Karlsruher Institut für Technologie

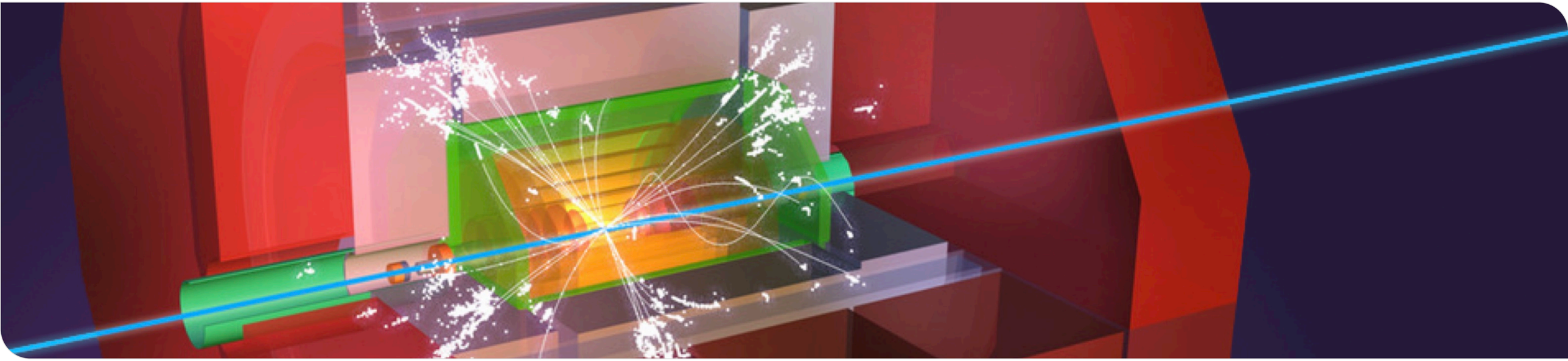
Institute for Data Processing and Electronics

Physics Drivers for Calorimeters

Frank Simon

ECFA HF WG3 Calorimetry & PID Workshop

CERN, May 2023



Outline

- The Physics Landscape
- Physics-driven Calorimeter Requirements
- Bottom Line

Disclaimer: No claim to completeness - and the usual personal bias.

Frank Simon (frank.simon@kit.edu)
Institute for Data Processing and Electronics

The Physics Landscape

With Calorimeter Glasses

Frank Simon (frank.simon@kit.edu)

The Higgs Factory Physics Menu

The Starting Point

The Higgs Boson

model-independent study
of all accessible couplings

The Higgs Factory Physics Menu

The Starting Point

The Higgs Boson

model-independent study of all accessible couplings

The Top Quark

a precise measurement of its properties.
A possible window to new physics due to its high mass!

The Higgs Factory Physics Menu

The Starting Point

Electroweak Precision

push down the uncertainties on all electroweak measurements to push the SM to (hopefully beyond) its breaking point

The Higgs Boson

model-independent study of all accessible couplings

The Top Quark

a precise measurement of its properties.
A possible window to new physics due to its high mass!

The Higgs Factory Physics Menu

The Starting Point

Electroweak Precision

push down the uncertainties on all electroweak measurements to push the SM to (hopefully beyond) its breaking point

The Higgs Boson

model-independent study of all accessible couplings

The Top Quark

a precise measurement of its properties.
A possible window to new physics due to its high mass!

Flavour Physics

use extremely large data sets to explore, resolve and understand the puzzles in the flavour sector

The Higgs Factory Physics Menu

The Starting Point

Electroweak Precision

push down the uncertainties on all electroweak measurements to push the SM to (hopefully beyond) its breaking point

The Higgs Boson

model-independent study of all accessible couplings

The Top Quark

a precise measurement of its properties.
A possible window to new physics due to its high mass!

Flavour Physics

use extremely large data sets to explore, resolve and understand the puzzles in the flavour sector

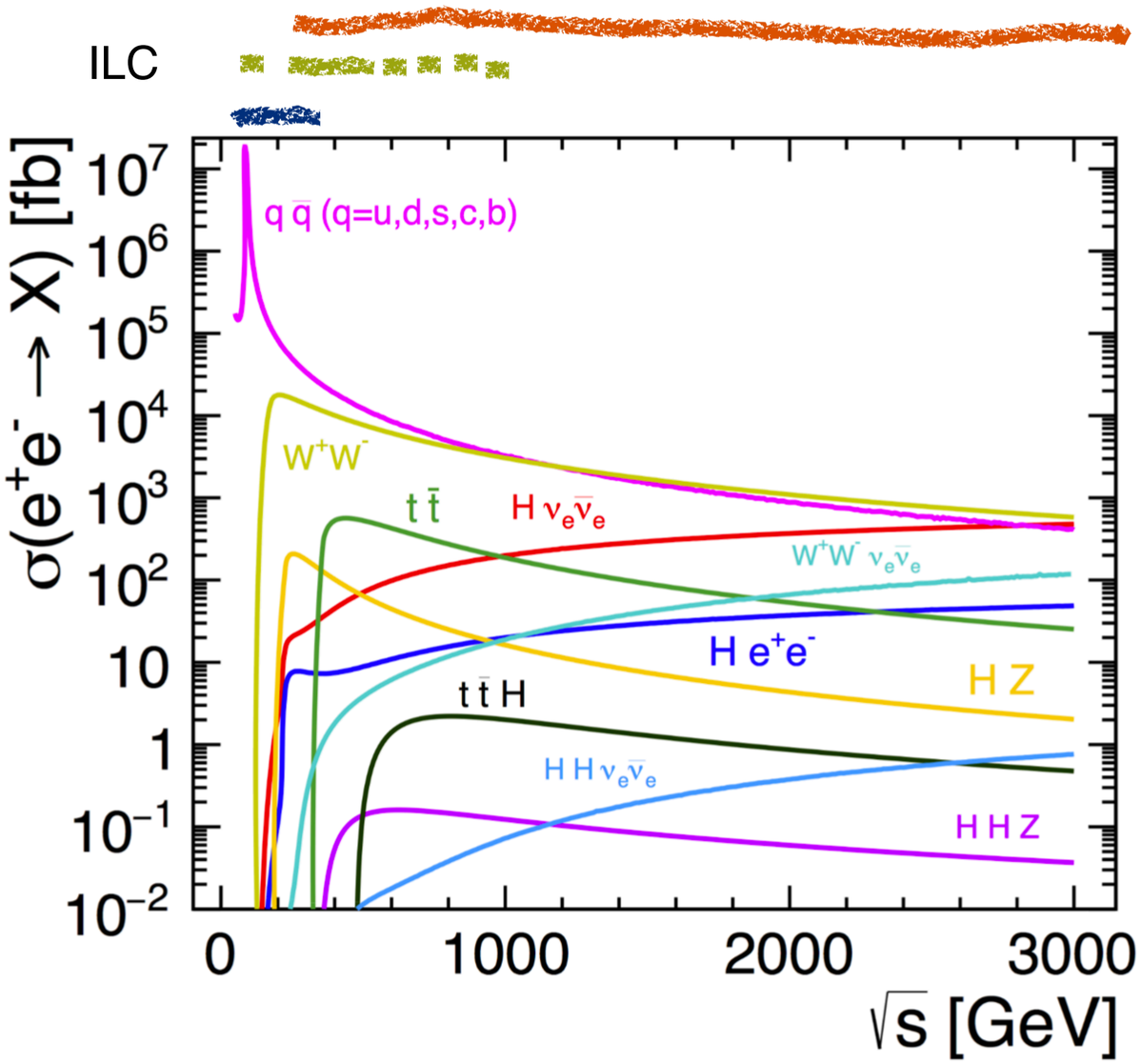
New Particles

searches for weakly coupled new particles with high luminosity / high energy in a clean environment

Frank Simon (frank.simon@kit.edu)

Cross Sections and Processes

Interesting Physics from 91 GeV into the multi-TeV regime



Main SM processes of Higgs-Top-EWK factories

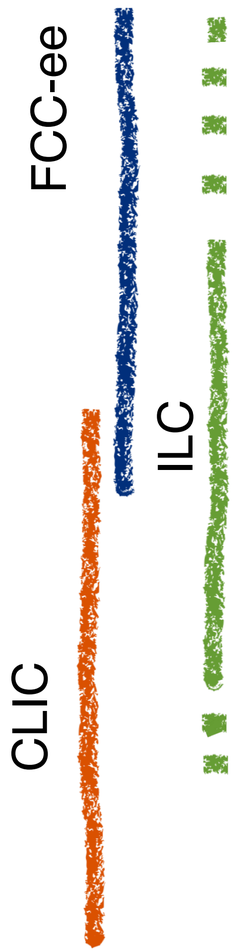
Cross sections low compared to hadron colliders.

Z-pole 3+ orders of magnitude higher than everything else.

Energy

Initial and Final States

- Collider dependent - but often less than you naively assumed



Z-pole: 91 GeV

WW: 160 GeV

HZ: 250 GeV

tt: 350 GeV

ttH, ZHH: 500 GeV

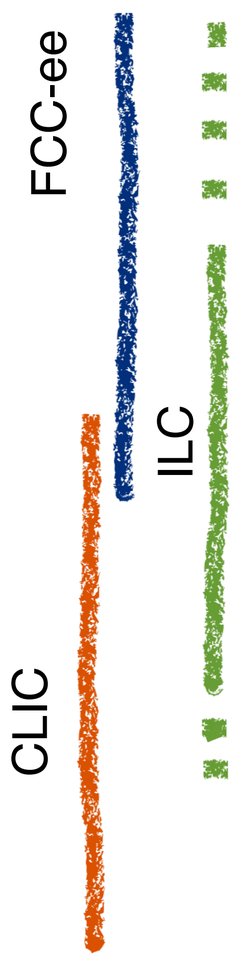
vvHH, BSM: 1+ TeV

Frank Simon (frank.simon@kit.edu)

Energy

Initial and Final States

- Collider dependent - but often less than you naively assumed



Z-pole: 91 GeV

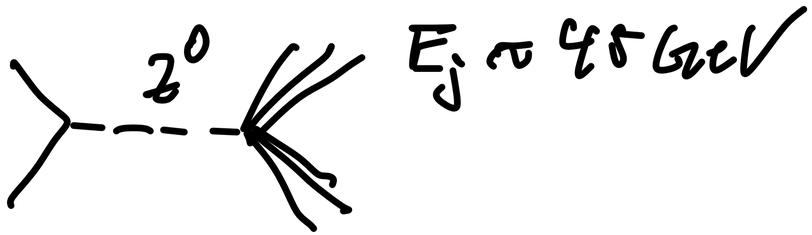
WW: 160 GeV

HZ: 250 GeV

tt: 350 GeV

ttH, ZHH: 500 GeV

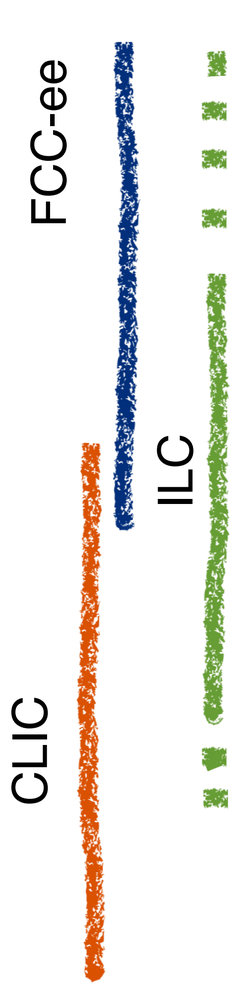
vvHH, BSM: 1+ TeV



Energy

Initial and Final States

- Collider dependent - but often less than you naively assumed



Z-pole: 91 GeV

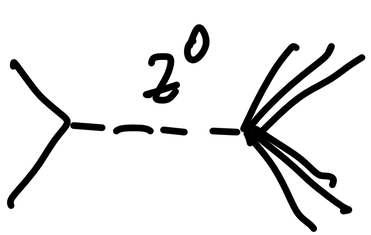
WW 160 GeV

HZ: 250 GeV

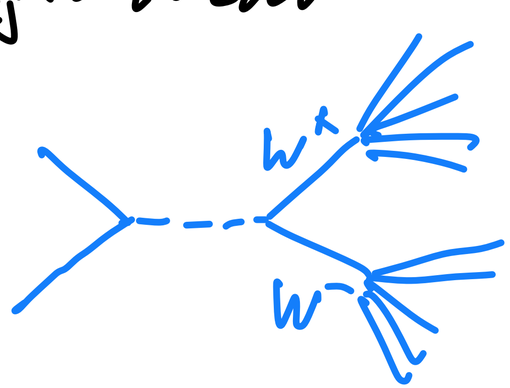
tt: 350 GeV

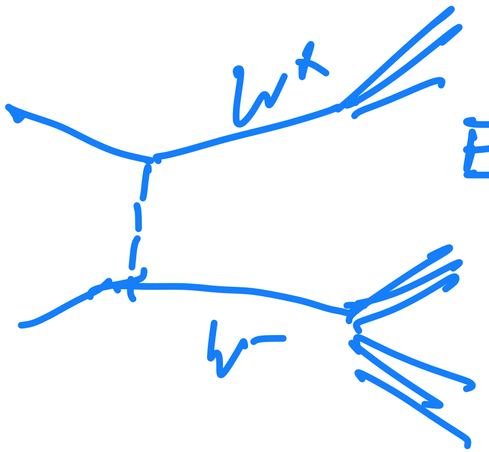
ttH, ZHH: 500 GeV

vvHH, BSM: 1+ TeV



$E_j \approx 45$ GeV





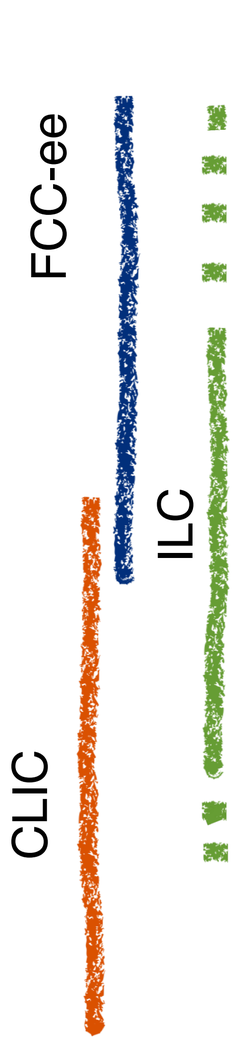
$E_j \sim 45$ GeV

Frank Simon (frank.simon@kit.edu)

