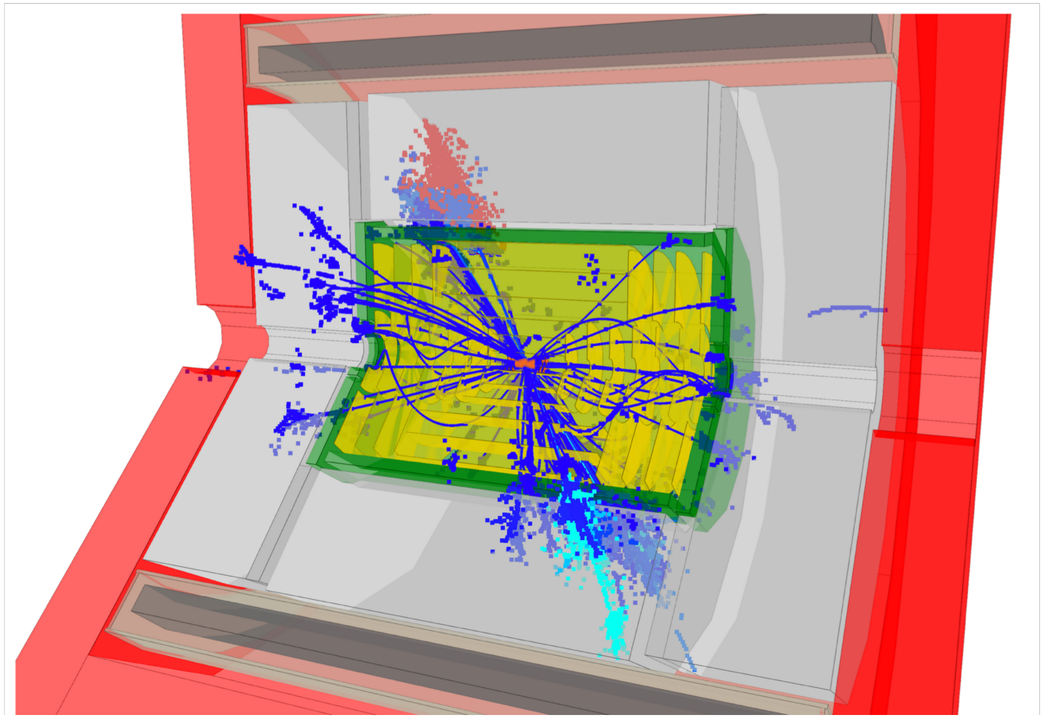
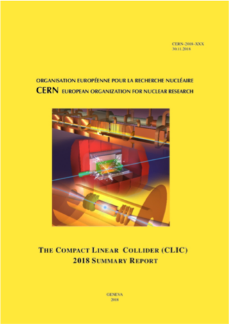
considerations for a future ≥10 TeV e^+e^- or $\gamma\gamma$ experiment



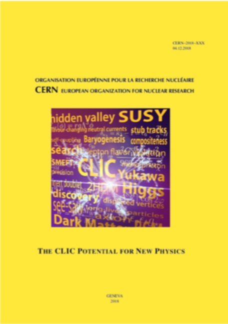
Lucie Linssen, CERN

Disclaimer: *work has not started*

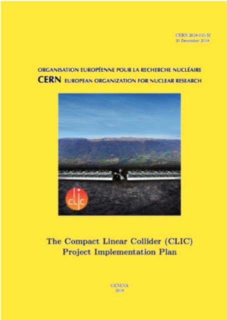
Recent CLIC overview documents


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
THE COMPACT LINEAR COLLIDER (CLIC)
2018 SUMMARY REPORT

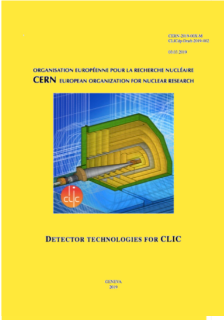
CERN-2018-005-M
http://dx.doi.org/10.23731/CYRM-2018-002


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
THE CLIC POTENTIAL FOR NEW PHYSICS

CERN-2018-009-M
http://dx.doi.org/10.23731/CYRM-2018-003


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
The Compact Linear Collider (CLIC)
Project Implementation Plan

CERN-2018-010-M
http://dx.doi.org/10.23731/CYRM-2018-004


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
DETECTOR TECHNOLOGIES FOR CLIC

in collaboration review

Covering: Accelerator
Detector
Physics

Links: http://clic.cern/european-strategy


The Compact Linear e^+e^- Collider (CLIC): Accelerator and Detector

Input to the European Particle Physics Strategy Update on behalf of the CLIC and CLICdp Collaborations

18 December 2018

Contact person: A. Robson

Editors: P.N. Burrows, N. Catalan Lasheras, L. Linssen, M. Petrič, A. Robson, D. Schulte, E. Sicking, S. Stapnes, W. Wuensch

The Compact Linear e^+e^- Collider (CLIC): Physics Potential

Input to the European Particle Physics Strategy Update on behalf of the CLIC and CLICdp Collaborations

18 December 2018

Contact person: P. Roloff

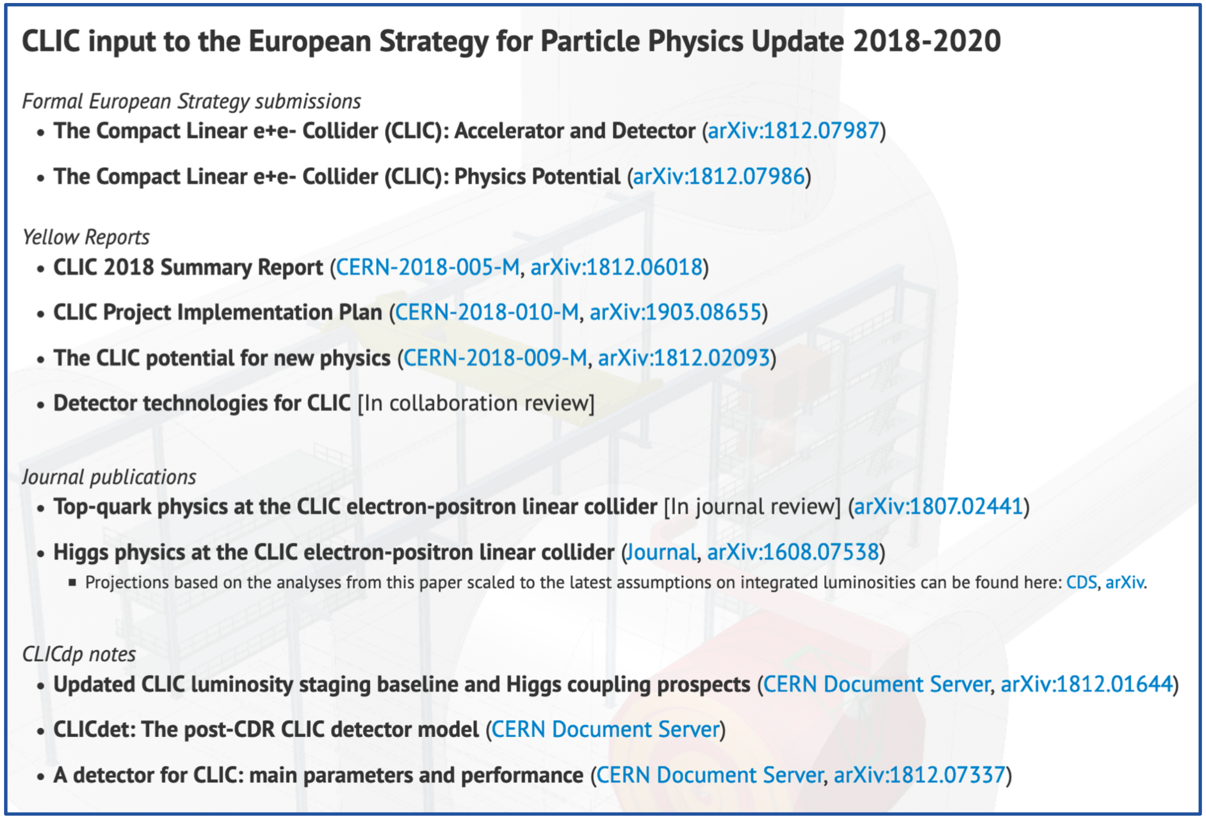
Editors: R. Franceschini, P. Roloff, U. Schnoor, A. Wulzer

Abstract

CLIC accelerator collaboration

CLICdp collab. (det&phys)

clic.cern


CLIC input to the European Strategy for Particle Physics Update 2018-2020

Formal European Strategy submissions
- **The Compact Linear e+e- Collider (CLIC): Accelerator and Detector** (arXiv:1812.07987)
- **The Compact Linear e+e- Collider (CLIC): Physics Potential** (arXiv:1812.07986)

Yellow Reports
- **CLIC 2018 Summary Report** (CERN-2018-005-M, arXiv:1812.06018)
- **CLIC Project Implementation Plan** (CERN-2018-010-M, arXiv:1903.08655)
- **The CLIC potential for new physics** (CERN-2018-009-M, arXiv:1812.02093)
- **Detector technologies for CLIC** [In collaboration review]

Journal publications
- **Top-quark physics at the CLIC electron-positron linear collider** [In journal review] (arXiv:1807.02441)
- **Higgs physics at the CLIC electron-positron linear collider** (Journal, arXiv:1608.07538)
  - Projections based on the analyses from this paper scaled to the latest assumptions on integrated luminosities can be found here: CDS, arXiv.

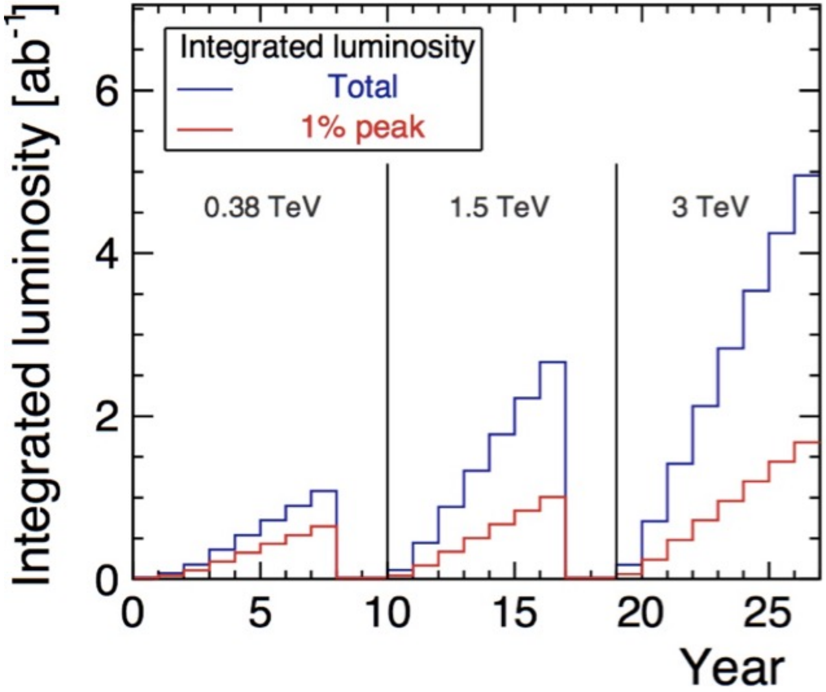
CLICdp notes
- **Updated CLIC luminosity staging baseline and Higgs coupling prospects** (CERN Document Server, arXiv:1812.01644)
- **CLICdet: The post-CDR CLIC detector model** (CERN Document Server)
- **A detector for CLIC: main parameters and performance** (CERN Document Server, arXiv:1812.07337)

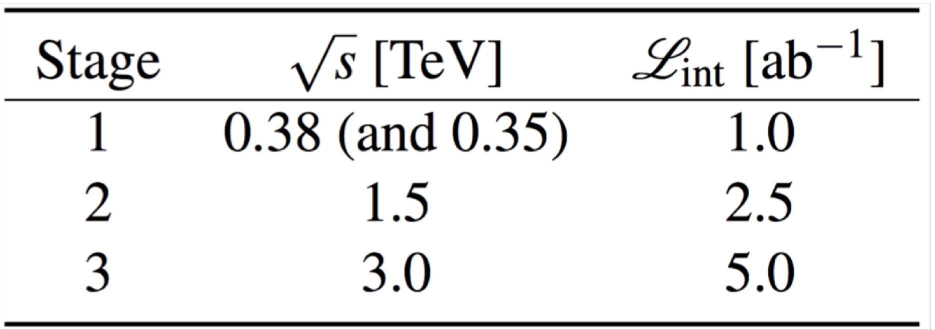
CLIC physics and staged operation

Linear e^+e^- collider, staging scenario motivated by maximum physics output

380 GeV (350 GeV) :	**precision Higgs and top physics**
1.5 TeV :	**BSM searches, precision Higgs, ttH, HH, top physics**
3 TeV :	**BSM searches, precision Higgs, HH, top physics**

BSM searches: direct (up to ~1.5 TeV), indirect (>> TeV scales)





Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0

Polarised electron beam (–80%, +80%)

Ratio (50:50) at $\sqrt{s}$=380GeV ; (80:20) at $\sqrt{s}$=1.5 and 3TeV

Coherent approach for CERN future colliders (running times, luminosity performance)

1.2×10^7 sec/year arXiv:1810.13022, Bordry et al.

CLIC experimental conditions

Parameter	380 GeV	1.5 TeV	3 TeV
Luminosity $\mathcal{L}$ (10^{34}cm^{-2}sec^{-1})	1.5	3.7	5.9
$\mathcal{L}$ above 99% of $\sqrt{s}$ (10^{34}cm^{-2}sec^{-1})	0.9	1.4	2.0
Repetition frequency (Hz)	**50**	**50**	**50**
Bunch separation (ns)	**0.5**	**0.5**	**0.5**
Number of bunches per train	352	312	312
Beam size at IP σ_x/σ_y (nm)	**149/2.9**	**~60/1.5**	**~40/1**
Beam size at IP σ_z (μm)	**70**	**44**	**44**

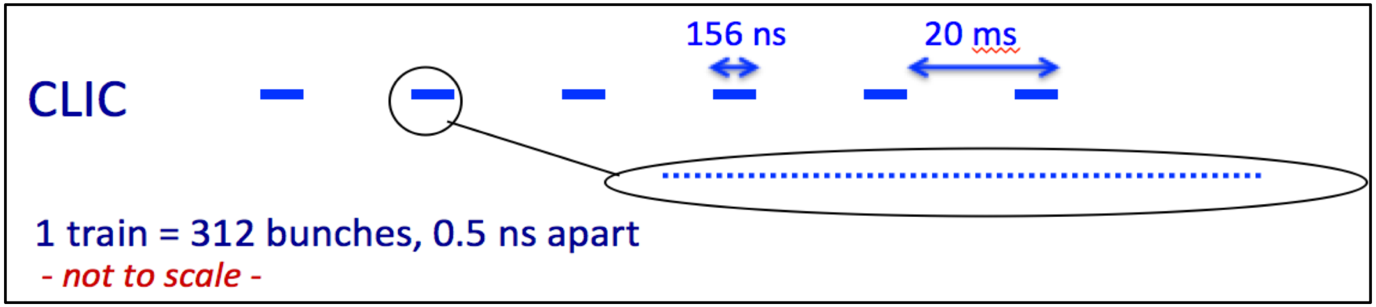
Drives timing requirements for CLIC detector

Very small beam

Crossing angle ~20 mrad, electron polarization ±80%

Very low duty cycle allows for:

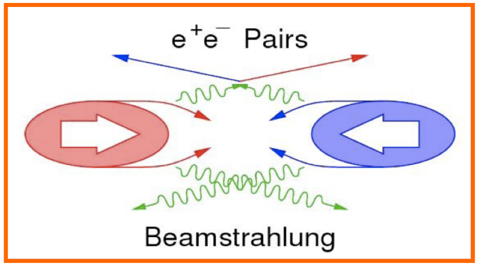
Triggerless readout
Power pulsing



1 train = 312 bunches, 0.5 ns apart

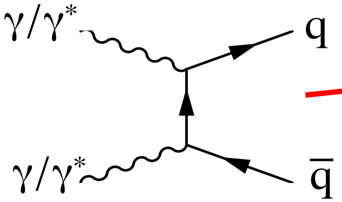
- not to scale -

beam-induced backgrounds at CLIC



Beam-beam background at IP:

- Small beams => very high E-fields
  - **Beamstrahlung**
  - **Pair-background**
    - High occupancies
  - **γγ to hadrons**
    - Energy deposits



