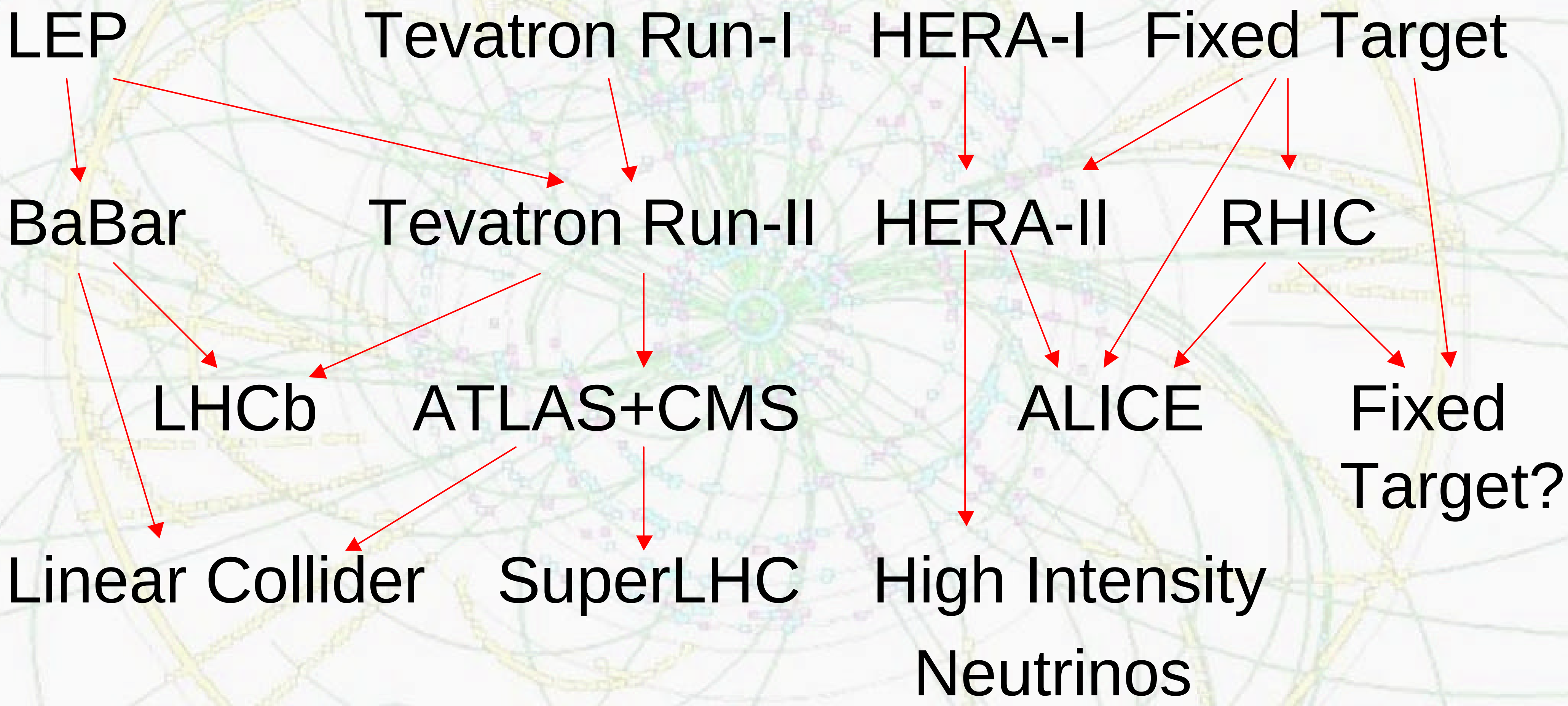
# Future Directions in Particle Physics

**The questions particle physics aims to address in the coming decades are:**

- **What are the scope and limitations of the Standard Model of particle physics?**
- **What is the origin of the masses of the fundamental particles?**
- **Why do their masses and couplings differ as they do?**
- **What is the reason for the matter – anti-matter asymmetry in the Universe?**
- **Can all the forces, including gravity, be understood in a single unified framework?**
- **What are the Dark Matter and Dark Energy that dominate the large scale evolution of the Universe?**

# What are the Scope and Limitations of the Standard Model of Particle Physics?



# What are the Scope and Limitations of the Standard Model of Particle Physics?

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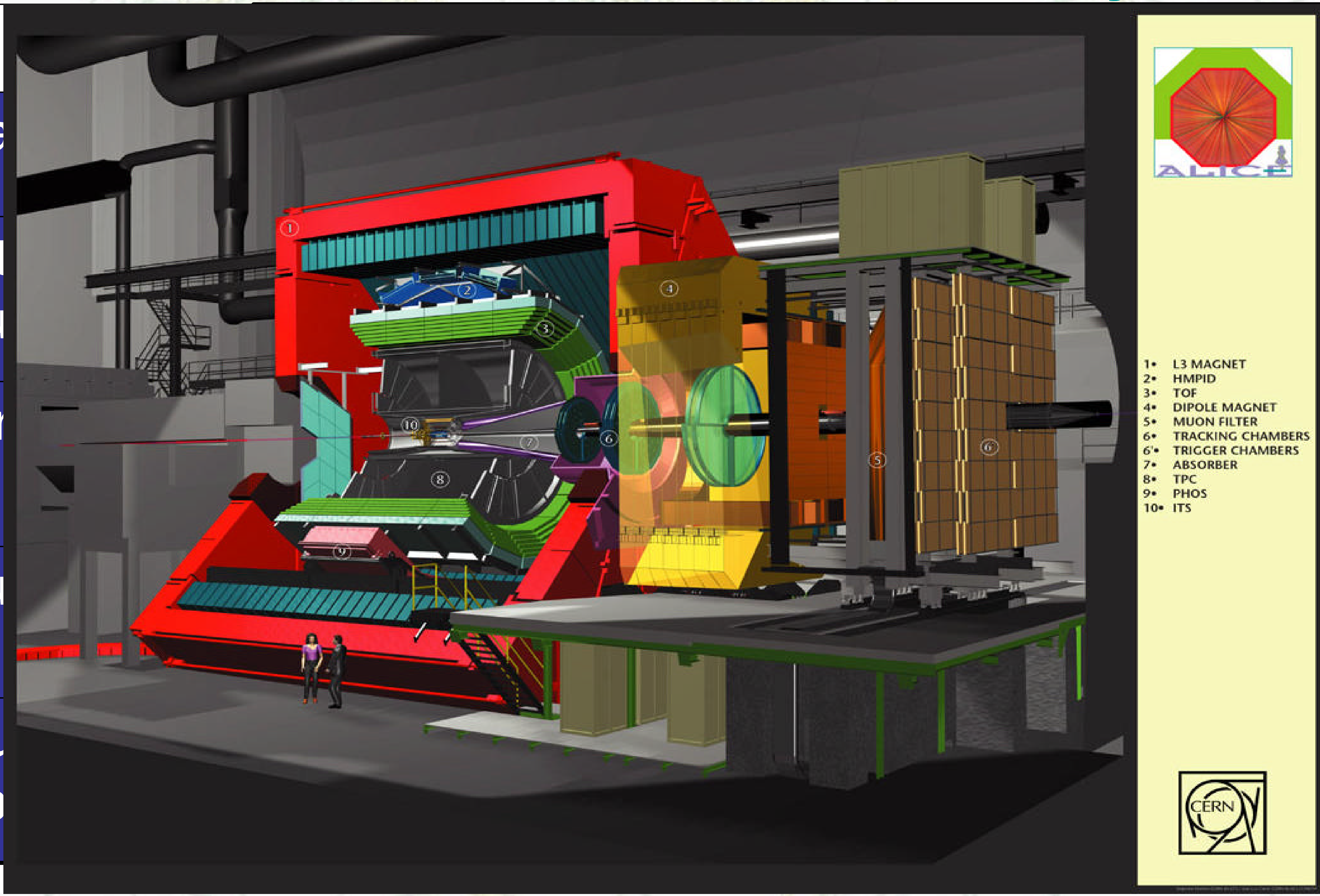
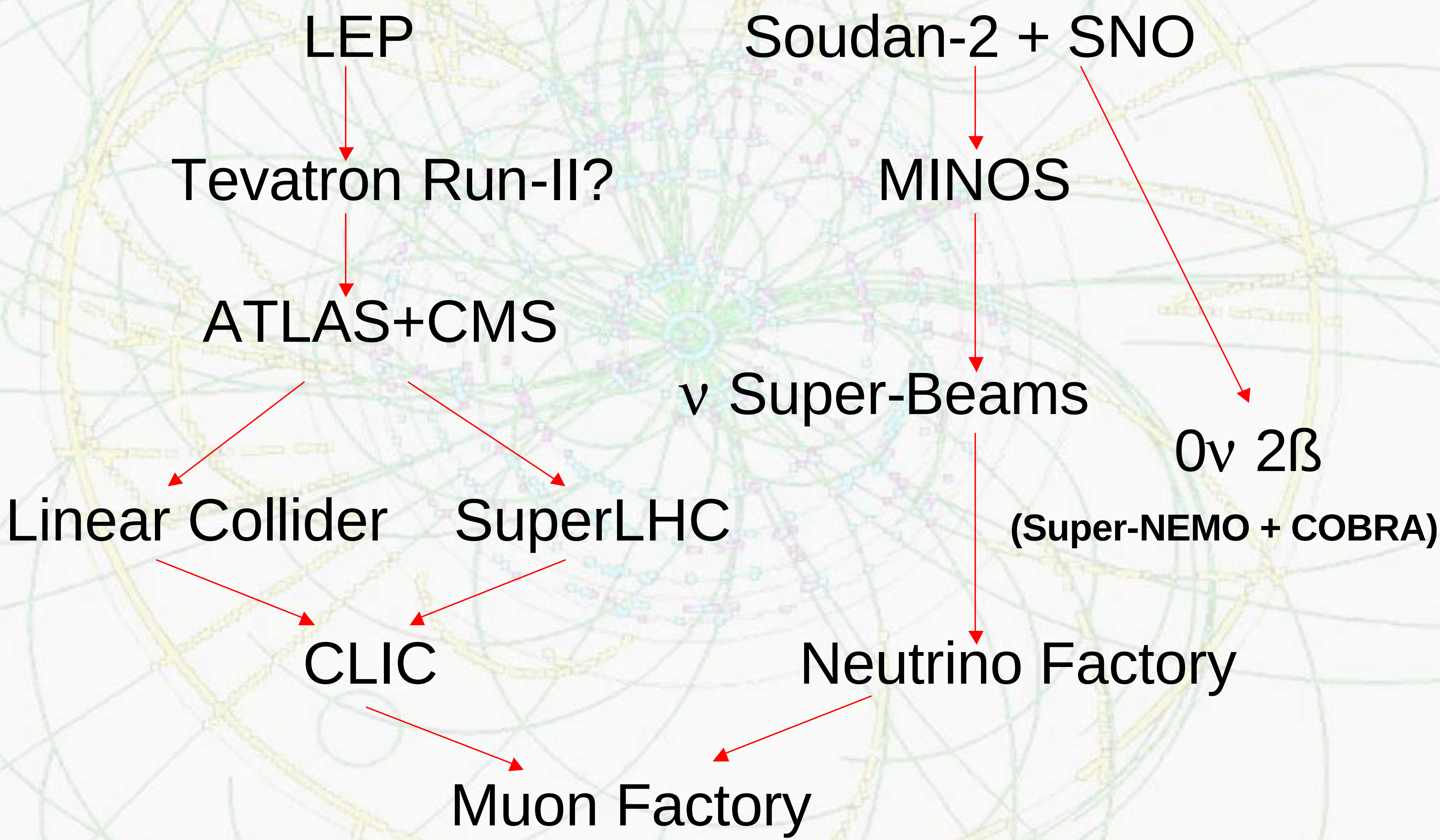


