ILD: a detector for the International Linear Collider

ILC

physics goals, detector requirements

ILD

design, reconstruction, performance

ECAL, photons, π^0, taus

project status

Daniel Jeans
The University of Tokyo
July 2015

we live in fascinating times...

The Standard Model of particle physics
has recently become complete

with the discovery of perhaps its most exotic member, the Higgs boson

a **triumph** of both theoretical and experimental physics *we live in fascinating times...*

The Standard Model of particle physics
has recently become complete

with the discovery of perhaps its most exotic member, the Higgs boson

a **triumph** of both theoretical and experimental physics

while, at the same time, our confidence in our own
understanding of the universe's constituents
is progressively deteriorating

~4 % matter we understand
~21 % dark matter for which theorists can hazard some guesses
but awaits positive identification from experiment
~75 % dark energy, about which we know even less

a **challenge** for both theoretical and experimental physics

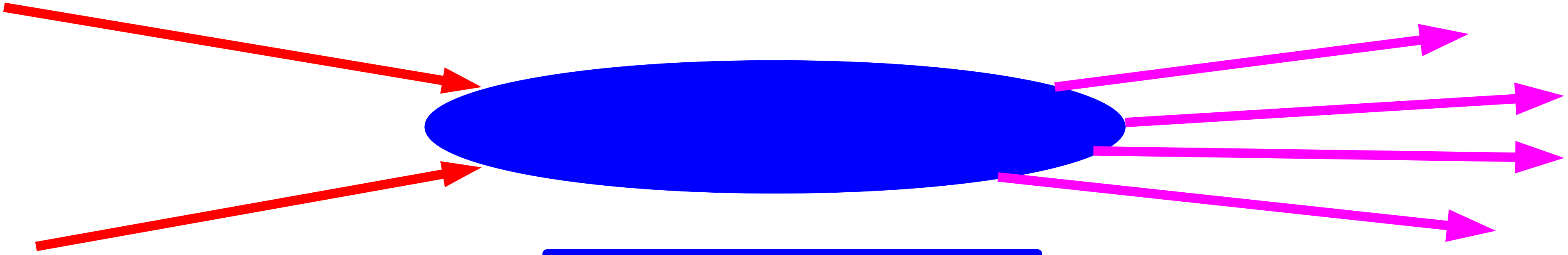
Particle colliders are one of the tools we can use to investigate further

- Direct creation of
  new particles/states

- Verify our description (models) by
  Precise measurement
    of
      precisely calculated
        quantities

The LHC runs beautifully, and has already made spectacular discoveries in proton & nuclear collisions

what is the interest in using lepton colliders to explore the same energy scale?



simple, well known,
controlled initial state

“democratic”
access to physics

clean final state

elementary initial particles
- no Parton Density Functions
- full centre-of-mass energy

control of initial state
- energy
- polarisation
  - (~80% e^-, ~30-60% e^+)
- dis-/favour specific processes

All processes induced by Electro-Weak interactions

no bias to QCD

“rare” processes are
not so rare

no trigger:
catch everything

no (or little) underlying event

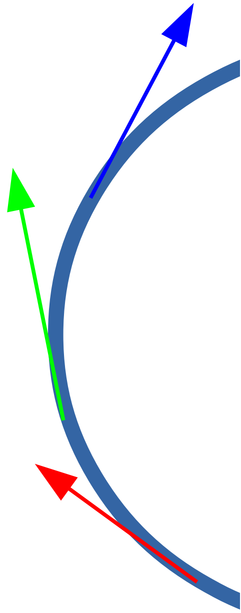
detection and analysis “easy”

lab ~ centre-of-mass

Why an electron-positron linear collider ?

electrons and positrons are easy to handle and accelerate
charged, stable

BUT, they have a low mass
→ synchrotron radiation in circular accelerator



$$\text{energy loss} \sim \frac{(\text{beam energy})^4}{(\text{radius of accelerator})^2 \text{ x } (\text{particle mass})^3}$$

e.g. LEP2 → ~100 GeV / beam
→ ~27 km circumference (in present LHC tunnel)
→ ~2 GeV lost per turn (and ~11000 turns/second)

for higher energies, energy loss and/or radius must increase
→ cost: running power and/or accelerator construction

Linear collider: radius → ∞
but beams cannot be reused

What physics can be measured at electron-positron colliders?

guaranteed

precision measurements of
- Higgs boson (ZH, ttH, ZHH)
  - *e.g.* %-level on absolute BRs
- Top quark
  - mass via threshold
  - anomalous couplings

m_H+m_Z → m_H+2m_t
250 → 500+ GeV

more precise measurement of Z, W bosons

m_Z → $2m_W$
90 → 160 GeV

possible

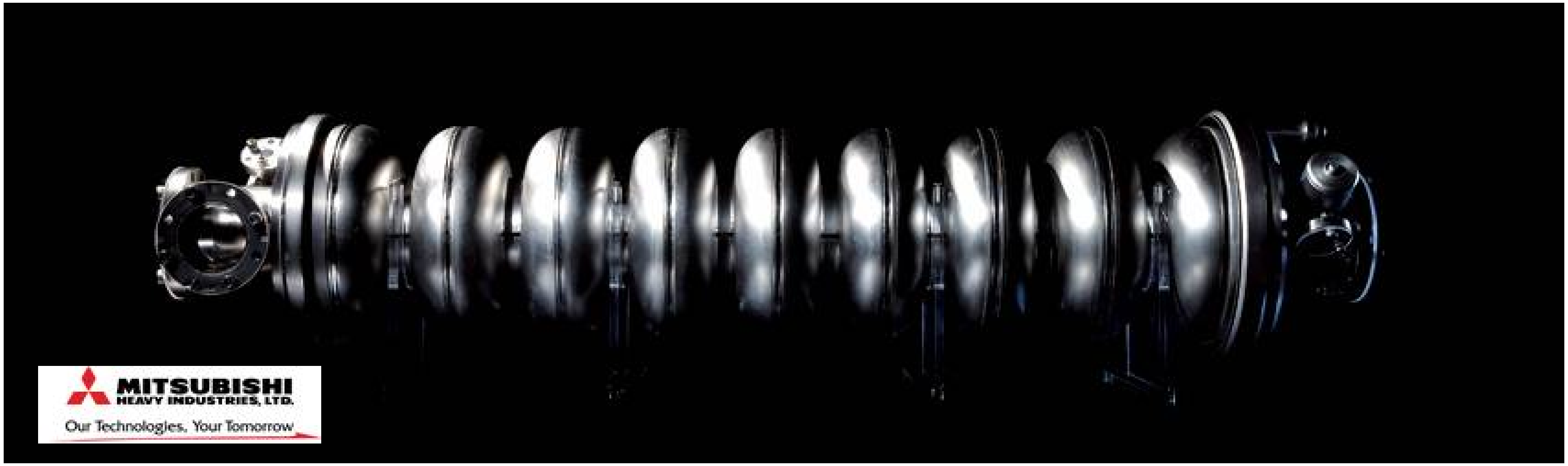
- new particles and resonances
  - threshold scans
- cover “blind spots” of e.g. LHC
  - (mostly thanks to trigger-less operation)
  - e.g. small mass differences

unknown energy scale
→ LHC 13 TeV may guide us
precision measurements can severely restrict quantum corrections due to new particles

International Linear Collider

Under study for > 20 years; single international project since ~2005
  designed for 250 → 500 GeV running

Accelerating technology:
  Niobium superconducting 1.3 GHz radio-frequency (RF) cavities
  now mature, industrialised production, becoming widely used
    e.g. at light sources: XFEL/DESY, LCLS-II/SLAC



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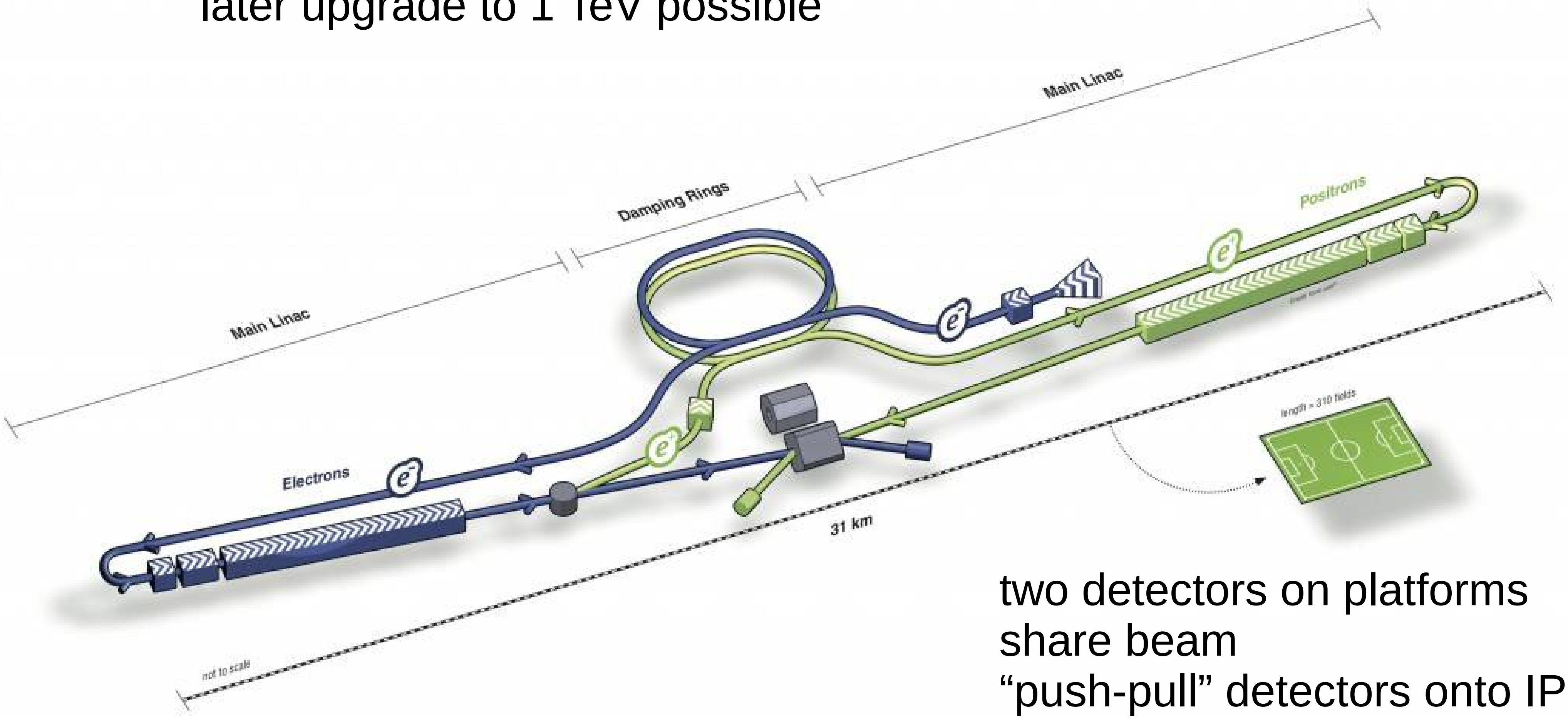
International Linear Collider

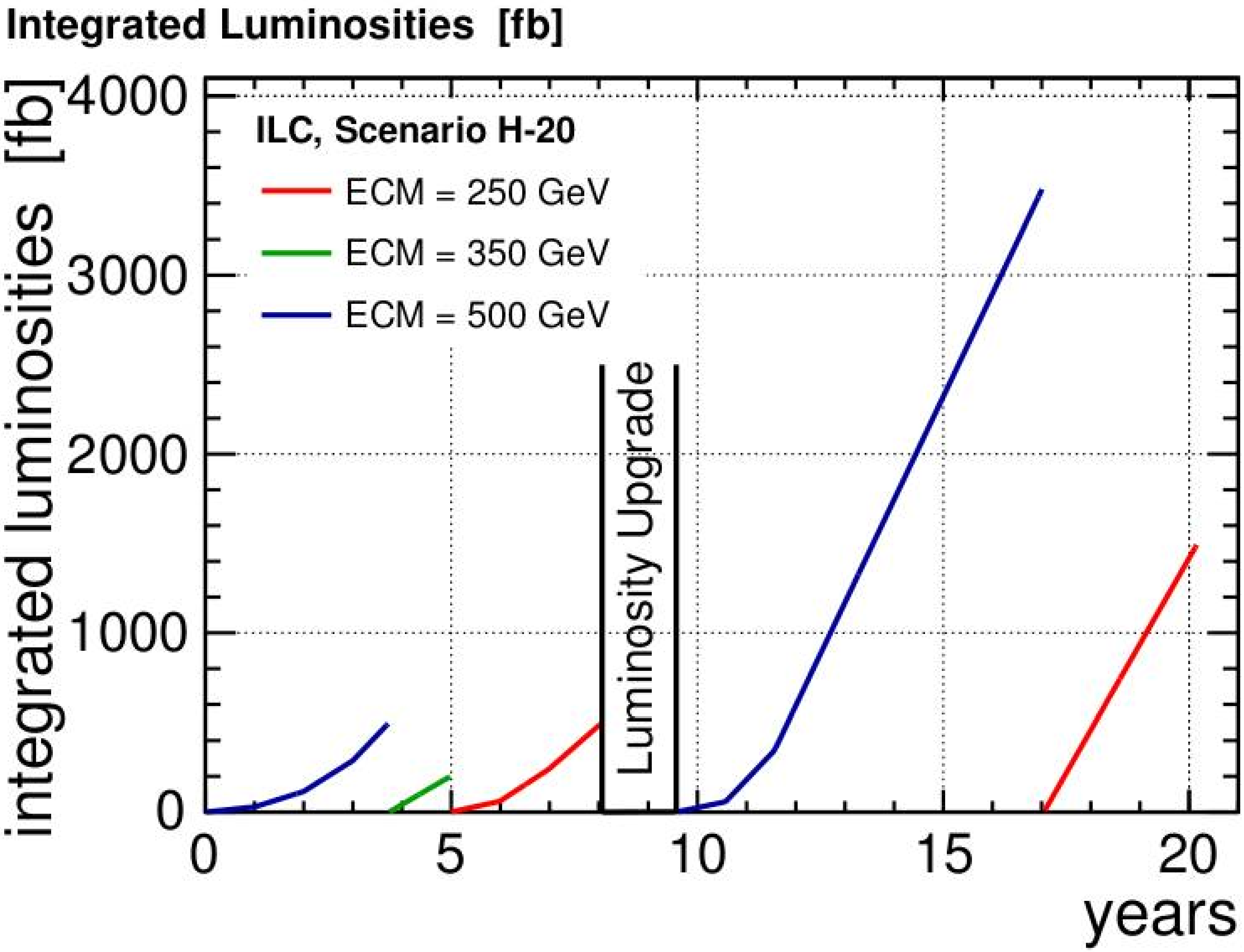
Technical Design Report published 2012
- 31.5 MV/m average accelerating gradient
- ~31 km total length
- Luminosity ~ 10^{34} cm^{-2} s^{-1}
- centre-of-mass energy 250 → 500 GeV
  - running at lower energies possible: e.g. 91 GeV for calibration
- later upgrade to 1 TeV possible



two detectors on platforms
share beam
“push-pull” detectors onto IP

The “default” ILC running plan

arXiv:1506.07830 [hep-ex]



Energy
upgrade?
downgrade?
other?
depends on
what is found

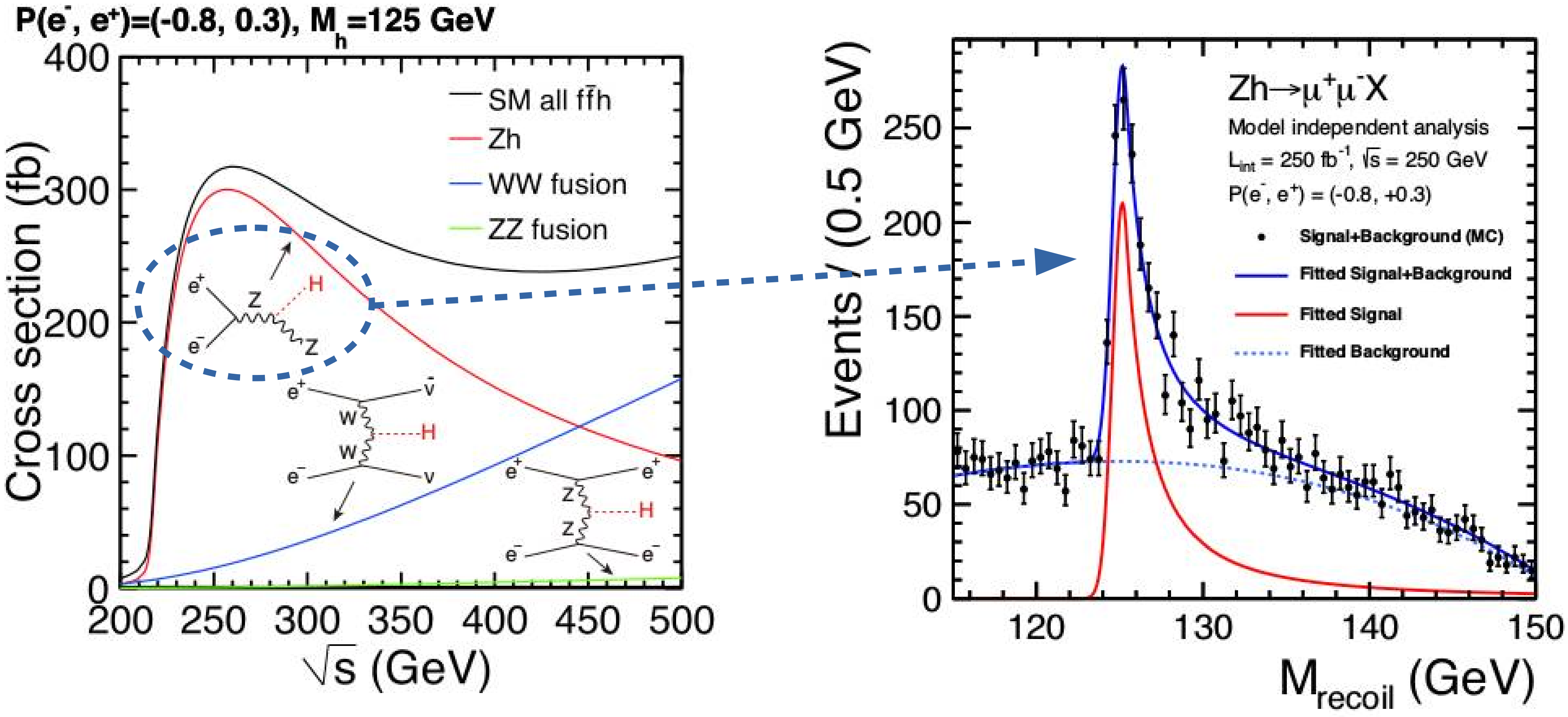
This optimises precision on measurement of Higgs boson properties
It would change if accessible new phenomena are discovered

