Snowmass Colloquium
“Energies beyond LHC”

Question: Can we design a detector to measure physics events at 100 TeV pp collider and luminosity of 10^{35} cm^{-2}sec^{-1}? Where are the limits in energy and luminosity beyond which solutions don't currently exist?

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Snowmass at Minnesota, August 2 2013

Why 10^{35} cm^{-2}sec^{-1}?

- Number of events produced: N = $\sigma(E)$ x Luminosity
- Tevatron (ppbar) $5 \cdot 10^{32}$ cm^{-2}sec^{-1}
- LHC (baseline design) $2 \cdot 10^{34}$ cm^{-2}sec^{-1}
- SSC $1 \cdot 10^{33}$ cm^{-2}sec^{-1}
- In all cases luminosity was/is mainly limited by the accelerator complex
- Luminosity of 10^{35} cm^{-2}sec^{-1} is at the edge of the accelerator capabilities for 100 TeV pp collider
  - Could detectors ultimately handle such luminosity?

Challenges of High Luminosity

- **Large number of soft interactions**
  - **Inelastic pp cross section is ~100mb at 100 TeV**
  - **At 10^{35} luminosity interactions rate is 10GHz of pp interactions in the center of the detector**

- **As a result**
  - **Substantial radiation doses on the detector elements**
  - **Large number of interactions per beams crossing: ~200**
  - **High rejection/speed trigger systems to select events for analysis required**
  - **Complex off-line reconstruction software**

Fundamental Advantages of Higher Energy

- Quantum mechanics

$$\text{Wavelength} = h/E$$

- Relativity

$$E = mc^2$$

- 100 TeV VLHC will provide an opportunity to <u>directly</u> study
  - Distances ~10 times smaller than LHC or ~10^{-19} cm
  - Particles with masses ~10 times above LHC or ~10s of TeV
- Addresses deepest questions of how the world around us works

