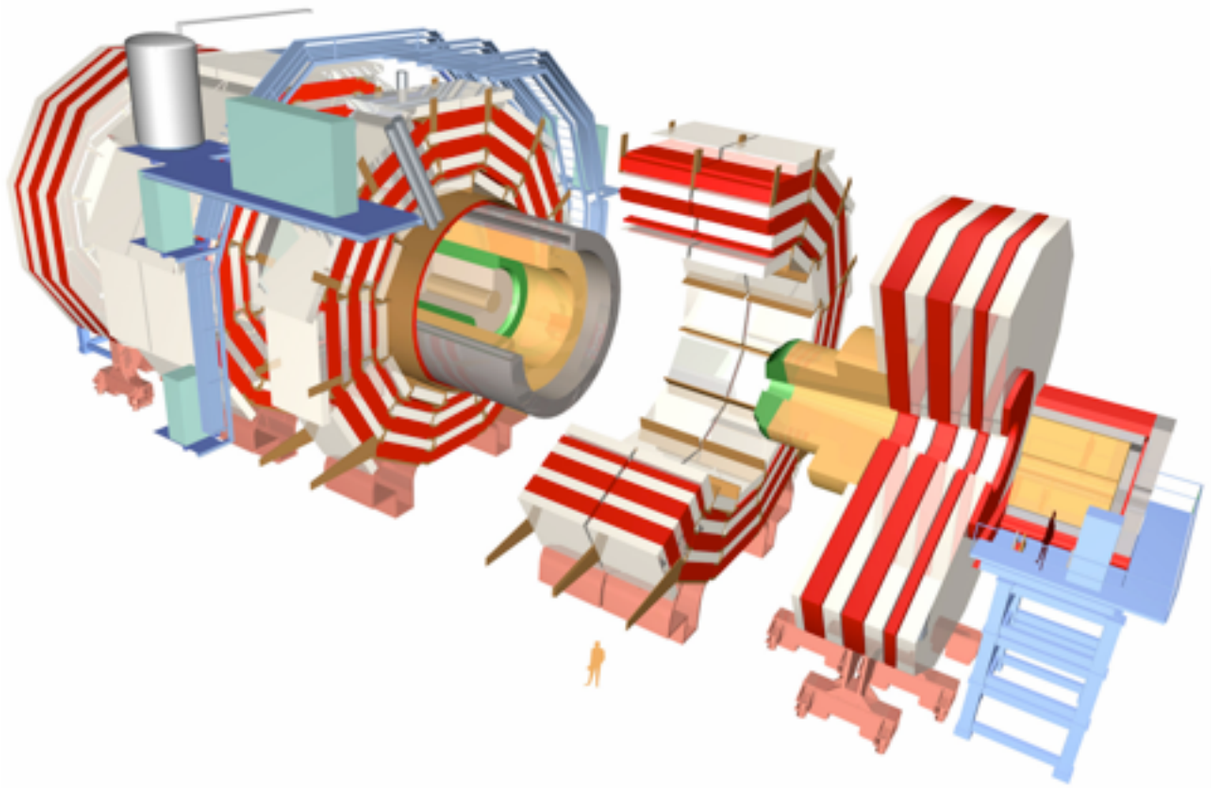
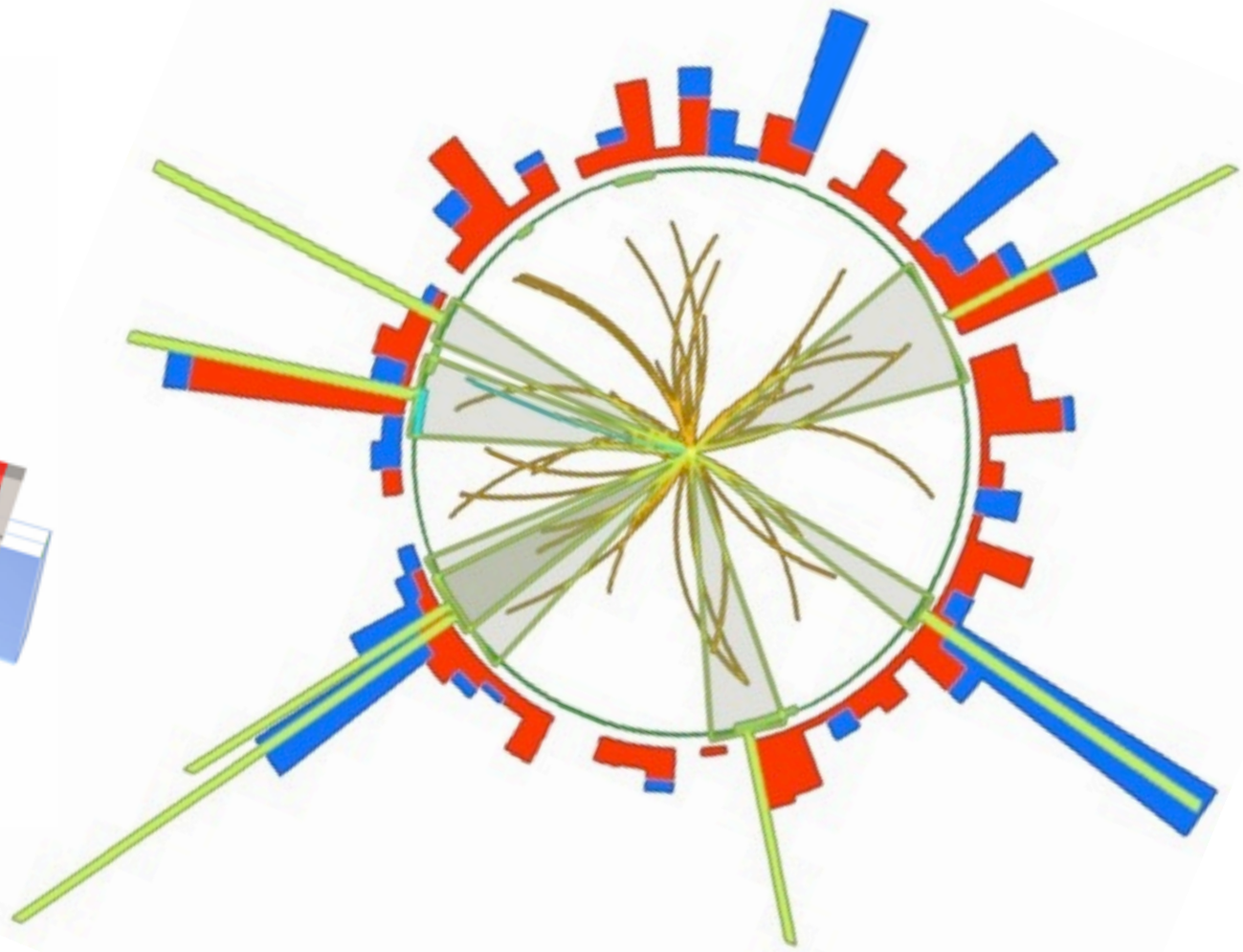
CMS: Status and Prospects

Dave Newbold – U. Bristol / RAL

On behalf of the CMSUK Collaboration

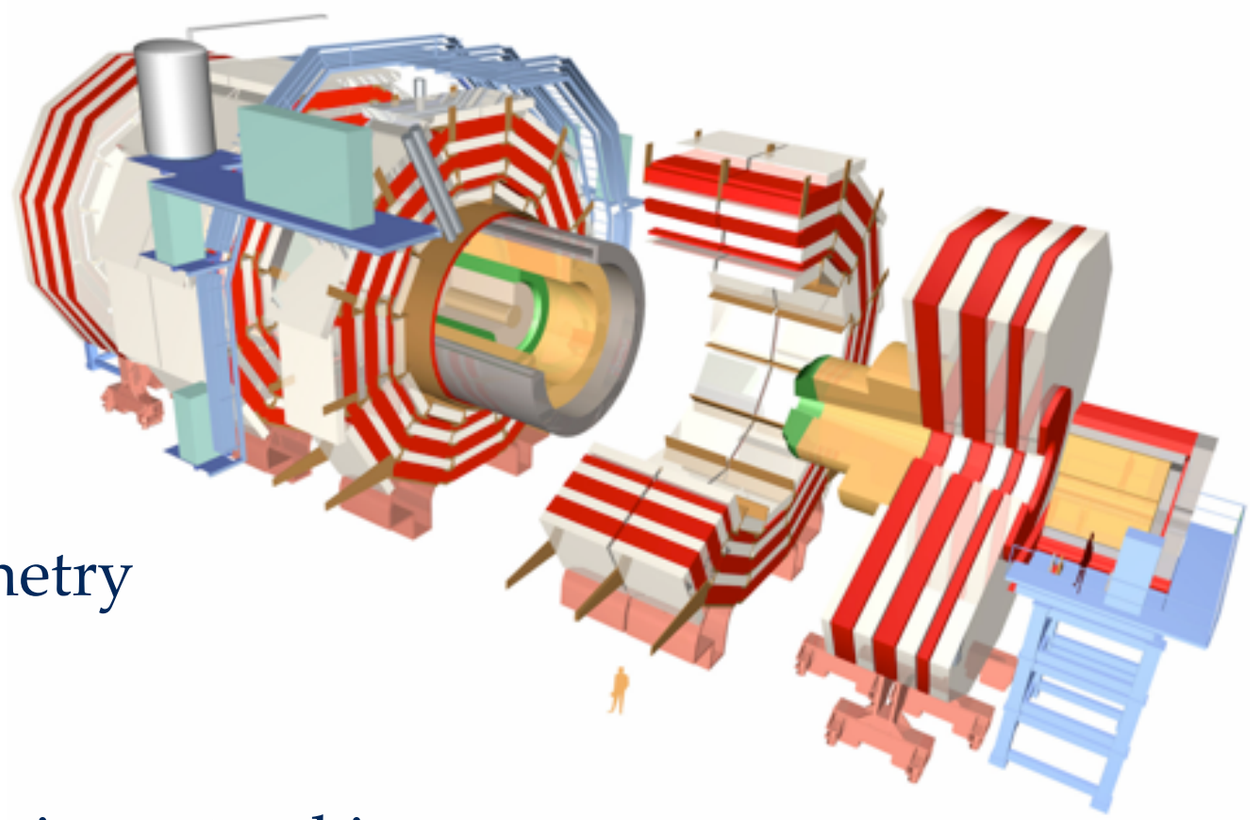




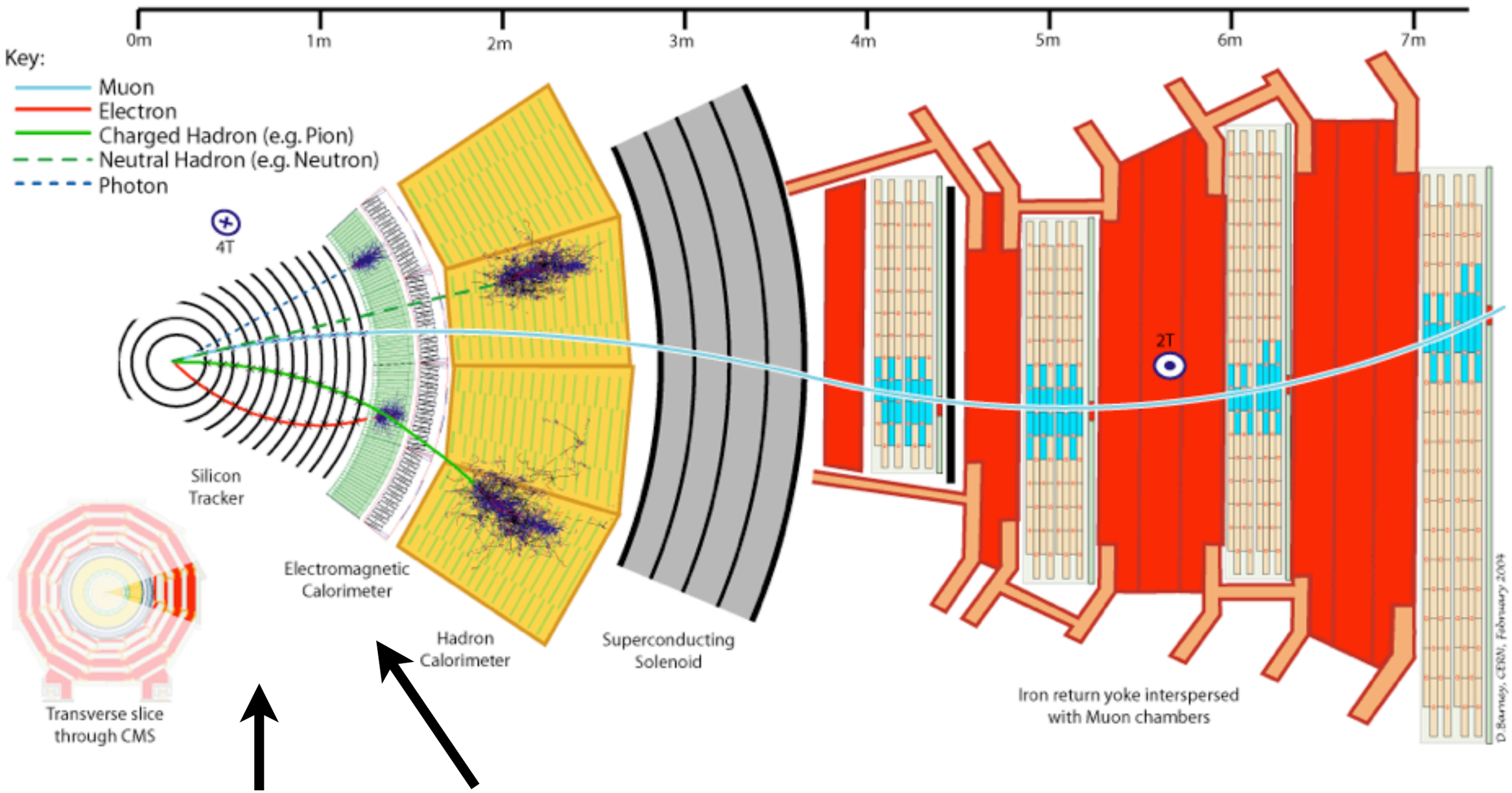
PPAP Review, September 2012

CMS Goals and Design

- General-purpose detector for LHC
  - Wide range of energy frontier and heavy ion physics
- Comprehensive programme
  - EWSB and TeV-scale physics
  - Direct BSM searches
  - (Some) QCD & flavour physics
- Detector characteristics
  - Hermetic, high-resolution calorimetry
    - Including precision crystal calorimeter
  - Highly redundant muon system
  - Highly redundant, high coverage, inner tracking
    - All-silicon system, pixels + strips
  - Flexible L1 and high-level trigger systems
    - We retain only around one per 100k crossings – trigger dictates physics reach
  - Durability, maintainability and rad hardness (20 year program)



The Detector



Silicon strip tracker

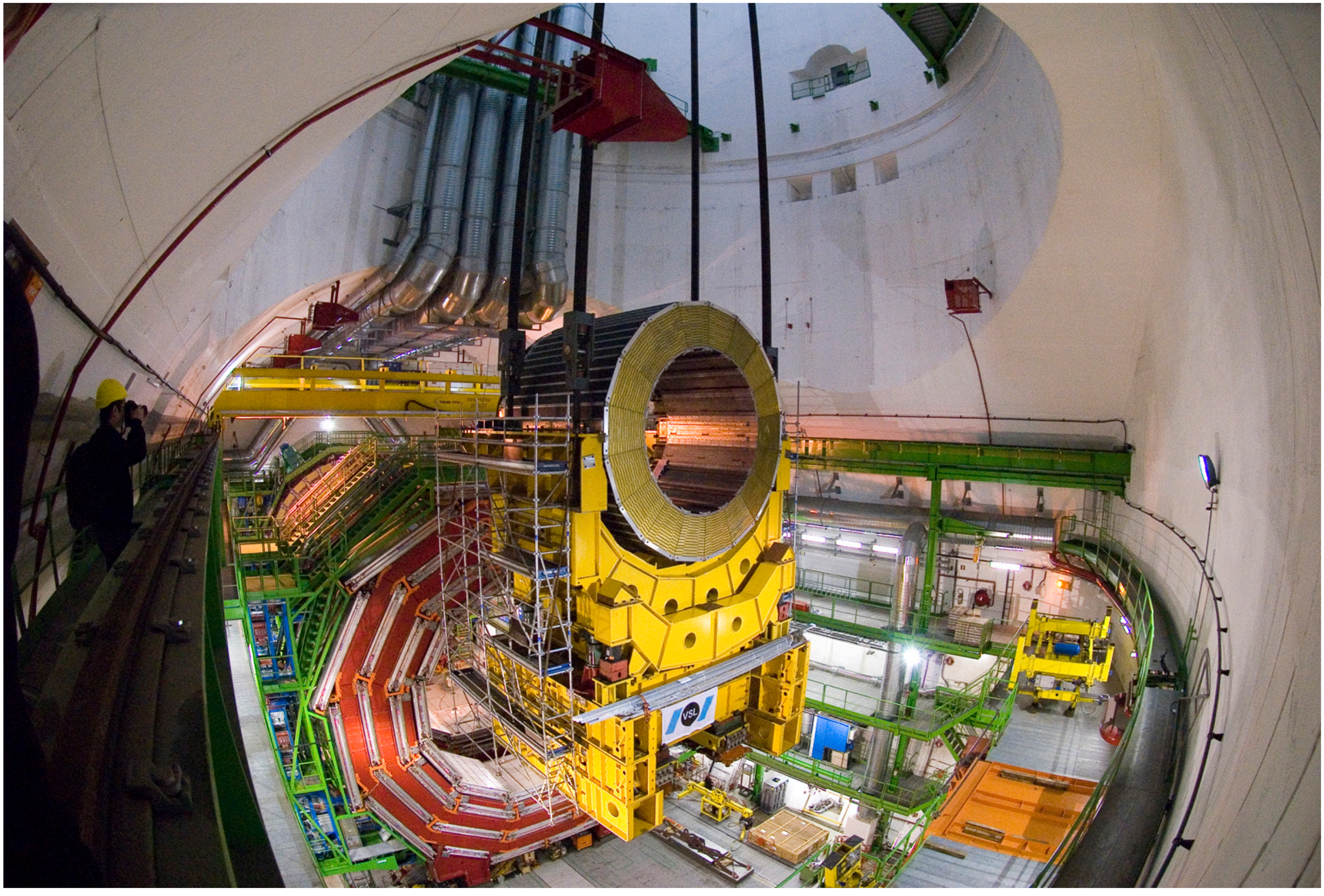
EM calorimeter (endcaps)

