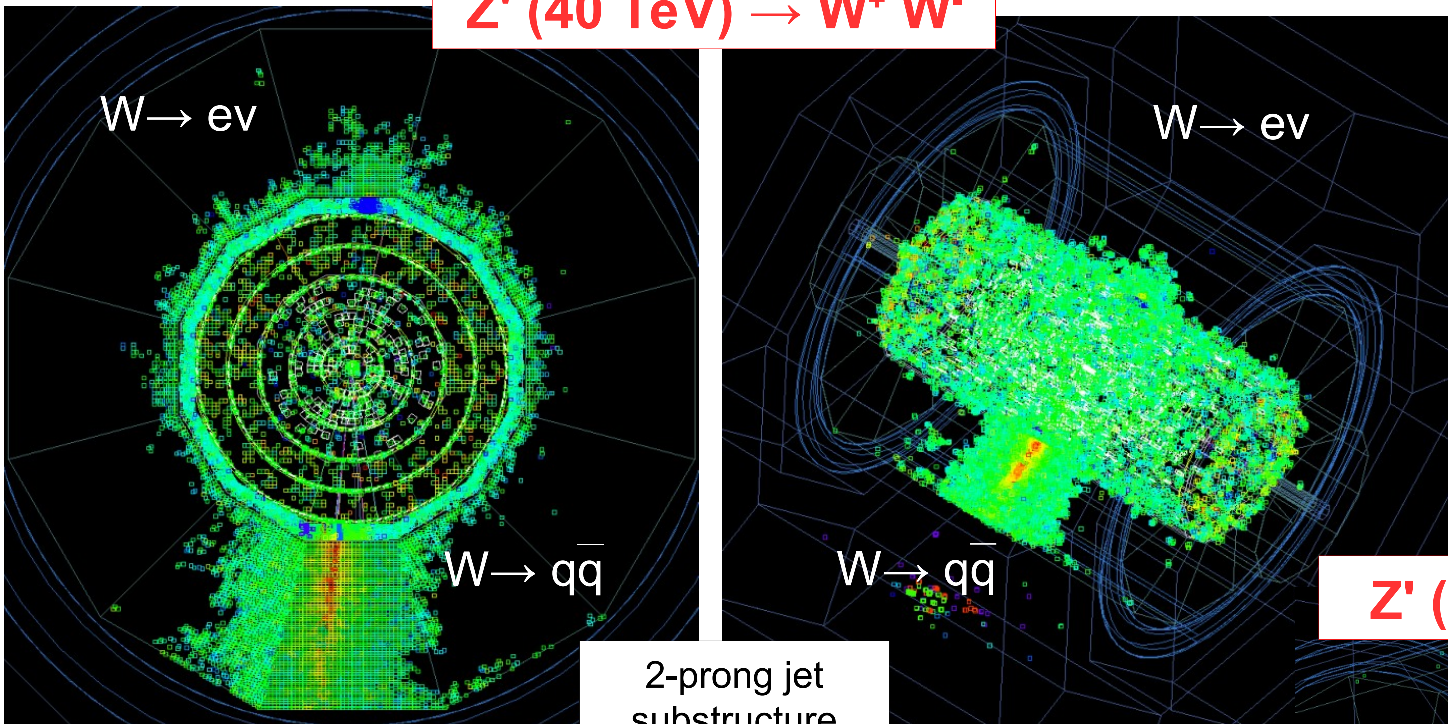
**antiKT R=0.5 jets from RecoClustes**

**Data analysis**

# 20 TeV hadronic jets from Z'

High-granularity HCAL with 1x1 cm cells,  10k hits in ECAL, 46k hits in HCAL

**Z' (40 TeV) → $W^+ W^-$**

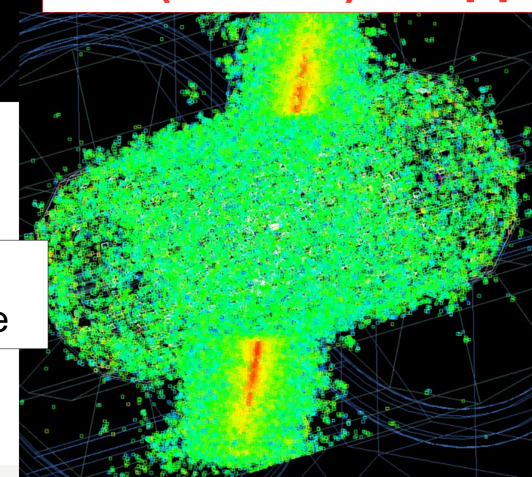



2-prong jet substructure

Event Displays created using Jas4pp

Events can be downloaded from HepSim

**Z' (40 TeV) → $q\bar{q}$**



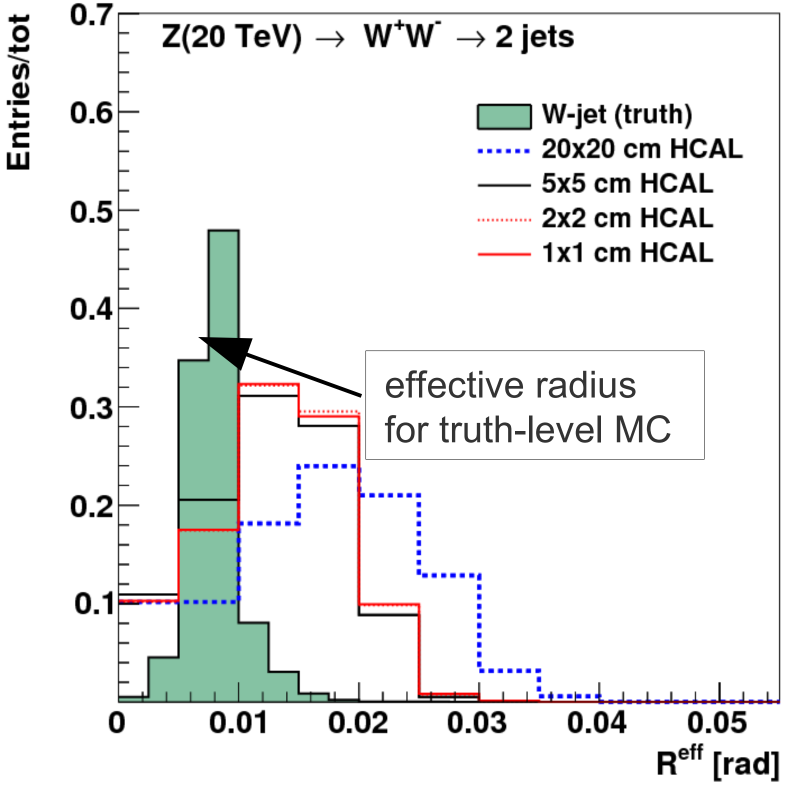
No jet substructure

Use boosted jets created in
Z' → W+W-  and Z' → $q\bar{q}$  events
using different granularity of calorimeter
**20x20 cm (~LHC),  5x5 cm,  1x1cm**

