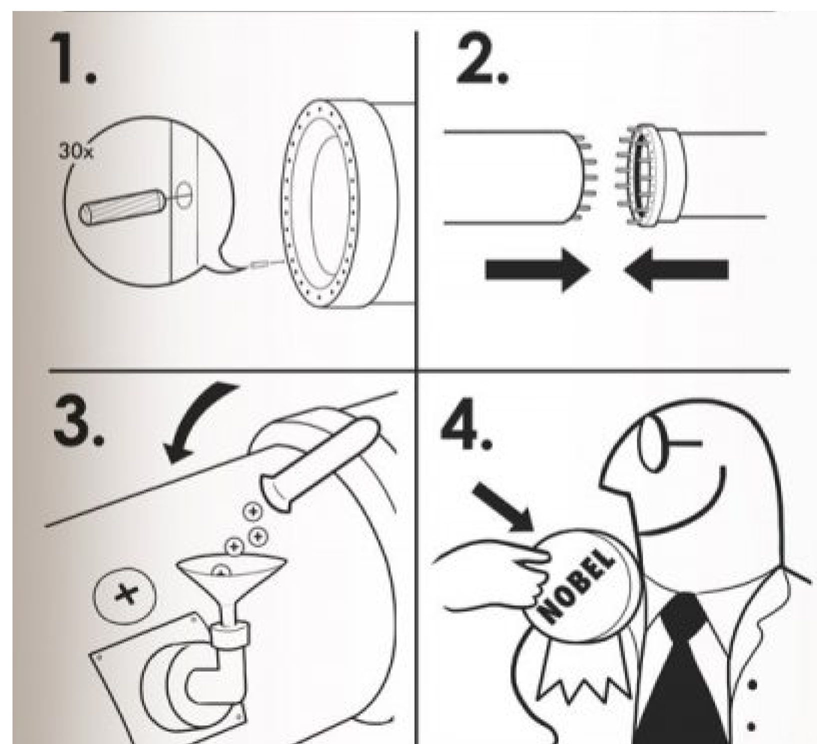
First year of CMS Operation: Operational Experience and First Physics Results

Anders Ryd

Cornell University
April 4, 2011



Outline

Introduction to CMS and the LHC

2010 Commissioning and Operation

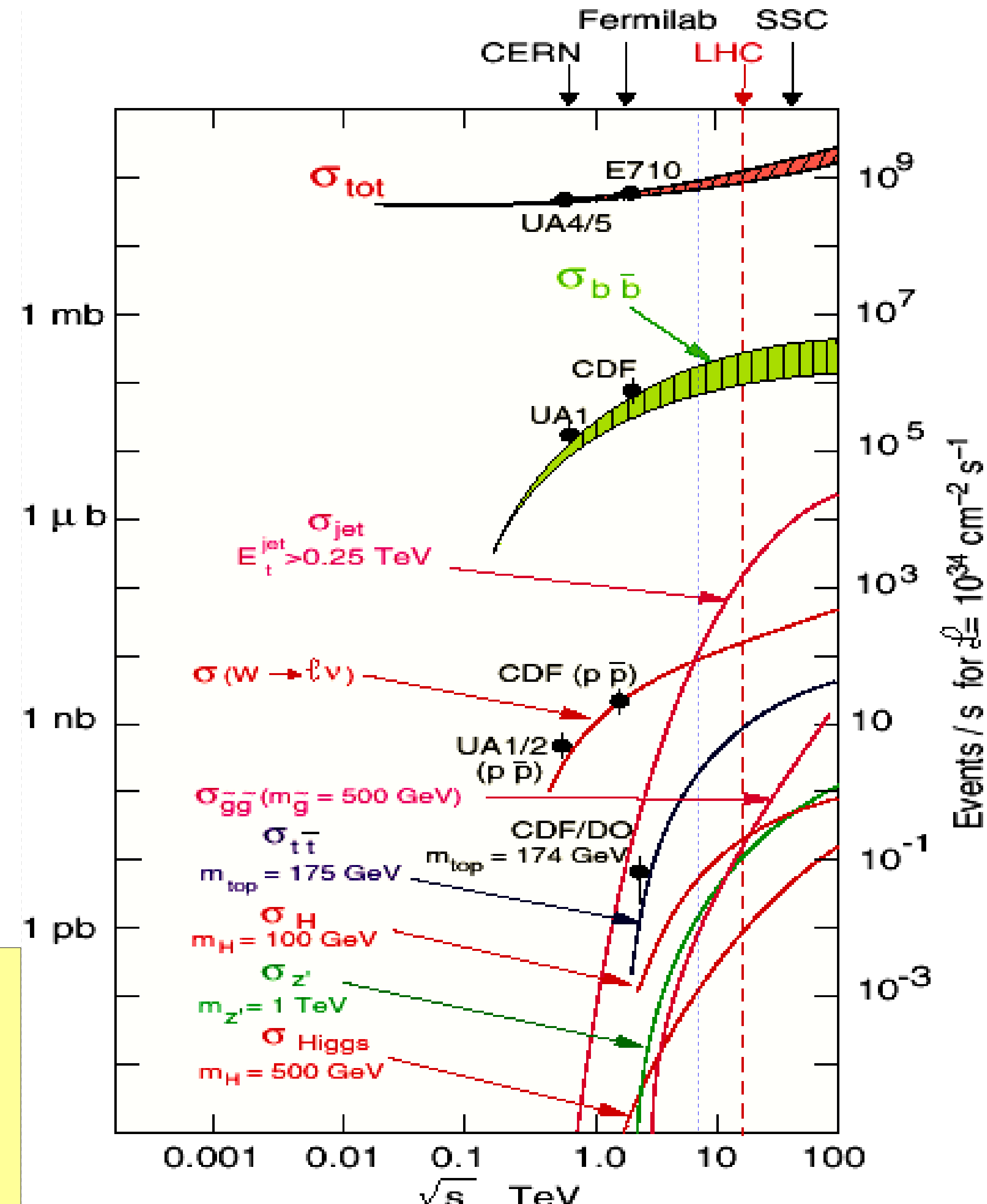
Physics Results

2011 (and 2012) Running

Summary

The LHC Challenge

- The LHC will collide protons on protons at E_{cm}=14 TeV
  - Currently operating at E_{cm}=7 TeV
- Collisions every 25 ns or 40 MHz
- Design luminosity is 10^{34} cm^{-2}s^{-1}
  - Required to produce the rare processes we are interested in, *e.g.* Higgs
- With a total inelastic cross-section of 100 mb we have ~20 interactions per bunch crossing

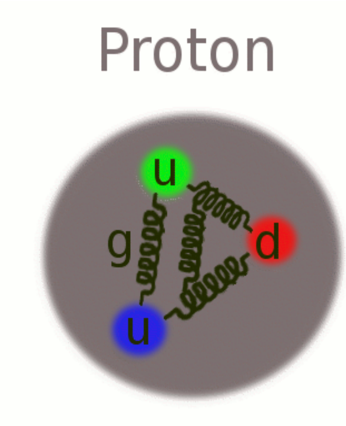


In particle physics luminosity is defined by:

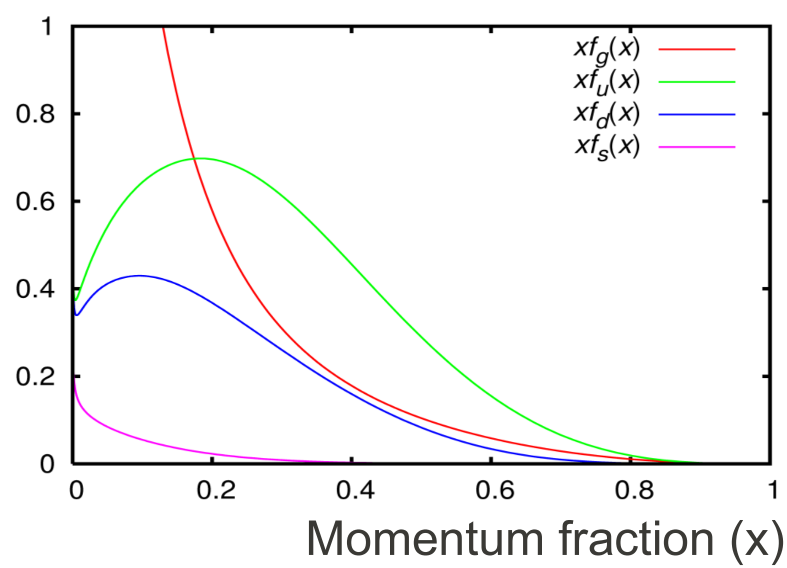
Rate=Luminosity × Cross-section

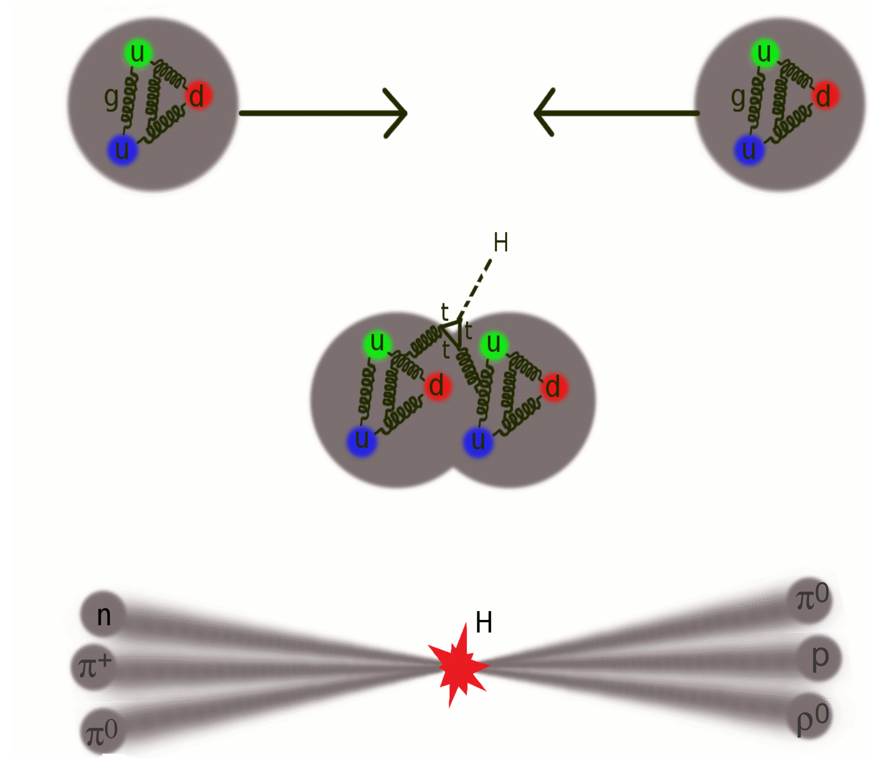
Proton-Proton Collisions

- Proton consists of three valance quarks: *uud*
  - plus the gluons that hold them together
  - and virtual $q\bar{q}$ pairs



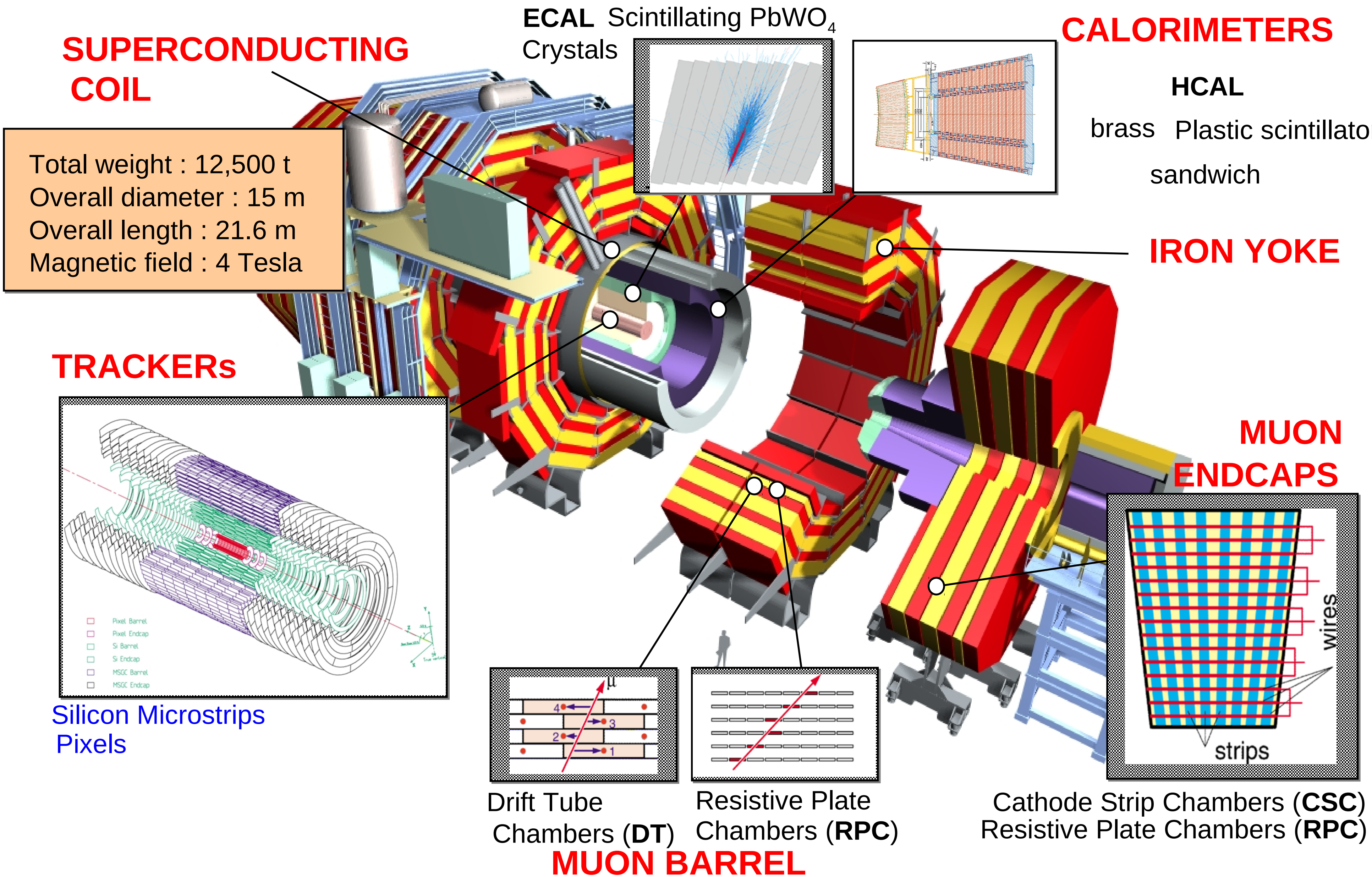
Parton momentum fraction



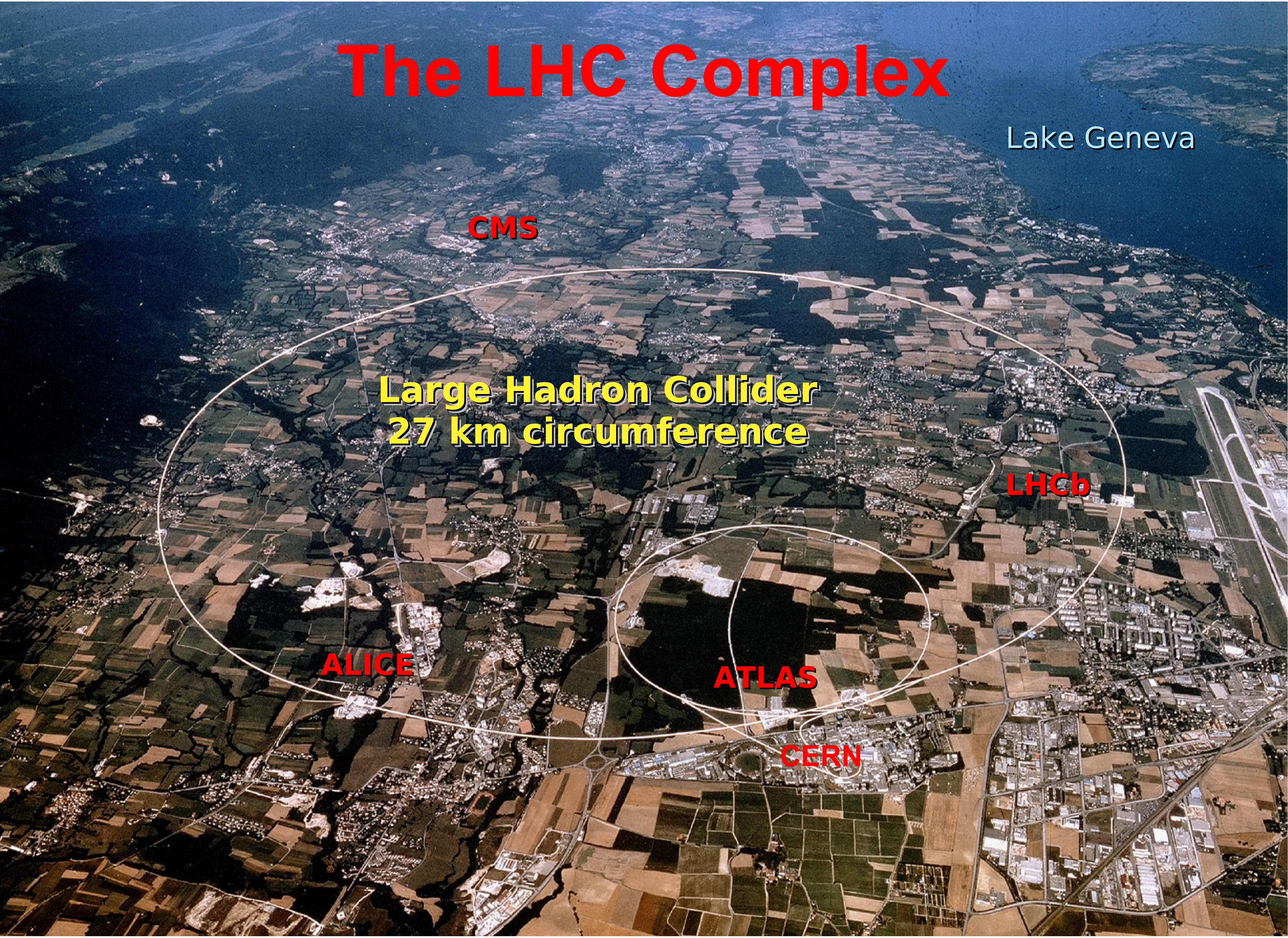


- For the produced particle or particles
  - Net transverse momentum ~zero
  - Longitudinal momentum can be large

CMS Detector



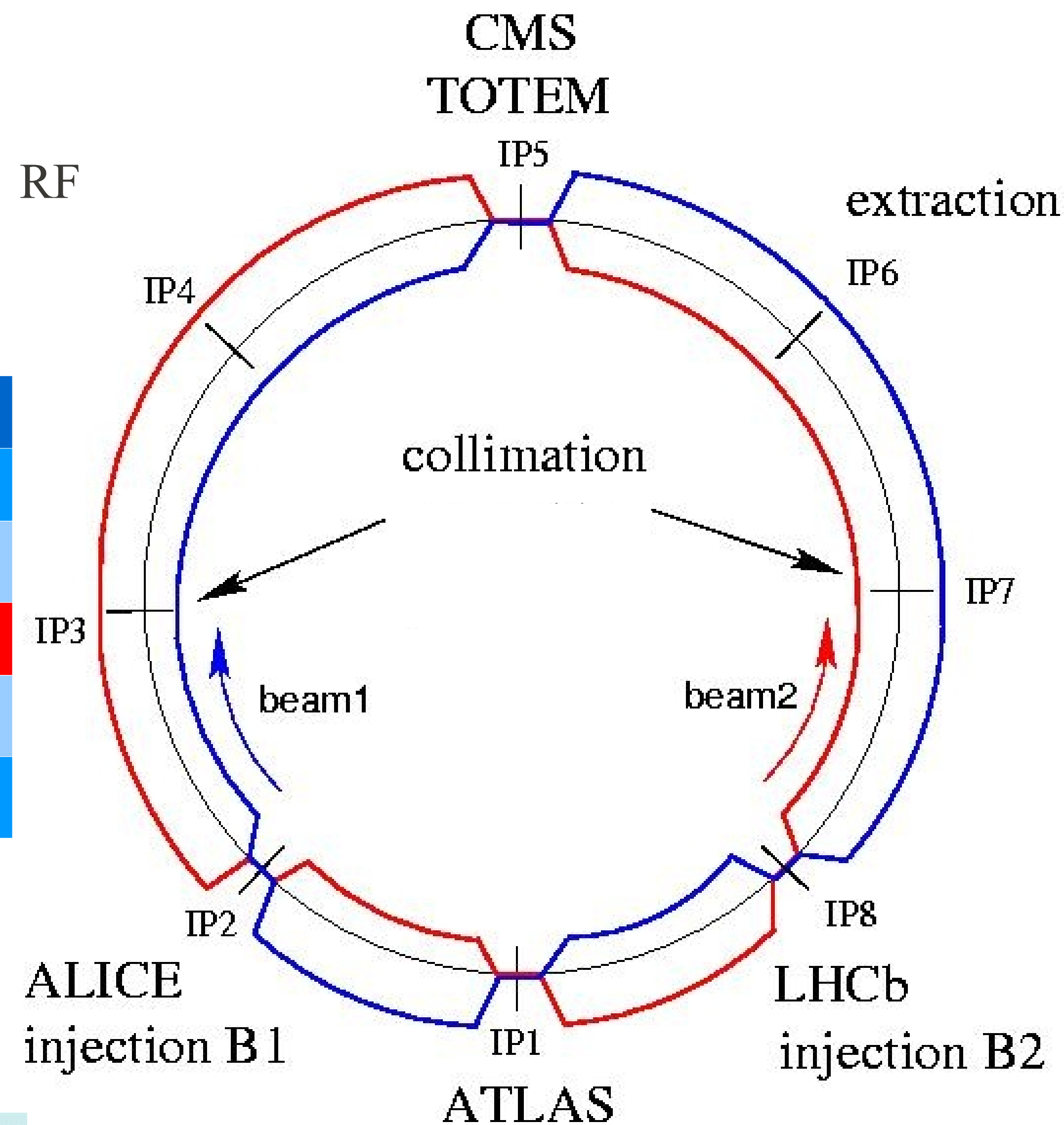
The LHC Complex



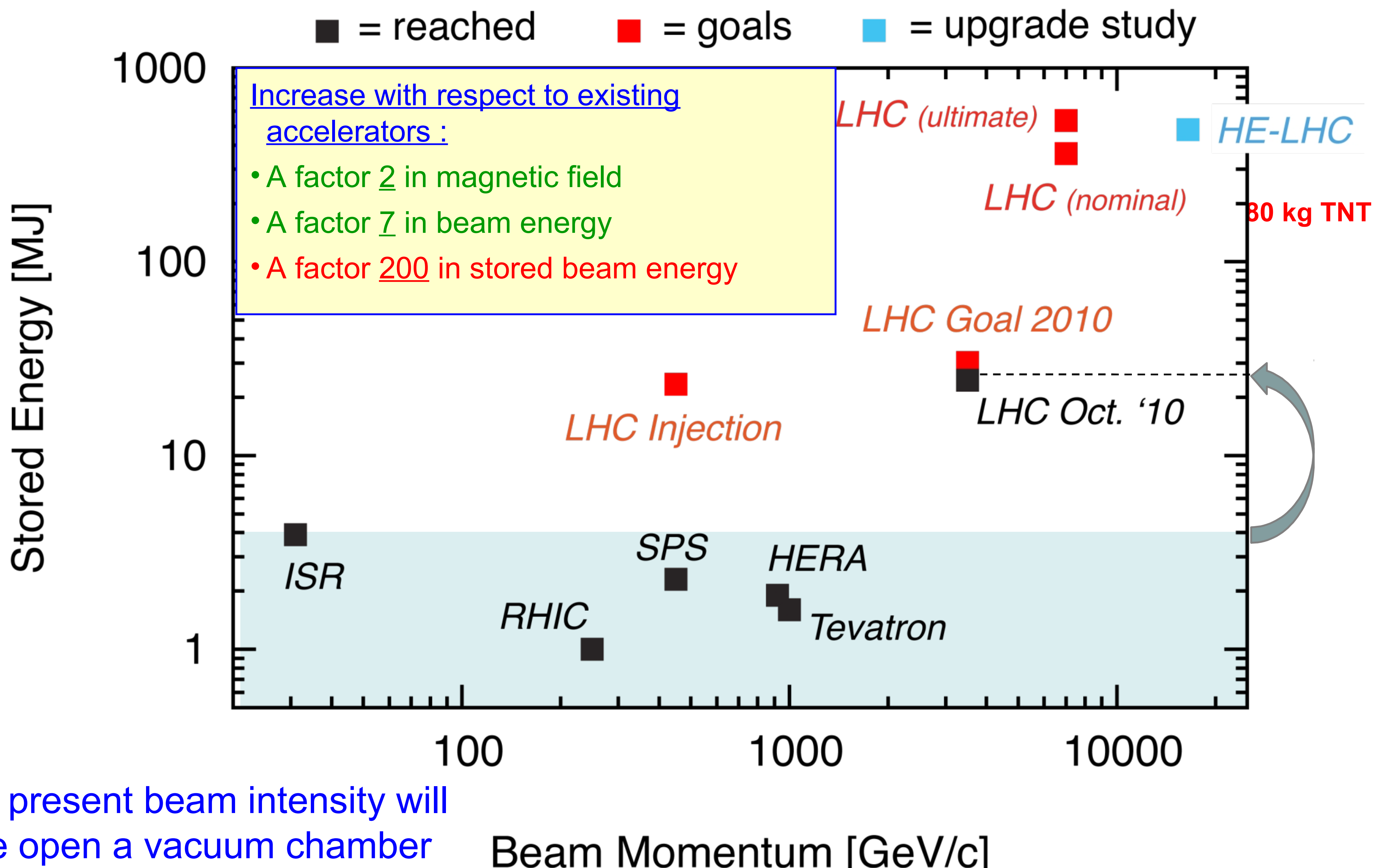
LHC Parameters

- 8 arcs (sectors), ~3 km each
- 8 long straight sections (700 m)
- Beams cross at 4 points

	Nominal	2010
Beam Energy	7 TeV	3.5 TeV
Protons per Bunch	1.15×10^{11}	1.2×10^{11}
No. of Bunches	2808	364
β^* (m)	0.55	3.5
Trans. Emittance (μm)	3.75	2.2



LHC Stored Energy



Increase with respect to existing accelerators :

- A factor 2 in magnetic field
- A factor 7 in beam energy
- A factor 200 in stored beam energy

The present beam intensity will slice open a vacuum chamber even at injection

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2009 Operation

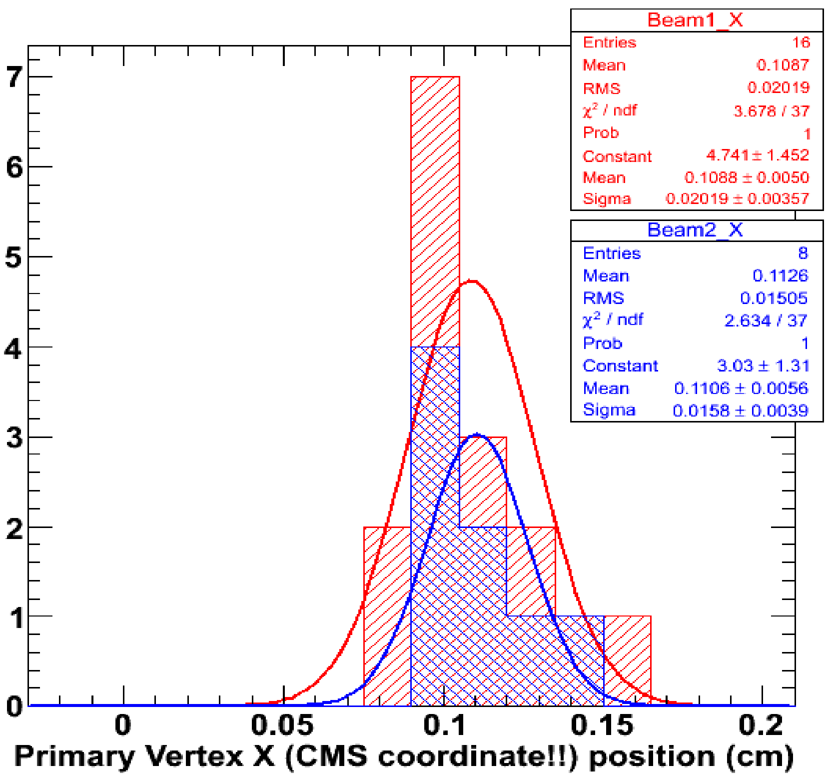
- The LHC operated for a few weeks in late 2009 – more than 12 months after the incident in 2008.
  - Collisions at E_{cm}=900 GeV
  - Collisions at E_{cm}=2.36 TeV
    - Highest energy collider
- Proved that the LHC could accelerate and collide bunches.
- After the winter technical stop the LHC came back operating at 7 TeV in the spring of 2010.

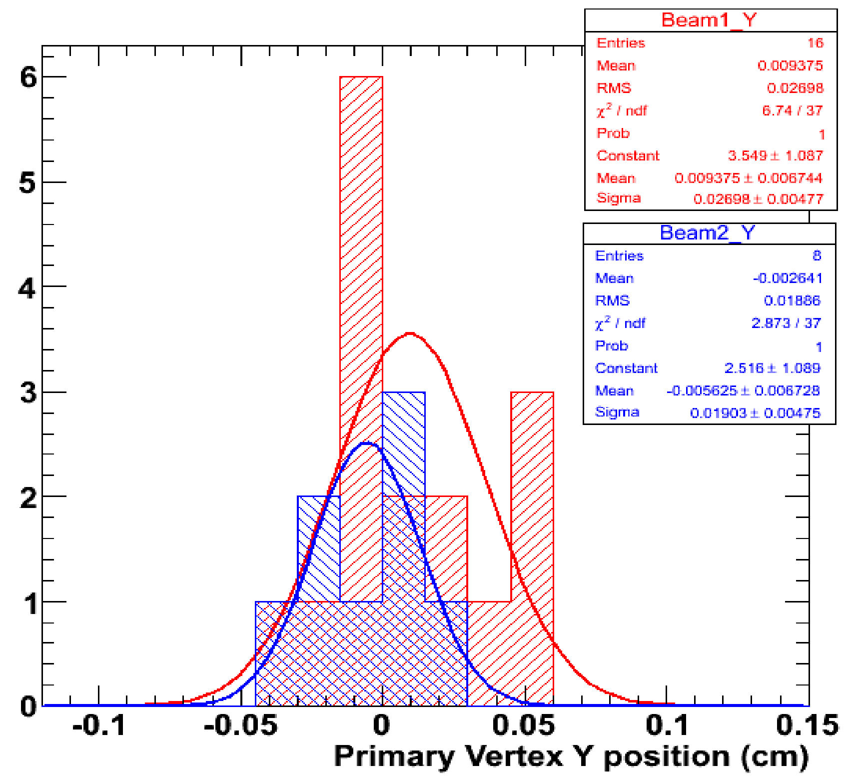
March 30, 2010, Media Event

- CERN had told several hundred media outlets that they would have collisions in the LHC before the end of March, and that they would give the media 7 days advanced notice.
  - On March 23 they announced the first day of collisions to be on the 30th of March – not many days to spare!
- In order not to allow any experiment to leak that there had been collisions – the LHC would not collide the beams even for a test before the 30th of March.
- How would we know that the beams would collide at CMS?
  - In an earlier similar try at 900 GeV in the fall CMS had not seen collisions as the beams did not collide.
  - Beams sizes a few 10s of μm – need precise steering of beams.