# What is the Origin of the Masses of the Fundamental Particles?



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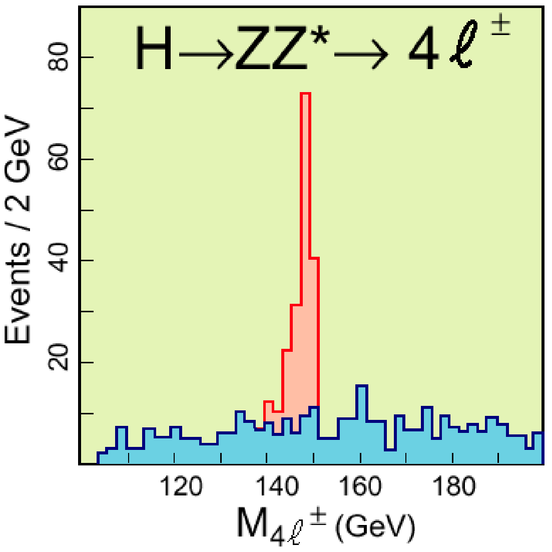
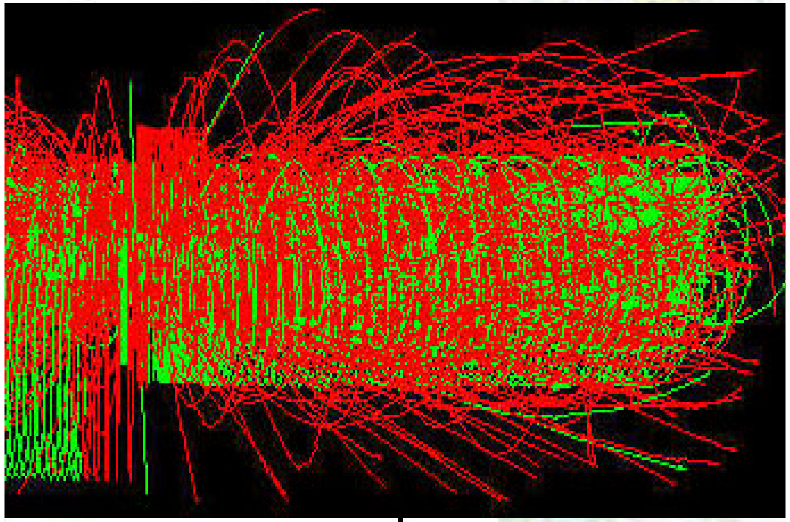
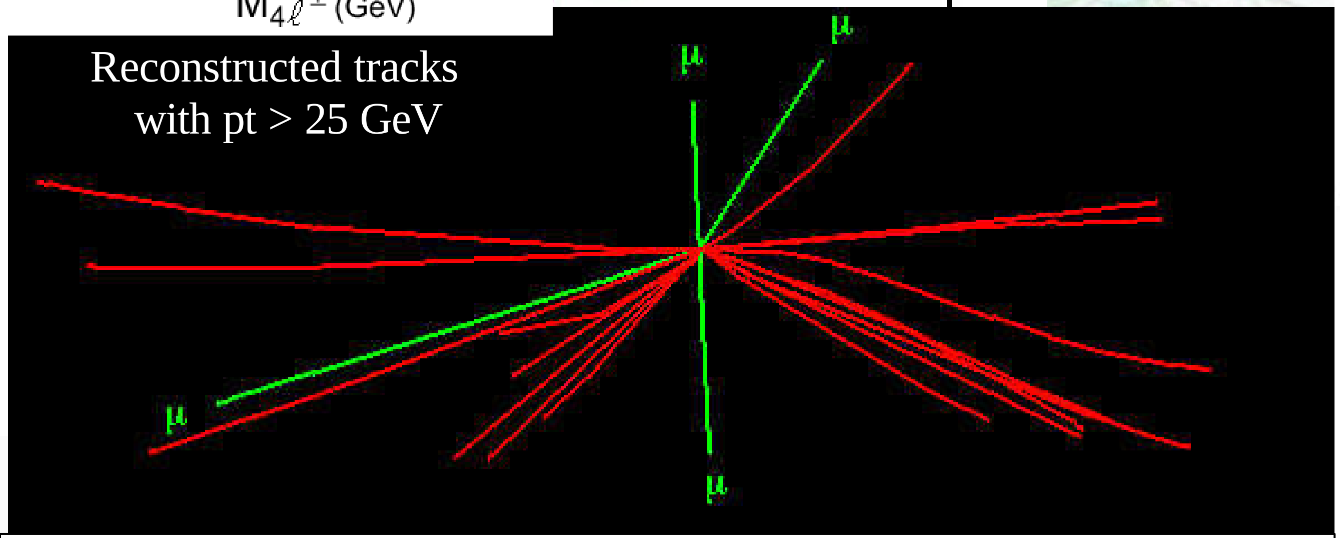
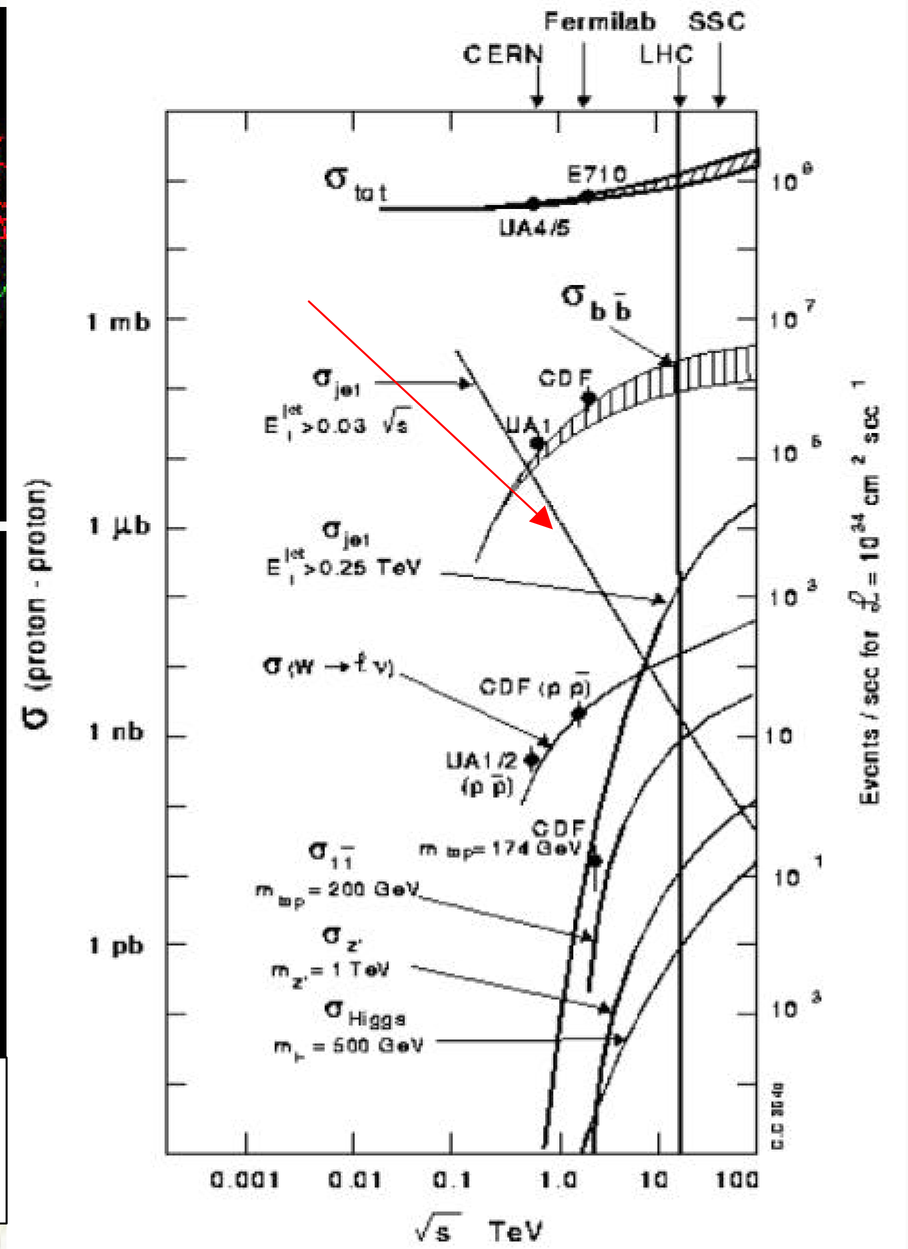


