SEARCH FOR SUPERSYMMETRY IN SAME-SIGN DILEPTONS AT CMS

Advancement to Candidacy Exam

C. A. George

UC-Santa Barbara

June 4, 2013

Outline

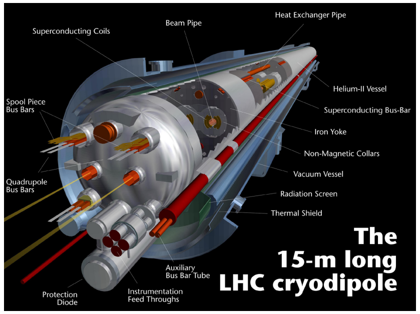
1. The LHC and the CMS Detector
2. Supersymmetry
3. The SS Analysis

Part One:

THE LHC
AND THE CMS DETECTOR

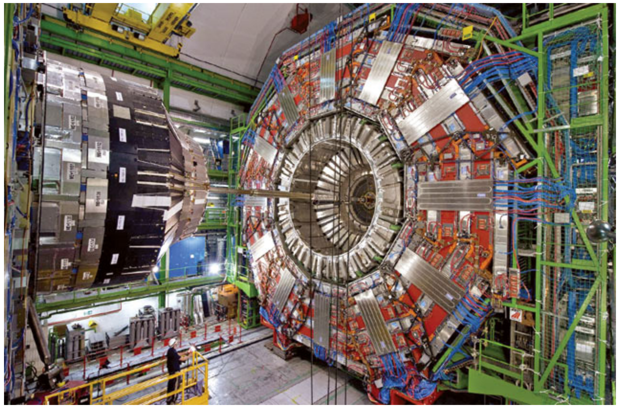
The Large Hadron Collider

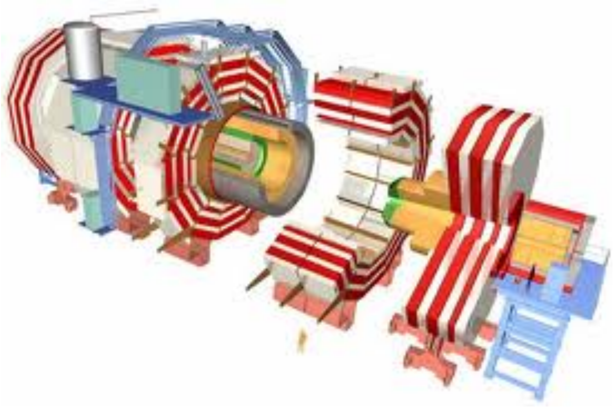
- High-speed proton-proton collisions
  - Collider experiment allows higher center-of-mass energy
  - Each beam will (after upgrades) run at 7 TeV, for a total $\sqrt{s} = 14$ TeV
    - Due to a design flaw in the magnets, currently running at $\sqrt{s} = 8$ TeV
    - This is a lot of energy!
      - One proton has about the same energy as a flying mosquito
      - The beam is broken into “bunches” of 10^{11} protons each – one bunch has about the same energy as an anti-tank shell
  - Circle a ring 27 km in circumference, steered by magnets
    - 1200 dipole magnets (plus 500 quadrupole magnets) of 8.35 T each
    - The magnets are superconducting and must be cooled to 1.9 K
  - The beam operates in a vacuum to avoid collisions with gas molecules



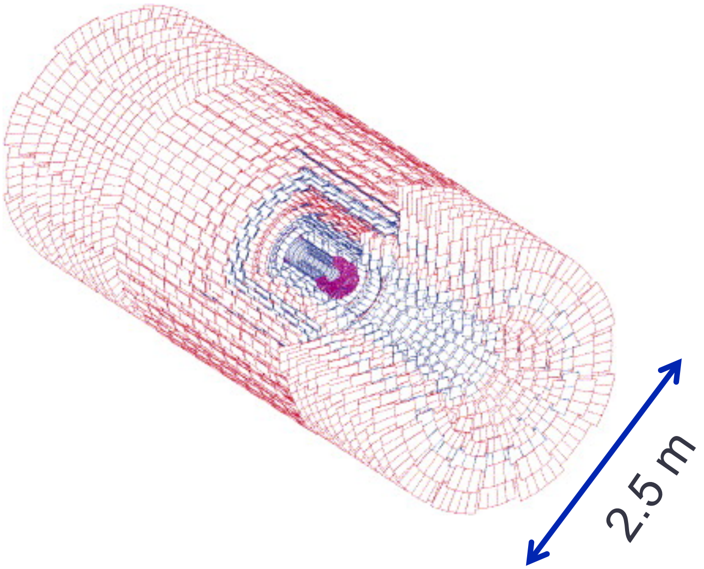
The Compact Muon Solenoid

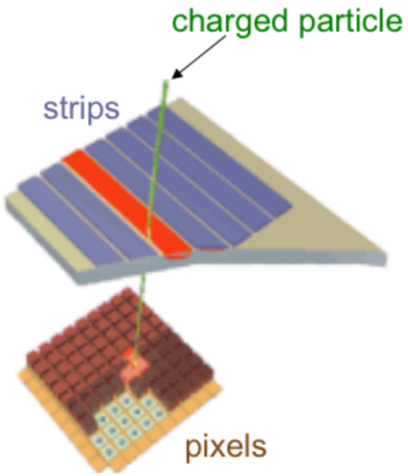
- Solenoidal particle detector
  - Several layers of particle detectors around the interaction point
  - 3.8 T magnetic field for better particle identification
  - Huge detector:
    - 21 m x 15 m x 15 m
    - 11 million kilograms
  - Excellent performance:
    - Spatial resolution of about 10 μm in places
    - Good pile-up response, despite having about 22 separate collisions per crossing, all of which are reconstructed separately
    - 1 TB/sec of data input, reduced to ~100 MB/sec by trigger
    - Remaining events are analyzed offline





CMS: Tracker

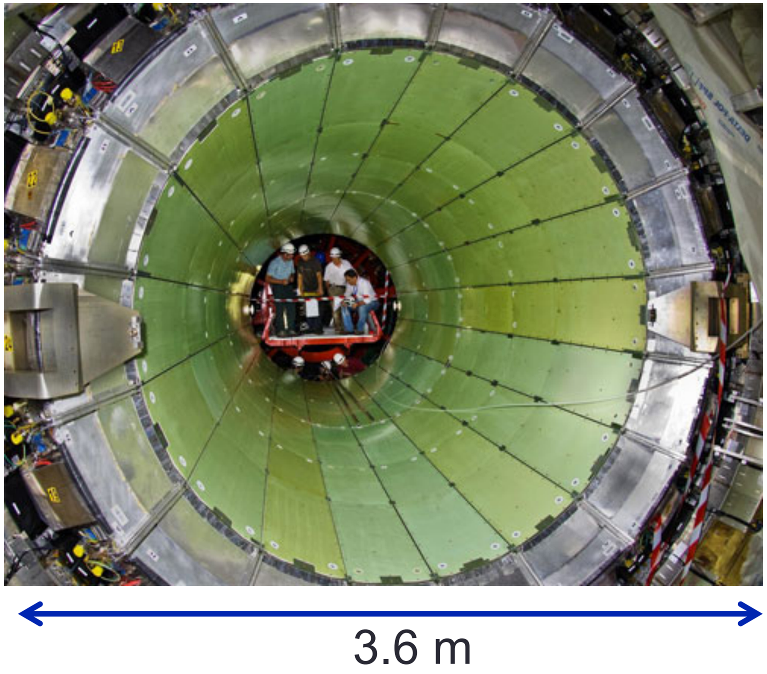


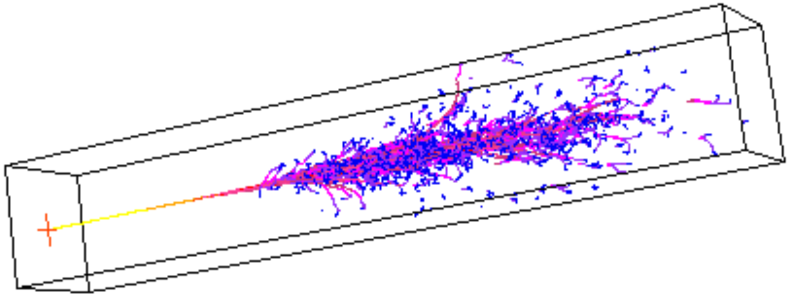


- Silicon tracker to reconstruct particles after collision
  - Charged particles pass through silicon, electrically knock electron-hole pairs loose
  - Electric field collects these at CCDs, where they are measured
  - The pattern of lit pixels allows reconstruction of particle paths
- Two layers:
  - Inner pixel detector: high granularity, but lots of material and high cost
  - Outer strips: less material/cost, but worse resolution
- Sensitive to all charged particles
  - Uncharged particles should pass through without leaving any trace.
- Largest silicon detector ever built
  - Parts will have to be periodically replaced due to radiation damage

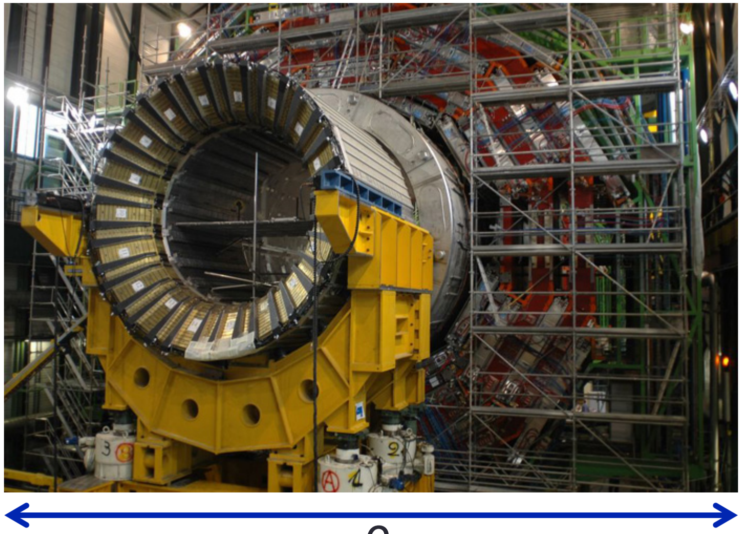
CMS: Electronic Calorimeter

- “Homogeneous” calorimeter filled with 80,000 lead tungstate crystals
    - These “scintillate” (give off light) as particles pass through and give off energy.
    - The light is captured in an avalanche photodiode, which determines the particle’s energy
- Lead tungstate is a good choice
    - The radiation length for electrons and photons is 0.89 cm, so all electrons and photons are stopped here
    - Crystal diameter (~2.2 cm) is comparable to the Molière radius (2.19 cm), so granularity is high.
    - Downside is light amplification is low (5% that of BGO), but photodiodes have enough gain to compensate
- Performance is enhanced by a preshower detector
    - π^0 rejection





CMS: Hadronic Calorimeter



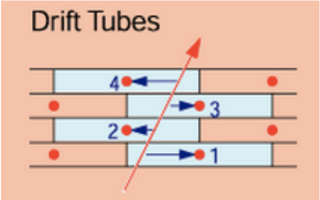
~6 m

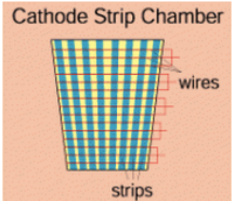
- "Sampling Calorimeter"
  - Steel plates on top and bottom of HCAL
  - Inside, brass layers interspersed with tiles of plastic scintillators
  - Charged particles are slowed and eventually stopped by the metal, and give light in the scintillator.
  - Wavelength-shifting fibers take the light from the scintillator to the photodiodes.
  - The dense metals are sufficient to stop anything except muons and neutrinos
- Four distinct parts:
  - Barrel, endcap: segmented brass
  - Outer: magnet & yoke
  - Forward: near beam axis, Čerenkov-based, 8x more energy per interaction than other parts of HCAL
    - quartz fibers are active medium, interspersed with iron
    - little energy is directly detected, so calibration (Cs-137 or UV light) is needed

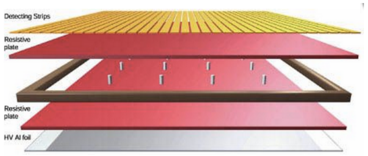
CMS: Muon Detector

- Muon chambers are useful for triggering and muon identification.

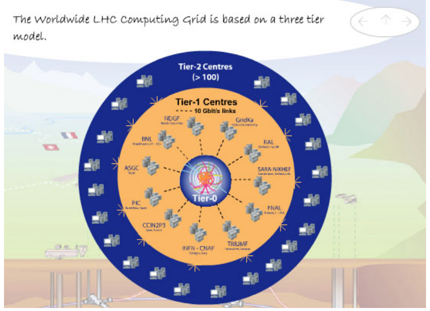
- Three technologies used in parallel:
  - DT (barrel): charged wire surrounded by gas, muons ionize the gas which is attracted to the wire and creates a current
    - resolution of ~150 micrometers
    - lots of material (~10^6 tubes)
    - low cost and well understood
  - CSC (endcap): charged wires and oppositely charged strips in gas volume; gives two position coordinates for each particle.
    - resolution of ~5 mm
    - faster, better with high particle rates and magnetic fields
  - RPC (in parallel with above, used for trigger): two parallel plates separated by gas. Ionized electrons are amplified by the electrodes, the signal is then picked up by a metallic strip.
    - resolution of ~cm
    - great rate capability
    - low cost
    - used for redundancy and a separate trigger system.







