The Discovery

"The Higgs boson has been the object of one of the greatest campaigns in the history of particle physics and a pop-culture icon. On 4 July 2012, the ATLAS and CMS Collaborations announced the discovery of a Higgs-boson candidate with mass near 125 GeV".
(C. Quigg, 1507.02977)

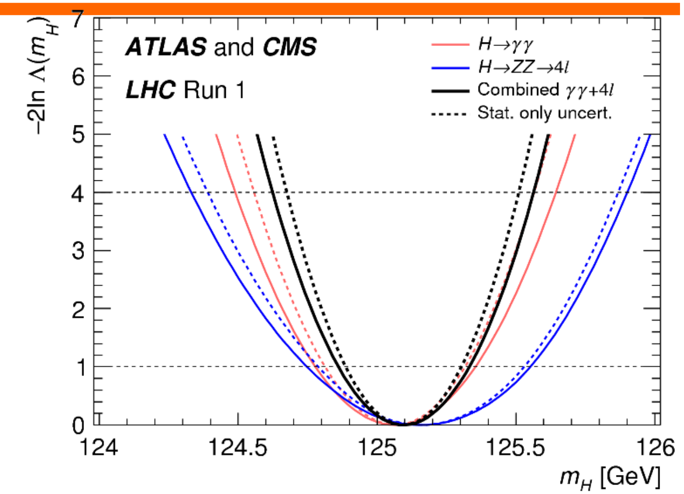
Report from the Higgs Group

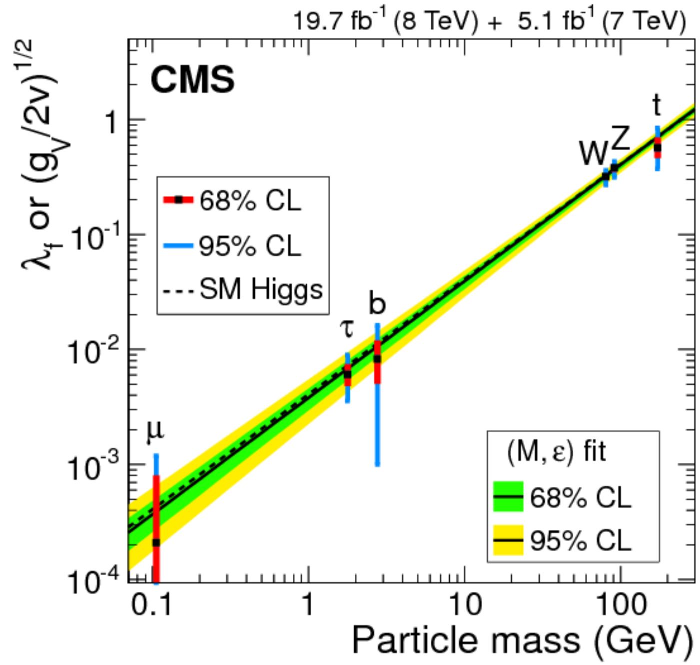
October 7, 2015

Ulrich Heintz, Ariel Schwartzman, Rick van Kooten

Higgs boson physics

- ATLAS and CMS
  - Higgs boson discovery
    - ATLAS Collaboration, Phys. Lett. B716 (2012) 1–29
    - CMS Collaboration, Phys. Lett. B 716 (2012) 30–61
  - $m_H = 125.09 \pm 0.21(stat) \pm 0.11(syst)\mathrm{GeV}$
    - ATLAS and CMS Phys. Rev. Lett. 114 (2015) 191803
- Given its mass, the SM predicts all properties of the Higgs boson without any free parameters. Any deviations are evidence for new physics
- The Higgs boson can be a portal to new physics





Session agenda

09:00 **The Higgs as a tool for discovery** *30'*
Speaker: Su Dong (SLAC)
Material: Slides

← plenary session

Parallel Session: Higgs

Conveners: Rick van Kooten (Indiana University), Ariel Schwartzman (SLAC National Accelerator Laboratory), Ulrich Heintz (Brown)

Location: Guadalupe

14:00 **Challenges for the ATLAS detector at the HL-LHC for Higg physics** *50'*
Speaker: Dr. Anadi Canepa (Fermilab)
Material: Slides

