New method to measure Higgs mass at CLIC collider

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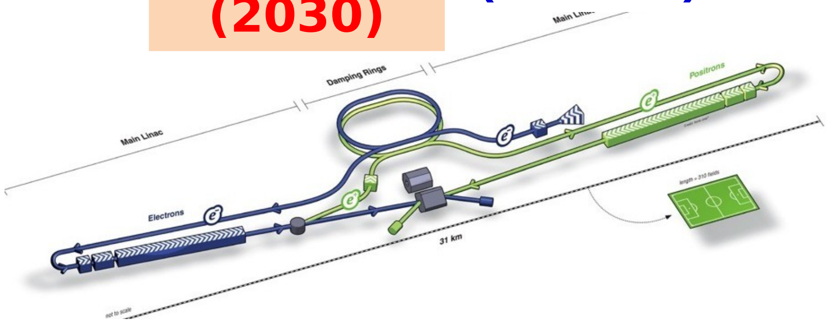
24 Feb 2020

Projects of future e^+e^- colliders

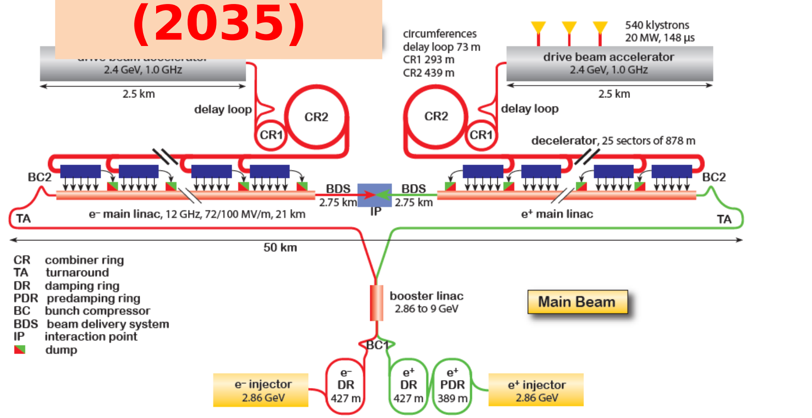
ILC (2030)

$ 4-5G (250 GeV)



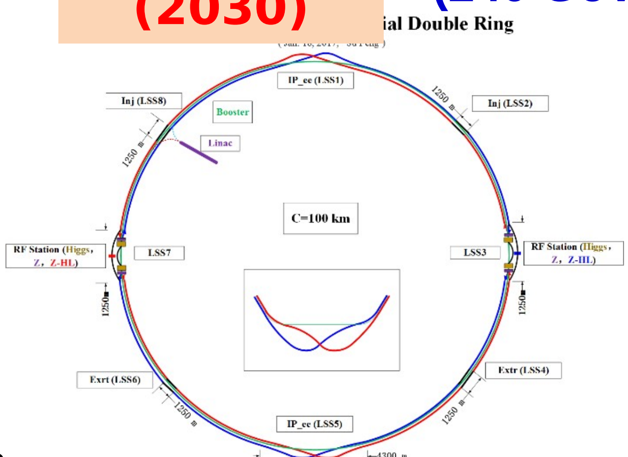
CLIC (2035)

$ 6.7G (380 GeV)
$13G (3000 GeV)



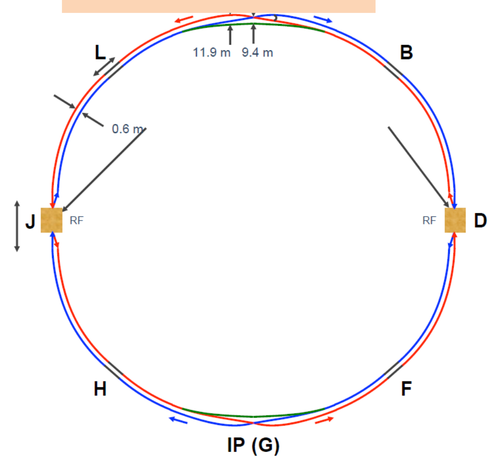
CEPC (2030)

$ 5.5G (240 GeV)



FCC-ee (2039)

$??? (360 GeV)



Energy landmarks of ee colliders

91 GeV: repeat LEP1 experiments: full LEP1 data every 5 min !!!!!

161 GeV: $E=2xM_W$, threshold scan

repeat 1996 at LEP2, 1000x lumi

240-250 GeV: Higgs factory

350 GeV: $E=2xM_t$, threshold scan

400 GeV: maximum top-pair cross-section

500-3000 GeV: discovery of new physics!

Need in precise M_H measurement

- M_H uncertainty is a parametric error of SM predictions, which limits the accuracy of any SM calculations
- For the HWW vertex, the parametric error:
  $\Delta(g)/g = 6.9 \cdot \Delta(M_H)/M_H$
  $\Delta(Br)/Br = 9.1 \cdot \Delta(M_H)/M_H$
- At CLIC: precision of HWW coupling measurement ~0.1% => $\Delta(M_H) \approx 20$ MeV needed

What precision do we expect?

- Higgs mass can be reconstructed as μμ recoil mass in $ee \to ZH \to \mu\mu H$ events
- CEPC: $\Delta(M_H)$=6 MeV
- FCC: $\Delta(M_H)$=11 MeV
- ILC: $\Delta(M_H)$=14 MeV
- CLIC: $\Delta(M_H)$=110 MeV ☹

Why recoil mass is so bad at CLIC?

