

Physics and Detectors at CLIC

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on behalf of the CLIC physics and detector study

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(Werner-Heisenberg-Institut)



Outline

- The CLIC Physics Program
- Experimental Conditions at CLIC
- Detectors at CLIC
 - Vertexing
 - Calorimetry
- Event Reconstruction
- Resulting Performance

The Physics Program at CLIC

- The Compact Linear Collider: e^+e^- collider with energies up to 3 TeV
 - Implementation several stages: Broad range of physics from the Higgs & Top thresholds up to the full energy at 3 TeV
- A full exploration of the Higgs sector
 - Measurements of couplings to gauge bosons & fermions, coupling to Z measured model-independently
 - Direct study of the Higgs potential via Higgs selfcoupling
 - Measurement of mass, spin, CP quantum numbers
- Precision Top physics: Mass, width, asymmetries
- Spectroscopy of and search for New Physics: In particular in the electroweak sector, Linear Colliders can substantially extend the reach beyond LHC
 - Intensively studied: Potential for SUSY studies - Provides a rich particle spectrum

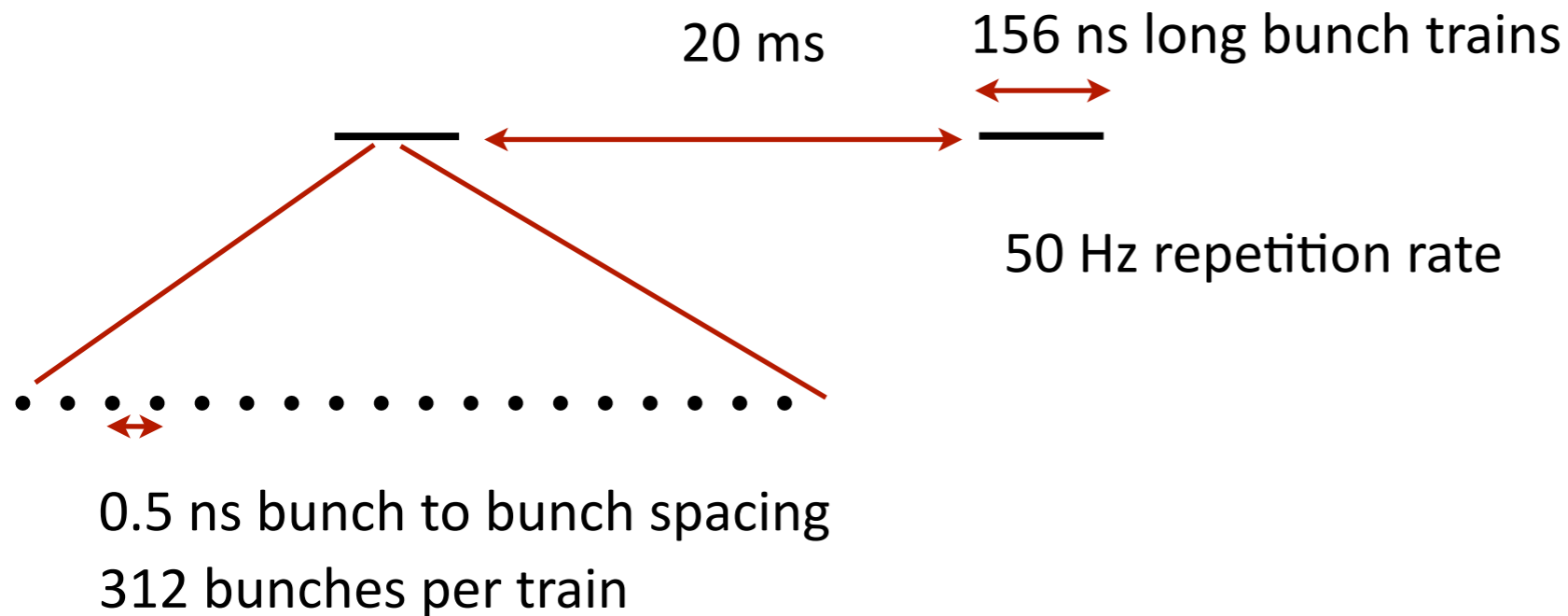
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Introduction of the Machine: S. Stapnes, morning session

Experimental Conditions at CLIC

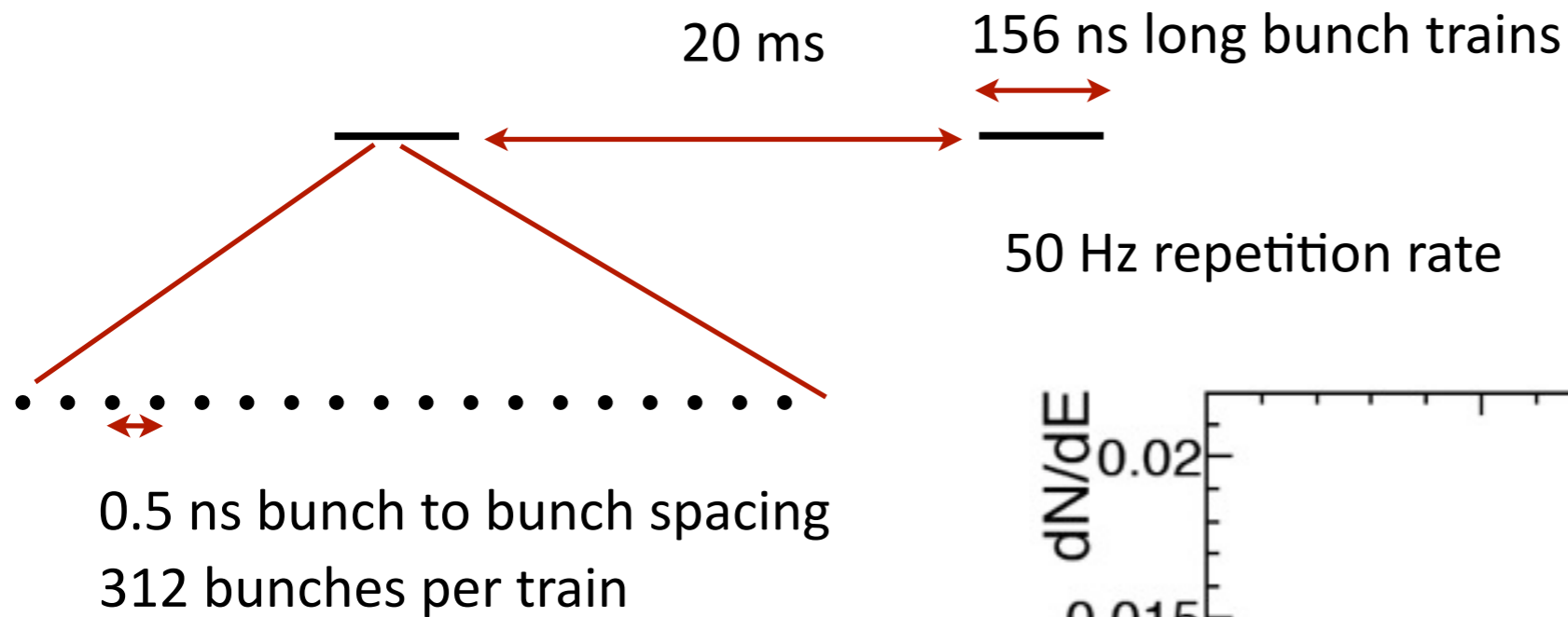
- Focus on the 3 TeV case: Experimentally most challenging, drives detector design
- The CLIC Bunch structure:



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

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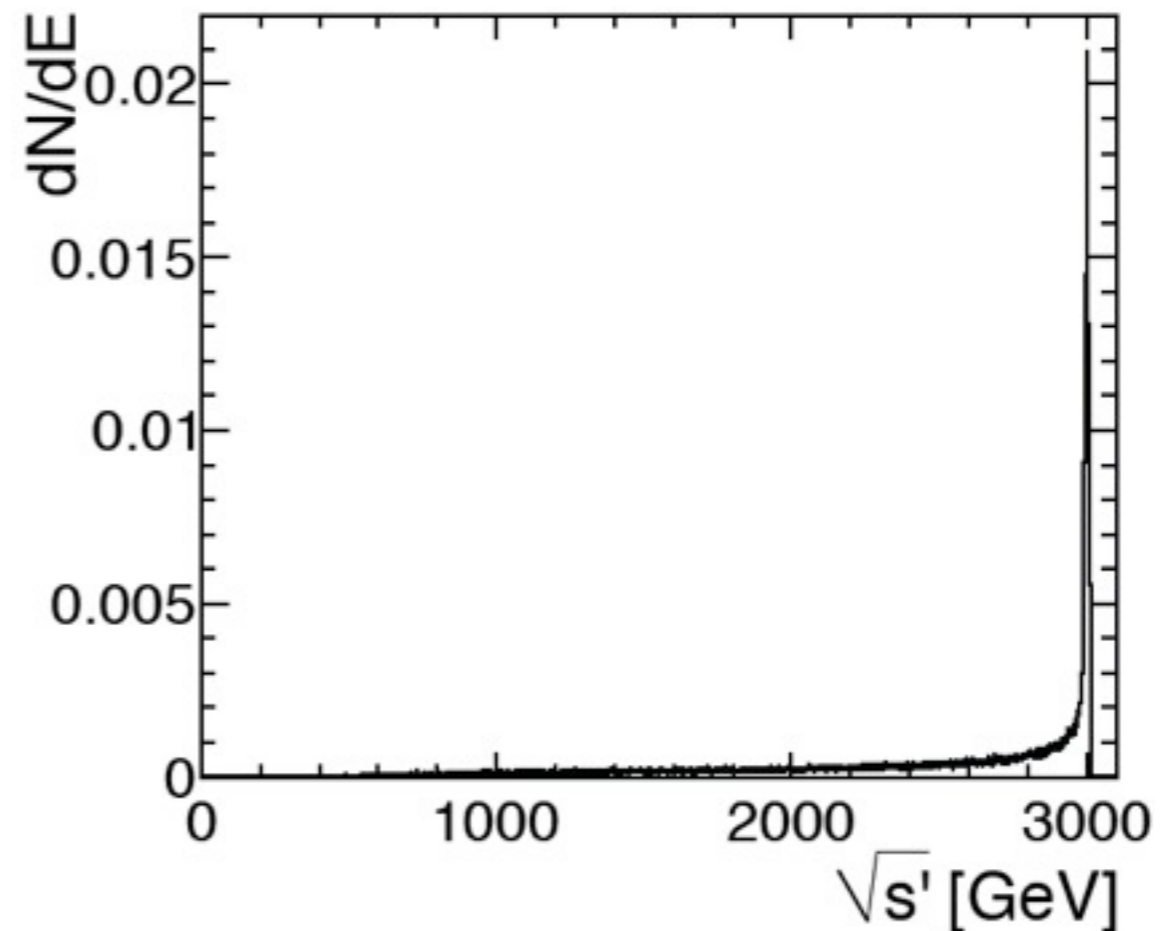
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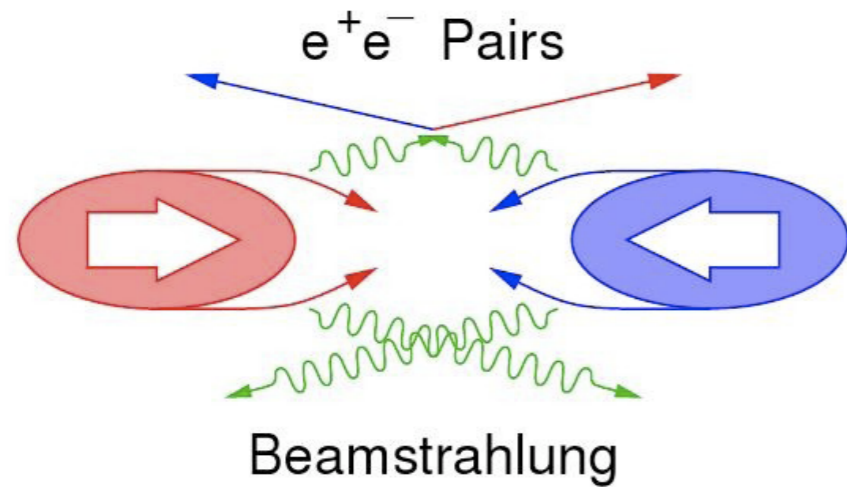
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At 3 TeV: Instantaneous luminosity
 $5.9 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
(35% in top 1% of energy)

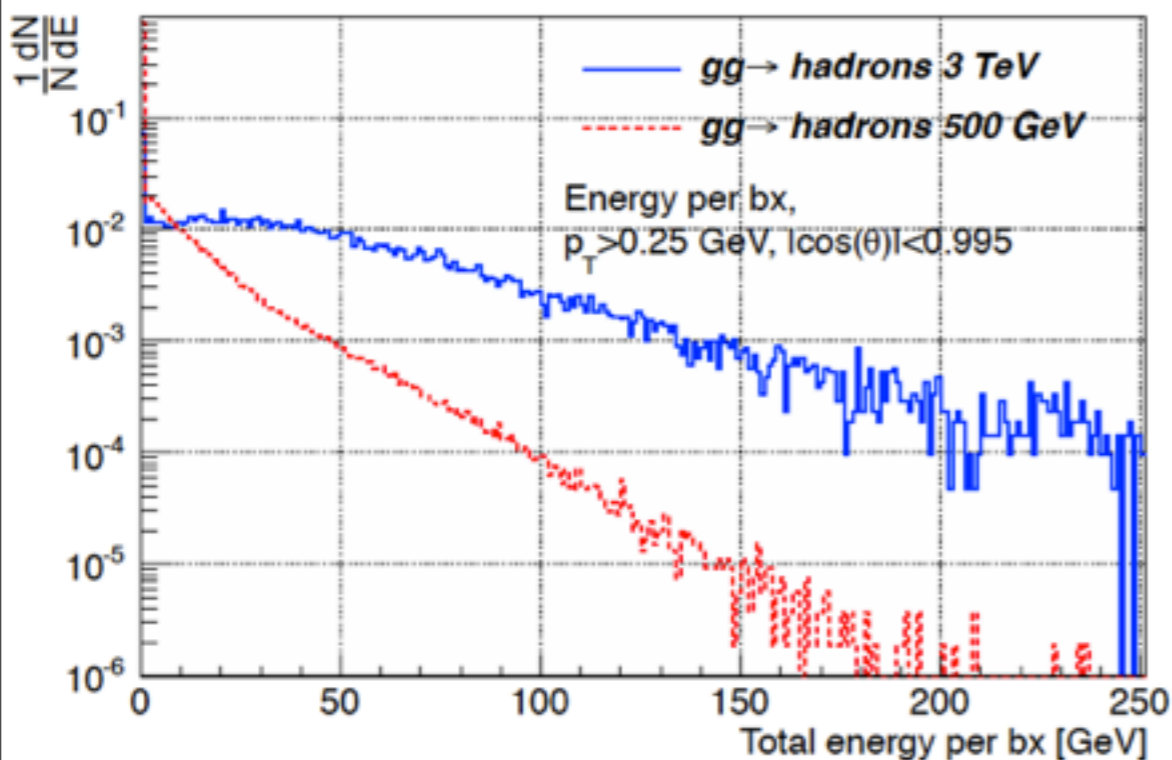


Conditions at CLIC: Beamstrahlung

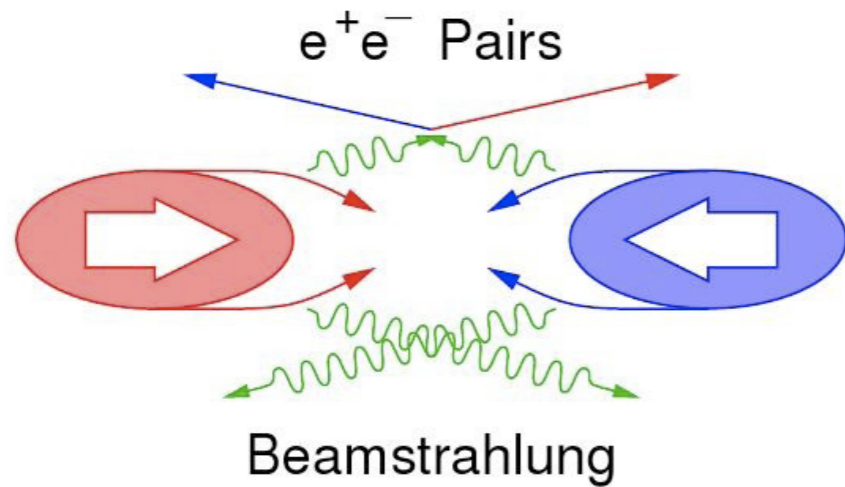


Beamstrahlung driven by energy and focusing:
mean bunch $\Delta E/E \sim 29\%$

- coherent e^+e^- pairs: 7×10^8 / bunch crossing (small angles < 10 mrad, defines 20 mrad crossing angle)
- incoherent e^+e^- pairs: 3.0×10^5 / bunch crossing (constrain innermost radius of vertex detector)

