Future Detectors
-
Detector R&D and Physics Studies for Linear Colliders

Frank Simon
MPI for Physics & Excellence Cluster 'Universe'

MPP Project Review, December 2011

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

TUM
LMU
Excellence Cluster
Universe

The Group

- The Core Group
  - PhD Students

    Katja Seidel, Christian Soldner, Michal Tesar, Lars Weuste
  - Diploma/Master Students

    Simon Pfau, Marco Szalay
  - Scientist

    Ron Settles
  - Group Leader

    Frank Simon

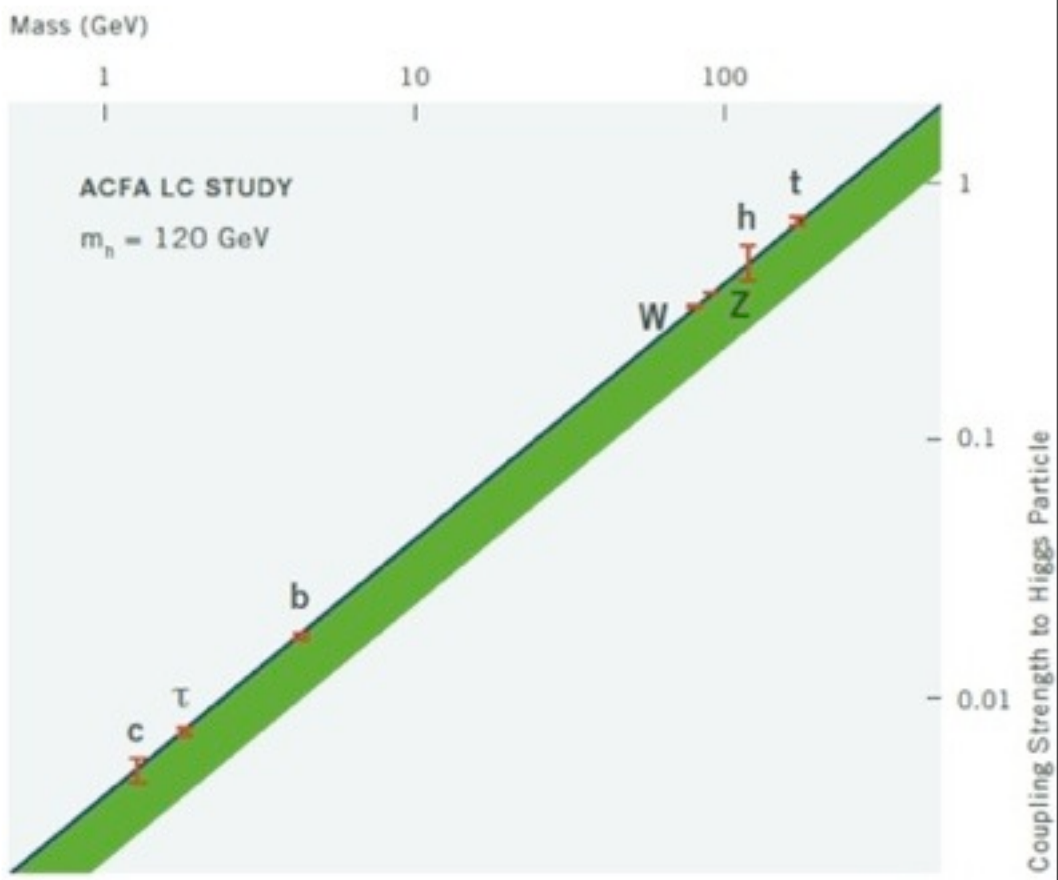
- Close collaboration with:
  - Belle / Belle-II - Excellence Cluster funded:

    Jeremy Dalseno, Andreas Moll, Kolja Prothmann; Student supervision: Christian Kiesling
  - HLL & Minerva Group

    Jelena Ninkovic, Christian Jendrysek, Hans-Günther Moser

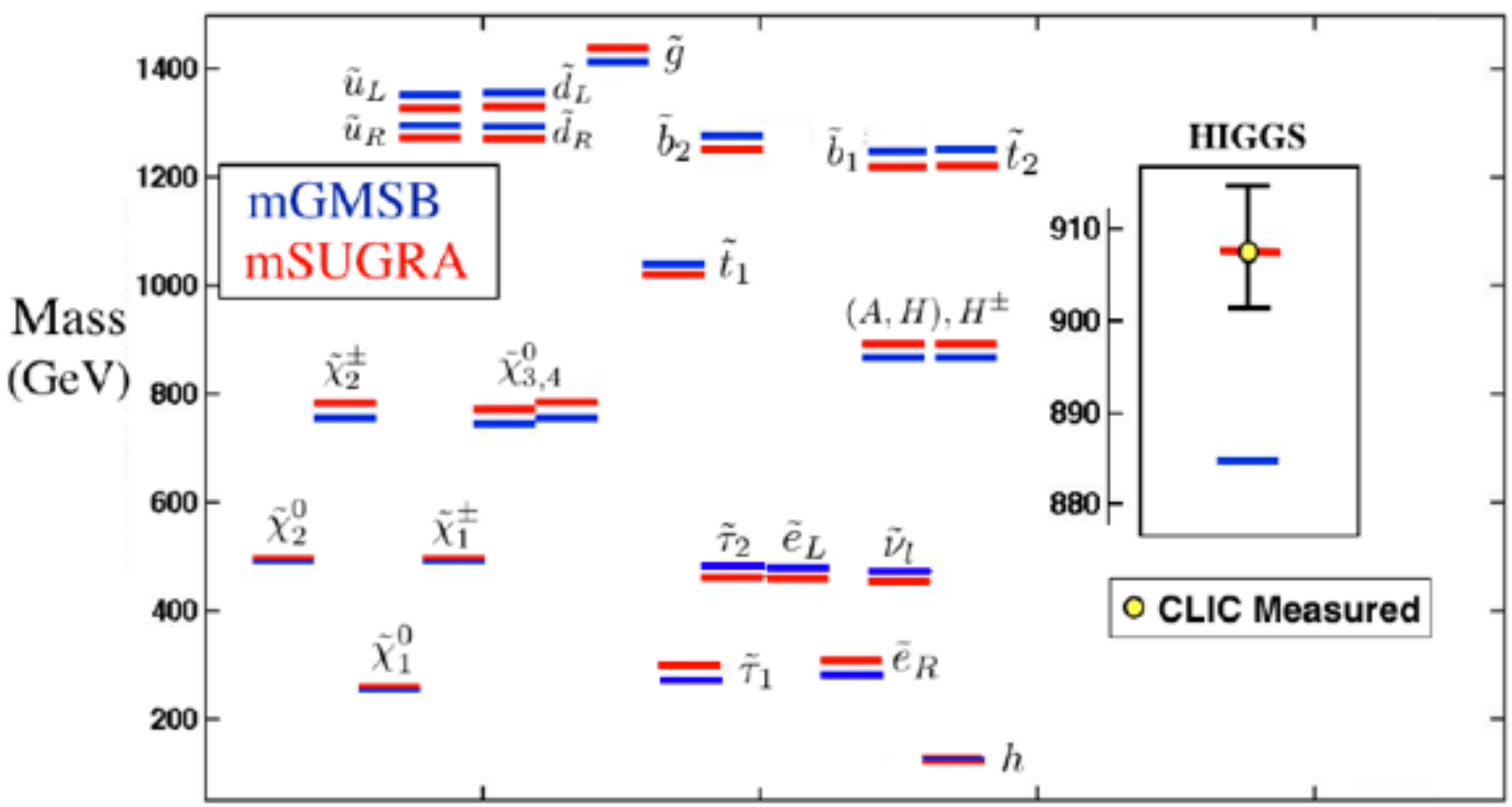
The Context: Linear Collider Physics

- Large international community planning for a future e^+e^- collider at the Terascale - Complementarity to the LHC
- The things we know:
  Precision measurements of SM Processes:
    - Top mass, width, asymmetry
    - WW production - Links to EW symmetry breaking
    - High statistics measurements at the Z pole
    - ...
- The things we expect:
  Precision Higgs studies:
    - Higgs mass, branching ratios
    - Higgs coupling to top, heavy bosons
    - Higgs self-coupling (quite a challenge!)



The Context: Linear Collider Physics

- The things we definitely have not given up on yet:
  Physics beyond the Standard Model
  - A linear collider provides excellent sensitivity to weakly interacting states that are more difficult to discover at LHC: Direct production vs occurrence in decay chains of strongly interacting heavy new particles

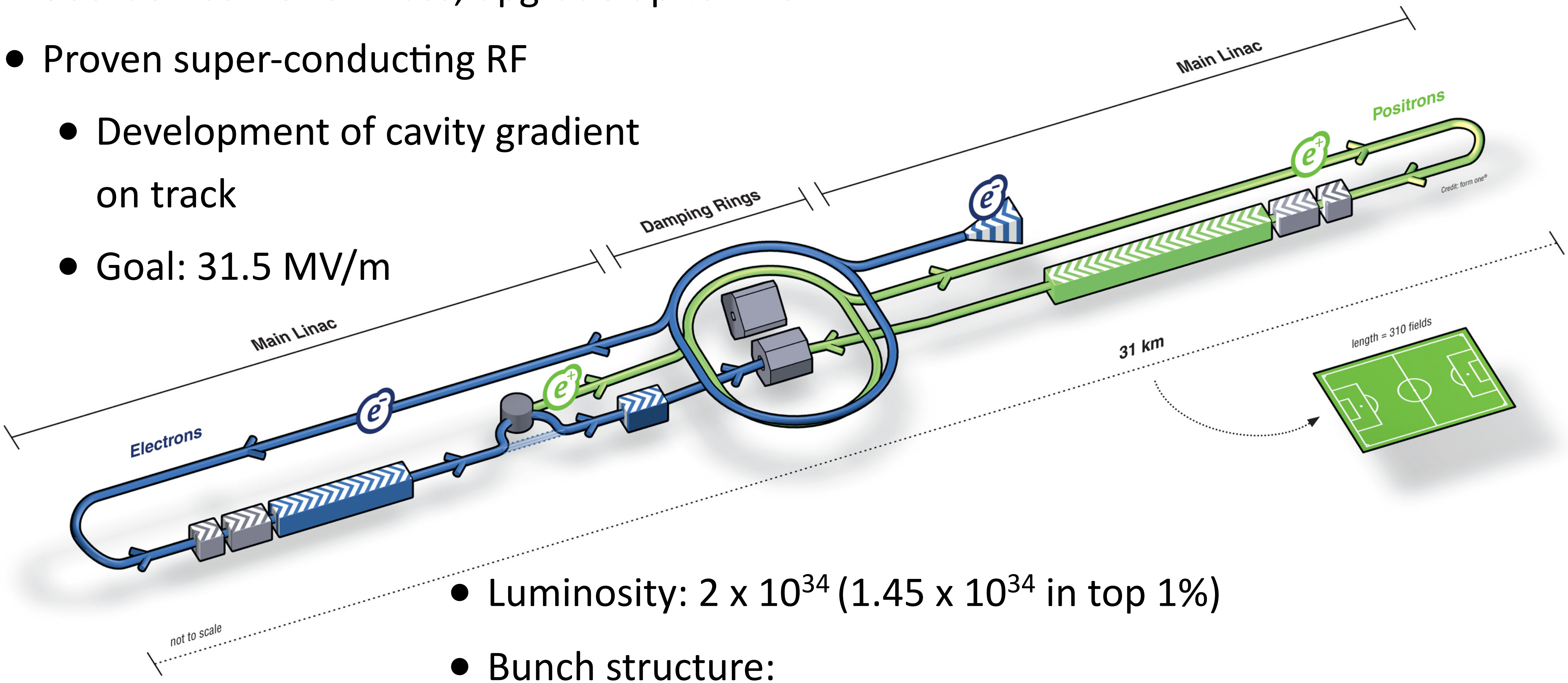


For example: Distinguishing SUSY breaking mechanisms through precision spectroscopy

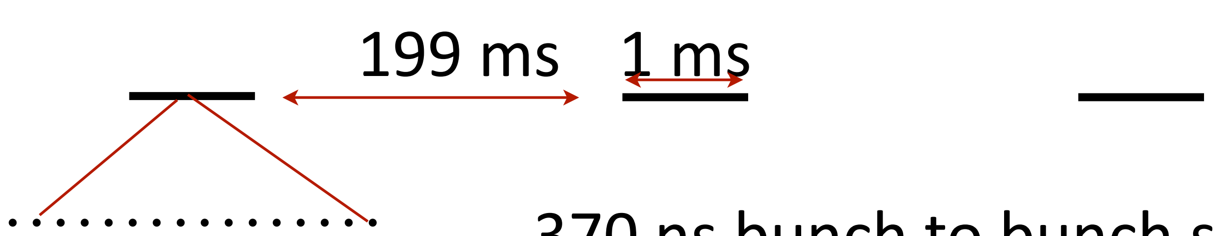
Also: Extended sensitivity to high-mass scales through precision measurements

The Context: Future Linear Colliders: ILC

- The International Linear Collider ILC
  - 500 GeV center of mass, upgrade up to 1 TeV
  - Proven super-conducting RF
    - Development of cavity gradient on track
    - Goal: 31.5 MV/m



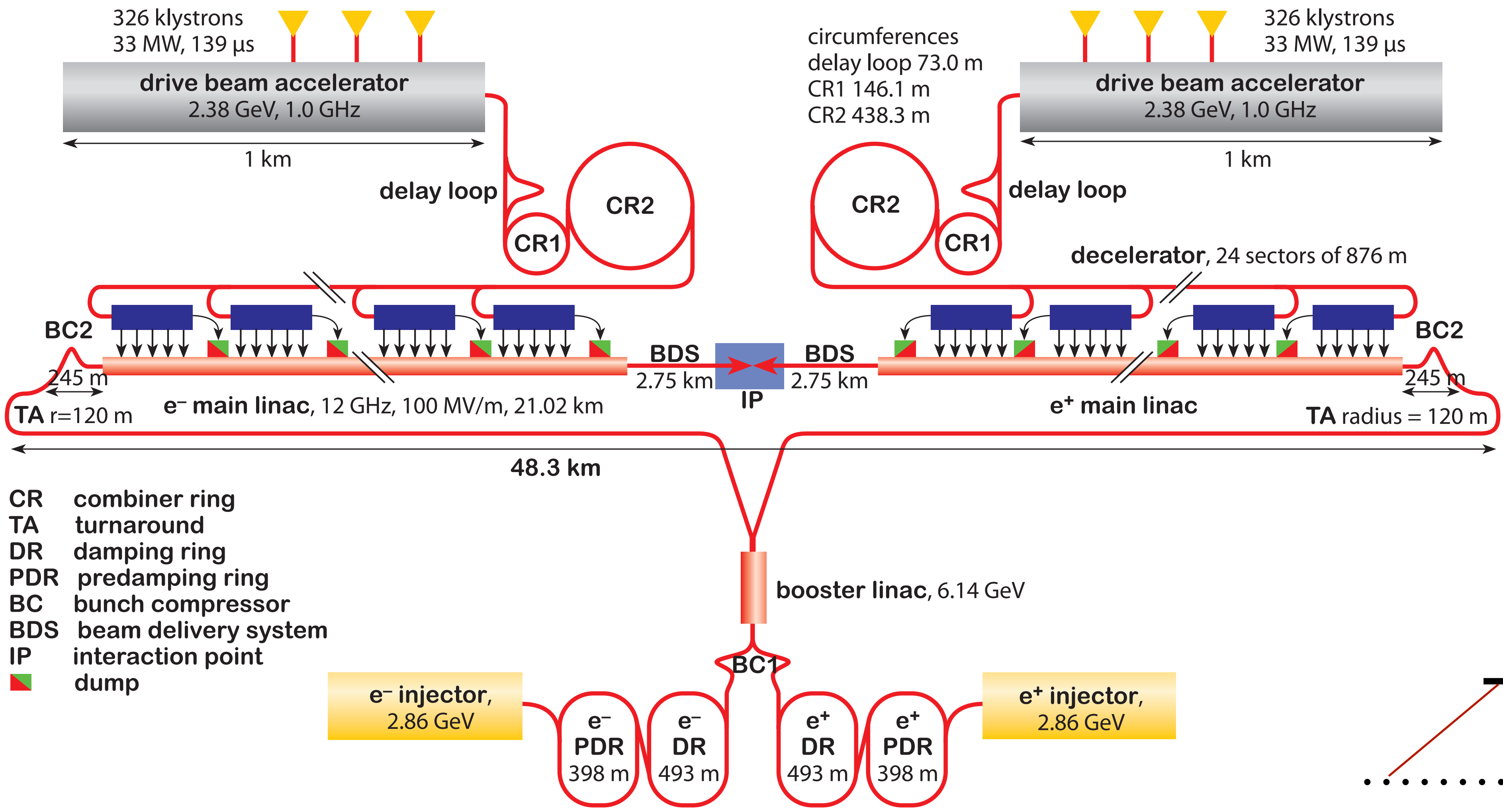
- Luminosity: 2 x 10^{34} (1.45 x 10^{34} in top 1%)
- Bunch structure:



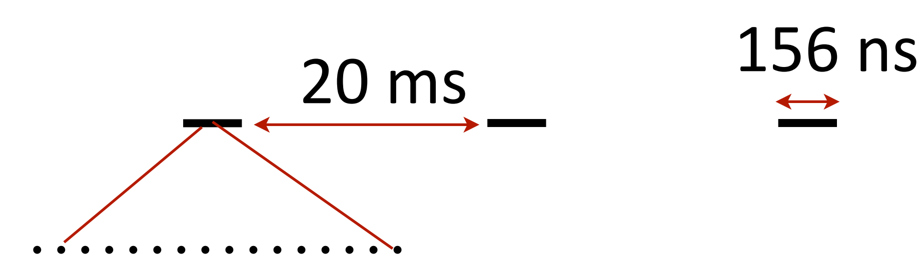
370 ns bunch to bunch spacing

The Context: Future Linear Colliders: CLIC

- The Compact Linear Collider CLIC
  - 3 TeV center of mass energy (staged construction: ~ 500 GeV initially)
  - 2-beam acceleration using warm cavities (in development): 100 MV/m gradient



- Luminosity: 5.9×10^{34} (2×10^{34} in top 1%)
- Bunch structure:



0.5 ns bunch to bunch spacing: Pile-up of hadronic background - 15 TeV per bunch train

