Background Suppression

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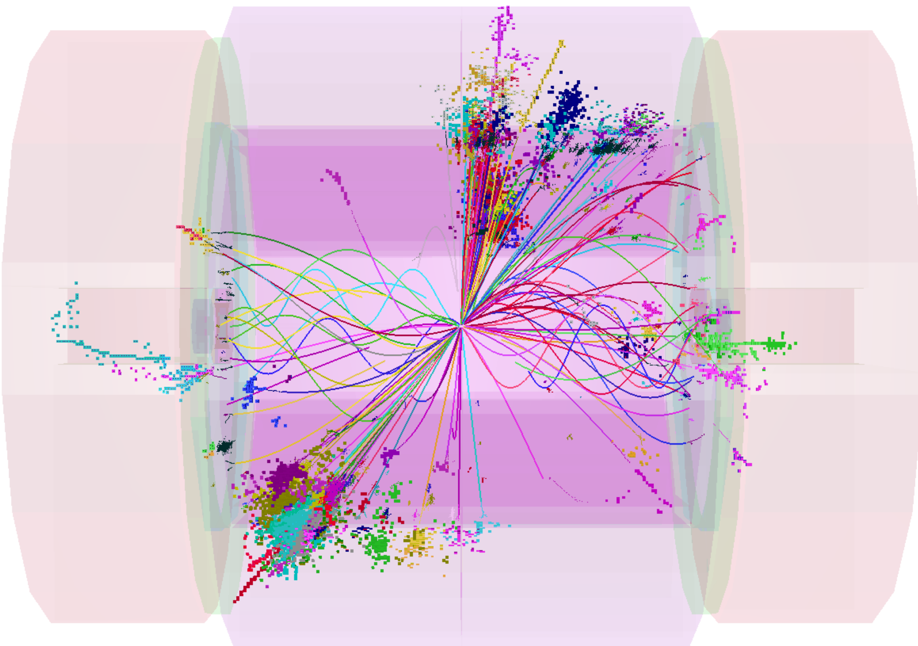
on behalf of CLIC Physics and Detector Study



This Talk:

- Introduction
- Simulation/Reconstruction
- Backgrounds and Timing
- Jet Finding
- Beam Halo Muons
- Conclusions

Introduction

- ★ CLIC provides the potential for e^+e^- collisions up to $\sqrt{s}$ = 3 TeV
  - But machine environment is much more challenging than ILC
    - Background levels are high
    - 0.5 ns bunch-structure ➡ integrate over multiple bunch crossings of background
  - One of the main aims of the CDR was to demonstrate possibility of precision physics measurements in this environment
  - A second aim was to understand the requirements for the detector readout – guide future R&D direction
- ★ Both aims require detailed simulation and reconstruction
  - Including pile-up from background is essential
  - Significant software challenge
  - Fortunately, not starting from scratch
    - builds on existing work developed for the ILC

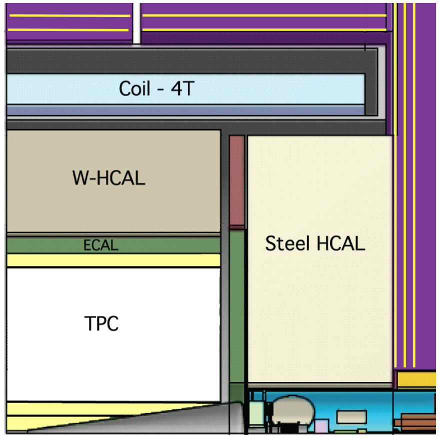
Simulation and Reconstruction

Simulation

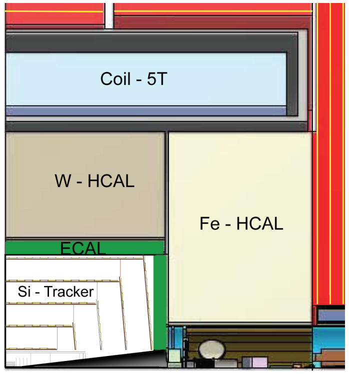
★ Both ILD and SiD have developed full GEANT 4 based detector simulations:
- Mokka (ILD) : already quite detailed, e.g. realistic gaps between detector elements for support/services
- SLIC (SiD): fairly detailed and very flexible

★ Extensively validated/used for the ILD and SiD LoI documents

★ For CDR defined two GEANT 4 detector models: CLIC_ILD and CLIC_SiD



	CLIC_ILD	CLIC_SiD
Tracker	TPC, r = 1.8 m	Silicon, r = 1.2 m
B-field	4 T	5 T
ECAL	SiW	SiW
HCAL barrel	W-Scint	W-Scint
HCAL endcap	Steel-Scint	Steel-Scint

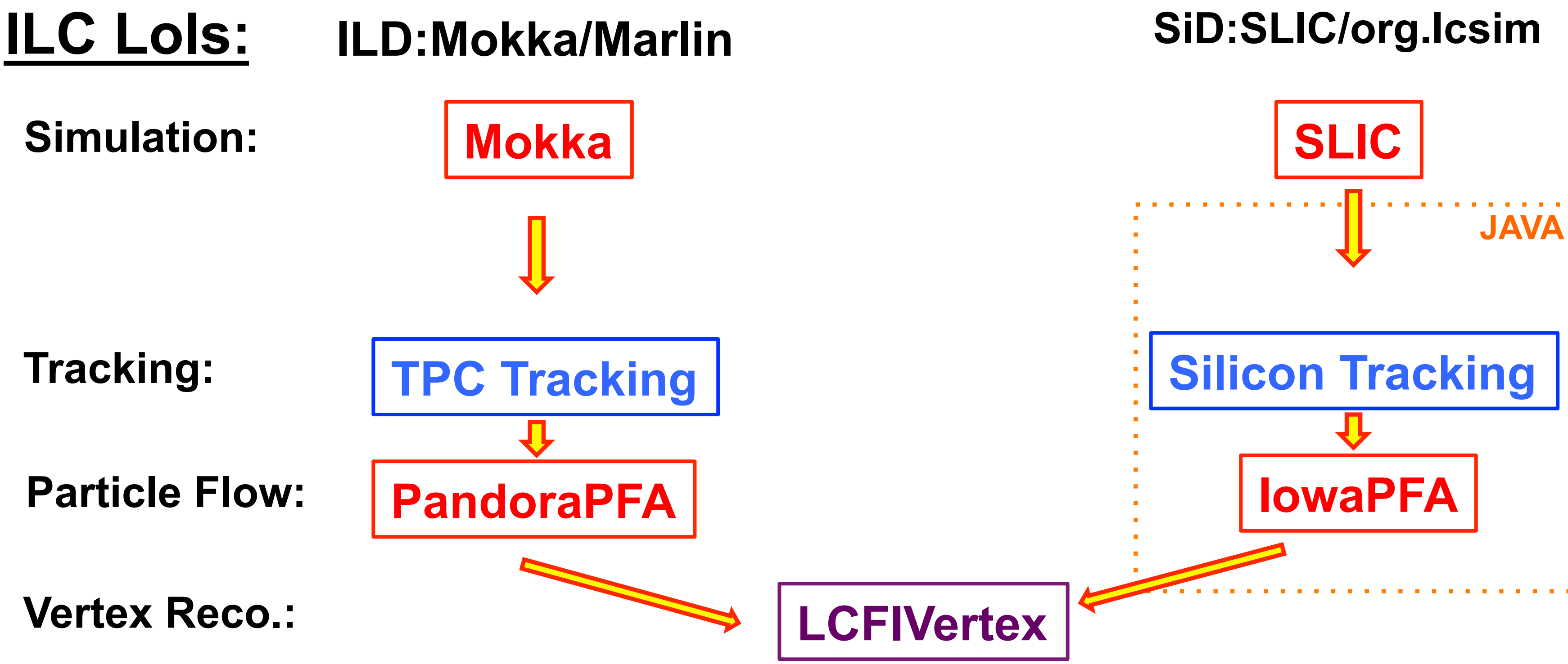


★ Main modifications to existing detector models
- Thicker HCAL + Tungsten absorber for HCAL barrel
- Design of forward region + location of inner detectors

Reconstruction

- ★ All studies use full event reconstruction
  - Highly non-trivial exercise
    - Need full reconstruction chain - developed for ILC (twice)
    - Needs to be able to cope with CLIC environment
    - Ideally would have common framework for CLIC_ILD and CLIC_SiD
      - but only had common data format (nevertheless important)