14:50 **Challenges for the CMS detector at the HL-LHC for Higgs physics** *50'*
Speaker: Ulrich Heintz (Brown)
Material: Slides

15:40 **Coffee Break** *20'*

16:00 **Challenges for an ILC detector for Higgs physics** *50'*
Speaker: Jenny List (DESY)

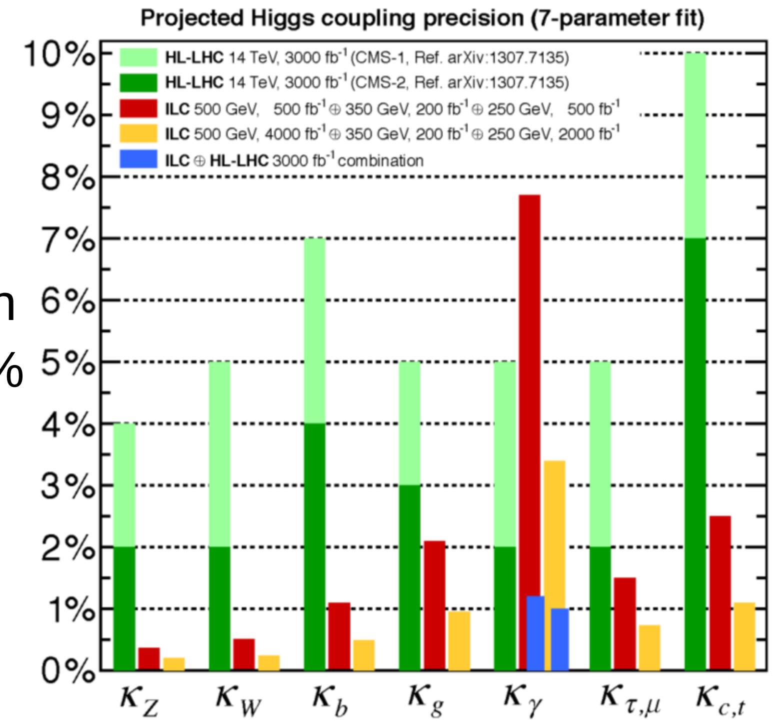
16:50 **Challenges for a detector at a 100 TeV hadronic collider for Higgs physics** *50'*
Speaker: Dr. Sergei Chekanov (ANL)
Material: Slides

Thanks to all speakers!

Evolution of Higgs boson physics

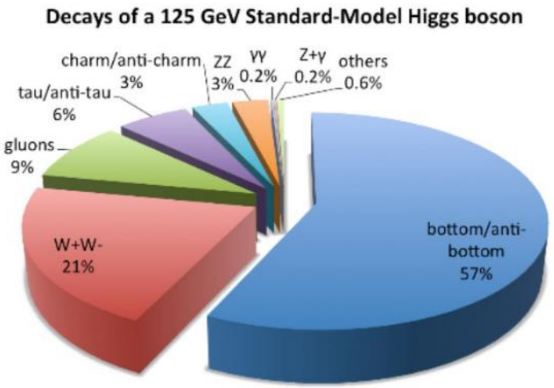
- LHC
  - The facility we have to study the Higgs boson in the next decade
  - Measure couplings to 5-10%, mass to 50 MeV, spin-parity structure
  - Probe rare decays
  - Measure Higgs trilinear coupling to 50%
  - Search for extended Higgs sector
- e^+e^- colliders
  - Measure of total ZH cross-section
    - Absolute normalization of all couplings
    - Access total width and invisible decays
  - Measure most couplings to sub% precision
  - Measure Higgs trilinear coupling to 50-10%
- 100 TeV pp collider
  - Measure Higgs trilinear coupling to 8%
- All
  - Higgs as a tool for discovery

