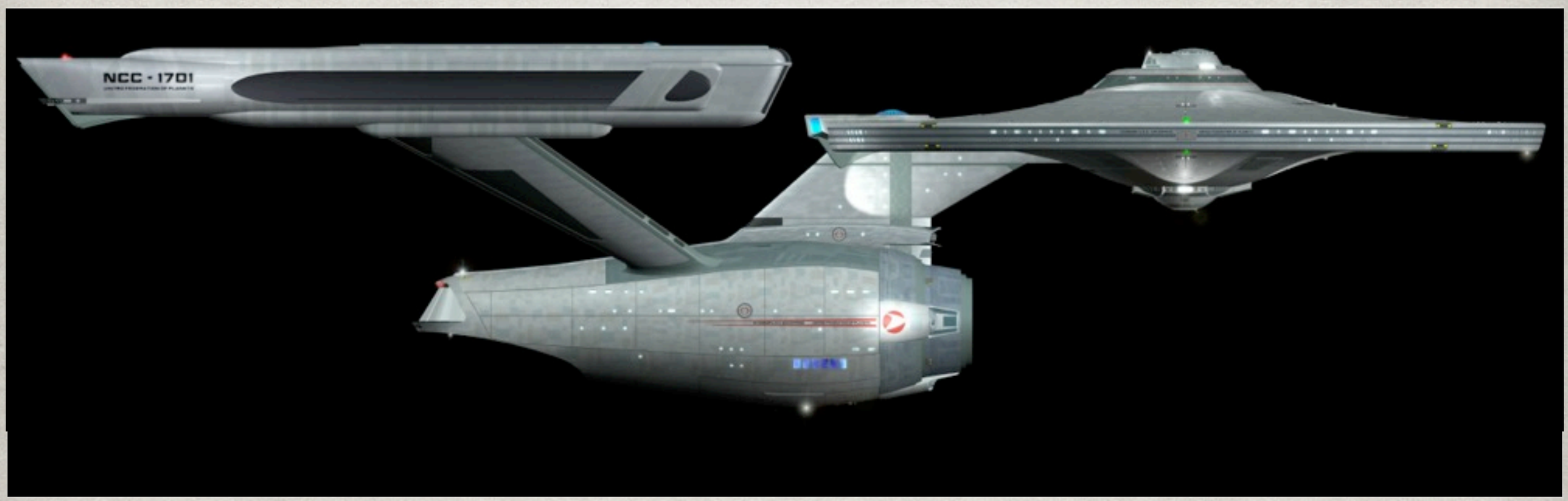
Recent CMS Results

Kevin Lannon
on behalf of
the CMS Collaboration

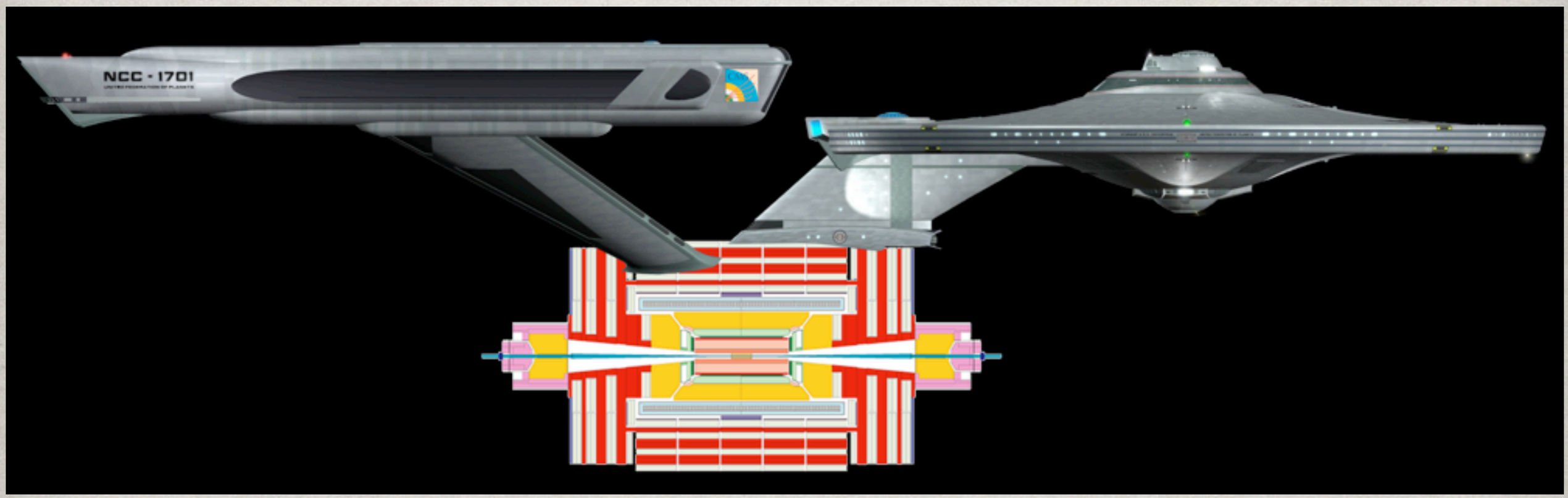
Frontiers

- Many frontier's mentioned during the lectures
  - Energy frontier
  - Intensity frontier
  - Cosmic frontier

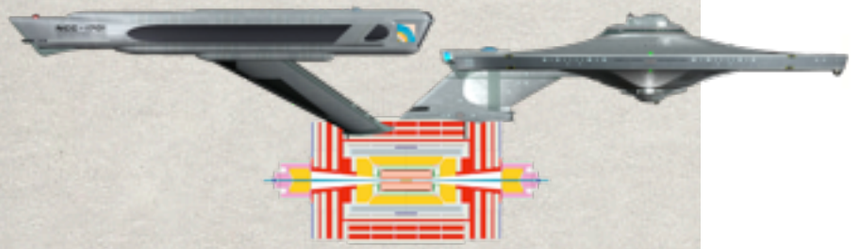
Exploring the Final Frontier



Exploring the Energy Frontier



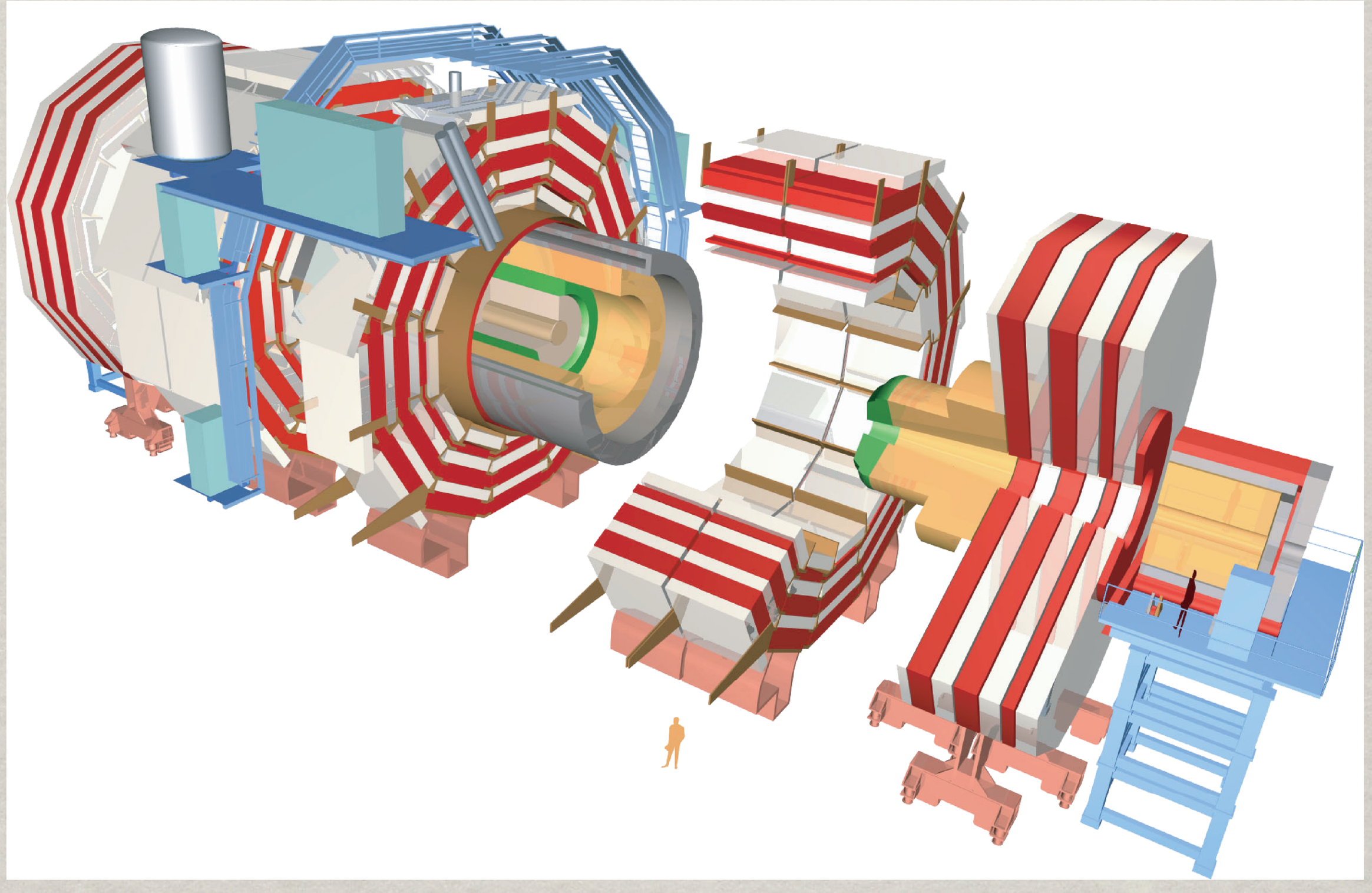
The Energy Frontier



Hitoshi Murayama

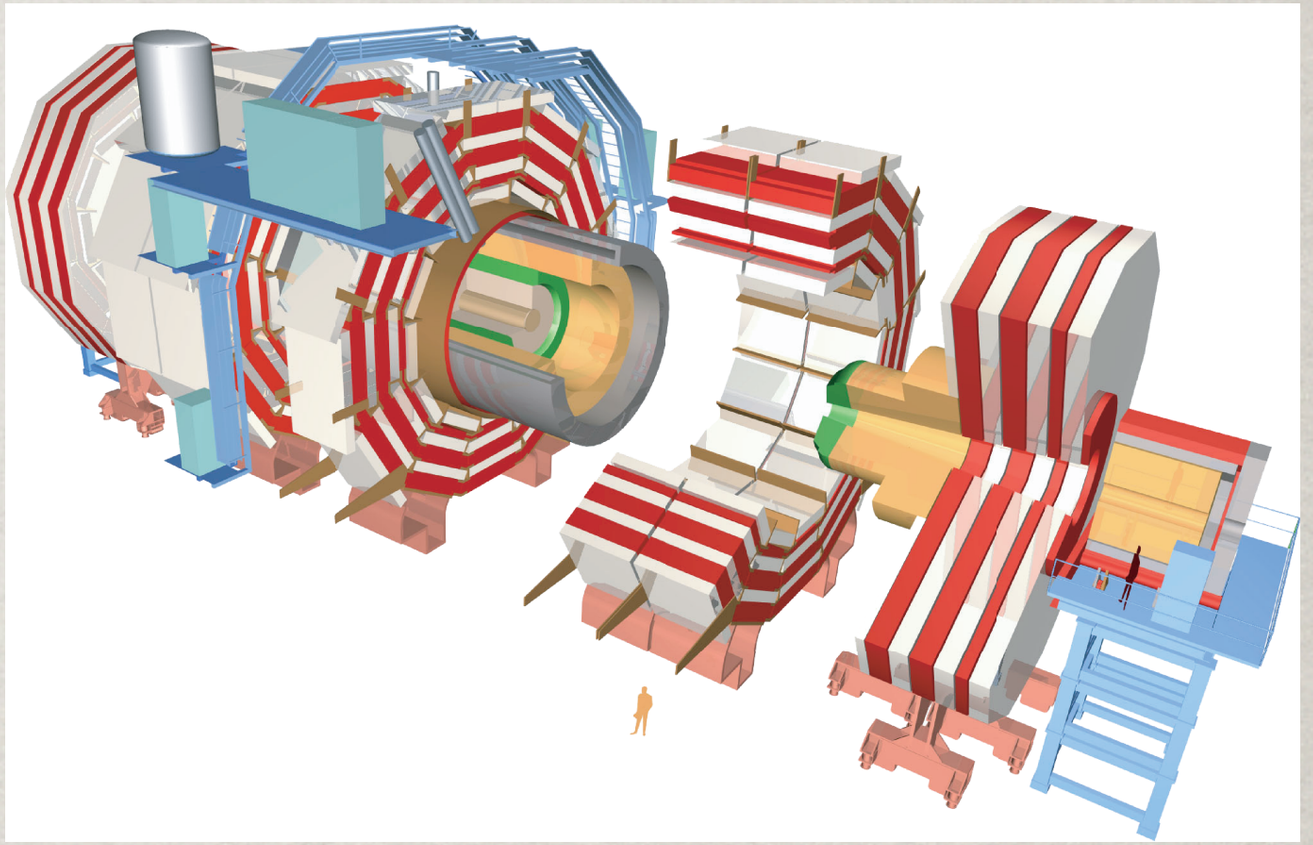
CMS Detector

CMS Detector

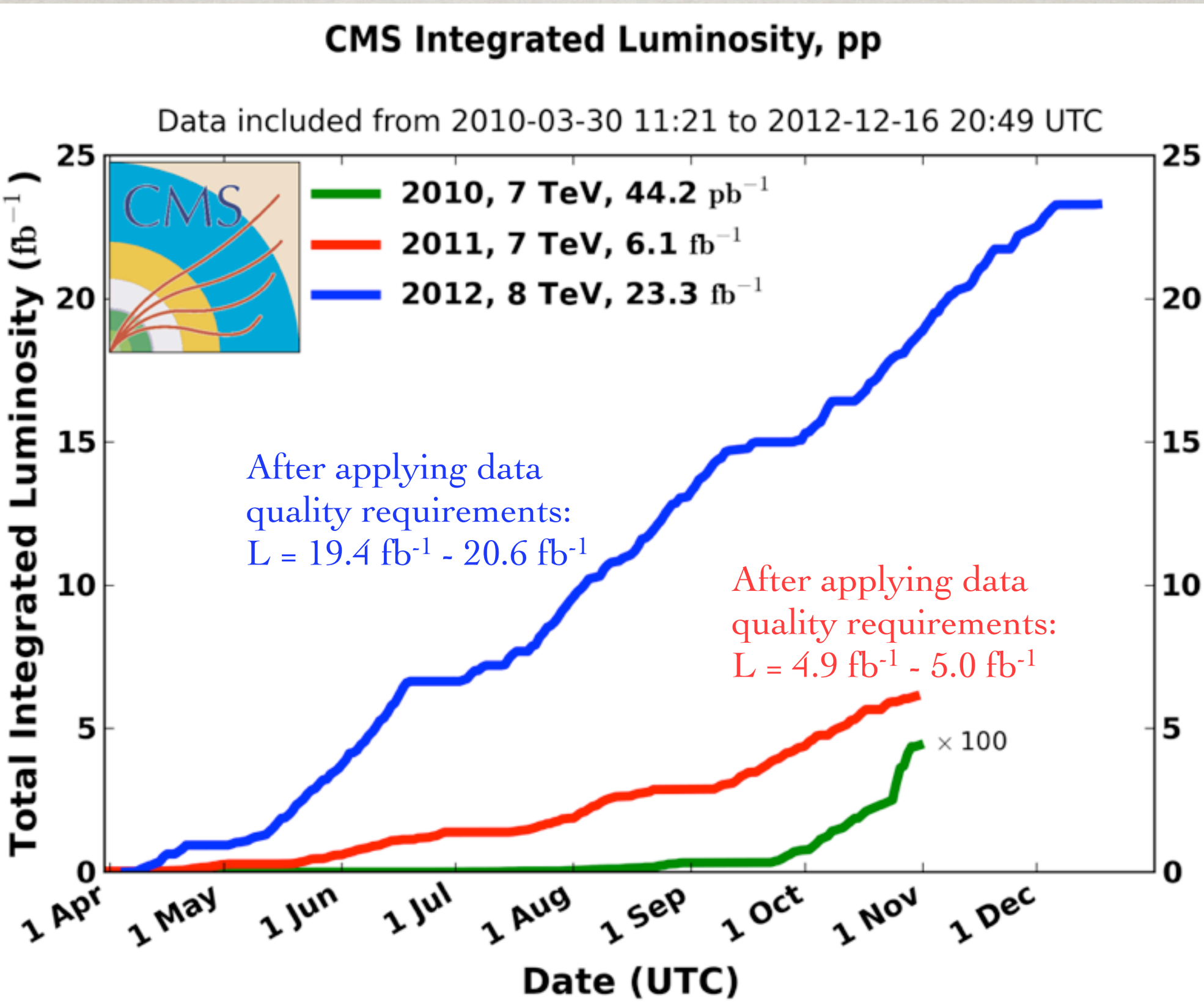


Distinguishing Features

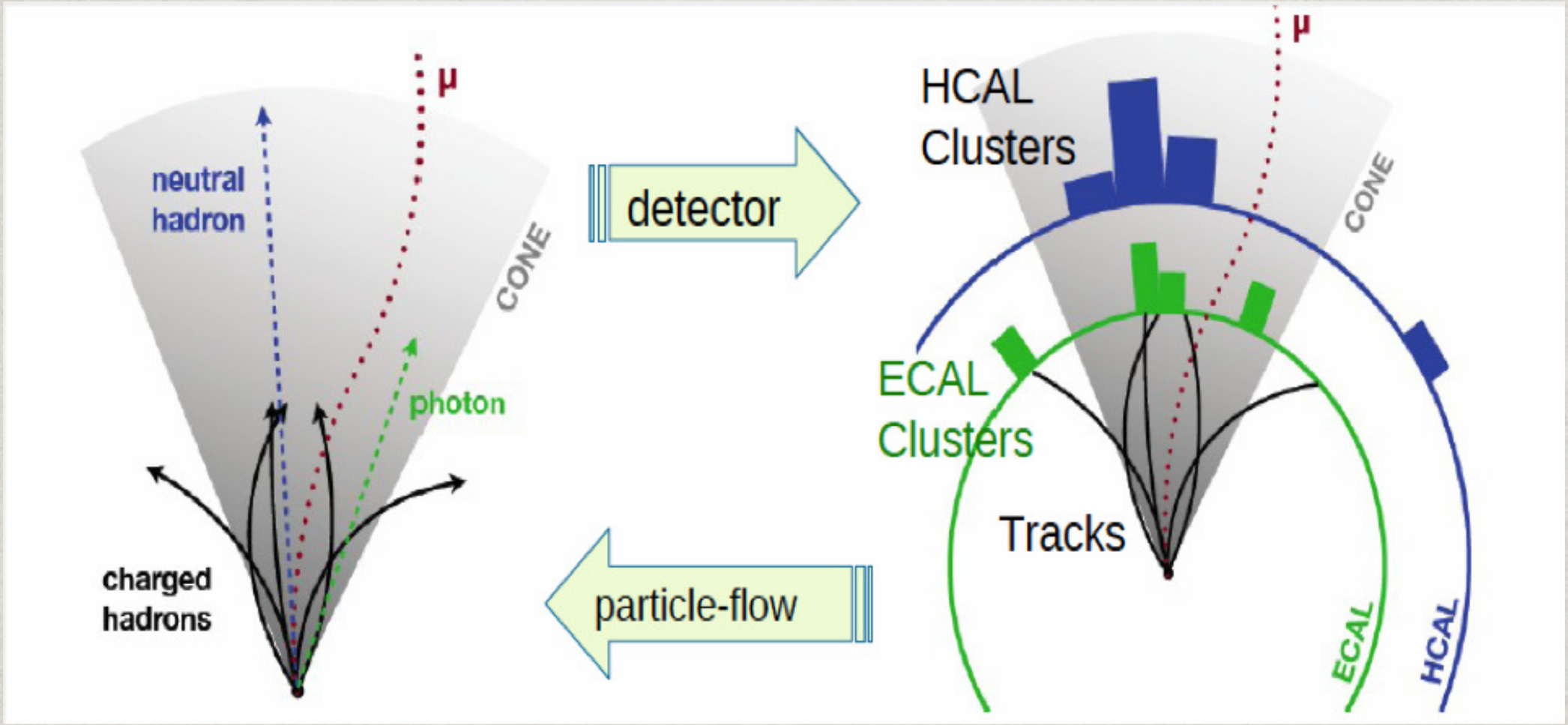
- All-Silicon Tracker
  - Over 200 m^2 silicon!
  - Pros: Great tracking resolution
  - Cons: Lots of material, photon conversion, etc.
- Muon System
  - 4 layers of DT/CSC with RPC for timing
  - Residual solenoid field gives ρ measurement
- ECAL
  - Excellent granularity and energy resolution



- HCAL
  - Coverage to $|\eta| < 5.0$ with HF
- Trigger
  - Only two levels: L1 and HLT


CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC
CMS
2010, 7 TeV, 44.2 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}
After applying data quality requirements:
L = 19.4 fb^{-1} - 20.6 fb^{-1}
After applying data quality requirements:
L = 4.9 fb^{-1} - 5.0 fb^{-1}
× 100
Total Integrated Luminosity (fb^{-1})
0
5
10
15
20
25
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Date (UTC)

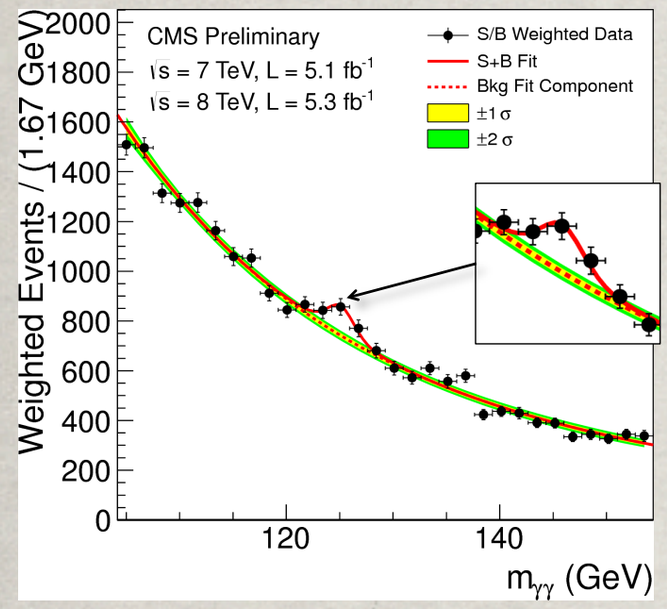
Particle Flow



- Make optimal use of detector information to reconstruct all particles
  - Improvements in jet energy resolution
  - Easily remove charged part of pileup (neutral part handled with standard "Fastjet" energy density subtraction.
- Unless stated otherwise, all CMS analysies use PF

Higgs Results

Discovery at LHC!



