CLIC detector and physics study overview

Rickard Stroem *(CERN)*
on behalf of the CLICdp Collaboration

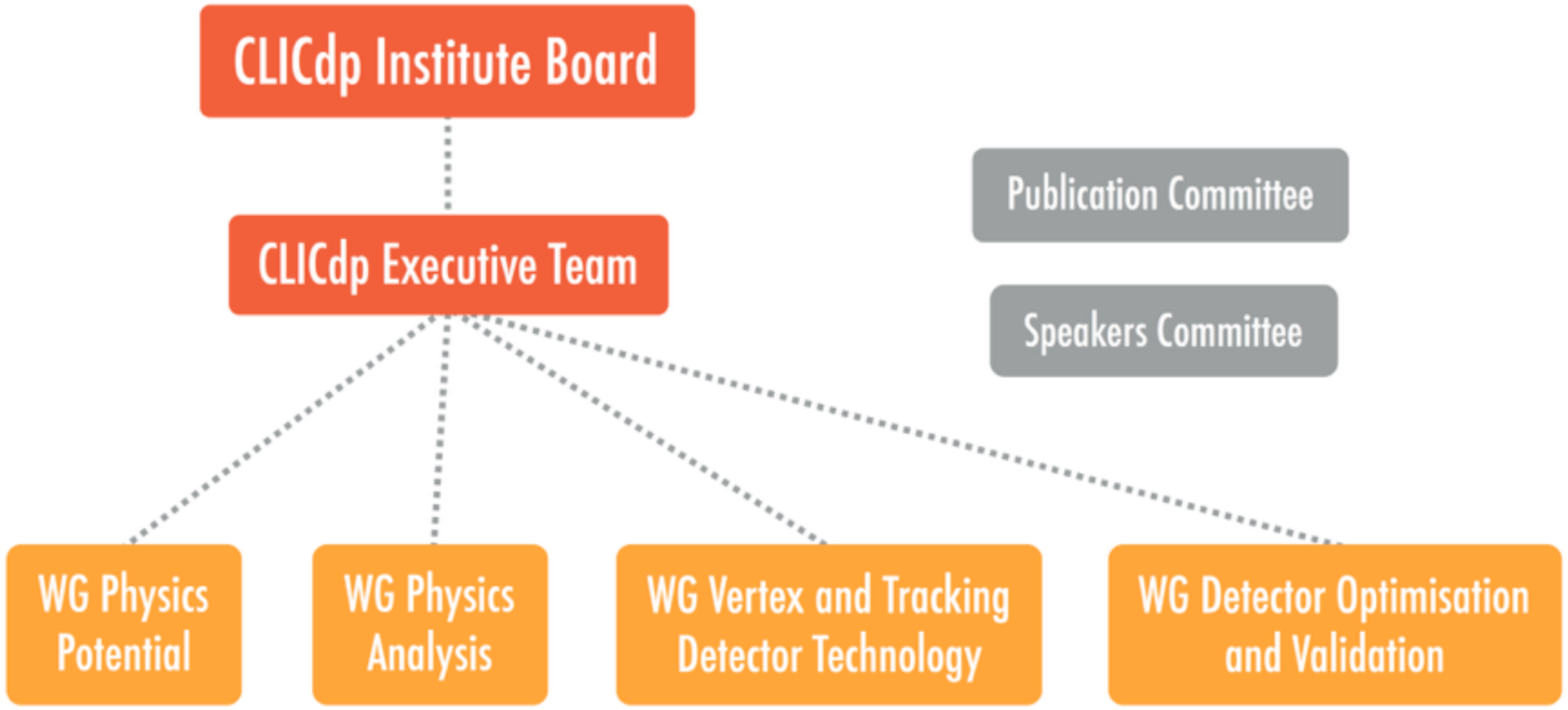
CLIC Week 2018, January 24, 2018

CLICdp Collaboration

CLIC detector and physics study (CLICdp)

- Physics studies
- Detector technology R&D
- Aim to produce a series of reports for the European Strategy for Particle Physics (ESPP)
- In total 158 members from 30 institutes in 18 countries
  - **New members**: AIBU, Bolu, Turkey (Haluk Denizli) and Universität Siegen, Germany (Wolfgang Kilian)
- **New spokesperson**: Aidan Robson (CERN/Uni. of Glasgow)
- Close connection to ILC detector concepts, CALICE, FCAL, AIDA-2020 project

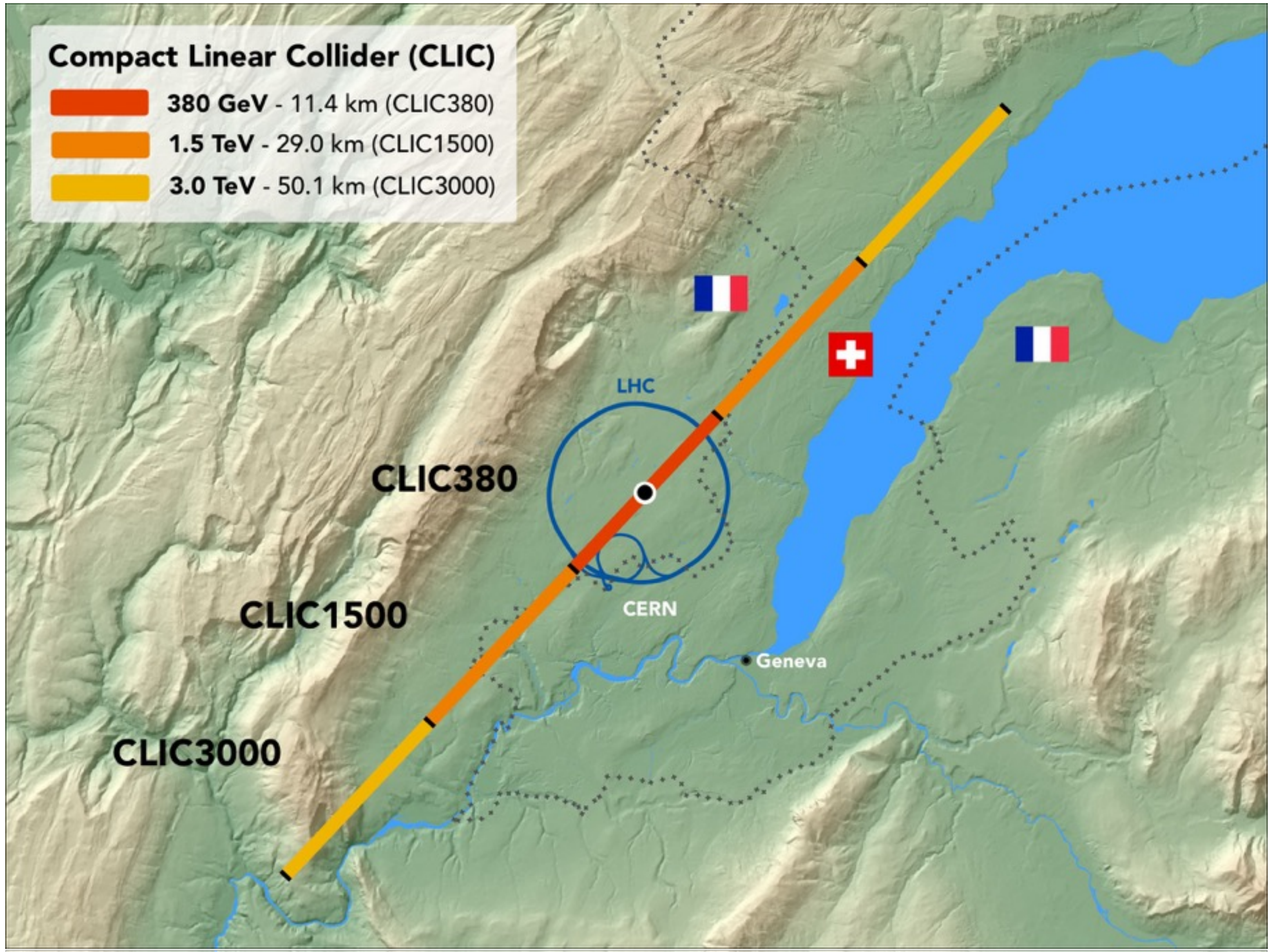
CLICdp working groups



More info: **clicdp.cern.ch**

Outline

CLIC accelerator footprint: https://cds.cern.ch/record/2297076



- A staged physics programme
- The CLIC detector ‘CLICdet’
- Detector technology R&D
- Simulation and reconstruction software
- Plans for the European strategy update

A staged physics programme

- To fully exploit physics potential, CLIC would be implemented in several energy stages going up to multi-TeV energies
- Defined by physics case w. considerations for technical constraints
- **380 GeV** / **1.5 TeV** / **3.0 TeV**
- Baseline scenario of 22 years (CERN Yellow report CERN-2016-004)
- **Initial stage** at 380 GeV **optimised for Higgs and top precision physics**
  - additional 100 fb^{-1} around 350 GeV for top mass threshold scan
- Electron beam polarisation at all energies

1) $\sqrt{s}$ = 380 GeV (500 fb^{-1})

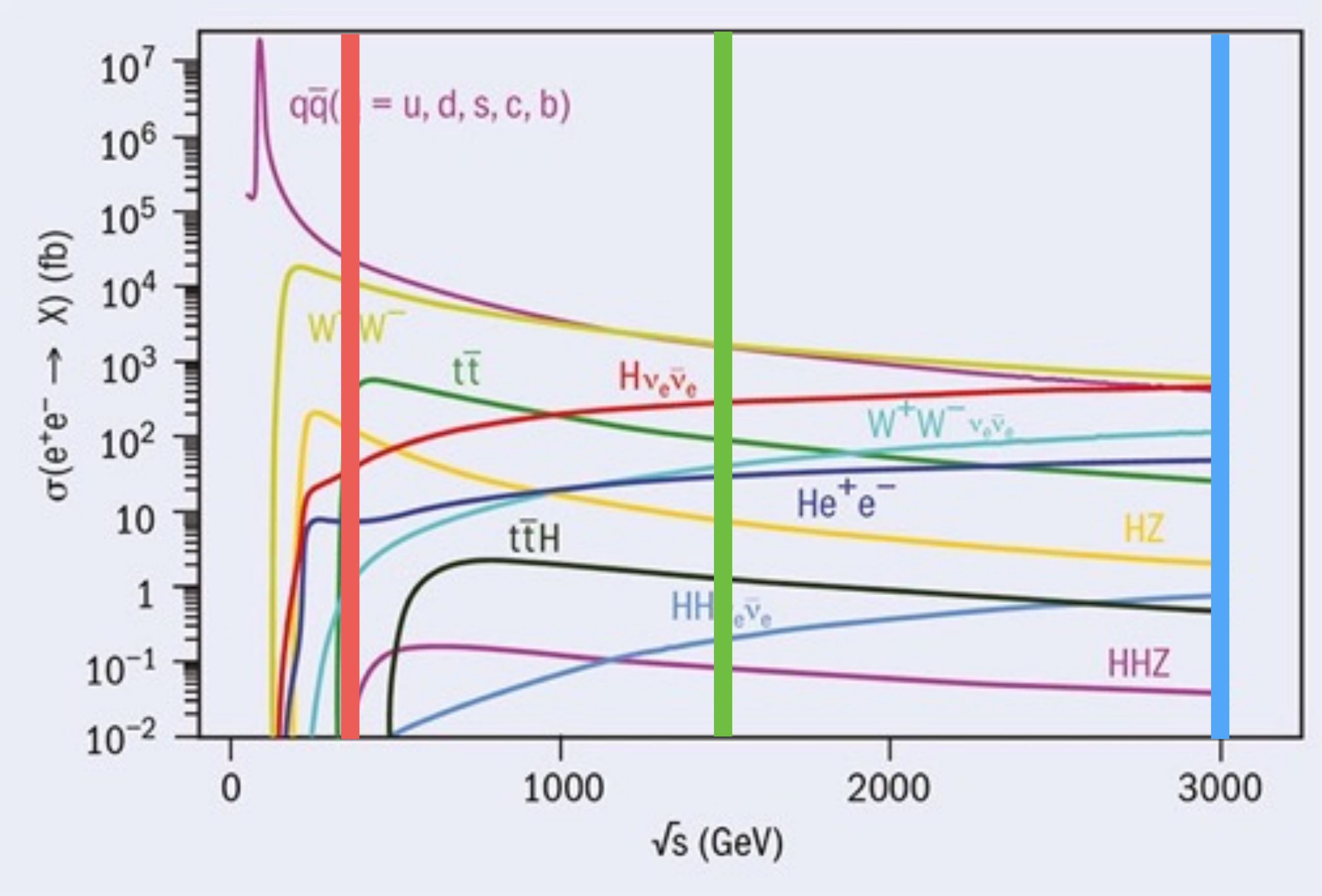
- Higgs/top precision physics
- Top mass threshold scan

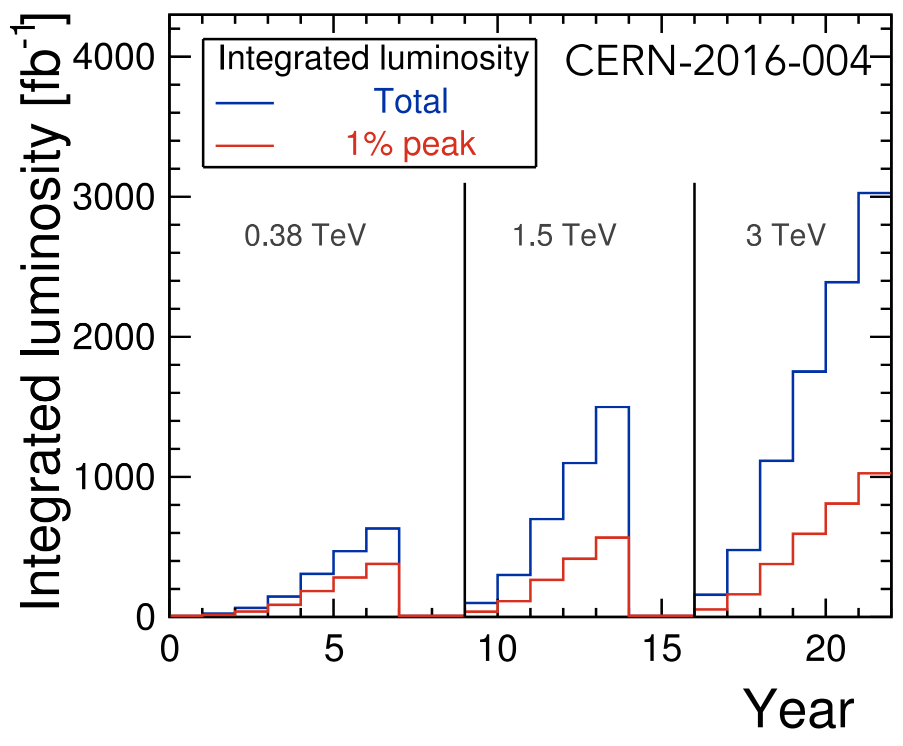
2) $\sqrt{s}$ = 1.5 TeV (1.5 ab^{-1})

- Focus: BSM searches
- Higgs/top precision physics

3) $\sqrt{s}$ = 3 TeV (3.0 ab^{-1})

- Focus: BSM searches
- Higgs/top precision physics





Luminosity at 3 TeV: 5.9×10^{34} $cm^{-2}s^{-1}$ of which 2.0×10^{34} $cm^{-2}s^{-1}$ is above 99% of $\sqrt{s}$

Staging can be adapted to possible LHC discoveries

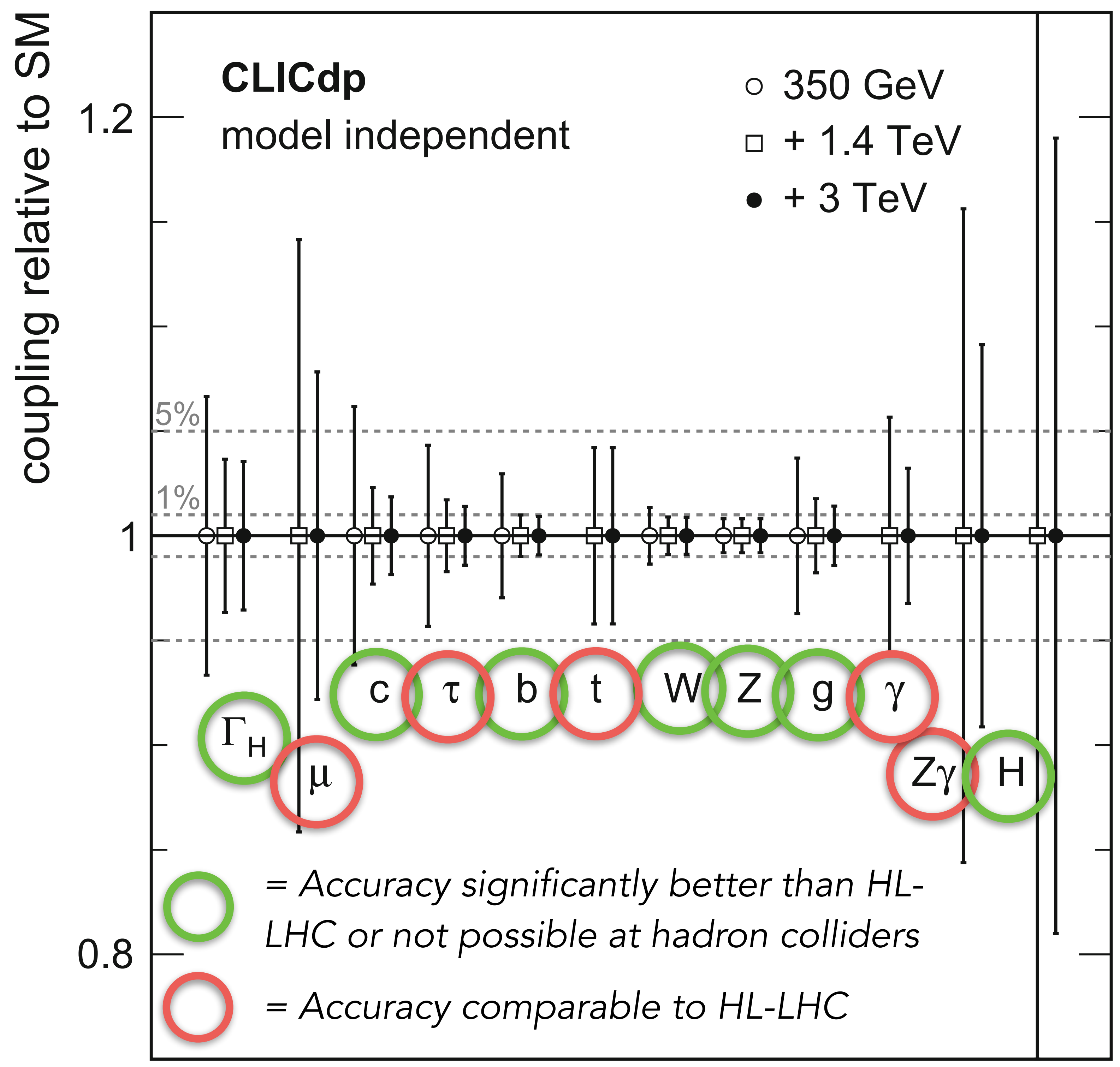
Higgs physics at CLIC

- CLIC covers **several Higgs production processes**
- **Comprehensive report** on our Higgs studies in Eur. Phys. J. C 77 (2017) 475

- **Highlights**
  - Higgsstrahlung $e^+e^- \to ZH$ - Higgs properties can be measured independent of the decay mode by studying the Z-recoil mass (unique to lepton colliders)
  - Vector-boson fusion (enhances the overall knowledge of the Higgs boson)
  - Extraction of top Yukawa coupling ($e^+e^- \to ttH$) + (new) CP violation in ($e^+e^- \to tt\phi$)
  - Double Higgs production - requires high luminosity and high centre-of-mass energy - simultaneous extraction of tri-linear self-coupling ($\Delta\lambda$ CLIC: ~10% from differential distributions) and quartic coupling (gHHWW: ~3%)
  - **Higgs couplings** and **width** can be determined with a **percent-level statistical uncertainty**

➽ **Talk by Yixuan Zhang "Measurement of ttH production"**
➽ **Talk by Goran Kacarevic "Results from H→gamma+gamma study at 3 TeV"**

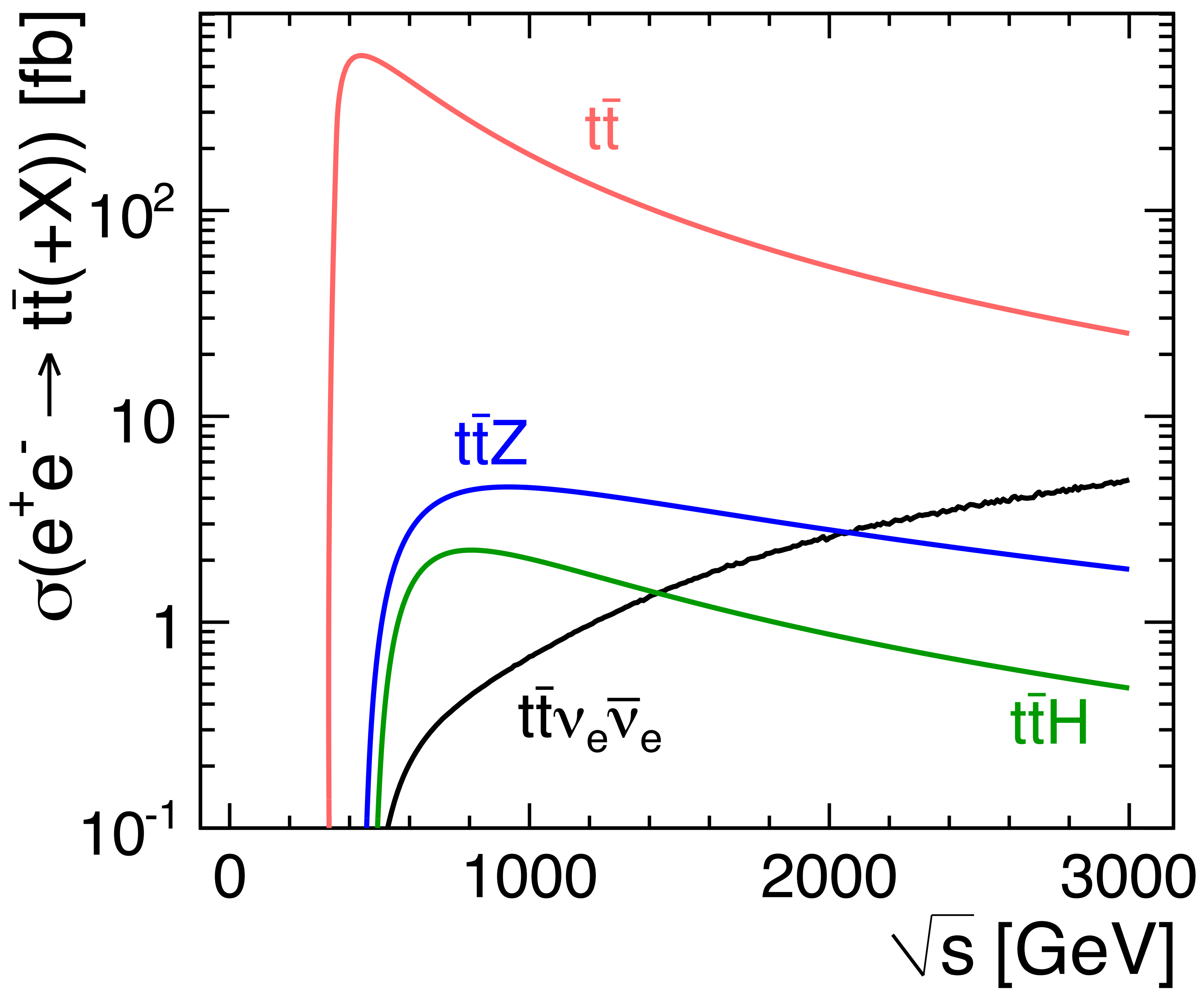
Model-independent (MI) global fits



Top physics at CLIC

- A **large number of top quark pairs** are produced at CLIC
- Top quarks have **not been studied in electron-positron collisions** yet
- The top quark is of particular interest:
  - Couples strongly to the Higgs field
  - Relation to SM gauge bosons
  - Connection to BSM scenarios
- CLICdp is preparing a **comprehensive top physics report**