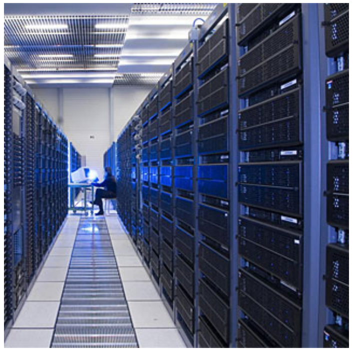
CMS: Trigger & Computing



The Worldwide LHC Computing Grid is based on a three tier model.

- The most interesting events are selected in real time by the trigger.
  - L1 trigger: hardware based, energy deposits in detectors are associated with particle candidates.
  - HLT: software based, partial reconstruction of events, most promising events are recorded
- The result is lots of recorded data: this is fully reconstructed and stored at computing centers worldwide.
  - This is complemented by MonteCarlo simulations, which allow simulation of exotic processes as well as standard model backgrounds.
- About 13 petabytes of data and MC were recorded in 2011 alone.

madgraph



Part Two:

SUPERSYMMETRY

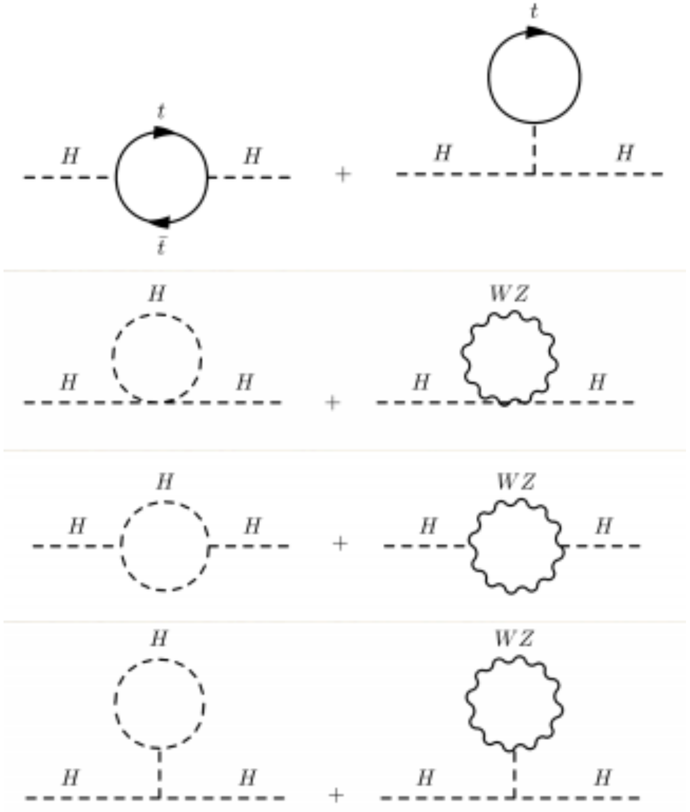
The Naturalness Problem

- These loop diagrams to the left will correct the Higgs mass. The result is:

$$M_H^2 = M_0^2 + \frac{3\Lambda_C^2}{8\pi^2 v^2}\left[M_H^2 + 2M_W^2 + M_Z^2 - 4M_t^2\right] + \ldots$$

- We expect Λ_C to be on the scale of the Planck mass. If so, then these corrections should cause the Higgs mass to be very large.
  - This is obviously not the case, so it follows that we get really really lucky, and the SM masses just happen to cancel.
  - Why does this "fine-tuning" occur?

- To put the problem another way ("hierarchy problem"), why is the weak force 10^{32} times stronger than gravity?



Supersymmetry

- Each fermion has a corresponding boson, and vice versa
  - Obviously broken symmetry; low-mass super-particles would have been found by now

- This would be a nice theory:
  - Solves the naturalness problem by introducing a second Feynman diagram which can cancel the quadratic divergence.
    - Resulting correction would be:

$$\Delta m_H^2 = m_{\text{soft}}^2 \left[\frac{\lambda}{16\pi^2} \ln(\Lambda_{\text{UV}}/m_{\text{soft}}) + \ldots \right]$$

where “soft” refers to the mass scale of “soft” supersymmetry breaking; the masses in the Lagrangian that leads to supersymmetry breaking without introducing new undesired divergences.

  - Would provide dark matter candidate if R-parity is conserved.

- Would expect some SUSY particles at ~TeV scale
  - “Using Λ_{UV} ~ M_P and λ ~ 1 in [this equation], one estimates that m_{soft}, and therefore the masses of at least the lightest few superpartners, should probably not be much greater than the TeV scale, in order for the MSSM scalar potential to provide a Higgs VEV resulting in m_W, m_Z = 80.4, 91.2 GeV without miraculous cancellations.”

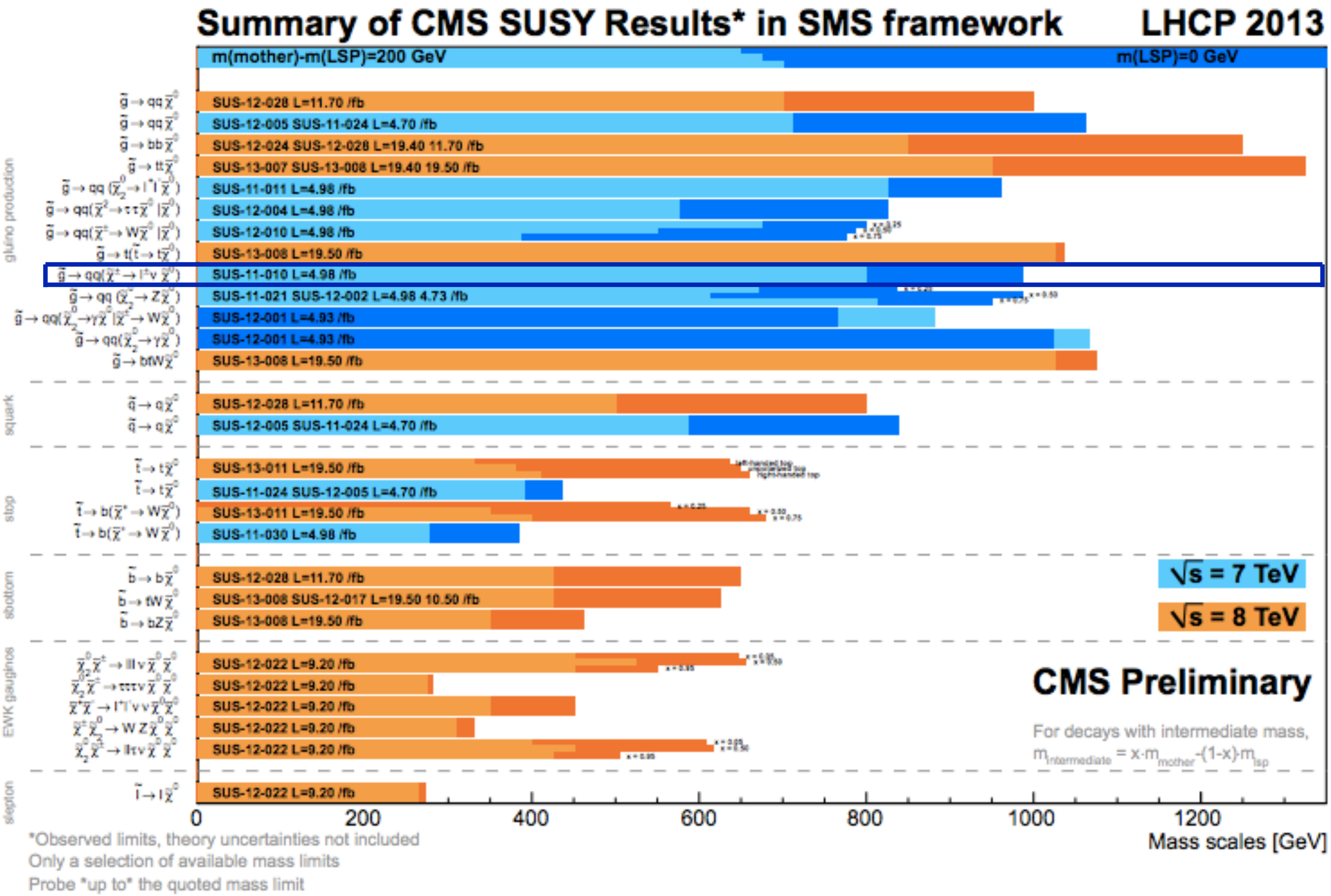
--”A Supersymmetry Primer,” S. Martin

The Search for SUSY

- SUSY had been searched for prior to the LHC:
  - LEP published SUSY exclusions around 2004:
    - Model-dependent
    - In many models, sparticles excluded below ~100 GeV
  - D0 set limits in 2008:
    - Model dependent
    - 379 GeV for squarks (in some models)
    - 308 GeV for gluinos (in some models)
- But all current results come from the LHC:
  - model-dependent
  - many models exclude squarks and gluinos below 1 TeV range.
- Options for SUSY in the absence of evidence:
  1. The "mainstream" models are still right, but the particle masses are higher than our current limits

     (the higher these limits get, the less useful SUSY is for the fine-tuning problem).
  2. Compressed spectrum. If m_{stop} (for example) is just above m_{LSP}, then standard model particles produced will be soft.
  3. Dead.

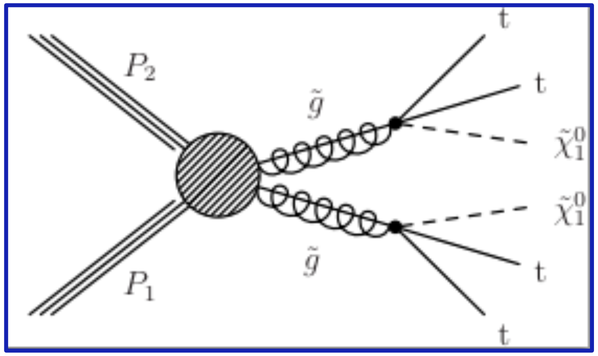
SUSY searches at CMS



Part 3:

THE SS ANALYSIS

Gluino Production



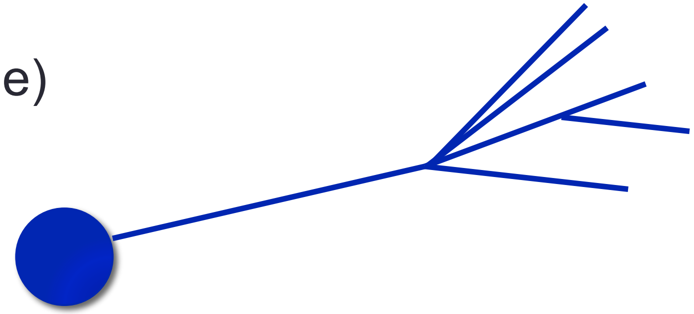
- One potential model of supersymmetry that we could observe at CMS is T1tttt, “gluino production”
- What would we observe?
  - 4 tops, 91% decay into W + bottom. So, likely to get 3-4 b-quarks, **2-3 b-tags**.
  - The 4 Ws will decay, recall about 1/3 of Ws decay leptonically. Works out to 27% chance of **dileptons.**
    - More likely to see fewer leptons, but too much background
    - We also specialize to **same-sign** dileptons; there is too much background in the OS channel due to Zs or ttbar events.
  - The LSP cannot decay if R-parity is conserved, so we expect to see **lots of missing E_T.**
- Our analysis will need to be sensitive to such signals

Data, Definitions

- 19.5 fb^{-1} of validated data
  - must pass dilepton trigger and other cuts that we apply

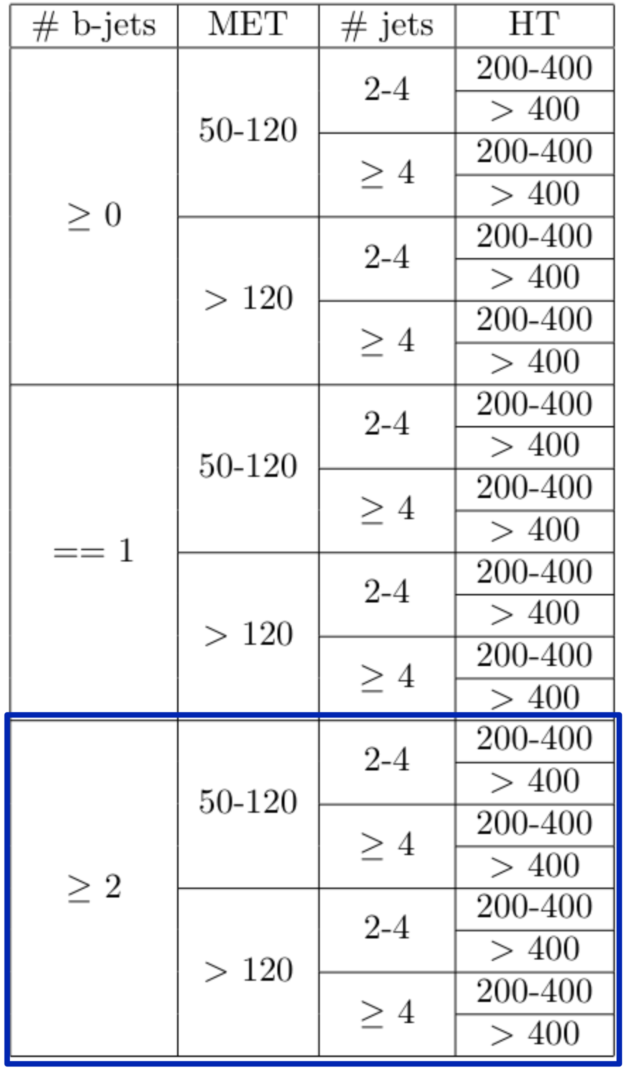
- We are mostly interested in a few observables:
  - njets: number of jets
  - nbtags: number of b-tagged jets
  - H_T: scalar sum of jet p_T
  - MET: vector of missing transverse energy
  - number of leptons: required to be (at least) two, and SS.

