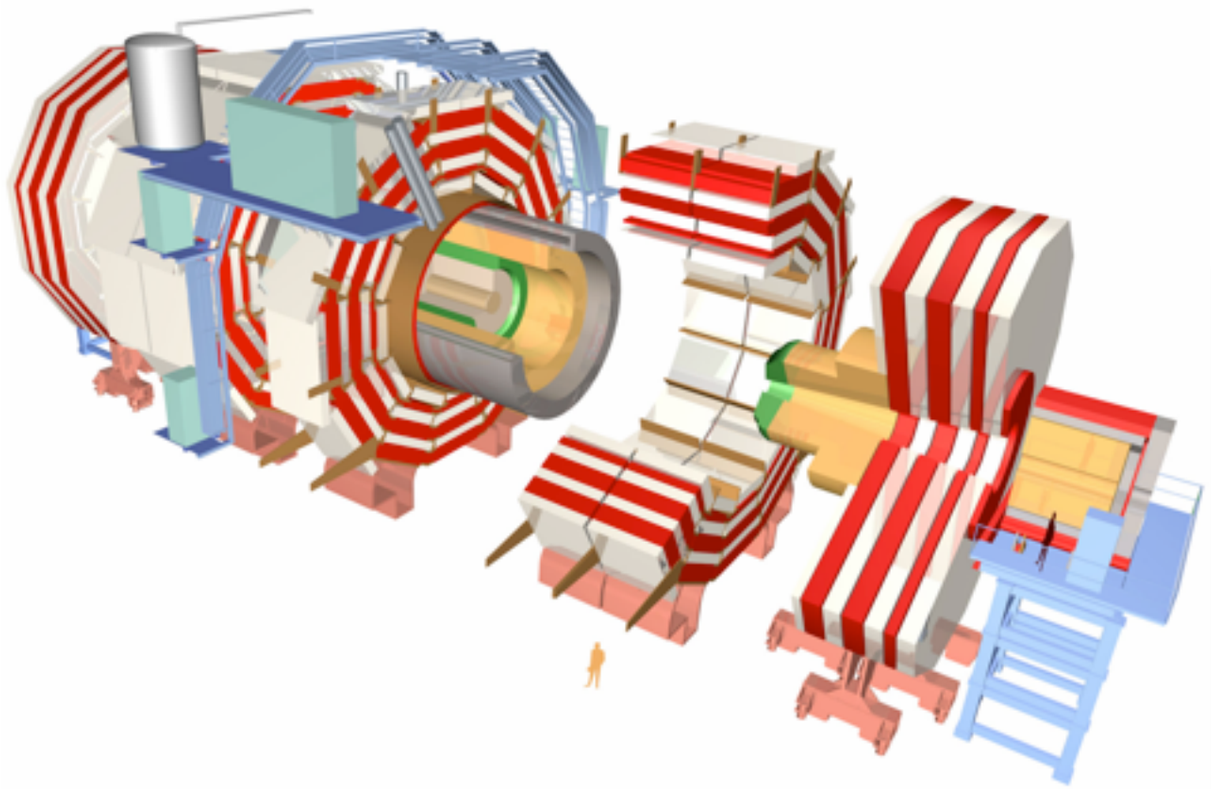
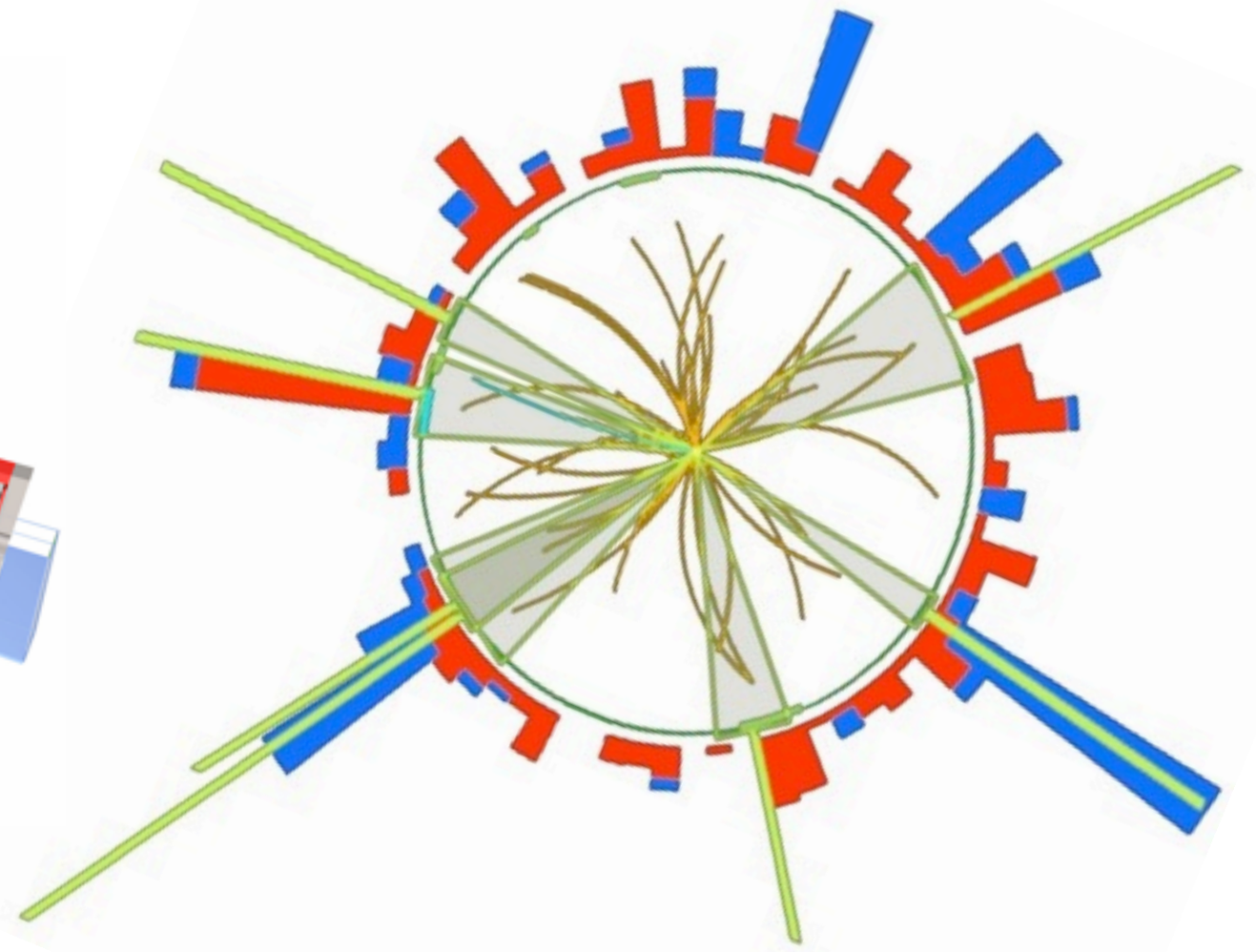
CMS: Today, Tomorrow and the Next Decade

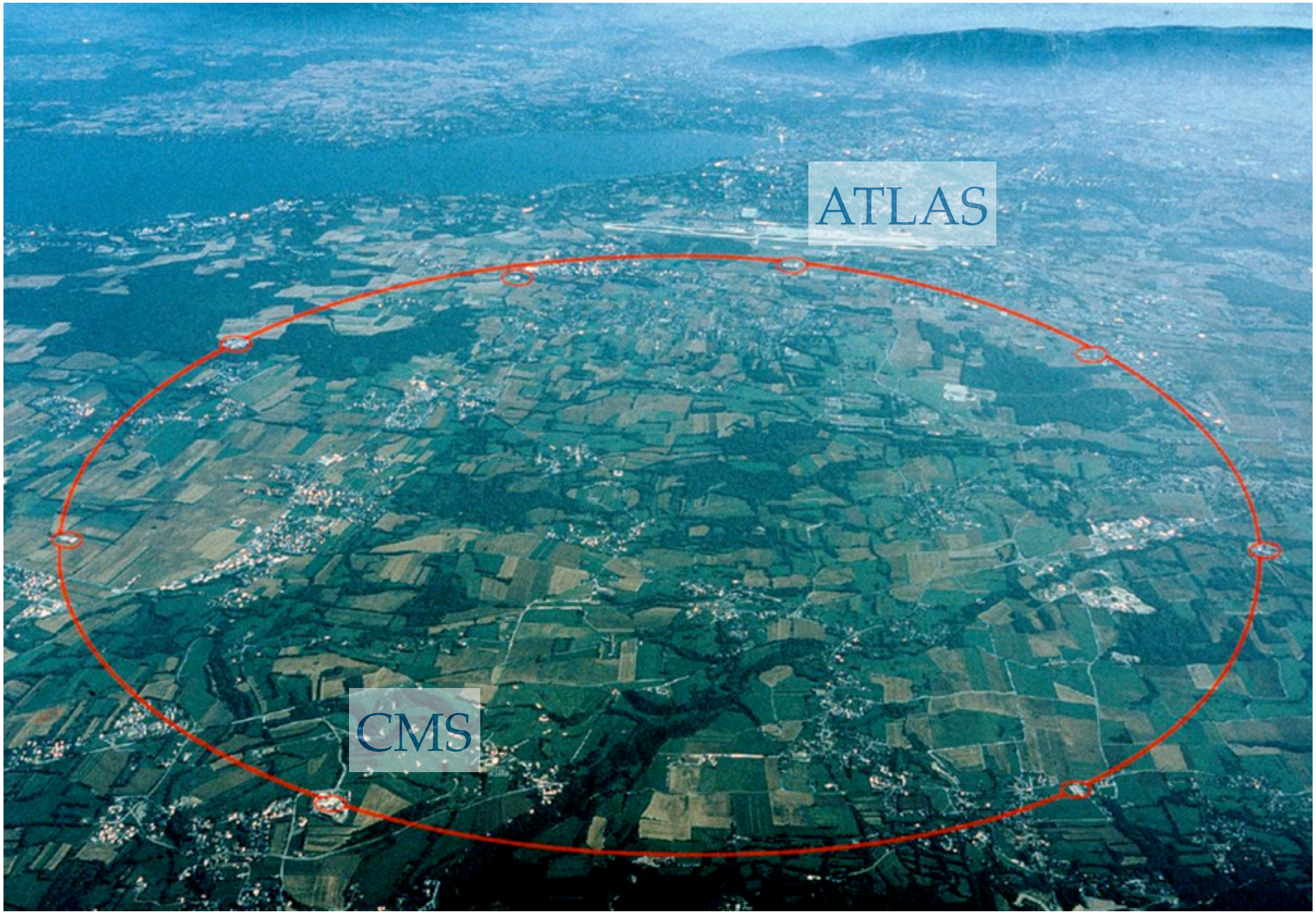
Dave Newbold – University of Bristol





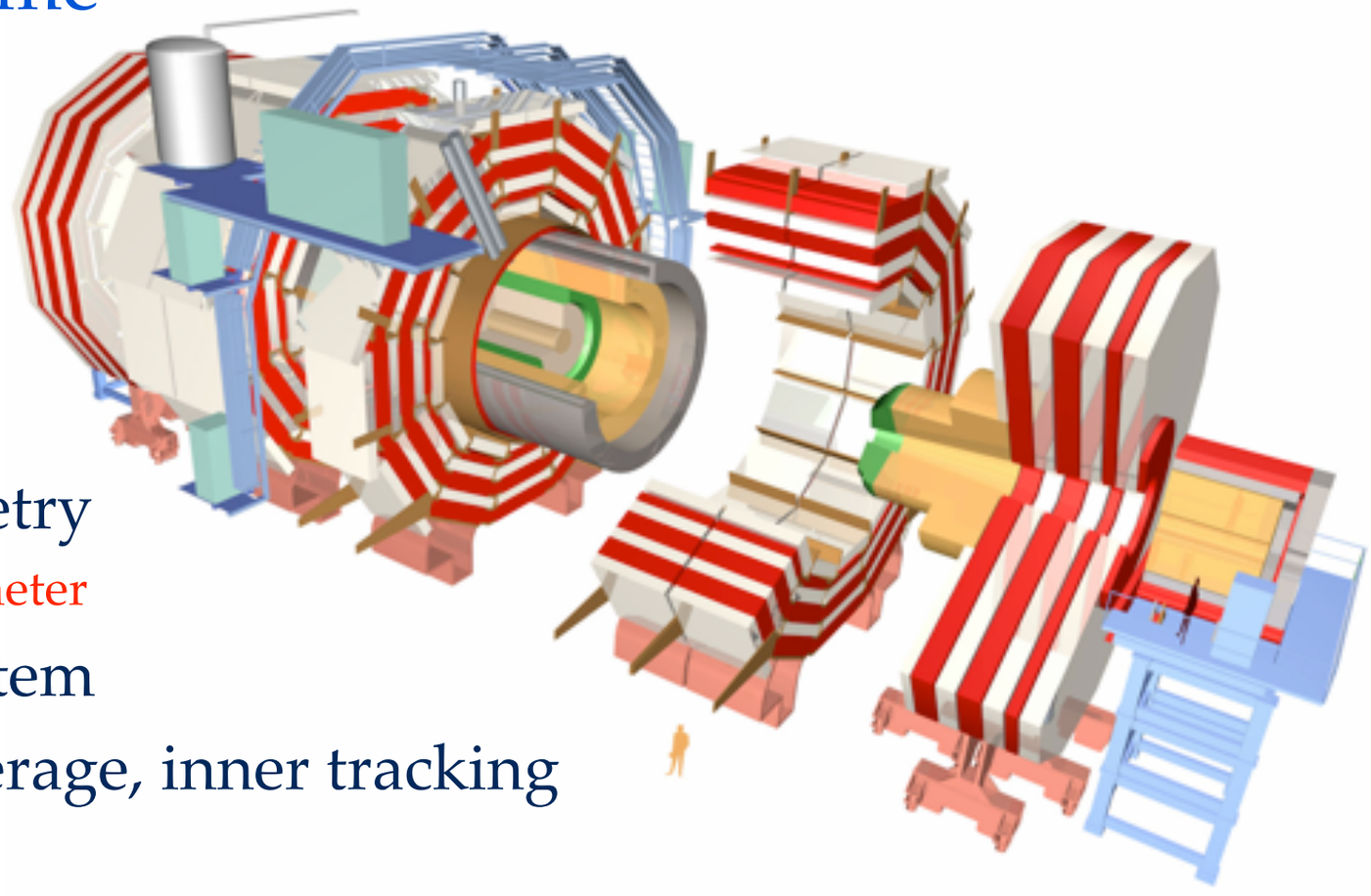
University of Birmingham, March 2013

"You are Here"



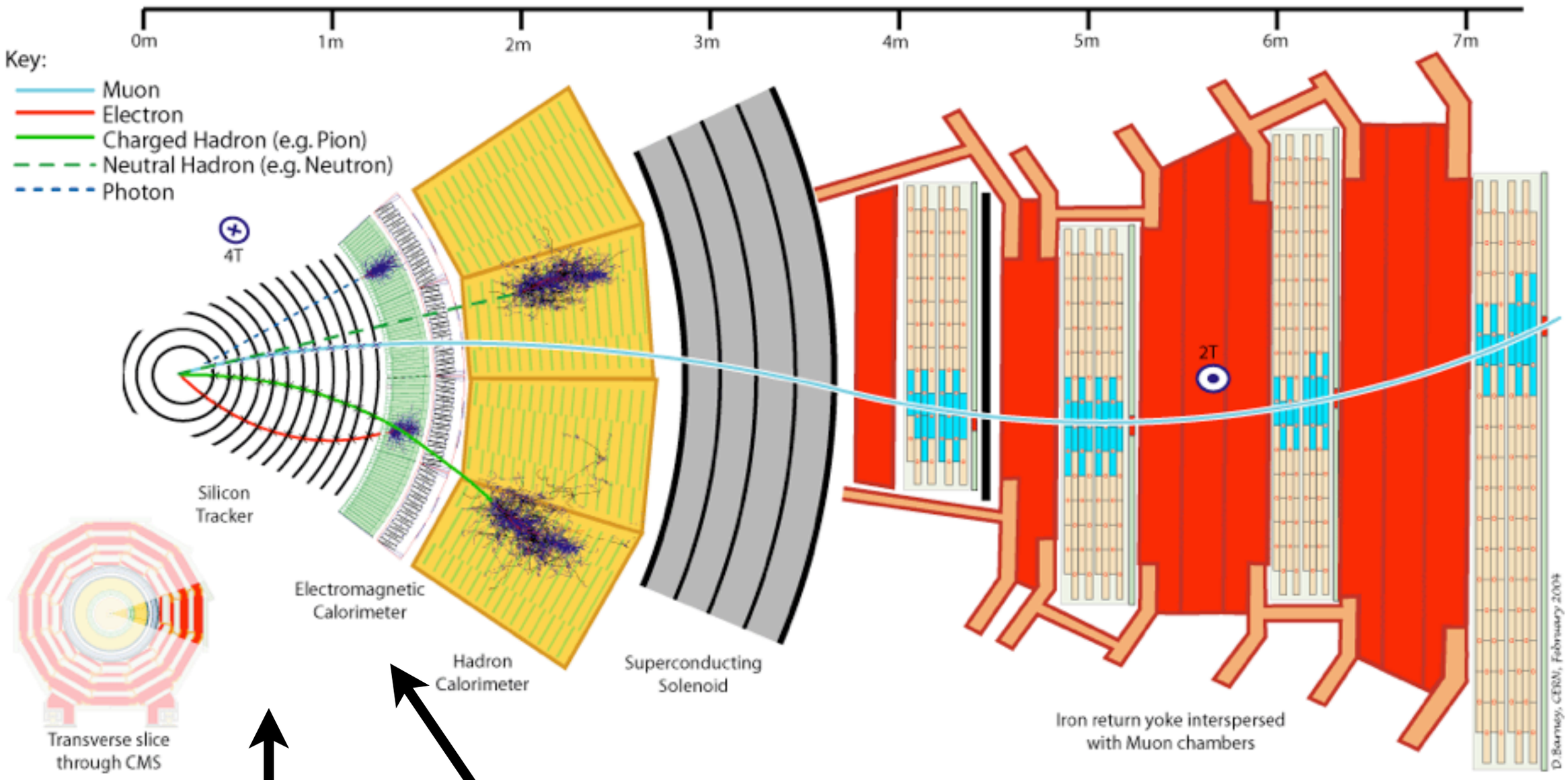
CMS Goals and Design

- General-purpose detector for LHC
  - Wide range of energy frontier and heavy ion physics
- Comprehensive programme
  - EWSB & TeV-scale physics
  - Direct BSM searches
  - (Some) QCD & flavour



- Detector characteristics
  - Hermetic, high-resn 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)

CMS Layout



Silicon strip tracker

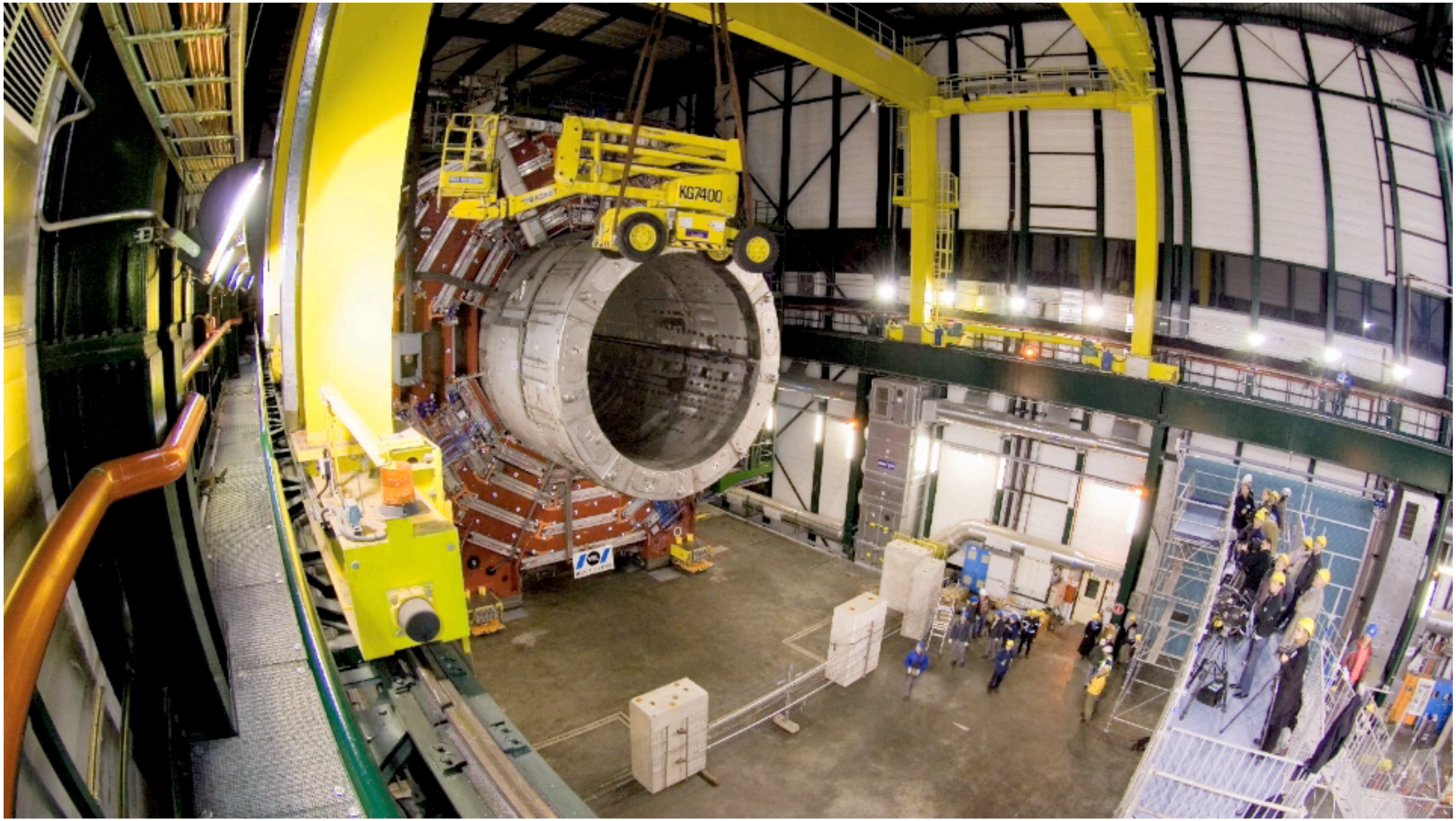
EM calorimeter (endcaps)

