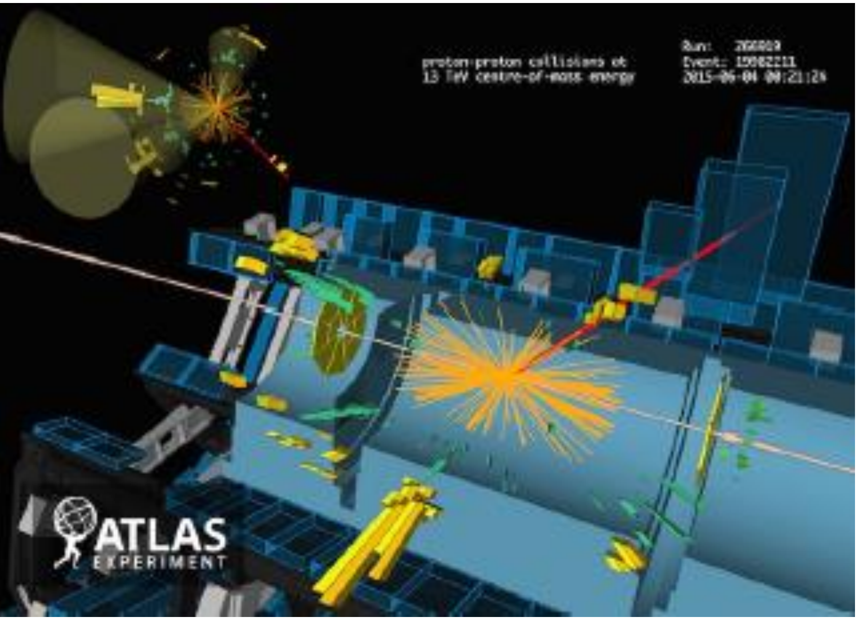
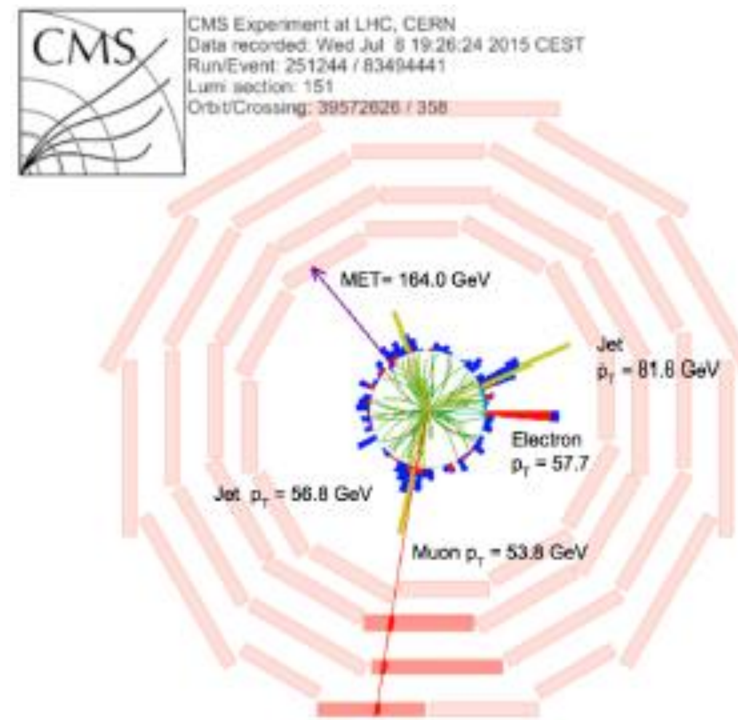


SM and BSM: experimental techniques and results

BSM



J. Cuevas

U. Oviedo (Spain)

TAE 2015,

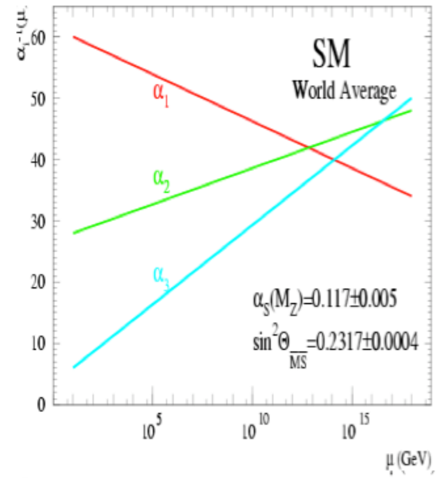
22th – 26th Sep 2015, Benasque

Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

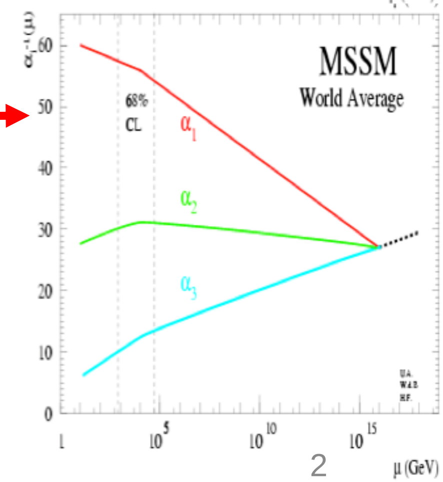
Discover physics beyond the Standard Model

Reminder: The Standard Model
- tells us **how** but not **why**
  3 flavour families? Mass spectra? Hierarchy? 19 parameters!
- needs fine tuning of parameters to level of 10^{-30} !
- has no connection with gravity
- no unification of the forces at high energy



Most popular extensions since 2000

- Supersymmetry
- Extra space dimensions

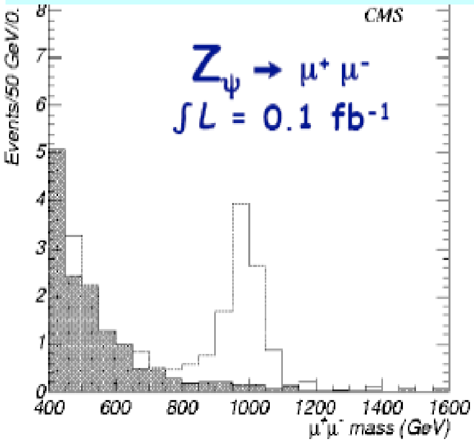


Many other ideas: More symmetry and gauge bosons, composite Higgs models, L-R symmetry, quark & lepton substructure, Little Higgs models, Technicolor, Hidden Valleys, 4th generation…

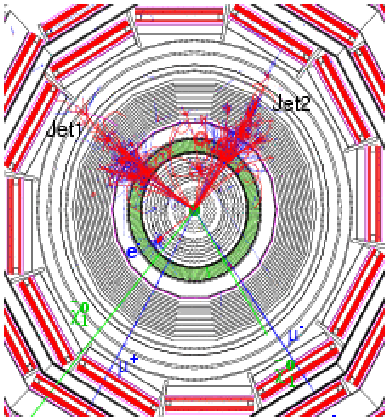
Higgsless models ***somewhat disfavoured these days***

New Physics?

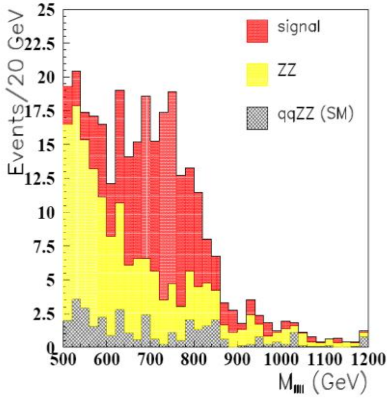
New Gauge Bosons?



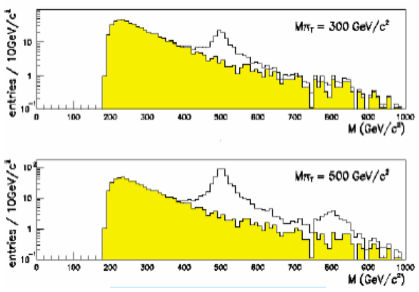
Supersymmetry



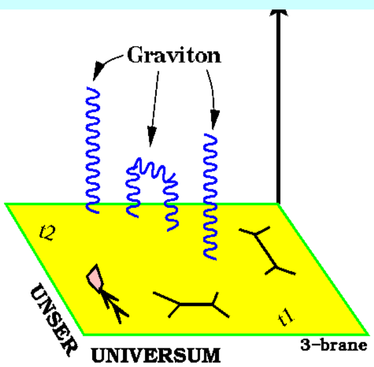
ZZ/WW resonances?



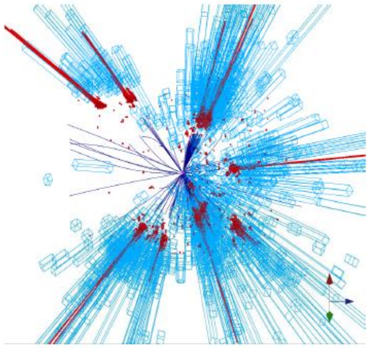
Technicolor?



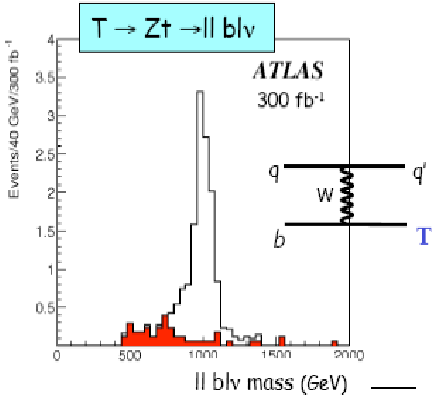
Extra Dimensions?



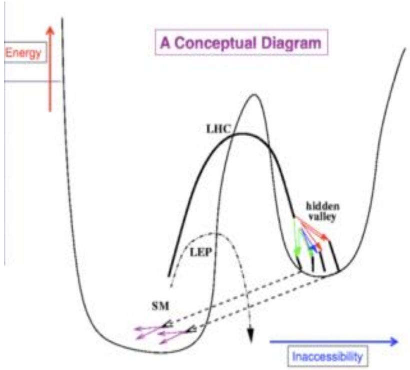
Black Holes???



Little Higgs?



Hidden Valleys?

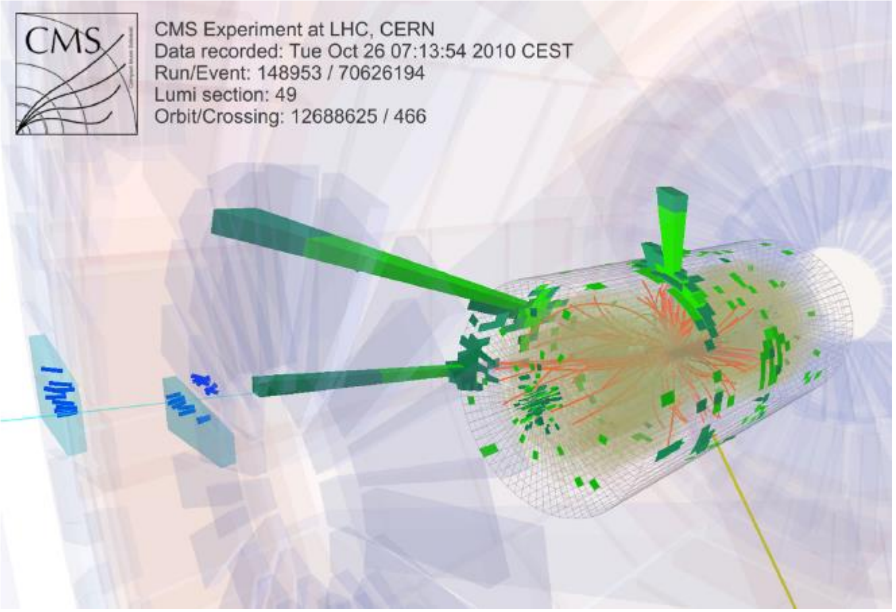


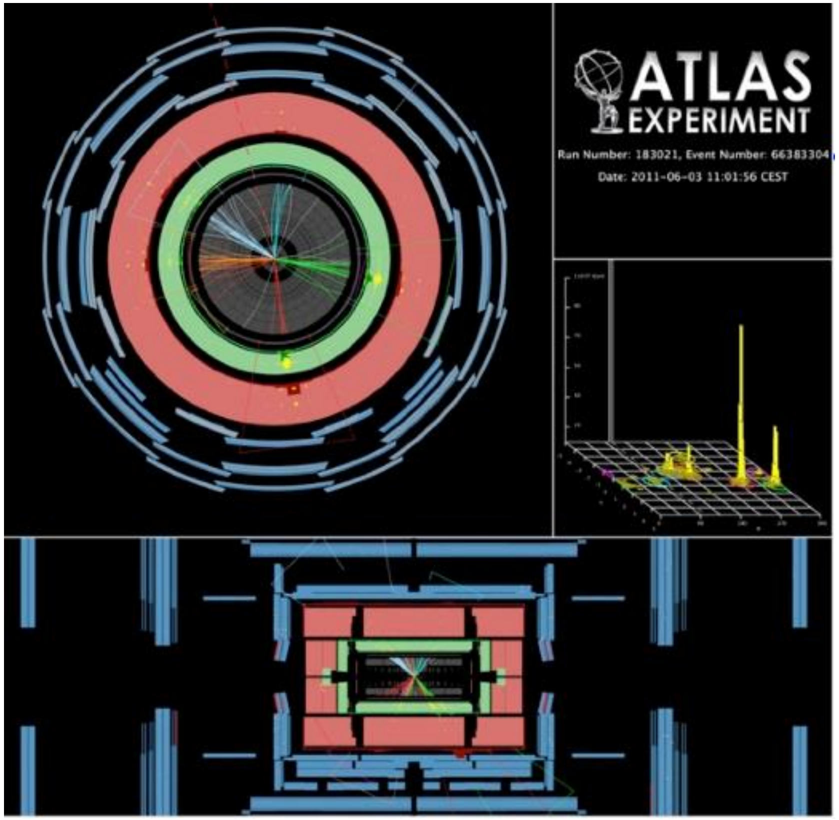
What stabilizes the Higgs Mass? Many ideas, not all viable any more

A large variety of possible signals. We have to be ready for that

Some Interesting Collisions

…already in 2010…





- Events with five jets of particles and large missing energy which could come from a possible dark matter particle
- But a few events is not enough to prove we have something new
  - No visible excess has been building up with time…

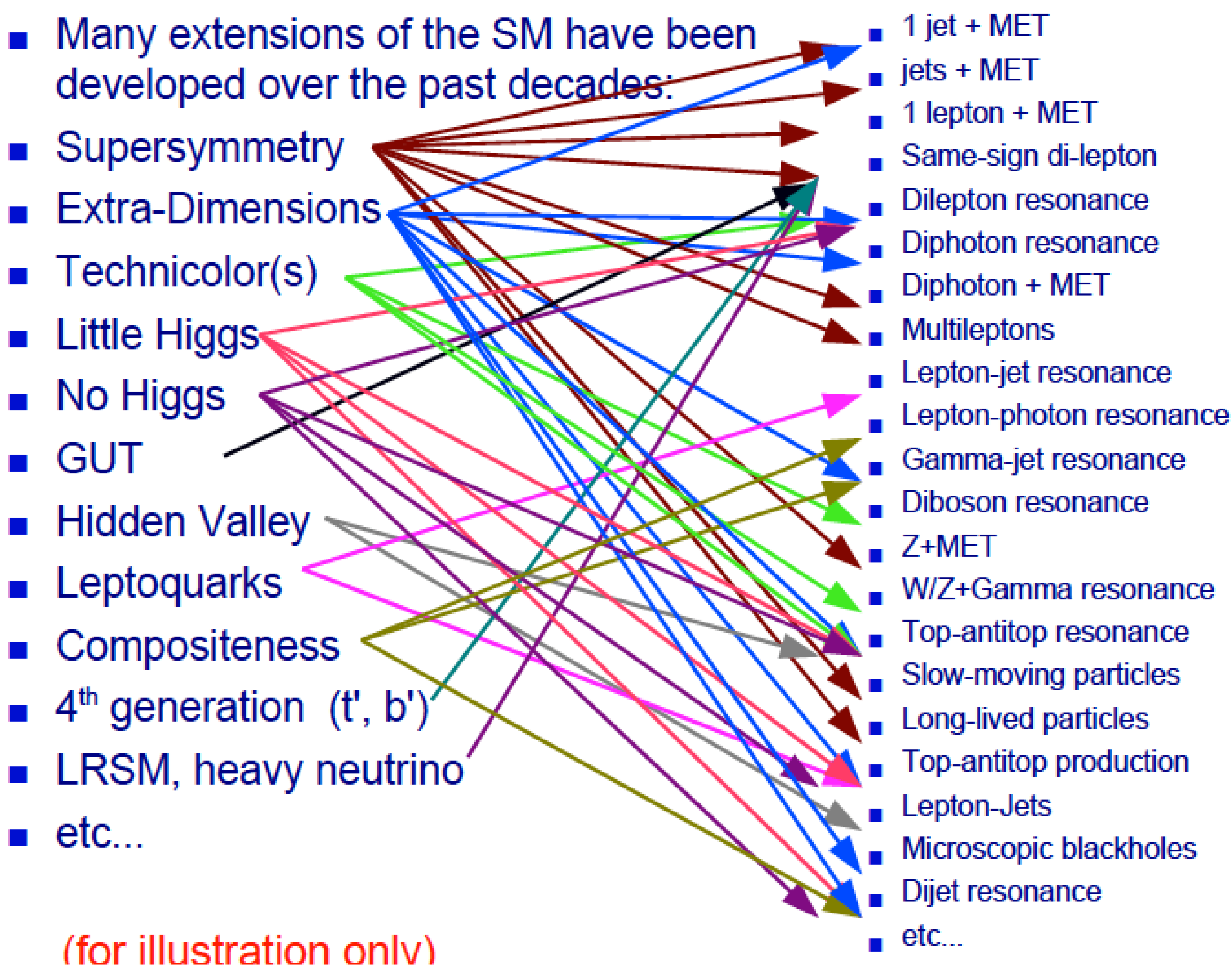
Beyond the Standard Model

- Apart from the naturalness argument:
  - Standard Model accommodates, but does not explain:
    - EWSB
    - CP-violation
    - Fermion masses (i.e., the values of the Yukawa couplings to the Higgs field)
  - It doesn't provide natural explanation for the:
    - Neutrino masses
    - Cold dark matter

- Logical conclusion:
  - **Standard model is an effective theory – a low-energy approximation of a more complete theory, which ultimately explains the above phenomena**
  - This new theory must take off at **a scale of ~1 TeV to** avoid significant amount of fine tuning

  - Three classes of solutions:
    - Ensure automatic cancellation of divergencies (SUSY/Little Higgs)
    - Eliminate fundamental scalar and/or introduce intermediate scale $\Lambda \sim 1$ TeV (Technicolor / Higgsless models) - basically dead now
    - Reduce the highest physics scale to ~1 TeV (Extra Dimensions)

BSM signatures



Models with Extra Dimensions

Large Extra Dimensions

Size: » TeV^{-1}; SM-particles on brane; gravity in bulk

KK-towers (small spacing); KK-exchange; graviton prod.

Signature: e.g. x-section deviations; jet+$E_{T,miss}$ ....

Warped Extra Dimensions

5-dimensional spacetime with warped geometry

Graviton KK-modes (large spacing); graviton resonances

Signature: e.g. resonance in ee, μμ, γγ-mass distributions ...

TeV-Scale Extra Dimensions

SM particles allowed to propagate in ED of size TeV^{-1}

[scenarios: gauge fields only (nUED) or all SM particles (UED)]

nUED : KK excitations of gauge bosons

UED : KK number conservation; KK states pair produced (at tree-level) ...

Signature: e.g. Z'/W' resonances, dijets+$E_{T,miss}$, heavy stable quarks/gluons...

Search for Large Extra Dimensions

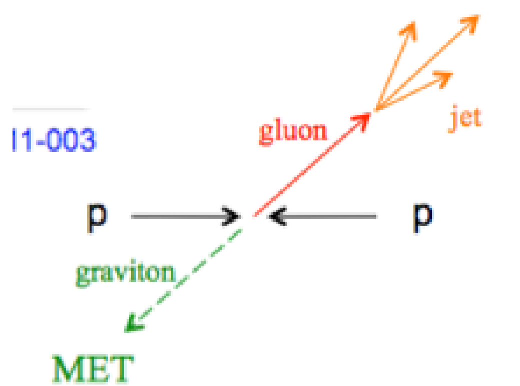
Mono-jet final state +Missing E_T (ADD)

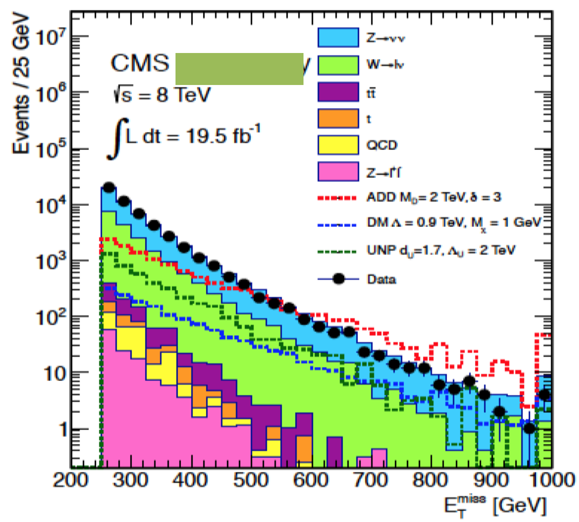
p_T jet > 110 GeV
MET > 200 GeV

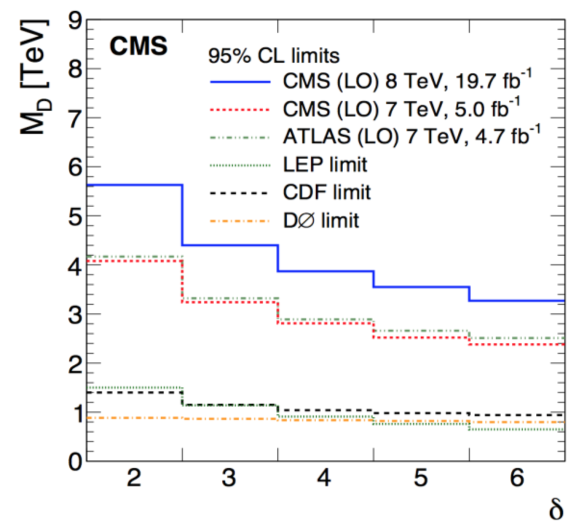
Limits on M_D between 3 and 4 TeV

arXiv:1408.3583

Lower limit on the Planck Scale versus number of extra dimensions

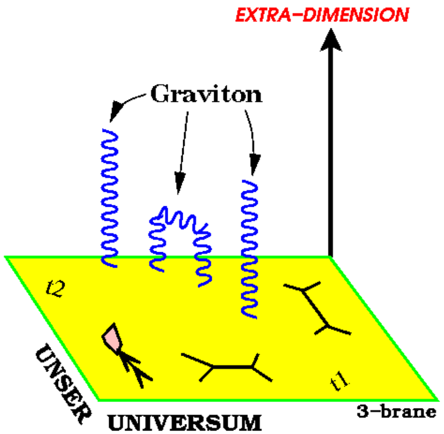






M_D (ADD) at LO 95% CL limits	$\sqrt{s}$ [TeV]	Lumi [fb^{-1}]	δ=3 Exp.	δ=3 Obs.	δ=6 Exp.	δ=6 Obs.
CMS Monojet	8	19.5	3.94	3.96	2.95	2.94

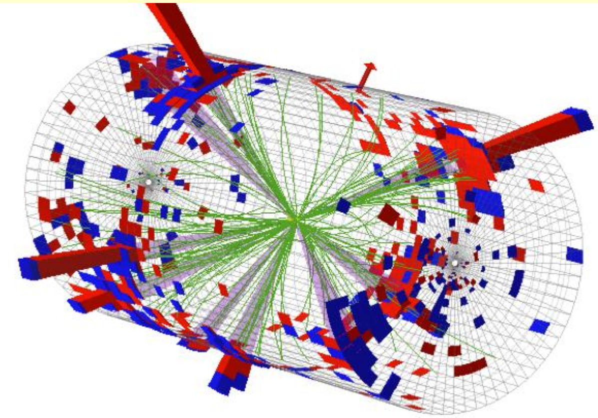
Search for Micro Black Holes



Extra Dimensions!