Energy

Initial and Final States

- Collider dependent - but often less than you naively assumed



Z-pole: 91 GeV

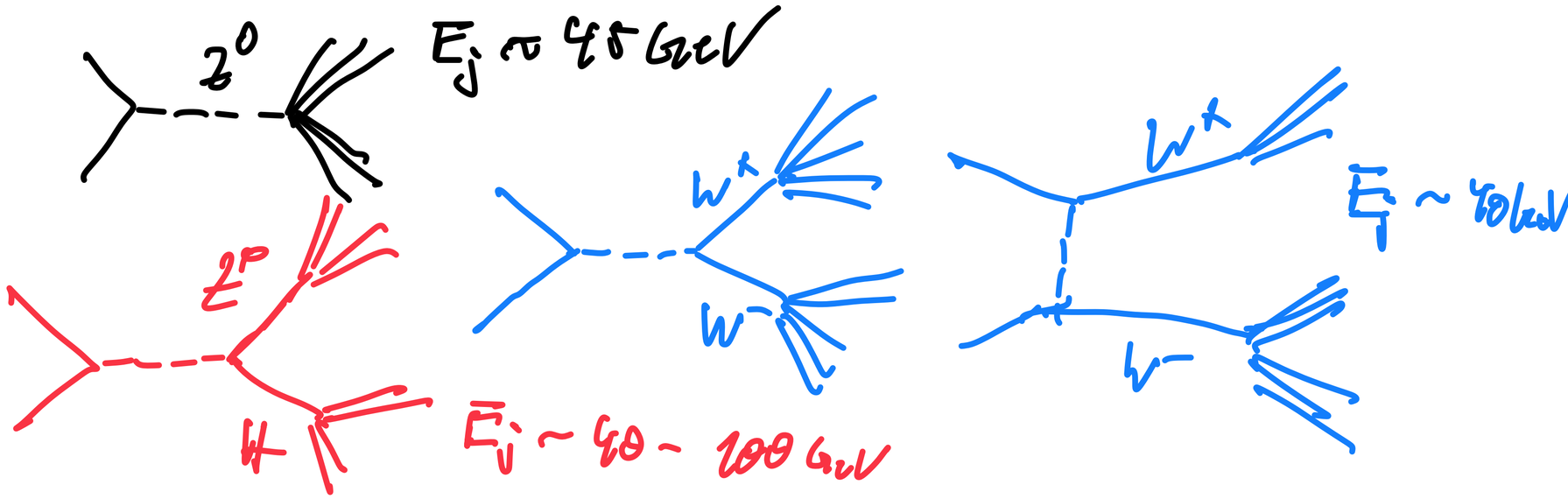
WW 160 GeV

HZ: 250 GeV

tt: 350 GeV

ttH, ZHH: 500 GeV

vvHH, BSM: 1+ TeV

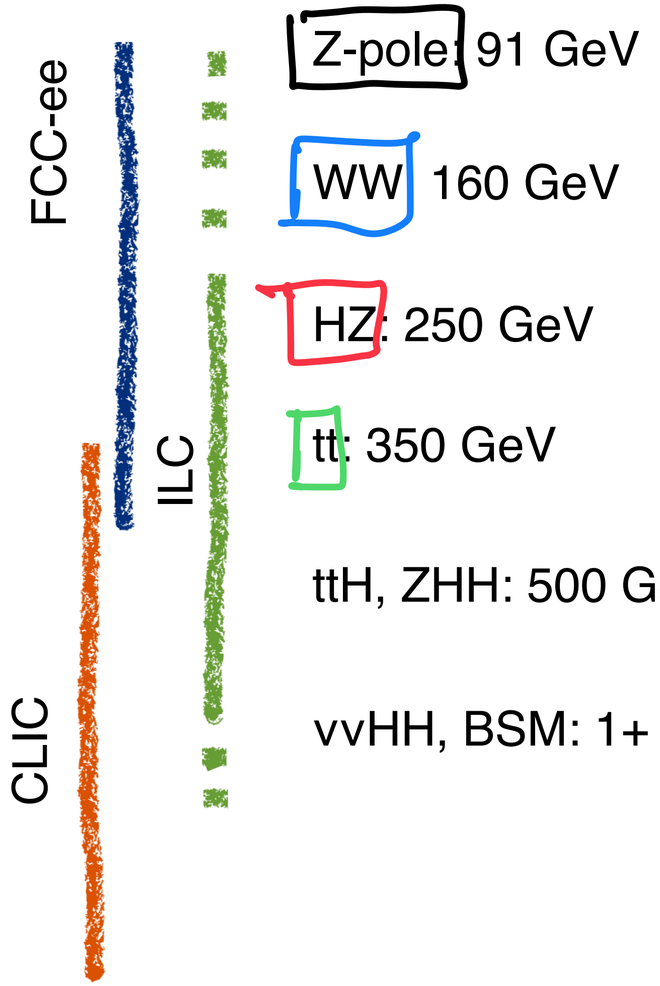


Frank Simon (frank.simon@kit.edu)

Energy

Initial and Final States

- Collider dependent - but often less than you naively assumed



Z-pole: 91 GeV

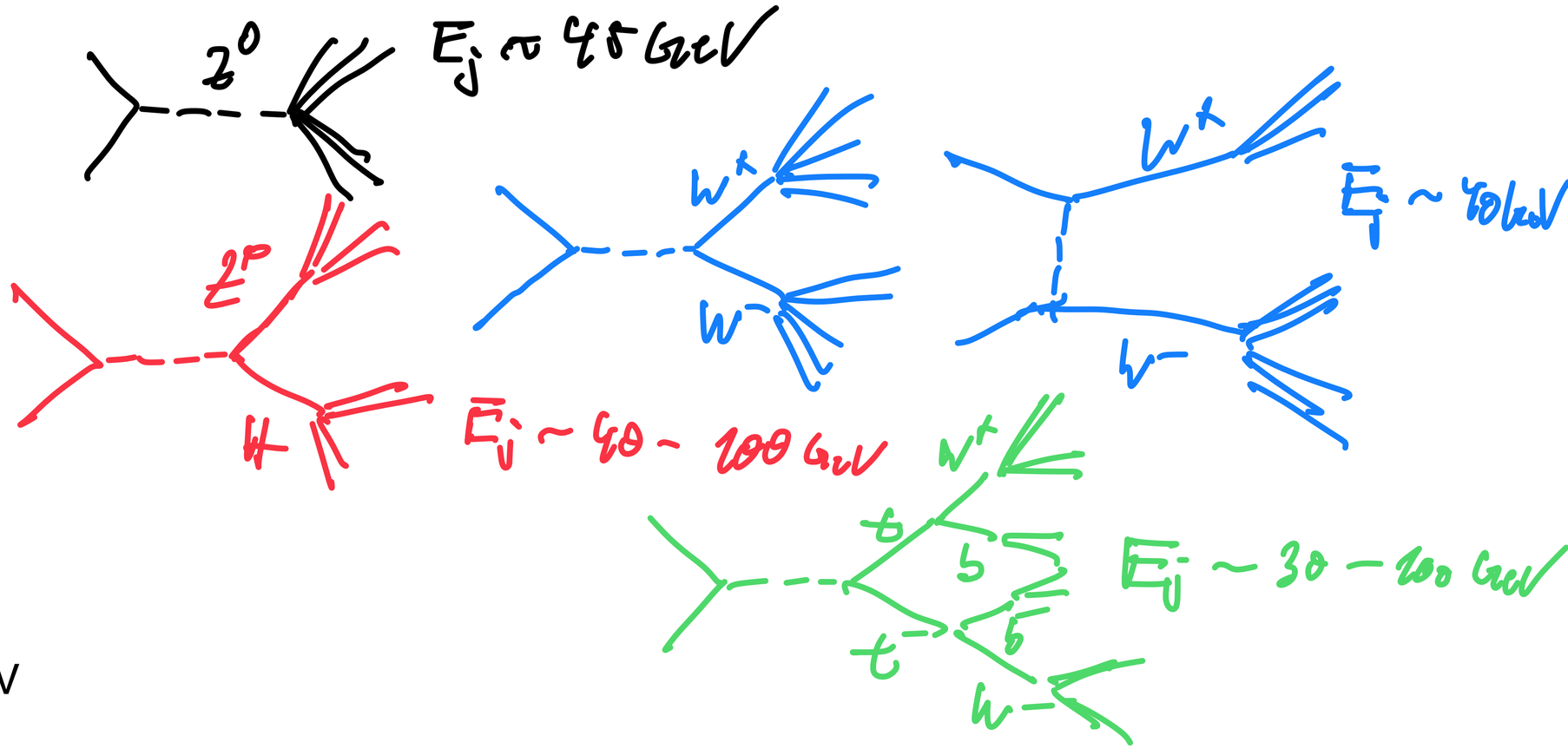
WW 160 GeV

HZ: 250 GeV

tt: 350 GeV

ttH, ZHH: 500 GeV

vvHH, BSM: 1+ TeV



Frank Simon (frank.simon@kit.edu)