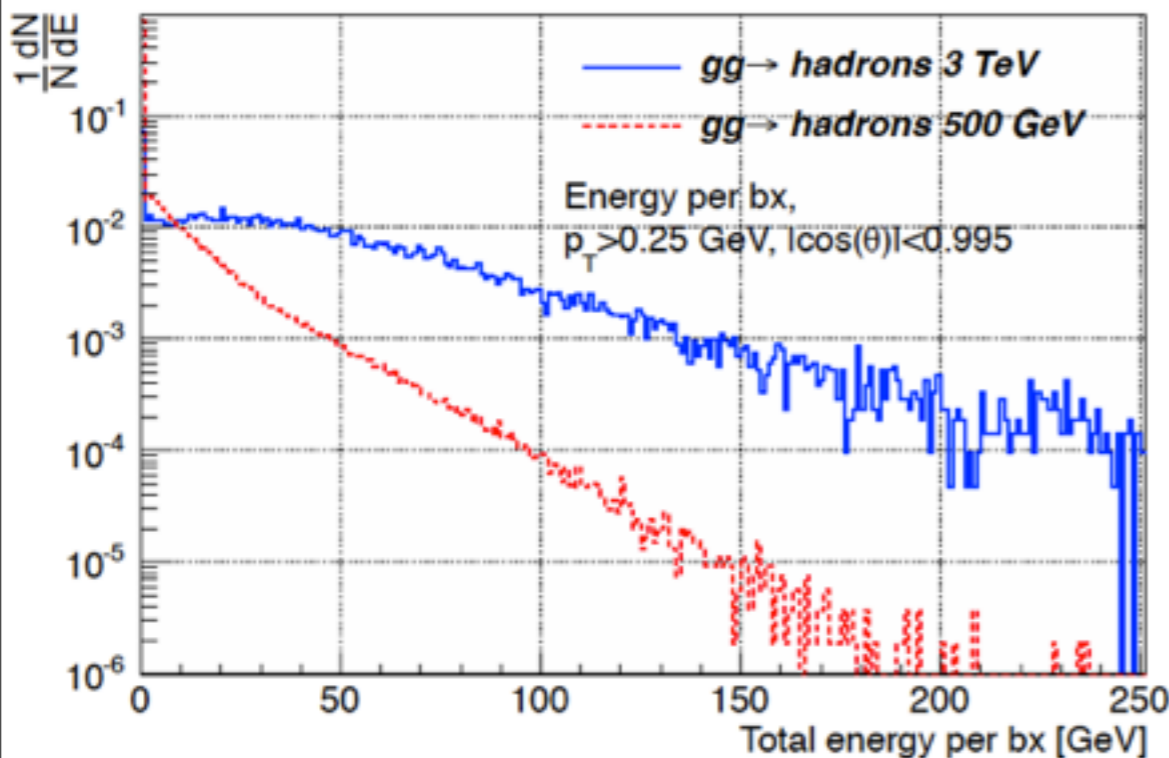


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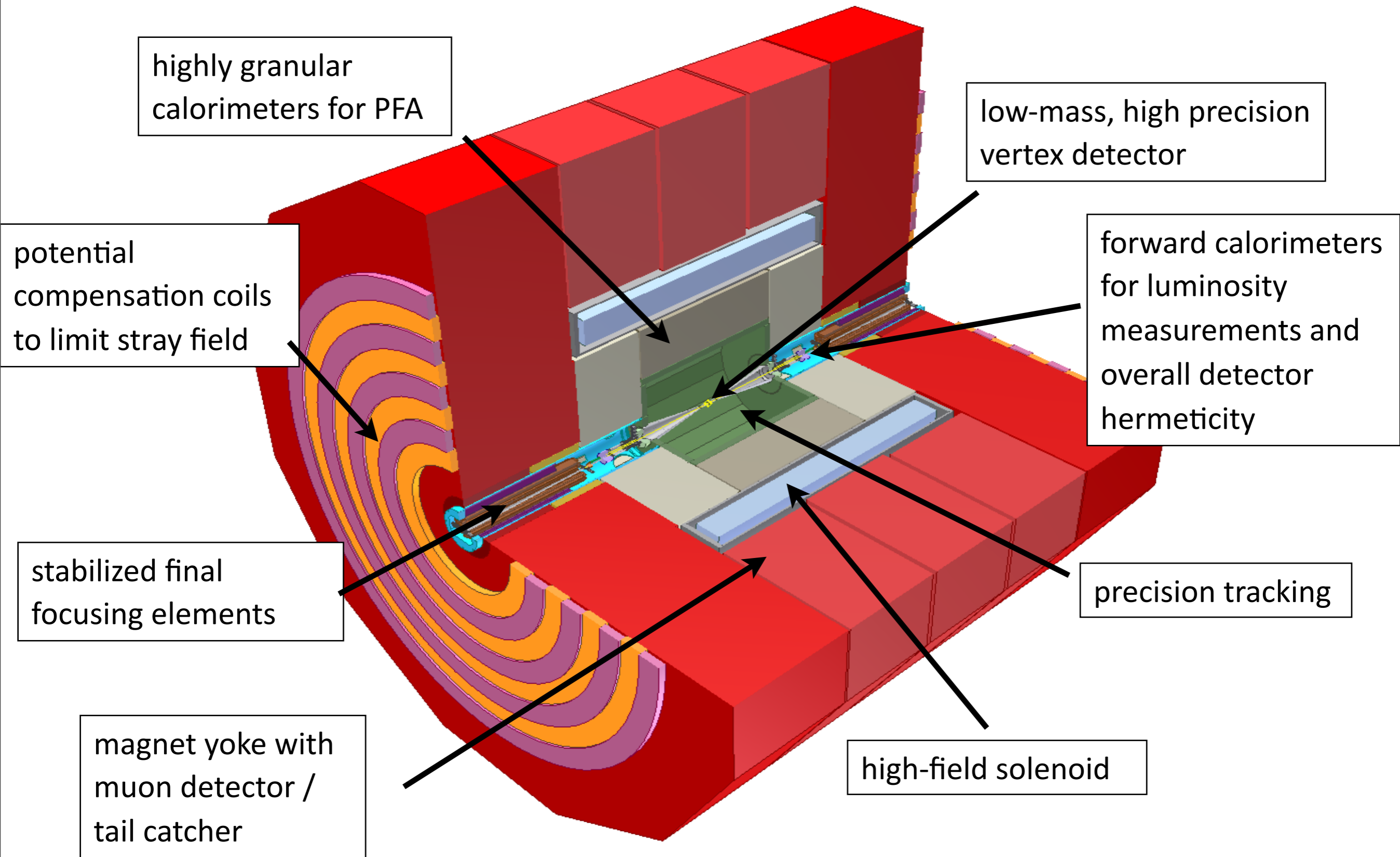
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- incoherent e^+e^- pairs: 3.0×10^5 / bunch crossing (constrain innermost radius of vertex detector)
- $\gamma\gamma \rightarrow$ hadrons: ~ 3.2 events / bx,
 ~ 28 ch. particles in detector acceptance
 ~ 60 GeV energy
 \Rightarrow 19 TeV dumped in detector during bunch train, forward peaked
Requires precise time stamping and clever event reconstruction



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

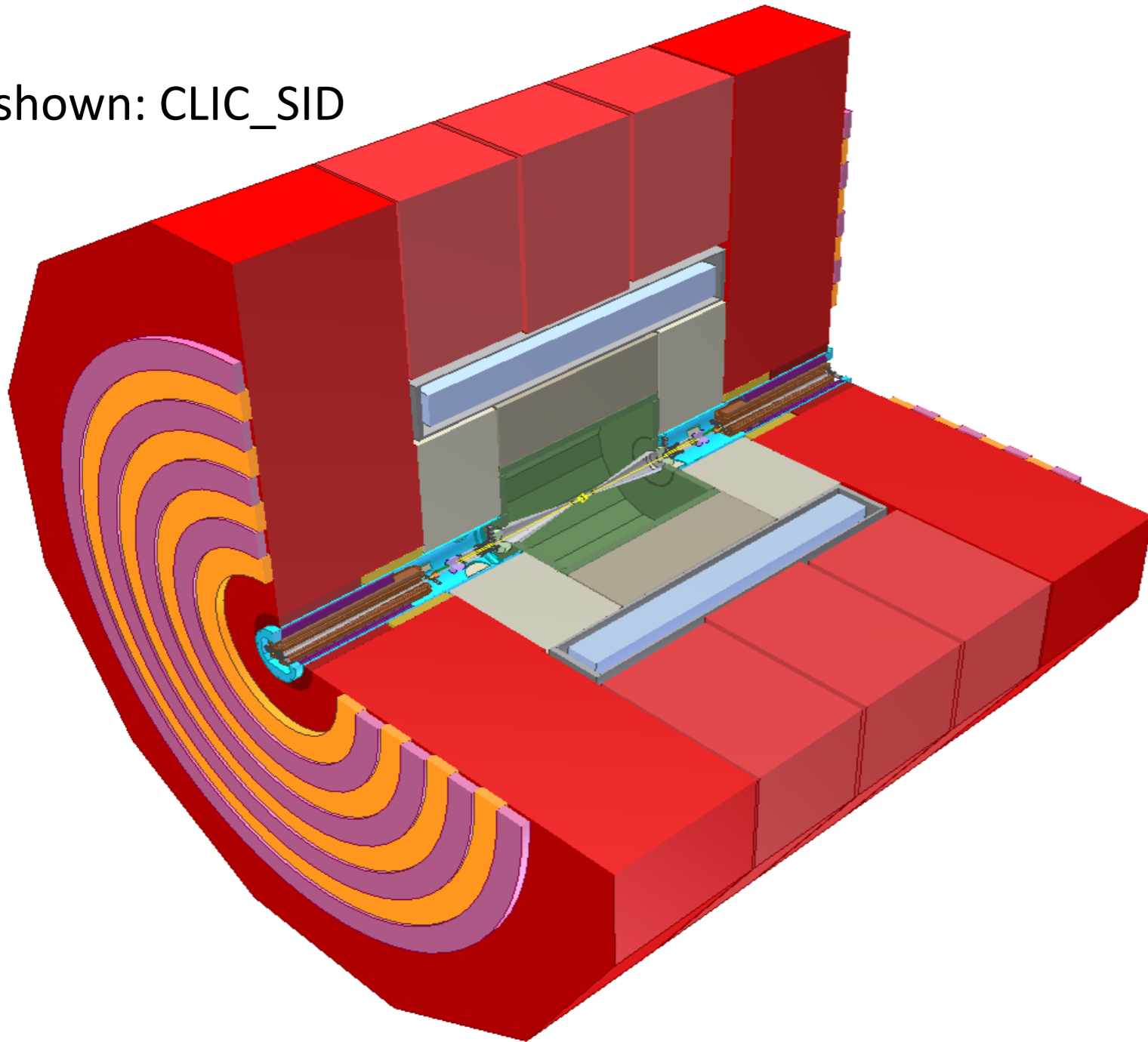
CLIC Detectors - Main Features



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 / Si pixel inner tracker

CLIC_ILD: TPC main tracker
CLIC_SID: Si strip main tracker

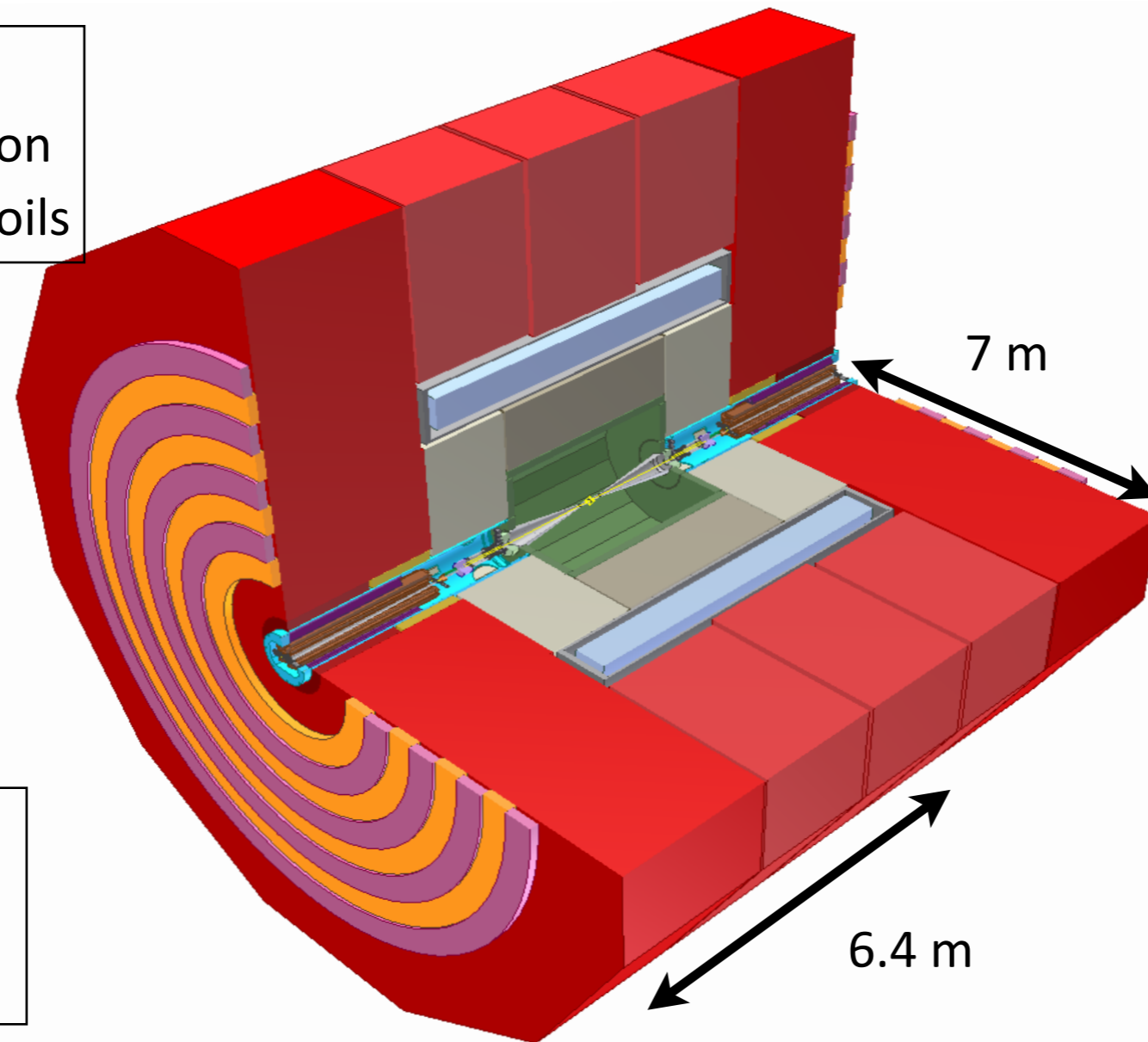
SiW electromagnetic calorimeter

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

Significant redesign
of forward region

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

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

Hadron calorimeter
increased in depth:
 $7.5 \lambda_1$

both CLIC concepts: same outer dimensions

Main tracker unchanged

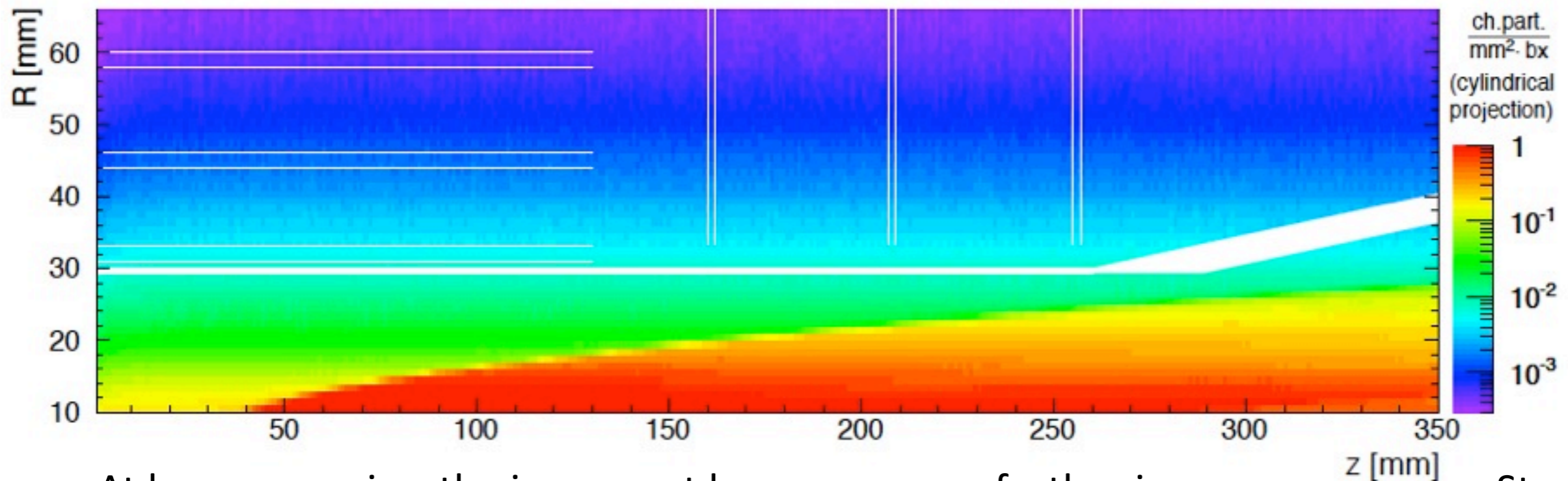
The Vertex Detector - Design Considerations

- Performance goal: Excellent secondary vertex resolution to identify heavy flavors, to discriminate between charm and bottom and tag τ decays

Resolution goal $\sigma(d_0) = \sqrt{a^2 + b^2 \cdot \text{GeV}^2 / (p^2 \sin^3 \theta)}$ with $a \sim 5 \mu\text{m}$, $b \sim 15 \mu\text{m}$

- Move innermost layer of detector as close as possible to the interaction point
⇒ limited by background!

