Towards a physics driven assessment of detector requirements

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Philosophy

- The interest in the TH/pheno community is to **assess the physics reach at the highest possible energies** sqrt(s) = 10, 14, 30 TeV

- Guiding principles for designing a detector are machine constraints and physics

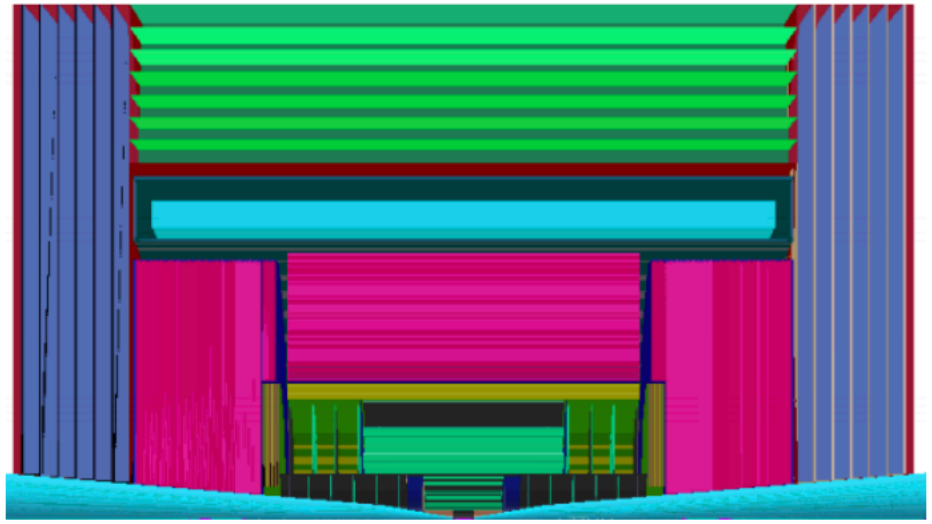
- A generic detector serves as a starting point for:
  - benchmarking physics reach of the machine
  - identify:
    - challenges of building such an experiment
    - topics where R&D needed

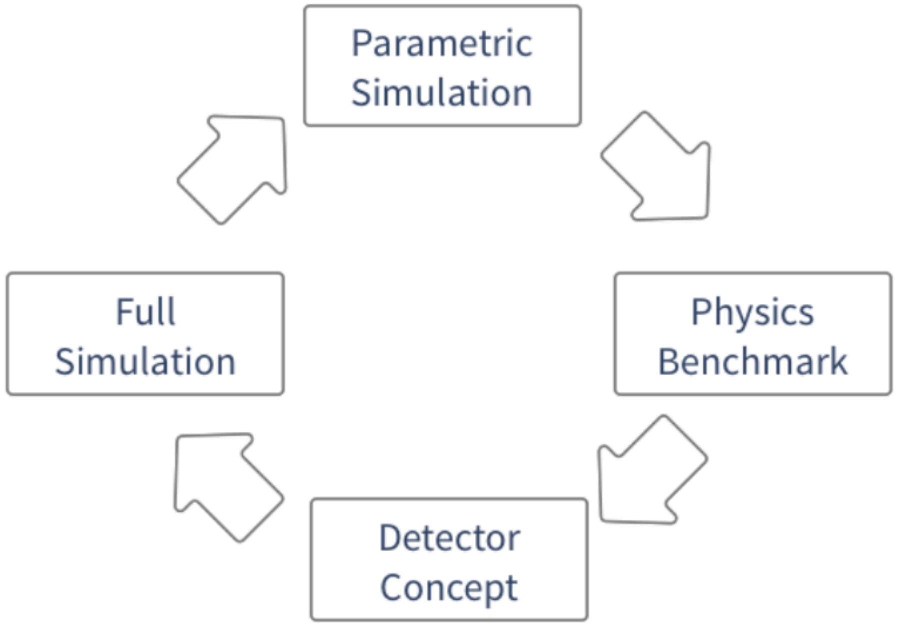
- Most likely, the outcome is not "THE OPTIMAL" detector. Maybe the optimal route will be to have several detectors optimized for specific signatures.

- Also, expected improvements in technology may lead to more ambitious and less-conventional approaches of detector concepts in the future

Approach

- Proposed approach:
  - Define **physics goals** via identifying key benchmark physics processes
  - **define a target** for the detector performance and **parameterise** it
  - **study benchmark physics** channels with **target performance**
  - study impact of **variations of detector performance** around nominal on physics
  - **iterate** on detector design



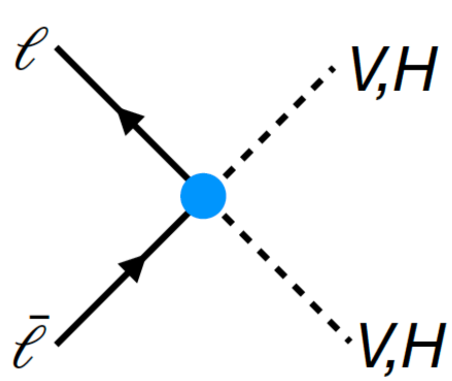


Physics goals for a high energy muon collider

- High energy (central) final states:
  - Precision via high energy probes:
    - μμ→XX:
      - ZH, WW, tt, cc, Hγ

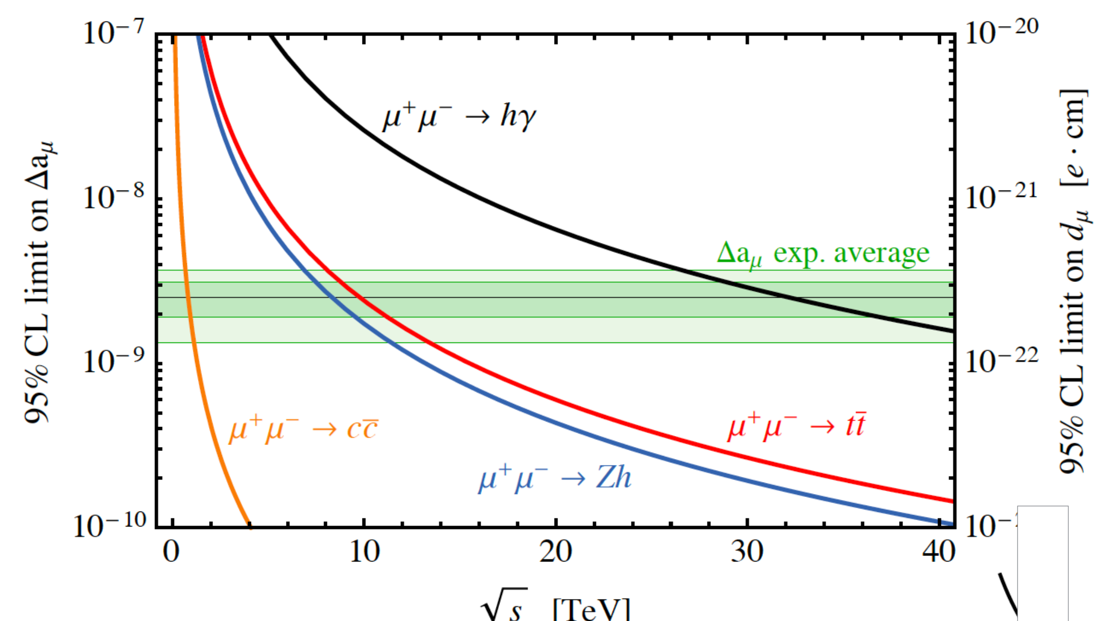
$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

⇒ **kinematic reach** probes large Λ



$$\ell^+\ell^- \to W^+W^-$$

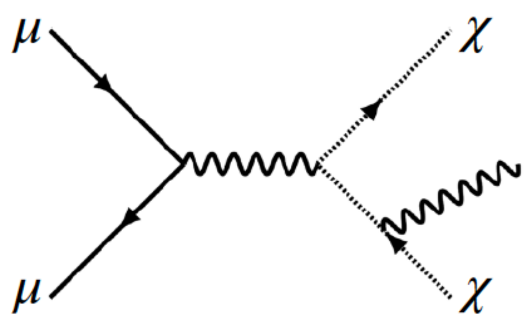
$$\ell^+\ell^- \to ZH$$

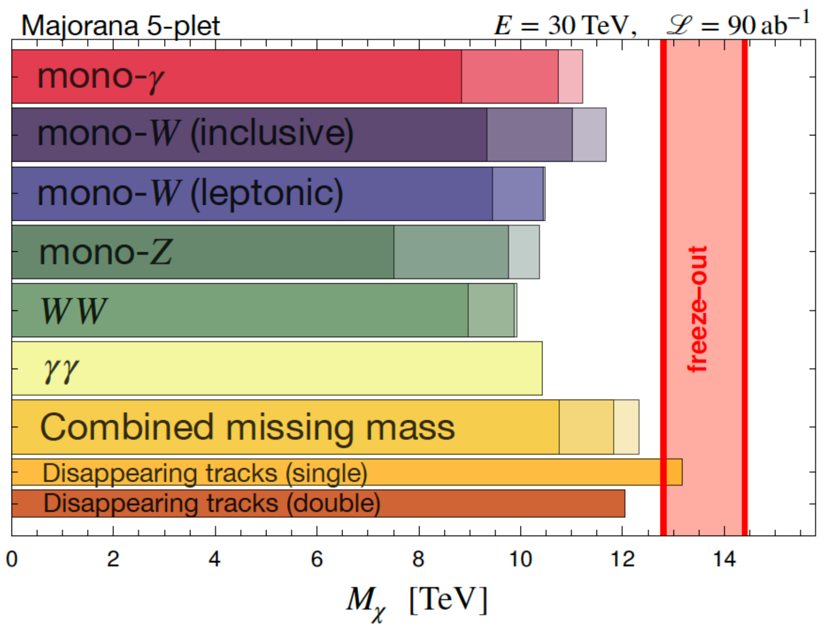


See talk D. Buttazzo for details

Physics goals for a high energy muon collider

- High energy (central) final states:
  - direct exploration at > 10 TeV for new EW produced states:
    - WIMP EW multiplets:
      - Mono(di)-X searches (X boosted)
      - Exotic (Disappearing Tracks)



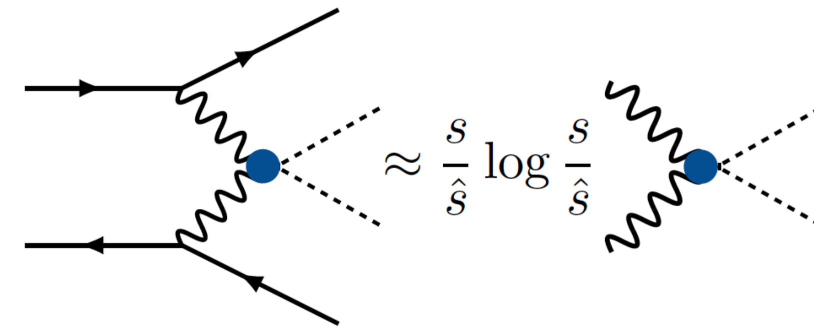


Need to be able to reconstruct central multi-TeV objects !