- These objects (jets/leptons/bjets) are defined by their:
  - p_T: transverse momentum
  - η: pseudo-rapidity (related to polar angle)
  - ID: how sure we are it's a lepton
  - iso: the degree of separation from other particles



Search Regions

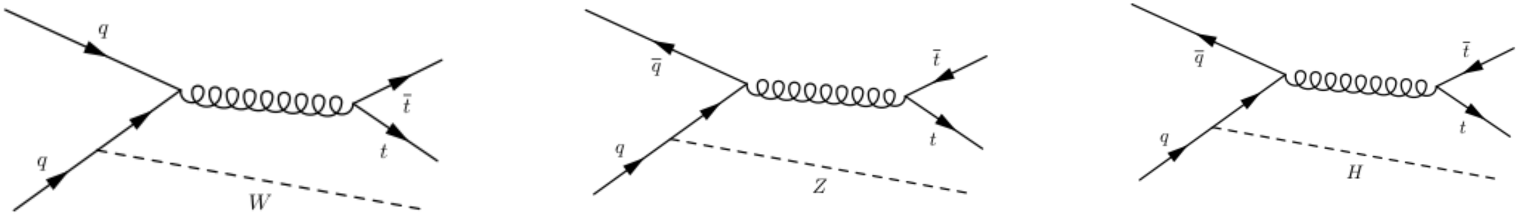
- We define 24 search regions (right):
  - Most SUSY models predict many b-jets, and so we expect most of our information to come from the SRs with # b-jets ≥ 2
- Actually, even more search regions!
  - These 24 regions are considered for different values of lepton p_T: high, low, and very low.
  - We expect RPV and SS top-production models to have less MET and more jets, so we define additional regions with these requirements.
  - Inclusive vs. exclusive search regions
- Here, we focus on the high-p_T analysis with b-jets



# b-jets	MET	# jets	HT
≥ 0	50-120	2-4	200-400
			> 400
		≥ 4	200-400
			> 400
	> 120	2-4	200-400
			> 400
		≥ 4	200-400
			> 400
$== 1$	50-120	2-4	200-400
			> 400
		≥ 4	200-400
			> 400
	> 120	2-4	200-400
			> 400
		≥ 4	200-400
			> 400
≥ 2	50-120	2-4	200-400
			> 400
		≥ 4	200-400
			> 400
	> 120	2-4	200-400
			> 400
		≥ 4	200-400
			> 400

Backgrounds: Rares

- Some standard model processes can produce same sign pairs: ttW, ttZ, or ttH, for example:



- We model these processes in MonteCarlo
  - To avoid contamination with other backgrounds, we use truth-matching
  - To account for differences between the detector and the simulation, scale factors are applied
  - We assign a 50% systematic
    - Campbell & Ellis performed a theoretical study of ttW uncertainties (the largest background, after b-tags). They find that the overall accuracy is 30% at best (NLO), and gets progressively worse as harder cuts on H_T are taken.
- Rares account for 40-60% of our background.

Backgrounds: Fakes

- Fake Lepton:
  - A hadron can fake an electron: for example, a π^+ might look like an e^+.
  - A jet can decay semi-leptonically: this will produce a real lepton, but it's nothing we care about. This is "non-prompt" => fake

- We define tight and loose leptons:
  - Loose: passes relaxed lepton selections ("fakeable object").
  - Tight: loose leptons that also passes full lepton selections.

- T-L Method (slightly simplified):
  - Consider QCD di-jet events (in data).
    - Loose leptons are OK; it's conceivable that a jet or a non-prompt lepton could slightly resemble a prompt lepton
    - But tight leptons are all fakes, as we don't expect any real leptons in this sample
  - We use this to define the fake rate:

    FR = tight/loose
  - Next, we go to our data set. We loop over the fakeable objects and sum over the fake rate per lepton, in order to determine the number of fakes.

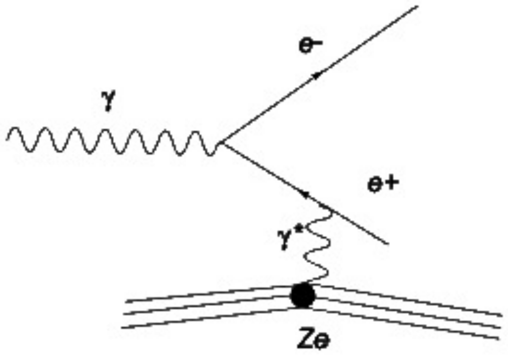
Background: Fakes, continued

- We take several steps to improve the purity of the fake rate definition.
- Then, this method is tested by deriving on QCD MC, and applying to ttbar and W + jets MC.
  - The results of this test are not very good: we over-predict by a factor of 2 in many signal regions. This is not unexpected:
    - Seen in previous iterations of this analysis
    - Small changes in the loose definition or QCD event selection leads to significant changes in prediction.
    - Fake rate is highly dependent on parent parton momentum, which is sample-dependent.
  - We take a 50% systematic.
- Fakes account for 20-40% of our background in many search regions

Backgrounds: Flips

- It is possible to mis-reconstruct the charge of an electron (a “charge flip”).
  - Reconstruction: if electron’s track is slightly mis-reconstructed, show opposite curve in beam
  - Conversion: electron gives (by Bremssstrahlung) a photon, which converts to e^+/e^-

- Flip Rate = Numerator/Denominator
  - Denominator:
    - Dielectron pairs with invariant mass between 76 GeV and 106 GeV
    - Full analysis selections. This includes attempts to reduce charge flips:
      - 3-charge requirement
      - missing hits veto
      - conversion rejection
      - |d0| < 0.01 cm
  - Numerator:
    - must pass all denominator requirements, and
    - SS only (for Z data)
    - truth-matched to a charge flip (in MC)

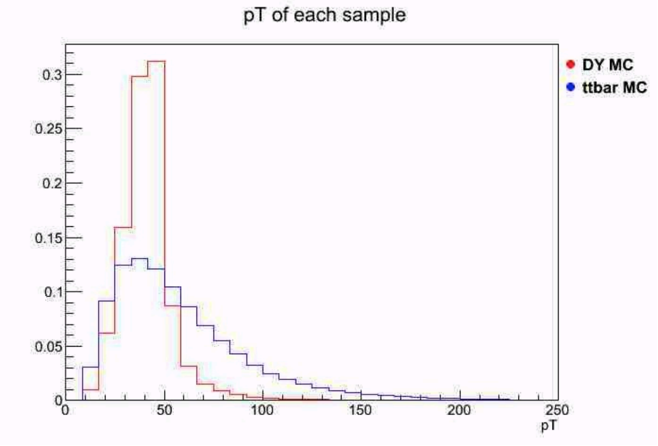


Background: Flips, continued

- We believe that flip rates will depend on p_T and $|\eta|$.
  - At higher p_T, less time to bend in field, so harder to reconstruct track curvature
  - At higher $|\eta|$, more material, so more conversions

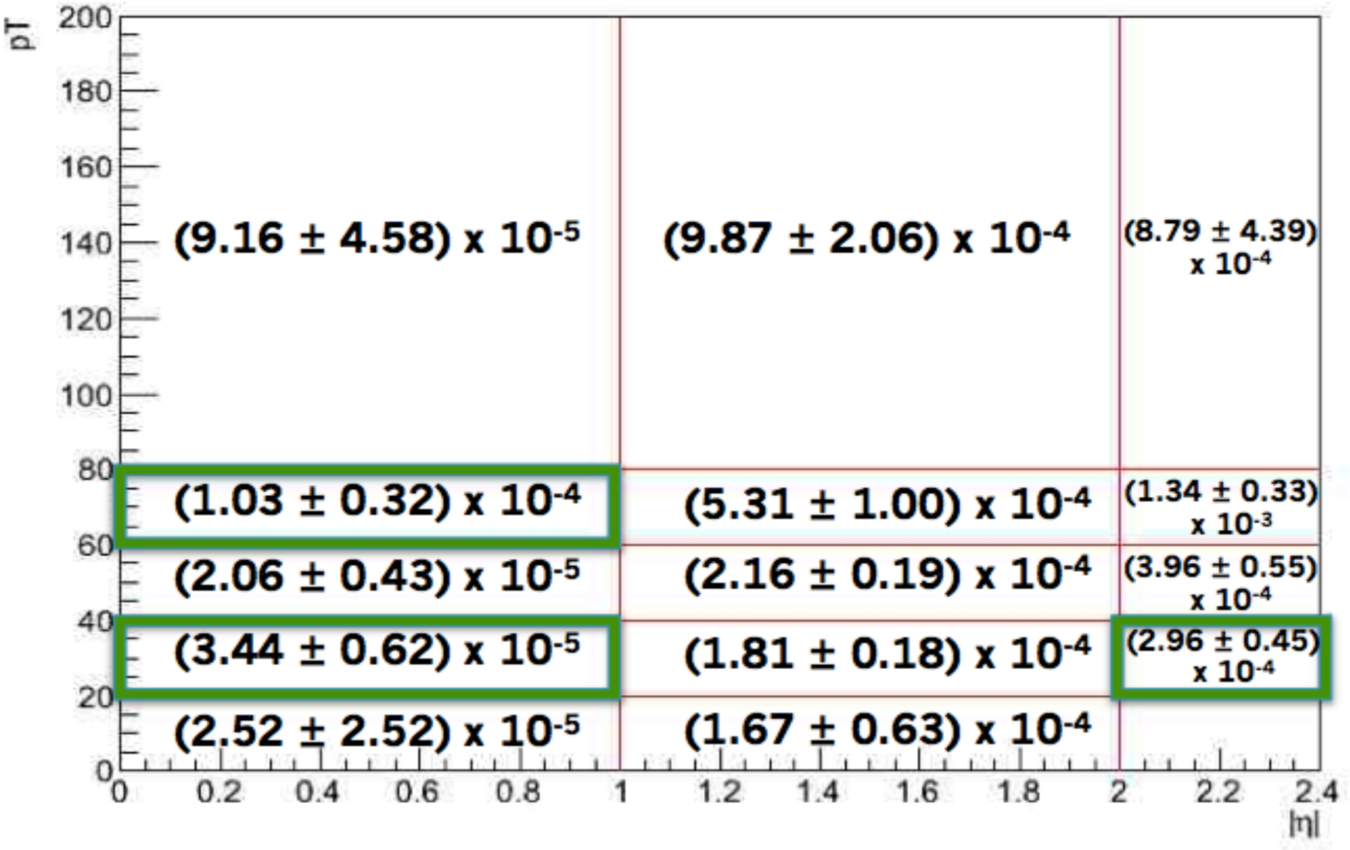
- We choose to measure the flip rate in MC
  - Flip rates in data are easy to measure in Z data, but Z data events have limited range of p_T.
  - We take a combination of DY and ttbar MC; these have a reasonable range of p_T and good statistics.