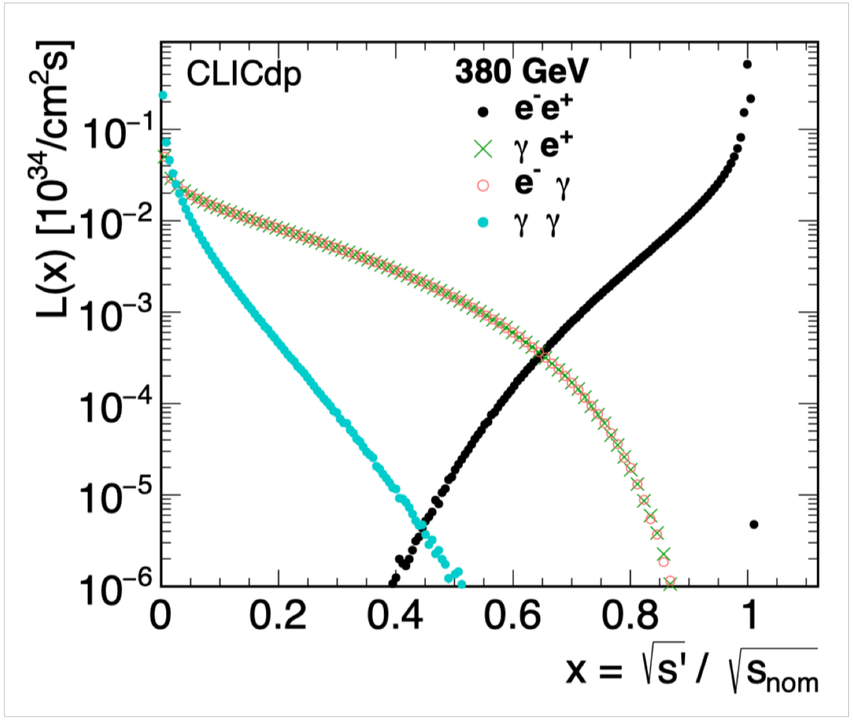
Simplified picture:
Design issue (small cell sizes)

Impacts on the physics
Needs suppression in data

Beamstrahlung ➔ important energy losses right at the interaction point

Most physics processes are studied well above production threshold => profit from full spectrum

Luminosity spectrum can be measured in situ using large-angle Bhabha scattering events, to 5% accuracy at 3 TeV
Eur.Phys.J. C74 (2014) no.4, 2833

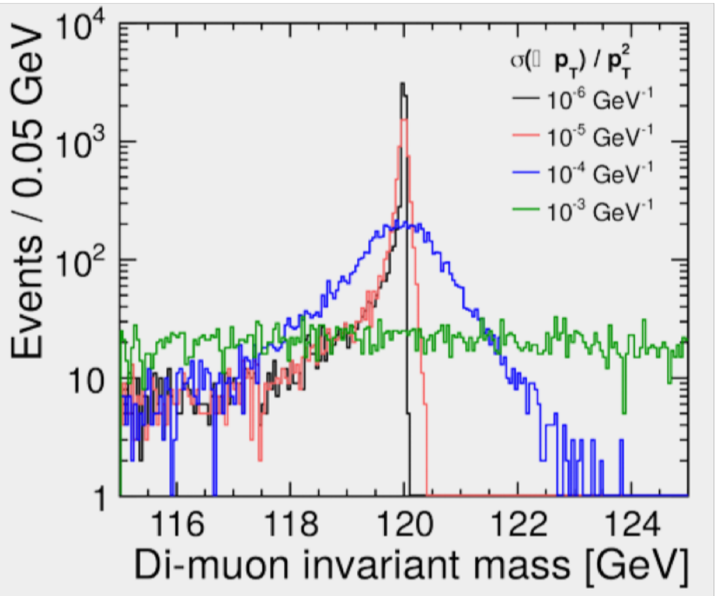


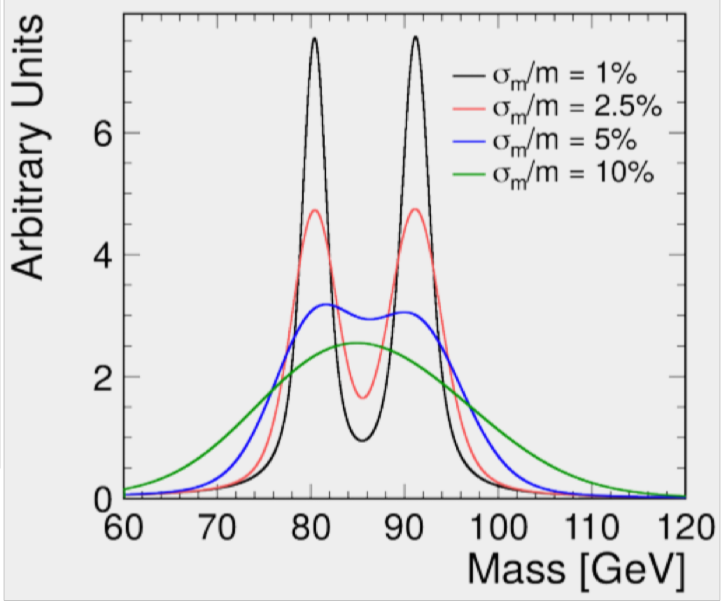
arXiv:1812.06018

Beam-induced backgrounds, luminosity spectrum and luminosity measurement are important ingredients for the design of a future experiment

detector performance requirements

- Momentum resolution
  - Higgs recoil mass, Higgs coupling to muons →
  - **$\sigma_{p_T}/p_T \sim 2 \times 10^{-5}$ GeV^{-1}** above 100 GeV
- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios
  - **$\sigma_{r\phi} \sim a \oplus b / (p[\mathrm{GeV}] \sin^{3/2}\theta)$ μm** with $a = 5$ μm, $b = 15$ μm
- Jet energy resolution
  - Separation of W/Z/H di-jets →
  - **$\sigma_E/E \sim$ 5% - 3.5%** for jets at 50 GeV – 1000 GeV
- Angular coverage
  - Very forward electron and photon tagging
  - Down to $\theta = 10$ mrad ($\eta = 5.3$)





Core performance requirements from the physics
are <u>not</u> expected to be very different at higher e^+e^- energies

high energies => t-channel => forward

Example: θ distr. Higgs physics CLIC

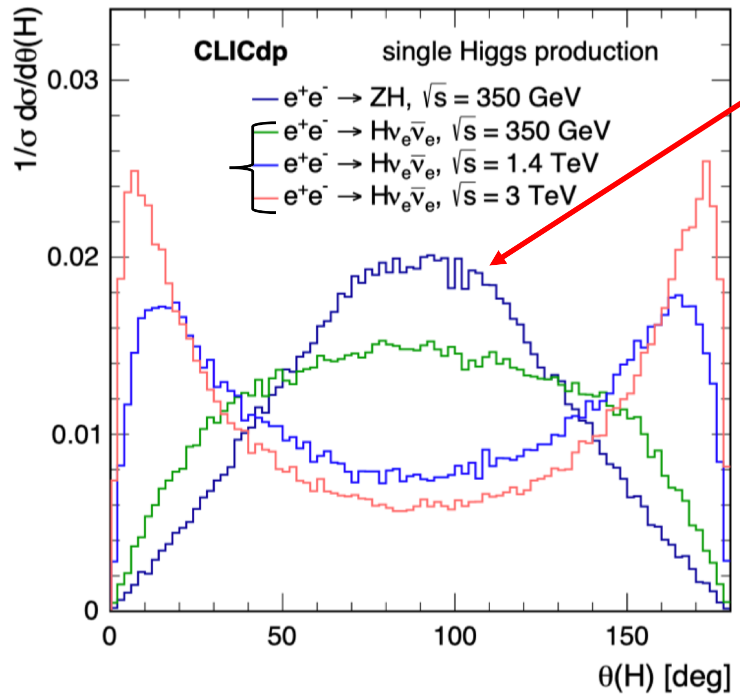
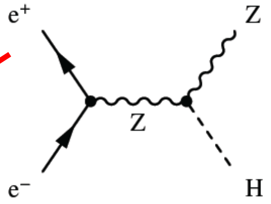
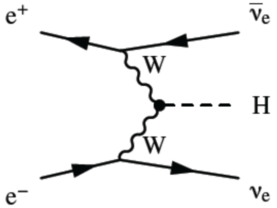


Fig. 6: Polar angle distributions for single Higgs events at $\sqrt{s} = 350\,\text{GeV}$, 1.4 TeV and 3 TeV, including the effects of the CLIC beamstrahlung spectrum and ISR. The distributions are normalised to unity.



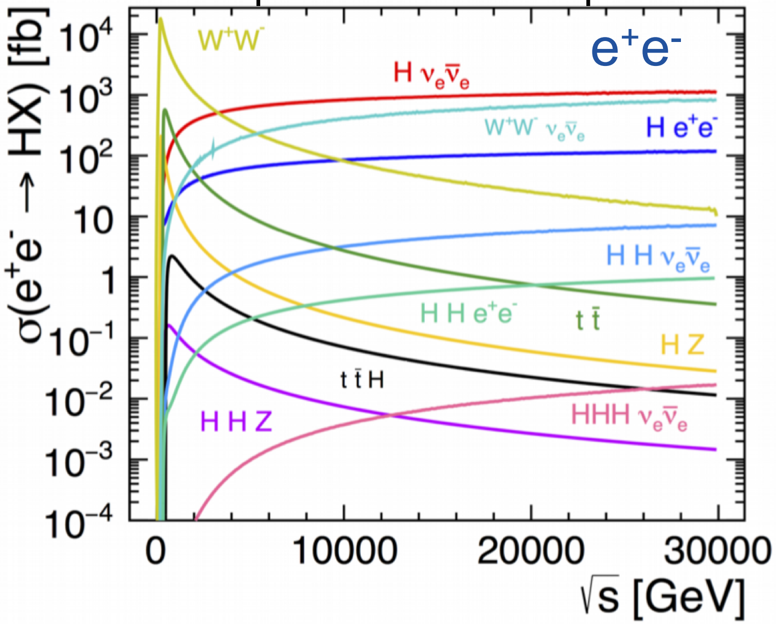
s-process
$\sigma \propto 1/s$
central

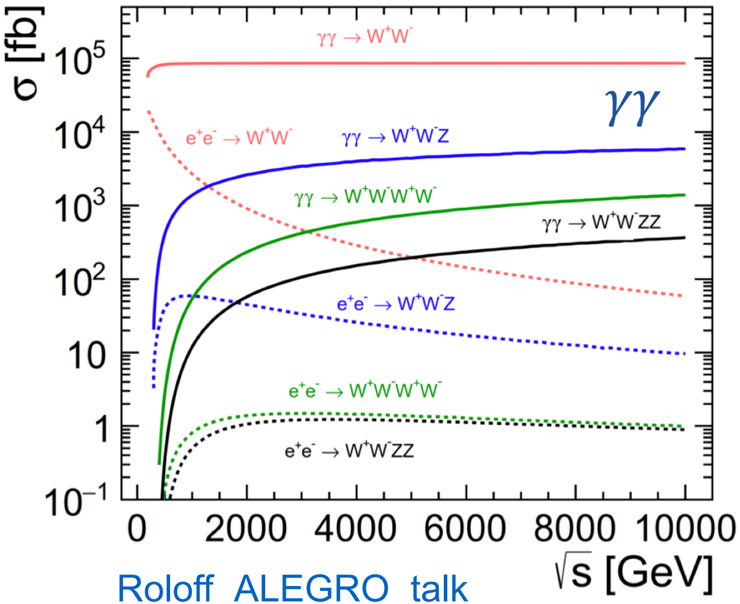


t-process
$\sigma \propto \log(s)$
forward

At very high energies, many of the prominent processes produce particles in forward direction
⇒ Forward acceptance needs to be increased
⇒ Conflict with final focusing

Example cross section plots:



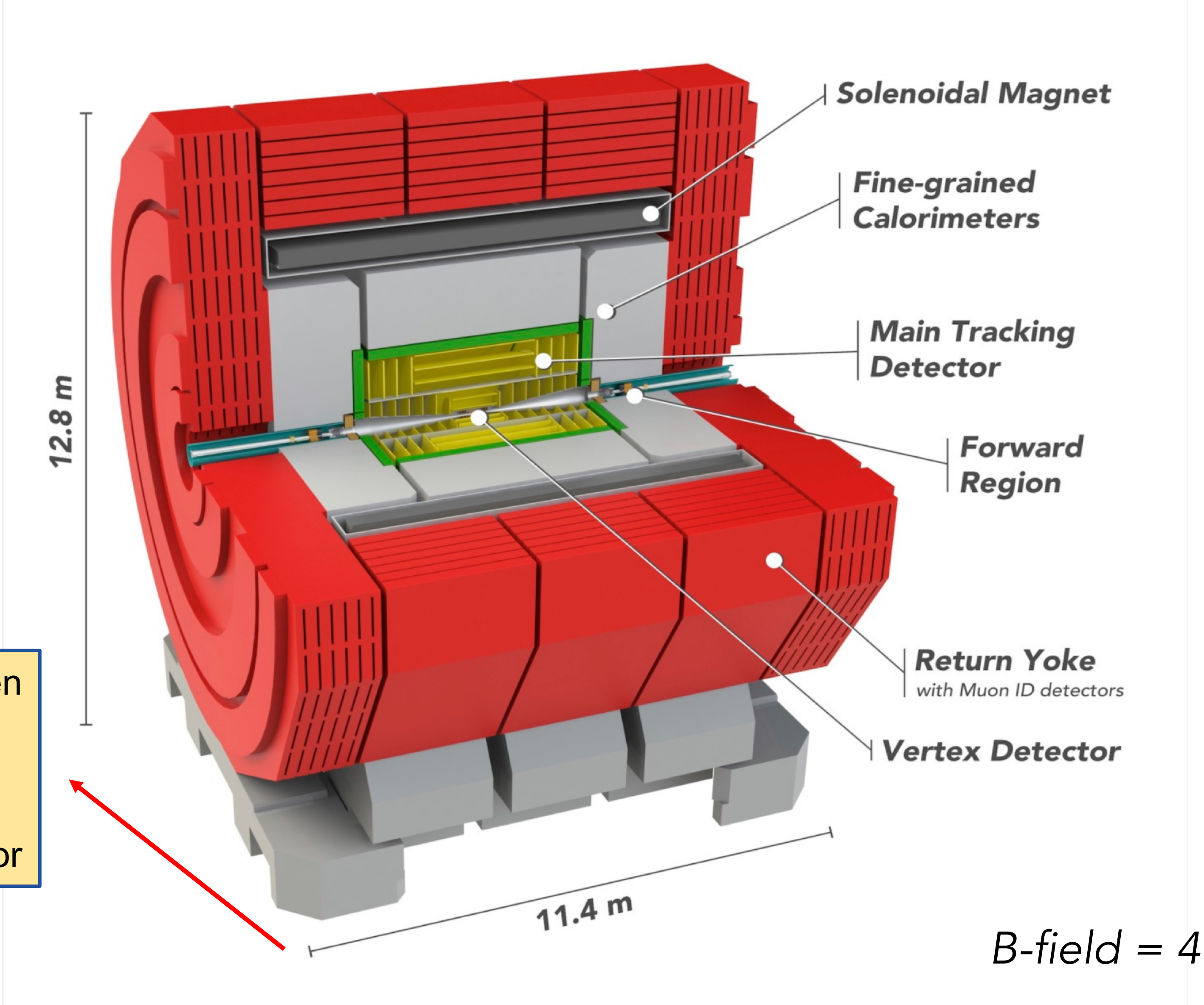


Roloff_ALEGRO_talk

CLIC detector

Since CDR → fully optimised detector

Fulfils requirements of:
- physics
- experimental conditions



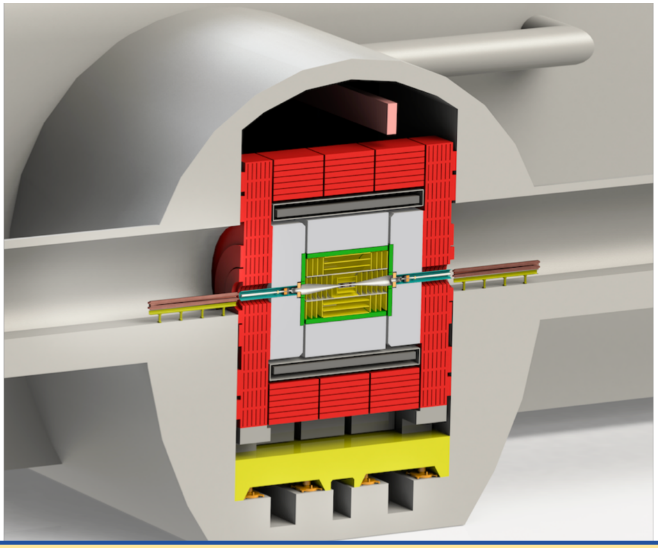
Short detector length is driven by final focus requirements.