CLIC_SiD: 27 mm, CLIC_ILD: 31 mm



At lower energies, the innermost layer can move further in:
6 mm closer at 500 GeV

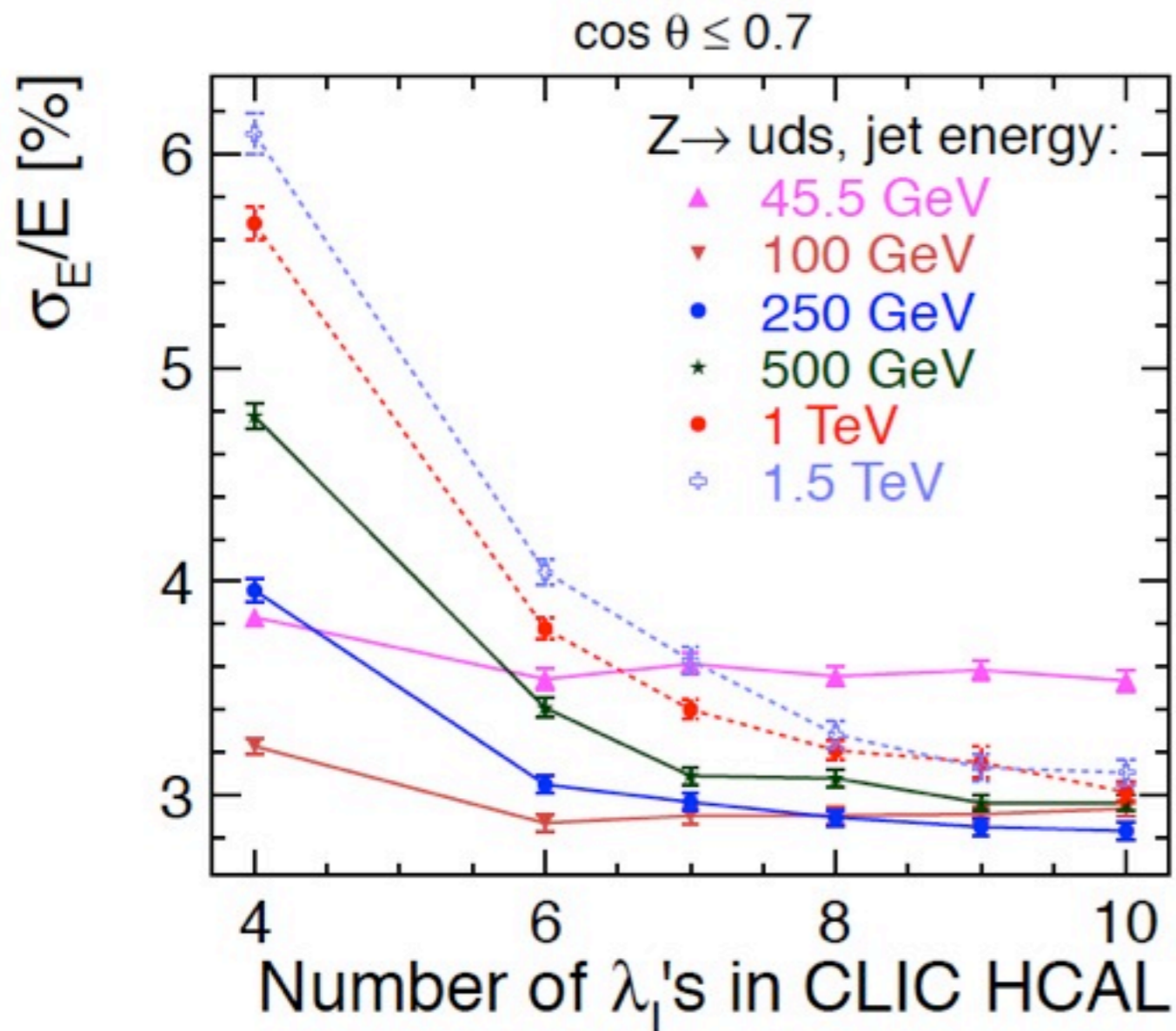
Study for
CLIC_ILD

Pixel Vertex Detector - Technology

- Resolution goals require $\sim 3 \mu\text{m}$ single hit resolution:
25 x 25 μm^2 pixels with analog readout
- Requirements for technology:
 - Low mass: $O 0.2\% X_0$ per detector layer (corresponds to just 200 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 $\sim 10^{10}$ $n_{\text{eq}} / \text{cm}^2 / \text{year}$, TID $\sim 100 \text{ Gy} / \text{year}$

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_1 thick HCAL

For reference:
ILD: 5.5 λ_1
SID: 4.8 λ_1

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 radiation length

Heavy nucleus: Richer time structure of shower?

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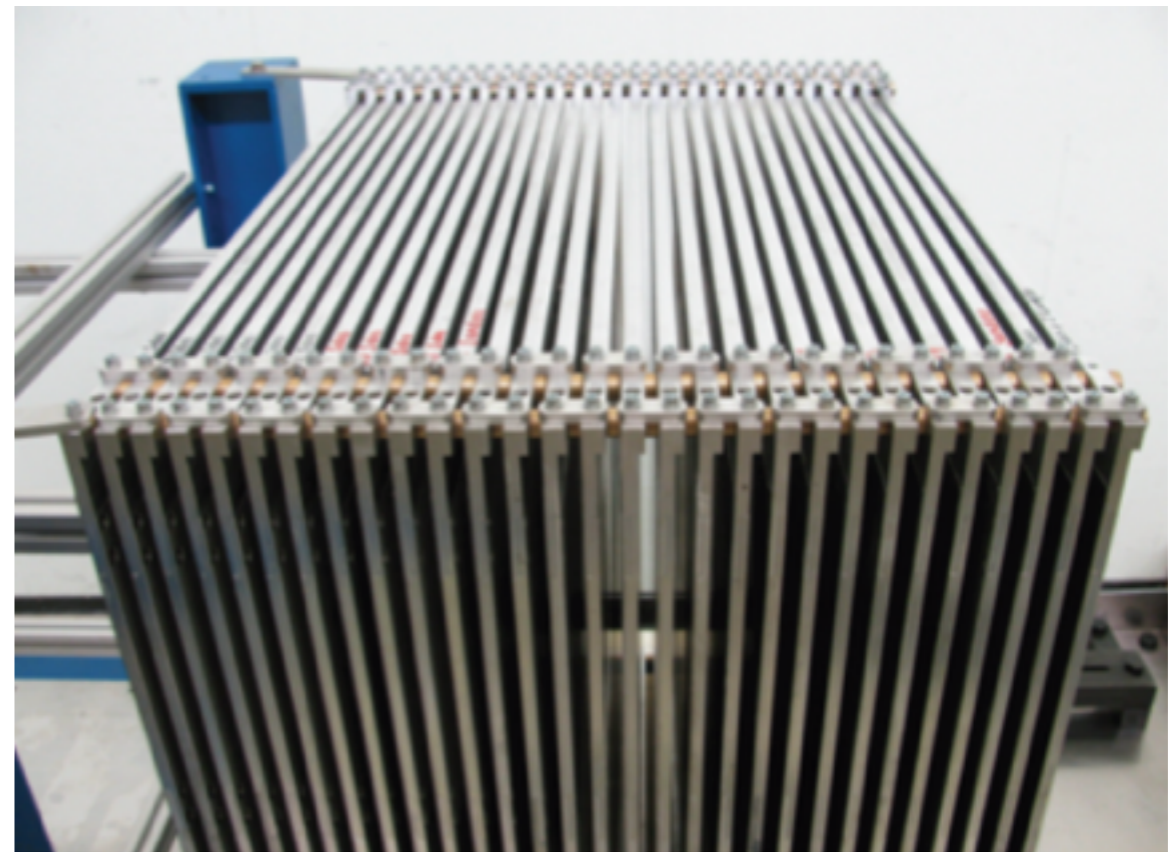
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Heavy nucleus: Richer time structure of shower?

Test beam required:

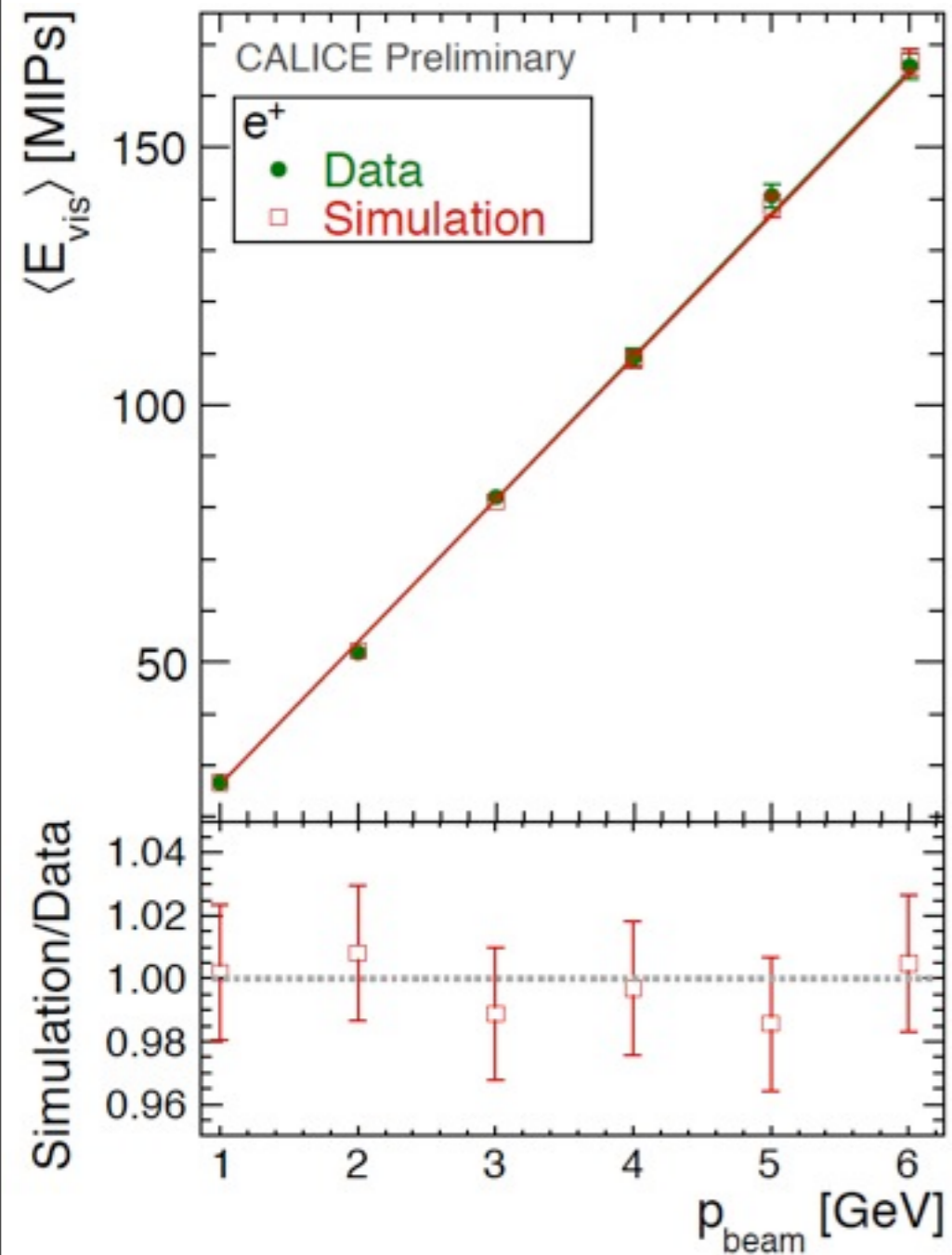
CALICE analog HCAL and RPC digital HCAL active layers, Tungsten absorber plates