- Then, the MC-derived flip rate is tested in a data control region



Background: Flips, continued

- The electron flip rate, as a function of p_T and |η|, is given by:



pT \ |η|	0–1	1–2	2–2.4
80–200	$(9.16 \pm 4.58) \times 10^{-5}$	$(9.87 \pm 2.06) \times 10^{-4}$	$(8.79 \pm 4.39) \times 10^{-4}$
60–80	$(1.03 \pm 0.32) \times 10^{-4}$	$(5.31 \pm 1.00) \times 10^{-4}$	$(1.34 \pm 0.33) \times 10^{-3}$
40–60	$(2.06 \pm 0.43) \times 10^{-5}$	$(2.16 \pm 0.19) \times 10^{-4}$	$(3.96 \pm 0.55) \times 10^{-4}$
20–40	$(3.44 \pm 0.62) \times 10^{-5}$	$(1.81 \pm 0.18) \times 10^{-4}$	$(2.96 \pm 0.45) \times 10^{-4}$
0–20	$(2.52 \pm 2.52) \times 10^{-5}$	$(1.67 \pm 0.63) \times 10^{-4}$	

Background: Flips, continued

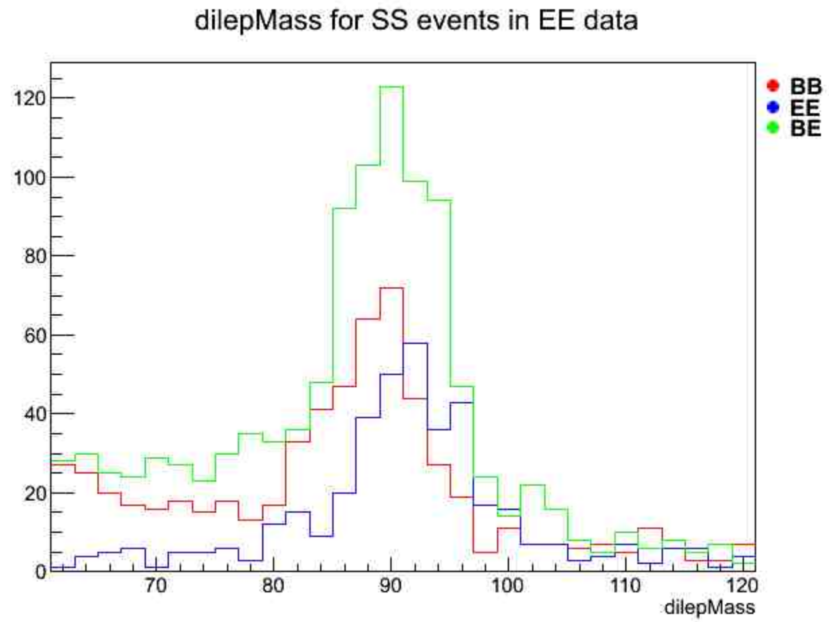
- Next we compare predictions with observations:
  - Observation: **1561** SS events
  - Prediction: loop over each OS event multiplying by:

$$\frac{\text{FR(electron 1)}}{\text{1-FR(electron 1)}} + \frac{\text{FR(electron 2)}}{\text{1-FR(electron 2)}}$$

where the denominator is because:

$$\frac{\text{FR}}{\text{1 - FR}} = \frac{\text{Num}}{\text{Den}} \cdot \frac{1}{1 - \frac{\text{Num}}{\text{Den}}} = \frac{\text{Num}}{\text{Den - Num}}$$

Result is **944** predicted flips



Invariant dilepton mass of the 1561 SS events, and those in sidebands

- Significant discrepancy! Consider the fact that we have nonzero counts outside the Z window ($76 < M_{ee} < 106$).
  - Some of these are actual flips from ttbar or off-shell Z events
  - Some are SM processes that give “honest” SS pairs
  - Others are fakes

Background: Flips, continued

- We assume as an approximation that everything in the upper sideband is a contamination.
  - Extrapolating over the Z window, we take a 16% correction to our number of observed events.

- This reduces our observation from 1561 to 1311
  - Prediction is still 944

- We reconcile these with a scale factor

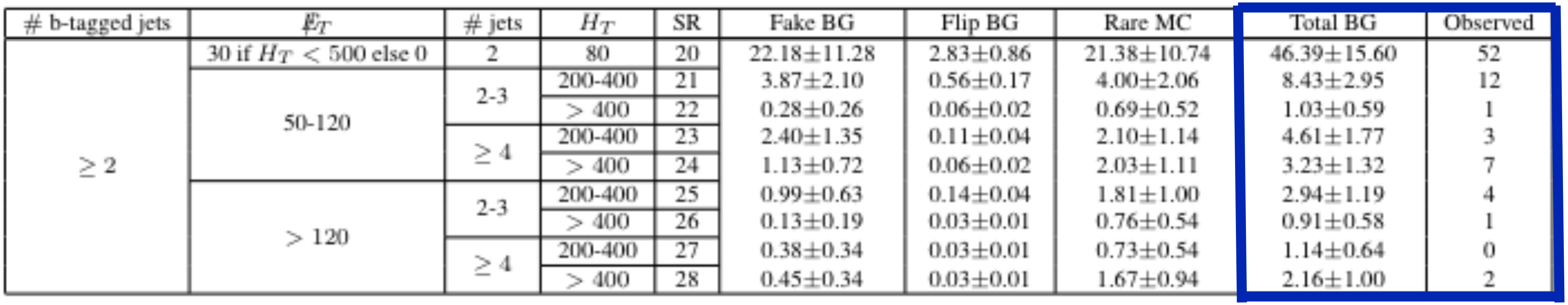
  Scale Factor = 1311/944 = 1.39

- Based primarily on this scale factor, we take a 30% systematic.

- Flips account for 5-10% of our expected background.

Results

- We did not discover evidence of supersymmetry.



# b-tagged jets	$\not\!\!E_T$	# jets	H_T	SR	Fake BG	Flip BG	Rare MC	Total BG	Observed
≥ 2	30 if $H_T < 500$ else 0	2	80	20	22.18±11.28	2.83±0.86	21.38±10.74	46.39±15.60	52
	50-120	2-3	200-400	21	3.87±2.10	0.56±0.17	4.00±2.06	8.43±2.95	12
			> 400	22	0.28±0.26	0.06±0.02	0.69±0.52	1.03±0.59	1
		≥ 4	200-400	23	2.40±1.35	0.11±0.04	2.10±1.14	4.61±1.77	3
			> 400	24	1.13±0.72	0.06±0.02	2.03±1.11	3.23±1.32	7
	> 120	2-3	200-400	25	0.99±0.63	0.14±0.04	1.81±1.00	2.94±1.19	4
			> 400	26	0.13±0.19	0.03±0.01	0.76±0.54	0.91±0.58	1
		≥ 4	200-400	27	0.38±0.34	0.03±0.01	0.73±0.54	1.14±0.64	0
			> 400	28	0.45±0.34	0.03±0.01	1.67±0.94	2.16±1.00	2

Search Region	Total Background	Observed
21	8.43 ± 2.95	12
22	1.03 ± 0.59	1
23	4.61 ± 1.77	3
24	3.23 ± 1.32	7
25	2.94 ± 1.19	4
26	0.91 ± 0.58	1
27	1.14 ± 0.64	0
28	2.16 ± 1.00	2

Limit Setting

- Last step is to set a limit on the T1tttt process
- CL$_s$ “shape analysis” with all 8 high-p$_T$ search regions with at least 2 b-tags
  - Our likelihood function is:

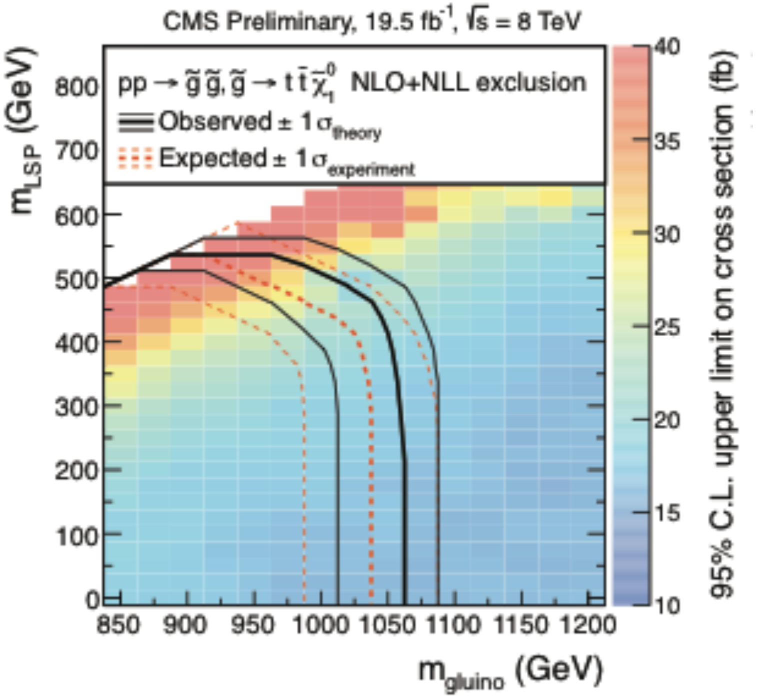
$$\text{Poisson}\left(\text{data}|\mu\cdot s(\theta)+b(\theta)\right)=\prod_i \frac{(\mu s_i+b_i)^{n_i}}{n_i!}e^{-\mu s_i-b_i}$$

    - where data is the observed yield, and:

$$\mathcal{L}(\text{data}|\mu,\theta)=\text{Poisson}\Big(\text{data}|\mu\cdot s(\theta)+b(\theta)\Big)\cdot p\left(\hat{\theta}|\theta\right)$$

    - Calculate acceptances and systematics in each region independently, then combine results in shape analysis

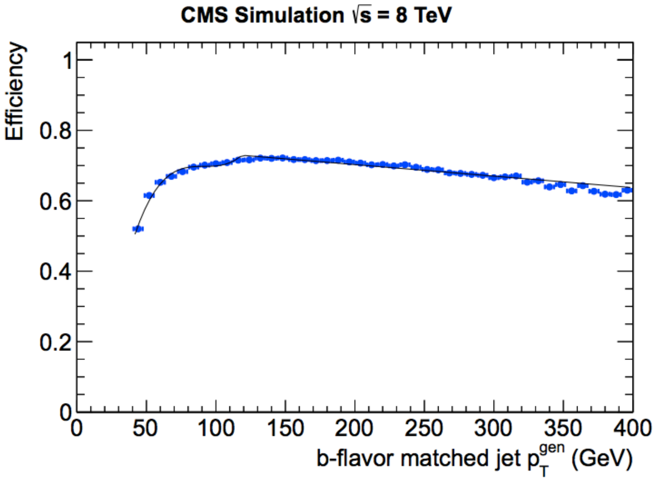
- The resulting exclusion curve is:

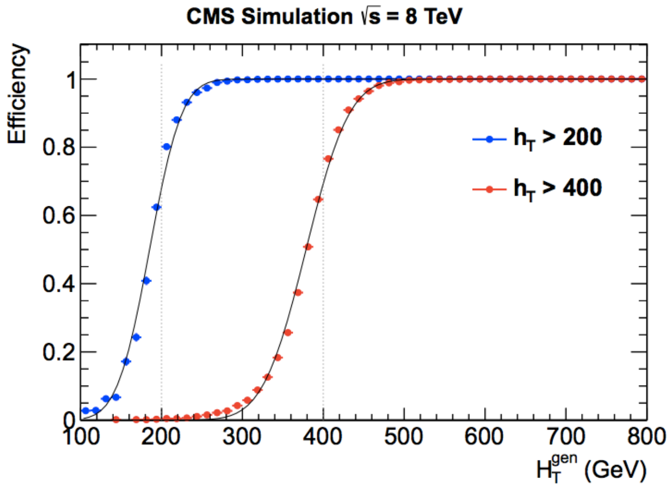


Outreach

- Given a generated event, what are the odds that our analysis will be sensitive to it?
  - This is an interesting question, because theorists can generate events using their favorite model, apply our efficiencies, and determine if the theory is consistent with observed results

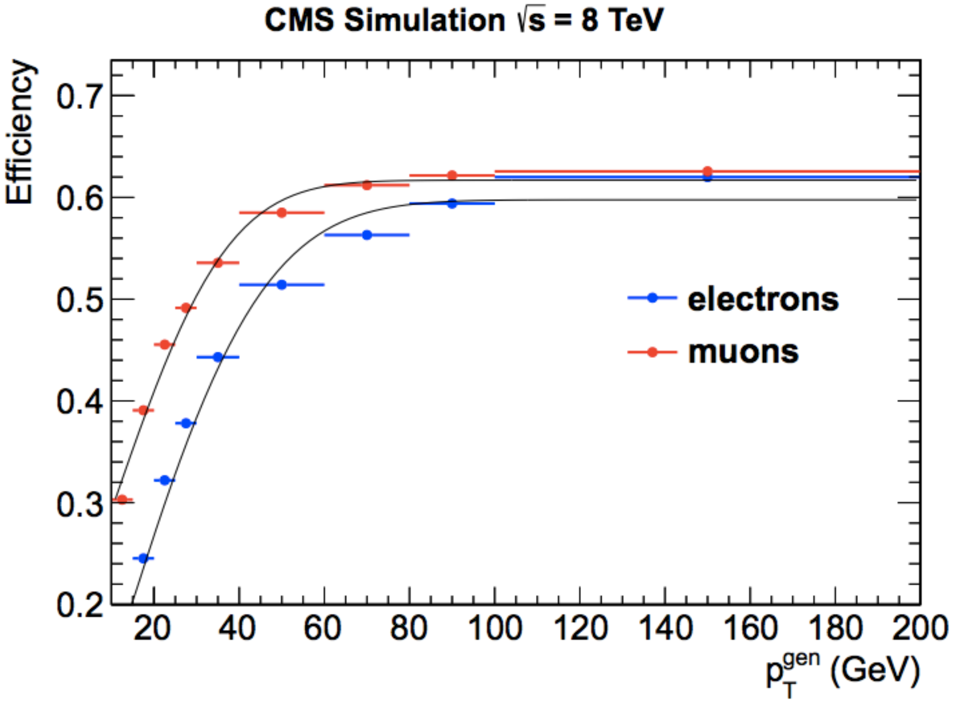
- We measure efficiencies as the likelihood that an event passing generator-level selections also passes the corresponding selections using offline reconstruction quantities
  - We derive the model from the T1tttt sample.





Outreach, continued

- Denominator: all generated events that pass selections for any of our signal regions
- Numerator: all denominator events that pass reconstruction lepton ID requirements
  - apply all needed scale factors, etc.