For physics reasons we would prefer a longer detector

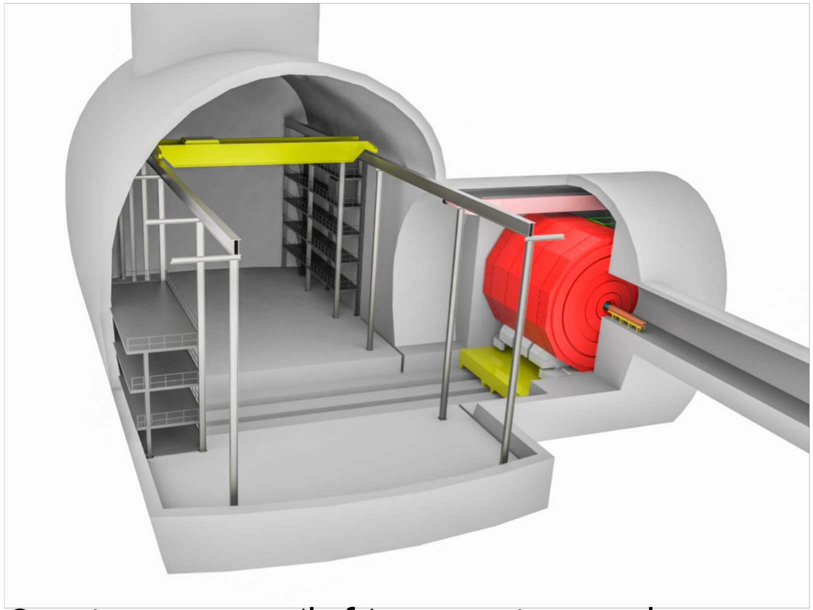
[arXiv:1812.07337](https://arxiv.org/abs/1812.07337)

B-field = 4 T

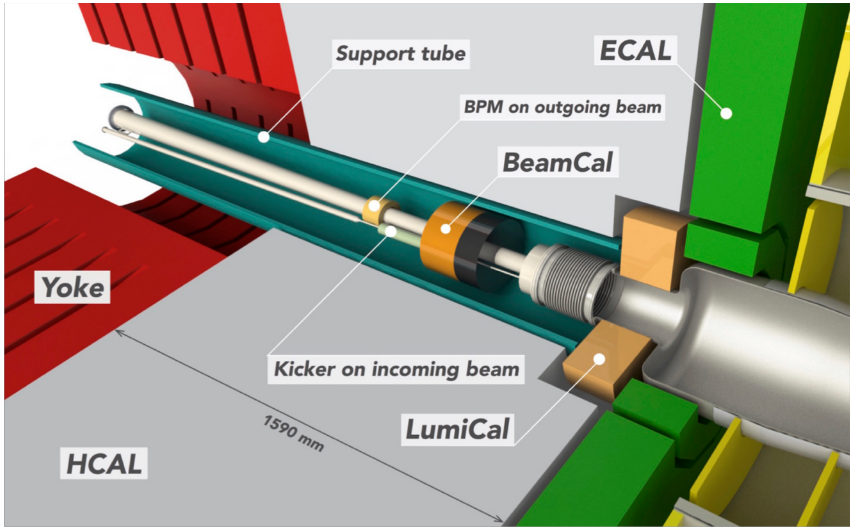
CLIC forward region and MDI



Last focusing elements in accelerator tunnel, L*=6 m. Detector kept short along beam line.



Service cavern (left), experimental cavern (right)



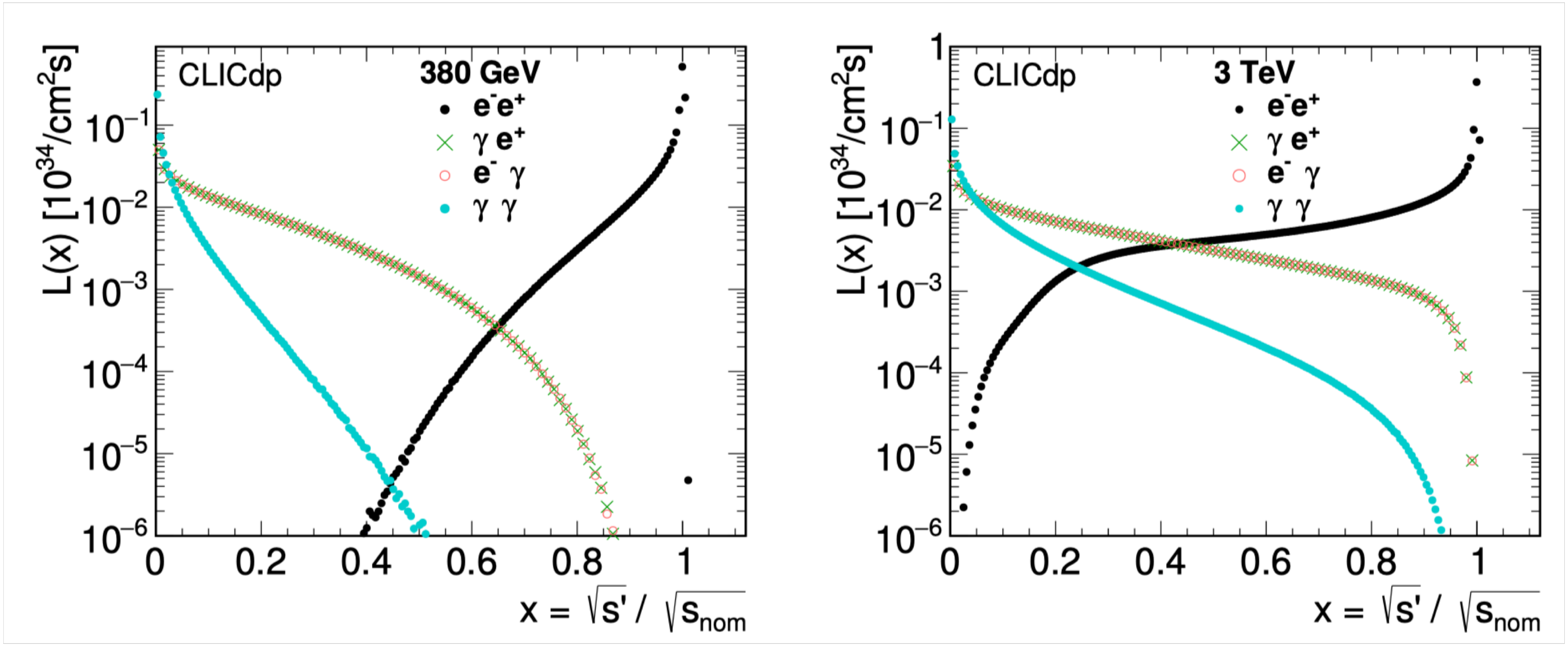
Forward detector region comprising beam feedback system and forward calorimeters: LumiCal/BeamCal (10 > θ >134 mrad)

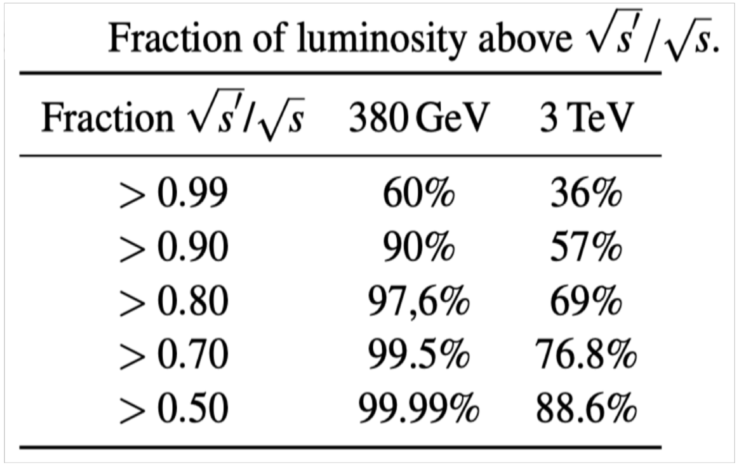
- Luminosity measurement to *few* 0.1% at 3 TeV
- Forward coverage for electrons/photons

Luminosity measurement => use Bhabha scattering in e^+e^-
Note: Bhabha cross section decreases with higher energy.

How are luminosity and γ energy spectrum measured in $\gamma\gamma$ collider?

CLIC luminosity spectra





Fraction of luminosity above $\sqrt{s'}/\sqrt{s}$.

Fraction $\sqrt{s'}/\sqrt{s}$	380 GeV	3 TeV
>0.99	60%	36%
>0.90	90%	57%
>0.80	97,6%	69%
>0.70	99.5%	76.8%
>0.50	99.99%	88.6%

Luminosity spectrum impacts on physics performance

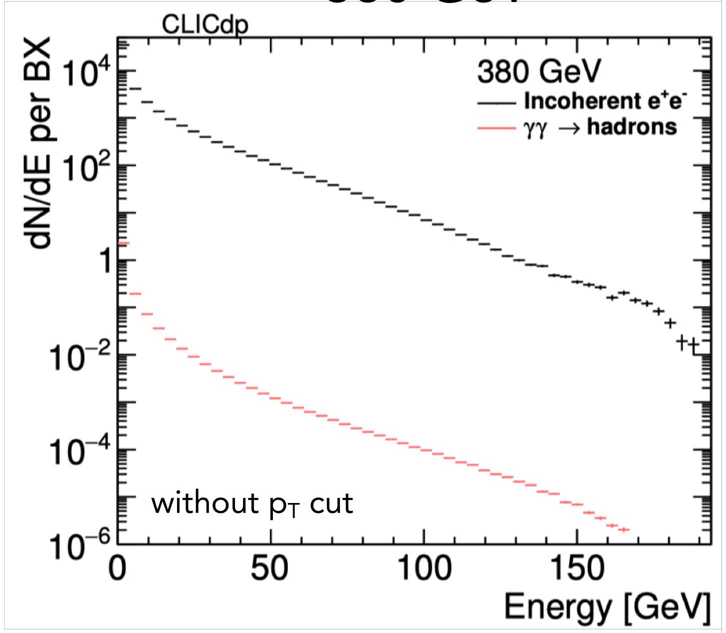
Very important to know the spectrum well.
Needs to be measured in situ.

CLIC detector performance note: arXiv:1812.07337
CLIC summary report: arXiv:1812.06018

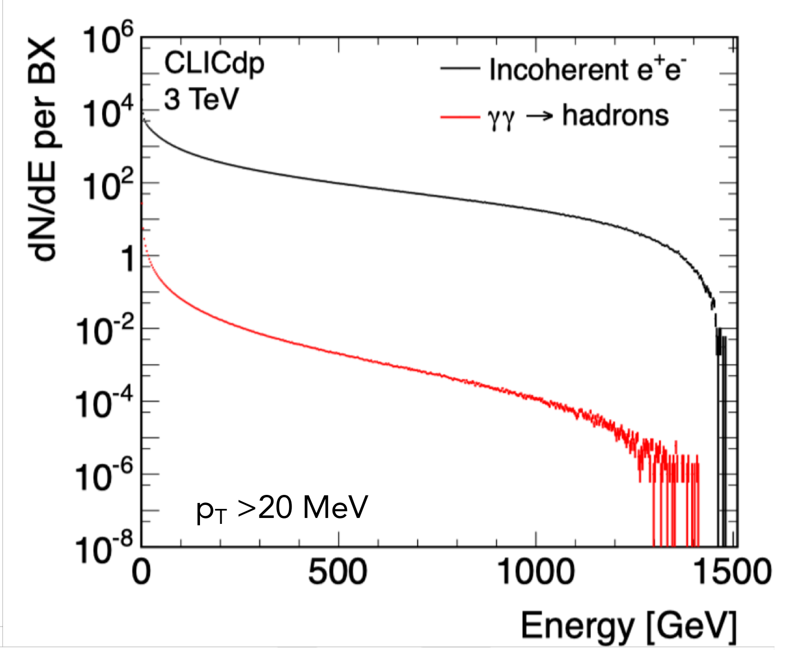
beamstrahlung 380 GeV / 3 TeV

arXiv:1812.07337
arXiv:1812.06018

380 GeV

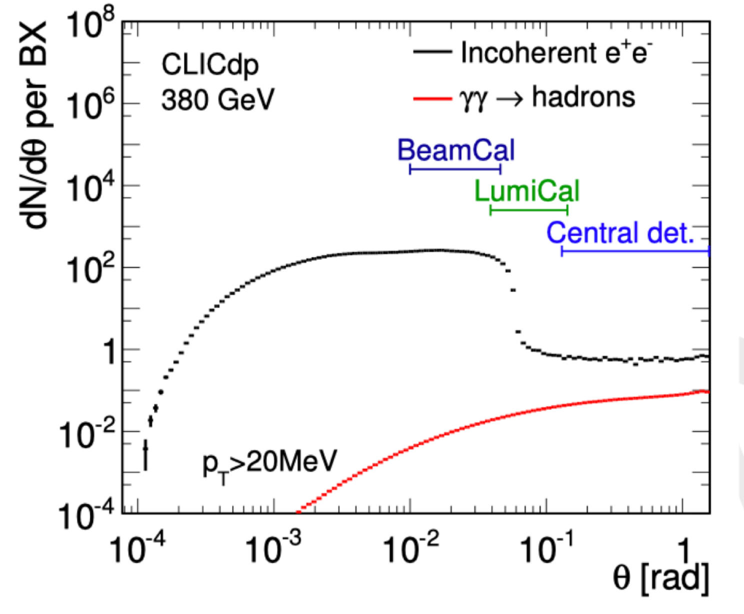


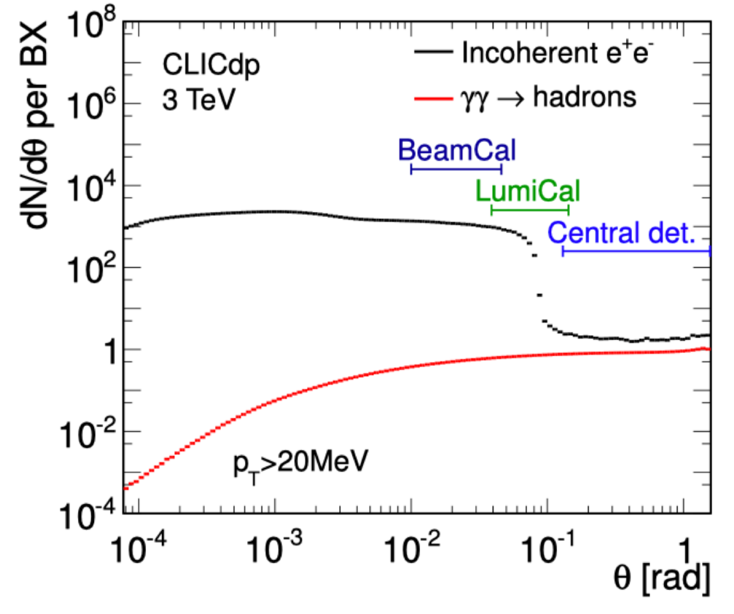
3 TeV



E_{cm}>2 GeV
for $\gamma\gamma$ →hadrons

Source: draft detector R&D report

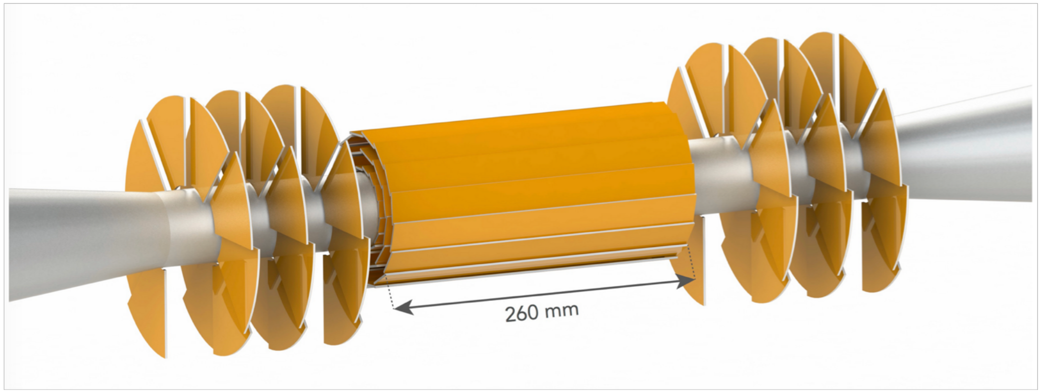




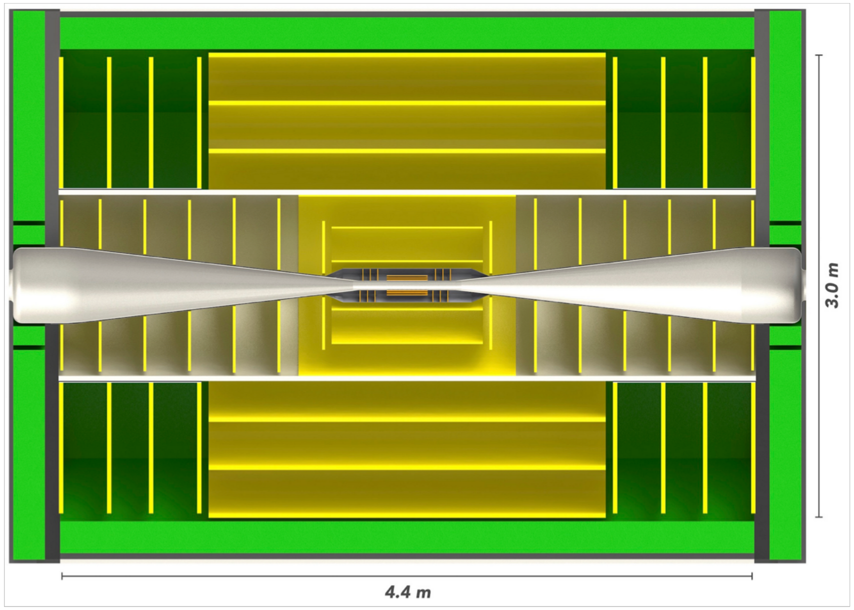
E_{cm}>2 GeV
for $\gamma\gamma$ →hadrons

vertex and tracking detectors

Vertex detector



Tracker



Requirements:

low mass: 0.2%X_0 per layer
low power: 50 mW/cm^2 for air cooling
single point resolution: 3 μm
maximum cell size 25*25 μm^2
hit time resolution: ~5 ns

driven by beamstrahlung

Implementation and R&D:

silicon-based (pixels, hybrid or monolithic)
3 double layers
spiraling petals to facilitate air cooling
power pulsing

Requirements:

low mass: 1-2%X_0 per layer
single point resolution: 7 μm
hit time resolution: ~5 ns

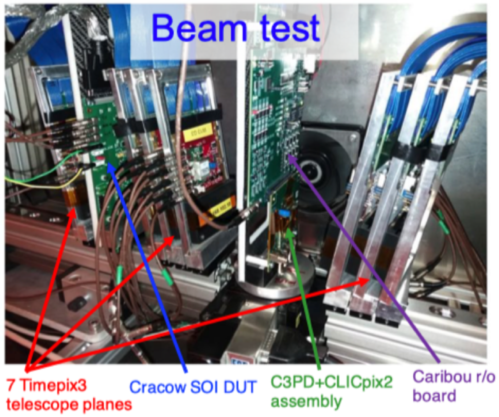
Implementation and R&D:

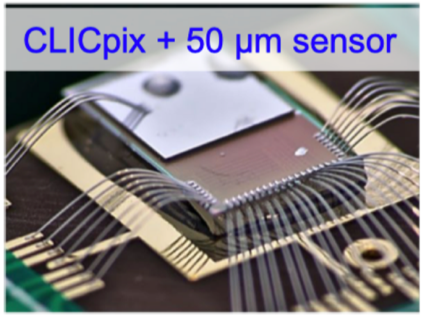
silicon-based (pixels, monolithic)
power pulsing
water cooling (below atm. pressure)

CLIC silicon vertex/tracker R&D

Sensor + readout technologies

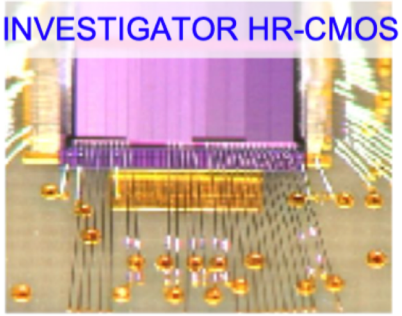
Sensor + readout technology	Currently considered for
Bump-bonded Hybrid planar sensors	Vertex
Capacitively coupled HV-CMOS sensors	Vertex
Monolithic HV-CMOS sensors	Tracker
Monolithic HR-CMOS sensor	Tracker
Monolithic SOI sensors	Vertex, Tracker




CLICpix + 50 μm sensor

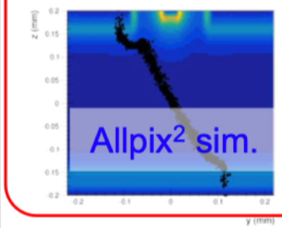

C3PD+CLICpix2 glue ass.

