Physics at CMS: Run I Highlight

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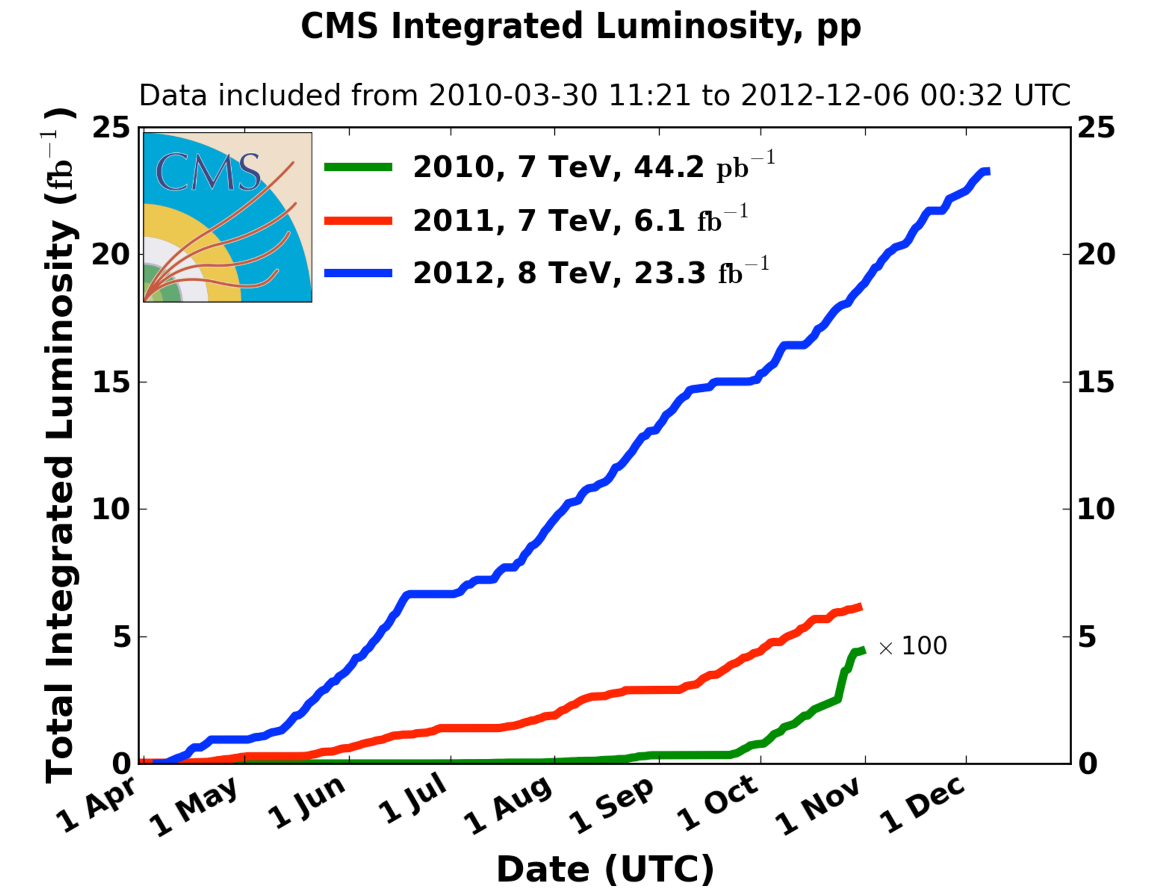
Yonsei Workshop, June 5th 2015

LHC Run I

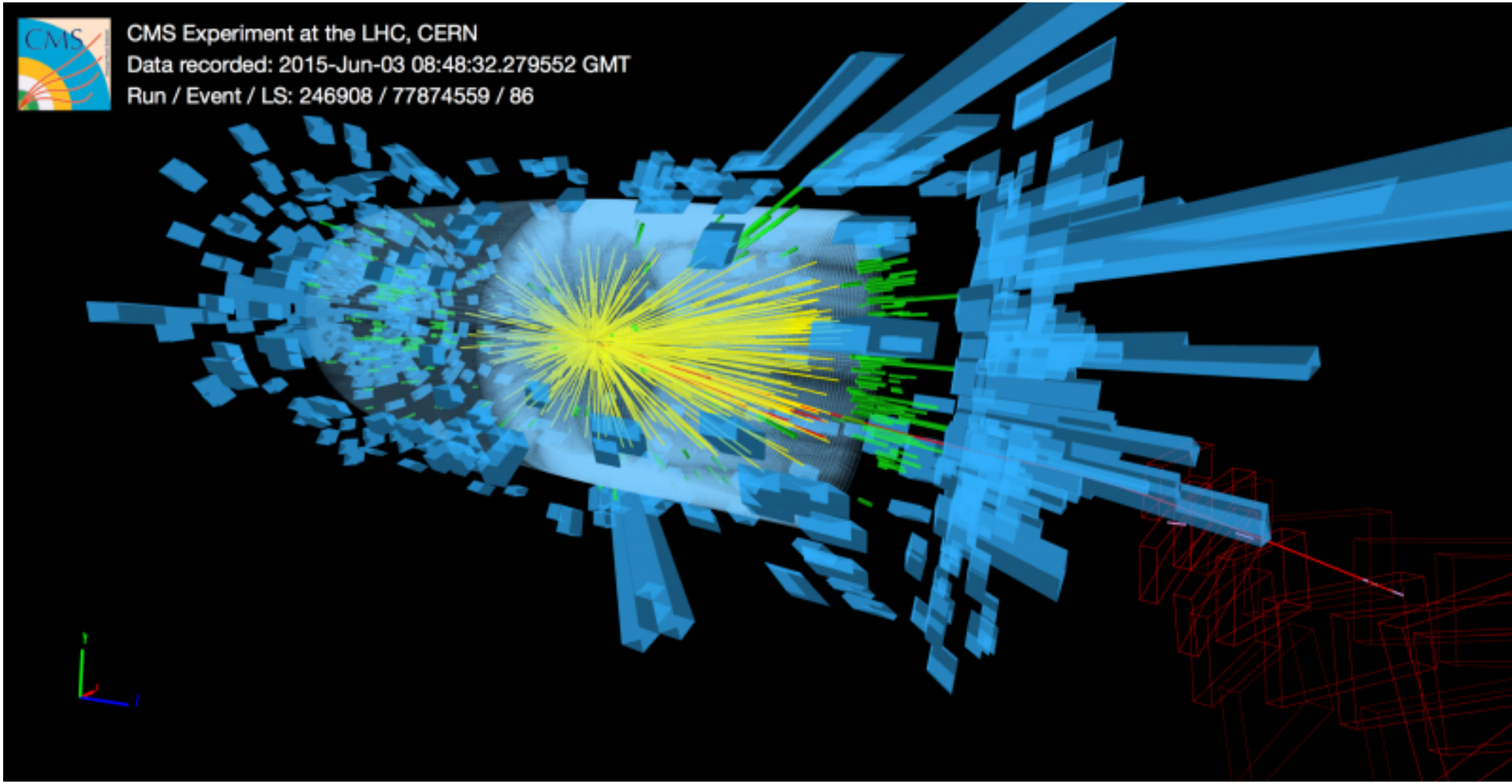
- Successful operation during Run I



- 2010: **0.04 fb^{-1}**
  - 7 TeV
  - **Commissioning**
- 2011: **6.1 fb^{-1} (exp 5)**
  - 7 TeV
  - **… exploring the limits**
- 2012: **23.3 fb^{-1} (exp 20)**
  - 8 TeV
  - **… production**

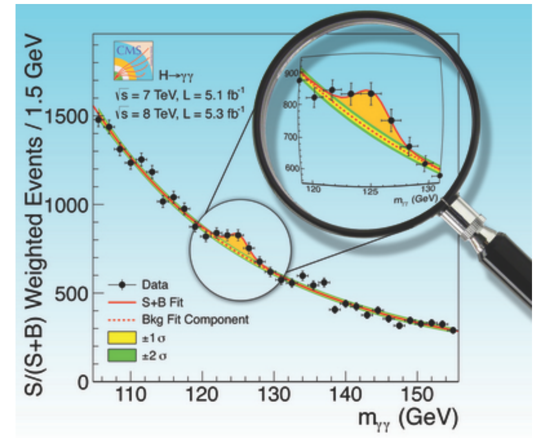
First 13 TeV Collision!!

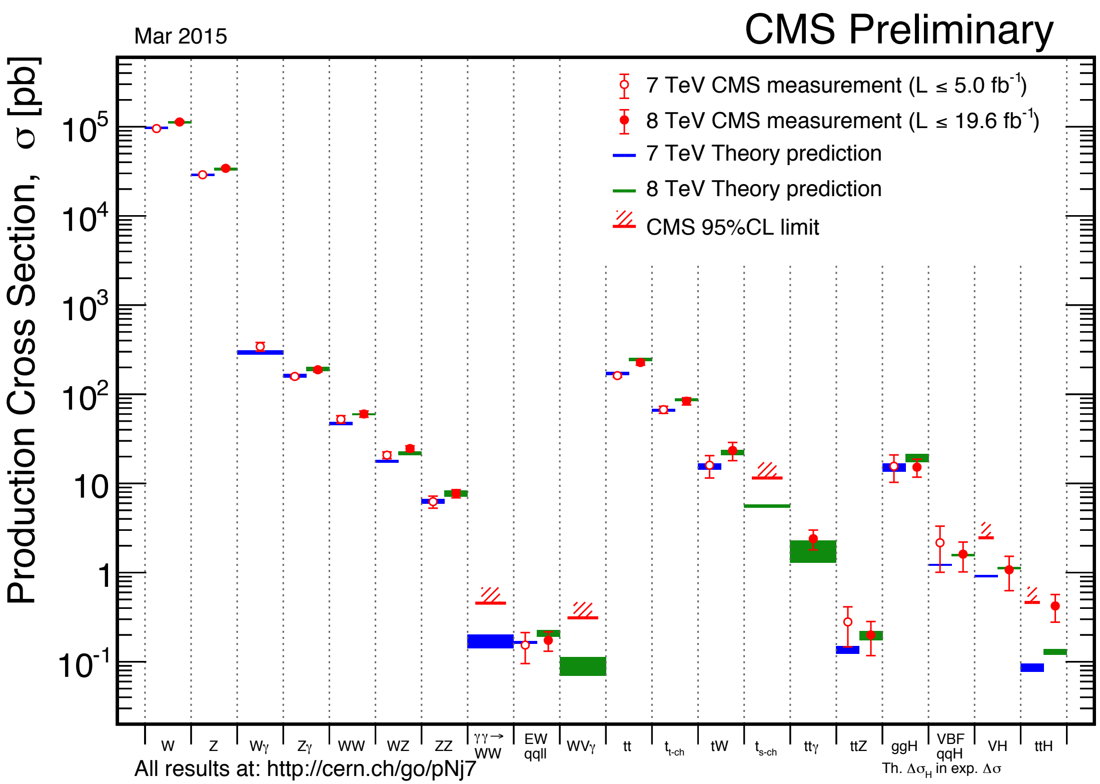
- LHC collides protons at 13 TeV to tune accelerator
  - Physics run starts from June 3rd!!!

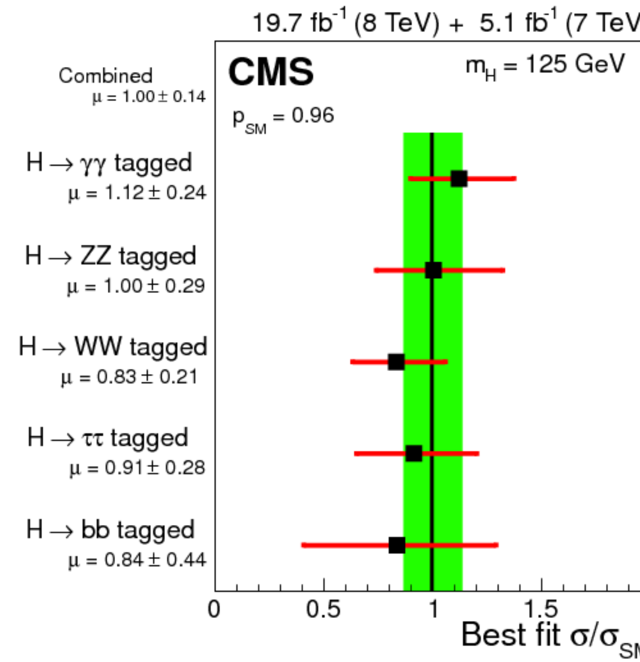


Success of Standard Model

- Discovery of a SM-like Higgs boson: precise measurement of mass, coupling strength, production and decay kinematics
- Impressive precision tests of the Standard Model over many order of magnitude

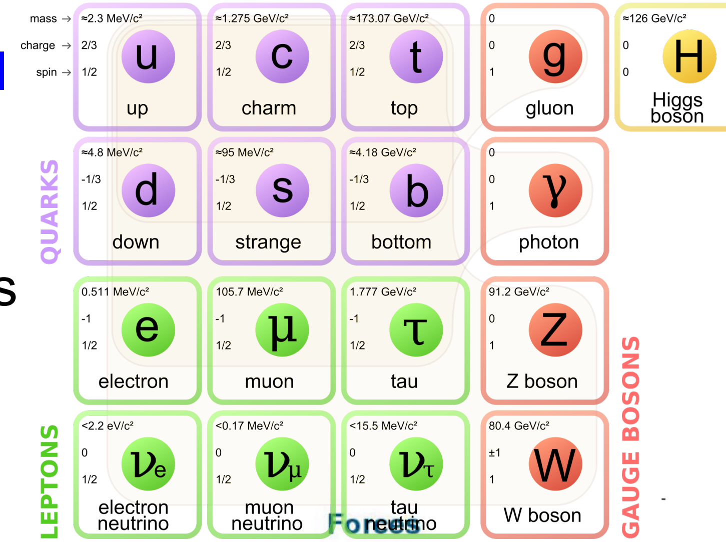


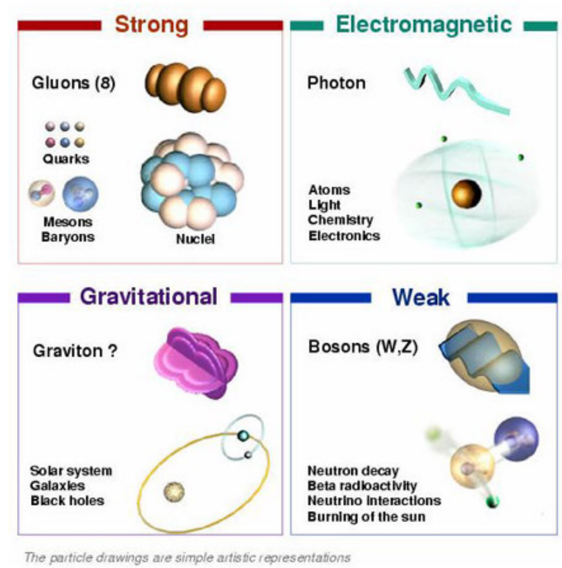




The Standard Model (SM)

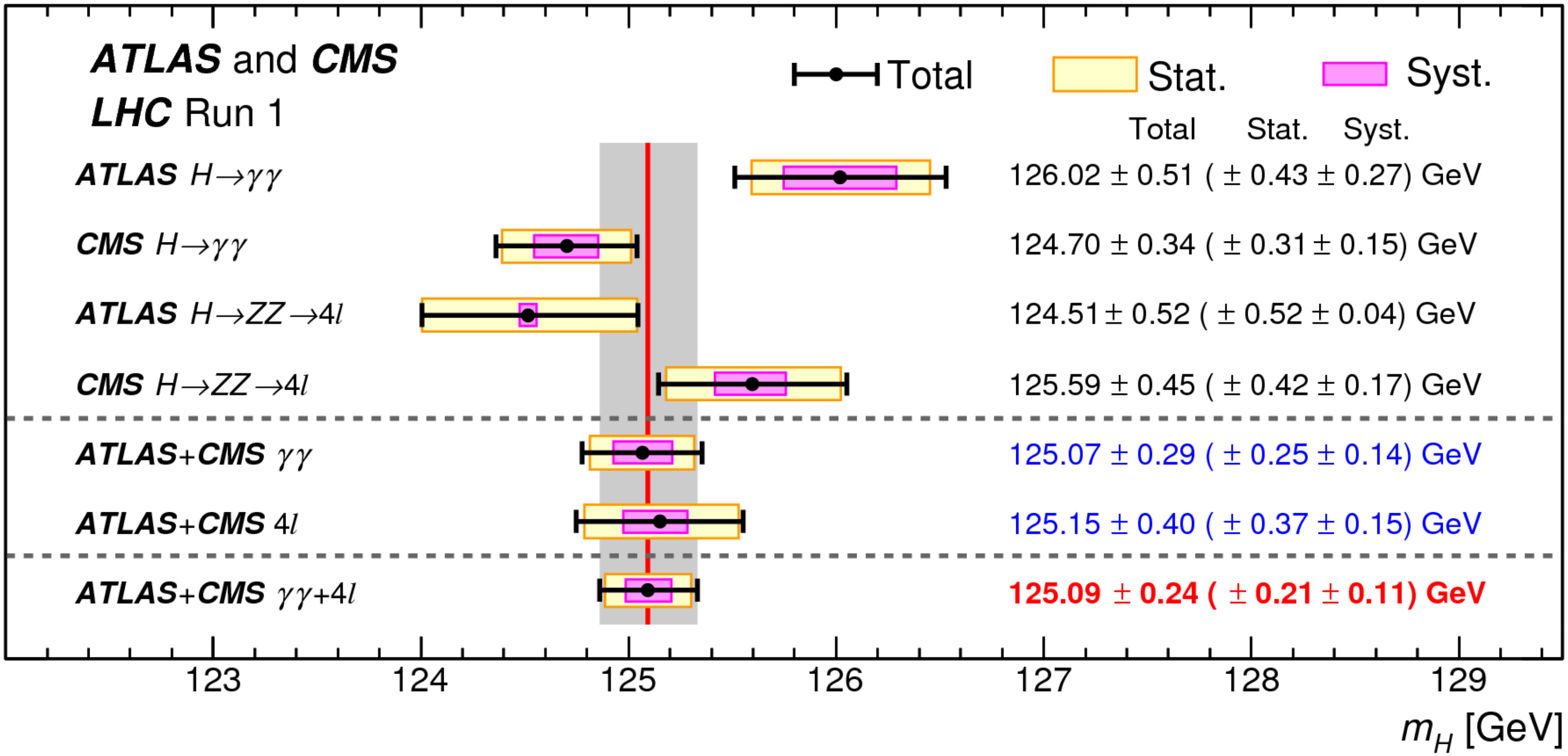
- The SM is the current theory of fundamental particles and how they interact
- Forces
  - Strong force: binds protons and neutrons to form nuclei
  - Electromagnetic force: binds electron and nuclei to form atoms
  - Weak force: causes radioactivity
  - Gravitational force: binds matter on large scales
- Higgs boson: explain why particles have a mass
- During last 3 decades, a lot of experimental observation support that the SM is correct





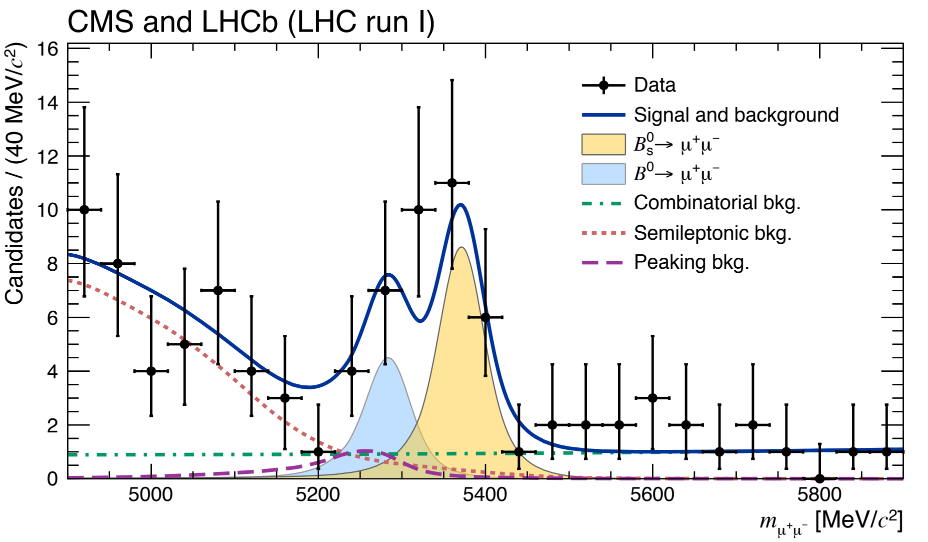
Combination of Higgs Mass

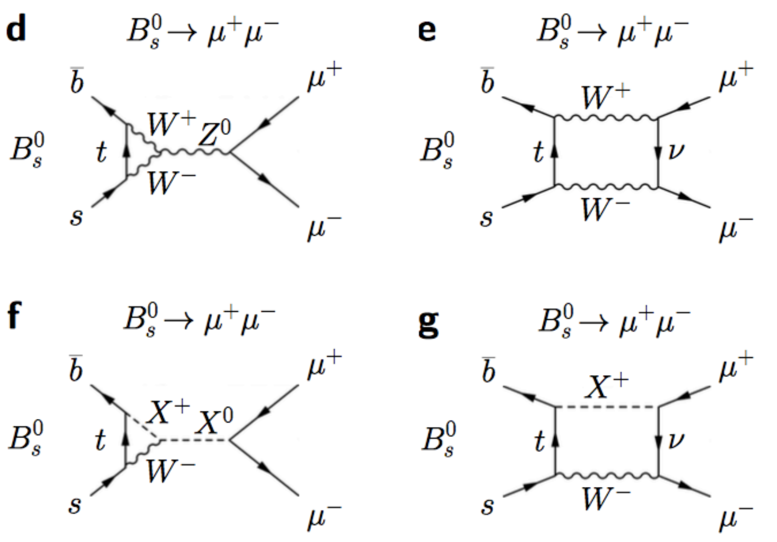
- Phys. Rev. Lett. 114, 191803 (2015)
- 0.19% precision!!

