CMS Physics Beyond LS1

Christopher S. Hill (OSU)
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I'll use two meanings of the word *physics* in this talk

- Part 1 - *Physics* (with capital "P") beyond LS1
  - Measurements/searches that we must perform at 14 TeV w. 300 fb^{-1}, 3000 fb^{-1}
  - Difficult because necessarily speculative - we do not yet know what will be the burning physics questions (though we have some hints and general ideas)
  - Even these have not been studied very much (yet)
- Part 2 - *physics* (with a lower case "p") beyond LS1, i.e. CMS physics organization (PAGs, POGs, etc) for the future
  - Perhaps less interesting, but it is important to discuss how to get prepared/ organized to perform needed physics studies to inform physics program (and related upgrades) post LS1
  - This process has started, and I will give an overview of the status and future plans of this activity
    - Potentially recruit new CMS collaborators to participate

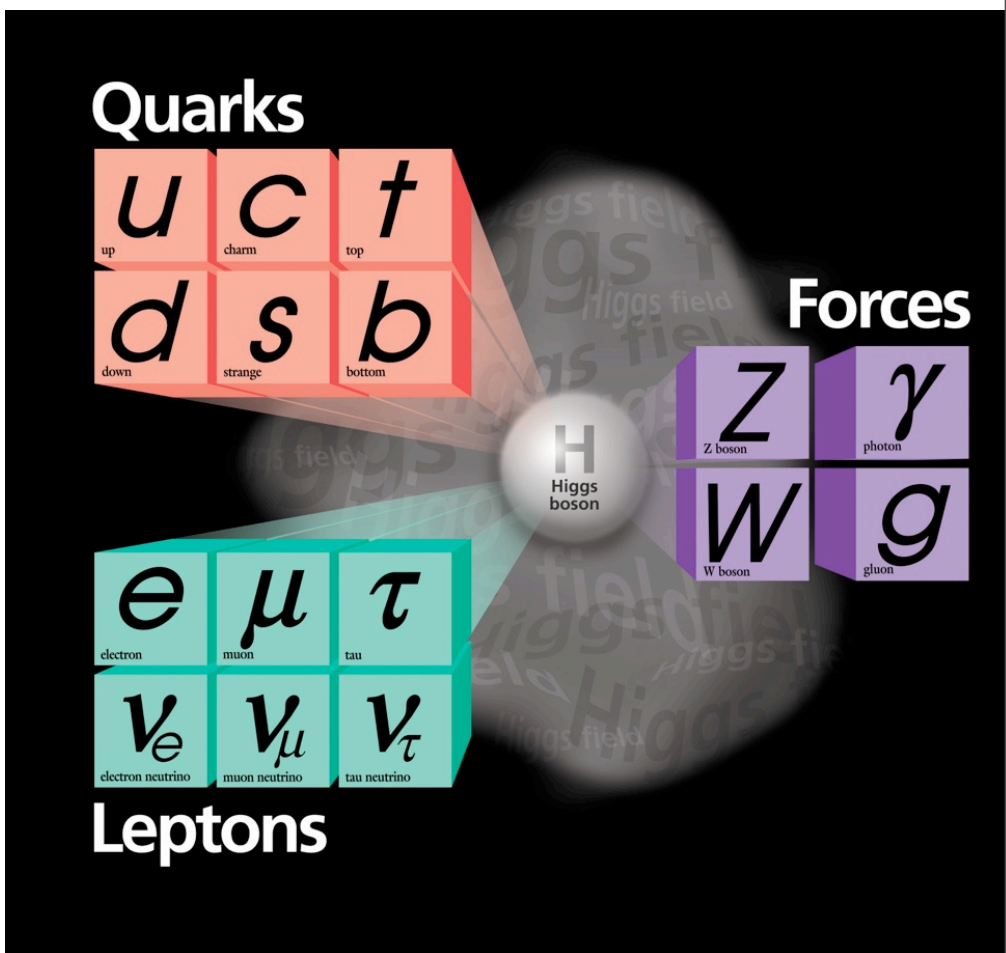
Part 1: Physics

What physics do we need to be ready to do with CMS post LS1?

- We should target the important physics questions that we will face in the next decade or so
- While I don't have a crystal ball, **2011 data from the LHC has already given hints about where the physics that we should target may/may not be**
  - We can speculate based on this *but i think it is important to note that for the first time in a long time in HEP collider physics*,
  - **We will know a great deal more about which direction to go very soon**
  - Possibly in as little as few months, but almost certainly by the time all the 2012 data are analyzed
- **However, given this caveat, I will tell you my thoughts**

Recall the main questions in physics we hope to address with CMS data

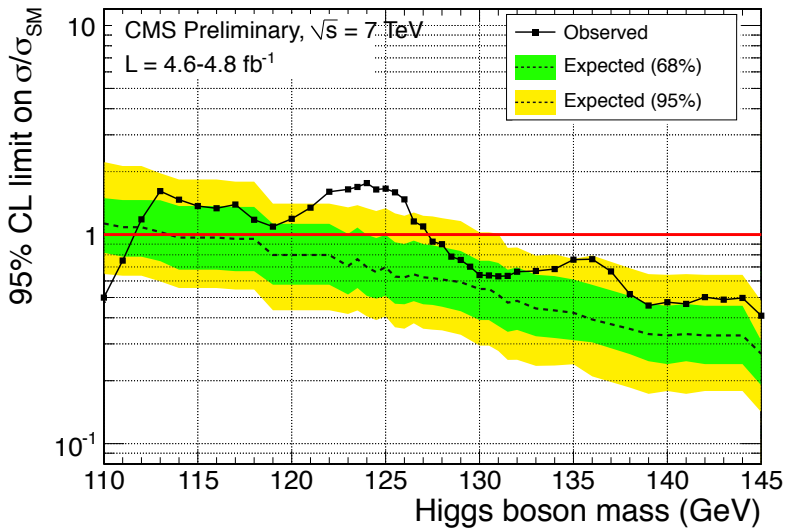
- What is the **nature of electroweak symmetry breaking**? Is this related to the **origin of mass** of the fundamental particles in the SM?
  - Long favored answer is Higgs mechanism, but then we must find a SM higgs boson
  - As I am sure you are aware, we have seen some hints and soon we will have the (beginning of) the experimental answer to this question
- Is there a **natural solution to the hierarchy problem? Or not?**
- Those are the **big two** for which LHC was built, (there are others below that we could get lucky and address, but they do not drive the LHC program (nor our upgrades, unless we see a signal …)
  - Are the particles of the SM fundamental?
  - Only 4 forces? Can they be unified?
  - What about gravity?
  - What is dark matter? e.g. SUSY LSP?

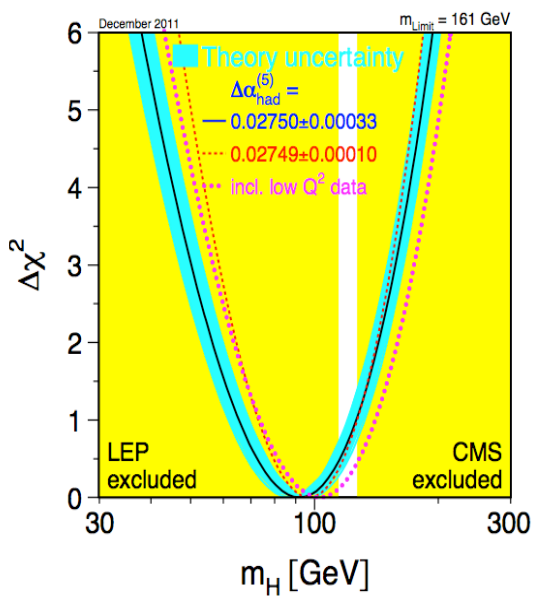


SM is a correct but incomplete description of Nature

What we will know as we head into LS1

- We will know a lot about the first big question (EWSB):
  - We will have either **discovered a particle that is a candidate Higgs boson**
    - We will have measured its mass, perhaps ~125 GeV
    - In which case we will have made preliminary measurements of sigma x BRs
    - But,these will not be precise enough to conclusively demonstrate it is a SM Higgs
  - **OR** we will have **ruled out a SM Higgs boson** over the entire plausible mass range