L1 trigger + DAQ

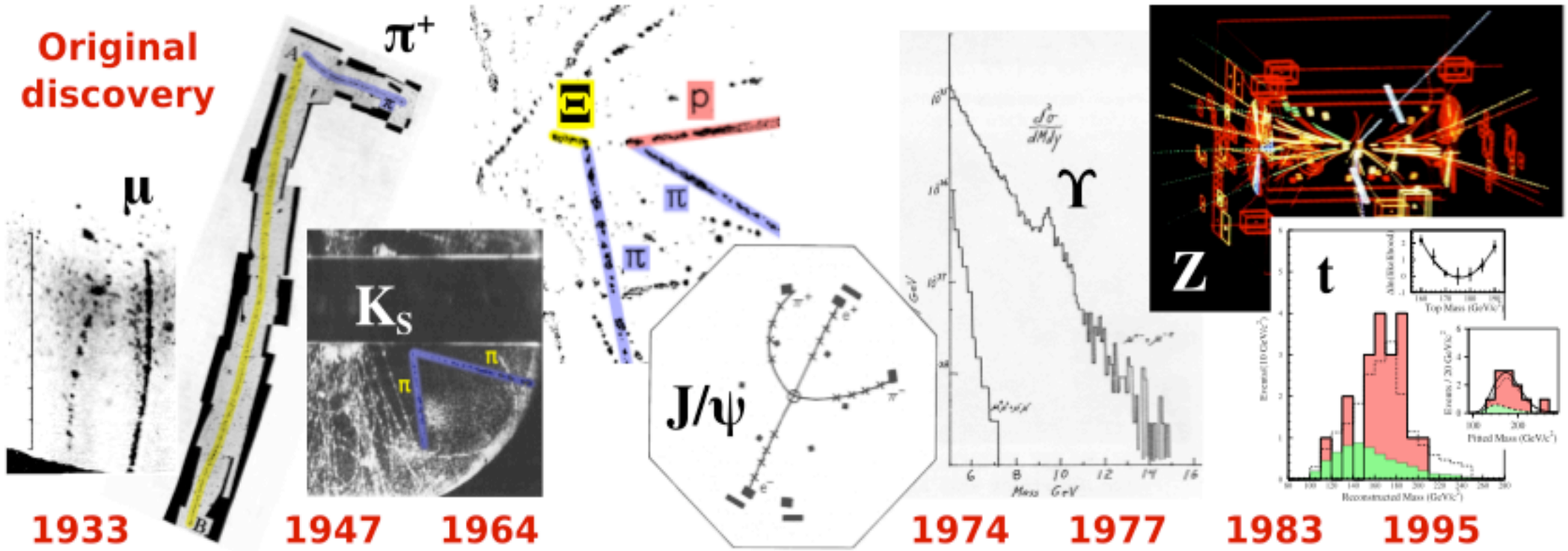
Computing system

UK = Bristol + Brunel + Imperial + RAL PPD (~60 PhDs)

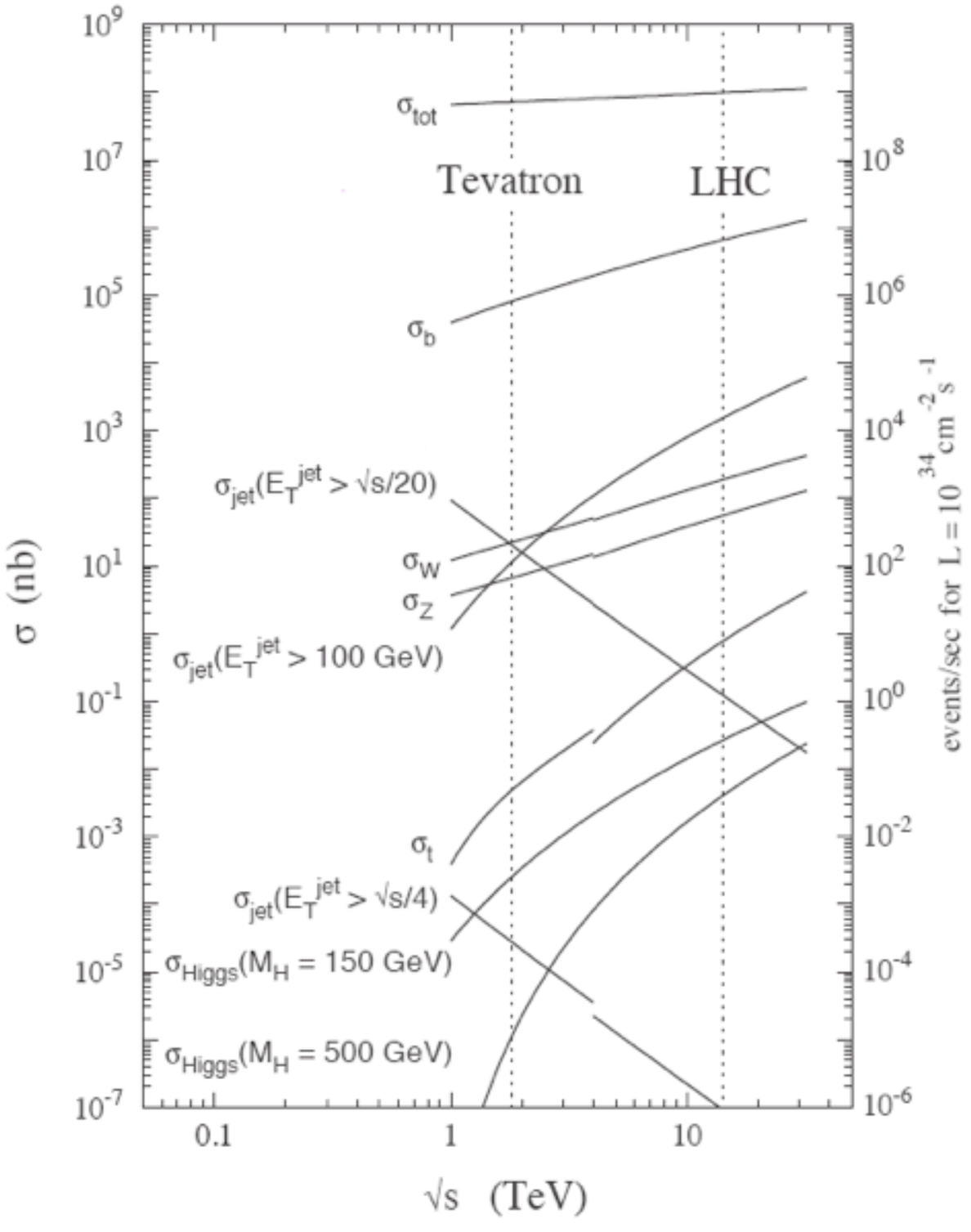
Five years ago



Successful Commissioning



The Program So Far



Alignment, commissioning — 2008

QCD, calibration, MC tune — 2009

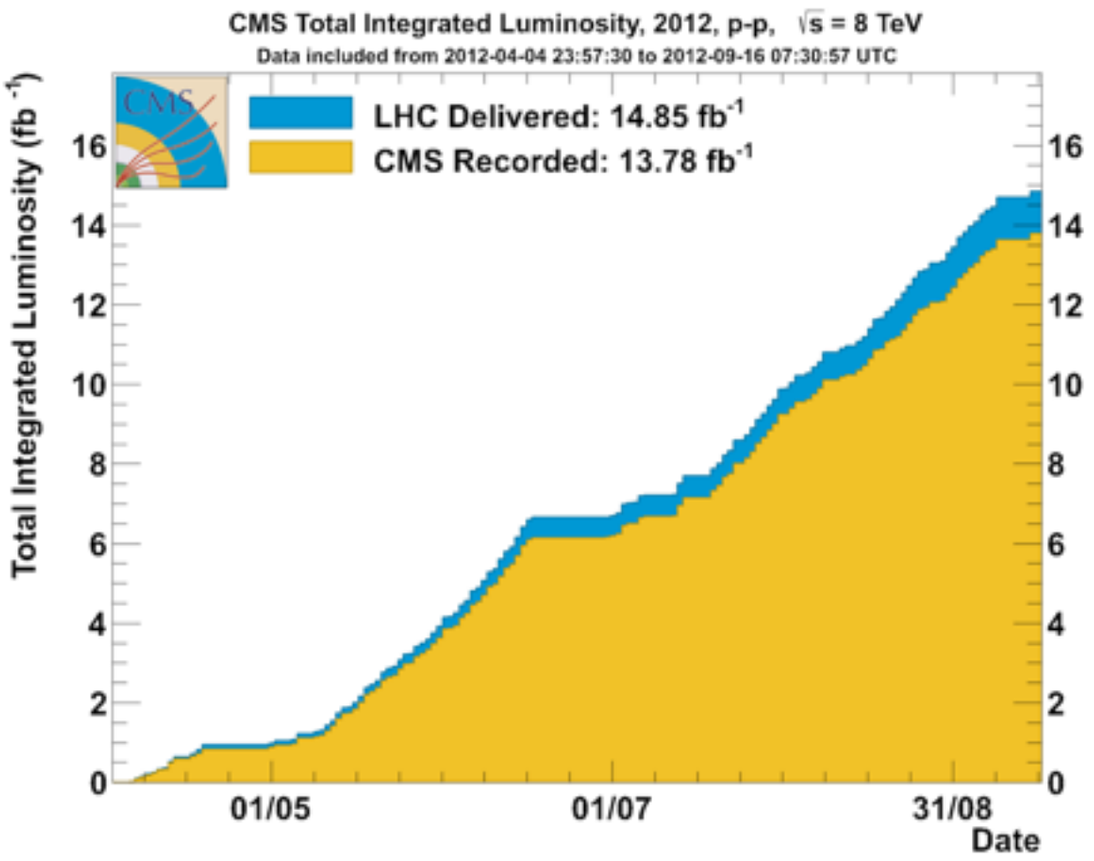
First W / Z; energy scale — 2010

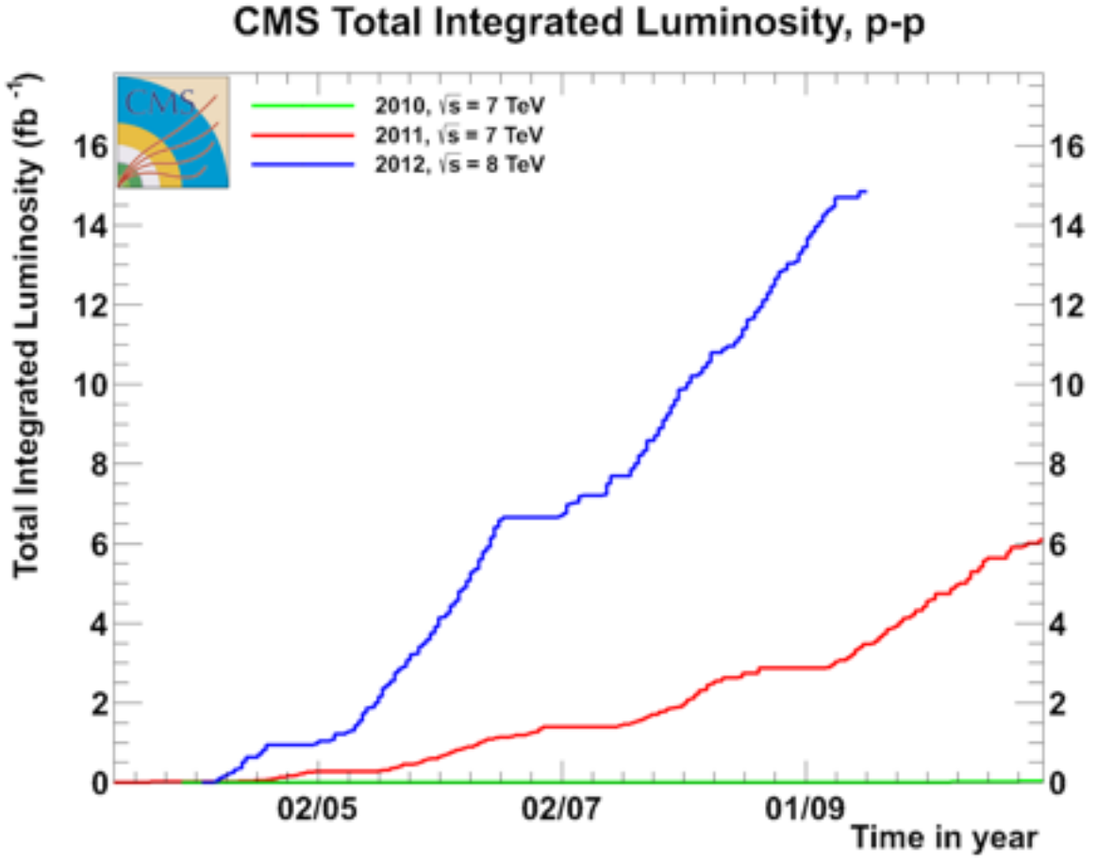
First top — 2010

W', Z' search; SUSY sens. — 2011

Higgs, TeV-scale SUSY — 2012

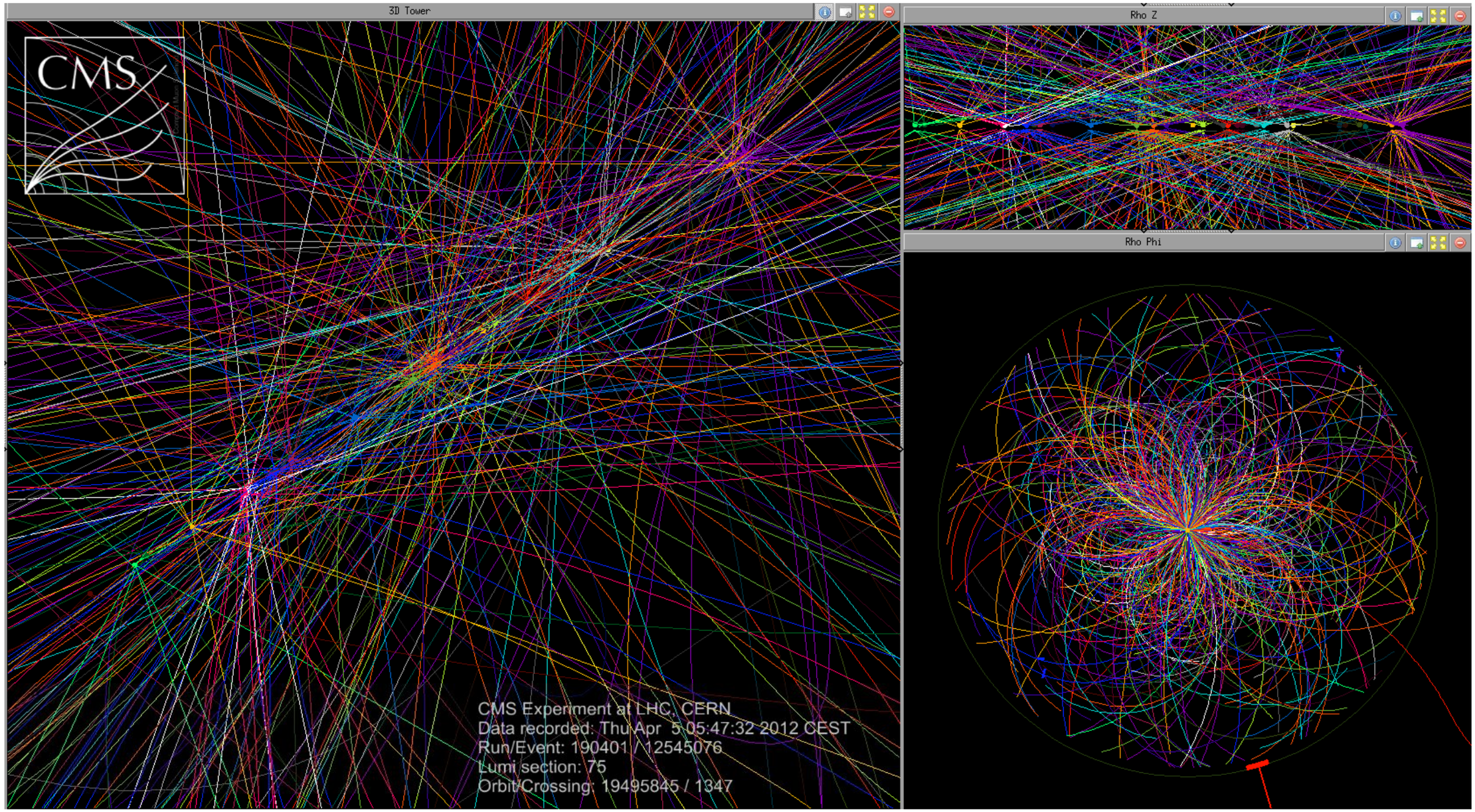
LHC Performance





- LHC ramp-up is remarkable and unprecedented
  - Increasing inst. lumi. ⇒ continuous re-optimisation of trigger, detector
  - Currently operating at > 7e33Hz/sqcm (LHC design lumi: 1e34)
  - But: 50ns bunch spacing: ⇒ 35 overlapping events (CMS designed for ~25)
  - Hoping for 25-30/fb by end of 2012 run

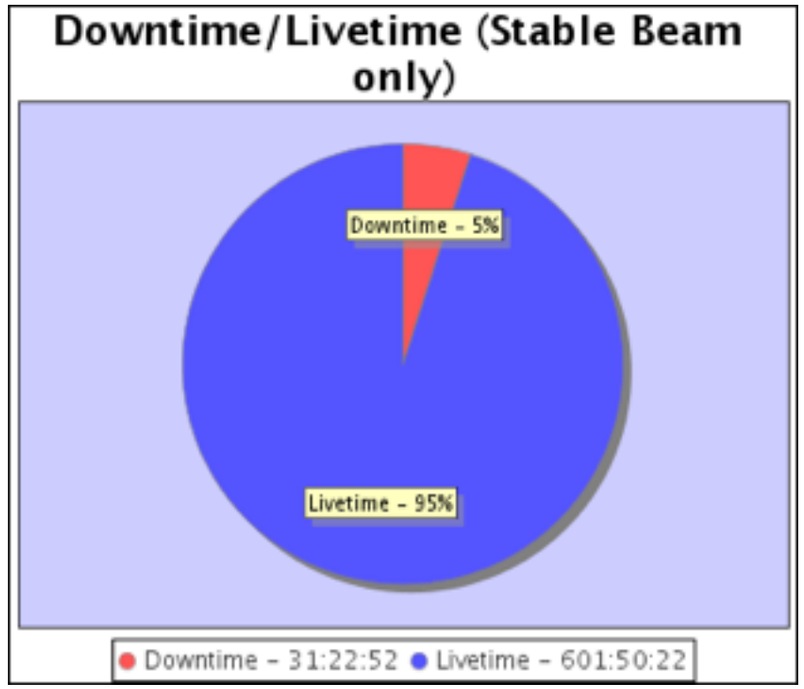
Typical 2012 Event

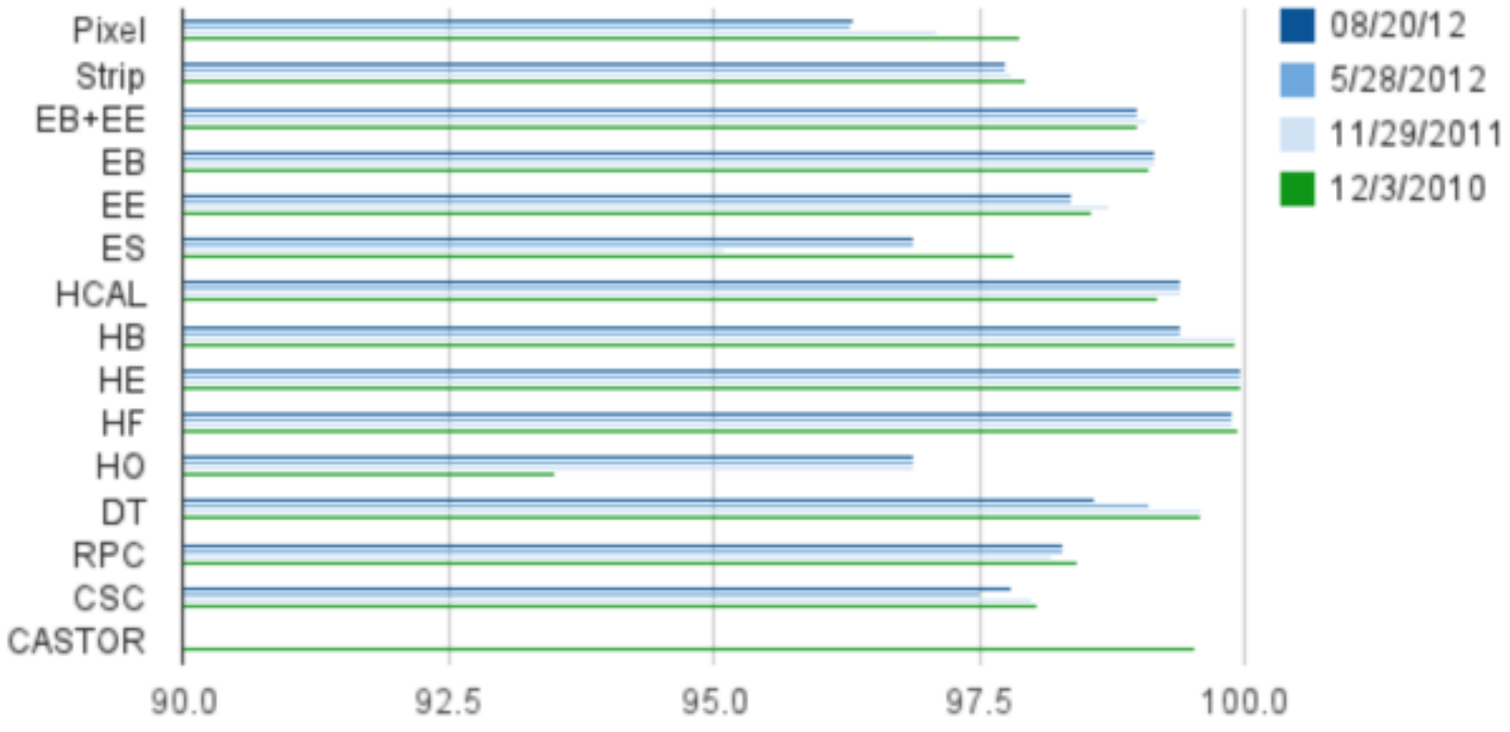


- Trigger rates & offline reconstruction time increase non-linearly with pileup levels

