Search for New Physics at LHC

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What Next at LHC

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Outline

- The Standard Model and the New Physics.
- What is this new physics?
- The current status of searches for physics beyond standard model.
- Have we been able to understand all the existing data so far?
- Future outlook

New Physics?

- Standard Model has been doing extremely well so far.
- All the precision measurements performed at different experiments matches with SM with a very few exception.
- Everything seems to work quite precisely.
- Life seems to be too good to believe.

New Physics!

- Nevertheless, there has to be some physics beyond standard model, in order to
- Account for the unseen 96% matter & energy combined.
- Unravel the mysteries of generations.
- Understand the matter dominance in the universe.
- And to answer many more questions ....

And LHC is the machine where this physics can be discovered

What is this New Physics

New Physics has to exist, but the question is, what form this new physics might take.

Supersymmetry

Large extra dimensions

Technicolor

Compositeness

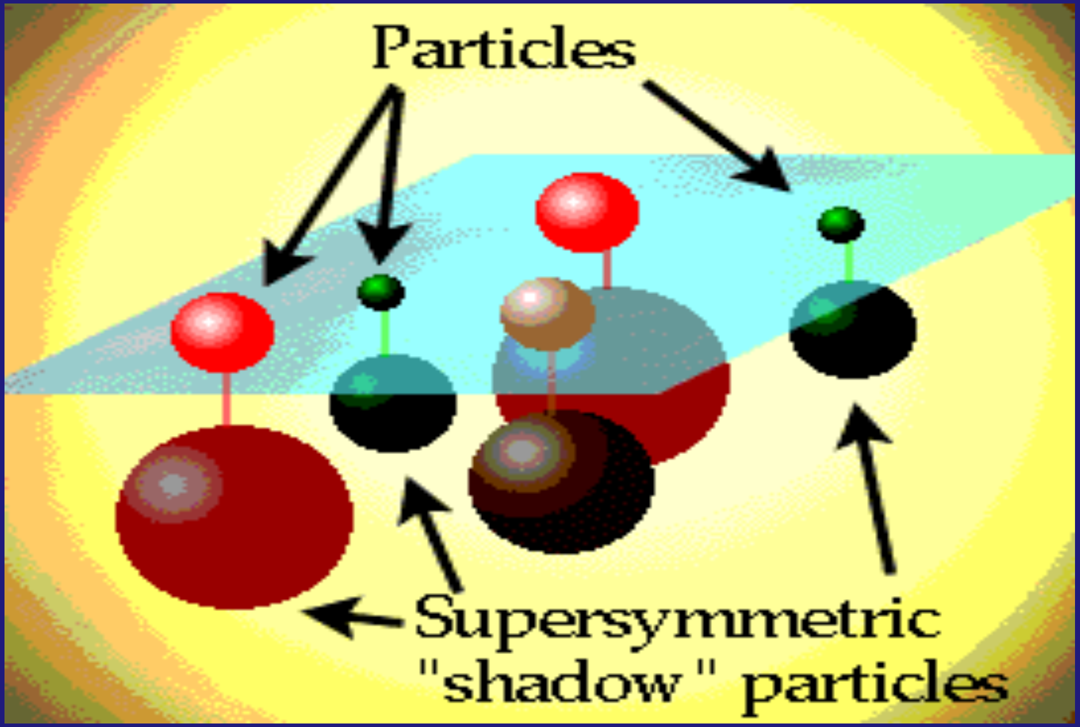
Leptoquarks

Fourth generation quarks

Little Higgs

GUT

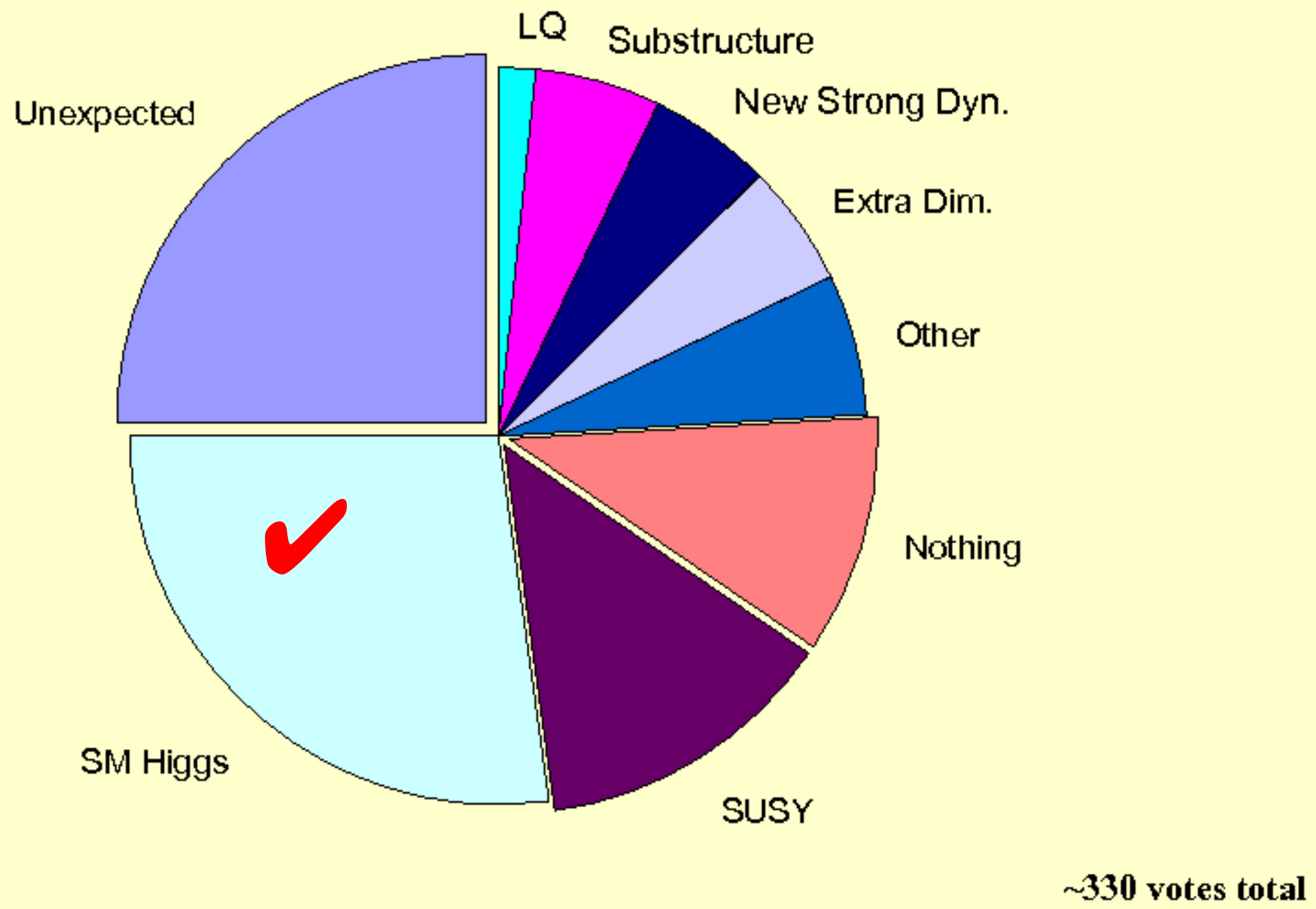
Some thing else



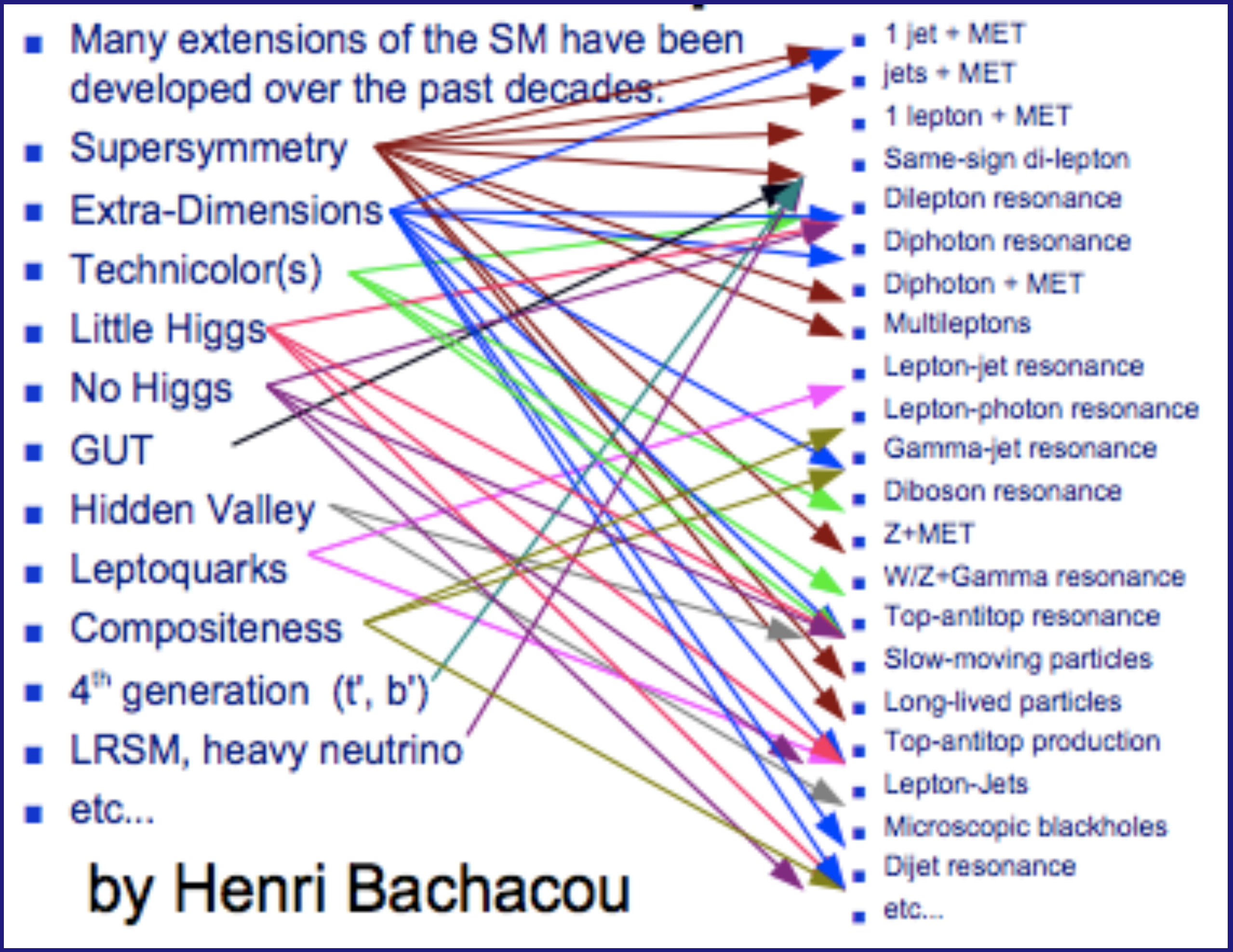
Opinion Also Matters

Lets look at an opinion poll done within Fermilab Graduate students and postdocs.

Q: What do you think would be discovered next?



New Physics Signatures



Many models gives the similar signatures

Searches : Heavy Resonances

Many models of physics beyond standard model predicts additional heavy resonances.

Extension of SM symmetry group
- SU(3) x SU(2) x U(1) x U(1)'

– Allow additional gauge boson (Z')
- SU(3) x SU(2) x U(1) x SU(2)'

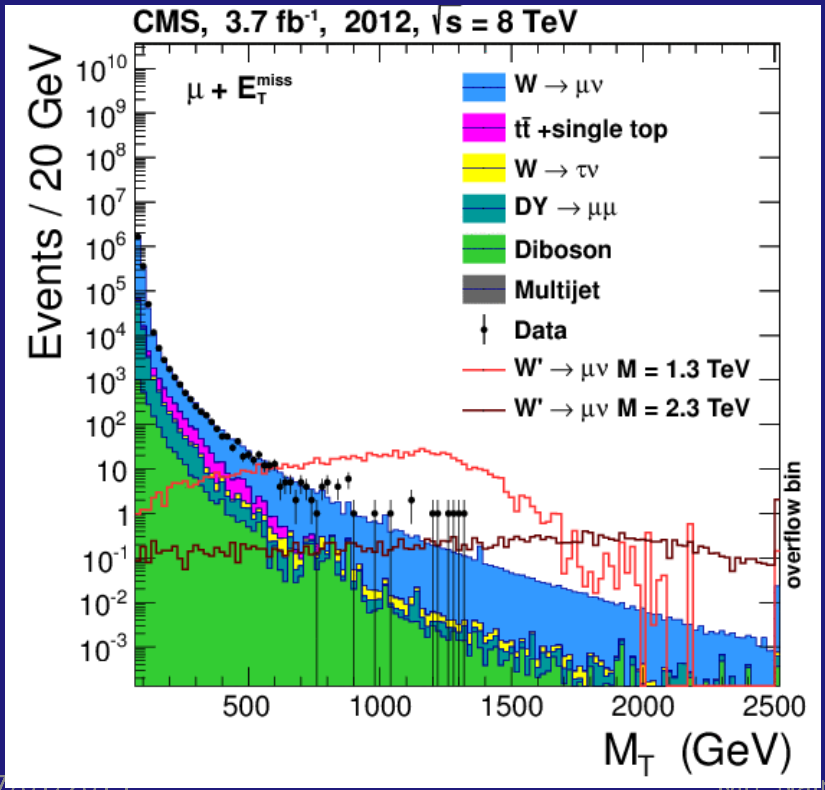
– Allow additional gauge bosons (Z', W')

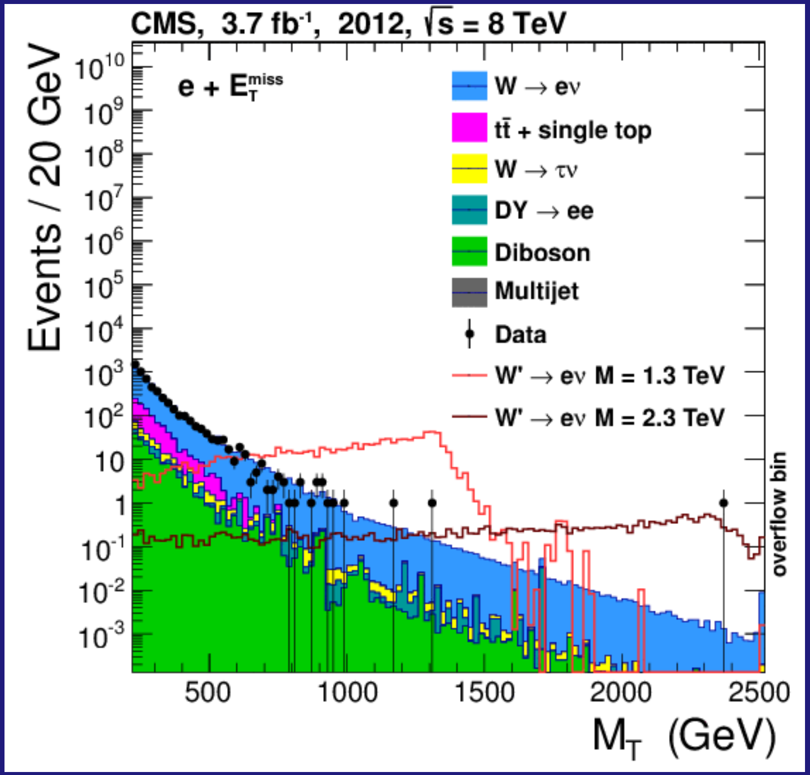
– Extra Dimensions
– Extended Technicolor
– LeftRight Symmetry
– Little Higgs

Searches : W′ → lν

- One isolated lepton with relatively high pT
- Electron pT>100 GeV, muon pT> 45 GeV
- Look for excess in transverse mass

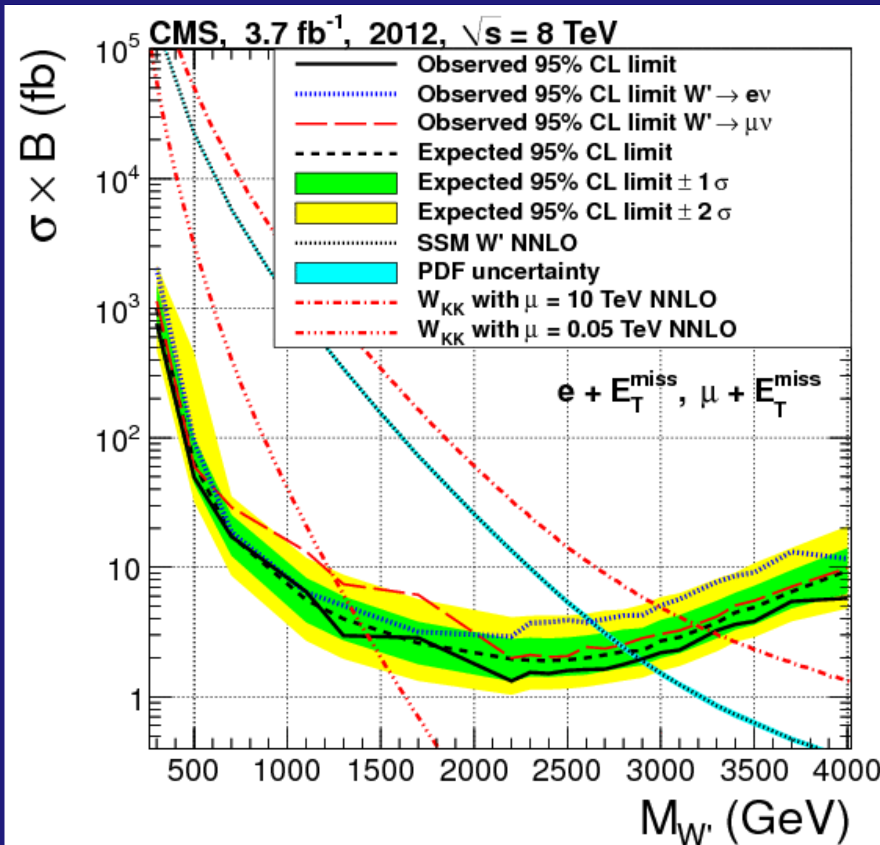
$$M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

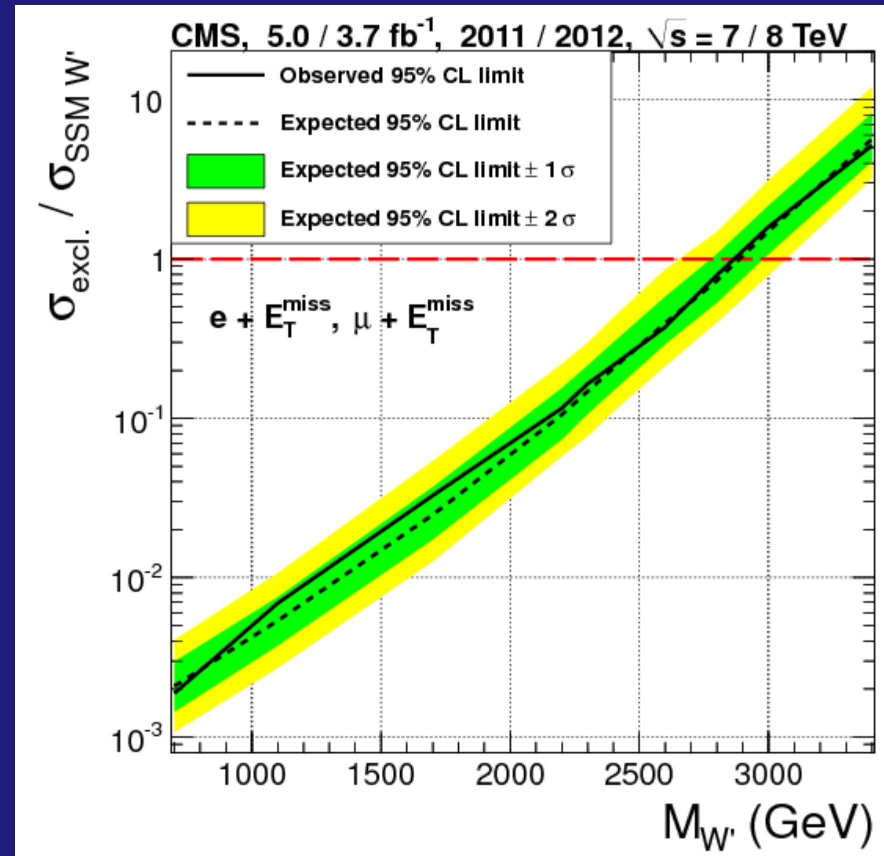




Data looks consistent with the SM ….. No excess observed.