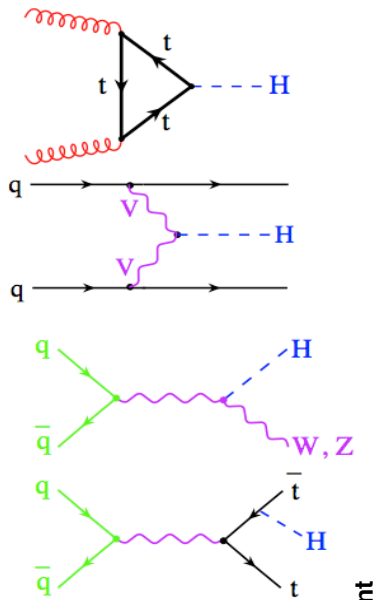


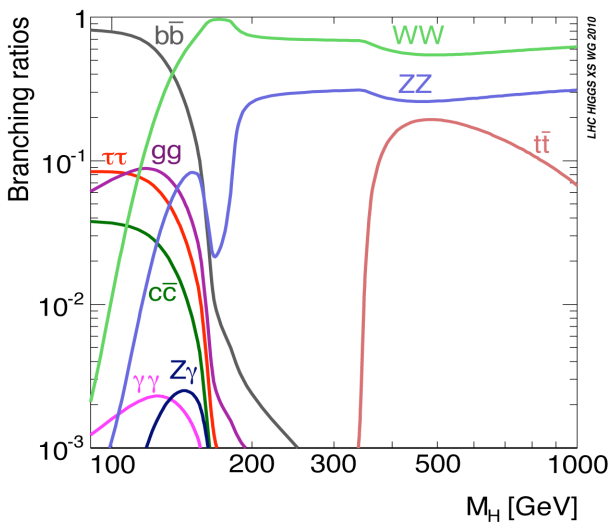


How long will it take to confirm the properties of SM higgs?

- We should be able to measure sigma x BR ~20% in the γγ mode during 2015-2017 run
- Other modes will take longer, post LS2
- Should also be able to measure the spin
  - H to ZZ to leptons

- **Gluon fusion**
- **VBF**
- **VH**
- **ttH**





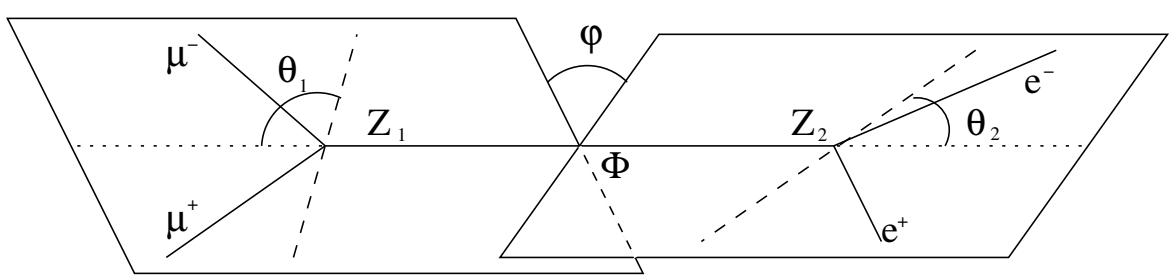
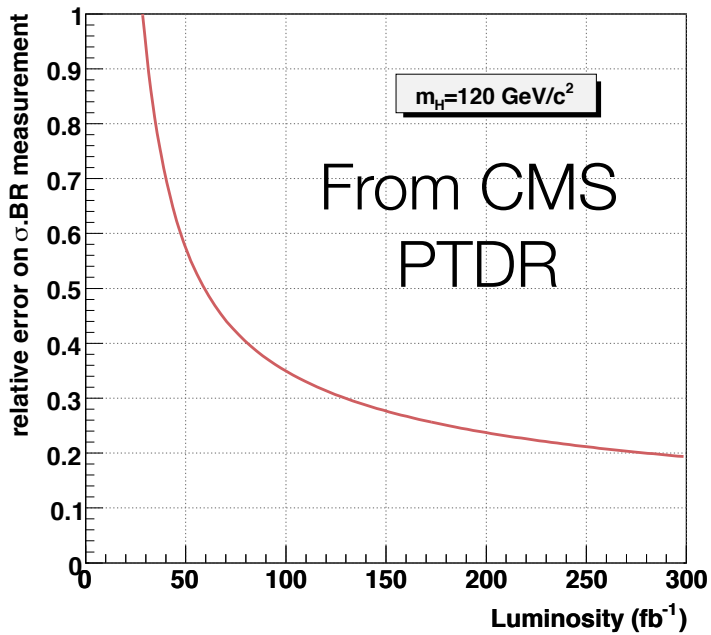
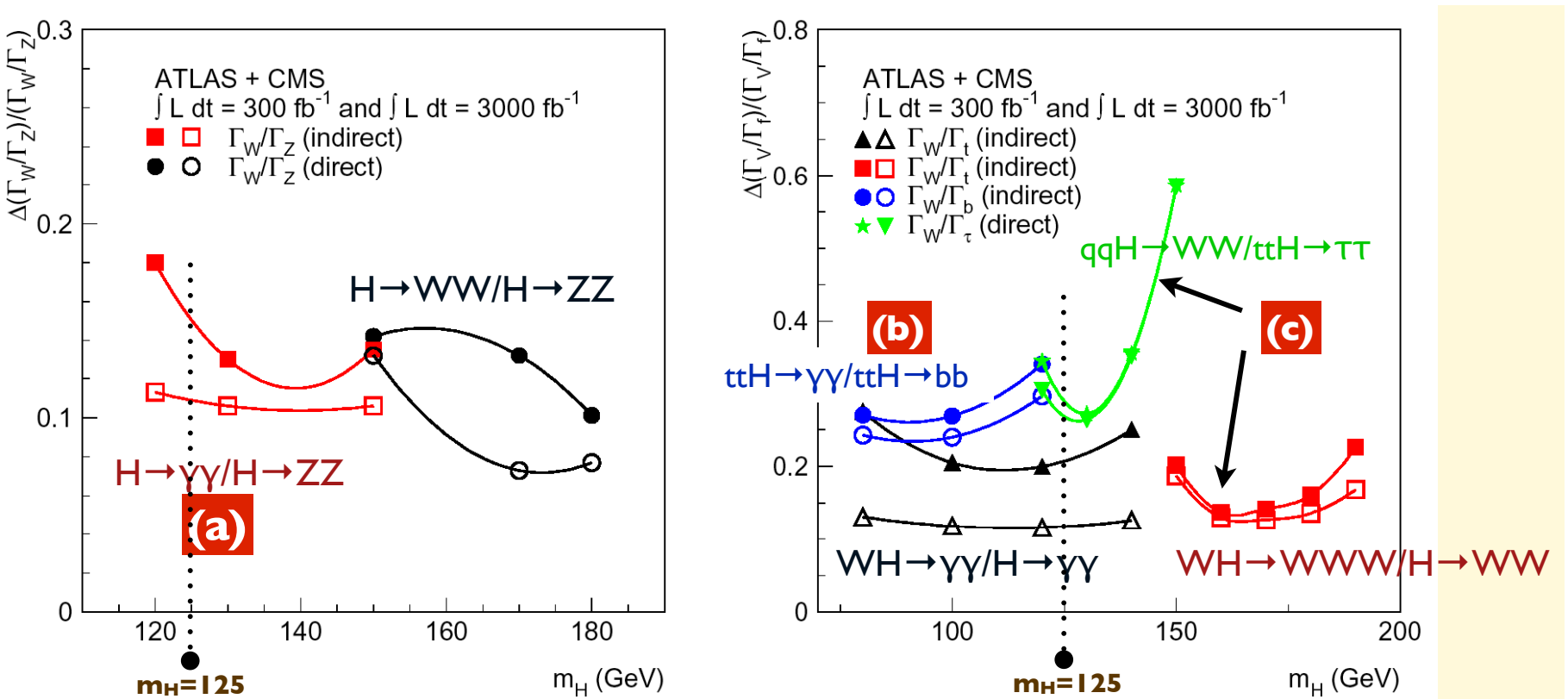


Figure 10.40: Definitions of the angles in the $\Phi \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$ process.