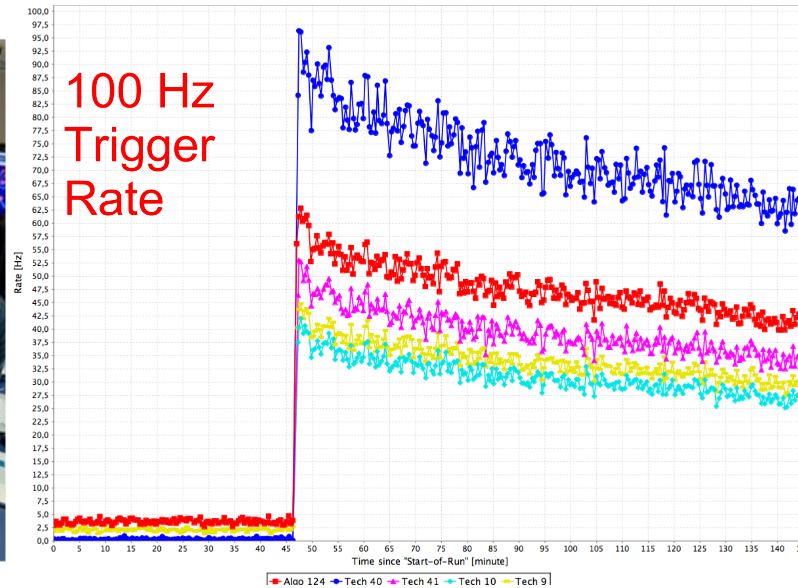
Beam-Gas Interactions

- At 01:00 on March 30th, 6 hours before the 'Media Event' the LHC injected particles in both beams, but in buckets such that no collisions took place at any of the four experiments.
- CMS recorded interactions between the beams and residual gas particles to measure the trajectories of the two beams.
  - It was established that we would see collisions at CMS!

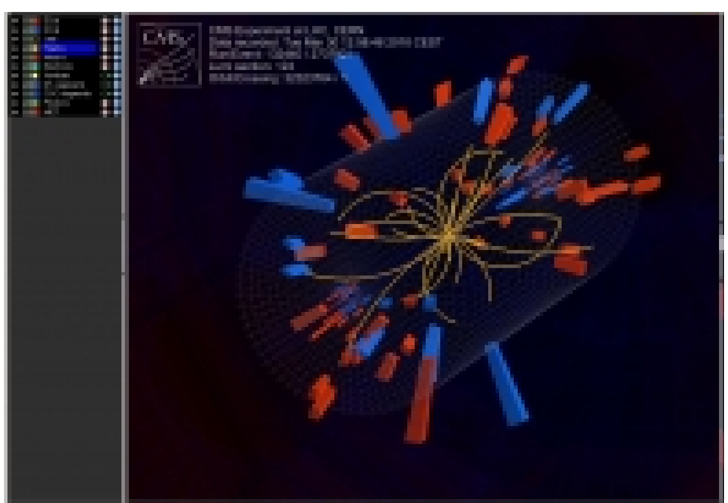




Media Event

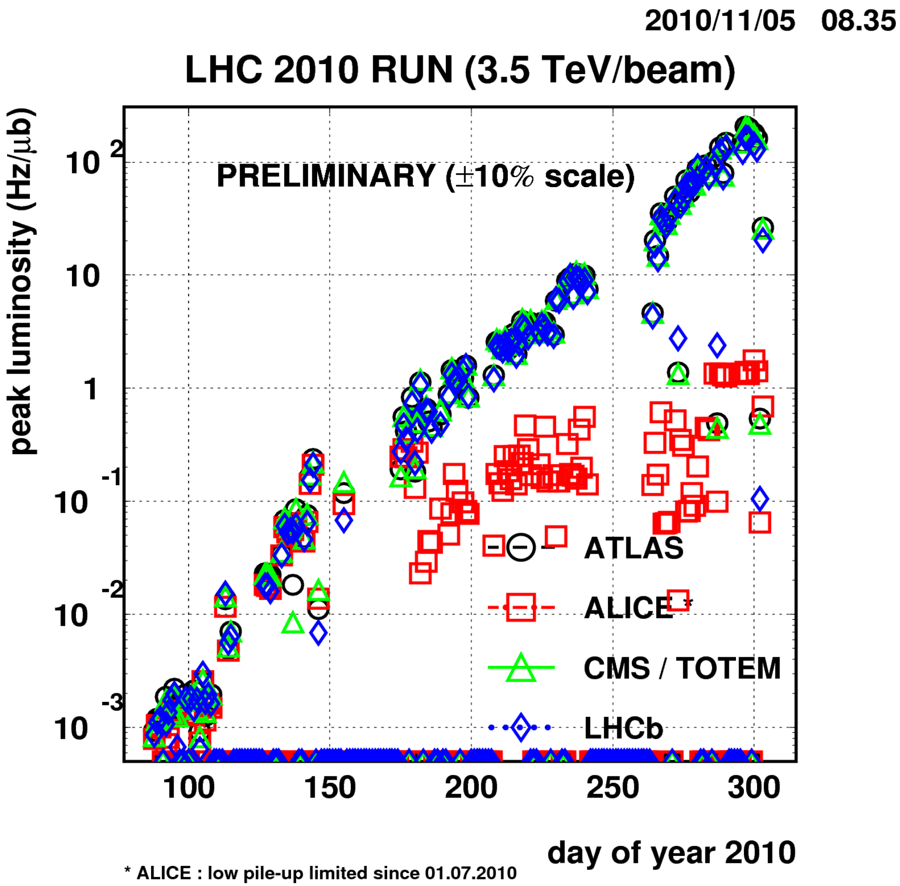


12:58, March 30, 2010

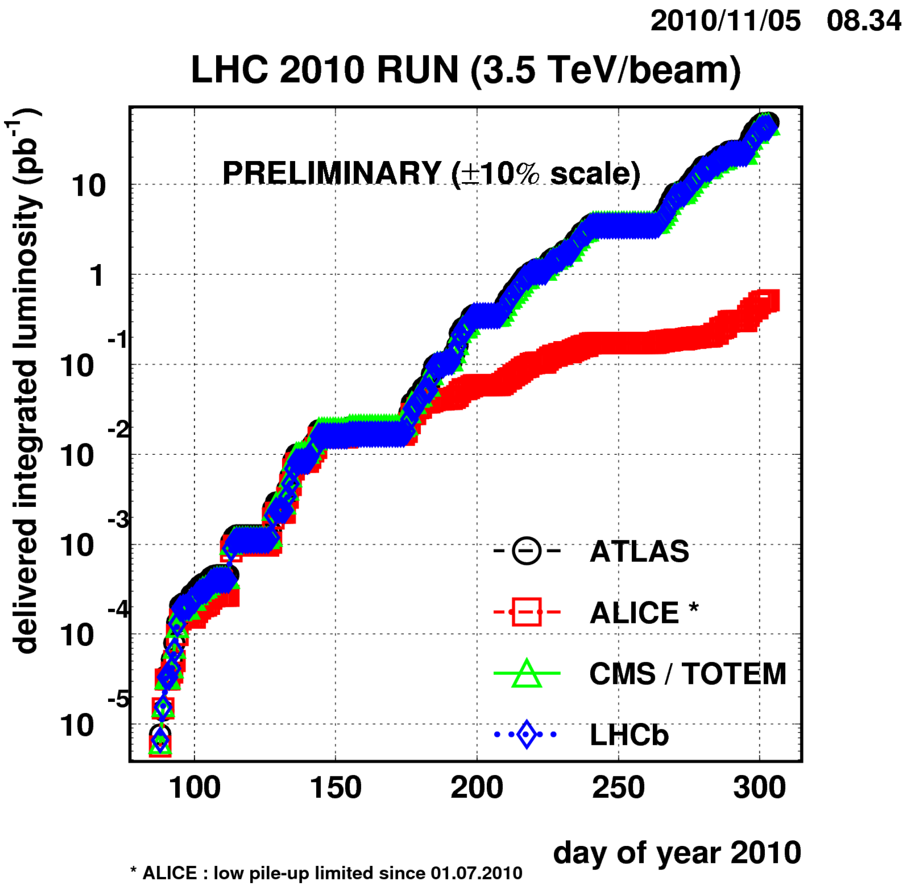


LHC Luminosity Evolution

Peak Instantaneous Luminosity

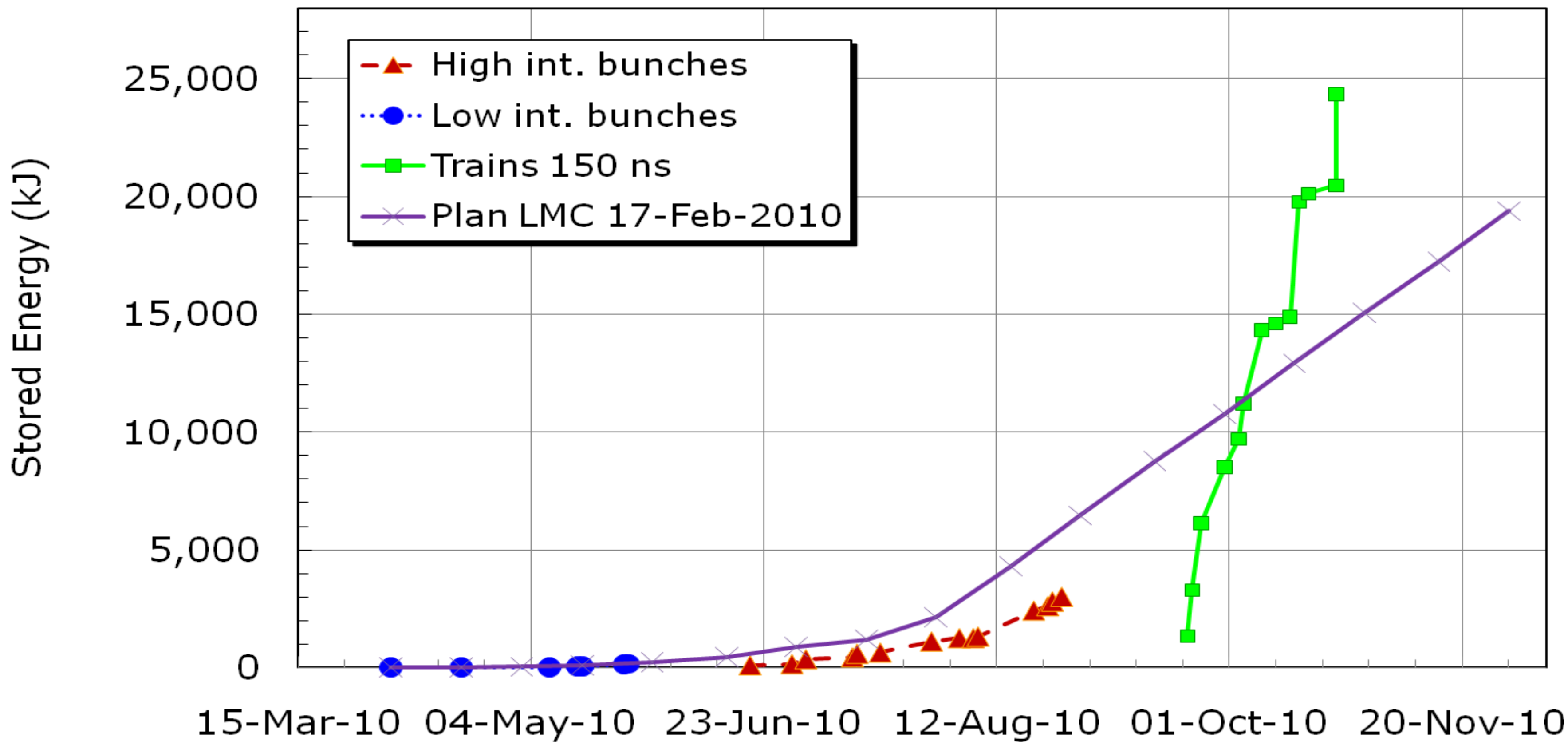


Integrated Luminosity



- Luminosity exponentially increasing over 5 orders of magnitude
  - Doubling time of inst. luminosity: 12 days
  - Constantly changing running conditions and triggers
- Want to go another factor of 10 in 2011.

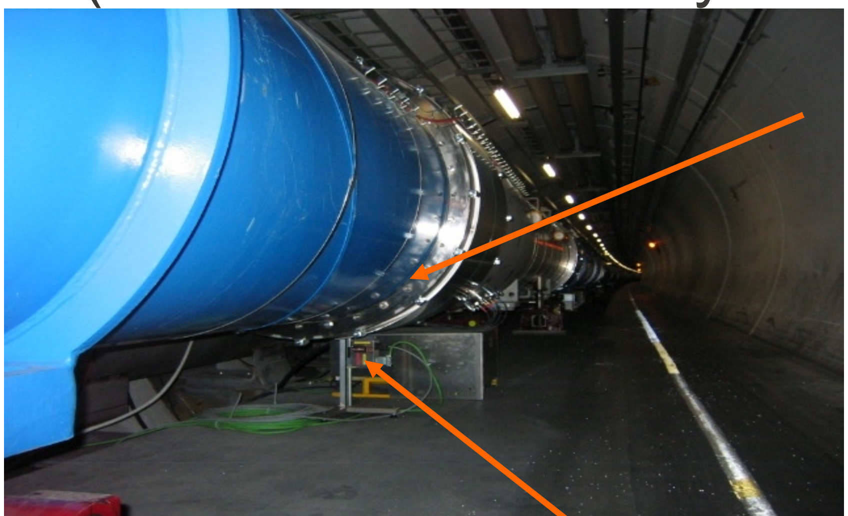
LHC Stored Energy in Beam



- As the intensity of the LHC beams increased a few problems came up that ultimately limited the 2010 performance:
  - Single Event Upsets (SEU)
  - 'Unidentified Flying Objects' (UFO)
  - Electron cloud effect (e-cloud)

Single Event Upsets (SEUs)

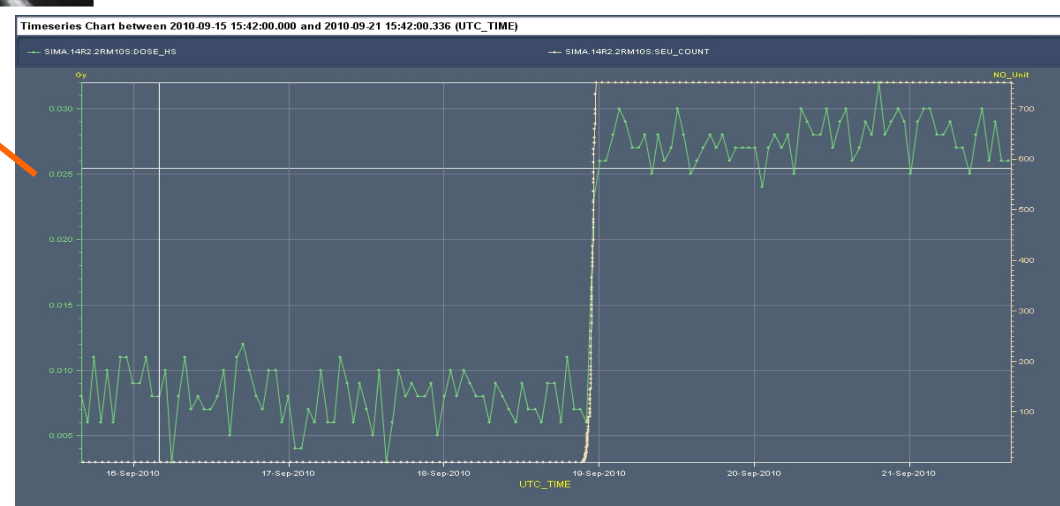
- Single Event Upsets are radiation induced changes to electronic states, *e.g.*, a bit flip in a register.
  - LHC has several sensitive components such as the QPS (Quench Protection System) near the LHC beam.



QPS crate

SEU count (RADMON) during off-momentum loss map

Thijs Wijnands



A few SEUs seen in 2010 operation. Not yet a problem, but has to watch carefully in 2011.

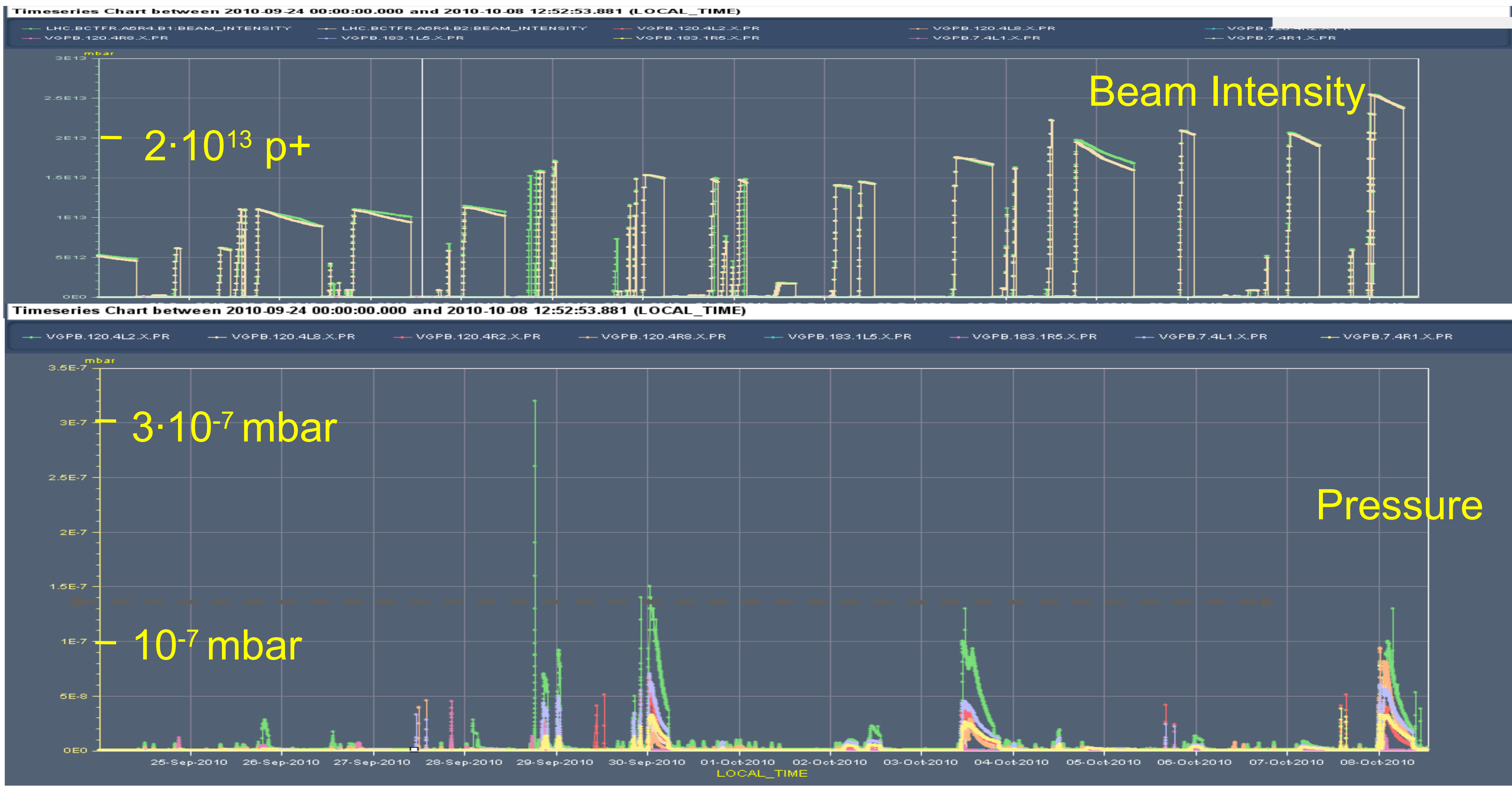
Unidentified Flying Objects - UFOs

- With increased beam intensity we started to see fast losses in super-conducting regions of the ring:
  - *Fast loss over ~0.5-2 ms, leading to a dump of the beam.*
  - *Most events occurred during 'rock' stable periods.*
  - *Losses in regions of very large aperture.*

- Beams don't hit aperture
  - *'Dust' particles 'falling' into the beam, estimated size ~100 μm thick Carbon-equivalent object.*
- Source not understood
  - *Induced by the beam – electromagnetic fields at the surface of the vacuum chamber?*
  - *Good news: signal amplitude seems to not depend on beam intensity*
- Strategy for 2011: increase the beam loss monitor thresholds

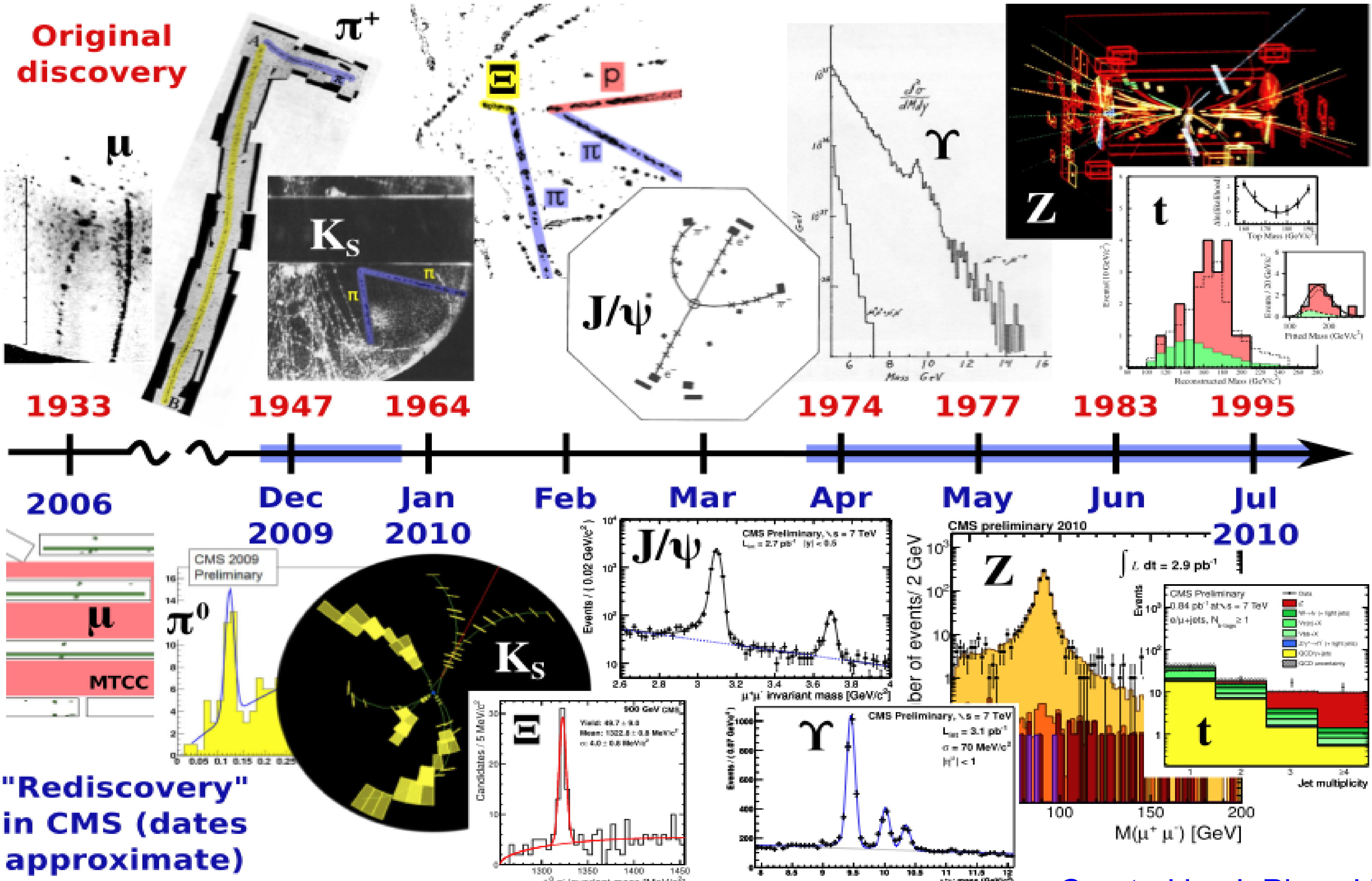
Beam Intensity and Vacuum

- Vacuum pressure increases were observed around the 4 experiments from the moment LHC switched to 150 ns train operation
- Each intensity step showed a step spike in the pressure
  - Electron Cloud Effect – need to condition the beam