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



Tungsten HCAL - First Beam Tests

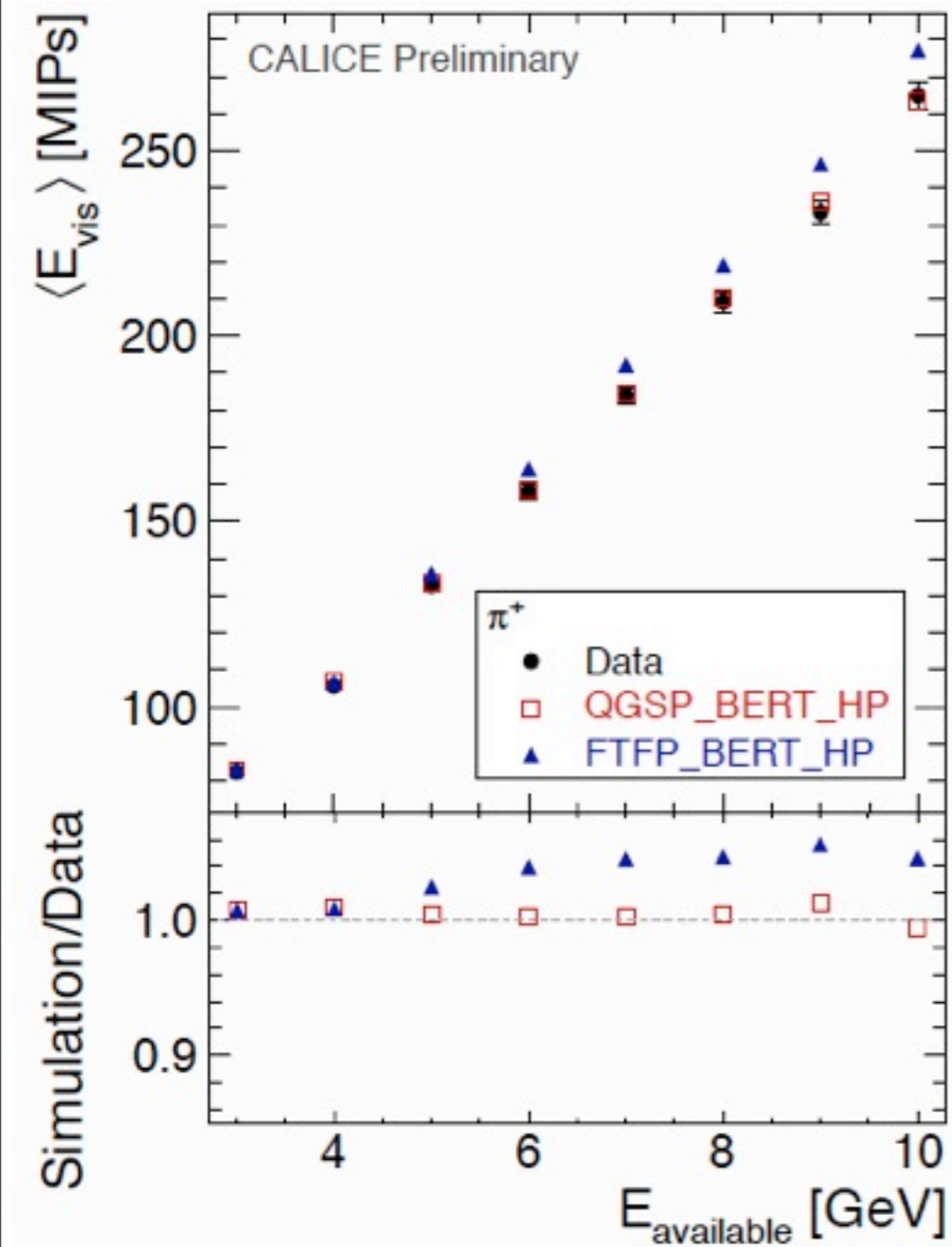
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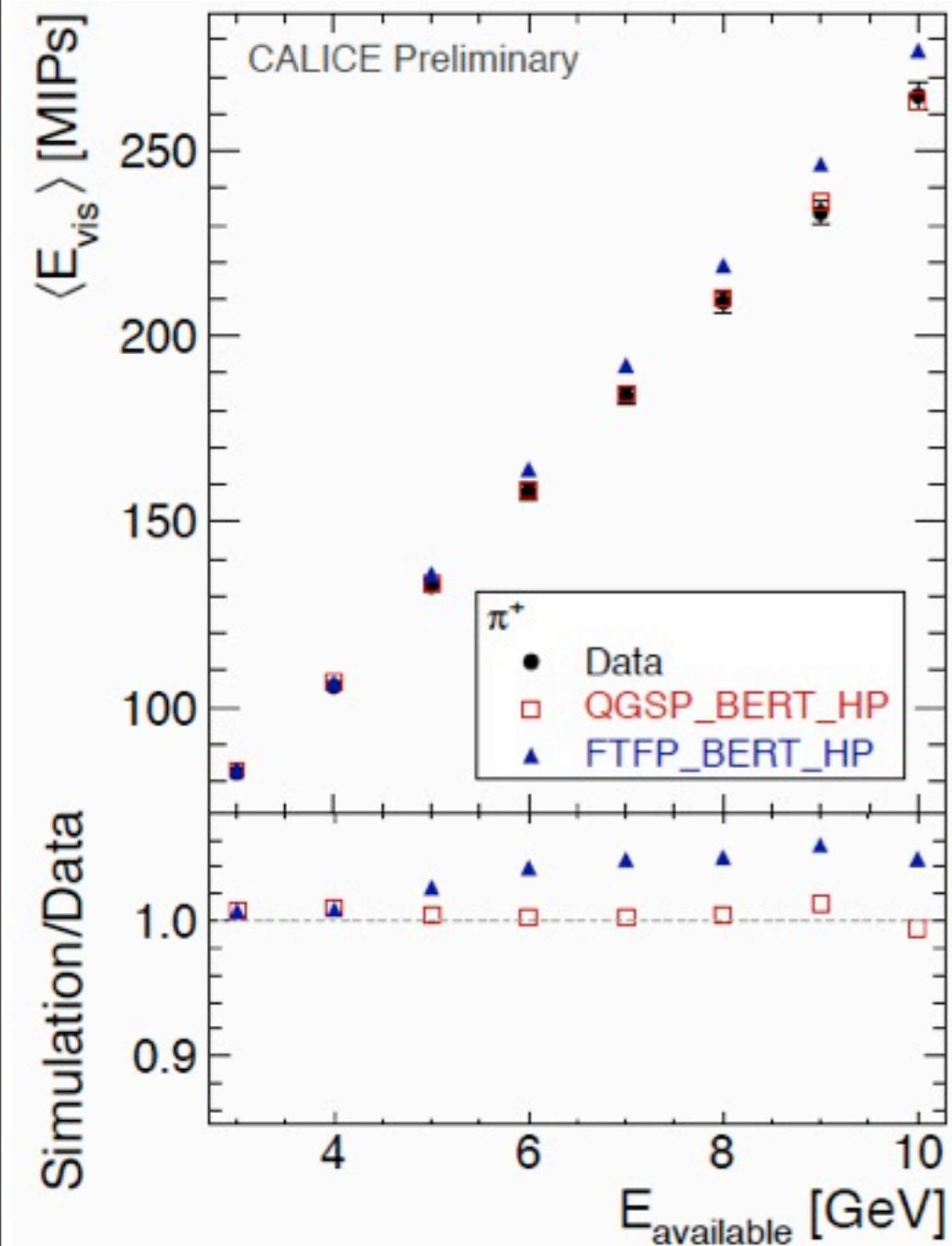
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- Simulations validated with electromagnetic showers
- Satisfactory agreement of reconstructed energy in hadronic data with simulations based on QGSP_BERT_HP Geant4 physics model
- Study of timing of hadronic showers in Tungsten: Again satisfactorily reproduced by QGSP_BERT_HP
- without high precision neutron tracking Geant4 overestimates the importance of late shower components: Simulations are conservative

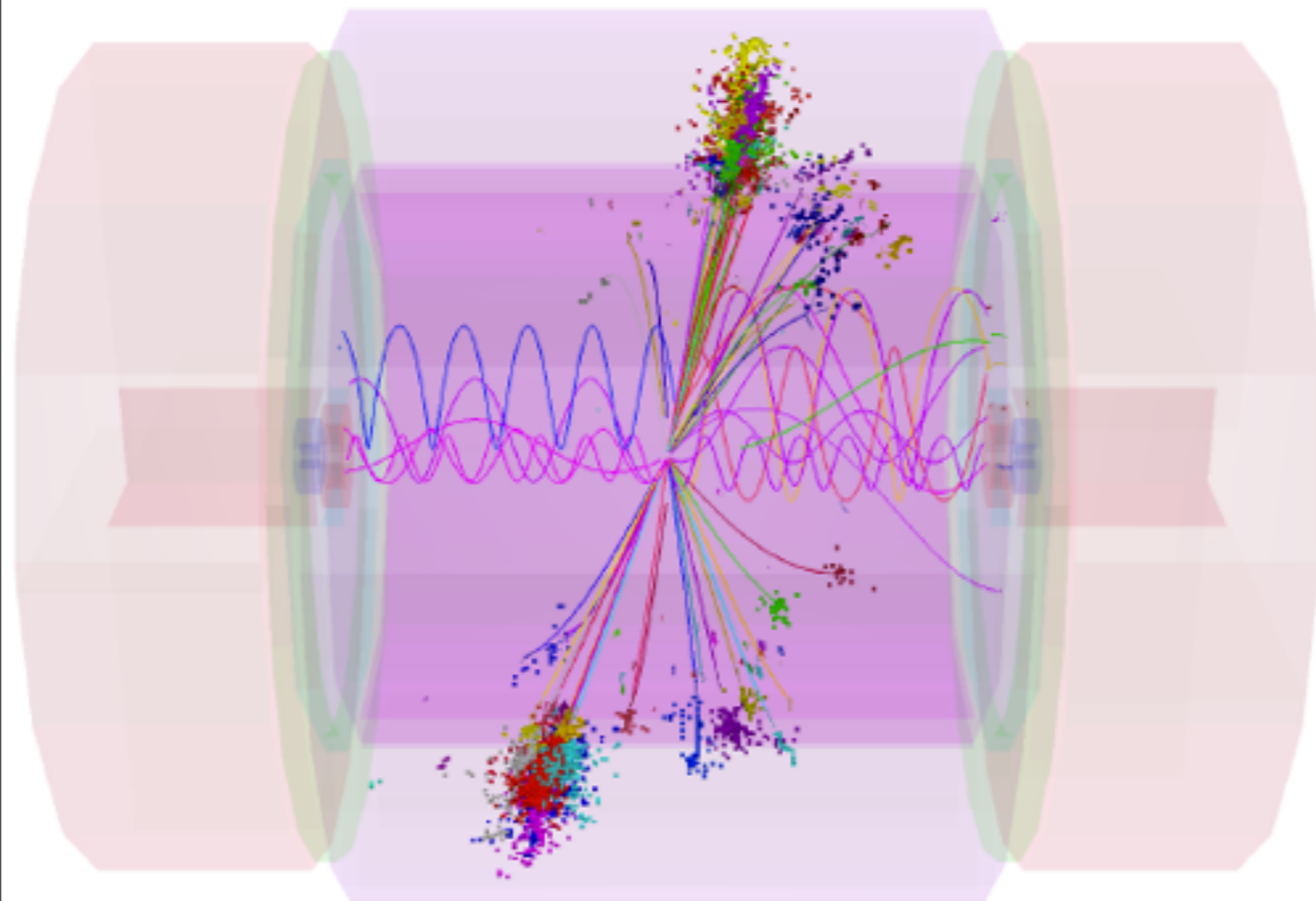
CLIC Event Reconstruction

- 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

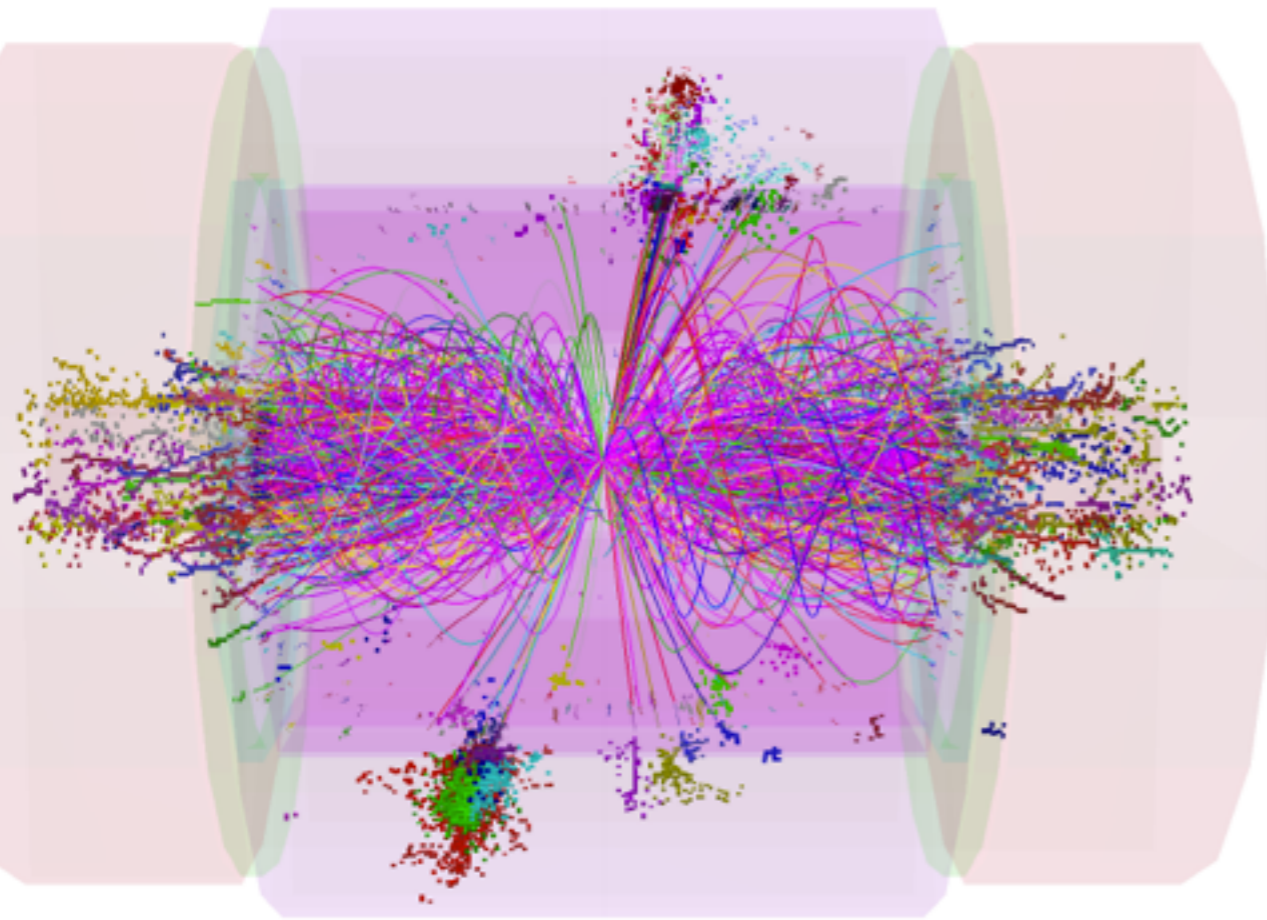
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1 TeV $Z \rightarrow uds$ + $\gamma\gamma \rightarrow$ hadrons background