To get to ~10% precision need HL-LHC

- Model independent measurements through ratios of rates for two different final states
  - Higgs cross-section, total width and luminosity cancel
  - Can get to ~10% precision in most measurements with HL-LHC



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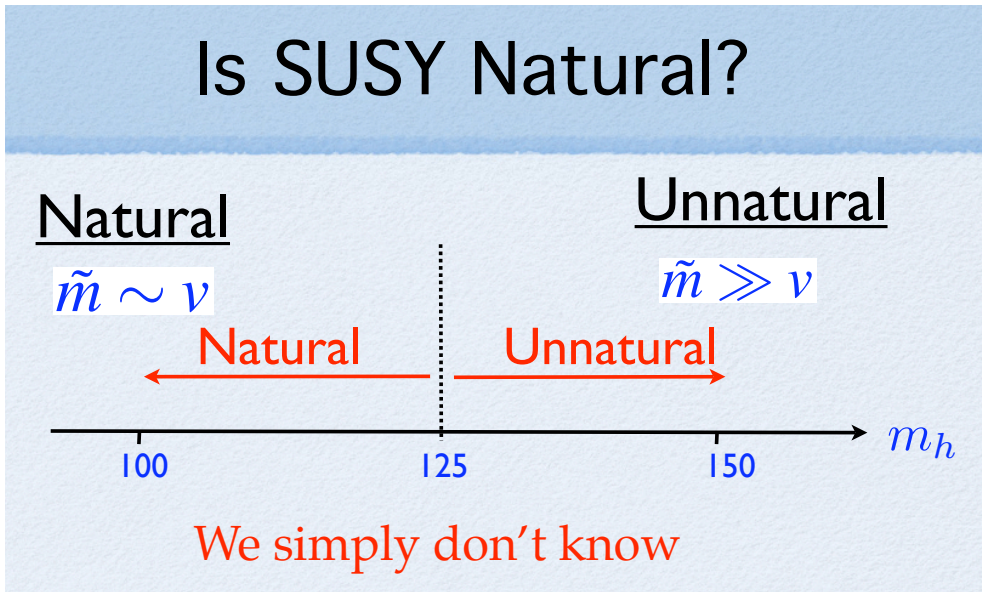
Next big question is Naturalness

- If M_H is ~125, this has implications for (natural) SUSY
- In (e.g MSSM), the lightest higgs can be 114-135, so **125 naively seems perfect**
- However, in MSSM, higgs mass is

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

- Even at large tanβ, the correction term must be ~87 GeV
  - Requires (comparatively modest) **fine tuning**
  - Or **non-miminal SUSY** (e.g. NMSSM)
  - (Or both)

L. Hall, SavasFest 2012



125 is close to the Z mass… but not close enough

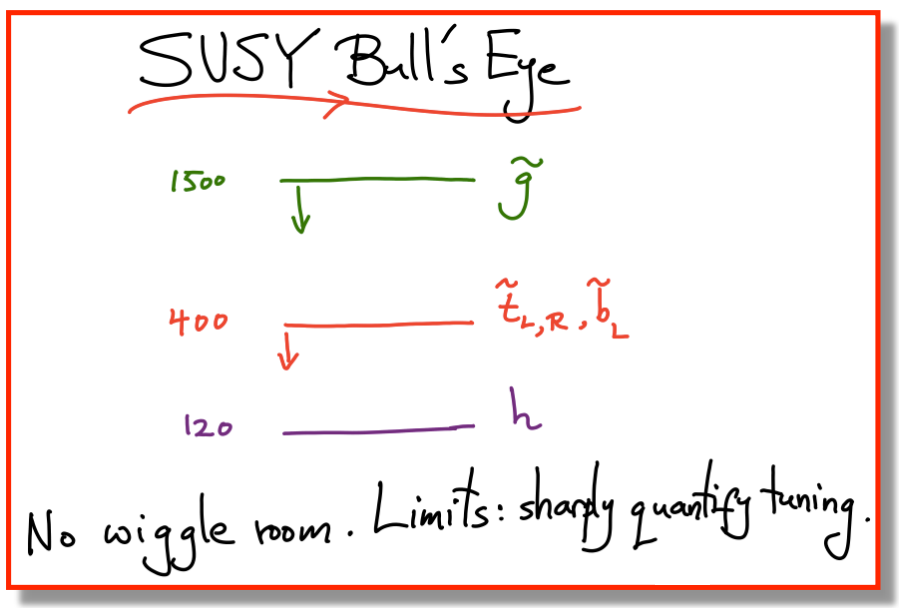
Natural SUSY in 2012 and beyond LS1

- Must continue the squark/gluino searches at least until we have reached the naturalness limit (~1.5 TeV)
- Targeted searches for 3rd generation squarks (stops & sbottoms) are needed/being performed
  - Signatures are more difficult, especially single stop/sbottom
  - Irreducible top backgrounds

$$\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow b\tilde{\chi}_1^{0}\ell\nu$$

- **If fail to see light stops, essentially have to give up naturalness**
- Of course if do observe light stops, requirements on upgraded detector to study them are "familiar" (from top physics)

Must cover stealth SUSY, RPV scenarios too



N. Arkani-Hamed, "Implications of LHC results for TeV-scale physics"

Other "Natural" Solutions still possible

- **Another solution to the hierarchy problem is extra spatial dimensions**
- Remember the hierarchy problem is that if one computes the quadratic corrections to the higgs mass, cut off at a scale $\Lambda_{cutoff} \sim M_{Pl}$ the fine tuning required to get an ~100 GeV Higgs is extreme
- **This is because M_{Pl} is a big number**
- Extra-dimensions (n of them, of radius R) **simply make true n-dim M_{Pl} a smaller number**

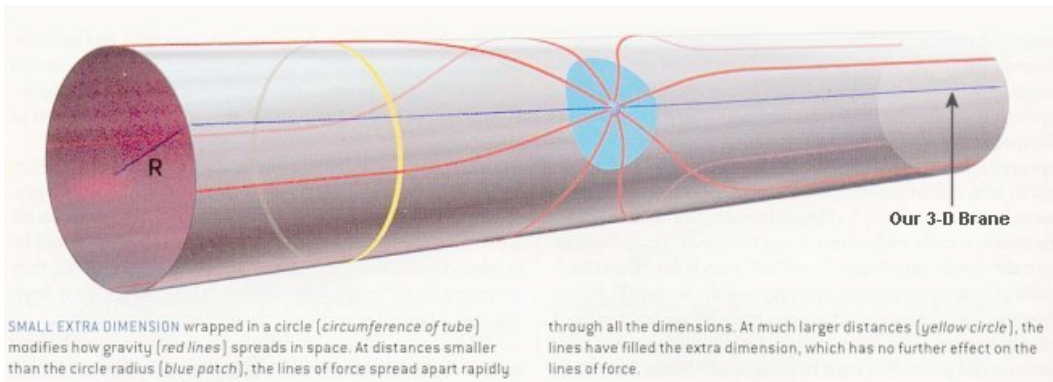
$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{r^{n+1}}, (r \ll R)$$

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2} R^n} \frac{1}{r}, (r \gg R)$$

big # $\rightarrow M_{Pl}^2 \sim M_{Pl(4+n)}^{n+2} R^n$

smaller # times factor

ADD scenario:



SMALL EXTRA DIMENSION wrapped in a circle (*circumference of tube*) modifies how gravity (*red lines*) spreads in space. At distances smaller than the circle radius (*blue patch*), the lines of force spread apart rapidly through all the dimensions. At much larger distances (*yellow circle*), the lines have filled the extra dimension, which has no further effect on the lines of force.

