Requirements from substructure and jet reconstruction
(open questions)

Snowmass Community Planning Meeting, October 5-8
Session 131. Physics requirements for HEP colliders

SnowMass2021

S.Chekanov (ANL), A.V.Kotwal (Duke U.), J.List (DESY), M.Vos (IFIC)

- Discussion of a group of LoIs submitted to Snowmass21
- Not covered by LoIs topics on general requirements
- Focus on missing opportunities that can be solved during Snowmass21

Note: Detailed overviews on detector requirements for jets can be found in numerous conference talks and CDR documents

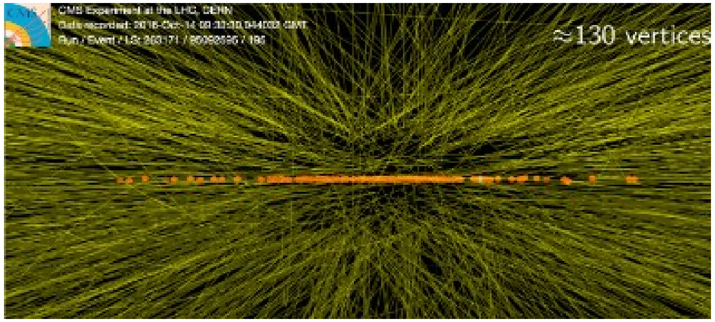
IMPACT FROM PRECISE TIMING INFORMATION

(for tracking requirements see #130)

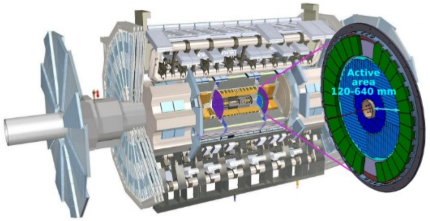
Based on LoIs: EF/SNOWMASS21-EF0-IF6-007.pdf,
IF/SNOWMASS21-IF6-EF9-002.pdf
EF/SNOWMASS21-EF8-IF6-008.pdf
Contributed paper: arXiv:2005.05221

Fast timing detectors for HL-LHC in ATLAS and CMS

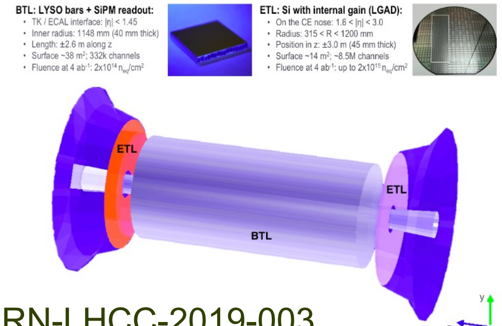
- **Main Motivation:**
  - **Mitigate pileup at the HL-LHC by improving track-to-vertex association**



- **ATLAS:** High-Granularity Timing Detector (HGTD)
  - Endcap: LGADiode technology with σ ~ 30ps



- **CMS:** MIP Timing Detector (MTD)
  - Barrel:ILYSO crystal + silicon photo-multiplier
  - Endcap: Low Gain Avalanche Detector technology



CERN-LHCC-2019-003

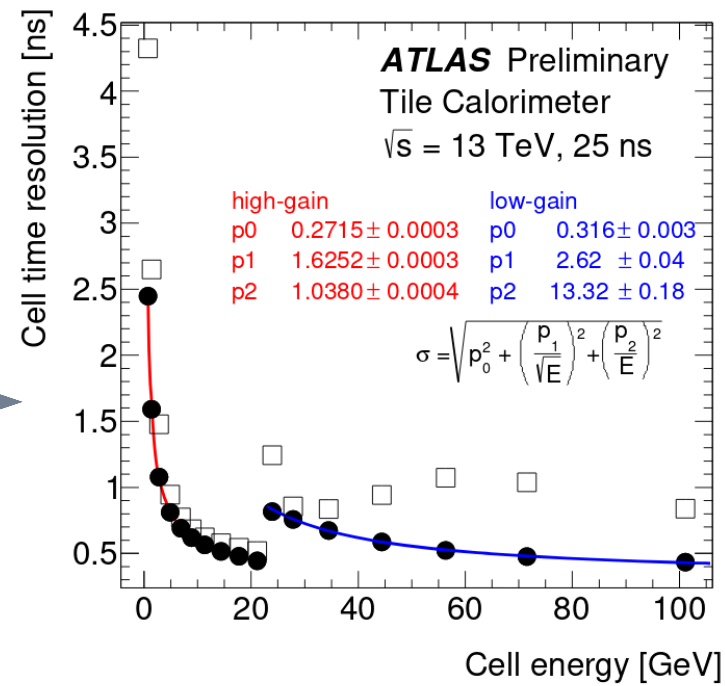
What about post-LHC experiments?

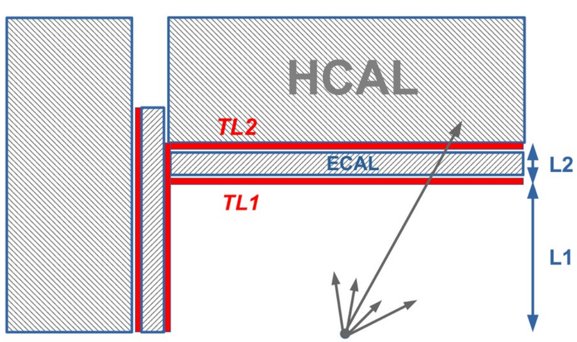
High granularity analog calorimetry

- All future HEP detectors will use “5D” design (position, energy, time)
- Baseline for ILC, CLIC, FCC is ***analog high-granularity*** calorimeter
  - Example: 5x5 mm^2 cells ECAL (Si/W), 3x3 cm^2 HCAL with SiPMT/Scint
- High-precision timing with tens-of-ps resolution for time-of-flight (TOF) ?