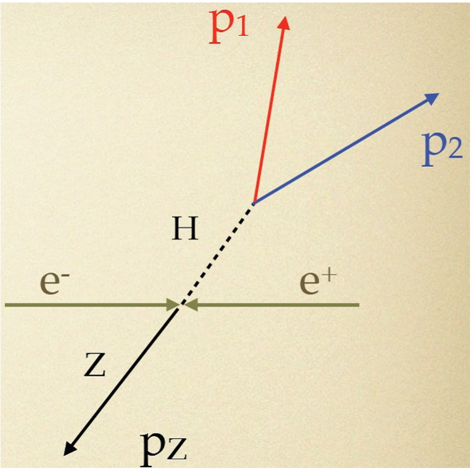
Conspiracy of several factors:

- Small statistics at CLIC, because
  - small int. lumi at 380 GeV (priority to high energy)
  - cross-section at 380 GeV is only ½ of 250 GeV
- Recoil mass method relies on precise knowledge of initial state kinematics. BUT:
  - Beam energy spread at CLIC 2.5 times bigger than at ILC
  - Beamstrahlung at CLIC!
  - ISR at 380 GeV – radiative return to 250 GeV (energy of maximum cross-sections)
- Boosted (at 380 GeV) muon: P_T reconstructed with less precision

New method to measure M_H

(proposed for ILC by Tian JunPing)

- Select $ee \to ZH \to \mu\mu bb$ events
- Reconstruct $Z \to \mu\mu$ system
- Reconstruct directions, not energies, of b-jets. (*Direction is measured much better than energy, both in resolution and in systematics)*
- Calculate momenta of b-jets by formula
- Due to additional constraint from jet direction, beam particles P_Z does not enter the formula
- Only assume P_T balance of beams



$$p_1 = \frac{p_T^{\mu\mu}}{\sin\theta_1}\frac{\sin(\phi_2 - \phi^{\mu\mu})}{\sin(\phi_2 - \phi_1)}$$

$$p_2 = \frac{p_T^{\mu\mu}}{\sin\theta_2}\frac{\sin(\phi_1 - \phi^{\mu\mu})}{\sin(\phi_1 - \phi_2)}$$

What we want to check at generator-level

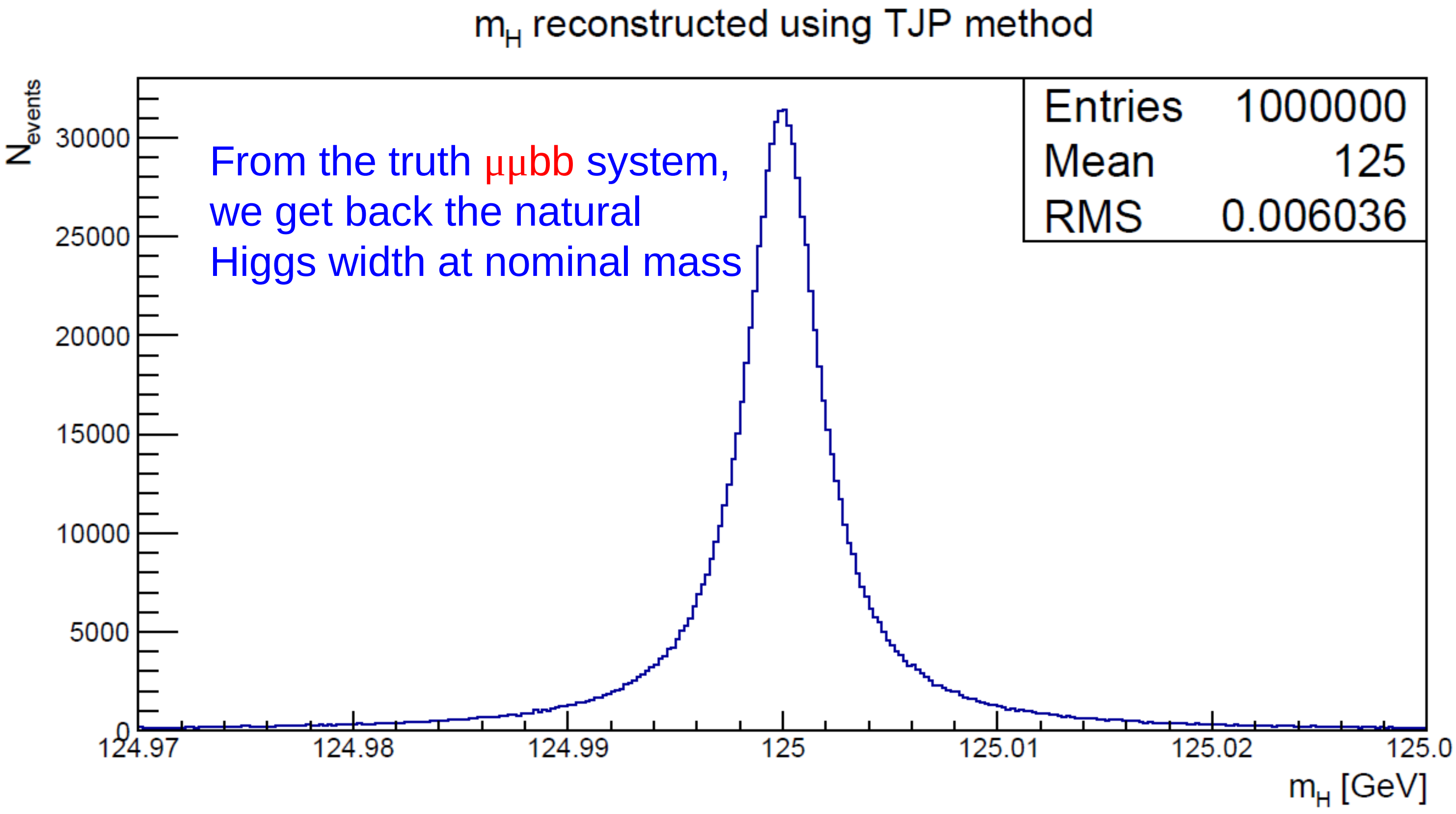
- …that method is robust against reasonably small imbalance of beam P_T
- …that typical CLIC resolution on muon momentum is sufficient
- We don’t care about resolution on muon direction – in any case it is much better than jet direction
- …but we want to check that jet direction resolution is good enough for our purposes

Estimation of experimental errors

- We estimate RMS of M_H reconstruction
- To estimate experimental errors, generated events are scaled to 1000 fb^{-1} (expected at 380 GeV)
- Selection efficiency is taken from the CLIC study (Eur.Phys.J.C 77 (2017) 7, 475)