VLHC is ~100 TeV Very Large Hadron Collider

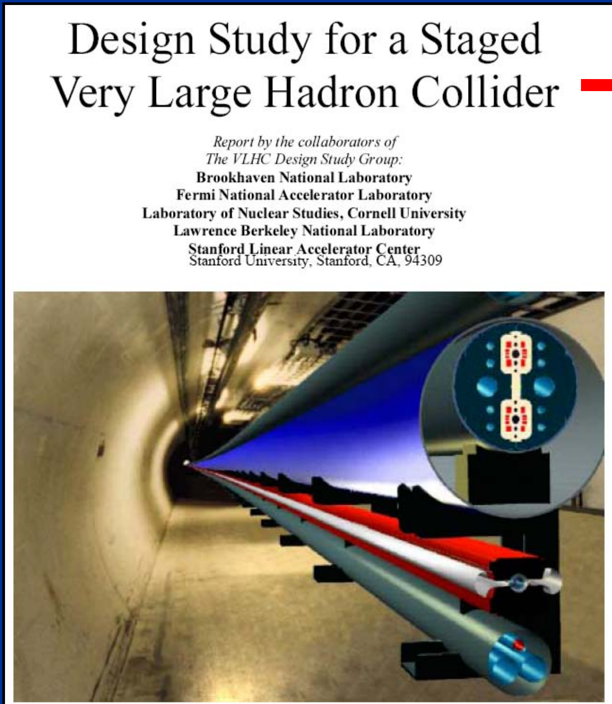
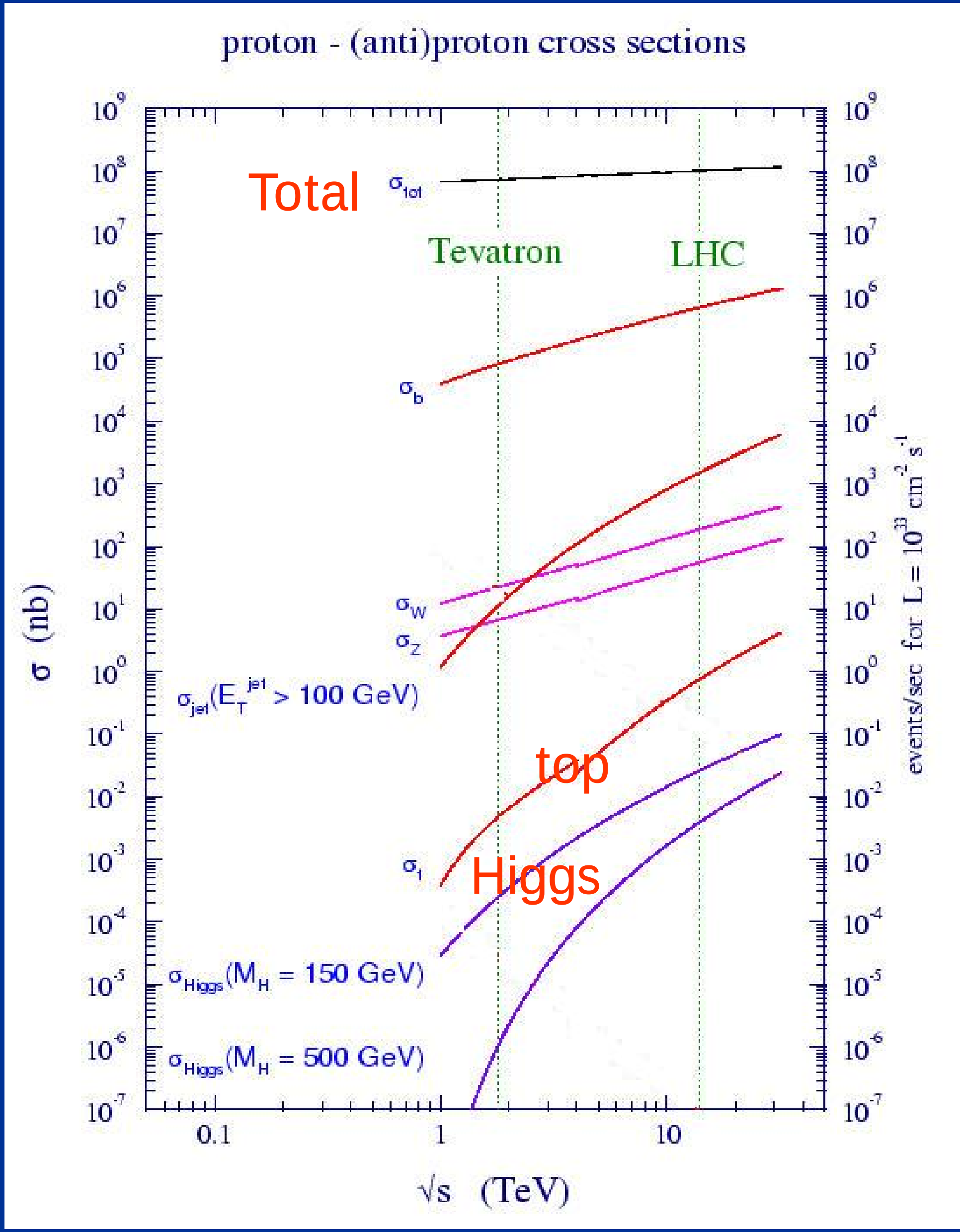


Table 1.1. The high-level parameters of both stages of the VLHC.

	Stage 1	Stage 2
Total Circumference (km)	233	233
Center-of-Mass Energy (TeV)	40	175
Number of interaction regions	2	2
Peak luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	2.0×10^{34}
Luminosity lifetime (hrs)	24	8
Injection energy (TeV)	0.9	10.0
Dipole field at collision energy (T)	2	9.8
Average arc bend radius (km)	35.0	35.0
Initial number of protons per bunch	2.6×10^{10}	7.5×10^{9}
Bunch spacing (ns)	18.8	18.8
β^* at collision (m)	0.3	0.71
Free space in the interaction region (m)	± 20	± 30
Inelastic cross section (mb)	100	130
Interactions per bunch crossing at L_{peak}	21	54
Synchrotron radiation power per meter (W/m/beam)	0.03	4.7
Average power use (MW) for collider ring	25	100
Total installed power (MW) for collider ring	35	250

