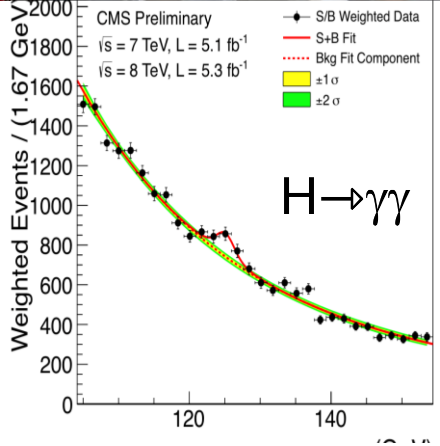
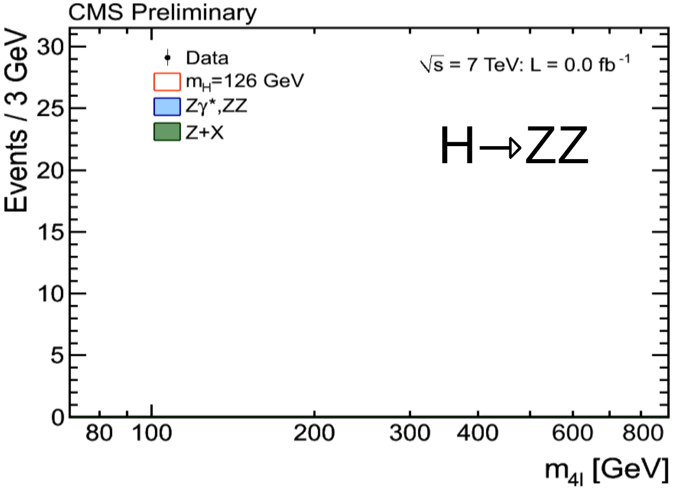
CMS:
Readiness for new energy frontier:
first 13 TeV data
Planning the long term future

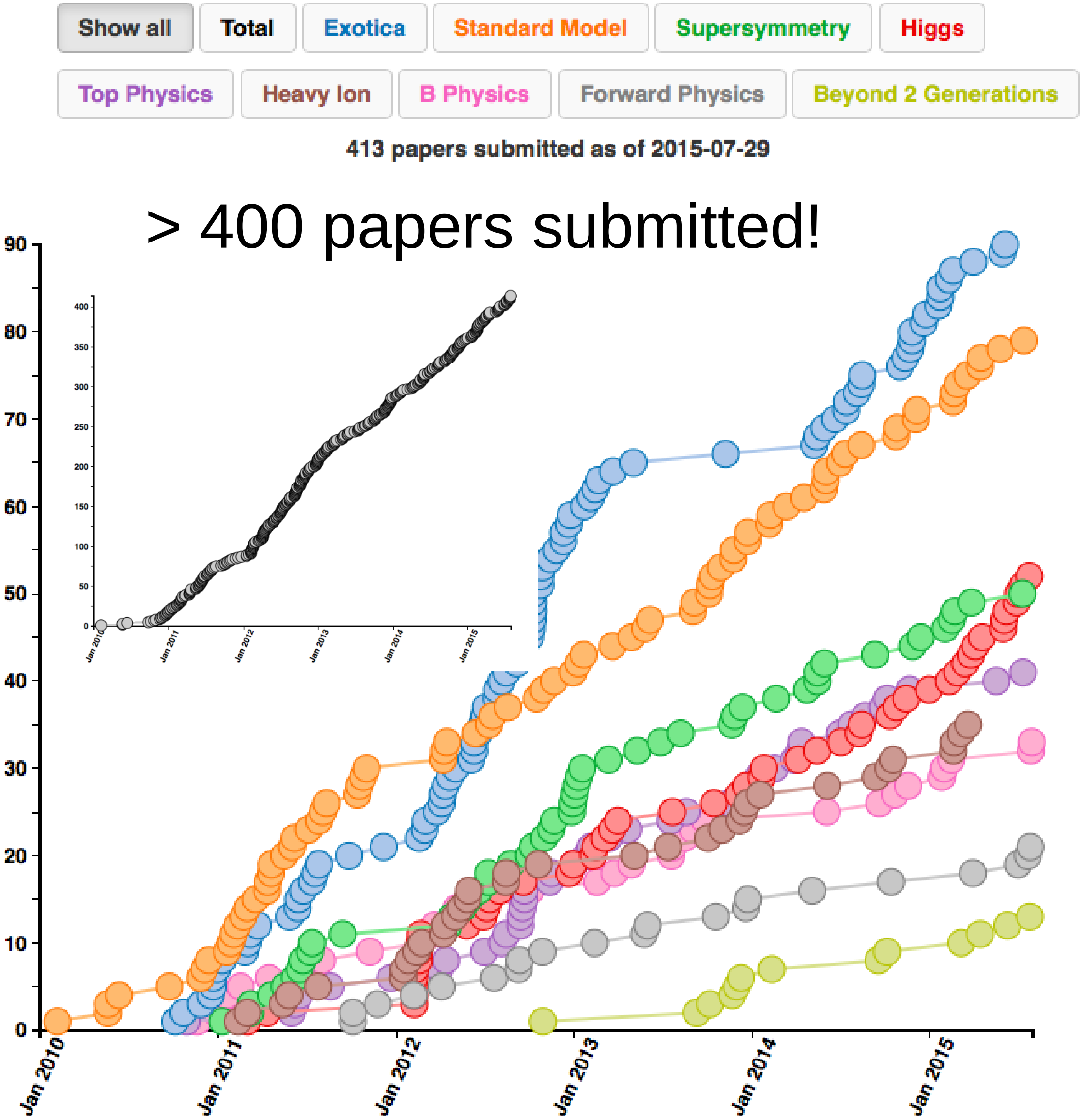
Outline

- Following the new boson discovery the success of Standard Model of Nature is paradoxically highlighting its limitations.
- There are fundamental questions which are not yet answered by the Standard Model.
- With the LHC restarting at 13 TeV and opening a new energy domain we expect to be able to address some of these fundamental questions.
- We have prepared this exciting run and we are preparing for the long term future





A rich legacy from Run1



> 400 papers submitted!

Pub rate steady, ~2.5/week

413 papers submitted:

+23 Cosmic ray based

+35 ready for CWR or later

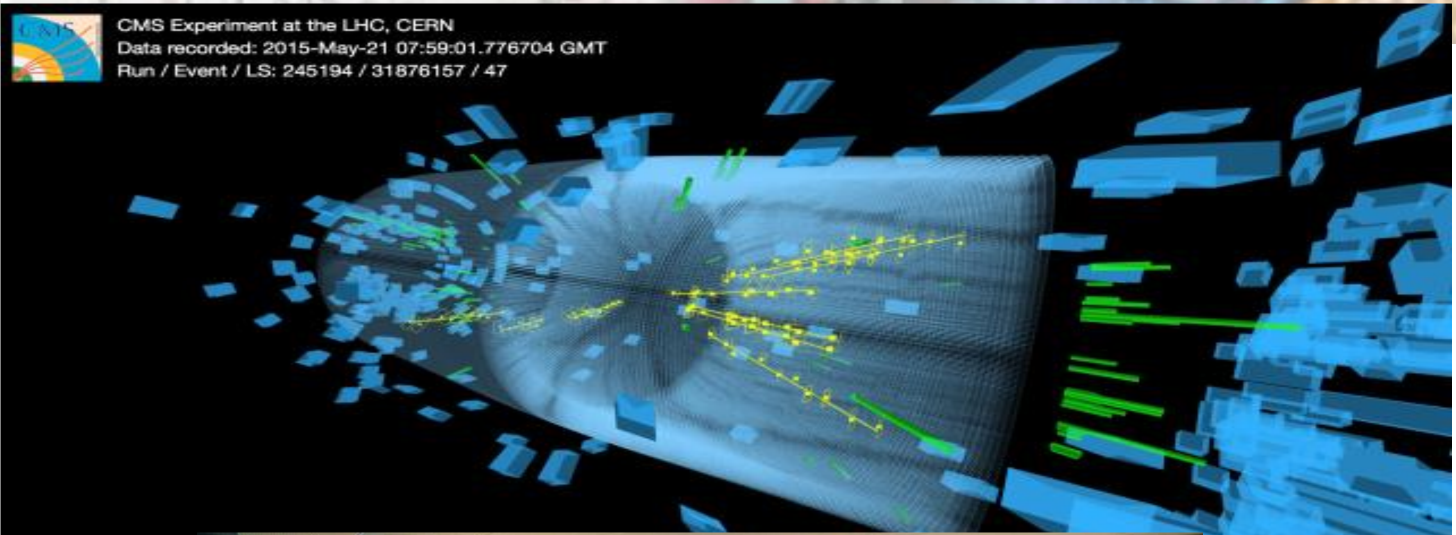
+17 PubDraft

In review process (115):

84 GoingToPreApp or higher

44 in PAG review

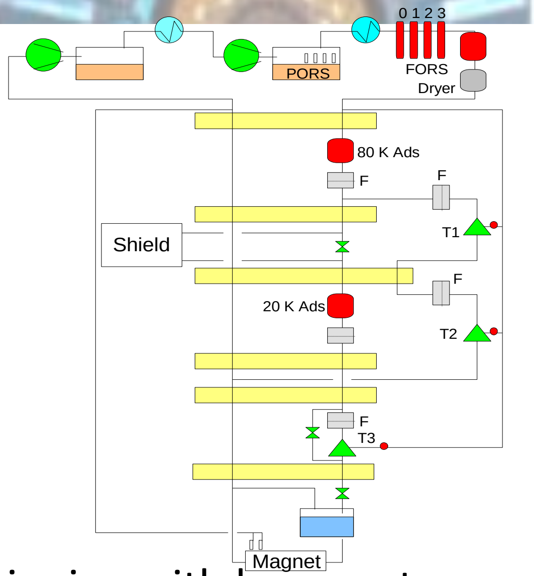
First collisions @ 13 TeV



Readiness for LHC Run2

- CMS has undergone major changes during the Long Shutdown, amongst other:
  - Added two new endcap planes of muon chambers
  - DAQ: changed the event building fabric and the Timing and control system
  - Replaced the readout devices of the Outer Hadron and the Forward Hadron calorimeter
  - Validated the readout at -20 degrees for the tracker and pixel
  - Implemented the first stage of the Upgraded level 1 calo trigger
- The setup has been re-commissioned using cosmic ray in progressive steps since July 2014: running 24/7 since early February
- The goal for the 2015 campaign is to collect ≤ 10 fb^{-1} of luminosity of proton collisions (a period of Heavy ion collisions is foreseen for the last month)

Magnet Cryogenics

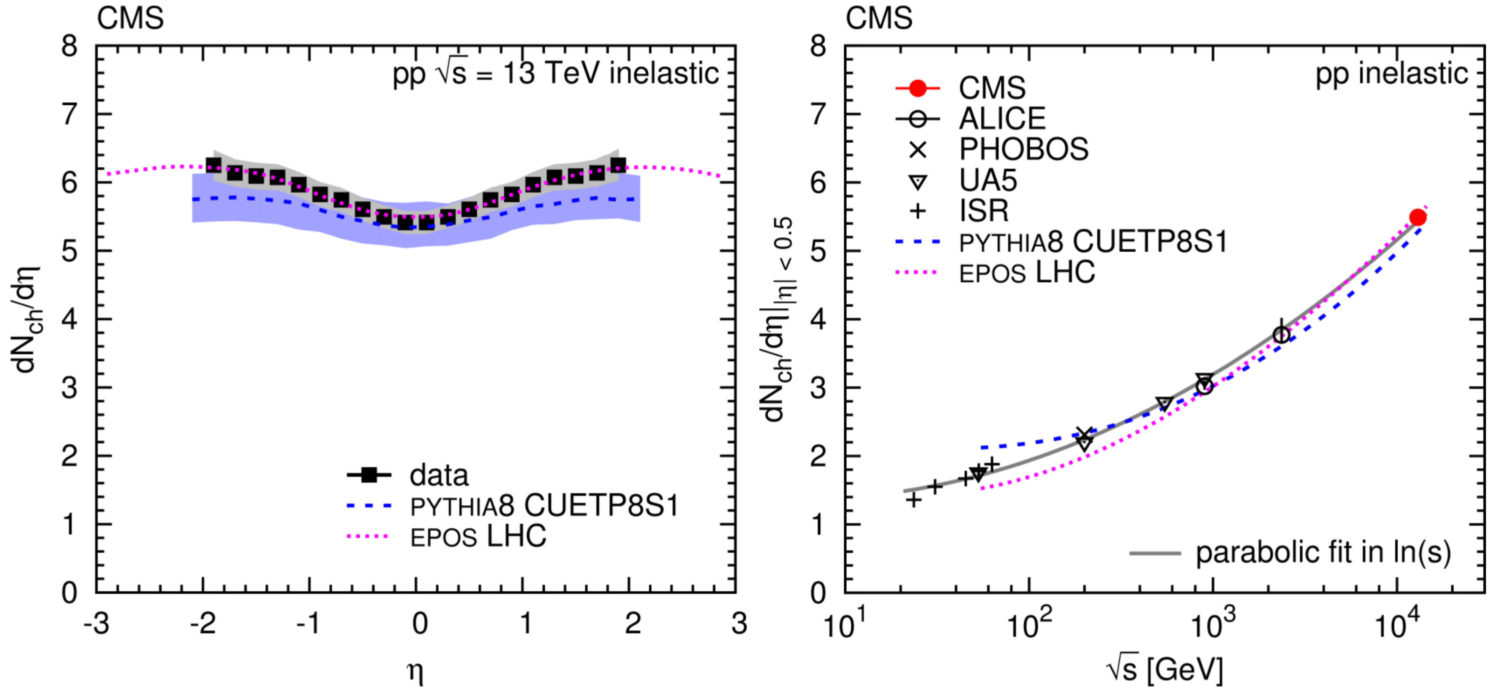


- The restart of the CMS magnet after LS1 was more complicated than anticipated due to problems with the cryogenic system in providing liquid Helium.
- Inefficiencies of the oil separation system of the compressors for the warm Helium required several interventions and delayed the start of routine operation of the cryogenic system.
- The data delivered during the first two weeks of LHC re-commissioning with beams at low luminosity have been collected with B=0
- Currently the magnet can be operated, but the continuous up-time is still limited by the performance of the cryogenic system requiring more frequent maintenance than usual.
- A comprehensive program to re-establish its nominal performance is underway. These recovery activities for the cryogenic system will be synchronized with the accelerator schedule in order to run for adequately long periods.
- A consolidation and repair program is being organized for the next short technical stops and the long TS at the end of the year.