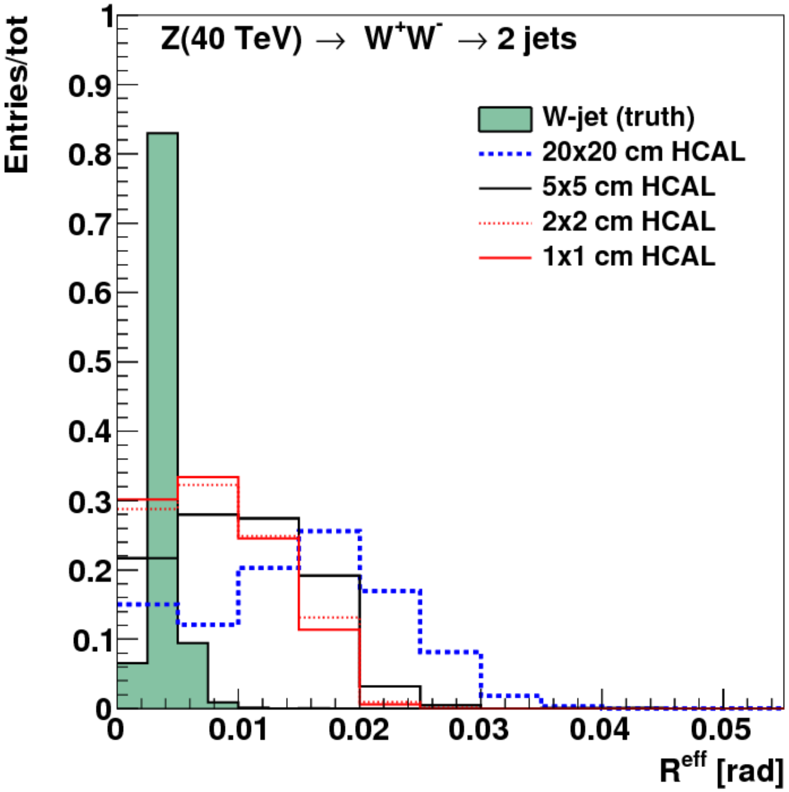
# Effective jet radius of antiKT5 jets from clusters

Sum over all distances between energy deposits and jet center, weighted with E(const) / E(jet)

**W-jets from Z'(20 TeV)**




**W-jets from Z'(40 TeV)**



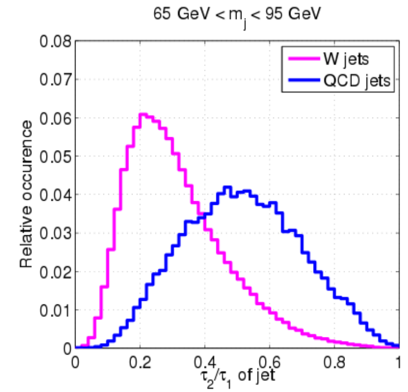

- Jets with pT>10,20 TeV, each from W→ $q\bar{q}$
- 5x5 cm (ΔηxΔφ = 0.022x0.022) shows improvement compared to 20x20 cm (ΔηxΔφ = 0.1x 0.1)
- Small difference between 2cm and 1cm cell sizes

ATLAS, CMS

# Studies of N-subjettiness

- Jesse Thaler, Ken Van Tilburg:
  - $\tau_{21} = \tau_2/\tau_1$ – used for boosted W tagging
- Use overlap between QCD and W jets as a benchmark for effectiveness of tau21 for boosted W reconstruction
- Use different HCAL granularity from 20x20 cm$^2$ to 1x1 cm$^2$ (no changes in ECAL)

J.Thaler and K. Van Tilburg, JHEP 1103 (2011) 015

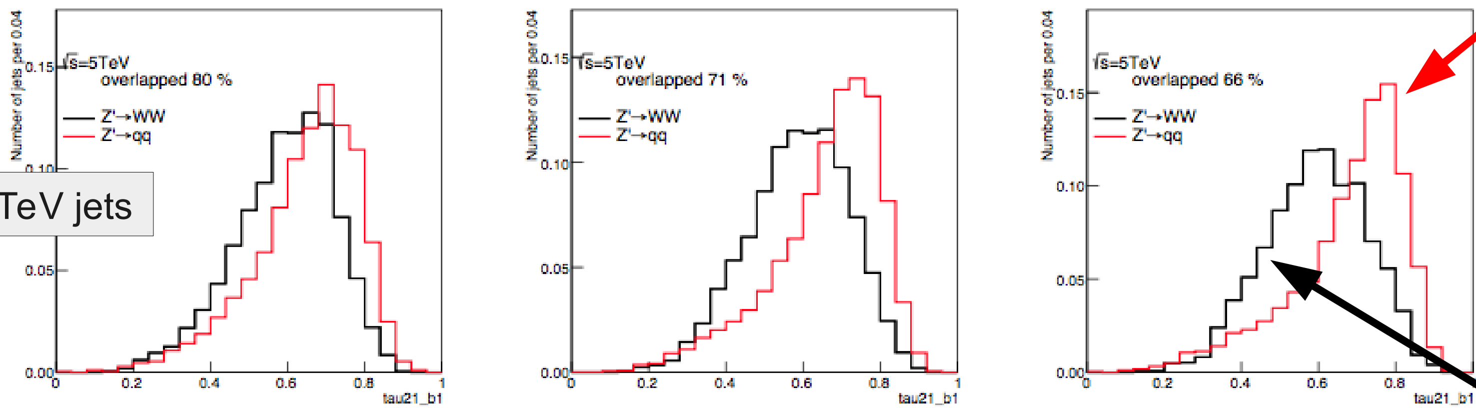



$\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ (20x20 cm$^2$ )

$\Delta\eta \times \Delta\varphi = 0.022 \times 0.022$ (5x5 cm$^2$ )

$\Delta\eta \times \Delta\varphi = 0.005 \times 0.005$ (1x1 cm$^2$ )