L1 trigger + DAQ

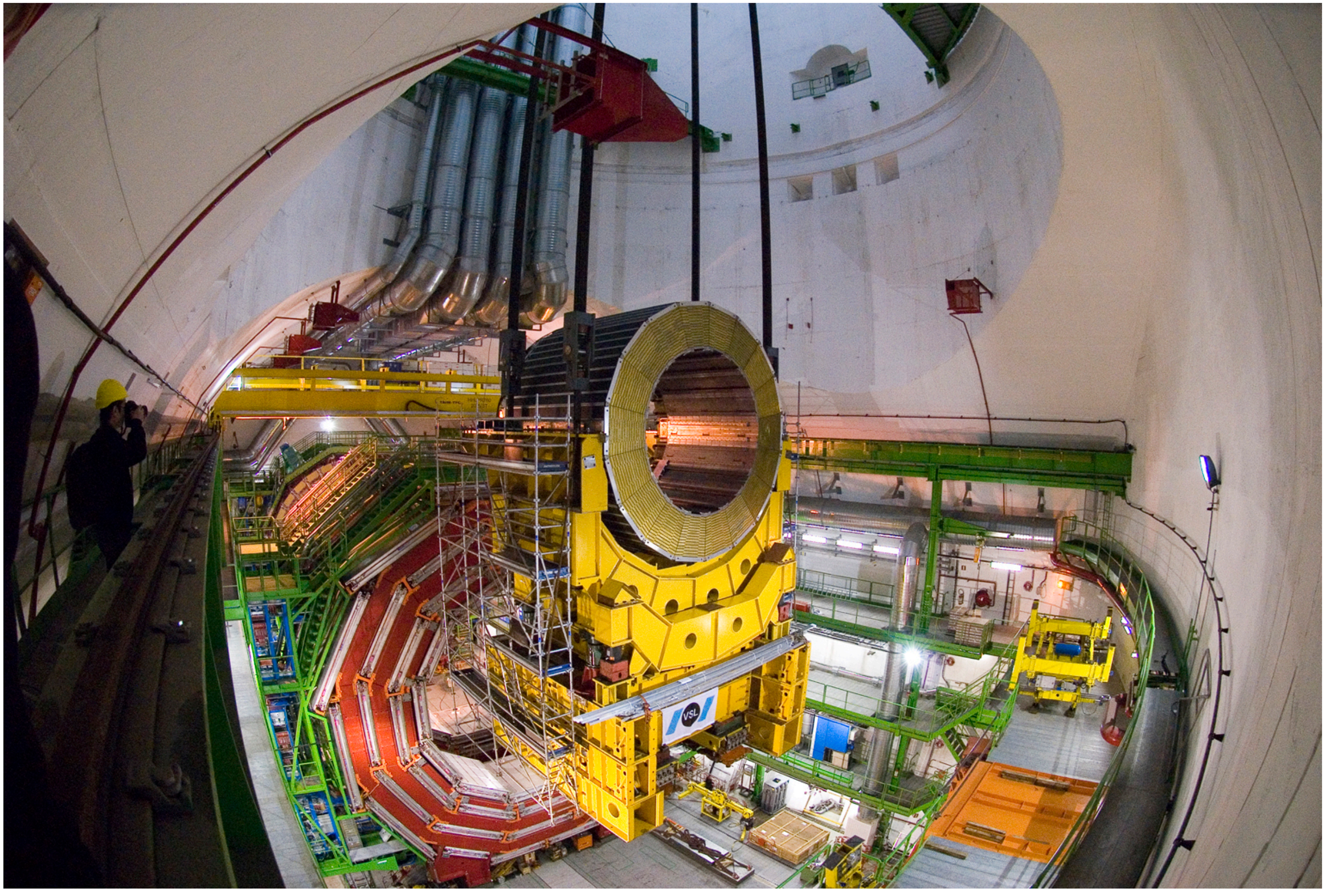
Computing system

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

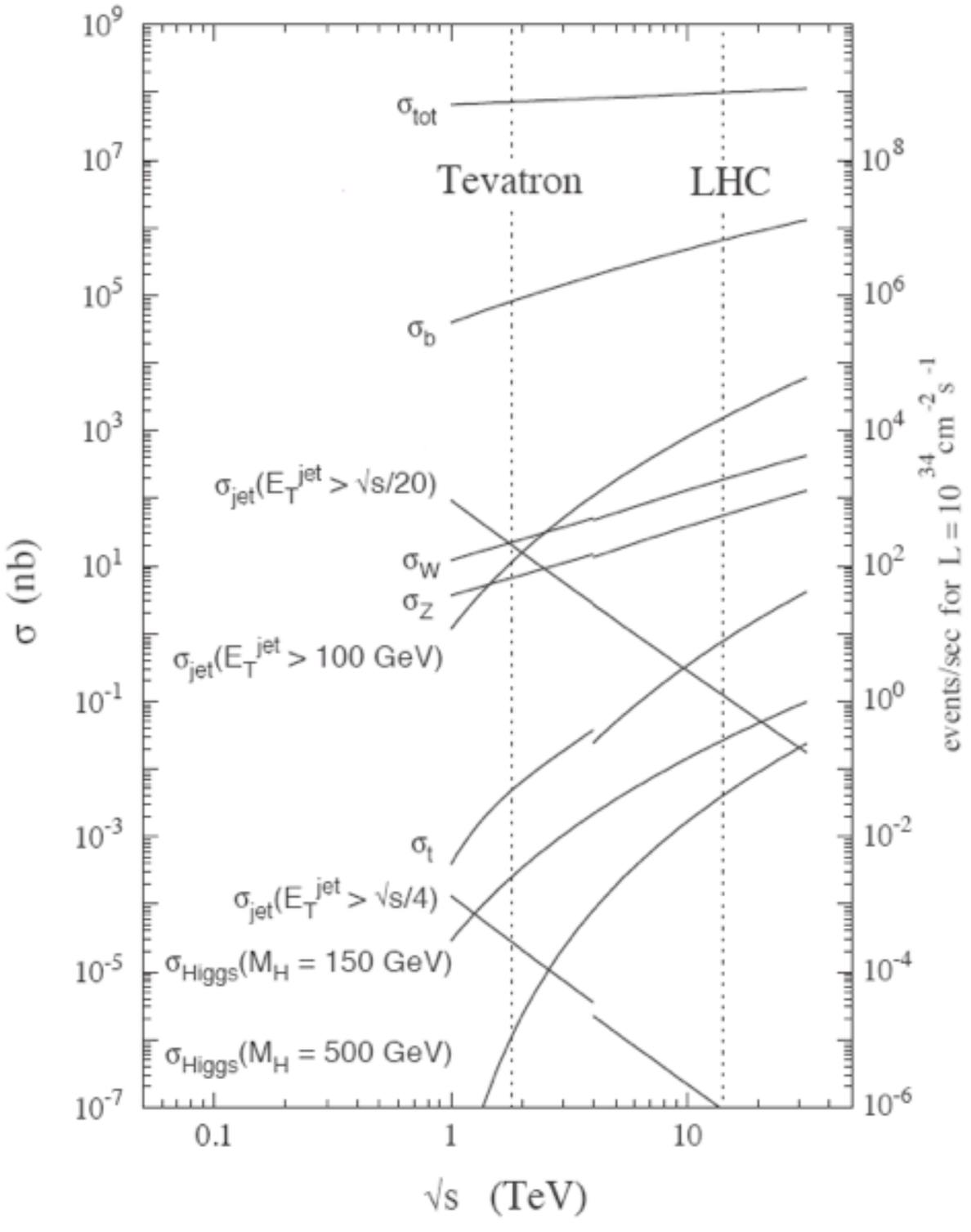
Lowering



Five Years Ago



CMS Programme



Alignment, commissioning — 2008

QCD, calib, MC tune — 2009

First W / Z; energy scale — 2010

First top

W', Z' search; first SUSY

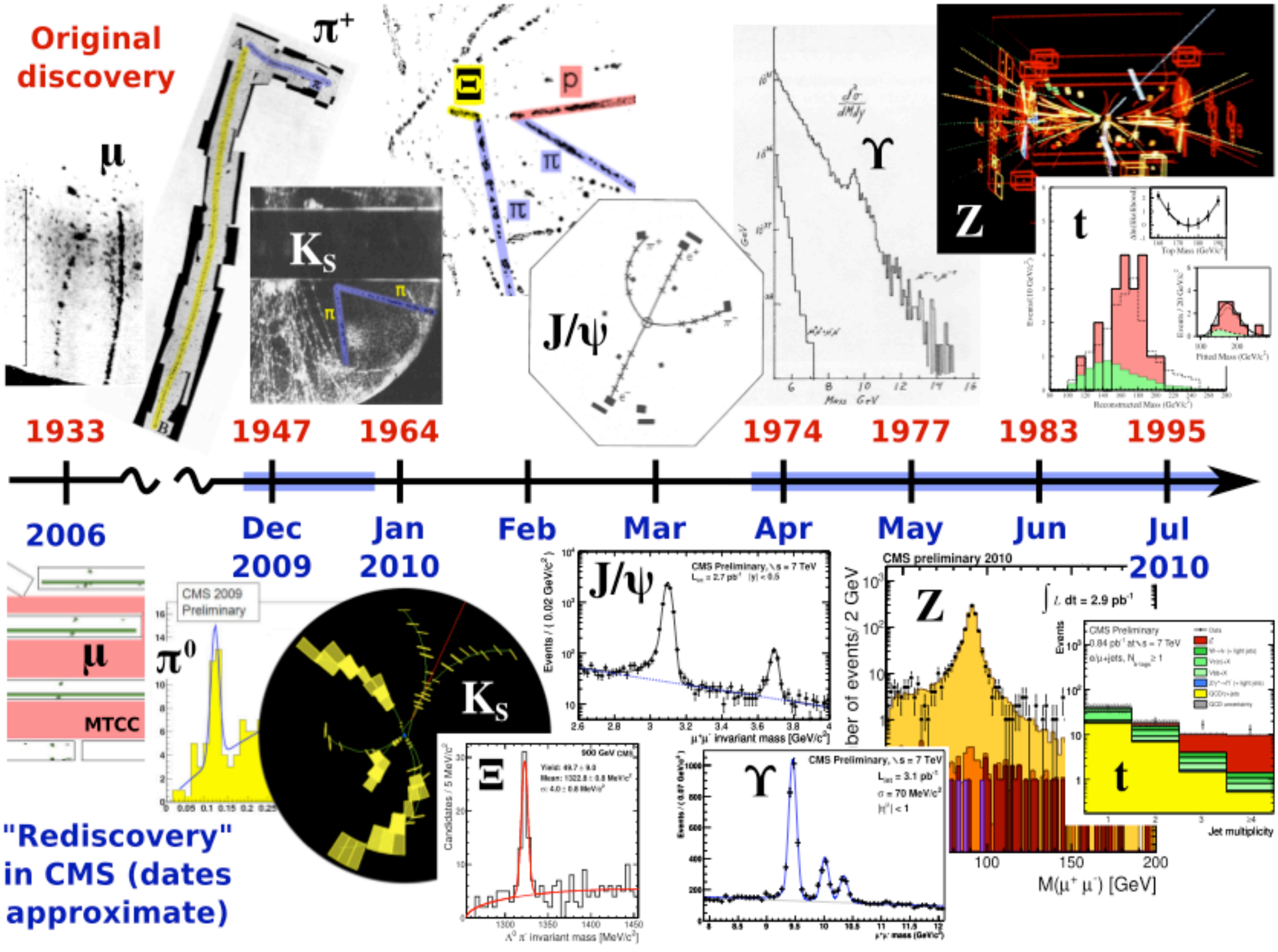
Higgs, TeV-scale SUSY — 2011

?

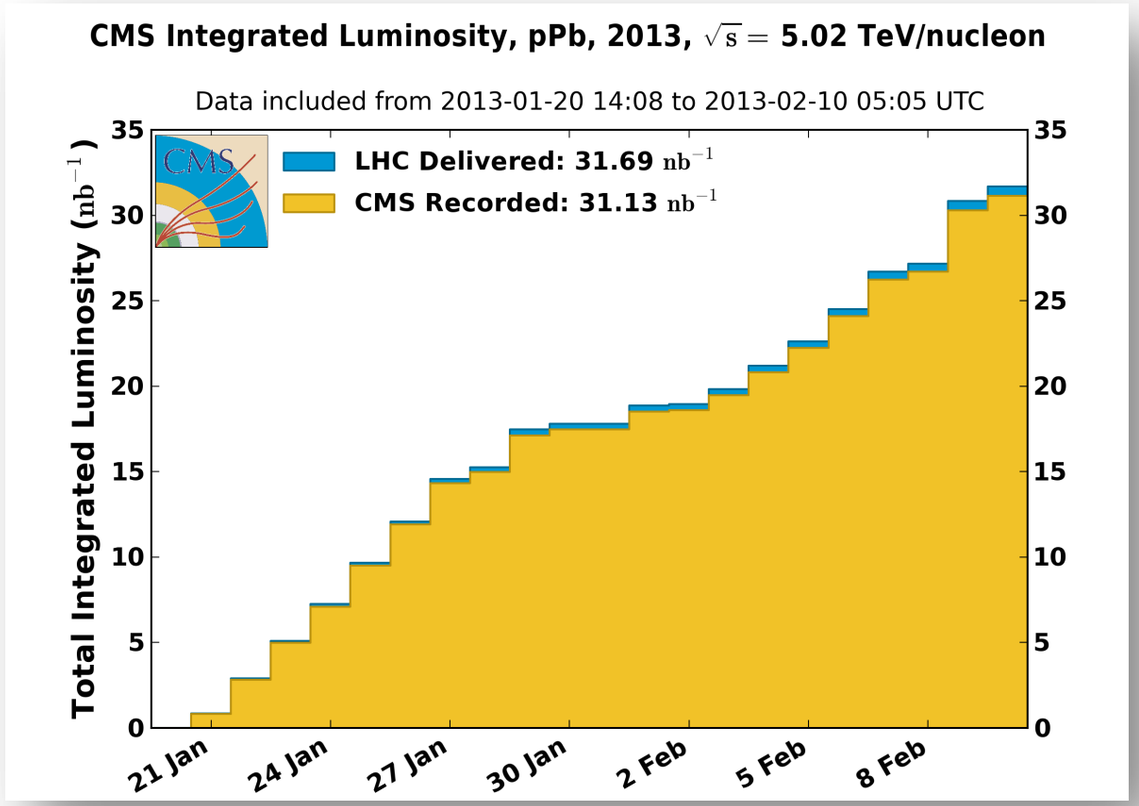
The Killer LHC Problem: Data-Handling

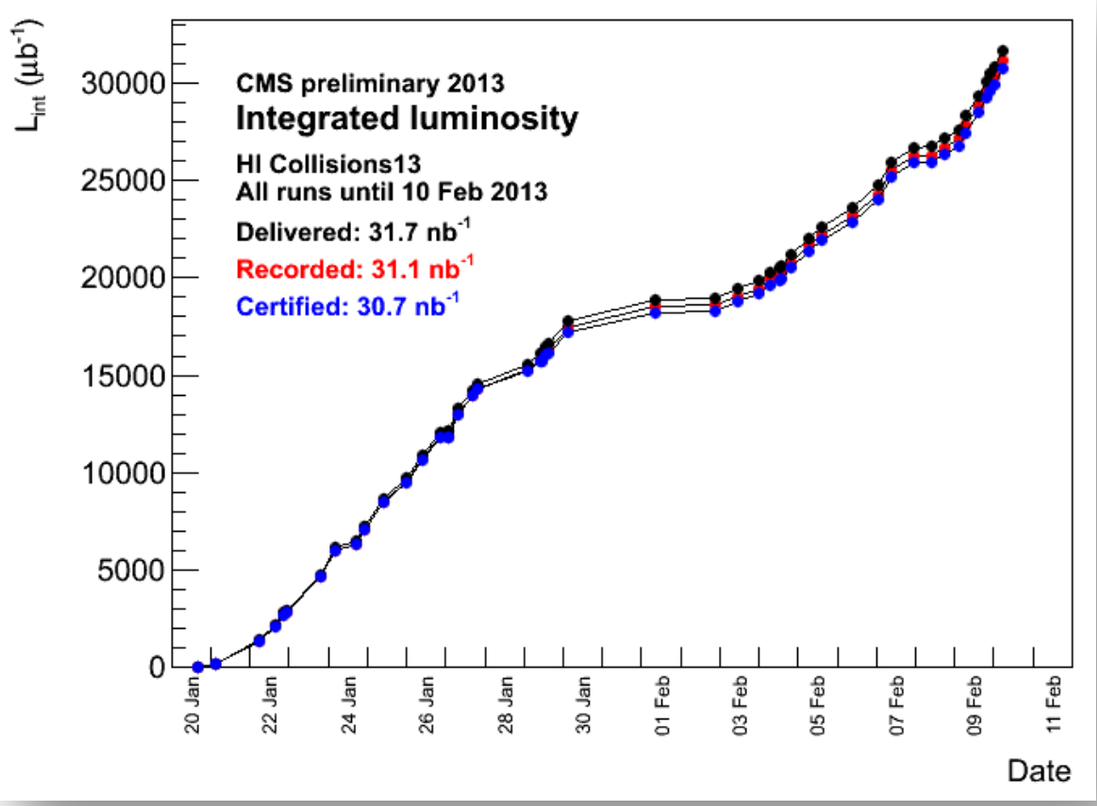
- 'Raw' data rate in experiment is ~40TB/s
  - Or 400 Exabytes per year – a stack of DVDs to the moon
- Heavy filtering is required
  - Level-1 Trigger (hardware): 40MHz -> 100kHz evt rate in real time (1us)
  - HLT (CPU farm): 100kHz -> 300Hz evt rate in real time (10ms)
  - Offline filtering and selection
- General trigger strategy at Level-1
  - Filter using coarse-grained calorimeter and muon data only
  - Identify leptons (e, μ, τ), γ, high-Et jets, total and missing energy
  - Impose transverse momentum thresholds to reduce QCD background
  - Trigger on several possible combinations of selected objects
- Trigger dictates physics reach of the experiment
- Offline handling of data is a 50MCHF per year project

Commissioning



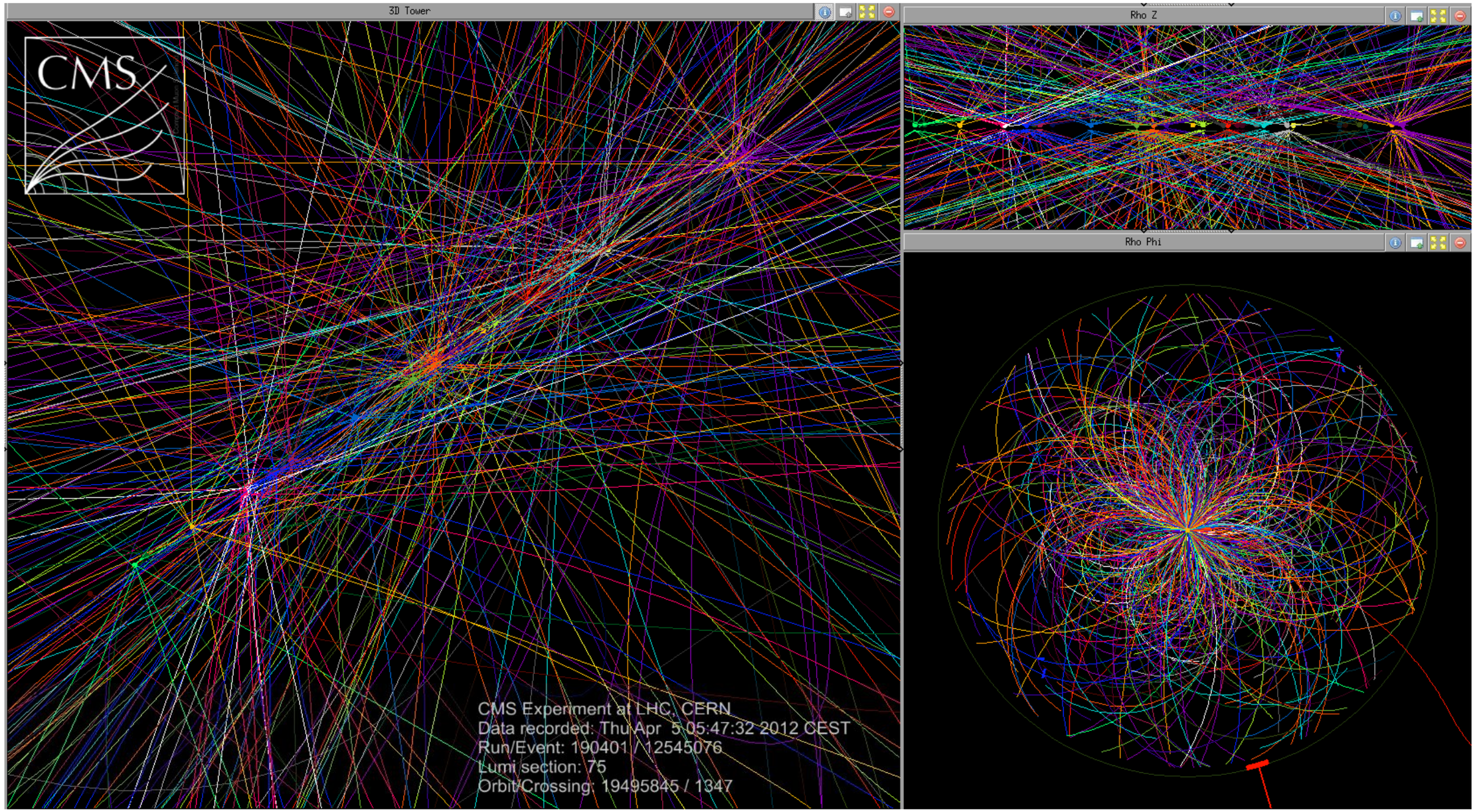
LHC Performance





- 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

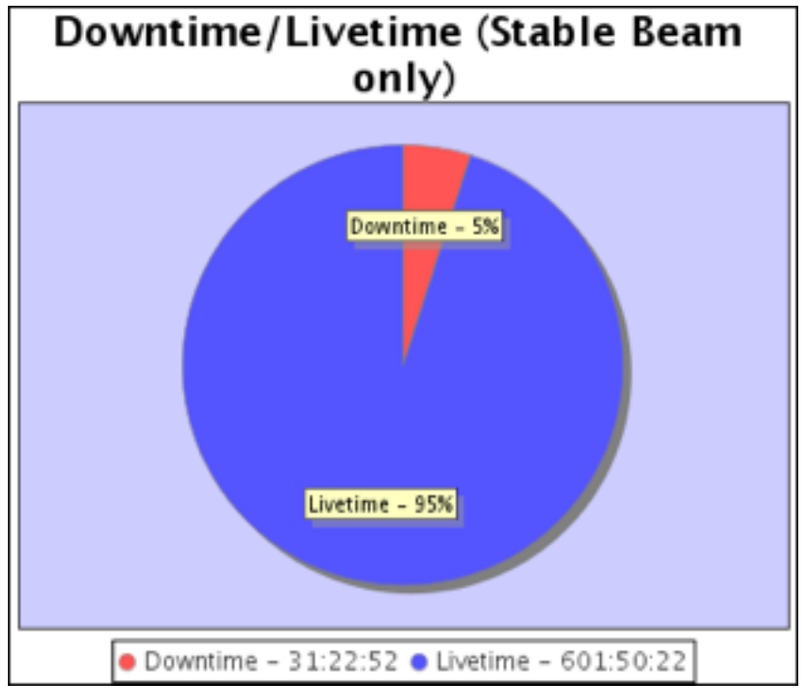
Typical 2012 Event

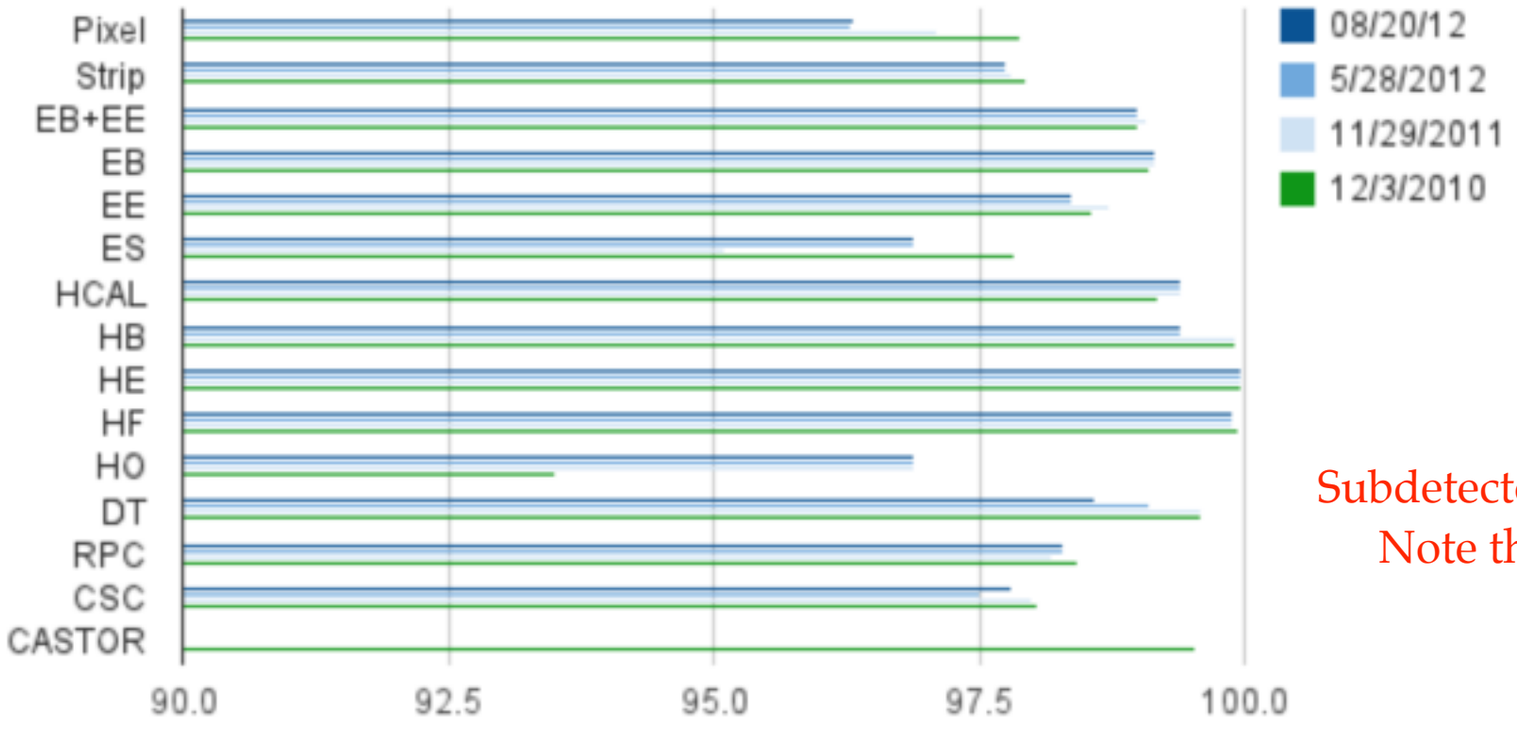


- Trigger rates & offline reconstruction time increase non-linearly with pileup levels

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...

