Detector Systems at CLIC

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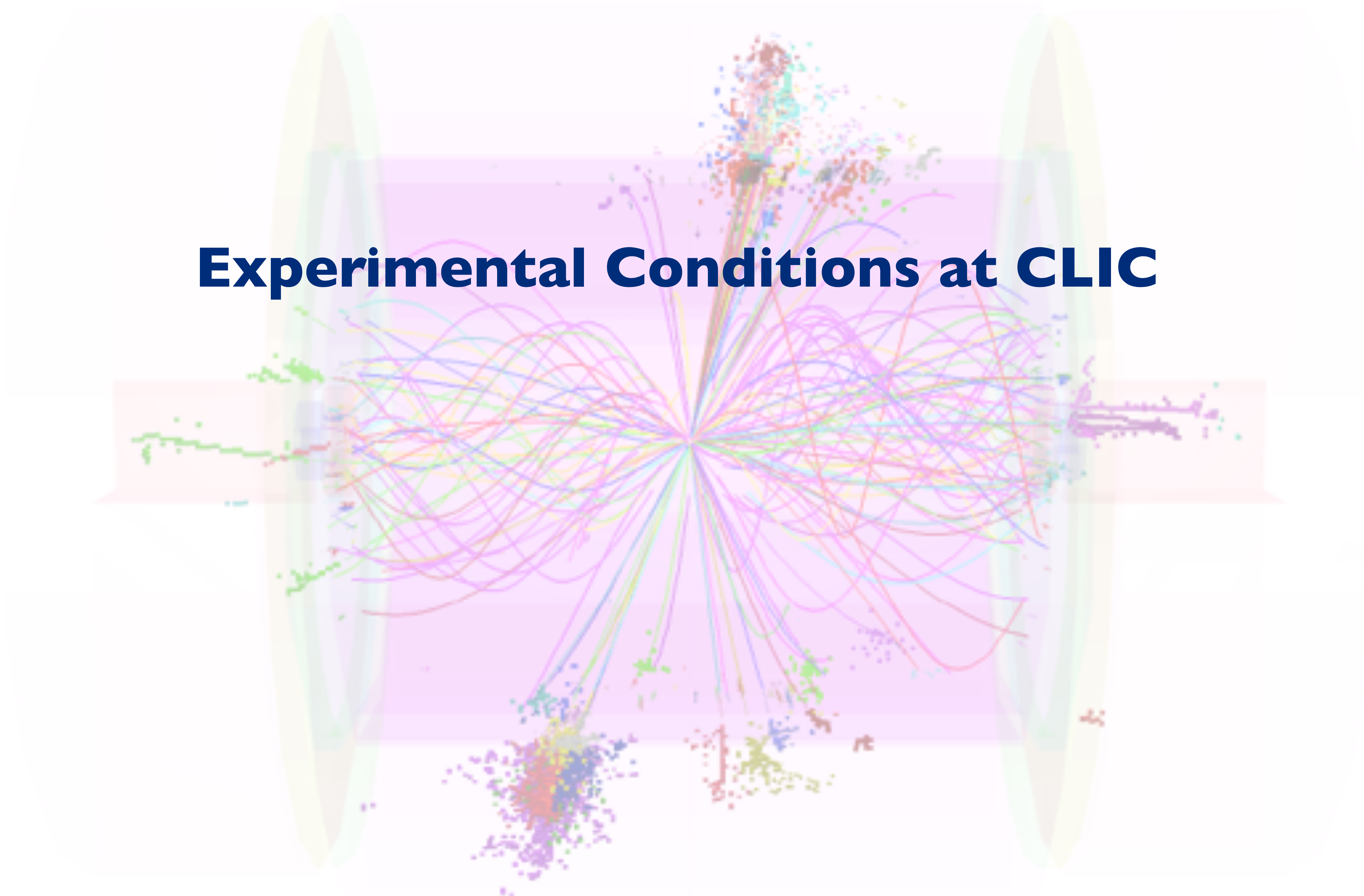
(Werner-Heisenberg-Institut)

Excellence Cluster
Universe

Outline

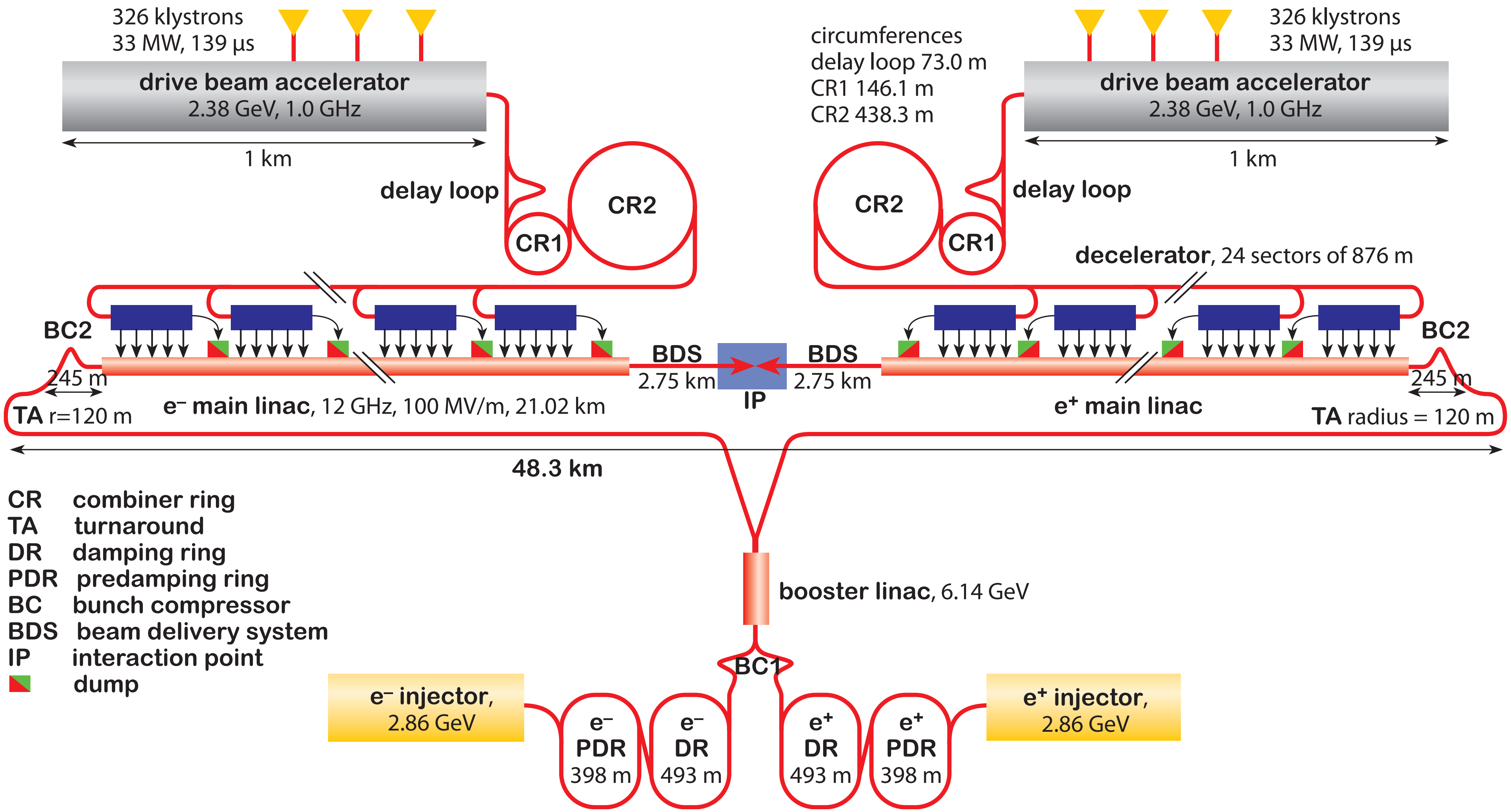
- Experimental Conditions at CLIC
- CLIC Detector Designs
  - General detector philosophy
  - Vertex detectors
  - Calorimetry
  - Engineering Studies
- Event reconstruction
  - Coping with backgrounds
- Summary/Outlook

Experimental Conditions at CLIC



CLIC: The Compact Linear Collider

- 3 TeV center of mass energy (staged construction possible: ~ 500 GeV initially)
- 2-beam acceleration using warm cavities: 100 MV/m gradient



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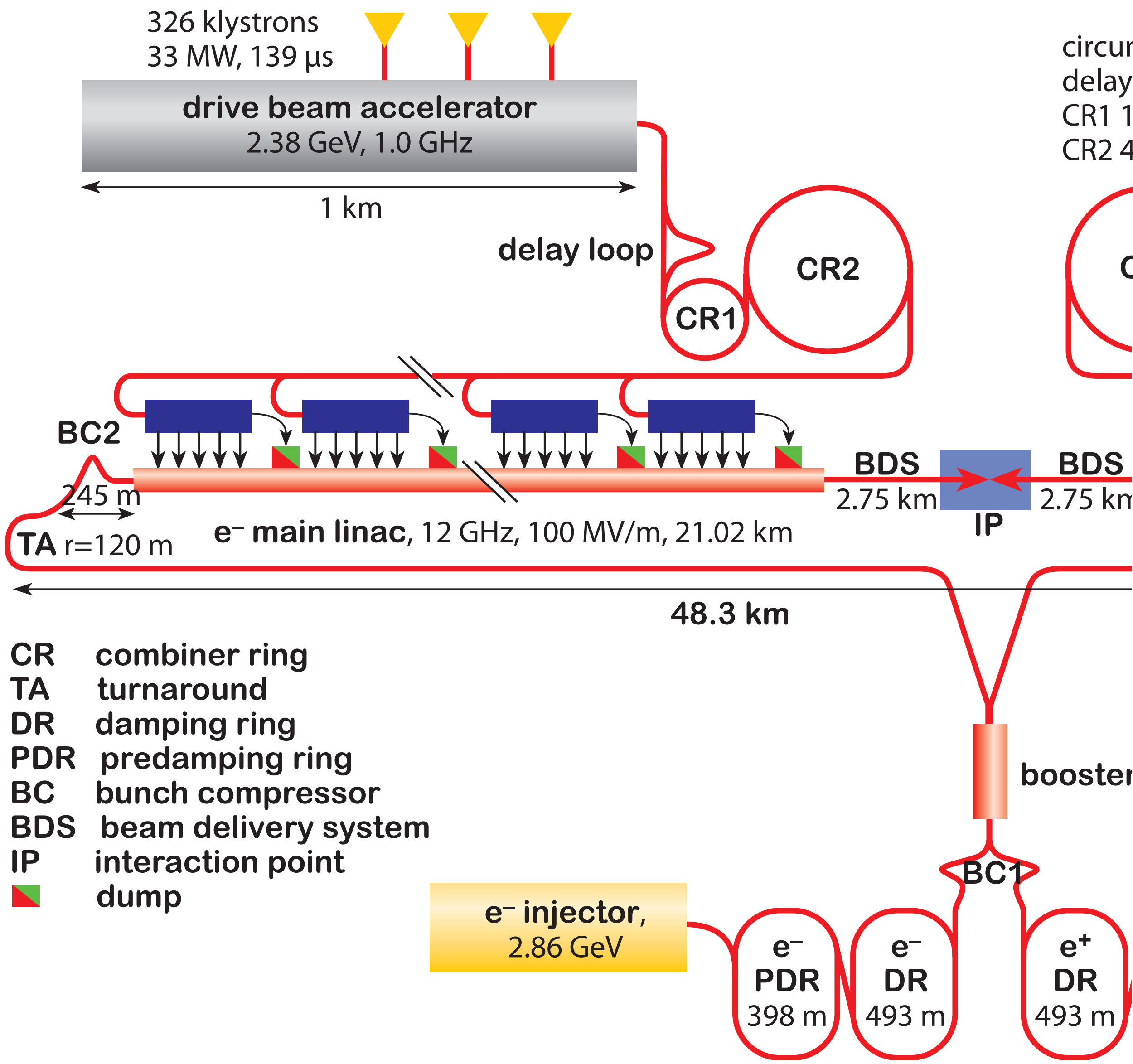
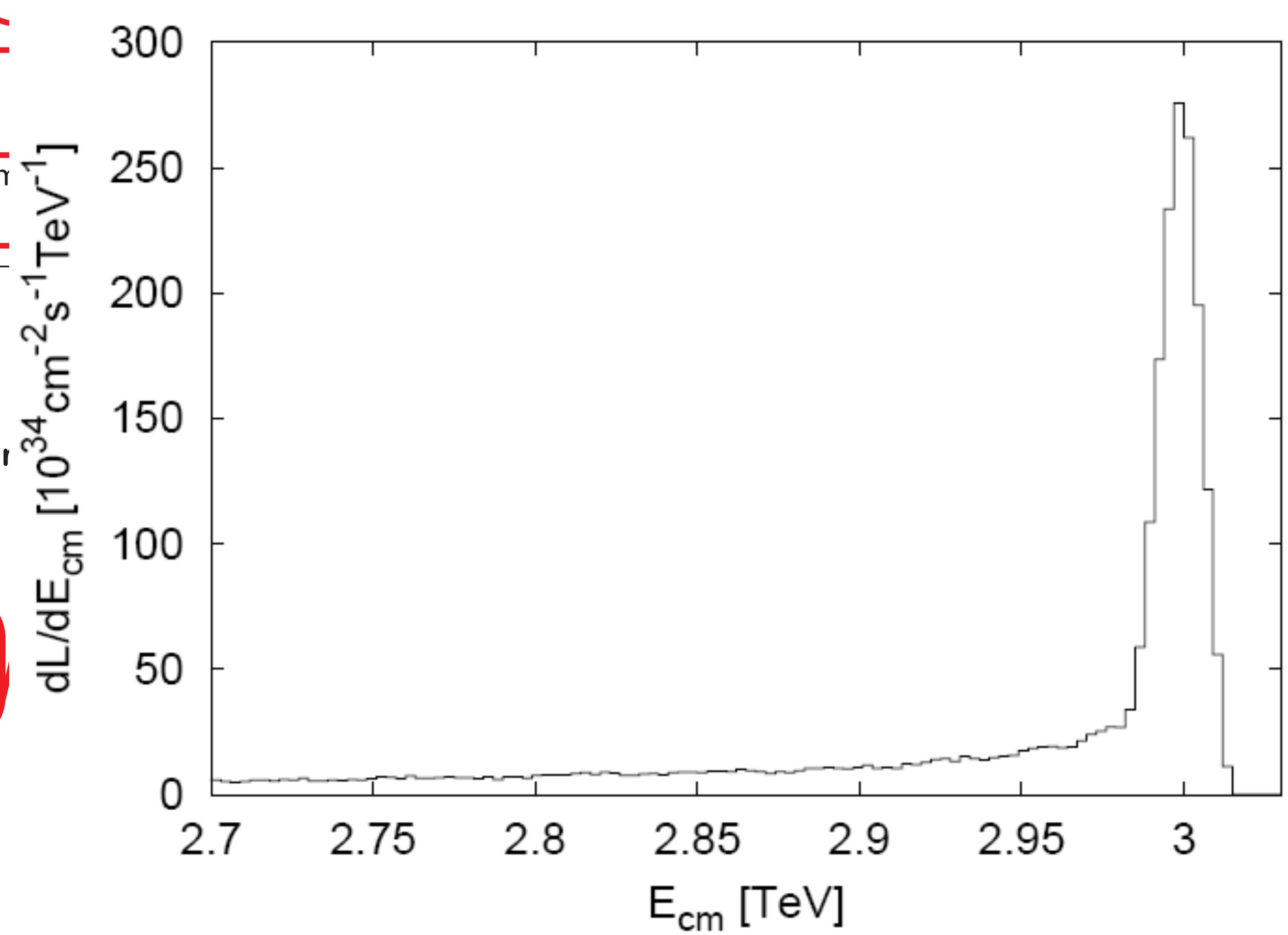
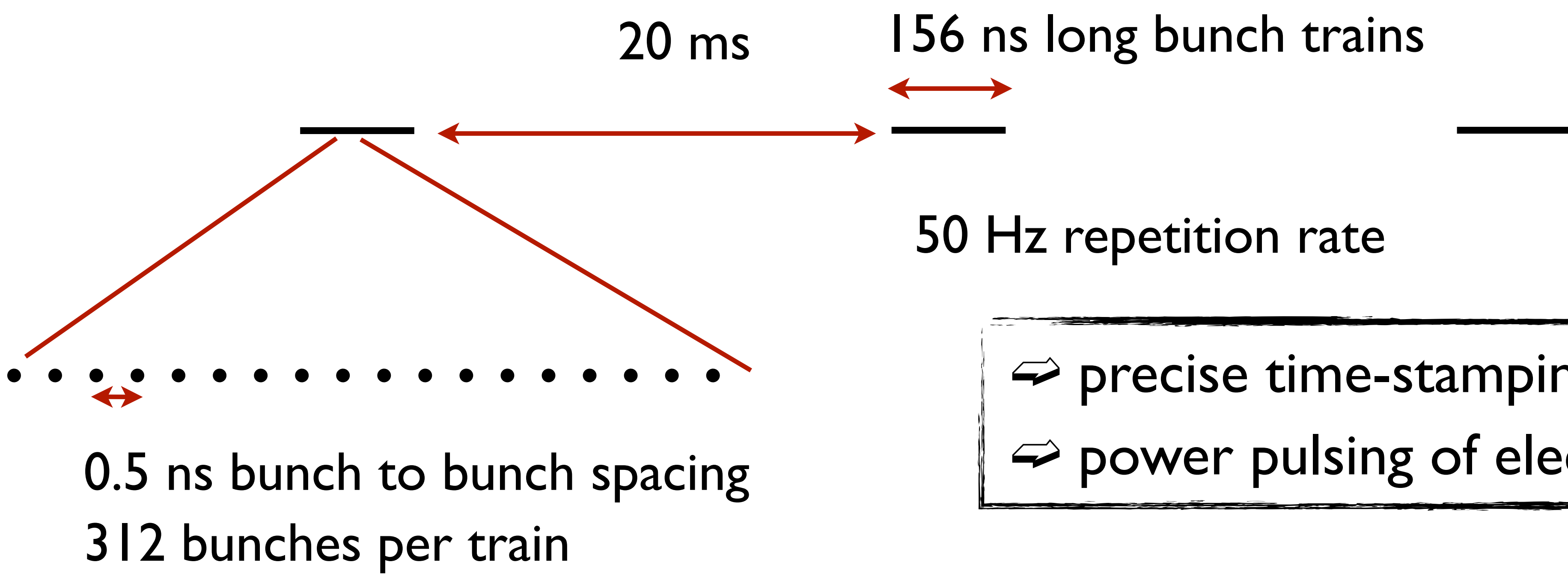