Planck scale
a few TeV?

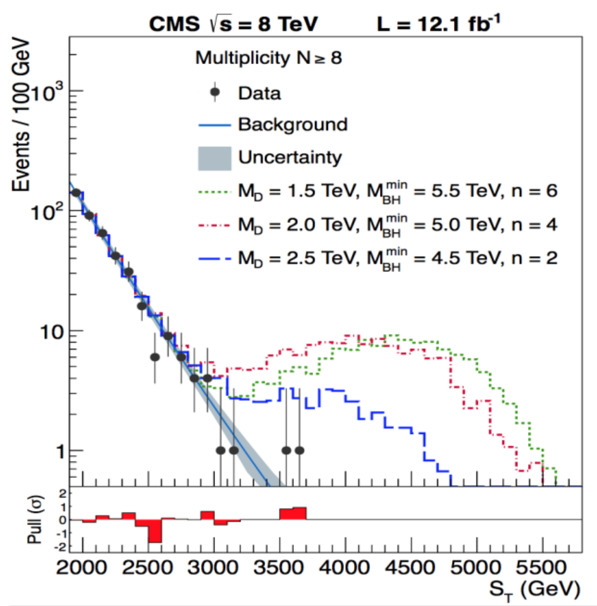
Nice events, eg a 10 jet event

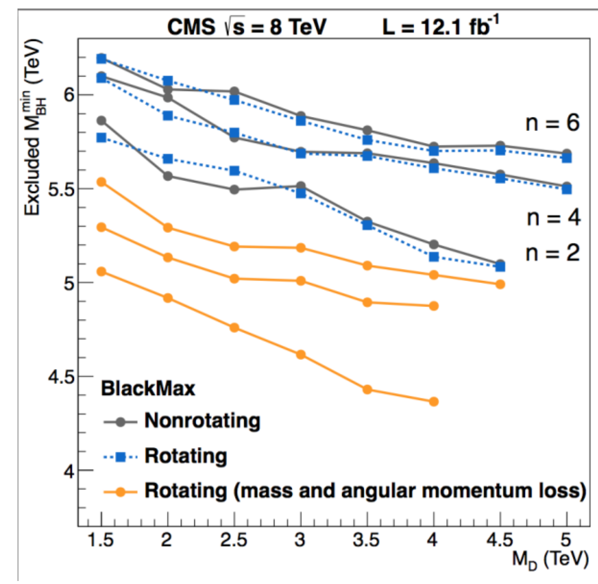


arXiv:1202.6396

Look for the decay producs of an evaporating black hole

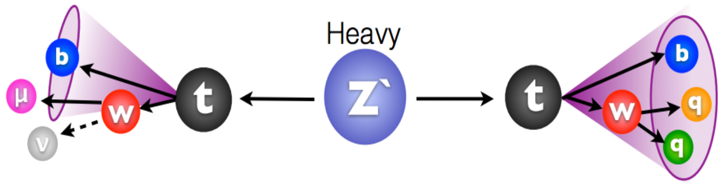
Define S_T to be the scalar sum of all high p_T objects found in the event
Look for deviations at high S_T





Black hole masses excluded in range below ~5 TeV depending on assumptions

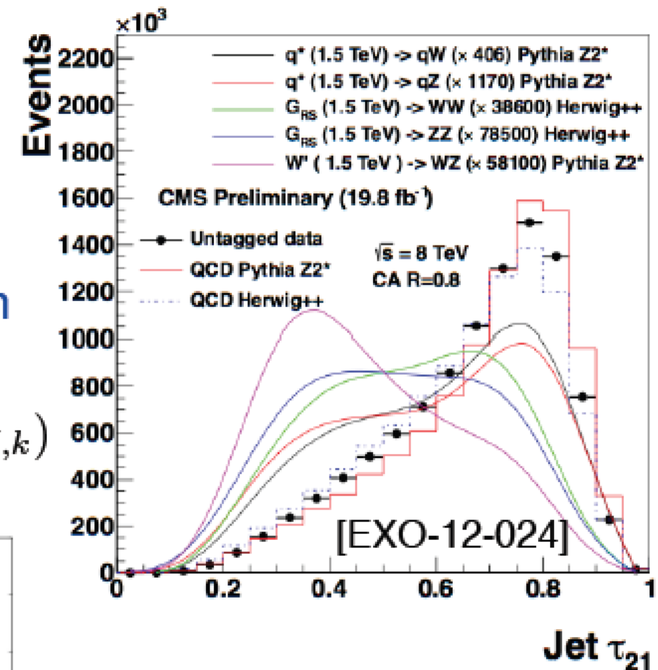
Searches with Boosted Objects

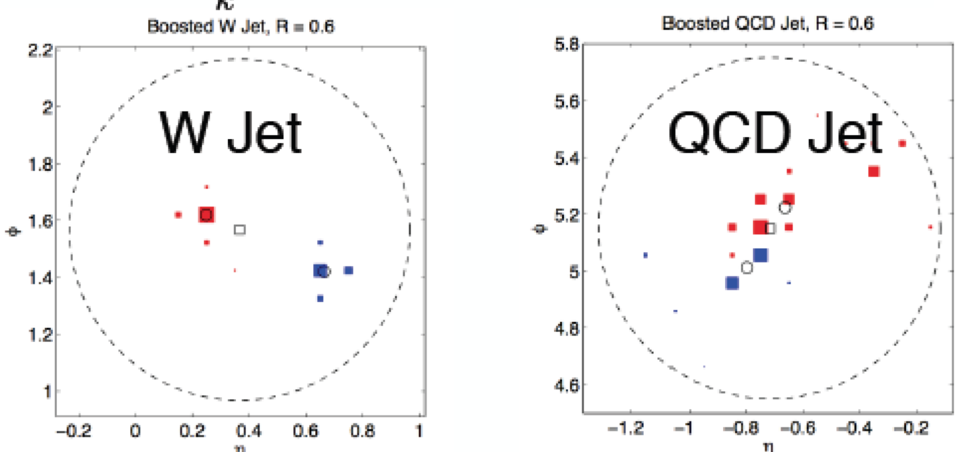


BOOST dedicated meetings
http://boost2015.uchicago.edu/

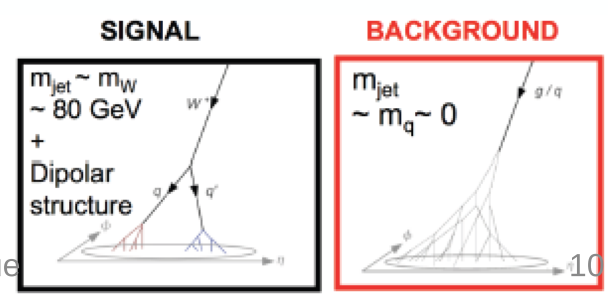
- Several different techniques to identify merged jets are on the market…
  - N-subjettiness, τ_N, uses $\tau_{21}=\tau_2/\tau_1$ as a discriminant to separate QCD jets from merged W/Z jets

$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k}\min\left(\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right)$$





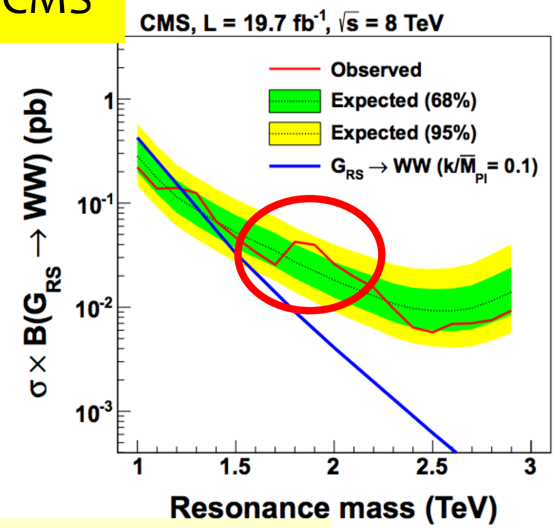
[Thaler, Tilburg, arXiv:1011.2268]

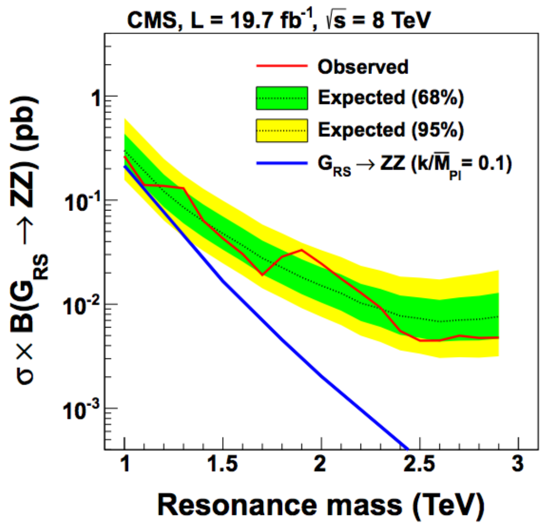


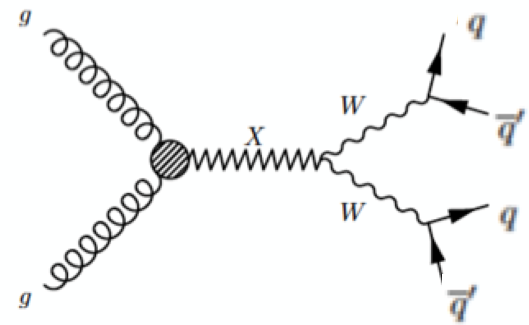
Resonances Decaying into qV or VV

Heavy resonances decaying into qZ or qW, or VV jets only (CMS) or llqq (ATLAS) using boosted jets and jet substructure analysis

CMS



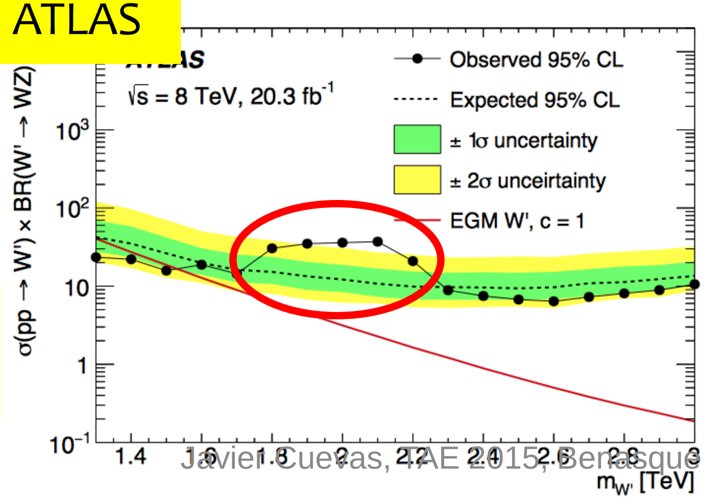




Jets start to merge for X = 700-900 GeV

arXiv:1405.1994

ATLAS

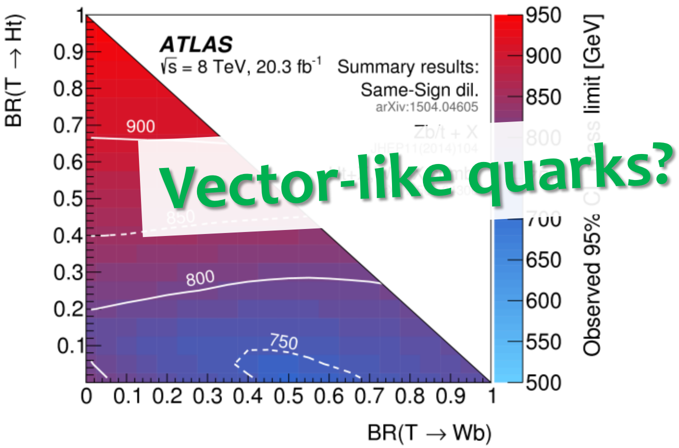


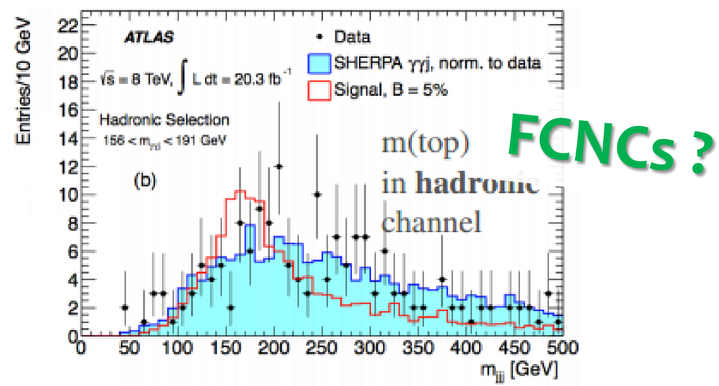
arXiv:1506.00962

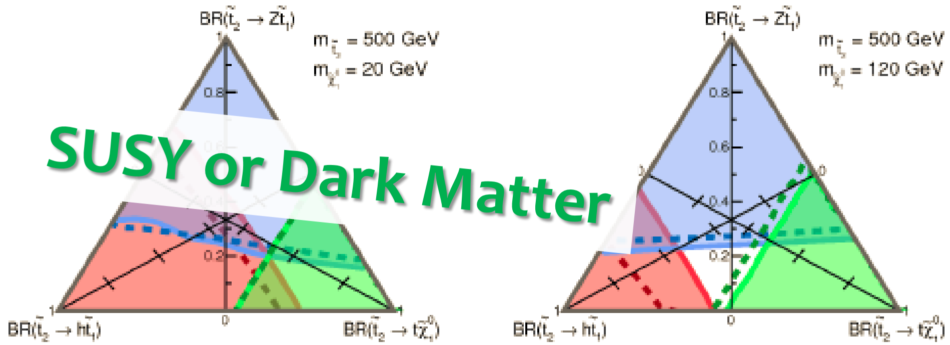
Excess in WZ of 3.4σ (2.5 with LEE)

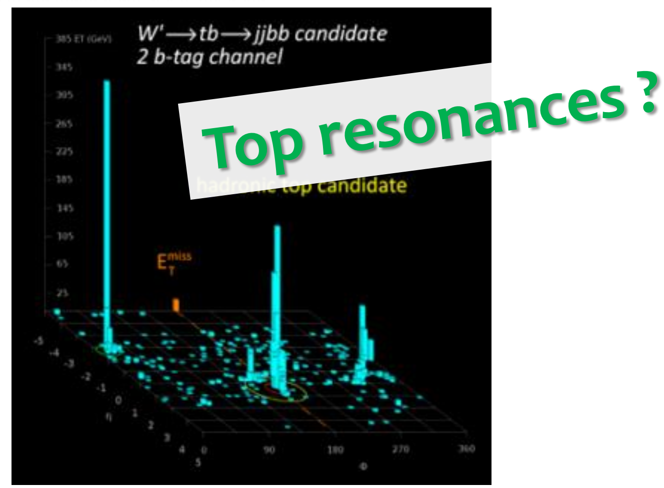
These type of analyses will get even more important at 13 TeV

Top: a window to BSM physics ?



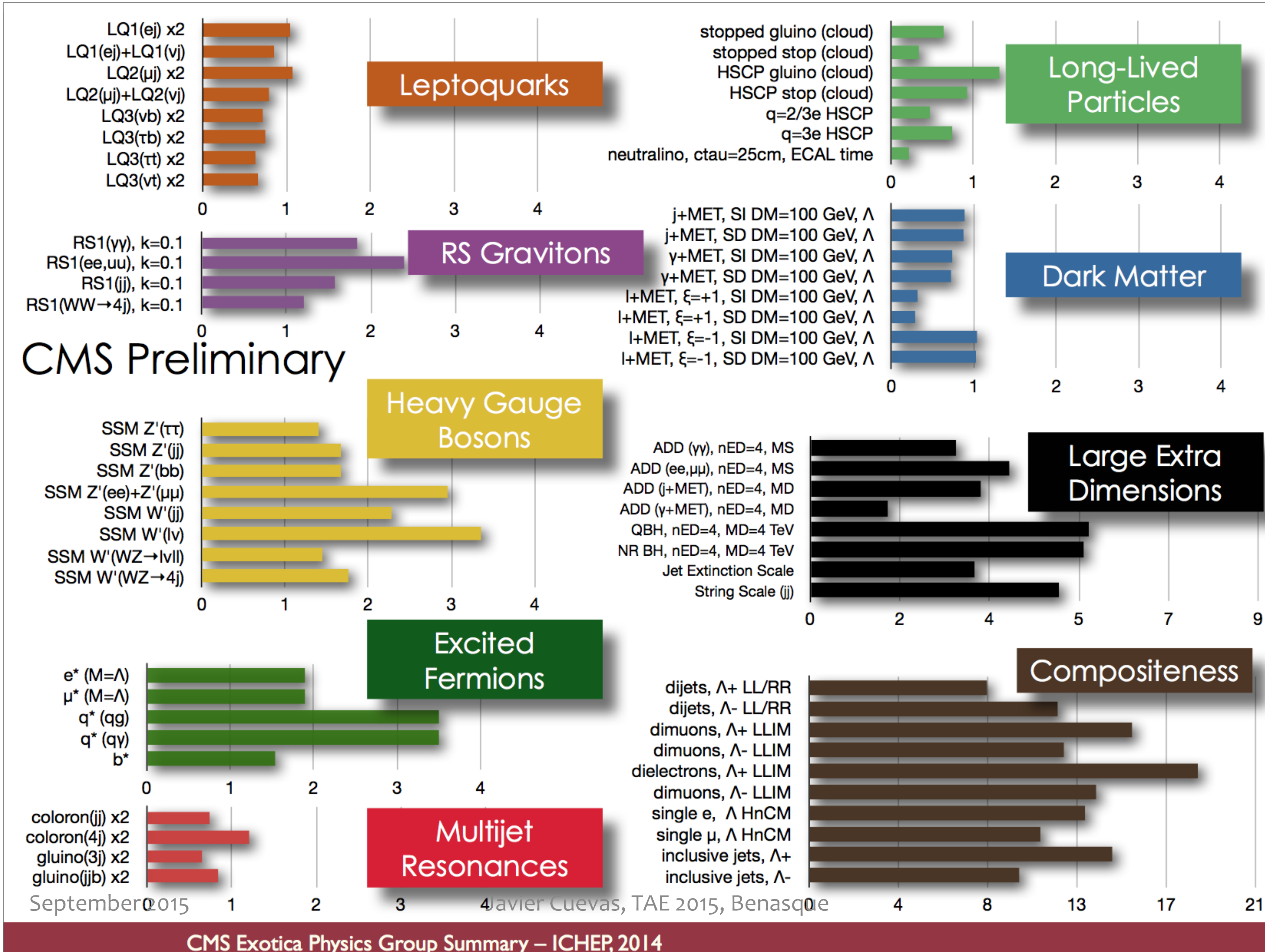






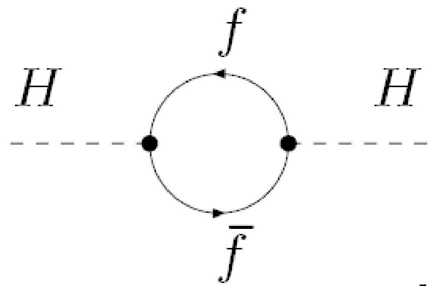
- No significant excess observed yet
- Eagerly await analysis of 13 TeV data

Summary of Exotica Searches



The Hierarchy Problem

- Higgs boson mass receives corrections from fermion loops:



- The size of corrections is ~to the UV cutoff (Λ) squared:

$$\Delta M_H^2 = \frac{\lambda_f^2}{4\pi^2}(\Lambda^2 + M_H^2) + \ldots$$

- In order for the Higgs boson mass to be finite, a fine tuning (cancellation) of various loops is required to a precision ~ $(M_H/\Lambda)^2 \sim 10^{-34}$ for $\Lambda \sim M_{Pl}$
- This is known as a "hierarchy problem" stemming from a large hierarchy between the electroweak symmetry breaking and Planck scales, and it requires new physics at $\Lambda \sim$ 1-10 TeV

Important properties of SUSY

- Elegant solution to the hierarchy problem (i.e., why the Higgs mass is not at the Planck scale)
- Dark matter candidate with the right abundance
- Gauge unification
- predicts a light Higgs $m_h < 130$ GeV
- consistent with EW precision tests

Searches for BSM Physics

- First Searches at the LHC (2010-2012)
  - Supersymmetry with MET plus jets, lepton(s), photons
  - Extra Dimensions and black holes, heavy resonances (in electrons, muons, taus, jets), leptoquarks, excited leptons and quarks, 4th generation, a few very exotic signatures (R-hadrons)…

- Evolved Searches (2013-…)
  - Supersymmetry on third generation squarks, compressed spectra, stealth SUSY, EWKinos, VBF processes…
  - Higgs in decays or as study object, vector-like quarks, boosted objects, long lived particles, fractional charges…
  - More dedicated Dark Matter searches!