…and we are ready

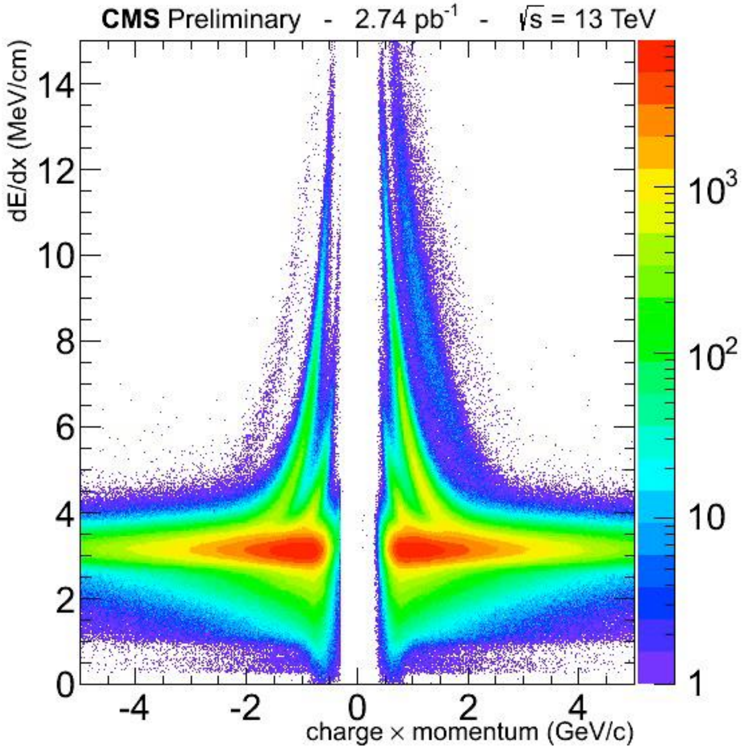
$$\frac{\mathrm{d}n_{\mathrm{ch}}}{\mathrm{d}\eta}\Big|_{|\eta|<0.5} = 5.49\pm0.01\ (\mathrm{stat})\pm0.17\ (\mathrm{syst})$$

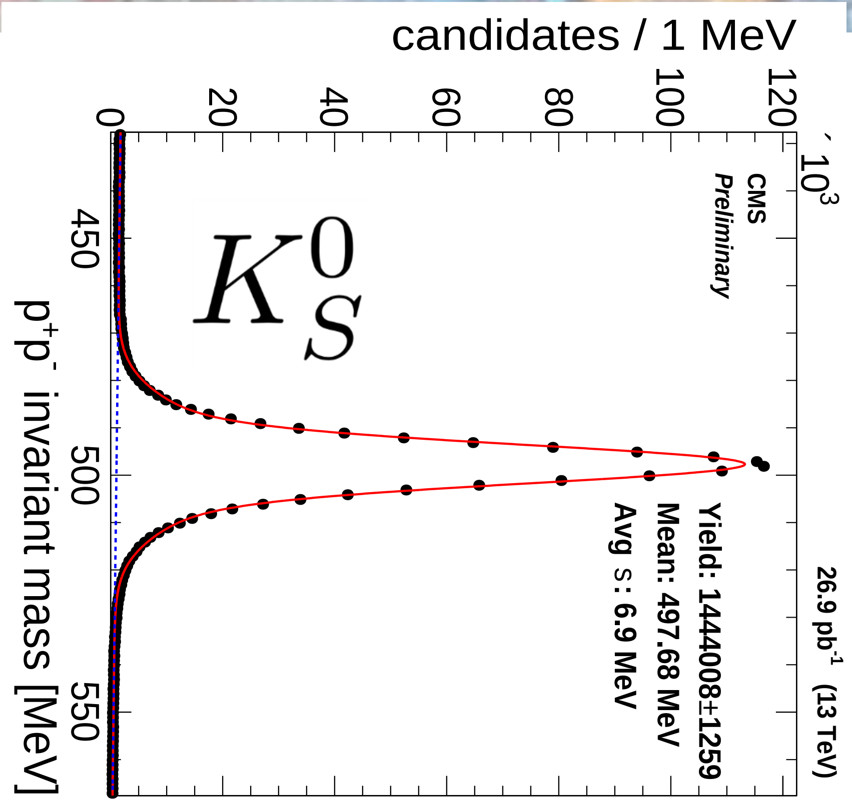
B=0



- **First measurement of inelastic $dN_{ch}/d\eta$ at 13 TeV pp collisions.**
- **First paper submitted by LHC experiment on the 13 TeV data**

Tracker Performance





From right to the left Deuteron, Proton and Kaon bands clearly visible. Particles shown depending on their charge → observe an expected asymmetry in the production of particles/antiparticles for pp collisions.

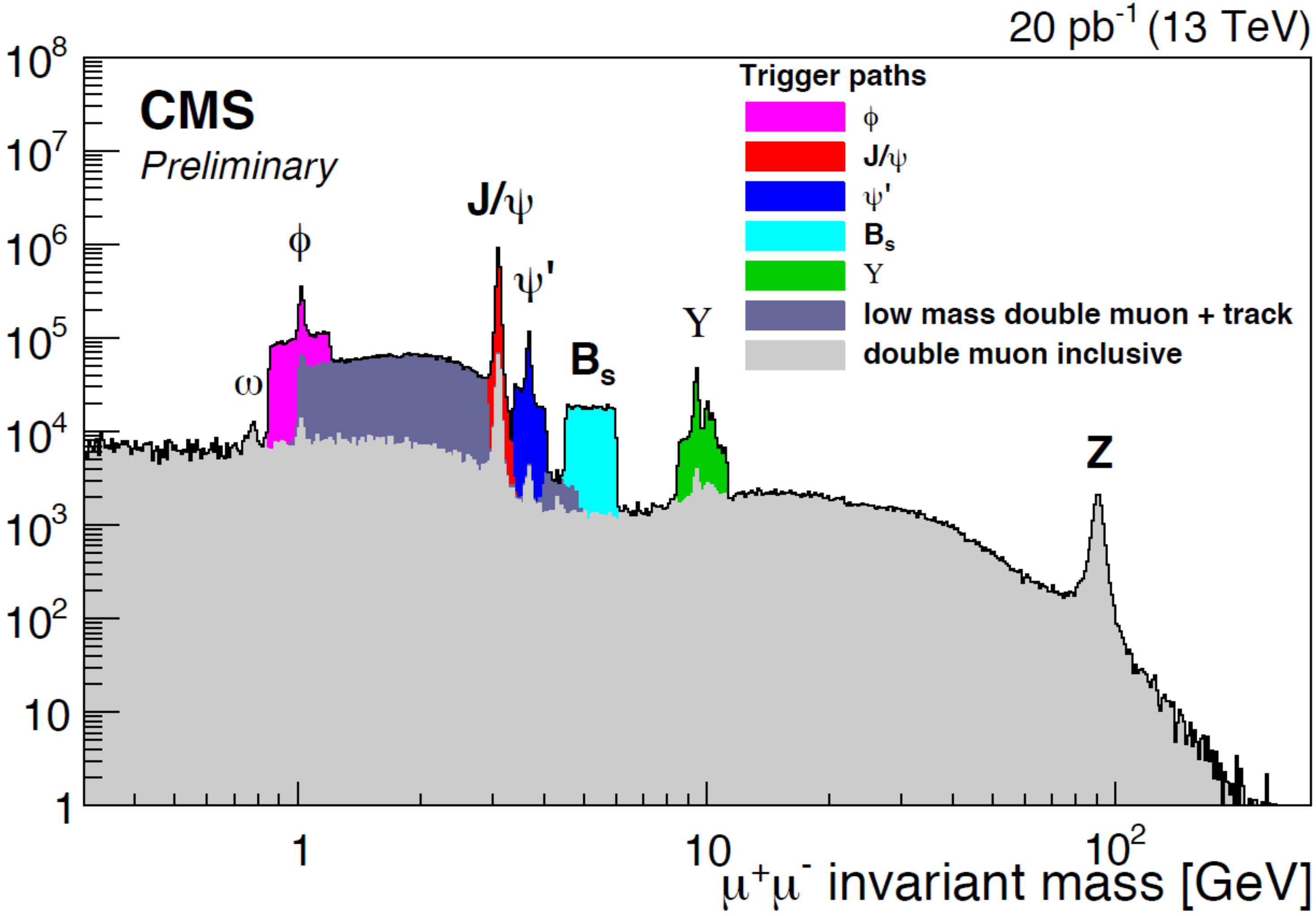
PDG: 497.614 ± 0.006 MeV

Invariant mass of the pion pairs fitted with a double gaussian and a first order polynomial for the background.