~1 ns is baseline for CLIC, ILC, FCC calorimeters (price/technology for high-granularity calorimeters)

Not a technological challenge:
Time resolution for TileCal (ATLAS) is already ~0.4 ns for large cell energies





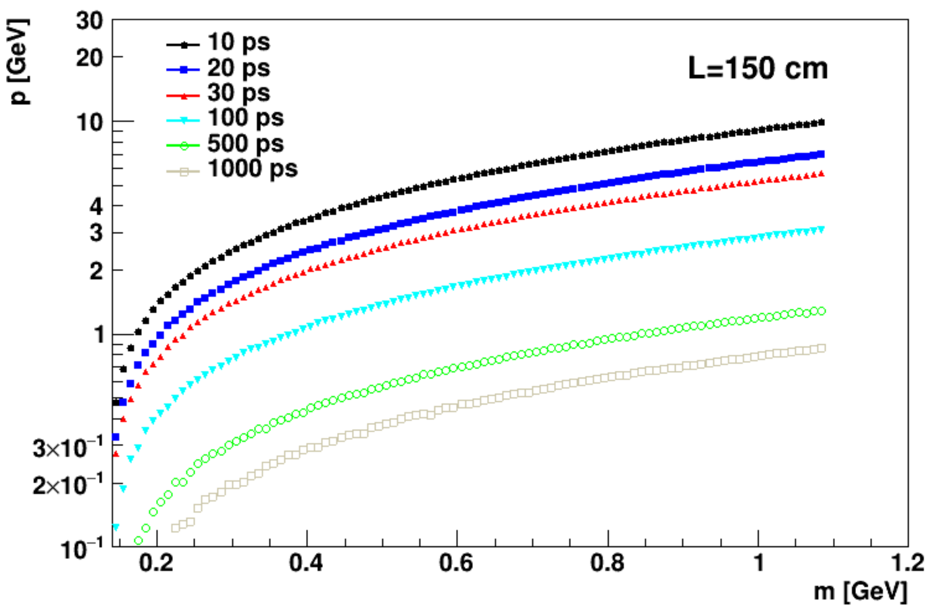
Timing layers (TL) with ~10 ps resolution around ECAL?

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

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



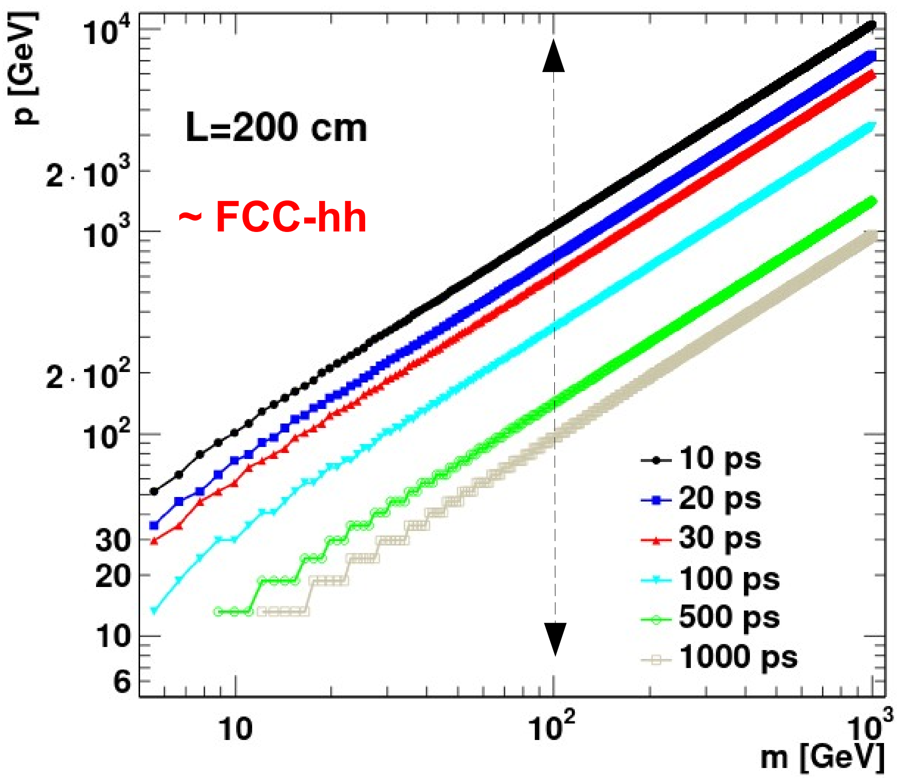
For ~20 ps detector:

- 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?

Reconstruction of stable massive particles
(for pp and e+e- colliders)

- 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 σ_{TOF}=20 ps
- 70 GeV in |p| for σ_{TOF}=1 ns

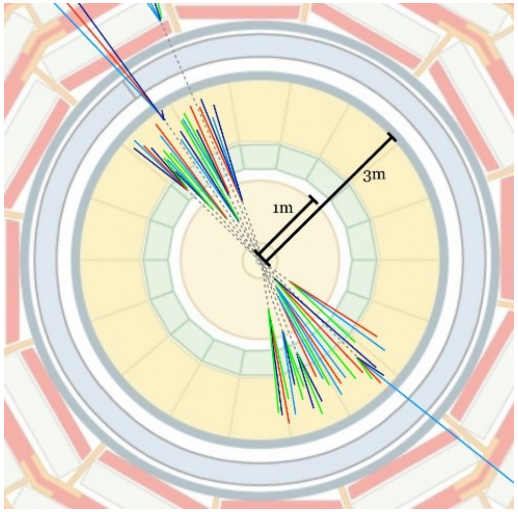
Can identify massive stable particles in very boosted regime!