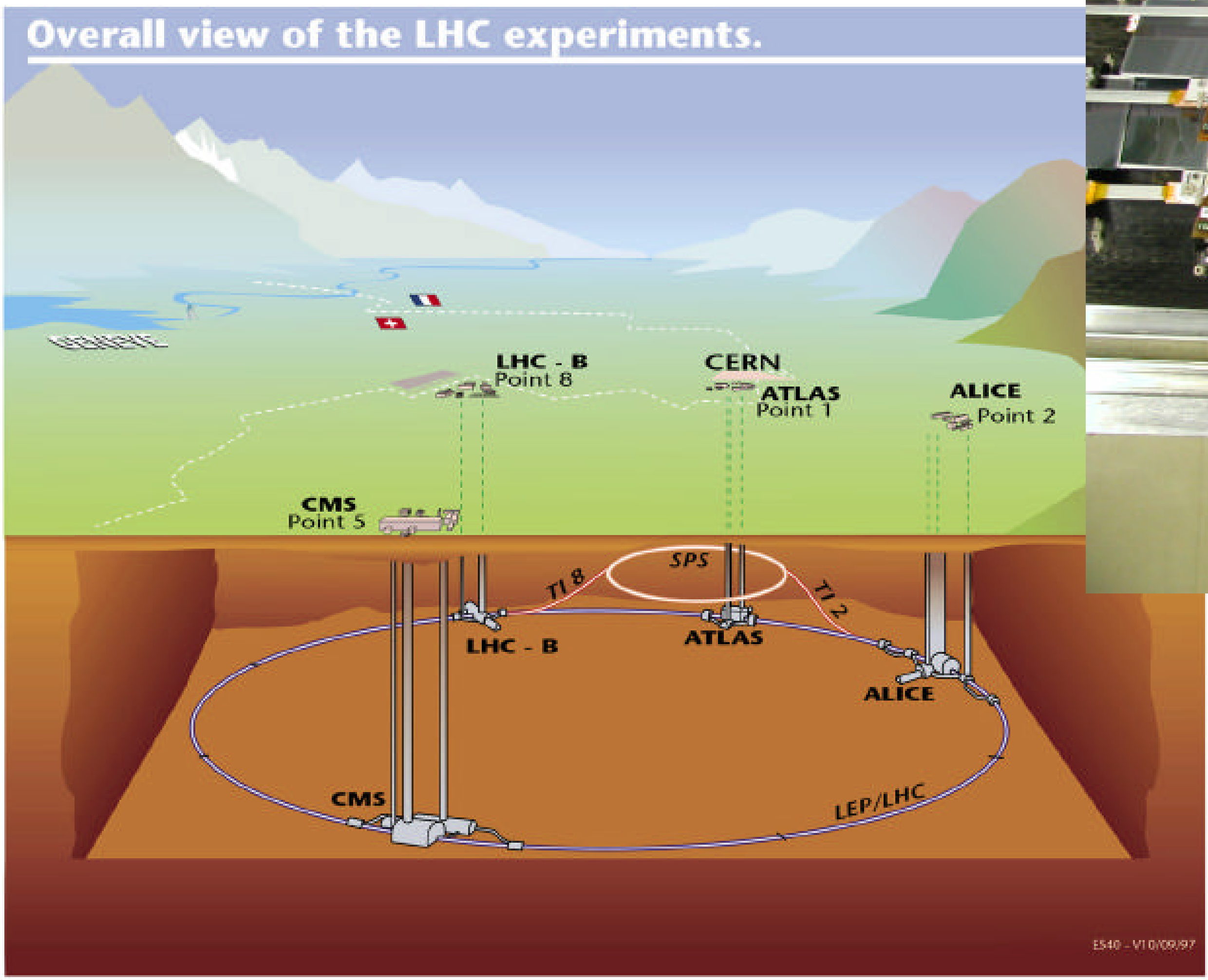


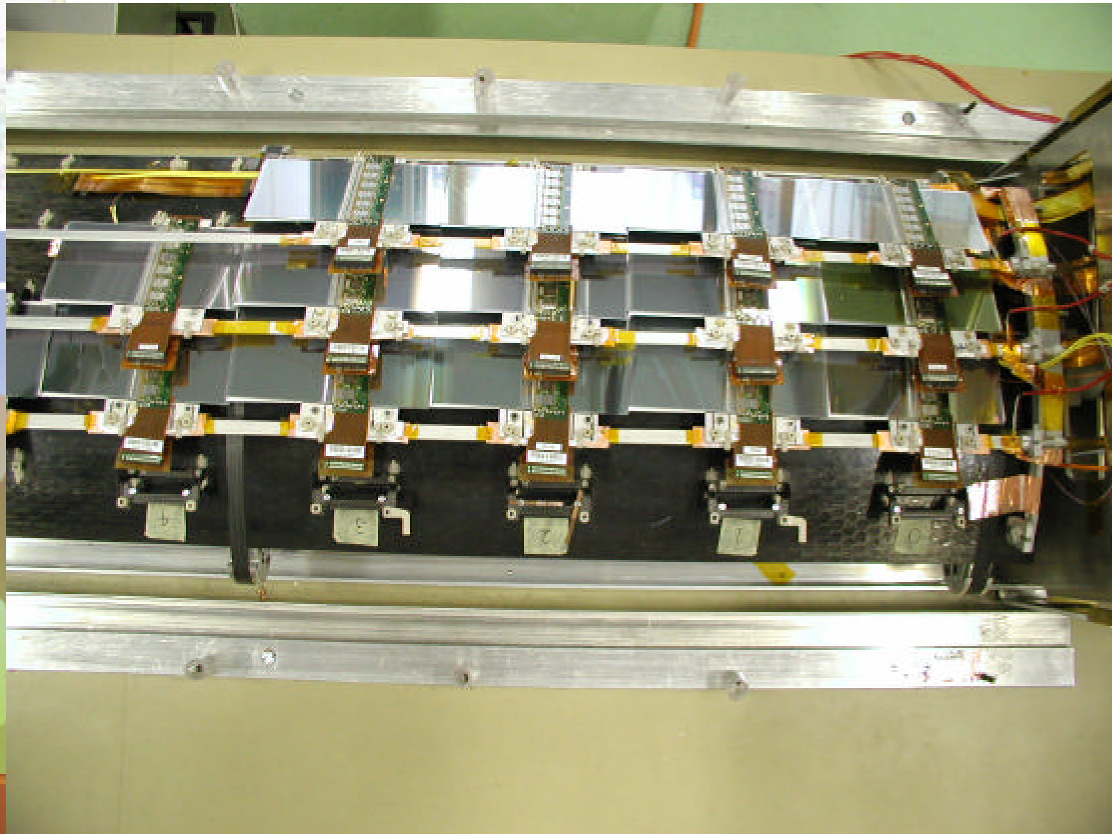



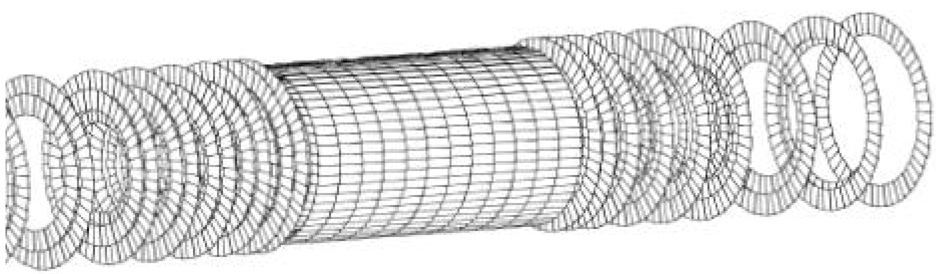

**Higgs ? $Z^0$ $Z^0$ ? μμμμ in CMS**

# The Semiconductor Central Tracker (SCT) of the ATLAS Experiment

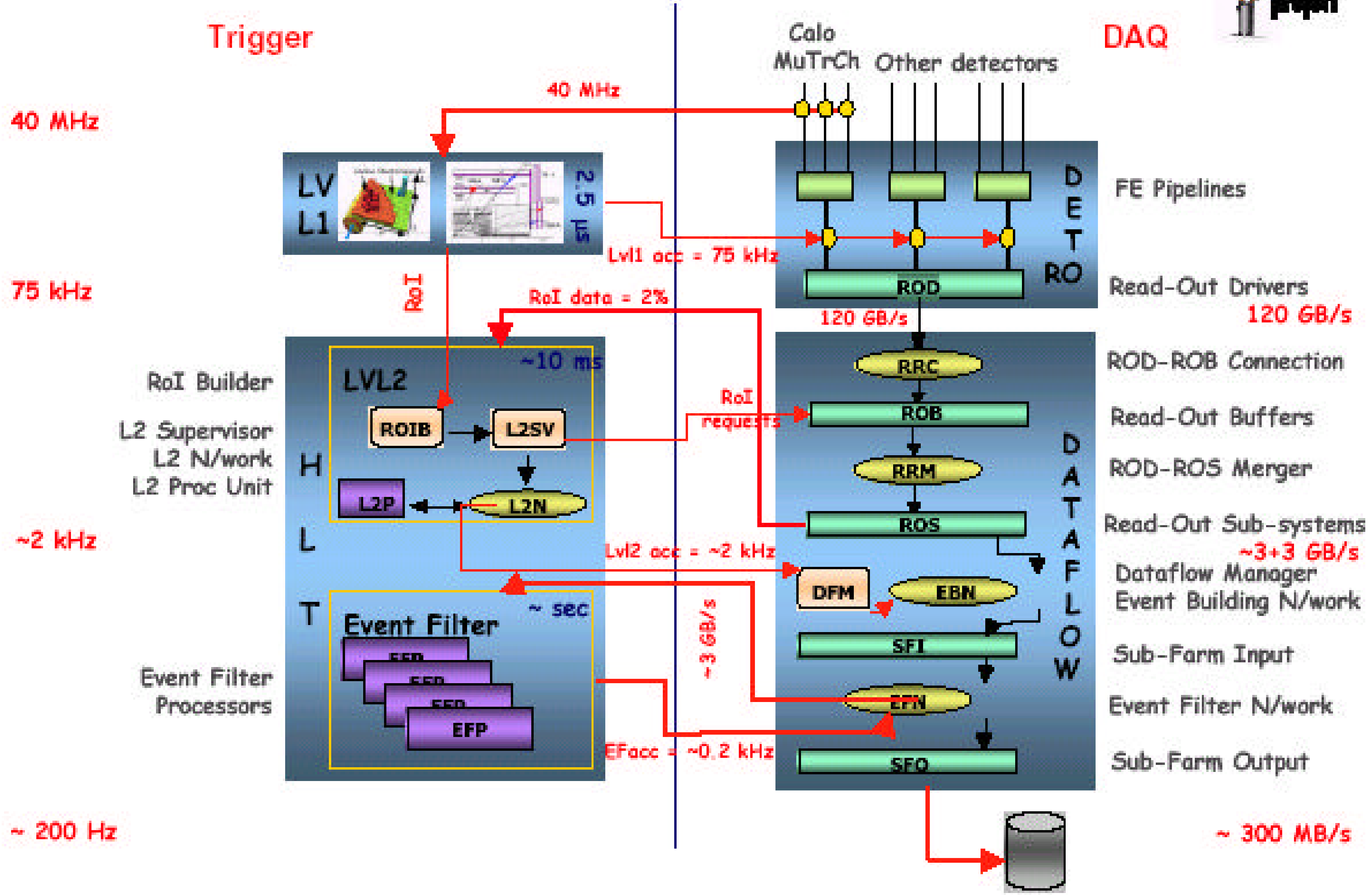
- The '**ATLAS**' experiment at the **LHC** is 22m high 46m long and has hundreds of millions of read-out channels reading out every 25ns.





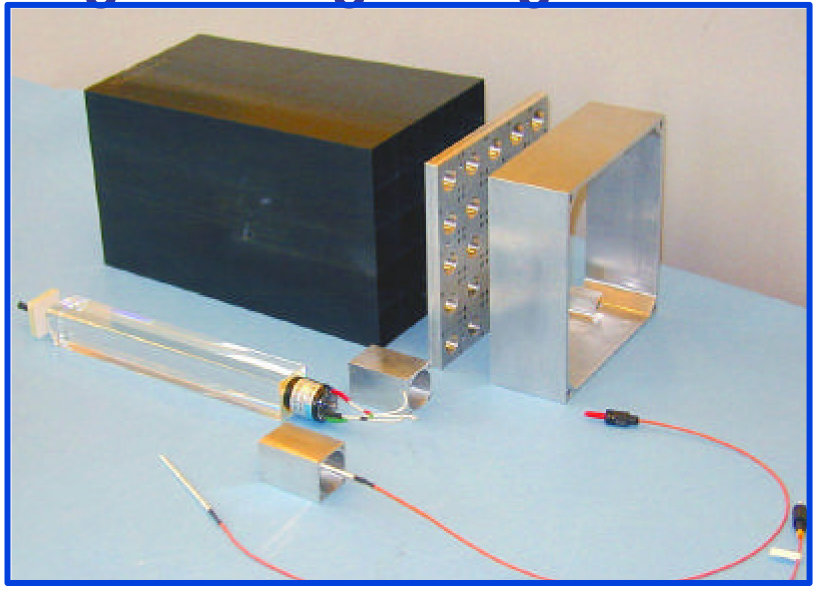
# Trigger / DAQ architecture

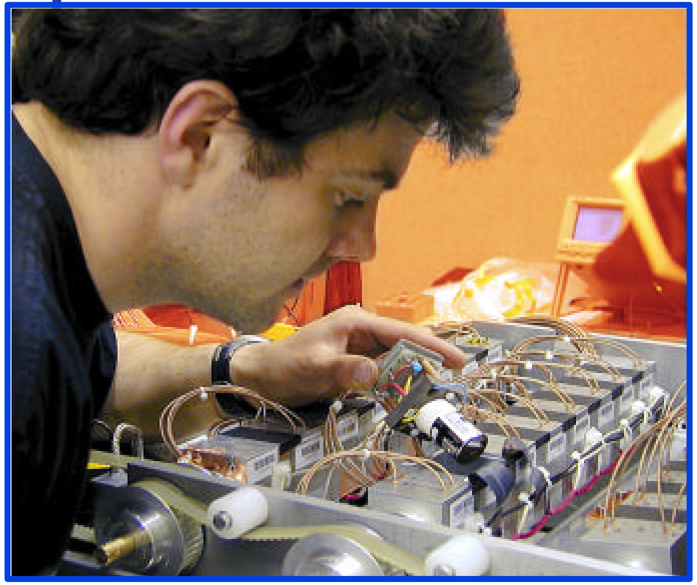


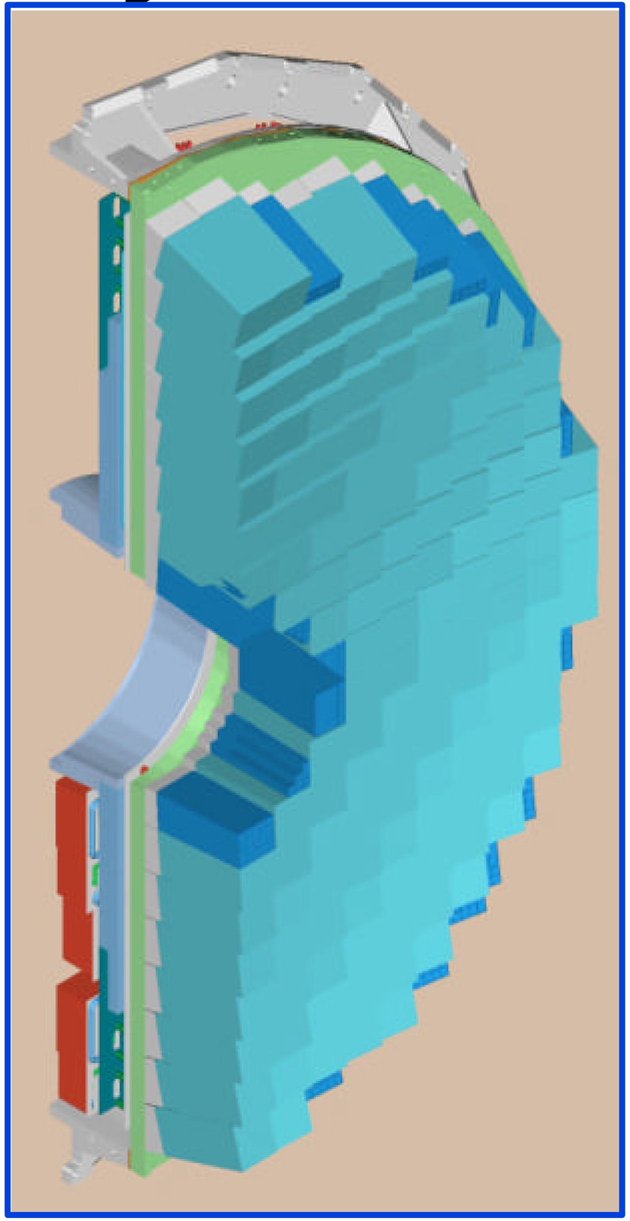
# CMS-UK at the LHC:

# CMS-UK at the LHC: End Cap Calorimetery

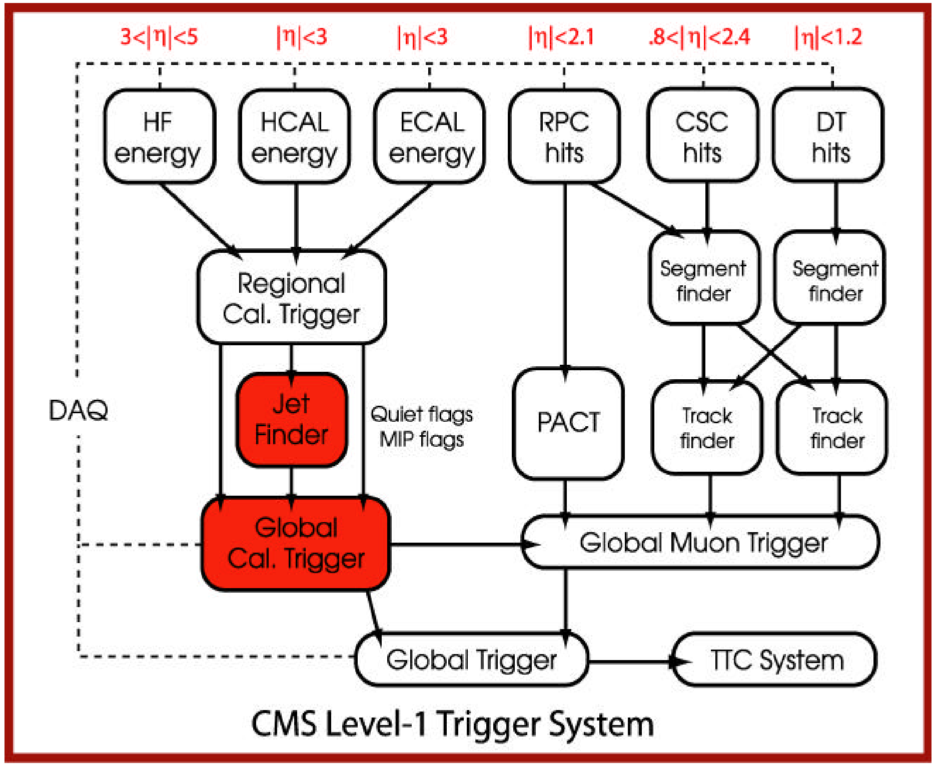
- Measure the energy of electons and gamma-rays: Scintillating $PbWO_4$ crystals with photodetectors
- Design optimised for discovering a Higgs decaying into two gamma-rays
- Bristol, Brunel, Imperial College, Rutherford Lab: UK Role: Develop photodetectors, engineering design of endcaps and build 50%



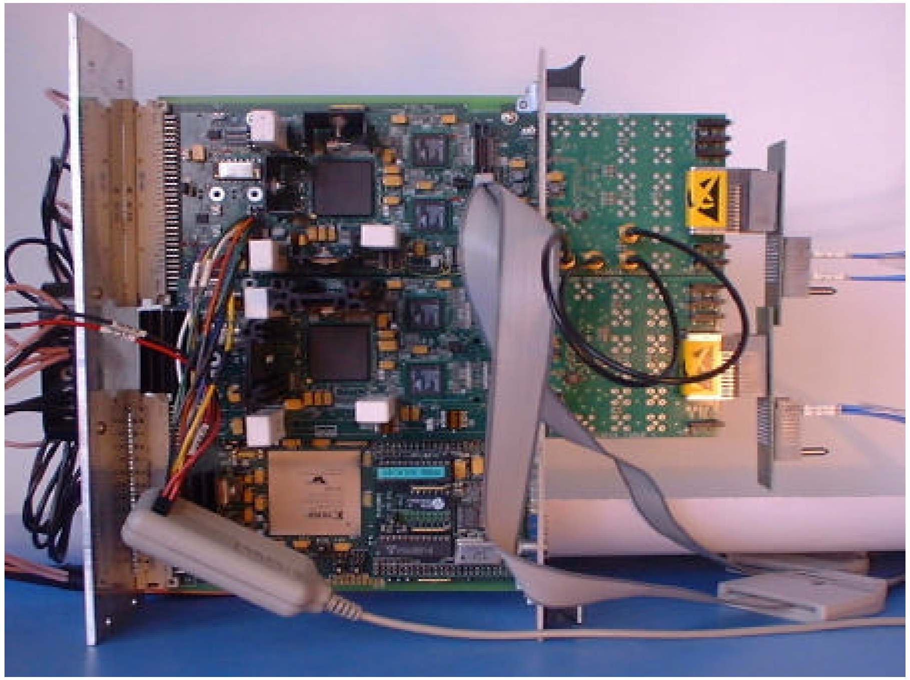




# CMS-UK at the LHC: Global Calorimeter Trigger




The GCT is central to the CMS L1 trigger system; it identifies and ranks e/γ, jets, and τ objects, and calculates scalar and vector $E_t$, and relative luminosity. Excellent performance is vital for all LHC discovery channels.



Design and testing of hardware and trigger algorithms at Bristol and RAL. The GCT uses several novel technologies to provide high performance and robustness at reasonable cost.

# Why Do the Masses and Couplings Differ as They Do?

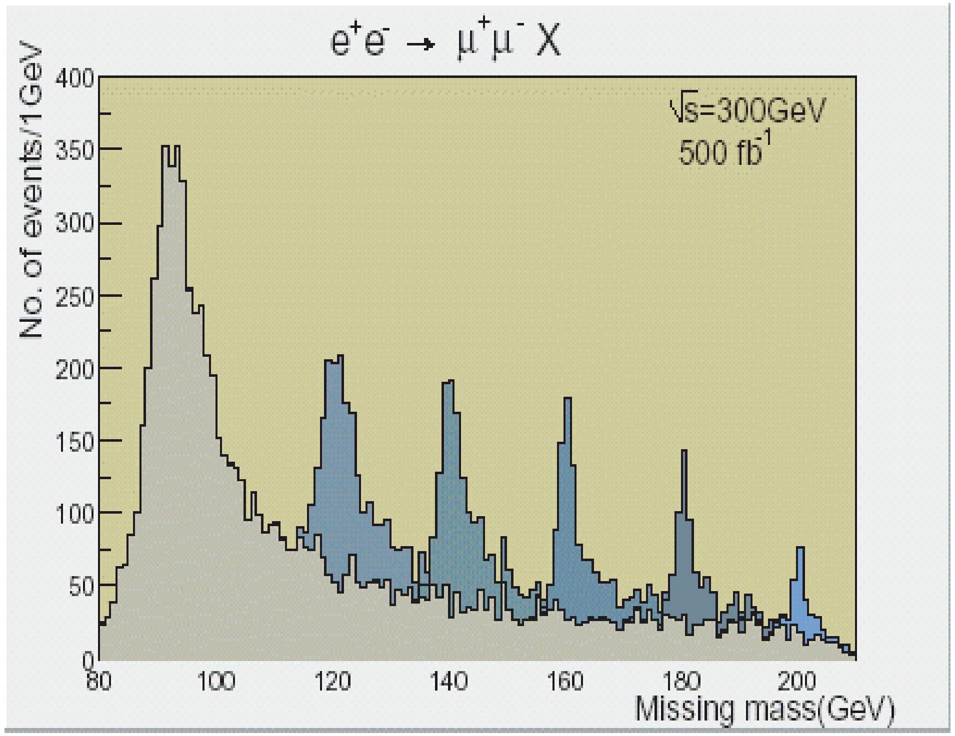



Figure 2.2: Distribution of the recoil mass of the $\mu^+\mu^-$ pair in $e^+e^- \to \mu^+\mu^-$ X, normalized to 500 fb$^{-1}$ at $\sqrt{s}$ = 300 GeV. The background from the $Z^0$-pair production process, $e^+e^- \to Z^0Z^0, Z^0 \to \mu^+\mu^-$ , and the SM Higgs boson signals with masses set to 120, 140, 160, 180 and 200 GeV are shown.

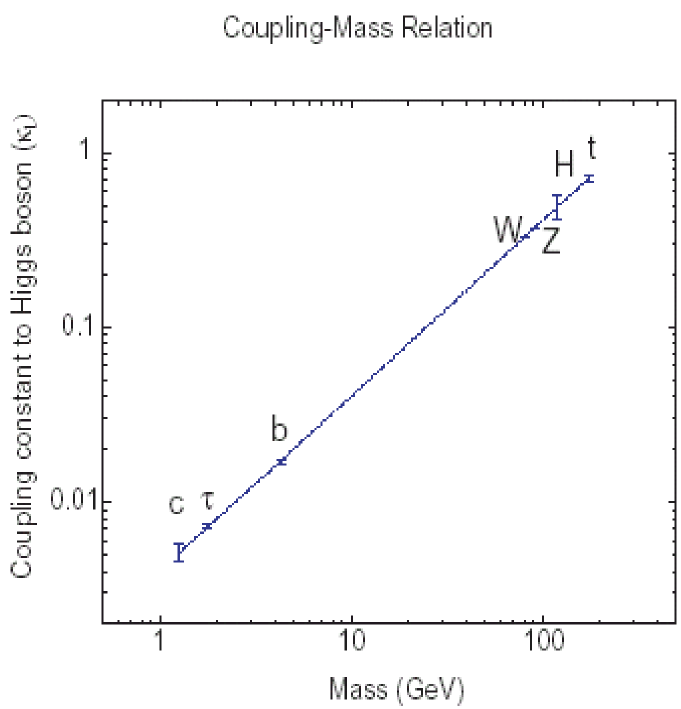
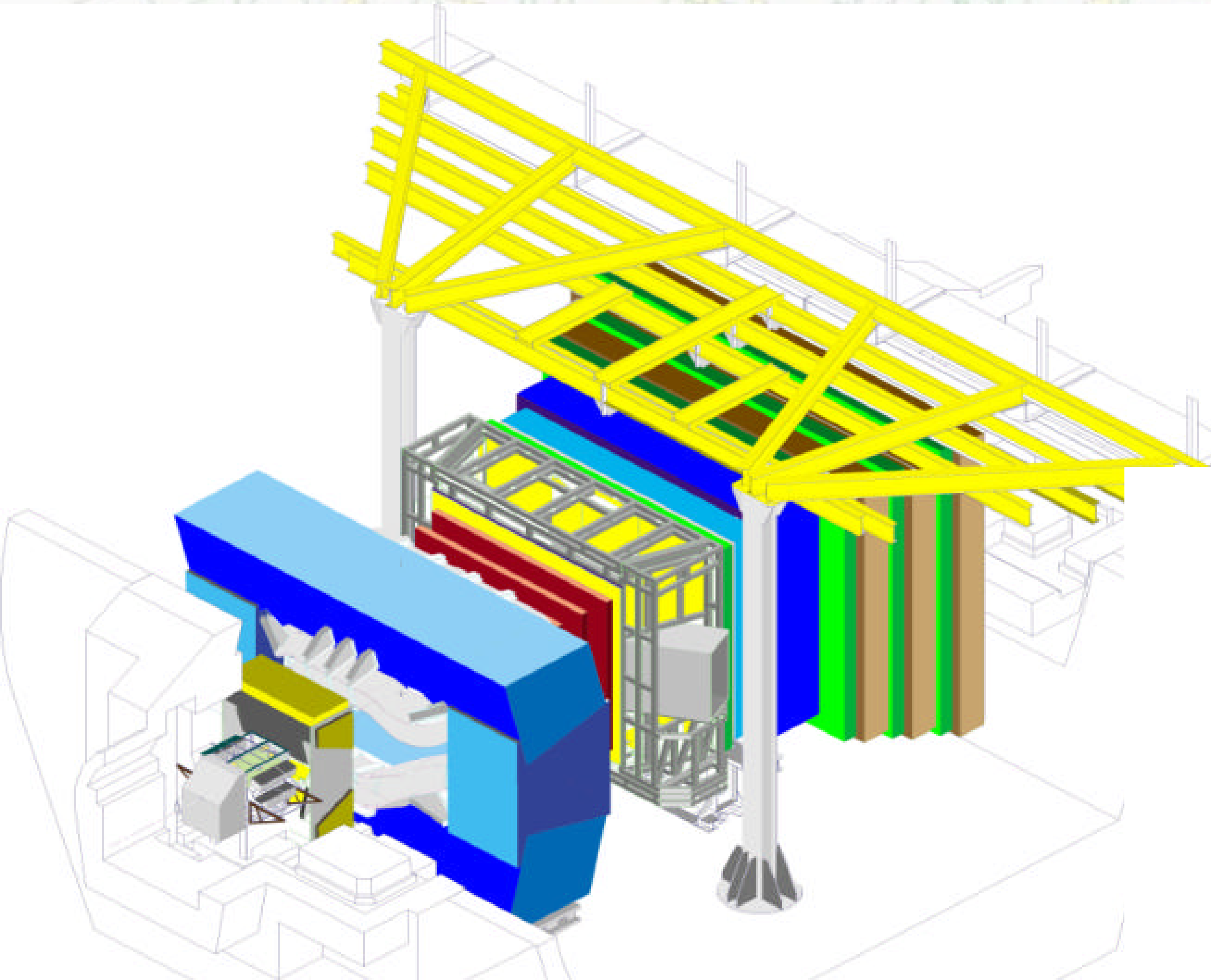
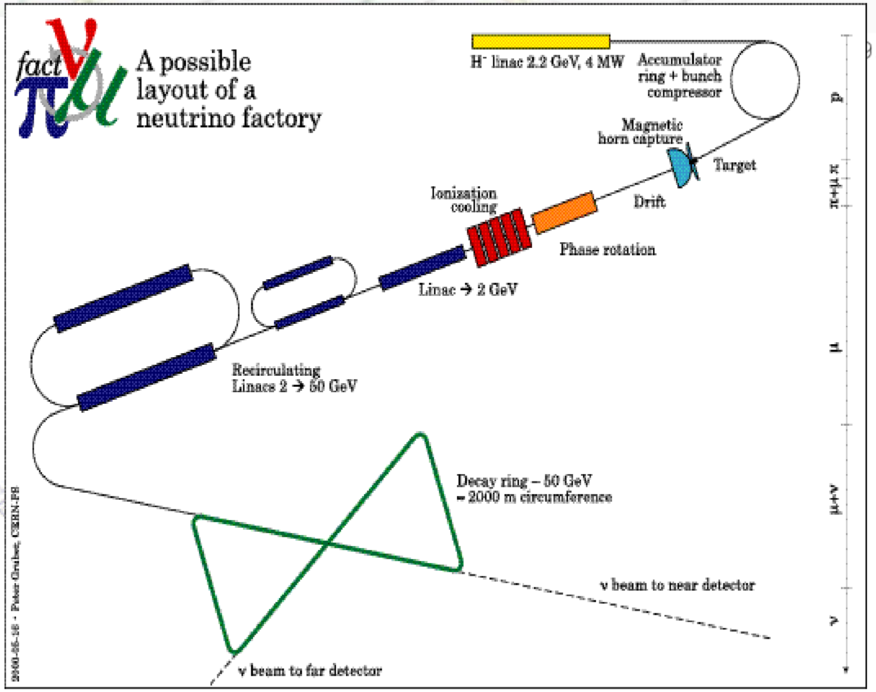
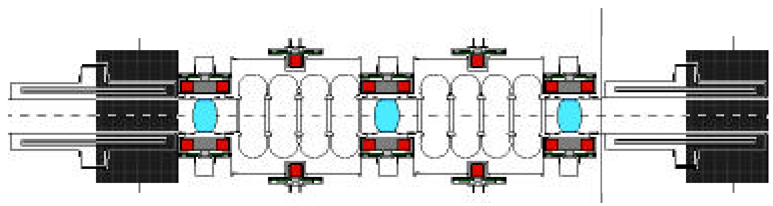