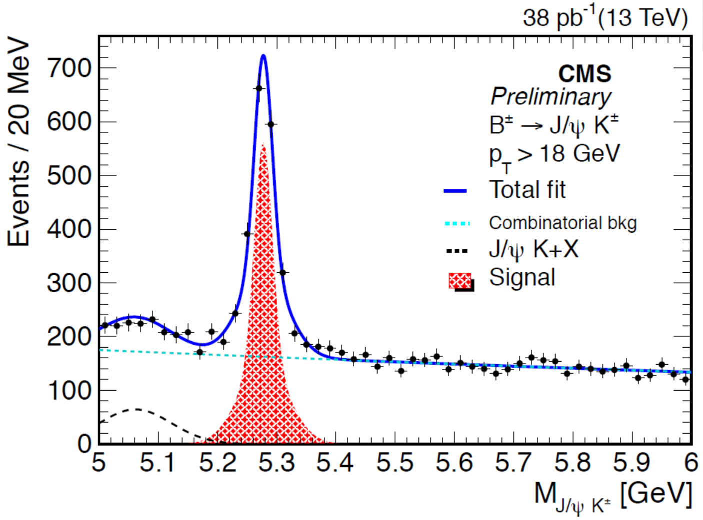
Trigger

Special Triggers

Selective mass regions and p_T cuts



Resonances

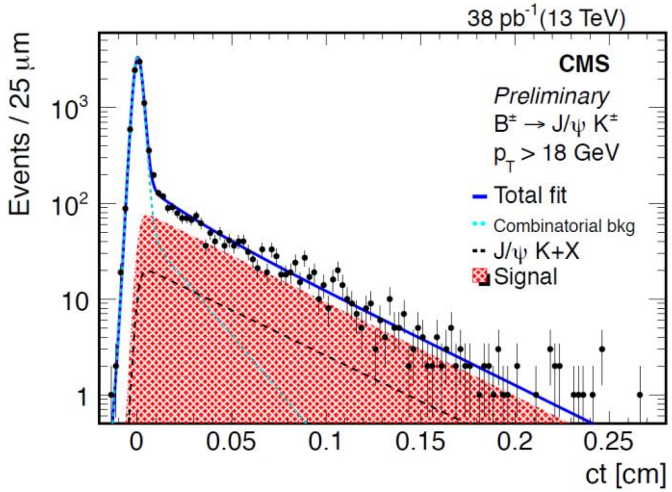


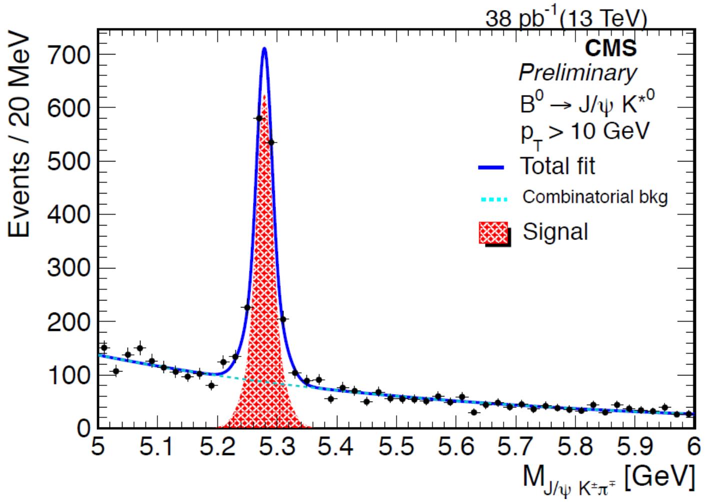
$B^{\pm} \rightarrow J/\psi\ K^{\pm}$

Inclusive J/ψ trigger with p_T >16 GeV

Mass: 5.277 ± 0.001(stat.) GeV

PDG: 5279.26 ± 0.17 MeV





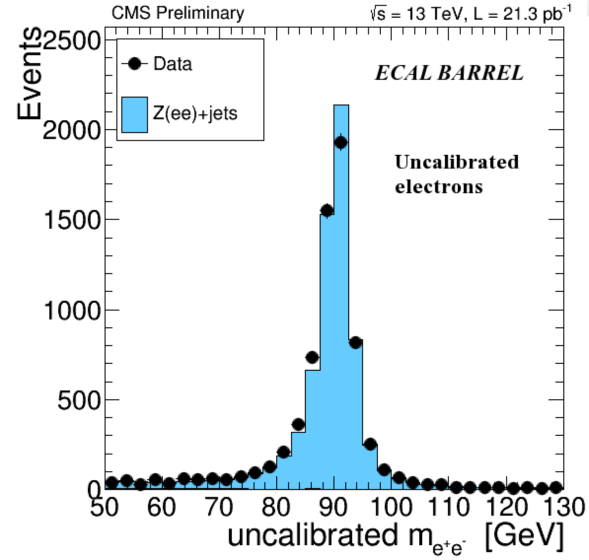
$B^0_s \rightarrow J/\psi\ \phi$

with displaced J/ψ and track trigger

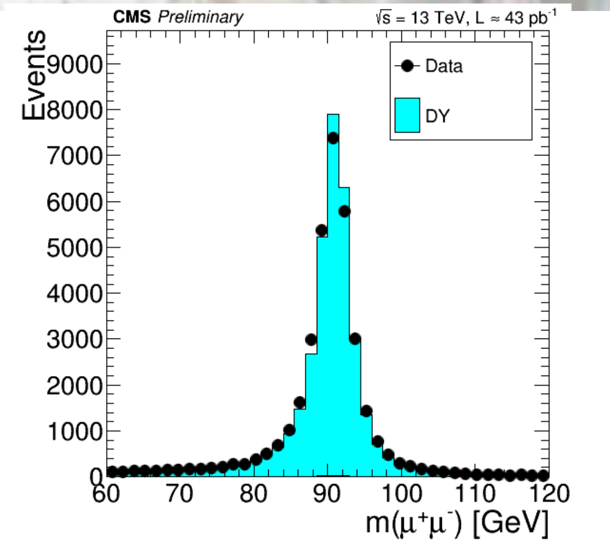
Mass: 5.369 ± 0.001(stat.) GeV

PDG: 5366.7 ± 0.4 MeV

Detector and Algorithm Performance

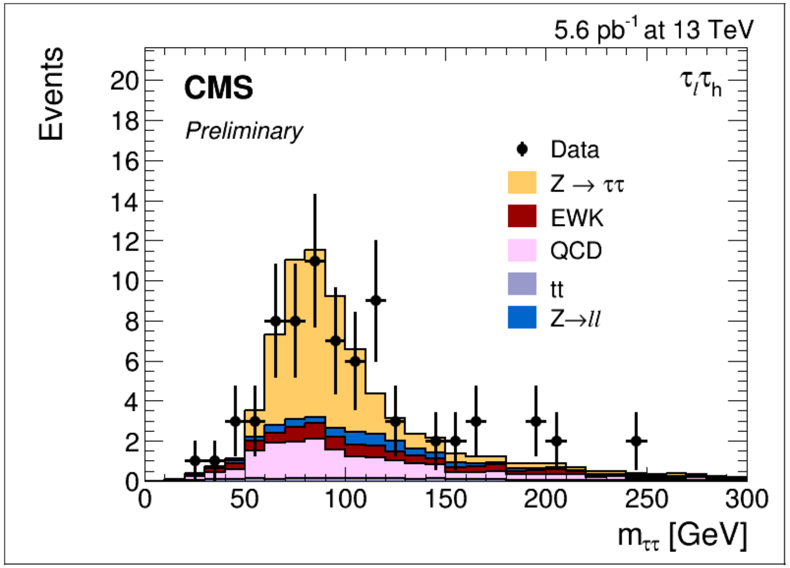


Z → ee



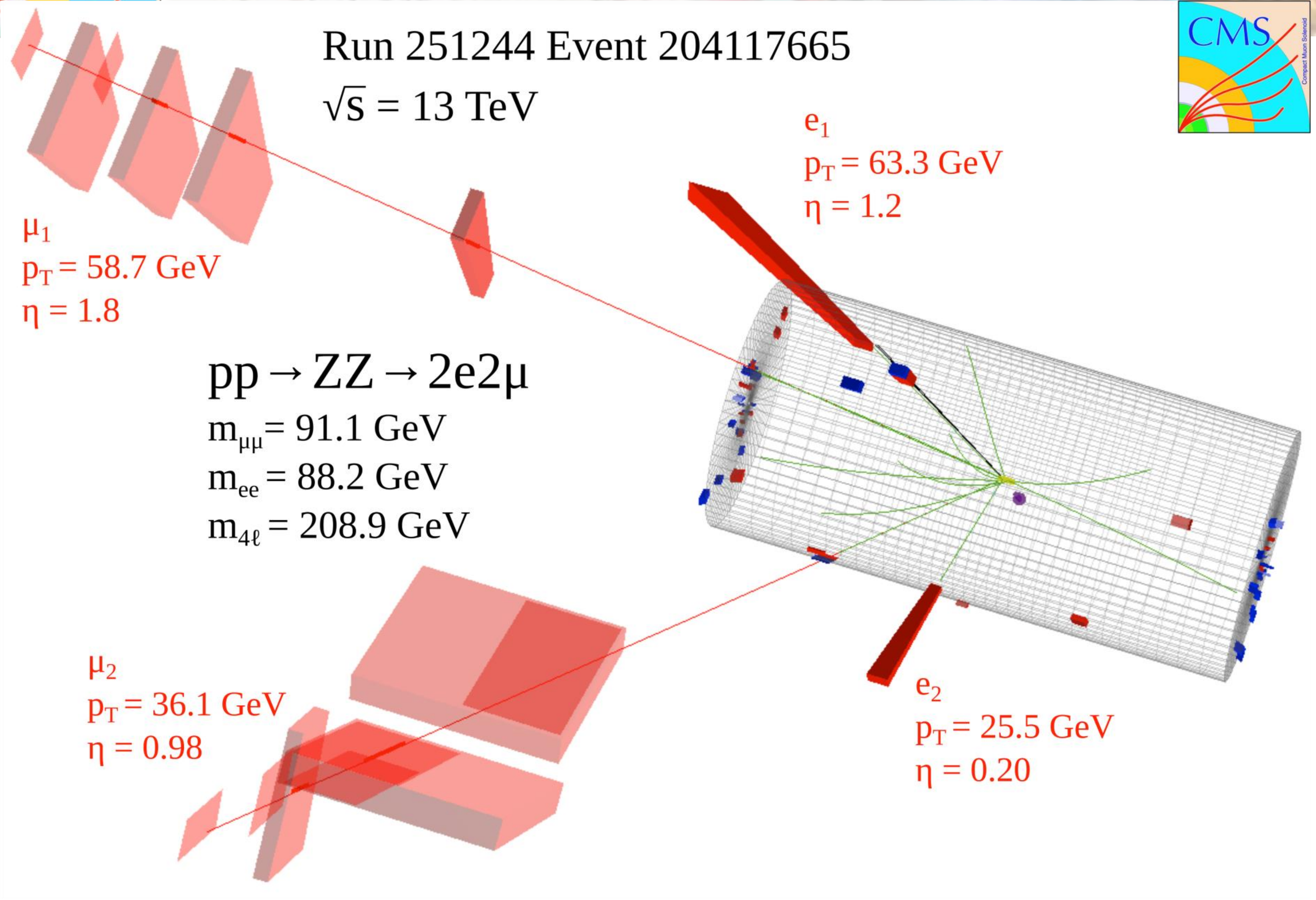
Z → μμ

Z → ττ



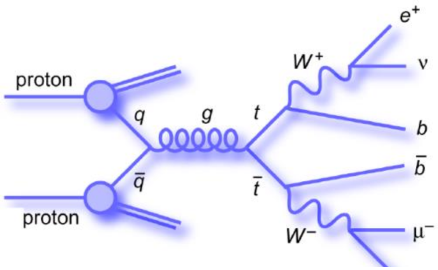
Z – Boson as standard physics candle

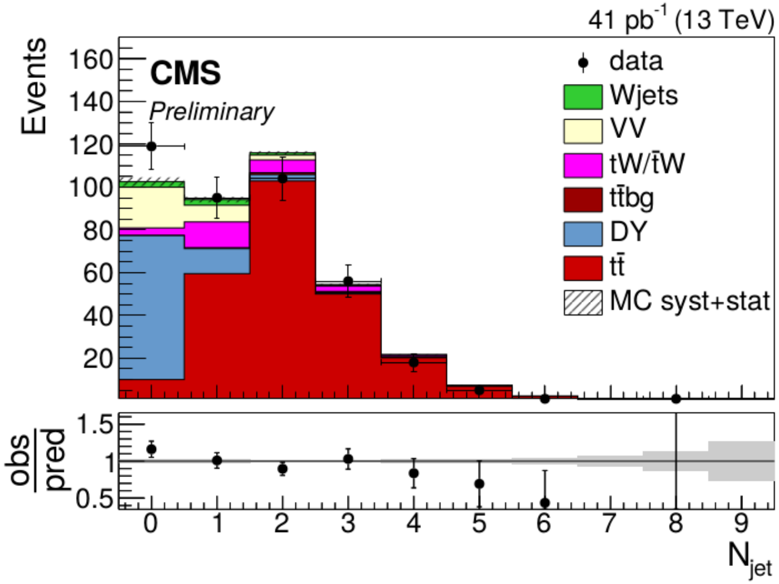
Spectacular ZZ in 4l decay



Top Re-Discovery

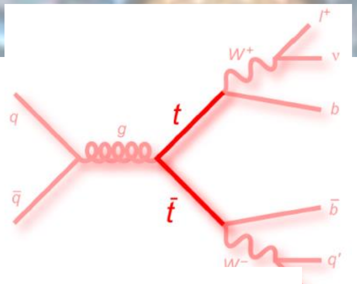
Top pair to di-leptons

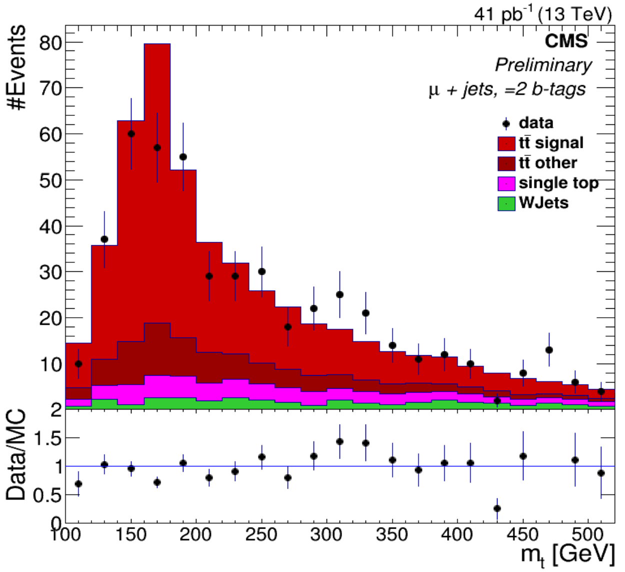




Number of hadronic jets for events containing one isolated muon and one isolated electron forming an invariant mass greater than 50 GeV.

Top pair to lepton+jets



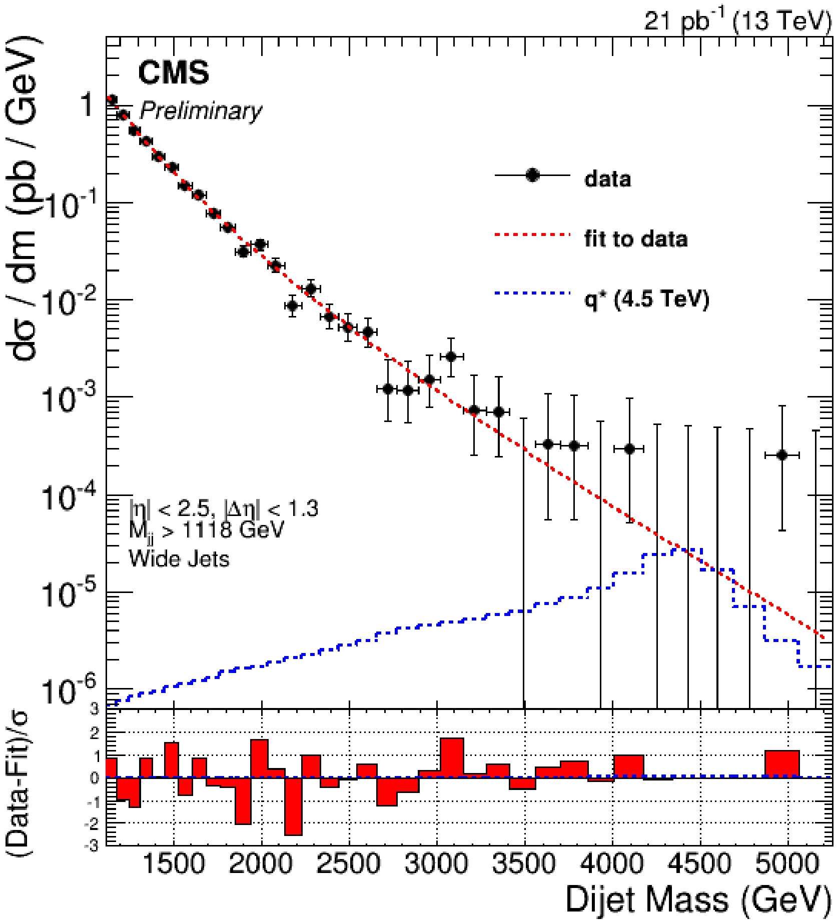


Reconstructed hadronic top quark candidate mass for events containing 1 isolated muon (p_T>30 GeV, $|\eta|$<2.4, passing medium identification), four jets (p_T>30 GeV, $|\eta|$<2.5), out of which 2 pass the tight b-tagging threshold.

Resonance Search with Di-Jets

- Data: black points
- Fit to the data:
  red dashed line
- Blue dashed line: superimposed signal shape of a q* → qg resonance with M=4.5 TeV
- Performed a maximum likelihood fit
- Rough estimate of the goodness of fit the χ^2 is calculated to

  $$\chi^2 / \text{ndof} = 31.84 / 31$$
- Good fit to the data using a background parameterization

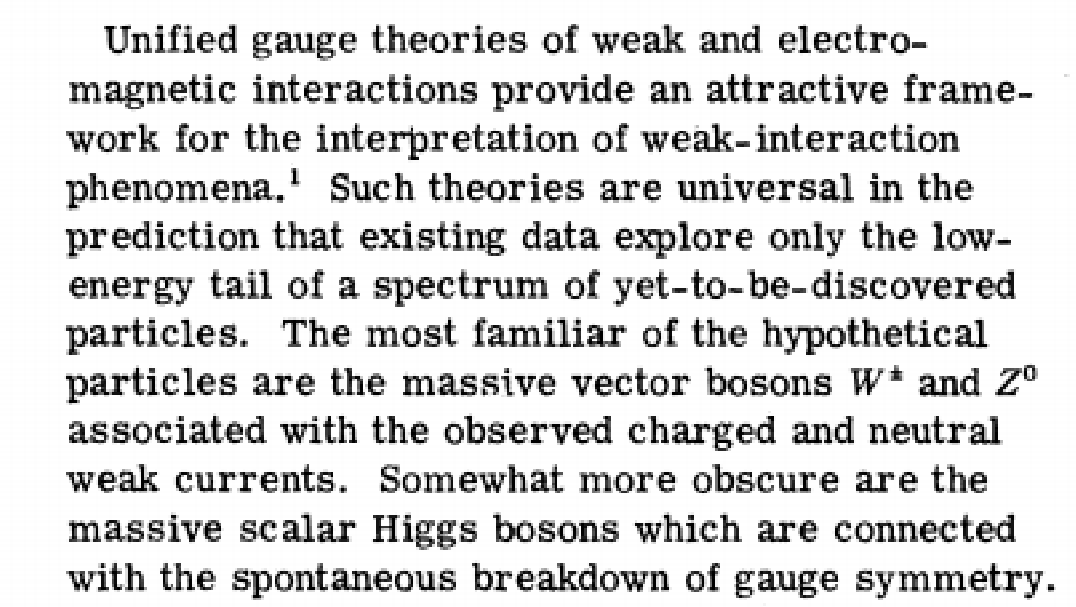


→ no evidence for a di-jet resonance.

The Physics objectives:

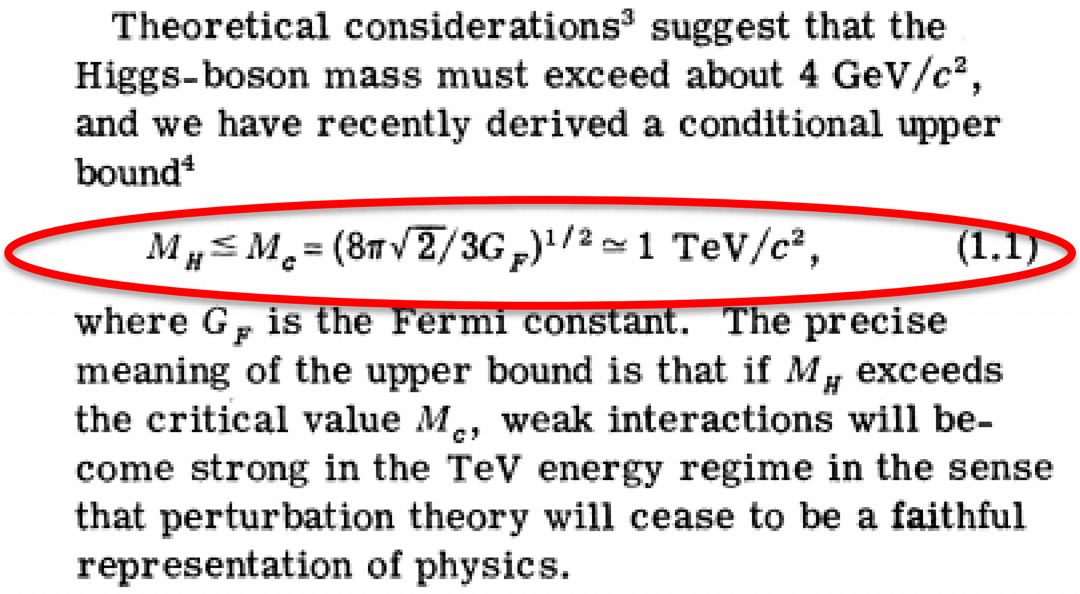
The next years are for frontier exploration

The past (pre July 4th,2012)



Unified gauge theories of weak and electromagnetic interactions provide an attractive framework for the interpretation of weak-interaction phenomena.[1] Such theories are universal in the prediction that existing data explore only the low-energy tail of a spectrum of yet-to-be-discovered particles. The most familiar of the hypothetical particles are the massive vector bosons $W^\pm$ and Z^0 associated with the observed charged and neutral weak currents. Somewhat more obscure are the massive scalar Higgs bosons which are connected with the spontaneous breakdown of gauge symmetry.

