Examples of ongoing detector R&D for CLIC

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on behalf of
CLIC detector & physics study

CLIC Project Meeting
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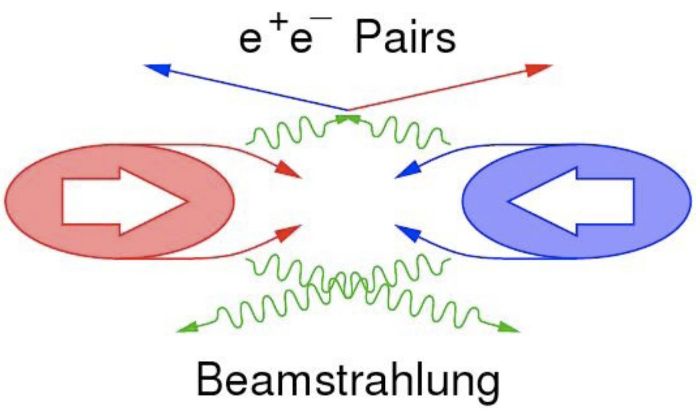
“Beam” imposed conditions

Low duty cycle at CLIC – 50 trains/sec, 312 BXs per train, 0.5 ns between BXs.

- All BXs read out in-between bunch trains. ***No trigger.***
- All subdetectors will implement power pulsing schemes at 50 Hz, to reduce needed cooling systems



Main backgrounds in detector:

- incoherent e^+e^- pairs: 19k particles / train
- $\gamma\gamma\rightarrow$hadrons: 17k particles / train

Need to:

- Reject **pile-up** in offline reconstruction.
- Include overlapping beam-induced background in **simulation**

Physics imposed conditions

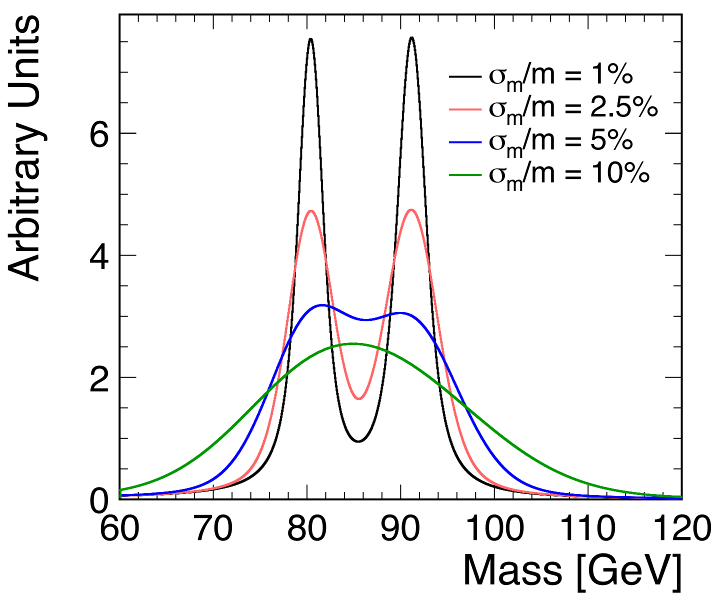
- High-resolution pixel detector for flavor tagging
  p = 1 GeV: σ_{d0}~20 μm (CMS: 90 μm)
  p = 100 GeV: σ_{d0}~5 μm (CMS: ~10μm)

- momentum resolution for high energy lepton final states

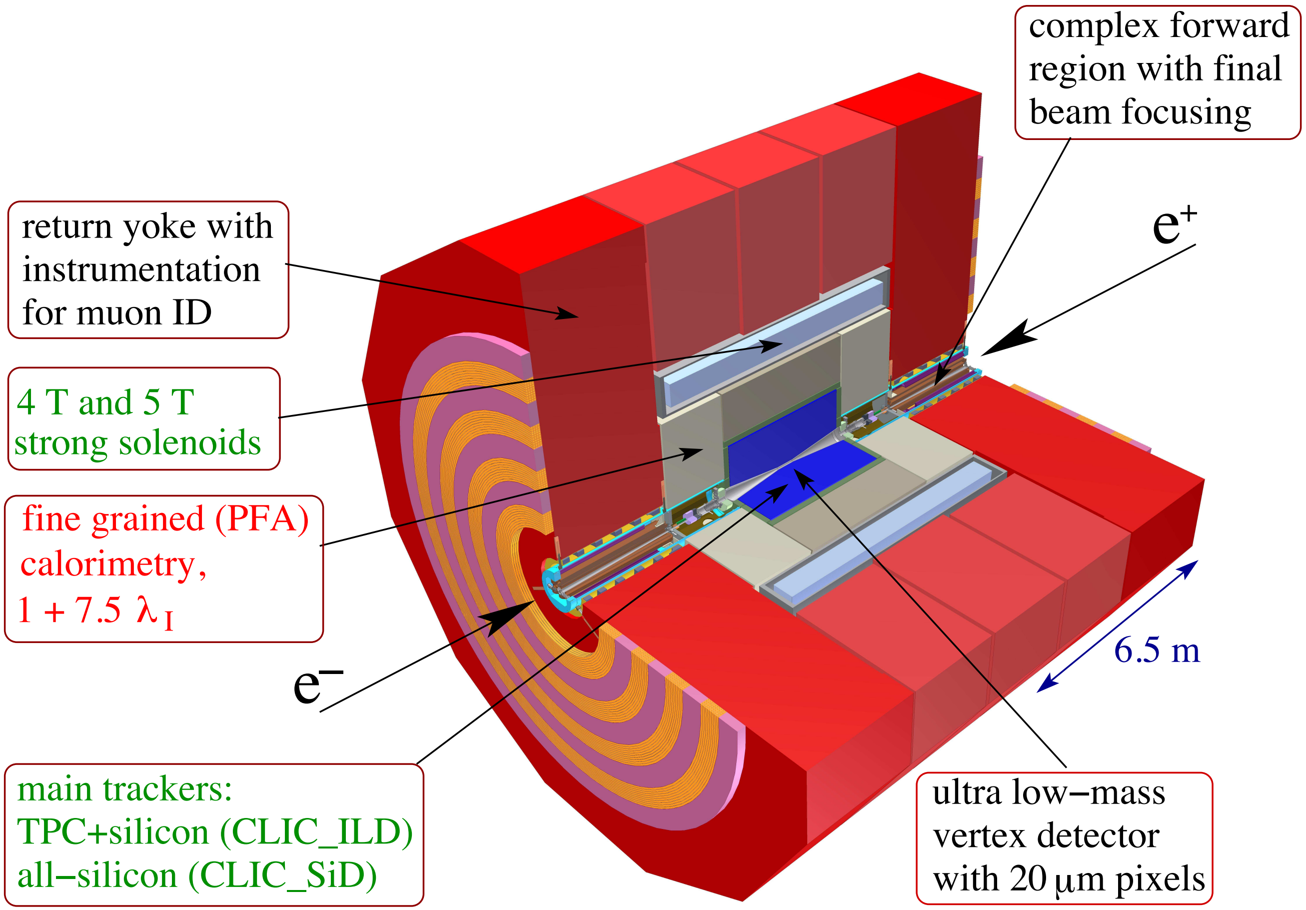
  p = 100 GeV: $\sigma(p_T)/p_T = 0.2\%$ (CMS: 1.5%) $\sigma_{pT} / p_T^2 \sim 2 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$

- Need very good jet-energy resolution to distinguish W / Z dijet decays (to be reached with PFA)

E	=	10^2	–	10^3 GeV:
$\sigma(E_j)/E_j$	~	5.0%	–	3.5%
ATLAS	~	8.0%	–	4.0%



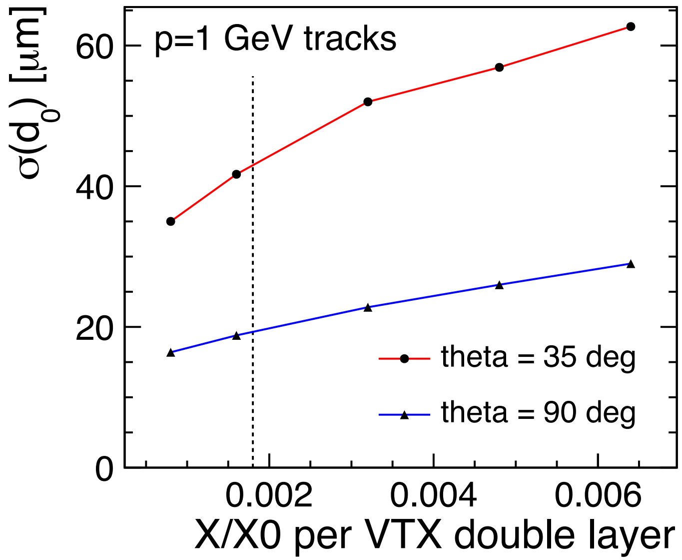
CLIC general purpose detectors



➢ Calorimeters to be placed inside the solenoid for accurate PFA

Vertex detector

	CLIC	ATLAS	CMS
$\sigma_{r\phi}$ [μm]			
$p_T = 1$ GeV	~20	75	90
$p_T = 1$ TeV	5	11	9



R&D aims at

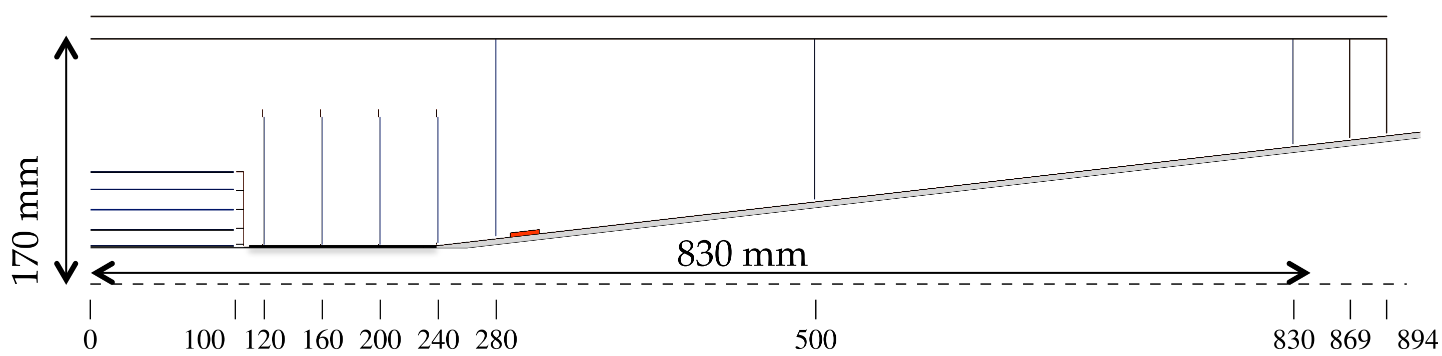
- Low material budget: X ≲ 0.2% X_0 / layer
  - Corresponds to ~200 μm Si, including supports, cables, cooling
- Low-power ASICs (~50 mW/cm^2) + air-flow cooling

- Maintaining high granularity and precise time stamping (~10 ns)

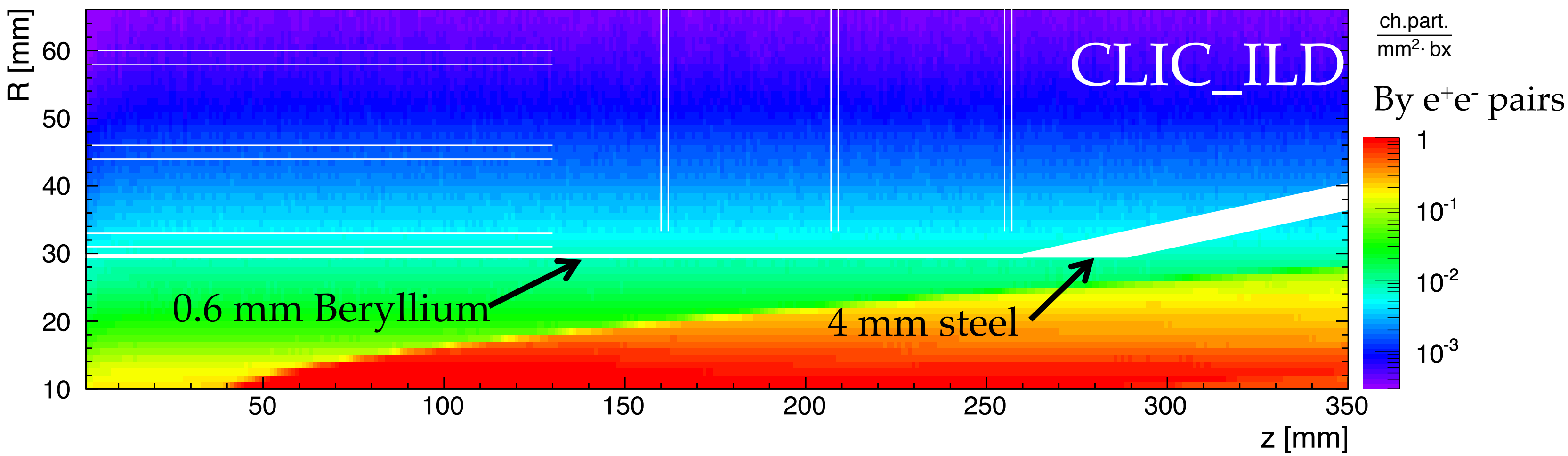
CLIC vertex detector

	CLIC	CMS
Material X/X_0 (90°)	~1.1% (5 layer)	~10% (3 layer)
Power/pixel	<~0.2 μW	28 μW
Pixel size	20 x 20 μm^2	100 x 150 μm^2
# pixels	2.76 G	66 M
Time stamping	5-10 ns	<~25 ns

- Low power is achieved by power pulsing (P_{avg} ~ 1/50 x $P_{cont.}$)
- To date: no technology option available fulfilling all requirements



Beam induced background constraints



	CLIC	ATLAS
Occupancy in 1st vertex det. barrel layer [# particles / mm²]	1.9 / train	0.05 / BX
Maximum pixel occupancy	2% / train	~0.1% / BX
NIEL in innermost layer [n_{eq} cm^{-2} y^{-1}]	$< 10^{11}$	$10^{14} – 10^{15}$
Total ionizing dose [Gy/yr]	200	$> \sim 10^5$

➢ For LHC a major issue is radiation hardness; minor concern at CLIC.

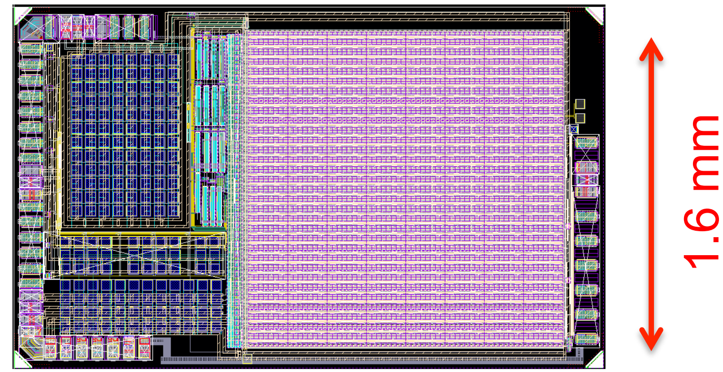
CLICPix power pulsing scheme

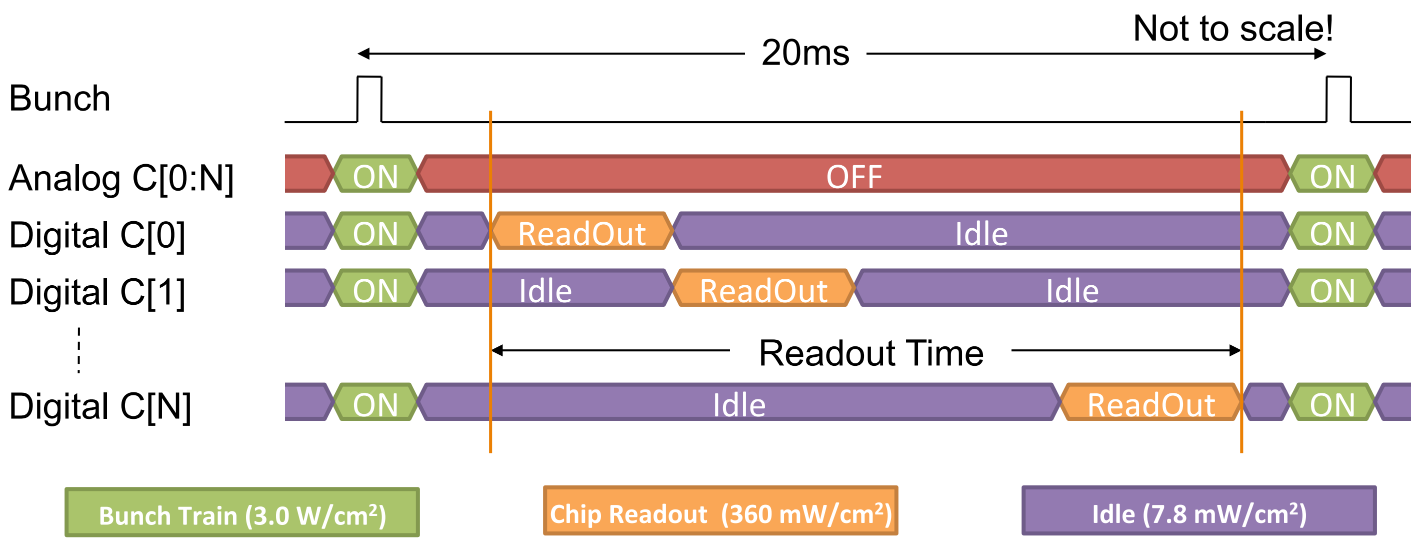
Estimation of newly designed CLICPix:

power consumption based on measurements with 65 nm test-chip & from current TimePix

- Total reduction factor of 40 (from 2 W / cm² to 50 mW / cm²)

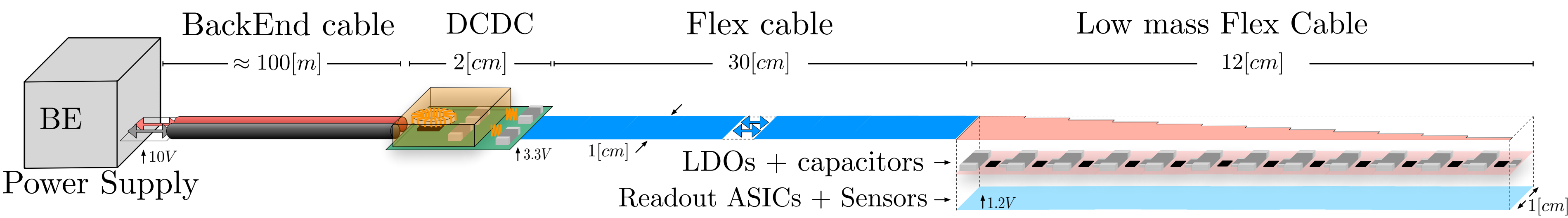
CLICpix demonstrator chip submitted for production





Power-delivery scheme

- DC/DC converters outside pixel-sensor area
- Flexible Kapton cables with Al conductor for power delivery
- local energy storage and Voltage regulation with Si capacitors and LDO regulators



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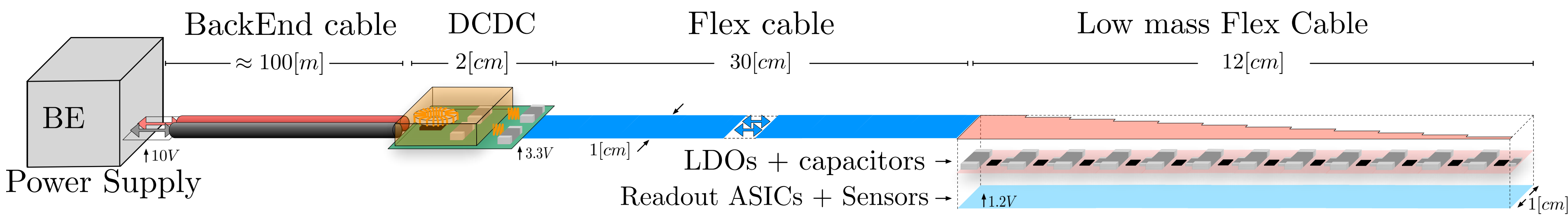
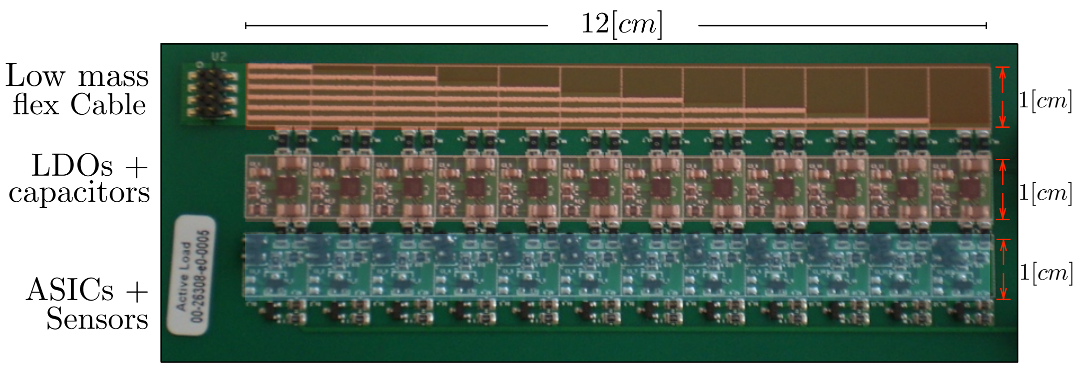
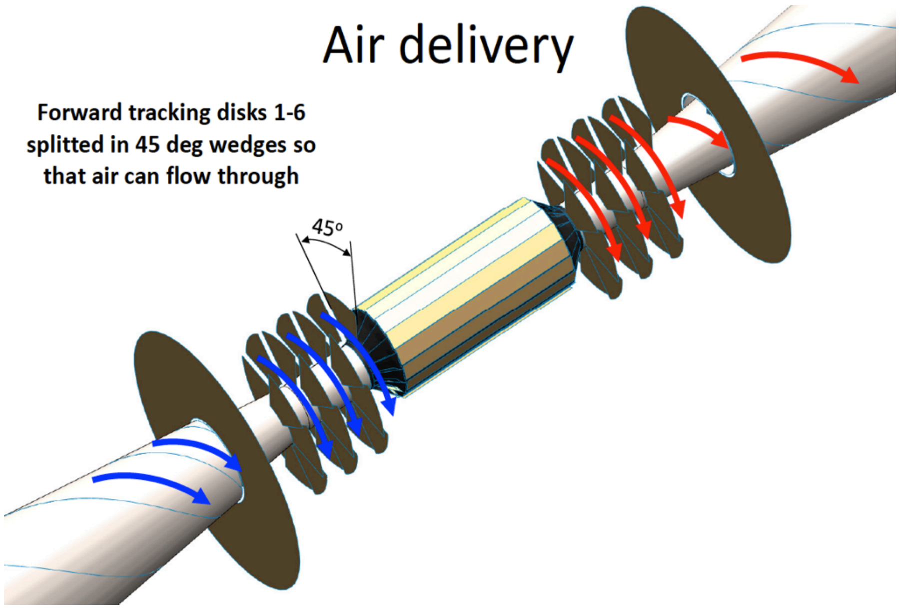


Test setup with active loads emulating analog pixel F/E

- Power pulsing at 50 Hz
- Load current of 2 A (half ladder) during ~20 μs
- Observed ripple < 20 mV, acceptable for CLICPix
- Agreement between measurement and simulation



Low-mass air flow cooling (P ~ 500W in VTX)