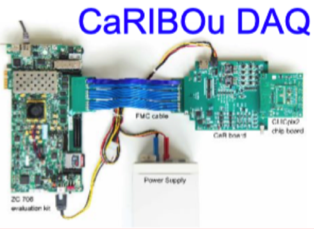

ATLASPIX HV-CMOS


INVESTIGATOR HR-CMOS

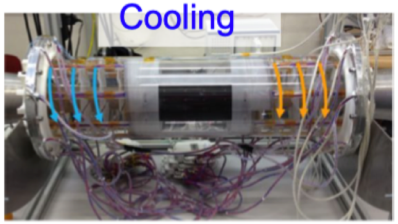

Cracow SOI

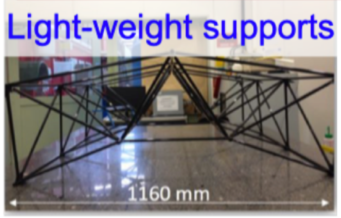
Simulation/Characterisation

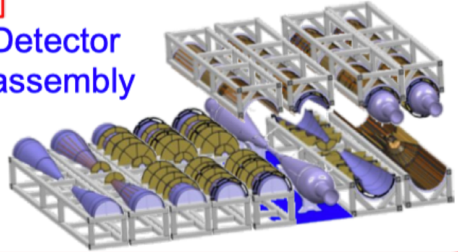

Allpix^2 sim.


CaRIBOu DAQ

Detector integration


Cooling


Light-weight supports


Detector assembly

~10 CLICdp institutes are participating
Cooperation with Medipix/Timepix, LHCb, ATLAS, ALICE, Mu3e, AIDA2020

VCI2019 talk

calorimetry and PFA

Jet energy resolution + background suppression for optimal detector design

=> => fine-grained calorimetry + Particle Flow Analysis (PFA)

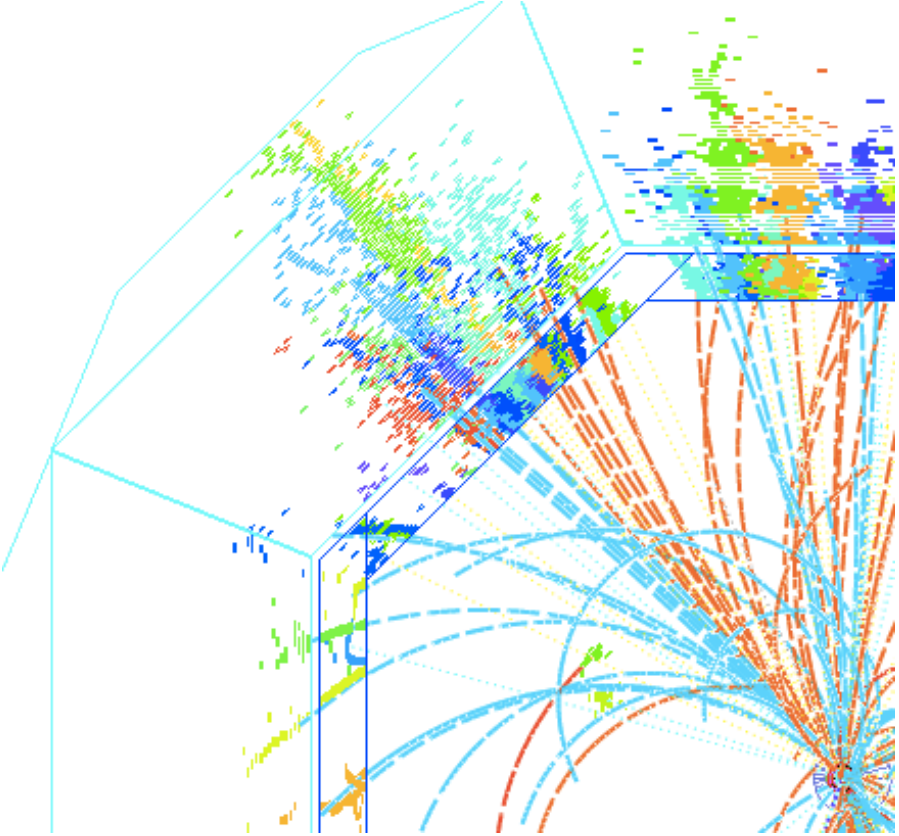
What is PFA?

Typical jet composition:
60% charged particles
30% photons
10% neutral hadrons

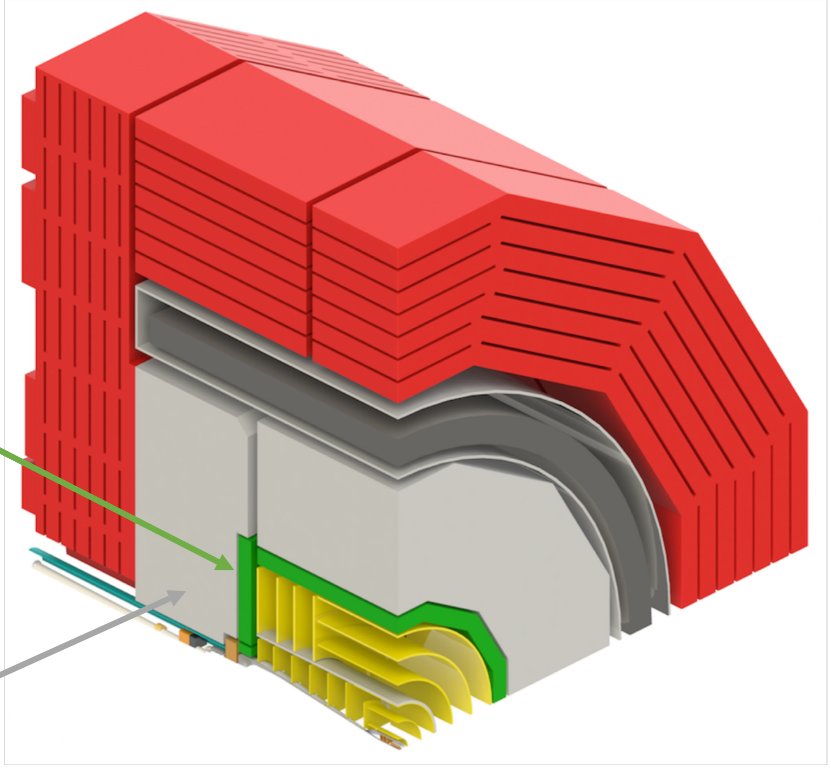
↓

Typical jet composition:
60% tracker 🙂 🙂
30% ECAL 🙂
10% HCAL ☹

Hardware + software !



calorimetry



Electromagnetic calorimeter: Silicon – tungsten
- 2 mm tungsten plates, 500 μm **silicon** sensors
- 40 layers, 22 X_0 or 1 λ_I, 5×5 mm^2 cells
- ~2500 m^2 silicon, 100 million channels

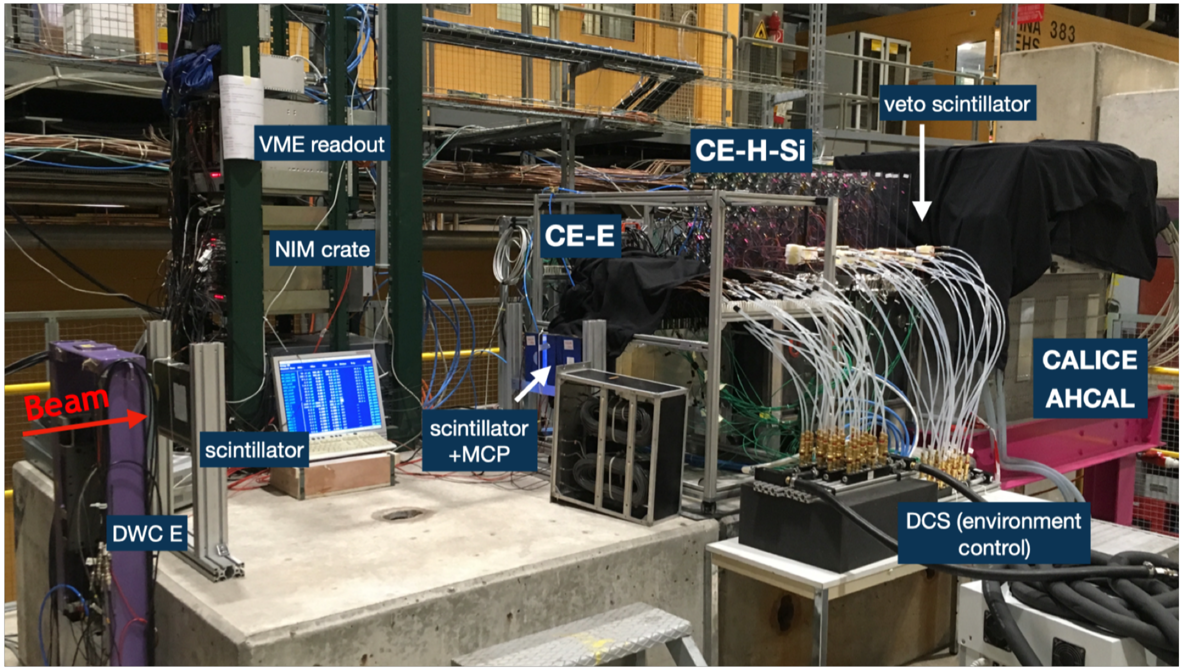
Hadronic calorimeter: Scintillator – steel
- 19 mm steel plates, 3 mm **plastic scintillators + SiPM**
- 60 layers, 7.5 λ_I, 30×30 mm^2 cells
- ~9000 m^2 scintillator, 10 million channels

⇧

Developed by CALICE collaboration

Technology choices similar to CMS HGCal upgrade project

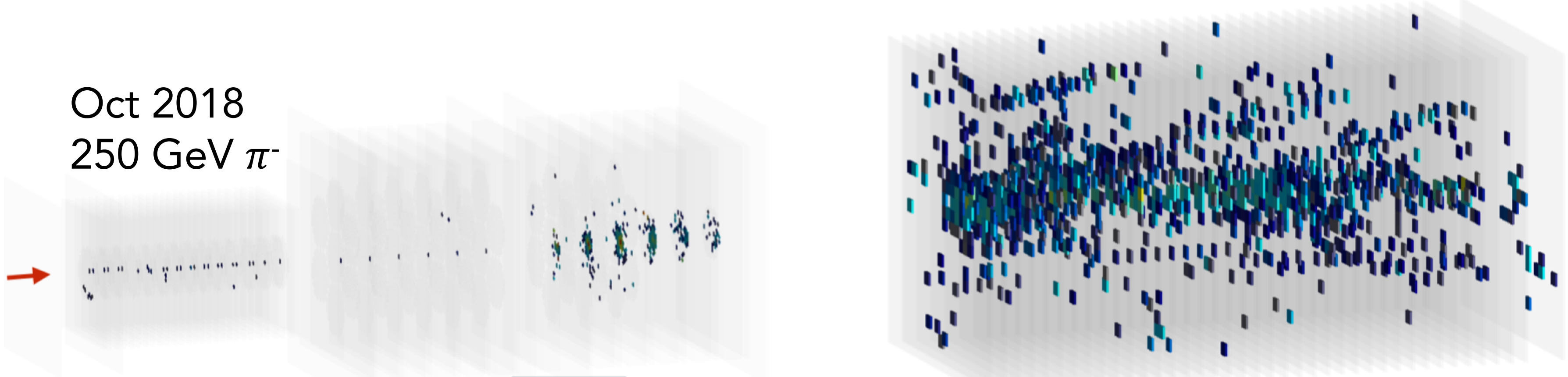
CMS HGCal + CALICE beam test



28 layers CE-E CMS silicon
12 layers CE-H CMS silicon
38 layers AHCAL CALICE
scintillator

[Dresden Terascale detector talk](#)

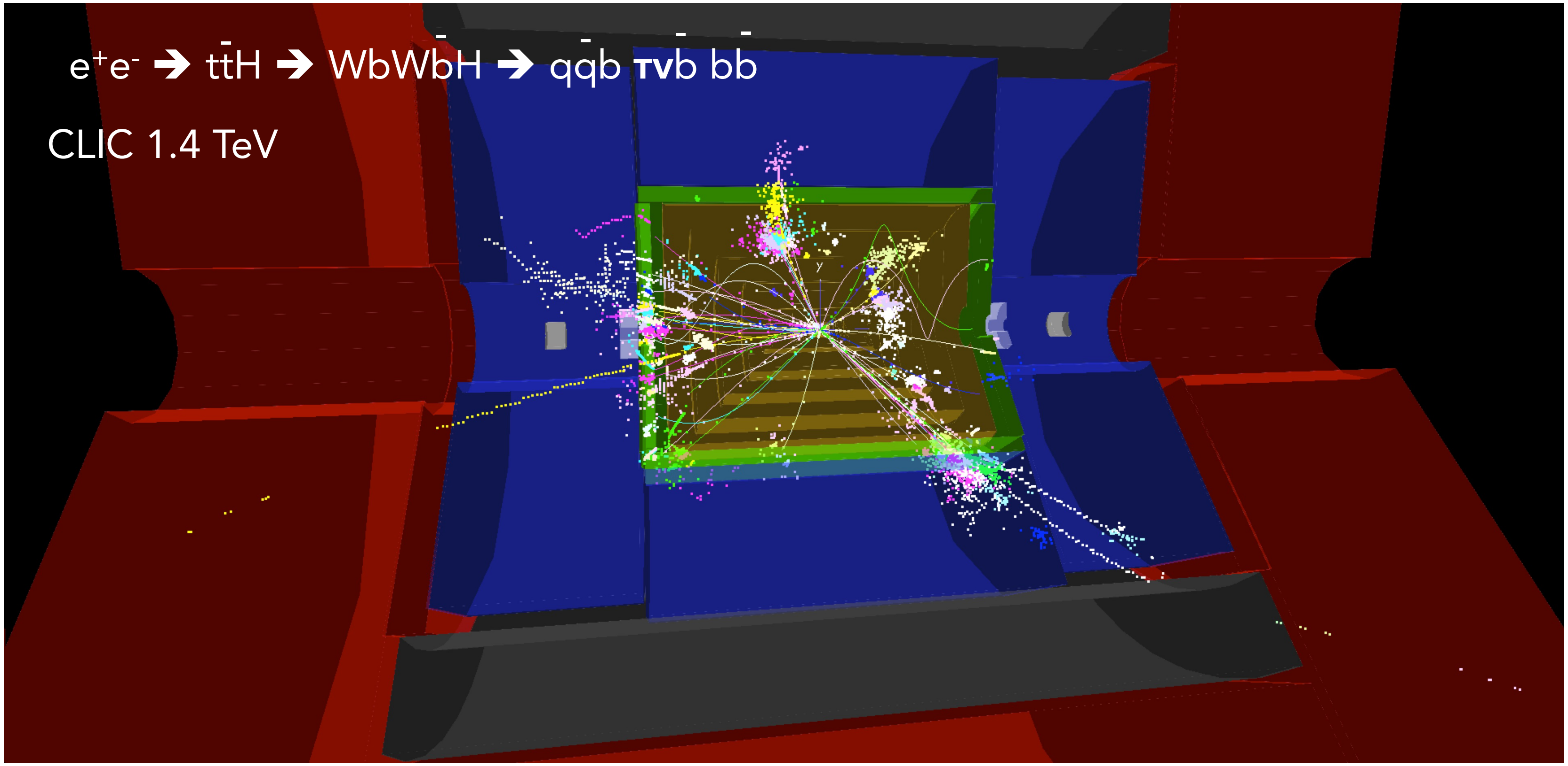
Oct 2018
250 GeV π^-



~1 cm^2 silicon pads

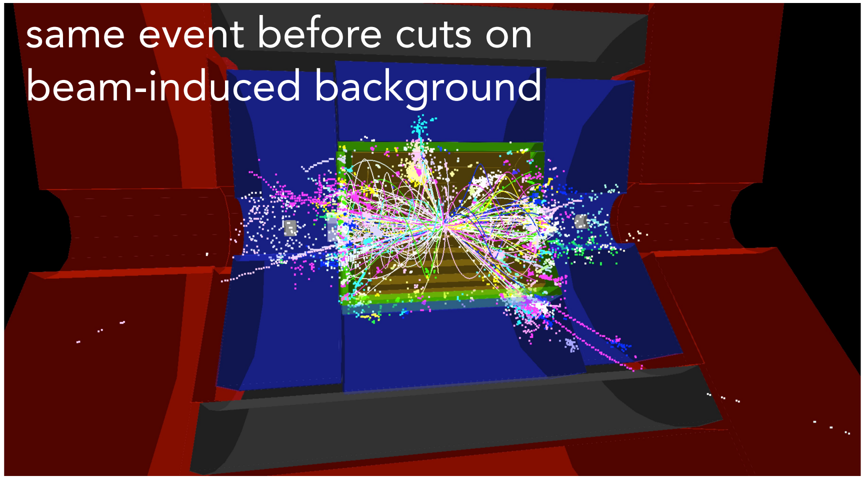
3×3 cm^2
scintillator pads

background suppression



$e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b\ \tau\nu\bar{b}\ b\bar{b}$