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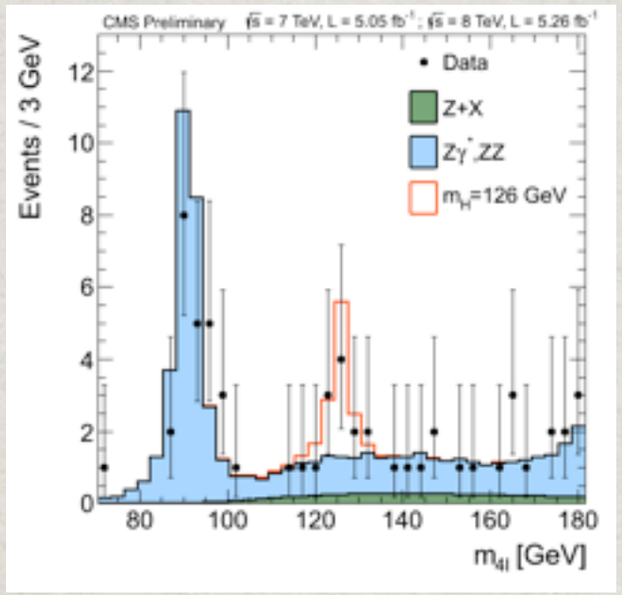

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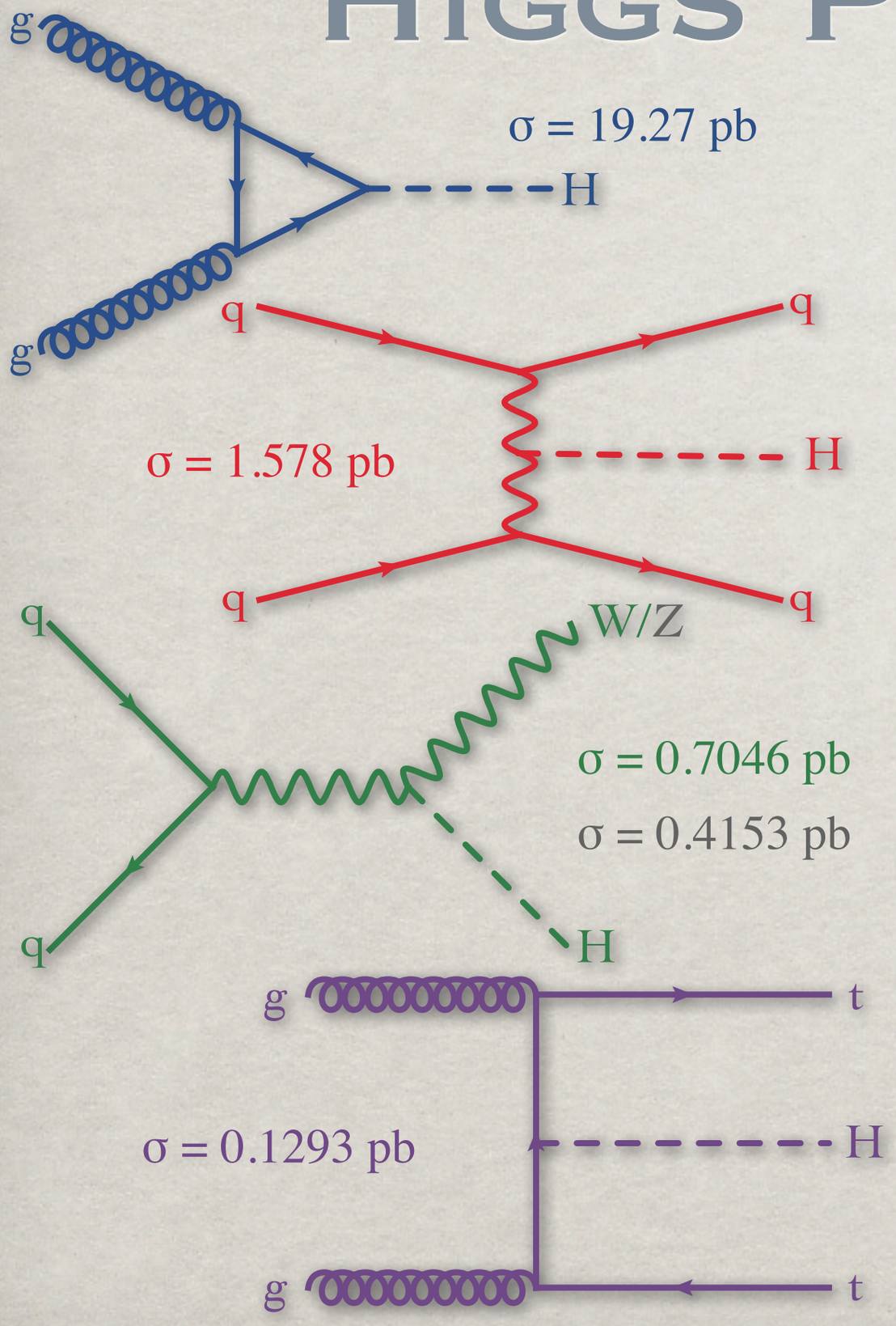
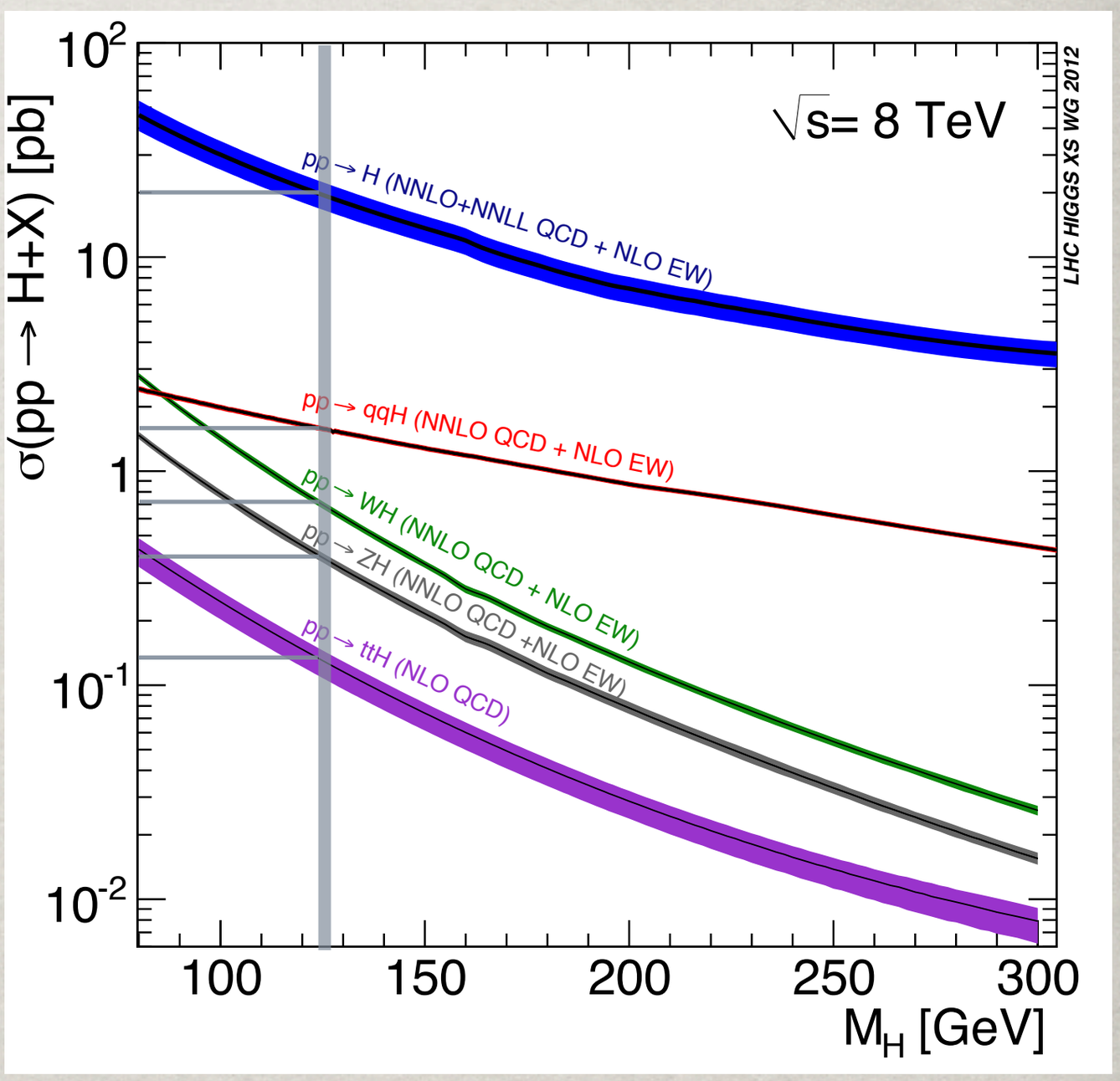
July 4, 2012

- Since then major focus of LHC physics program to verify whether this new particle has properties of (SM) Higgs
  - Is it produced and does it decay at the right rates? (Couplings to SM particles)
  - Does it have the right spin?

Higgs Production





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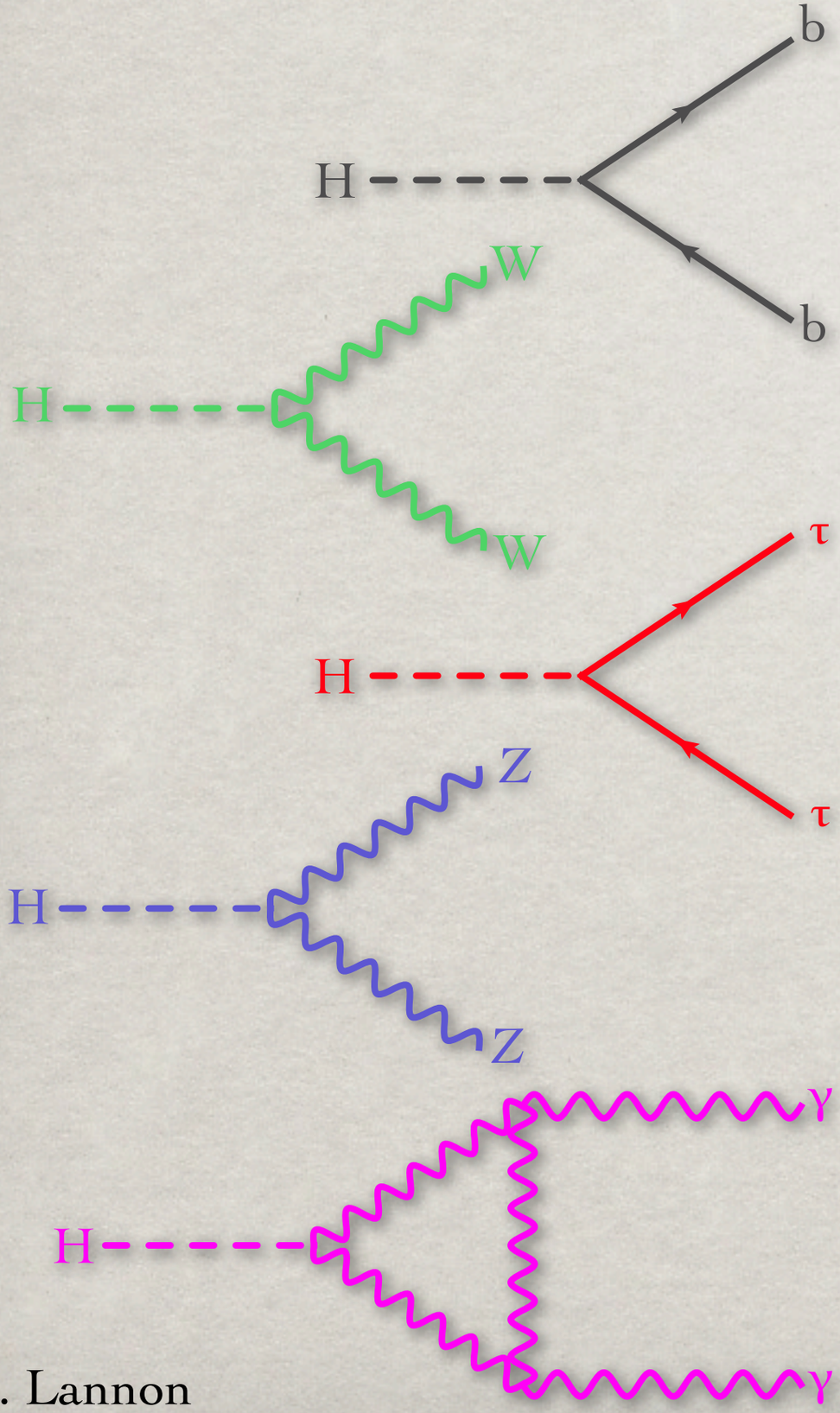
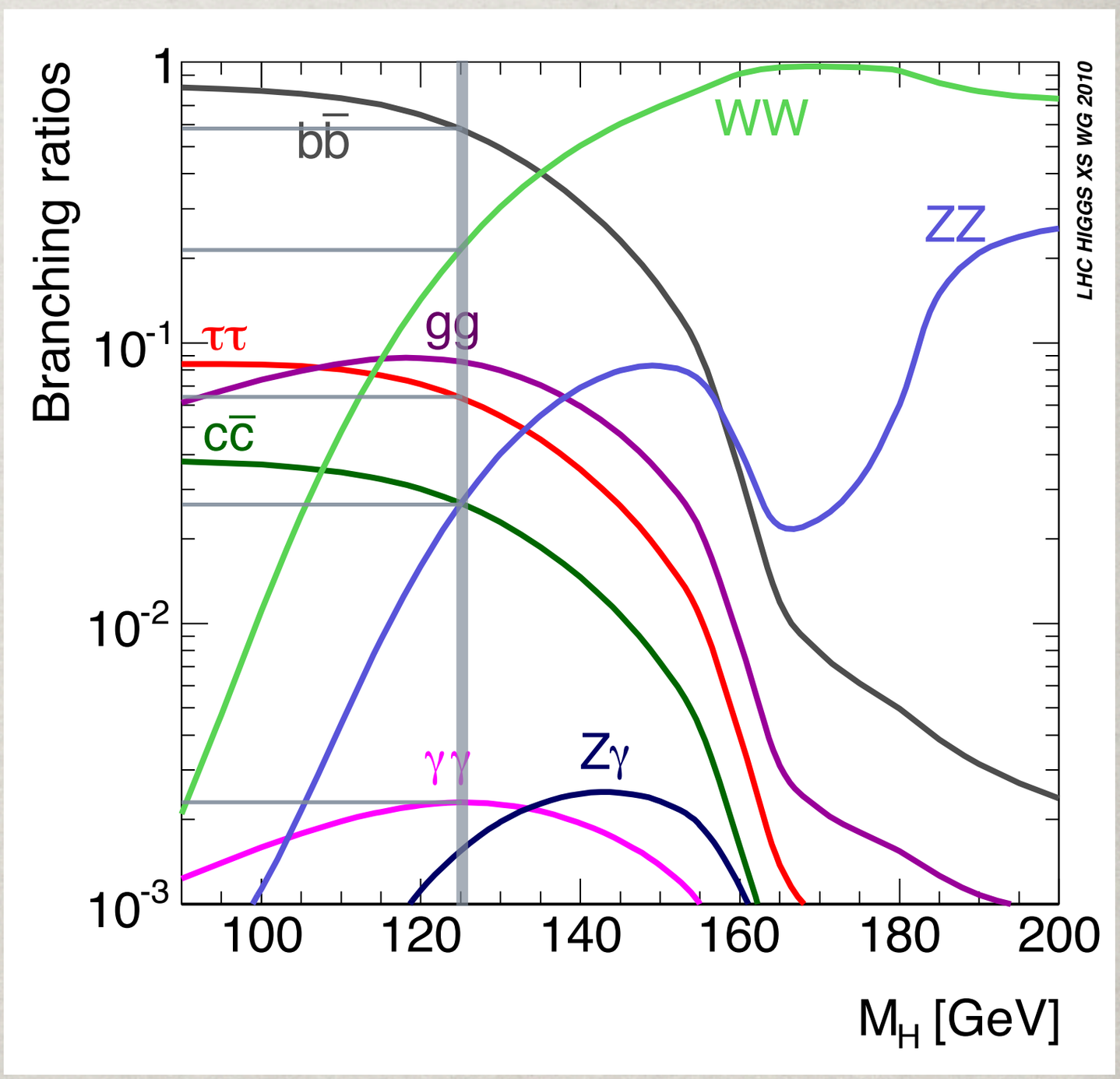
Higgs Decays





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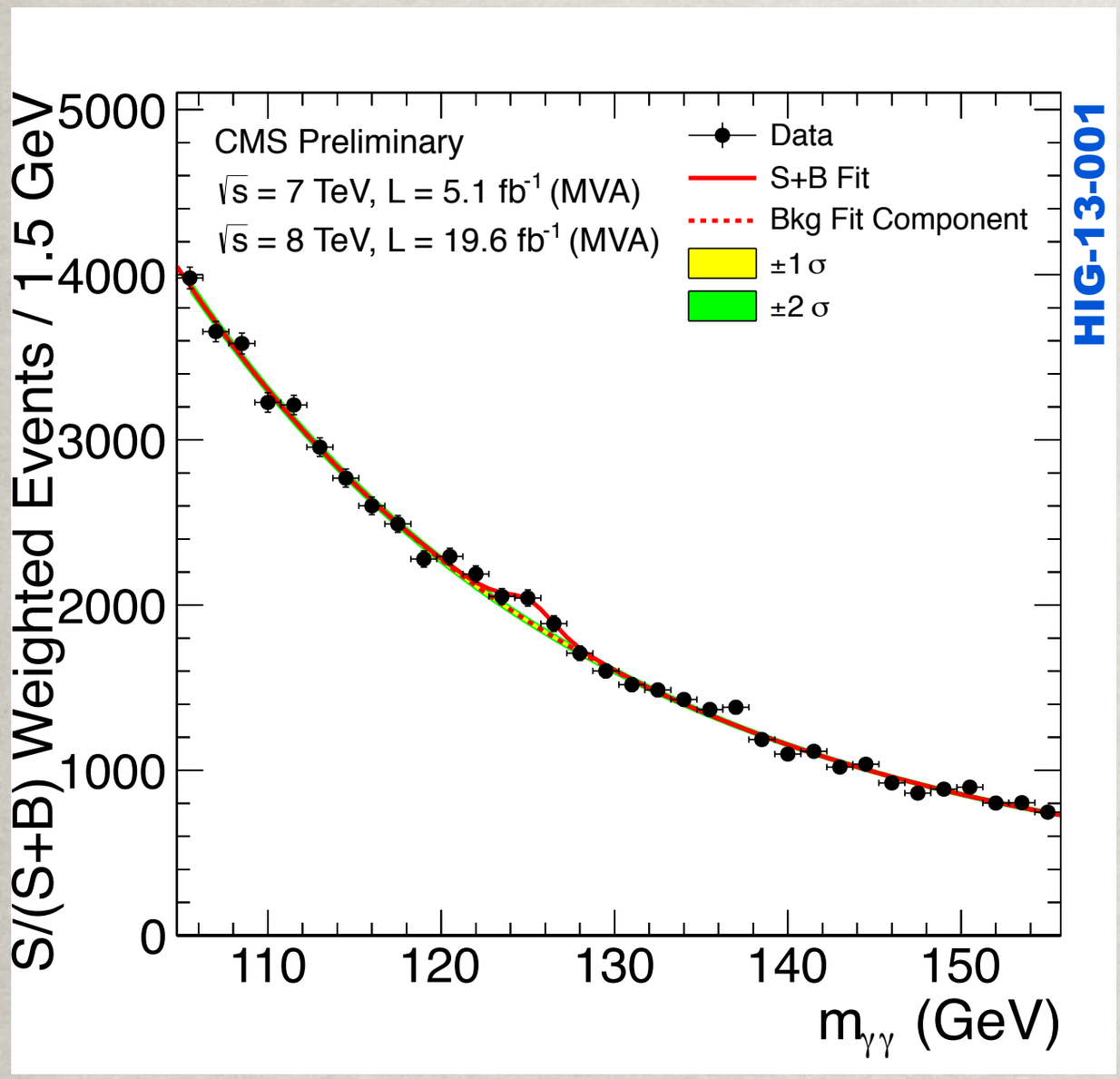
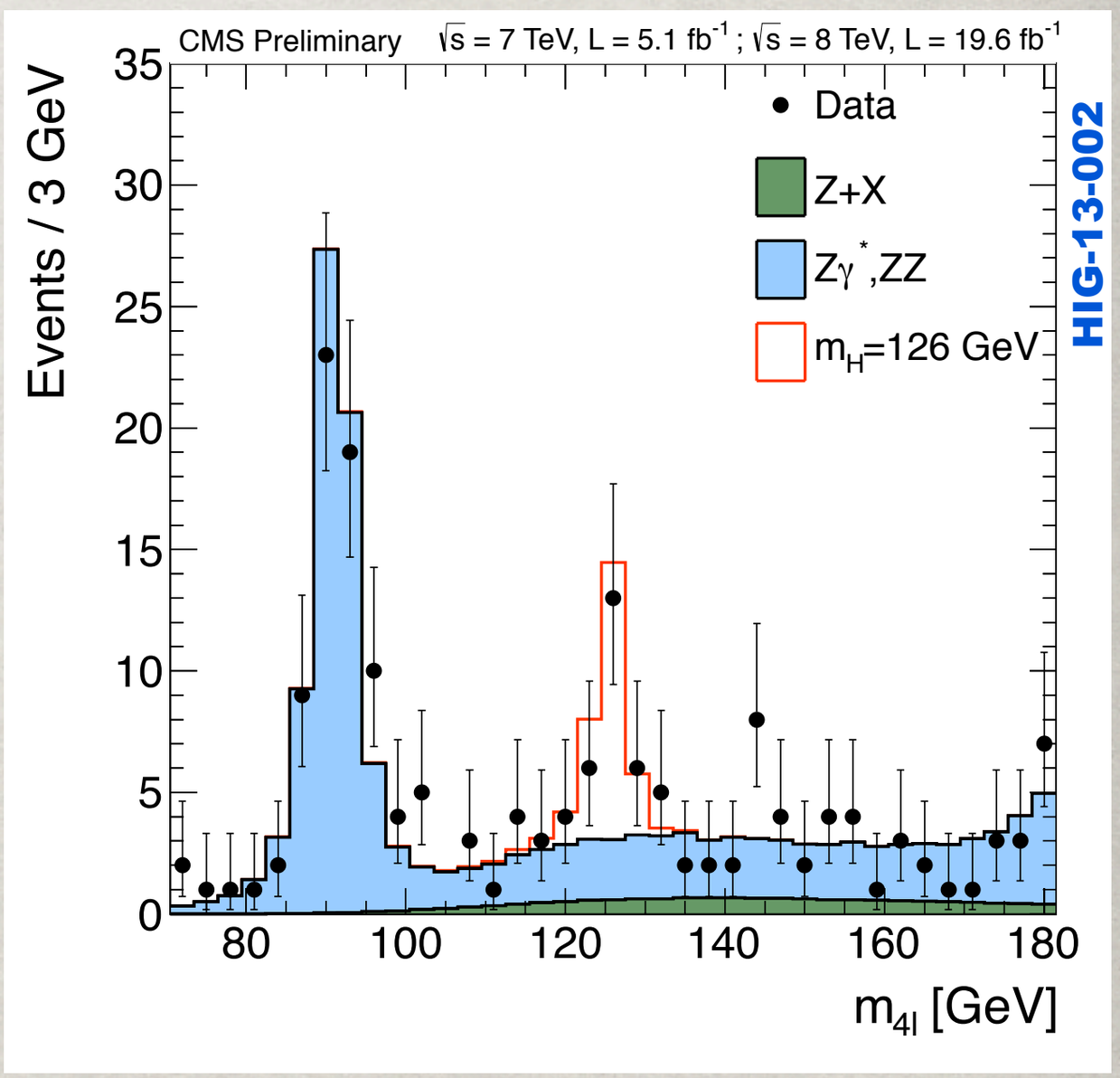
Signatures Studied

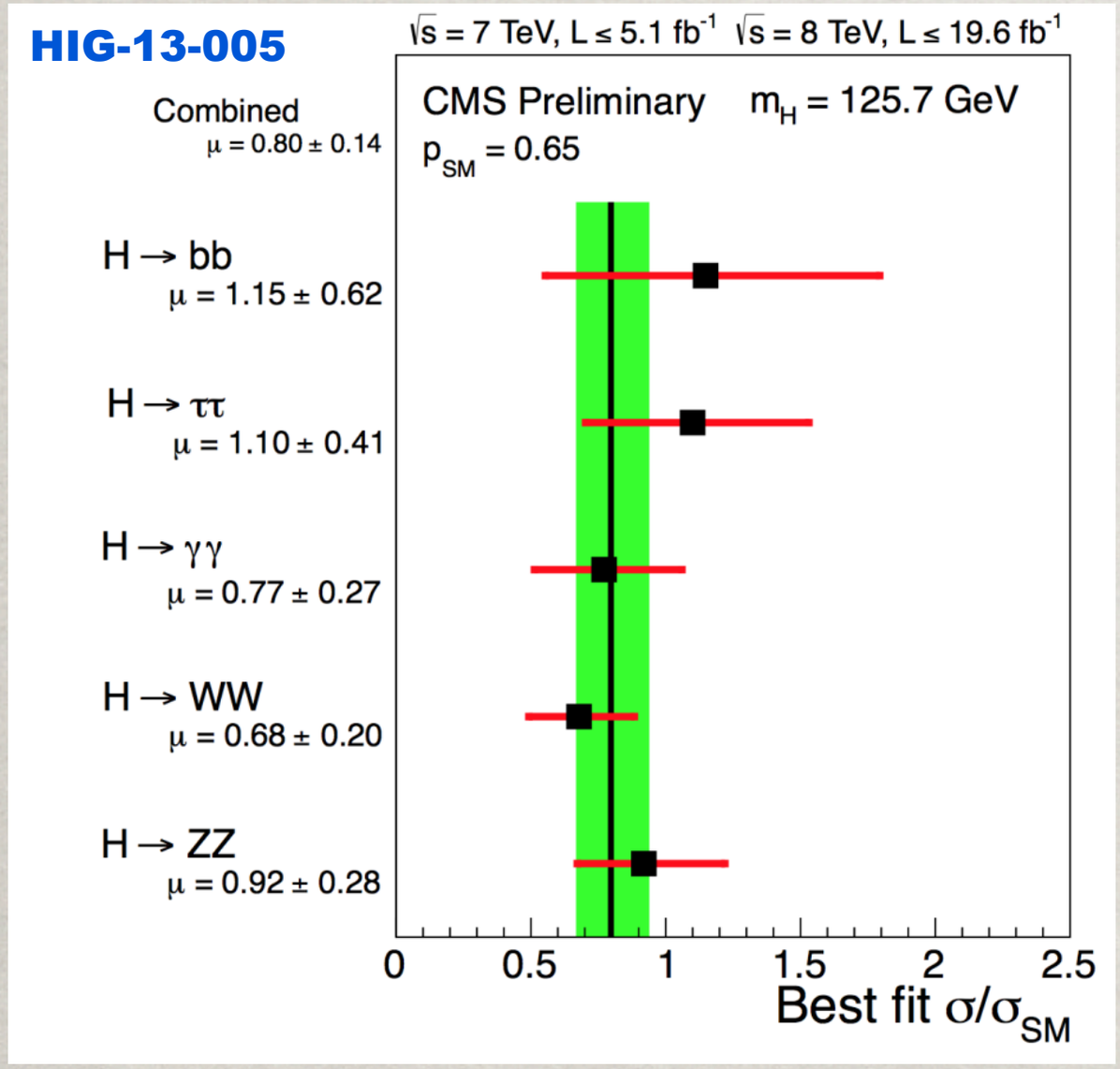
Decay / Prod.	H→γγ (0.2%)	H→ZZ (3%)	H→WW (22%)	H→ττ (6%)	H→bb (58%)	H→Zγ (0.15%)	H→μμ	H→ invisible
Gluon Fusion (19.3 pb)								
VBF (1.6 pb)								
VH (1.1 pb)								
ttH (0.1 pb)								