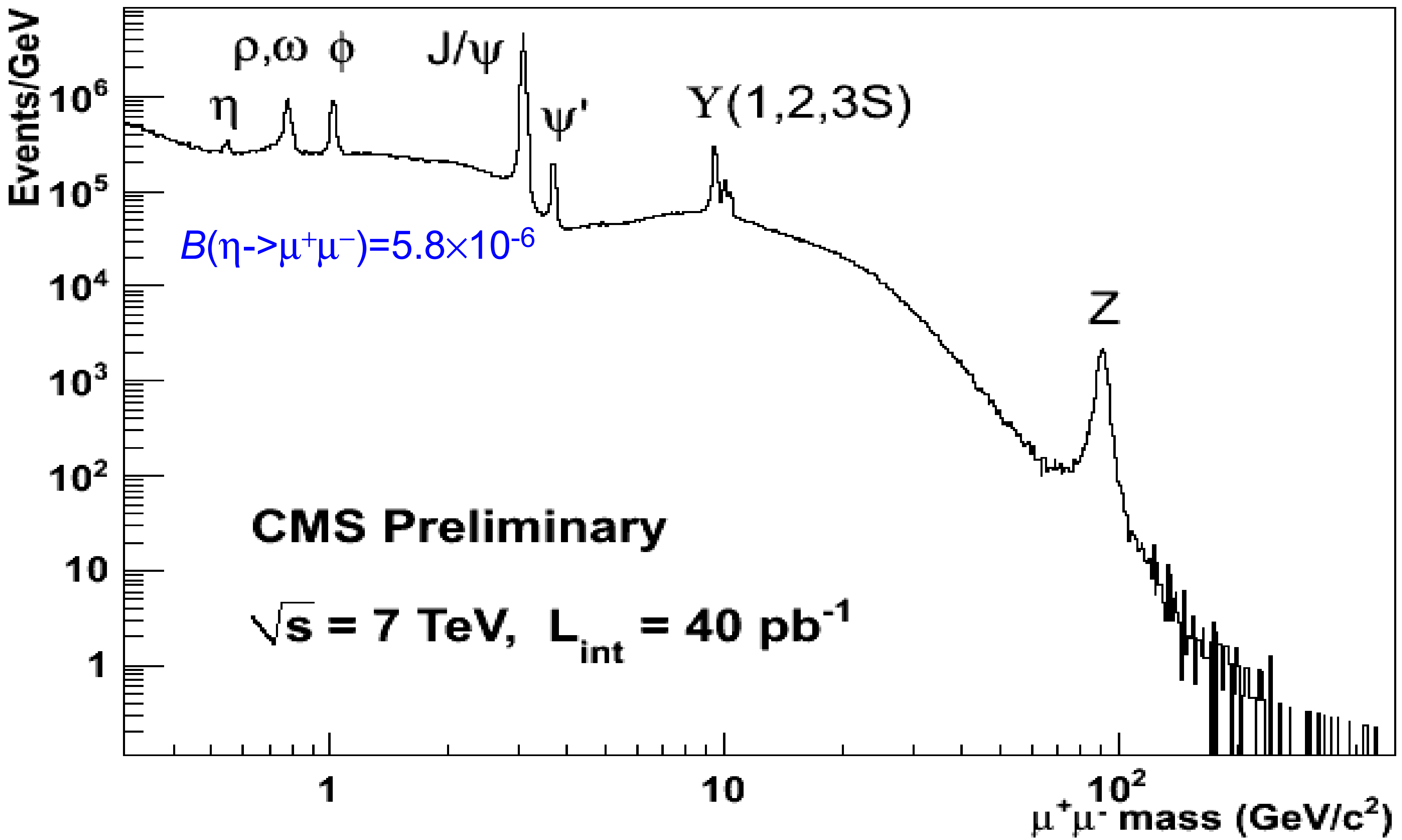
Sept. 24, 2010 Oct. 8, 2010

CMS Rediscovers the SM



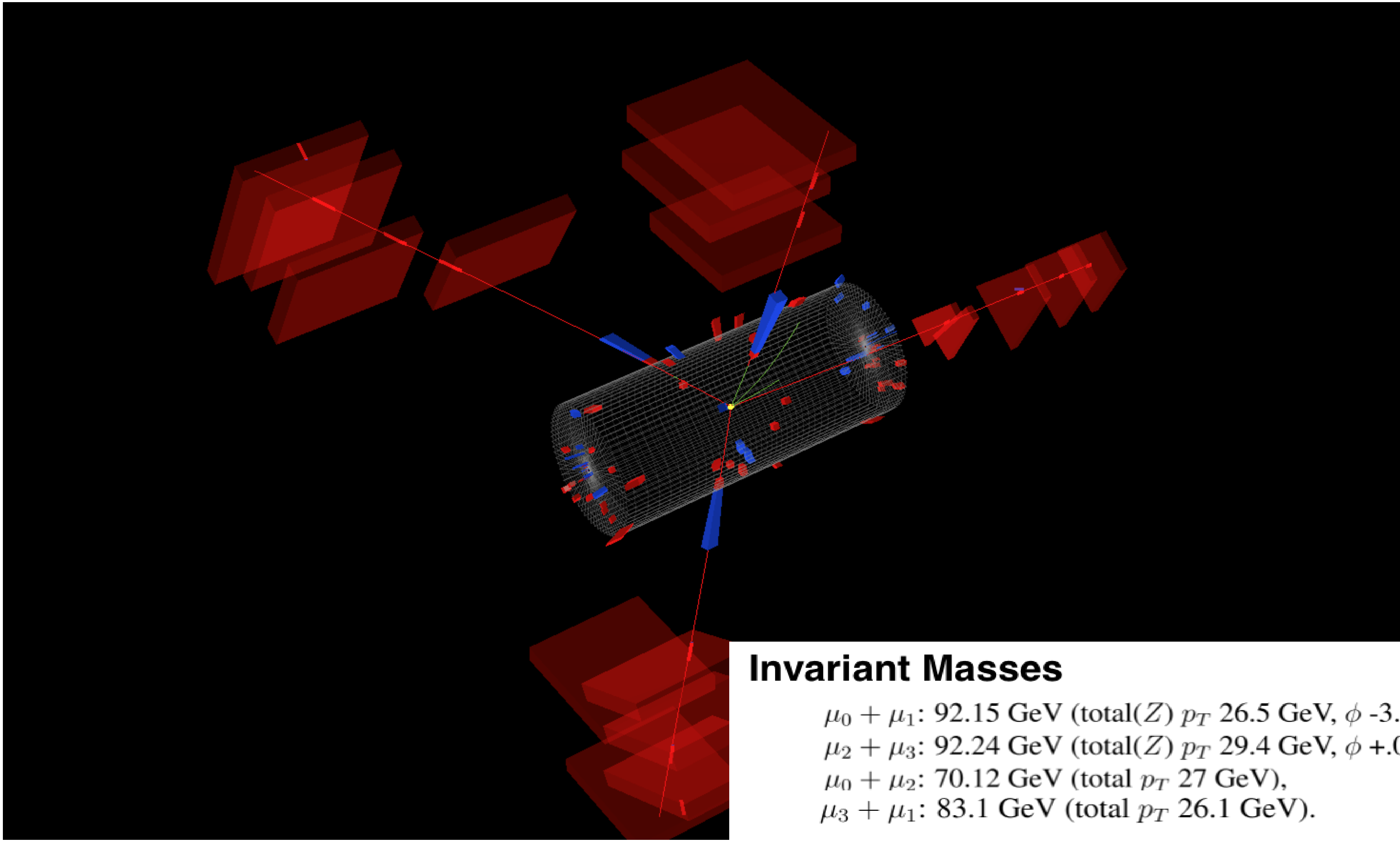
Created by J. Pivarski

Di-muon Mass Spectrum



Impressive plot of the power of the CMS muon detectors and trigger

ZZ→4μ Event

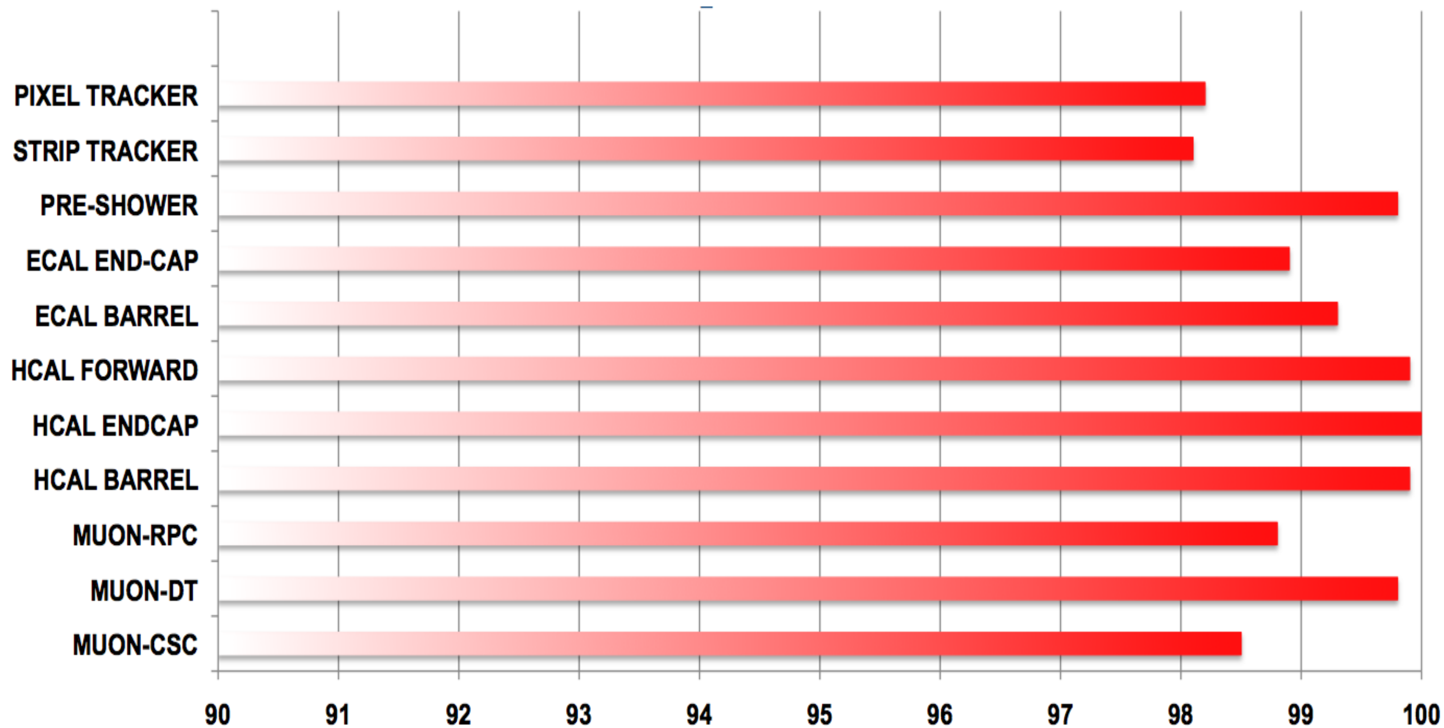


Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

Invariant Mass of 4μ: 201 GeV

CMS Active Detector Channels



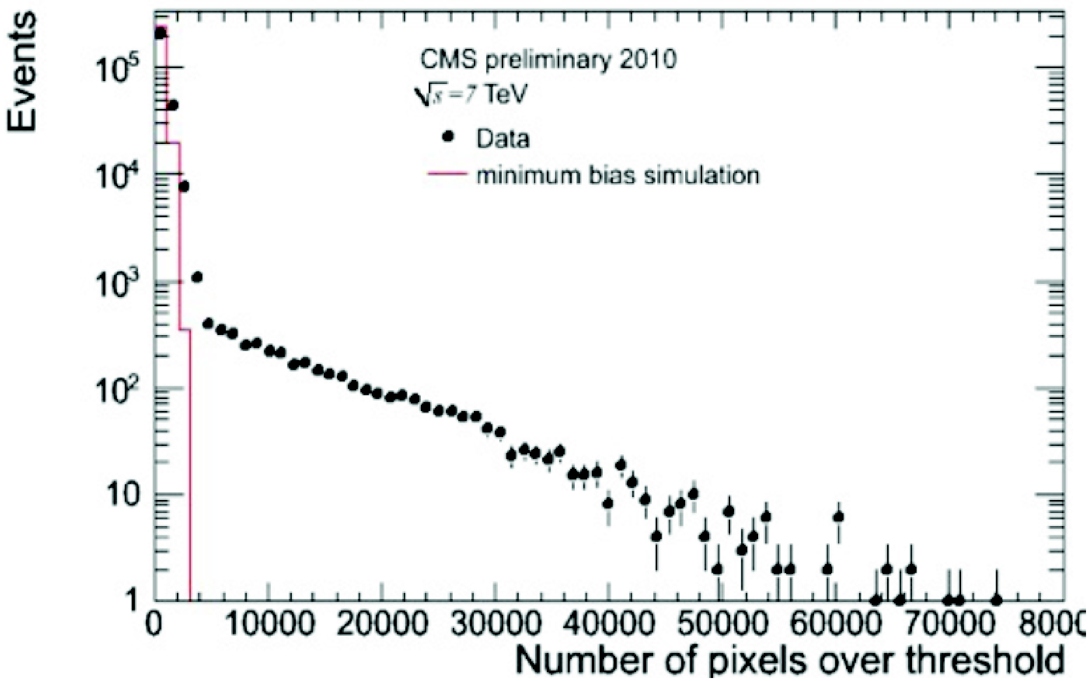
	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER	
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2	

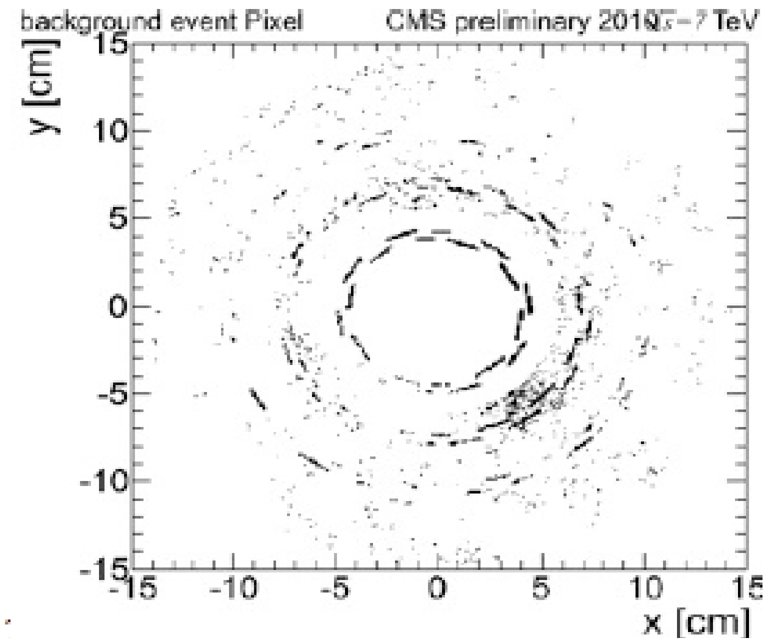
All subsystem over 98% working in 2010

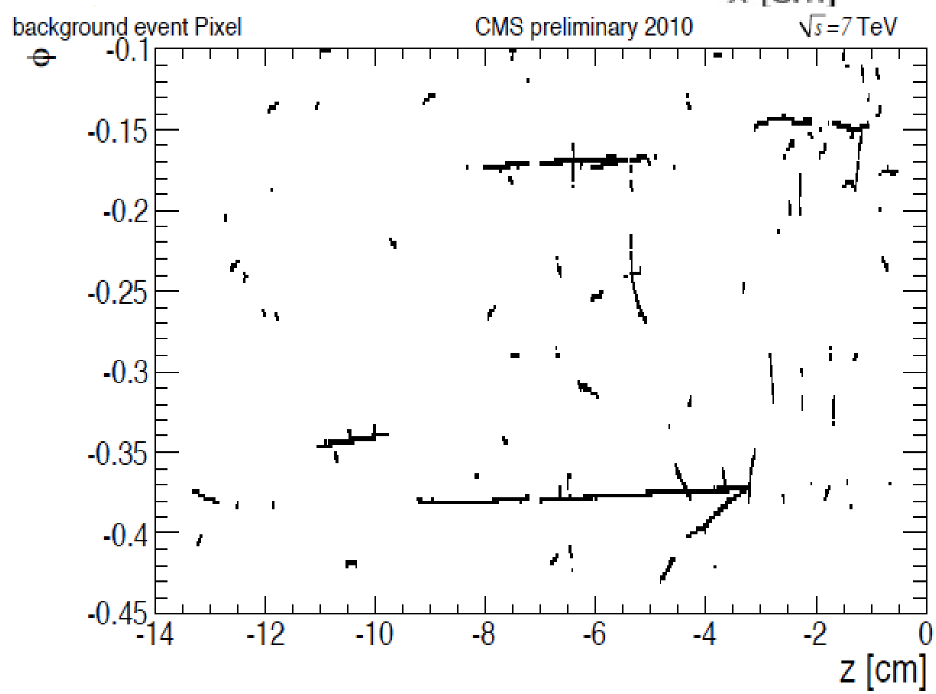
Some Surprises

- As the LHC luminosity increased we ran into a few surprises that required significant work to resolve.
- High occupancy in Pixel detector
- Spikes in ECAL and HCAL energy deposits
  - Discussed in the backup slides

High Pixel Occupancy Events



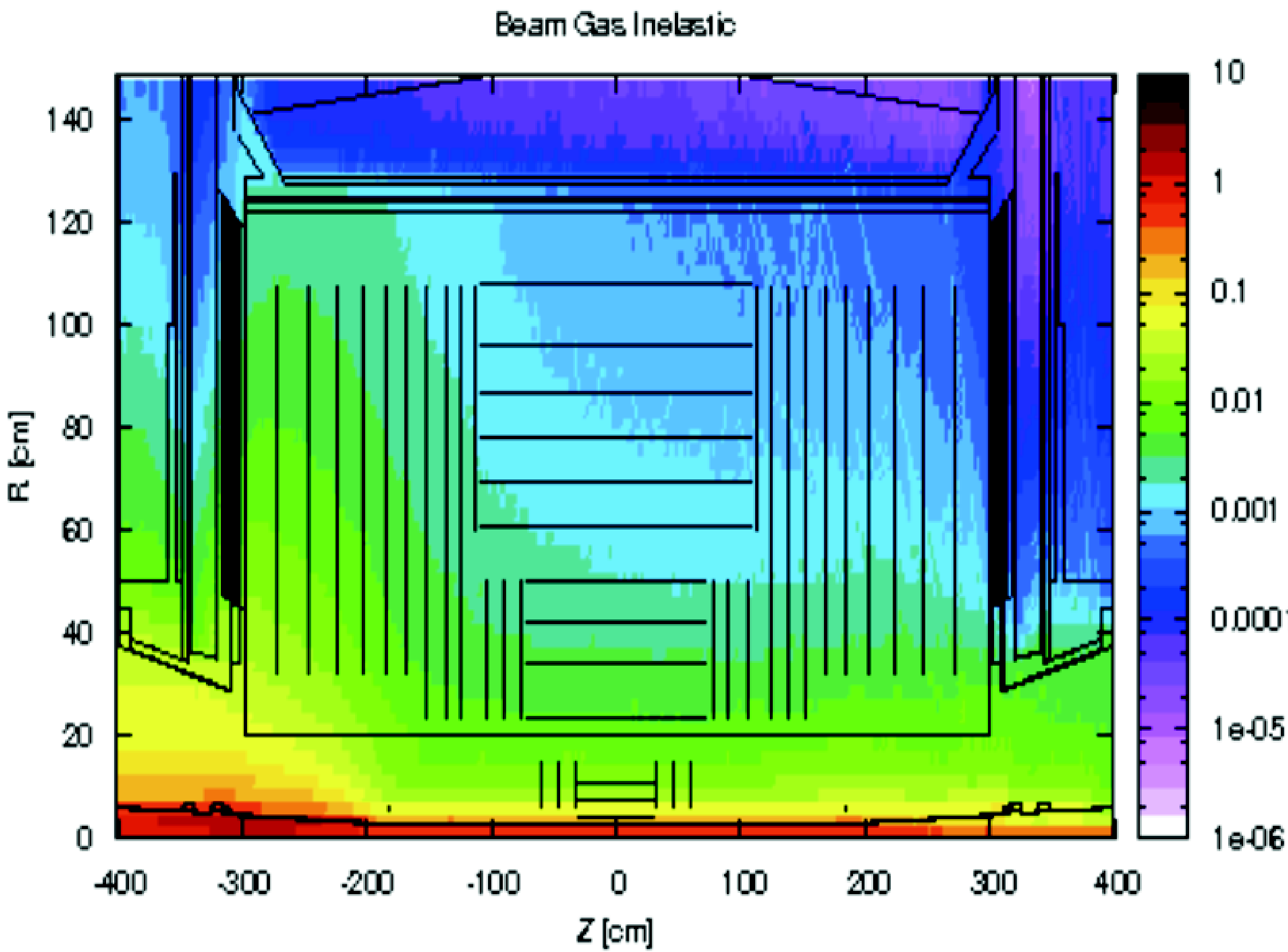




- Events with occupancy much larger than expected from minbias events seen in the pixel detector.
  - Tracks parallel to the barrel pixel modules – source along beam line.
- Readout of these high occupancy events in the pixels takes long time.

Beam-Gas Interactions

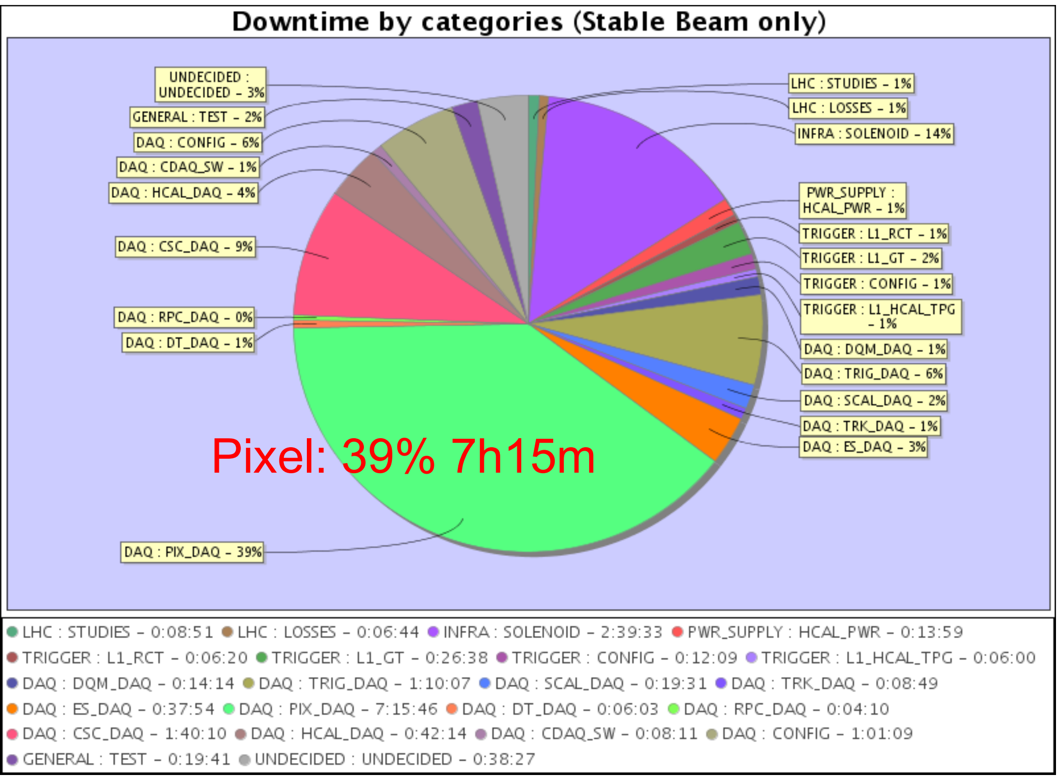
- The source of these large pixel events is beam-gas interaction outside detector area.



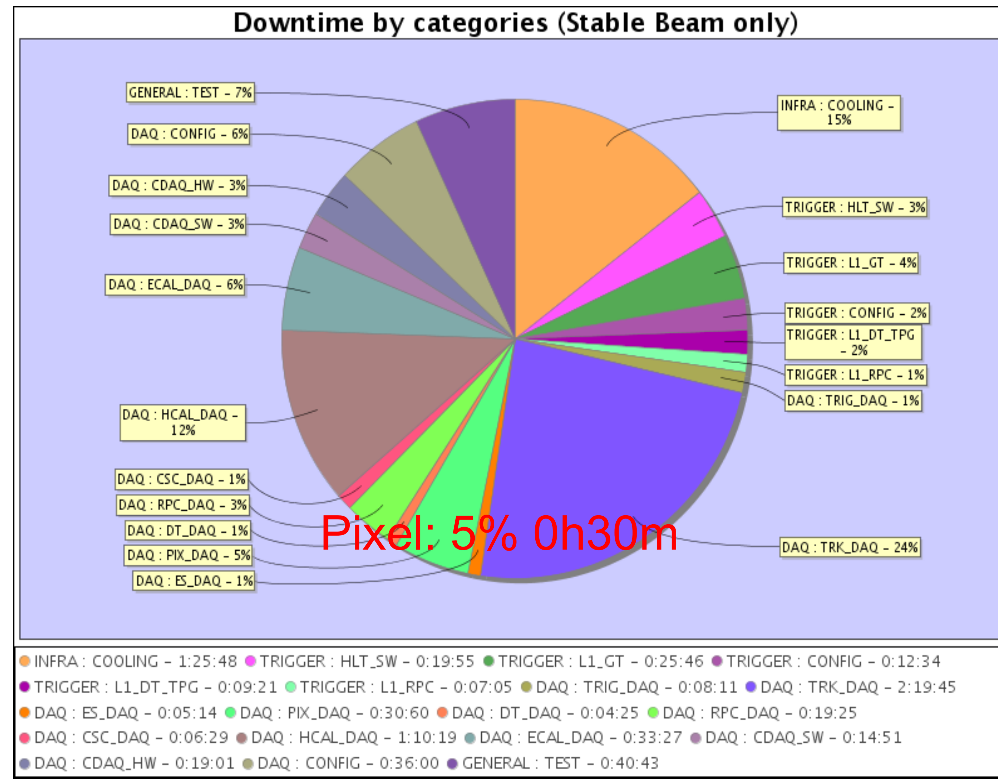
- Simulation of beam-gas interactions shows that the rate and radial distributions of particles are qualitatively in agreement with the observations.
- Readout and recovery modified in frontend readout firmware.

CMS Downtimes

July: before pixel problem solved

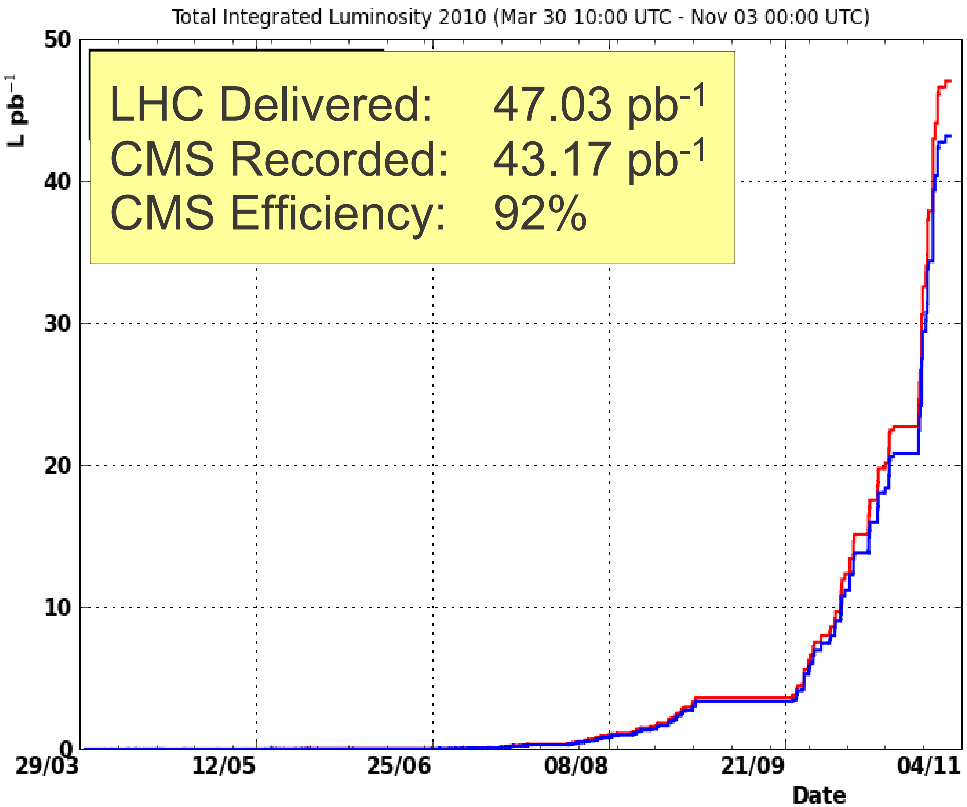


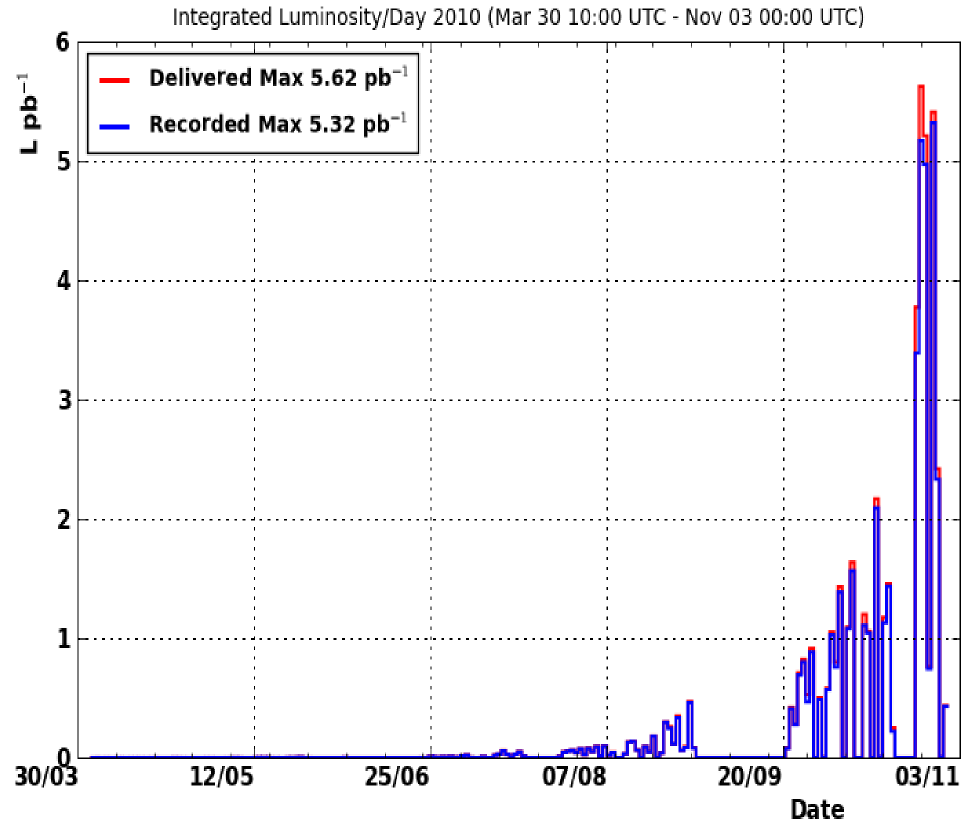
October: after pixel problem solved



- Spent time with the LHC beam in the summer to debug and solve the readout problem for large pixel events.
  - Efficiency greatly improved after problem understood and fixed.

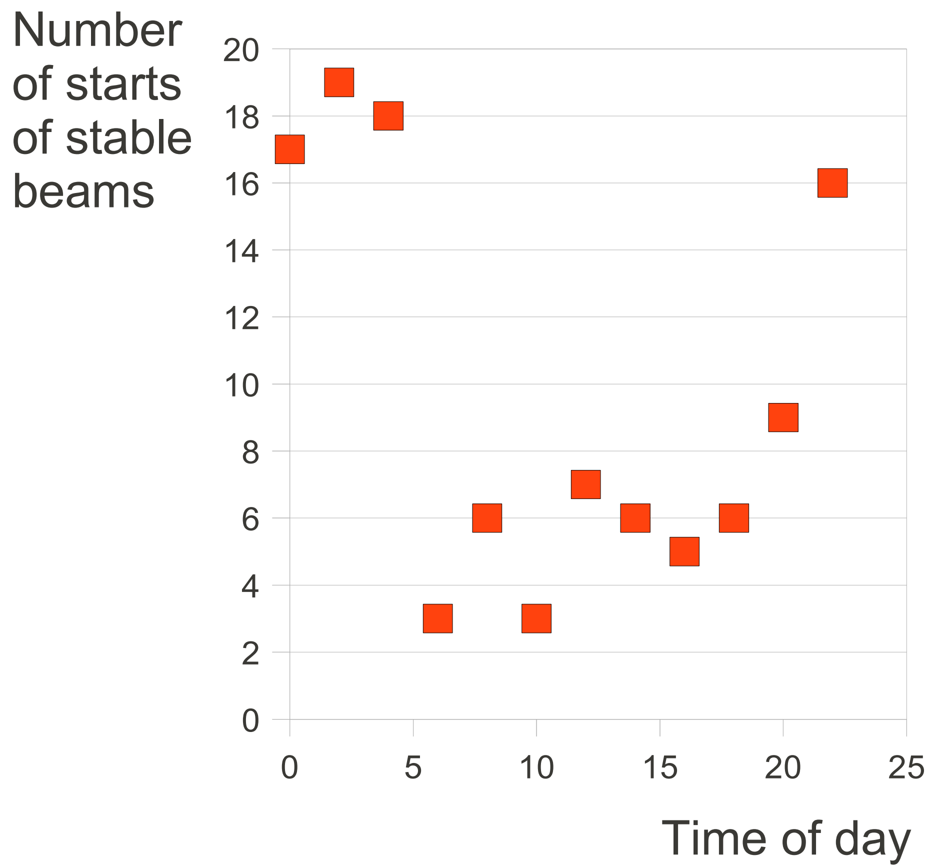
CMS 2010 Data Sample





- Most of the data recorded in the last few weeks of operation
  - CMS had high data taking efficiency
- Data used in physics analysis range from 36 to 40 pb^{-1} depending on the analysis

Start of Runs at Night



- ~70% of LHC fills started during the owl shift!
- Weekends were also more productive...