ANSYS finite element simulation

- Spiral disk geometry for air flow into barrel

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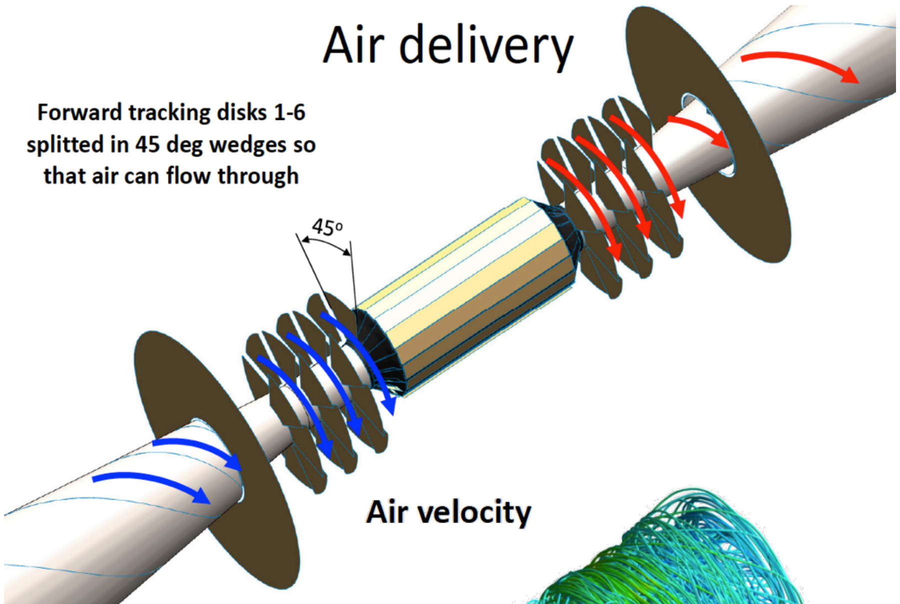
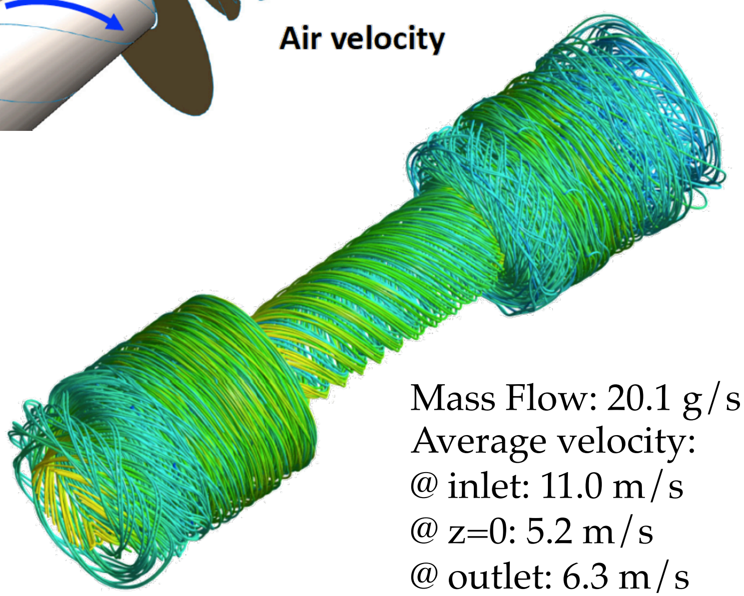




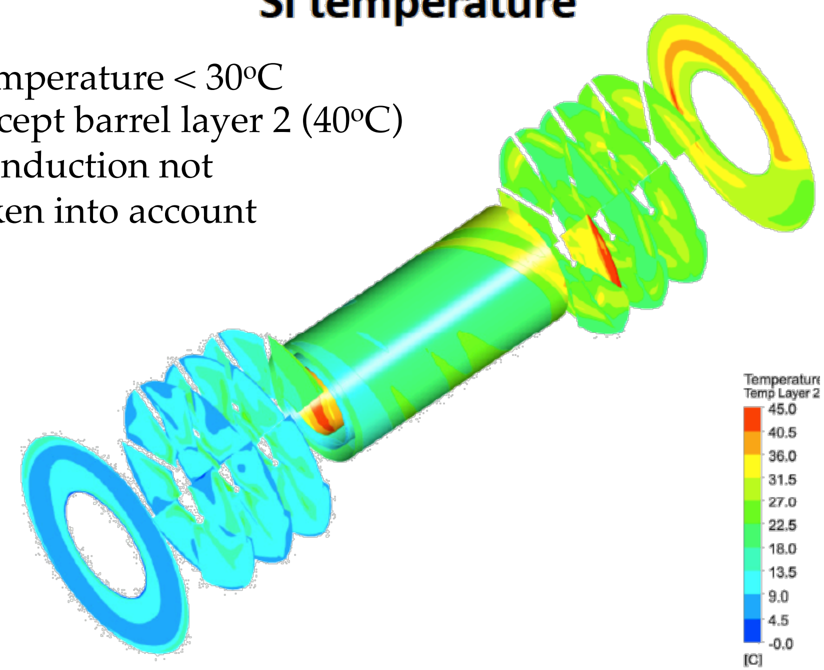
Mass Flow: 20.1 g/s
Average velocity:
@ inlet: 11.0 m/s
@ z=0: 5.2 m/s
@ outlet: 6.3 m/s

ANSYS finite element simulation

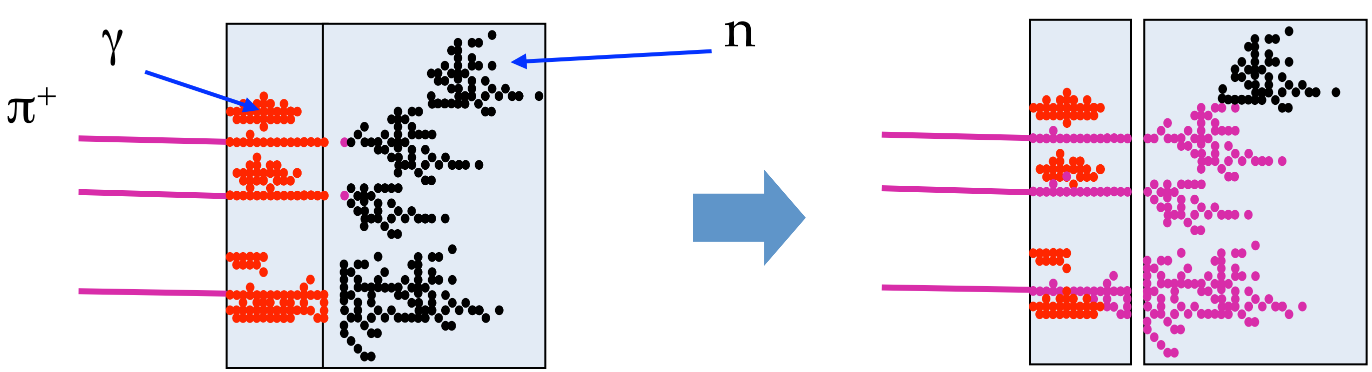
- Spiral disk geometry for air flow into barrel
- Sufficient heat removal
- Temperature gradient between two endcaps of ~15°C

Si temperature

- Temperature < 30°C
- Except barrel layer 2 (40°C)
- Conduction not taken into account



Particle Flow Principle



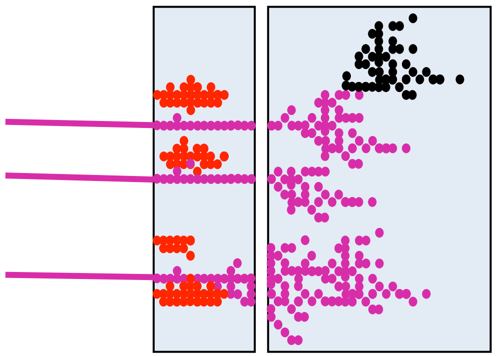
$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

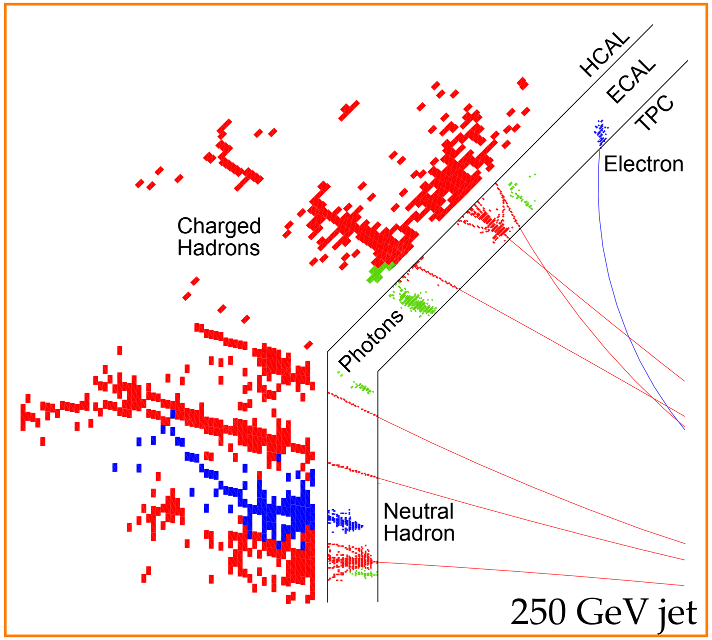
Reconstruct each particle inside a jet by:

- Measuring charged particle energies (60% of jet) in tracker.
- Measuring photon energies (30%) in ECAL
  $\sigma E / E < 20\% / \sqrt{E(GeV)}$
- Measuring only neutral hadron energies (10%) in HCAL
  $\sigma E / E > 50\% / \sqrt{E(GeV)}$

Particle Flow Principle



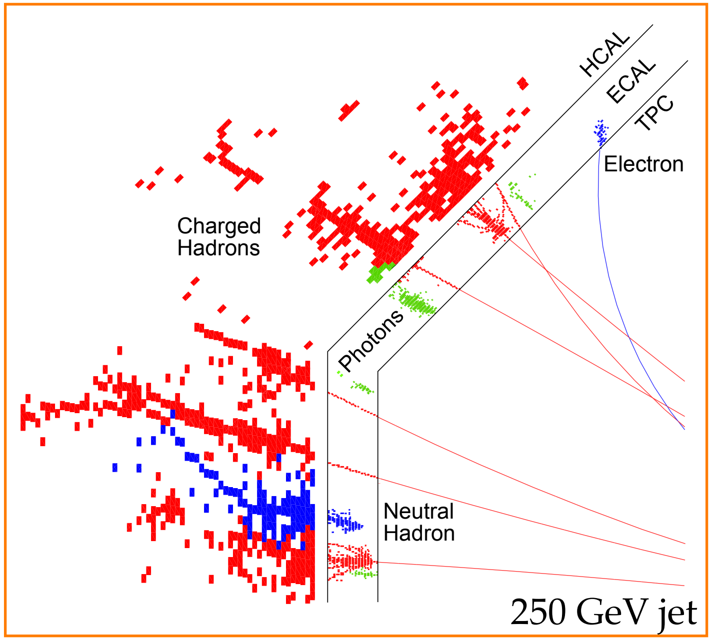
$$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$$

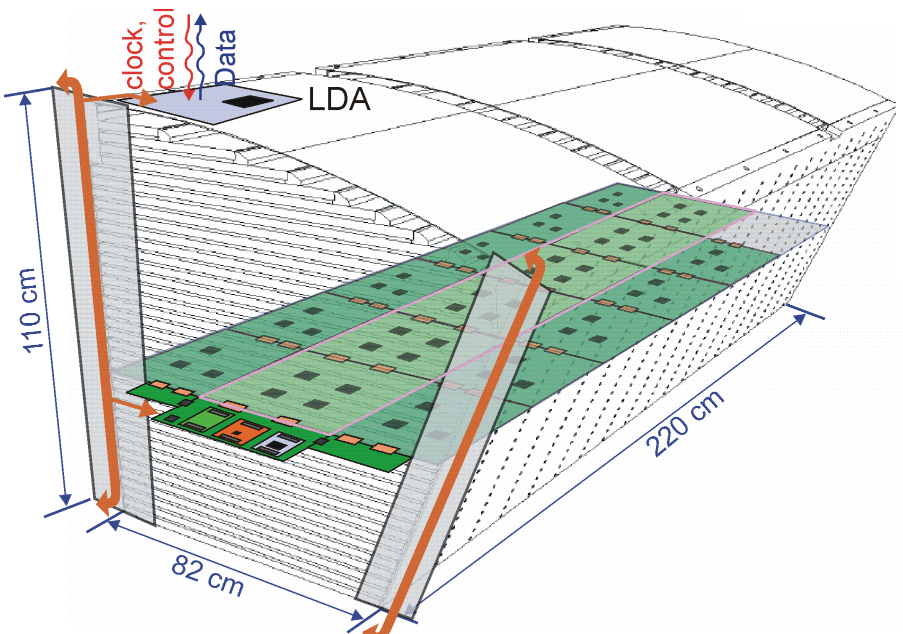


- Need calorimeters with very high granularity and pattern recognition → Imaging calorimeters

Hadronic calorimetry

	CLIC HCAL
Absorber (Barrel/Forward)	Tungsten / Steel
Sampling layers (B/F)	75x10 mm / 60x 20 mm (~ 0.1 λ_{I})
Cell size	30 × 30 mm² (analog, Scint.) or 10 × 10 mm² (digital, e.g. RPC)
λ_I	7.5





Hadronic calorimeter (barrel, at 90°)

Based on stand-alone test-beam measurements:

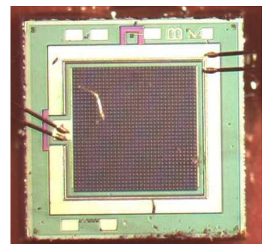
		CLIC 3 TeV	ATLAS	CMS
Intrinsic energy resolution **$\sigma_E / E = a / \sqrt{E} \oplus b$**		a = ~60% b = ~2.5%	a = 45% b = 1.3%	a = 100% b = 7%
Jet energy **σ_E / E**	**p = 45 GeV** **p = 0.5 TeV**	5% 3.5%	15% 4%	19%, PFA → 12% 5%

- ATLAS has higher segmentation and more λ_I than CMS. The nominal resolutions are therefore better.
  - CMS results with PFA are preliminary.
- Where ATLAS has 20k channels, CLIC has 10M channels.
- CLIC & CMS coil sizes are similar, yet HCAL depth at CLIC is higher, due to the different absorber materials used

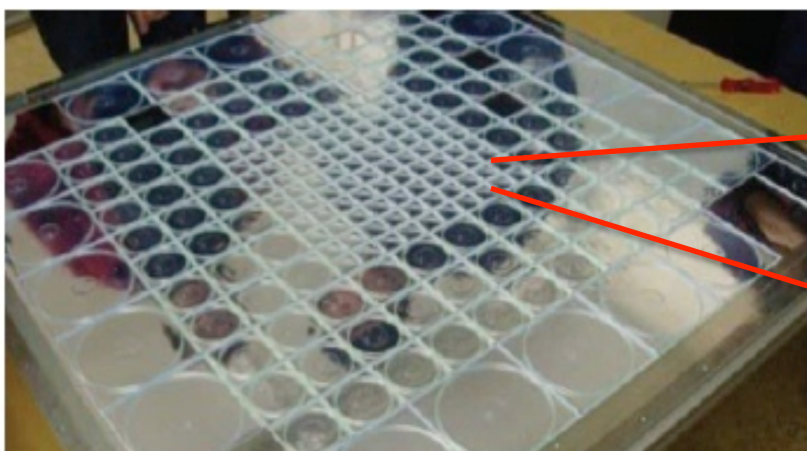
Tungsten analog HCAL prototype

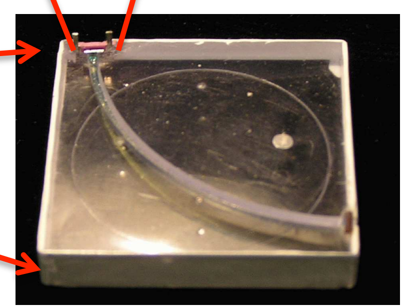
Main purpose: Validation of Geant4 simulation of hadronic shower development in tungsten

Analog HCAL:
2010/11 testbeams at CERN

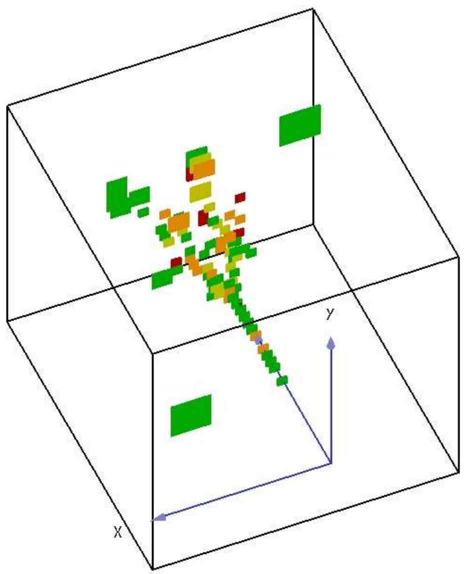


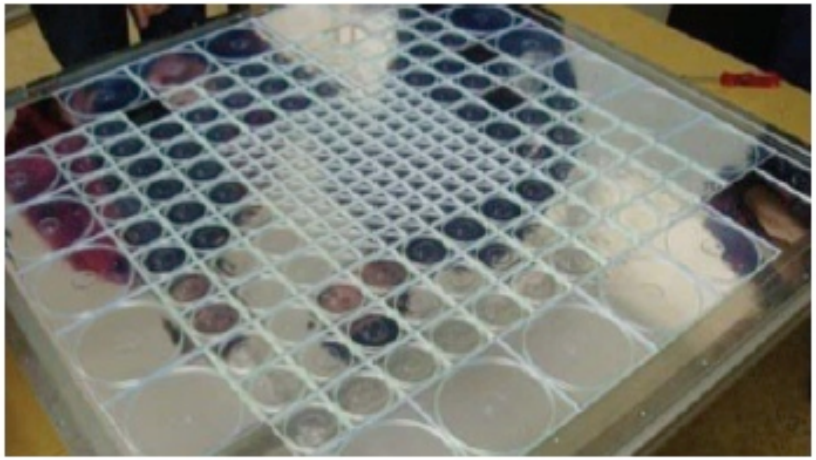
- Scintillator tiles 3x3 cm^2 (in centre)
- Read out by SiPM



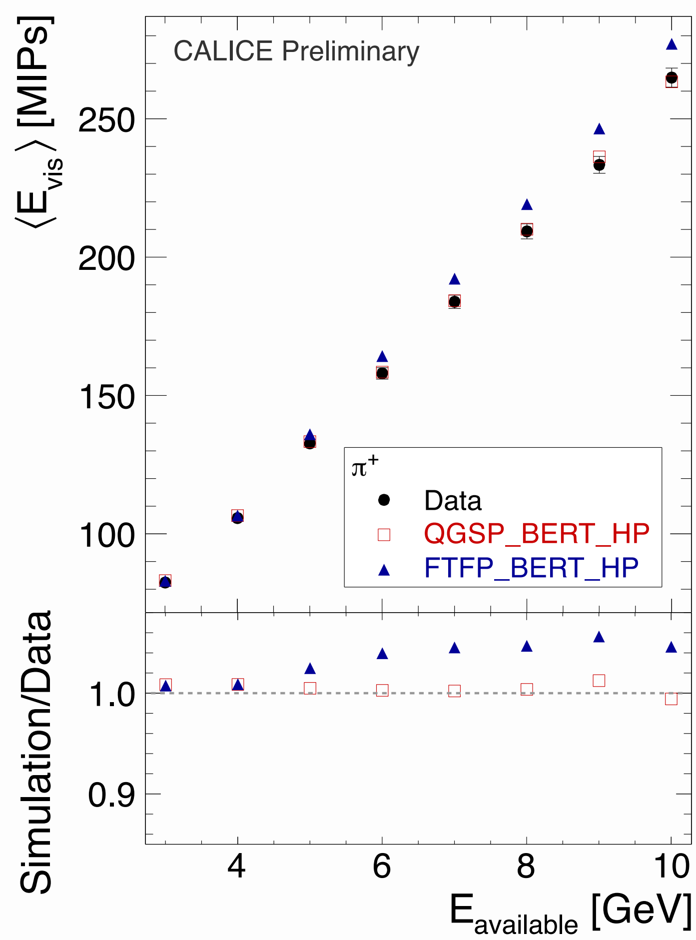


10 GeV pion:



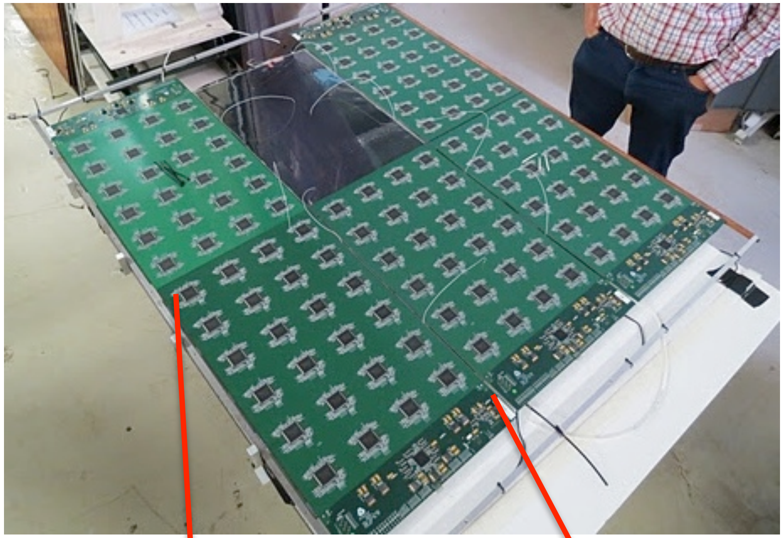


QGSP_BERT_HP is found to give very good agreement for both pions and protons



Tungsten digital HCAL prototype

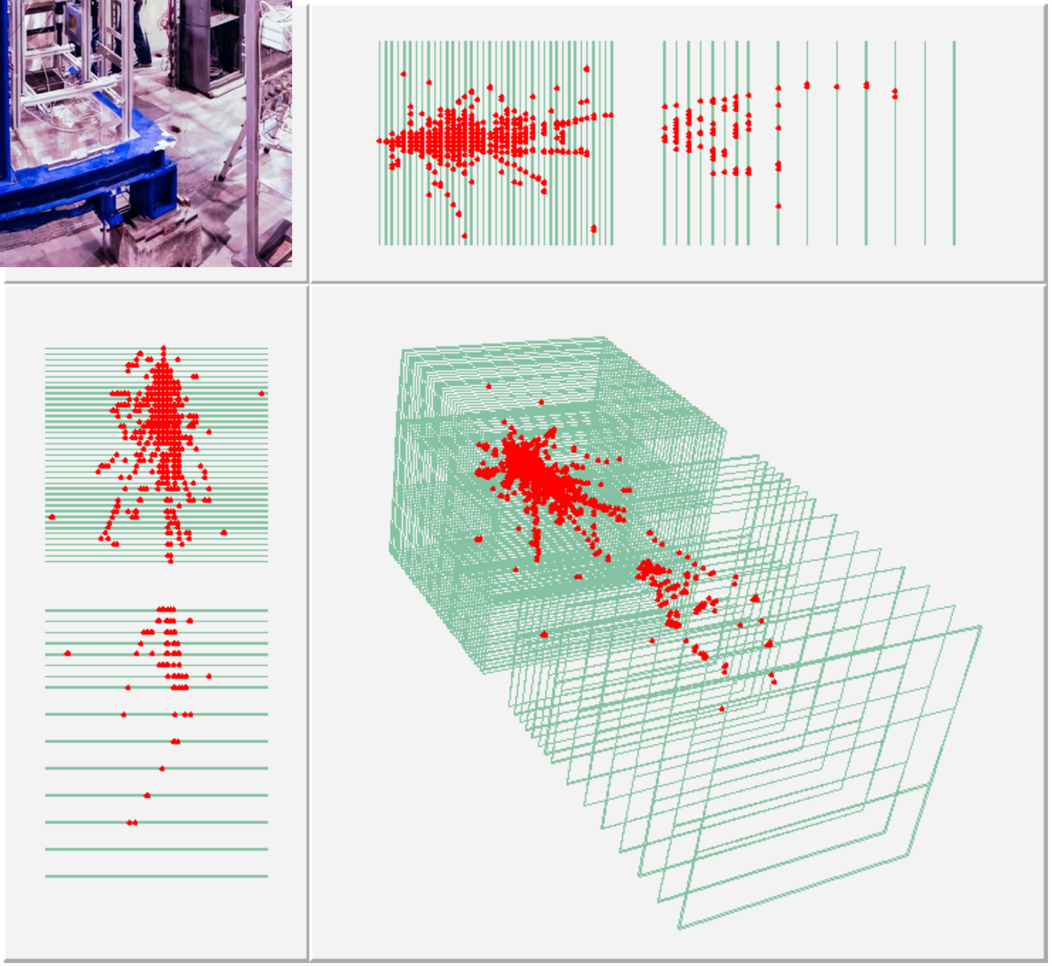
Main purpose: Validation of Geant4 simulation of hadronic shower development in tungsten