Discovery Channels Today





Results by Decay



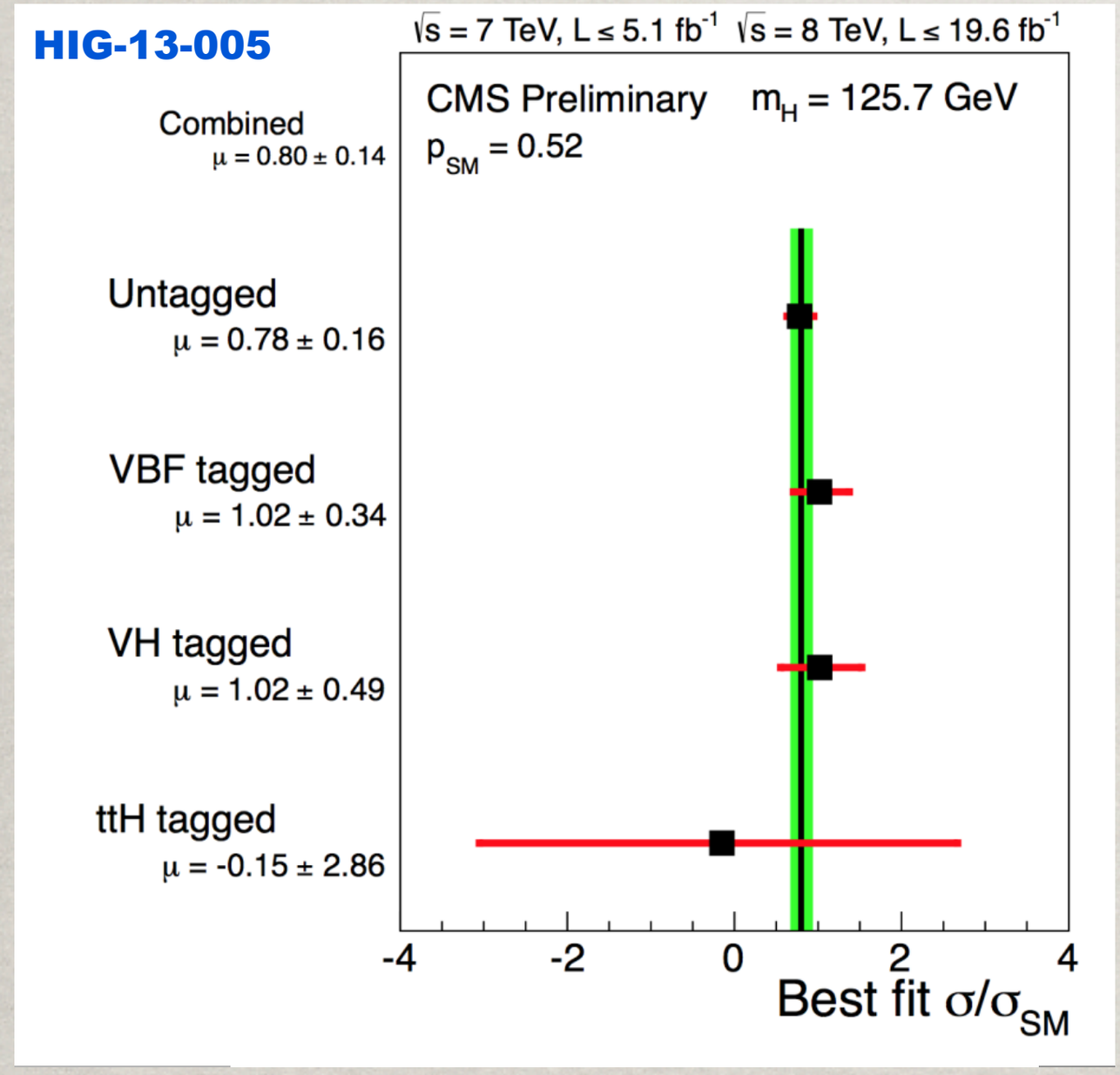
Combined signal strength: $\sigma/\sigma_{SM} = 0.80 \pm 0.14$

Significance of the Signal

Decay	Exp.	Obs.
bb	2.2σ	2.1σ
ττ	2.6σ	2.8σ
γγ	3.9σ	3.2σ
WW	5.3σ	3.9σ
ZZ	7.1σ	6.7σ

3.4 σ

Results by Prod. Mech.



Combined signal strength: $\sigma/\sigma_{SM} = 0.80 \pm 0.14$

All consistent with SM, but some, like ttH, have large uncertainties (still room for surprises)

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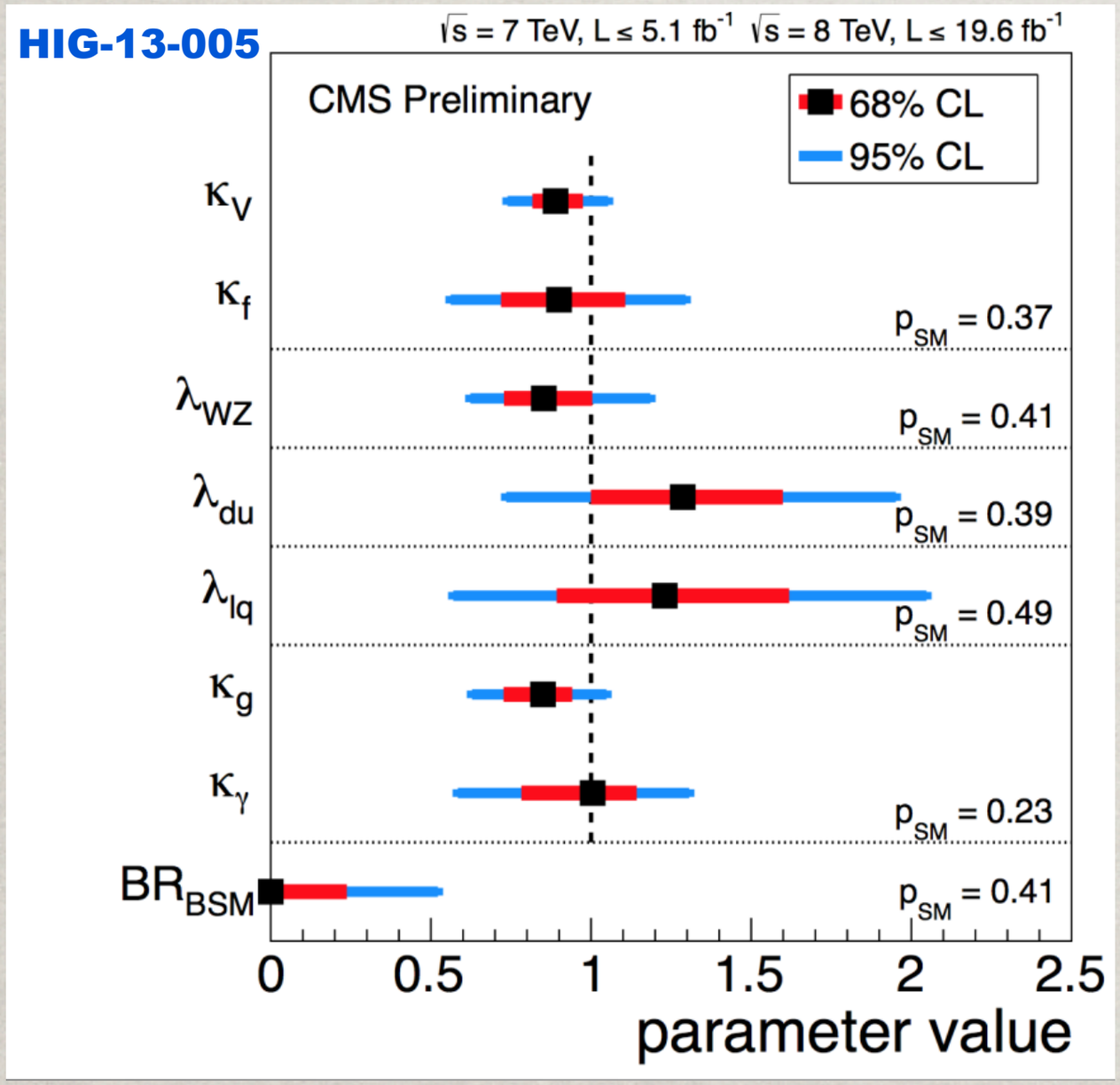
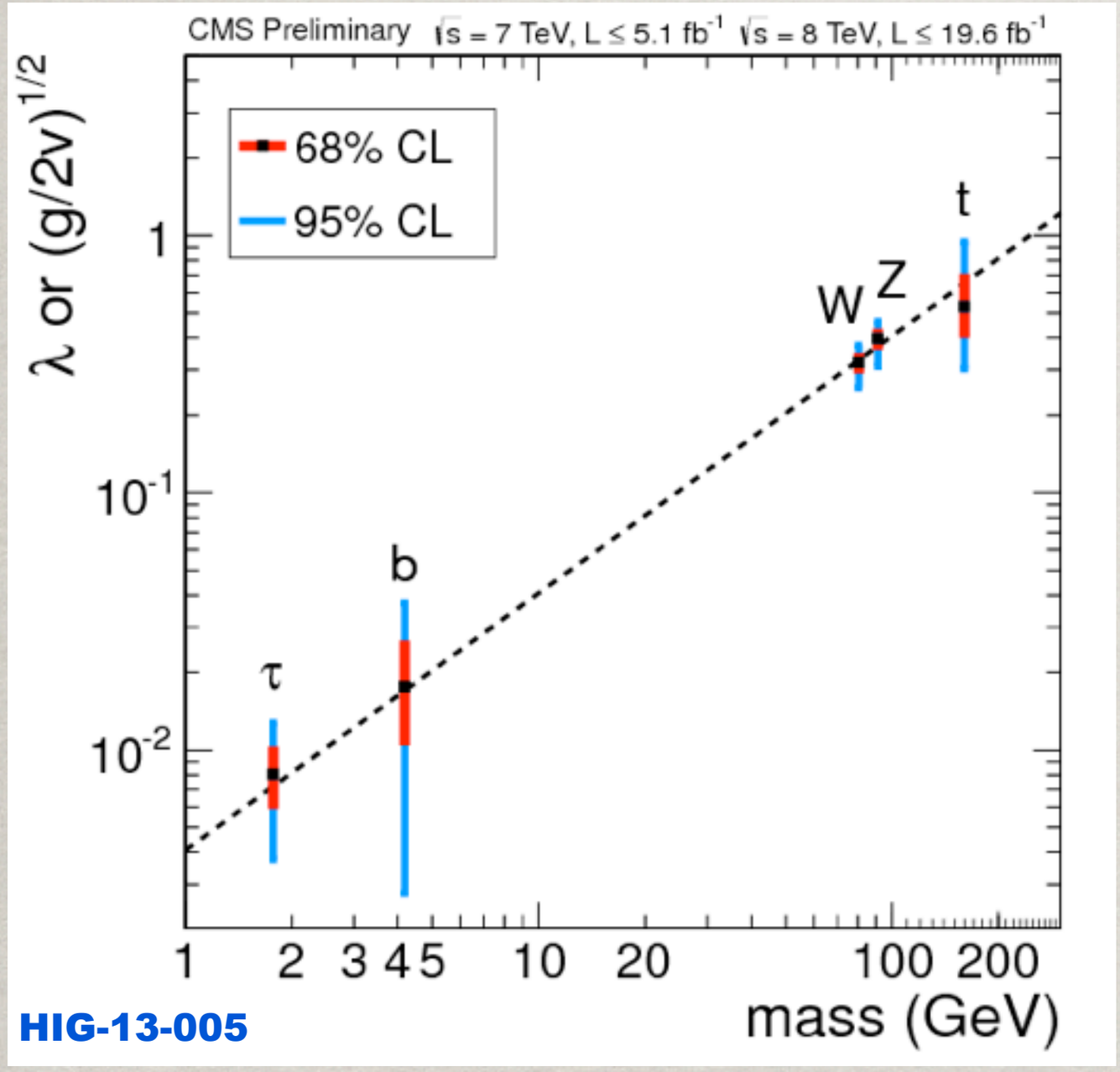
Couplings



- Overall, very consistent with SM so far
- Large enough uncertainties that could still find surprises
- BR_{BSM} prefers zero, but fairly large values still allowed

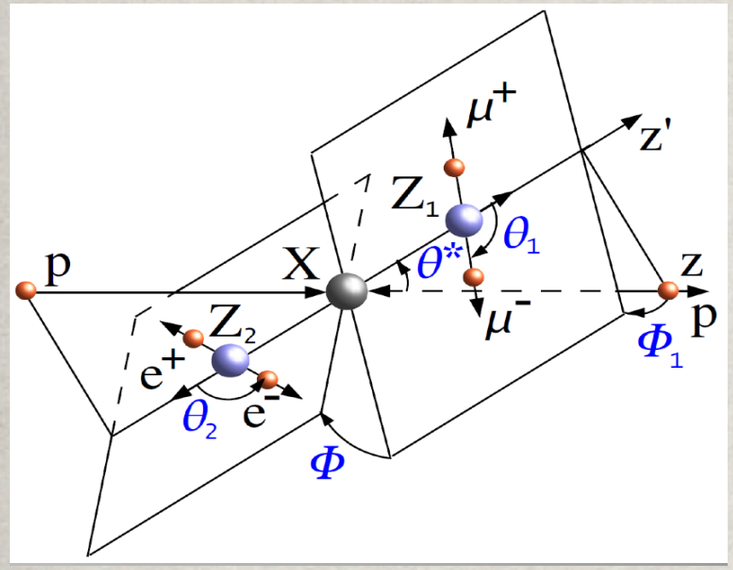
Couplings vs Mass



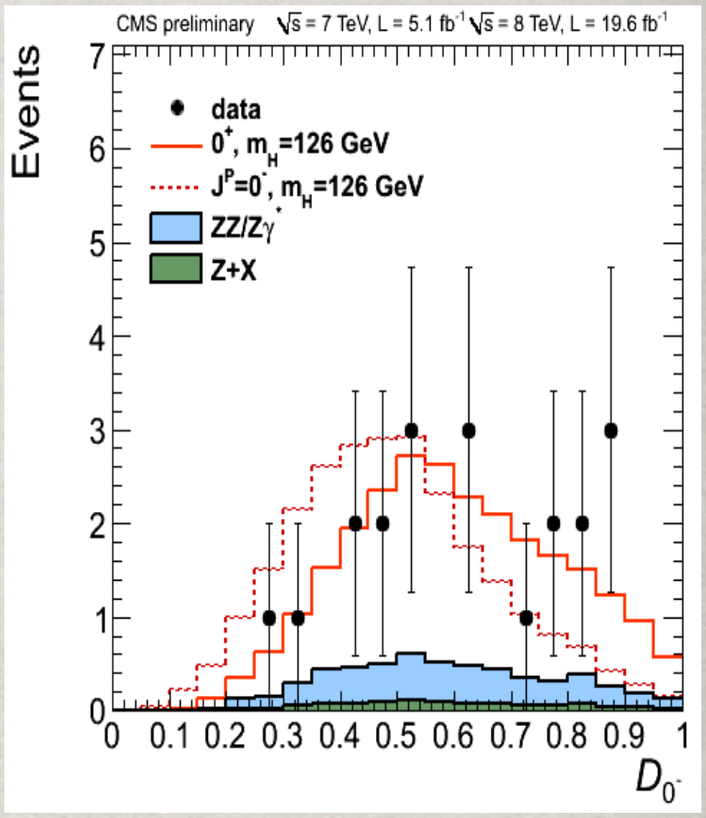
- In this case allow couplings to τ, b, W, Z, and top to float independently
- So far, again, everything looks consistent with SM

Spin/Parity

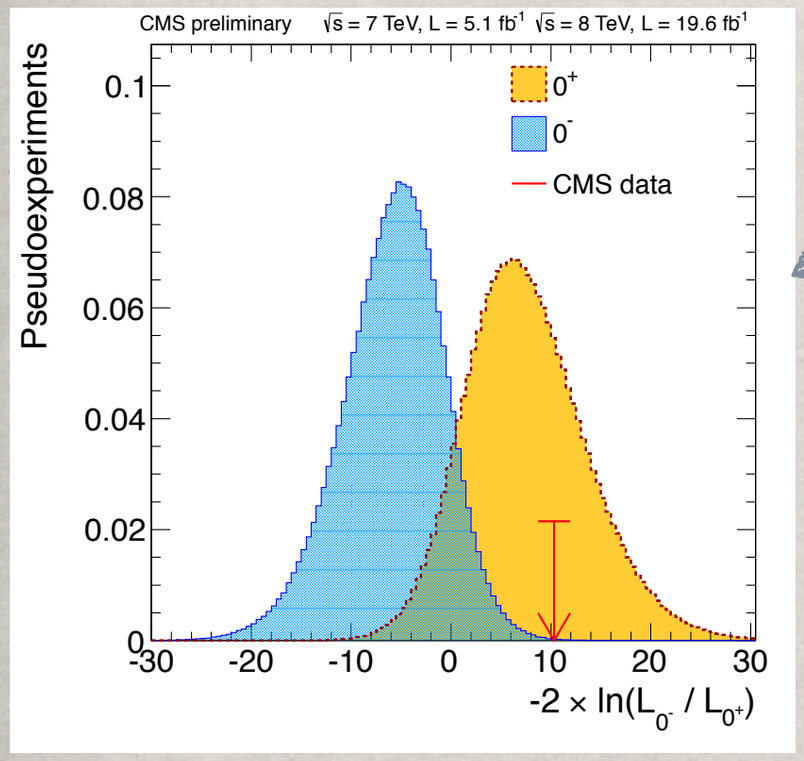
HIG-13-002



Design a variable that's sensitive to J^P of Higgs



Test 0^+ Hyptothesis against others



Repeat for other hypotheses

J^P	CL_s
0^-	0.16%
0^+_h	8.1%
2^+_{mgg}	1.5%
$2^+_{mq\bar{q}}$	<0.1%
1^-	<0.1%
1^+	<0.1%

Uses H→ZZ→4l channel

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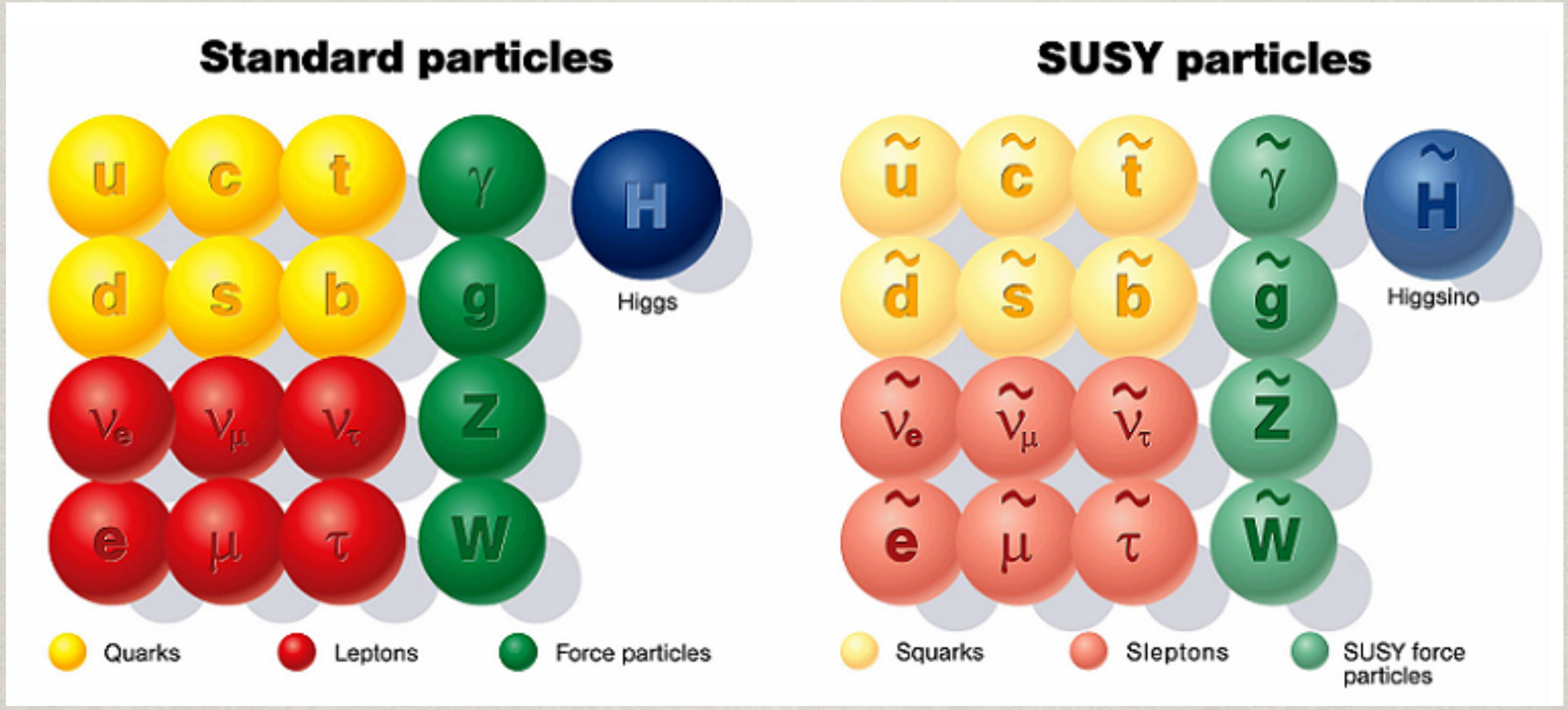
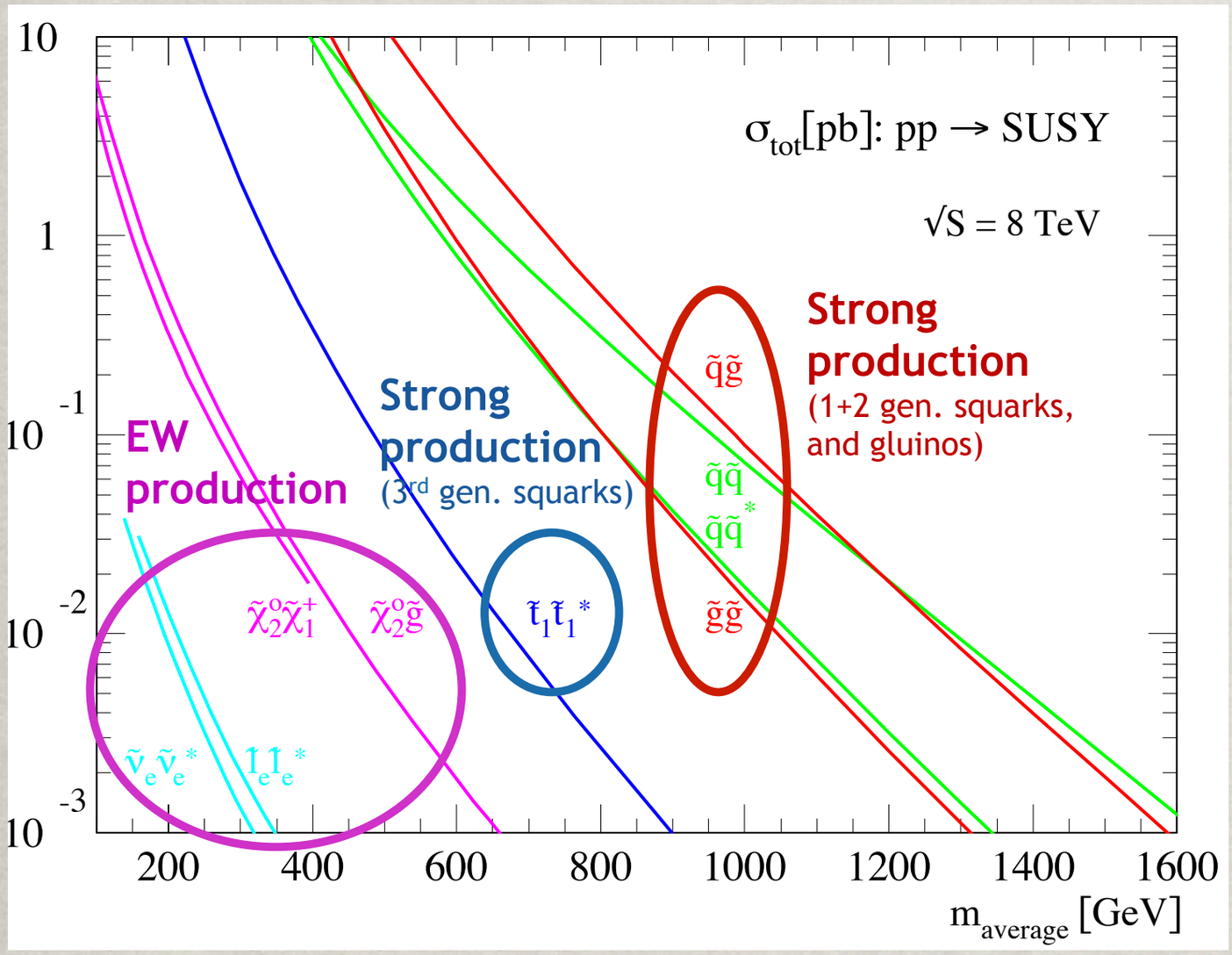
Susy Results

SUSY Extension to SM



- Tells us what particles to expect, but not masses
- Mass spectrum determines phenomenological properties

SUSY Production



Assumption: Lightest SUSY particle (LSP) is stable (i.e. Dark Matter). Does not have to be the case.