Focus: Z+Higgs production at threshold

At lepton colliders, Higgs can be selected by looking **only** at Z decay products

- we know initial e^+e^- 4-momentum (lepton collider)
- we precisely measure 4-momentum of Z (decay to muons is easiest)
- we can trivially extract 4-momentum of “H”

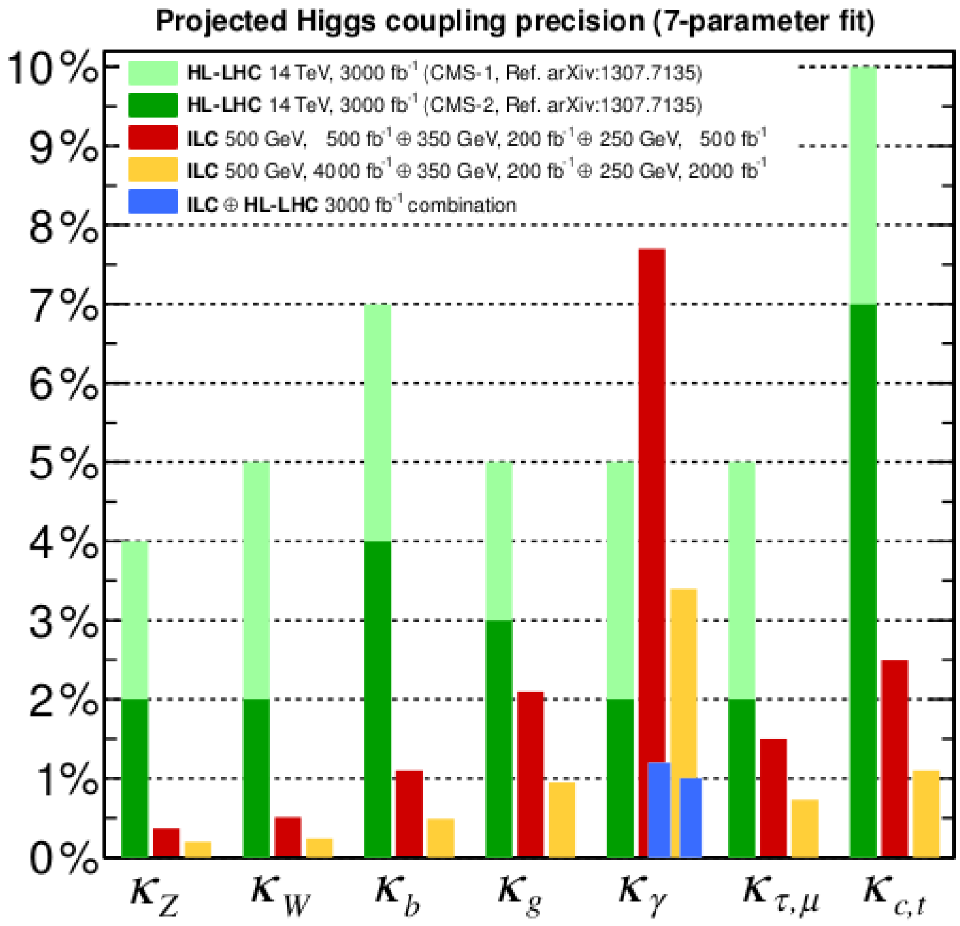
select Higgs events with **no decay mode bias** (e.g. invisible Higgs)

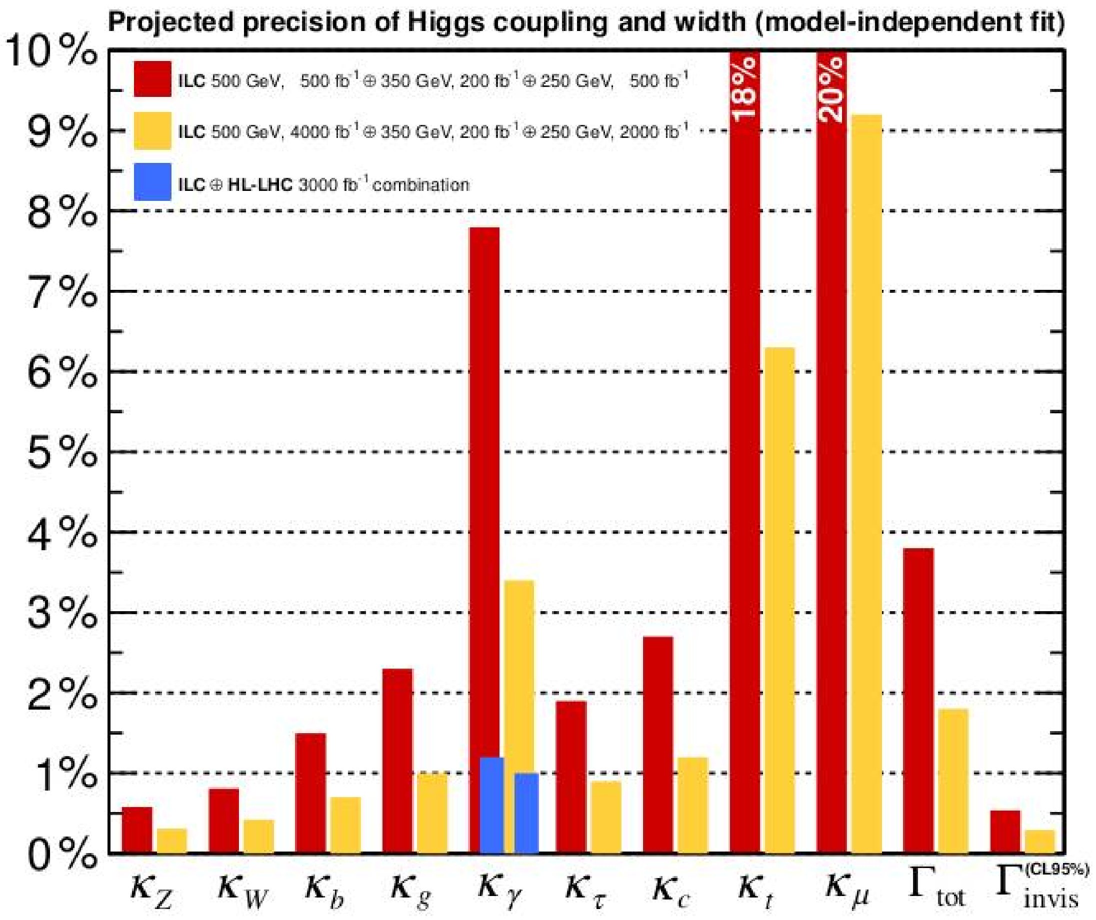


How well can Higgs couplings to other particles be measured?
key aim of ILC

Model-dependent
compared to LHC/CMS

Model-independent





HL-LHC
initial 8 years of ILC
full 20 year program

arXiv:1506.05992 [hep-ex]

Detectors

Two detector concepts are being developed for ILC

- ILD: International Large Detector (historically mostly EU/JP) ←I will discuss this one
- SiD: Silicon Detector (historically mostly US)

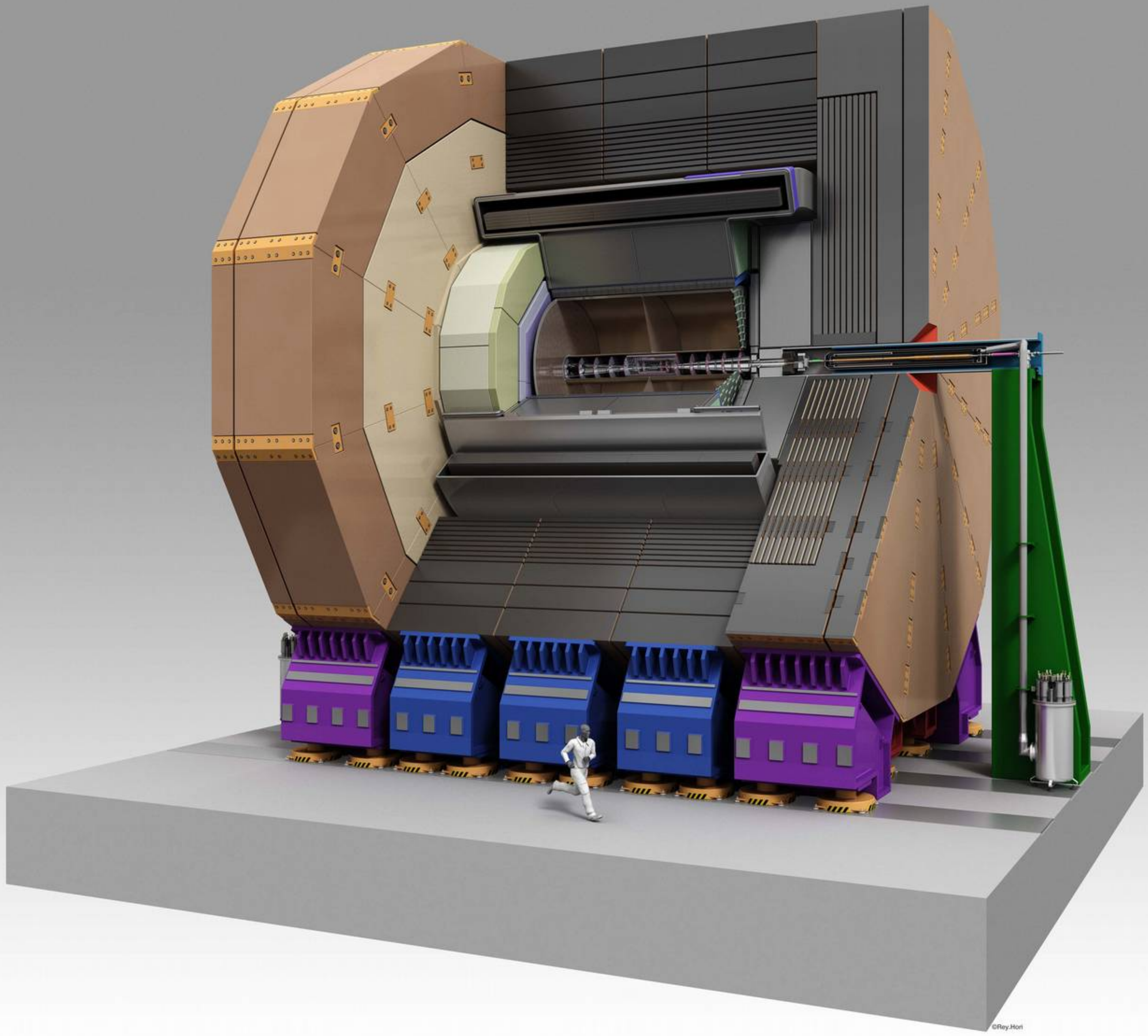
ILC detector requirements

In our quest to understand what happens in particle collisions,
ideally want to measure the full final state of Feynman diagrams

charged leptons (electrons, muons, taus)
quarks (up down charm strange top bottom)
neutrinos
photons
W, Z, H bosons ← these are becoming “normal” particles:
tools to measure & search for new phenomena

which ever direction they are produced in
hermetic detector covering ~4π solid angle
(also needed to infer presence of neutrinos)

as precisely as necessary / possible



©Rey.Hori

the International **L**arge **D**etector

charged leptons
quarks
neutrinos
photons
W, Z, H bosons

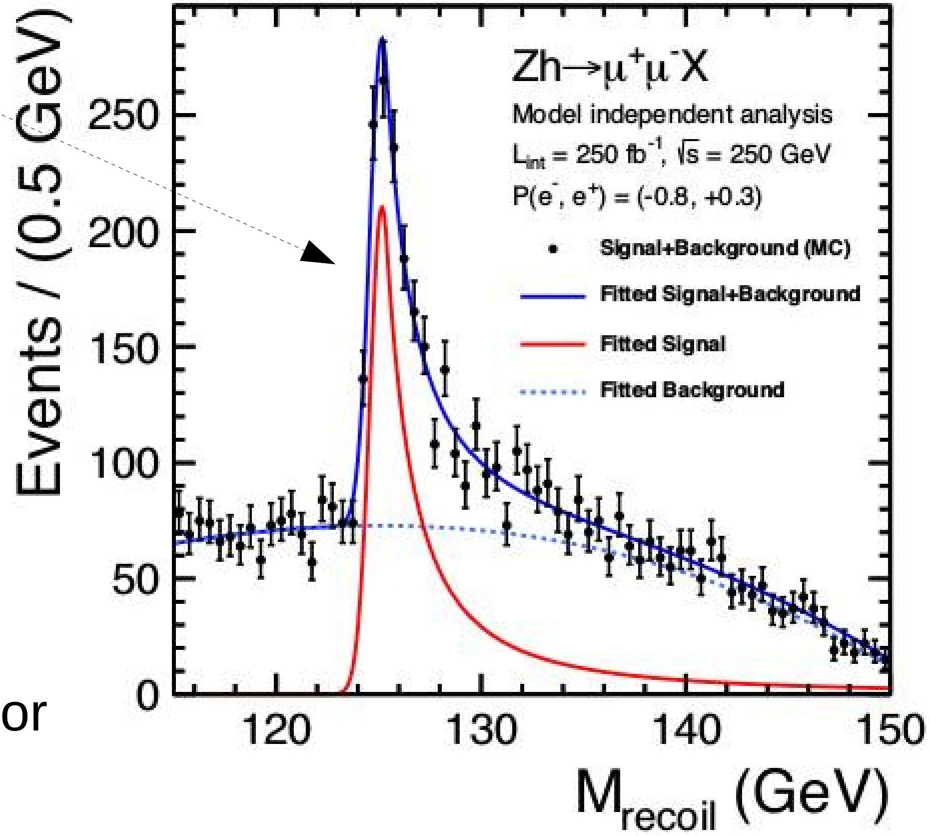
Charged particle tracking

momentum
→ curvature in magnetic field
impact parameter
→ primary or secondary vertex?

width of Higgs recoil peak
depends on
momentum resolution
spread of ILC beam energy

$dp_T/p_T \sim$ few $10^{-5}\, p_T$ leads to
similar contributions from two effects
→ “sufficiently good”

required **impact parameter resolution** set
by lifetimes and typical energies of
tau leptons and c hadrons.
→ high precision low mass vertex detector



track momentum resolution

large size
strong B field
low mass

Time Projection Chamber
- read out by Micro Pattern Gas Detectors (GEM, MicroMegas, …)

advantages:
- trivial track finding ← TPC measures up to 192 hits / track
- very light ← minimise multiple scattering
- dE/dx measurement ← many measurements of ionisation along track allow reasonably good particle ID

complications:
- maximum drift time in gas > time between collisions
- limited position resolution of individual points along track

TPC enclosed in silicon strip layers
- improved momentum resolution @ high momentum
- unambiguous time-stamp for each track

Hadronic Jet Energy Resolution

charged leptons
quarks
neutrinos
photons
W, Z, H bosons

quarks are dominant decay products of W,Z,H

produce jets of hadrons

E_{JET} ~ 50-100 GeV , $\Gamma_{W,Z}$ ~ GeV

need relative energy resolution ~ few %

Jets are mixtures of

charged hadrons	← ~65% of energy on average
photons (mostly from pi0)	← ~25%
neutral hadrons	← ~10%

these fractions fluctuate wildly from jet to jet

Traditional calorimetry

measure hadrons in the Hadronic (and Electromagnetic) calorimeters

typical resolution for particle of energy E: dE/E ~ (50 → 100) % / √ E

measure photons in the Electromagnetic calorimeter

typical resolution for photon of energy E: dE/E ~ (5 → 20) % / √ E

Energy Flow method *e.g.* at LEP experiments

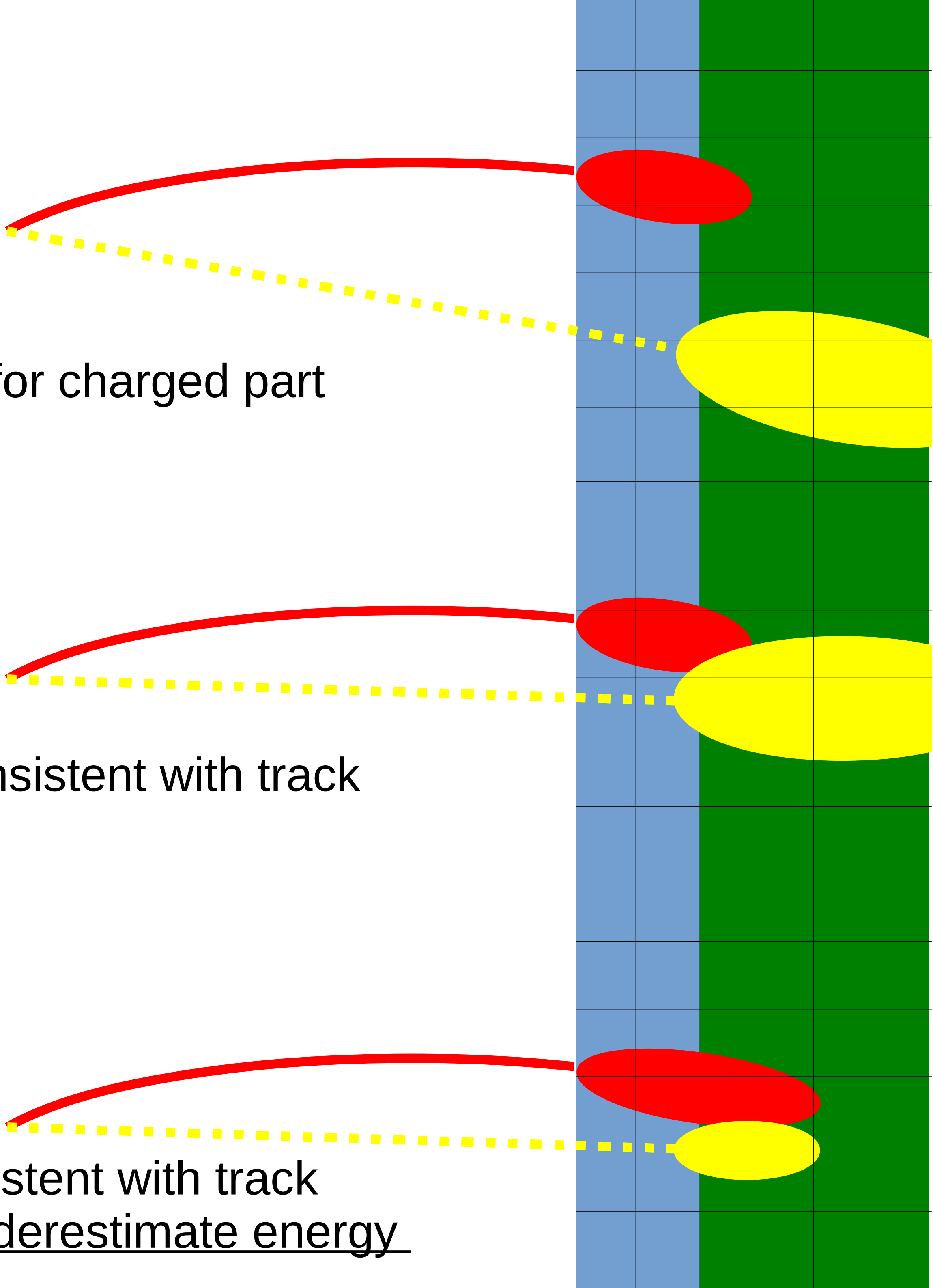
note that typical tracker momentum resolution: $dp_T/p_T \sim 10^{-5} \rightarrow 10^{-3}\, p_T$