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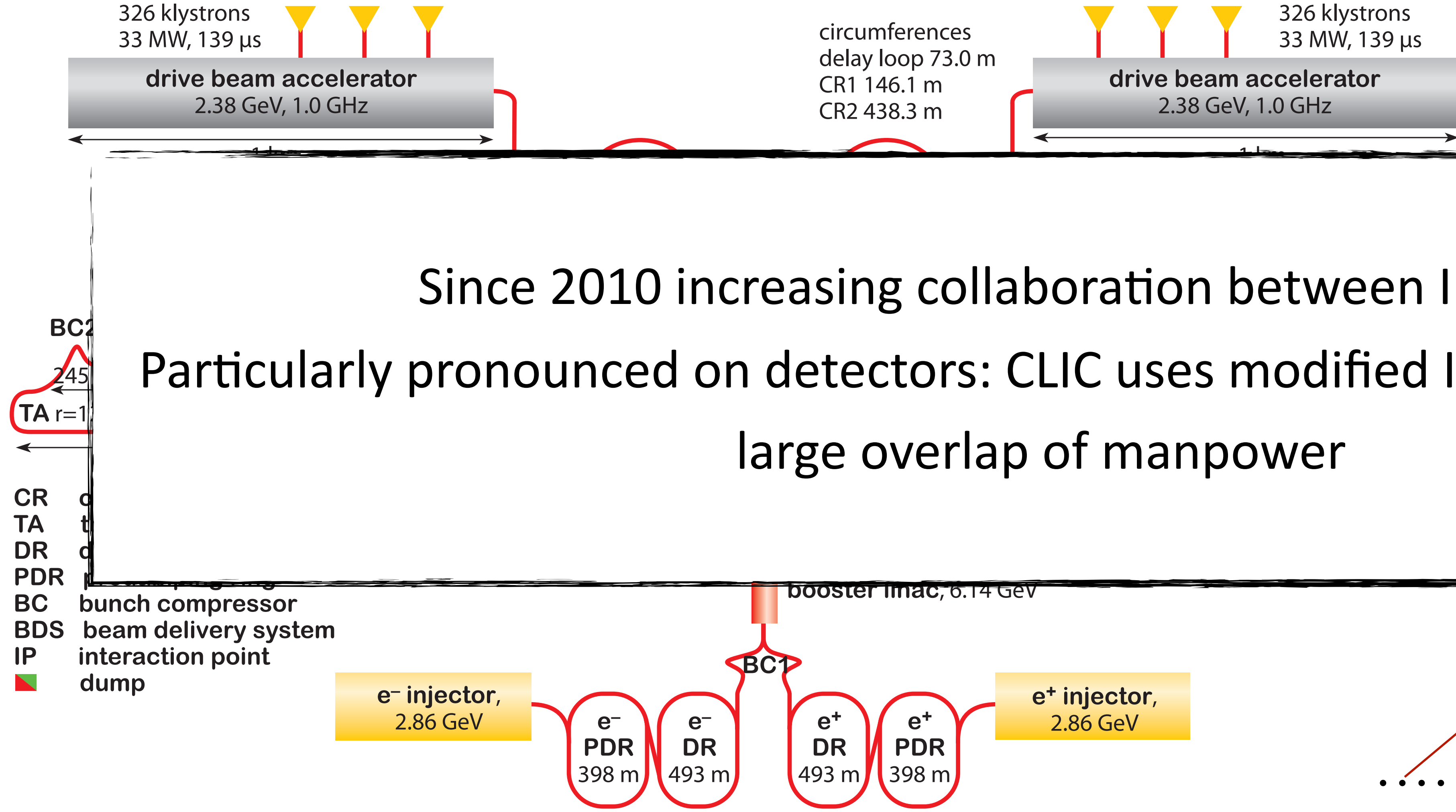
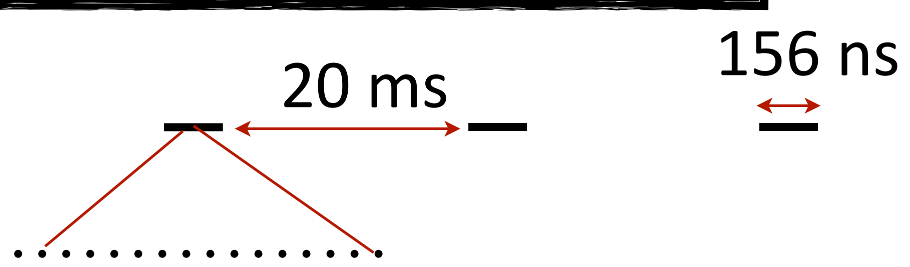


Since 2010 increasing collaboration between ILC & CLIC

Particularly pronounced on detectors: CLIC uses modified ILC detector concepts, large overlap of manpower

10^{34}

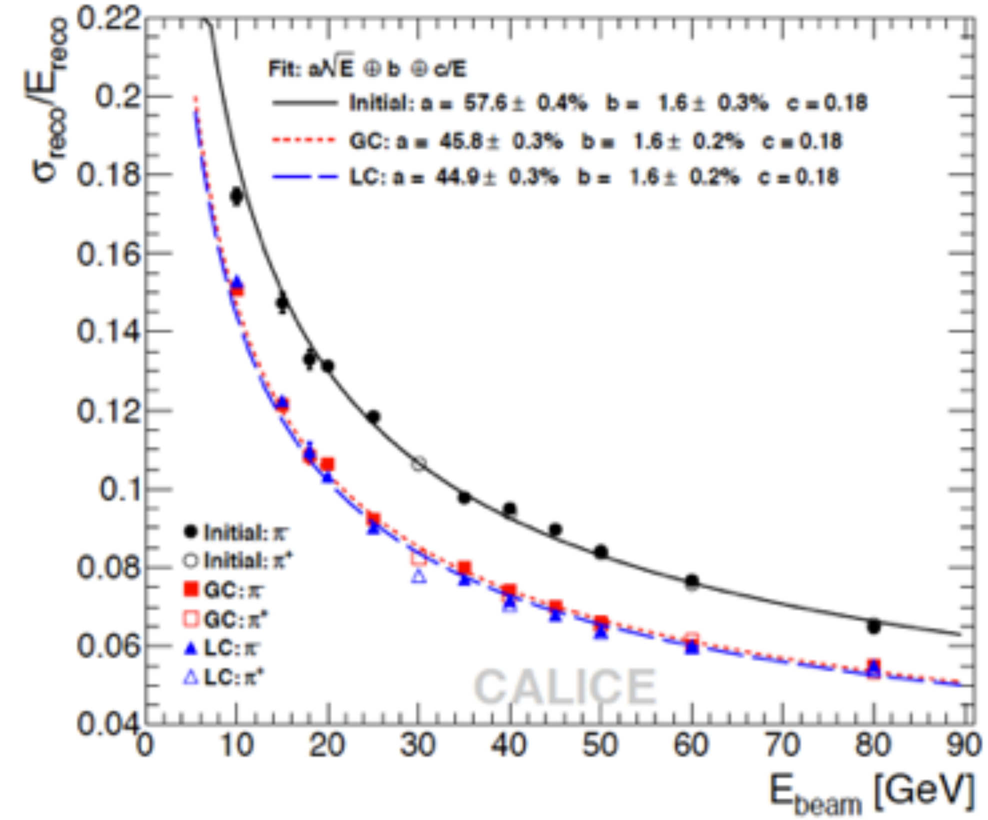
%)



0.5 ns bunch to bunch spacing: Pile-up of hadronic background - 15 TeV per bunch train

Hadron Calorimetry at Linear Colliders

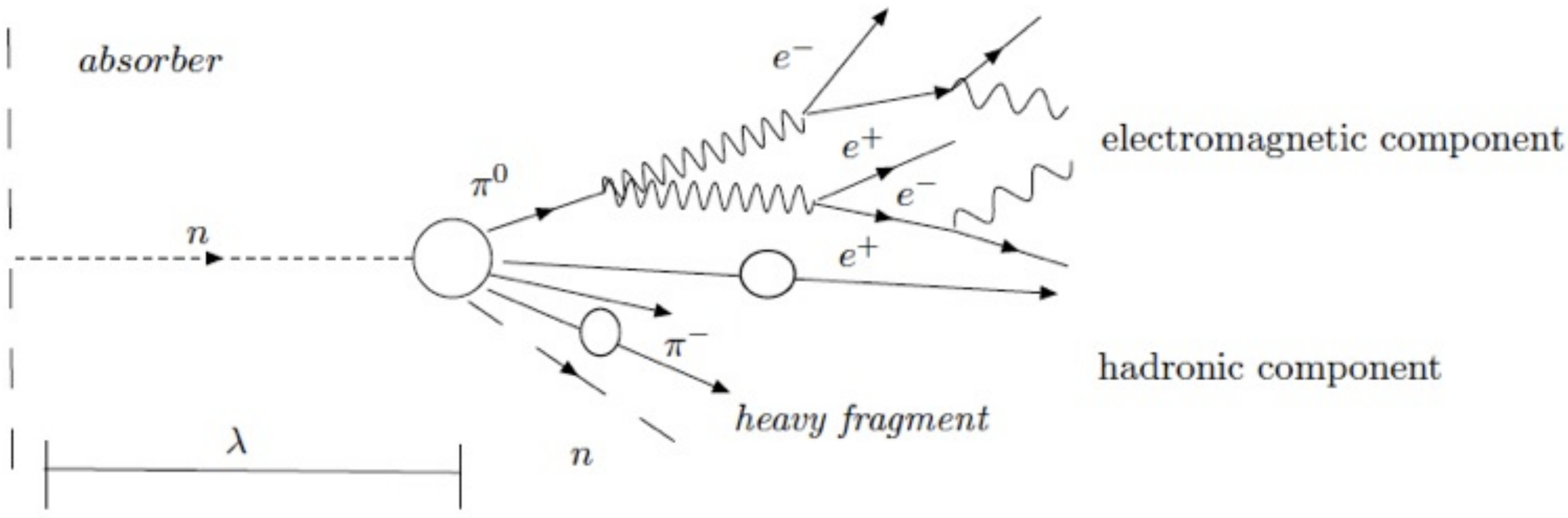
- Imaging calorimeters with high granularity crucial for precise jet energy reconstruction using particle flow
  - Requires the use of new technologies: small scintillator tiles with SiPM readout
    Extensively studied within CALICE collaboration
    MPP results being prepared for publication:
    - Energy resolution
    - Shower substructure
    - Calibration



- Particular challenges at CLIC: Very high energy, requires deep calorimeters
  - Use Tungsten absorbers to satisfy space constraints:
    Requires extensive test beam program to evaluate - Carried out in 2010 and 2011

Hadronic Showers: Complex (Time) Structure

- Hadronic showers have a rich substructure:



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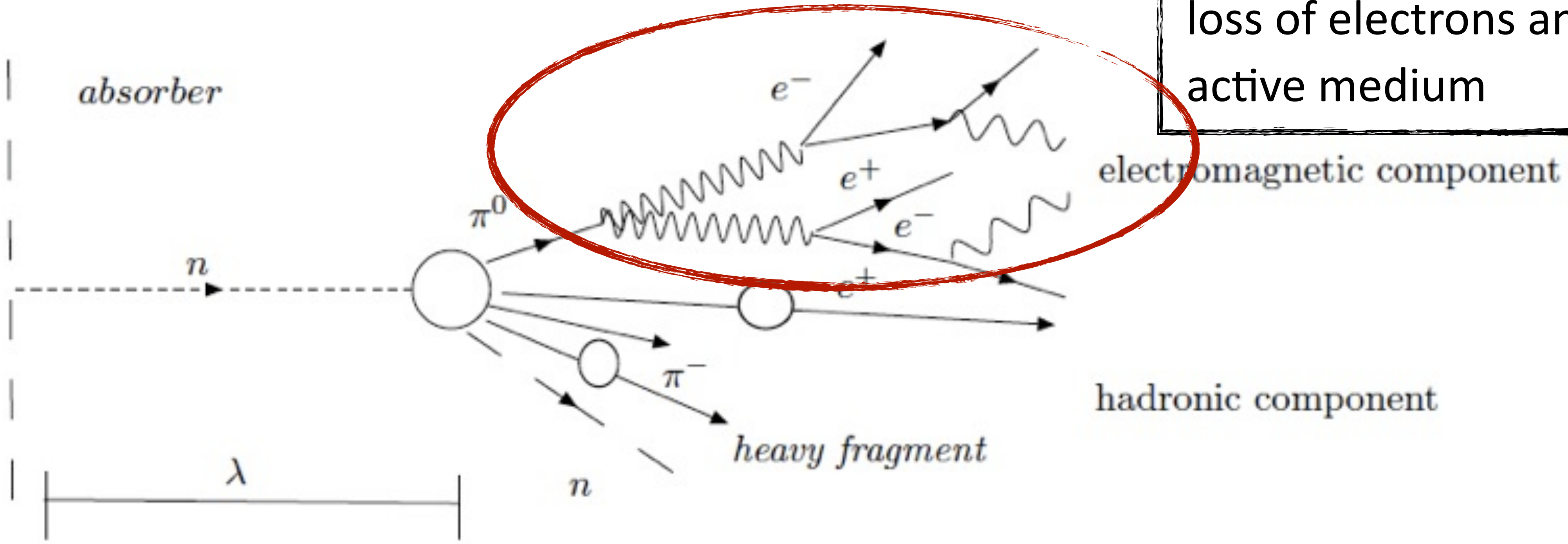
instantaneous, detected via energy loss of electrons and positrons in active medium



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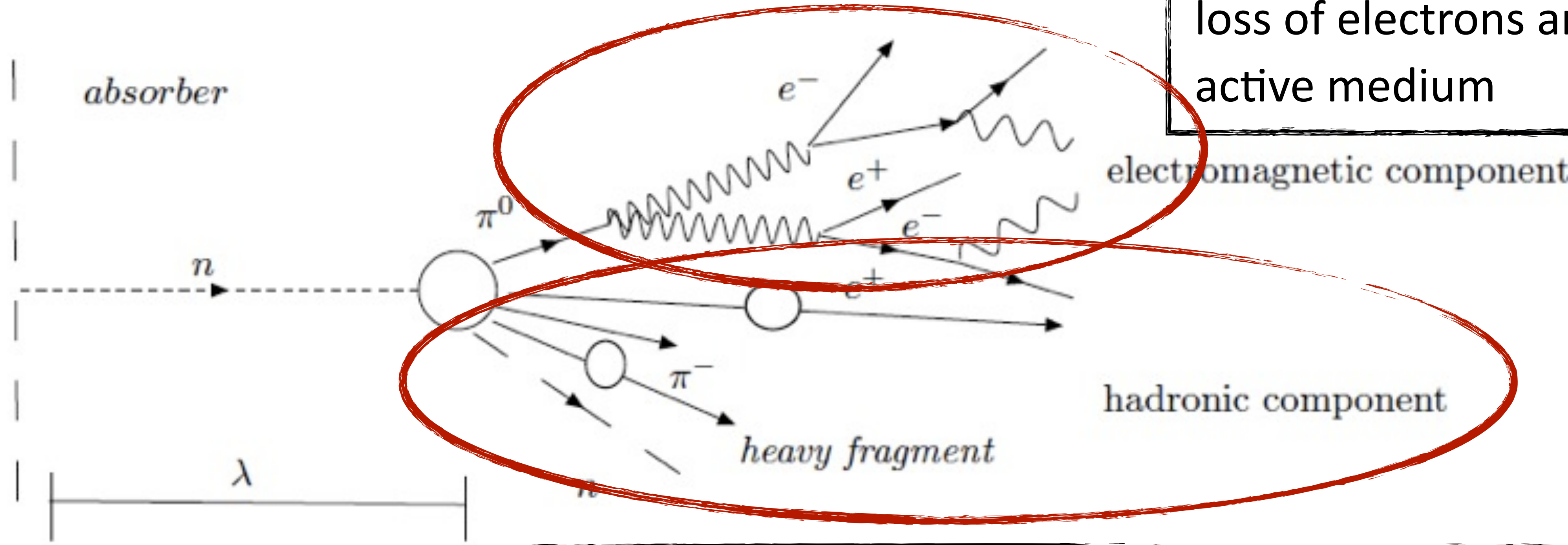

- instantaneous component: charged hadrons detected via energy loss of charged hadrons in active medium
- delayed component: photons, neutrons, protons from nuclear de-excitation, detected via e^+e^-, momentum transfer to protons in hydrogenous active medium, energy loss, contributions from time of flight of low energy particles

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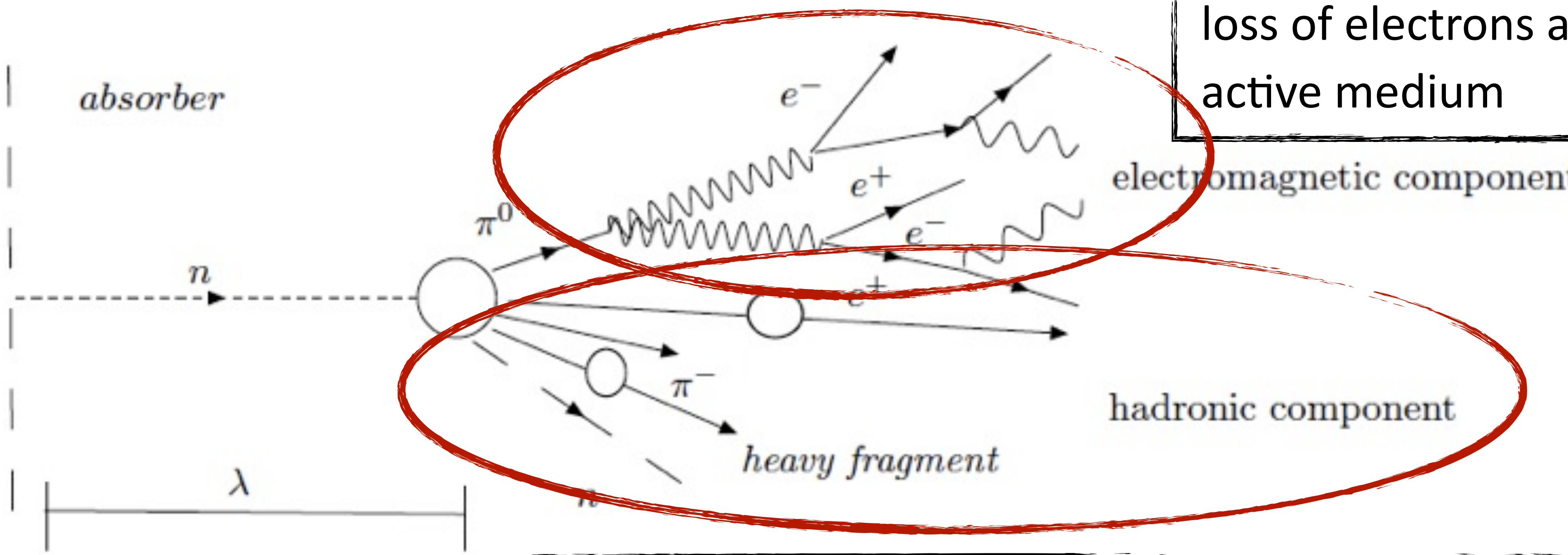

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➯ Importance of delayed component strongly depends on target nucleus

➯ Sensitivity to time structure depends on the choice of active medium

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- Hadronic showers have a rich substructure:

instantaneous, detected via energy loss of electrons and positrons in active medium

Detector optimization and performance studies rely on Geant4:

How well do the simulations reproduce the time structure of the response in the CLIC HCAL?