Searches : W′ → lν





Masses below 2.9 TeV for heavy charged gauge boson (W’) in the sequential standard model is excluded.

Searches : W′ → WZ → 3l+MET

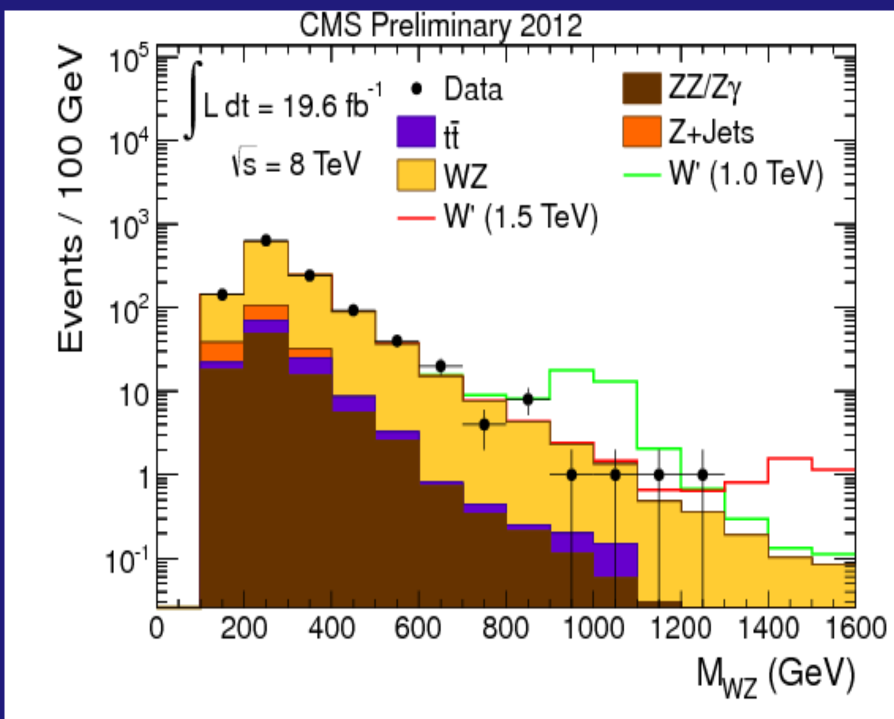
Compute M_{WZ}, taking MET into account

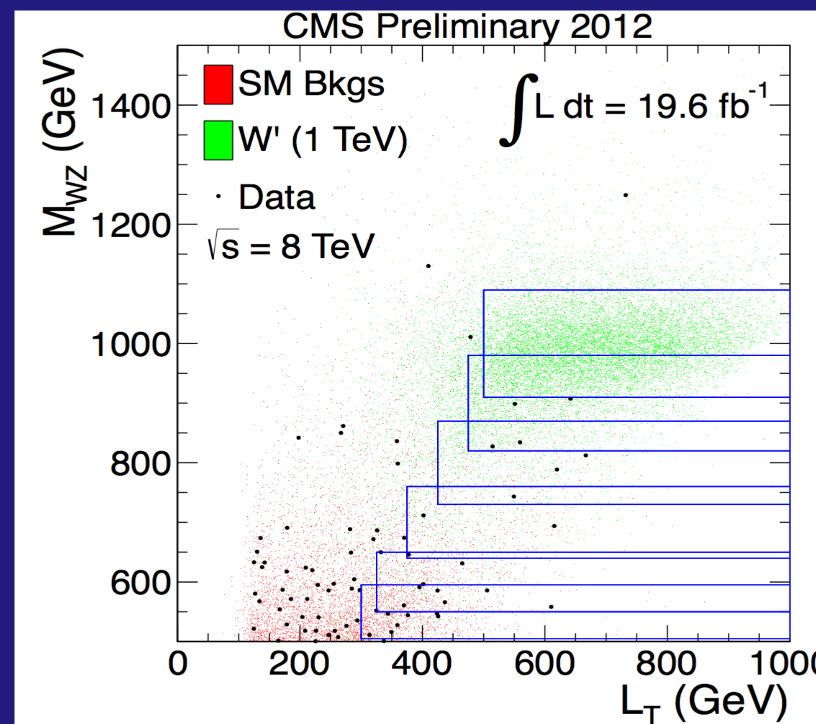
M_{WZ} and L_T (defined to be $\sum P_T[l]$)

Main backgrounds from WZ, use simulation (with generous systematics)

Special identification and isolation for μ's (from boosted Z)

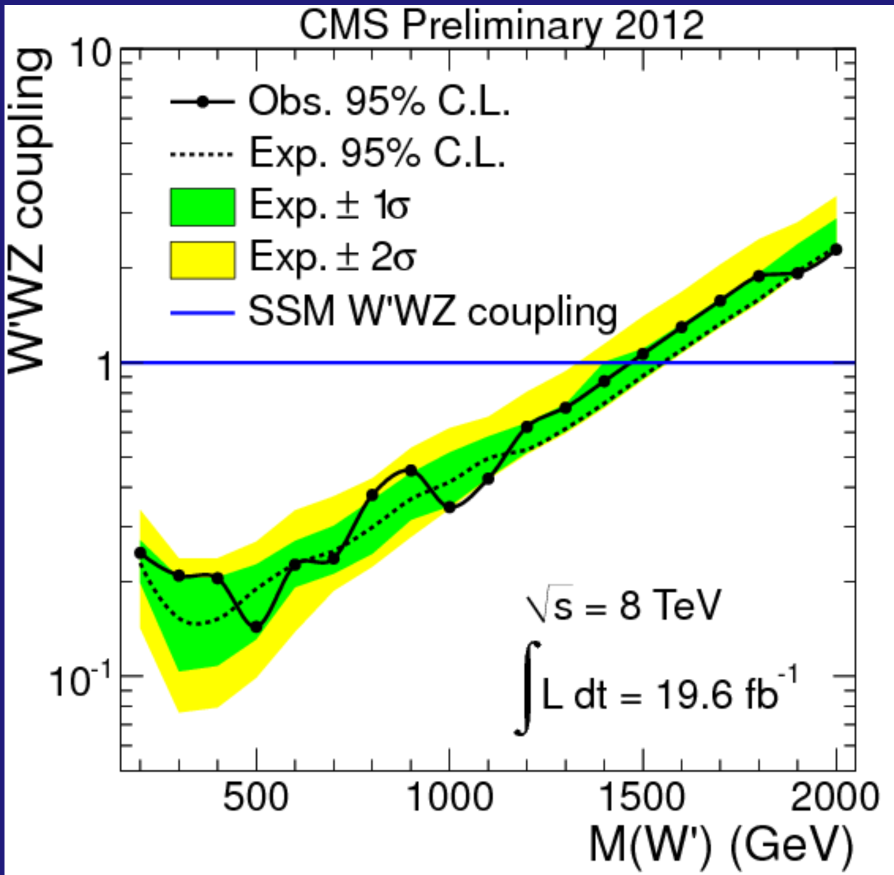
Cuts optimized for each signal mass (cut and count - boxes shown in blue)

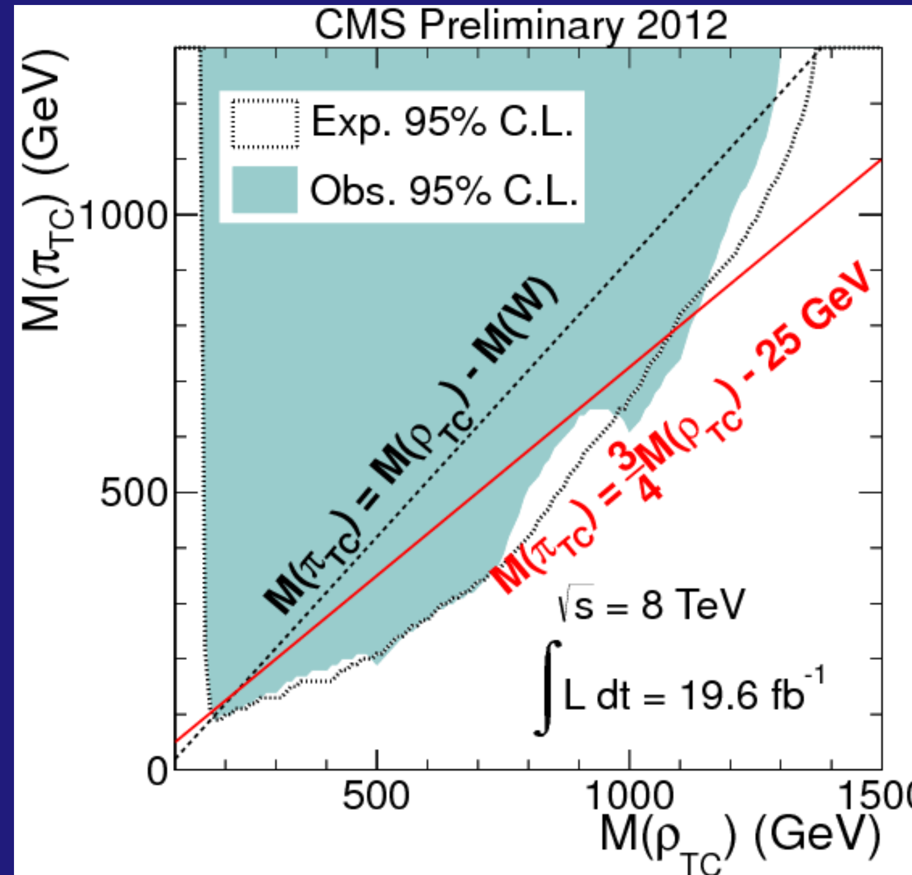




Searches : W′ ➔WZ➔ 3l+MET

Limit-setting: counting experiment in each signal box





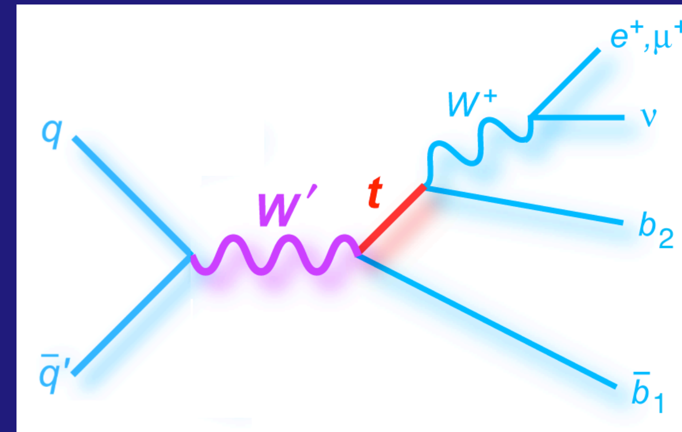
W’ ⟶ WZ excluded in range 0.17 to 1.45 TeV, stringent limits on ρ_{TC}

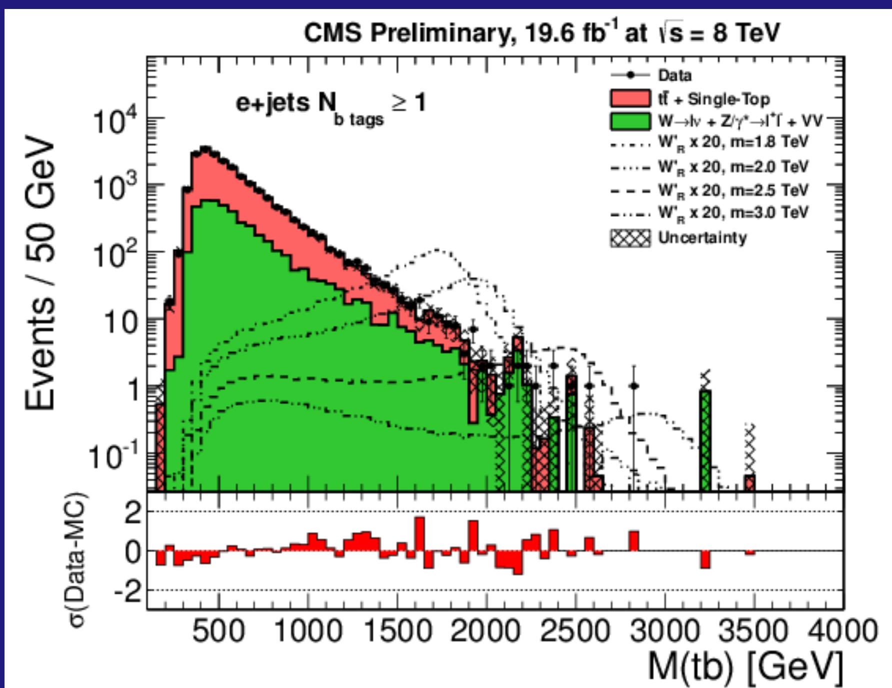
Searches : W′ to Top + Bottom

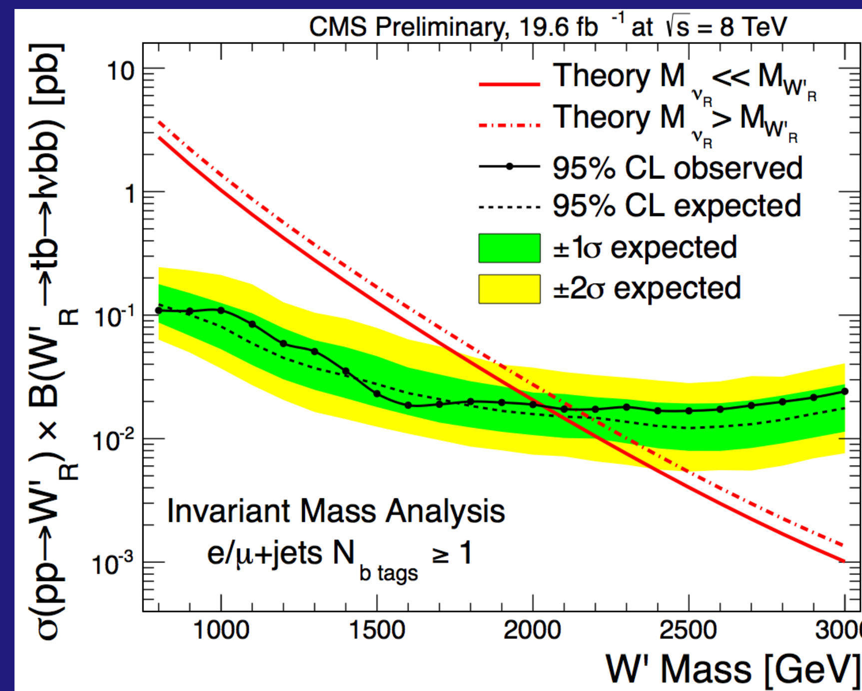
Search lepton (e, μ) plus jets and E_T^{miss} for decays
$W' \longrightarrow tb$, $t \longrightarrow bW \longrightarrow bl\nu$,

Several jets, with $\geq$ 2 b-tag(s), small E_T^{miss} (20–35 GeV) to reduce QCD

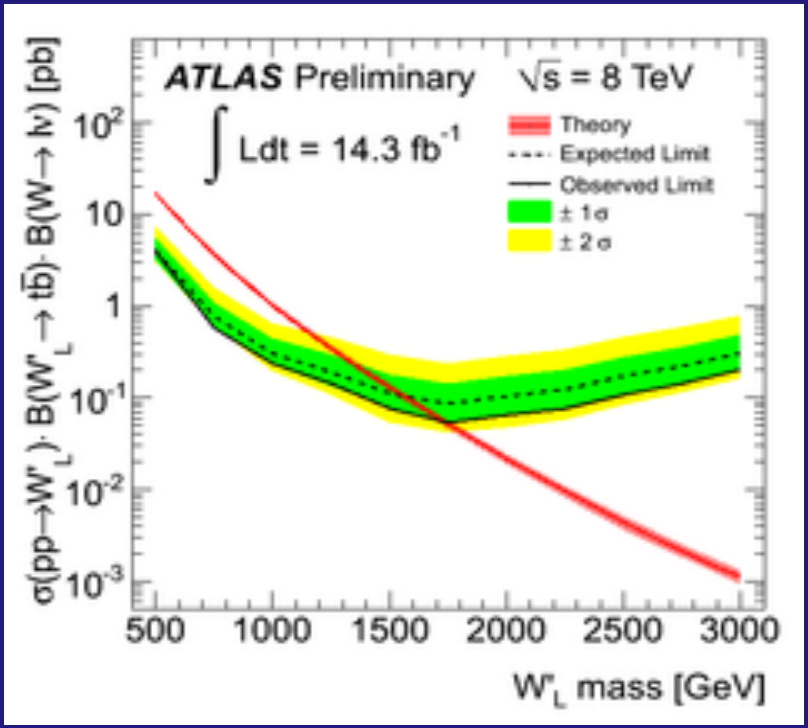
Kinematic cuts to enhance signal (e.g. p_T^{top} or $E_T^{miss} + m_T(W)$)

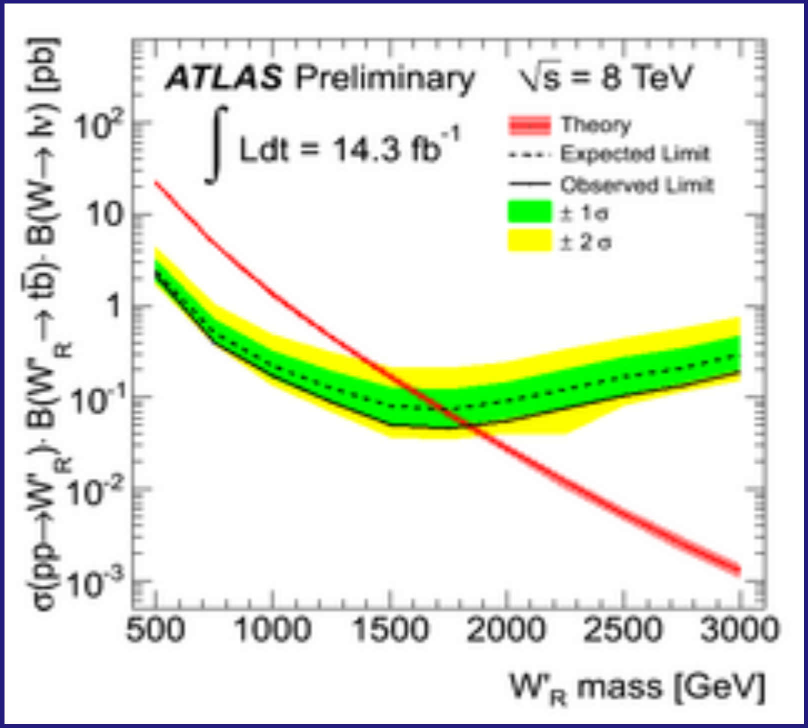






Searches : W' to Top + Bottom





$M_{W'_R(tb)}$ 95% CL	Luminosity (fb^{-1})	Expected	Observed
ATLAS W'_R	14.3	> 1.72 TeV	> 1.84 TeV
CMS W'_R	19.6	> 2.09 TeV	> 2.03 TeV

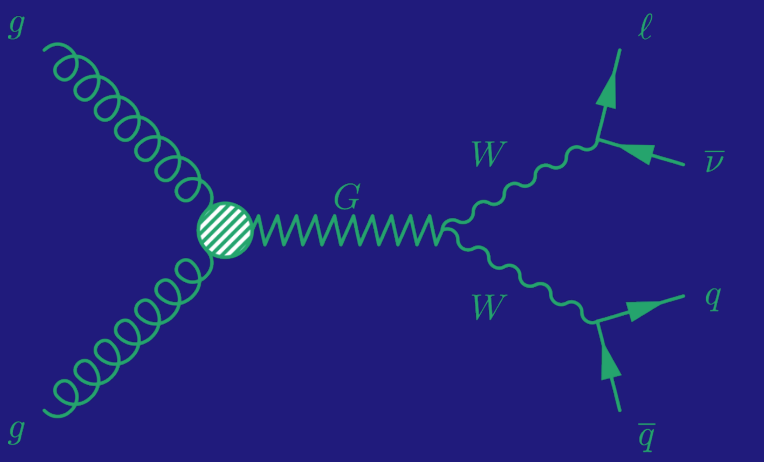
Searches : Semileptonic WW resonance

Search for WW resonance at high mass

Identify boosted W-jets with "N-subjettiness"

Ratio of 2-to-1 jets: $\tau_2/\tau_1 = \tau_{21}$

$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k} \min\{\Delta R_{1.k}, \Delta R_{2.k}, ..., \Delta R_{N.k}\}$$