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2010 Commissioning and Operation

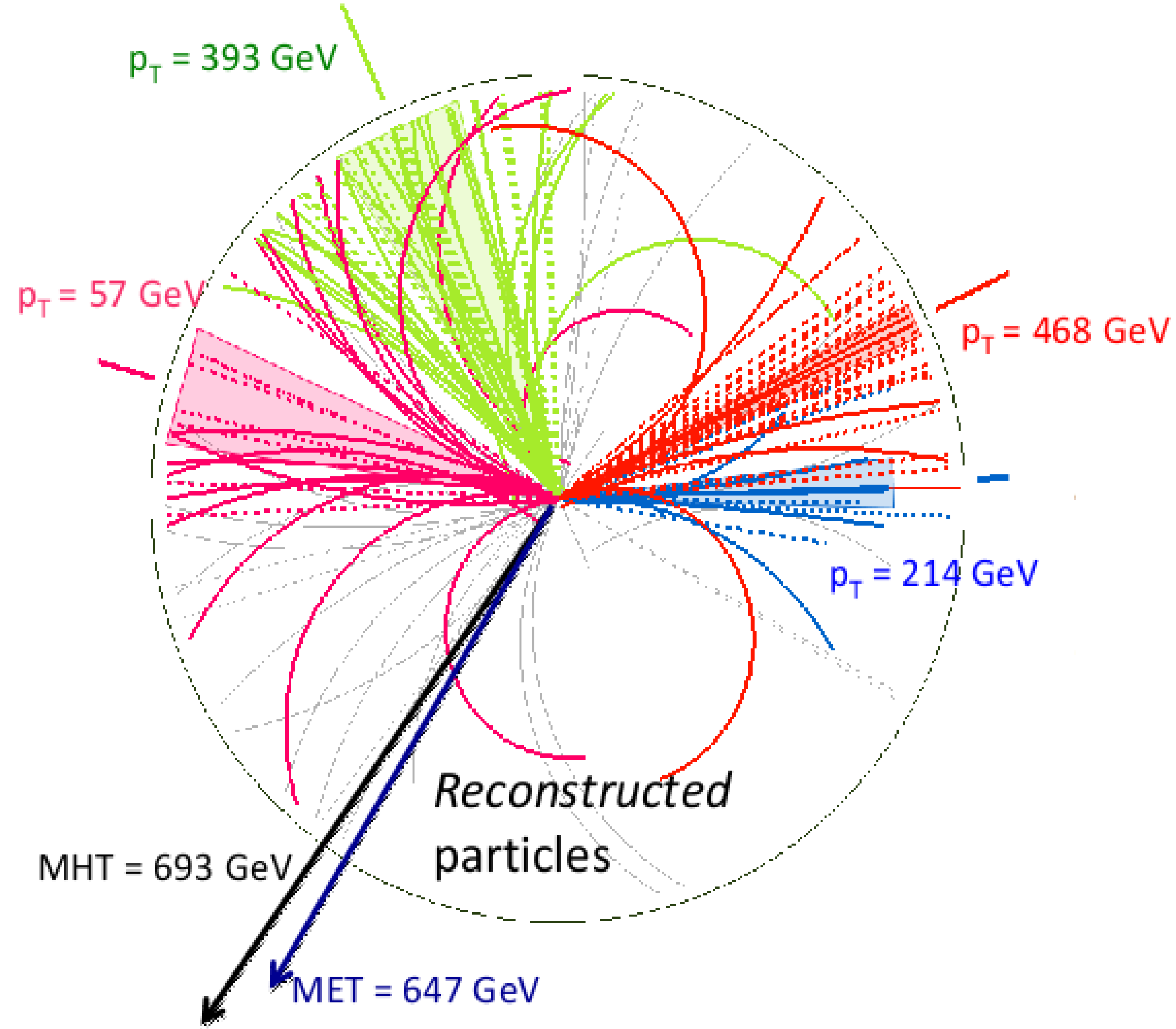
Physics Results

- SM: EWK + top
- Searches for New Physics

2011 (and 2012) Running

Summary

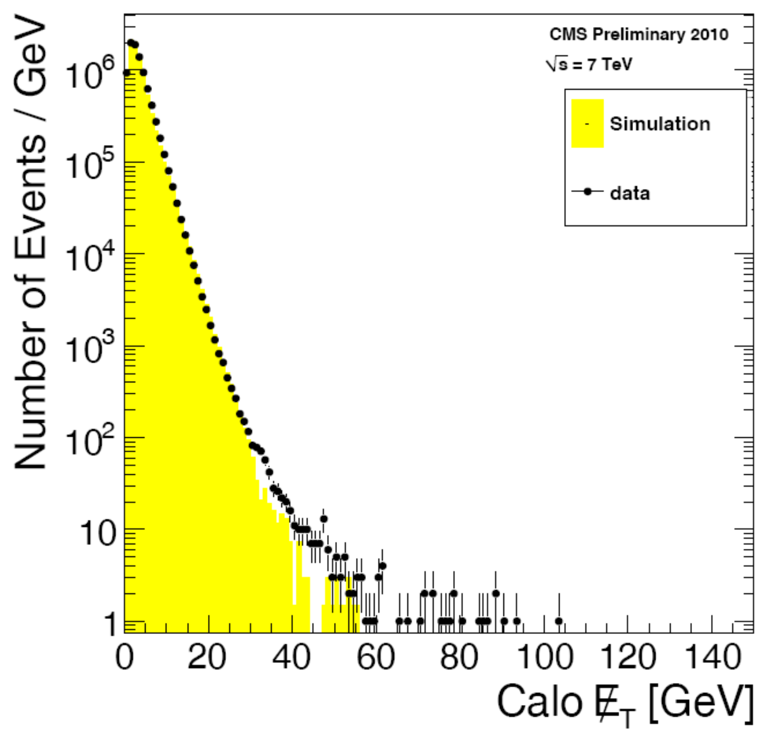
MET, MHT and HT



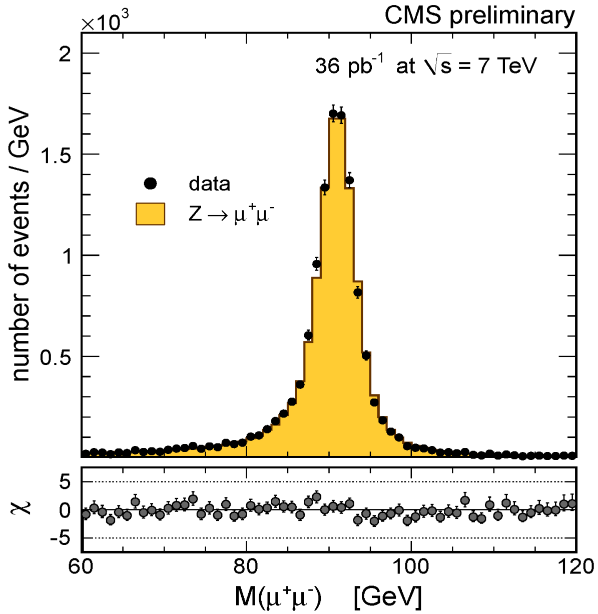
$$E_T^{\text{miss}} = \overrightarrow{MET} = -\sum_{\text{particles}} \vec{p}_T$$

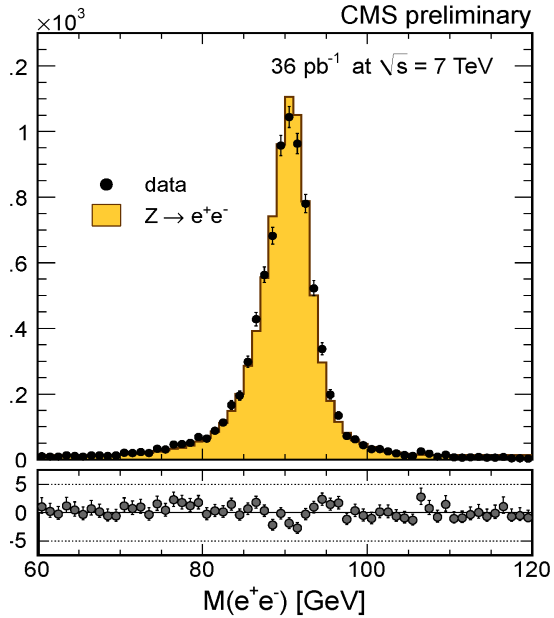
$$\overrightarrow{MHT} = -\sum_{\text{jets}} \vec{p}_T$$

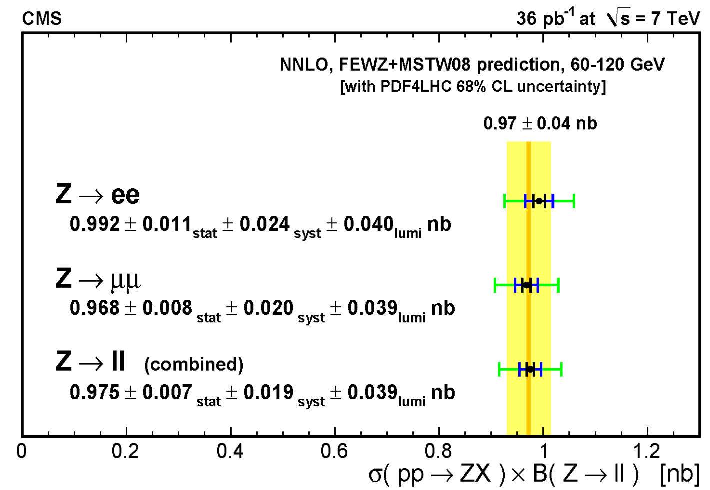
$$HT = \sum_{\text{jets}} p_T$$

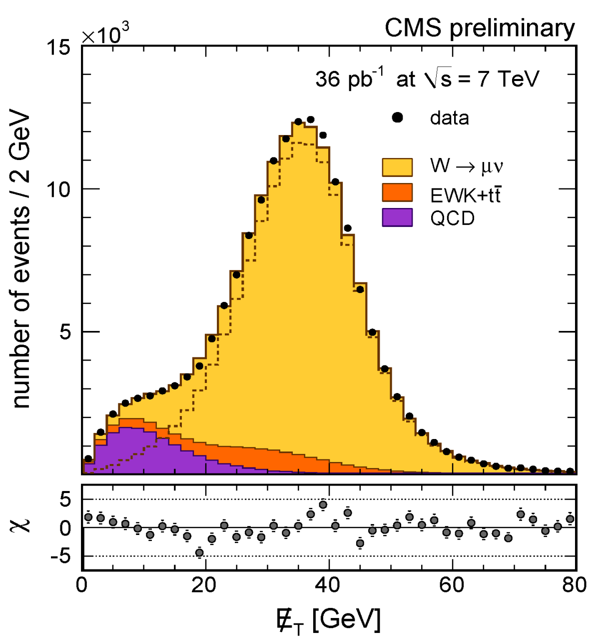


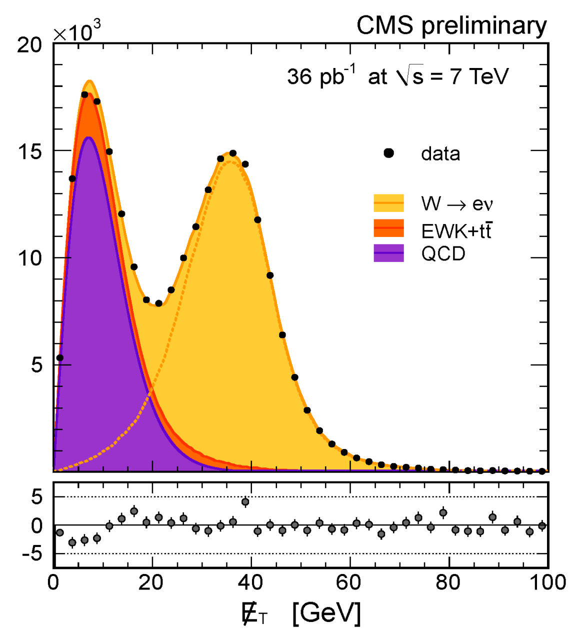
W and *Z* Production

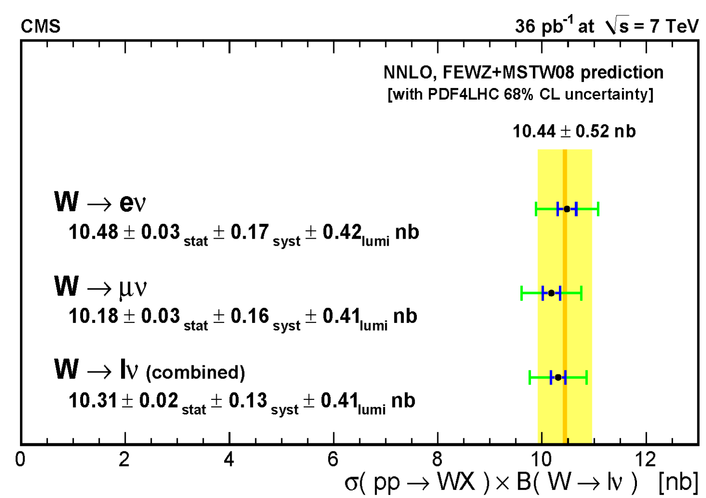




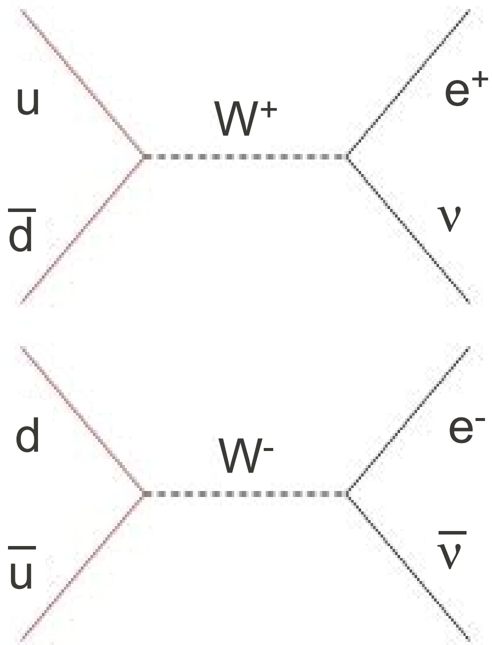




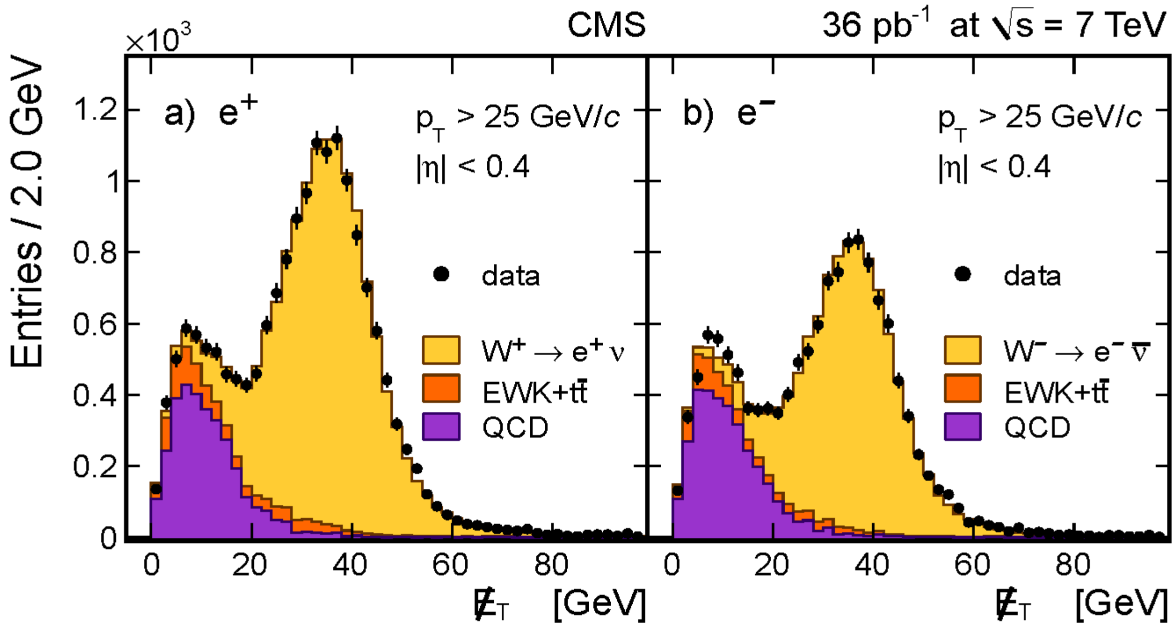


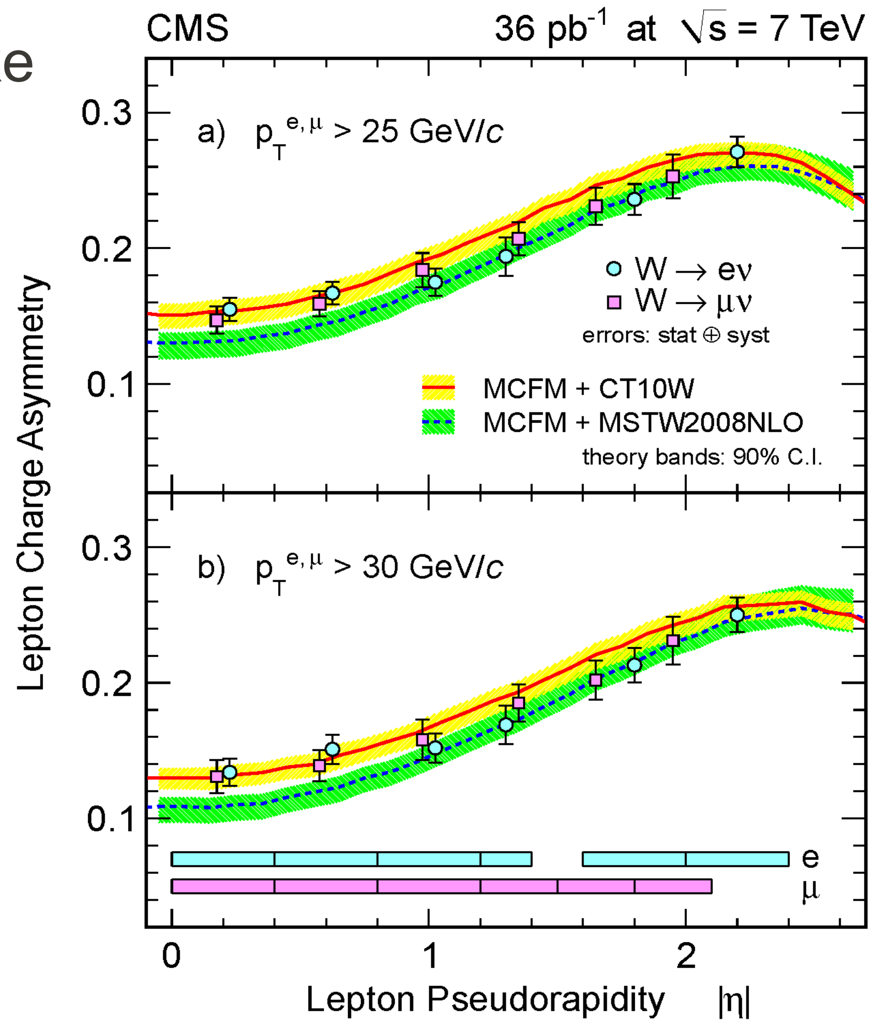


W Charge Asymmetry



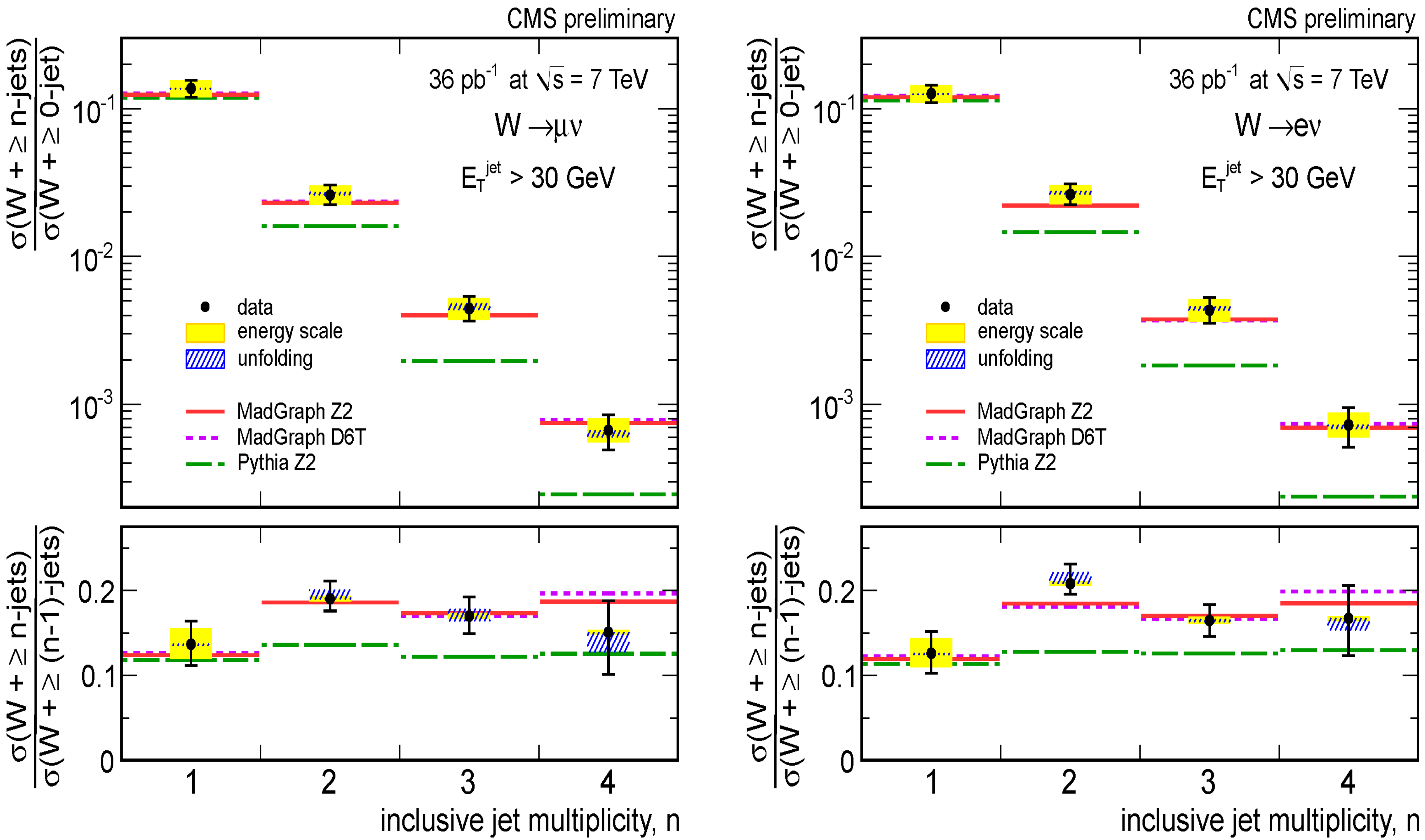
p=uud so we are more likely to make W^+ than W^-.





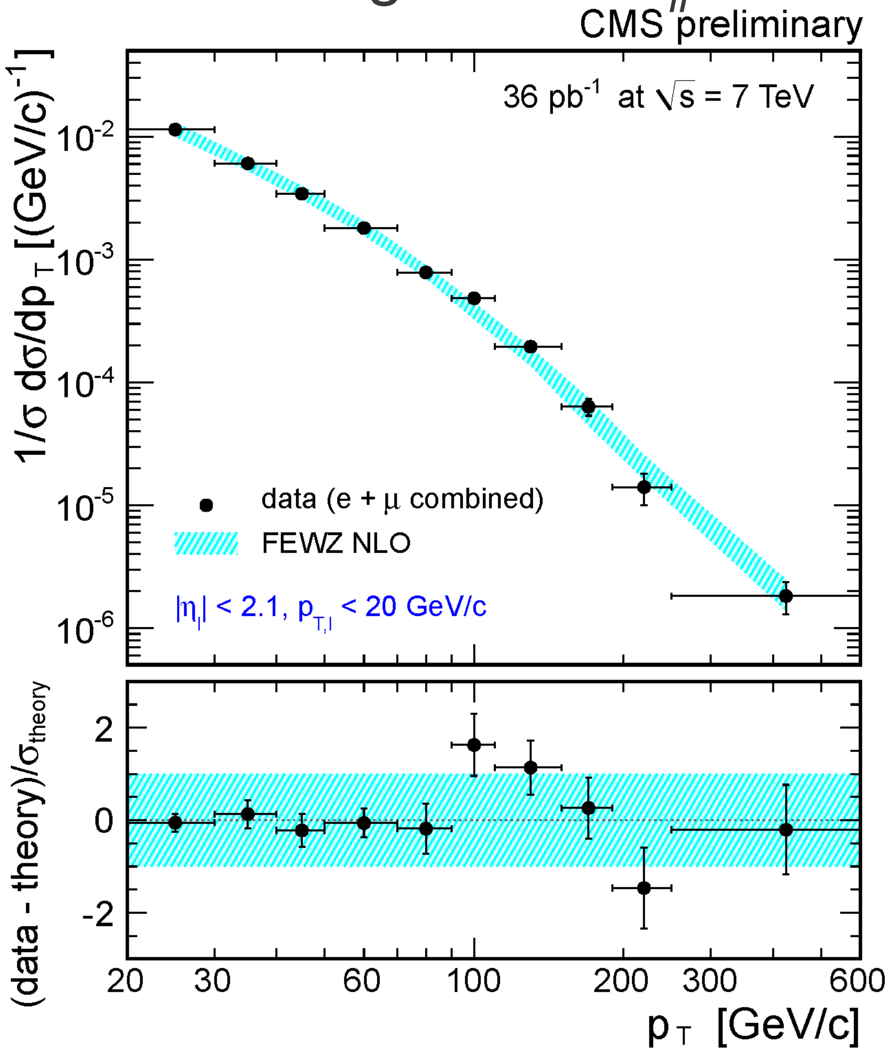
$\eta = -\ln\tan(\theta/2)$

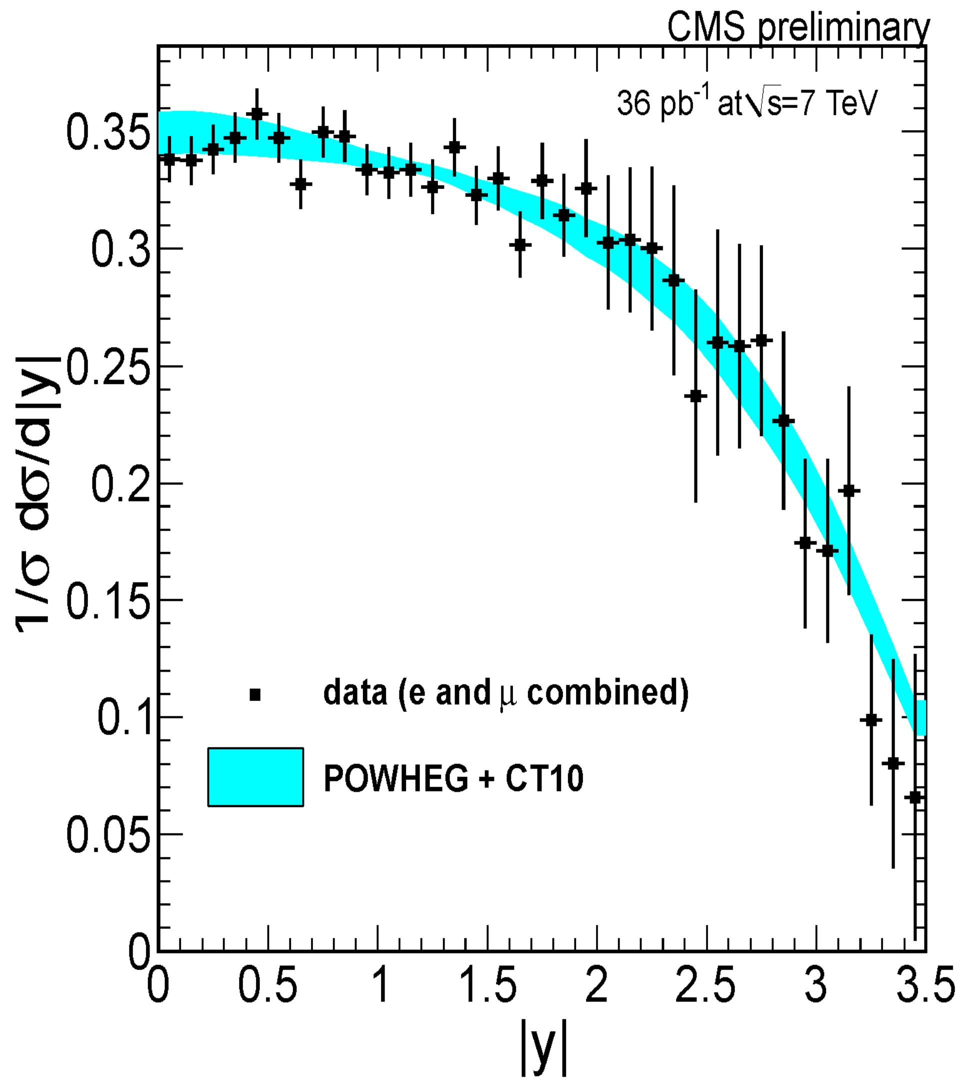
W+jet Production



Inclusive p_T and η Distributions

- Differential distributions for Drell-Yan lepton (*e* or μ) pairs in the *Z* mass region $60<m_{ll}<120$ GeV.