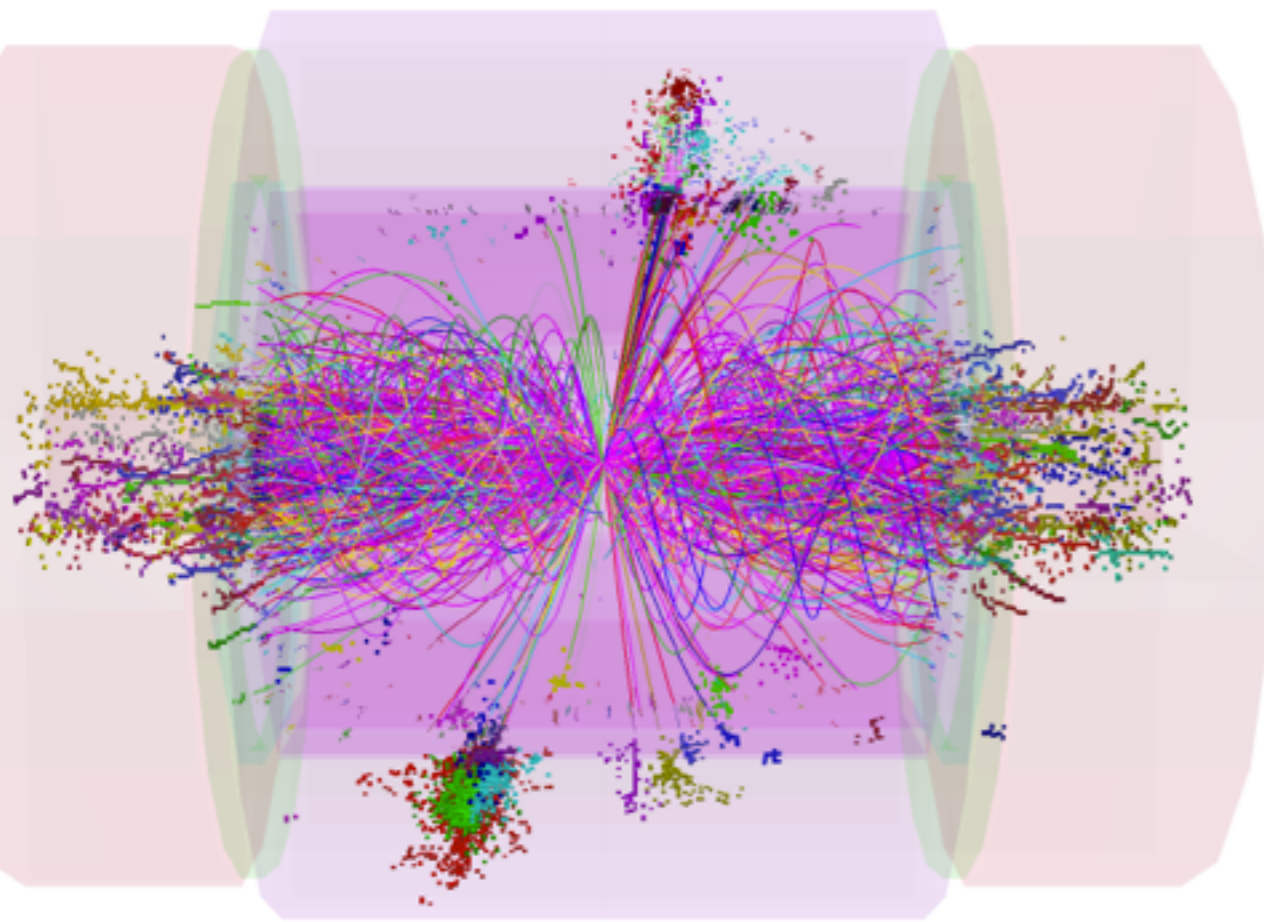


~ 60 BX, 1.4 TeV

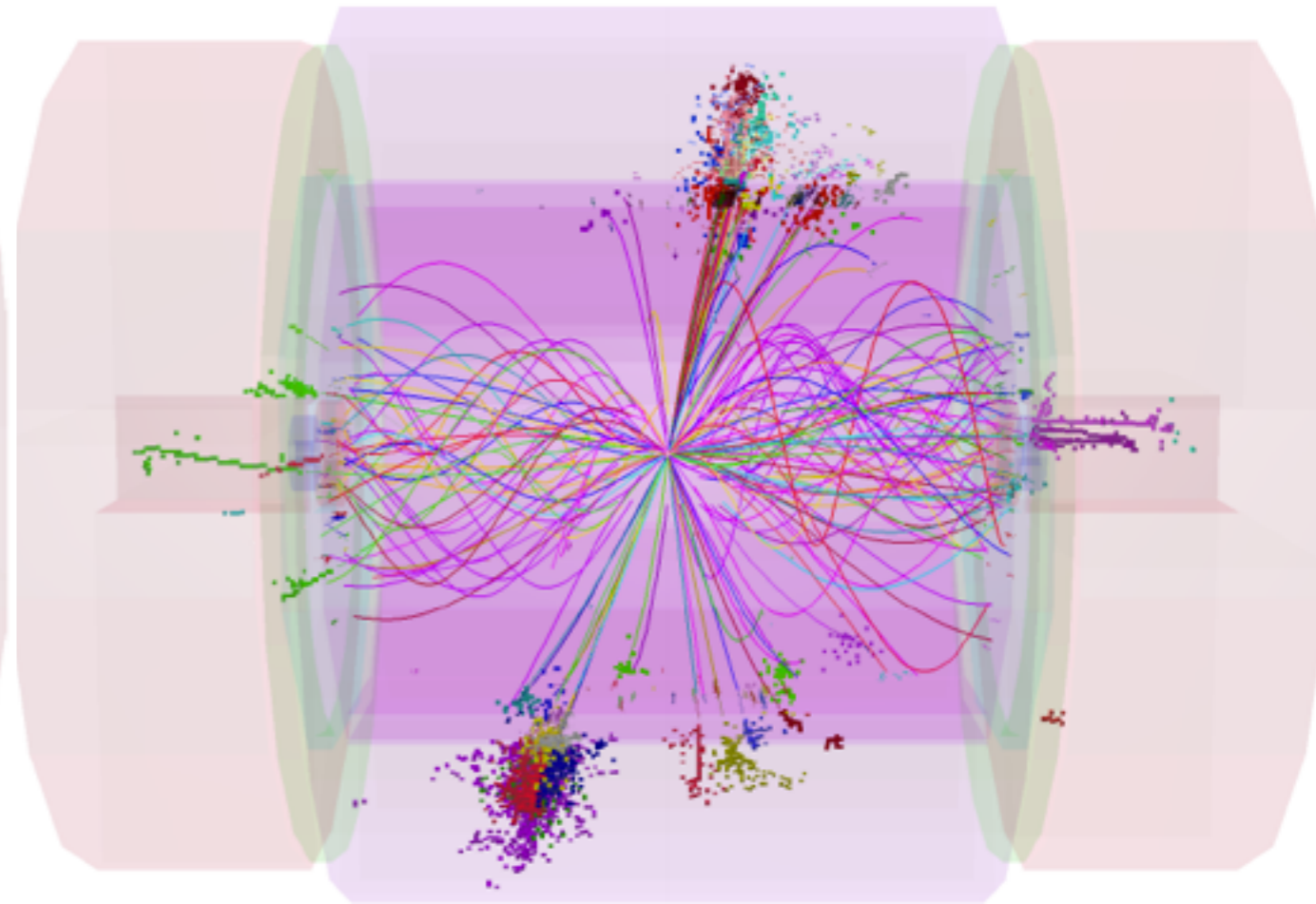
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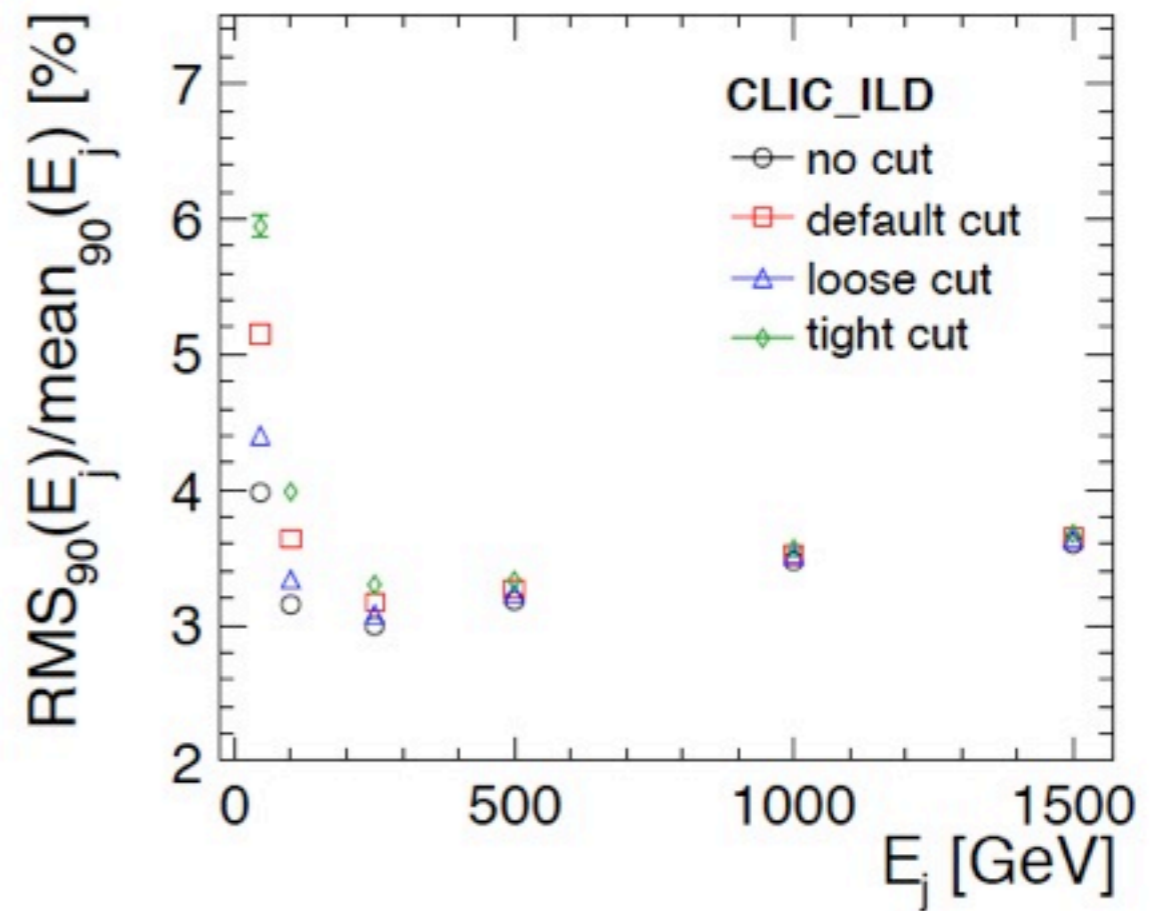
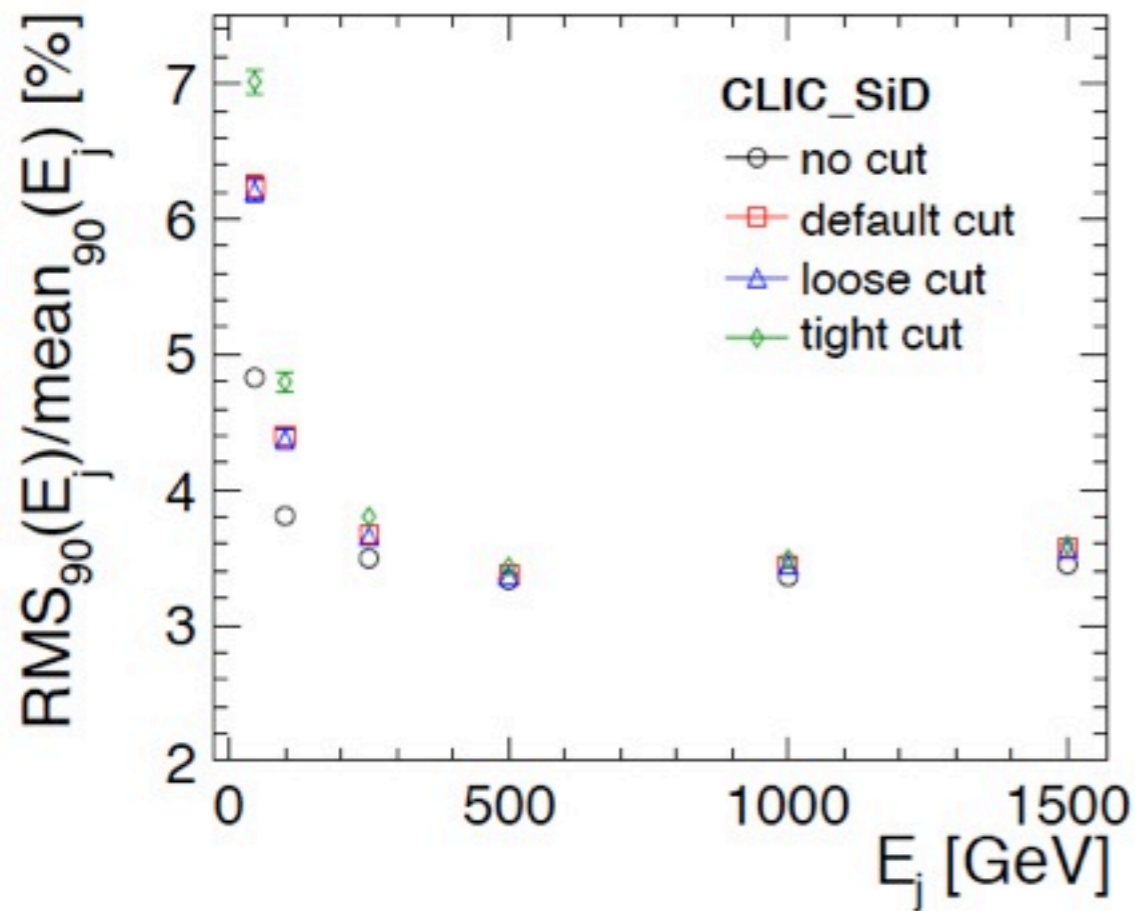


realistic timing assumptions: 200 GeV

- 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



- For lower energy operation (500 GeV), relaxed cuts are used to recover performance also for lower energy jets: Background is much reduced (virtually non-existing at 350 GeV, rather small at 500 GeV)

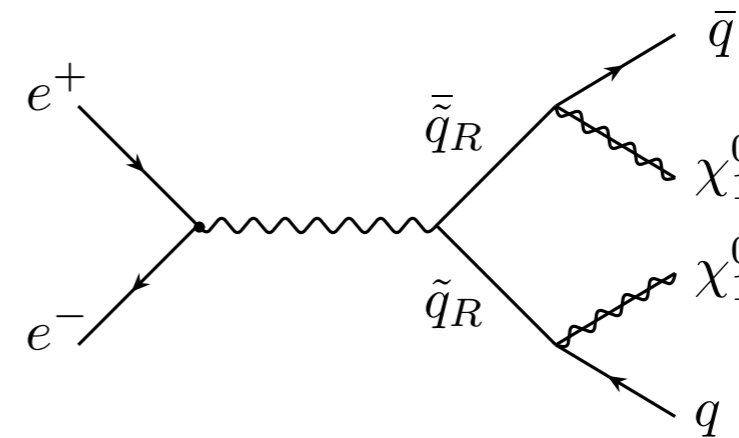
Background Reduction in Physics Analysis

- 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!