Figure 2.4: Precision of the coupling-constant determination at JLC with $\mathcal{L}$ = 500 fb$^{-1}$. The coupling constant $\kappa_i$ is defined from the Higgs boson coupling to the "i" particle. $m_i = \kappa_i v$ holds in the Standard Model. The Higgs boson mass is taken to be 120 GeV. For the charm, tau, bottom, W and Z coupling measurements, $\sqrt{s}$ = 300 GeV is assumed. $\sqrt{s}$ = 500 GeV (700 GeV) is taken for the Higgs self-coupling ($t\bar{t}H$) coupling measurement.

# What is the Reason for the Matter Anti-matter Asymmetry in the Universe?



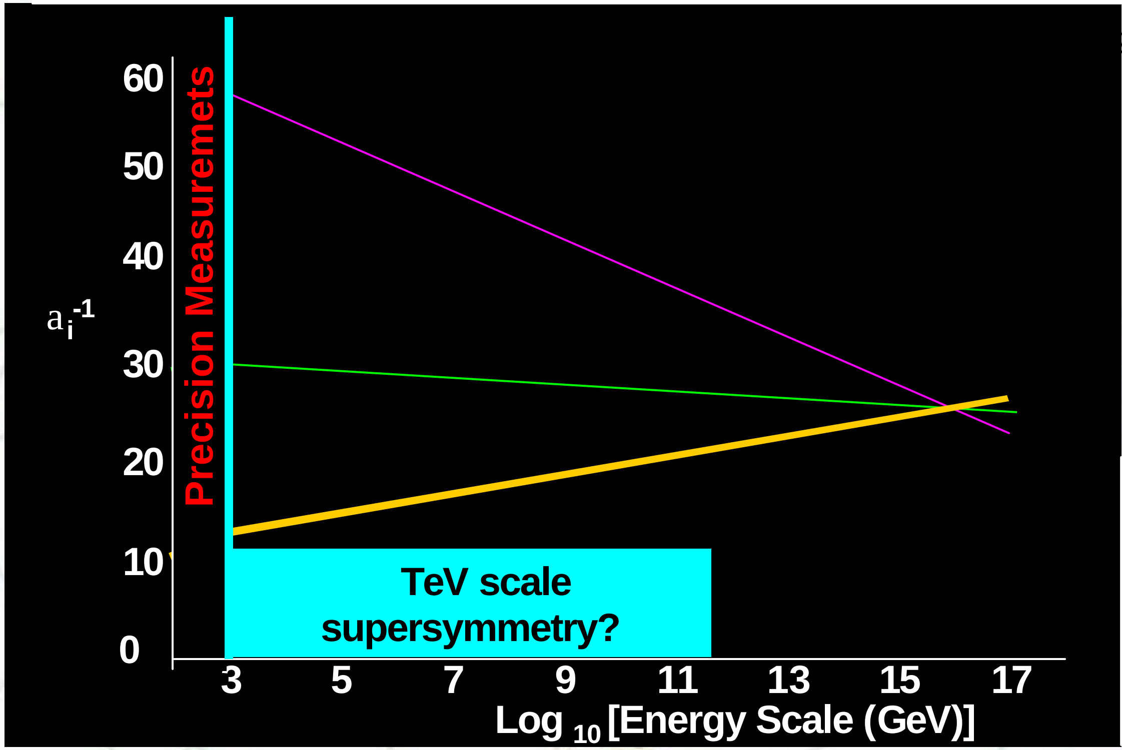


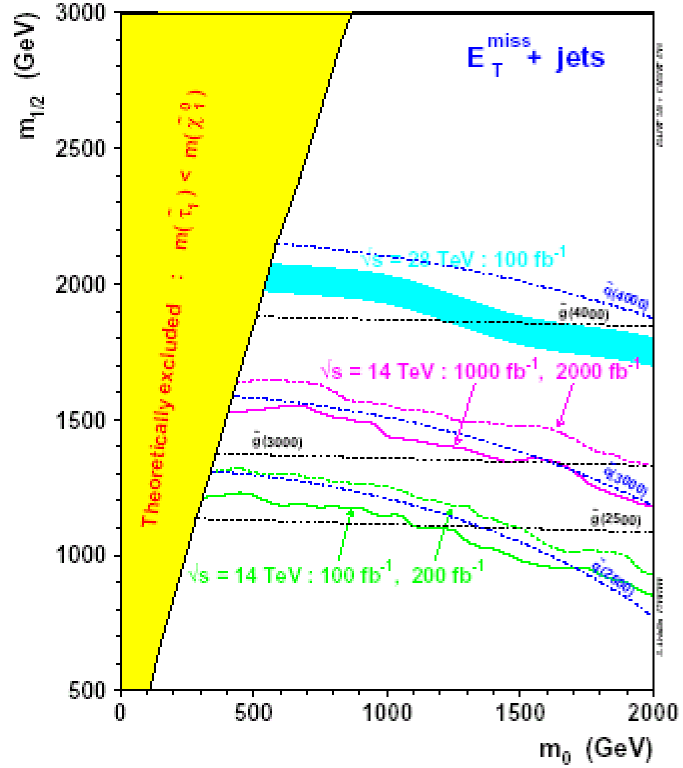



**MICE**

**LHCb UK Responsibilities: RICH-1, RICH-2 and VeLo**

# Can all the Forces, Including Gravity, be Understood in a Single Unified Framework?

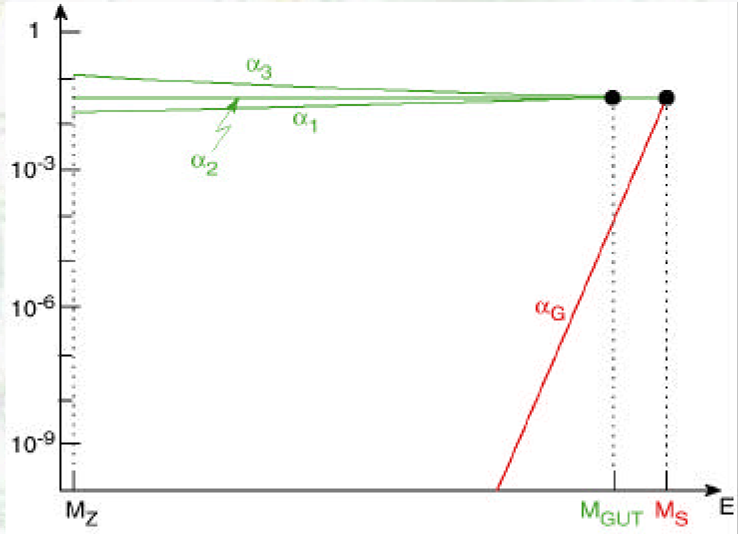


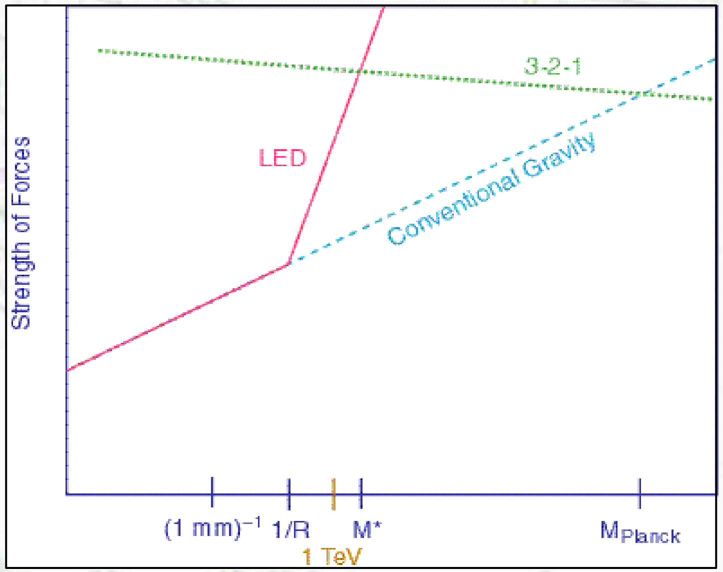




g. 13: Expected $5\sigma$ discovery contours in the mSUGRA plane $m_0$ versus $m_{1/2}$ for $A_0 = 0$, $\tan\beta$=10 and $\mu < 0$. The various urves show the potential of the CMS experiment at the standard LHC (for luminosities of 100 $fb^{-1}$ and 200 $fb^{-1}$), at the SLHC or 1000 $fb^{-1}$ and 2000 $fb^{-1}$), and (for comparison) at a machine with a centre-of-mass energy of 28 TeV.