CMS Performance

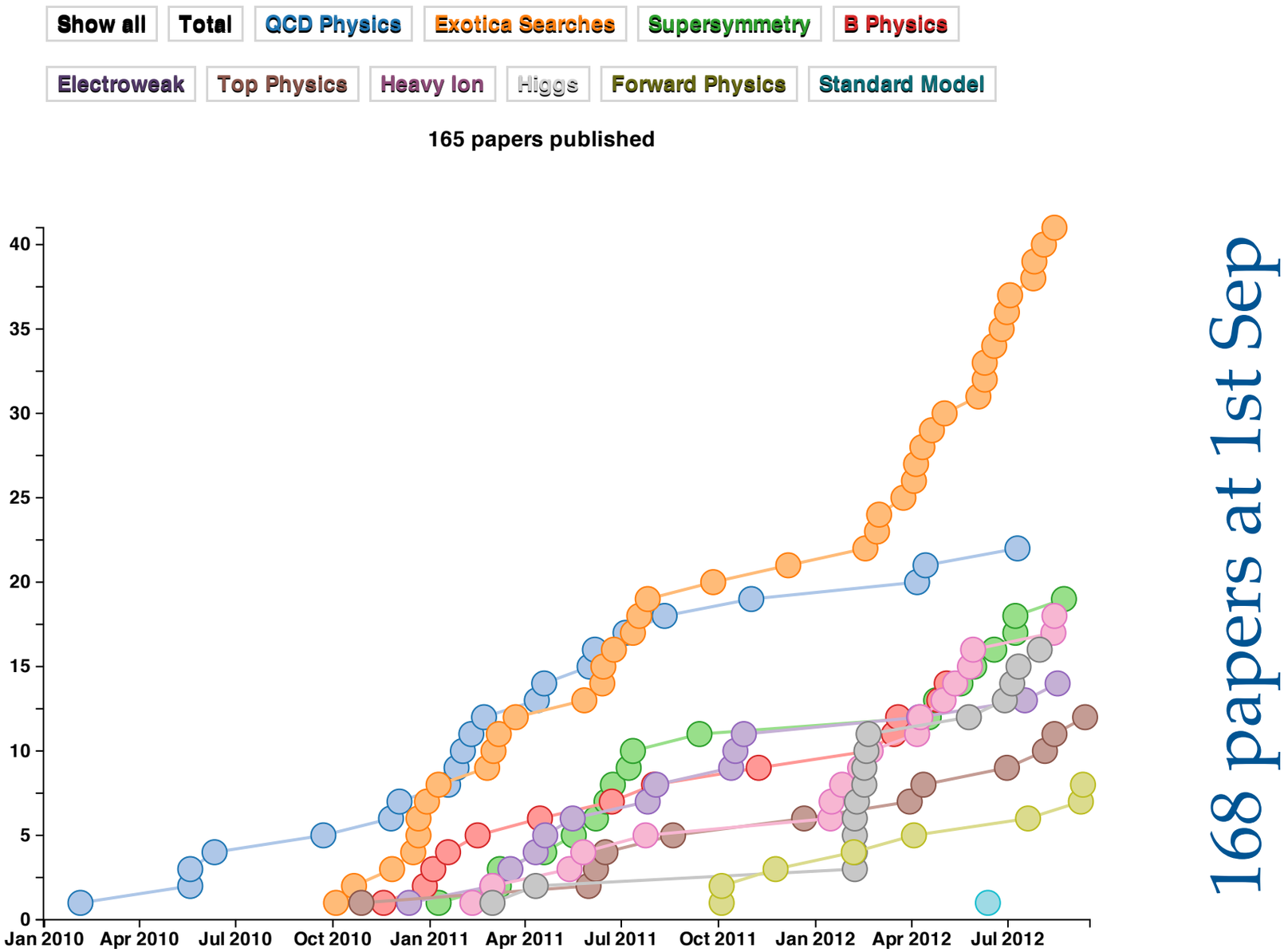
- Exceptional data-taking efficiency
- Most downtime now due to external 'technical incidents'
  - Power loss, cooling loss, etc
- Safety systems 100% reliable so far
  - 3GJ stored in the CMS magnetic field...





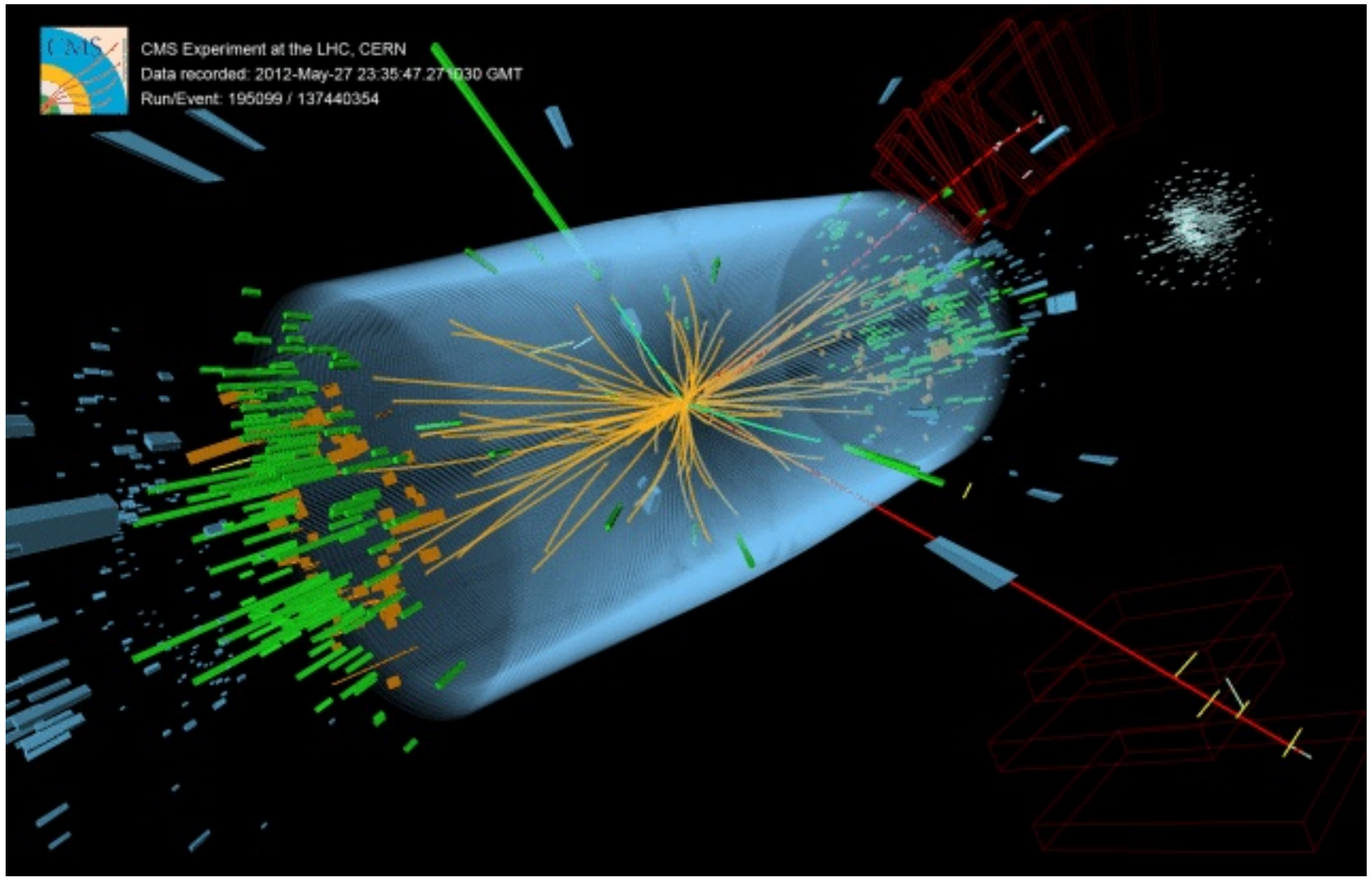
Month of July 2012

Physics Publications



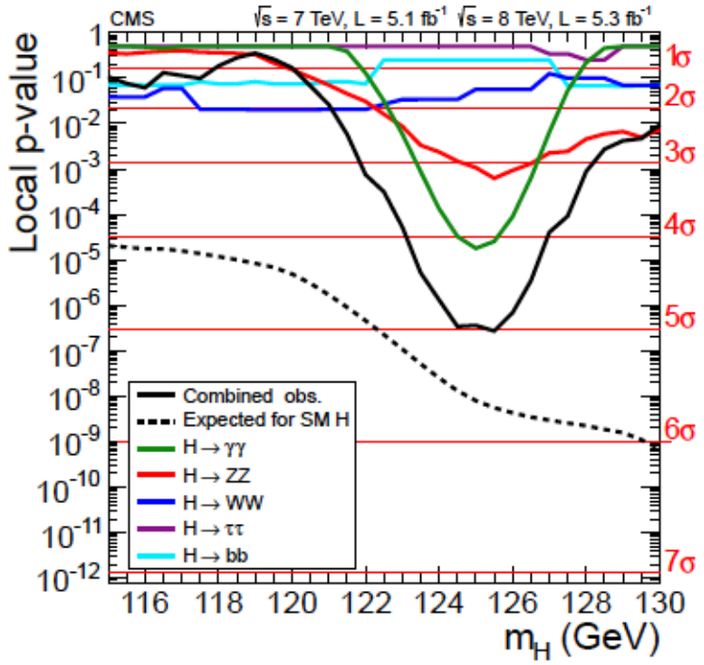
- Quantity has not been allowed to override quality
- All results: http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

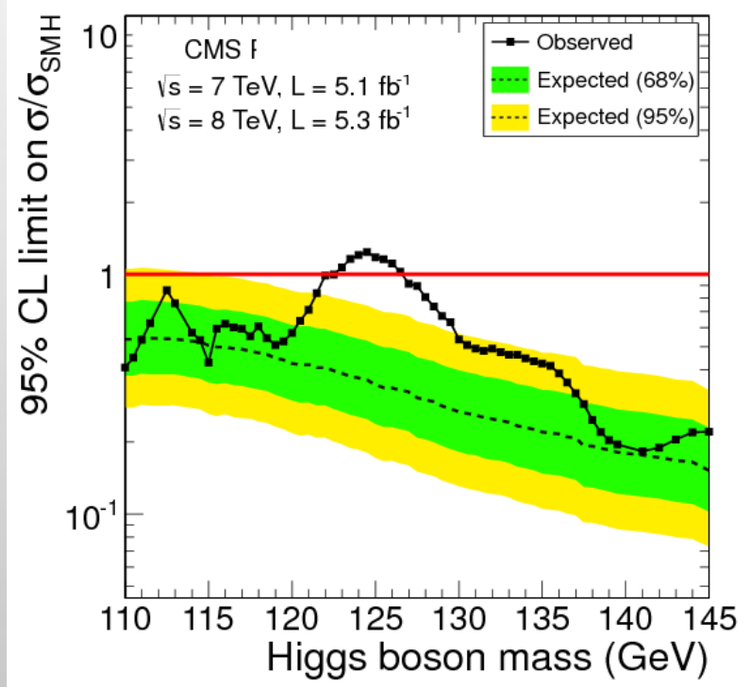
‘The Boson’



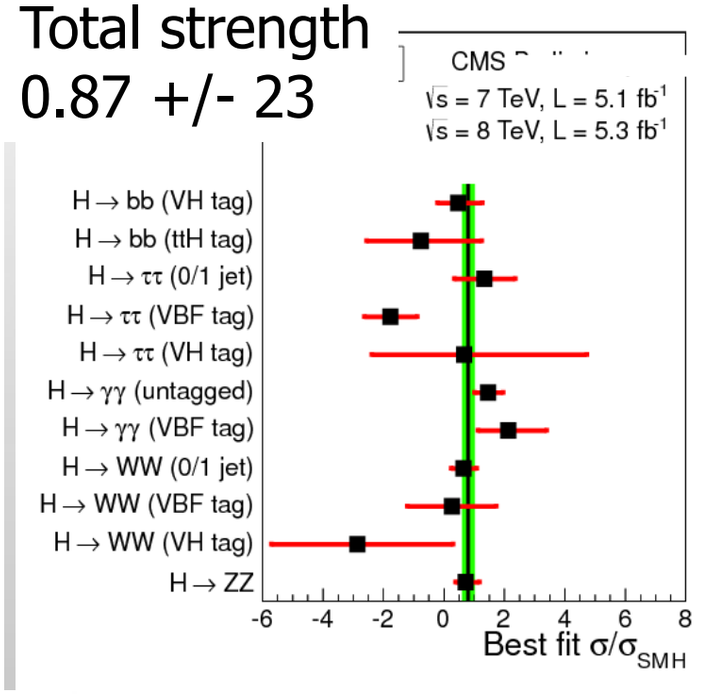
- In numbers
  - Mass: 125.3 +/- 0.6 GeV ; Cross-section: 0.87 +/- 23 of SM prediction (!)
  - ~ 700 direct CMS analysis contributors to 4th July results
  - Subject of >5000 TV broadcasts (1B audience), 17000 news articles

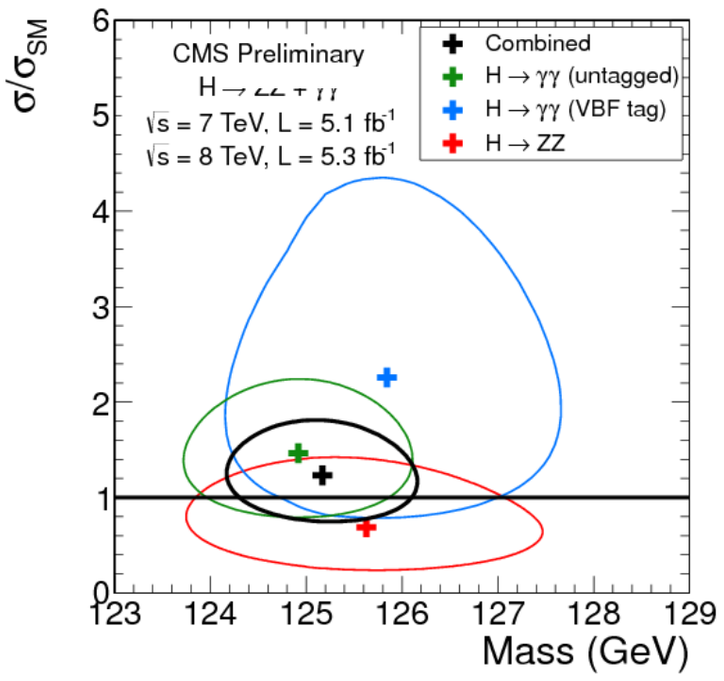
‘The Boson’