  ➽ **Talk by Philipp Roloff "Top paper overview"**



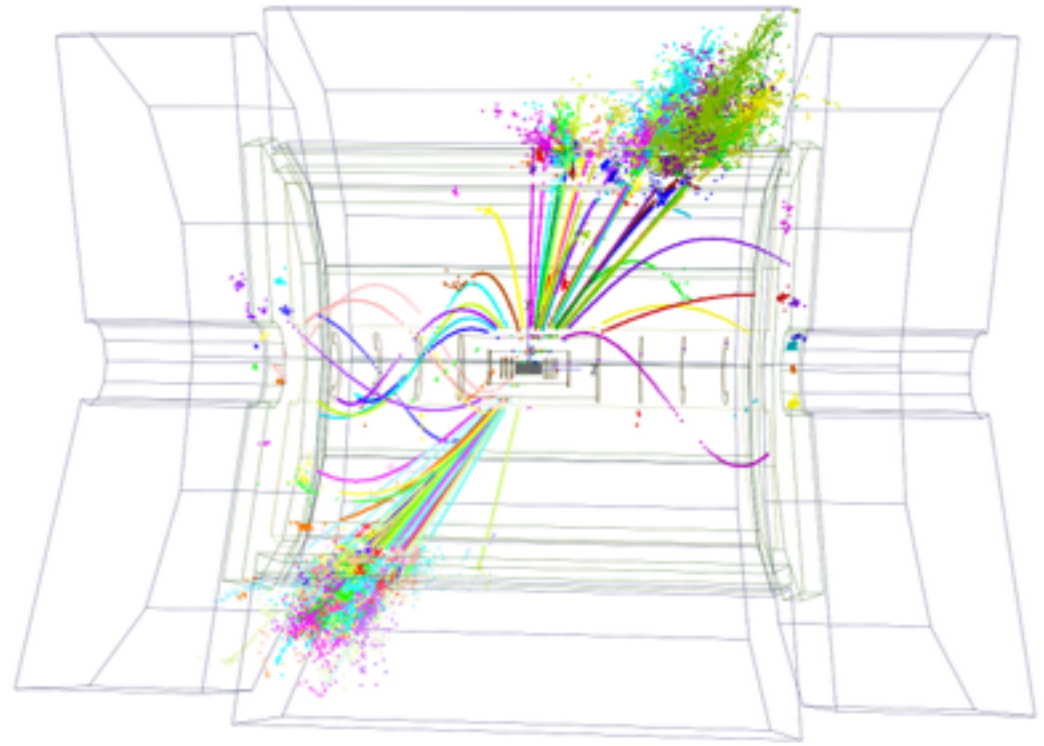
Dominant top production at CLIC

- **Highlights**
  - **FCNC top decays** - competitive limits on rare decays such as $t \to cH$ and $t \to c\gamma$

    ➽ **Talk by Filip Zarnecki "Top FCNC decays"**
  - **Phenomenological interpretations**

    ➽ **Talk by Andrea Wulzer "CLIC Physics Potential"**

Boosted $e^+e^- \to tt$
$\sqrt{s}$ = 3.0 TeV



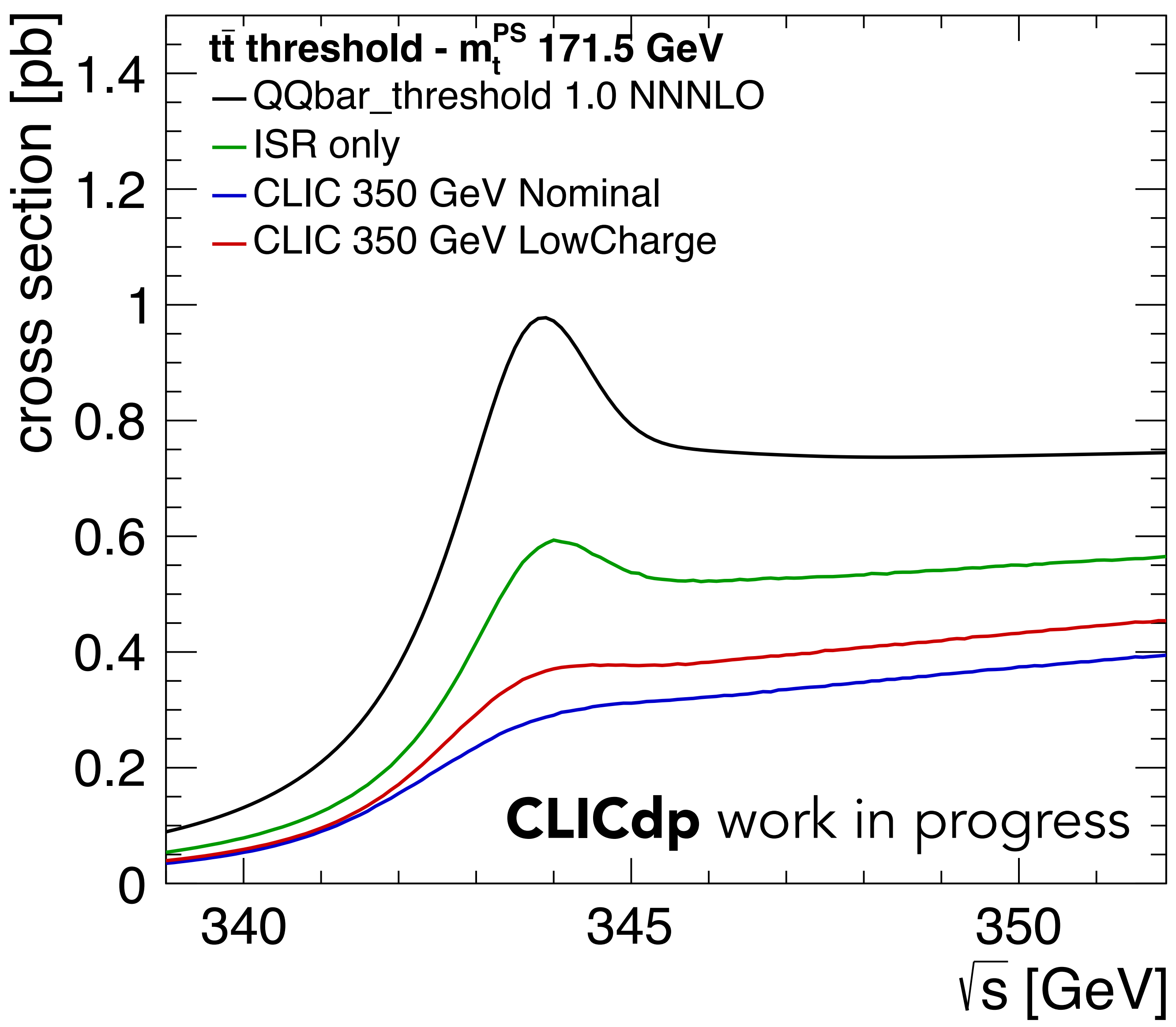
Top physics at CLIC

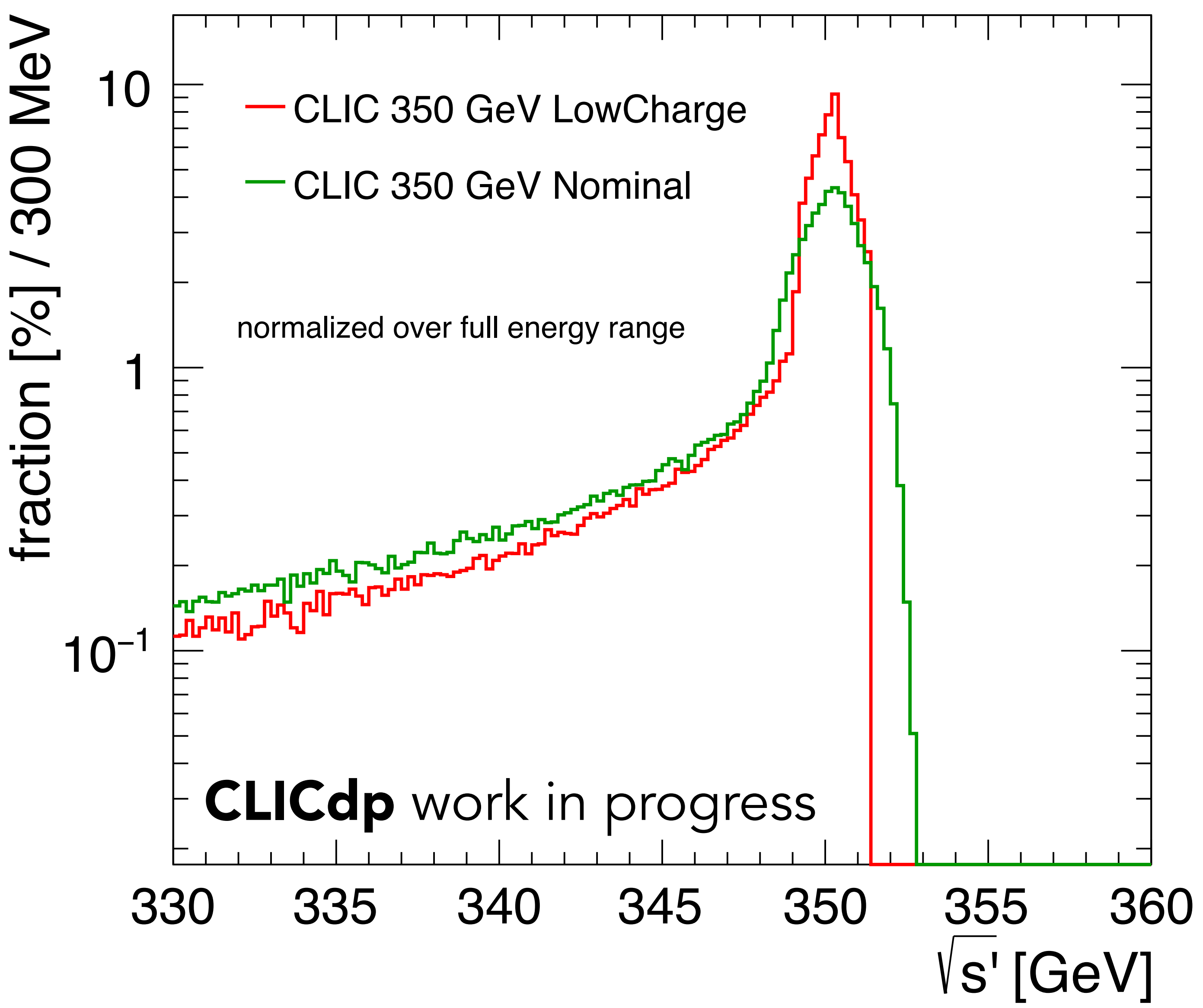
- **Highlights**
  - **Top quark threshold scan** around 350 GeV (extract mass and width), smearing due to ISR and LS (new luminosity spectra optimisation), ~50-75 MeV (LHC: 500 MeV)

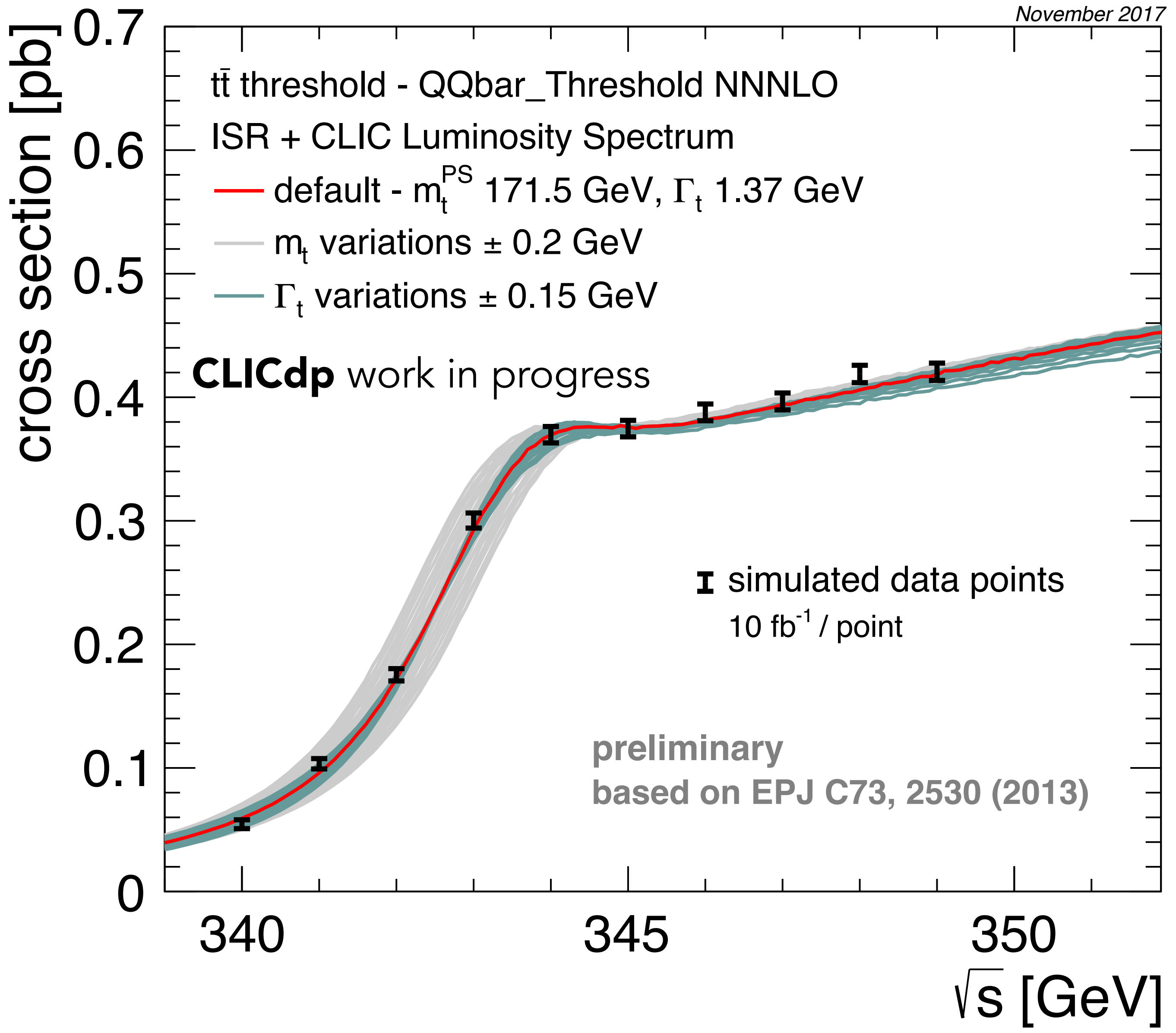
    ➽ **Talk by Frank Simon "Luminosity spectra optimisation for the mass determination in threshold scan"**
  - **Top quark mass from radiative events** ($e^+e^- \rightarrow$ tt+ISR) (380 GeV)

    ➽ **Talk by Esteban Fullana Torregrossa**

New: using new optimised CLIC luminosity spectrum with lower bunch charge:

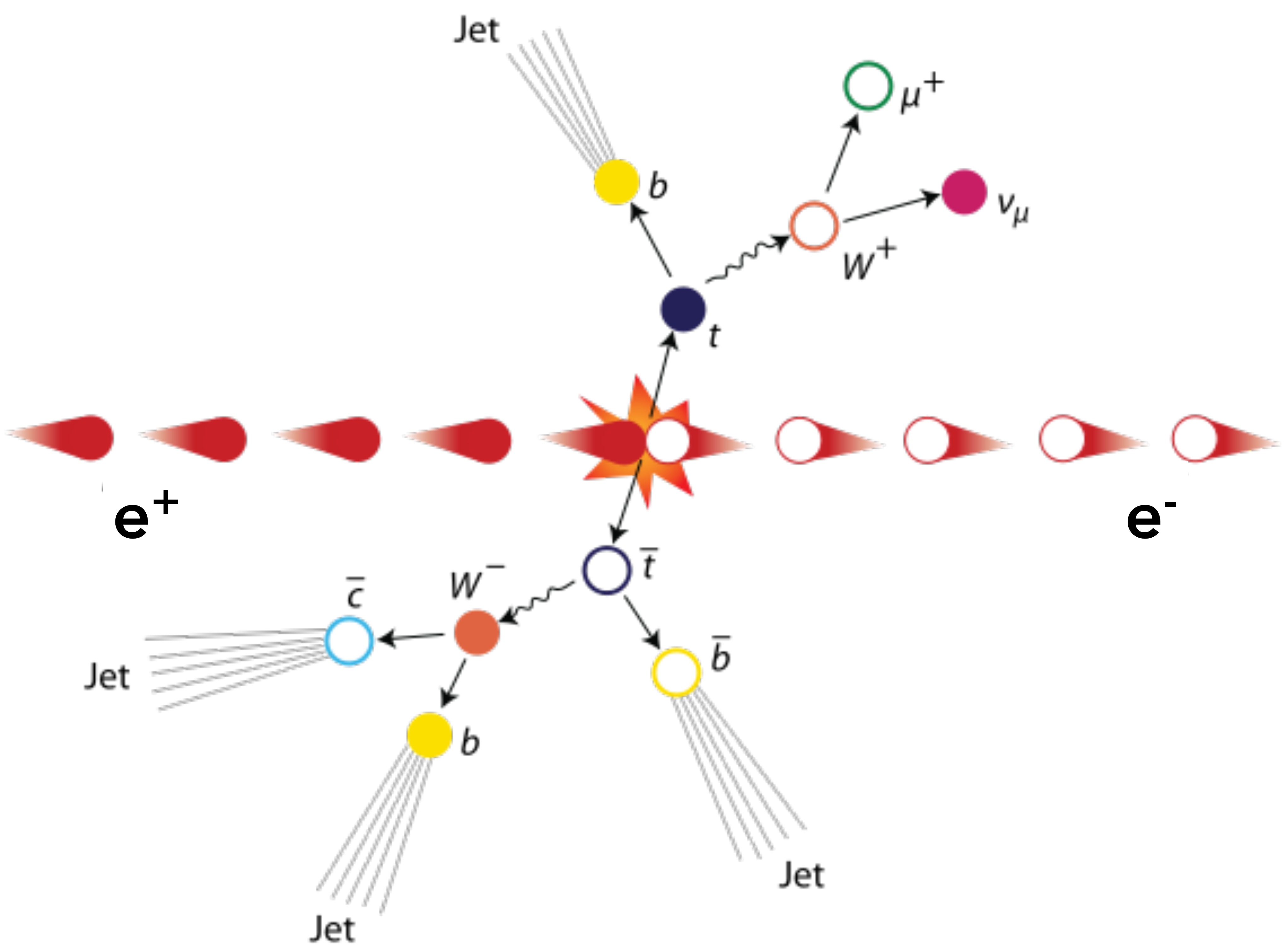






Top physics at CLIC

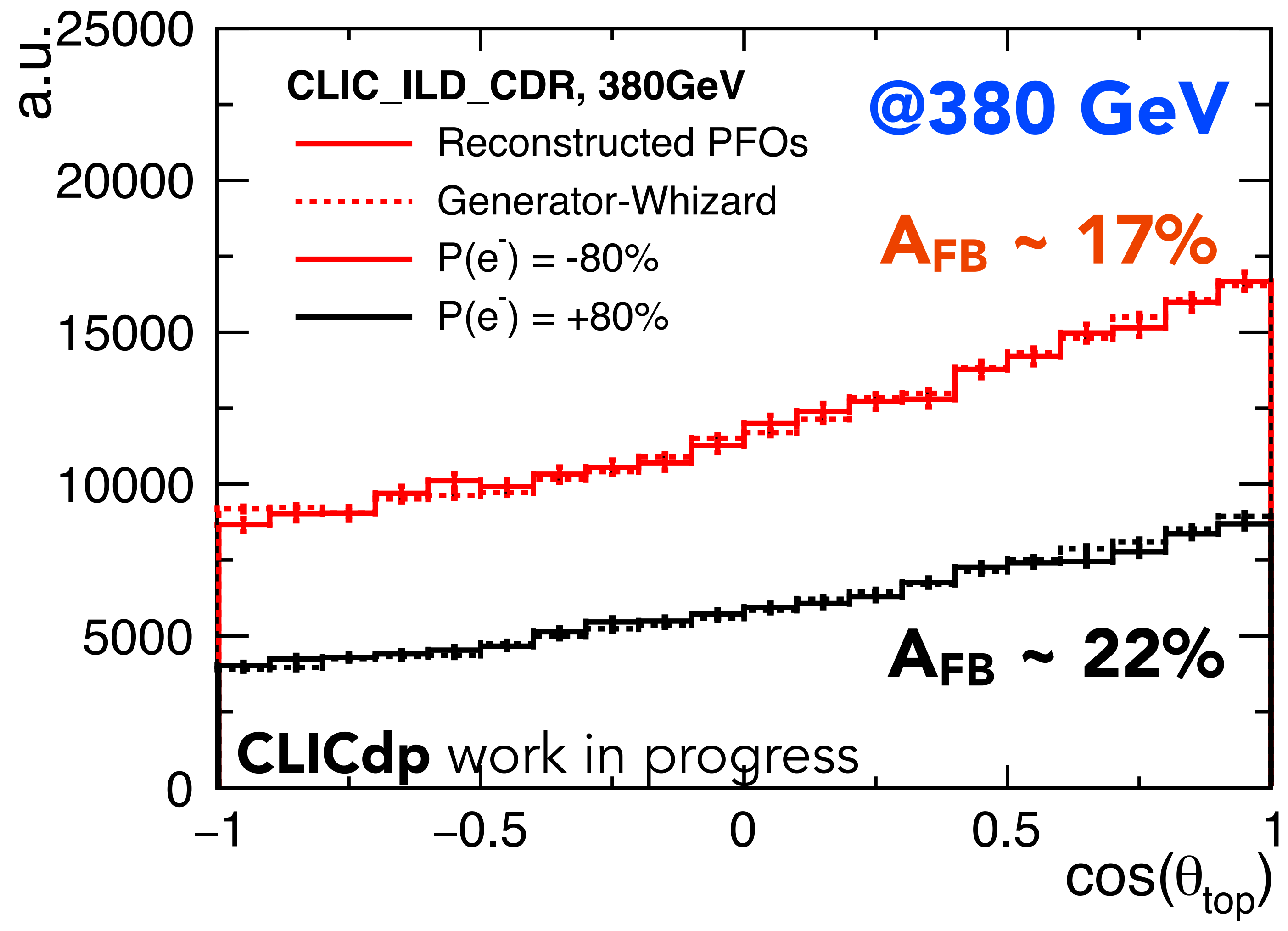
- **Highlights**
  - **Top quark couplings to Z and** γ are among the main focuses and a priority for the top physics programme at CLIC
  - **Substantial improvements in the last year**
  - **Complete tt study at all three stages**: 380 GeV, 1.5 TeV, 3 TeV (ongoing work)
  - Semi-leptonic ttbar (tt → qqqqlv), lepton charge used to reconstruct the charge of the top/anti-top
  - Cross-section and forward-backward asymmetry
  - Set of statistically optimal observables
  - **Combined EFT interpretation**, dim-6 operators (TeV operation provides better sensitivity to contact-interaction operators)