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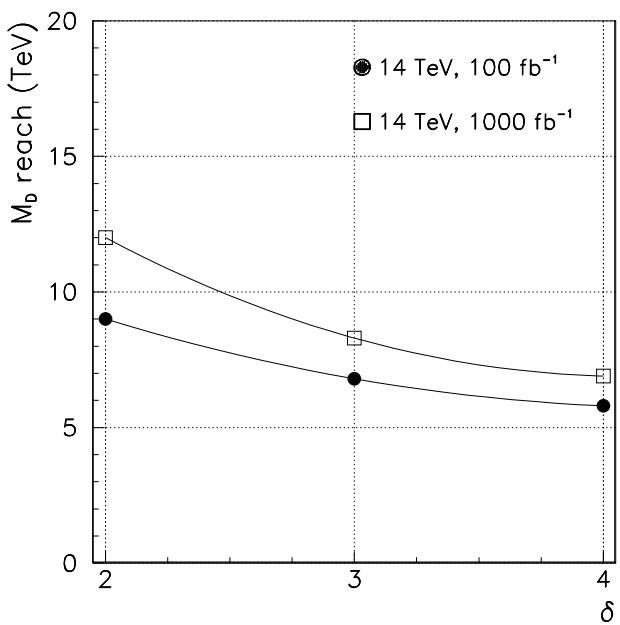
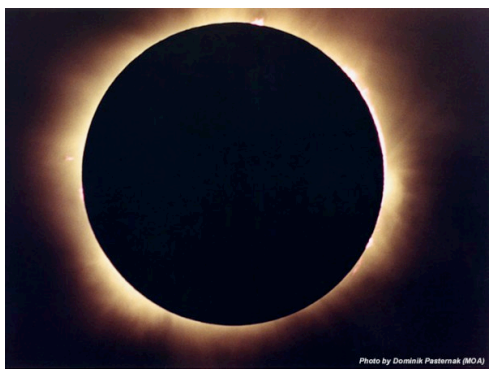
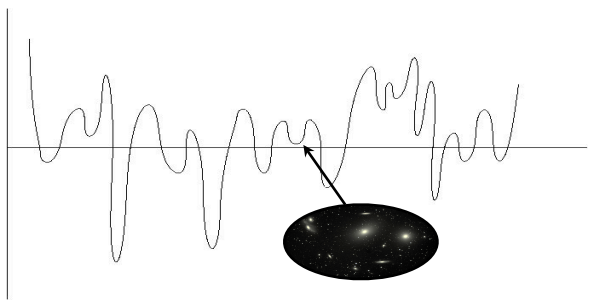
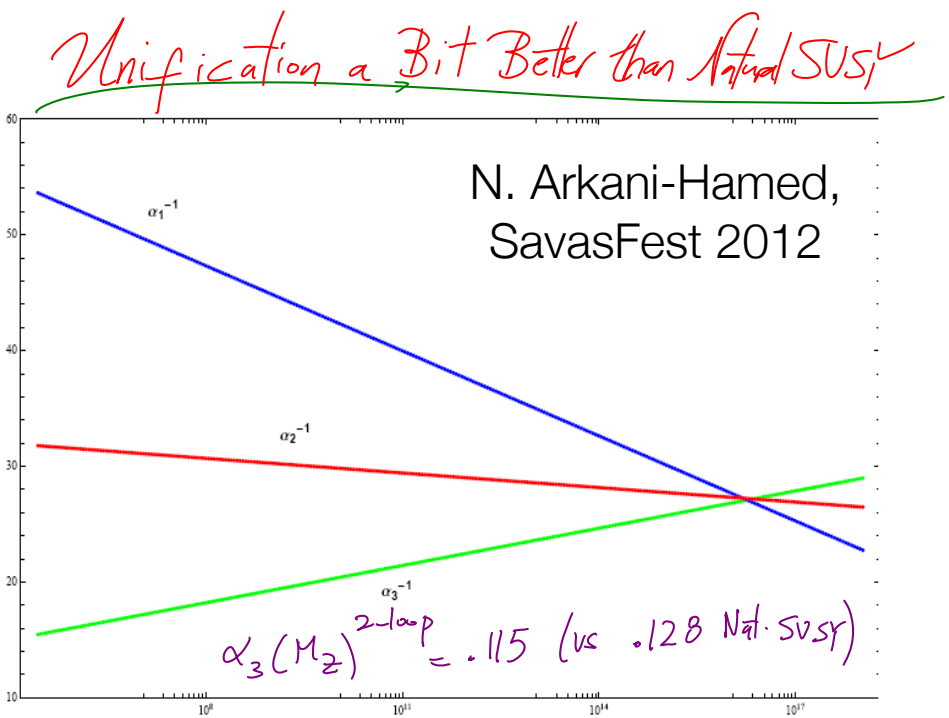


What if there is no natural solution to the hierarchy problem?

- *Split Susy* is a scenario which is not motivated by solving the hierachy problem
- It **ignores the fine-tuning** of the Higgs mass
  - From string theory landscape suggests it might be a statistically reasonable coincidence (like the apparent sizes of the sun and moon)
- In the end the models look very much like supersymmetry (with most of its desirable consequences) but with one big difference
  - **Large mass splitting between new scalars & fermions**
    - *Long-lived gluinos*