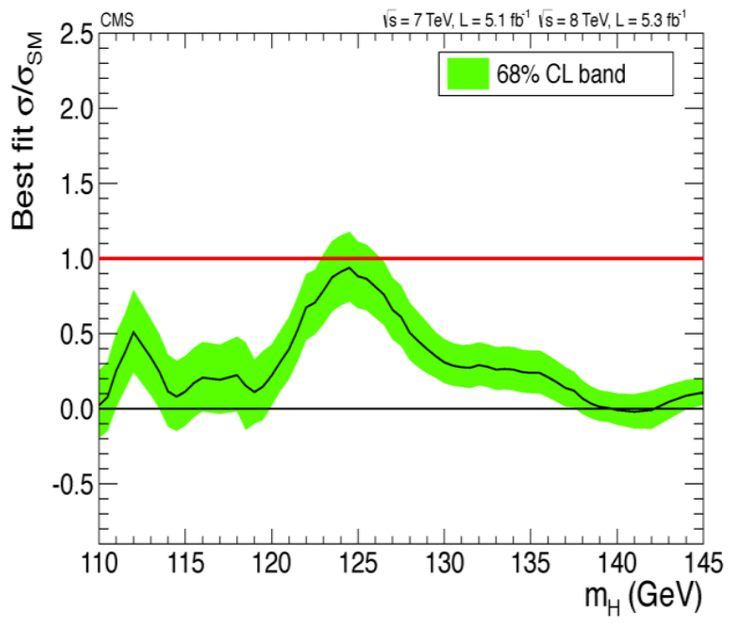


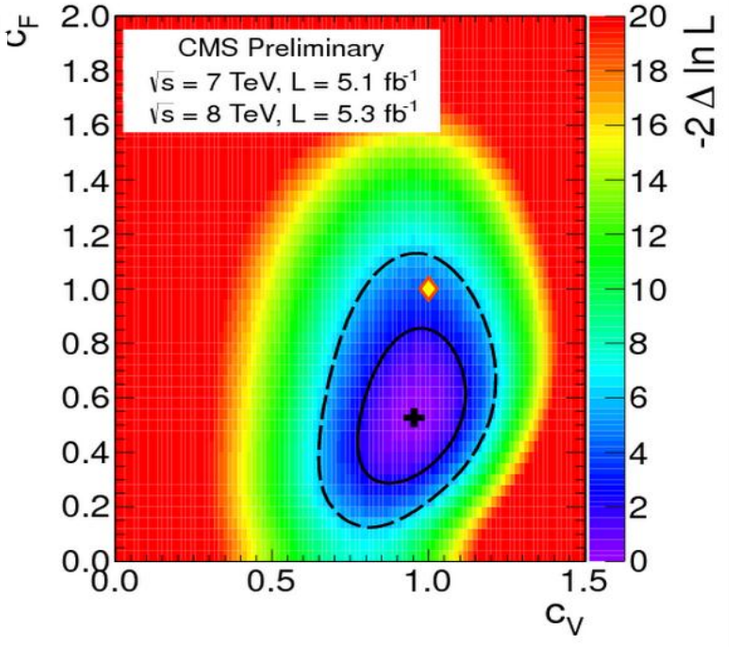


Total strength
0.87 +/- 23





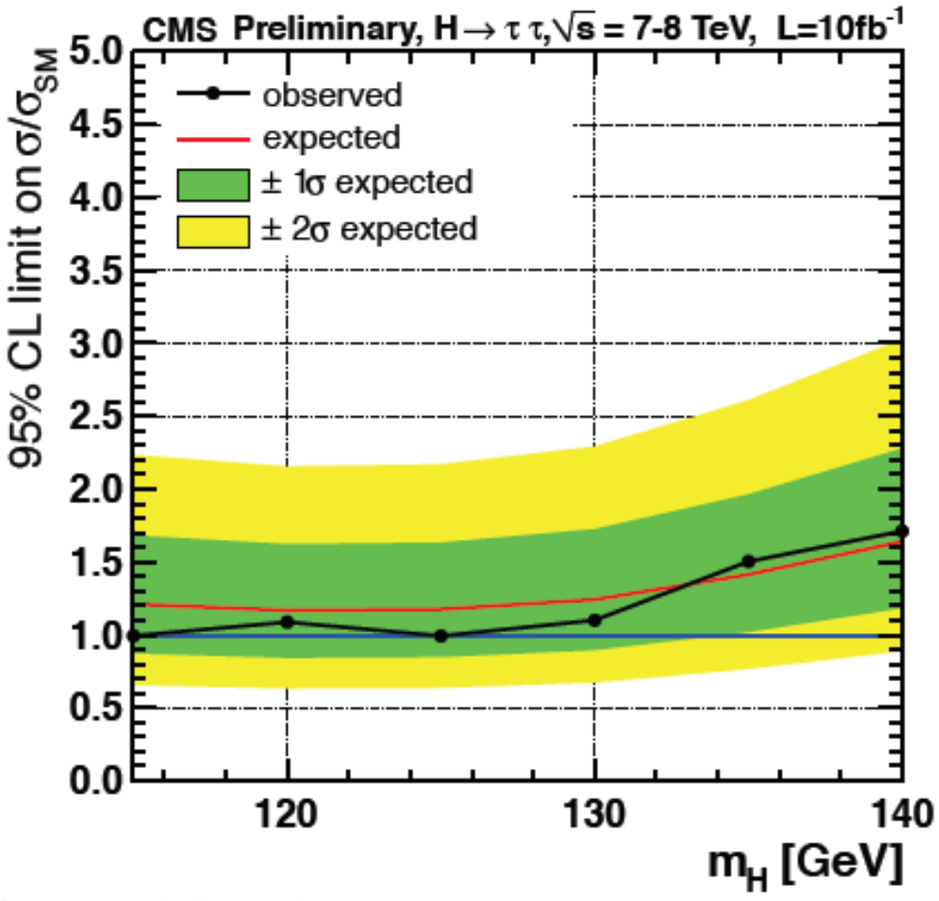




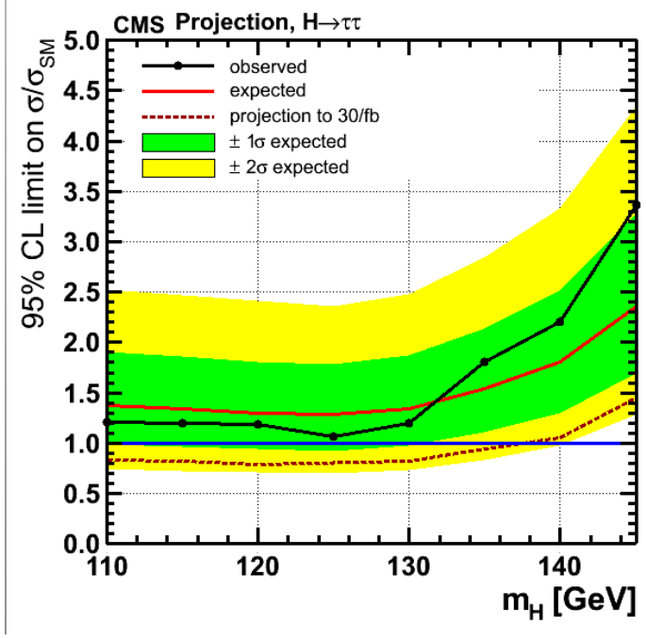
Particle Mass = 125.3 +/- 0.4 +/- 0.5 GeV

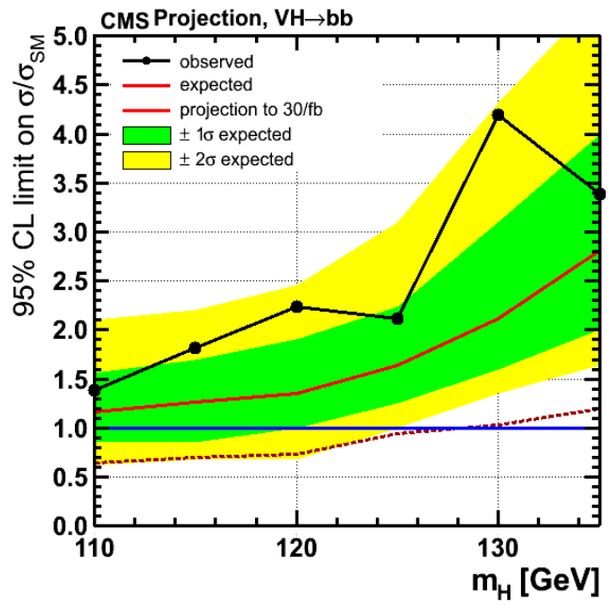
SM Higgs-like within 2σ but certainly not definite yet…

Fermion Couplings?



Latest combined H -> tau tau result

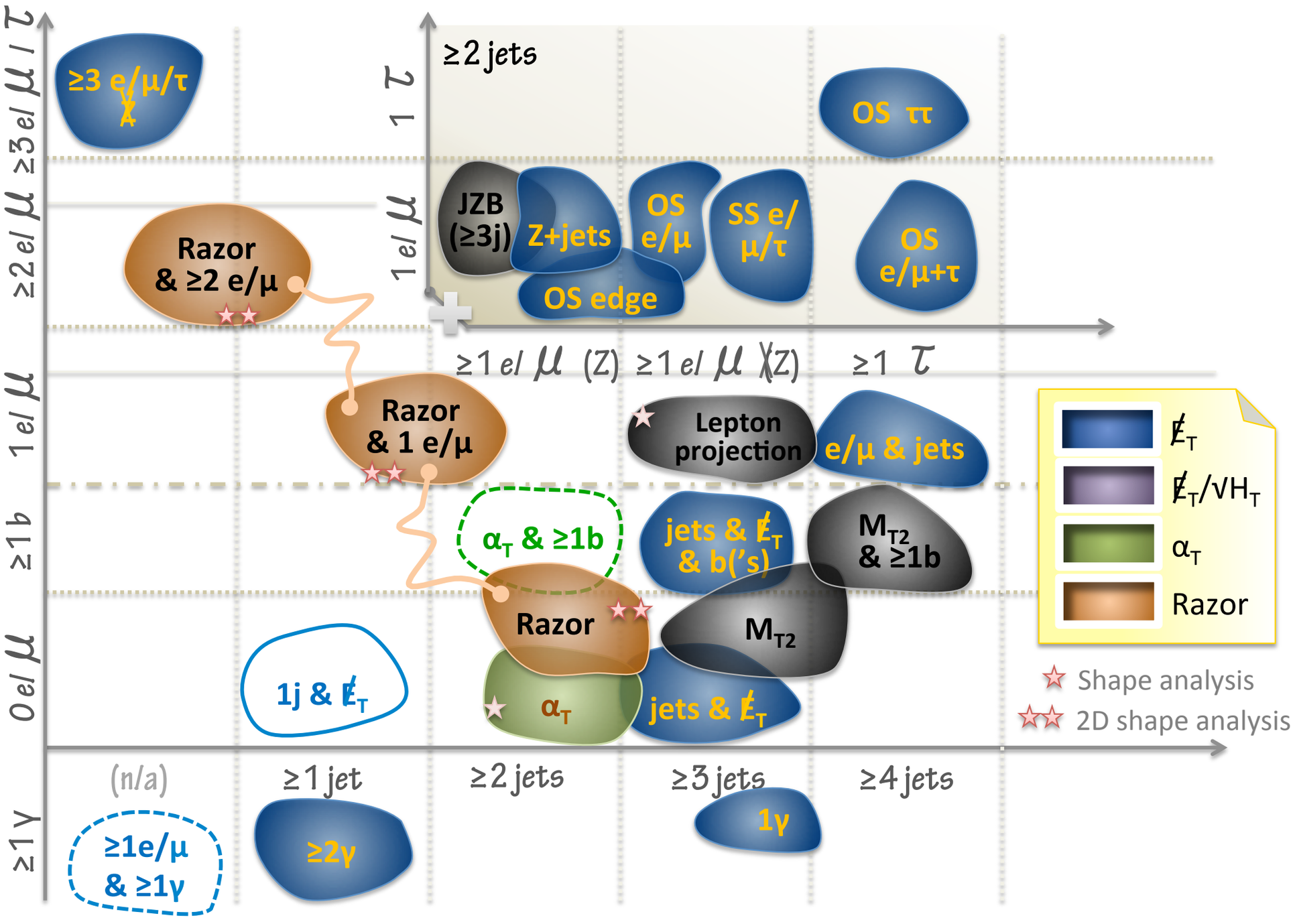




Projection to 30/fb

- The facts
  - Seen at 5 sigma significance in three channels (WW, ZZ, gg)
  - Independent confirmation of coupling to fermions next crucial step
    - Will know a lot more based on the expected 2012 dataset
  - NB: coupling to t is confirmed to 10% by gluon fusion production...

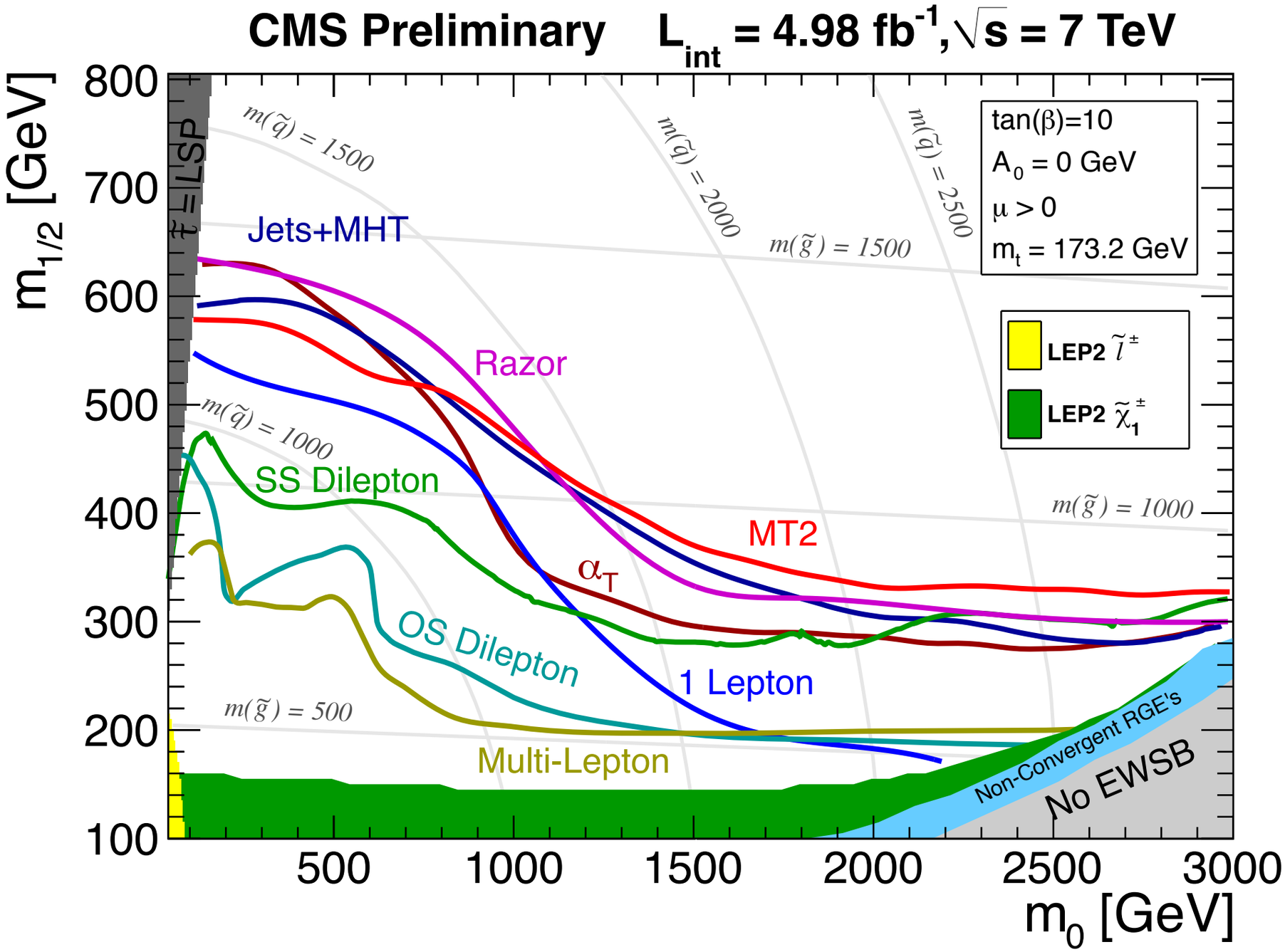
SUSY Searches



Slide by S-A Koay

- Panoply of channels, covering wide range of phenomenology

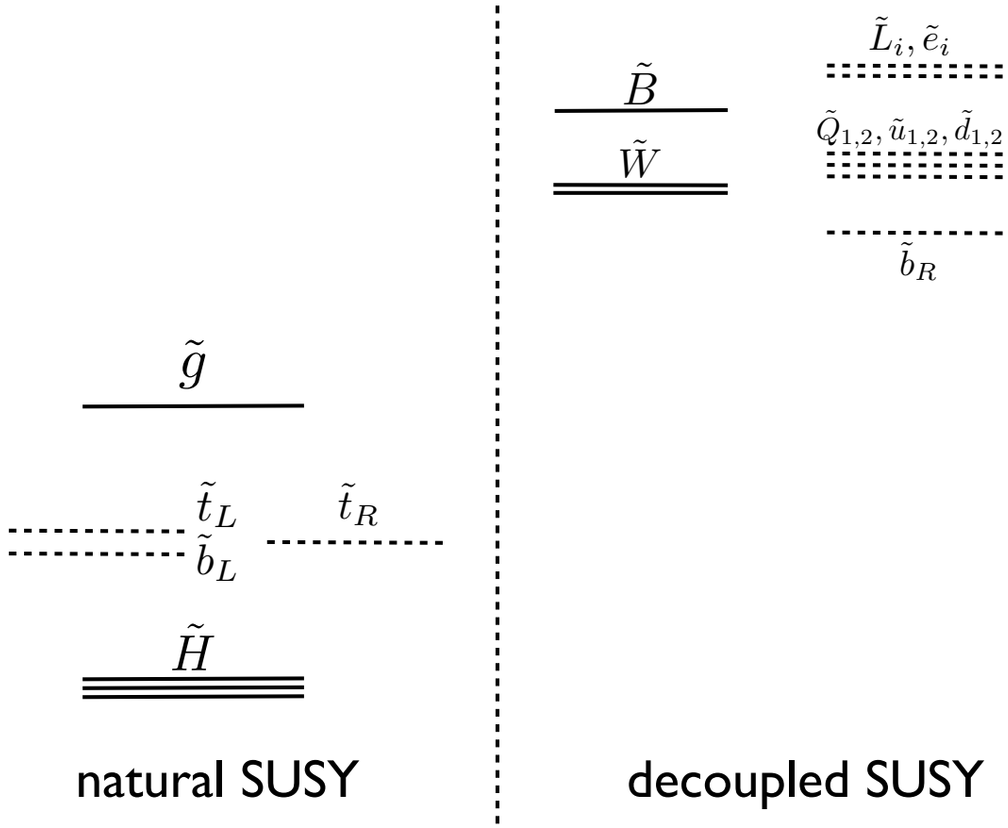
SUSY cMSSM Limits

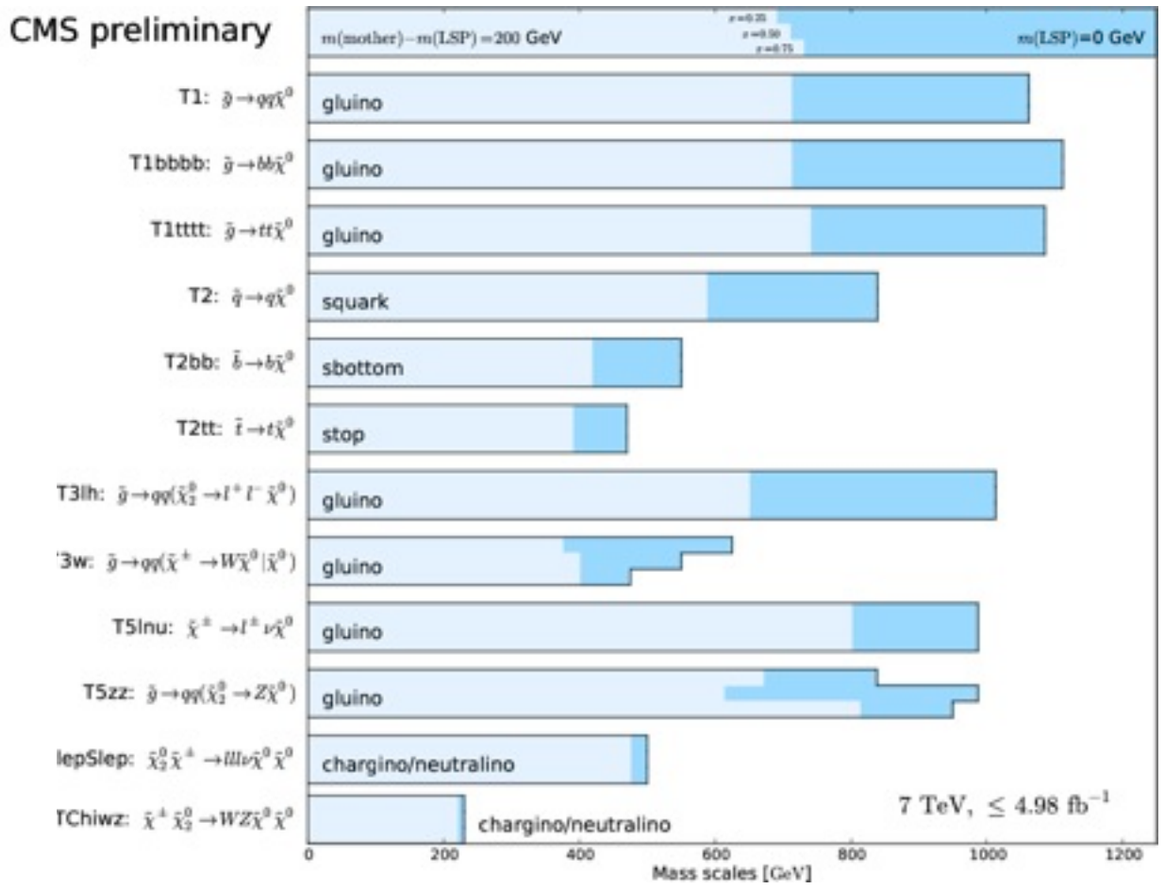


- Hadronic searches still leading the way (updates soon)

Alternative Approaches

- Simplified model spectra
  - Recast experimental limits in term of squark / gluino masses
  - Direct limits now around 1TeV