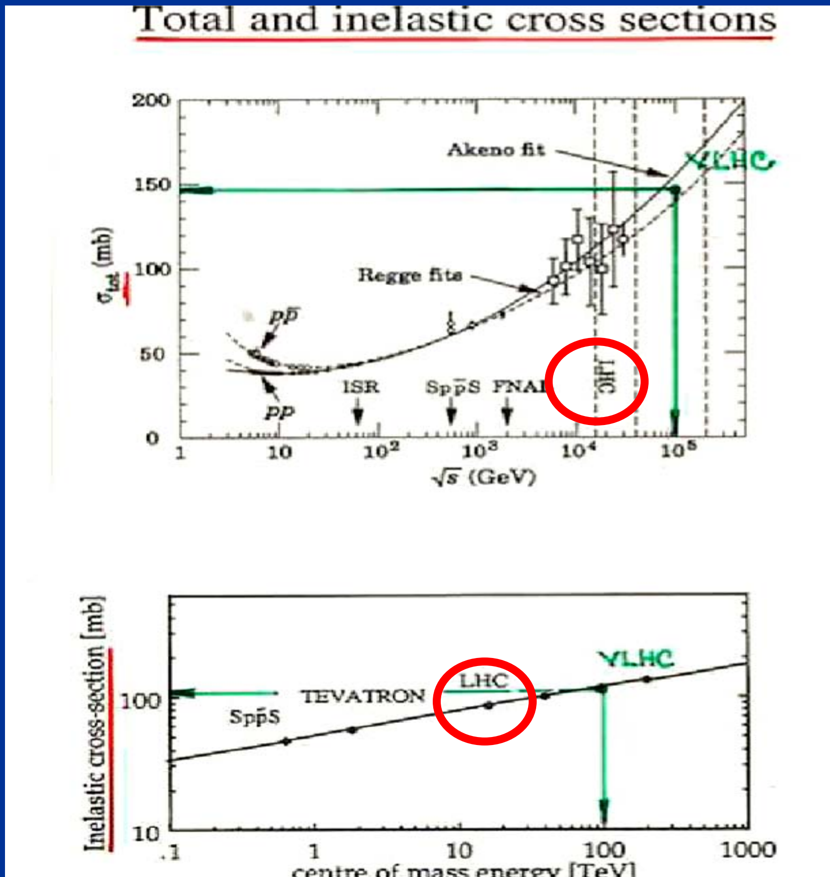
- **Vast amount of documented studies exists**
- **Including design study for previous Snowmass meeting (above picture) and 2001 Snowmass proceedings (SLAC-R-599)**
- **ATLAS/CMS upgrades studies are deeply relevant**

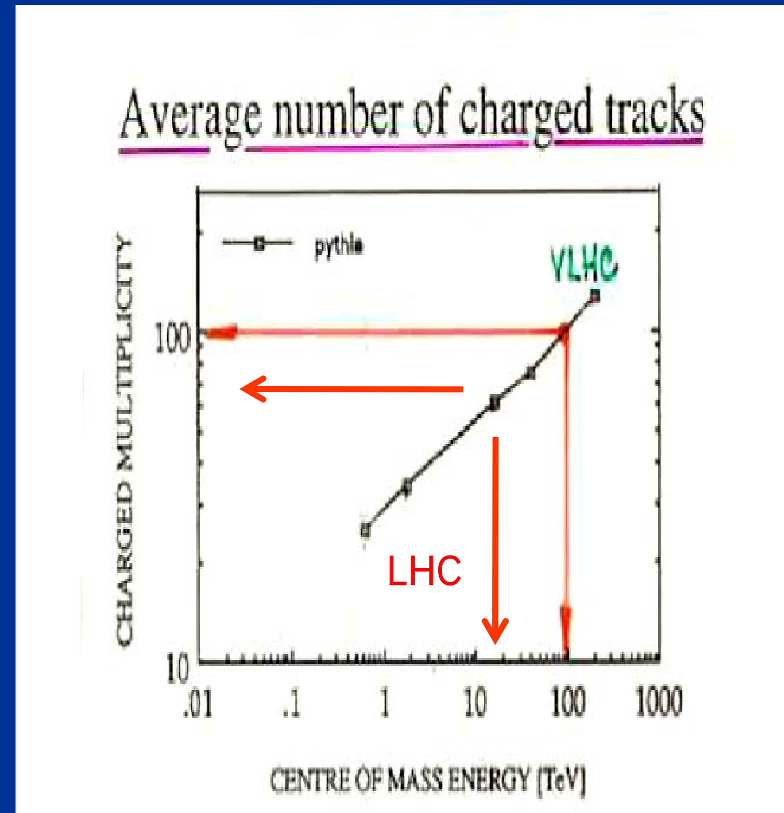
Cross Sections vs Colliding Energy



- **Total cross sections (read backgrounds) are barely changing with energy**
- **Cross sections for interesting (read high mass) objects are rapidly increasing with energy**
- **Increase in the energy provides access to high mass objects much more efficiently then increase in luminosity**
  - **And we can't make 2.1 TeV mass object at 2.0 TeV collider**