Energy

Initial and Final States

- Collider dependent - but often less than you naively assumed

FCC-ee

ILC

CLIC

Z-pole: 91 GeV

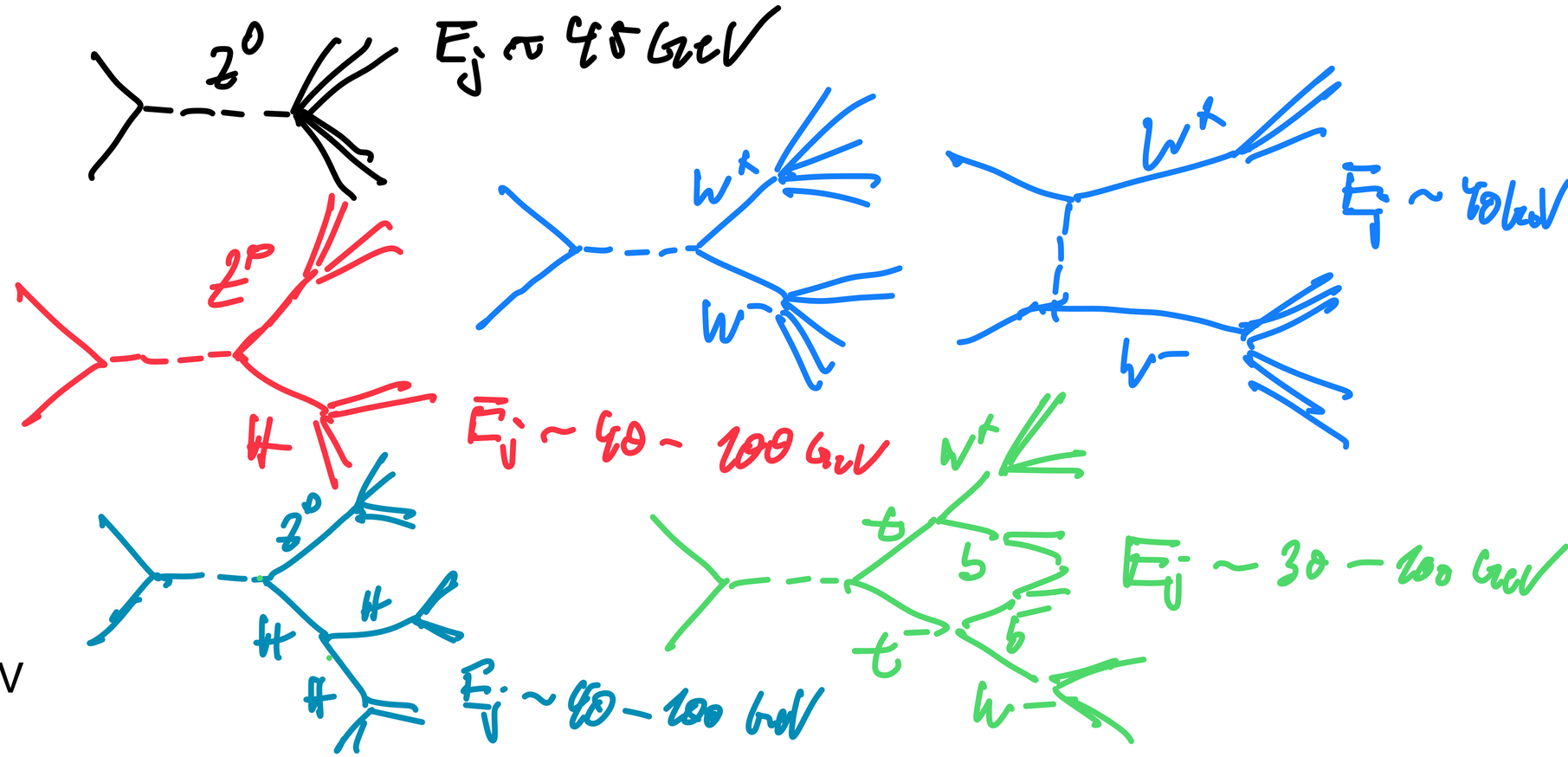
WW: 160 GeV

HZ: 250 GeV

tt: 350 GeV

ttH, ZHH: 500 GeV

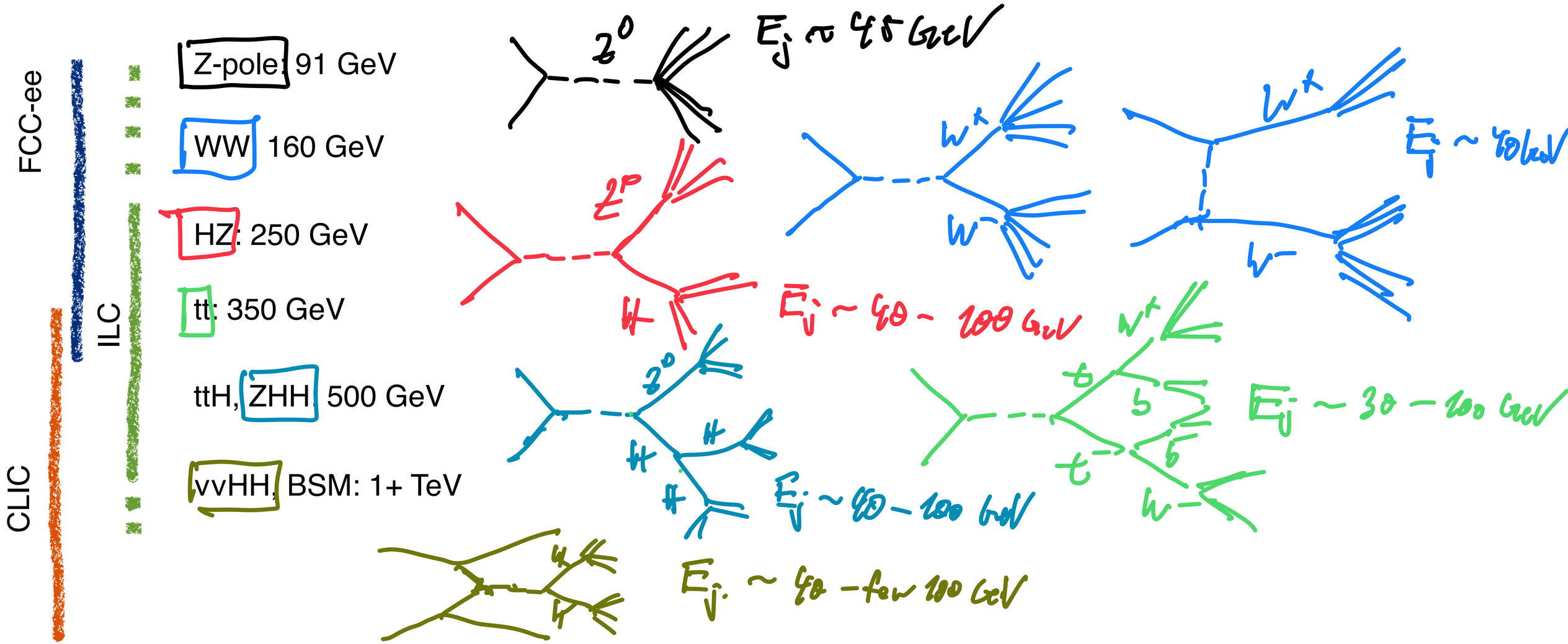
vvHH, BSM: 1+ TeV



Energy

Initial and Final States

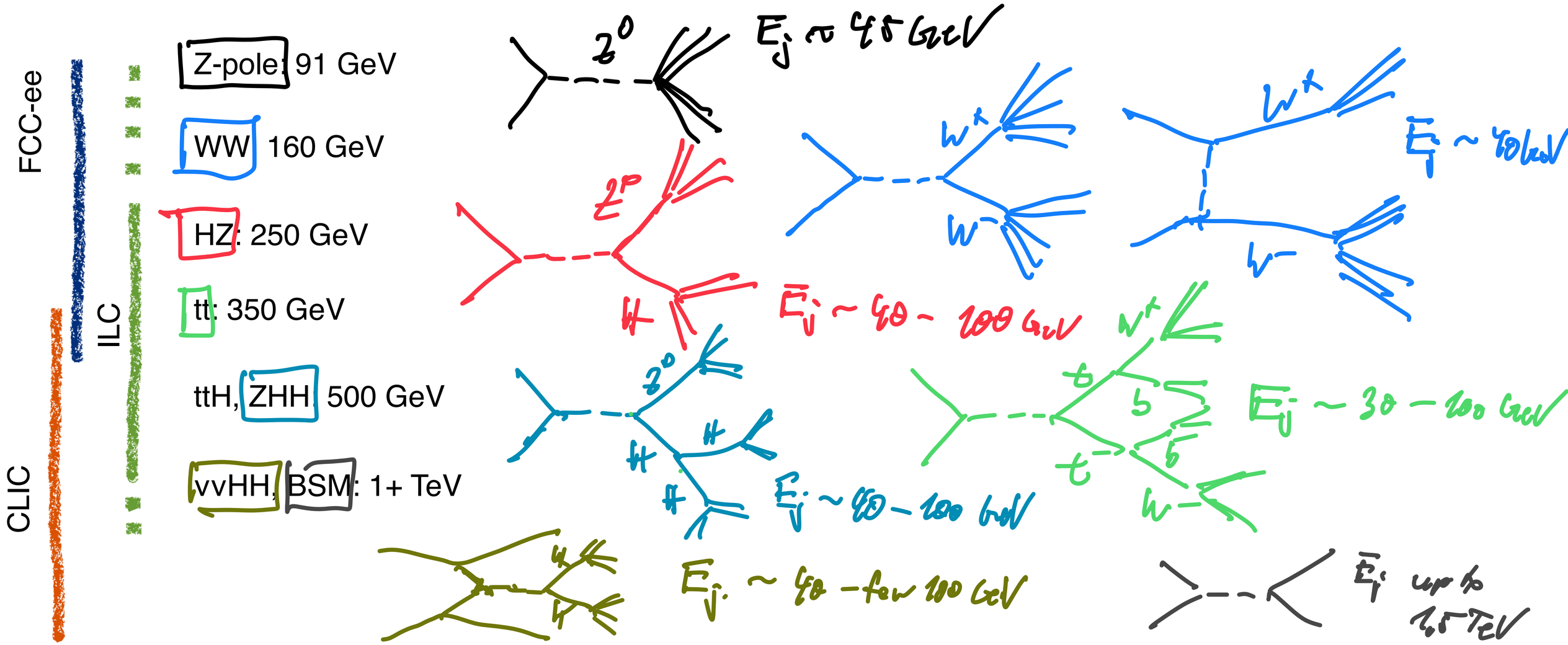
- Collider dependent - but often less than you naively assumed



Energy

Initial and Final States

- Collider dependent - but often less than you naively assumed



Frank Simon (frank.simon@kit.edu)

The Main Drivers

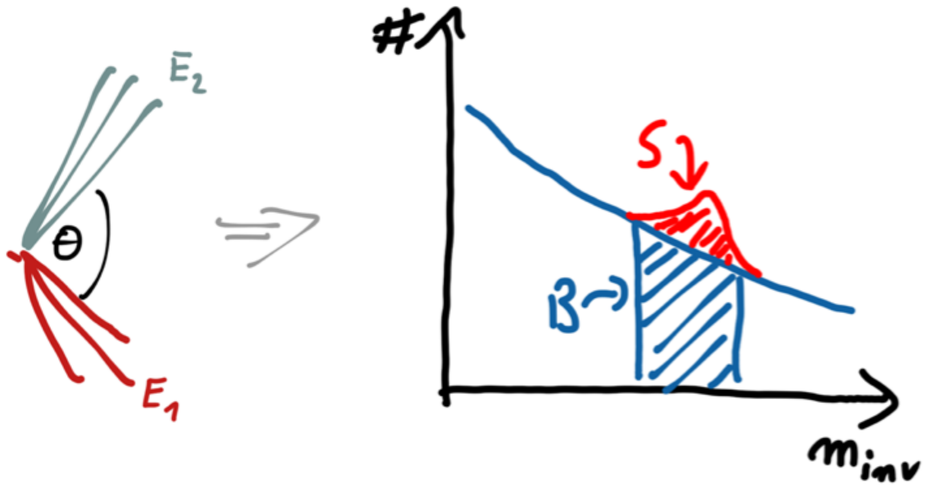
Physics - Evolving with Collider Energy

Frank Simon (frank.simon@kit.edu)
Institute for Data Processing and Electronics

The Jet Case

A new level of Jet Energy Resolution

- A common element in final states: two-jet decays of heavy bosons



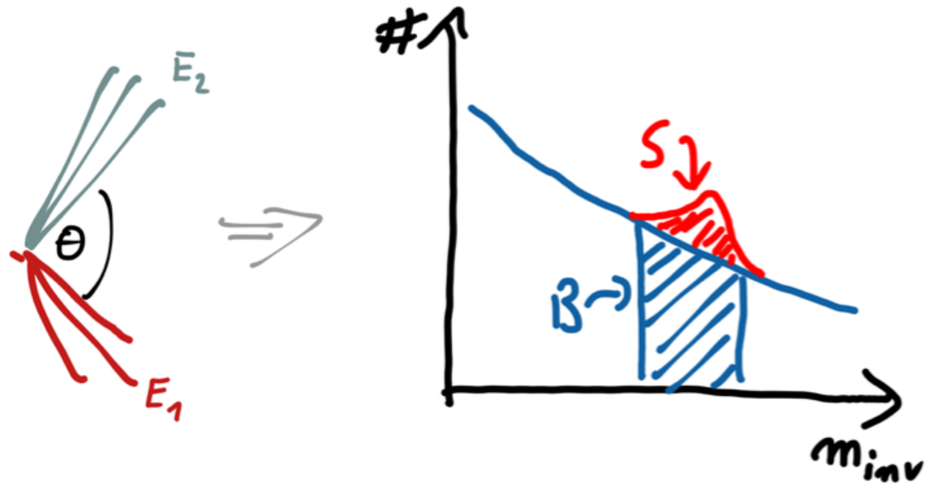
significance: $\frac{S}{\sqrt{S+B}}$ directly depends on invariant mass resolution