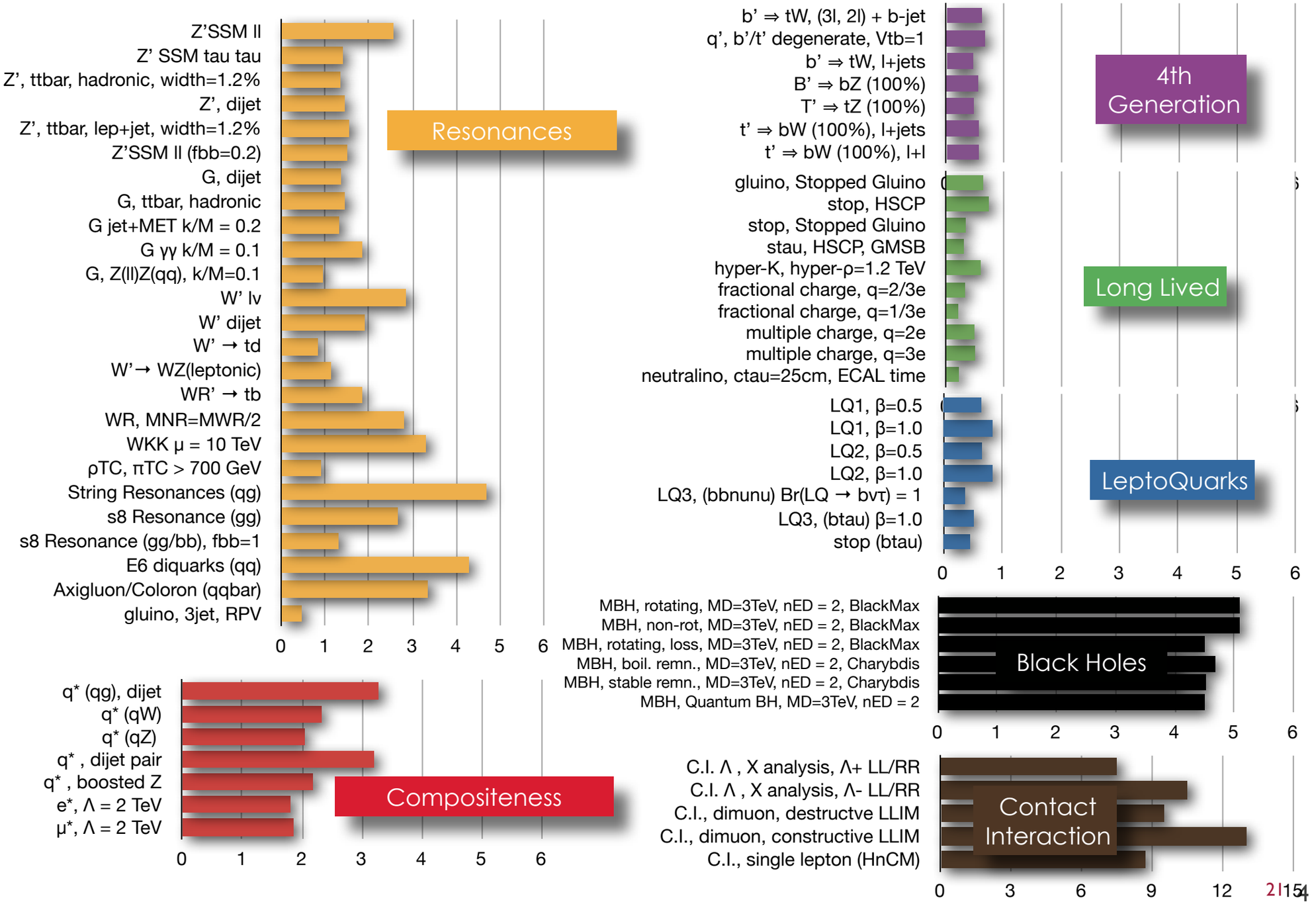




- Where now?
  - Move towards 'natural SUSY'
  - Focus on third-gen decays, including small mass splitting / heavy gluino scenarios

Only worry about what matters!

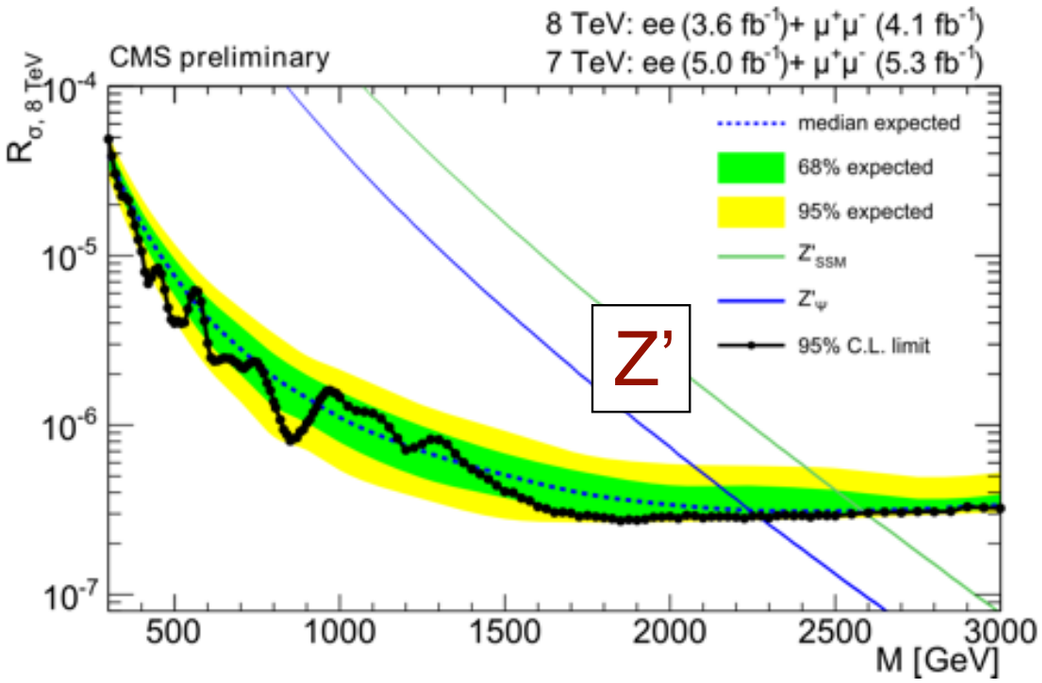
Exotica Overview

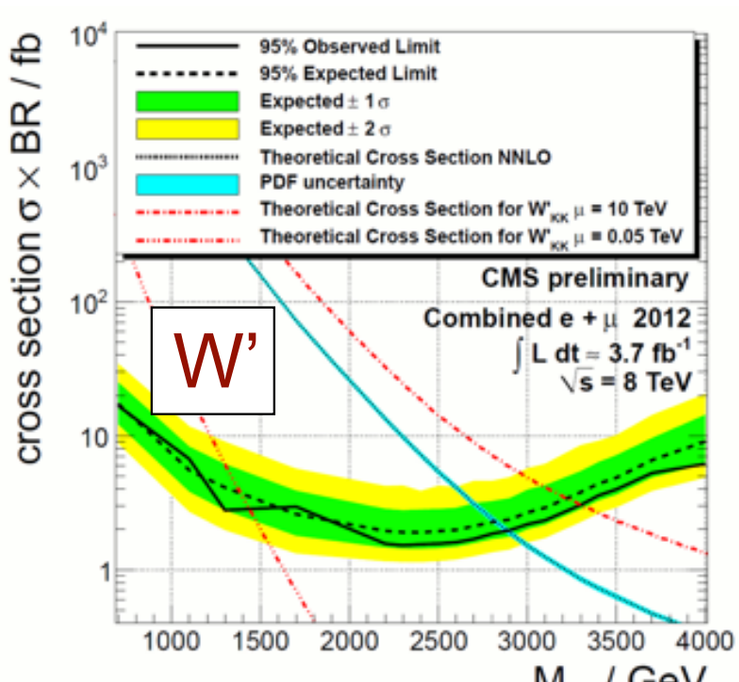


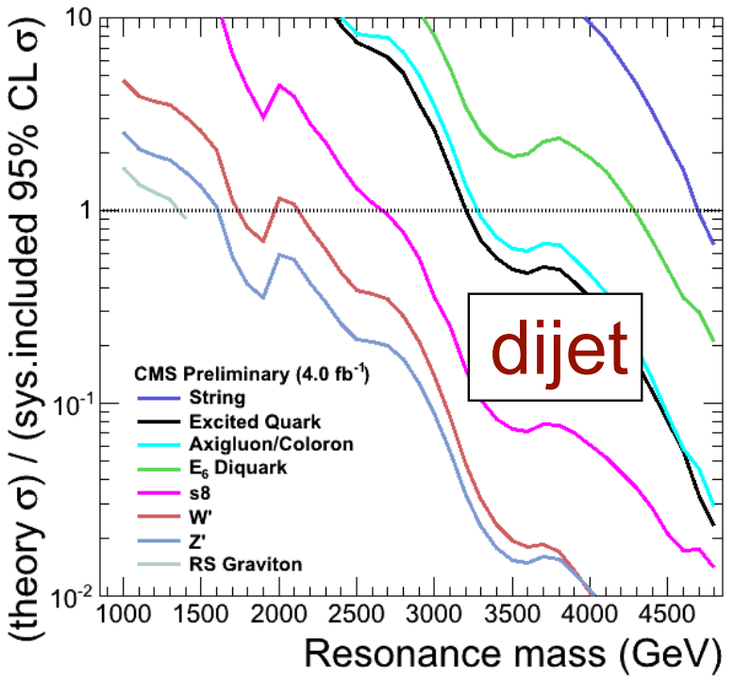
- The graveyard

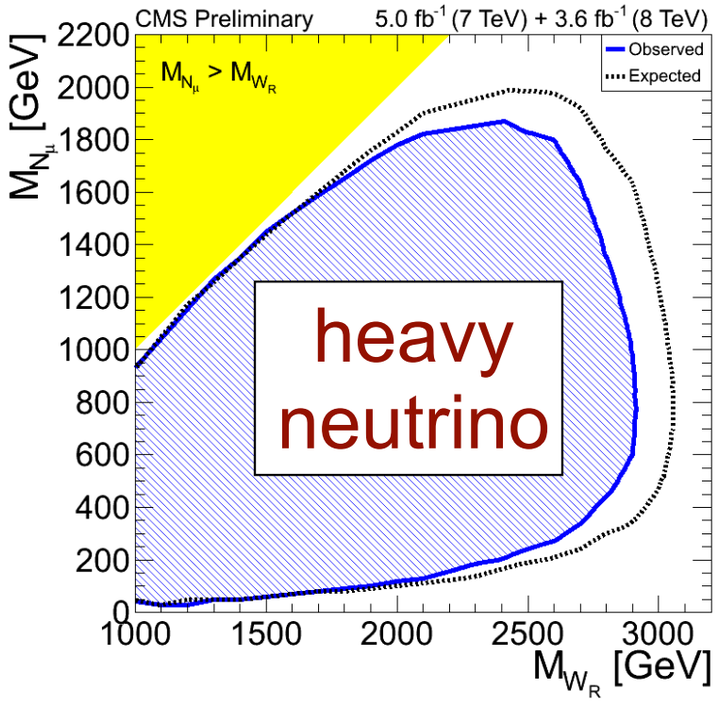
(horiz. scale is mass limit or scale limit)

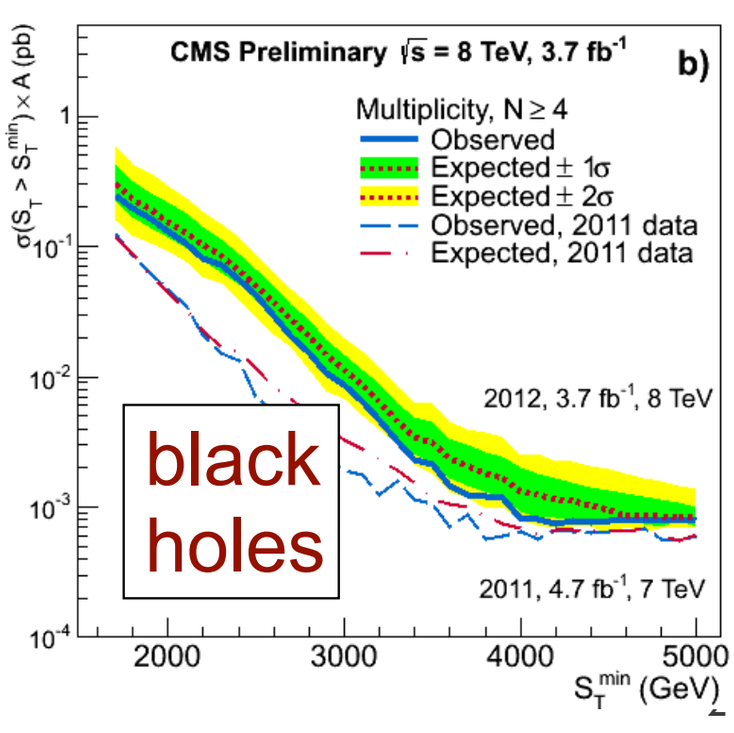
Exotica Searches











Parked Data & Data Scouting

- What are the fundamental bottlenecks in data recording?
  - Ability to move and process data offline
  - Safety factors in planning trigger menu
  - Available effort to analyse the data
- Data parking
  - We pragmatically use up the *full* capacity of the L1 and HLT output
    - 100kHz at L1, up to 1kHz at HLT; approximately doubles the recorded data sample
  - This 'non-core' data is not reconstructed or distributed promptly
  - The parked dataset will be a major aspect of our 2013 physics programme
- Typical use cases
  - VBF-tagged inclusive sample – around 10% eff. for VBF H production
  - Extended SUSY reach in hadronic channels
  - Rare decays, quarkonium studies, etc
  - Others being added for last part of the 2012 run

Parked Data

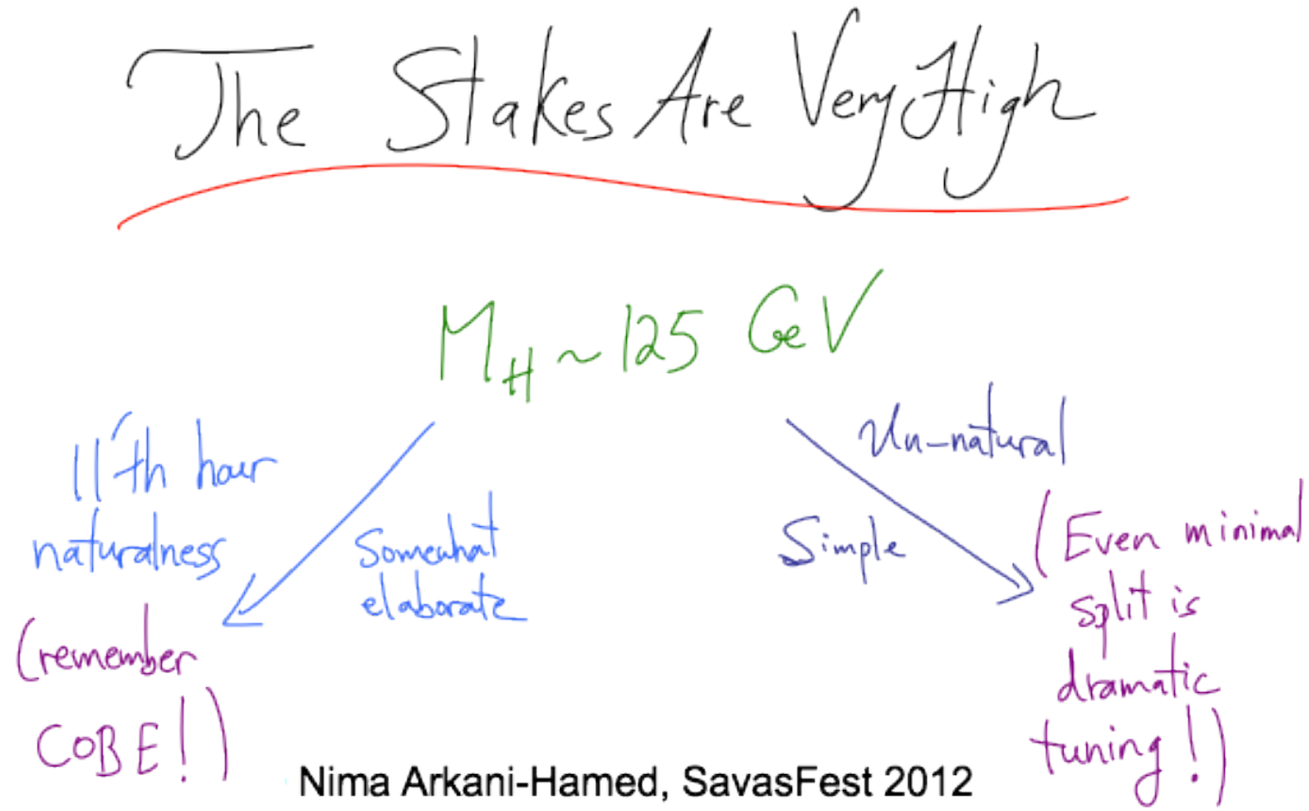
Data Parking Triggers (1)

Trigger Selection for Data Parking	Main Physics Motivation	Average Rate (Hz) over typical LHC fill	Tighter / complementary version in the "core" trigger menu
M_{jj}>650 GeV , $\|\Delta\eta_{jj}\|$>3.5	Generic final state produced via Vector Boson Fusion (VBF)	130	QuadJet75_55_38_20: 1 b-jet + 2 "VBF" jets
At least 4 jets with p_T>50 GeV (QuadJet50)	Pair production of stops → top (hadronic decay) + neutralino in models with small mass splitting between stop and neutralino	75	QuadJet60 + DiJet20 OR QuadJet70
R^2*M_R>45 GeV + R^2>0.09	Extend SUSY hadronic searches with "razor" variables (M_R,R^2): compressed mass spectra and light stop searches	20	R^2*M_R>55 GeV + R^2>0.09 + M_R>150 GeV
H_T>200 GeV , α_T>0.57	Extend SUSY hadronic searches with α_T variable	10	H_T>250 GeV , α_T>0.55 H_T>250 GeV , α_T>0.57 H_T>300 GeV , α_T>0.53 H_T>350 GeV , α_T>0.52 H_T>400 GeV , α_T>0.51
Dimuon: $p_T(\mu_1)$ > 13 GeV , $p_T(\mu_2)$ > 8 GeV	PDF constrains using Drell-Yan events at low $M_{\mu\mu}$	10	$p_T(\mu_1)$ > 17 GeV $p_T(\mu_2)$ > 8 GeV
DiTau: $p_T(\tau_{1,2})$ > 35 GeV, $\|\eta(\tau_{1,2})\|$<2.1, isolation, $N_{trk}(\Delta R<0.15)$<5	Include 3-prong tau decays. h→ττ measurements: i.e. spin, parity, CP measurement	25	1-prong decay (N_{trk}<3) OR "same" but $p_T(\tau_{1,2})$>30 GeV + 1 jet p_T>30 GeV