2.5 TeV jets

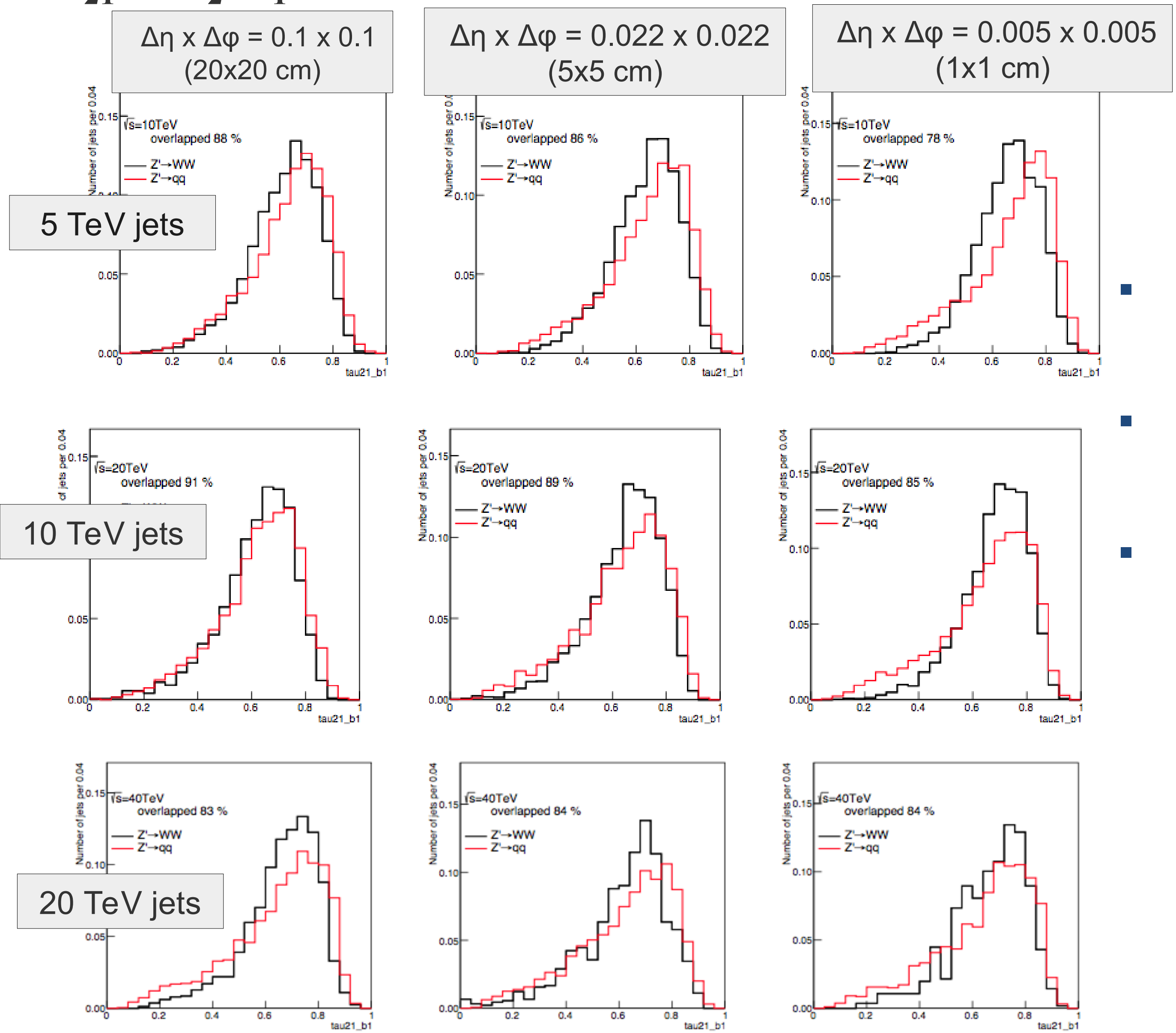



Z'→ $q\bar{q}$
**Expected:**
No jet structure

Z'→ WW→ 2 jets
**Expected:**
2-prong substructure
(W → $q\bar{q}$)

**2.5 TeV jets show reduction in overlap (80% →71% → 66%) going from 20x20 cm$^2$ to 1x1 cm$^2$ for HCAL cells**

# $\tau_{21} = \tau_2/\tau_1$ for different HCAL granularity

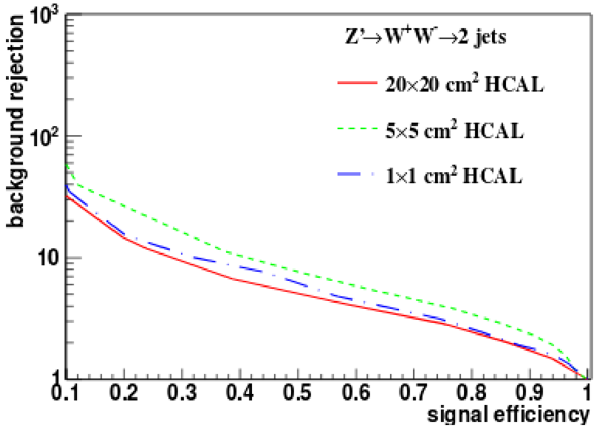



- **5 TeV jets:**
  - 88% → 78% overlap
- **10 TeV jets:**
  - 91% → 85% overlap
- **20 TeV jets:**
  - change in HCAL granularity does not modify overlap

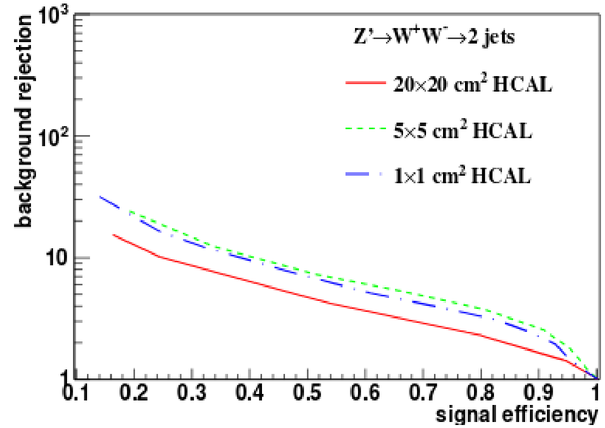
# Efficiency vs background rejection for different cell sizes

C.-H. Yeh JINST 14(2019) P05008

$$\tau_{21} = \tau_2 / \tau_1$$

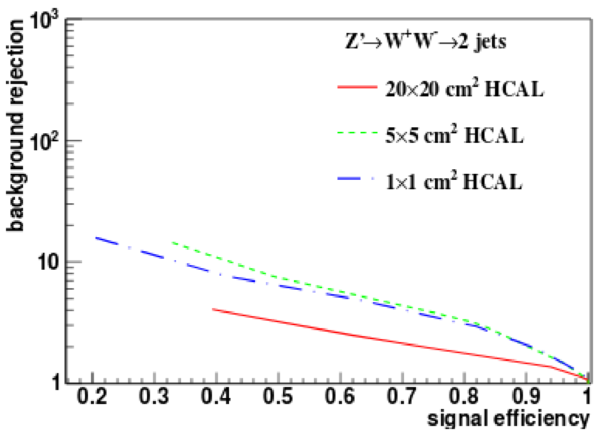


(a) $M(Z') = 5$ TeV

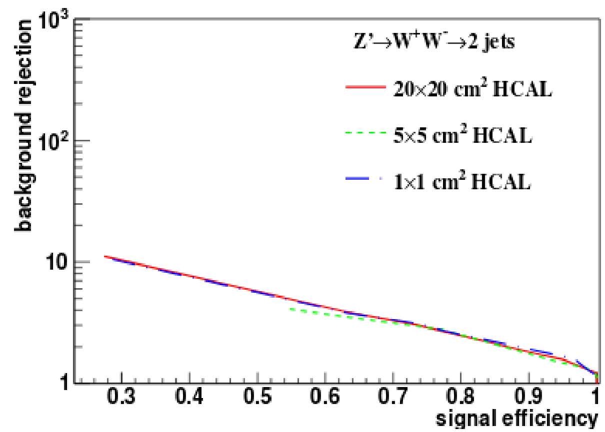


(b) $M(Z') = 10$ TeV

Significant improvements after reducing cells from 20x20 cm$^2$ to 5x5 cm$^2$



(c) $M(Z') = 20$ TeV



(d) $M(Z') = 40$ TeV

**1x1 cm$^2$ cells show no improvements compared to 5x5 cm$^2$**

# Summary of jet substructure studies

- Boosted jets studied up to 30 TeV in transverse momentum using Geant4 simulation with realistic energy reconstruction
- Jet substructure benefits from HCAL granularity
- HCAL cell size $\Delta\eta \times \Delta\varphi = 0.022 \times 0.022$ (5x5 $cm^2$) shows significant improvement for physics events compared to $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ (~ CMS, ATLAS)
- Smaller than 0.022 x 0.022 cells show minor improvements for >20 TeV jets

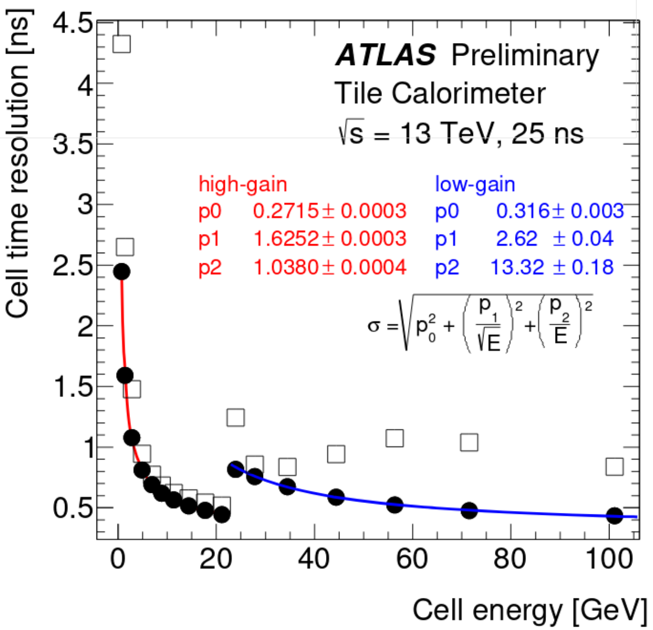
# From the CPAD report: https://arxiv.org/pdf/1908.00194.pdf

## Section: 4.1.5 Critical Needs

- Picosecond time resolution
- Modern image processing technology, both hardware (GPUs) and software (image processing and deep learning)
- Low-cost, high-light-yield, fast and radiation-tolerant .. scintillators
- Advances in Silicon Photomultiplier (SiPM) technology.  Improved UV detection, larger dynamic range though smaller pixels, direct coupling to, or integration with readout electronics
- Low-cost radiation-tolerant electro-optical transceivers at ~10 Gbps or more.
- Continued development of GEANT..