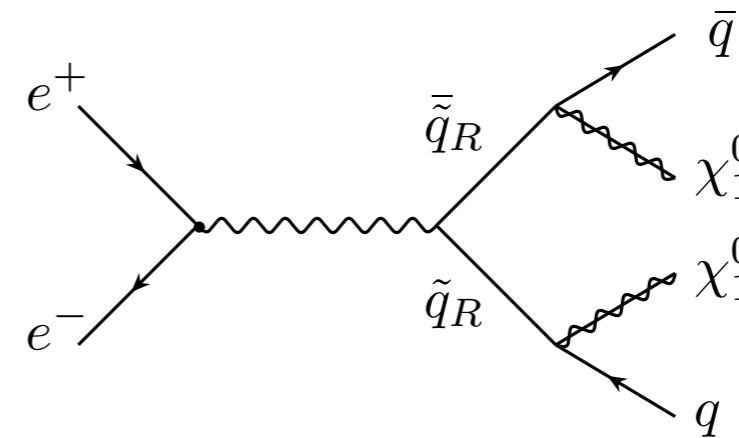
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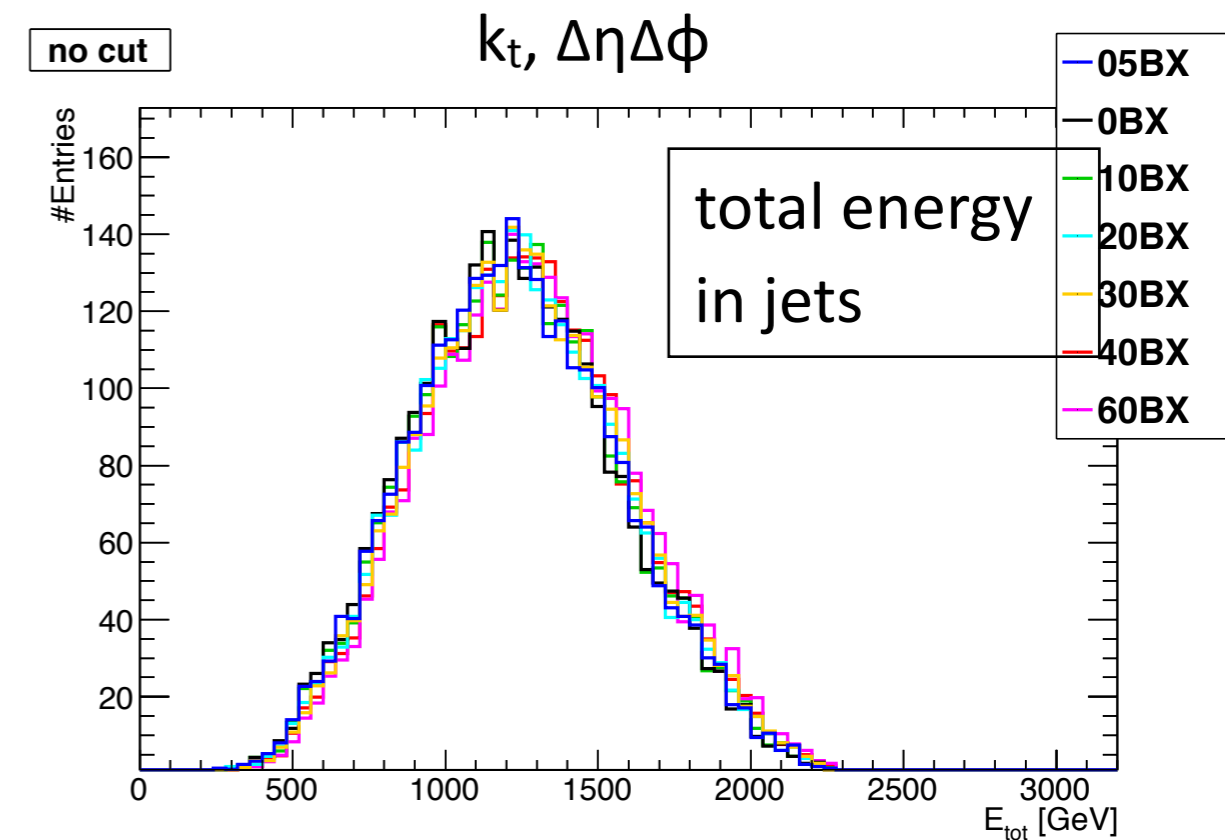
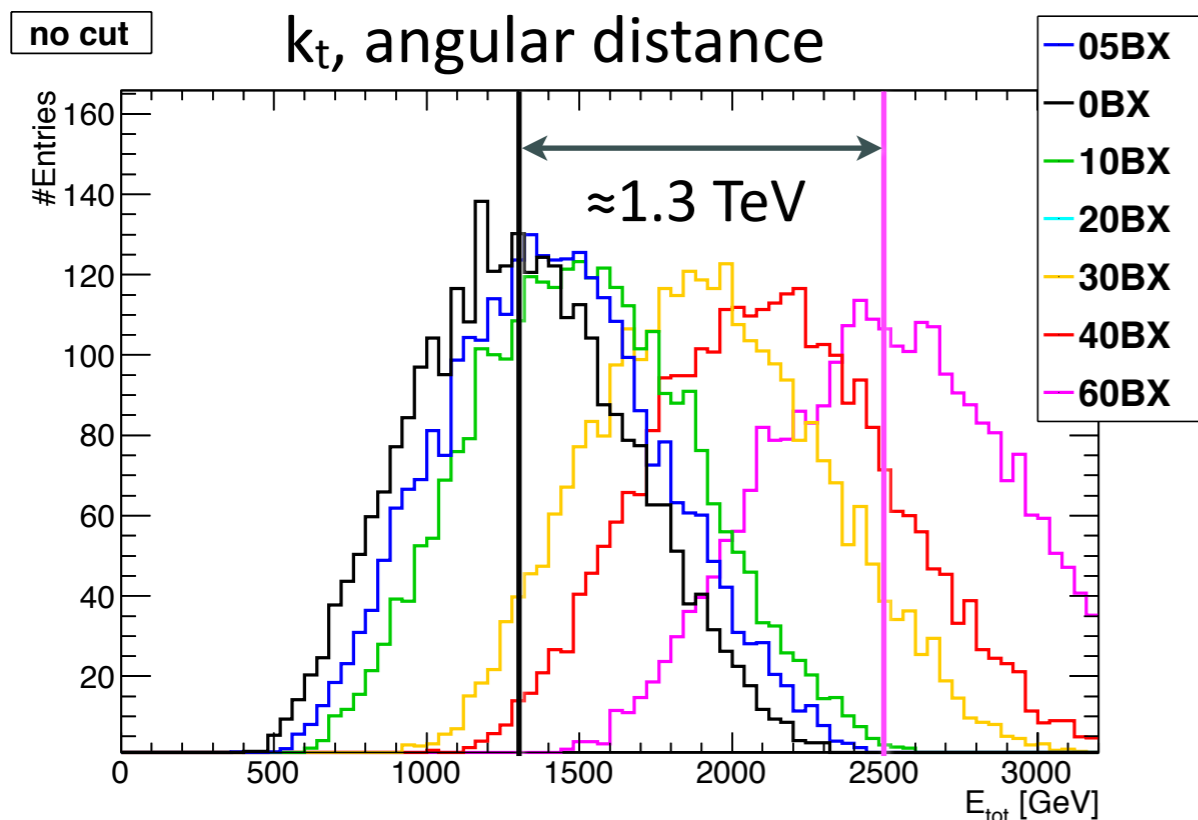
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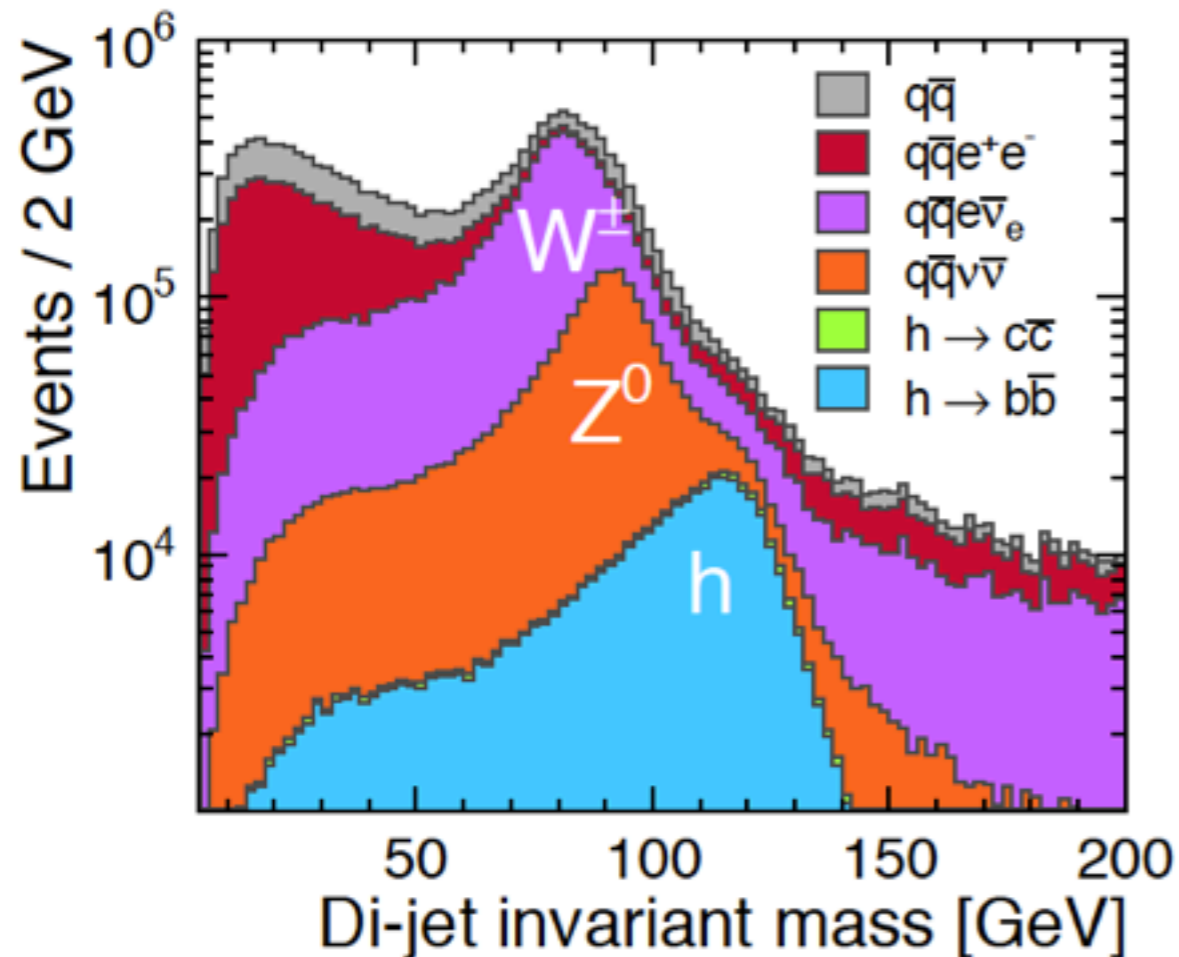


Jet finding can reduce background effects considerably: Choose the right finder / metric!



Resulting Performance - Higgs at 3 TeV

- Full simulation studies: Geant4 detector models, inclusion of $\gamma\gamma \rightarrow$ hadrons background, full particle flow reconstruction
- Precision Higgs Physics possible at 3 TeV: Exploit large cross section and high luminosity - Here: Measurements of $\sigma \times \text{BR}$



$$\int L = 2 \text{ ab}^{-1}$$

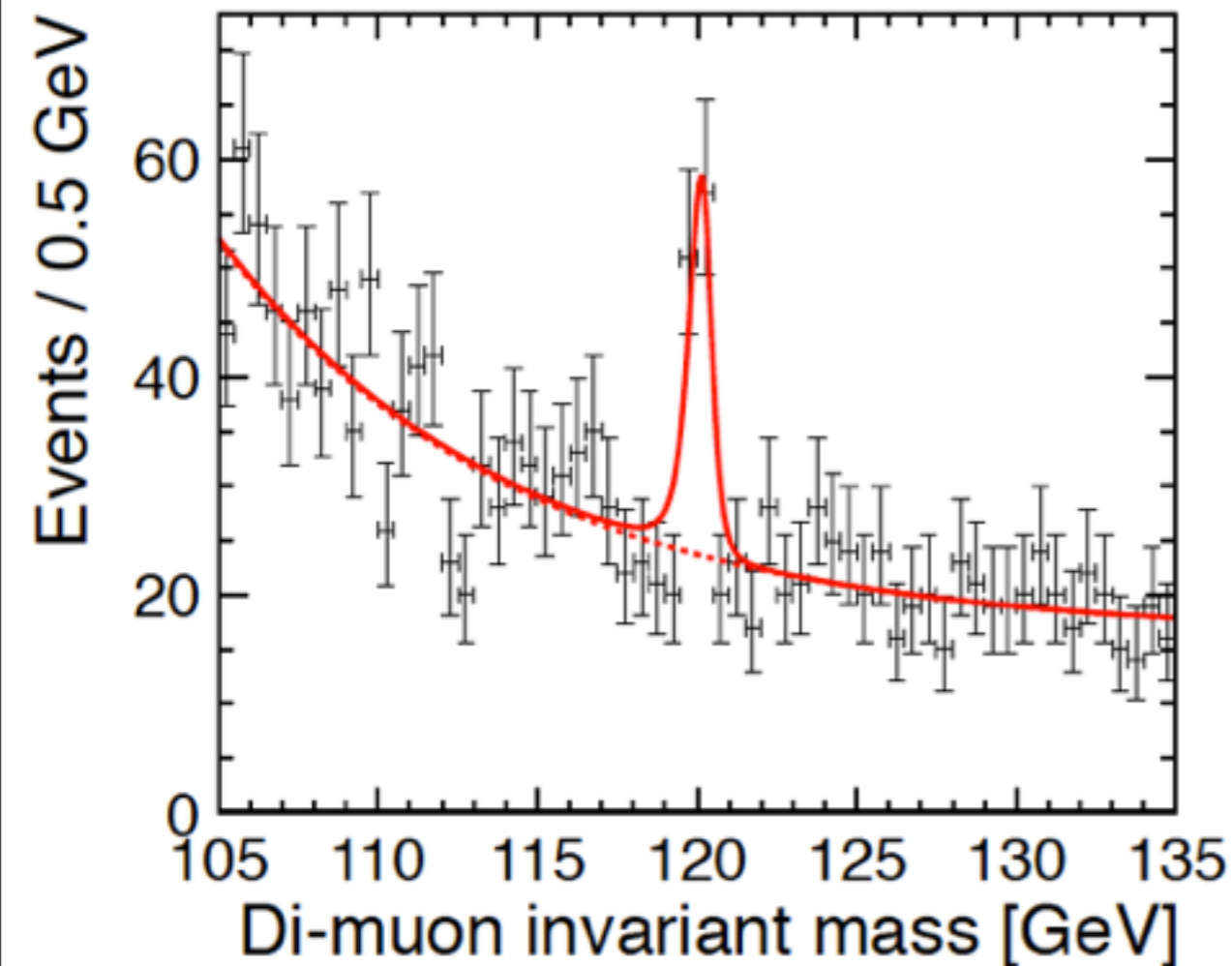
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H \rightarrow cc with 3.2% statistical accuracy

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(background rejection with multivariate techniques)

H \rightarrow $\mu\mu$ with 15.7% statistical uncertainty
(BR only 0.03%!)

Resulting Performance - SUSY at 3 TeV

- Extensively studied for various channels
- One example: Chargino and Neutralino production

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow W^+W^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

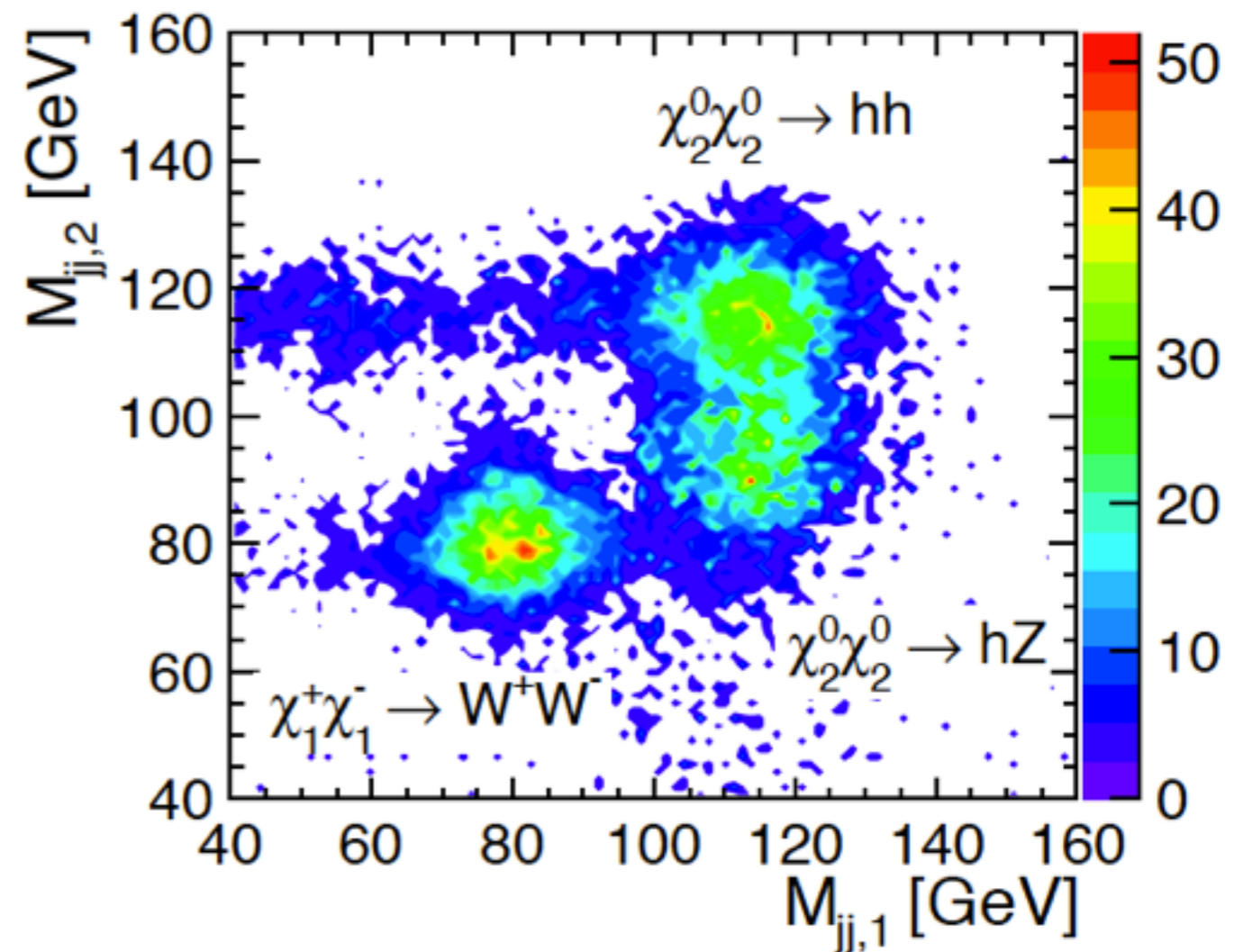
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow h(Z)h(Z) \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

Masses: 643 GeV

- Key challenge: Separation of heavy bosons in hadronic final states in the presence of background: A showcase for particle flow performance