See talk D. Buttazzo for details

Physics goals for a high energy muon collider

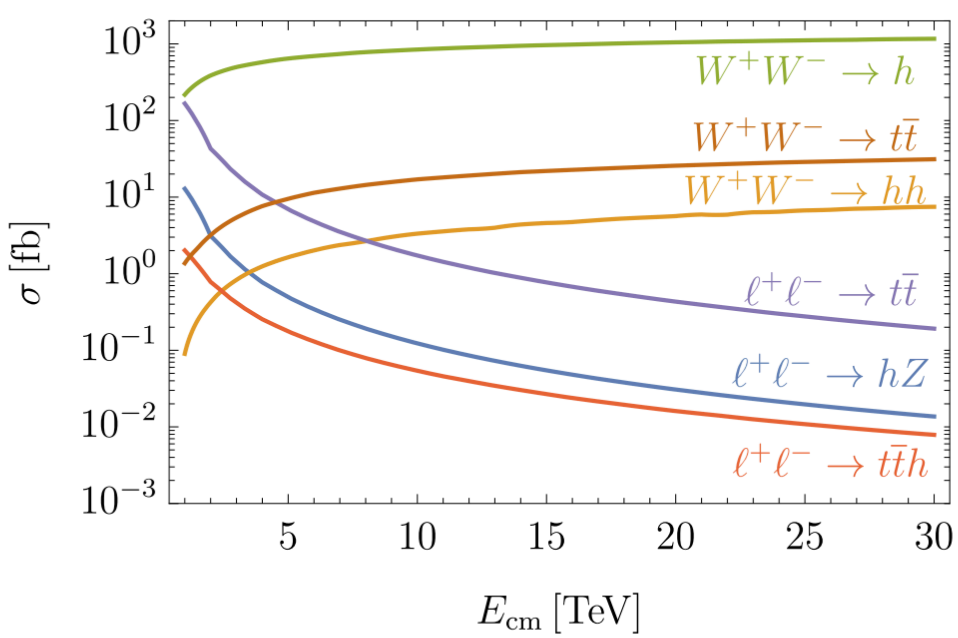
- Low energy (forward) final states:



  - Precision via high rate, e.g:
    - λ_3, λ_4 via HH/HHH production
    - Neutral VBS ZZ → H

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2$$

2012.11555



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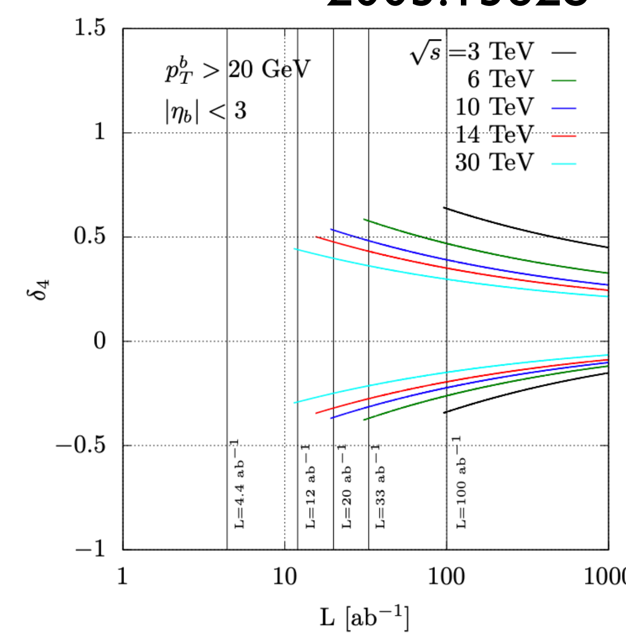


Need to be able to reconstruct objects ~ 10-100 GeV

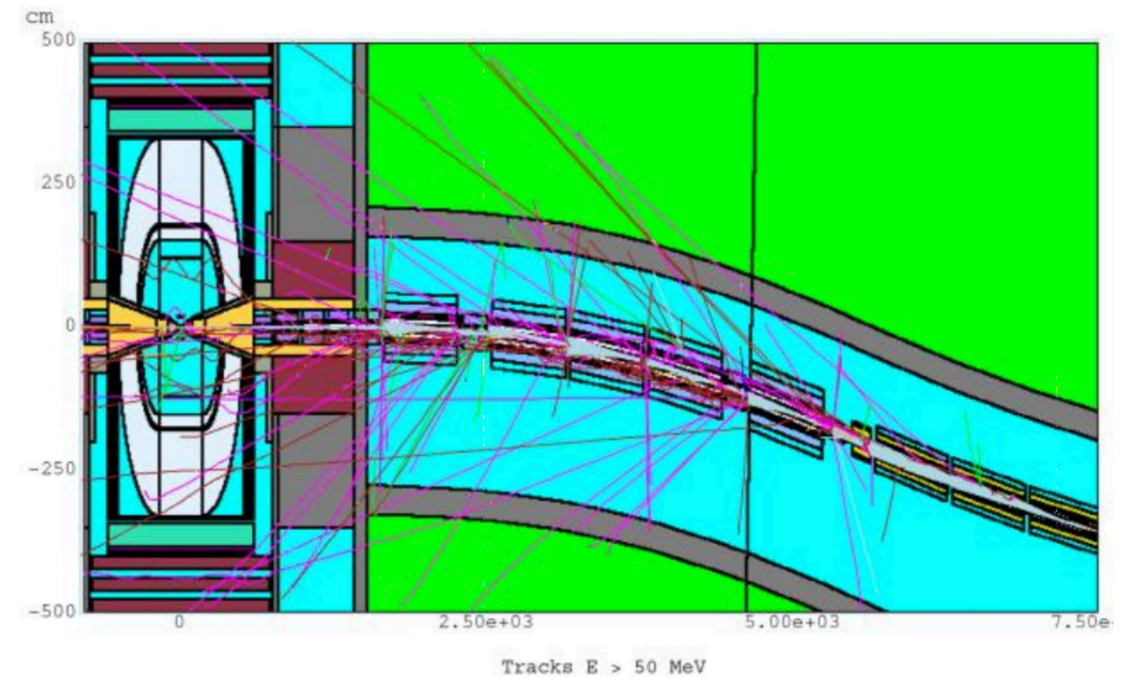
See talk D. Buttazzo for details

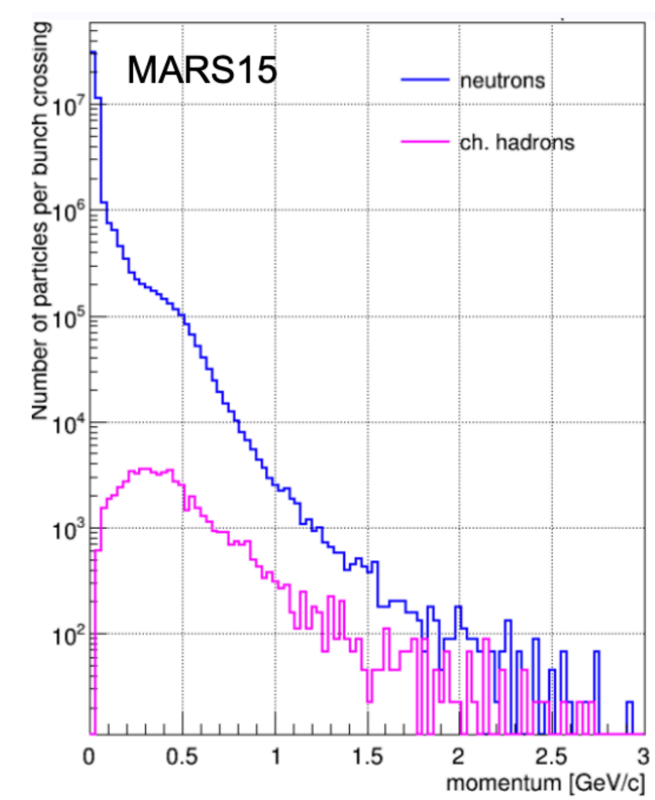
Beam induced background

- High energy Muon collider specs are not known yet, can only extrapolate from low energy:

- Beam-induced background:
    - For 0.75 TeV beams, N = 2e12 muons/bunch → 4e5 muon decays/m
    - For 7.5 TeV beams → 4e4 muon decays/m
        - But x10 more energetic, more forward
    - Conservatively assume ~ similar energy deposited in detector (will be distributed differently however)

- vs. pile-up at hadron collider:
    - ~ diffuse low energy deposit in detector
    - ≠ not pointing towards beamspot, much wider time profile
        - more handles

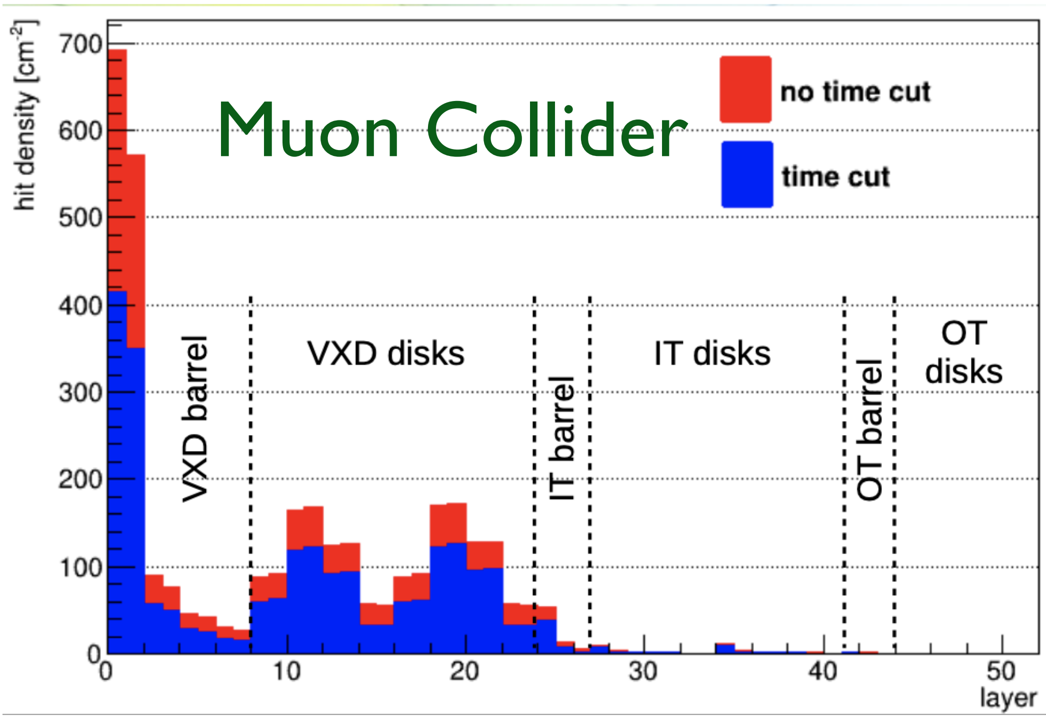




Occupancy

@first pixel ~ 2 cm from beam-pipe

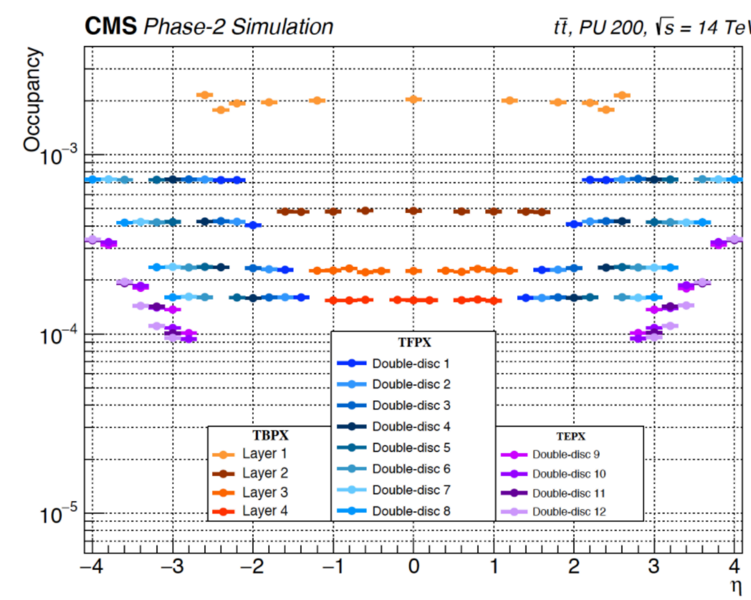
FCC-hh



charged fluence: 400-700 (cm^{-2} / BX)

