Calibration and timing for the HGCAL detector

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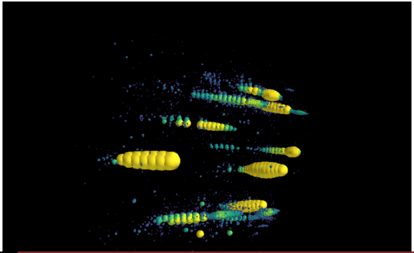
on behalf of the CMS-HGCAL collaboration

4th June 2021, PPTAP Detectors Workshop



The HL-LHC schedule

- Not possible to increase luminosity without increasing PU.
- Enormous challenges to detector upgrade programs.

Two scenarios

Scenario	$\mathcal{L}$	$< PU >$	Vertex Density	$\int \mathcal{L}/\text{year}$
Baseline	5×10^{34} cm^{-2}s^{-1}	140	0.8 / mm	250 fb^{-1}
Ultimate	7.5×10^{34} cm^{-2}s^{-1}	200	1.2 / mm	$>$ 300 fb^{-1}

The upgrade of the CMS detector

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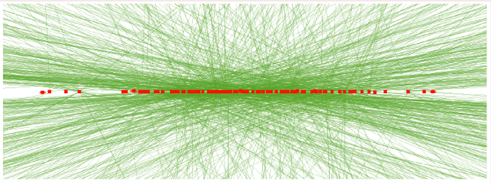
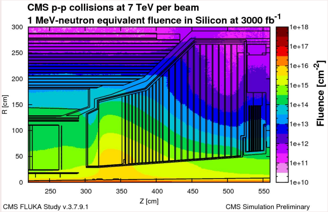
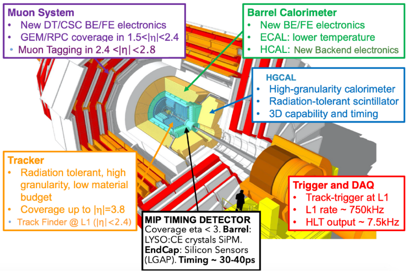
High PU ⇒ High Occupancy



⇒ High Radiation



- Current detector unable to sustain such levels whilst keeping similar performance as of now, particularly in the end-cap regions.
- CMS upgrade design driven by the need to sustain radiation damage and separate hard scattering from PU vertices.



Muon System
- New DT/CSC BE/FE electronics
- GEM/RPC coverage in 1.5<|η|<2.4
- Muon Tagging in 2.4 <|η|<2.8

Barrel Calorimeter
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: New Backend electronics

HGCAL
- High-granularity calorimeter
- Radiation-tolerant scintillator
- 3D capability and timing

Tracker
- Radiation tolerant, high granularity, low material budget
- Coverage up to |η|=3.8
- Track Finder @ L1 (|η|<2.4)

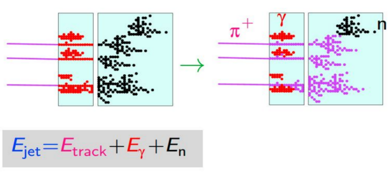
MIP TIMING DETECTOR
Coverage eta < 3. **Barrel**: LYSO:CE crystals SiPM. **EndCap**: Silicon Sensors (LGAP). **Timing ~ 30-40ps**

Trigger and DAQ
- Track-trigger at L1
- L1 rate ~ 750kHz
- HLT output ~ 7.5kHz

The CMS approach

Pattern recognition

- high granularity: "imaging calorimeter"
- particle-flow detector by design



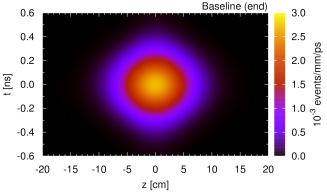
$E_{\text{jet}} = E_{\text{track}} + E_\gamma + E_n$

Charged hadrons	60%	Tracker p reso
Photons	30%	EM reso
Neutral hadrons	10%	Hadronic reso

- End game: minimize confusion, from source of calo deposit **and** overlapping of particles.
- Additional complexity: identify and remove energy from PU ⇒ "Denoising"....