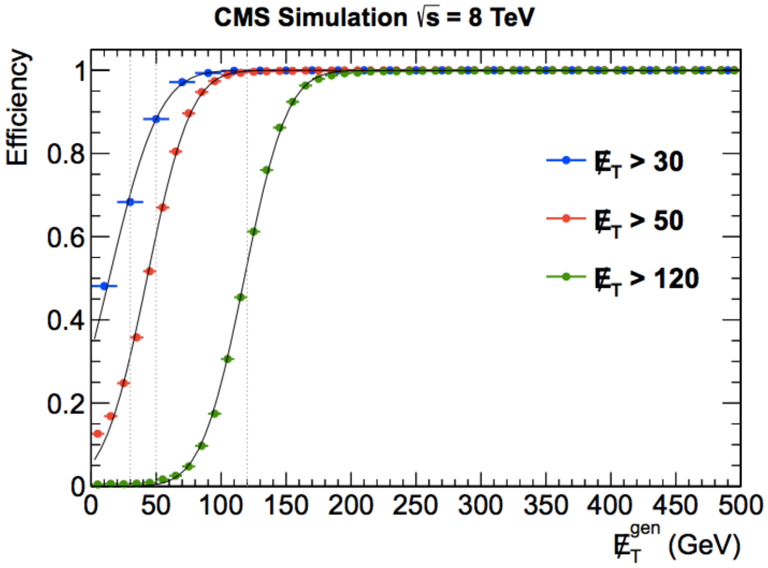


$$\mathrm{eff} = A\,\mathrm{erf}\left(\frac{x-20}{B}\right) + C\left[1 - \mathrm{erf}\left(\frac{x-20}{B}\right)\right]$$

	A	B	C
electron	0.6682	46.9272	0.449973
muon	0.6982	23.7055	0.601643

Outreach, continued

- We make similar curves for:
    - jet reconstruction
    - b-tagging efficiency
    - MET cut efficiency (right)
    - H_T cut efficiency
- Then we perform a closure test, looping over the generated T1tttt sample and applying the scale factors.
    - Closed to 99.8%.
- We tested further by applying to T1tttt search regions, as well as search regions for a different model (T6ttww, “sbottom production”).
    - Results are to the right, most regions close to within 30%.



SR	$T1tttt$	$T6ttWW$
SR 21	0.81 ± 0.09	0.74 ± 0.07
SR 22	1.43 ± 0.17	0.79 ± 0.05
SR 23	0.77 ± 0.04	0.79 ± 0.05
SR 24	0.97 ± 0.02	0.83 ± 0.02
SR 25	0.81 ± 0.07	0.77 ± 0.06
SR 26	1.17 ± 0.07	0.95 ± 0.05
SR 27	0.88 ± 0.04	0.90 ± 0.04
SR 28	1.03 ± 0.01	0.82 ± 0.01

Acknowledgements

The analysis I discussed here (CMS AN 2013/120) is a collaborative effort among the following:

C. Campagnari, A. George, F. Golf, J. Gran, D. Kovalskyi,
V. Krutelyov, R. Magaña-Villalba
(UCSB)

G. Cerati, D. Evans, R. Kelley, I. MacNeill, D. Olivito, S. Padhi,
M. D'Alfonso, Y. Tu, C. Welke, F. Würthwein, A. Yagil, J. Yoo
(UCSD)

L. Bauerdick, K. Burkett, I. Fisk, Y. Gao, O. Gutsche,
B. Hooberman, S. Jindariani, J. Linacre, V. Martinez Outschoorn
(FNAL)

BACKUP

Part One:

THE LHC
AND THE CMS DETECTOR
(BACKUP)

Collider vs. Fixed Target Experiments

- In a collider experiment, the center of mass frame is the lab frame. Thus:

$$p_1 = -p_2 = (E_{cm}, \vec{p}_{cm})$$
$$p_1 + p_2 = (2E_{cm}, 0)$$
$$s = 4E_{cm}^2$$

- In a fixed-target experiment, the center of mass frame is different from the lab frame:

$$p_1,\ \mathrm{lab}{=}(E_1,\ \vec{p}) \qquad p_2,\ \mathrm{lab}{=}(M{,}0)$$
$$(p_1 + p_2)_{\mathrm{lab}} = (E_1 + M, \vec{p}) = \left(E_1 + M, \sqrt{E_1^2 - M^2}\right)$$
$$s = 2E_1M + 2M^2$$

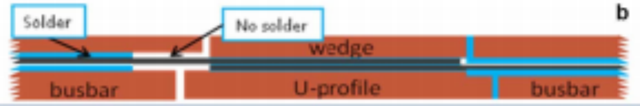
- Equating the invariant, we find:

$$E_1 = \frac{2E_{cm}^2}{M} - M^2$$

- Thus, to go from two beams to one beam, we have to (approximately) square the beam energy, not double it as we might have hoped.
  - This is why fixed-target experiments are so rare, despite the practical advantages.

“The Incident”

- September 2008: Magnetic field is being increased to ~6.5 T.
  - Unknown to the physicists, one of the connections between the magnets had developed a resistance 367 times too high
  - The resistance caused the supplied current to fall. Without moving charges, the magnetic field started to decrease, and with it all the energy stored in the magnetic field had to be released as heat.
  - This heat caused the superconductor to “quench”, or become non-superconducting. The conductor can no longer sustain the very high currents, and will quickly be damaged.
- There was a safeguard in place.
  - Voltmeters should immediately detect the quench
  - Diodes should immediately move the current away from the magnets
  - Dump resistors should burn the current in ~104 s.



- But, there were some bad contacts between the magnet and the stabilizer.
  - As a result, the magnet continued to be exposed to the current for the ~104 s it took to burn the energy.
  - It was able to last only 1 s.
  - After that, an electrical arc (lightning) developed
  - This punctured the helium
  - Then the temperature rose and other magnets quenched
  - The beam vacuum was penetrated, causing forces such that the magnets were ripped from the floor

Upgrades in 2013-14

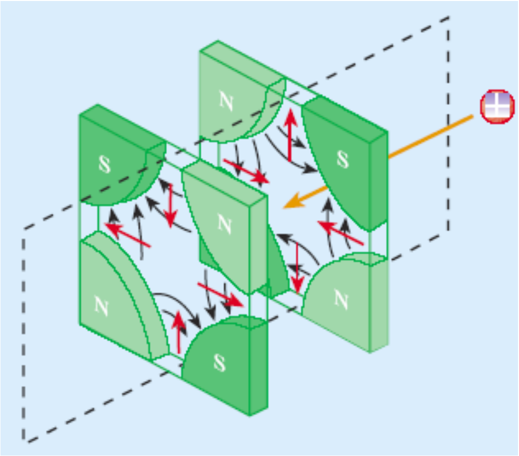
- Pixel System replaced
  - New tracker designed:
    - Four layers in barrel (as opposed to three); three endcap discs (as opposed to two)
    - New optical readout electronics
    - Replace C_6F_{14} cooling system with CO_2 evaporation
    - Performance at PU = 60 will be better than current performance at PU = 25
  - A slice of this is going to be inserted this year for *in situ* validation

- HCAL upgrades
  - Replace photodiodes with silicon photomultipliers
  - Upgrade to multi-anode photodiodes
  - New optical links
  - Should allow upgrades to trigger

- Spectacular results expected:
  - HCAL will refine lepton isolation measurements, MET
  - New pixel detector will improve signal by 60-140% in some regions

Superconducting Magnets

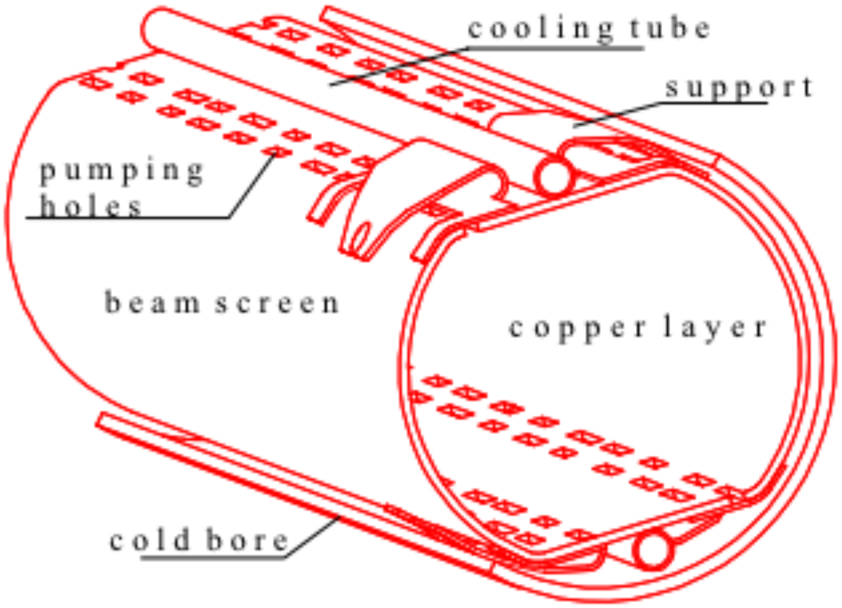
- How do superconductors work? (BCS theory, in a nutshell)
  - BCS pairs/Cooper pairs: incoming electrons attract many protons from the surrounding material. Due to mutual proton attractions, the electrons form pairs despite their mutual repulsion.
  - Quantum mechanically, it is an electron/phonon interaction.
  - These pairs form bosons, so many of them can exist in the same state simultaneously
  - Low temperatures are required, as the pairing interaction is only on the order of meV; thermal energy could easily break this.
  - These cooper pairs form and break up often, but the overall effect – one electron moving with no resistance – propagates
- The LHC uses superconducting magnets: dipoles to turn the beam, quadrupoles to focus it.



The LHC Vacuum

- Very necessary:
  - Collisions with gas molecules could introduce background and damage equipment
  - Synchotron radiation will produce heat; heat needs to be removed to prevent magnetic quench

- Operation
  - Cryodynamic pumping will achieve the vacuum
  - Beam screen will absorb heat from synchrotron radiation



CMS: Trigger

- Reduces, online, data rate by a factor of ~10^6

- Example: triggering on an electron.

  L1

  - 25 ECAL crystals are connected to one trigger tower.
  - The trigger towers send their information “trigger primitive” to the regional calorimeter trigger, which combines trigger primitives to form trigger candidates
  - The global calorimeter trigger chooses the four most energetic candidates
  - The global trigger applies threshold cuts (H/E, E_T, iso); gives final L1 decision.

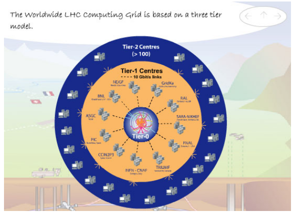
  HLT

  - L2: clusters energy in ECAL and estimates electron’s energy and position. Reject if location is bad or E_T is too low.
  - L2.5: require track in ECAL to match in pixel detector only
  - L3: full tracker reconstruction, require good match to high-p_T track, E/p rejection, further H/E cuts.

CMS: Trigger, again

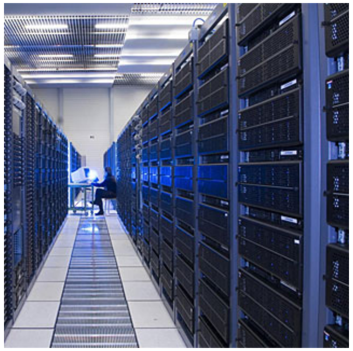
- Two components, each with 1/1000 acceptance rate:
  - Level-One (L1): Hardware, FPGA based
  - High-Level (HLT): Software, farm of computers, similar capabilities as offline analysis
- L1 trigger:
  - looks for energy deposits in the calorimeters or muon chambers
  - assembles a ranked list of trigger objects, such as electron or muon candidates
  - uses data based on algorithms and the trigger readiness to make a decision
- HL Trigger
  - L2: reconstruction in the calorimeters and muon chambers
  - “L2.5”: partial reconstruction in the tracker pixels. Little time for Bremssstrahlung; before most material, so few conversions.
  - L3: full tracker reconstruction, trick is to recover all energy.
- New crossing every 25 ns, so no component can take longer than that, or bottleneck will result.

CMS: Computing



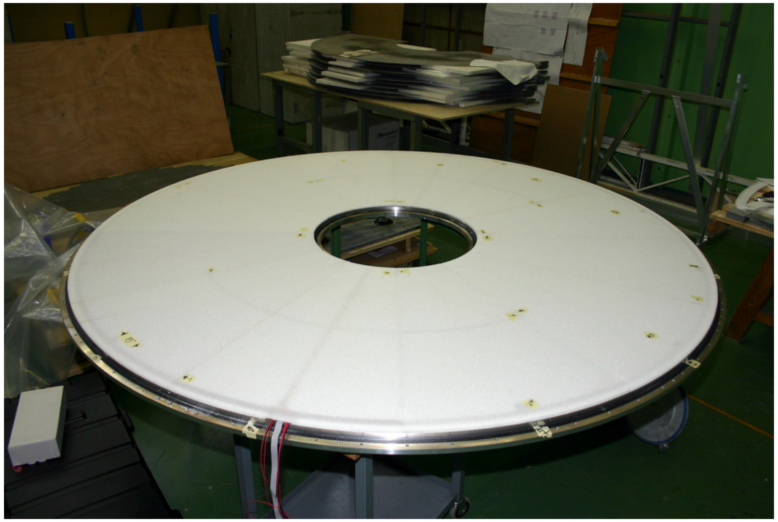
The Worldwide LHC Computing Grid is based on a three tier model.

madgraph



- The result of this is a large amount of data, which must be processed:
  - RAW, detector readout and trigger information
  - RECO, reconstruction of object and cluster candidates from raw data
  - AOD, subset of RECO
- In addition to data, CMS must make predictions against which the data can be compared. These are done via Monte Carlo simulations:
  - Software such as Madgraph, Pythia, and Geant decay the particle and simulate the detector’s reaction to the process.
  - The simulated detector readouts are then reconstructed in the same way as the data: RAW, RECO, AOD.
- This is a huge logistical challenge; it is not unusual to produce millions of events for each of dozens of points in parameter space.
  - In 2011, 1.7 PB of data, 1.4 billion events in prompt AOD
  - In 2011, 11.5 PB of MC

ECAL: Preshower Detectors



- Preshower Detectors:
  - Pion problem: what if a pion decays into 2 photons? The photons are so boosted that they might appear to be one, high energy particle, like an electron.
  - The problem is compounded because the ECAL crystals are 3 cm wide!
  - Preshower has two layers of lead (which start shower), followed by silicon detector.