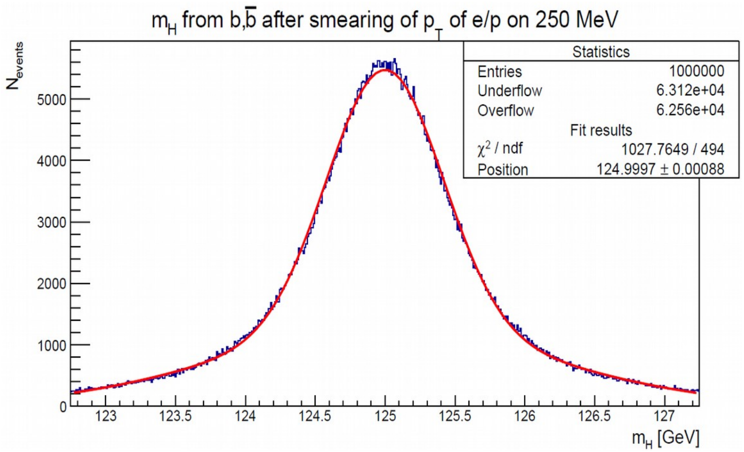
Simplest test: parton truth level

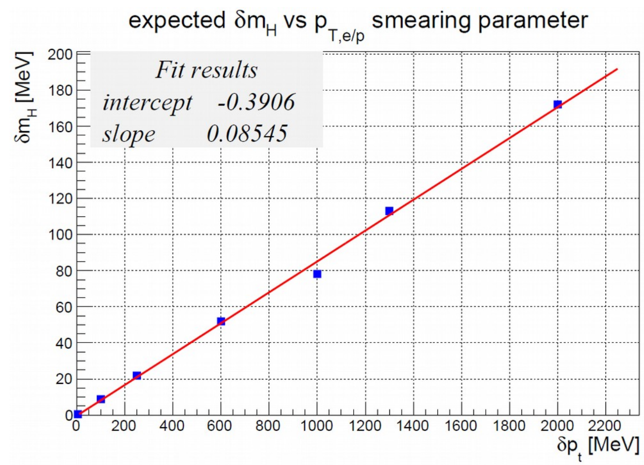
Generator level simulation: Pythia8



Beam P_T balance

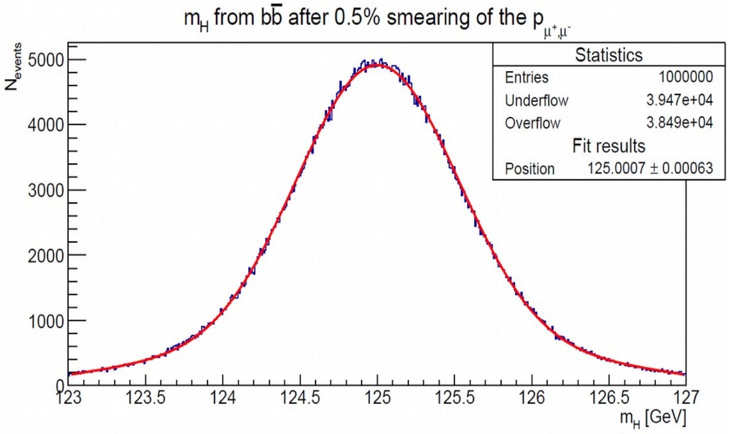
- We (independently) smear P_T of both beam particle by a Gaussian
- Uncertainty $\Delta(M_H)$=20 MeV is observed for beam smearing $\sigma(P_T)$=250MeV
- It seems, we are completely safe from this side

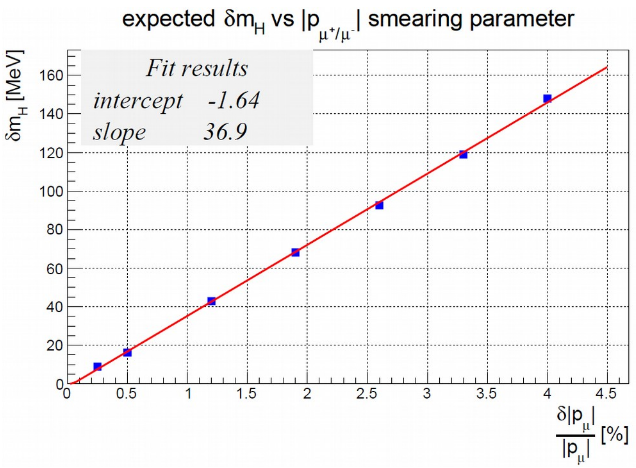




Muon momentum resolution

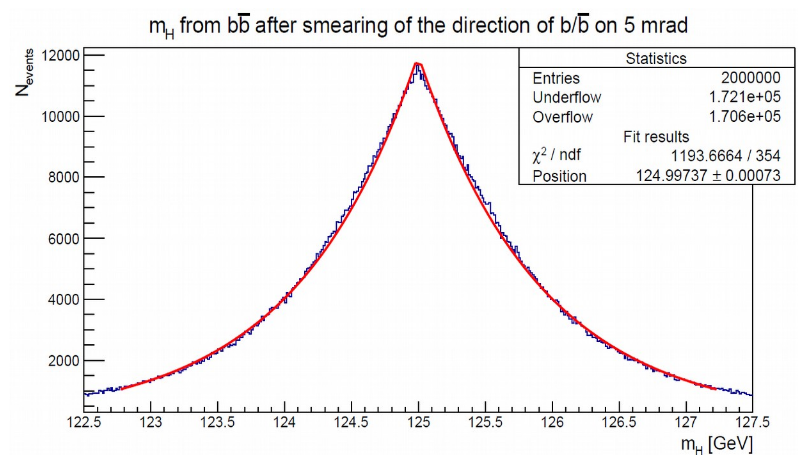
- We (independently) smear momentum of both muons by a Gaussian (b-quark kept with truth parameters)
  - Ignore angular dependence of resolution and all other details
- Uncertainty $\Delta(M_H)=20$ MeV is observed for momentum smearing $\sigma(P_T)/P_T=0.6\%$
- Much better resolution is expected at CLIC ($\sigma(P_T)/P_T=2\cdot10^{-5}\,P_T$)   Safe!

