Preparing for discovery: Supersymmetry searches at the LHC

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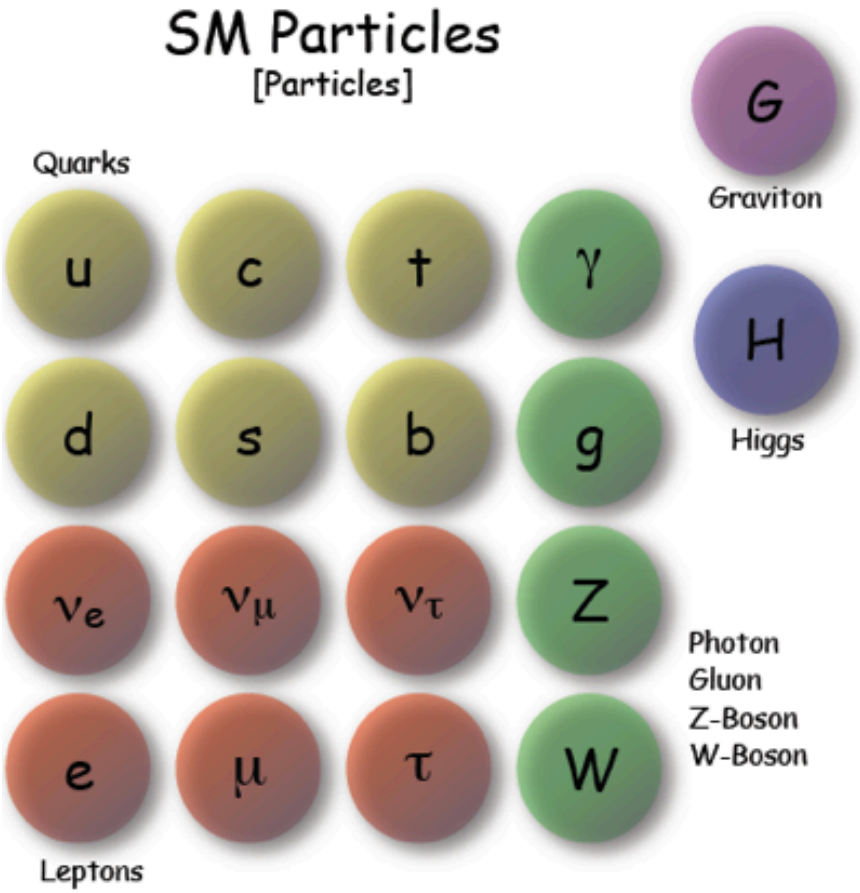
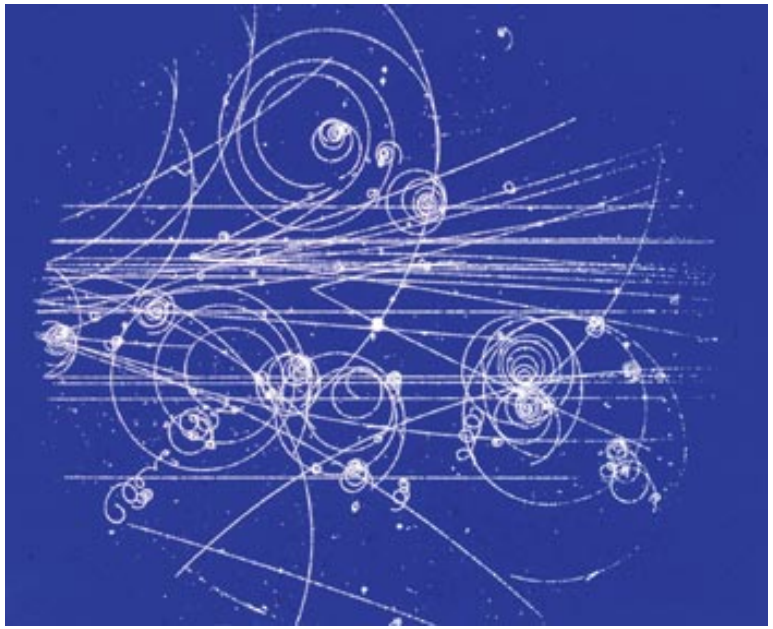
The Standard Model

- The prevailing paradigm:

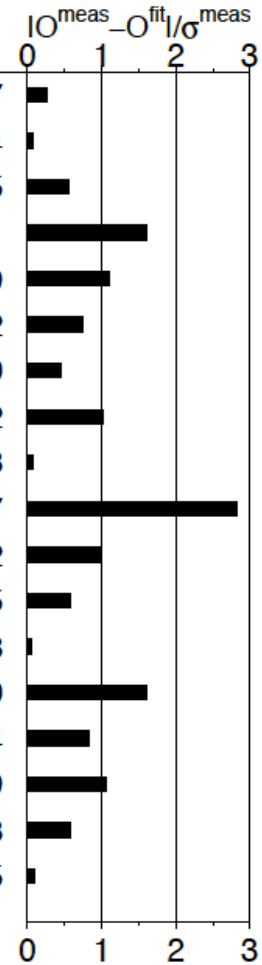


The Standard Model

- Experimental observations described extremely well by the Standard Model



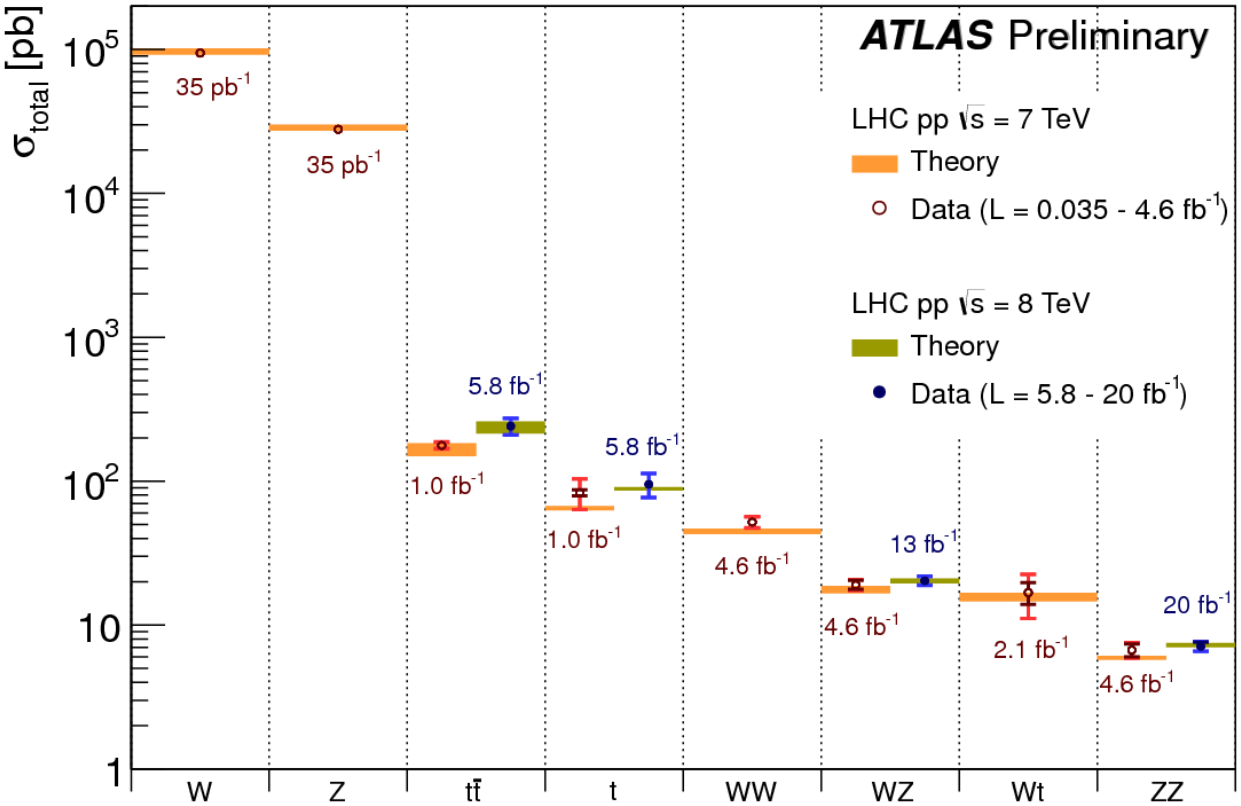
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
$A_l(SLD)$	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5

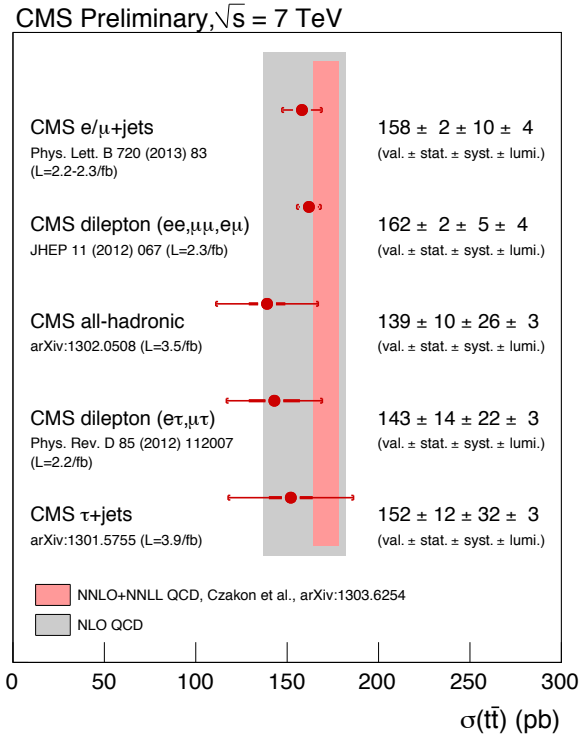


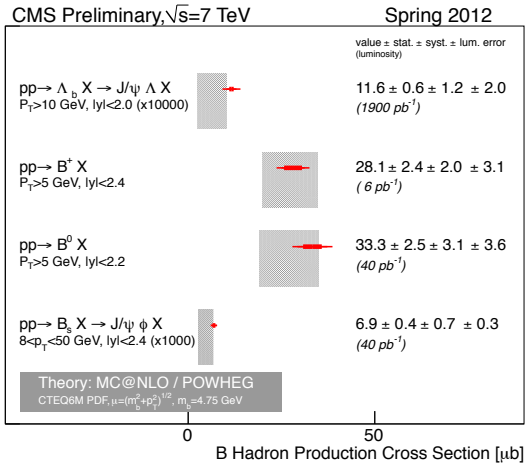
ALEPH, DELPHI, L3, OPAL, SLD, hep-ex/0509008

The Standard Model

- Including many, many LHC measurements…







Evidence for New Physics

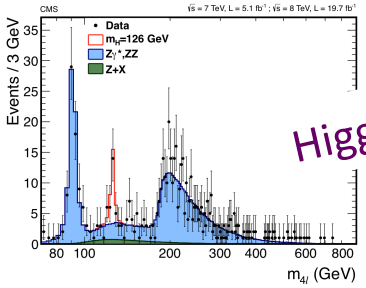
- While accurate, the Standard Model can't be complete
  - No explanation for dark matter
  - No explanation for dark energy
  - Not enough CP-violation to describe matter/anti-matter asymmetry in the universe
  - Does not include gravity
- The Standard Model also leaves interesting questions unanswered
  - Why 3 generations?
  - Hierarchy Problem: why is gravity so much weaker than SM forces?

NASA/CXC/CfA/M.Markevitch et al.; NASA/STScI; ESO WFI, Magellan/U.Arizona/ D.Clowe et al.

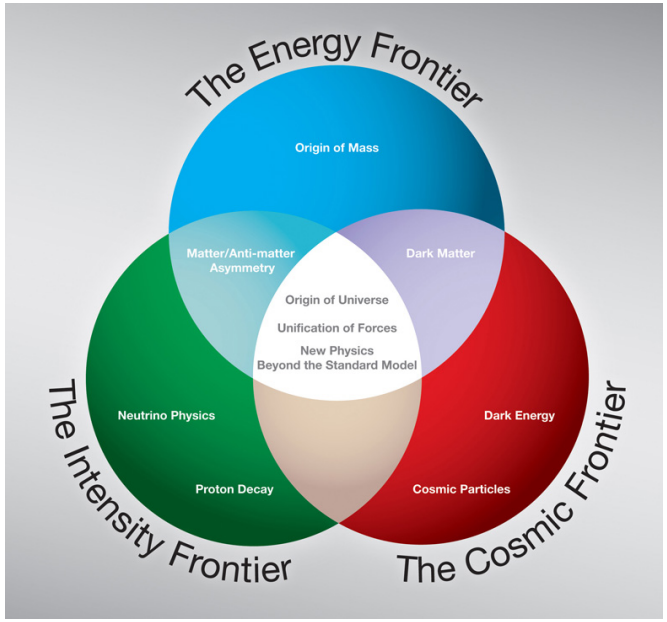
Why use the LHC?

- Energy frontier offers access to direct production of new particles
  - 2015: 8 TeV → 13 TeV
- Complementary to lower energy measurements
  - Neutrino: $\sin^2(2\theta_{13})$, CP-violation in lepton sector, …
  - Precision: g-2, μ→e, super B-factory, …
  - Direct dark matter
  - Cosmology: CMB, BAO, SNe …
- Many other LHC applications beyond high mass searches, too
  - Top factory
  - Precision EW and jet cross sections
  - Flavor physics
  - Rare branching fractions

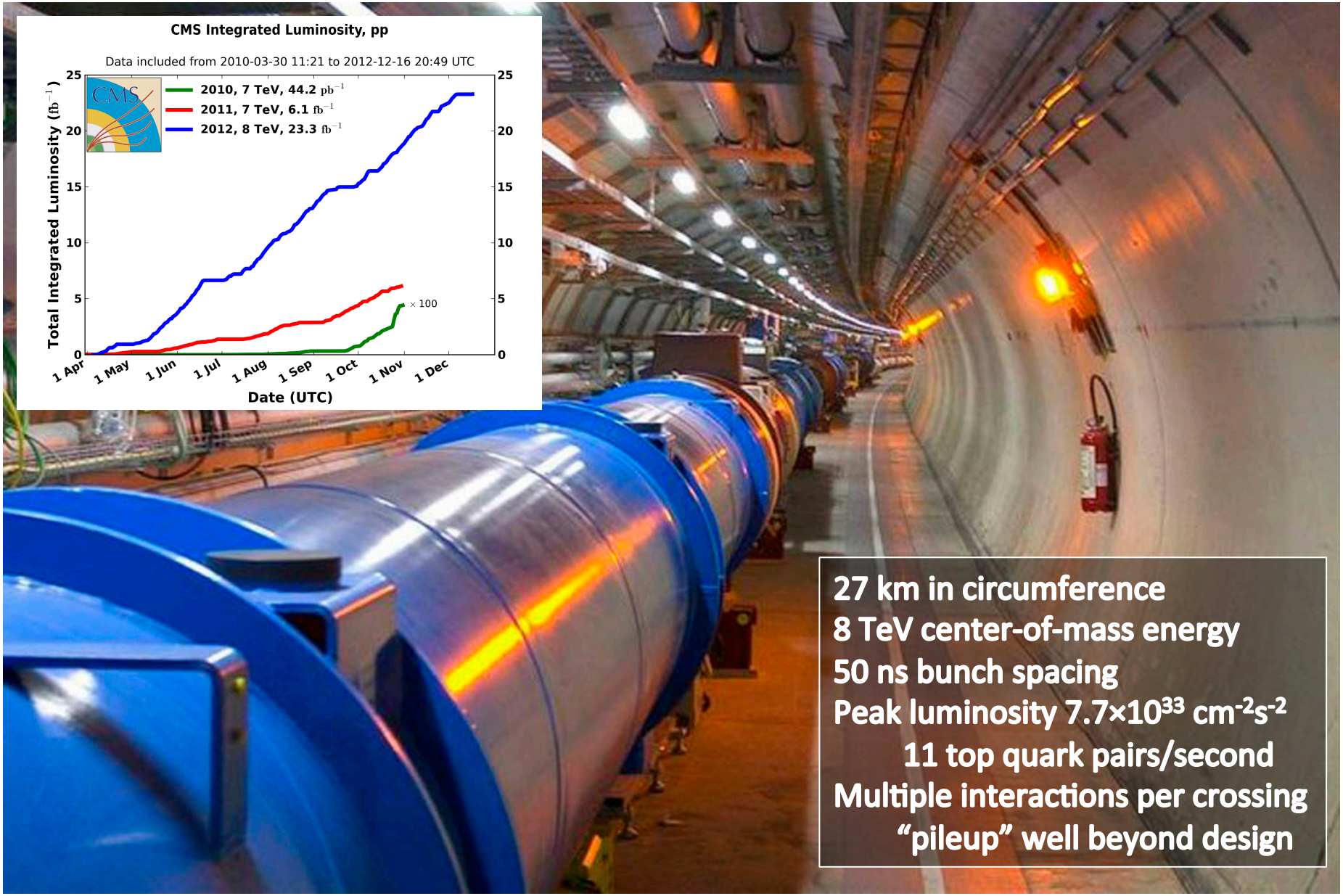
Ex:



Higgs Discovery!