- Luminosity at 3 TeV: 5.9 x 10^{34} $cm^{-2}s^{-1}$
(2 x 10^{34} $cm^{-2}s^{-1}$ in top 1%)

Conditions at CLIC

- The bunch structure at CLIC



➯ precise time-stamping required
➯ power pulsing of electronics possible

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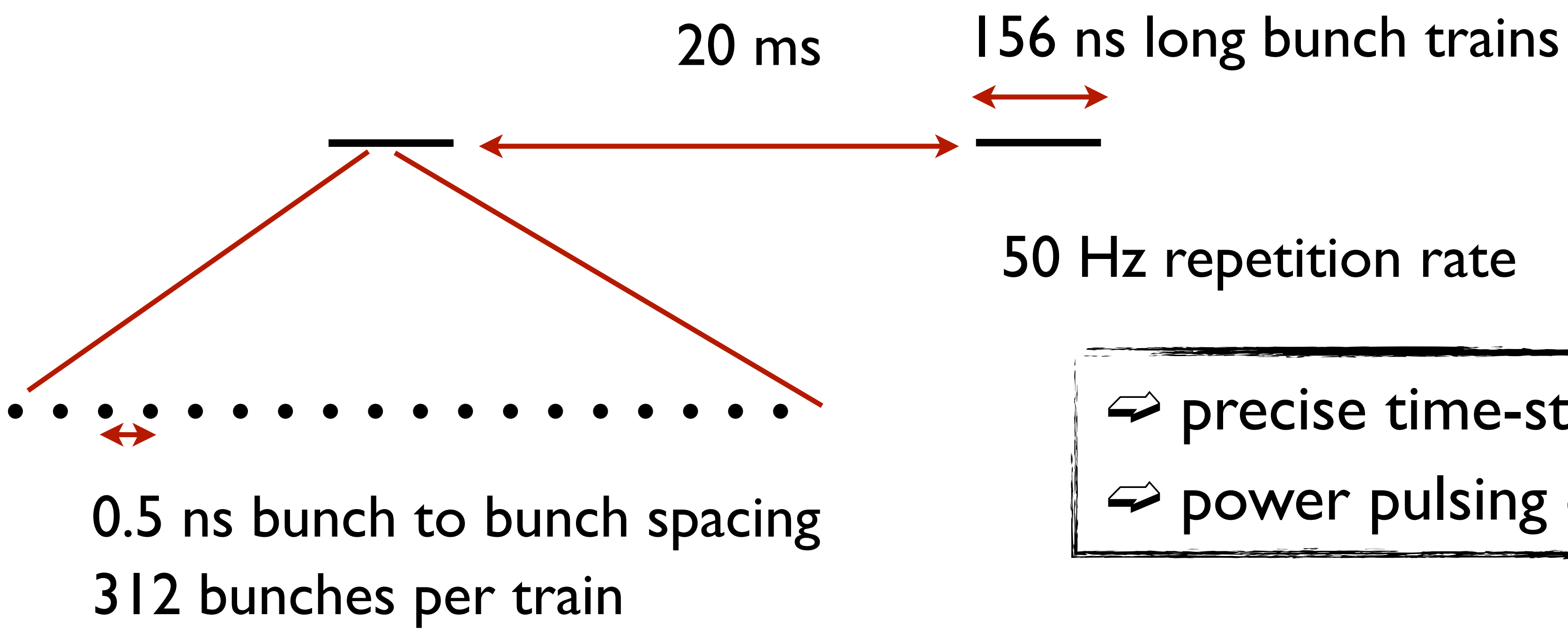

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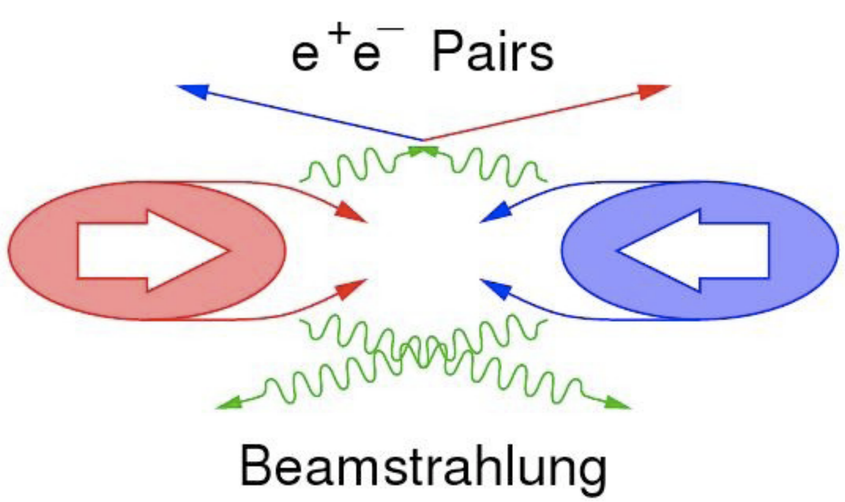
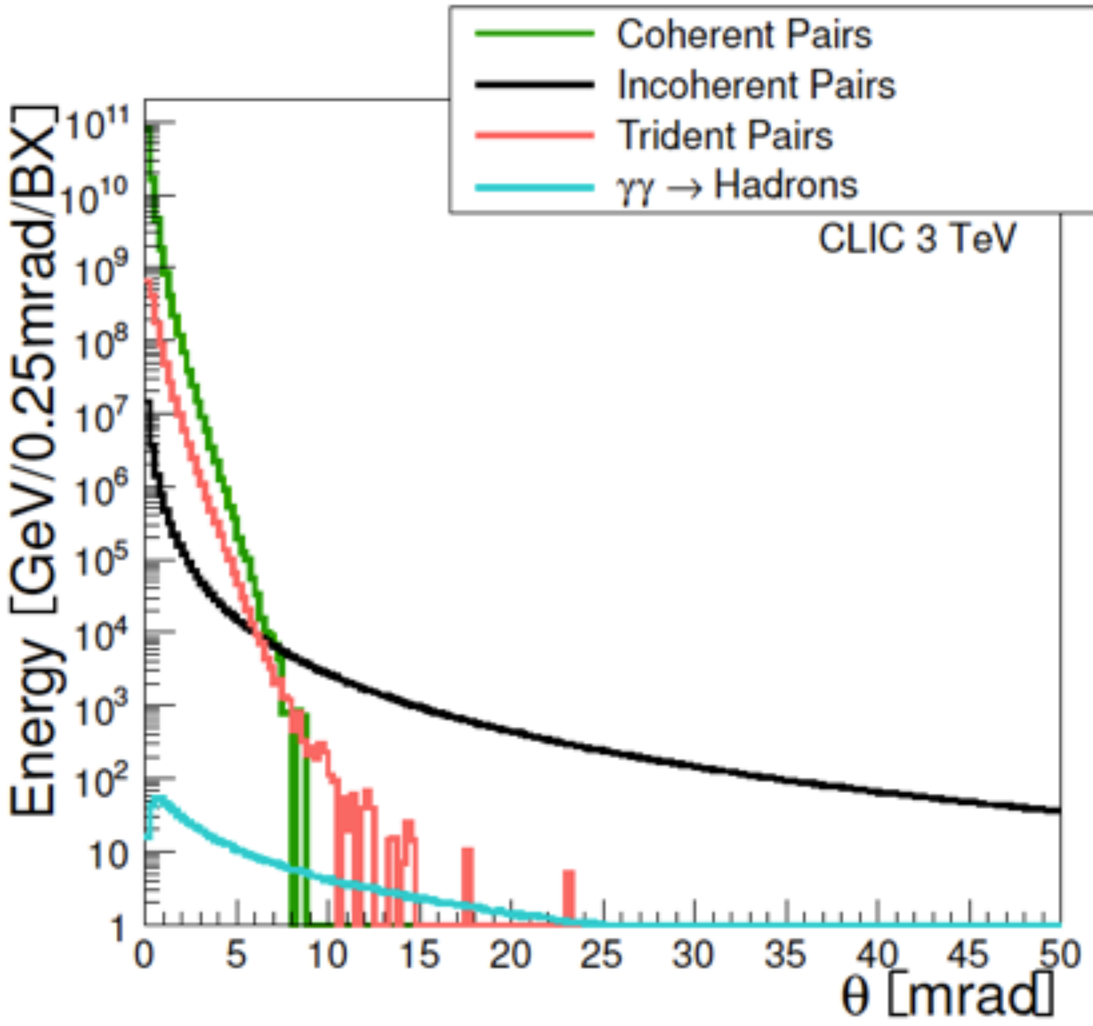


Beamstrahlung driven by energy and focusing:
mean bunch ΔE/E ~ 29%

- coherent e^+e^- pairs: 3.8 x 10^8 / bunch crossing
- incoherent e^+e^- pairs: 3.0 x 10^5 / bunch crossing
- $\gamma\gamma \rightarrow$ hadrons interactions: 3.2 / bunch crossing

Conditions at CLIC: Beamstrahlung Details



- Coherent e^+e^- pairs with angles < 10 mrad
  - Crossing angle at CLIC: 20 mrad
    beam pipe opening angle ± 10 mrad
    for outgoing beam:
    coherent pairs disappear in beampipe
- incoherent pairs: swept away by solenoidal field, constrain innermost radius of vertex detector

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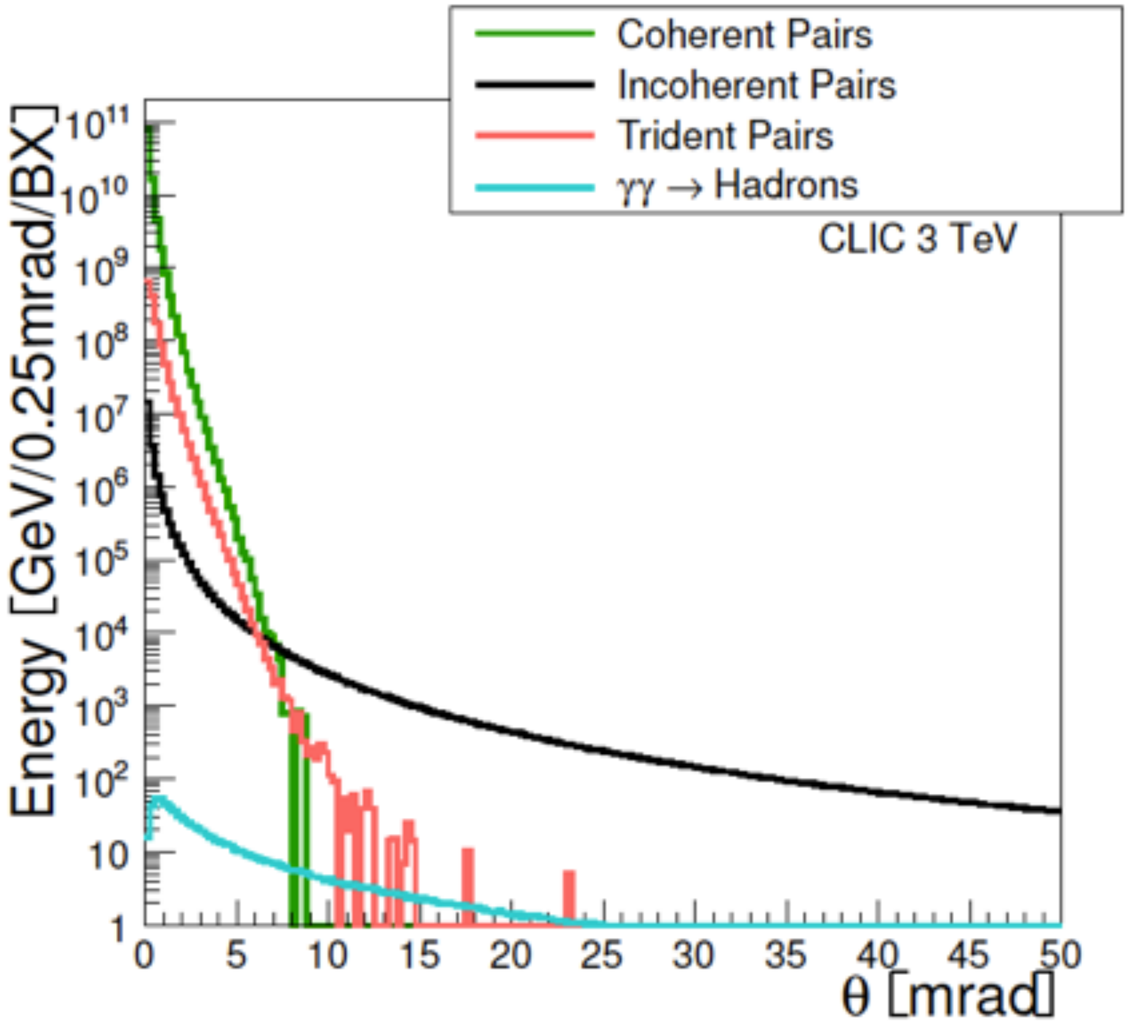

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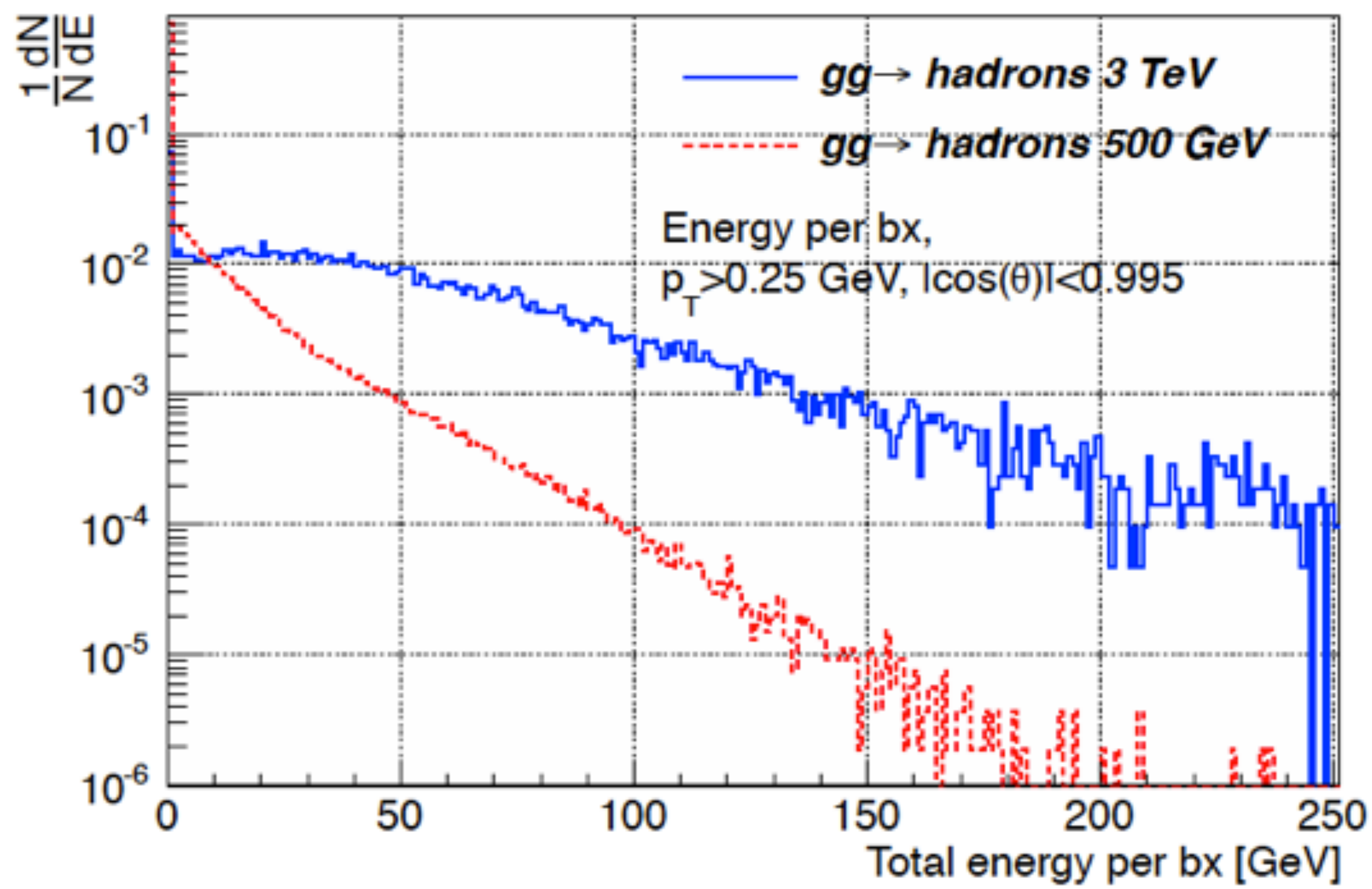
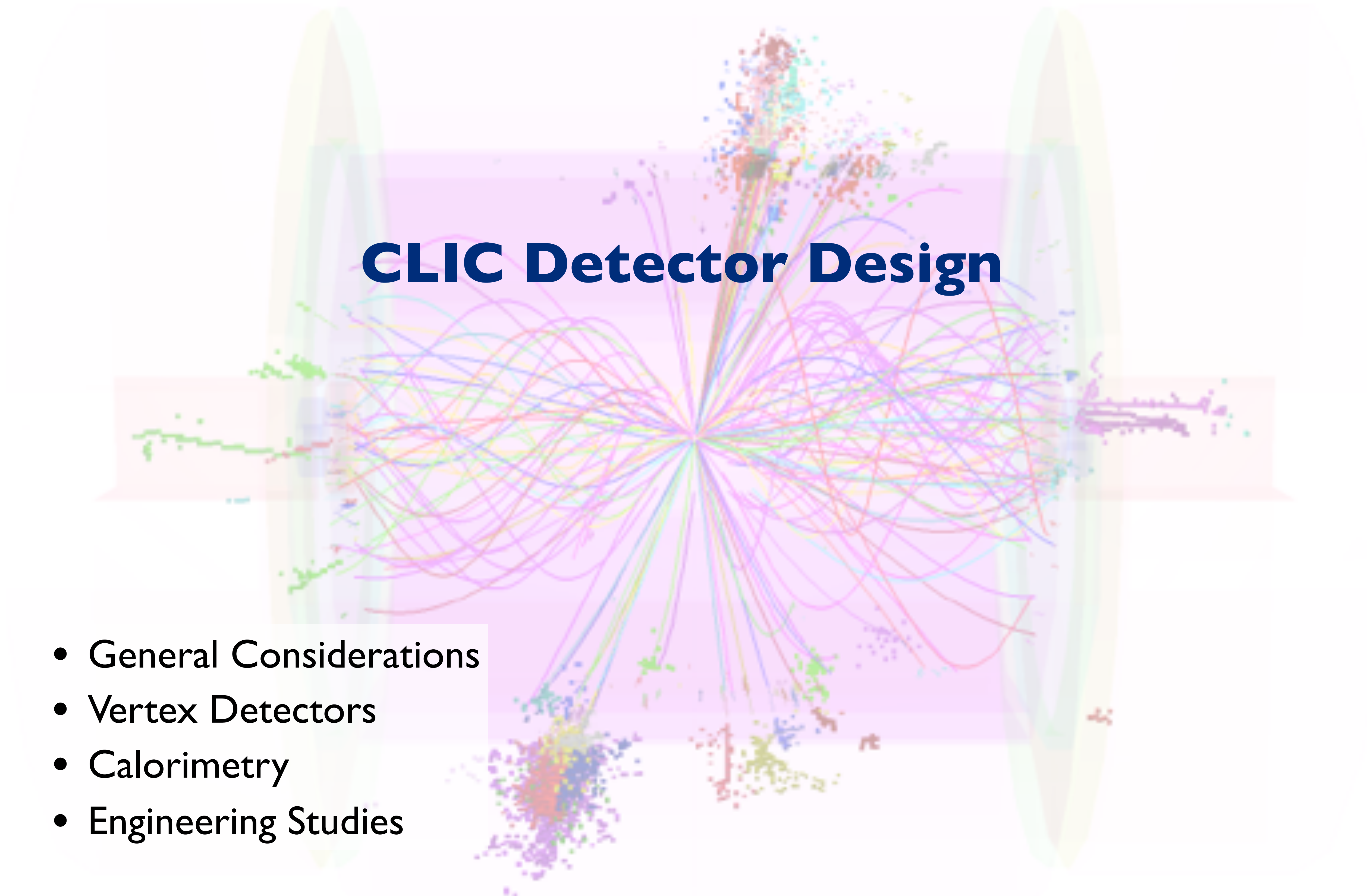
- γγ → hadrons: ~ 3.2 events / bx,
  ~ 28 ch. particles in detector acceptance
  ~ 60 GeV energy
  ➩ 15 TeV dumped in detector during bunch train, forward peaked
  Requires precise time stamping and clever event reconstruction