CLIC 1.4 TeV



same event before cuts on beam-induced background

Highly granular calorimetry + precise hit timing

↓

Very effective in suppressing backgrounds
for fully reconstructed particles

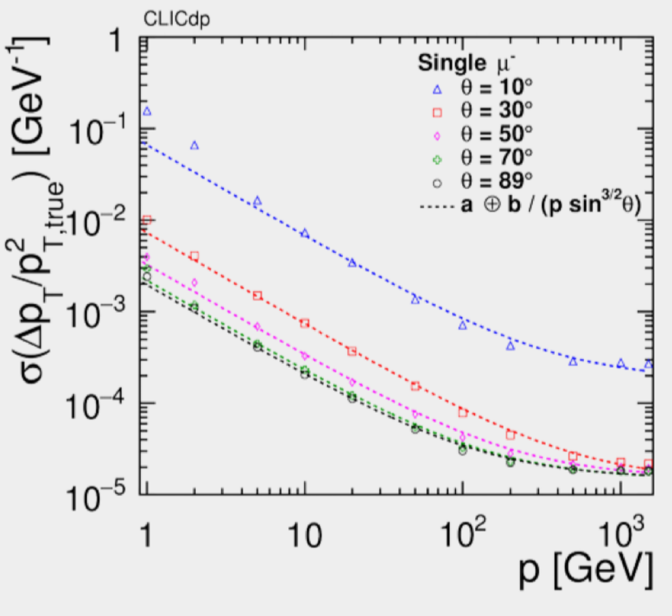
↓

General trend for **e^+e^-** and **pp** colliders

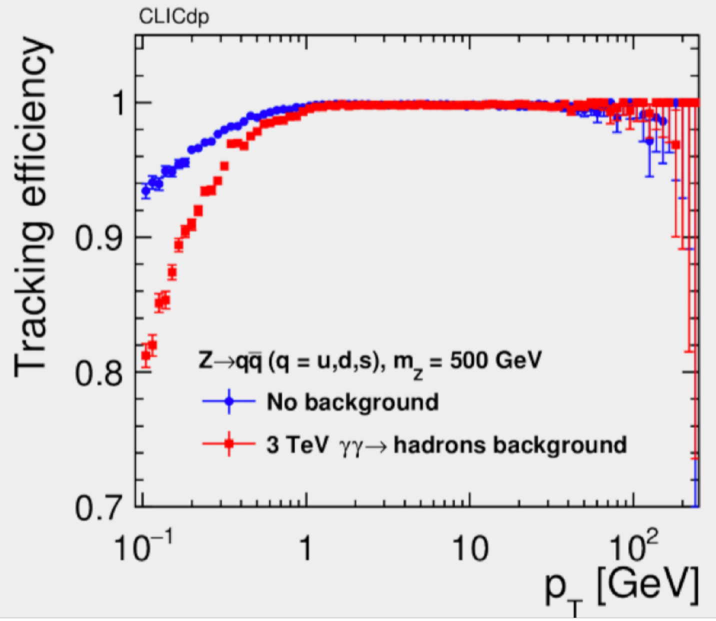
CLIC tracking performance

Detector description (*in DD4hep*), detector simulation (*in Geant4*) and reconstruction implemented in **iLCSoft framework**

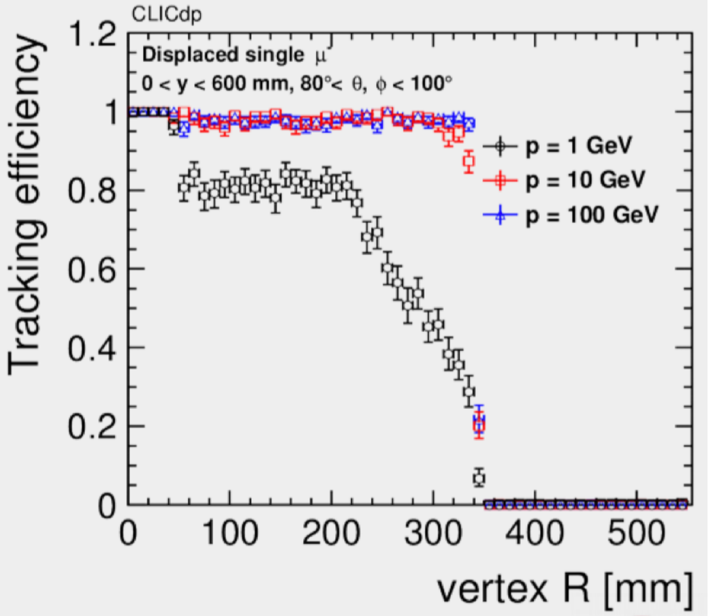
Tracking based on **conformal tracking** and **Kalman-filter based fit**



Track momentum resolution for single particles
2×10^{-5} dp_T/p_T^2 achieved for high-momentum tracks



Tracking efficiency within light quark jets
With and without background



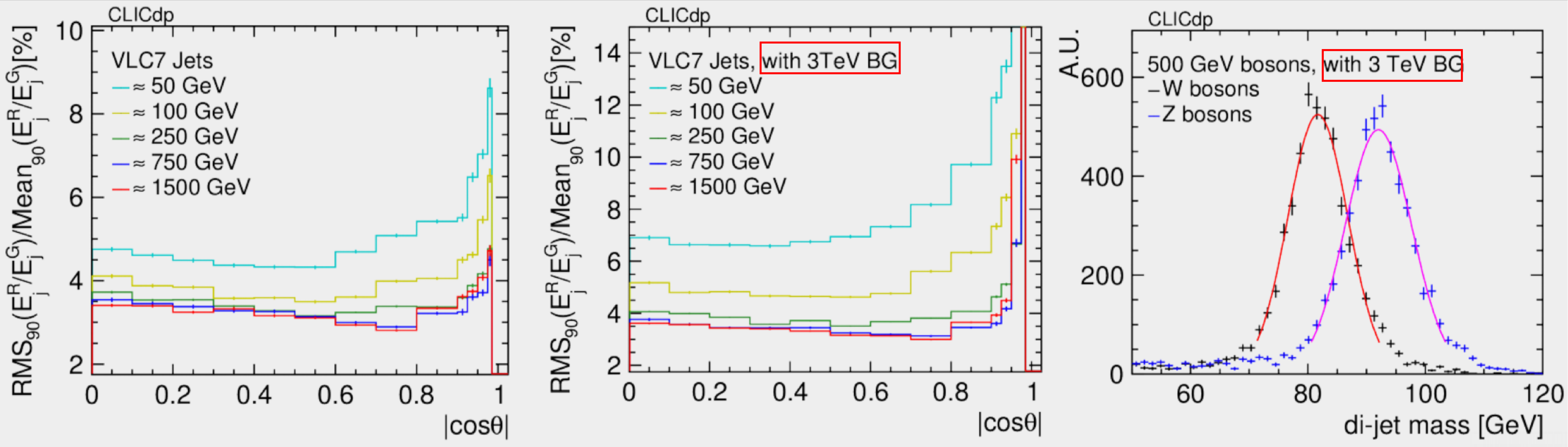
Tracking efficiency for displaced tracks
(min 4 hits required)

arXiv:1812.07337

PFA, jet energy reconstruction

PandoraPFA particle flow analysis used for jet energy reconstruction and particle ID.
Combined with **jet clustering optimized for e^+e^-** (**VLC** Valencia algorithm)

- Jet energy resolution from $Z/\gamma^* \rightarrow qq$, compare reconstruction with MC truth
  - → Objective of 3.5-5% jet energy resolution achieved for high-E jets in most of angular range
  - → Impact from 3 TeV backgrounds largest for low-energy jets, resolution 6-8%
- W/Z mass separation in 2-jet events: 2σ separation with VLC7 jets, including 3 TeV bkg

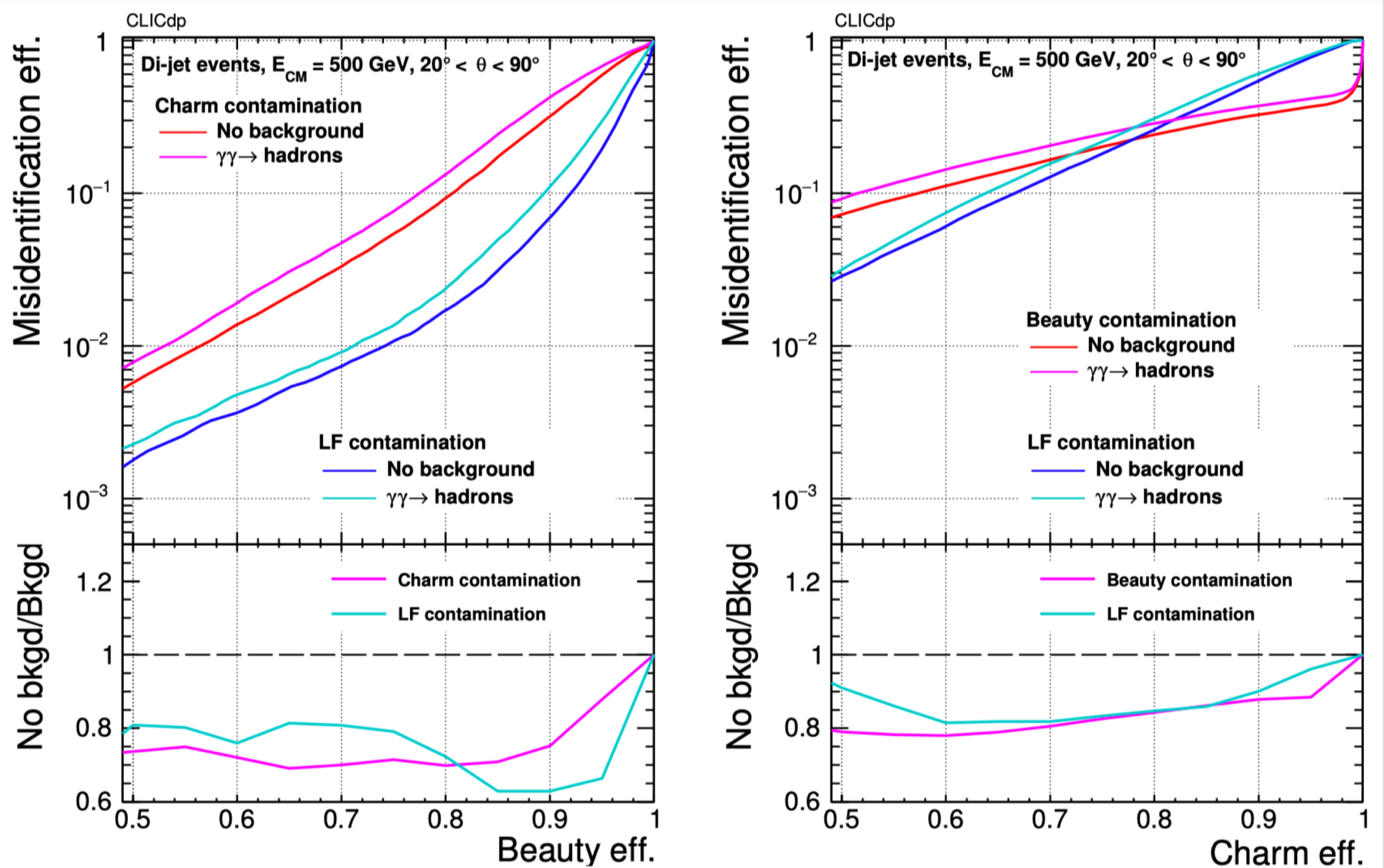


[arXiv:1812.07337](https://arxiv.org/abs/1812.07337)

flavour tagging performance

LCFIplus package used for flavour tagging

Studied in 500 GeV di-jet events, with and without $\gamma\gamma \rightarrow \text{hadrons}$ background (3TeV equivalent)



arXiv:1812.07337

required calorimeter depth

Required depth of electromagnetic calorimeter increases very weakly with energy

Required depth of hadron calorimeter increases logarithmically with energy.

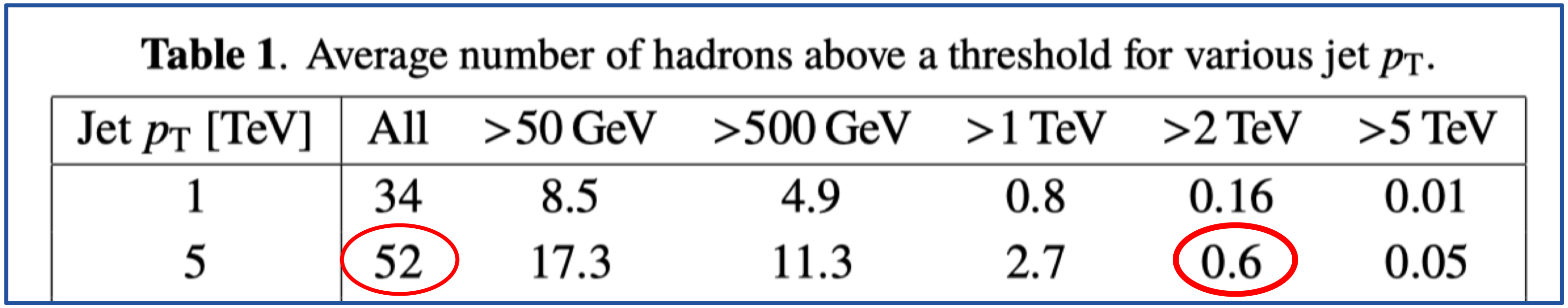


Table 1. Average number of hadrons above a threshold for various jet p_T.