Properties of 100 TeV pp Collisions

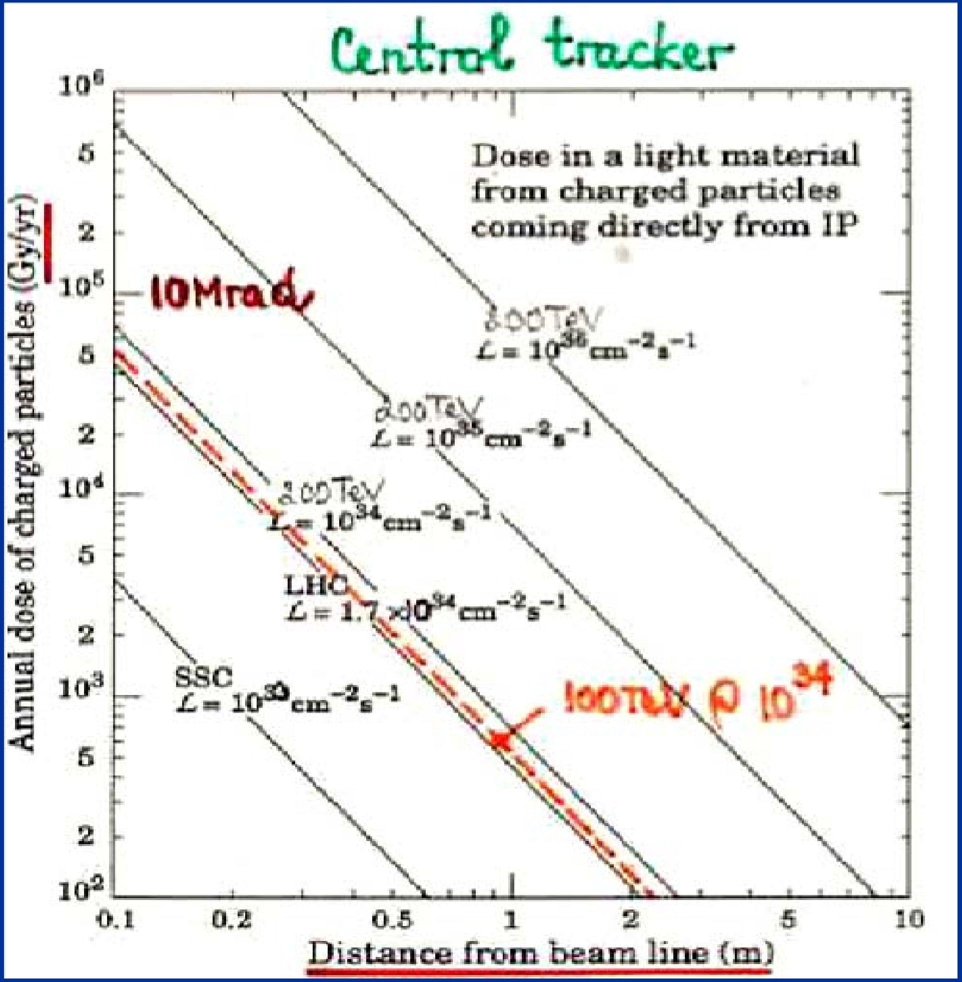




Properties of copious soft pp interactions at 100 TeV are similar to LHC: ~30% increase in cross sections and charged particles multiplicities only

Momentum spectra are similar as well with typical P_t of ~0.5 GeV

What about Radiation Doses?