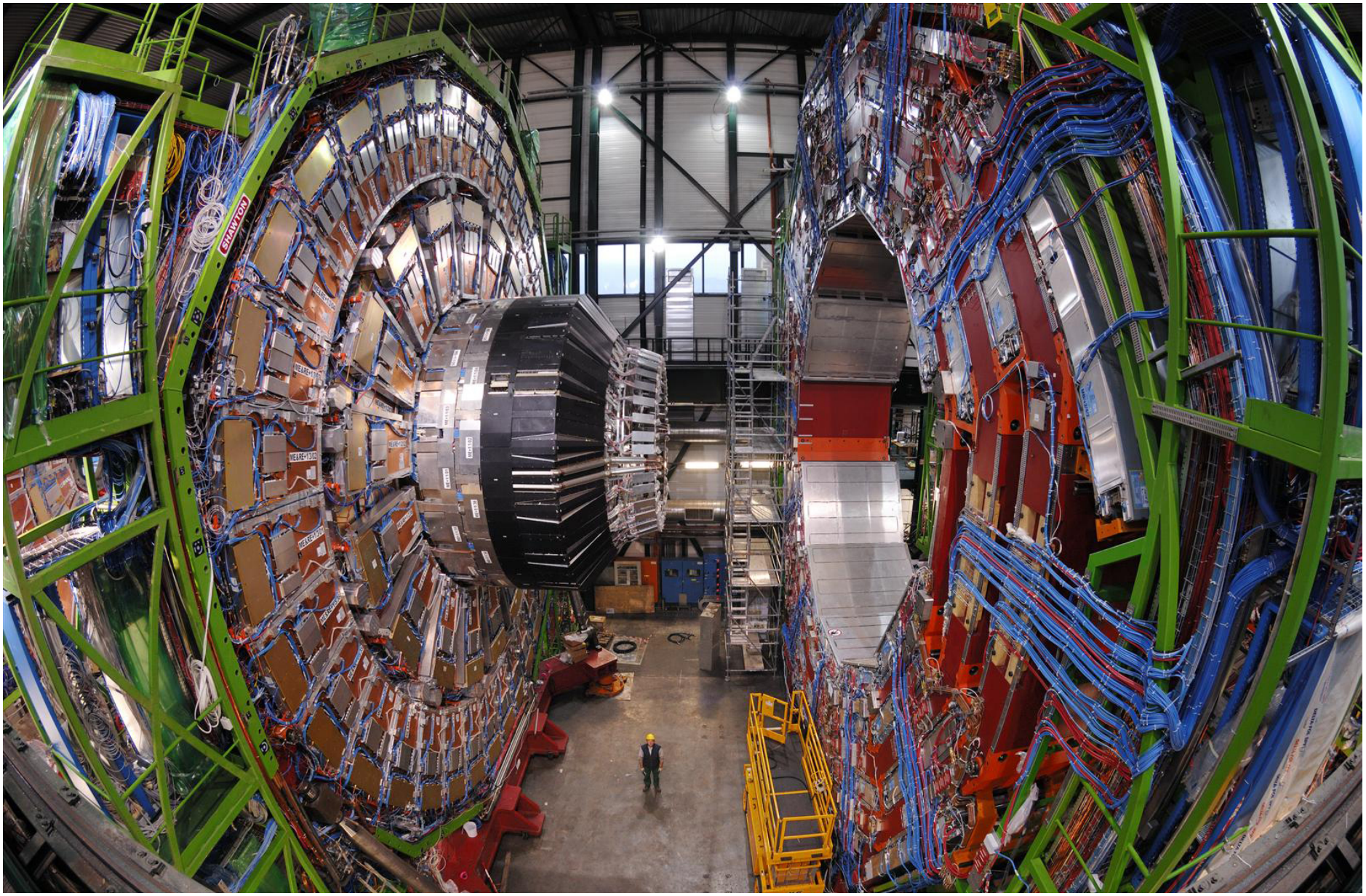


The LHC



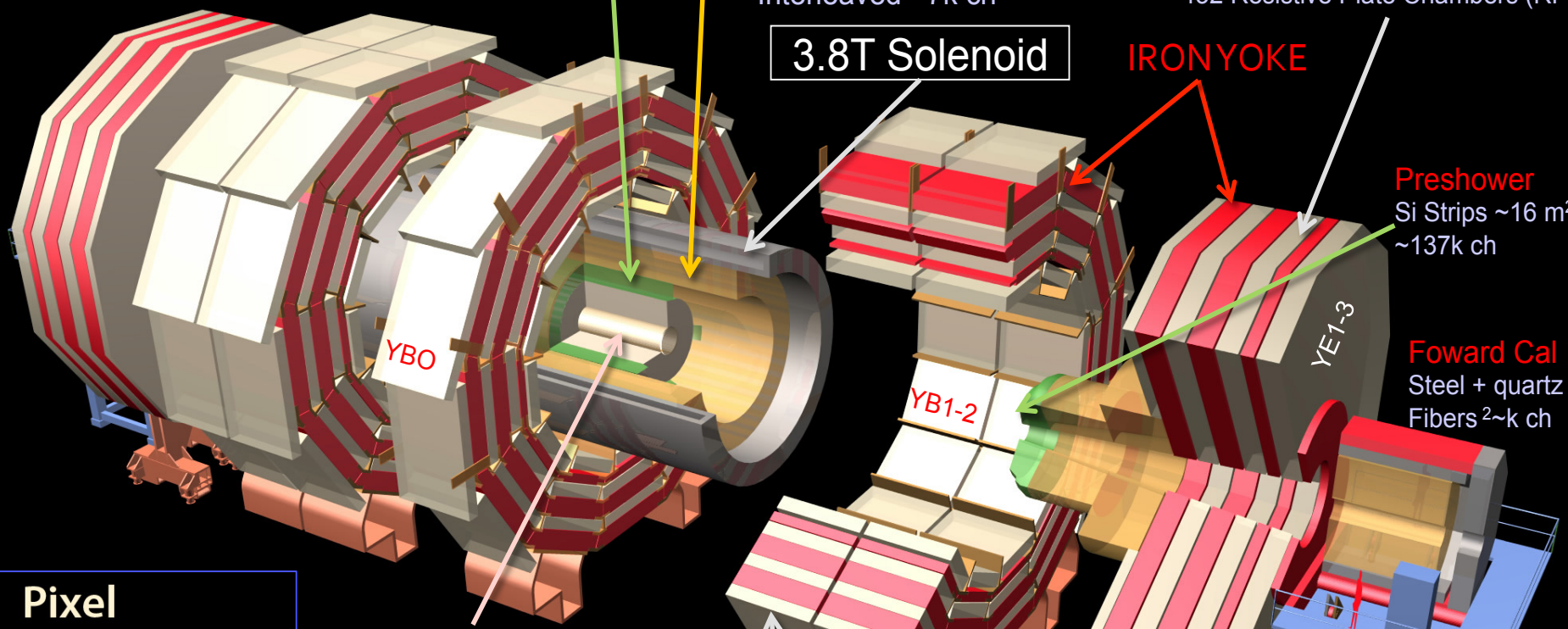
27 km in circumference
8 TeV center-of-mass energy
50 ns bunch spacing
Peak luminosity 7.7×10^{33} cm^{-2}s^{-2}
11 top quark pairs/second
Multiple interactions per crossing
"pileup" well beyond design

CMS detector



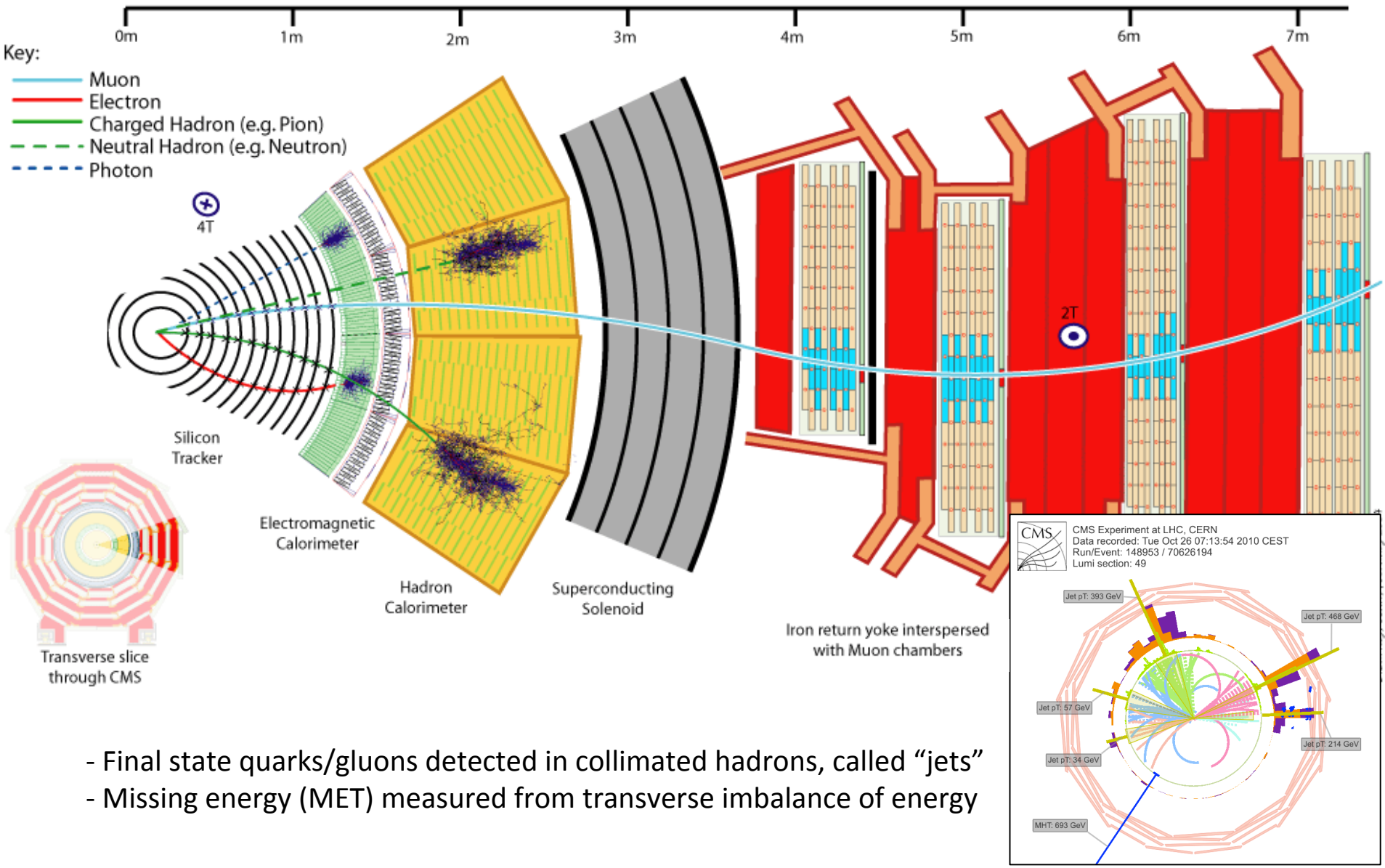
CMS

L1 hardware trigger
HLT software trigger



Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

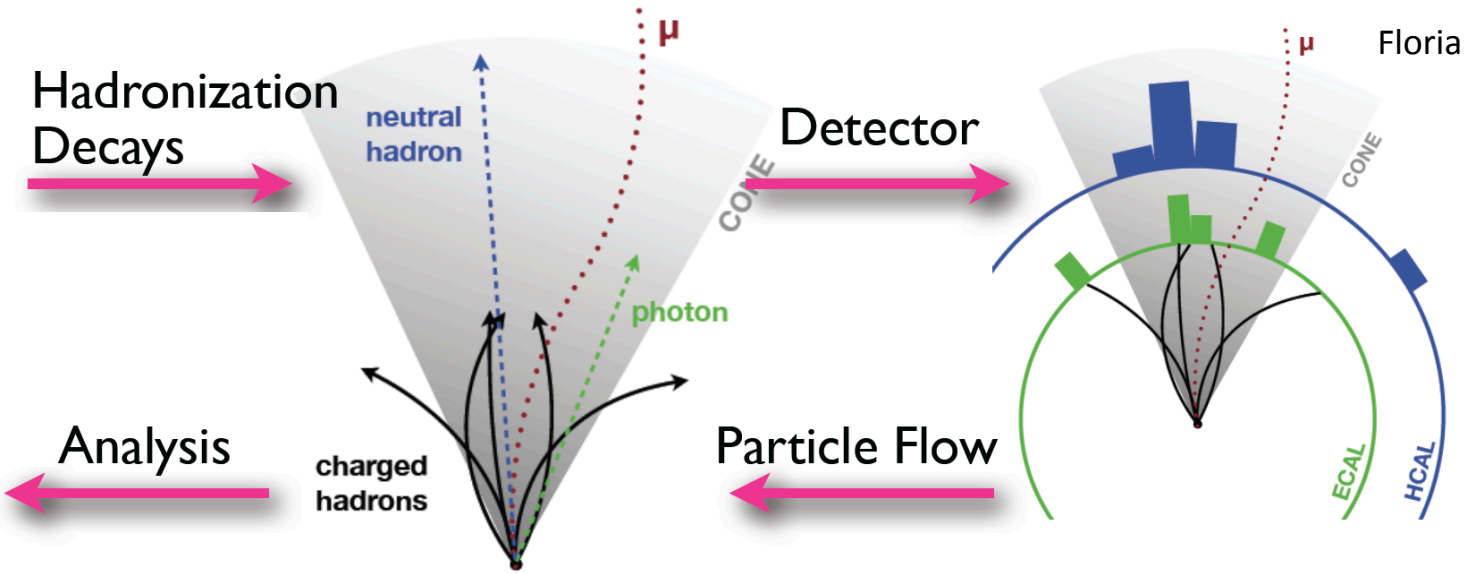
CMS (in action!)



- Final state quarks/gluons detected in collimated hadrons, called “jets”
- Missing energy (MET) measured from transverse imbalance of energy

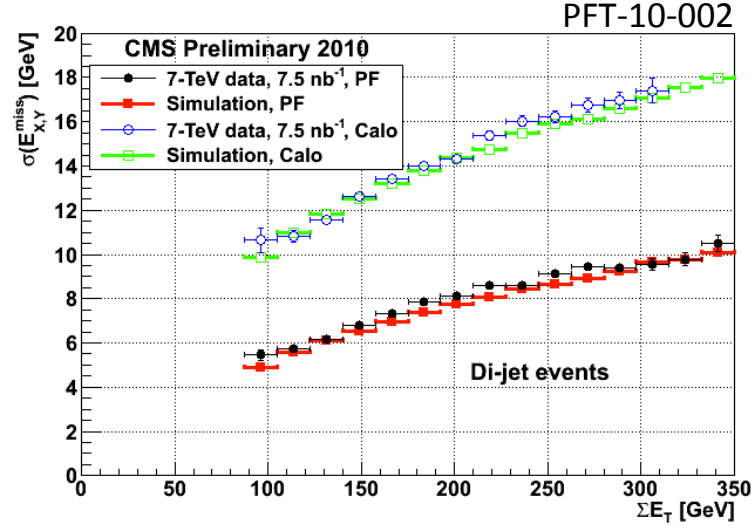
Particle flow

- Use full detector information to identify all stable particles



Florian Beaudette

PFT-10-002

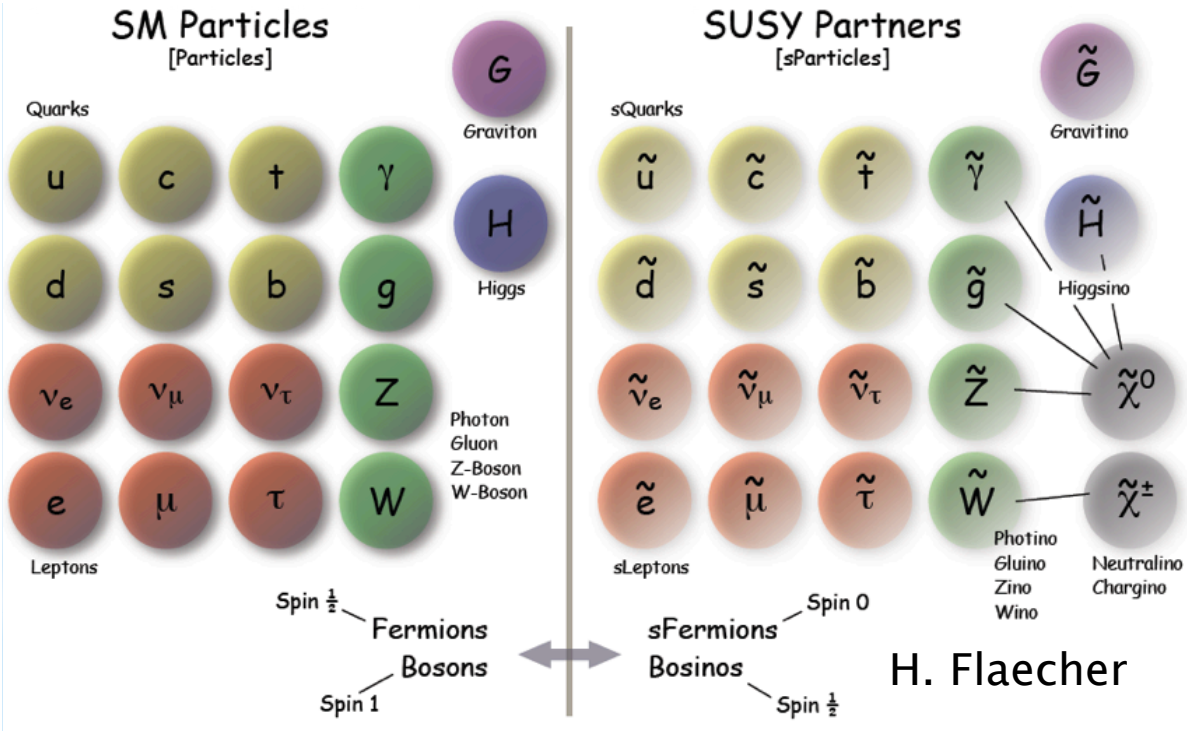


- Cluster jets from PF particles, not just calorimeter deposits
- Improves jet energy resolution, angular resolution, isolation, and MET resolution
- Also helps deal with pileup by associating charged hadron energy to different vertices