Barrel layer:	1	2	3	4	5	6
Average radius [mm]	25	60	100	150	260	380
Maximum fluence [cm^{-2}]	328.1	79.7	35.1	16.9	6.8	3.3
Module occupancy [%]	1.63	0.39	0.18	0.10	0.28	0.15

charged fluence: 330 (cm^{-2} / BX)



At MuonCollider can afford **low power pixel** sensors thanks to **low BX rate** (70 kHz) e.g MAPs (30 μm x 30 μm):

→ occupancy: 0.6% (700 / (1cm^2 / 30 μm^2)) ~ **2x HL-LHC** or **0.5x FCC-hh**

Definitely challenging, but not impossible …

Data rates

- LHC Phase II :

  - Raw Event size ~ 5 Mb
  - ATLAS/CMS calorimeters/muons readout @40MHz and sent via optical fibres to Level 1 trigger outside the cavern to create L1 trigger decisions (25 Tb/s)
  - Full detector readout at @1MHz ~ 5 Tb/s (@40MHz ~ 200 Tb/s)

- FCC-hh:

  - Raw Event size ~ 25 Mb
  - At FCC-hh Calo+Muon would correspond to 250 Tb/s (seems feasible)
  - However full detector would correspond to 1-2 Pb/s
    - Seems hardly feasible (30 yrs from now)

At MuonCollider, we collide at much lower rate ~ 10-20 μs bunch crossing (@ 50 kHz)

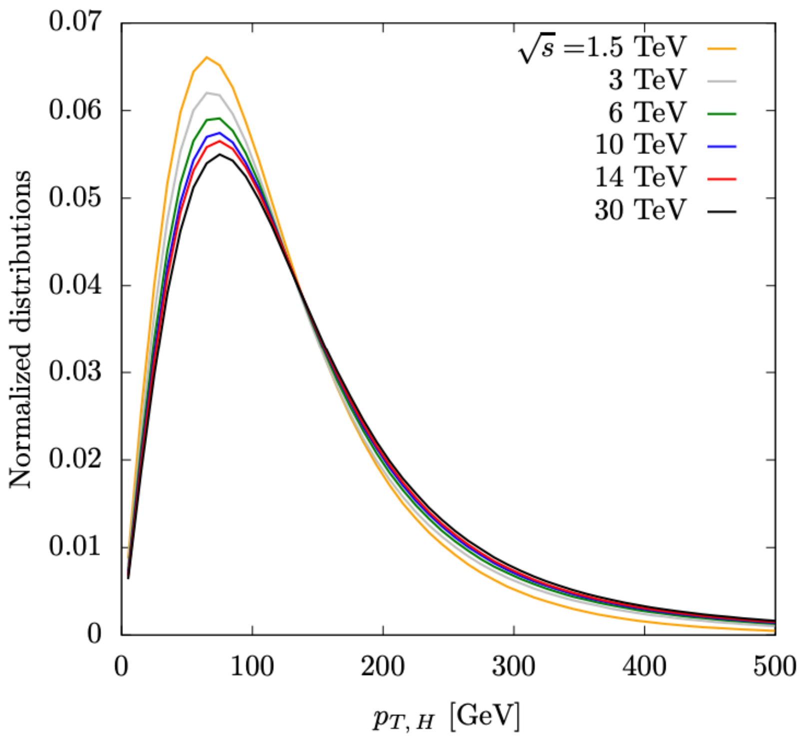
Assuming similar event size as FCC-hh → 1 Tb/s, we can probably read full detector without triggering

Low p_T physics, high rate

At high energy, the SM particles are increasingly:

- produced via weak boson fusion (at threshold)
- more forward

In order to maintain sensitivity in such measurements need **large rapidity** (with tracking) and **low p_T** coverage



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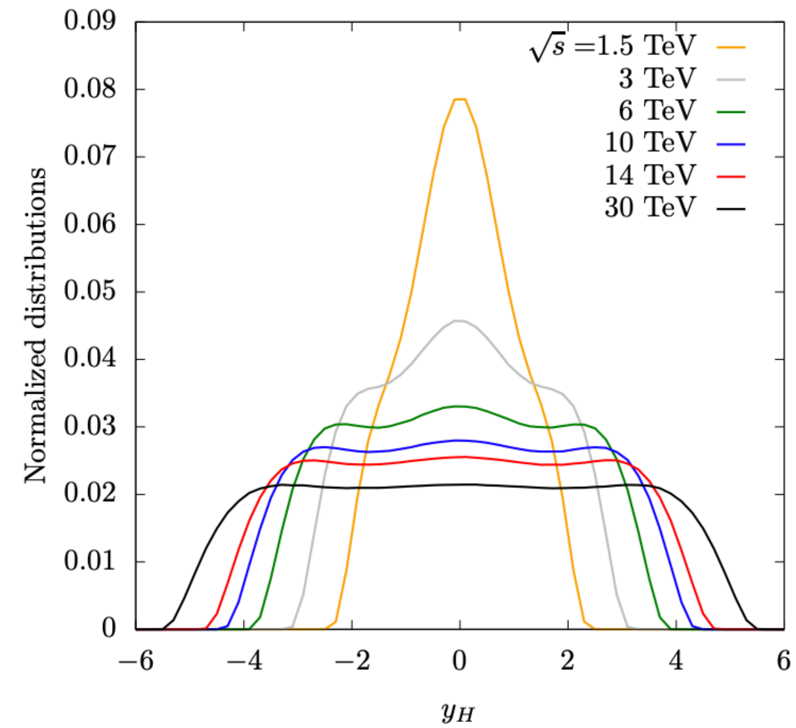
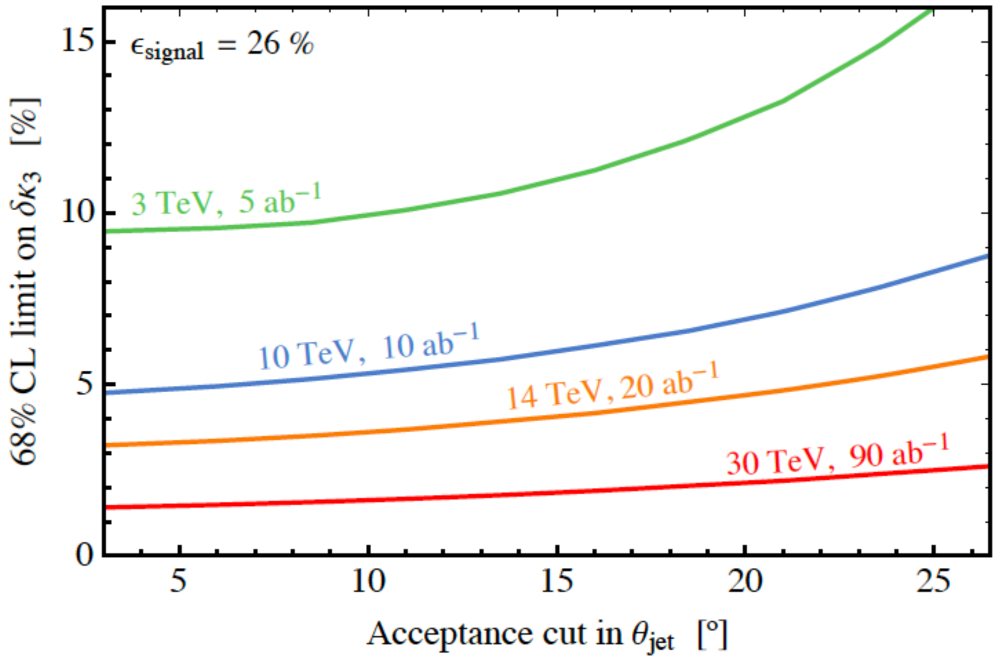


Low p_T physics, high rate

- Recording on tape low p_T objects is probably ok (assuming triggerless)
- Constraints the acceptance on the shielding coverage (nozzle)
- Challenge:
  - Maintain high performance at low momenta:
    - relative impact of BIB on low p_T objects is larger, will dominate resolution of jets (crucial for Higgs processes)

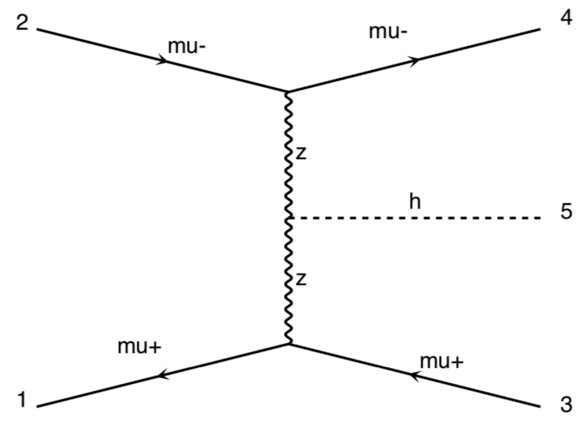


- LHC lesson for pile-up identification:
  - high granularity (tracking + HG calorimetry required) , finer segmentation can be afforded here
  - timing (~ 10's ps resolution)