Top physics at CLIC

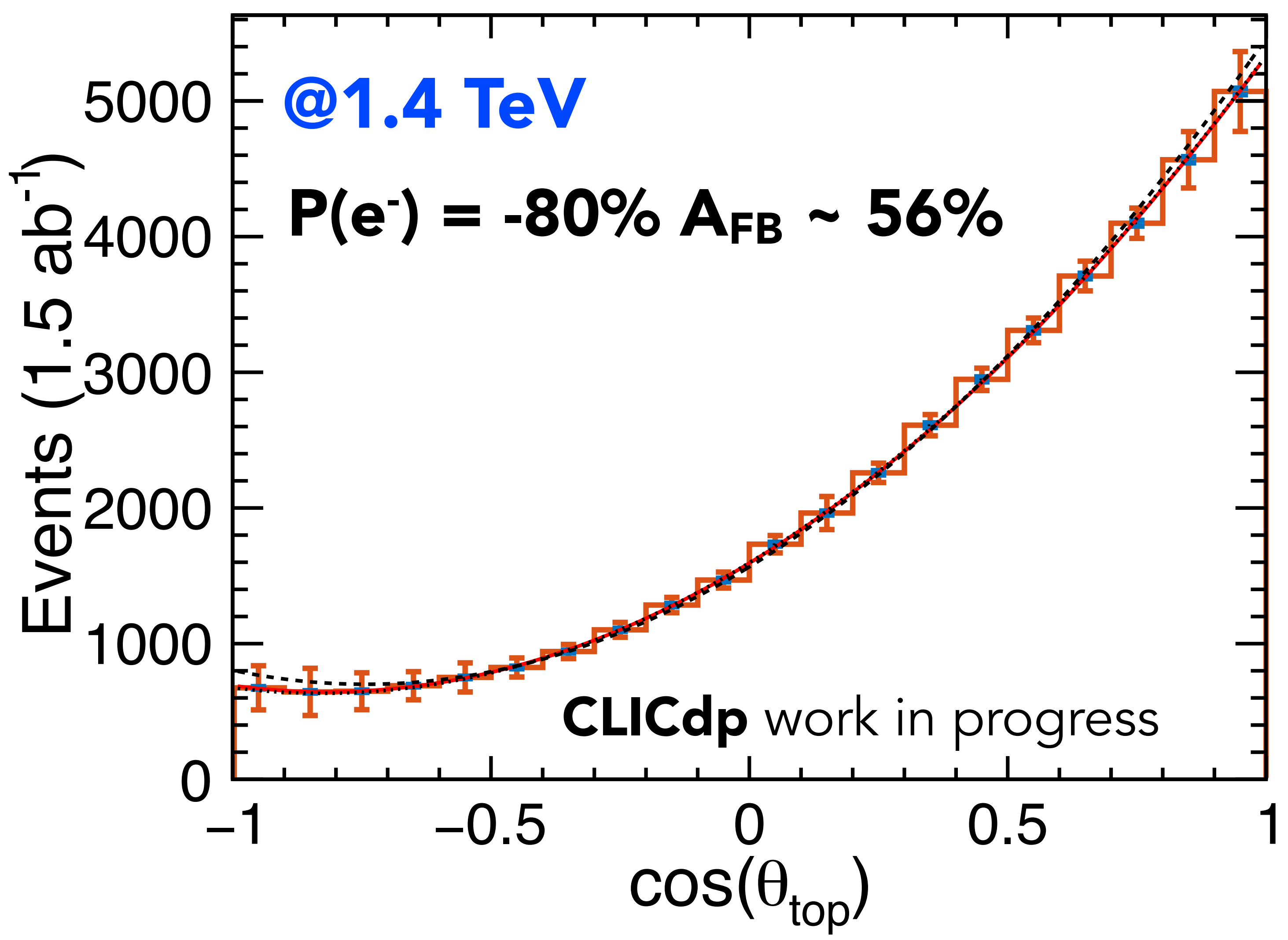
- **Resolved analysis (380 GeV)**
  - Production near threshold (lower effective centre-of-mass due to ISR and beamstrahlung)
  - Use b-tagging, search for W, or 3 jets with a combined invariant mass near m_t

➳ **Talk by Ignacio Garcia Garcia “Top coupling extraction” (380 GeV + EFT)**



- **Semi-resolved/semi-boosted analysis (500 GeV - 1.5 TeV)**
  - Lower effective centre-of-mass due to ISR and beamstrahlung
  - Jet sub-structure variables

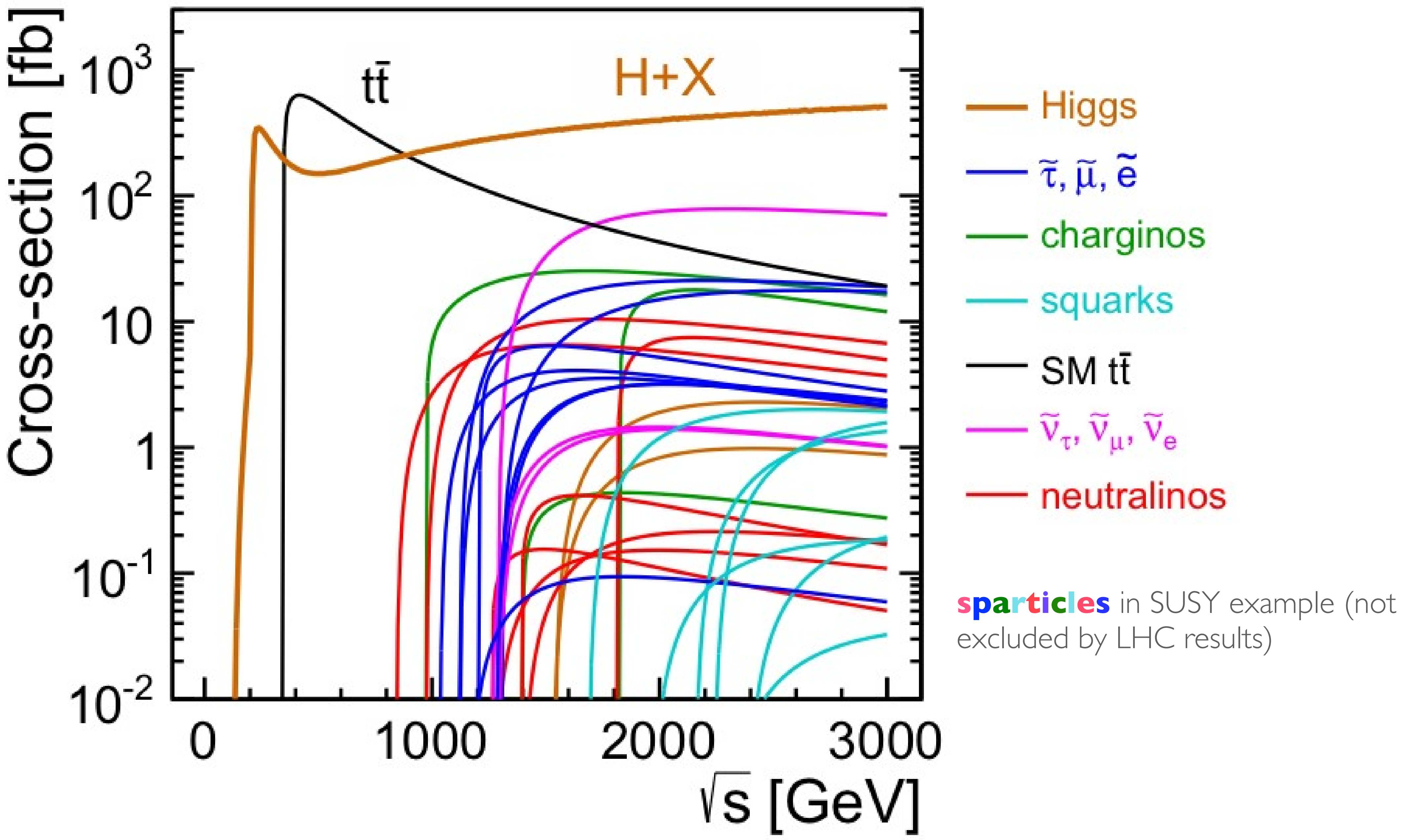
- **Boosted analysis (large R-jets) (1.5 TeV, 3 TeV)**
  - Standard identification techniques may not work:
    - b-tagging not foreseen, tracks are very close to each other
    - W decay products not isolated from each other or b-jet
  - Idea: tag tops by identifying prongy structure + kinematic cuts



➳ **Talk by Nigel Watson “Top pair production at 1.4 TeV” (semi-resolved + boosted)**

Beyond SM physics at CLIC

- The clean collision environment CLIC is particularly suited to study non-coloured TeV-scale particles such as sleptons, gauginos, neutralinos, etc.
- CLICdp is preparing a report on the BSM studies and physics potential
- **Indirect searches** through precision observables
  - Allow discovery of BSM signals beyond the centre-of-mass energy of the collider
- **Direct production** of new particles
  - Possible up to the kinematic limit ($\sqrt{s}/2$ for pair production)
  - Precision measurements - in general always able to measure the mass and production cross-sections to percent-level
  - Complements the HL-LHC program to measure heavy SUSY partners



Beyond SM physics at CLIC

- **Highlights**
  - **Vector boson scattering (VBS)** CLICdp-Conf-2017-018
    - Studied $e^+e^- \to W^+W^-\nu\nu$ and $e^+e^- \to Z^0Z^0\nu\nu$ using fully hadronic events (largest branching fraction and sensitivity)
    - Sensitive to anomalous gauge couplings
    - Clean experimental signal
    - CLIC has competitive results, factor ~10 more sensitive at 3 TeV (**new**) compared to 1.5 TeV → illustration of the benefit of multi-TeV operation
  - **Di-photon production** $e^+e^- \to \gamma\gamma$ (3 TeV) CLICdp-Conf-2017-018
    - Search for deviations from QED, sensitive to finite electron size, extra dimensions, etc.
    - Clean experimental signal + accurate theory predictions
    - Expected sensitivities ~15-20 times better than limits set by LEP (Physics Reports Volume 532, Issue 4, 2013, p. 119-244)

Example models (CLIC 3 TeV, up to 2 ab^{-1})

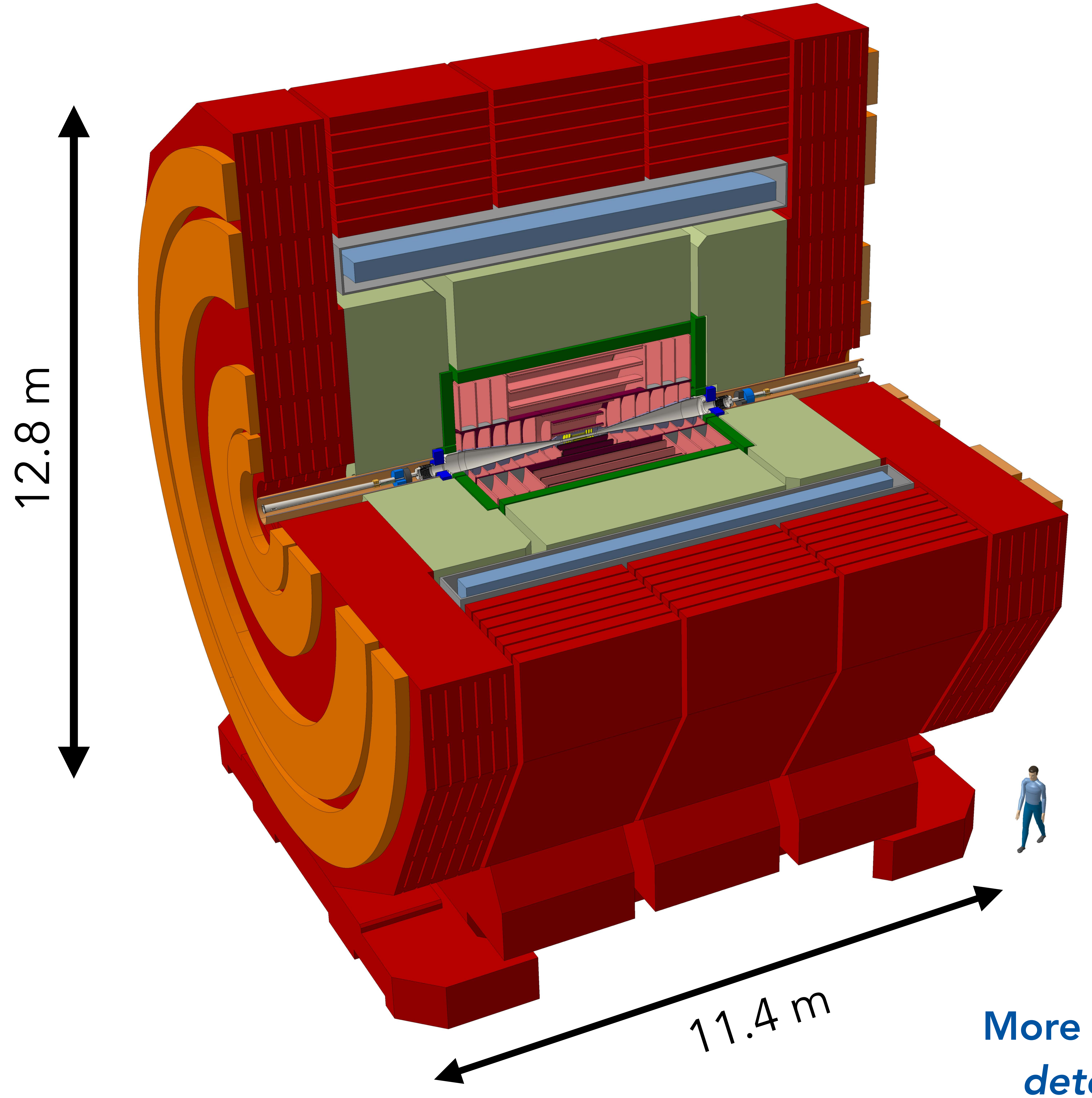
New particle/scenario	CLIC3000 reach
Anomalous gauge couplings*	$-0.001 < \alpha_4 < 0.0011$ $-0.00070 < \alpha_5 < 0.00074$
Extra dimensions $M_S/\lambda^{1/4}$ (95% CL)	~16 TeV
Contact interactions (Λ') (95% CL)	~21 TeV
Chargino, neutralinos	≲1.5 TeV
Sleptons	≲1.5 TeV
Z' (SM couplings)	~20 TeV
Triple gauge coupling (95% CL)	λ_γ: 0.0001
Higgs composite scale	~70 TeV

CLIC detector model 'CLICdet'

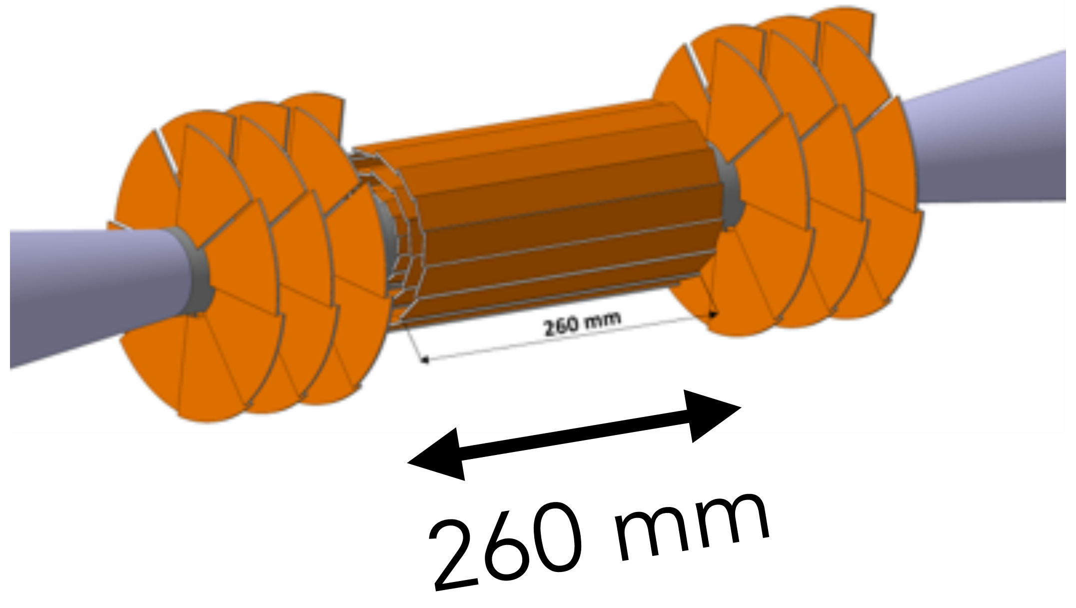
- Iron **return yoke** instrumented with muon detectors, for muon identification
- 4 T superconducting **solenoid magnet** (R_{in} = 3.4 m, L = 8.3 m)
- Fine grained calorimetry system (ECAL and HCAL) using particle flow algorithm
  - Strong contribution to the CALICE and FCAL calorimeter R&D collaborations

➽ Talks at the CLICdp calorimeter R&D session (Thursday)

➽ Talk by Felix Sefkow "Calorimetry from LC to the LHC"



- Low-mass tracking system with separate tracker and vertex detector



- Enclosed in forward region: LumiCal (luminosity monitoring), BeamCal (extended coverage)

➽ Talk by André Sailer "FCAL: validation and performances"

More details: *"CLICdet: The post-CDR CLIC detector model"*, CLICdp-Note-2017-001

CLIC detector requirements

Vertex detector requirements

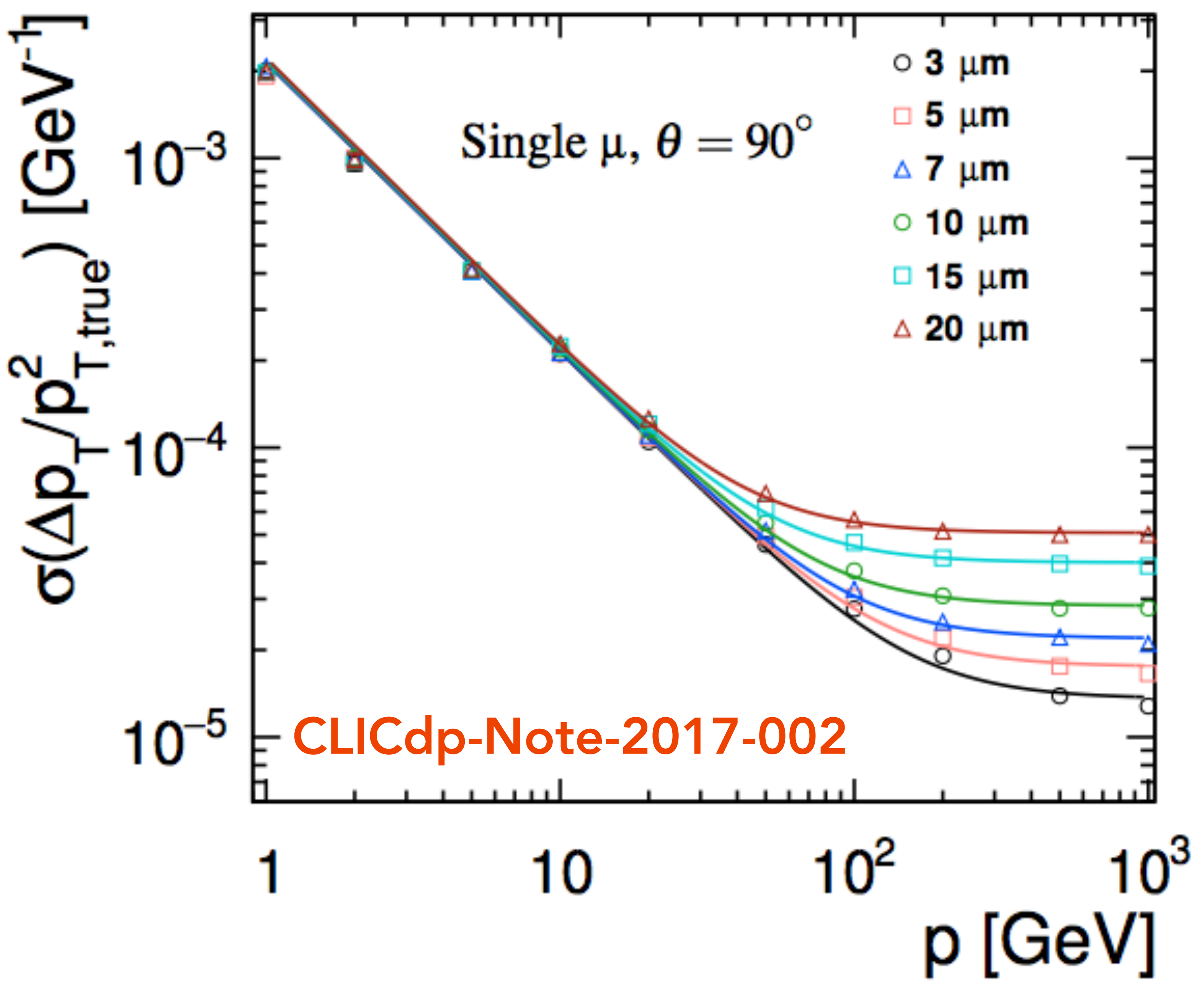
- Driven by displayed vertices resolution + increased precision for low-p_T tracks
  - High single-point resolution: **~3 µm**
  - Ultra-thin: ≲ **0.2% X_0 / layer** (50 µm active silicon)
  - Air cooling, low-power ASICs