Beyond the Standard Model

- Many BSM models proposed over the years: Supersymmetry, extra dimensions, little Higgs, technicolor, ….
- SUSY remains among the most popular

  (even after decades of null results…)
  - Fermion/boson symmetry with superpartner of different spin for each SM particle
  - A rich new phenomenology to explore



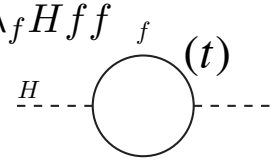
H. Flaecher

The appeal of supersymmetry

- Solution to Hierarchy Problem
  - Extreme fine tuning needed to keep SM valid all the way up to Λ_{UV} = Planck scale
  - SUSY gives natural cancelation of quadratically divergent Higgs mass terms
- Dark matter candidate
  - Lightest SUSY particle stable(with R-parity conservation)
- Gauge coupling unification

SUSY → $|\lambda_f|^2 = \lambda_S$

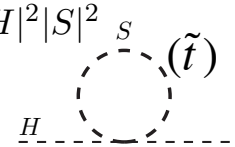
$-\lambda_f H \bar{f} f$



$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \ldots$$

problematic

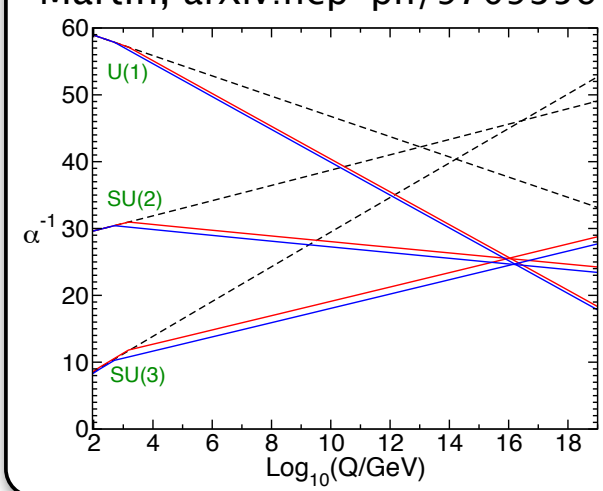
$-\lambda_S |H|^2 |S|^2$



$$\Delta m_H^2 = \frac{\lambda_S}{8\pi^2}\Lambda_{UV}^2 + \ldots$$

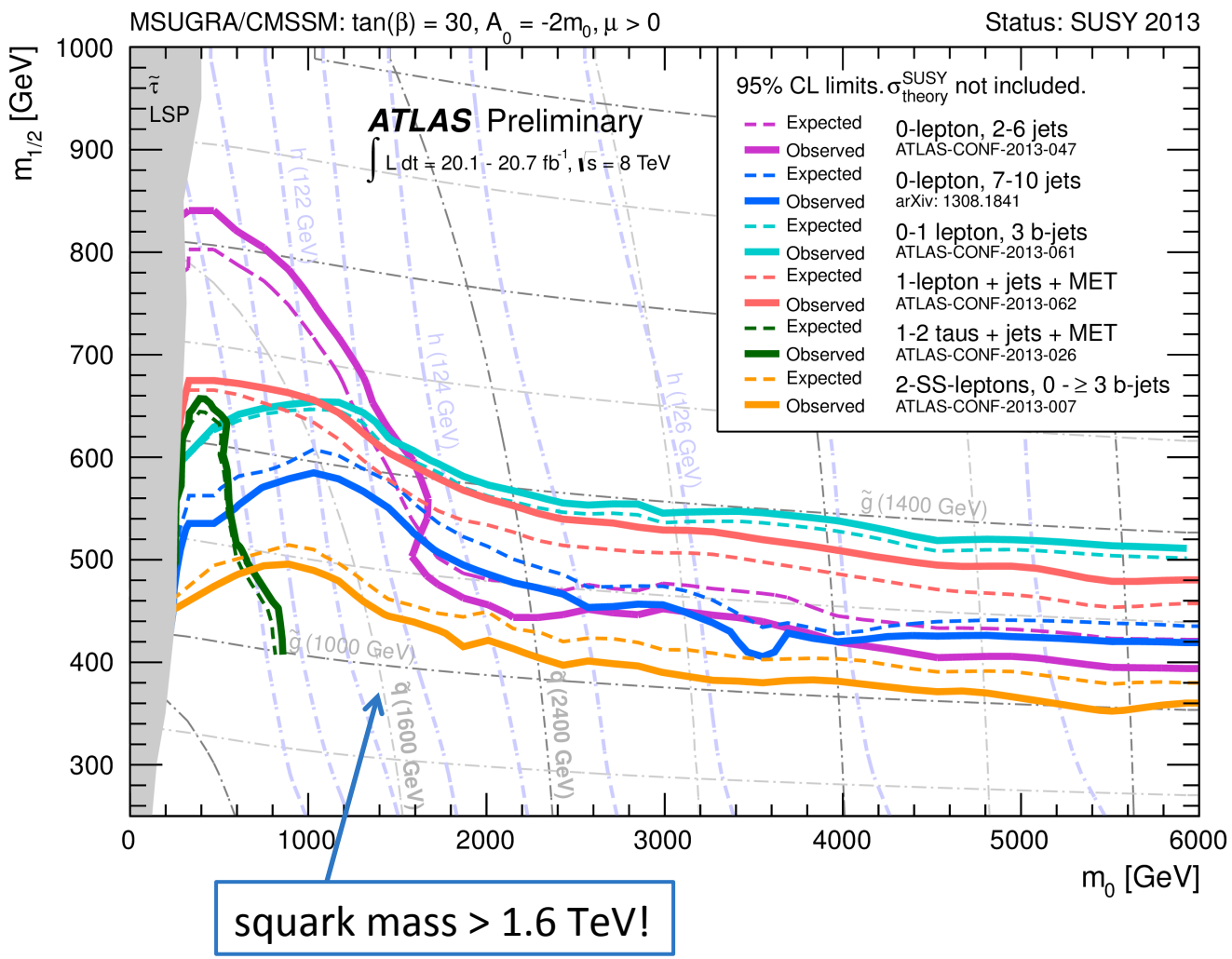
unless canceled

Martin, arXiv:hep-ph/9709356



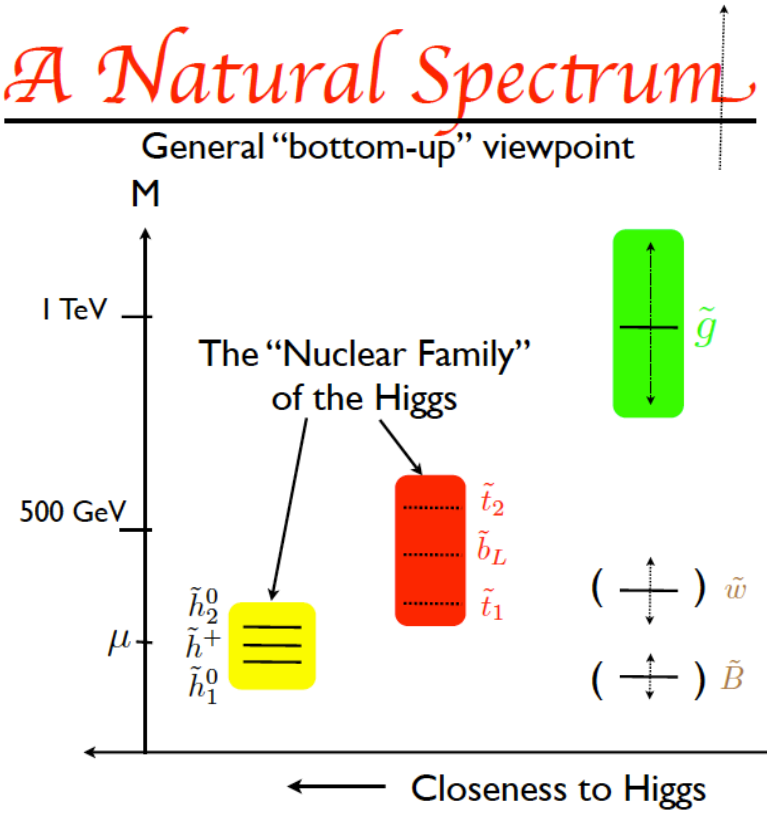
Status of SUSY searches

- Many searches performed; no signals observed
- Limits on SUSY particle production are very strong; if real, SUSY must be "broken"
- Many previously popular models under serious pressure

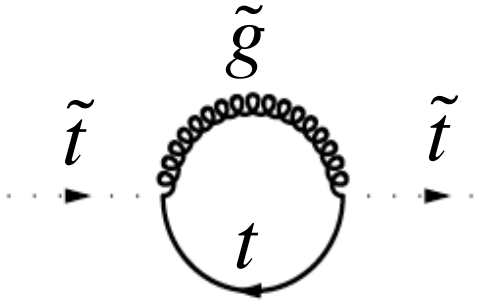


Confronting naturalness

- Higgs discovery = hierarchy problem
- SUSY's main appeal is a natural solution (minimal fine tuning) to hierarchy problem
  - Need "low mass" SUSY for cancelation of divergent Higgs mass terms
  - Hence "just around the corner…"
- Minimal natural requirements
  - Some sparticles are more important than others for naturalness
  - Essential to have a light stop to cancel top quark loop
    - Brings along a light-ish gluino by 1 loop contribution
  - Light Higgsinos because mass terms coupled to Higgs mass (μ)



Lawrence Hall, SUSY Searches @LHC, 2011

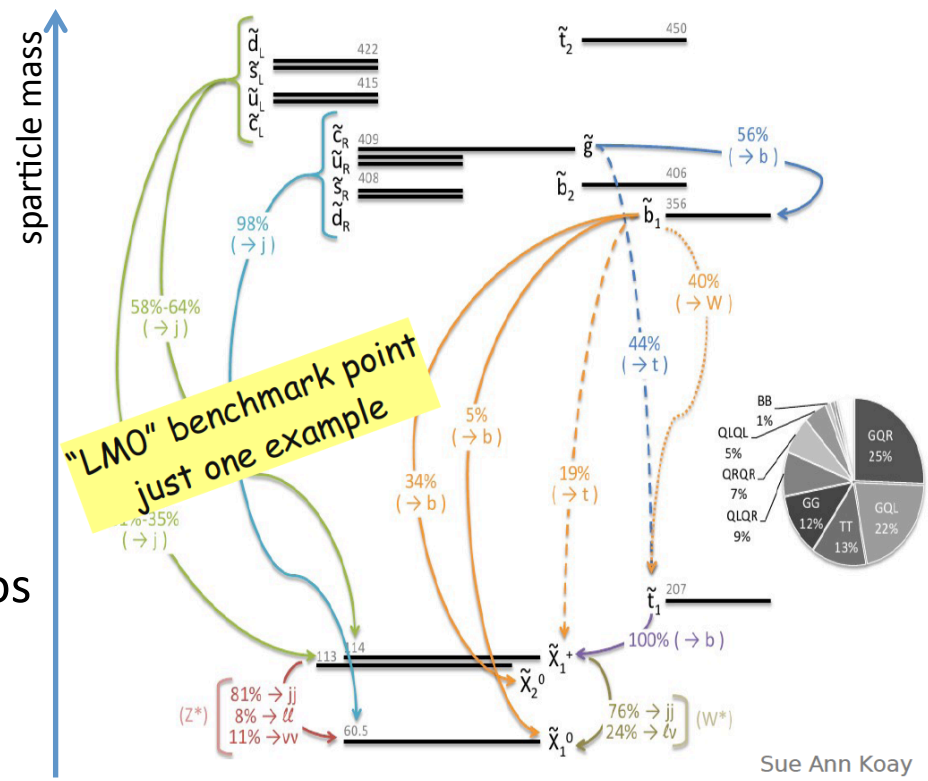


Searching for natural SUSY

- Describe two complementary natural SUSY searches
- An inclusive search:
  - Broad signature space with Jets + missing energy
  - Sensitive to many gluino and 3rd generation squark decays
- An exclusive search:
  - Target a specific, challenging decay
  - This example: Higgsinos in decays to H→bb + LSP
- This approach models the broader SUSY search strategy

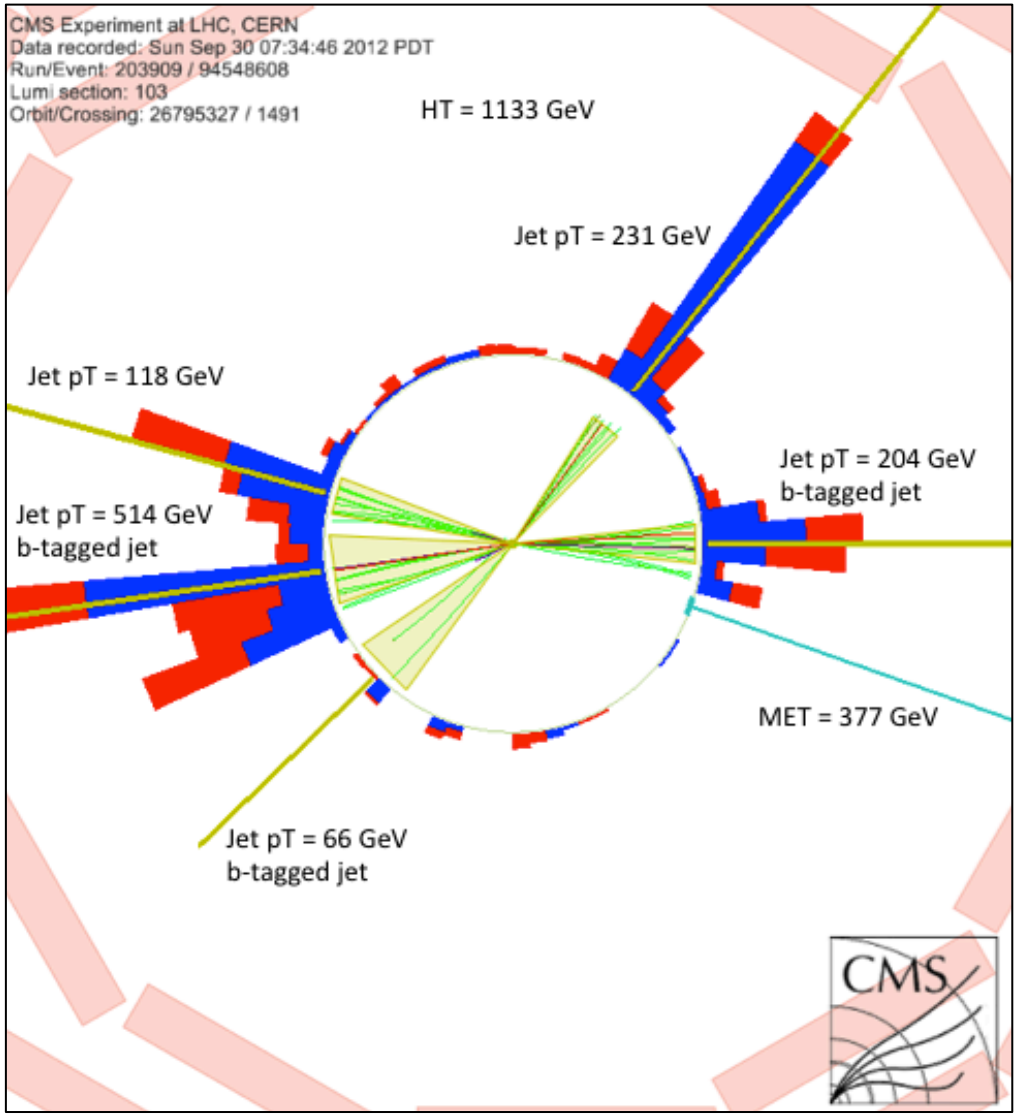
Inclusive SUSY search

- SUSY can produce rich, varied spectra
- Must keep our eyes wide open!
  - Inclusive search to cover broad range of possible signatures
  - Goal is to discover: Robust background strategy
- Strong SUSY production
  - Highest cross sections for gluinos and squarks
  - Colored sparticles leave jets in their decays
- A stable LSP carries away missing energy
- Naturalness suggests 3rd generation squarks are abundant



Inclusive selection

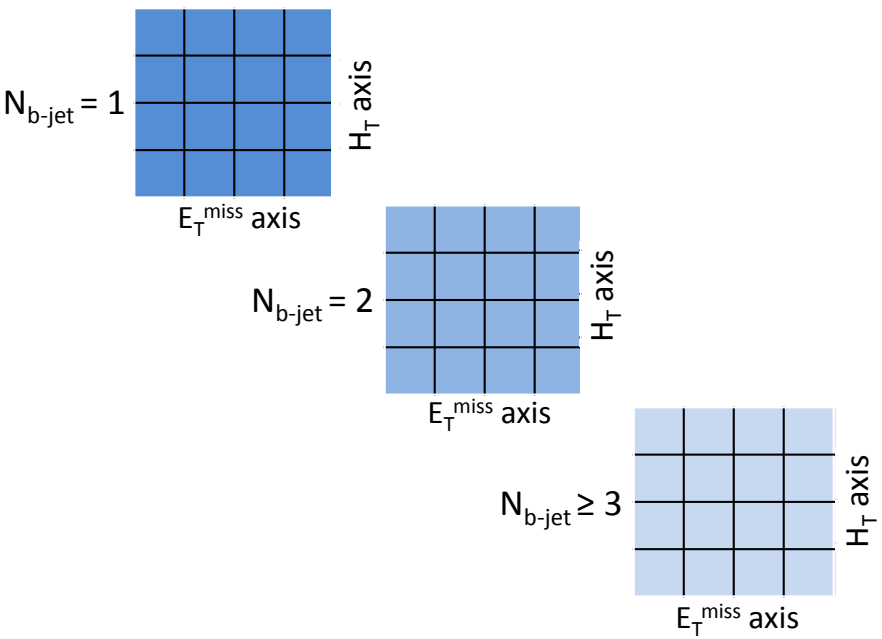
- Search requires
  - ≥ 3 jets
  - ≥ 1 b-jet (nB)
  - Σ (jet p_T) ≥ 400 GeV (HT)
  - Transverse missing energy ≥ 125 GeV (MET)
  - No isolated, charged lepton in event