→ replace calorimeter energy with track momentum

if unambiguous matching can be made and tracking precision better

Energy Flow method

based on energy matching
between track and calorimeter



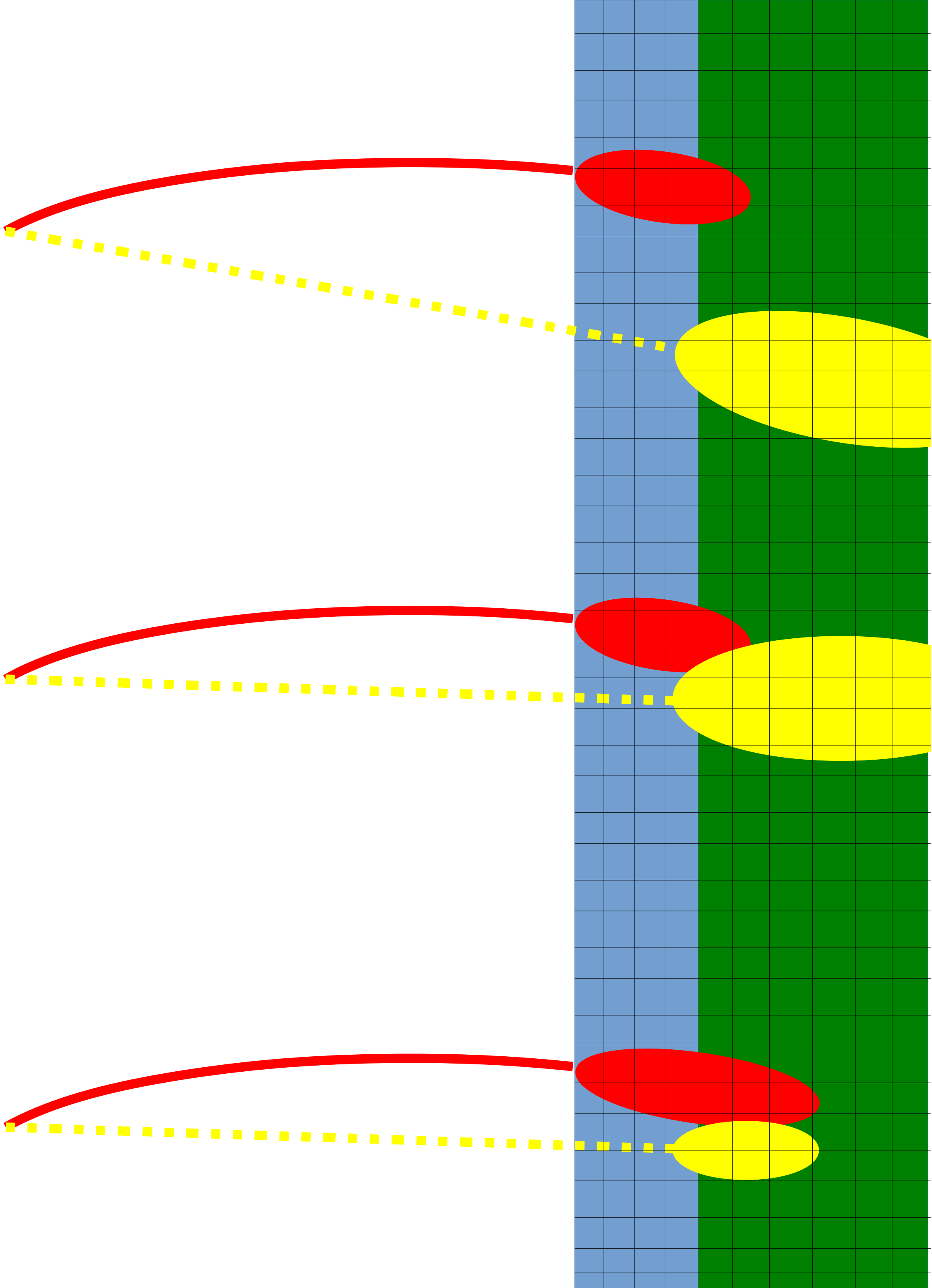
showers well separated:
use track momentum for charged part

showers overlap,
calorimeter deposit not consistent with track
→ use calorimeter

showers overlap,
calorimeter deposit ~ consistent with track
→ use calorimeter : underestimate energy

Particle Flow method

based on topological matching between track and calorimeter



If the granularity of the calorimeter is high enough, it becomes “easy” to distinguish nearby showers: we see the substructure of each shower

Then we can (almost) always see which energy is associated to a track, and which is due to neutrals

		Traditional	Particle Flow
charged hadrons	~65%	E+HCAL	Tracker
photons	~25%	ECAL	ECAL
neutral hadrons,	~10%	E+HCAL	E+HCAL

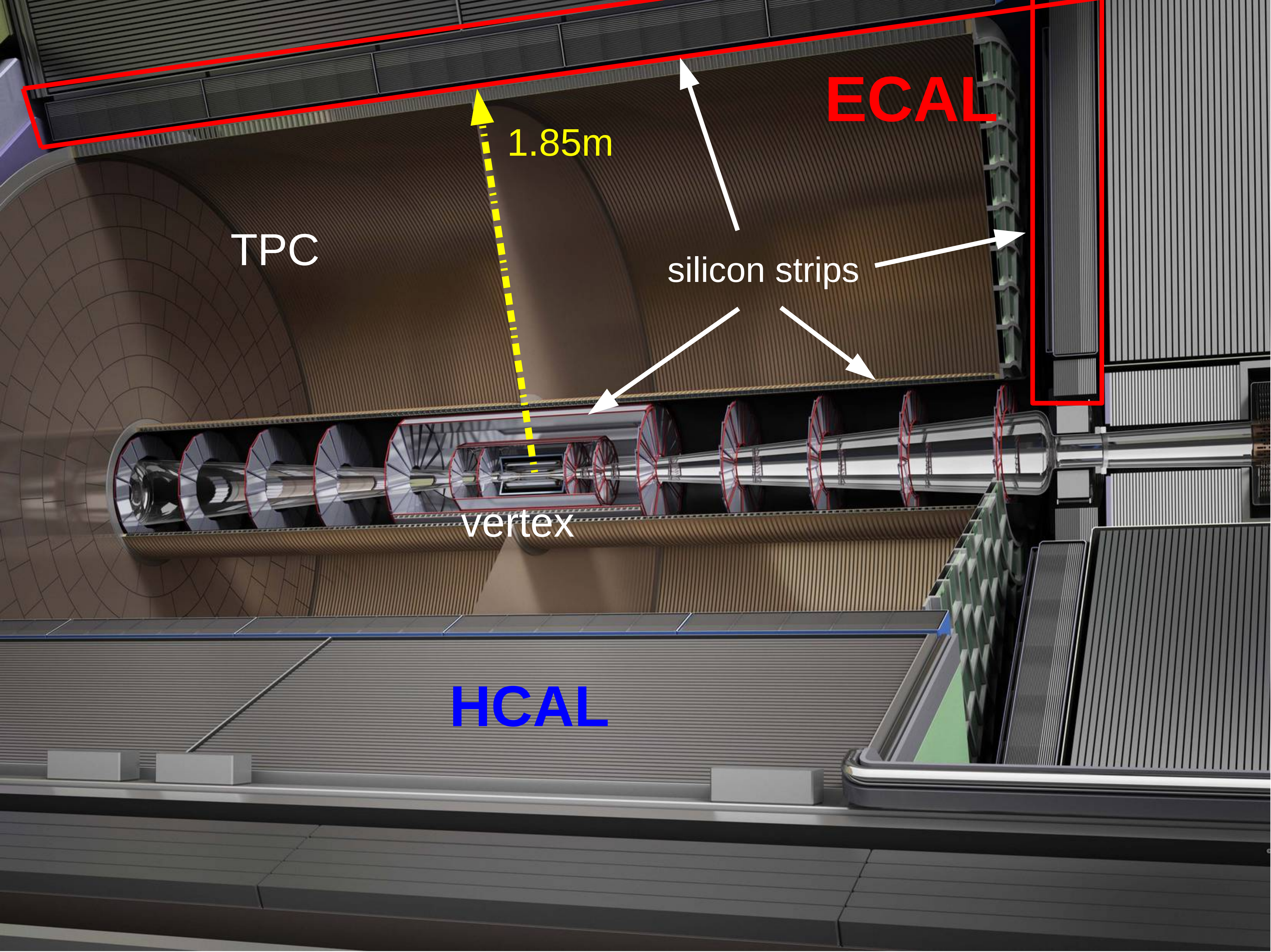
Traditional approach uses
- least precise detector to measure ~75% of energy

Particle Flow uses
- most precise detector to measure ~65%
- least precise detector to measure only ~10%

to optimally apply Particle Flow:

large IP-ECAL distance **high B field**	increase distance between particles in calorimeter
highly granular calorimetry	better topological separation of particles
minimise material before CALO (e.g. calorimeter within solenoid)	hadronic interactions before calorimeters can confuse PFA

this approach will give unprecedented Jet Energy Resolution
- $\delta E/E$ 3~4 % over a wide range of jet energies 45 ~ 250 GeV
  - most relevant for ILC physics


ECAL
1.85m
TPC
silicon strips
vertex
HCAL

Calorimeter technologies being considered for ILD

Layered sampling calorimeters natural choice:
 provides granularity in one direction

several options for active medium:

gas (HCAL)
 Resistive Plate Chambers, GEM, or Micromegas
  1x1cm^2 granularity, 1 or 2-bit readout

scintillator (ECAL and HCAL)
 scintillator strips or tiles, individually read out by SiPM
  5x45 mm^2 (ECAL) 30x30 mm^2 (HCAL)

silicon (ECAL)
 5x5 mm^2 PIN diode matrices ← I will discuss this
 50x50 μm^2 MAPS pixels, 1-bit readout

Overview of silicon-tungsten ECAL

- longitudinally segmented layer structure

Tungsten to induce photons and electrons to shower

- small radiation length
  - *compact ECAL*
- small Molière radius
  - *small showers*
  - *reduce overlap of nearby showers*
- relatively large nuclear interaction length
  - *hadronic showers tend to develop deeper*

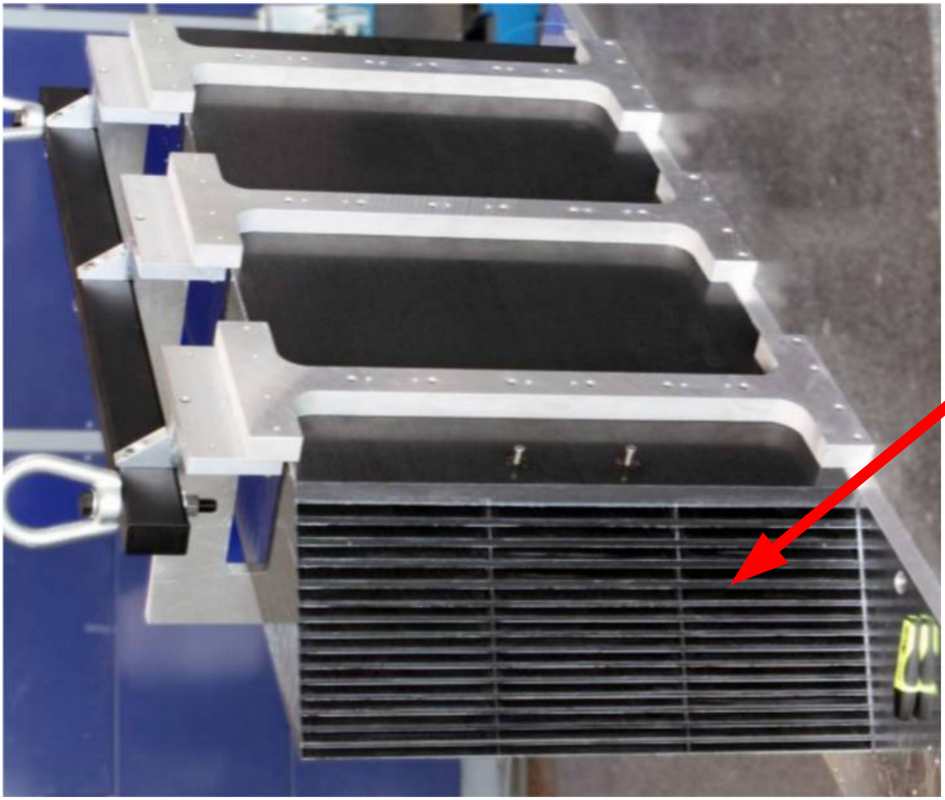
Silicon PIN diodes to measure the shower

- easily segmented readout
  - *to achieve required granularity*
- compact
  - *avoid degradation of ECAL density*
- stable response
  - *reliable and simple operation*

France
LAL
LLR
LPC
LPNHE
LPSC
Omega

Japan
Kyushu U.
Tokyo U.