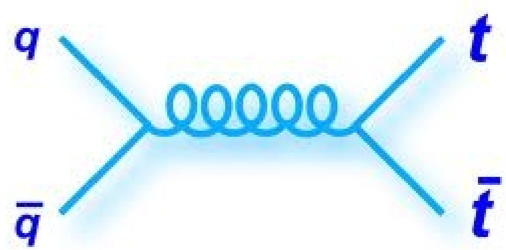




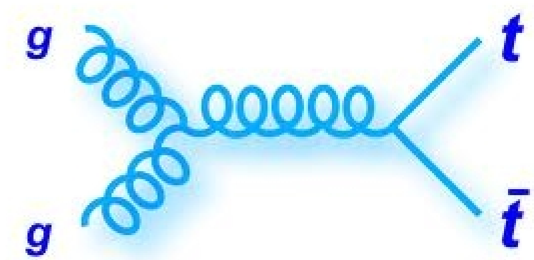
Good agreement between data and simulations

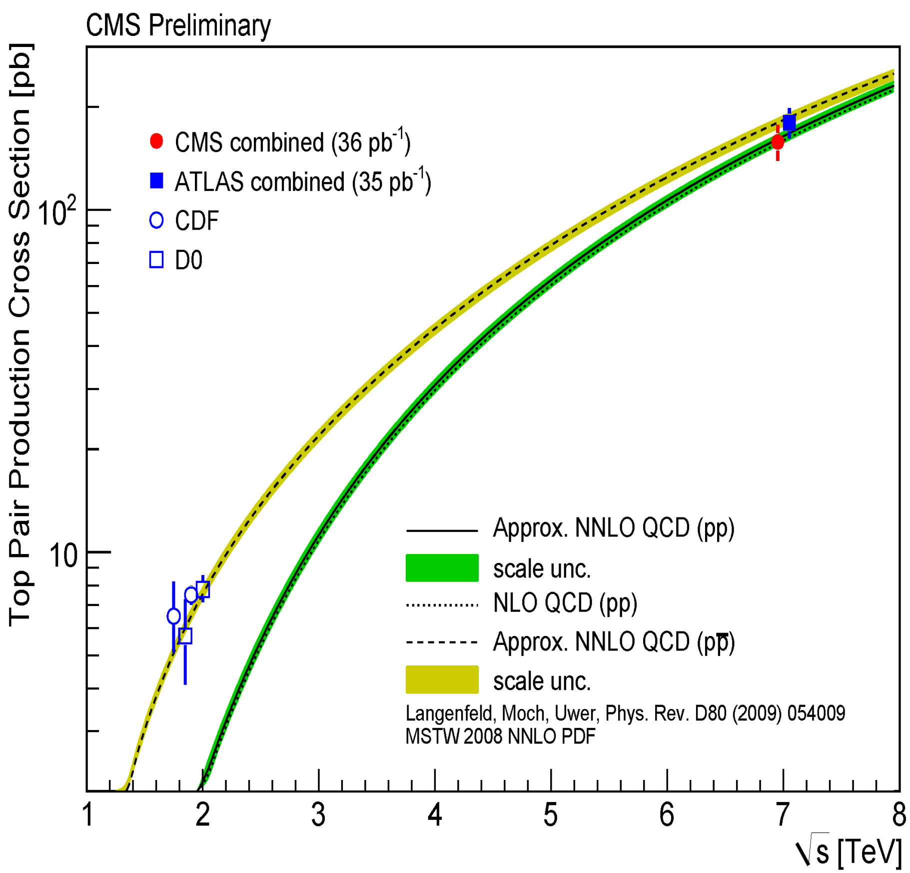
Top Results

Tevatron
$p\bar{p}$

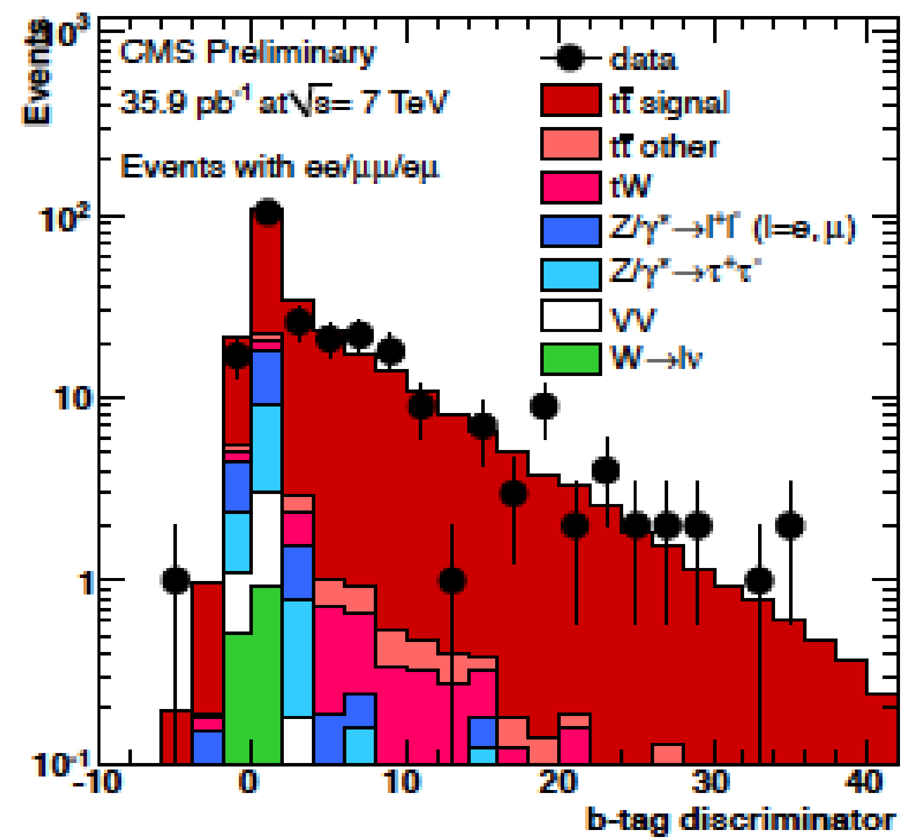


LHC
pp



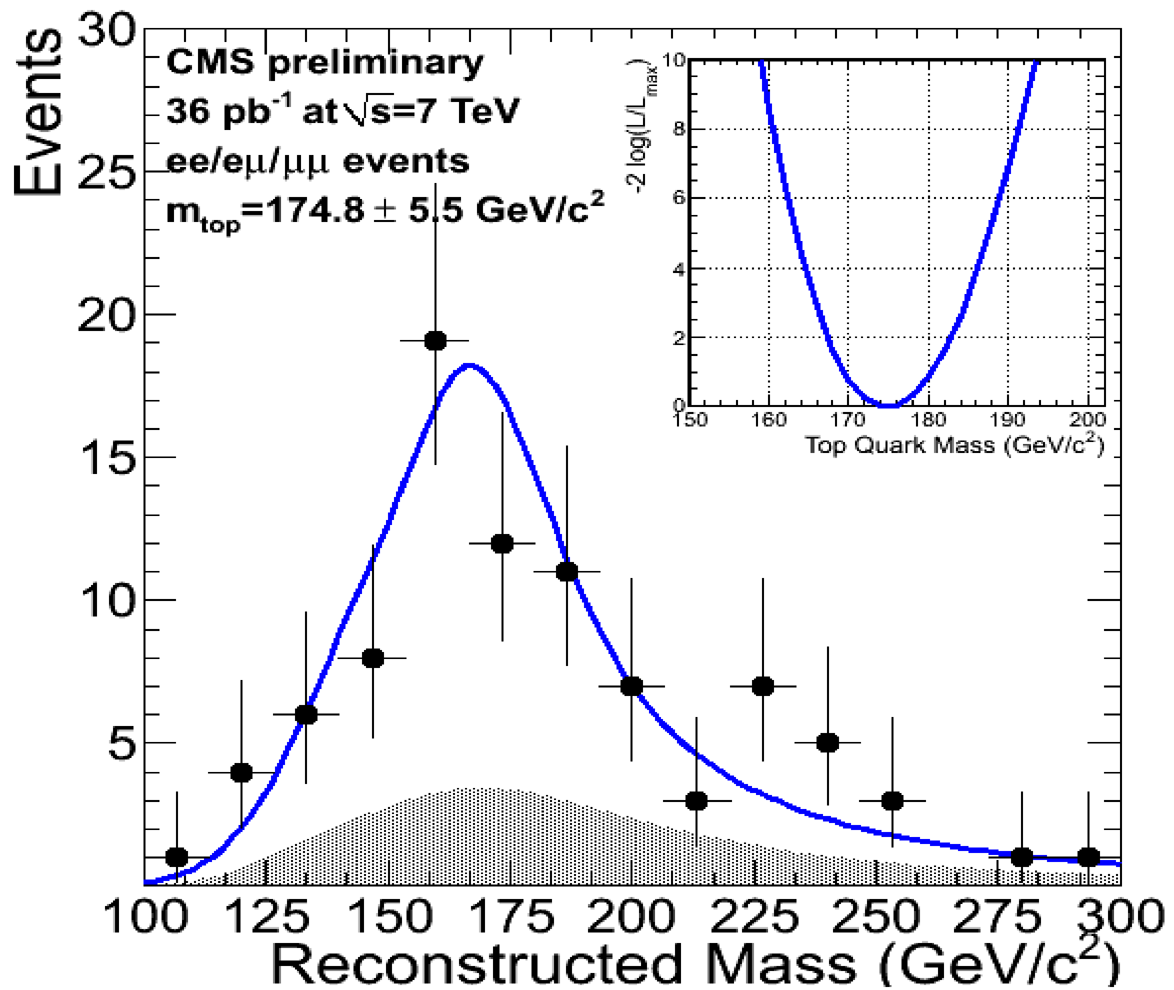


Both top decay leptonically: $t \to Wb \to l\nu b$

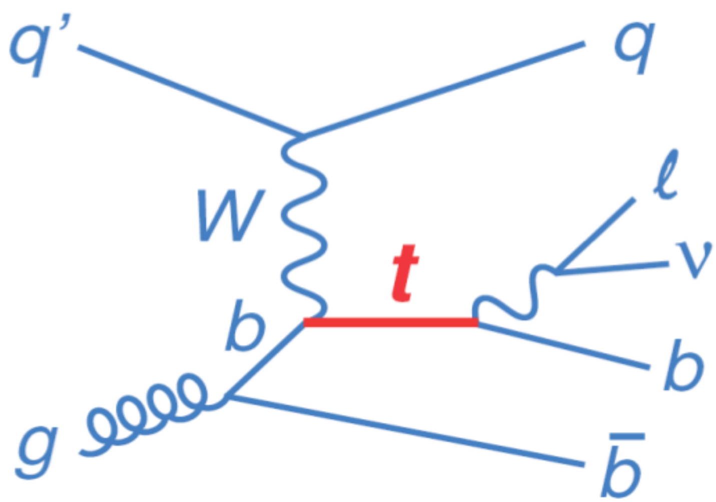


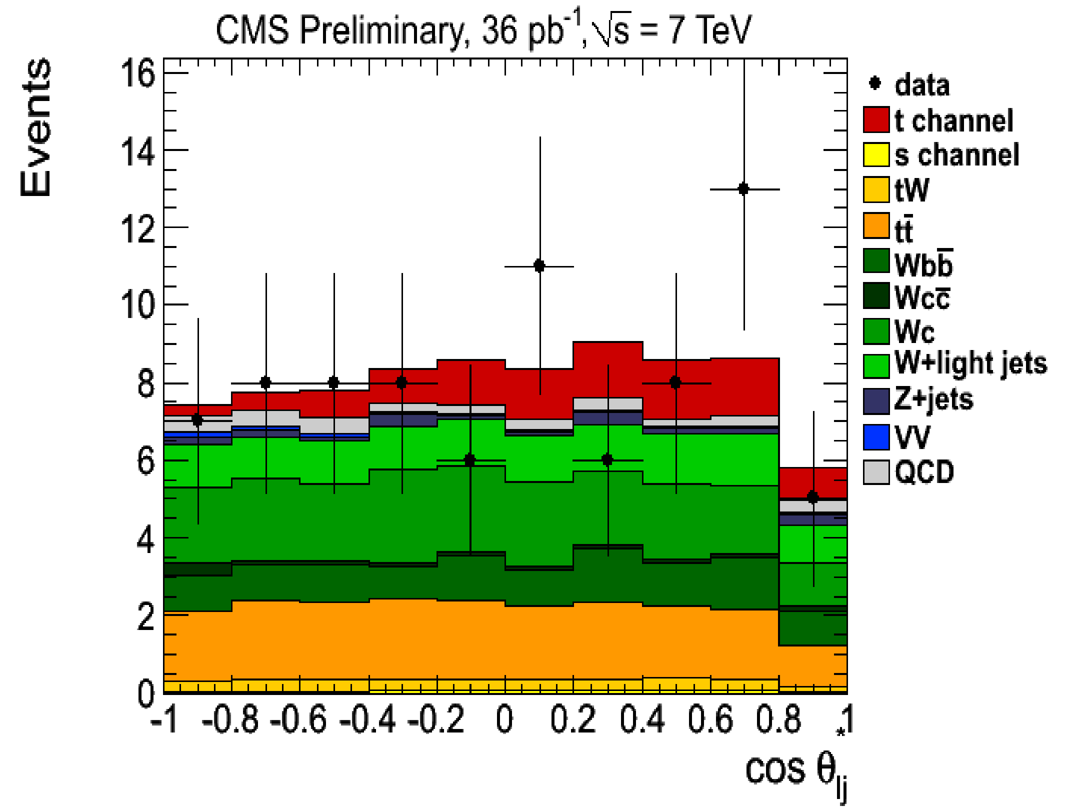
Top Mass

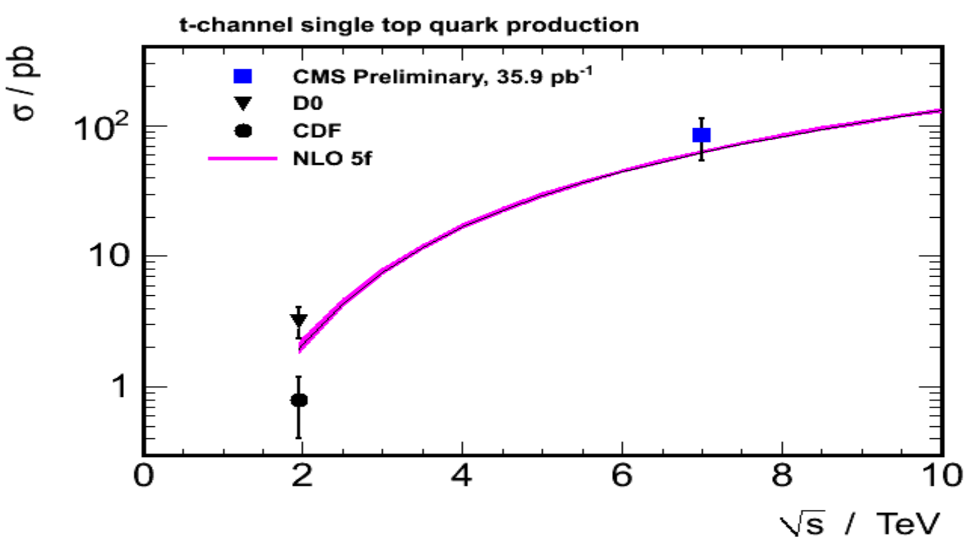
- Used final state where both tops decay to leptons: $t \rightarrow Wb \rightarrow l\nu b$
- Measurement still statistics and systematic limited with respect to the world average: $m_t=(172.0\pm0.9\pm1.3)$ GeV



Single Top

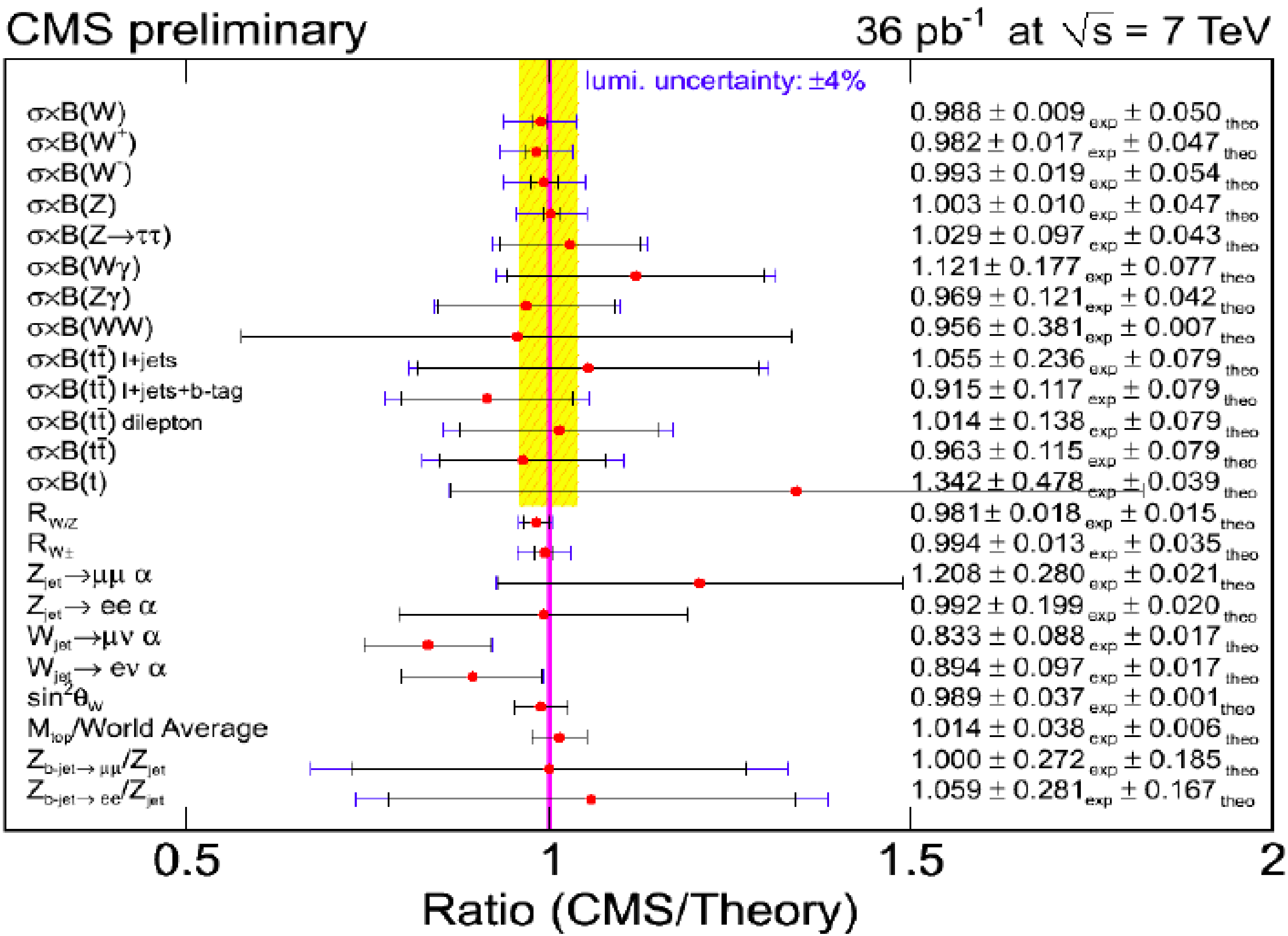






- Require lepton (e or μ) + *b*-jet + forward jet
- Measure top cross-section:
  - (83.6±29.8±3.3) pb
  - 1.6σ significance
- Theory: 59.1 pb

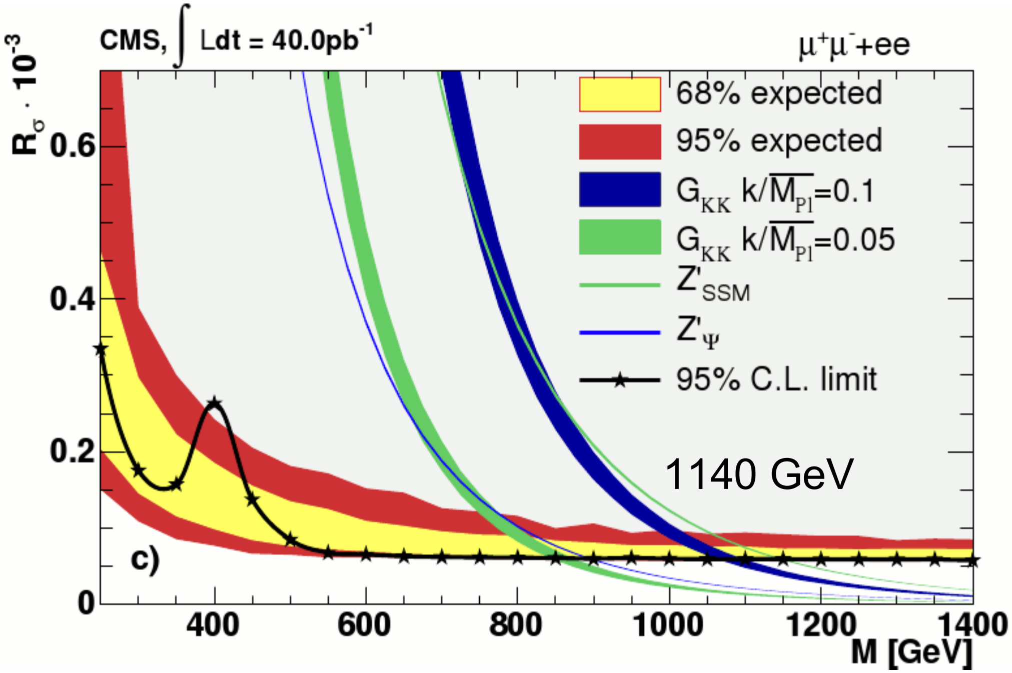
CMS *vs.* Standard Model



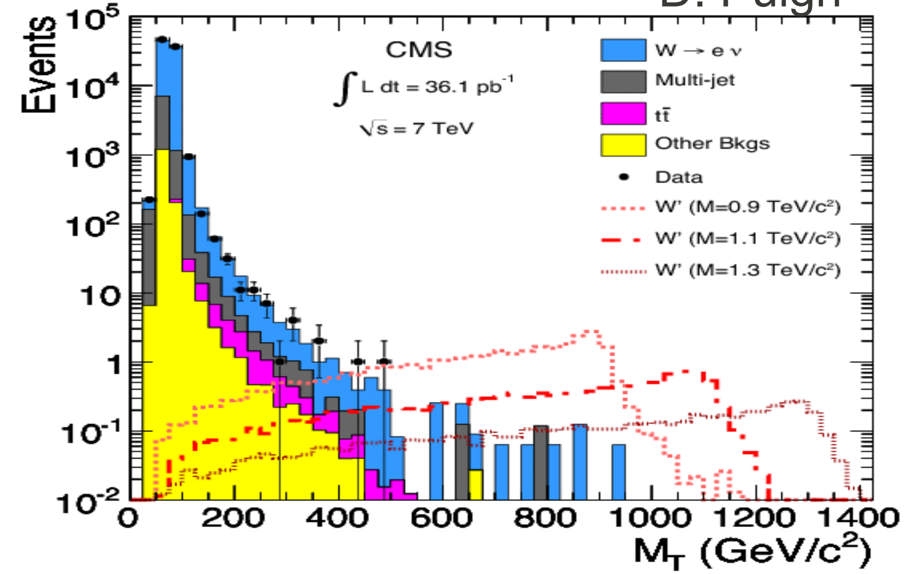
Searches for New Physics

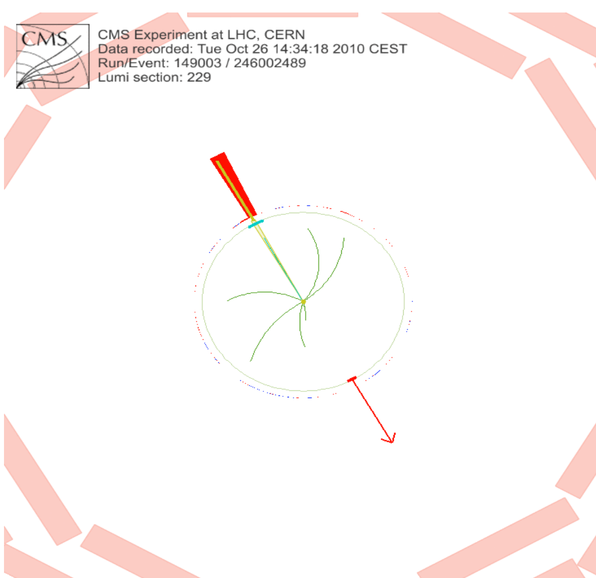
- Exotica
- Higgs
- SUSY

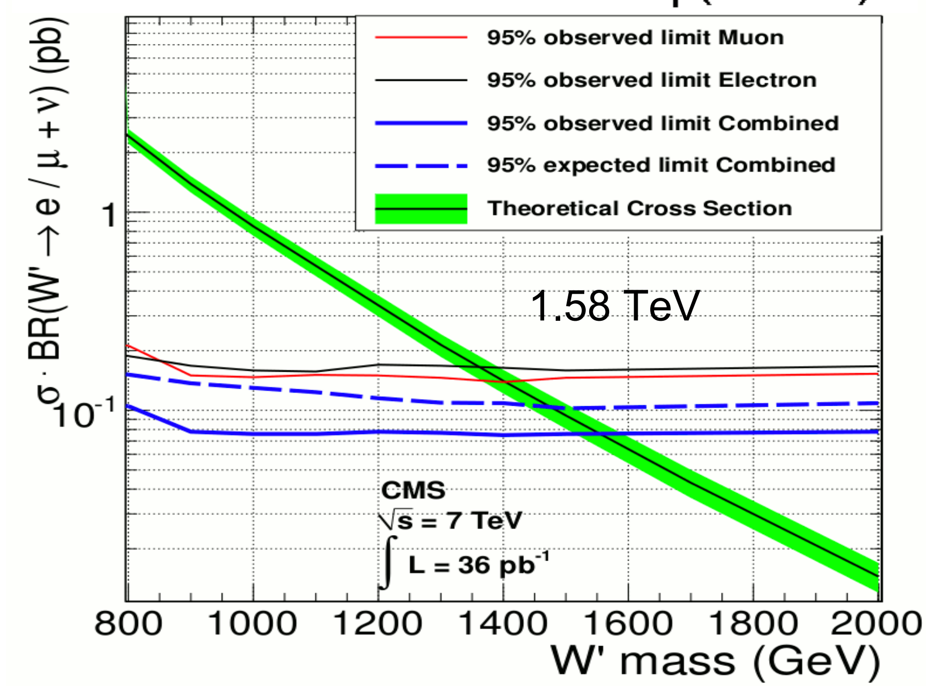
Z' and *W'* Searches



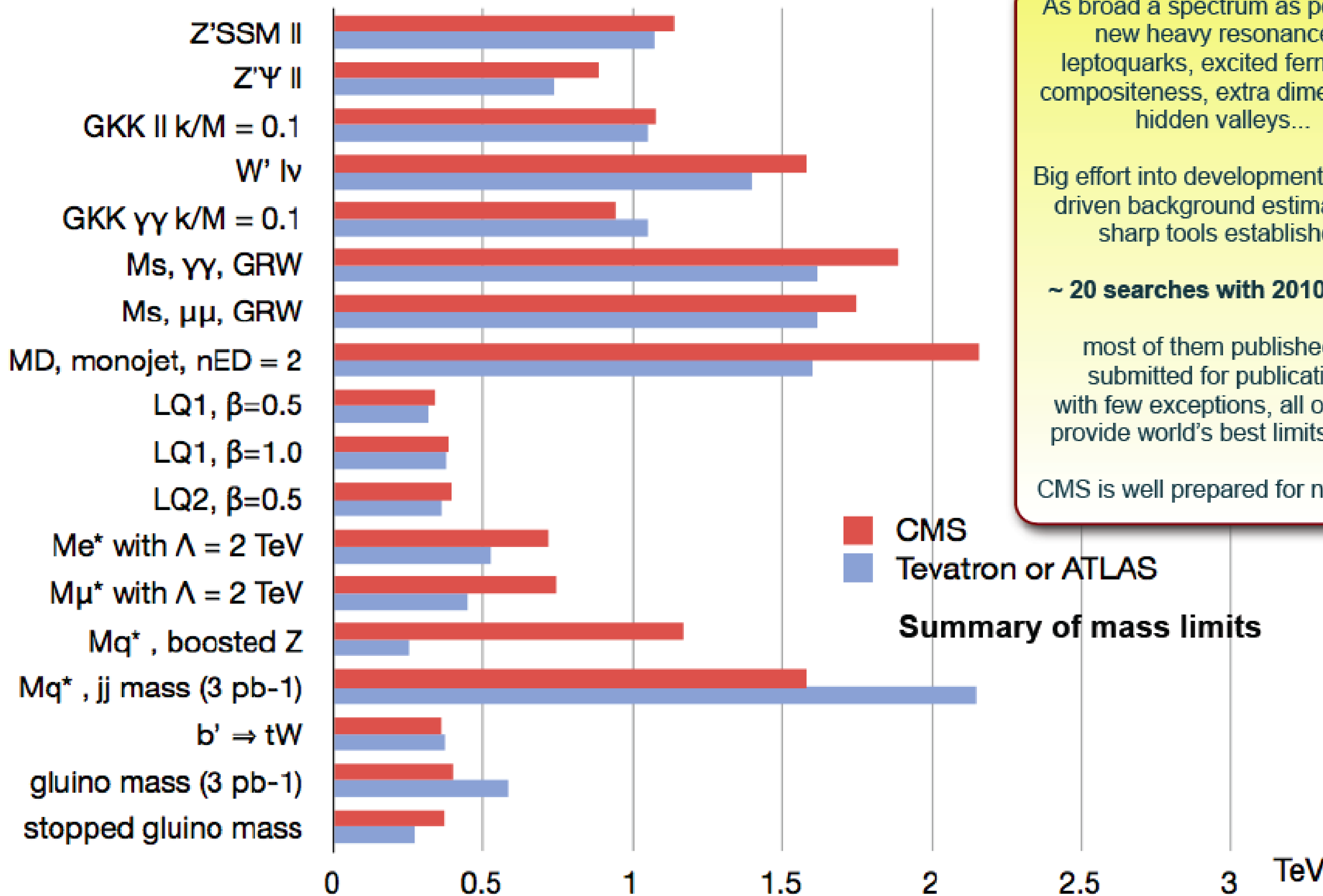
D. Puigh







Plus Many Other Searches...



As broad a spectrum as possible: new heavy resonances, leptoquarks, excited fermions, compositeness, extra dimensions, hidden valleys...

Big effort into development of data-driven background estimations: sharp tools established

~ 20 searches with 2010 data !