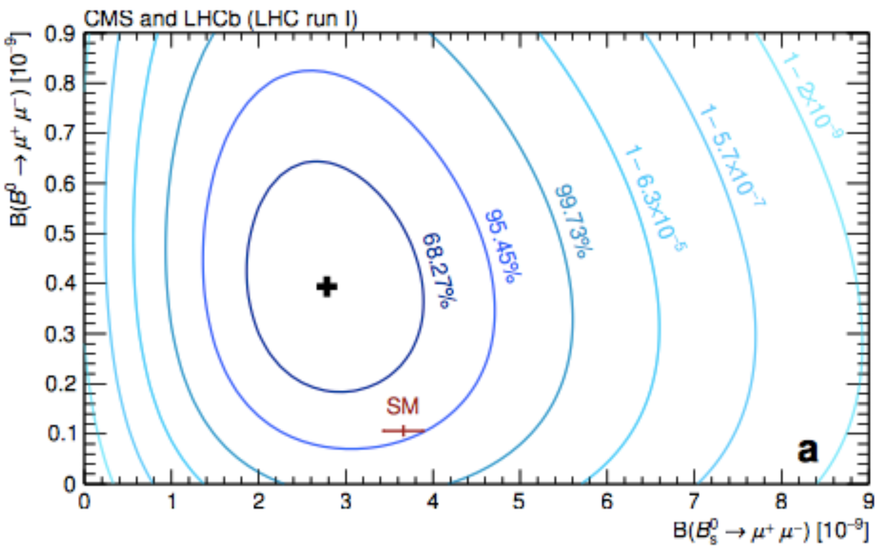


Observation of $B_s \rightarrow$ mumu

- First observation of the very rare dcay of the B^0_s into two muons
- BSM particles can contribute on the excess of SM prediction on the decay rate





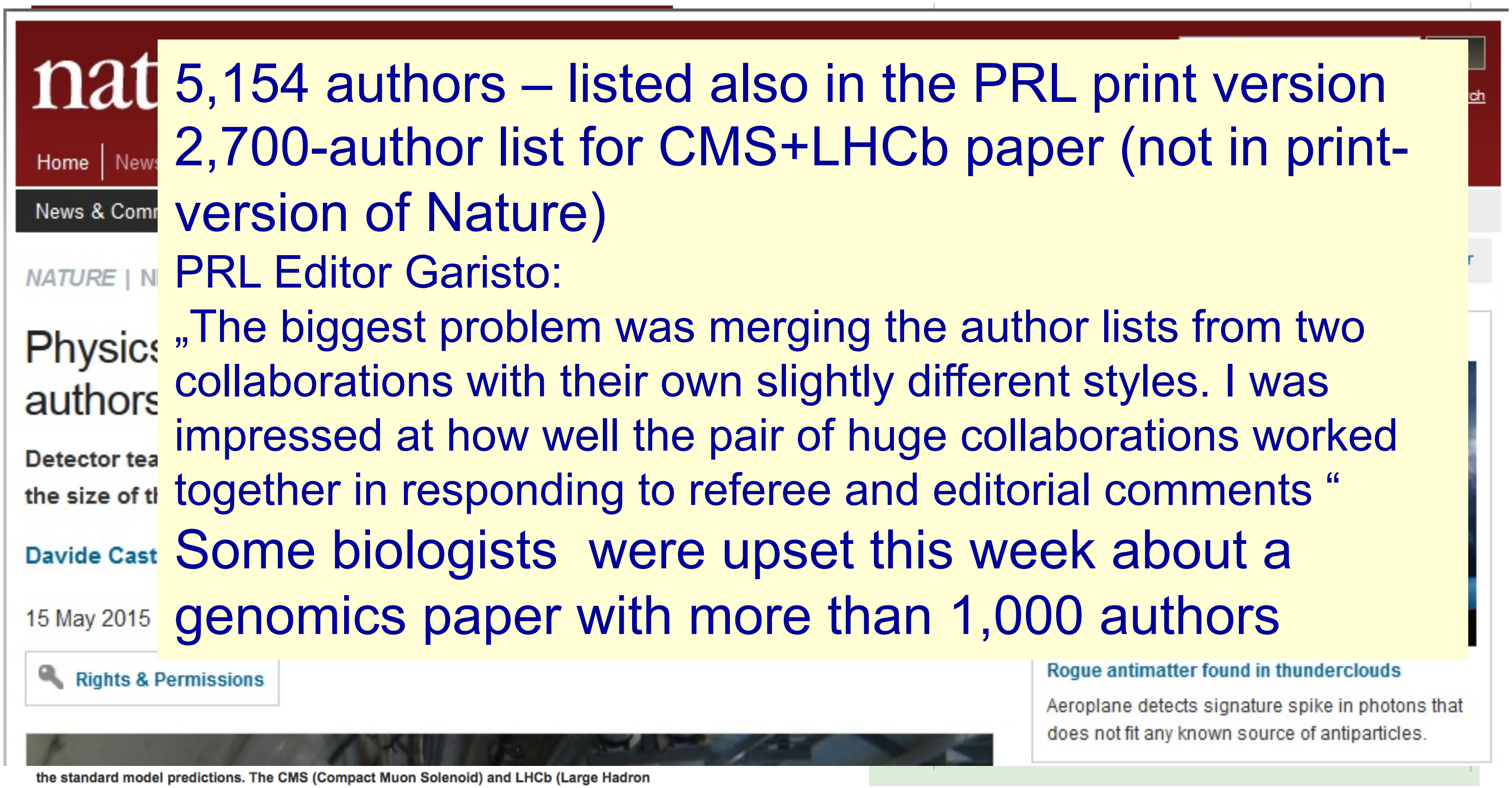


Deviation 6.2σ from B_s SM prediction

New Record!

Another Record broken ….

http://www.nature.com/news/physics-paper-sets-record-with-more-than-5-000-authors-1.17567



5,154 authors – listed also in the PRL print version

2,700-author list for CMS+LHCb paper (not in print-version of Nature)

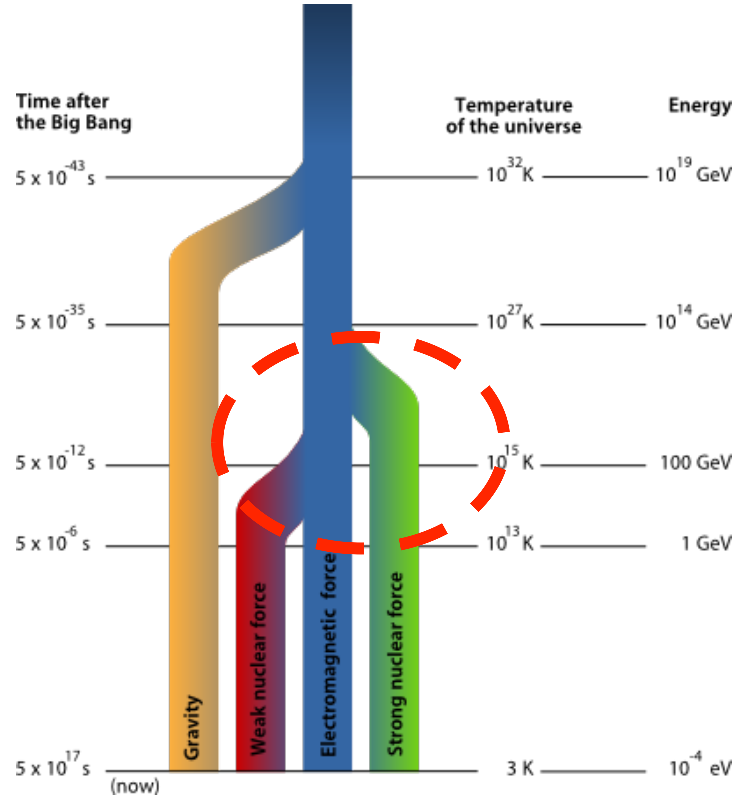
PRL Editor Garisto:

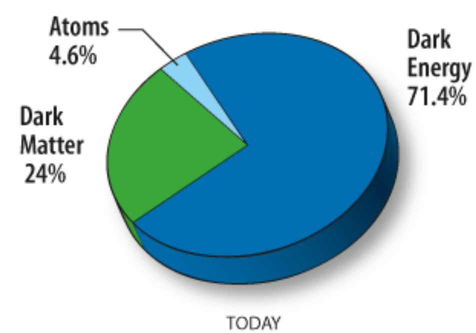
„The biggest problem was merging the author lists from two collaborations with their own slightly different styles. I was impressed at how well the pair of huge collaborations worked together in responding to referee and editorial comments "

Some biologists were upset this week about a genomics paper with more than 1,000 authors

Beyond the Standard Model

- We are exploring the EWK symmetry breaking scale
- The SM does not correctly account for
  - Hierachy problem: fine-tuning required for Higgs mass at EWK scale
  - Dark matter: cosmological evidence. Can we produce the DM particles in the LHC?
  - Unification of forces: gauge coupling divergence at unification scale
  - … And the unexpected: probe unknown and unexpected territory!
- Therefore, the SM falls short of being a complete theory of fundamental interactions





Beyond the Standard Model

Heavy gauge bosons

Extra dimension

Long-lived particles

RS Gravitons

Dark Matter

Supersymmetry

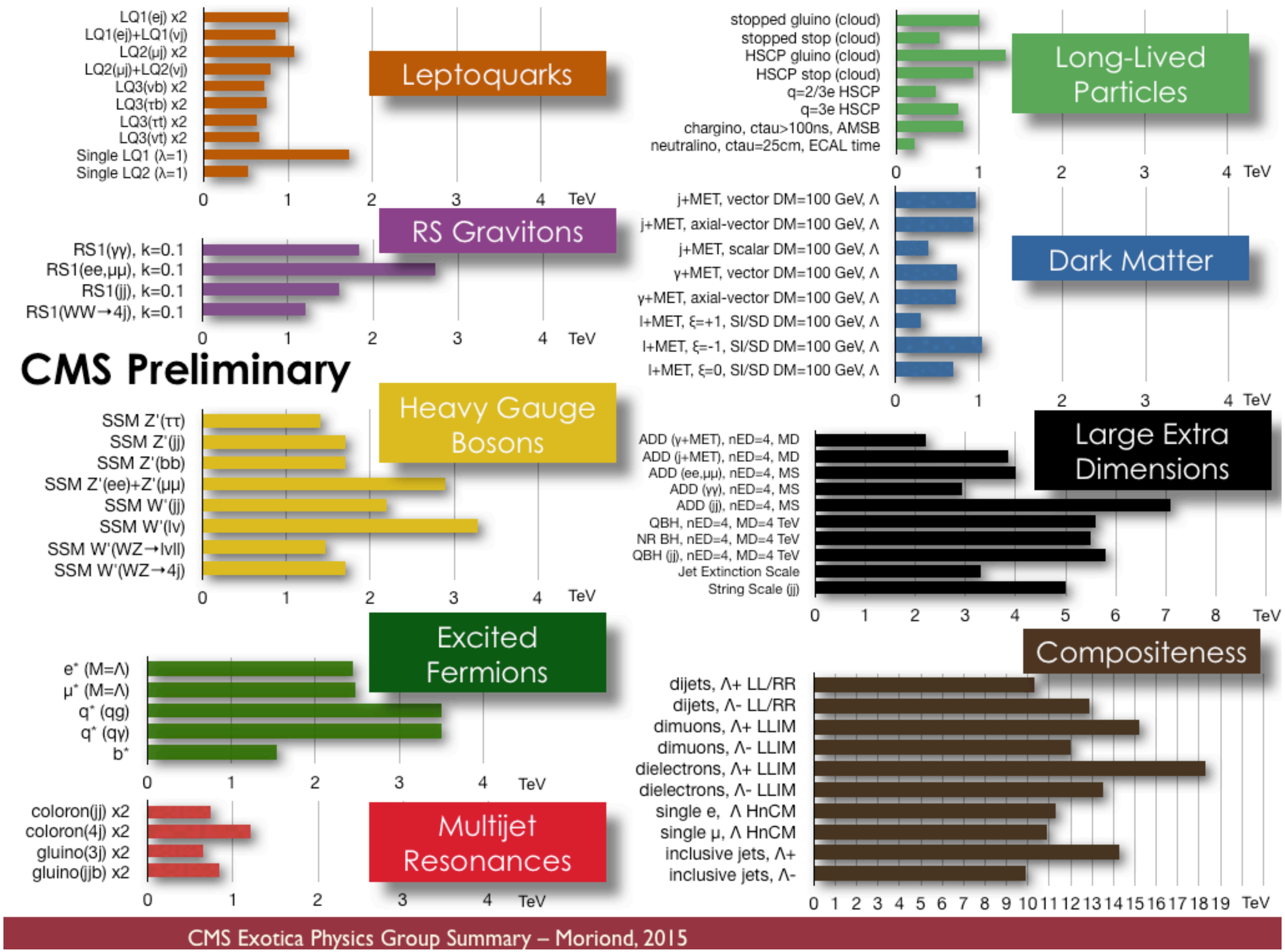
Excited fermions

Multijet resonances

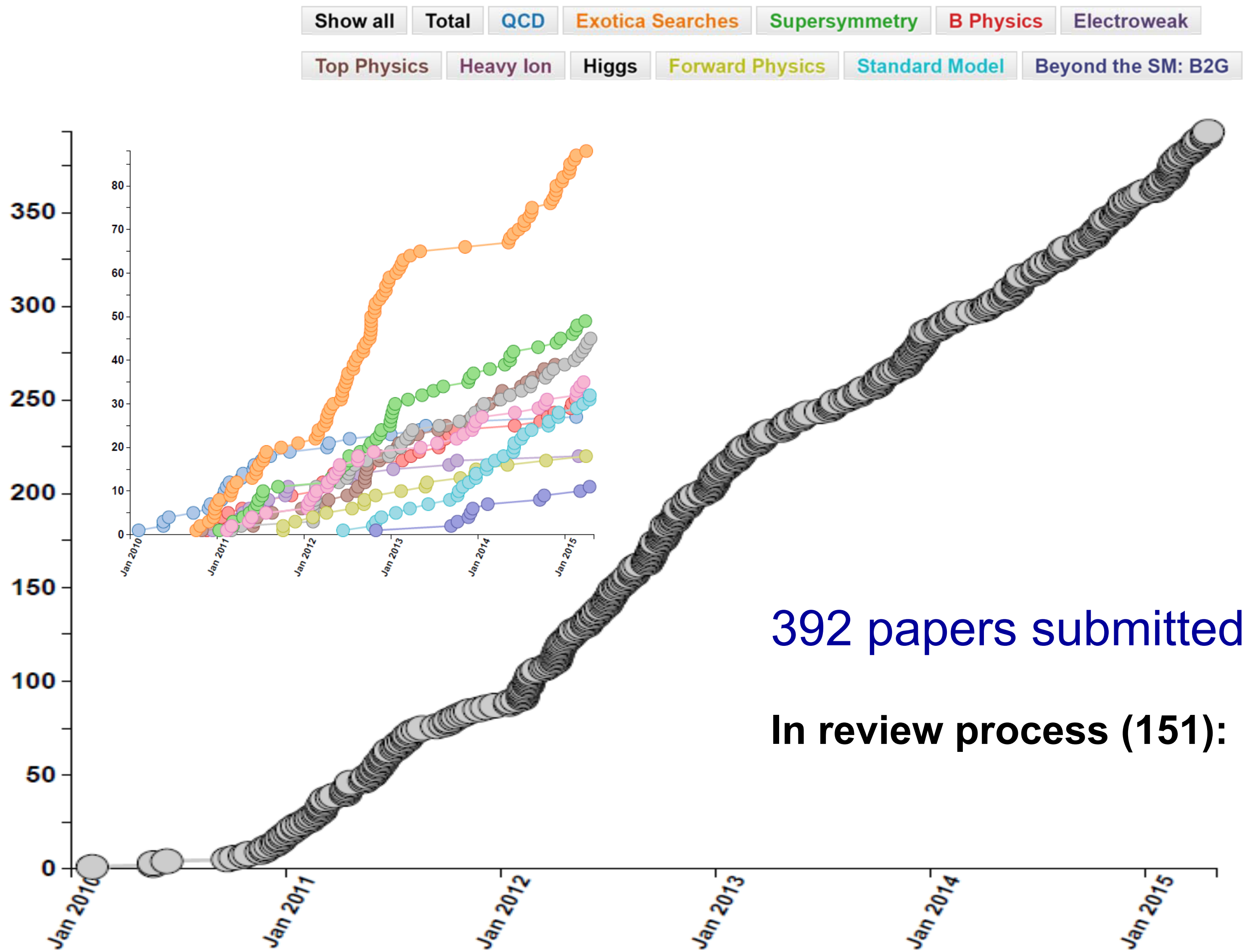
Leptoquarks

Compositeness

BSM Results from Run I data



CMS Run I Publication



392 papers submitted:

In review process (151):

CERN was founded 1954: 12 European States

"Science for Peace"

Today: 20 Member States

~ 2300 staff
~ 1050 other paid personnel
> 11000 users
Budget (2012) ~1000 MCHF

Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

Candidate for Accession: Romania

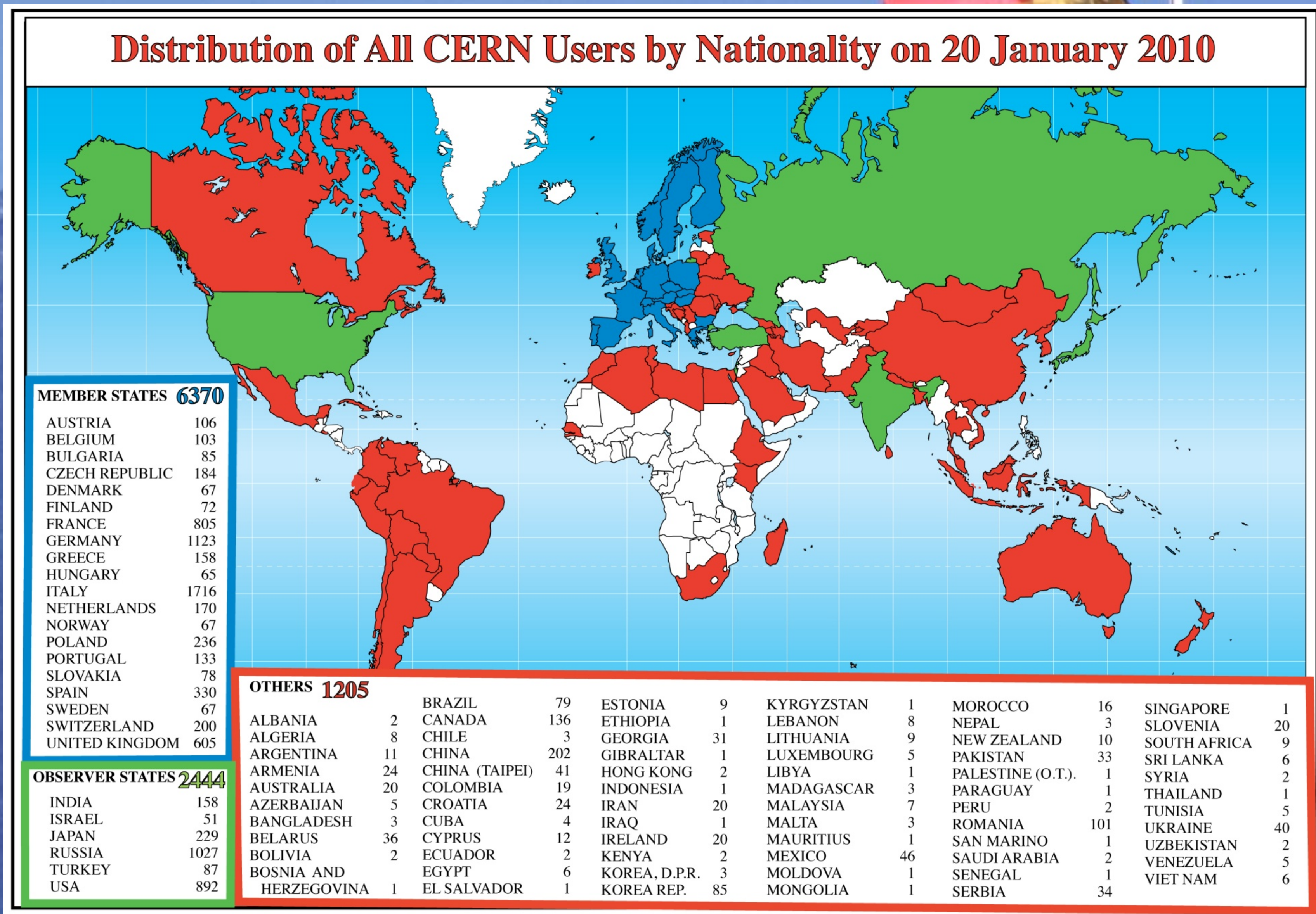
Associate Members in the Pre-Stage to Membership: Israel, Serbia

Applicant States: Cyprus, Slovenia, Turkey

Observers to Council: India, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and UNESCO

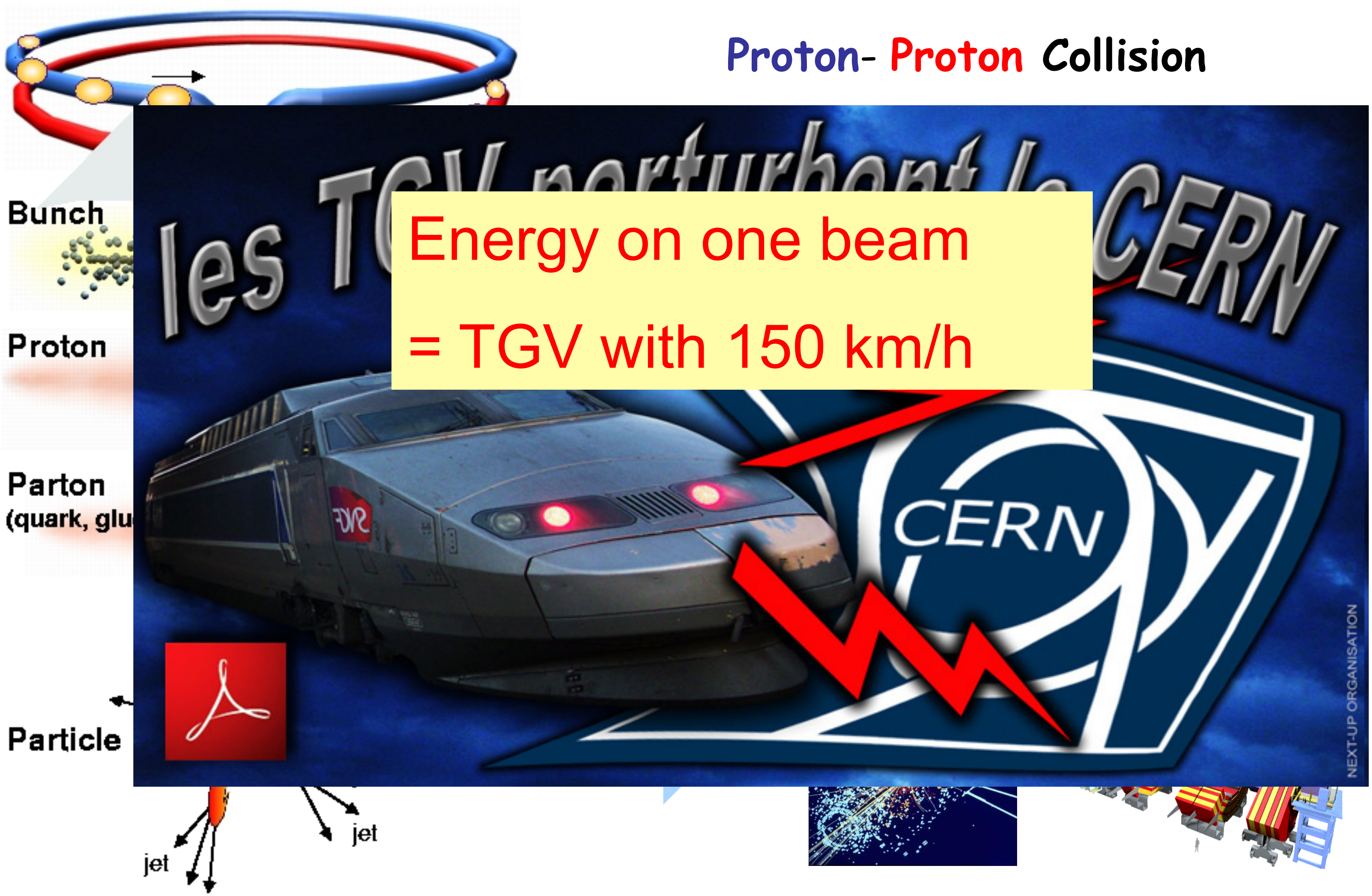
CERN

CERN in Numbers



Large Hadron Collider (LHC)