CLIC Detector Design

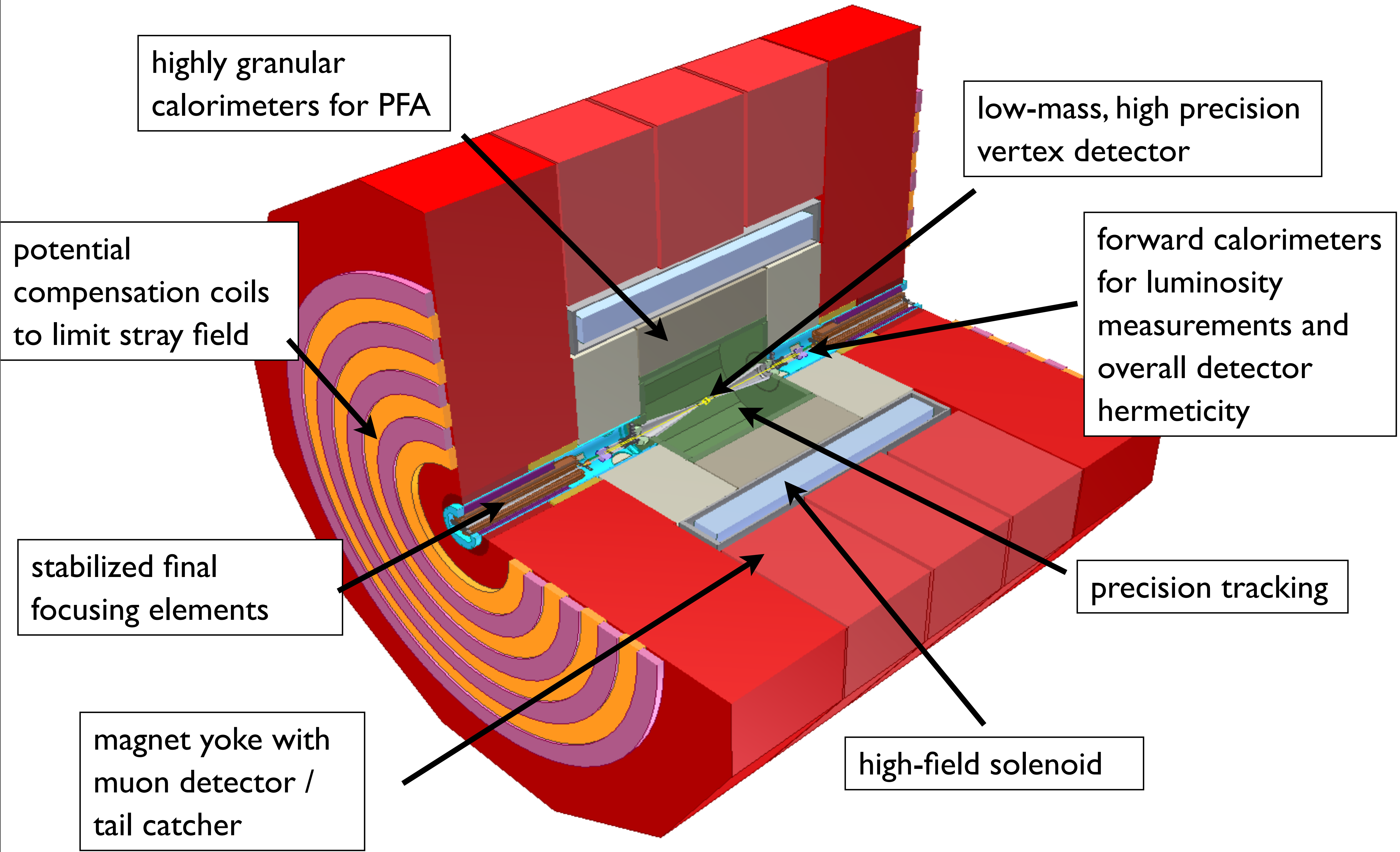


- General Considerations
- Vertex Detectors
- Calorimetry
- Engineering Studies

General Considerations

- Requirements for CLIC detectors driven by physics:
  - Excellent resolution for multi-jet final states
  - Hermetic coverage for missing energy measurements
  - Precise track reconstruction
  - Excellent flavor tagging: b & c identification and separation
- These requirements are satisfied by the validated ILC detector concepts ILD and SID
  - Detector systems with large solenoid, event reconstruction based on Particle Flow
- Modifications are necessary to account for CLIC-specific issues:
  - Higher energy: Jets up to the TeV region
  - Higher backgrounds due to high energy and small beam size, combined with high bunch crossing rate

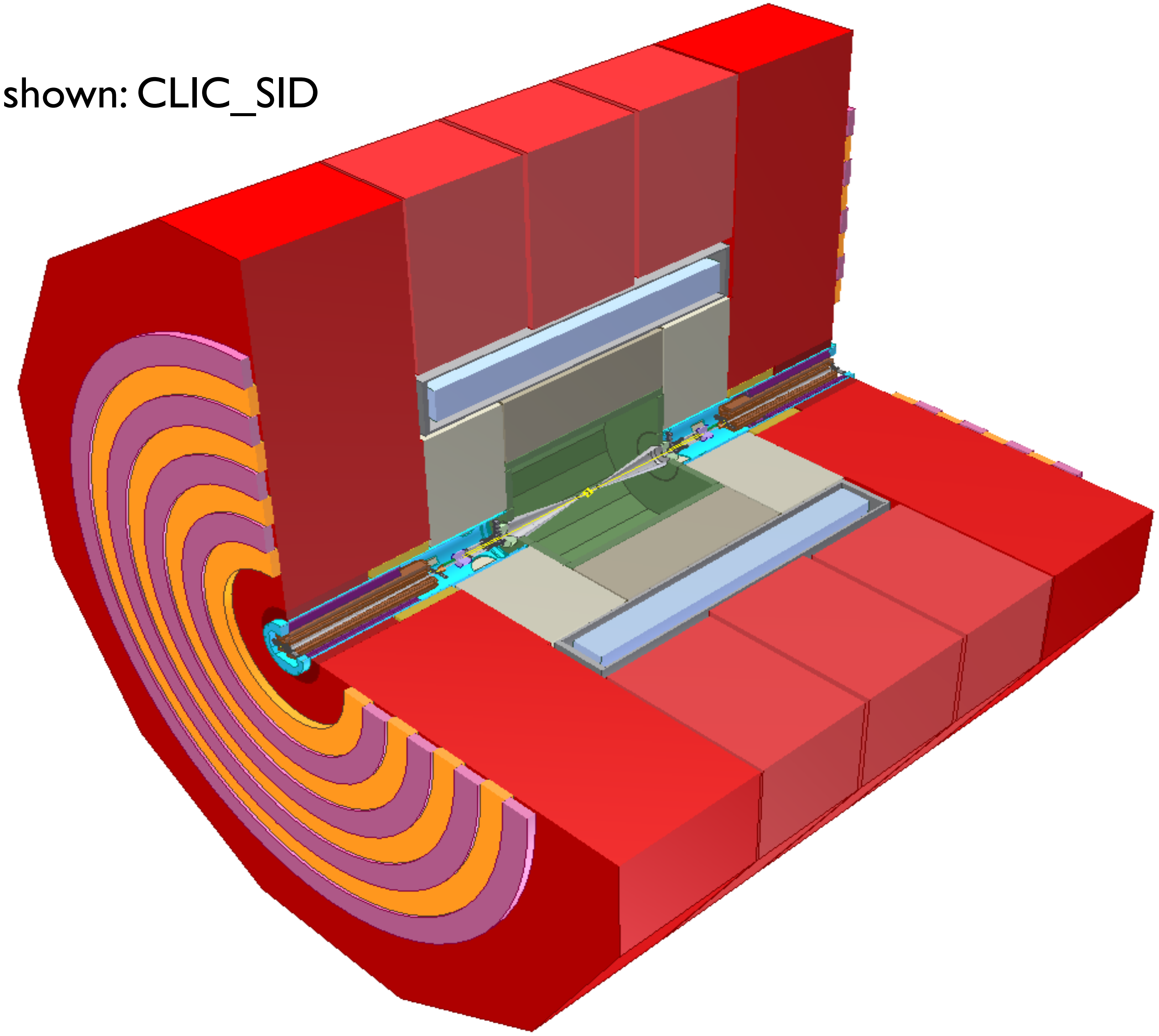
CLIC Detectors - Main Features



Overview: The CLIC Detector Concepts

- Two detectors, following the ILC designs: CLIC_ILD and CLIC_SID

shown: CLIC_SID



Si pixel vertex detector
Si strip inner tracker

CLIC_ILD: TPC main tracker
CLIC_SID: Si strip main tracker

SiW electromagnetic calorimeter

Hadronic calorimeter with tungsten absorbers in barrel, steel in endcaps
Active medium: Scintillator tiles with SiPM readout currently studied, digital calorimeter with gas detectors also an option

All inside large solenoid

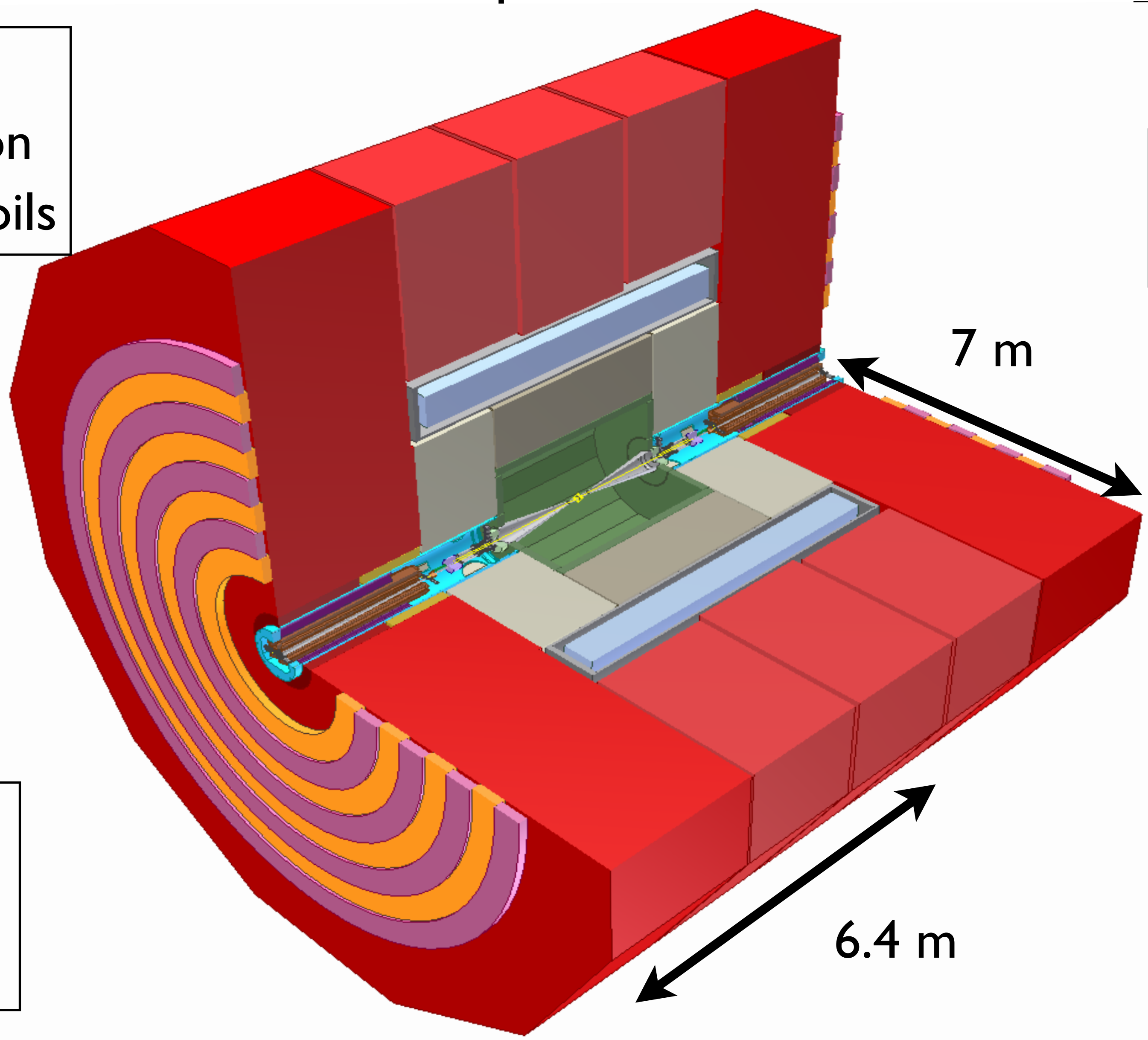
Changes to ILC Detector Concepts

- The overall detector philosophy, and the general design remains unchanged with respect to the ILC concepts
  - Still, many changes to address CLIC-specific issues in both CLIC_ILD and CLIC_SID:

redesigned yoke,
changed instrumentation
added compensation coils

Solenoid dimensions roughly the same, CLIC_ILD at 4 T, CLIC_SID at 5 T

Hadron calorimeter increased in depth: 7.5 λ_I



Significant redesign of forward region

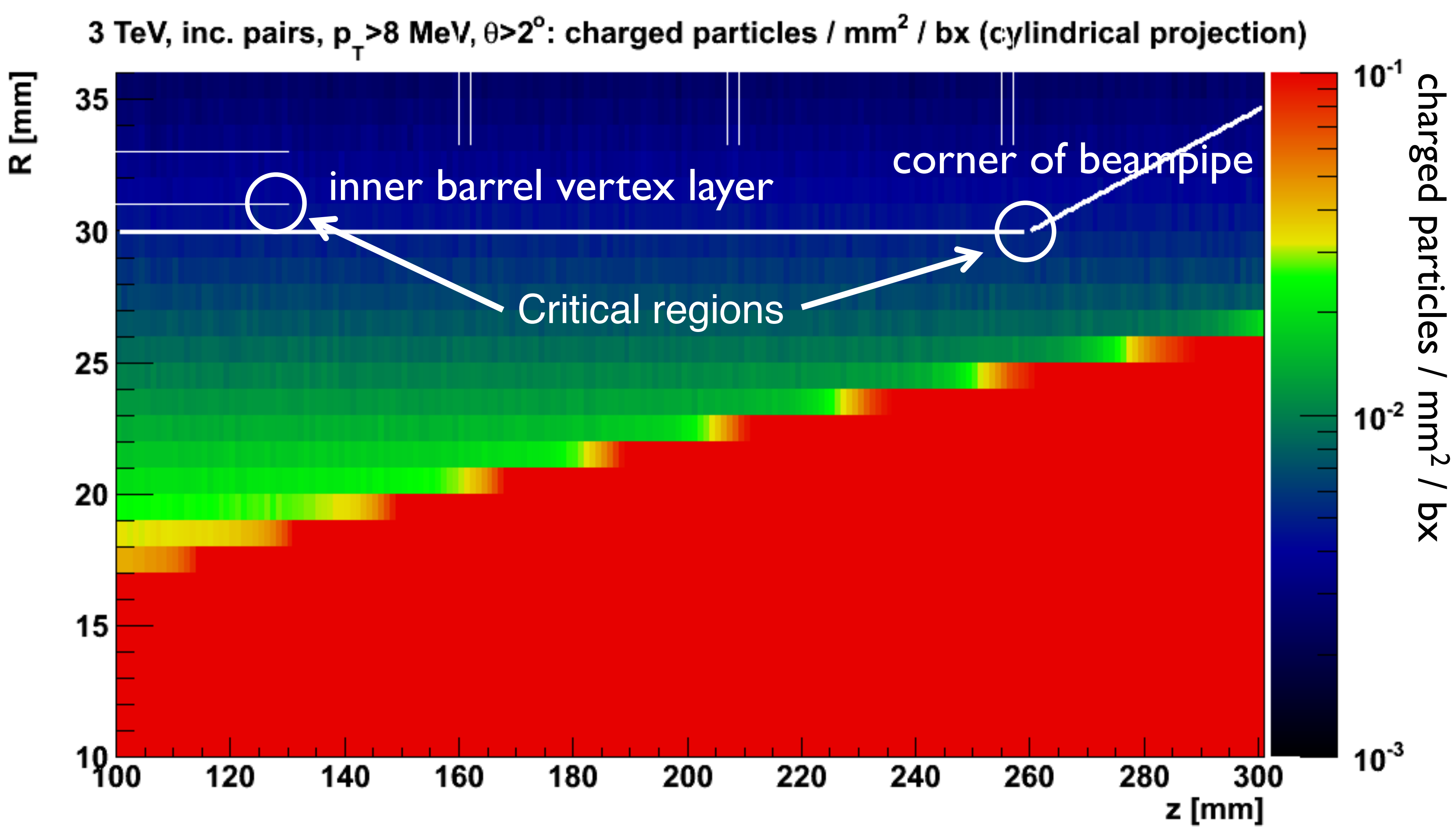
Vertex/inner detector: increased radius, changed beam pipe
Modified forward tracking

both CLIC concepts: same outer dimensions

Main tracker unchanged

The Vertex Detector - Design Considerations

- Performance goal: Excellent secondary vertex resolution to identify heavy flavors, to discriminate between charm and bottom and tag τ decays
  Resolution goal $\sigma_{IP}(p_T) = \sqrt{a^2 + \frac{b^2}{p_T^2}}$,with $a = 5\ \mu\text{m}$ and $b = 15\ \mu\text{mGeV}$
  - Move innermost layer of detector as close as possible to the interaction point
    ➩ limited by background!