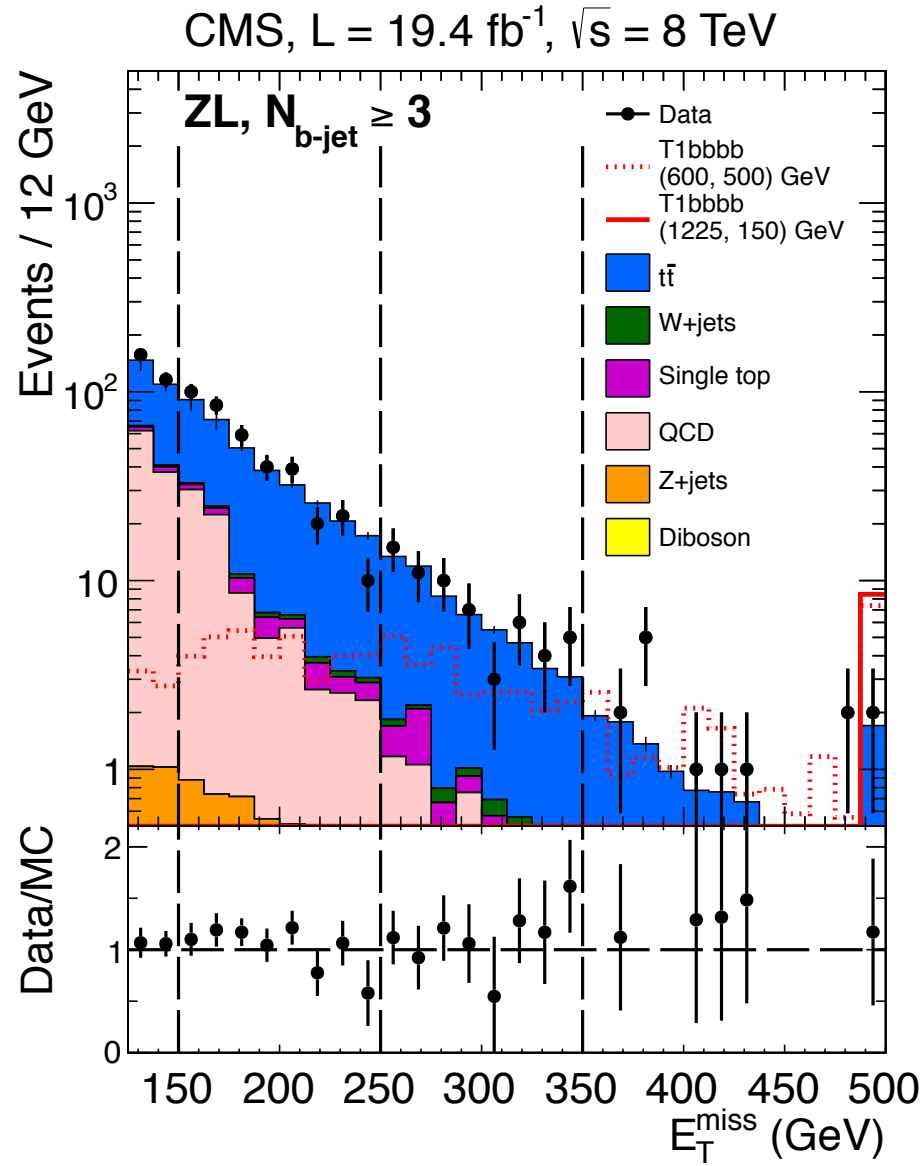


SUS-12-024 PLB 725, 243 (2013), SUS-12-003 PRD 86, 072010 (2012), SUS-11-006 (2011)

Search fit

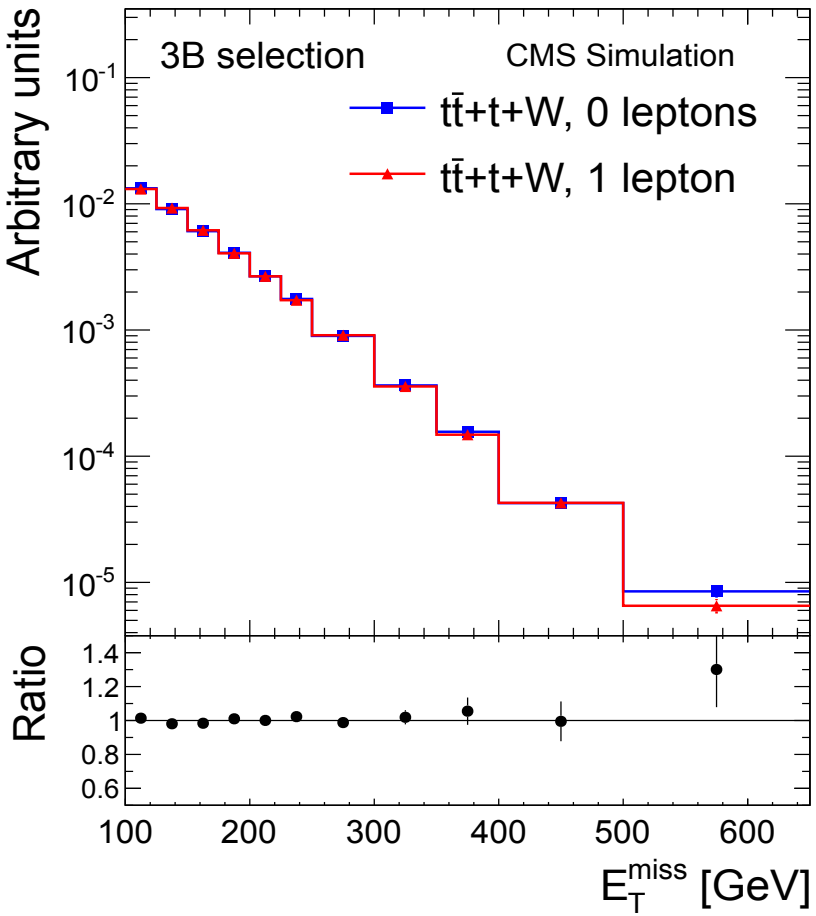
- Perform analysis with simultaneous fit in 3-D to HT, MET, and number of b-jets
  - Background shapes estimated independently of signal hypothesis
  - Sensitive to many different signal shapes within one search





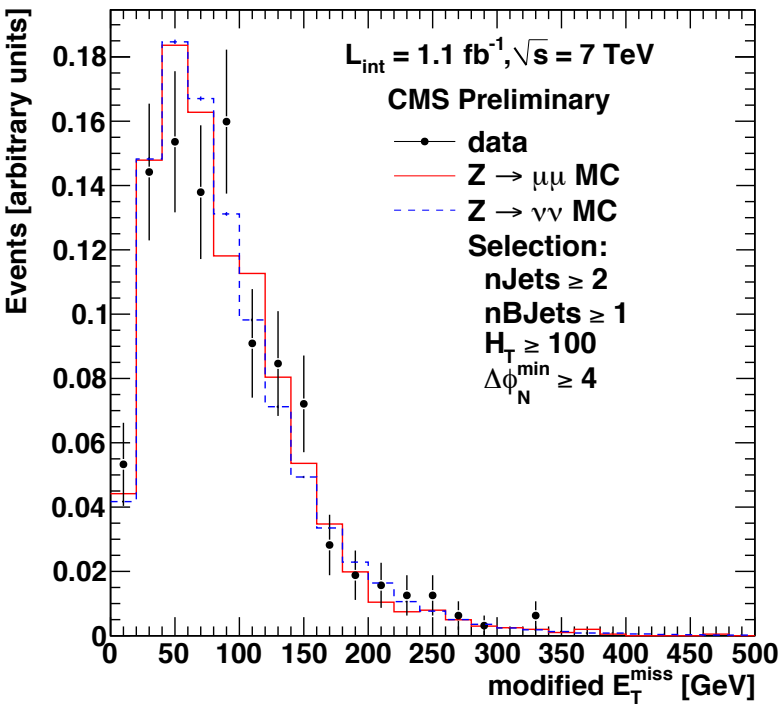
Backgrounds: top and $W^{\pm}$

- Main background from tt
  - Real b-jets
  - Real missing energy from a semi-leptonic top decay
  - Additional real jets from a hadronic top decay
- Mostly rejected with lepton veto
- Measure remaining contribution with robust approach based on data
  - Use data single lepton control sample to determine (nB,HT,MET) shape of background
  - With shape fixed within uncertainties, float normalization in signal fit



Backgrounds: Z→νν + jets

- Z→νν + (b)-jets is an irreducible background
  - Real MET from Z→νν
  - Suppressed by nJet, nB, and HT requirements



- Measure remaining contribution with Z→l^+l^- events
  - Treat Z p_T as MET to simulate invisible decay
  - Reconstruct Z→$\mu^+\mu^-$ and Z→e^+e^- events in data to measure background

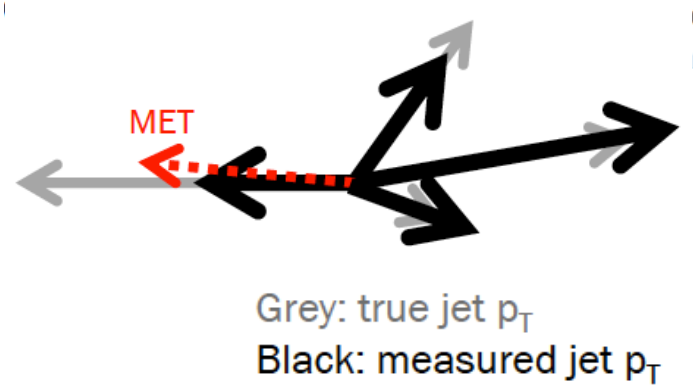
$$N(Z \to \nu\bar{\nu}) = N(Z \to l^+l^-) \cdot R / eff.$$

$$R \equiv Br(Z \to \nu\bar{\nu}) / Br(Z \to l^+l^-) \approx 3$$

  - Factorize dependence on HT/MET and nB to gain back statistics

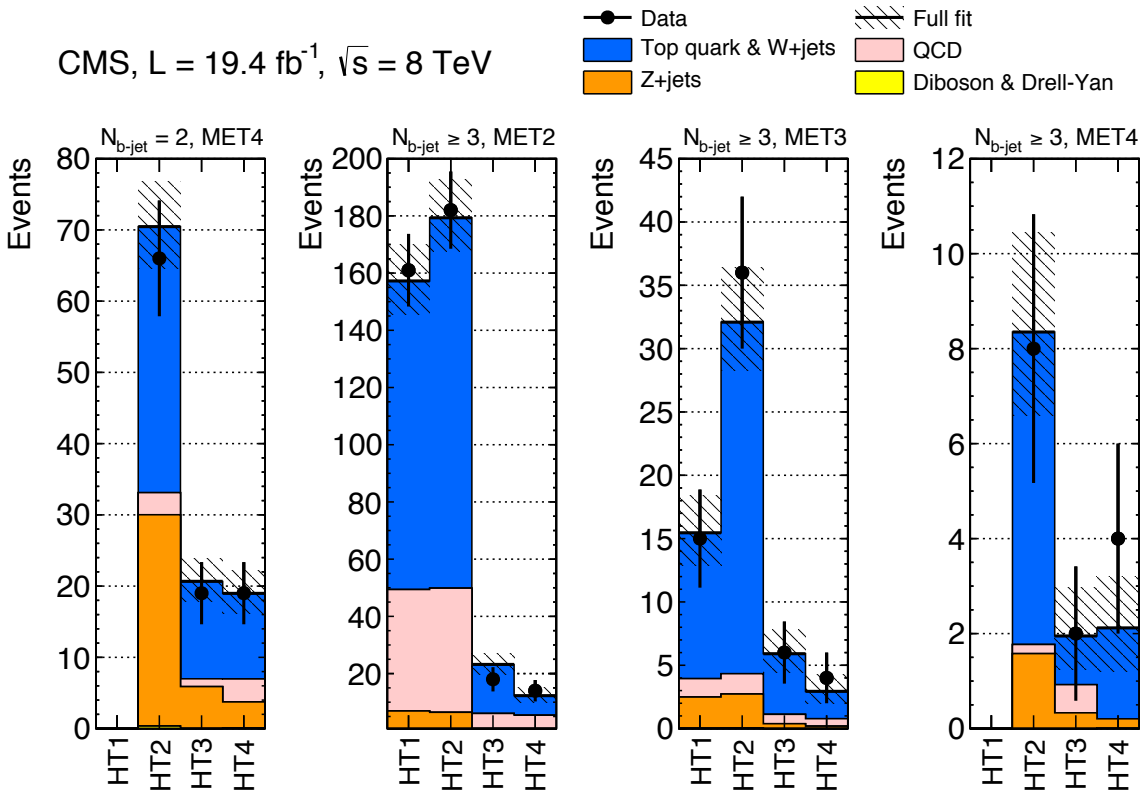
Backgrounds: Others

- Multi-jet events ("QCD")
  - Missing energy faked by wrongly measured jet momentum
  - Remove events with MET in same direction as a jet
  - Measure remaining contribution in data
- Simulation used for other very small contributions
  - Diboson, ttH, etc. (~1% of background)
- Total background uncertainty dominated by statistical uncertainty in 1 lepton control sample for top+W background



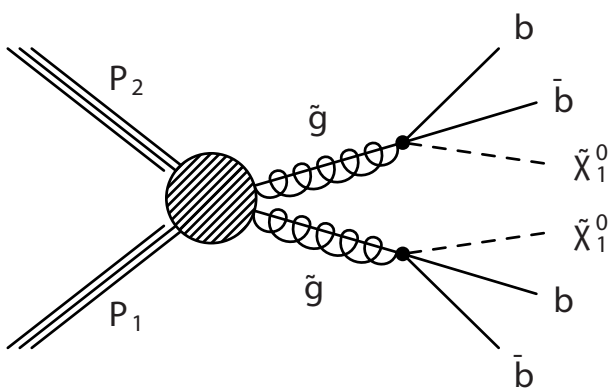
Inclusive search results

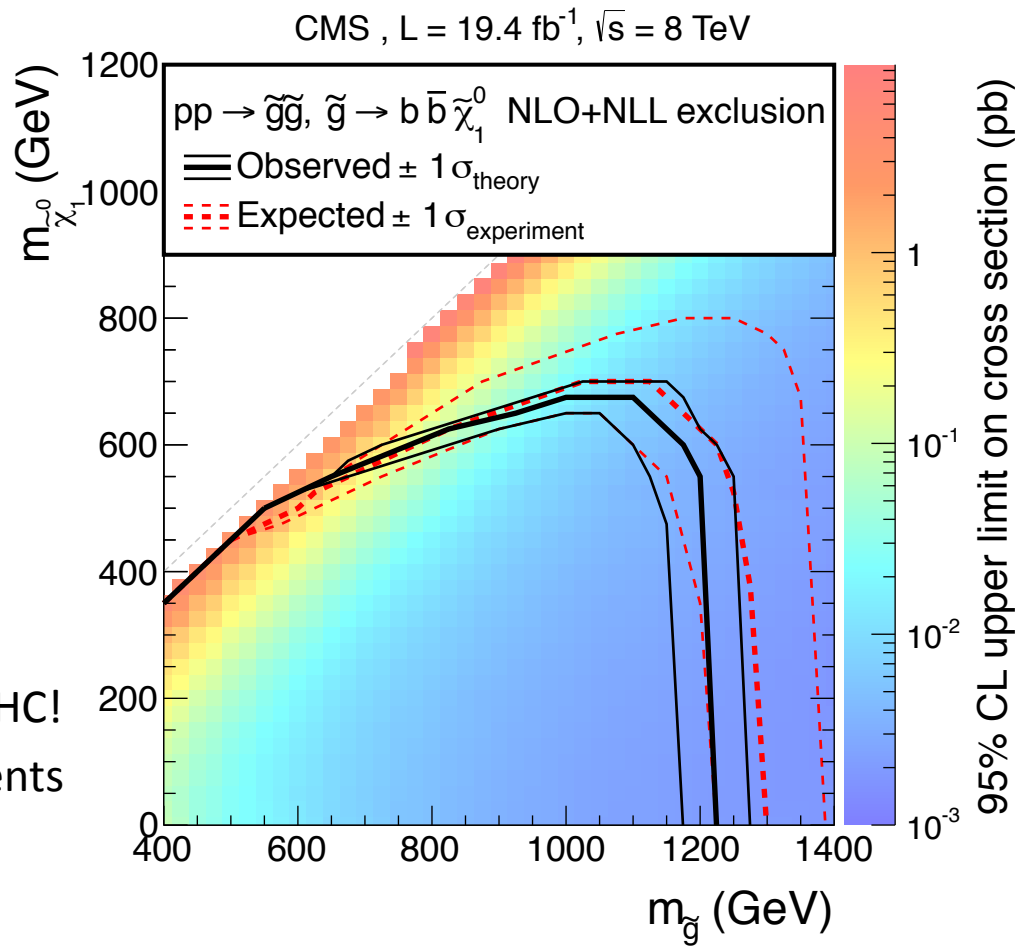
- Observed data consistent with measured SM backgrounds
- Most sensitive search bins shown in plots
- Use results to set stringent limits on contribution from new physics