**~1 ns is baseline for CLIC/FCC calorimeters  (technology / price)**

Time resolution for TileCal (ATLAS) is already ~0.4 - 2 ns (jets)

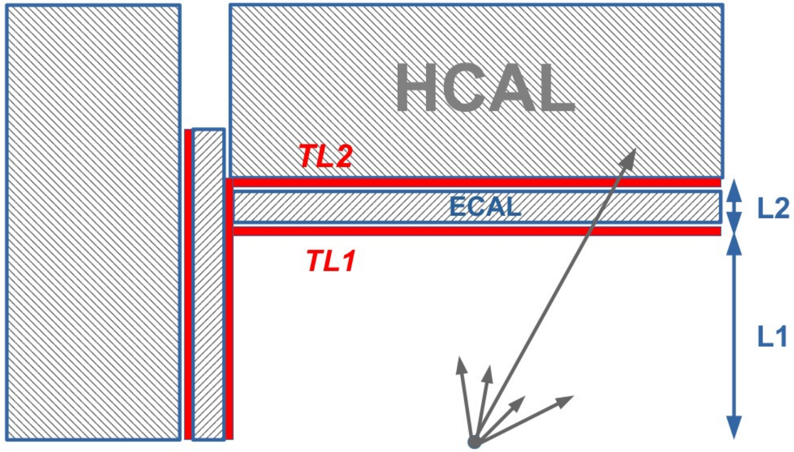


# Benefits of timing information for future experiments

- **All post-LHC experiments (CLIC, EIC, ILC, FCC-ee, FCC-pp ..):**
  - Particle ID from time-of-flights (TOF)
  - Particle flow object reconstruction: Reducing confusion term (mis-matching  in energy depositions and particles)
  - Identification of BSM long-lived particle for new physics
  - Physics objects reconstruction, lepton isolation, b-tagging, etc.
- **CLIC (e+e-):**
  - Background rejection (coherent and coherence e+e- production)
  - ~500 ps assumed
- **FCC, HE-LHC**
  - Pileup rejection → significant impact when using ~20 ps

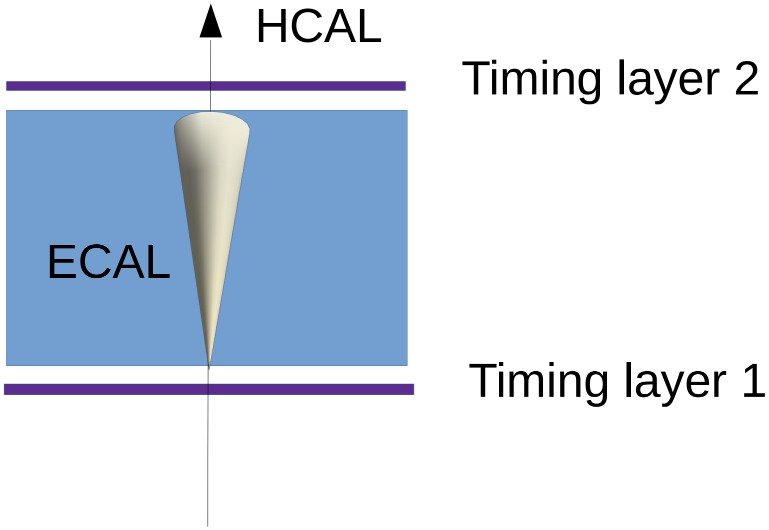
# Idea: Use timing layers before and after ECAL

- Directional capability that will allow correlated hits with calorimeter
- Redundancy
- TOF between TL2 and TL1 for heavy long-lived particles




**Can it work?**

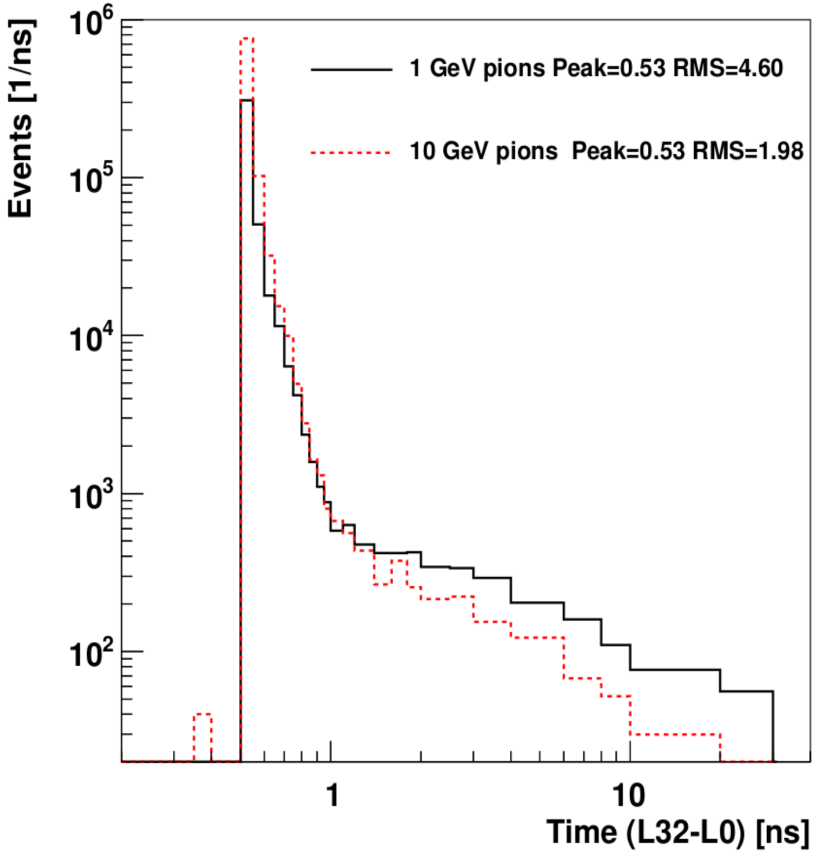
- only if EM shower propagates through ECAL with small RMS and time delays
- Need full Geant4 simulations