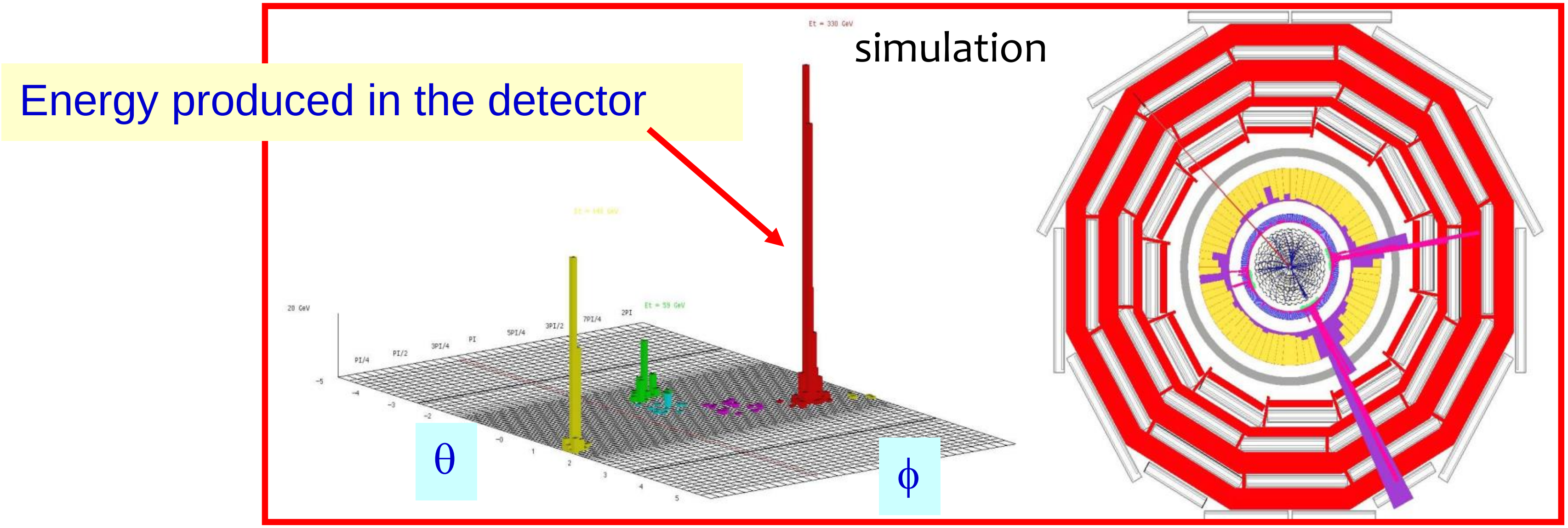
- We are now facing a restart of the machine at 13/14 TeV…

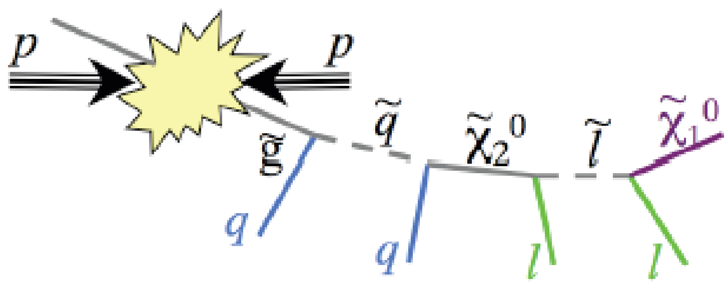
  Back to the basics or do we change paradigm?

MSSM and cMSSM

- SUSY is a renormalizable and calculable theory and has been thoroughly studied theoretically over the last four decades
- MSSM has just two Higgs doublets; nevertheless the number of parameters describing the model is still very large: 124
  - 18 are the SM ones + Higgs boson mass (now known!)
  - 105 genuinely new parameters:
    - 5 real parameters and 3 CP-violating phases in gaugino sector
    - 21 squark/slepton masses and 36 mixing angle
    - 40 CP-violating phases in the sfermion sector
- This makes it very challenging to search for generic SUSY, and simplifying assumptions are typically made
- One of these simplifications is constrained MSSM, or cMSSM, which assumes gaugino unification and degenerate squark/slepton masses at high energy (typical of gravity-mediated SUSY breaking)
- That results in just five parameters fixing all the SUSY interactions: common scalar and fermion masses ***M0***, ***M1/2***, ratio of the vacuum expectations of the two Higgs doublets ***tanβ***, sign of Higgsino mass term ***sign(μ)***, and trilinear coupling ***A0***

Detecting Supersymmetric Particles



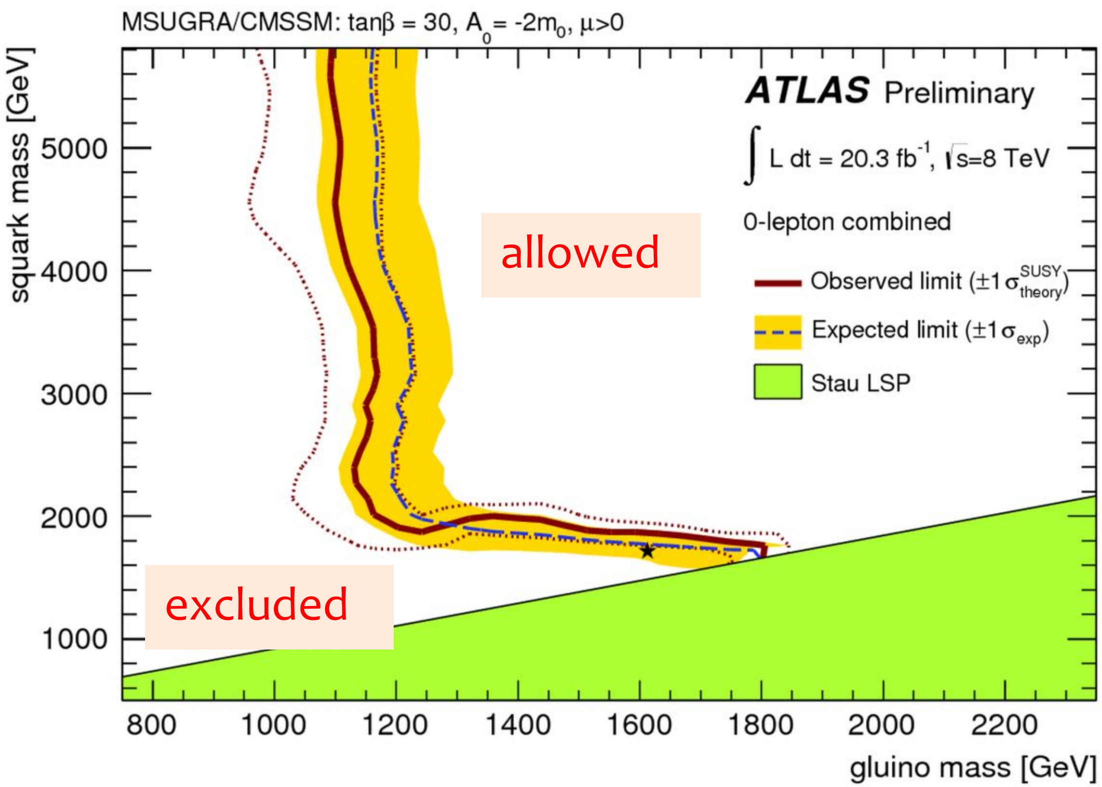


Super-symmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping ‘dark matter’ particle candidates

Very prominent signatures in CMS and ATLAS

SUSY Searches: No signal yet to date

Status in 2013



- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- Searches will continue for the higher energy in 2015

Plenty of searches ongoing: with jets, leptons, photons, W/Z, top, Higgs, with and without large missing transverse energy

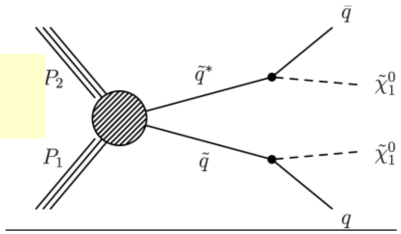
Also special searches for contrived model regions

CMS SUS-11-015

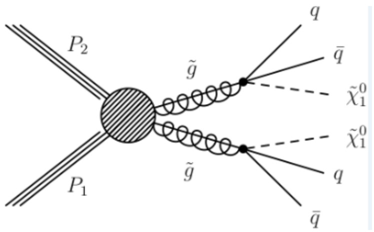
Limits on Squarks and Gluinos

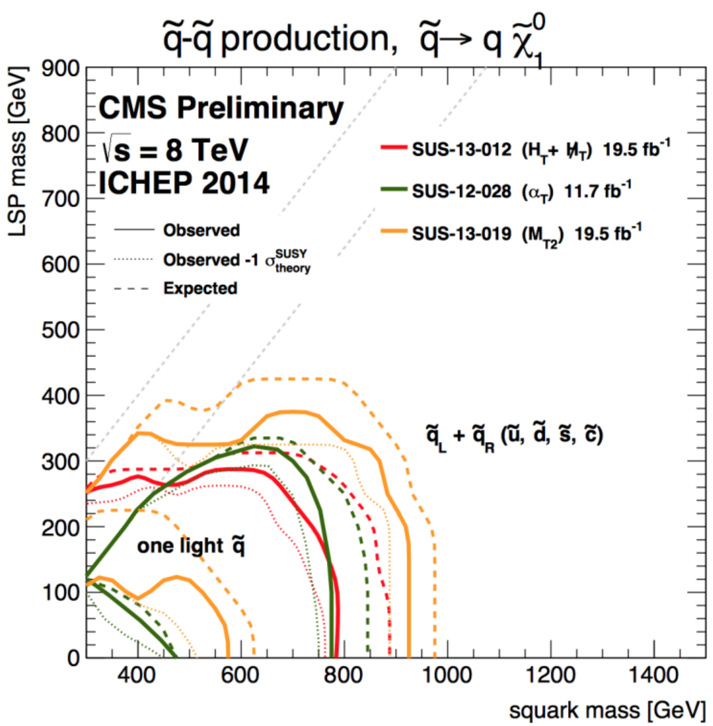
Results depend on the topologies studies, assumed mass of the LSP etc.

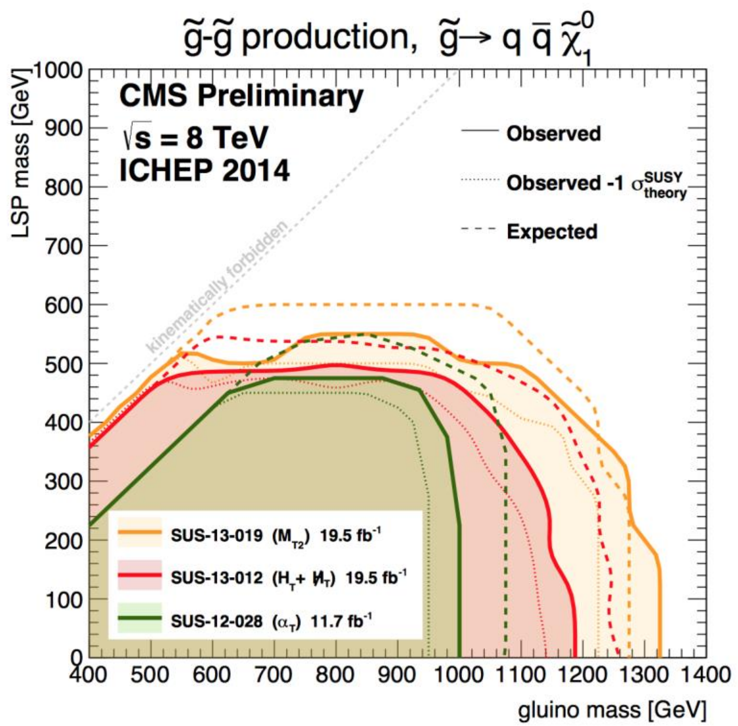
Examples



Popular presentation of data:
Simplified ModelS (SMS)







Combined limits typically > 1-1.3 TeV on sparticle masses

What is really needed from SUSY?

End 2011: Revision!

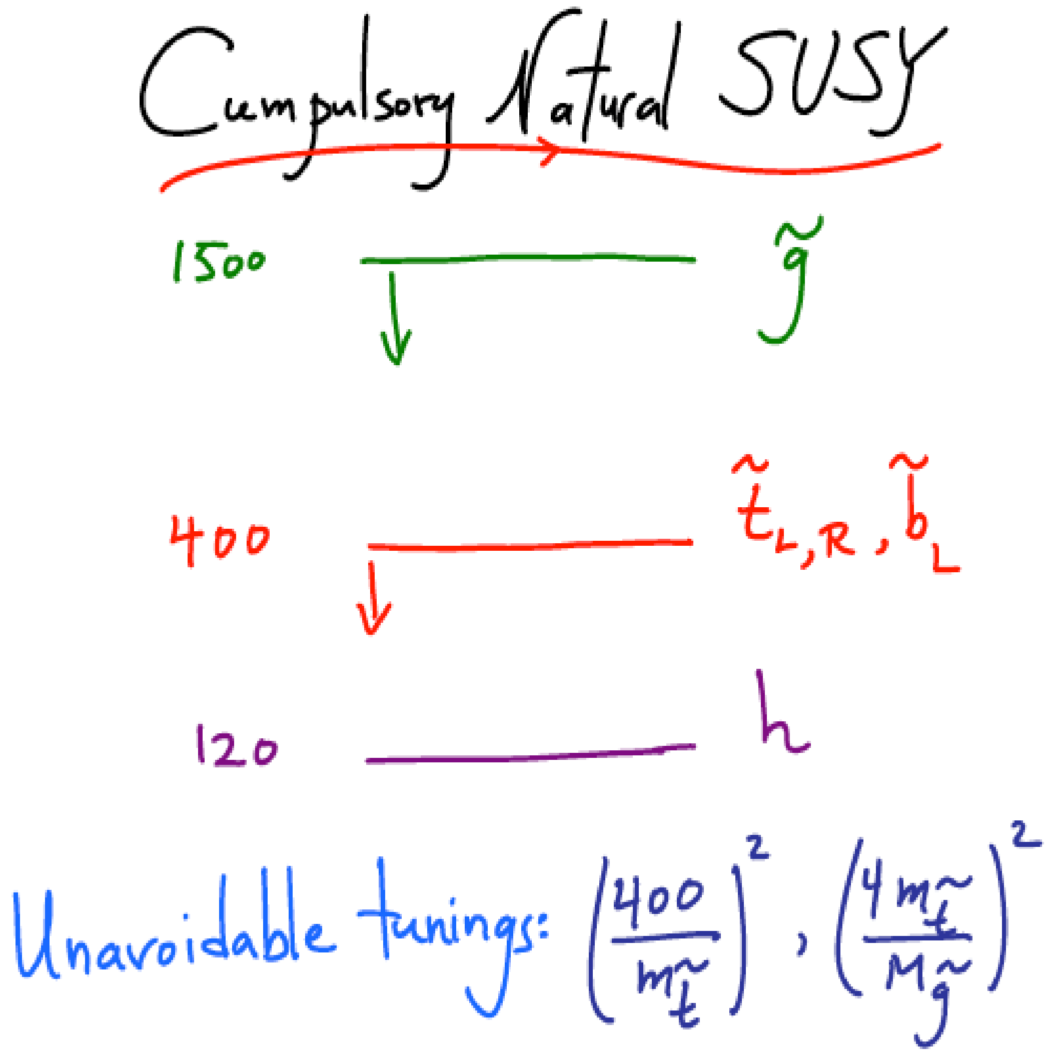
N. Arkani-Ahmed
CERN Nov 2011

Papucci, Ruderman,
Weiler arXiv:1110.6926

LHC data end 2011
Stops > 200-300 GeV
Gluino > 600-800 GeV

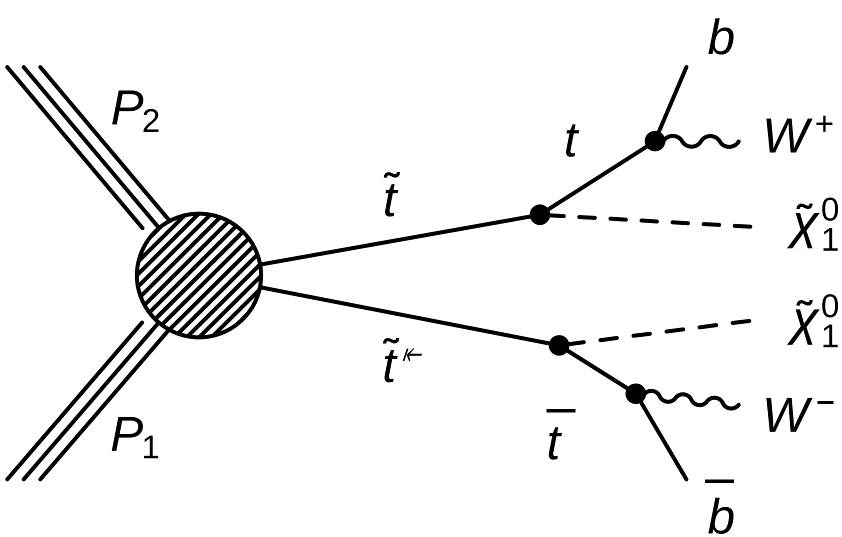
Moving away from constrained SUSY models to ‘natural’ models

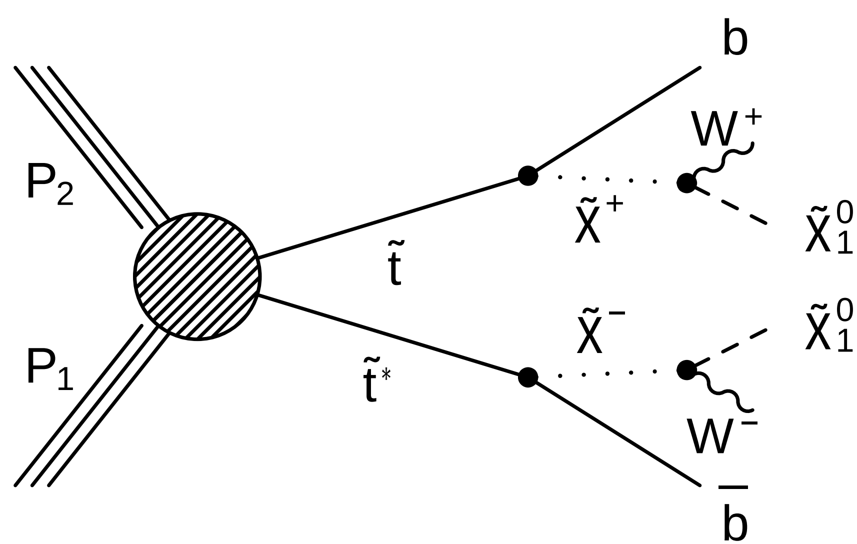
Natural SUSY survived LHC so far, but we are getting close to push it to its limits!