★ **ILC LoIs:**



Reconstruction

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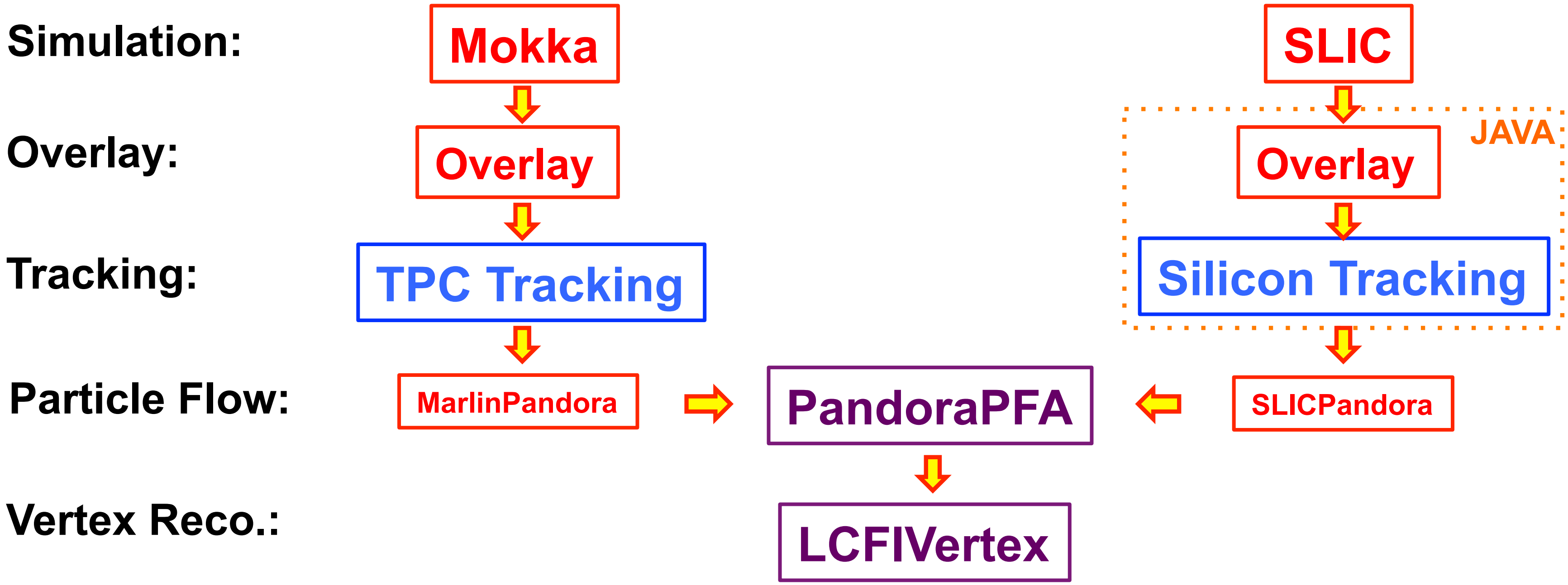
★ **CLIC CDR:** ILD:Mokka/Marlin SiD:SLIC/org.lcsim

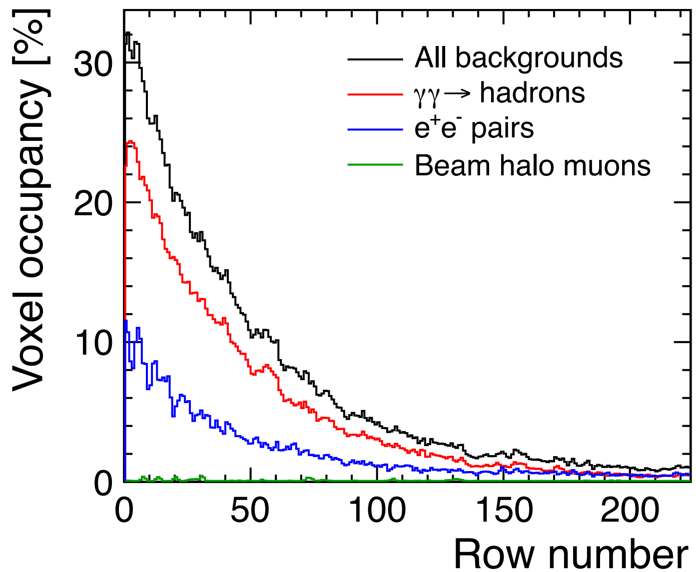


Software Challenges

★ Major effort to develop and validate software for CLIC CDR
 ▪ + two parallel software frameworks

★ A number of significant challenges
 ▪ Tracking work in high occupancy environment
 ▪ High hit multiplicities in calorimeters
 ▪ Reconstruction times/memory footprint
 ▪ GRID production with background overlay

Fig. 5.9



★ Despite challenges and a few remaining rough edges …
 ▪ All studies in CDR use full reconstruction including overlay from most significant background $\gamma\gamma \to$ hadrons

Backgrounds and Timing Requirements

Background from $\gamma\gamma \rightarrow$ hadrons

- ★ Pair Background largely affects very low angle region
- ★ Background in calorimeters, central tracker dominated by $\gamma\gamma \rightarrow$ hadrons "mini-jets"
- ★ At 3 TeV, average 3.2 events per BX (approximately 5 tracks per event)
- ★ For entire bunch-train (312 BXs)
  - 5000 tracks (mean momentum 1.5 GeV) giving total track momentum : 7.3 TeV
  - Total calorimetric energy (ECAL + HCAL) : 19 TeV
- ★ Largely low p_T particles

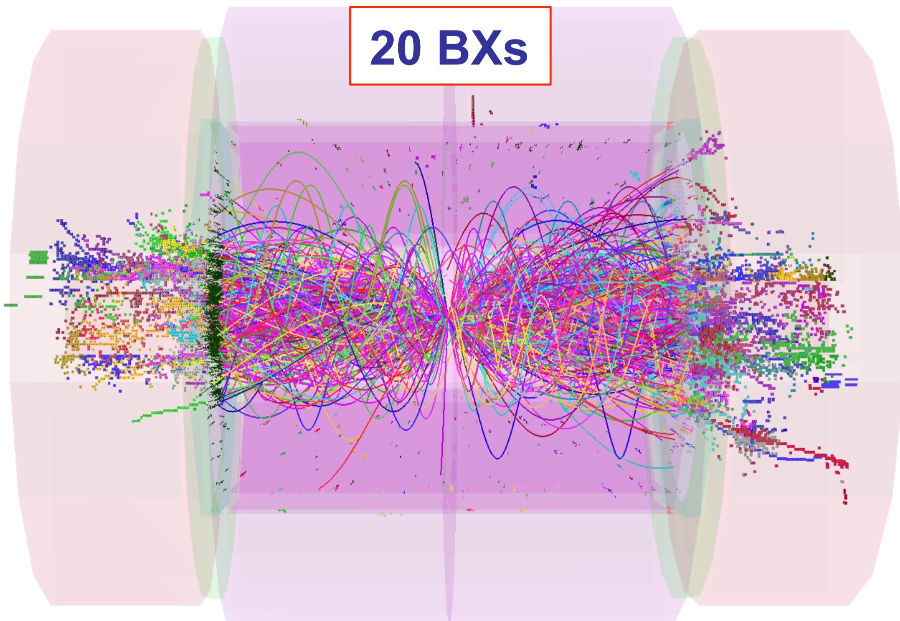
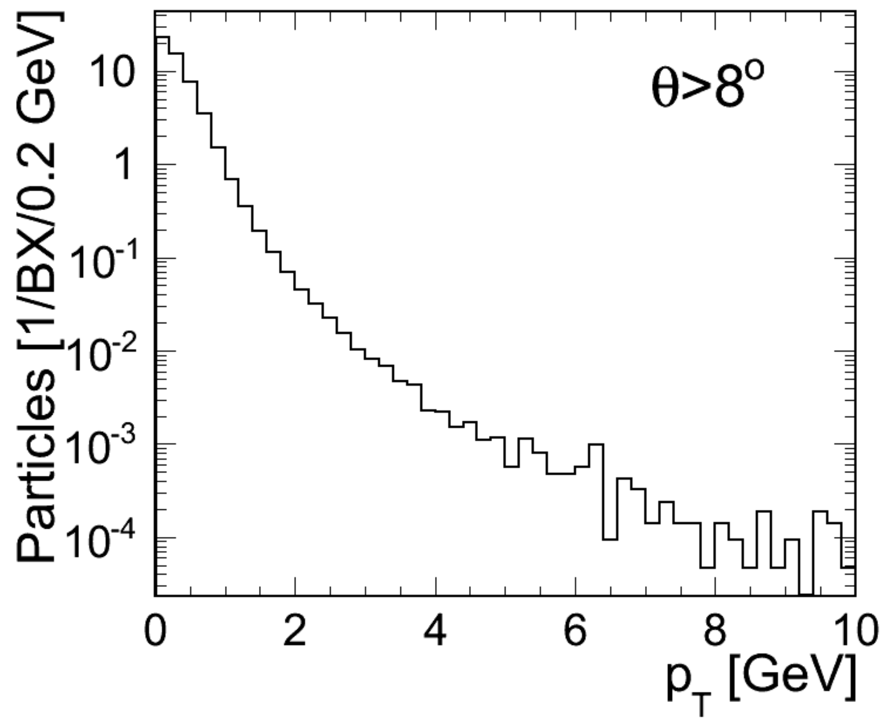