Jet p_T [TeV]	All	>50 GeV	>500 GeV	>1 TeV	>2 TeV	>5 TeV
1	34	8.5	4.9	0.8	0.16	0.01
5	52	17.3	11.3	2.7	0.6	0.05

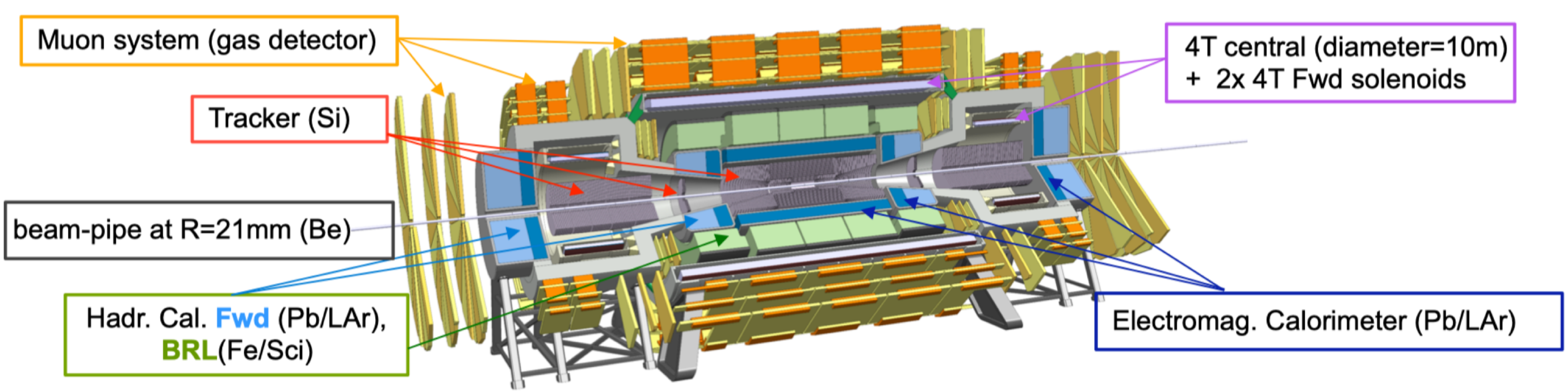
From: Carli&al._FCC_containment

~1% of particles in jet
have very high energies

Detailed study on calorimeter depth to be done.
Most likely need CLIC calorimeter depth + 2-3 λ_I => ~40-60 cm deeper
This has an impact of the solenoid radius and a significant impact on cost

See also slides 18 and 22 for tracker radius considerations….

some lessons from FCChh study



Muon system (gas detector)

Tracker (Si)

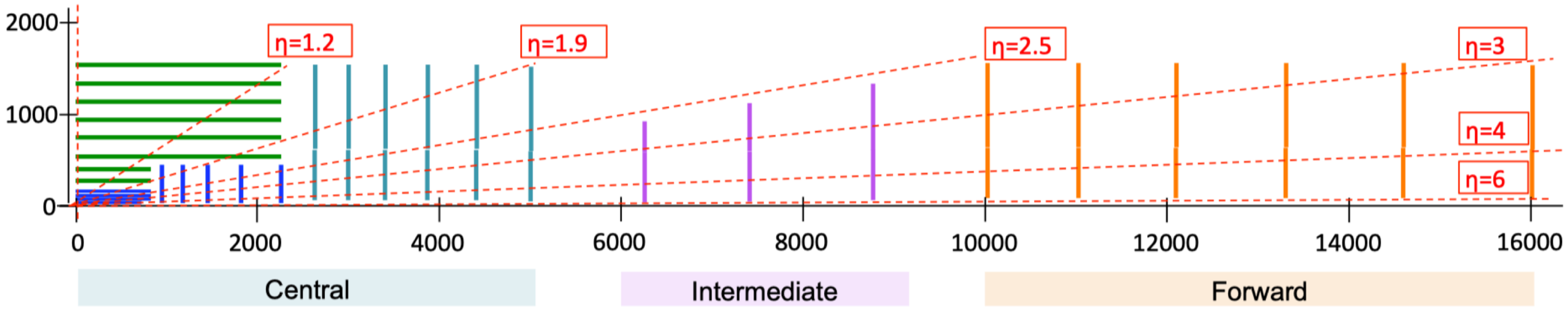
beam-pipe at R=21mm (Be)

Hadr. Cal. **Fwd** (Pb/LAr),
BRL(Fe/Sci)

4T central (diameter=10m)
+ 2x 4T Fwd solenoids

Electromag. Calorimeter (Pb/LAr)

Tracker radius: 1.6m , half-length: 16m , 4T solenoidal B-field



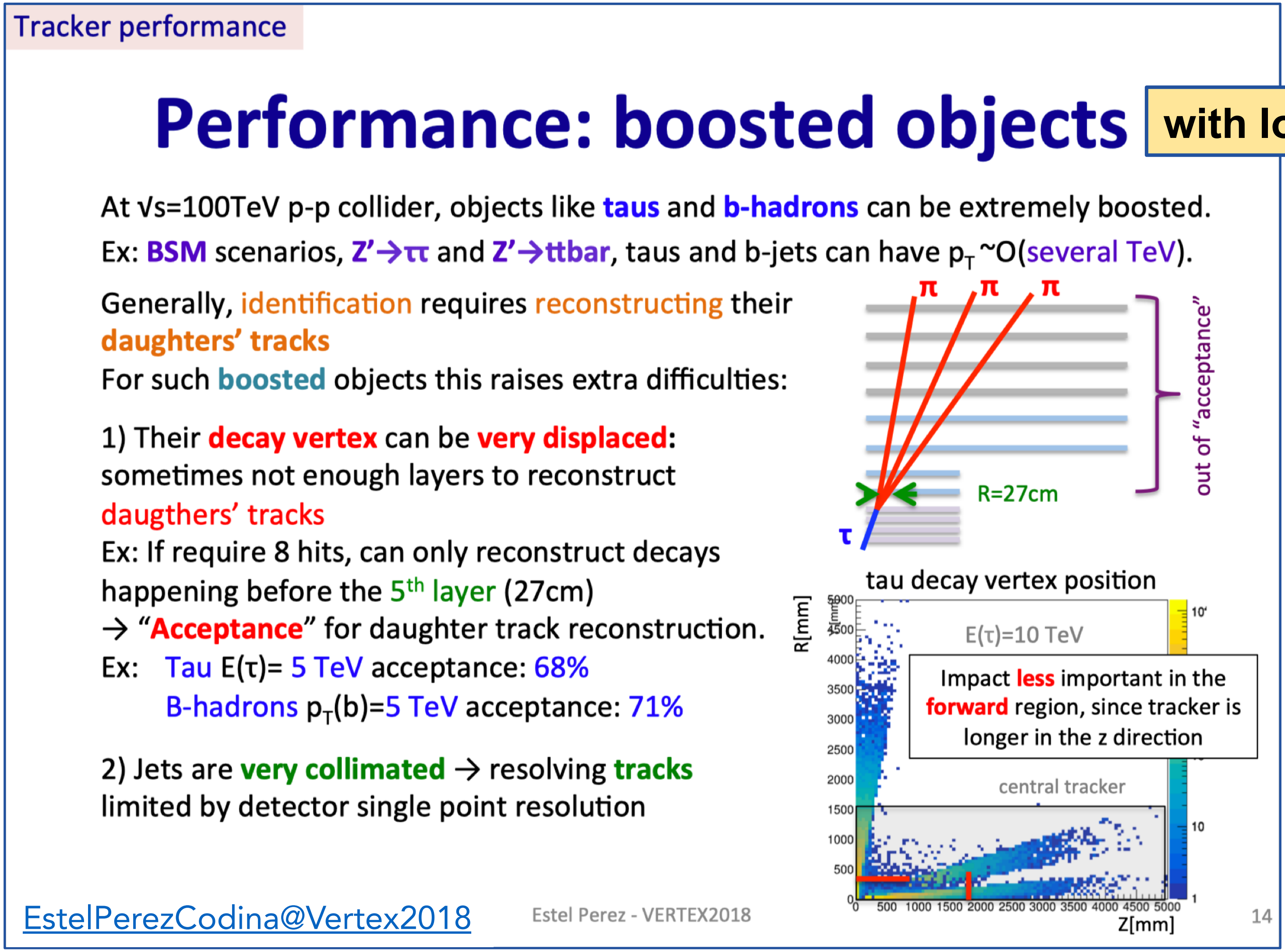
100 TeV pp collisions

⇒ Requires very forward coverage

⇒ Need to measure highly boosted objects (e.g. jets, tau decays)

⇒ Particles with longer lifetimes => decay lengths are stretched

FCChh => boosted objects



Tracker performance

Performance: boosted objects

At √s=100TeV p-p collider, objects like **taus** and **b-hadrons** can be extremely boosted.

Ex: **BSM** scenarios, **Z'→ττ** and **Z'→ttbar**, taus and b-jets can have p_T ~O(several TeV).

Generally, identification requires reconstructing their **daughters' tracks**

For such **boosted** objects this raises extra difficulties:

1) Their **decay vertex** can be **very displaced**: sometimes not enough layers to reconstruct daugthers' tracks

Ex: If require 8 hits, can only reconstruct decays happening before the 5th layer (27cm)

→ "**Acceptance**" for daughter track reconstruction.

Ex: Tau E(τ)= 5 TeV acceptance: 68%

B-hadrons p_T(b)=5 TeV acceptance: 71%

2) Jets are **very collimated** → resolving **tracks** limited by detector single point resolution

Impact **less** important in the **forward** region, since tracker is longer in the z direction

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14

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with longer life times

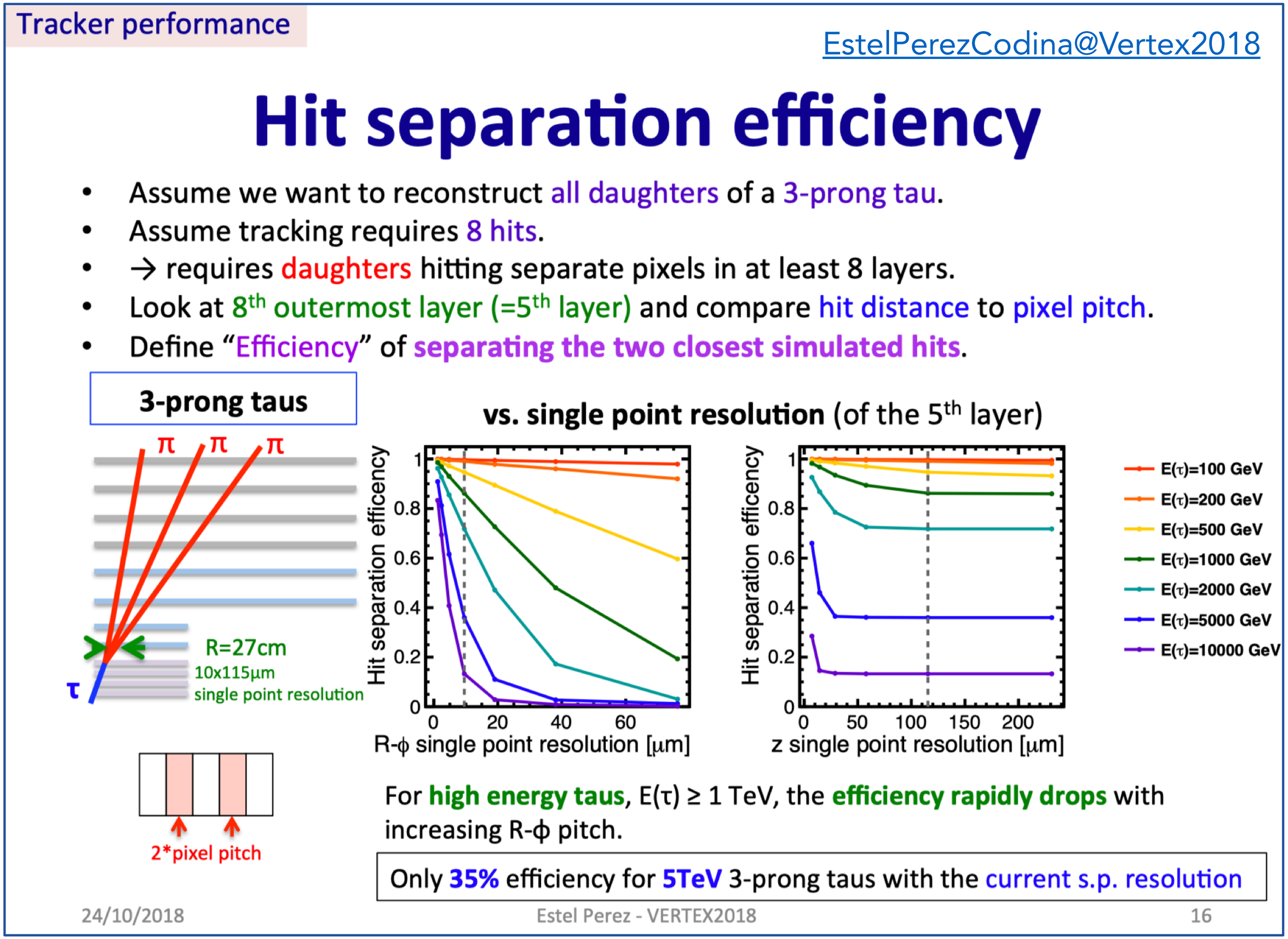
↓

stretched decay lengths

Minimum number of hits per track required => but late decays have fewer hits

5 TeV tau decays have only 68% acceptance
5 TeV B-hadrons have only 71% acceptance
} in central region, where tracker length is shortest

FCChh => boosted tau



Tracker performance

EstelPerezCodina@Vertex2018

Hit separation efficiency

- Assume we want to reconstruct all daughters of a 3-prong tau.
- Assume tracking requires 8 hits.
- → requires daughters hitting separate pixels in at least 8 layers.
- Look at 8th outermost layer (=5th layer) and compare hit distance to pixel pitch.
- Define "Efficiency" of separating the two closest simulated hits.

3-prong taus

vs. single point resolution (of the 5th layer)

For **high energy taus**, E(τ) ≥ 1 TeV, the **efficiency rapidly drops** with increasing R-ϕ pitch.

Only **35%** efficiency for **5TeV** 3-prong taus with the current s.p. resolution

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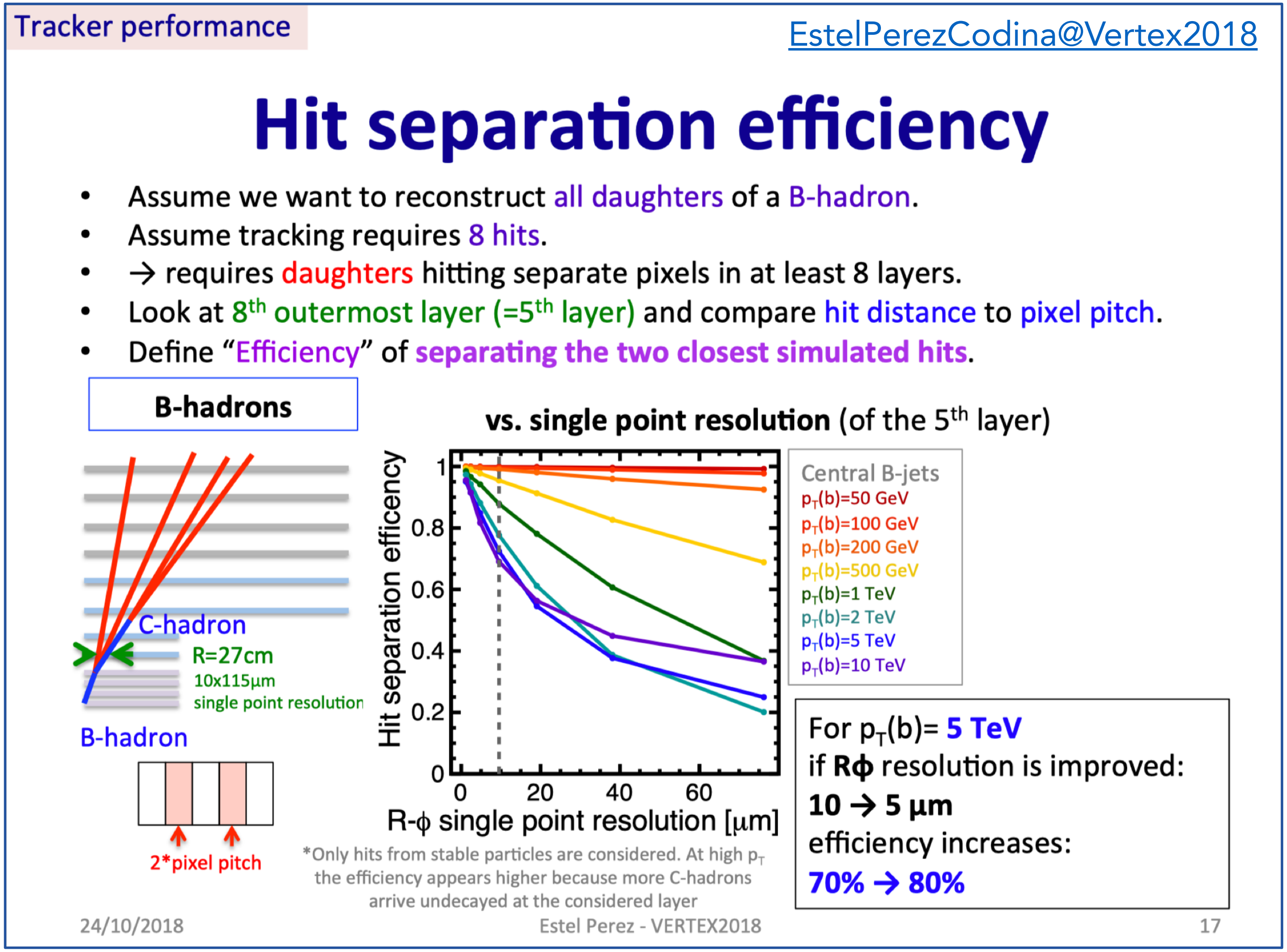
Example: boosted tau decay (5 TeV) => 3-prong decay products very close together

Reduced efficiency due to close-by tracks: ≈35% for 10 μm single point resolution

≈60% for 5 μm single point resolution

FCChh => boosted B-jets



Tracker performance

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Hit separation efficiency

- Assume we want to reconstruct all daughters of a B-hadron.
- Assume tracking requires 8 hits.
- → requires daughters hitting separate pixels in at least 8 layers.
- Look at 8th outermost layer (=5th layer) and compare hit distance to pixel pitch.
- Define "Efficiency" of separating the two closest simulated hits.