given by opening angle and jet energies

The Jet Case

A new level of Jet Energy Resolution

- A common element in final states: two-jet decays of heavy bosons

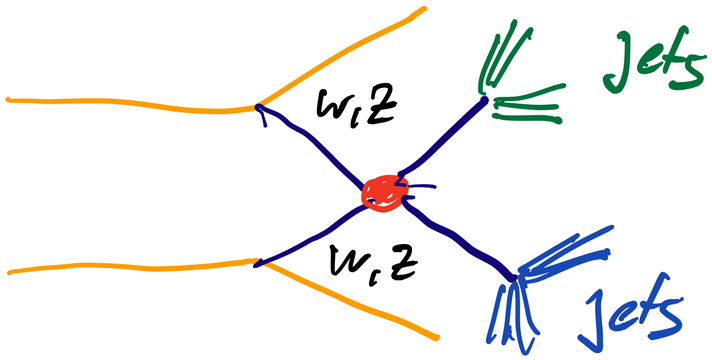


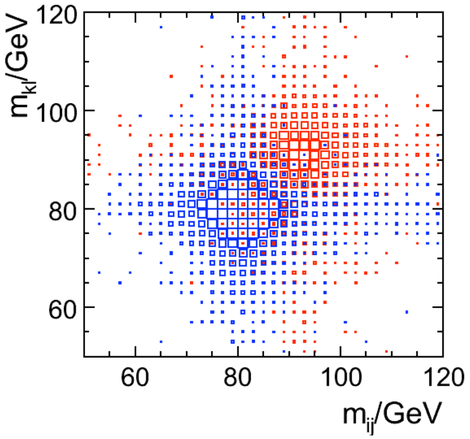
significance: $\frac{S}{\sqrt{S+B}}$

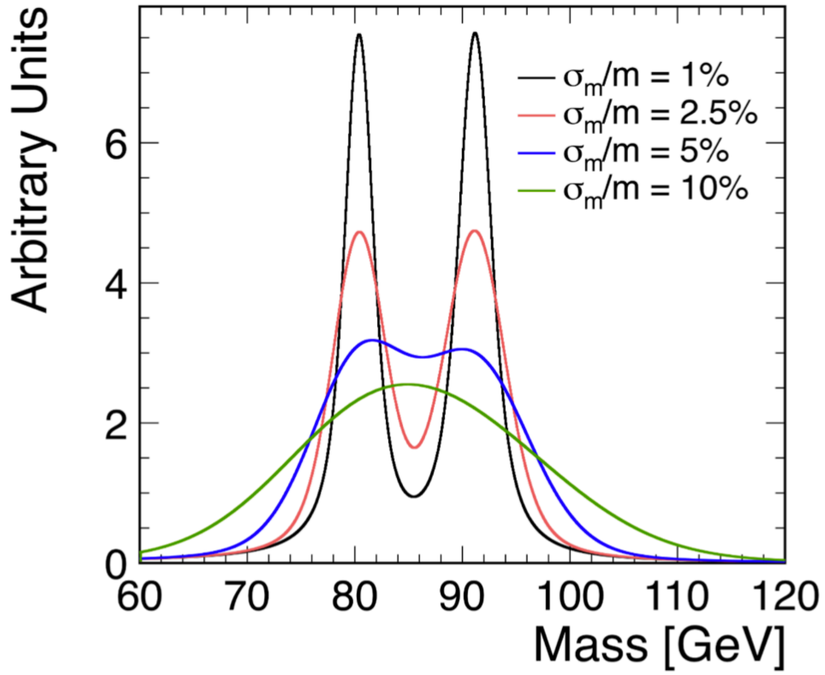
directly depends on invariant mass resolution

given by opening angle and jet energies

The classic PR example: Separation of Ws and Zs







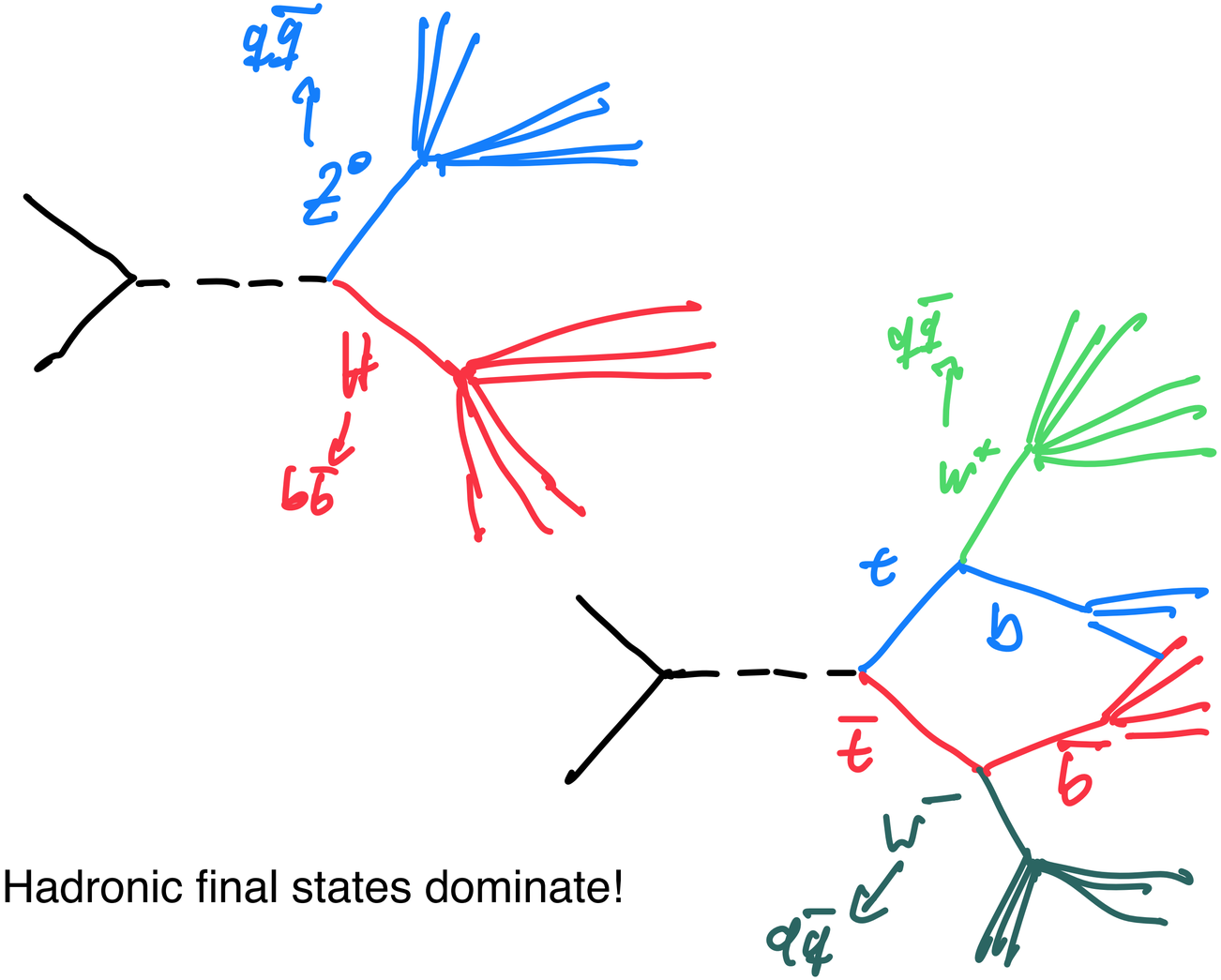
want:

JER 3 - 5%

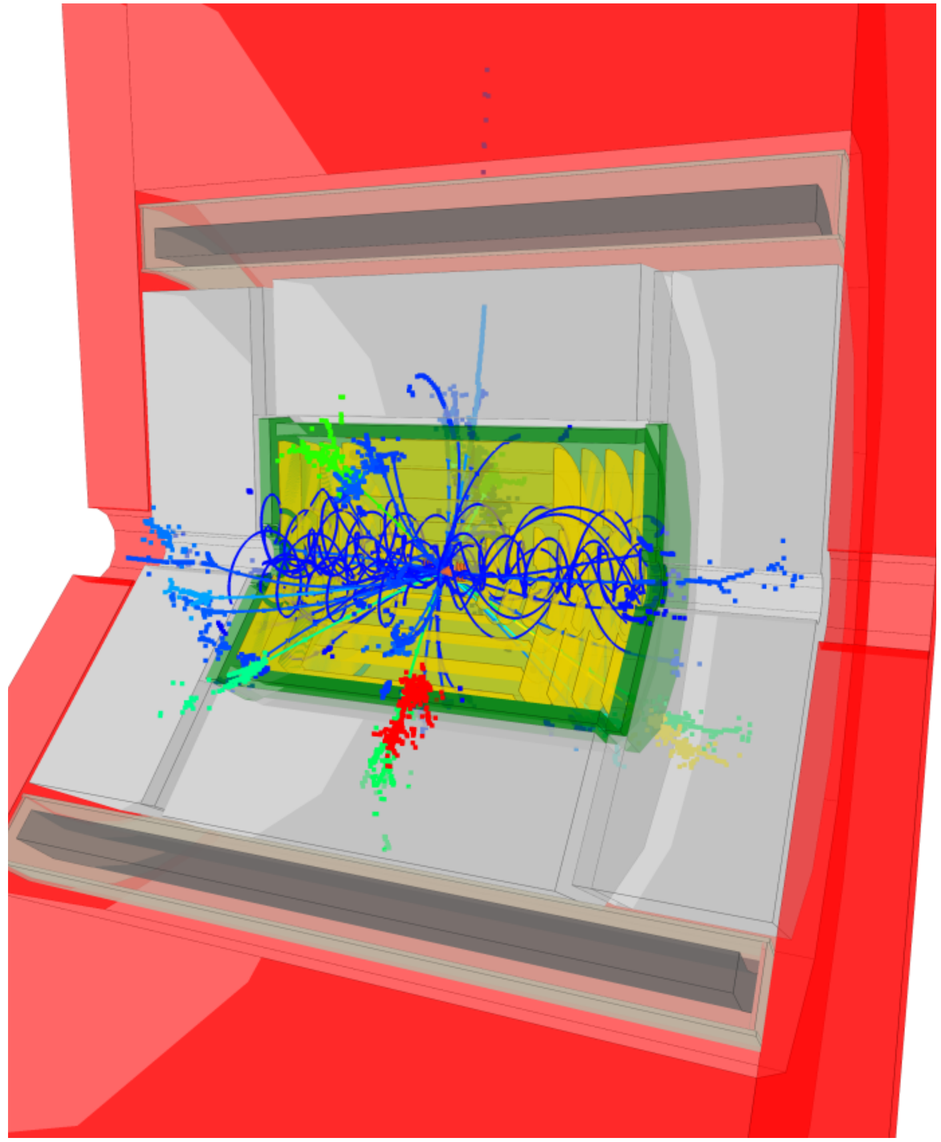
The Jet Case

Physics Examples

- Higgs and top pair events as key drivers for jet performance



Hadronic final states dominate!



The Jet Case

The Origin of the PFA Calorimeter Concept

- The challenge of jets: A mix of particles, primarily hadrons - which are measured in the “weakest” detector: The HCAL

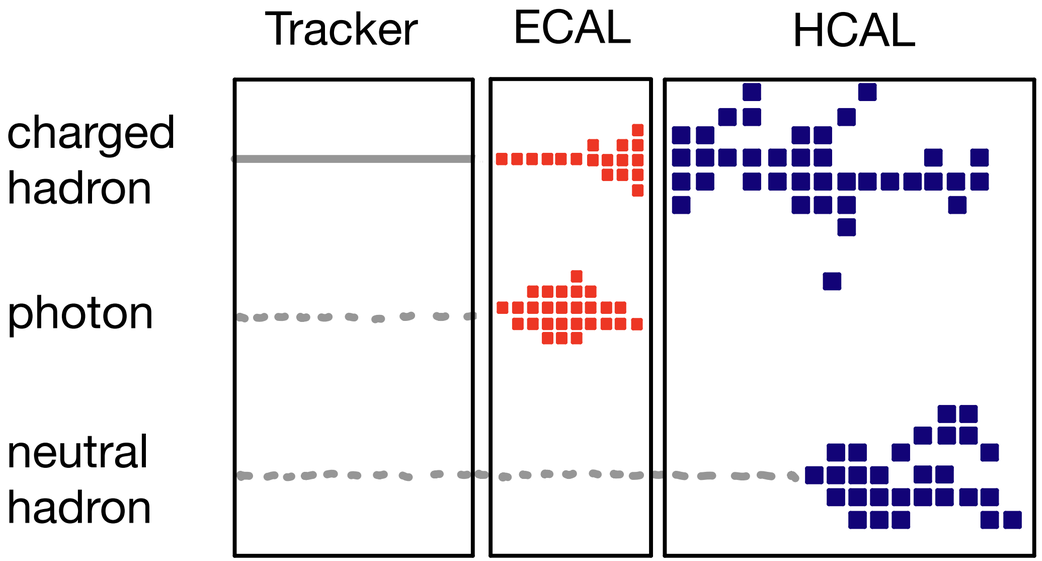
- The typical jet composition:
  - 60% charged (primarily $\pi^{+/-}$)
  - 30% photons (from π^0 decay)
  - 10% neutral hadrons (n, K_L)