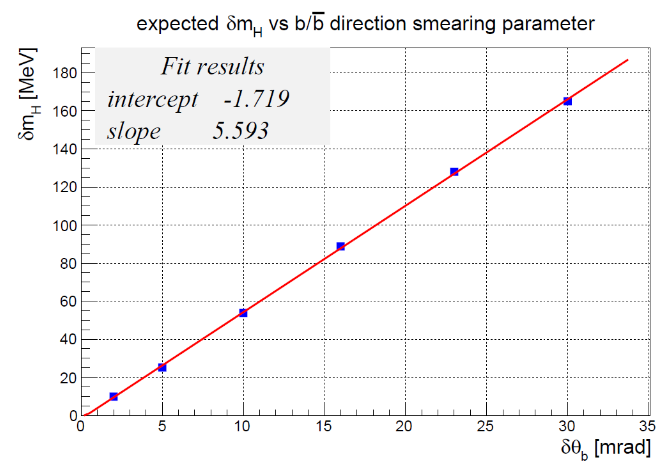




b-quark direction smearing

- We (independently) smear directions of both b-quarks by a Gaussian (muons kept with truth parameters)
- For smearing by 0.5º (will be seen at full-simulation level), uncertainty $\Delta(M_H)$=45 MeV is observed
- Significant! We'll carefully check this result in full detector simulation



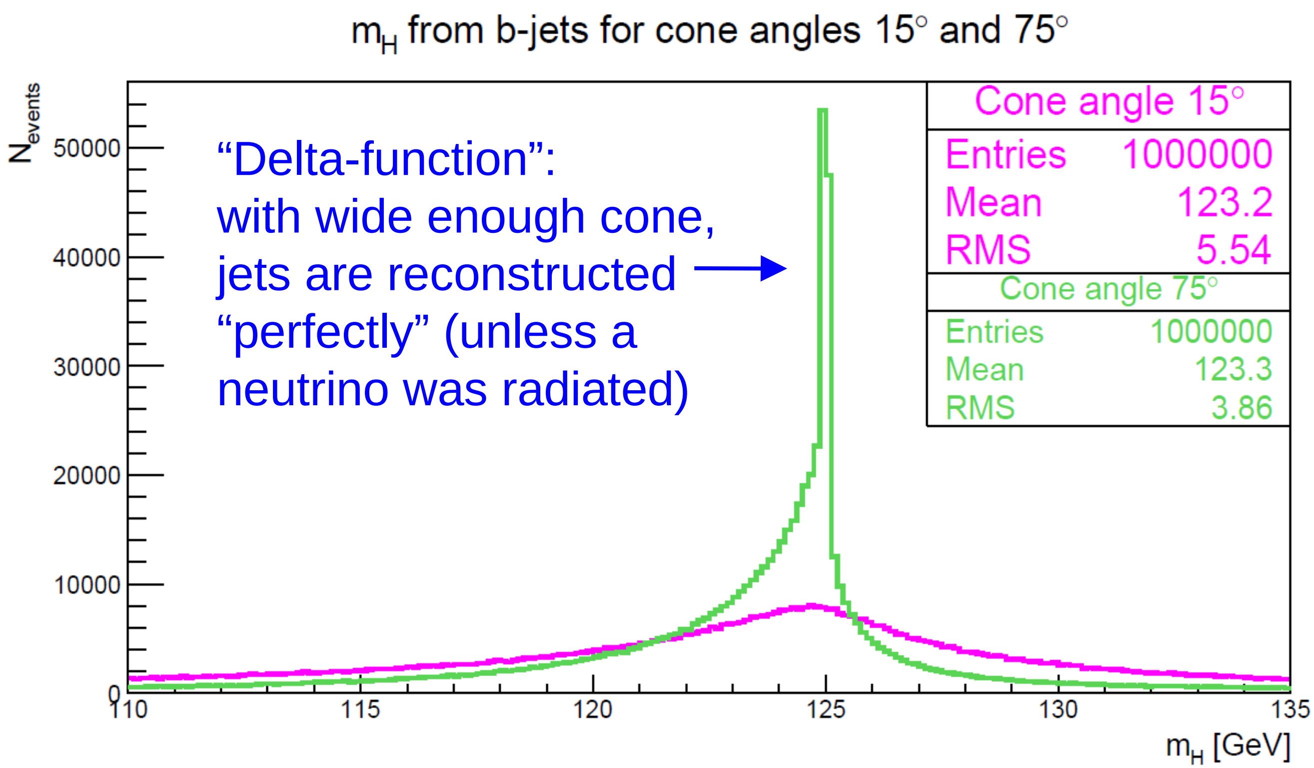


Truth jets

- We assume 0.5º resolution of jets reconstructed in calorimeter with respect to the truth jet. But how well the truth jet represents the truth b-quark?
  - Hadronization
  - Gluon radiation, parton showers
  - Escaping neutrino from leptonic decays
- Let's reconstruct M_H not from b-quarks, but from b-jets constructed from truth particles

M_H reconstructed from b-jets

- Influence of jet formation from partons is very significant
- The effect strongly depends on jet clustering



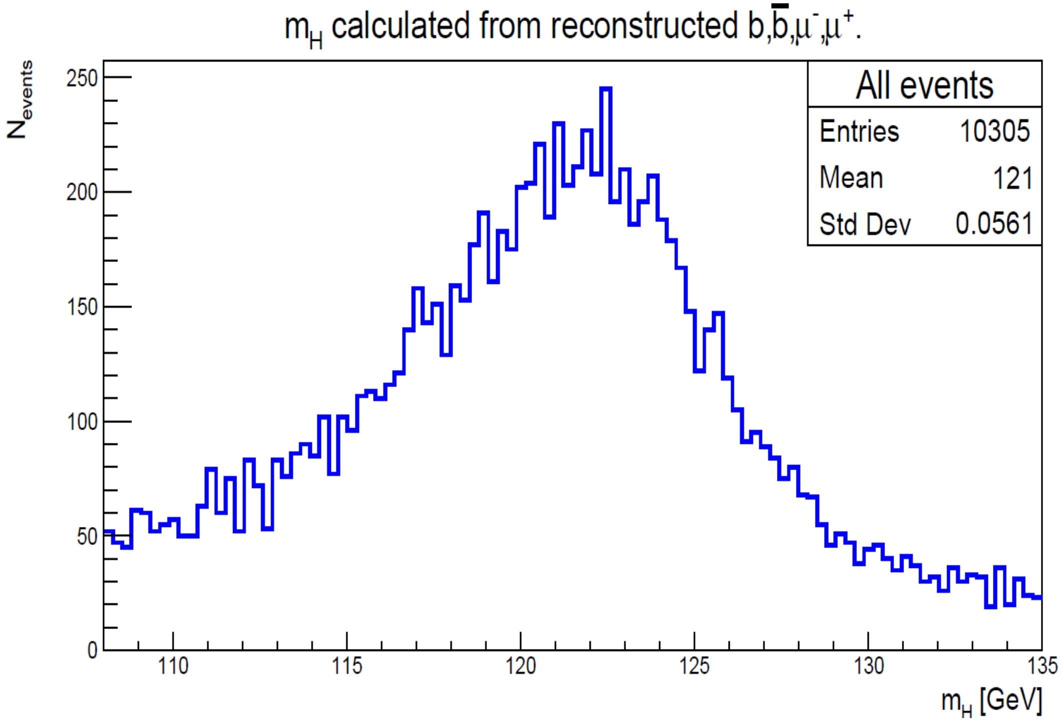
Must look at the full simulation of jets in calorimeter!