Tracker detector requirements

- Driven by momentum resolution: **σ_{p_T} / p_T^2 ~ 2 x 10^{-5} GeV^{-1}**
  - Single-point resolution: **~7 µm** (large pixels / small strips)
  - Material budget **1-2% X_0 / layer**
  - Many layers, large outer radius ➞ has to cover ~100 m^2 surface area ➞ integrated sensors w. large pixels (≲ 30 µm × 1 mm) + low-mass supports, cabling and cooling

Calorimeter detector requirements

- Need very good jet-energy resolution (Particle Flow Algorithm (PFA))
  - **σ_E / E ~ 3.5%** in the range 100 GeV - 1 TeV

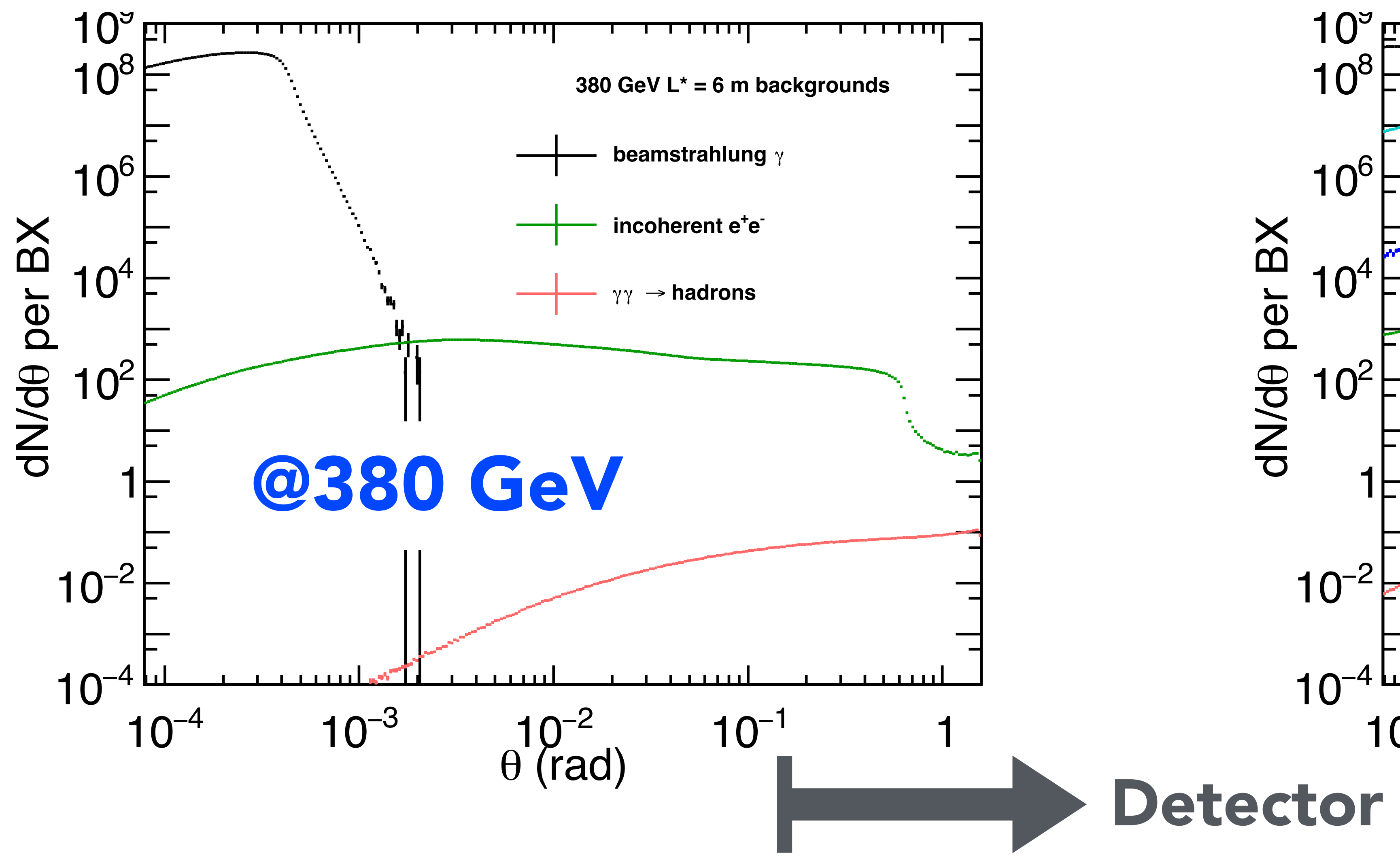


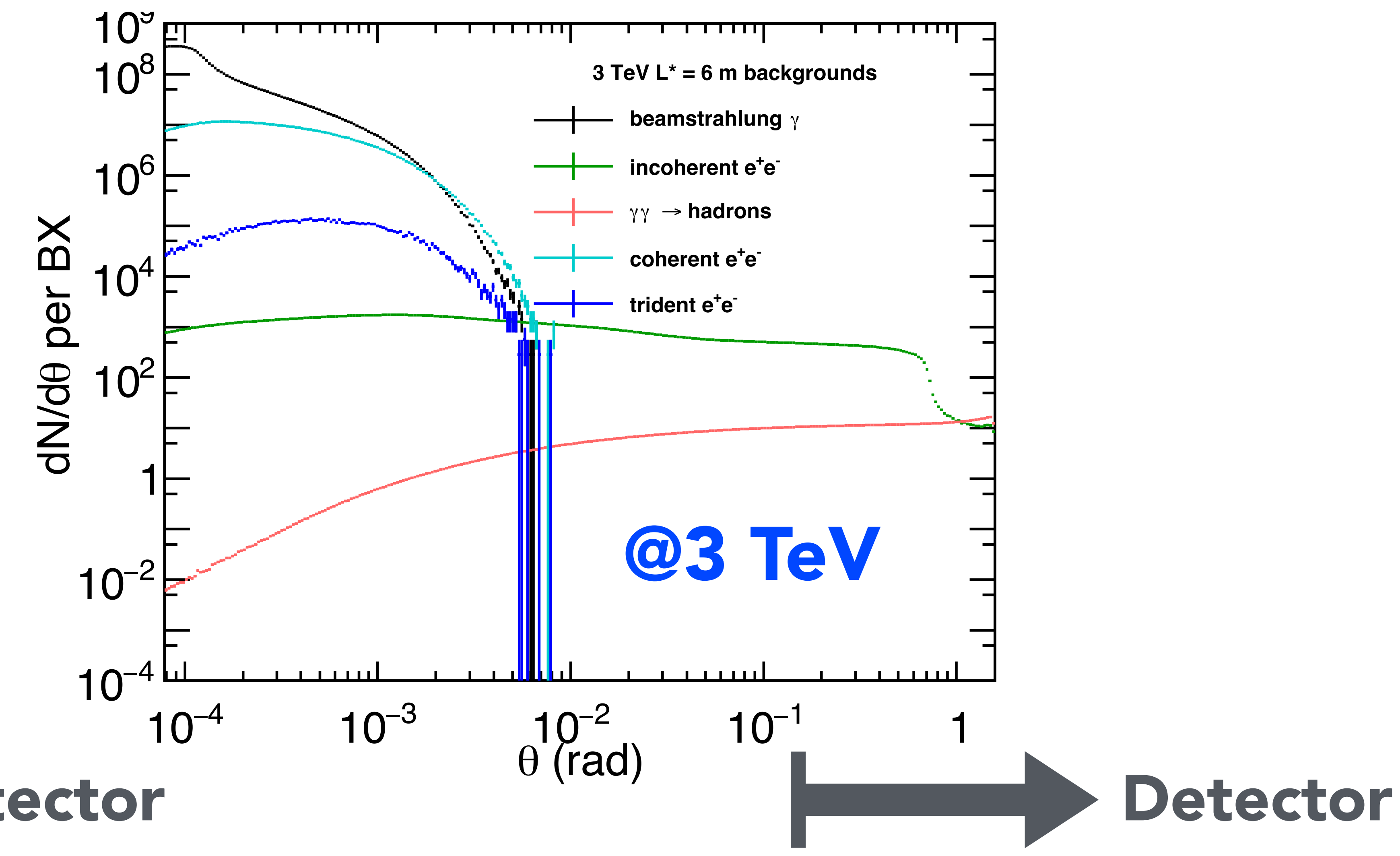
Transverse-momentum resolution in the CLIC tracking detector for various single-point resolution

CLIC detector requirements

Aspects of detector design driven by CLIC machine environment

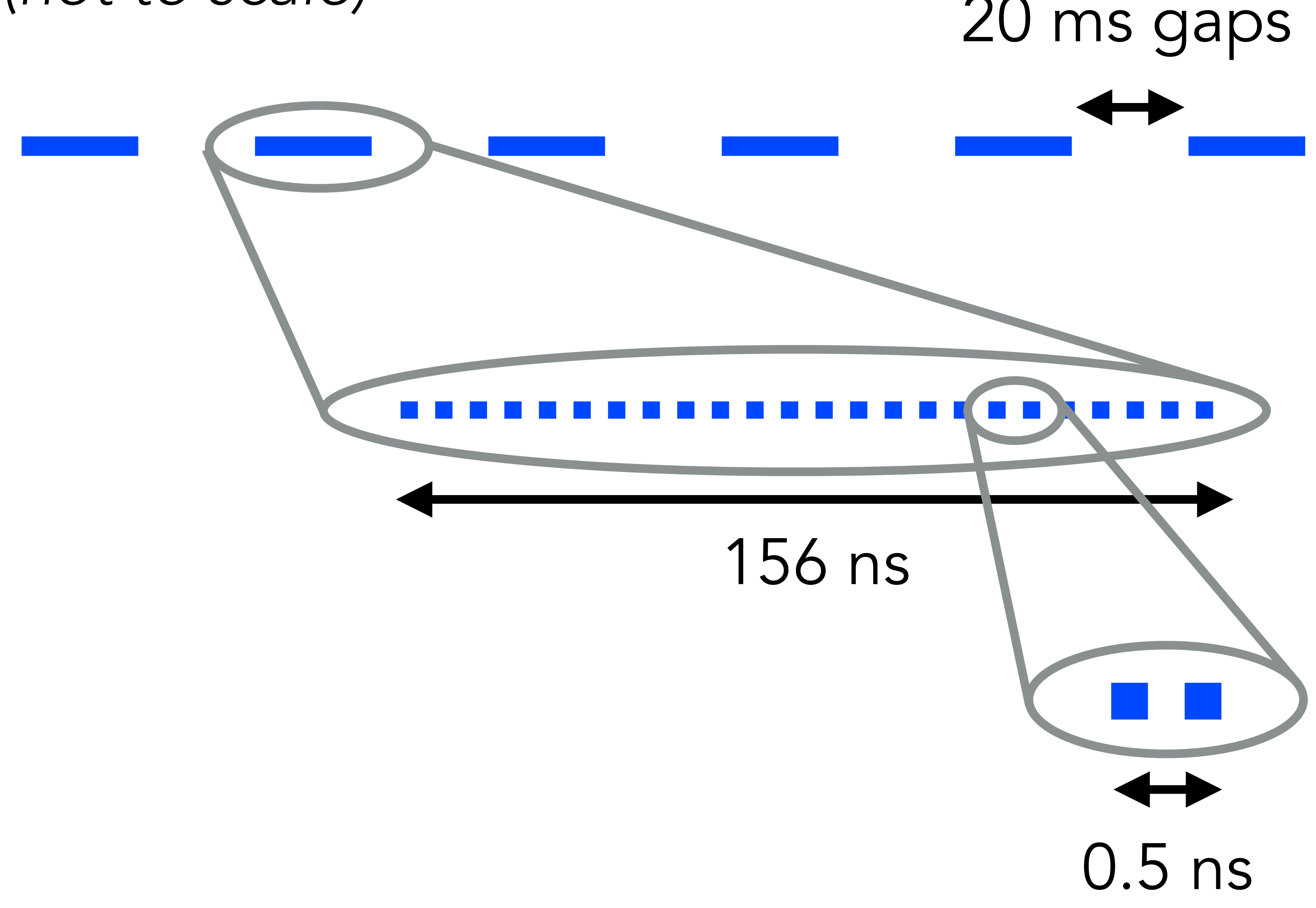
- 20 ms gaps between bunch trains → **power pulsing**, trigger-less readout
- Large beam-induced background → **few % maximum occupancy**
  - **limits cell size and sets inner radius**
  - Overall need for **precise timing to suppress background**
  - ~10 ns hit time-stamping in vertex/tracker detector
    - use of depleted sensors (electron drift + matched readout)
  - 1 ns accuracy for calorimeter hits
  - Reconstruction software requirement: pattern recognition





CLIC beam structure illustration

(not to scale)



CLIC pixel-detector technology R&D

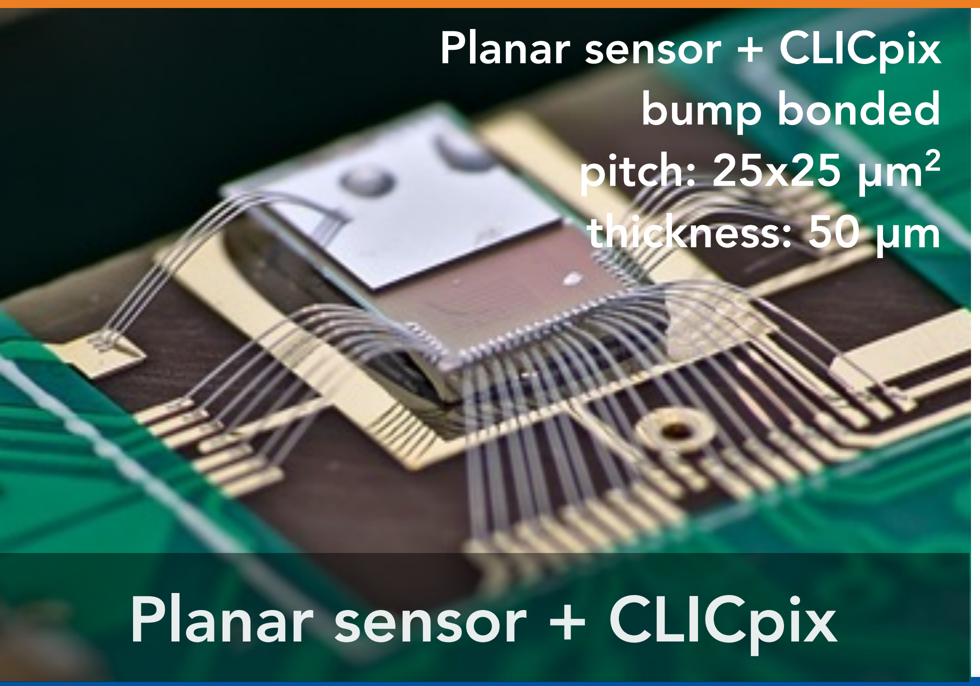
Broad R&D program on sensors, readout, powering, interconnects, mechanical integration and cooling

- Beam tests: of both hybrid (readout ASICs down to 65 nm) and monolithic assemblies
- Ongoing R&D to find a technology that simultaneously fulfils all the CLIC requirements
- Challenging: position-resolution target of ~3 μm for the vertex detector
- New concept to increase charge sharing: use of sensors with deep implantations that alter the electric field (**ELAD**)
- Future developments:
  - Concept for tracker based on monolithic HR-CMOS (following promising studies in view of the requirements)
  - New SOI prototypes in the pipeline

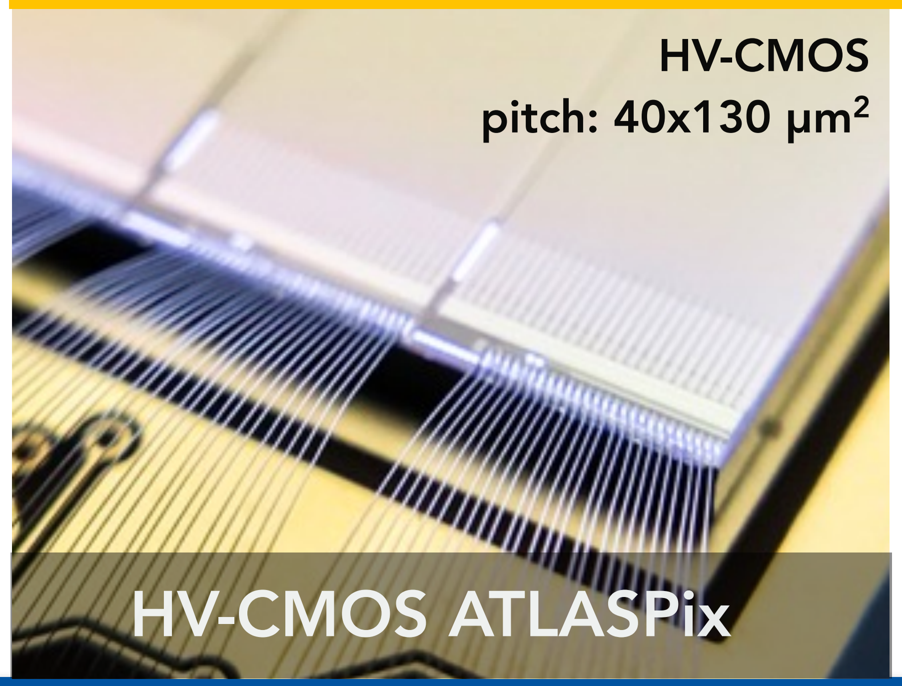
➽ **Talk by Hendrik Jansen "ELAD Sensor Development"**

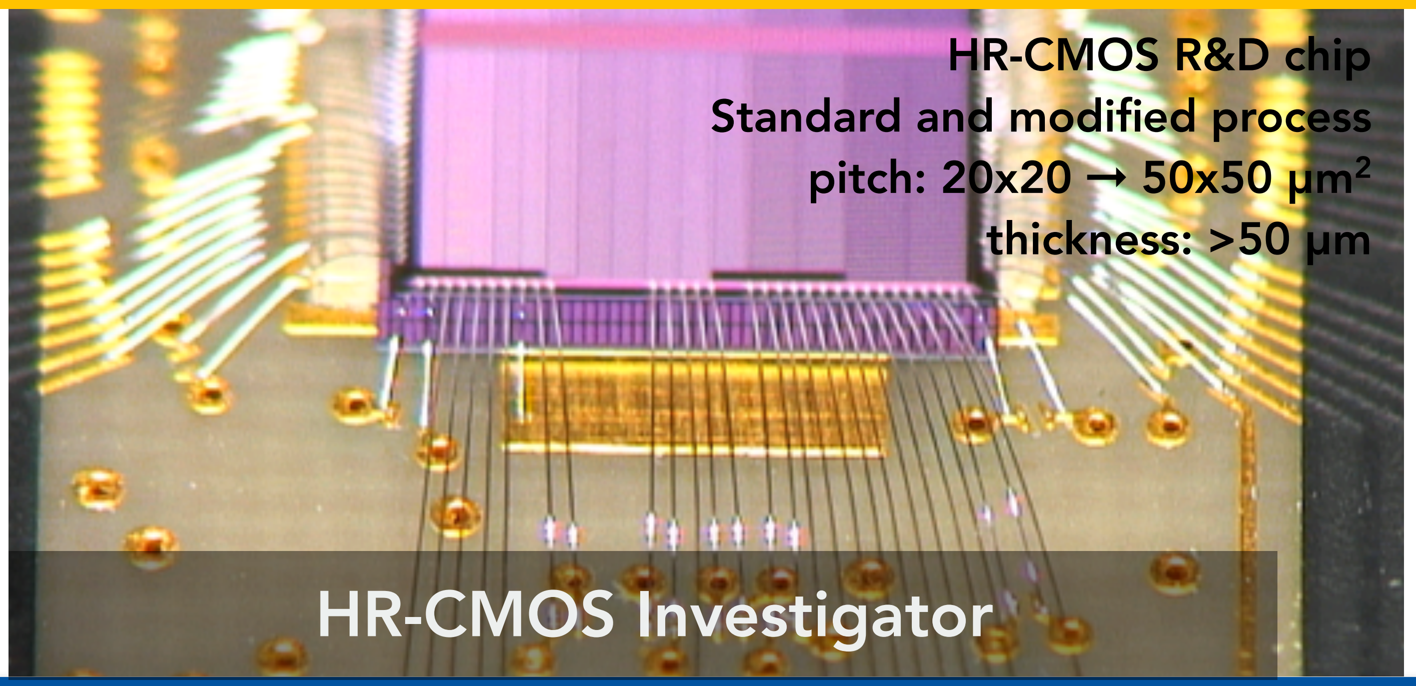
➽ **Please see the "Vertex and Tracker R&D session" (Tuesday+Wednesday)**