Snowmass21 contributed paper: arXiv:2005.05221

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

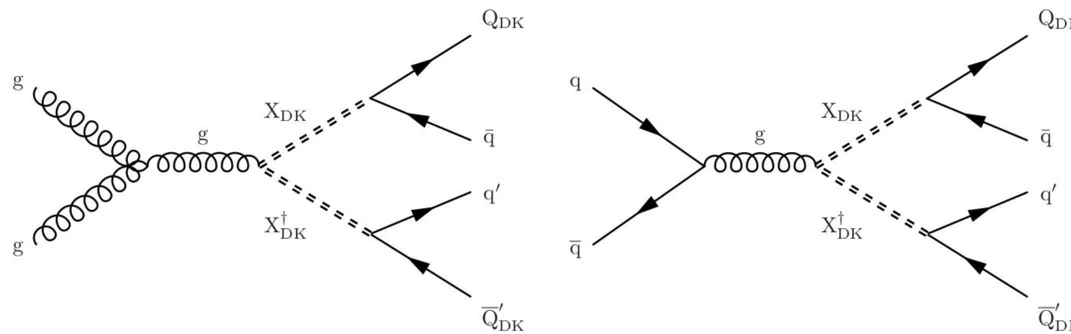
Emerging jets

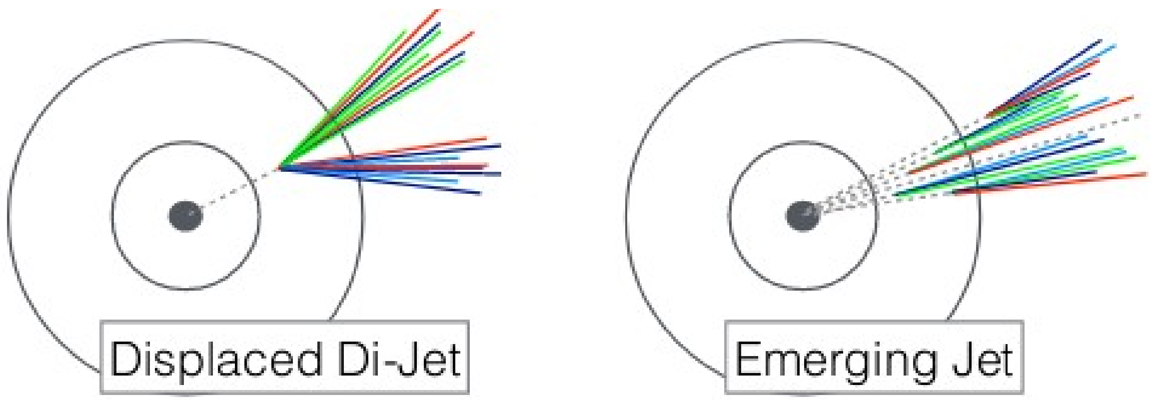
Y. Bai and P. Schwaller, Phys. Rev. D 89 (2014) 063522,
P. Schwaller, D. Stolarski, and A. Weiler, JHEP 05 (2015) 59,



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.





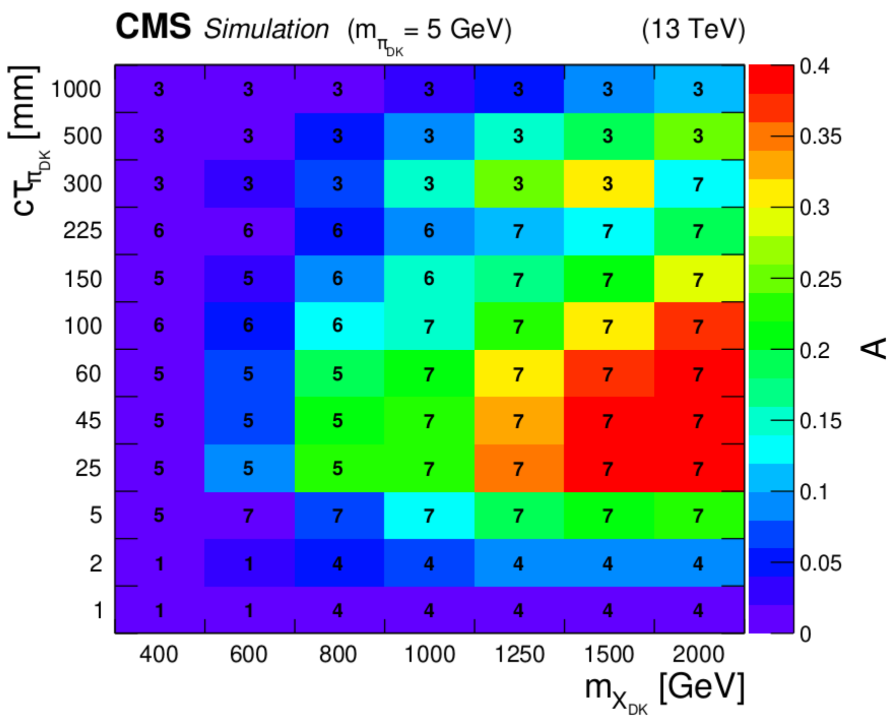
Fight background by vetoing prompt and secondary tracks.
Alternatively: Use timing information for jets