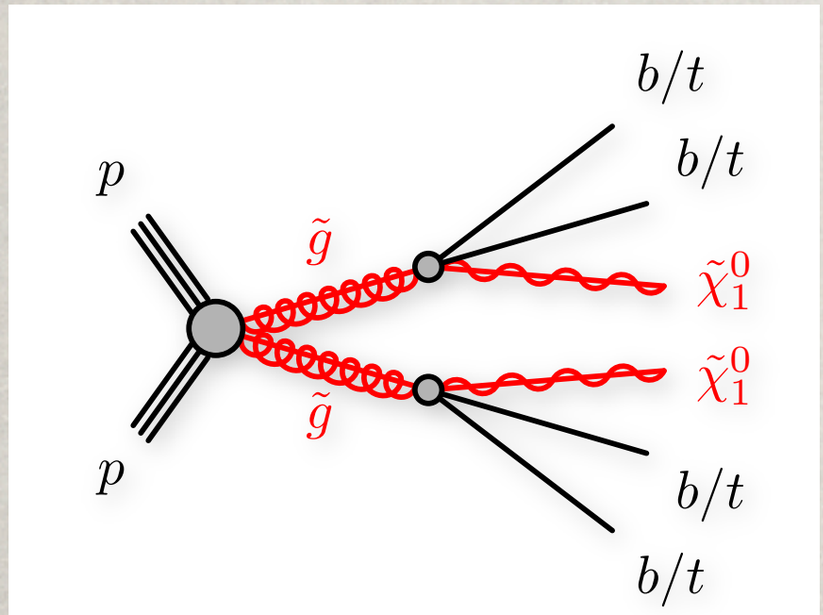
- Largest production would come from light squarks and gluinos
  - Could have been the first LHC discovery if masses were light enough
- Considering observed Higgs mass: "Natural SUSY"
  - Having light 3rd generation (especially stop) and gluinos avoids fine tuning for Higgs mass
- If all charginos/neutralinos the lightest, then EWK production will dominate
  - Smaller cross sections → Harder to detect

Simplified Models

- SUSY has many free parameters
  - Determine the masses of SUSY particles
  - Many different models with different simplifying assumptions
- To make it possible to quote general results, use "simplified models"
  - Focus on production of X → LSP + SM
  - Quote results
    - As limit on cross section for X assuming 100% BR to LSP+SM
    - As function of masses of X and LSP
    - **Also set explicit limits on benchmark model (usually CMSSM)**

Gluino Results

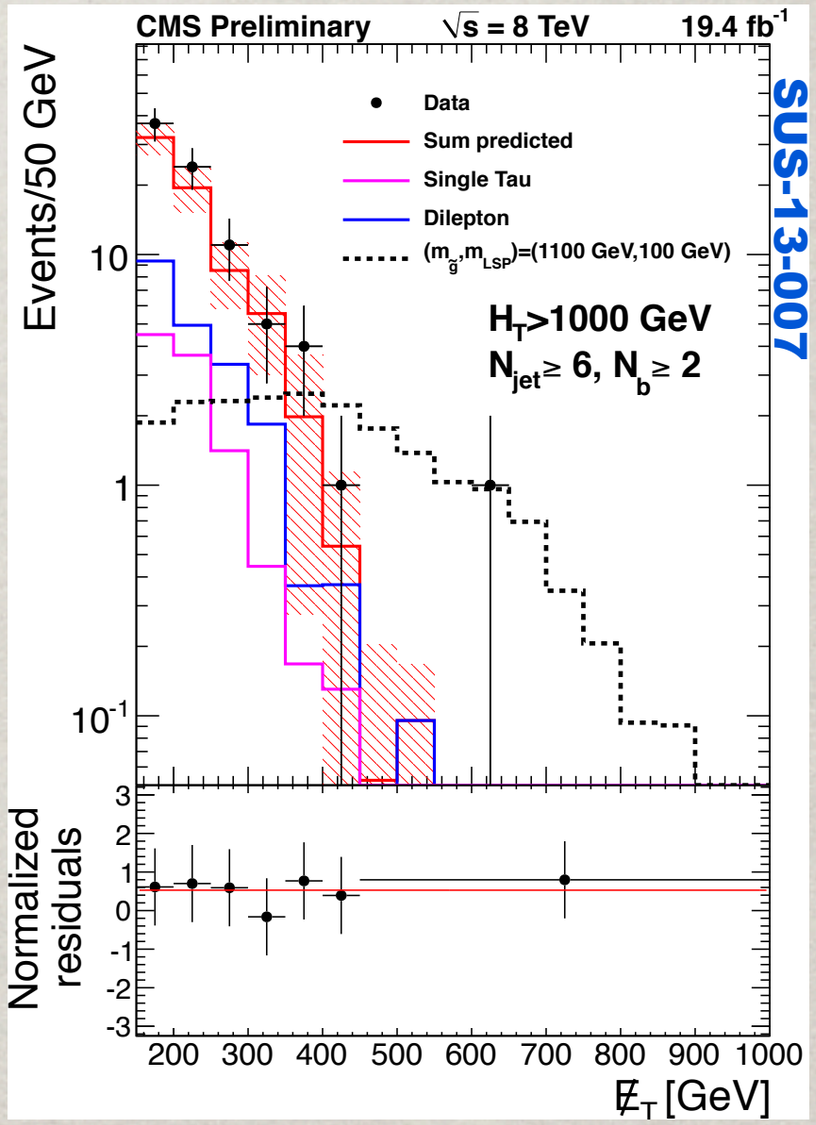
- Looking for gluinos in a "natural" scenario (gluino decays to stop or sbottom quarks



Spectacular events with 4 bottom or top quarks + MET

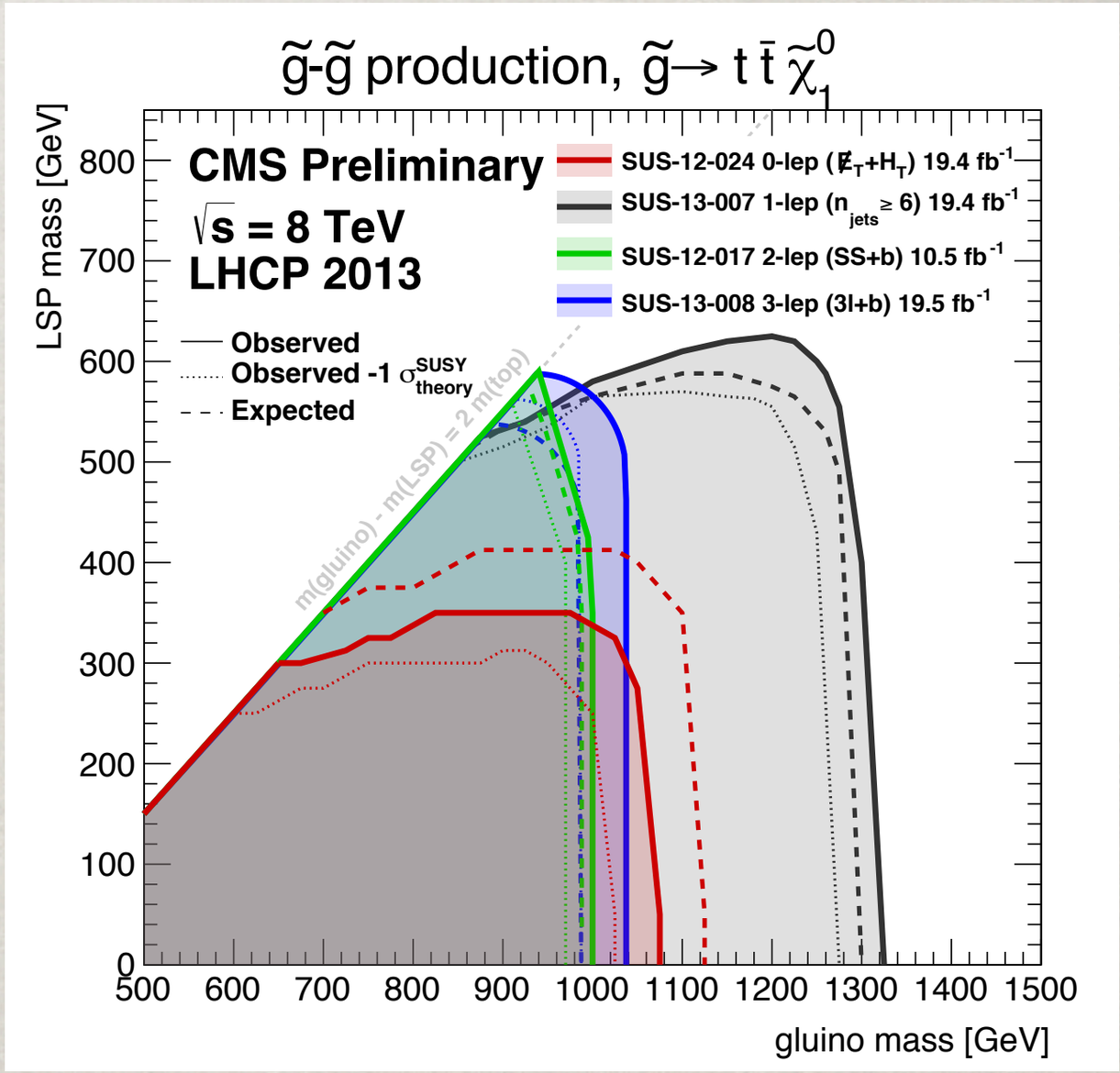
Select events with one isolated lepton, multiple jets (at least two tagged), large H_T, look for excess in MET from LSP

Can also look at events with multiple isolated leptons plus b-jets.



Gluino Results

- No signal seen: Limits set in terms of gluino and LSP mass
- Shown here: combination of several different anlayses
- Depending on LSP mass, exclude gluinos with mass up to ~1.3 TeV
- Similar results for gluino to bottom pair plus LSP



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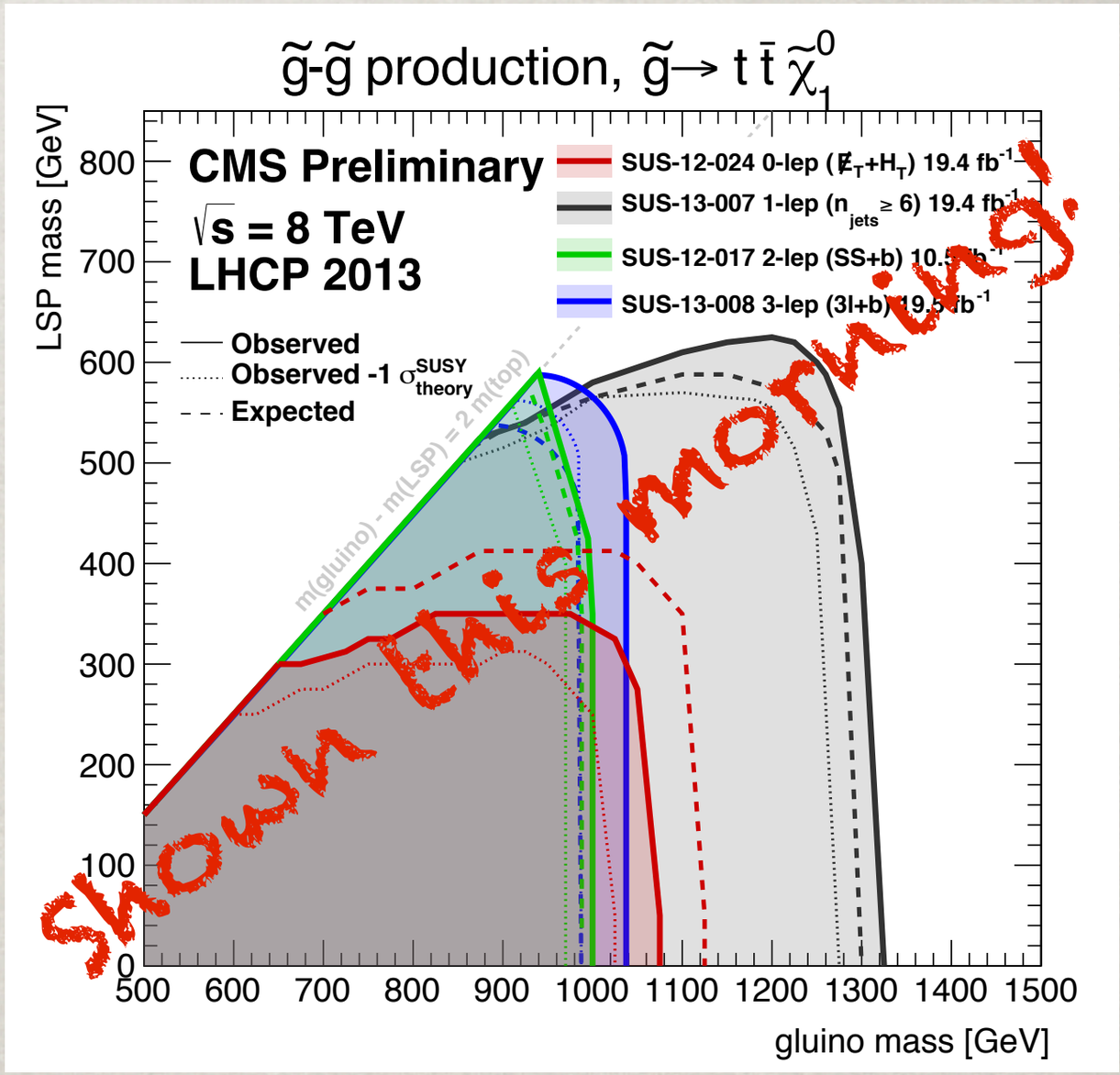

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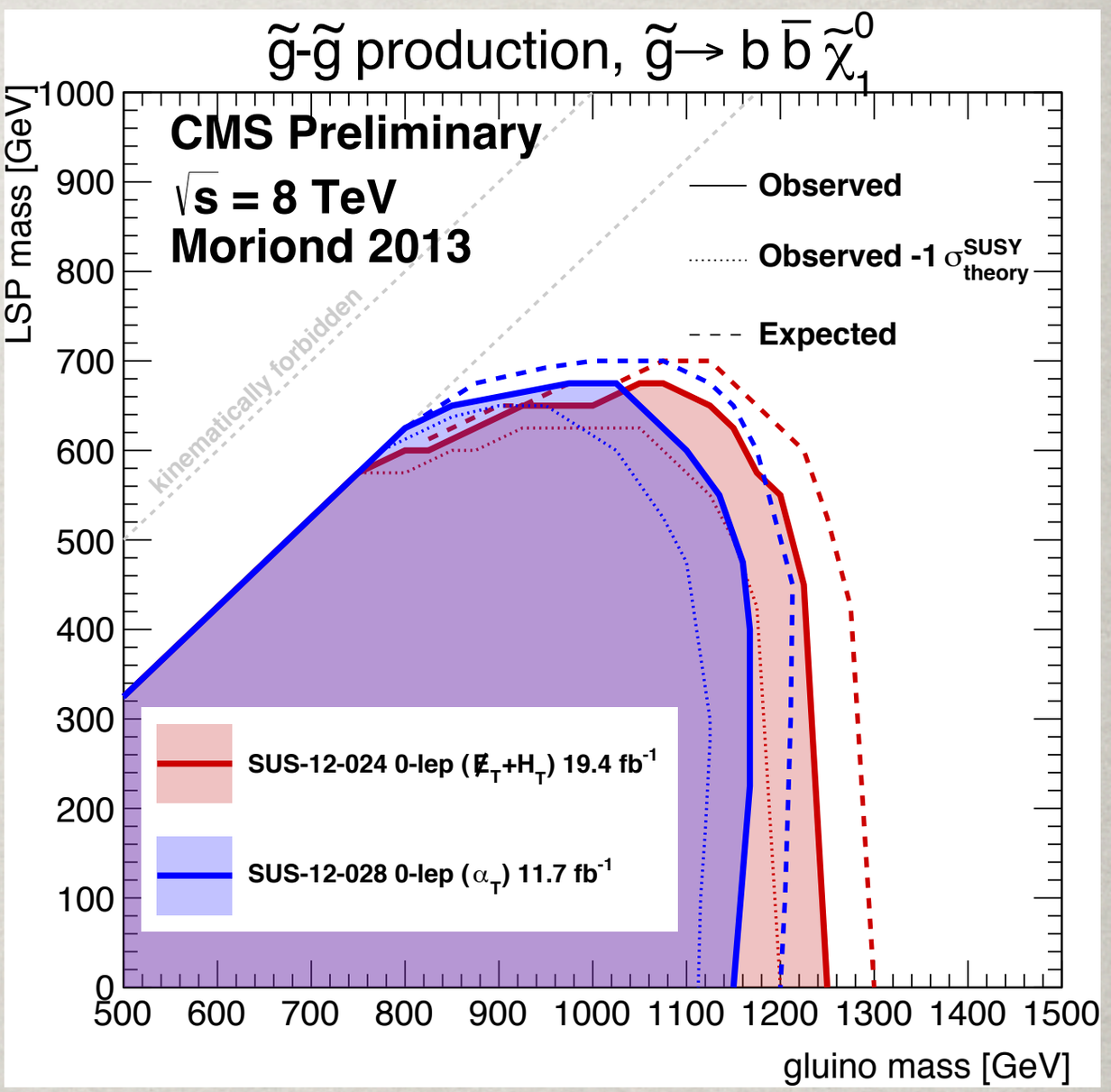

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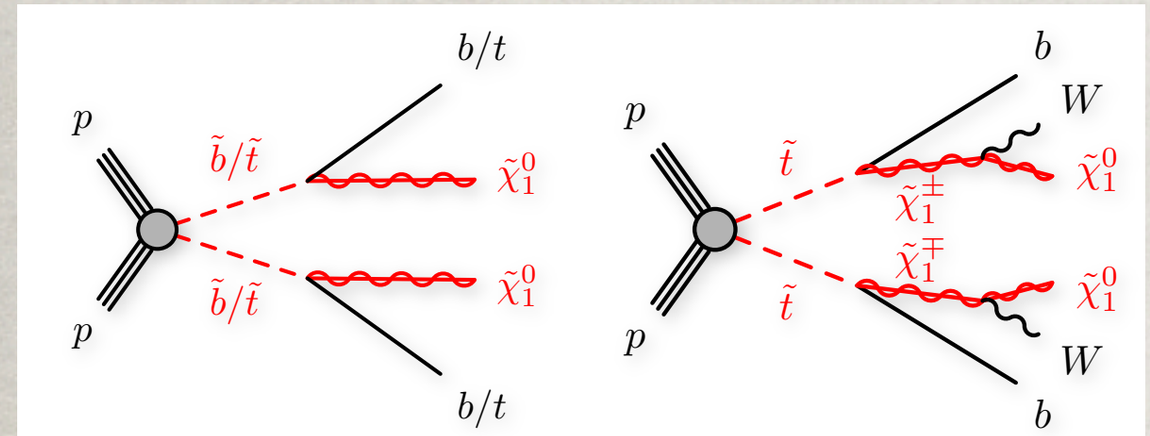
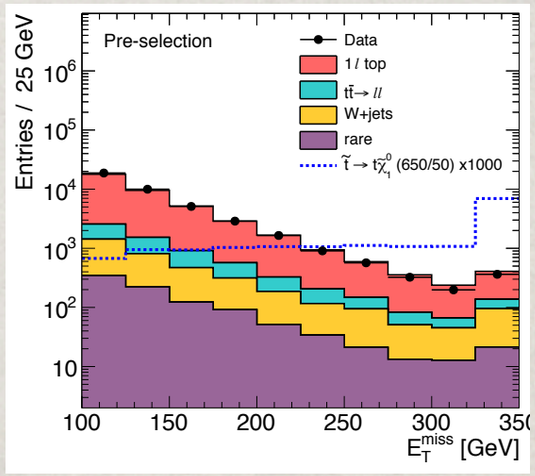
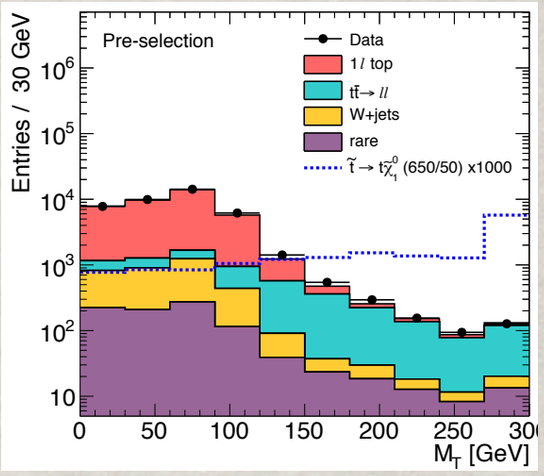
Stop Results

- If gluino too heavy, look for direct stop production



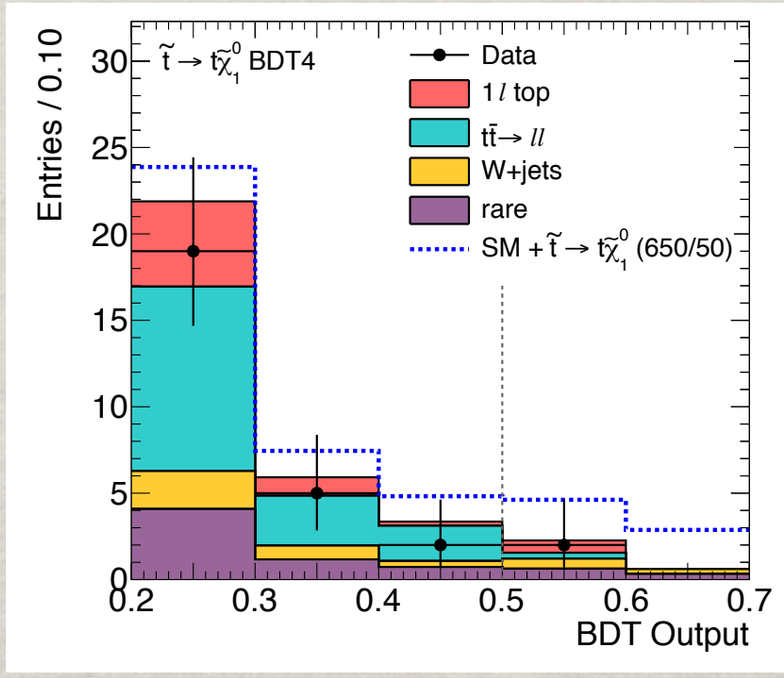




Less spectacular signature: Looks very much like ttbar background, but with extra MET

Look at variables that distinguish regular semileptonic top decay from semileptonic top + LSP: MET, M_T, M_{T2}, etc.