Jet reconstruction with *calorimeters only*

~ 60% - 100+% / Sqrt(E)

~ 10% - 20% / Sqrt(E)

~ 60% - 100+% / Sqrt(E)



The Jet Case

The Origin of the PFA Calorimeter Concept

- The challenge of jets: A mix of particles, primarily hadrons - which are measured in the “weakest” detector: The HCAL

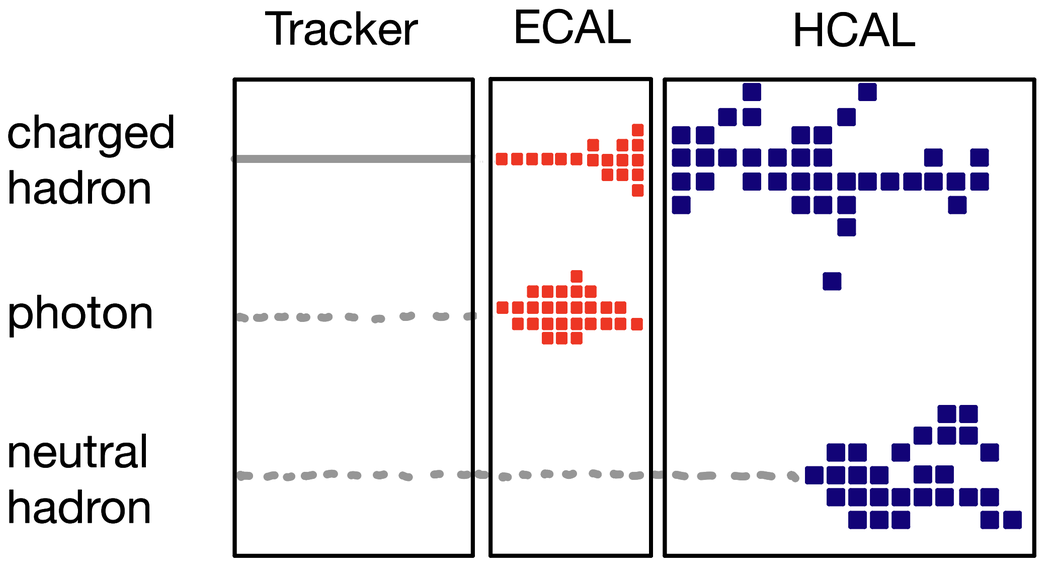
- The typical jet composition:
  - 60% charged (primarily $\pi^{+/-}$)
  - 30% photons (from π^0 decay)
  - 10% neutral hadrons (n, K_L)

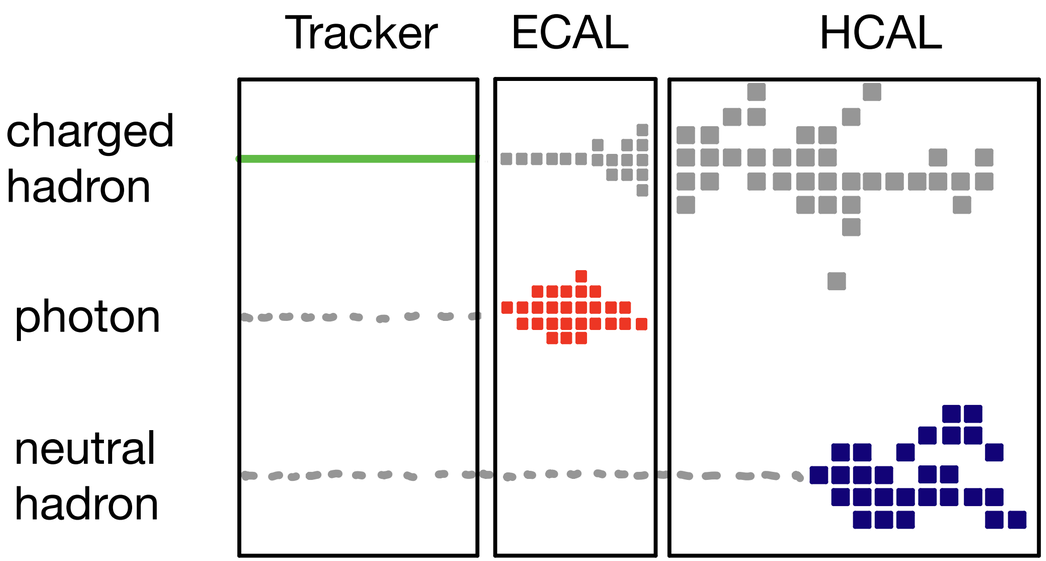
Jet reconstruction with *Particle Flow*

excellent measurement in tracker, negligible resolution

~ 10% - 20% / Sqrt(E)

~ 60% - 100+% / Sqrt(E)





The Jet Case

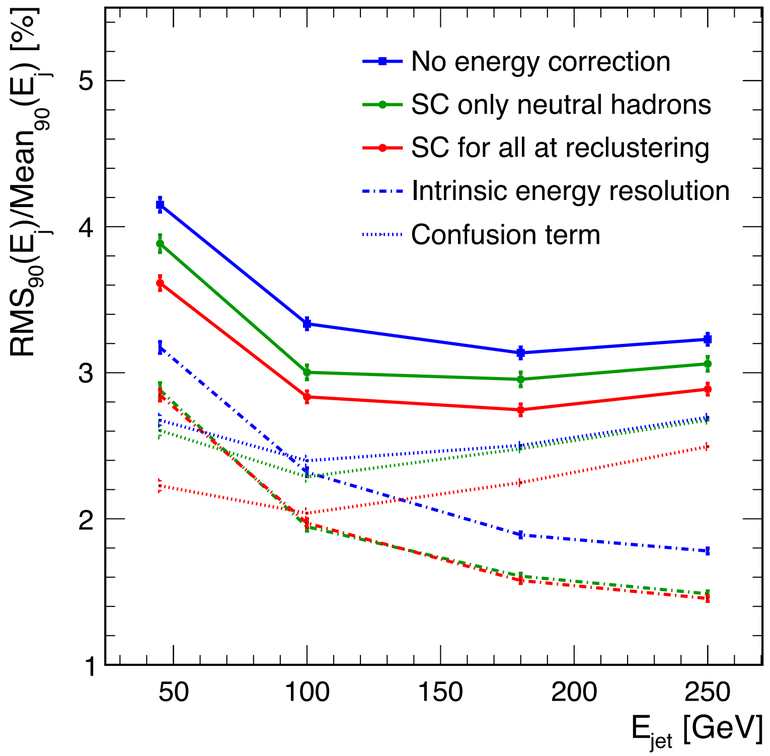
Depending on Energy, Energy Resolution

- When using PFA, confusion (= shower separation, pattern recognition) and intrinsic energy resolution of the calorimeter system drive performance. System details determine “cross-over”

A CALICE-like calorimeter,

PandoraPFA + SC

EPJC 77, 698 (2017)



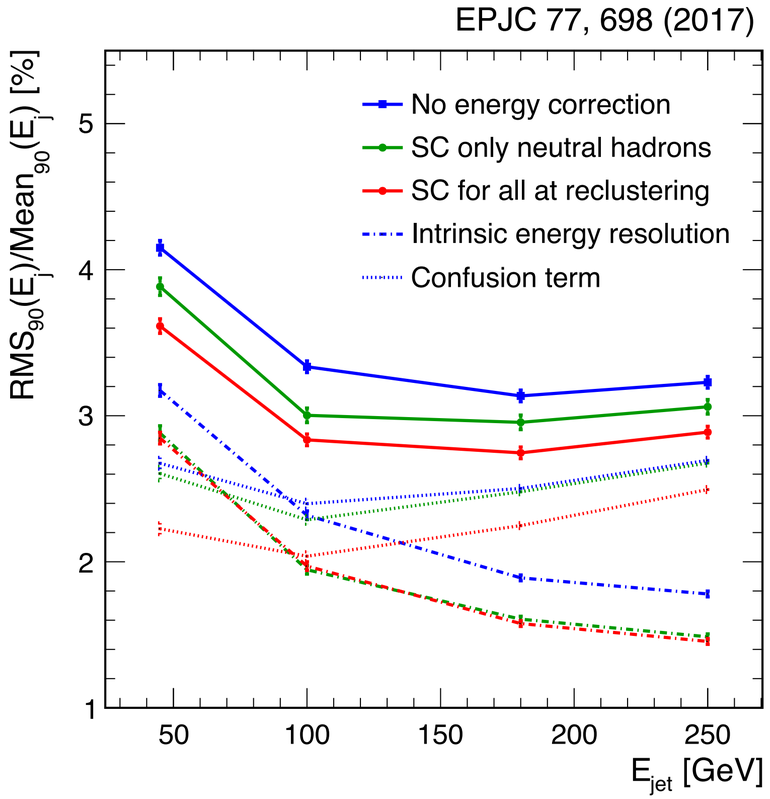
Frank Simon (frank.simon@kit.edu)

The Jet Case

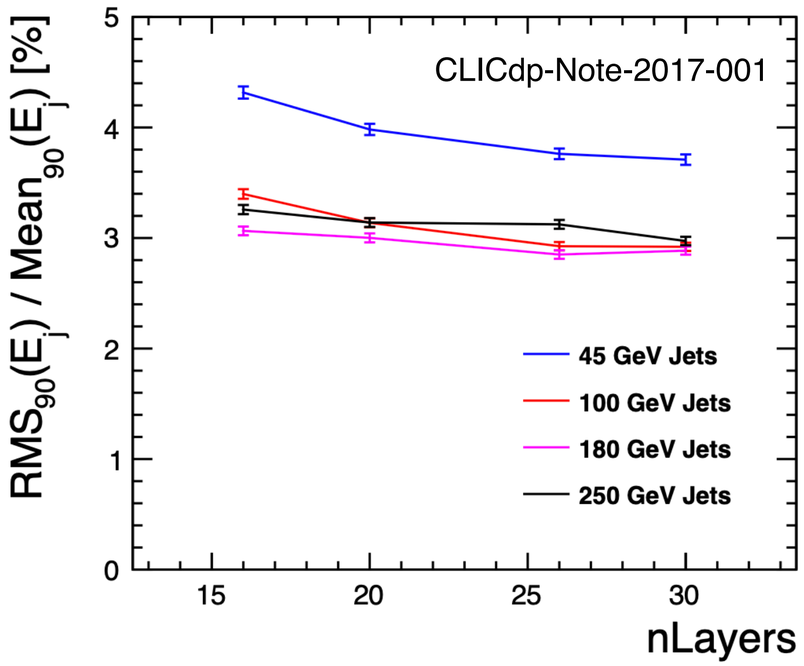
Depending on Energy, Energy Resolution

- When using PFA, confusion (= shower separation, pattern recognition) and intrinsic energy resolution of the calorimeter system drive performance. System details determine “cross-over”

A CALICE-like calorimeter, PandoraPFA + SC



Jet energy resolution only very weakly depends on ECAL resolution for higher-energy jets (> ~ 75 GeV)