Lee, Quigg, Thacker,
PRD, 1 September 1977



Theoretical considerations[3] suggest that the Higgs-boson mass must exceed about 4 GeV/c^2, and we have recently derived a conditional upper bound[4]

$$M_H \le M_c = (8\pi\sqrt{2}/3G_F)^{1/2} \simeq 1 \text{ TeV}/c^2, \qquad (1.1)$$

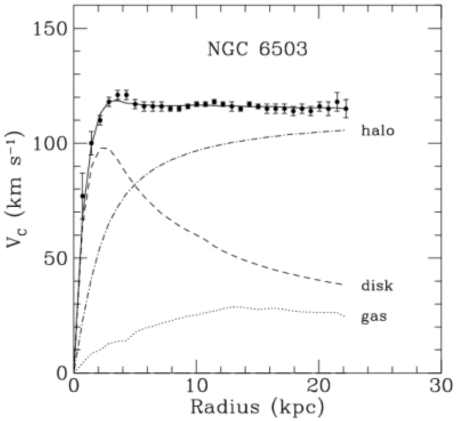
where G_F is the Fermi constant. The precise meaning of the upper bound is that if M_H exceeds the critical value M_c, weak interactions will become strong in the TeV energy regime in the sense that perturbation theory will cease to be a faithful representation of physics.

The beacon for the
last 40 years

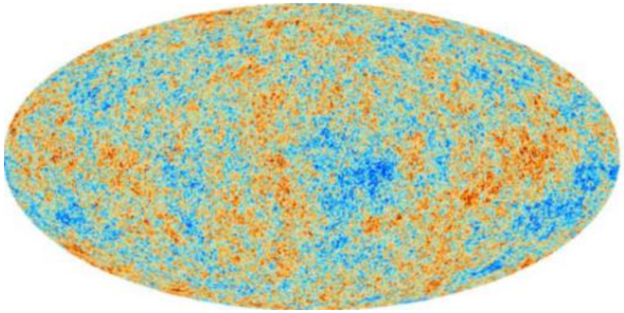
Today: answers missing

- Many evidences of physics beyond the Std Model

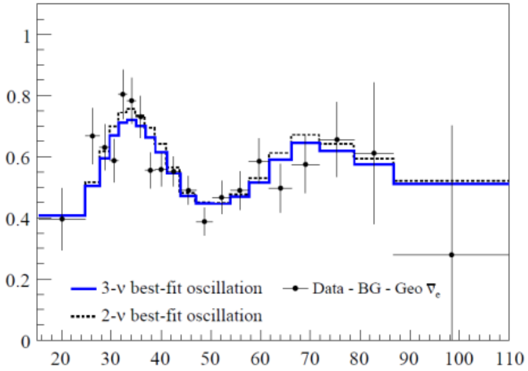
Dark Matter



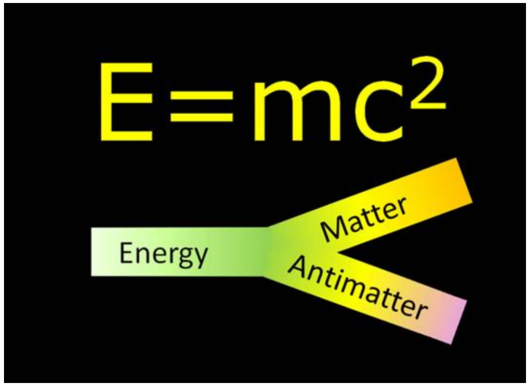
Inflation



Neutrino masses

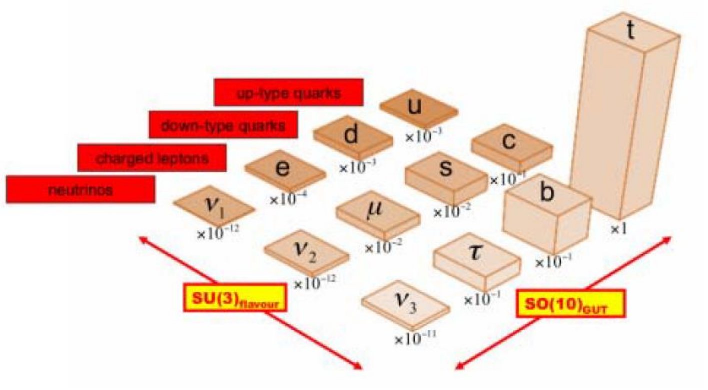


Matter-Antimatter asymmetry

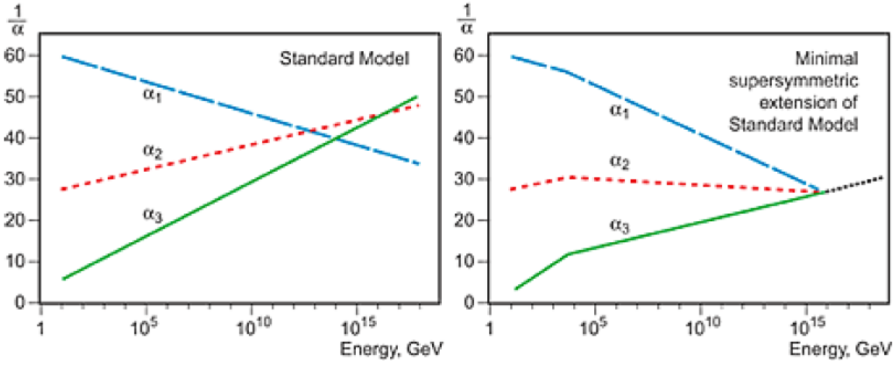


Today: SM cannot explain

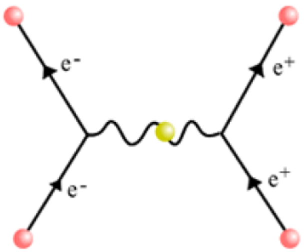
- Flavor families
  and mass Hierarchy

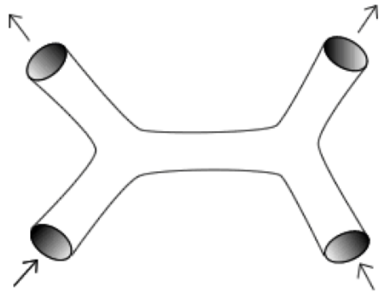


- Unification of forces



- Quantum gravity





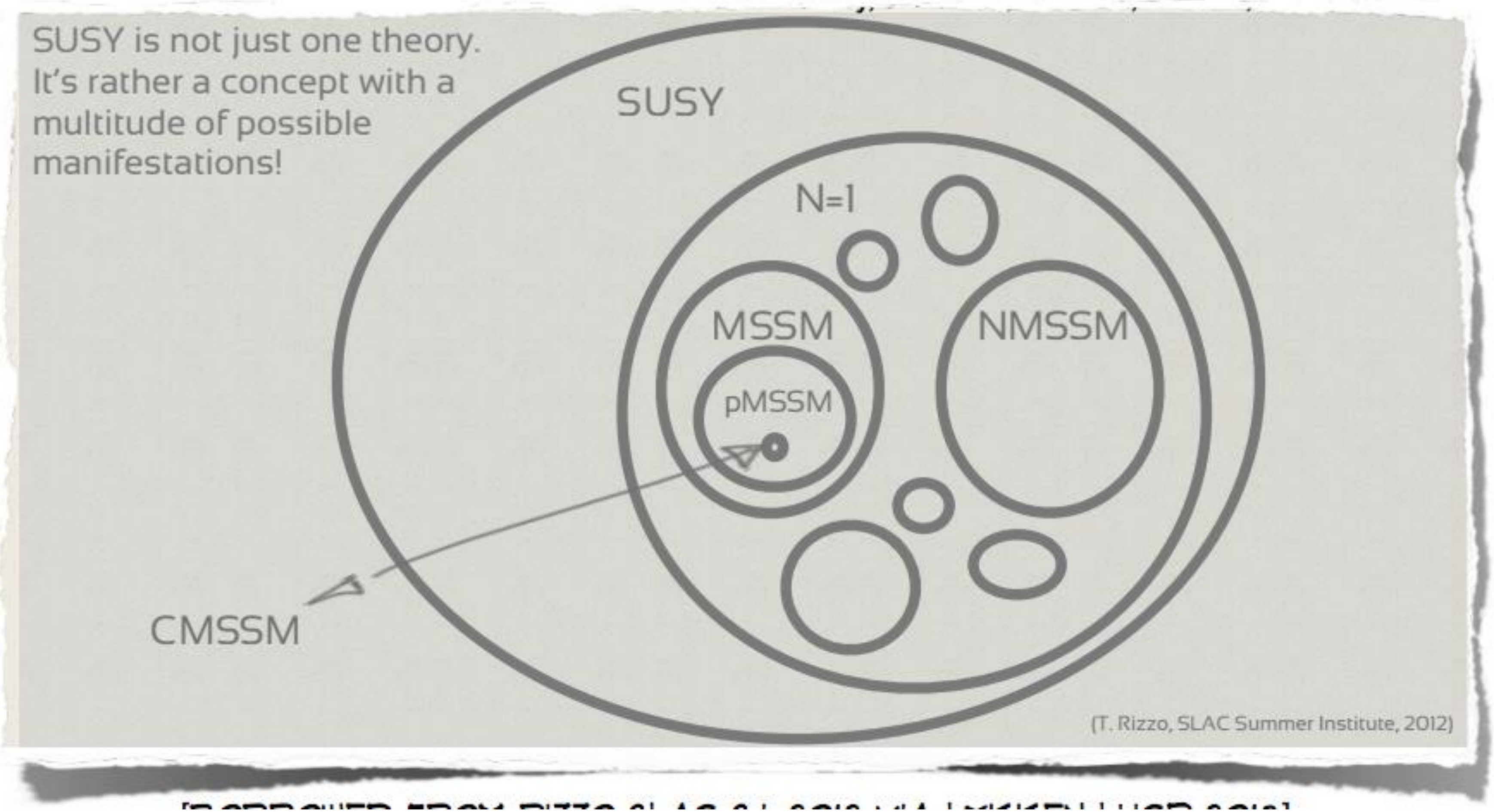
Today: we lack a beacon

- The heuristic principle of ‘Naturalness’ DOES NOT WORK: the fact that LHC has not yet found any BSM evidence is EVIDENCE of fine tuning at sub permill level….
- … so the ‘scale’ of new physics (Λ_{NP})is not at E-weak scale … but it is hard to think that the unanswered questions and the internal difficulties of the SM do not imply some new interactions/state of matter
- Lacking a ‘guiding light’ it is now up to the experiments to trace the route !

Beyond the Std Model theories

Is SUSY still worth seeking?

SUSY ‘space’ has been excluded only for the easiest part so far (CMSSM… still a lot to explore..but it might not be easy)



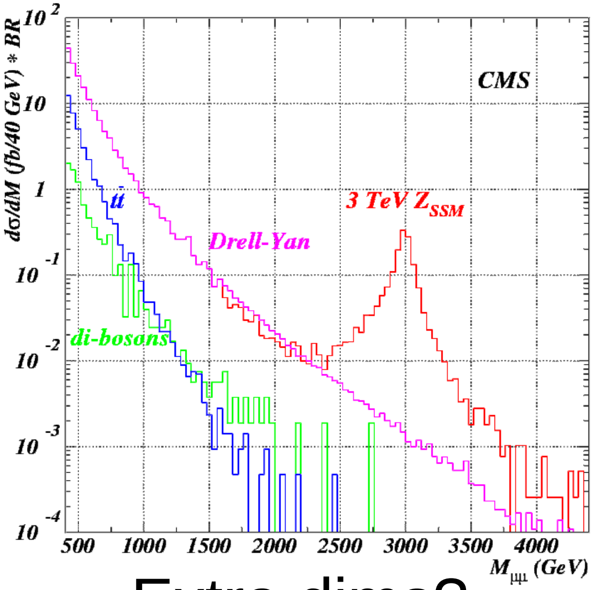
SUSY is not just one theory. It’s rather a concept with a multitude of possible manifestations!

(T. Rizzo, SLAC Summer Institute, 2012)

2015 and RUN2

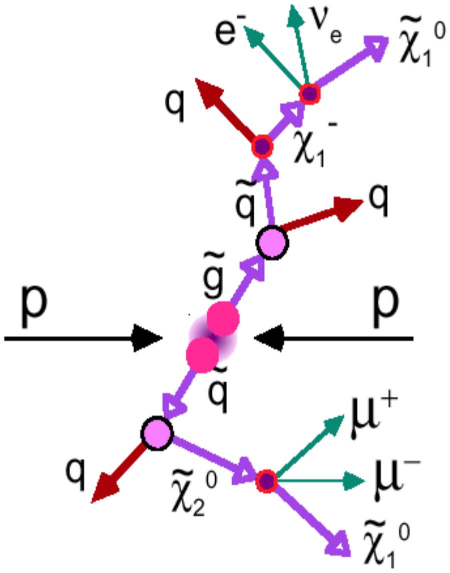
A lot at stake!

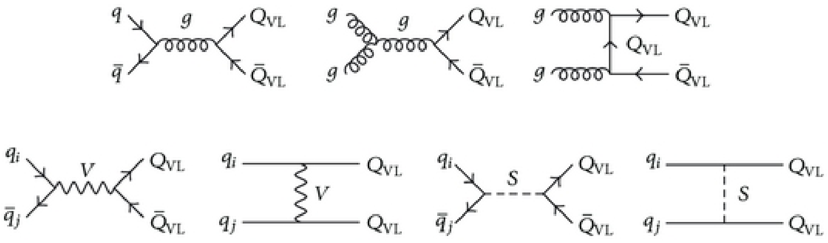
We know that there must be more than the new scalar boson…and that in order to make things simple the new physics should be around the corner: we have to make sure that we do not miss the corner!



Extra dims?

Susy?