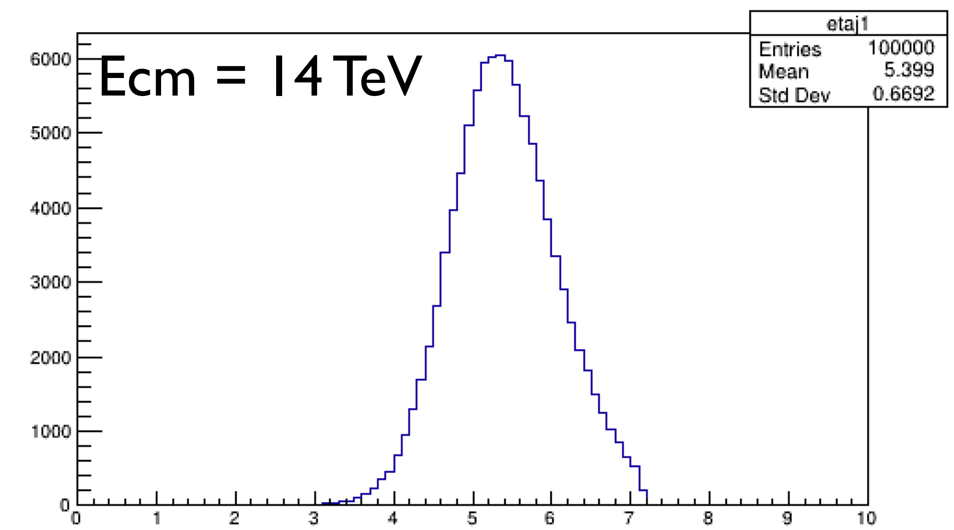
See talk P. Harris for details

Very forward physics

Neutral ZZ → X scattering:



- Very speculative, but equally interesting possibility to be explored:
    - Extremely high energy muon (~ E_{beam})
    - Highly forward (θ ~ m_H / E_{beam})
- Would require dedicated outside detector cavern
- To be investigated:
    - Needed resolution?
    - BIB impact?
    - Acceptance?



most forward muon

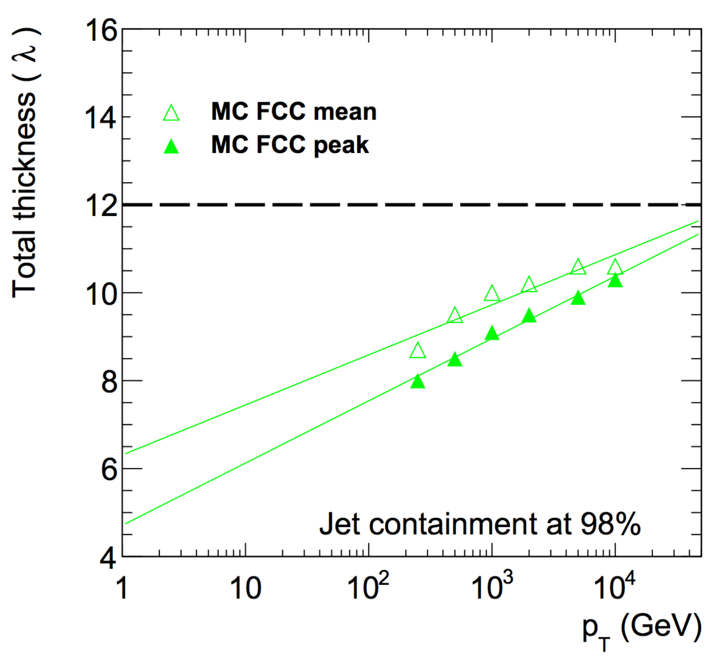
Boosted physics

- The boosted regime:

→ measure multi-TeV leptons, photons, muons, jets

Tracking: $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$ Calorimeters: $\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \bigoplus B$

→ target specifications:



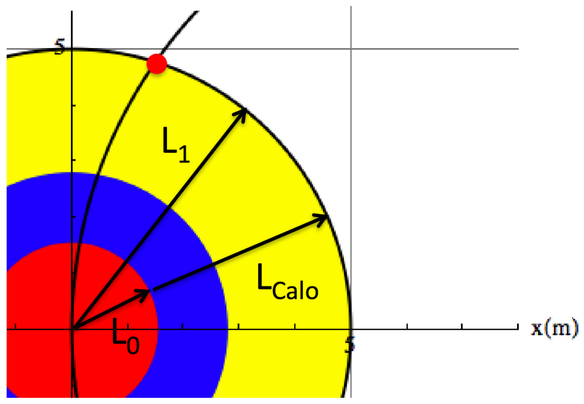
≳11 λ_I for EM + Had

- Tracking target : **σ / p = 20% @10 TeV**
- Muons target: **σ / p = 10% @20 TeV**
- Calorimeters target: containment of p_T = 20 TeV jets

→ should be studied carefully (maybe no need for extreme energy momentum/resolution)

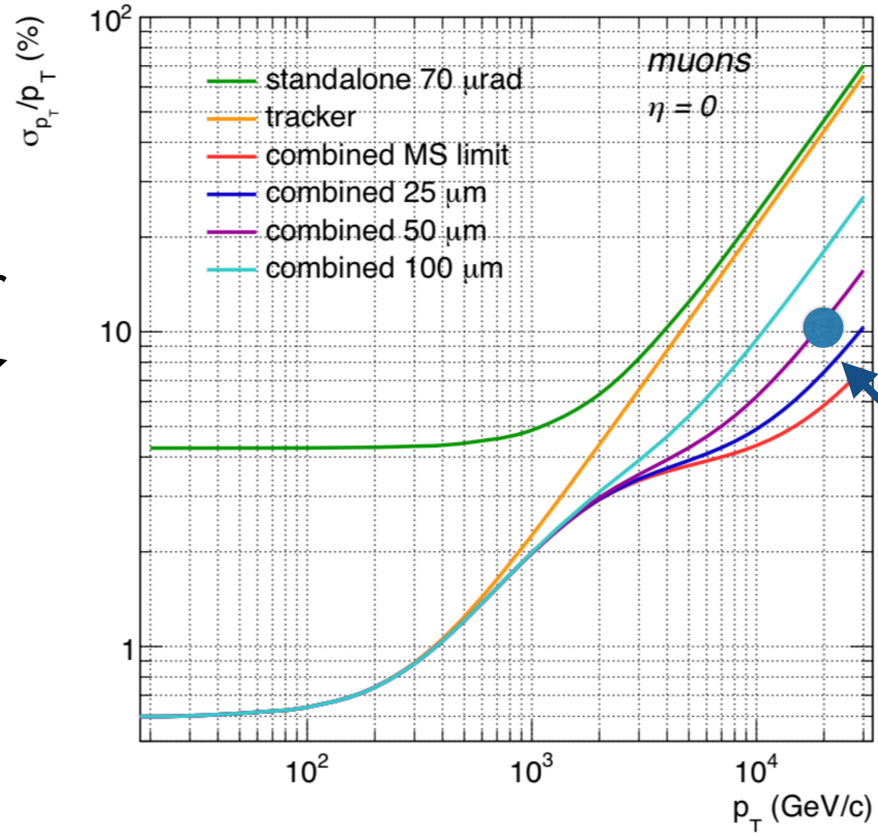
- Calorimeter depth determines size of solenoidwhich in turn drives detector cost

High p_T muons



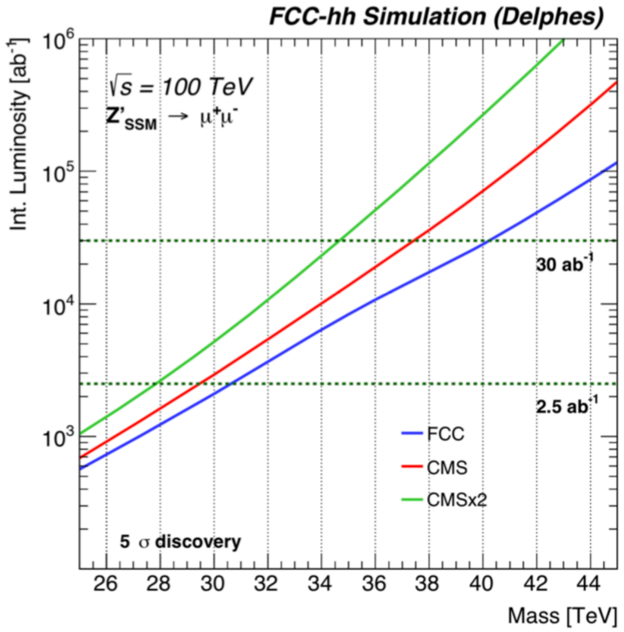
pen & paper

W. Riegler formulae



$\sigma_p/p = 10\%$ @20 TeV

Delphes



- pT = 4 GeV muons enter the muon system
- pT = 5.5 GeV leave coil at 45 degrees

- Standalone muon measurement with angle of track exiting the coil
- Target muon resolution can be easily achieved with 50 µm position resolution (combining with tracker)
- Good standalone resolution below |η| < 2.5

Boosted physics

→ measure W, H, top jets from multi-TeV resonances

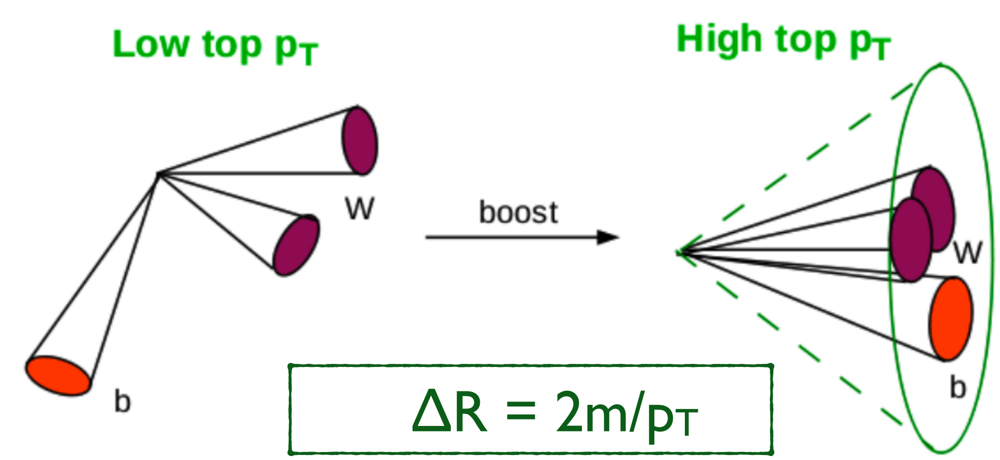
- Highly boosted hadronically decaying SM heavy states (W, Z, H or t) will have highly collimated decay products

- The ability to distinguish such boosted states from vanilla QCD light jets is an essential tool for

  $\mu\,\mu \rightarrow j\,j\,/\,t\,t\,/\,VV\,/\,ZH$

  ex: W(10 TeV) will have decay products separated by DR = 0.01 = 10 mrad

- need highly granular sub-detectors:
  - Tracker - pixel: 10 µm @ 2cm → $\sigma_{\eta\times\varphi} \approx$ 5 mrad
  - Calorimeters: 2 cm @ 2m → $\sigma_{\eta\times\varphi} \approx$ 10 mrad



Boosted physics

Physics constraints

- The boosted regime:
  → measure b-jets, taus from multi-TeV resonances
- Long-lived particles live **longer**:

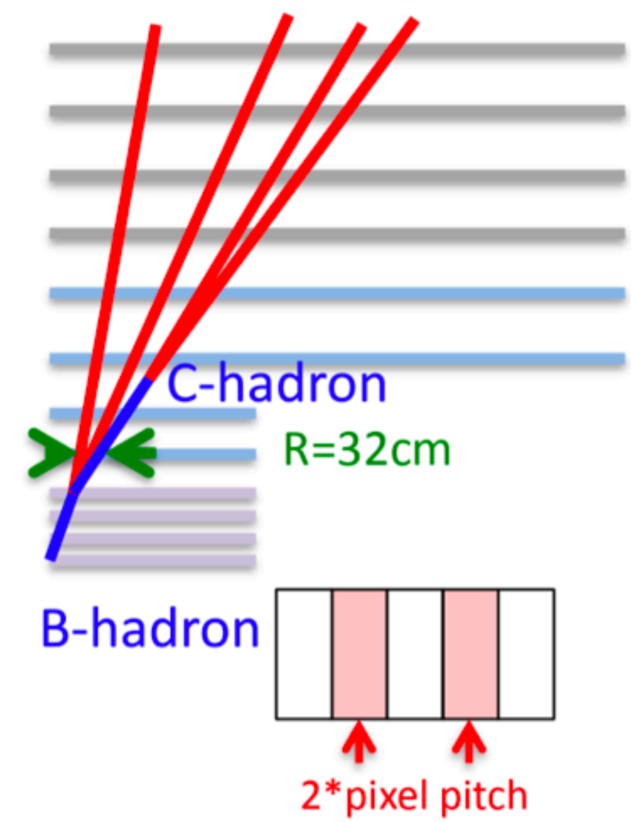
ex: 5 TeV **b-Hadron** travels **50 cm** before decaying
5 TeV cHadron/**tau lepton** travels **10 cm** before decaying

→ extend pixel detector further?

- useful also for exotic topologies (disappearing tracks and generic BSM Long-lived charged particles)
- number of channels over large area can get too high

→ re-think reconstruction algorithms:

- hard to reconstruct displaced vertices
- **exploit hit multiplicity discontinuity**



Only 71% 5 TeV b-hadrons decay < 5th layer.

- displaced vertices

Parametric simulation

- The interest in the TH/pheno community is to **assess the physics reach at the highest possible energies** sqrt(s) = 10, 14, 30 TeV

  (at any rate, such a detector would perform great also at 1.5, 3 TeV)

- Need to be able to reconstruct: mu, ele, jets, tops, V from **few GeVs** up to **p_T = 15 TeV**

  - $\mu\ \mu \to \mu\ \mu$, e e , j j, t t~ (hadronic) ,V V (hadronic)
  - $\mu\ \mu \to$ v v X, $\mu\ \mu$ X (X=V,H,VV, HH…)

With many respects, the constraints from physics at high p_T are similar: to the **FCC-hh** and **CLIC** (also easier to start from existing detector concept)

→ parameterised simulation for muon collider detector concept is an **hybrid** of the FCC-hh and CLIC card

Muon Collider card

```
#######################################
# Order of execution of various modules
#######################################

set ExecutionPath {
    ParticlePropagator
    TrackMergerProp

    DenseProp
    DenseMergeTracks
    DenseTrackFilter

    ChargedHadronTrackingEfficiency
    ElectronTrackingEfficiency
    MuonTrackingEfficiency

    ChargedHadronMomentumSmearing
    ElectronMomentumSmearing
    MuonMomentumSmearing
```

```
#########################################
# Muon Collider Detector TARGET model
#
# Michele Selvaggi michele.selvaggi@cern.ch
# Ulrike Schnoor ulrike.schnoor@cern.ch
#
#
# !!! DISCLAIMER !!!
#
# The parameterisation of the Muon Collider
# has to be intended as a target performance.
# This has not been validated by full simulation.
# Hybrid between FCC-hh and CLIC performance.
#
#
#########################################
```

- v0 can be found here:
  - https://github.com/delphes/delphes/blob/master/cards/delphes_card_MuonColliderDet.tcl
  - https://github.com/delphes/delphes/tree/master/cards/MuonCollider

Possible detector variations studies

- **p_T acceptance:**
  - final state objects (pt = [10-50]) in particular HH→4b
- **angular detector acceptance:**
  - the baseline detector card assumes a maximum rapidity of $|\eta|$=2.5.
  - ranges between [1.5, 3.0] can be studied.
  - simulates various assumptions on the dead cone introduced by the nozzle shielding.
- **forward muon detector performance:**
  - no detector concept currently exists for reconstructing muons in the challenging BIB environment at small angles.
  - both the acceptance and the resolution for reconstructing such muons can be explored.
  - This can be studied in the context of neutral vector boson scattering.

Possible detector variations studies

- **Track and Calorimeter resolutions:**
  - can be degraded by factor 2-4 in physics studies that involve (non-)resonant signals.
  - alternatively, the jet energy resolution can also be degraded by similar factors.
  - this can be studied for instance in the context of double and triple Higgs production in fully hadronic final states.

- **Calorimeter granularity:**
  - study impact on highly boosted hadronic decays (H,W,top)

- **Identification efficiencies:**
  - in particular lepton, photons ID, and heavy flavour tagging.
  - in the context of double and triple Higgs production where b/c/light flavour discrimination can be important.

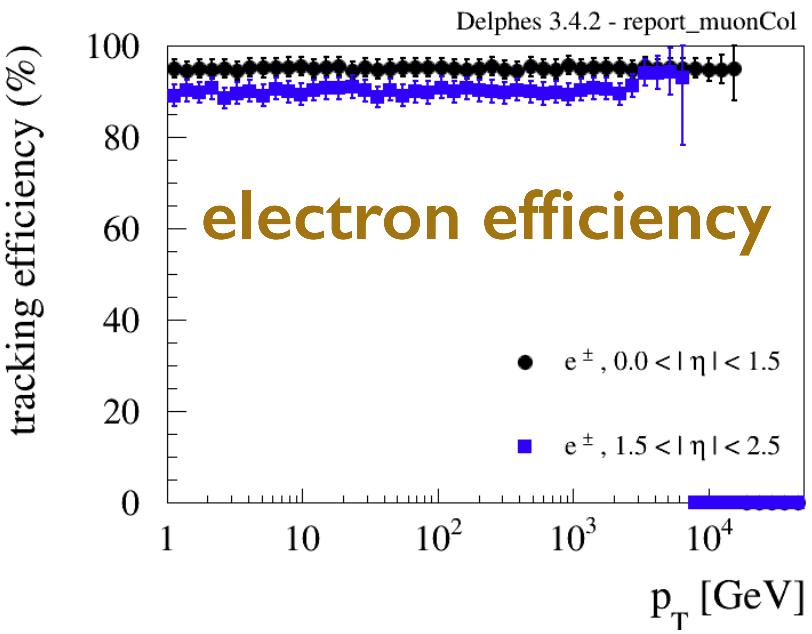
- **LLP studies:**
  - **detector volume**
  - **timing resolution**
  - track reconstruction efficiency as a function of **displacement** for **LLP studies** and exotic signatures

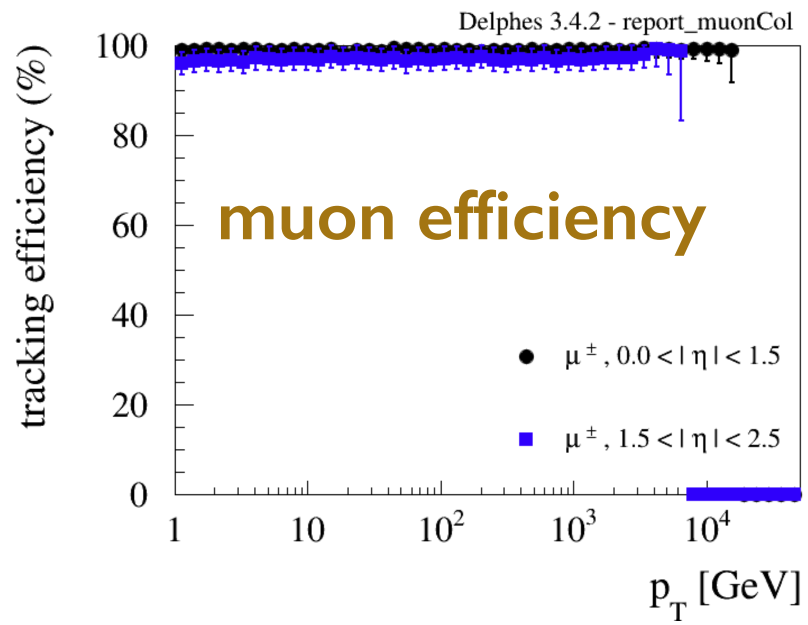
Conclusions

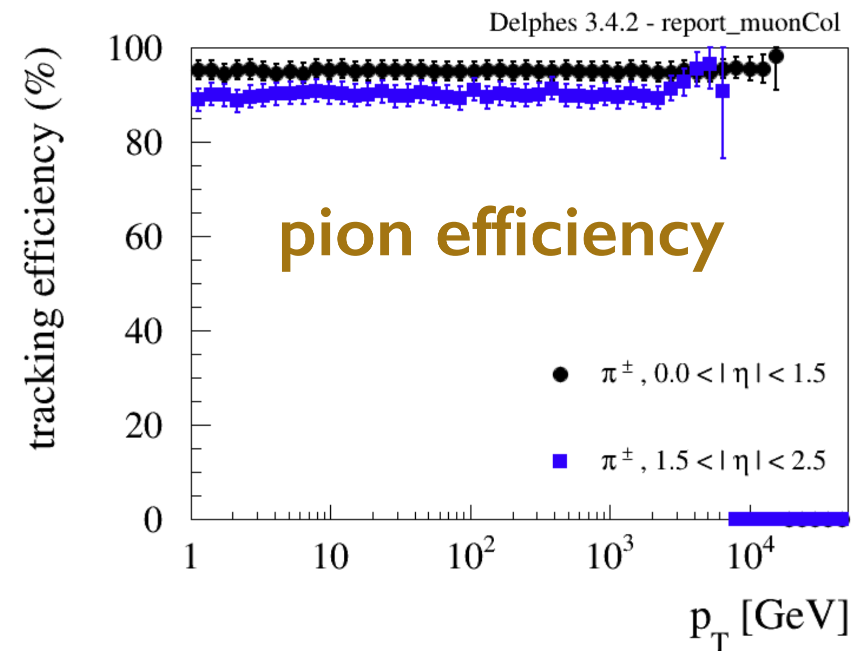
- A detectors able to extract all the physics potential from such a machine can be built, but a high profile R&D programme for detectors and electronics technologies has to be conducted (picosecond timing, granularity, high speed low power optical links)
- A general purpose target detector has been designed to set the scale of the challenges of performing experiments with such machine
- Its performance has been parameterised in Delphes for phenomenological investigations
- Impacts of variations around nominal (target performance) have been investigated using benchmark physics channels and used to:
  - identify areas of needed improvement (timing, granularity etc ..)
  - further optimise detector design (e.g. reduce cost for instance)