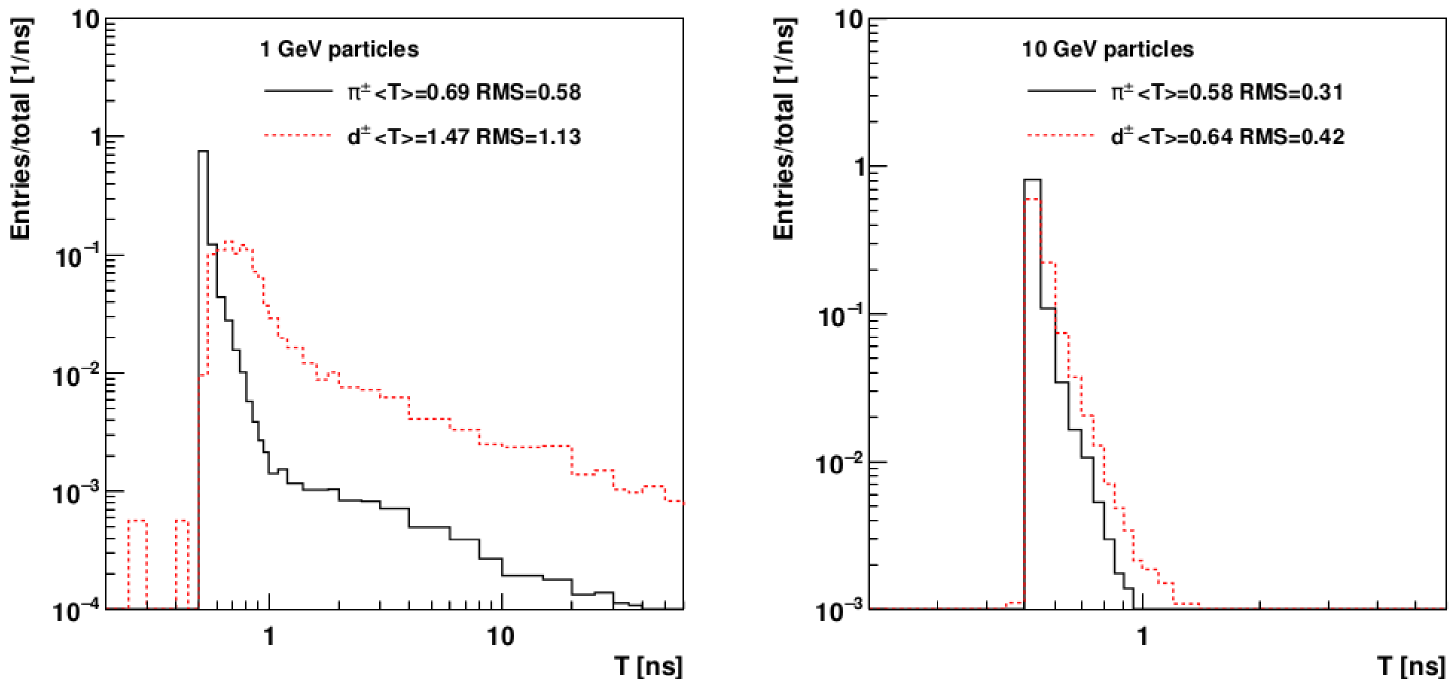
# Full simulation studies using Geant4 (from HepSim)

- Use Geant4 and FCC-like geometry with 32 Si/W layers (~20 cm distance)
- Use single pion "guns" with 1 and 10 GeV
- Calculate time difference between TL2 and TL1 for first arriving hits in Si
- On average, time that requires for hits to propagate through ~20 cm of ECAL cells is ~0.6 ns, with RMS < 5 ns
- For standard 1 ns detector TL1 and TL2 signals will be seen as single hit in both layers

TOF for Geant4 hits for pions traveling a distance between TL2 and TL1 (~0.2 m)



# TOF for TL2 - TL1 for deuterons (d±)




Deuterons (m=2.04 GeV) for a proof-of-concept test:

- Heavier than pions
- Well understood simulations of interaction with material
- Can be produced in material (and primary interactions)

TOF difference between deuterons and pions is ~200-700 ps for p~1 GeV

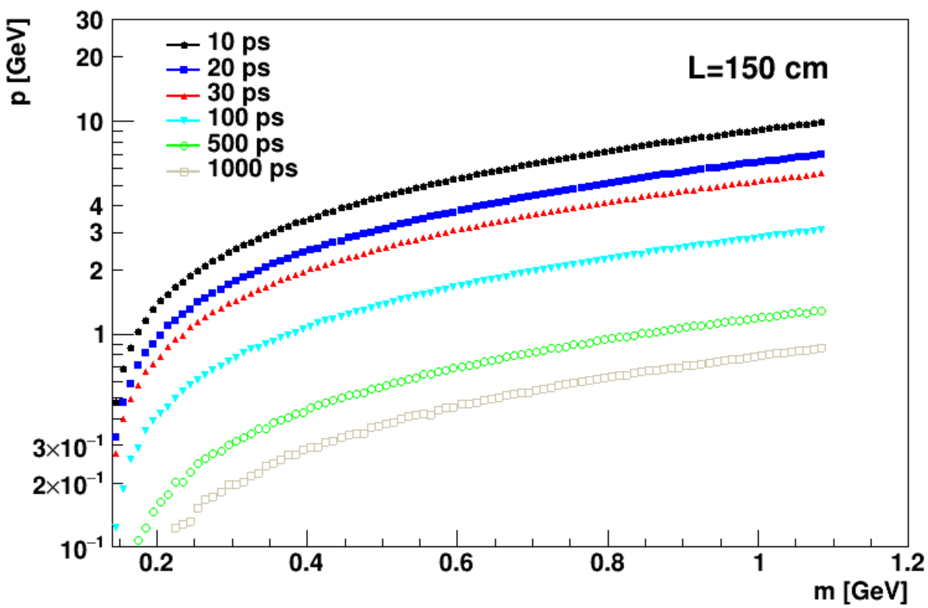
- Can be detected by a 20 ps detector

→ a particle heavier than a d± can also be separated for p > 1 GeV

# Single-particle separations



- Assume TOF measurements in the 1st layer of ECAL (TL1)
  - ECAL inner radius R=1.5 m (Example for CLIC_o3_v13)
- 3 σ separation of a particle with mass “m” from the pion hypothesis




**For ~20 ps detector:**

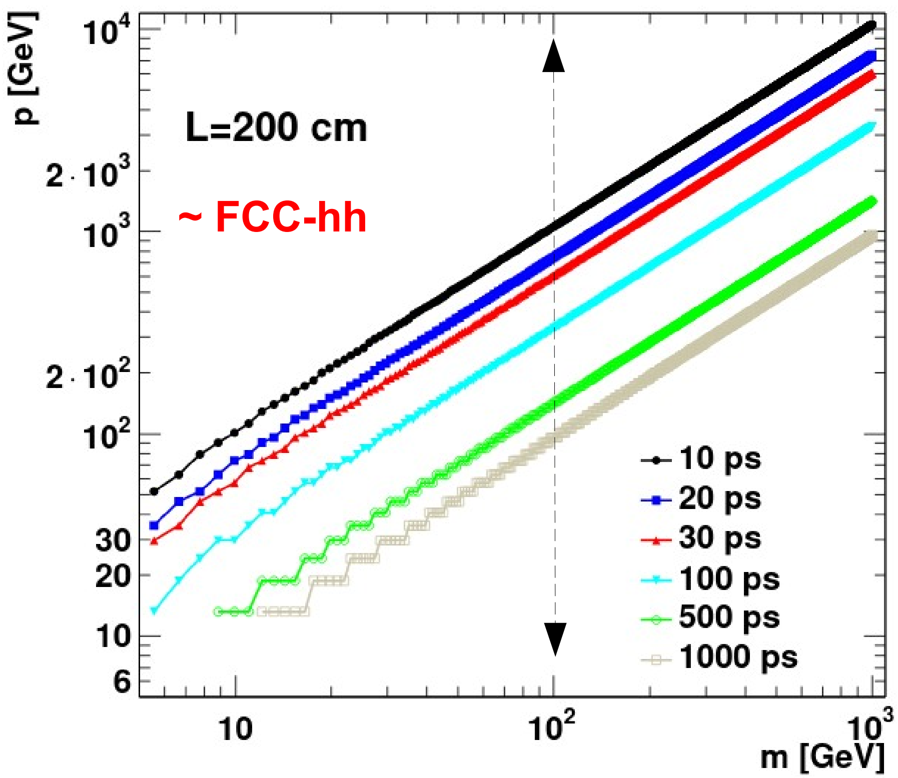
- K-mesons can be separated from pions up to p~3 GeV
- p/n can be separated from pions up to p~7 GeV

- Particle Flow Reconstruction: Reconstruct momenta of individual particles avoiding double counting, i.e. separate energy deposits from different particles
- Particle ID from TOF can improve particle flow object reconstruction (reducing confusion terms) → Study this at Snowmass21?