# TeV-scale Gravity

- The scale of gravity may actually not be given by $M_{PL}$ but by $M_{EW}$
  - Strings live in >4 dimensions. Compactification → 4D "SM". $M_{PL-4}$ related to $M_{PL-(4+d)}$ via volume of extra dimensions:
    - $M_{PL-4}^2 \sim V_d \, M_{PL-(4+d)}^{2+d}$
  - Conventional compactification: very small curled up dims, $M_{PL-4} \sim M_{PL-(4+d)}$
    - $V_d \sim (M_{PL-4})^d$
  - Alternative: volume is large; large enough that $V_d >> (M_{PL-(4+d)})^d$
    - Then $M_{PL-(4+d)}$ can be ~ TeV (!)
    - "our" Planck mass at $\log(\Lambda) \sim 19$: an artifact of the extrapolation



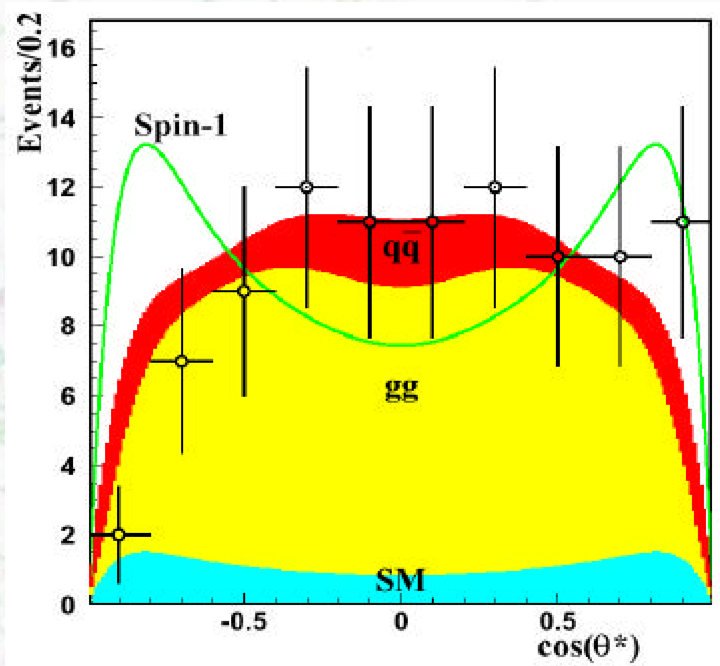



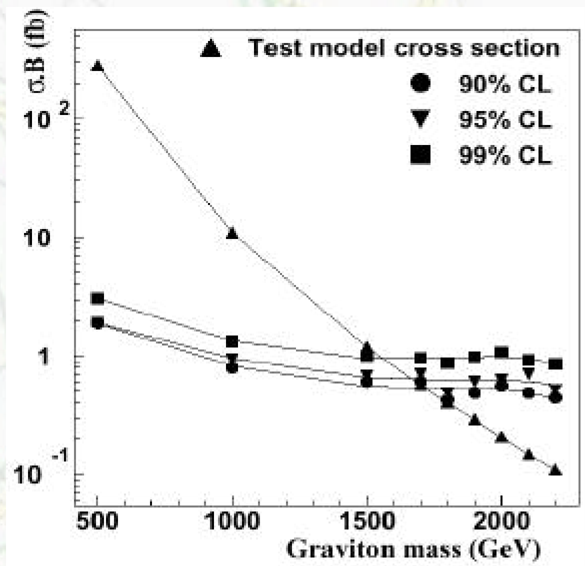
# Kaluza-Klein Resonances

- If graviton excitations are present, these can be searched for like a higher mass version of the $Z^0$.
  - Added bonus: spin-2 (instead of spin-1 for Z)
    - Case shown: $G^* \to e^+e^-$ for M(G)=1.5 TeV (LHC signature)
    - Extract minimum σ.B for which spin-w hypothesis is favored (at 90-95%CL)

* B.Allanach,K.Odagiri,M.Parker,B.Webber JHEP09 (2000)019

100 $fb^{-1}$

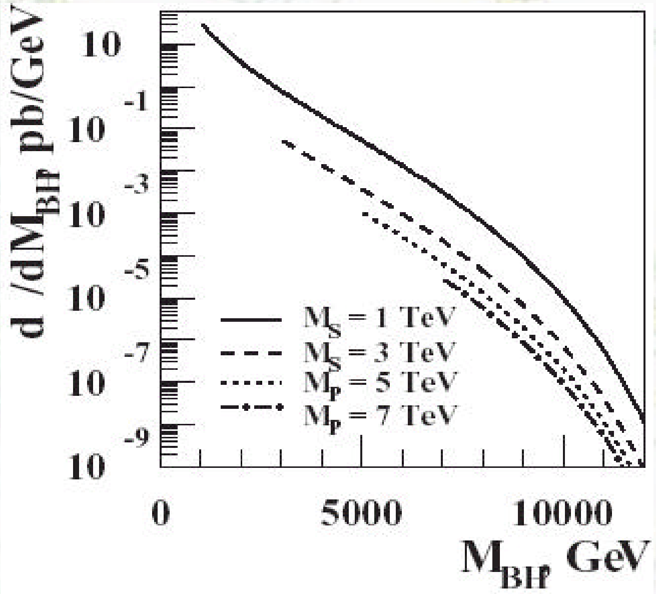


# Black Holes at the LHC

- Within context of “TeV-scale gravity”
  - Semi-classical argument: two partons approaching with impact parameter < Schwarzschild radius, $R_S \rightarrow$ black hole
    - $R_S \sim 1/M_P \, (M_{BH}/M_P)^{(1/d+1)}$

    (Myers & Perry; Ann. Phys 172, 304 (1996)
  - From dimensions: $\sigma(M_{BH}) \sim \pi R_S^2$; $M_P \sim 1\text{TeV} \rightarrow \sigma \sim 400$ pb
    - Absence of small coupling like $\alpha$
  - LHC, if above threshold, will be a Black Hole Factory:
    - At minimum mass of 5 TeV: 1Hz production rate



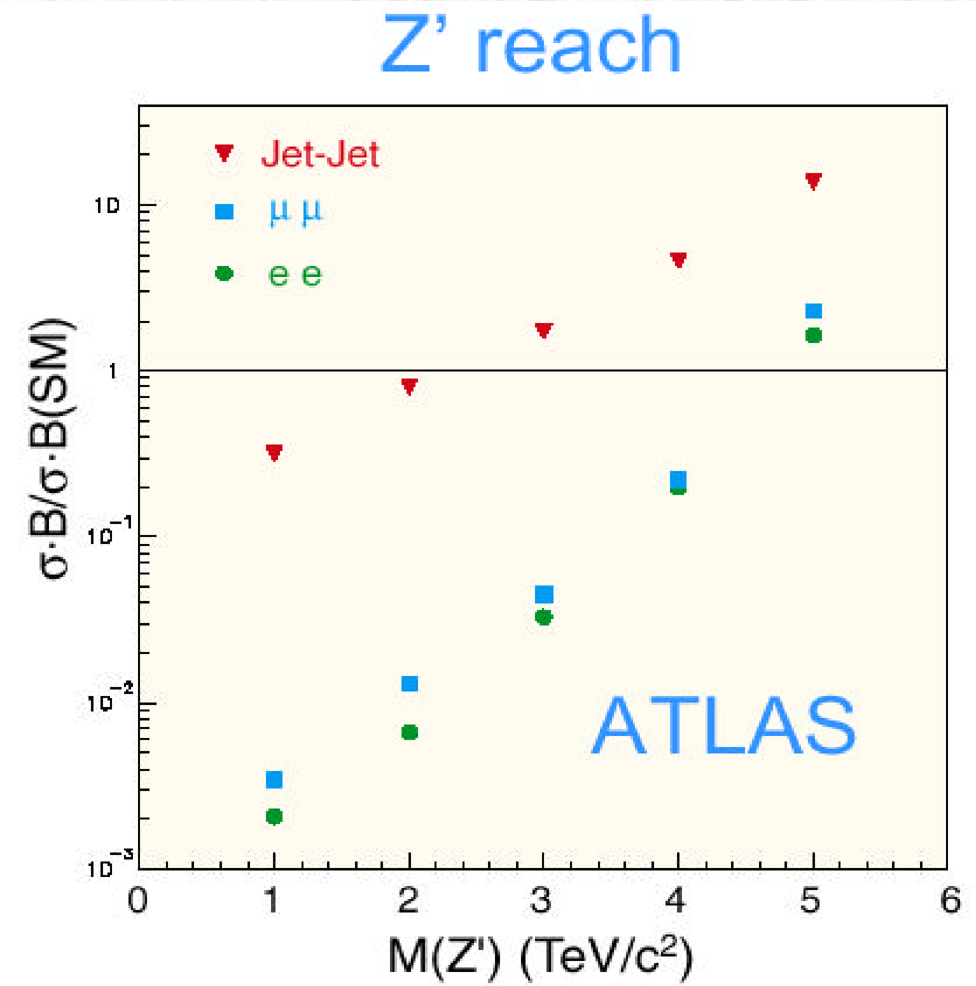

Giddings & Thomas hep-ph/0106219

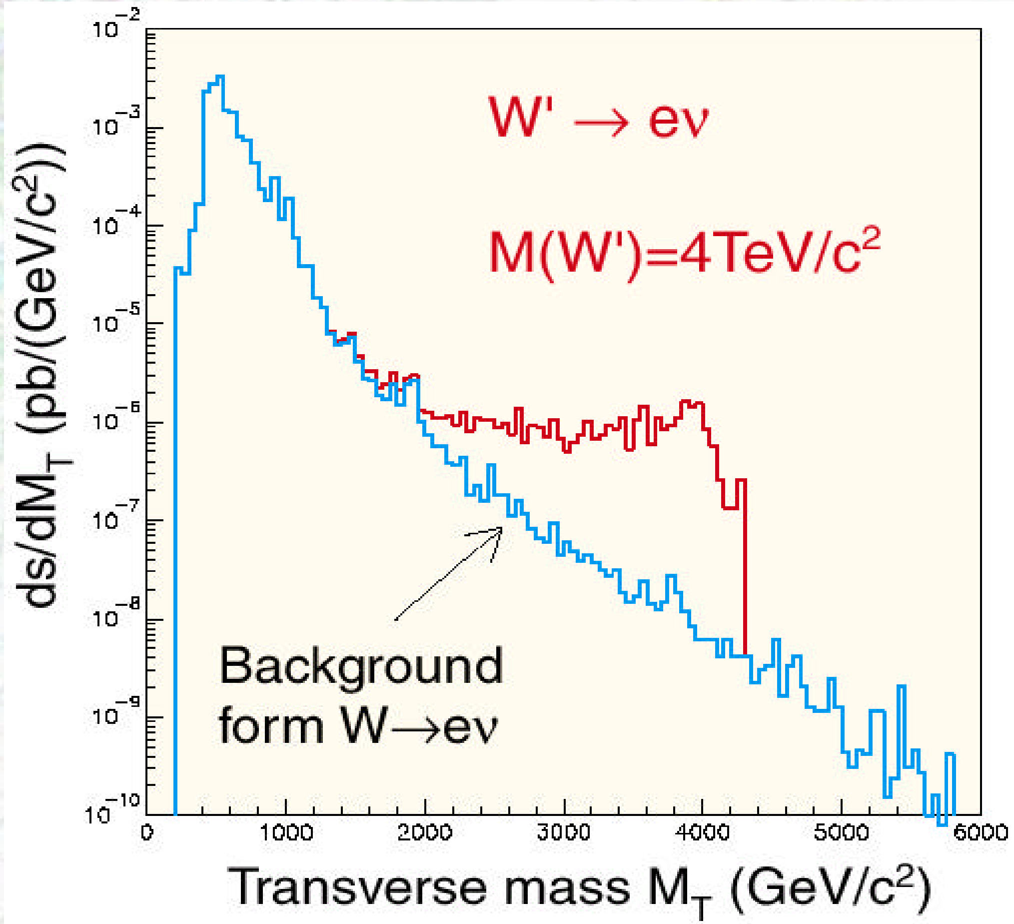
Dimopoulos & Landsberg hep-ph/0106295

**Assumptions:**

$M_{BH} >> M_P$; in order to avoid true quantum gravity effects… clearly not the case at the LHC – so caution

# LHC Reach for Heavy IVBs



# UK Linear Collider Activity


Particle Sources

CLF
ASTeC
Liverpool
Strathclyde

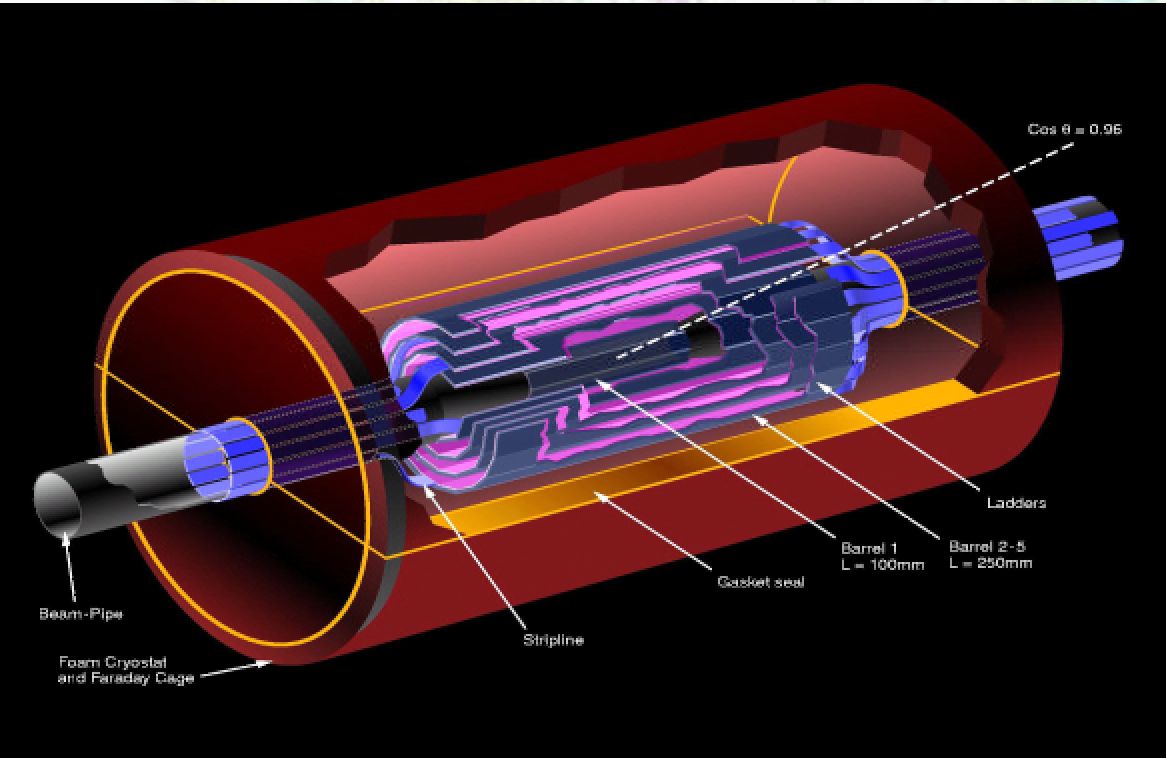
Faraday:
Lancaster, Nottingham
Oxford, QMUL, Strathclyde
ADC,TMD, TWI, Elekta,
E2V Technologies,
C-Tech Innovation