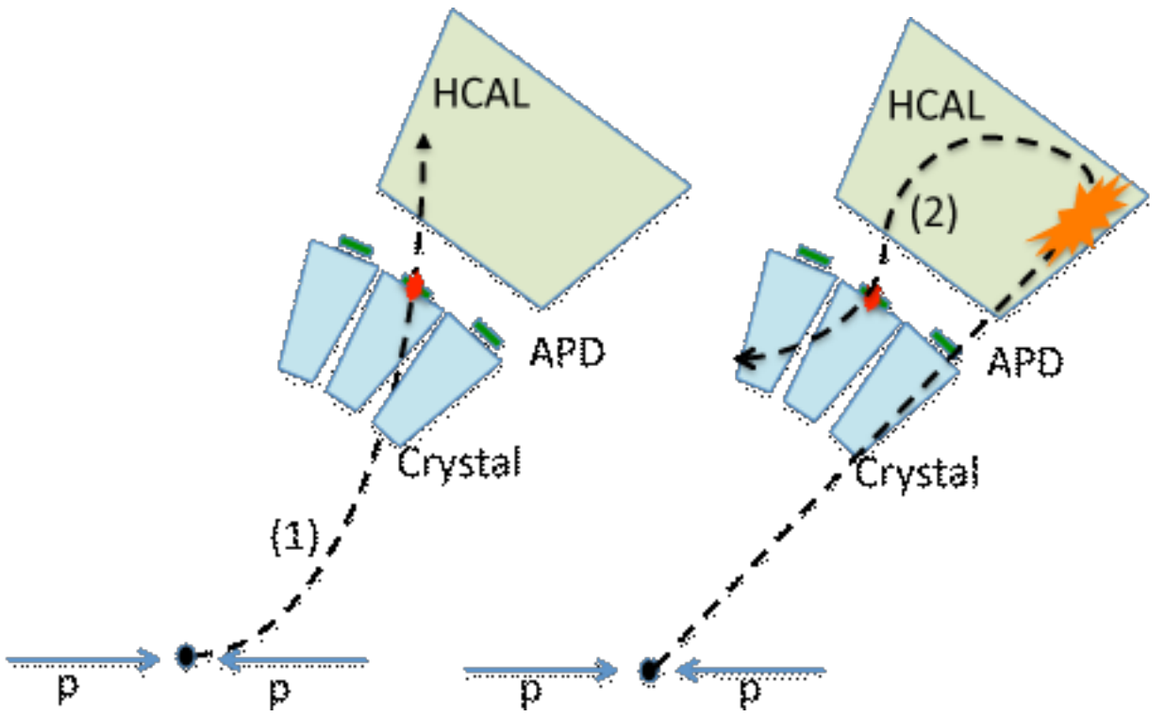


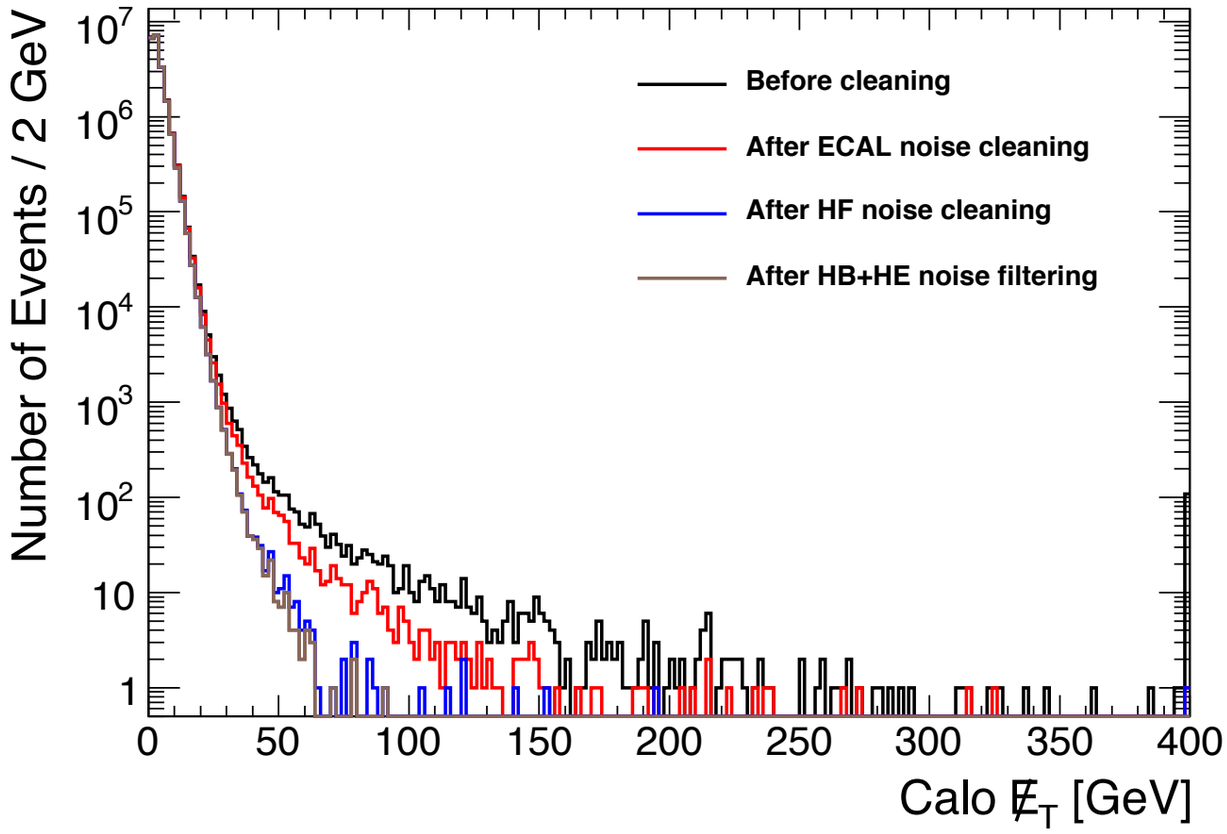


Month of July 2012

Subdetector channel availability
Note the suppressed zero!

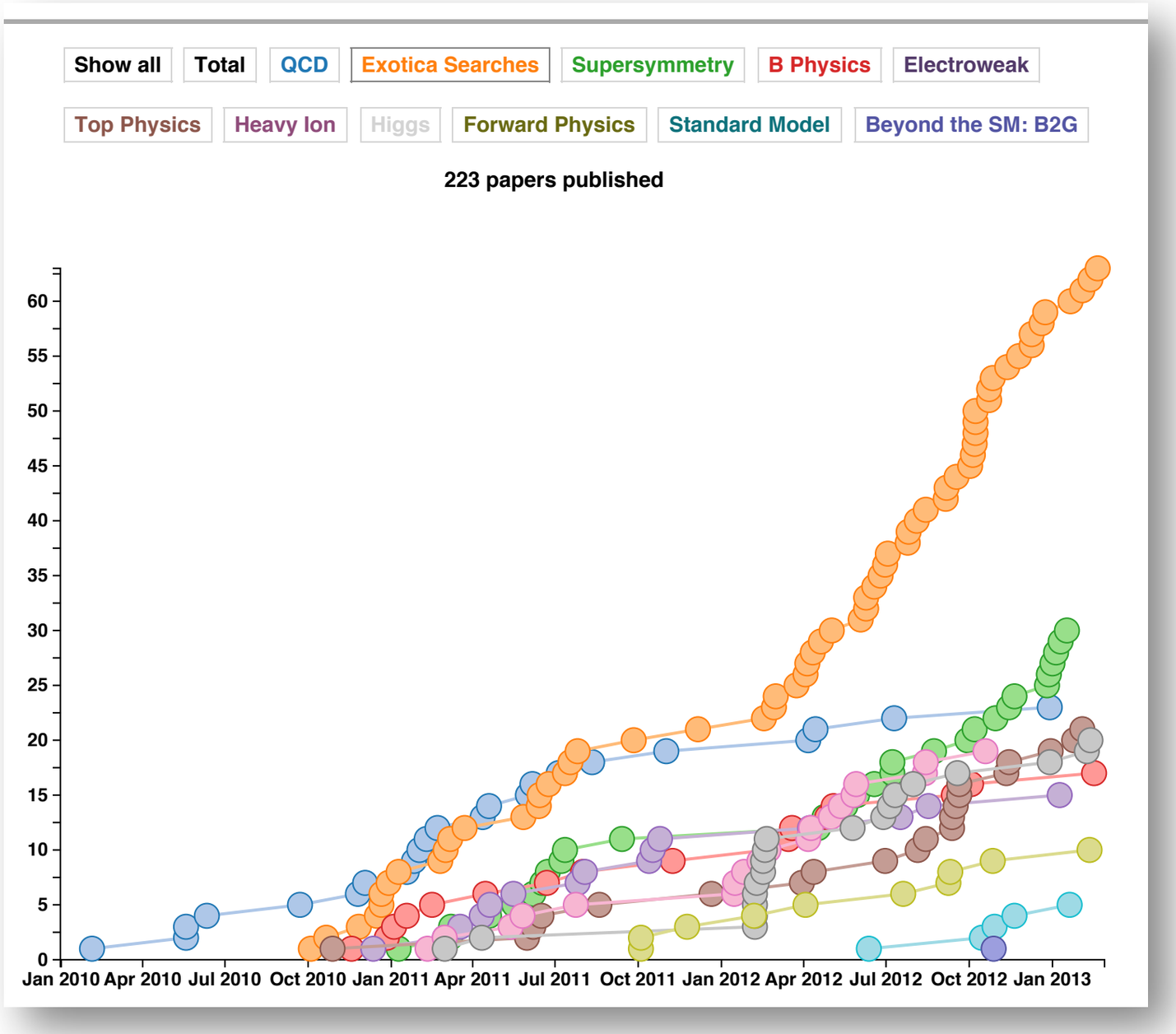
Detector Challenges





- Rare, but significant, calorimeter noise events
  - ECAL: 'Spikes' at a low rate, but with extremely large signal
    - Fixed with a combination of online processing (trigger) and offline cuts
  - HCAL: 'Pattern' noise in photodetectors, uncorrelated with event activity
  - FCAL: Spikes caused by Cherenkov light in passive materials
- Buffer overflows in pixel readout system

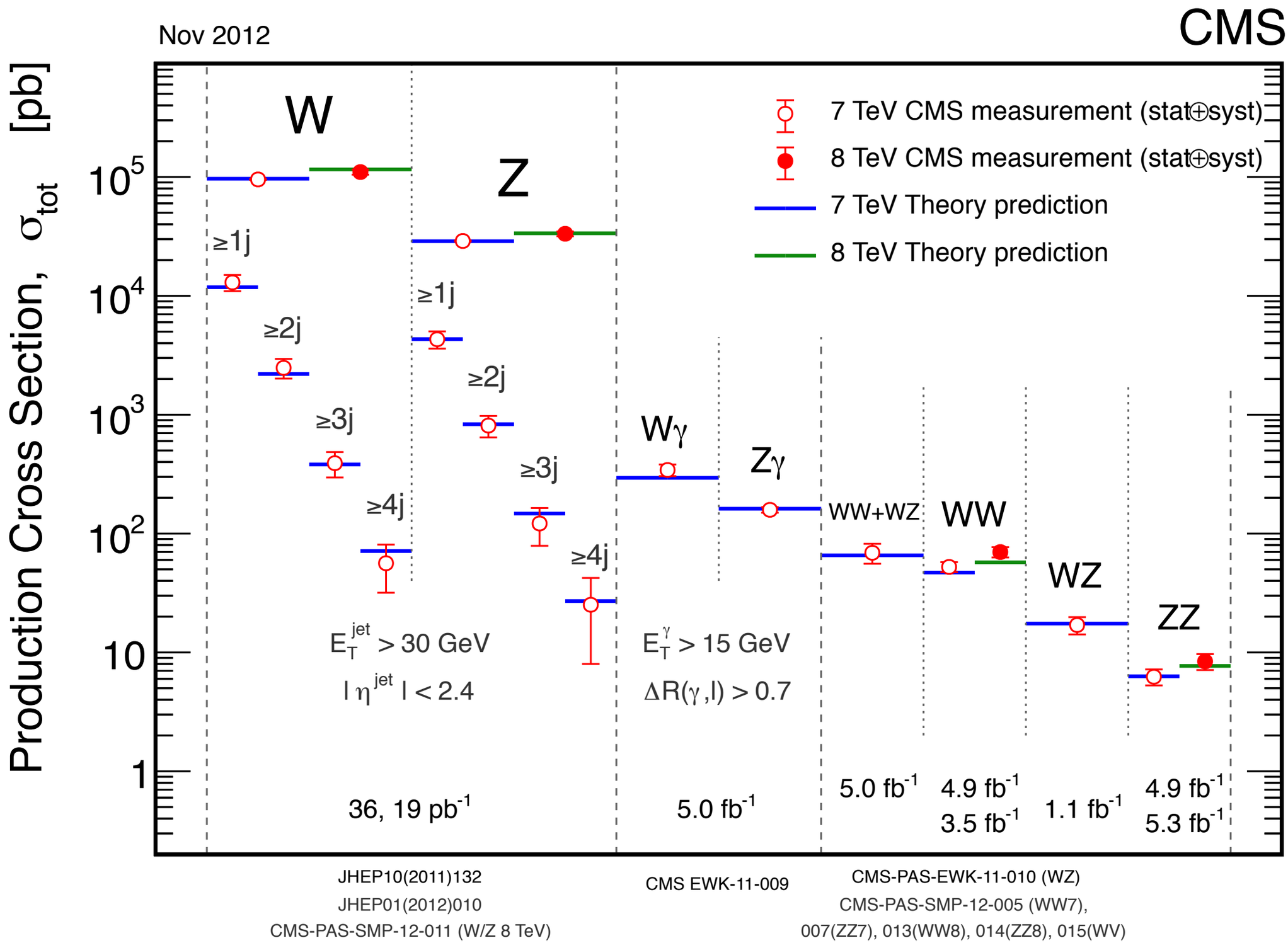
Physics Publications



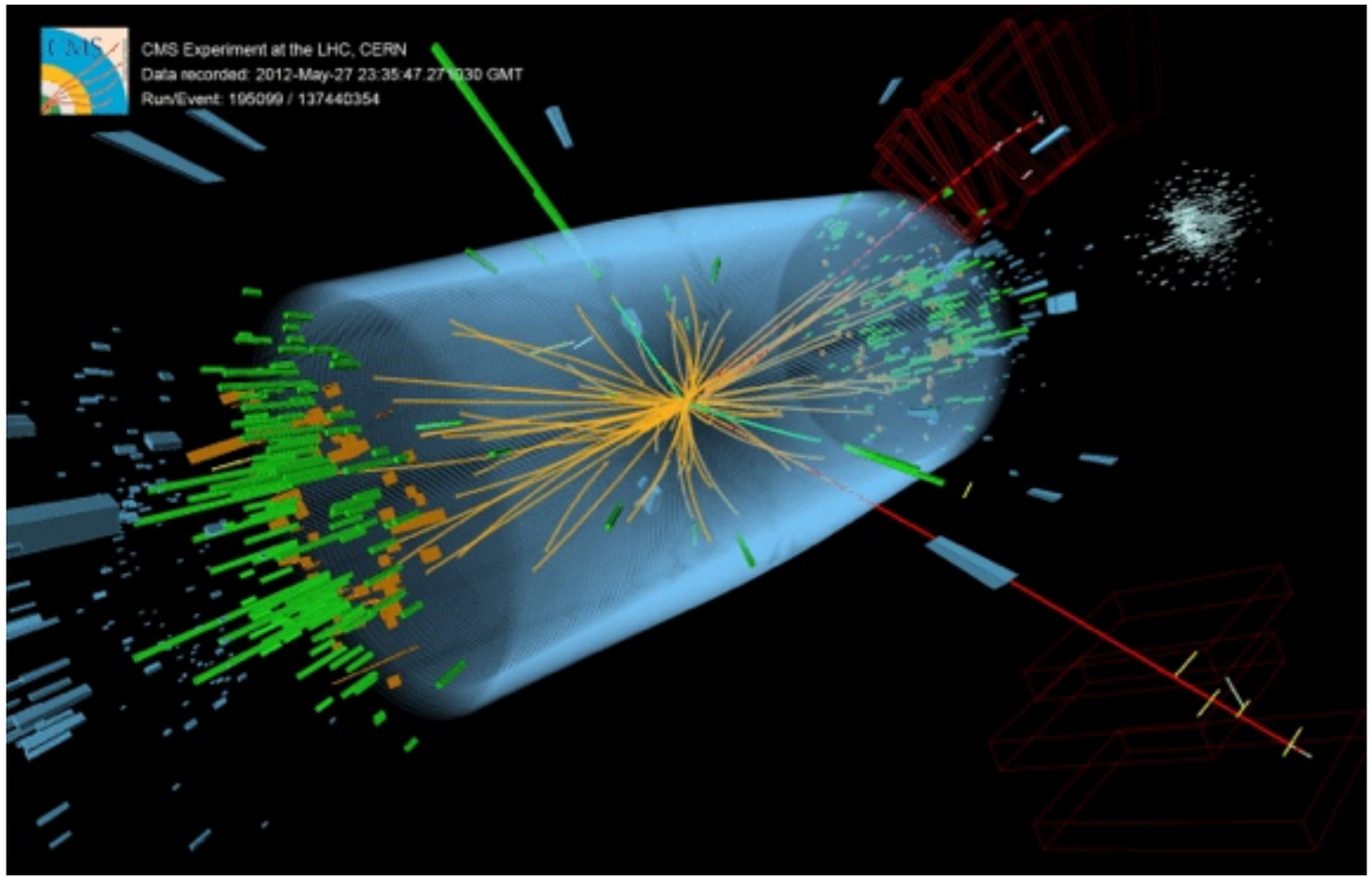
223 papers at 1st Feb

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

SM Electroweak Tests

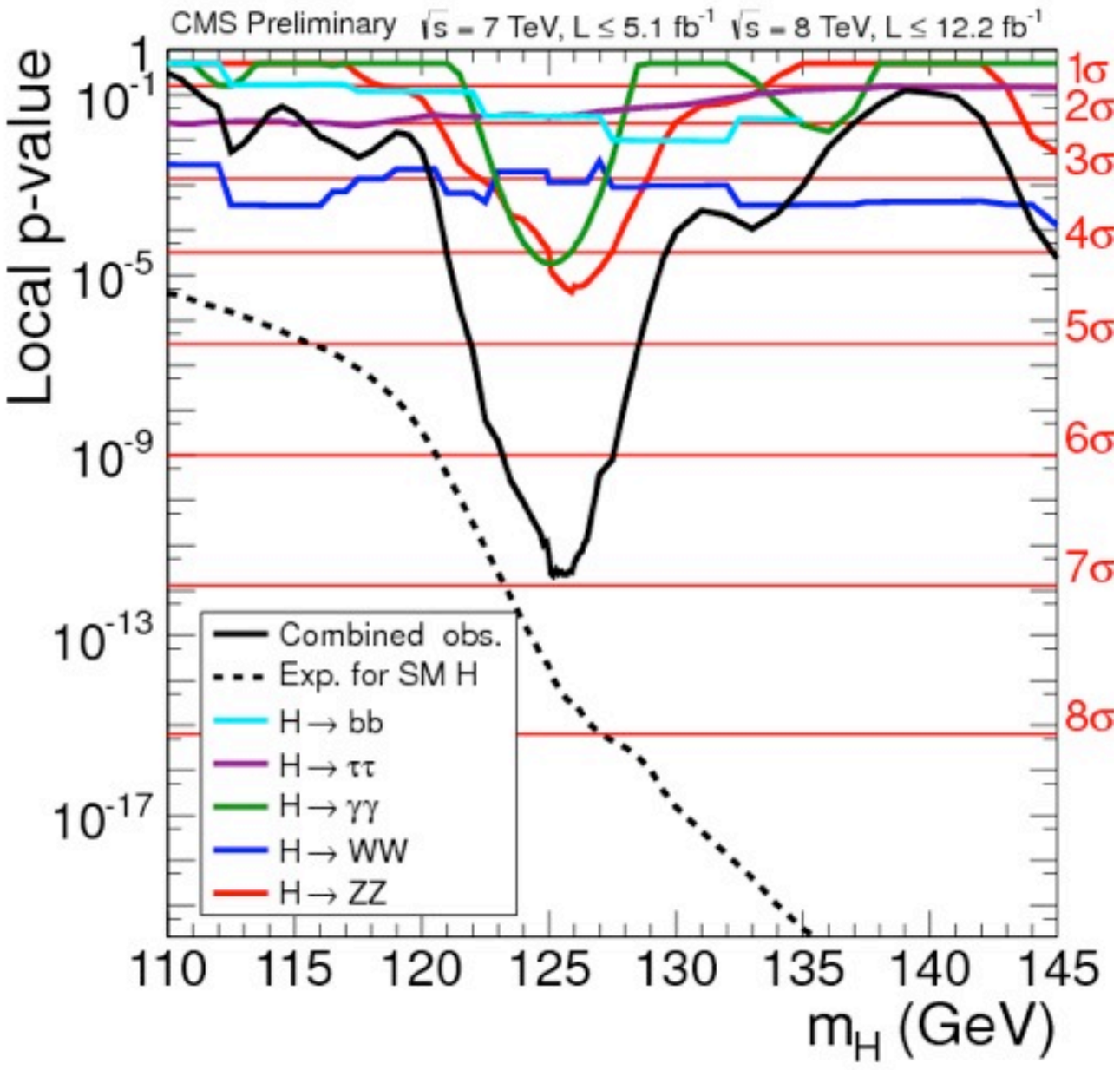


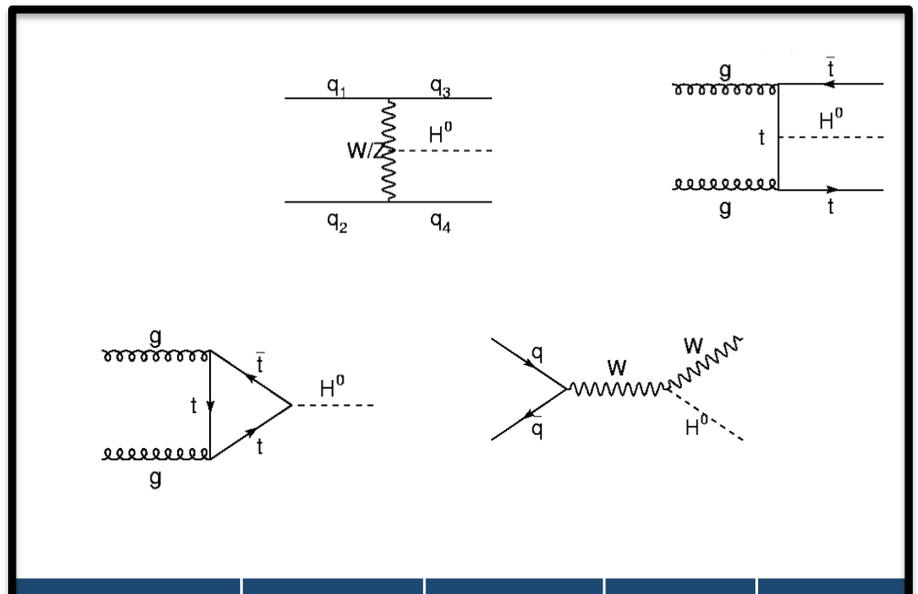
Higgs Boson



- Summary numbers
  - $m_H = 125.8 \pm 0.5(\text{stat}) \pm 0.2(\text{sys})$ GeV – dominated by 4l channel
  - Combined significance: 6.7 s.d. (7.2 expected)
  - $\sigma / \sigma_{SM} = 0.91 \pm 0.3$ – dominated by 2l2nu channel
  - ~ 700 direct CMS analysis contributors to July 2012 results