N-subjettiness: $\tau_{21} < 0.5$ for high purity, and

$0.5 < \tau_{21} < 0.75$ for low

Study performance of "W-tagging" in data

derive data/MC scale factor (SF) for each analysis

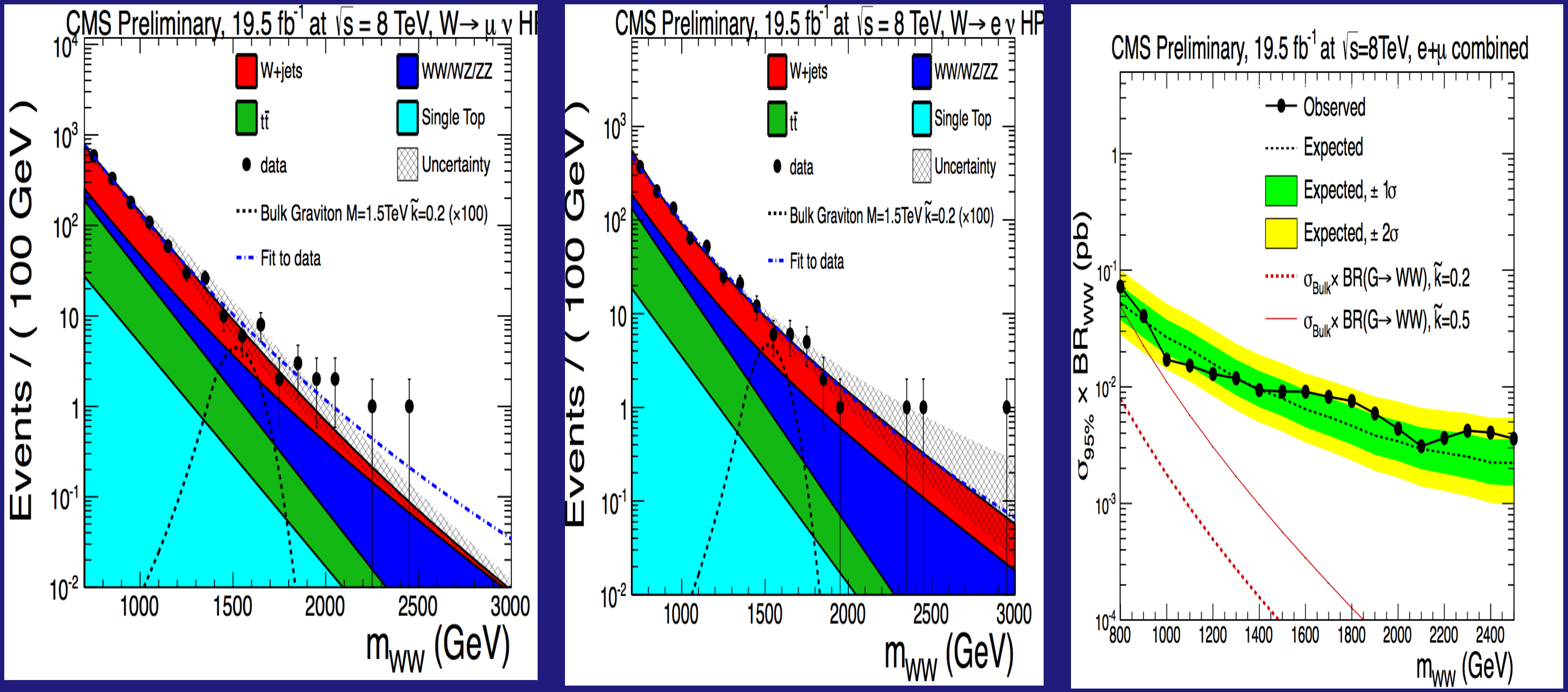
error on "substructure SF" ⟶ systematic on signal

Study merged hadronic W's from tt

boosted enough to merge jets from W

not so boosted that the b quark also merges

Searches : Semileptonic WW resonance



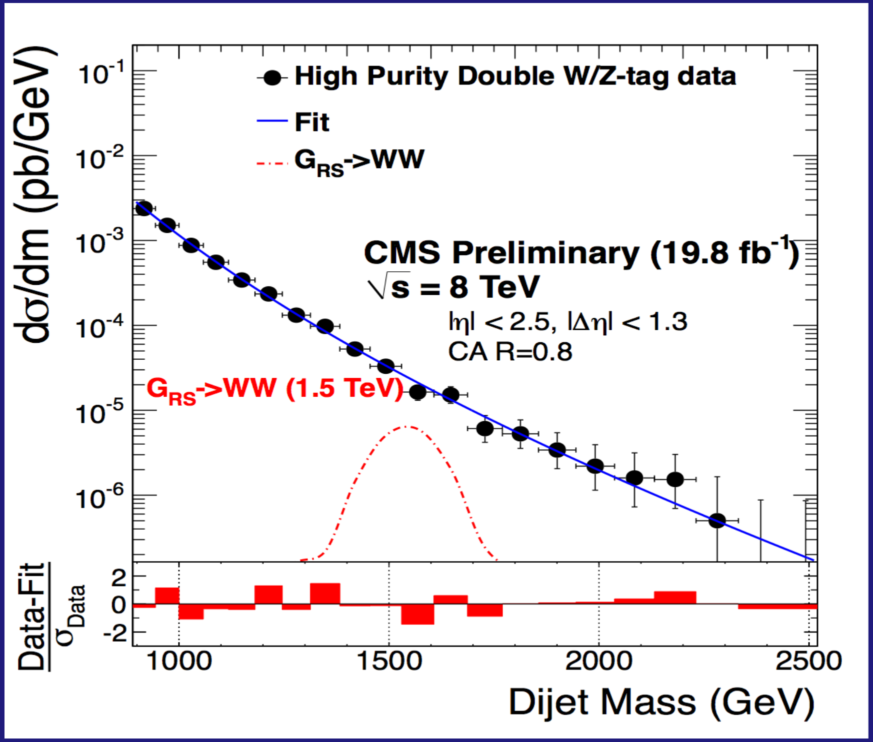
Limits set on bulk graviton production cross section times BR

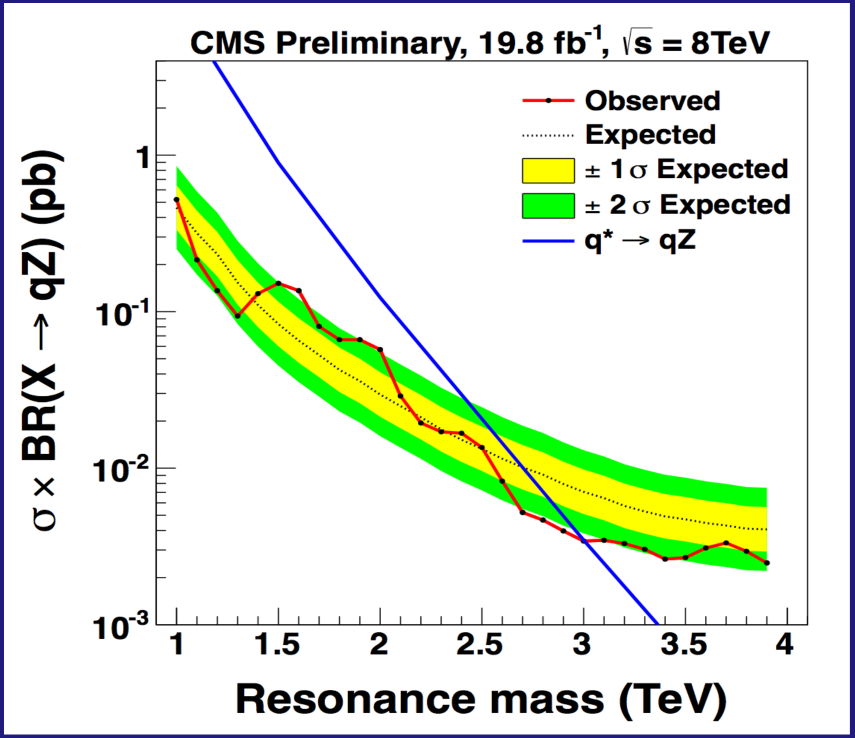
70 fb to 3 fb for mass between 0.8 TeV to 2.5 TeV mass

Searches : WW / ZZ / WZ in dijets

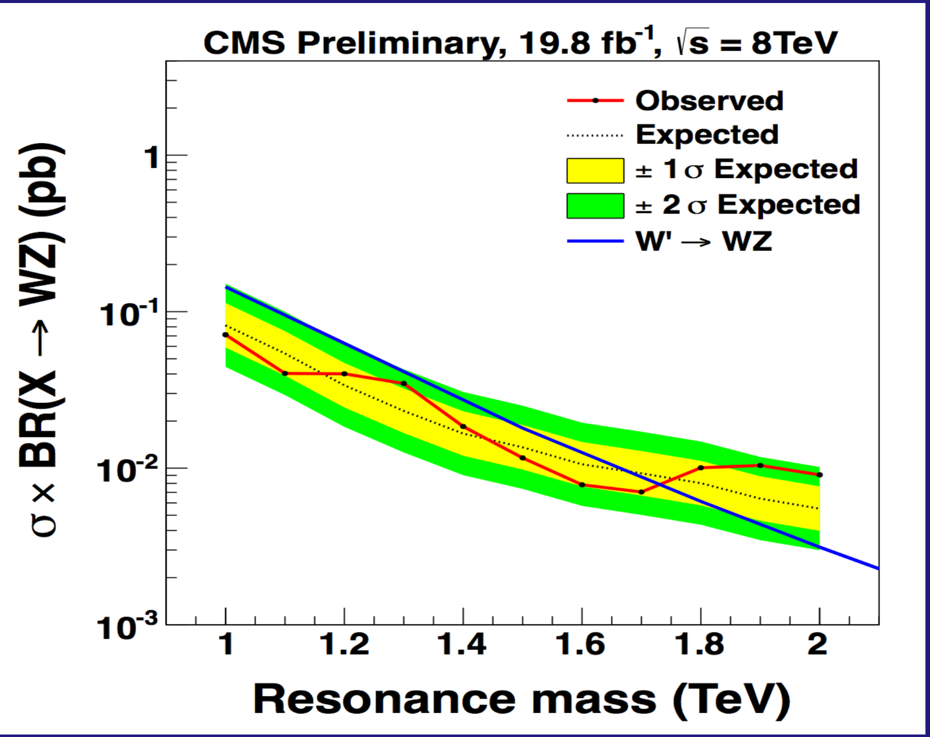
$G_{RS} \longrightarrow WW/ZZ$ and $W' \longrightarrow WZ$ in dijets

- Fully hadronic VV decays, $W \longrightarrow jj$ and/or $Z \longrightarrow jj$
- Jets from W/Z typically boosted and merged into a single jet
- QCD only significant background, suppressed by $|\eta_{jet1} - \eta_{jet2}| < 1.3$





Searches : WW / ZZ / WZ in dijets

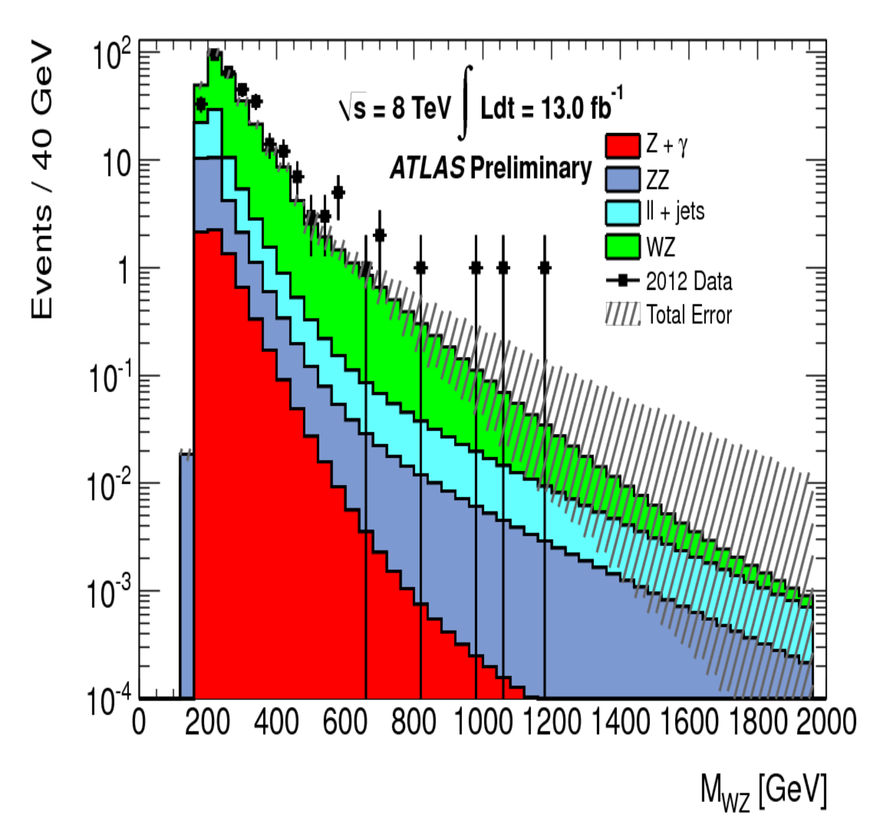


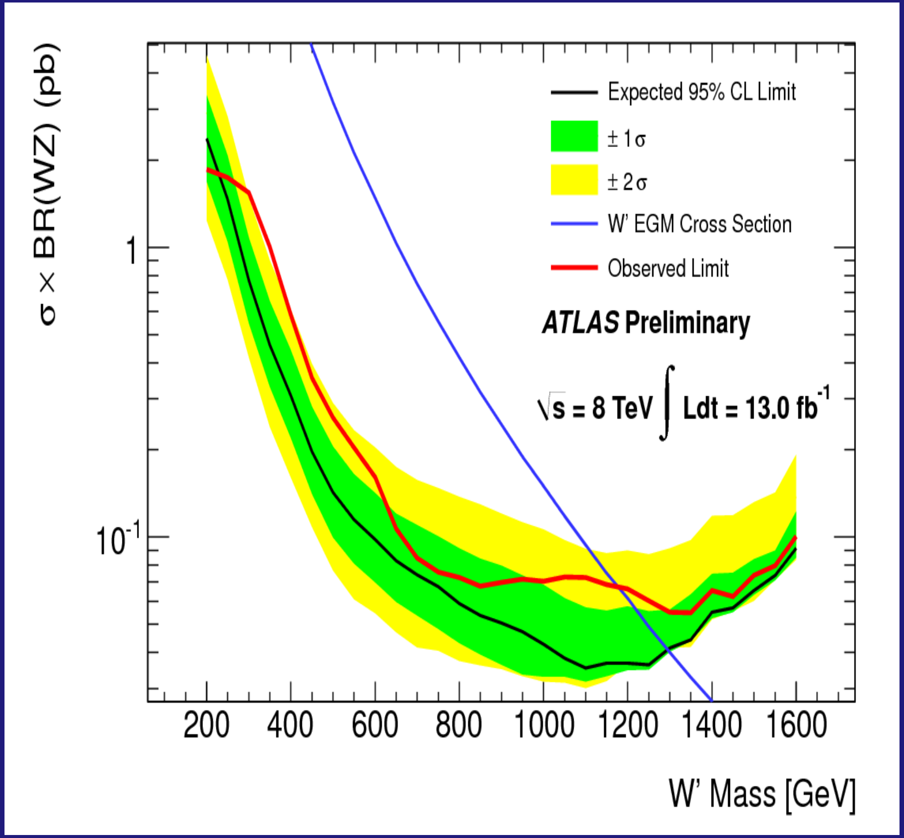
G_{RS1} (k/M_{PL}=0.1) ⟶ WW(ZZ) excluded in mass range 1.0 to 1.59(1.17) TeV

W′ ⟶ WZ excluded in mass range 1.0 to 1.73 TeV

q* ⟶ qW(qZ) excluded in mass range 1.0 to 3.23(3.00) TeV

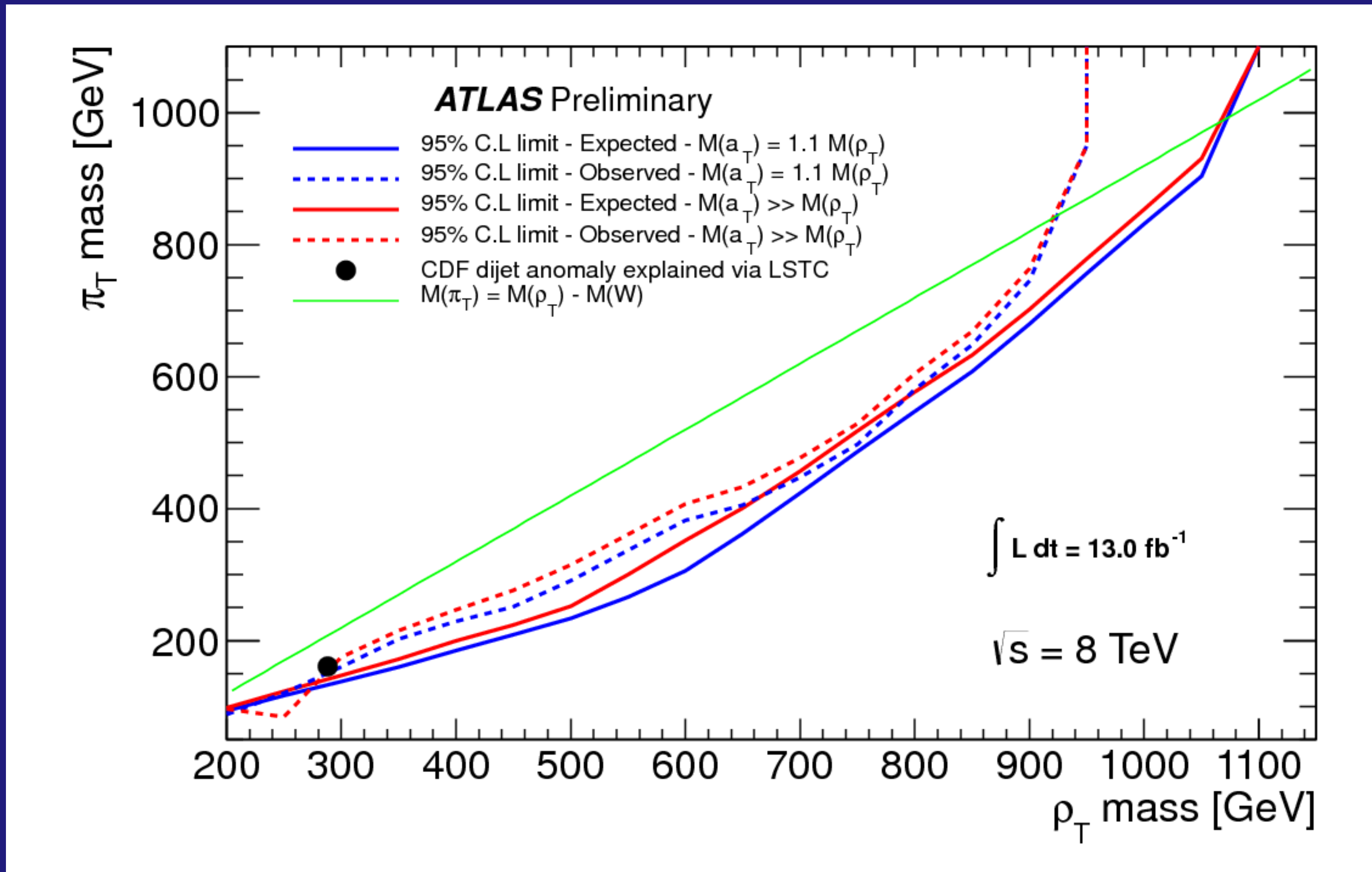
Searches : WZ → lvll





Combined limit assuming W′→WZ in the context of Extended Gauge and Low Scale Technicolor

Searches : WZ → lvll

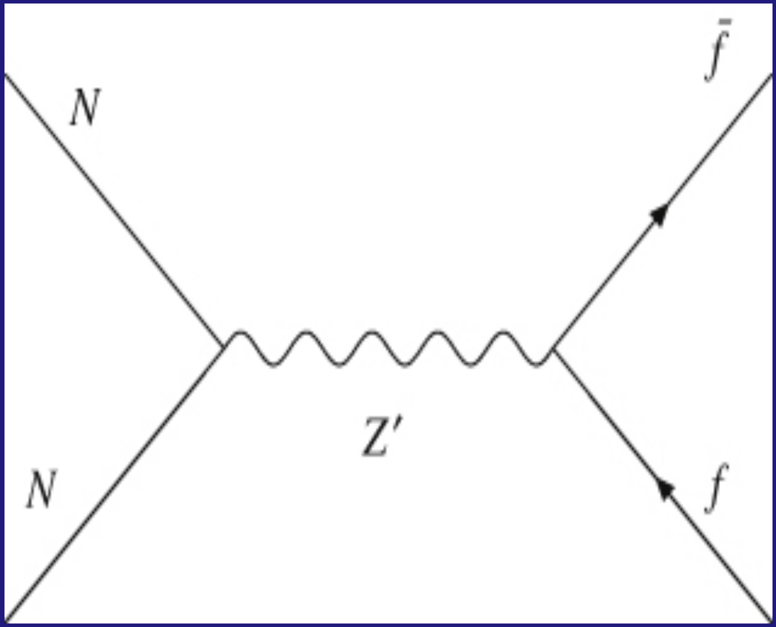


The 95% CL expected and observed excluded mass regions in the $M(\rho_T)$ versus $M(\pi_T)$ plane, using the combined final state assuming the $\rho_T \rightarrow WZ$ signal.