Crucial for background rejection at CLIC!

nergy

ear

tons

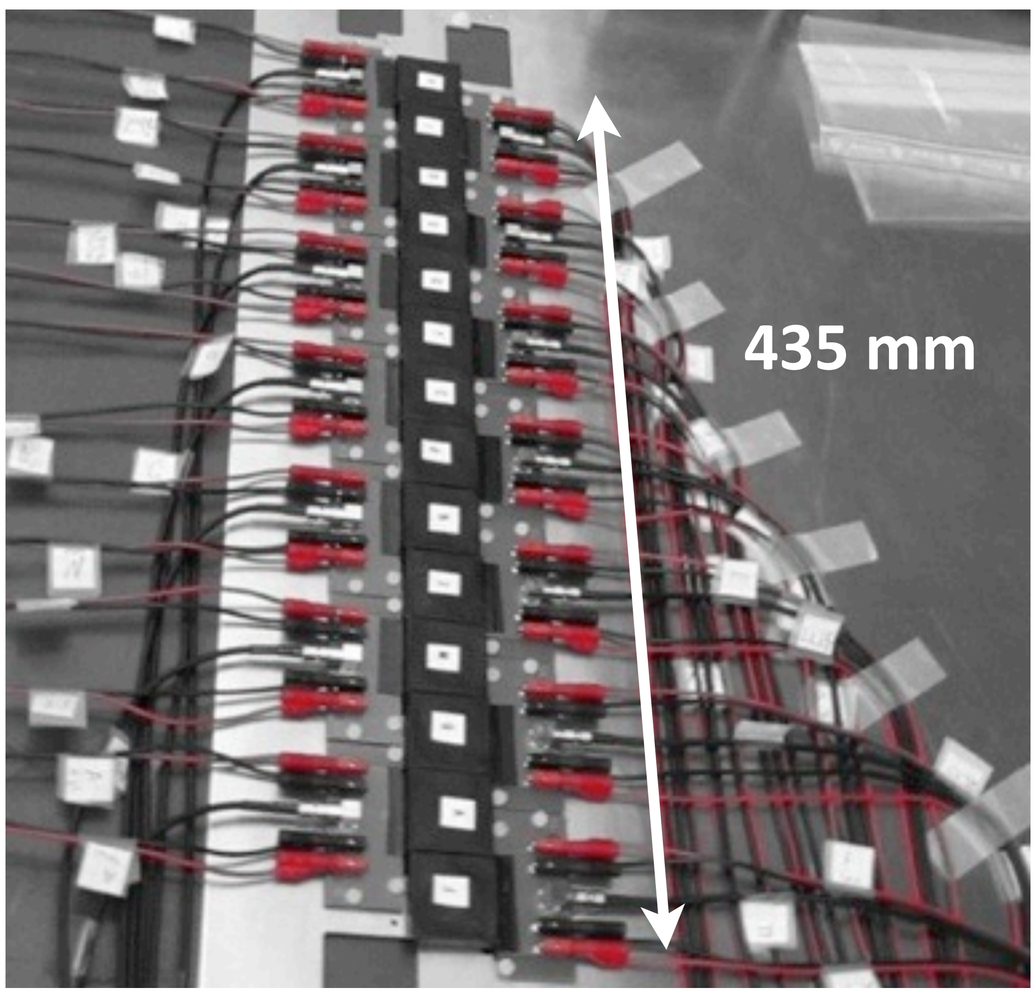
in hydrogenous active medium, energy loss, contributions from time of flight of low energy particles

➩ Importance of delayed component strongly depends on target nucleus

➩ Sensitivity to time structure depends on the choice of active medium

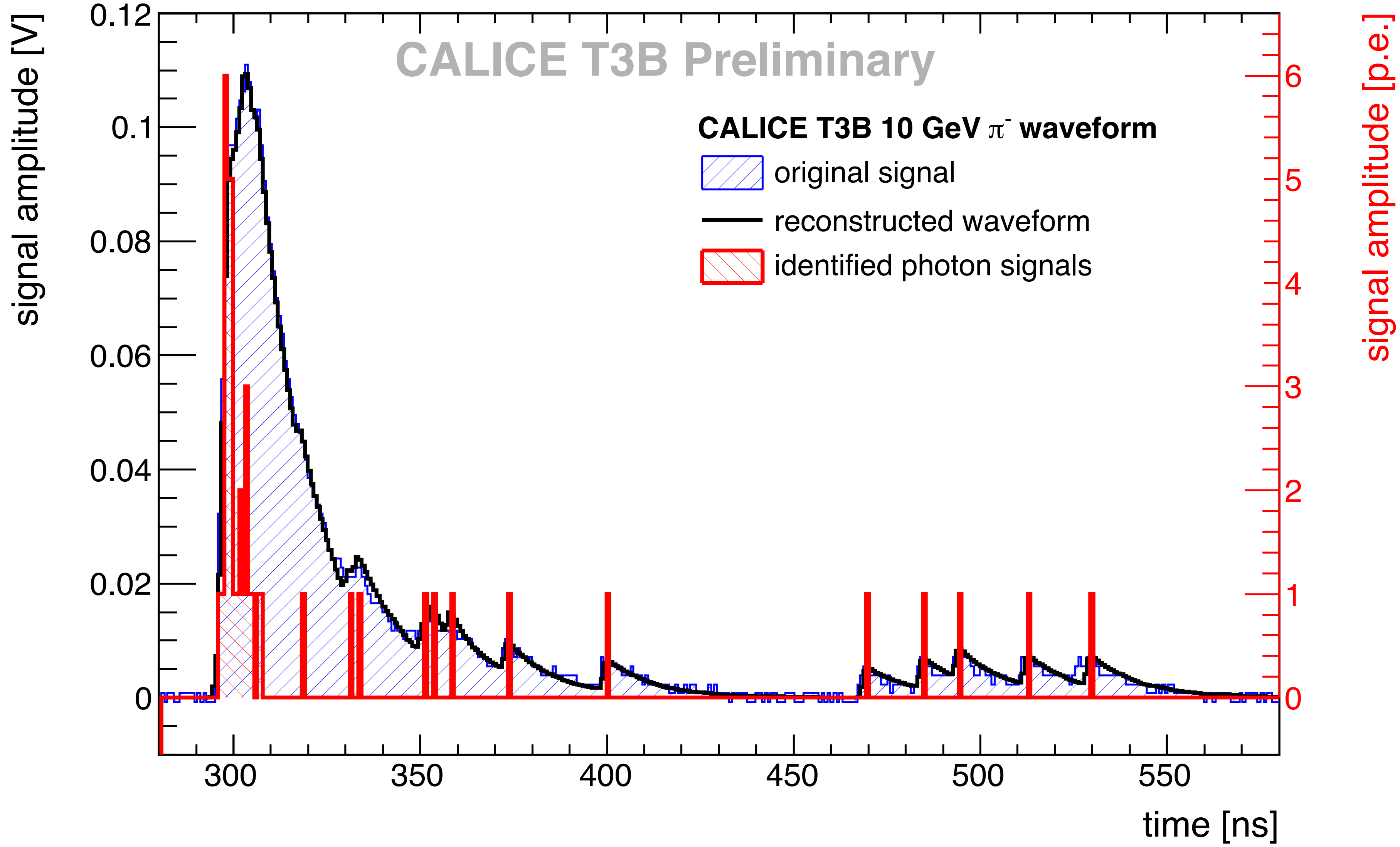
T3B - A Dedicated Detector to Study Timing

- Detector simulations rely on GEANT4 - How well does G4 reproduce the time structure of hadronic showers?
- T3B - 15 scintillator tiles with SiPM readout behind the CALICE WHCAL, DAQ with fast digitizers (USB oscilloscopes) 0.8 ns resolution, 2.4 μs acquisition window

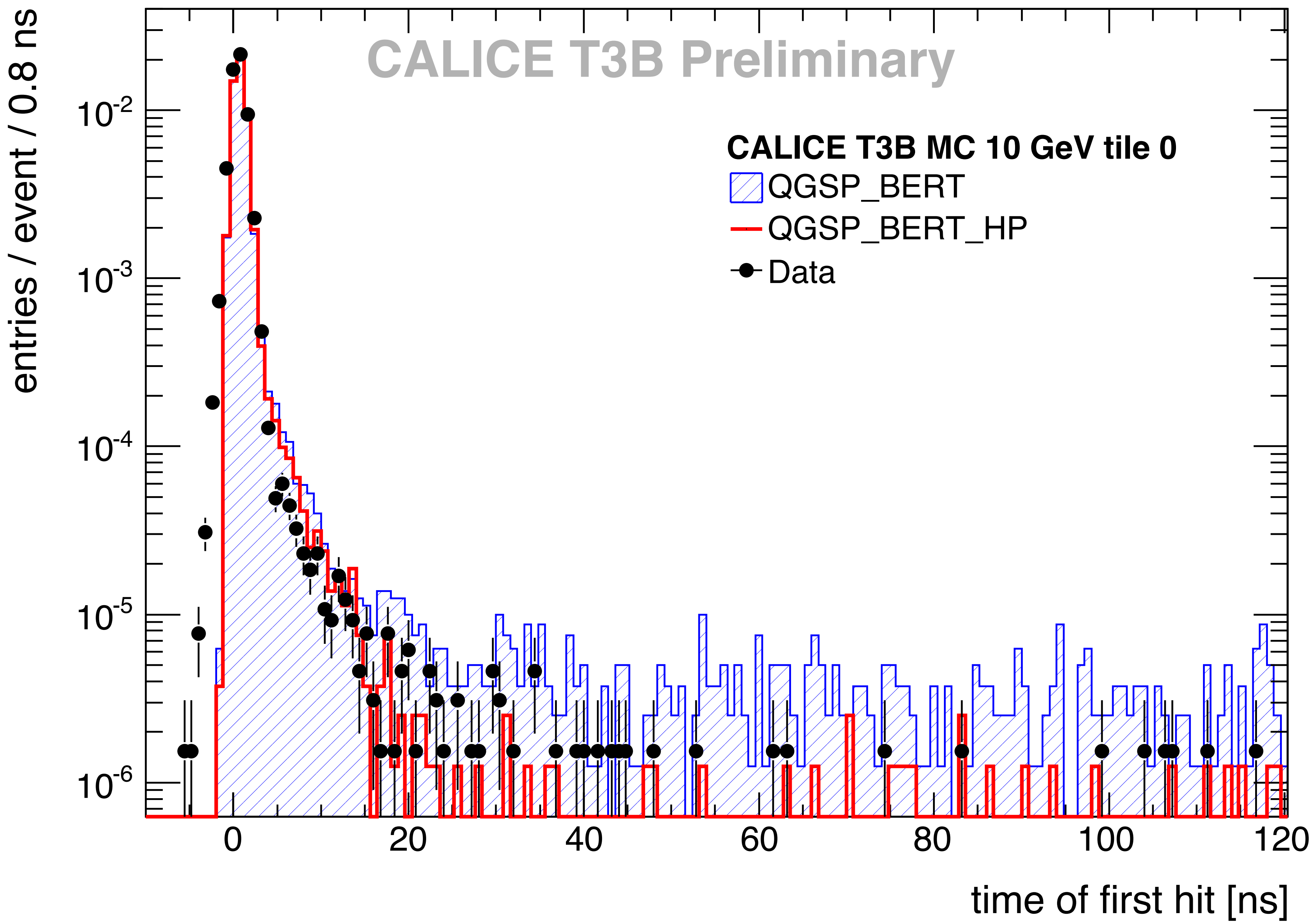


Data Analysis - Technique

- For each channel, a complete waveform with 3000 samples (800 ps /sample) is saved
- Waveform decomposed into individual photon signals, using averaged 1 p.e. signals
  - Average single photon signal taken from calibration runs between spills, refreshed every 5 minutes: Continuous automatic gain calibration
- Reconstruction of the time of each photo-electron



Data & Simulations - First Results



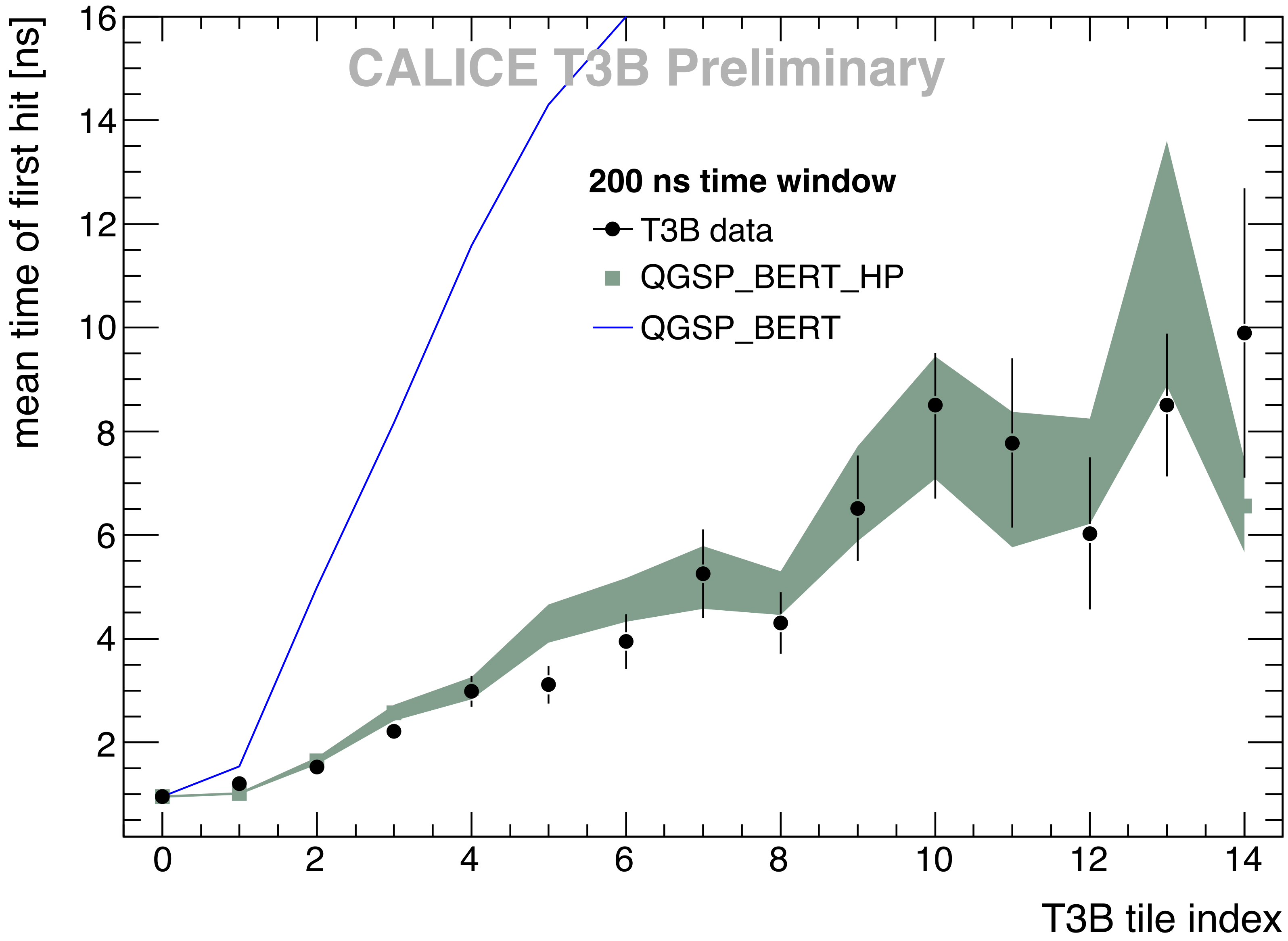
Central T3B cell:

Distribution of the

Time of First Hit

- QGSP_BERT shows a pronounced tail of late energy depositions
- Data agrees better with QGSP_BERT_HP - Reduced activity beyond 20 ns

Data & Simulations - First Results



Compact Comparison:

Mean Time of First Hit

- calculated in a time window of 200 ns (-10 ns to 190 ns from maximum in tile 0)
- Data consistently described by QGSP_BERT_HP
    - QGSP_BERT deviates strongly

Here: tail of the shower, where late deposits are most prominent!

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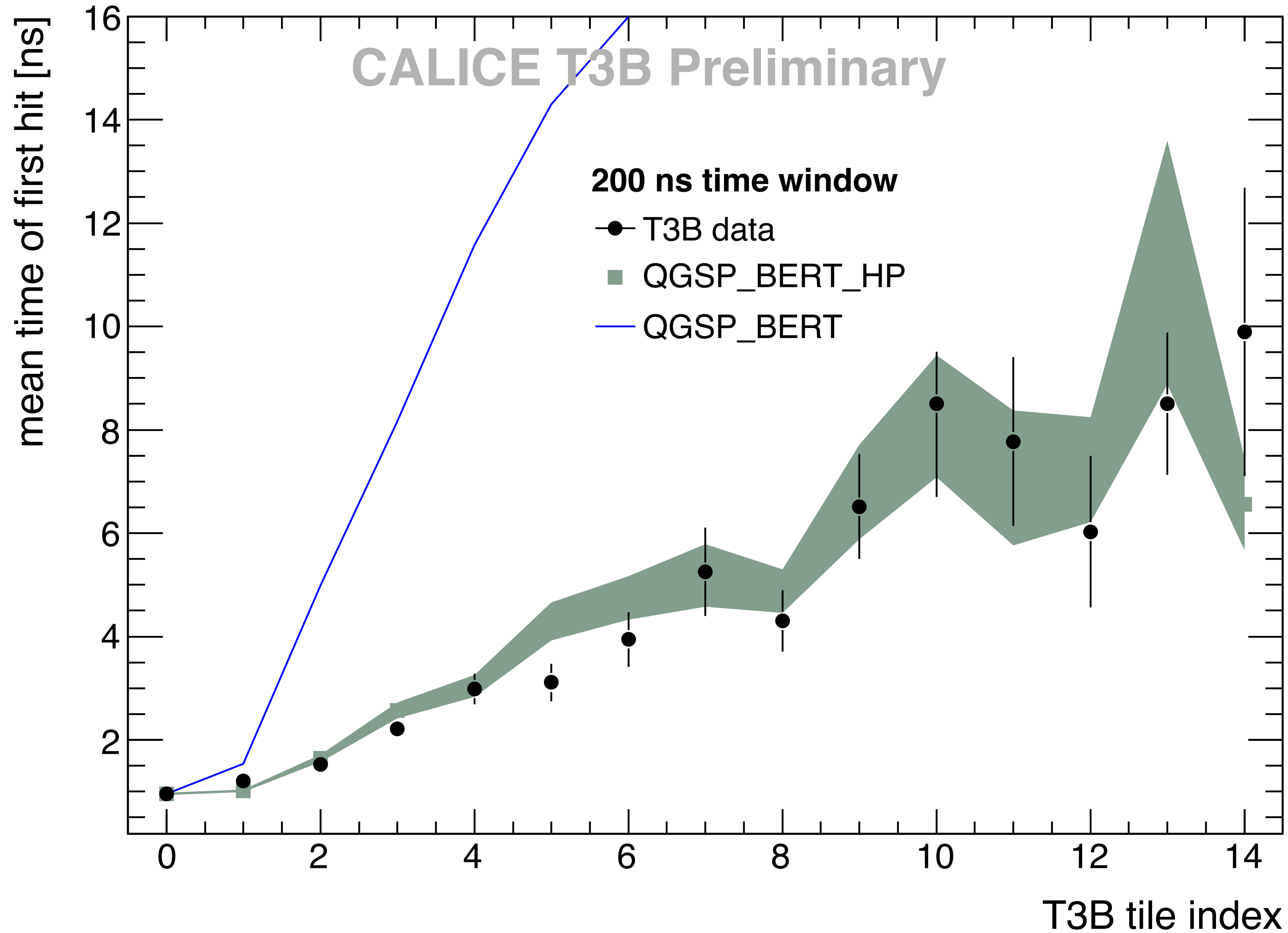

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➡ High precision neutron tracking or other means to suppress excessive late energy depositions necessary to describe observed time structure in T3B