Digital HCAL: 2012 testbeam @ CERN

- Single gap glass RPCs
- With 1x1 cm^2 readout pads

Imaging calorimetry – digital HCAL

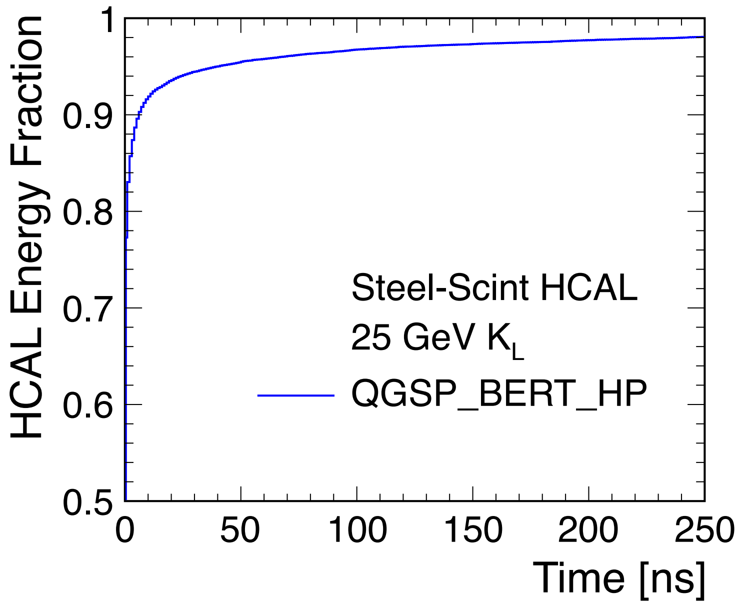


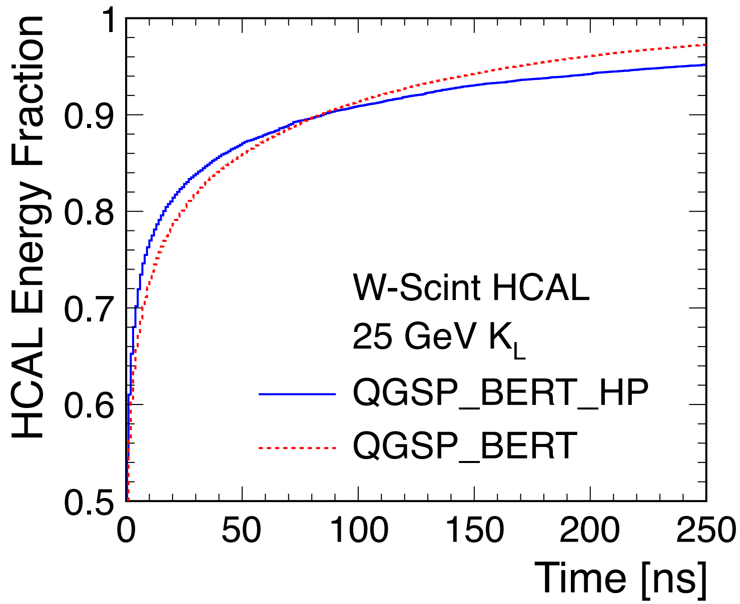
Digital HCAL at SPS:

- 210 GeV pion event display

	# channels
ATLAS	**20k**
DHCAL in testbeam	**450k**

Time development in hadronic showers





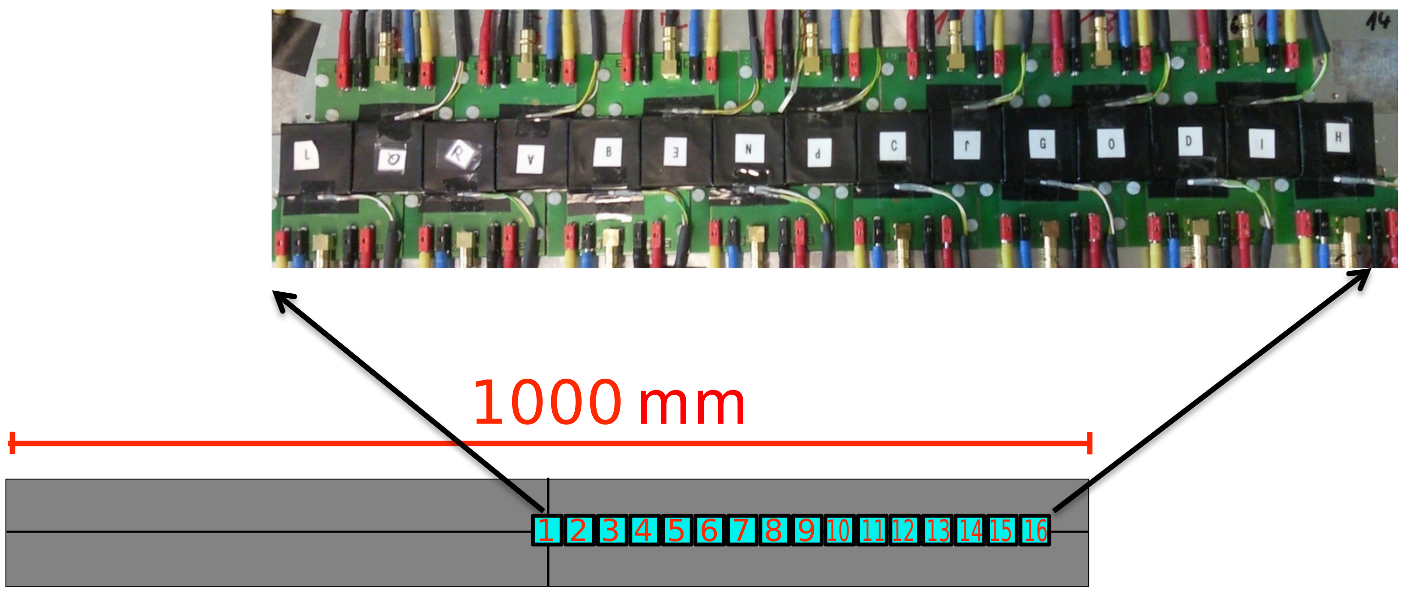
- In steel 90% of the energy is recorded within 6 ns (corrected for time-of-flight).
- In tungsten this takes almost ~100 ns.
  - Response is slower due to the much larger component of the energy in slow neutrons.

➢ Need to integrate over ~100 ns in reconstruction, keeping out pile-up hits…

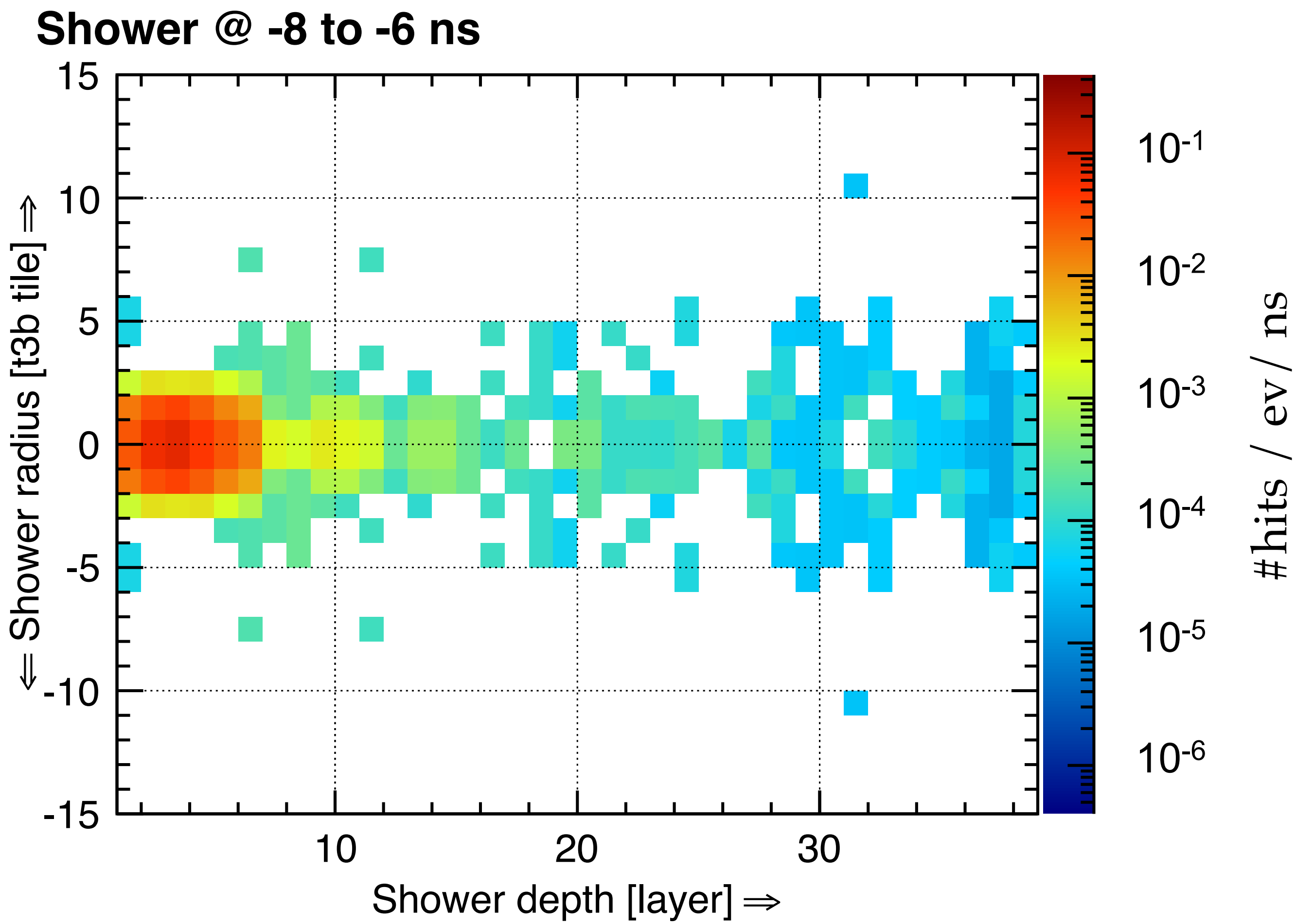
Tungsten Timing Tests – T3B

Run together with AHCAL

- 15 scintillator cells (direct coupling), read out with fast digitizers over 2.4 μs with 800 ps sampling
- Identify the time of arrival of each photon on the SiPM.
  Measure time development of hadronic shower by averaging over many events

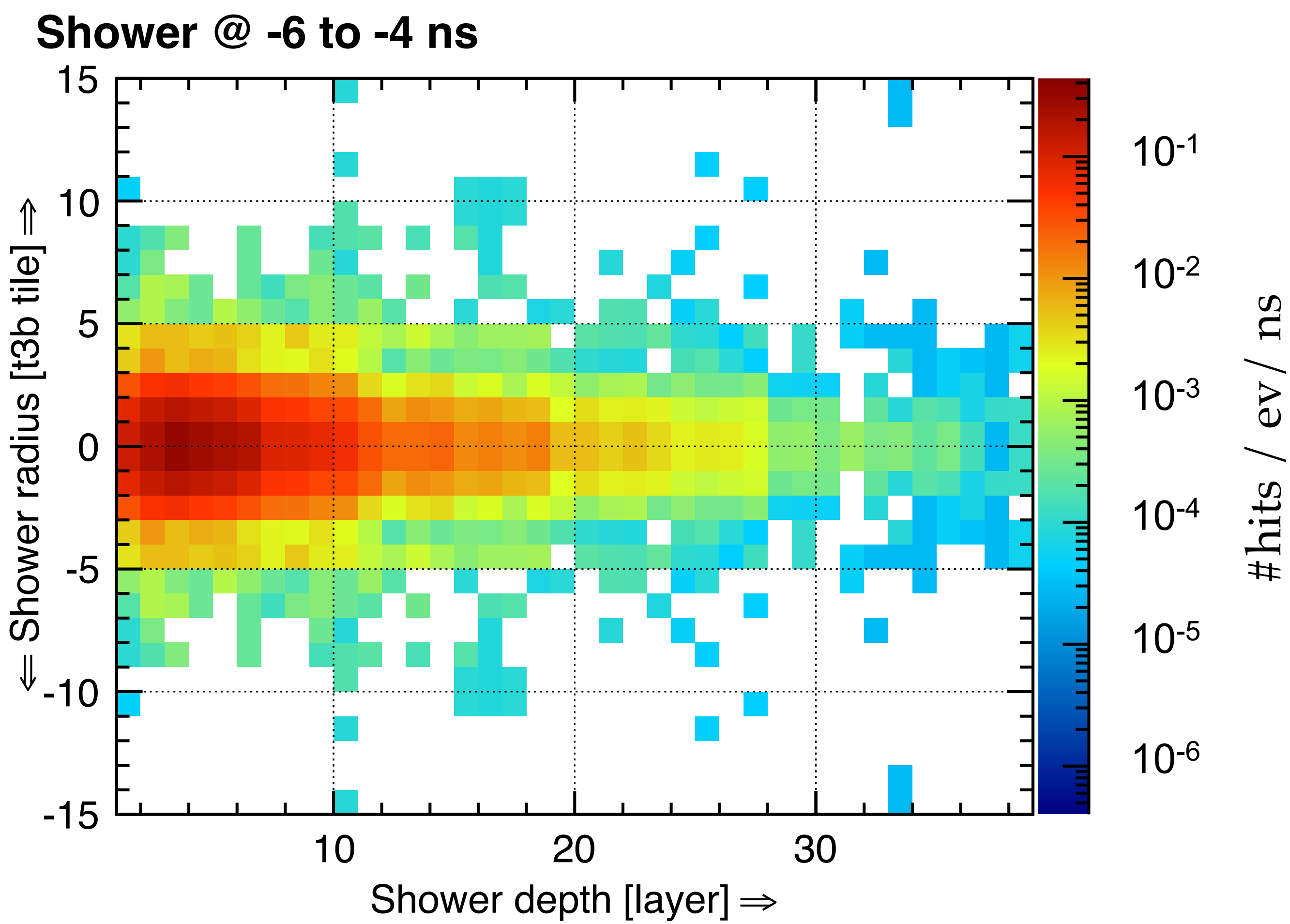


T3B – Timing tests



- t = 0: Activity peak in T3B (layer 39)
- Depth in calorimeter by identification of shower start layer

T3B – Timing tests



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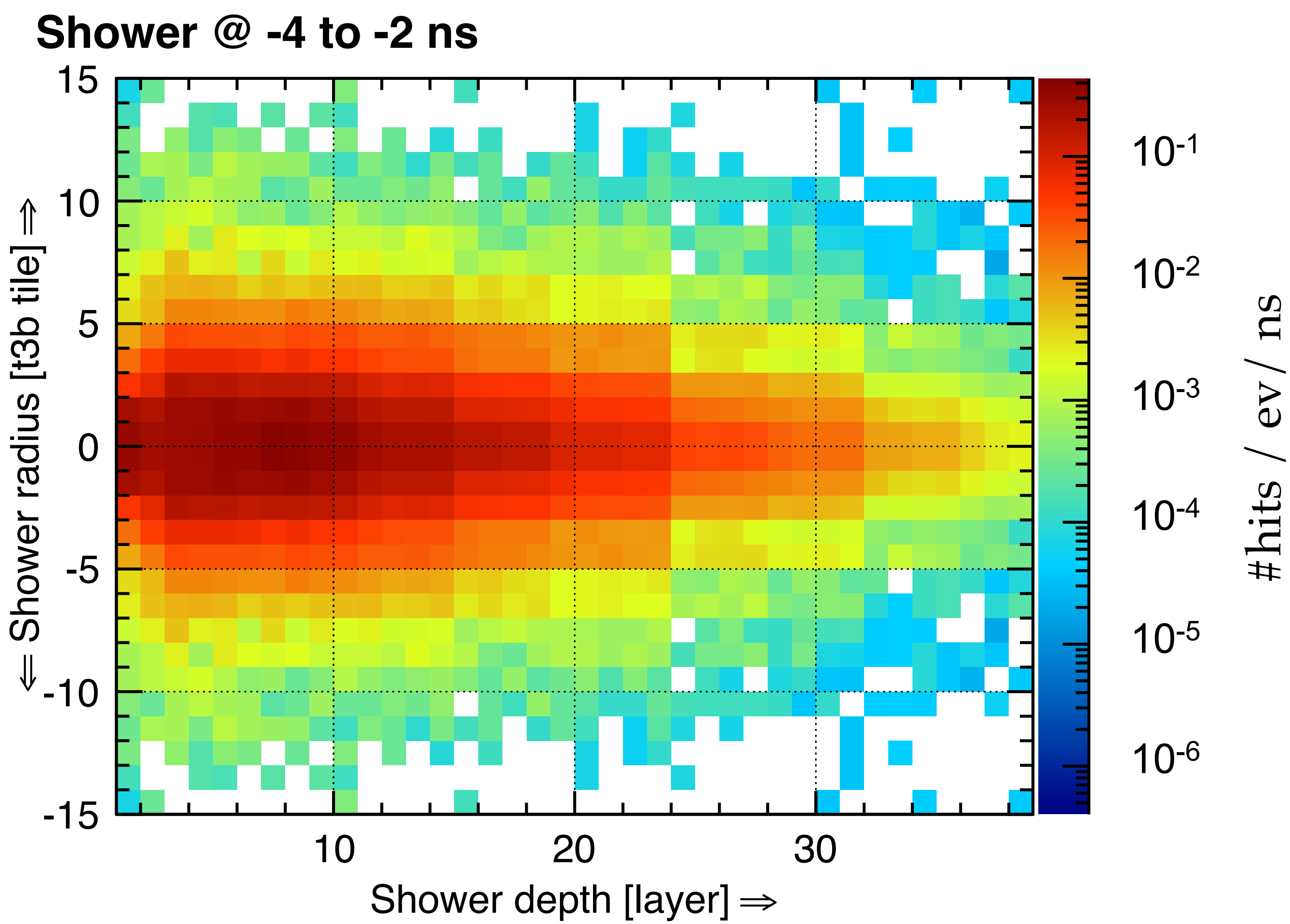

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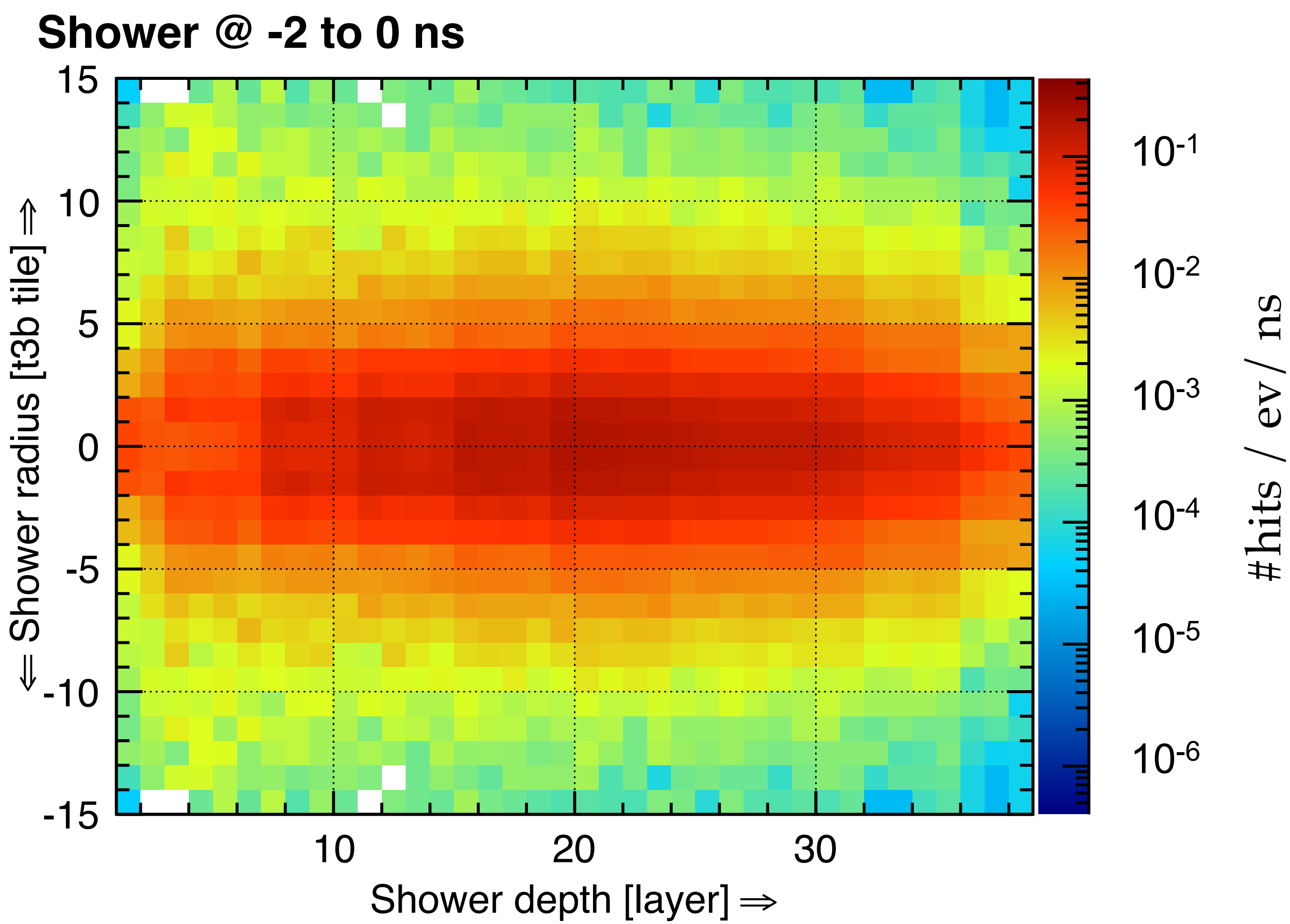

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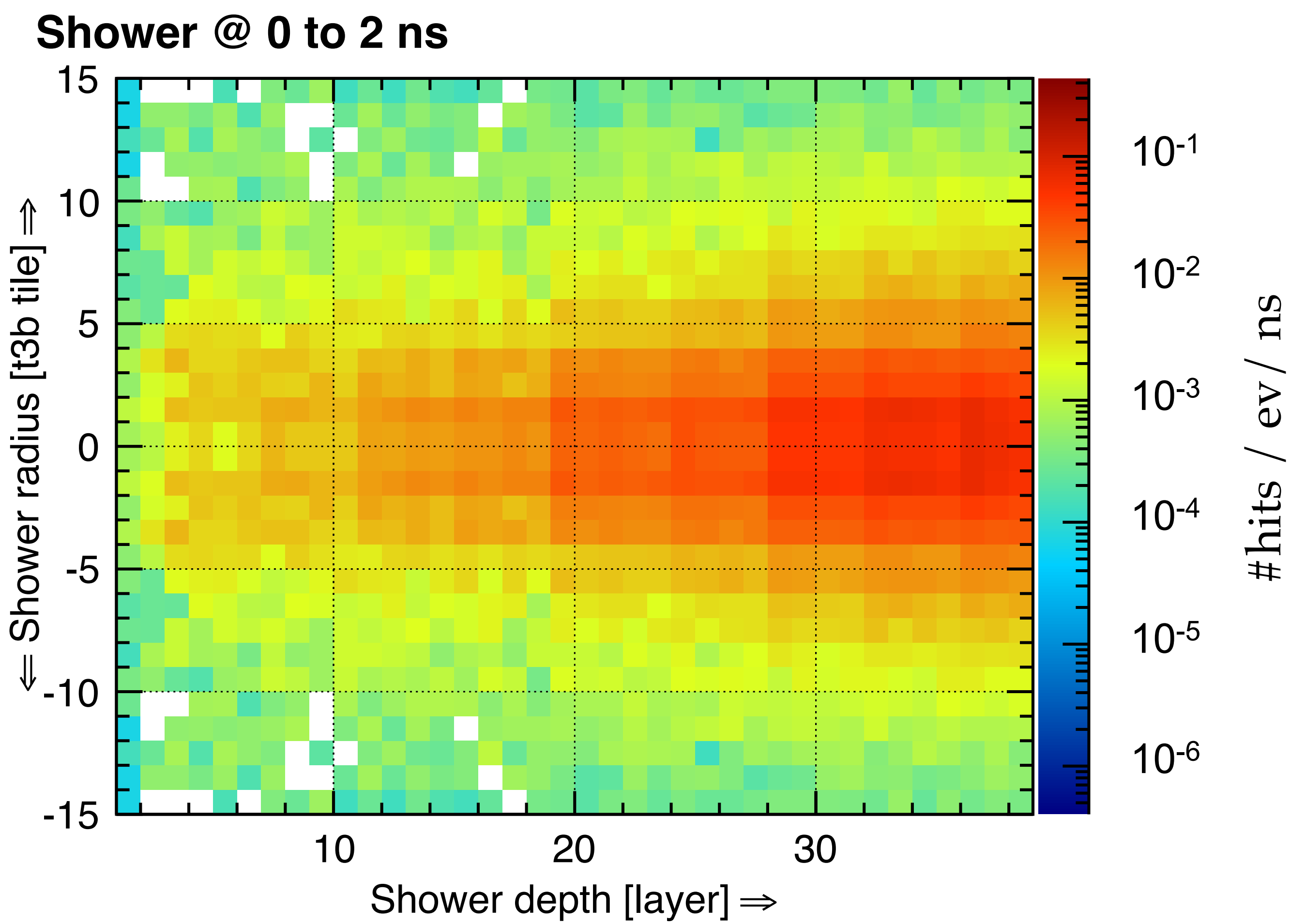