Backup

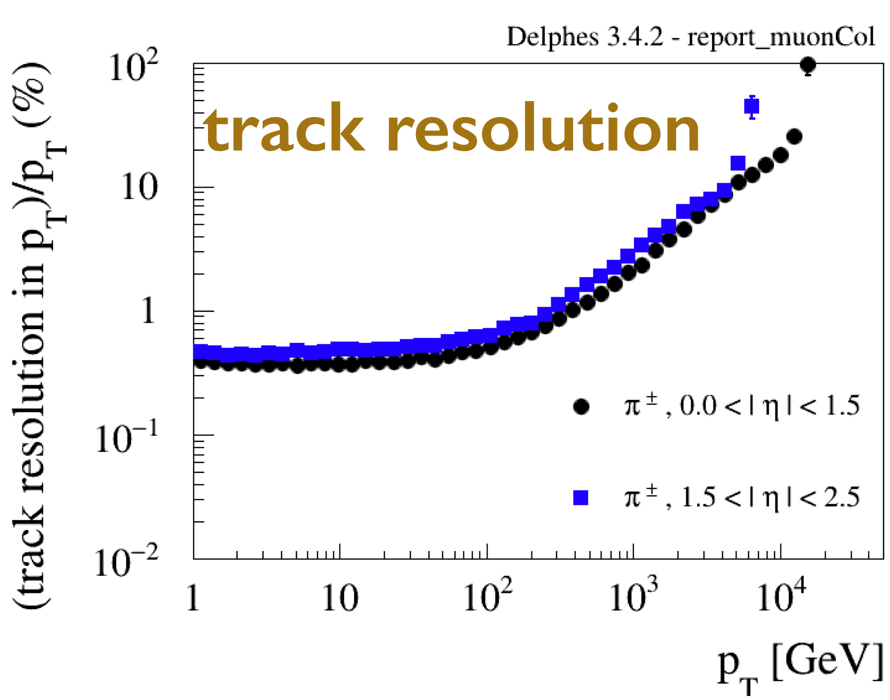
Tracking efficiency/resolution

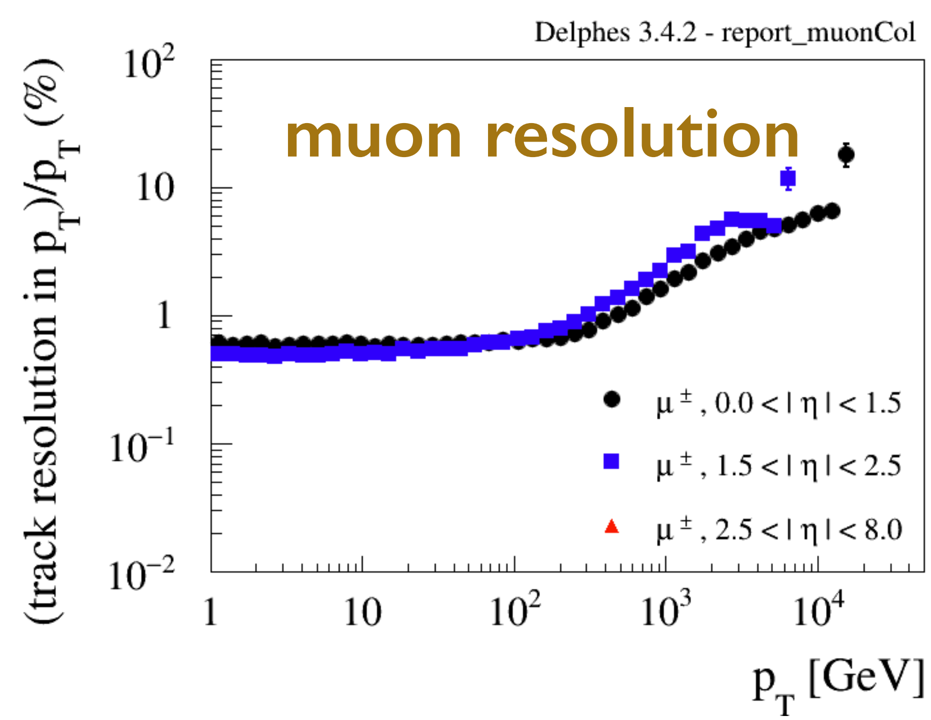




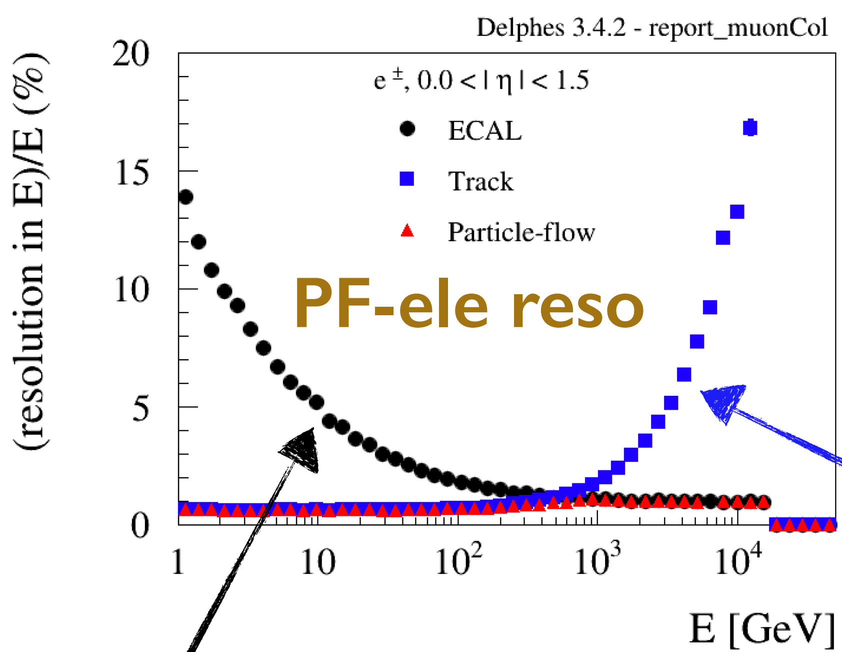


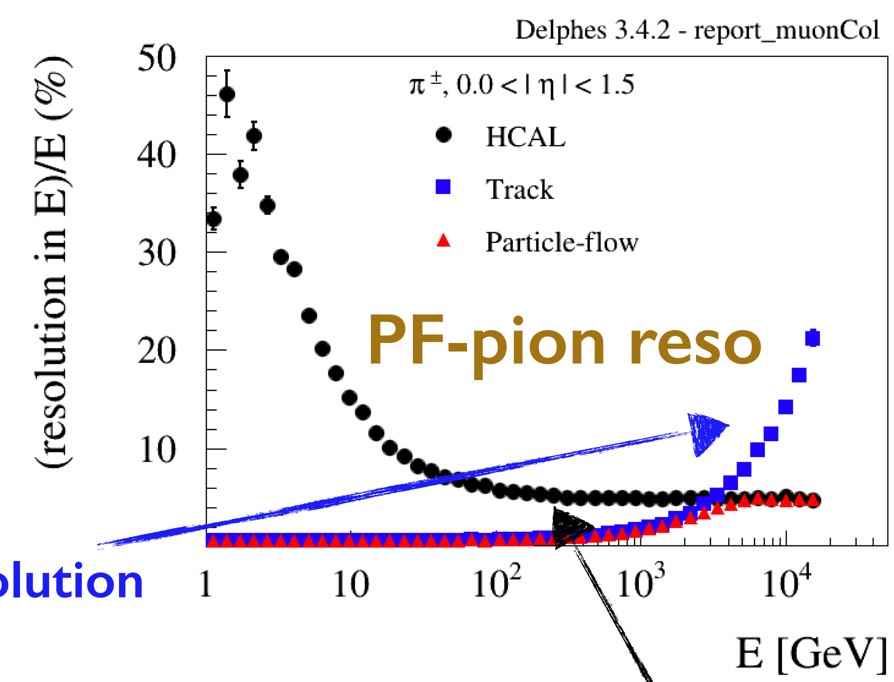
inspired from FCC-hh





Calorimeters/PF



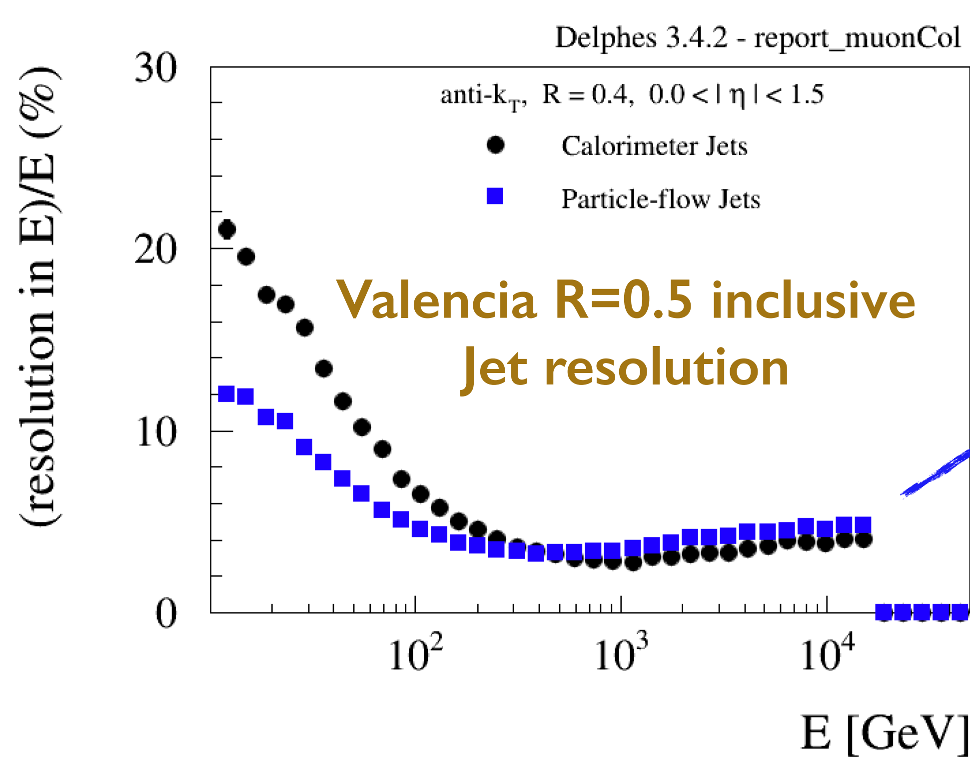


Tracking resolution
from FCC-hh

Calorimeters inspired from CLIC

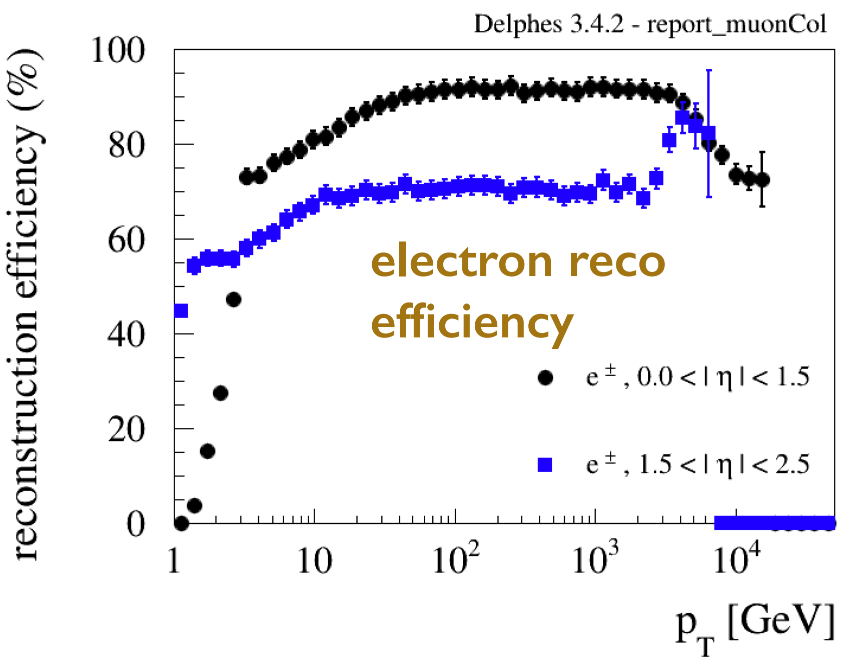