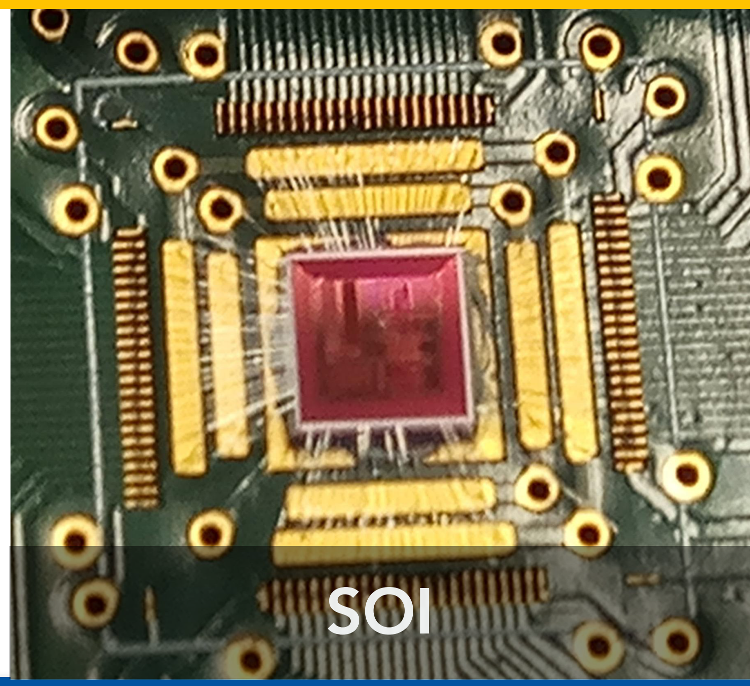
Hybrid assemblies (considered for vertex detector)



Monolithic assemblies (currently considered for tracker)







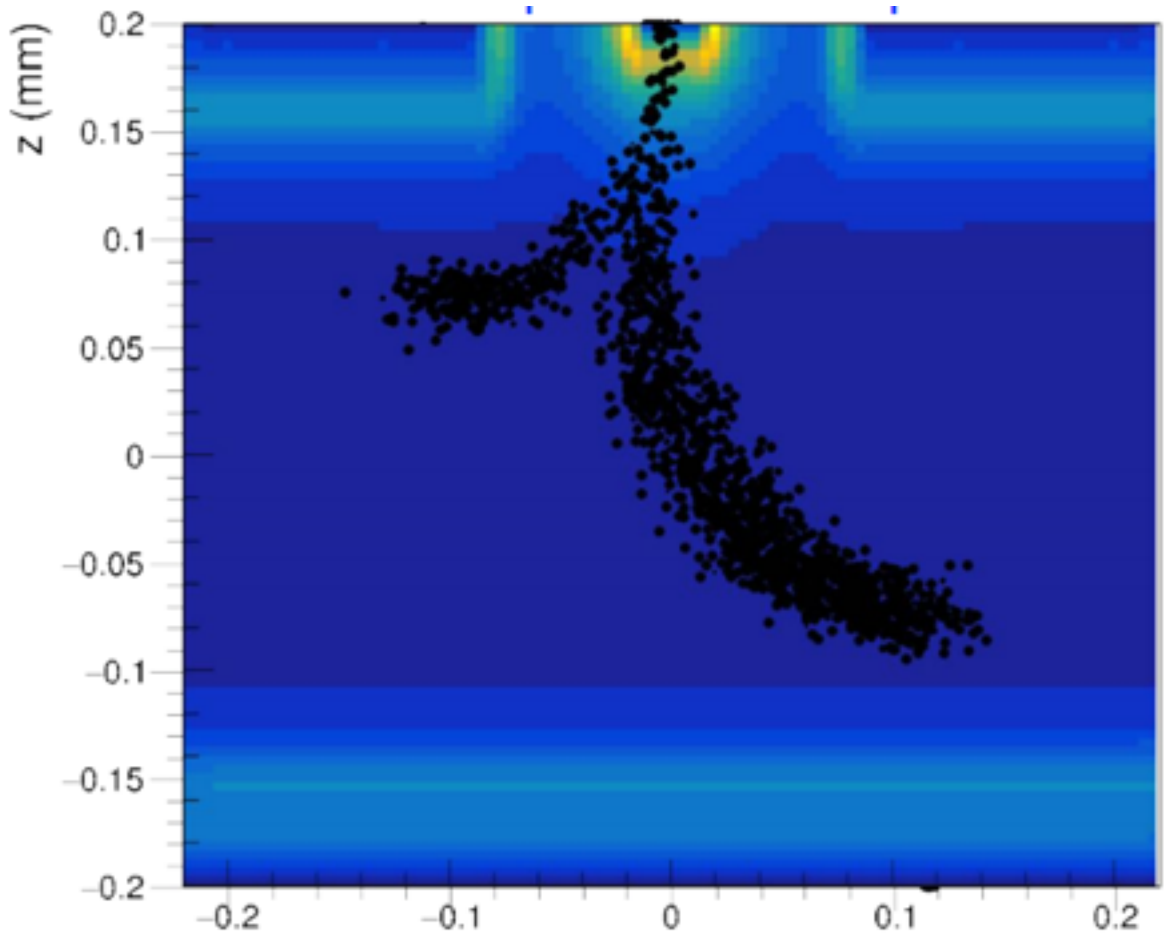
CLIC pixel-detector technology R&D

Development of DAQ/software frameworks

- **CaRIBOu** is a versatile readout system targeting a multitude of detector prototypes (commissioned for CLICpix2+C3PD)
- **Allpix²** - generic pixel detector simulation framework (understand/ predict sensor+readout response)

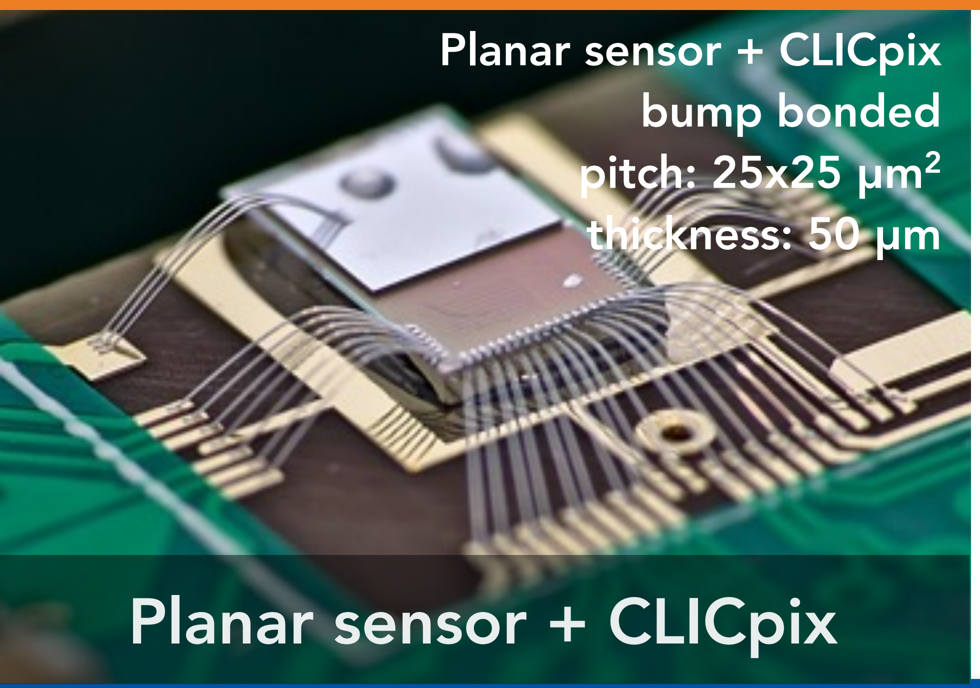
➸ Talk by Simon Spannagel "Allpix Squared - A Generic Pixel Detector Simulation Framework"

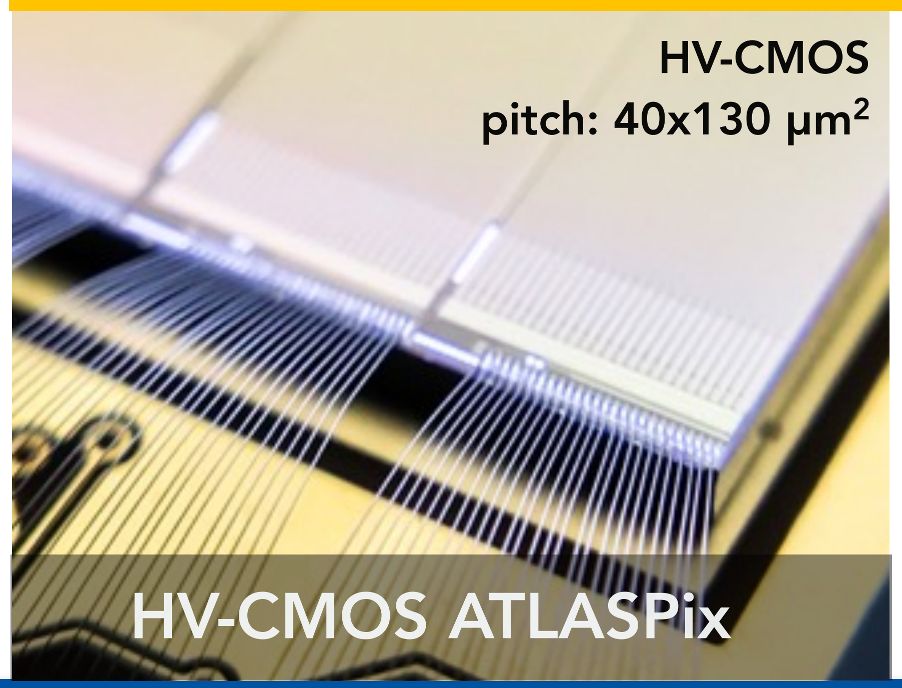
Si pixel simulation using AllPix² illustrating charge collection

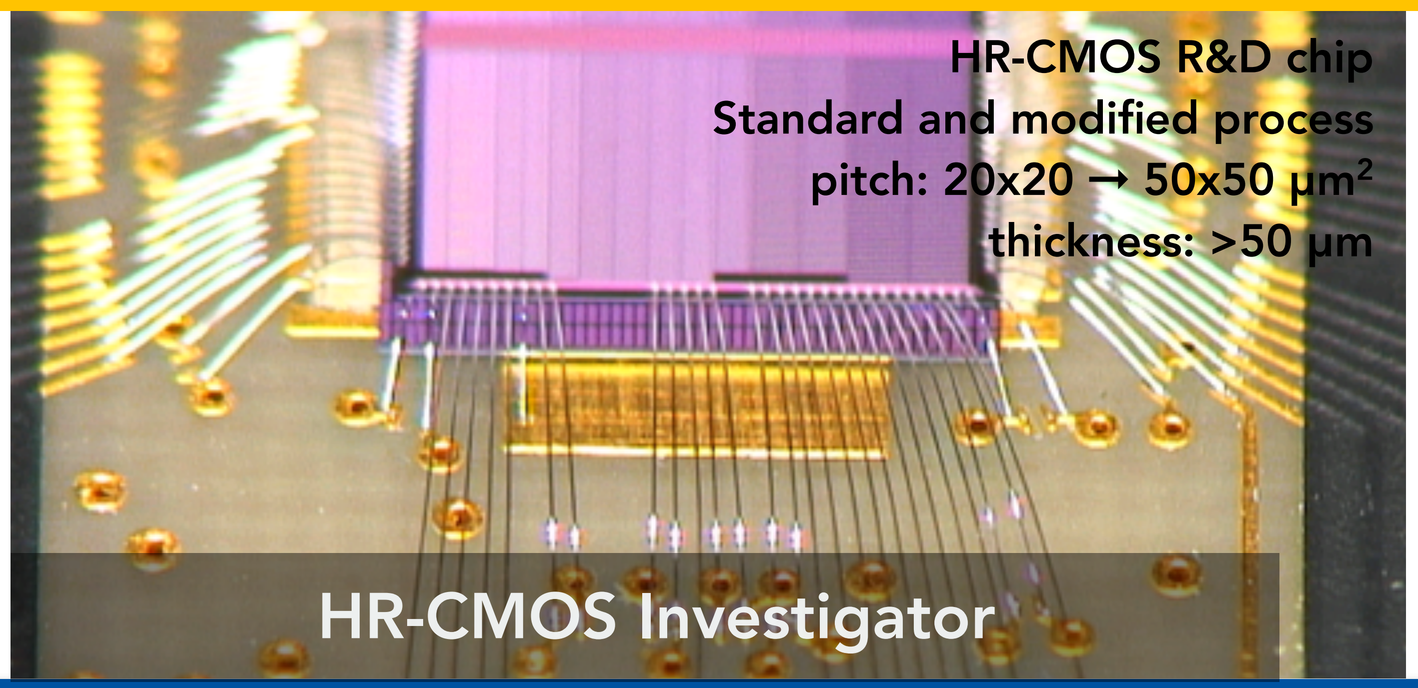


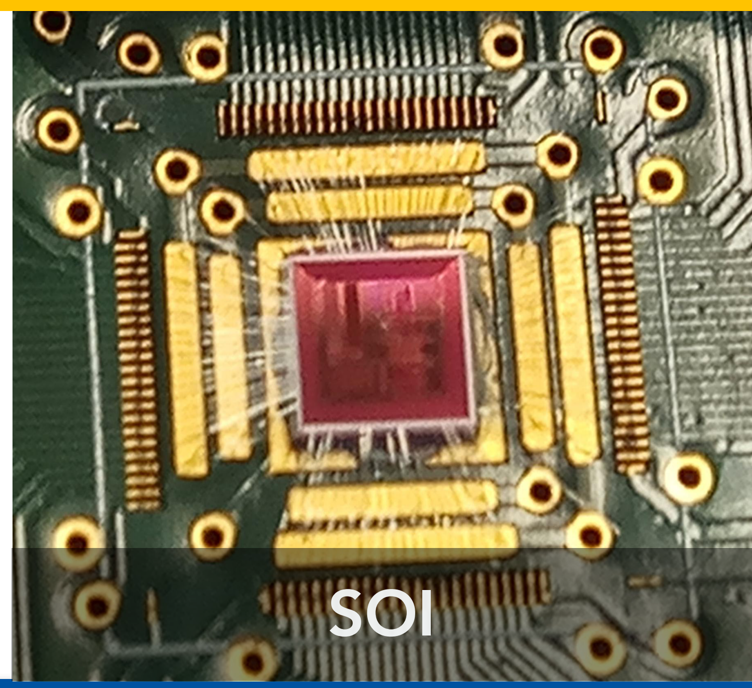
Hybrid assemblies (considered for vertex detector)

Monolithic assemblies (currently considered for tracker)





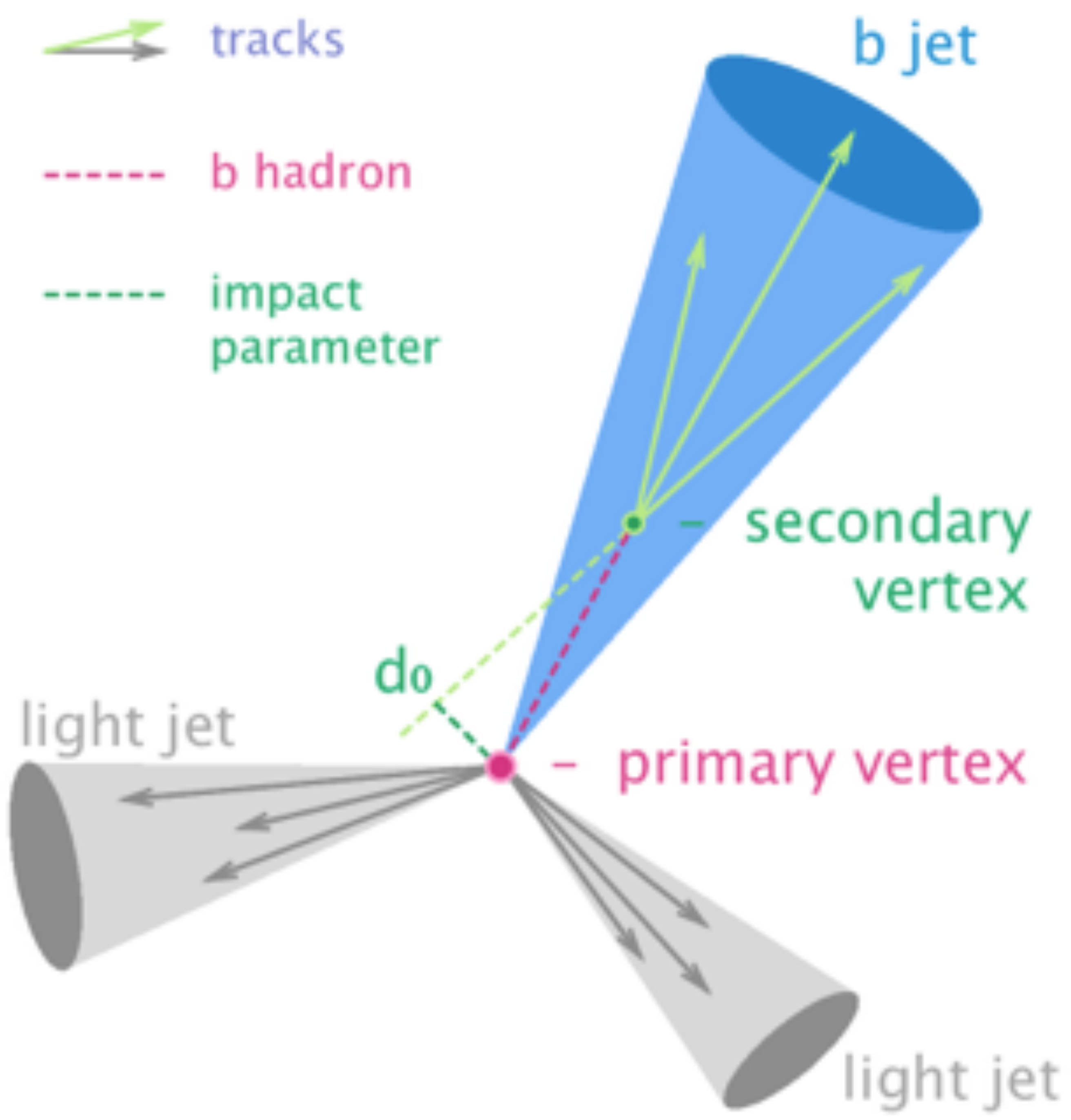




Validation of CLICdet

Ongoing validation studies with CLICdet

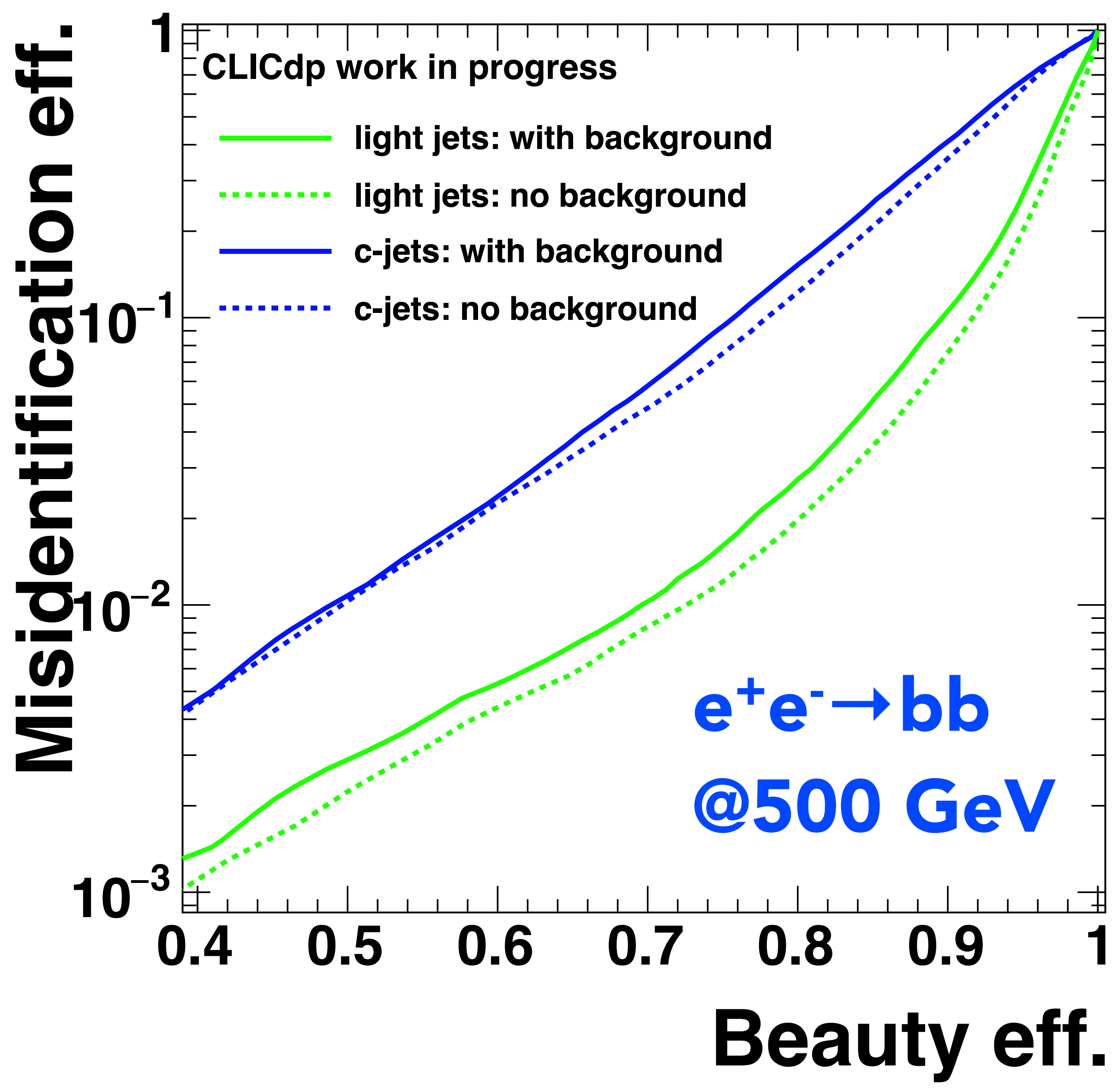
- Ensure that performance meets requirements
- Validate new simulations and reconstruction chain
  - Flavour tagging, tracking, PFA, forward region