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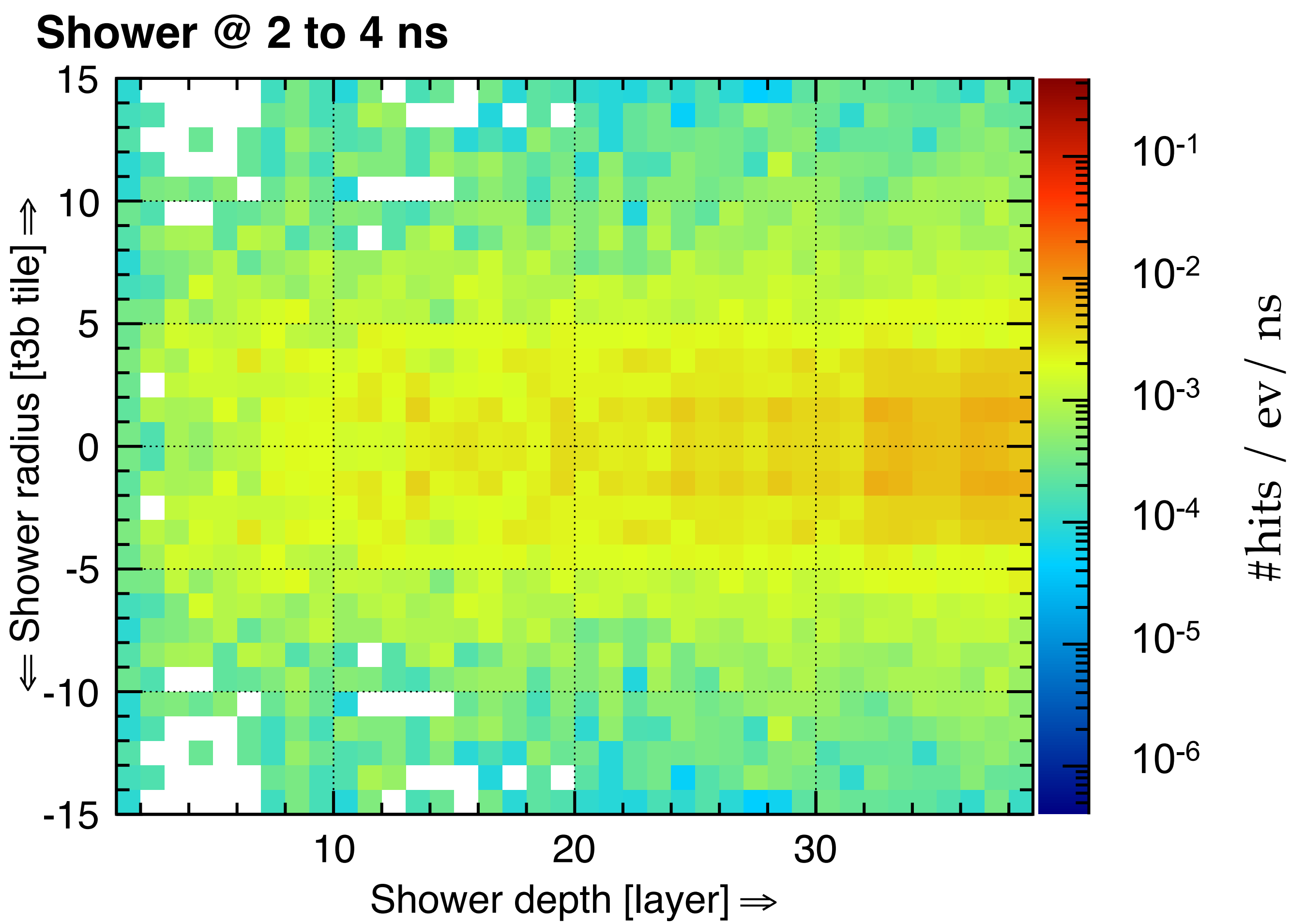

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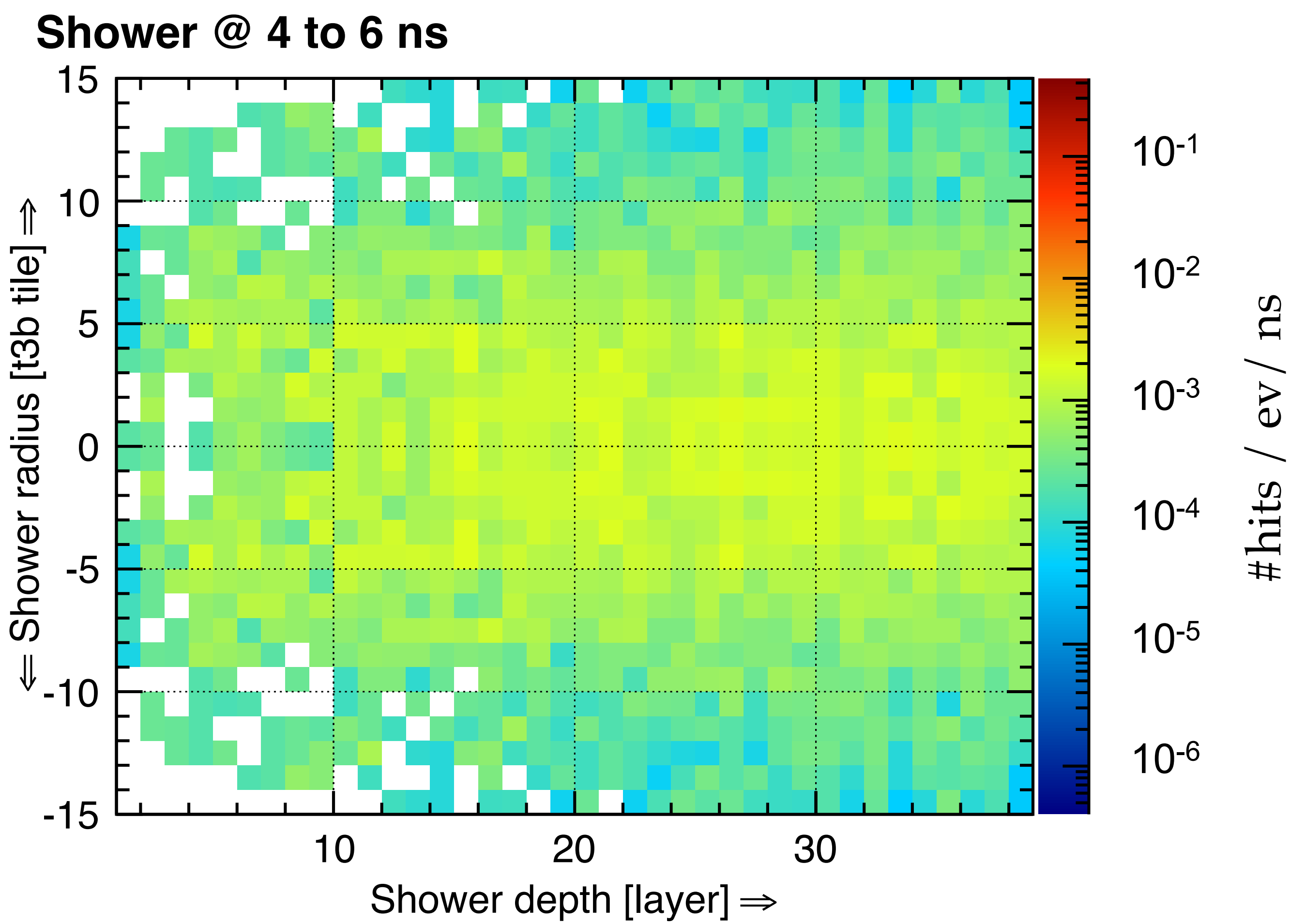

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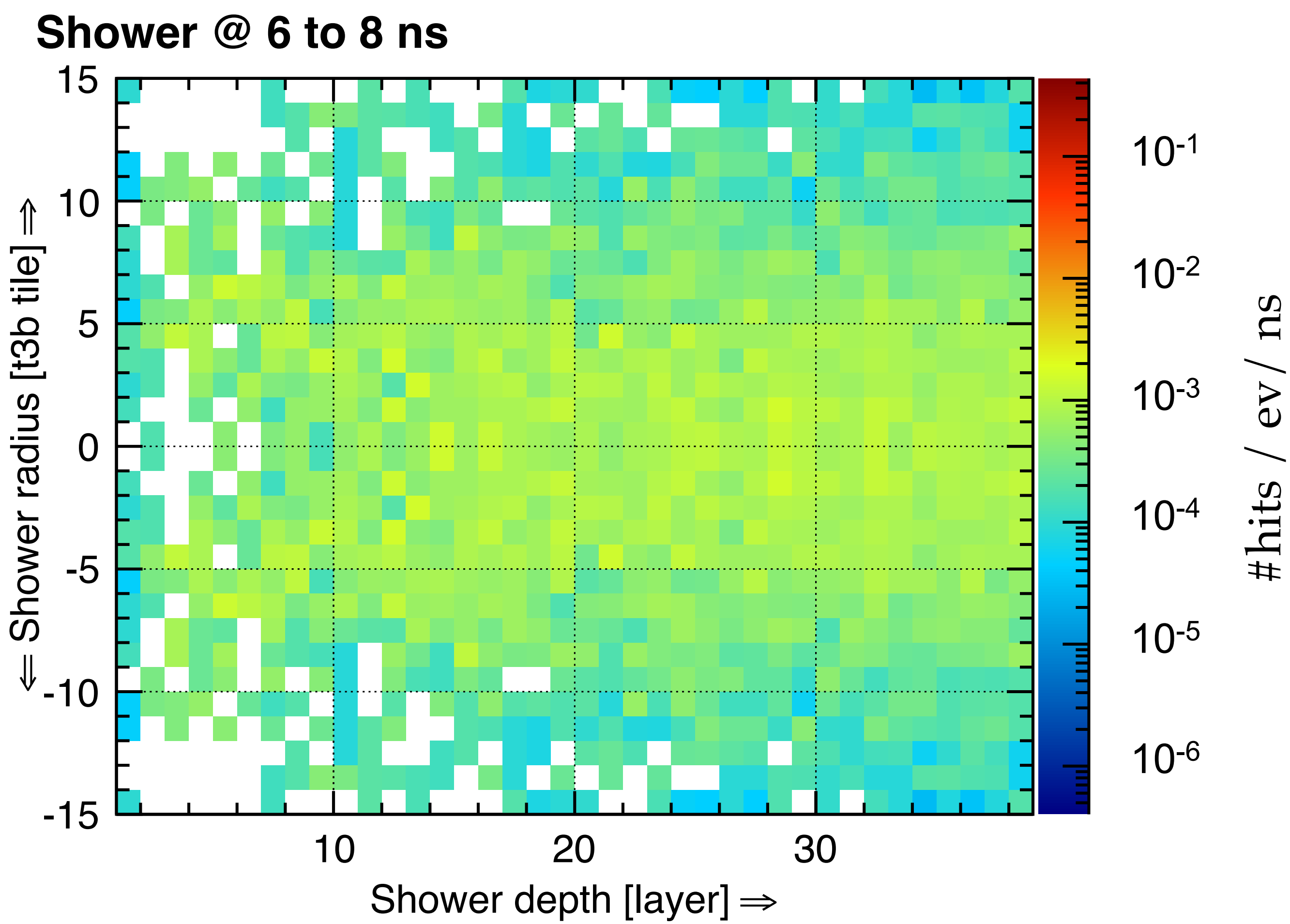

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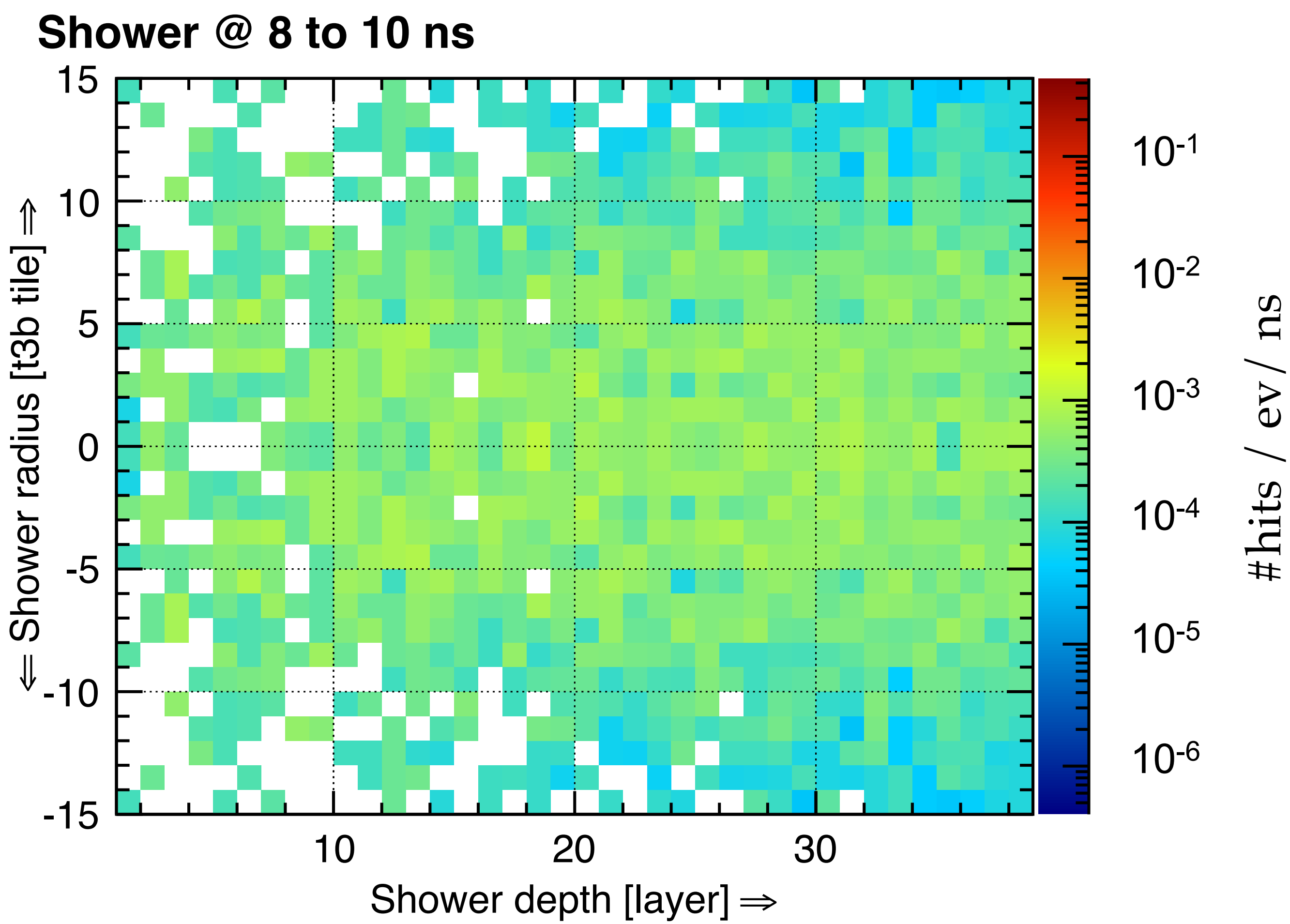

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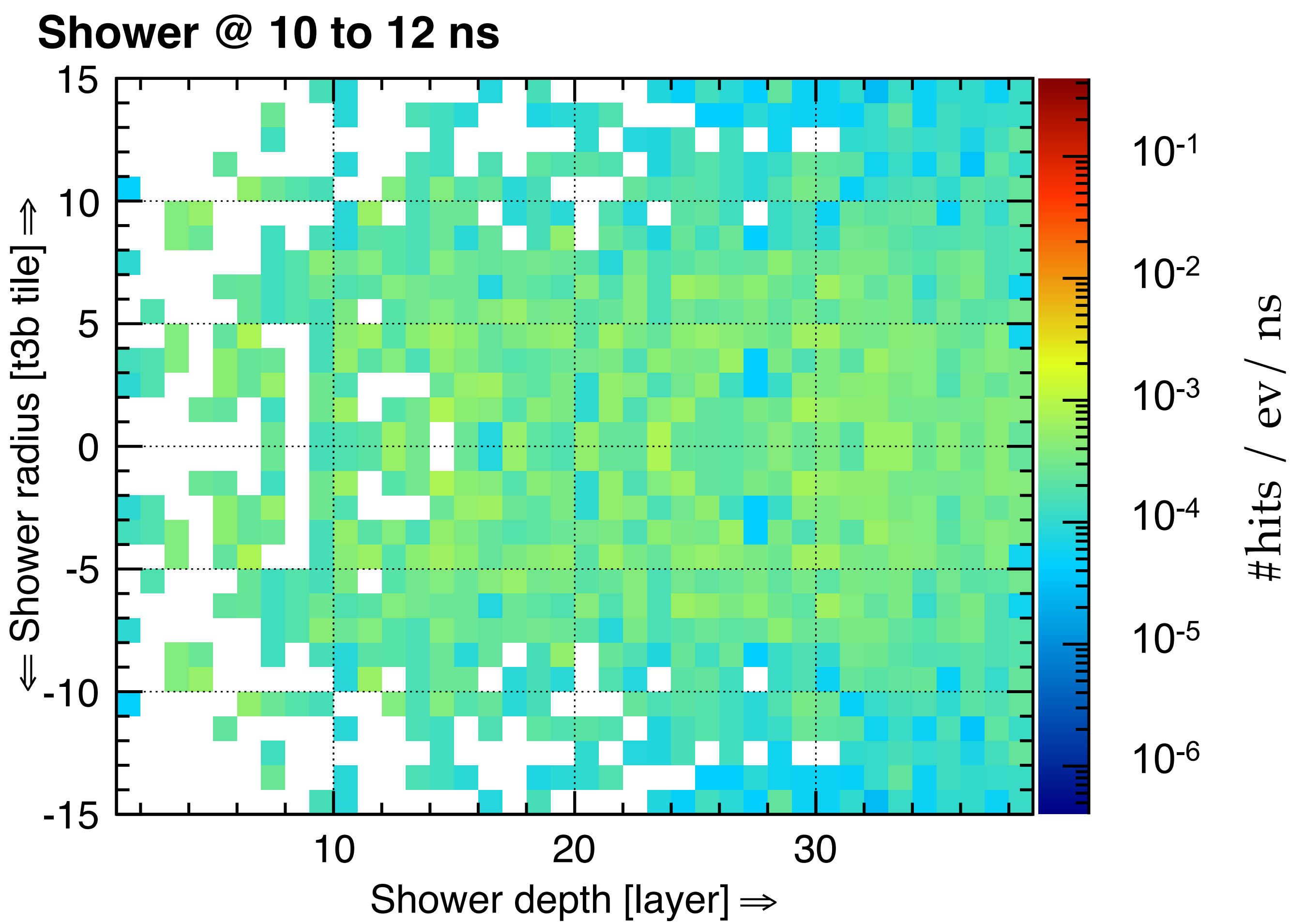

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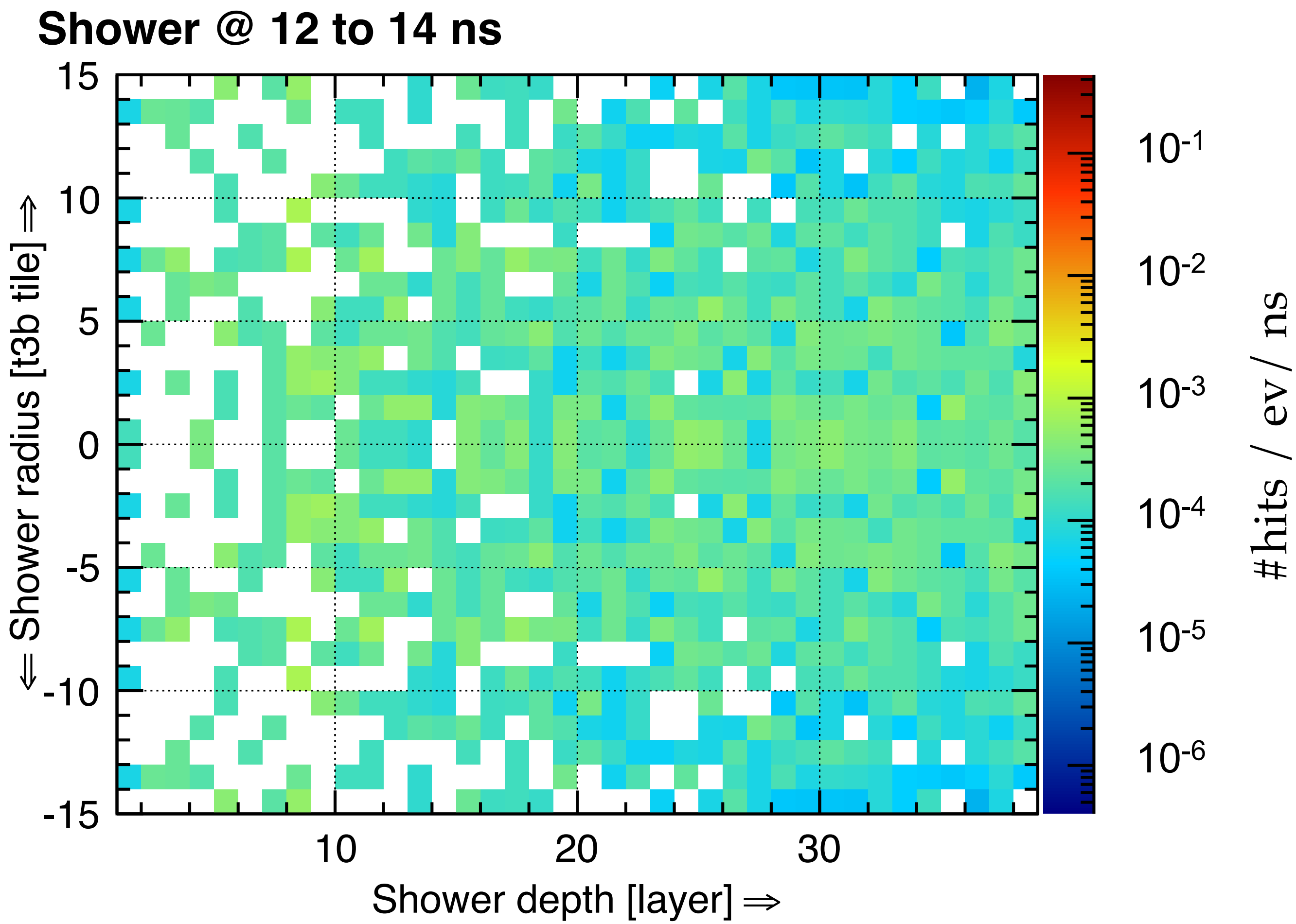

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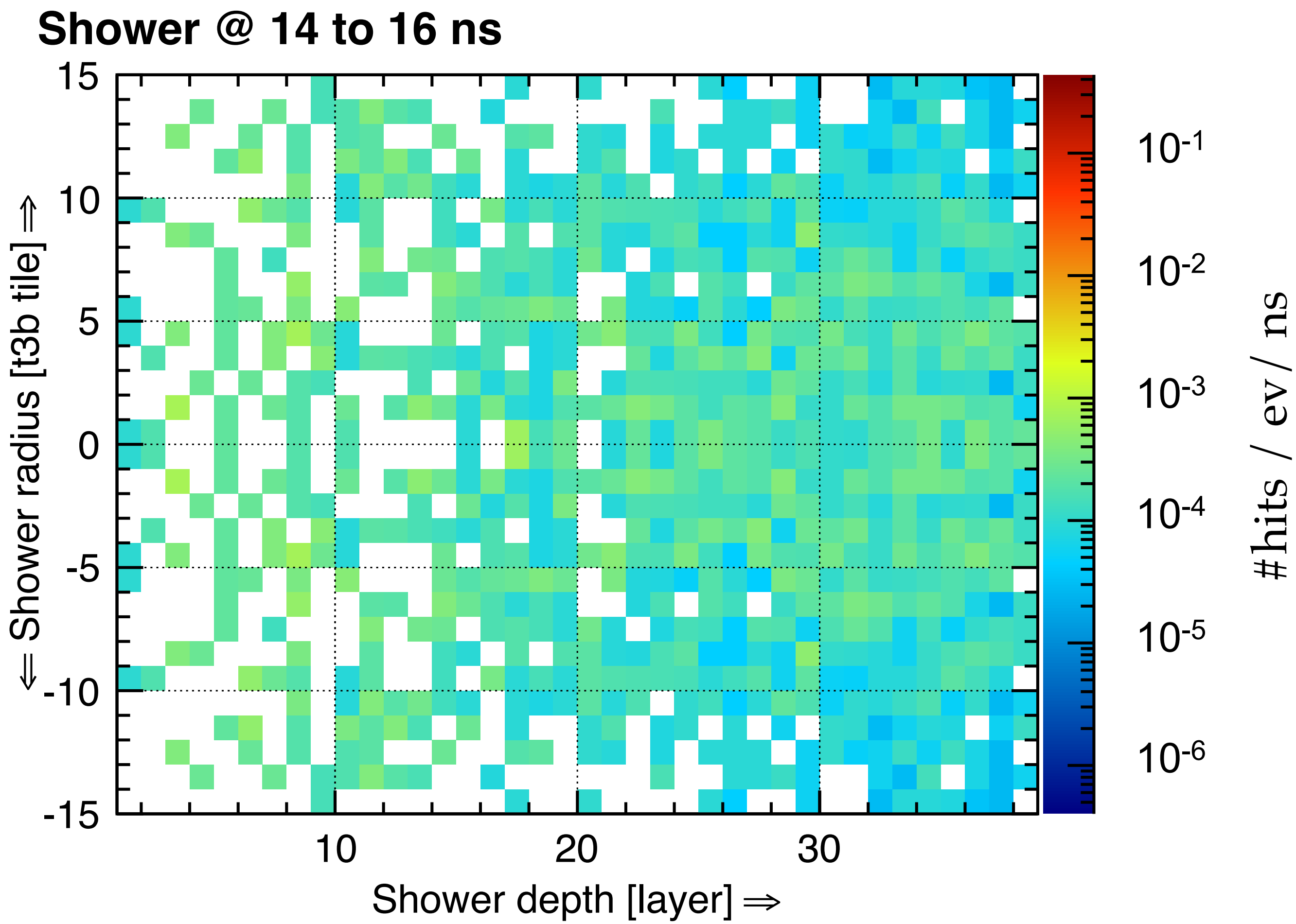