Combine in Boosted Decision Tree (BDT)



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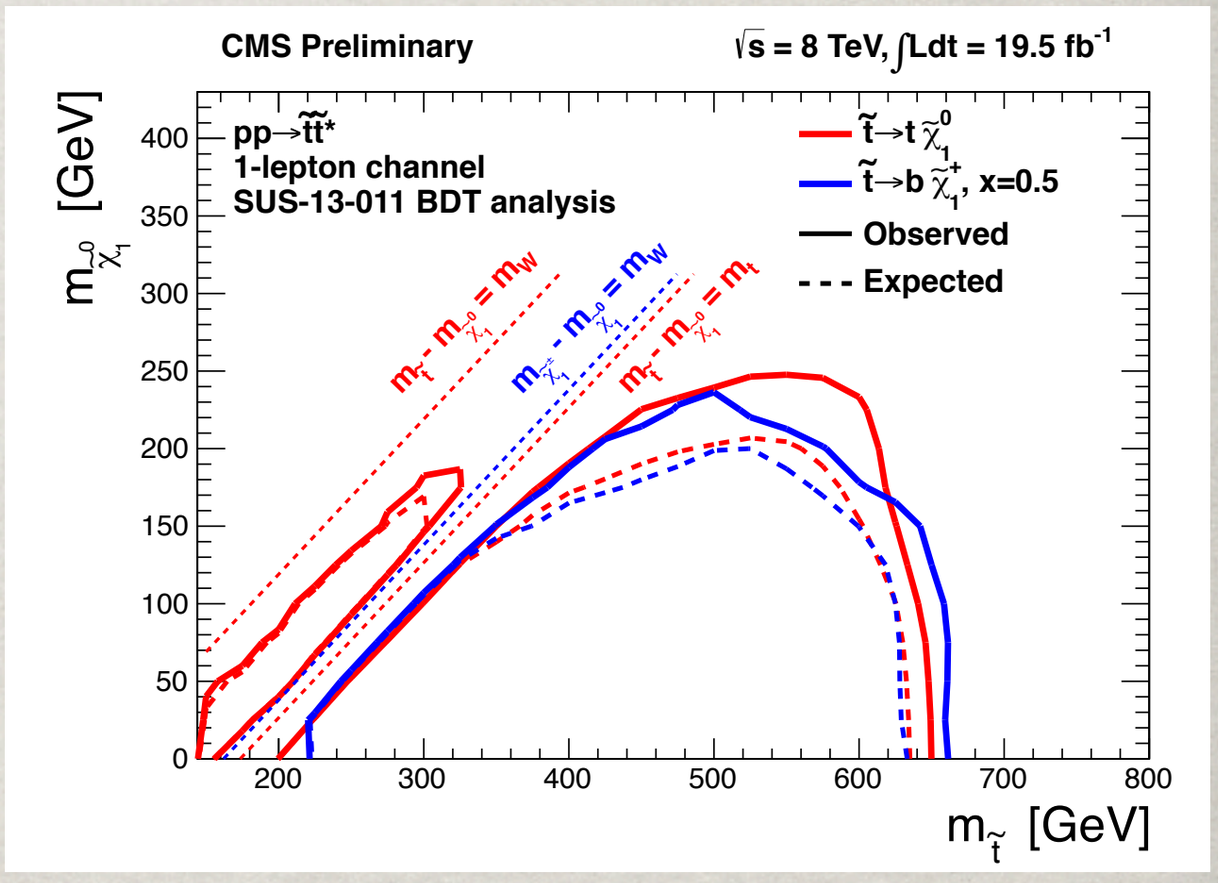
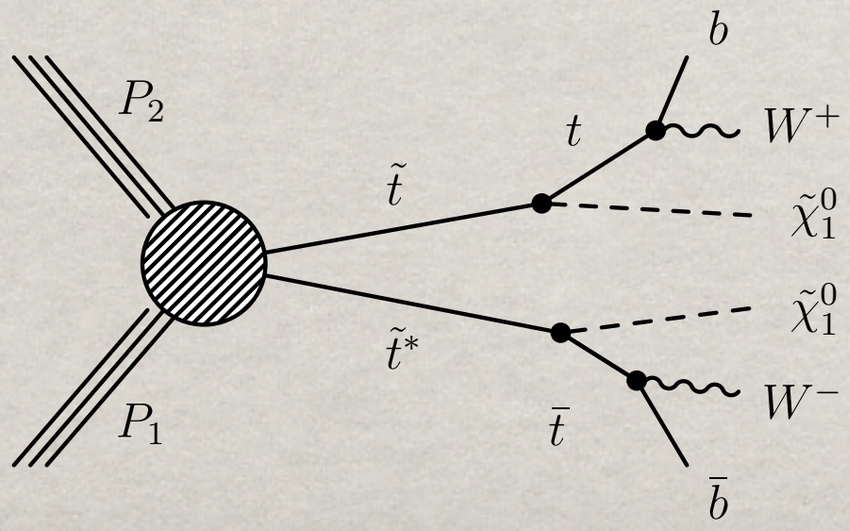
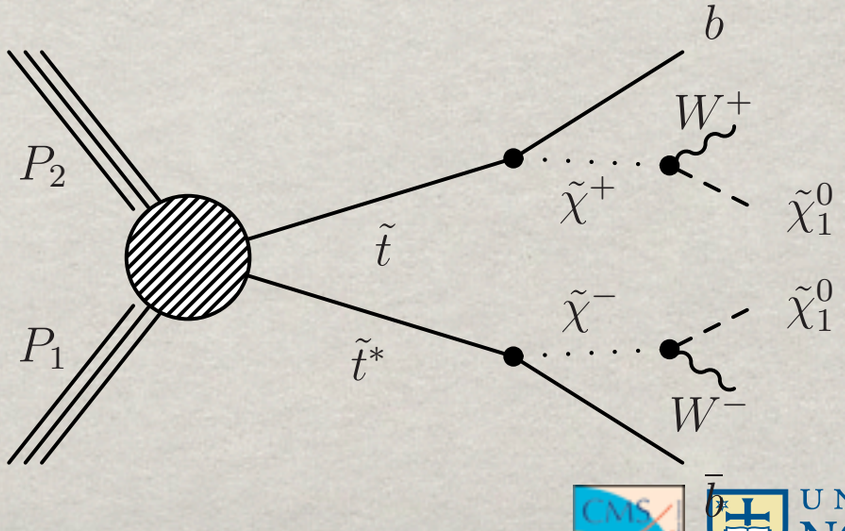
Stop Results

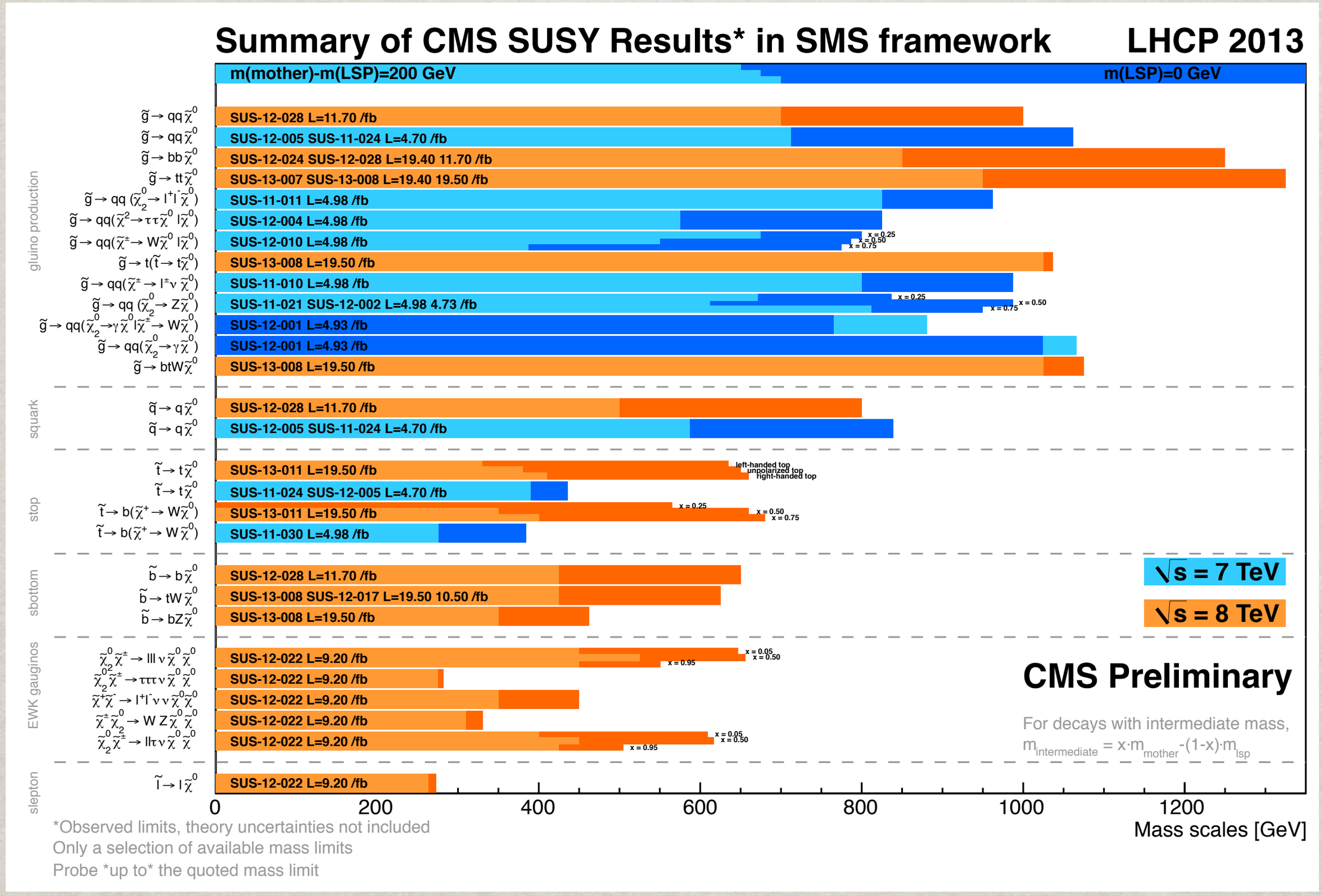
- No signal seen; set limits in terms of stop and LSP mass
- Interesting behavior when LSP mass gets too large (off shell top, etc.)
- Limits:
  - Stop: ~650 GeV for massless LSP, lower for masive LSP
  - No limit if LSP mass ≳ 250 GeV







Summary


Summary of CMS SUSY Results* in SMS framework
LHCP 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
SUS-12-028 L=11.70 /fb
SUS-12-005 SUS-11-024 L=4.70 /fb
SUS-12-024 SUS-12-028 L=19.40 11.70 /fb
SUS-13-007 SUS-13-008 L=19.40 19.50 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 L=19.50 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 L=19.50 /fb
SUS-12-028 L=11.70 /fb
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SUS-12-028 L=11.70 /fb
SUS-13-008 SUS-12-017 L=19.50 10.50 /fb
SUS-13-008 L=19.50 /fb
SUS-12-022 L=9.20 /fb
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SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
SUS-12-022 L=9.20 /fb
left-handed top
unpolarized top
right-handed top
x = 0.25
x = 0.50
x = 0.75
0
200
400
600
800
1000
1200
Mass scales [GeV]
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother -(1-x)·m_lsp
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

Exotic Results

Bigger Picture

- Higgs and SUSY attractive because solve multiple problems with single theory:
  - Higgs: EWSB + particle masses
  - SUSY: Hierarchy problem, DM, new source of CP violation
- No guarantee that nature provides a single simple solution
  - Many alternatives that solve these problems

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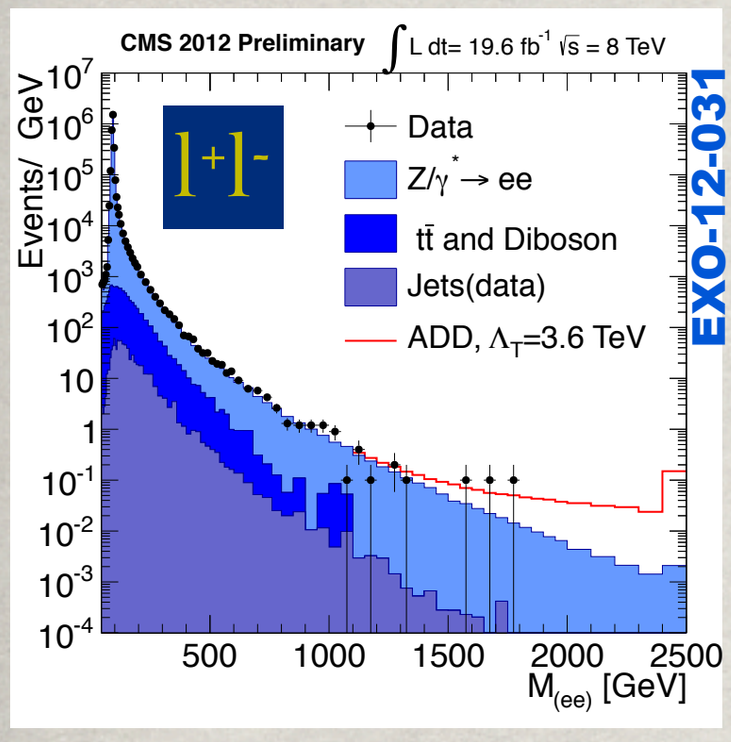
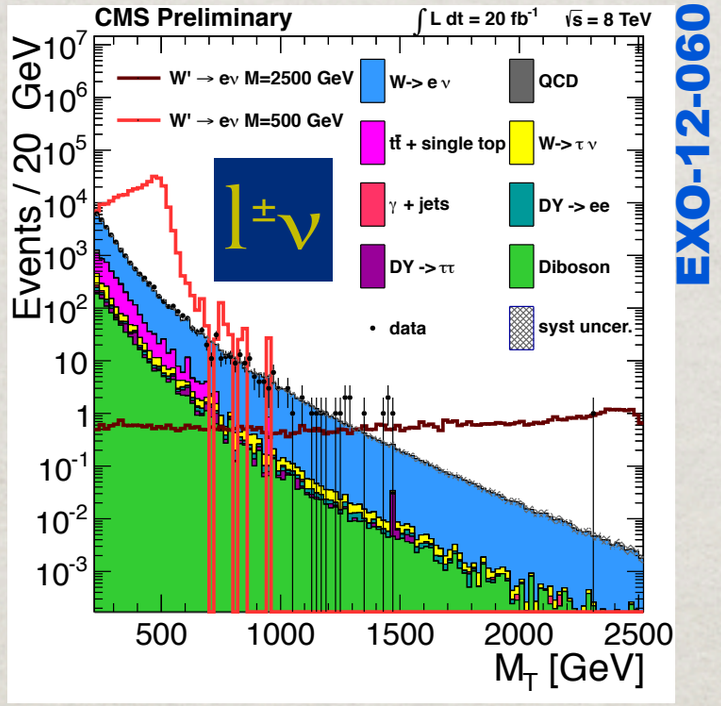
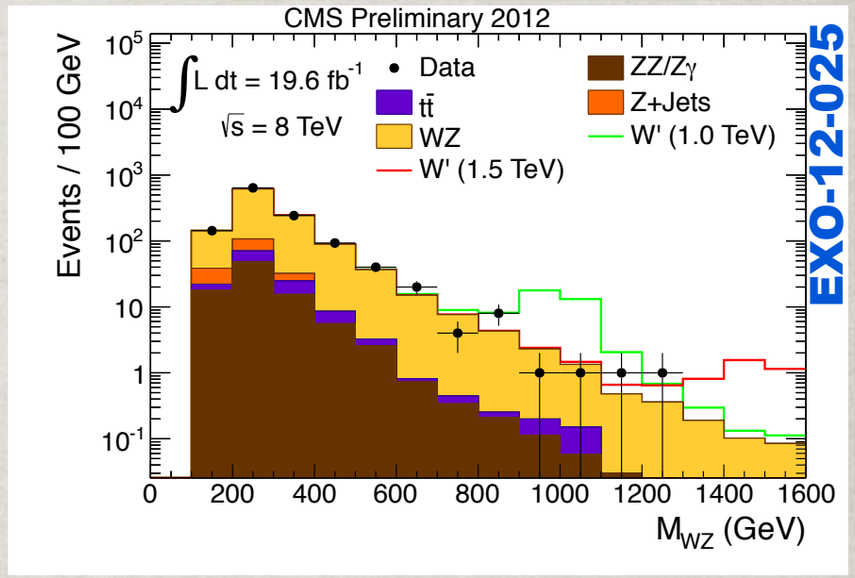
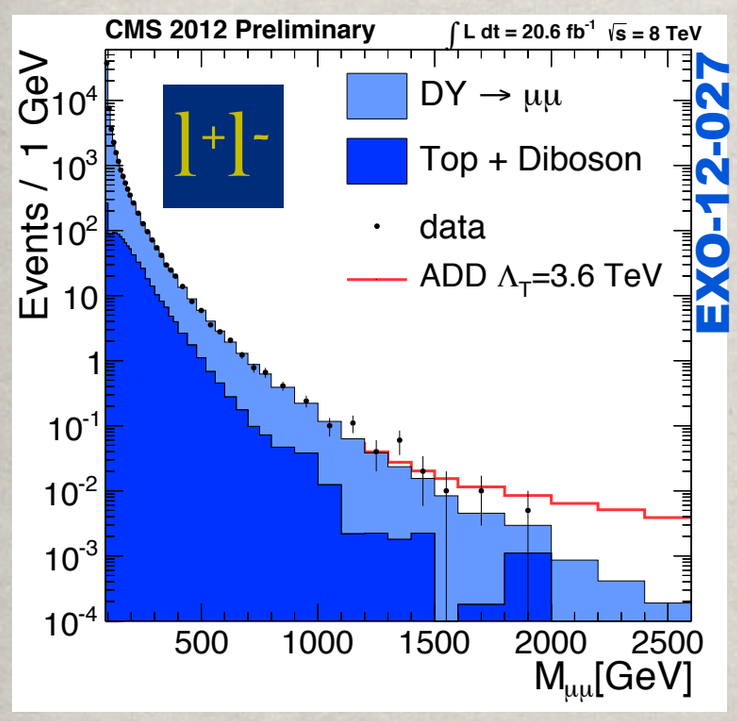
Resonance Searches

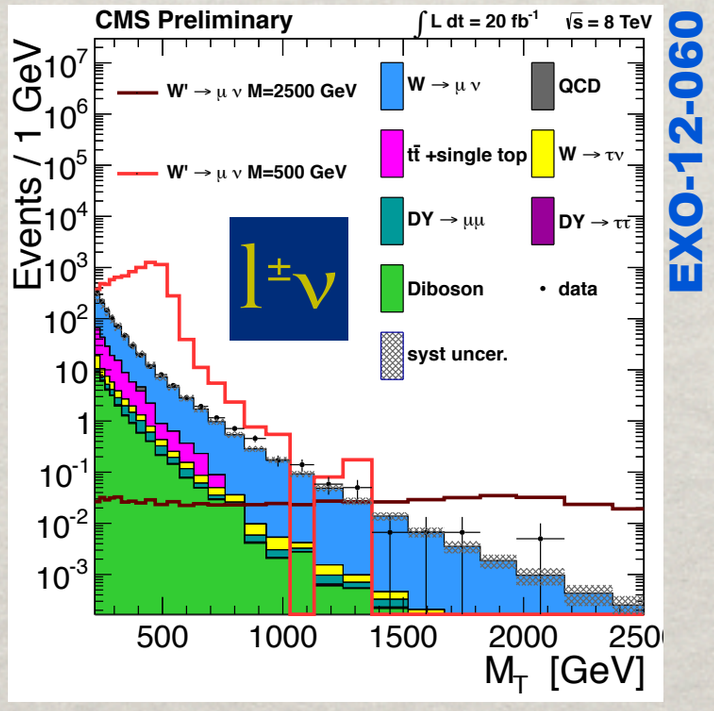




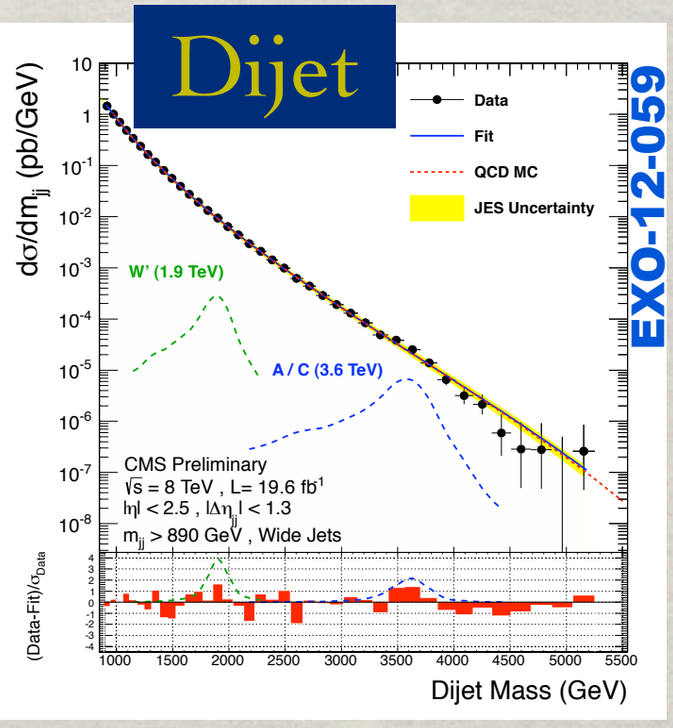
WZ → l+l- l±ν





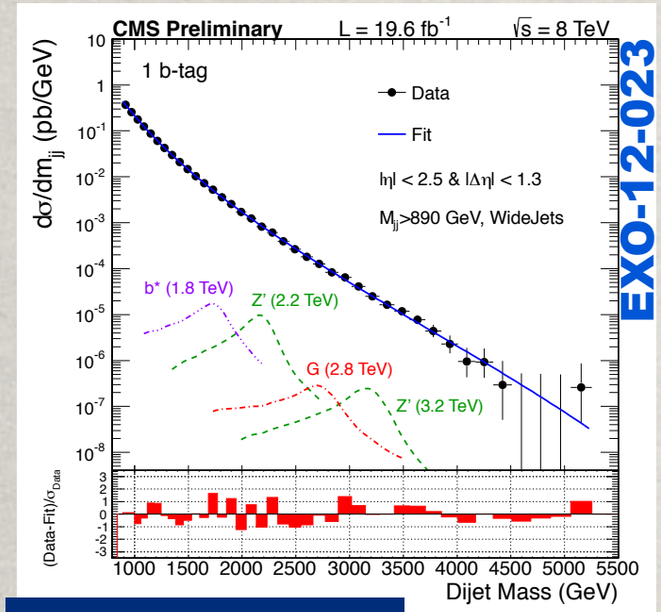


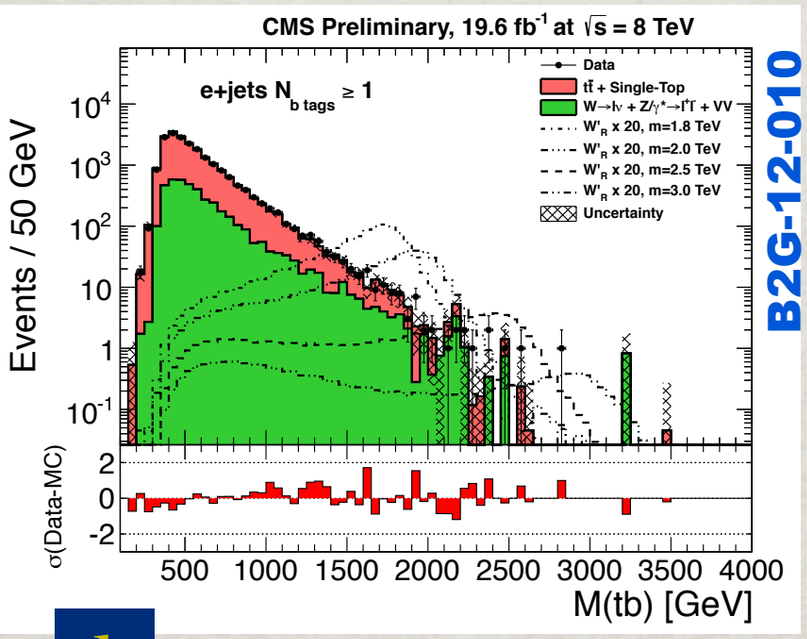
Dijet

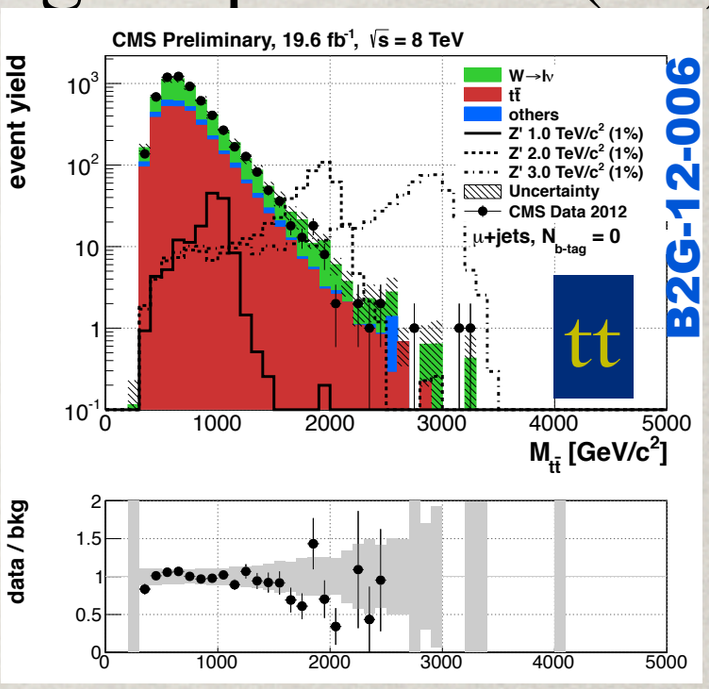


Resonance Searches

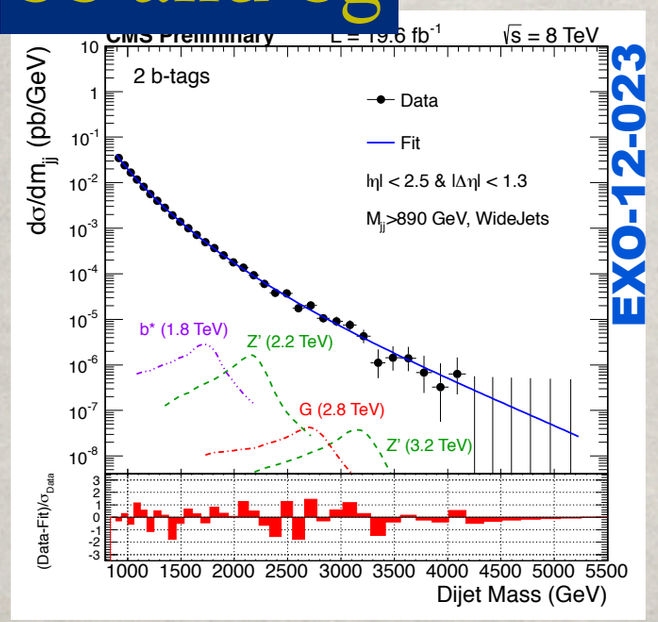
- Interesting to look for resonances in 3rd gen. particles (t/b)