Proton- Proton Collision

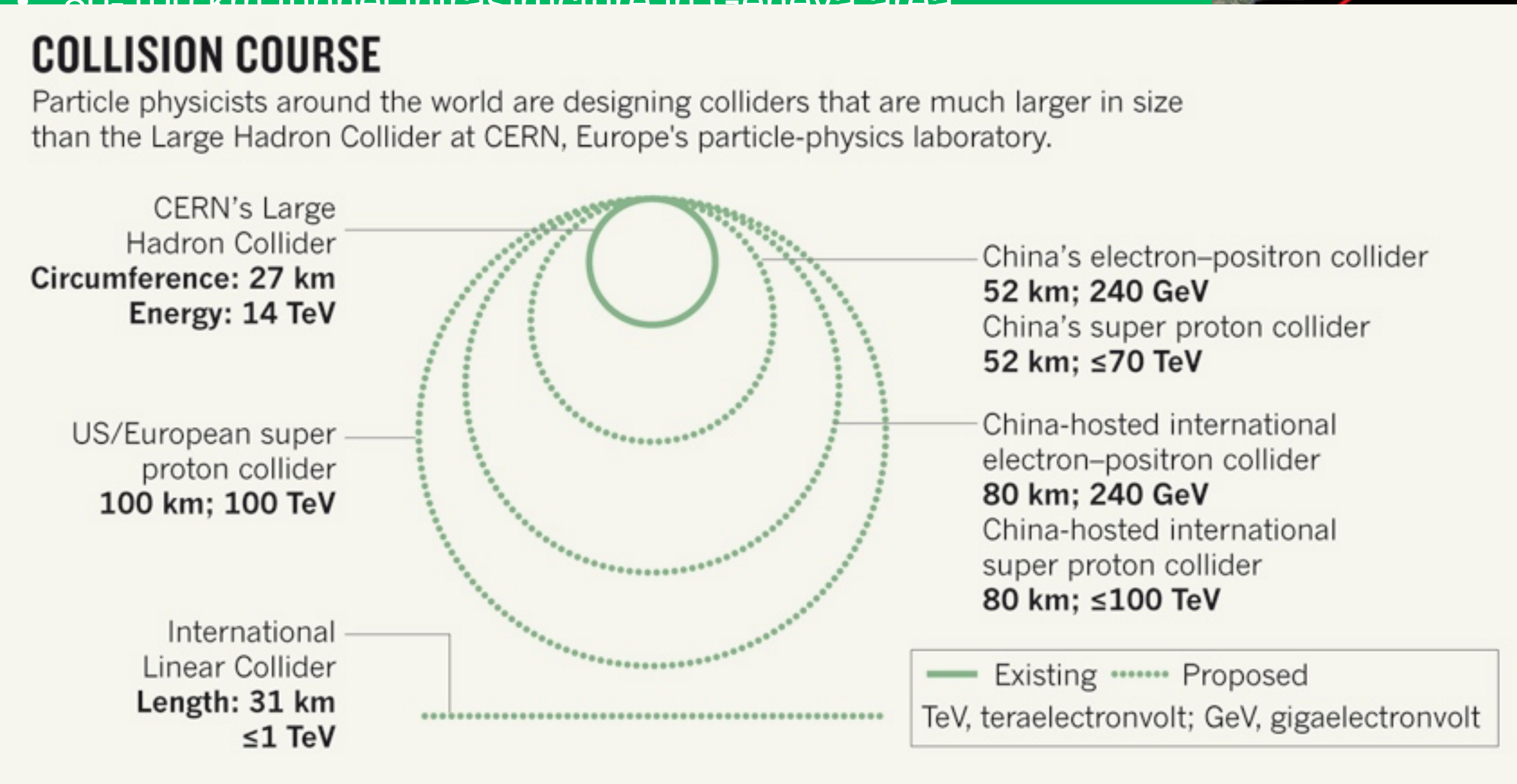


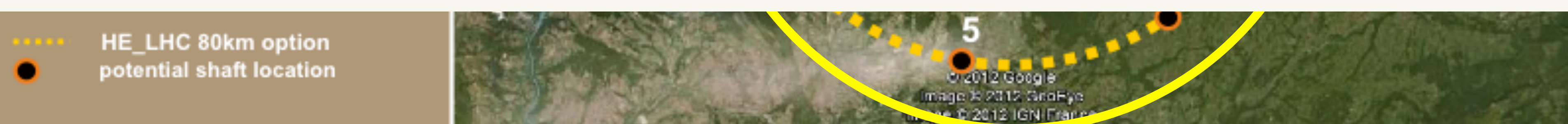
Energy on one beam

= TGV with 150 km/h

Future Circular Collider (100 TeV)

- 80-100 km tunnel infrastructure in Geneva area





Why High Energies?

- Accelerator and detector are instrument to study smaller and smaller structures and heavy short-lived objects with a detector

- Wavelength of probe radiation needs to be smaller than object to be resolved

$$= \frac{h}{p} = \frac{h \times c}{E}$$

$$|\vec{p}| = 1\,\frac{\mathrm{GeV}}{\mathrm{c}} \rightarrow \lambda = 1.24 \cdot 10^{-15}\,\mathrm{m} \simeq \text{size of a proton}$$

$$|\vec{p}| = 10^{3}\,\frac{\mathrm{GeV}}{\mathrm{c}} \rightarrow \lambda = 1.24 \cdot 10^{-18}\,\mathrm{m} \simeq \text{size of proton substructures, e.g. quarks.}$$

Why Make Larger?

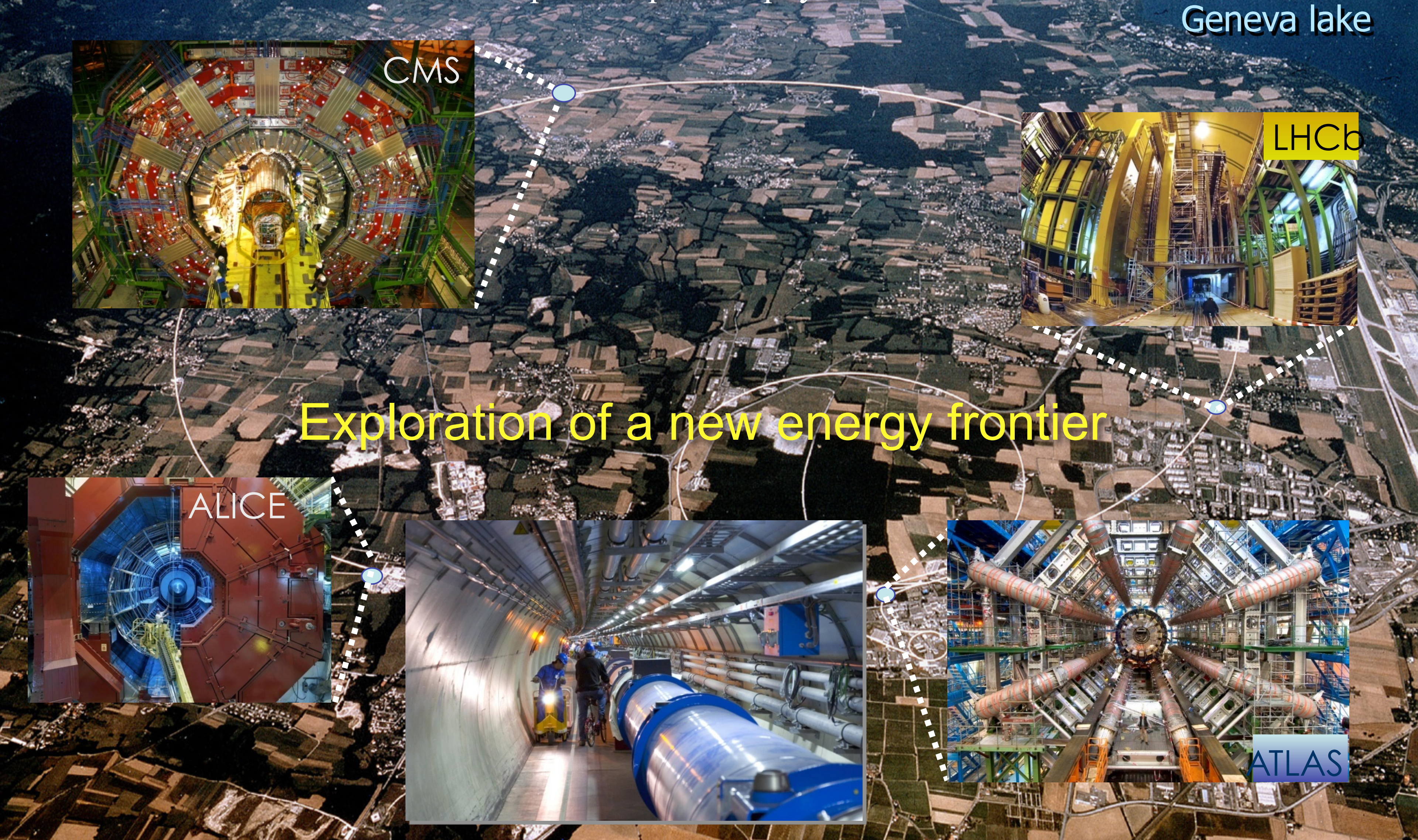
- This is due to technological limitations

- Magnetic field, accelerating gradient, …

- Circular machine
  - The higher the particule momentum, the higher the magnetic field to keep beam on trajectory
  - The higher bending angle, the higher the magnetic field

Enter a New Era in Fundamental Science

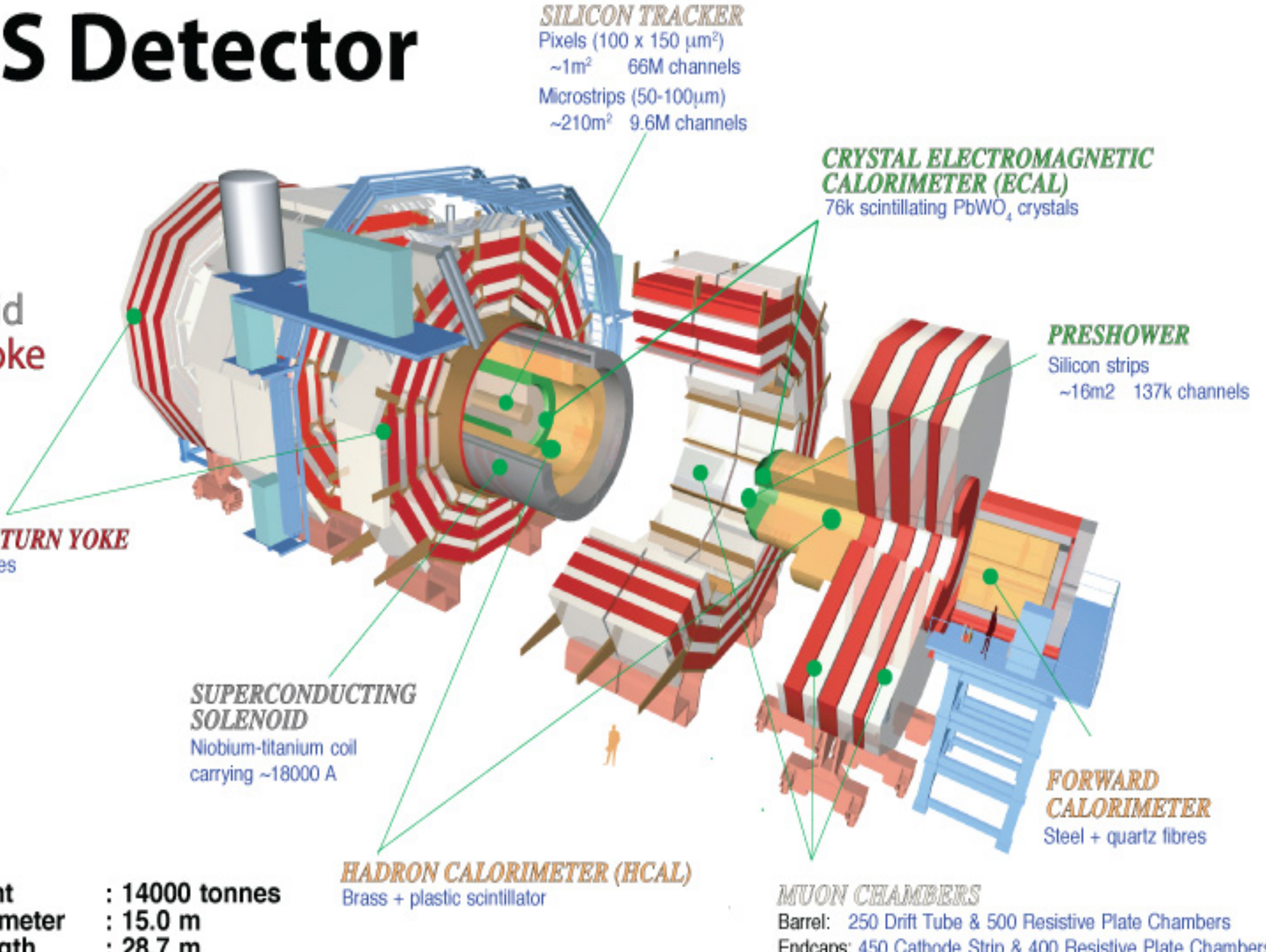
Start-up of the LHC, one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.



Exploration of a new energy frontier

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

CMS Collaboration

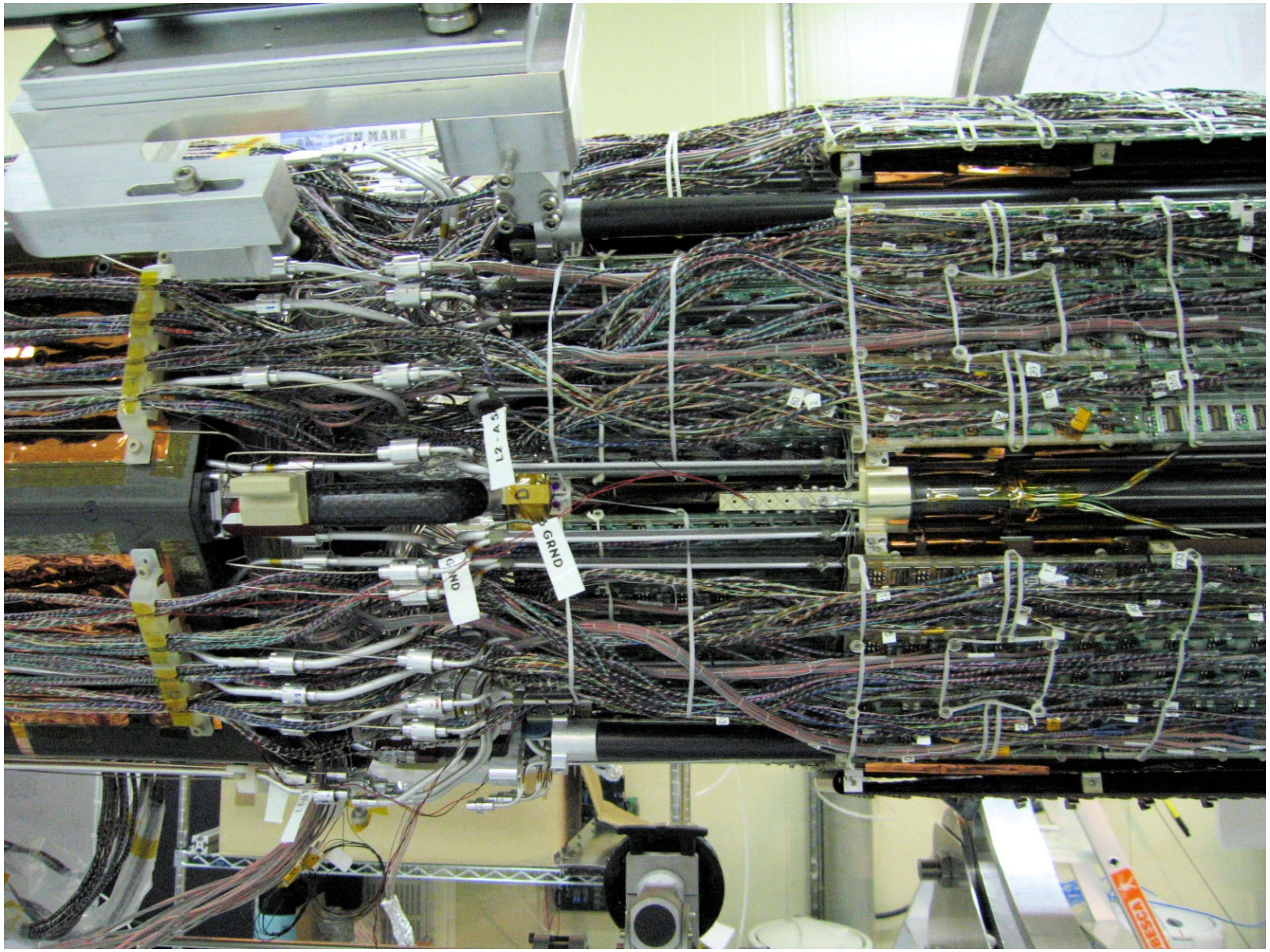
- Approximately 3800 scientists (43 countries, 200 institutions)

Why This is Not An Easy Task

This is part of the ATLAS detector (one of the pixel patch panels).

This is typical of what experiments look like on the inside.

You can see how modeling this by simple geometrical shapes is likely to introduce inaccuracies.



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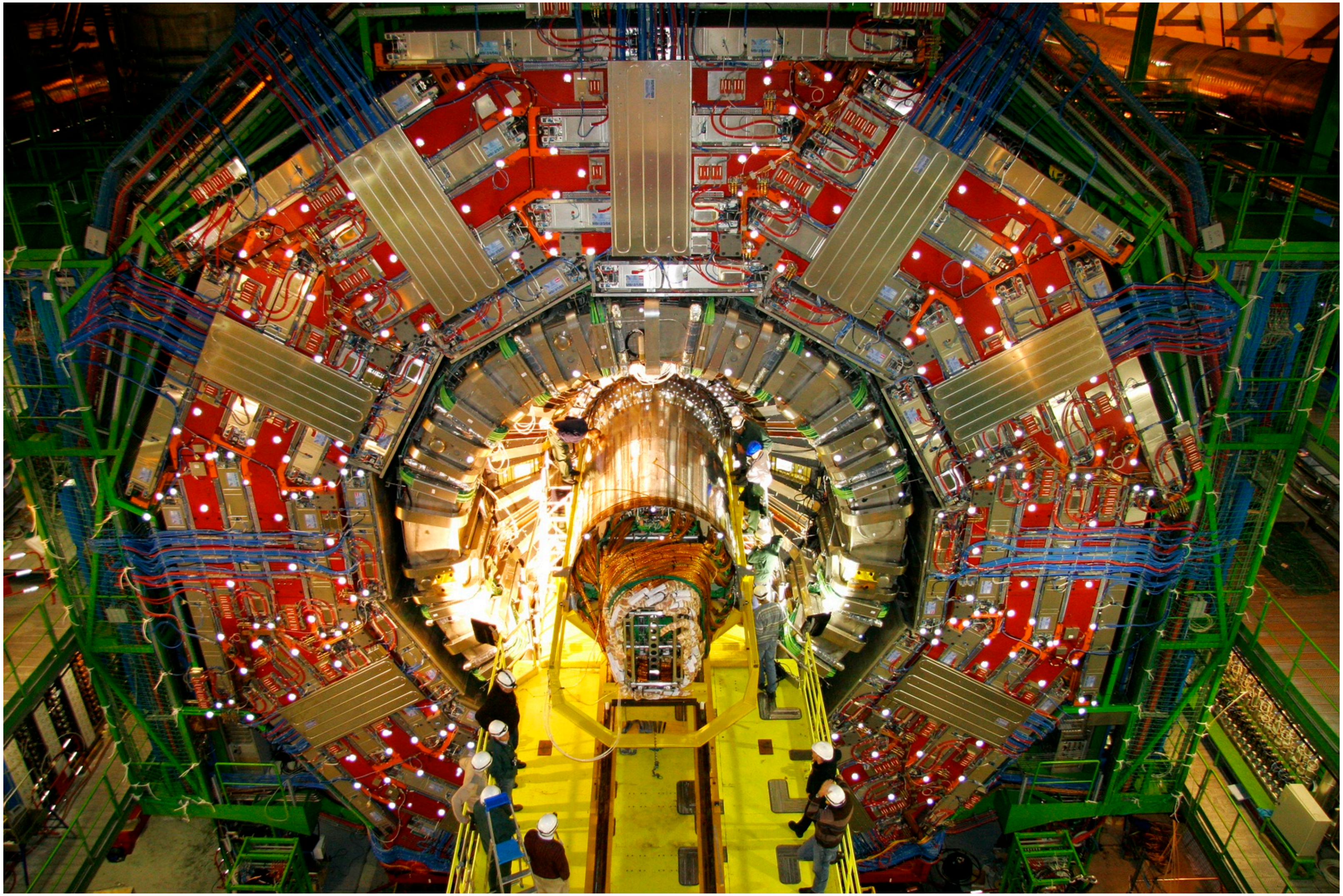
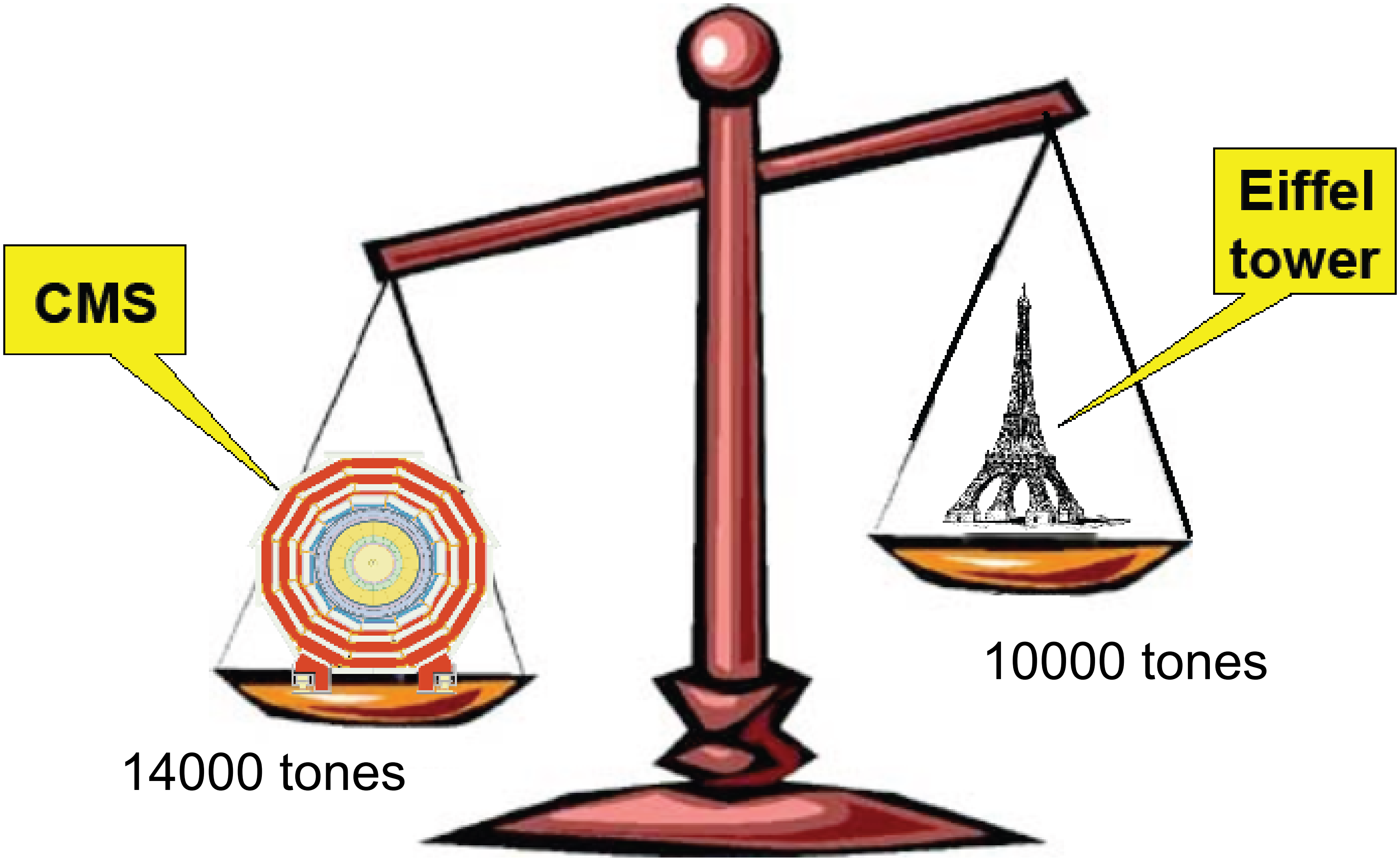
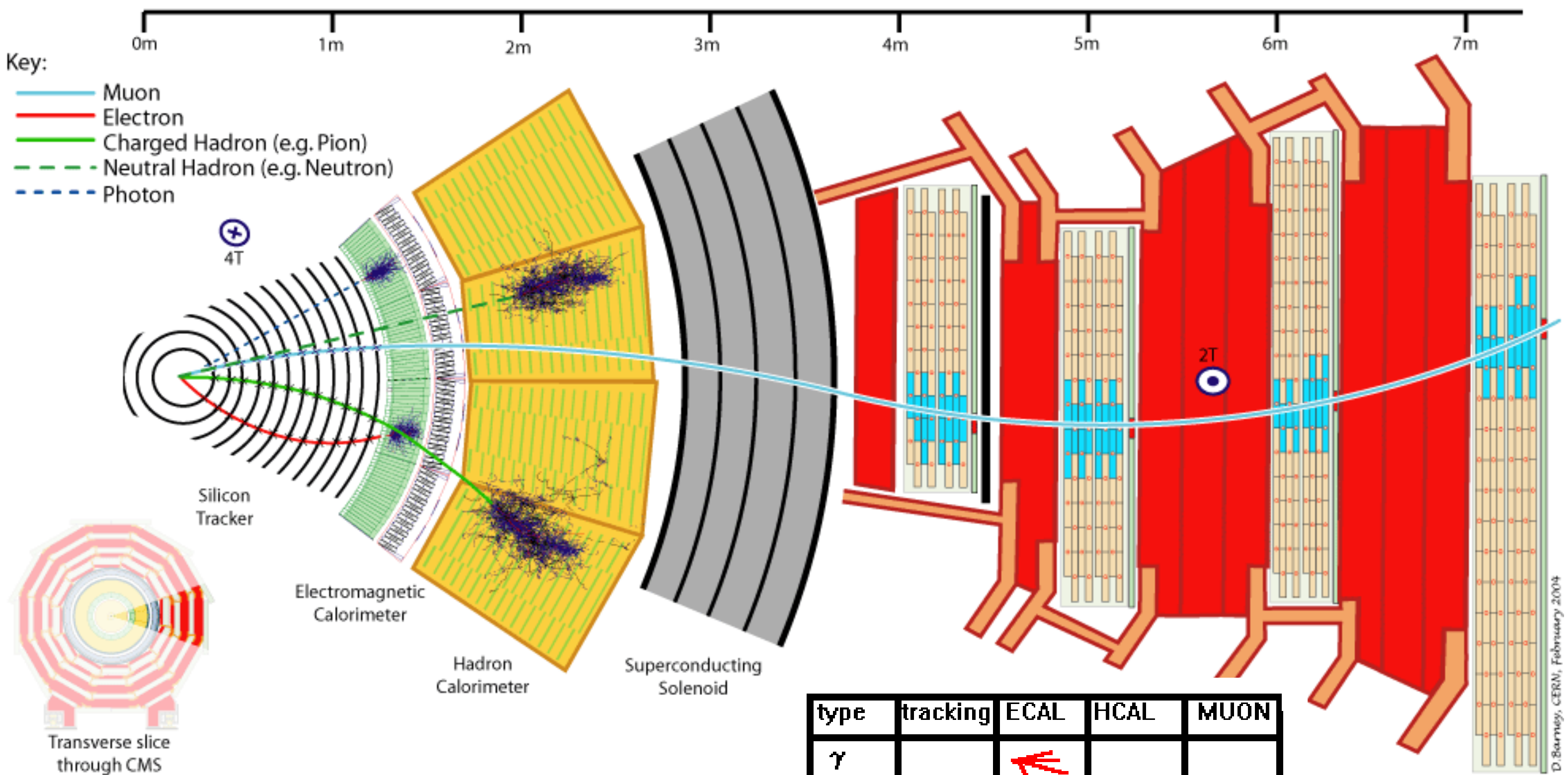