Study for CLIC_ILD

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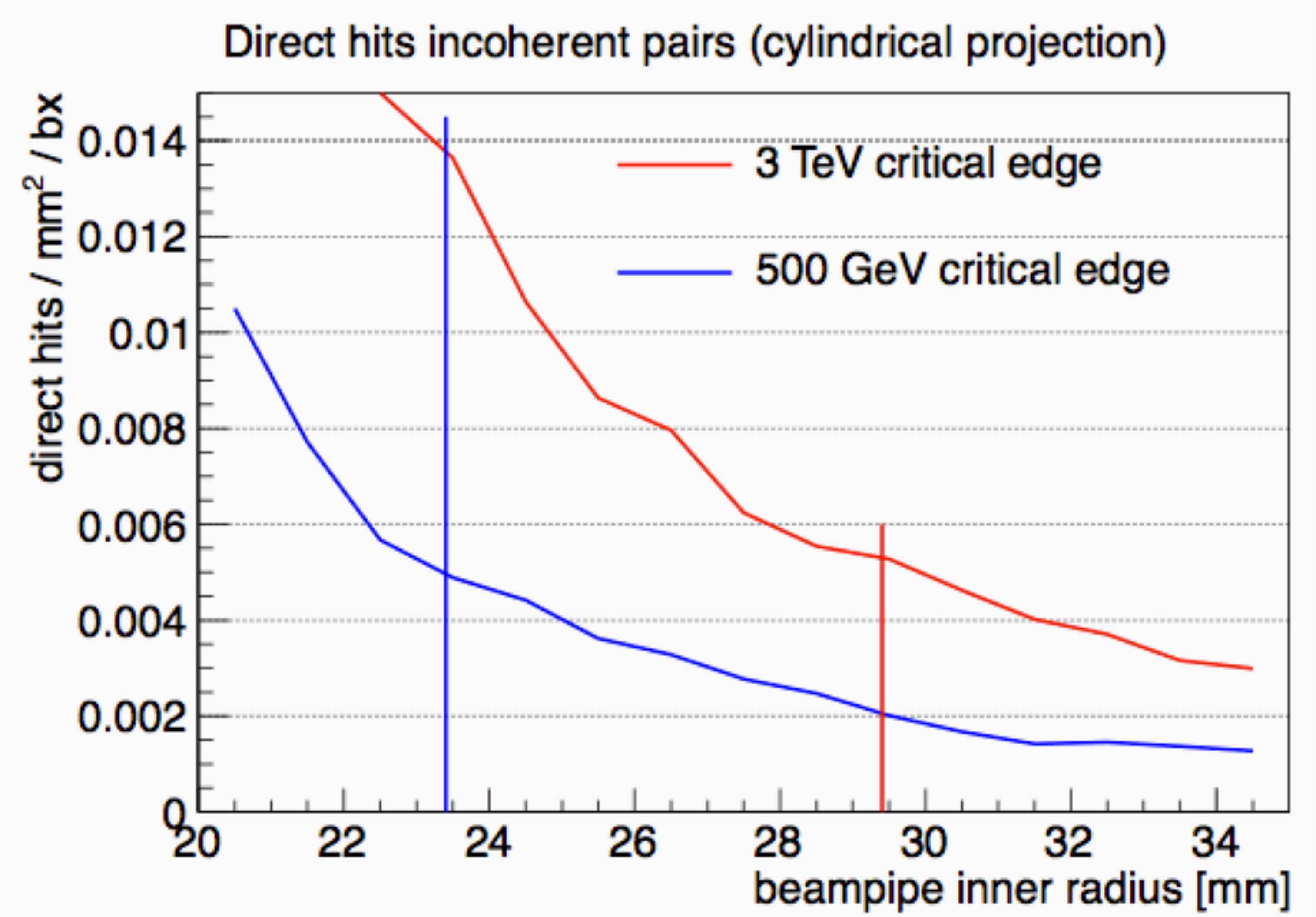
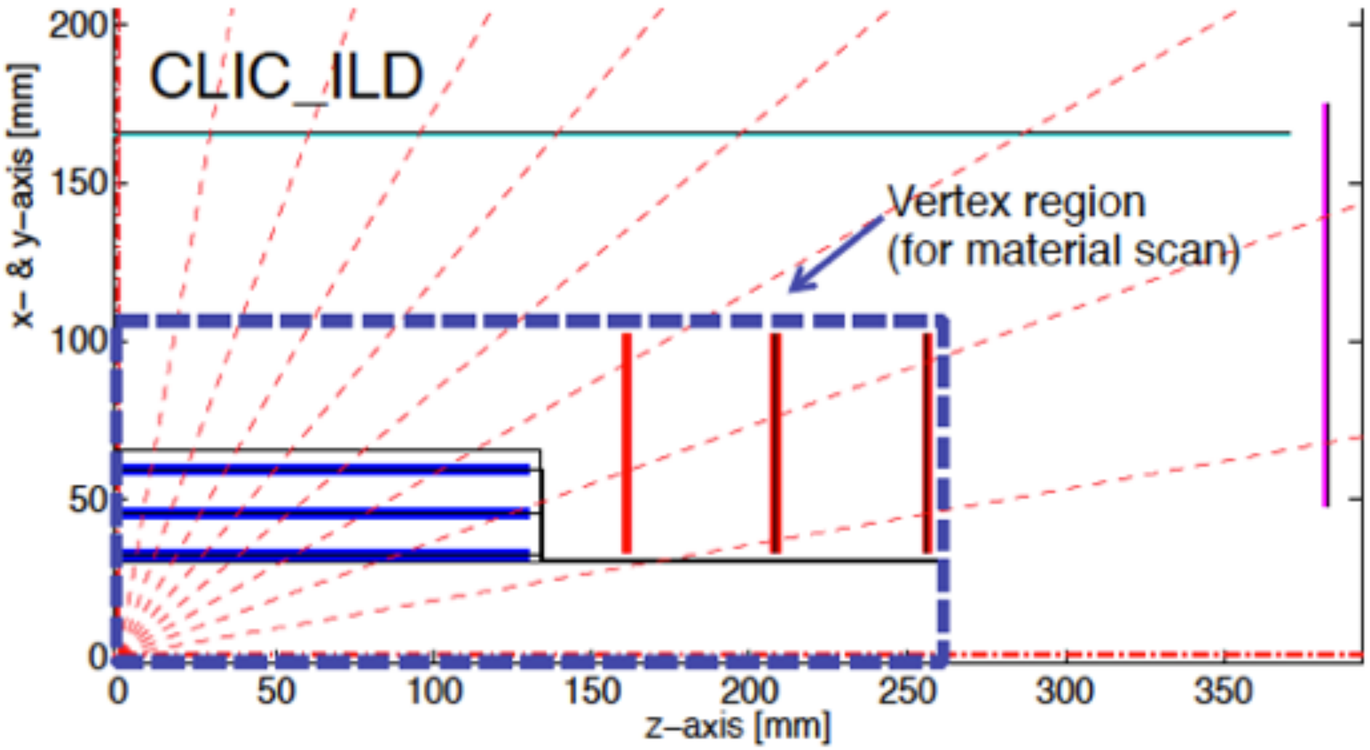


Study for CLIC_ILD

At innermost layer of vertex detector: total of 0.04 hits / mm^2 / ns

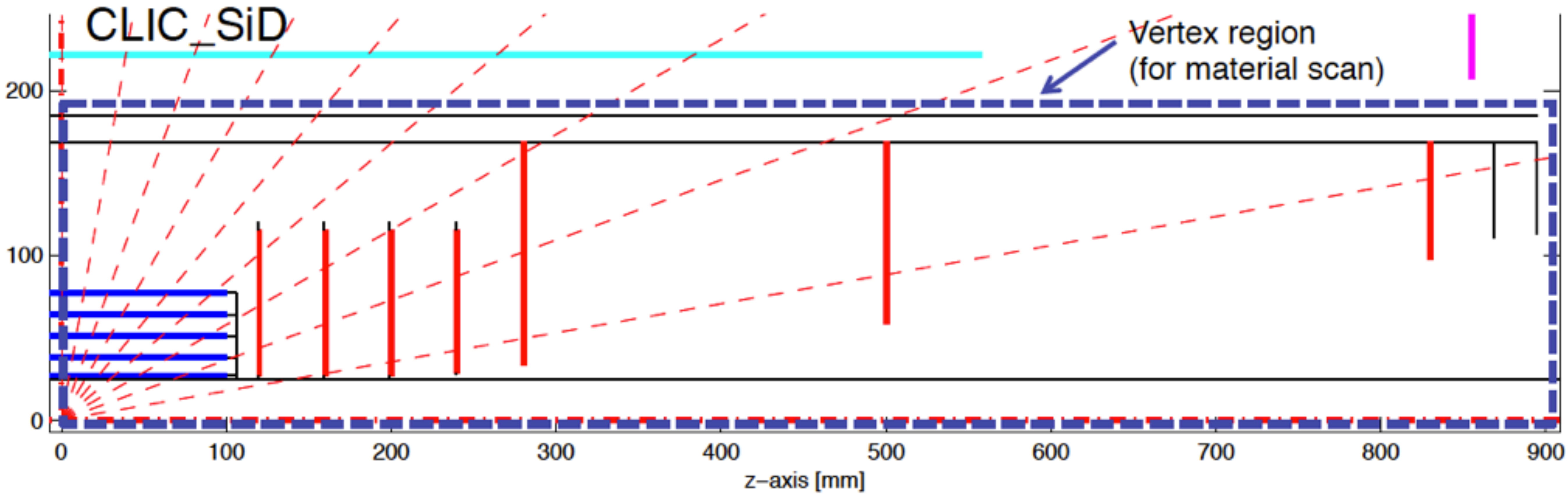
For a low-energy CLIC option at 500 GeV, the inner layer can move in by about 6 mm

Pixel Vertex Detector Design



Resulting designs for CLIC_ILD / CLIC_SID:

- ILD:
  Be beam pipe at 29.4 mm, 0.6 mm thick
- SID:
  Be beam pipe at 25 mm, 0.5 mm thick
- ILD: 3 double layers, 3 forward DL discs
- SID: 5 single layers, 8 forward discs

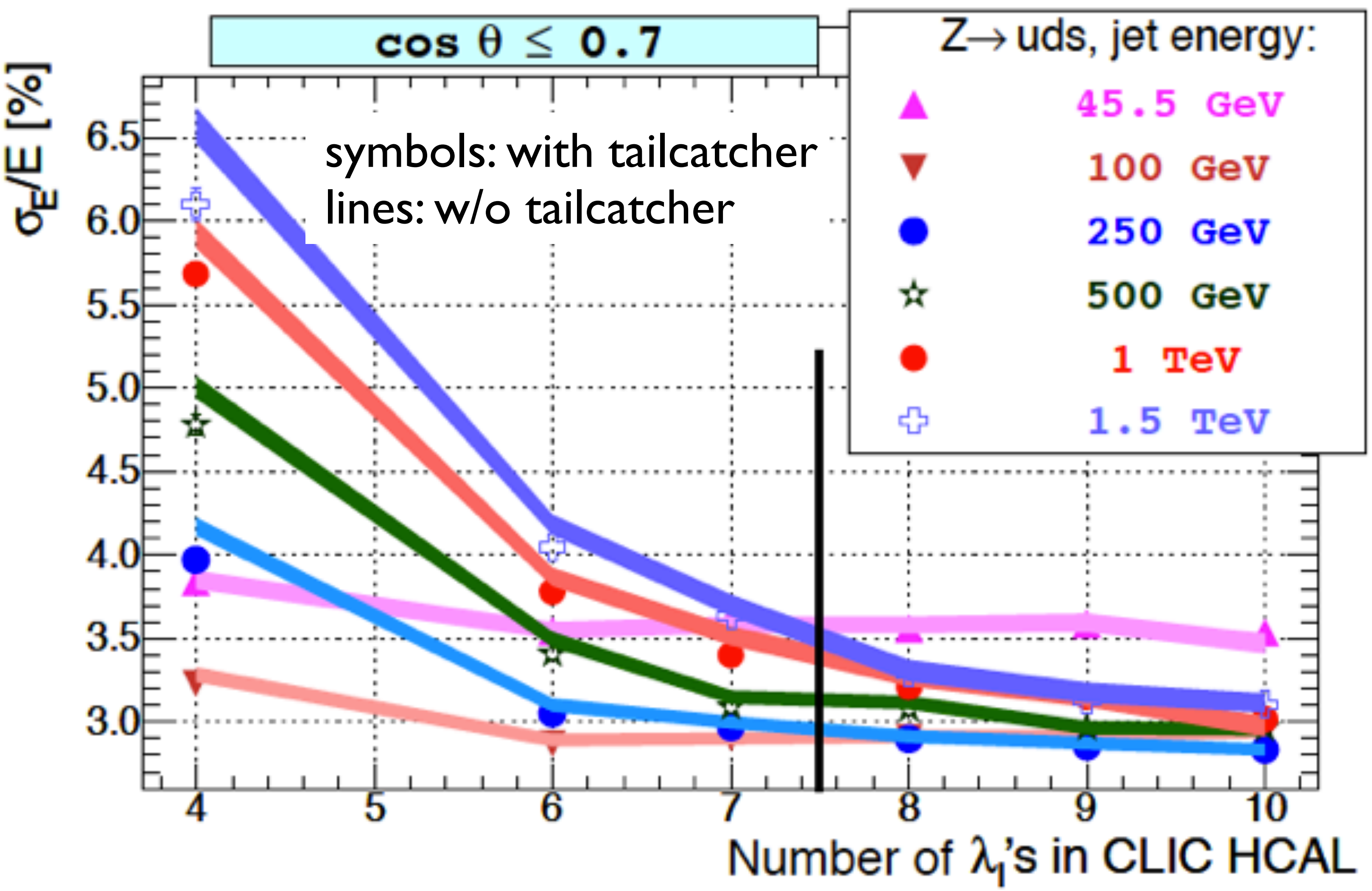


Pixel Vertex Detector - Technology

- Resolution goals require ~ 3 μm single hit resolution:
  20 x 20 μm^2 pixels with analog readout
- Requirements for technology:
  - Low mass: *O* 0.1% X_0 per detector layer (corresponds to just 100 μm Si!)
    CLIC_ILD: 0.18% X_0 per DL 2 x 50 μm Si, 134 μm carbon support)
    CLIC_SID: 0.12% X_0 per SL (50 μm Si, 130 μm carbon support)
    - Only achievable with low power: Powerpulsing at 50 Hz
    - Forced gas-flow cooling wherever possible - Barrel layers
    - Integrated liquid cooling solutions: micro-channel cooling in support structures
  - Time stamping on the few ns level
    - "Classical" solution: thinned hybrid pixels with 3D interconnects, small feature size for readout chips
    - Alternatives: Semi-integrated CMOS active pixel sensors, SOI, ...
  - Rad-hardness not a critical issue:
    NIEL ~10^{10} n_{eq} / cm^2 / year, TID ~ 100 Gy / year

The Calorimeters

- Based on the Particle Flow concept: Highly granular to provide shower separation within hadronic jets
  - CLIC-specific: Increased depth to contain higher energies



Simulation study of PFA performance in CLIC_ILD

Performance goal of 3.5% jet energy resolution over full energy range requires 7.5 λ_I thick HCAL

For reference:

ILD: 5.5 λ_I

SID: 4.8 λ_I

The Hadron Calorimeter: Dense Absorbers

- No dead material between tracker and calorimeters for optimal PFA performance: Calorimeter has to be inside solenoid - Compactness required!
- Promising absorber material: Tungsten

Material	Fe	W
λ_I [cm]	16.77	9.95
X_0 [cm]	1.76	0.35
dE/dx [MeV/cm]	11.4	22.1
R_M [cm]	1.72	0.93

Significantly reduced interaction length

Reduced sampling for electromagnetic subshowers due to short interaction length

Heavy nucleus: Richer time structure of shower?