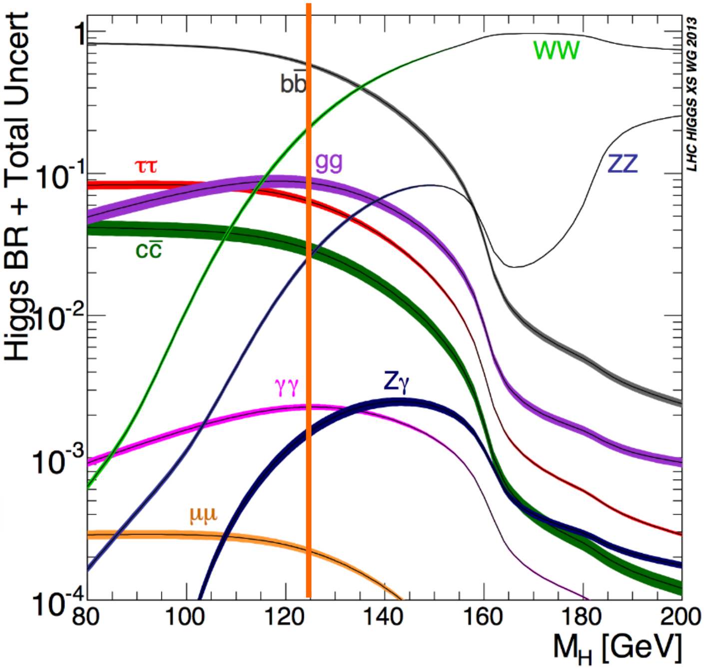
Projections based on arXiv:1310.8361



Detector requirements

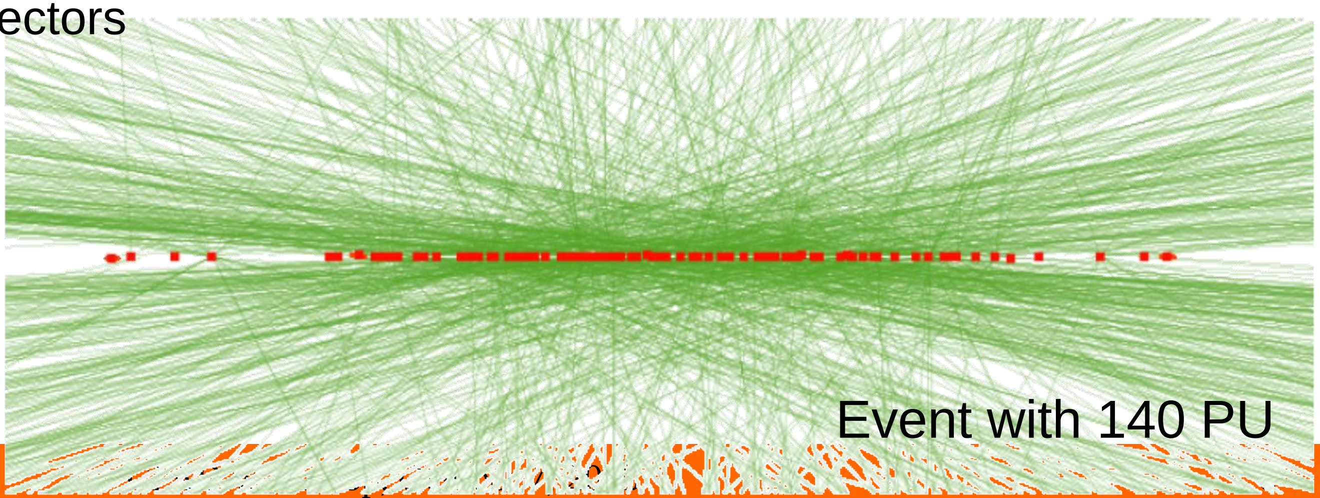
- All facilities
  - Reconstruct all particles with high efficiency and resolution, low fake rate
  - Higgs → $\gamma\gamma$, ZZ, WW, $\mu\mu$
    - Excellent electron, photon, and muon reconstruction
  - Higgs → bb
    - b-quark tagging and precision reconstruction of primary and secondary vertices.
  - Higgs → $\tau\tau$
    - Tracking of charged hadrons
    - measurement of electromagnetic energy
    - muon and electron reconstruction
  - tt +Higgs
    - jet reconstruction and b-quark tagging
- At e^+e^- colliders
  - Higgs → cc
    - Flavor tagging
- At pp colliders
  - Low trigger thresholds
  - Vector Boson Fusion
    - Acceptance at high η
  - Boosted Higgs