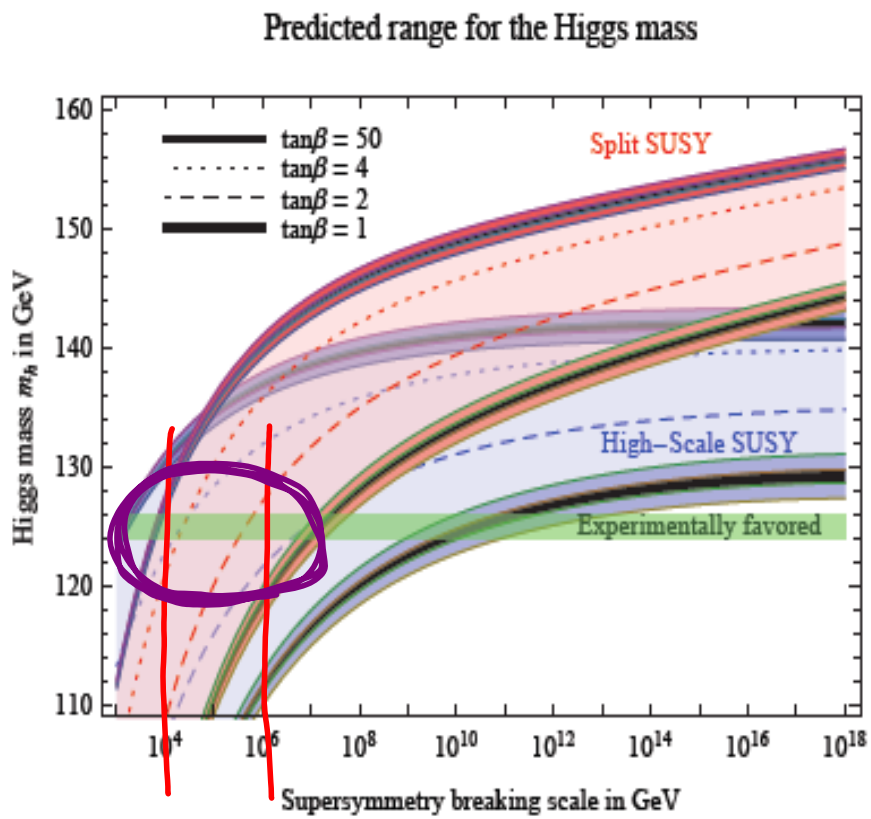






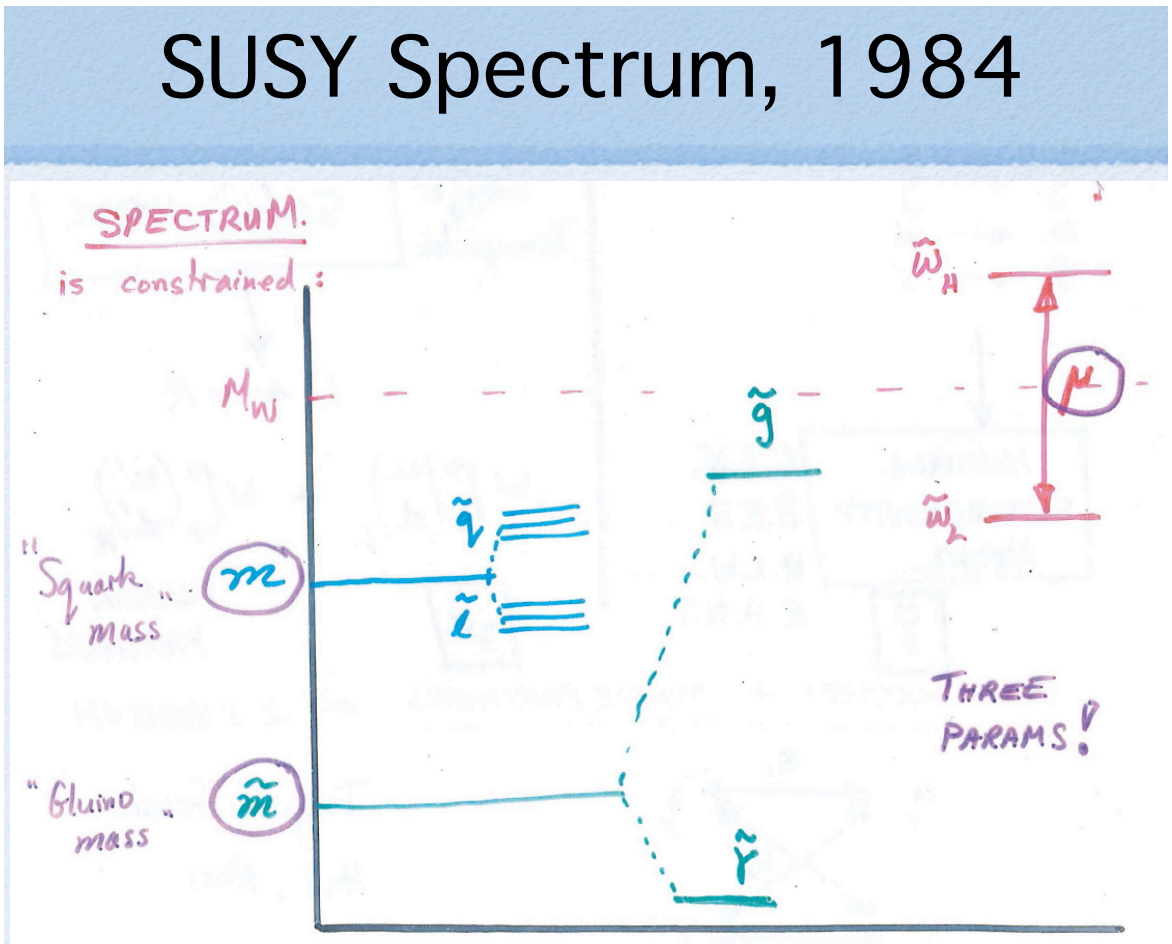
Impact of MH on Split SUSY = "Mini Split"

- If the Higgs is ~125 GeV, the SUSY breaking scale in split SUSY can't be that high **(i.e. the "split" is *smaller*)**
- **Long-lived particles, not that long-lived**
  - *cτ of ~100 μm to ~1 cm*
  - An experimentally accessible (but currently mostly overlooked range)
- *If Nature is not natural, we may need a detector optimized for SUSY with this type of displaced decays*



[Giudice, Strumia]

Should be skeptical of theoretical predictions



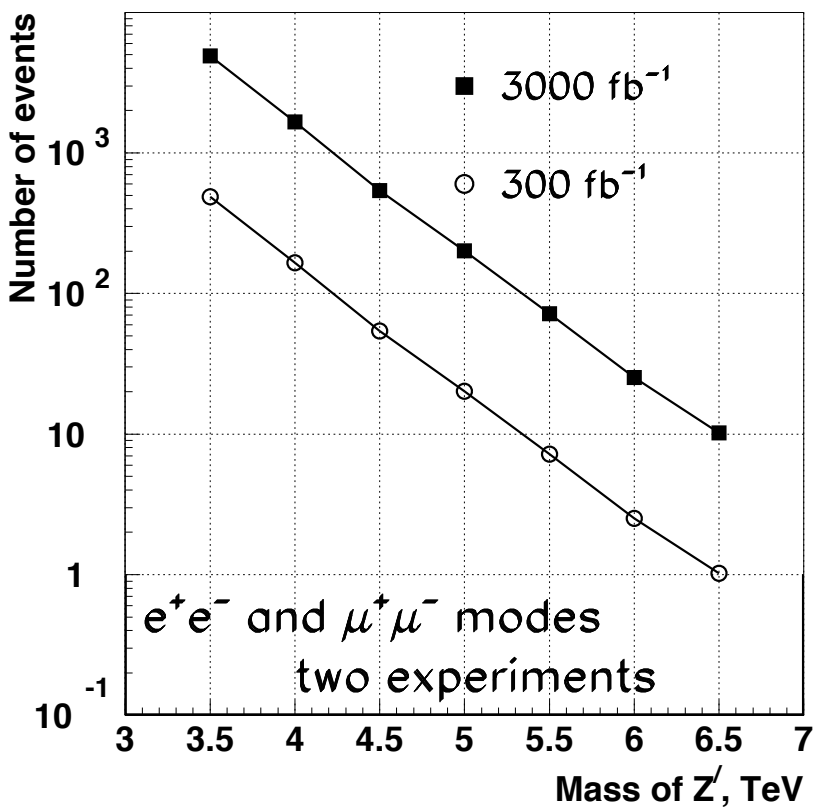
L. Hall, SavasFest 2012

- Until we know what the new physics will be, we should be skeptical
- Two things we can do in any event
  - *State generic physics goals that are broadly well motivated*
  - *Ask what is limiting physics in the current detector, or will be limiting it at higher luminosities*

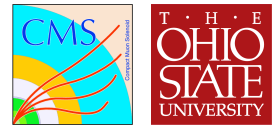
Generic Physics case for HL-LHC/HE-LHC

- Can say some general things (mostly taken from talk by M. Mangano in 2008). Will need HL-LHC to:
  - **Improve measurements of new phenomena** seen at the LHC. e.g.
    - *Higgs couplings and self-couplings*
    - *Properties of SUSY particles (mass, decay, BR, etc)*
    - *Couplings of new Z' or W' gauge bosons (e.g. L-R symmetry restoration)*
  - **Detect/search low-rate phenomena** inaccessible at the LHC. e.g.
    - *$H \to \mu^+\mu^-$, $H \to Z\gamma$*
    - *top quark FCNCs*
    - *WW scattering (especially if no higgs observed)*
  - **Push sensitivity to new high-mass scales**. E.g.
    - *New forces (Z',W_R)*
    - *Quark substructure*
    - *Though these more of an argument for HE-LHC*

hep-ph/0204087



Actual CMS detector limitations in current physics program should also drive upgrade



- **Looking at current physics performance, asking the PAGs/POGs, what are potential limitations of CMS?**
- Too much material, especially in forward region (effects ECAL and tracker performance)
  - *Perhaps we have too much redundancy in tracking?*
- Large extrapolation between last pixel layer and first TIB layer means track seeds can only come from pixels
  - *Addressed in upgrade pixel detector, but should bear in mind for Phase 2 tracker*
- At present, high pT btagging is problematic. Breaks down completely above 1.5 TeV
  - *If SUSY is high pT and displaced (a la mini split) this would be an issue.*
- L1 trigger thresholds on single leptons are high and rising
  - *Issue for SUSY with compressed spectra AND Higgs physics*

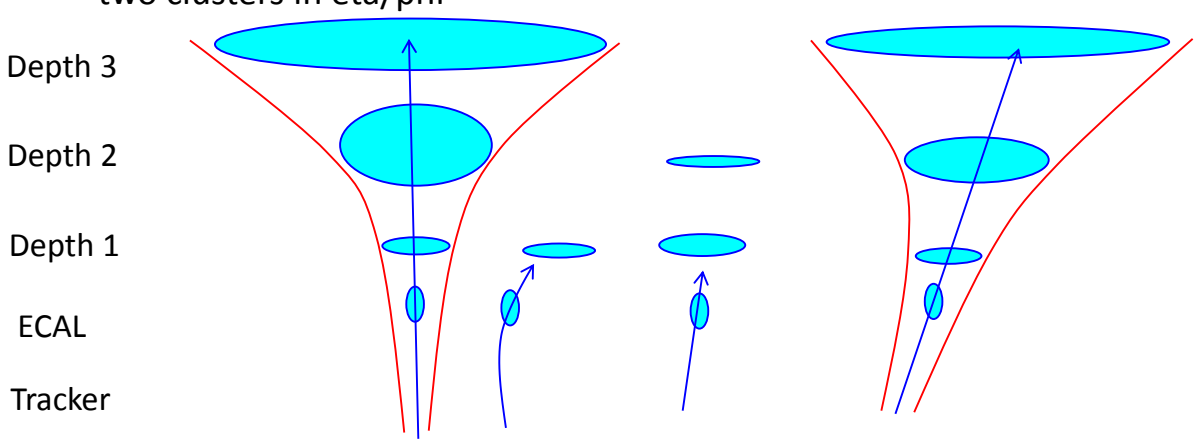
Importance of physics input to future upgrades

- These responses (some of which are contradictory) raise important questions about any upgraded CMS detector that can only be guided by physics input, based on latest knowledge of what physics we need to do and how actually perform the analyses.