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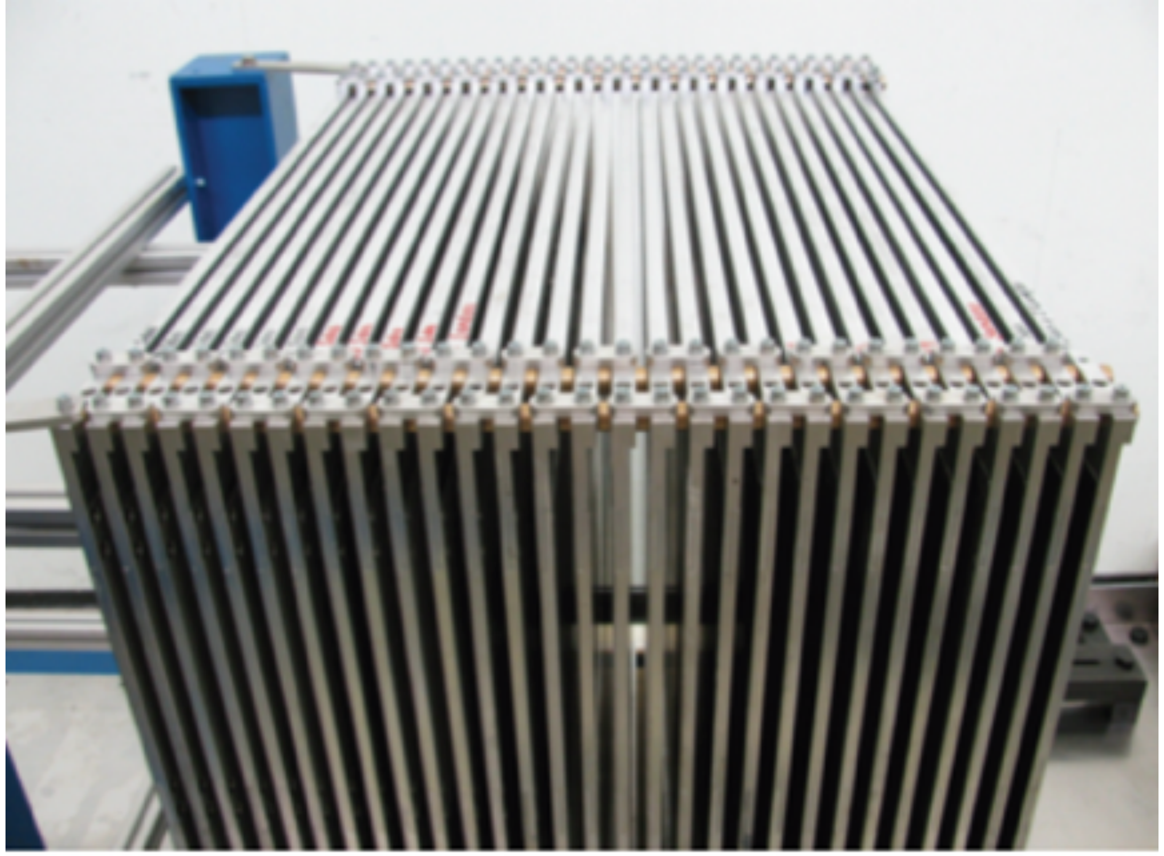
Test beam required:

CALICE analog HCAL active layers

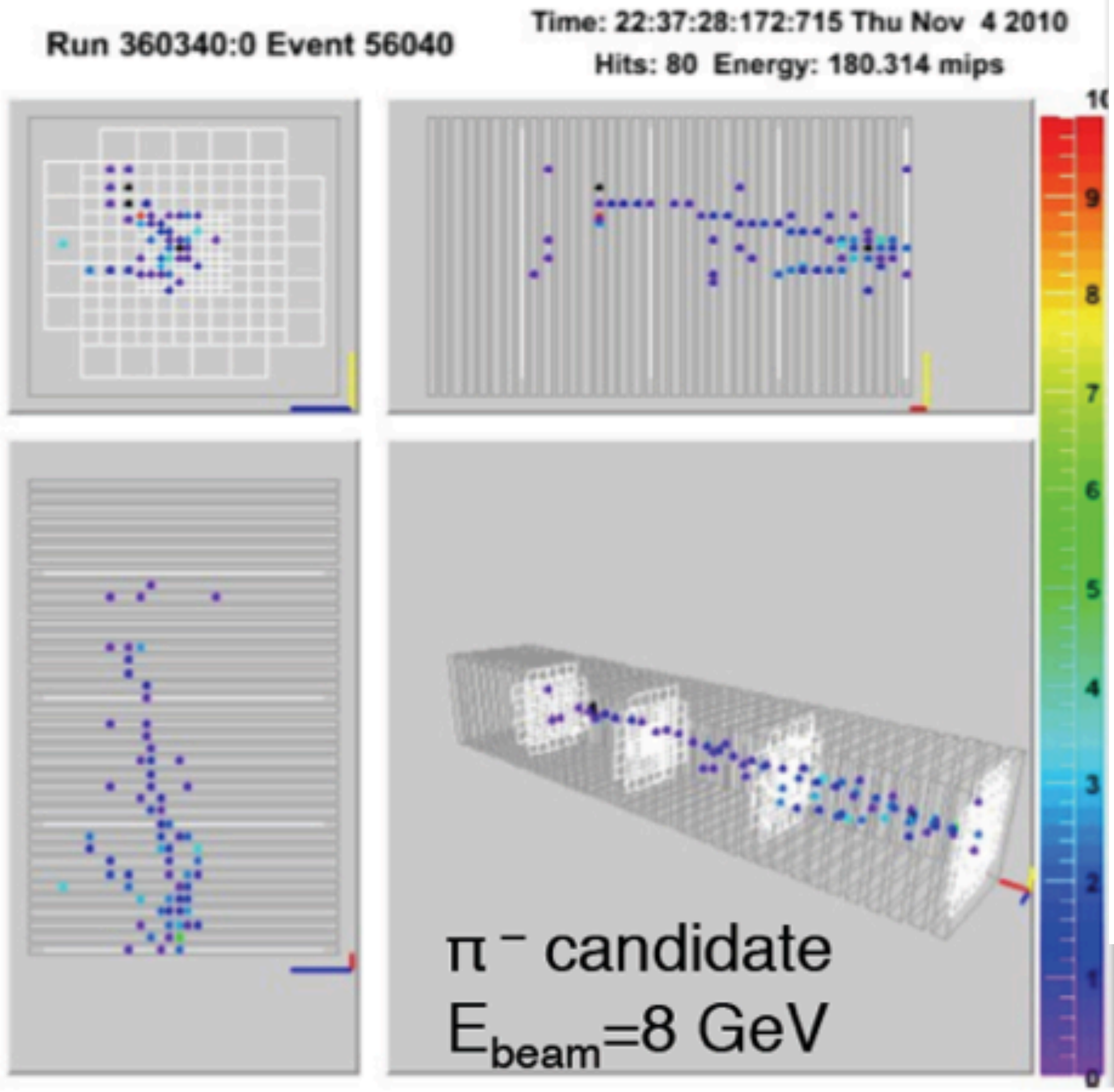
Tungsten absorber plates

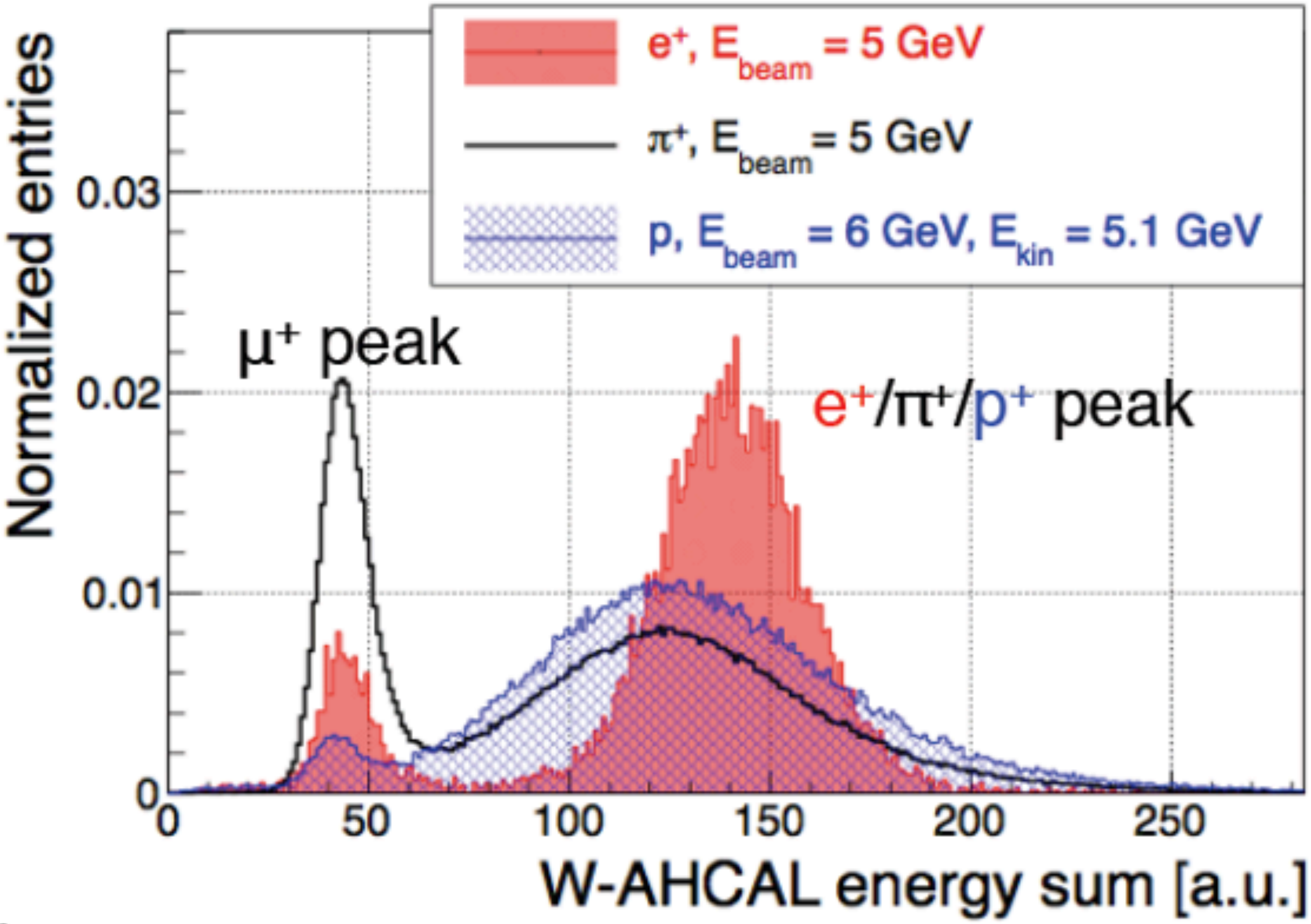
- Validation of Geant4 simulations used to evaluate full detector performance
- Study of energy resolution, shower shapes, time structure



- First beam campaign at CERN PS in 2010

  Muon, hadron, electron beams up to 10 GeV





More data coming:

Tests at SPS starting next week!

Tungsten HCAL - First Beam Tests

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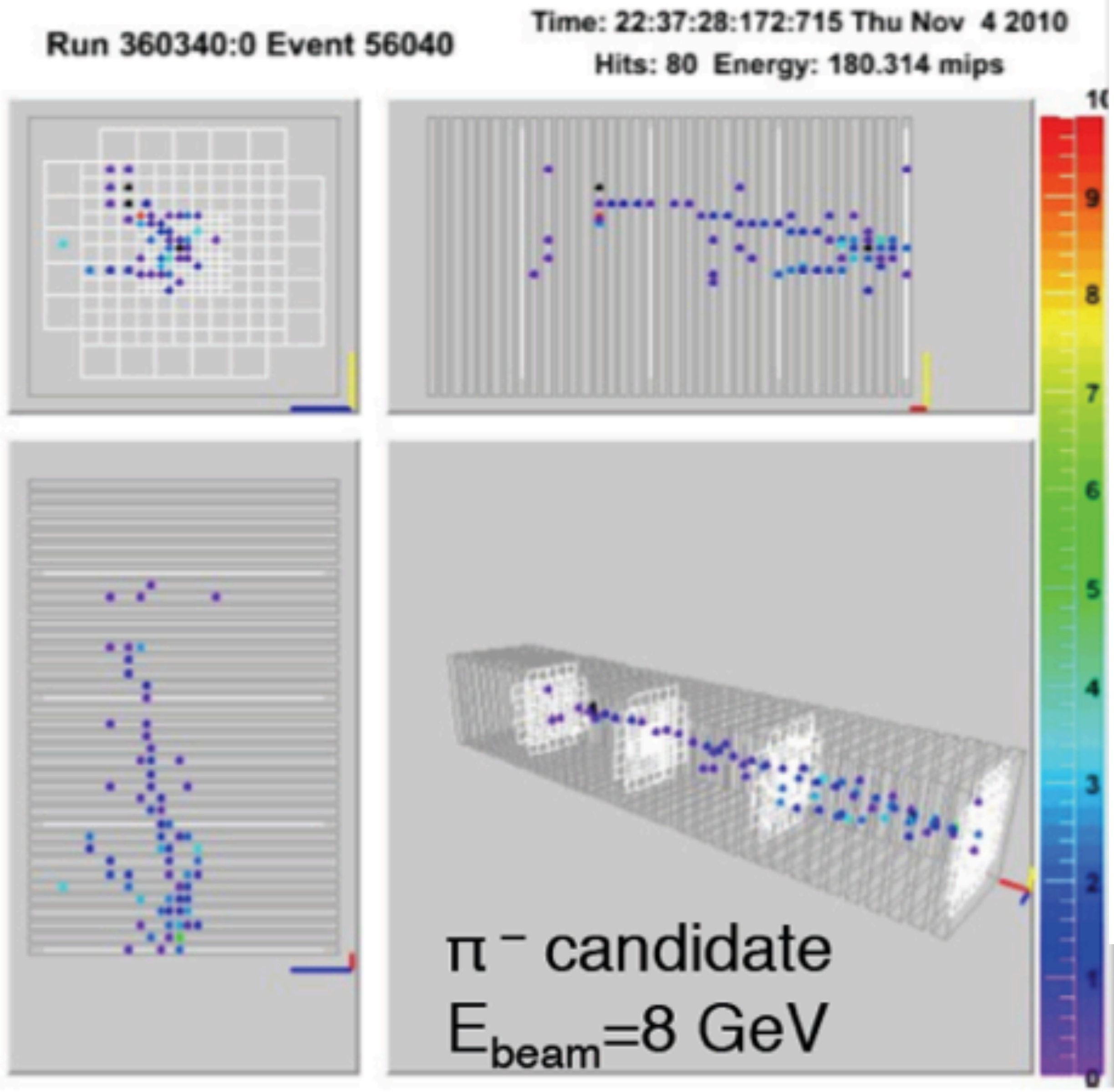

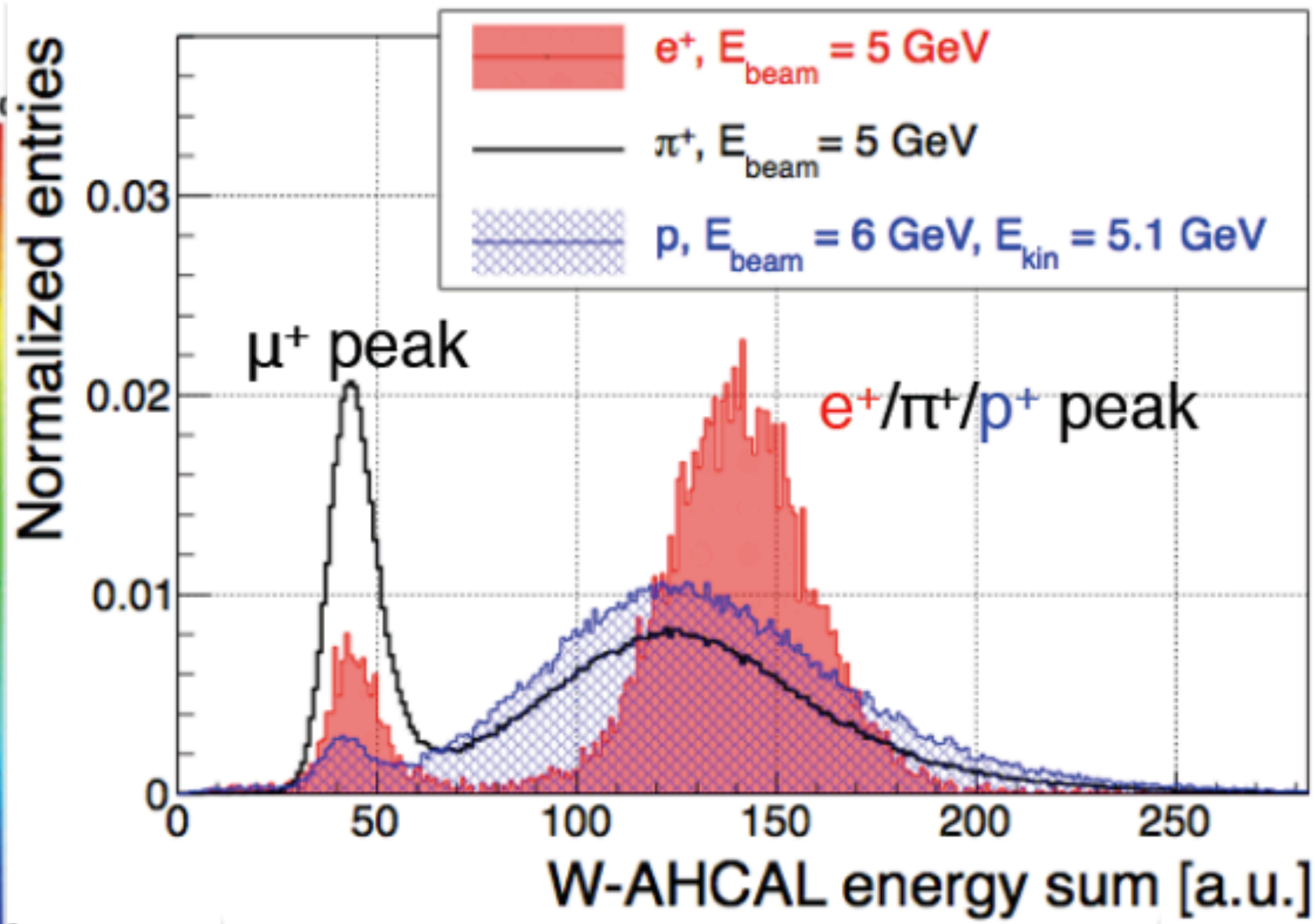

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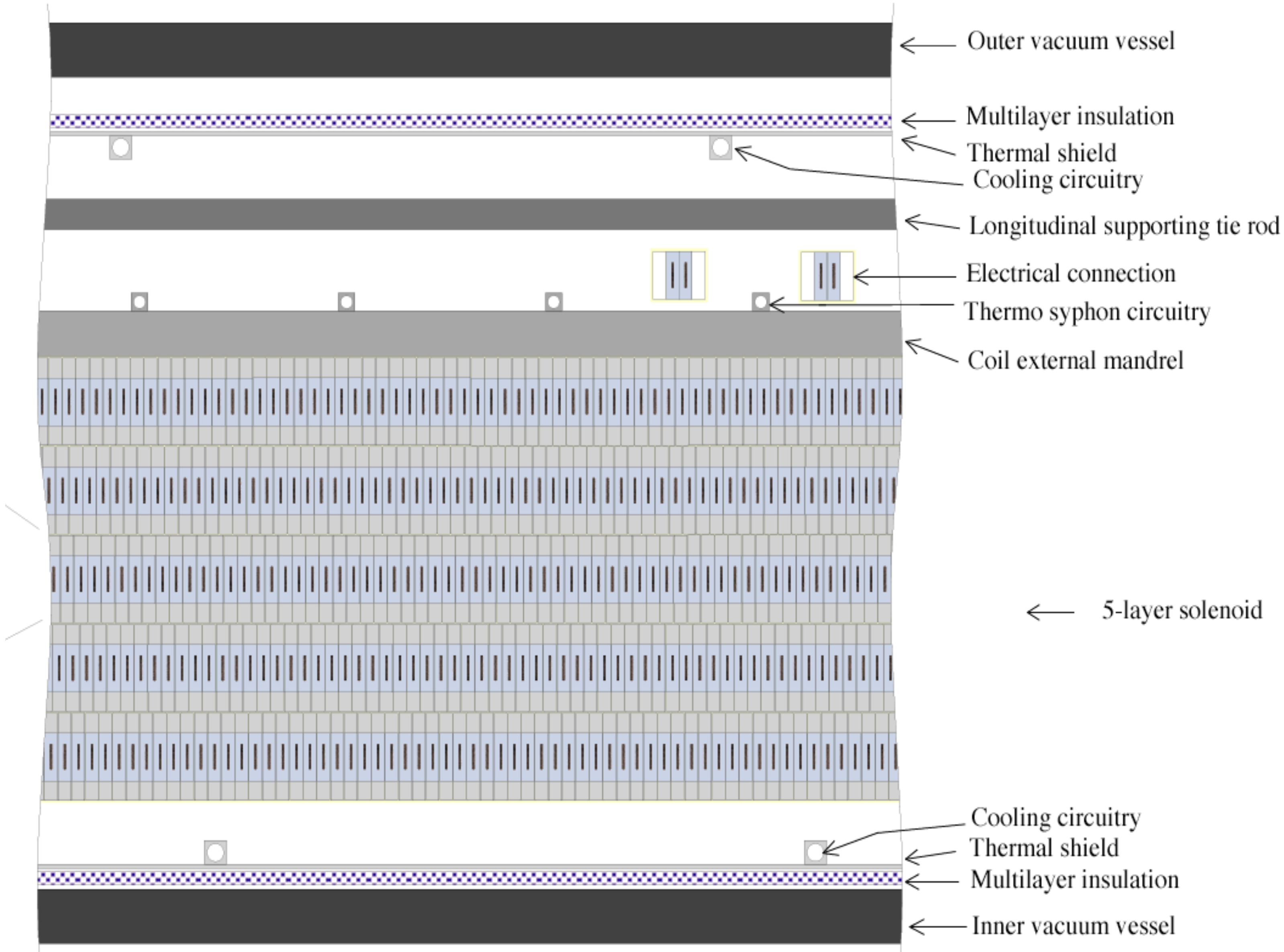
Measurements of time structure of hadronic showers in Tungsten HCAL: Calo Session, Ontario, 15:00 today