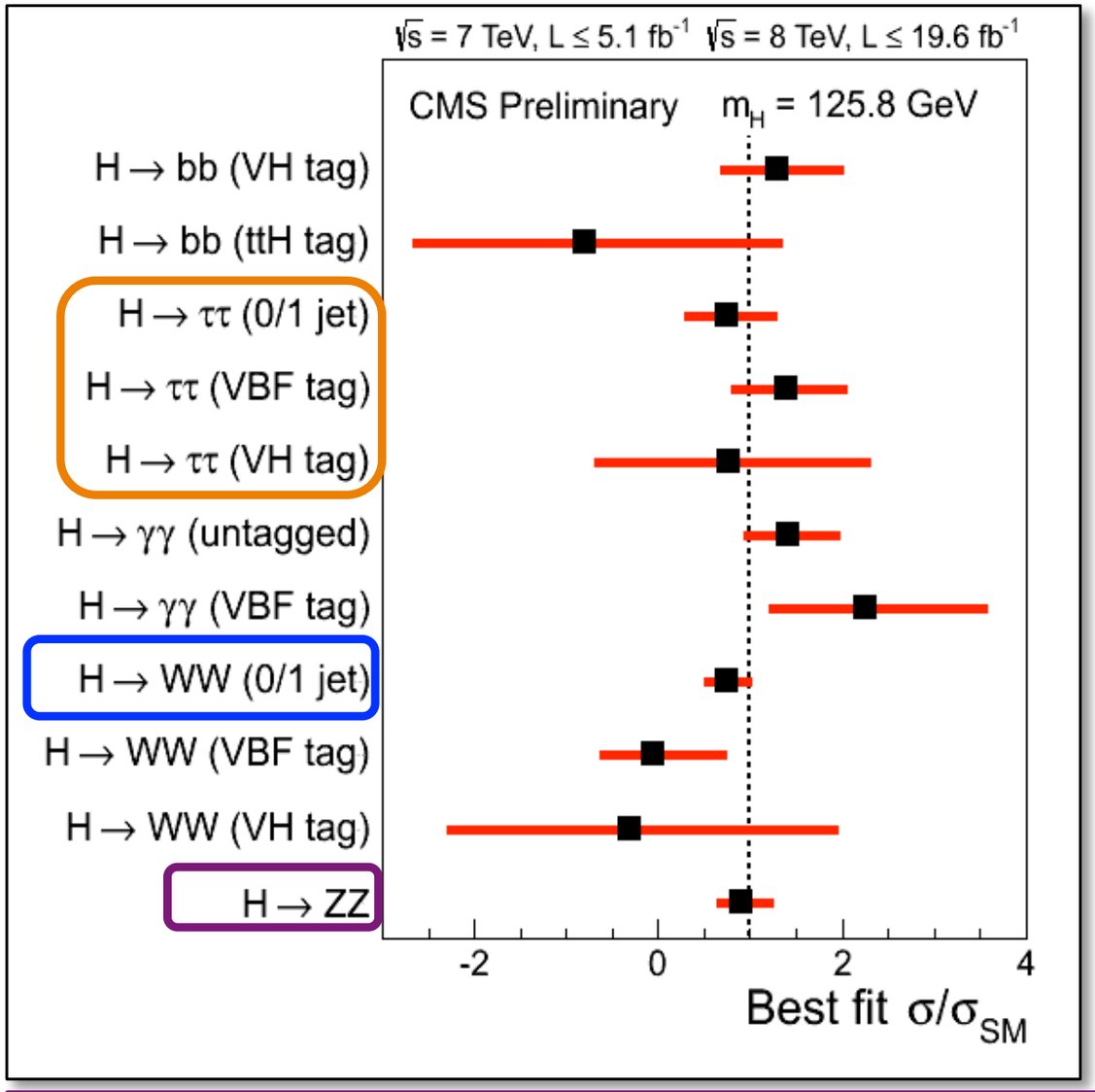
Higgs Boson

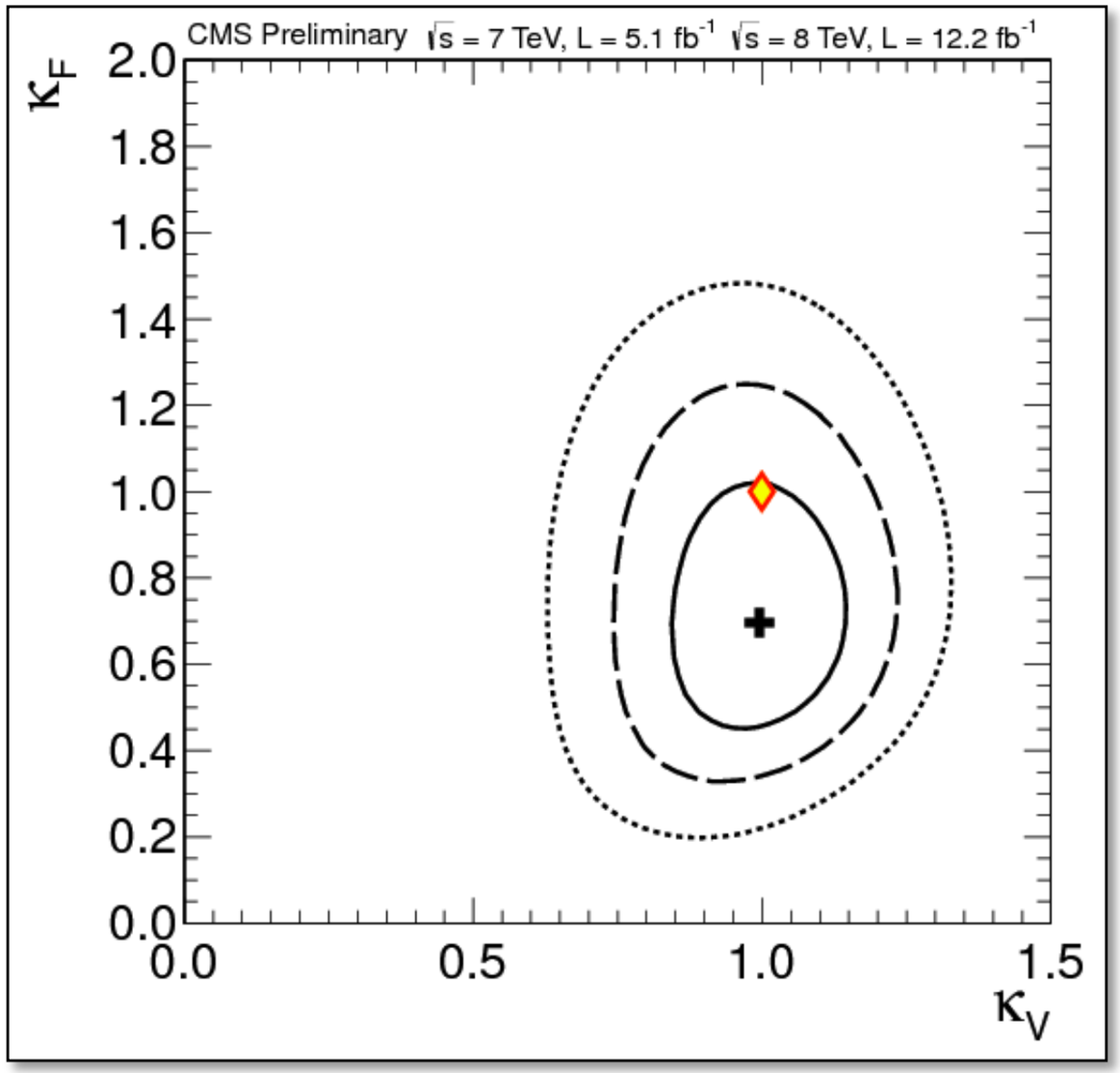




	un-tagged	VBF-tag	VH-tag	ttH-tag
γγ	✔	✔		
bb			✔	✔
ττ	✔	✔	✔	
WW(lvlv)	✔	✔	✔	
ZZ(4l)	✔			

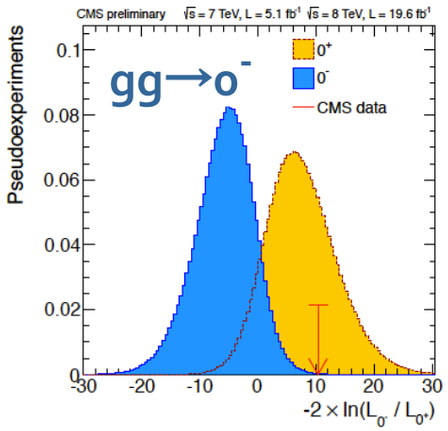
Higgs: Properties

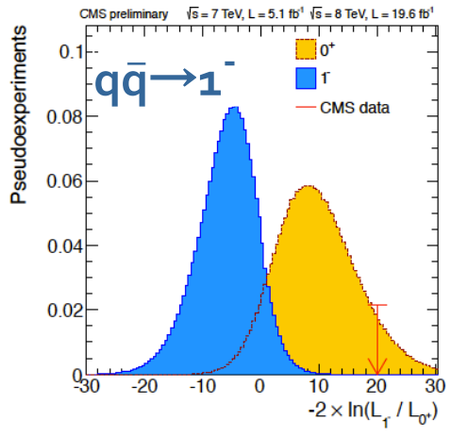


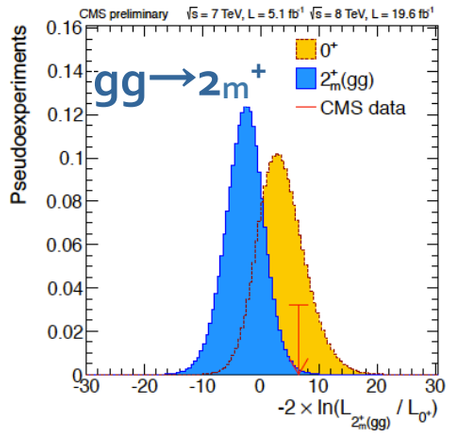


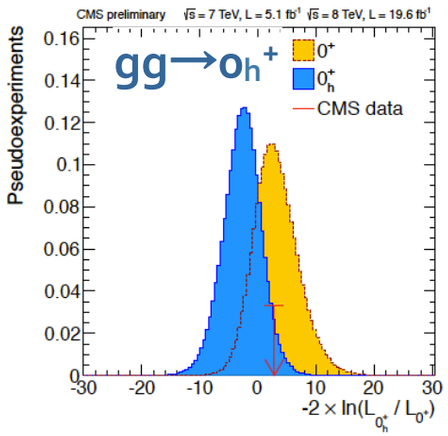
- Appears that we have a good old-fashioned SM Higgs boson
  - Of course, it may have friends (high-mass $H_{SM\text{-}like}$ search public this week)

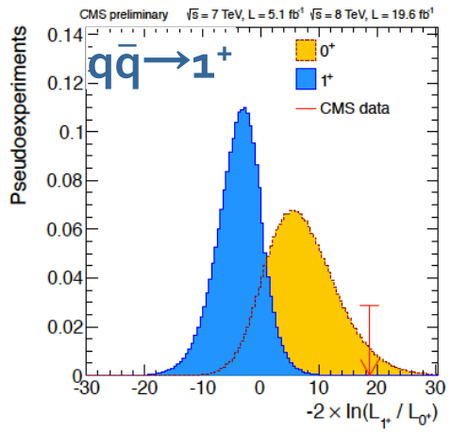
Higgs: Spin-Parity

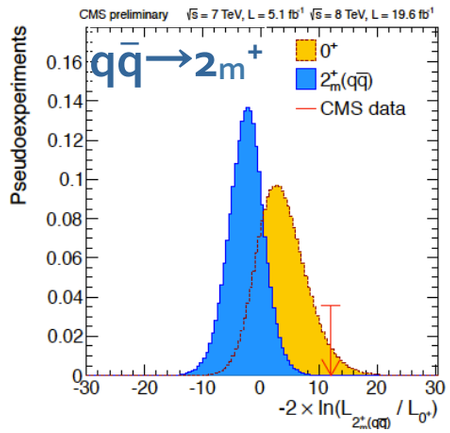












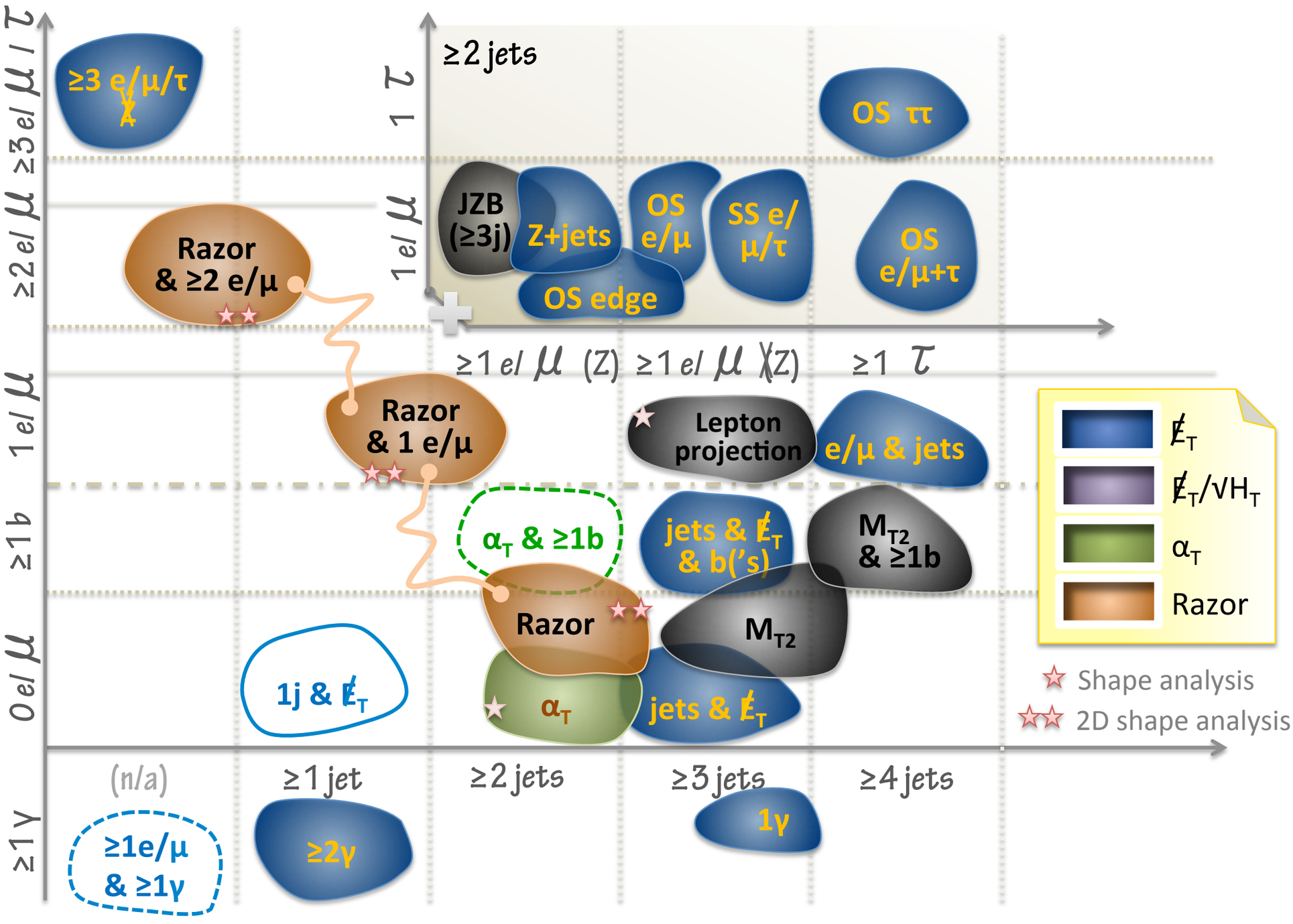
Yellow: 0+ hypothesis

Blue: alternative s-p assignment

Red marker: CMS measurement

	Expected [σ]		Observed (μ from data)		
	μ=1	μ from data	P(q > Obs | alternative) [σ]	P(q > Obs | SM Higgs) [σ]	CLs [%]
gg → 0⁻	2.8	2.6	3.3	-0.5	0.16
gg → 0h⁺	1.8	1.7	1.7	+0.0	8.1
qq → 1⁺	2.6	2.3	> 4.0	-1.7	< 0.1
qq → 1⁻	3.1	2.8	> 4.0	-1.4	< 0.1
gg → 2m⁺	1.9	1.8	2.7	-0.8	1.5
qq → 2m⁺	1.9	1.7	4.0	-1.8	< 0.1

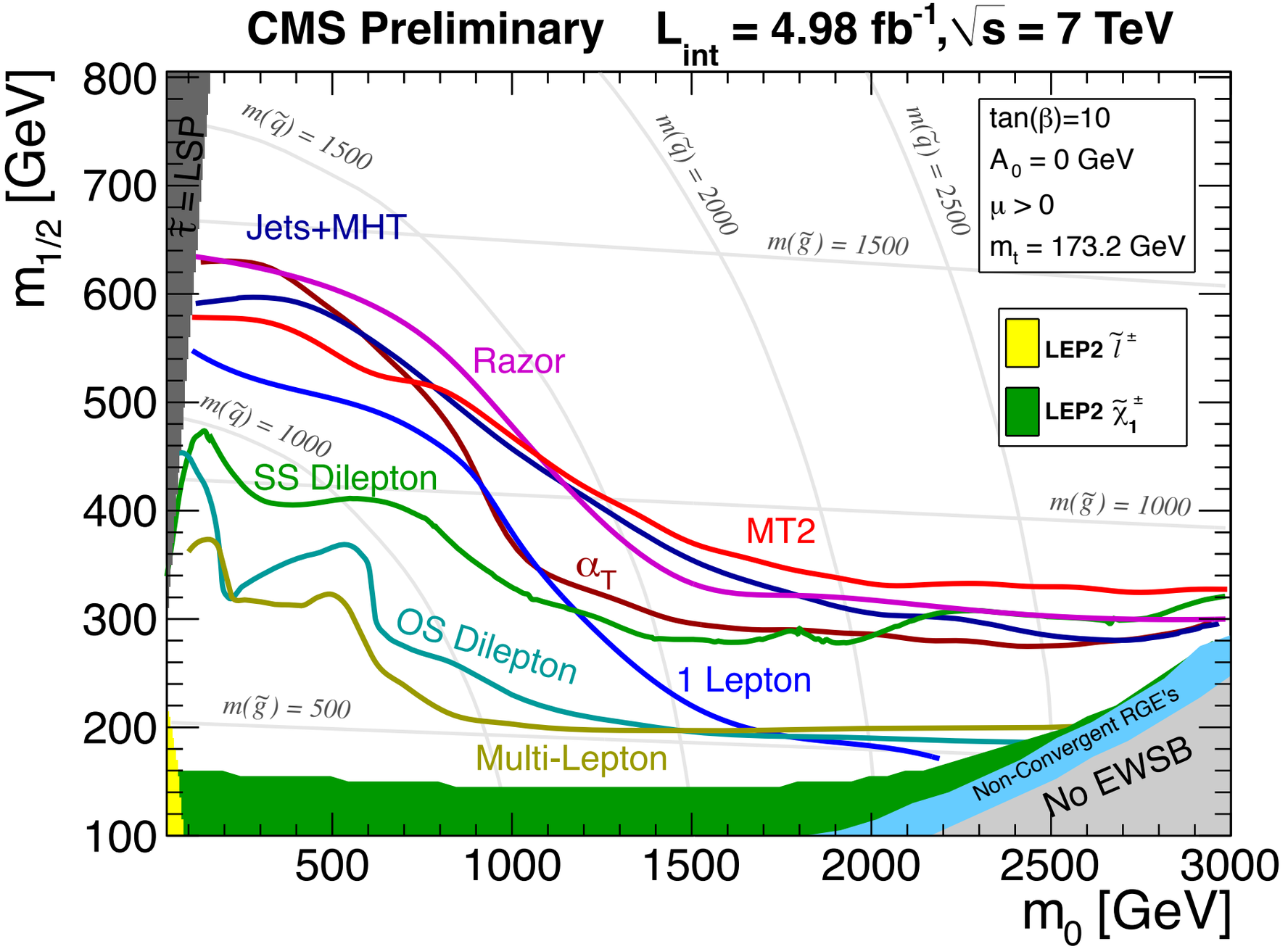
SUSY: Channels



Slide by S-A Koay

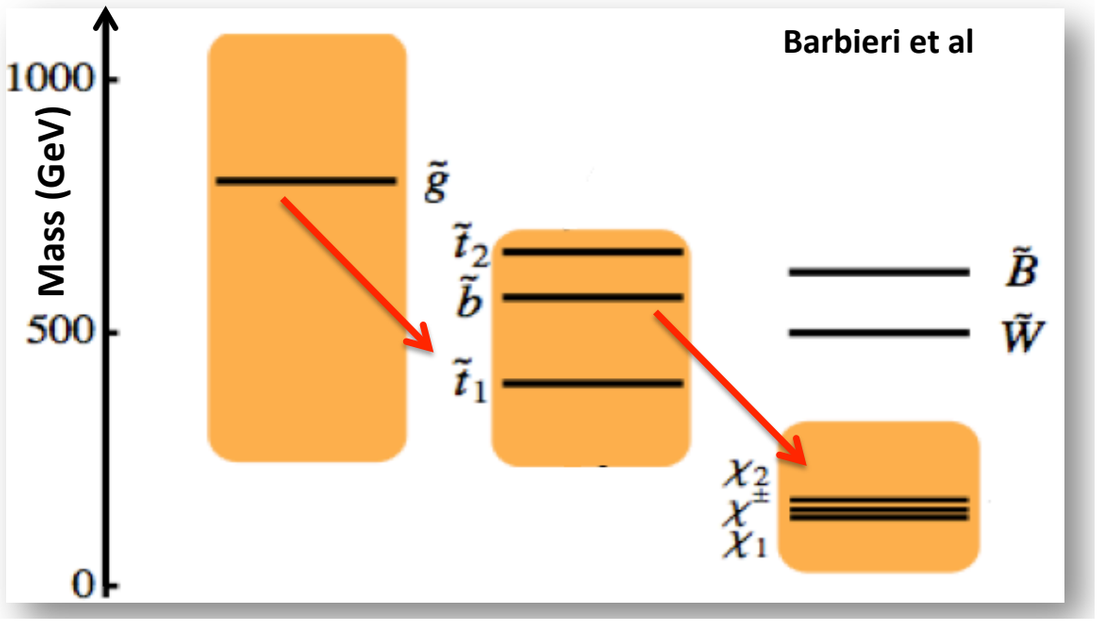
- Panoply of channels, covering wide range of phenomenology

SUSY cMSSM Limits



- Old news...
  - The hunt has now turned to model-independent searches

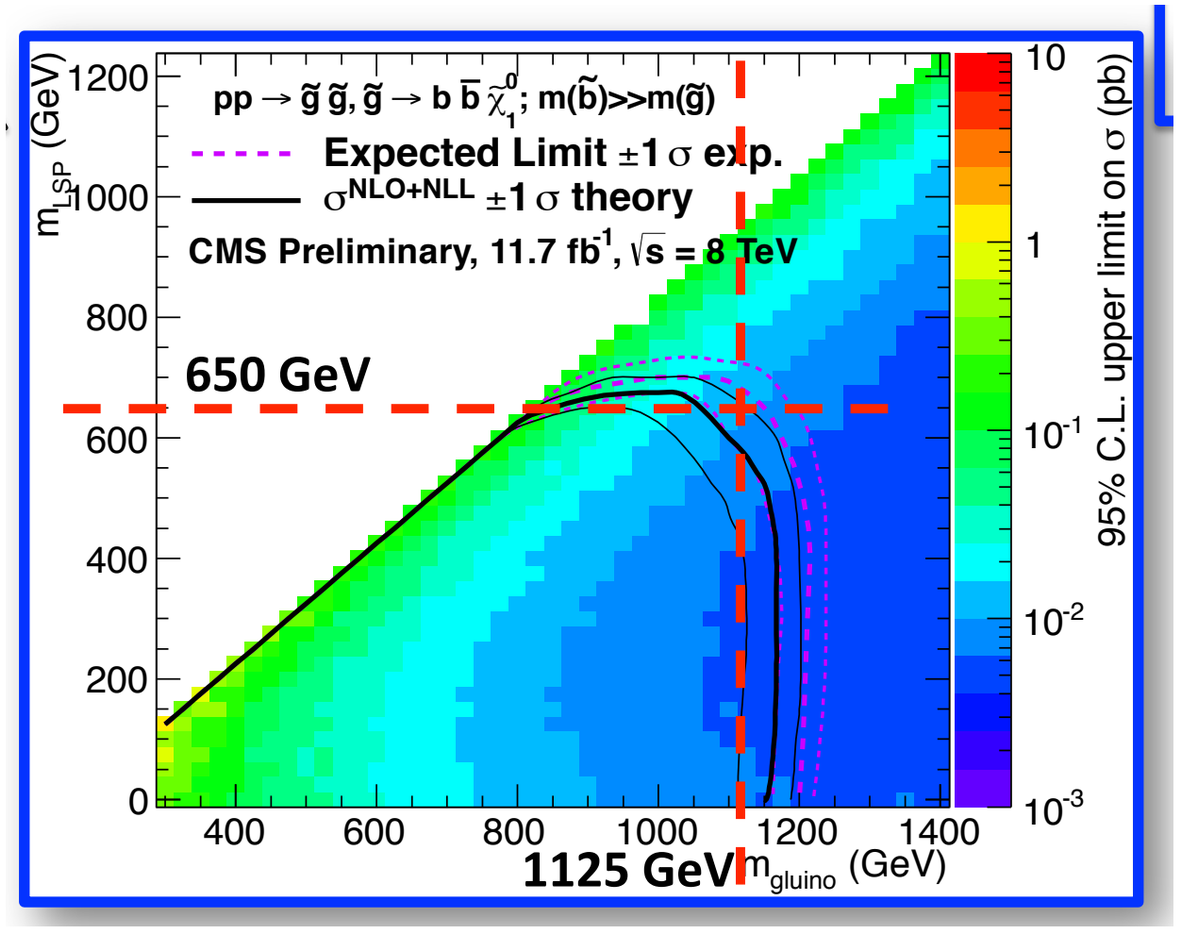
Alternative Approaches



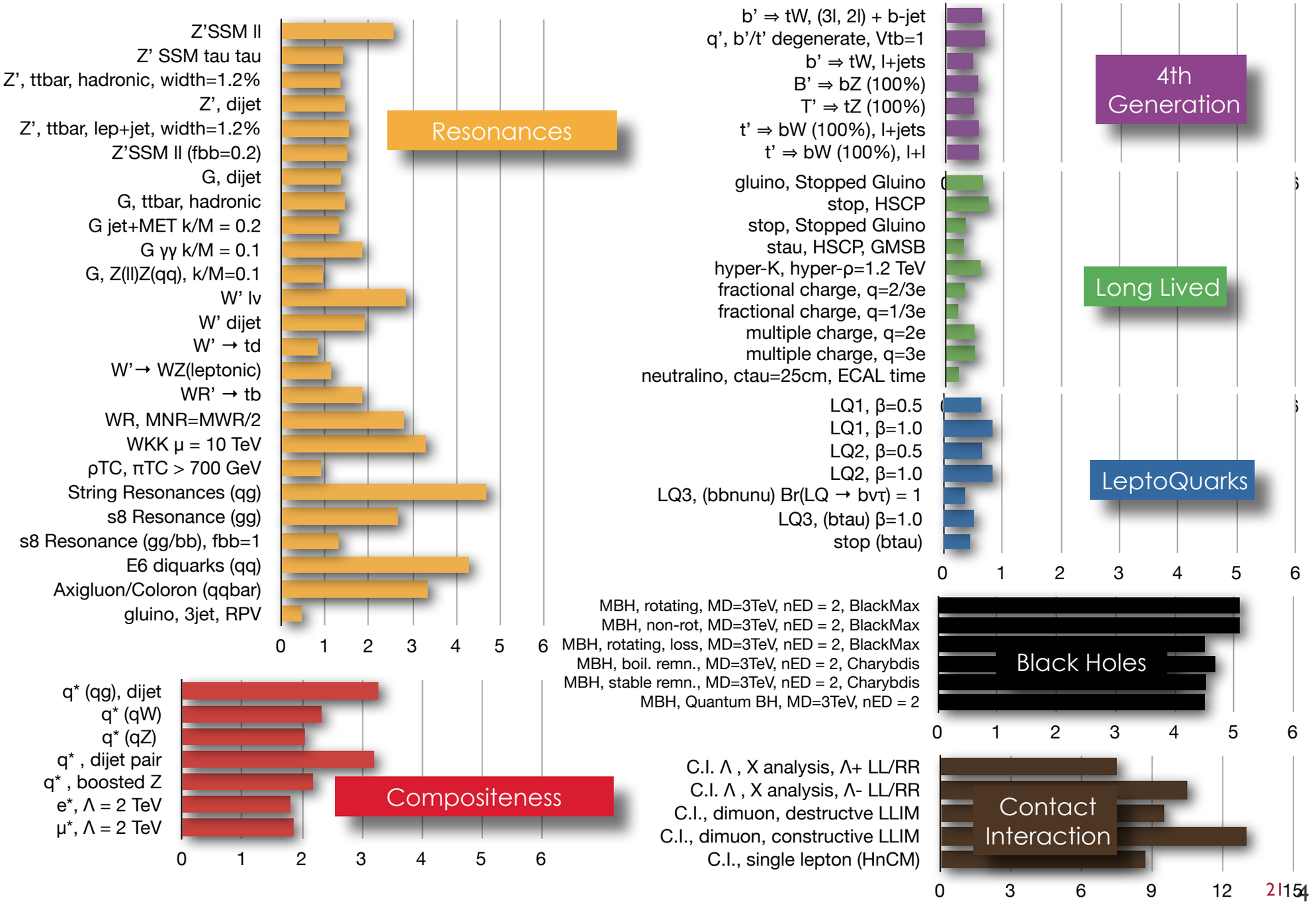
Only worry about what matters!