HL-LHC environment

- High pileup: up to 140-200 additional interactions per bunch crossing
  - Largest source of hits in the tracking system
  - Adds extra energy to calorimeter measurements, creates additional (fake) jets, degradation of jet energy resolution
  - Increased execution time for event reconstruction and trigger
  - Increased trigger rates
    - Need to maintain low thresholds to preserve acceptance for Higgs production
- Radiation damage:
  - Detector elements and electronics are exposed to high radiation dose
  - Degrades signal, requires continuous calibration
  - Limits lifetime of detectors
- High energy:
  - Boosted and complex topologies

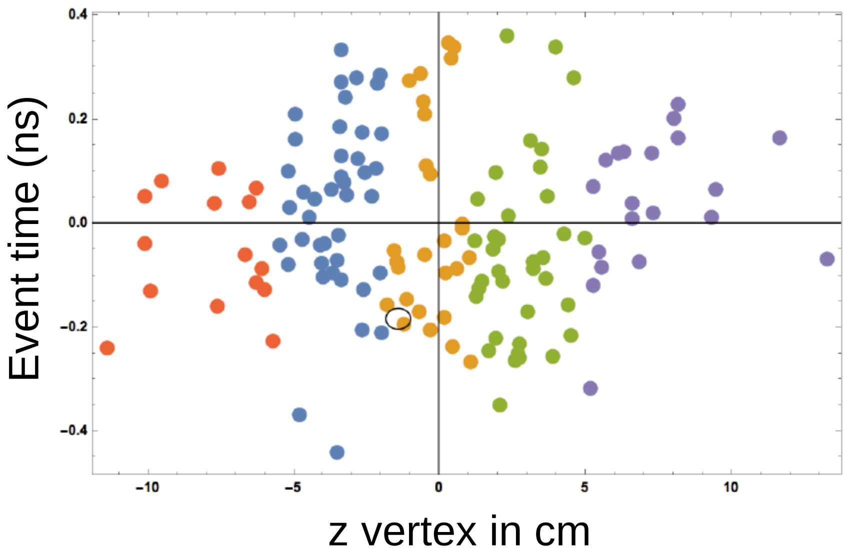


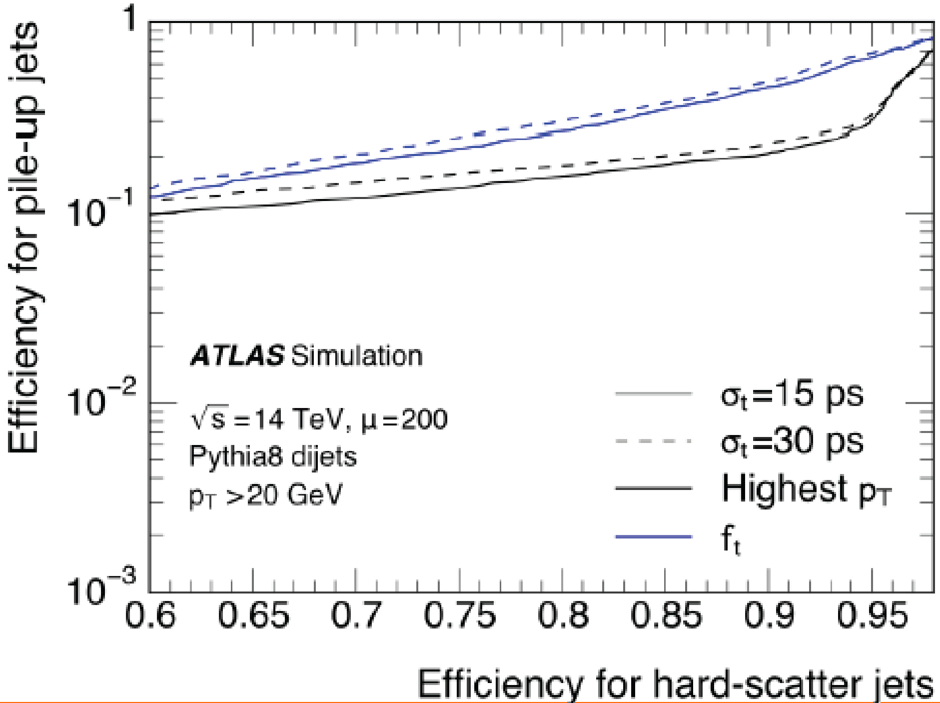
LH-LHC detector requirements

- ATLAS and CMS Detector upgrades will maintain (or improve) physics event reconstruction in the much higher luminosity environment
  - Tracker
    - Rad. tolerant, high granularity, significantly less material, extend coverage to the forward region (eta<4.0) for increased VBF Higgs physics acceptance and pileup mitigation
  - Calorimeters
    - Rad. tolerant, high segmentation, new electronics