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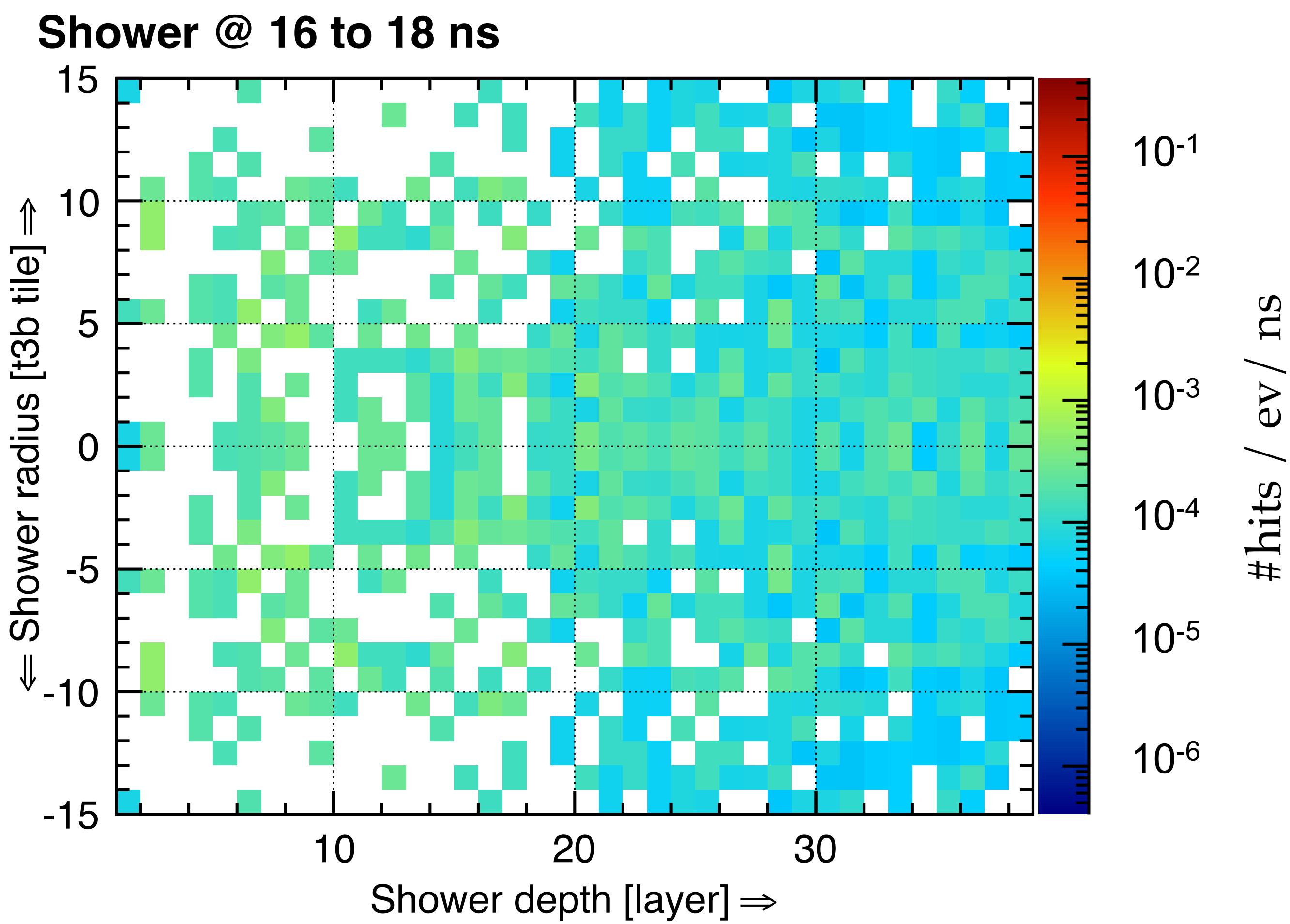

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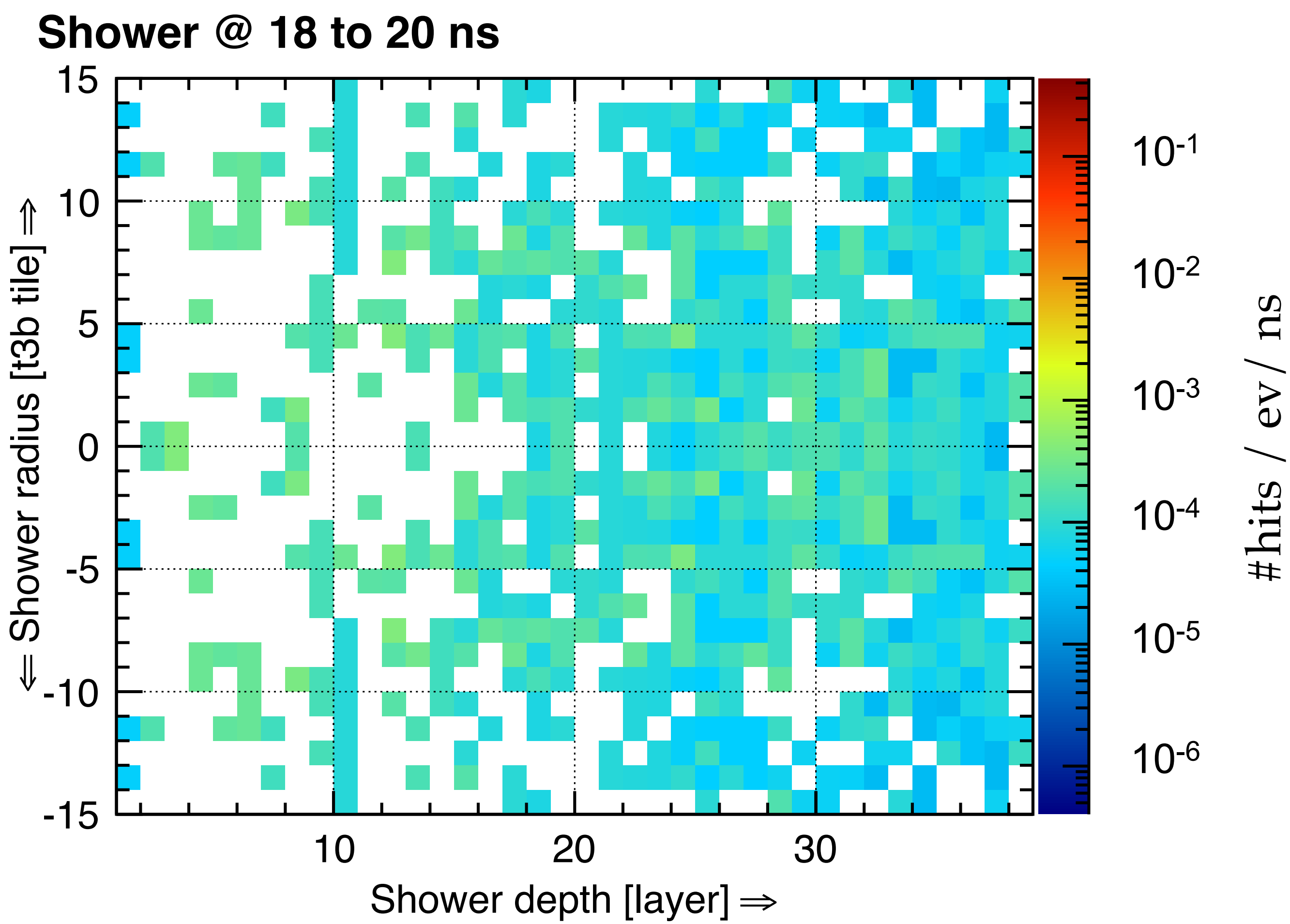

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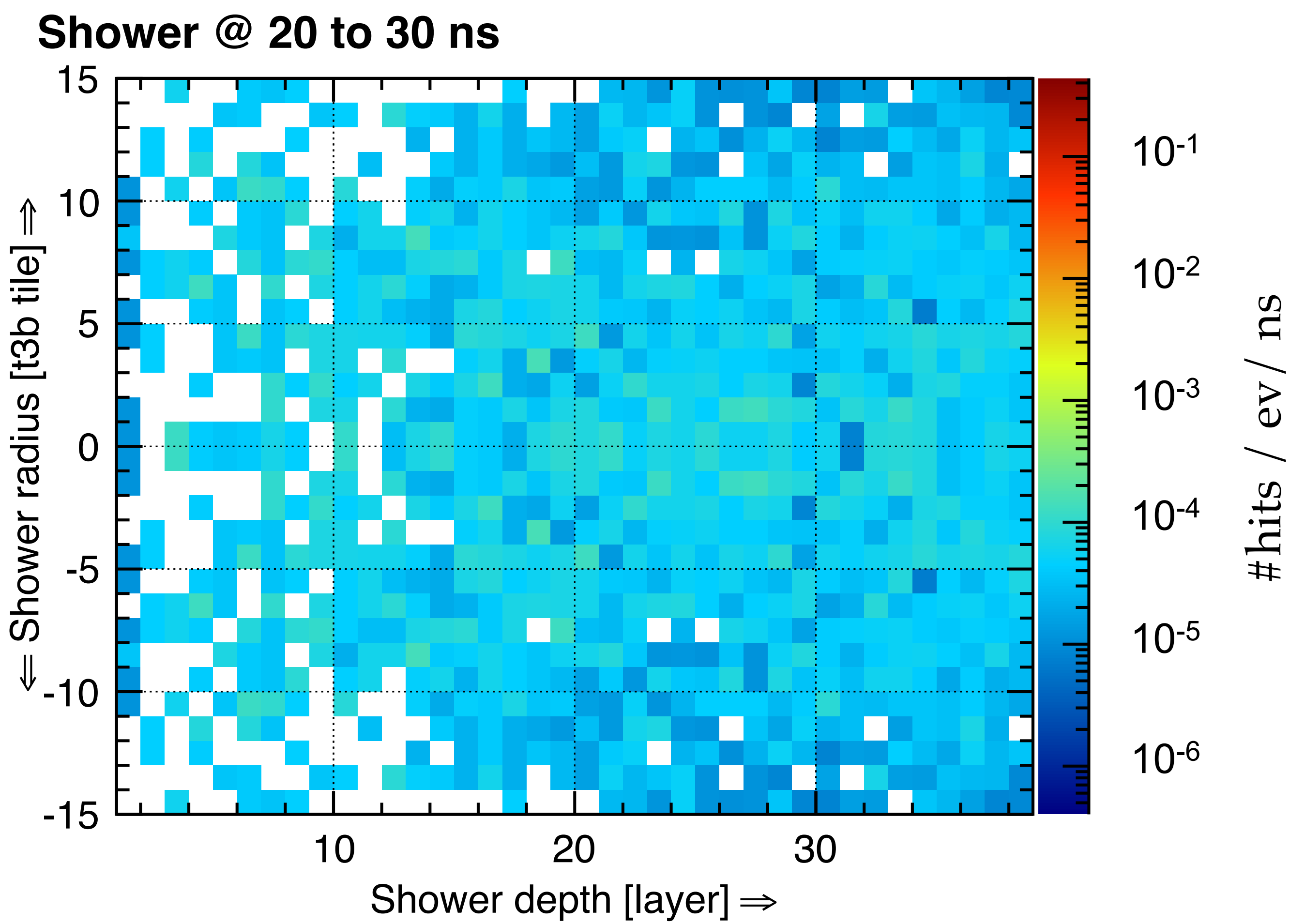

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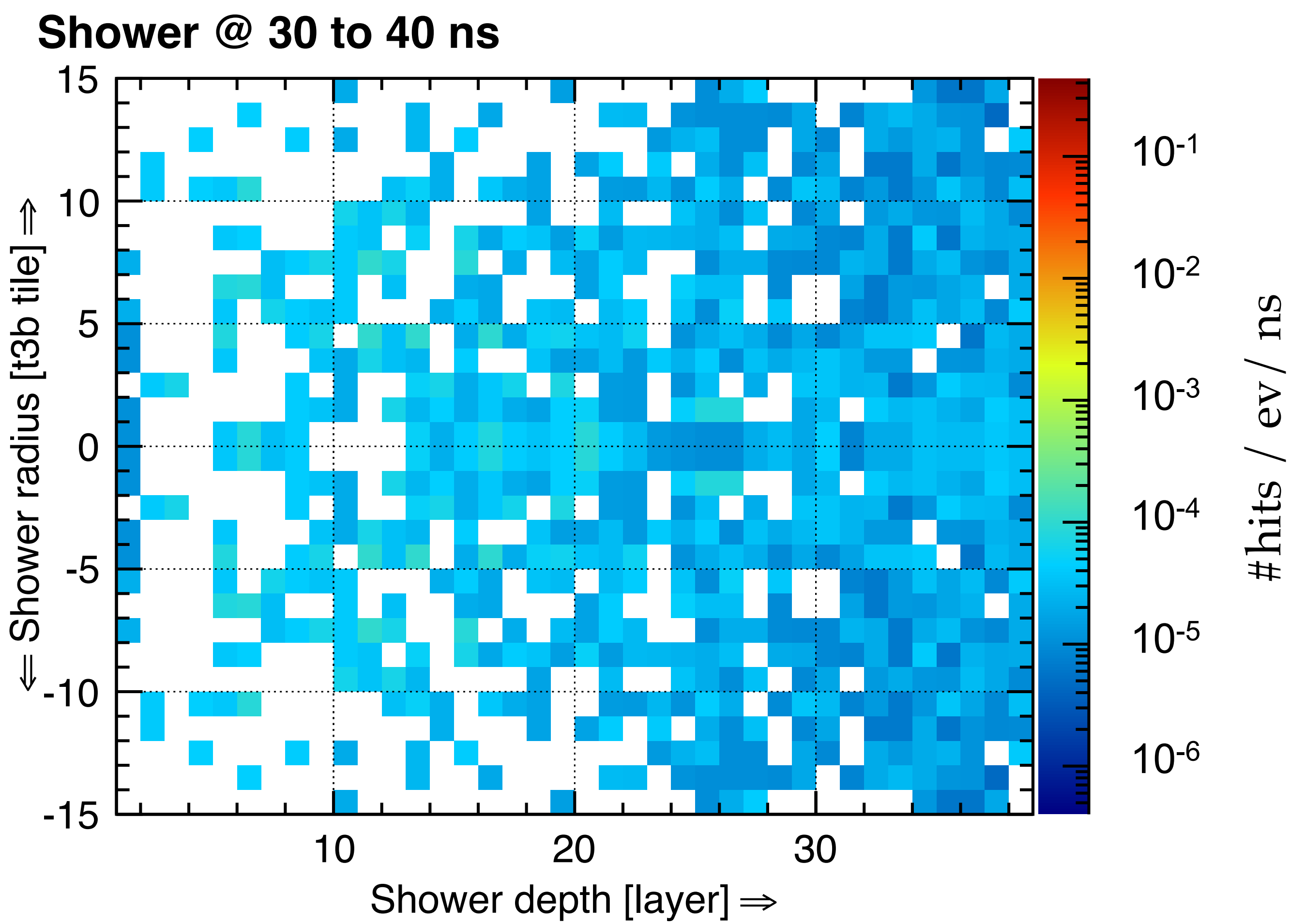

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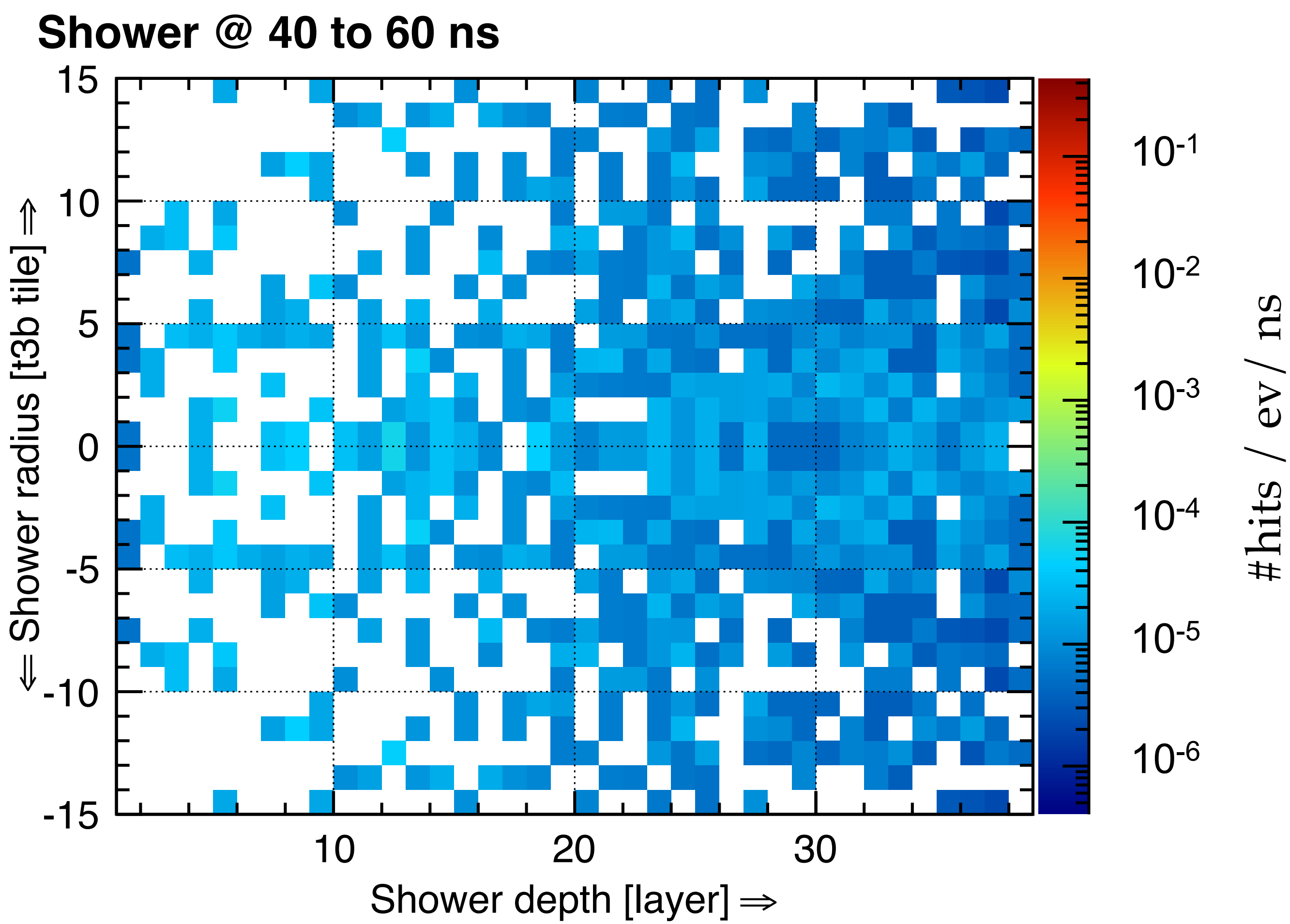

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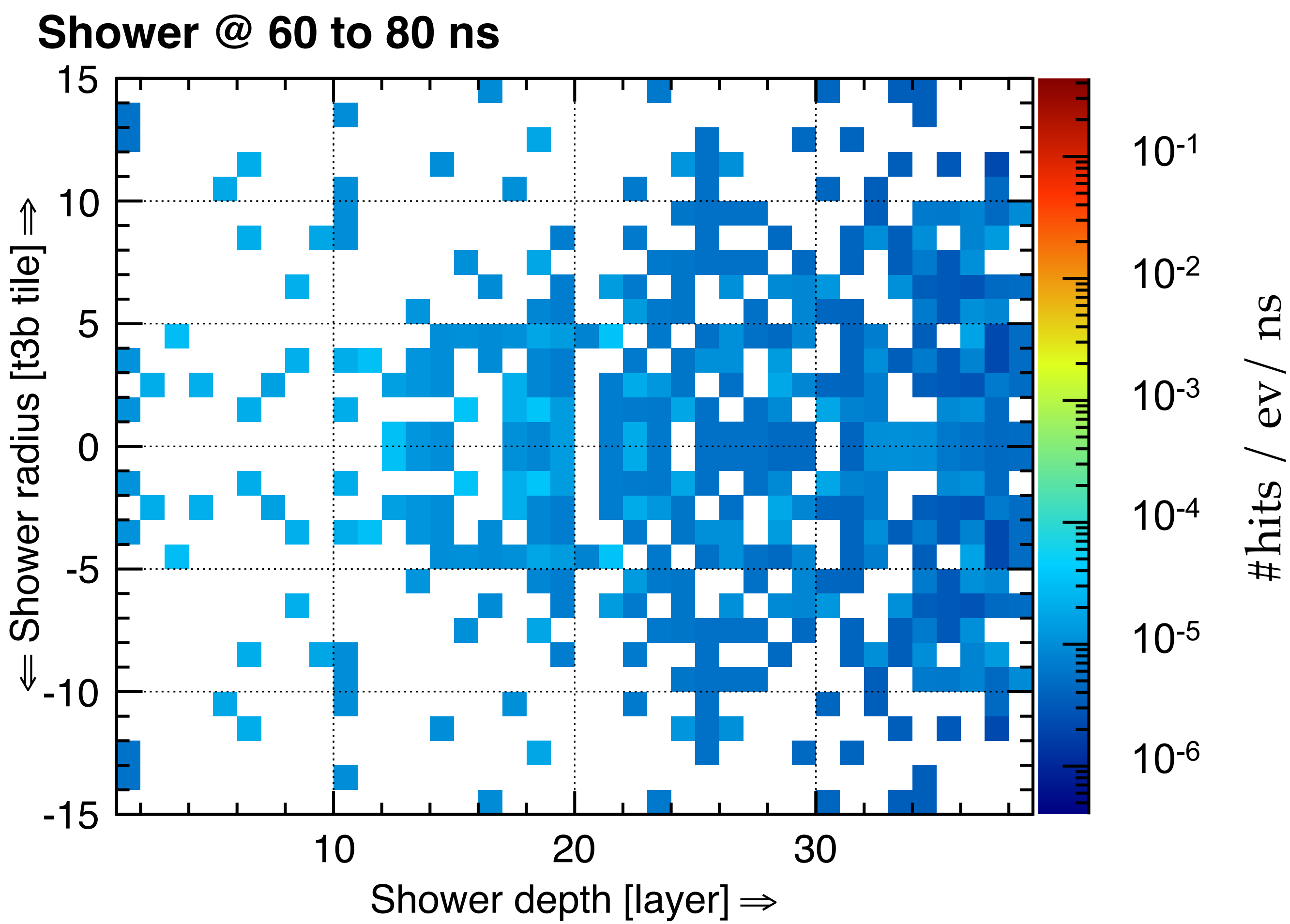