Part Two:

SUPERSYMMETRY (BACKUP)

Planck Mass

- Defined by:

$$m_P = \sqrt{\frac{\hbar c}{G}} \approx 1.2209 \times 10^{19} \mathrm{GeV/c^2}$$

  - about the mass of a flea egg

- Significance:
  - scale at which quantum effects become important

Hierarchy Problem & Fine-Tuning

- Recall Fermi's constant, the coupling constant for the 4-point V-A interaction in weak decay:

$$\frac{G_\mathrm{F}}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{m_\mathrm{W}^2} = 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^{-2}\ .$$

- This is related to the Higgs Vacuum Expectation Value.
  - The SU(2) x U(1) symmetry is spontaneously broken when we give our Higgs a potential, such as:

$$V(\phi) = \frac{1}{4}\lambda(\phi^\dagger\phi - \frac{1}{2}v^2)^2$$

  - Eventually, we recognize that in order to renormalize, we must rewrite the current 4-vector in the SU(2) symmetry in terms of A, Z, W, and H. The potential becomes:

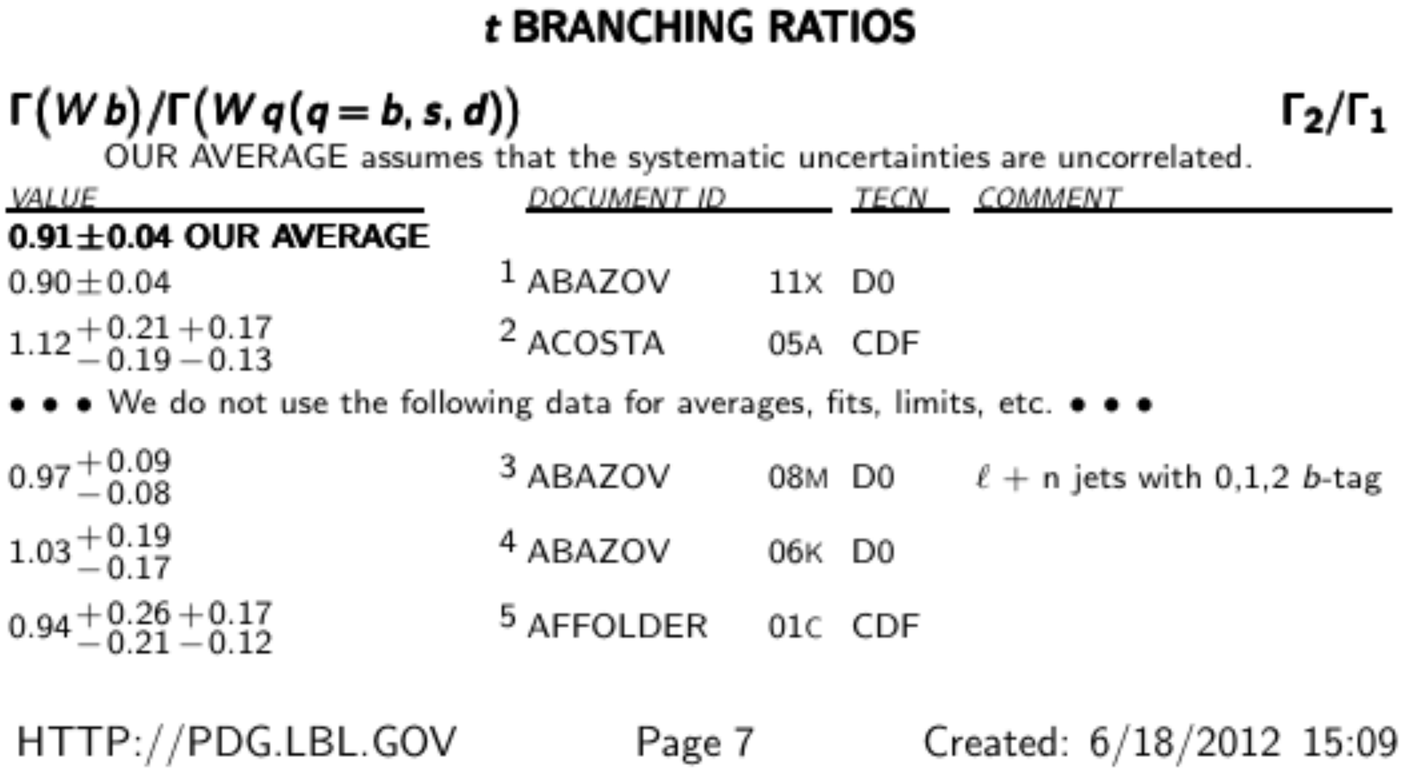
$$V(\phi) = \frac{1}{4}\lambda v^2 H^2 + \frac{1}{4}\lambda v H^3 + \frac{1}{16}\lambda H^4$$

  - This allows us to recognize:

$$m_H^2 = \frac{1}{2}\lambda v^2$$

  - where λ ~ G_F. Thus, the Higgs mass is related to the strength of the weak coupling, and so the hierarchy problem logically implies the quadratic divergence problem.

Top Quark Decays



t BRANCHING RATIOS

$\Gamma(Wb)/\Gamma(Wq(q=b,s,d))$ Γ_2/Γ_1

OUR AVERAGE assumes that the systematic uncertainties are uncorrelated.

VALUE	DOCUMENT ID	TECN	COMMENT
0.91 ± 0.04 OUR AVERAGE			
0.90 ± 0.04	[1] ABAZOV 11X	D0	
$1.12^{+0.21}_{-0.19}{}^{+0.17}_{-0.13}$	[2] ACOSTA 05A	CDF	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.97^{+0.09}_{-0.08}$	[3] ABAZOV 08M	D0	ℓ + n jets with 0,1,2 *b*-tag
$1.03^{+0.19}_{-0.17}$	[4] ABAZOV 06K	D0	
$0.94^{+0.26}_{-0.21}{}^{+0.17}_{-0.12}$	[5] AFFOLDER 01C	CDF	

HTTP://PDG.LBL.GOV Page 7 Created: 6/18/2012 15:09

Part 3:

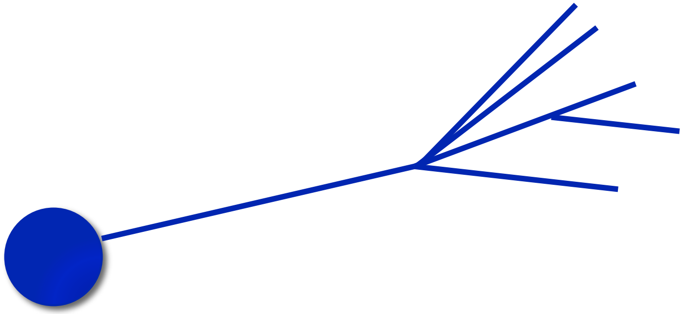
THE SS ANALYSIS (BACKUP)

Data & Baseline Event Selections

- 19.5 fb^{-1} of validated data
- Unprescaled Dilepton Trigger
  - Trigger is not perfect:
    - efficiency ranges from 81 to 96 percent
    - scale factors are taken to compensate in MC.
- Require dilepton pair
  - Matched to same good vertex
  - If more than one, choose pair with most muons. If still ambiguous, choose one with highest scalar-sum of p_T.
- Vetos to remove background:
  - General: Veto events with dilepton mass < 8 GeV
  - WZ: Veto events that have a third lepton which forms a OS Z candidate with either of the dileptons in the SS pair.
  - γ^*: same as above, except the OS pairs is vetoed if invariant dilepton mass is below 12 GeV.
- H_T/MET requirement:
  - RPV models predict many jets and low MET. So, if $H_T > 500$ GeV, then no MET requirement.
  - Otherwise, we expect a W decay into a neutrino, so MET > 30 cut

Object Definitions

- Electrons/Muons
  - p_T > 20 GeV, $|\eta|$ < 2.4
  - Relative isolation < 0.09/0.10
  - Impact parameter < 100/50 μm
  - Prompt
  - Various identification requirements, as approved by POG
    - Also a few others!
- Jets
  - Reconstructed with anti-kT algorithm
  - Particle-flow jets, loose pfJet ID requirement
  - p_T > 20 GeV, $|\eta|$ < 2.4
  - ΔR(lepton, jet) > 0.4
  - L1FastL2L3(residual) corrections
- B-tags:
  - b-quarks are long-lived (~10^{-12} s) enough to travel a few mm.
  - the b is much heavier than anything it decays into, so the resulting jets should have high momentum.
  - The CVSM tagger decides whether jets are b-tagged



Identification

- Electrons
  - |d0| < 0.01 cm
  - valid vertex
  - no missing hits
  - H/E < 0.1/0.075 in barrel/endcap
  - |eta| < 2.4
  - $\Delta R > 0.1$ with respect to any muon passing muon selections
  - dZ < 0.1 cm (z-coordinate of GSF track within 1 mm of primary vertex)
  - missing expected inner hits must be zero
  - Conversion rejection. Reject vertices if:
    - No tracker hits toward beam
    - Fit probability above 10^{-6}
    - Displacement above 2 cm
    - CTF track matching to electron is part of conversion vertex.
  - SuperCluster/Track have $d\eta < .004/.007$, $d\varphi < 0.06/0.03$
  - Weighted cluster RMS < 0.01/0.03
- Muons
  - at least one matched muon station
  - χ^2/ndof < 10
  - >5 silicon layers
  - >0 valid pixel hits
  - |d0| < 0.005 cm
  - |dZ| < 0.1 cm
  - ECAL energy deposit < 4 GeV
  - HCAL energy deposit < 6 GeV

Rapidity

- A Lorentz Boost can be represented by:

$$\begin{pmatrix} t' \\ x' \end{pmatrix} = \begin{pmatrix} \cosh\phi & -\sinh\phi \\ -\sinh\phi & \cosh\phi \end{pmatrix} \begin{pmatrix} t \\ x \end{pmatrix}$$

- where

$$\gamma = \cosh\phi$$

$$\beta\gamma = \sinh\phi$$

- We also have:

$$E = mc^2 \cosh\phi$$

$$|\vec{p}| = mc \sinh\phi$$

- Thus:

$$\phi = \tanh^{-1}\frac{|\vec{p}|}{E} = \frac{1}{2}\ln\left[\frac{E+|\vec{p}|}{E-|\vec{p}|}\right]$$

  - We sometimes define p to be the component along the beam axis rather than the total p.

- We prefer to use rapidity rather than speed:
  - Can add rapidities linearly

- By modifying the formula slightly (little effect in high-energy limit), we have pseudorapidity, which is a function only of the polar angle.

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

- We prefer to use pseudorapidity rather than polar angle, because rapidities are a Lorentz-invariant phase space.
  - Particles are produced uniformly in CM frame, but boosted in lab frame
  - Thus, lab frame sees non-flat particle distribution in polar angle space – but flat in pseudorapidity space.