# Identification of LLP particles

Snowmass21: arXiv:2005.05221

- Identification of heavy long-lived (or quasi-stable) particles
- 3 σ identification requirement




BSM particle with M=100 GeV can be identified up to momentum:

- 700 GeV in |p| for $\sigma_{TOF}$=20 ps
- 70 GeV in |p| for $\sigma_{TOF}$=1 ns

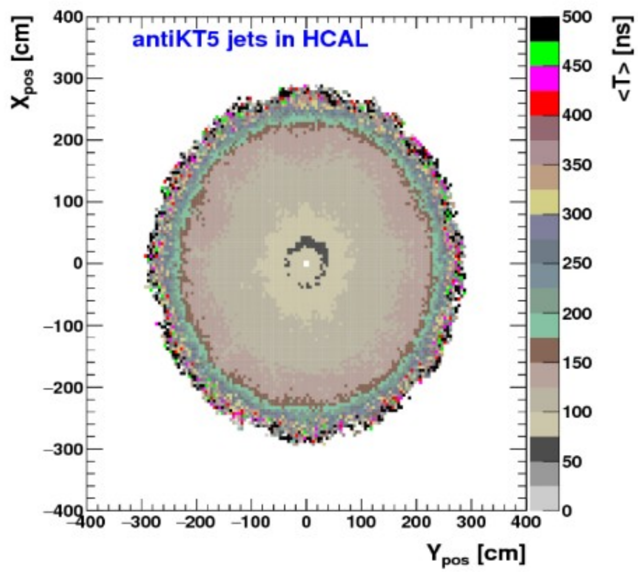
**Can identify massive stable particles in very boosted regime!**

Increase in physics reach by a factor 10 using calorimeters with ~20 ps resolution

# Effect of timing information on jets

Snowmass LoI : SNOWMASS21-EF8-IF6-008.pdf  See also *M.Klimek (arXiv:1911.11235)*

- Explore temporal structure of a jet using full Geant4 simulations
  - Jet constituents may have different velocity, particle masses, b-jets
- Is time in addition to "spatial features" useful for boosted jet tagging?




*Time profile of Geant4 hits for 12 TeV antiKT5 jets from $q(\bar{q})$ using FFC-like geometry from HepSim*

Signal: $Z' \rightarrow W+ W-$
Background: $Z' \rightarrow q\bar{q}$

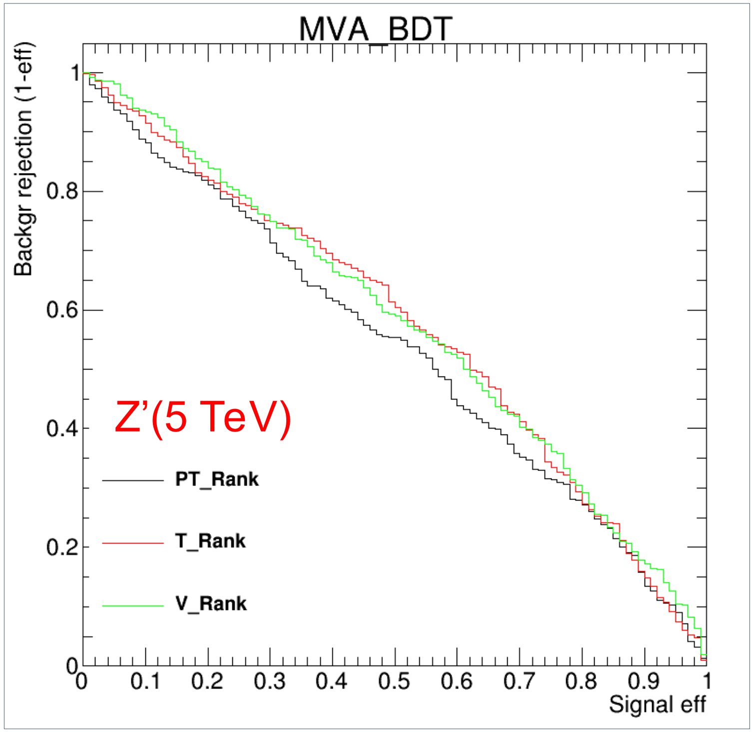
**Calculate "background rejections" vs "signal efficiency" using 5 variables for BDT**

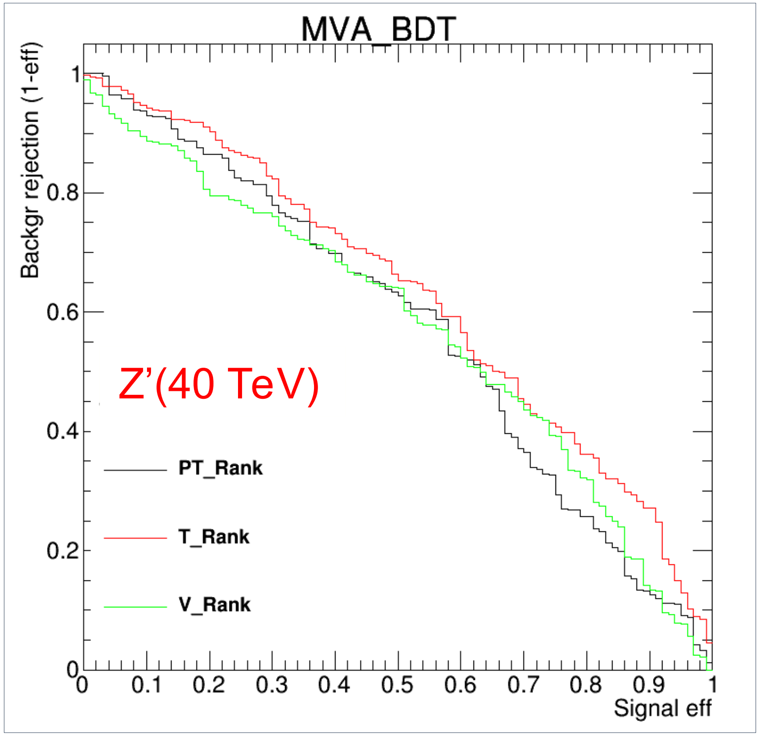
Variables $\Delta R_i$ (i=1,..5) defined as distance between the highest $P_T$ particle in a jet and the five trailing particles ranked in

- Momentum (P):
- Time (T):
- Velocity (V=|P| / E)

# Effect of timing information on jets

Signal: $Z' \rightarrow W+ W-$
Background: $Z' \rightarrow q\bar{q}$




- No significant difference between different variables used for BDT
- Timing slightly improves selection of Z'(40 TeV) but the origin of this small improvement needs to be understood