- 0-lepton search summary
  - Colour scale represents upper limit on cross-section (pb)
  - Assumes 100% BR
  - $m_{gluino} > 1125$GeV
  - $m_{LSP} > 650$GeV
- 14TeV data needed

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



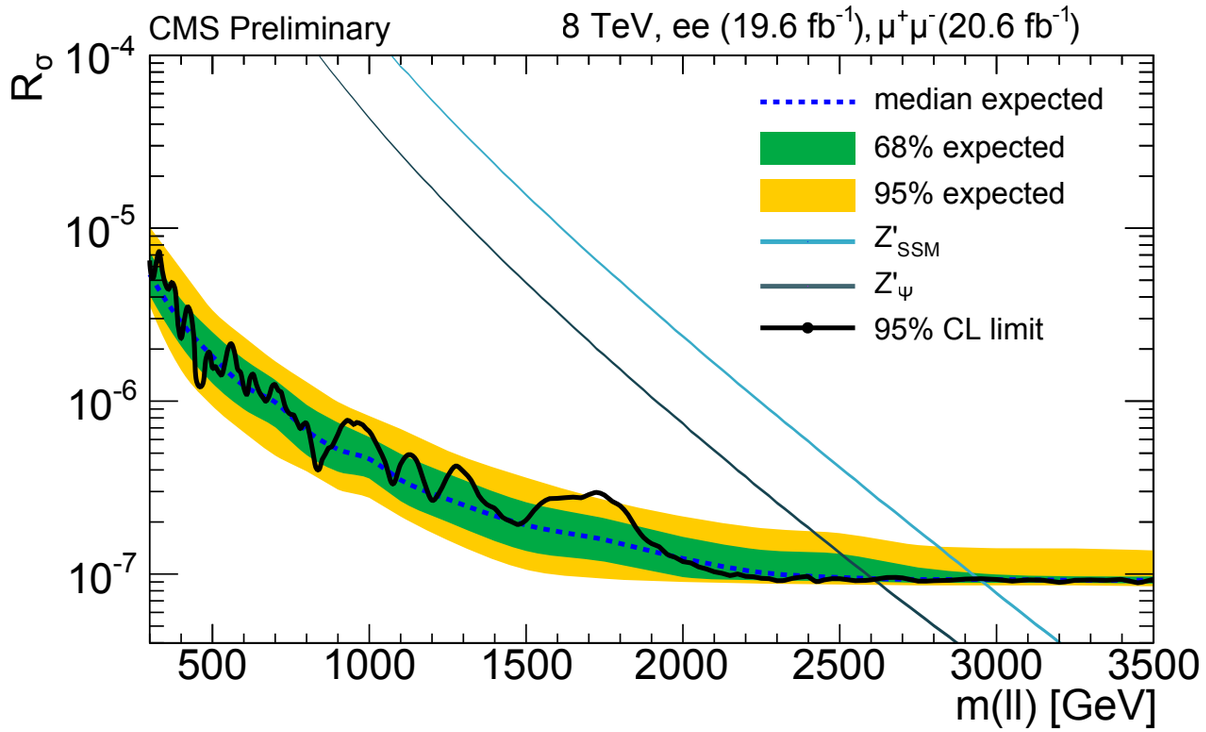
Exotica Overview

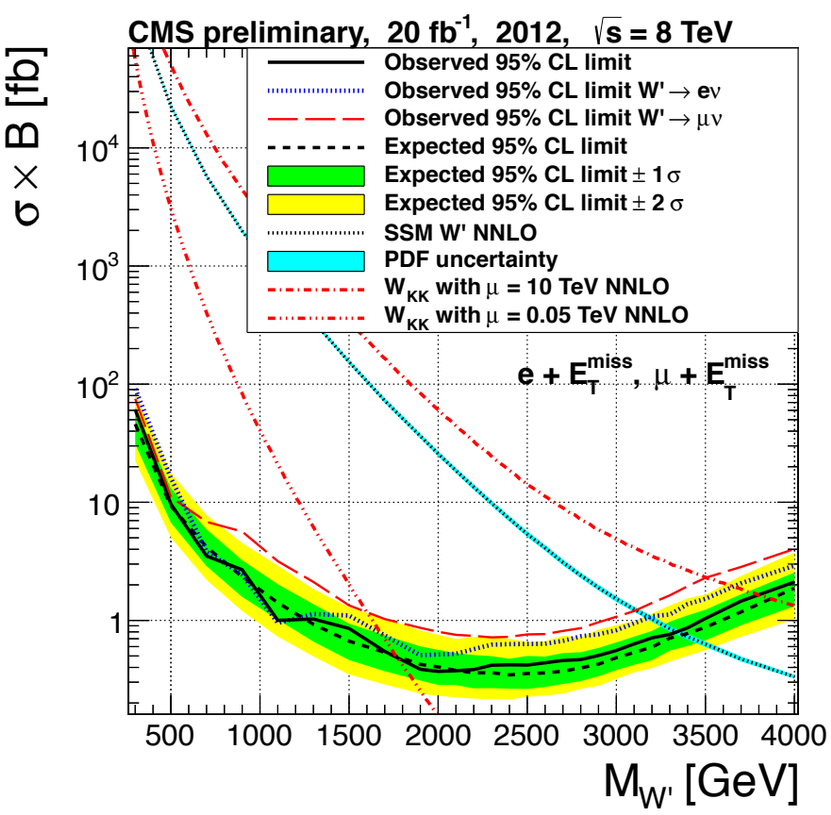


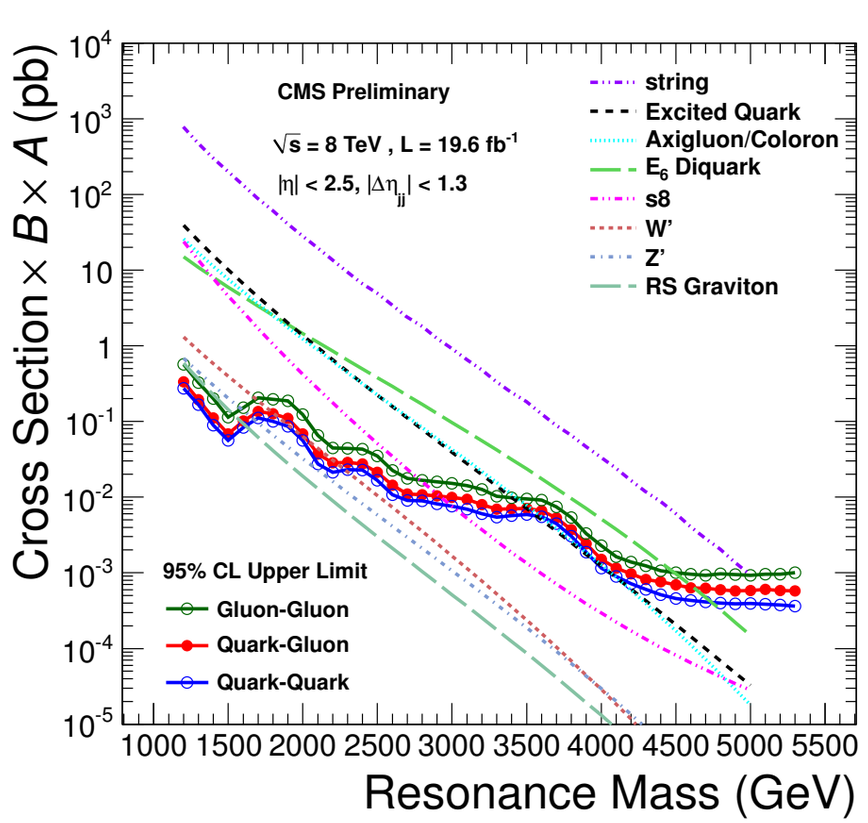
- The graveyard

(Mass or Λ limit)

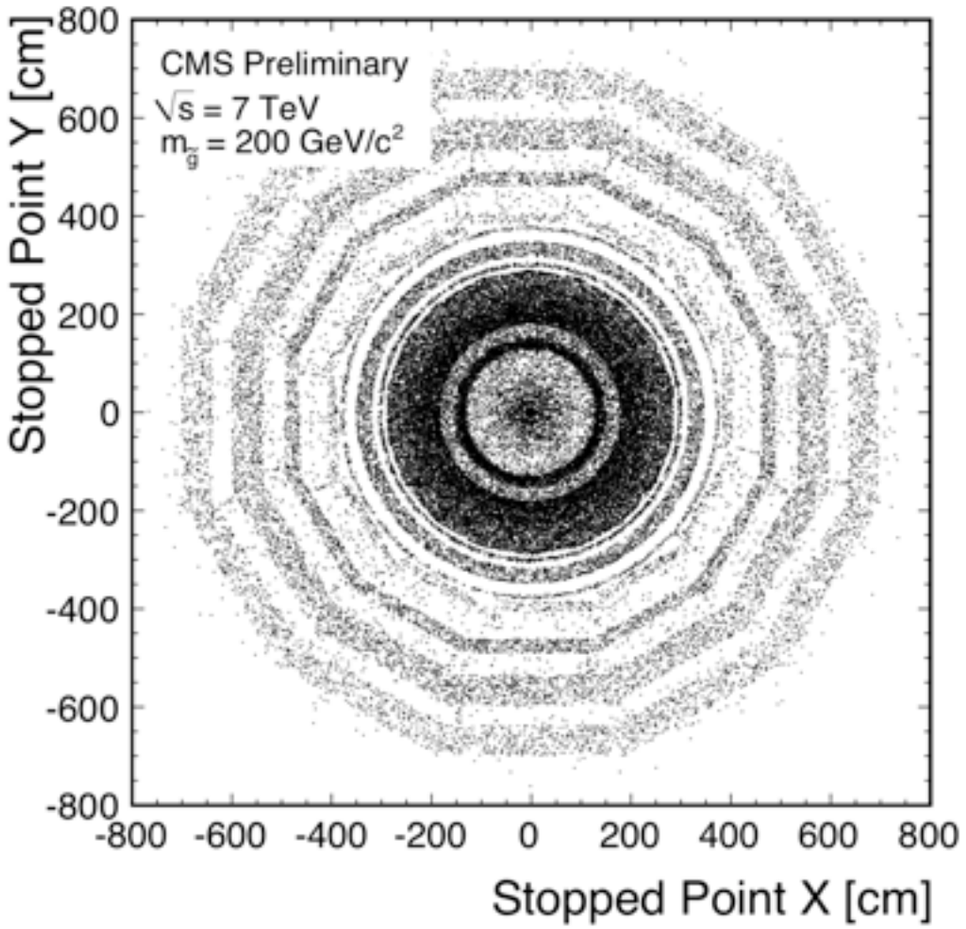
Exotica Searches

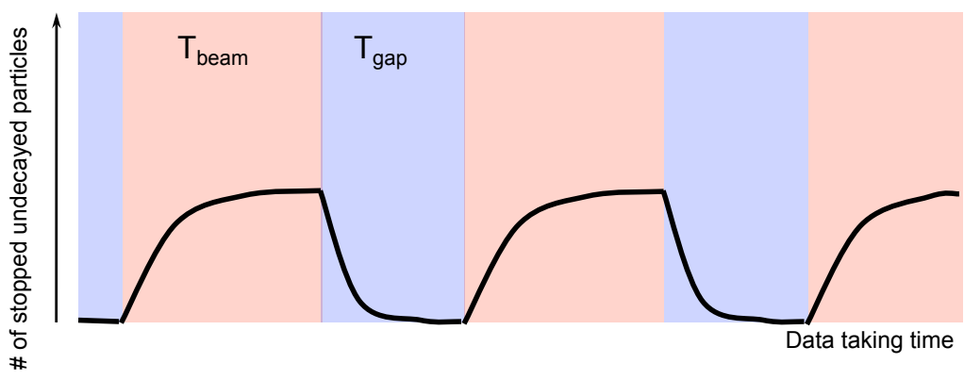


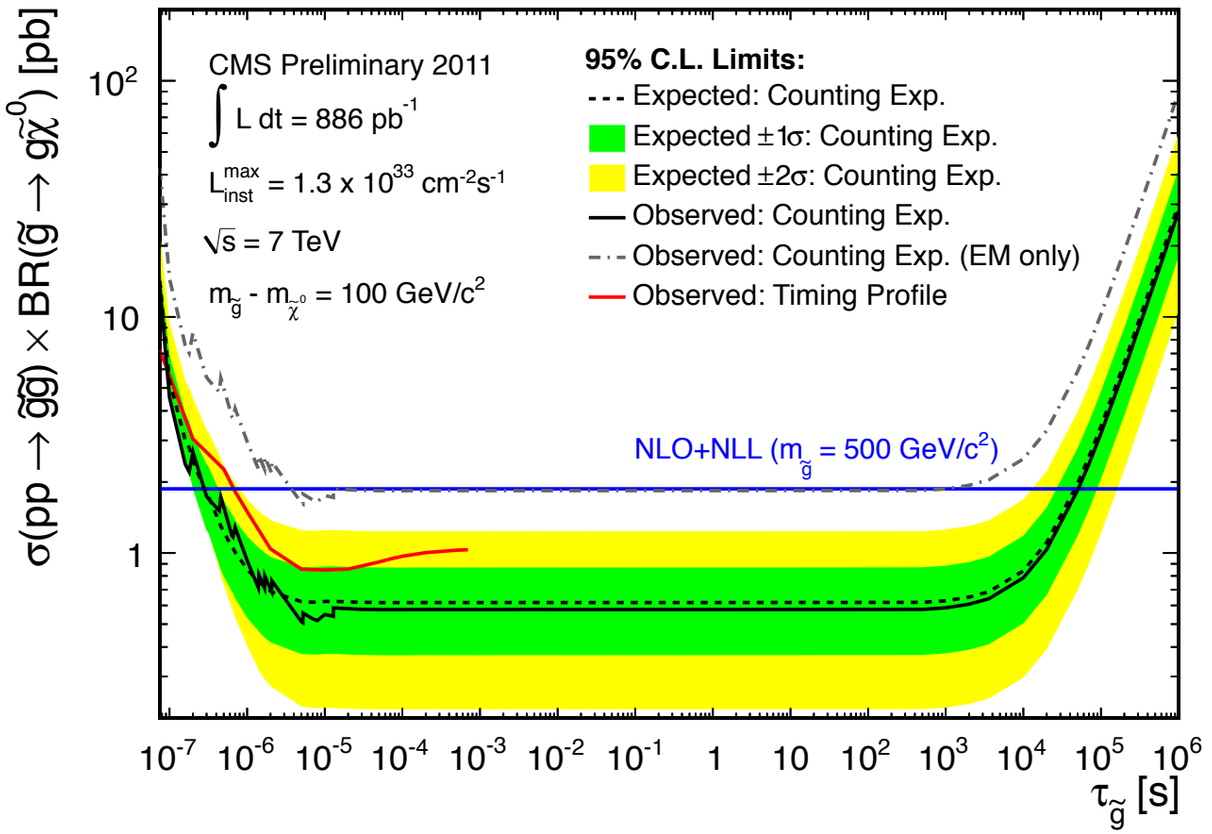




Exotica: Stopped HSCPs

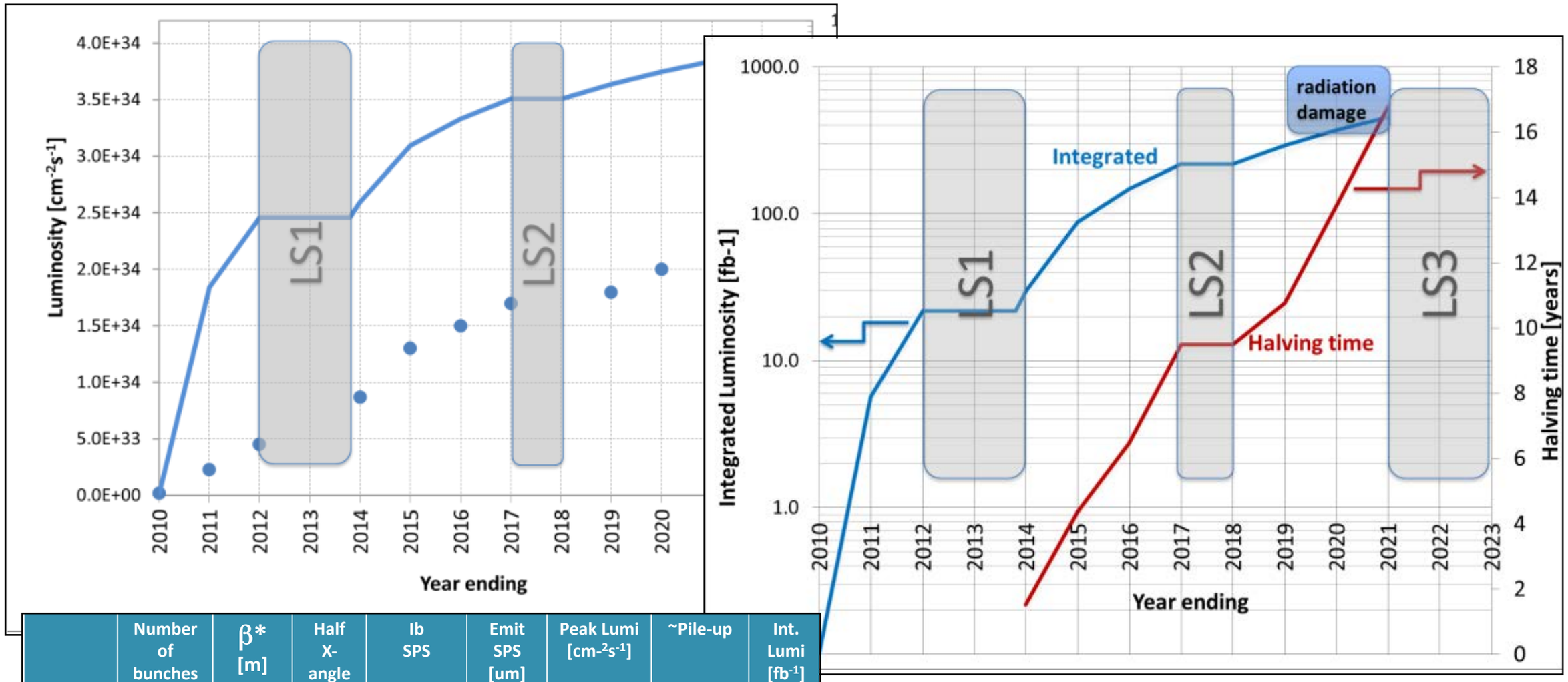






- Hidden valley / split-SUSY
  - Long-lived state hadronises & stops
  - Dedicated trigger for stopped R-hadrons in CMS calorimeter
  - Run in gaps / stops / shutdowns
  - Sensitive over 13 OoM lifetime

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

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
  - How will the physics unfold?
  - Original design / build took ten years

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

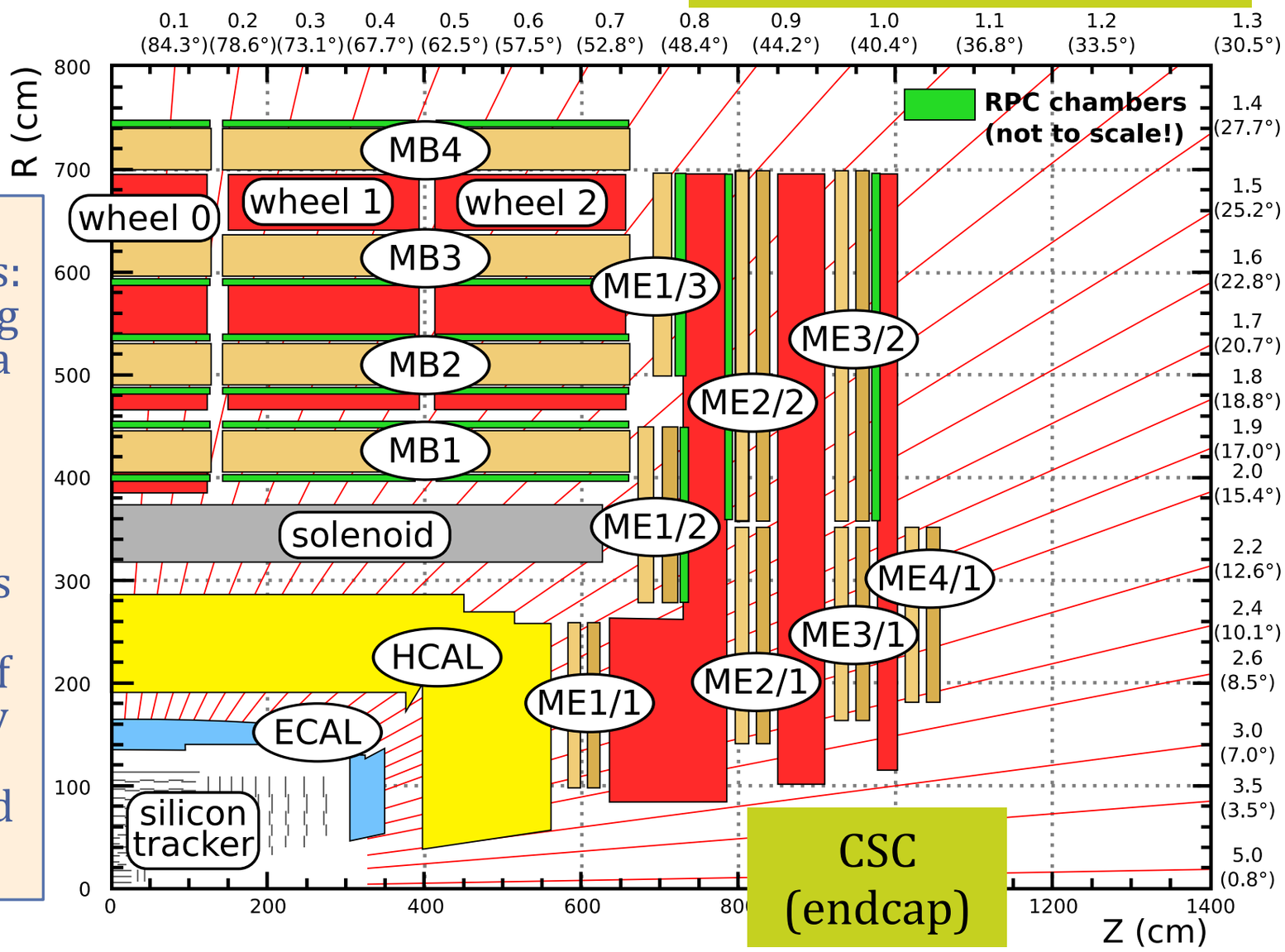
- Some guiding principles and lessons
  - All-hadronic / MET signals will likely become buried
  - Third-generation objects will continue to be important
  - Capability for SM measurements must be maintained
  - Inclusive high-mass searches will continue, no matter what
  - Trigger performance (mainly 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