ASTeC, CLF,
LC-ABD:
Abertay, Liverpool,
Manchester,Oxford,
QMUL, RHUL, UCL

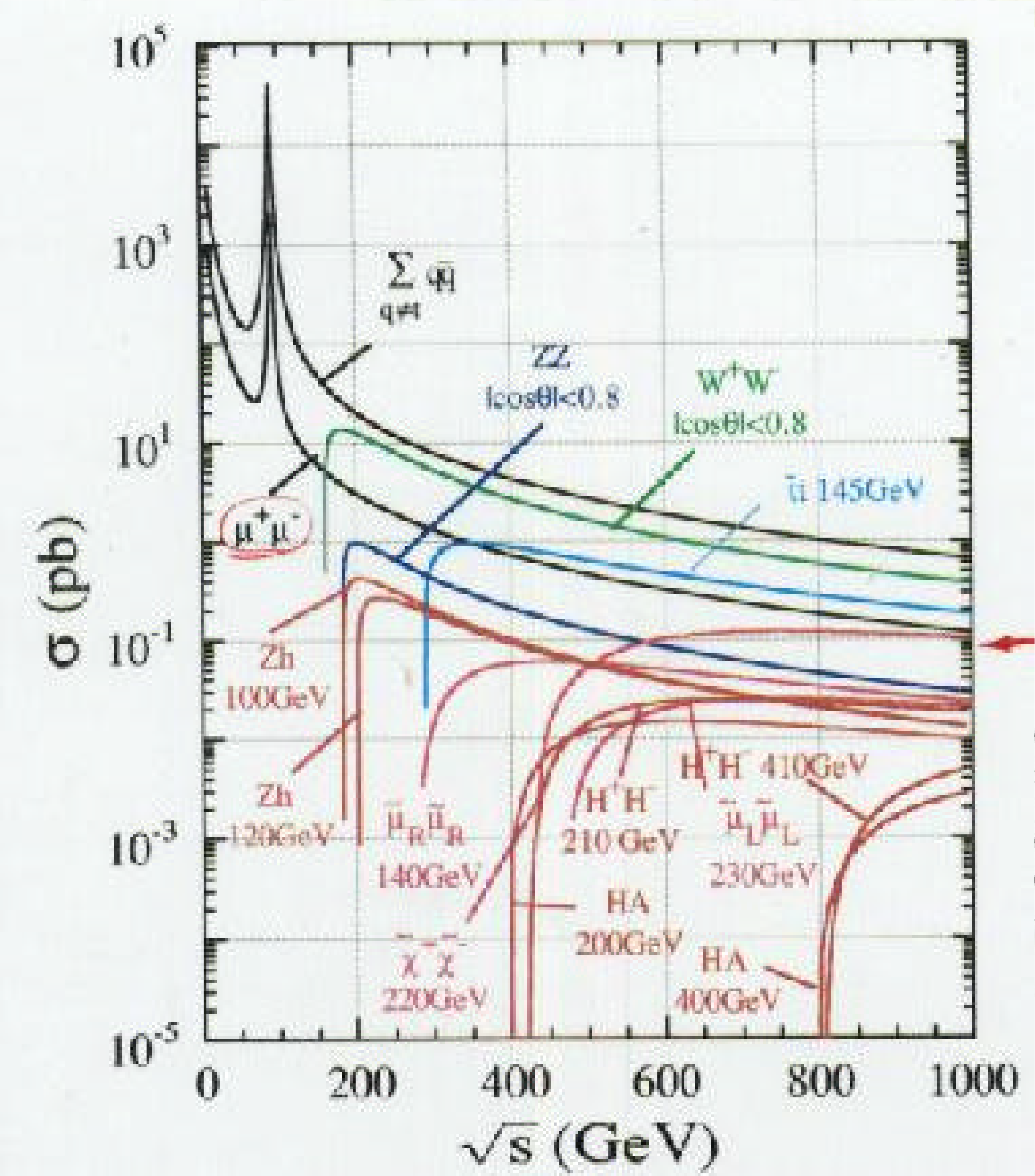
# Future Linear Collider: Vertex Detector

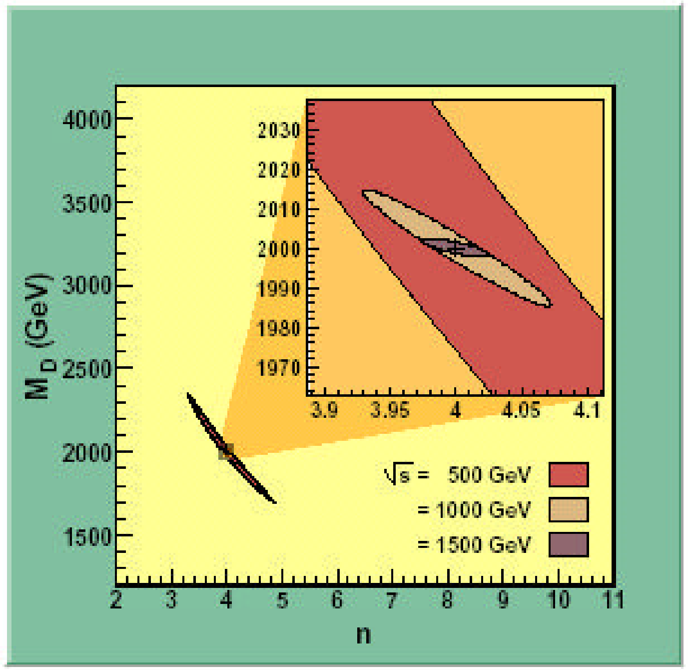
## Large area, high speed Pixels (CCDs or Active Pixel Sensors)

- Inner layer pixels: 100´13 mm$^2$, 2500(V)´650(H) pixels per end;
- Outer layers: 2 sensors with size 125´22 mm$^2$, 6250(V)´1100(H) pixels;
- 120 detectors, 8´10$^8$ pixels (20 μm square) in total;
- Depending on accelerator design, readout time could be 8 ms, <u>not easy</u> to achieve with standard CCDs, or as little as 50 μs for the inner layer, requiring Column Parallel CCDs R/O with <u>50 Mpix/s</u> from each column or FAPS with up to 20 in-pixel storage cells