Fig. 2.3

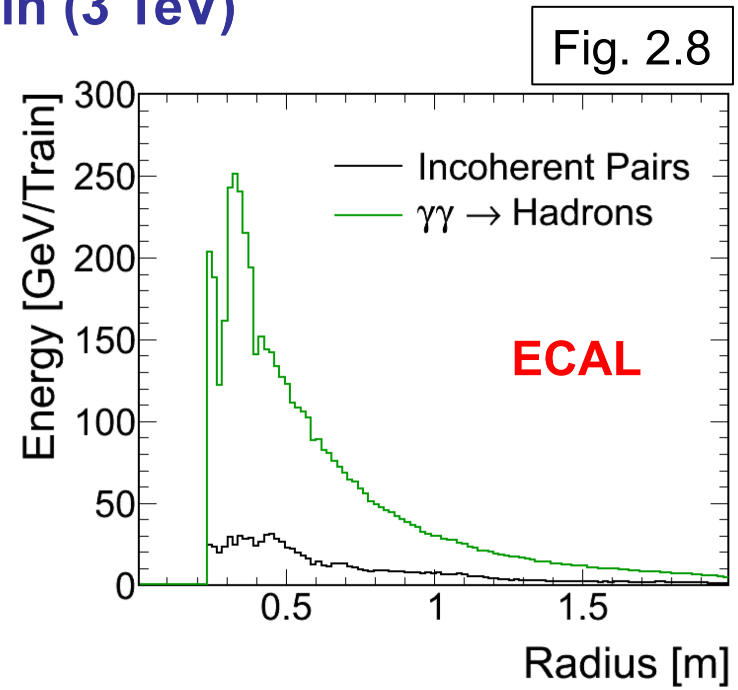


- ★ Irreducible background – it is physics

Backgrounds in the Calorimeters

★ **Calorimeter backgrounds per bunch-train (3 TeV)**

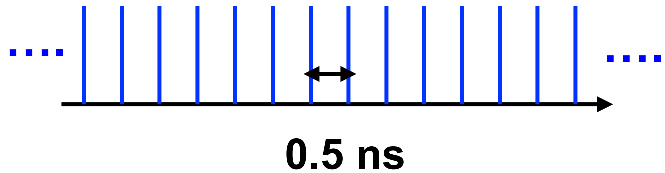
Detector	**$\gamma\gamma \rightarrow$ hadrons**
ECAL endcaps	**11 TeV**
ECAL barrel	1.5 TeV
HCAL endcaps	**6 TeV**
HCAL barrel	0.3 TeV
Total	19 TeV



★ **Calorimeter backgrounds per bunch-crossing are manageable, ~ 60 GeV**

★ **Hence want to integrate over as few as possible BXs**

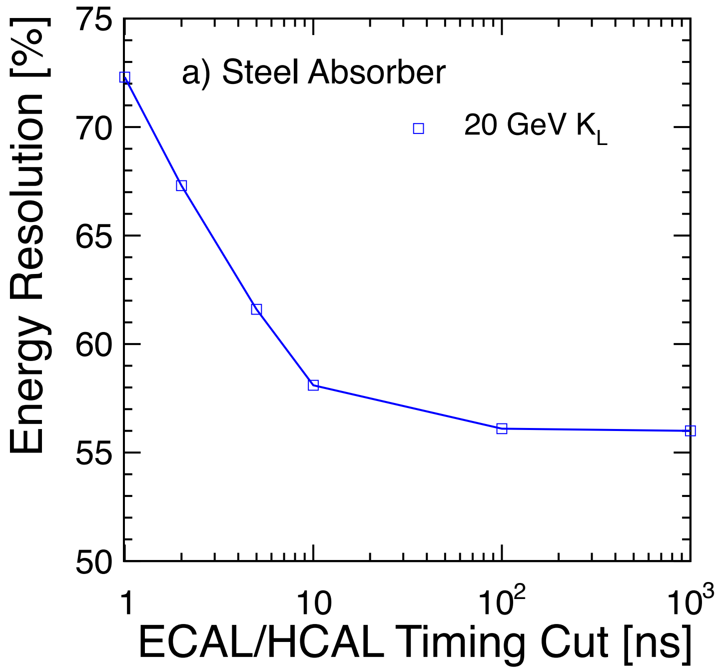
★ **Tight timing requirements – *O*(ns) !**



Calorimeter Timing

- ★ But at ns timescale there are issues…
- ★ Can't just "assume" arbitrarily short time-stamping capability
- ★ **Time needed to accumulate all calorimetric energy** (due to low energy particles, nuclear break-up etc.) significant compared to **0.5 ns** Bx
- ★ **HCAL resolution** depends on time window

Fig. 6.3



Steel (Endcap): ~10 ns

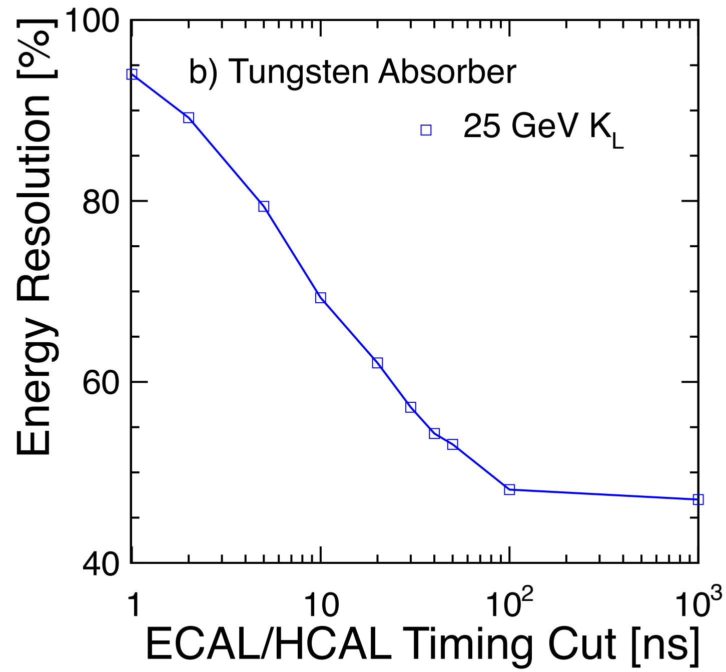


Fig. 6.3

Tungsten (Barrel): ~100 ns

CLIC Timing cont.

★ **Tension** between calorimeter integration time and desire to minimize number of BXs of $\gamma\gamma \rightarrow$ **hadrons** background

- e.g di-jet mass resolution from isolated $W \rightarrow q\bar{q}$ decays

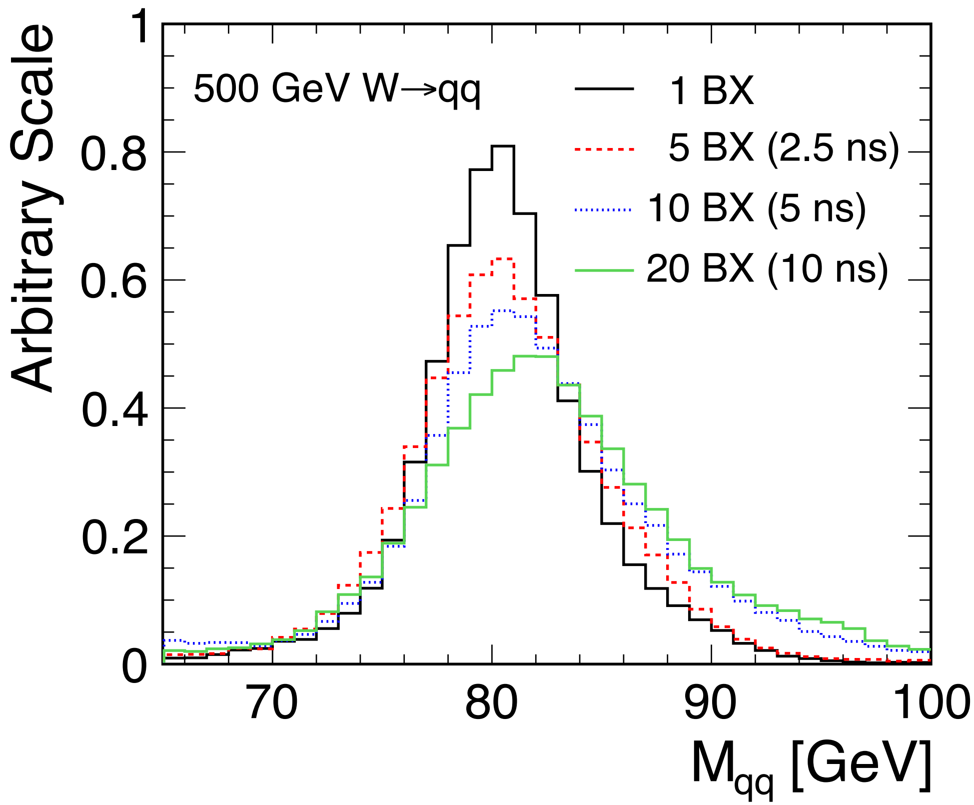
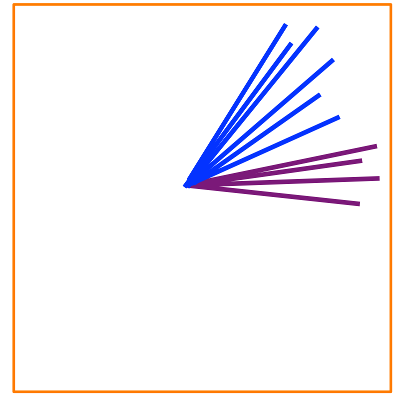


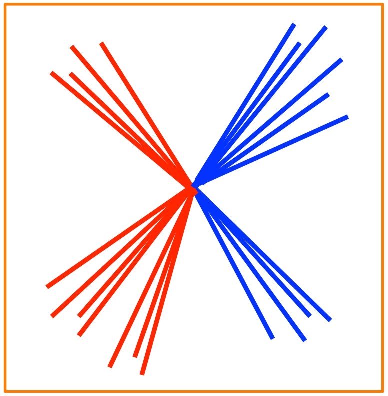
Fig. 2.10



⇒ **< 10 BX**

CLIC Timing cont.