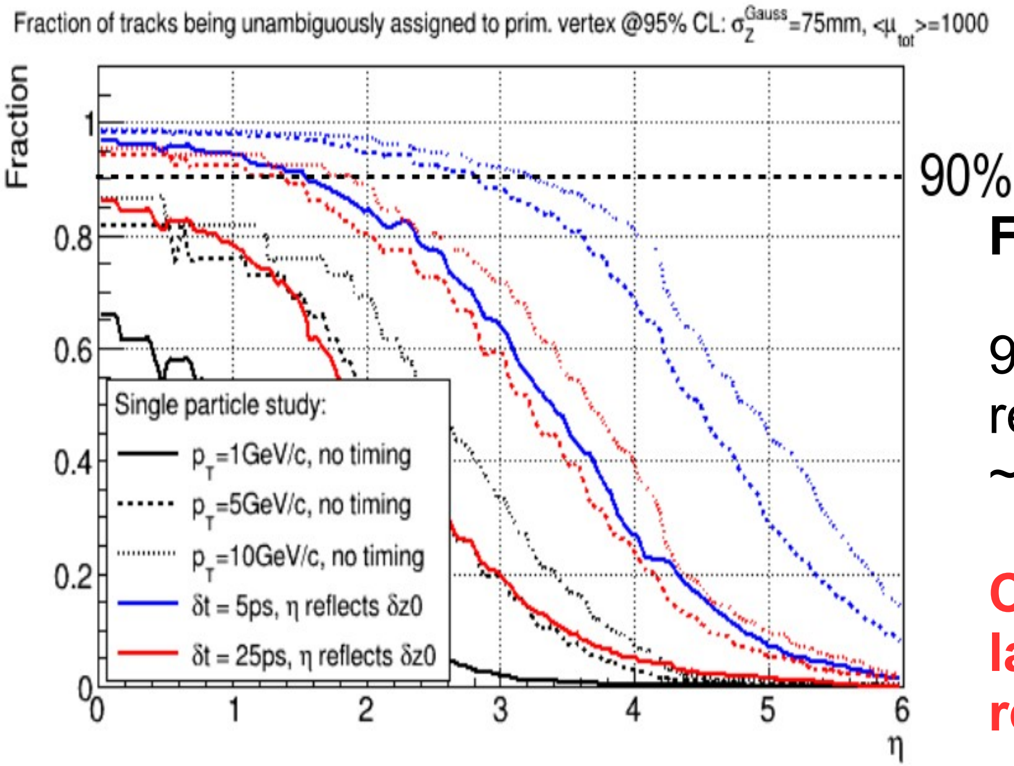
# Summary of timing layers studies

- Timing layers with tens of picosecond capabilities complements calorimeters with the standard ~0.5 - 1 ns readout
- Proof of principle for 2 timing layer design (before and after ECAL)
  - in combination with highly-granular ECAL/HCAL can lead to cost optimized calorimeter designs
- Timing layers can be used for:
  - Pile-up mitigation
  - Particle identification (baryons vs pions vs kaons etc.)
  - Reducing confusion terms in PFA → improvements for jets etc.
  - b-tagging, lepton-isolation
  - BSM long-lived particles → *See concrete example in backup*
- Timing for boosted jets will further be studied during Snowmass21

# Backup

# pp collisions at FCC-hh

Fraction of tracks being assigned to primary vertex for different timing cuts




HL-LHC scenario shows with dashed lines

**For baseline FCC-hh scenario:**

90% assigned tracks in the central region can be achieved with ~5 ps timing cut

**Conclusion: Several timing layers necessary with resolution below 25 ps**

**Impacts low-to-medium pT jets**

Z.Drazal (FCC meeting)

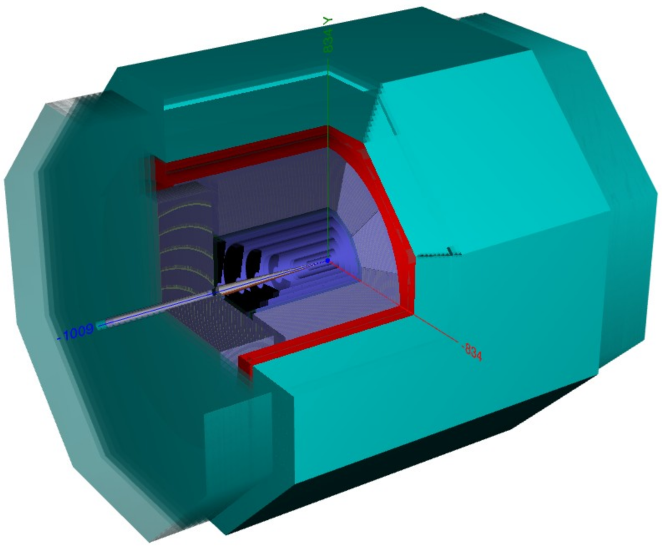
https://indico.cern.ch/event/650511/contributions/2651562/attachments/1488103/2312560/EffectivePU_ZDrasal.pdf

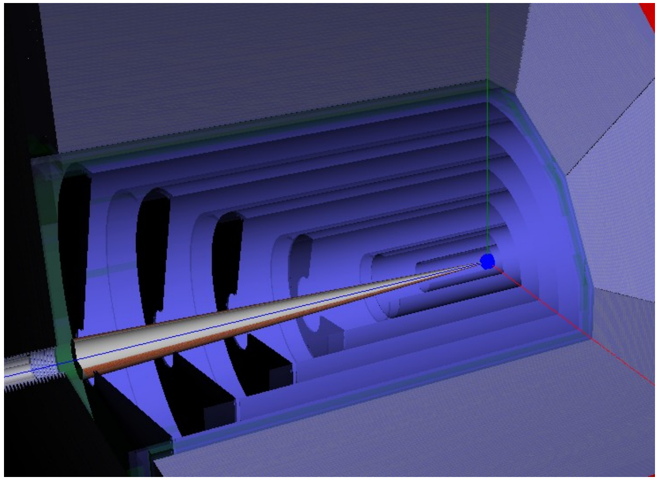
# Characteristics of SiFCC

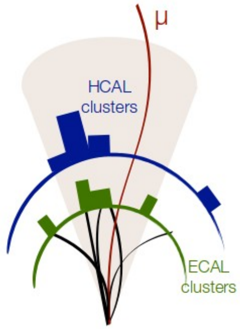
WWW link to explore this detector

http://atlaswww.hep.anl.gov/hepsim/detectorinfo.php?id=sifcch7

- **5 T solenoid outside HCAL**
- **Si pixel and outer trackers (5 + 5 layers):**
  - 20 μm pixel (inner), 50 μm (outer)
- **ECAL (Si/W):** 2x2 cm. 32 layers, ~35 X0
- **HCAL (Scint. / Fe)** **~ FCC-hh reference**
  - 5x5 cm cells: $\Delta\eta \times \Delta\varphi = 0.022 \times 0.022$
    x4 smaller than for CMS & ATLAS
  - 64 longitudinal layers → 11.3 $\lambda_I$
  - 3.1% sampling fraction
- > 150 M non-projective cells (ECAL+HCAL)