Track acceptance vs calorimeter with timing layers

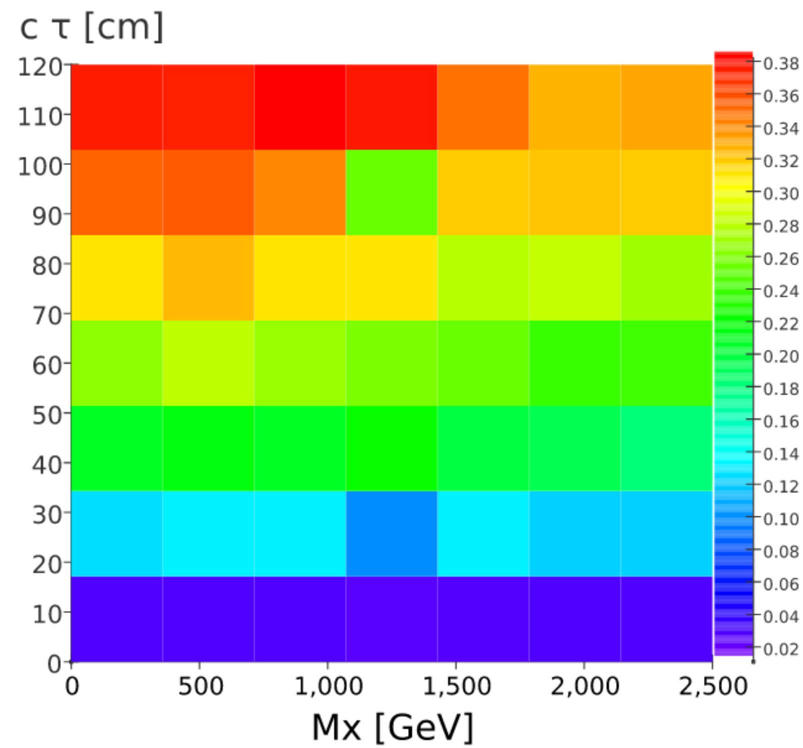
Snowmass21 contributed paper: arXiv:2005.05221

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



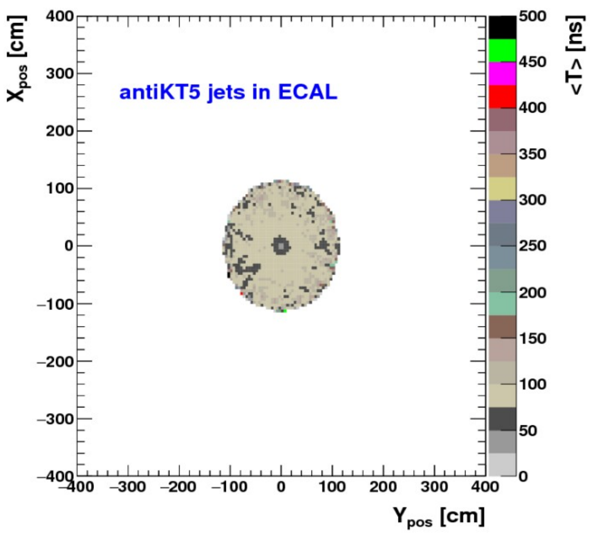
Timing layer on front of ECAL leads to large acceptance for small Mx

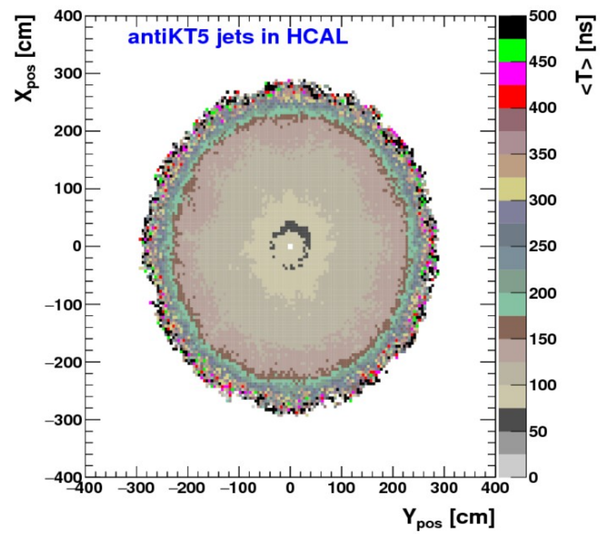
Tagging Boosted Objects with Timing Detectors

Matthew Klimek (arXiv:1911.11235)

LoI to study this effect using Geant4 simulation with FFC-hh: SNOWMASS21-EF8-IF6-008.pdf

- Explore temporal structure of a jet using full Geant4 simulations
  - Jet constituents may have different velocity, particle spectra, b-jets
- If confirmed, this will add “time” in addition to “spatial” dimension for boosted jet tagging. May significantly impact BSM searches
- Investigate during Snowmass21. Geant4 simulations are available





<u>Simulations are available!</u>

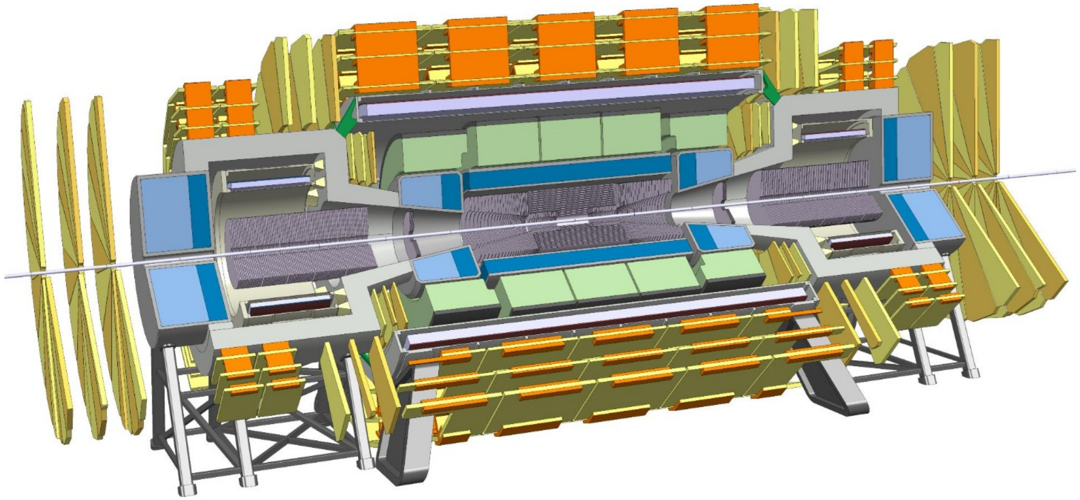
← Time profile of hits for antiKT5 jets at 12 TeV using FFC-like geometry and Geant4 simulations from HepSim