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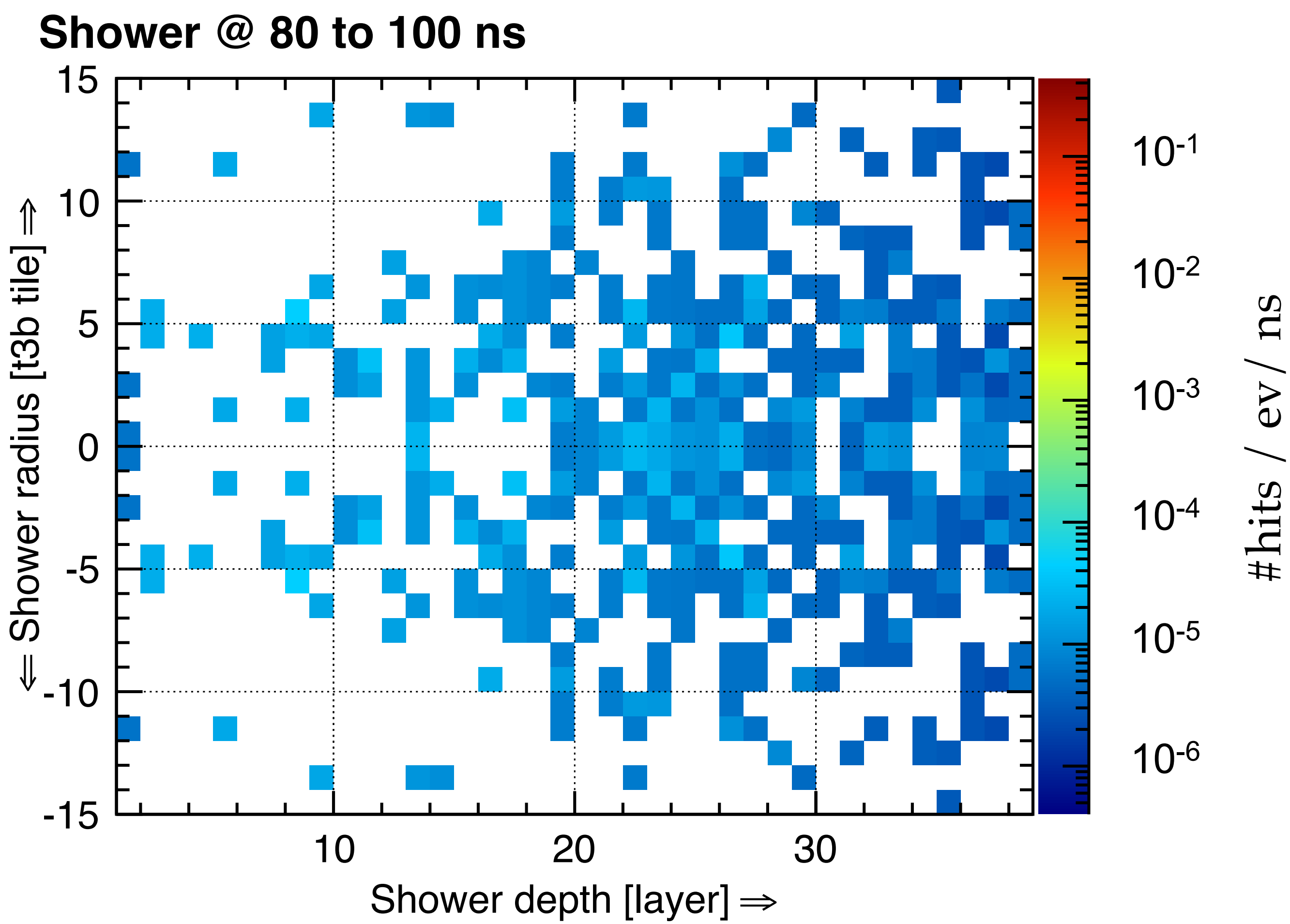

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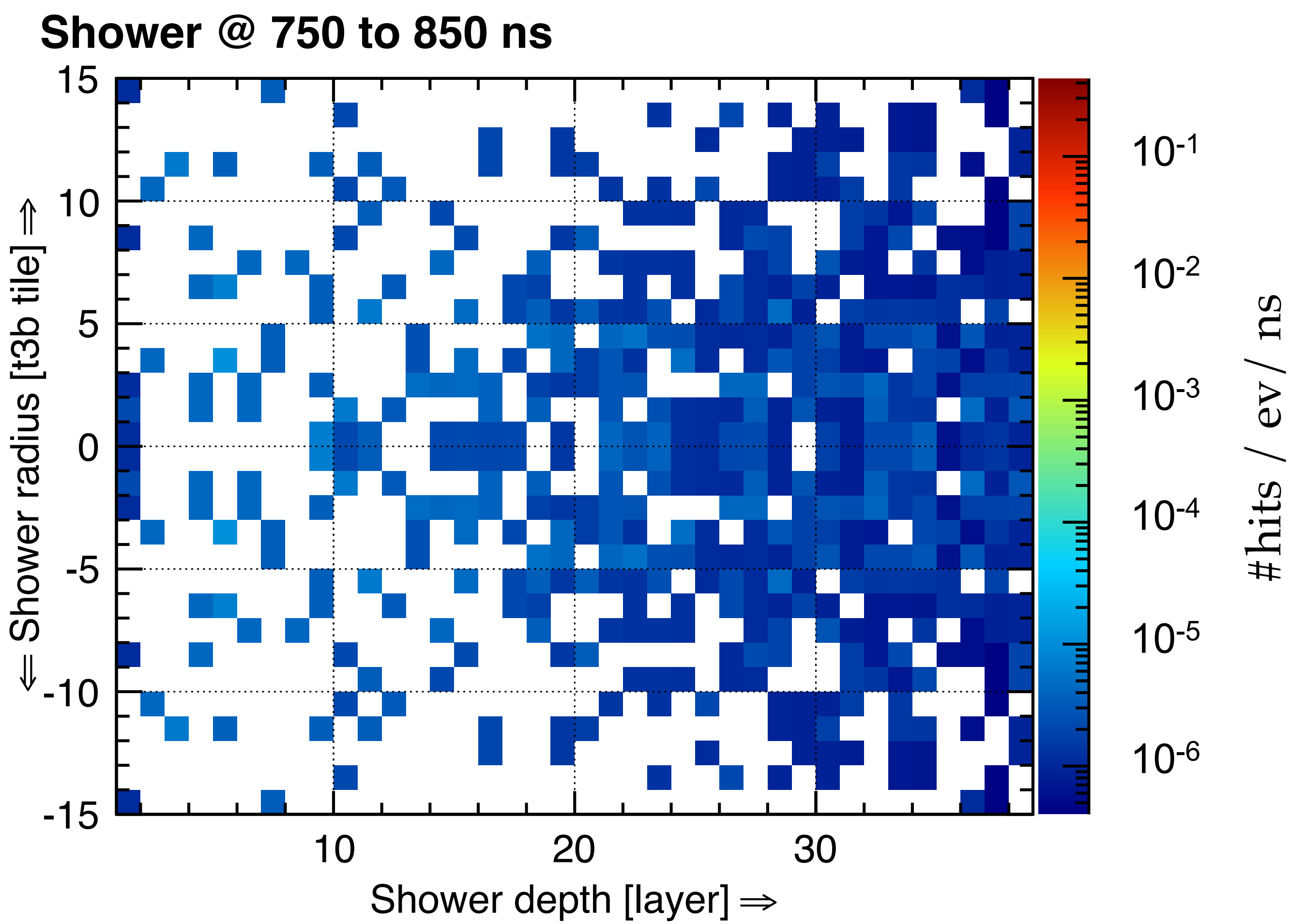
- Depth in calorimeter by identification of shower start layer

T3B – Timing tests



- t = 0: Activity peak in T3B (layer 39)
- Depth in calorimeter by identification of shower start layer

Conclusion

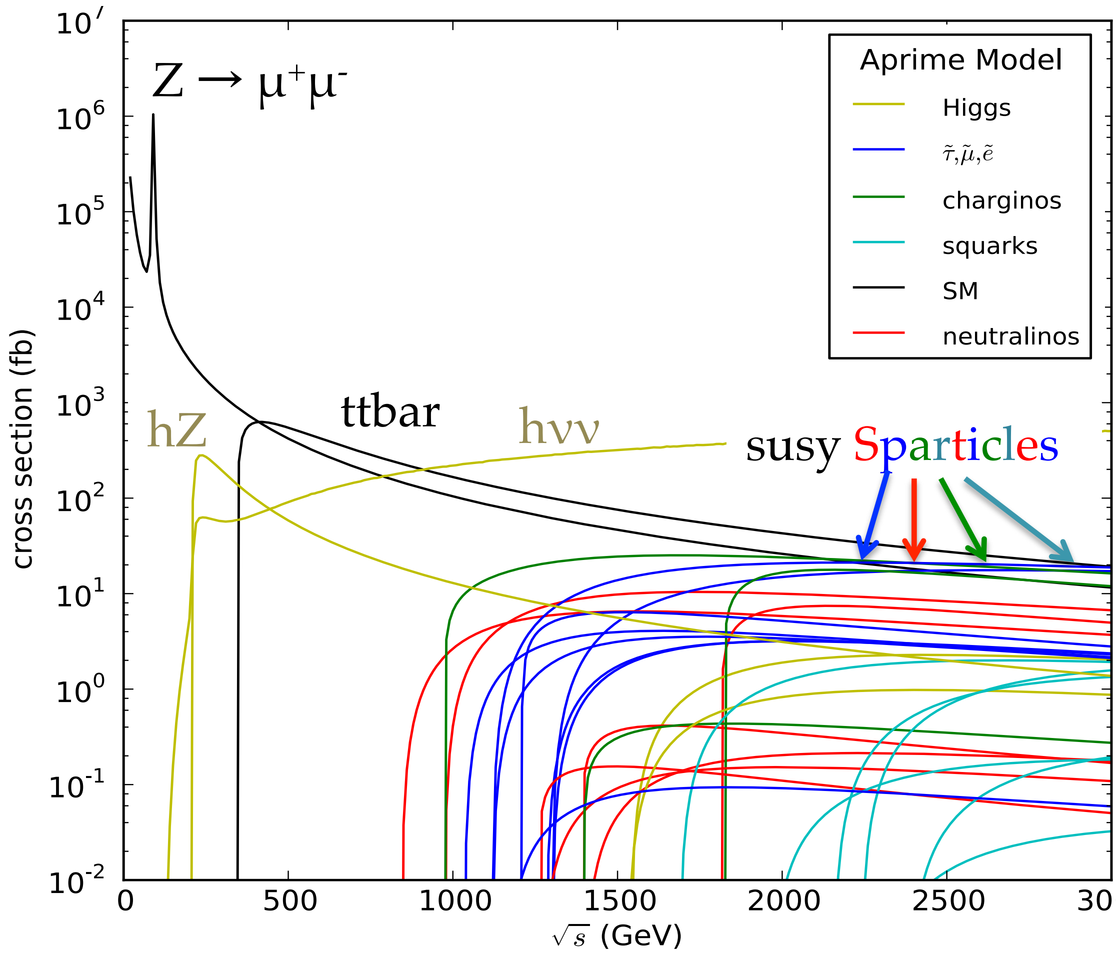
- The e^+e^- CLIC physics requirements and accelerator environment pose challenging conditions.

- This requires:
  - Detectors with high granularity in space and in time, and
  - Sophisticated offline reconstruction to disentangle signal and background

- Many more R&D projects ongoing than shown.

BACKUP SLIDES

CLIC e^+e^- physics

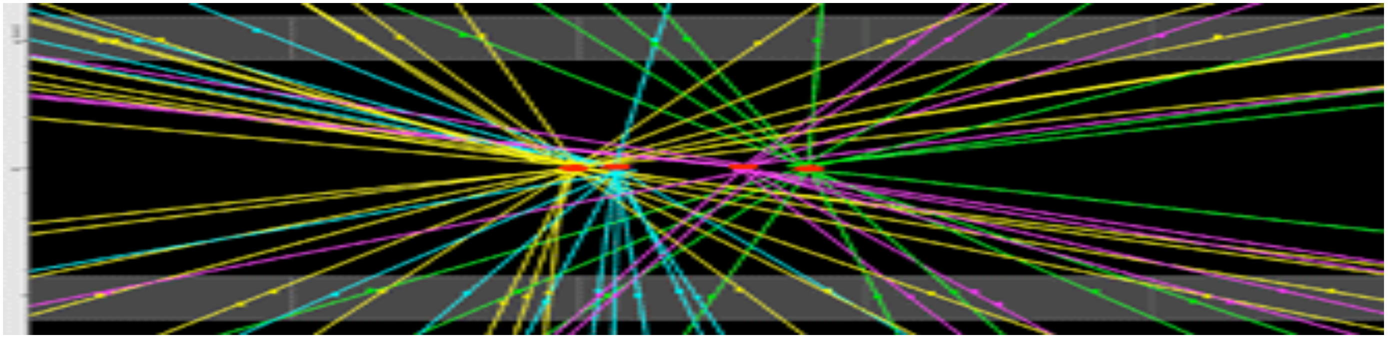


Precision measurements of SM and new particles:
- Higgs, NP, …
- Discrimination between competing models

As a lepton collider, discover new physics in Electro-Weak states at TeV scale not accessible by LHC.

e^+e^- collisions up to $\sqrt{s}$ = 3 TeV
- Built in stages, lower energies can be studied first.

Pile up at interaction point



ATLAS

	CLIC 3 TeV	LHC 14 TeV (ATLAS)
IP size in x / y / z direction	45 nm / 1 nm / 40 µm	15 µm / 15 µm / ~5 cm

Pile up of:

- LHC: 23 minimum bias over triggered event, each 25 ns.
  - Interaction Points smeared over 5 cm.
- CLIC with 312 BXs / train:
  - Overlapping beam-induced background, *all* at one interaction point.

- At CLIC the IP-spot can be used as constraint in track-reconstruction, at LHC it cannot.

Readout challenge

CLIC frequency of interesting events < ~ 1 / train.

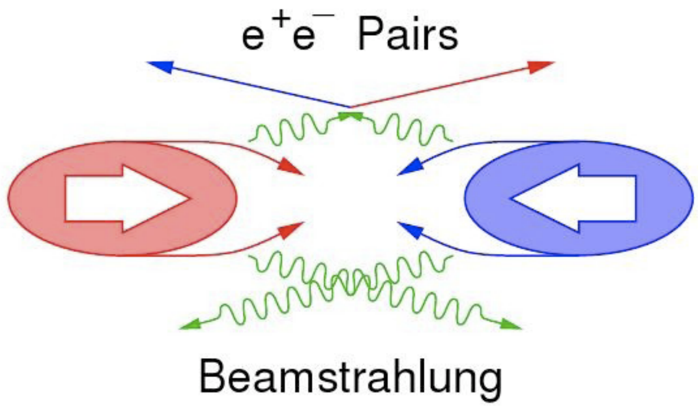
- In high occupancy regions, need multi-hit storage / readout
  With accurate time stamping
- Electronics do not need trigger
- Offline background suppression

	CLIC 3 TeV	LHC 14 TeV (ATLAS)
Trigger [# selected events : # total events]	1 : 1	200 : 10^9
Total data rate after trigger [GBytes/sec]	200	0.3

LHC:

- Major challenge in the (multiple levels of) trigger

Beam-induced backgrounds at 3 TeV

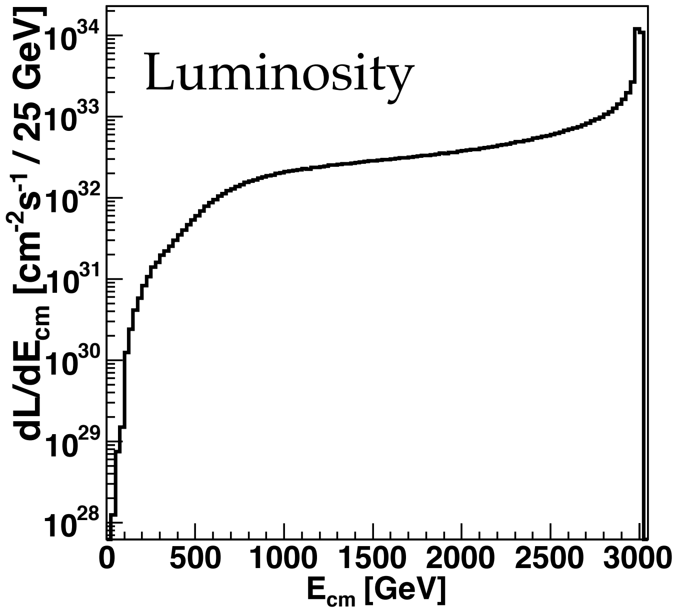


Main backgrounds in detector:

- incoherent e^+e^- pairs: 19k particles / train
- $\gamma\gamma \rightarrow$hadrons: 17k particles / train

Need to:

- ➢ Include overlapping beam-induced background in **simulation**
- ➢ Reject **pile-up** in offline reconstruction.

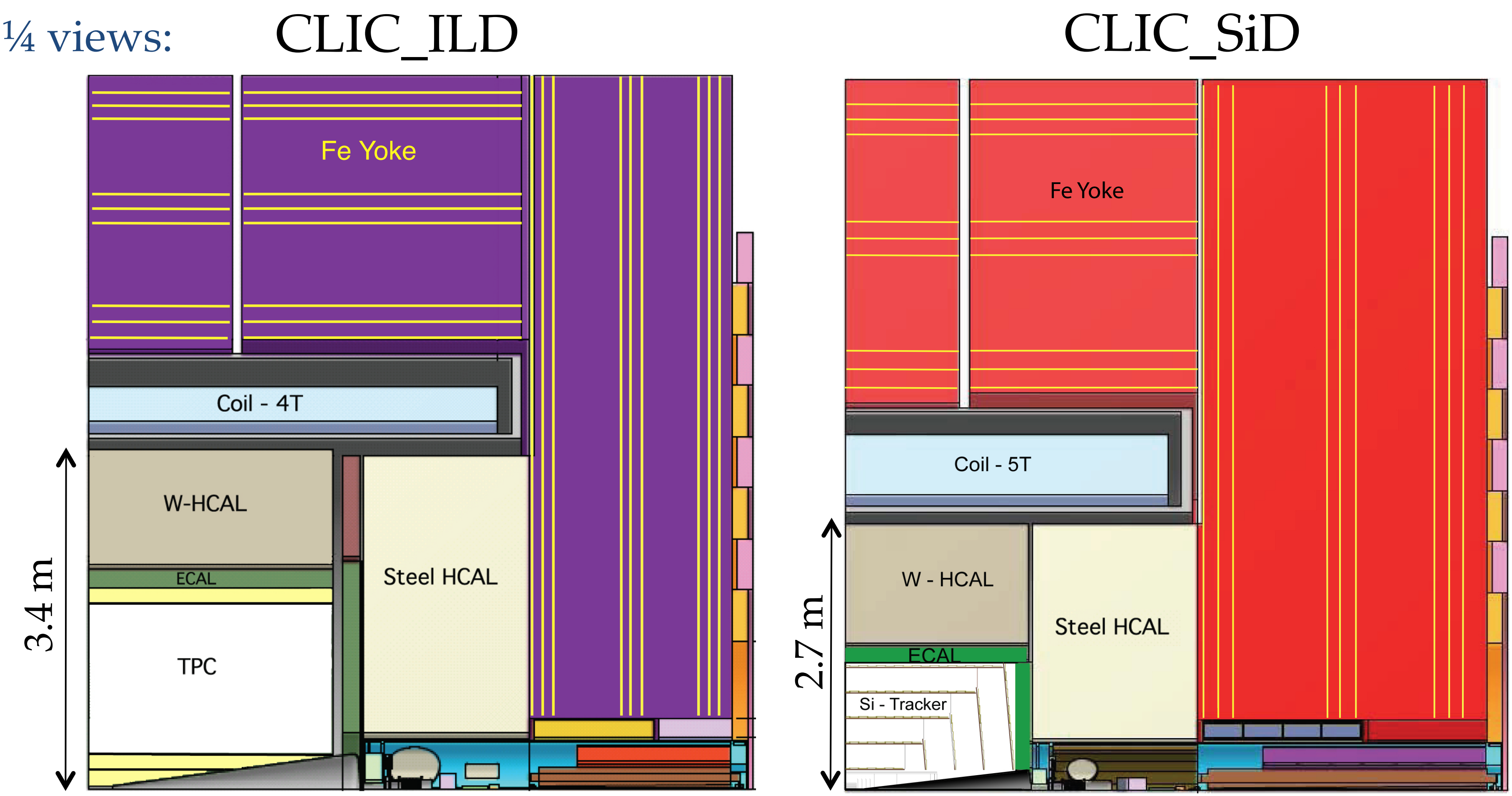


30% in "1% highest energy"

- ➢ √s is not known per event
- ➢ Much like the Initial State Radiation, need to fold in luminosity spectrum in reconstruction

Two general purpose CLIC detector concepts

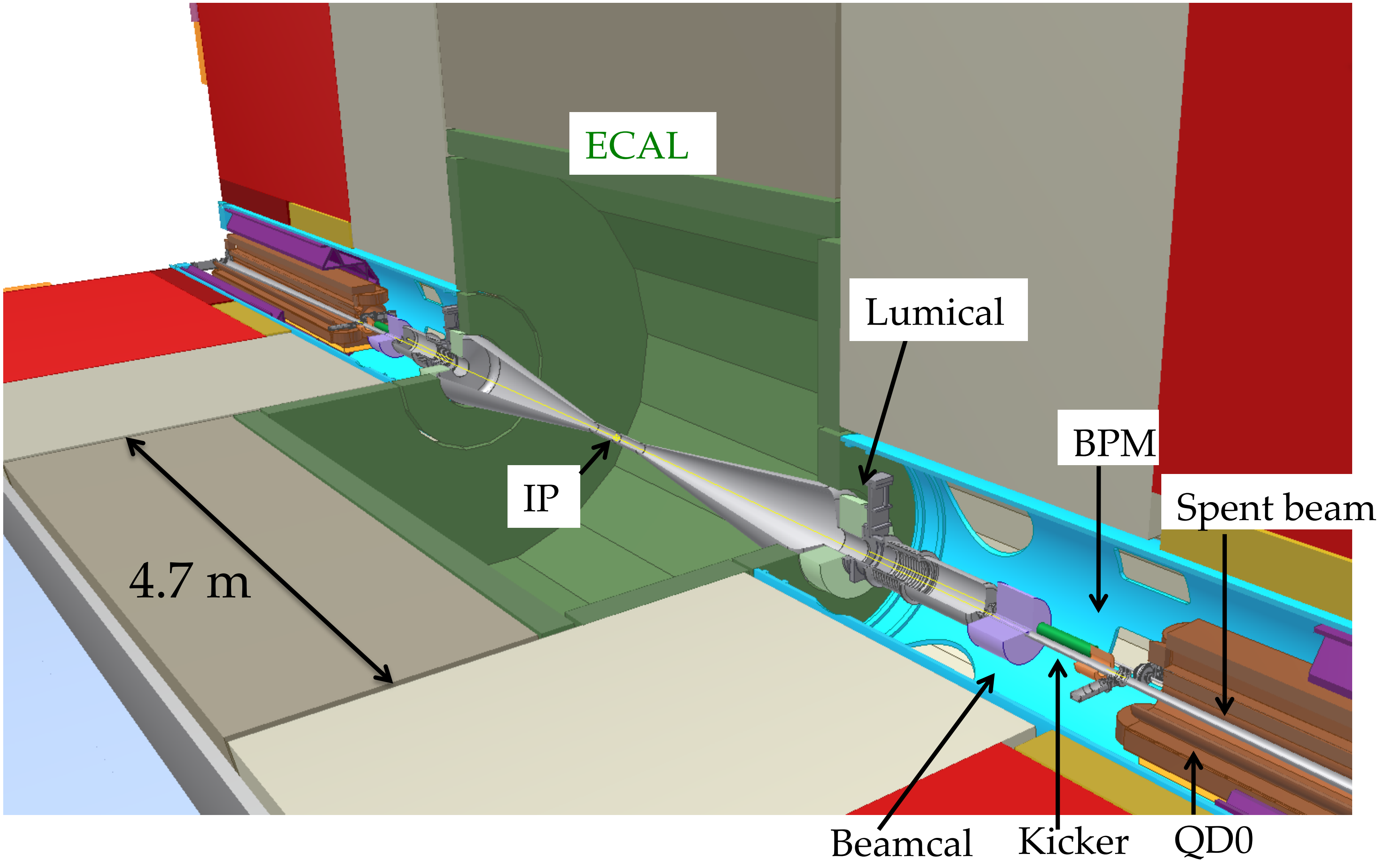
¼ views:



- Difference in tracking systems
- Both have Tungsten in the barrel HCAL, to have a highest possible density and keep the coil radius limited.

Very Forward Region

- Including instrumentation and final focusing quadrupole.