Searches : Z' → ll

Event selection

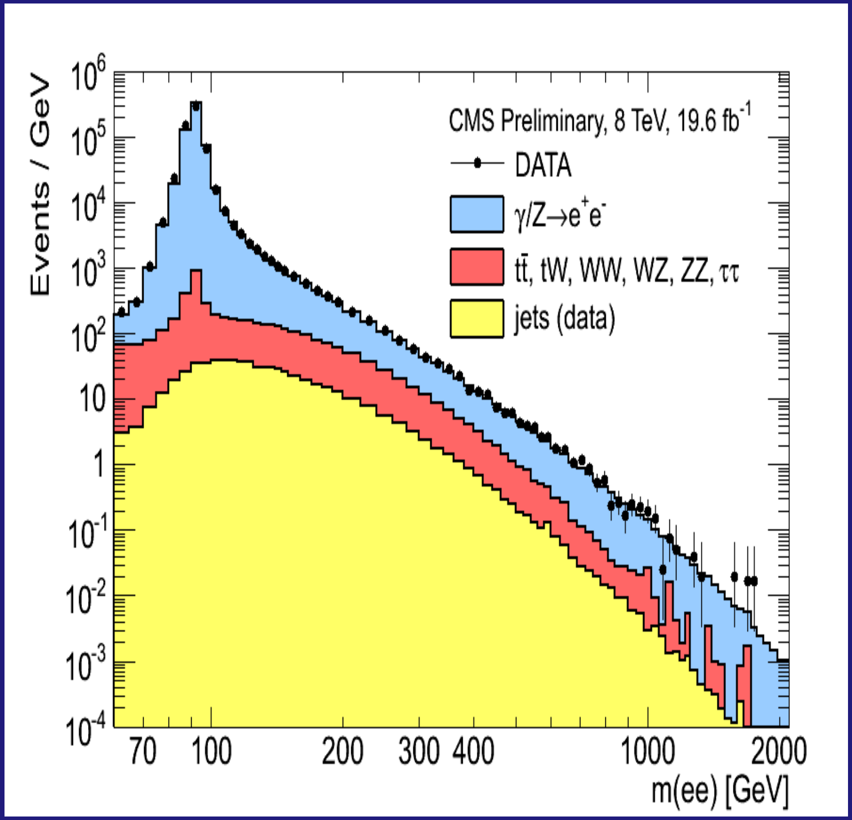
- CMS: E_T (e1,e2) > 35 GeV, p_T (μ1,μ2) > 45 GeV, plus isolation criteria
- ATLAS: E_T (e1,e2) > (40,30) GeV, p_T (μ1,μ2) > 25 GeV, plus isolation criteria

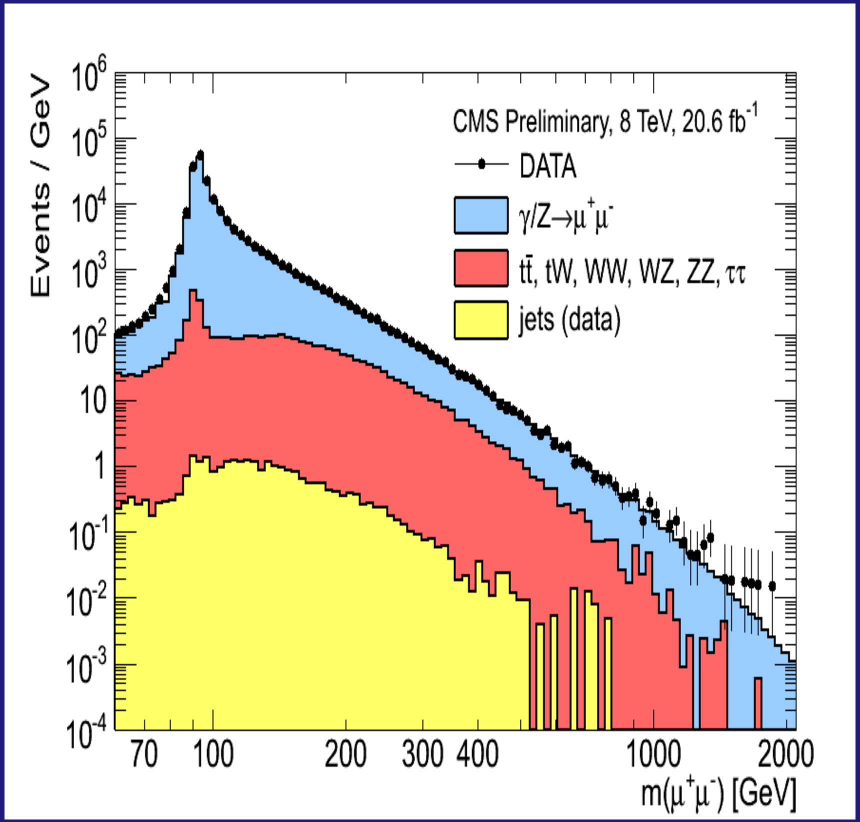


Backgrounds

- Z/γ*, tt, tW, VV, Z ⟶ ττ, multijets
- with ≥1 jet reconstructed as lepton
- estimated by functional fit

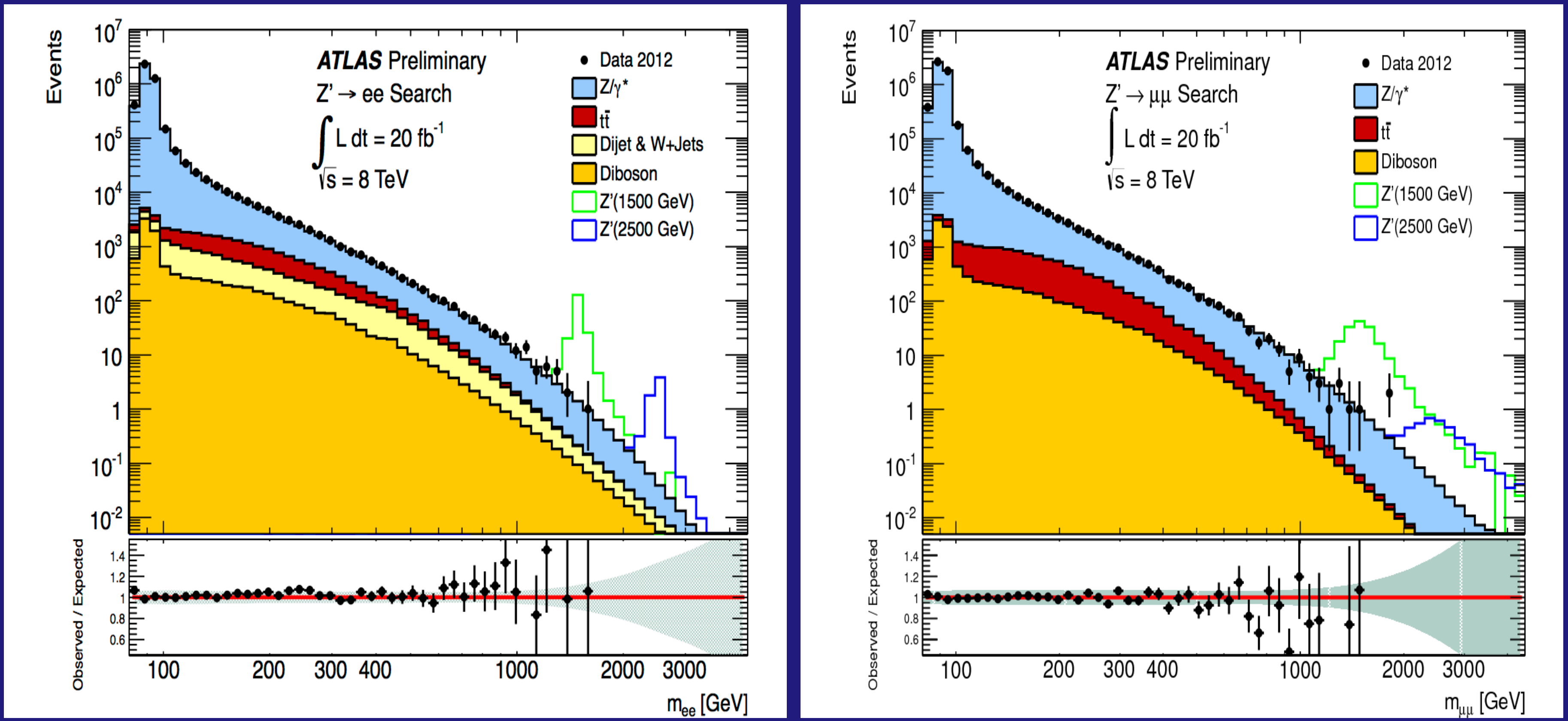
Searches : Z' → ll





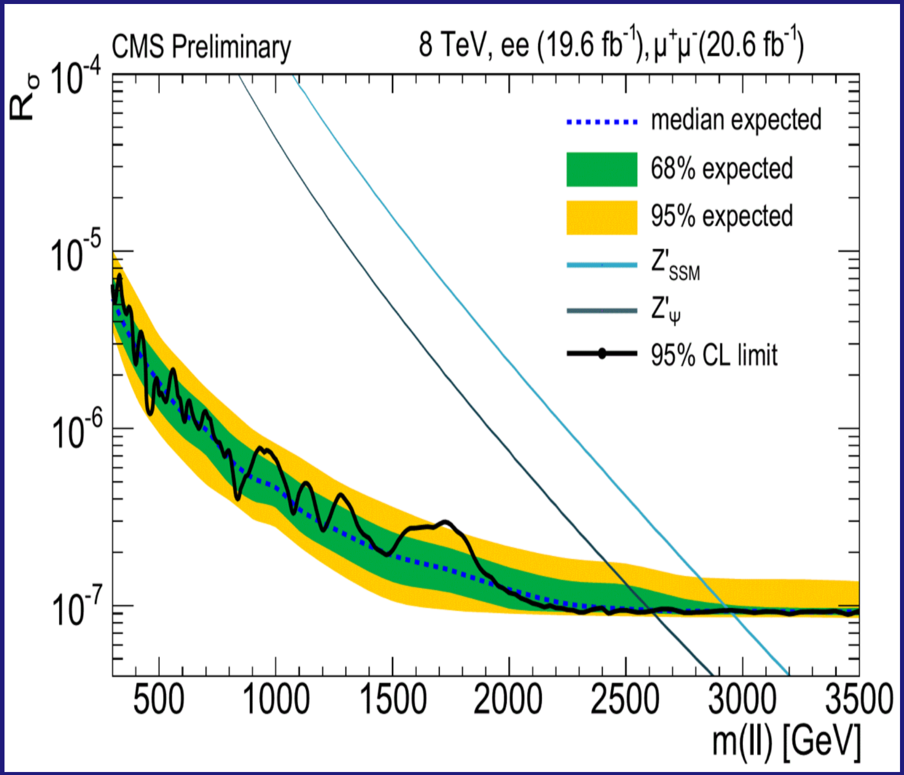
Excess seen in 7 TeV data just below 1 TeV not confirmed in 8 TeV.

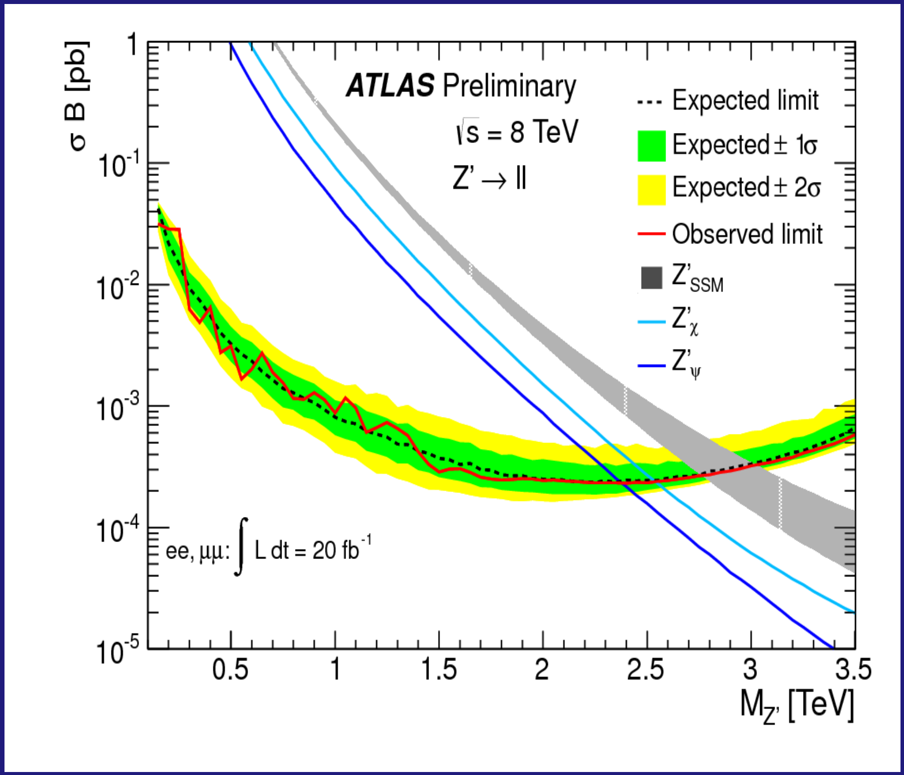
Searches : Z' → ll



Data consists with the SM background ….. No excess observed.

Searches : Z' → ll





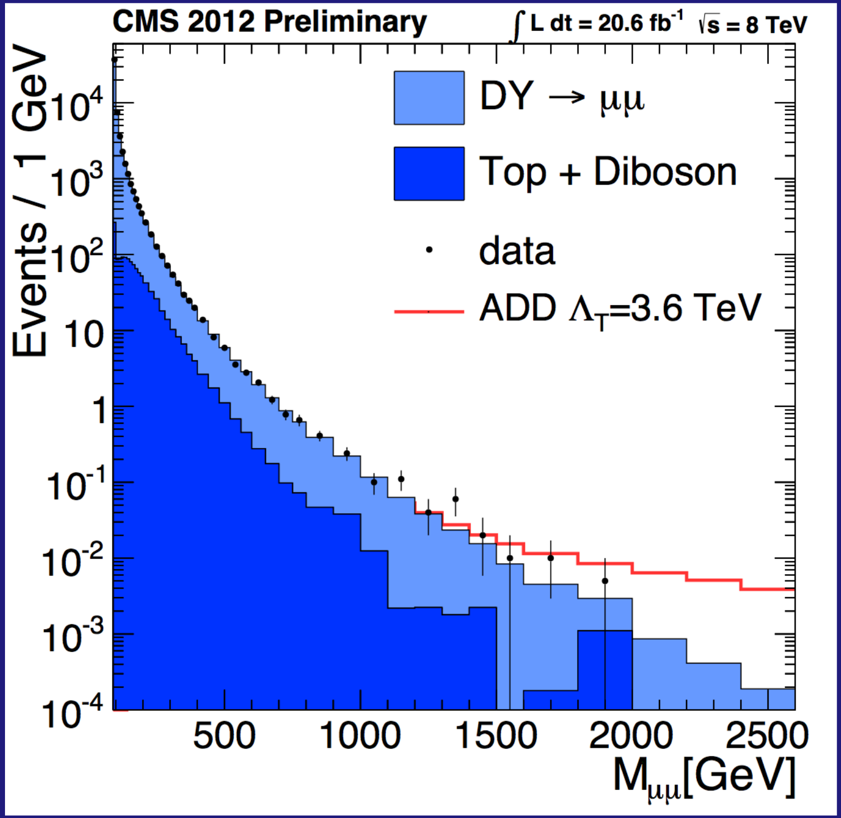
$M(Z'_{SSM})$	expected	observed
CMS	> 2.96 TeV	> 2.96 TeV
ATLAS	> 2.85 TeV	> 2.86 TeV

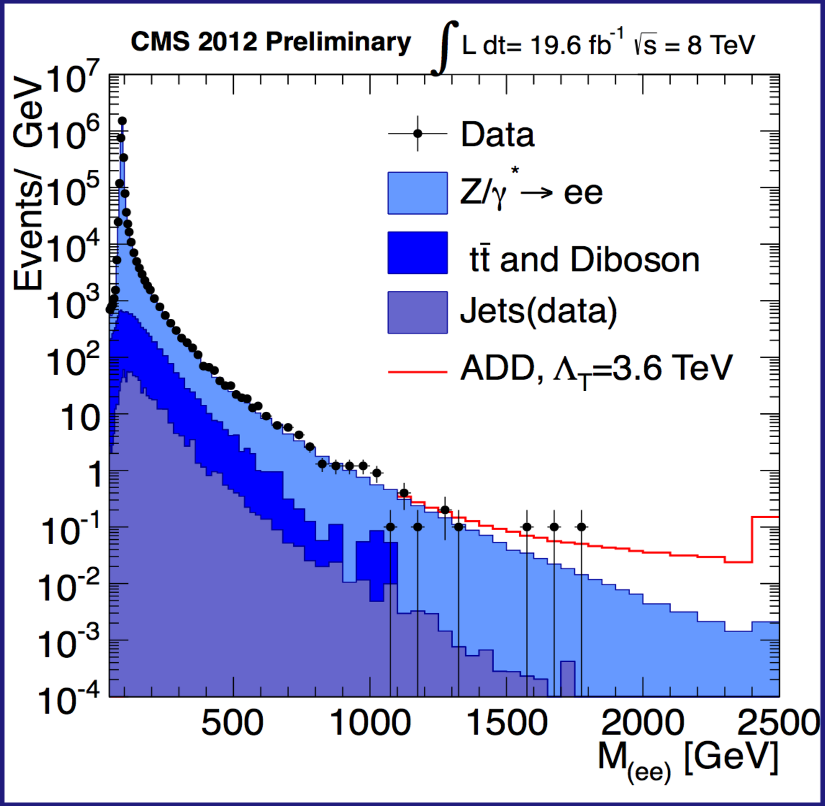
Searches : Extra Dimension in Dilepton

Extra Dimension search in dilepton invariant mass spectra (same as Z')

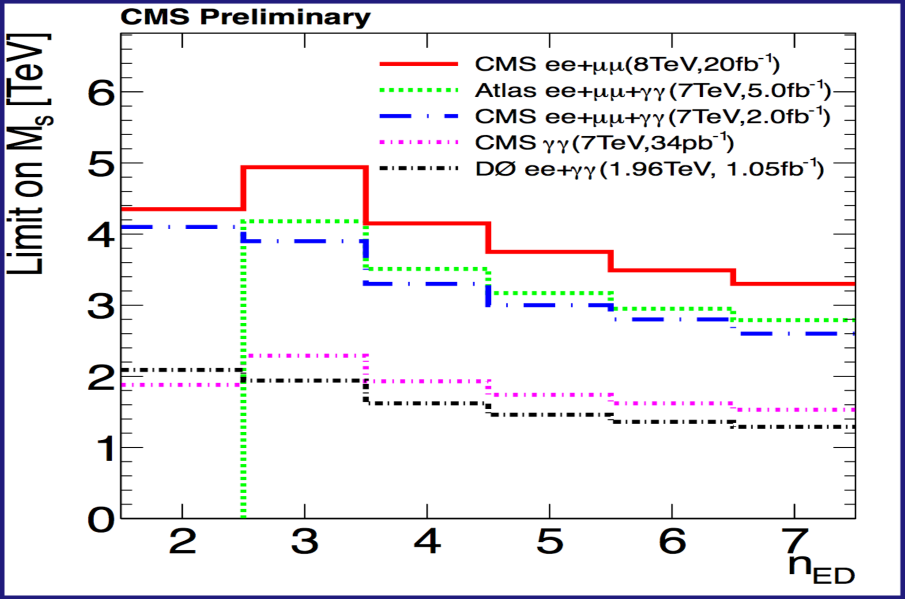
Simple counting experiment on integral above a mass threshold