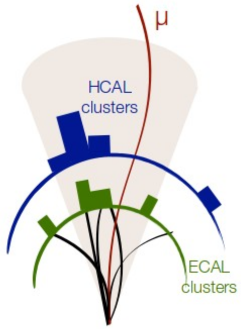
Summary for timing layers studies

- Timing layers with tens of picosecond capabilities complement calorimeters with the standard ~0.5 - 1 ns readout
- Many benefits:
  - For BSM long-lived particles
  - For particle identification (baryons vs pions vs kaons etc.)
  - Reducing confusion terms in PFA → improvements for jets etc.
    - Studied in the past (not recently).
  - b-tagging, lepton-isolation
    - Requires studies in the context of FCC/e+e- experiments!
- Jet tagging using timing will be quantified using realistic simulations
  - To be studied during Snowmass21 (see a dedicated LoIs)

Open questions for 100 TeV pp colliders

(for tracking requirements see #130)





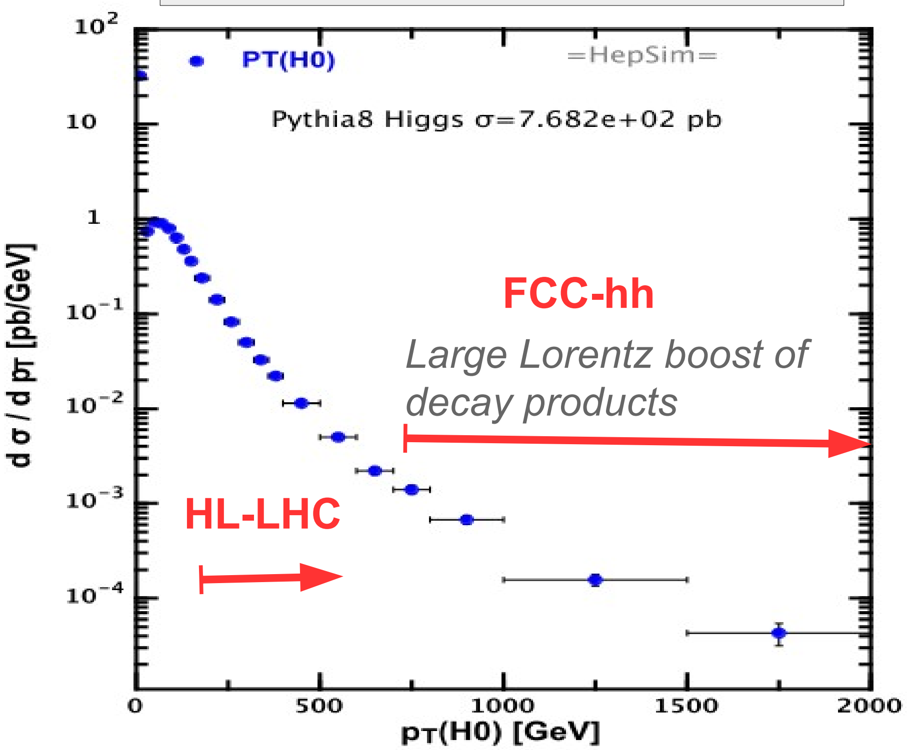
Calorimeter is primary instrument for tens-of-TeV physics that require jet substructure

Snowmass "BOOST" LoI :
SNOWMASS21-EF5_EF7-TF7_TF0-IF6_IF3CompF3_CompF0_Ben_Nachman-140.pdf
→ for a broad overview of various techniques (with references)

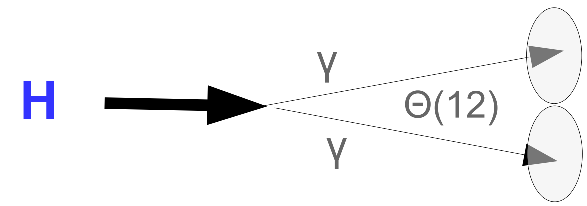
Design challenges for ECAL (Higgs example)

- 100 TeV collider will hunt for M~30 TeV particles decaying to Higgs/W/Z bosons
- SM example: detectors must be optimized to reconstruct SM Higgs at large pT

100 TeV pp
Differential Higgs cross section



SM predictions: ~100,000 Higgs / ab^{-1} for pT>1 TeV



Just kinematics:
pT(H)>2 TeV → **~ 5 deg** between γ's
pT(H)>10 TeV → **~ 1 deg** between γ's

Instrumental challenges:
- identify 2 photons separated by 1 degree
- reject $\pi^0 \rightarrow \gamma\gamma$ background at the same time!
- similar problems for electron, b-jets decays

Need realistic (Geant4) studies of ECAL granularity for high-pT Higgs reconstruction? (Reference: 2x2 cm LArg for FCC-hh baseline)

HCAL requirements driven by physics at 100 TeV

- **Good containment up to pT(jet)~30 TeV: 12 λ_I for ECAL+HCAL** ✓
  - affects jet energy resolution, leakage biases, etc.

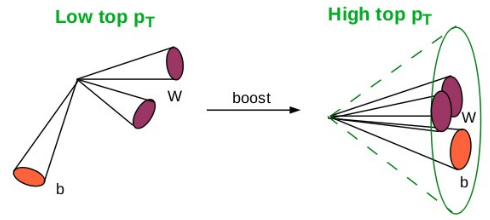
- **Small constant term for energy resolution: $c < 3\%$** ✓
  - Studied in the past in the context dijet masses
  - dominates jet resolution for pT>5 TeV
  - important for heavy-mass particles decaying to jets

- **Longitudinal segmentation → open question** ?