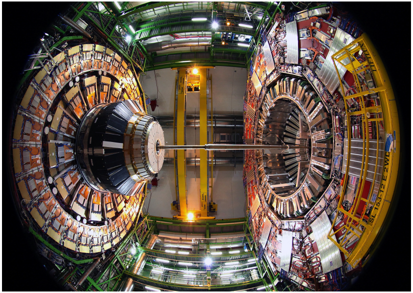
Pile-up mitigation

- Addition of timing information
- Discrimination of PU vertices



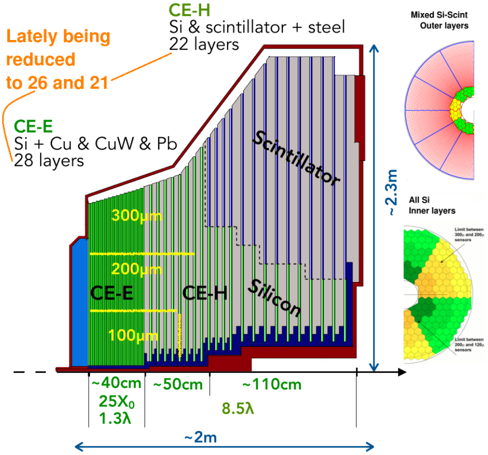
- Bunches within 25 ns.
- Vertices within 200 ps.
- At $v = c$, 100 mm = 330 ps.

The HGCAL project



Both endcaps	Silicon	Scintillators
Area	**~620 m^2**	**~400 m^2**
Channel size	0.5 - 1 cm^2	4 - 30 cm^2
#Modules	~30'000	~4'000
#Channels	**~6 M**	240 k
Op. temp.	-30 °C	-30 °C

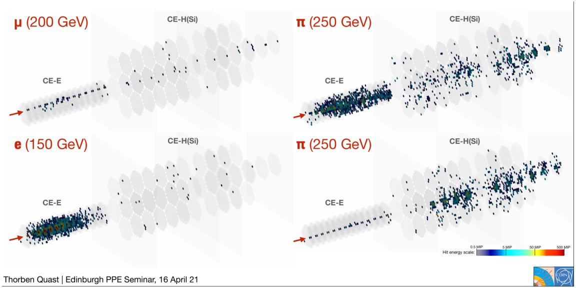
Lots of valuable input from the CALICE collaboration !



Lately being reduced to 26 and 21

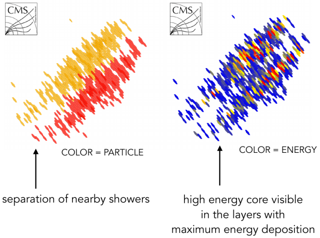
HGCAL is an imaging calorimeter

Real showers from 2018 test beam at CERN



Thorben Quast | Edinburgh PPE Seminar, 16 April 21

$e^+ e^-$ showers from γ conversion



separation of nearby showers

high energy core visible
in the layers with
maximum energy deposition

- Clustering of cells in 2D and 3D, using spatial+energy information.
- Considering adding time information too with $\mathcal{O}(30)$ ps resolution, with external time reference from MTD layers.

⇒ importance of calibration for the energy measurement, and feasibility of timing to reject deposits from PU vertices⇒ both UK contributions.

Calibration requirements

Targets

- Two types of sensors: Si and scint tiles + SiPM
- After irradiation: lower Signal from sensitive material + higher Noise from readout electronics.
- At end-of-life, target is MIP-S/N $\simeq 2.5$ in Si, $\simeq 5$ in Scint. tiles.
- May have to go even lower, worst affected cells of both Si and scint tiles have MIP-S/N $\simeq 2$.
- "Absolute calibration" $\Rightarrow$ given by physics candles like Z/γ.
- What matters: intercalibration of the cells, to accuracy driven by impact on energy resolution: 3% in CE-E, $\mathcal{O}(15\%)$ in CE-H.

Challenges

- Isolate MIP deposits to perform regular calibration.
- Need to be able to see MIPs, and reject noise even at end-of-life.
- Need the triggers + acceptable rate to have required precision.
- Need selection with good enough purity + efficiency.

Options available

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MIPs from non-interacting pions, within showers

✓ high rate in minimum bias collisions

X "not-quite" MIPS: mixture of momentum and particle type

⇒ for EM calibration ?

MIPs from muons, using tracks

✓ proper MIPs

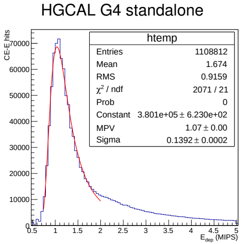
X low rate

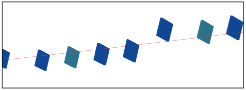
⇒ for hadronic calibration ?