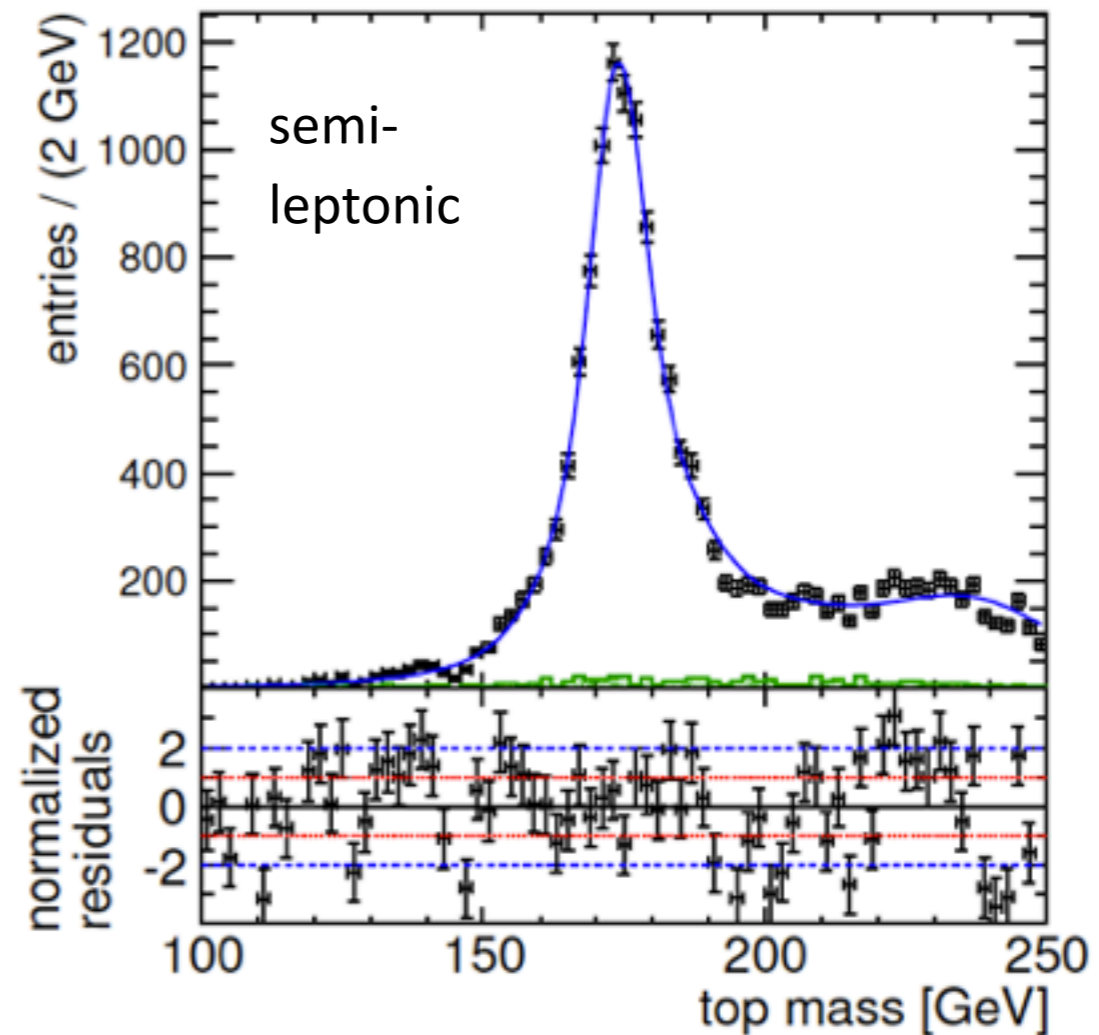
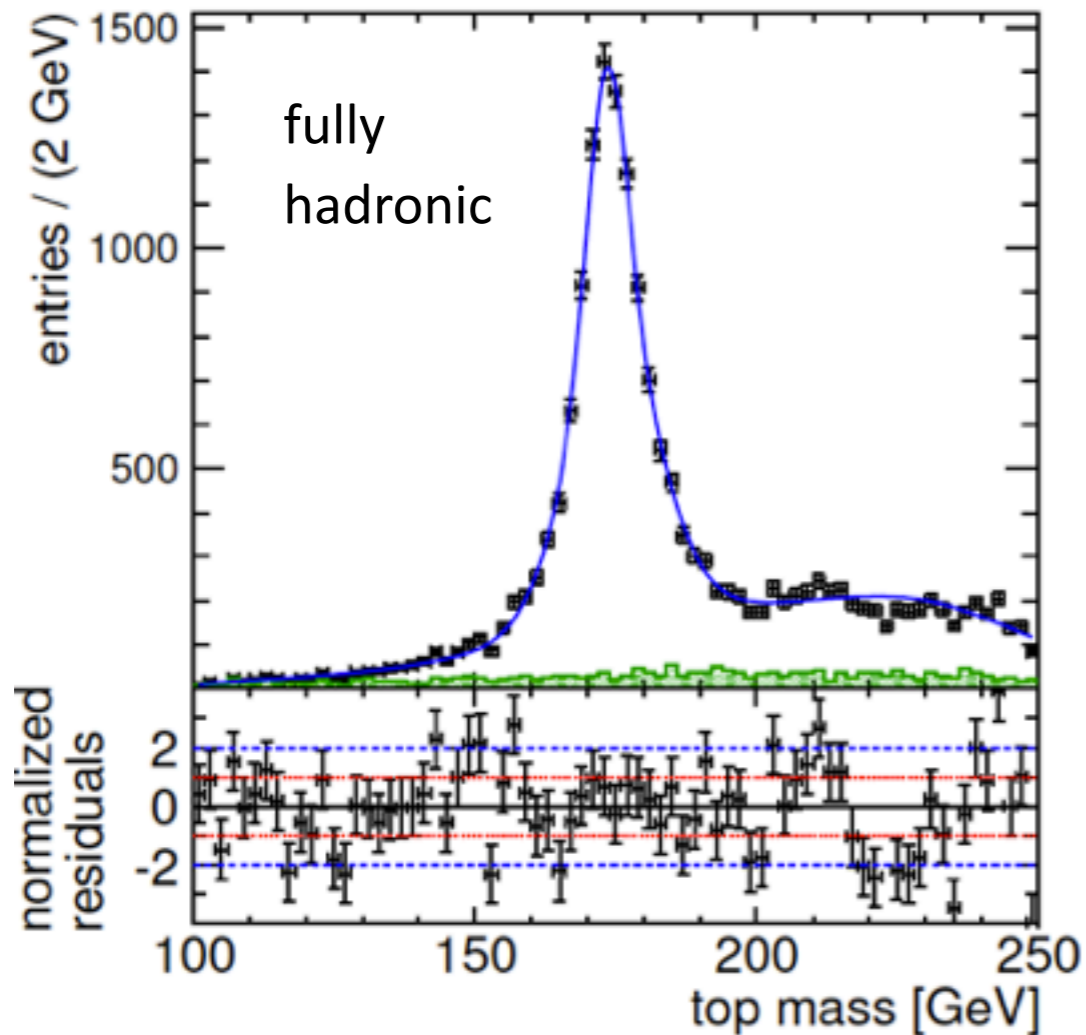
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Mass measurement at the 1% level, cross sections at the 2% level



Resulting Performance - Top at 500 GeV

- High precision also in the reconstruction of the top quark mass from the invariant mass of the decay products of top pairs in the all jets and lepton+jets channel



- approximately 100 MeV statistical precision with 100 fb^{-1} : comparable to ILC

Summary

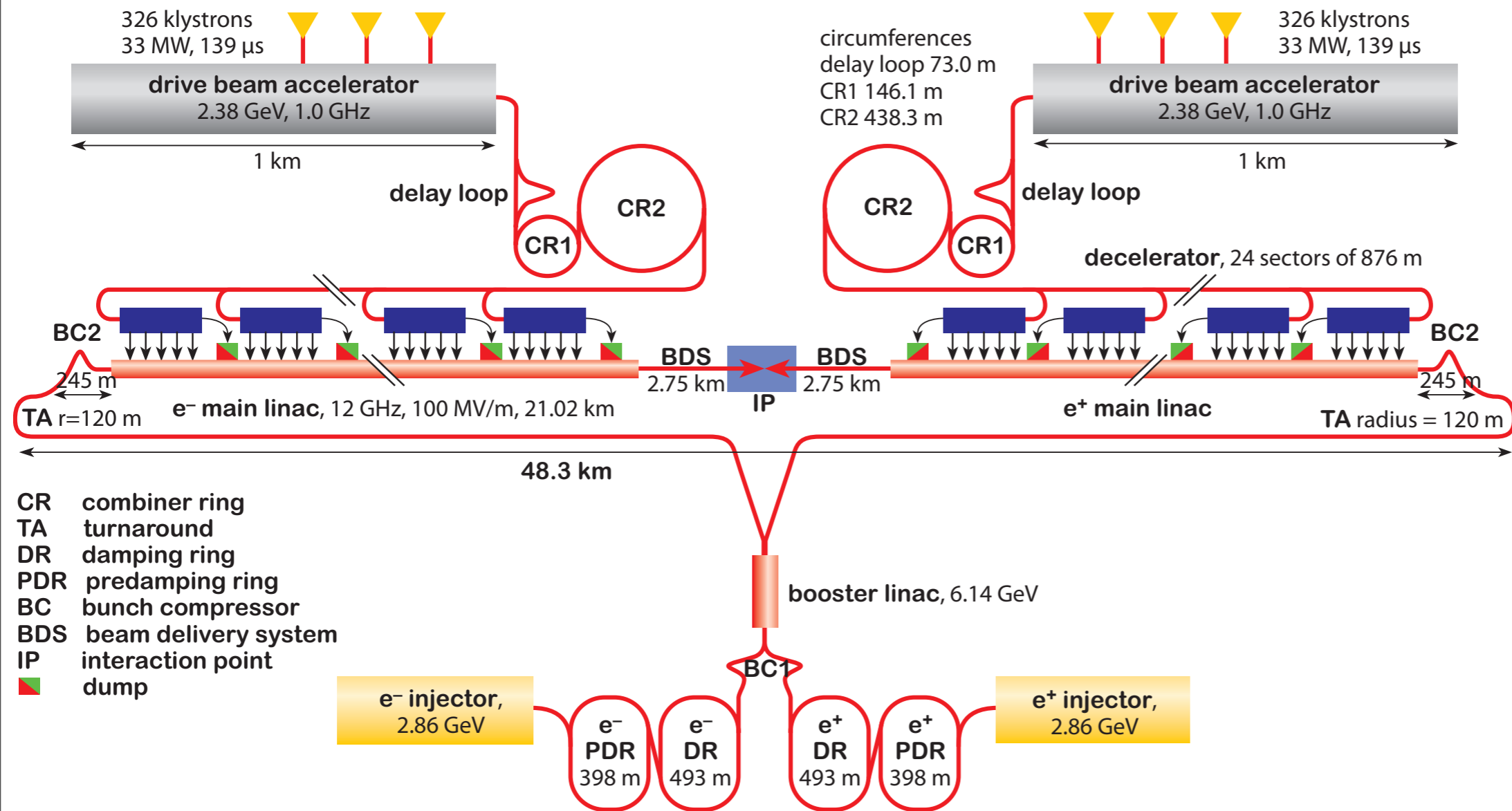
- CLIC and its detectors are optimized for precision physics in the Higgs sector, in the Standard Model and beyond over a wide energy range
- The detector systems are based on the ILC concepts ILD & SiD: comparable performance goals
- The experimental conditions at CLIC require substantial modifications:
 - Fast, low mass vertex detectors
 - Deep calorimeters using tungsten absorbers
 - Precise timing in all detector systems
- The addition of timing to particle flow algorithms provides the required background rejection in the event reconstruction
- Detailed benchmark simulations demonstrate that precision measurements are possible



Backup

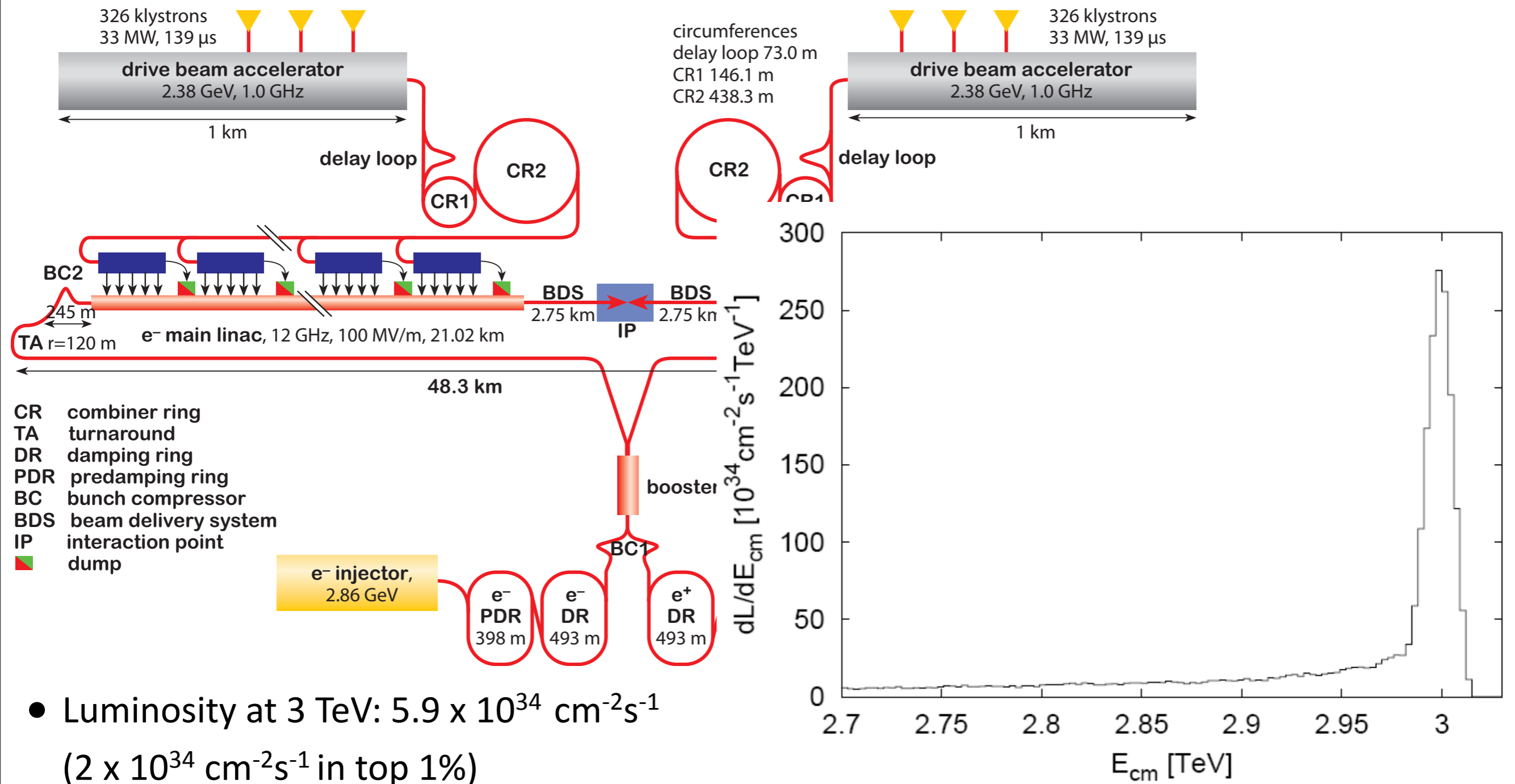
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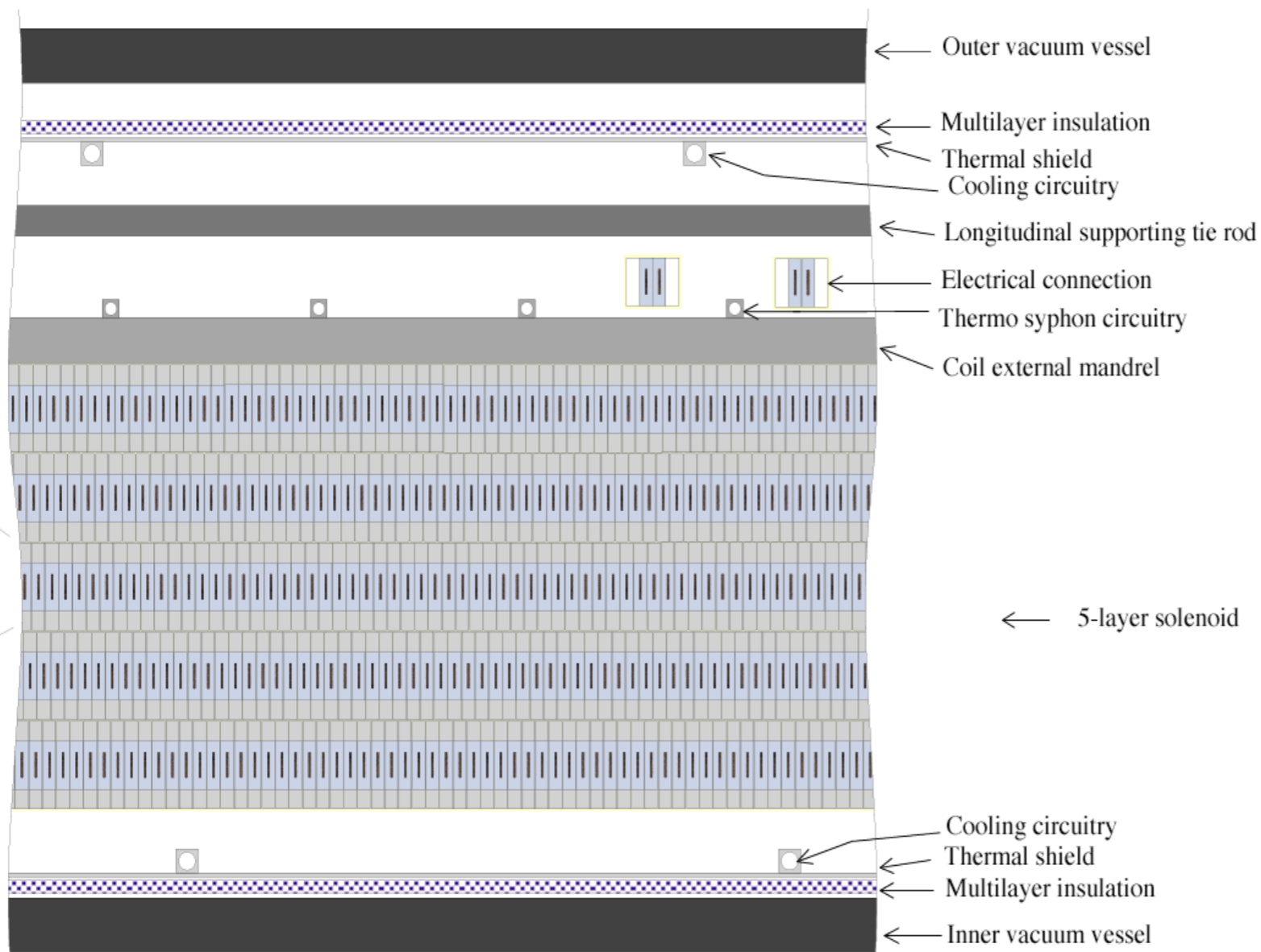
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- Luminosity at 3 TeV: $5.9 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
($2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in top 1%)