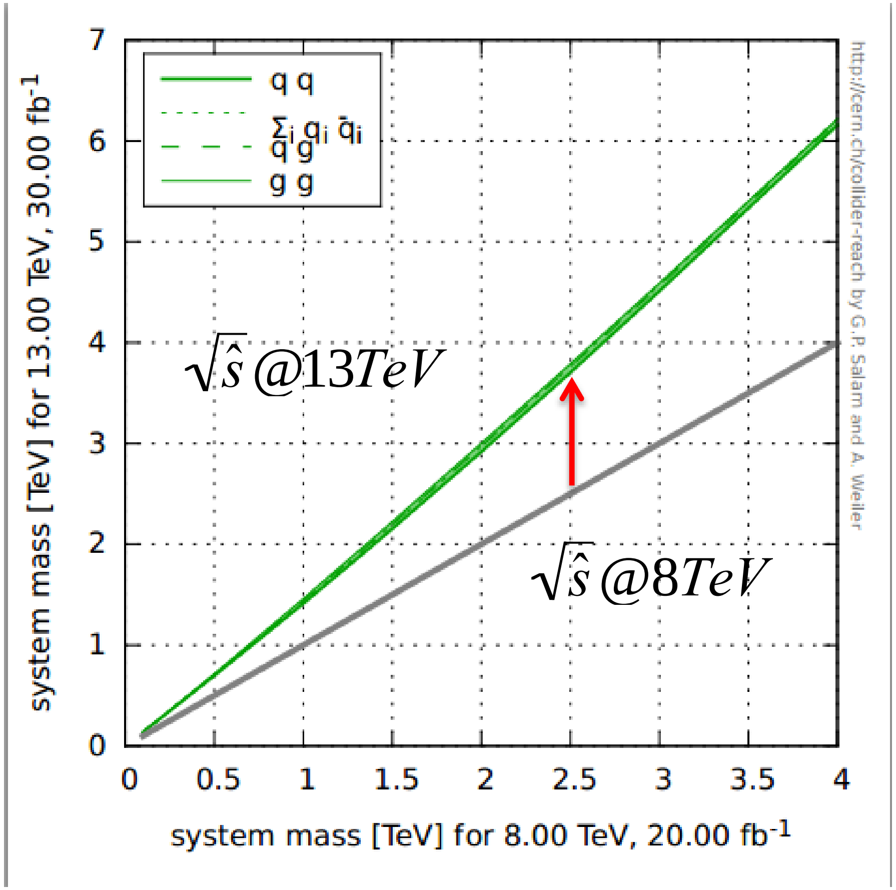
Something else?

Discoveries come early

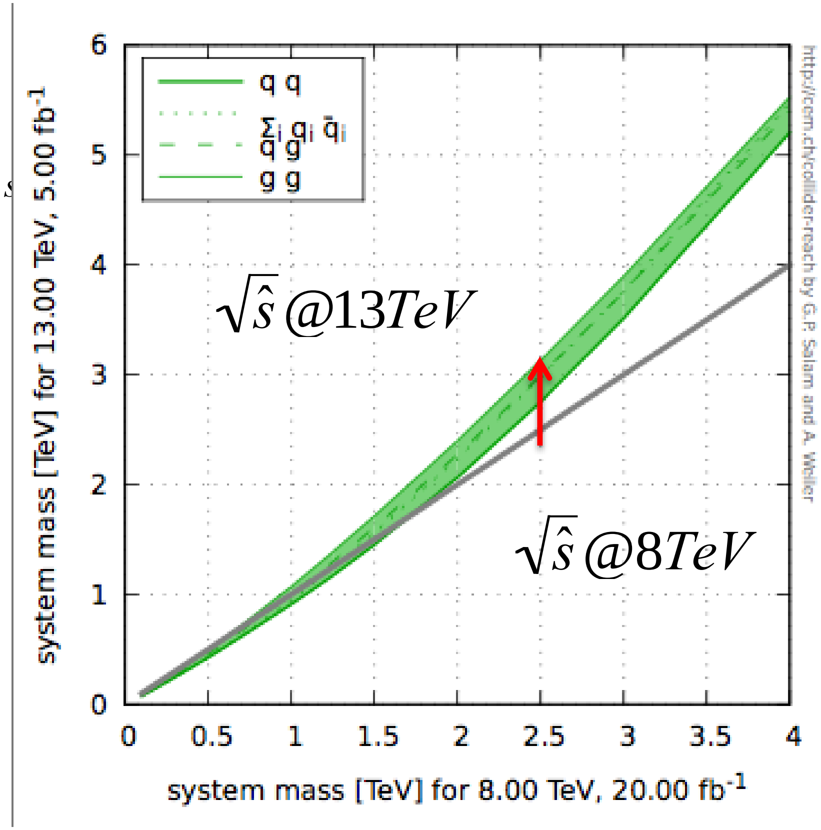
Courtesy of Gavin Salam

Discovery potential comparison 20fb^{-1} @8TeV vs X fb^{-1} @13 TeV

30 fb^{-1} @ 13 TeV



5 fb^{-1} @ 13 TeV



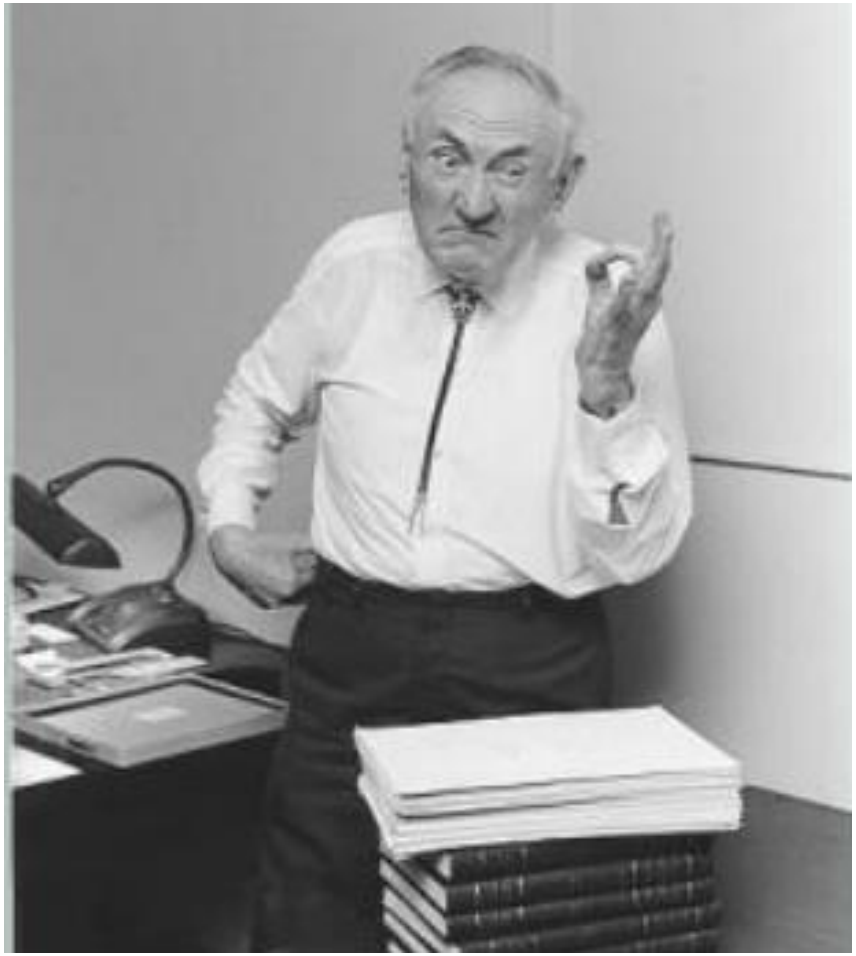
A primary Energy Frontier objective for the future: Dark matter

Fritz Zwicky : 1933

Galaxies in the Coma cluster were moving too rapidly.

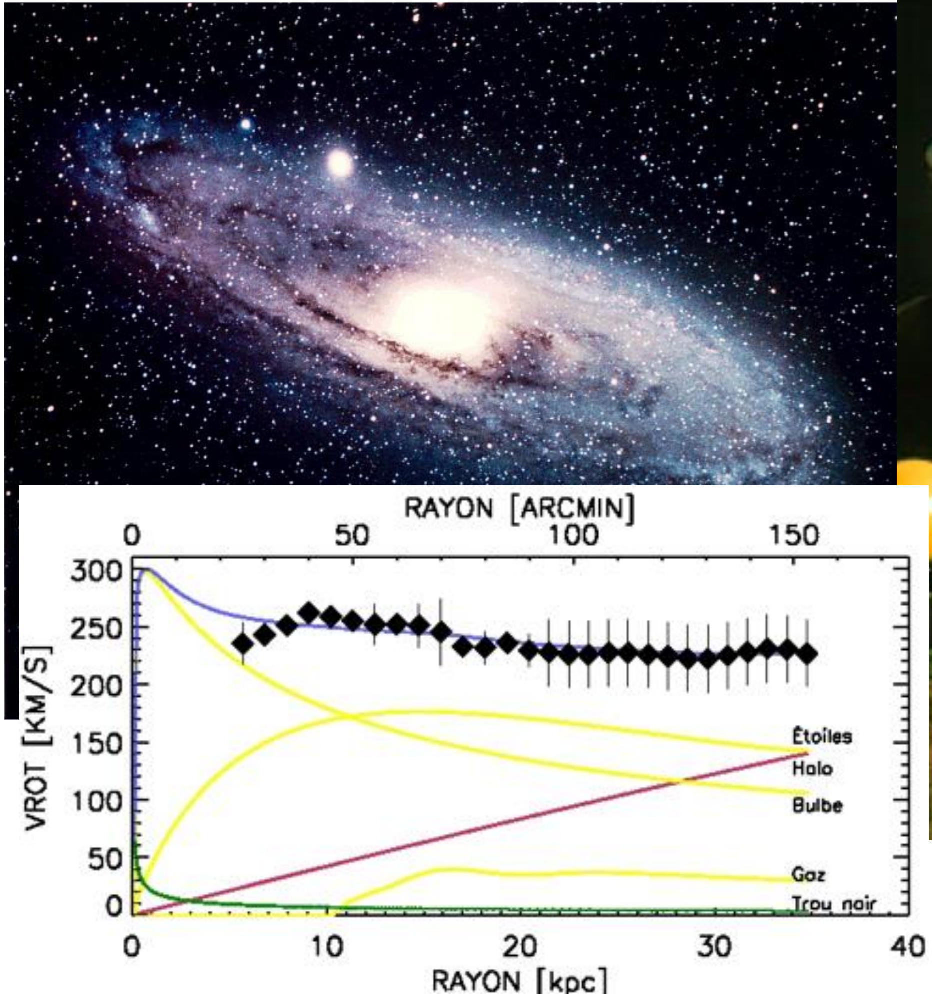
He proposed “Dunkle Materie” as the explanation.

The beginning of the Dark Matter mistery



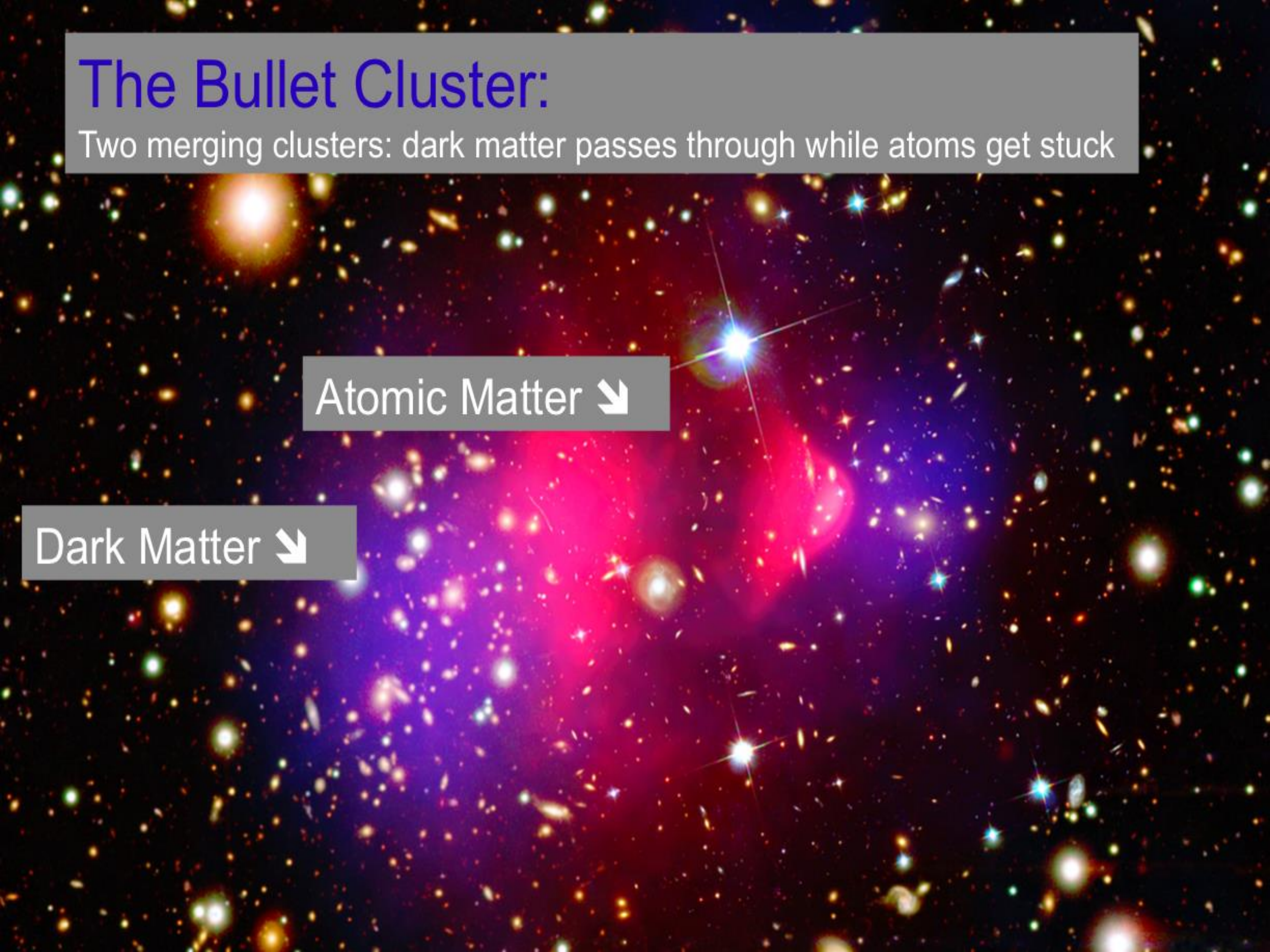
Vera Rubin (1970s)