- **Sufficient transverse segmentation for resolving boosted particles:** ✓ ?
  - FCC-hh baseline **$\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$** from fast simulation
    Confirmed using Geant4 simulations (JINST 14 (2019) P05008)

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

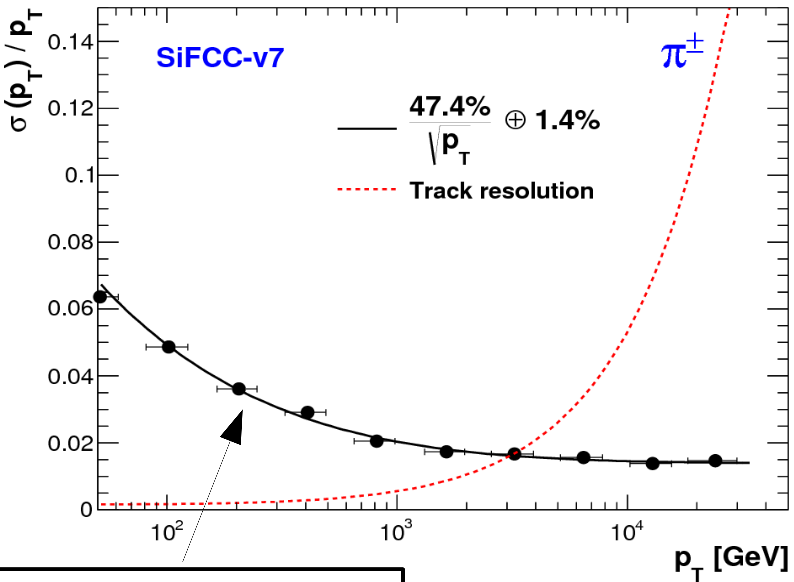
Jet substructure and resolution



- **Jet substructure:** Large performance gains from neutral-particle information and from improved calorimetry in cases where jet mass resolution drives the discrimination power *(E.Colleman etc. 2018 JINST 13 T01003)*
- **Jet resolution:** Calorimeter has a significant impact on jet resolution above 3 TeV (track resolution is significantly larger)

S.C. etc. JINST 12 (2017) P06009

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



Geant4 full simulation: optimal granularity for complex substructure variables for jets above 10 TeV is ~ λ_I /4 ($\Delta\eta \times \Delta\varphi$ = 0.022 x 0.022)

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

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

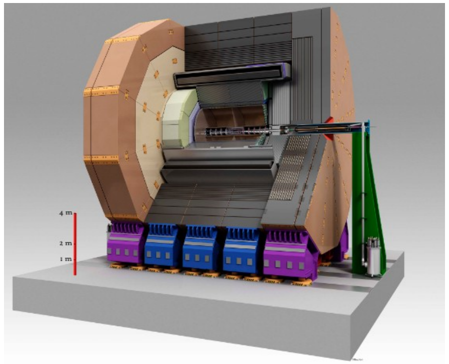
Is any physics that requires smaller cell sizes .. and can it be resolved using realistic simulations?

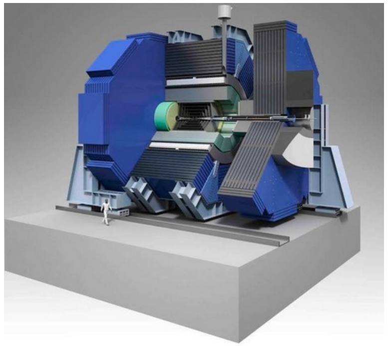
a – stochastic/sampling term,
b- constant term

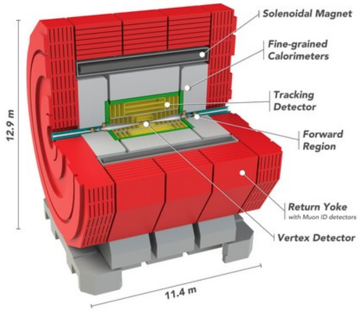
Open questions for e+e- colliders: ILC, CLIC, CEPC

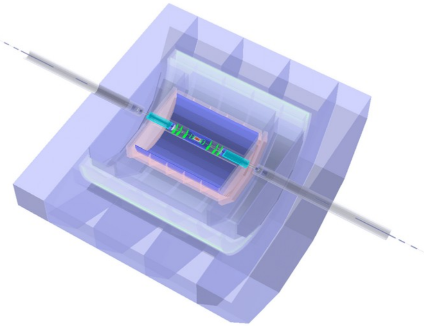
(for tracking requirements see #130)

Prepared by M. Vos (IFIC) & J. List (DESY)





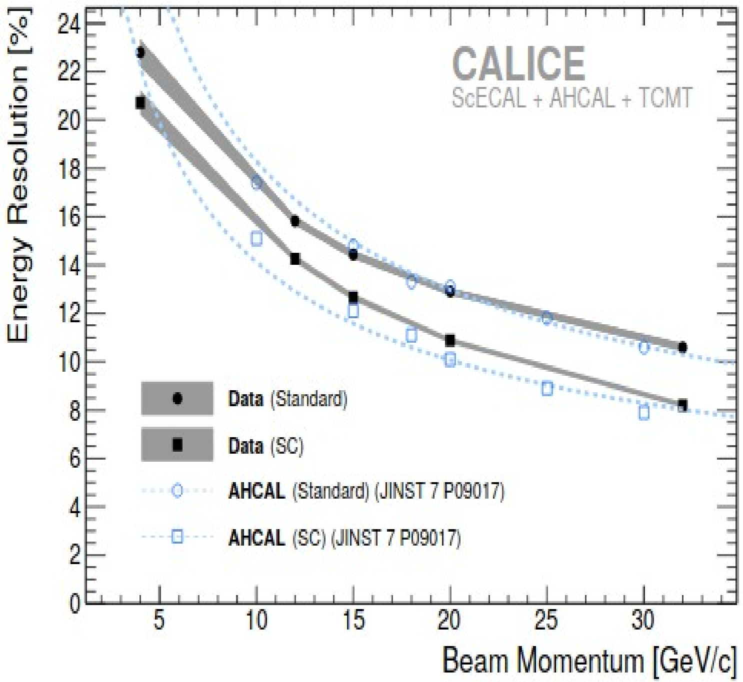




Jet reconstruction

- **Excellent jet energy reconstruction is THE guiding principle for ILC detectors**
  - Highly granular calorimeters for optimal particle flow
  - Hermetic detector with highly efficient tracking: > 99%
  - Minimal amounts of dead material

Detailed full MC simulation studies on detector concepts for ILC and CLIC have validated the particle flow concept. An extensive R&D program by CALICE, LCTPC and silicon tracking groups make sure this is science, not science fiction. Particle flow detector concept adopted by CEPC/FCCee, but not yet adapted to cooling requirements at a DC machine.