Pseudorapidity from Rapidity

Claim:

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

Proof:

$$\eta = -\ln\left(\frac{\sin\theta}{1+\cos\theta}\right)$$

$$\eta = \ln\left(\frac{1+\cos\theta}{\sin\theta}\right)$$

which from geometry is

$$\eta = \ln\left(\frac{p_L + p_{tot}}{p_T}\right)$$

Next:

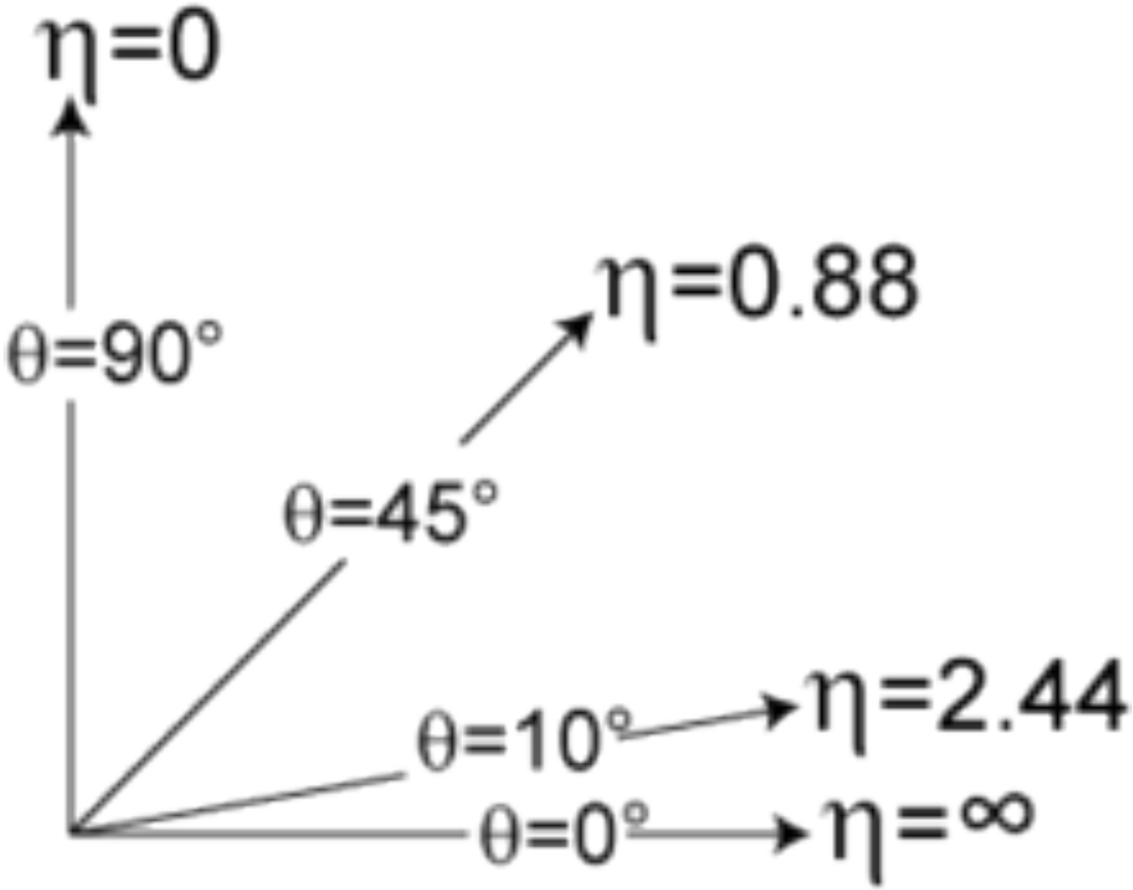
$$\eta = \ln\left(\frac{p_L + p_{tot}}{\sqrt{p_{tot}^2 - p_L^2}}\right)$$

$$\eta = \ln\left(\frac{\sqrt{p_{tot} + p_L}}{\sqrt{p_{tot} - p_L}}\right)$$

$$\eta = \frac{1}{2}\ln\left(\frac{p_{tot} + p_L}{p_{tot} - p_L}\right)$$

which, as advertised, is the same as rapidity in the high-energy limit, where p_{tot} --> E

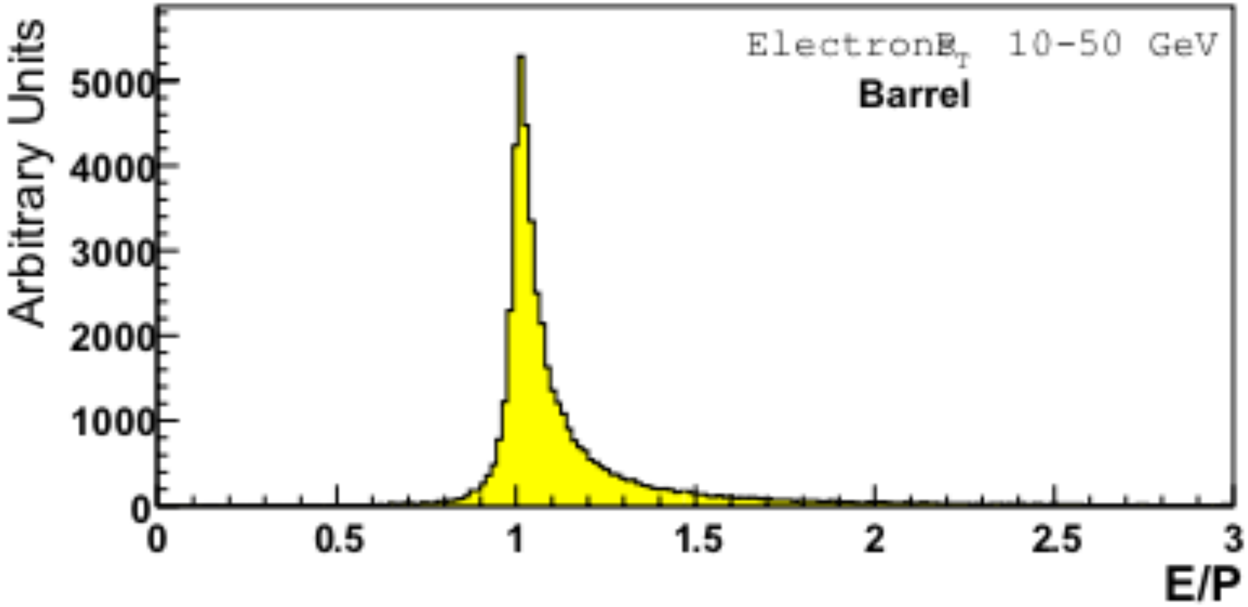
Pseudorapidity Diagram



Trigger Efficiency Measurement

1. Find events that pass another random trigger. This trigger should be completely uncorrelated with the trigger we use in the analysis.
2. Define:
   A. Denominator = number of events that pass this trigger as well as the cuts we expect our trigger to apply (ie require two leptons with a given p_T, id, iso, …)
   B. Numerator = number of events in denominator that pass our analysis trigger
3. Efficiency is numerator/denominator

E/P

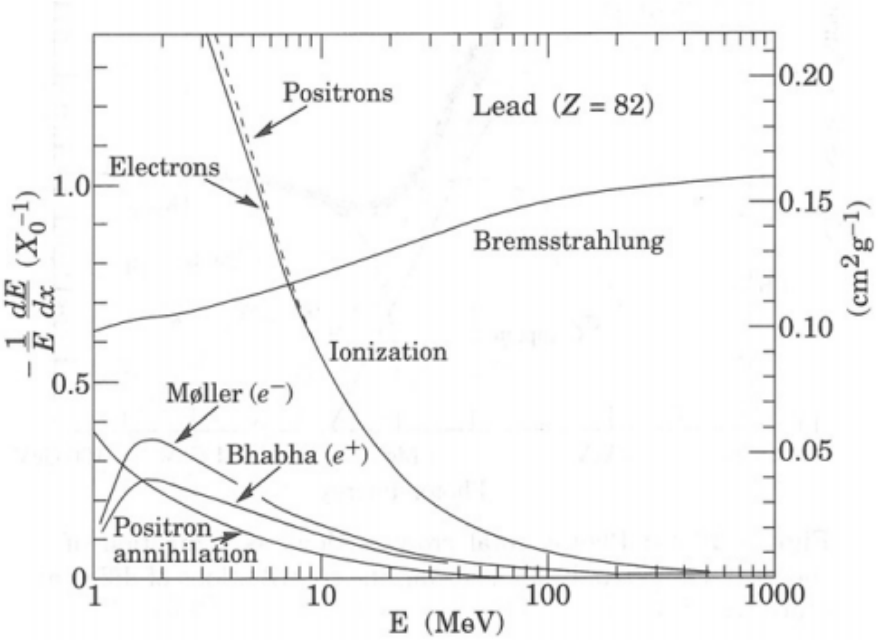


- P: electron momentum in tracker
  - Probably a little low, since electrons are giving energy by Bremssstrahlung; photon will be invisible to tracker
- E: electron energy in ECAL
  - Probably pretty accurate, the Bremssstrahlung products will reach the ECAL and be detected.
- So, cut requiring E/P < ~1.5 will greatly reduce background.

Molière Radius

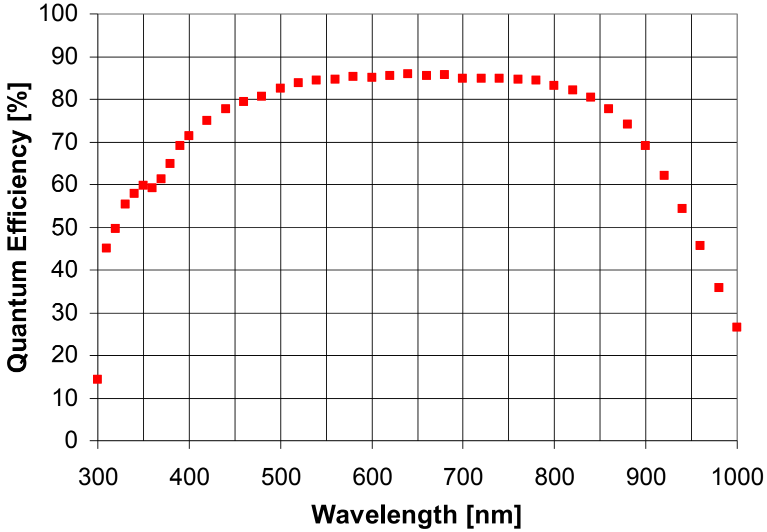
- Critical Energy: energy at which a particle's dE/dX_0 (X_0 being the radiation length) equals the energy of the particle
  - Thus, the particle has an energy such that it will completely stop within one radiation length (actually less, because as the particle loses energy, it ionizes more and more).
  - But doesn't that defeat the definition of a radiation length?
    - No, because radiation lengths are for Bremssstrahlung only

- What is the transverse size of a shower in a given material?
  - More specifically, the shower of a particle at the critical energy?
  - Draw a cylinder as long as you like. What must the radius of the cylinder be, to contain 90% of the shower's energy?
  - This is called the Molière Radius.

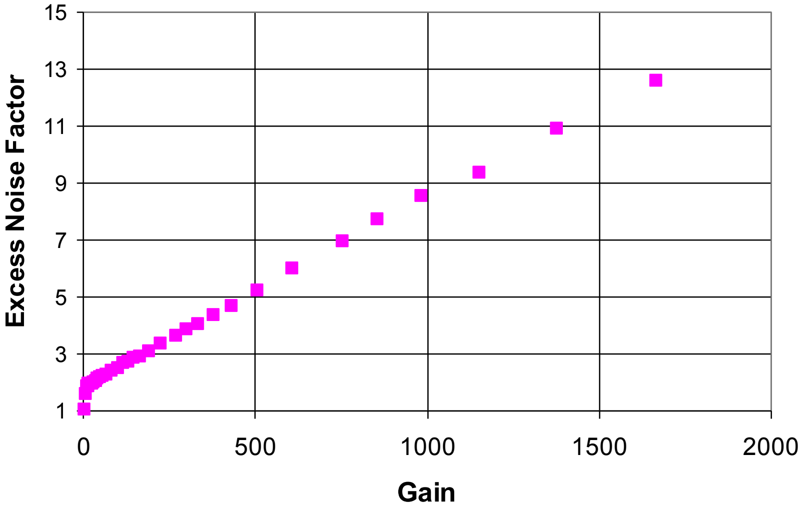


Avalanche Photodiodes

- Photon releases electrons by photoelectric effect
- Large applied voltage makes it easy for these electrons to release other electrons, resulting in avalanche
- Good performance: dark current and gain are shown to be stable in 99.9% of photodiodes after radiation tests
  - To achieve this, photodiodes had to be substantially tested, and faulty ones rejected.



below: CMS uses gain = ~50



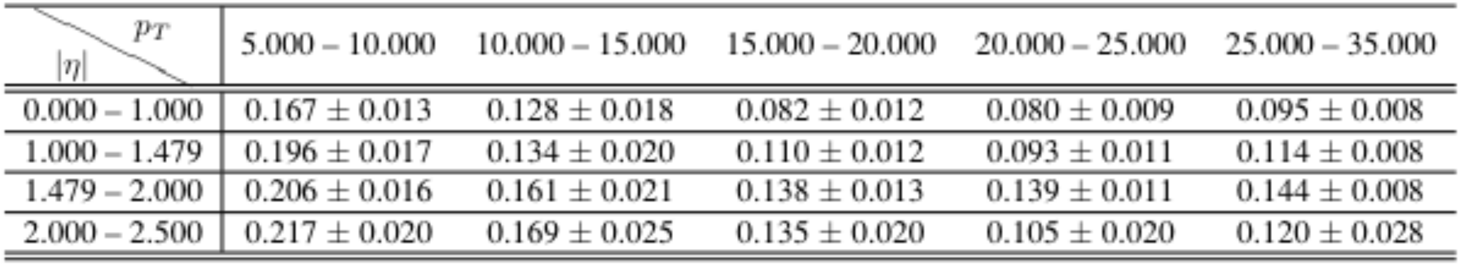
Backgrounds: Fakes

- Next, we go to our data set. We loop over the fakeable objects and sum over the fake rate per lepton, in order to determine the number of fakes.
  - In fact, it doesn't make sense to look at the chance that a tight lepton could be mis-reconstructed as tight (it is already tight). Therefore, we loop over only the leptons that are loose but not tight.
  - Because of this, we sum over FR/1-FR, not just FR:

$$\frac{\text{FR}}{\text{1-FR}} = \frac{\text{tight}}{\text{loose}} \cdot \frac{1}{1 - \frac{\text{tight}}{\text{loose}}} = \frac{\text{tight}}{\text{loose - tight}}$$

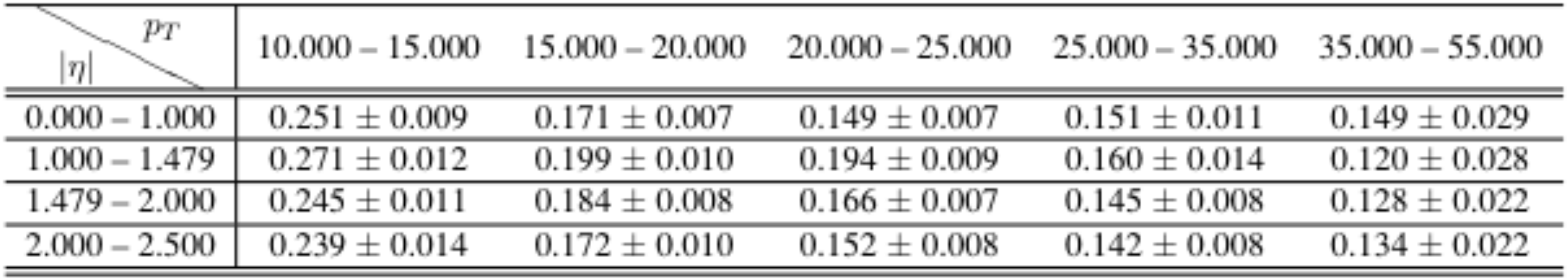
- We take several steps to improve the purity of the fake rate definition:
  - W events are suppressed by requiring that MET < 20 GeV, M_T < 25 GeV
  - Z events are suppressed by, for example, removing dielectron and dimuon events with invariant pair mass between 71 and 111 GeV, with a third lepton passing the looser ID & isolation requirements.
  - Further corrections are made by using the Monte Carlo to subtract off contamination.