★ **Similar conclusions for reconstruction of high mass states**
- **e.g. reconstructed di-jet mass in** $e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$



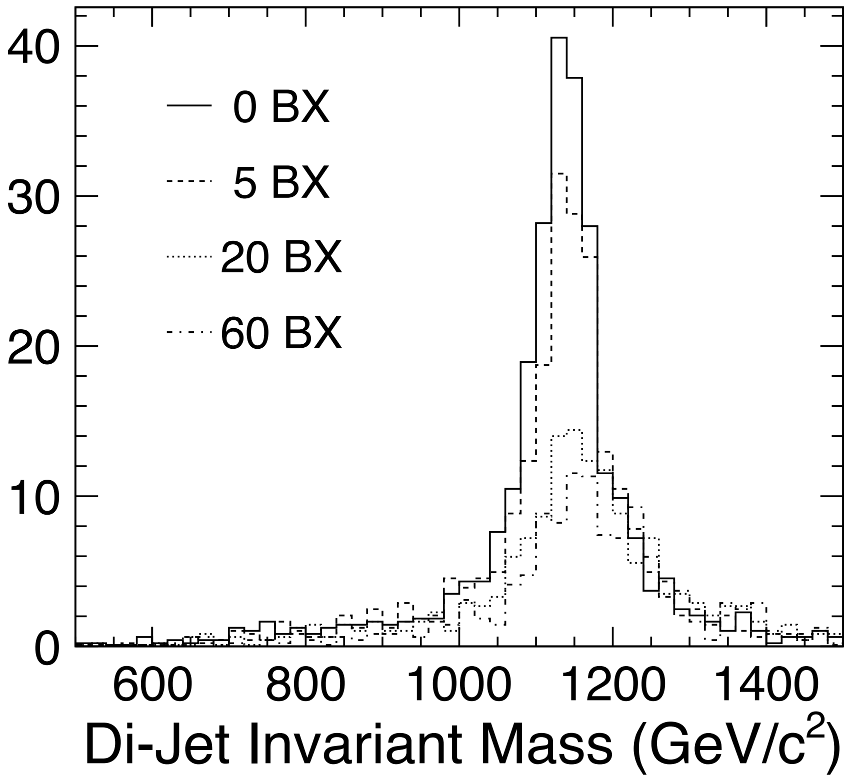


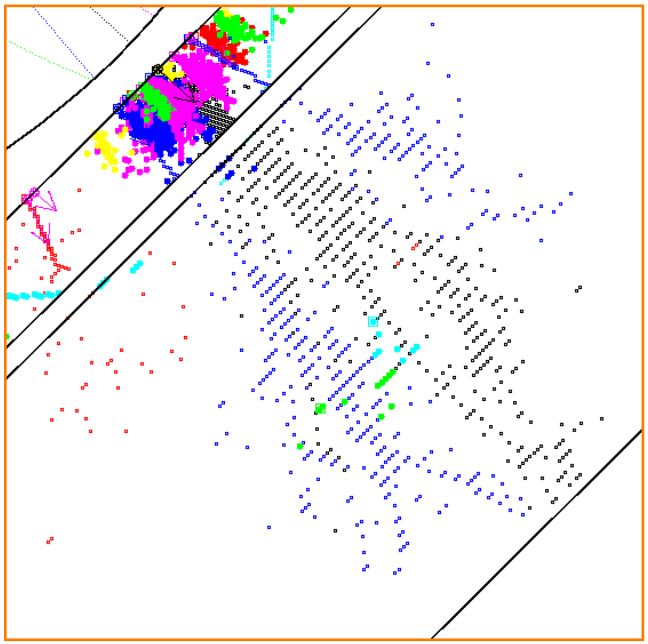
Fig. 2.10

⇒ **< 10 BX**

But < 2.5 ns not long enough for calorimetry

★ **Timing Requirements:**

- integrate over **> 20 BXs** to accumulate calorimetric signals
- integrate over **< 5 BXs** for acceptable $\gamma\gamma \rightarrow$ **hadrons** backgrounds
- …

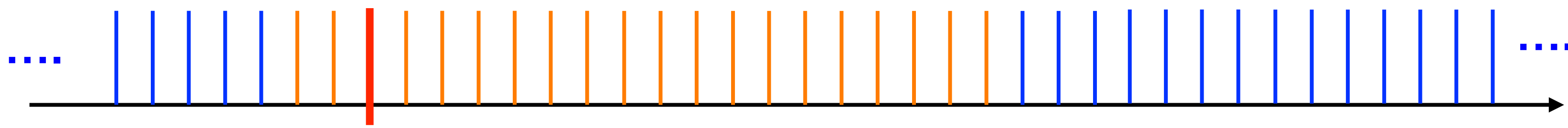


★ **The Solution - a combination of:**

- **excellent time resolution**
- **high granularity calorimetry**
- **sophisticated reconstruction**

CLIC Timing Strategy

- ★ **Based on trigger-free readout of detector hits all with time-stamps**
  - **assume multi-hit capability of 5 hits per bunch train**
- ★ **Assume can identify t0 of physics event in offline trigger/event filter**
  - **define "reconstruction" window around t0**



- ★ **Hits within window passed to track and particle flow reconstruction**

Subdetector	Reco Window	Hit Resolution
ECAL	10 ns	1 ns
HCAL Endcap	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	10/√12
TPC (CLIC_ILD)	Entire train	n/a

Sufficient calorimeter integration window (ECAL, HCAL Endcap, HCAL Barrel)

CLIC hardware requirements (Silicon Detectors)

Reconstruction in Time

Input to reco:

TPC : 30 ns*
Si trackers : 10 ns
→ **Tracking**

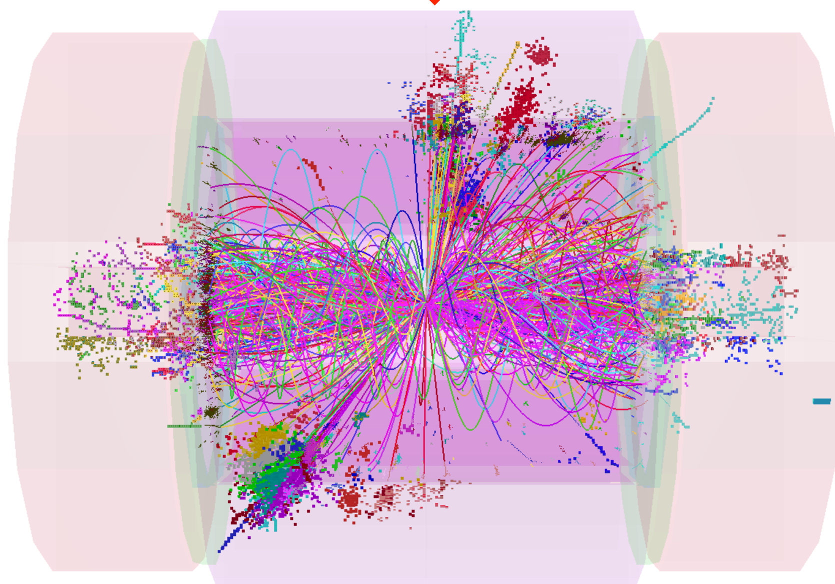
↓ "10 ns of tracks"

Sufficient time window for calorimetry
ECAL: 10 ns
HCAL (End): 10 ns
HCAL (Barrel): 100 ns
→ **PandoraPFA**

↓

$\gamma\gamma \rightarrow$ **hadrons**

1.2 TeV



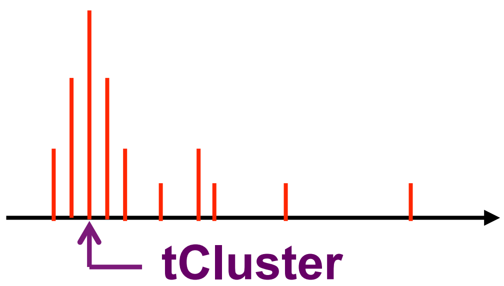
★ **Additional background rejection still required post reconstruction**

*TPC readout integrates over whole train – only 60 BXs used due to limitations in heritage (LEP) tracking software