ATLAS and CMS in Berlin
ATLAS
CMS

Detector Mass in Perspective



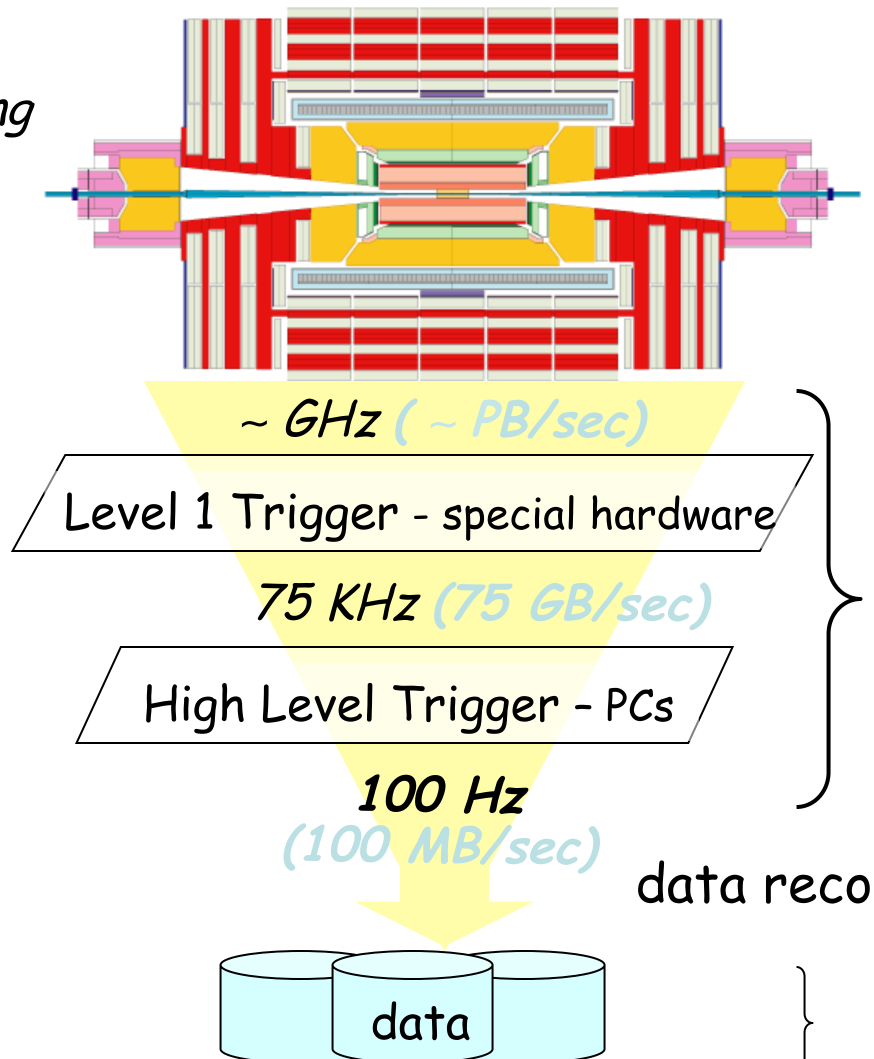
CMS Slice



type	tracking	ECAL	HCAL	MUON
γ				
e				
μ				
Jet				
Et miss				

CMS Trigger and Data Acquisition

Bunch crossing
40 MHz



1 event is ~ 1MB in size

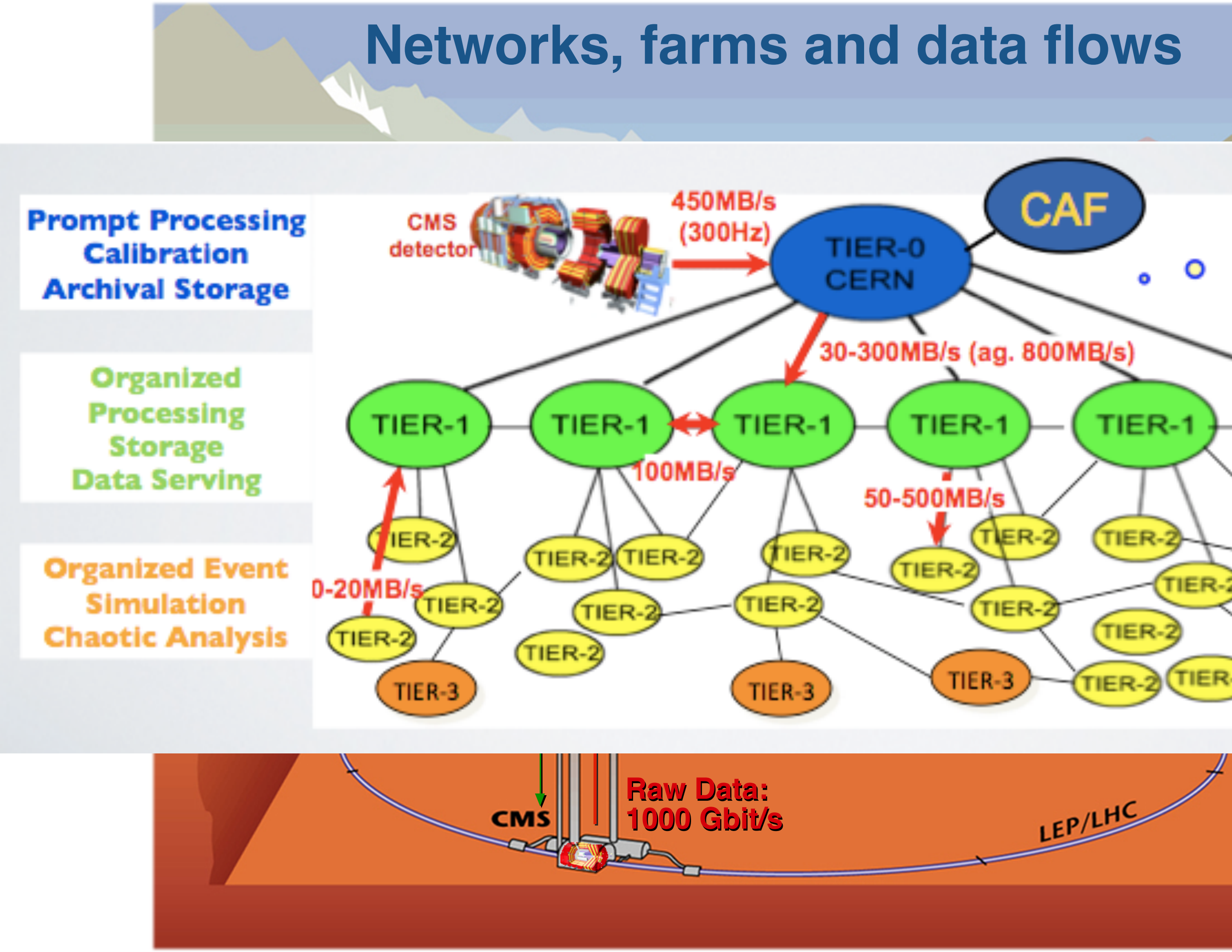
Online system

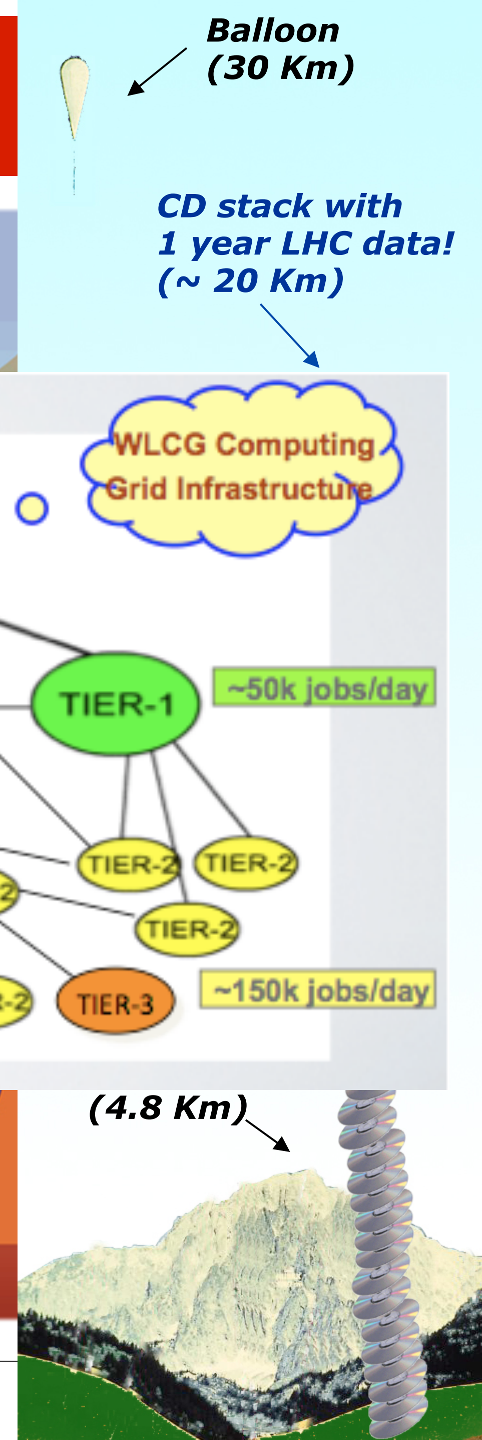
multi-level trigger to:
- filter out not interesting events
- reduce data volume

data recording

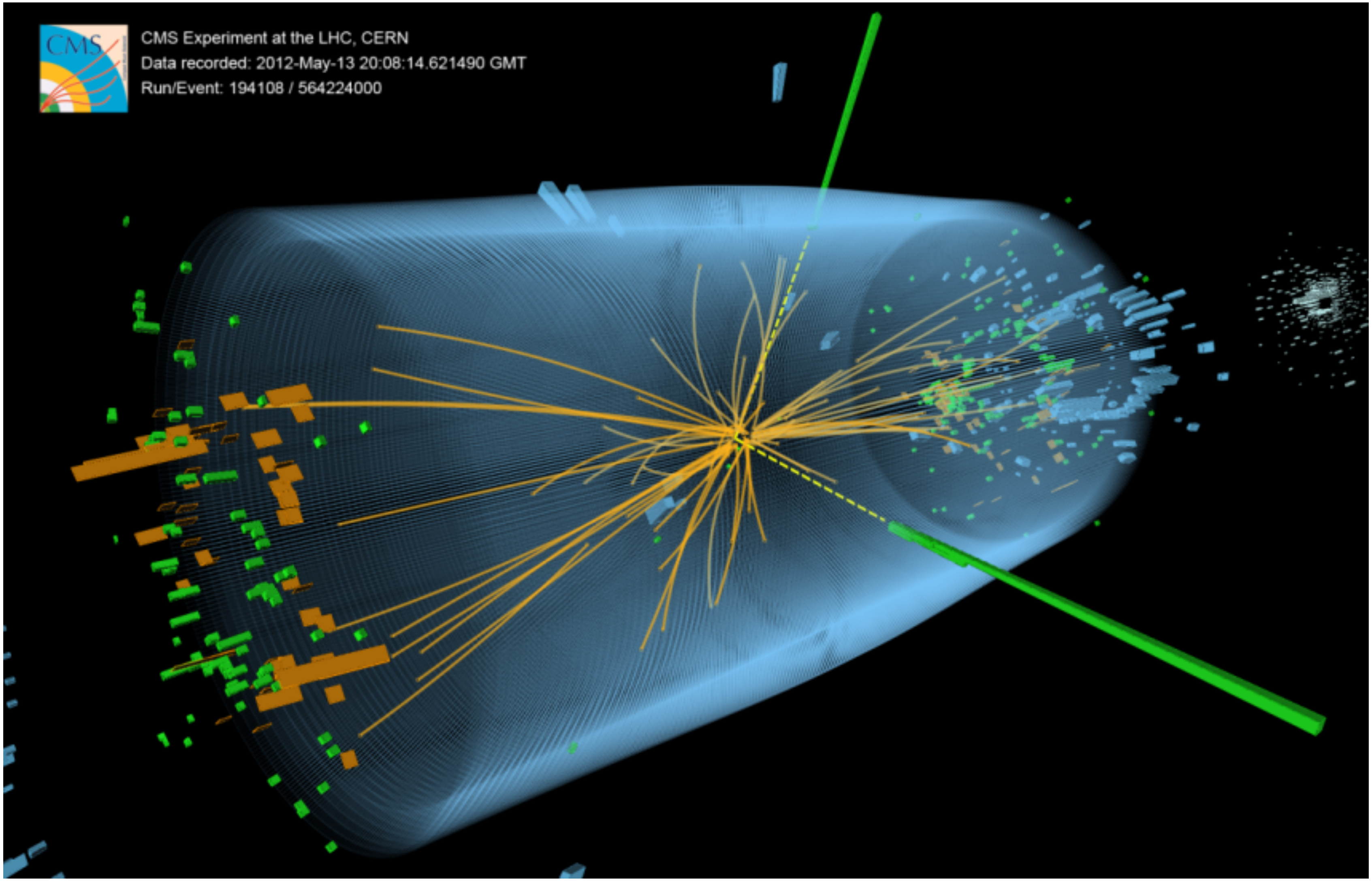
Offline analysis

On the Tape (Grid)



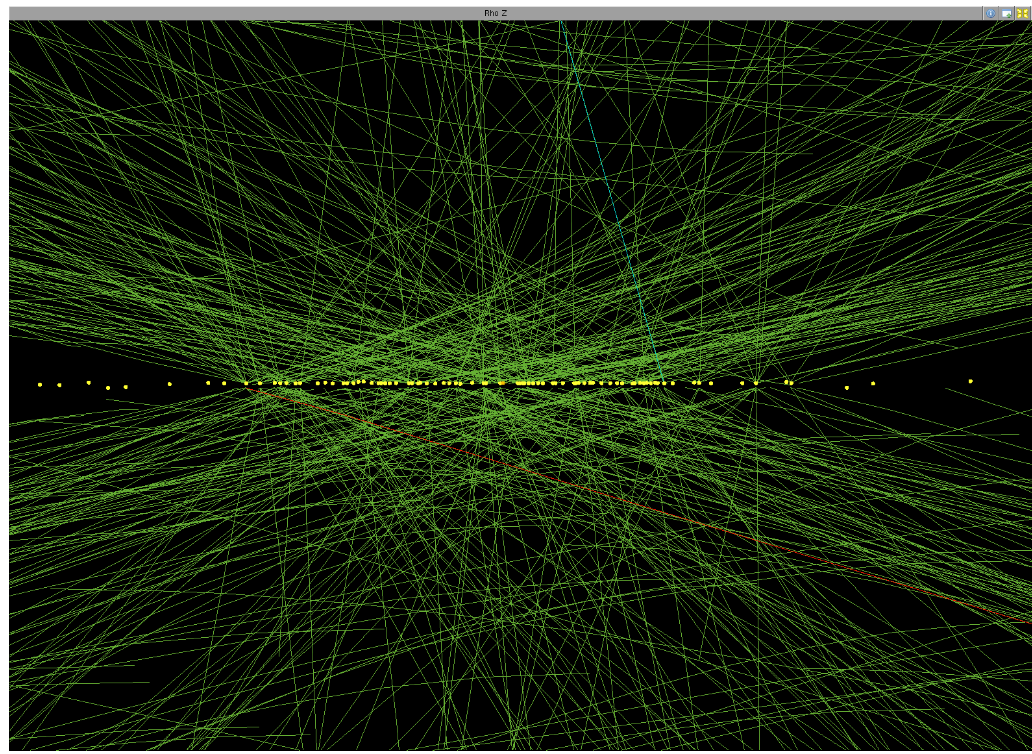


Collision Data



Pile-up

- LHC delivers collisions with more than one interaction per bunch crossing
- Origins of pile-up
  - In-time: real (typically) QCD multijet events emerging from non-primary vertex
  - Out-of-time: energy deposit in calorimeters which is coming from other bunch crossing due to long readout time
  - Stochastic: random energy fluctuations combined by cluster algorithm



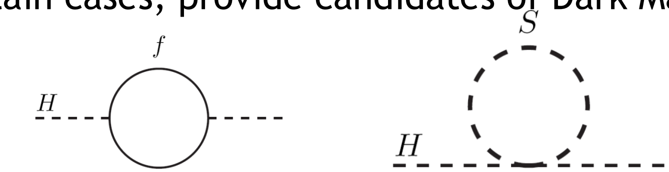
78 vertices

Highlight of Run I Results

SuperSymmetry

Supersymmetry (SUSY) is a family of weakly-coupled theories that give solutions to the Naturalness problem, realize unification at the GUT scale and, in certain cases, provide candidates of Dark Matter

fundamental space-time symmetry between fermions and bosonds that regularizes the Higgs boson mass



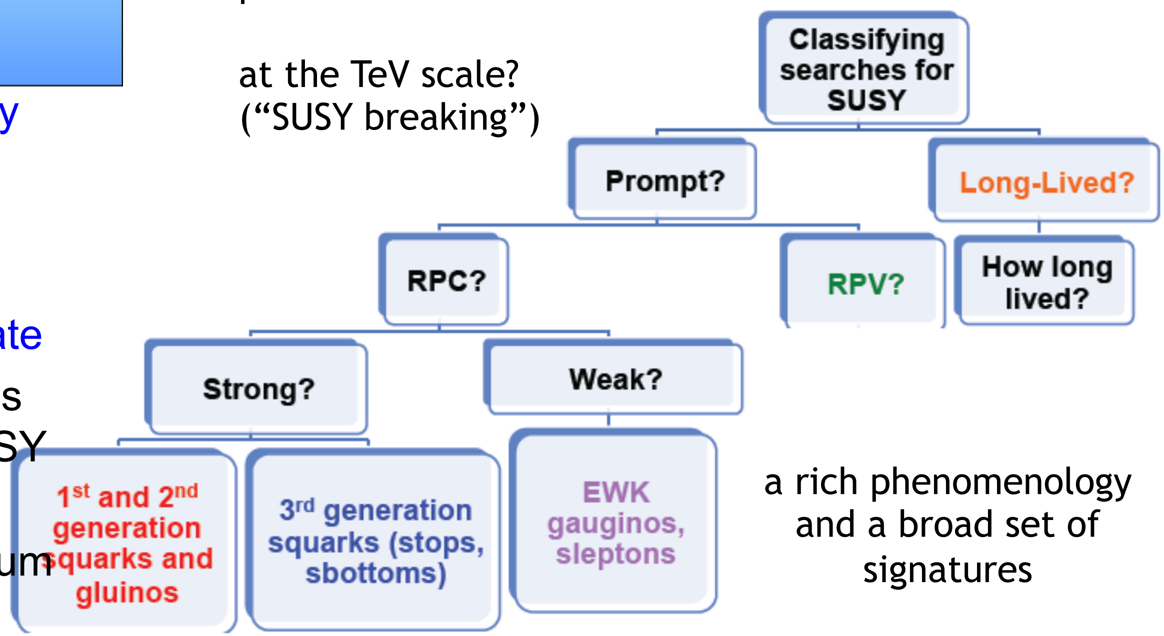
Spin 0	Spin 1/2	Spin 1	Spin 3/2	Spin 2
sleptons	leptons		gravitino	graviton
squarks	quarks			
Higgs	Higgsino			
	photino	photon		
	Zino	Z		
	Winos	W+ W-		
	gluinos	gluons		