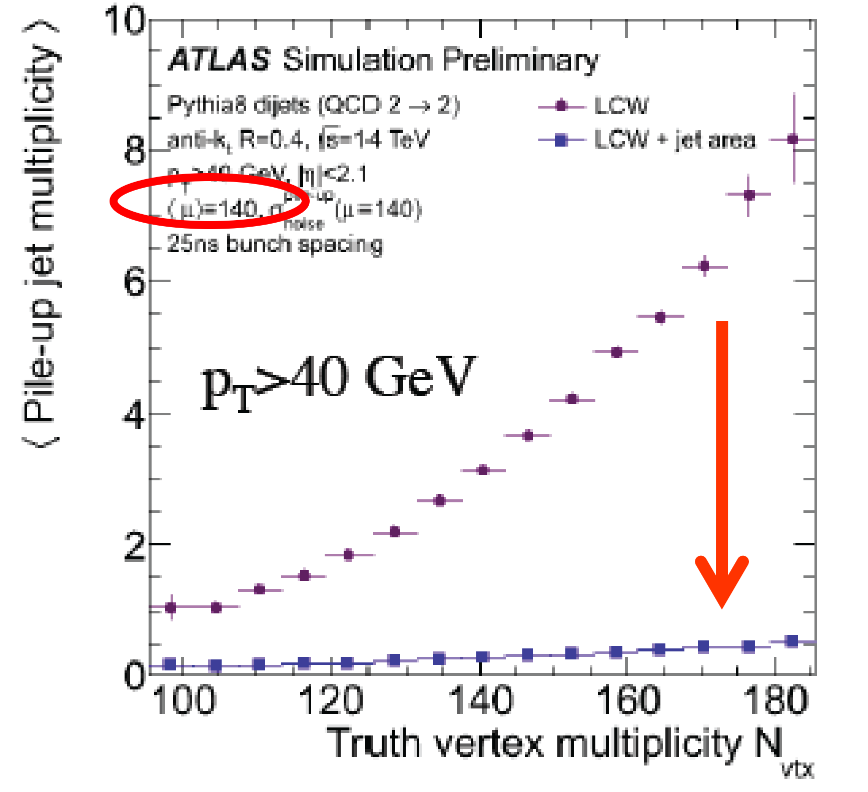
Radiation doses scale with luminosity, not with energy

Radiation doses of ~50 Mrad/year at 10 cm: challenging, while manageable with progressing R&D for LHC upgrade

“High-luminosity LHC” (2022+) design luminosity is $5\cdot10^{34}$ cm^{-2} sec^{-1}

Handling High Pile-up

For 140 events per crossing pile up (high luminosity ATLAS/CMS upgrades) excellent improvements in algorithms (based on highly segmented detectors) are developed



Very small number of false jets associated with pp collision: standard algorithm (LCW) vs improved (LCW+jet area)