Leading systematics from momentum scale (muons) and PDF (electrons)



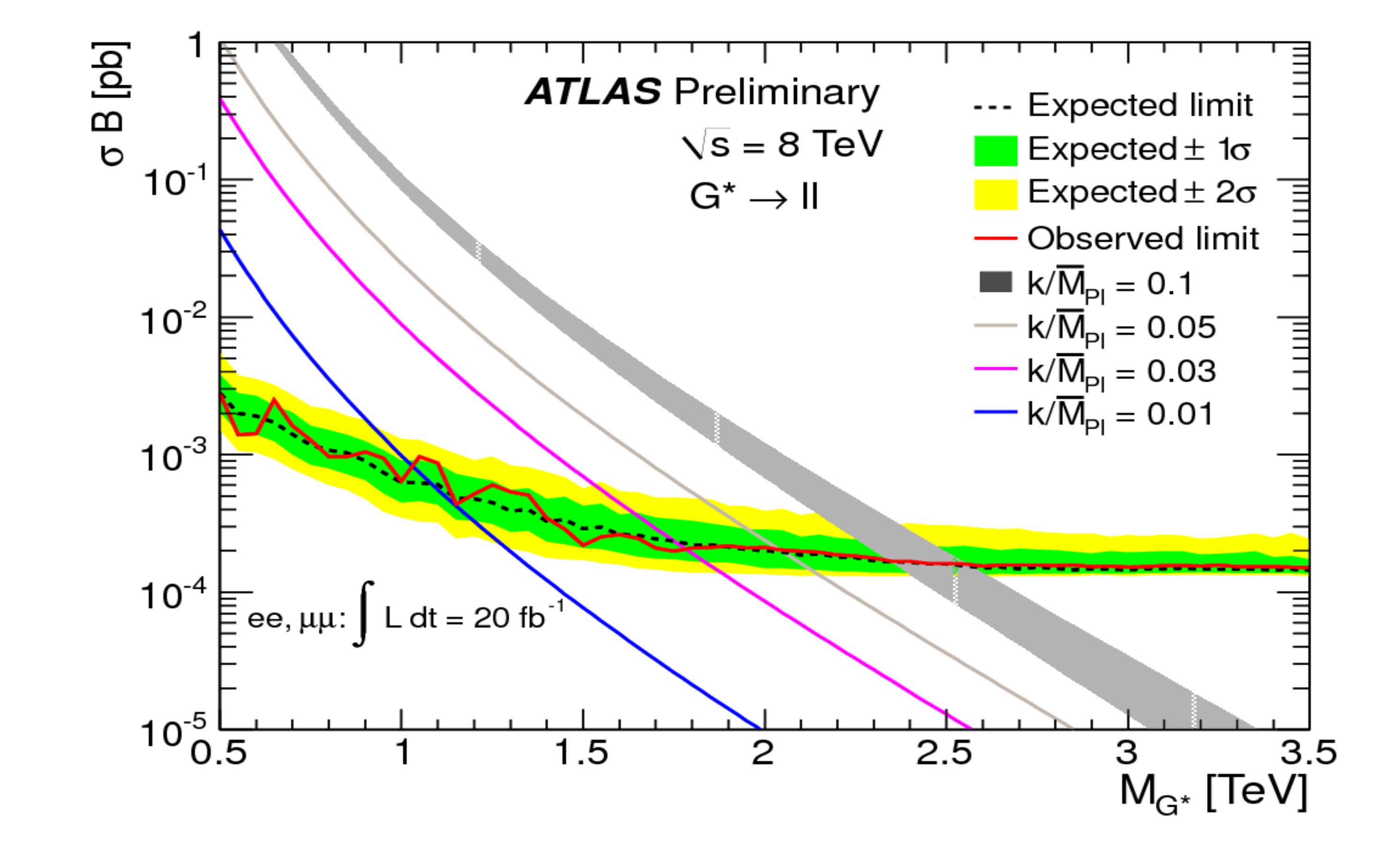


Searches : Extra Dimension in Dilepton



M_S (ADD) at LO 95% CL limits	Lumi. [fb^{-1}]	δ=3 Exp. [TeV]	δ=3 Obs. [TeV]	δ=6 Exp. [TeV]	δ=6 Obs. [TeV]	Λ_T (GRW) [TeV] (GRW)
CMS dimuon	20.6	4.34	4.33	3.07	3.06	3.64
CMS dielectron	19.6	4.62	4.64	3.27	3.28	3.90
Combined:	20.6+19.6	4.76	4.77	3.37	3.37	4.01

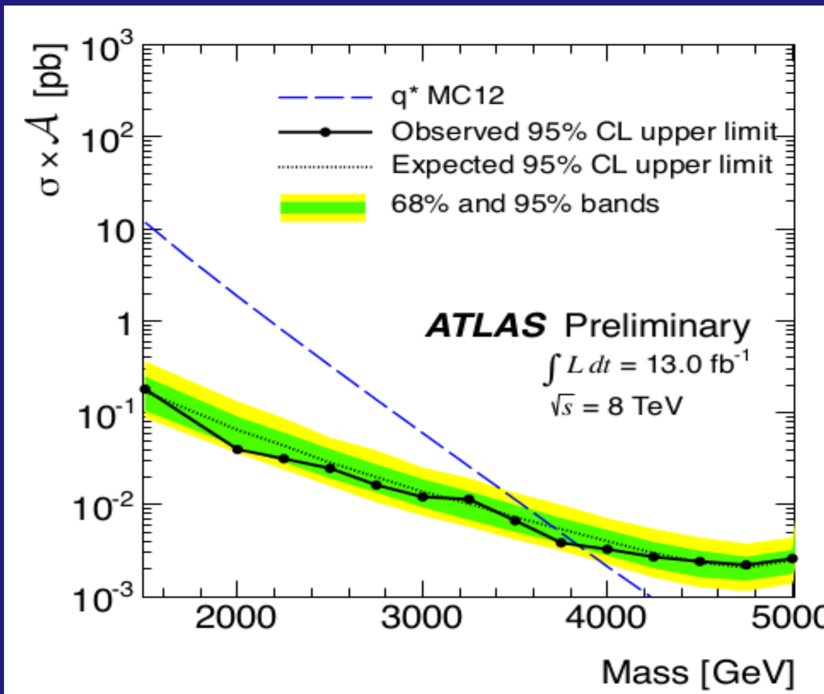
Searches : Graviton in Dilepton

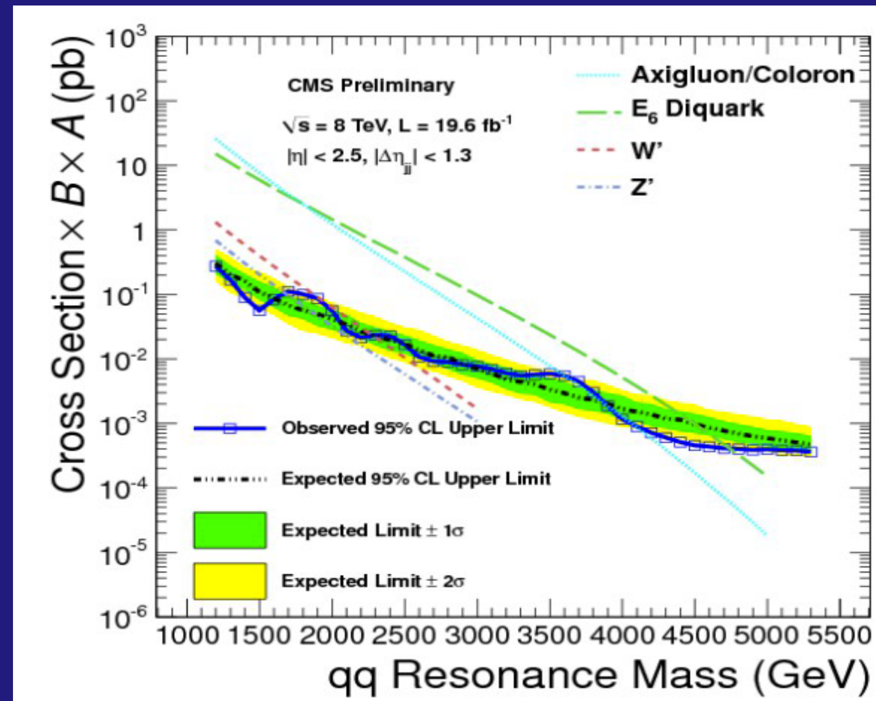


σB limits for graviton (G*) production for the combination of the dielectron and dimuon channels.

Searches : Dijet Resonances

Search dijet spectrum for narrow resonance





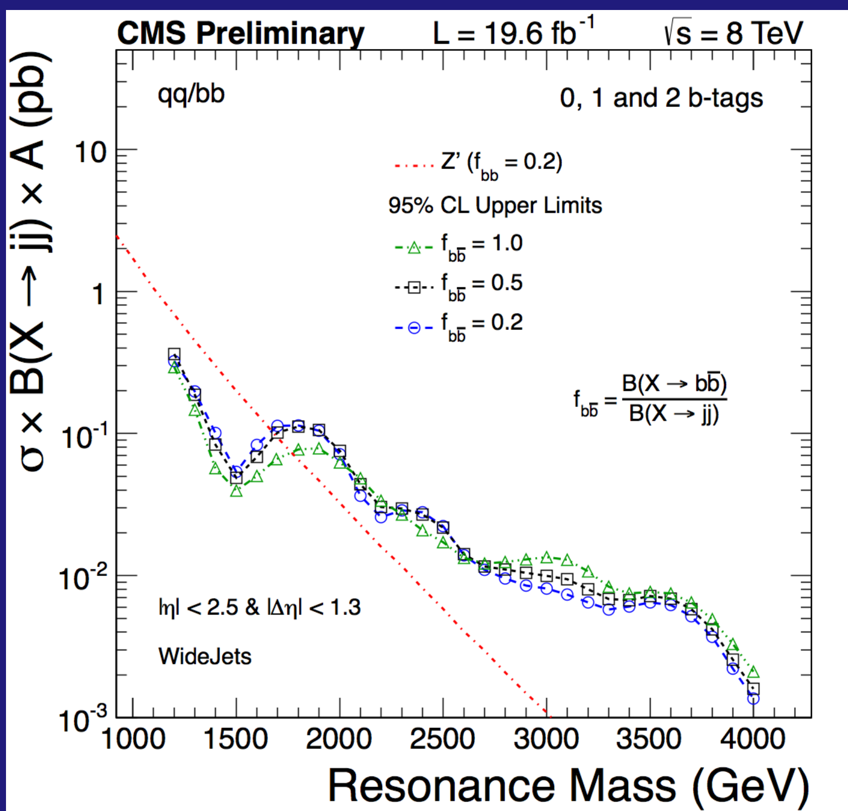
M(q*) 95% CL	Luminosity	Expected	Observed
ATLAS 2011	4.8	> 3.09 TeV	> 3.55 TeV
CMS 2011	5.0	> 3.27 TeV	> 3.05 TeV
ATLAS 2012	13.0	> 3.70 TeV	> 3.84 TeV
CMS 2012	19.6	> 3.75 TeV	> 3.50 TeV

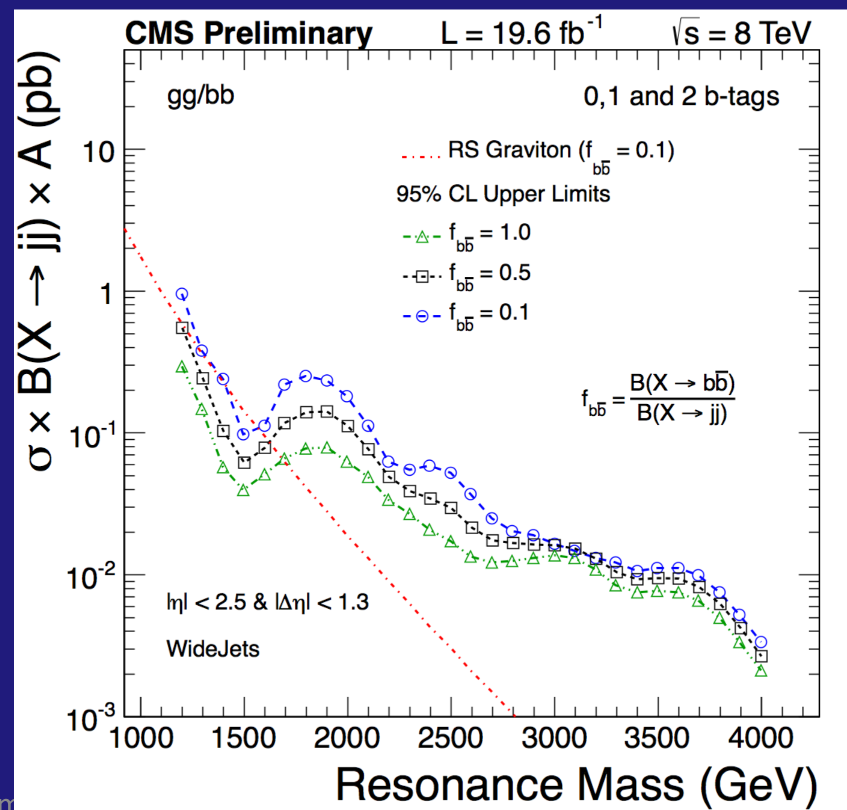
Searches : Dijet with b-tag

Dijet with 0, 1, 2 b-tags

- model-independent limits vs. BR
- Simultaneous search in 0, 1 and 2 b-tags
- Limits set on qq, gg and bg (Z’ , G_{RS} and b* models)

$$f_{b\bar{b}} = \frac{BR(X \to b\bar{b})}{BR(X \to jj)}$$



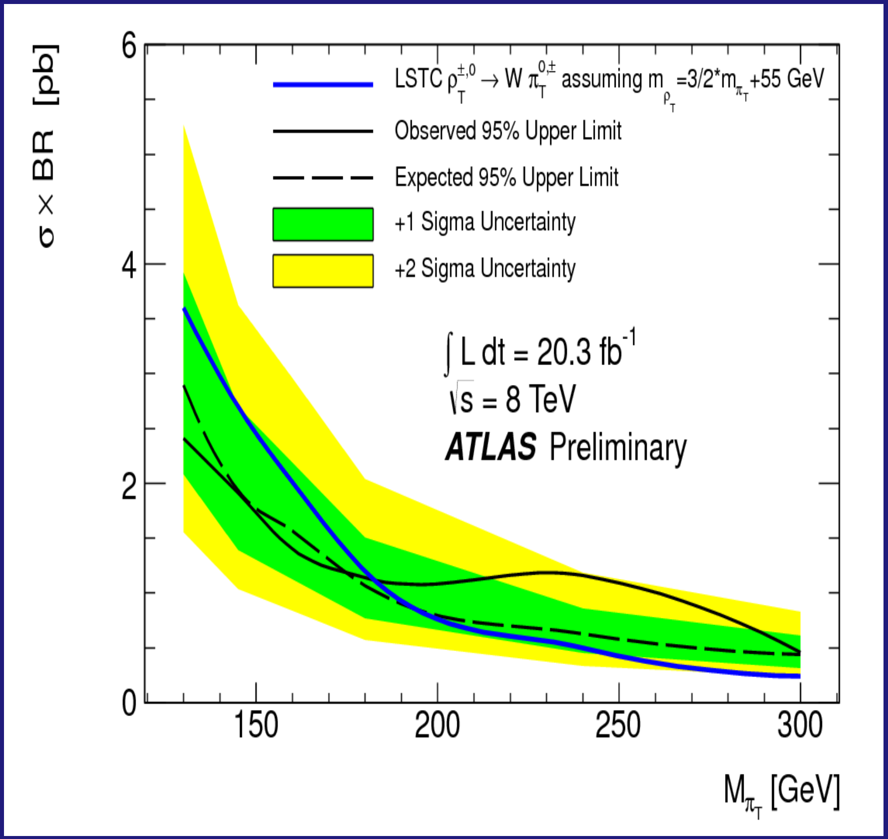


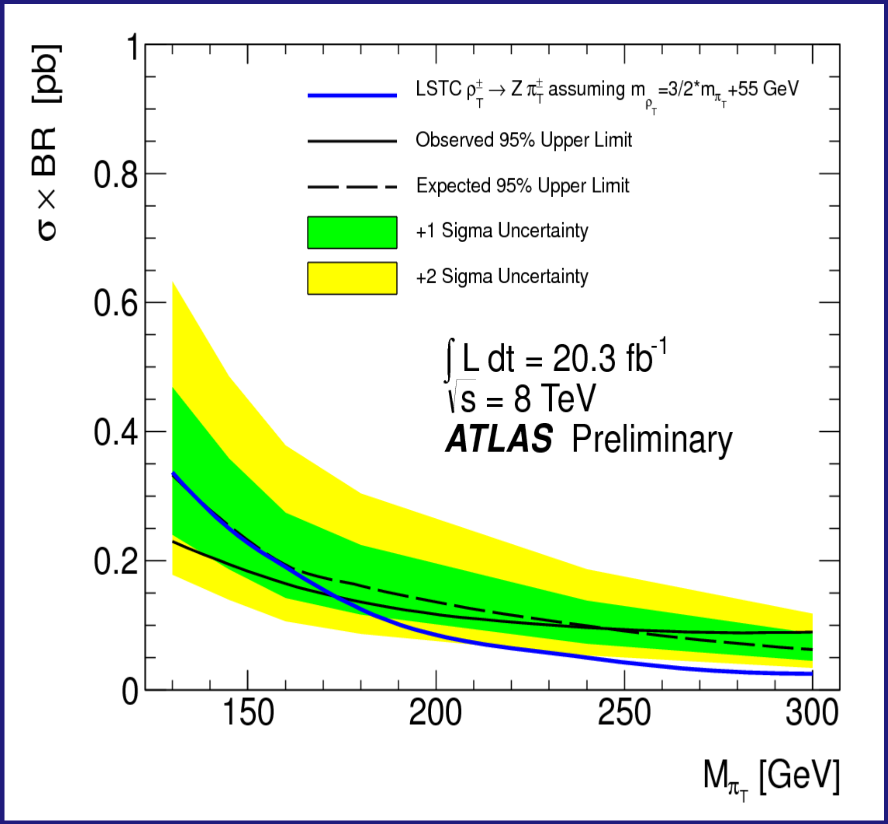
Searches : Dijet with leptonic V

Dijet produced in association with leptonically decaying W or Z.

Zjj where Z decays to mumu or ee.

Wjj where W decays to munu or enu.