Each SM particle has a supersymmetric partner

at the TeV scale? (“SUSY breaking”)

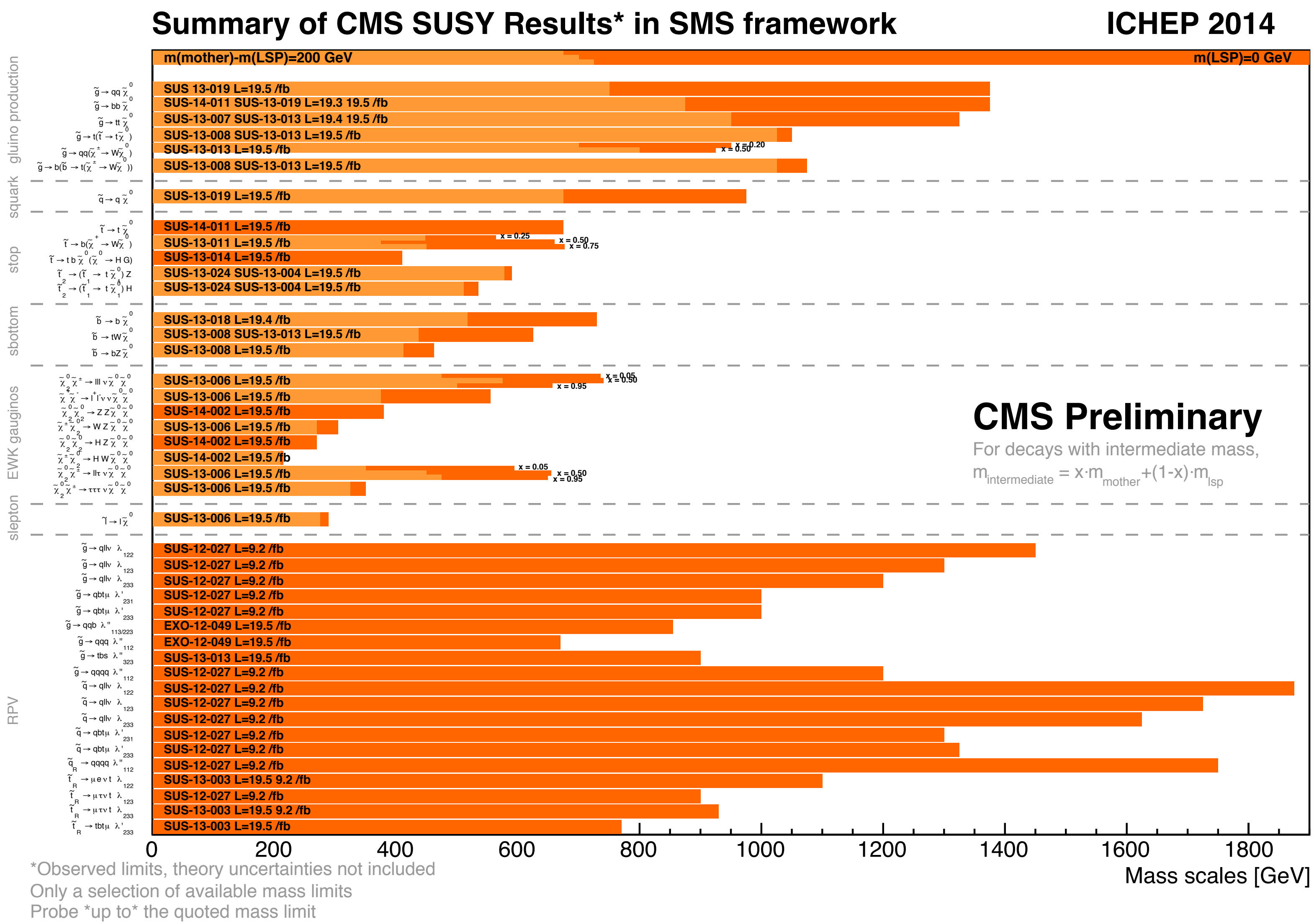
- Provides solution to the hierarchy problem
  - “Natural” (not-so-fine-tuned) SUSY: TeV scale
- Can provide dark matter candidate
  - If RP is conserved, sparticles pair produced & lightest SUSY particle is stable
  - Missing transverse momentum signature in detectors

Search for SUSY partners



a rich phenomenology and a broad set of signatures

SUSY Results from Run I…

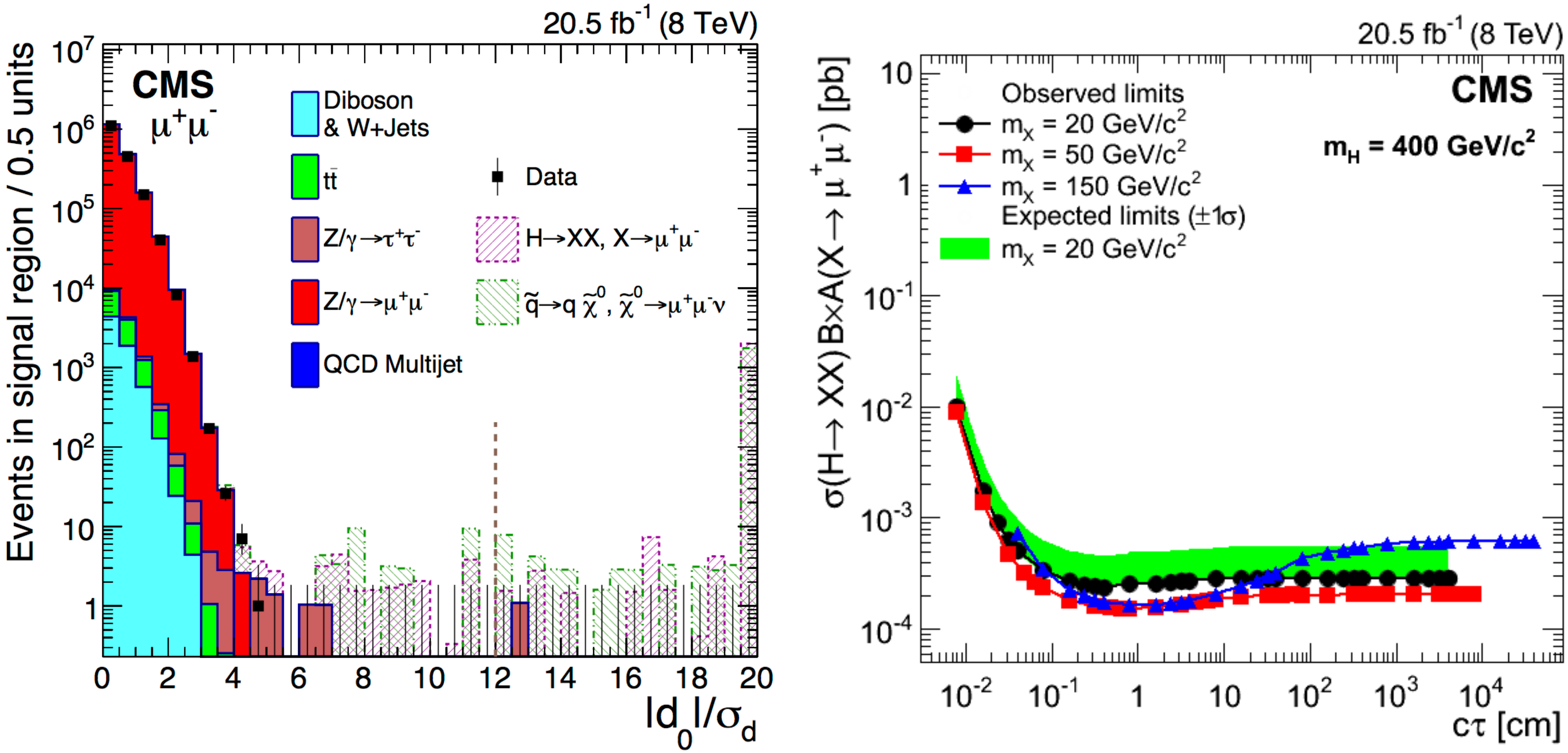


Long-Lived Particles

- Several BSM models (including SUSY) could give rise to new, massive particles with (relatively) long lifetimes
  - SUSY with weak RPV
  - Minimal B-L extension of the SM
  - "Split" SUSY
  - Magnetic monopoles
  - Stable charged leptons and R-hadrons
- Striking signatures including:
  - Disappearing tracks
  - Displaced vertices in tracking detector
  - Displaced muonic lepton-jets
  - Decays in the calorimeter

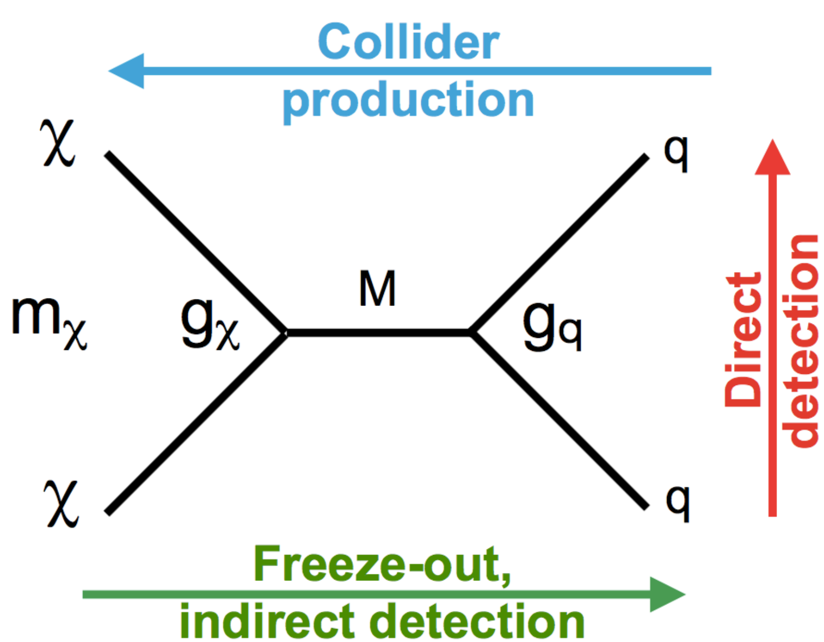
Displaced Lepton Pairs

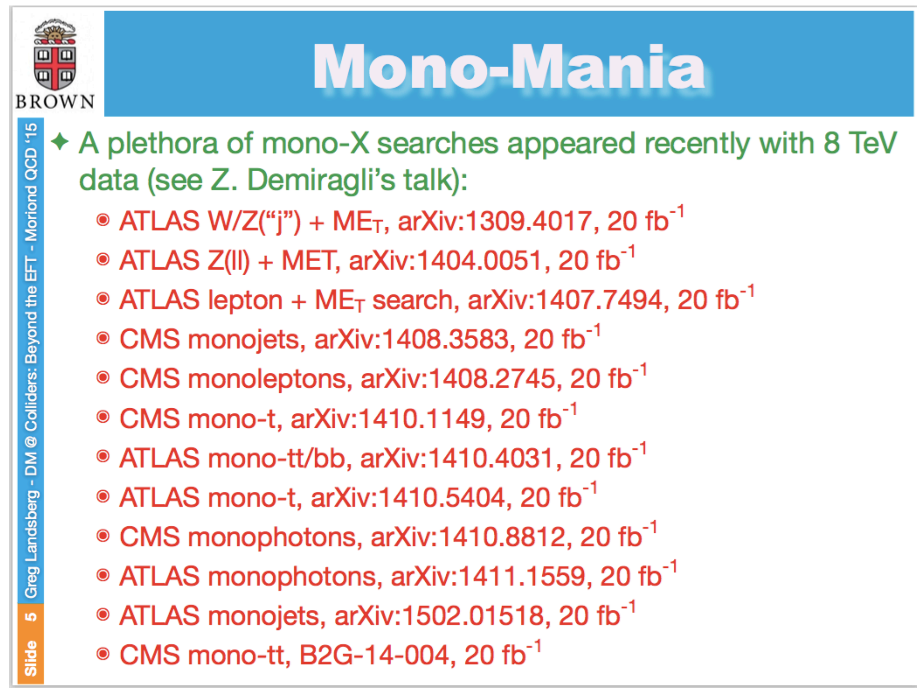
- Search for non-SM Higgs boson decaying to spinless, long-lived boson X which can decay to leptons
- Require leptons associated with tracks to have $|d_0|/\sigma(d_0) > 12$



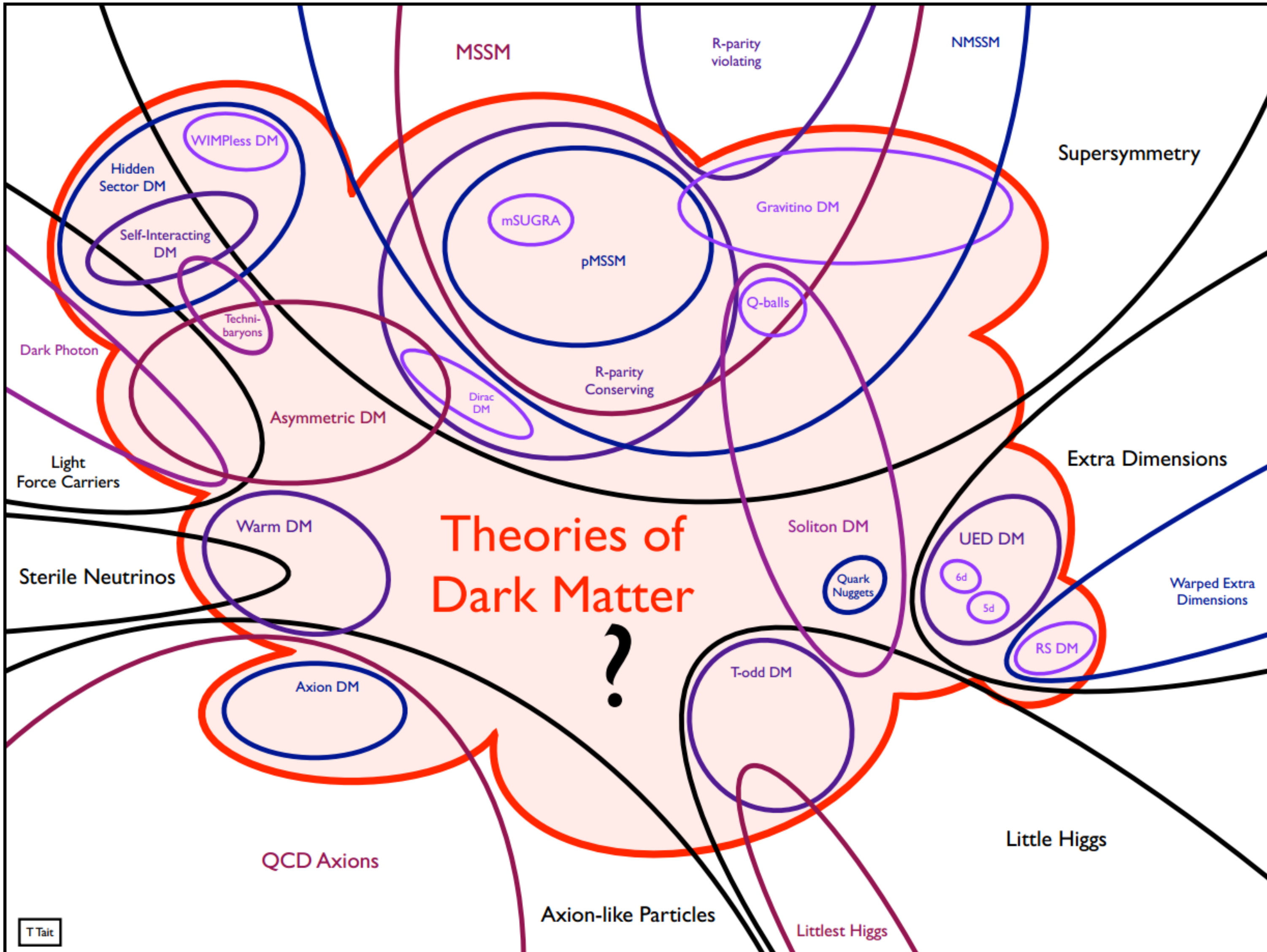
Search for Dark Matter

- TeV scale DM search motivated by the “WIMP (weakly interactive massive particle)”
  - Effective Field Theories, simplified models
- Dark matter particles escape detection: tag events using recoiling objects, measure the missing transverse energy ($E_T^{missing}$)
- Mono-X + $E_T^{missing}$ (X = jet, W/Z/γ, top, ttbar/bbbar)