Magnet Systems

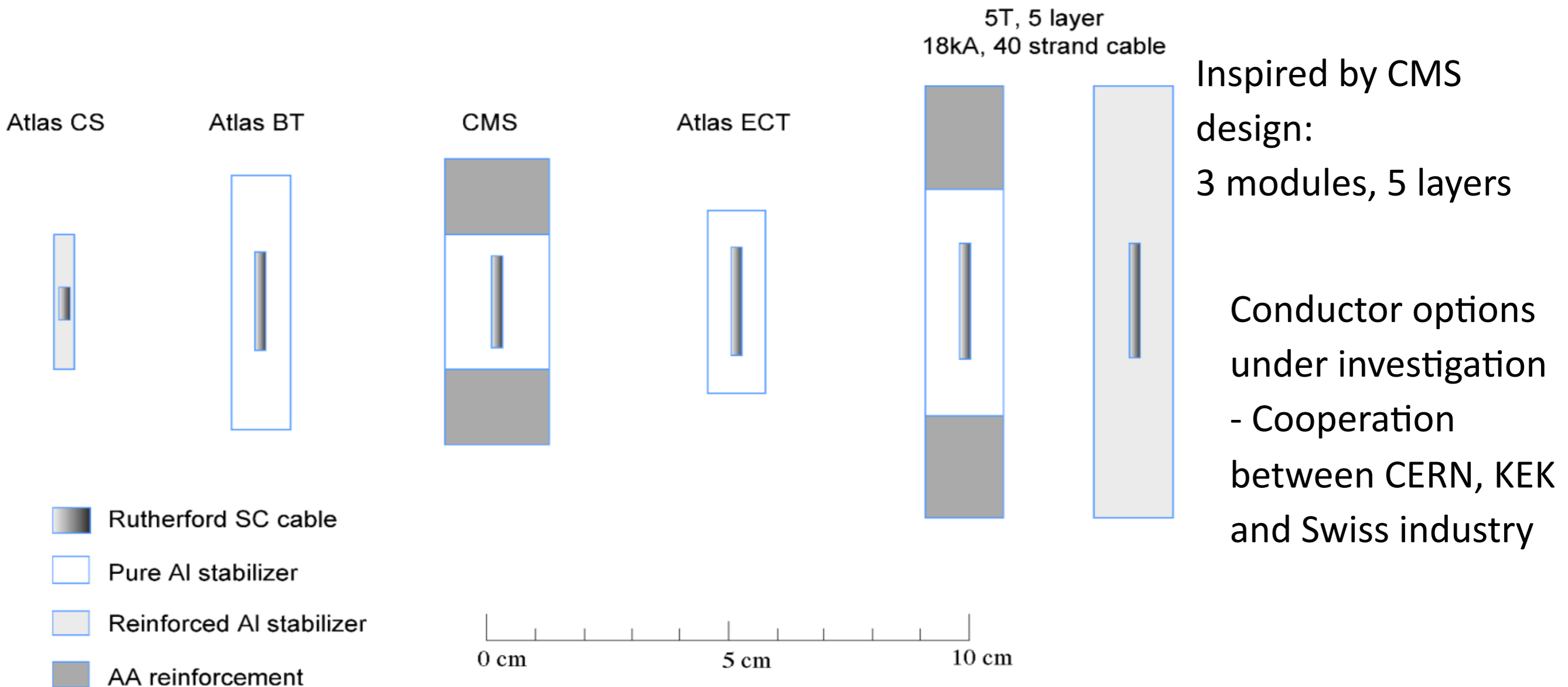
- Large solenoids for CLIC detectors push the technological limits
 - CLIC_SID most challenging: 5 T field - Extreme pressure on SC cable
Free bore 5.5 m, Length 6.2 m, Stored energy ~ 2.3 GJ, Energy/Mass ~ 14 kJ/kg
(CMS: 6 m, 12.5 m, 2.6 GJ, 11.6 kJ/kg)



Inspired by CMS
design:
3 modules, 5 layers

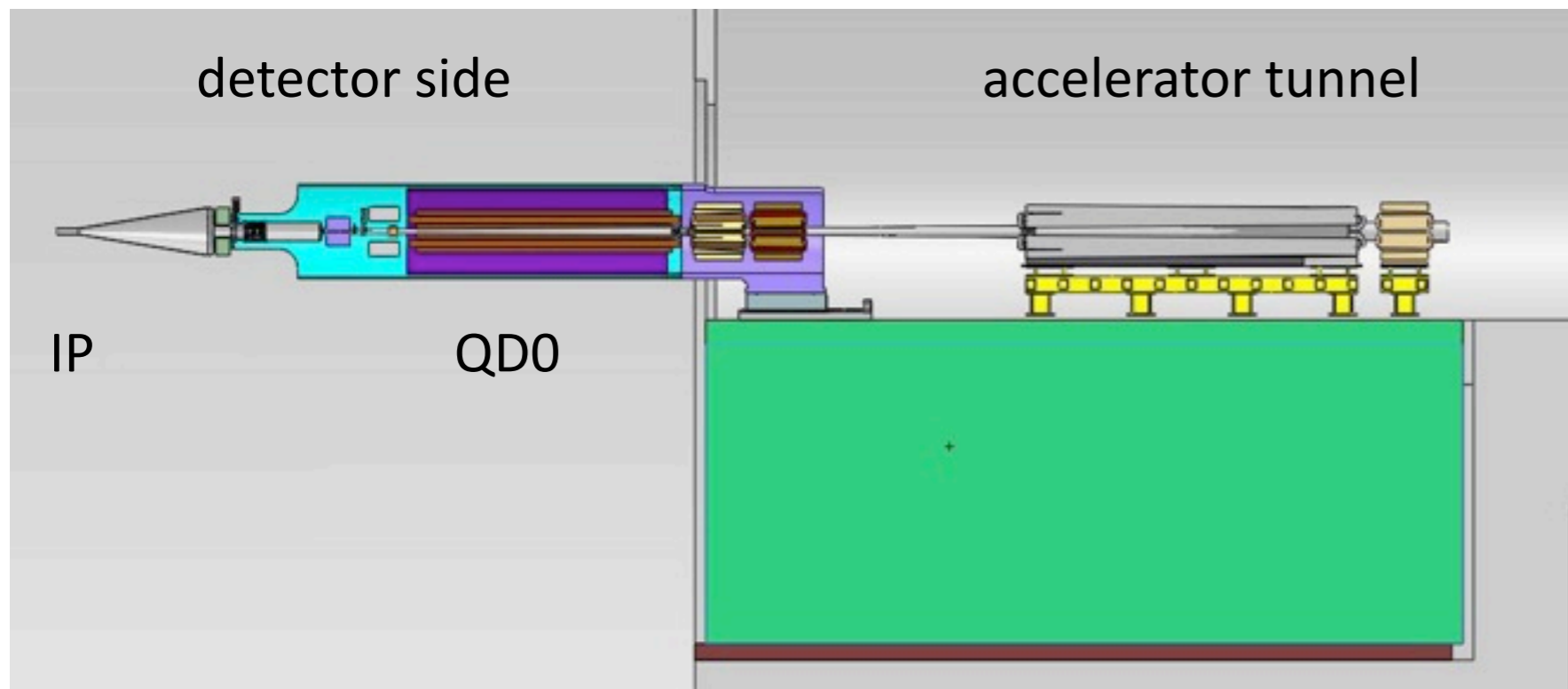
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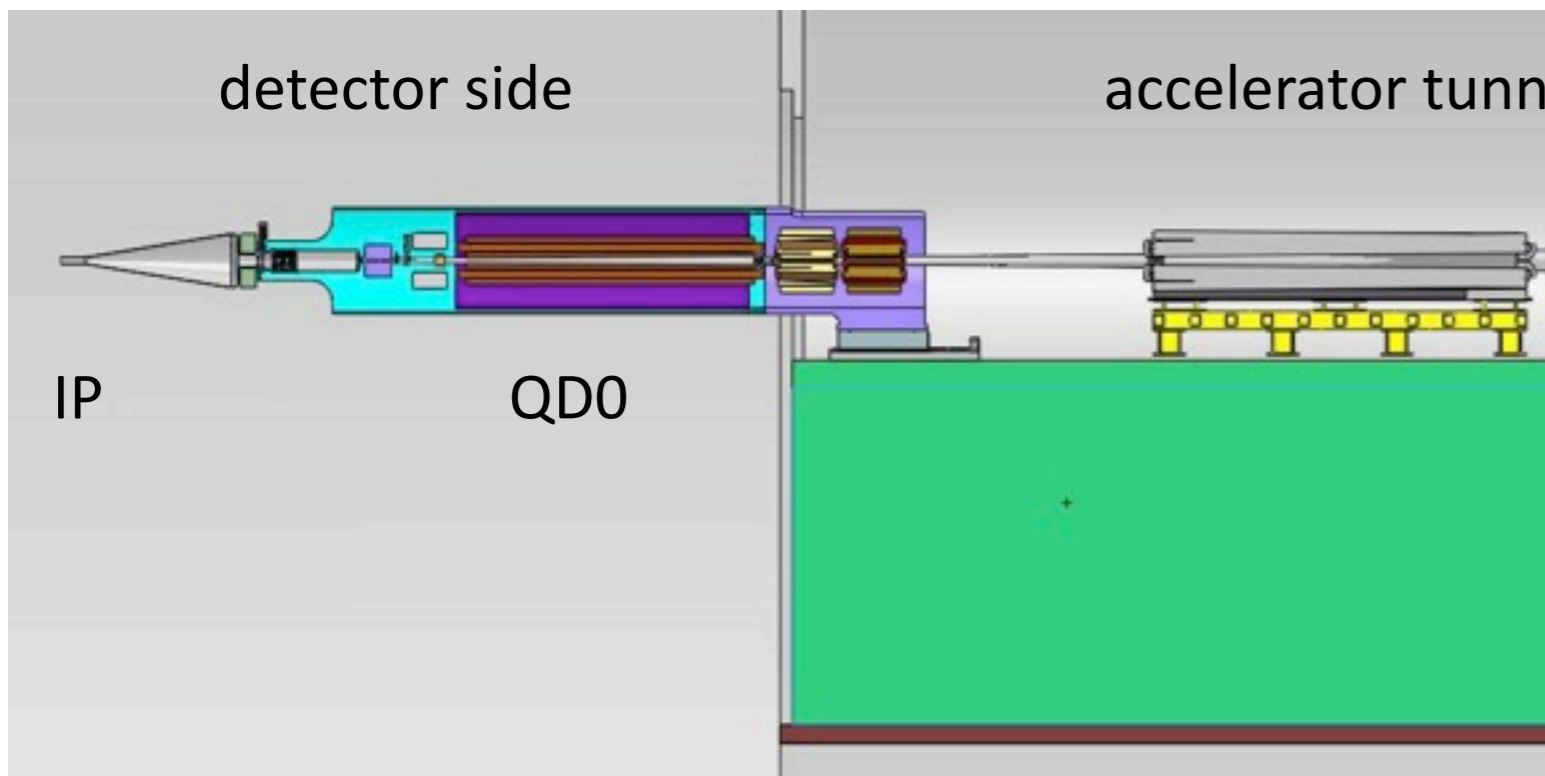
Mechanical Stability

- 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

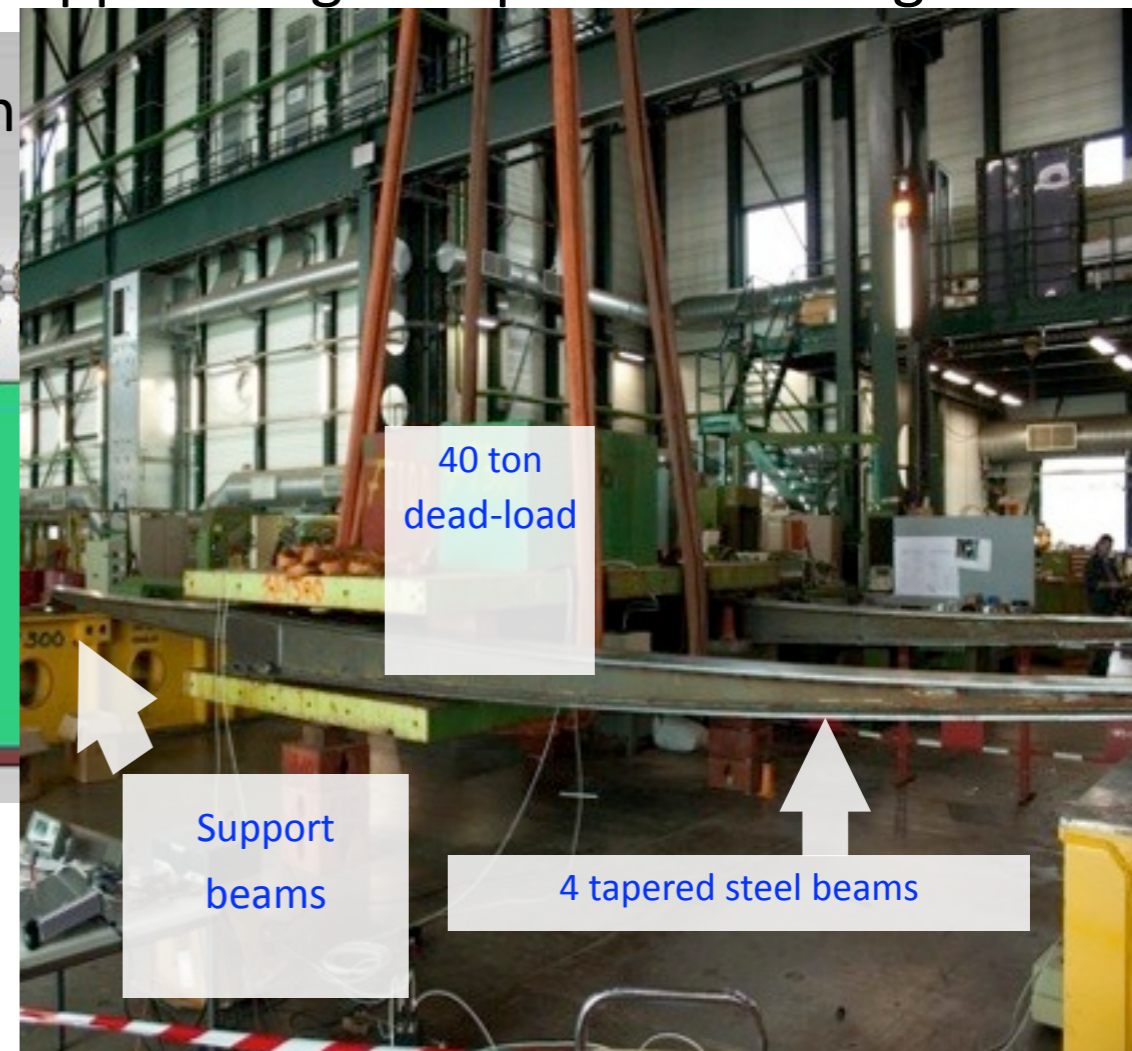


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Damping system under development,
simulations validated with mechanical experiment



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