  - Trigger and DAQ
    - Track information at L1
    - Increased output rate ~7.5kHz
    - Boosted object triggers
  - Muon system
    - Increase coverage, better performance to maintain low thresholds
  - Precision timing capabilities
    - New handle to mitigate pileup at pp colliders!

Precision timing

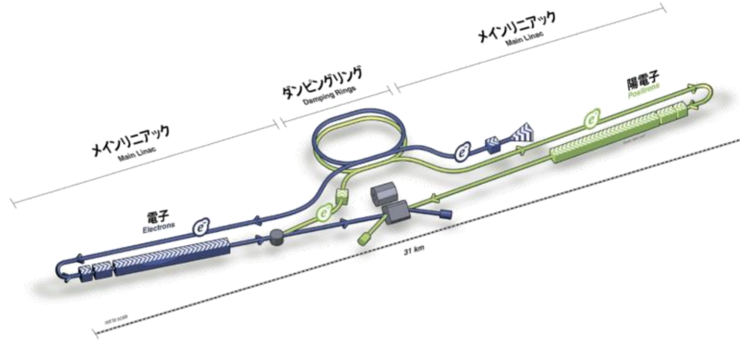
- Pileup interaction vertices are distributed in space and time
  - A timing detector can restrict the region along the z-axis from which tracks emanate, reducing the contribution of pileup
  - "5D" event reconstruction
  - Jet-vertex tagging in the forward region
- Need 10-30ps time resolution
  - Several technologies under consideration



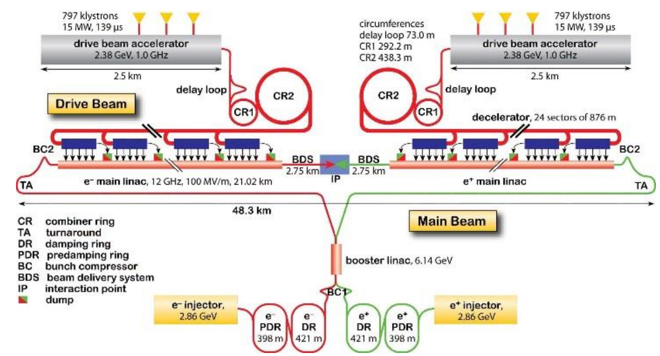


Possible e^+e^- facilities

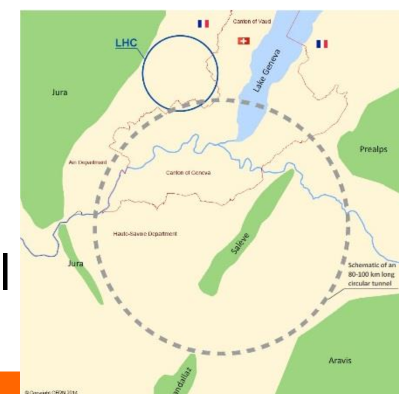
- ILC (200-500 GeV → 1 TeV)
  - Trains of 1315/2625 bunches
  - 530/270 ns bunch spacing
  - Pulsed at 5-10 Hz
  - Triggerless readout
  - Power pulsing → no cooling → 0.0015 X_0/tracker layer, dense calorimeter



- CLIC
  - 350 GeV – 3 TeV
  - Trains of 312 bunches, 0.5 ns bunch spacing
  - Pulsed at 50 Hz
  - Power pulsing possible?
  - Large beamstrahlung background – can be dealt with