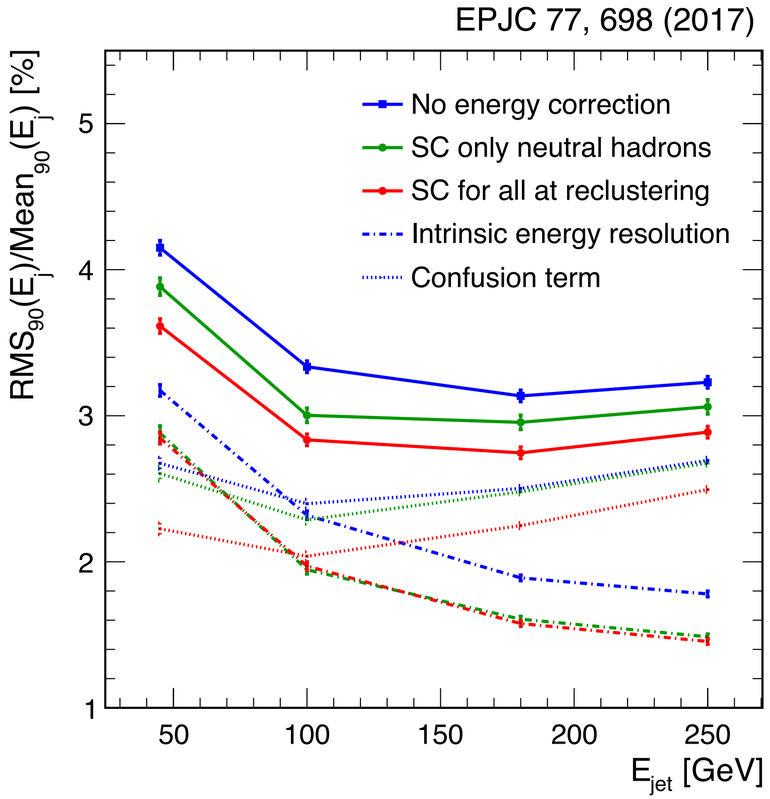


The Jet Case

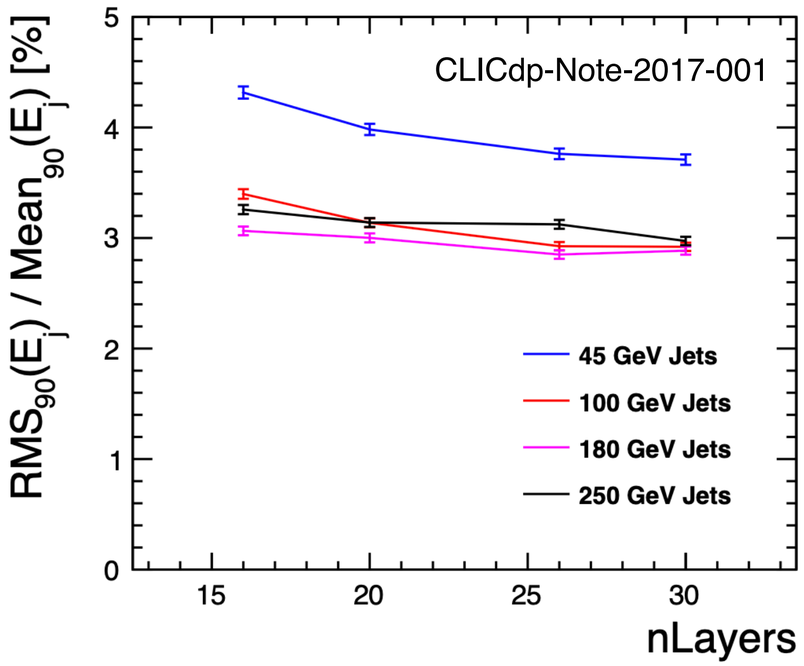
Depending on Energy, Energy Resolution

- When using PFA, confusion (= shower separation, pattern recognition) and intrinsic energy resolution of the calorimeter system drive performance. System details determine “cross-over”

A CALICE-like calorimeter, PandoraPFA + SC



Jet energy resolution only very weakly depends on ECAL resolution for higher-energy jets (> ~ 75 GeV)



Emphasis on granularity vs resolution depends on collider energy / physics focus

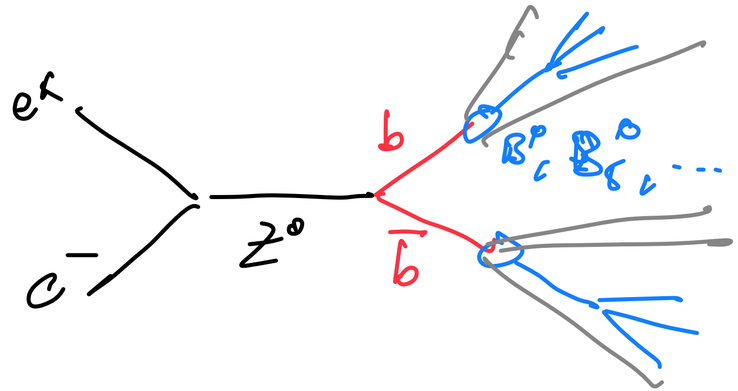
The Flavor Case

Possible with a Tera-Z Program

- Exploits extreme number of b pairs at FCC-
  Still less developed than other aspects of the HF physics program

  Comes with relative unique detector challenges - also for calorimetry:

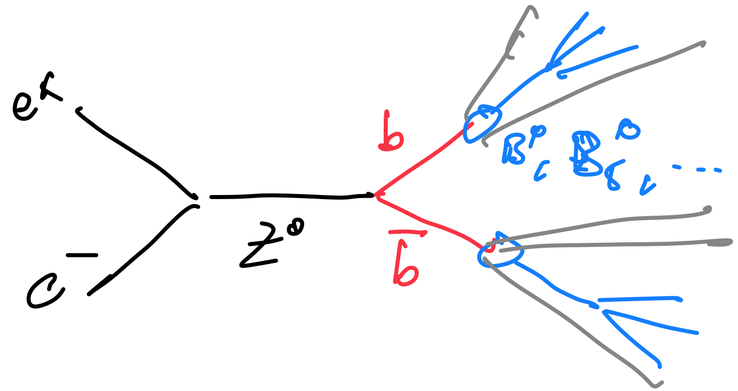
  Emphasis on “decay chains”, individual particles rather than partons from decay of heavy states.



The Flavor Case

Possible with a Tera-Z Program

- Exploits extreme number of b pairs at FCC-
  Still less developed than other aspects of the HF physics program

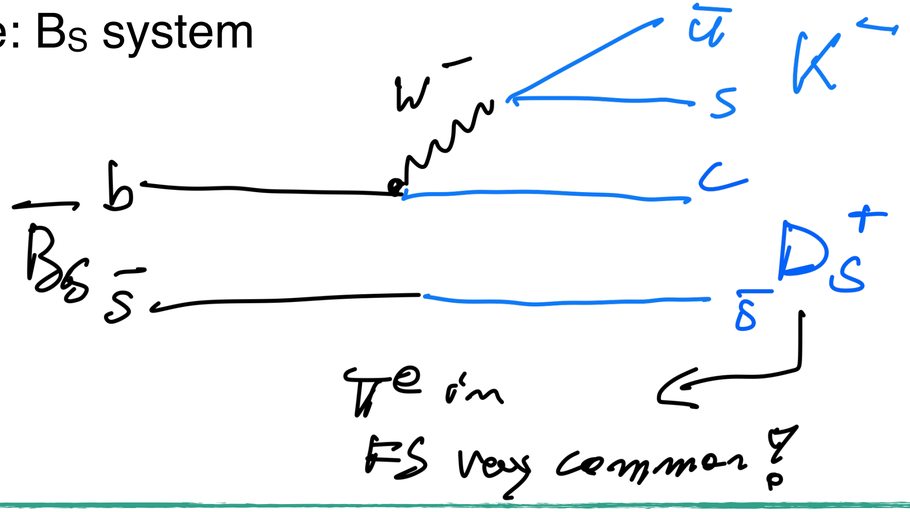


Comes with relative unique detector challenges - also for calorimetry:
Emphasis on “decay chains”, individual particles rather than partons from decay of heavy states.

Vertexing often in focus - but calorimetry also highly relevant: Neutral particles in final states!

CKM measurements, CP violation

Here: B_S system



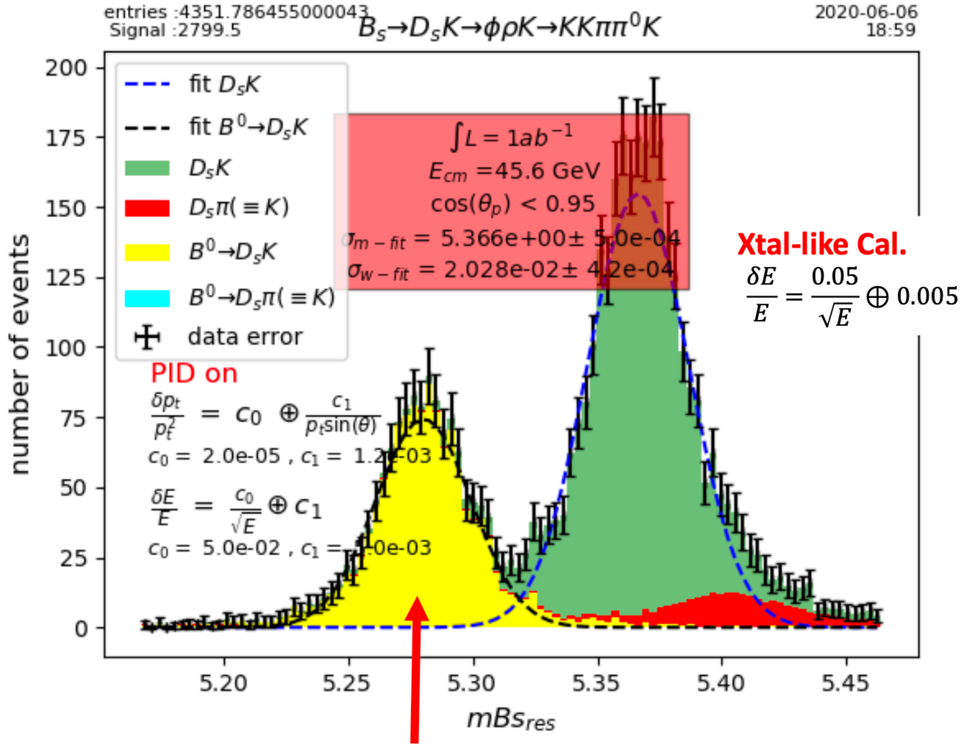
A few 10 GeV B’s

=> Energy of final state particles typically a few GeV - 10 GeV - incl. γ from π^0

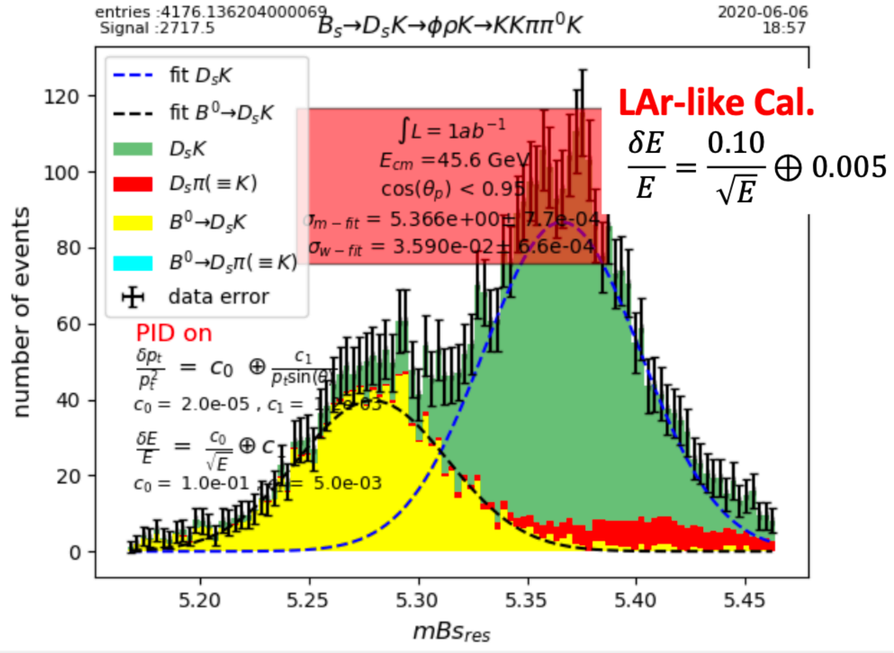
The Flavor Case

The B_s -> D_sK Example

- Here photon energy resolution *really* matters:
  Clean identification and good reconstruction of π^0, separation of D and D_s



« Irreducible bkg » , only mass resolution can beat it



One case for excellent photon energy resolution.