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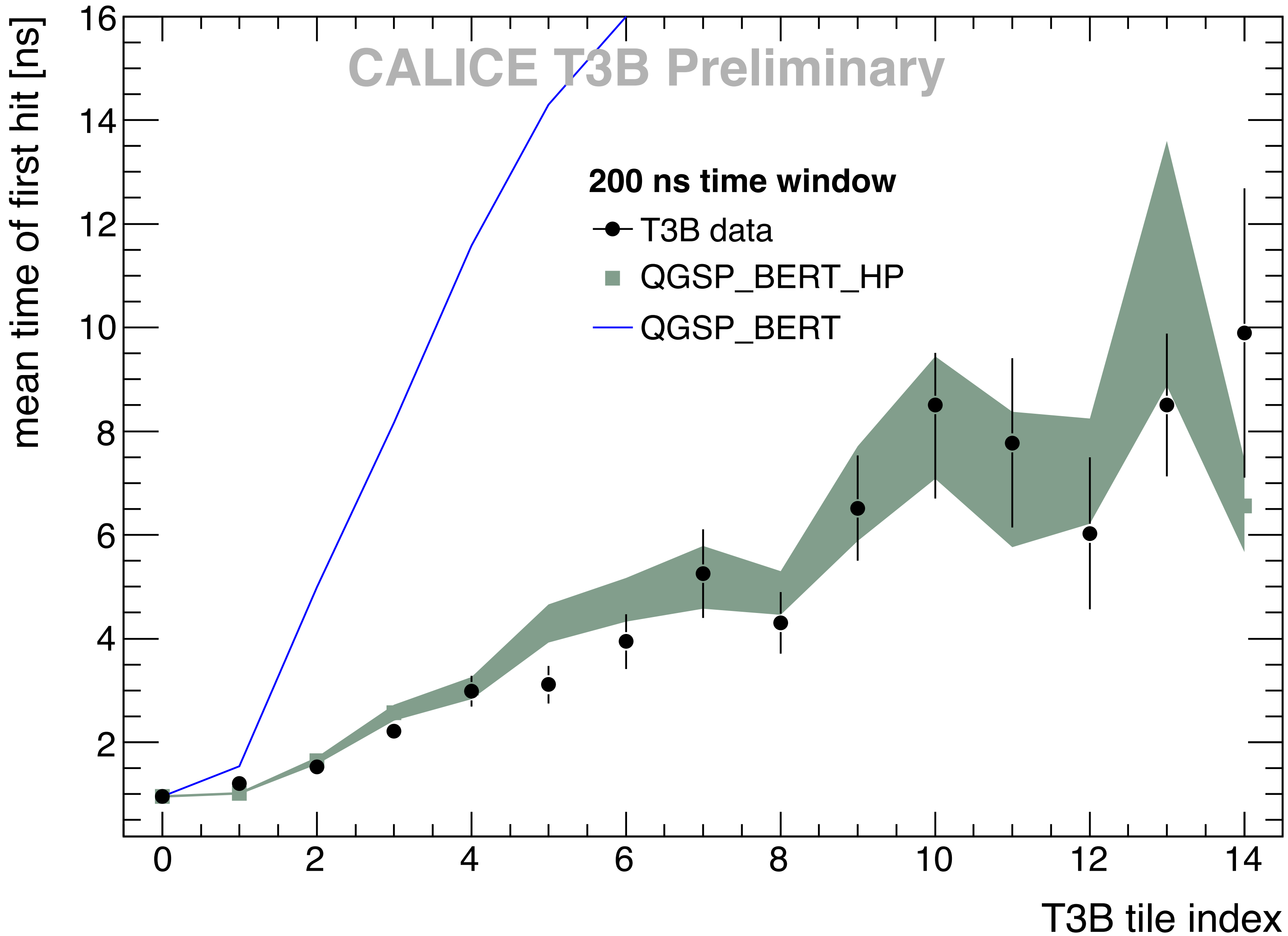

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➯ High precision neutron tracking or other means to suppress excessive late energy depositions necessary to describe observed time structure in T3B

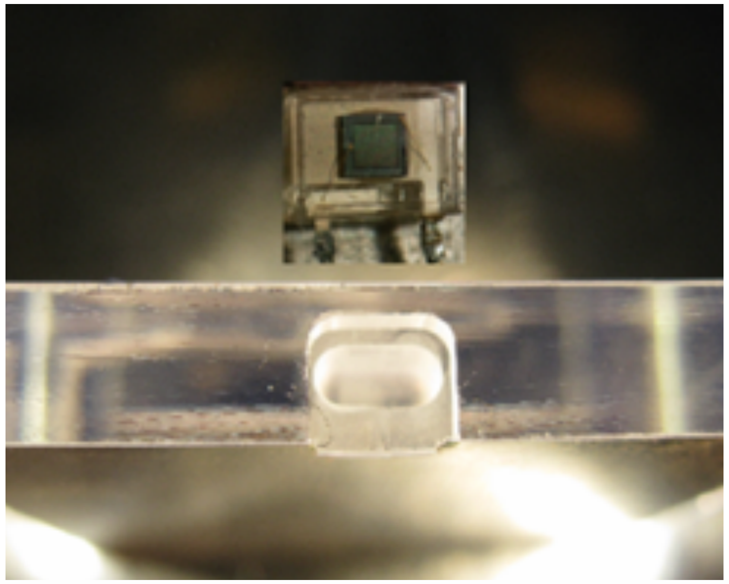
➯ Simulations with QGSP_BERT give a pessimistic estimate of the duration of hadronic showers: Real timing performance of CLIC HCAL probably better!

Technology Development - Scintillators & SiPMs

- Currently transferring developed scintillator tile geometry for fiberless SiPM readout to mass production - Collaboration with ITEP, DESY, UHH

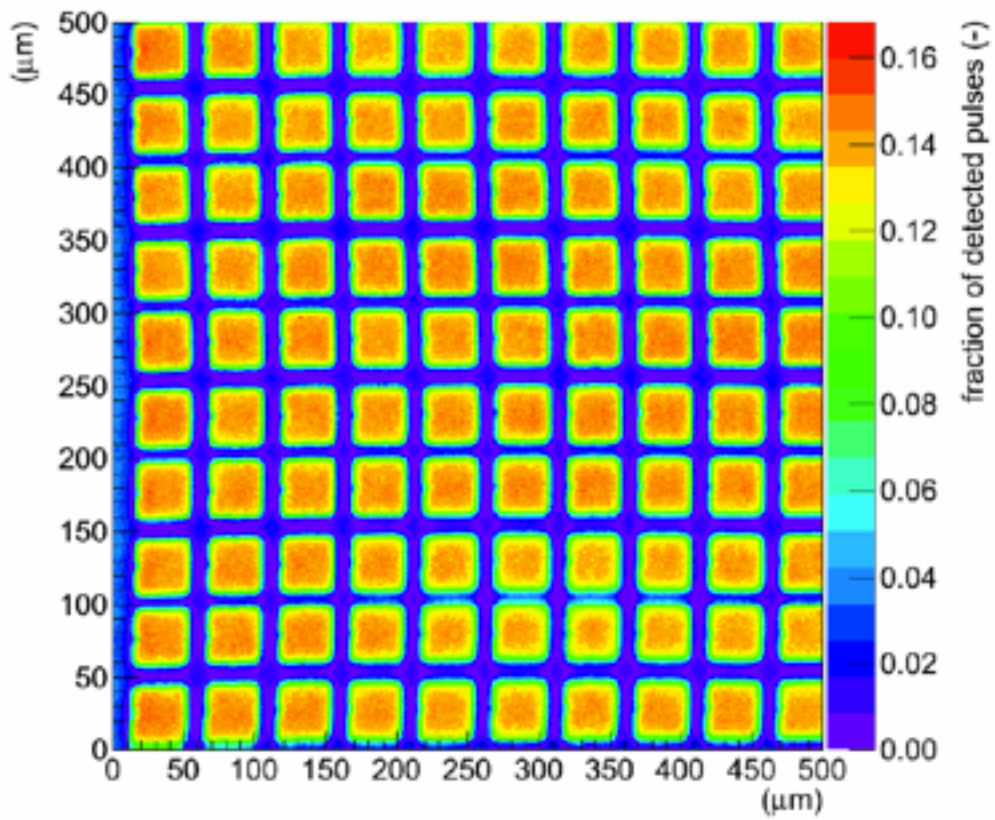
Studying performance of different coatings, different manufacturing techniques, scintillation material, ...

Timing studies with fast UV LED pulses



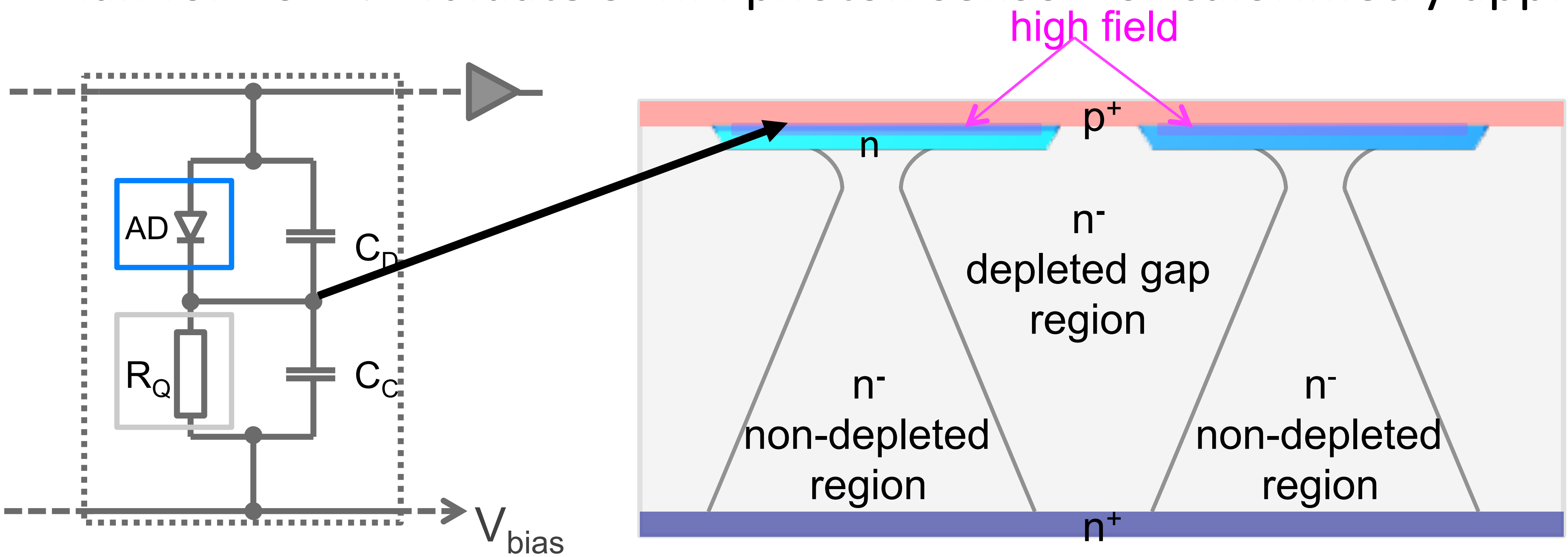
- Developed a scanning setup for precision measurement of SiPM properties:
  spacial features of light detection efficiency, cross talk, ...

- Detailed studies of environmental effects

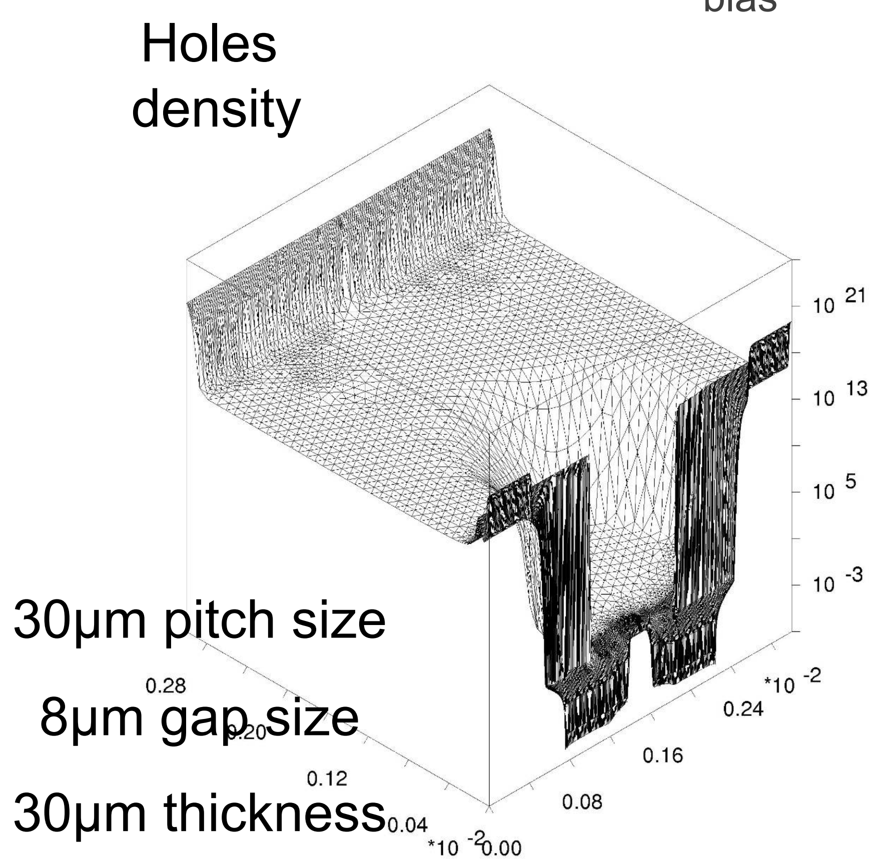


Detector Development - Scintillators & SiPMs

- Plan for 2012: Evaluate SiMPl photon sensor for calorimetry application



J. Ninkovic et al.



- Designs for small pixel devices exist and have been extensively simulated
  - Provides large dynamic range needed for calorimetry
  - Expect improved sensitivity and reduced noise compared to presently available photon sensors

Physics Studies for CLIC CDR

- In 2011: Preparation of the Conceptual Design Report for CLIC
  Strong participation in Detector Volume: 1 Editor (Detector Concepts), 2 out of 7 benchmark analyses performed in the group
  - CLIC CDR available at http://lcd.web.cern.ch/lcd/CDR/CDR.html
    Signatures are invited!

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The goal of the benchmark studies: evaluate the performance for rather generic physics processes

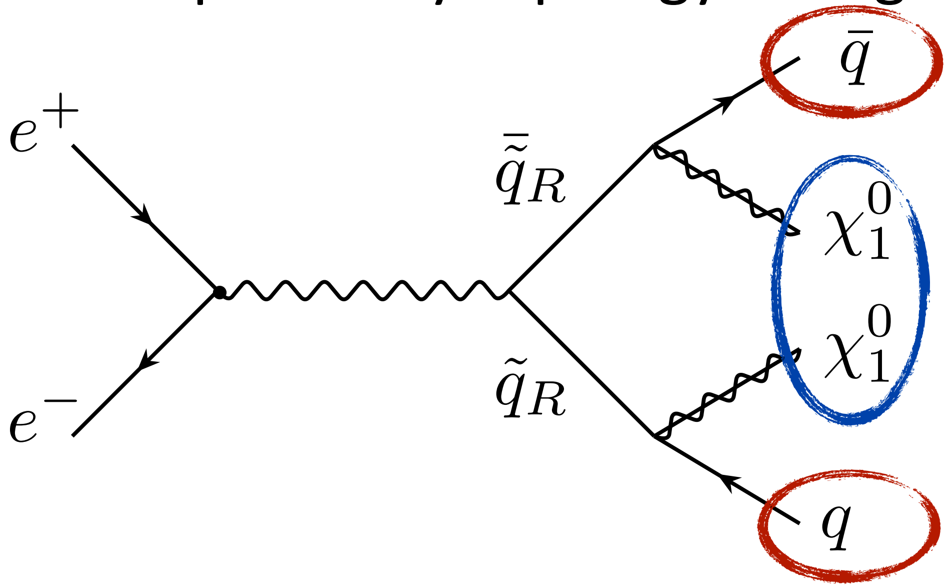
The main challenges: Pile-Up of hadronic background, luminosity spectrum

Studies at MPP:

- Right-squark production and decay at 3 TeV, squark mass 1.12 TeV
- Top quark pair production at 500 GeV, direct comparison to ILC studies

Right-Squark Production

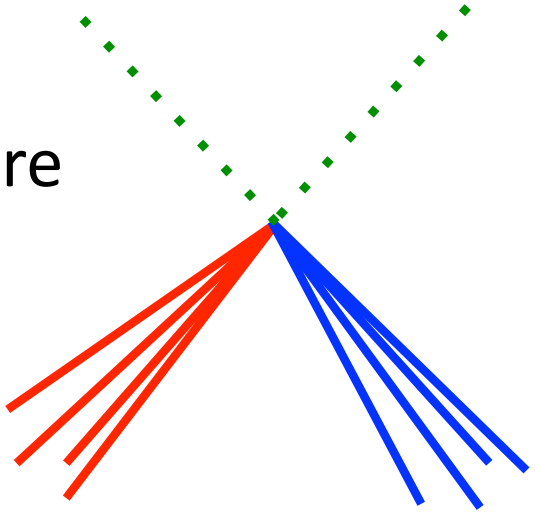
- Light-flavored squarks: typically among the heaviest SUSY particles - Jets + missing Energy as a generic new physics signature
  - Simple decay topology for right squarks:



two highly energetic jets

missing energy

mass 1.12 TeV, cross section: 1.45 fb



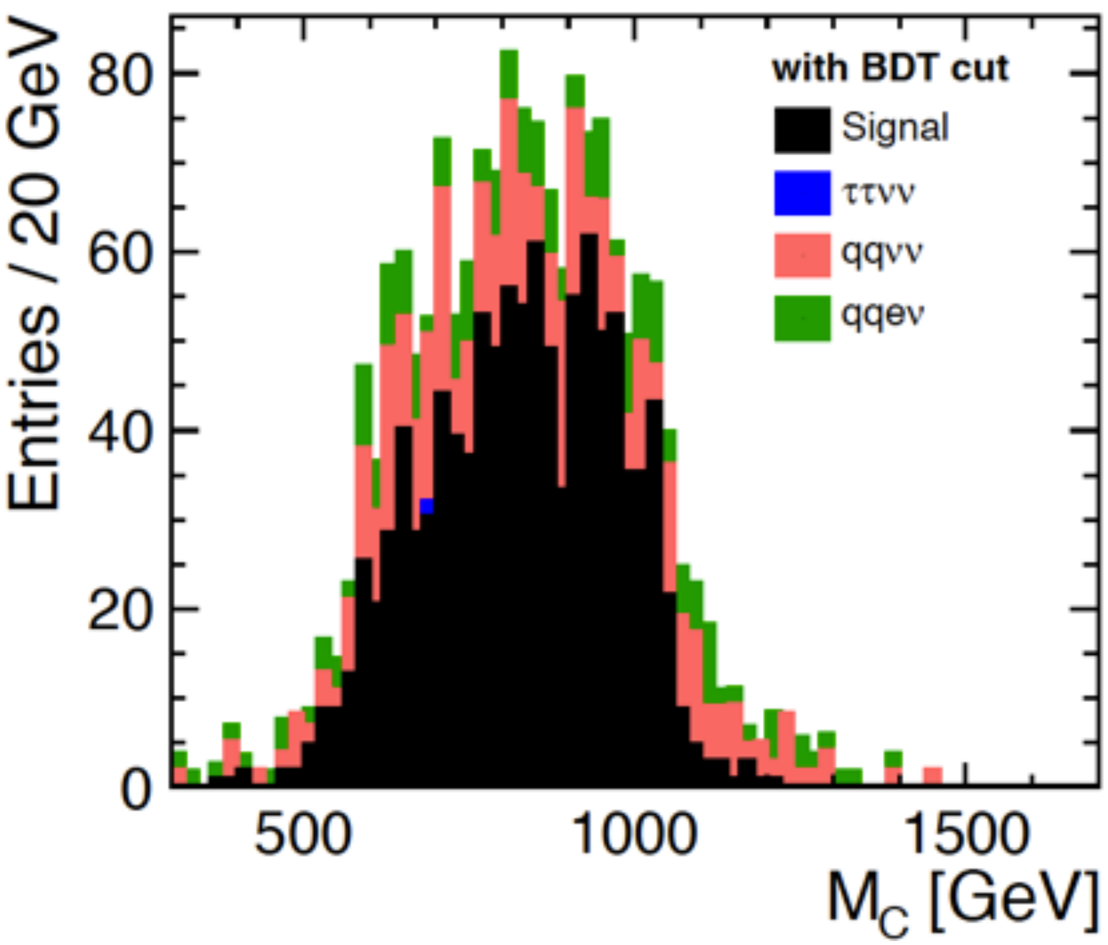
Extensive study of jet finders to reduce background effects:

Use techniques developed for hadron colliders -

Adopted as general solution for all CLIC physics studies

Right-Squarks - Analysis

- Main analysis challenges:
  - Suppression of SM background (4 orders of magnitude larger cross section than signal)
  - Jet finding in presence of background
- Strategy: Missing transverse momentum cut of 600 GeV, Boosted Decision Tree using jet and event shape information
- Mass measurement: $M_C = \sqrt{2(E_1 E_2 + \vec{p}_1 \cdot \vec{p}_2)}$ (independent of s)

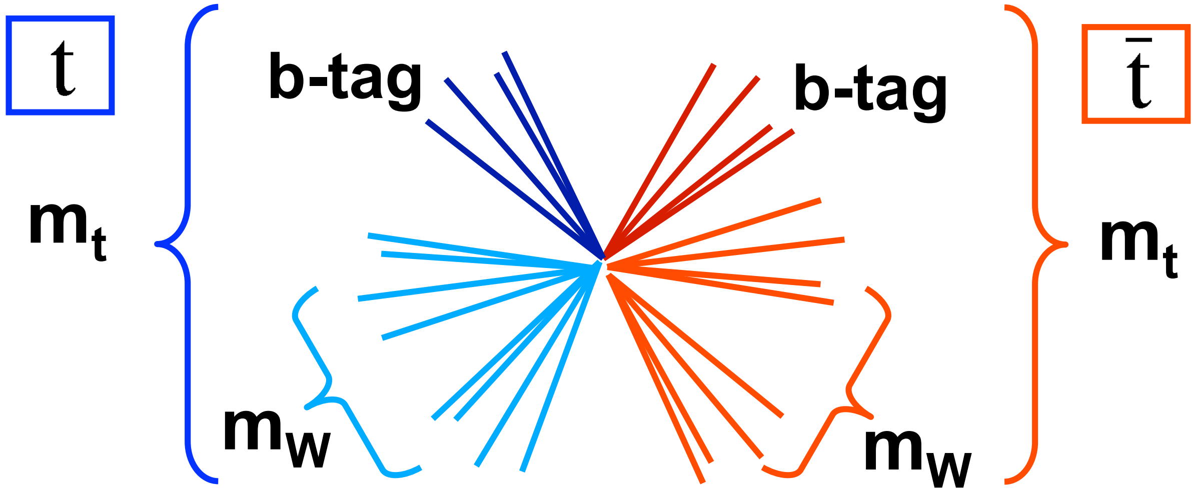


Mass determined with template fit:
Resolution: 6 GeV (stat.), 0.52% for 2 ab^{-1}

Systematics from luminosity spectrum determination negligible: 0.3 GeV
(s independence of mass extraction!)

Top Pair Production at 500 GeV

- Top mass and width - a classic Standard Model measurement at Linear Colliders
  - Multi-jet final state at ILC energies



Reconstruction of invariant mass from decay products

- Reconstruction of intermediate W bosons
- Kinematic fit to improve masses

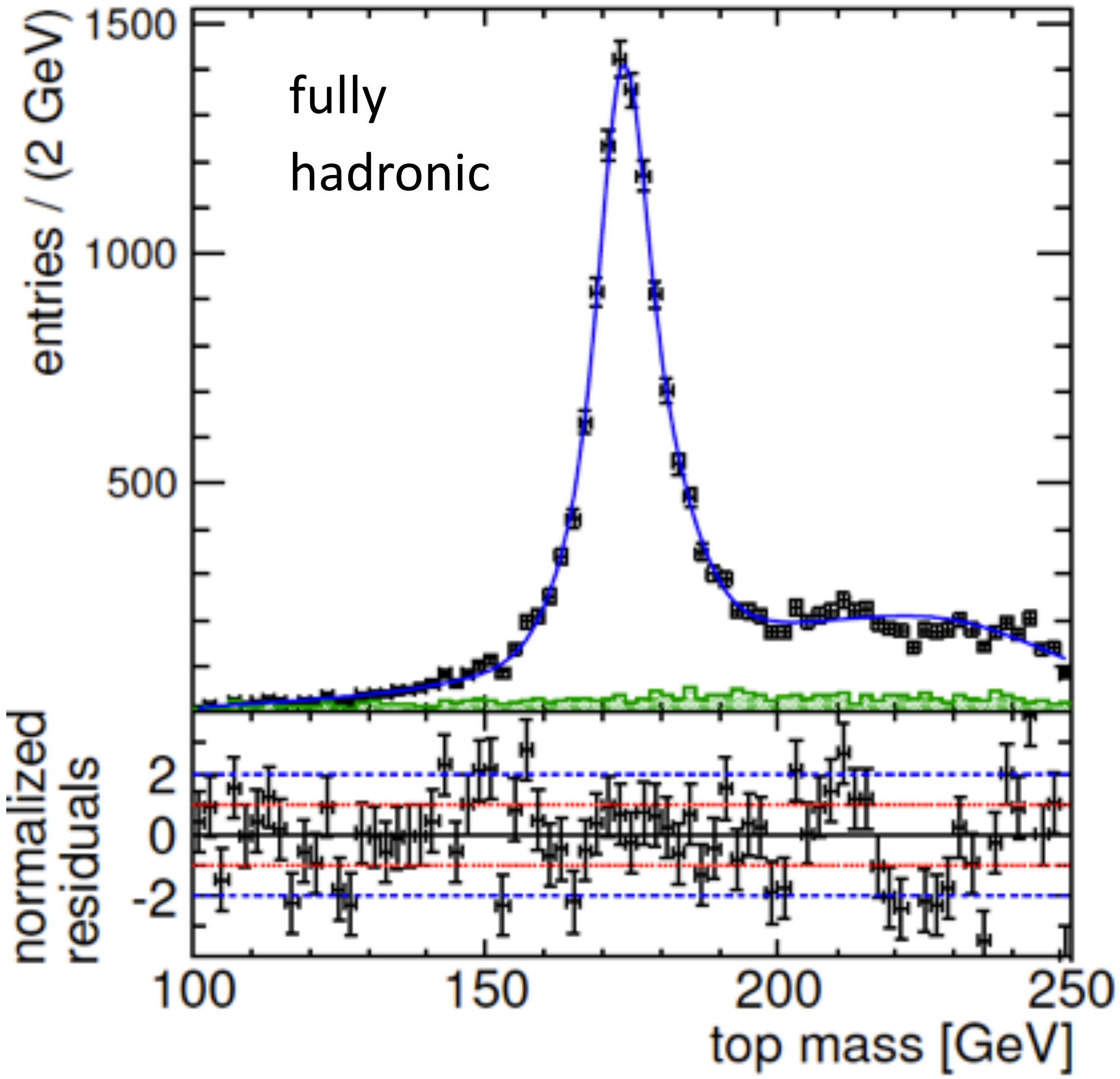
Key detector performance aspects:

- Mass reconstruction in a multi-jet final state for low energy jets
- Flavor tagging

In addition: Evaluation of the impact of CLIC beam conditions at 500 GeV compared to those of the ILC

Top Pairs - Results

- Unbinned maximum likelihood fit of mass distributions



Statistical precision for 100 fb^{-1}:

80 MeV all hadronic (220 MeV on width)

90 MeV semi-leptonic (260 MeV on width)

Slightly better than ILC - ILD LOI mass resolution (0.11 GeV in all-hadronic final state)

Caveat: Invariant mass theoretically not well defined: sizable theory uncertainty!
Ongoing theoretical work - A.Hoang et al.
Experimental alternative: Threshold scan, feasibility at CLIC to be studied

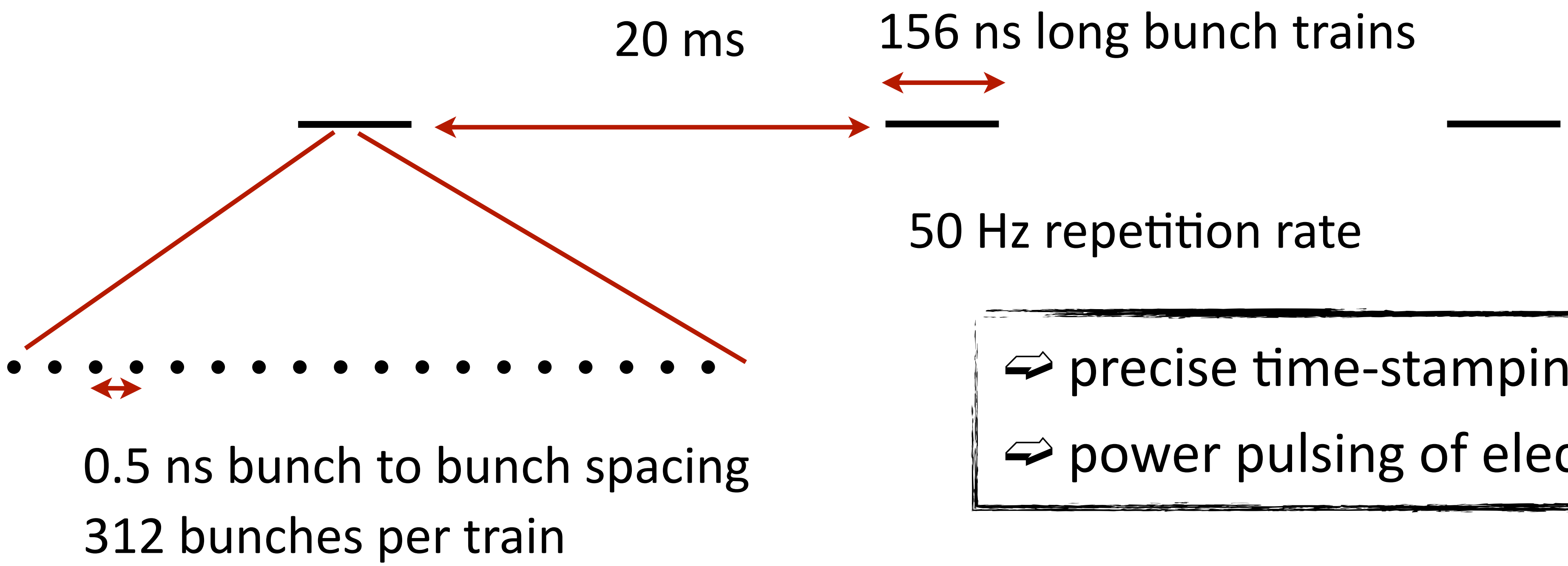
Summary & Outlook

- Intense preparations for future linear colliders: ILC, CLIC
- MPI involvement in:
  - Detector R&D - Highly granular calorimeters, highly visible contributions
    - Hadronic shower physics, advanced algorithms for energy reconstruction,...
    - Scintillator tiles, silicon photomultipliers
  - Physics studies - Performance studies for future experiments
- The road ahead:
  - Completion of CLIC CDR, ILC TDR in 2012 - In time for European strategy update
  - No firm decisions yet, but the world of particle physics is changing fast at present: Promising signs in Japan with a kick-off meeting with highest political participation last week, increased linear collider activities at CERN

Backup

Conditions at CLIC

- The bunch structure at CLIC



➡ precise time-stamping required

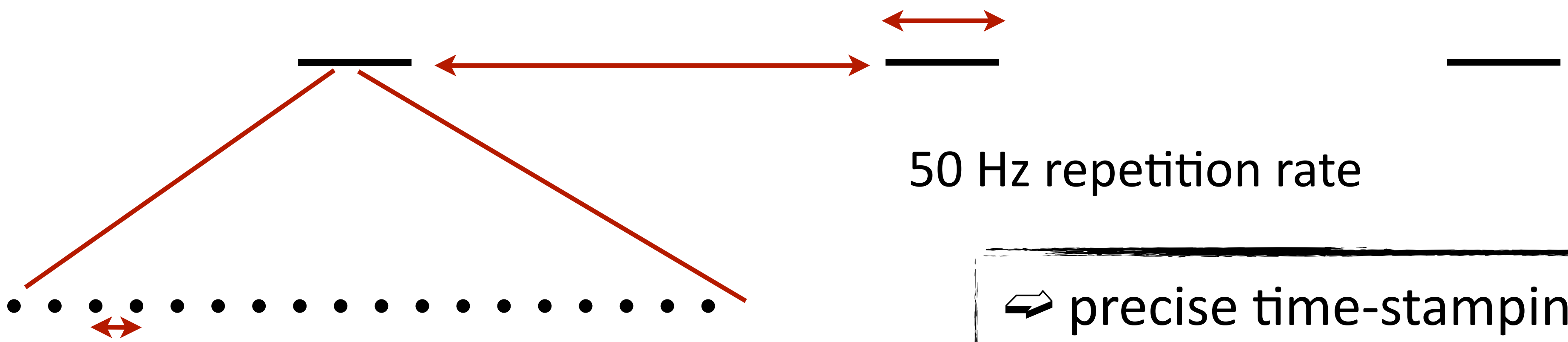
➡ power pulsing of electronics possible

Conditions at CLIC

- The bunch structure at CLIC

20 ms

156 ns long bunch trains



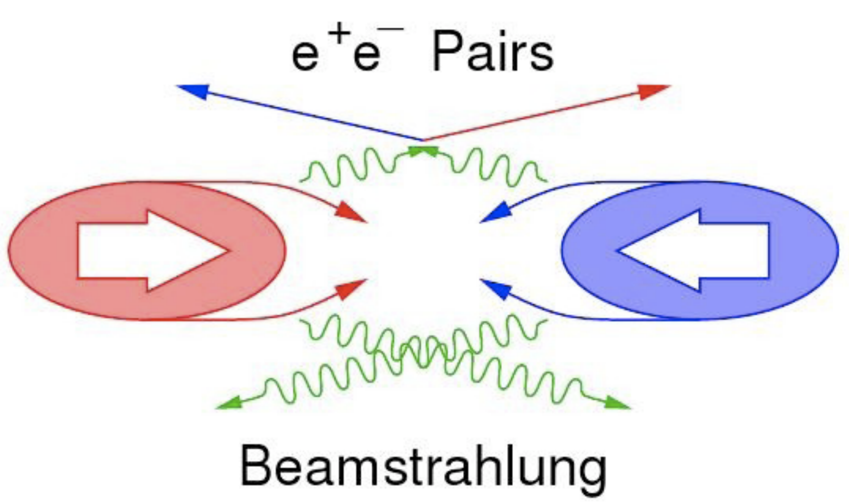
50 Hz repetition rate

0.5 ns bunch to bunch spacing

312 bunches per train

➯ precise time-stamping required

➯ power pulsing of electronics possible

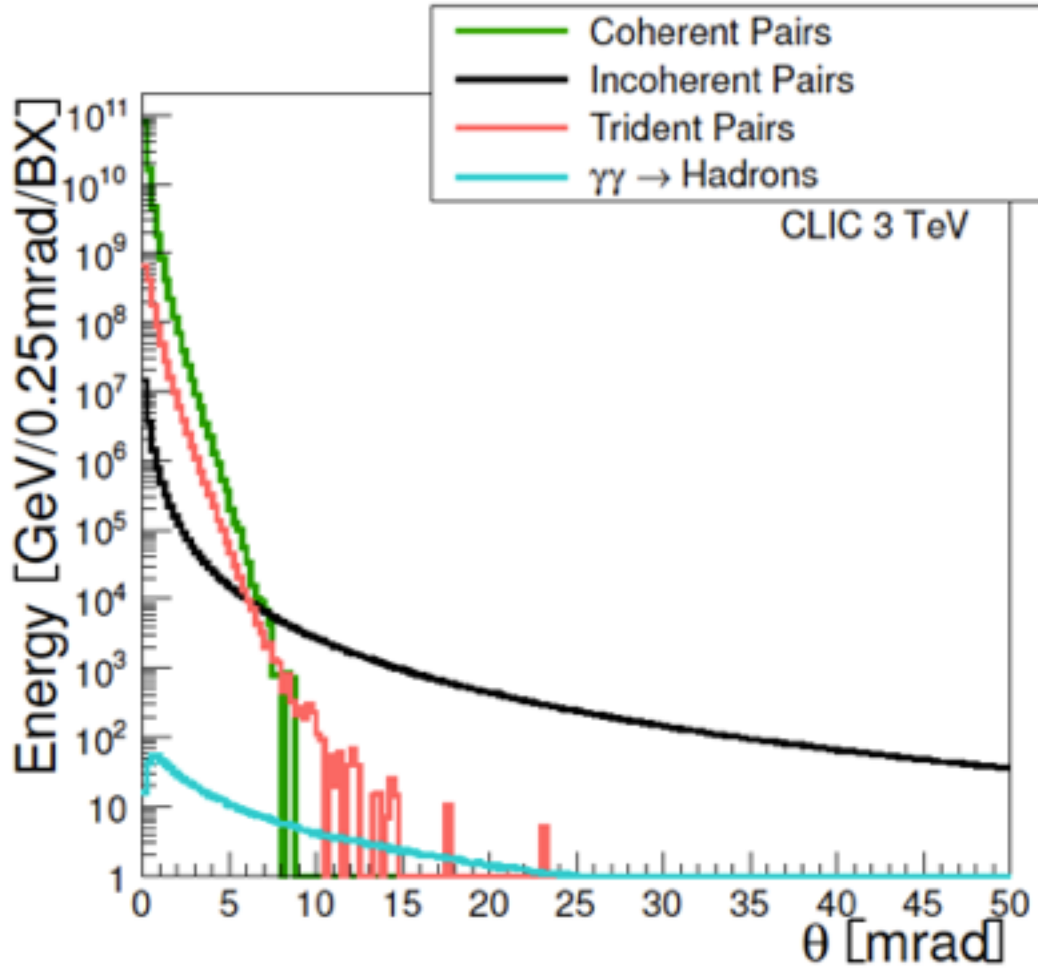


Beamstrahlung driven by energy and focusing:

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
- γγ → 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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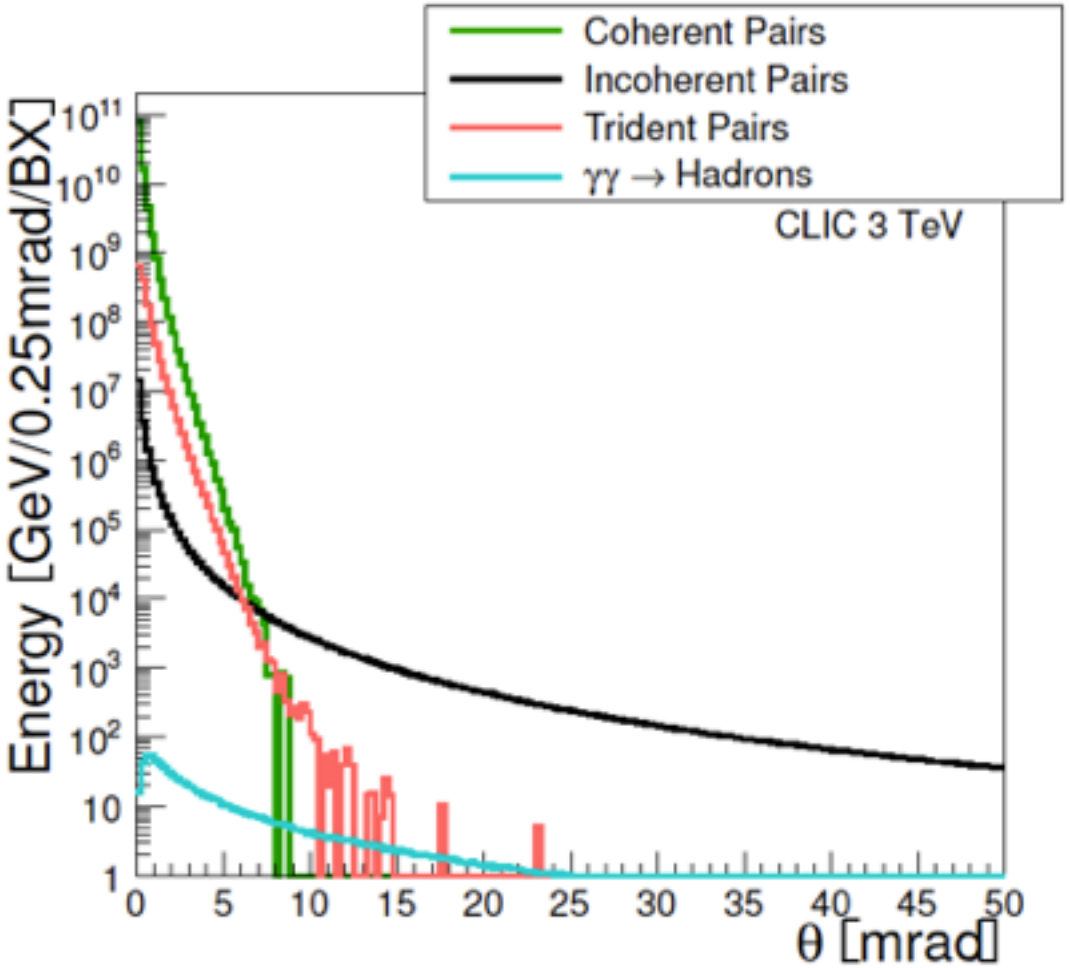

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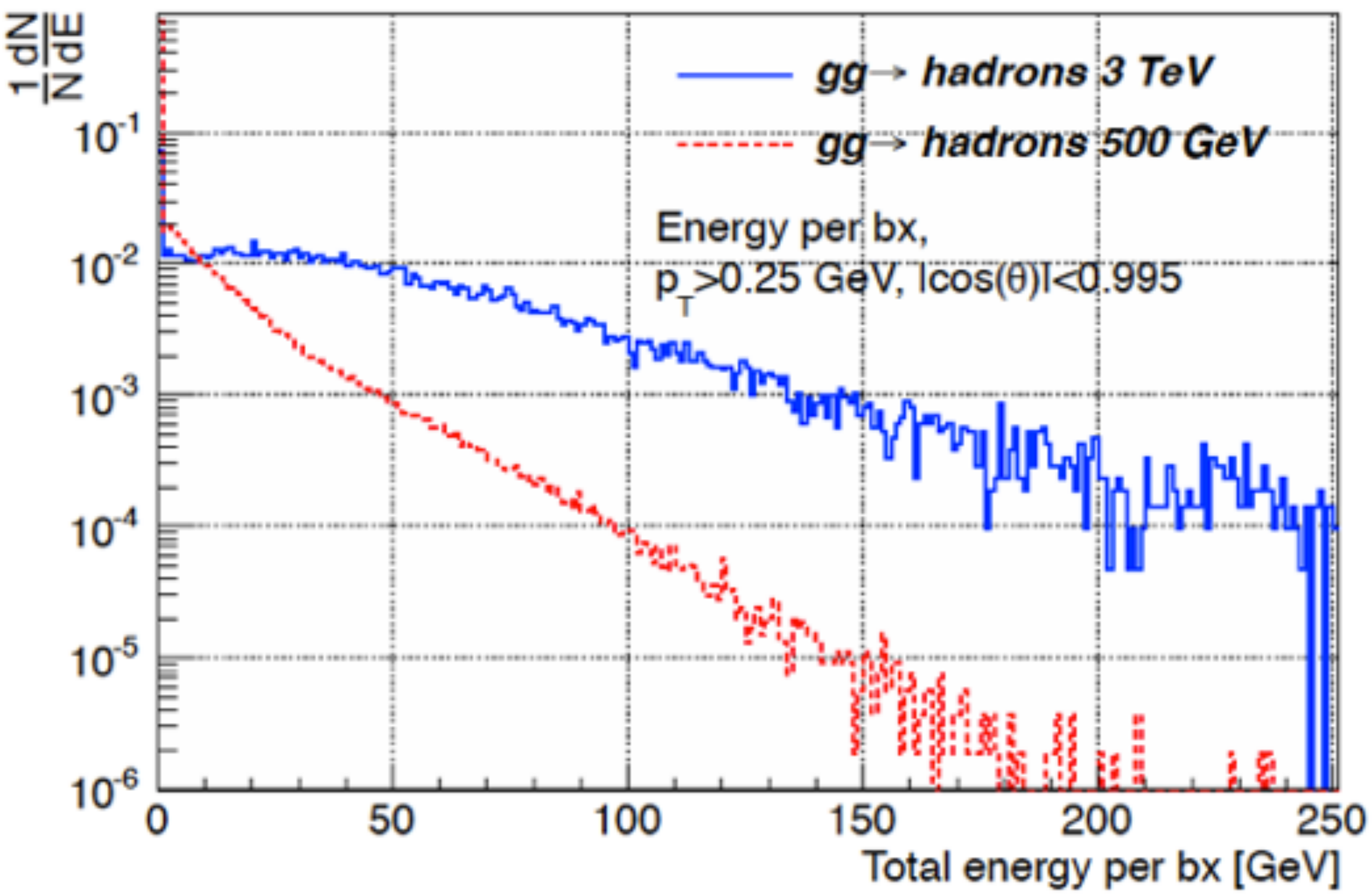
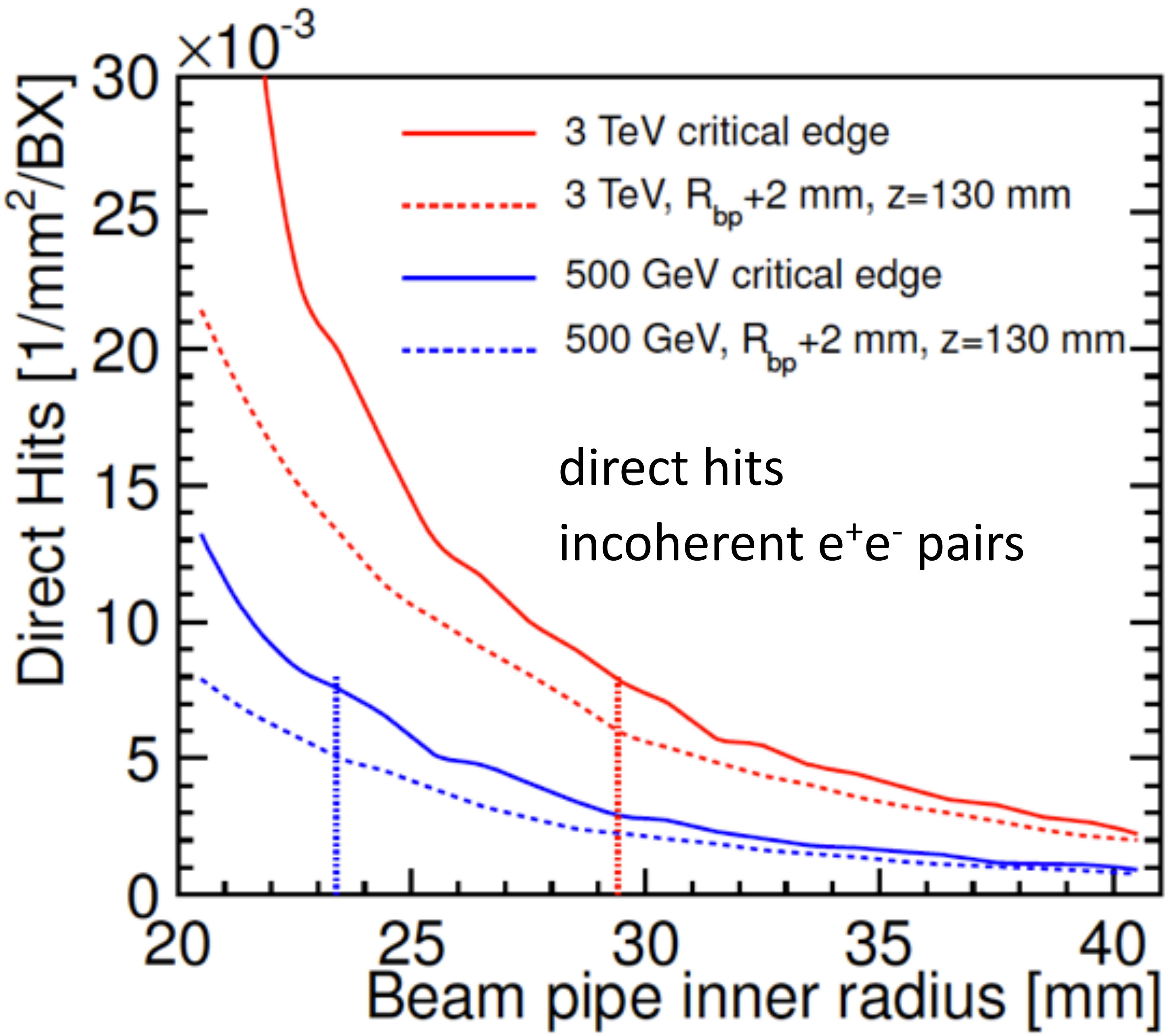


- γγ → hadrons: ~ 3.2 events / bx,
  ~ 28 ch. particles in detector acceptance
  ~ 60 GeV energy
  ➩ 15 TeV dumped in detector during bunch train, forward peaked
  Requires precise time stamping and clever event reconstruction

Detector Modifications at 500 GeV

- The background conditions at 500 GeV are substantially less severe than at 3 TeV

- Lower rate of incoherent pairs (8×10^4/BX vs 3×10^5/BX): Allows a reduction of the beam pipe radius at the IP, and a smaller radius of the vertex detector (25 mm vs 31 mm): Improved flavor tagging for lower jet energies