Reconstruction in Time

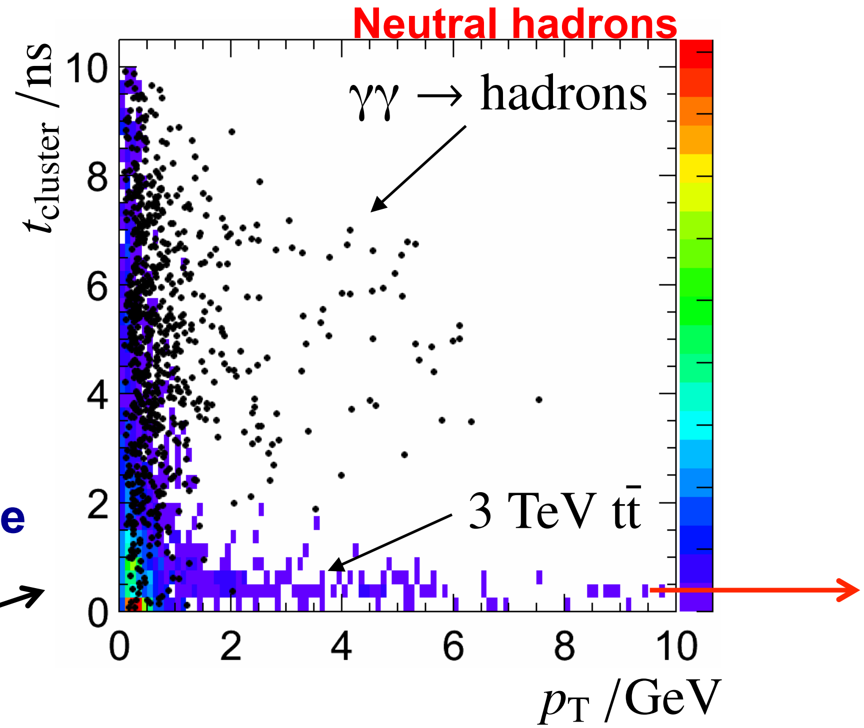
★ After reconstruction have a list of particles (PFOs):
- charged particles – mostly matched to clusters
- photons – EM clusters
- neutral hadrons – clusters

★ High granularity calorimeter - even low energy clusters have many hits
- calculate energy weighted truncated mean time of each cluster
  - calo hit times corrected for time-of-flight (straight-line)
  - sub-ns resolution



- use times to reject clusters
- also can reject associated tracks
  - account for helical propagation time

★ Reject PFOs from background
- e.g. neutral hadrons in Endcap



PFOSelection

- Only apply to "low" p_T PFOs
- Three sets of timing cuts applied in reconstruction
  - Loose, Default, Tight

Table B.2

Region	p_T range	time cut
Photons		
central	$0.75\ \text{GeV} \leq p_T < 4.0\ \text{GeV}$	t < 2.0 ns
$\cos\theta \leq 0.975$	$0\ \text{GeV} \leq p_T < 0.75\ \text{GeV}$	t < 1.0 ns
forward	$0.75\ \text{GeV} \leq p_T < 4.0\ \text{GeV}$	t < 2.0 ns
$\cos\theta > 0.975$	$0\ \text{GeV} \leq p_T < 0.75\ \text{GeV}$	t < 1.0 ns
neutral hadrons		
central	$0.75\ \text{GeV} \leq p_T < 8.0\ \text{GeV}$	t < 2.5 ns
$\cos\theta \leq 0.975$	$0\ \text{GeV} \leq p_T < 0.75\ \text{GeV}$	t < 1.5 ns
forward	$0.75\ \text{GeV} \leq p_T < 8.0\ \text{GeV}$	t < 2.0 ns
$\cos\theta > 0.975$	$0\ \text{GeV} \leq p_T < 0.75\ \text{GeV}$	t < 1.0 ns
charged particles		
all	$0.75\ \text{GeV} \leq p_T < 4.0\ \text{GeV}$	t < 3.0 ns
	$0\ \text{GeV} \leq p_T < 0.75\ \text{GeV}$	t < 1.5 ns

Impact of Timing Cuts

1.2 TeV

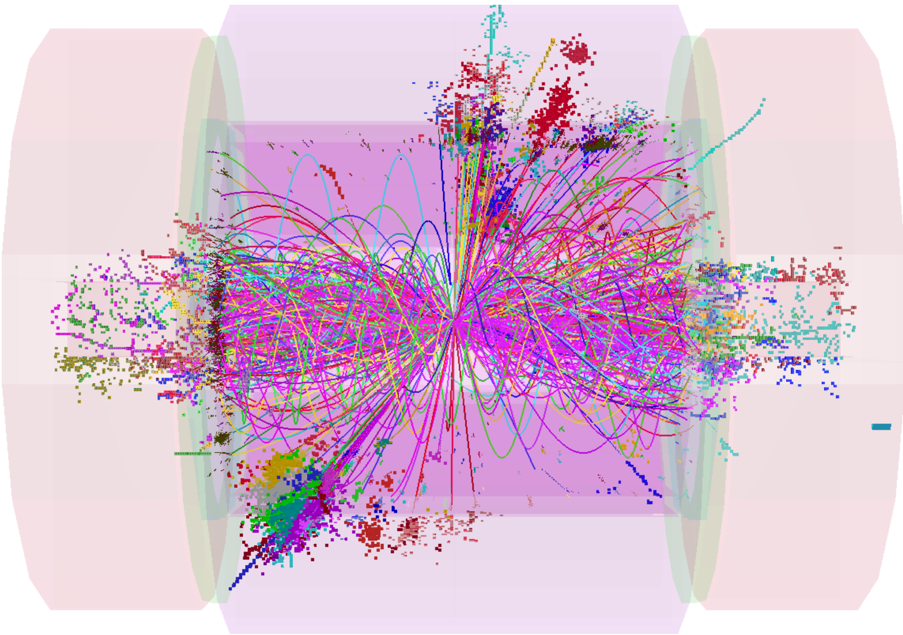
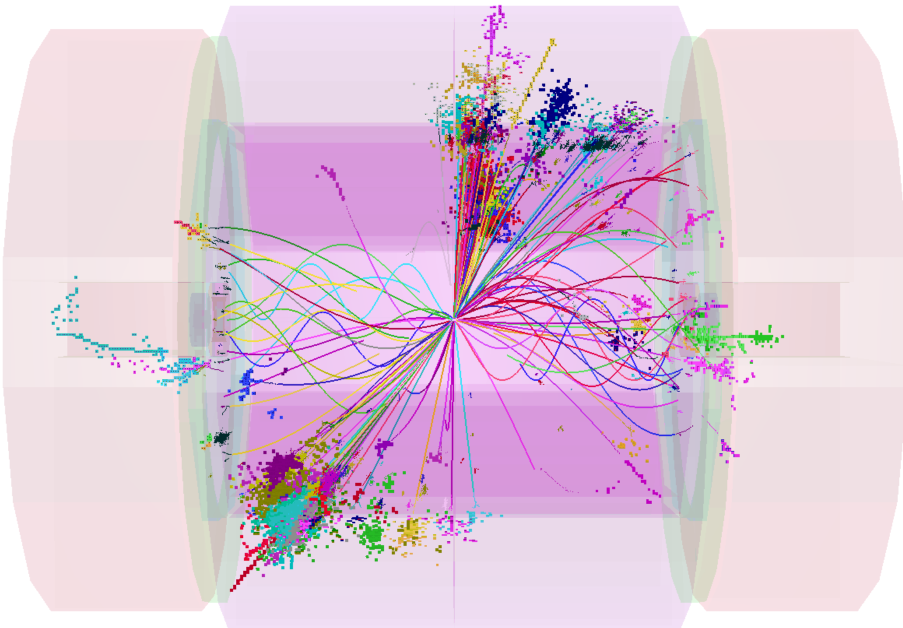


Table 12.1

Cut	$\gamma\gamma \rightarrow$ hadrons Energy (GeV)	500 GeV di-jet Energy (GeV)	500 GeV di-jet energy loss
No cut	1210	500.2	0%
Loose	235	498.8	0.3%
Default	175	498.0	0.5%
Tight	85	496.1	0.8%
$p_T > 3.0$ GeV	160	454.2	9.2%

Impact of Timing Cuts

1.2 TeV ⇒ **85 GeV**



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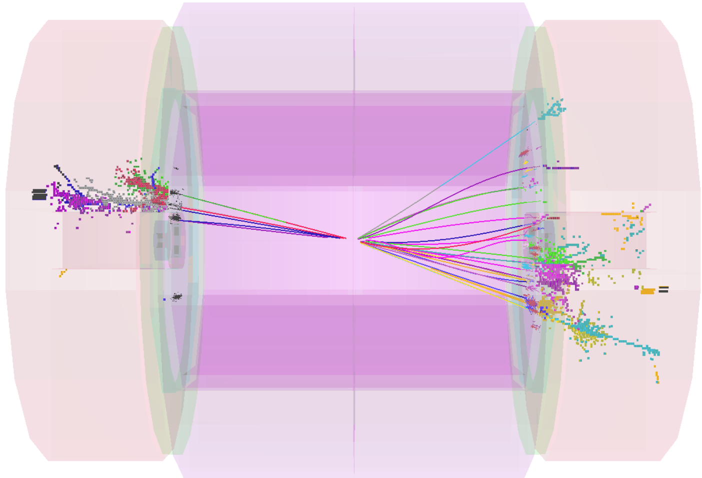
- ★ **Reject 93 % of background energy and < 1% of physics event**
  - **much more effective than simple p_T cut**