3

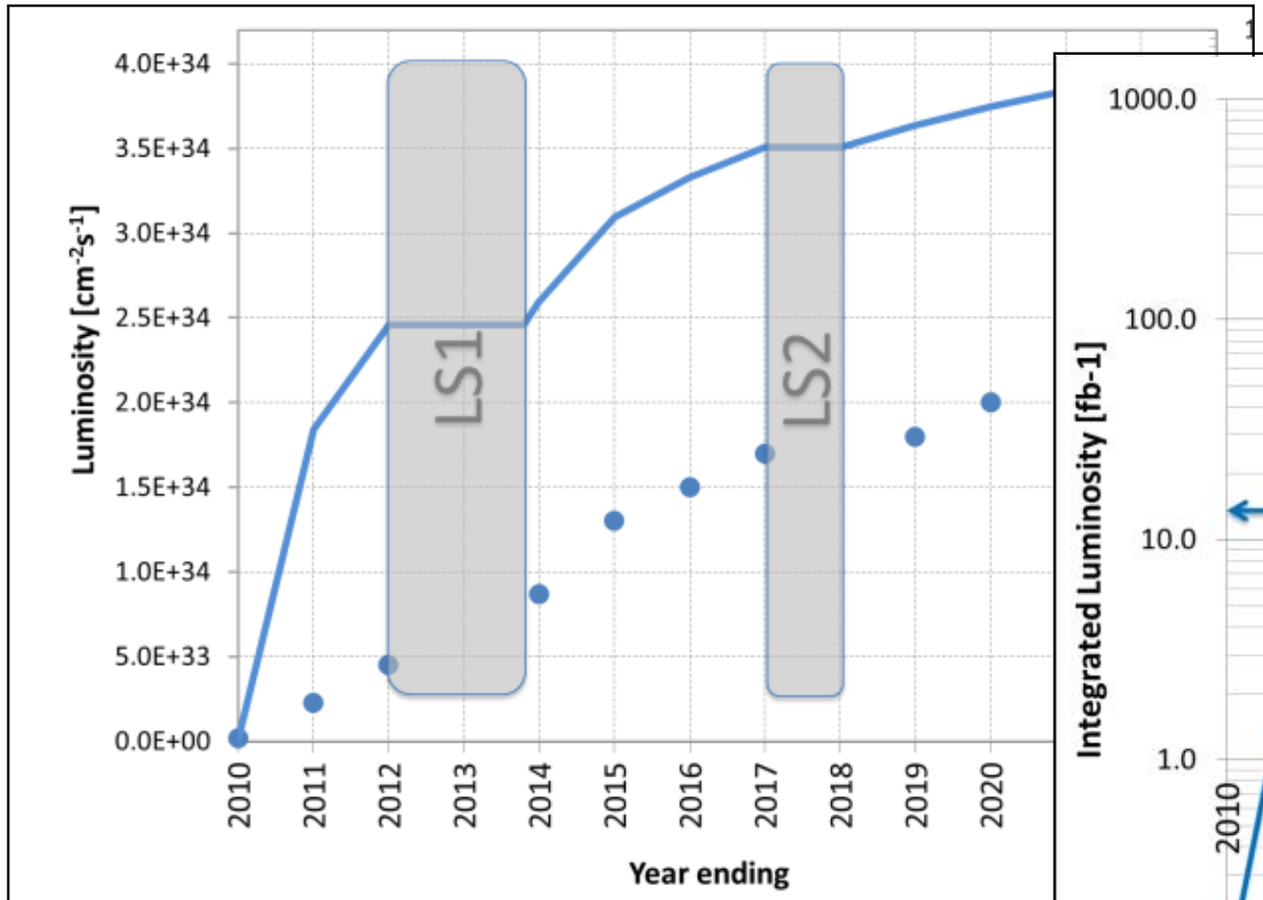
Physics Outlook: 2012-13

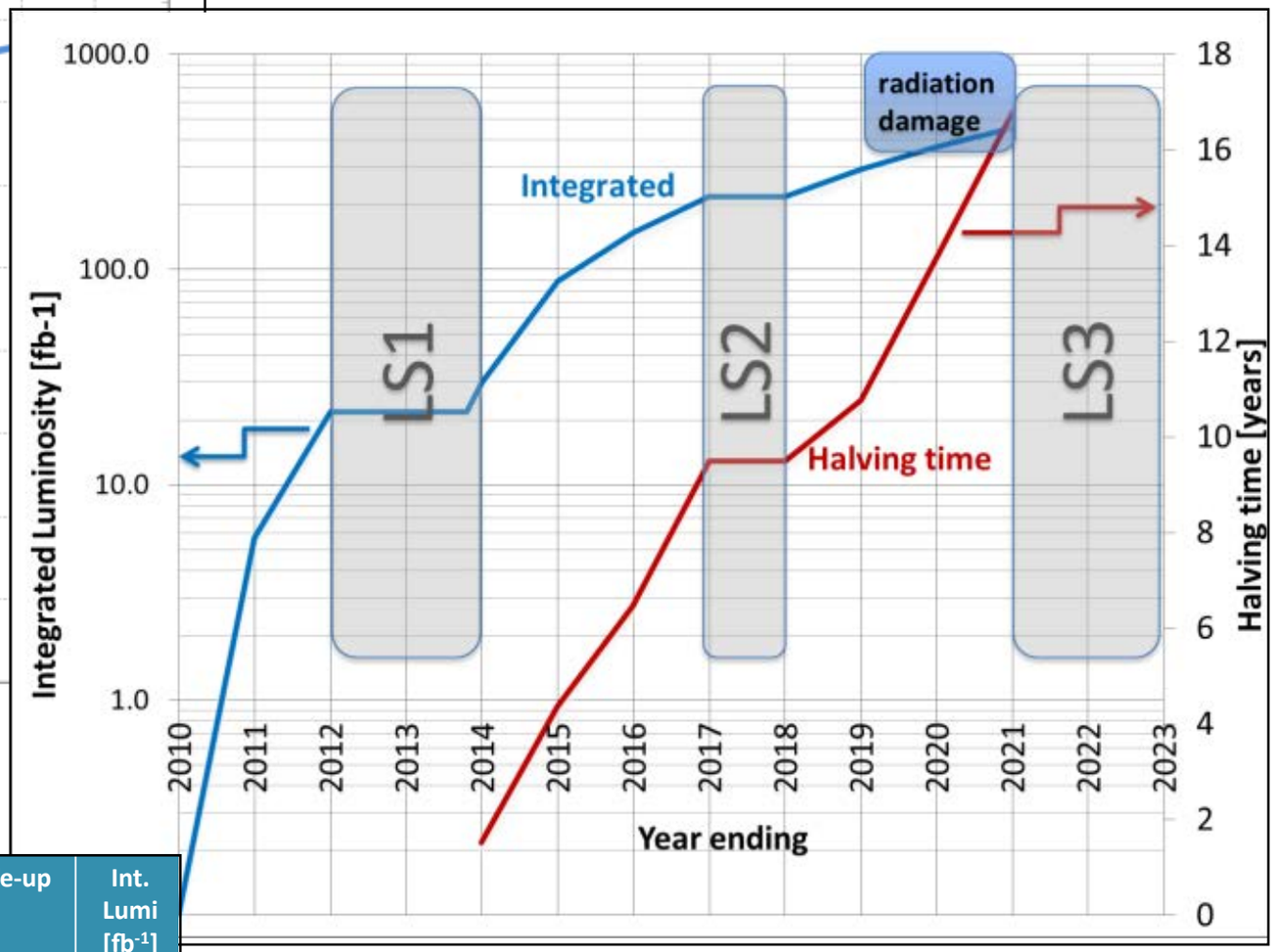
- Higgs
  - Branching fraction / cross section measurements
  - Search for exotic decays (e.g. invisible branching fraction)
  - Comprensive look at VBF production, associated production
  - Spin-parity determination (to the extent possible); Combinations
- "Attack on Naturalness"
  - Will drive our 2013 SUSY and Exotica efforts
  - SUSY: Effort toward 3rd generation searches
  - EXO: Long-lived particles
- However...
  - Maintain a broad front



- $B_s \to \mu\mu$ update also due ~end of year

LHC Evolution

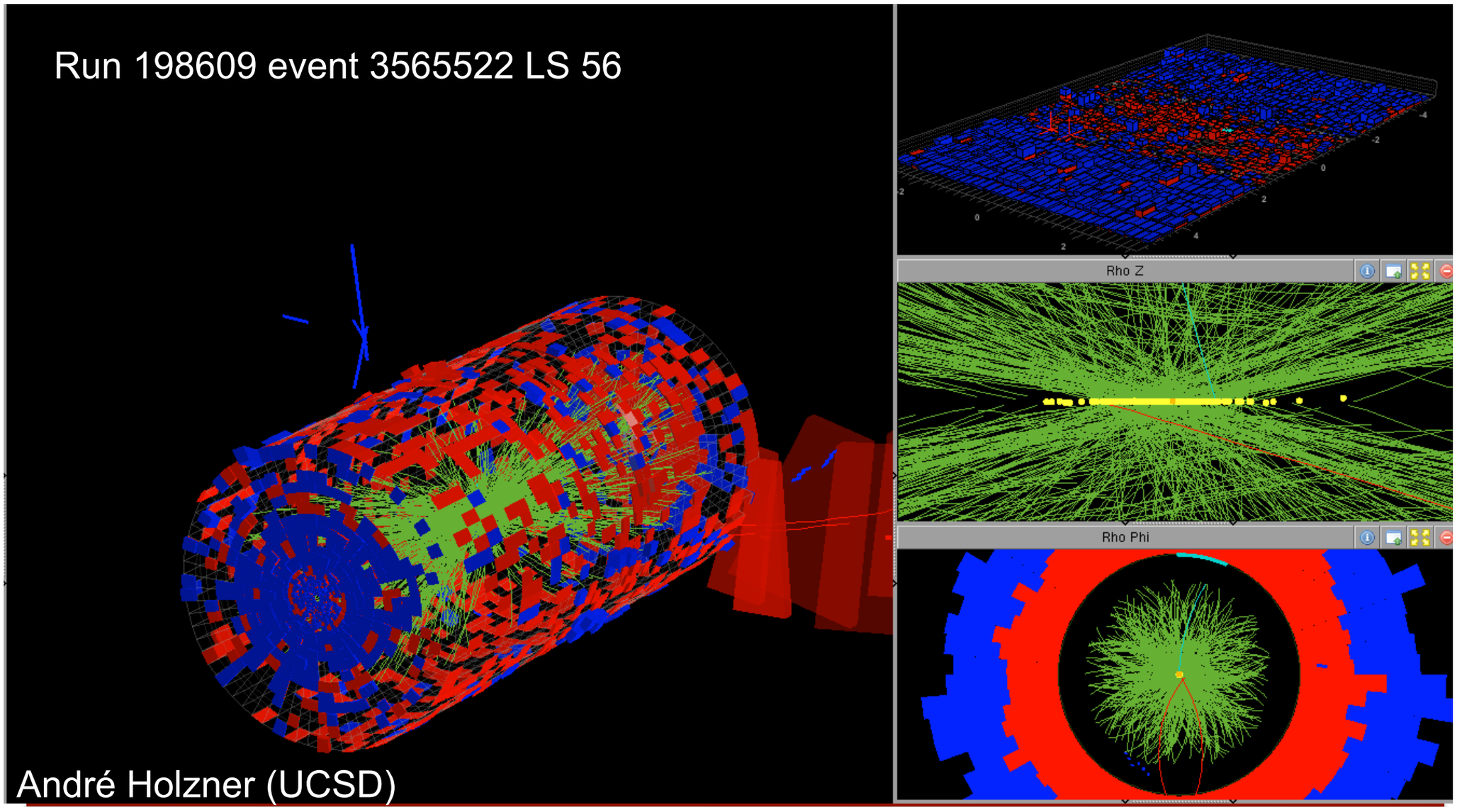




	Number of bunches	β* [m]	Half X-angle [μrad]	Ib SPS	Emit SPS [um]	Peak Lumi [cm-2s-1]	~Pile-up	Int. Lumi [fb-1]
25 ns	2800	0.50	190	1.2e11	2.8	1.1e34	23	~30
50 ns	1380	0.40	140	1.7e11	2.1	1.8e34 β* level	81 β* level	?
25 ns low emit	2600	0.40	150	1.15e11	1.4	2.0e34	48	52
50 ns low emit	1200	0.40	120	1.71e11	1.5	2.2e34	113	?

- LHC mode not yet known
  - 25ns / 50ns BS both on table for LS1 – LS2 period
  - Lumi levelling an option

A Taste of Things to Come



78 overlapping collisions!
Recorded during special high-PU fill

- 50ns currently the preferred machine option
  - Not clear if optimal for physics

CMS Upgrade Motivation

- LHC *is* the energy frontier
  - ... for the foreseeable future
  - Lifetime of apparatus is finite
  - Increase in reach with stats falls away
- The problem
  - What does nature have in store?
  - Design / construction took ten years
    - More difficult than the first time around

H properties & couplings

Fine-tuning mechanism? Or not?

SUSY spectrum measurements?

High mass GUT signals (Z', KK)?

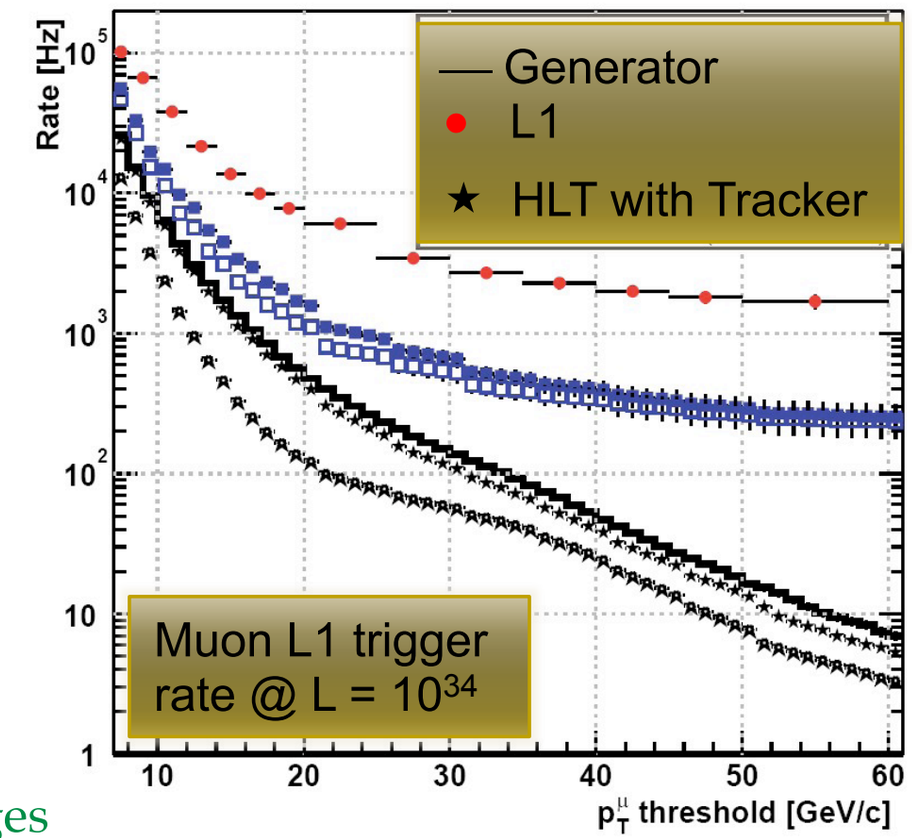
Long-lived particles?

Huge stats required in each case

- Some guiding principles and lessons
  - All-hadronic signals will likely become buried
  - Third-generation objects will continue to be important
  - Inclusive high-mass searches will continue, no matter what
  - Trigger performance (mainly at L1) is *the* key issue
    - Energy scale of final state objects still set by ESB scale and W, Z mass
    - Compromises between pileup and increased stats need to be carefully examined

Trigger and Computing

- Basic CMS L1 trigger strategy
  - e, mu, tau, gamma, jets; above threshold
    - Thresholds become unsustainably high
  - Use isolation where possible
    - Simple isolation cones contaminated by PU
  - Trigger on global event variables
    - Noise becomes too high for stand-alone triggers
  - Use of topological, kinematic info
    - Not much used – will become very important now
    - Improve quality of objects entering global trigger stages



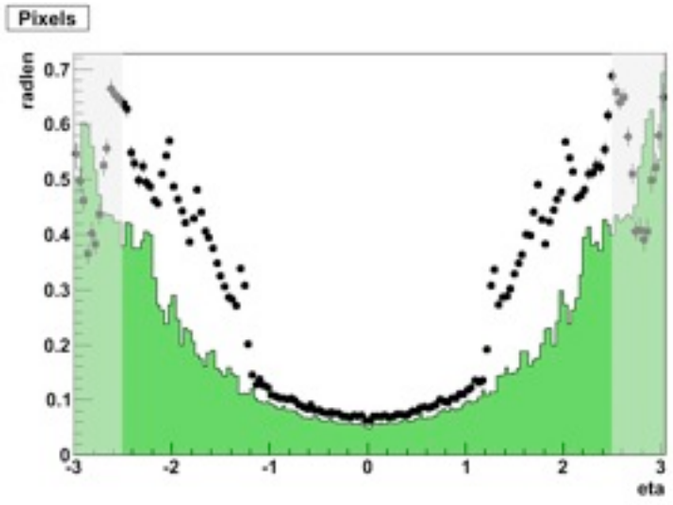
- Computing
  - End of 2012: 4.5Gevt core sample, 2.5Gevt parked sample, 10.5Gevt MC
  - Can reprocess approximately 1Gevt per month at T1 / T2
    - 'Luxury computing model' is over; revert to the CDF / D0 style of working
- Both these factors imply that strong *choices* will be made...
  - Target the most important studies – some things will be inaccessible

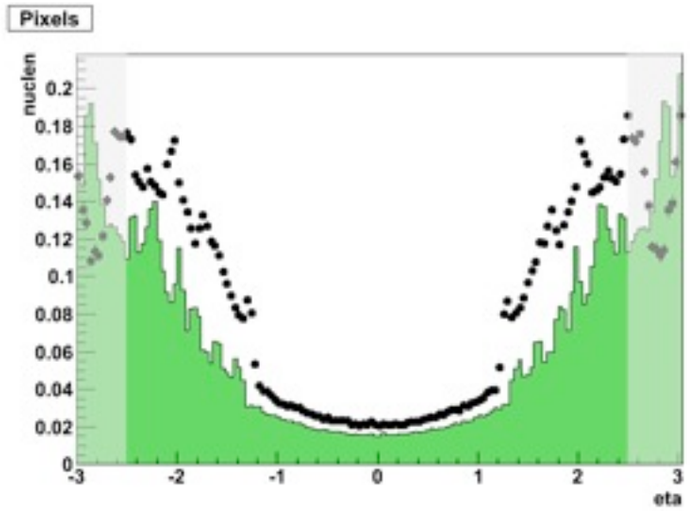
Detector Upgrade Planning

- Technical goals for 'Super-CMS'
  - Replacement of failed / end-of-life subsystems
  - Restoration of 'high luminosity detector'
  - Consolidation and updating of electronics
  - Preservation of trigger performance