UK
(pre 2007)
Cambridge
Imperial
UCL

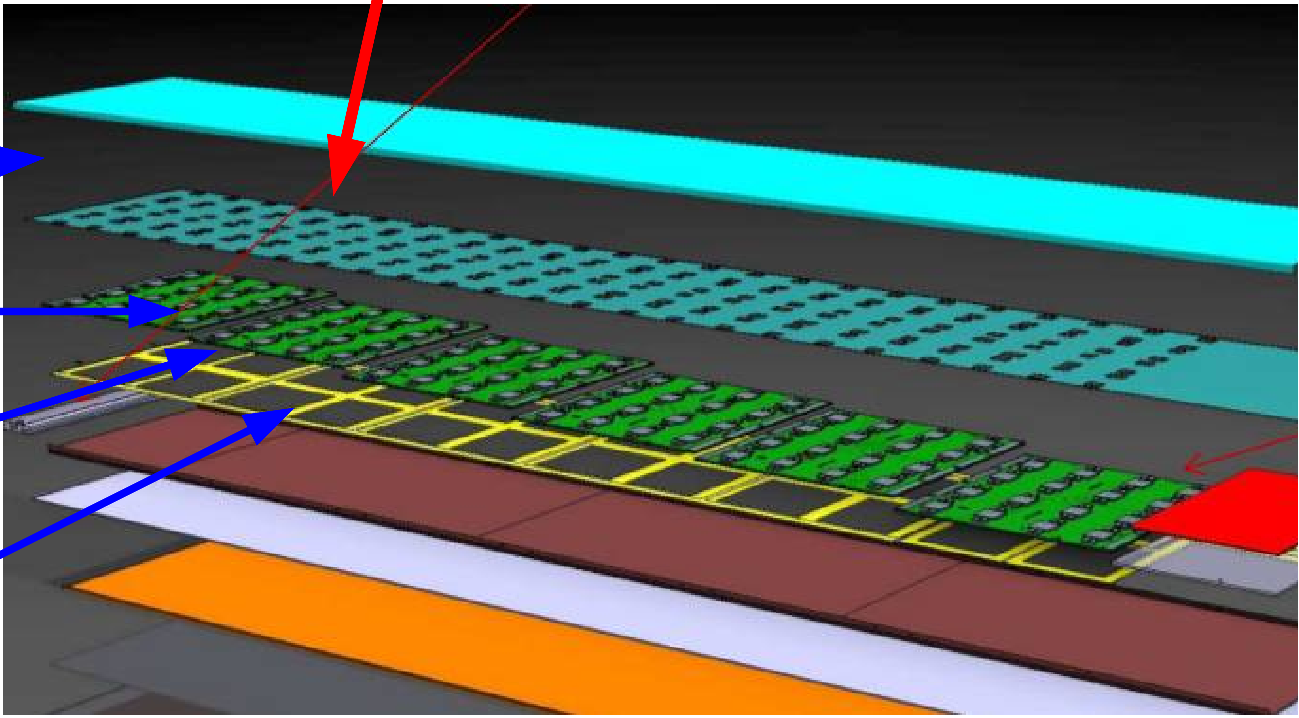


ECAL structure

Carbon fibre / tungsten
mechanical housing

into which are inserted

20-30 layers of
sensitive detector elements

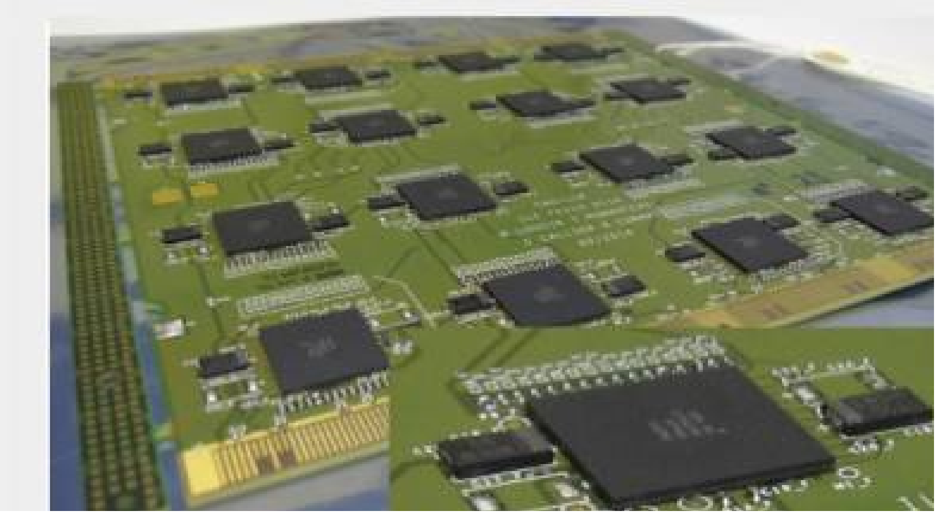


Shielding

Front-end boards &
readout electronics

Silicon sensors
~5X5 mm^2 segmentation

High voltage supply

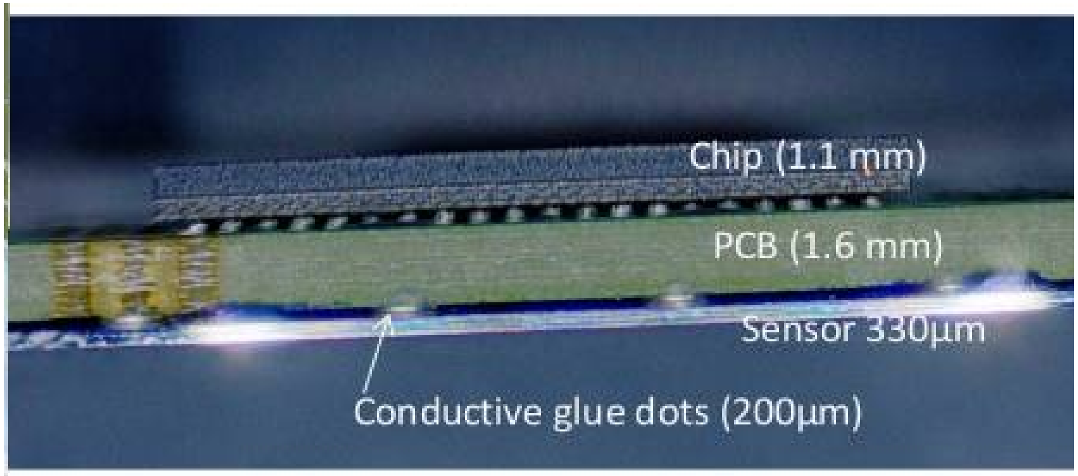


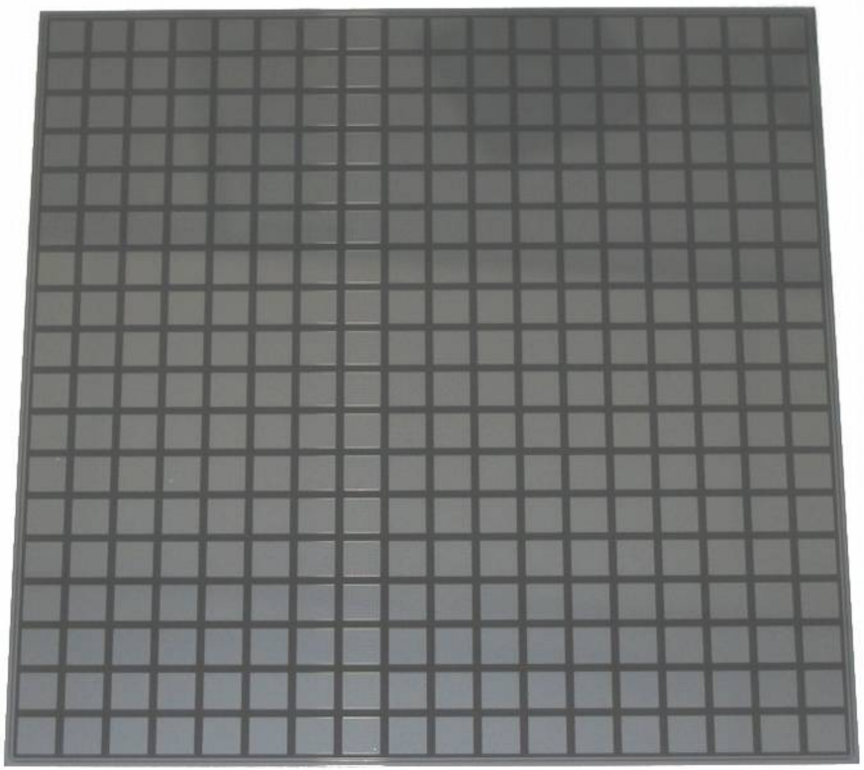
Si-ECAL detector element: "Active Sensor Unit"

18x18 cm^2 9-layer PCB

- 16 SKIROC2 ASICs (64 channels each) (BGA package)

- four 9x9 cm^2 sensors, each segmented into 256 PIN diodes glued to PCB





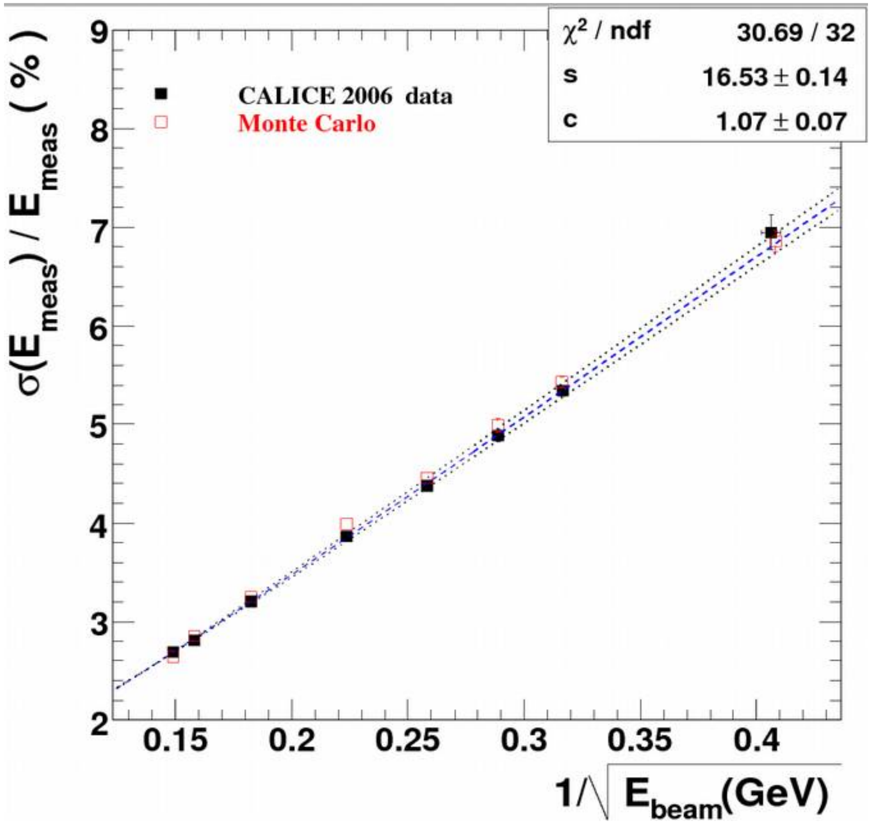
active area of ECAL (~2500 m^2) is an array of ~60k such units

requires highly automated assembly and testing procedures

~30 longitudinal samplings in a total thickness of ~24 X^0

→ energy resolution $\sigma_E/E \sim 17\%/\sqrt{E}$
→ effective Moliere radius ~20 mm

reliable, stable operation
and
accurate description of performance by simulation
demonstrated in detector prototypes



reconstruction techniques using an ILC detector

photons, π^0, τ

The highly granular ECAL provides a wealth of information for reconstruction

each photon fires 10s → 100s of detector cells
    distribution of hits in space and energy
high density core of shower

complication:
    hadrons also contain EM sub-showers (from π^0)

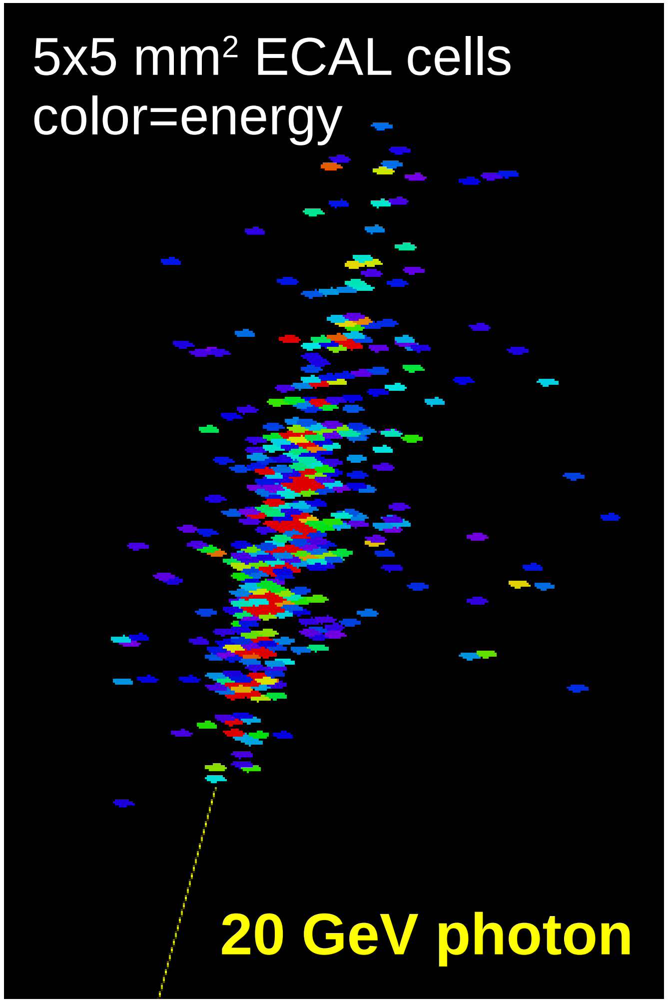
“Gamma Reconstruction at a LInear Collider” (GARLIC)

specialised clustering for electromagnetic showers

- make use of characteristic shape:
  - narrow core containing most of energy
  - surrounded by looser, lower energy halo

- use multivariate techniques to make final selection between clusters from primary photons and hadrons

Jeans et al, JINST_008P_031



5x5 mm^2 ECAL cells
color=energy

20 GeV photon

GARLIC performance in hadronic jets

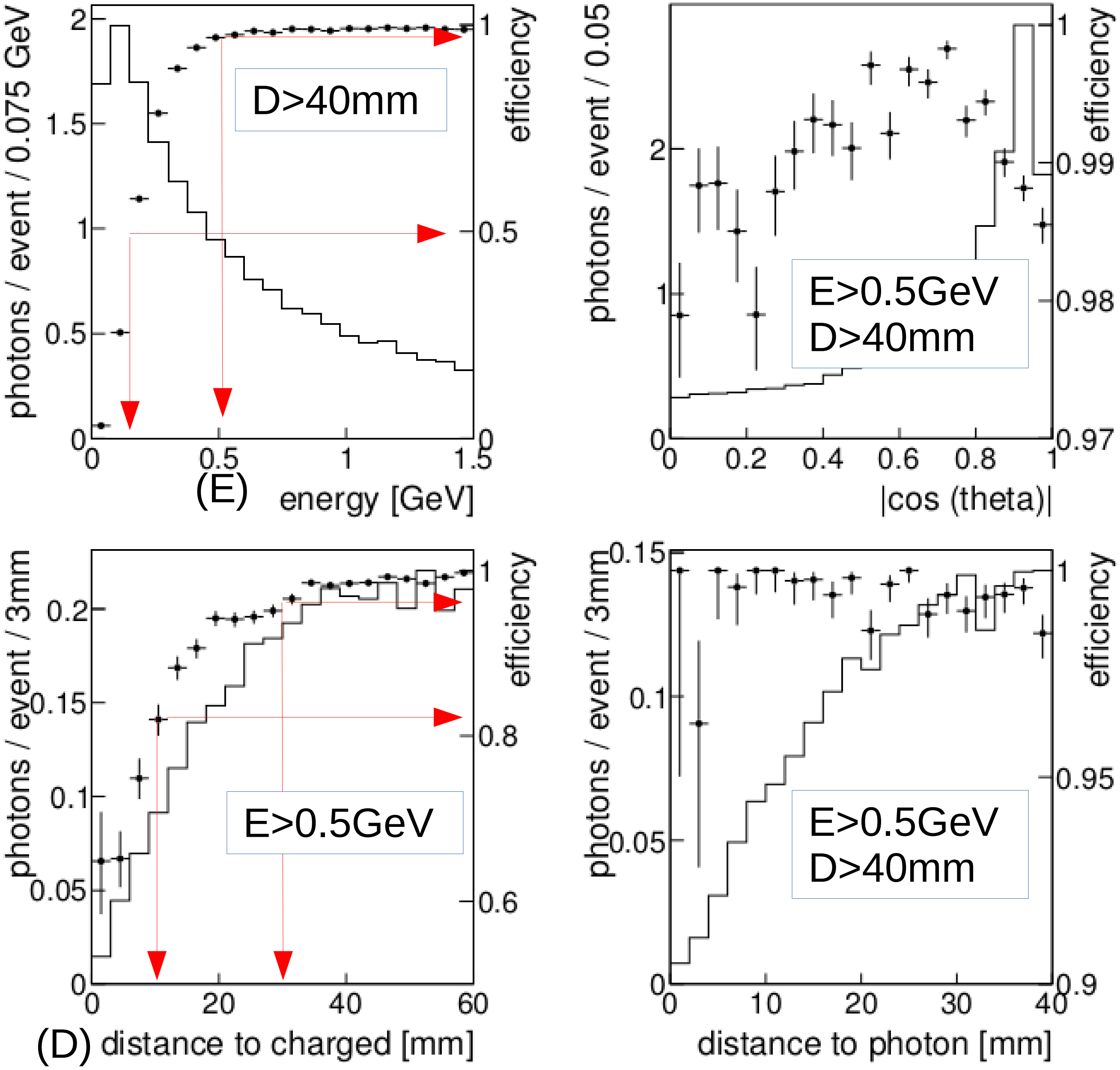
Solid histogram:
distribution of photons in jets

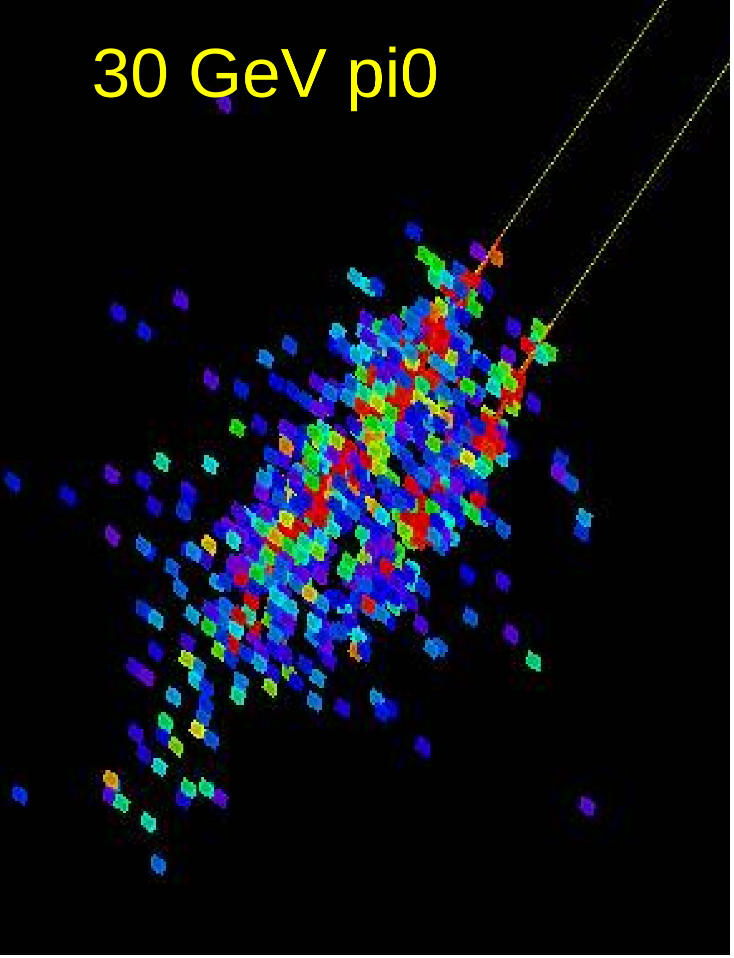
Points:
efficiency to correctly collect photon energy

depends on

- photon energy E
  OK above 0.5 GeV

- distance D from photon to nearest charged particle at the ECAL
  OK above 20~30mm