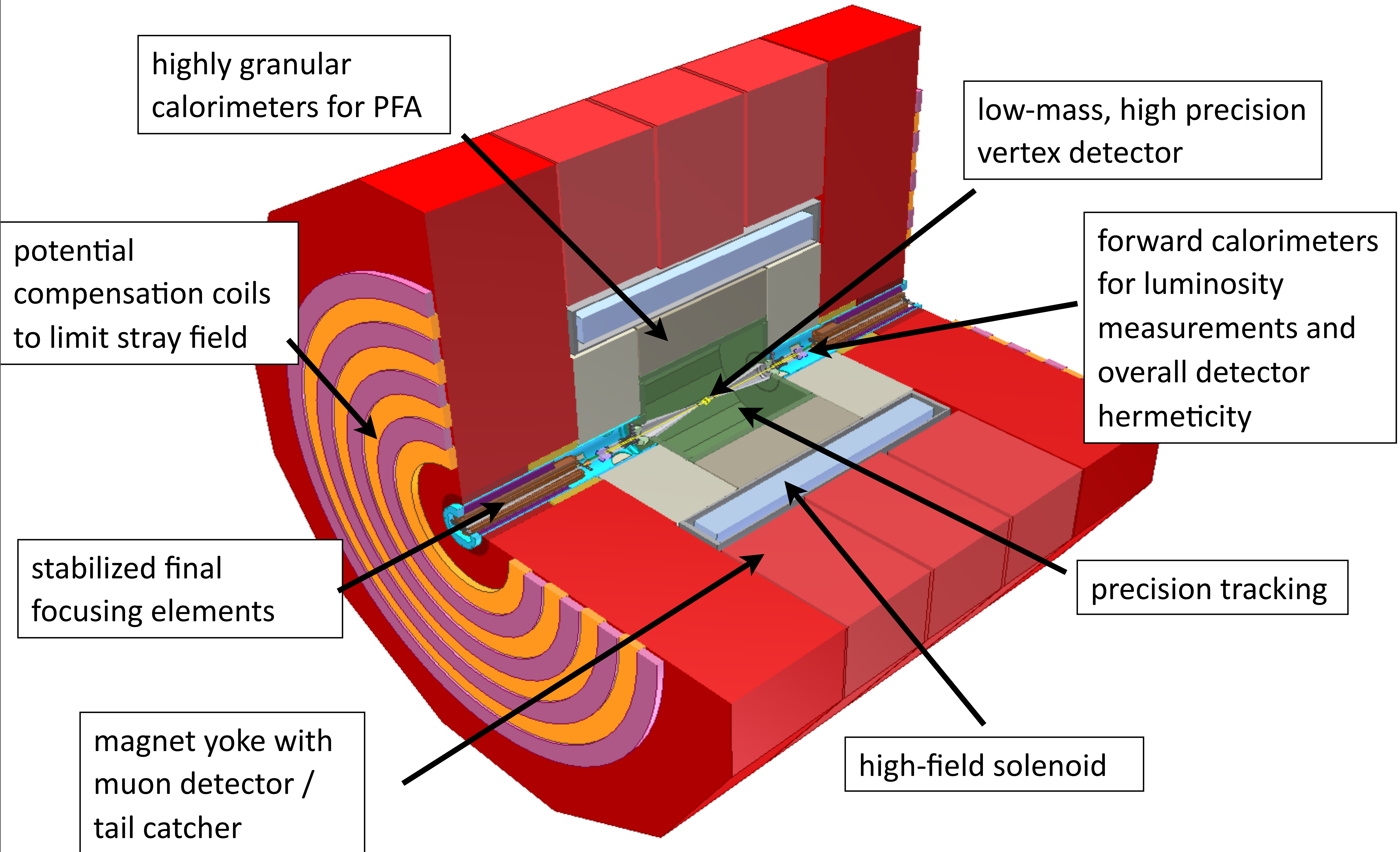


LCD-Note-2011-021

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

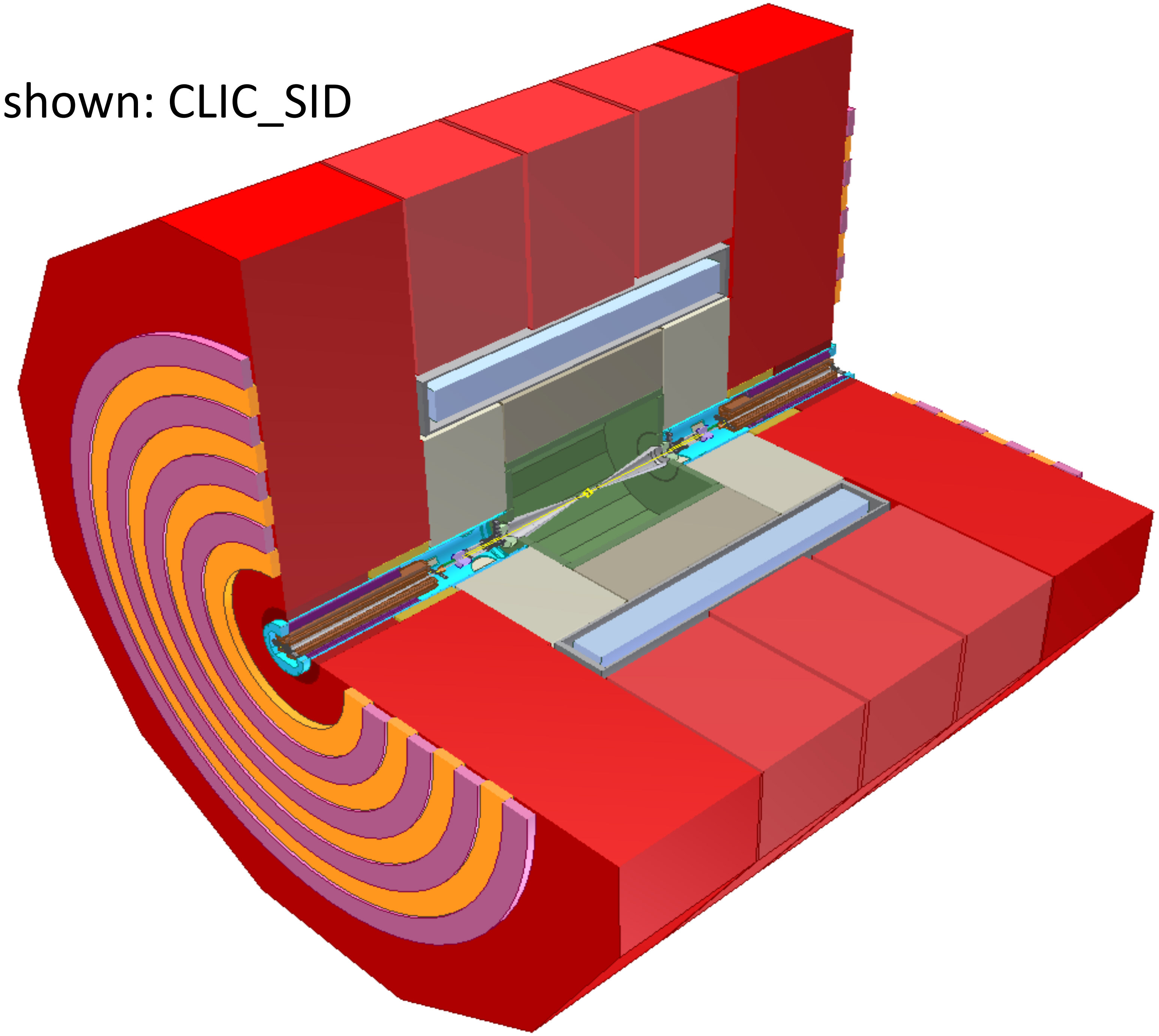
CLIC Detectors - Main Features



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

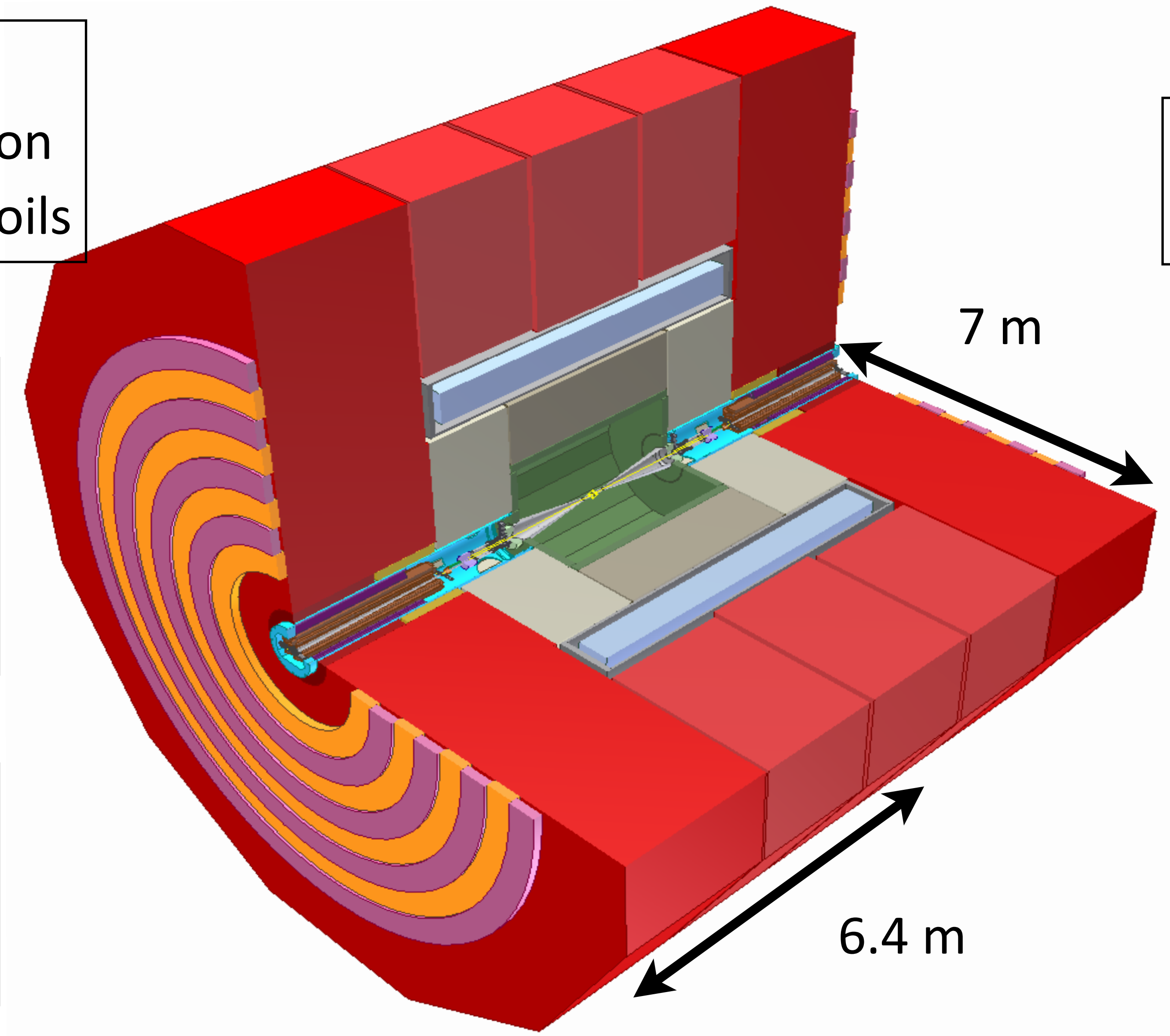
Changes to ILC Detector Concepts

- 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

CLIC Event Reconstruction

- Event reconstruction technique: Particle Flow
  - Relies on imaging capabilities of calorimeters:

    Separation of particle showers to reconstruct each particle in an event

    ➫ Make optimal use of all available detector information

    (tracking & calorimetry)

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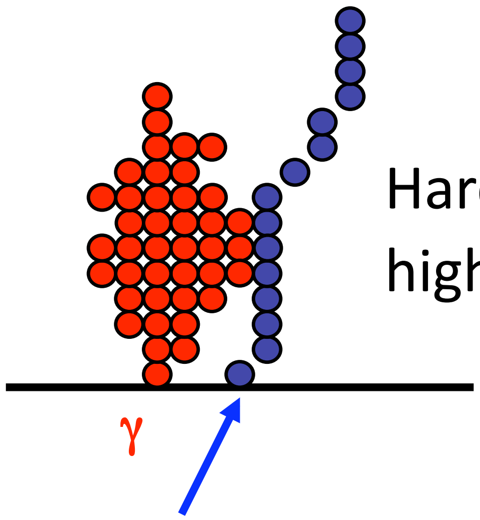
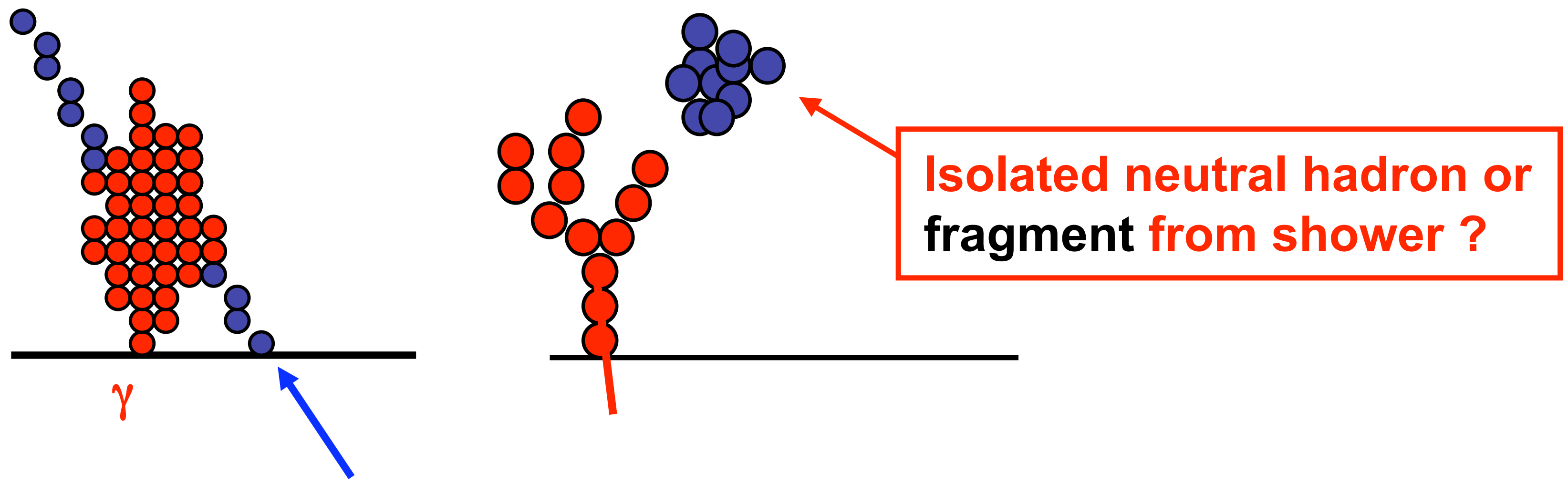
PFA Requirements:

Software: very sophisticated algorithms



Hardware:
high granularity



The success of PFA is decided in the calorimeters: Development of novel technologies for high granularity:

The Key Reconstruction Challenge: Backgrounds

- Background conditions at CLIC are challenging
  - In particular: High rate of γγ ➝ hadrons processes

NB: This background scales with energy and luminosity, and is not a CLIC-specific issue
... but: The short bunch-to-bunch spacing of 0.5 ns leads to a pile-up of background events

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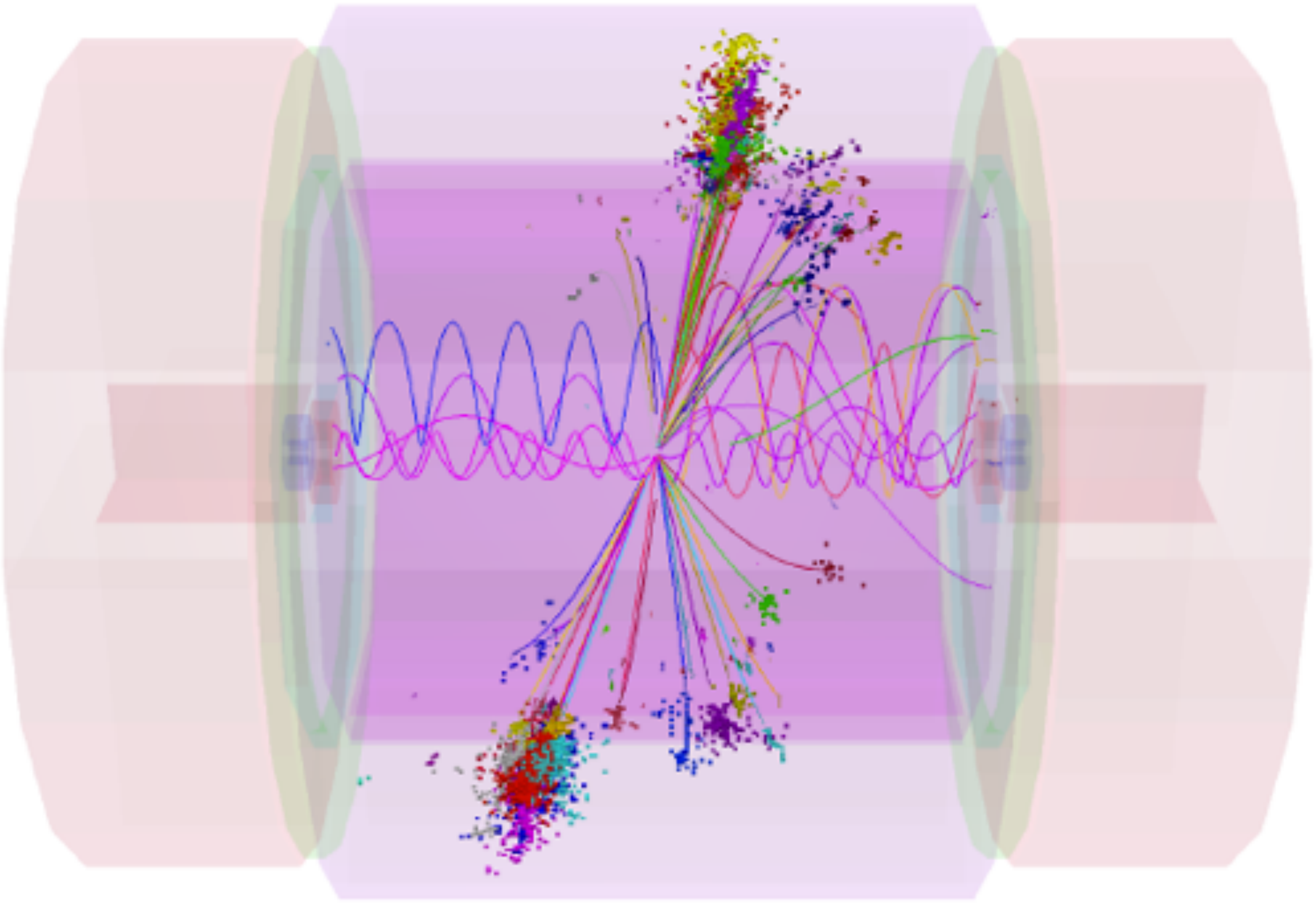
- The way to reject these types of background: Timing
  - Match the time of all reconstructed physics objects with the time of the event
  - Assume ~ 10 ns timing in vertex detectors and Si trackers
  - Key detectors: Calorimeters with ~1 ns cluster timing
    - Long integration time in the HCAL to account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

Good time resolution mandatory for all CLIC detector subsystems, most critical in the calorimeters!

Background Removal

- Beam related background from γγ → hadrons processes adds significant energy to events, in particular in the forward region - simulation chain fully validated

1 TeV Z → uds



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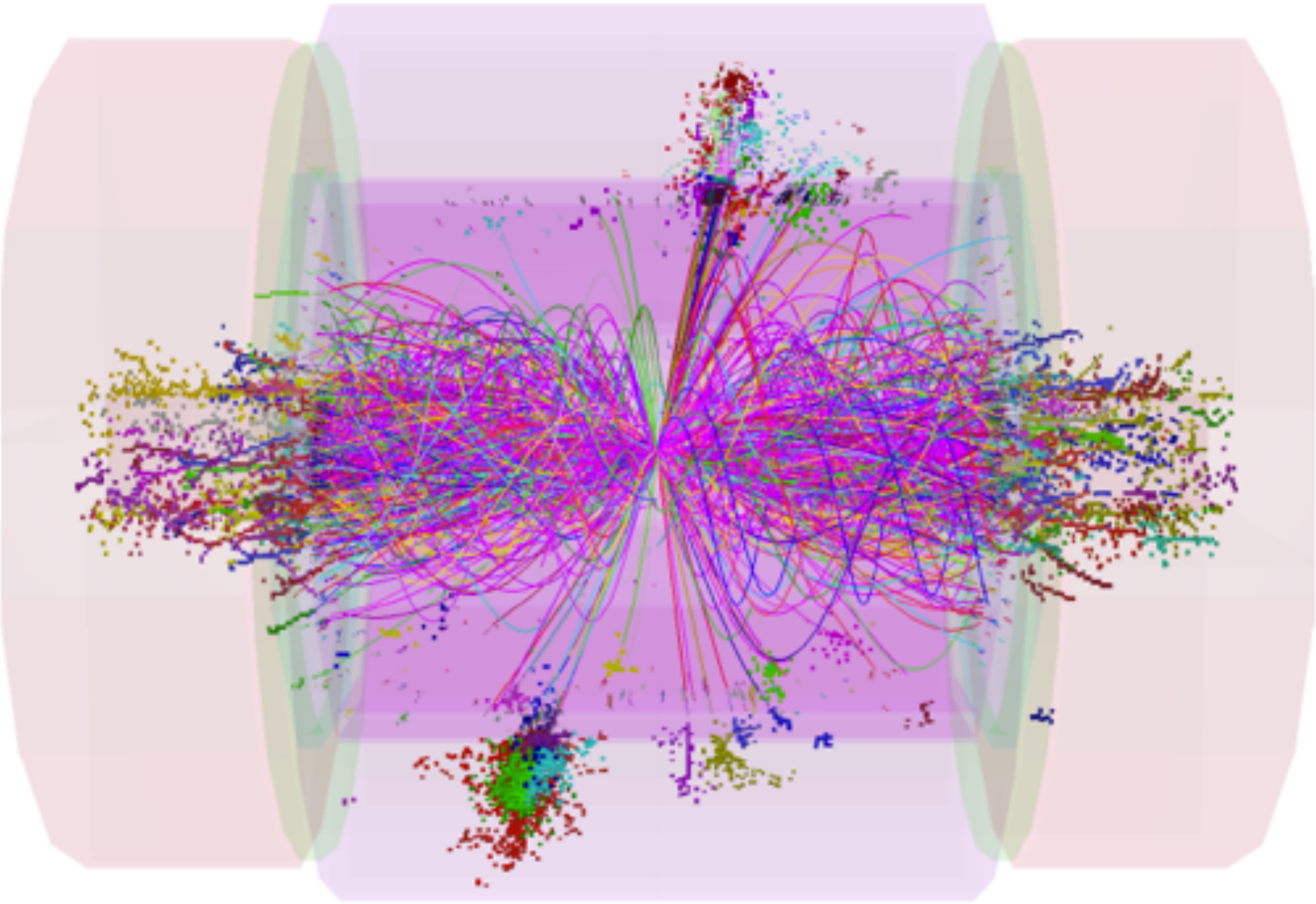
1 TeV Z → uds + γγ → hadrons background



~ 60 BX, 1.4 TeV

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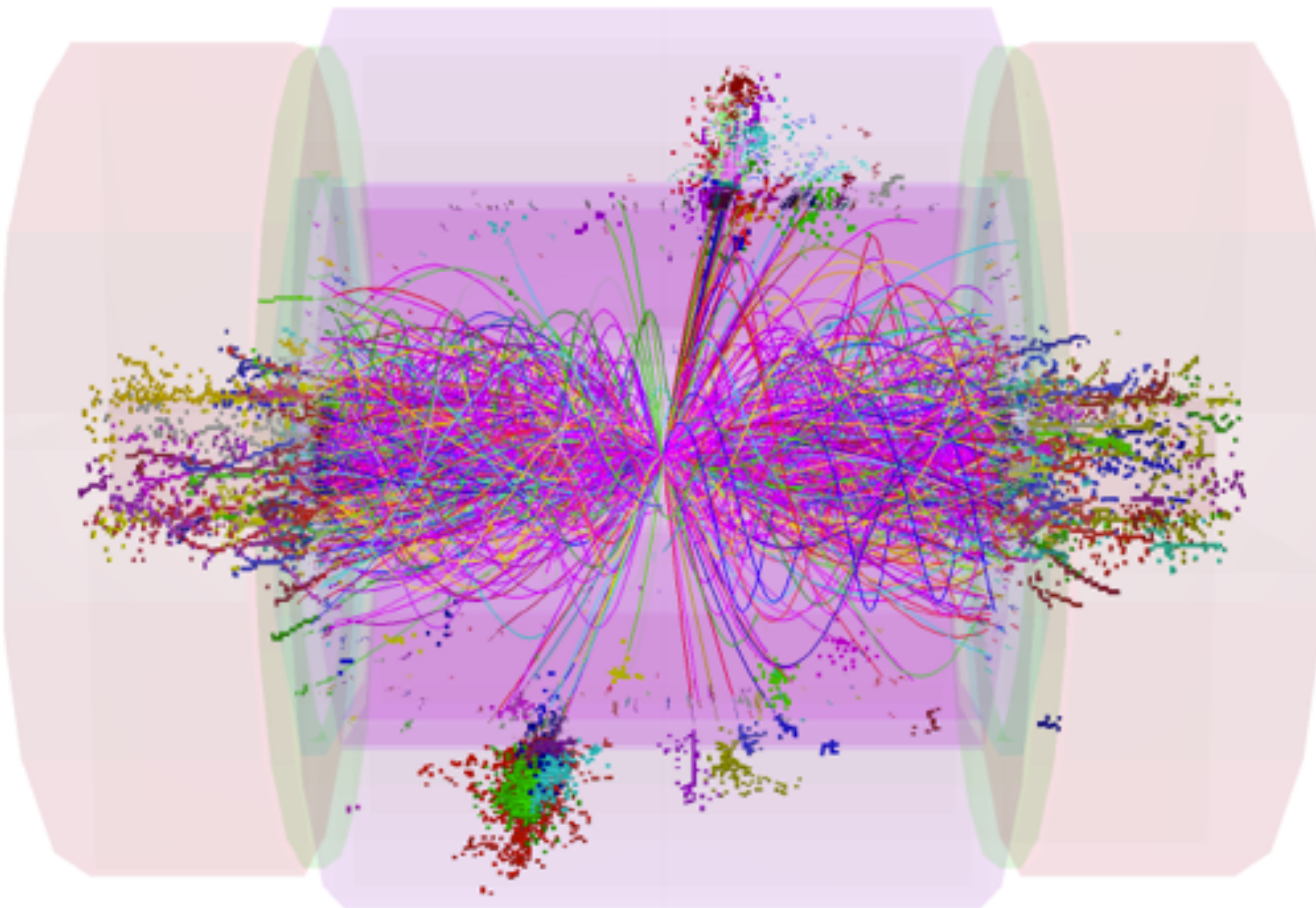