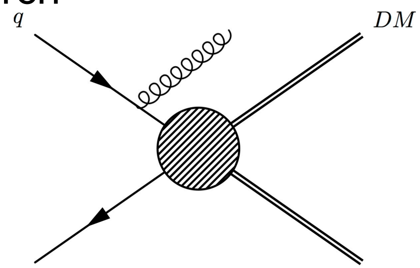


Theories of Dark Matter

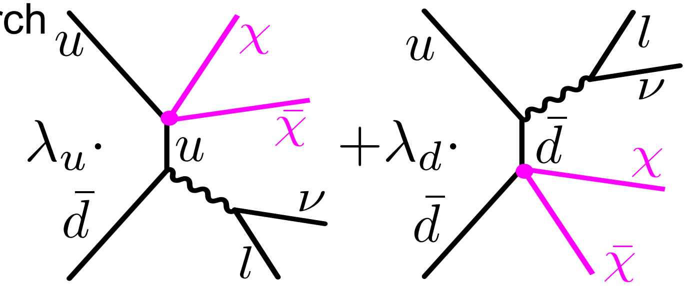


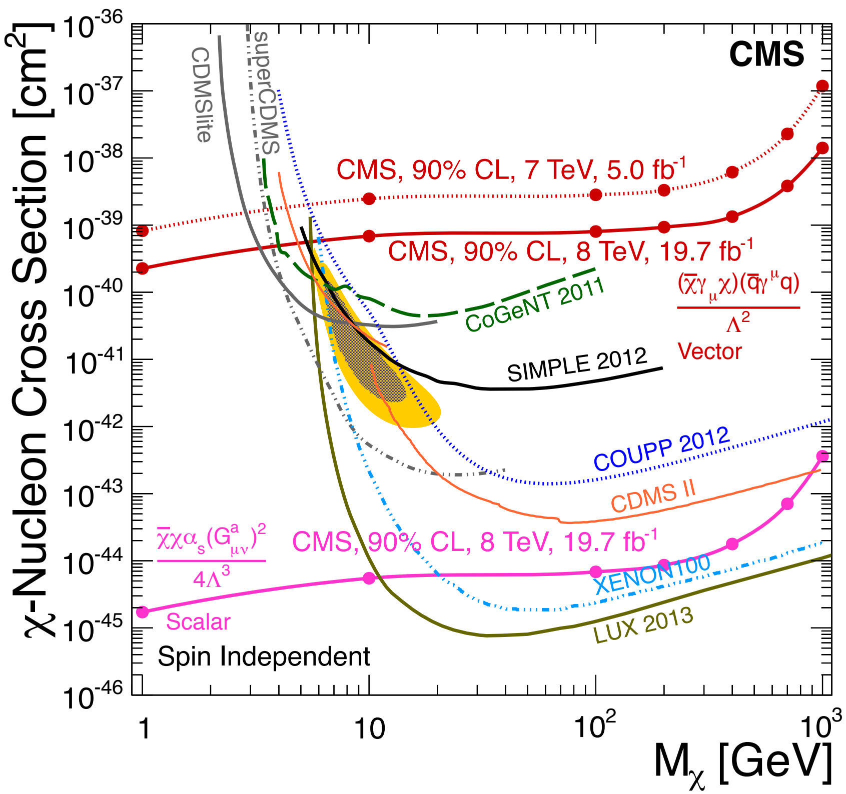
Search for Dark Matter

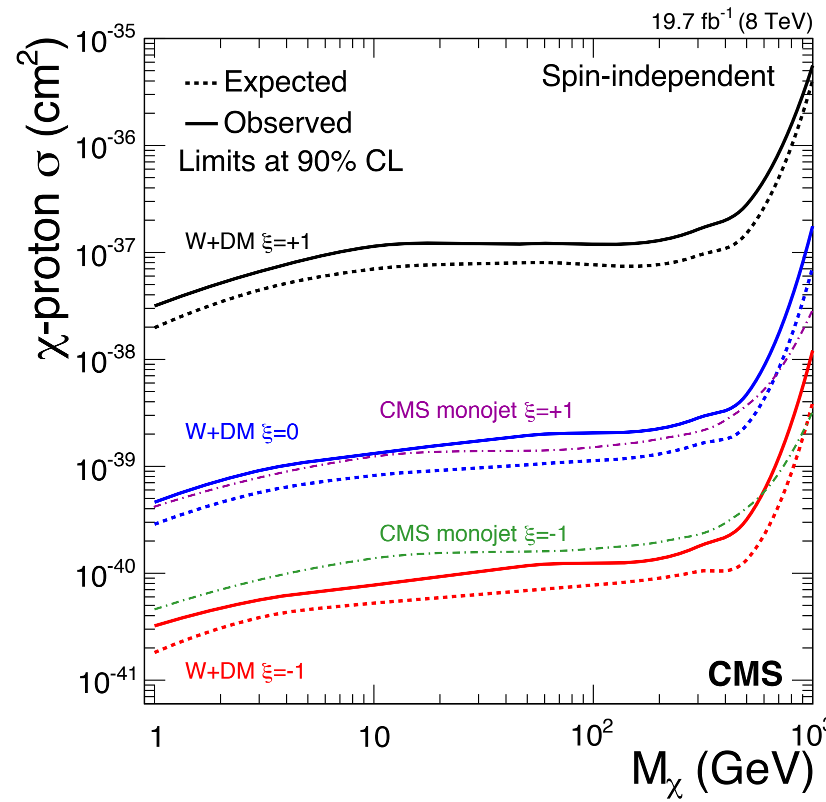
Mono-jet search



Mono-W search

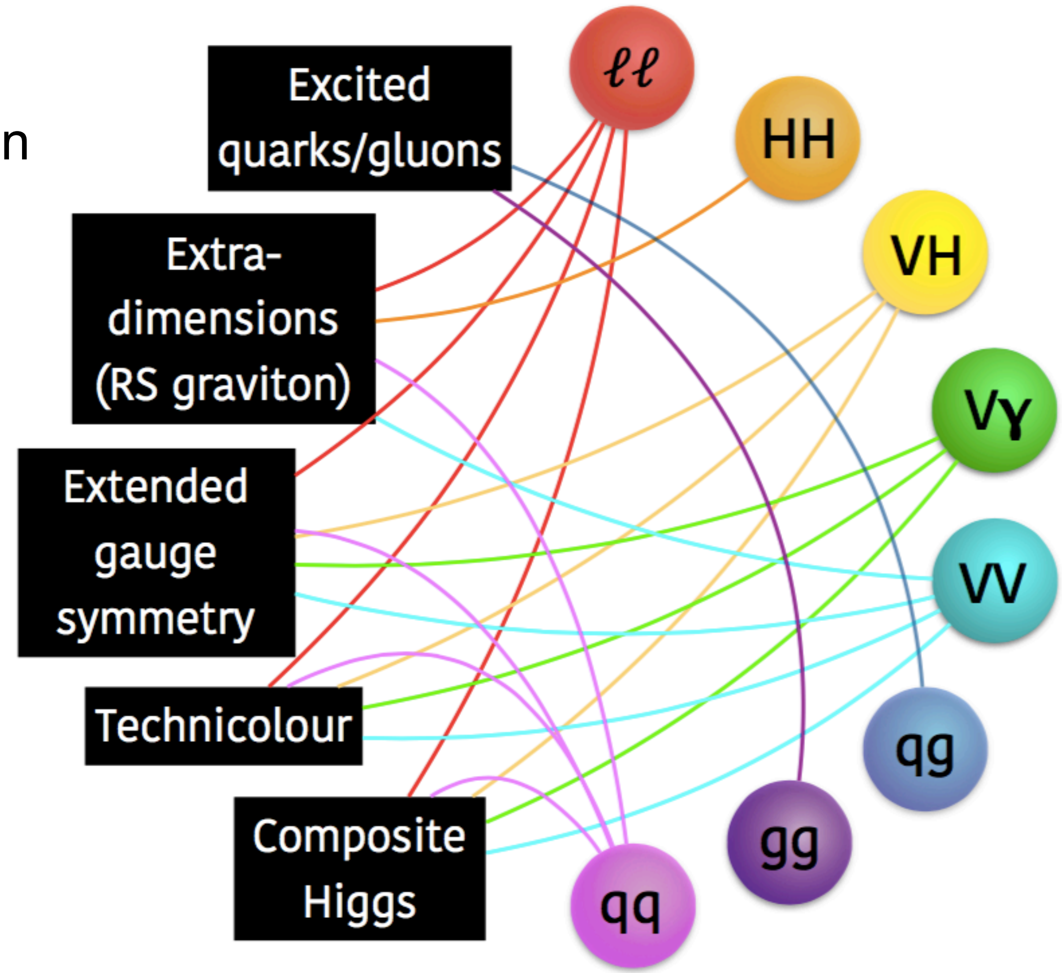






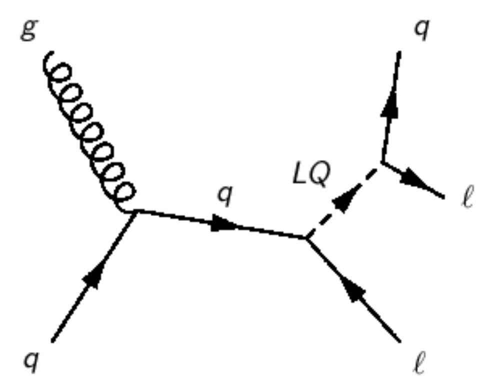
Resonance Searches

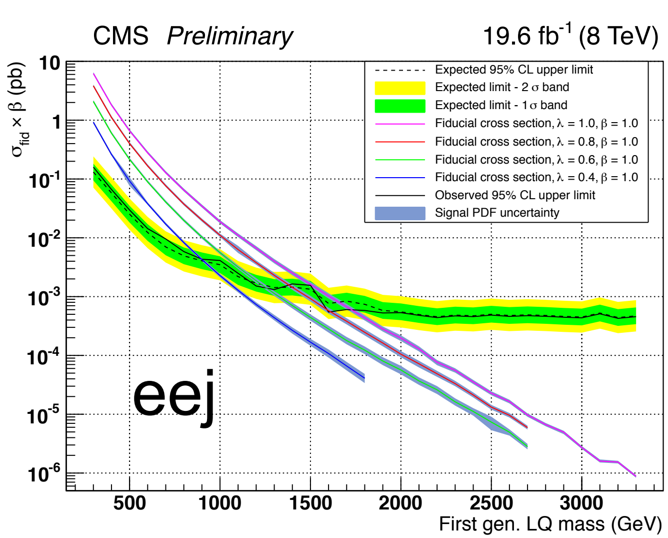
- Many BSM theories predict narrow resonances at the TeV mass scale
  - Clear “bump” over SM prediction
  - Almost any combination of 2 SM particles can form a resonance in BSM mode

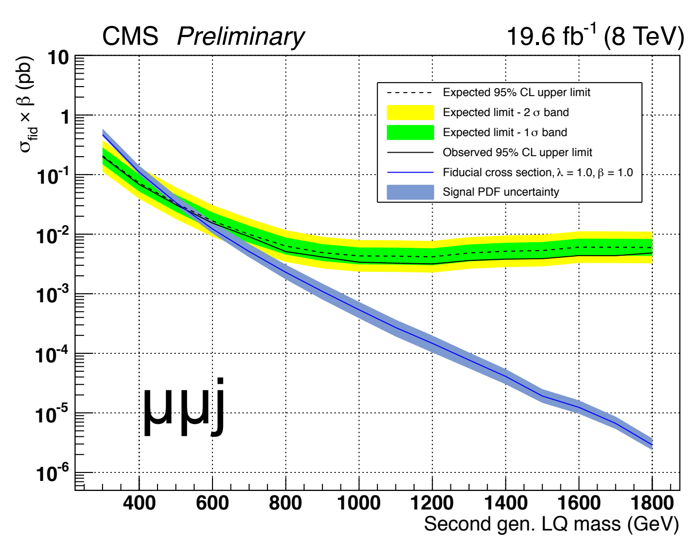


Leptoquarks (LQs)

- Search for singly produced 1st and 2nd generation leptoquarks (eej or μμj final state)
- Single LQ production x-section depends strongly on $\lambda_{LQ\text{-}l\text{-}q}$
- Additioinal non-resonant contributions
  - Enhancement in low mass tail of M_{lj} distribution
- Initial state has quark flavour
  - Anything beyond 1st generation is suppressed

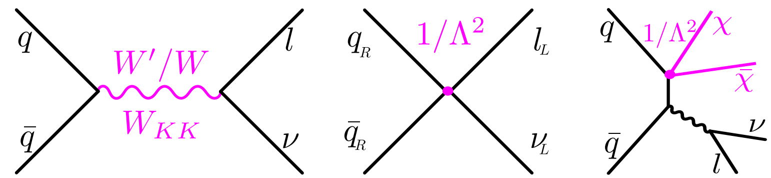




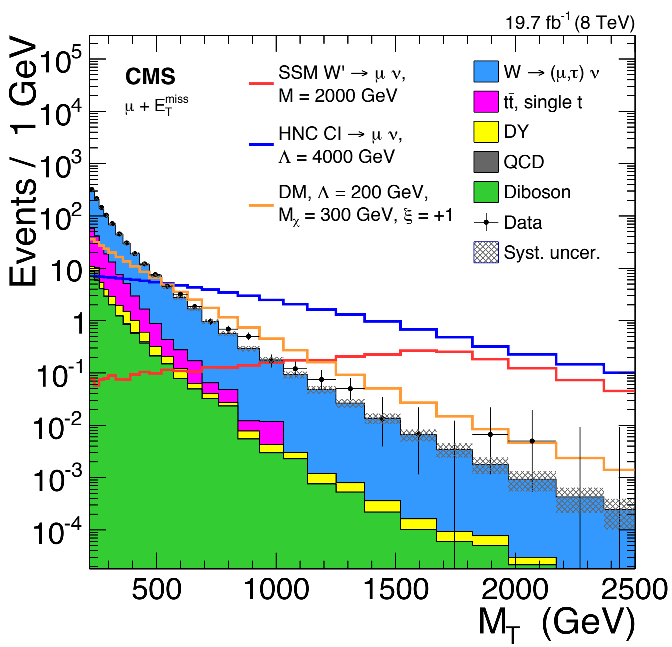


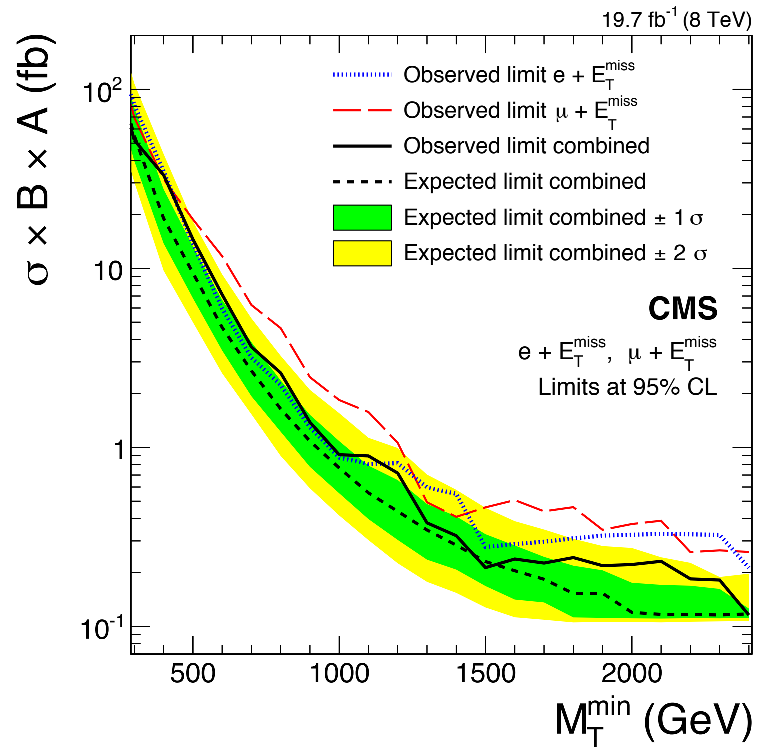
Search for W' and Z'

- New heavy gauge bosons can appear in many BSM models
  - SSM, RS gravitons, composite Higgs, etc.
  - Signature based to cover all possible scenarios and interpret in many benchmark signal models



- W' couples to fermions as the SM W





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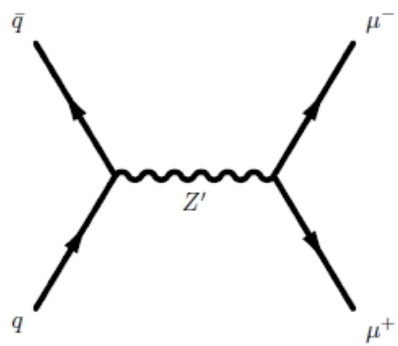
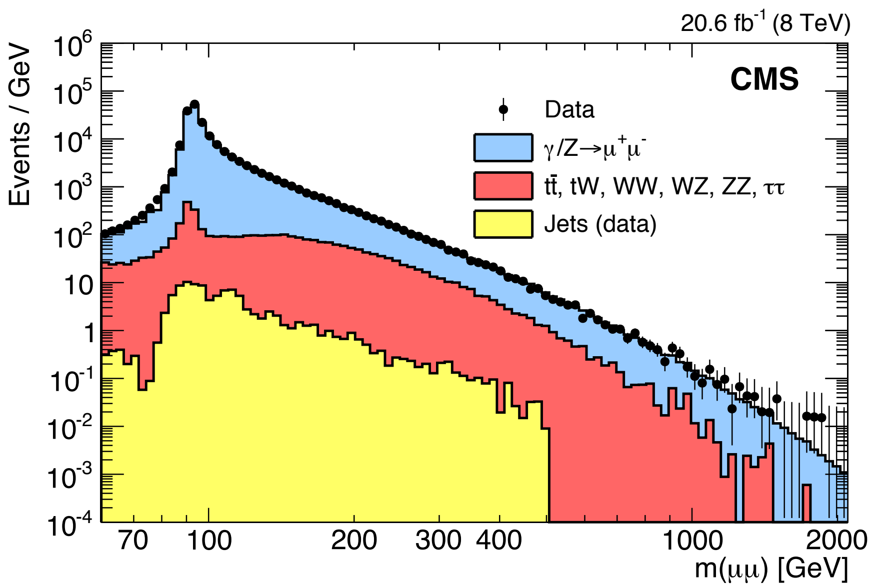
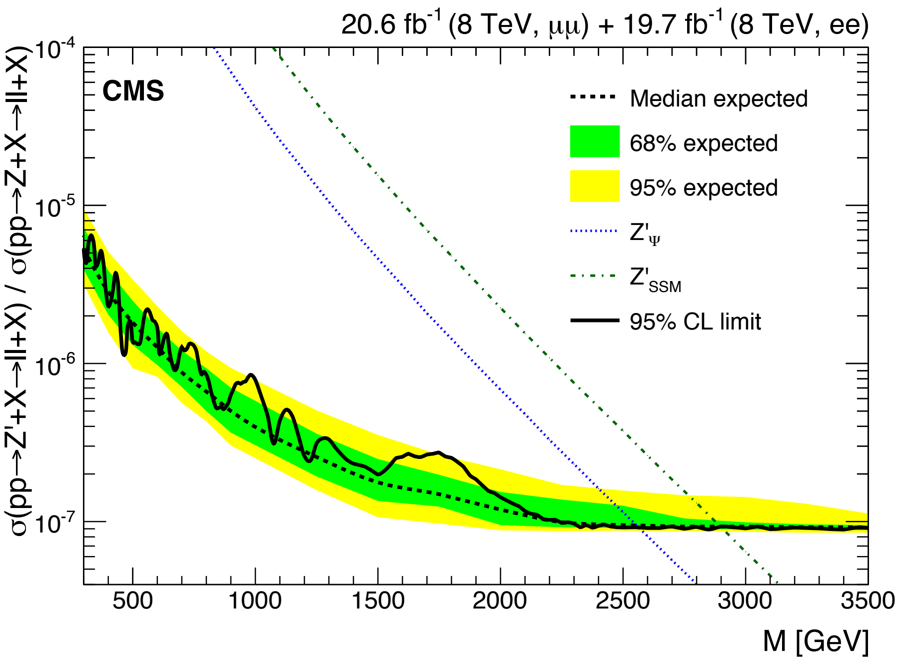
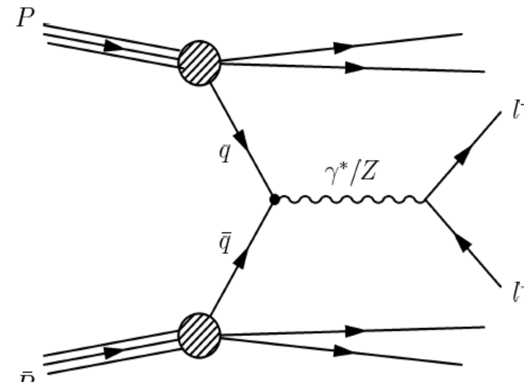


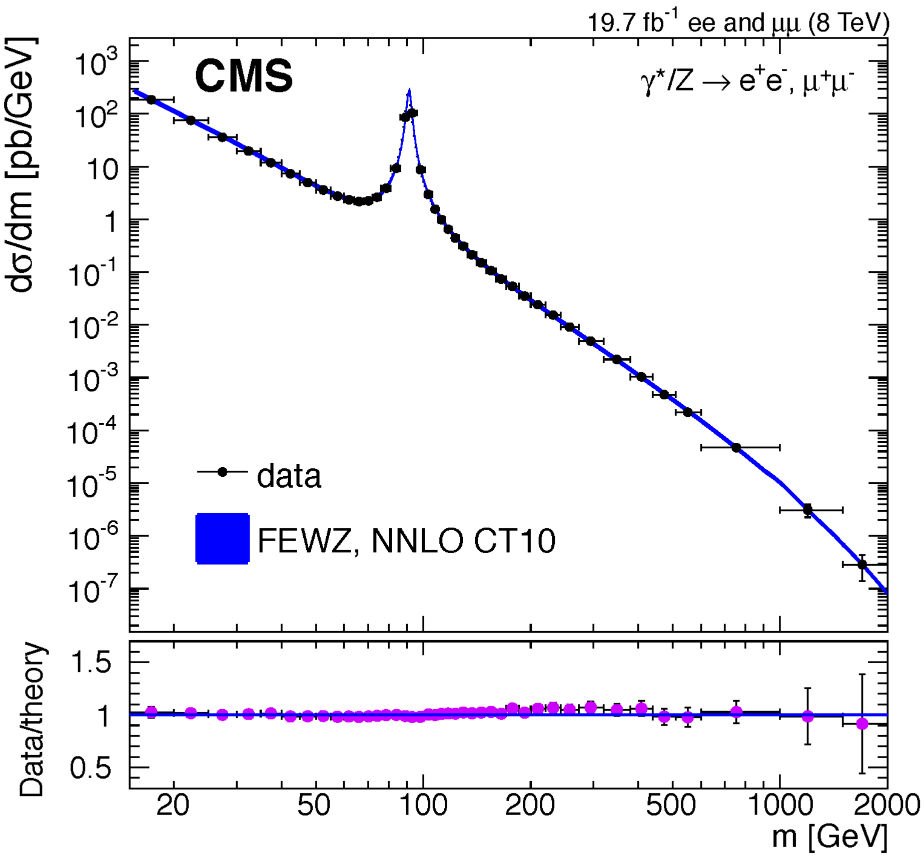


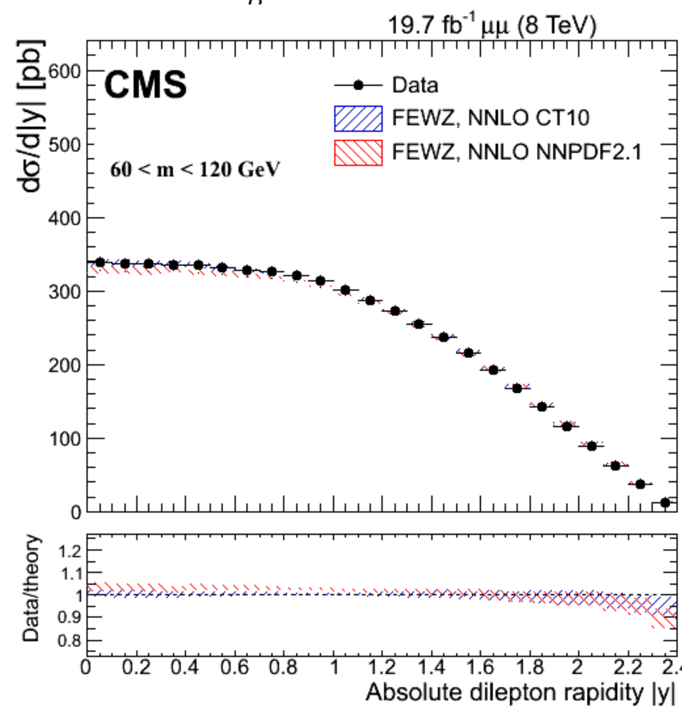


Drell-Yan Differential Cross Section

- Imporatnt SM benchmark channel to test pQCD at NNLO
- Dominant background of BSM searches in dilepton channel

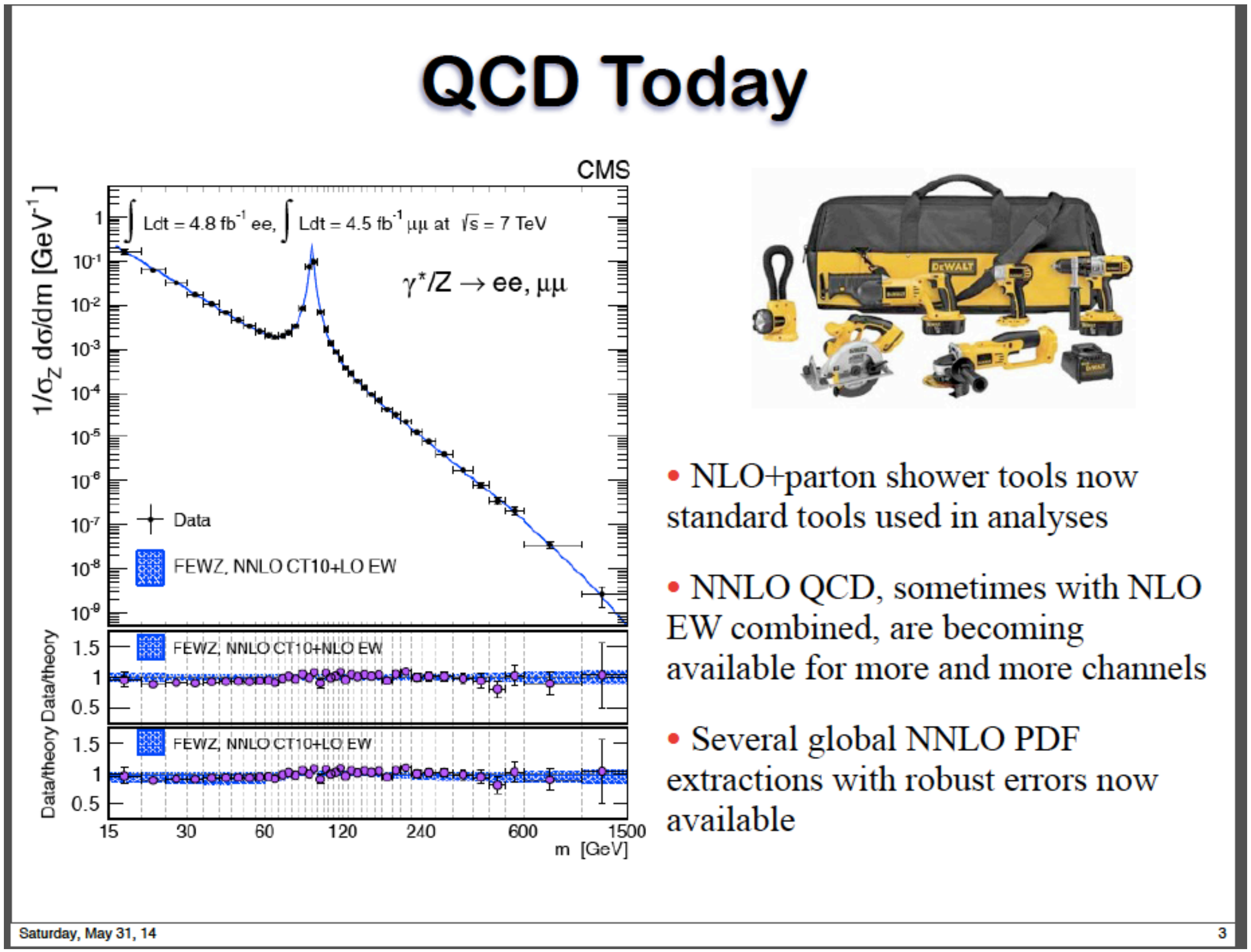






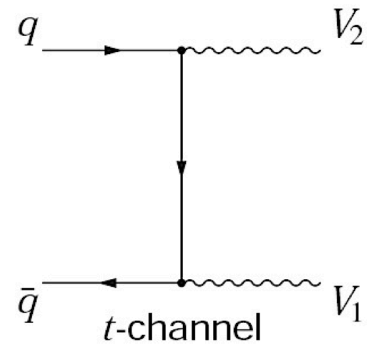
DY Results at LHCP 2014

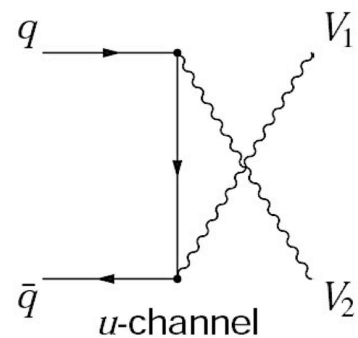
- This result was introduced as an example of QCD triumph in LHCP 2014 plenary talk: “Precision QCD Theory” by Radja Boughezal (ANL)