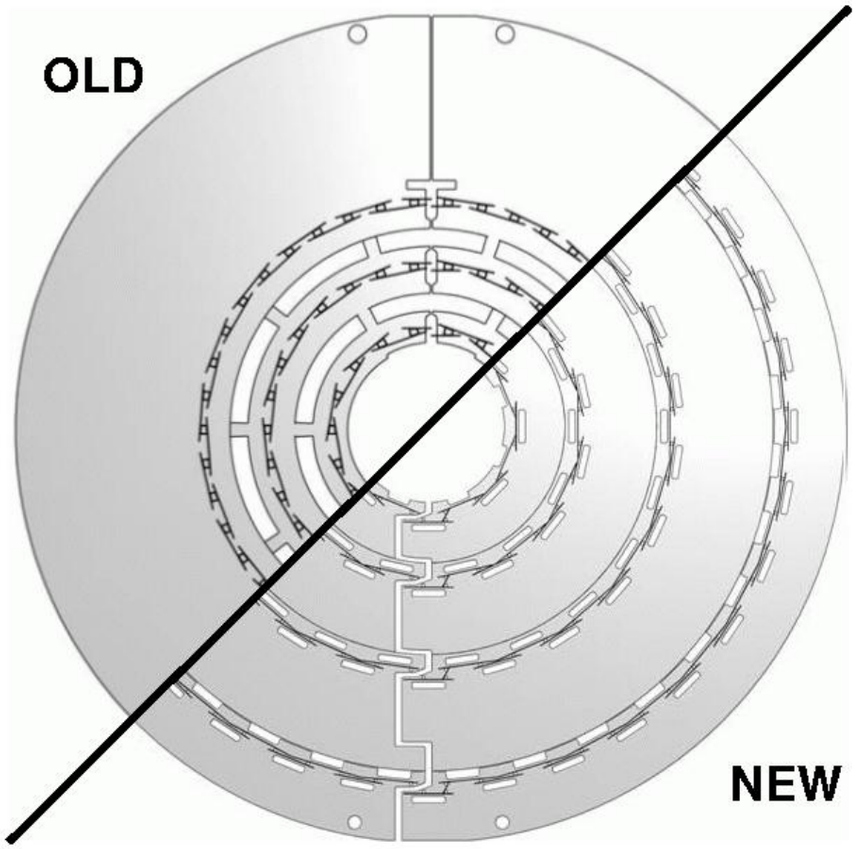
- Multi-phase programme (alongside running in some cases)
  - 2013-4: High-lumi muons, HCAL pilot; pixel pilot; L1 optical infrastucture
  - 2015-6: Replacement of L1 trigger system (brought forward)
  - 2017-8: New pixels, new HCAL photodetectors, new L1 trigger
  - 2022+: New silicon tracker; L1 track trigger; new forward detectors?
- DAQ and computing systems are continuously upgraded
- Physics impact documented in subsystem TDRs
  - There is of course no single 'killer case' for the upgrade
  - We will of course optimise some decisions (L1...) based on results

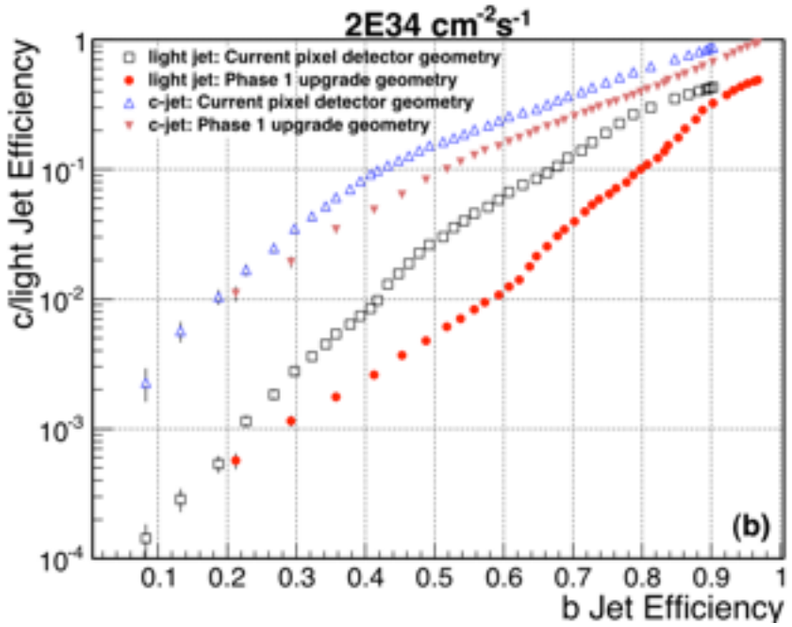
UK Upgrade Plans: Pixels





Plots produced with UK software



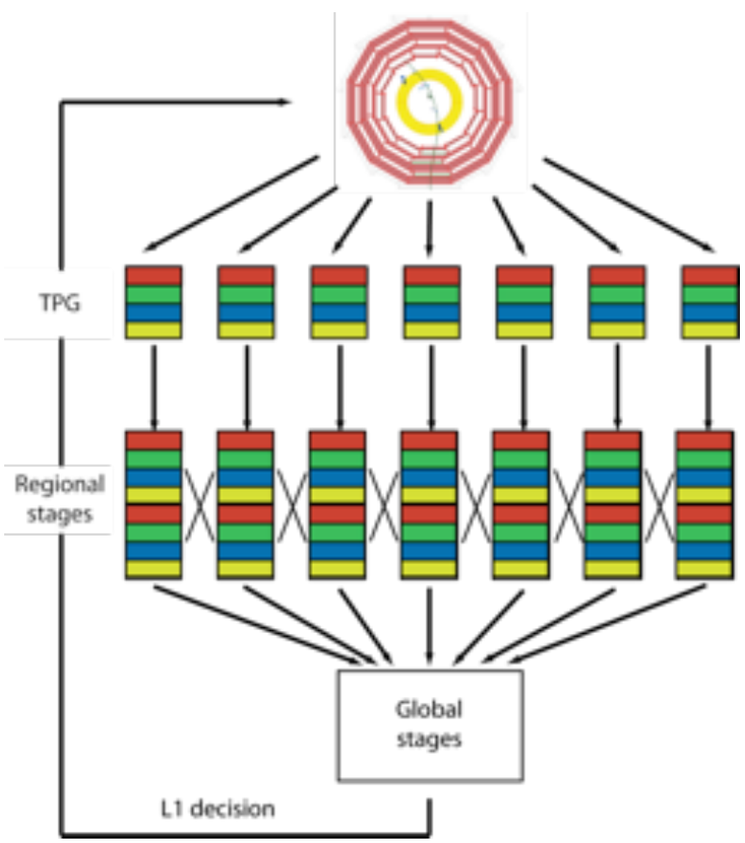


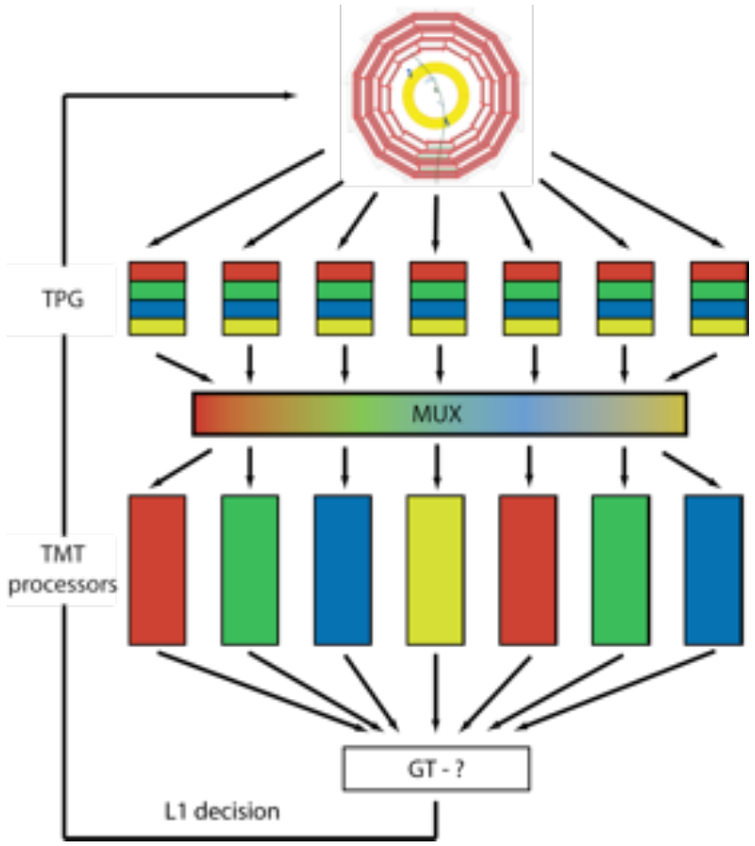
20% gain in b-jet tag efficiency for constant 1% mistag probability

- Pixels can be replaced independently of inner detector
  - Additional 4th barrel / 3rd e.c. layer; CO2 cooling; fully digital readout
  - UK contribution: upgrade of the entire readout and control system

UK Upgrade Plans: L1 Trigger

Pipelined architecture

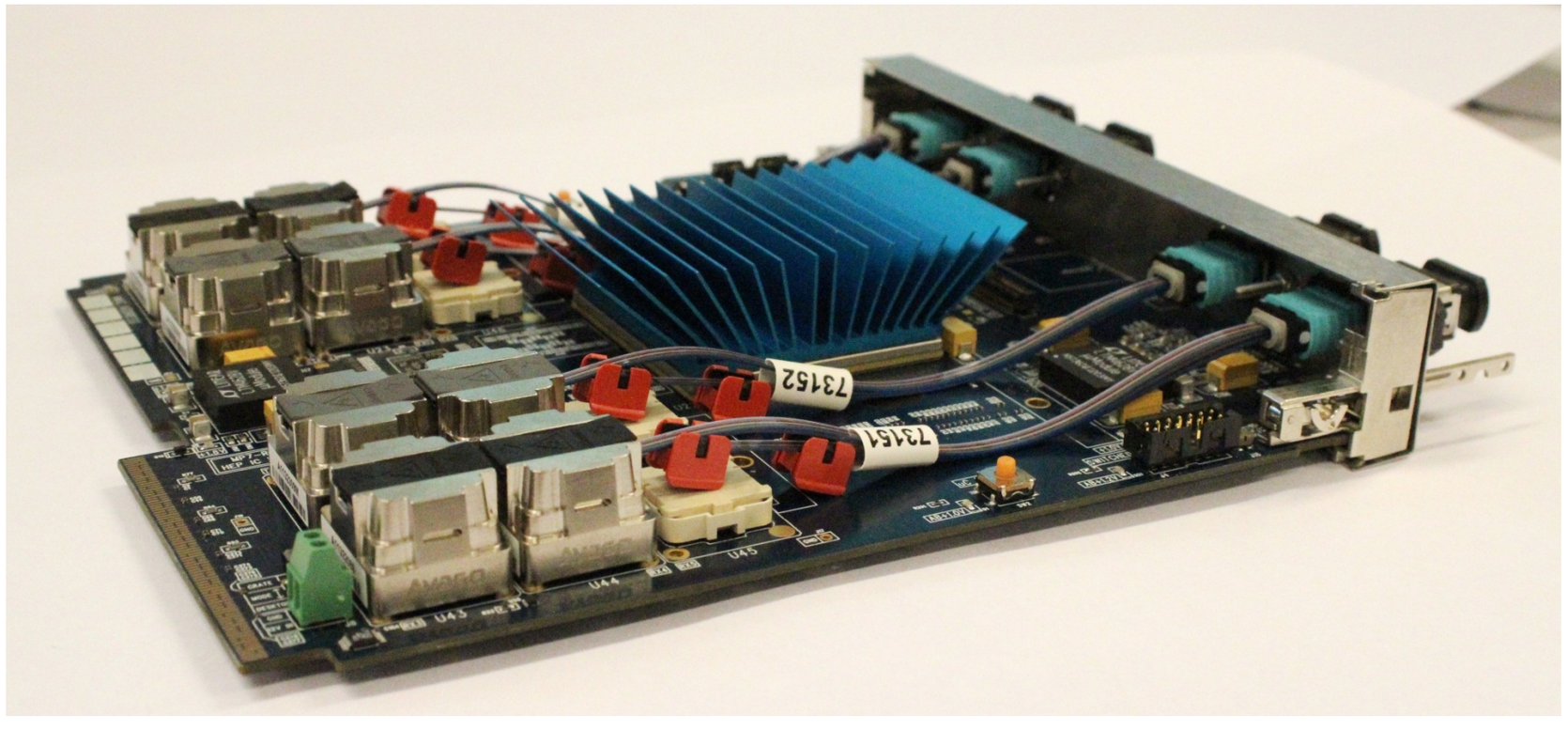




Time-muxed architecture

- Maintain or improve L1 performance at high PU
  - Make full use of all information available from the detector
  - Some additional information available from muons, HCAL, later
- Time-multiplexed concept for L1 calorimeter trigger
  - Allows much greater flexibility, redundancy, cross-subsystem algorithms
  - Paves the way for inclusion of tracking information later on

UK Upgrade Plans: Hardware Development



- MP7 card is the building block for L1 and pixel systems
  - Large Virtex-7 series FPGA (700k logic cells); 144Mb fast RAM
  - 1.4Tb/s of low-latency IO on optical links; 50Gb/s backplane IO
  - Fully integrated into uTCA software / hardware environment
- Variety of trigger / DAQ architectures can be constructed
  - Production funds for upgrade sought via PPRP – this week
  - New L1 commissioning *in parallel* with existing system during 2015 run

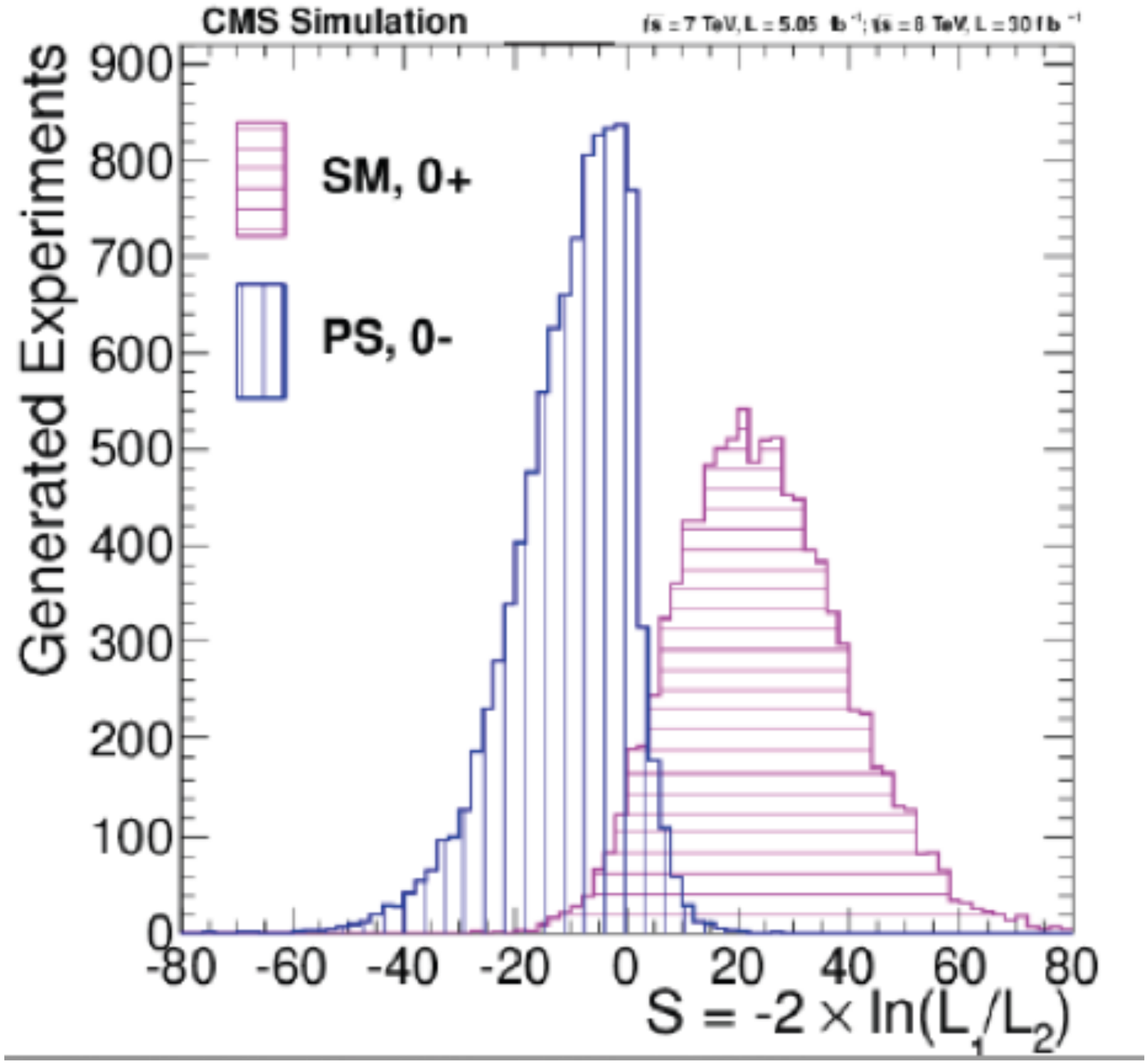
Conclusions

- An excellent start to the LHC programme
  - Accelerator performing beyond expectations
  - CMS detector is reliable and above expected performance
  - No serious technical issues so far – but much care and planning needed
- Physics
  - The first major discovery made – ahead of time!
  - A huge programme of detailed work unfolds before us
  - The ‘attack on naturalness’ is a primary topic for 2012/13
  - The pace of work will not slacken during the shutdown
- Upgrades
  - Progressive upgrades to key CMS subsystems – much to do in LS1
  - L1 trigger probably the most important and challenging area
  - Must maintain the capability for a broad range of physics
- UK has leading roles in physics, operations and upgrades

Backup

Higgs: Spin-Parity

- Projection to 30/fb

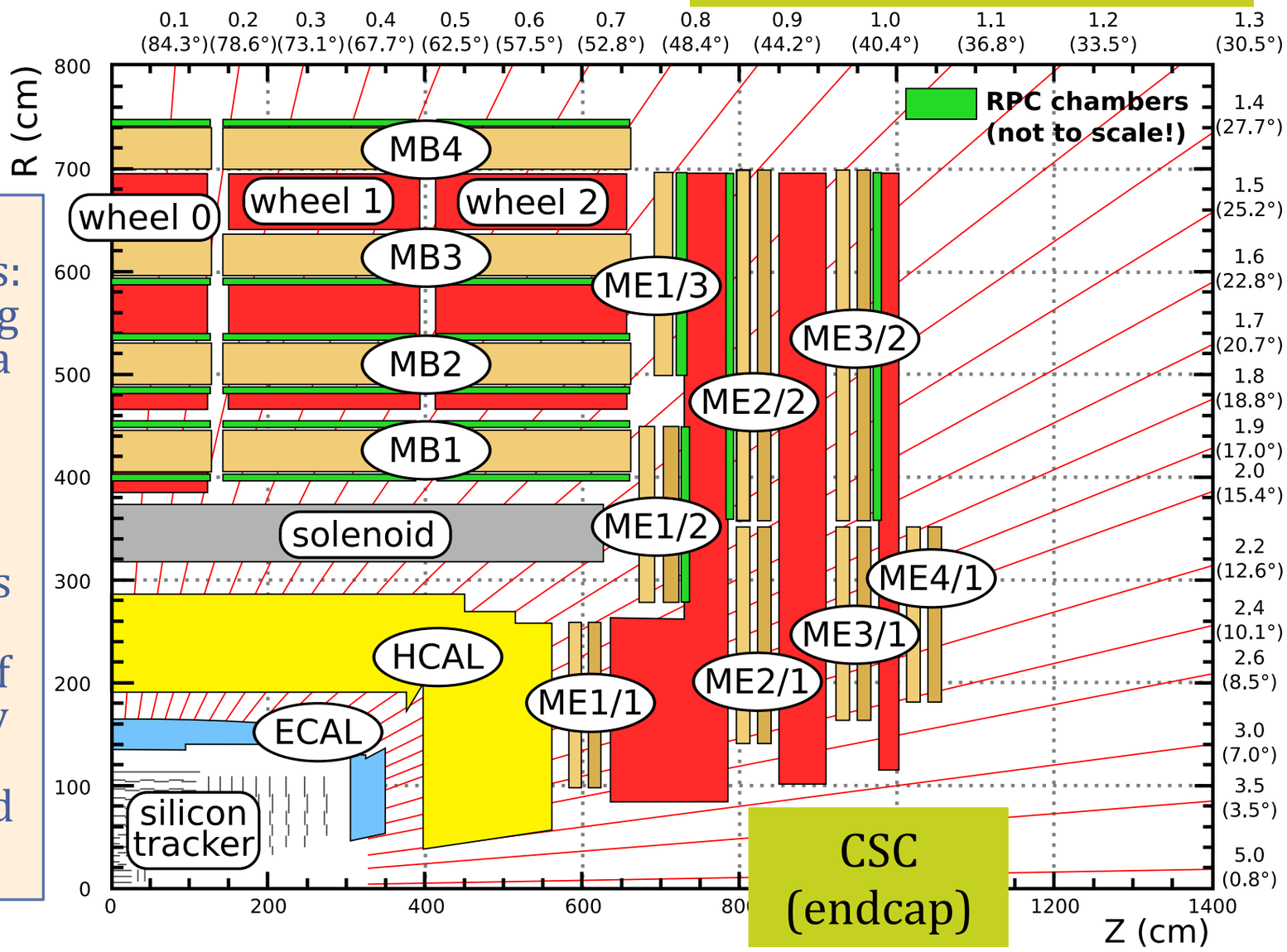


Muons to 2020

RPC (barrel and endcap)