The high granularity also allows good π^0 reconstruction

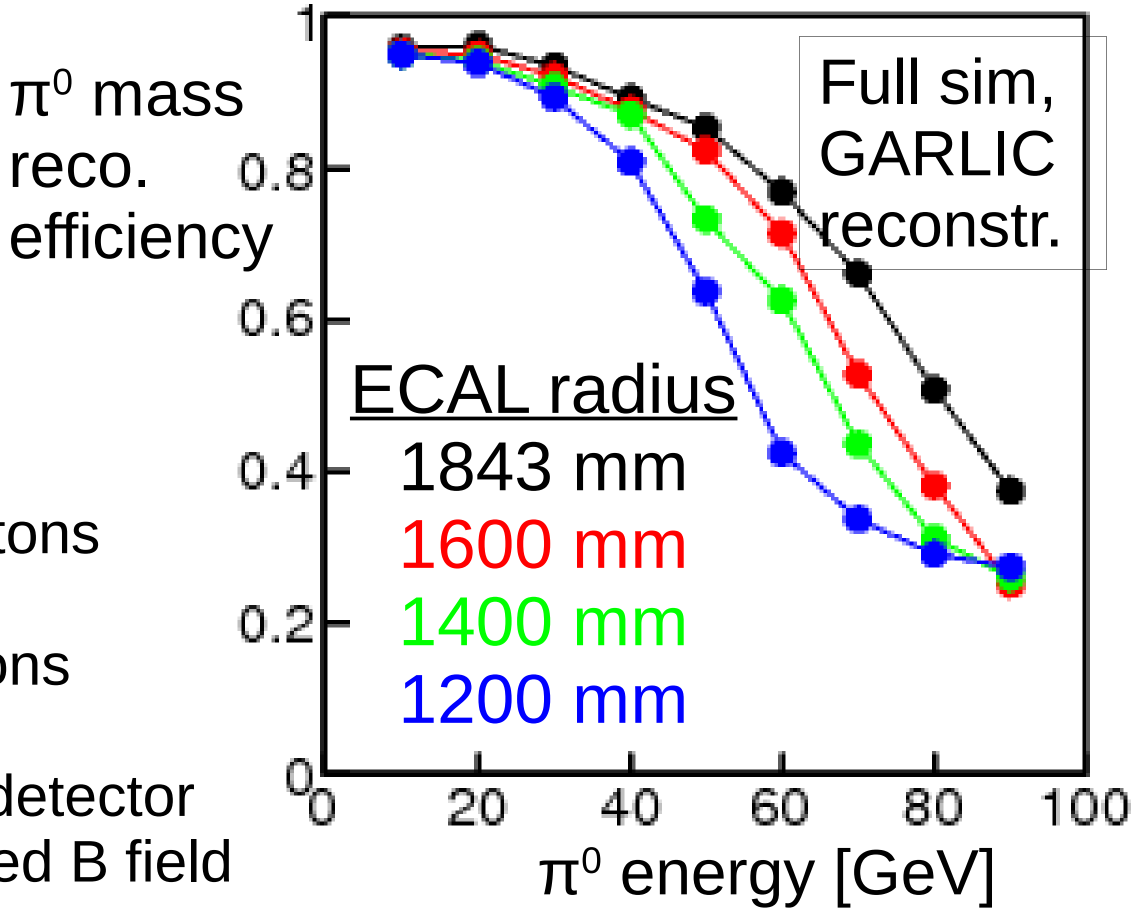
useful in

- identifying τ decay modes
- improving jet energy resolution by kinematic fitting of π^0 candidates

reconstruction efficiency strongly affected by

- π^0 energy
  - → angular opening of photons
- detector size
  - → distance between photons

maybe only argument for a large detector which cannot be offset by increased B field



advertisement (unpaid)

for MAPS-based ECAL technology (as proposed by Nigel)

~50x50 μm^2 pixels, digital readout

I think that an ECAL with especially the earlier layers with fine pixel readout could:

- significantly improve reconstruction and resolution for low energy photons
    - better clustering with more hits
    - digital readout suppresses Landau fluctuations
        - (even with large pixels, hit counting is advantageous @ low energy)

- significantly help π^0 identification at high energy

recent studies on tau reconstruction

Jeans, arXiv:1507.01700 [hep-ex]

Tau leptons play an interesting role in study of Higgs
- dominant leptonic decay mode
- unstable
  - distribution of decay products depends on spin
    - → by reconstructing tau decay, can reconstruct it's spin state

- correlation between the spins of tau from Higgs decays
  - depends on CP nature of Higgs

- fully reconstructed taus provide most complete information

hadronic tau decays (~65% of total) have one neutrino in the final state
- leptonic decays have two → maybe impossible to reconstruct fully

~11%	$\tau^+ \to \pi^+ \nu$	simplest case
~25%	$\tau^+ \to \pi^+ \pi^0 \nu$	largest branching fraction
~35%	$\tau^+ \to (e/\mu)^+ \nu \nu$	two missing neutrinos ← limited information

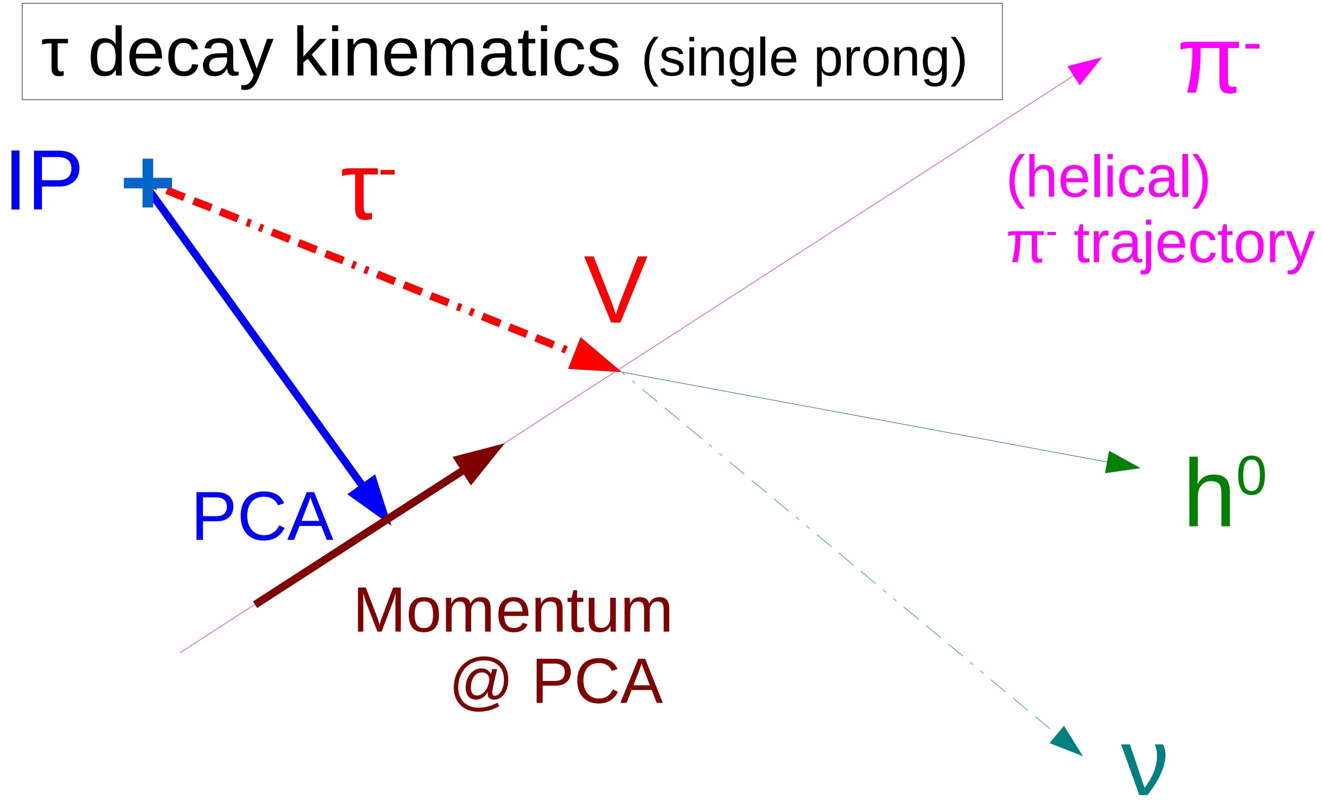
taus often produced in pairs (e.g. from Higgs, Z, y*)

Traditional tau reconstruction (hadronic decays):
- assume rest frame of tau pair, and its invariant mass
- constrain the invariant mass of each tau
  - these inputs allow neutrino momenta to be calculated

Such an approach is degraded by Initial State Radiation (ISR),
which, if undetected, invalidates assumptions

It turns out that **vertex detector** can provide sufficient extra information to make assumptions unnecessary

τ decay kinematics (single prong)



tau momentum direction must intersect with π- trajectory

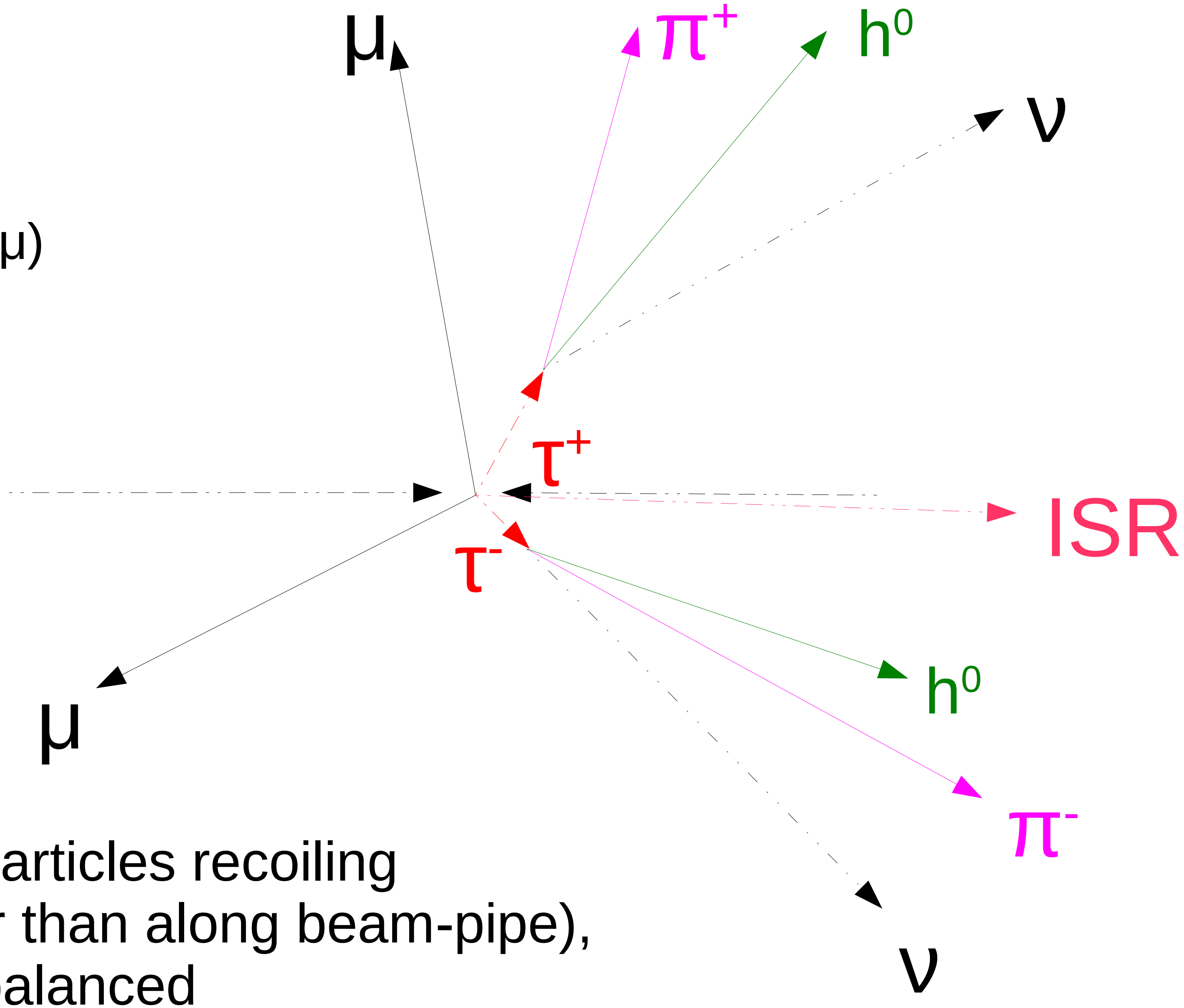
tau mass constraint then allows neutrino momentum to be reduced to a single parameter

required information:
- precise π- trajectory
- precise IP

consider whole event

e.g. $e^+ e^- \rightarrow (H \rightarrow \tau\,\tau)\,(Z \rightarrow \mu\,\mu)$

muons and beam line
used to define the IP

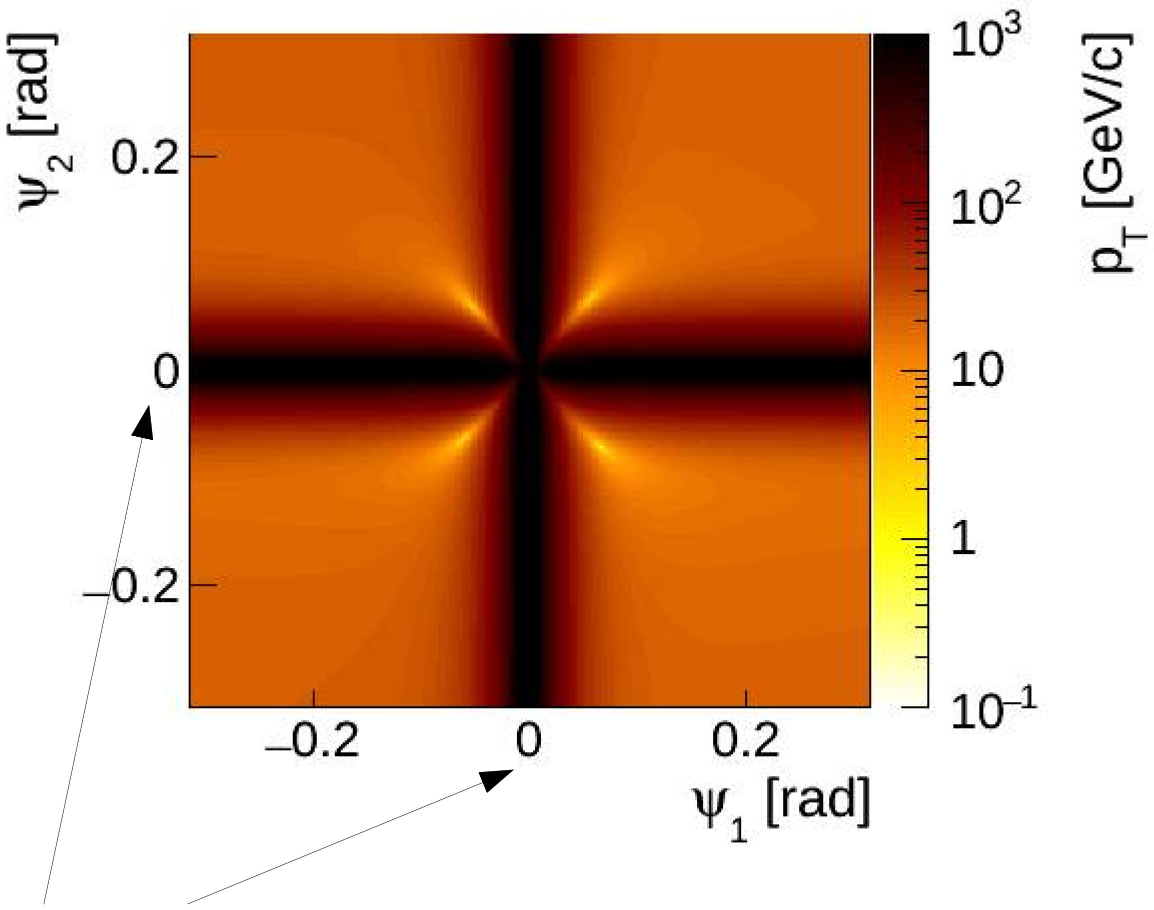


If there are no invisible particles recoiling
against τ-τ system (other than along beam-pipe),
p_T of event must be balanced

because of ISR/beamstrahlung, can't make requirements on pz

This additional constraint gives us sufficient information
to solve for the neutrino momenta
without any assumptions about tau pair rest frame or mass

Neutrino momentum reduced to function of 1 parameter ψ
How does event p_T depend on ψ chosen for two taus?