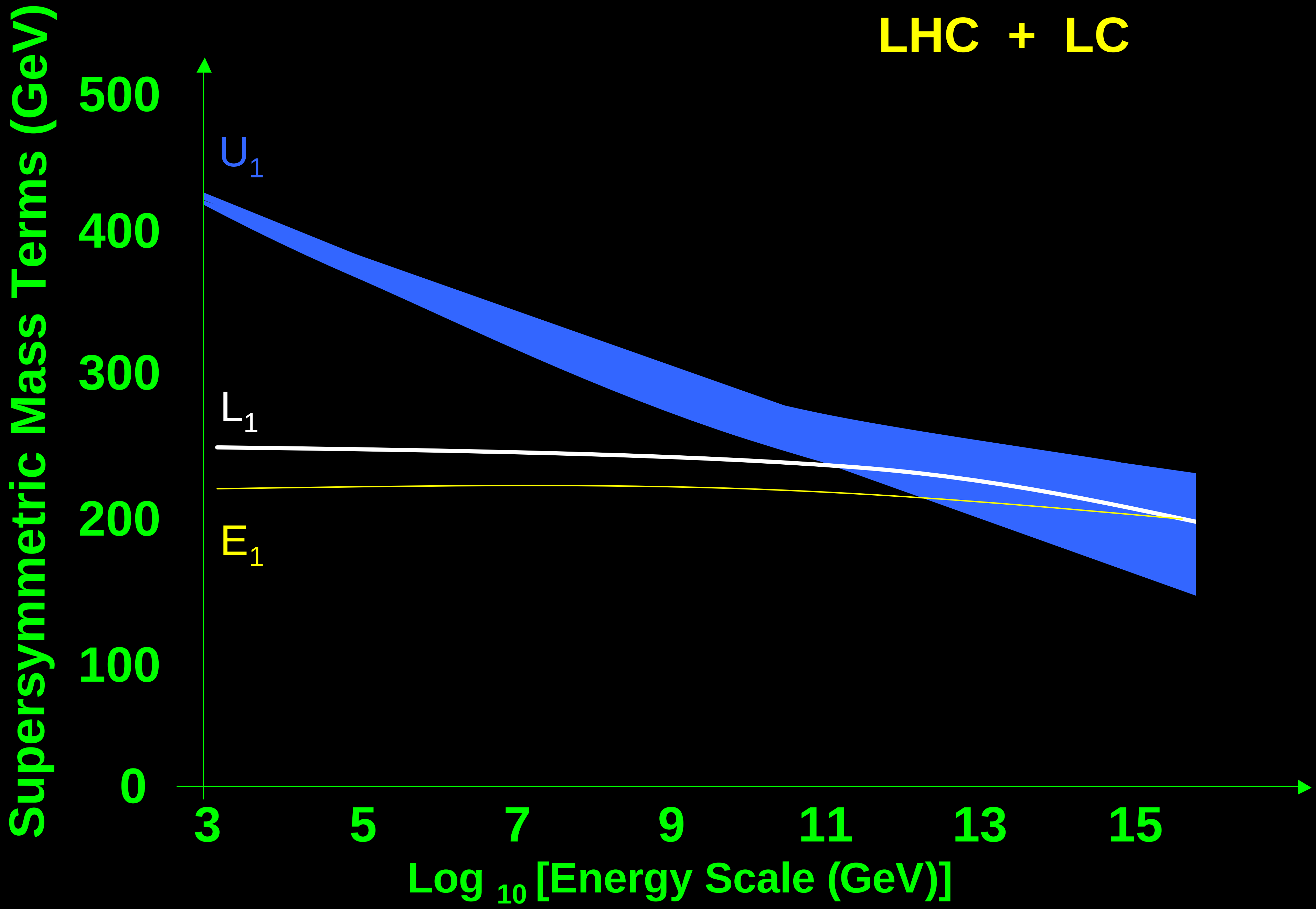

# Future Linear Collider: Physics



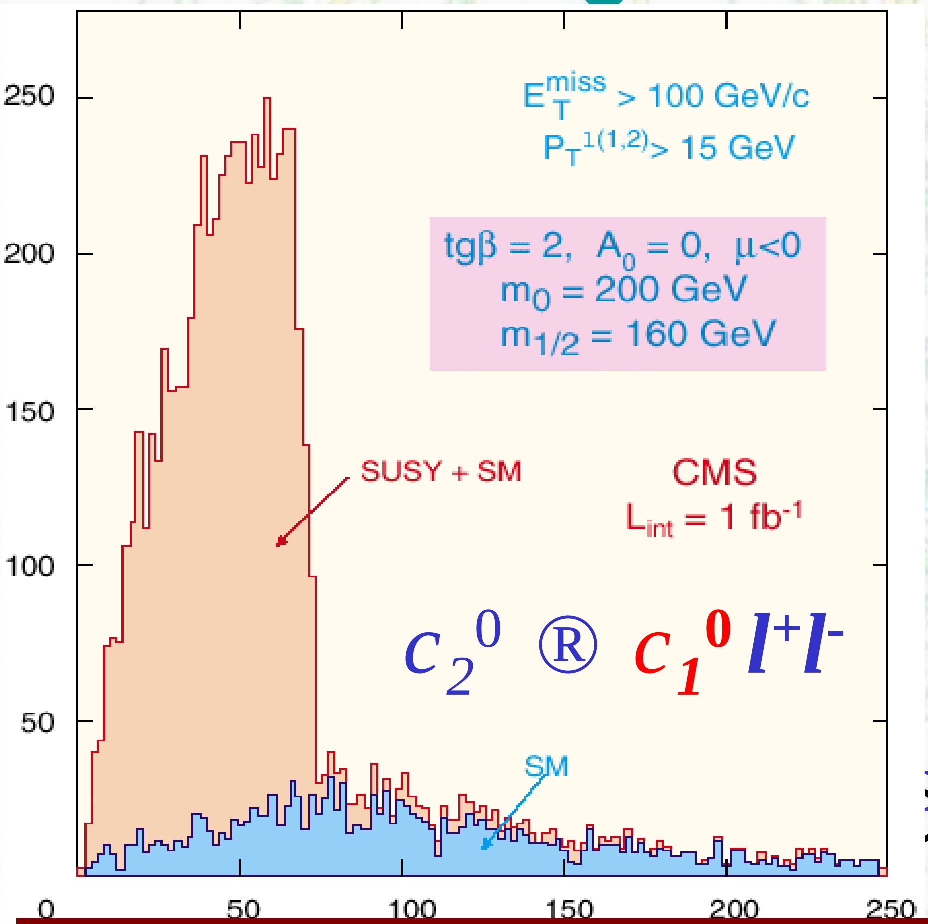




2.14: $\chi^2-\chi^2_{min}=4$ contours in the $M_D$ vs. $n$ plane, where $n$ is the number of extra dimensions
is the fundamental scale in $4+n$ dimensions. Three values are taken for the center-of-mass
at $\sqrt{s}$ = 500 GeV, 1 TeV and 1.5 TeV. The integrated luminosity is 500 fb$^{-1}$. The input
ters are $M_D$ = 2 TeV and $n$ = 4. The Standard Model background due to $e^+e^- \to \nu\bar{\nu}\gamma$ is
d. A cut on the minimum transverse energy of photon is set at $E_T^{min} = 0.1\sqrt{s}$. No cut on the
um photon energy is taken.

# TeV Precision Physics



# What are the Dark Matter and Dark Energy that dominate the large scale evolution of the Universe?




$m_{l+l-}$

Direct Searches
UKDMC

Astro-particle
Physics Experiments

Cosmology

| $M_{sp}$(GeV) | s (pb) | Evts/yr |
|---|---|---|
| ***500*** | 100 | $10^6$-$10^7$ |
| ***1000*** | 1 | $10^4$-$10^5$ |
| ***2000*** | 0.01 | $10^2$-$10^3$ |

# Tevatron Diphoton Events

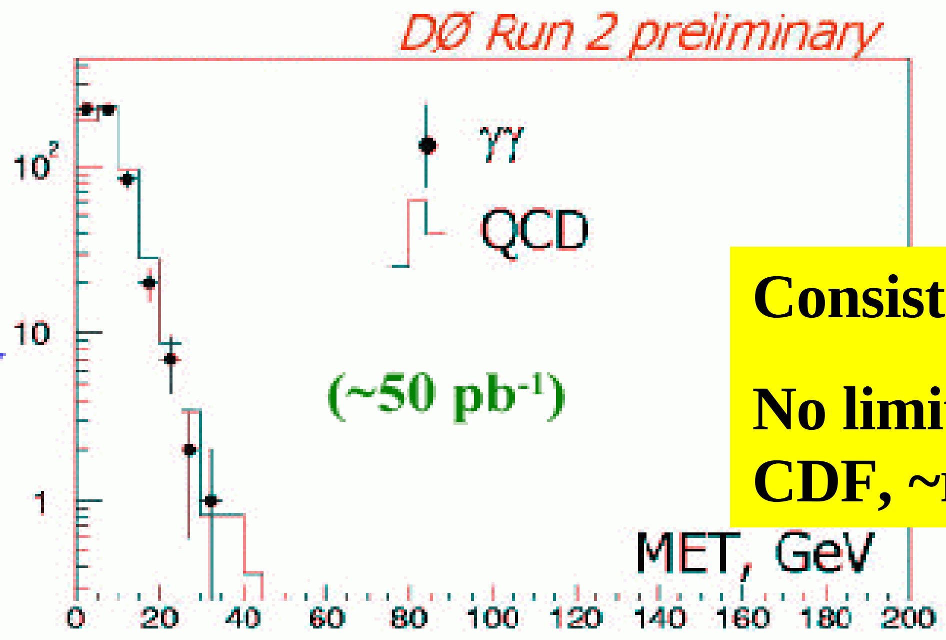
**Diphoton:**

GMSB: radiative decay to LSP (gravitino)

If neutralino NLSP:

$$\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$$

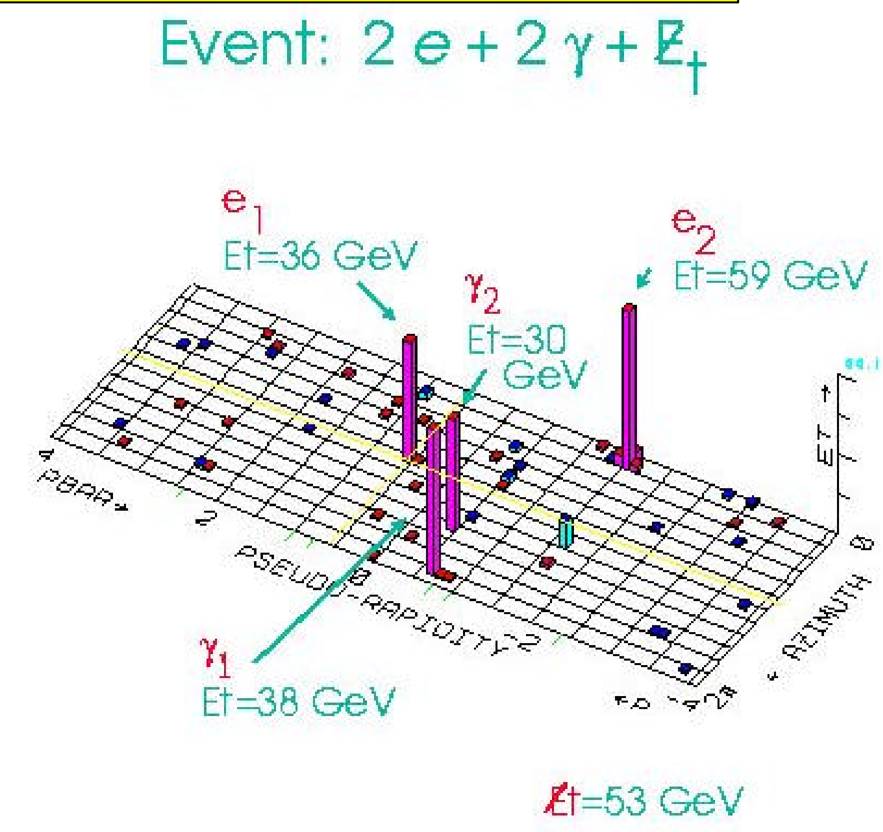
Search for γγ + E̸t




**Consistent:**

**No limits yet for CDF, ~run 1 for D0**

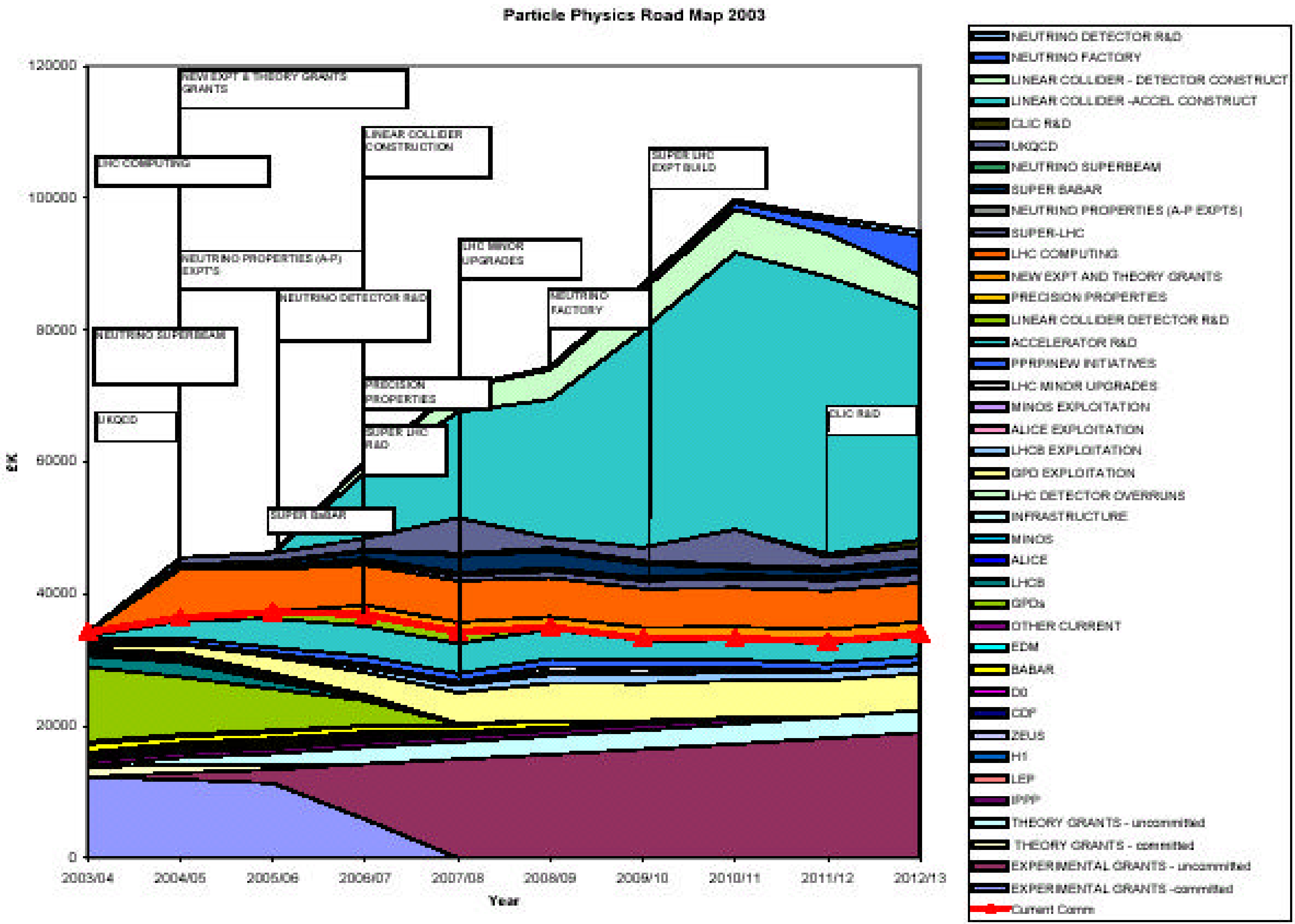
**Motivated by Run 1 CDF event**




**pp ® $c_i^{+} c_j^{-}$**

**® $c^0_1\ c^0_1$ + X**

**® g g G G + X ???**


Particle Physics Road Map 2003
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NEW EXPT & THEORY GRANTS
LHC COMPUTING
LINEAR COLLIDER CONSTRUCTION
SUPER LHC EXPT BUILD
NEUTRINO PROPERTIES (A-P) EXPTS
LHC MINOR UPGRADES
NEUTRINO DETECTOR R&D
NEUTRINO FACTORY
NEUTRINO SUPERBEAM
PRECISION PROPERTIES
UKQCD
SUPER LHC R&D
CLIC R&D
SUPER BaBAR
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LINEAR COLLIDER - DETECTOR CONSTRUCT
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ACCELERATOR R&D
PPRP/NEW INITIATIVES
LHC MINOR UPGRADES
MINOS EXPLOITATION
ALICE EXPLOITATION
LHCB EXPLOITATION
GPD EXPLOITATION
LHC DETECTOR OVERRUNS
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EXPERIMENTAL GRANTS -committed
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# Summary

- The UK has a highly focused programme in running particle physics experiments which is concentrated in the areas internationally agreed to be at the frontiers and we play central roles in these experiments.
- The construction of the LHC Detectors is well under way and our highest priority has to be ensuring we meet our very major hardware deliverables to these.
- The internationally agreed next facilities for particle physics are identified as the Linear Collider and Neutrino Factory. With our accelerator and detector R&D programmes, we are well positioned to be central to international activities in these areas.
- Our greatest asset is our skill base, which has allowed the UK to take on <u>leadership roles</u> in many areas of theoretical physics, in e-science developments, in the build for the LHC experiments, in the development of the accelerator and detector R&D programmes and in many core areas of physics analysis.