B-hadrons

vs. single point resolution (of the 5th layer)

For p_T(b)= **5 TeV**
if **Rϕ** resolution is improved:
10 → 5 μm
efficiency increases:
70% → 80%

*Only hits from stable particles are considered. At high p_T the efficiency appears higher because more C-hadrons arrive undecayed at the considered layer

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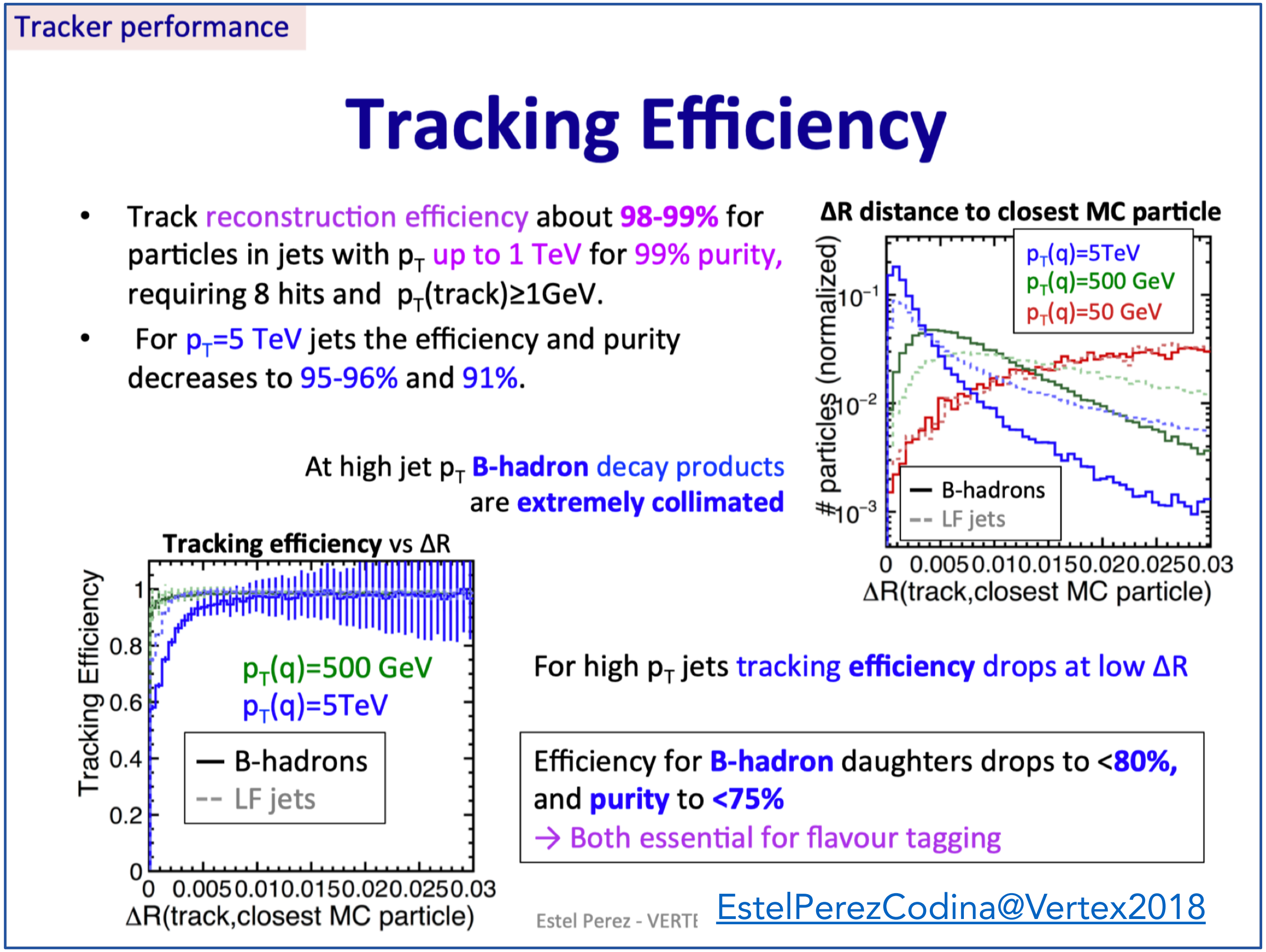
Example: boosted B-hadron decay (5 TeV) => decay products very close together
Reduced efficiency due to close-by tracks: ≈70% for 10 μm single point resolution
≈80% for 5 μm single point resolution

FCChh => boosted jets and tracking eff.



Tracker performance

Tracking Efficiency

- Track reconstruction efficiency about **98-99%** for particles in jets with p_T up to 1 TeV for 99% purity, requiring 8 hits and p_T(track)≥1GeV.
- For p_T=5 TeV jets the efficiency and purity decreases to 95-96% and 91%.

ΔR distance to closest MC particle

At high jet p_T **B-hadron** decay products are **extremely collimated**

Tracking efficiency vs ΔR

For high p_T jets tracking **efficiency** drops at low ΔR

Efficiency for **B-hadron** daughters drops to <**80%,** and **purity** to **<75%**
→ Both essential for flavour tagging

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EstelPerezCodina@Vertex2018

Tracking efficiency <u>down</u> and impurity <u>up</u> for boosted jets in general
More prominent for B-jets than for light-flavour jets.
Track separation smaller at small detector radii => impact on flavour tagging

Summary

No "real" work has gone into ~10 TeV e^+e^- or $\gamma\gamma$ experiment so far

Some open questions need to be answered first

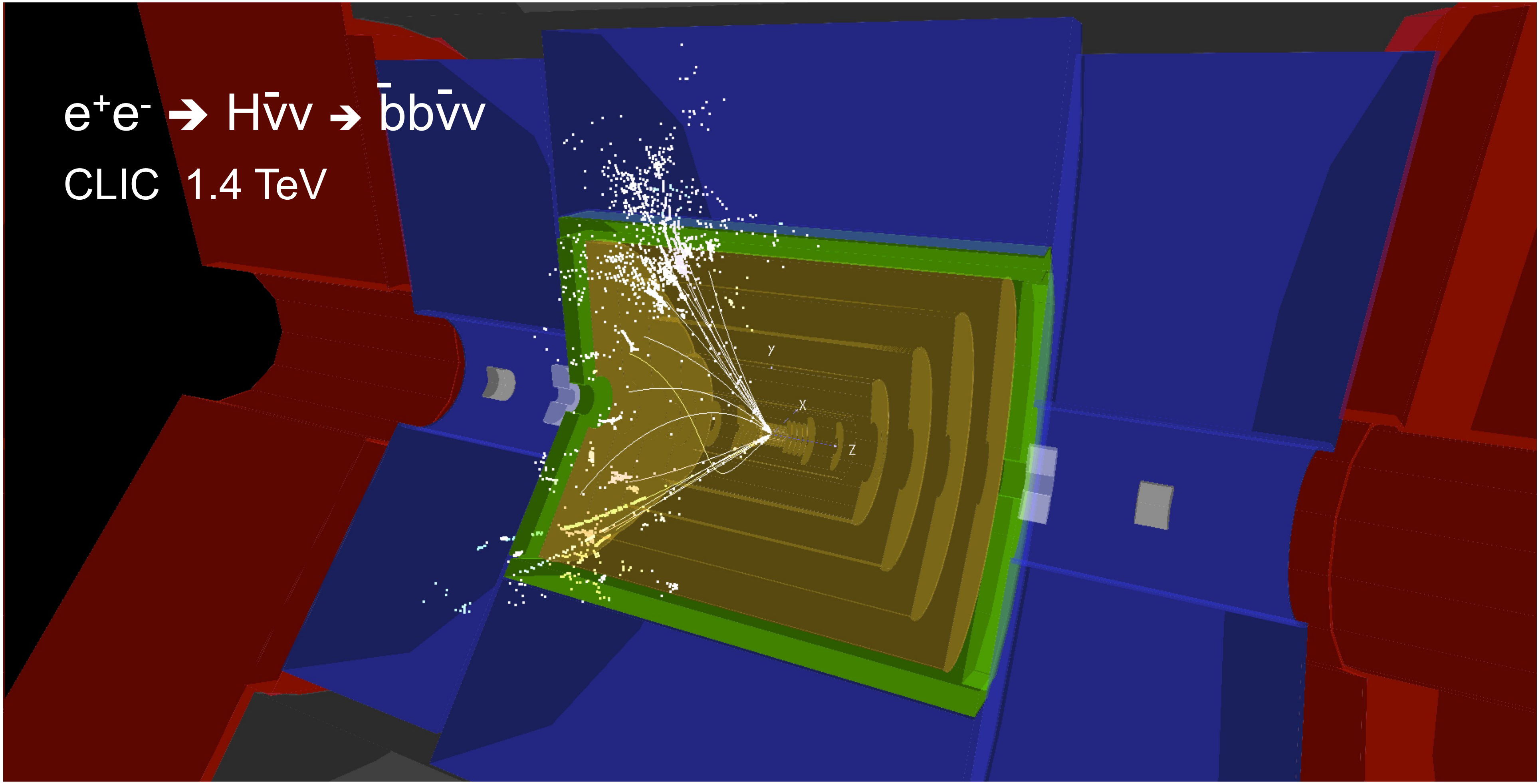
After that, detailed parametric + full simulation studies are needed

Some of the open questions:

- Beam-induced background conditions
- Beam structure (pulsed, bunch trains ?)
- Final focus requirements and crossing angle
- Infrastructure+space required to create the photons in $\gamma\gamma$ collider
- How can luminosity (and luminosity spectrum) be measured?
  - Enough Bhabha events in e^+e^-?
  - $\gamma\gamma$ luminosity and spectrum?

From physics side: Generate physics events (signal + background) to get a feel of relevant particle spectra

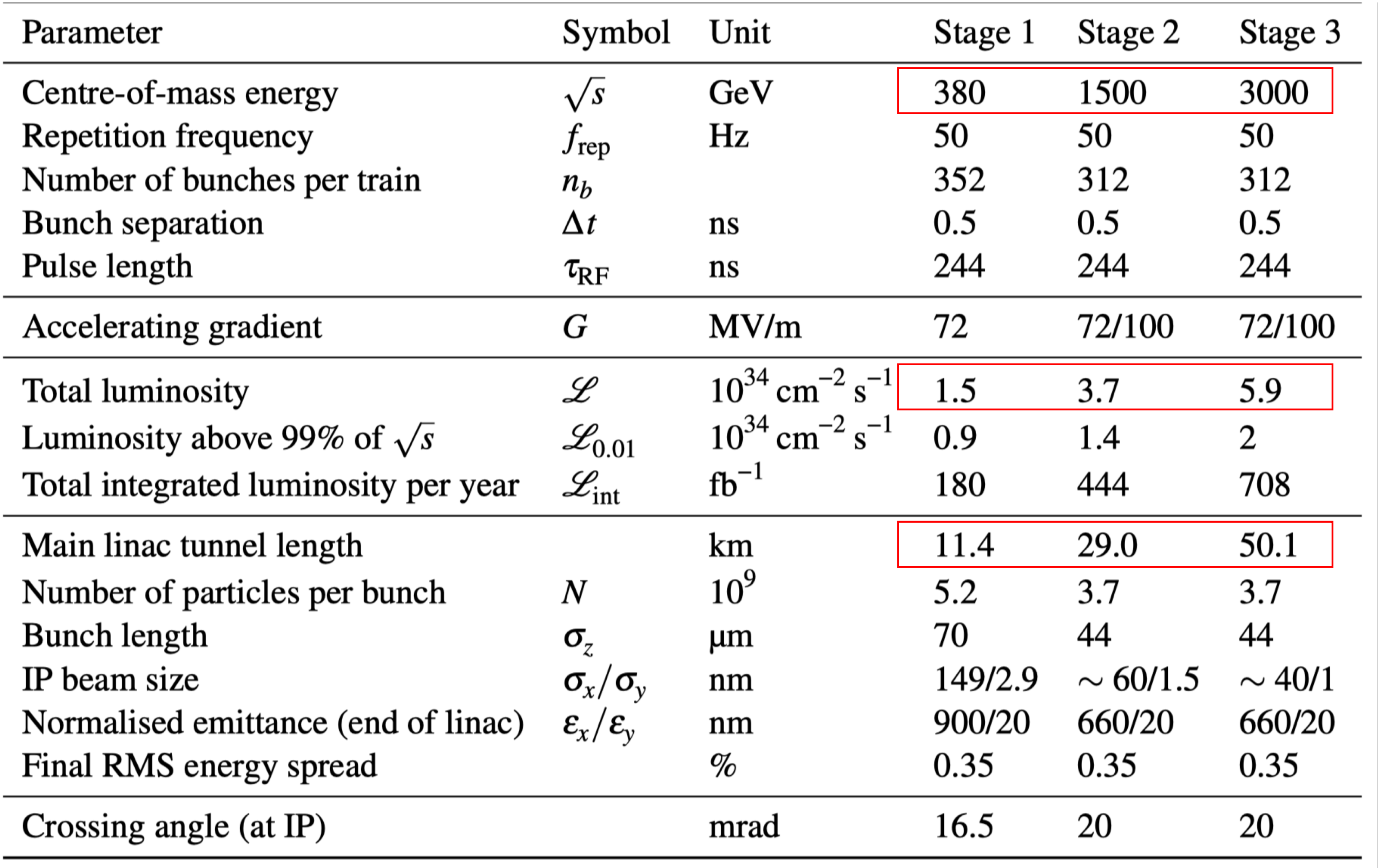
THANK YOU !



H → $b\bar{b}$ (58% BR): selection efficiency ~40% (1.4 TeV), ~50% (380 GeV)

reserve slides

overview of CLIC parameters



Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	$10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

arXiv:1812.06018

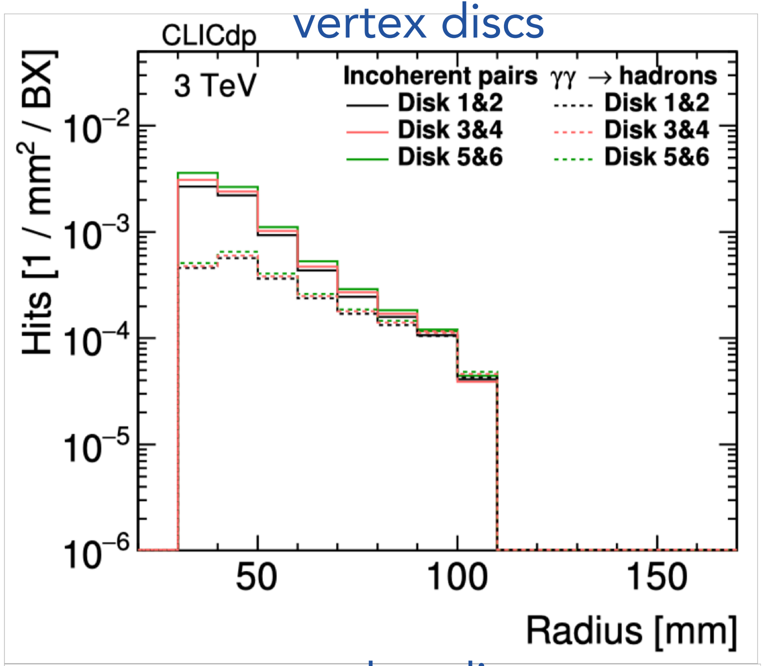
detector occupancies

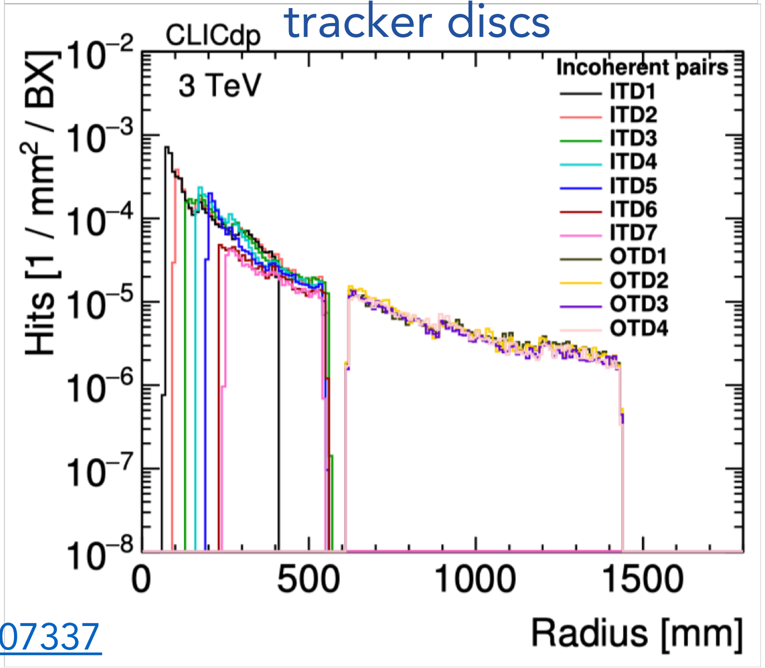
Triggerless readout, once per full (156 ns) bunch train

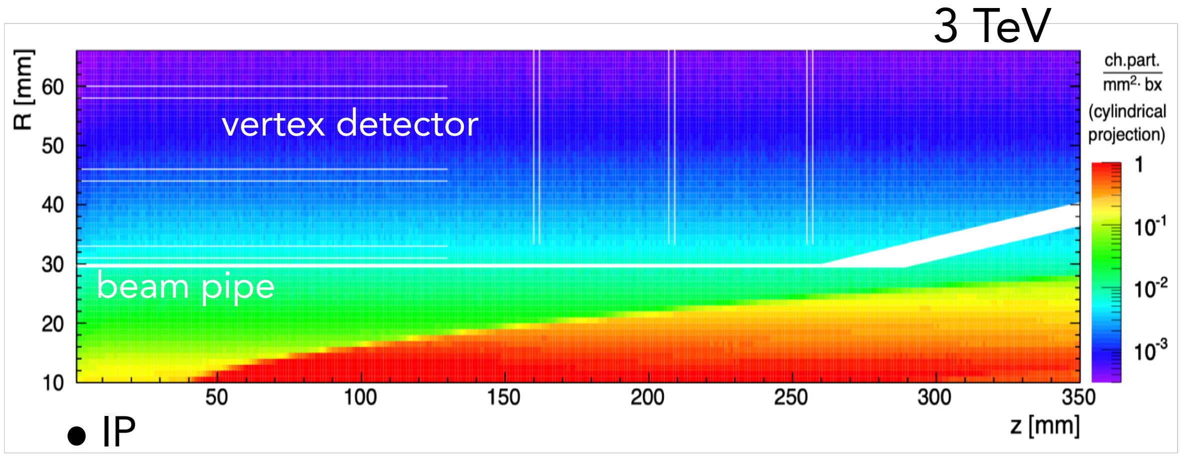
Expect at most one hard e^+e^- collision per bunch train
Detector occupancies dominated by beamstrahlung