Muons to 2020

DT (barrel)

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

RPC (barrel and endcap)



CSC (endcap)

New RE4 RPC

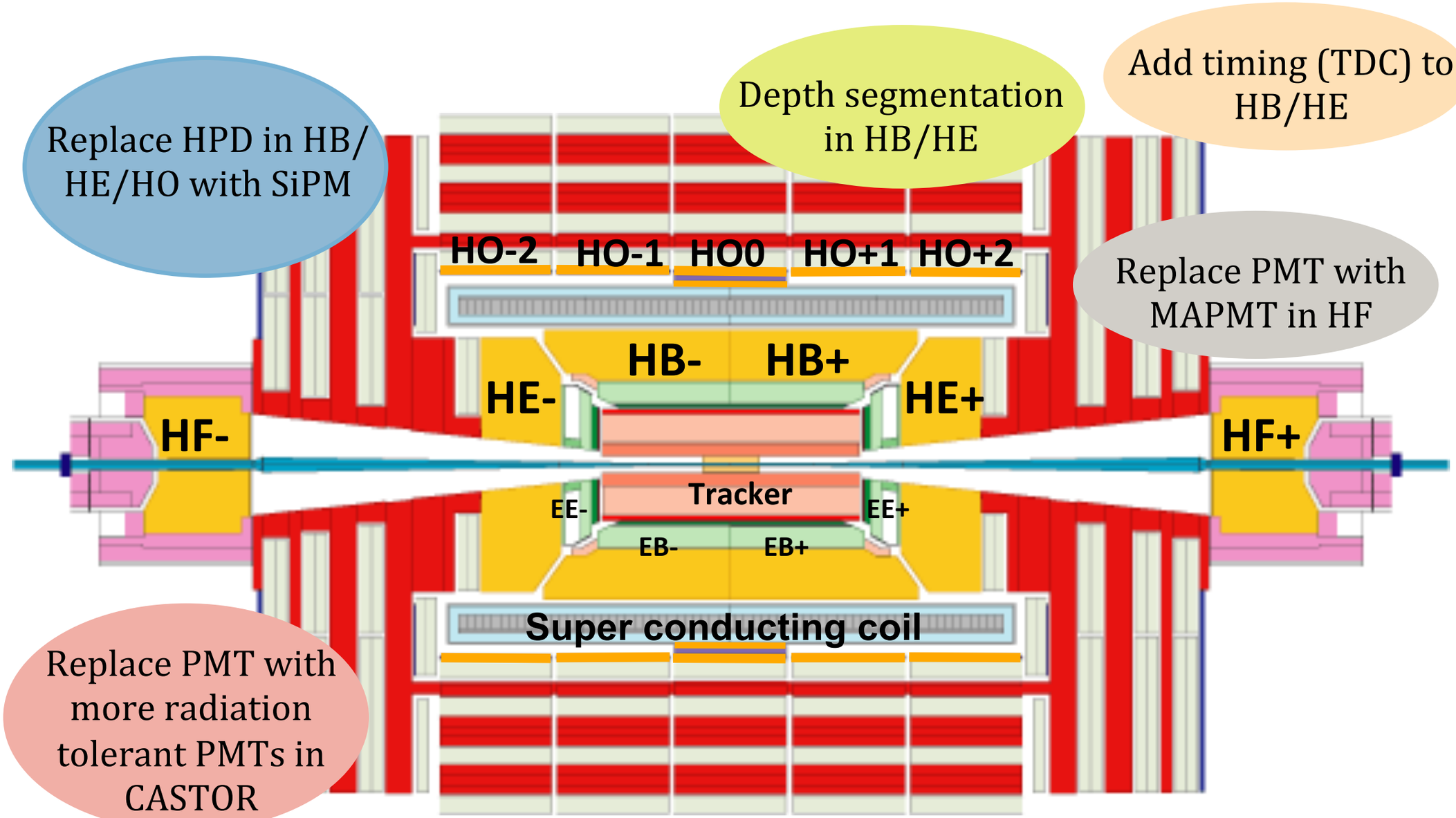
New ME4/2 CSC

Work on ME1/1 and trigger

Extend eta range of RPC

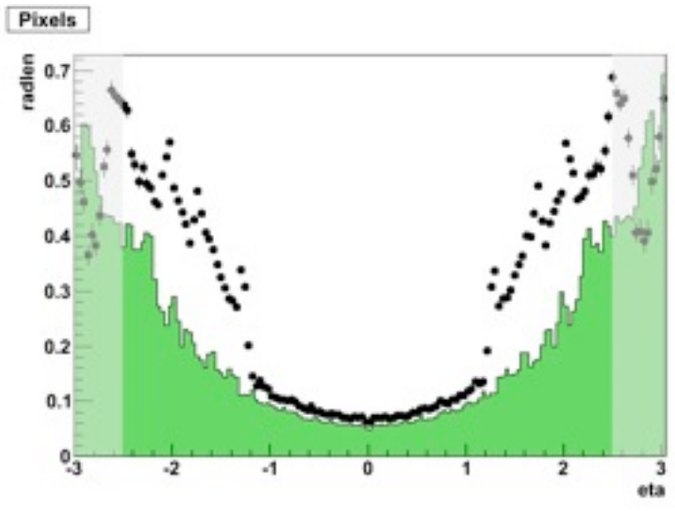
- Performance improvements & trigger / tracking robustness against high luminosity

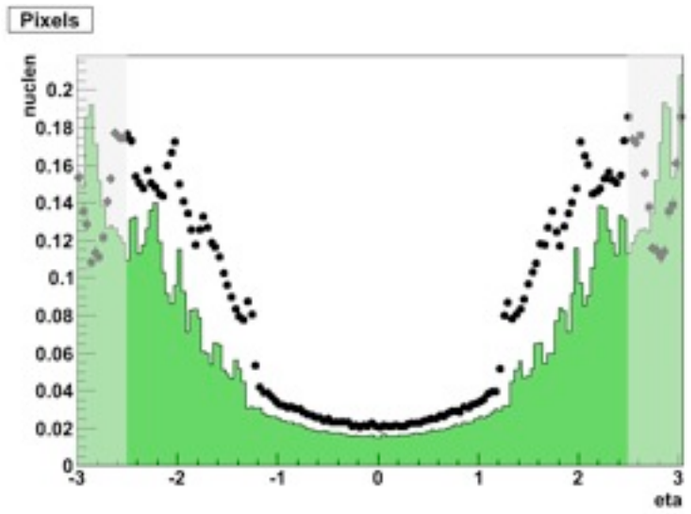
HCAL to 2020



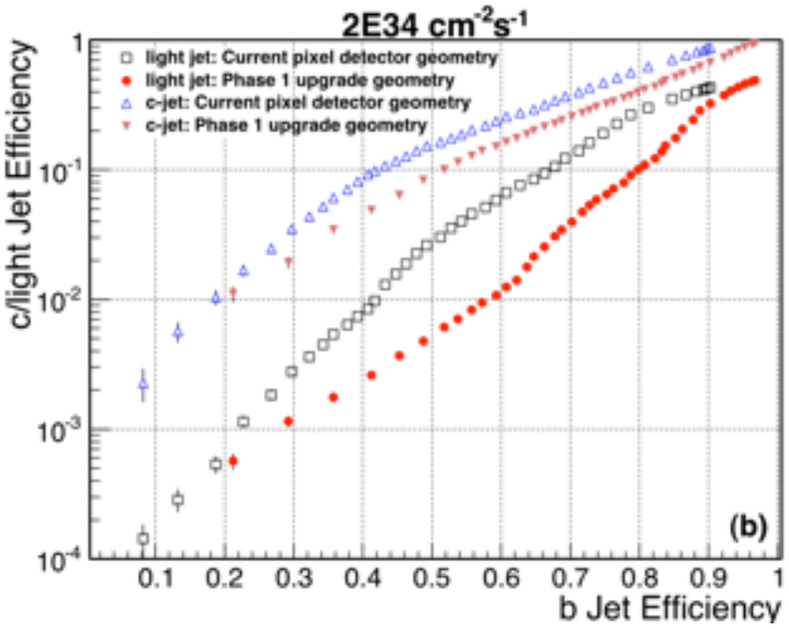
- Replacement of noisy HPDs, addition of depth segmentation to combat light loss
- Adds robustness for both trigger and offline analysis

Pixel Upgrade: 2017

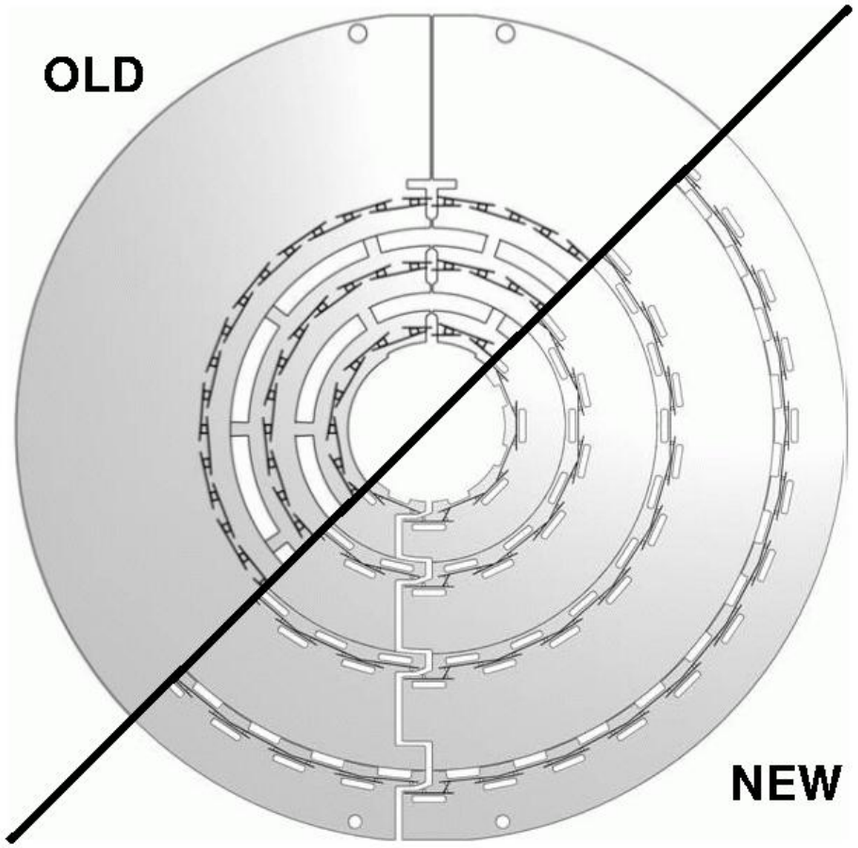




Plots produced with UK software



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

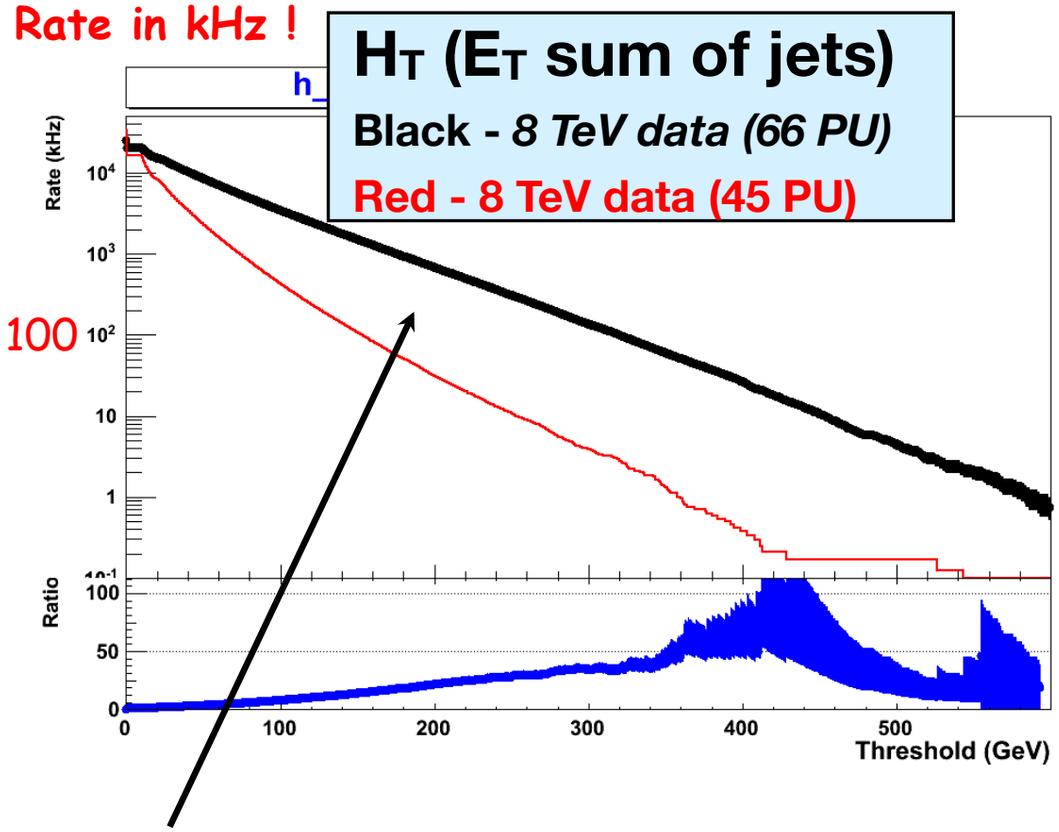


- Pixels can be replaced independently of inner detector
  - Additional 4th barrel / 3rd e.c. layer; CO2 cooling; fully digital readout
  - UK contribution: upgrade of the entire readout and control system

L1 Performance at High Pileup

Rates shown for $L_{inst}=2\times10^{34}cm^{-2}s^{-1}$

Rate in kHz !

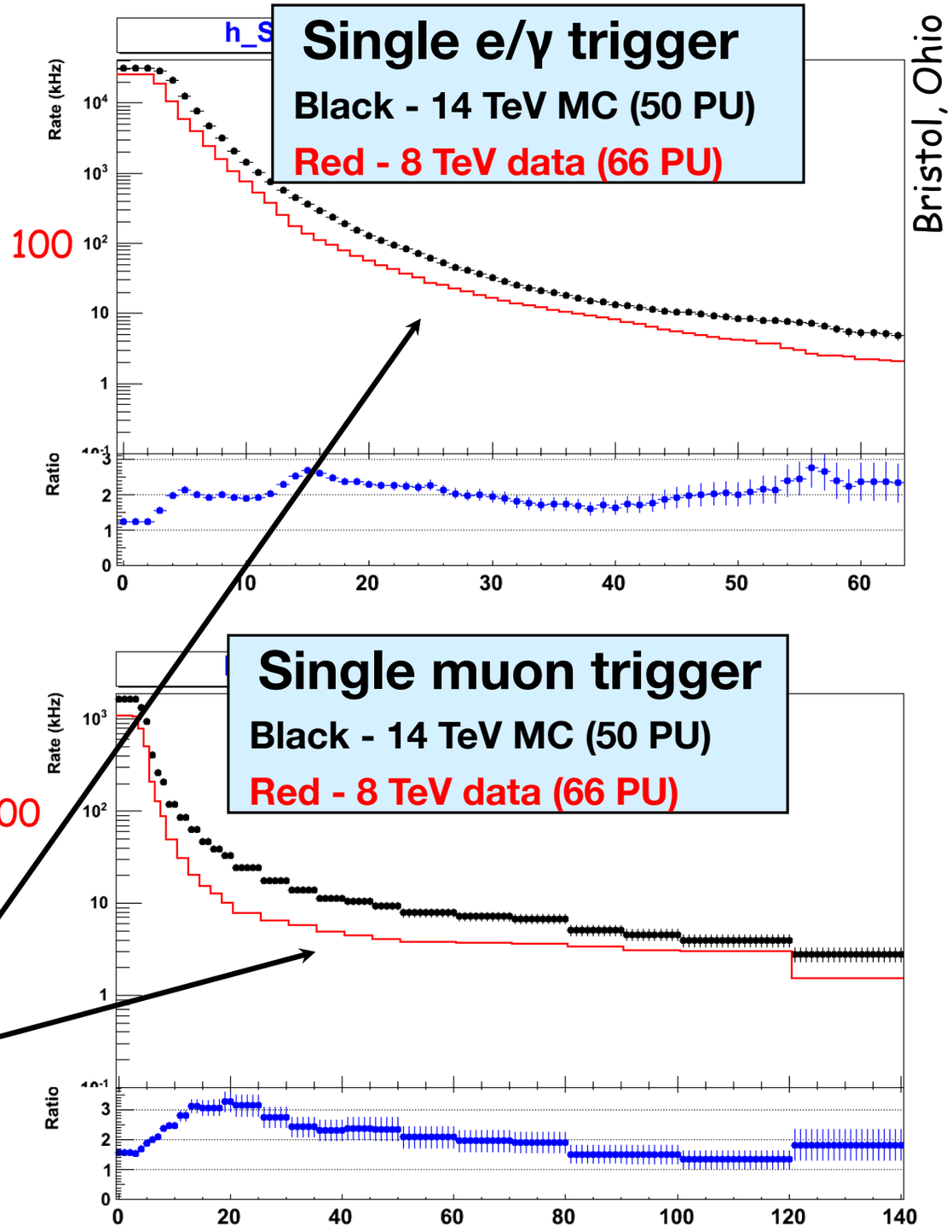


H_T (E_T sum of jets)

Black - *8 TeV data (66 PU)*

Red - 8 TeV data (45 PU)

Jet trigger rates strongly dependent on PU



Single e/γ trigger

Black - 14 TeV MC (50 PU)

Red - 8 TeV data (66 PU)

Single muon trigger

Black - 14 TeV MC (50 PU)

Red - 8 TeV data (66 PU)

Poor control of lepton rates at high thresholds due to p_T resolution

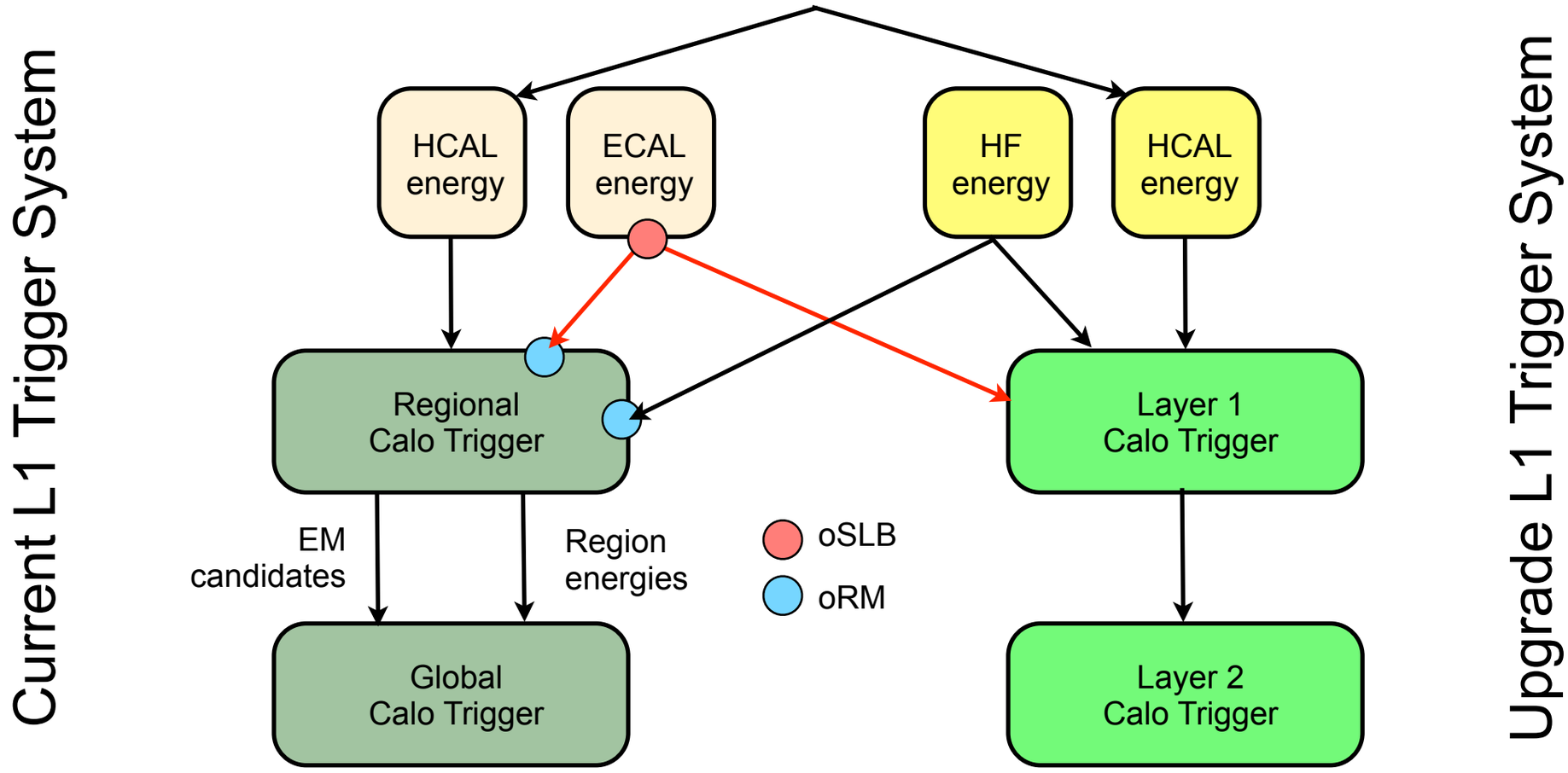
Bristol, Ohio

L1 Rate Predictions

Algorithm	8 TeV 7E33 ~25 PU		14 TeV 2E34 50 PU	
	Thresh (GeV)	Rate (kHz)	Thresh (GeV)	Rate (kHz)
Single EG	22	10	46	10
Single IsoEG	18	9	31	9
DoubleEG	13, 7	9	22, 12	9
Single Muon	16	9	50	9
Dble Muon	10, open	5	35, open	5
EG+Mu	12, 3.5	3	21, 6	3
Mu+EG	12, 7	2	25, 15	2
SingleJet	128	2	188	2
DoubleJet	56	10	132	10
QuadJet	36	2	96	10
Double Tau	44	2	56	2
MET	36	7	84	7
HTT	150	2	511	2

- Performance of current (non-upgraded) system at 50PU
  - Estimates from combination of high-PU data and simulation