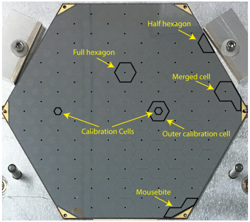
Special calibration pads: 1 per readout chip

✓ higher MIP-S/N, charged injection system for linearity measurement.

⇒ independant verification of MIP calibration at startup + monitor charge collection efficiency vs time.

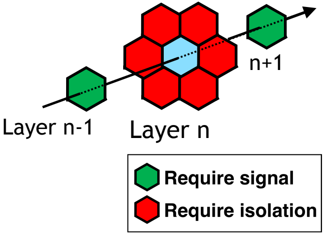




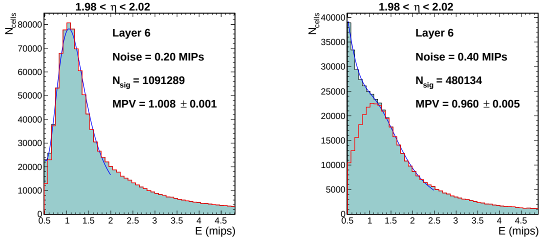


MIPs in standard minimum bias collisions

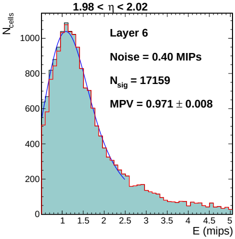
- The only advantage of high PU: high rate of (non-interacting) hadrons ⇒ MIP tracklets.
- Check performance with simple mip-tracking algorithms: 3- or 5-layer tracklets.
- Estimated rate to obtain 3% accuracy, assuming negligible systematic effects: 50M events for MIP-S/N$>$ 2.5 ($>$ 120 M for smaller MIP-S/N).



3-layer tracking $S/N = 5$ and 2.5



5-layer tracking $S/N = 2.5$



Issues to address: systematics

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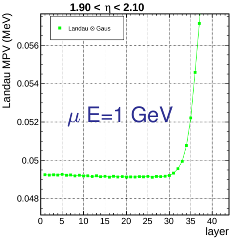
- Minimum bias tracklets = mixture of "not-quite MIPs"
- MPV variations theoretically well-known, from Bethe-Block.
- With <200> PU simulation: found layer-to-layer variations $\mathcal{O}(6\%) \Rightarrow$ too large !
- Three major effects identified: ✓reduce systematics to $\mathcal{O}(1)\%$.

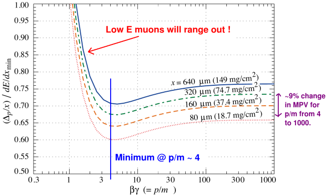
① Correction for particle local direction: cos$\theta \simeq$ 0.9(0.99)@$\eta =$ 1.5(2.5)

② Tightening of the selection to reject e/γ contributions: increase lever arm.

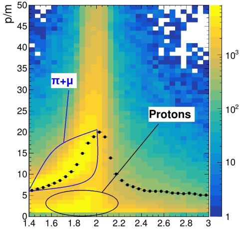
③ Rejection of proton contribution: more elaborate tracker-driven selection of $\pi^{\pm}$ and $\mu^{\pm}$ tracklets.



HGCAL G4 standalone



G4 tracks matched to 3-lay tracklets

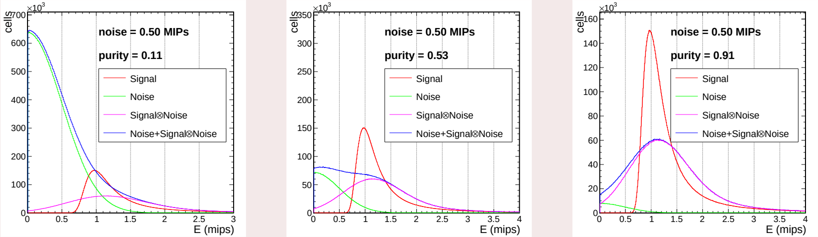


HGCAL G4 standalone

Issues to address: availability of the data

Impact on readout electronics and data volume

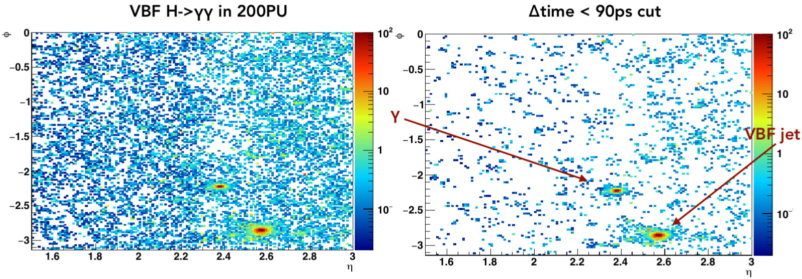
- Visibility of the peak: digitisation not lower than 10 ADC/MIP.
- Fitting of the noise+signal component using rising left edge: readout threshold not lower than 0.5 MIP.