Stop Searches

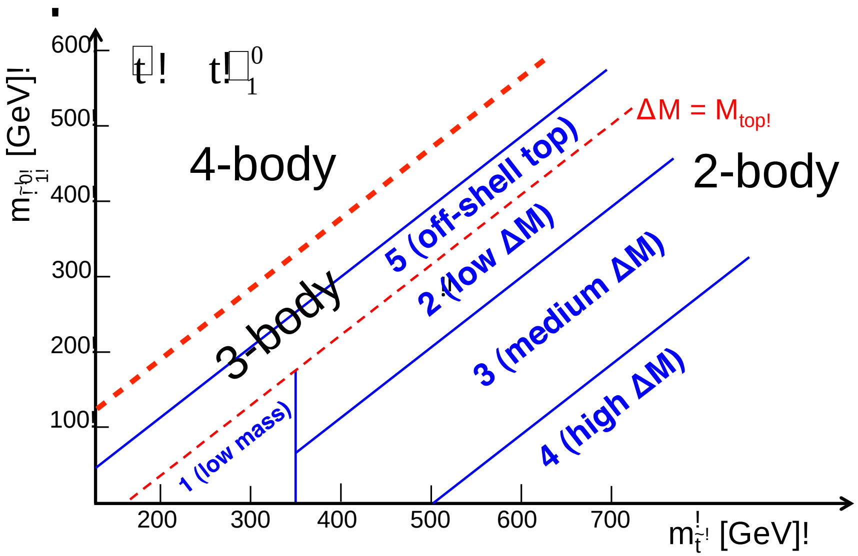
- **Stop is special for "naturalness" → directly cancels the top loop**
- **Search depends on stop mass and decay channels – broad program…**
- Focus on just two Feynman diagrams representing relevant production and decay: **t → t+χ and t → b+χ**
  - Both result in the same signature: **bbW$^+$W$^-$+MET**
  - This is the same signature as **tt production** (unless both W's decay hadronically) - gives you an idea of the dominant background

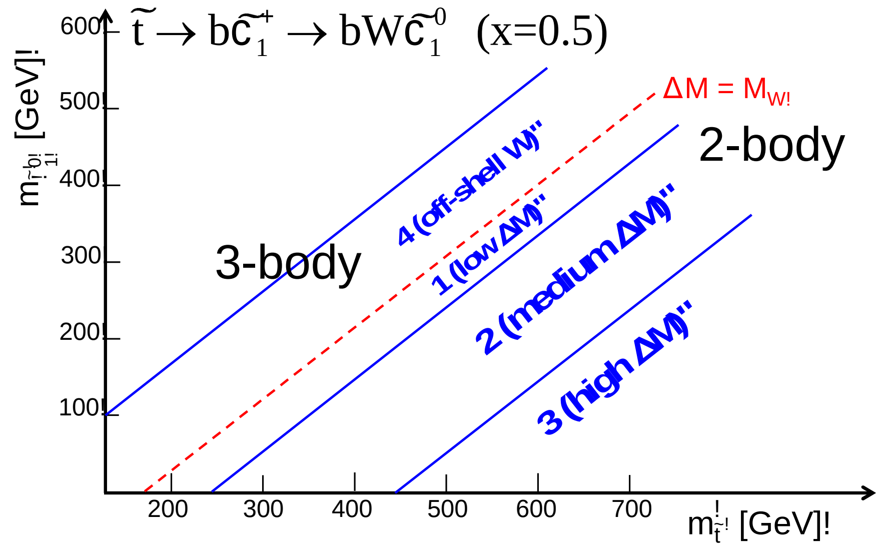




Stop Searches

- Depending on the mass differences between the stop and neutralino (chargino), several kinematic regions are defined:





- Different regions correspond to different challenges, so search strategy generally depends on the region
- Given that 4-body decays are enormously suppressed kinematically, the region ΔM < M_W in the tχ0 mode is usually covered by other channels, e.g. FCNC t →cχ decay

Stop searches: what's the best final state to pursue the search

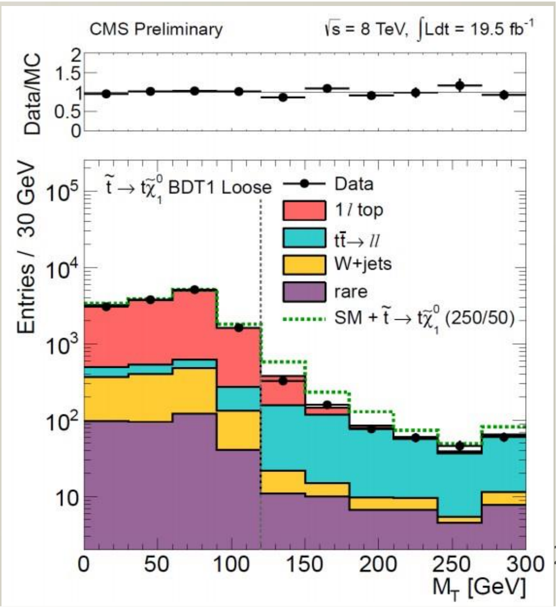
- The final state depends on the W boson decay channels
  - All hadronic channel has the highest branching fraction, but backgrounds are huge
  - Dilepton channel is clean but the branching fraction is tiny
  - Tau channels are tough
- **Single-lepton (e+jets,μ+jets) channels as a compromise between BR (30%) and purity**
- Standard variable when dealing with MET: MT
- MT2 or stransverse mass (Lesters & Summers, hep-ph/9906349):

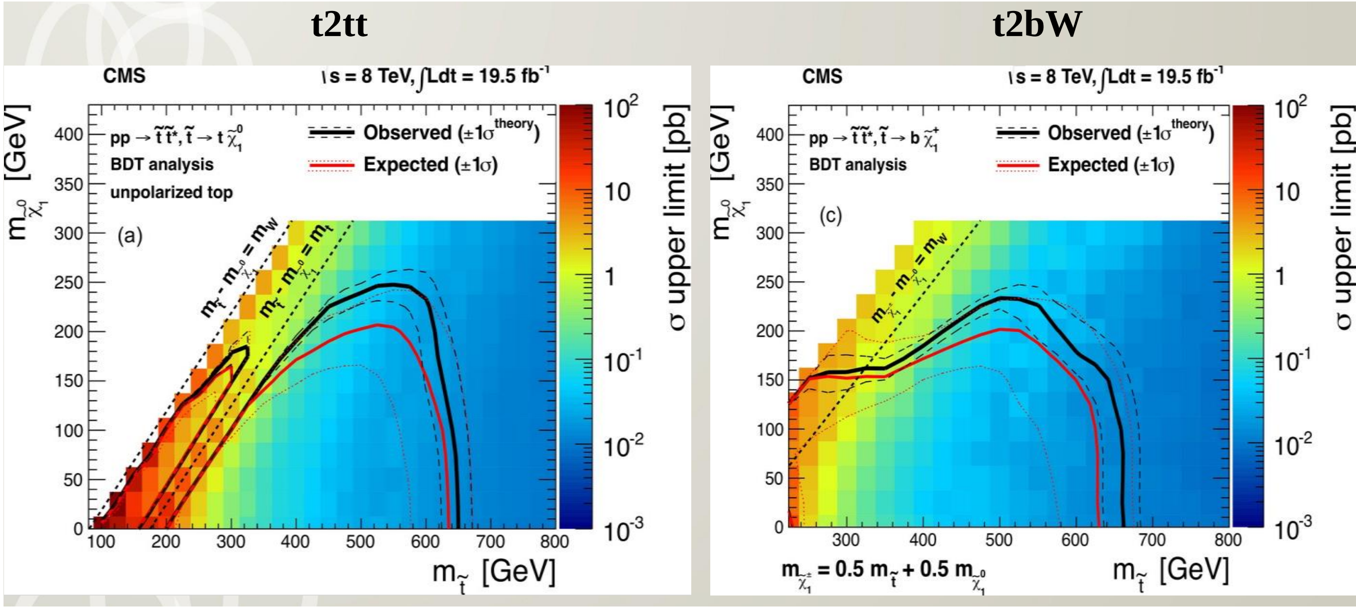
$$M_T = \sqrt{2 p_T \not{E}_T (1 - \cos\Delta\varphi)}$$

$$M_{T2} = \min_{p_T^{1} + p_T^{2} = \not{p}_T} \left[\max\left(m_T^{(1)}, m_T^{(2)} \right) \right]$$

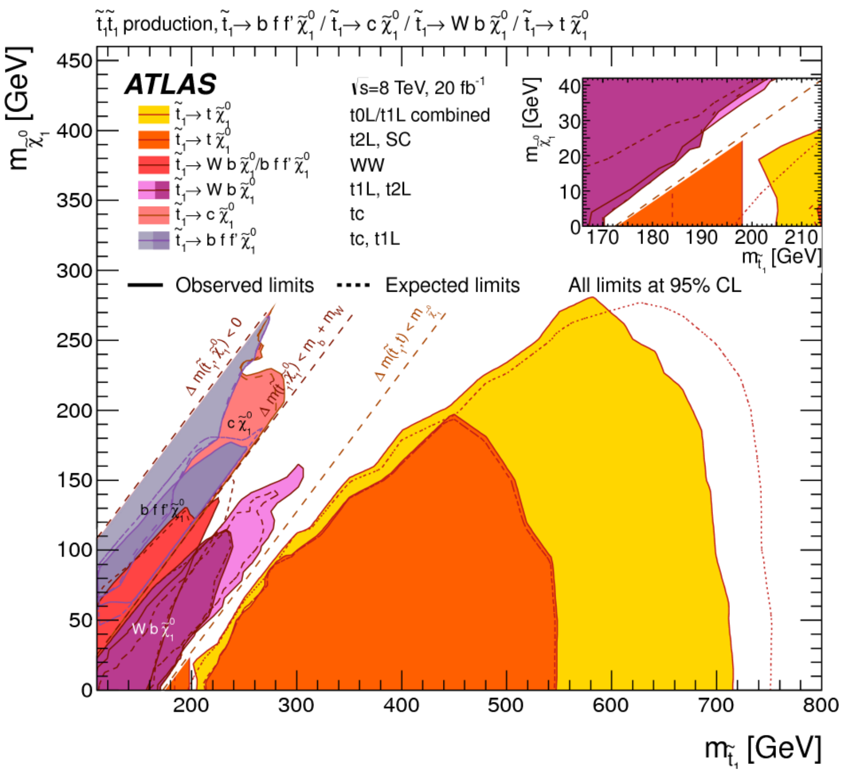
Final optimization

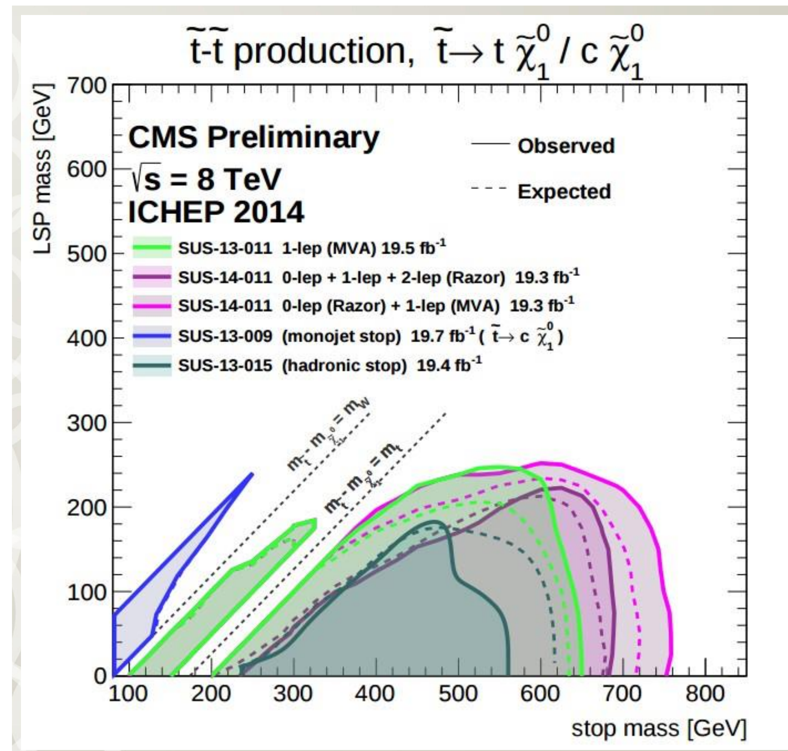
- Cut-based approach, variables are treated independently putting a cutoff in each of them.
- Multivariate: all variables are combined in a likelihood, BDT or ANN reflecting how signal-like they are.
- Select events with MT > 120 GeV
- Several signal regions defined with a cut-based or MVA approach (~ 40 % improvement)





stop: Combination of channels:

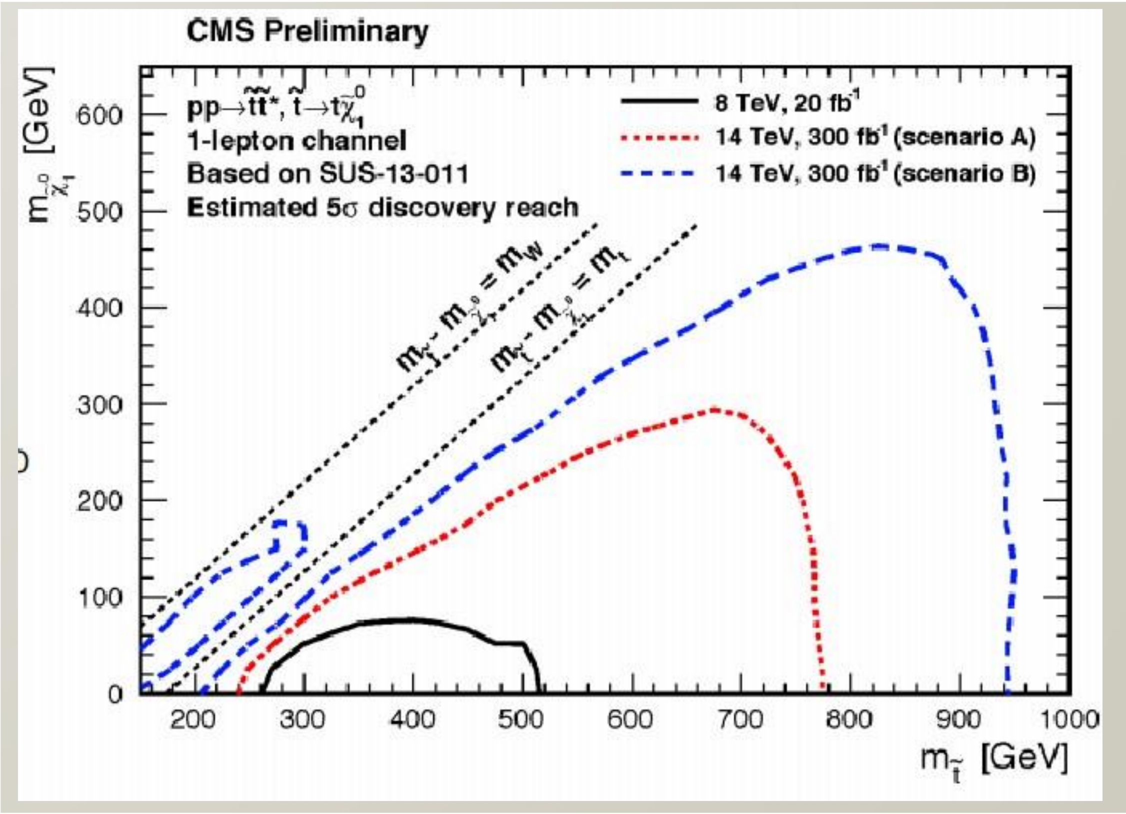




Start to filling holes with new ideas:
indirect search (from tt cross-section)

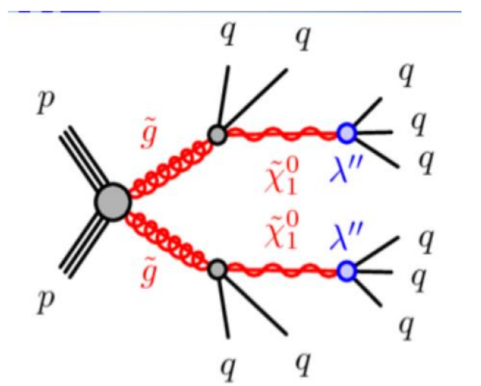
Prospects for run 2

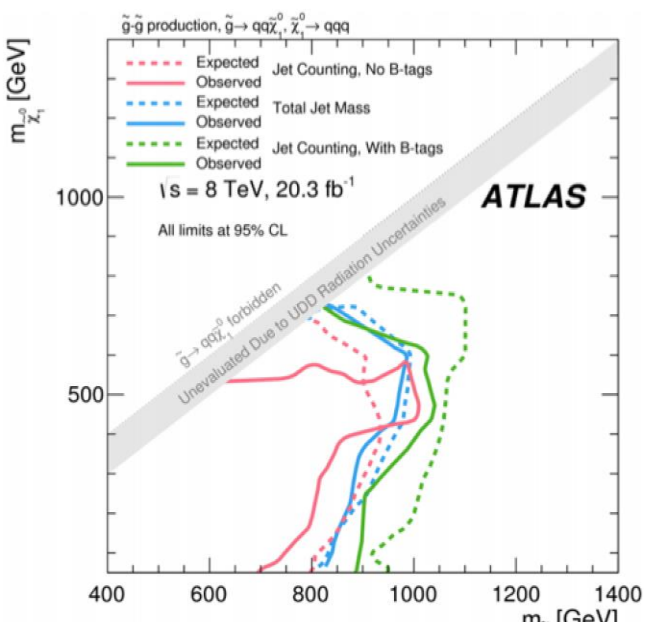
- **Discovery reach in stop mass will reach to 800 GeV in a conservative scenario**
- **Crucial region for testing naturalness and whether SUSY has a role in Electroweak symmetry breaking**
- Naturalness prefers m_{stop} lighter than 700 GeV
- Higgs mass of ~125 GeV prefers m_{stop} heavier than 300 GeV