Now we go to the full detector simulation/reconstruction

- Whizard_1.9 for event generation
- ILC soft for simulation, reconstruction, analysis
- FastJet_3.3 for jet clustering

Spectrum of reconstructed Higgs masses

- Poor resolution
  $\Delta(M_H) = 215$ MeV
- VLC was chosen among several algorithms
- Its parameters were optimisated
- => tiny improvements!

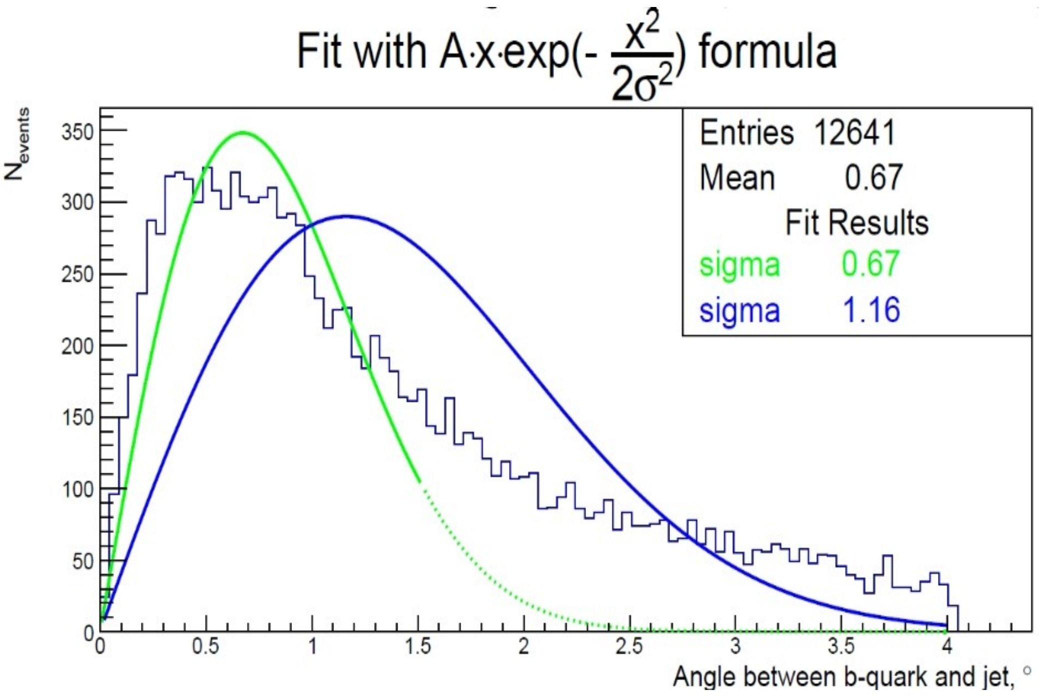


Distance between truth quark and reconstructed jet

- Most probable values have gaussian shape

σ~0.67°

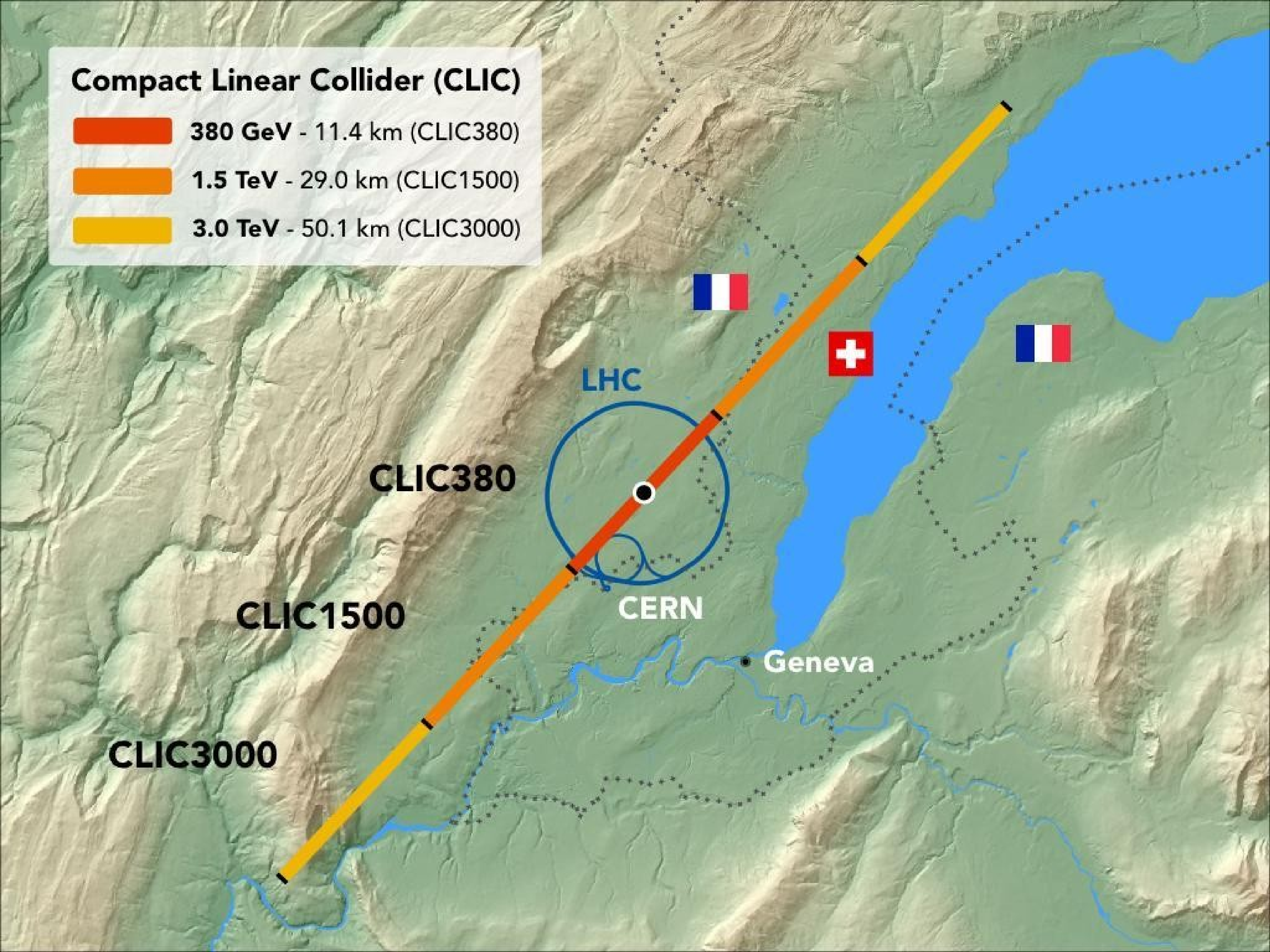
- Non-gaussian tail worsens the resolution
- Need to understand origin of this tail
- Work in progress …