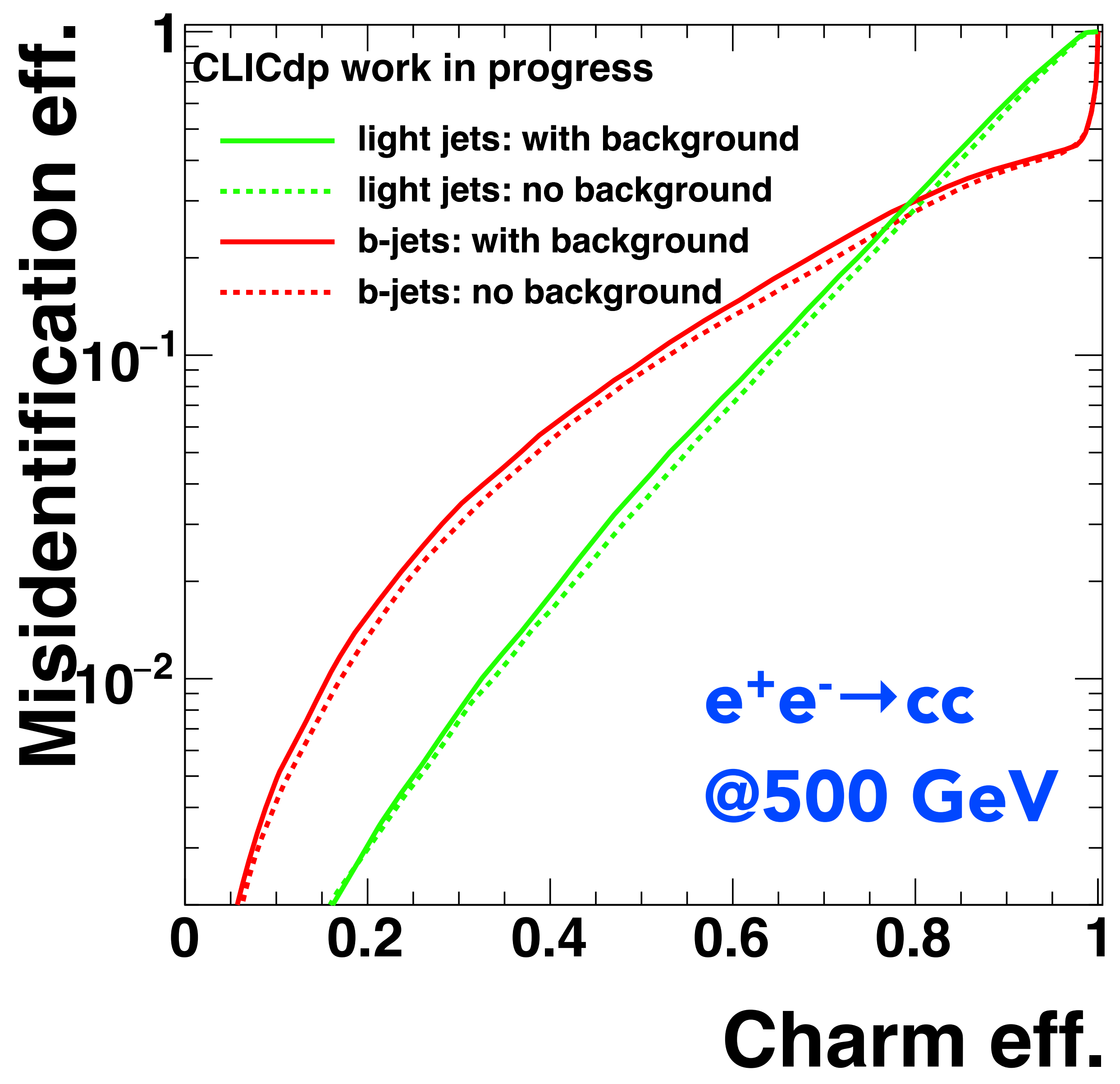


Flavour tagging

- Studied flavour-tagging for di-jet samples (bb, cc, qq (uds))
- b- and c-tagging performance as function of vertex-detector design parameters

➼ **Talk by Ignacio Garcia Garcia "Flavour tagging: validation and performances"**



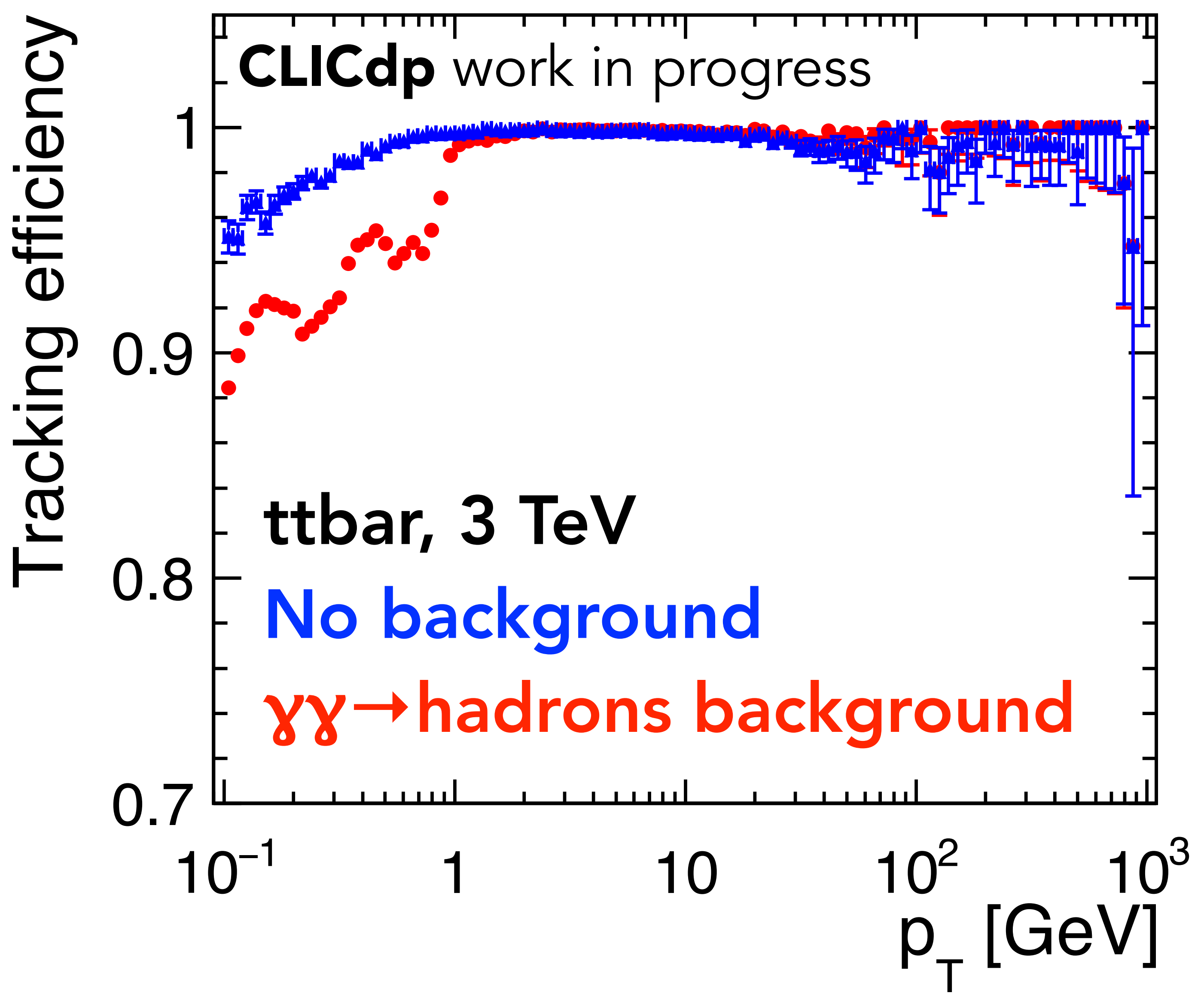


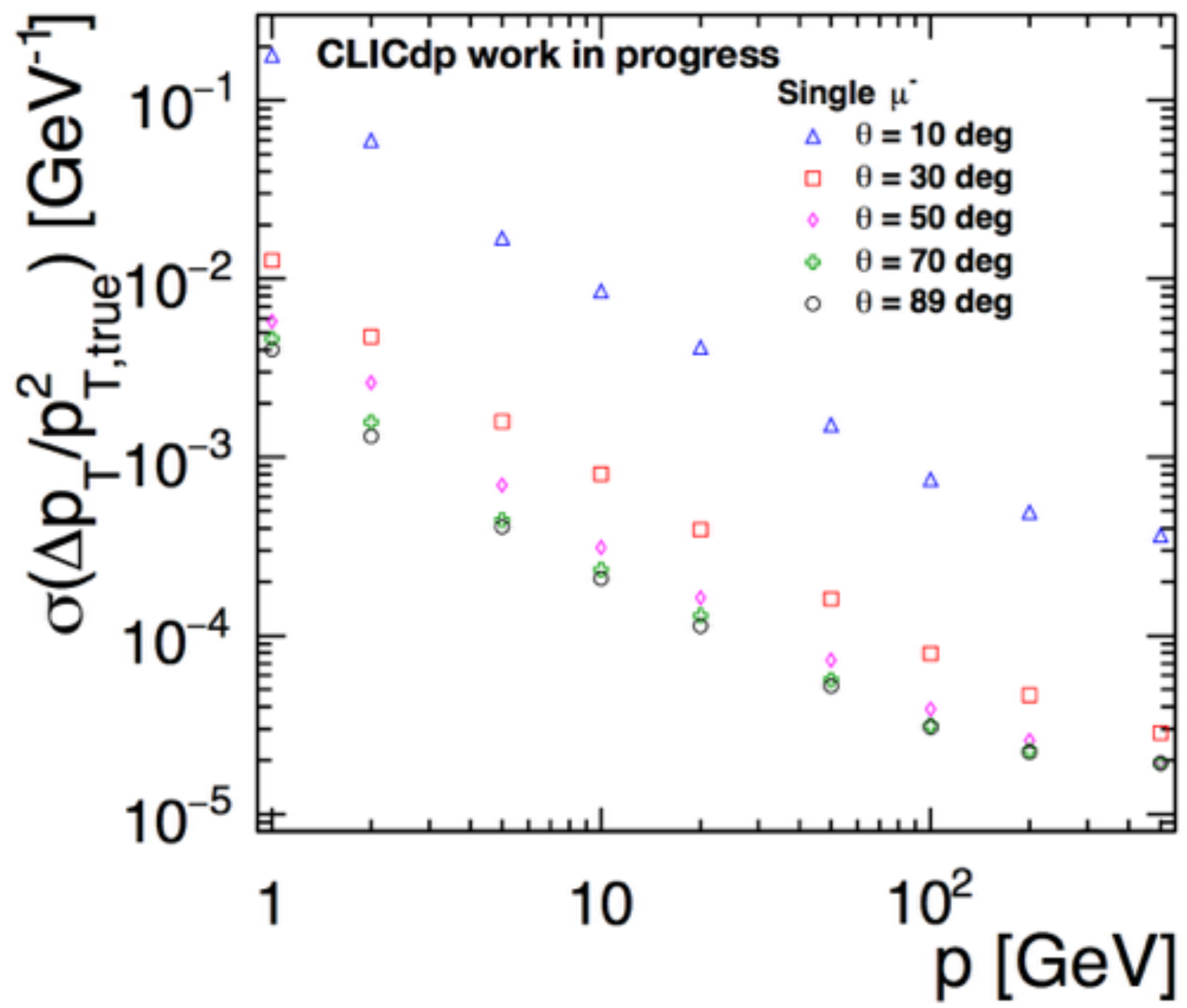
Validation of CLICdet

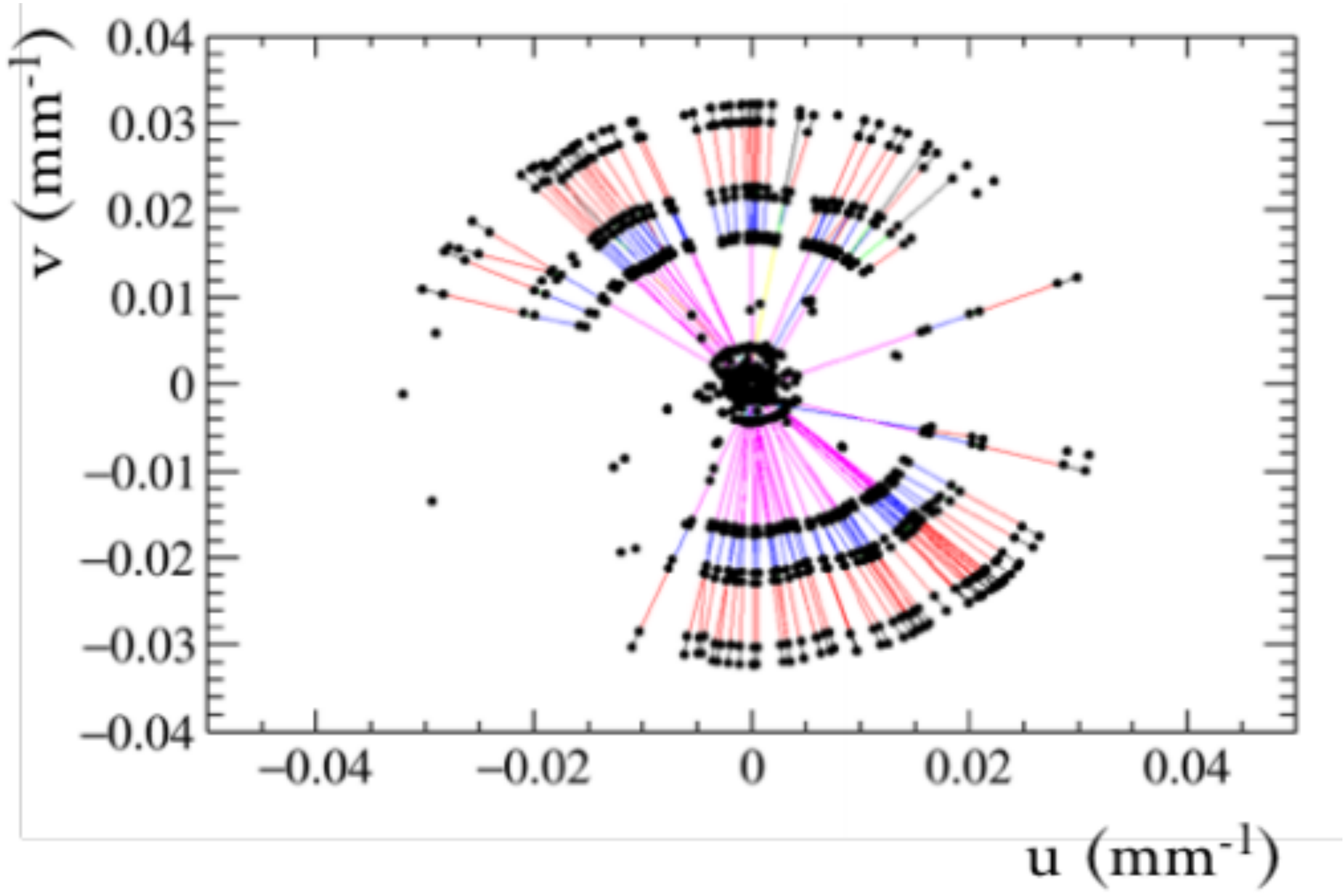
Tracking

- Developed track finding tool based on **conformal transformations**
- Kalman fit for helix track fitting
- Performs well down to 10° in CLIC case
- **Achieved momentum** resolution **2 x 10^{-5} GeV^{-1}** for high energy muons in the barrel (impact parameter resolution ~2 μm)
- Jet performances mostly unaffected by bkg overlay > 1 GeV