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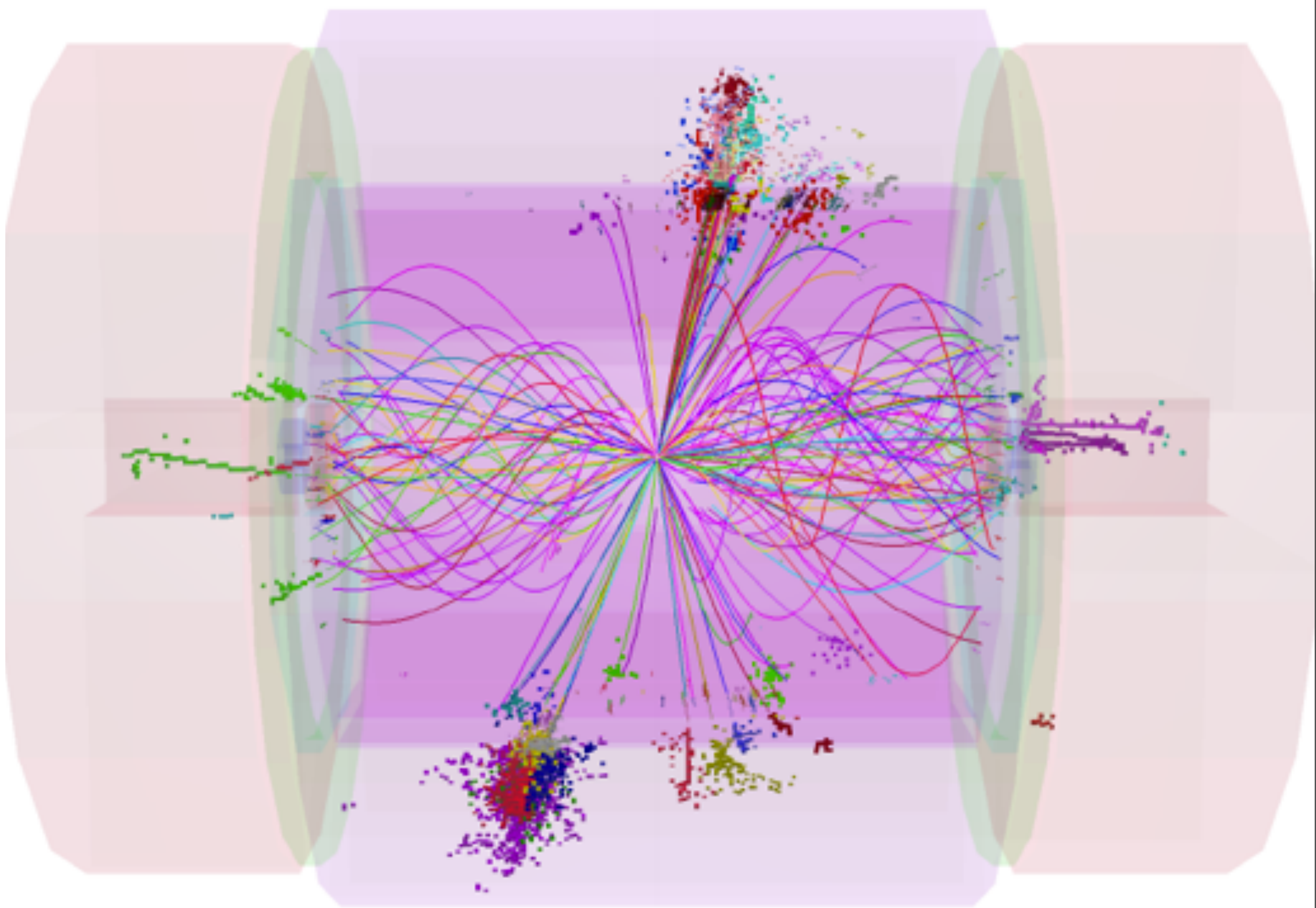


realistic timing assumptions: 200 GeV

- Timing cuts reduce the impact of background significantly

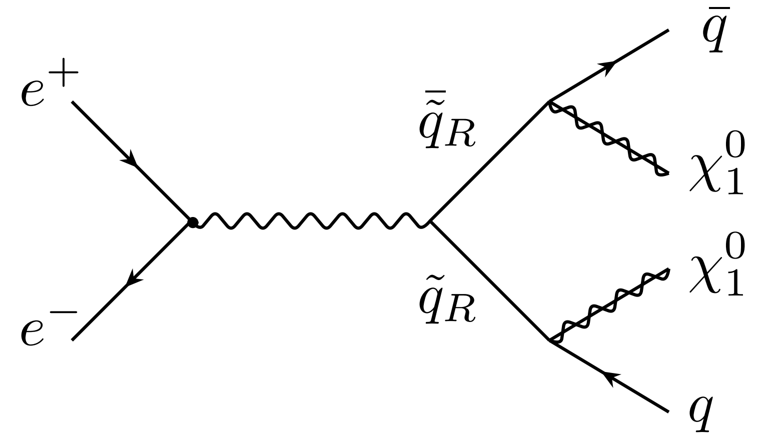
Background Reduction in Physics Analysis

- 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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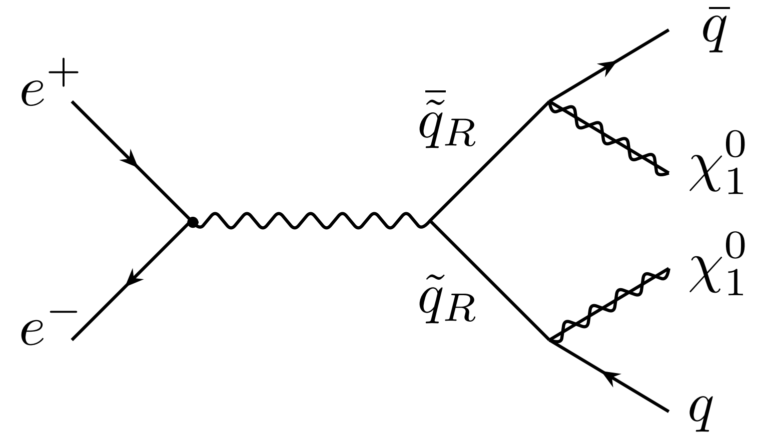
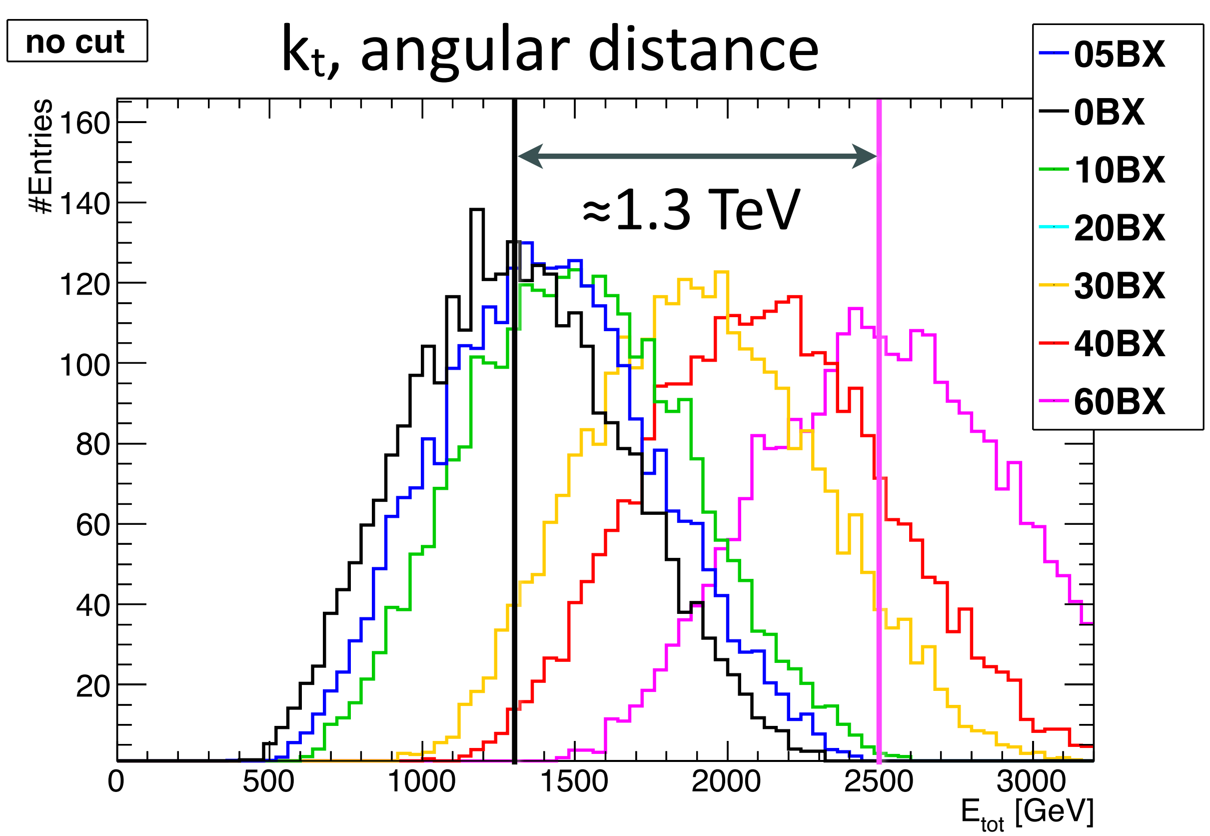
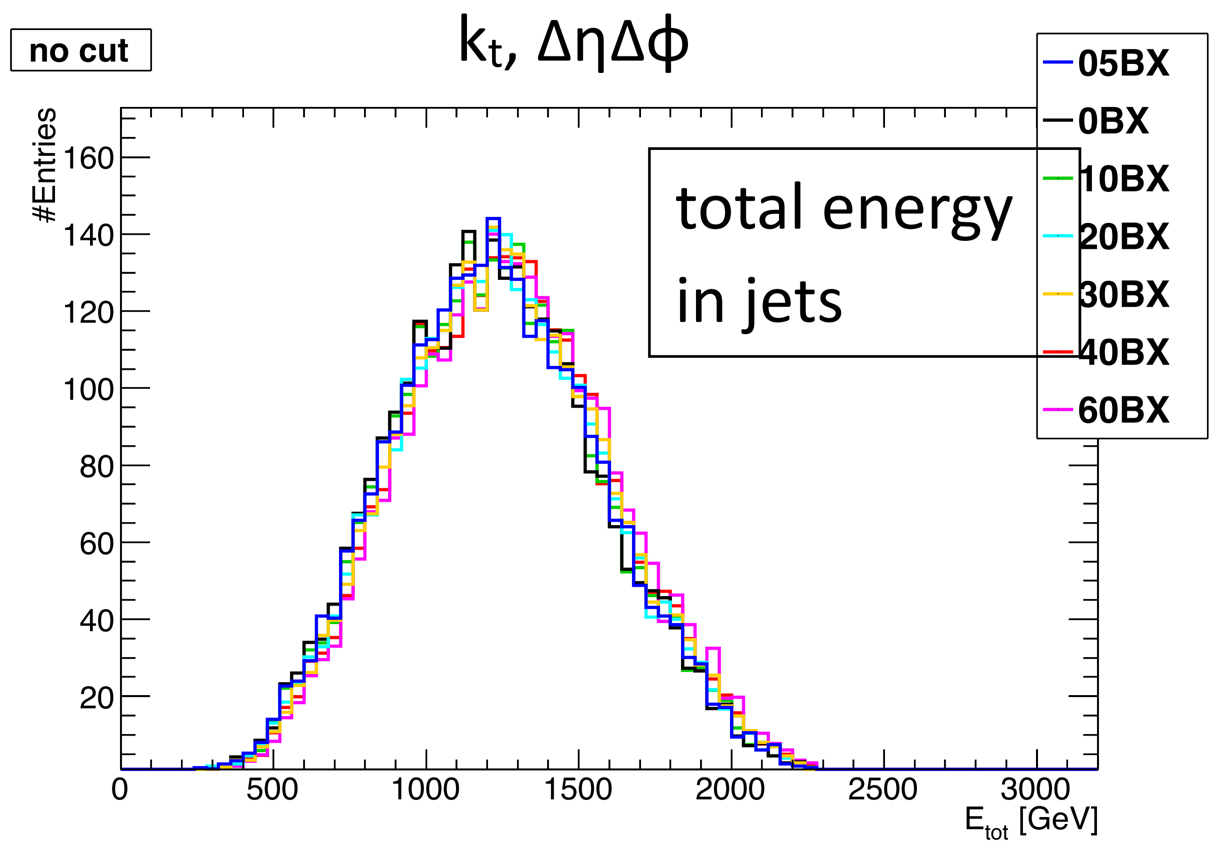


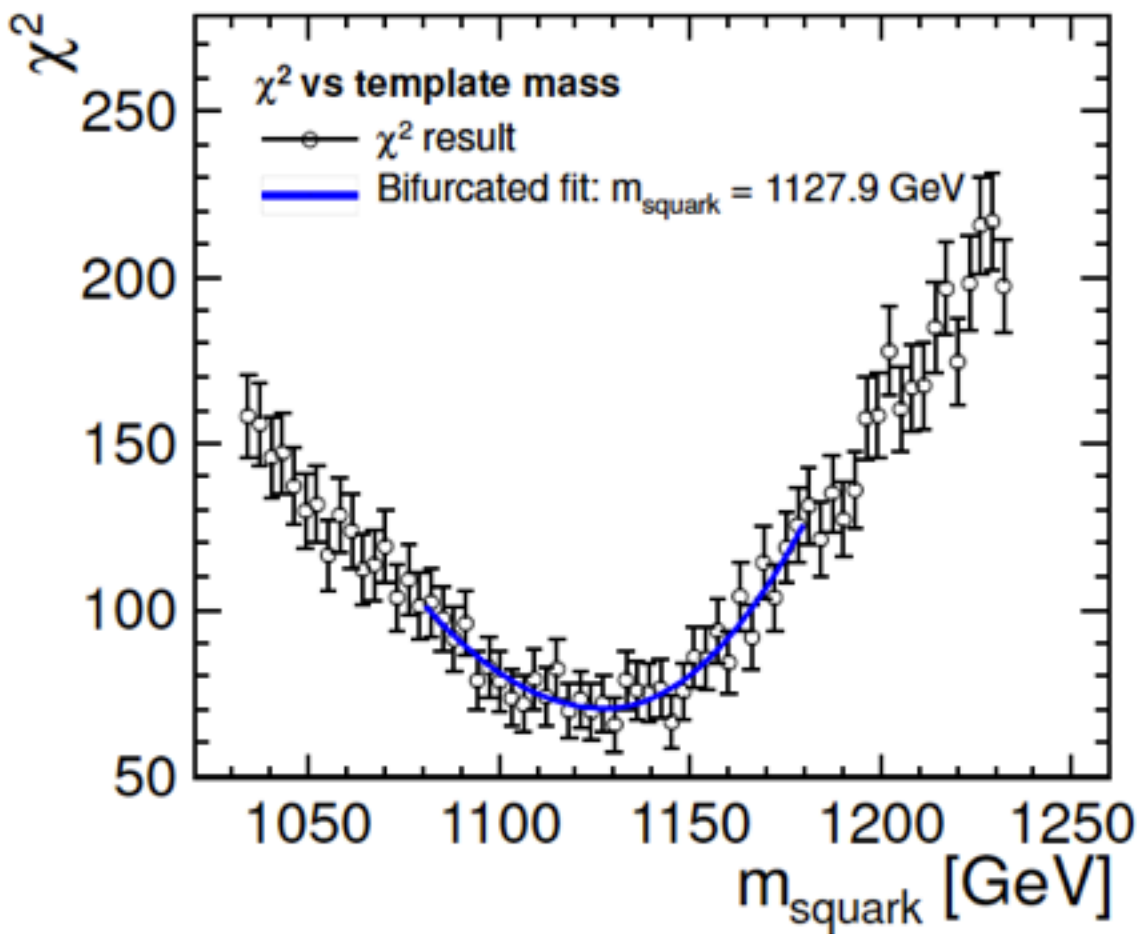
Jet finding can reduce background effects considerably: Choose the right finder / metric!

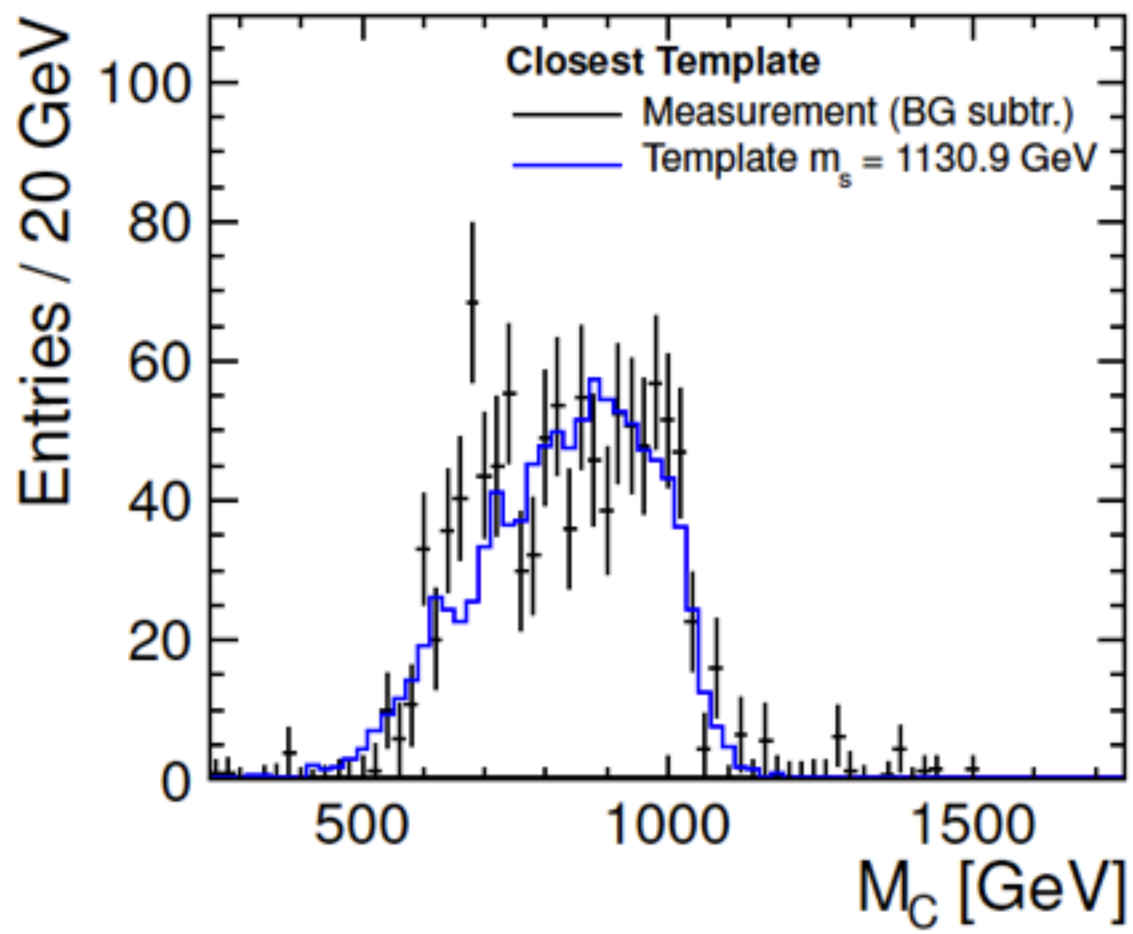




Right Squarks - Results

- Mass determined with a template fit - Generator-level (including hadronization) simulations with various different squark masses, stat. errors from toy MC





Observable	Result	Generator value	
Averaged right-squark mass	1127.9 GeV ± 5.9 GeV	1123.7 GeV	0.52%
Combined cross section	1.51 fb ± 0.07 fb	1.47 fb	4.6 %