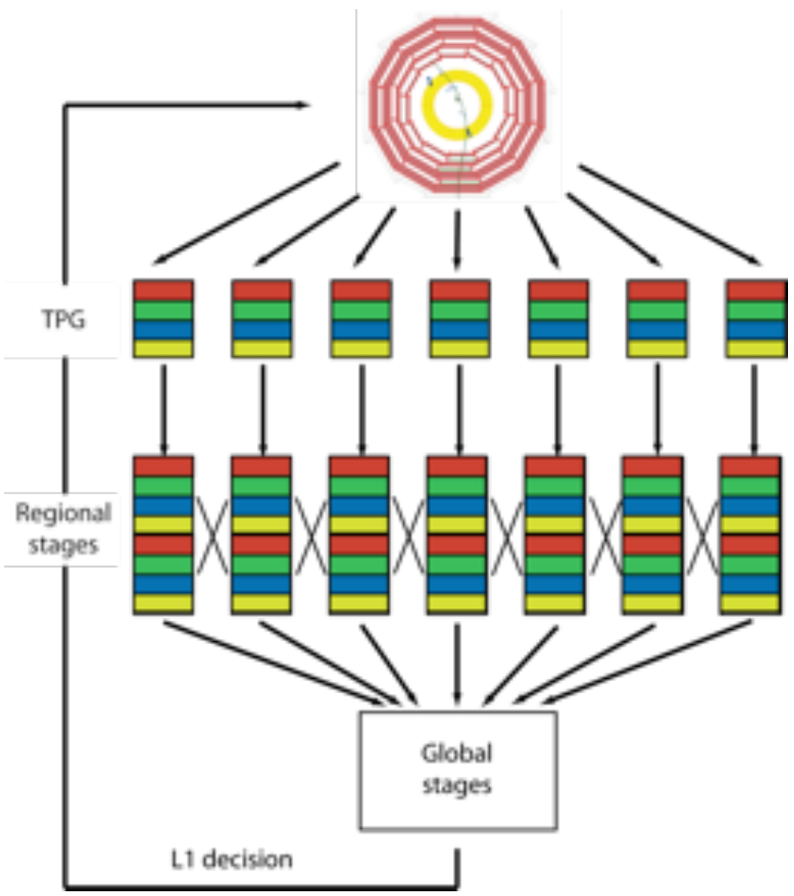
Parallel Trigger Systems

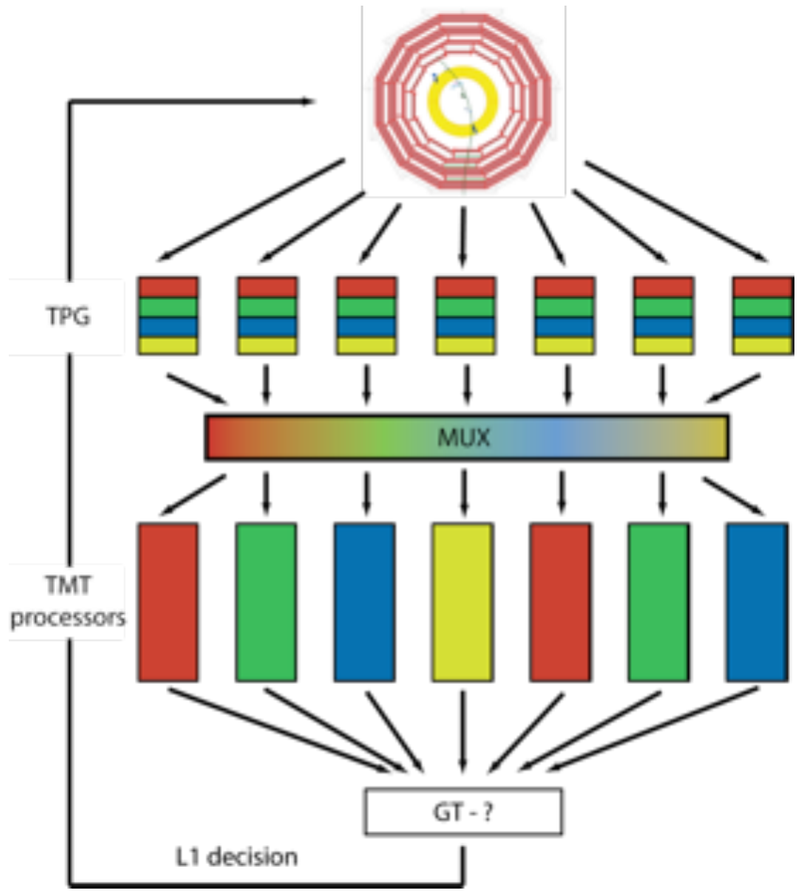


- Split detector data
  - Passive splitters before buffers for HCAL; dual optical outputs for ECAL
- Run parallel trigger systems
  - Commission new trigger in 2015; switch is purely a software change

UK Upgrade Plans: L1 Trigger

Pipelined architecture

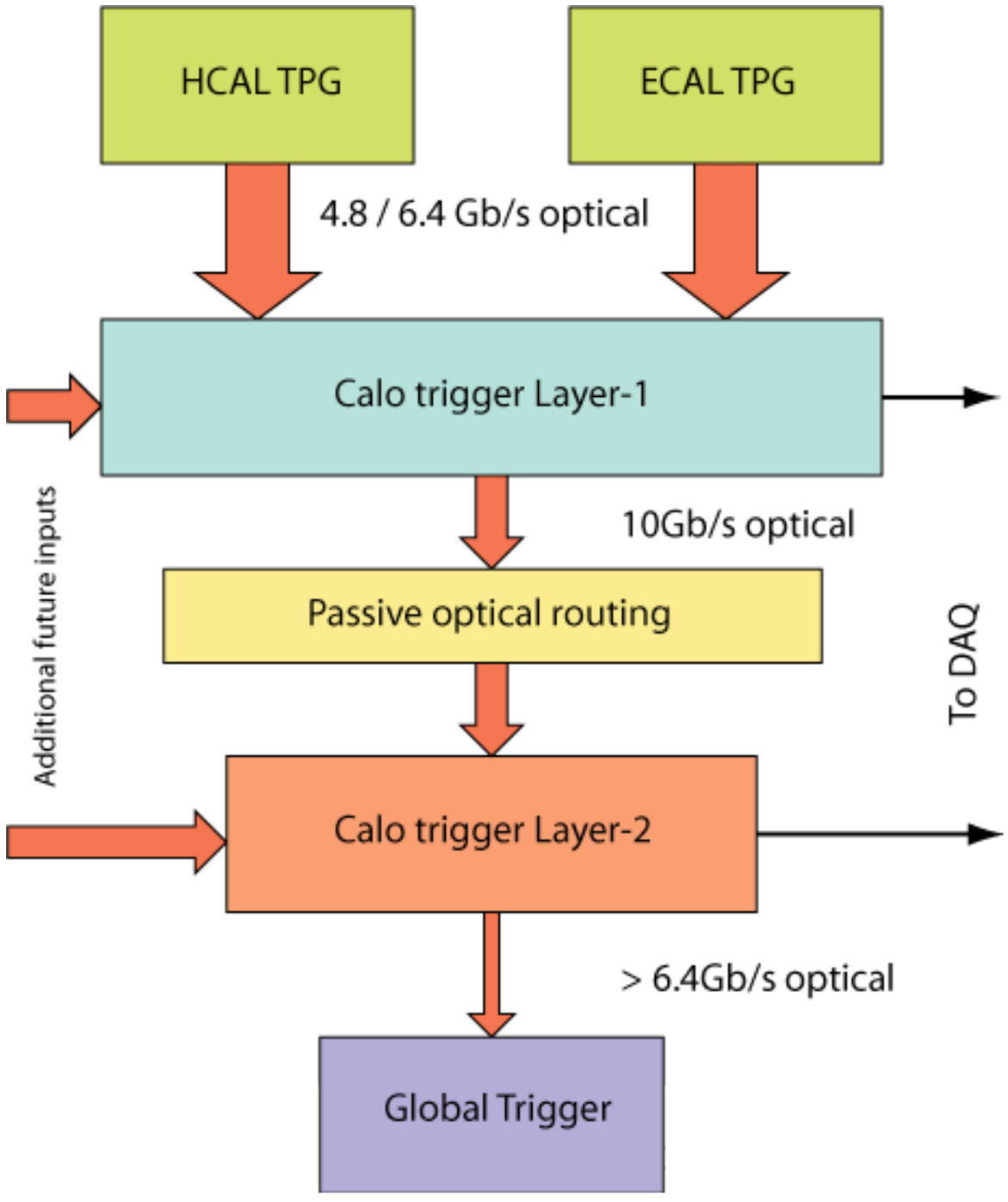




Time-muxed architecture

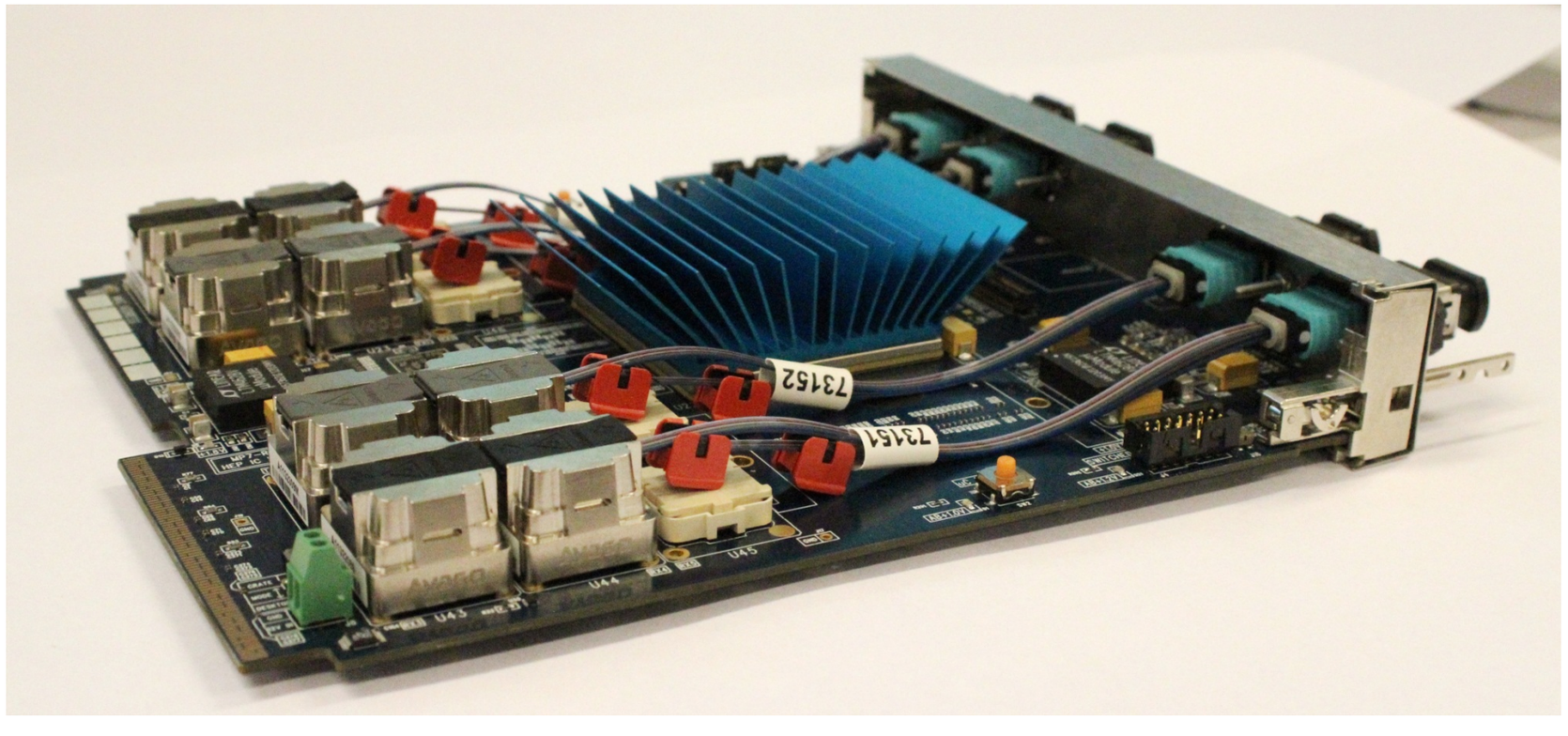
- Maintain or improve L1 performance at high PU
  - Use *full* detector data today; more from upgrade muons, HCAL, later
- Time-multiplexed concept for L1 calorimeter trigger
  - Allows much greater flexibility, redundancy, cross-subsystem algorithms
  - Paves the way for inclusion of tracking information later on

System Design



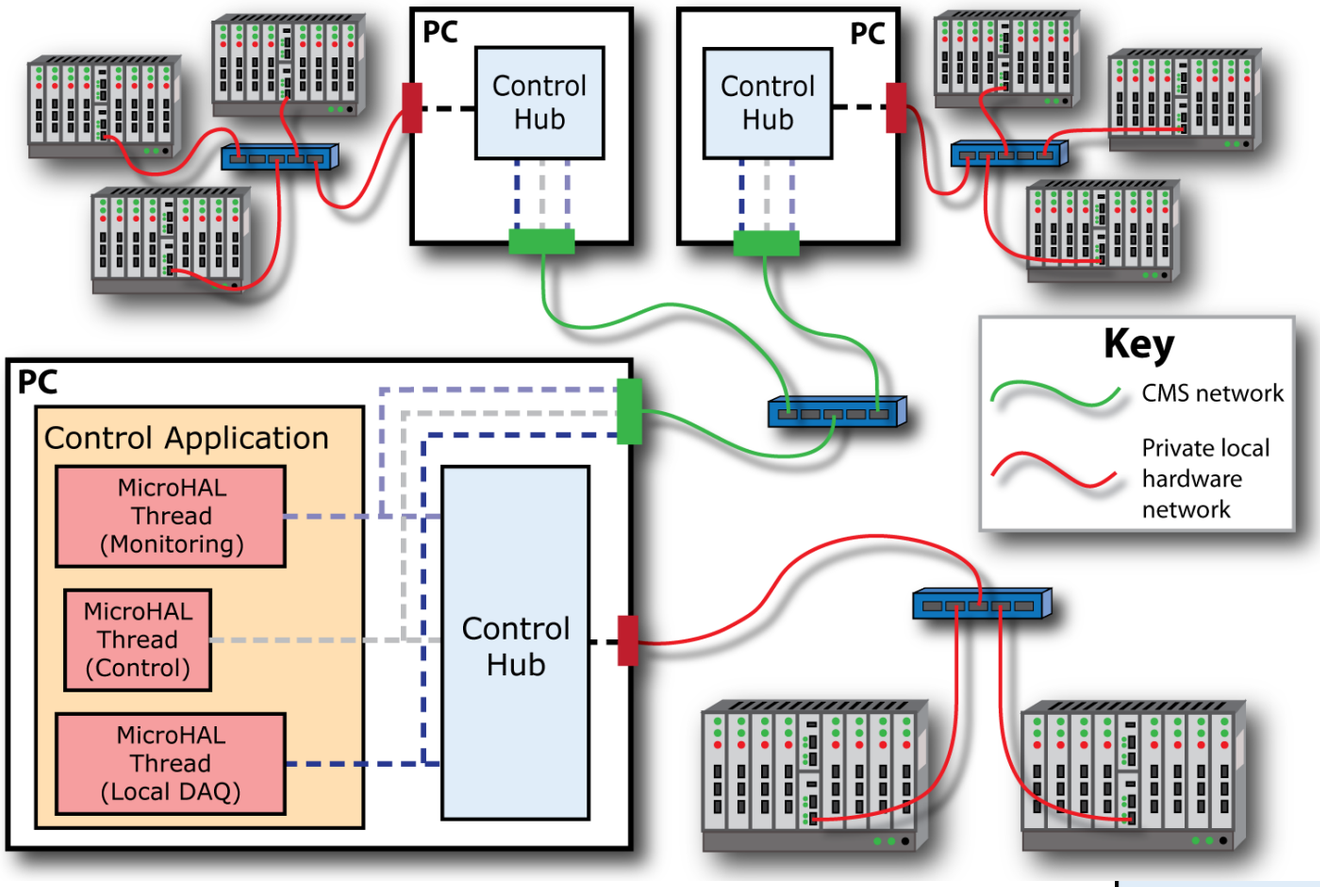
- Classic two-layer system
- Layer-1
  - Data reformatting / reduction
- Layer-2
  - Object identification, sorting
- Inputs
  - oSLB inputs from ECAL
  - uHTR inputs from HCAL / HF
  - Spare capacity for future inputs
- Outputs
  - Trigger objects to GT
  - Monitoring data to DAQ via one AMC13 per crate

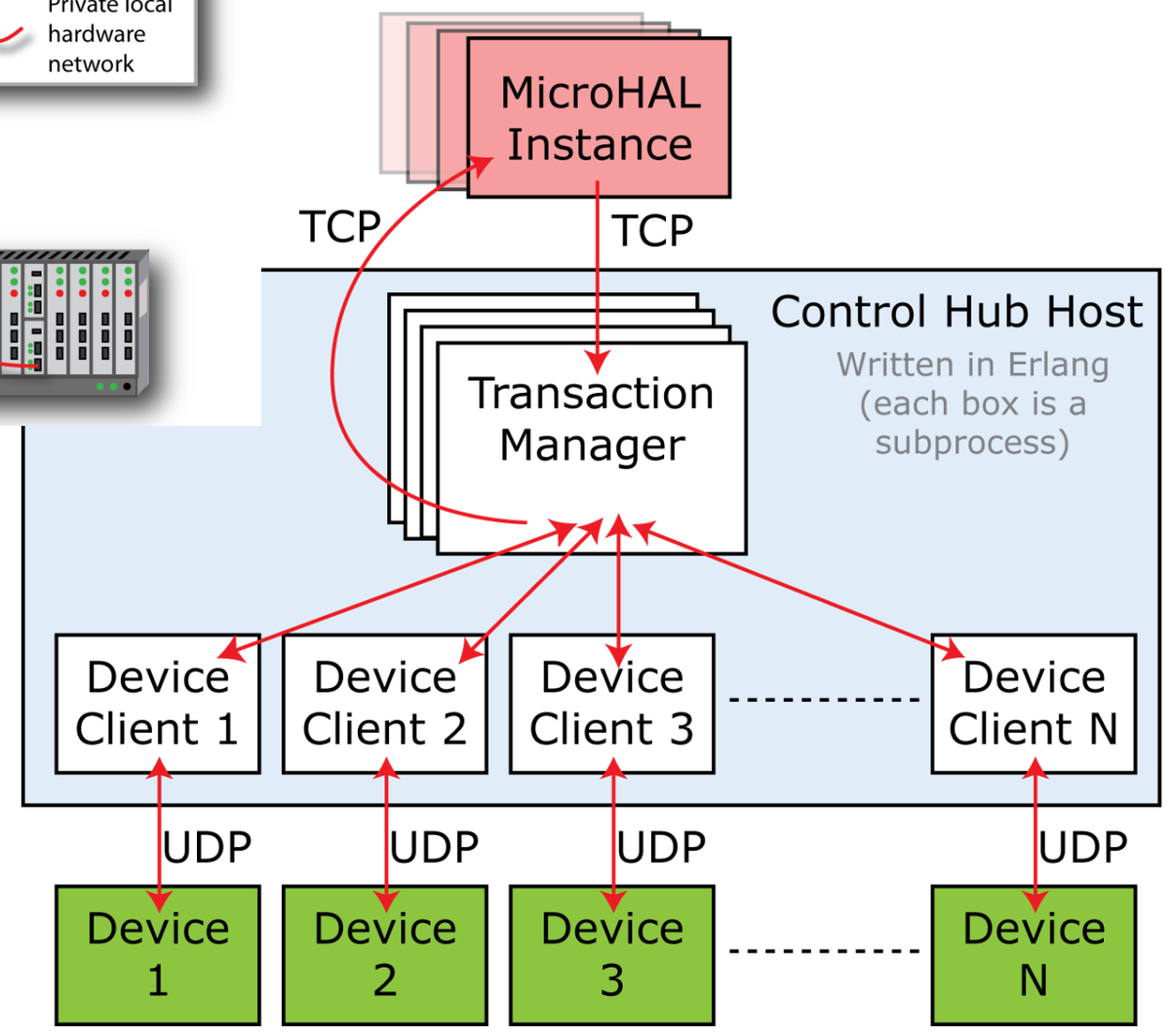
UK Upgrade Plans: Hardware Development



- 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
  - STFC funds now allocated for full L1 upgrade hardware by 2015
  - New L1 commissioning *in parallel* with existing system during 2015 run

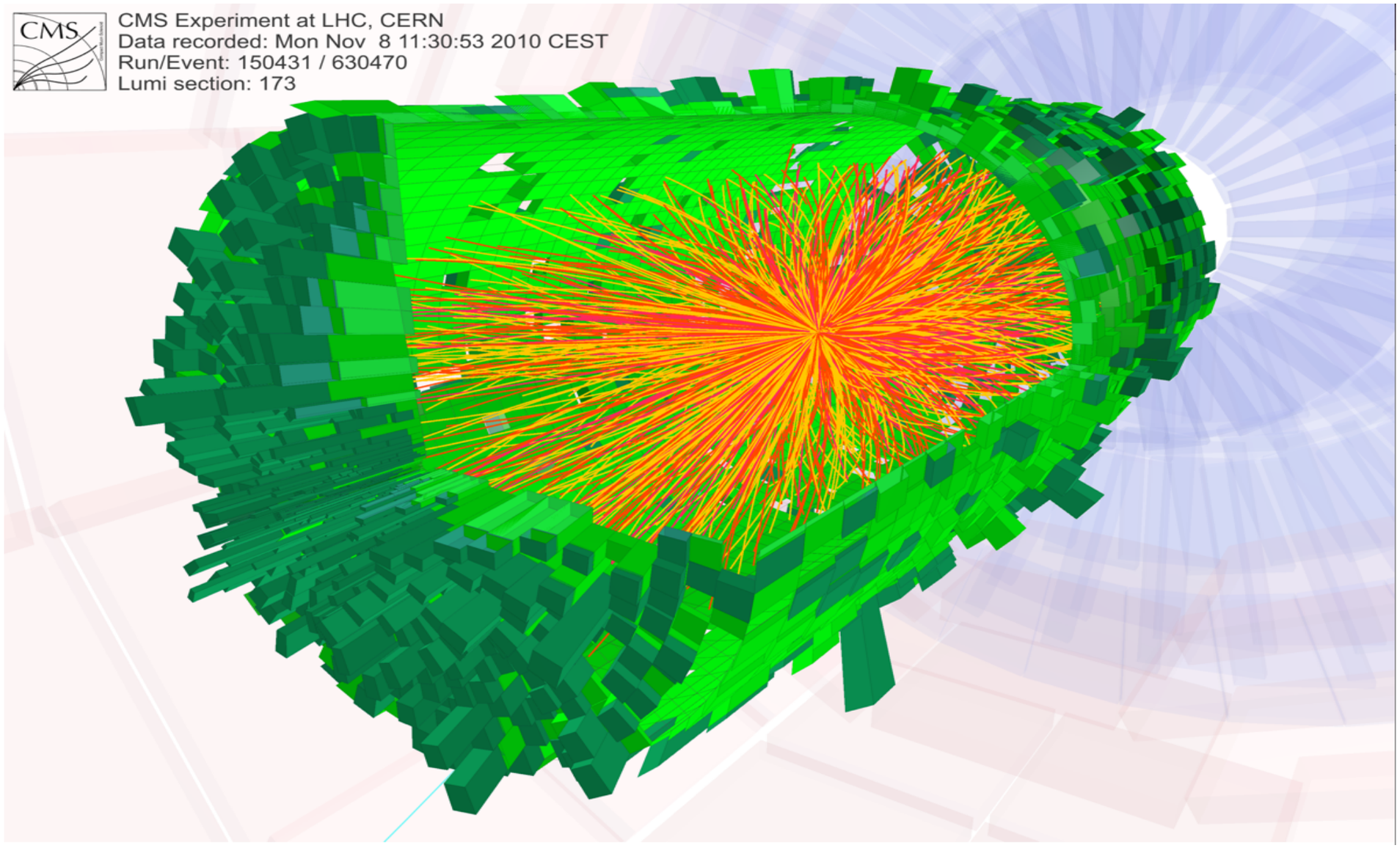
IPbus xTCA Control System





- Combined firmware / software control system
  - "VME replacement"
  - In use by ~10 non-CMS projects
  - Under study by ATLAS