- ***All analyses now critically dependent on PF***
- *Need to make sure upgraded detector is designed with PF in mind*
- Likewise need to do PF studies of upgraded geometries to inform this process
  - *Dedicated effort that looks at CMS holistically needed (GED for upgrade)*

– Hadronic showers develop longitudinally with finite uncertainties in the cluster centroid locations in eta/phi

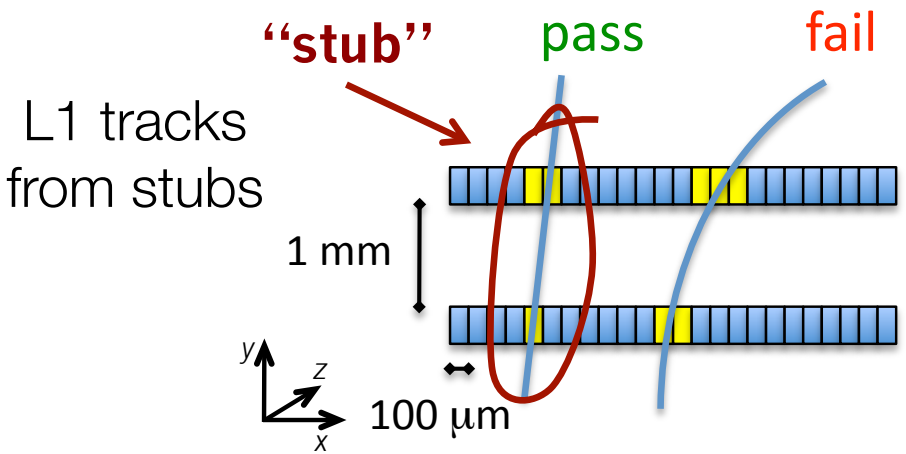
– Granularity should be thought of as “Granularity significance” of separatir two clusters in eta/phi



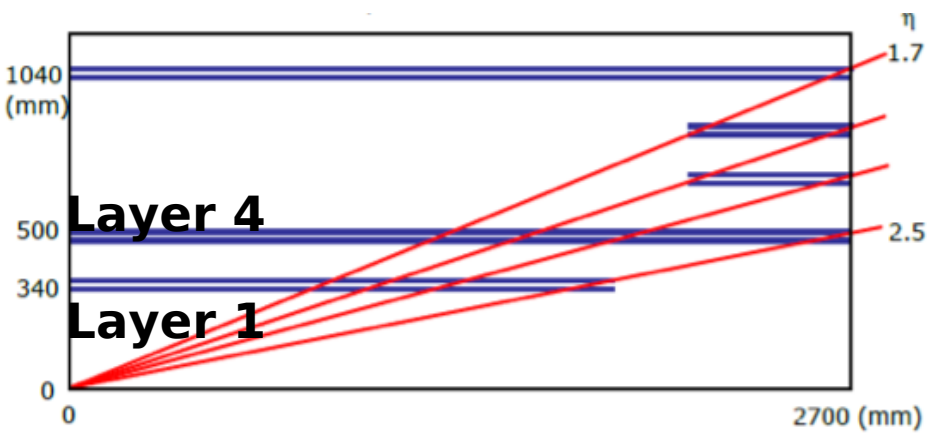
Upgrade algorithm allows a wider window to associate HCAL clusters
With a charged track and thereby reduces the rate of false neutral hadron
Identification – neutral hadrons are the primary limitation in the PFlow MET

C. Tully’s talk CMS upgrade week

Another example where physics input is needed, proposed Track Trigger



"Long Barrel" Design

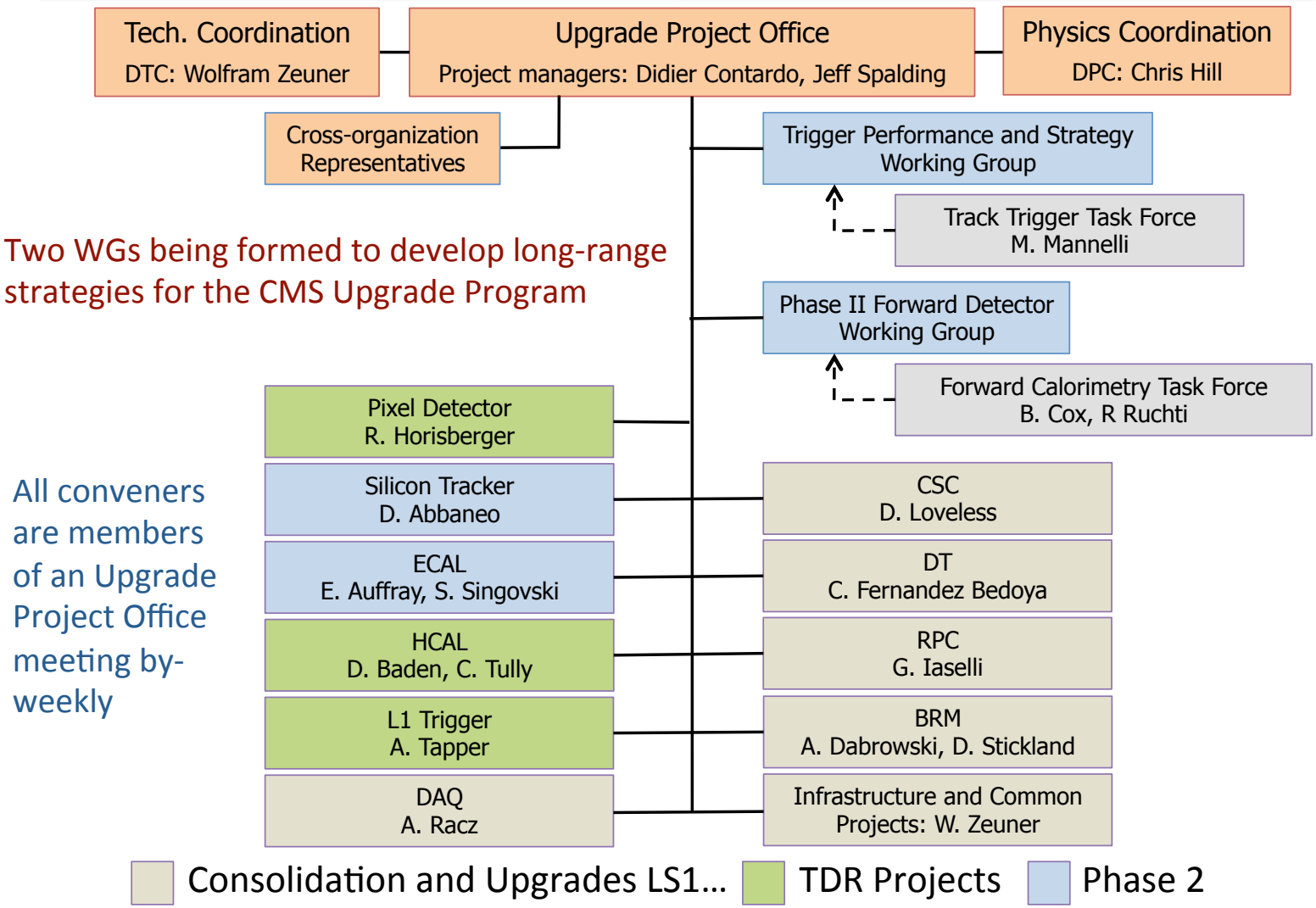


Could less material in forward region be more important than triggering there?