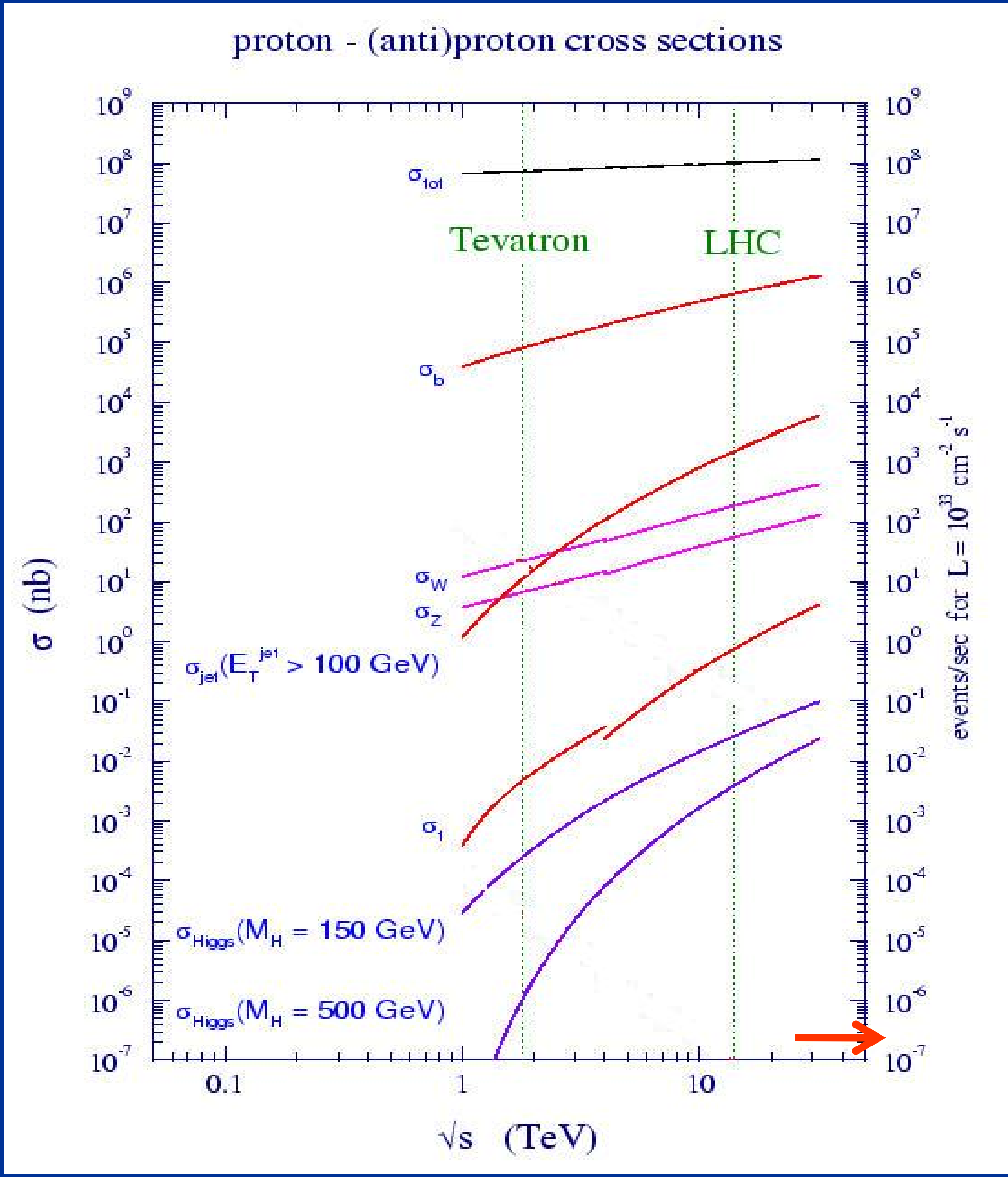
No pile up effects for jets with energies above ~300 GeV:

detection of jets from excited quarks with 10 TeV mass is not an issue

Detectors for 100 TeV Collider

- ~4π general purpose detector with layers of tracking, calorimetry and muon detectors
  - Similar to ATLAS/CMS/CDF/DZero
- Central tracker
  - Most challenging is to preserve momentum resolution for high momentum (almost straight lines) tracks
    - More and higher accuracy tracking layers, larger magnetic field
- Calorimetry
  - Getting better with energy! Hadronic energy resolution ~50%/√E, 2% at 1TeV
    - Back to DZero Run I detector based on calorimetry?
  - Length of shower increase has log(E) dependence – not an issue
- Muon system
  - Main challenges are momentum resolution and showering of muons (muons are becoming "electrons" due to large γ factor)

VLHC Events Yields



For 10^{35} cm^{-2} sec^{-1} luminosity typical yields

- 40 kHz Z bosons
- 2 kHz top quarks
- 20 Hz Higgs (~200 millions per year)
- Z' with mass of 30 TeV: 100 events per year!

VLHC Triggering

- VLHC bunches collisions rate is ~50 MHz

- W/Z bosons production rate is over 100 kHz

- Triggering strategy
  - Increase trigger bandwidth: Level 1 trigger rate 2 kHz at DZero vs 100 kHz for LHC detectors
  - Increase threshold as VLHC is designed to study high mass objects
  - Dedicated "forward" detectors for boosted production studies
    - LHCb (b-quark) → VLHCt (top quark)

- Write large fraction of 50 MHz collisions to "tapes"?
  - Continuing rapid improvements in electronics and computing