Magnet Systems

- Large solenoids for CLIC detectors push the technological limits
  - CLIC_SID most challenging: 5 T field - Extreme pressure on SC cable
    Free bore 5.5 m, Length 6.2 m, Stored energy ~ 2.3 GJ, Energy/Mass ~14 kJ/kg
    (CMS: 6 m, 12.5 m, 2.6 GJ, 11.6 kJ/kg)



Inspired by CMS design:
3 modules, 5 layers

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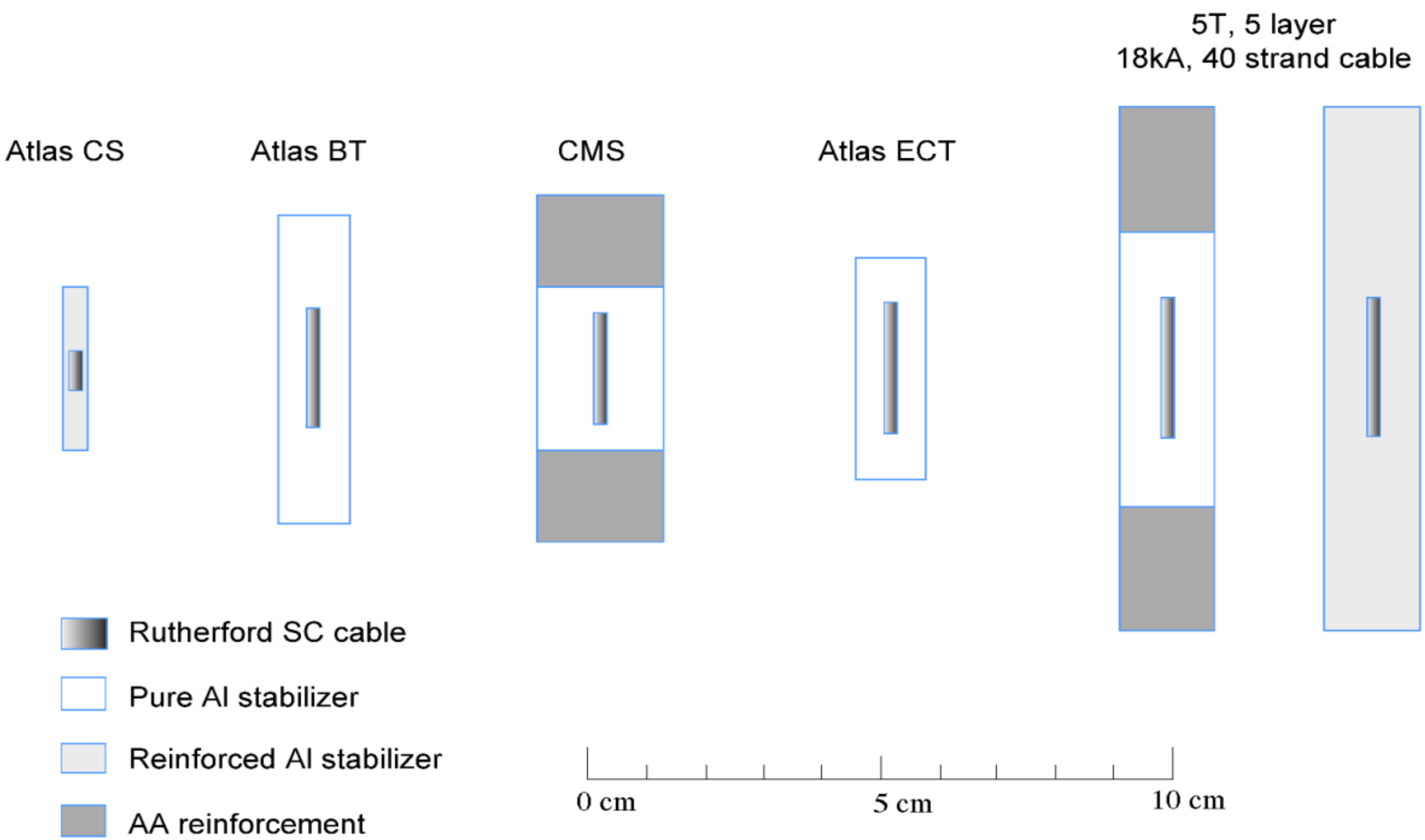
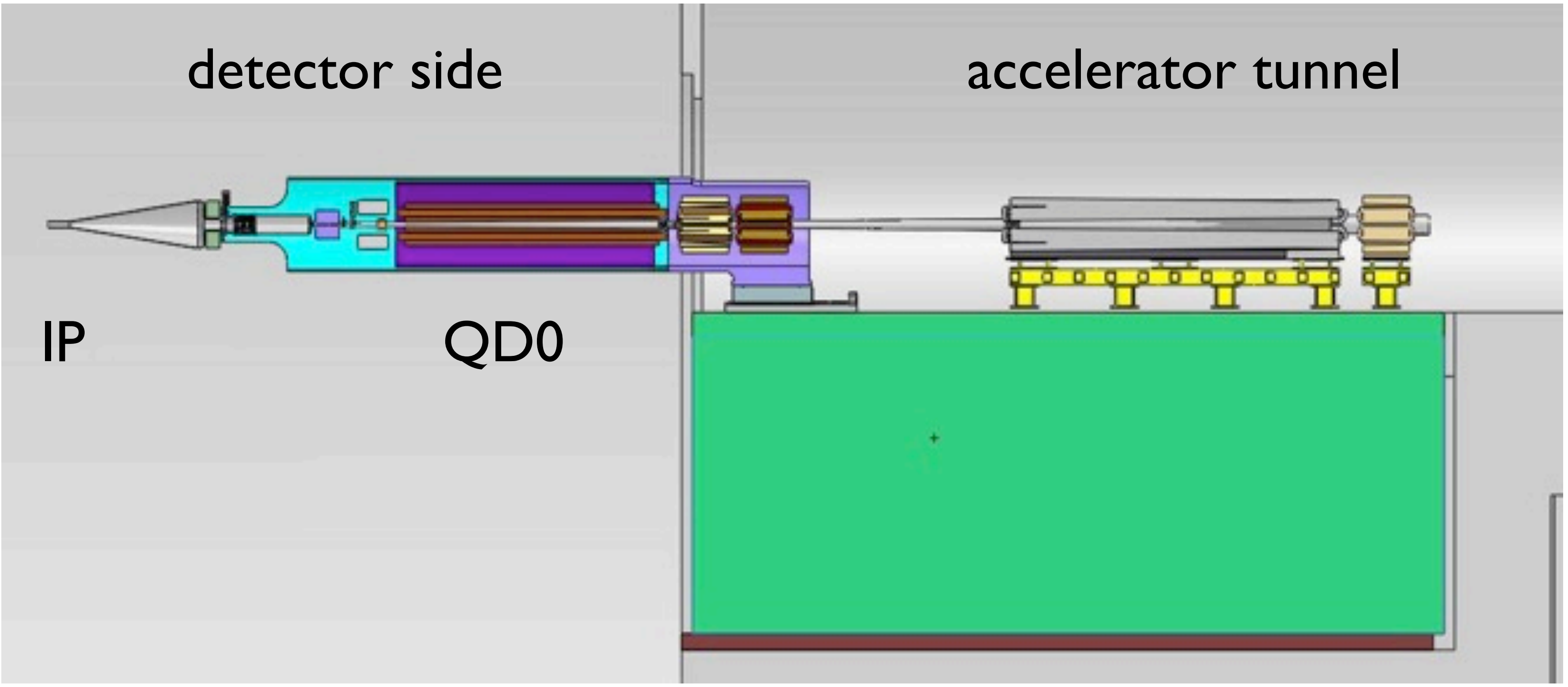


CMS design:
, 5 layers

Conductor options under investigation - Cooperation between CERN, KEK and Swiss industry

Mechanical Stability

- Final focusing magnets need extreme stabilization:
  Vertical position of final quadrupole better than 0.15 nm RMS for $f > 4$ Hz
  Required because of small beam size: vertical 1 nm, horizontal 40 nm, longitudinal 45 μm
  - Permanent magnets + warm magnet for QD0 to reduce vibrations
  - Supported from active stabilization, decoupled from detector
  - Passive high-mass low stiffness spring system to suppress high frequencies from ground



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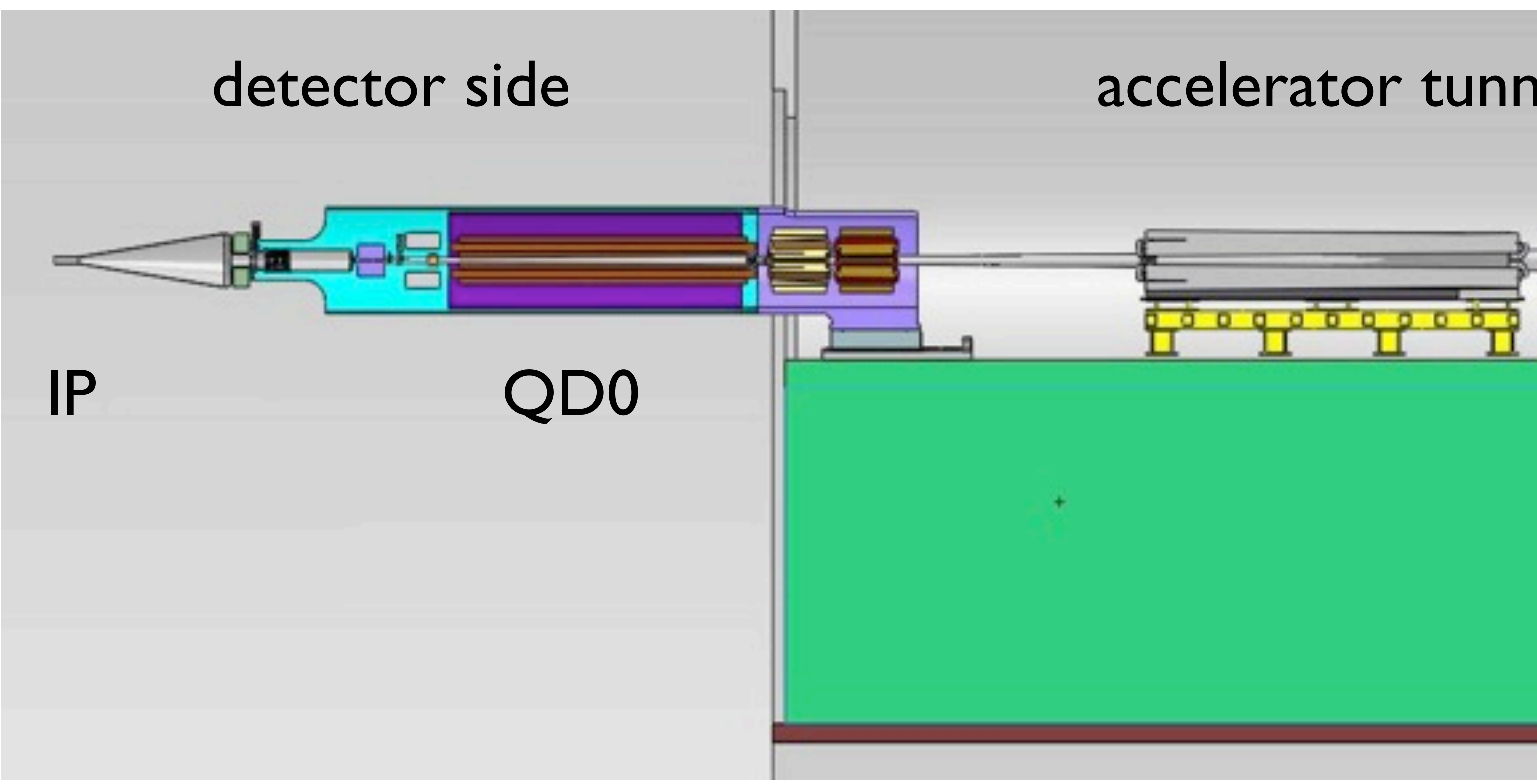
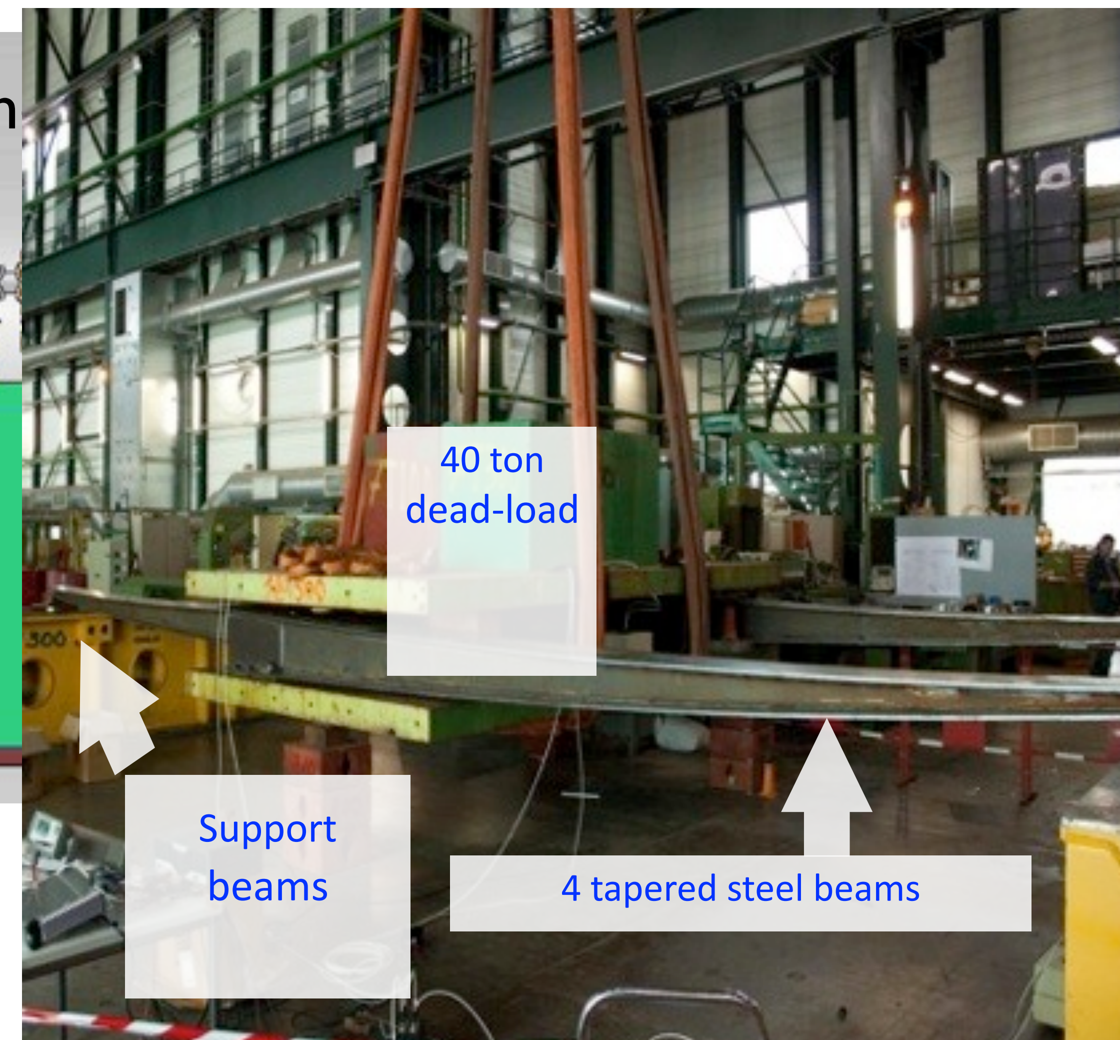
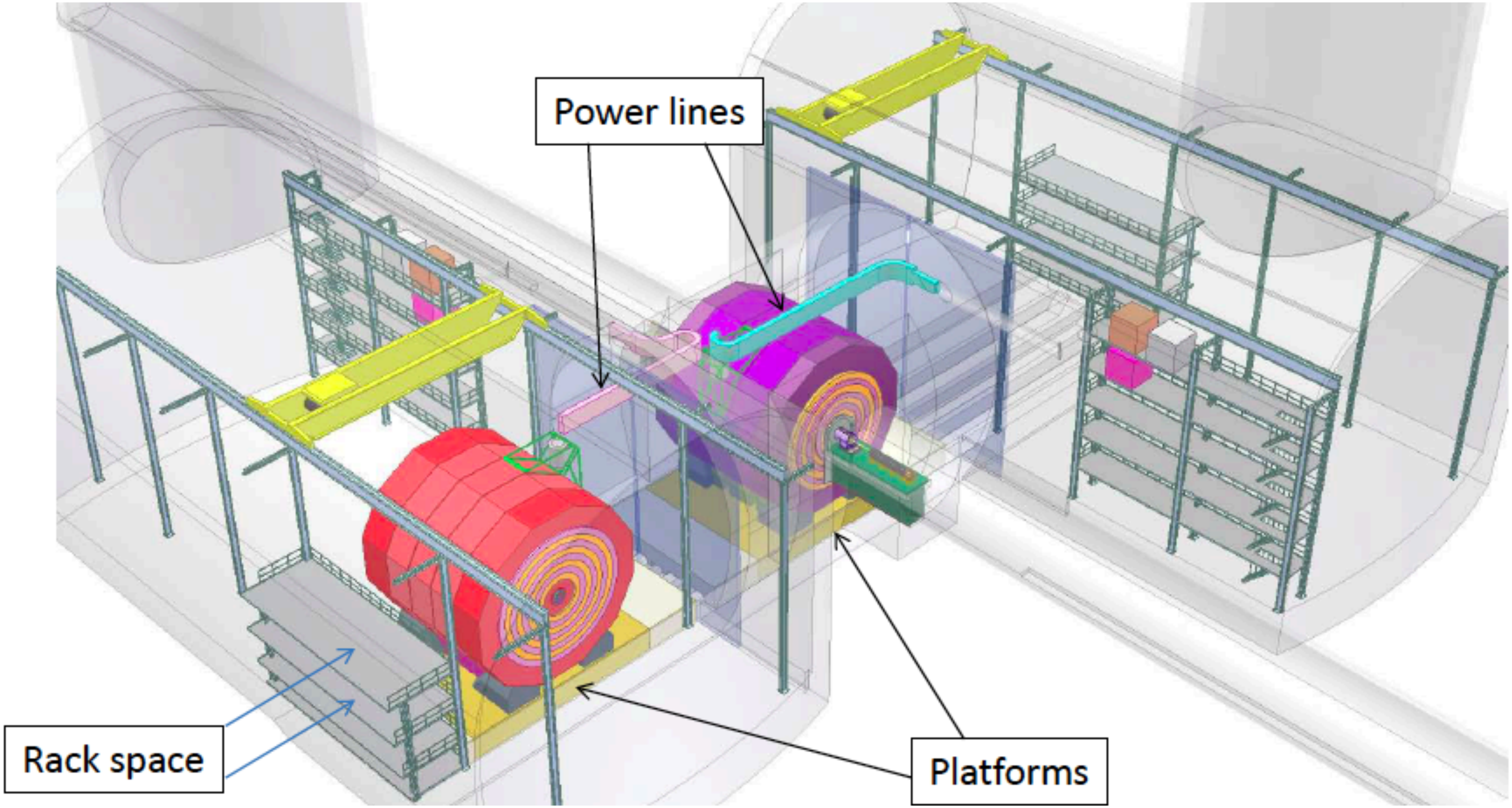