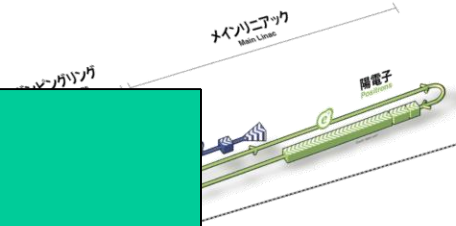


- Circular e^+e^- colliders (CepC, FCC-ee)
  - 90-350 GeV
  - Continuous operation with 10 ns – 10 μs bunch spacing
  - Power pulsing not possible → need cooling – adds material

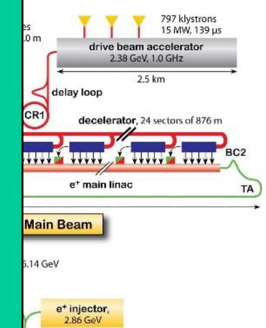


Possible e^+e^- facilities

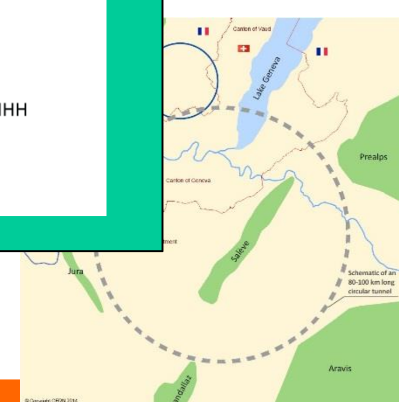
- ILC (200-500 GeV → 1 TeV)
  - Trains
  - 530/27
  - Pulsed
  - Trigger
  - Power