- Proposed design is for a triggering tracker, not necessarily an optimal tracker
- Assumption is that need a track trigger to cope with L1 muon rates (w/ 2012 data this seems to be justified)
- But also assumes that **need** to trigger on muons out to eta of 2.5
  - This comes from TDR requirement that need to trigger on > 50% W's
  - A good rule of thumb for the physics program of the last 20 years, it may/may not be the best benchmark for the next 20 years
  - **Whether this is or not is a (new) physics question**

CMS Upgrade Organization

Part 2: physics after LS1



Physics studies in PAGs since January

- **Since January, physics coordination has been asked to take on upgrade studies**
  - *Bring physics expertise*
  - *Provide resources*
- **This activity has begun in earnest in April** (after Moriond)
  - *HIG and SUS are pursuing several upgrade analyses (status reports in TDR sessions this week)*
  - *These studies are being supported by PPD, Offline, Computing*
  - *So far, due to the urgency of the timescale, these efforts have been limited to studies for the LS1 TDRs*
- **Need to expand these activities to physics studies for HL-LHC (and HE-LHC)**
  - *EXO getting involved now (e.g. heavy gauge bosons - W',Z')*
  - *If existing efforts being done in upgrade community, need to be brought into PAGs*
- **Should expand activity to POGs, coordinated by GED effort**

General Strategy for Physics Case for TDRs

- Early on agreed upon general statements about what physics can demonstrate upgrade
  - Pixels - **analyses with b's, photons (e.g. Higgs, SUSY)**
  - Trigger **- analyses with tau's (e.g. Higgs)**
  - HCAL - **analyses with jets, MET (e.g. VBF, SUSY)**
- Based on this, HIG & SUS were targeted as critical PAGs that must undertake upgrade studies
- **Overall theme more compelling than disjointed studies** (possibility of a physics TDR)
  - E.g. If Higgs signal observed in 2012, clear physics goal is measuring Higgs couplings to establish conclusively if a SM Higgs (or not)
    - Fermionic modes are thus critical, i.e. bb, tau tau
- For specific analyses to pursue**,** needed to iterate with conveners to **select appropriate physics studies that make the physics case, but can also be delivered on time (and with minimal disruption to PAG data analysis)**
  - Manpower & expertise availability

Overview of HIG Studies (M. Klute)

- New Higgs SubGroup formed - “Future Higgs Analyses” (M. Klute & P. Giacomelli)
  - started operating Mar 21st with first meeting
  - mandate to study future, beyond 2012 data taking, Higgs physics program
    - Higgs properties (mass, spin, width, couplings)
    - add (explore) rare decays and difficult channels (self coupling)
    - untapped non-SM modes
    - VV scattering

- Samples requested at 14 TeV, <PU> = 50:
  - standard candles (1M events each)
    - Z boson production to e, μ and τ
    - top-pair production
  - signal processes (200k events each)
    - H → bb: VH, ttH
    - H → ττ: ggH, VBH, VH
    - H → γγ: ggH, VBF, VH
    - H → ZZ(4l): ggH, VBF

Overview of HIG Studies (M. Klute)

- Ongoing Studies:
  - perform POG-like studies in the context of Higgs searches
    - Jets/MET
    - forward jet tagging
    - b tagging
    - lepton (e,μ,τ) identification
    - photon identification
  - evaluate impact on Higgs measurements by comparing with current analysis (default geometry)
    - VBF channels: jet tagging, (di-jet mass resolution)
    - Higgs strahlung (ZH): lepton id
    - H ➛ bb: b-tagging, (di-jet mass resolution)
    - H ➛ ττ: MET resolution, jet tagging, tau id
    - H ➛ γγ: photon id

Talks on status of studies by M. Grimes last week, CMS Upgrade Week

Overview of SUS Studies (D. Stuart)

- We have identified the following SUSY analyses to motivate the upgrades:
  - **γγ+MET**
  - **All-hadronic + b's search with MT2**
  - **Searches with taus**
  - **Stop analysis in single lepton channel**

Important but potentially difficult SUSY searches

Analyses which will benefit from more than one (or all) upgrades

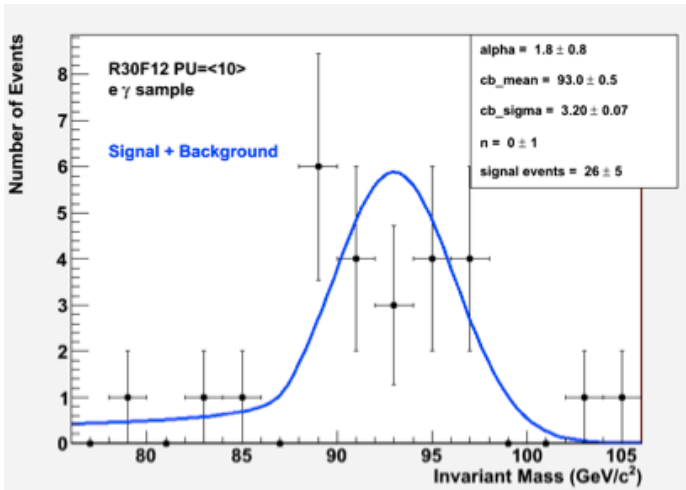
- We will be using our meeting time and/or hold special meetings for this work to be discussed

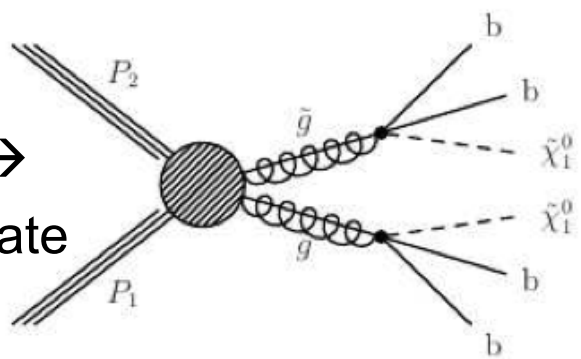
Talks on status of studies by R. Stringer & T. Kamon last week, CMS Upgrade Week

Overview of SUS Studies (D. Stuart)

– Pixels

1. γγ+MET (R. Stringer)
   - – Upgraded Pixel has:
     - » Less material (less conversions)
     - » Fourth layer (another chance for hit in pixel)
   - – Should improve efficiency and fake rate.
2. MT2 + b (ETH)
   - – e.g. could study channels such as T1bbbb →
   - – sensitive to changes in efficiency and fake rate for additional tags beyond the two real b's

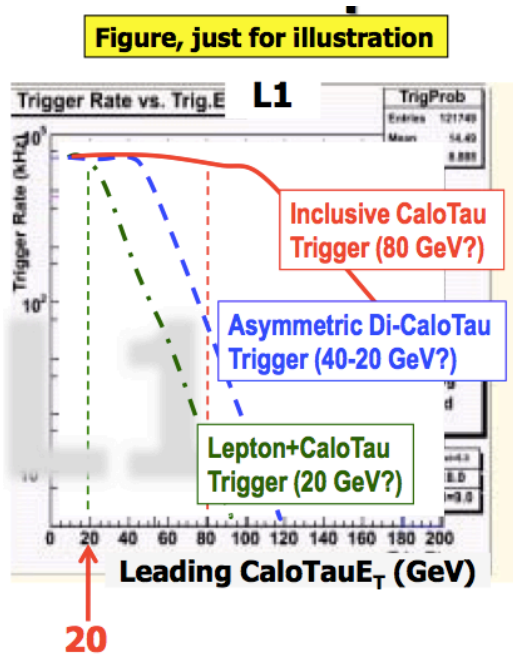


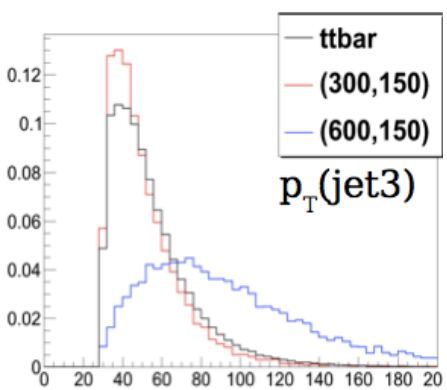


Overview of SUS Studies (D. Stuart)

– L1 trigger

- SUSY benchmarks for studying improvements in tau trigger (T. Kamon)
  - e.g. important for searches with taus especially in all hadronic environment
  - Will rely on flexible requirements of a global trigger
- Issues for compressed SUSY and stop production (P. Bargassa)
  - e.g. important to be able to select low pT leptons and soft jets
- In general, need volunteers to help out (some candidates with interest).