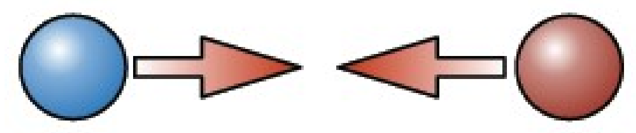
Summary

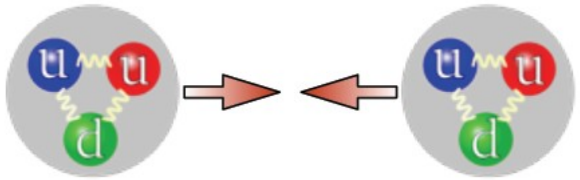
- The method proposed for ILC seems to be especially good for CLIC
  - It is safe against large beam energy spread and hard photon radiation
- Beam P_T imbalance and muon momentum resolution contribute negligible uncertainty
- $\Delta(M_H)$=45 MeV is expected from jet direction resolution of 0.5°
- With jets from Full Simulation we observe most probable angle < 0.67° but with a huge tail. The tail destroys completely the precision on $\mathbf{M_H}$ (215 MeV)
- Need to understand the shape of jet angular resolution!

Backup slides


Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva

Future collider candidates

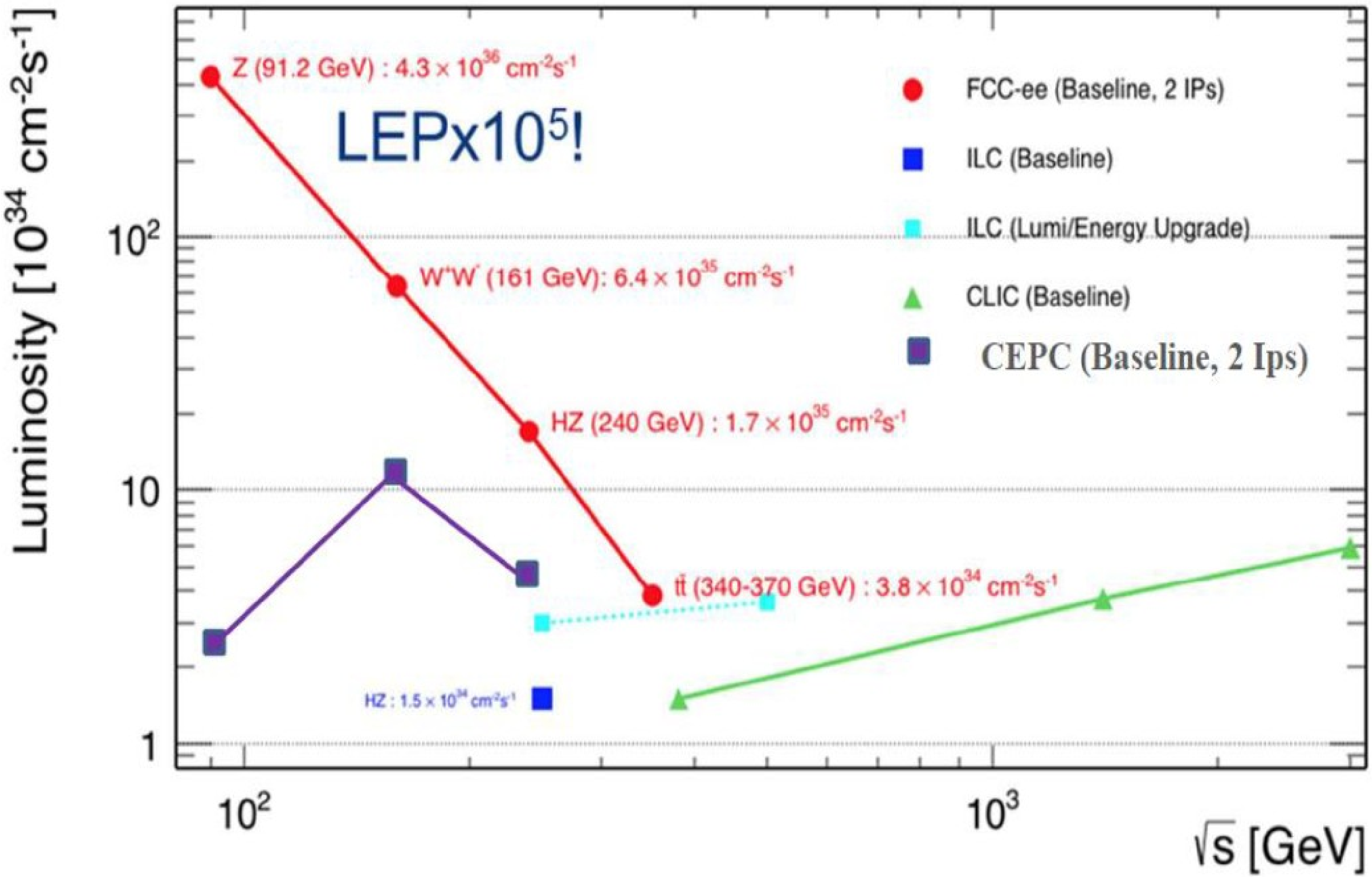




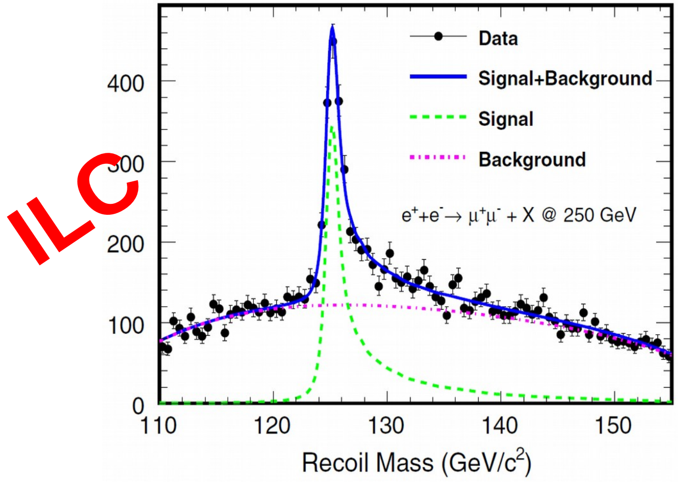
- ILC: 20 (30?) km, 250 (500?) GeV, Higgs factory (Giga-Z possible)
- CLIC: 50 km, 3000 GeV, Higgs, Top, discoveries
- CEPC: 100 km, 250 GeV, Higgs physics + Giga-Z
- FCC: 100 km, 350 GeV, Higgs + Tera-Z

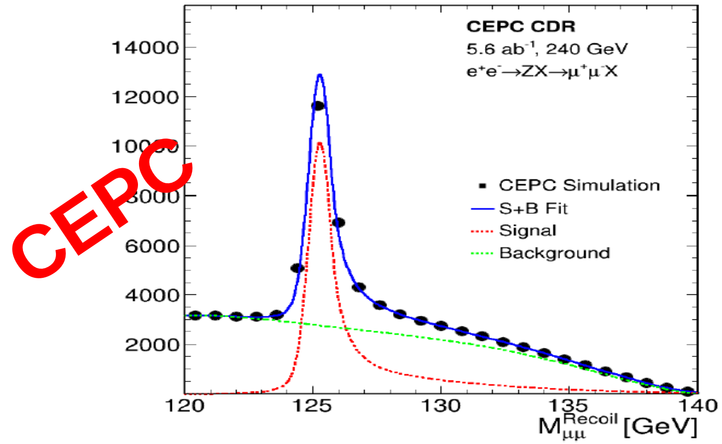
- HL LHC: 14 TeV, 3 ab^{-1}
- HE-LHC: 33 TeV, 2 ab^{-1}
- CEPC-pp: 70 TeV, 10 ab^{-1}
- FCC-pp: 100 TeV, 5 ab^{-1}

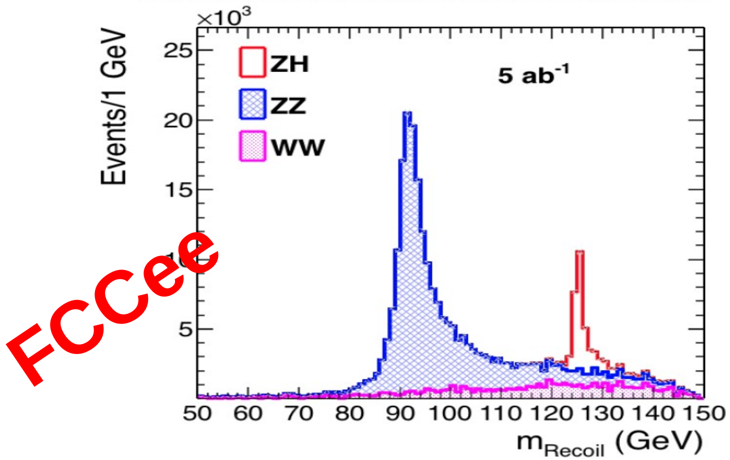
Comparison of e^+e^- projects

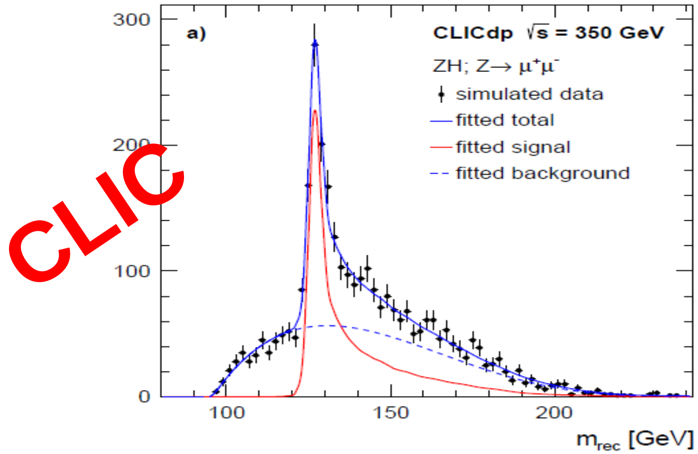


Why recoil mass is so bad at CLIC?