➳ **Talk by Emilia Leogrande "Tracking: validation and performances"**





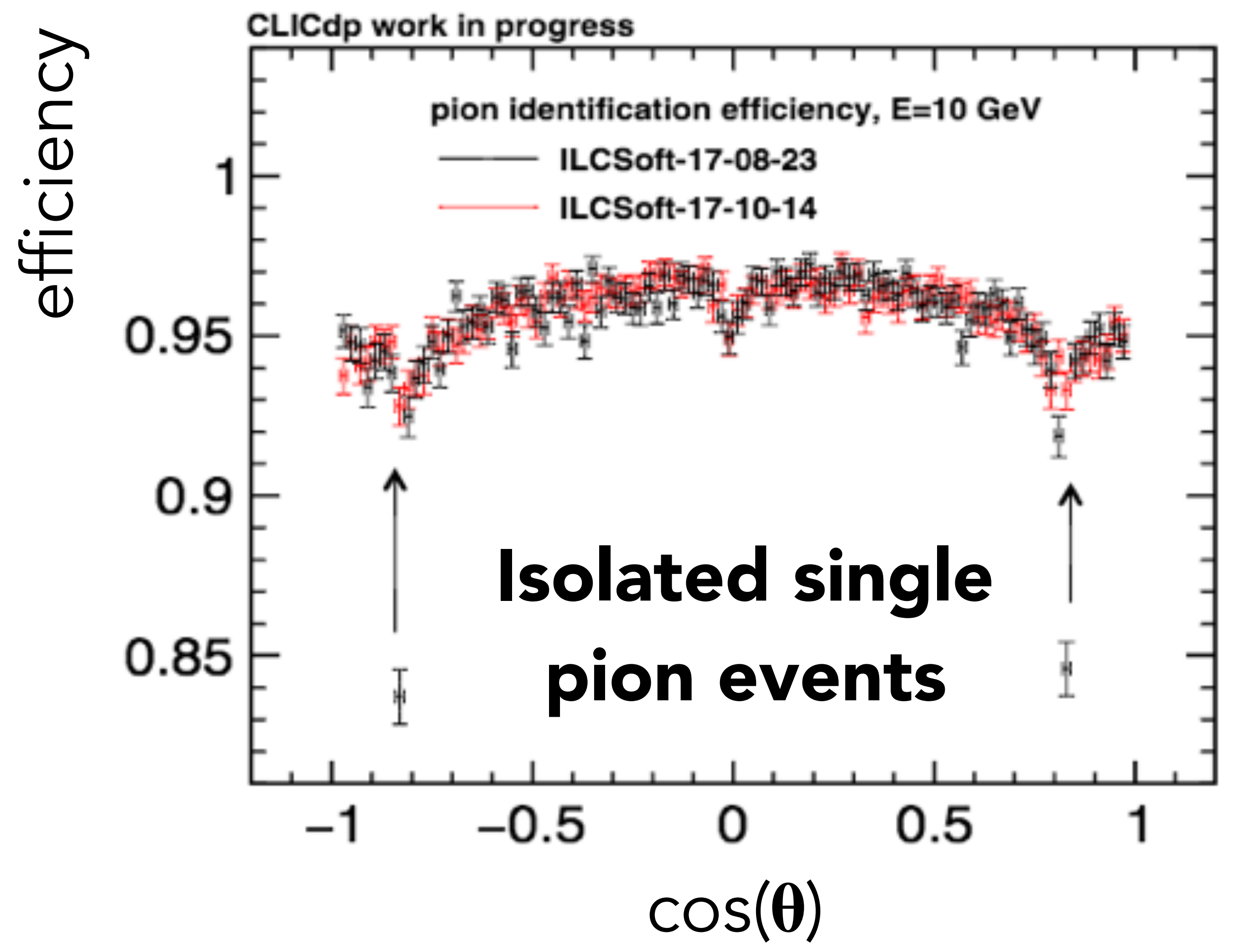


Example of tracking in conformal space

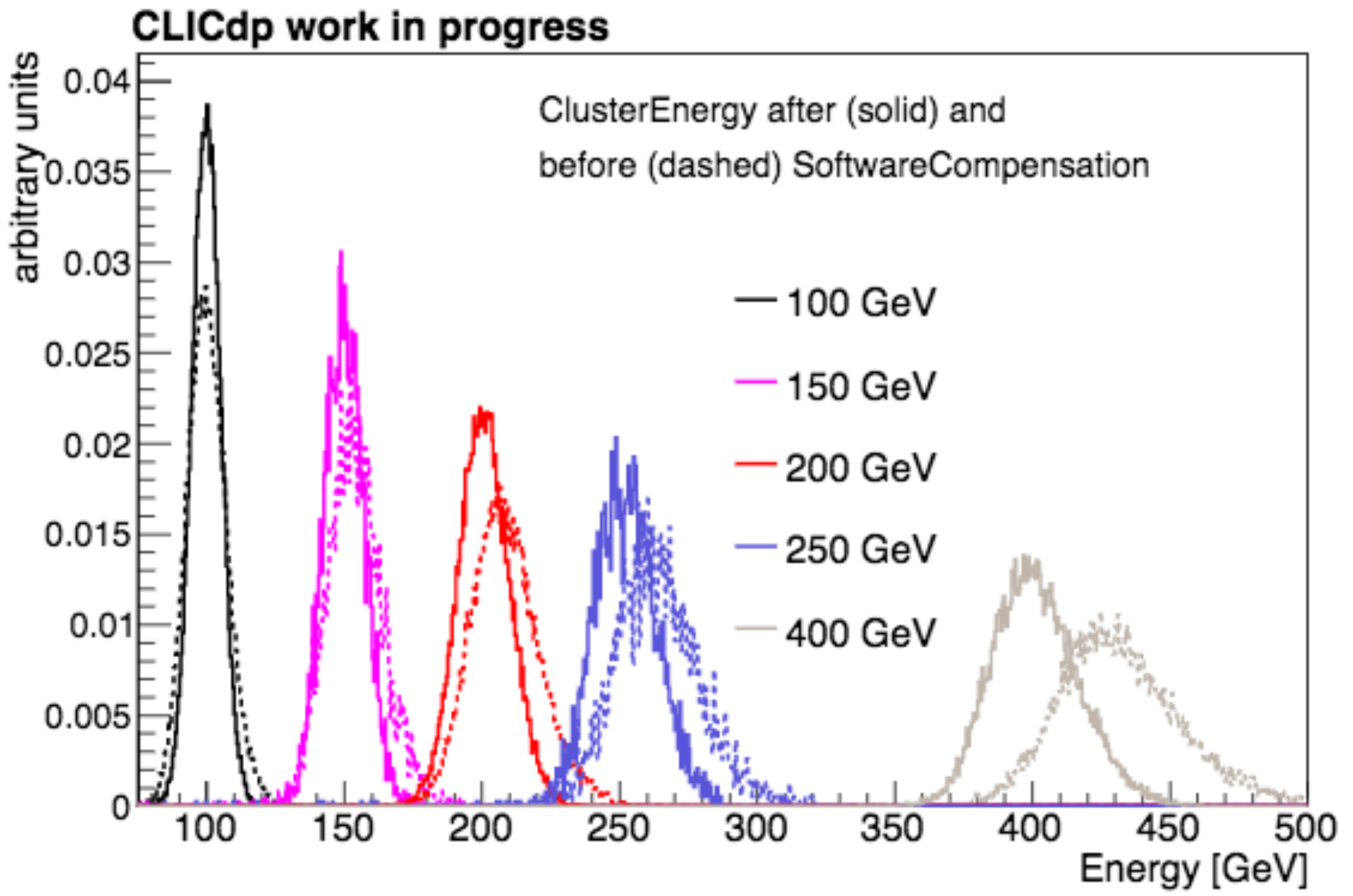
Validation of CLICdet

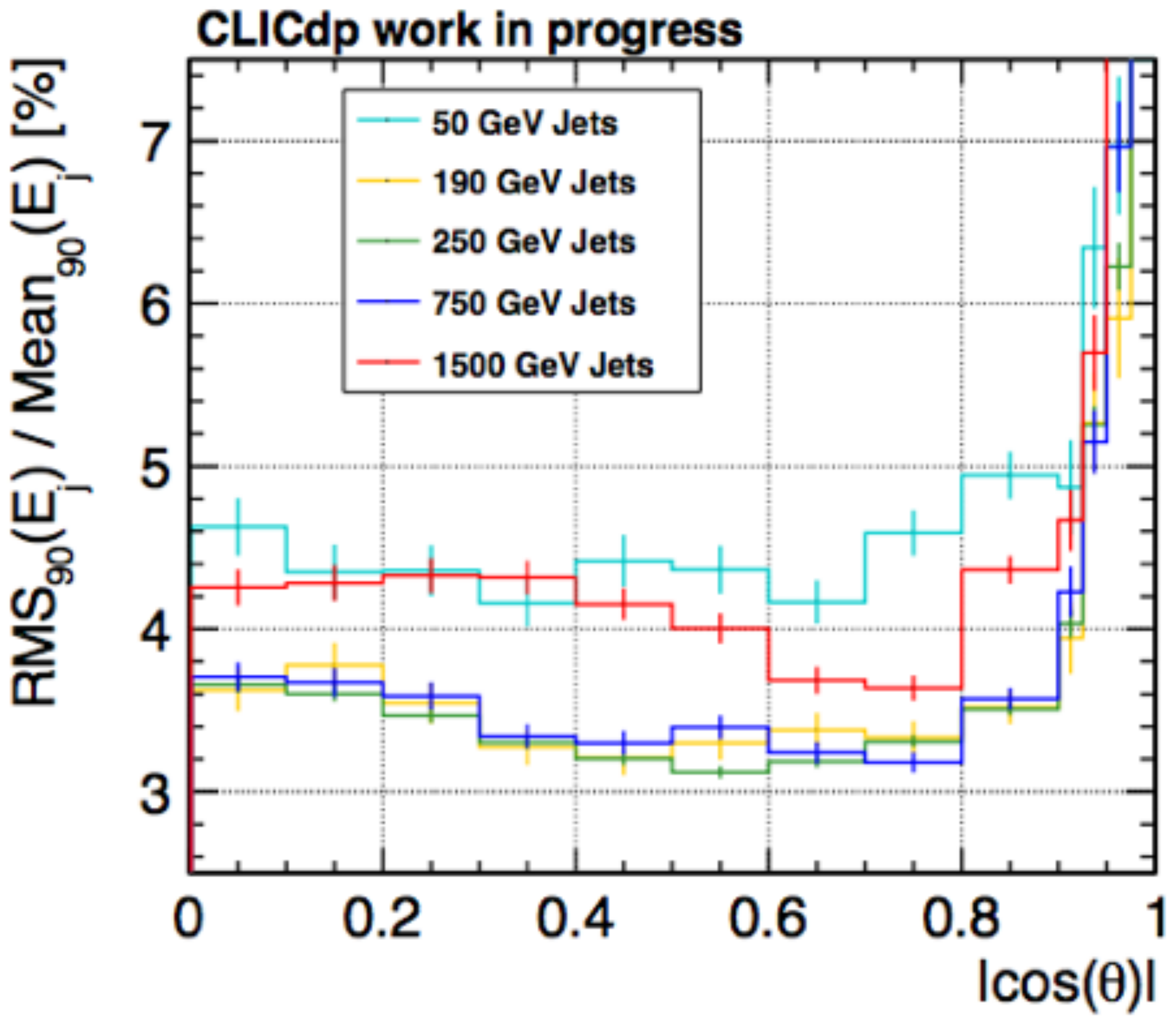
Validation of Particle Flow Algorithm (PFA) performance

- Modification in PFA to address long standing issues of inefficiency of charged particle ID in calorimeter transition region (only minor effect of gap remaining)
- Adopted software compensation with CLIC specific weights (applied to all HCAL hits)
- Achieved jet energy resolution between 3.1-4.5%
  - Comparable to the performance using default weights for jets up to 190 GeV, improvements ~10% for larger jet energies



➳ **Talk "Calorimetry: validation and performance" by Matthias Weber**





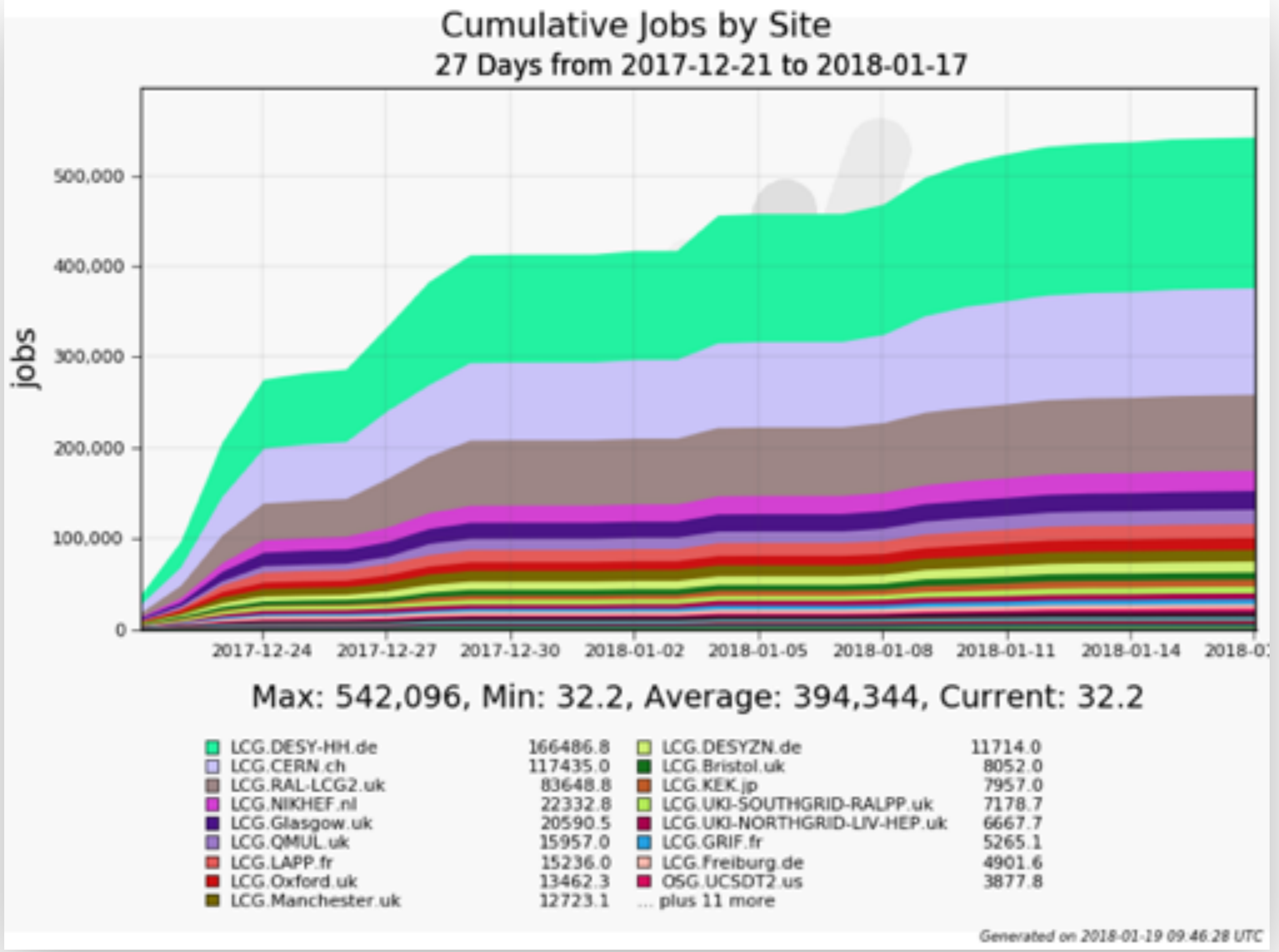
Forward region

- Detailed look at performance
- Good reconstruction efficiencies, energy resolution as expected
- Applied reconstruction for BeamCal to LumiCal: better control over cluster merging
- Achieving expected polar angle resolution

➳ **Talk "FCal: validation and performances" by André Sailer**

Simulation and reconstruction software

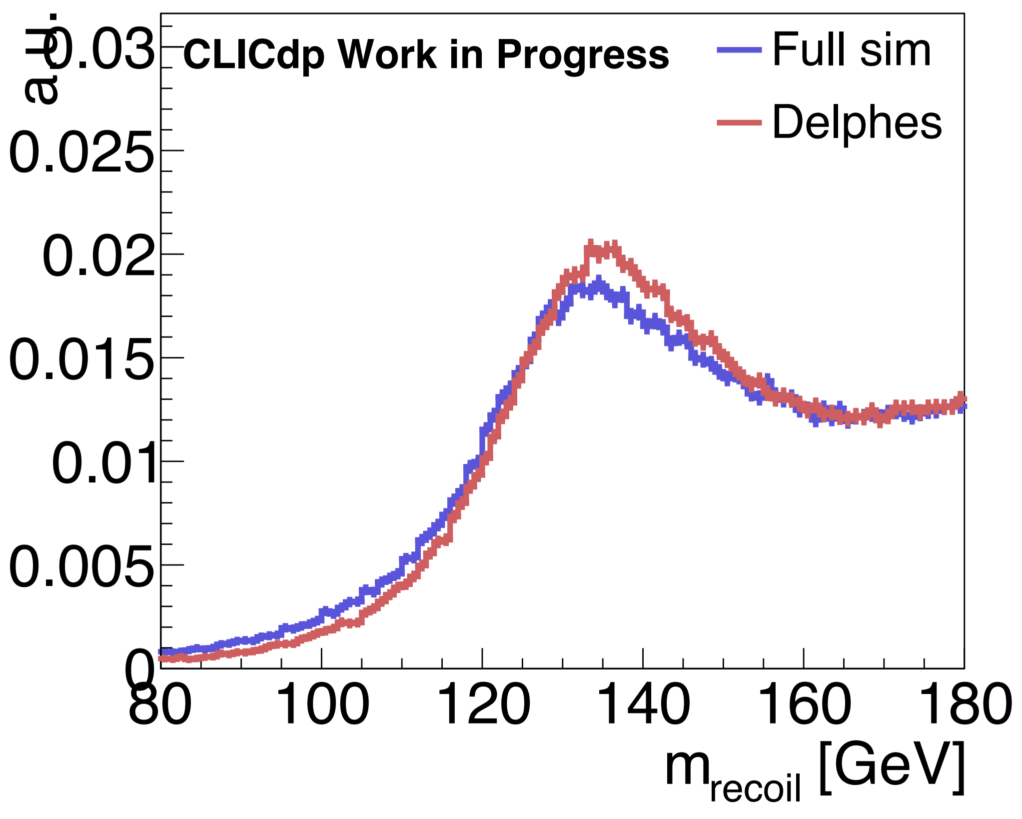
- **Simulation and reconstruction framework (iLCSoft)** - important part in physics analysis, detector optimisation/ validation
- **Transitioned to DD4hep-based detector description** for CLICdet (strong participation from CLICdp) - growing user base in HEP: CLIC, ILC, FCC (LHCb, CMS)
- New simulation and reconstruction chain is ready
  - Promising results from test production
  - **Preparing large scale production chain**
- Physics simulation and reconstruction for CLICdp performed on the grid (**iLCDirac** for managing submissions)
- Progress in creating a **CLICdet Delphes card**, validation is ongoing (Delphes is a framework for fast simulation of a generic collider experiment)

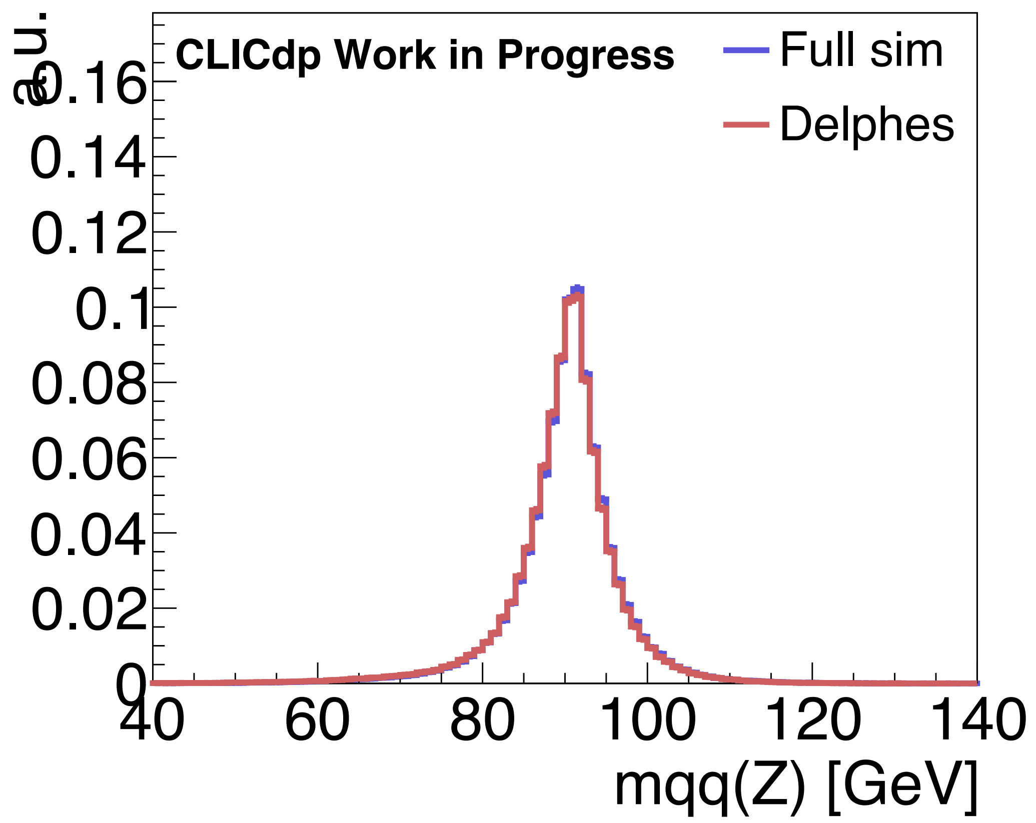


Production with the new software and reconstruction chain

➼ **Talk by Marko Petrič "Software devel. and detector model"**

➼ **Talk by Hamza Zafar "ILCDirac Status and Plans"**





CLICdet Delphes card validation - Higgsstrahlung $e^+e^- \to ZH$ ($Z \to qq$)

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

CLICdp documents for European Strategy

- **Updated Baseline** for a Staged Compact Linear Collider
  - CERN-2016-004 ✔
- **Higgs Physics** at the CLIC Electron-Positron Linear Collider
  - Eur. Phys. J. C77 (2017) no.7, 475 ✔
- The **new optimised CLIC detector model** CLICdet
  - CLICdp-Note-2017-001 ✔
  - Detector performance report in progress ✔
- **Top physics** at the CLIC Electron-Positron Linear Collider
  - Complete draft in progress for early 2018 ✔
- Extended **BSM studies**
  - CLIC BSM overview report in 2018
- **Detector technologies for CLIC**
  - Summary report in 2018
- Plan for the period ~2019-2025 in the case CLIC is supported by next strategy

- The CLICdp Collaboration is **preparing** for the European Strategy Update for HEP in 2019-2020
- CLICdp reports will serve as **ingredients** for CLIC(dp) summary report
- CLICdp **advisory board** (review: 17-18 April 2018)
  - Chair: **Dave Charlton** (Univ. Birmingham)

Summary and conclusions

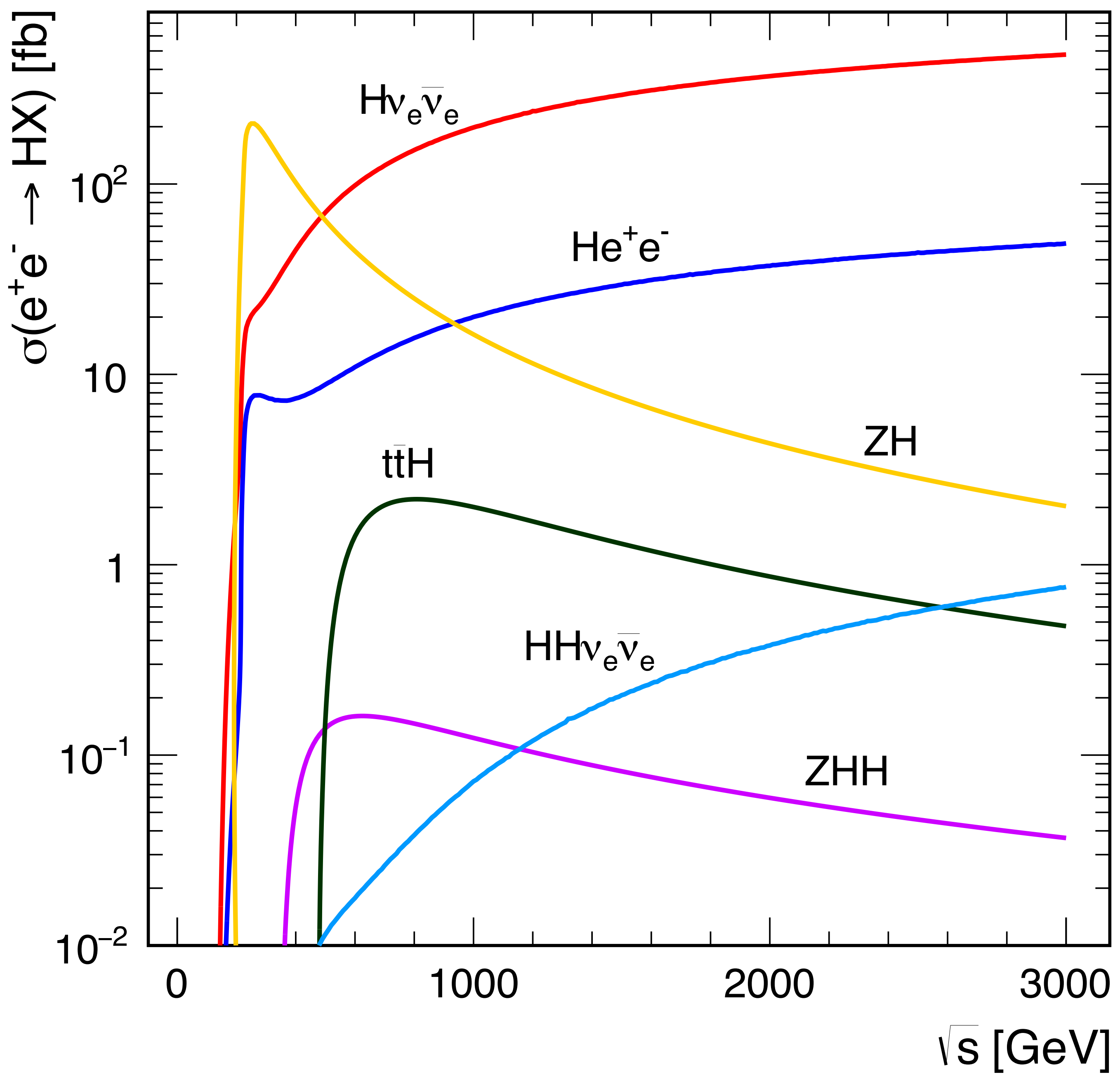
- The CLIC **staging scenario is optimised for a broad precision physics program** (Higgs, top, BSM)
- Optimisation studies of the CLICdet **detector model finalised**, now under validation
- **Broad and active R&D on the vertex and tracking detectors** with focus of finding technologies that simultaneously fulfil all the CLIC requirements
- The CLICdp collaboration **contributes to the CALICE and FCAL calorimeter R&D collaborations**. They have constructed and tested fine-grained prototypes of SiW ECALs, ScW HCAL, and forward calorimeters
- The CLICdp Collaboration is currently preparing a series of reports and summary documents for the European Strategy Update

Thanks to everyone who provided material for this talk!