Inclusive search interpretation

- Use simplified model approach to characterize sensitivity
  - Assume only a minimal spectrum and decouple the rest of SUSY
  - Set cross section limits on specific processes





- Best published gluino-mediated sbottom production limits from LHC!
- Challenging naturalness requirements

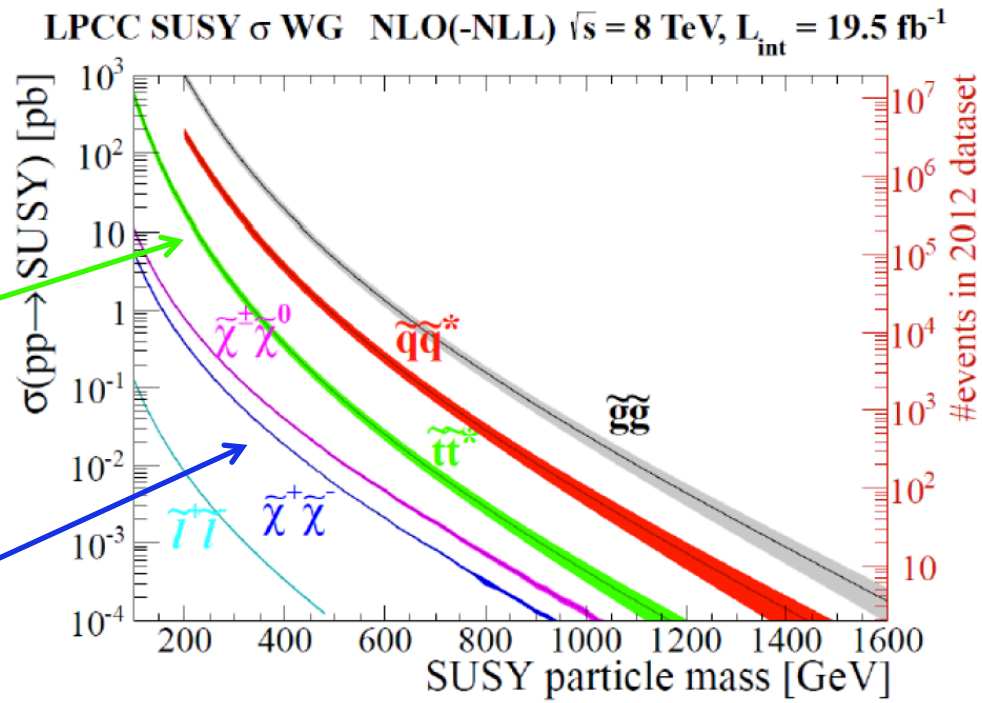
PLB 725, 243 (2013)

Dedicated SUSY searches

- Inclusive searches broadly cover lots of phase space
- For specific, well motivated decays, we can do better
- With more data, rarer processes become accessible
  - Softer decay products
  - More difficult signatures

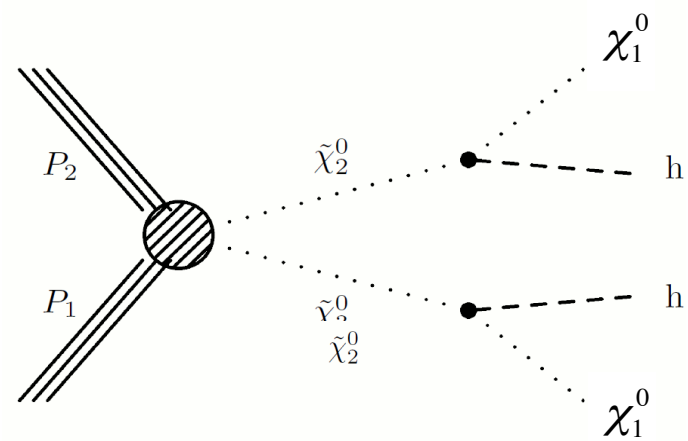
Direct stop production
-top tagging
-Multivariate techniques

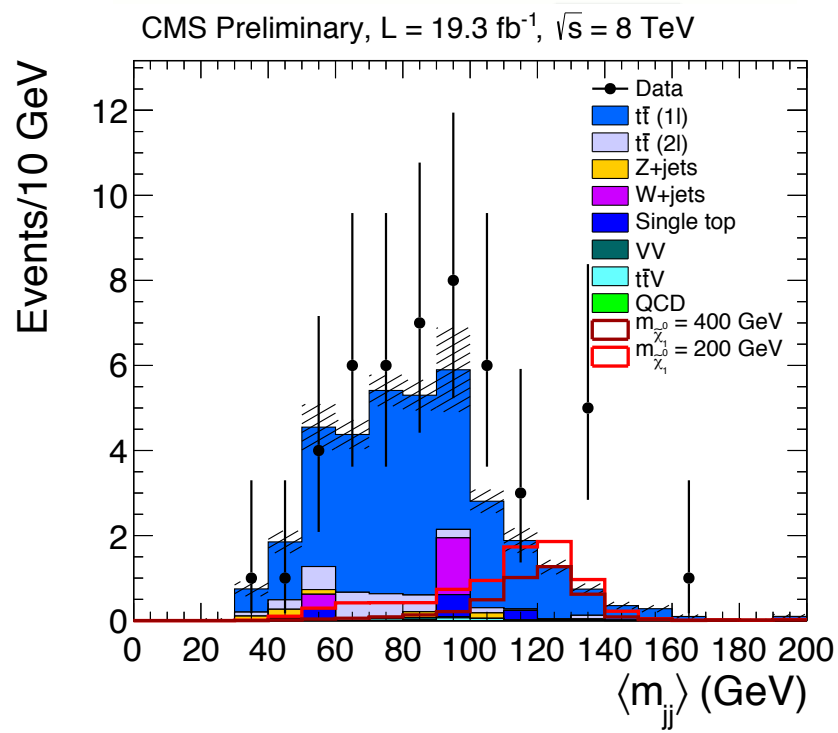
Electroweak SUSY production



Dedicated Higgsino search

- Target specific all hadronic final state:
  2 H→bb + MET
- Highly optimized selection
  - 4-5 jets
    - 2 with p_T > 50 GeV, rest with p_T > 20 GeV
    - 4 b-tagged jets
  - 2 H(bb) candidates
    - Of 4 b-jets, select pairs with smallest m_{jj} difference
    - Select events with average m_{jj} near Higgs mass
  - Missing energy
  - No isolated, charged leptons

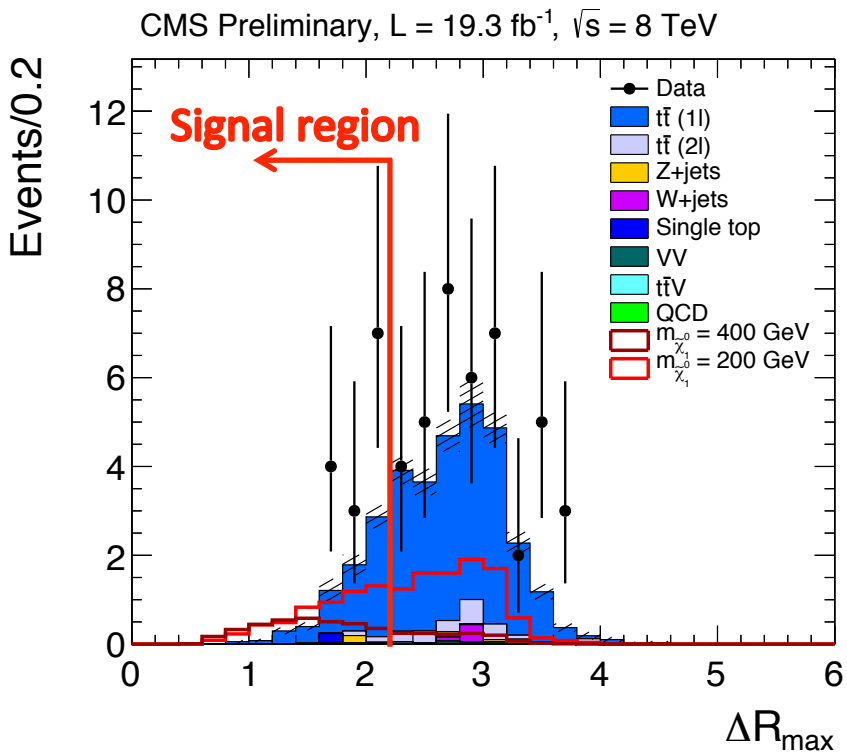


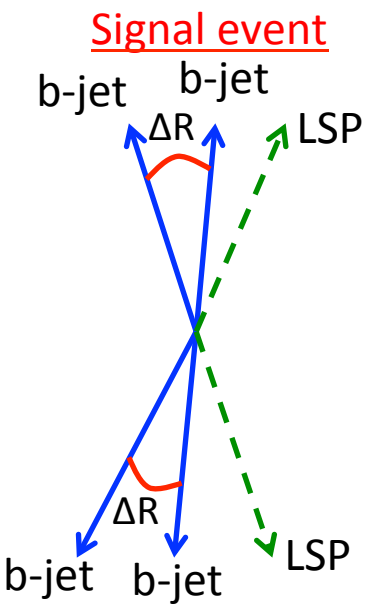


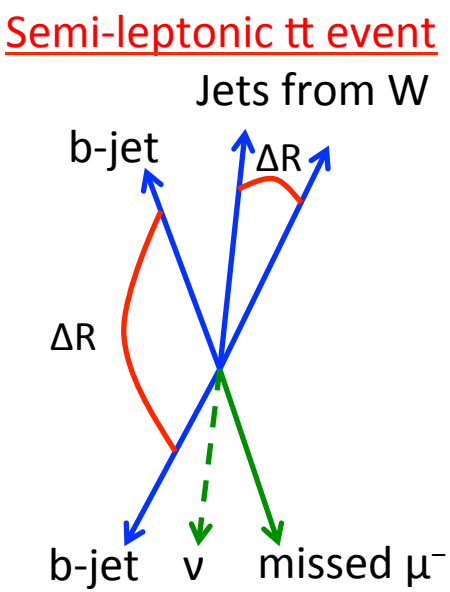
CMS-SUS-13-022 (New!)

Angular selection

- Separate signal from main semi-leptonic tt background with angular information
- Both HH and tt generally produced back-to-back
  - Jet pairs from signal are close together
  - One jet pair from tt will have large opening angle

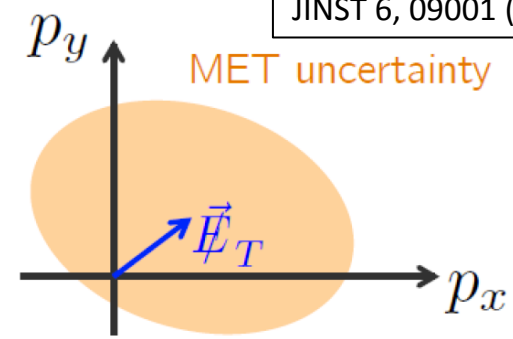






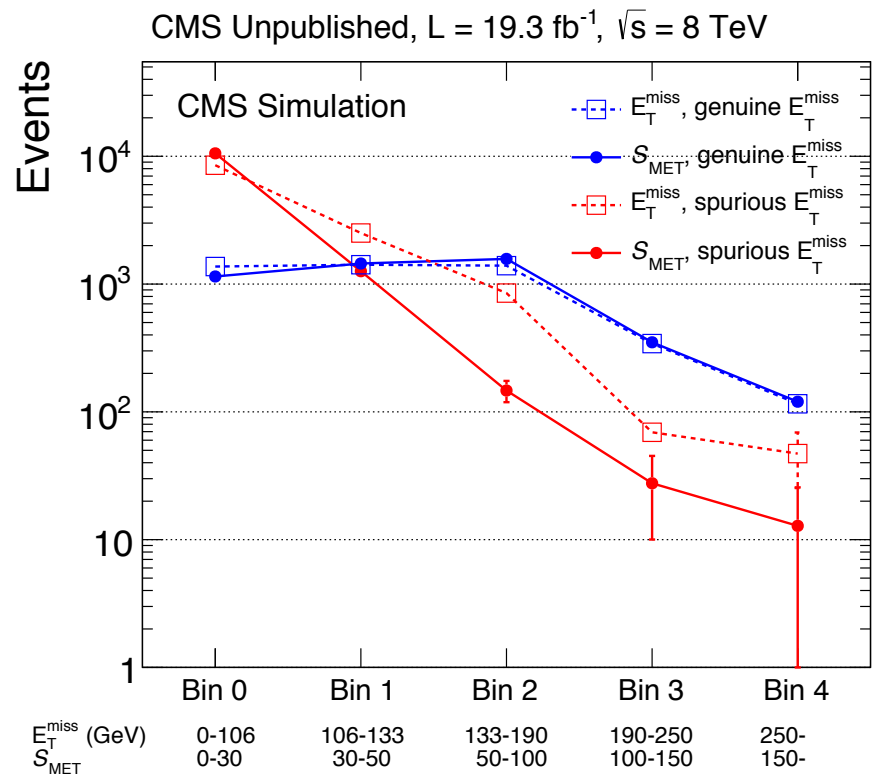
MET significance

JINST 6, 09001 (2011)



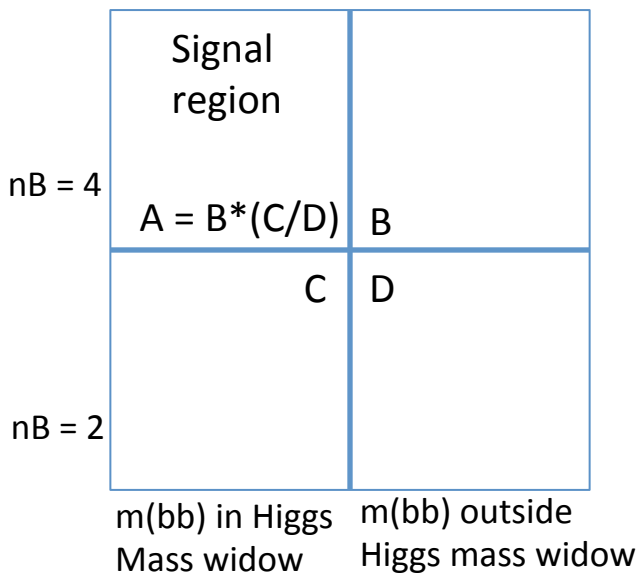
Nathan Mirman

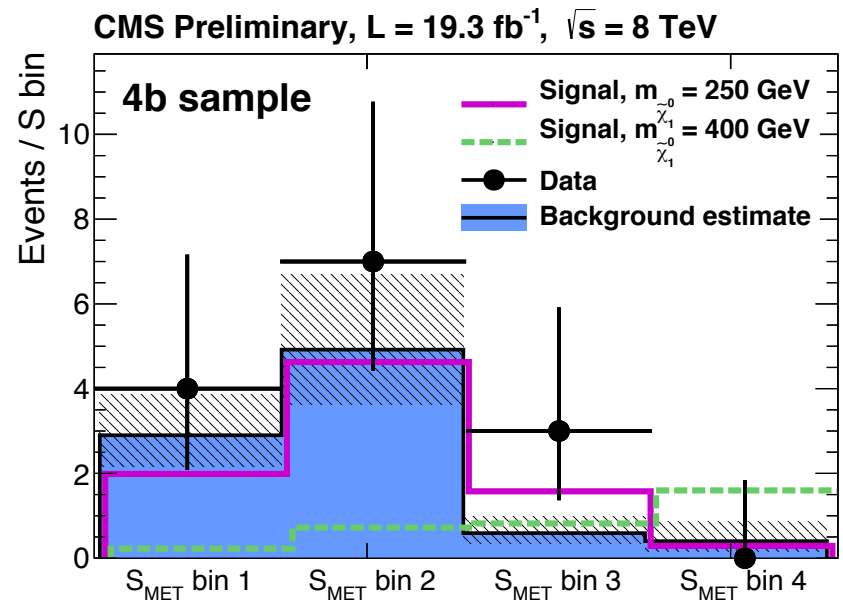
- Fake MET can arise from energy measurement resolution
- Use particle-by-particle energy resolution to compute uncertainty on MET
- Define MET significance as likelihood ratio of observed MET and null hypothesis MET
  - Small values are likely to be fake MET
- Improvement in fake MET rejection by ~4x



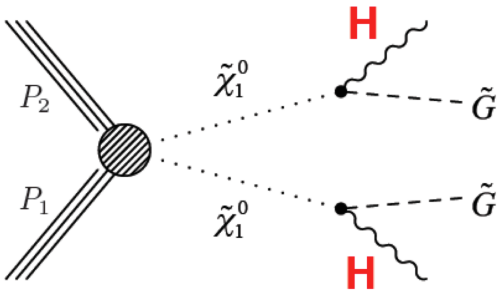
Higgsino search results

- Apply data-driven prediction of SM contribution to the signal region
  - Measure all backgrounds together (almost entirely tt)
  - Exploit lack of correlation between number of b-tags and di-Higgs mass selection for "ABCD" method prediction
  - Full result from simultaneous likelihood fit to
    - nB = 2, 3, and 4 regions
    - 4 MET significance bins
- No significant excess observed over data, though some hint…