- CLIC
  - 350 Ge
  - Trains
  - Pulsed
  - Power
  - Large

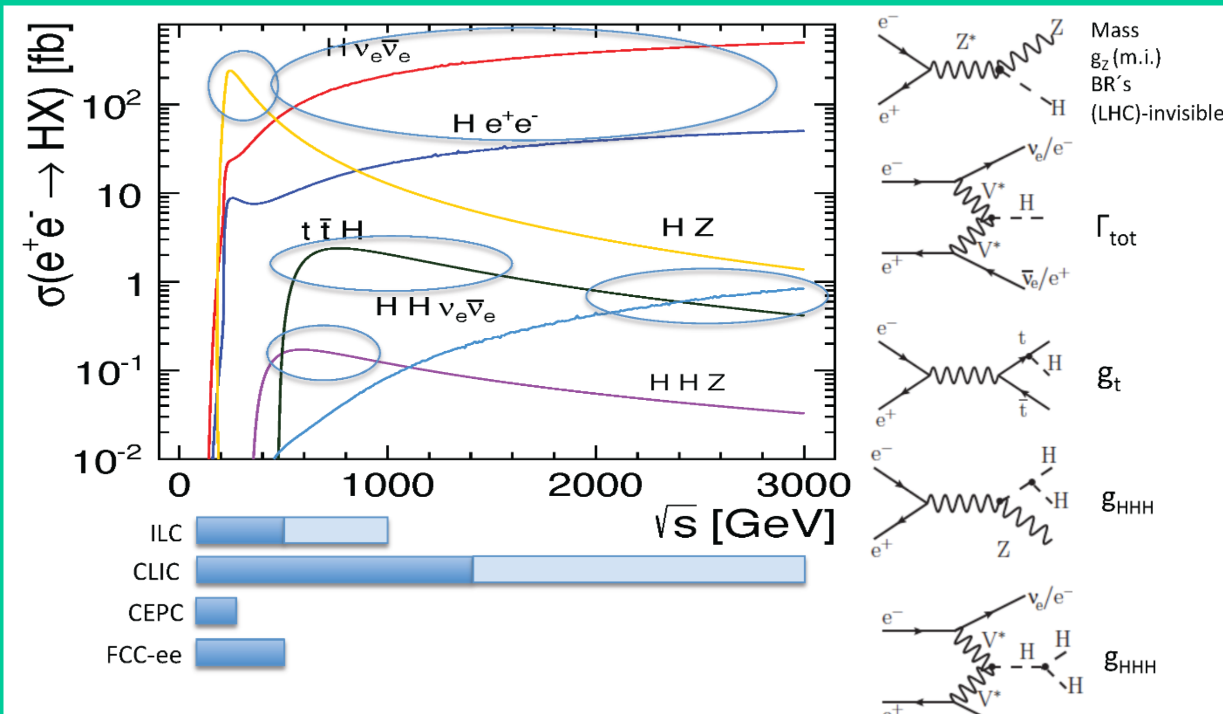


- Circular
  - 90-350
  - Contin
  - Power pulsing not possible → cooling



orimeter

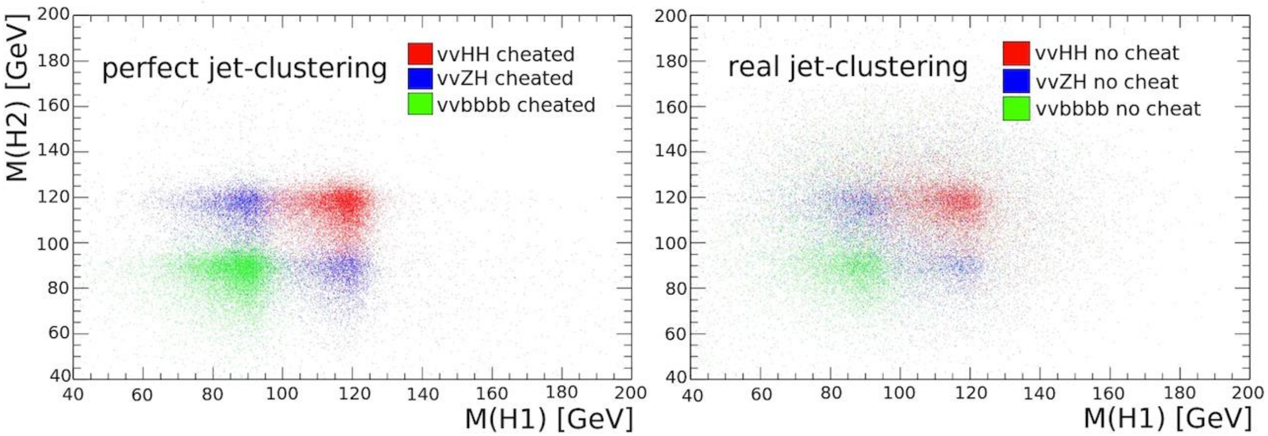
There is no "right" c.o.m. energy



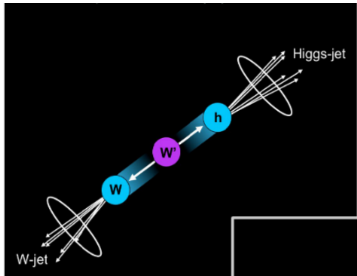
- Many processes at different √s needed & accessible

Higgs at e^+e^- colliders

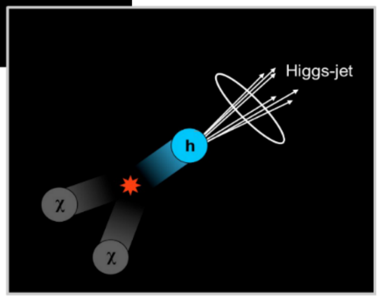
- Superior precision puts the onus on systematics control
- underestimated / not sufficiently studied
  - particle ID: impact on flavor tag
    - H→cc, H→ττ statistically limited
  - JER, helper measurements: eg neutral hadron fraction => K_S^0
  - reconstruction and ID of low momentum particles (< 2 GeV)
    - compressed spectra, e.g. Higgsinos
  - alignment / calibration / stability
- The JER challenge: Higgs self-coupling
  - Relies on jet resolution (dominated by clustering)