Choice of data-taking mode

- Minimum bias trigger rate: on-the-fly using full L1 bandwitdh: 500 (750) kHz for baseline (ultimate) scenarios ?
- Single muon rate in 5kHz HLT menu for CE-H calibration ?

How timing can help for PU mitigation



- Cleaning of "time-displaced" energy deposits.
- Cleaning of PV candidates using measurement of time of tracks from the chosen hard-scattering PV: rejection of charged hadrons associated to time-displaced PU vertices.
- Questions: what is the time precision we can expect from the detector ? What is the typical time distribution of a photon/pion shower ?

Precision timing

- Intrinsic timing capability of Si sensor with ideal electronics: resolution $\simeq$ 10 ps for high S/N.
- Complemented by timing layer to be placed in front of the ECAL.
- Adds a dimension to assist in PU rejection, and identification of primary vertex.
- Simple algo tested, to select hits (highest density time interval, reject tails): time resolution of showers $<$ 30 ps, also with PU.
- But, significant tails from signal showers in particular for hadrons: further studies needed.

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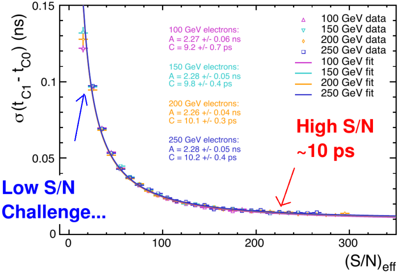
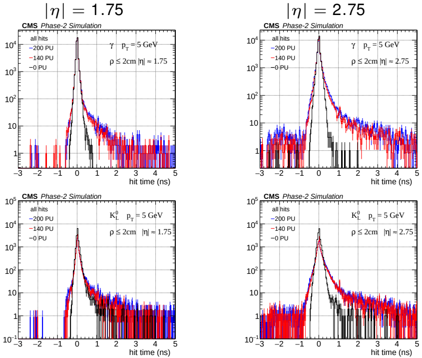


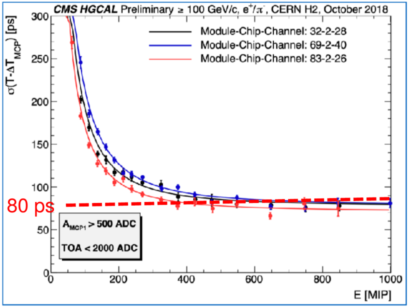
High S/N ~10 ps

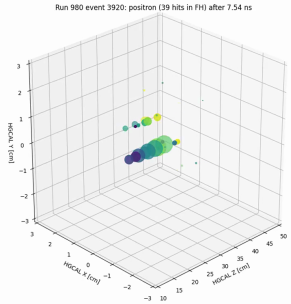
Low S/N Challenge...


$|\eta| = 1.75$ $|\eta| = 2.75$

Timing performance in beam test

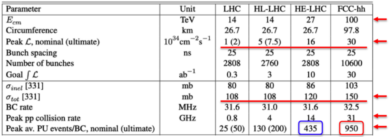
- TB prototype with full readout achieving 80 ps single-cell resolution: not the final chip yet (targeting $\simeq$ 20 ps, or say $<$ 50 ps).
- First exploration of time shower developement!
- Important setup to benchmark the simulation against real data.
- Still lots to do for the full HGCAL setup: time calibration, correlation effects, implementation in PF reco.



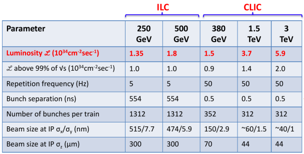


Outlook

- The HGCAL for HL-LHC is an ideal guinea pig for high-granularity detectors with timing precision at future colliders.
- Calibration issues to be understood early on.
- Timing as a 5th dimension, complementing 3D position and energy, is being explored.
- Future detectors: even more challenging conditions !