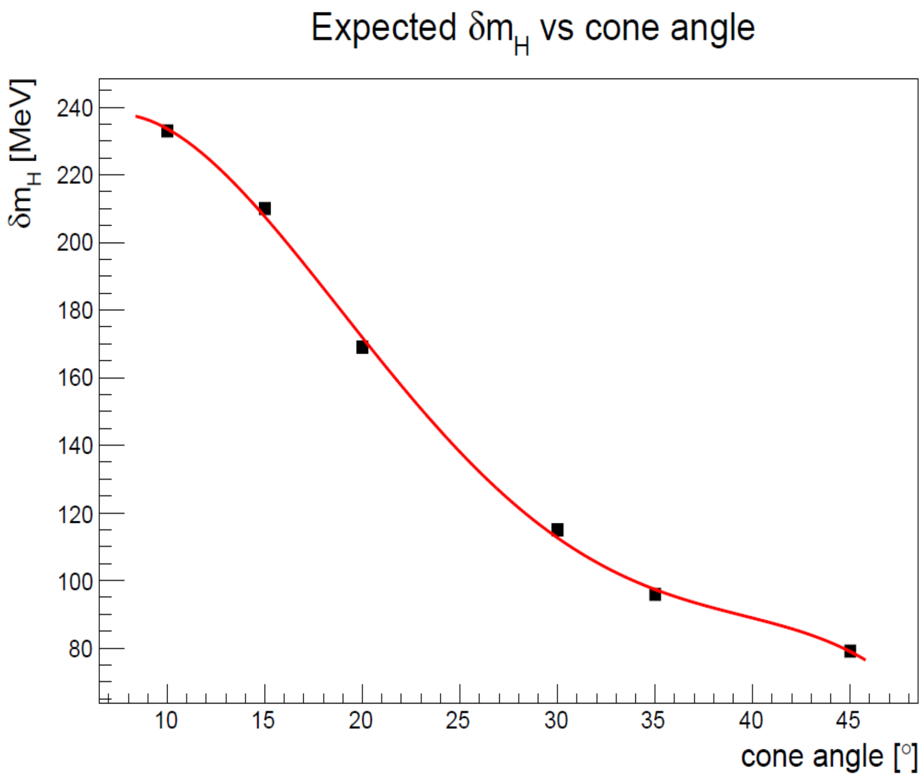


Note the horizontal scale !!!

Remark about jet directions

- Our M_H formula works at the level of partons (b-quarks)
- There are two steps where b-quark direction can be distorted:
  - 1) from b-quarks to truth jets
  - 2) from truth jets to jet reconstruction in calorimeter
- At generator level we can only look at step 1.

M_H uncertainty versus cone opening angle



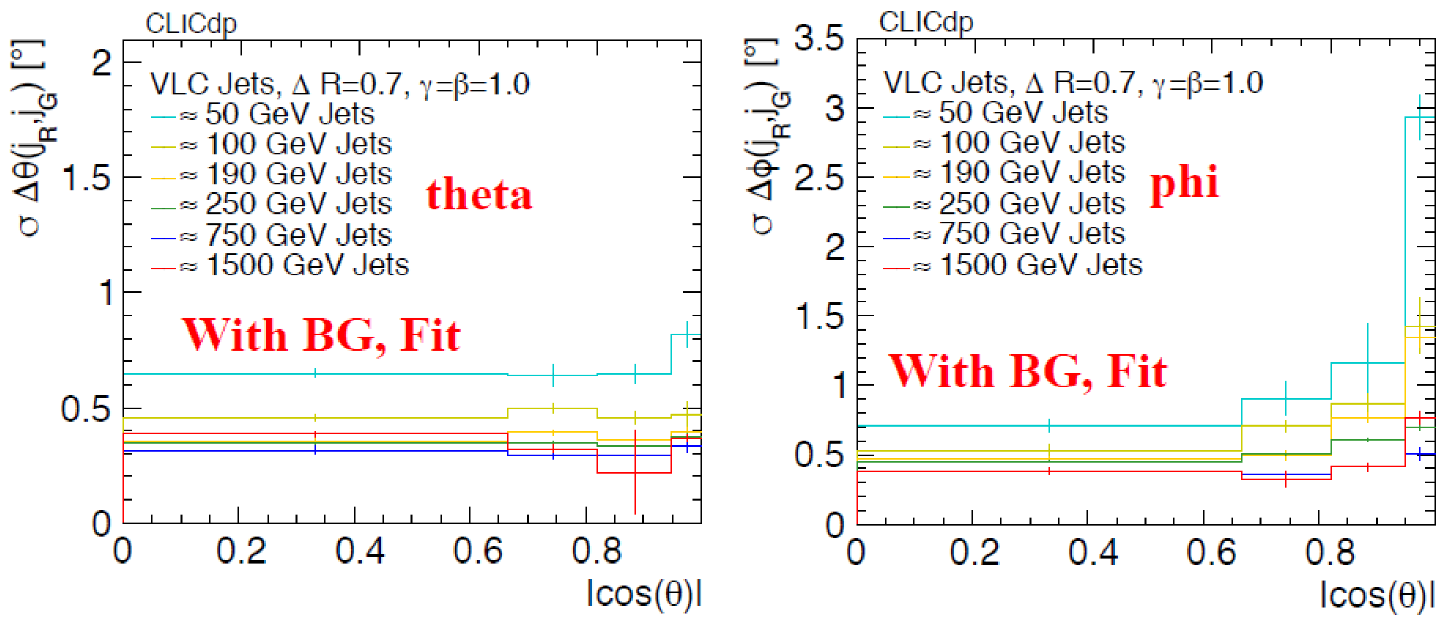
- Influence of jet formation from partons is very significant
- At least, it is not killing the method completely
- The effect strongly depends on jet clustering
- Our conclusion: it is pointless to study the effect at generator level
- Must look at the full simulation of jets in calorimeter

Why such a poor resolution?

- We tried several jet clustering algorithms: Durham, kt, anti-kt, Cambridge, Valencia
  - VLC is found to give the best result, but not dramatically better
- We varied VLC parameters. Found optimum, but improvement is small
  - Optimal VLC parameters: $\Delta R=0.4$, $\beta=\gamma=1.0$
  - Optimization on y_{23} gives tiny improvement

Jet direction resolution

Jet Phi and Theta Resolution



Theta and Phi resolutions below 1 degree for most detector regions, for forward and endcap jets larger phi resolution values