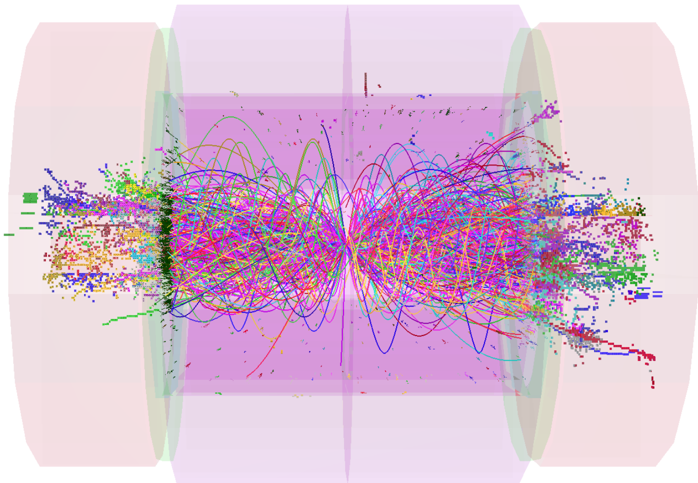
Forward Events

★ **Also effective in forward region**
- **qualitative example for hard case,**
  3 TeV $W^+W^- \to q\bar{q}q\bar{q}$

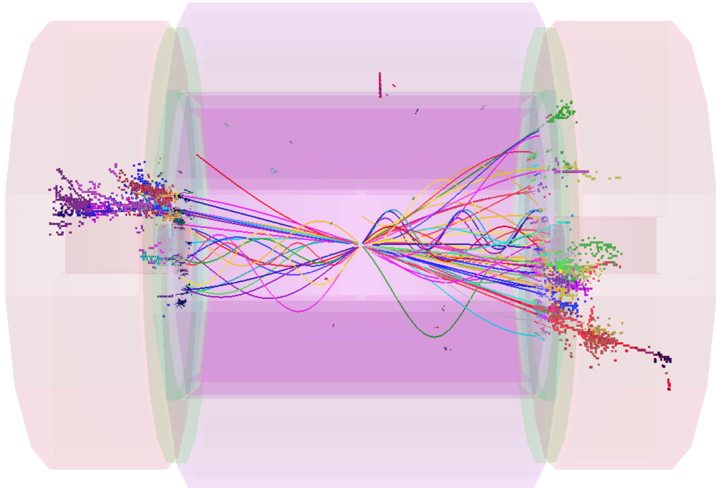
$W^+W^- \to q\bar{q}q\bar{q}$



$W^+W^- \to q\bar{q}q\bar{q}$ + $\gamma\gamma \to$ hadrons



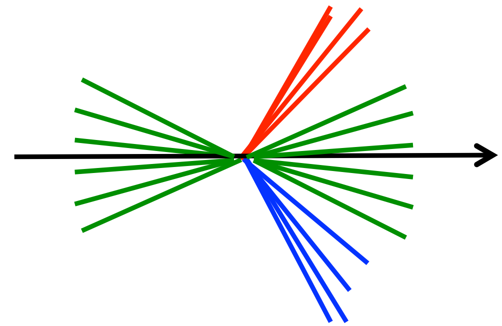
TightSelectedPFOs



Jet Finding

Jet Finding at CLIC

★ At LEP, preferred jet-finding algorithm: Durham k_T
- all particles in event clustered into the jets
- not appropriate for CLIC



★ Events at CLIC
- significant background from forward-peaked $\gamma\gamma \rightarrow$ hadrons
- events are often boosted along beam axis (beamstrahlung)
- "hadron collider" type algorithms more appropriate

★ Jet finding at CLIC
- studied for benchmark physics analyses (FASTJET package)
- preferred option "k_T" with distance measure $\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$
  - invariant under longitudinal boosts
- particles either combined with existing jet or beam axis
  - reduces sensitivity to $\gamma\gamma \rightarrow$ hadrons

Jet Finding at CLIC

★ **e.g.** $e^+e^- \rightarrow \tilde{q}_R\tilde{q}_R \rightarrow q\bar{q}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$

- **two jets + missing energy**

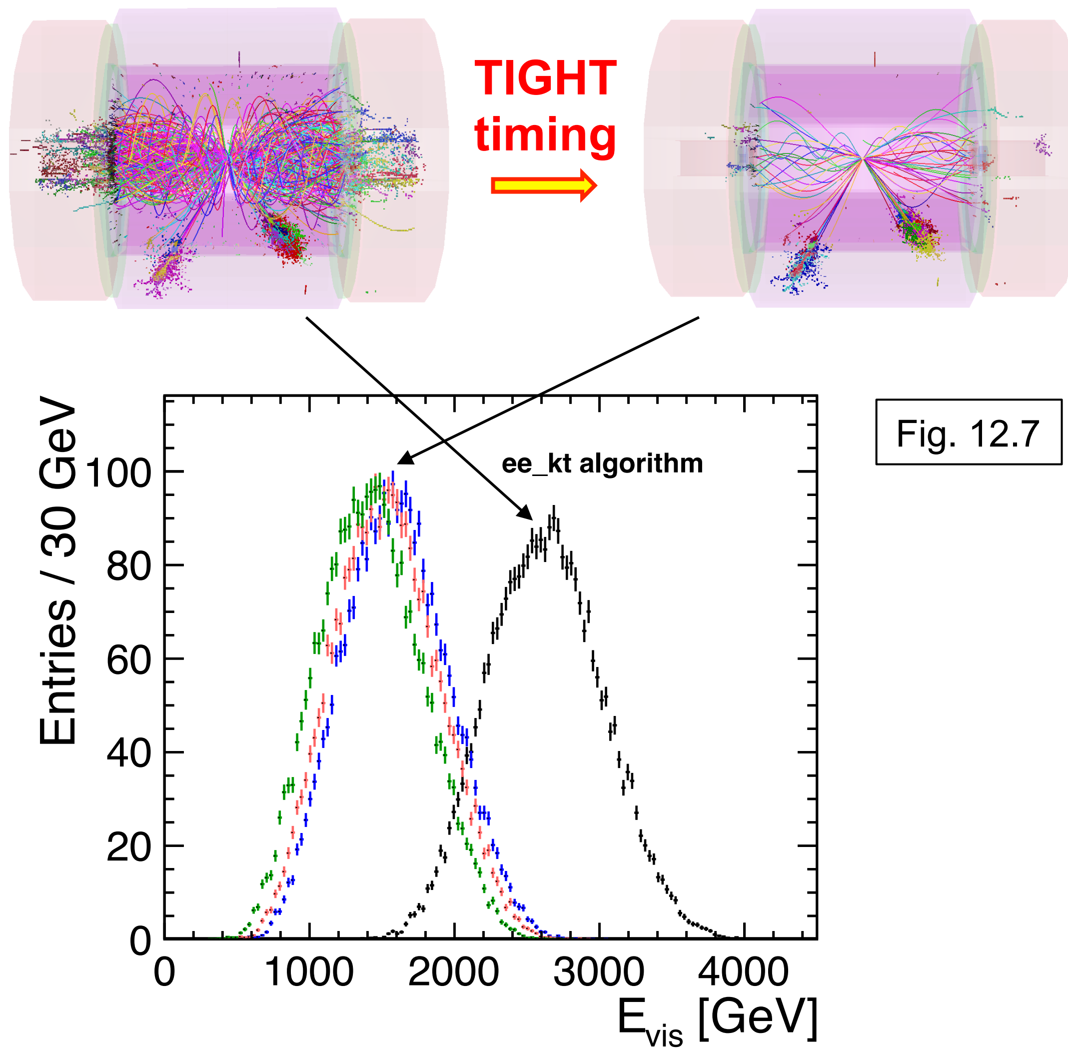


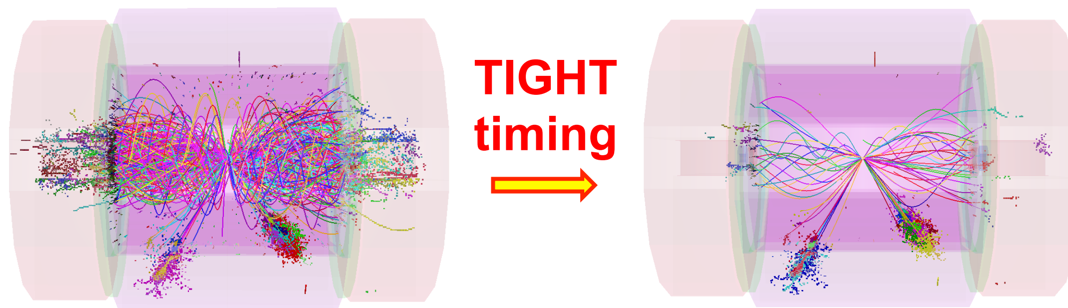
Fig. 12.7

★ **Using Durham k_T à la LEP**

- **all particles clustered**
- **timing cuts are effective**

Jet Finding at CLIC

★ e.g. $e^+e^- \rightarrow \tilde{q}_R\tilde{q}_R \rightarrow q\bar{q}\,\tilde{\chi}^0_1\,\tilde{\chi}^0_1$
- two jets + missing energy