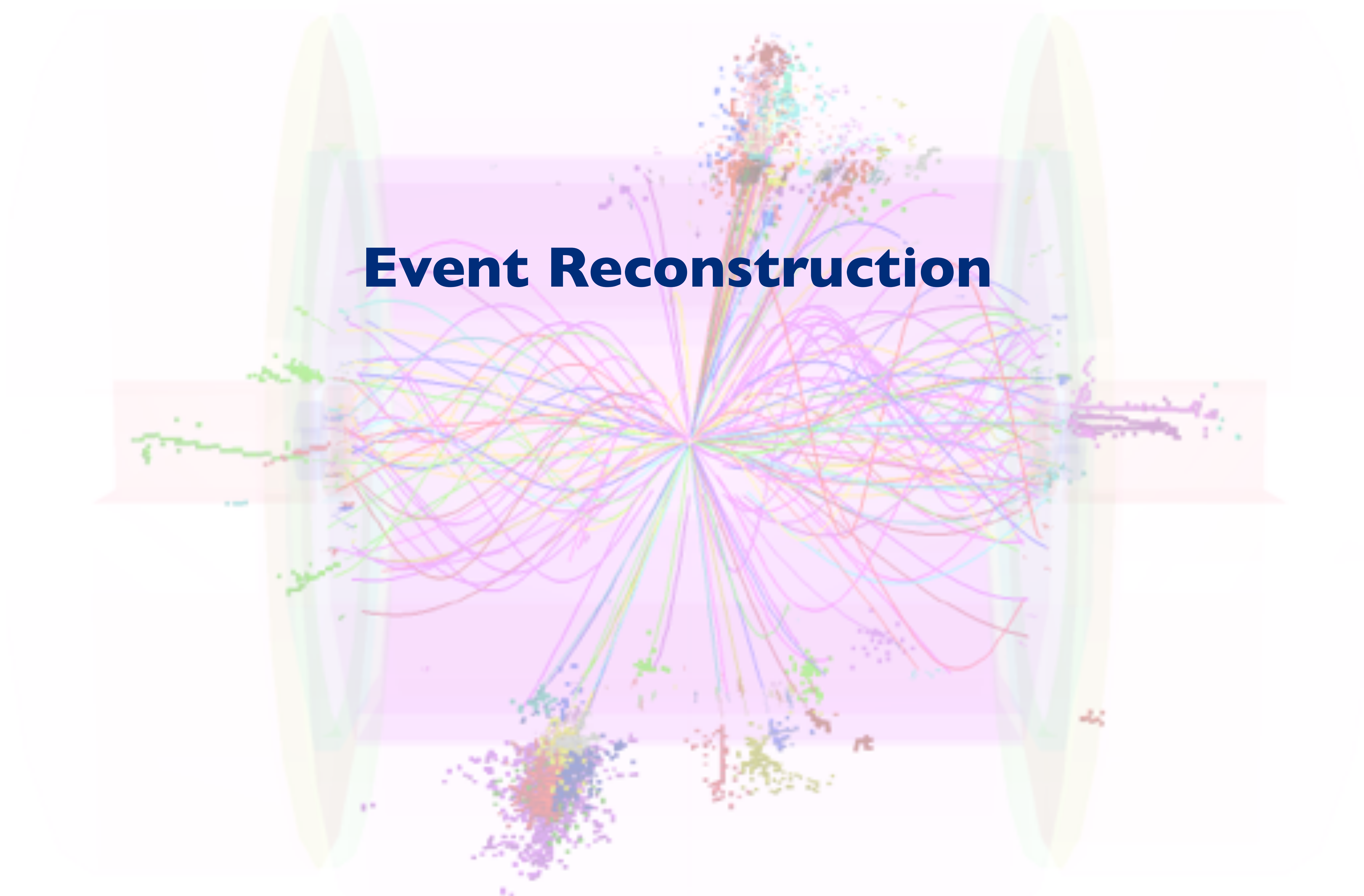
Damping system under development,
simulations validated with mechanical experiment

Two Detectors: Push-Pull

- Two detectors share one IR: Push-pull scheme also adopted by ILC
- CLIC Detector designs: Both detectors have equal outer dimensions: facilitates push-pull operations



Event Reconstruction



CLIC Event Reconstruction

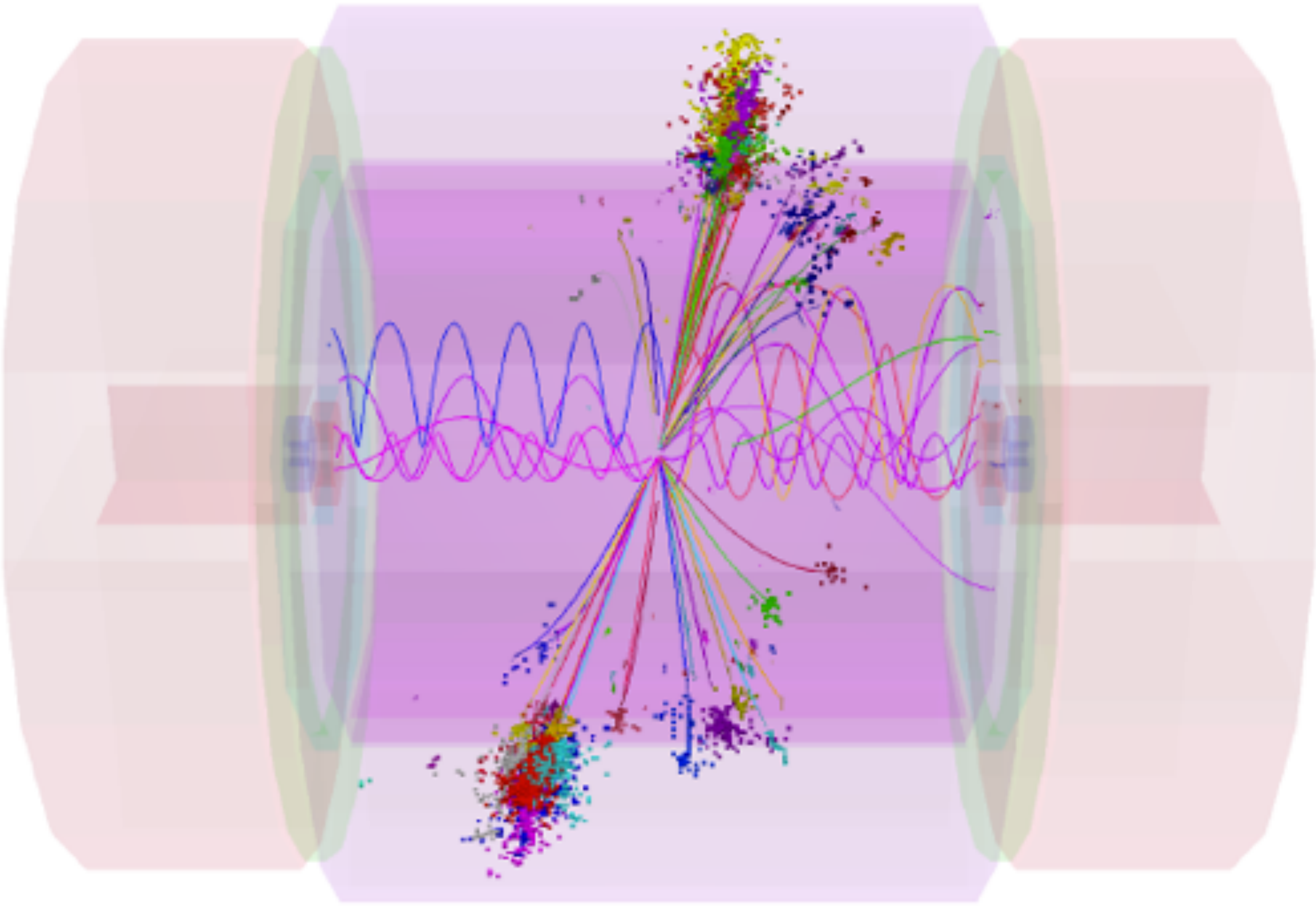
- Event reconstruction technique: Particle Flow
  - Key challenge: Backgrounds from two-photon processes
    - e^+e^- pairs in the vertex detectors
    - hadrons in the main tracker and in the calorimeters

- The way to reject backgrounds: Timing
  - Match the time of all reconstructed physics objects with the time of the event
  - Assume ~ 10 ns timing in vertex detectors and Si trackers
  - Key detectors: Calorimeters with ~1 ns cluster timing
    - Long integration time in the HCAL to account for shower time structure
  - More stringent cut on low p_t particles (more likely to be background)

Background Removal

- Beam related background from $\gamma\gamma \rightarrow$ hadrons processes adds significant energy to events, in particular in the forward region - simulation chain fully validated

1 TeV $Z \rightarrow uds$



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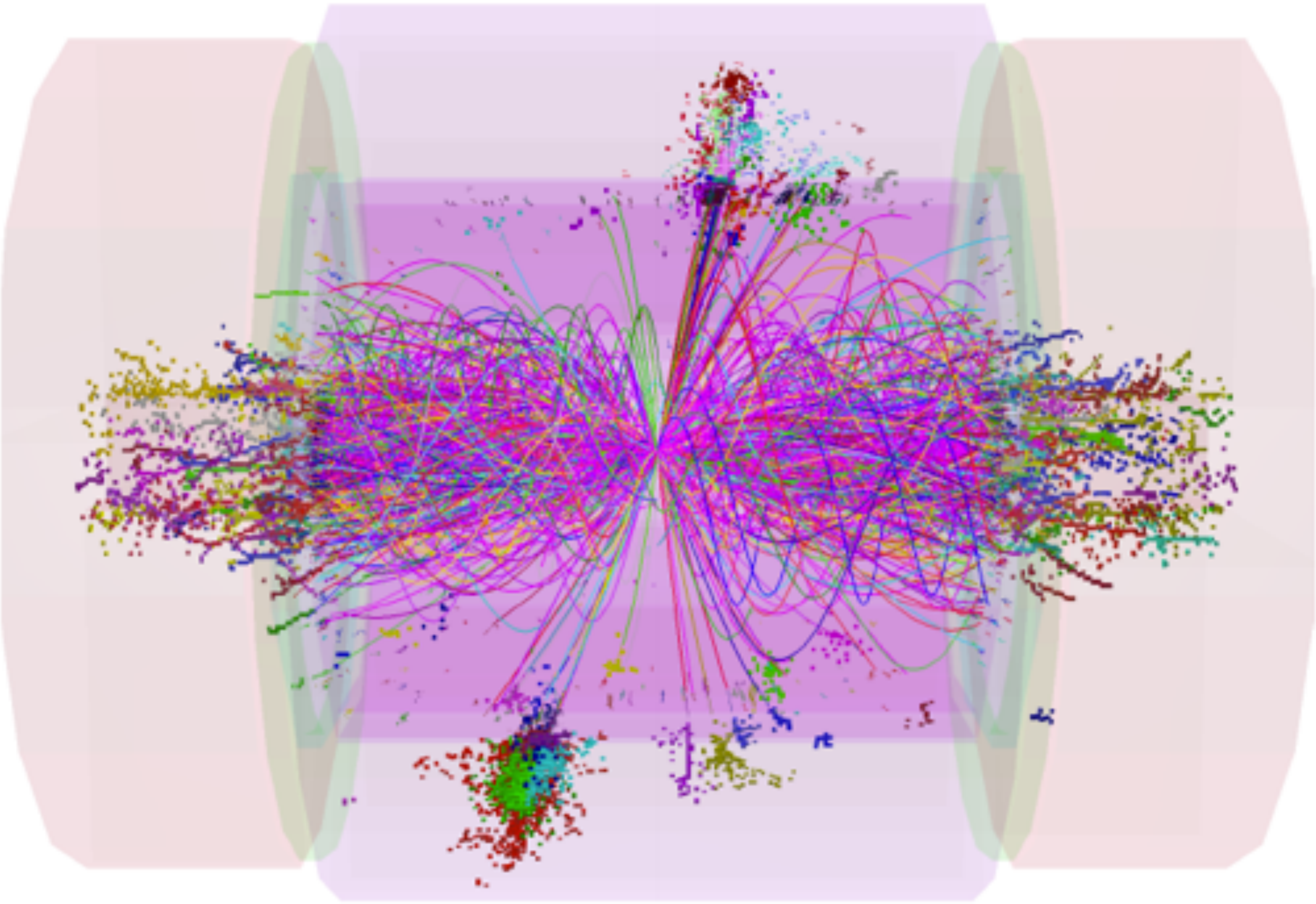

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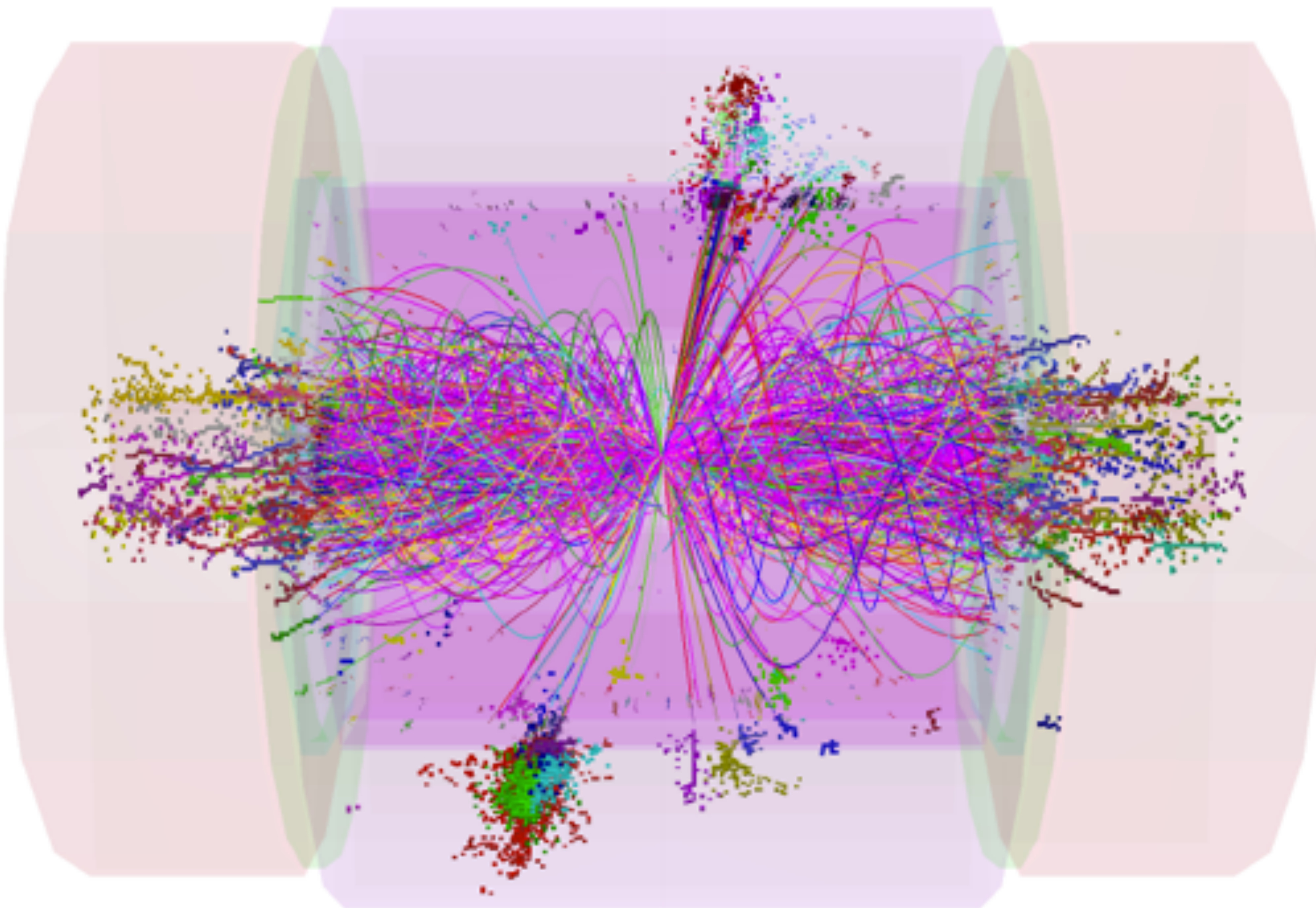