Additional material

Higgs physics at CLIC

Eur. Phys. J. C 77 (2017) 475



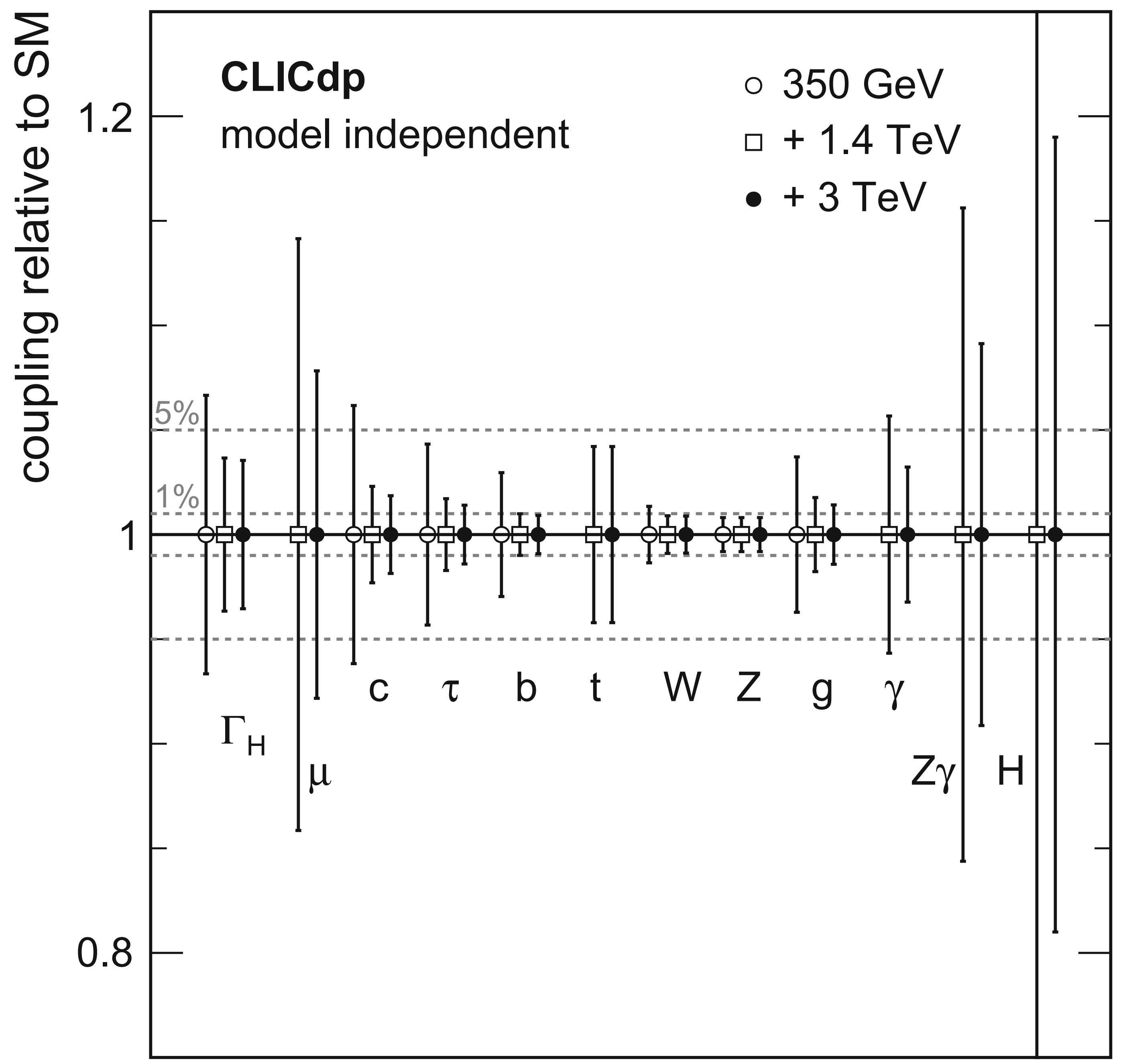
Dominant Higgs production at CLIC
Cross-section for unpolarised beams (no ISR or beamstrahlung effects included)

- Some **highlights**:
  - Higgsstrahlung $e^+e^- \to ZH$ - Higgs properties can be measured independent of the decay mode by studying the Z-recoil mass (unique to lepton colliders)
  - Vector-boson fusion (enhances the overall knowledge of the Higgs boson)
  - Extraction of top Yukawa coupling ($e^+e^- \to ttH$)
  - Double Higgs production - requires high luminosity and high centre-of-mass energy - simultaneous extraction of tri-linear self-coupling (Δλ CLIC: ~10%) and quartic coupling (gHHWW: ~3%)
  - Higgs couplings and width can be determined with a percent-level statistical uncertainty
  - Unique sensitivity to invisible decay modes: $\Gamma_{invis}/\Gamma_H < 1$ % at 90 % C.L.
  - High flavour-tagging efficiencies → Higgs branching fractions

➻ **Talk by Yixuan Zhang "Measurement of ttH production"**
➻ **Talk "Results from H→gamma+gamma study at 3 TeV"**

Higgs physics at CLIC

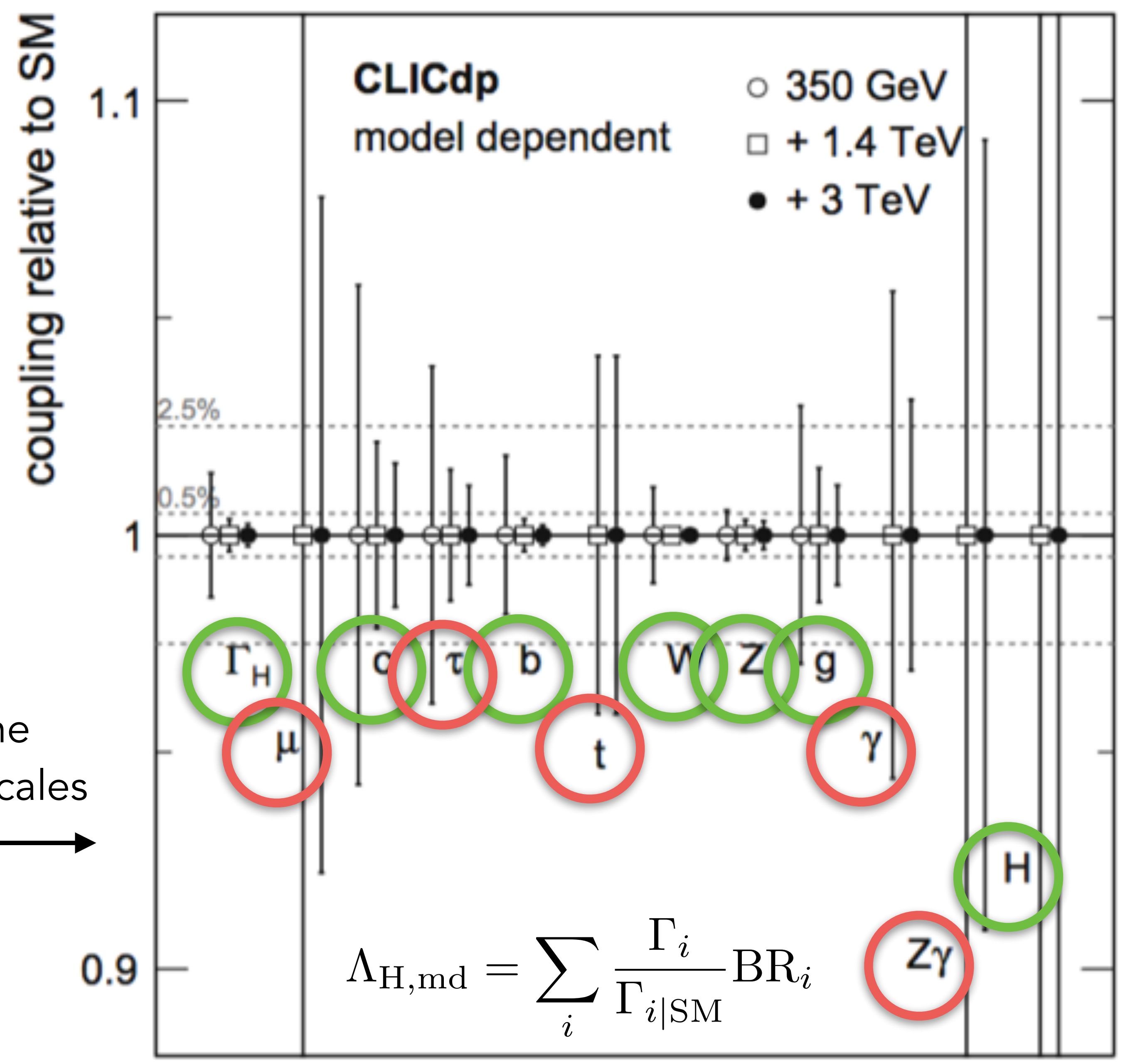
Model-independent (MI) global fits



Higgs width is a free parameter allows for additional non-SM decays.

Note the different scales

Model-dependent (MD) global fits



Constraining “LHC-style”, assuming no invisible Higgs decays (model-dep.), fit to deviations from SM BR’s

Model-independent extraction only possible for lepton colliders

(green circle) = *Accuracy significantly better than HL-LHC or not possible at hadron colliders*

(red circle) = *Accuracy comparable to HL-LHC*

Results from the full CLIC programme:

~5 years of running at each stage incl. e⁻ polarisation above 1 TeV

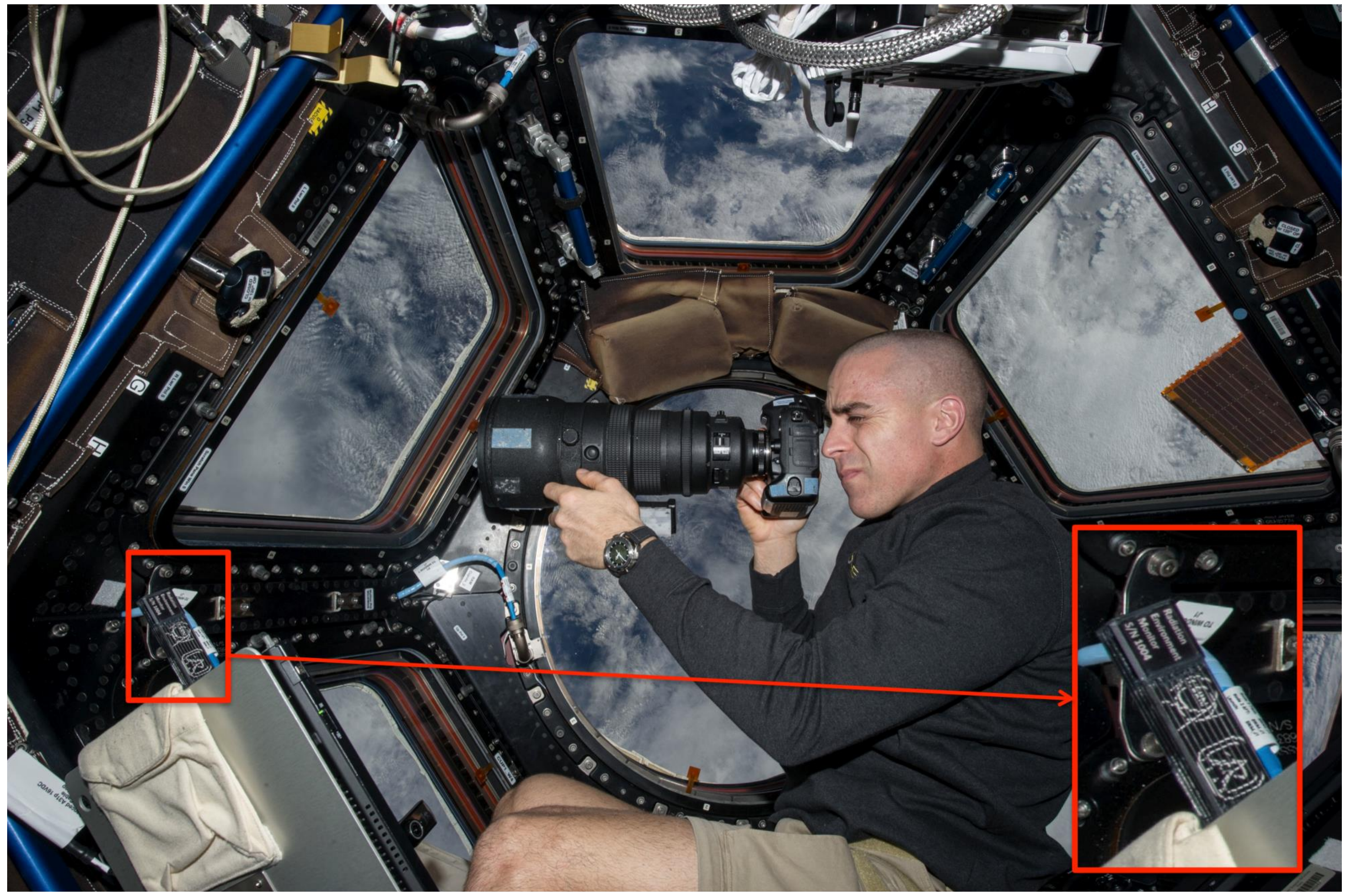
- MI: down to ~0.8 % for most couplings (only at lepton colliders)
- MD: ~0.1-1 % for most couplings
- Accuracy on Higgs width:
  - ~3.6 % (MI)
  - ~0.3 % (MD)
- Higgs mass with 24 MeV precision for 1.5 TeV and 3 TeV operation combined (HL-LHC: ~50 MeV per experiment)

More details: “Higgs physics at the CLIC electron–positron linear collider”

CLIC detector R&D - other applications

- Compared to LHC, **CLIC detectors** need to have **smaller** individual detector cells, **better** position resolution and **more accurate** time stamping
- Such general features are of interest for other applications as well
- Technologies developed for CLIC are now being used within particle physics and society applications
- Silicon pixels detectors co-developed by CLICdp within the Medipix/Timepix collaborations are used in e.g. material analysis with X-rays, medical imaging, dosimetry in space missions, dosimetry for hadron therapy, school projects, electron cryo-microscopy (2017 chemistry Nobel prize), LHCb detector upgrade, CAST experiment

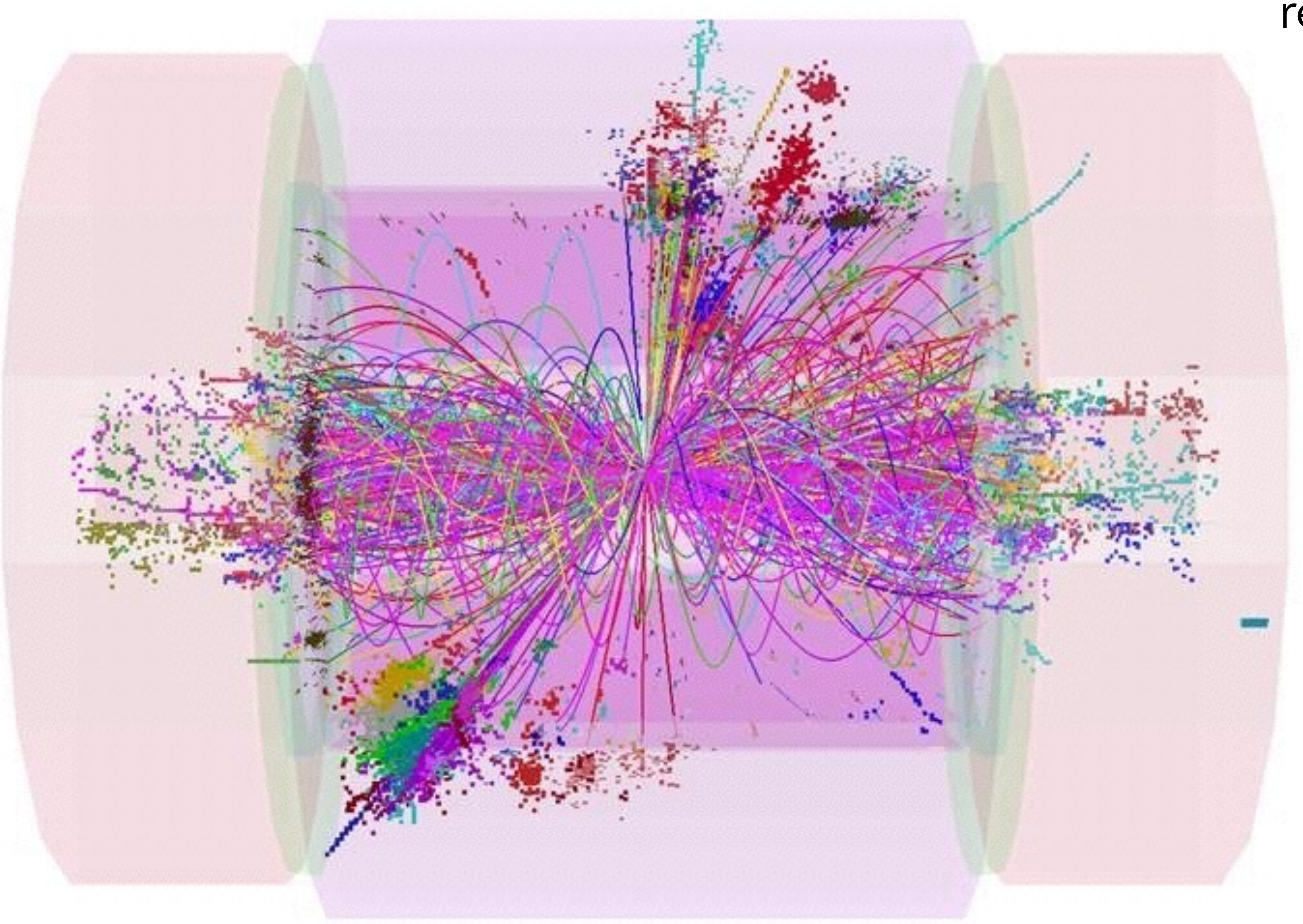
- Fine-grained calorimetry, initially developed for linear collider experiments, is now adopted by other experiments (e.g. CMS and ATLAS detector upgrades).
- The silicon photomultipliers developed for linear collider hadron calorimeters are now used in time-of-flight assisted Positron Emission Tomography (PET)



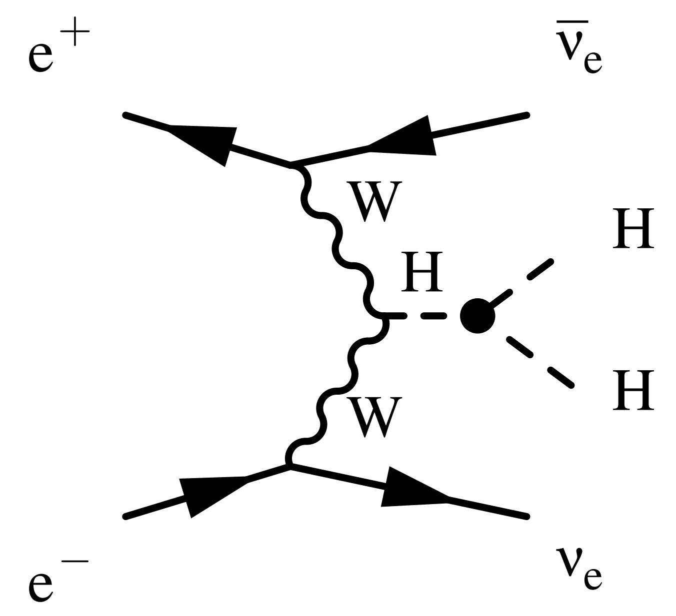
Timepix detector at ISS, Astronaut Chris Cassidy, 2013, NASA

Combined p_T and timing cuts

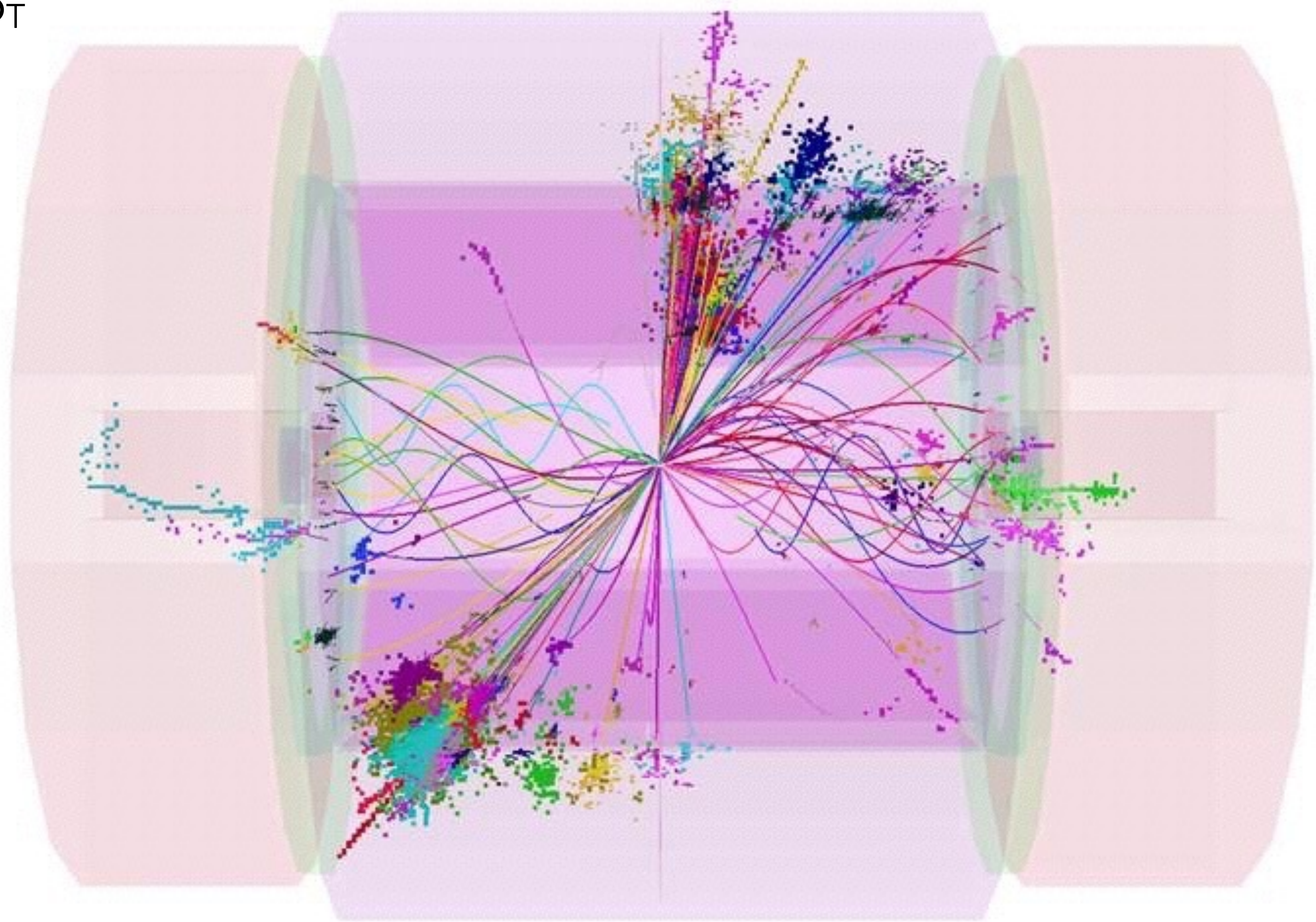
1.2 TeV background in reconstruction time window



Cuts depend on particle-type, p_T and detector region, protect high-p_T physics objects



85 GeV background after tight cuts



$$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t} \rightarrow 8\,\text{jets}$$