★ "hadron collider" k_T : R = 0.7
- much of background clustered with beam axis
- timing cuts do less work
- relative impact of timing and jet-finding depends on event topology

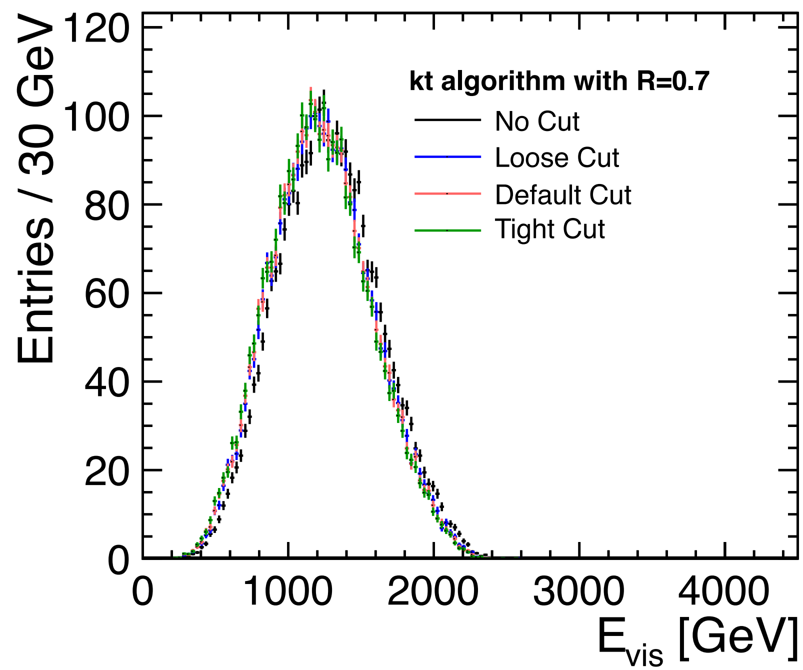


Fig. 12.7

★ Two "weapons" against background: timing cuts + jet finding

Does it all work ?

- ★ Aim was to show that can make precise measurements in CLIC environment
  - topic of talk by Frank Simon (quantitative results)
- ★ Here - just a taster (a particularly challenging case)

Fig. 12.9

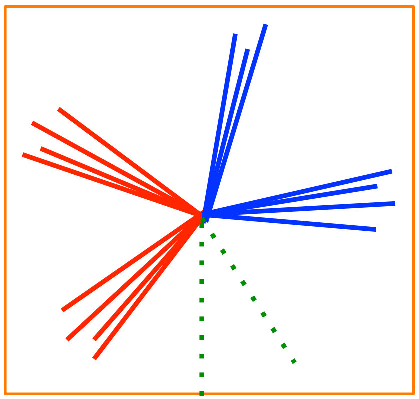
★ Pair production and decay:

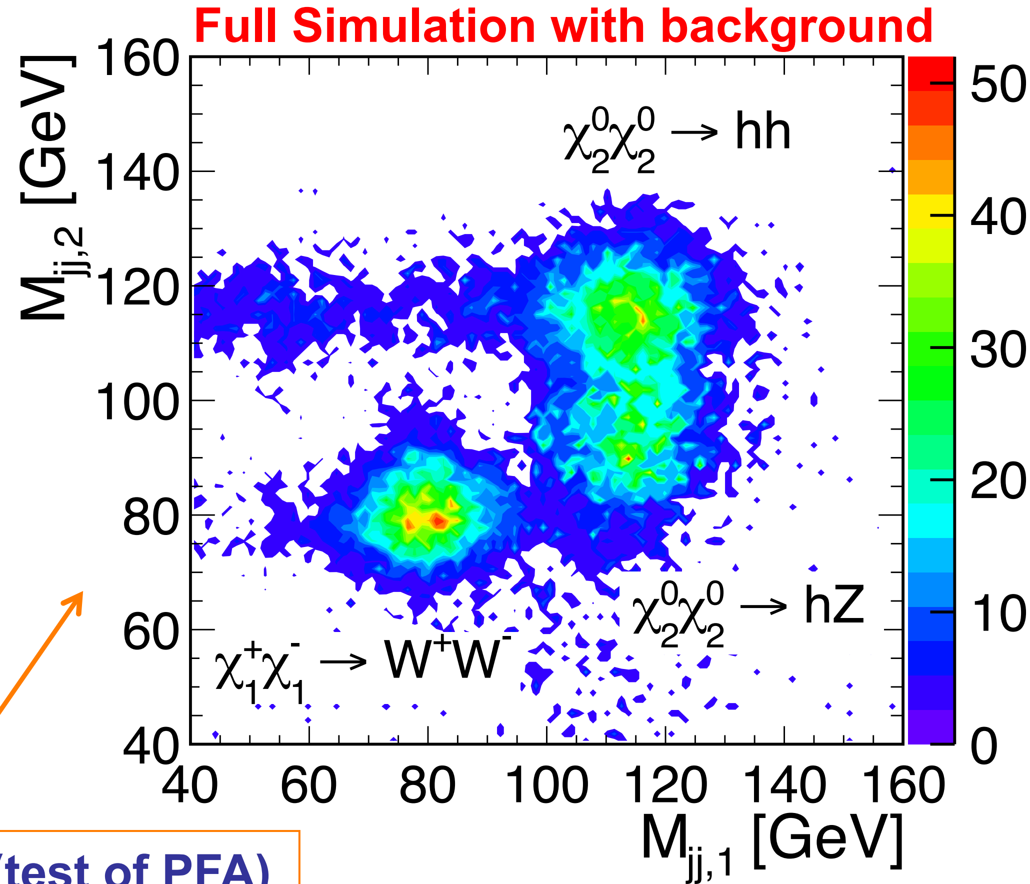
$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+W^-$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad \textbf{82 \%}$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow Zh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad \textbf{17 \%}$$

★ Test of di-jet mass reconstruction



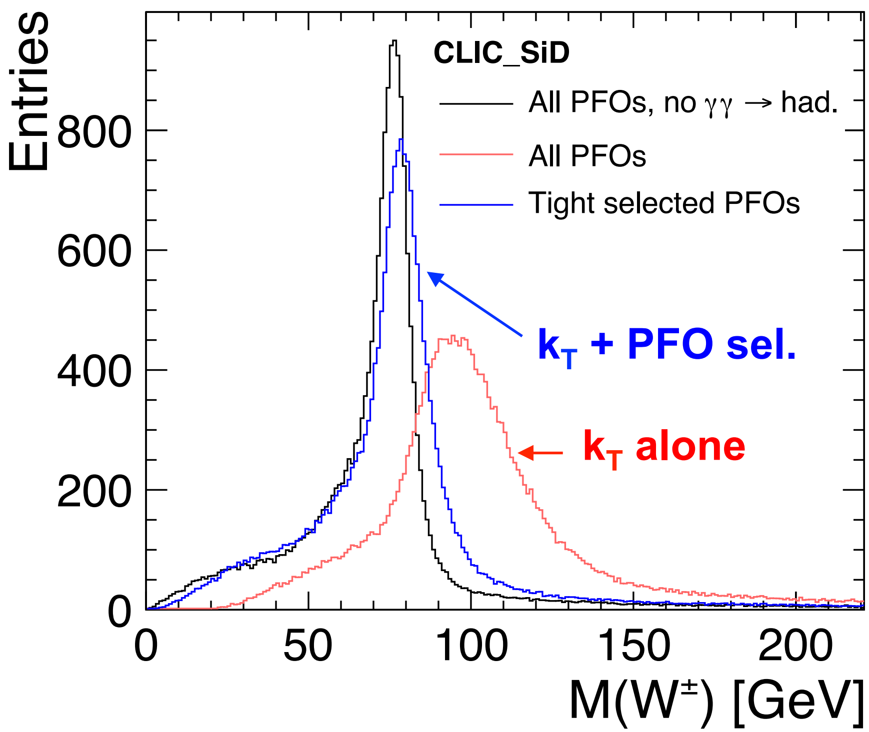


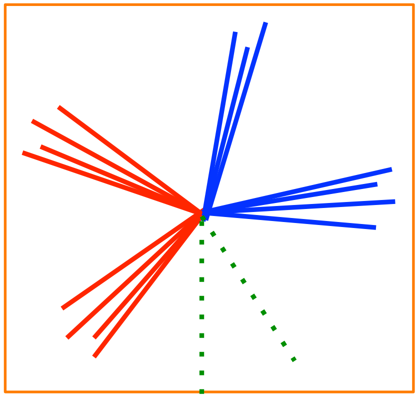
★ Separate using di-jet invariant masses (test of PFA)

★ **Take a close look at the reconstructed W mass in** $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$

- **here the timing cuts do most of the work…**
- **jet finding alone gives broad peak at 100 GeV**
- **with timing cuts not too far from ideal no background case**

Fig. 12.25





Beam Halo Muons

Beam Halo Muons

★ Most work for CDR concentrated on impact of $\gamma\gamma \rightarrow$ hadrons
- also looked at beam halo muons

★ Simulated events with entire bunch train of beam halo muons
- for study assumed a bad case: 5 muons/BX crossing detector