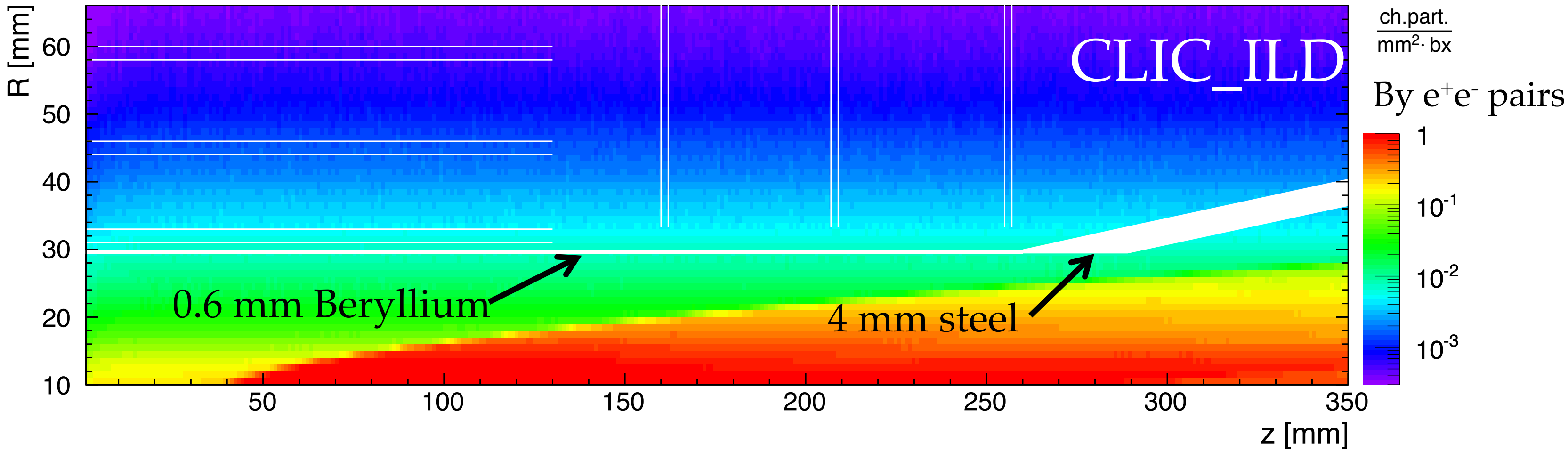


Overall sizes

- For CLIC the design resembles CMS
  - Calorimeters to be placed inside the solenoid for accurate PFA analysis
- CLIC detectors are much shorter than CMS

	CLIC_ILD	CLIC_SiD	CMS	ATLAS
Full detector height & length [m]	H: 14 L: 14	H: 14 L: 14	H: 15 L: 20	H: 22 L: 46
Magnetic field [T]	4	5	3.8	2.0 (solenoid) 0.5 – 1.0 (toroid)
Solenoid inner radius + thickness [m]	3.4 + 0.7	2.7 + 0.8	3.0 + 0.6	1.2 + 0.2
Yoke inner radius + thickness [m]	4.5 + 2.7	3.8 + 2.9	4 + 3	HCAL: 2.3 + 1.6
Yoke mass – Detector mass [10^3 tons]	10 – 12	11 – 12.5	10 – 12.5	4 – 7

Beam induced background constraints



	CLIC	ATLAS
Occupancy in 1st vertex det. barrel layer [# particles / mm²]	1.9 / train	0.05 / BX
Maximum pixel occupancy	2% / train	~0.1% / BX
NIEL in innermost layer [n_{eq} cm^{-2} y^{-1}]	< 10^{11}	10^{14} – 10^{15}
Total ionizing dose [Gy/yr]	200	> ~10^5

- For LHC a major issue is radiation hardness; minor concern at CLIC.

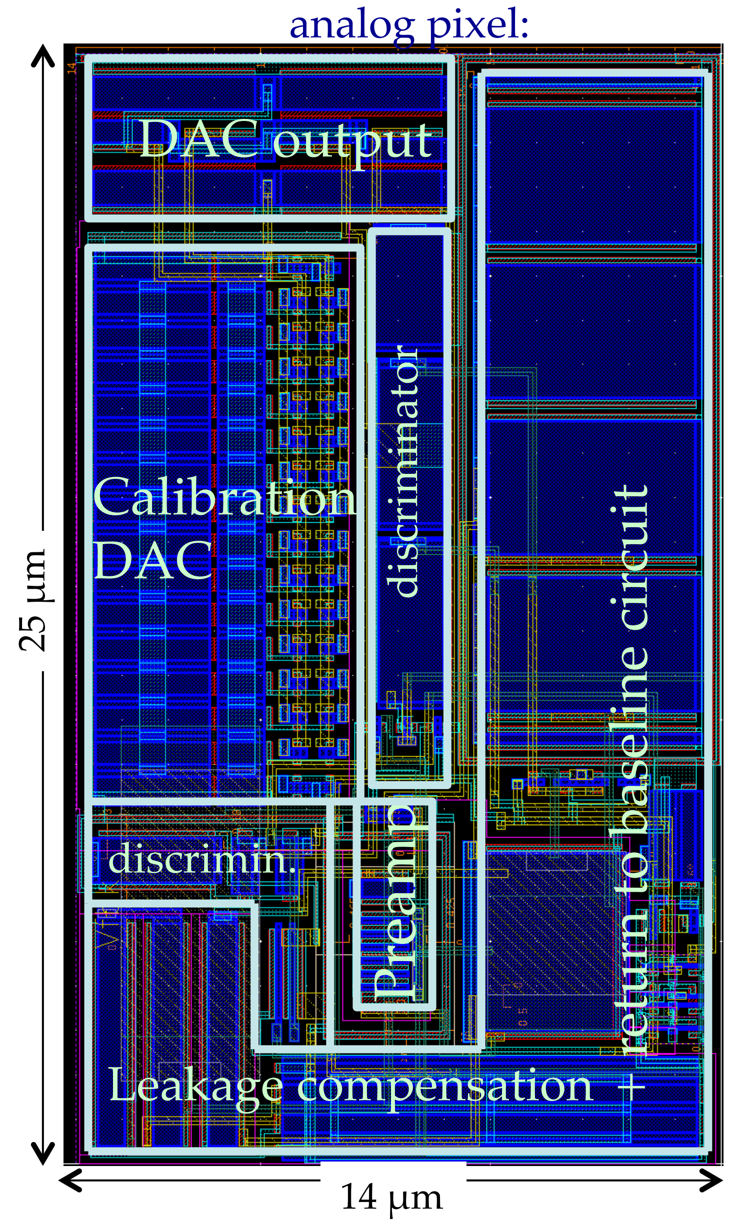
CLICPix 65 nm demonstrator chip

- Demonstrator chip designed with fully functional 64 by 64 pixel matrix
- Submission November 2012 in Multi-Project Wafer run

- 65 nm CMOS
- Small pixel pitch (25 μm)

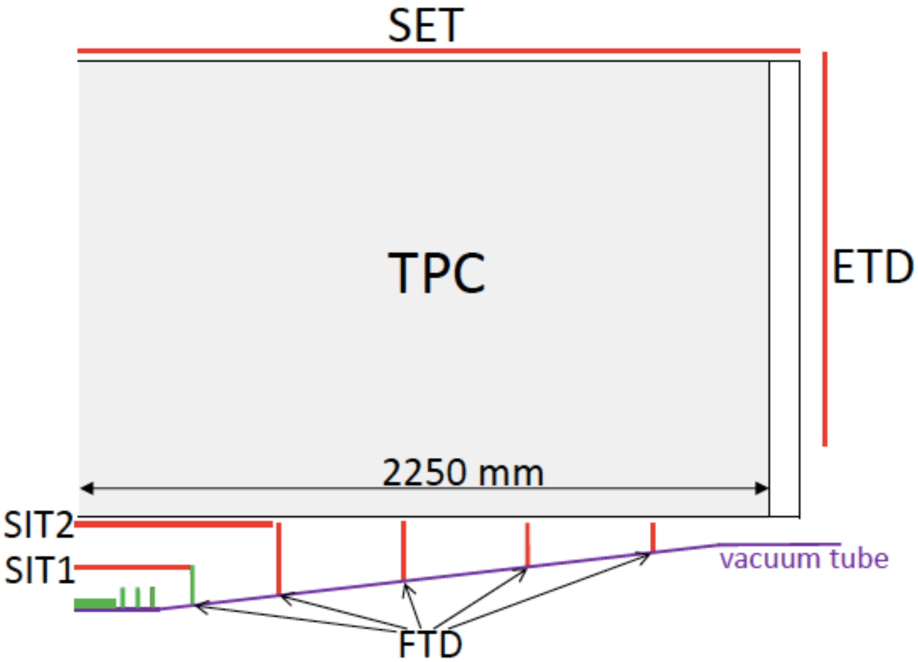
- Simultaneous 4-bit TOA and TOT per pixel
  - Front-end time slicing < 10 ns
- Selectable zero suppression:
  - pixel-, cluster- or column-based.

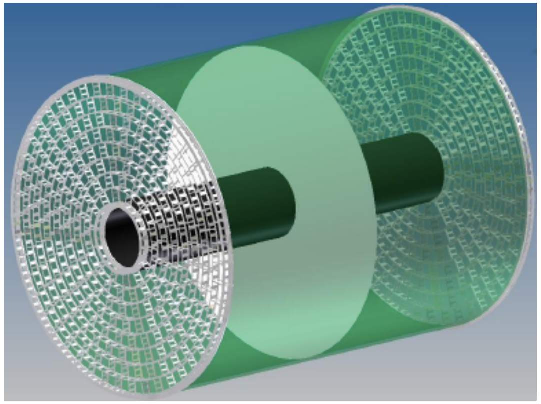
- P_{analog}~2 W/cm² (peak)
  - power pulsing → P_{avg}< 50 mW/cm²



Trackers

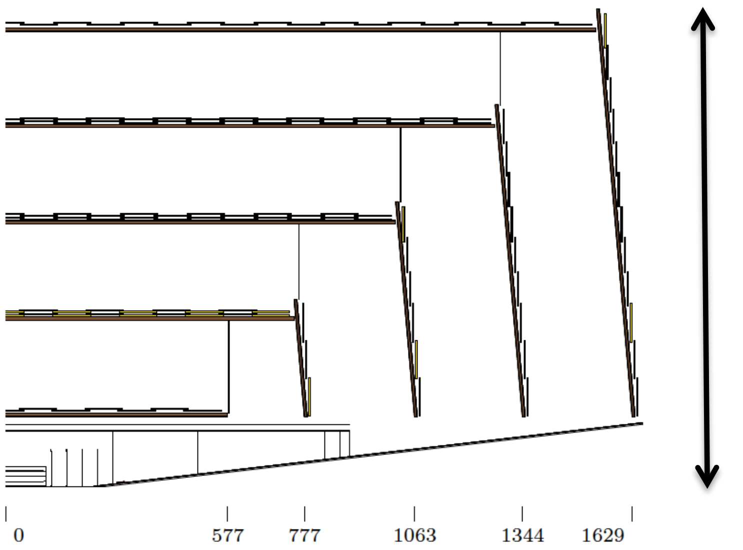
CLIC_ILD:
TPC + silicon tracker in 4 T field



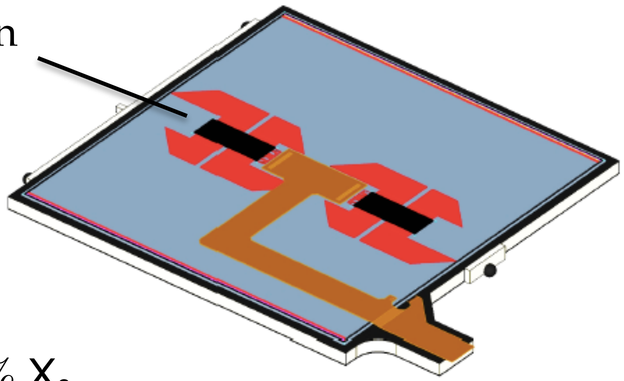


- Drift time of 30 μs.
- MPGD readout

CLIC_SiD:
all-silicon tracker in 5 T field



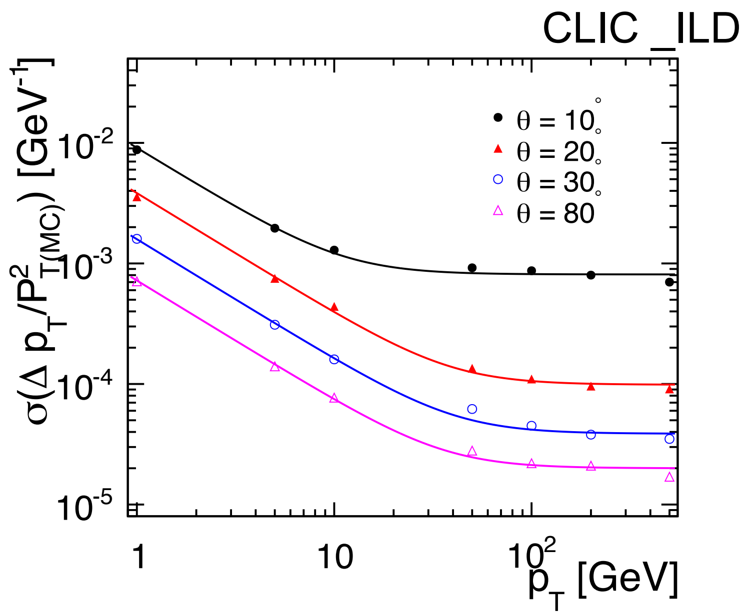
chip on sensor



Each layer:
Total < 0.8% X_0

Track momentum resolutions

- CMS tracker, with high point resolution, is very accurate in strong magnetic field
- Large ATLAS air-core muon spectrometer results in better momentum reconstruction in the forward region.
- CLIC muon system is not used for momentum measurement.



		CLIC_ILD	ATLAS	CMS
Inner Detector (at 90°)	**p = 100 GeV**	0.2%	3.8%	1.5%
Incl. muon sys. (at 90°)	**p = 1 TeV**	2%	10.4%	4.5%
Incl. muon sys. (~ θ = 15°)	**p = 1 TeV**	10%	4.4%	7.0%

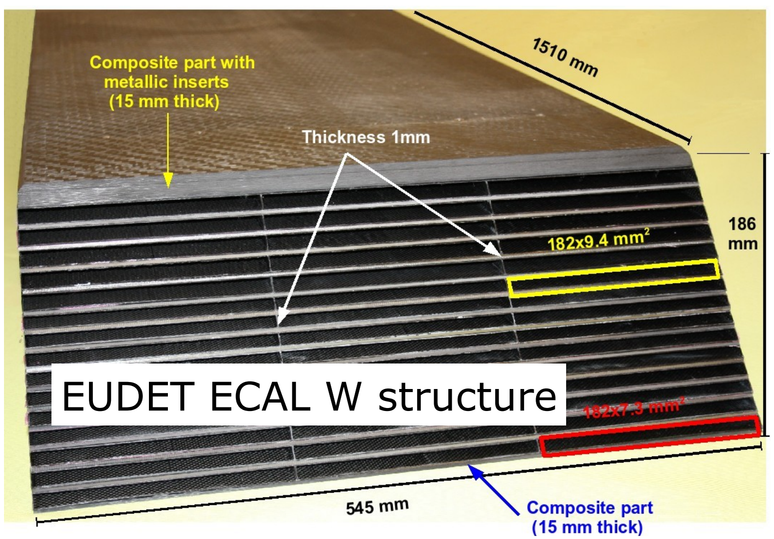
η ~ 2

EM calorimetry

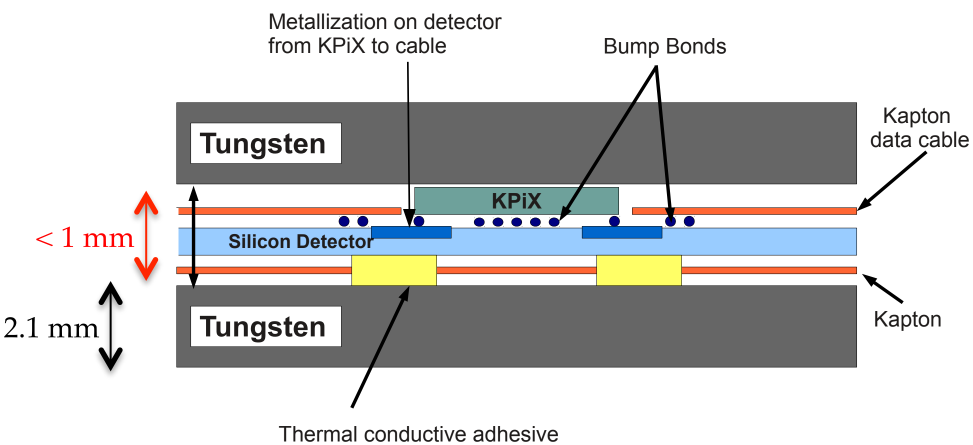
Need fine transverse and longitudinal segmentation

ECAL	CLIC_ILD, B = 4 T
Absorber / Active element	Tungsten / Si pads
Sampling layers	20x 2.1 mm, 10x 4.2 mm
Cell size	5.1 × 5.1 mm²
X_0 and λ_I	24 and 1

← below 1 X_0
← below Moliere radius



Example – SiD approach:



EM Calorimeter (barrel, at 90°)

	CLIC 3 TeV	ATLAS	CMS
Technology	Tungsten / Si pads	Lead / LAr	Lead tungstate crystals
# longitud. readout segments	30	4	1
Readout segment size [cm^3] (longitudinal × 'tilesize')	0.3 x 0.5 x 0.5 For first 19 layers	47 x 4 x 4 (main layer)	23 x 2.2 x 2.2
Depth (radiation length) [X_0]	24	22	26

Note:

- ECAL # channels at ATLAS: 0.2 M
  at CLIC: 100 M
- Silicon surface in CMS tracker is 200 m^2
  CLIC_ILD ECAL has 2600 m^2.
  CLIC_SiD ECAL has 1100 m^2.

EM Calorimeter (barrel, at 90°)

Based on stand-alone test-beam measurements:

	CLIC 3 TeV	ATLAS	CMS
Intrinsic energy resolution $\sigma_E / E = a / \sqrt{E} \oplus b$	a = 17% b = 1%	a = 10% b = 0.2%	a = 3% b = 0.5%

The resolution of the CLIC ECAL is worse than at LHC.

- Intrinsic resolution less important for jets.
  → Want to 'track' the particles inside shower for optimal jet resolution.

- Granularity is more important to distinguish depositions by different particles
  → Electron energies come from the tracking.
  → Only photons are measured with CLIC ECAL resolution.

Overall sizes

- For CLIC the design resembles CMS
  - Calorimeters to be placed inside the solenoid for accurate PFA analysis
- CLIC detectors are much shorter than CMS

	CLIC_ILD	CLIC_SiD	CMS	ATLAS
Full detector height & length [m]	H: 14 L: 14	H: 14 L: 14	H: 15 L: 20	H: 22 L: 46
Magnetic field [T]	4	5	3.8	2.0 (solenoid) 0.5 – 1.0 (toroid)
Solenoid inner radius + thickness [m]	3.4 + 0.7	2.7 + 0.8	3.0 + 0.6	1.2 + 0.2

#channels and total surfaces

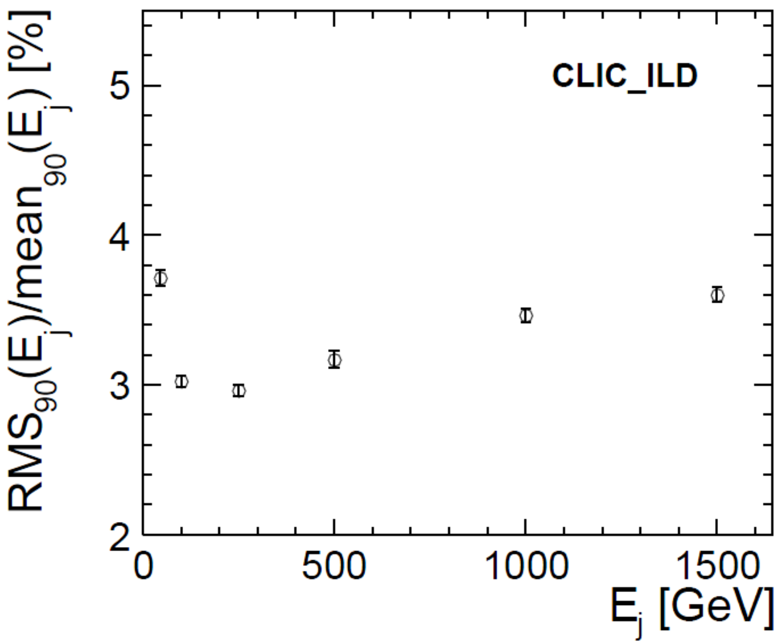
	ATLAS	CMS	CLIC_ILD	CLIC_SiD
#channels in VTX [x 10^6] **Total silicon surface [m^2]**	80 1.7	66 1.0	2035 0.81 (VTXpix)	2760 1.1
#channels in TCK [x 10^6] **Total silicon surface [m^2]**	6.2 (strip) + 0.35 (tubes) 60	9.6 200	455(FTDpix) +11.6(strips) +3(TPC) 182 (only strips!)	97.
#channels in ECAL [x 10^6] **Total surface [m^2]**	$0.17 \cdot 10^6$ –	$0.08 \cdot 10^6$ –	104 2600.	44 1100.
#channels in HCAL [x 10^6] **Total surface [m^2]**	$0.02 \cdot 10^6$ –	$0.007 \cdot 10^6$ –	8.9 8010.	
#channels in MUON [x 10^6] **Total surface [m^2]**	$1.1 \cdot 10^6$ –	$0.83 \cdot 10^6$ –	3.8 5827	3.3 4572

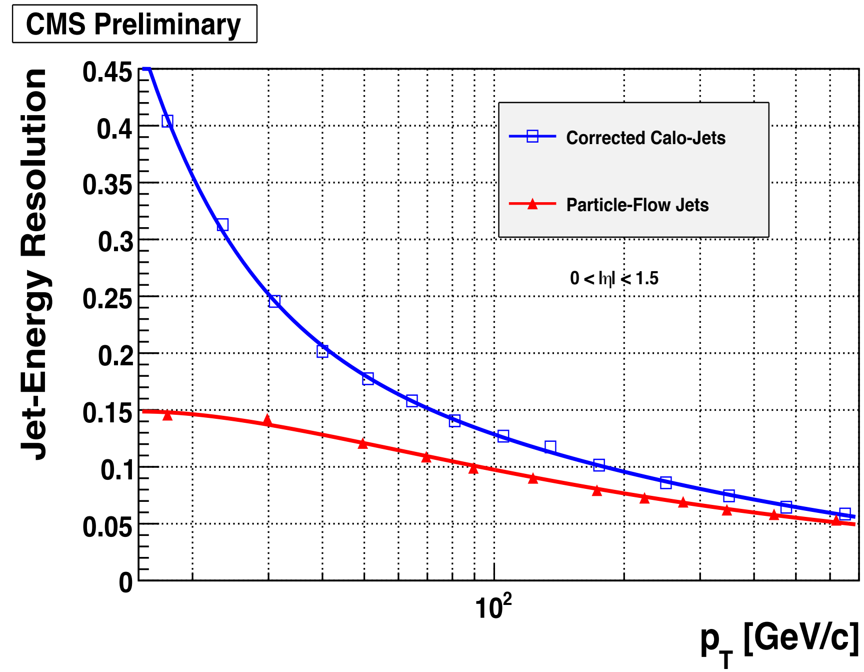
Hadronic calorimeter (barrel, at 90°)

	CLIC 3 TeV	ATLAS	CMS
Technology	Tungsten / scint.	Iron / scint.	Brass / scint.
# longitud. readout segments	75	3	1
Readout segment size [cm³] (longitudinal × 'tilesize')	1.7 x 3.0 x 3.0	~ 20 x 20 x 20 For the first layer	96 x 20 x 20
Interaction length [λ_I]	7.5 (+1 for ECAL)	~7.5	~5.5 (+3 for coil & tailcatcher)

- Where ATLAS has 20k channels, CLIC_ILD has 10M channels.
- CLIC & CMS coil sizes are similar, yet HCAL depth at CLIC is higher, due to the different absorber materials used
- LHC calorimeters are φ-η segmented, for CLIC it will be one-size tiles.

Barrel region |cos θ| < 0.7.
PFA, without background:

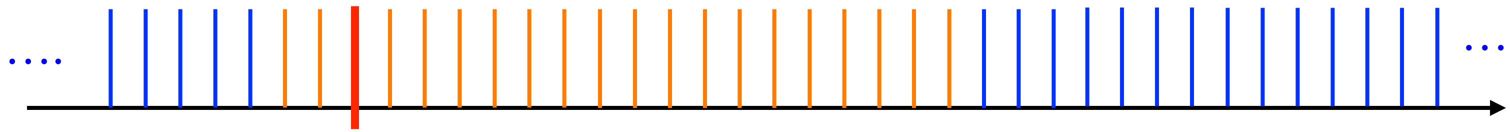




CLIC: At higher energies, particle separation becomes more difficult:

- Confusion term dominates energy resolution, particle flow can become energy flow.

Reconstruction timing strategy



Assume can identify t_0 of physics event in offline event filter

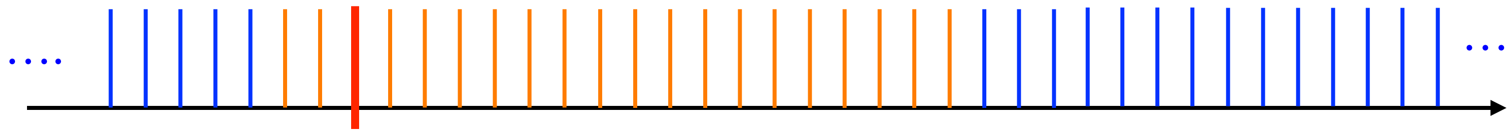
- define "reconstruction" window around t_0
- All hits and tracks in window are passed to reconstruction.