Rotation Curves of Galaxies are Flat



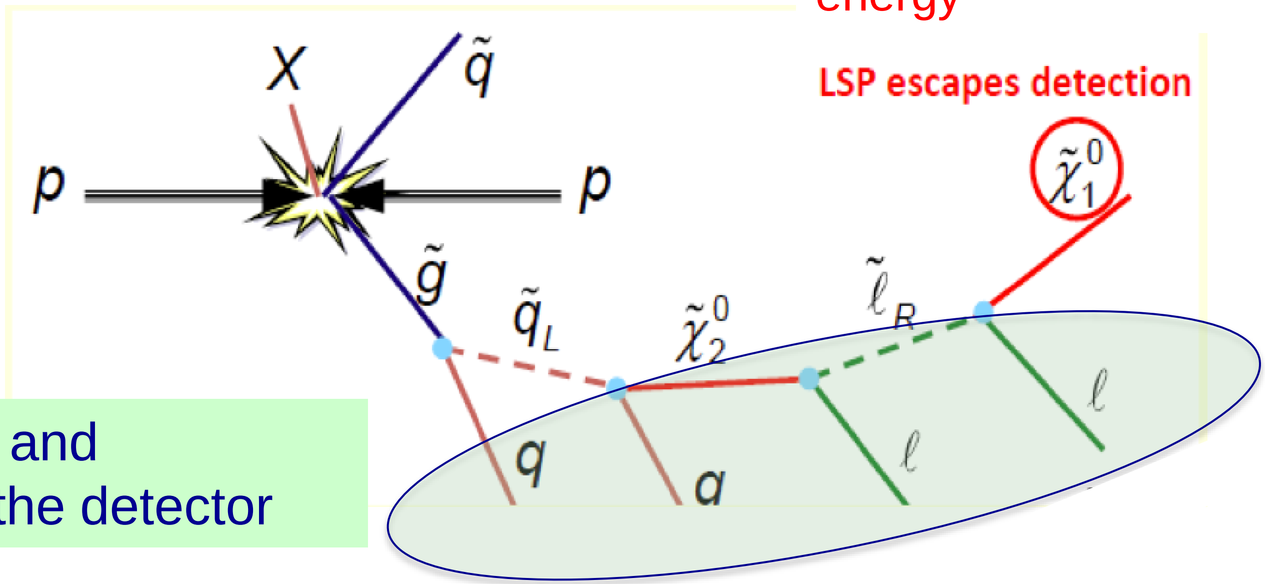
The Bullet Cluster:

Two merging clusters: dark matter passes through while atoms get stuck



How could we ‘detect’ Dark Matter particles

- Direct way is by detecting anomalous Missing energy from final states



Dark Particle which carries ‘away’ invisible energy

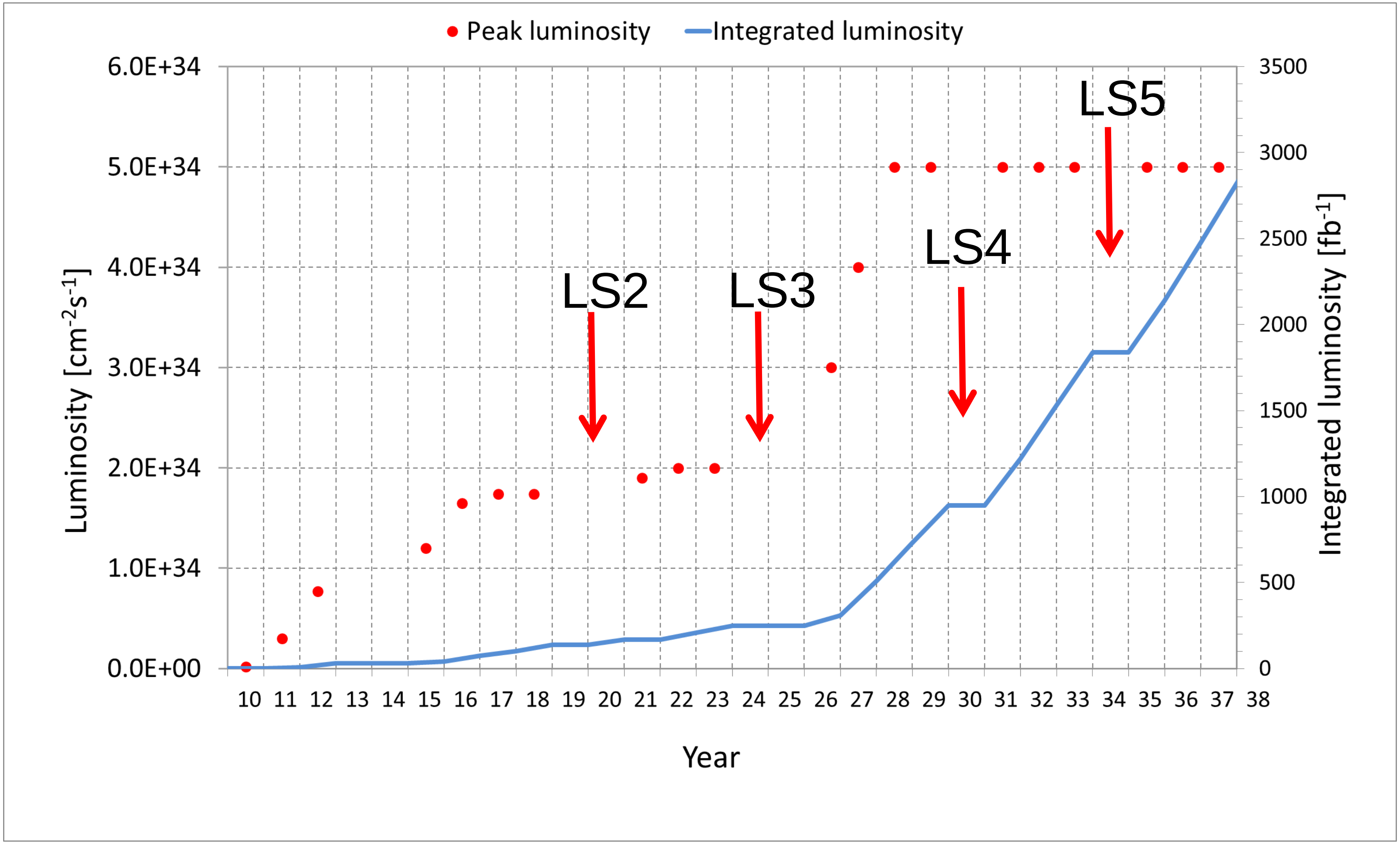
Particles visible and measurable in the detector

Will not be easy…
but we have built our detectors to be able to do it !

The long term future

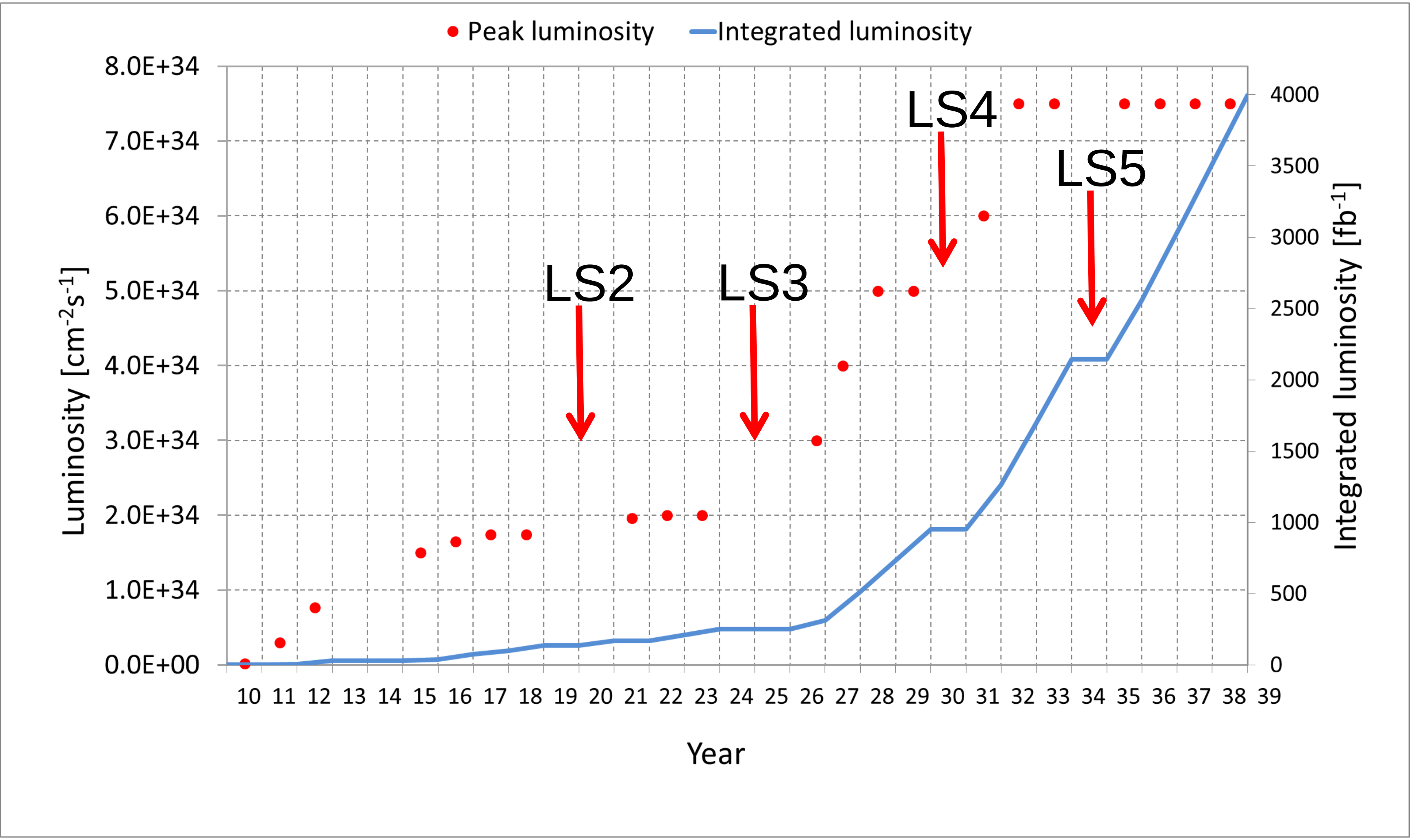
- The CERN council has approved the extension of the LHC program beyond the initial phase (meant to deliver 300 fb^{-1} of integrated luminosity)
- The High Luminosity LHC program is now a project : a three years shutdown (LS3) will mark the start of new era with an accelerator able to to reach 10^{35} Hz/cm^2 luminosities (levelled to 5 10^{34}, possibly 7 10^{34} Hz/cm^2) and aiming to deliver in excess of 3000 fb^{-1}
- This will require major upgrades to the LHC detectors where several components will have reached their end of lifetime limits and other will have to be upgraded to exploit the higher instantaneous luminosities and radiation levels
- *US P5 :Recommendation 10*:
  Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator
  and both general-purpose experiments (ATLAS and CMS).
  The LHC upgrades constitute our highest-priority near-term large project.
- **US and EUROPE are in synch regarding priorities !**

The future: $5x10^{34}$ levelling: a draft plan



LRossi@13 HL-LHC Coord Group

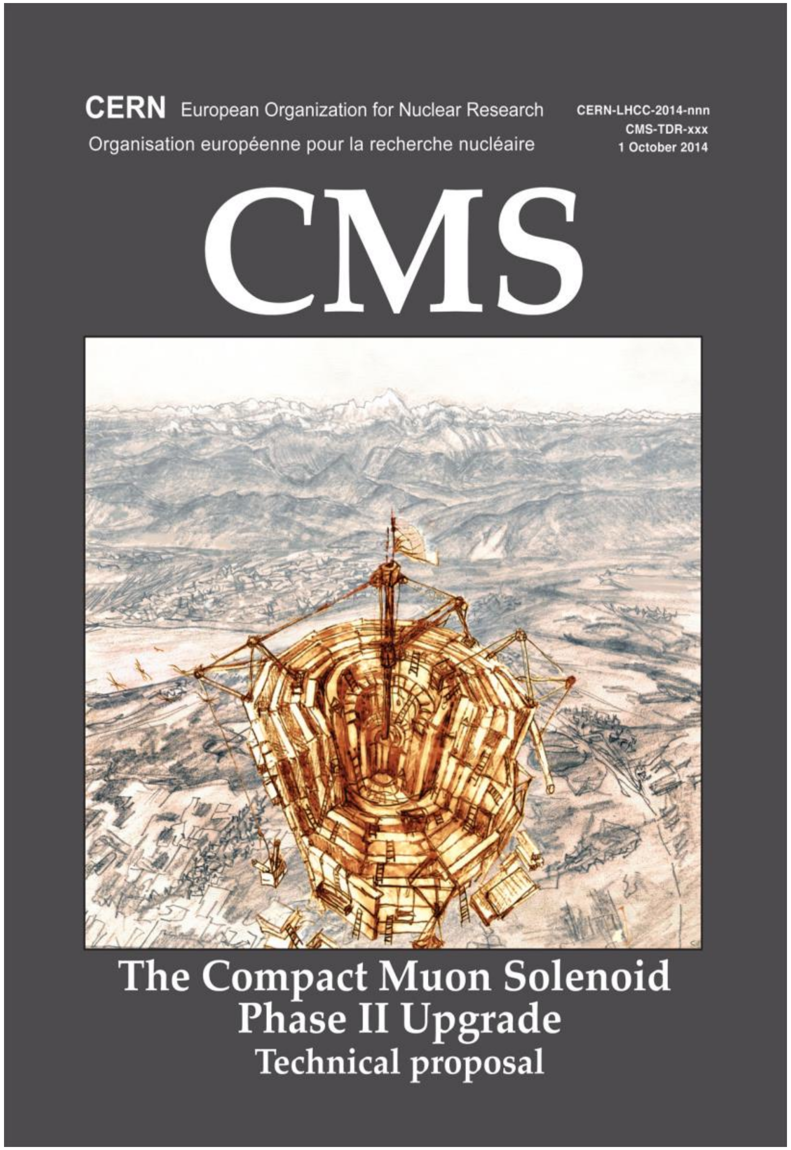
The future: same beam, leveling at 7.5 10^{34} (PU 200 in average)



LRossi@13 HL-LHC Coord Group

CMS Upgrades

We have submitted in June our Technical Proposal for the High Luminosity LHC upgrade



CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

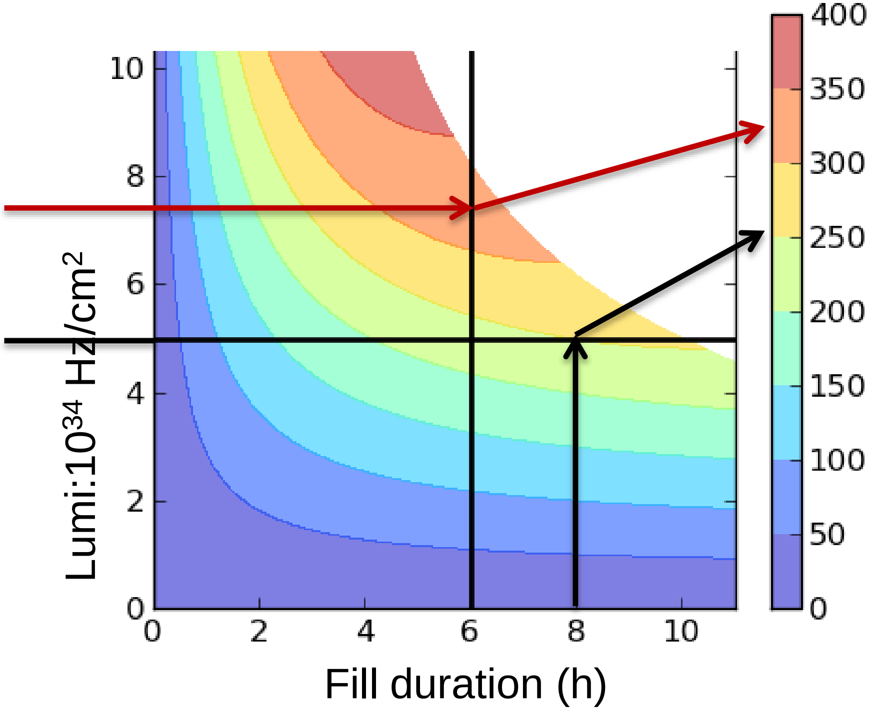
CERN-LHCC-2014-nnn
CMS-TDR-xxx
1 October 2014