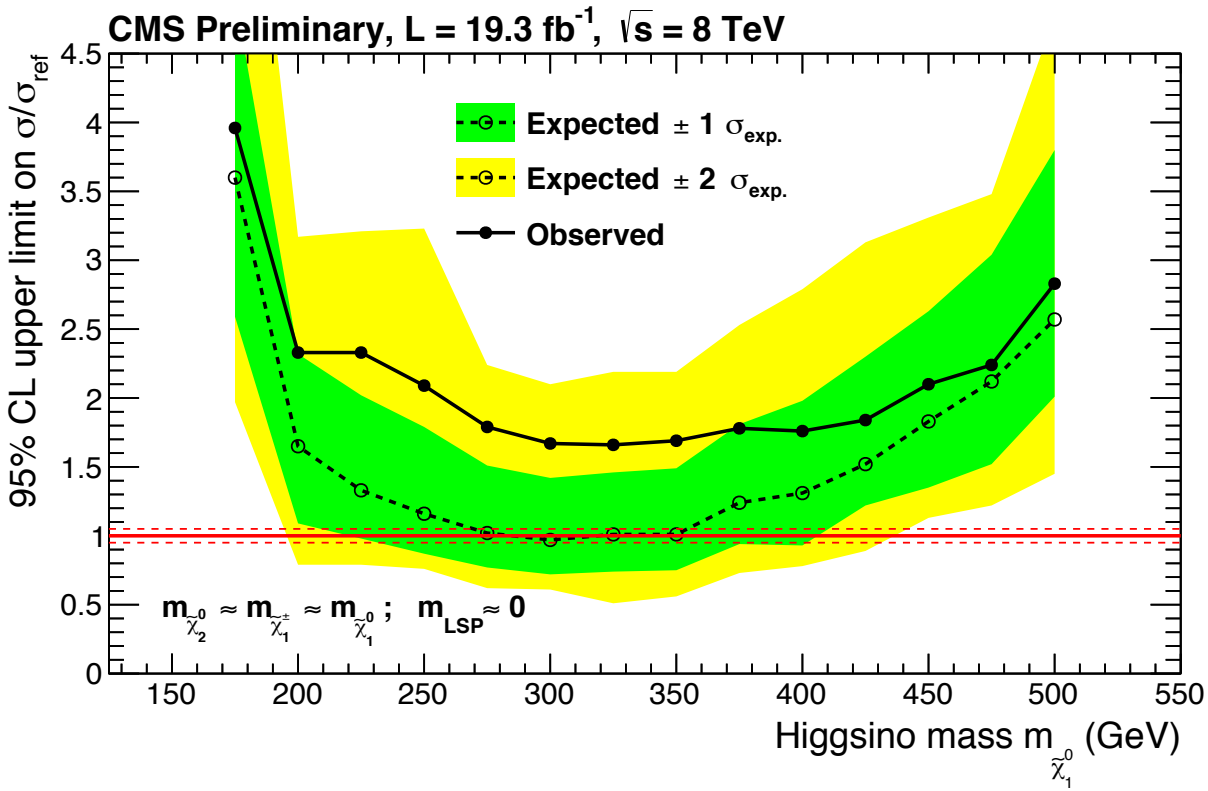




Higgsino interpretation



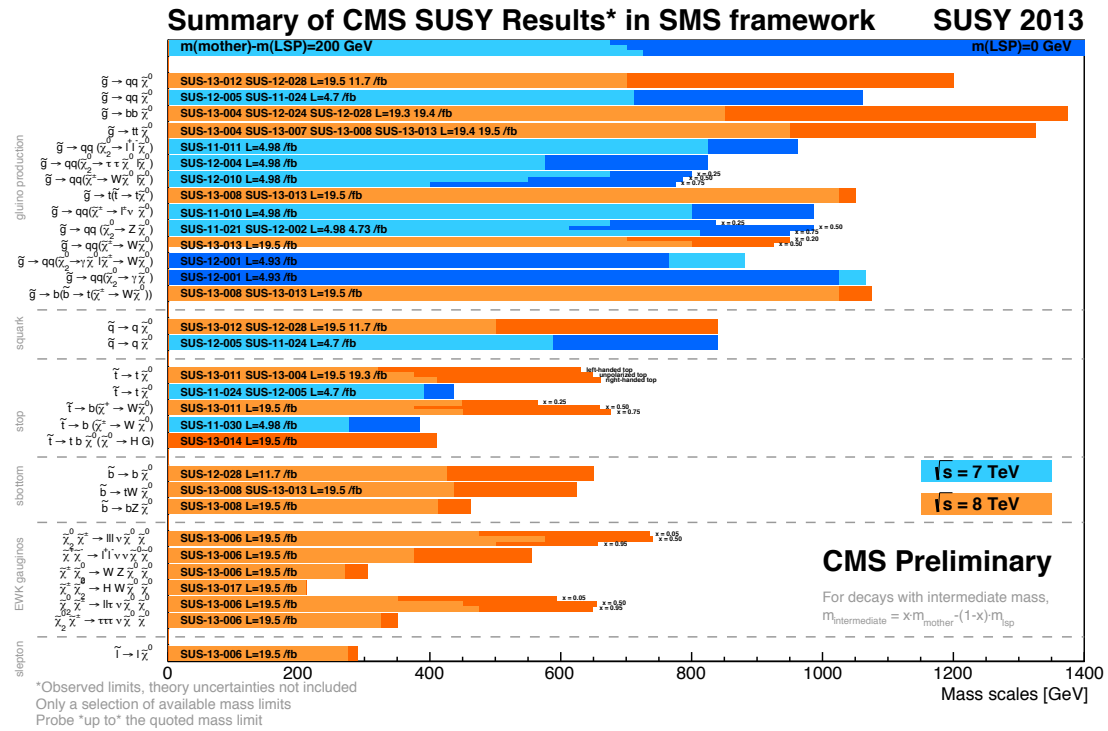
- Interpret as Higgsino production with 100% BF to H+LSP
- Reference cross section is a GMSB model with
  - ~massless Gravitino LSP
  - Nearly degenerate Higgsinos as only other SUSY particles
- Just on the edge of sensitivity with 2012 data
- First search of its kind!



CMS-SUS-13-022

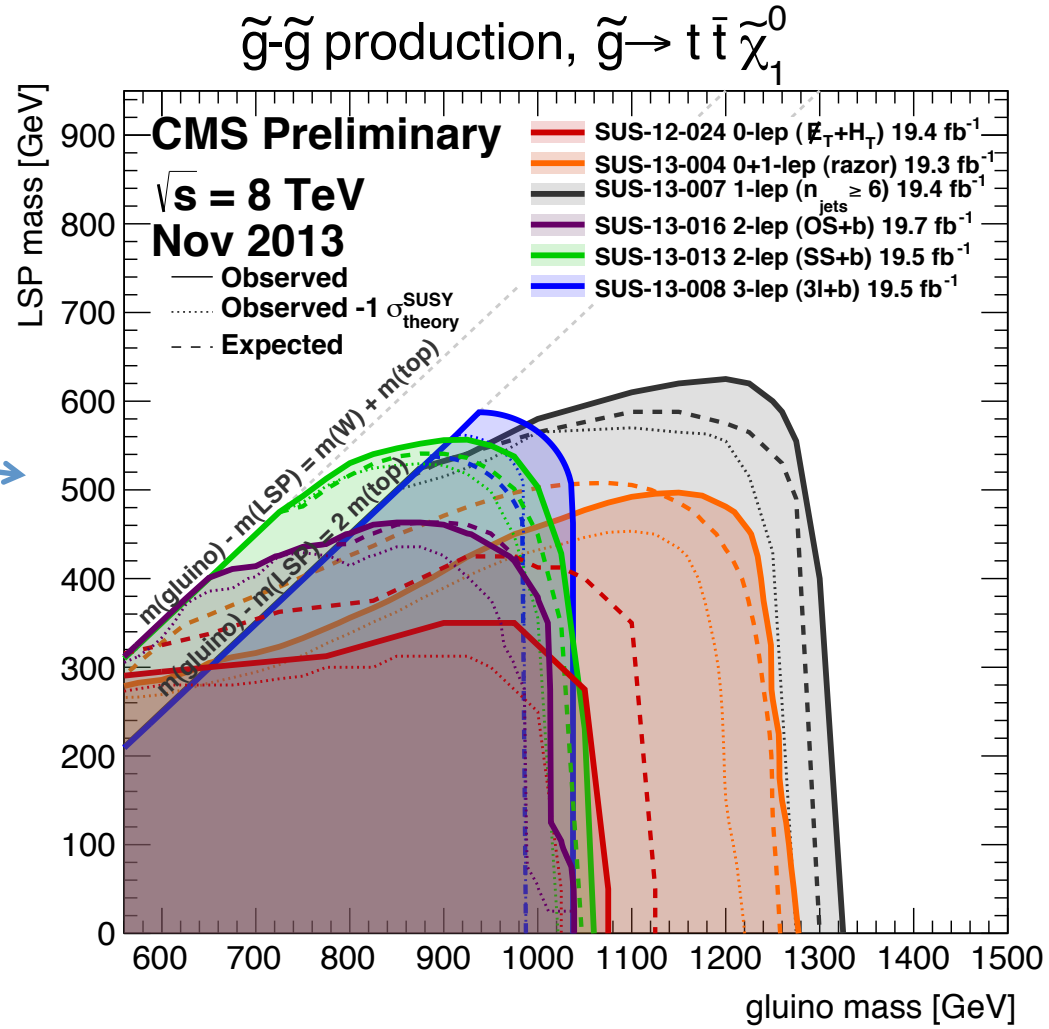
What's next?

- Most 8 TeV searches are now complete (or close)
- No new data for awhile, so a chance to organize where we are
- Projects for 2014 include
  - Take stock of what we've learned, and what's still to cover
  - Prepare for 2015



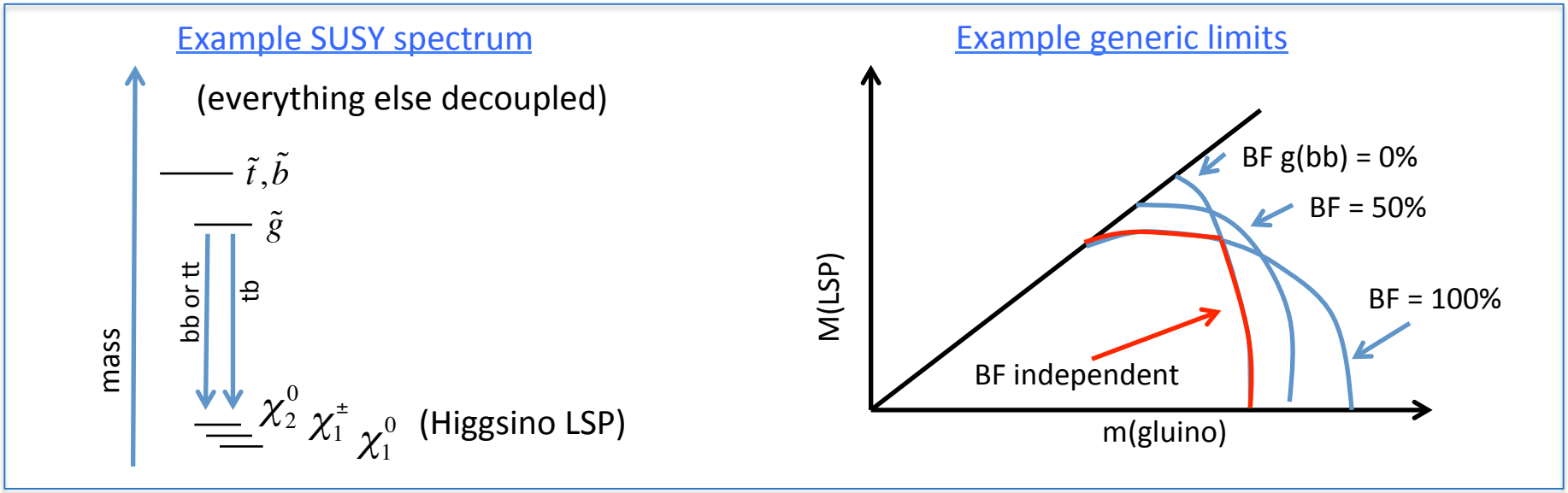
Combination of multiple searches

- Searches organized along topological lines
- Mutually exclusive final states are complementary
- For some signatures, multiple final states can be combined
  - Ex. gluino-mediated stop production with 0,1,2,3,4 charged leptons
  - Extends the individual limits for now
- When a discovery starts to pop up, will be essential to corroborate in multiple channels
  - Establish technological feasibility of combinations now
- Can also be done for direct stop, EWino, etc.



Toward model independent results

- Simplified models give a nice picture, but it's inherently incomplete
- Can we stitch together different results for a more model independent picture?
  - Ex. In gluino vs LSP plane, what conclusions can we draw for natural models?
- Have results for gluino → b,b,LSP with 100% BF and gluino→t,t,LSP with 100% BF, but what about mixed cases? Or gluino→t,b,LSP?



- Ignores some clear caveats (ex. other EW states, on shell stops and sbottoms)
- Moving in a more universal direction to give clearer picture of where we are with all searches combined

Outlook for 2015

- A very exciting time: Last major LHC energy increase in 2015
  - Likely 8→13 TeV in √s
  - Some time now to prepare (and think!)
- First opportunities for early searches with high mass due to large cross section increase
  - New wave of inclusive searches first—new territory with ~1 fb^{-1}
  - Then new ground on targeted searches
    - Stops with ~5 fb^{-1}
    - EW production with ~10 fb^{-1}

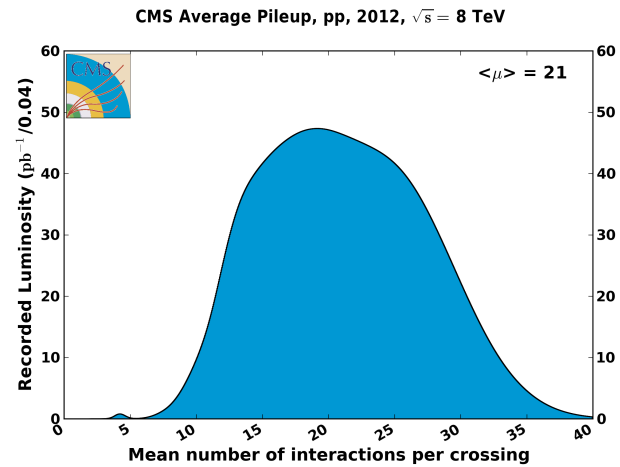
Signal cross section comparison (fb)	8 TeV	14 TeV	14 TeV/ 8 TeV
gluino 1.5 TeV	0.34	19.50	57
gluino 2.0 TeV	0.006	1.50	250
stop 600 GeV	23.5	222.0	9
stop 1.0 TeV	0.4	8.3	21
$\chi^+\chi^0$ 400 GeV	36	130	4
$\chi^+\chi^0$ 800 GeV	0.65	5.53	9

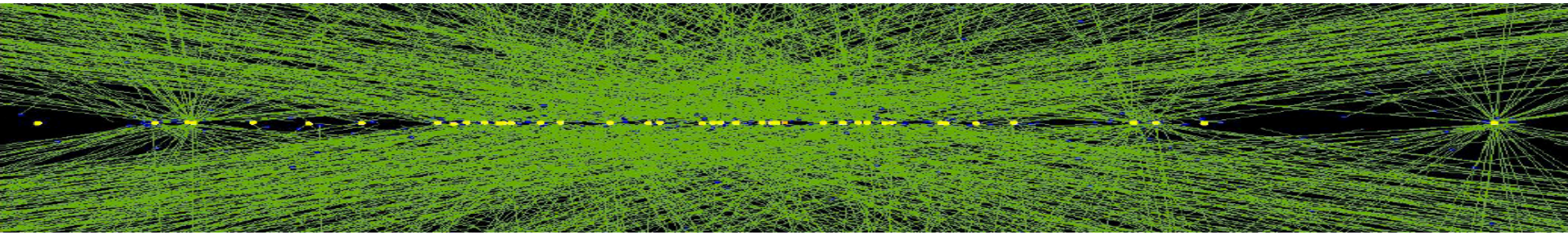
SM cross section comparison (pb)	8 TeV	14 TeV	14 TeV/ 8 TeV
ttbar	249	965	4
W+bb	43.4	84.9	2
WW	56	121	2

Preparations for 2015: Triggers

- Significant challenges in going from 8 → 13 TeV
  - Energy goes up by ~60%
  - Instantaneous luminosity goes up by ~30%
  - Pileup profile still TBD (possibly up to mean ~50)
- First challenge to maintain triggers for search program
  - Total bandwidth
    - Total 8 TeV triggered rate goes up factor ~4
    - To avoid pure threshold increases, try to move offline selection to trigger
  - Timing requirements
    - Additional rate must be absorbed in ~same time
    - More sophisticated online techniques must be fast
  - Pileup hurts
    - Tracking timing grows exponentially with occupancy
    - Isolation more difficult with extra energy

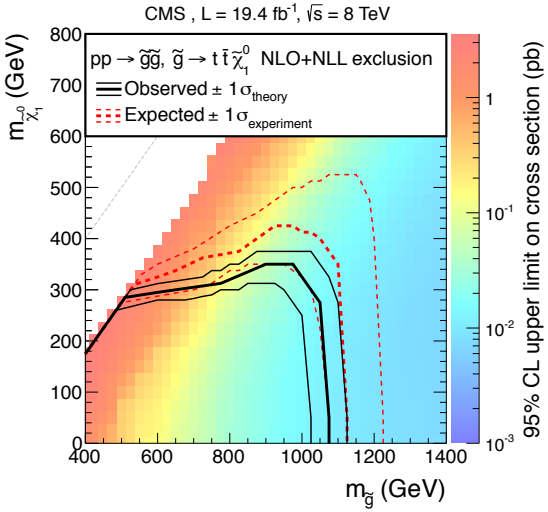
	2012	2015 (hope)	LHC Design
√s energy	8 TeV	13 TeV	14 TeV
Peak luminosity	7E33 $cm^{-2}s^{-1}$	1E34 $cm^{-2}s^{-1}$	1E34 $cm^{-2}s^{-1}$
<PU>	21**	~25	~25
Bunches	1380	2808	2808
Bunch spacing	50 ns	25 ns	25 ns