Currently in the CLIC PFA:

Subdetector	Reco Window	Hit Resolution
ECAL	10 ns	1 ns
HCAL Endcap	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$ ns
TPC (CLIC_ILD)	Entire train	n/a

Achievable in the calorimeters with a sampling each ~25 ns

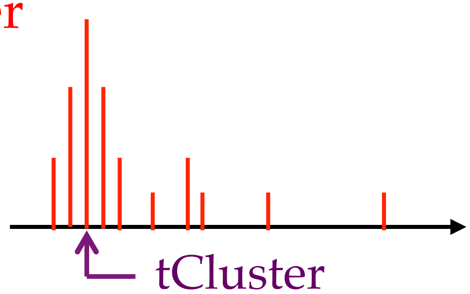
Reconstruction timing strategy



Assume can identify t_0 of physics event in offline event filter

- define "reconstruction" window around t_0
- All hits and tracks in window are passed to reconstruction.

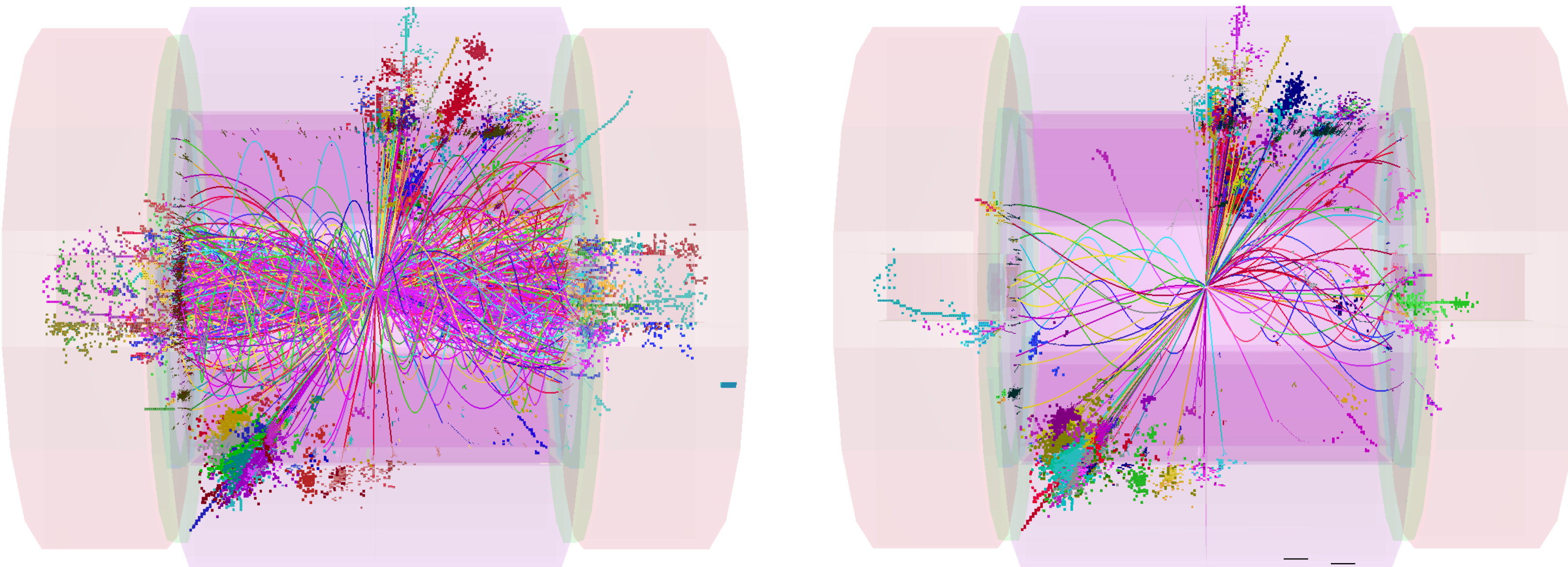
- Calculate energy weighted mean time of each cluster
  - Obtain sub-ns resolution
  - Use to reject out-of-time clusters and associated tracks



Impact of filters

8 jet final state, $\sqrt{s} = 3$ TeV, $e^+e^- \rightarrow H^+H^- \rightarrow tbbt$ + 60 BX $\gamma\gamma \rightarrow$ hadrons

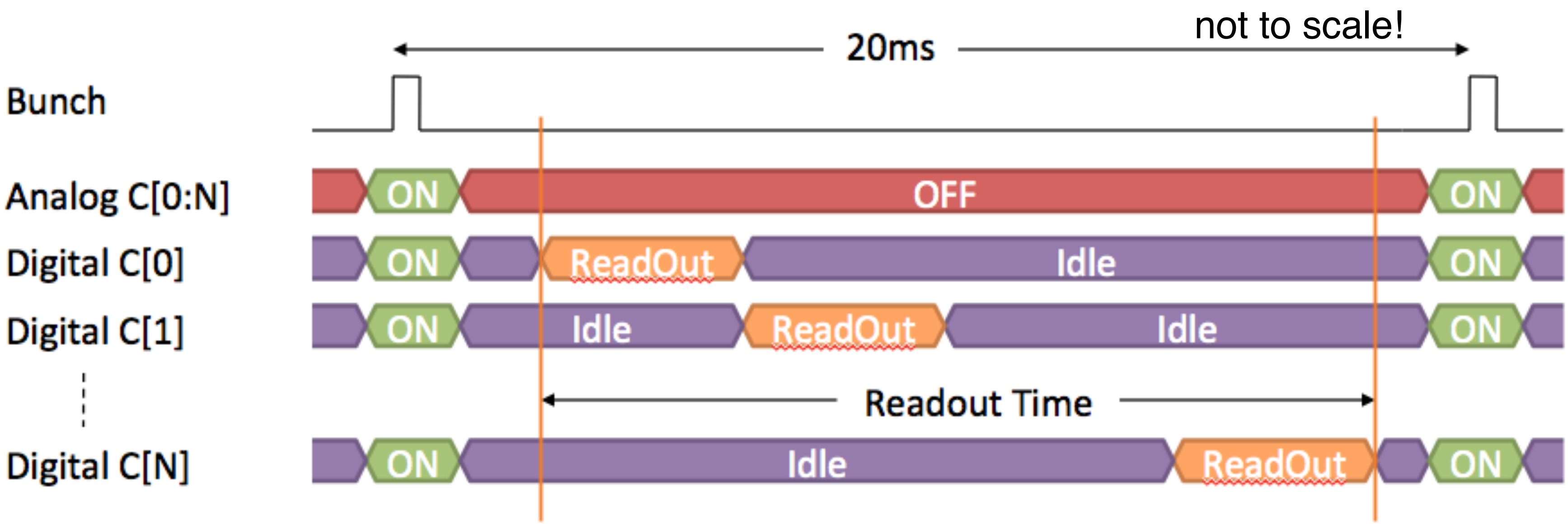
1.2 TeV background ⇨ 85 GeV



Excellent performance:

- Reject 93 % of background energy and < 1% of physics event

CLICPix power pulsing requirements



Bunch Train (3.0 W/cm²)

Pixel Analog	ON
Pixel Digital	ON
Periphery Analog	ON
Periphery Digital	ON
IO LVDS Pads	OFF

Chip Readout (360 mW/cm²)

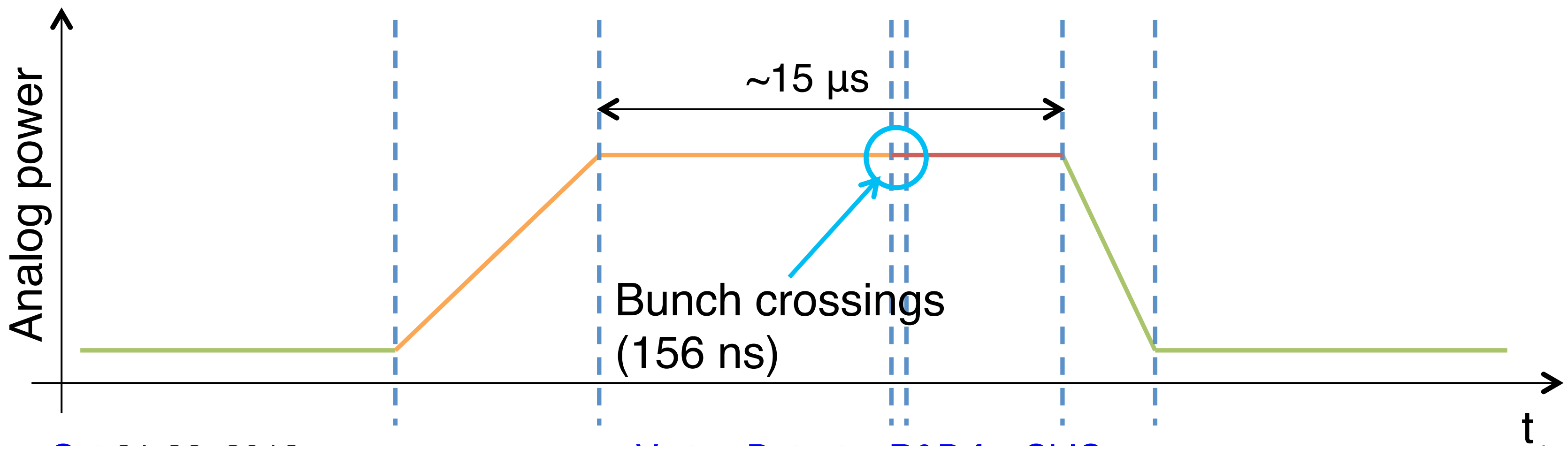
Pixel Analog	OFF
Pixel Digital	ON
Periphery Analog	OFF
Periphery Digital	ON
IO LVDS Pads	ON

Idle (7.8 mW/cm²)

Pixel Analog	OFF
Pixel Digital	Idle
Periphery Analog	OFF
Periphery Digital	ON
IO LVDS Pads	OFF

CLICPix power pulsing requirements

- Overall power budget: P_{avg} ~ 50 mW / cm2
- Estimation of power consumption for analog and digital blocks of CLICPix readout chip
- Based on measurements with 65 nm test-chip and projections from current TimePix
- Power pulsing with On/Idle/Off states, to reduce average power!
- Very small duty cycle for analog power
  → Favors local energy storage.



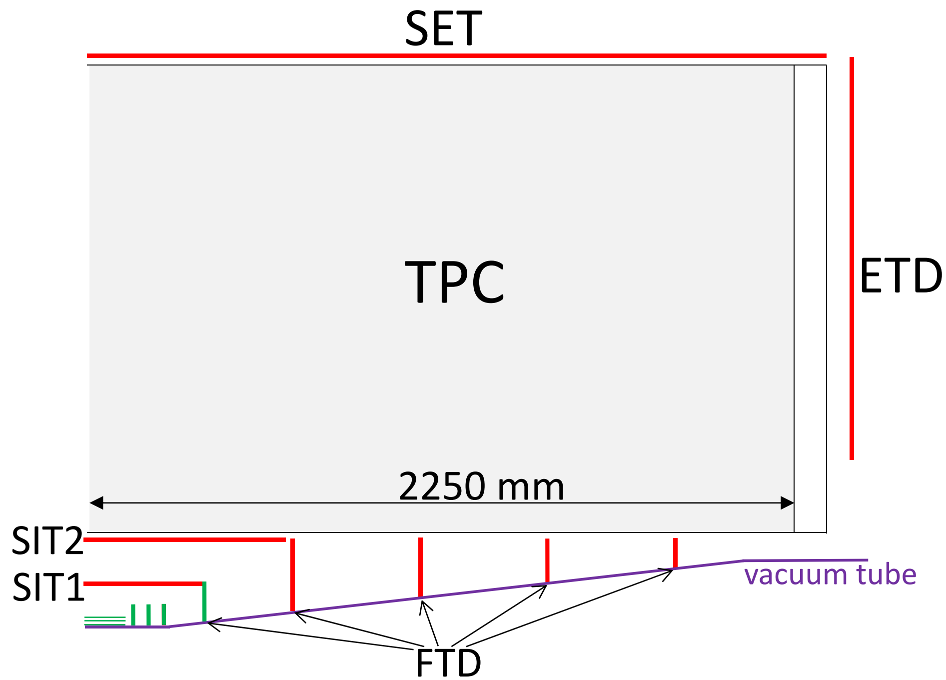
CLIC_ILD: TPC based tracking

Large TPC (329 < R < 1808 mm) for highly redundant continuous tracking (~ 200 measured points)

- Particle ID through dE/dx
- Little material in tracking volume (5% X_0); <25% X_0 in endcap

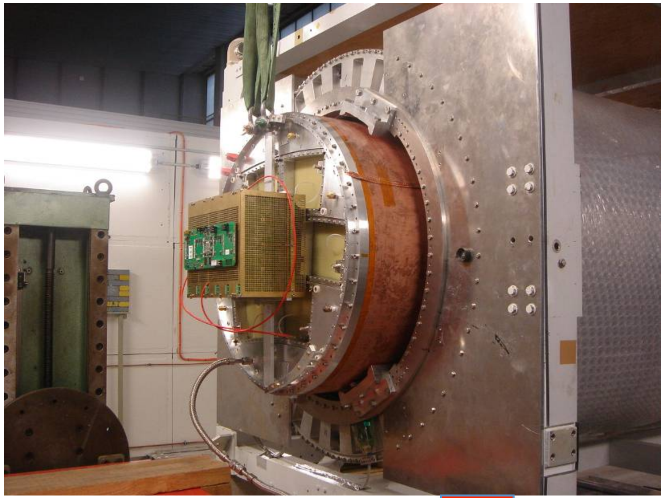
Complemented by silicon tracking system:

- Independent tracking at low angles (FTD)
- Silicon tracking layers surrounding TPC for timing and precision points (SIT, SET, ETD)

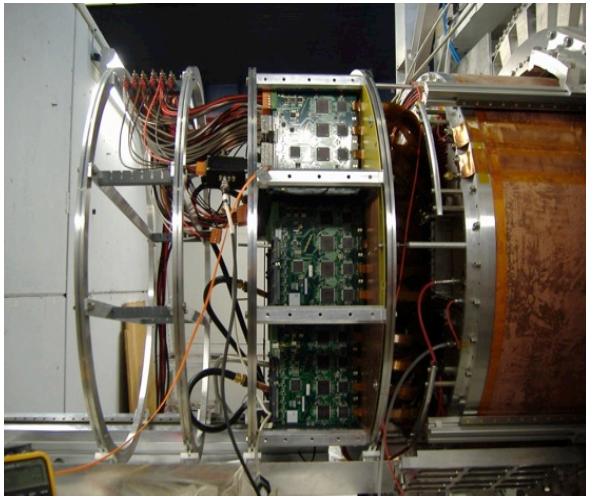


- TPC acceptance down to 12^0 (>10 measurement points)
- SIT acceptance down to 25^0
- FTD acceptance down to 7^0

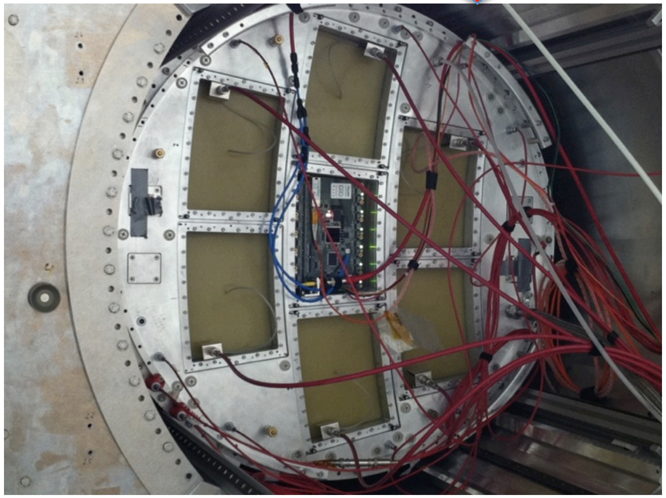
Micromegas (T2K readout)



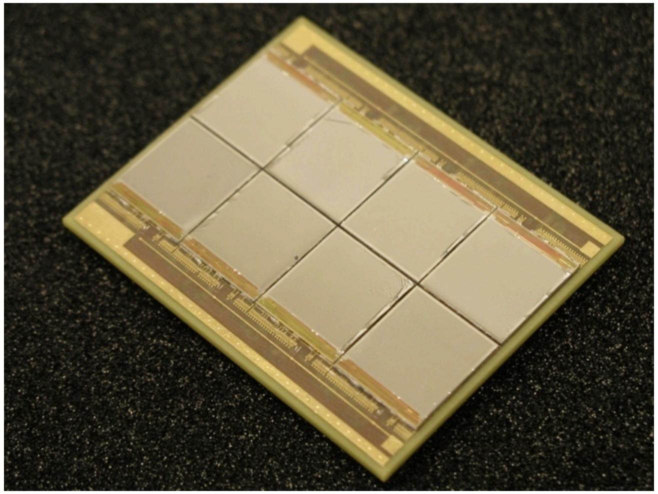
GEMs (Altro readout)



Integrated version

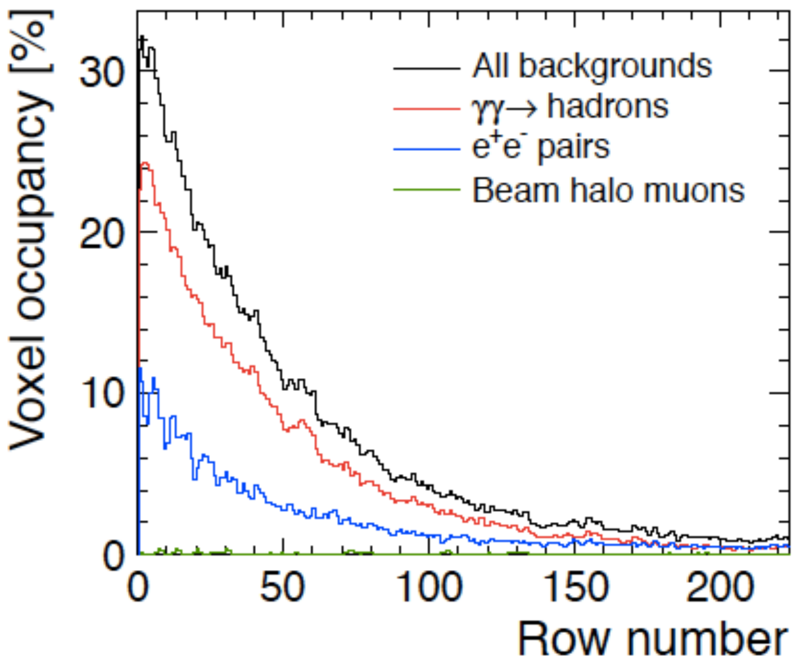


8-chip Ingrid module



TPC occupancies

Full detector simulations:

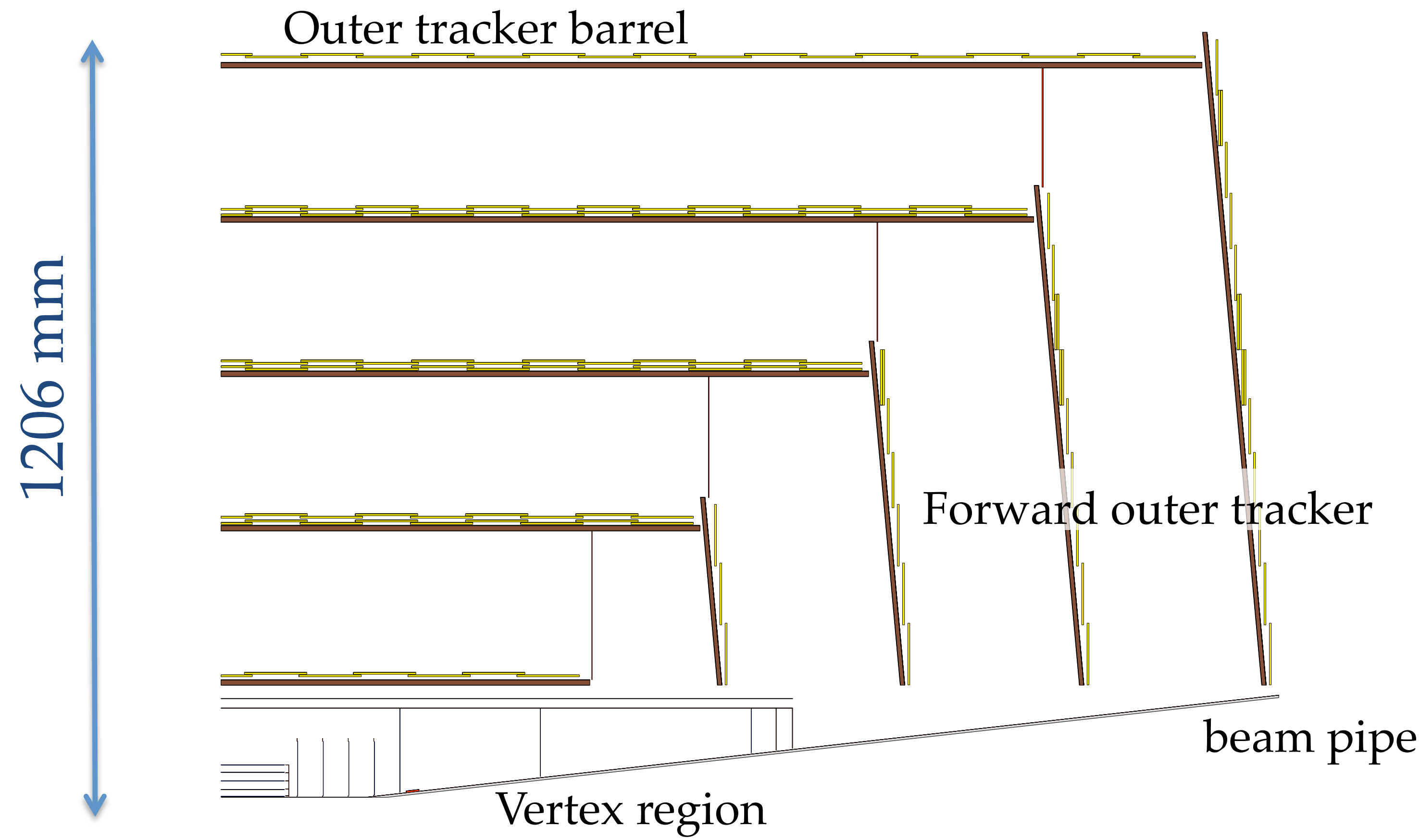


High occupancies in the TPC, mostly due to γγ → hadrons.

- Consider pixelized readout in this region or suppress the inner pad rows.

➢ **Requires technology/layout changes**

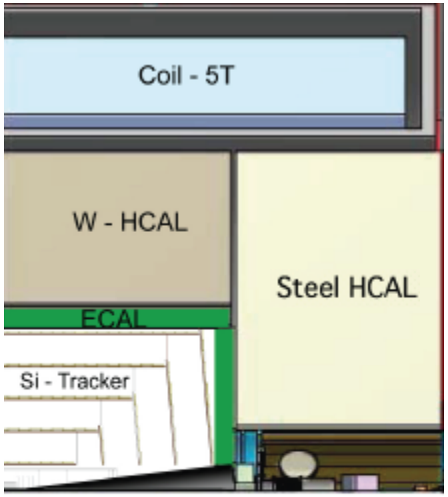
CLIC_SiD: all-silicon tracker

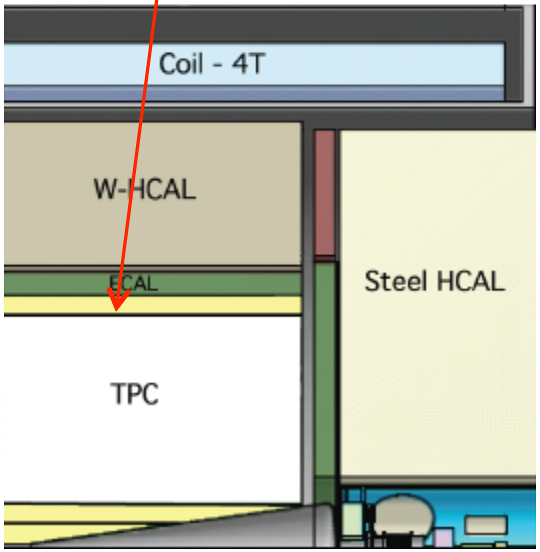


Vertex and tracker detector designed as one, to have 10 hits over all angles

Tracking System

Barrel Tracker	CLIC_ILD	CLIC_SiD
Technology	TPC+Silicon strips	Silicon strips
Inner radius	329	230
Max. samples	2(Si), 224(TPC), 1(Si)	5
Outer radius	1808	1239
Max. Z	2250	578 to 1536





Forward Tracker	CLIC_ILD	CLIC_SiD
Technology	Silicon strips	Silicon strips
Inner radius	47 to 218	207 to 1162
Max. samples	5	4
Outer radius	320	1252
Max. Z	1868	1556

T3B movie

Correlation of T3B and WAHCAL events provides a powerful addition:

- Event-by-event measurement of the depth of T3B relative to the shower start
- By combining large data samples, the average time structure of hadronic showers can be measured over a depth of 5 λ_I

→ 4D shower images with unprecedented granularity