EM resolution from CLICdet

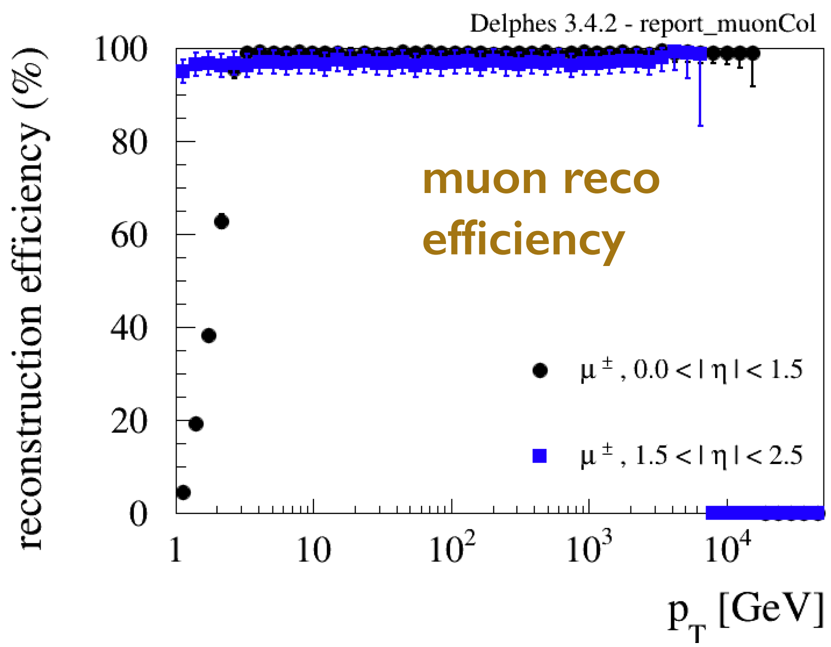
Hadronic resolution
from CLICdet

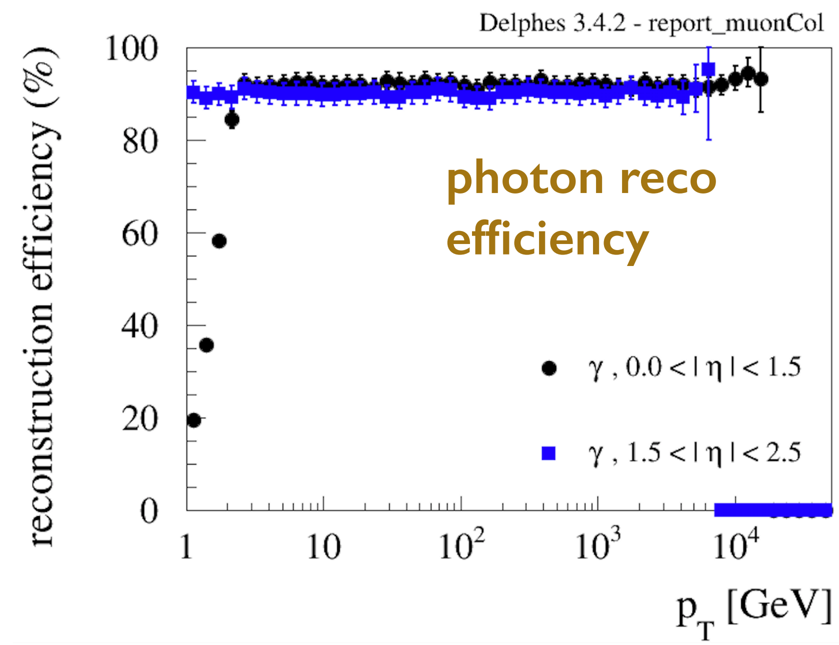


PF jet
include BIB smearing
from CLIC stage 3

E/mu/gamma efficiency

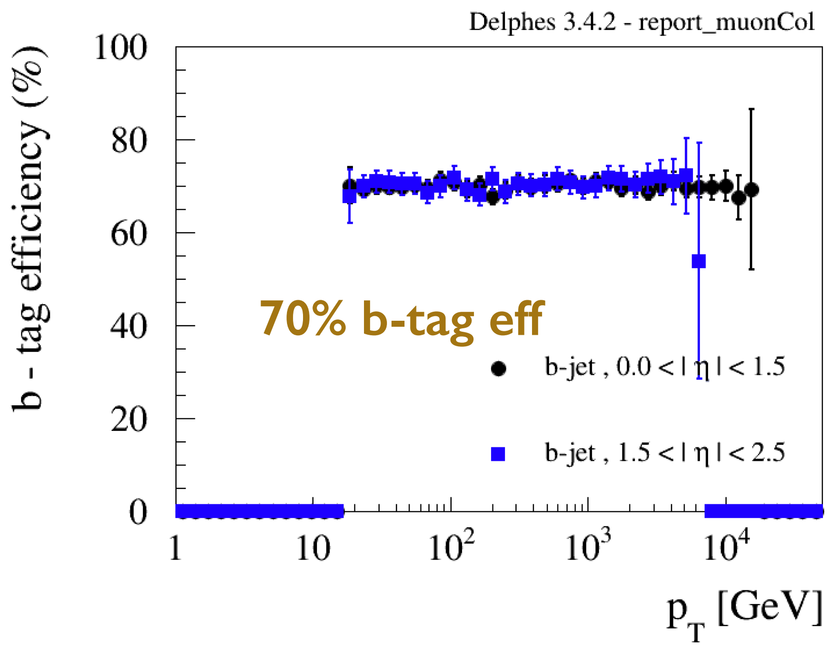


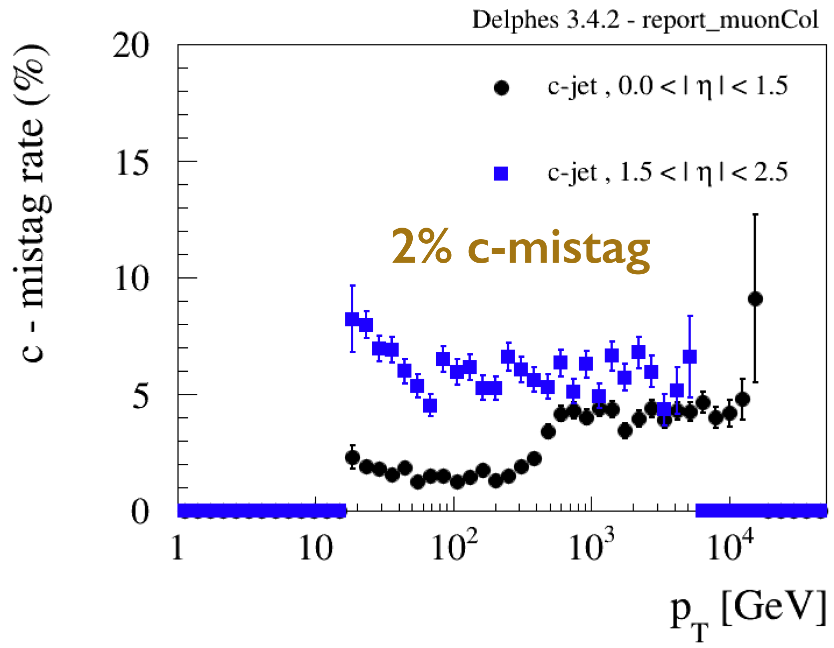


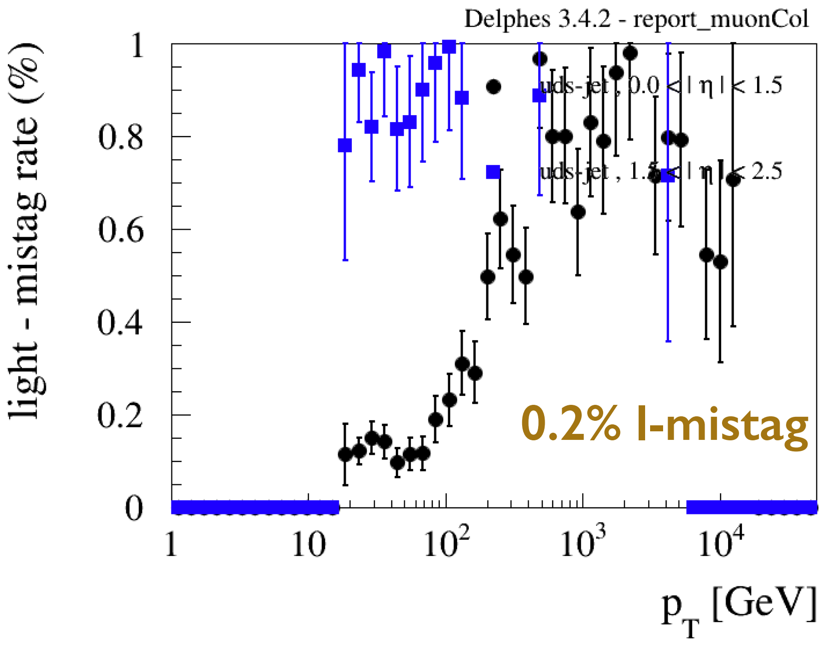


inspired from CLIC det

BTagging (Medium Working point)