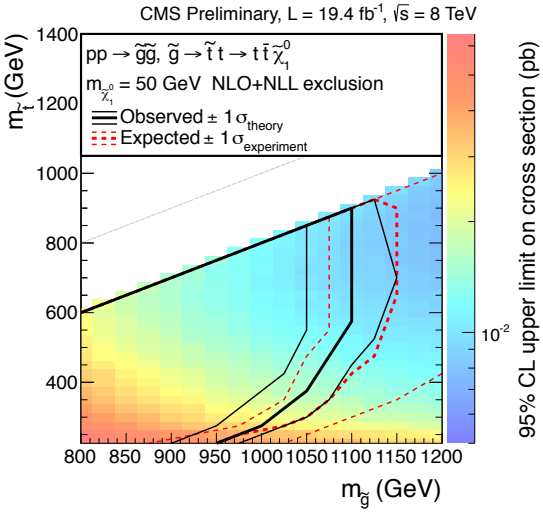




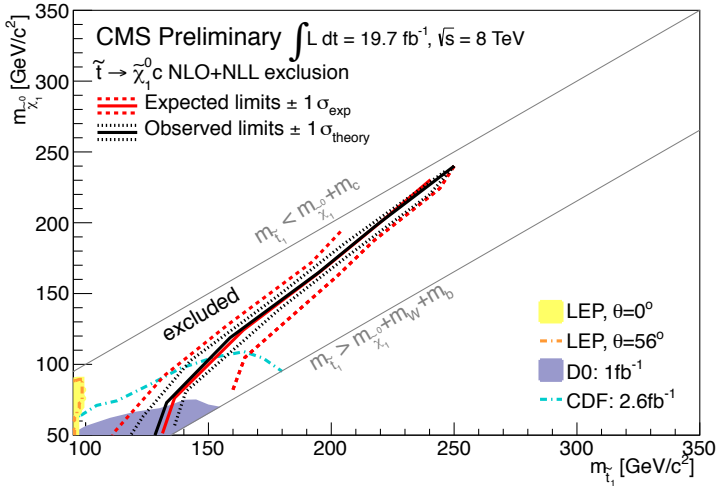
Preparations for 2015: Signals

- Beyond maintaining trigger performance from 8 TeV, we must consider more challenging signals that we might miss
- SUSY did not show itself in the "easy" channels at 8 TeV, and may not at 13 TeV either
- May need to push toward remote corners of SUSY space
  - Compressed spectra
    - Lower MET/jet p_T





    - Even completely missed decay products: Monojet+X etc.



  - Long, complicated decay chains
  - Rarer processes such as stau production
  - Low MET as in R-parity violating or stealth scenarios

Further future

- LHC upgrade schedule:

Run 1
25 fb^{-1}
$\sqrt{s}$ = 7/8 TeV
L ~6E33 $cm^{-2}s^{-1}$
<PU> = 21

→ To design energy/ luminosity

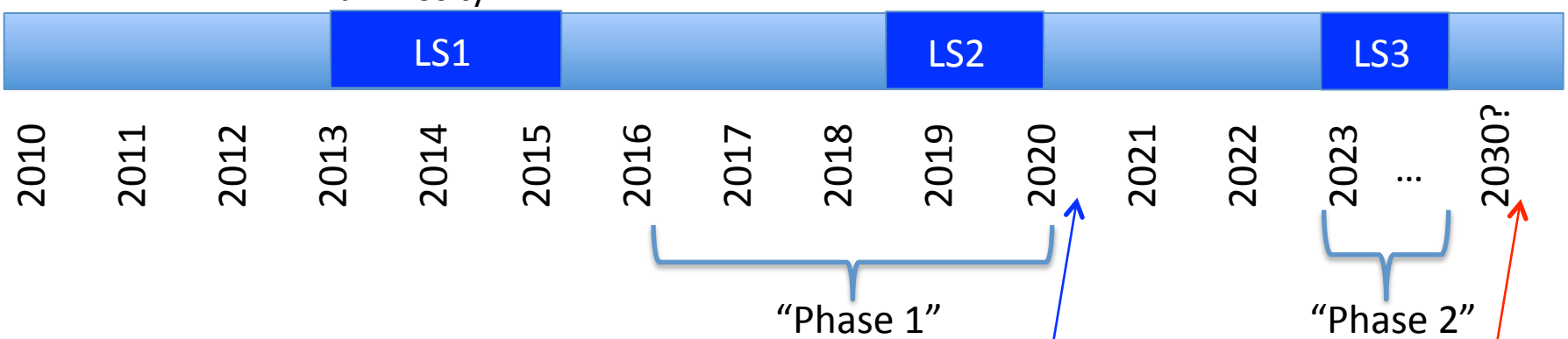
Run 2
~75-100 fb^{-1}
$\sqrt{s}$ = 13/14 TeV
L ~1E34 $cm^{-2}s^{-1}$
<PU> = 25

→ To 2x design luminosity

~350 fb^{-1}
$\sqrt{s}$ = 14 TeV
L ~2E34 $cm^{-2}s^{-1}$
<PU> = 50

→ HL-LHC

~3000 fb^{-1}
$\sqrt{s}$ = 14 TeV
L ~5E34 $cm^{-2}s^{-1}$
<PU> = 128



- Physics reach:

Higgs discovery!

Observe $B_s \rightarrow \mu\mu$!

Natural SUSY
Gluino discovery up to ~2 TeV
Stop discovery up to ~1 TeV
Higgsino discovery up to ~500 GeV

Higgs coupling to W,Z ~5%

Higgs potential: observe gg→HH

EWSB: observe WW scattering

Higgs coupling to t,b,τ ~5%

Z'→ll discovery reach ~6 TeV

CMS Snowmass white paper 1307.7135

Upgrade overview

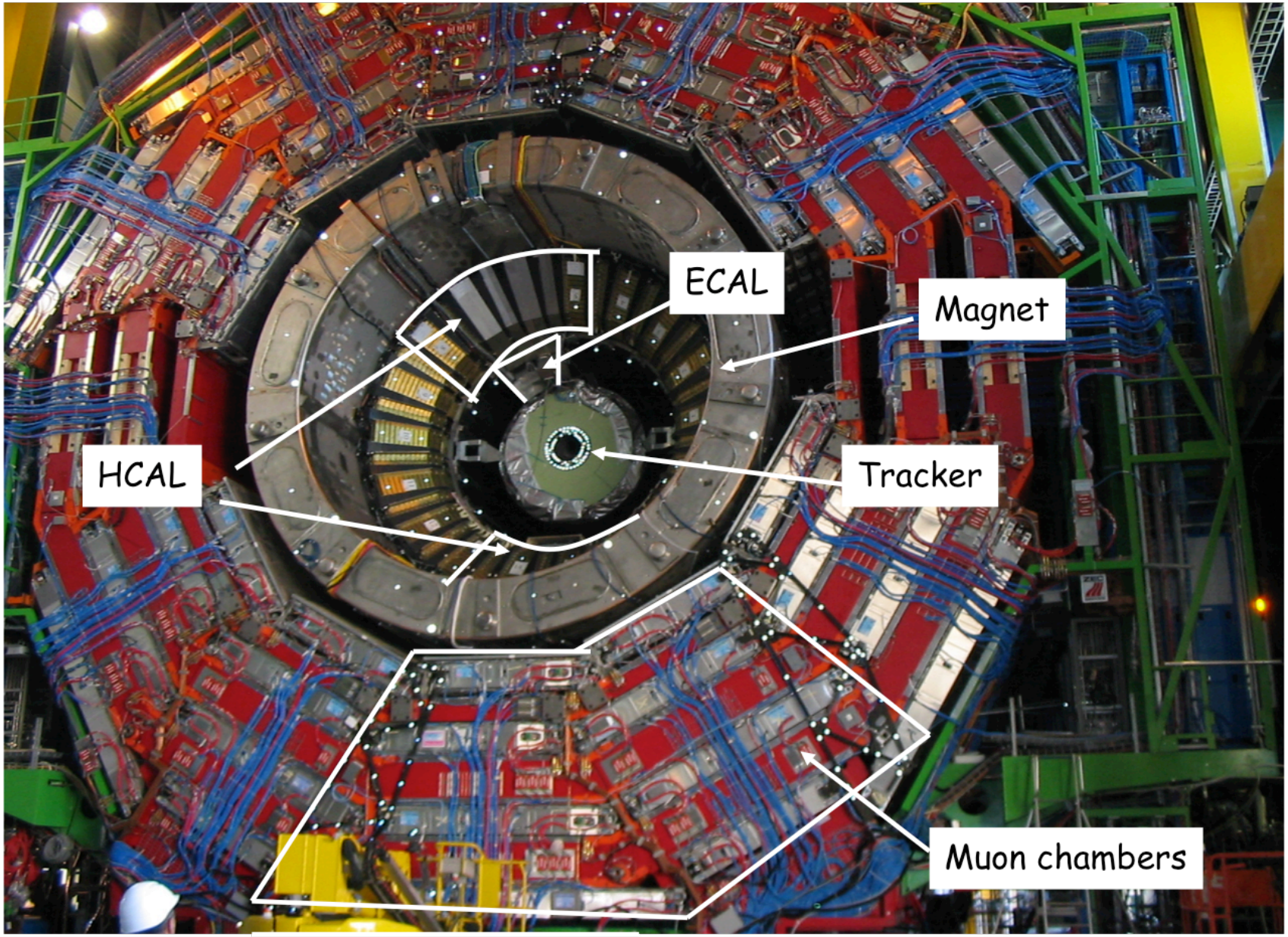
- CMS and ATLAS must be upgraded for HL-LHC
- Must address: radiation levels, detector occupancy, event rates, pileup
- Goal: Maintain/extend detector performance at higher-than-design luminosity
- Intense radiation exposure makes replacement of detectors near the beamline essential for even minimal physics performance
  - Completely replace inner tracker
  - Replace calorimeter readout electronics
- High rate and pileup present unique challenges for the trigger
  - Ex. single lepton triggers required for W and Z physics threatened already at hardware trigger level (L1)
  - Solution requires tracking → a real challenge involving the tracker upgrade and fast tracking algorithms implemented in the hardware

Conclusions and outlook

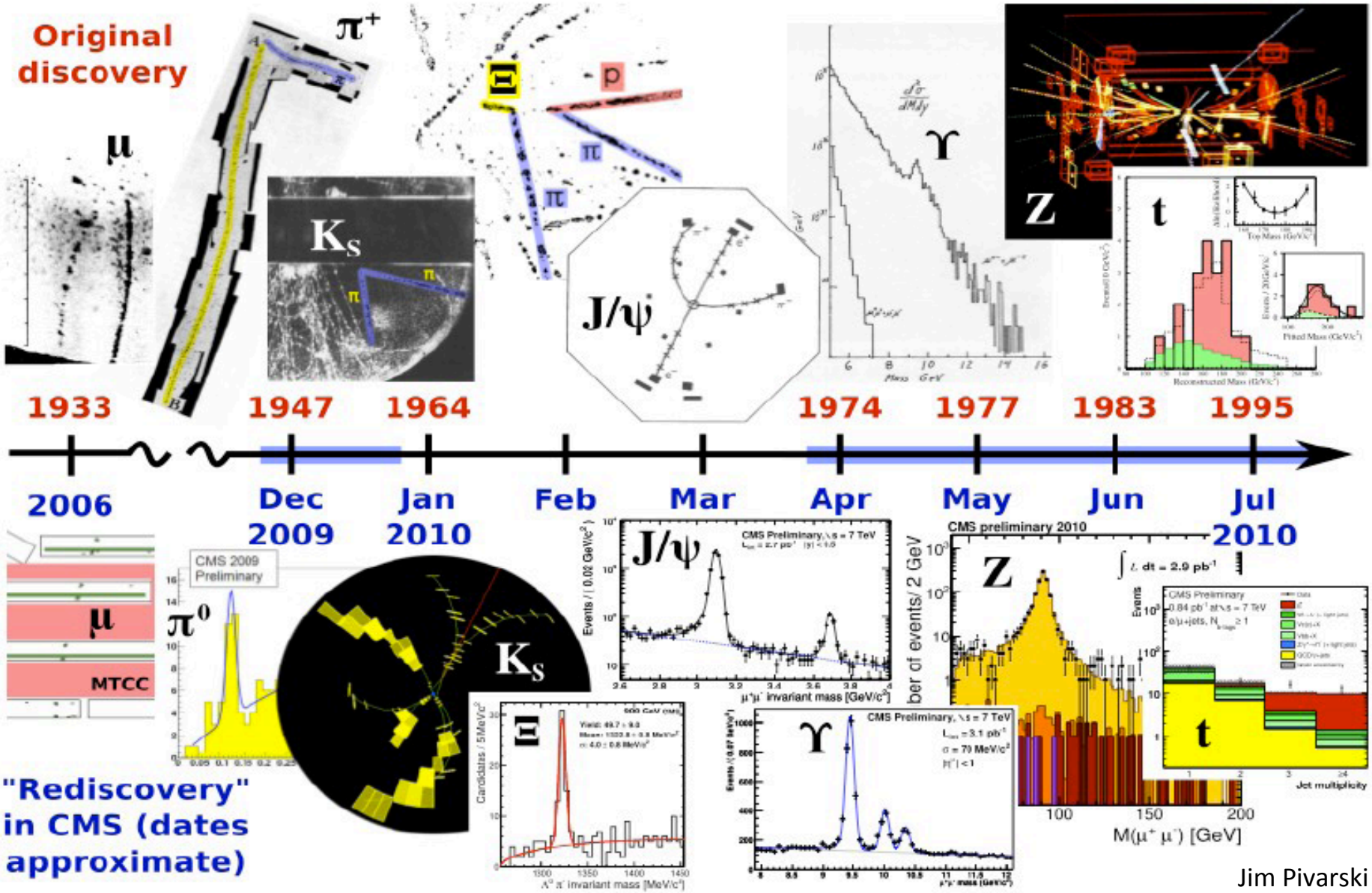
- The LHC is a discovery machine and 2015 brings the (near) ultimate energy reach
  - If a fantastic discovery
    - SUSY search program set up to discover and cross check with complementary approaches
    - Great challenge to characterize the new physics
    - Will paint complete picture through many varied search channels
  - If natural SUSY ruled out
    - SUSY search program needs rethinking
    - Dark matter still motivates MET + X searches
    - BSM may prove more elusive to tease from high luminosity datasets
- Above all, I aim to
  - Remain flexible in my approach and to take advantage of opportunities that arise
  - Enjoy the ride!

Extra slides

CMS

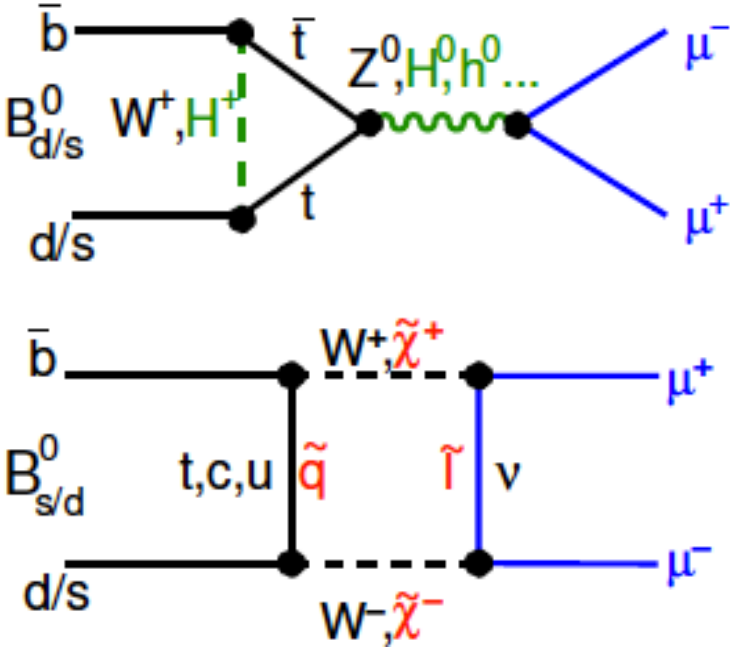


Rediscovery of the Standard Model



Interlude on $B_s \rightarrow \mu^+\mu^-$

- $B \rightarrow \mu\mu$ branching fraction a great place to search indirectly for NP
  - Very heavily suppressed in SM: FCNC, helicity suppression
  - Well controlled theoretically
  - NP effects potentially very large compared to SM



$$BR(B_s^0 \rightarrow \mu^+\mu^-) = (3.56 \pm 0.18) \times 10^{-9}$$
$$BR(B^0 \rightarrow \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$$

SM prediction:
A. Buras 1012.1447
A. Buras 1303.3820

A long journey

Low Mass Dimuon Production at the CERN Proton-Antiproton Collider.