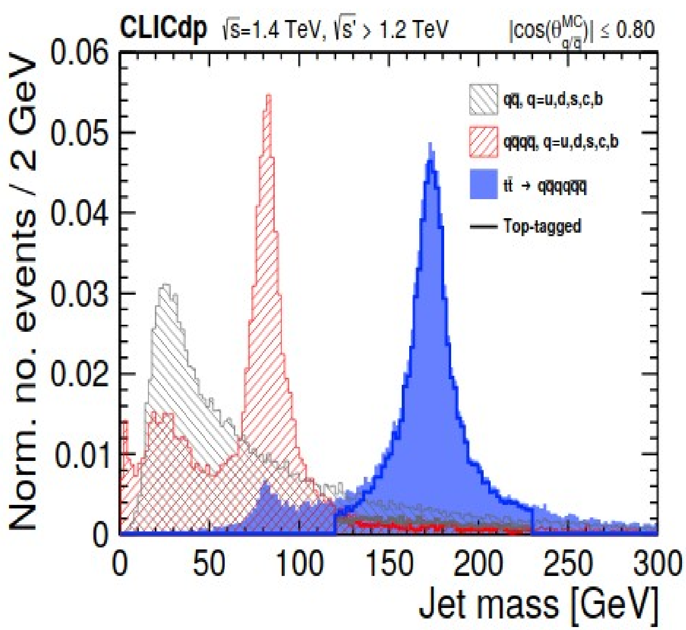
Jet reconstruction algorithms

- **Electron-positron collisions are not like the LHC**
  - we should be informed and inspired by new developments in jet reconstruction at the LHC, but cannot use LHC solutions out-of-the-box
  - A new electron-positron collider is not like LEP/SLC
- **Current state-of-the-art:**
  - jet reconstruction is considerably more challenging at the Higgs factory than at the Z-pole, due to higher jet multiplicity, harder gluon emissions and beam-induced backgrounds
  - Retain exclusive clustering with kT algorithm
  - Use robust clustering algorithms where needed (see arXiv:1607.05039)

Executive summary
the modest background levels at lepton colliders can be dealt with effectively, but clustering remains a real bottle neck in important multi-jet final states

Jet substructure

- Particle-flow detector concept is perfect for jet substructure
  - Quark/gluon tagging and QCD at the Higgs factory (H→ gg)
  - Adapt LHC substructure techniques for boosted objects at high energy see arXiv:2008.05526, arXiv:1911.02523



Executive summary
Detectors and environment allow for very detailed jet substructure studies, starting at the Z-pole and Higgs factory. Boosted objects (nearly) without pile-up for > 1 TeV.

Challenges and areas for improvement (I)

Overlay from gg → low pt hadrons (esp. at 500 GeV and above)

- Improved, robust jet clustering algorithms exist, further studies needed
- Exploit also vertexing? (bunch length = ~200 um)

Use kinematically constrained V0s: improve p→gg, h→gg, K0 →pp, L→pK etc

Jet clustering (especially in complex multi-jet events):

- Theory and machine learning experts are welcome!
- Which detector information could help?
- **Important application example: Higgs self-coupling**

Challenges and areas for improvement (II)

b- / c-jets:

- use lepton ID and 2ary/3ary vertices to estimate neutrino momentum in semi-leptonic decays
- use mass constrained fits of B- / D- decay chains

Exploitation of PID capabilities (dE/dx, TOF)

- use PID information in track and vertex re-fitting to improve momentum estimate
- use correct mass in PFO energy estimate

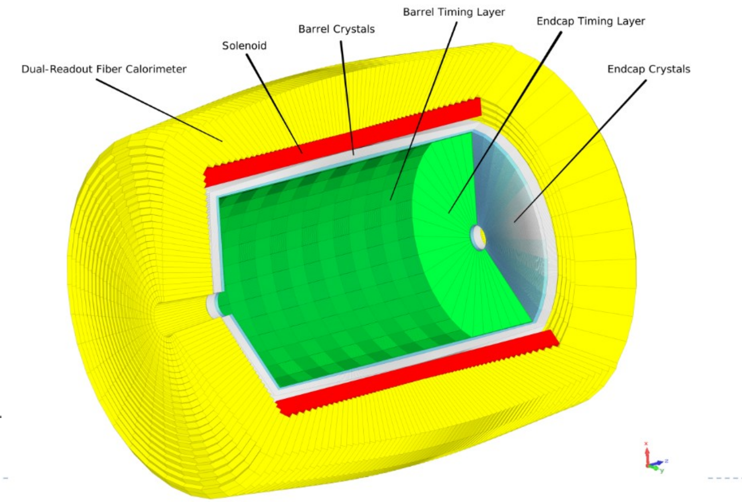
5D particle flow:

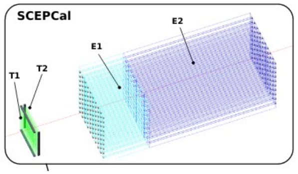
- use time information in calorimeter to reduce confusion in particle flow, eg: “late” neutrons (→ see timing layers part)

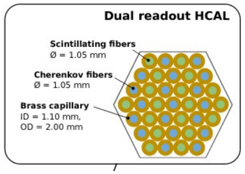
Crystal ECAL with dual-readout fiber calorimetry