Detector designed to achieve occupancies below 3-4%

Drives cell sizes:
- Max. vertex pixel size 25*25 μm^2
- Max. tracker cells size depends on location:
  max 0.05 mm² – 0.5 mm²







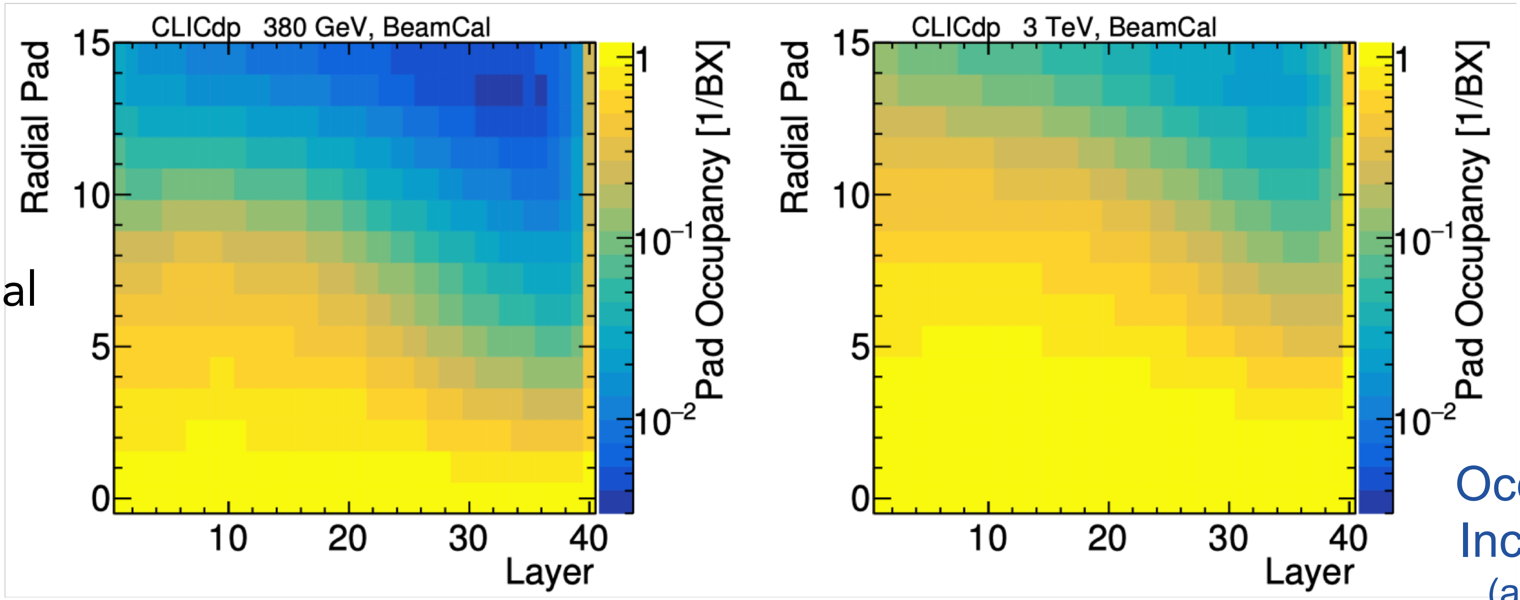
arXiv:1812.07337

occupancies in BeamCal and LumiCal

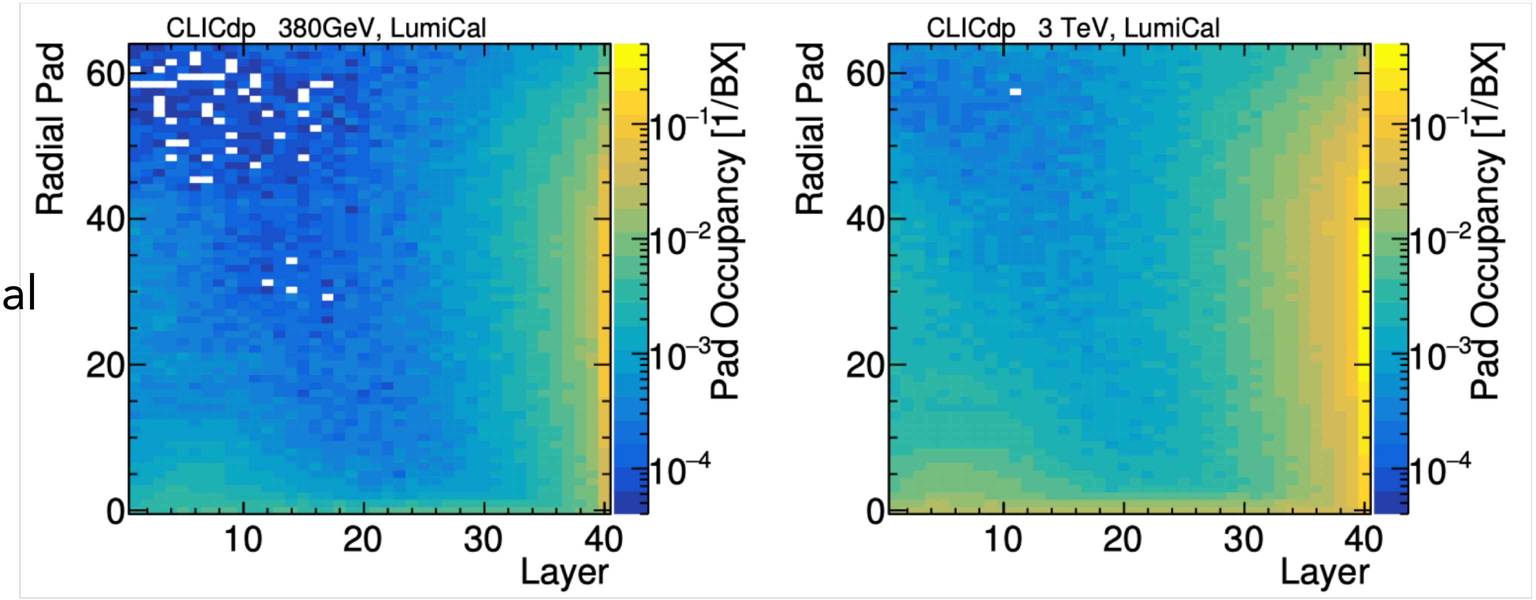
380 GeV

3 TeV

BeamCal



LumiCal

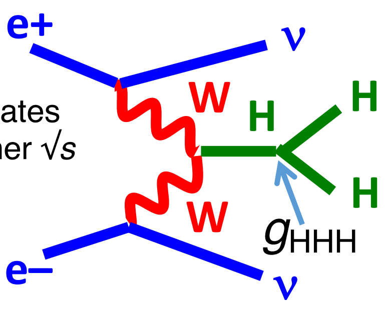


Occupancies per pad
Incoherent pairs only
(averaged over all pads
with same radius)

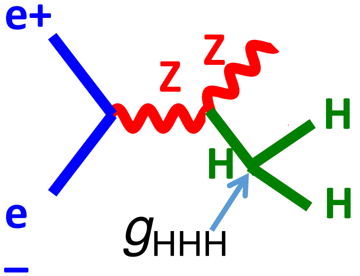
arXiv:1812.07337

Higgs self-coupling

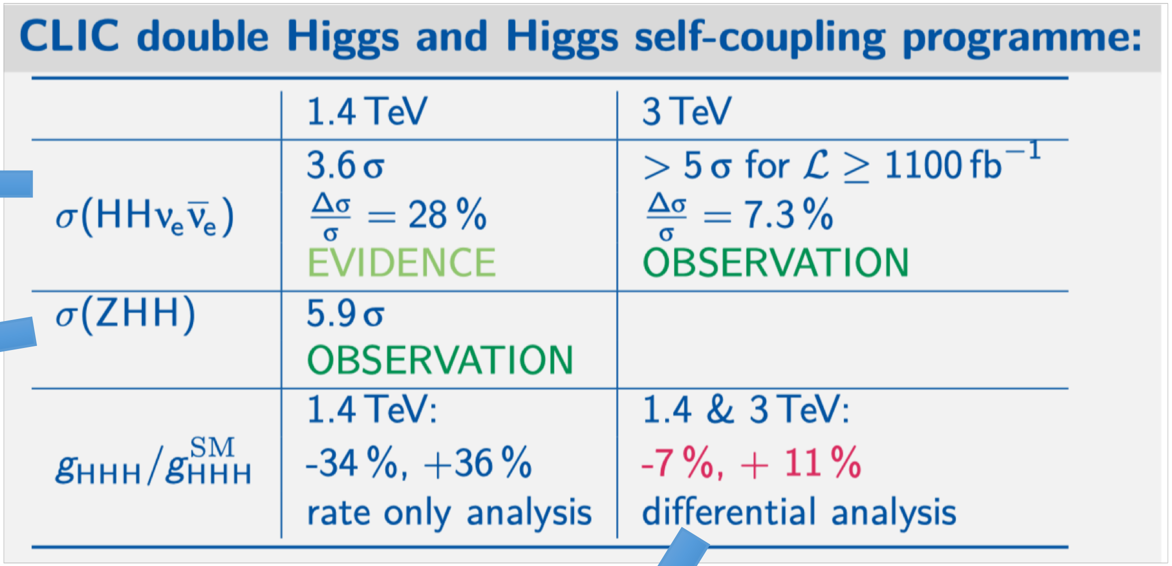
Higgs self-coupling requires high energy



dominates at higher √s

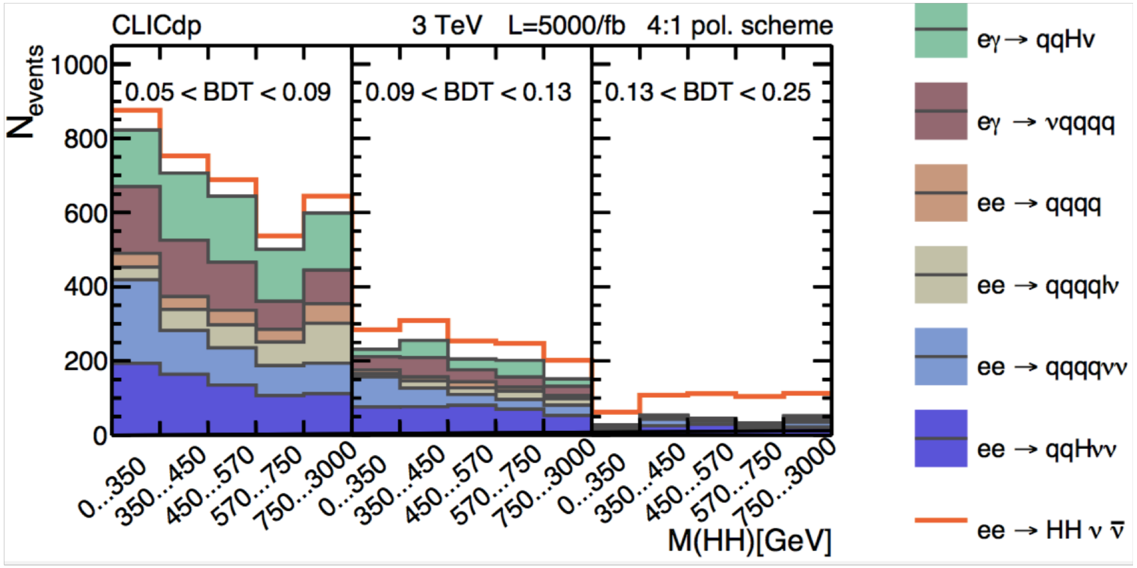


complementary at 1.5TeV



CLIC double Higgs and Higgs self-coupling programme:

	1.4 TeV	3 TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	$3.6\,\sigma$ $\frac{\Delta\sigma}{\sigma} = 28\,\%$ EVIDENCE	$> 5\,\sigma$ for $\mathcal{L} \geq 1100\,\mathrm{fb}^{-1}$ $\frac{\Delta\sigma}{\sigma} = 7.3\,\%$ OBSERVATION
$\sigma(ZHH)$	$5.9\,\sigma$ OBSERVATION	
g_{HHH}/g_{HHH}^{SM}	1.4 TeV: -34 %, +36 % rate only analysis	1.4 & 3 TeV: -7 %, + 11 % differential analysis



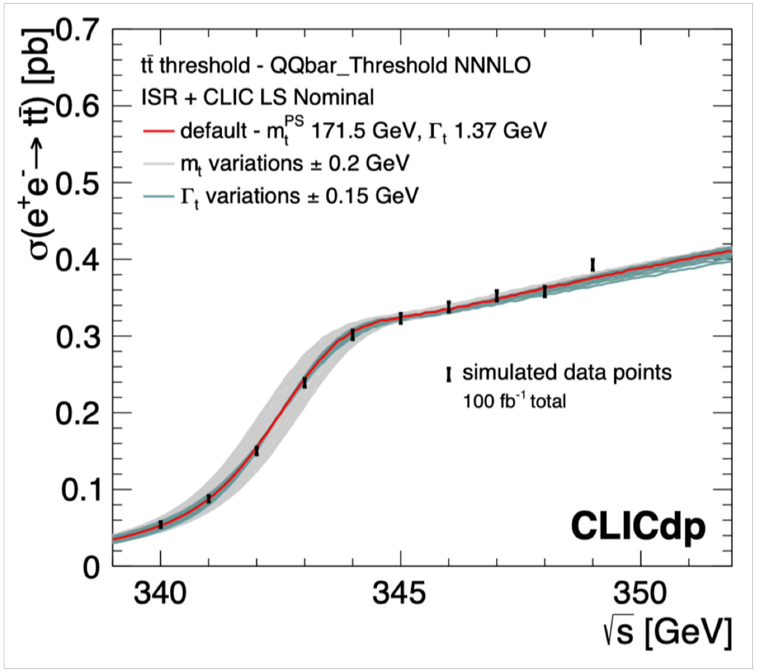
Template fit at 3TeV using two variables: *M*(HH) differential distribution and BDT score

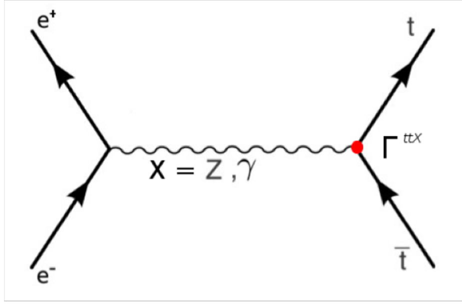
Gives unrivalled sensitivity to Higgs self-coupling:

$$\Delta g_{HHH}/g_{HHH} = {}^{+11\%}_{-7\%}$$

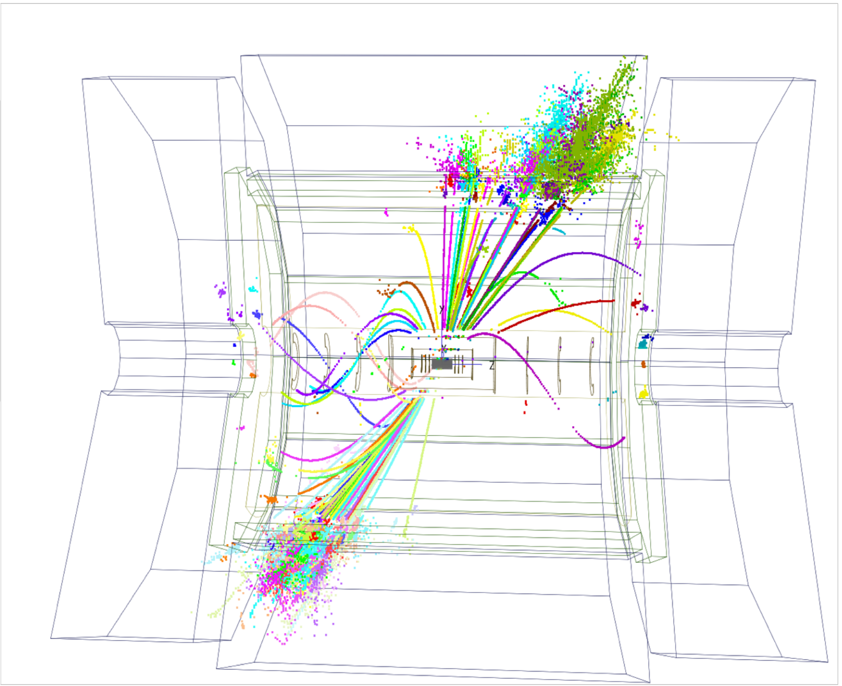
arXiv:1901.05897

top quark physics at CLIC





$e^+e^- \to tt \to WbWb$



Top mass from threshold scan around 350 GeV (100 fb^{-1})

observe 1S 'bound state', Δm_t ~ 50–75 MeV

$e^+e^- \to tt$ at all CLIC energies

→ complementarity

- coupling to Z and γ
- forward-backward asymmetry
- EFT interpretation

also:

- FCNC top decays
- ttH incl. CP analysis

arXiv:1807.02441

First e^+e^- study of boosted top production, using jet substructure in reconstruction