neutrino co-linear
with hadrons in
track plane

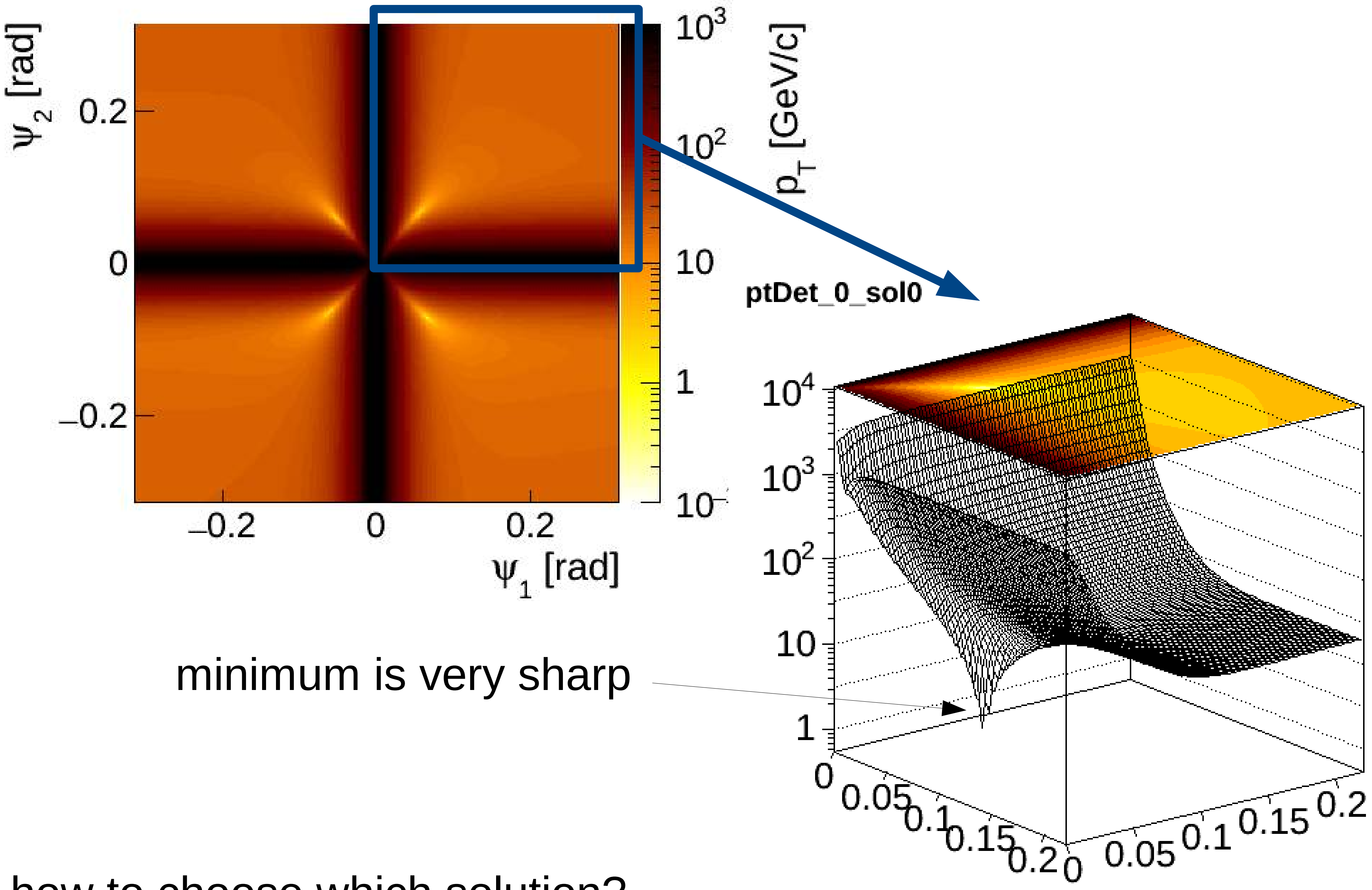
one event @ 250 GeV
$e^+e^- \rightarrow (H \rightarrow \tau\tau)\ (Z \rightarrow \mu\mu)$

both $\tau \rightarrow \pi\, \nu$

simulated and
reconstructed in ILD
detector

Four possible solutions with small p_T
easy to find minima using e.g. MINUIT

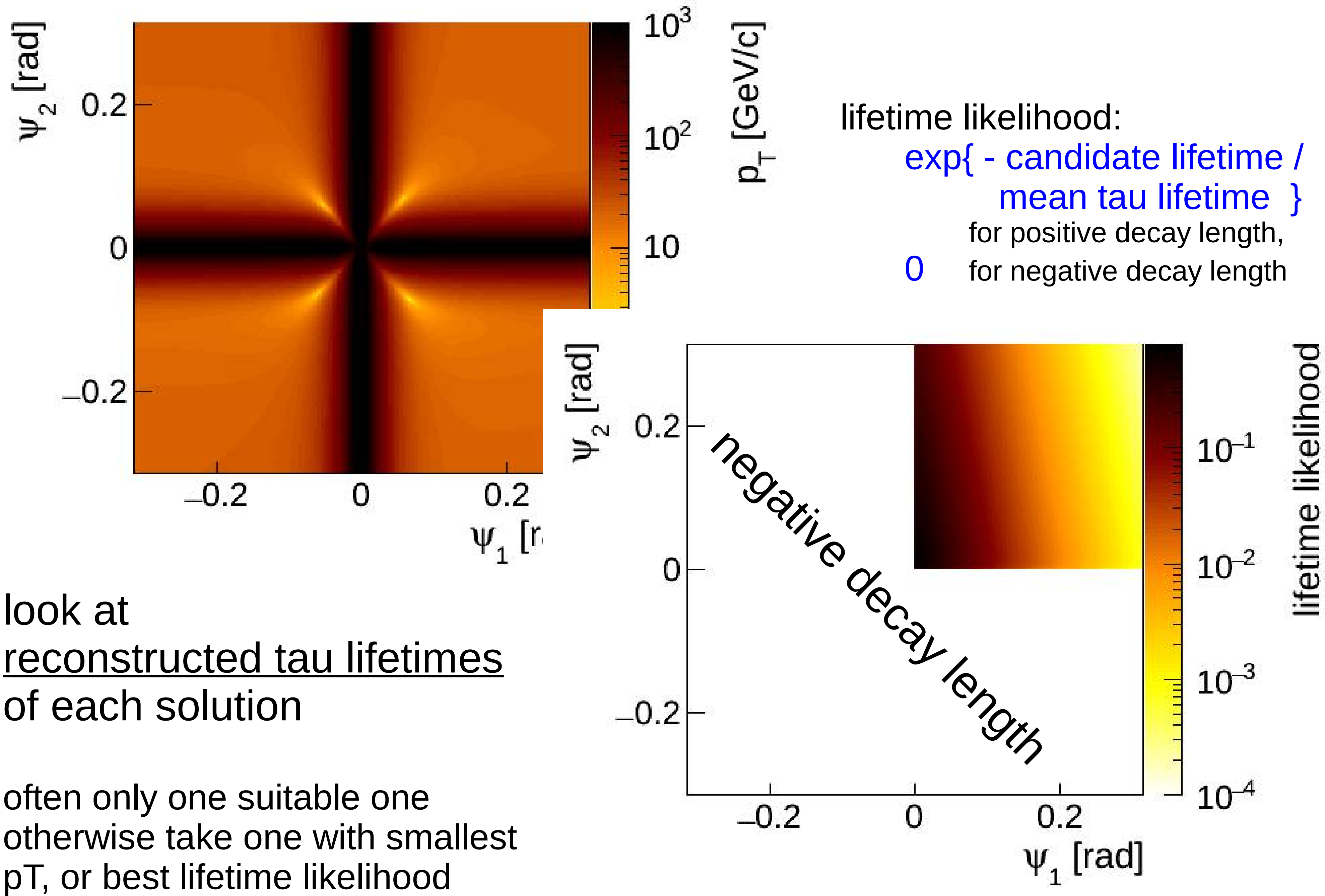
How does event p_T depend on ψ chosen for two taus?



minimum is very sharp

how to choose which solution?

How does event p_T depend on ψ chosen for two taus?



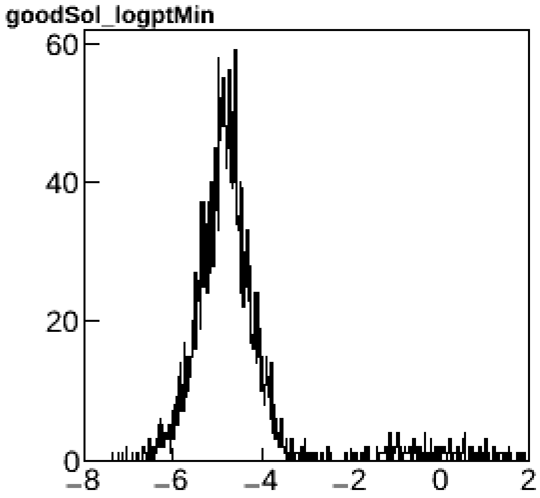
lifetime likelihood:
exp{ - candidate lifetime / mean tau lifetime } for positive decay length,
0 for negative decay length

look at
<u>reconstructed tau lifetimes</u>
of each solution

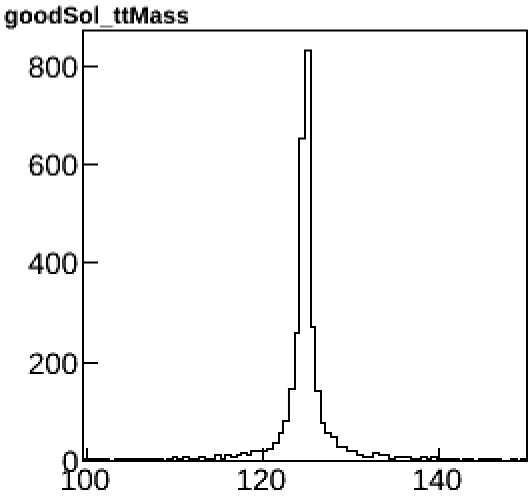
often only one suitable one
otherwise take one with smallest
pT, or best lifetime likelihood

Full simulation results

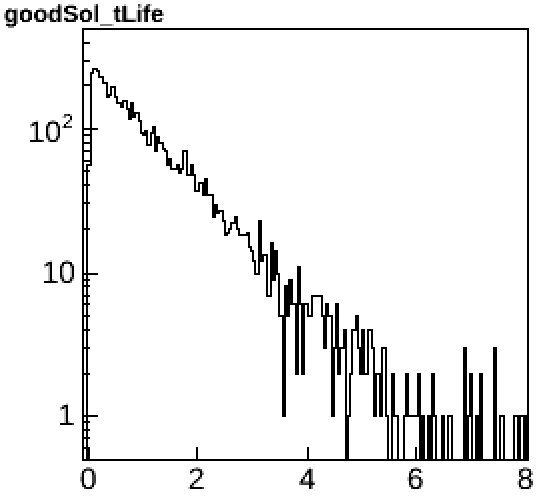
both τ → π ν



log10(pT) at best solution [GeV]



tau-tau mass [GeV]



reconstructed lifetime/ 87 um/c

Method works very well (on hadronic tau decays)

- in this example, get a rather sharp Higgs peak

method requires:

- good knowledge of IP:
  - tau produced with other charged particles
  - small interaction region helps
- excellent impact parameter resolution
- no extra neutrinos in event

no other assumptions on properties of tau-tau system, or on ISR

presently I'm working on applying this to measurement of Higgs CP
is H a CP eigenstate? mixture of even and odd states?

Summary

The ILC is a powerful tool to address some of the big questions before us

- precision measurements of Higgs and Top
  - direct or indirect signals of new physics
    - surprises

The detectors being designed for ILC will provide incredibly detailed information

- which can be used in wonderful ways

Efforts in Japan towards hosting the ILC

...a personal perspective

Efforts in Japan towards hosting the ILC

Hosting a large, truly **international institution** is a powerful motivation to many sectors in Japan

impressively multi-prong approach; to name a few:

- MEXT (government ministry)
  - commission reviews, initiate discussions with foreign governments

- Federation of Diet Members (i.e. MPs) for ILC (est. 2008)
  - cross-party support from >150 members
    - including several ex-ministers
  - regularly visit esp. Washington to lobby congress members

- AAA – Advanced Accelerator Association (est. 2008)
  - Industry (~100 companies represented)
  - Academia (~40 universities, insititutes)

- Local governments in Tohoku region (proposed ILC site)
  - developing ideas for campus, housing
  - planning for influx of foreigners (hospitals, schools...)

- Public understanding
  - traditional media, youtube, science cafés

Timeline of ILC

1980's
Project Start

Design &
Manufacturing Processes

2004

Technology choice

OECD Ministerial Statement

Discussions w/ Funding Agencies

Site-related studies
by scientists/civil engineers

2007

Baseline Design

First Cost Estimate

2008

Begin cooperation
Government/Industry/Academica

Site studies by
local groups

Global Design

International R&D

XFEL Experience

Cost/Design Optimization

Geological studies

CERN/LHC
Higgs Discovery

Technical
Design Report

Science Council
of Japan Report

Domestic Site
Evaluation

2013

2014

Today

Government budget for project evaluation
Project reviews by MEXT start

Site-specific design
International collaboration
Setting regulations
Engineering design
Preparing construction

Government reviews
Talks between governments

Greenlight /
International Agreement

Site-specific design
Environmental assessment

Establish International Laboratory

Construction (~9 yrs)

Operation (~20 yrs)

2012:

- <u>Japan Association of High Energy Physicists</u> JAHEP proposes to host
  ILC in Japan if light Higgs discovered [4 July: condition satisfied]
- ILC Technical Design Report published

2013:

- <u>Ministry of Education, Culture, Sport, Science, Technology</u> (MEXT) asks Science Council of Japan (SCJ) to report on ILC
  SCJ suggests further study by government on:
    physics case, funding, domestic organisation, human resources
- Candidate site selected (Kitakami region in northern part of Japan)
- <u>European strategy for Particle Physics</u>
  “ILC....Europe looks forward to a proposal from Japan.”
- <u>AsiaHEP/ACFA</u>
  “welcomes proposal...for ILC to hosted in Japan”

2014

- MEXT sets up internal ILC task force
  recruits external expert review committee: report expected ~March 2016
  commissions report on ripple effects (Nomura Research Inst.)
- <u>ICFA</u>
  “pleased to note the great progress...linear collider built in Japan”
- <u>P5 report (US)</u>
  “interest expressed in Japan in hosting the ILC is an exciting development”

2015
- MEXT review committee continues work: regular requests to ILC
- Asian Linear Collider Workshop (@KEK)
  - ILC Tokyo event: symposium and “Food Festa”
    - politicians, embassies, industry, physicists

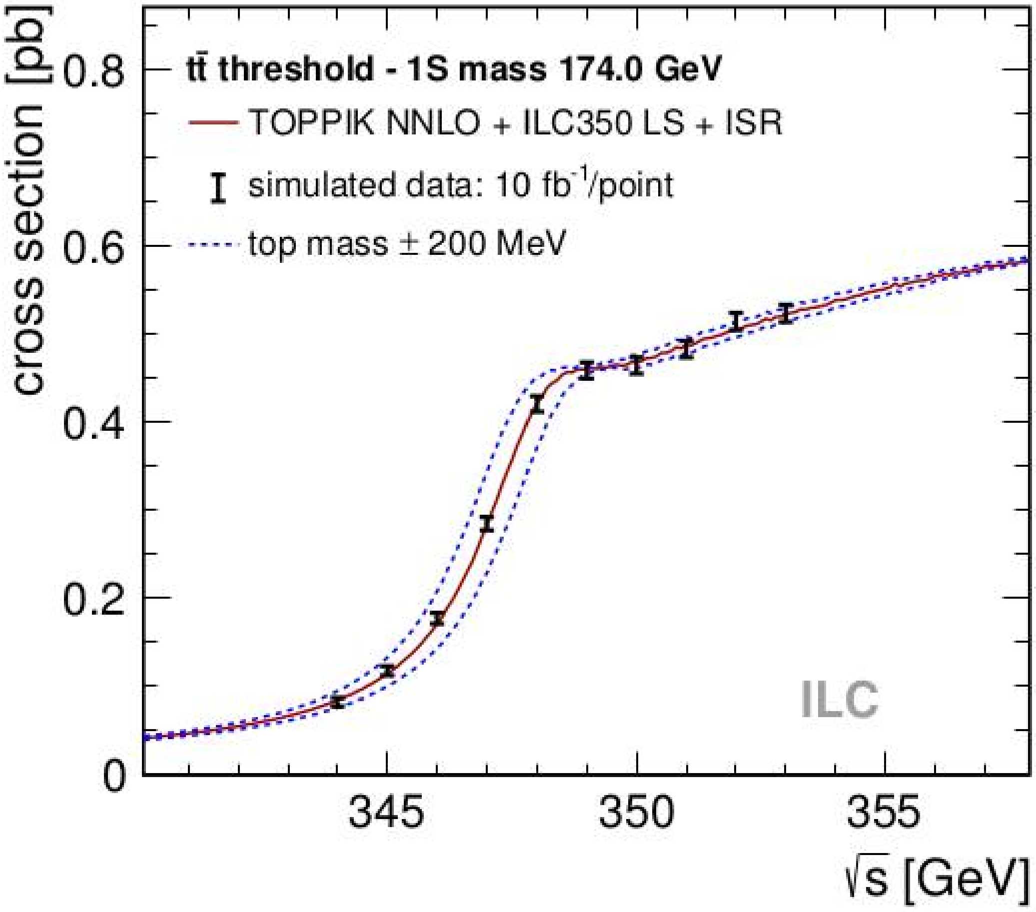
My impression is that key point for ILC approval is its **international** nature

The Japanese government needs to feel and see <u>your</u> enthusiasm for the project

#mylinearcollider ← upload a short video message, now >500 and counting

and also <u>your government</u>'s interest

BACKUP slides

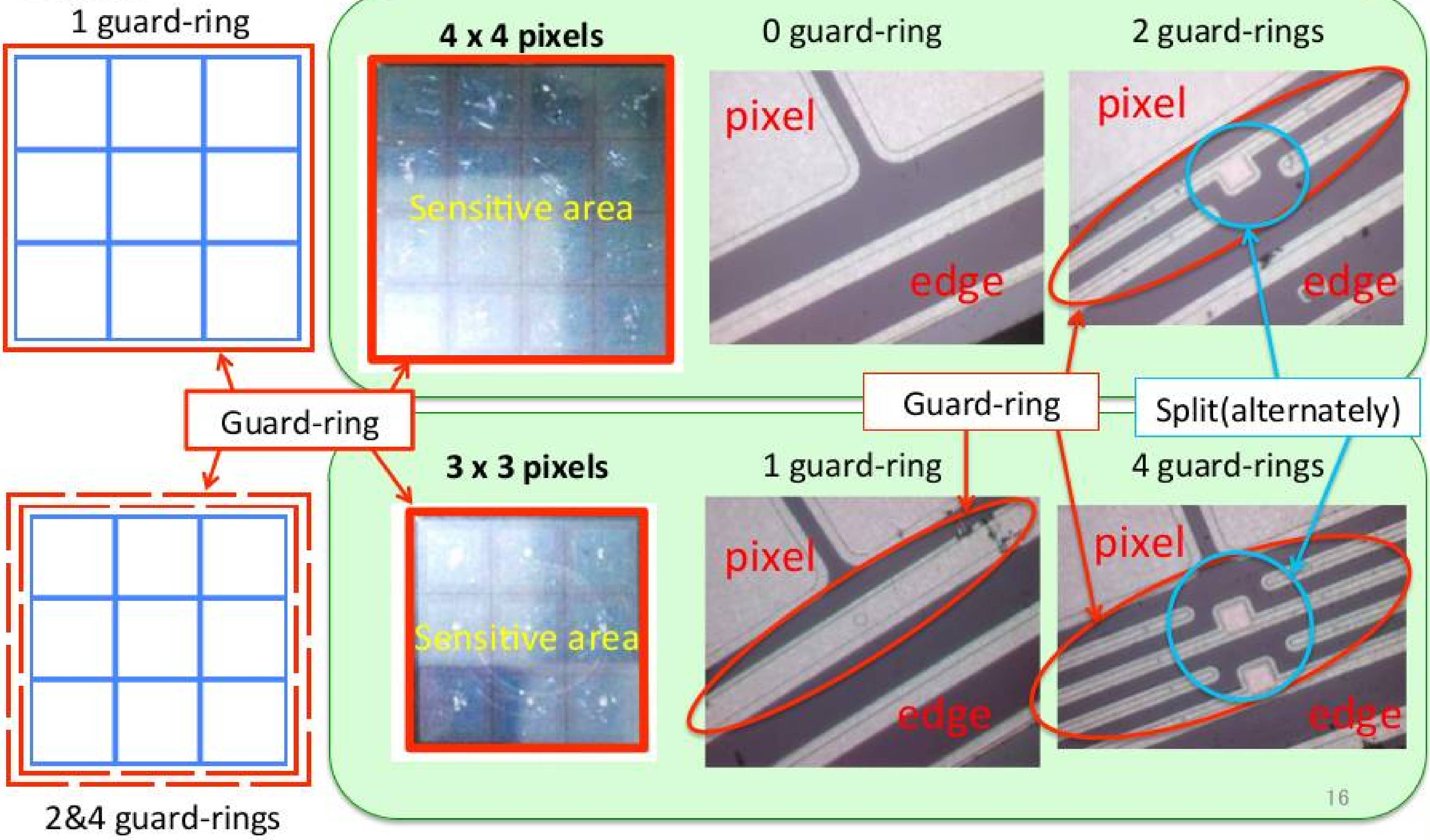

$t\bar{t}$ threshold - 1S mass 174.0 GeV
TOPPIK NNLO + ILC350 LS + ISR
simulated data: 10 fb^{-1}/point
top mass ± 200 MeV
ILC
cross section [pb]
0
0.2
0.4
0.6
0.8
345
350
355
$\sqrt{s}$ [GeV]

Baby chip(to compare guard rings)

These chips are made to compare the effect of different guard ring structures.