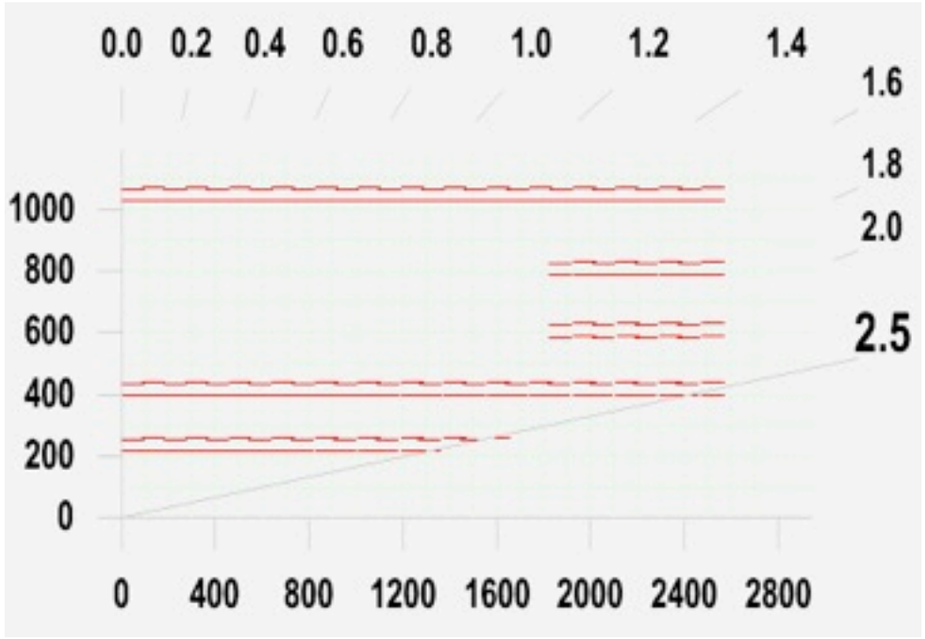
Conditions after LS3

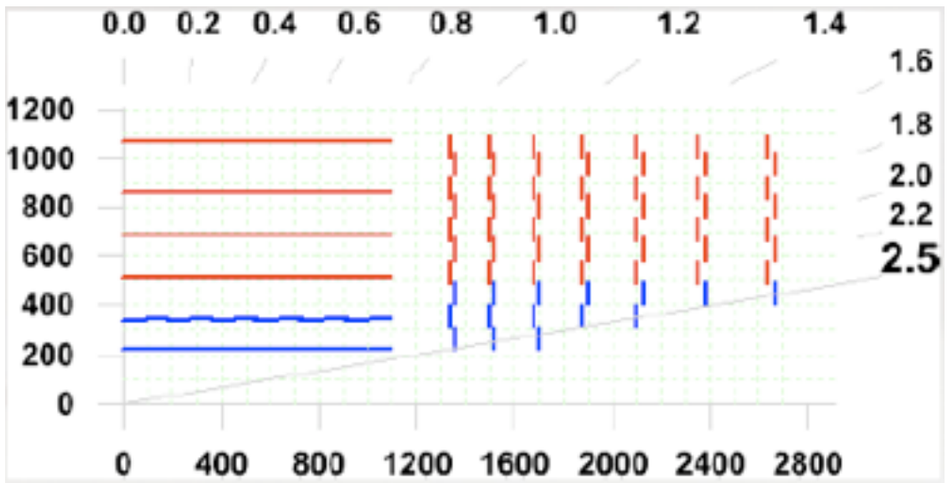


Central collision in 2010 HI run

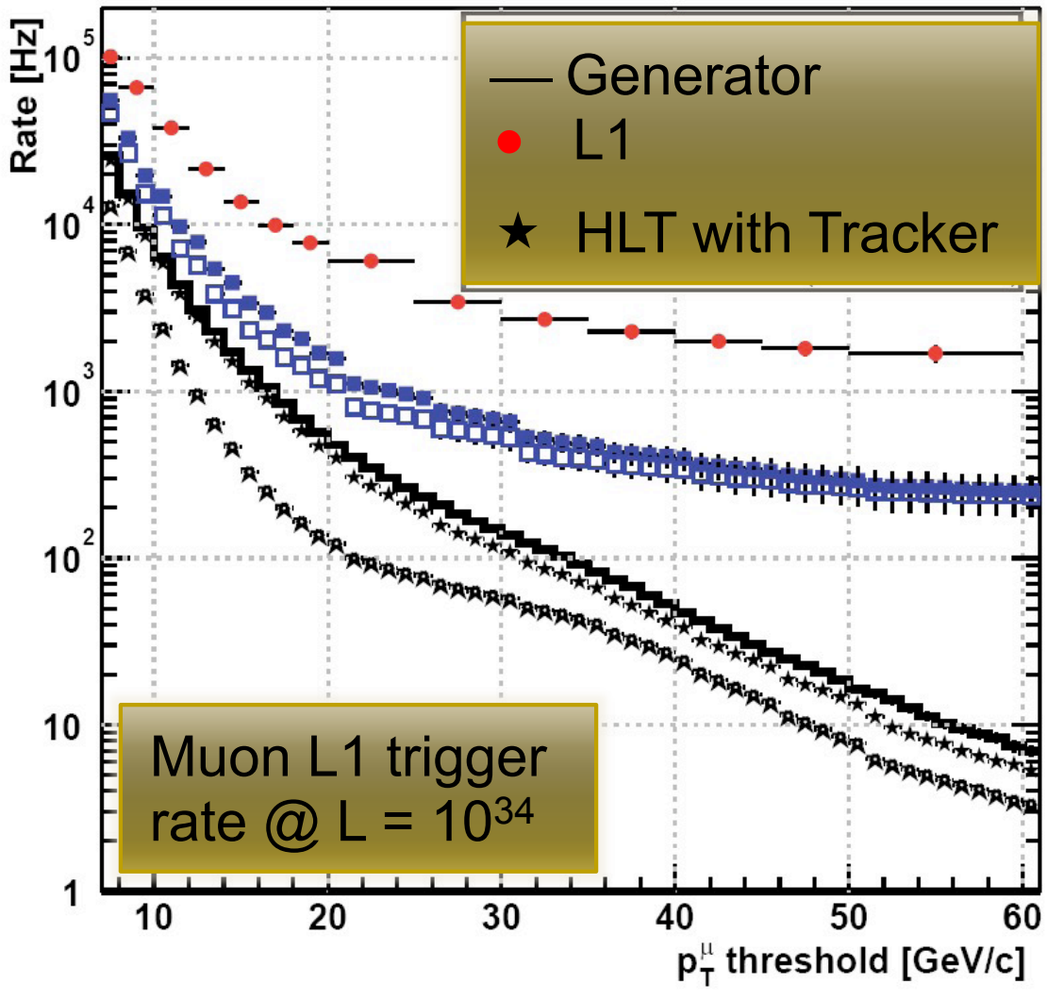
- HI runs give a forward look at ~10^35 conditions
  - Good: tracking, calorimetry, EWK boson ID, are all possible
  - Bad: trigger algos ineffective, event size huge, vertexing difficult

Phase 2: Tracker



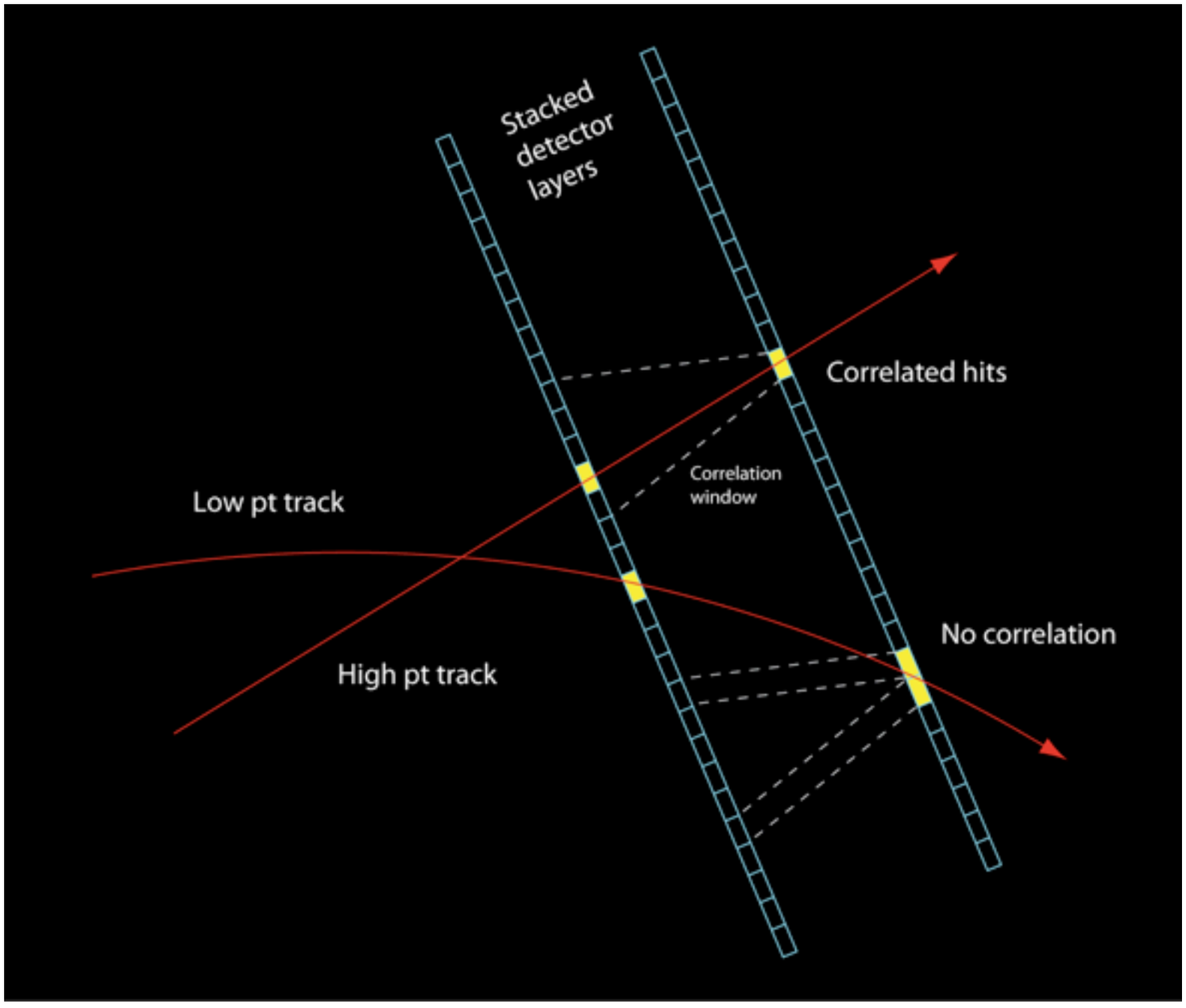


Red Layers = Pt Modules
For Tracking Trigger



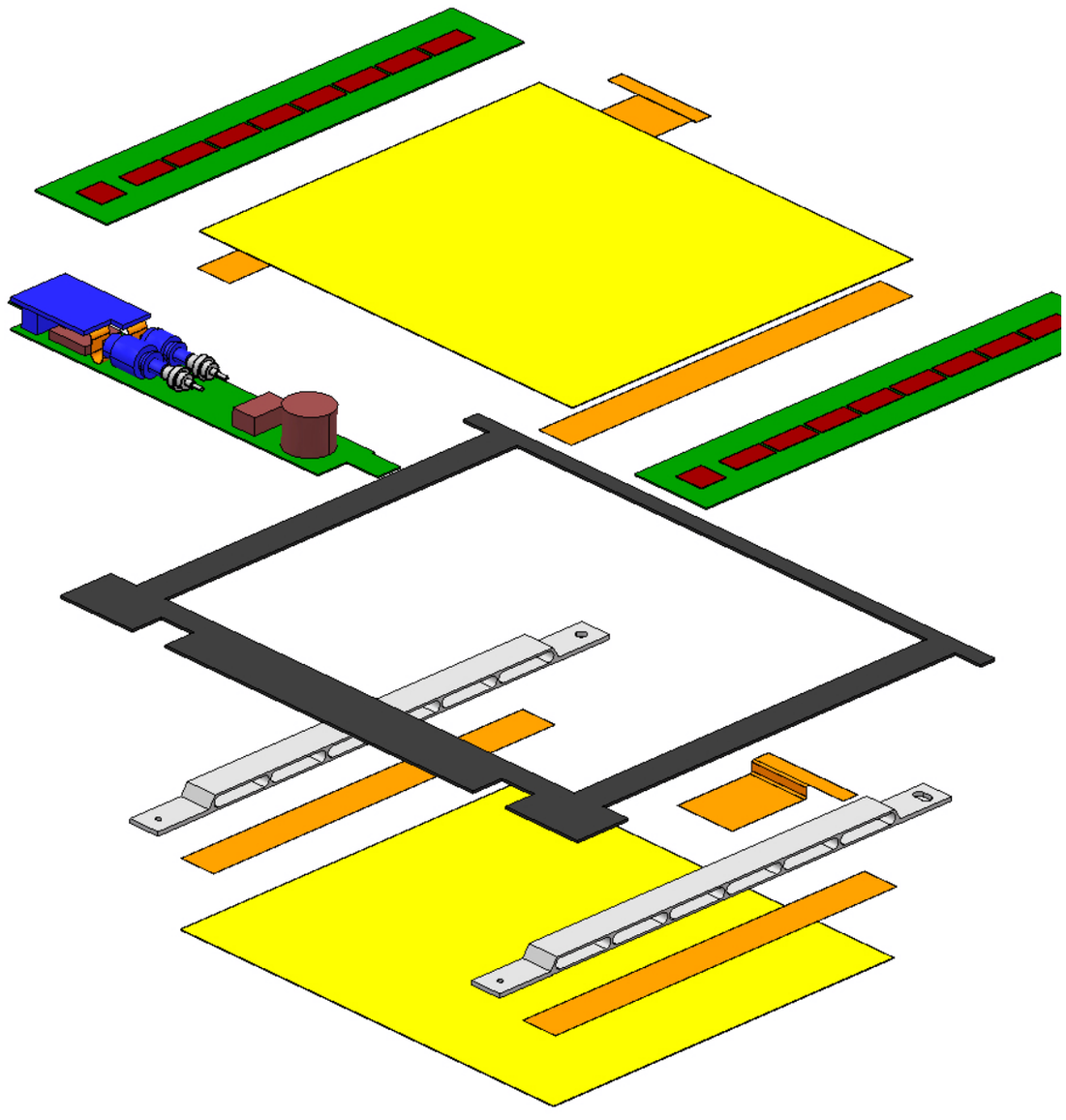
- Complete inner tracker replacement
  - Tenfold improvement in granularity to cope with >10^35 luminosity
  - Key issues are powering & cooling; readout; material budget; triggering

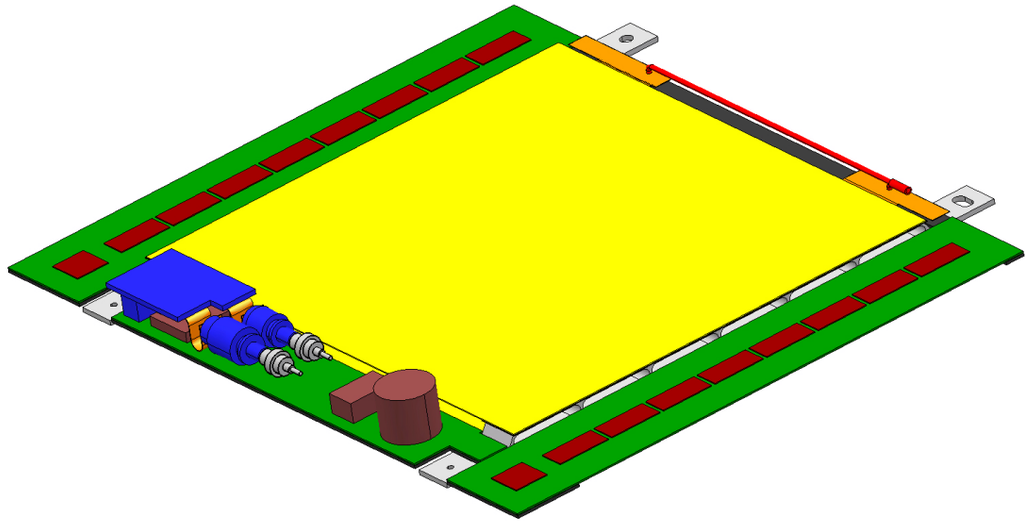
Phase 2: Track Trigger

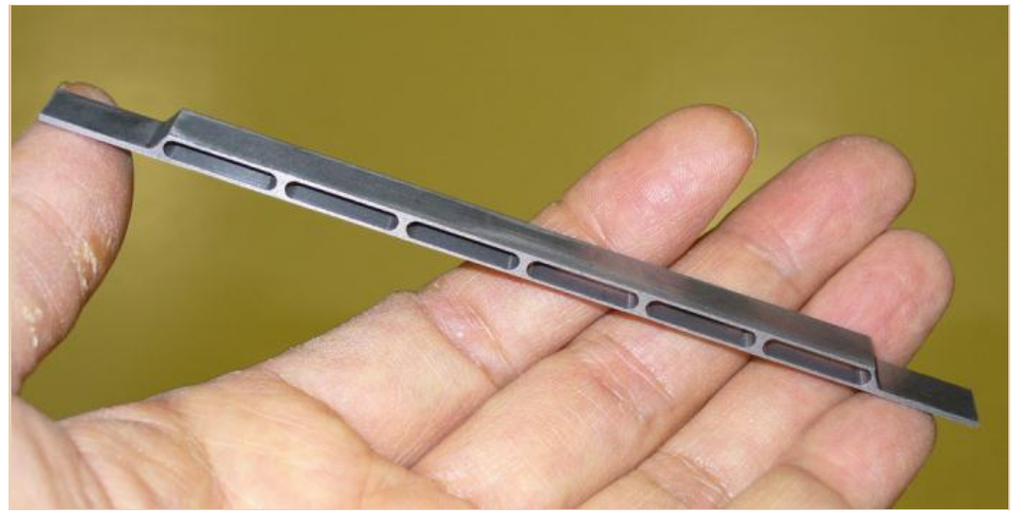


- "Stacked tracking" (short strips) an R&D focus - early stages
  - Trigger output from modules is a fixed-length list of identified stubs

Module Prototypes

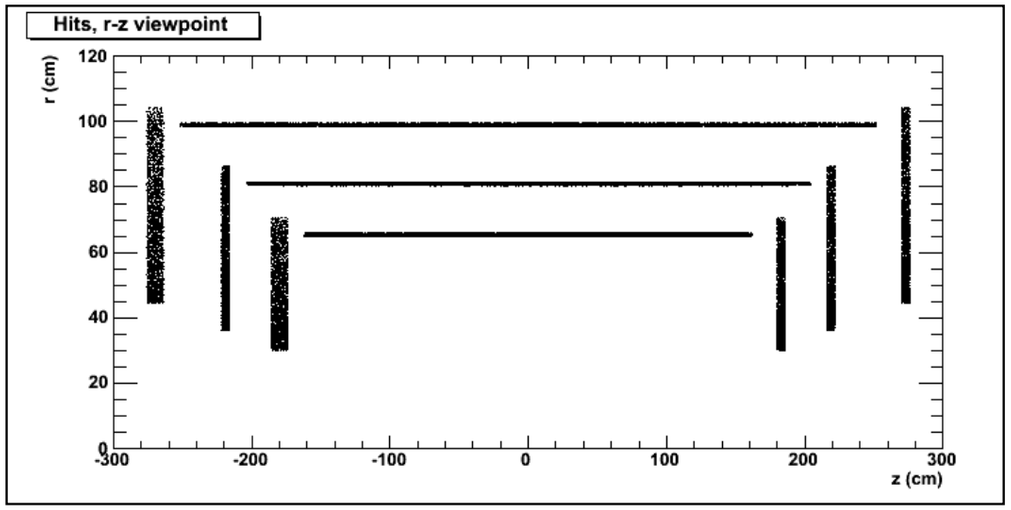




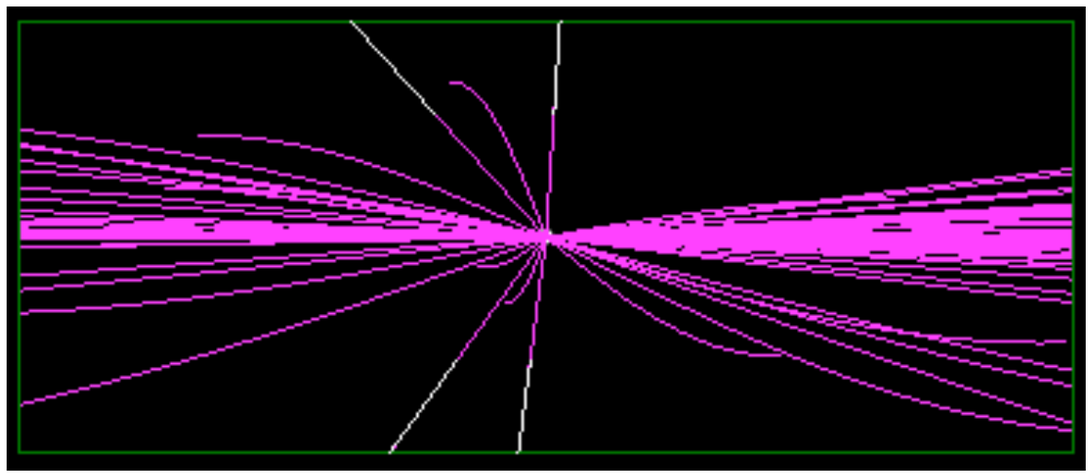


- ‘Double strips’ module now becoming a technical reality
  - v2 of readout ASIC (UK) now in hand; beam tests in 2013 & 14

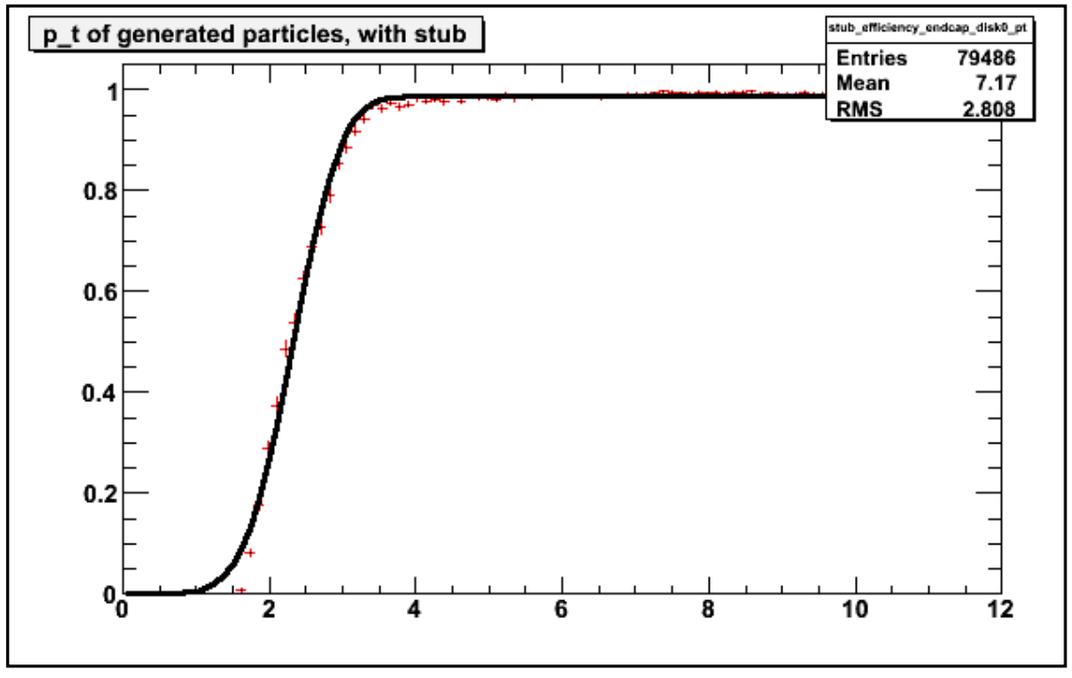
Phase 2: Track Trigger



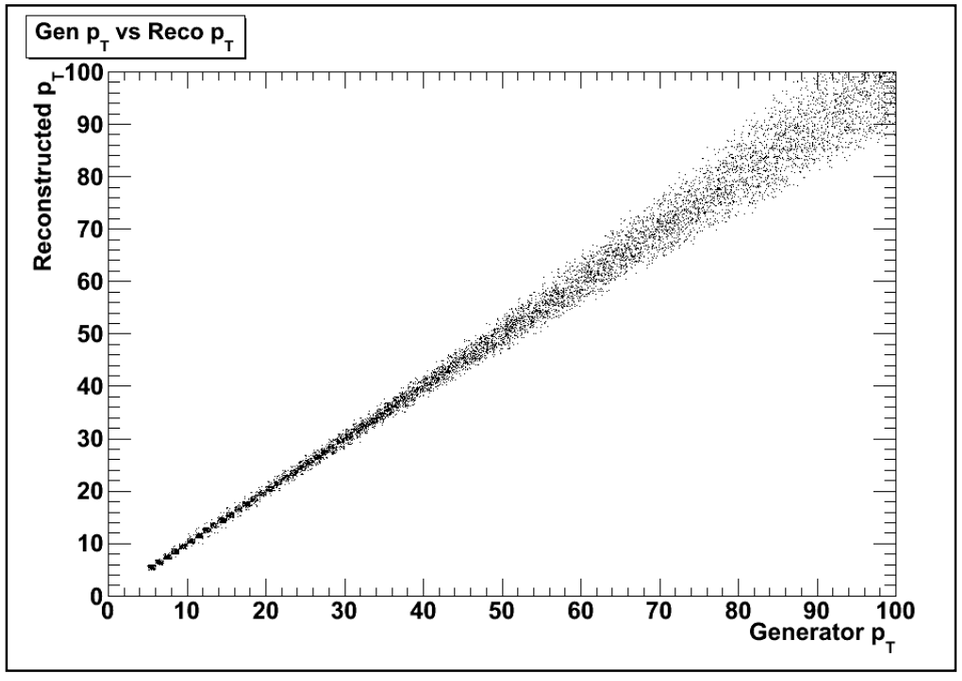
"X-ray" hit positions of three-stack trigger geometry with endcaps



Trigger track objects in three-stack geometry (Fireworks plot of H->Z->4μ)



Turn-on curve for endcap stub finding (disk0, 2mm stack, n_phi=1, n_r=1)



Trigger track finding algorithm pt reconstruction (single muons, gen vs trigger pt)

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
- The real work starts here...