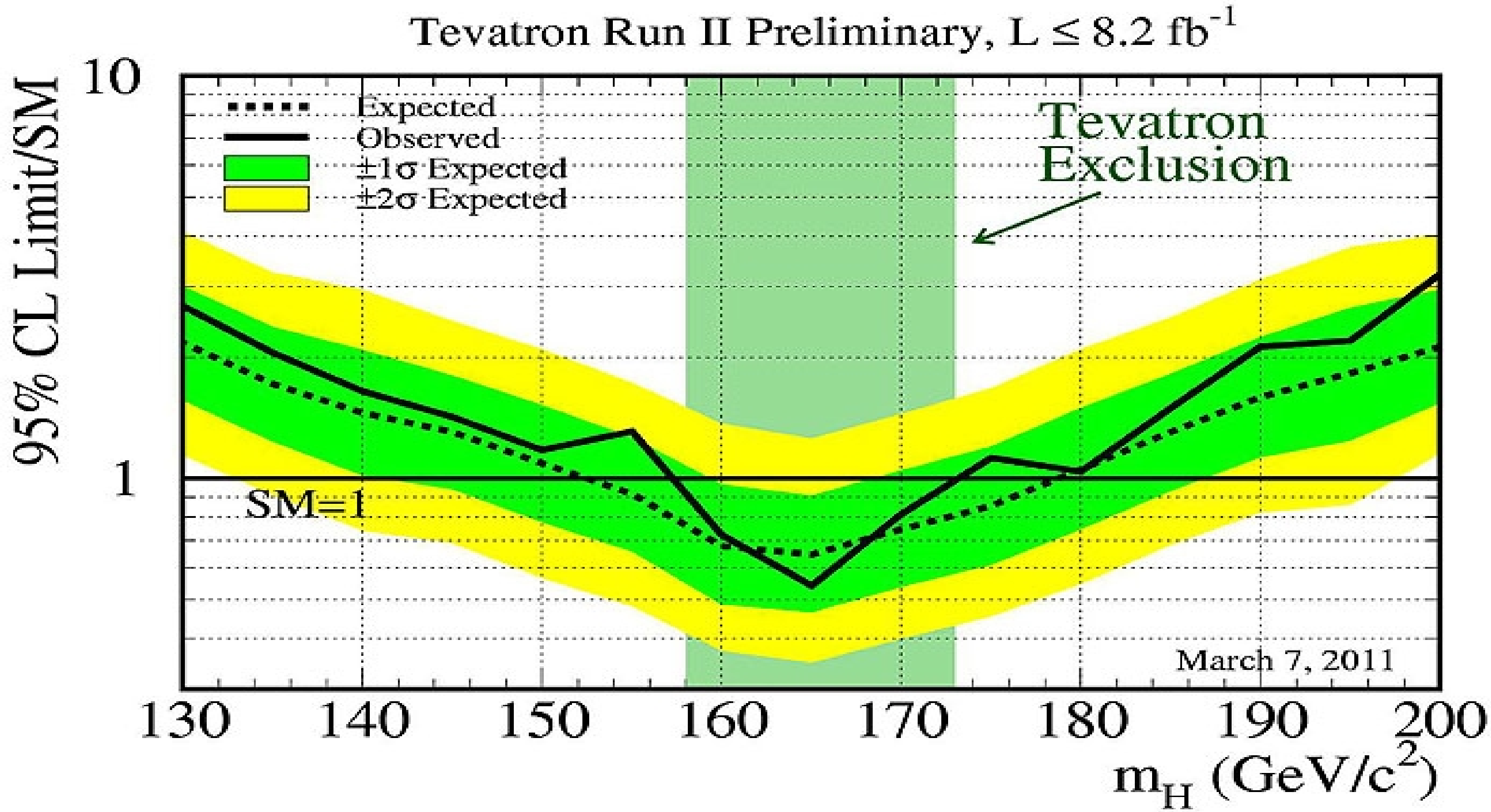
most of them published or submitted for publication; with few exceptions, all of them provide world's best limits so far

CMS is well prepared for new data

Summary from G. Dissertori

Higgs Searches

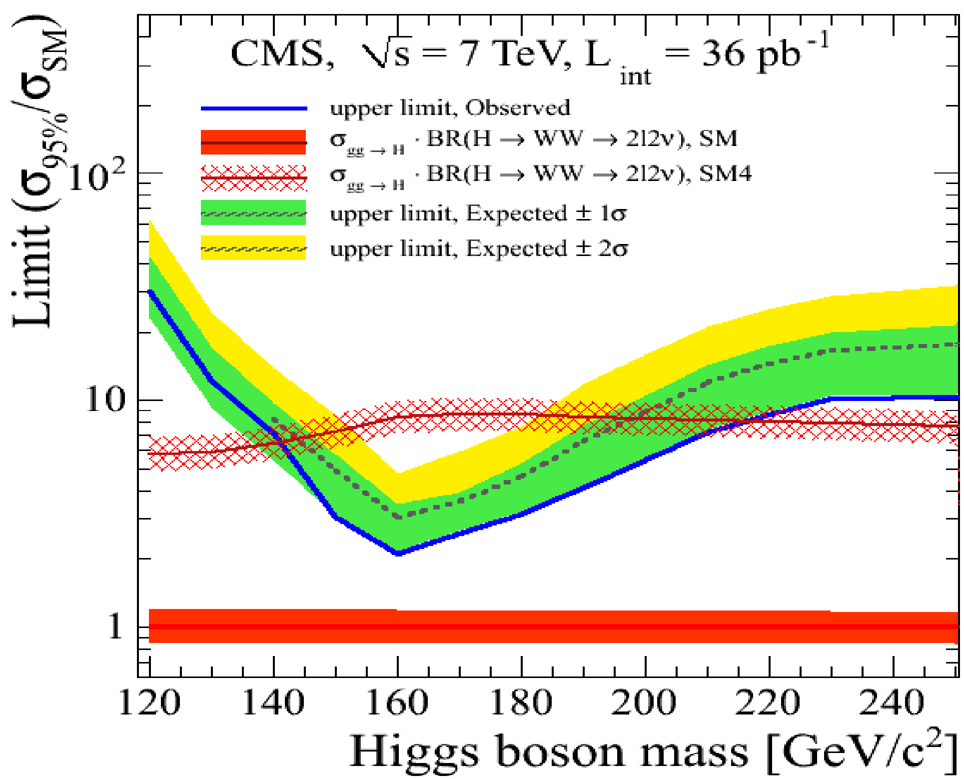
- LEP II ruled out $m_H < 114$ GeV
  - Tevatron is excluding $158 < m_H < 173$ GeV

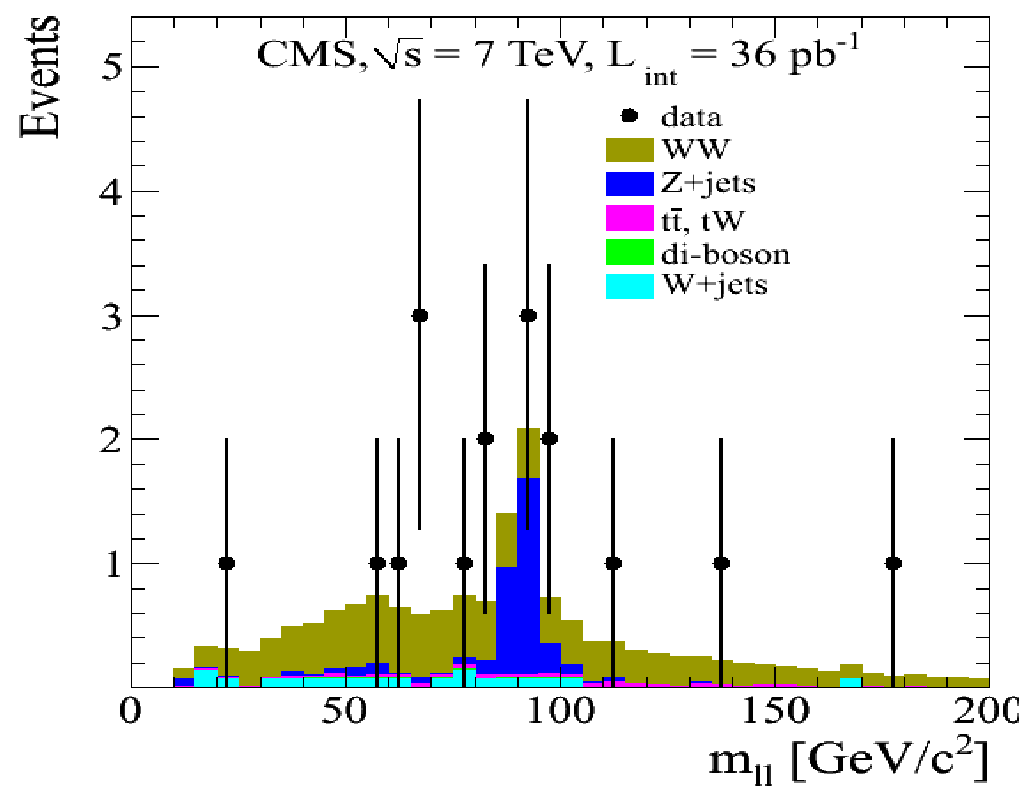


- The LHC experiments are now joining the Higgs search

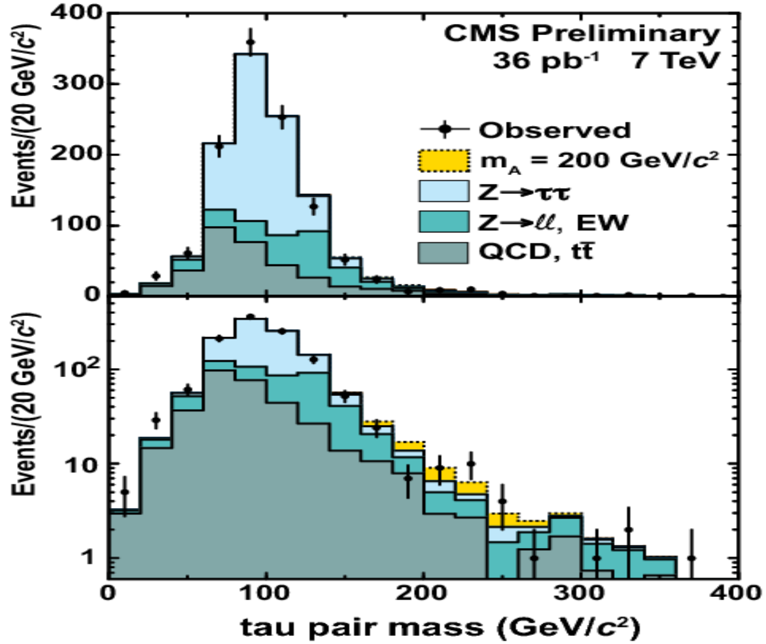
Higgs to WW

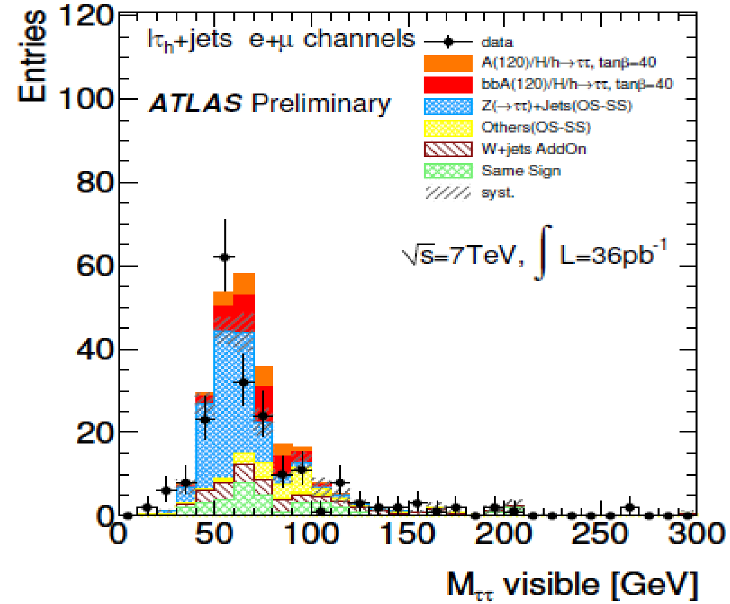
- Studied final state with 2 opposite charge leptons + MET
  - Measured $\sigma(pp \to W^+W^-) = (41.1 \pm 15.3_{stat} \pm 5.8_{syst} \pm 4.5_{lumi})$ pb
- Placed limits on Higgs production
  - At around 160 GeV – within a factor of 2 of the SM prediction

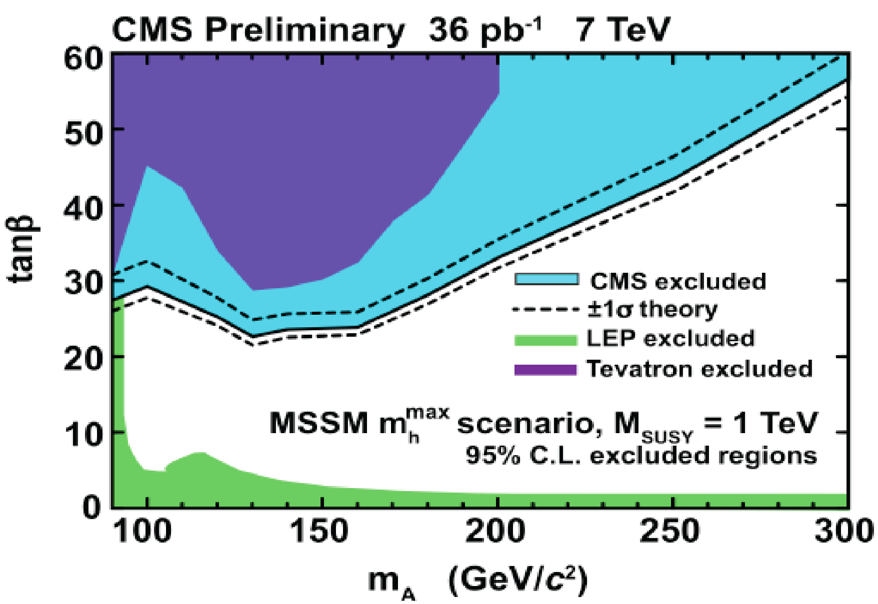


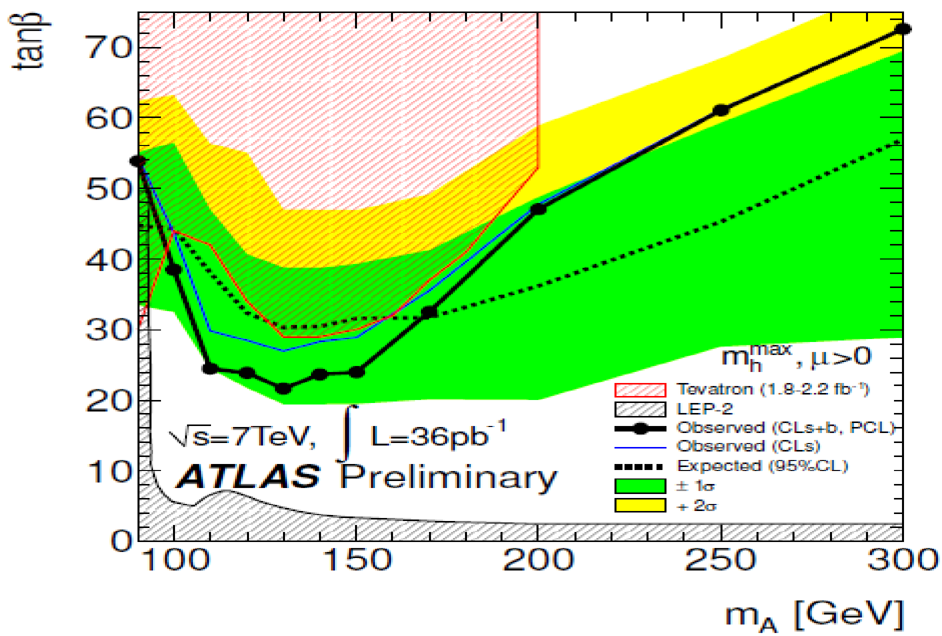


MSSM Higgs to $\tau\tau$





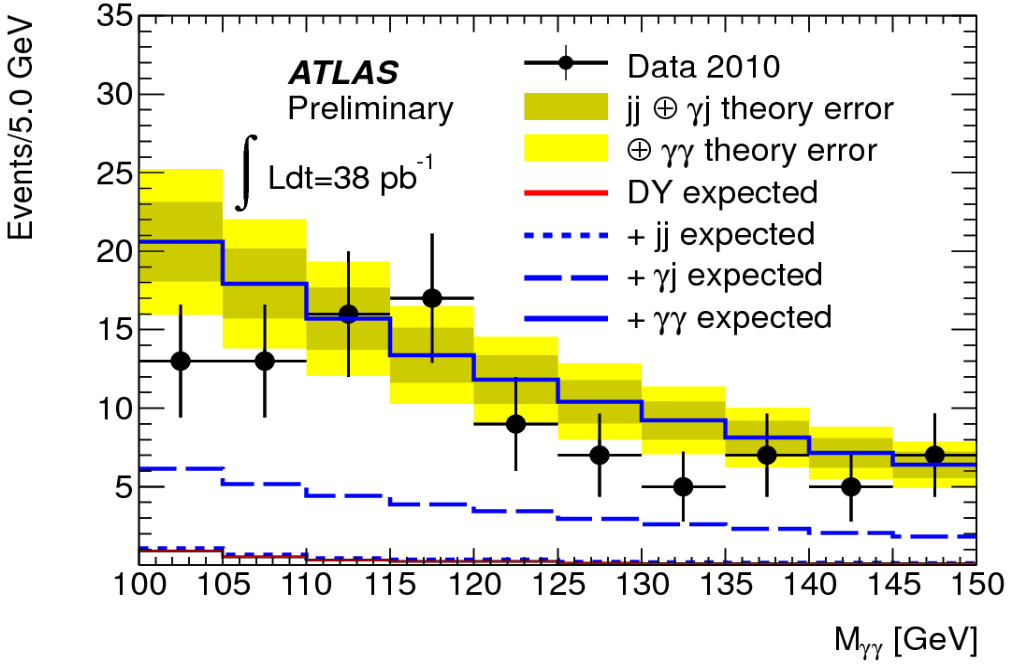


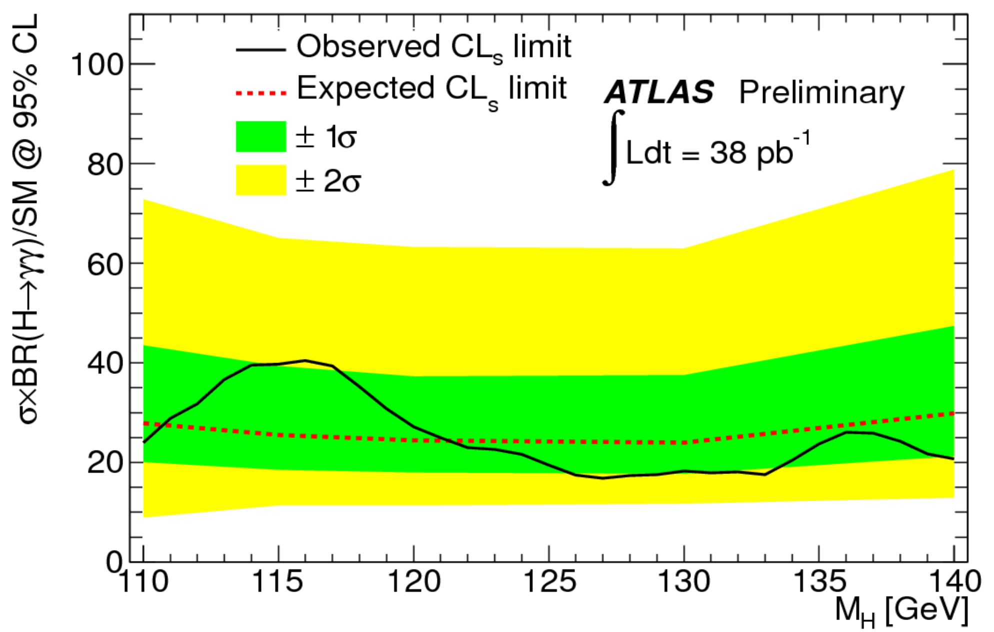


CMS and ATLAS reach very similar – significantly better than Tevatron

ATLAS: SM Higgs to $\gamma\gamma$

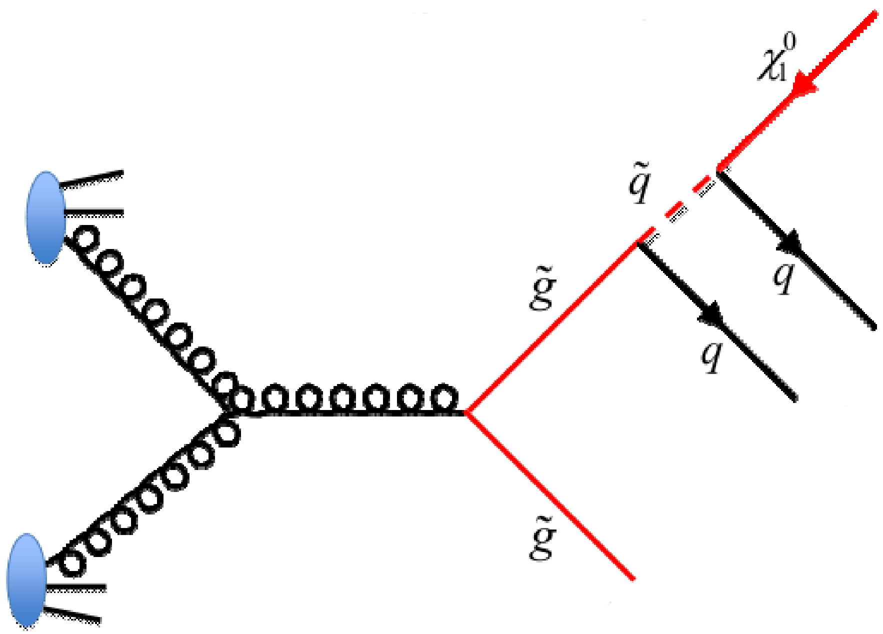
- Key mode for the discovery of a low mass Higgs.
- ATLAS presented first results on $H\rightarrow\gamma\gamma$.
- Expected limit about a factor of 20 beyond SM
- CMS has not yet shown results in this mode.
  - CMS should do very well in this channel with our electromagnetic calorimeter.
- This mode will be very interesting with ~1 fb^{-1}.

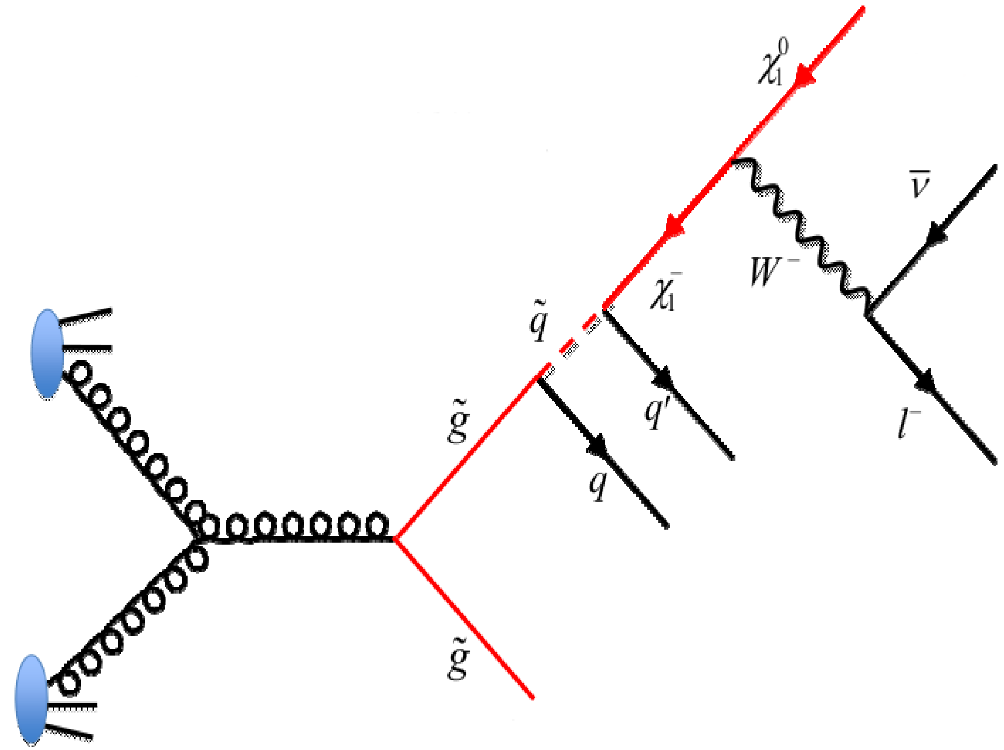




SUSY Searches

- SUSY produced strongly – large cross section
- Long decay chains – lot of activity in the detector

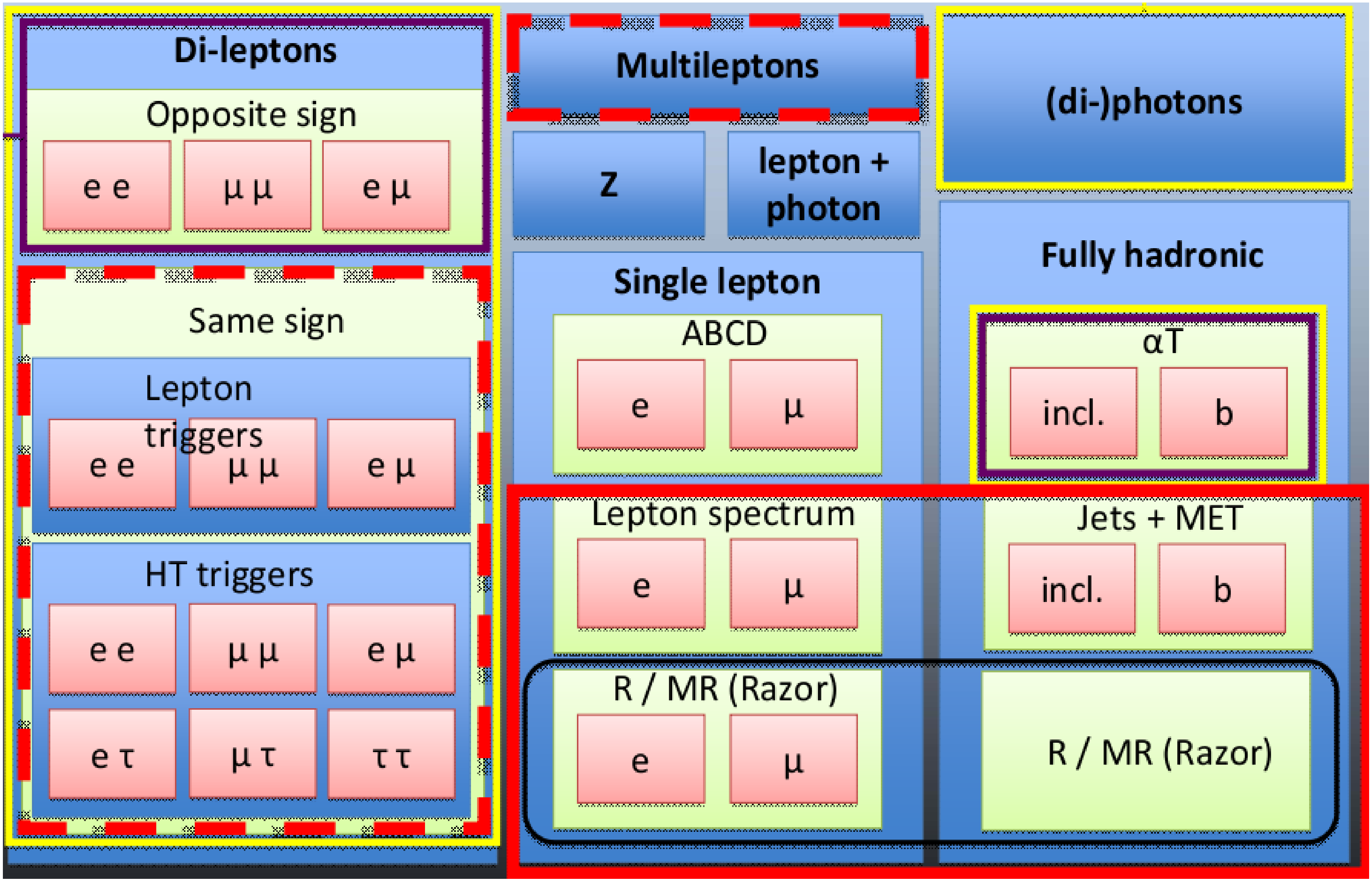




- Many different possible final states
  - Many different searches

Illustrations from C. Bernet

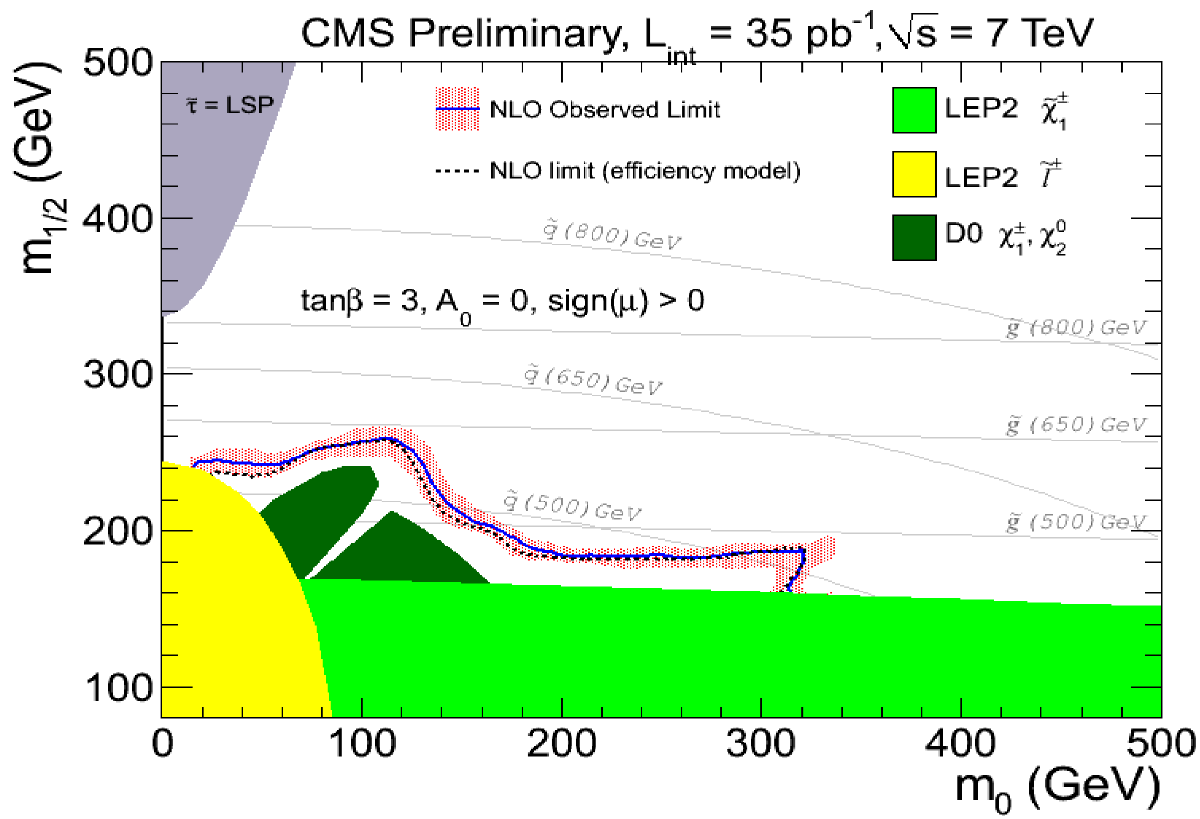
CMS SUSY Searches



From C. Bernet

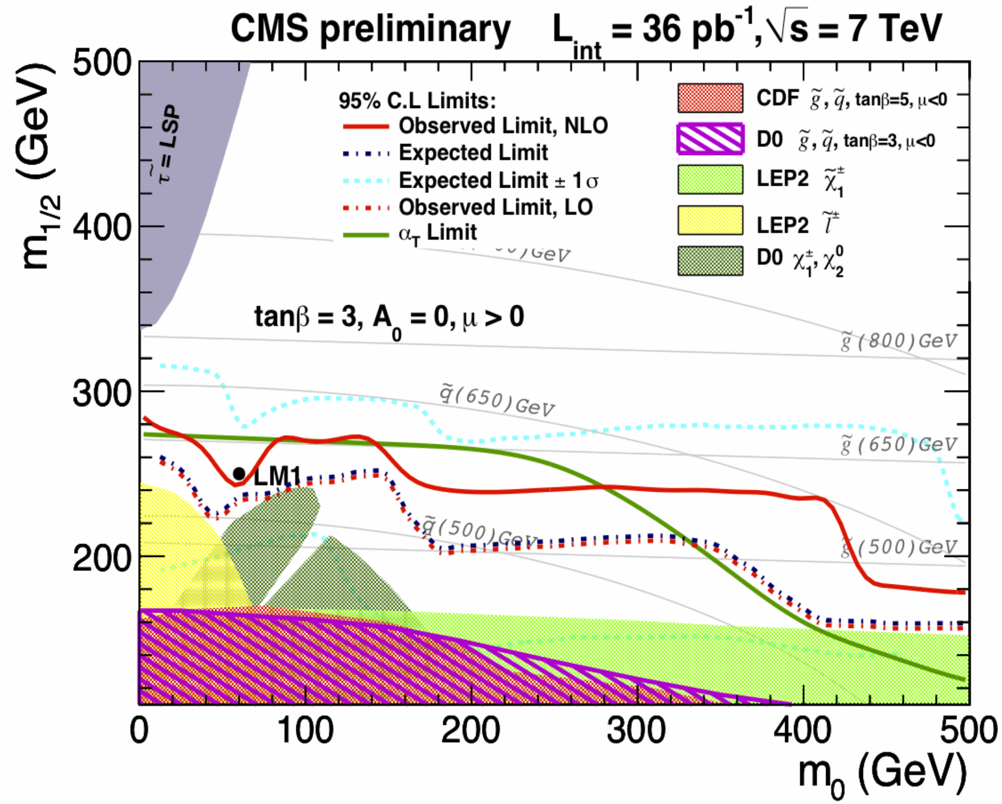
Two Leptons + MET + Jets

- Two isolated same sign leptons (e or μ)
  - $p_{T,1}$ > 20 GeV,
  - $p_{T,2}$ > 10 GeV
- At least 2 jets
  - p_T > 30 GeV, $|\eta|<2.5$
- Missing transverse energy
  - MET > 30 GeV (ee and $\mu\mu$)
  - MET > 20 GeV ($e\mu$)
- Main background:
  - Fake leptons in b decays from top