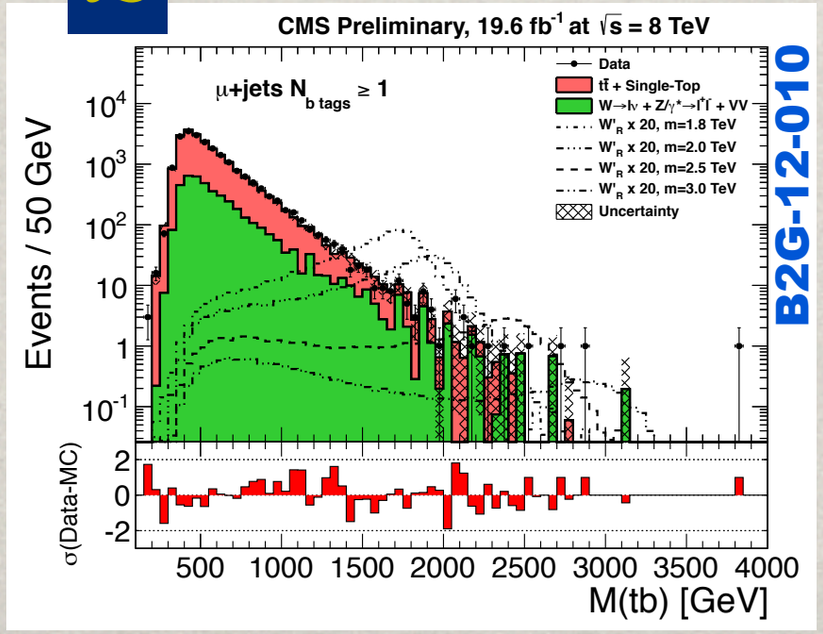


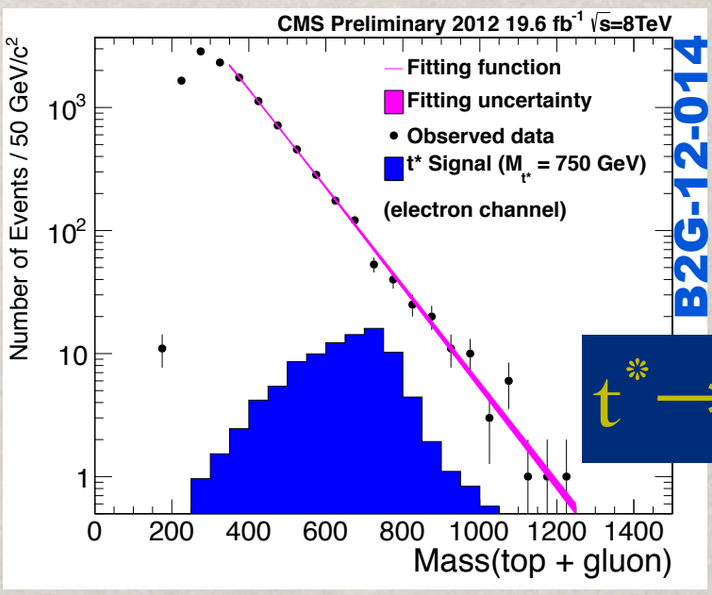


bb and bg



tb





t* → tg

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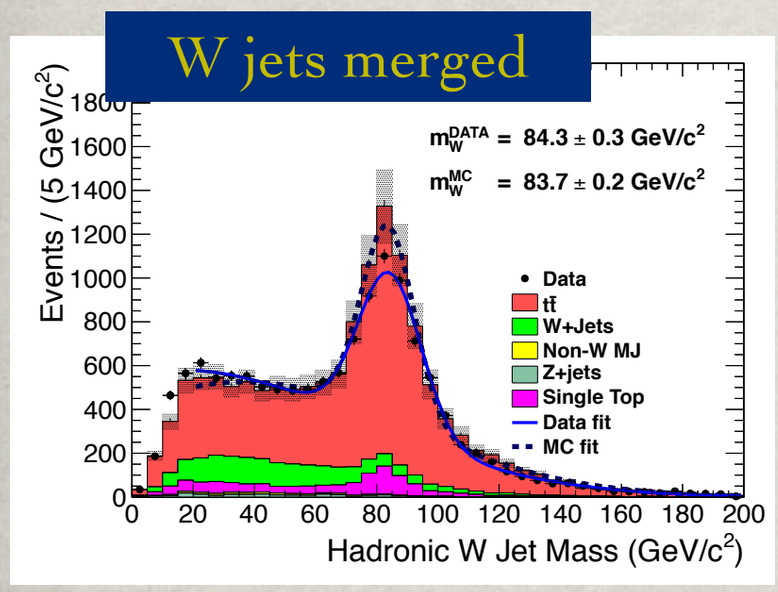
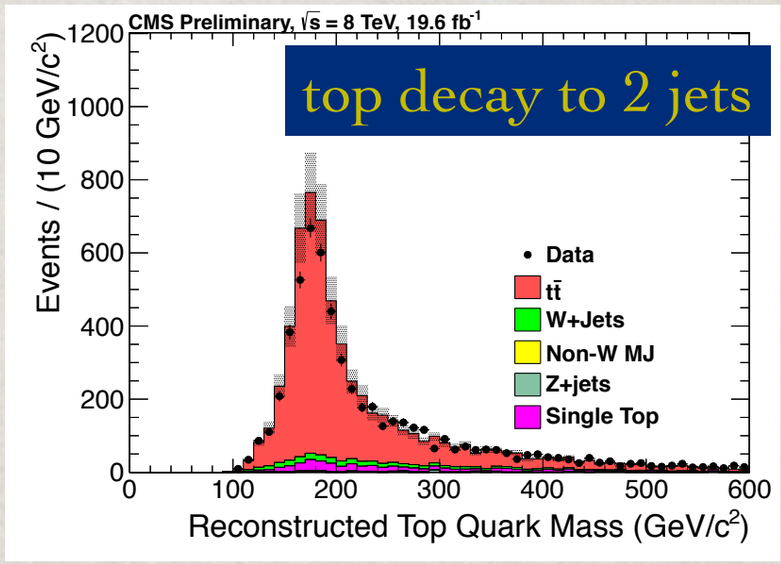
Boosted Topologies

- For really massive particles, decay products become highly collimated



+ jet =



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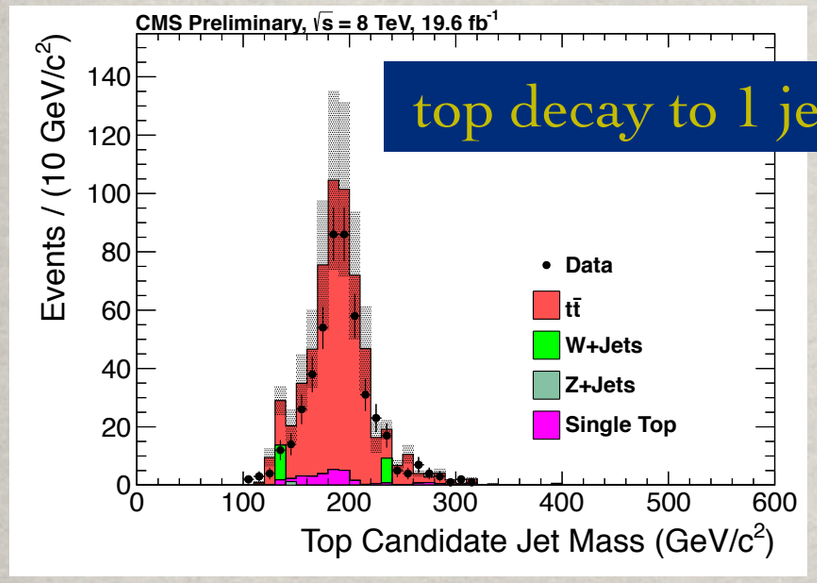

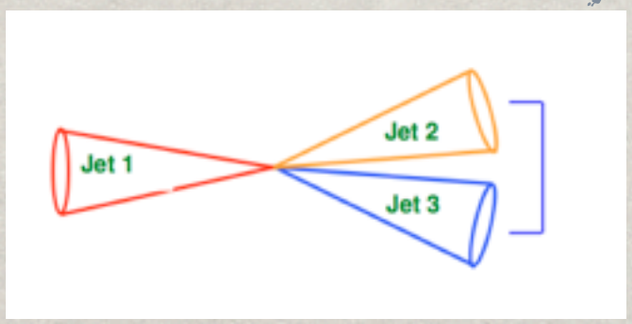

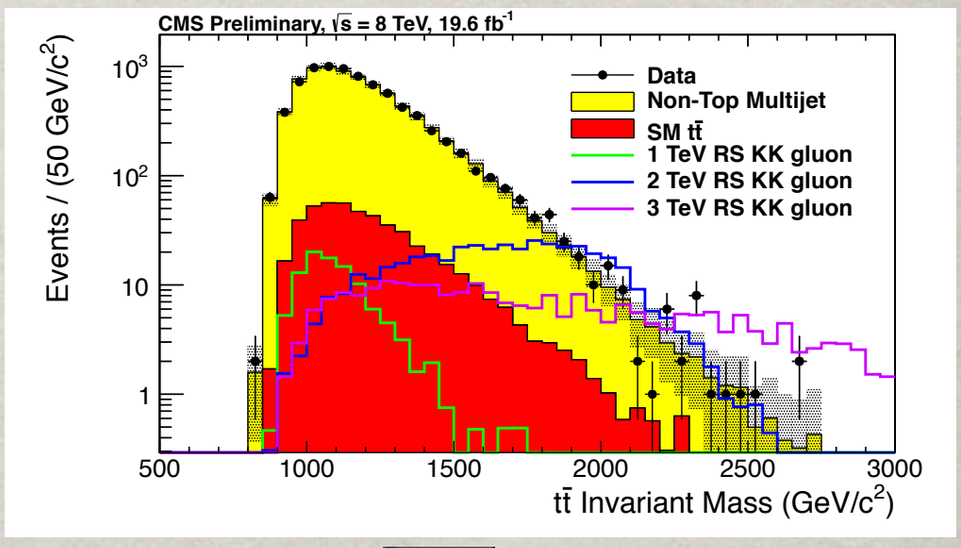

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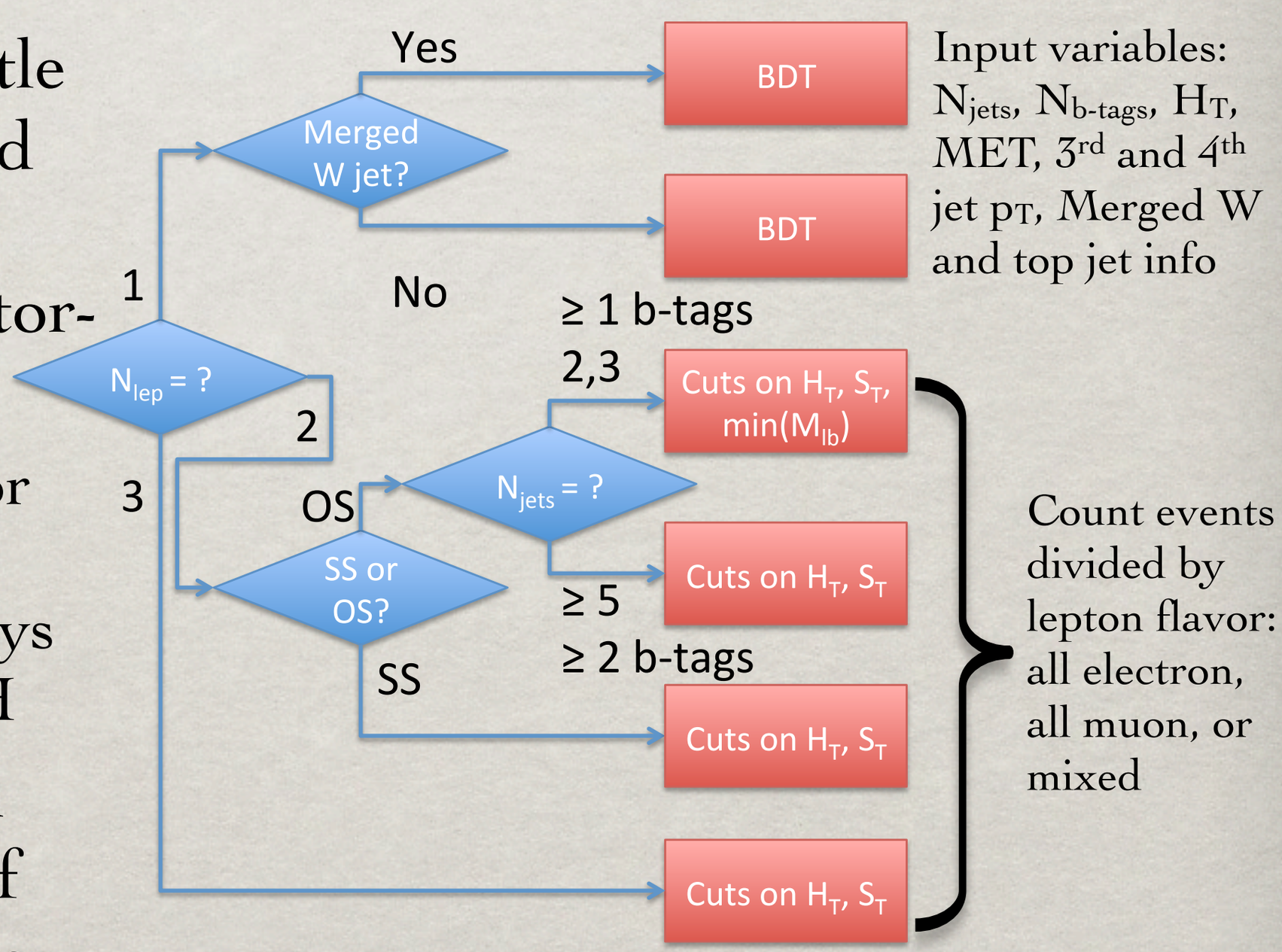
Quark Partners

- A number of models (like Little Higgs mentioned yesterday) have extra heavy vector-like quarks
  - Example, vector like top quark partner T, decays to bW, tZ or tH
- Inclusive search for T using all of the above decays

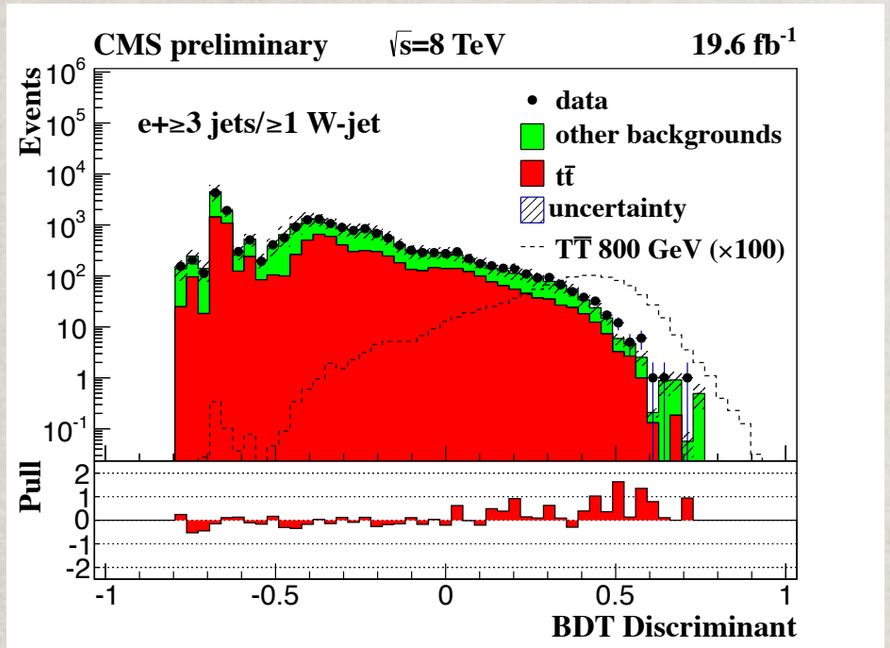


Input variables: N_{jets}, $N_{b\text{-}tags}$, H_T, MET, 3rd and 4th jet p_T, Merged W and top jet info

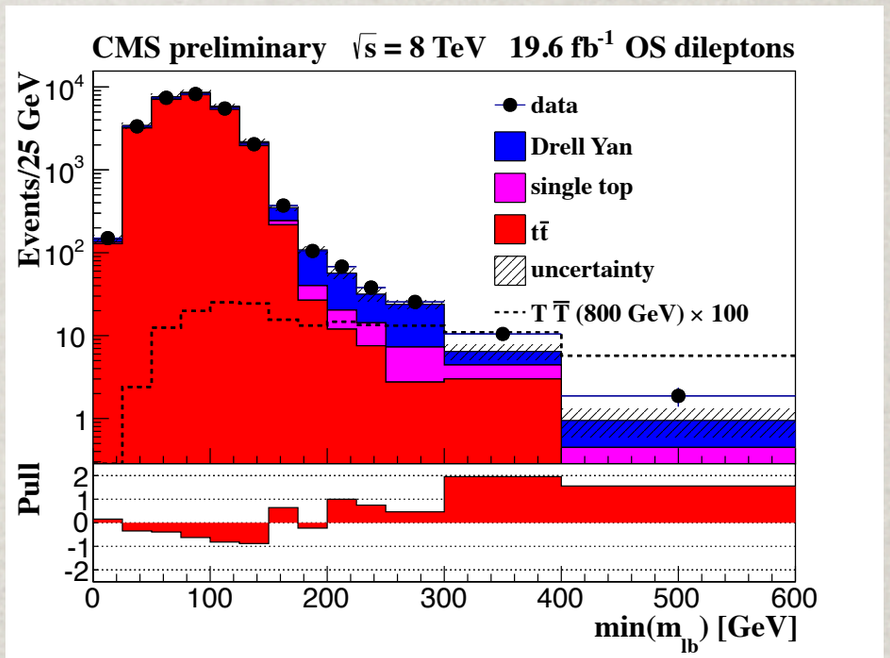
Count events divided by lepton flavor: all electron, all muon, or mixed

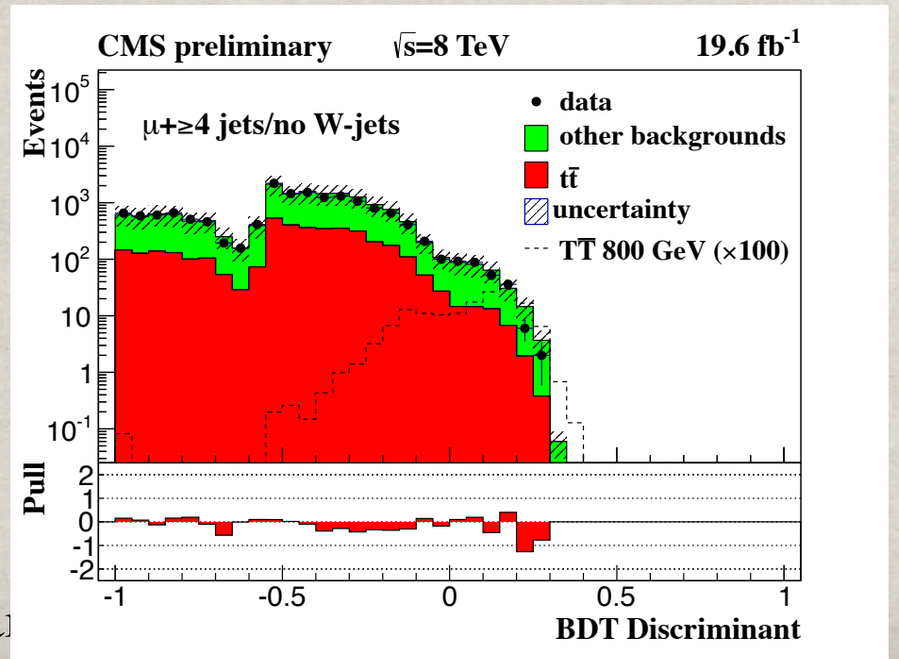
Quark Partners

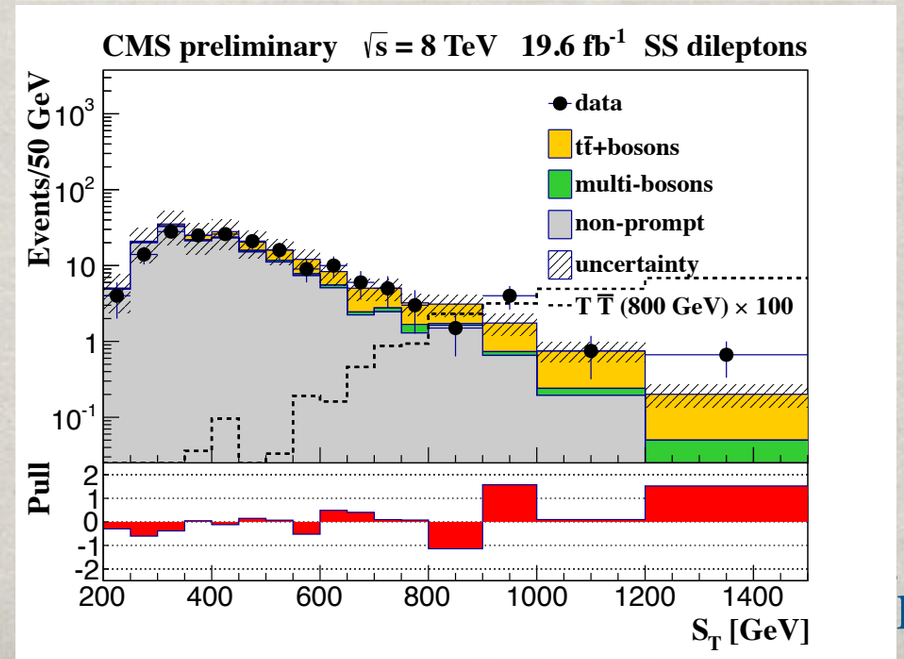
- No signal observed; set limits between 687 GeV to 782 GeV, depending on decay fractions to bW, tZ, and tH