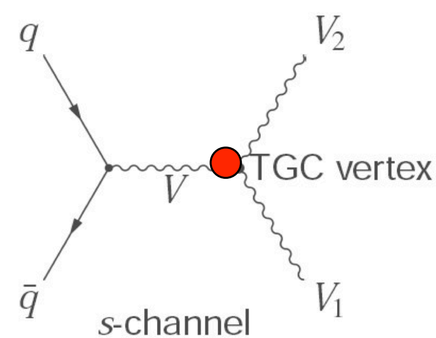


Diboson Production

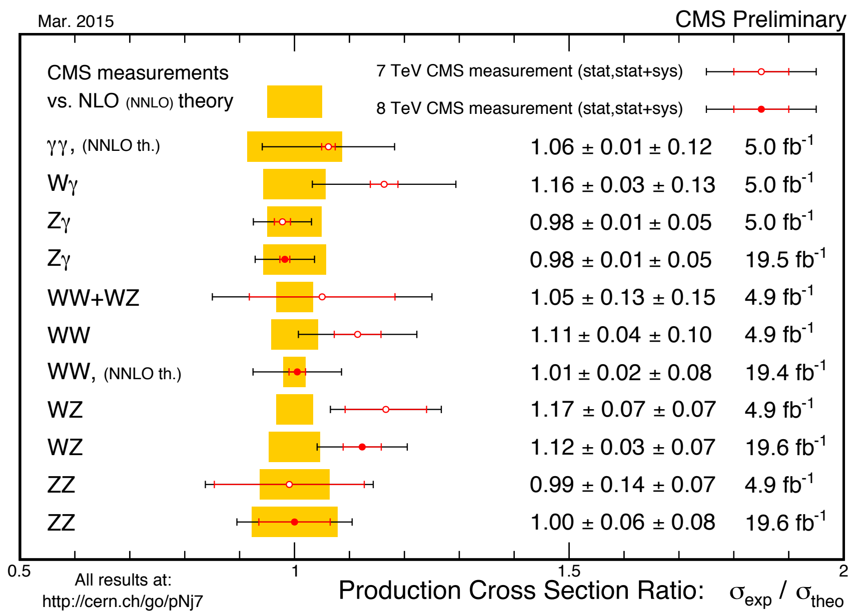
- Important test of the gauge sector of the SM
- Irreducible background for Higgs and searches
- Test of triple gauge couplings
  - Charged TGC (WWZ, WWγ) allowed in SM
  - Neutral TGC (ZZZ, ZZγ) forbidden in SM
- Anomalous couplings generally lead to larger cross sections, especially in the high transverse momentum tails



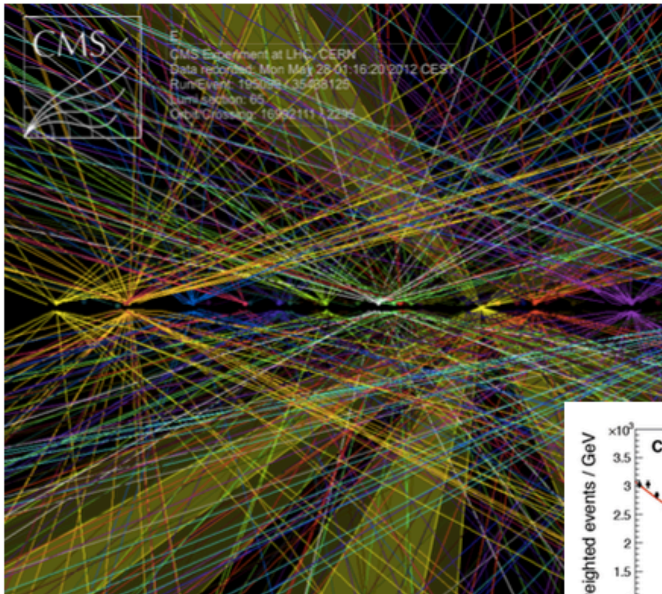


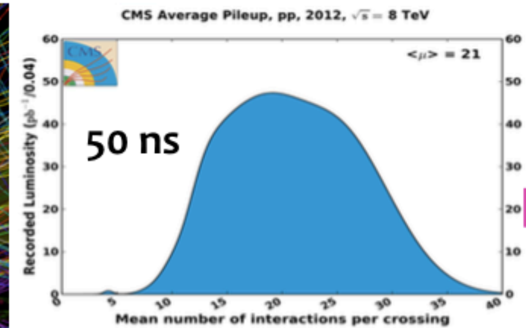


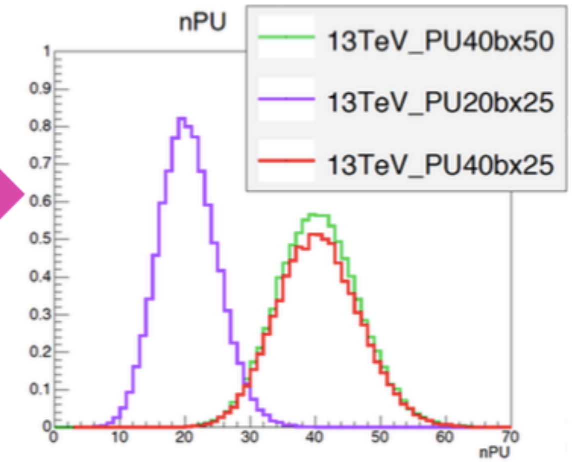
Good agreement with SM NLO prediction

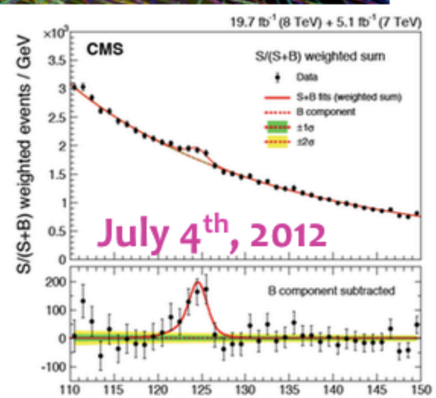


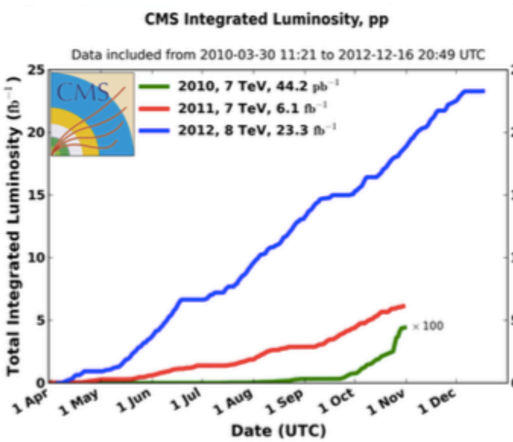
From Run I to Run II



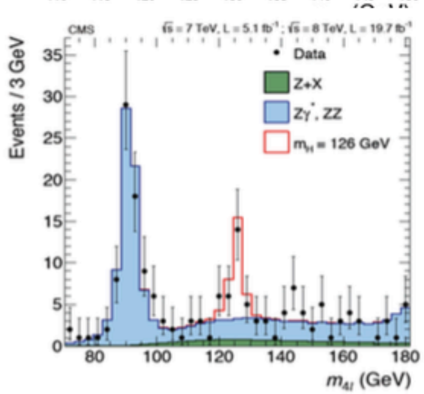








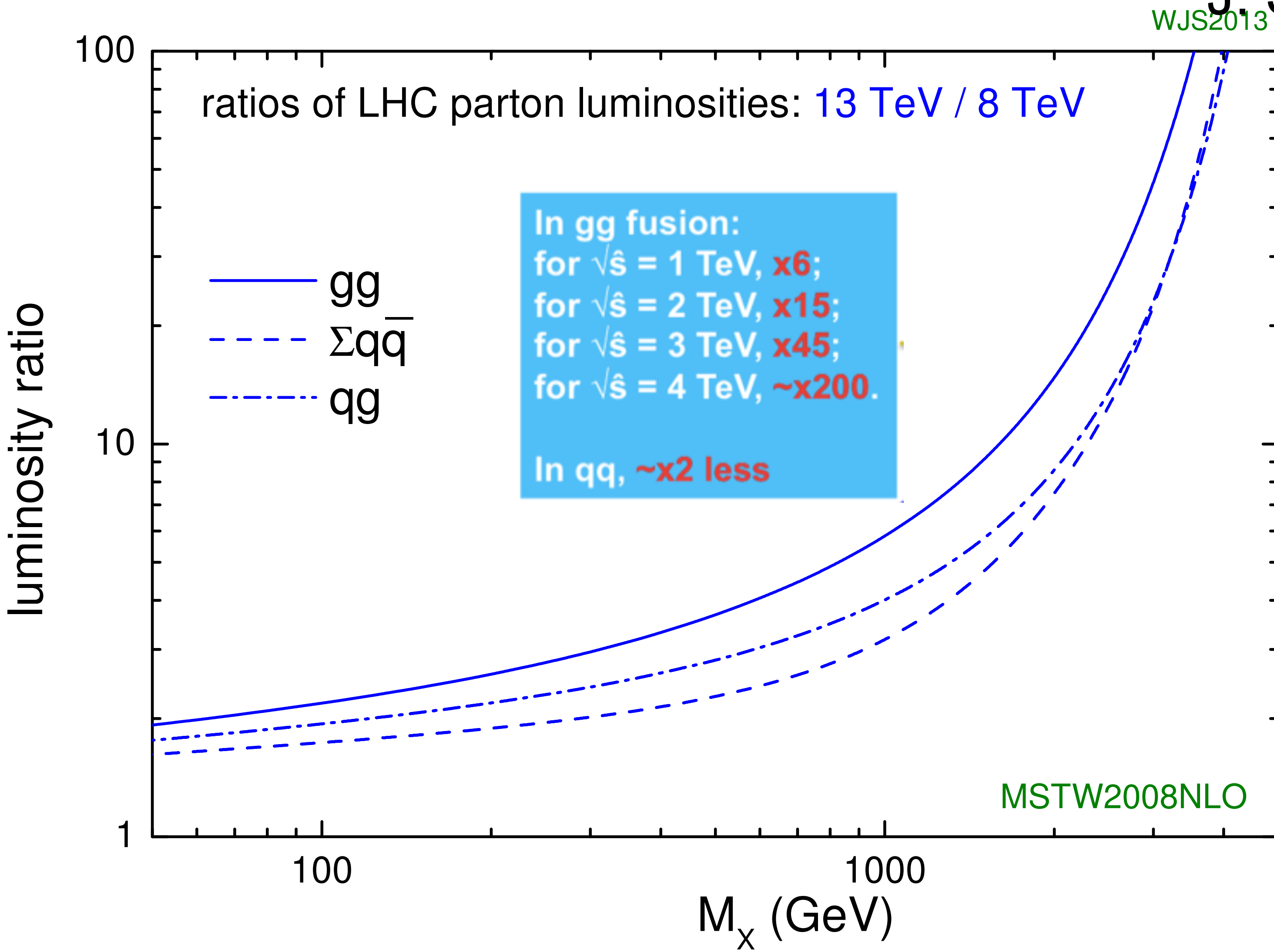
√s = 7,8 TeV



- ❑ √s = 13 TeV
- ❑ Higher luminosity
- ❑ Larger number of interactions per BX
- ❑ Reduced time between BXs
  (40@50ns or 20@25ns)

Luminosity Ratio

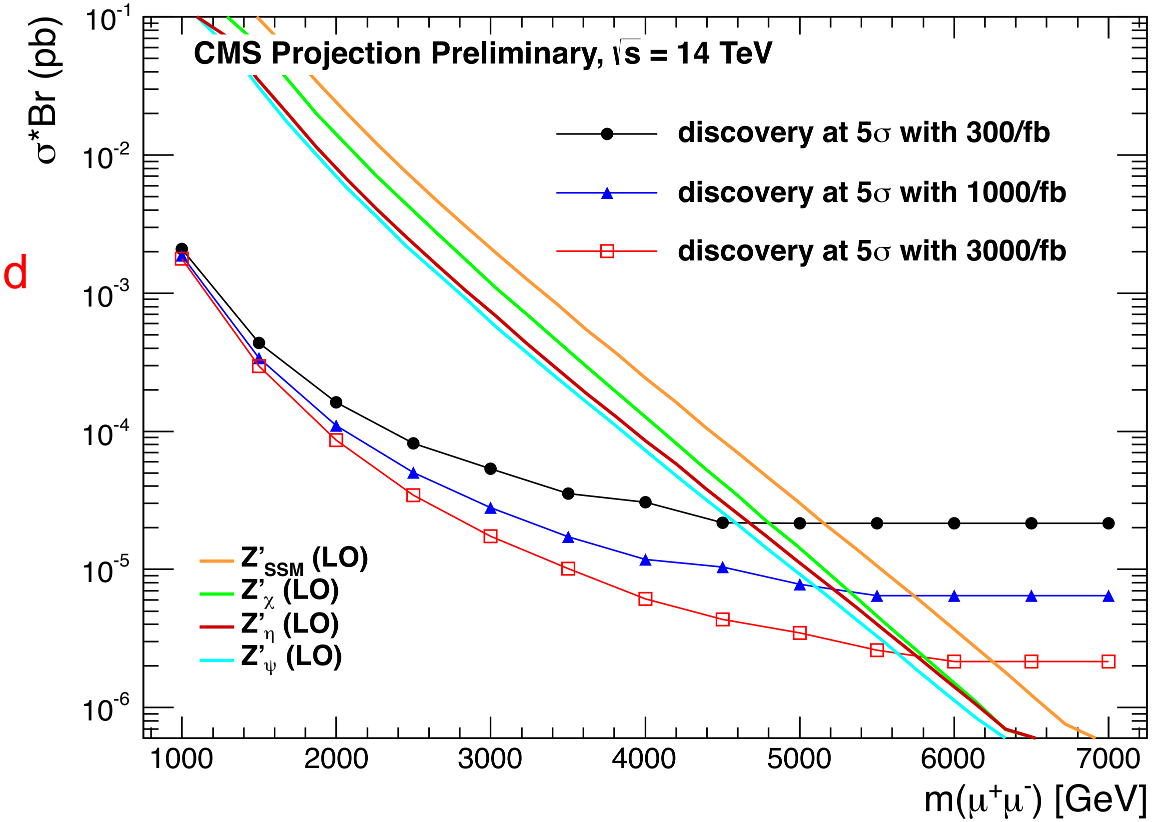
J. Stirling



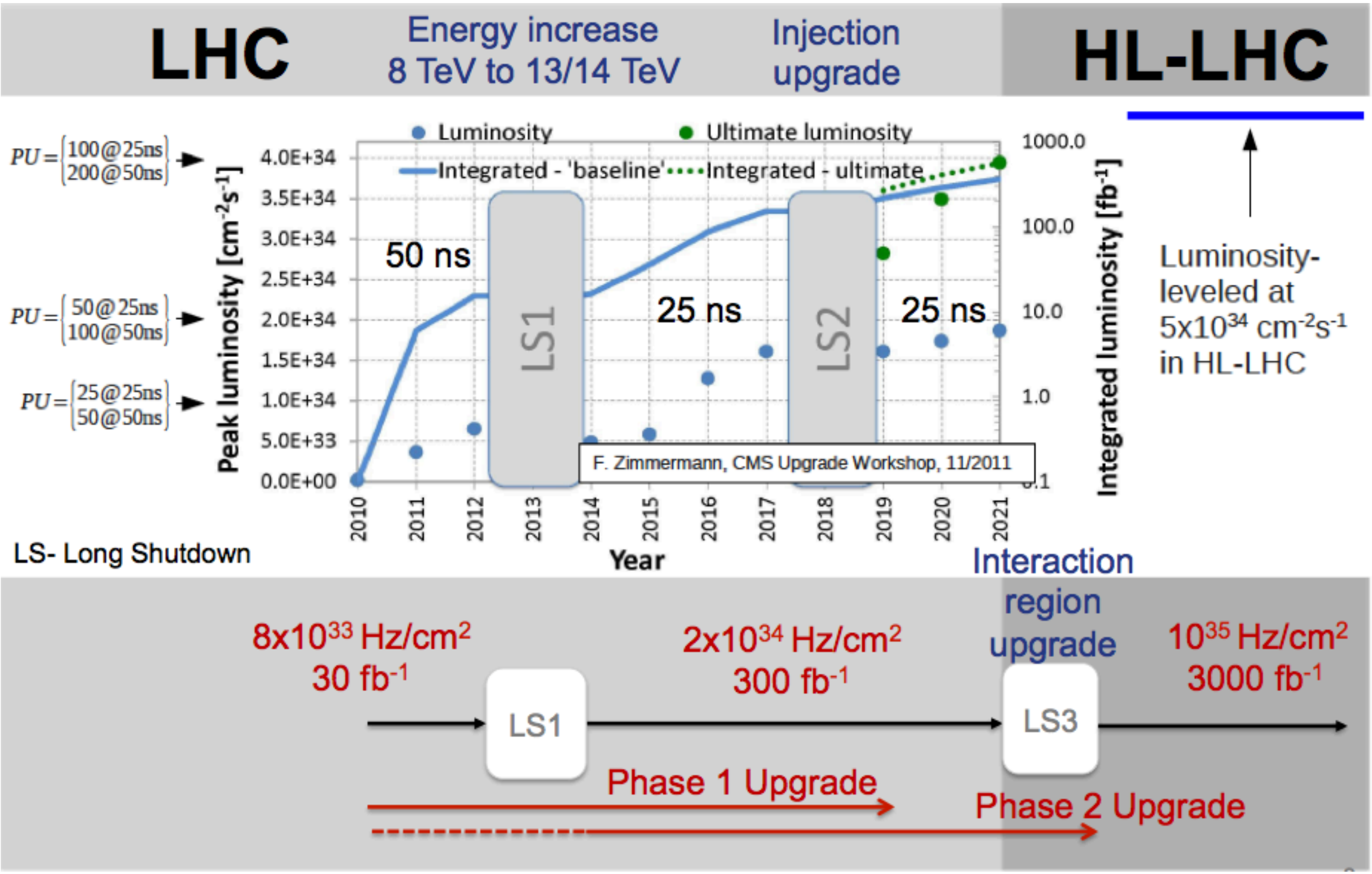
Z' Projection at 14 TeV

- Projection of discovery reach at 14 TeV with 300, 1000, 3000/fb
- Used in Snowmass white paper
- Studies are based on generator level extrapolations and scaling of 8 TeV results

Important to understand the future expectation to decide the detector upgrade plan

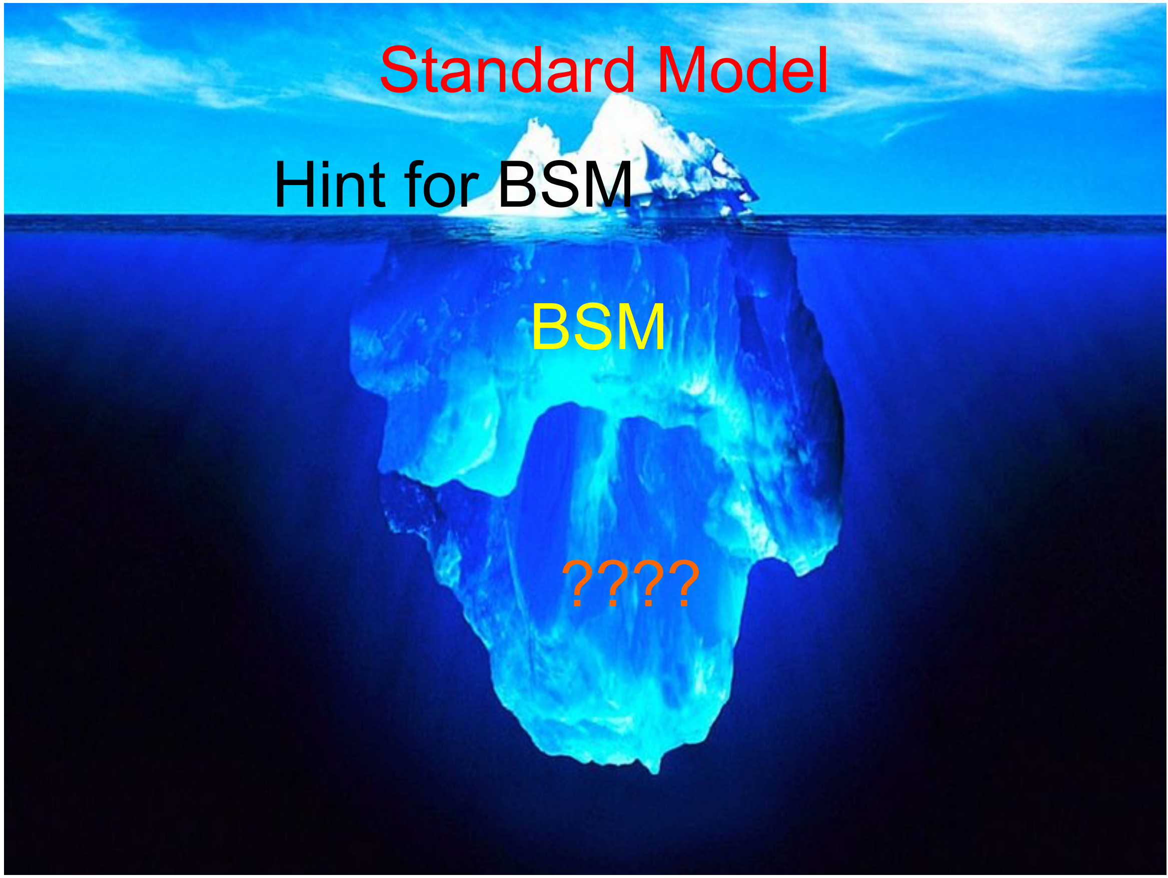


LHC Operation

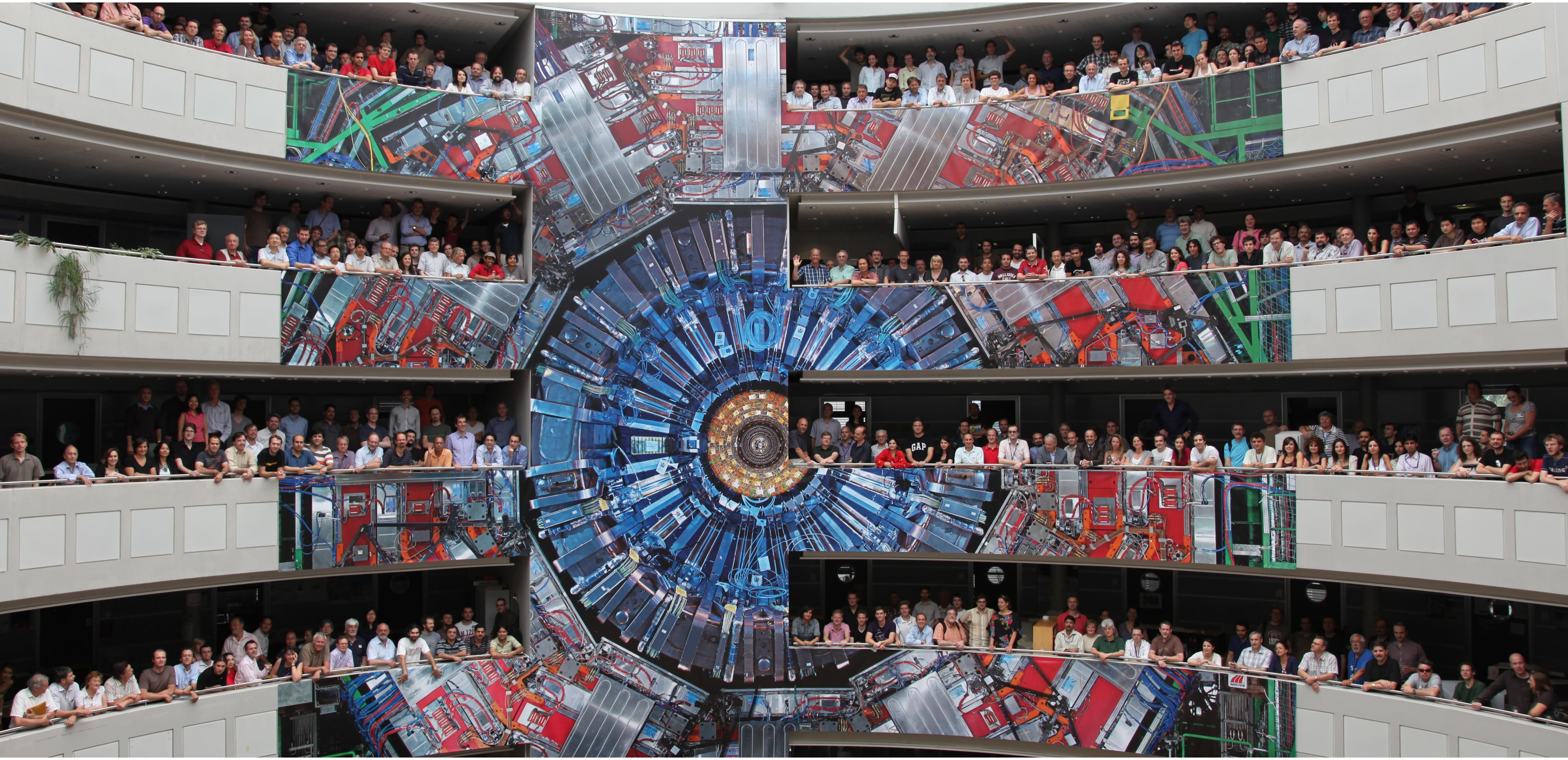


Summary

- Many searches for new physics and SM tests are on-going at LHC
- While a bit frustrating that we haven't found anything yet, it's definitely not a time to give up
- New LHC energy may very well cross the threshold and plethora of new phenomena will open up in the forthcoming run
- Stay tuned with new 13 TeV results from CMS!!