Pixel size : 5.5 mm x 5.5 mm Thickness: 320μm

Outline



1 guard-ring

4 x 4 pixels

0 guard-ring

2 guard-rings

Guard-ring

Guard-ring

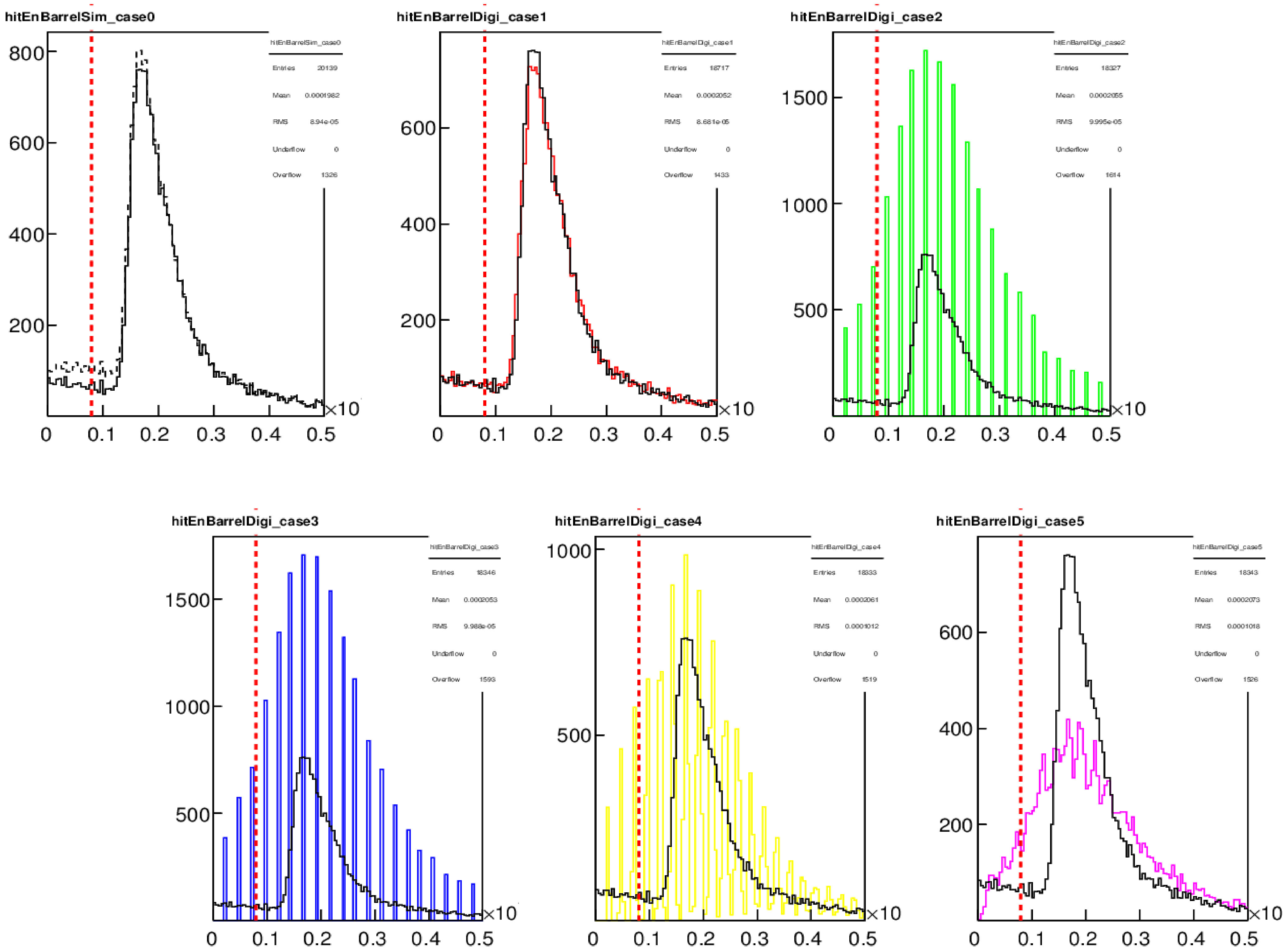
Split(alternately)

3 x 3 pixels

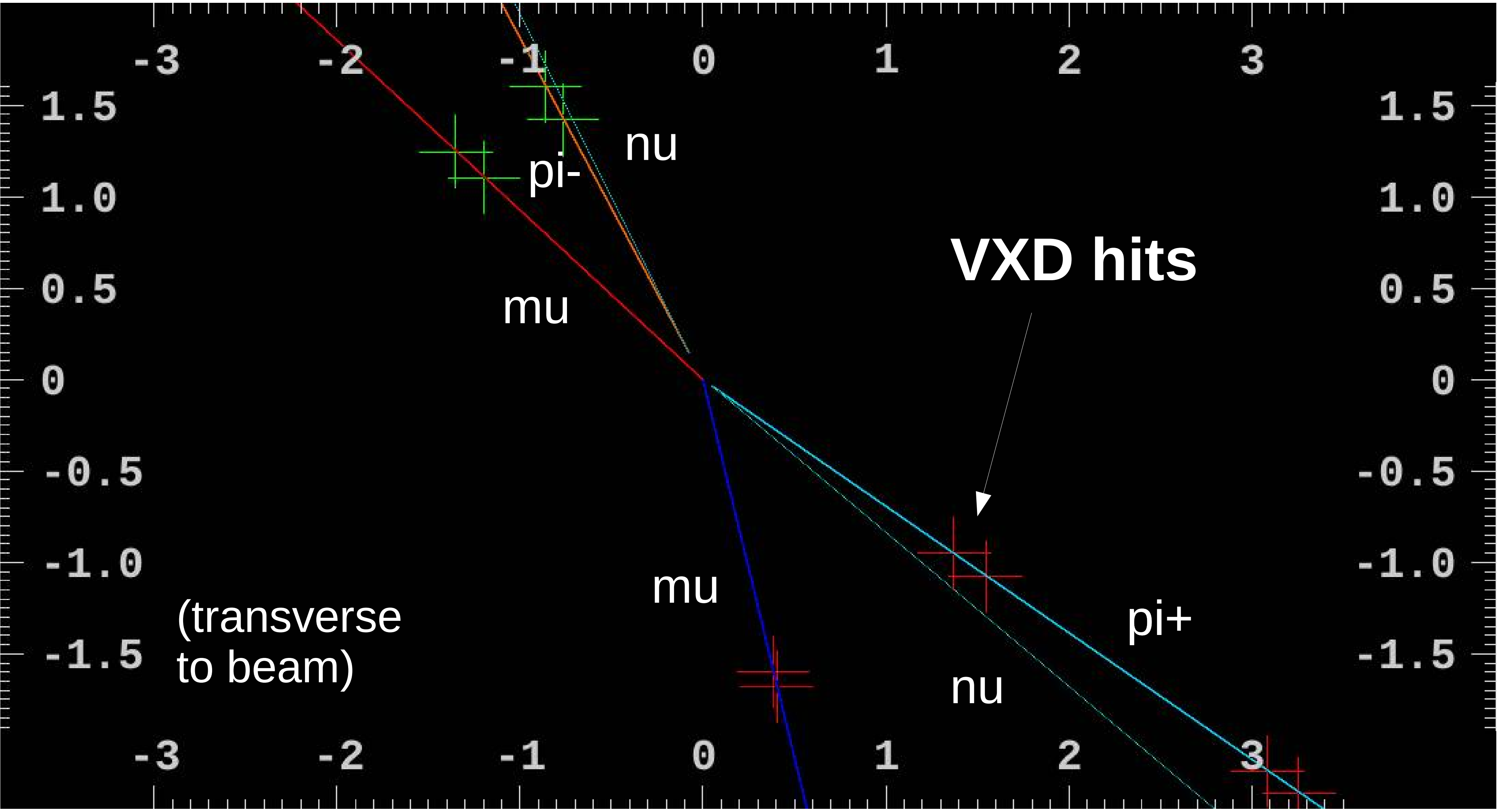
1 guard-ring

4 guard-rings

2&4 guard-rings

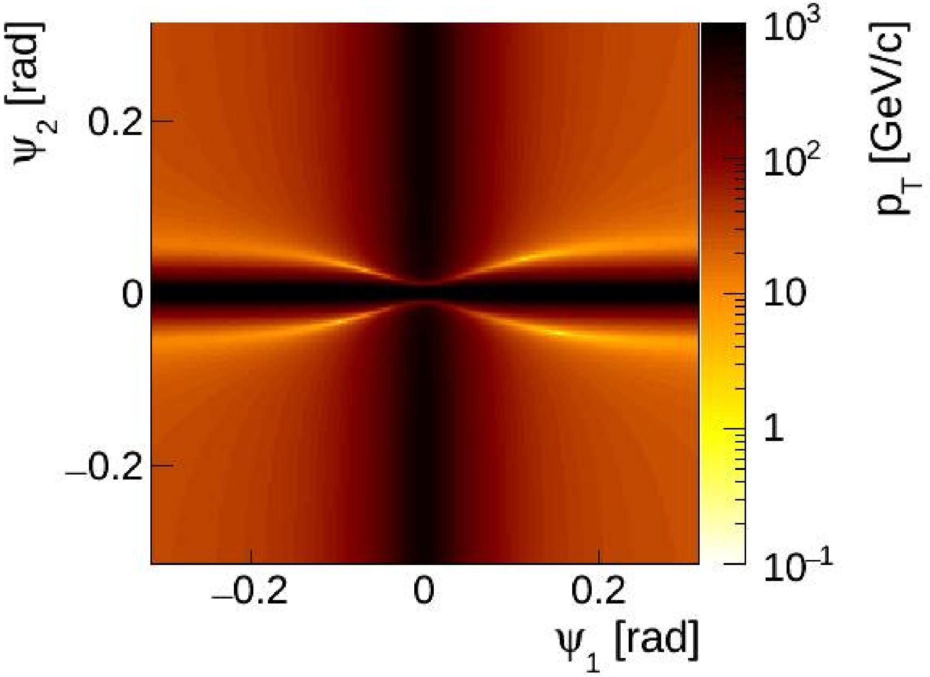

hitEnBarrelSim_case0
hitEnBarrelSim_case0
Entries 20139
Mean 0.0001982
RMS 8.94e-05
Underflow 0
Overflow 1326
800
600
400
200
0
0.1
0.2
0.3
0.4
0.5
×10
hitEnBarrelDigi_case1
hitEnBarrelDigi_case1
Entries 18717
Mean 0.0002052
RMS 8.681e-05
Underflow 0
Overflow 1433
600
400
200
0
0.1
0.2
0.3
0.4
0.5
×10
hitEnBarrelDigi_case2
hitEnBarrelDigi_case2
Entries 18327
Mean 0.0002055
RMS 9.995e-05
Underflow 0
Overflow 1614
1500
1000
500
0
0.1
0.2
0.3
0.4
0.5
×10
hitEnBarrelDigi_case3
hitEnBarrelDigi_case3
Entries 18346
Mean 0.0002053
RMS 9.988e-05
Underflow 0
Overflow 1593
1500
1000
500
0
0.1
0.2
0.3
0.4
0.5
×10
hitEnBarrelDigi_case4
hitEnBarrelDigi_case4
Entries 18333
Mean 0.0002061
RMS 0.0001012
Underflow 0
Overflow 1519
1000
500
0
0.1
0.2
0.3
0.4
0.5
×10
hitEnBarrelDigi_case5
hitEnBarrelDigi_case5
Entries 18343
Mean 0.0002073
RMS 0.0001018
Underflow 0
Overflow 1526
600
400
200
0
0.1
0.2
0.3
0.4
0.5
×10

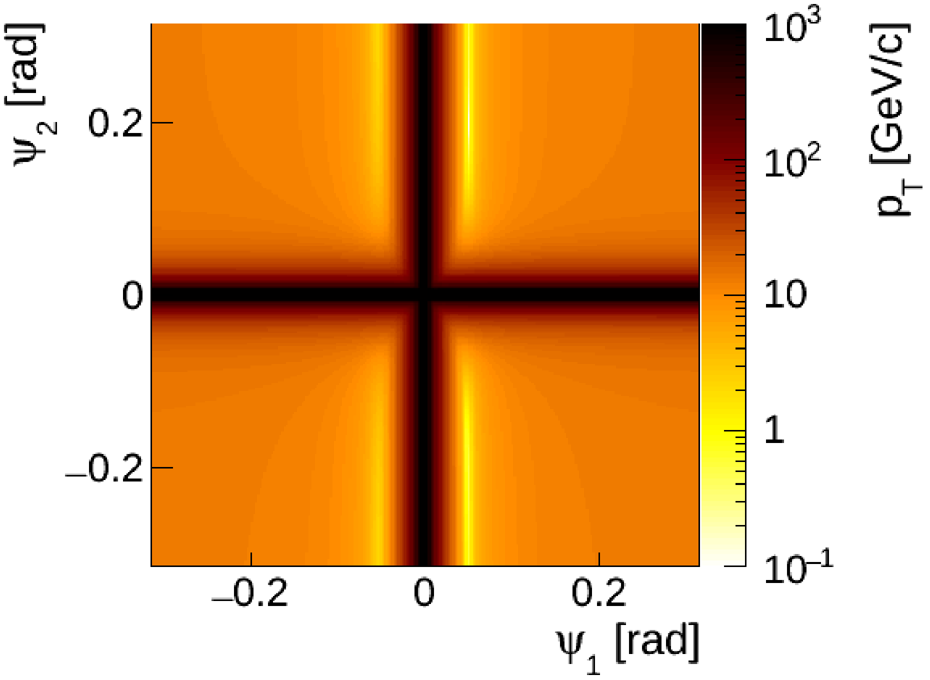
$e^+ e^- \to (H \to \tau \tau) (Z \to \mu \mu)$ event @ 250 GeV



VXD hits

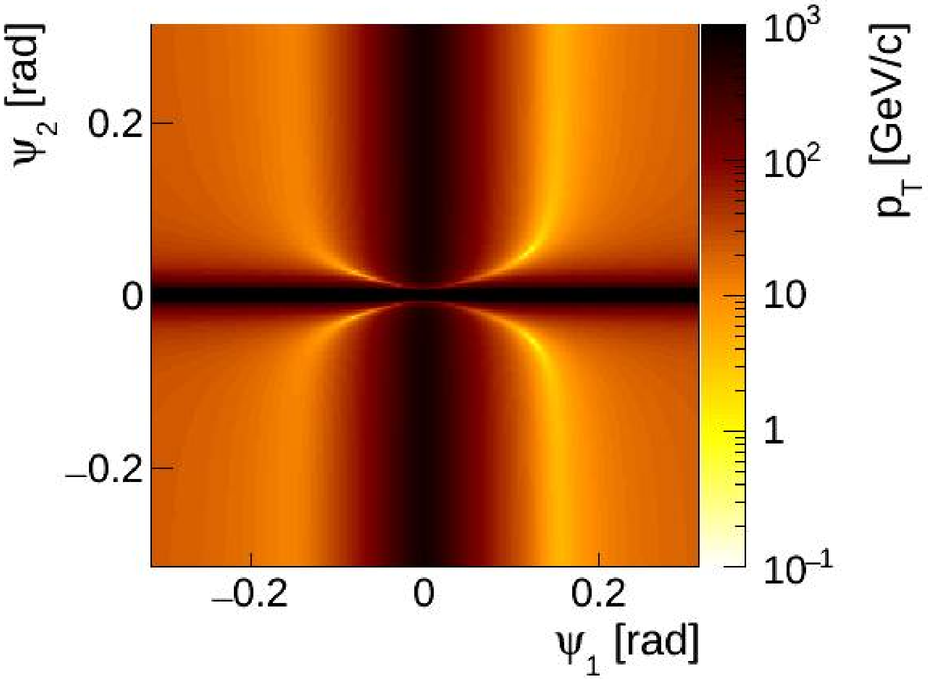
(transverse to beam)