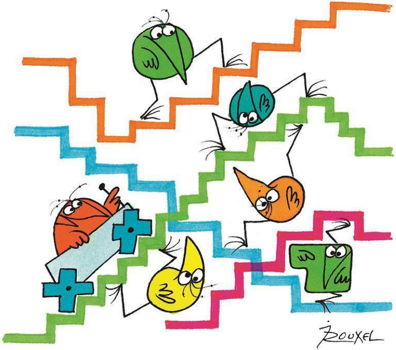
Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [331]	mb	80	80	86	103
σ_{tot} [331]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950



	ILC		CLIC		
Parameter	**250 GeV**	**500 GeV**	**380 GeV**	**1.5 TeV**	**3 TeV**
Luminosity $\mathcal{L}$ ($10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$)	**1.35**	**1.8**	**1.5**	**3.7**	**5.9**
$\mathcal{L}$ above 99% of √s ($10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$)	1.0	1.0	0.9	1.4	2.0
Repetition frequency (Hz)	5	5	50	50	50
Bunch separation (ns)	554	554	0.5	0.5	0.5
Number of bunches per train	1312	1312	352	312	312
Beam size at IP σ_x/σ_y (nm)	515/7.7	474/5.9	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (µm)	300	300	70	44	44

Drives timing requirements CLIC detector

Shadok's Mottos



With stairs designed for going up, one often manages to go up lower than going down stairs designed for going down.

... and vice versa...

Backups

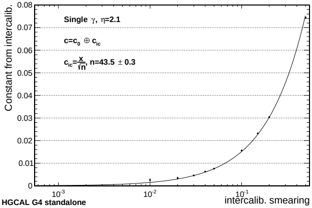
BACKUPS

Aim for the impact on energy resolution

- Sampling calorimeter:

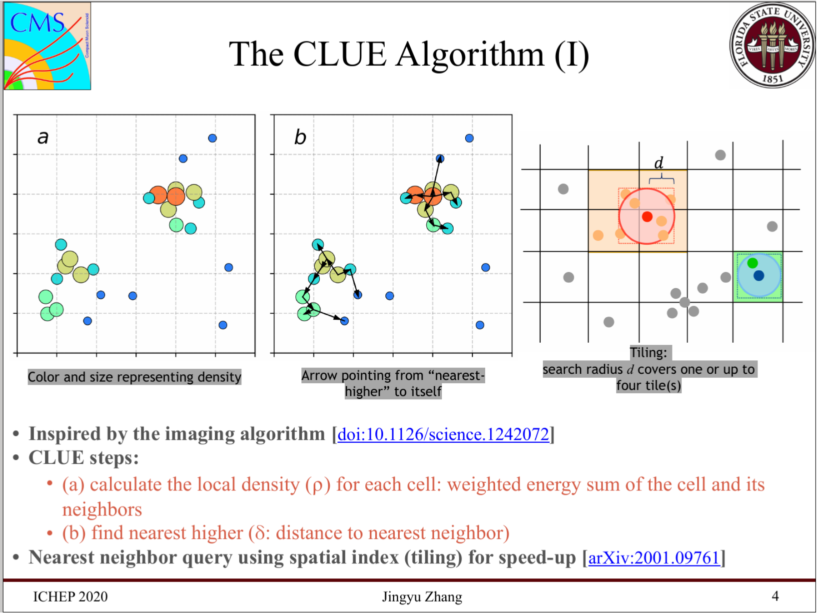
$$\sigma/E = c \oplus s/\sqrt{E} \oplus n/E$$

- High-energy photon showers: requirement to keep the constant term c below 1% $\Rightarrow$ intercalibration of CE-E cells within 3%.
- Hadronic energy resolution: affecting "only" 10% of full jet energy, accepting intercalibration at the level of 15 to 20%.



Final accuracy required

- In CE-E: $<$ 3% up to MIP-S/N$\simeq$ 2.5 in Si.
- In CE-H: $<$ 20% up to MIP-S/N$\simeq$ 2.5 in Si and 5 in Scint.