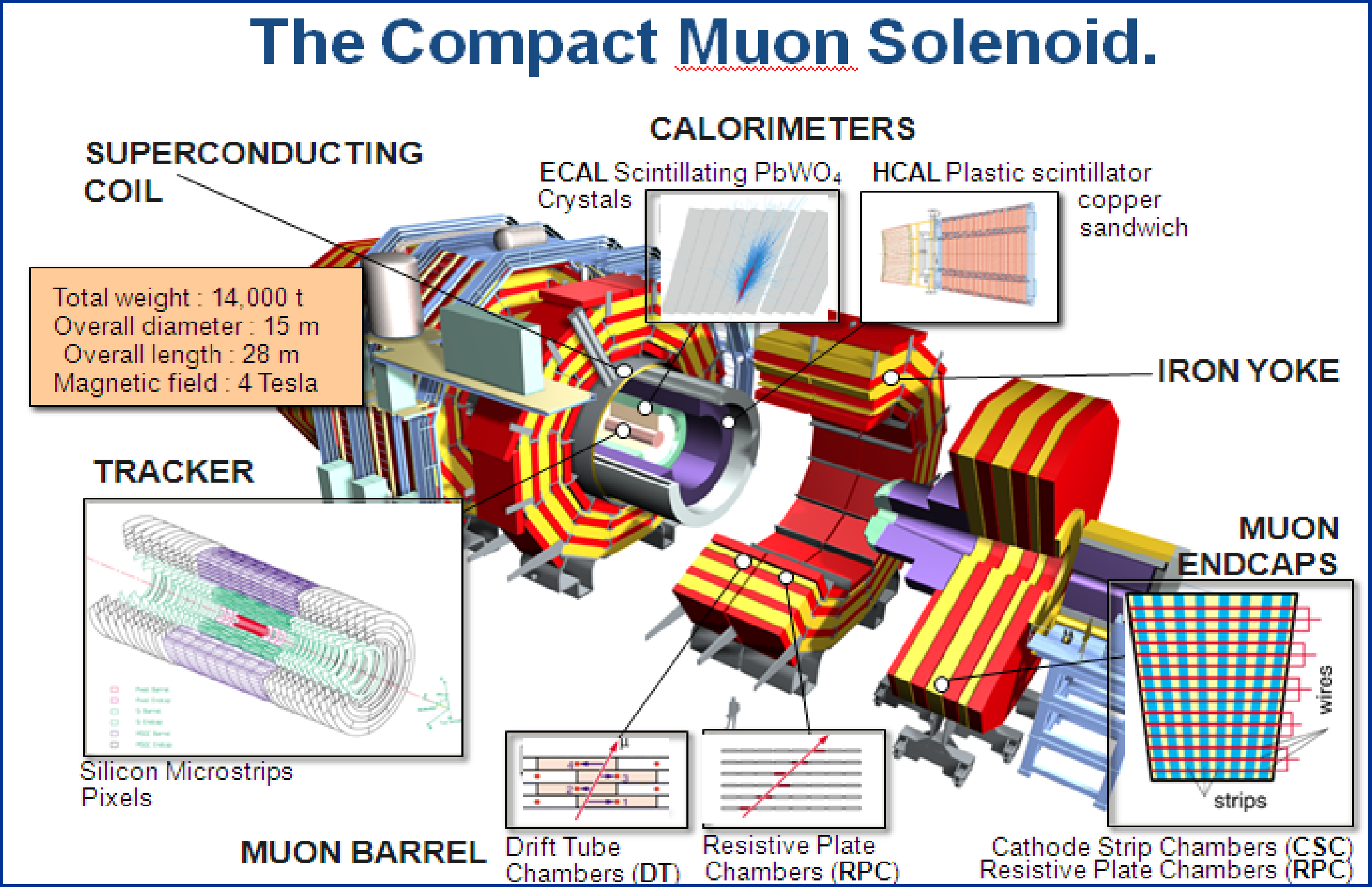
VLHC Detectors Concluding Remarks

- VLHC detectors for the luminosity of 10^{35} cm^{-2} sec^{-1} are feasible
  - Detectors R&D to improve performance and reduce costs is important

- Limits in luminosity and energy for the detectors
  - Luminosity well above 10^{35} cm^{-2} sec^{-1} will be challenging for modern technologies in many respects: radiation doses, occupancies, reconstruction

  - Above 100 TeV collision energies could be handled by existing detector technologies
    - At ~500 TeV synchrotron radiation will become limiting factor in reaching even higher energies (for circular pp machines)

Typical VLHC Detector



Could look similar to ATLAS, CMS, CDF or DZero

History of Colliders