Searches : 3-Jet Resonances

Search for strongly coupled resonances decaying to three jets

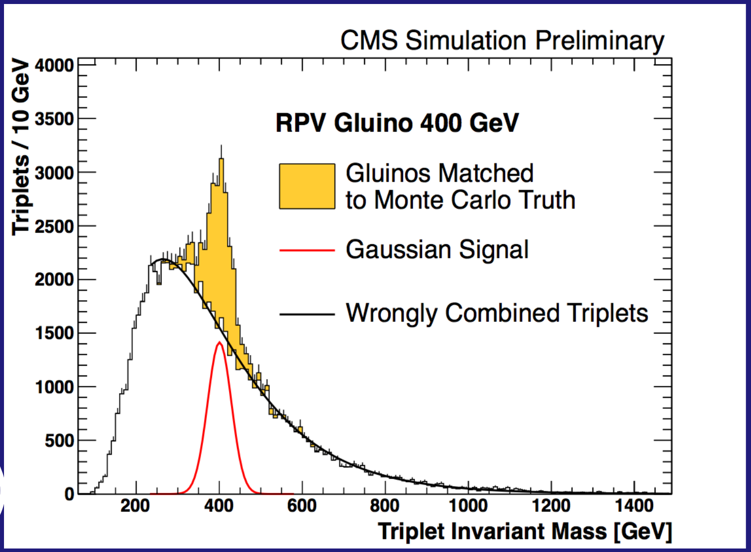
Benchmark: pair produced gluinos to three jets through UDD RPV coupling

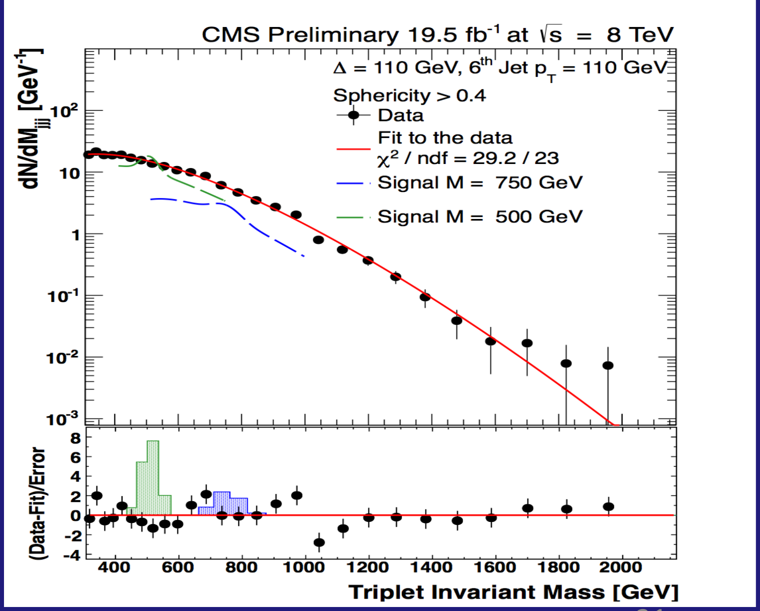
Event Selection

- ≥6 jets > 60 GeV (1^{st}–4^{th} jet > 80 GeV)
- Use sphericity to suppress backgrounds at high mass
- Apply b-tagging for gluino ⟶ udb/csb scenario

Combine the six highest p_T jets into 20 unique triplet combinations

To suppress wrong combinations and QCD, only accept triplets that satisfy

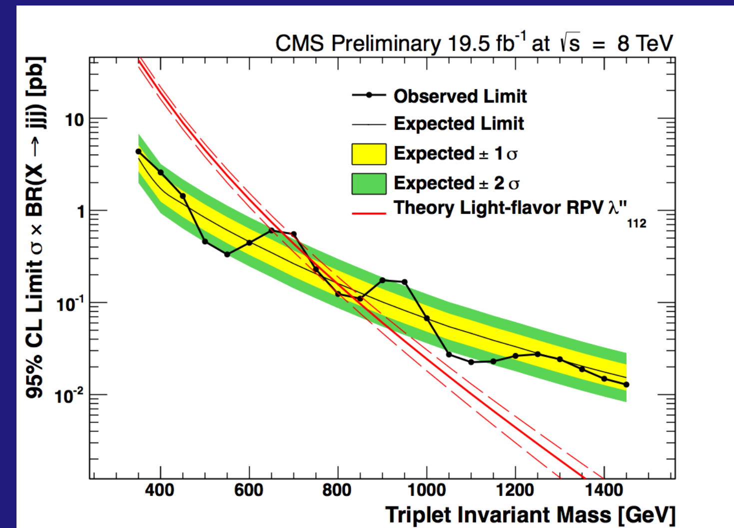




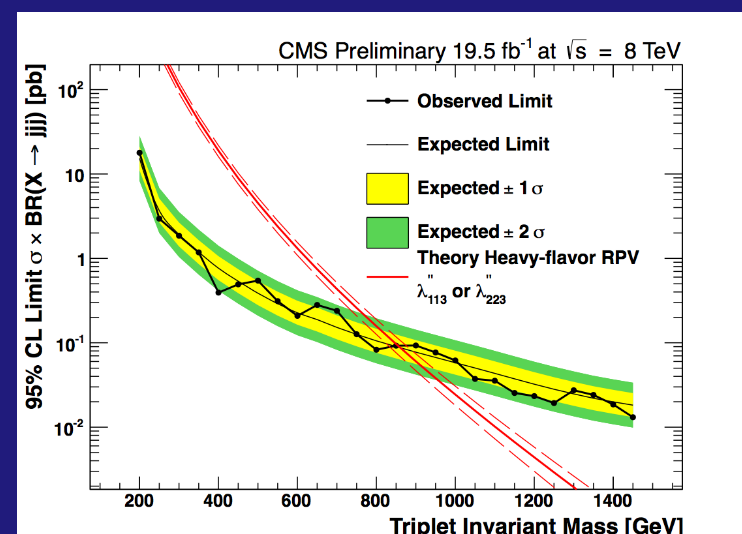
Searches : 3-Jet Resonances

Look for bump in falling spectrum

- For b-tagged result, QCD shape from b-vetoed data
- All-hadronic top bkgnd consistent w/ SM rate



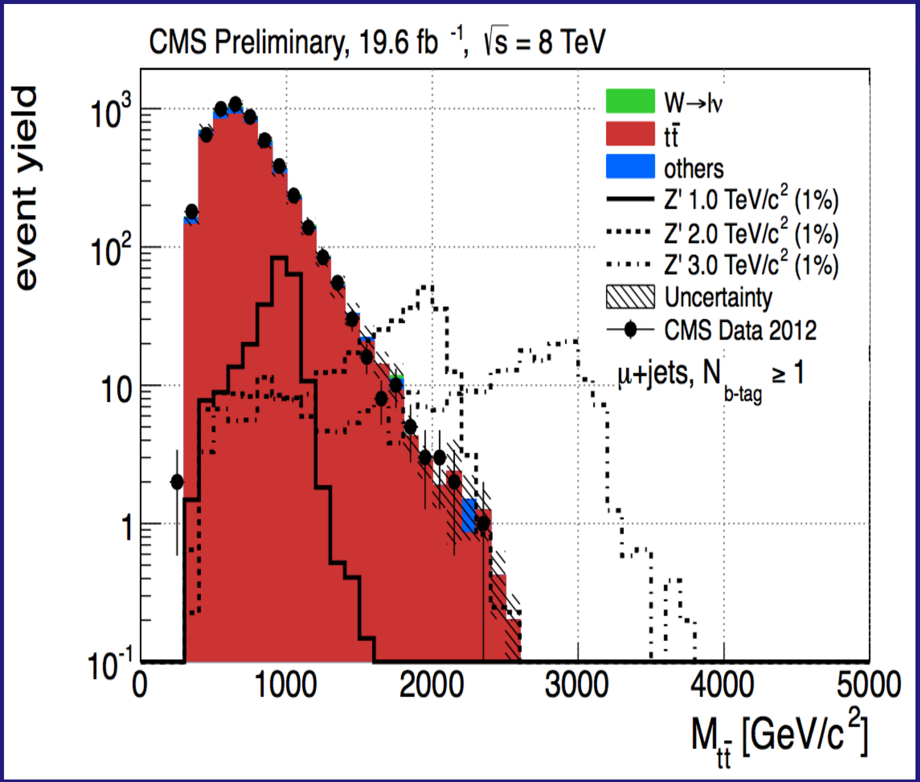
For a gluino decaying into light-flavour jets, a lower limit of 650 GeV on the gluino mass is set at a 95% confidence level, and for a gluino decaying into one heavy- and two light-flavour jets, gluino masses between 200 and 835 GeV are

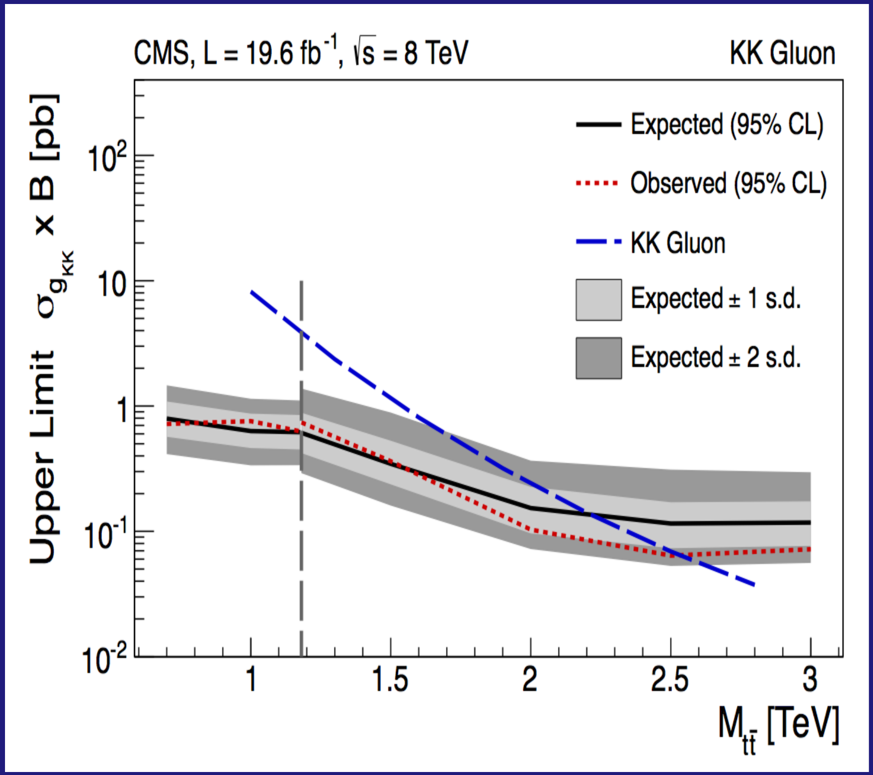


Searches : Semileptonic X⟶ tt Resonance

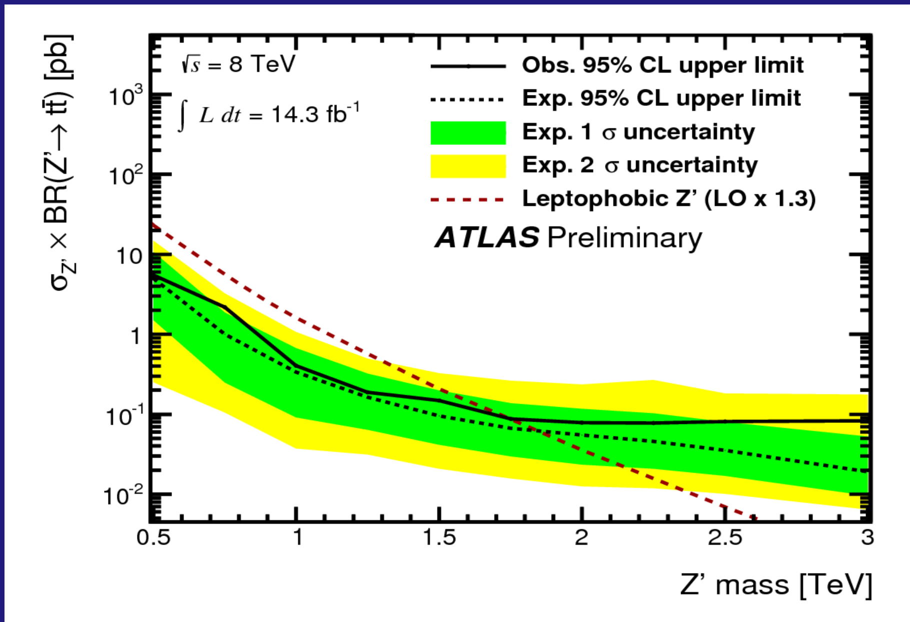
Search for heavy resonance decaying to ttbar in e or μ plus ≥2 jets

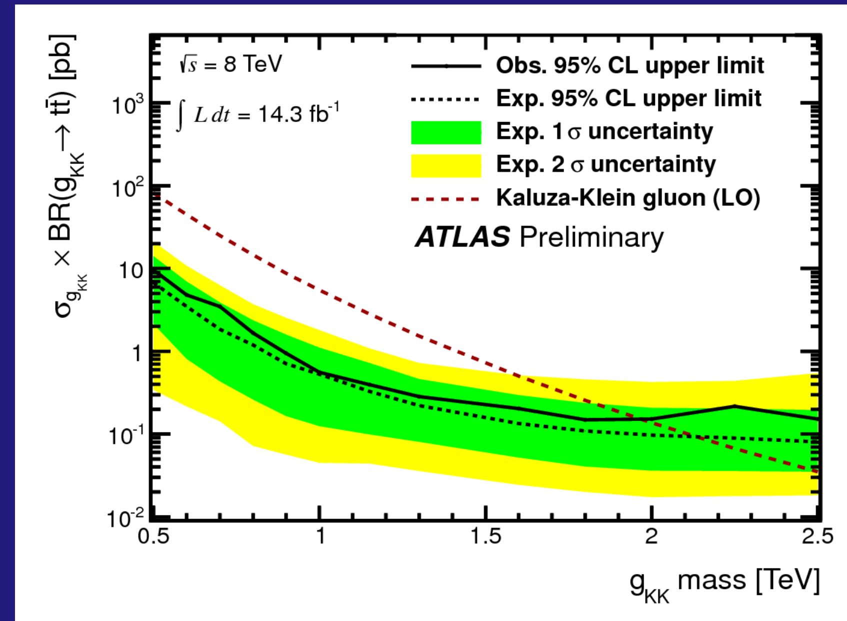
- Two search regions; resolved jets and high Lorentz boost (above ~1 TeV)
- ttbar and single top main backgrounds (especially after b-tagging), some W+jets
- Data-driven techniques used for some backgrounds





Searches : Semileptonic X⟶ tt Resonance





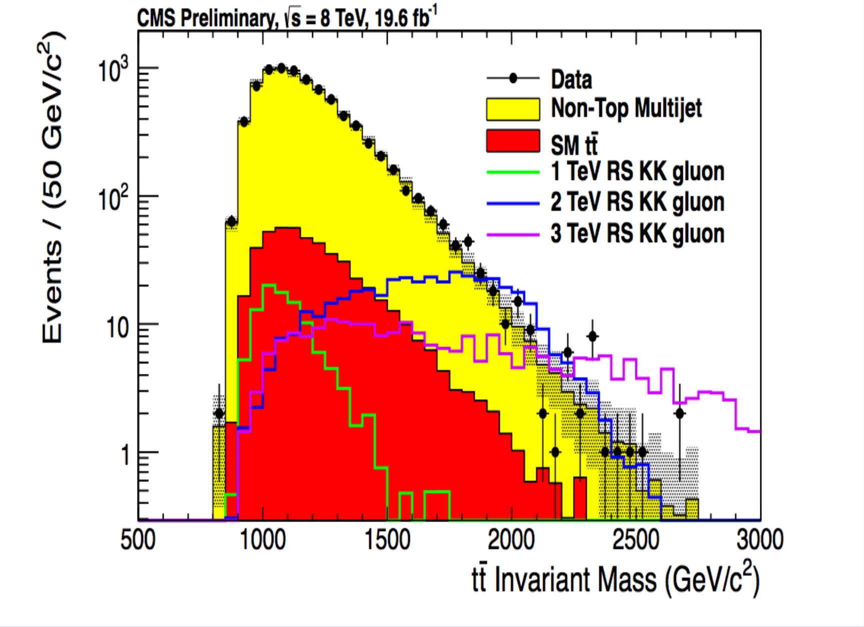
M(Z' or g_{KK}) 95% CL	Luminosity	Expected	Observed
ATLAS Z'	14.3	> 1.9 TeV	> 1.8 TeV
CMS Z'	19.6	> 2.0 TeV	> 2.1 TeV
ATLAS g_{KK}	14.3	> 2.1 TeV	> 2.0 TeV
CMS g_{KK}	19.6	> 2.2 TeV	> 2.5 TeV

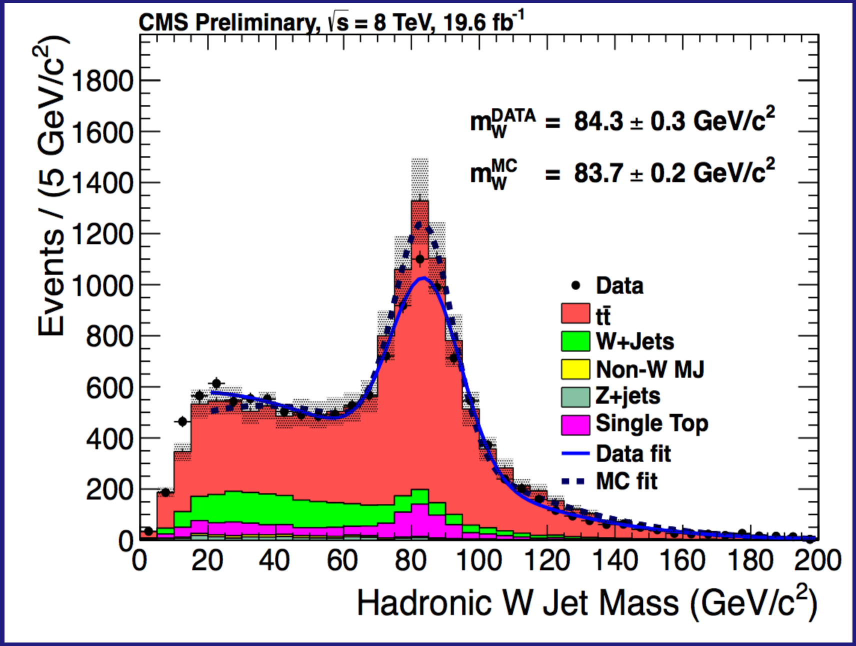
Searches : Hadronic X⟶ tt Resonance

Selection and tagging:

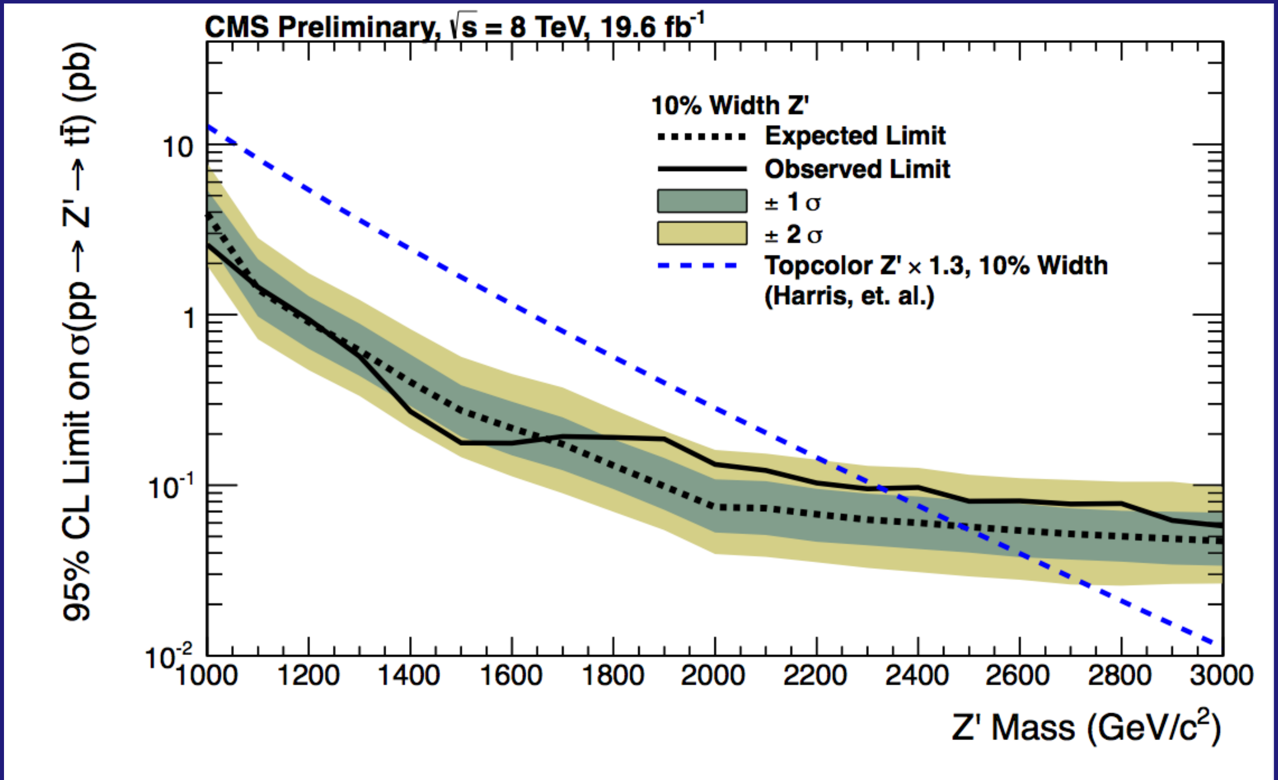
- Top-tagging: requirements on # of subjets, jet mass, minimum pair- wise mass (W)
- 2 jets, Cambridge-Aachen with R=0.8
- Scale factor measured in orthogonal muon+jets sample