The Tau Case

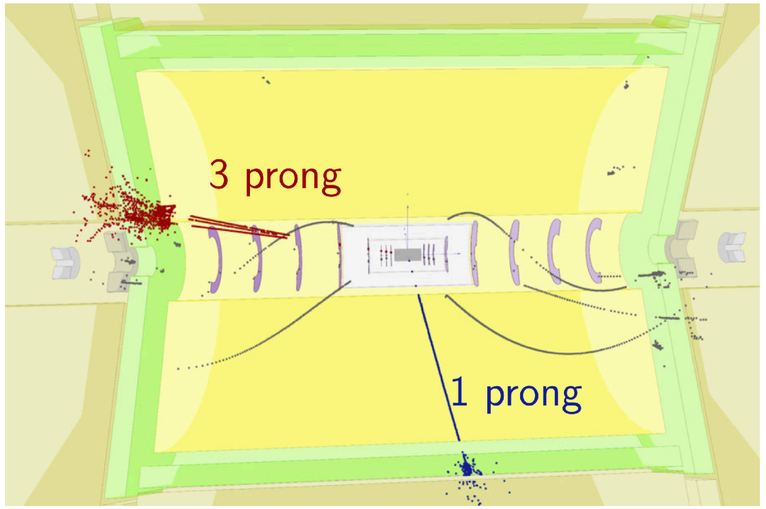
Relevant in different scenarios

- Some diversity:
  - Low-energy τ's as part of the flavor physics program: In decay chains of B's

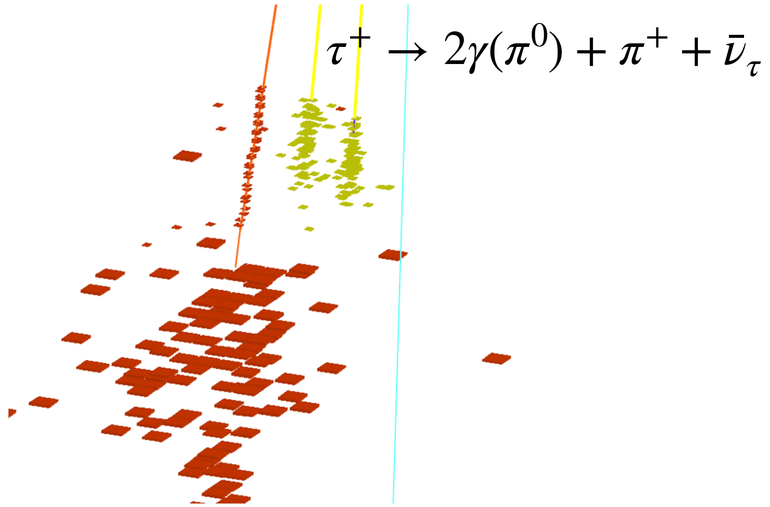
Vertexing, PID,
π^0 reconstruction

  - High-energy τ's: From heavy boson decays: Z, H, (W)

Typical signature:
Low-multiplicity jet: charged pions,
photons (from π^0)



CLIC 1.4 TeV Hvv, H-> ττ



Key calorimeter features: (lateral) granularity, em energy resolution

The Precision Case

Requirements at the Z Pole

- A few 10^{12} Zs -> Extreme statistical precision, requires pushing down systematics.
  Of relevance to calorimeters:
  - Luminosity measurement - highly precise acceptance of luminosity calorimeters
  - Long-term stability of detector

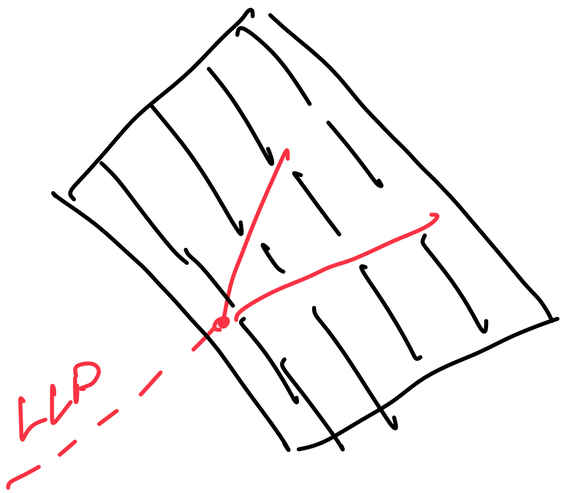
- Resolution requirements primarily from additional programs pursued at the Z pole, in particular flavour

The BSM Case

Rough Ideas

- Rich spectrum of physics possibilities - two examples:

LLPs



Calorimeter features:

tracking capability,

granularity,

timing (= TOF),

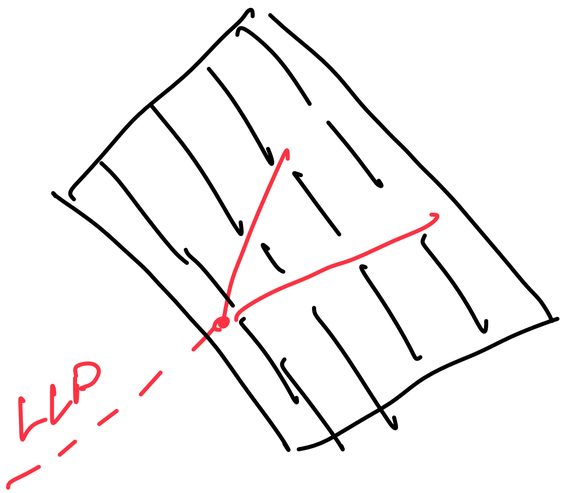
hermeticity

The BSM Case

Rough Ideas

- Rich spectrum of physics possibilities - two examples:

LLPs



Calorimeter features:

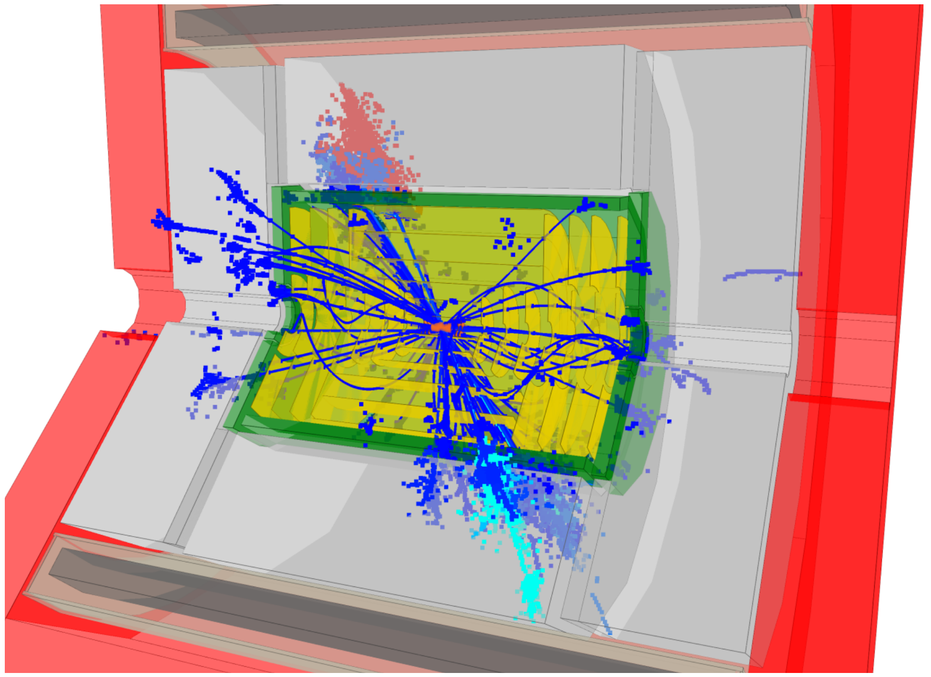
tracking capability,

granularity,

timing (= TOF),

hermeticity

Measurements at highest energies:



Capability for 1.5 TeV jets:

depth for containment

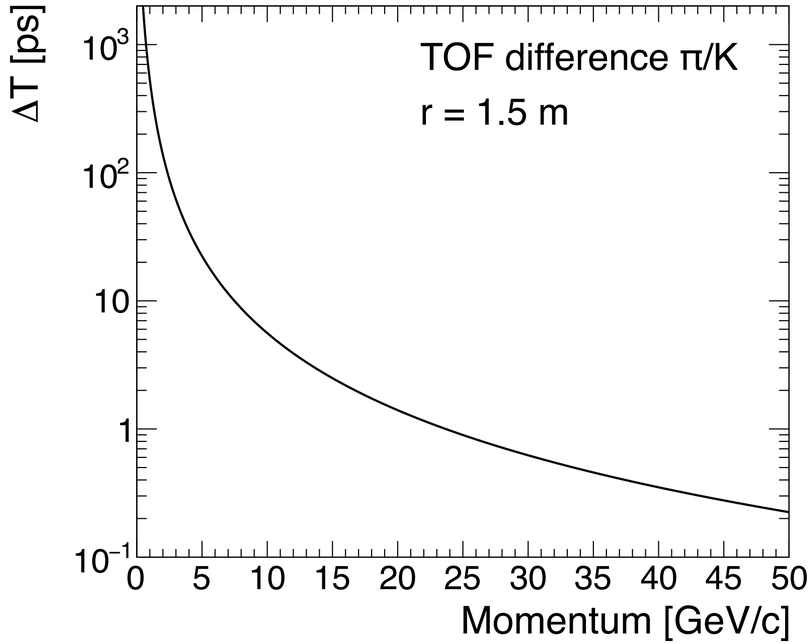
(timing to cope with CLIC conditions)

tt @ 3 TeV

A Case For Timing

Still developing

- The obvious application: TOF for PID - could be provided by calorimeter systems

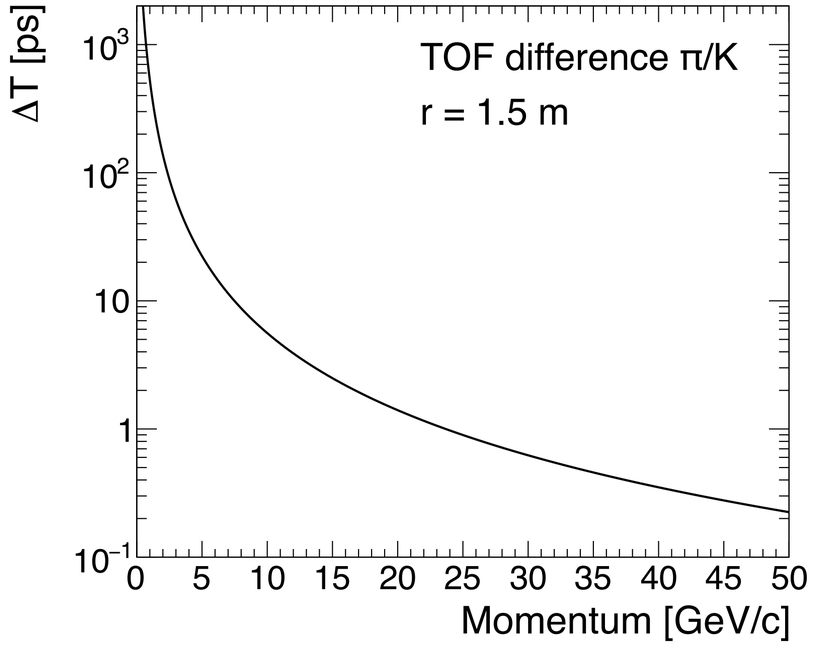


Frank Simon (frank.simon@kit.edu)

A Case For Timing

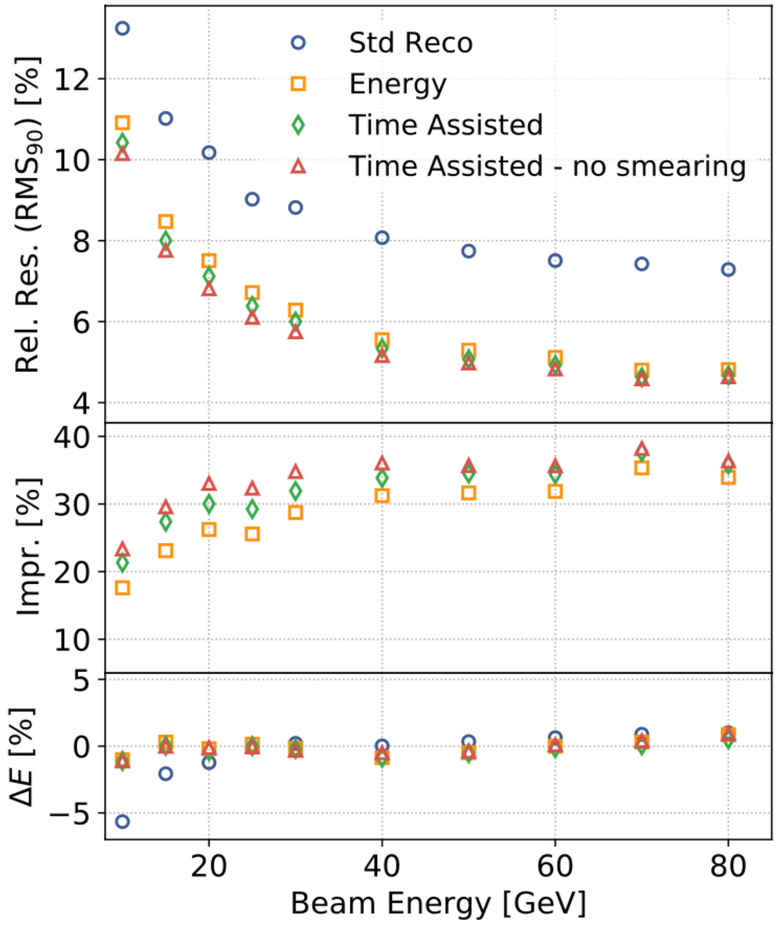
Still developing

- The obvious application: TOF for PID - could be provided by calorimeter systems



Timing also beneficial for hadronic energy reconstruction (= software compensation). More potential with ML techniques?