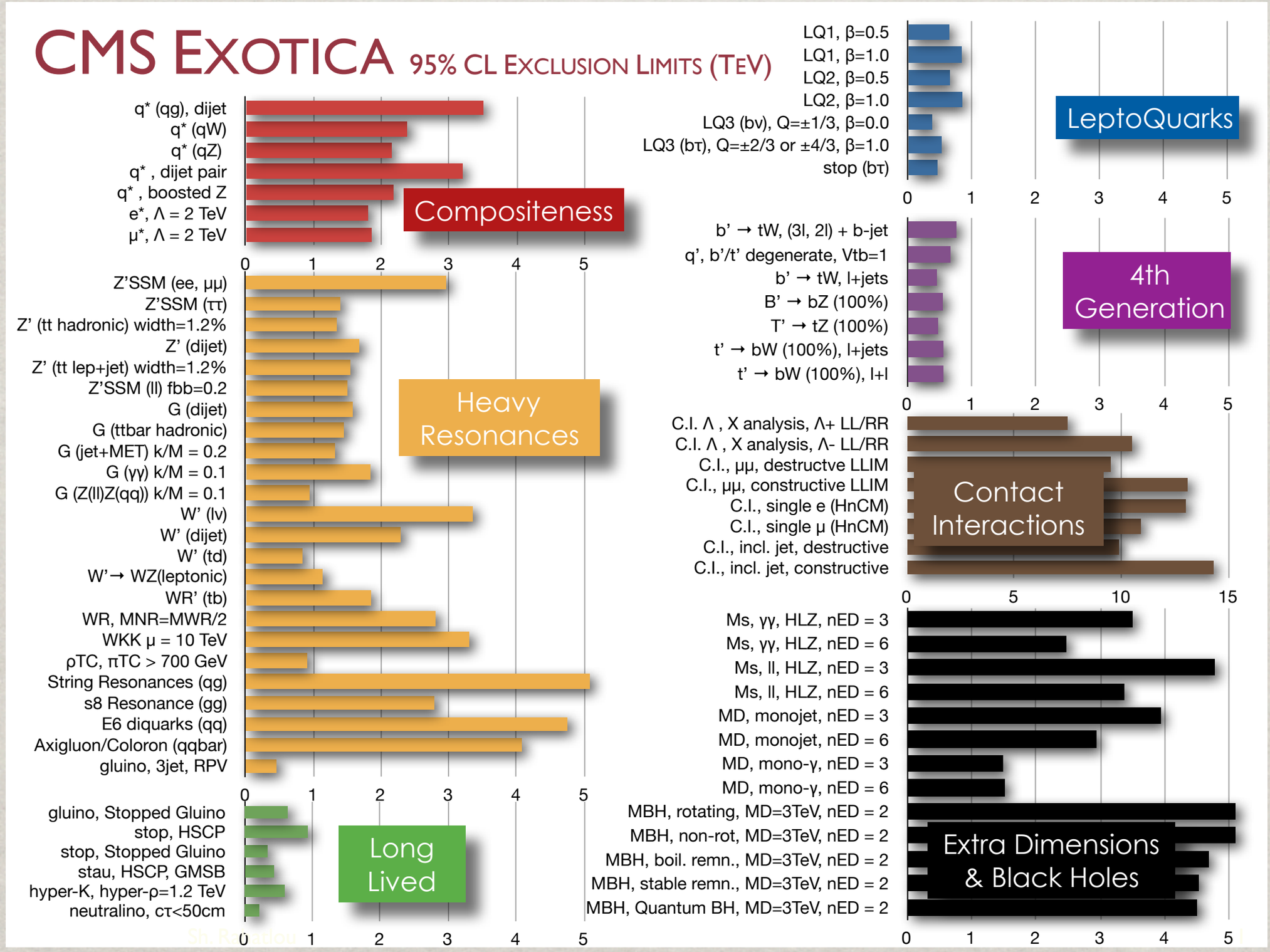
B2G-12-015







Summary

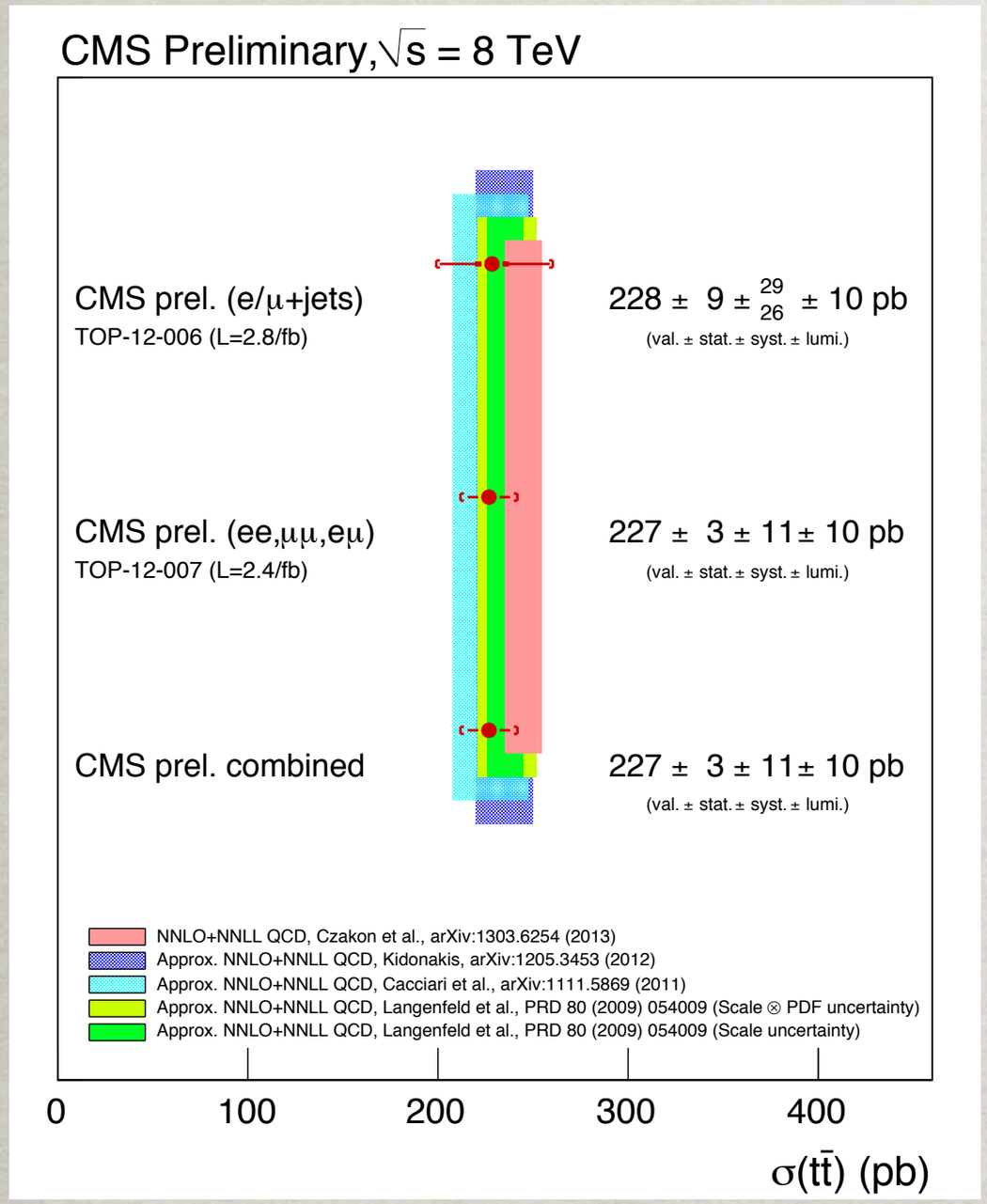

CMS Exotica 95% CL Exclusion Limits (TeV)
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Compositeness
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lν)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Heavy Resonances
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
Long Lived
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
LeptoQuarks
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
4th Generation
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Contact Interactions
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
Extra Dimensions & Black Holes

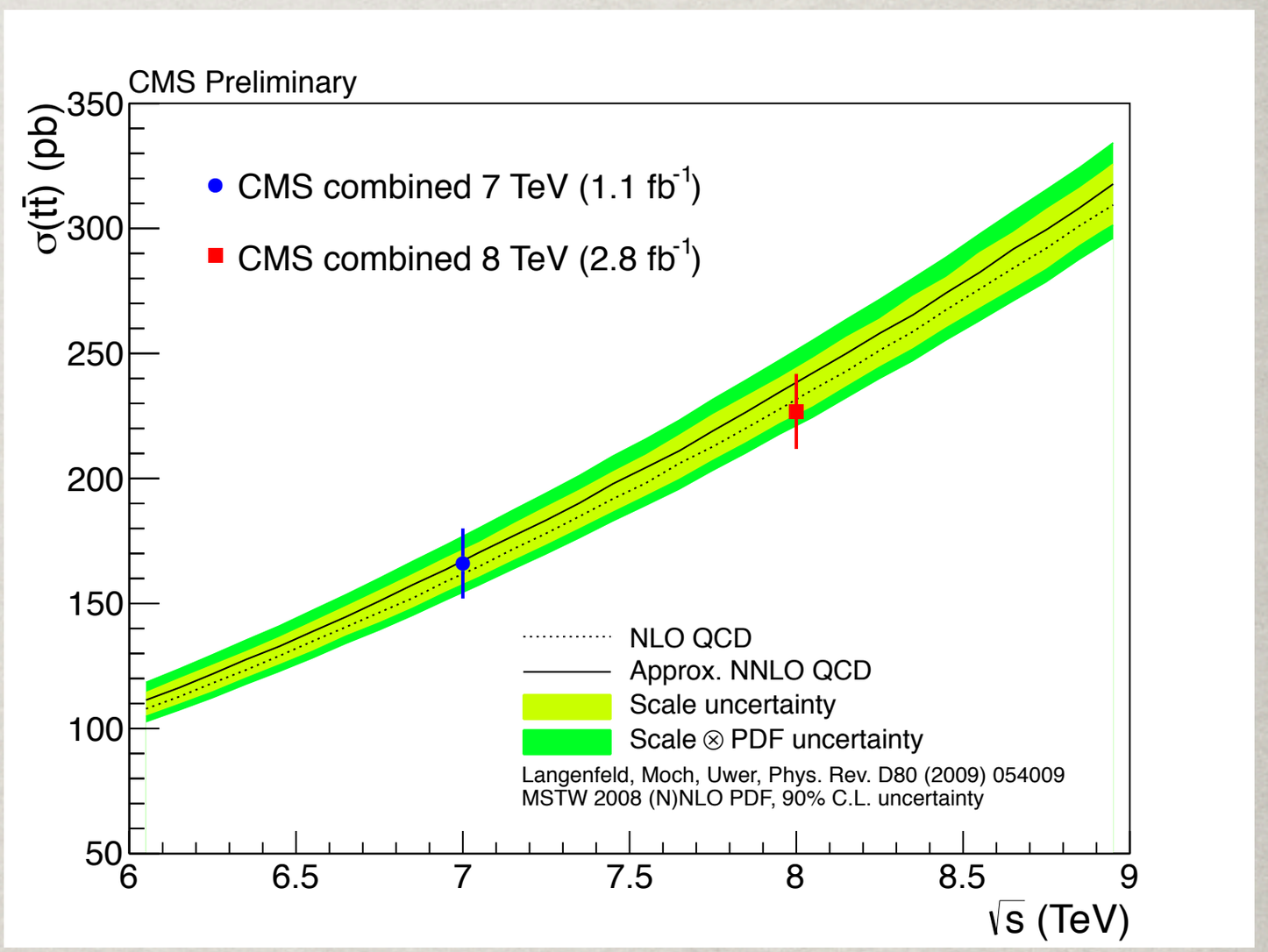
Standard Model Results

Overview

- Success of preceding searches depends on good understanding of background from SM
- Wealth of LHC data with showing no signs of new physics (yet) means many measurements to help refine SM predictions

Top Production

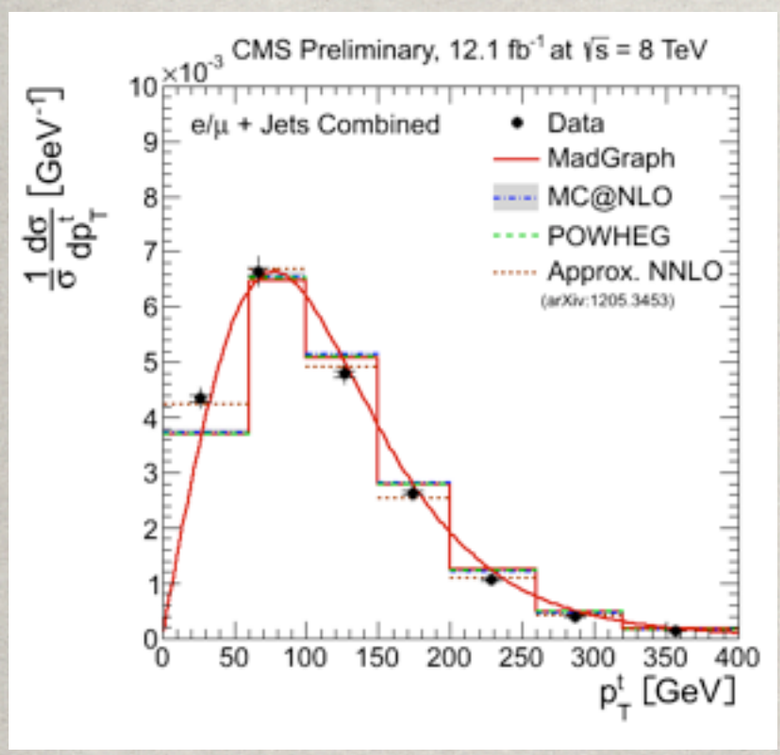


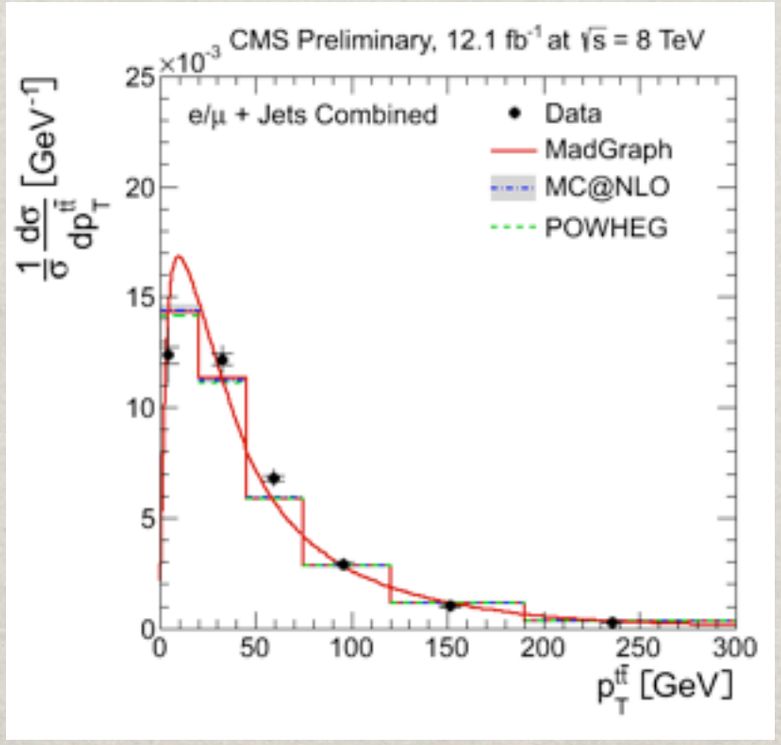


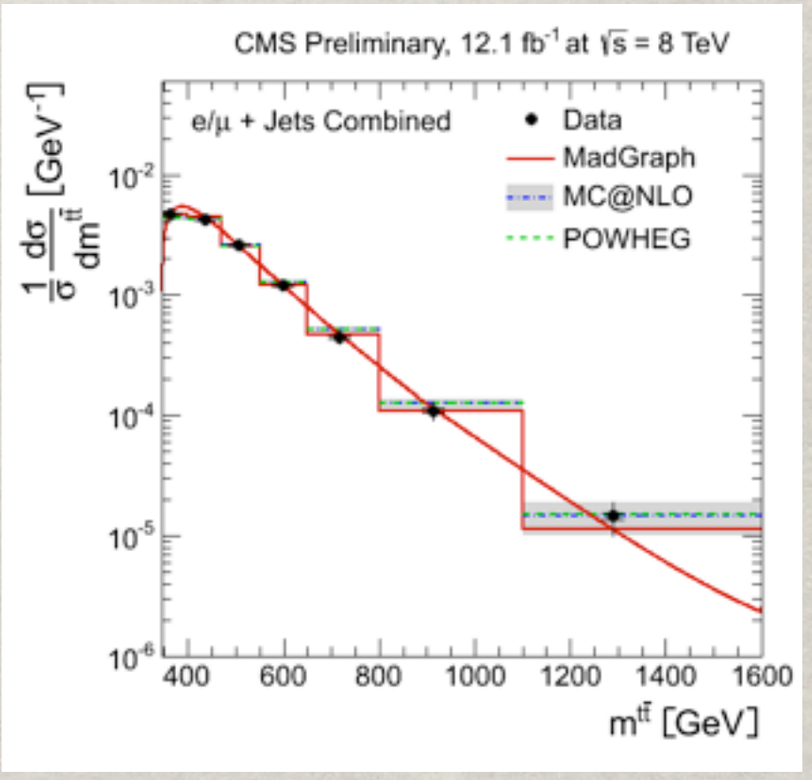
Differential cross Sections

- Move beyond inclusive cross section
- Unfolded to correct for detector resolution
- Generally good agreement
  - Can be used to improve MC tuning

TOP-12-027

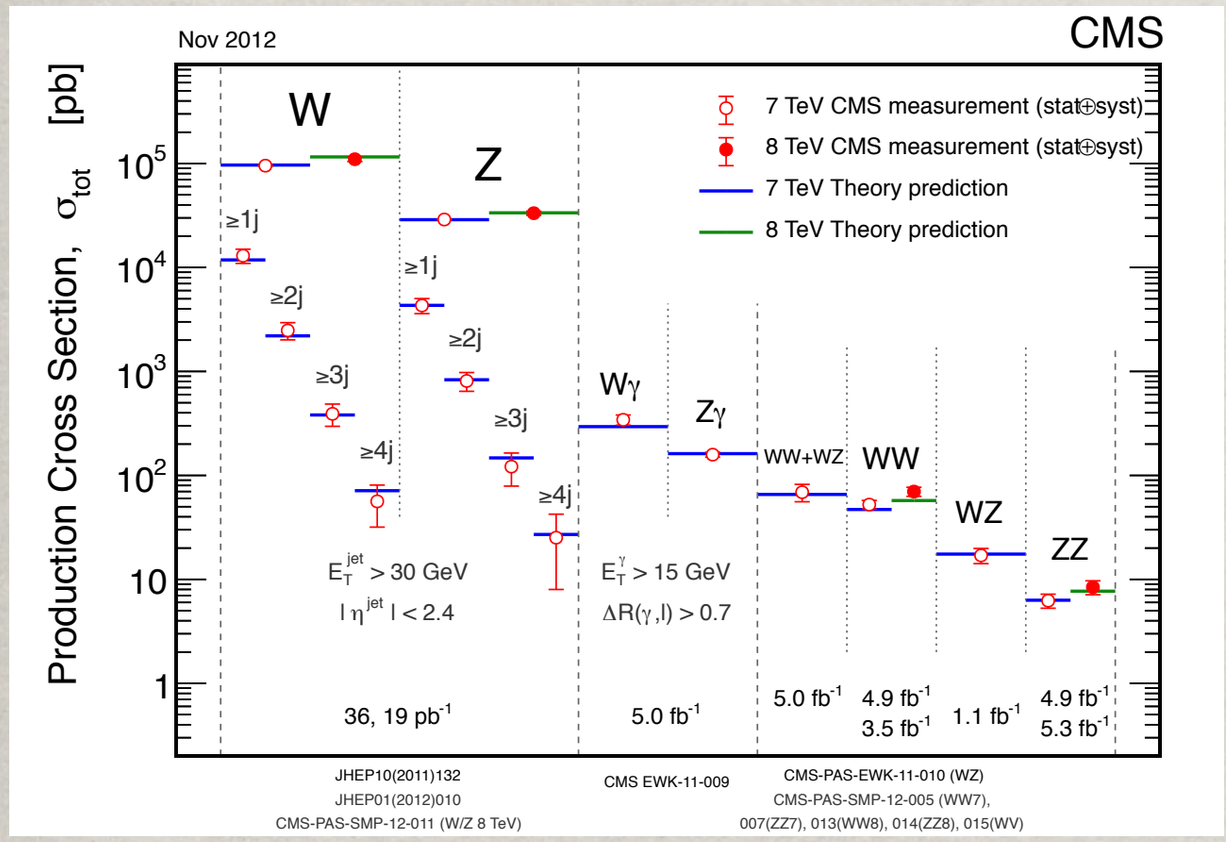




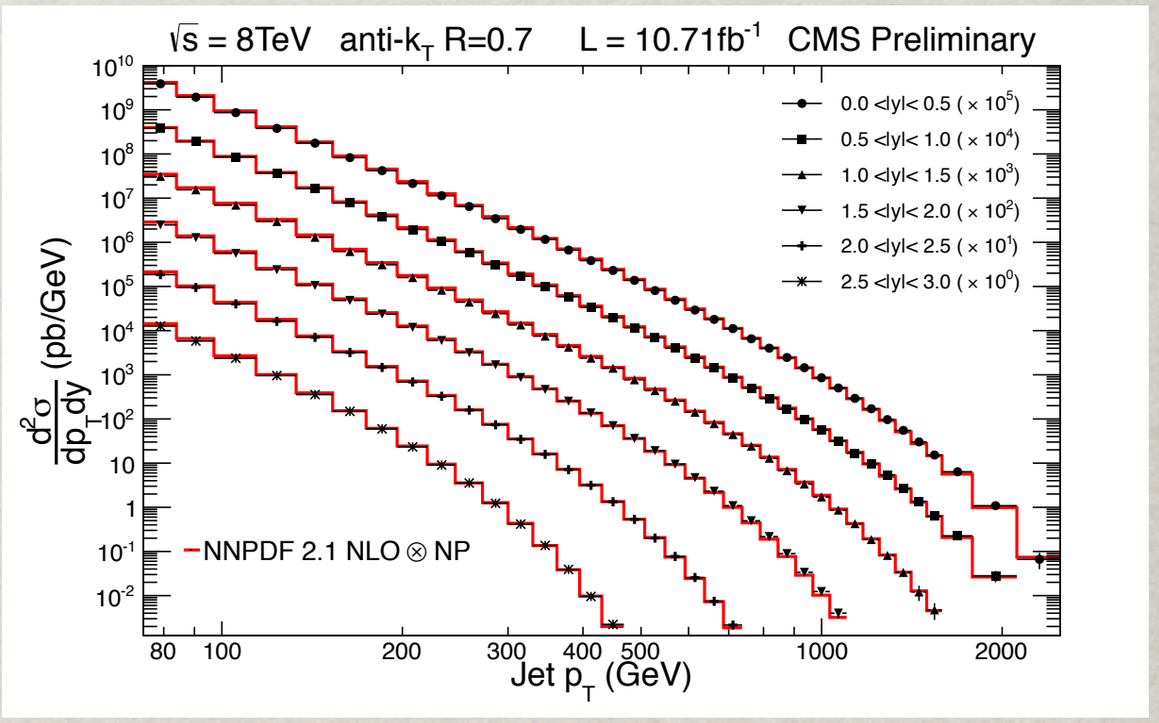


EWK and QCD Processes

- Excellent agreement across many processes and many orders of magnitude

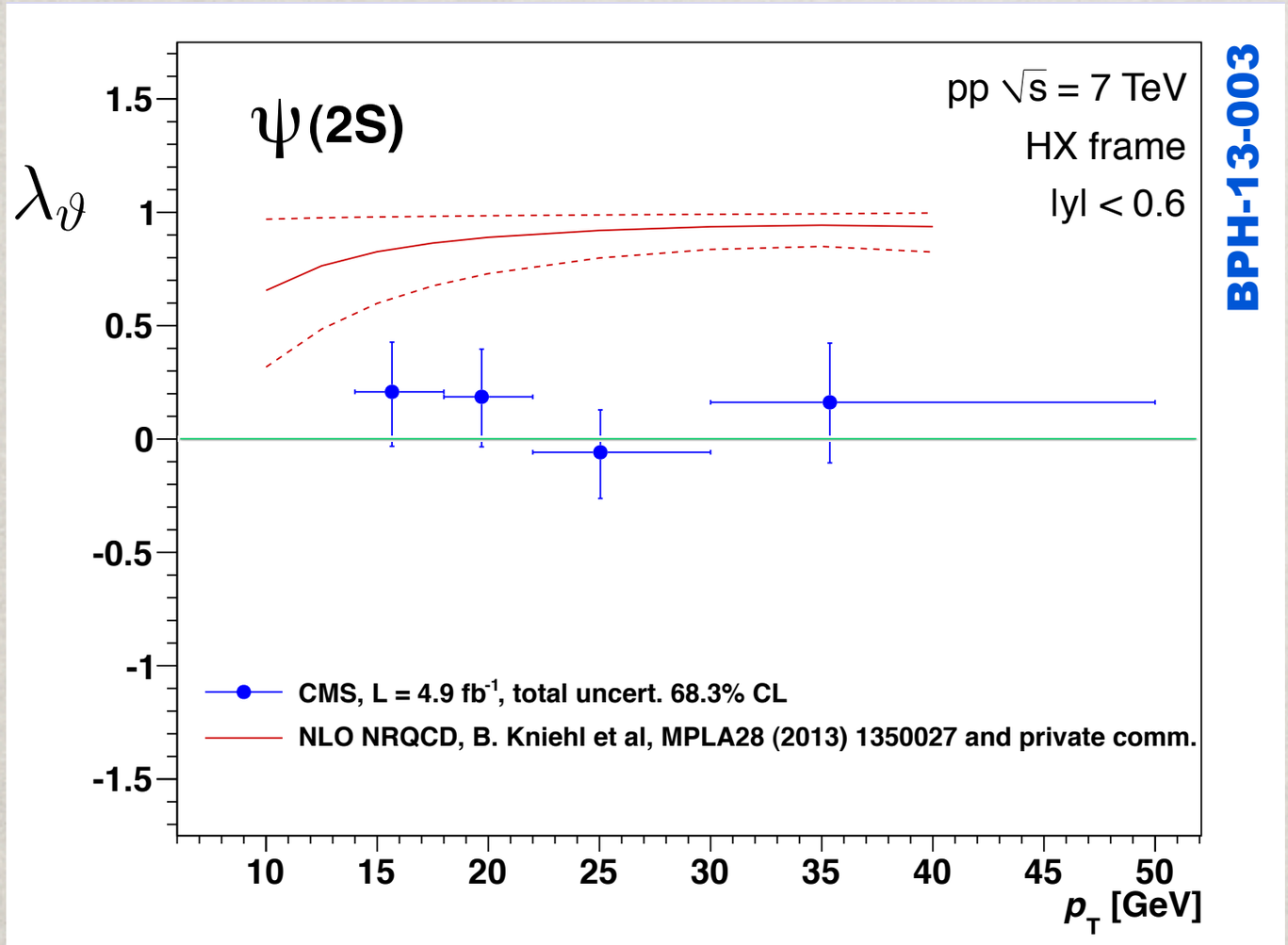


SMP-13-002



J/Psi Polarization

- Occasionally, still run into unexpected disagreement



Highlighted in Theory Summary Talk at LHCP by Joseph Lykken:

My conclusion: there is a big problem here

Summary

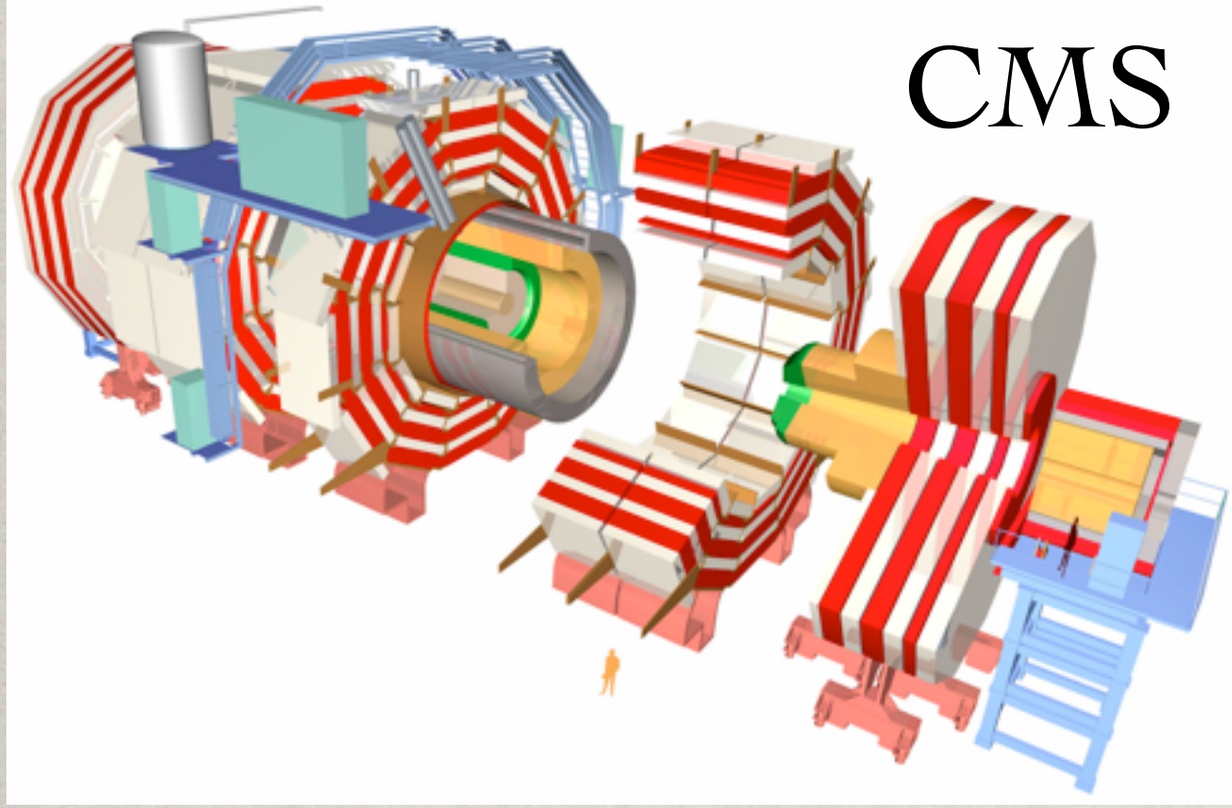
Summary of CMS Results

- After a little more than two years of data taking
  - One major new discovery
  - Many limits on new physics
  - Wealth of precision measurements to help tune description of SM backgrounds
- Reasons to anticipate new particles still as valid as ever
  - Perhaps next big breakthrough is just around the corner in 13 TeV running
  - If not, we will learn something about our (lack of) understanding of nature
- Stay tuned!

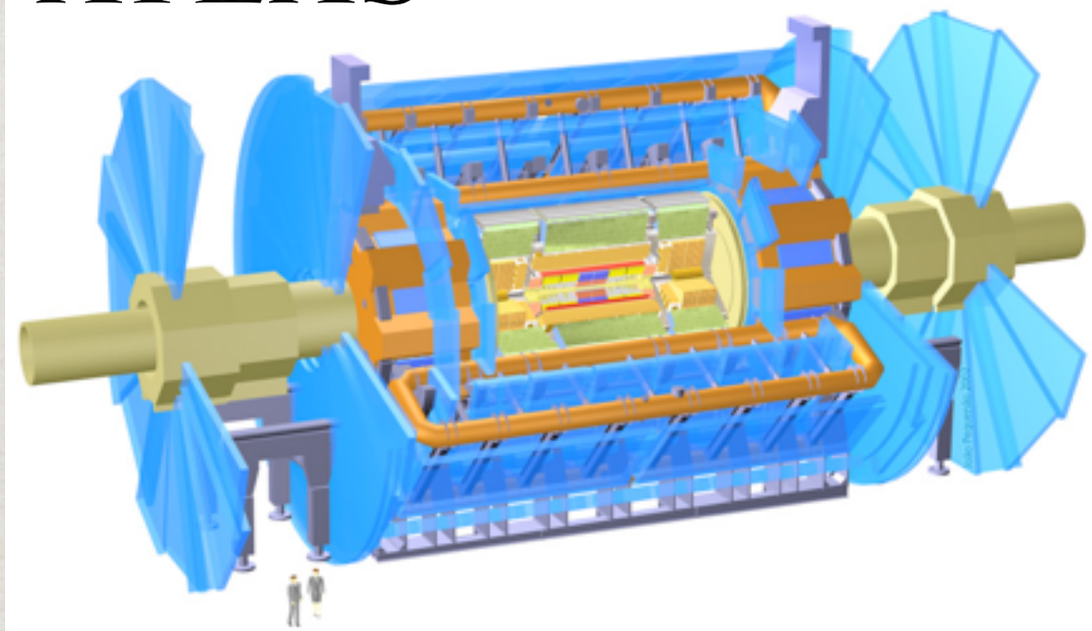
Backup

Compact Muon Solenoid

CMS



ATLAS

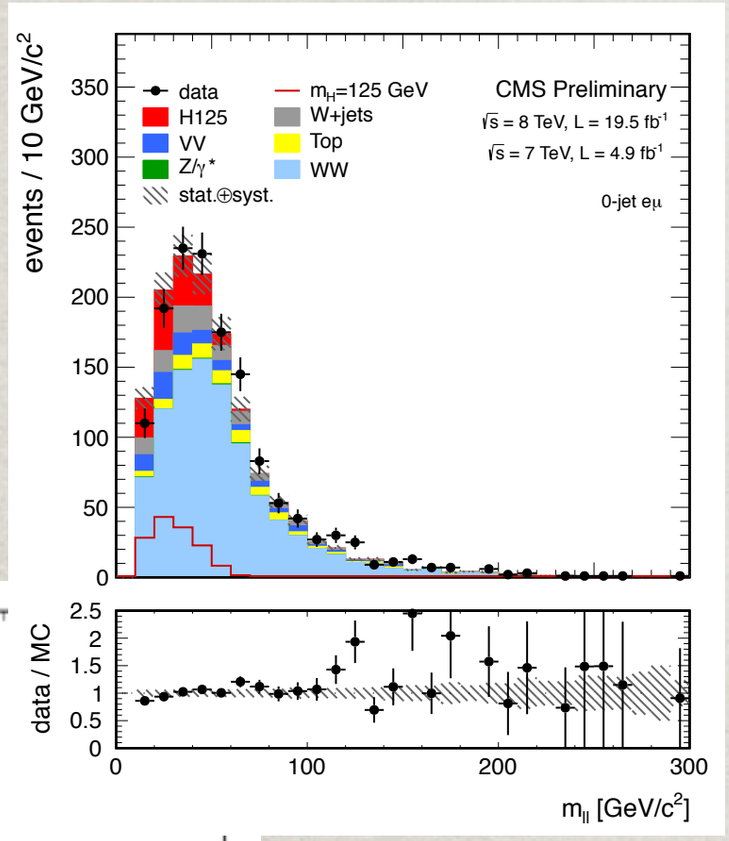


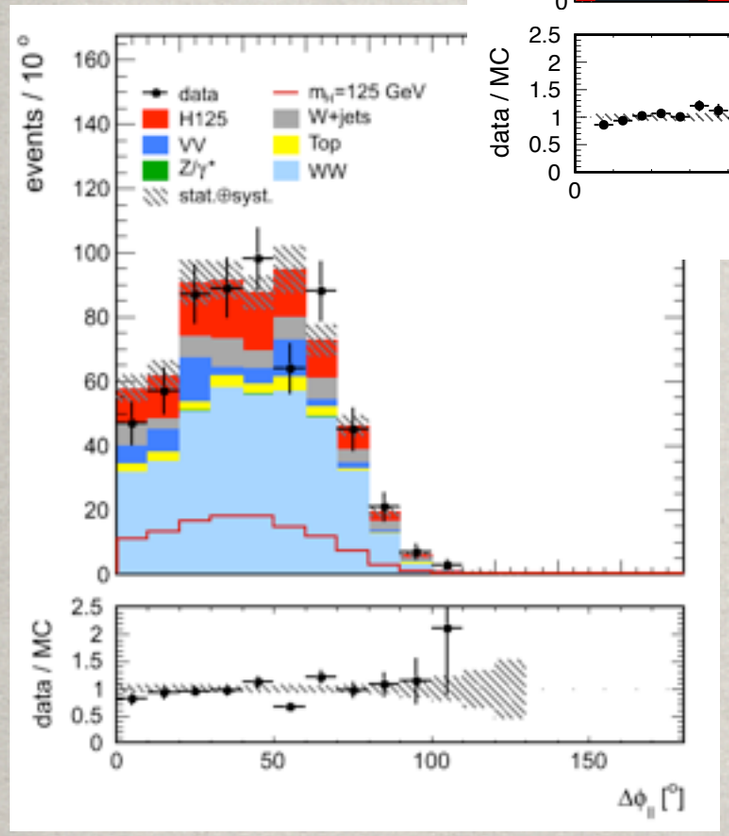
Total Weight: 12500 T
Diameter: 15 m (50 ft)
Length: 21.5 m (70 ft)

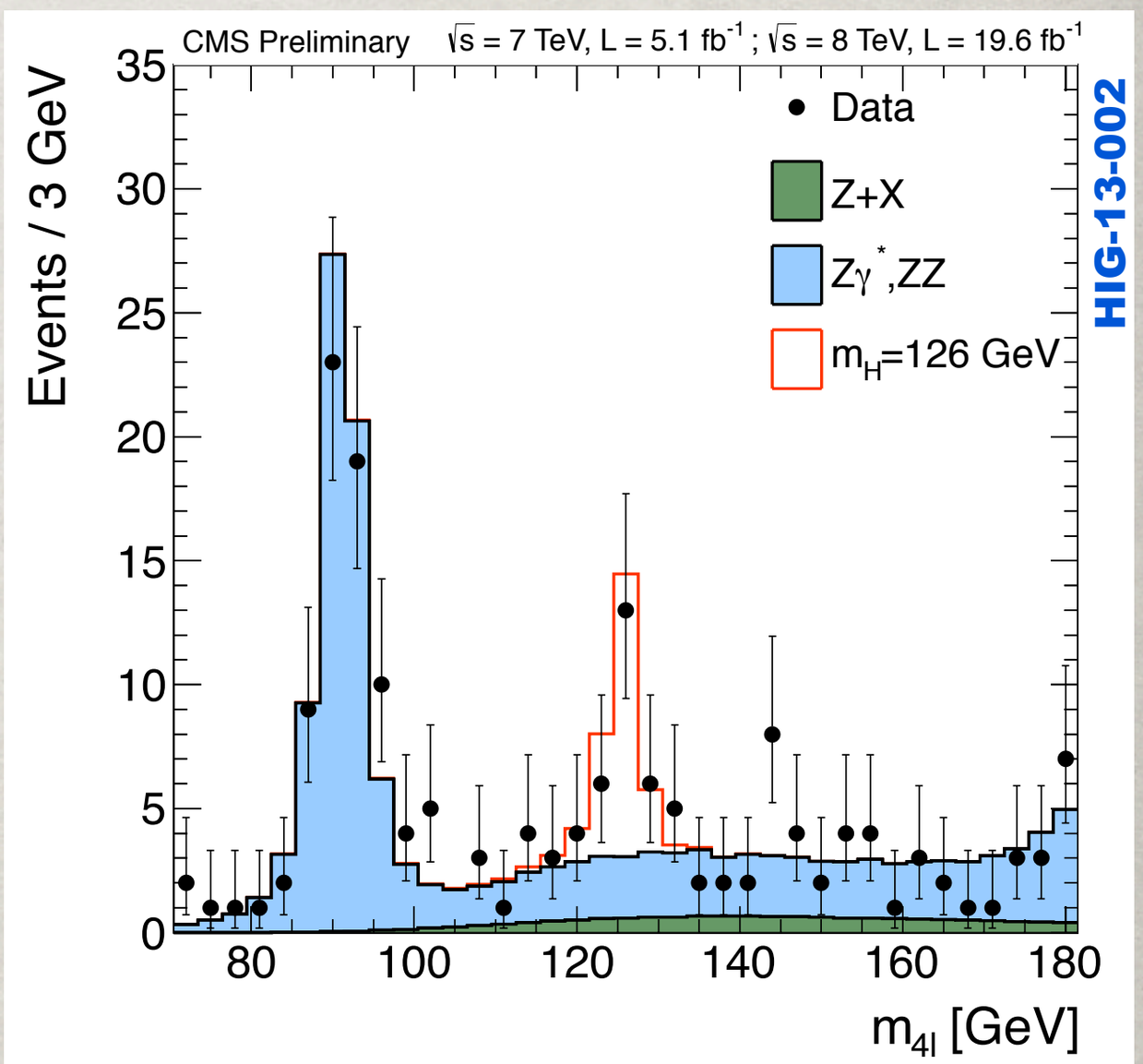
Total Weight: 7000 T
Diameter: 25 m (82 ft)
Length: 46 m (151 ft)

Compact = 2× mass in 20% of the volume!

WW vs ZZ







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SUSY Signatures

- Decays of SUSY particles to SM produce jets and leptons
- Exact nature of signature depends on whether SUSY can decay to only SM particles
  - No (SUSY → SM + SUSY): R-Parity Conserving (RPC)
  - Yes (SUSY → SM): R-Parity Violating (RPV)

RPC

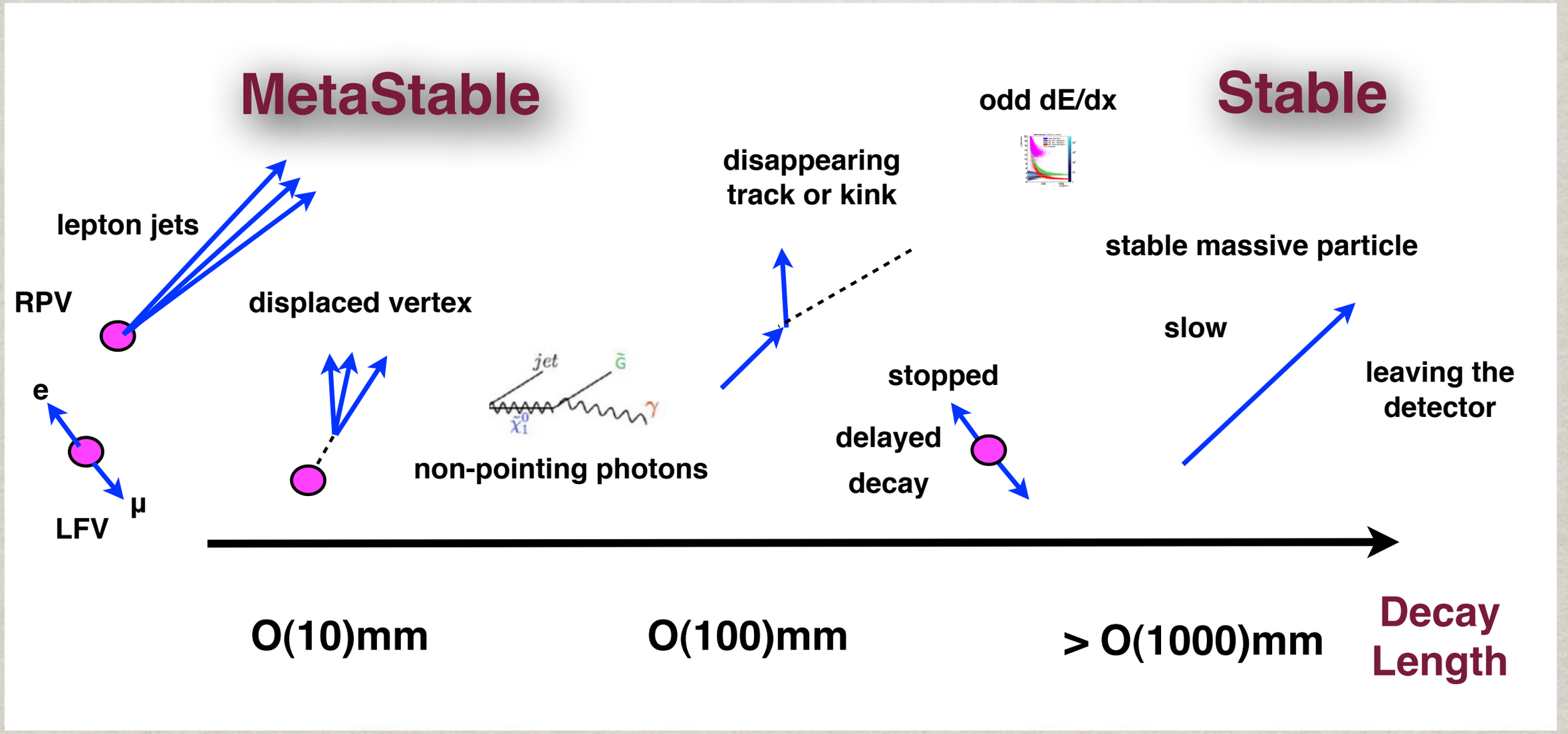
Lightest SUSY particle (LSP) does not decay
→ MET
Discriminate with variables that key in on presence of MET and masses of mother particles:
MET, m_T, m_{T2}, α_T, etc...

RPV

Lightest SUSY particle (LSP) does decay
Look for jet+lepton resonances
or
Non-standard signatures: Stable charged particles, stopped particle decays, lepton jets, etc.

Unusual Results

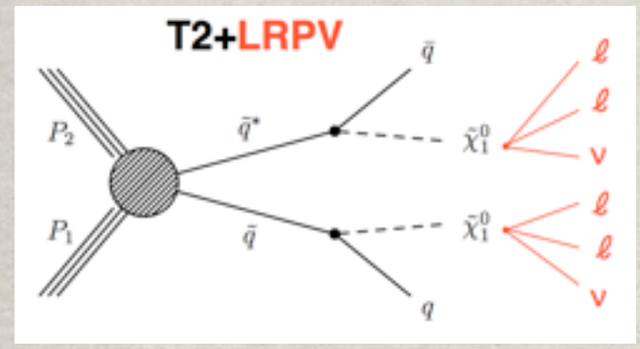
- If we allow RPV, many unusual signatures possible

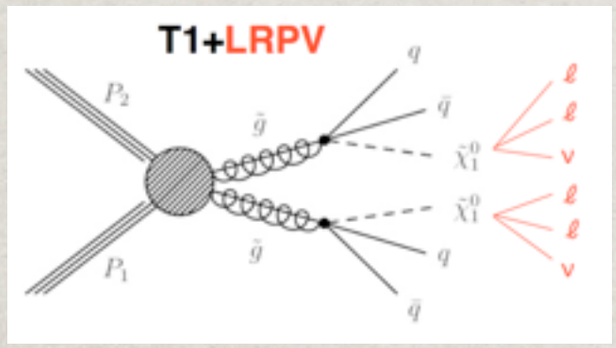


Sigve Haug, AEC University of Bern, LHC2013

RPV Search with 4-Lep. Events

- Look for excess of events with for charge leptons above SM backgrounds



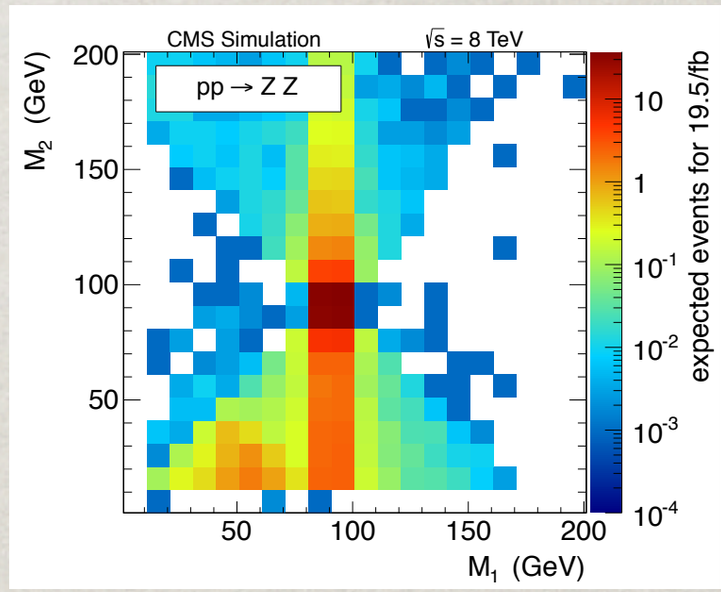


No signals seen so far. Set limits:

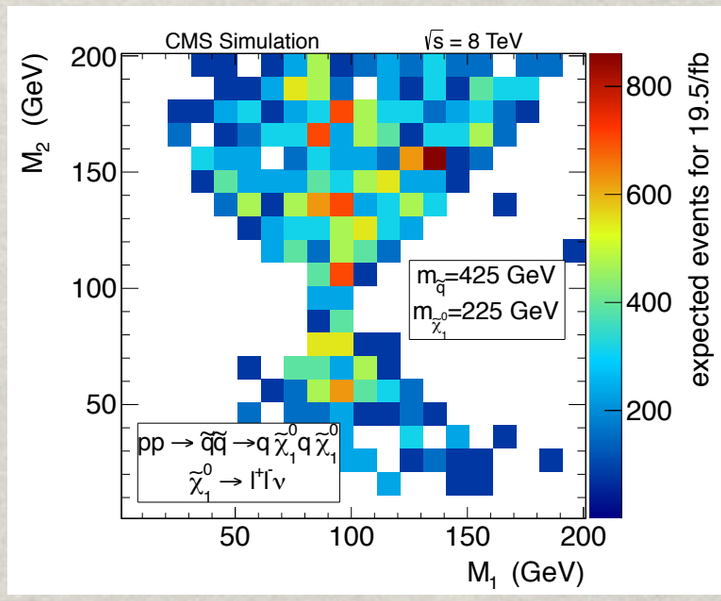
Gluinos: Exclude masses below ~1.4 TeV (for neutralino mass above 400 GeV

Top squark: Exclude masses below ~950 GeV

As always, limit depend on model assumptions, masses of LSP and other SUSY particles, etc.



SUS-13-010



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