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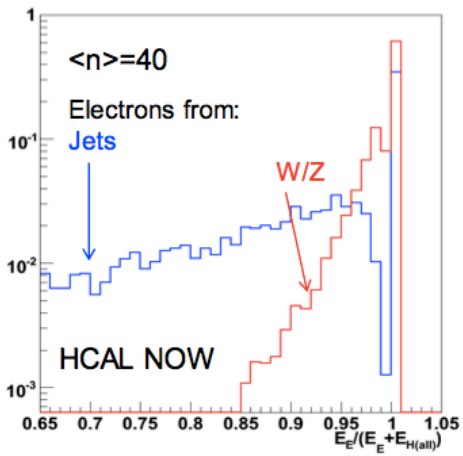
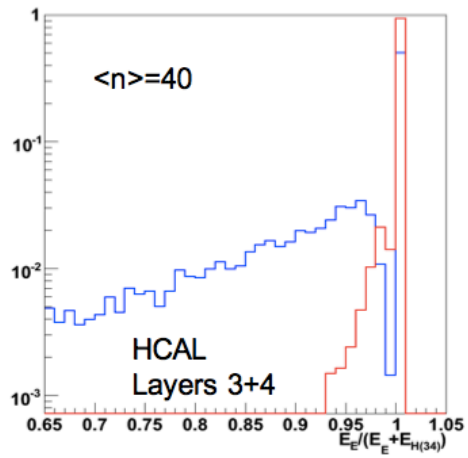
Overview of SUS Studies (D. Stuart)

– **HCAL**

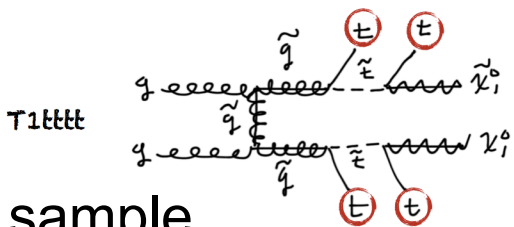
1. γγ+MET (C. Tully, et al)
   – Improvement to photon ID
   

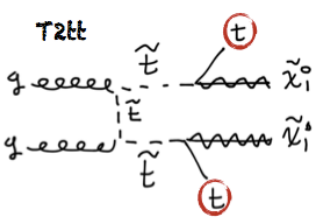
   

      » Current focus is on photon object ID and triggers
      » Separation of layer-0 directly removes the bulk of pileup contributions and their fluctuations from HCAL isolation & H/E
      » Techniques like rho-subtraction suffer from E/H fluctuations
      » HCAL energies have higher S/N – more sensitivity
      » Timing information suppresses out-of-time pileup
   – MET improvements have not been studied

Overview of SUS Studies (D. Stuart)

- **HCAL**
  2. stop analysis using single lepton channel (Rochester, DESY)
     For example:
     - T1tttt
       - » gives 4 b's
       - » likely most sensitivity from the >=3 tag sample
       - » Again, sensitive to changes in efficiency and fake rate for additional tags beyond the two real b's from the dominant top background
     - T2tt
       - » 2 b's just like top
       - » being able to fully reconstruct the event will be important for understanding the background and that will benefit from maintaining efficiency
       - » Lower pT leptons and lower MET challenge
       - » Can also use this analysis to also study the Pixels and/or L1. Need (wo-)manpower





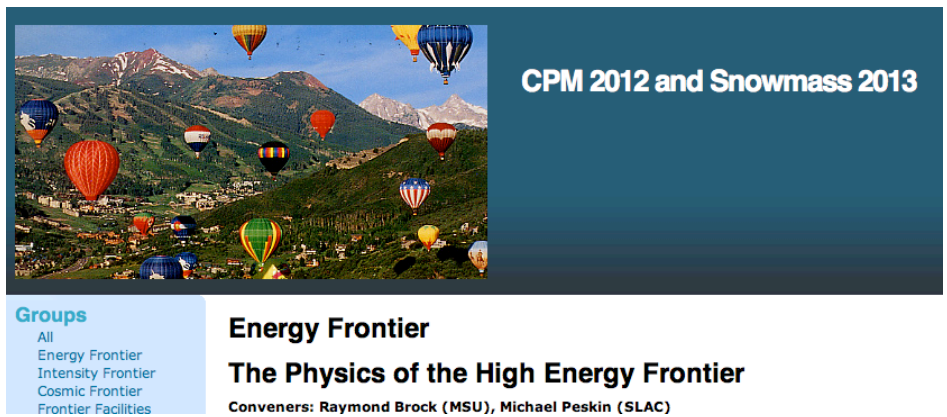
Looking Further Ahead

- The post LS1 (~300 fb^{-1} at 14 TeV) physics case is (while still very dependent on this year's results) relatively easy to define
- The case for HL-LHC (~3000 fb^{-1}) is less easy to state now
  - Nevertheless, must define/update physics goals, supported by (new) studies
  - **Guide detector design; long lead-time for upgrades**
  - **ESPG, Snowmass, TDRs, etc.**
- *As we have been doing for post LS1 studies, need to expand upgrade activities within physics (with offline & computing support) to studies for HL-LHC (and HE-LHC)*
  - Existing efforts being done in upgrade community need to be brought into PAGs
  - PAGs other than HIG, SUS need to get involved **(EXO is starting**)
  - Start POG activities on improvement needed for reconstruction
    - **GED workshop on June 15th**

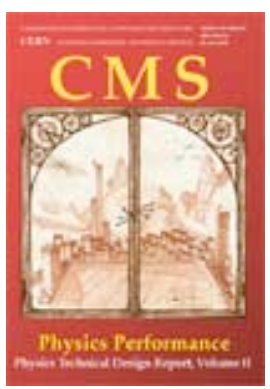
How to organize LS2, LS3+ studies?

- It seems that **dedicated PAG sub-group (a la HIG) is way to go**
- Some efforts already exist at varying levels for various sub-detector upgrades
- As a first step I have emailed each of the PM's to have them bring any ongoing studies to my attention
  - From the responses I have received, it seems there is not so much activity, and what is there is limited to performance studies
  - **Clear that physics has a role to play to bring these activities (or launch them where they are absent) under one umbrella**
    - *Establish (important) physics benchmark measurements/searches for proposals to be evaluated against*
    - *Allow a unified look at performance of the entire upgraded detector rather than sub-systems in isolation - crucial to get best performance for CMS as well as to avoid over-design*

European Strategy Group Report, Snowmass 2013, etc.



- Long term studies are not just for upgrade design and TDRs, also inform national/international strategic planning
  - **HIG, SUS, EXO are preparing studies for European Strategy Group Report due this summer**
  - Next year **in the US, there will be Snowmass 2013** which we should likewise prepare studies for
    - Since more time, analyses can be more elaborate
  - **Perhaps we will produce a new PDTR** next year



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Summary & Next Steps

- **Right now two big questions in LHC physics is EWSB and Naturalness**
  - These questions have guided design & construction of CMS
  - But very soon we will know the answer to the first and not that long after the second
  - **Answers to this will determine HL-LHC program and should guide design of upgrades**
    - *Detector requirements may be different depending on the physics*
- **Structure now in place, and activities launched, to carryout physics studies to support upgrade TDRs**
- But **TDRs are not the end of this story**, beginning to think about **structure that will endure through LS1** and into 13/14 TeV operation (and **planning beyond towards HL-LHC**)
  - Clear that coordination of activities, with input from physics, is needed
  - Opportunity for involvement in studies to shape design of future CMS detector