JINST 17, P08027 (2022)

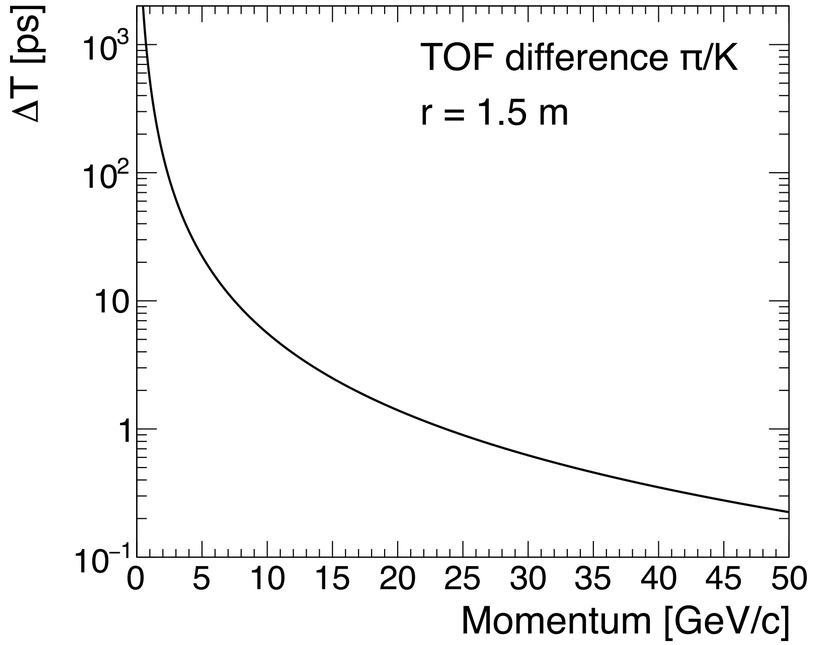


Frank Simon (frank.simon@kit.edu)

A Case For Timing

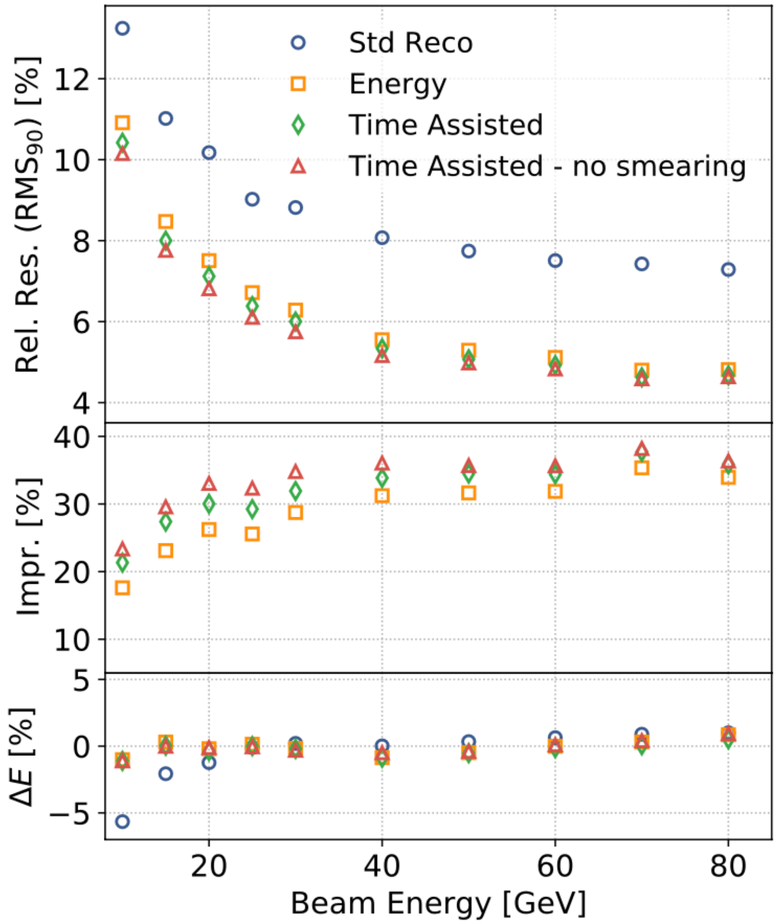
Still developing

- The obvious application: TOF for PID - could be provided by calorimeter systems



Timing also beneficial for hadronic energy reconstruction (= software compensation). More potential with ML techniques?

JINST 17, P08027 (2022)



Still a lot to explore:

Possible benefit of timing for pattern recognition in PFA calorimeters, …

Putting Things Together

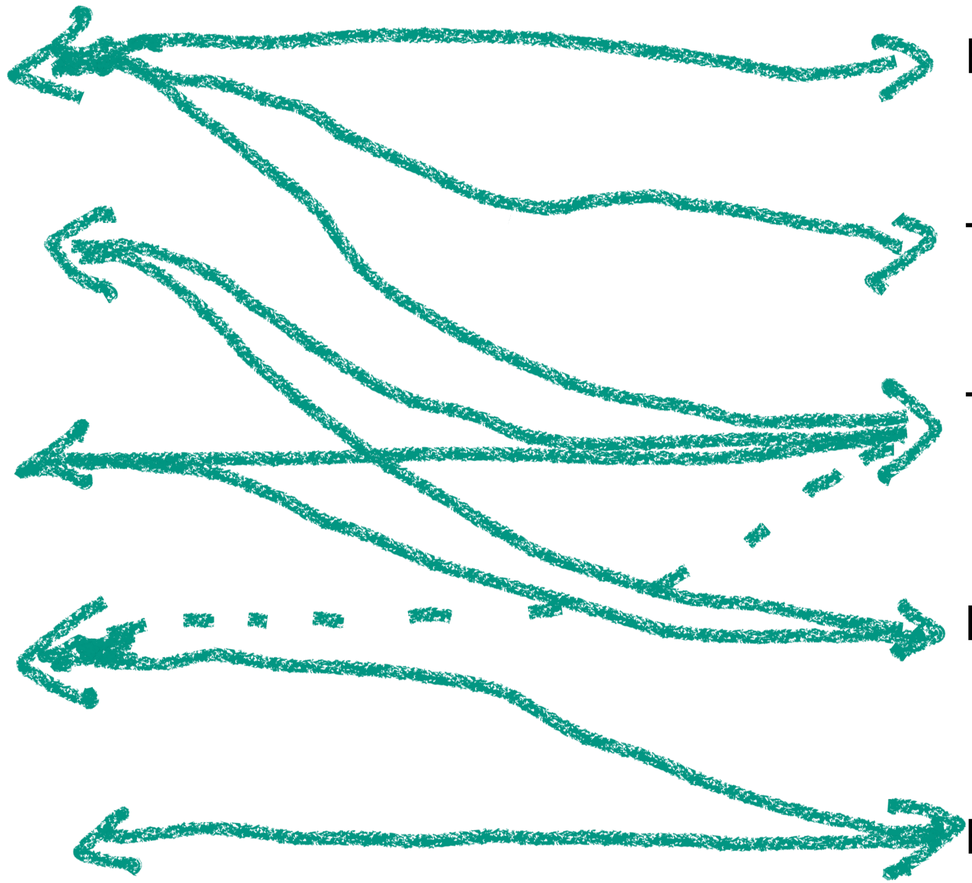
An Attempt to draw some Conclusions

Frank Simon (frank.simon@kit.edu)

Main Observations

What do we need from Calorimetry?

- The main performance criteria for a Higgs Factory calorimeter system:



Jet energy resolution

Electromagnetic resolution

Lateral segmentation

3D Granularity

(NB: Can also help JER: PFA)

Timing

(NB: Can also help JER: PFA, had. resolution)

Higgs

Top

Tau (NB: Also some relevance for Higgs)

Flavor

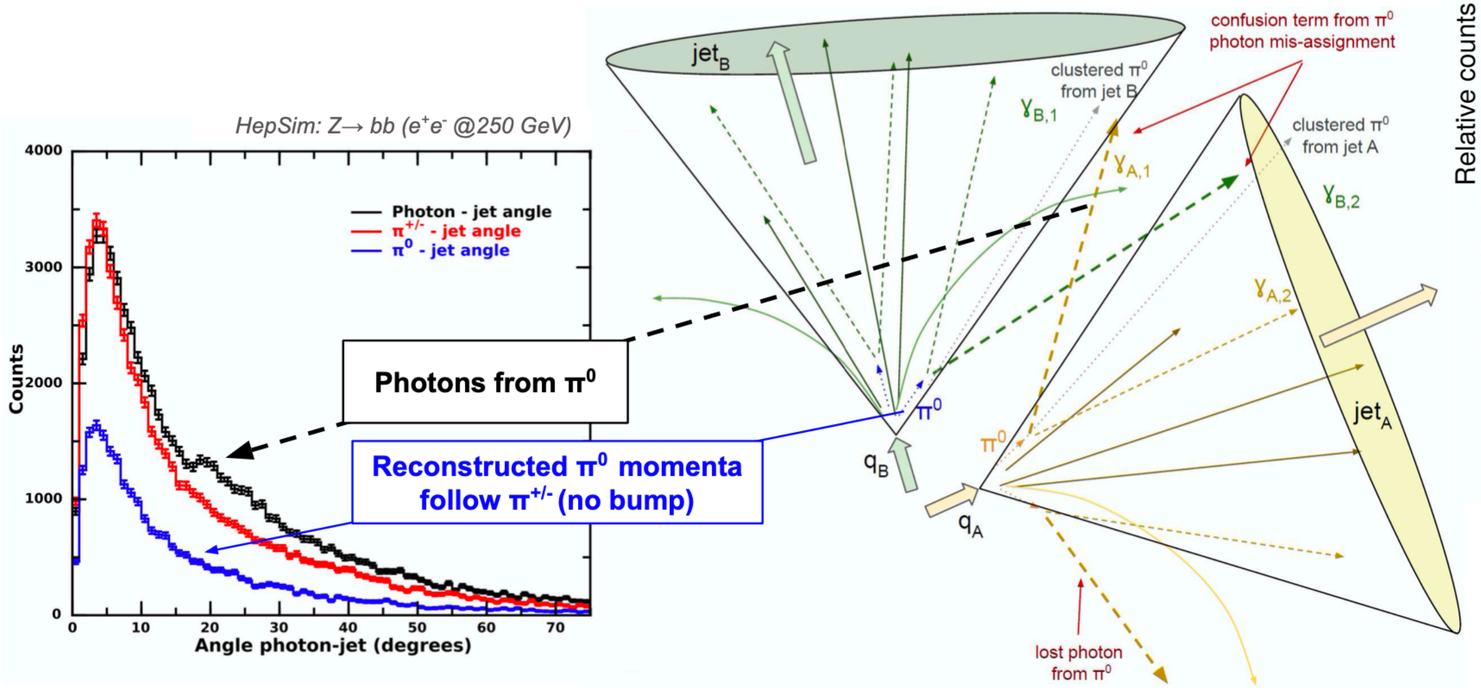
BSM (LLPs)

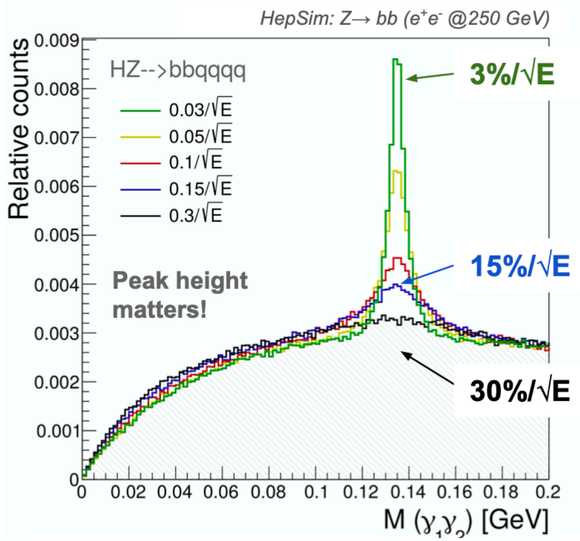
Mixing Requirements

Things are more "greyscale" than they appear…

- One example: electromagnetic resolution.

Photons from π^0 increase confusion between jets





Could be addressed by explicit π^0 reconstruction in PFA. Requires excellent γ energy resolution.

Bottom Line

And further studies

- Calorimeters are central systems for future Higgs Factories

- The “core program” common to all proposed facilities emphasizes jet energy resolution
  - Detector concepts around PFA calorimeters well established; dual readout; also LAr
- Flavor physics (at the Z pole) revives interest in excellent em resolution
- BSM signatures (LLPs et al.) impose explicit granularity and timing requirements
- Stability particularly important for extreme EW precision

⇨ FCC-ee with its Tera-Z program adds diversity to the requirements - not all satisfied by a single current concept simultaneously

- Significant need for further studies:
  Further understand requirements - and the match to possible technological solutions
  Fully establish benefits (and requirements) for timing - depending on technology