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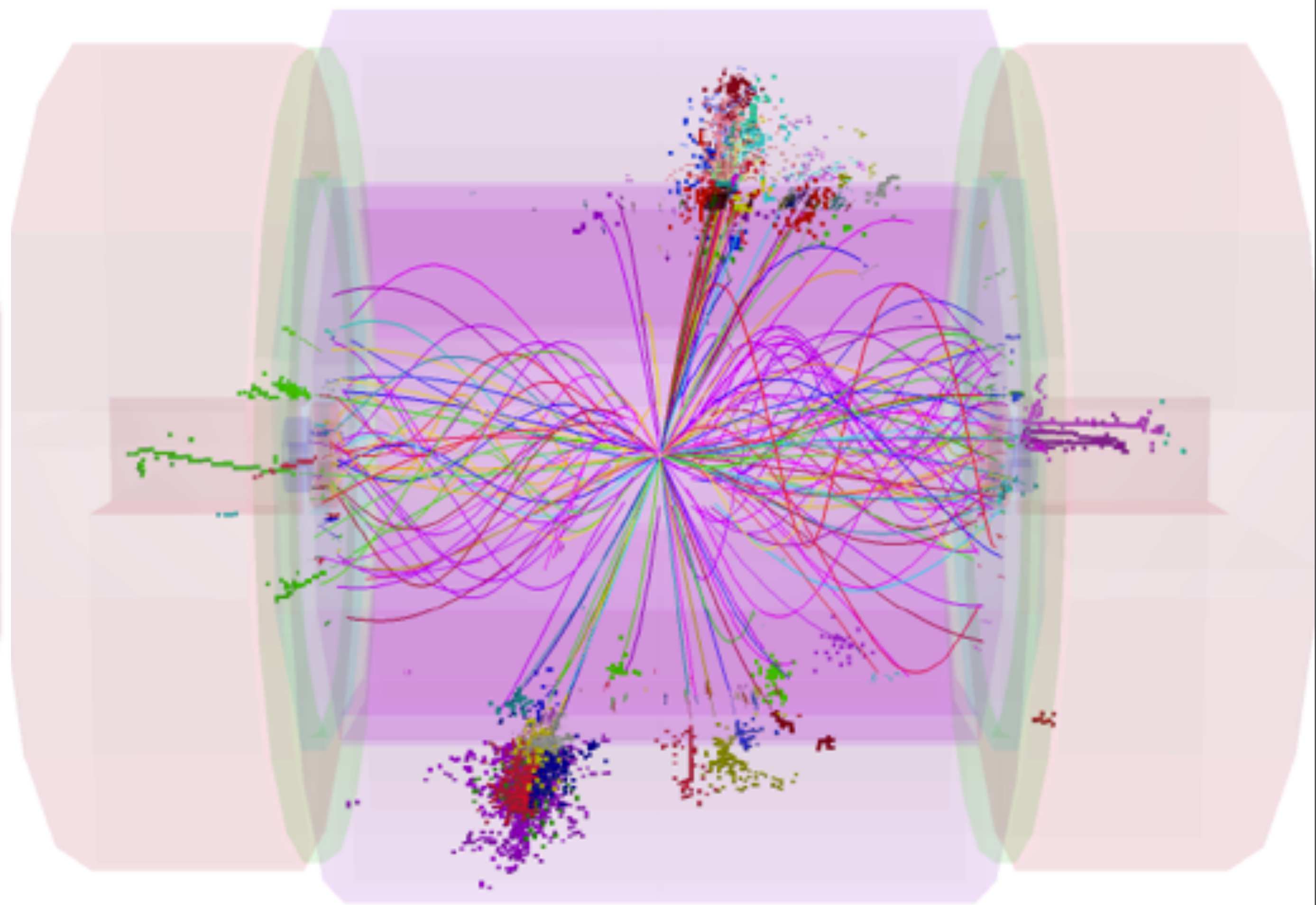


realistic timing assumptions: 200 GeV

- Timing cuts reduce the impact of background significantly

Impact of Timing Cuts

- Tight timing cuts in particular on low momentum particles affect jet energy resolution for low-energy jets
  - For jets in the region of interest for a 3 TeV machine, the impact is small

jet energy resolution (RMS_{90}) in %

E_j	45GeV	100GeV	250GeV	500GeV
CLIC_ILD_CDR, v01-11, new config	3.74 ± 0.05	3.02 ± 0.04	3.00 ± 0.04	3.20 ± 0.06
CLICTrackSelector, 50ns cut	3.90 ± 0.05	3.13 ± 0.04	3.03 ± 0.04	3.21 ± 0.06
CLICPfoSelection, loose	4.40 ± 0.06	3.34 ± 0.04	3.12 ± 0.04	3.27 ± 0.06
CLICPfoSelection, default	5.18 ± 0.07	3.65 ± 0.05	3.20 ± 0.04	3.30 ± 0.06
CLICPfoSelection, tight	6.00 ± 0.08	3.99 ± 0.05	3.35 ± 0.04	3.37 ± 0.06

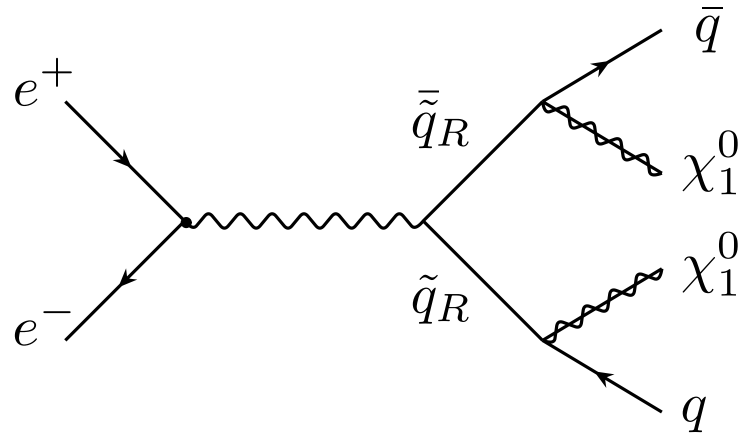
- For lower energy operation (500 GeV), relaxed cuts will be used to recover performance also for lower energy jets

Background Reduction in Physics Analysis

- Use of specific jet algorithms, momentum and geometry cuts, ...
  are studied to obtain best possible precision - Depends on physics channel

Example: Squark pair production

Signature: 2 jets + missing energy
- susceptible to hadronic background!



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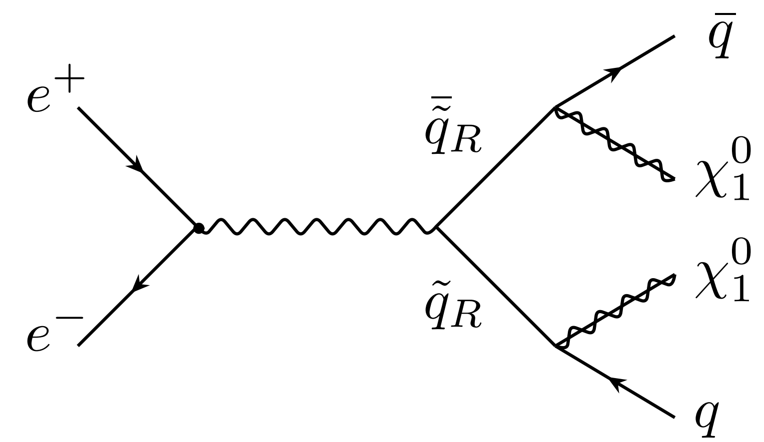
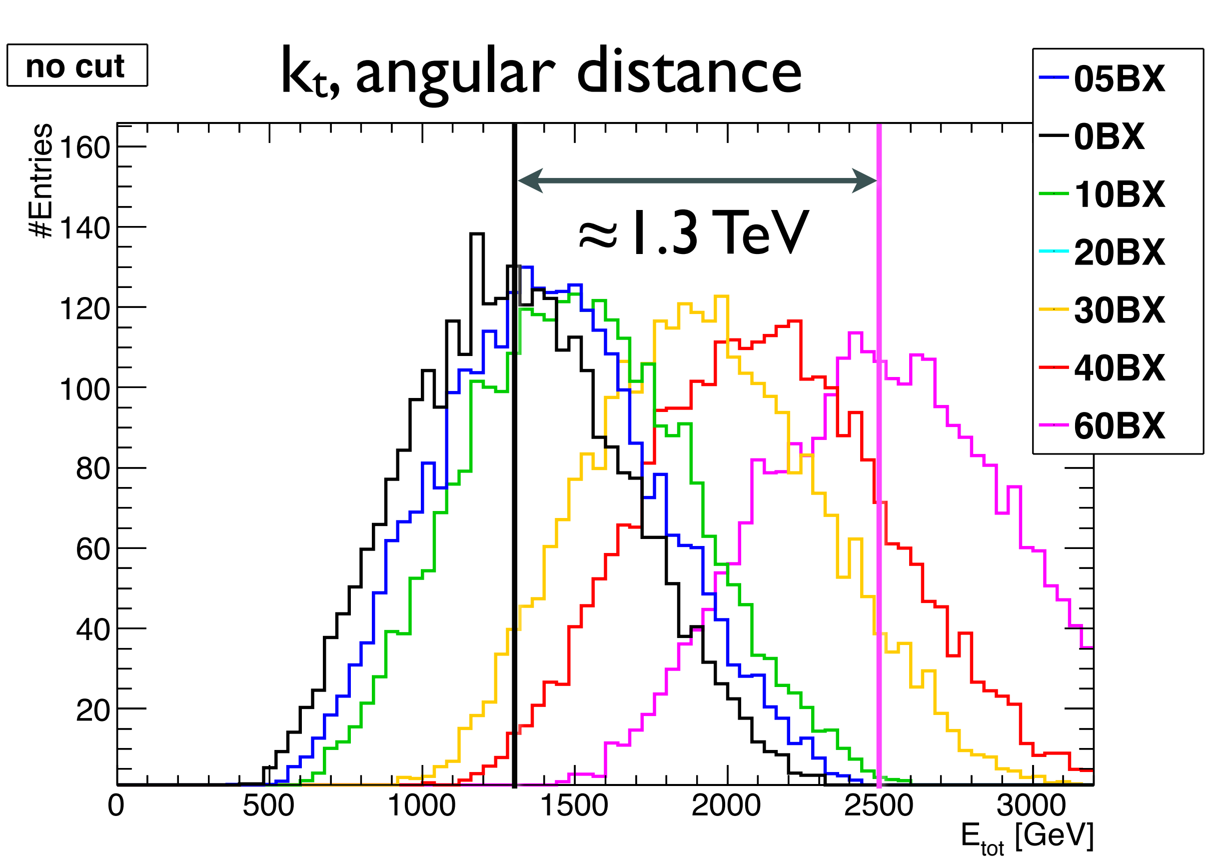
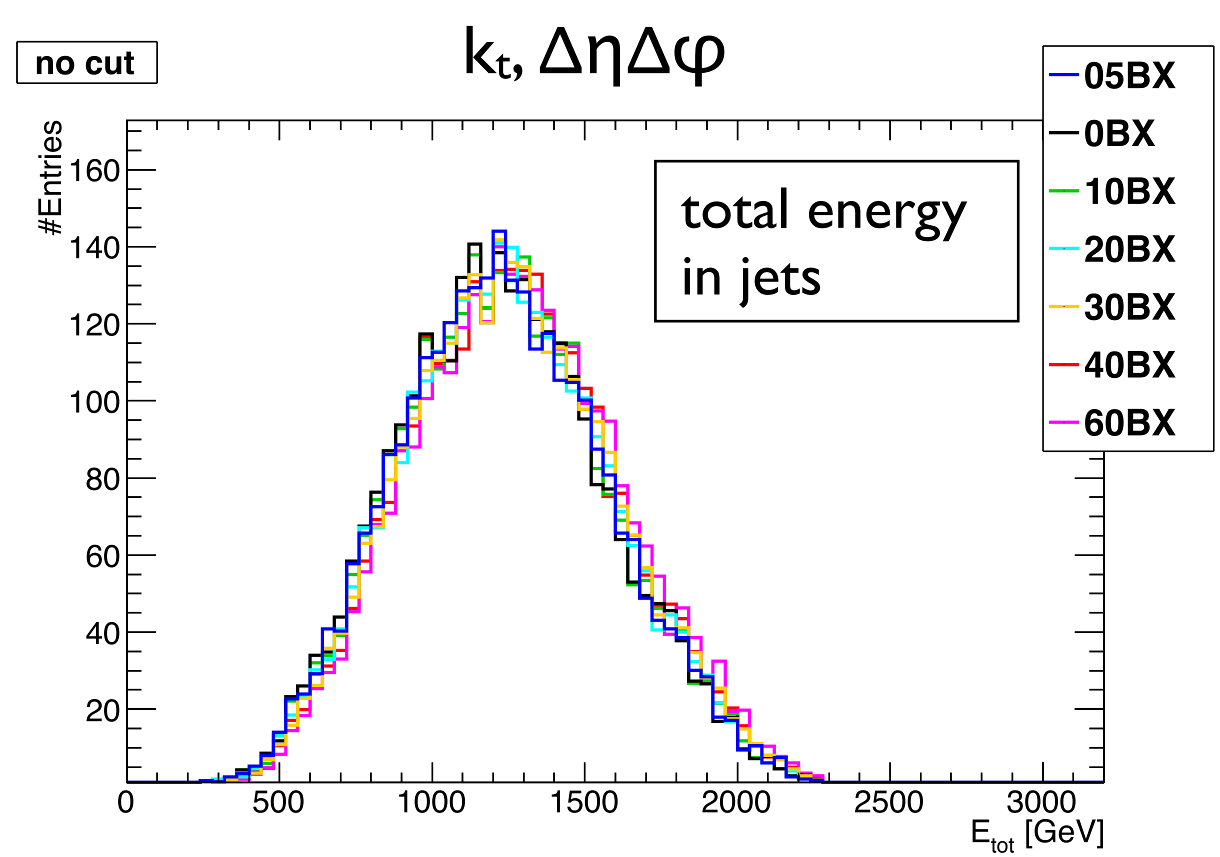
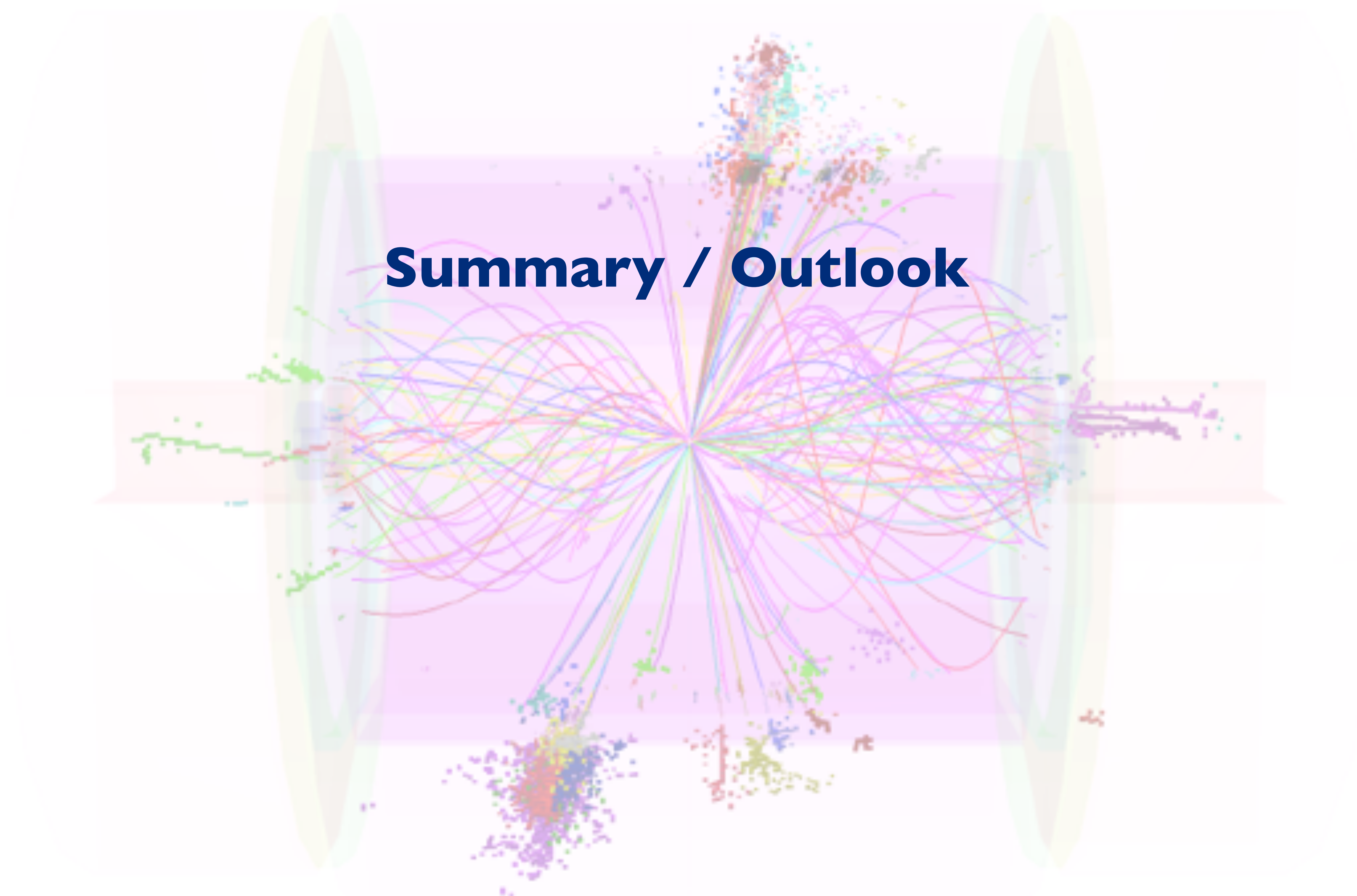


Jet finding can reduce background effects considerably: Choose the right finder / metric!





Summary / Outlook



Summary: Detector Concepts and Challenges at CLIC

- Experimental conditions at CLIC put stringent demands on the detector systems:
  - Highly precise jet energy reconstruction up to TeV energies, precision tracking and powerful flavor tagging to meet the physics goals
  - Time stamping in all detector systems to handle high background levels

- The starting point: ILC detector designs - Optimized for Particle Flow: Meet already most of the performance requirements (with the exception of high energy jets) - Specific modifications:
  - Increased depth of calorimeters - More compact absorbers
  - Changed vertex detector geometry
  - Increased mechanical stabilization of final focusing elements - small beam size!
  - Redesigned forward region - not discussed here
  - Time stamping on the few ns level in all detector systems to reduce background
  - Use of time information in Particle Flow Algorithms to reduce background

Outlook: R&D Challenges for CLIC Detector Systems

- Vertex detector:
  Combine extremely low mass and low power with time stamping
  Power pulsing very likely indispensable to achieve the mass and power goals

- Calorimeters:
  Explore tungsten as absorber material for the barrel HCAL
  Time stamping in the calorimeters - Coming with the new generation of CALICE Electronics

- Mechanics:
  Active and passive stabilization of beam focusing elements

- Magnets:
  Develop conductors suited for a compact large-bore 5T solenoid

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... several talks on some of these issues at this conference!