The CLUE Algorithm (I)

Color and size representing density

Arrow pointing from "nearest-higher" to itself

Tiling:
search radius *d* covers one or up to four tile(s)

- **Inspired by the imaging algorithm [doi:10.1126/science.1242072]**
- **CLUE steps:**
  - (a) calculate the local density (ρ) for each cell: weighted energy sum of the cell and its neighbors
  - (b) find nearest higher (δ: distance to nearest neighbor)
- **Nearest neighbor query using spatial index (tiling) for speed-up [arXiv:2001.09761]**

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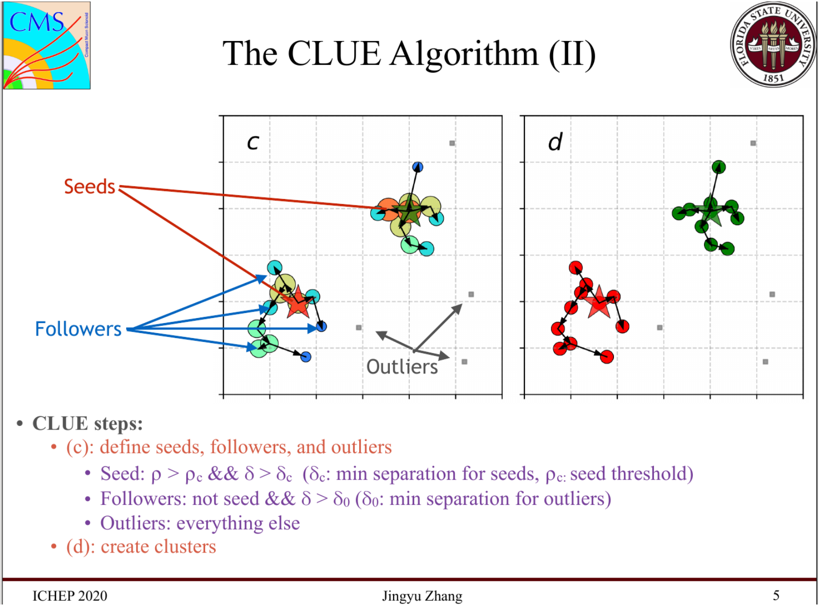

The CLUE Algorithm (II)

- **CLUE steps:**
  - (c): define seeds, followers, and outliers
    - Seed: $\rho > \rho_c$ && $\delta > \delta_c$ (δ_c: min separation for seeds, $\rho_{c:}$ seed threshold)
    - Followers: not seed && $\delta > \delta_0$ (δ_0: min separation for outliers)
    - Outliers: everything else
  - (d): create clusters

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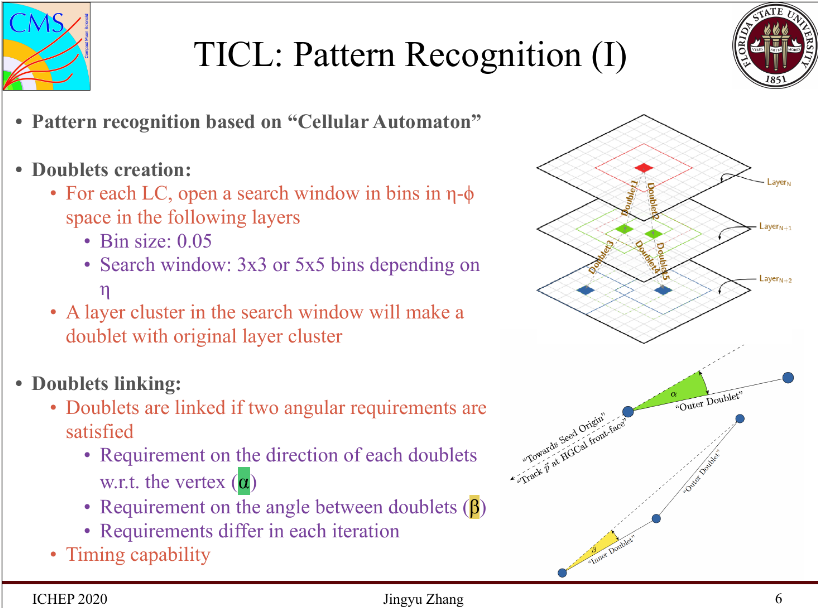

TICL: Pattern Recognition (I)

- **Pattern recognition based on "Cellular Automaton"**
- **Doublets creation:**
  - For each LC, open a search window in bins in η-ϕ space in the following layers
    - Bin size: 0.05
    - Search window: 3x3 or 5x5 bins depending on η
  - A layer cluster in the search window will make a doublet with original layer cluster
- **Doublets linking:**
  - Doublets are linked if two angular requirements are satisfied
    - Requirement on the direction of each doublets w.r.t. the vertex (α)
    - Requirement on the angle between doublets (β)
    - Requirements differ in each iteration
  - Timing capability

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