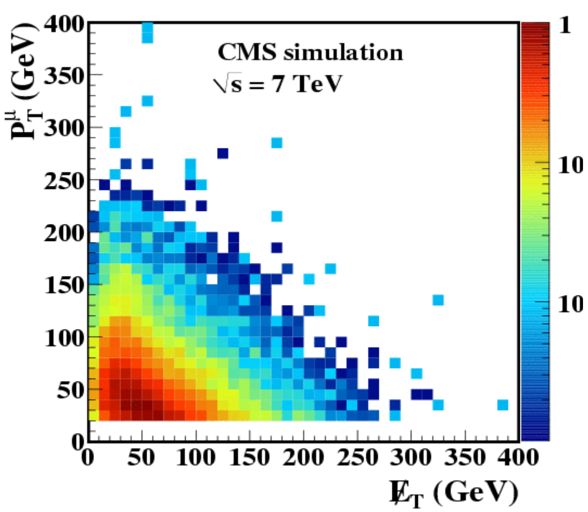


Lepton + Jet + MET

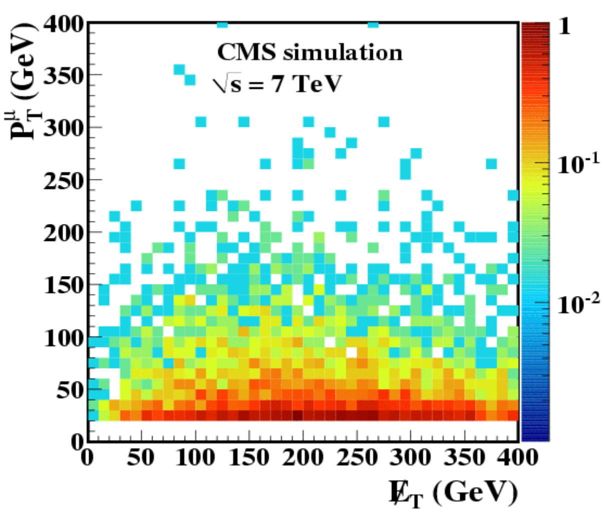
- One leptons (e or μ)
  - p_T > 20 GeV
- At least 4 jets
  - p_T > 30 GeV, $|\eta|<2.4$
- Look for signal at high MET
- Main background:
  - Top and W+jets

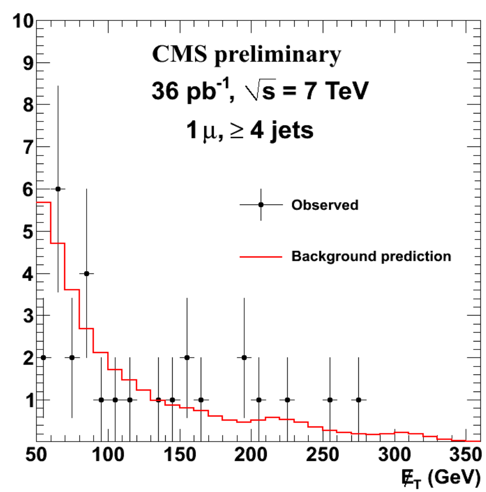


SM Backgrounds



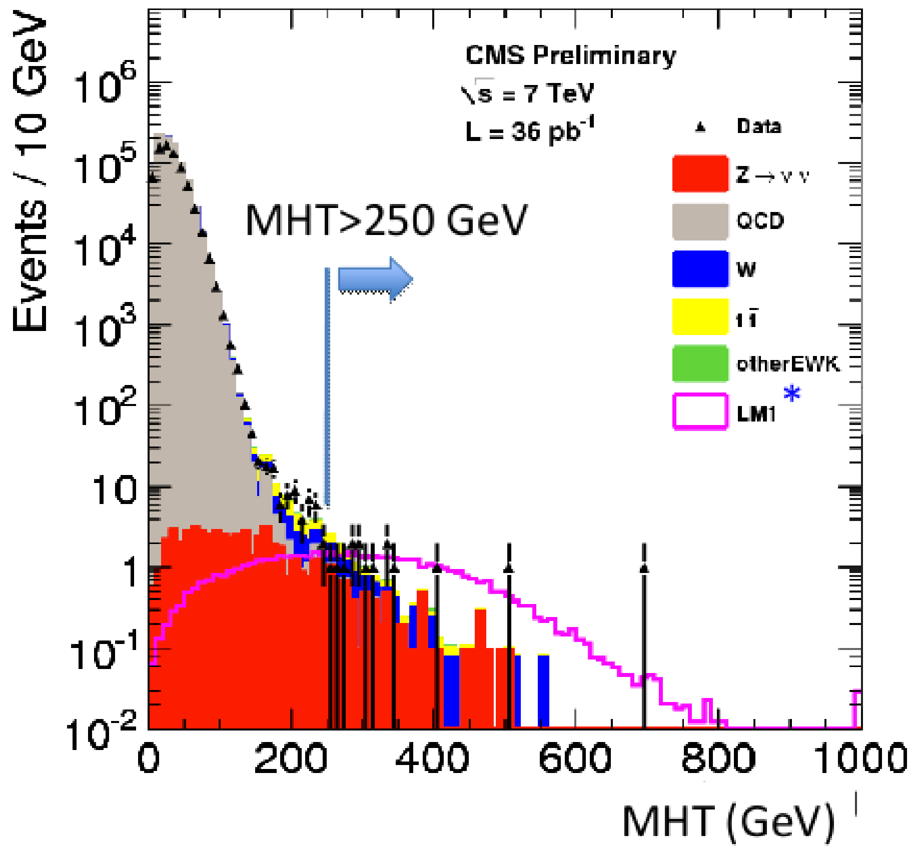
SUSY LM1





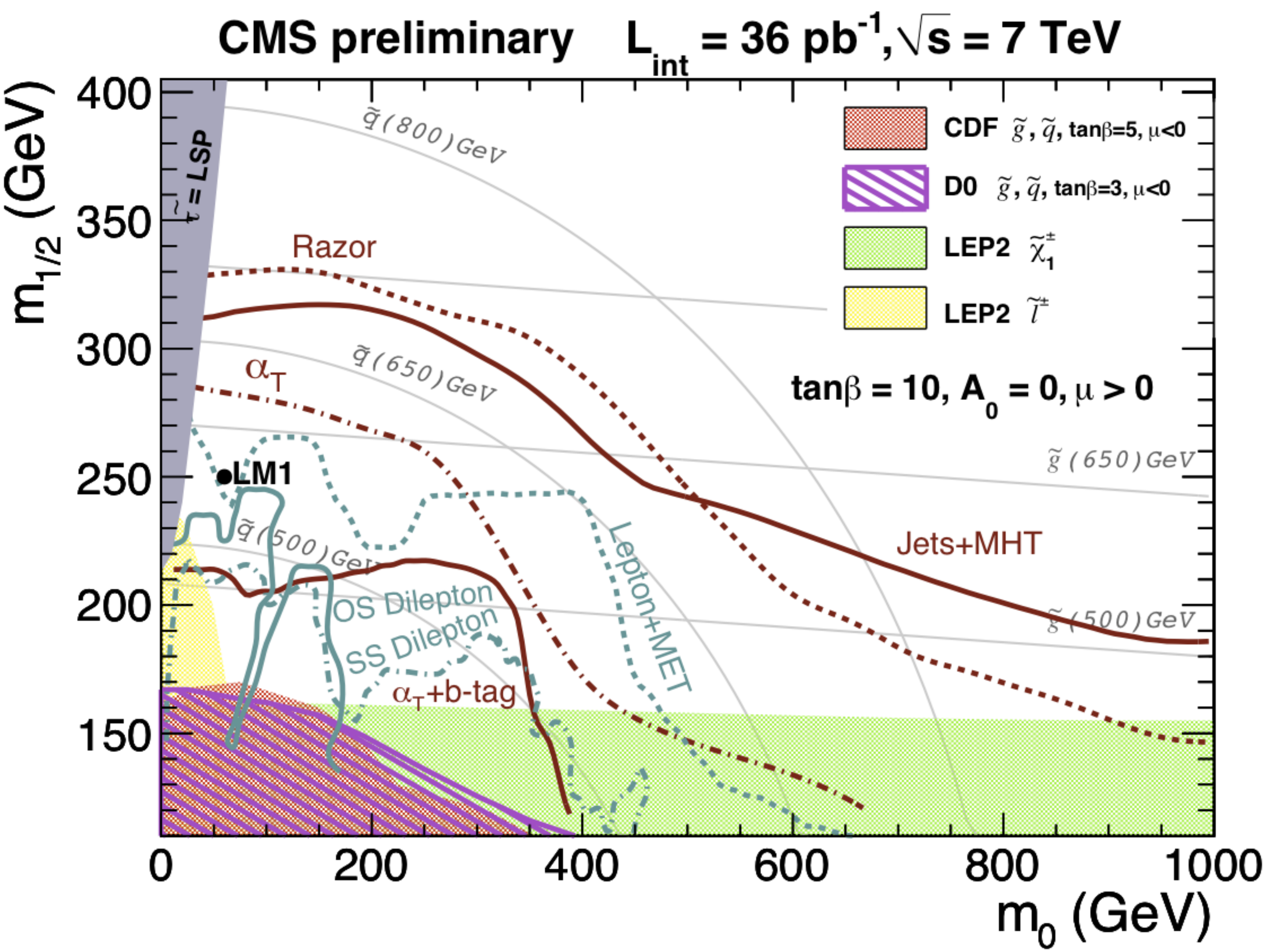
0 Leptons: Jets + MHT

- At least 3 jets
  - $p_T > 50$ GeV, $|\eta|<2.5$
- HT > 300 GeV
  - Efficient trigger
- Veto e or μ.
- Jets separated from MHT
- Background
  - QCD modeled after measuring jet resolutions in data.
  - $Z\rightarrow\nu\nu$ modeled from $Z\rightarrow ll$.



	expected	Observed
MHT>250 GeV	18.8 ± 3.5	15

SUSY Summary



The LHC has taken a serious bite into the SUSY parameter space

Physics Summary

- This results were only a small number of about 60 physics analysis that were approved for presentation two weeks ago at Moriond.
  - So far the Standard Model is standing strong.
  - But CMS (and ATLAS) has only a small data sample compared to what the future will hold.
- CMS is getting into 'search mode' now.
  - We will have a data sample that will double on the time scale of a week or so when LHC operation starts again.
  - By the summer we might have 1 fb^{-1}.

Outline

The CMS Experiment

The LHC

2010 Commissioning and Operation

Physics Results

2011 (and 2012) Running

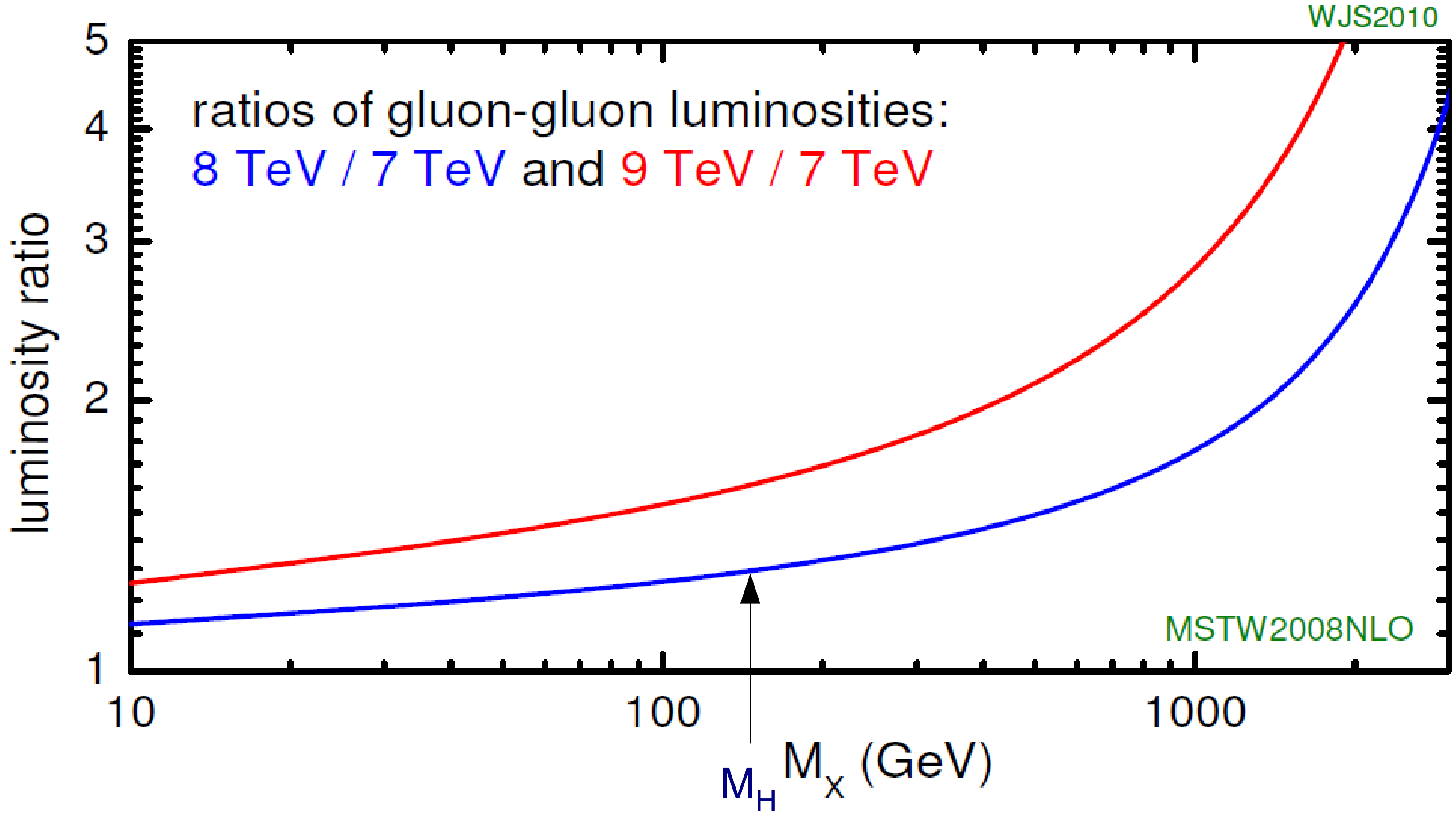
Operation in 2011

- Can we increase energy?
- What is the achievable β^*?
- Can we operate at 50 ns bunch spacing?
- How long time is needed to commission the LHC and intensity and ramp up the intensity?

- These and other questions were discussed during the LHC Operations workshop in Chamonix Jan. 24-28, 2011.

- It has been agreed to operate the LHC in 2012.
  - Long shutdown Dec. 2012 – Mar. 2014 to consolidate the splices for operation at 14 TeV.

Increase in Energy?



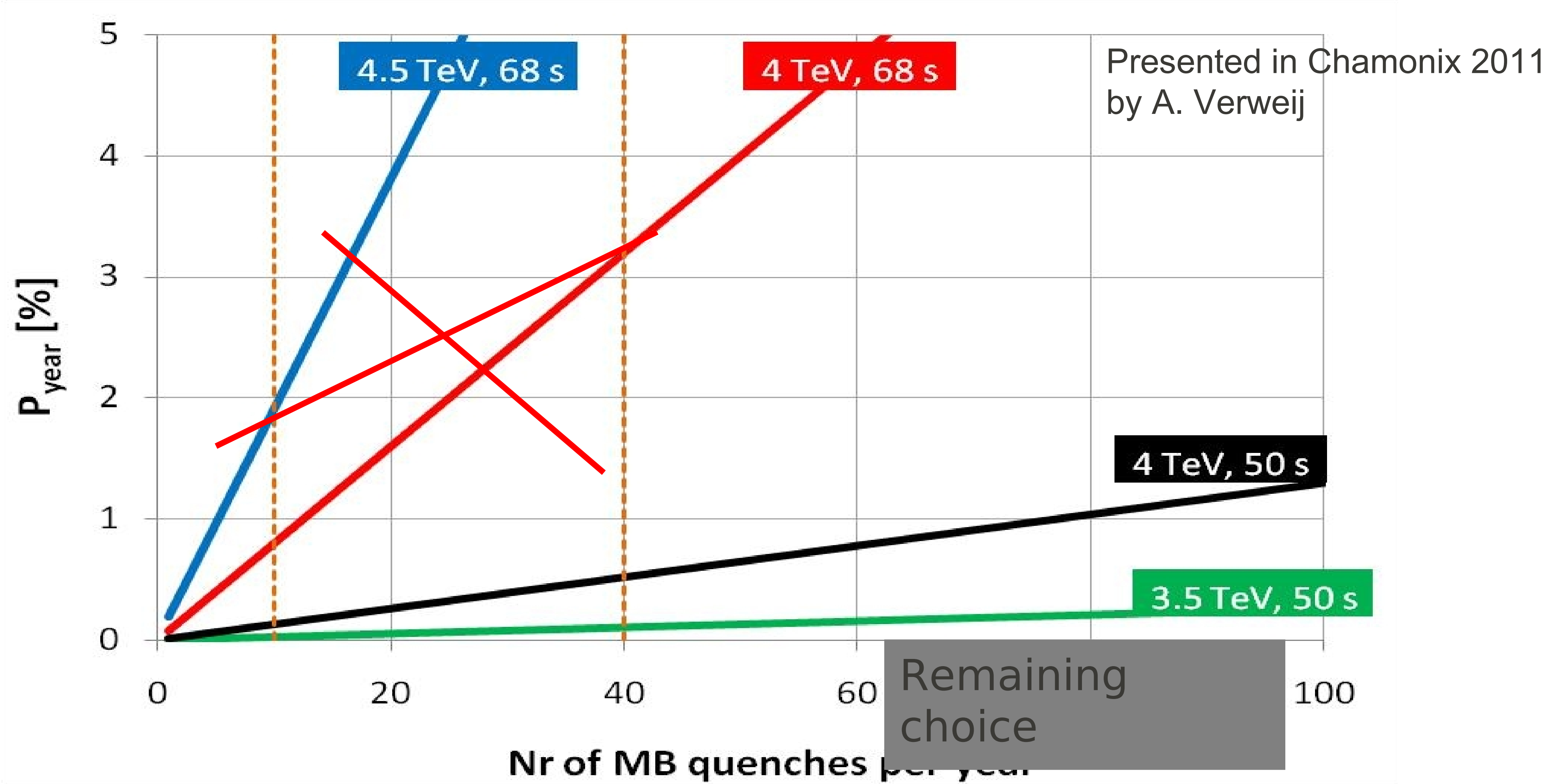
For a Higgs search, increasing E_{CM} from 7 TeV to 8 TeV would gain you about 20%.

Higher Energy Increases Risks!

We don't want a repeat of the Sept. 19, 2008 accident!

Risk Analysis

Probability per Year of burning an interconnect



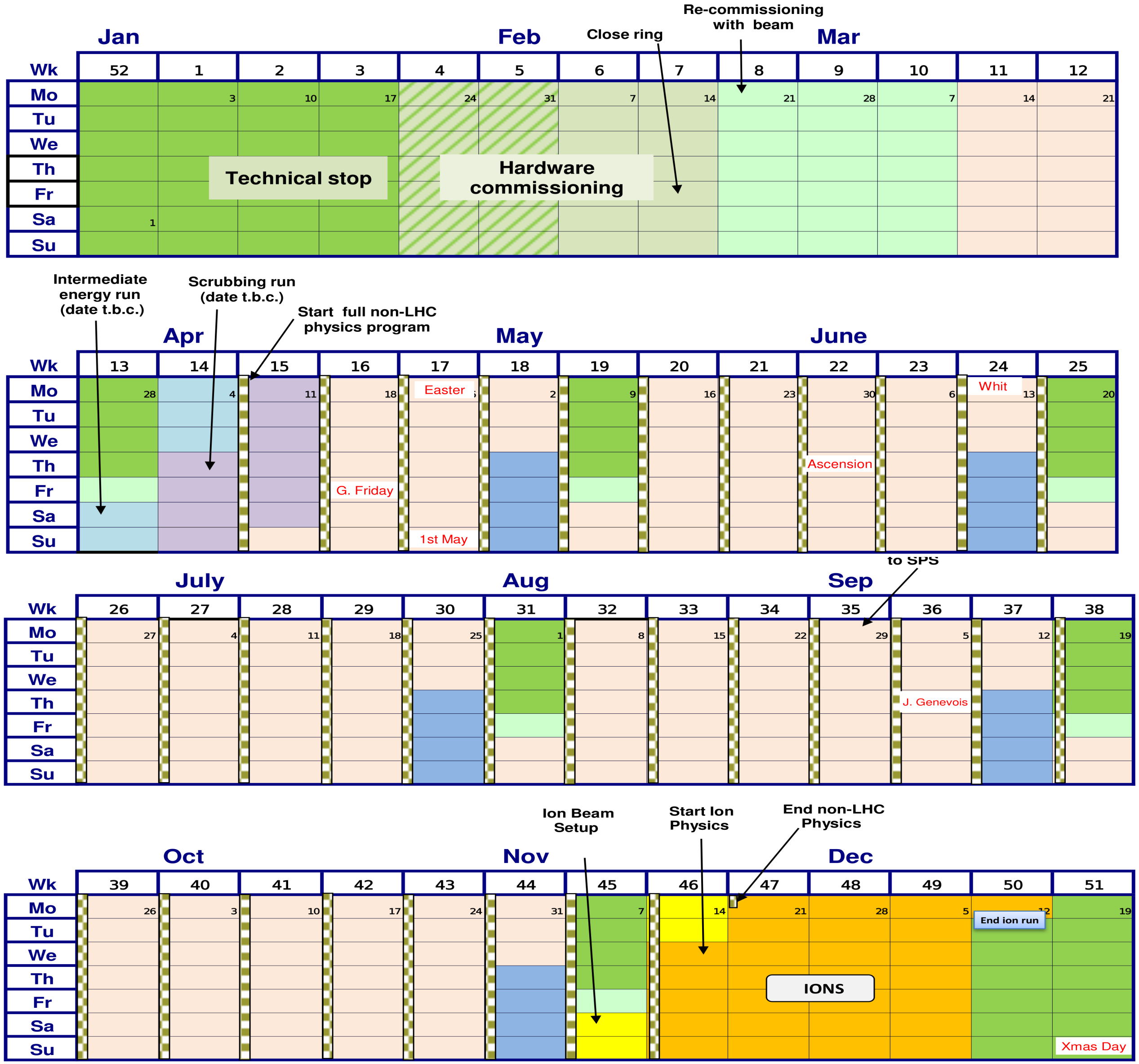
- Increasing beam energy to 4 TeV (E_{CM}=8 TeV) increases the risks.
  - Stay at 3.5 TeV.
- In 2010 we had about 40 quenches – none with beam in the machine.

Other Machine Parameters

- What is the achievable β^*?
  - Geometric interpretation of β^* is the distance from interaction point (IP) where the beam is twice as large.
  - Smaller beams at the IP means larger beams elsewhere – Liouvilles theorem. Limited by aperture in machine.
  - Luminosity is proportional to $1/\beta^*$ - smaller value better.
  - Last year LHC used (mostly) $\beta^*=3.5$ m.
  - In 2011 they will use $\beta^*=1.5$ m.
- Can we operate at 50 ns bunch spacing?
  - Limited by e-cloud.
  - Will perform conditioning of the machine (scrubbing) over next 10 days to learn about the limitations from e-cloud.

LHC Schedule – Why There Are Only 125 Days in the Year?

- Subtracting off time for:
  - Technical Stops
  - Machine Commissioning
  - Heavy Ions
  - Special Runs
  - Machine Development
  - Luminosity Ramp
  - Scrubbing Run
- We find that there are about 125 to 135 days of high intensity proton-proton running in a year.



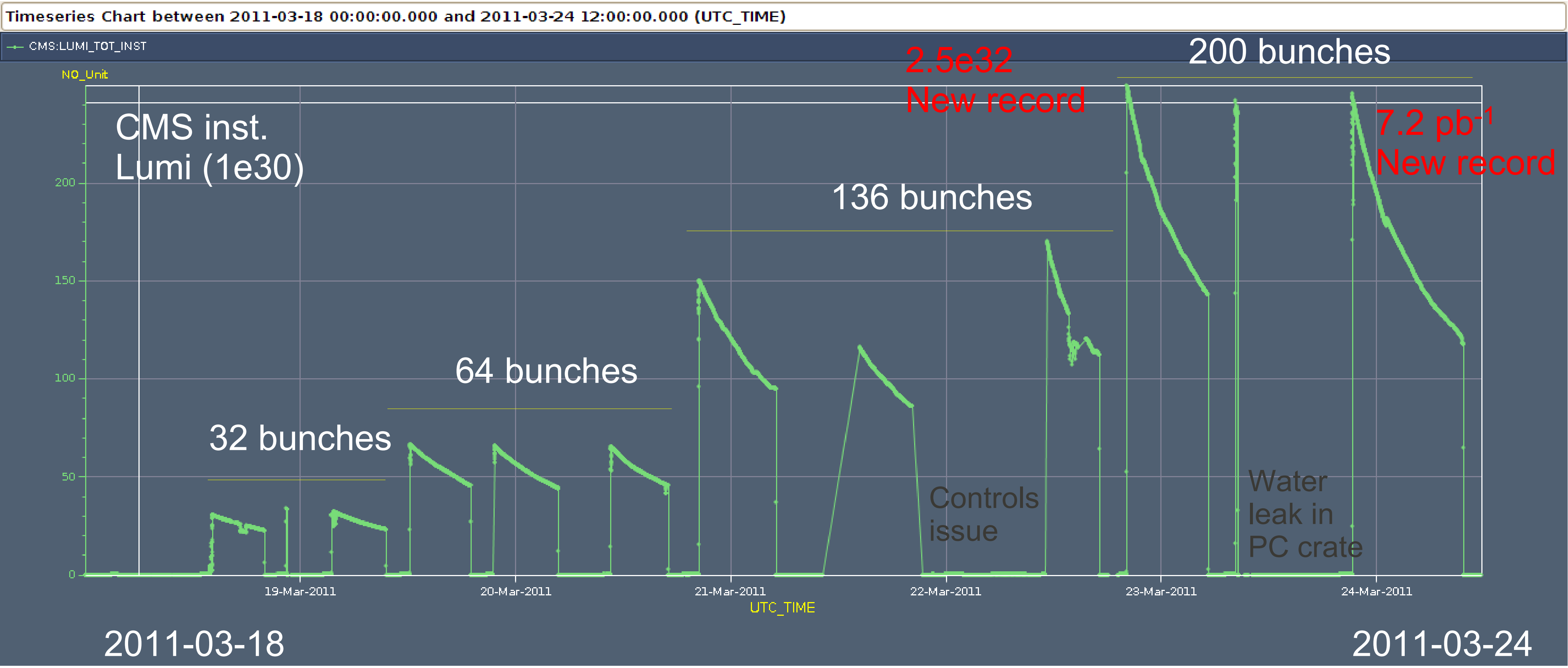
LHC Parameters for 2011

- Baseline for 2011 is 2e32 Peak and 1fb^{-1} (integrated)
  - Already after 5 days of operation reached 2.5e32
- Will likely do much better

value for β^* = 1.5m in IP1/ 5

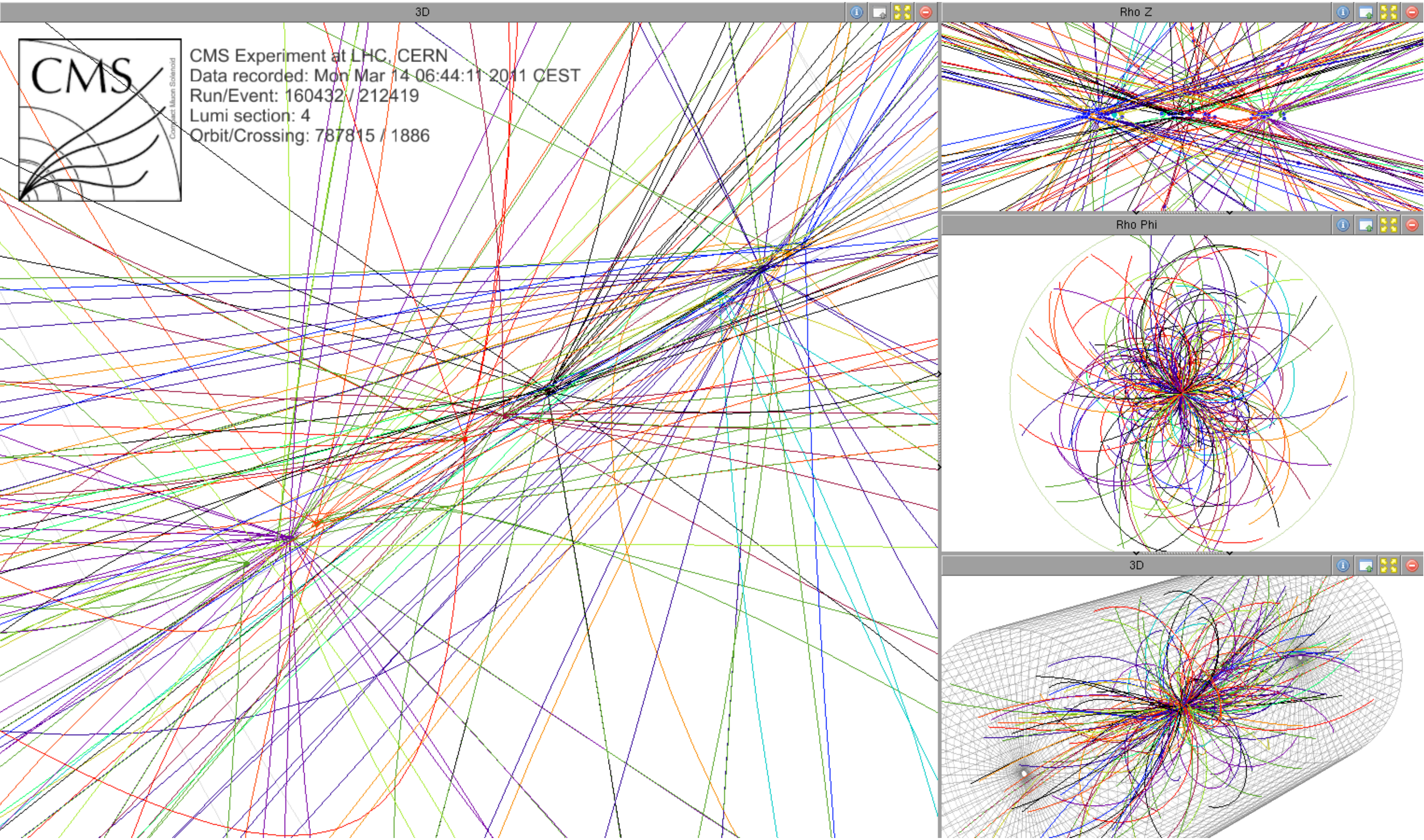
days	Hubner Factor	Fills with	kb	Nb e11	ε μm	L Hz/cm^2	Stored energy MJ	L Int fb^{-1}
160	0.3	150 ns	368	1.2	2.5	~5.2e32	~30	~1.9
135	**0.2**	**75 ns**	**936**	**1.2**	**2.5** **2** **1.8**	**~1.3e33** **~1.6e33** **~1.8e33**	**~75**	**~2.7** **~3.3** **~3.7**
125	0.15	50 ns	1404	1.2	2.5	~2e33	~110	~2.8