CMS

The Compact Muon Solenoid
Phase II Upgrade
Technical proposal

Upgrade scope: the issue is Pileup

Pileup= number of concurrent pp interactions when 2 bunches cross



“Ultimate” leveling
7.5 x 10^{34} (Hz/cm^2)
200PU

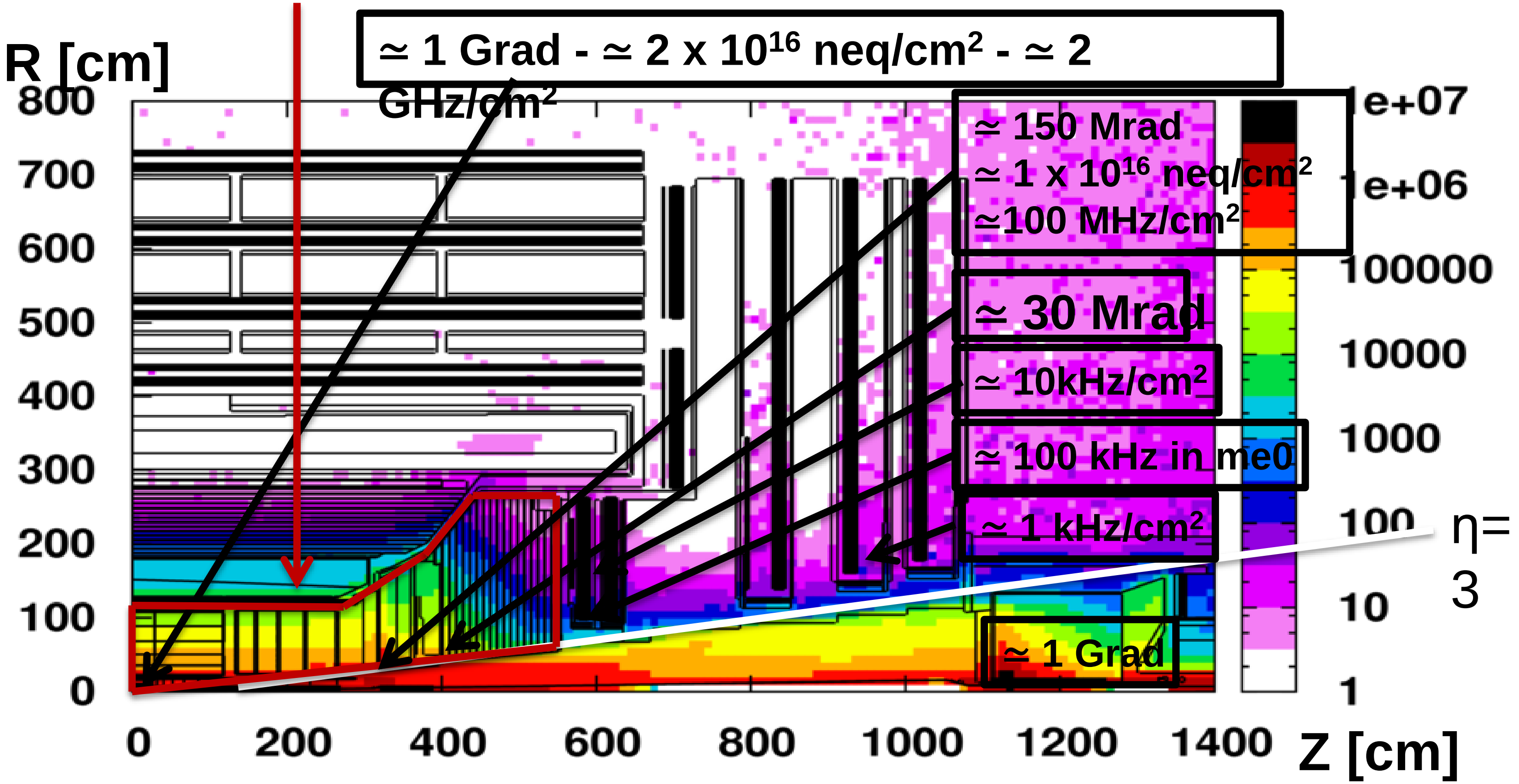
“Nominal” Leveling
5 x 10^{34} (Hz/cm^2)
140 PU

Integr. Lumi./year (fb^{-1})
160 days operation

CMS upgrades enable operation at 200 PileUp,
maintain current performance at 140 PU,
allowing moderate degradation up to 200 Pileup
and radiation tolerance ≥ 3000 fb^{-1}

Radiation dose - neutron fluence - particle rates

- 3000 fb^{-1} Dose map in [Gy] simulated with MARS and FLUKA
- Numbers in boxes indicate maximum doses - neutron equivalent fluence - particle rates (for 5 x 10^{34} Hz/cm^2) seen by the various detectors
- **These studies show that Tracker & End cap Calorimeters need replacement due to aging**



≃ 1 Grad - ≃ 2 x 10^{16} neq/cm^2 - ≃ 2 GHz/cm^2

≃ 150 Mrad
≃ 1 x 10^{16} neq/cm^2
≃100 MHz/cm^2

≃ 30 Mrad

≃ 10kHz/cm^2

≃ 100 kHz in me0

≃ 1 kHz/cm^2

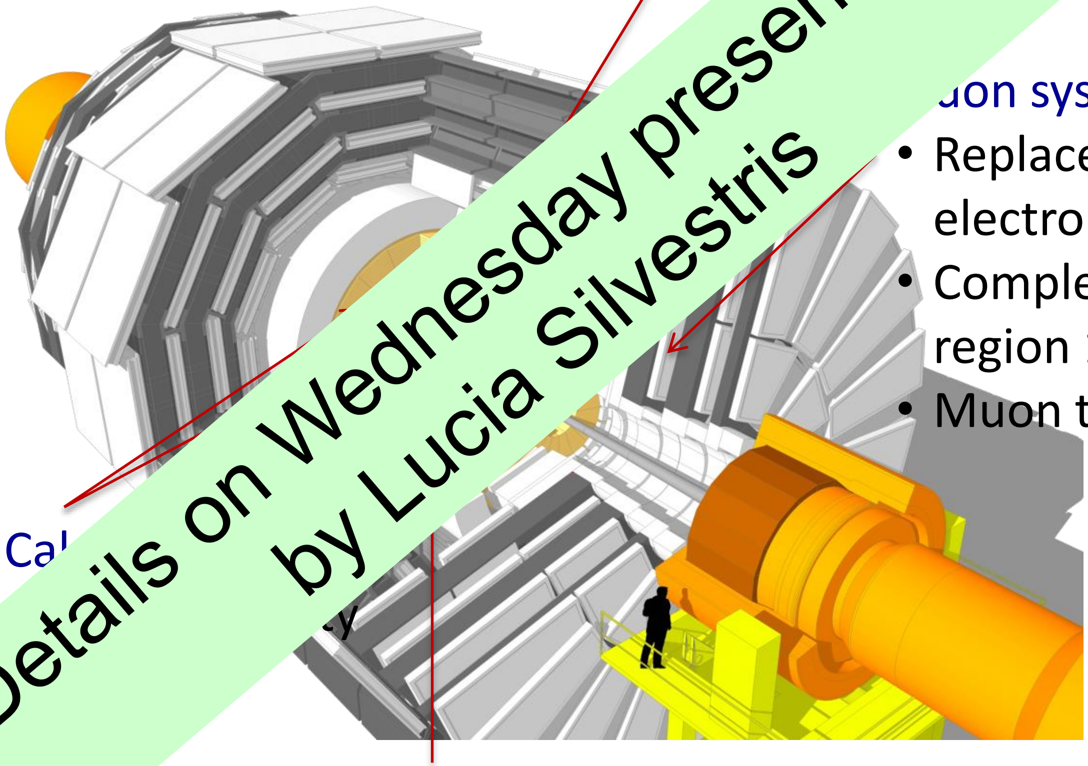
≃ 1 Grad

Summary of the CMS upgrades for Phase-II

Trigger/HLT/DAQ
- Track information at L1-Trigger
- L1-Trigger: 12.5 µs latency - output 750 kHz
- HLT output ≃7.5 kHz

Barrel EM c eter
- Repla ctronics
- L temperature (8∘)

uon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region 1.5 < η < 2.4
- Muon tagging 2.4 < η < 3

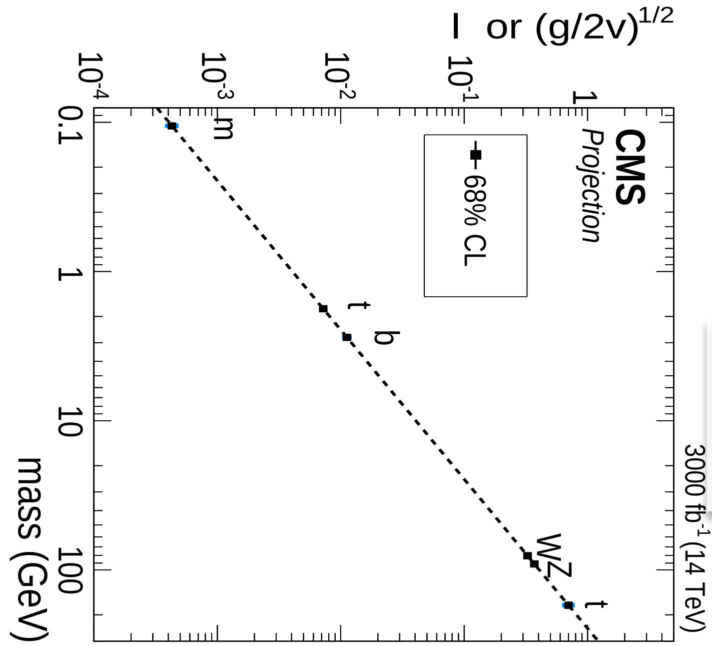


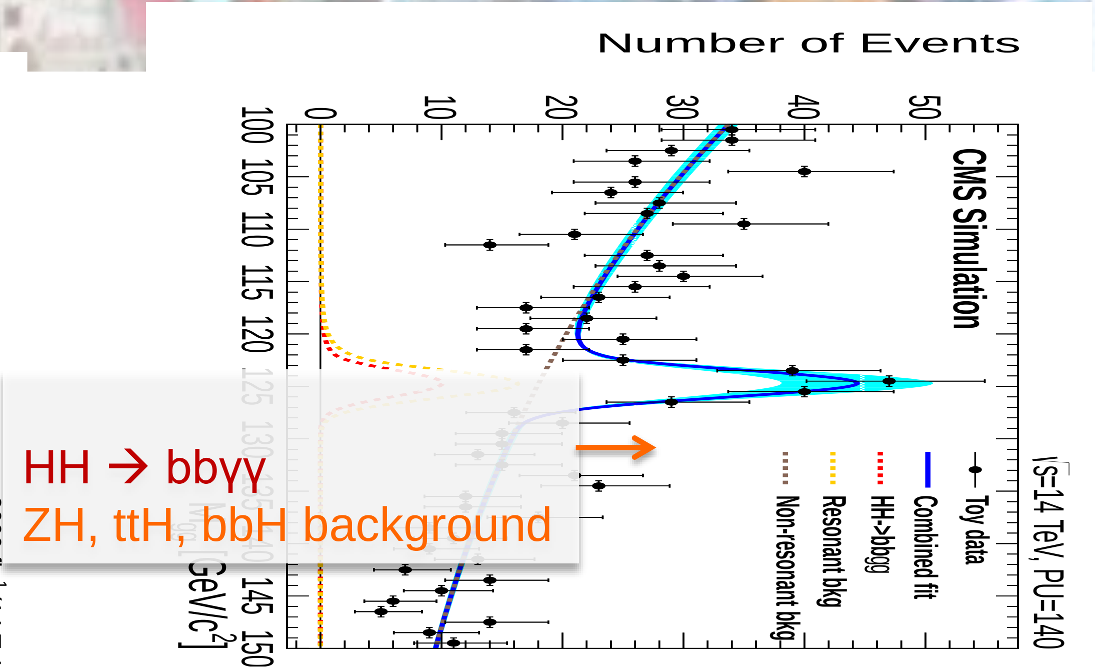
Details on Wednesday presentation by Lucia Silvestris

Replace Endcap Cal
- Rad. tolerant y
- 3D capabi

Replace Tracker
- ad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to η = 3.8