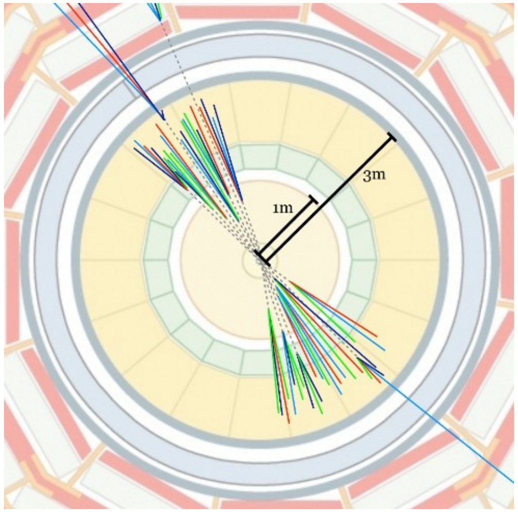





*JINST 12 (2017) P06009*
https://arxiv.org/abs/1612.07291

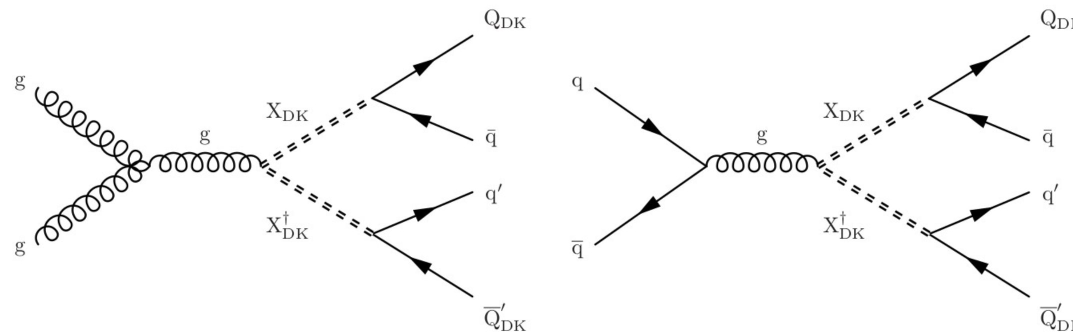
# Emerging jets

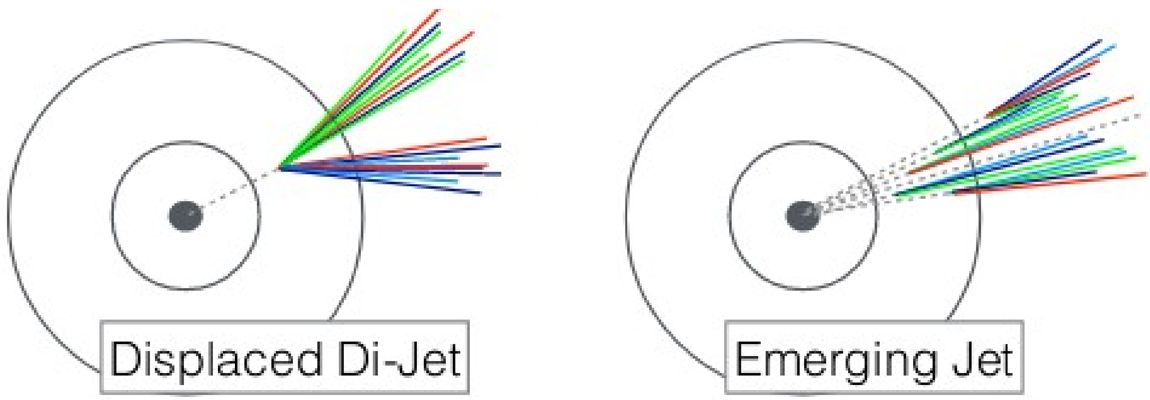
Y. Bai and P. Schwaller, Phys. Rev. D 89 (2014) 063522,
P. Schwaller, D. Stolarski, and A. Weiler, JHEP 05 (2015) 59,




CMS: arXiv:1810.10069v2

Searches for a new heavy particle that acts as a mediator between a dark sector and SM, and that decays to a light quark and a new fermion called a dark quark.



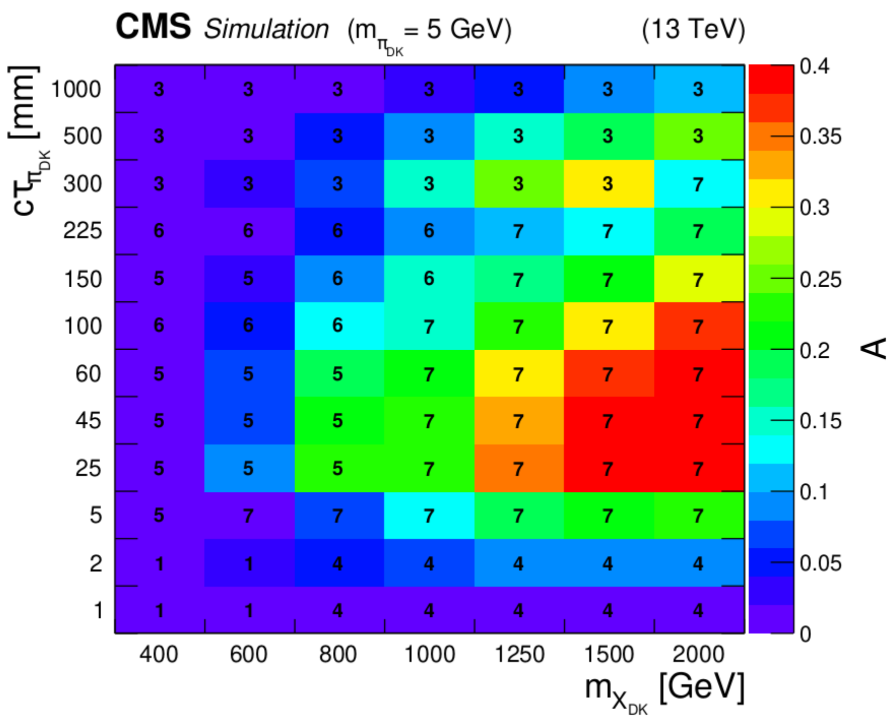

**Fight background by vetoing prompt and secondary tracks.**
**Alternatively: Use timing information for jets**

# Track acceptance vs calorimeter with timing layers

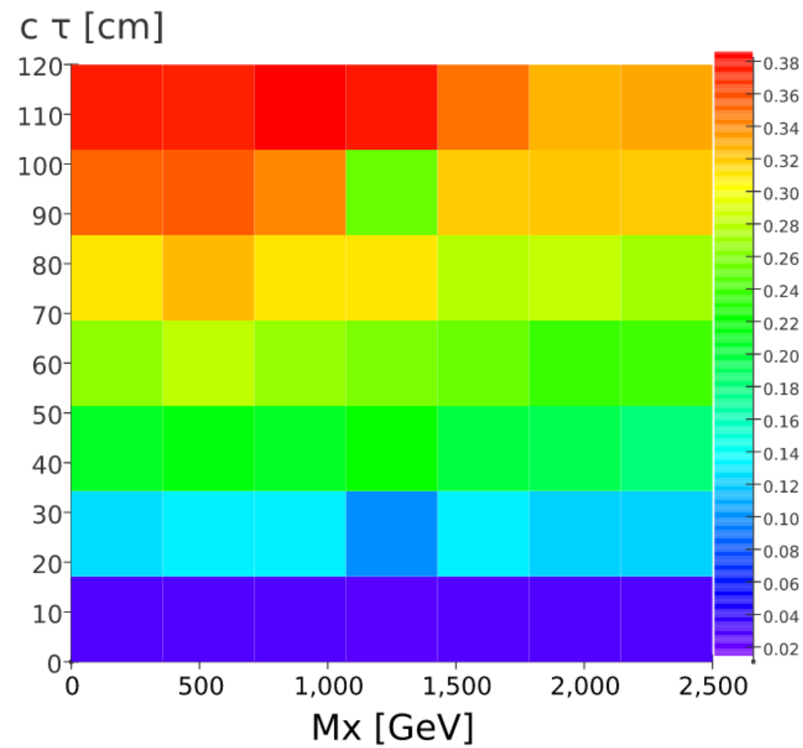
Snowmass21 contributed paper: arXiv:2005.05221

Acceptance as a function of decay length (mm) and mass of the mediator that decay to dark pions

**Tracks-only acceptance**




**Calorimeters with Timing Layer assuming 20 ps resolution R=2m**




**Timing layer on front of ECAL leads to large acceptance for small Mx**