Thank You!



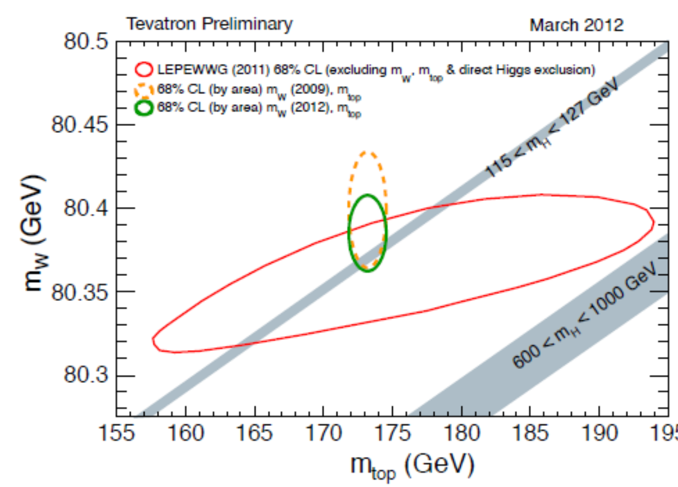
Back Up

Drell-Yan Cross Section (2)

- Improved knowledge on PDFs is very important at the LHC
  - Current best measurement of W mass from CDF/D0 is dominated by PDF uncertainties
  - Implications for indirect new physics searches
  - Especially at the LHC, where new x-Q^2 kinematic regions are probed
- Applications of the double differential cross section measurement to PDF constraints
  - Replace the existing DY data with fixed-target in the PDF fit
  - Purpose to constraint PDFs
    - In particular d quark and anti-quarks

Source	Uncertainty 2.2 fb^{-1} (MeV)
Lepton energy scale	7
Lepton energy resolution	2
Recoil energy scale	4
Recoil energy resolution	4
Lepton removal	2
Backgrounds	3
p_T (W) model	5
PDFs	10
QED radiation	4
Total systematics	*15*
W statistics	12
Total	***19***

B. Jayatilaka, Moriond 2012

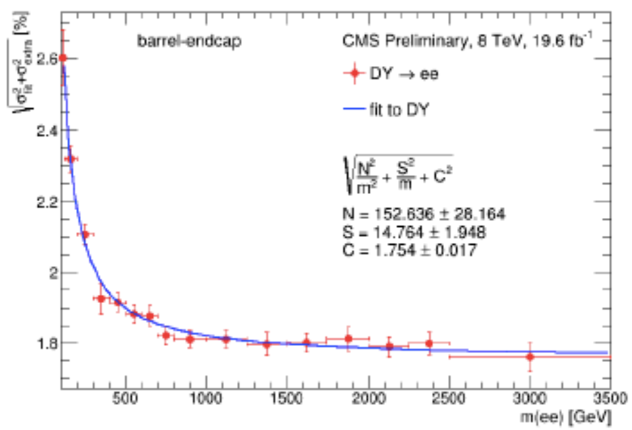


Model and Limit Setting

Signal model & signal region

- Shape signal model: $\mathrm{BW}(M_{\ell\ell}|M_{Z'}, \Gamma_{Z'}) \otimes \mathrm{Gauss}(M_{\ell\ell}|\sigma_{resolution})$
- Shape background model: Parameterized function, shape from fit to simulation
- Data considered: Events with $M_{\ell\ell} > 200$ GeV
- Mass window: $M_{Z'} \pm 6$ times mass resolution

relative resolution (electron barrel-endcap)



Limit setting

Shape analysis using an extended unbinned likelihood function of invariant mass
Bayesian 95% CL upper limits on Z' to Z cross section ratio R_σ

$$R_\sigma = \frac{\sigma\left(pp \to Z' + X \to \ell^+\ell^- + X\right)}{\sigma\left(pp \to Z + X \to \ell^+\ell^- + X\right)} = \frac{N\left(Z' \to \ell^+\ell^-\right)}{N\left(Z \to \ell^+\ell^-\right)} \cdot \frac{A\left(Z \to \ell^+\ell^-\right)}{A\left(Z' \to \ell^+\ell^-\right)} \cdot \frac{\epsilon\left(Z \to \ell^+\ell^-\right)}{\epsilon\left(Z' \to \ell^+\ell^-\right)}$$

$\sigma(Z')$ evaluated in mass range $M_{Z'} \pm 40\%$, $\sigma(Z)$ evaluated in 60 GeV $< M_{\ell\ell} <$ 120 GeV

- Uncertainty on the luminosity cancels in the ratio R_σ
- Uncertainties on the absolute values of $\epsilon_{trigger}$, $\epsilon_{reconstruction}$ and mass scale reduce to uncertainties on their evolution from the Z peak to high mass

]

Systematic Uncertainties

Systematic uncertainties

- Dominant uncertainty on the limits:
  Ratio of acceptance times efficiency between Z' and Z
  3% for dimuon, 4% for barrel-barrel and 6% for barrel-endcap dielectron channel
- Z/γ^* background:
  Shape uncertainty on the background fit from PDFs and higher order corrections
  ranges from 2% at $M_{\ell\ell} = 200$ GeV to 20% at $M_{\ell\ell} = 3000$ GeV
- Uncertainties on the subleading backgrounds studied but less important
- Impact of uncertainty on the muon momentum scale studied with different detector misalignment scenarios and found to be negligible

Test of limit setting

- Impact of variations of the background shape and normalization on the observed limits is small
- Impact of variations of the mass window used for limit setting on the observed limits found to be small

Benchmark Signal Modeling (1)

- Z' → 4 leptons
  - Generator: CalcHep 3.4.1 + PYTHIA
  - Tree-level matrix element calculation by CalcHEP
  - Model files provided by authors of theory paper
  - Generate 10 mass bins (12000 events each) for expected limit calculations: M = 750-3000 GeV with 250 GeV bin size
  - Five channels: μμμμ, μμμe, μμee, μeee, eeee
  - Additional MC samples with various M(ϕ) are currently underway
- Simulation and reconstruction
  - Use Full-Sim: https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideSimulation
  - PV smearing, pile-up mixing, L1/HLT emulation, physics object reconstructions
  - CMSSW_5_3_4 with Summer12 S10 Pile-up scenario
  - Global tag for reconstruction: START53_V7C which includes the latest mis-alignment scenario

Benchmark Signal Modeling (2)

- Assumptions on the intermediate particle (Φ)
  - Mass: 50 GeV to allow for on-shell decays of the Z´
  - Width: < 0.1 GeV
    - It is insensitive as long as it is sufficiently smaller compared to its mass
  - Coupling constant to dilepton: 0.01
    - The value is the boundary of the coupling constant to dilepton of the sneutrino in SUSY model recommended by theory model author
    - R. Barbier et al, "R-parity violating supersymmetry"
- Dependency of Φ parameters
  - Φ mass: it has relatively strong dependency on the results of σ*Br, in particular, Br
  - Φ width, coupling constant: they have negligible dependency on the results of σ*Br
    - Test the coupling constant with 0.005 and 0.05 and observe negligible difference

Benchmark Signal Modeling (3)

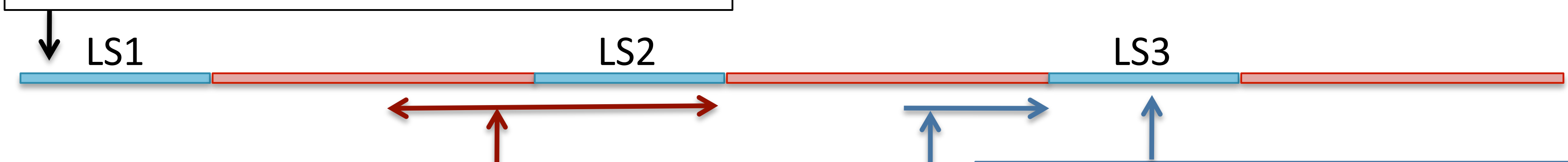
- Summary of parameters

Parameter	Value
4G leptons' $U(1)'$ charge	-4
SM quarks' $U(1)'$ charge	1/3
Φ mass	50 GeV, 5–40% of the Z'mass
Φ width	$<$ 0.1 GeV
$\Phi \to \ell\ell$ coupling	0.01
Z' gauge coupling constant	0.1
Z' mass	250-3000 GeV
Z' width	automatically calculated by CalcHep

Table 2: Summary of masses, coupling constants and widths.

CMS Upgrade Program

LS1 Projects: in production
- Completion of muon coverage (ME4)
- Improve muon operation (ME1), DT electronics
- Replace HCAL photo-detectors in HF (new PMTs) and HO (HPD→SiPM)



Phase 1 Upgrades: TDRs
- Pixel detector replacement
- HCAL electronics upgrade
- L1-Trigger upgrade

Phase 2: Working Groups
- Tracker replacement, Track Trigger
- Forward Region: Calorimetry, and Muons?
- Further Trigger upgrade?

- Longevity → Phase 2
- Phase 2 Scope
- Targeted R&D program

} 2013

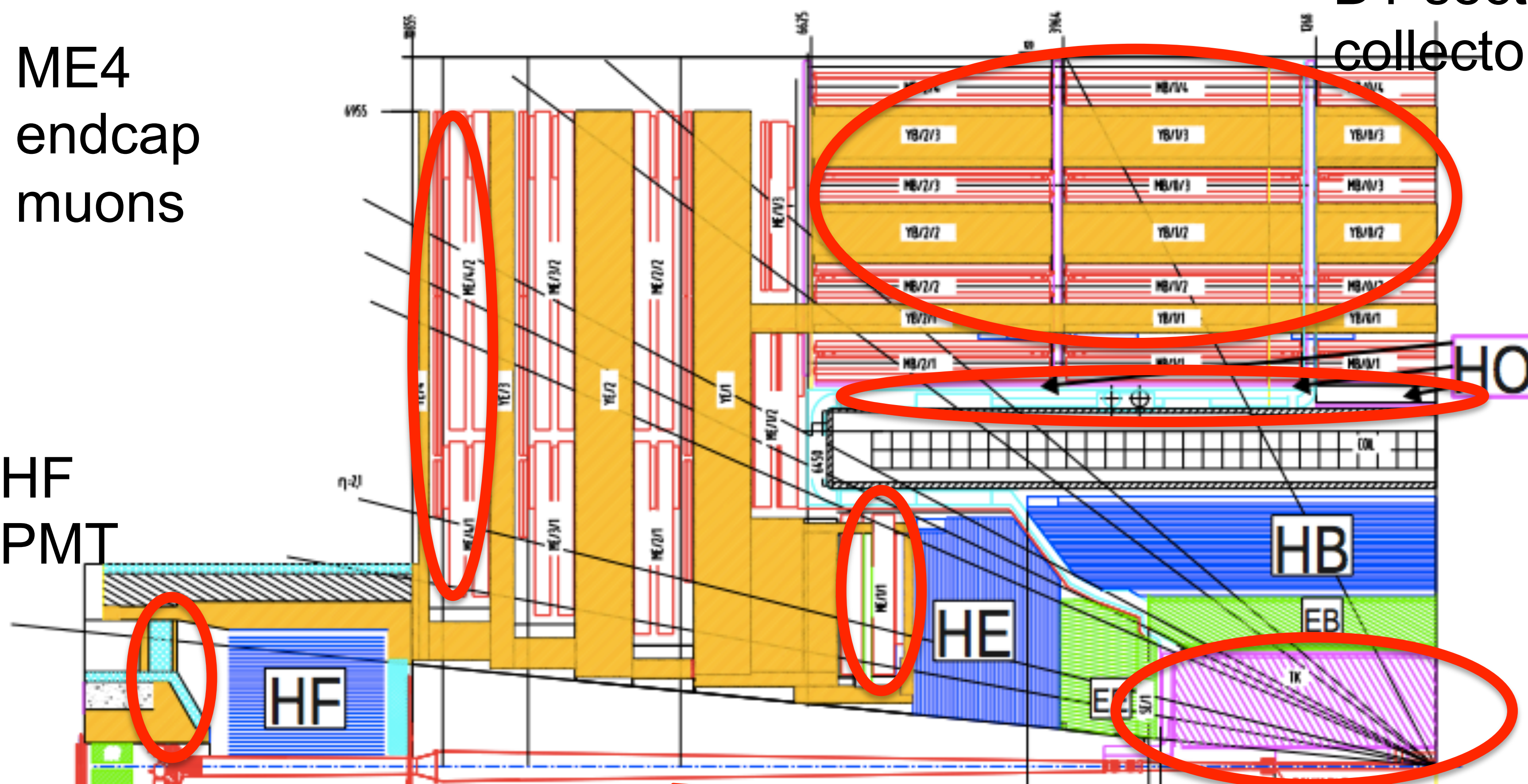
- Technical Proposal 2014

Detector Upgraded in LS1

ME4 endcap muons

DT sector collectors

HF PMT



ME1 FE electronics

Cold trackrer operation

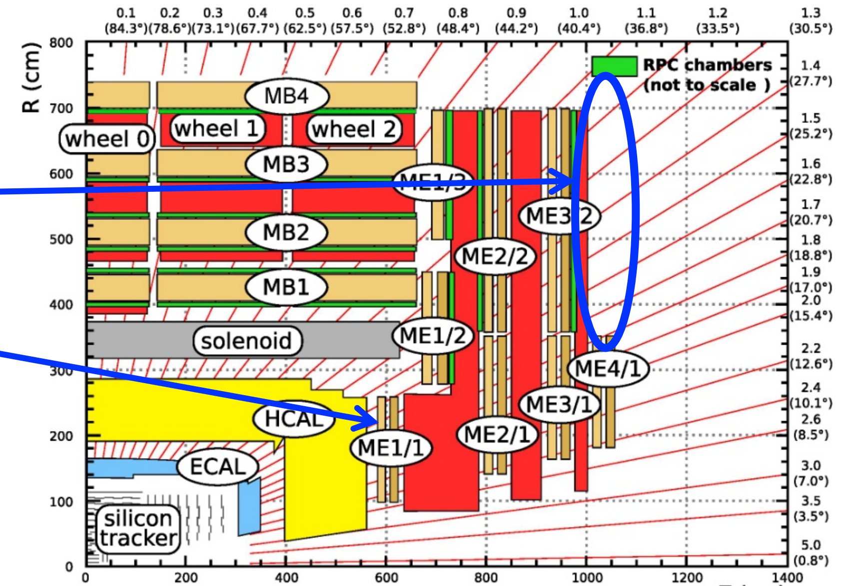
New beampipe

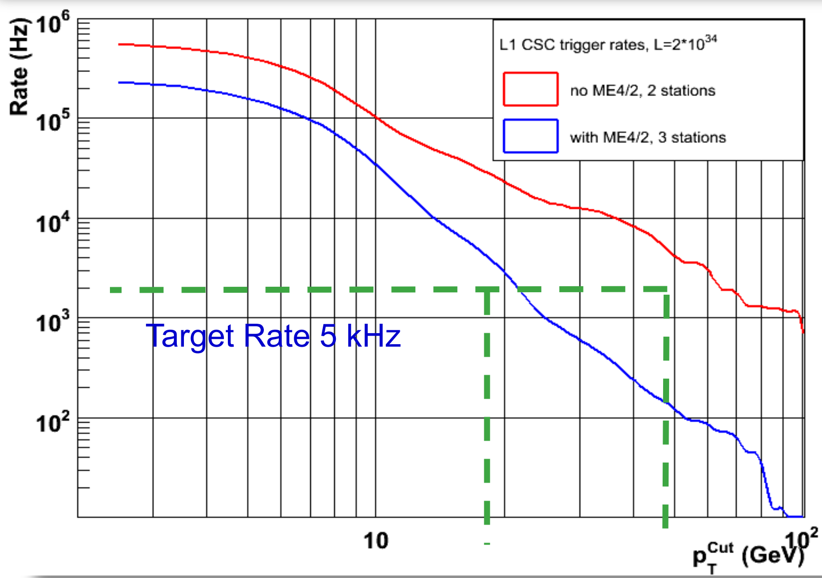
LS1: Exercutive Summary

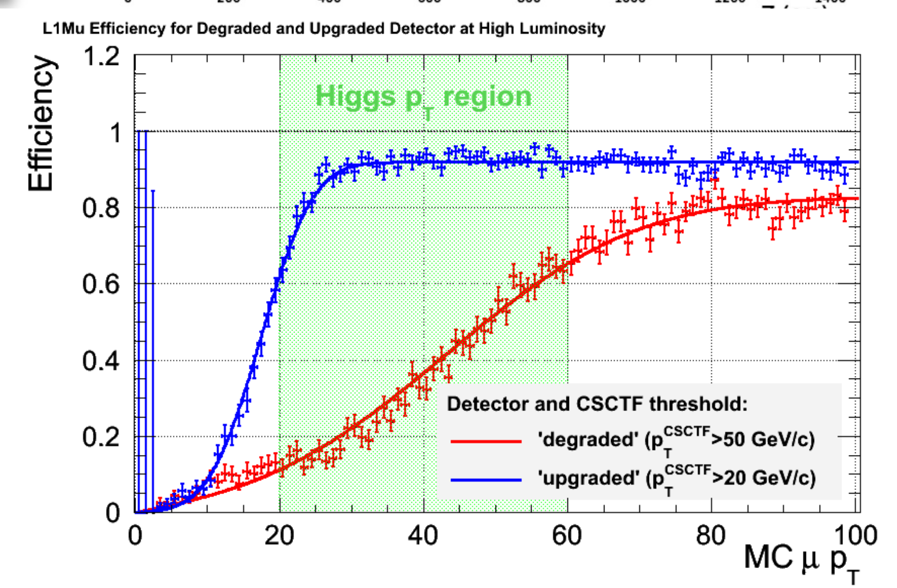
- Detector: LS1 has achieved its main goals
  - Main deadline in the near future:
    - Pixel insertion
- Trigger: on track
  - ORM-OSLB is now part of the system
  - Major milestones ahead
- Commissioning and Run:
  - DAQ2 and new Timing & Control Distribution System are actively tested in regular global runs
- Software:
  - Large amount of development to cope with 25 ns, increased pileup
  - Release strategies being discussed
- Computing:
  - No change in resources
  - Lots of work in improving processes and performance
- CSA14:
  - Well engaged, valuable feedback in software and computing areas
- PHYS14:
  - In preparation

LS1 Muon Upgrades

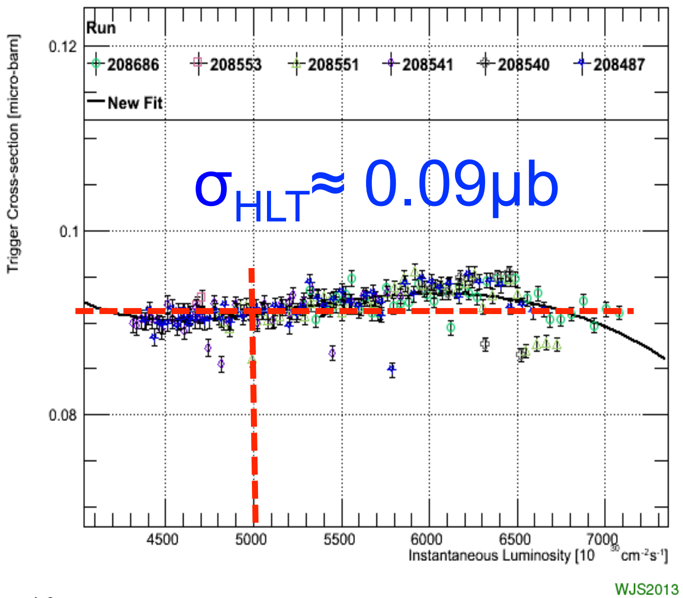
Trigger performance: significantly lower threshold for same rate
CSC and RPC: ME4/2 (1.25<|η|<1.8)
More hits, lower rates
CSC: ME1/1 (2.1<|η|<2.4) new digital boards and trigger cards : higher strip granularity
Electronics reliability
DT: new trigger readout board and relocation of sector collector from UXC55 to USC55 (new optical links)

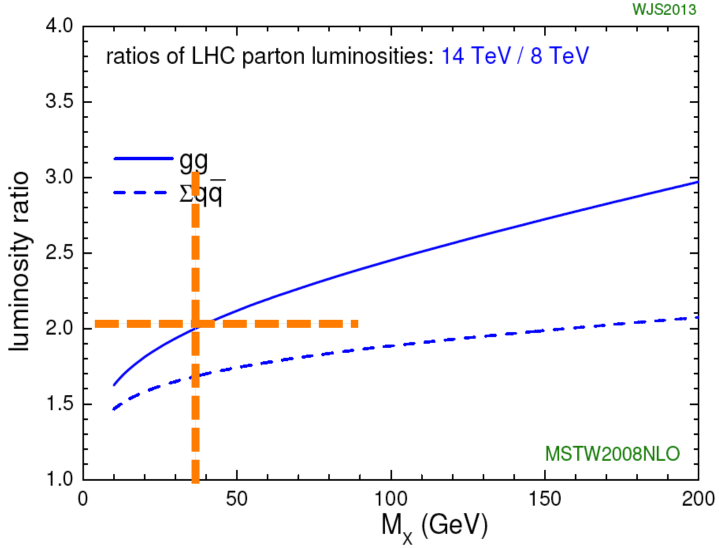






HLT: Challenges for 2015





- 2012: 8 TeV HLT σ ~0.09 µb
  - PU=25, small dependence on PU
- 8 TeV→ 14TeV ⇒ rates double
  - Average output rate of ~ 1.2kHz at $10^{34}cm^{-2}s^{-1}$ if menu untouched.
- To keep the present acceptance:
  - Improve HLT object reconstruction
    - Allowing tighter cuts
  - Reconsider strategies
    - More cross triggers
  - Will need more CPU
    - e.g. to extend PF usage
    - Particularly if PU <> grows above 25