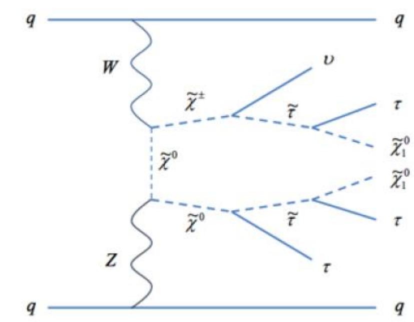
Recent New Directions

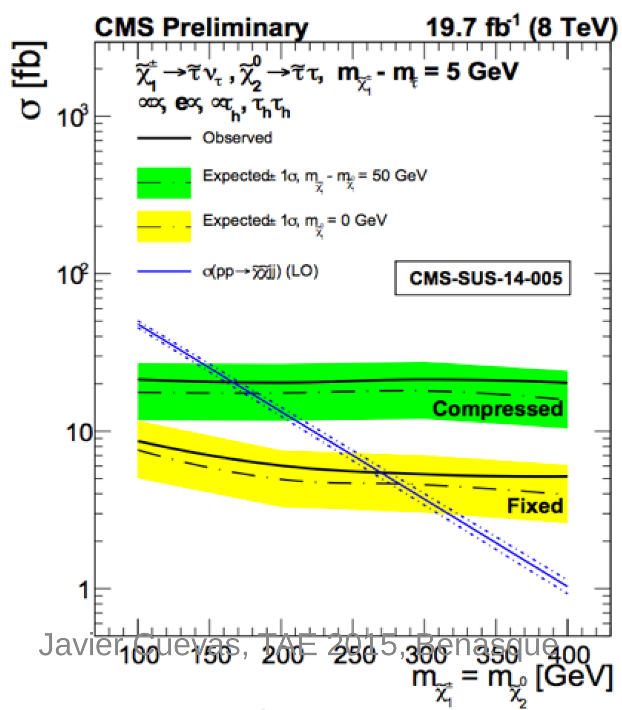
Multi-jet (≥6), no MET



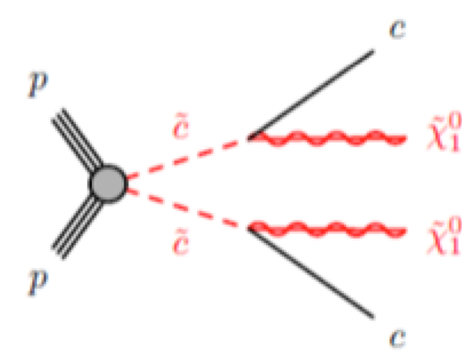


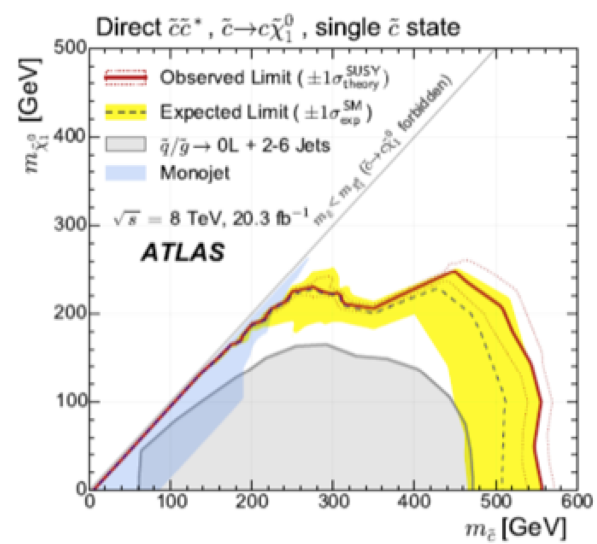
VBF EWKino production





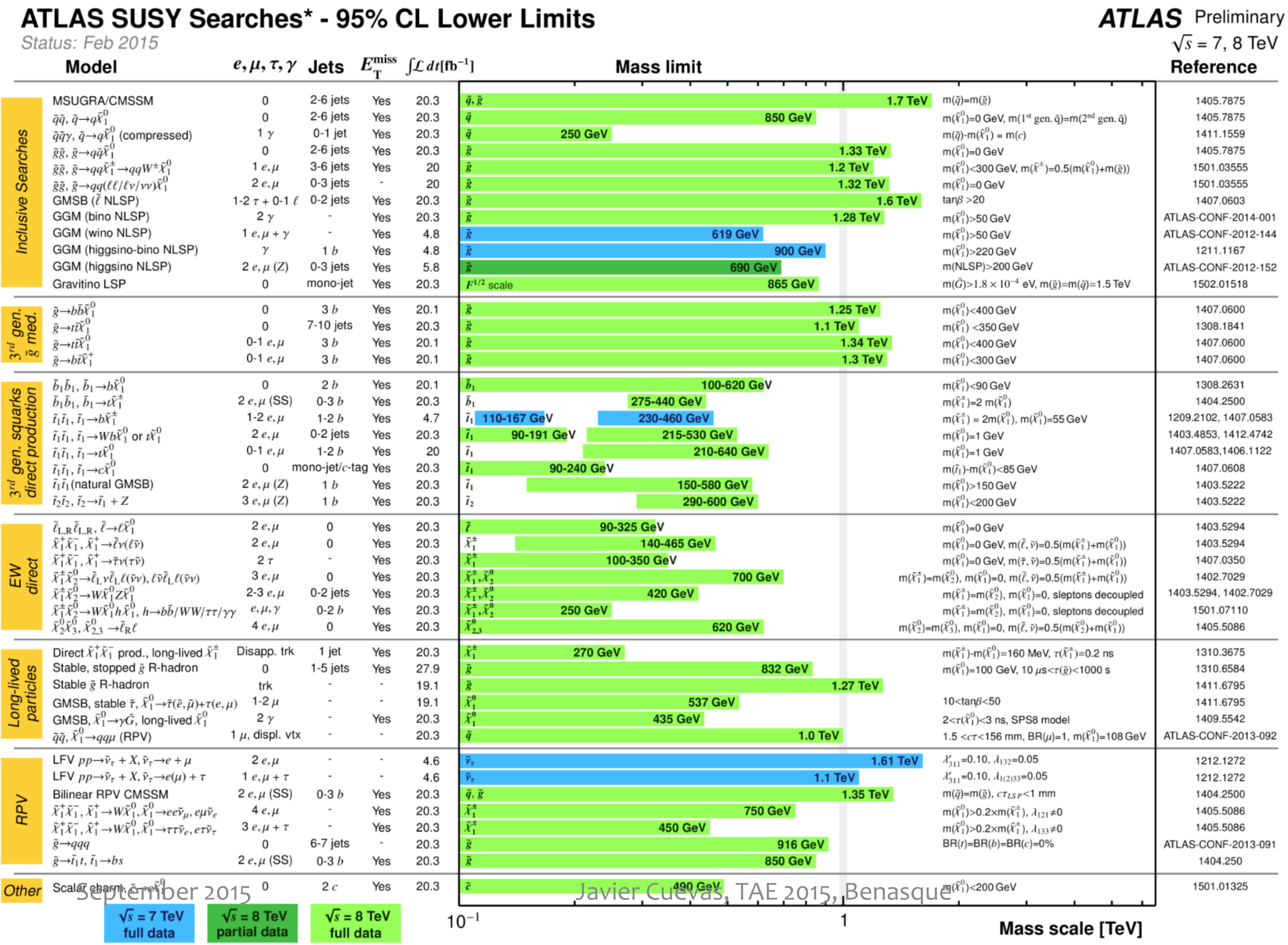
Scalar charm quark





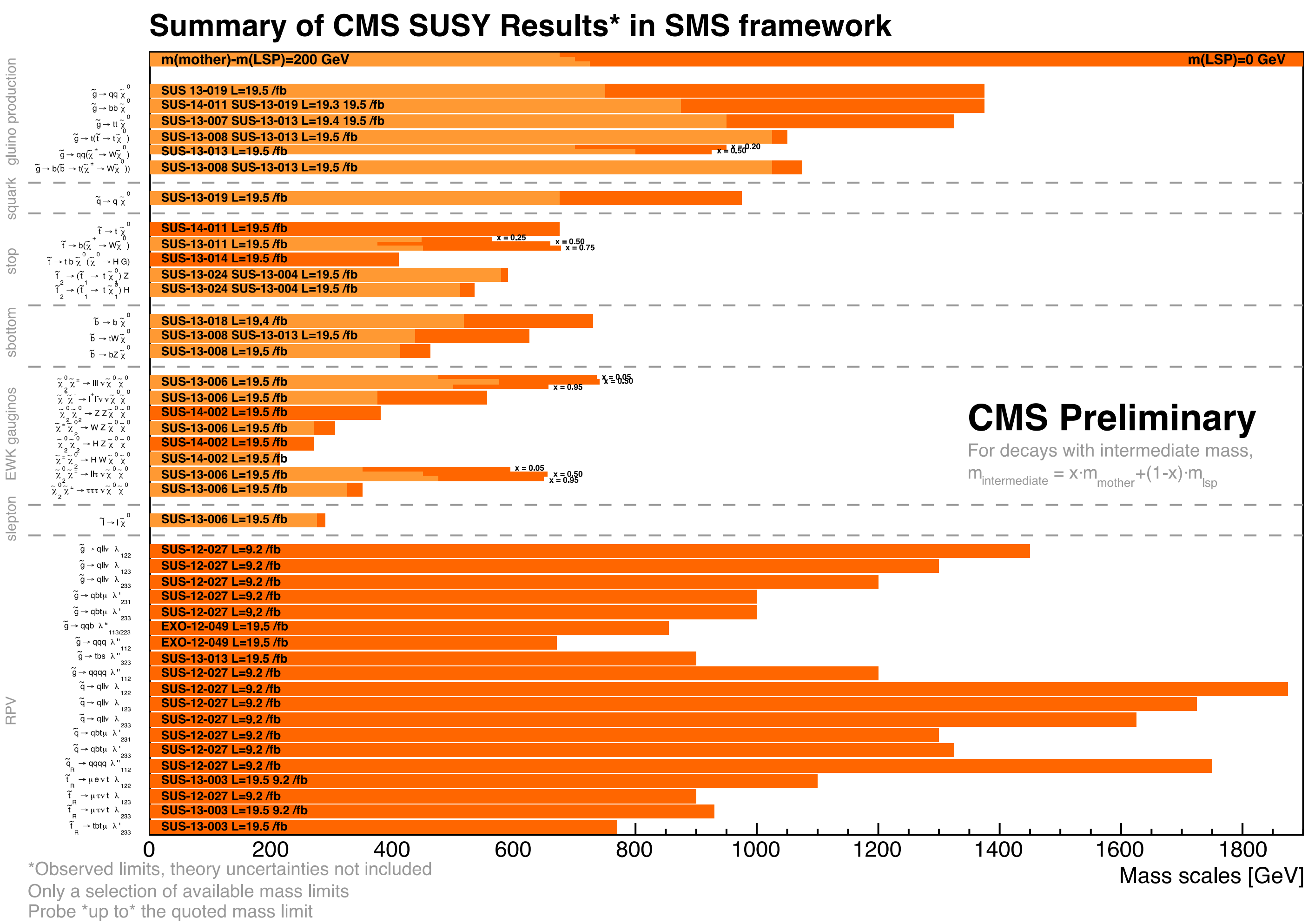
Summary of SUSY Searches (ATLAS)

In short: no sign of SUSY with the data collected so far



Summary of SUSY Searches (CMS)

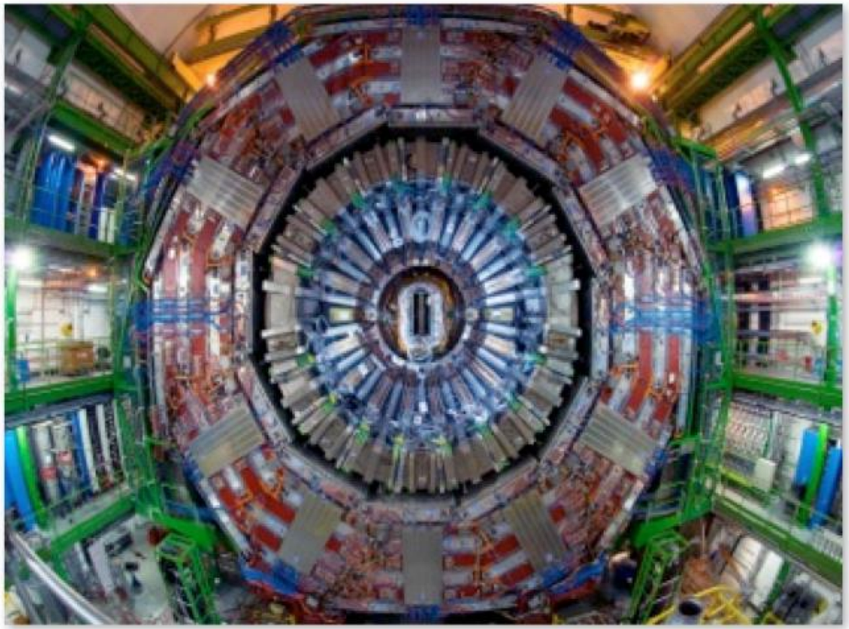
In short: no sign of SUSY with the data collected so far



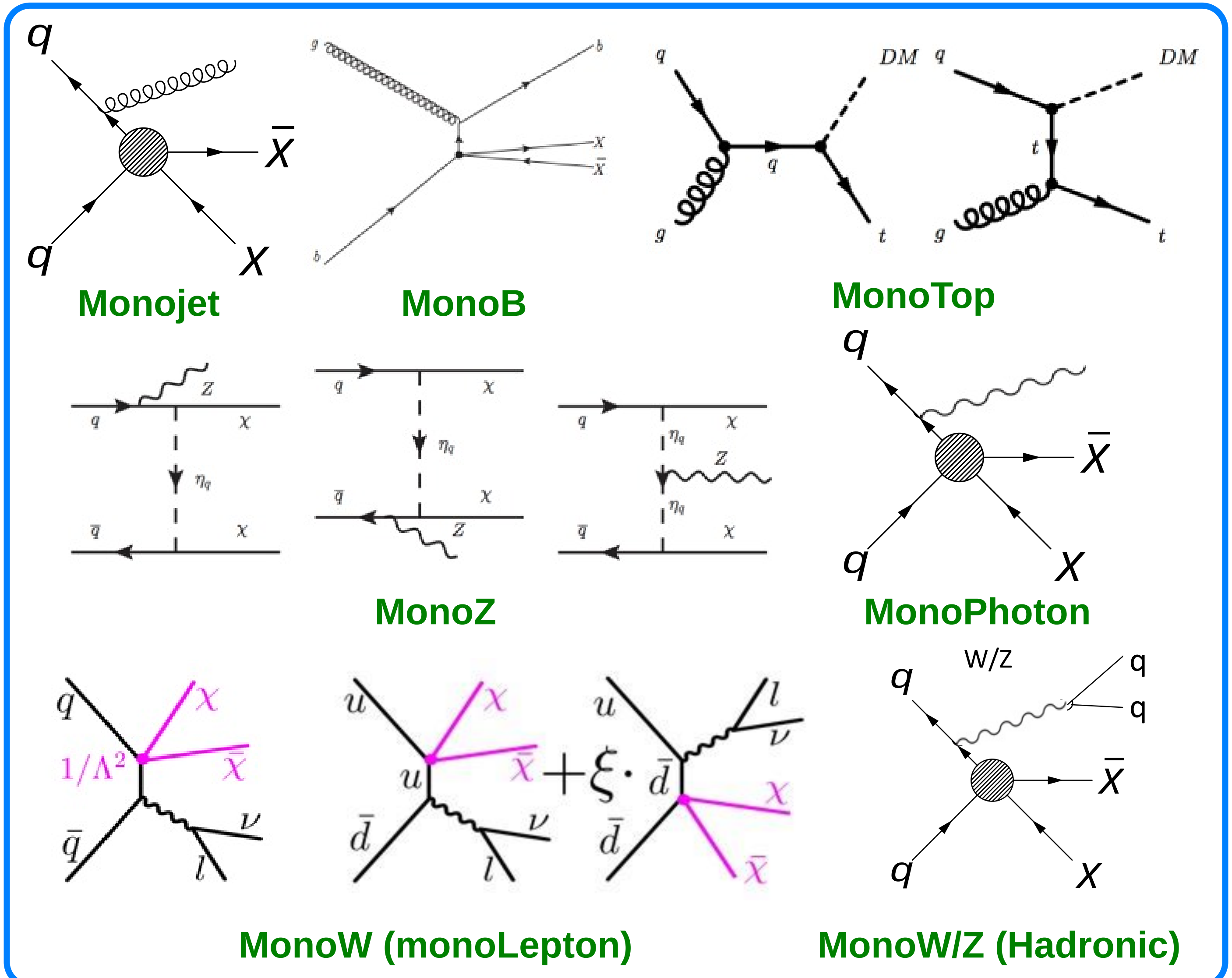
Dark Matter: Complementary Searches?

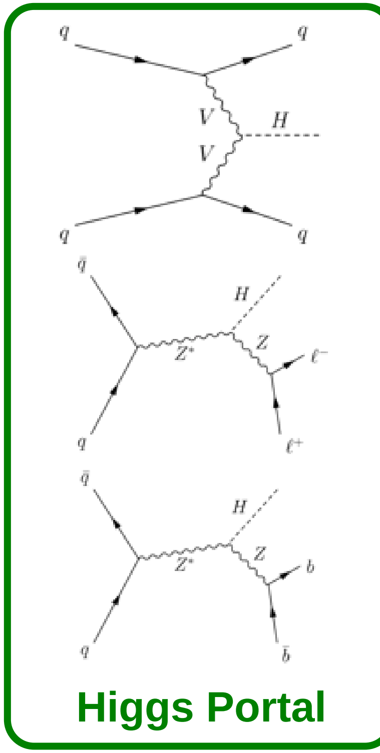
After the discovery of the Higgs particle @ the LHC:
Dark matter is the next important physics problems to tackle for the LHC

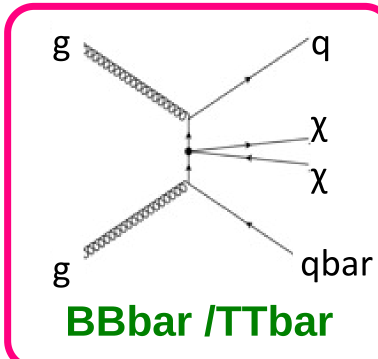
The search is complementary to other experimental techniques used.



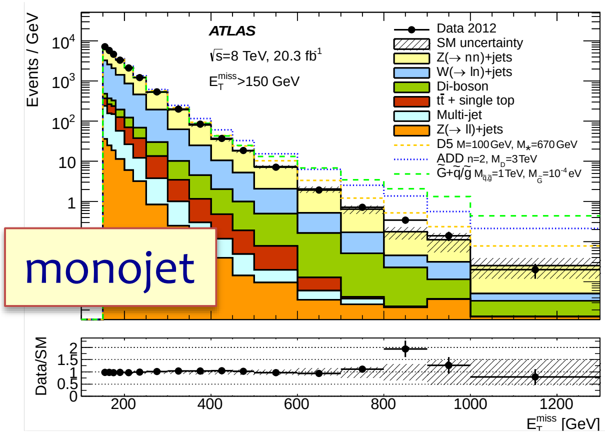
Mono-X signatures

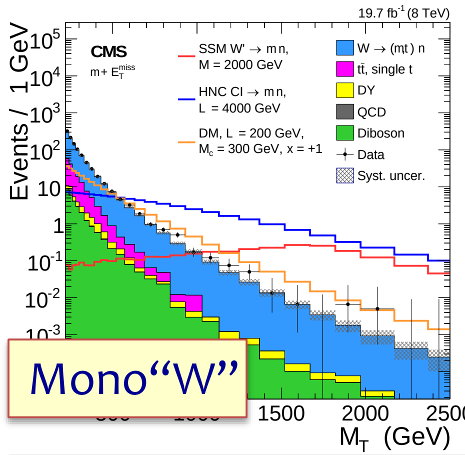


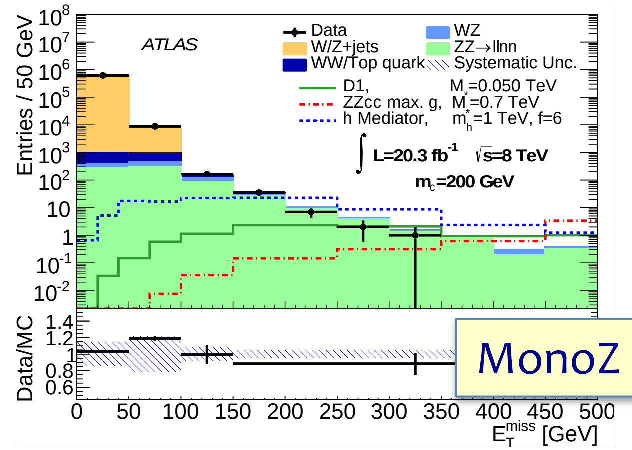


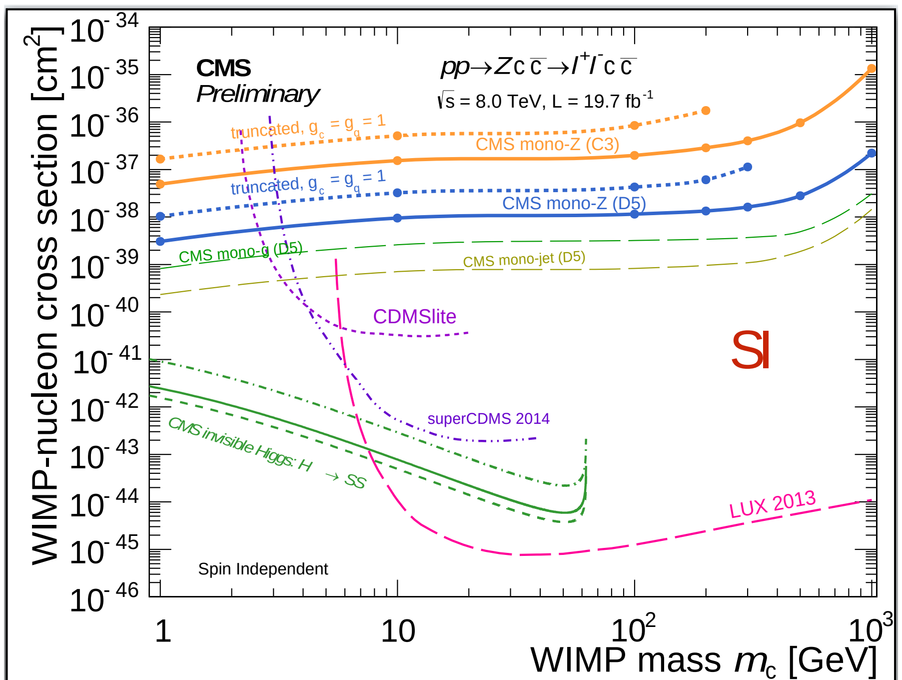


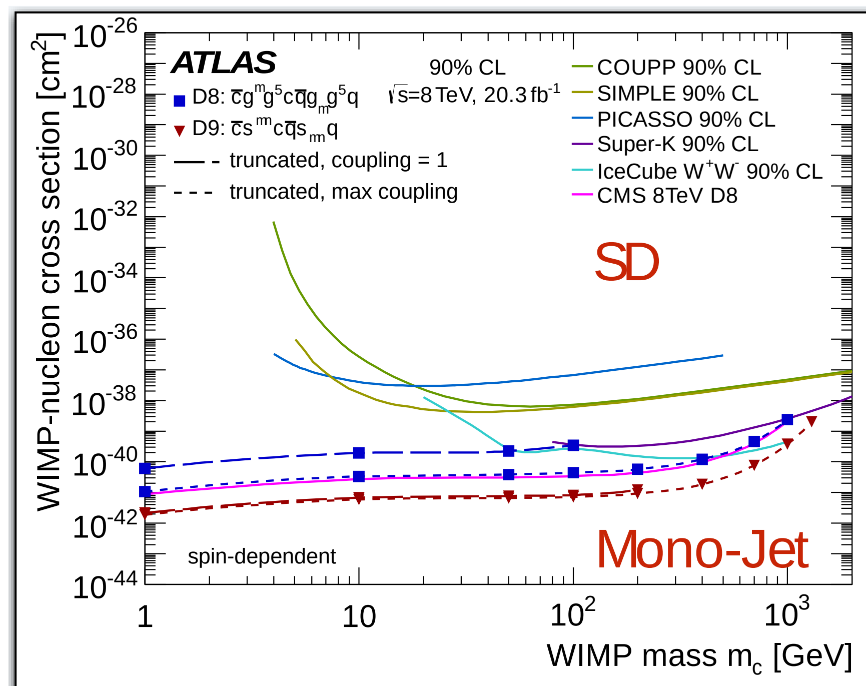
No signal → limits on “traditional”



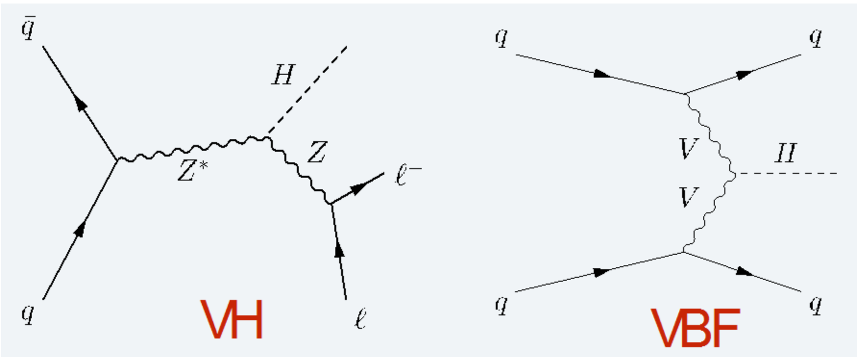


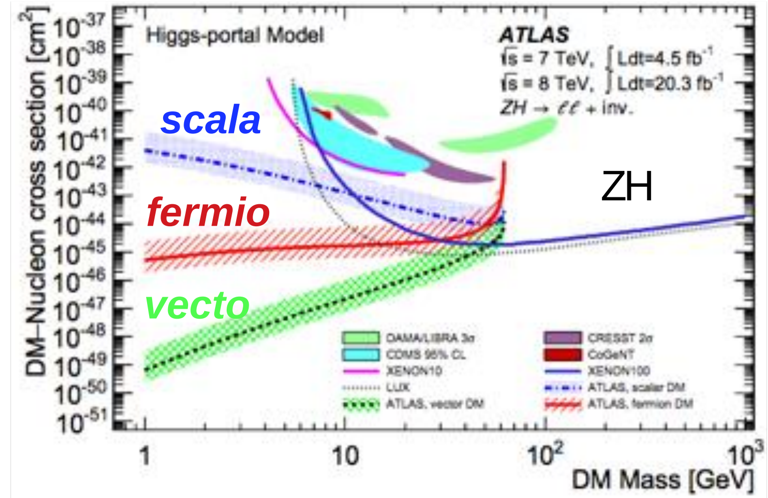






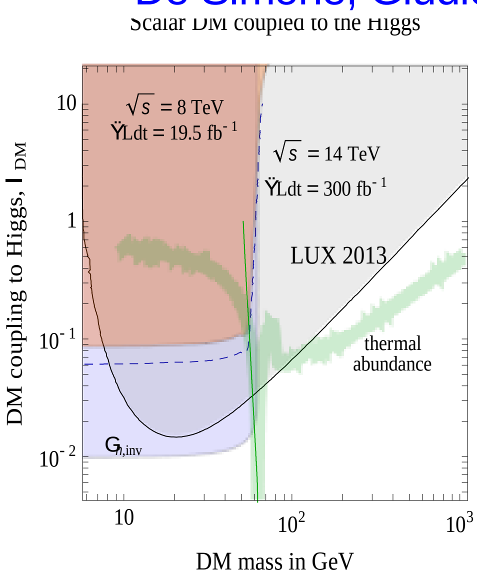
Does the Higgs "see" DM?

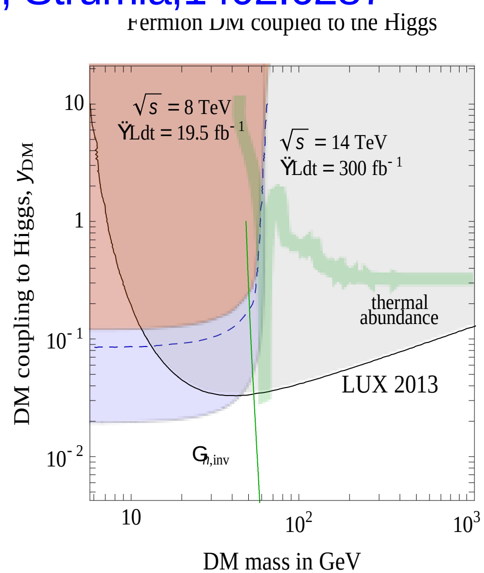




- IFF Higgs is the mediator…

De Simone, Giudice, Strumia,1402.6287





Then DM cannot be too light

Moreover, future searches (direct) will remove the $M_H/2$ strip

The LHC Run 2 has started

… but not without challenges!