***(IDEA LoIs** SNOWMASS21-EF1_EF4-IF3_IF6-096.pdf, M.Lucchini, arXiv:2008.00338)*

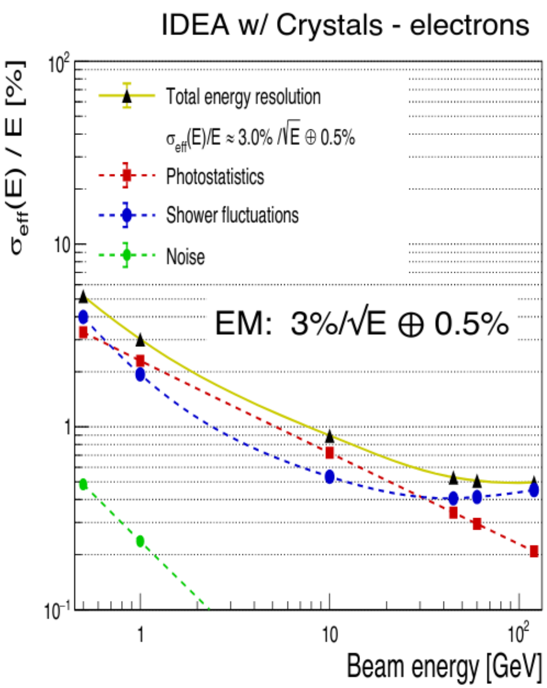
- A calorimeter design that has the highest energy resolution for both photons and neutral hadrons
- Open questions related to jets:
  - Jet resolution?
  - Jet substructure variables?

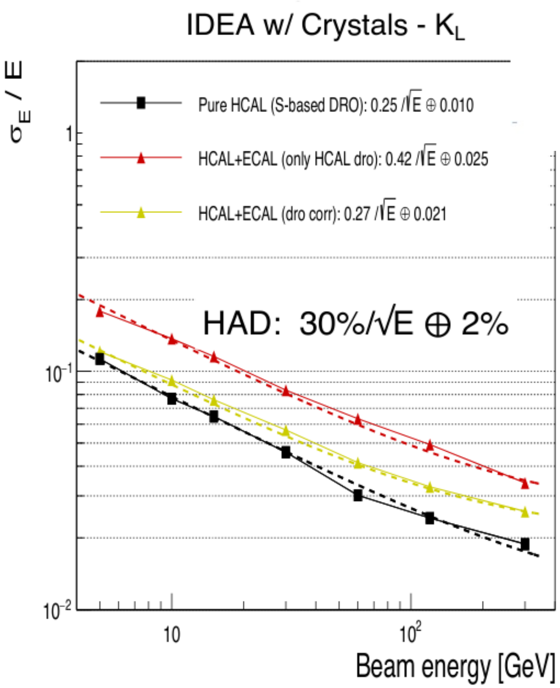






ECAL & HCAL with dual readout





Summary

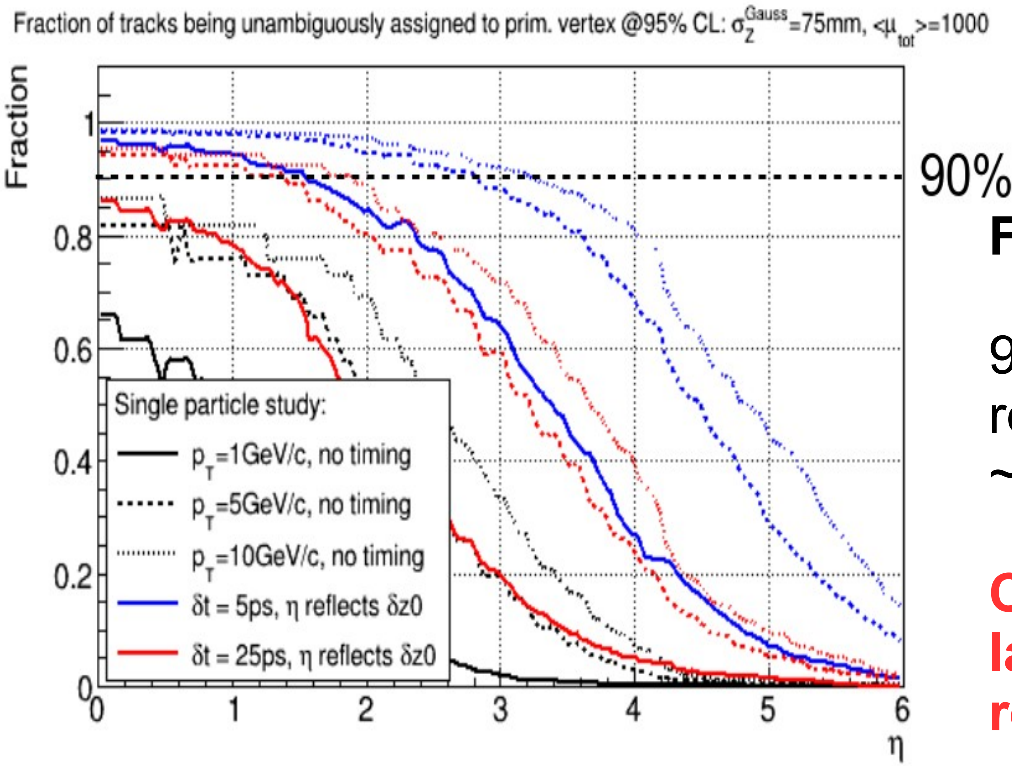
- Jets and jet substructure techniques play essential role in exploring the TeV scale of pp collisions and high-precision physics at e+e-
- Full consensus about importance of high-granularity calorimeters with tens-of-picosecond resolution, but many details on parameters of such detectors need to be verified using realistic simulations
- Particle flow concept is the main trend for jet reconstruction in e+e- and pp but the impact of precise timing information needs to be studied
- Many interesting ideas related to jet reconstruction and jet substructure variables during this Snowmass 2021. We hope many ideas described in LoIs will be verified and included in the Snowmass contributed papers

Thanks to all who contributed to this presentation

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