QCD background determined from applying mistag rate to un-tagged dataset





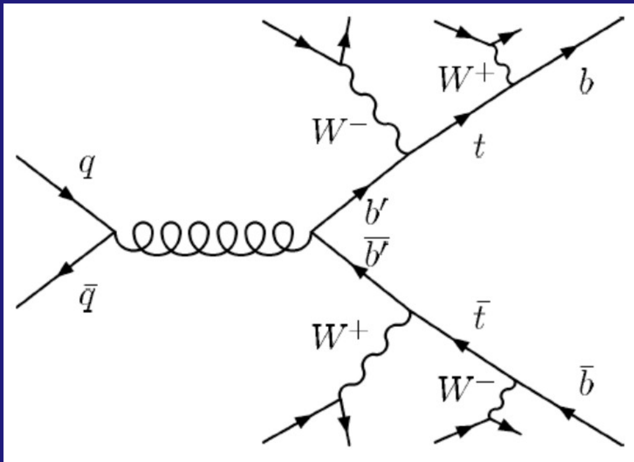
Searches : Hadronic X⟶ tt Resonance



Limits on $M(G_{KK}) < 1.8$ TeV, $M(Z') < 2.5$ TeV

Searches : 4th Generations

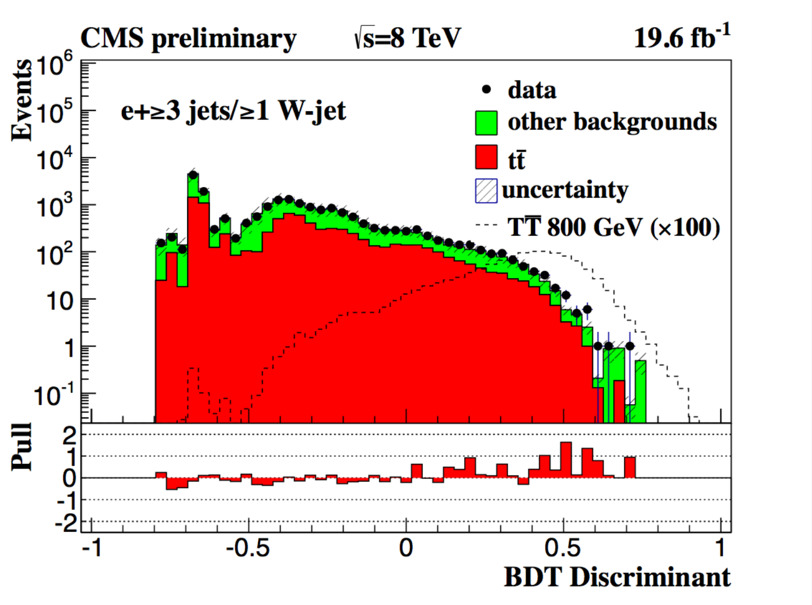
A non-SM 4th generation or massive partner to top quark
–Can enhance CP violation, heavy ν could be a DM candidate, could help stabilize Higgs mass in absence of MSSM
–Vector-like T predicted in Little Higgs models and in warped extra dimensions
•Inclusive search for:
–$pp \rightarrow TT$: $2(T \rightarrow bW, tZ, tH)$ BF 0.50, 0.25, 0.25
: leptons + jets (bjets) (W-jets)

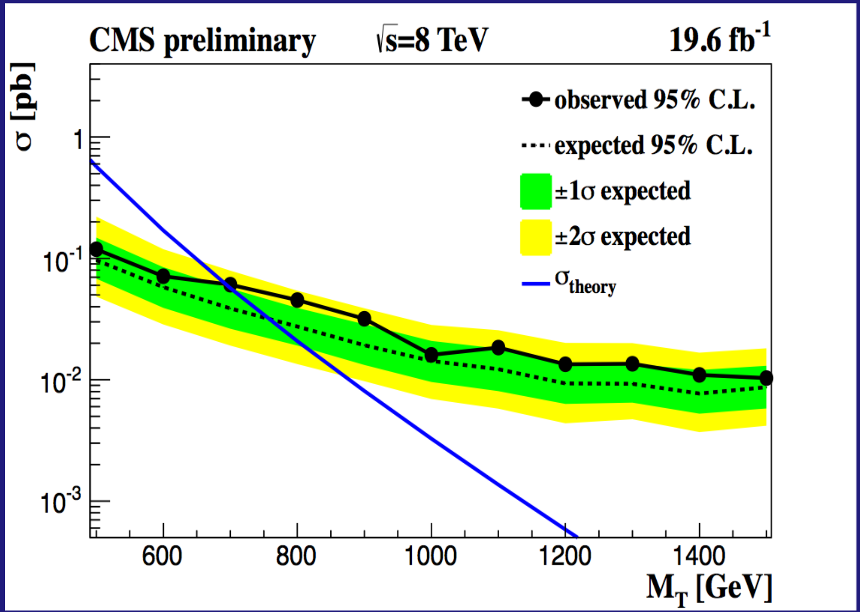


–**Single lepton channel:** 1 Isolated high pt lepton ($e\mu$) + ≥ 3 jets with 1 W-jet or 4th jet pT>35 GeV
–**Multi-lepton channel:** exactly 2 or 3 (SS/OS) leptons with n-jets/b-jets consistent with topology
–Use jet substructure techniques used to refine the merged jets "W-jets"

–Single lepton + jets uses a BDT (max sensitivity)
–Multi-lepton (2 or 3 leptons) 12 cut & count categories OS, SS …
–All channels combined in limits.

Searches : Vector Like T'⟶ tZ/tH/bW



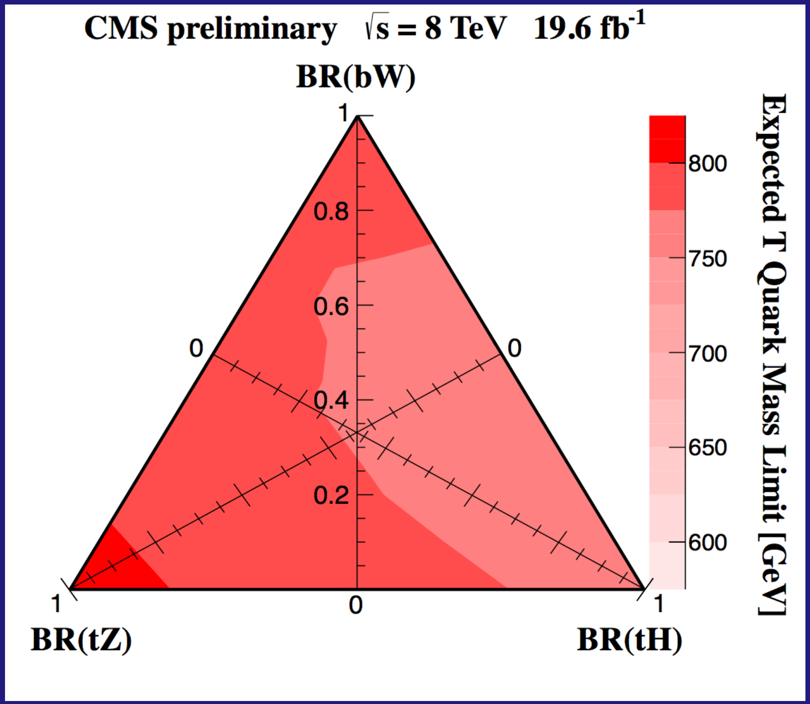


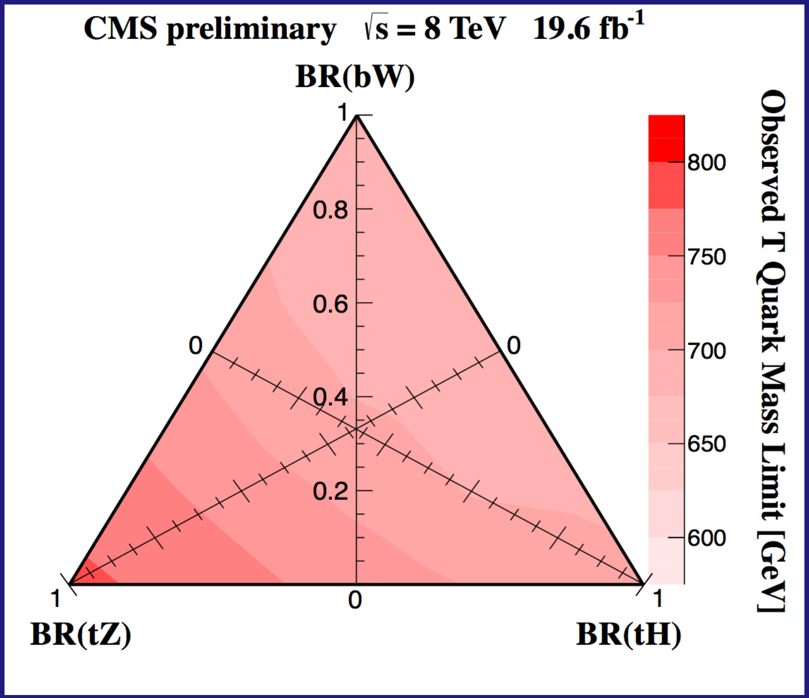
Combined information from single lepton, SS and OS dilepton, trilepton (+jets)

Separate bins by W-tags, #jets, #b-jets, H_T, MET, lepton p_T, 3rd/4th jet p_T

- Opposite-Sign targeting tZtZ & bWbW
- Same-Sign targeting tZ or tH + further categorization based on lepton flavor
- Multilepton category targeting tZ or tH + further categorization based on lepton flavor