Initial 2011 LHC Operation

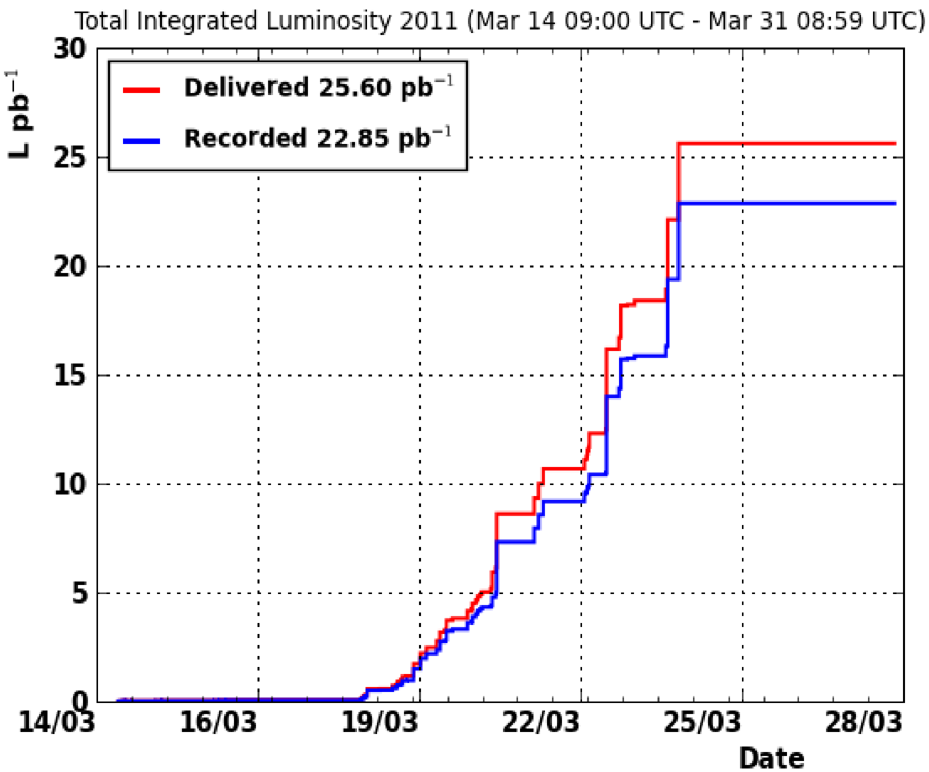


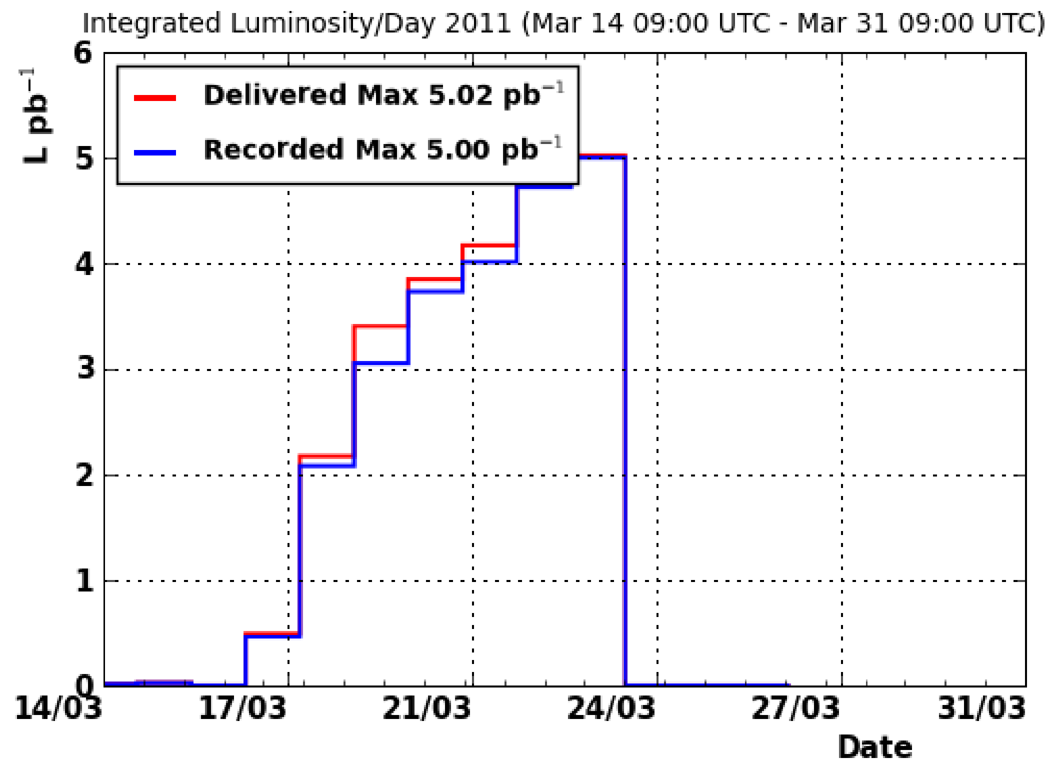
- Increase bunches: 32, 64, 136, and 200 bunches.
- Achieved around 2.5 hours between stable beams many times
  - Very impressive operation – some software/controls issues

Pile-up: 13 Reconstructed Vertices



2011 Run so Far





- In 7 days of operation in 2011 LHC delivered ½ of all 2010 data
  - Just a warm-up exercise.
- CMS recorded 89% of the delivered luminosity.
  - CMS performed commissioning that reduced data taking eff.

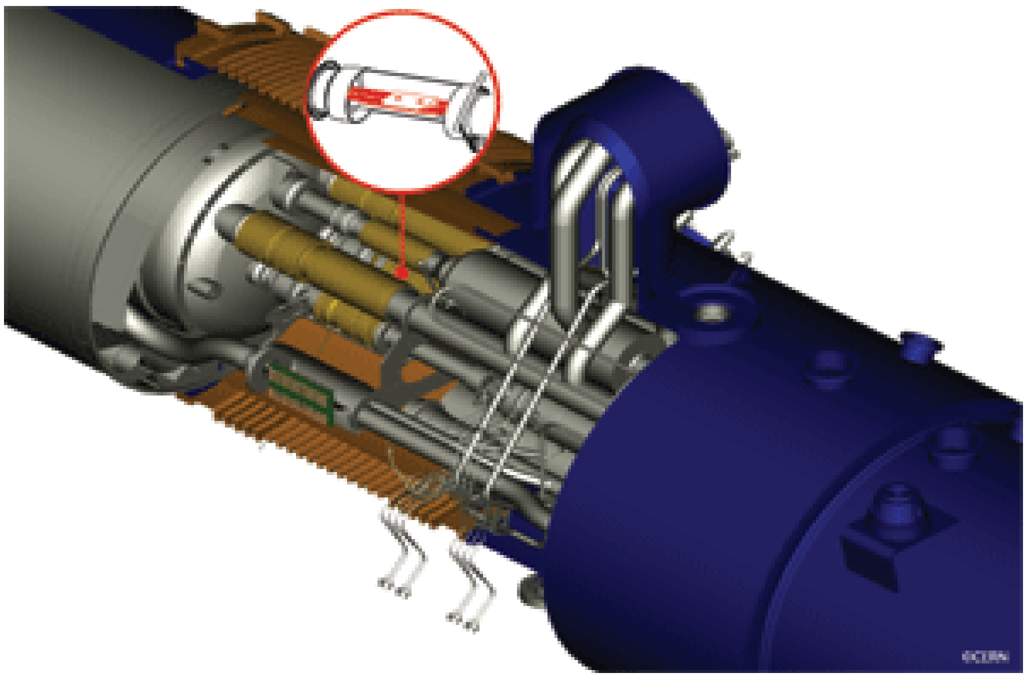
Summary

- LHC progressed greatly during the 2010 commissioning run
  - Reached an instantaneous luminosity of 2×10^{32} cm^{-2}s^{-1}.
- CMS recorded high quality data
  - 36 to 40 pb^{-1} used for producing $O(100)$ physics results.
- LHC has addressed many operational issued in preparation for the 2011 run.
  - LHC has started the 2011 run with reaching a new luminosity record, 2.5×10^{32} cm^{-2}s^{-1}, within about 1 week of beam operation.
- The LHC will now spend about 10 days on the 'scrubbing' run to mitigate e-cloud and the real physics run will start around April 15.
  - 1 fb^{-1} is possible before the summer conferences
  - 3 to 5 fb^{-1} is possible by the end of 2011
  - The official goal of the LHC is 1 fb^{-1} by the end of 2011.
- The LHC will also run for physics in 2012.
- Looking forward to a very interesting few years
  - We are interested is new students to join

Backup

September 19 Incident

- A connection between two magnets failed
- This damaged about 20 dipole magnets and a few quadrupoles
- Will need to replace about 100 magnets
  - Some soot in the beampipe has to be cleaned up
- Plan to start operations again in May 2009
  - After winter shutdown and injector maintenance



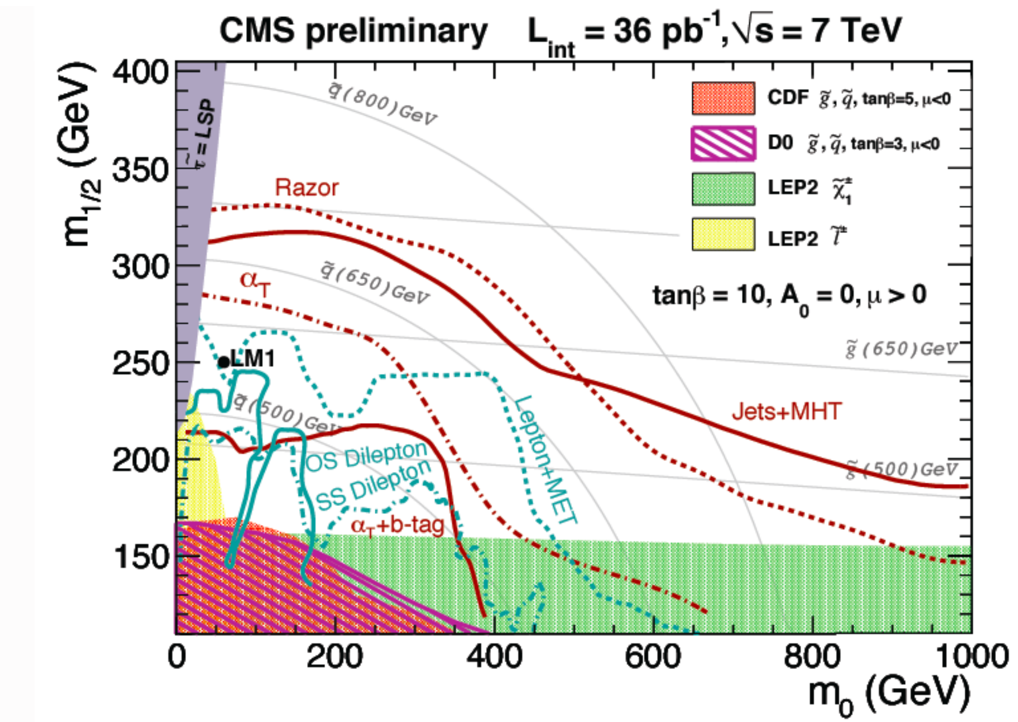
The LHC and the experiments are complex instruments. I'm confident that these initial problems will be overcome.

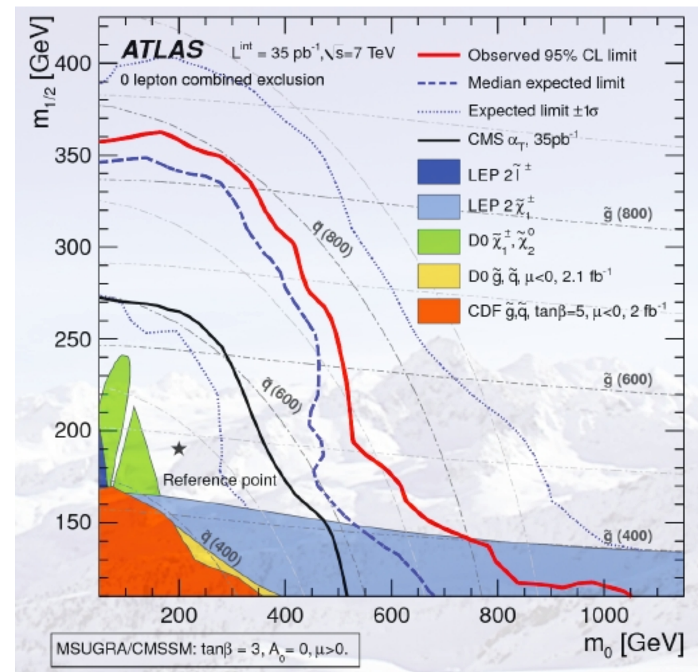
Item	Days
Total proton operation	264
5 MDs (4 days)	- 20
6 TS (4+1 days)	- 30
Special requests	- 10
Commissioning	- 20 to -30
Intensity ramp up	- 30 to -40
Scrubbing run	- 10
Total High intensity	124 to 144 (135 days for integrated L)

Assume 135 days at peak luminosity

Stable period shrinks quickly if there are many exotic requests !

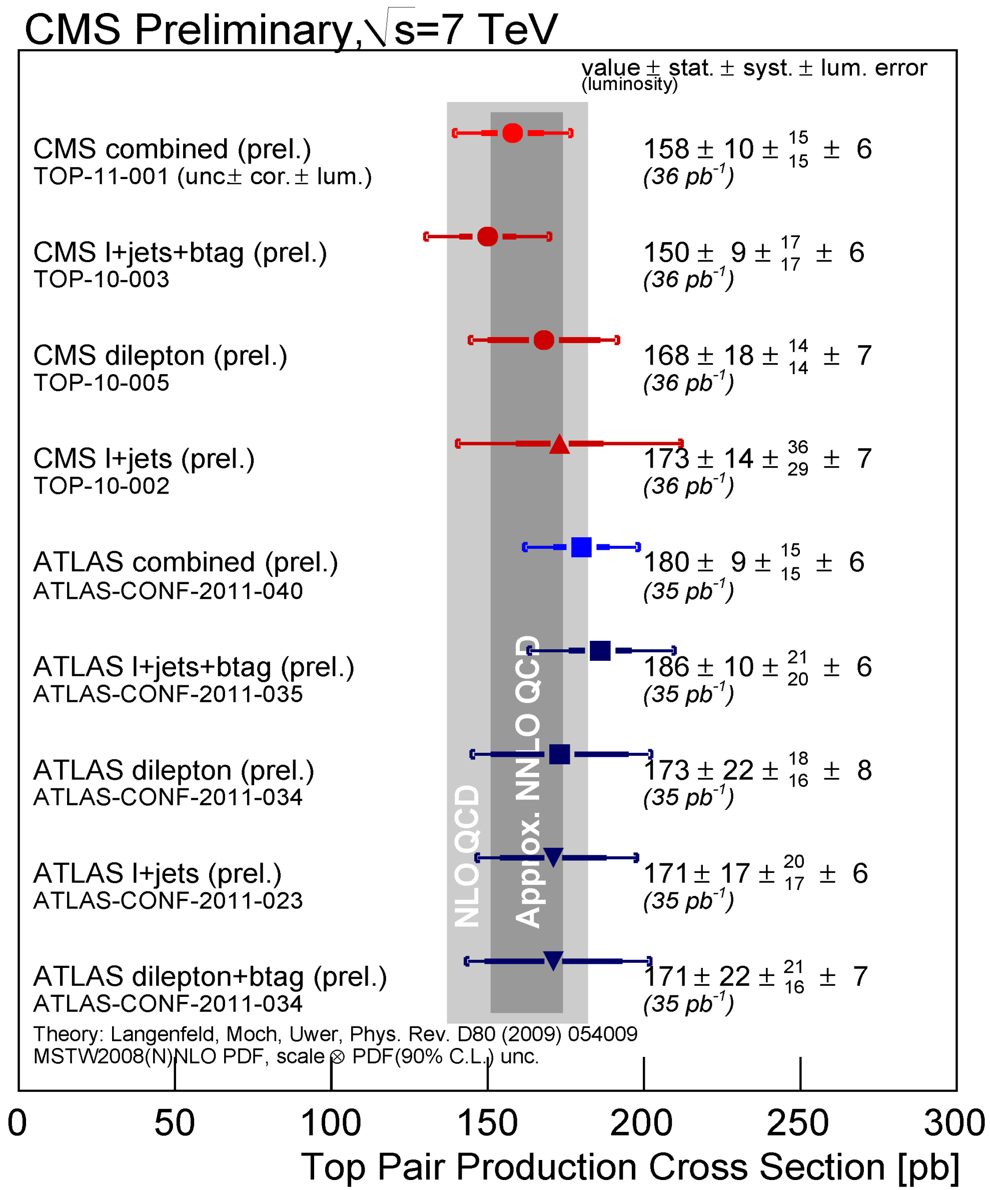
SUSY Searches CMS *vs.* ATLAS





Top Cross Section Combined Result

New measurements of the top cross section (leptons+jets with and without btag) ~36pb^{-1}



LHC Parameters

The LHC surpasses existing accelerators/colliders in 2 aspects :

- The energy of the beam of 7 TeV that is achieved within the size constraints of the existing 26.7 km LEP tunnel.

LHC dipole field	8.3 T
HERA/Tevatron	~ 4 T

A factor 2 in field

A factor 4 in size

- The luminosity of the collider that will reach unprecedented values for a hadron machine:

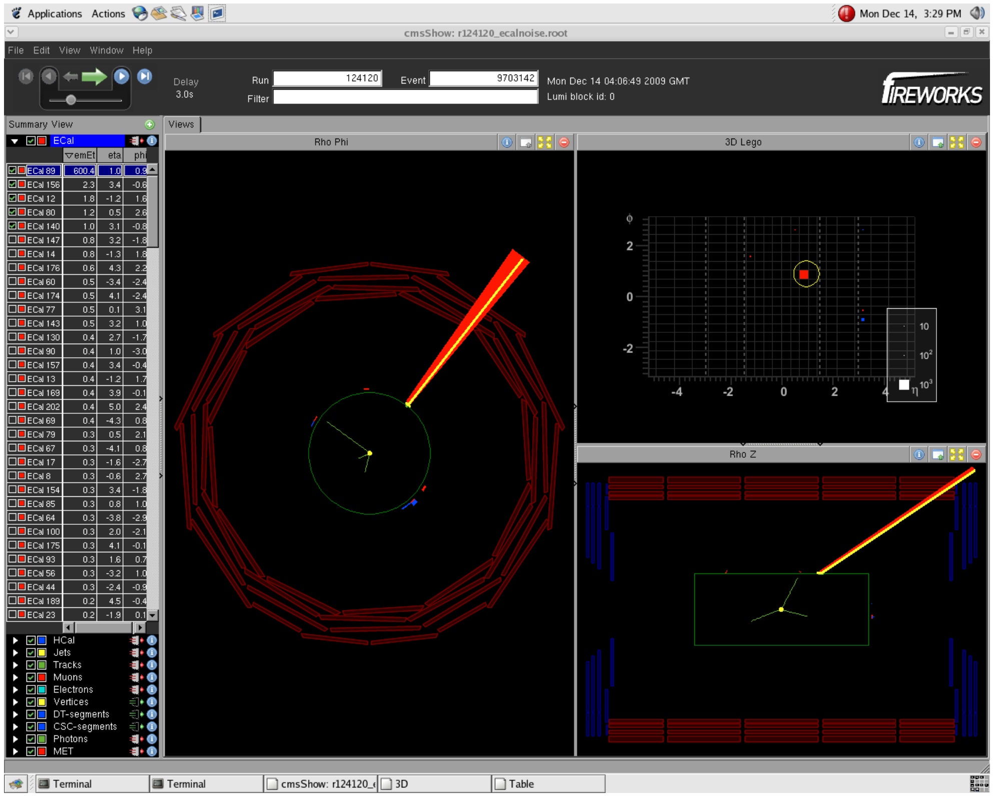
LHC	pp	10^{34} cm^{-2} s^{-1}
Tevatron	pp	3×10^{32} cm^{-2} s^{-1}
SppS	pp	6×10^{30} cm^{-2} s^{-1}

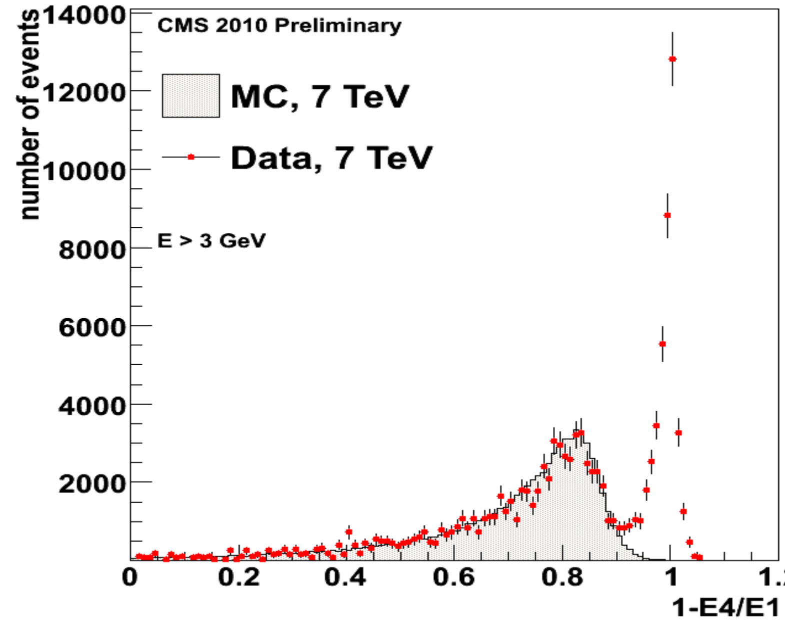
A factor 30 in luminosity

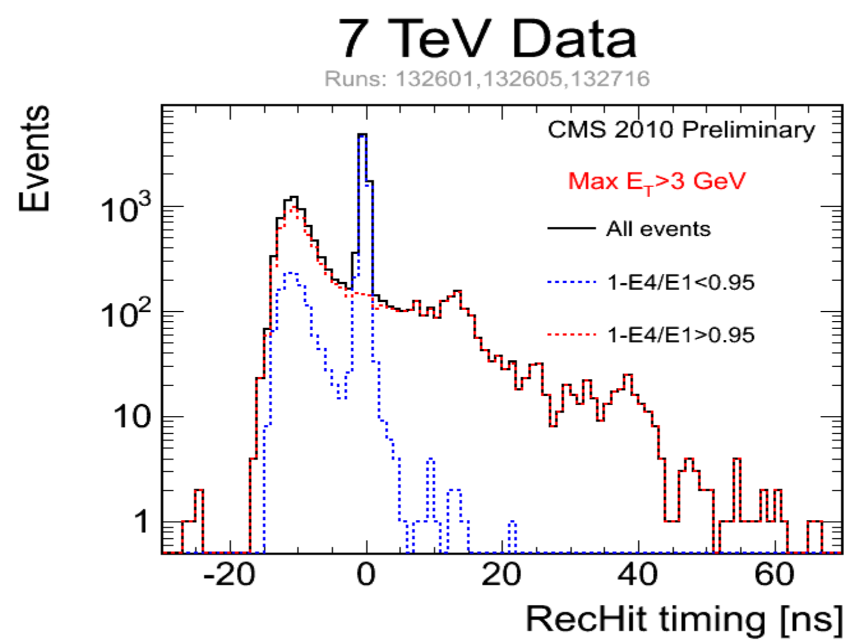
Very high field magnets and very high beam intensities:

- Operating the LHC is a great challenge.
- There is a significant risk to the equipment and experiments.

ECAL Anomalous Energy Deposits



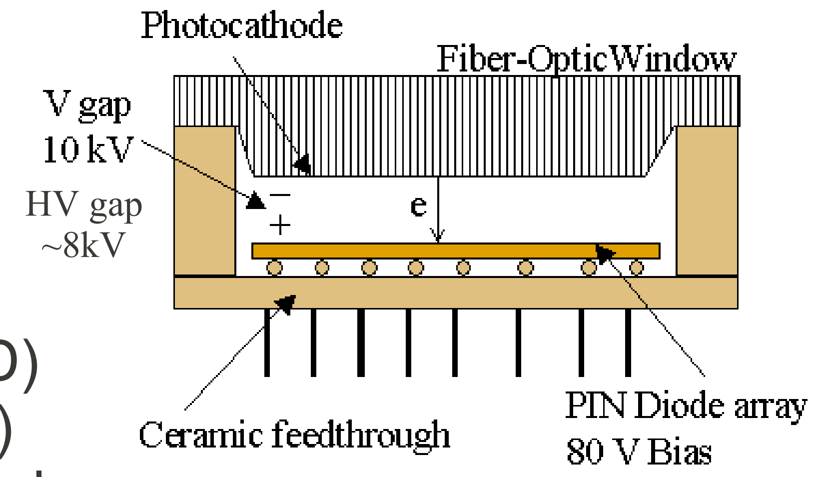


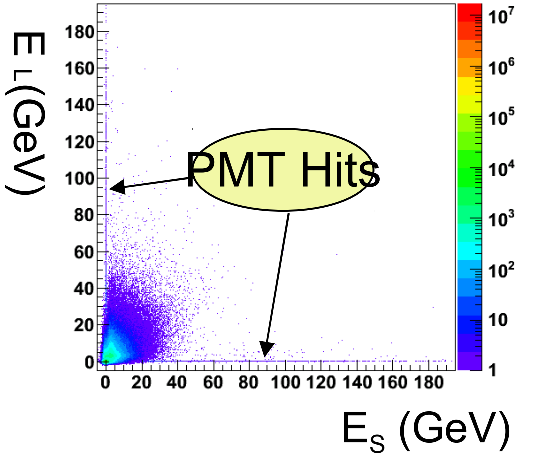


- Large energy deposits in single crystal in barrel. Barrel uses avalanche photodiodes (APD). Not seen in endcap which use vacuum phototriodes (VPT).
- Source: Energy deposited in APD by heavy ionizing particles.
- Can be rejected based on 'shower shape' and timing.

HCAL Anomalous Signals

- Electronic noise from Hybrid Photo Diodes (HPD), used in Barrel, Endcap, and Outer HCAL
  - HPD Ion Feedback (1 channel)
  - HPD Discharge (up to 18 channels = 1 HPD)
  - Readout Box Noise (up to 72 ch. = 4 HPDs)
- 10-20 Hz for E>20 GeV from all 288 barrel and endcap HPDs.
- Noise is random and very small overlap with physics.
- Filters developed to remove this noise based on timing, pulse shape, and EM fraction. (*JINST 5 T03014*)
- Cherenkov light produced by interactions in the window of the Forward Calorimeter PMTs, can also be filtered out based on energy asymmetry in long vs. short fibers. (*Eur. Phys. J. C53, 139-166, 2008*)





Vacuum Effects

- It was not possible to operate the LHC with bunch spacing of 50 ns for experiments data taking because the vacuum pressure increases were already too large at injection.
  - *Pressures easily exceeded $4x10^{-7}$ mbar (normal is 10^{-9} or less) leading to closure of the vacuum valves.*
- Signs of cleaning by beam, with strong dependence on bunch intensity and bunch spacing.

  *Consistent with the signature of **electron clouds**.*
- e- cloud drive pressure rise, beam unstabilities and possibly overload the cryogenic system by the heat deposited on the chamber walls !

→ The cloud can 'cure itself': the impact of the electrons cleans the surface (Carbon migration), reduces the electron emission probability and eventually the cloud disappears – ***'beam scrubbing'***

- Inject as much beam as you can (run at the limit of the vacuum / beam stability), operate for some time and Iterate until conditions are acceptable / good *(several days) – experience from the SPS.*

LHC 2010 Proton Parameters

Parameter	End 2010	Nominal
N (p/bunch)	**1.2×10^{11}**	**1.15×10^{11}**
k_b (no. bunches)	368	2808
ε (μm rad)	**2.4-4**	**3.75**
β* (m)	3.5	0.55
σ* (μm)	45-60	16
L ($cm^{-2}s^{-1}$)	2×10^{32}	10^{34}

$$L = \frac{N^2 k_b f \gamma}{4\pi\beta^* \varepsilon} F$$

Improvements for 2011:

- Reduction of β* to 1.5 m (measured aperture larger than design).
- Increase of N to 1.4×10^{11} or higher if possible.
- Increasing number of bunches using 50 ns or 75 ns spacing.
  - *Must overcome e-clouds effects.*

Multi Lepton Final States: e, μ, τ

In Gravity Mediated Symmetry Breaking the gravitino is the Lightest SyperSymmetric Particle. If sleptons are the next lightest particle we get $2\times(\chi^0 \rightarrow \tilde{l}^+\tilde{l}^- \rightarrow ggl^+l^-)$

- 3+ Isolated leptons
  - PT > 8 GeV
- Two different searches
  - MET > 50 GeV
  - MHT > 200 GeV
- 55 channels