- ULOs, UFOs, DUFOs, MUFOs, QPS, TDIs, Earth faults
- Main issue (25 ns): electron-cloud

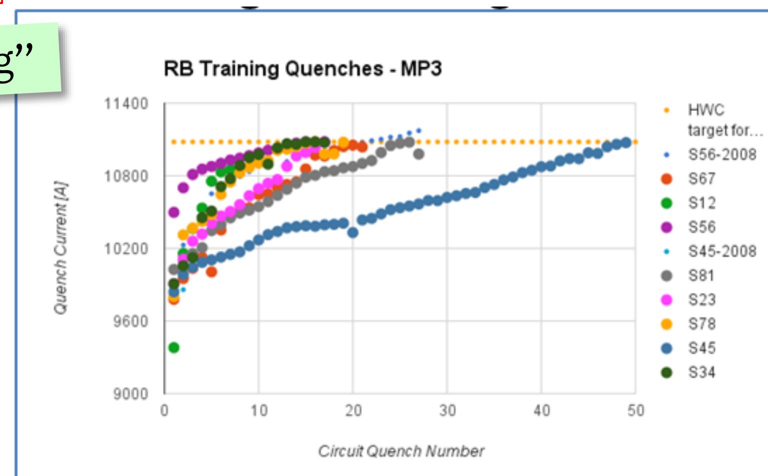
Painful for 2015 – a commissioning year – but these shouldn't be long term issues for Run 2

"lot's of things can go wrong"

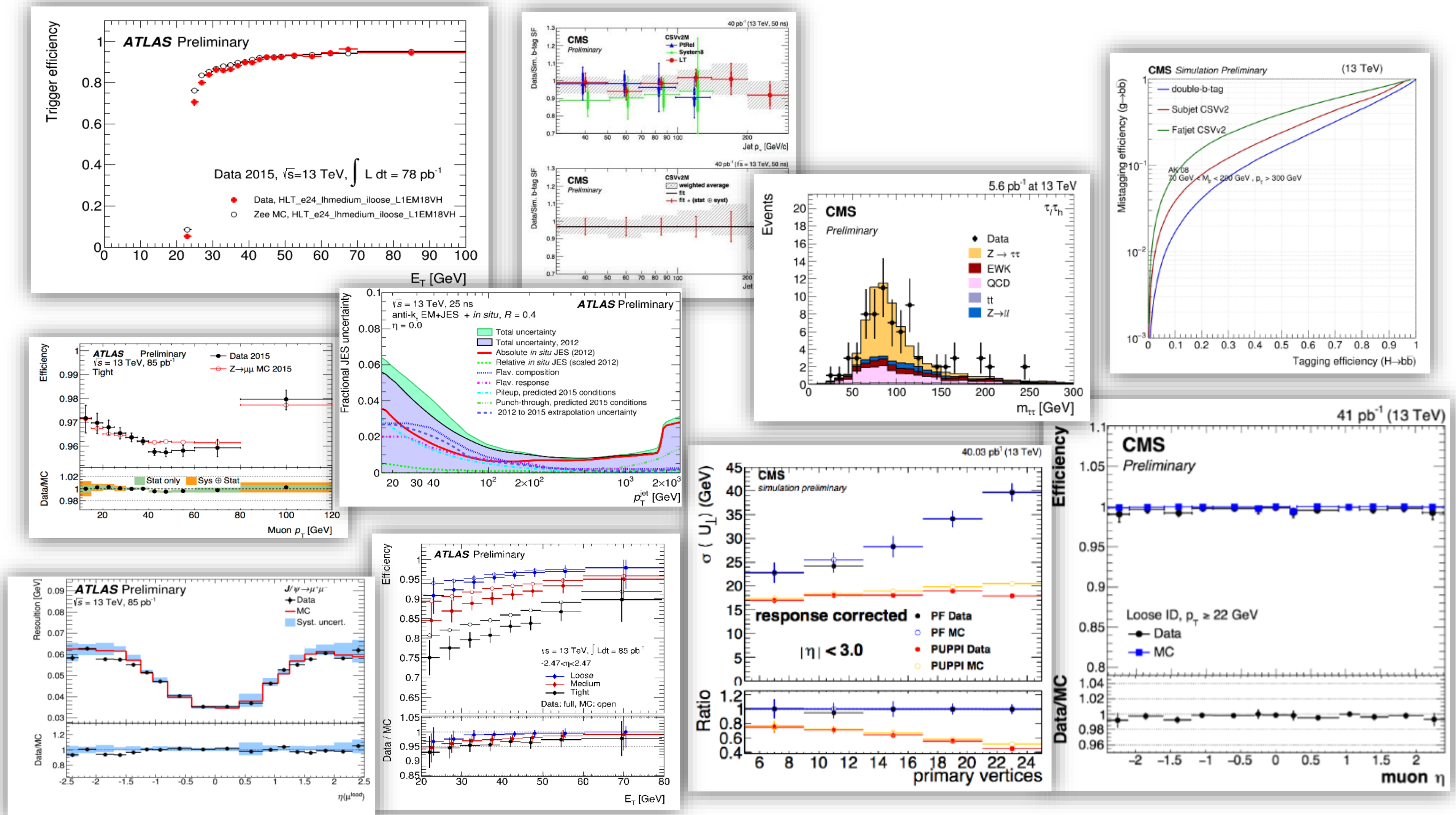
"it is a miracle that this is working at all"

- Still 13 TeV data has [illegible] to arrive
- Big thanks to our LHC colleagues!

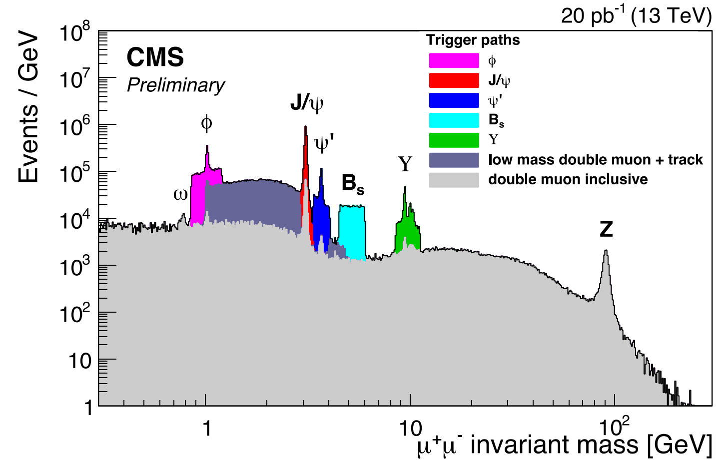
>> Respect! <<



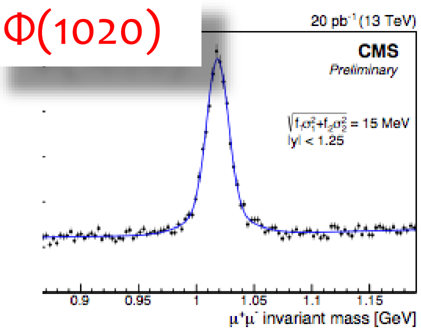
Performance Jets, (double) b-tag, lepton ID…

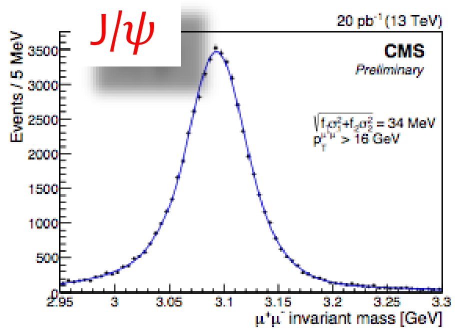


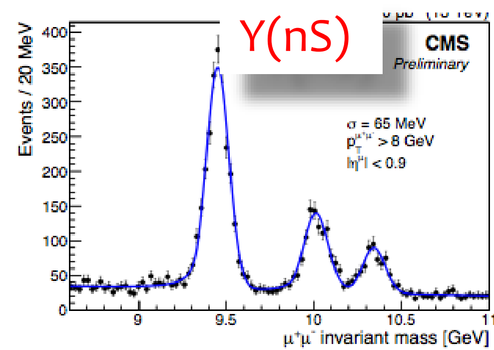
Run2 performance: Di-muon spectroscopy

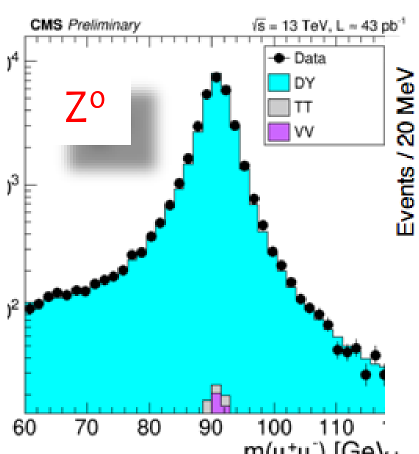


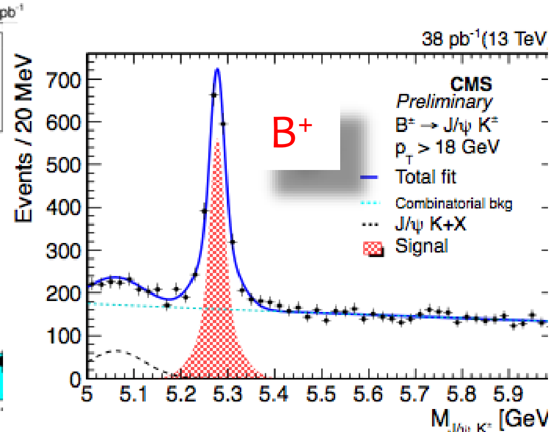
Maintaining a CMS Hallmark: trigger flexibiltity

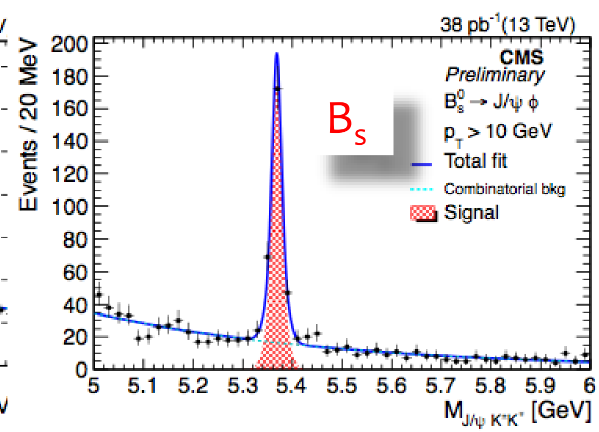








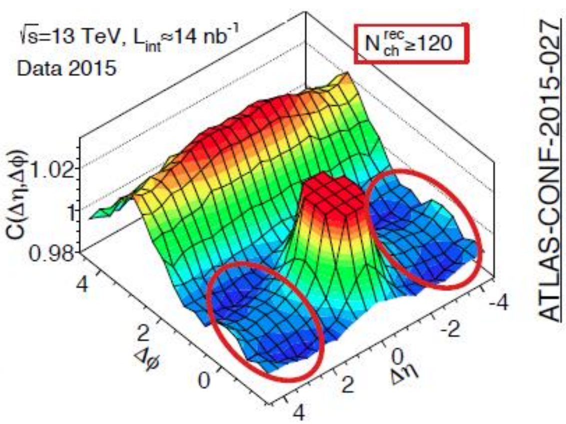




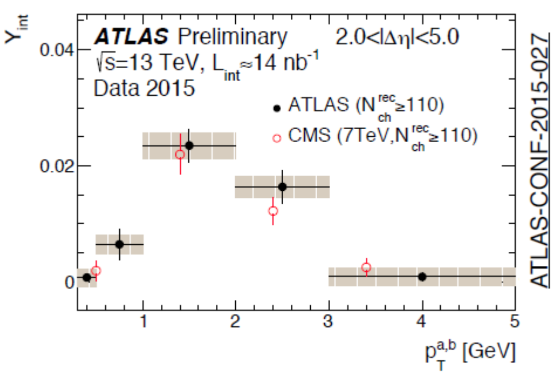
13 TeV SM measurements

Impressive to see these very nice results so early !!

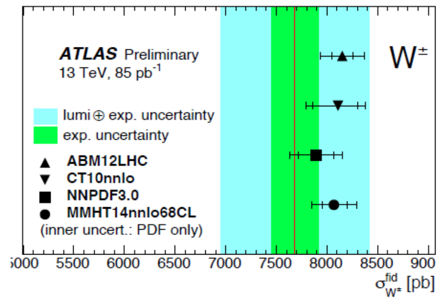
The "CMS Ridge" in ATLAS:

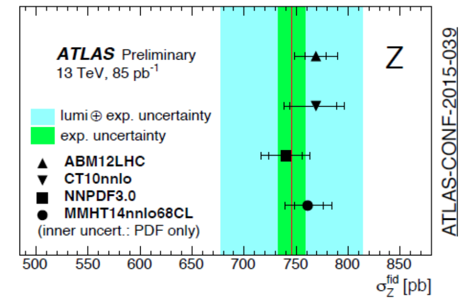


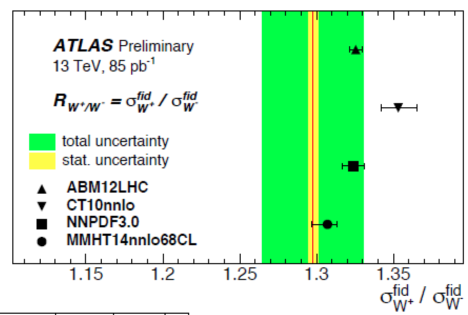
→ Same behavior as at 7 TeV ?

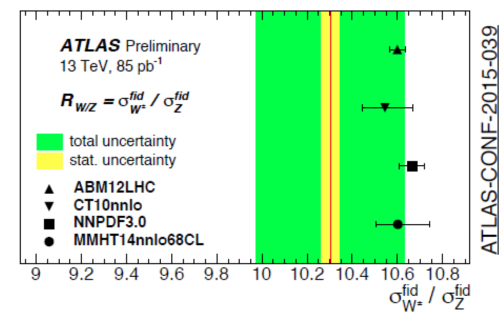


1 million Ws and 100k Z --> rates and ratios:

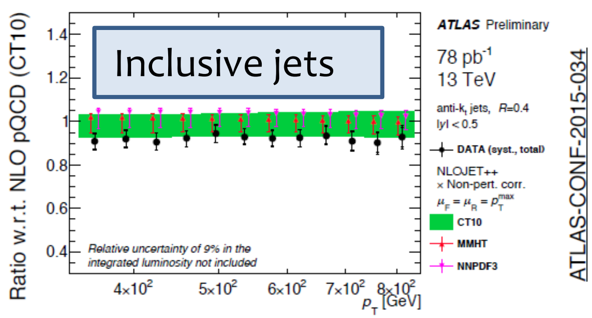




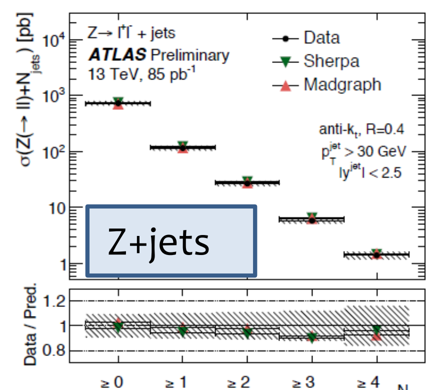




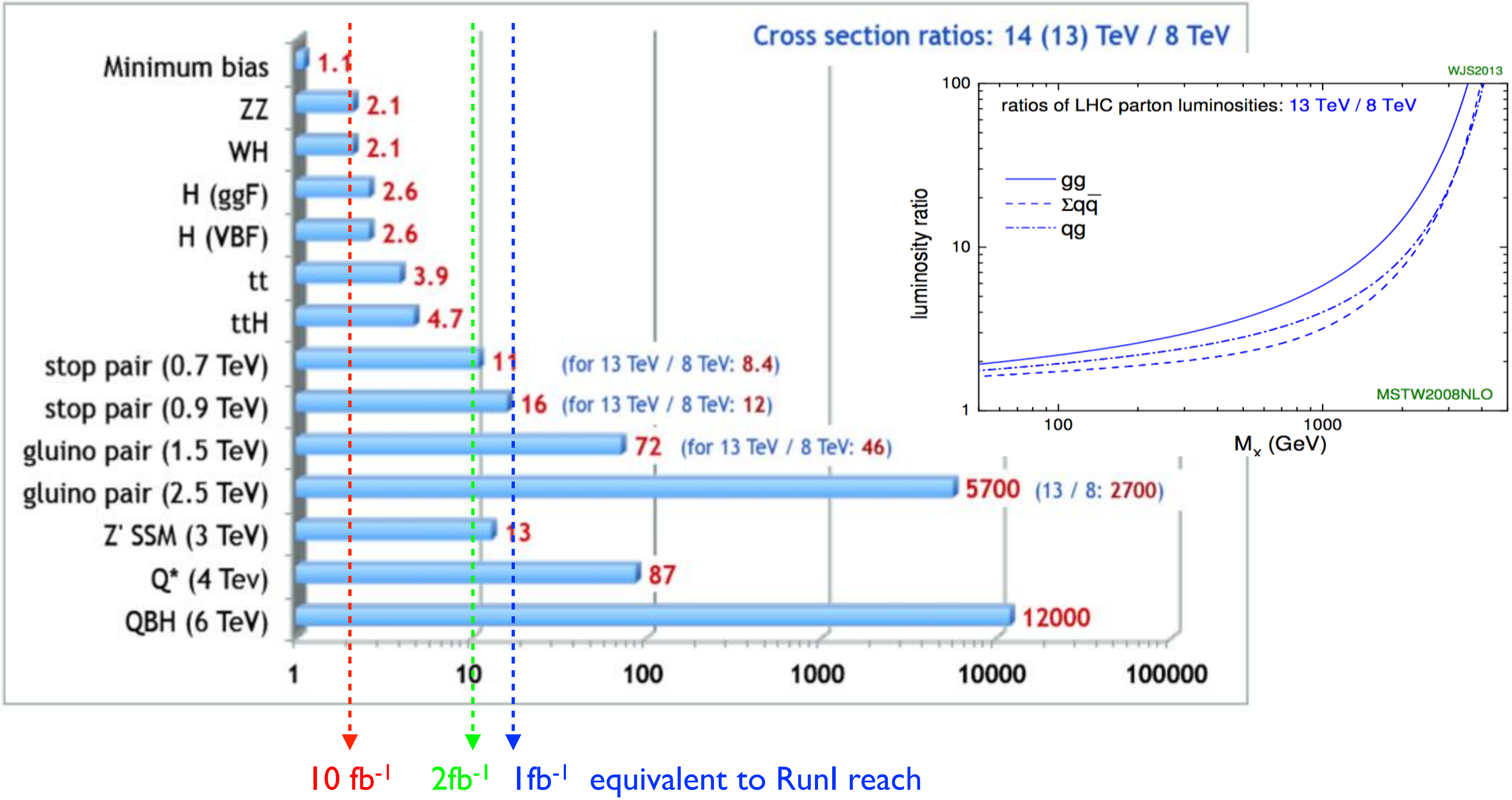
Inclusive jets



Z+jets



Run 2 perspectives



Exponential increase of parton luminosities respect to Run1

Run1 limits surpassed after few fb^{-1} of luminosity collected at Run2

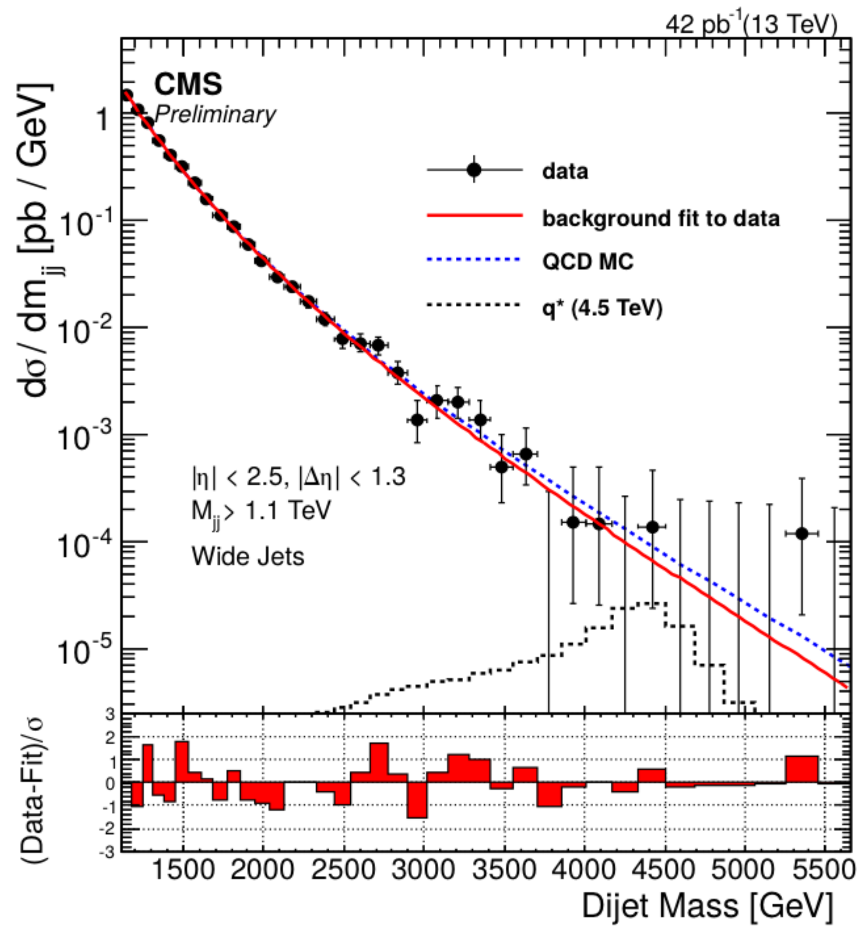
High mass searches immediately interesting

- Data is fit with a 3 parameter function inspired by QCD:

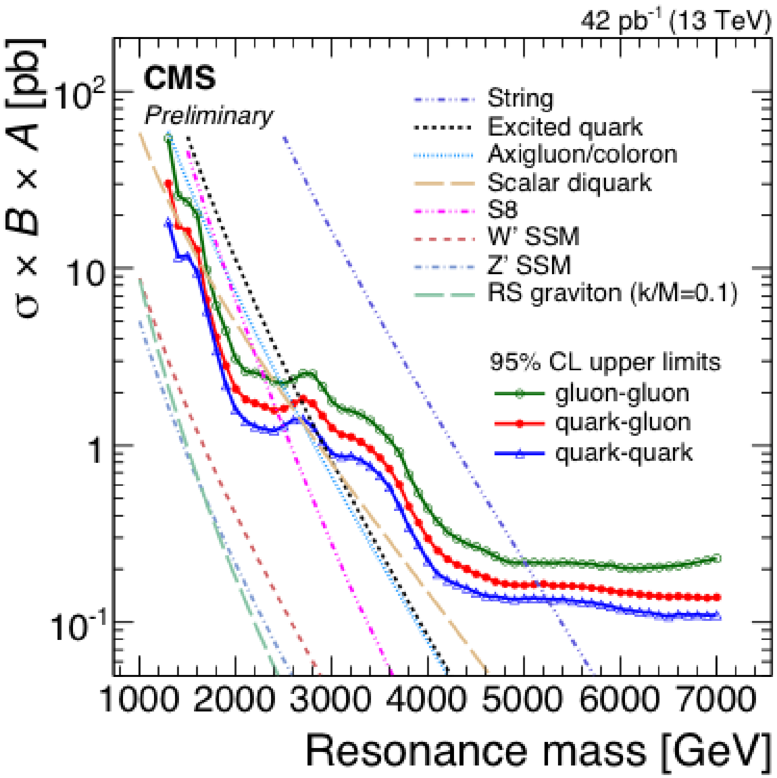
$$\frac{d\sigma}{dm_{jj}} = p_0 \frac{(1-x)^{p_1}}{x^{p_2}}, \qquad x = \frac{m_{jj}}{\sqrt{s}}$$

- Above 3.5 TeV
  - ~5 background events are expected (from fit to data) and
  - ~1 events of signal from the considered q* model (4.5 TeV).
  - 4 events are observed in data.
- With the current integrated luminosity we expect to exceed the sensitivity of the 8 TeV Run1 analyses only for narrow resonances with masses greater than about 5 TeV.