★ In 150 ns from start of bunchtrain:
- ECAL
  - Total = 1.5 TeV (54k hits)
  - Barrel = 0.8 TeV (18k)
  - Endcap = 0.7 TeV (36k)
- HCAL
  - Total = 10.8 TeV (128k hits)
  - Barrel = 5.3 TeV (32k)
  - Endcap = 5.5 TeV (96k)

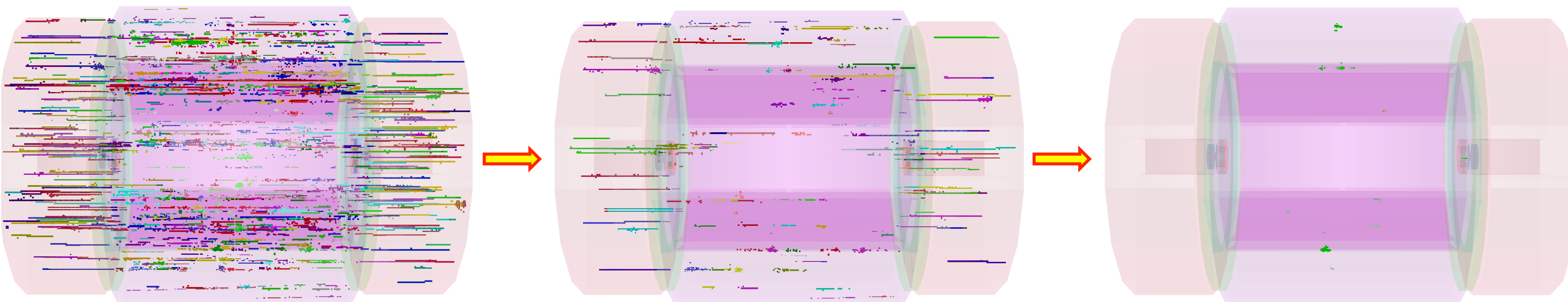
For this very conservative level of background:

12 TeV

Software Mitigation

- ★ **Three steps of background reduction**
  - **Initial reconstruction window of 10 ns (50 ns in HCAL barrel)**
  - **Timing cuts at cluster level** (TightPFOSelection)
  - **Build in beam halo muon rejection into particle flow reconstruction**
- ★ **For very conservative assumption of 5 muons per BX**

Readout window | TightPFOSelection | + dedicated reco. Alg.



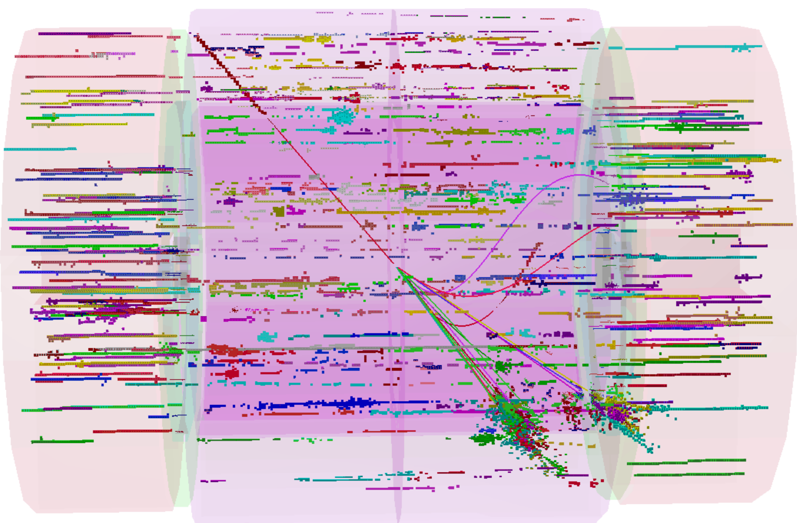
2.2 TeV | **420 GeV** | **30 GeV**

- ★ **Background rejection very effective: due to high granularity of calorimeters**

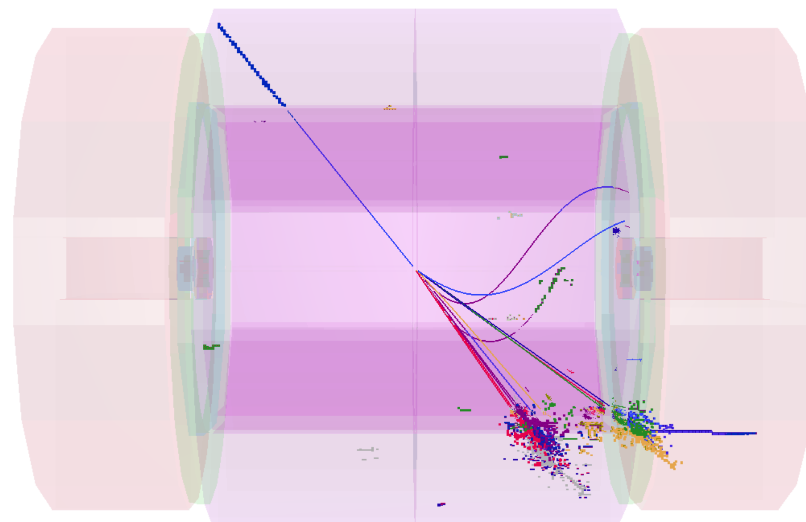
Impact on Physics

- Tested in by looking at W reconstruction in $W^+W^- \rightarrow q\bar{q}\mu\nu$
  - Sample of 500 GeV hadronic W decays
  - Again very conservative assumptions (5 muons/BX)
- Two effects observed
  - Extra energy from clusters from beam halo muons: **30 GeV**
  - Energy of reconstructed jets also biased "pick" up hits from muons: **30 GeV**

Readout window



TightPFOSelection + reco. alg.

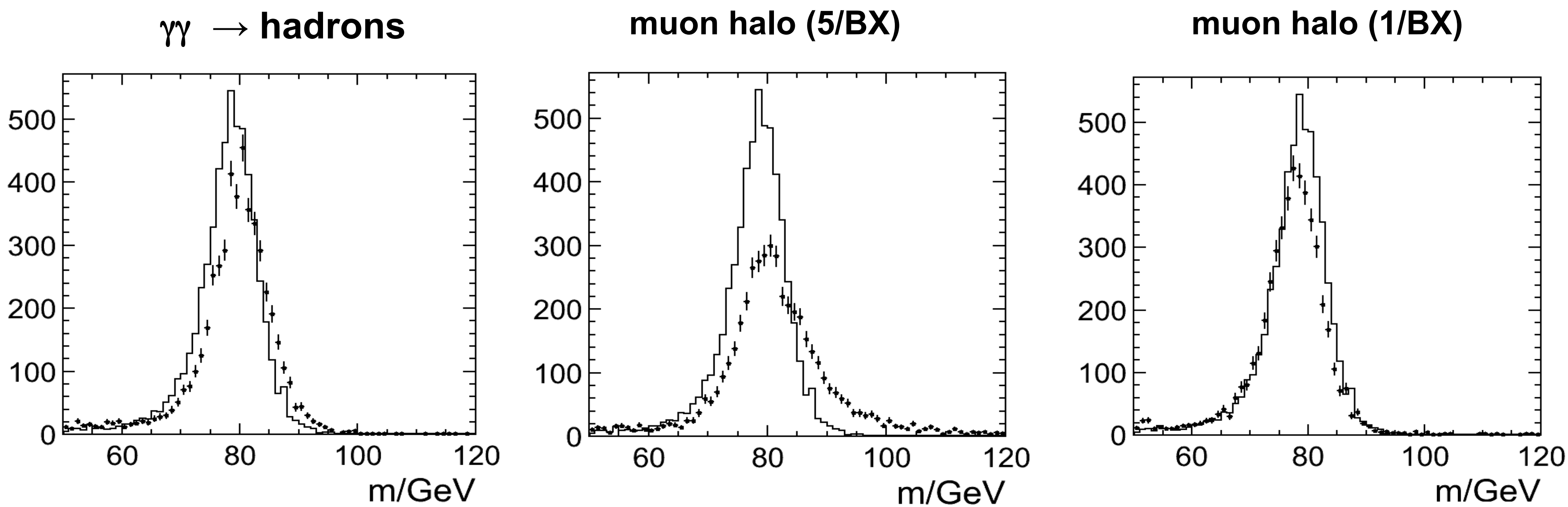


Impact on W Reconstruction

★ **Compare W mass reconstruction**

- **no background**
- **$\gamma\gamma \rightarrow$ hadrons**
- **5 muons per BX (very conservative)**
- **1 muon per BX (conservative)**

} **Worst case as pattern recognition not optimal**



★ **Conclude: a beam halo muon background of 1 muon/BX is acceptable**

- **Machine background likely to be much lower than this**

Conclusions

★ Understanding of impact of background studied in detail
- Full GEANT 4 simulation + full reconstruction
- Developed strategy to mitigate effects of background
  - requires high granularity in space and time
- Defines detector timing requirements - guide future R&D

★ I believe we have achieved the initial goal
- Demonstrated ability to perform high precision physics measurements in CLIC machine environment

[More in Frank Simon's talk on physics benchmarks]