Fakes: Figures



p_T $\lvert\eta\rvert$	5.000 – 10.000	10.000 – 15.000	15.000 – 20.000	20.000 – 25.000	25.000 – 35.000
0.000 – 1.000	0.167 ± 0.013	0.128 ± 0.018	0.082 ± 0.012	0.080 ± 0.009	0.095 ± 0.008
1.000 – 1.479	0.196 ± 0.017	0.134 ± 0.020	0.110 ± 0.012	0.093 ± 0.011	0.114 ± 0.008
1.479 – 2.000	0.206 ± 0.016	0.161 ± 0.021	0.138 ± 0.013	0.139 ± 0.011	0.144 ± 0.008
2.000 – 2.500	0.217 ± 0.020	0.169 ± 0.025	0.135 ± 0.020	0.105 ± 0.020	0.120 ± 0.028

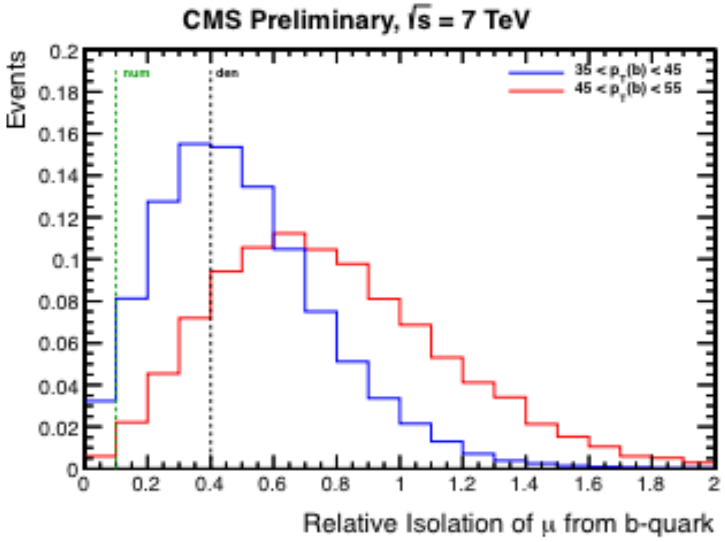
muon fake rate

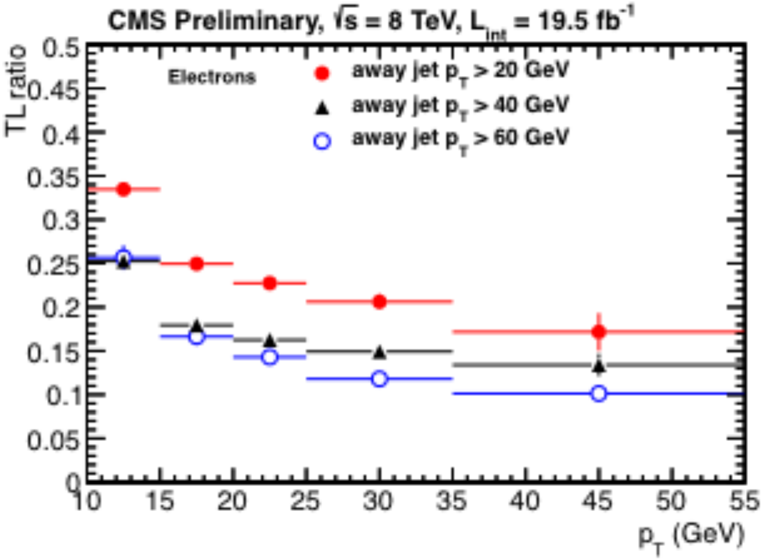


p_T $\lvert\eta\rvert$	10.000 – 15.000	15.000 – 20.000	20.000 – 25.000	25.000 – 35.000	35.000 – 55.000
0.000 – 1.000	0.251 ± 0.009	0.171 ± 0.007	0.149 ± 0.007	0.151 ± 0.011	0.149 ± 0.029
1.000 – 1.479	0.271 ± 0.012	0.199 ± 0.010	0.194 ± 0.009	0.160 ± 0.014	0.120 ± 0.028
1.479 – 2.000	0.245 ± 0.011	0.184 ± 0.008	0.166 ± 0.007	0.145 ± 0.008	0.128 ± 0.022
2.000 – 2.500	0.239 ± 0.014	0.172 ± 0.010	0.152 ± 0.008	0.142 ± 0.008	0.134 ± 0.022

electron fake rate

Fakes: Figures, Continued

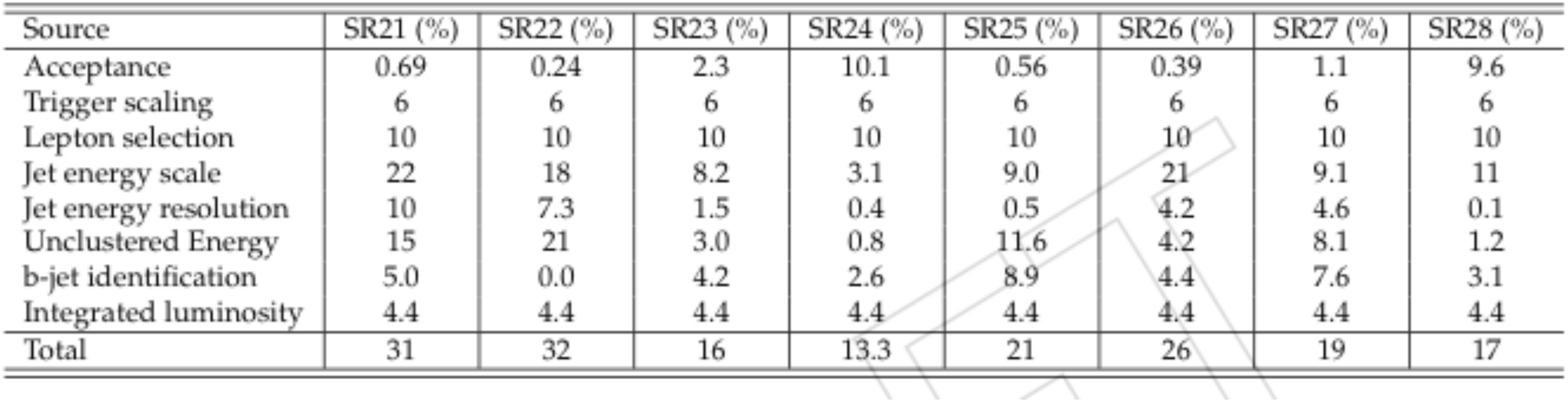




left: shows difference in isolation (and therefore loose selection) is strongly dependent on kinematics

right: shows how much TL ratio changes based on fairly small definition changes

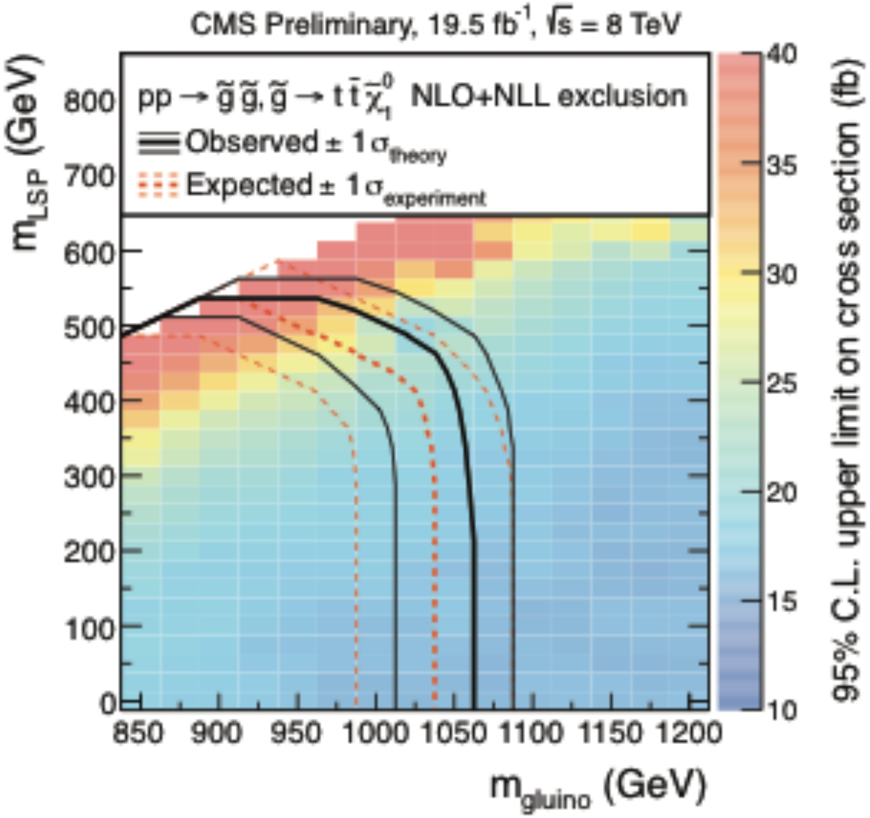
Limit Setting: Acceptances and Systematics



Source	SR21 (%)	SR22 (%)	SR23 (%)	SR24 (%)	SR25 (%)	SR26 (%)	SR27 (%)	SR28 (%)
Acceptance	0.69	0.24	2.3	10.1	0.56	0.39	1.1	9.6
Trigger scaling	6	6	6	6	6	6	6	6
Lepton selection	10	10	10	10	10	10	10	10
Jet energy scale	22	18	8.2	3.1	9.0	21	9.1	11
Jet energy resolution	10	7.3	1.5	0.4	0.5	4.2	4.6	0.1
Unclustered Energy	15	21	3.0	0.8	11.6	4.2	8.1	1.2
b-jet identification	5.0	0.0	4.2	2.6	8.9	4.4	7.6	3.1
Integrated luminosity	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Total	31	32	16	13.3	21	26	19	17

Limit Setting: Result

- The cross-section depends on m_{gluino} only.
  - as m_{gluino} falls below 1060 GeV, the cross-section becomes so high that we would have seen something.
  - Based on this, we see a vertical line around 1060 GeV
- As we approach the diagonal, we have less sensitivity.
  - Only one signal region (high hT and MET) will give sensitivity here
  - Thus, limit becomes more conservative at high m_{gluino}.
- The "expected" limit is the background-only hypothesis
  - In this case, we got lucky: limit is better than expected.
  - We could just as easily have been unlucky, had worse limit.
  - If limit were much worse than expected, that could be a hint of new physics!



CL_S

$\text{CL}_{\text{S+B}}$

- Let’s say that we have:
  - 3 background events
  - 2 predicted signal events
  - 5 total expected events
  - 0 observed events
- Can we exclude our theory at 95% confidence?
  - We hope NOT – in general, 0 events vs. 3 or 5 is pretty inconclusive.
- If the theory were correct, we’d expect a Poisson peaked around 5 (“likelihood function”).
  - The odds of getting 0 are .0062
  - So, $\text{CL}_{\text{S+B}}$ = .0062, ie we exclude the hypothesis at 99.3%.
    - Too strong a limit when we have signal below background

CL_s

- CL_S is a way to fix this.

$$CL_s = \frac{CL_{s+b}}{CL_b}$$

- $\text{CL}_{\text{S+B}}$ is still .0062
- CL_B is the odds of getting 0 events from a Poisson peaked around 3. CL_B = .0497.
- Thus, CL_S is .1348. Cannot exclude at the 95% level or even the 90% level!