New RE4 RPC

DT (barrel)



New ME4/2 CSC

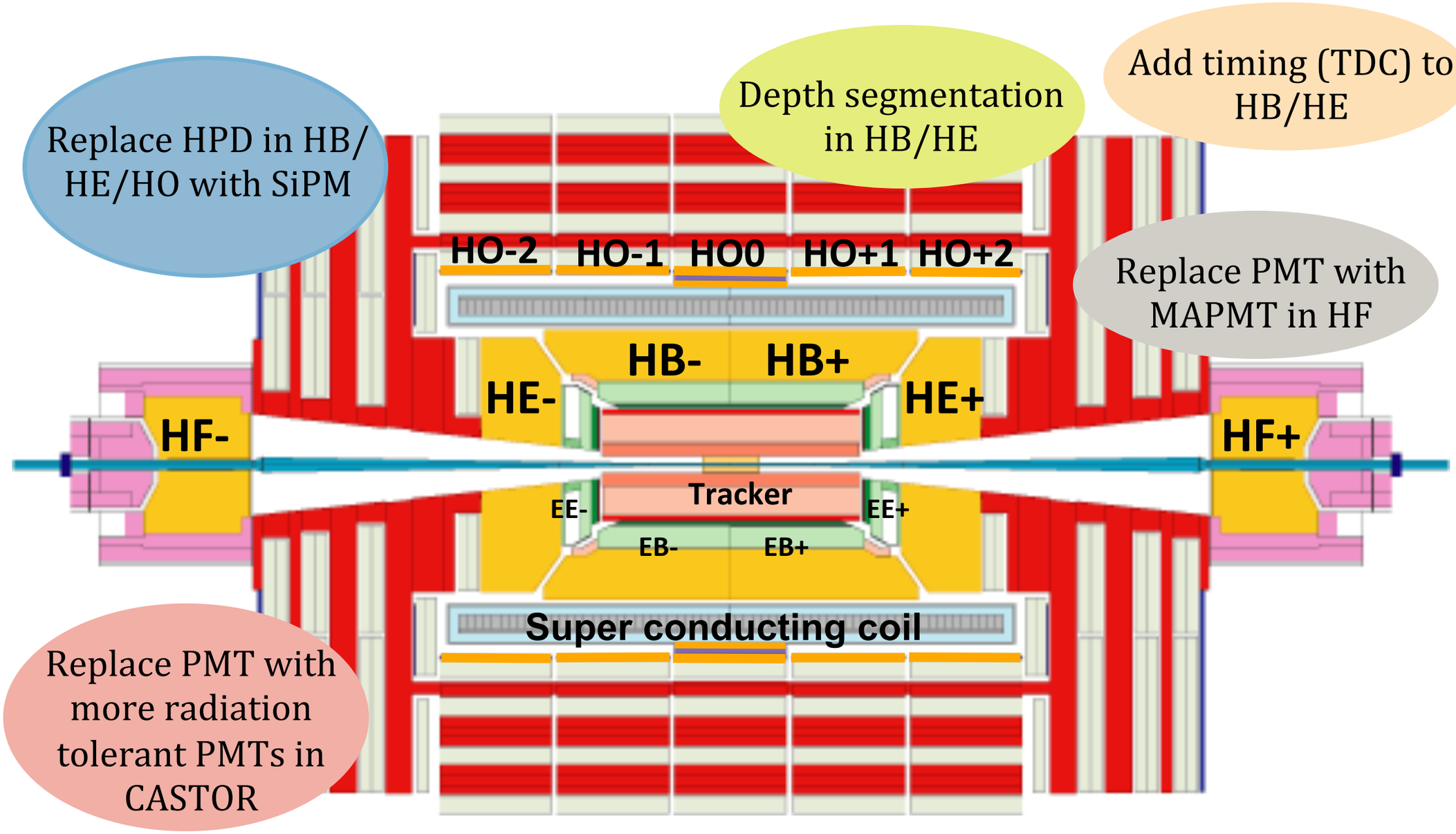
Work on DT trigger boards: Replace failing ASICs in theta boards with FPGAs (improves resolution); recover ASICs for spares; move parts of trigger to low radiation/ magnetic field region

Work on ME1/1 and trigger

Extend eta range of RPC

- Performance improvements & trigger / tracking robustness against high luminosity

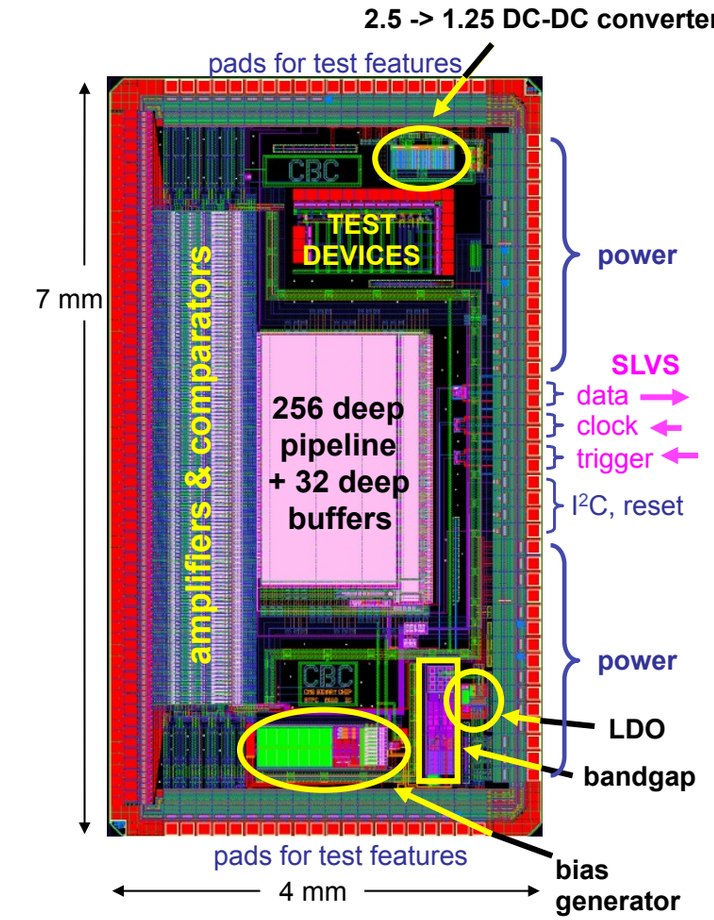
HCAL to 2020

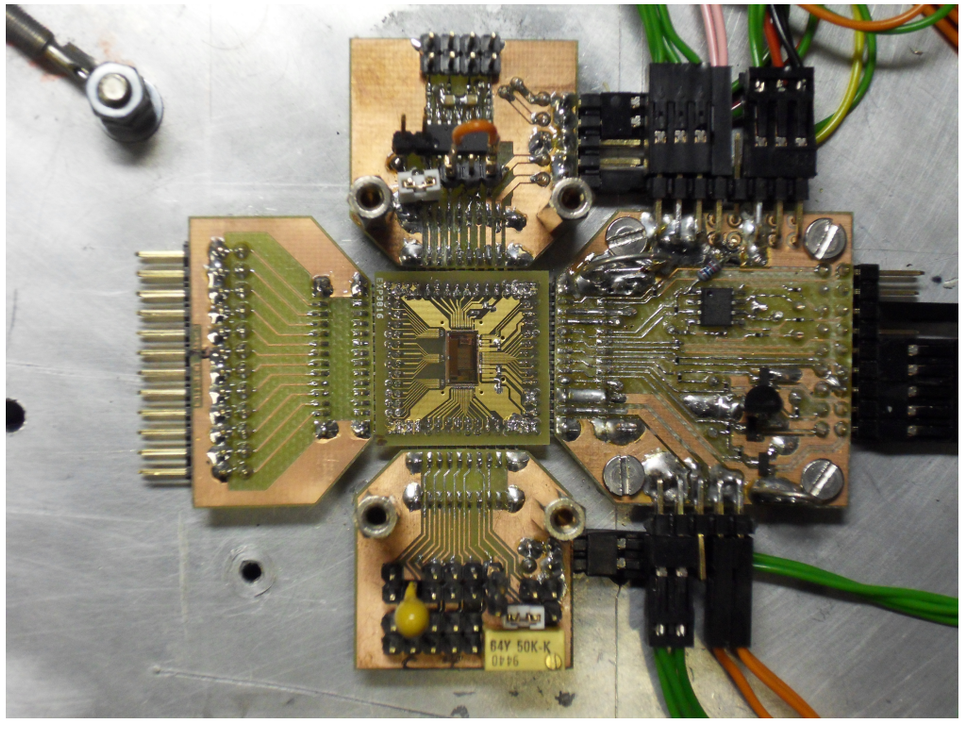


- Replacement of noisy HPDs, addition of depth segmentation to combat light loss
- Adds robustness for both trigger and offline analysis

UK: CBC Readout ASIC

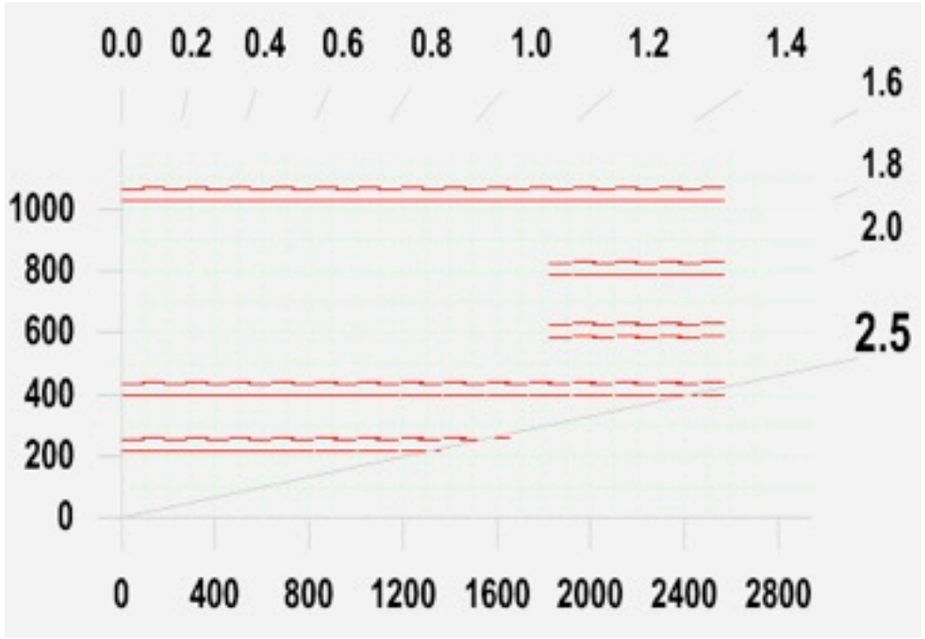
- Phase-2 tracker technical drivers
  - Channel count increases substantially
  - Existing services cannot be replaced
  - Power, readout b/w are critical
- CBC
  - Short-strip unsparsified binary readout
  - 0.5mW/ch; DC-DC converter included

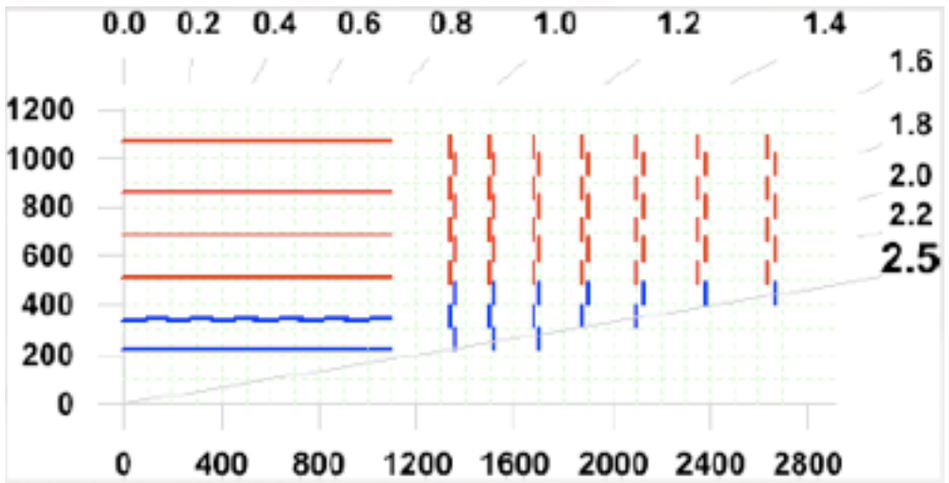




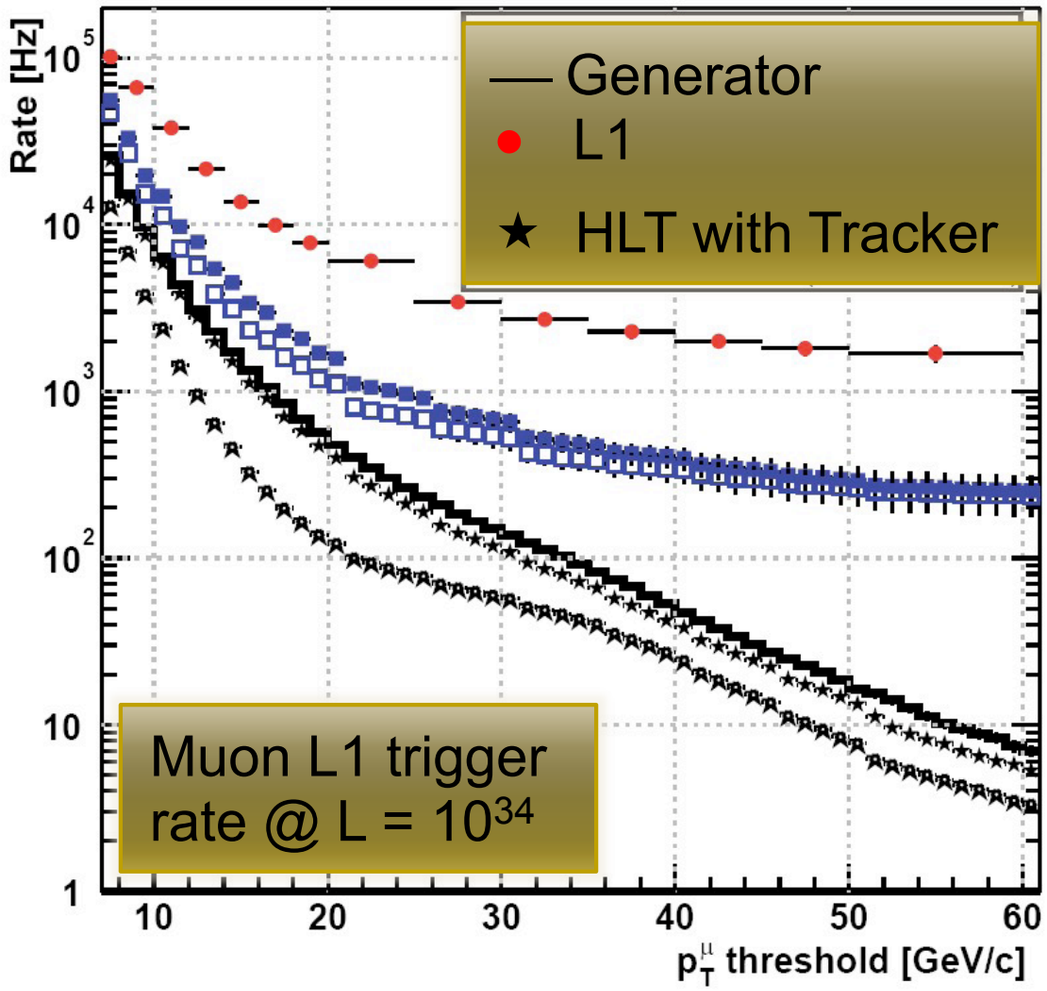
- Current prototype
  - 130nm, 128 channels
  - Chip under study at UK institutes
    - Early results are very positive
    - An extensive test programme awaits
  - Future developments
    - Bump bonded version ; Trigger functionality?

Tracker Replacement





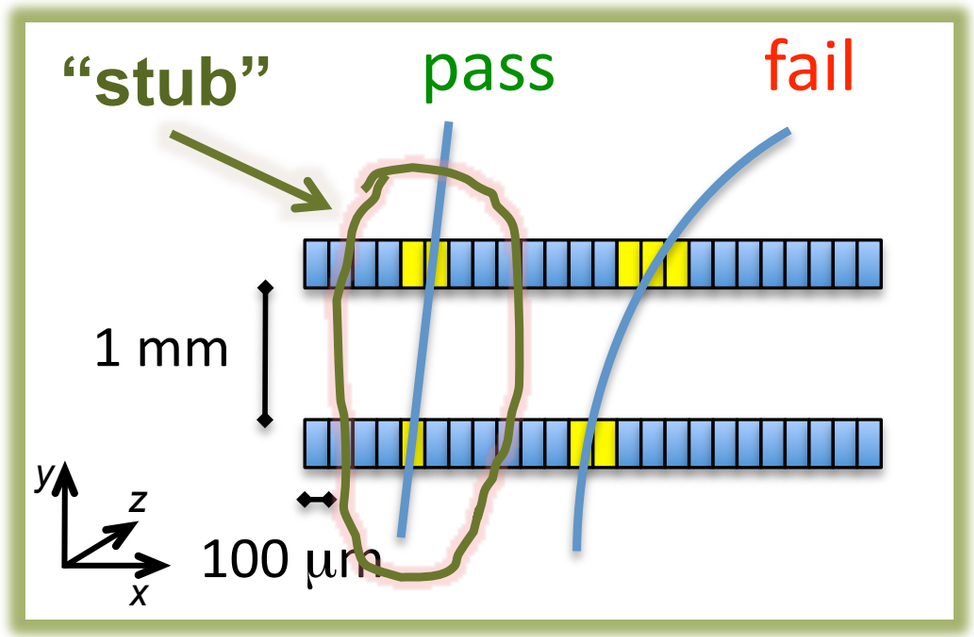
Red Layers = Pt Modules
For Tracking Triggers



- Inner tracker replacement at Phase-2 (2020+)
  - Improvements in granularity to cope with >10^35 luminosity
  - Tracking into L1 trigger; moderate threshold increase at constant rate

Track Trigger

- Requirements on upgrade tracker:
  - High granularity; low power; low material
  - Power, cooling is constrained
  - L1 functionality appears to be vital
  - Vast R&D programme required
- Potential long-term UK contribution
  - Original UK proposal for 'stacked' trigger
  - Expertise in strip readout devices & DAQ
    - Previous UK responsibility in CMS construction
  - Expertise in trigger algorithms and simulation
  - Expertise in trigger and readout electronics
    - Including construction and integration of Phase-1 L1 upgrade
  - A contribution to pixels upgrade also helps pave the way
- Long term goal: major responsibility for track trigger
  - UK leadership seems a realistic prospect if the resources are available



'Stacked tracking' trigger concept, originated in UK