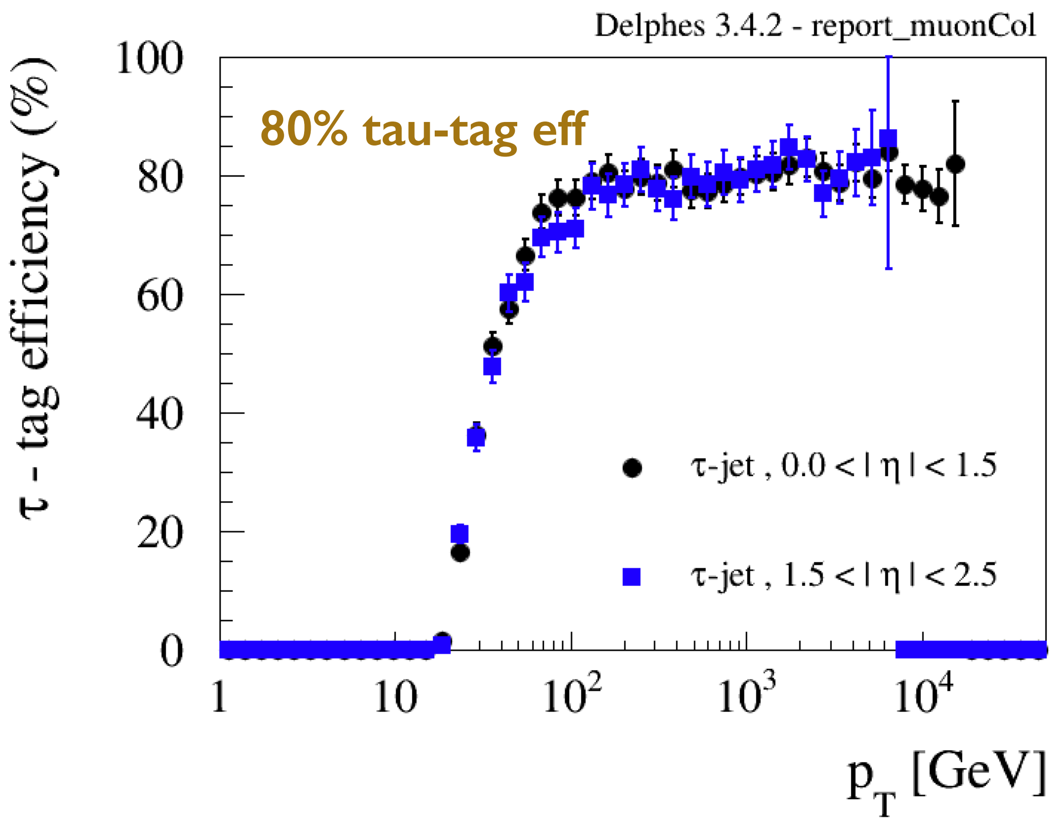


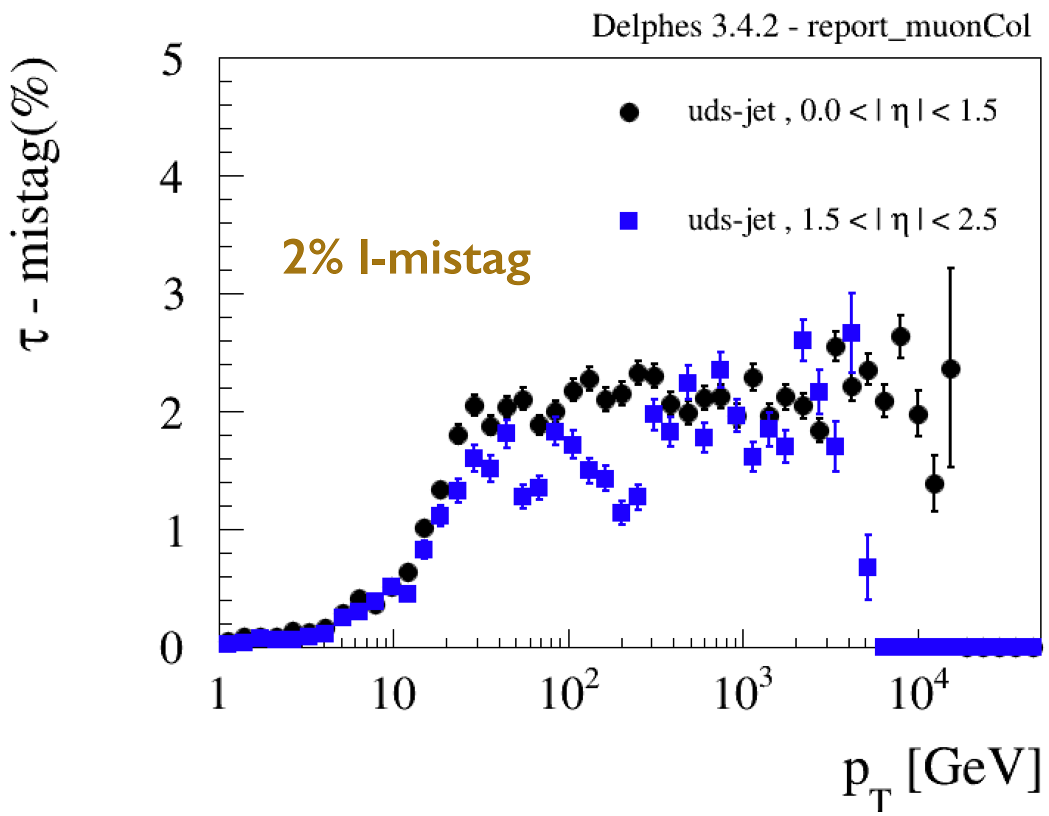




inspired from CLIC det

Tau-tagging

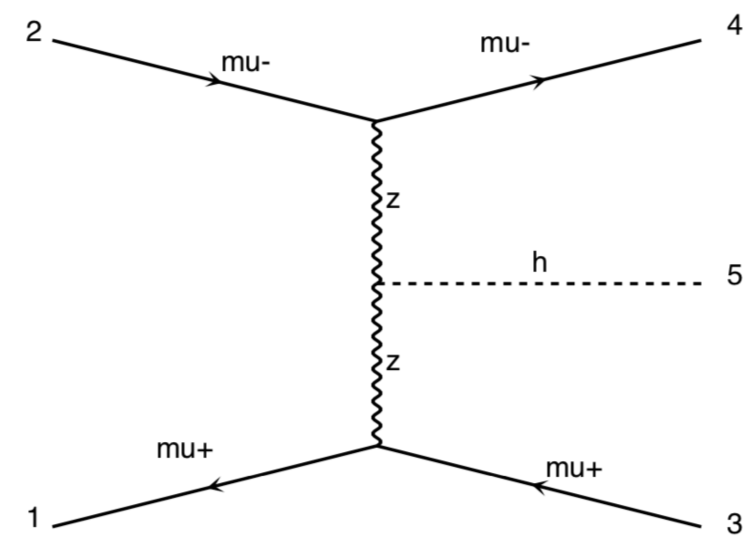


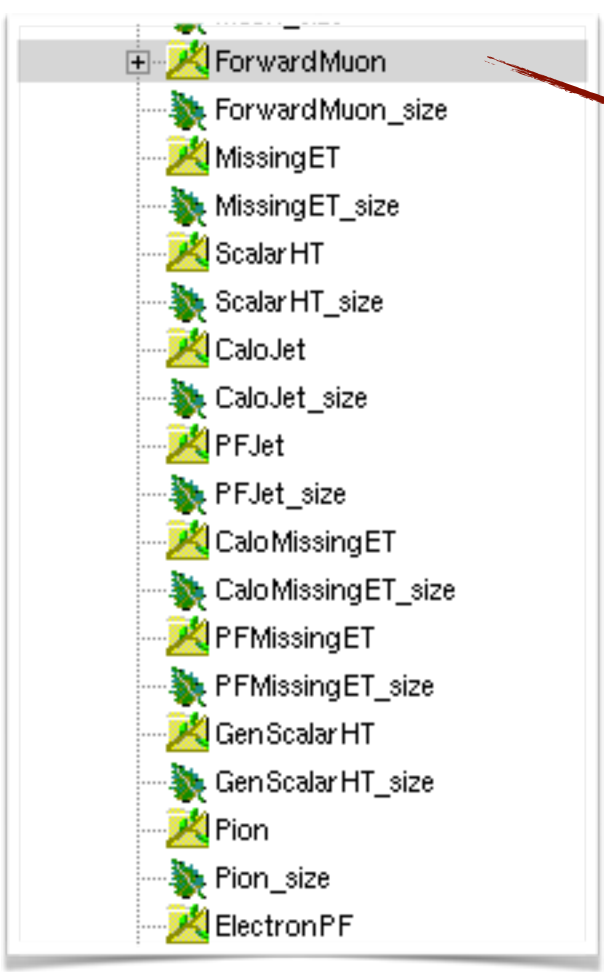


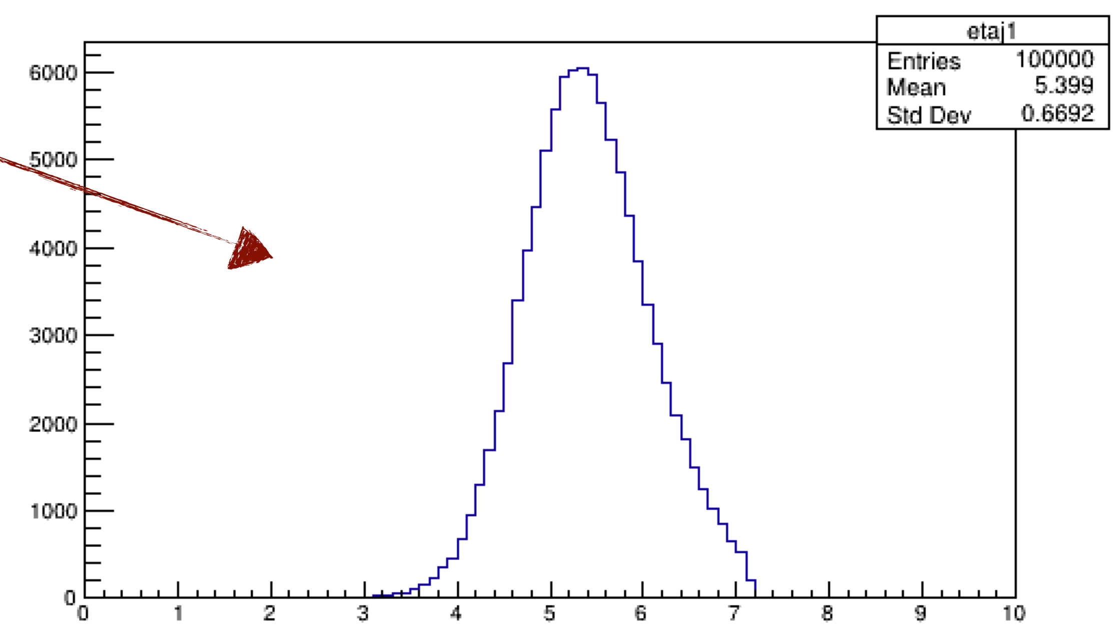
inspired from CMS/FCChh

Forward muon collection

- Forward **Muon collection:**
  - 2.5 < |η| < 8.0
  - energy resolution: 10%







most forward muon |η|