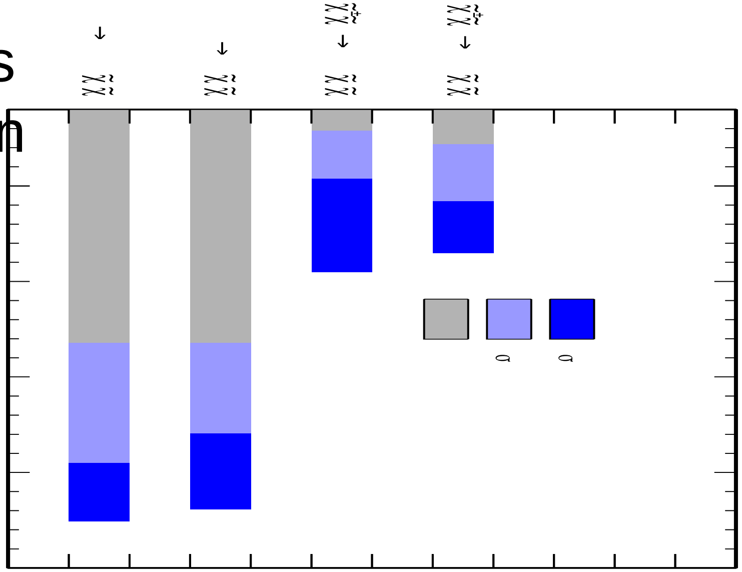
Examples of physics reach





HH → bbγγ

ZH, ttH, bbH background

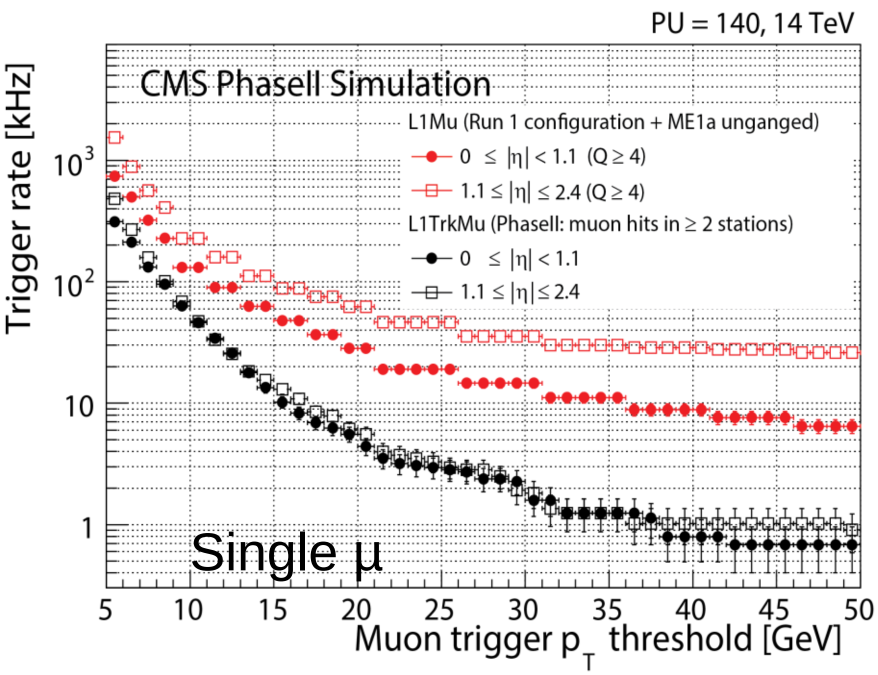


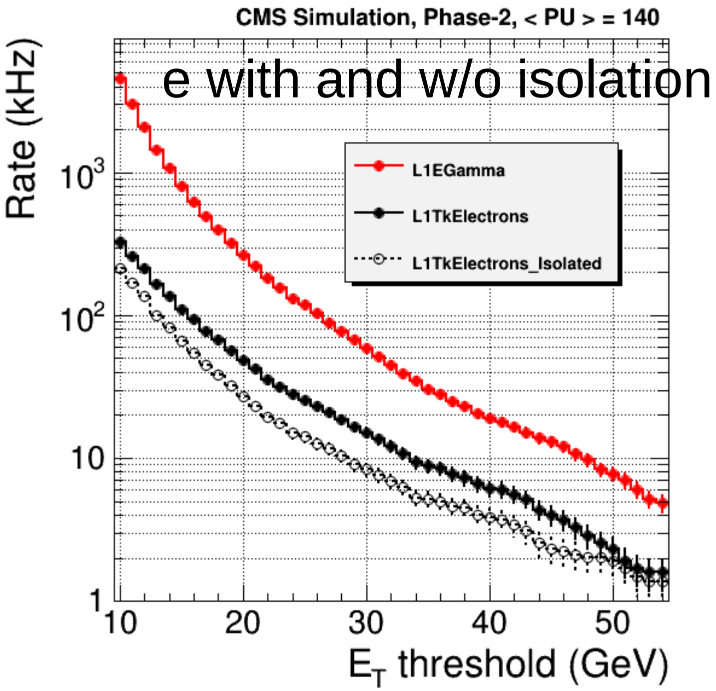
- 2 to 10% precision on BEH couplings
- Evidence of di-BEH boson production
- Access to small cross section SUSY processes
- Several other SM rare processes and BSM physics predictions
- And increased mass range

A major improvement: first level track trigger

Powerful scheme to control all inclusive trigger rates at first 40 MHz stage

- Single μ rate divided by 10
- Single e rate divided by 5(10) w/o (with) isolation
- γγ rate/5 from isolation
- τ efficiency x 2 at same rate
- Vertex ≃ 1 mm resolution → HT & MET rates divided by 10 to 100

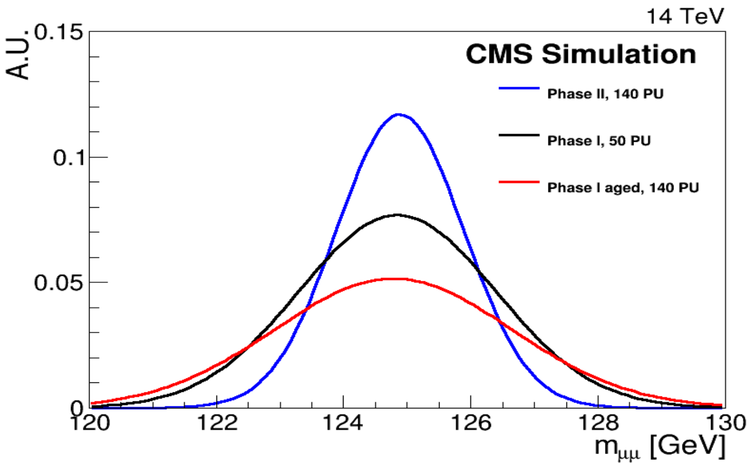




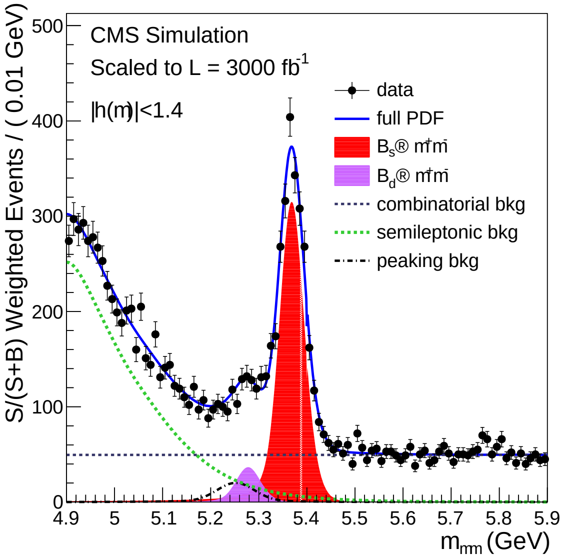
L1-Trigger studies with Phase-I menu thresholds including Track-Trigger:

- Requires ≃ 500/750 kHz rate at 140/200 PU (with 1.5 safety margin)

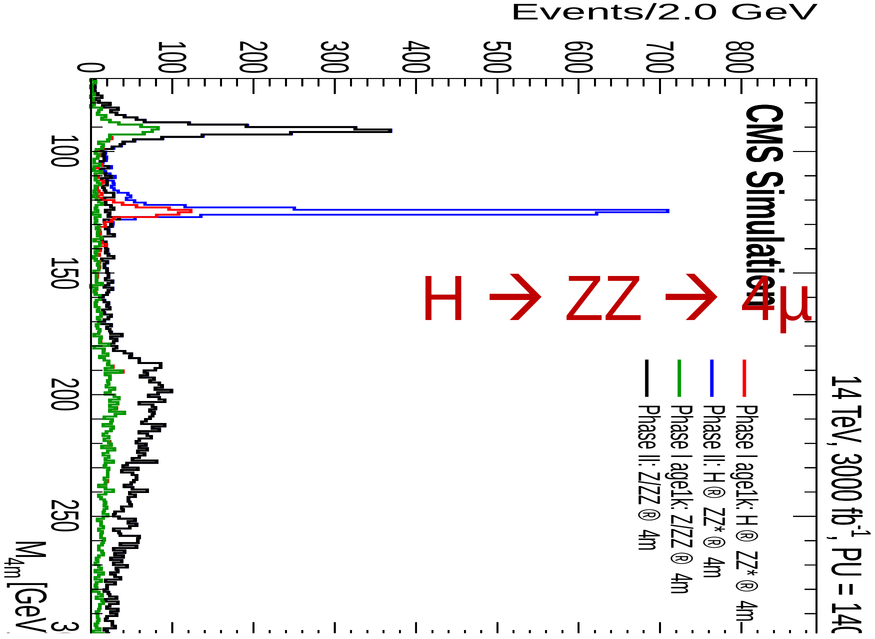
○ Tracker momentum resolution



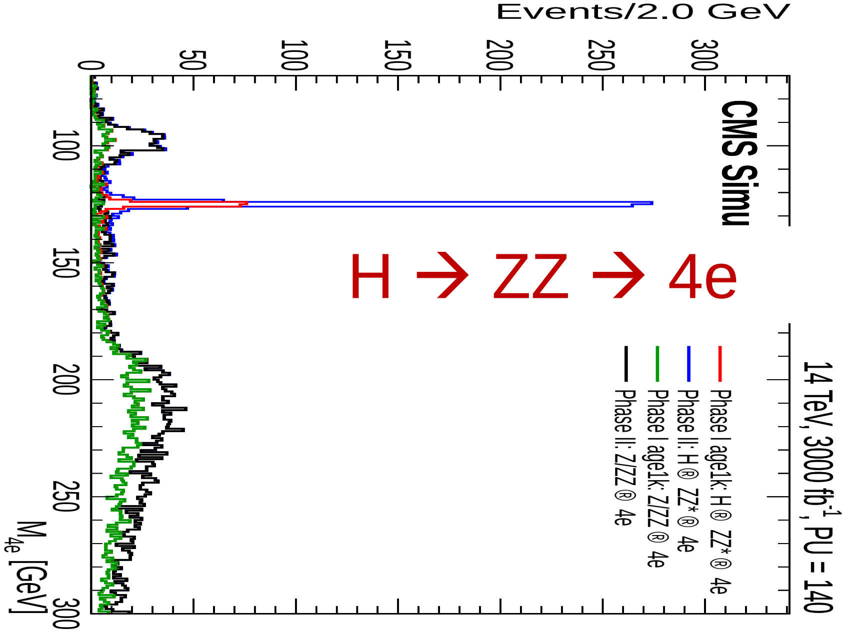
H→μμ - 20% efficiency & 40% mass resolution improvement



B_d/B_s → μμ resolved two decay peaks measure enabled by Track-Trigger



H → ZZ → 4μ



H → ZZ → 4e

With aged Phase-I Tracker huge loss of efficiency for H→ ZZ → 4l
Upgrade restores efficiency and extensions increase the acceptance by 20%

Discovery can come early …or late

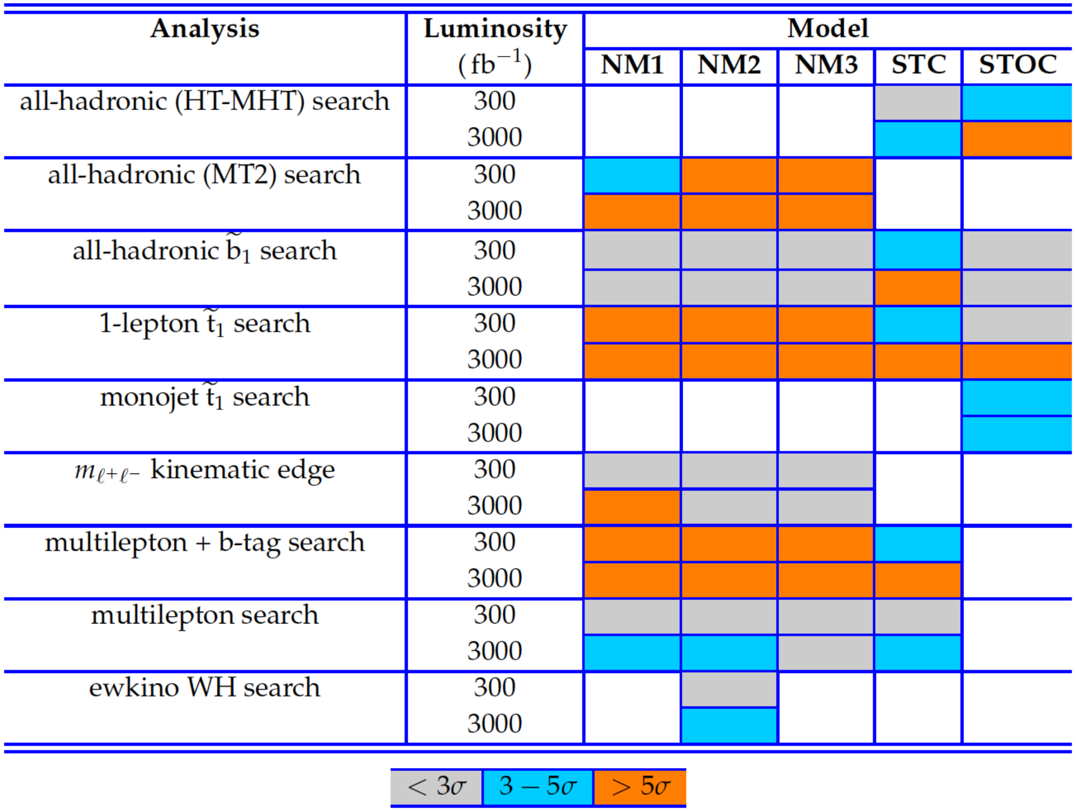
Explored:

- 9 different experimental signatures.
- 5 different types of SUSY models.

Different types of SUSY models lead to different patterns of discoveries in different final states after different amounts of data

Exploring SUSY model space

Exploring experimental signature space



Analysis	Luminosity (fb^{-1})	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (HT-MHT) search	300				▨	🟦
	3000				🟦	🟧
all-hadronic (MT2) search	300	🟦	🟧	🟧		
	3000	🟧	🟧	🟧		
all-hadronic $\tilde{b}_1$ search	300	▨	▨	▨	🟦	▨
	3000	▨	▨	▨	🟧	▨
1-lepton $\tilde{t}_1$ search	300	🟧	🟧	🟧	🟦	▨
	3000	🟧	🟧	🟧	🟧	🟧
monojet $\tilde{t}_1$ search	300					🟦
	3000					🟦
$m_{\ell^+\ell^-}$ kinematic edge	300	▨	▨	▨		
	3000	🟧	▨	▨		
multilepton + b-tag search	300	🟧	🟧	🟧	🟦	
	3000	🟧	🟧	🟧	🟧	
multilepton search	300	▨	▨	▨	▨	
	3000	🟦	🟦	▨	🟦	
ewkino WH search	300		▨			
	3000		🟦			

▨ $< 3\sigma$	🟦 $3-5\sigma$	🟧 $> 5\sigma$

Conclusion

- CMS is ready to continue the exciting journey into the mysteries of Nature
- We are all excited by exploring the new energy frontier
- We are preparing our long term future: CMS has been conceived as an Energy frontier experiment, but has demonstrated that with adequate detector a proton collider is also a precision measurement tool
- Stay posted for exciting times ahead !

Backup

Dark matter : reachable at LHC?

- **Weakly Interacting Massive Particles are the best motivated dark matter candidates**, Annihilation rate in the early universe determines the density today.
- The annihilation rate comes purely from particle physics and automatically gives the right answer for the relic density!

$$W_X h^2 = \frac{3\cdot 10^{-27}\, cm^3/s}{\langle sn \rangle_{ann}}$$

- This is the mass fraction of WIMPs today, and gives the right answer (23%) if the dark matter is weakly interacting and the **WIMP mass in the range GeV – 10 TeV**