CMS PAS EXO-15-001



Di-jet resonance searches



CMS PAS EXO-15-001

- Observed limits at 95% CL on cross section of qq, qg, gg resonances
- Get worse when there are gluons in the final state because radiation increases and resolution degrades
- Extend to 7 TeV in di-jet mass for the first time
- plateaus at high mass due to absence of events

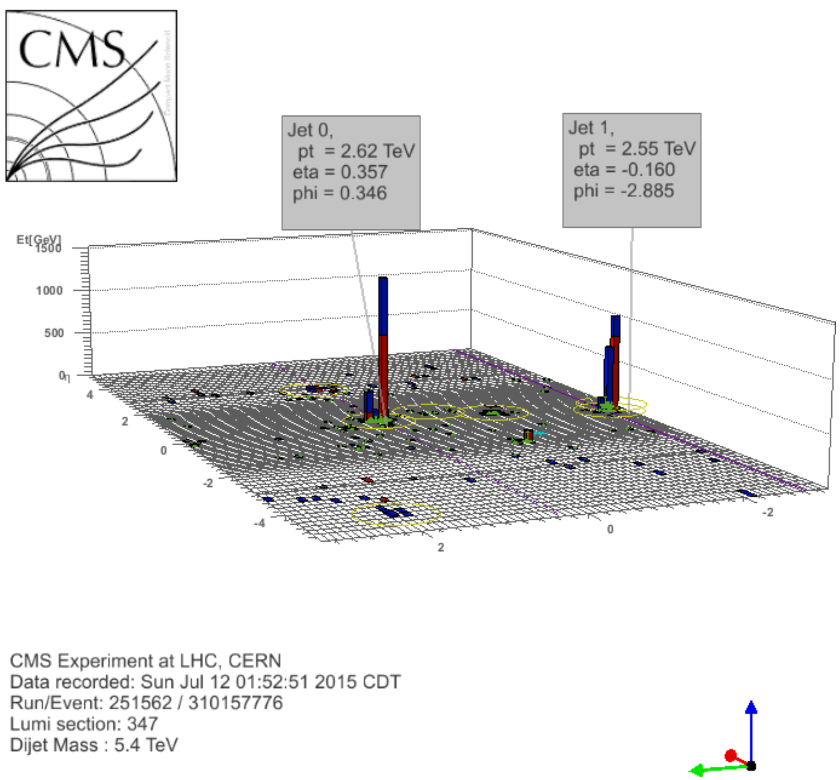
Confirms Run2 is already more sensitive than Run1 for M> 5 TeV

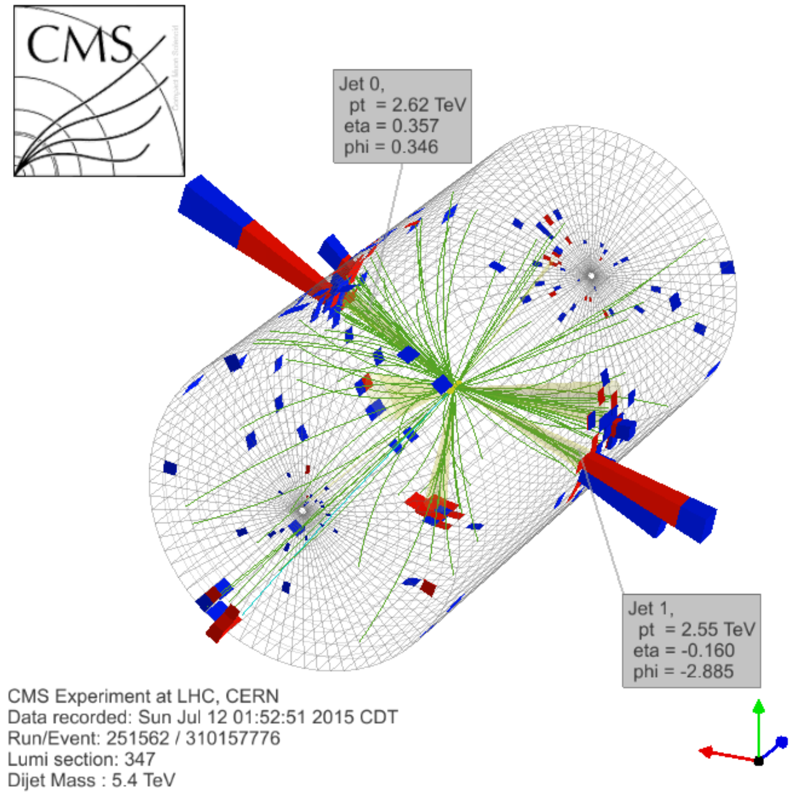
Model	Mass Limits (TeV)			
	Run 1 (20 fb^{-1})		Run 2 (42 pb^{-1})	
	Observed	Expected	Observed	Expected
String Resonance (S)	5.0	4.9	5.1	5.2
Excited Quark (q*)	3.5	3.7	2.7	2.9
Axigluon (A) / Coloron (C)	3.7	3.9	2.7	2.9
Scalar Diquark (D)	4.7	4.7	2.7	3.3
Color Octet Scalar (S8)	2.7	2.6	2.3	2.0

Di-jet resonance searches

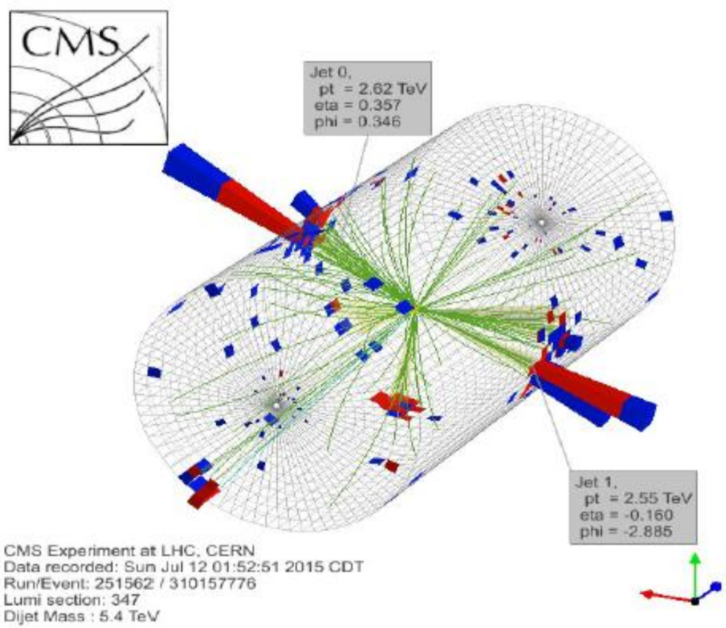
Highest Mass di-jet event M =5.4 TeV

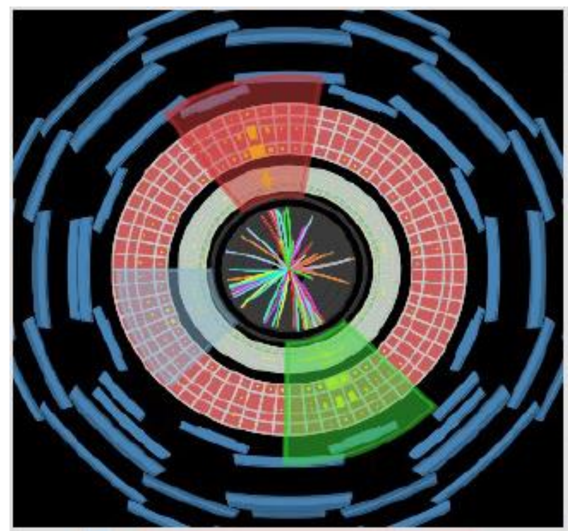
CMS PAS EXO-15-001

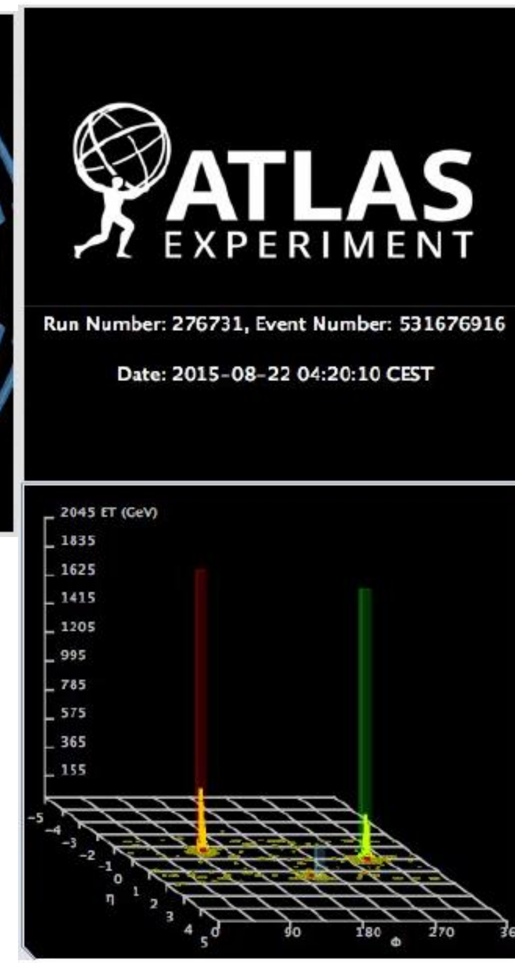




Di-jet events with Mjj > 5 TeV



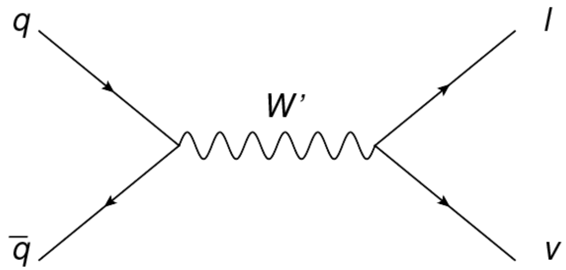




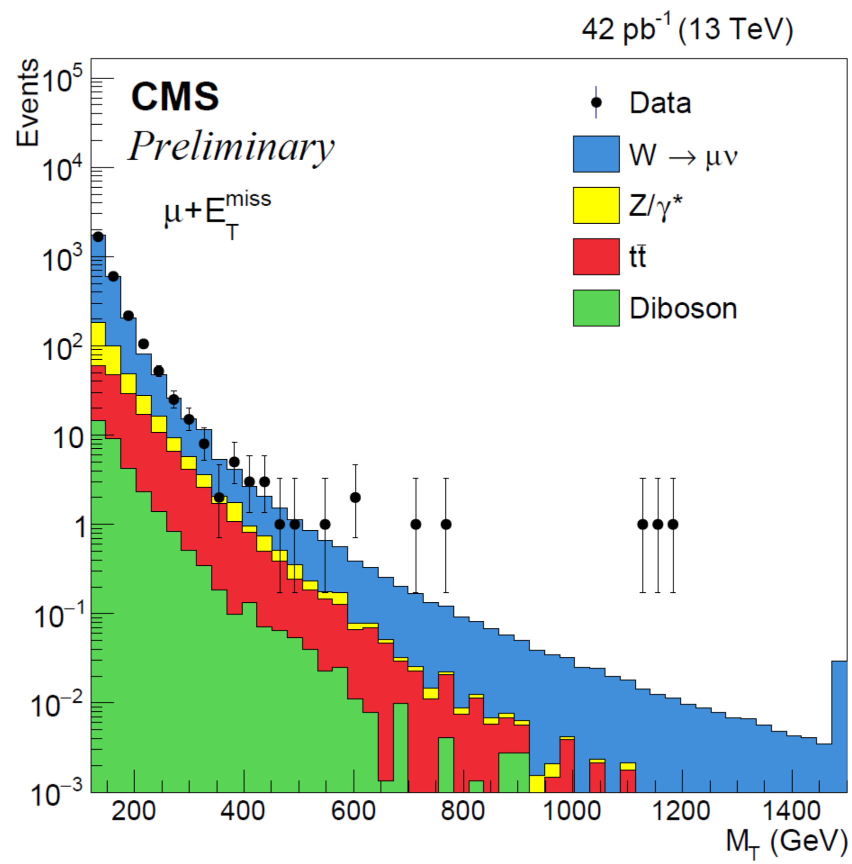
CMS: Mjj = 5.4 TeV

ATLAS: Mjj = 5.2 TeV

Muon + MET resonance search



Early Alignment used in data



transverse mass

last bin includes overflow

Muon selection

Good-quality isolated high-p_T muon with $p_T > 55$ GeV and $|\eta| < 2.4$

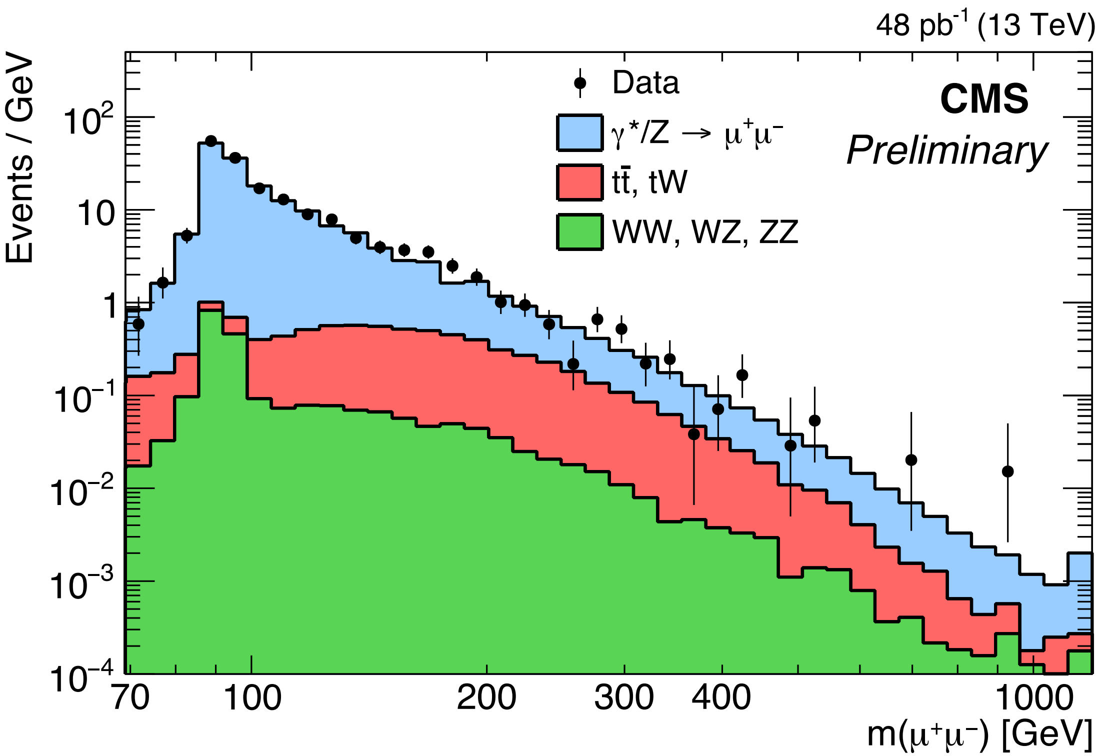
Event selection

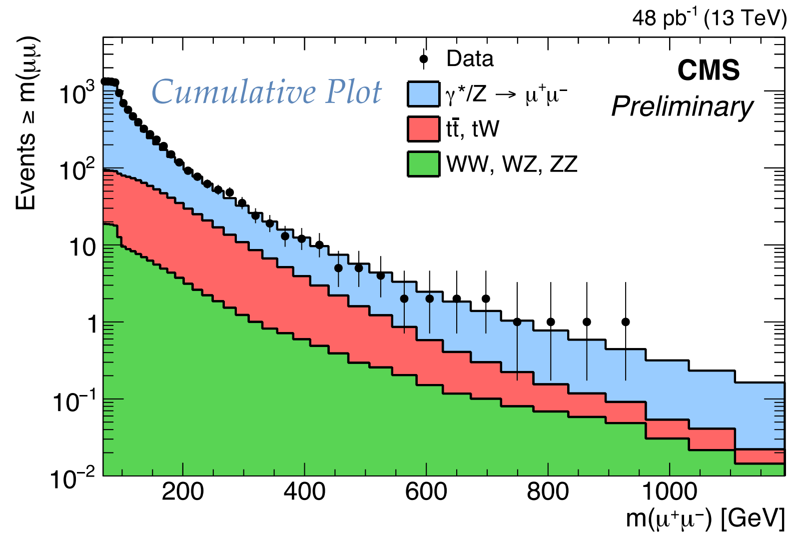
- Single high-p_T muon accompanied by a large missing transverse energy (E_T^{miss}).
- Events containing additional muons with $p_T > 25$ GeV are vetoed
- Kinematic selection:

$0.4 < p_T(\mu)/ E_T^{miss} < 1.5$

$\Delta\Phi(\mu, E_T^{miss}) > 2.5$

Di-muon resonance search





last bin includes overflow

Highest mass event = 920 GeV

Early alignment of Muon system and Tracker used in data

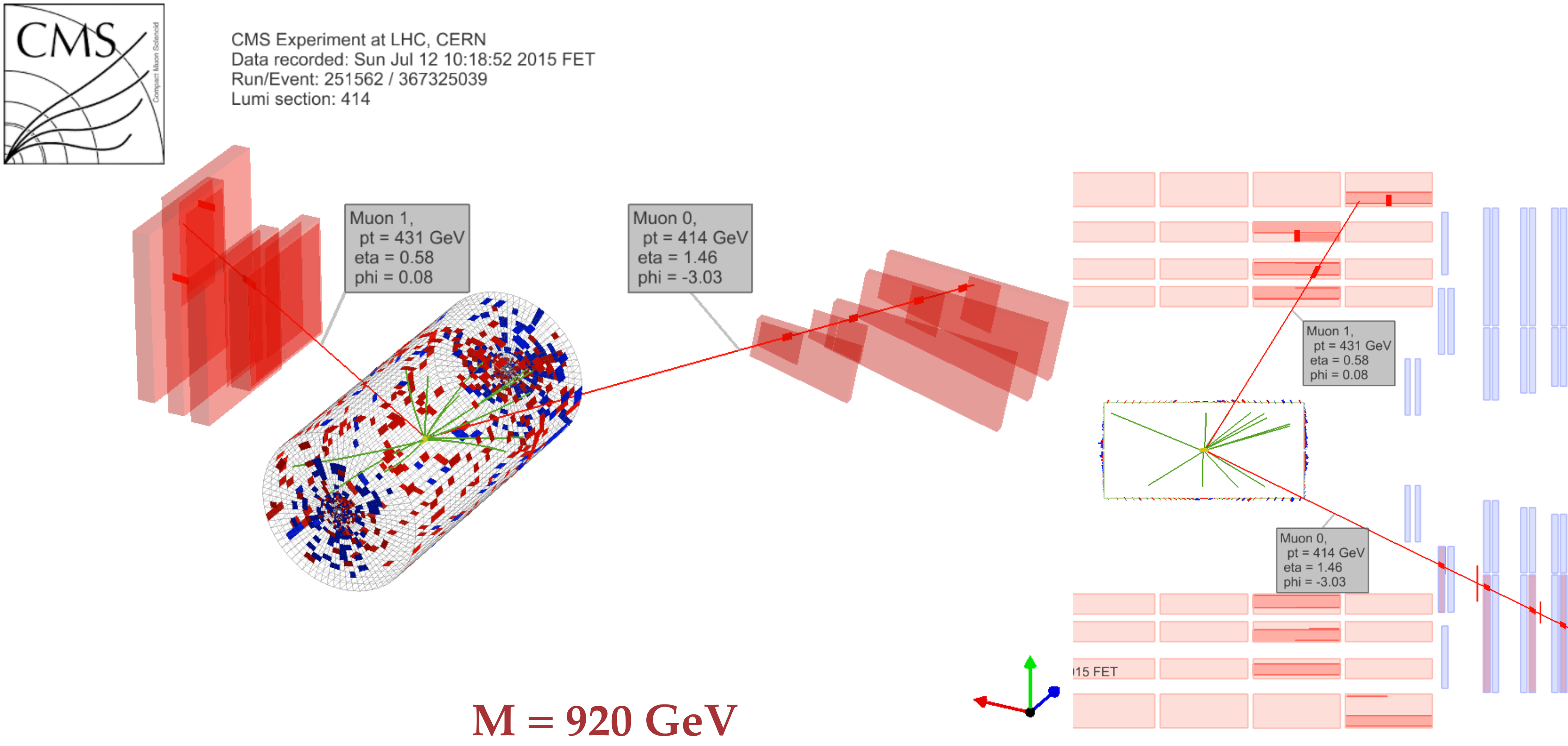
contribution from di-jets negligible and not shown