Higgs @ 100 TeV: a window to new physics



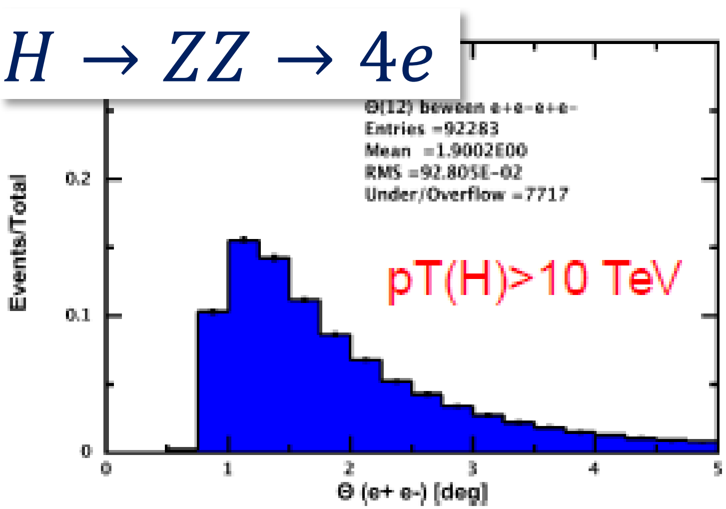
From. B Tweedie



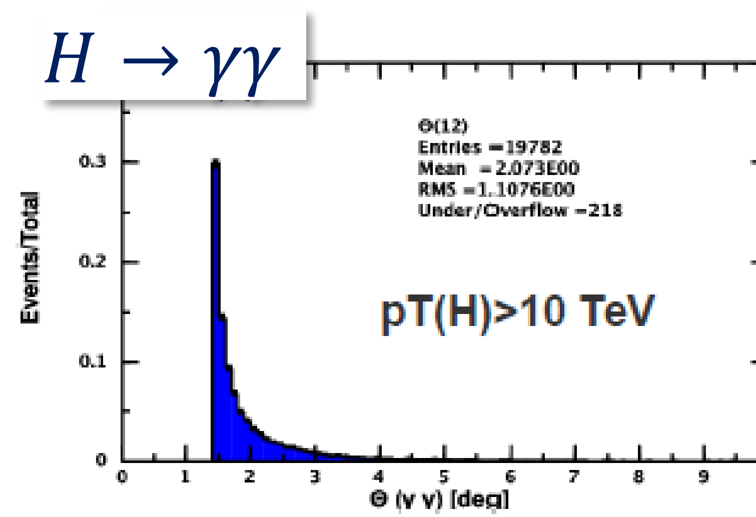
- 100 TeV collider will hunt for M~20-30 TeV particles that may decay to Higgs
- The detector must be optimized to reconstruct Higgs at **pT~10 TeV**

Increased importance of boosted Higgs

How bad is this for Higgs reconstruction in the "golden" decay channels: γγ, Z*Z, W*W, ττ, $b\bar{b}$?



6 T Magnetic field, 2.5 m outer radius, proposed baseline for FCC pixel size is 5 μm



identify 2 photons separated by 1 degree reject $\pi^0 \to \gamma\gamma$ background at the same time

100 TeV Collider

- Many challenges.. but enough time to solve them
- Tracking
  - 5μm pixel sizes & a lot of silicon
- Muon spectrometer
  - Important for high-pT Higgs
  - Combine with high-granular pixel tracking
- Calorimeter
  - Deep HCAL (12 λ_0 depth)
  - High granularity: cell size in ECAL <2 cm, in HCAL <5 cm
  - HCAL resolution with constant term ~3% and below
  - Longitudinal segmentation for 3D clusters
  - Cell dynamic range extended by a factor 10
  - Extended coverage to |η| < 6 is desired

Findings

- HL-LHC
  - ATLAS and CMS are well suited to deal with HL-LHC requirements
  - Challenge: pileup mitigation, high η acceptance, trigger
  - R&D: precision timing
- e^+e^- colliders
  - ILC – basic technology exists, CLIC/circular colliders face more challenges
  - Challenge: high performance detector to reach ultimate precision measurements – control of systematics is critical
  - R&D: optimization of physics performance (jet clustering in high multiplicity final states), low mass of cooling systems
- 100 TeV pp collider
  - Pushes envelope of technology in all aspects – new ideas needed
  - Challenge: dynamic range increases for all measurements
  - R&D: high granularity, calorimeter containment, forward acceptance

Possible Grand Challenge Ideas

- Precision timing for all subdetector systems
- Low mass cooling systems
- Highly granular tracking detectors
- Calorimeters for multi TeV showers