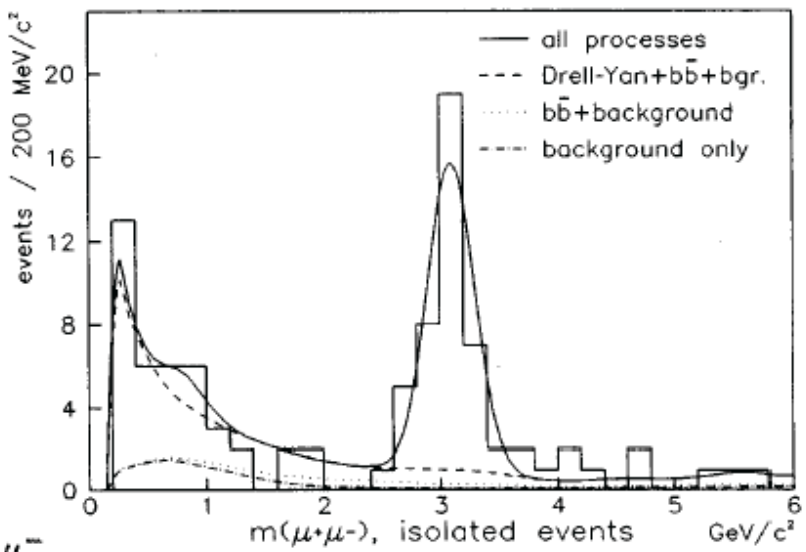
CERN-EP/88-46
April 6th, 1988

UA1 Collaboration, CERN, Geneva, Switzerland

PLB 209, 397 (1988)

Abstract

p_T beauty and Drell-Yan production are derived. A limit for the branching fraction for the exotic decay $B^o \to \mu^+\mu^-$ is also obtained. The cross section

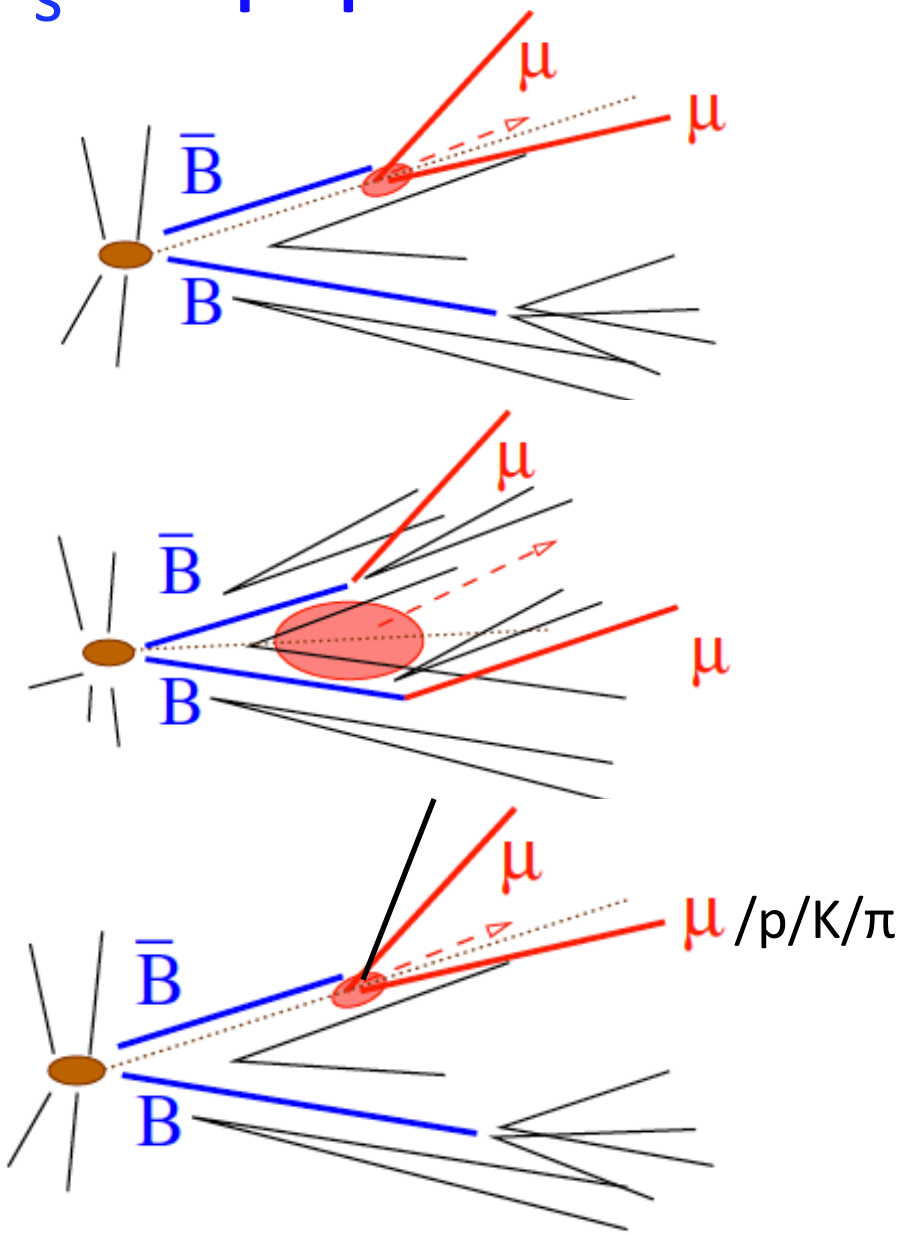


7. Limit for the decay $B^o \to \mu^+\mu^-$

only one (with mass 5.39 ± 0.15 GeV/c^2) has $p_T(\mu\mu) > 5$ GeV/c. Assuming that a b quark picks up a light quark in the same way as a u quark, the measured K to π ratio for leading particles [13] suggests a corresponding B_s^o:B_d^o ratio of 1:2. Using a $B^\pm$:B_d^o

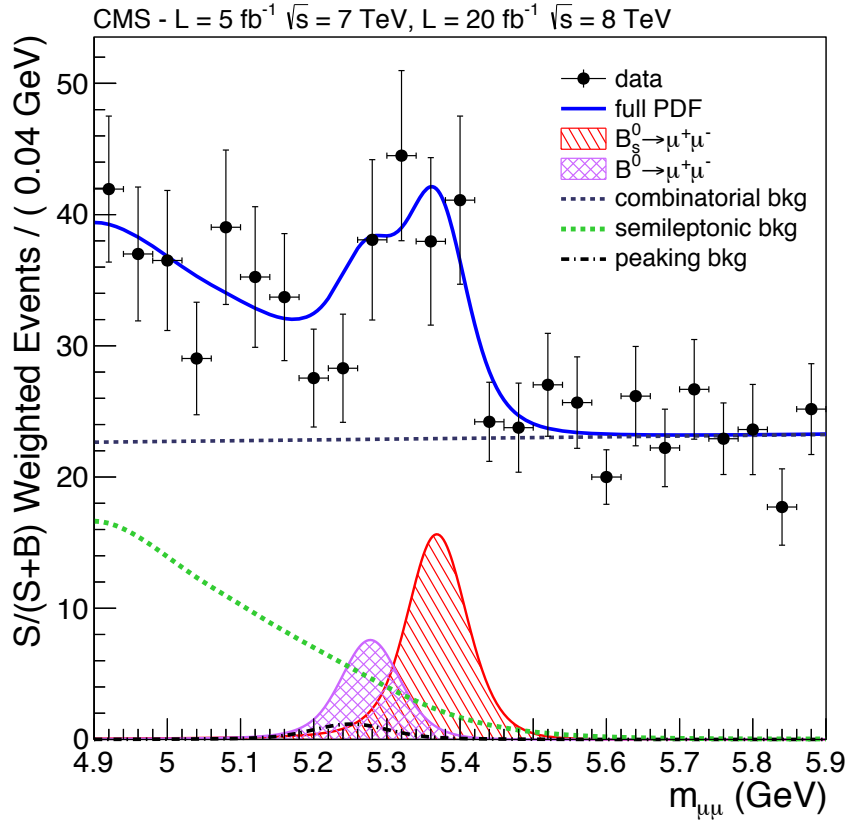
Search for $B_s \rightarrow \mu^+\mu^-$

- Isolated dimuon signature with B mass
- Stringent vertex constraint displaced from and pointing to primary vertex
- Very pure muon candidate selection
- Utilizes: low p_T muon triggering, outstanding muon momentum resolution, strong muon ID, huge B meson sample



$B_s \rightarrow \mu^+\mu^-$ results

- Train multivariate discriminators to
  - Select ultra pure muon candidates
  - Select signal-like dimuon events
- Fit dimuon mass for signal
  - Normalized to $B^+ \rightarrow J/\Psi K^+$ yield
- Observed significance of 4.3σ (4.8σ expected)



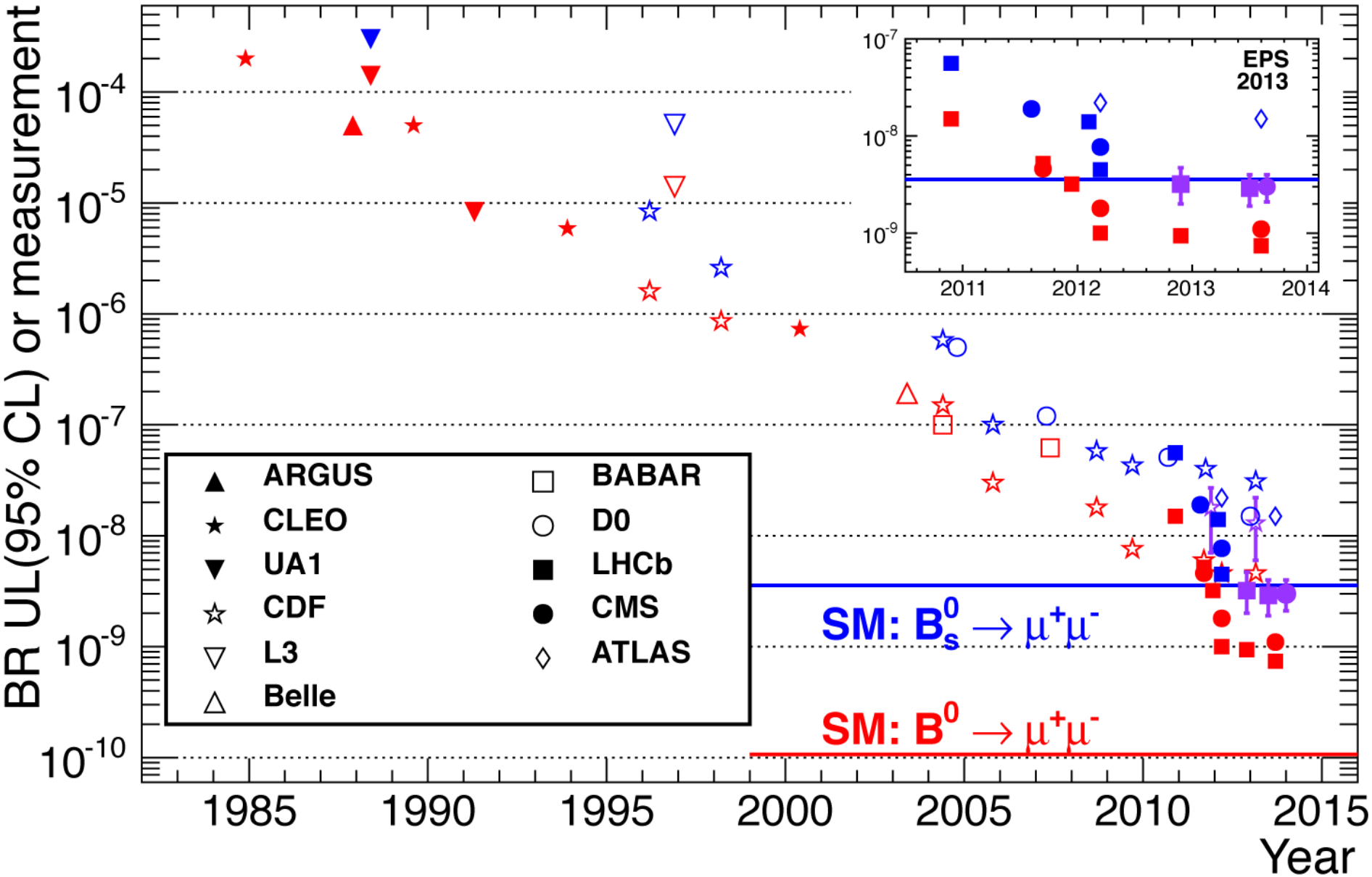
$$BR(B_s^0 \rightarrow \mu\mu) = (3.0^{+0.9+0.6}_{-0.8-0.4}) \times 10^{-9}$$

First observation when combined with 4.0 σ result from LHCb

$$BR(B_s^0 \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

arXiv: 1307.5024, 1307.5025

$B \rightarrow \mu^+\mu^-$ history

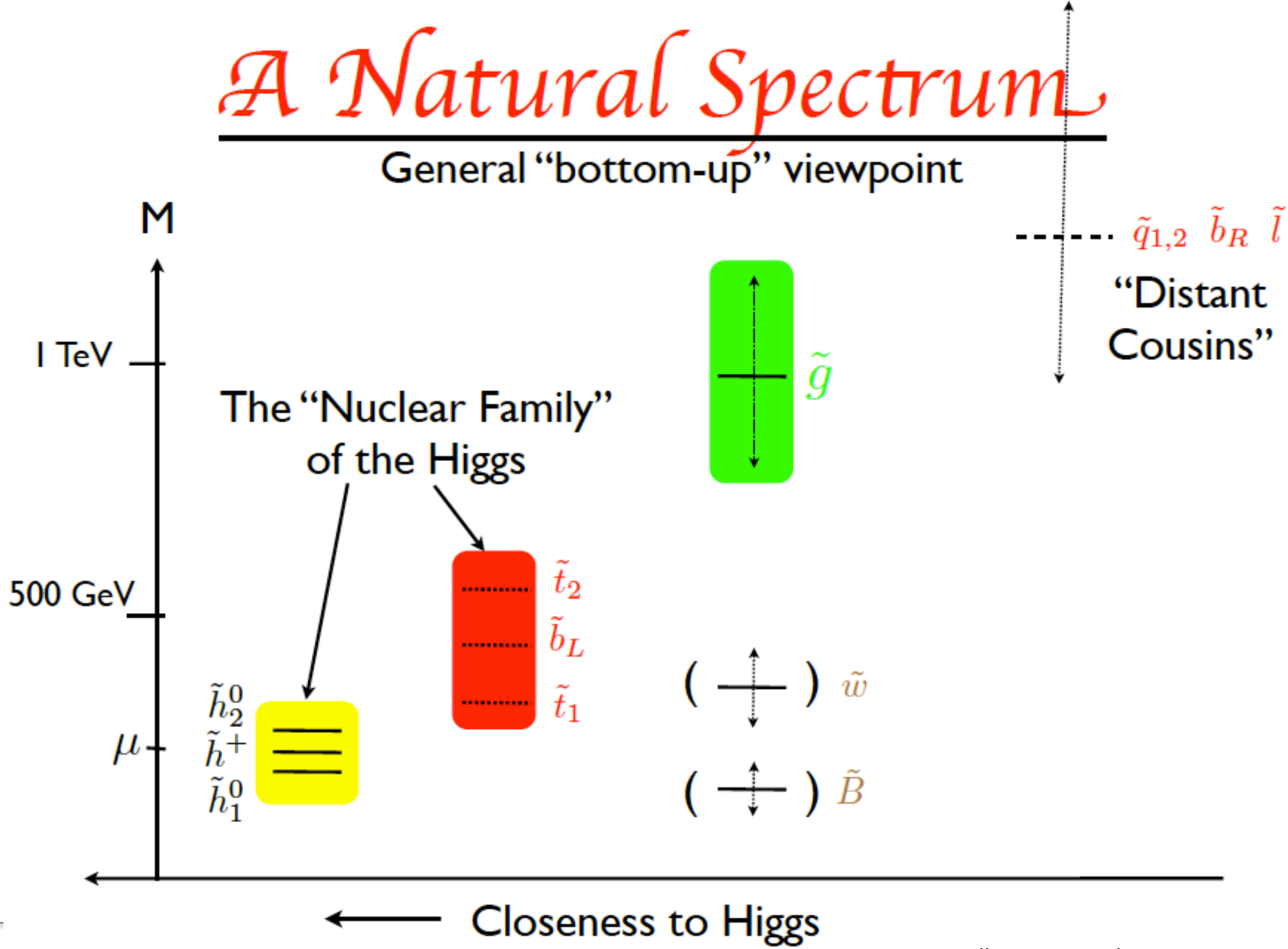


“Supersymmetry” searches

- Really means searches for a broad class of new physics signatures
  - Motivated by SUSY, but could easily find something else
    - Pair produce something new and have it decay to SM particles plus a dark matter candidate
    - Even the dedicated search is for a specific topology, not a specific model
  - Dark matter motivates this sort of search, too, even independent of supersymmetry
- Keep our minds open to make sure we don’t miss anything

A Natural Spectrum

General "bottom-up" viewpoint



The CMS SUSY group

Keith Ulmer, Frank Wuerthwein

Gluino, with 3rd gen
Seema Sharma
Markus Stoye

Razor inclusive
Inclusive α_T
3L + b + MET
Multi-jet + MHT
SS dilepton + b
OS dilepton + b
1L + multi-b low MET
MT2 inclusive
MET + HT + b
1L gluino inclusive

+1 in progress

Stop, sbottom, stau
Josh Thompson
Filip Moortgat

1L stop
Hadronic stop
stop → charm, LSP
stop2 → Higgs,stop1

+5 in progress

Leptonic
Petar Maksimovic
Wolfgang Adam

EW with leptons
Inclusive multi-lep
RPV with 3 lep + b
RPV with 4 leptons
EWino with Higgs
RPV stop 3L + b

+4 in progress

Photon
Yuri Gerstein
Yurii Maravin

Inclusive ϒ+MET
Stop → H(gg) + X

+4 in progress

MC/Trigger
Frank Golf
Pablo Martinez

Coordinate cross Group Monte Carlo and Trigger issues

+1 in progress

Future studies
Kenichi Hatakayama
Isabell Melzer-Pellmann

Coordinate studies for upgrades and future performance

Public 8 TeV results listed. 19 more papers from 7 TeV 2011 data.