2 isolated muons muons are required to satisfy:

$p_T > 48$ GeV and $|\eta| < 2.4$

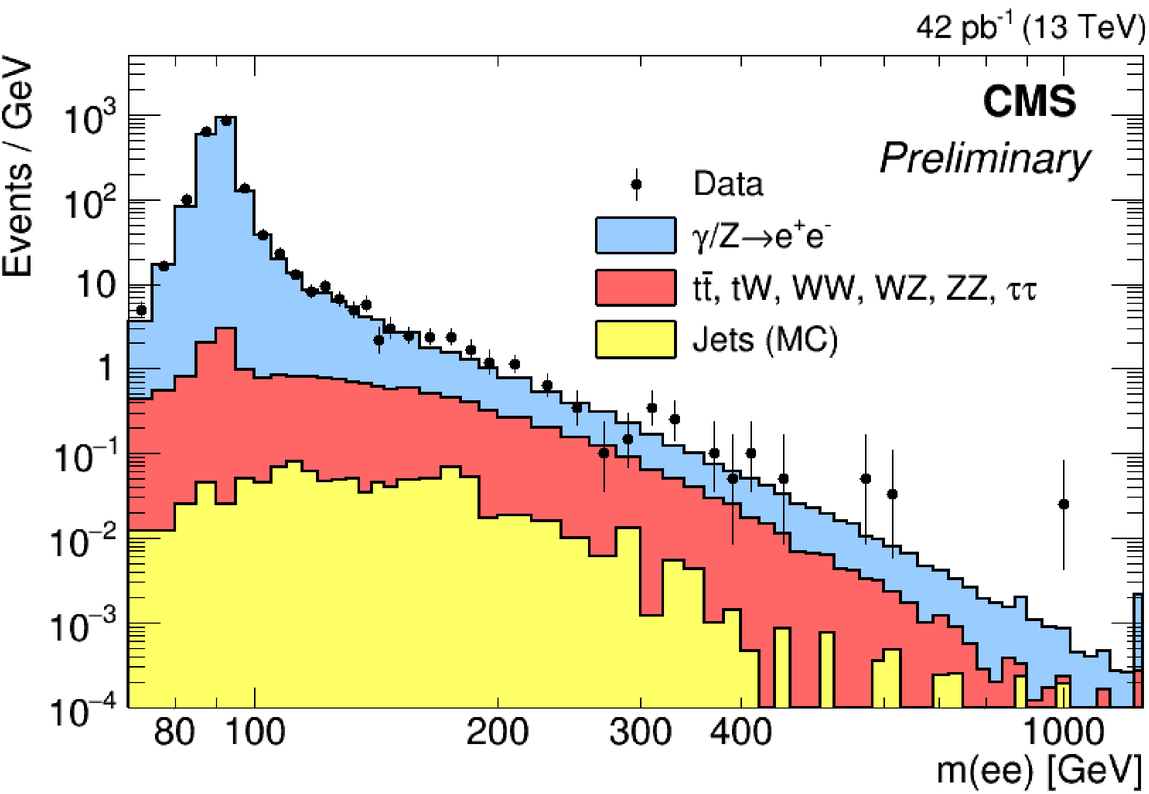
MC samples: aMC@NLO for Drell-Yan, POWHEG for ttbar and dibosons

Di-muon resonance search

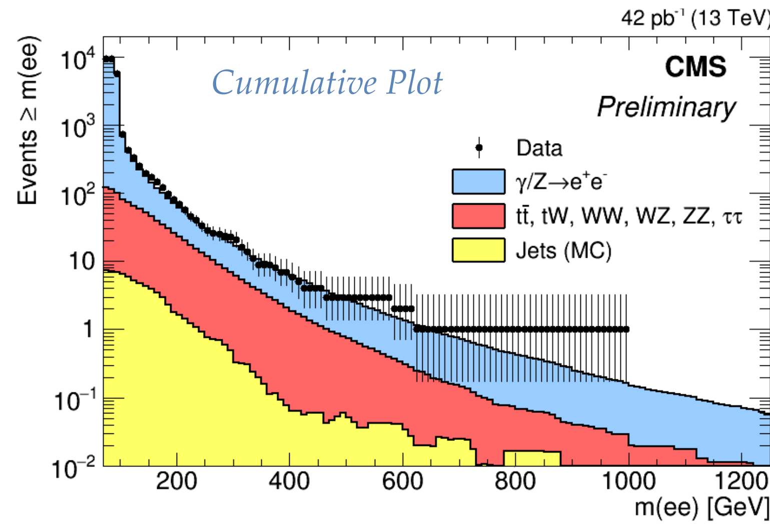


M = 920 GeV

Di-electron resonance search



last bin includes overflow



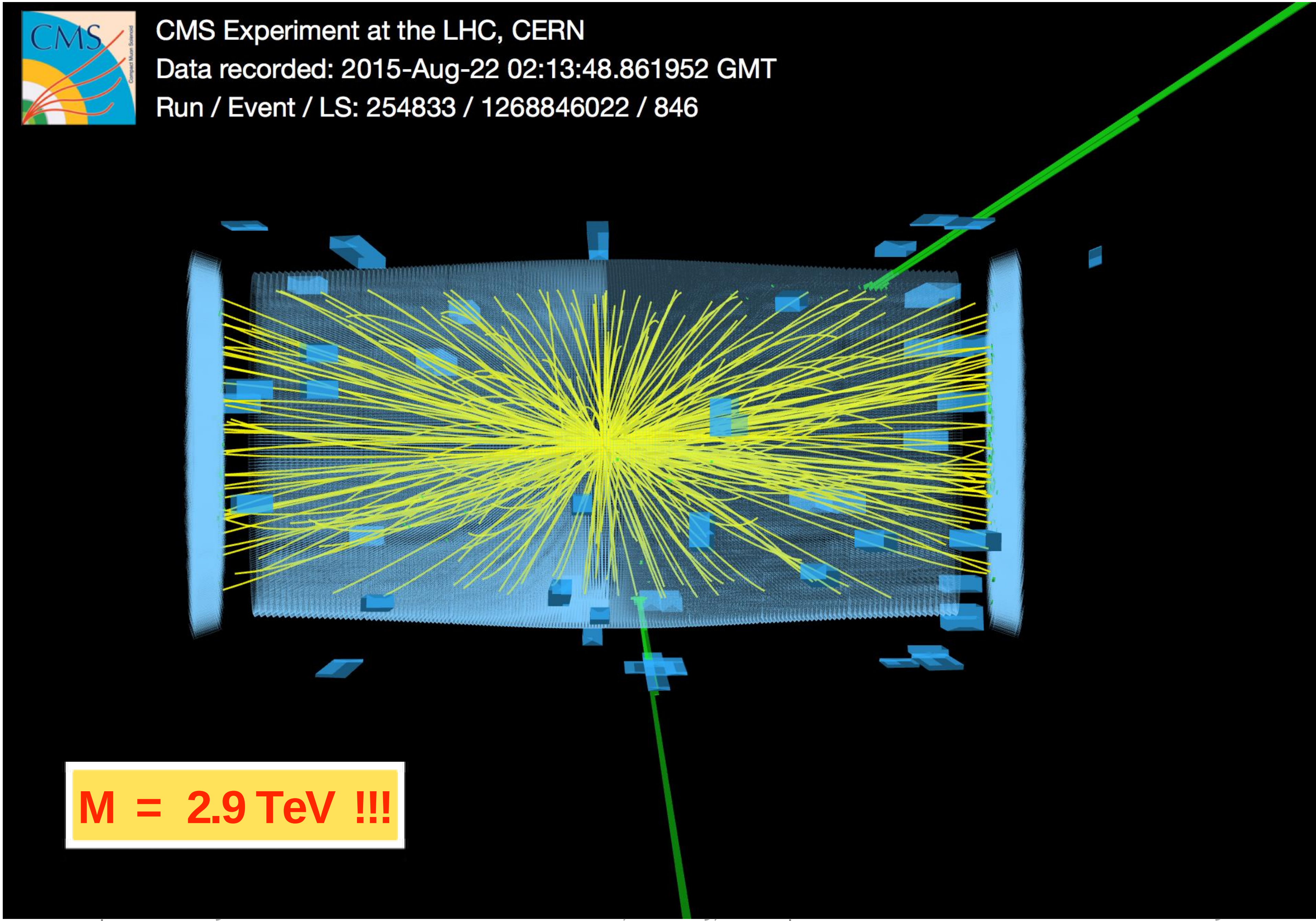
Highest mass event ~ 1 TeV

Run1 Limit for SSM Z′ < 2.9 TeV

Run1 sensitivity will be reached after about 2 fb^{-1}

2 electrons in ECAL with $E_T > 35$ GeV and at least one electron in the ECAL barrel

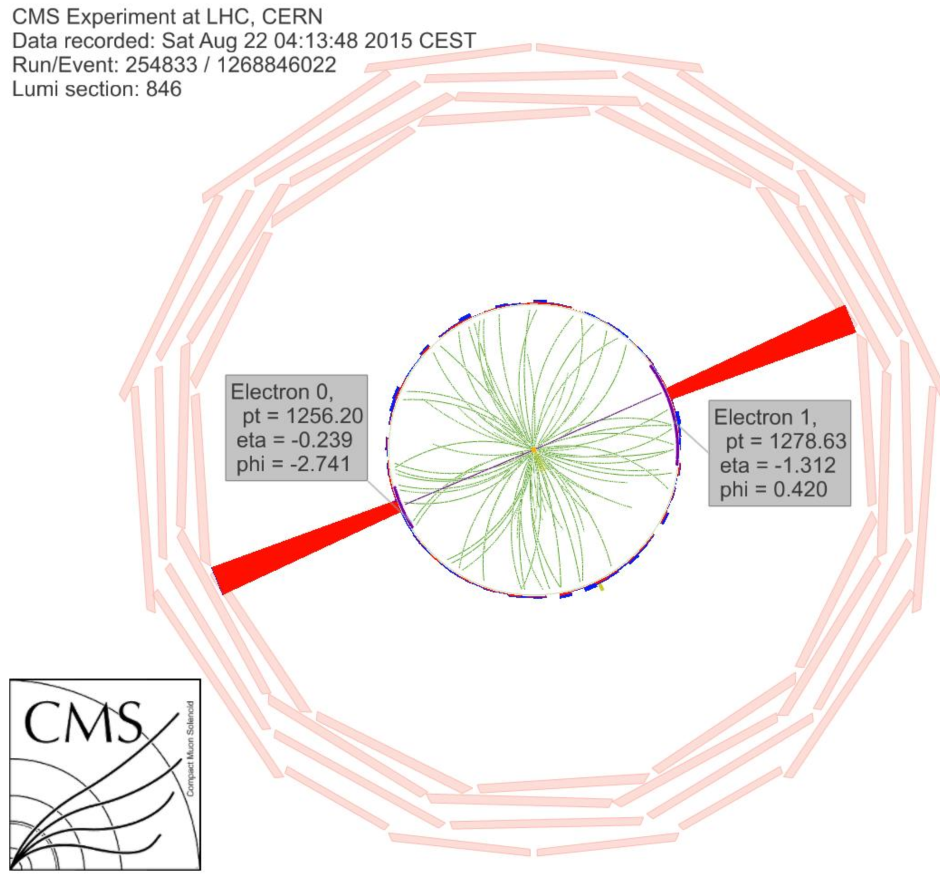
($|\eta| < 1.4442$ or $1.566 < |\eta| < 2.5$ with one electron within $|\eta| < 1.4442$)


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2015-Aug-22 02:13:48.861952 GMT
Run / Event / LS: 254833 / 1268846022 / 846
M = 2.9 TeV !!!

Di-electron resonance search

An event with a di-electron mass of 2.9 TeV has been observed

The event consists in two perfectly balanced electrons and no other significant activity



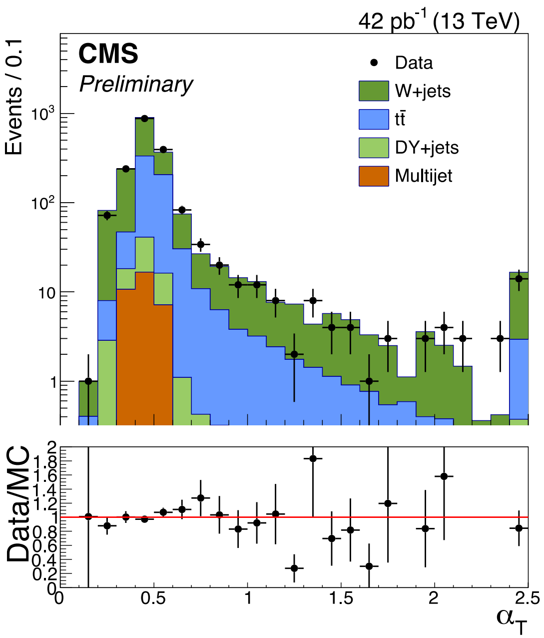
M = 2.9 TeV !!!

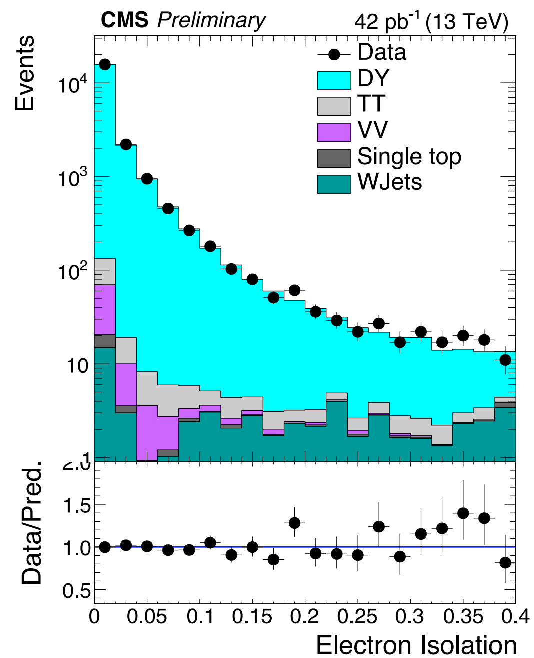
High mass di-electron event

	electron 0	electron 1
E_T	1260 GeV	1280 GeV
η	-0.24	-1.31
ϕ	-2.74 rad	0.42 rad
charge	-1	+1
mass	2.91 TeV	
$\cos\theta^*_{CS}$	-0.49	
y	-0.78	

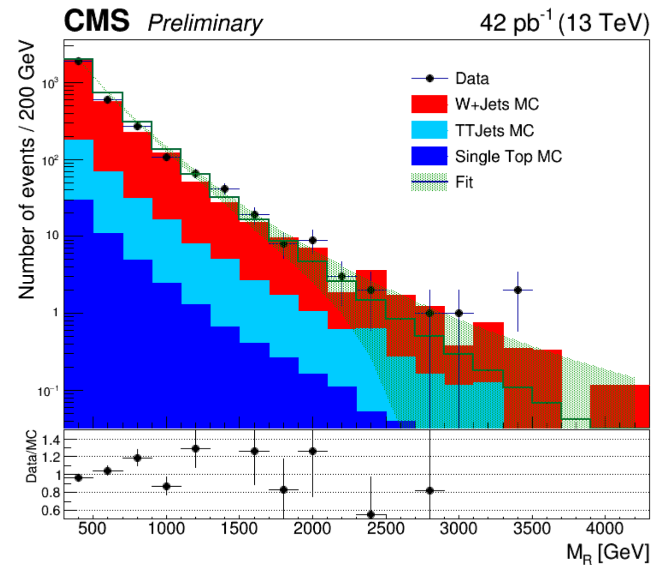
"Collins-Soper" angle, $\cos\theta_{CS}$, negative while DY bkg peaks at positive $\cos\theta_{CS}$.
The rapidity of the di-electron is rather large
Background is very low but not negligible ~ 0.002 events for M>2.5
Background uncertainty studies are ongoing (theory uncertainties expected to dominate)

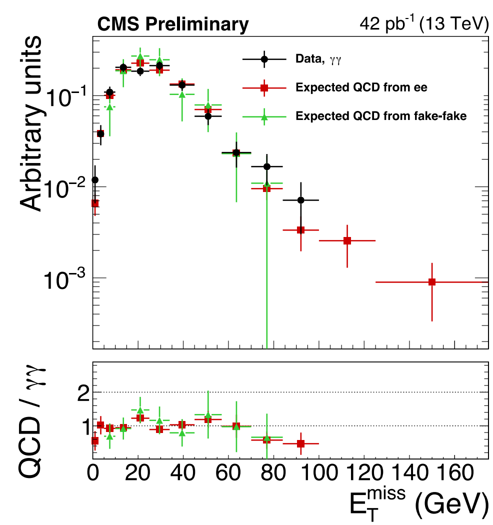
SUSY Searches Commissioning





CMS DP-2015/035



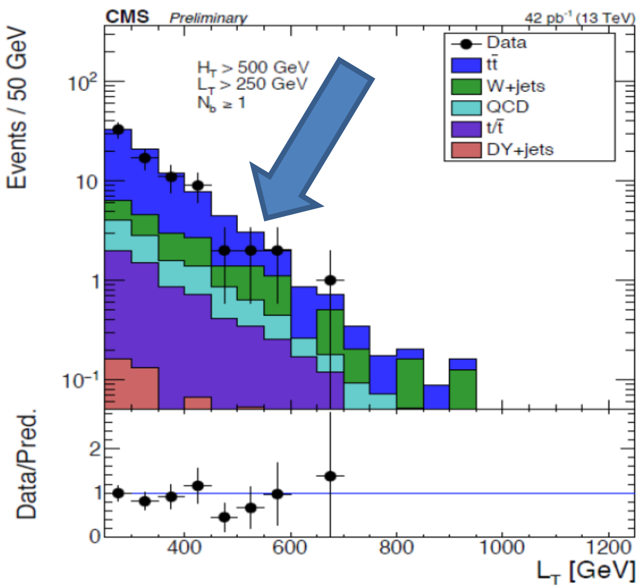


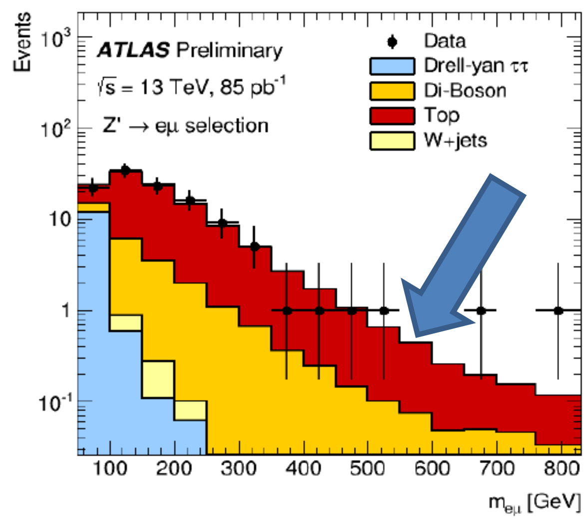
Key observables shape checked with MC

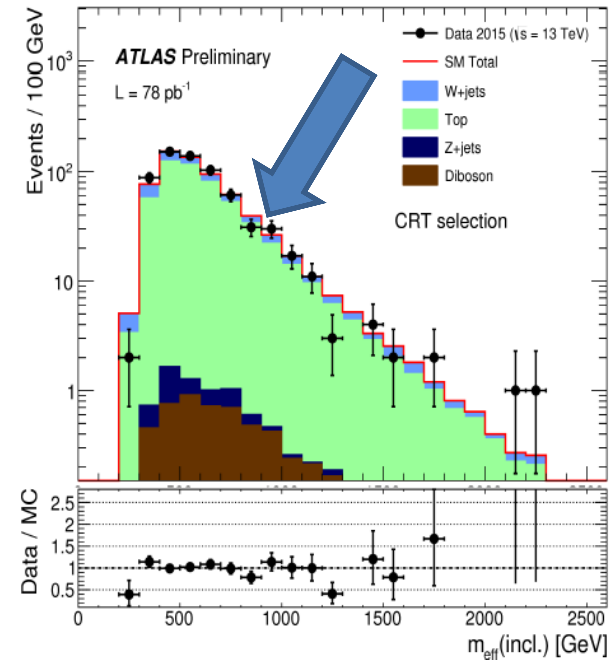
Trigger efficiencies measured

bkg estimation methods tested

BSM Searchers validating Top at 13 TeV







Not yet sensitive → use relaxed cuts to validate data
Top is an important background for many BSM searches

Summary

- **Standard Model: Our understanding of the strong and electroweak interactions has improved dramatically.**
  - Amazing NLO and NNLO calculations that describe the data!
- **A fundamental scalar that couples to mass. At 125 GeV**
  - Is it the very Higgs of the SM? Elementary or Composite? First scalar of many? Is it "natural"? Does it couple to Dark Matter? Connection to matter-antimatter asymmetry? …
- **No new physics has been discovered (yet)**
  - **Supersymmetry** is ever elusive;
  - **Exotica** are, for now, just that;
- We will get answers to some of these questions soon (LHC Run II and beyond) Run II has started and is on and we'll soon be crossing the "few fb^{-1} at 13 TeV" mark

	Peak lumi E34 $cm^{-2}s^{-1}$	Days proton physics	Approx. int lumi [fb^{-1}]
2015	~0.5	65	3
2016	1.2	160	30
2017	1.5	160	36
2018	1.5	160	36