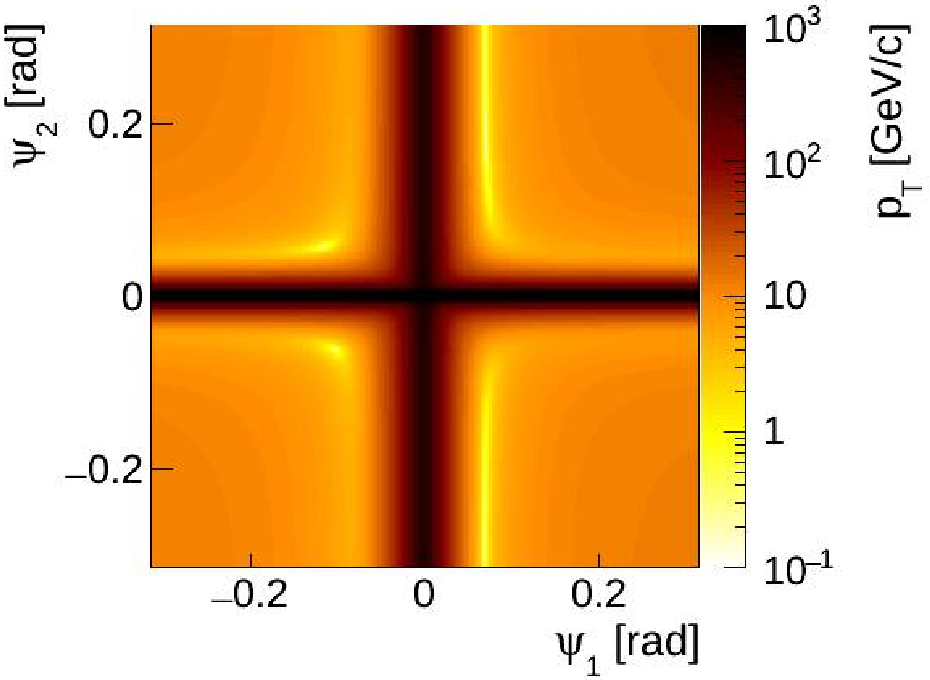




a few more events

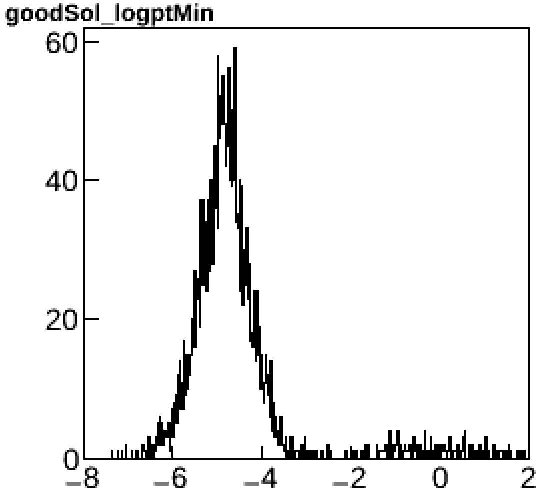
both τ → π ν



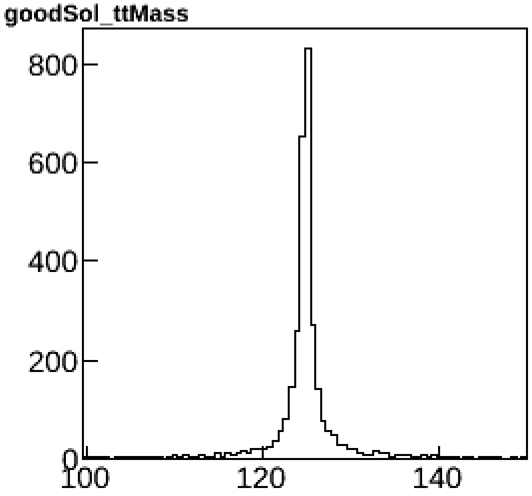


Full reconstruction

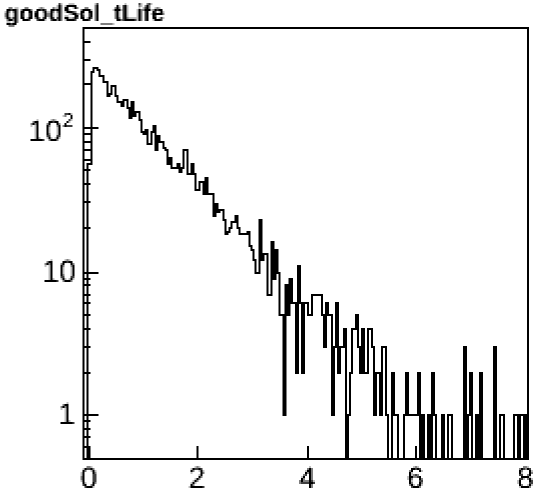
both τ → π ν



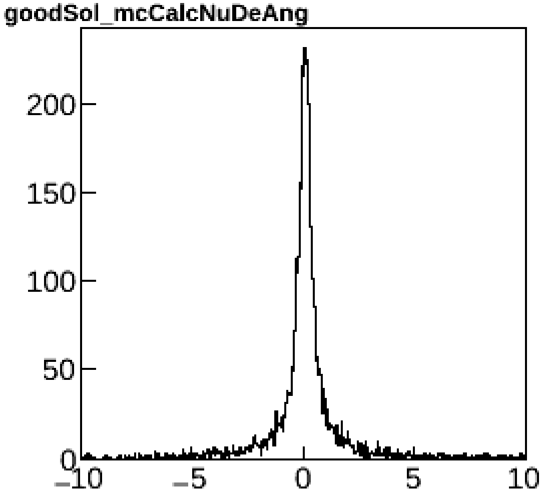
log10(pT) at best solution [GeV]



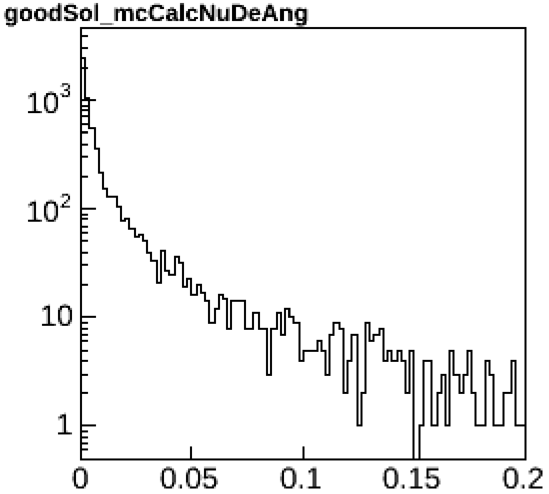
tau-tau mass [GeV]



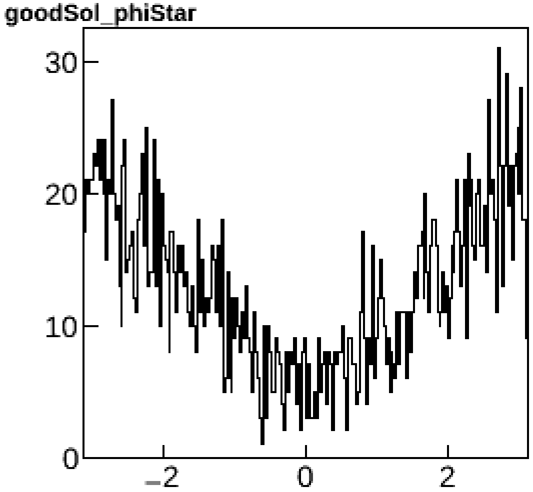
reconstructed lifetime/ 87 um/c



difference between true and reco neutrino energy [GeV]



angle between true and reco neutrino [rad]



angle used to measure Higgs CP

both τ → π ν

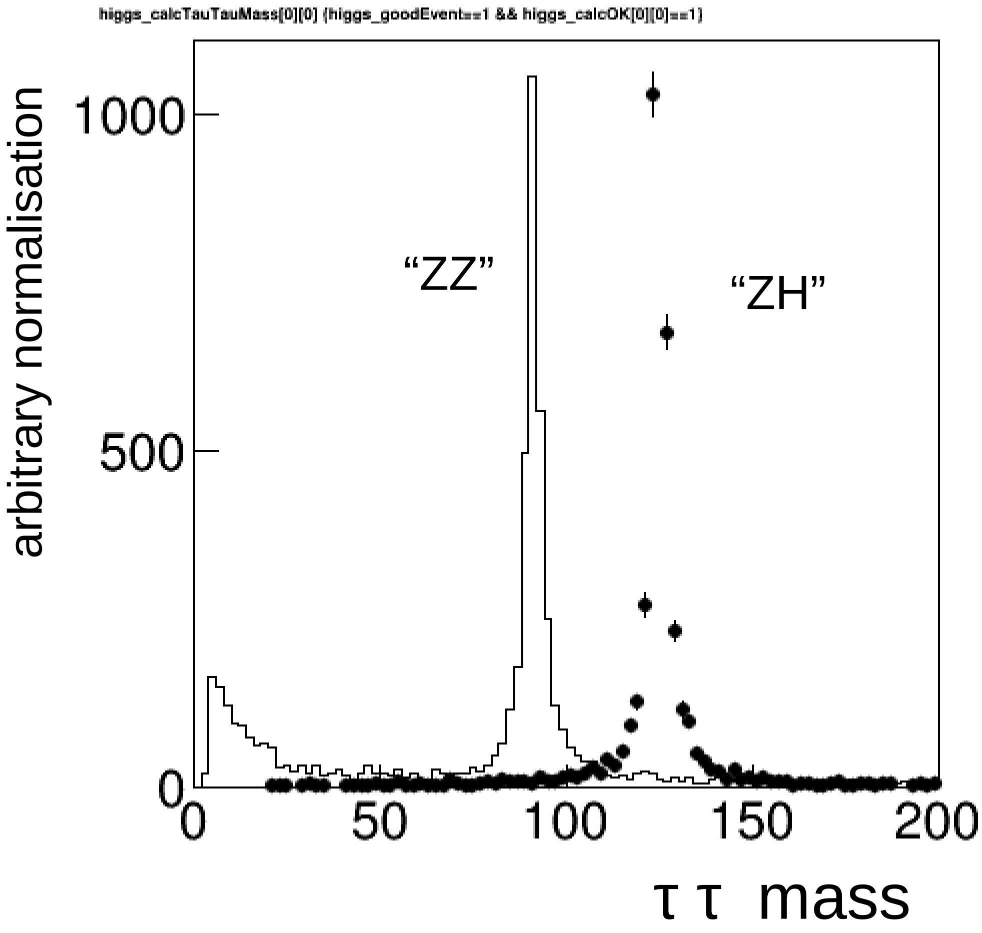
compare

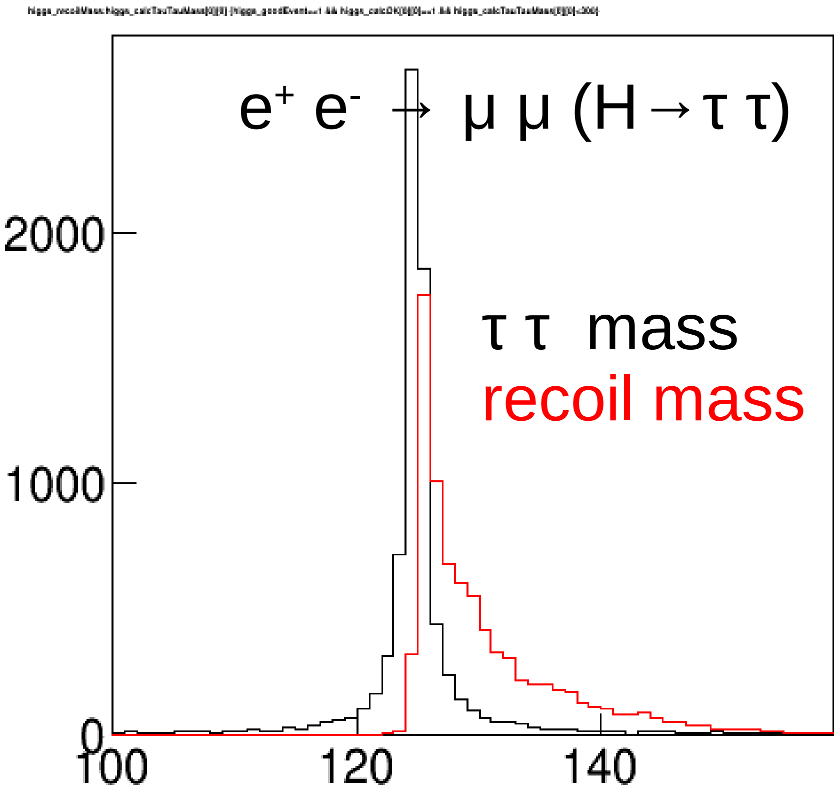
$e^+ e^- \rightarrow \mu\mu (H \rightarrow \tau\tau)$

to its major irreducible background

$e^+ e^- \rightarrow \mu\mu\tau\tau$

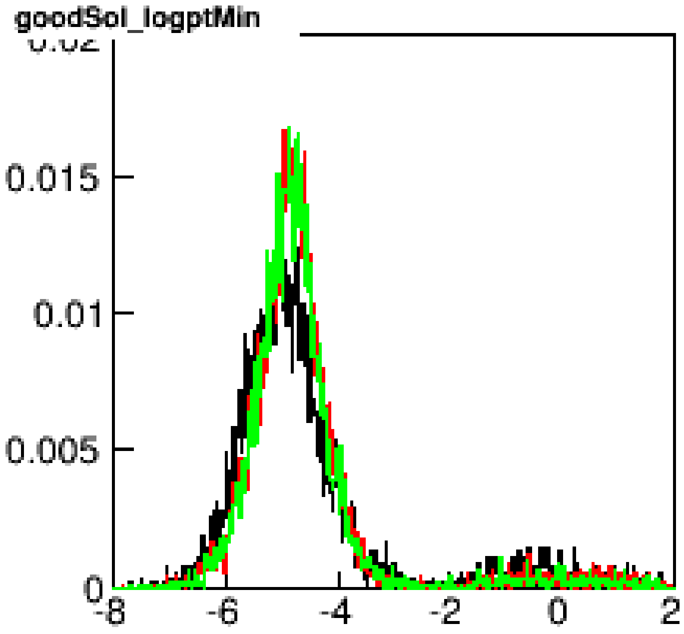
(without H contribution: Z, gamma*)



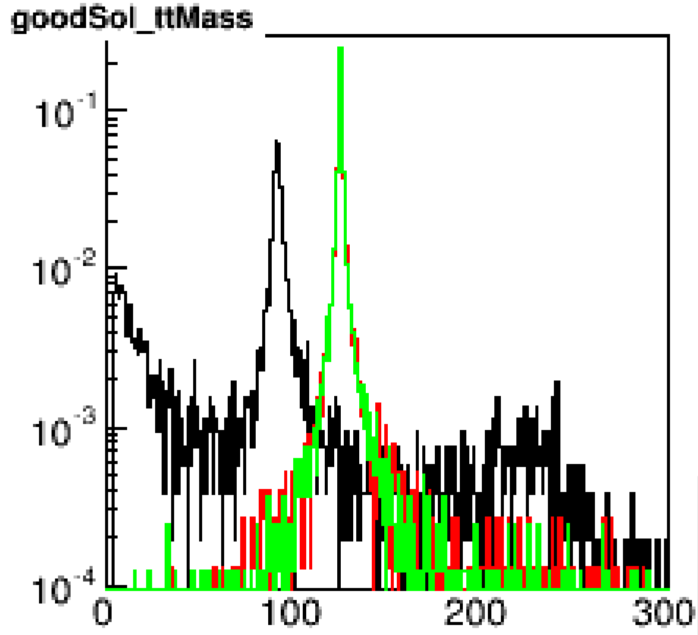


arbitrary normalisation

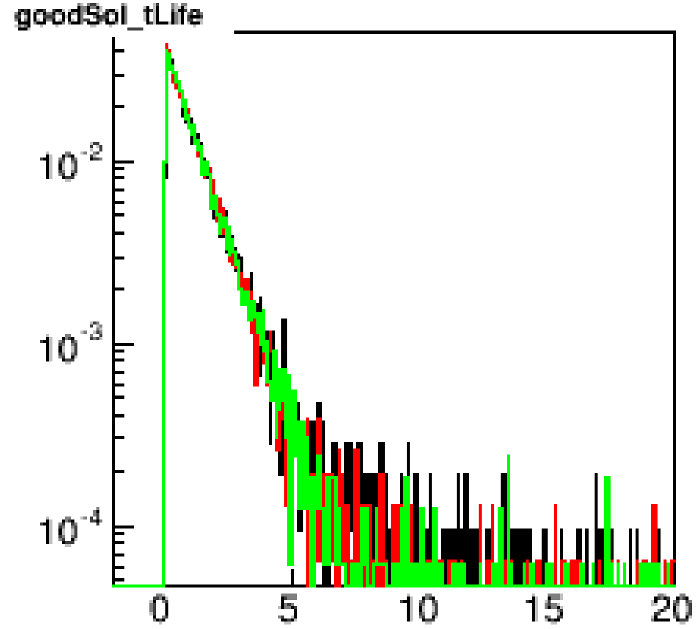
both τ → π ν



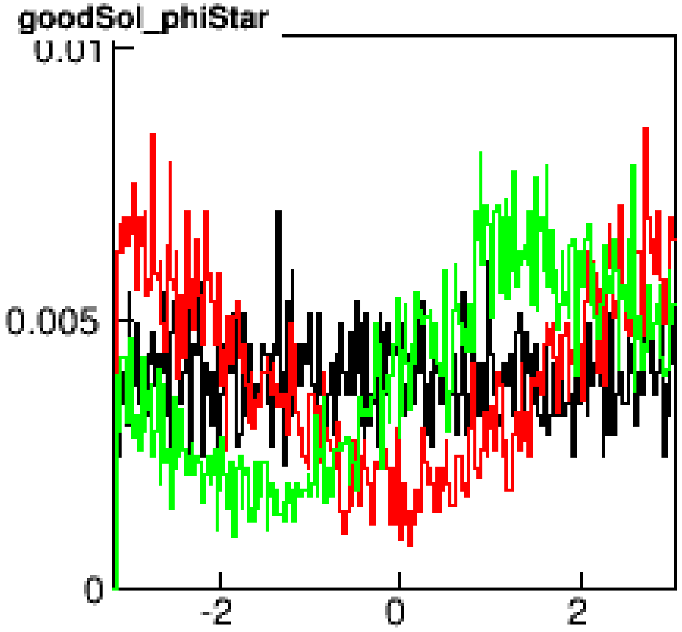
pT at minimum



tau-tau mass



reconstructed lifetime



CP-sensitive angle

CP^{+} Higgs

H = cos (π/4) CP^{+}
+ sin (π/4) CP^{-}

non-Higgs μμττ