Searches : Vector Like T'→ tZ/tH/bW



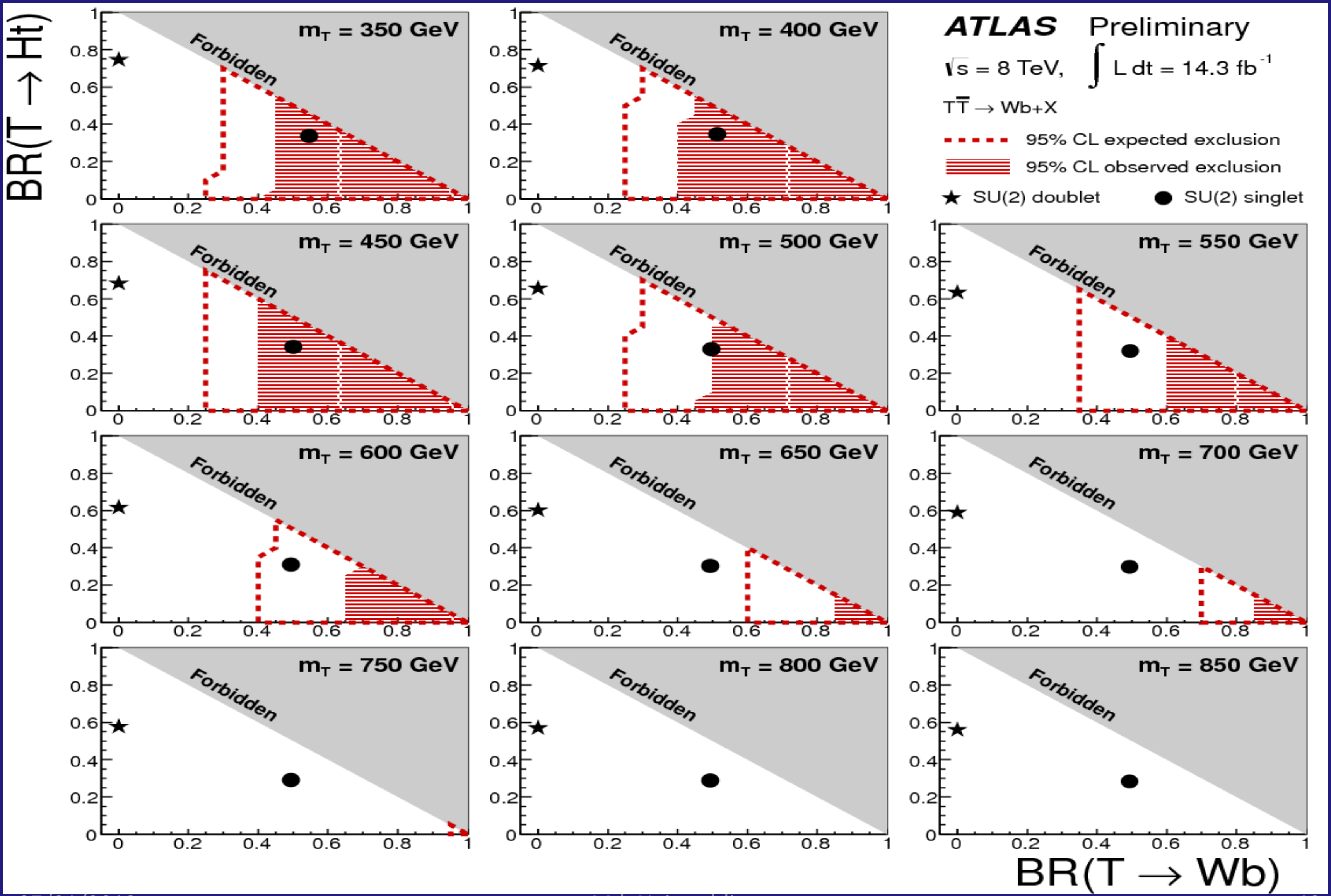


Limits for all possible BR

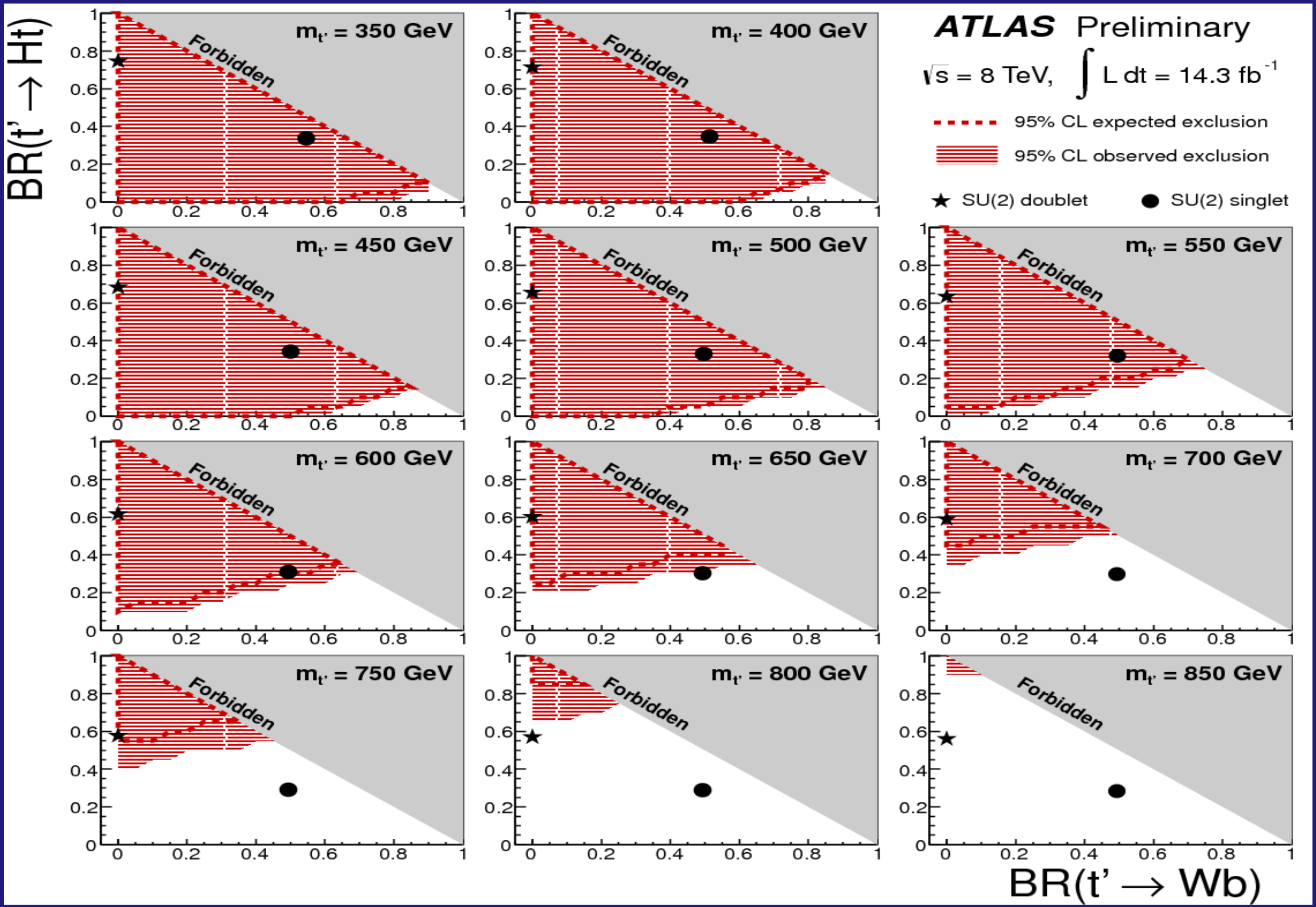
Combined limits for all channels

specific BR assumption of
BR(T' →bW/tH/tZ)=50/25/25%

Searches : Vector Like T'→ tZ/tH/bW



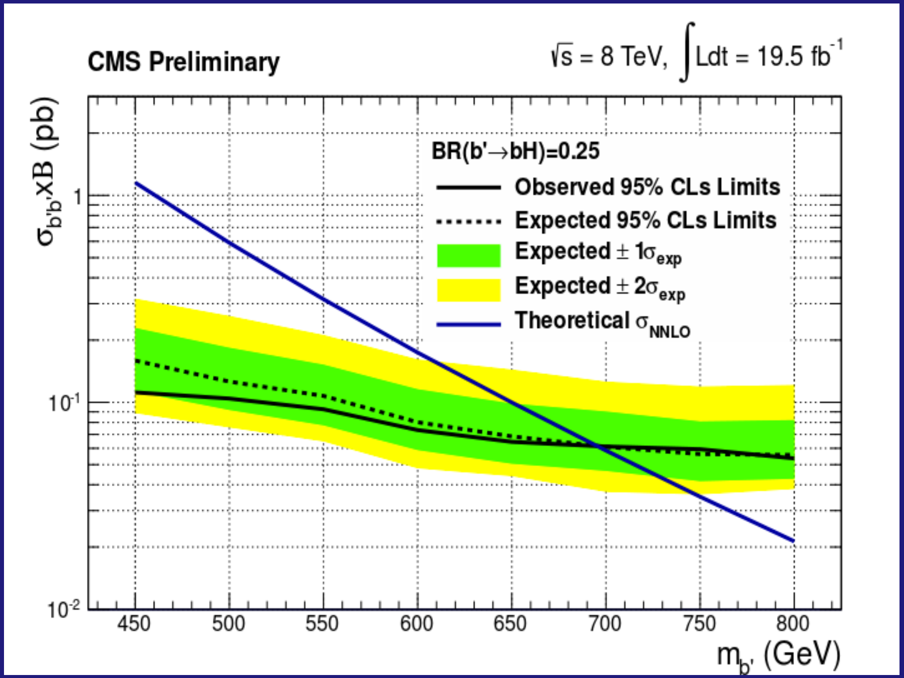
Searches : Vector Like T'→ tZ/tH/bW

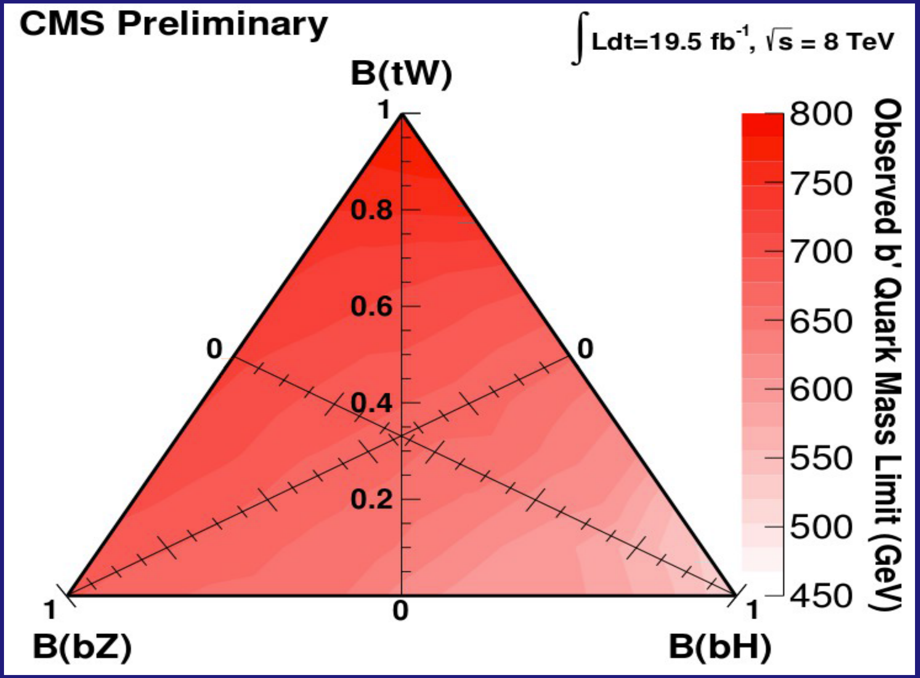


Searches : Vector Like b′→ tW/bH/bZ

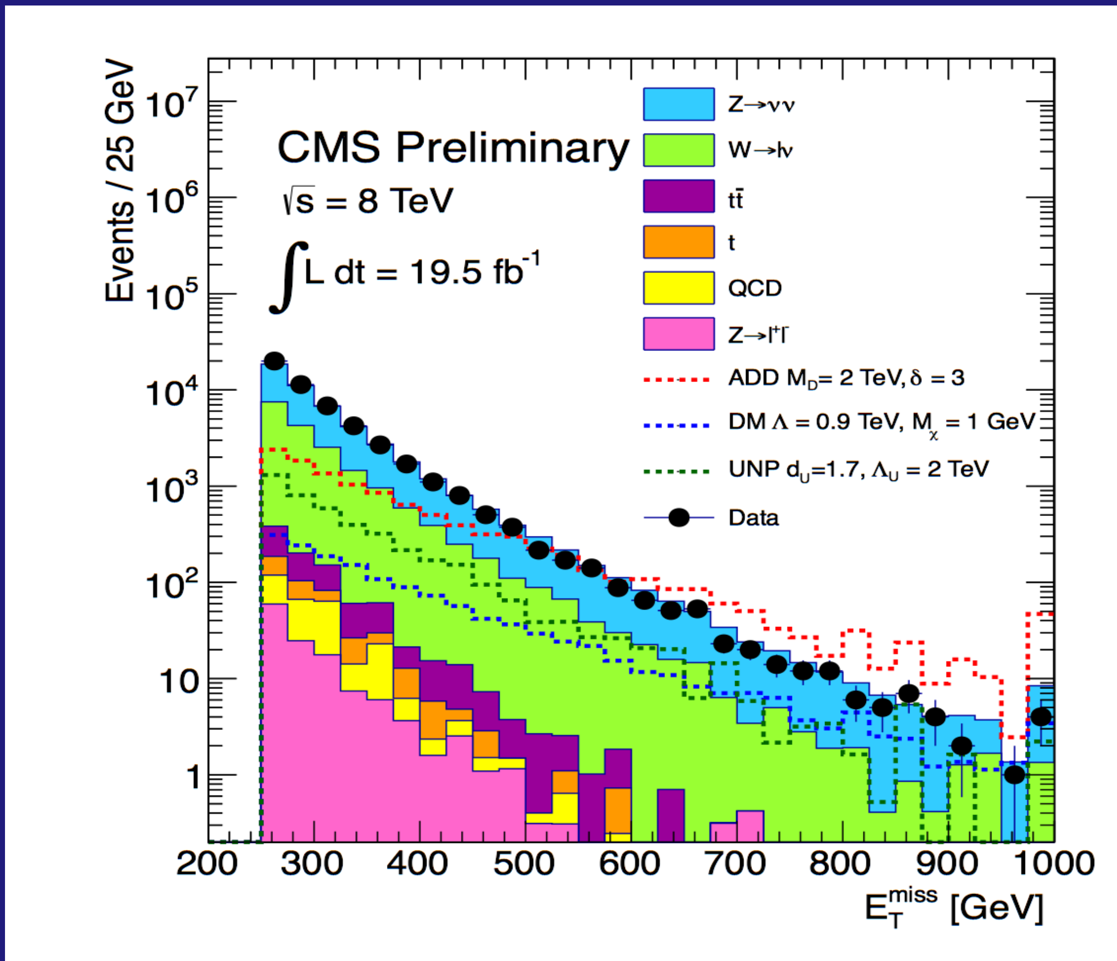
Vector like b quarks → tW, bZ and bH final states
Multi-leptons (> 2) + jets study (bZbZ; tWtW; bHbH; bZtW; bZbH; and tWbH)
SM Higgs with mass of 125 GeV is assumed
Both on- and off-shell Z mass ranges are considered
Main backgrounds: ttbar, dibosons and rare decays

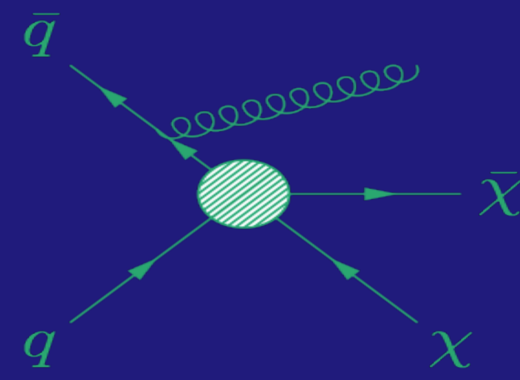
b → tW (50%), bZ (25%), bH (25%)





Searches : ADD from Monojets



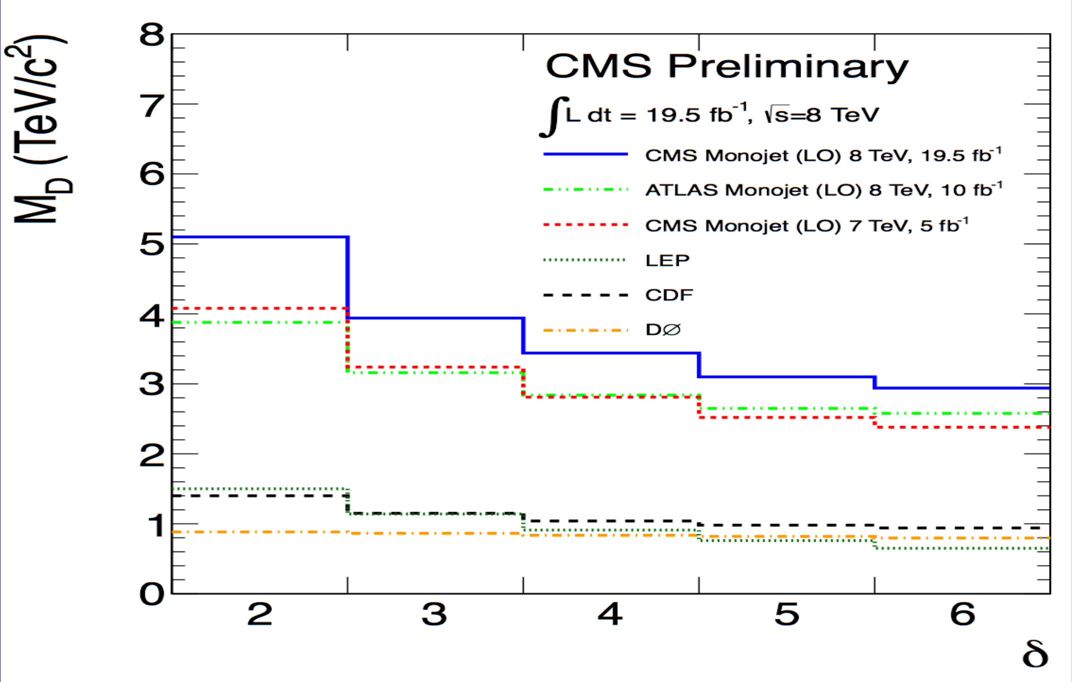


Search for Dark Matter in monojet and monophoton final states.
Limits are somewhat model-dependent as they are sensitive to the mass of the mediator; yet competitive
Offer unique sensitivity to DM-gluons couplings

$$M_{Pl}{}^2 \sim M_D{}^{2+n} R^n$$

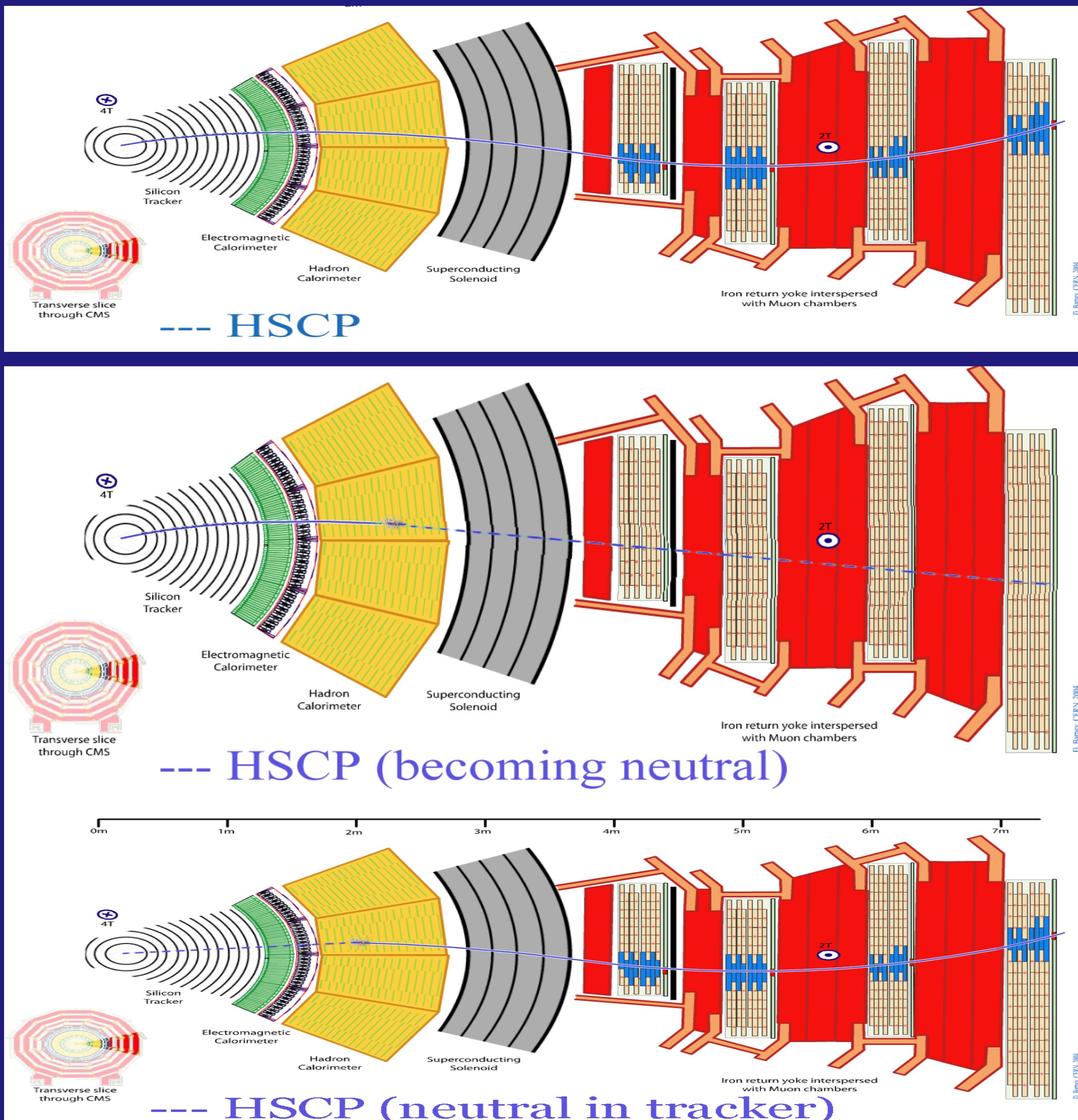
M_{Pl} = 4-dimensional Planck scale
M_D = fundamental (4+n)-dimensional Planck scale
n = number of the extra dimensions
R = size of the extra dimensions

Searches : ADD from Monojets



M_D (ADD) at LO 95% CL limits	√s [TeV]	Lumi. [fb^{-1}]	δ=3 Exp. [TeV]	δ=3 Obs. [TeV]	δ=6 Exp. [TeV]	δ=6 Obs. [TeV]
ATLAS Monojet	8	10.5	3.39	3.16	2.69	2.58
CMS Monojet	8	19.5	3.94	3.96	2.95	2.94

Searches : Long Lived



Heavy, (quasi-)stable, also charged: slow (β<1), high dE/dx, long time-of-flight

basic selection:

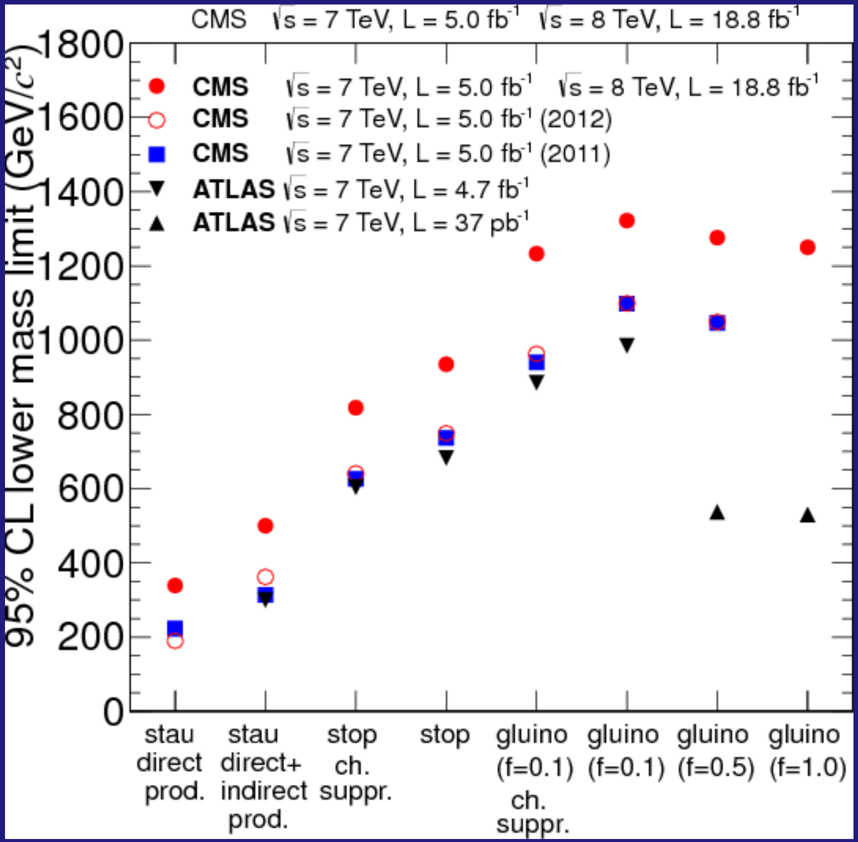
p_T > 45 GeV, $|\eta|$ < 2.1, $|d_{xy}|$ and $|d_z|$< 0.5 cm, very loose isolation, etc.

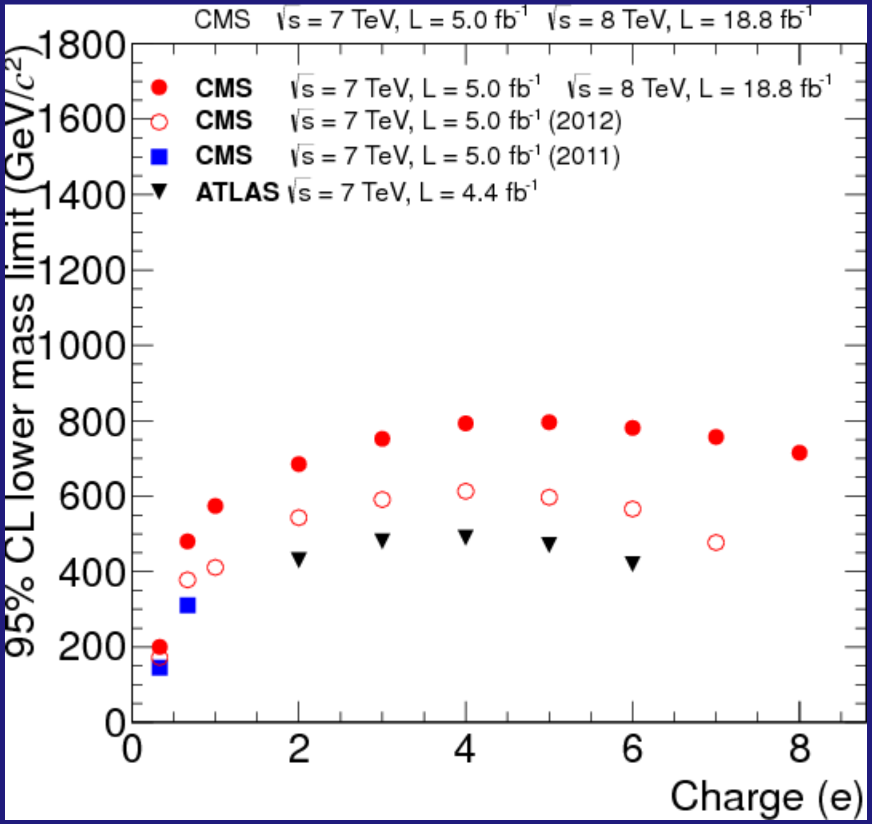
Track p_T : inner tracker transverse momentum

Muon 1/β : measured by muon system

Track I_{as} : incompatibility of the track energy loss w.r.t MIP expected dE/dx

Searches : HSCP

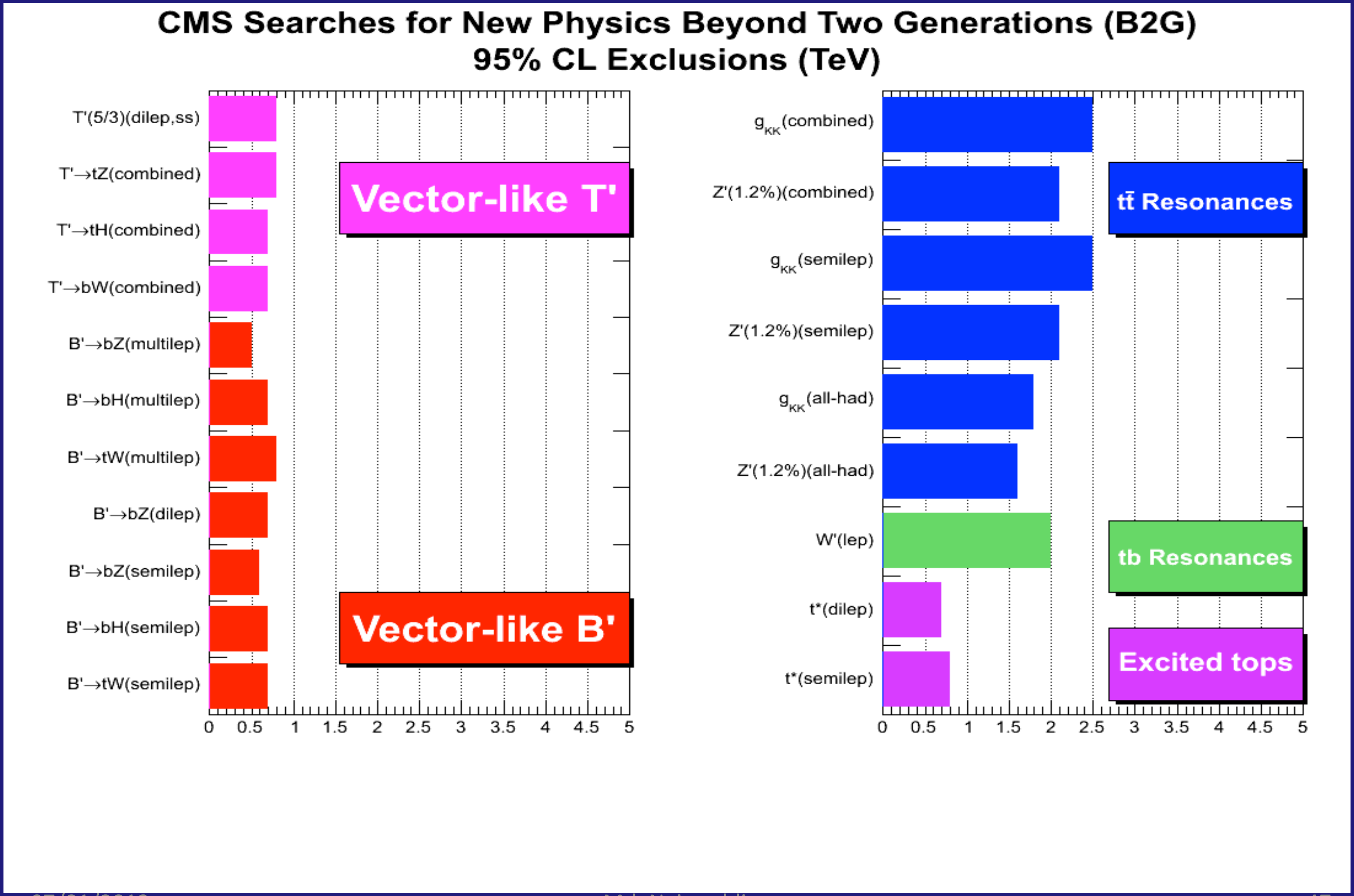




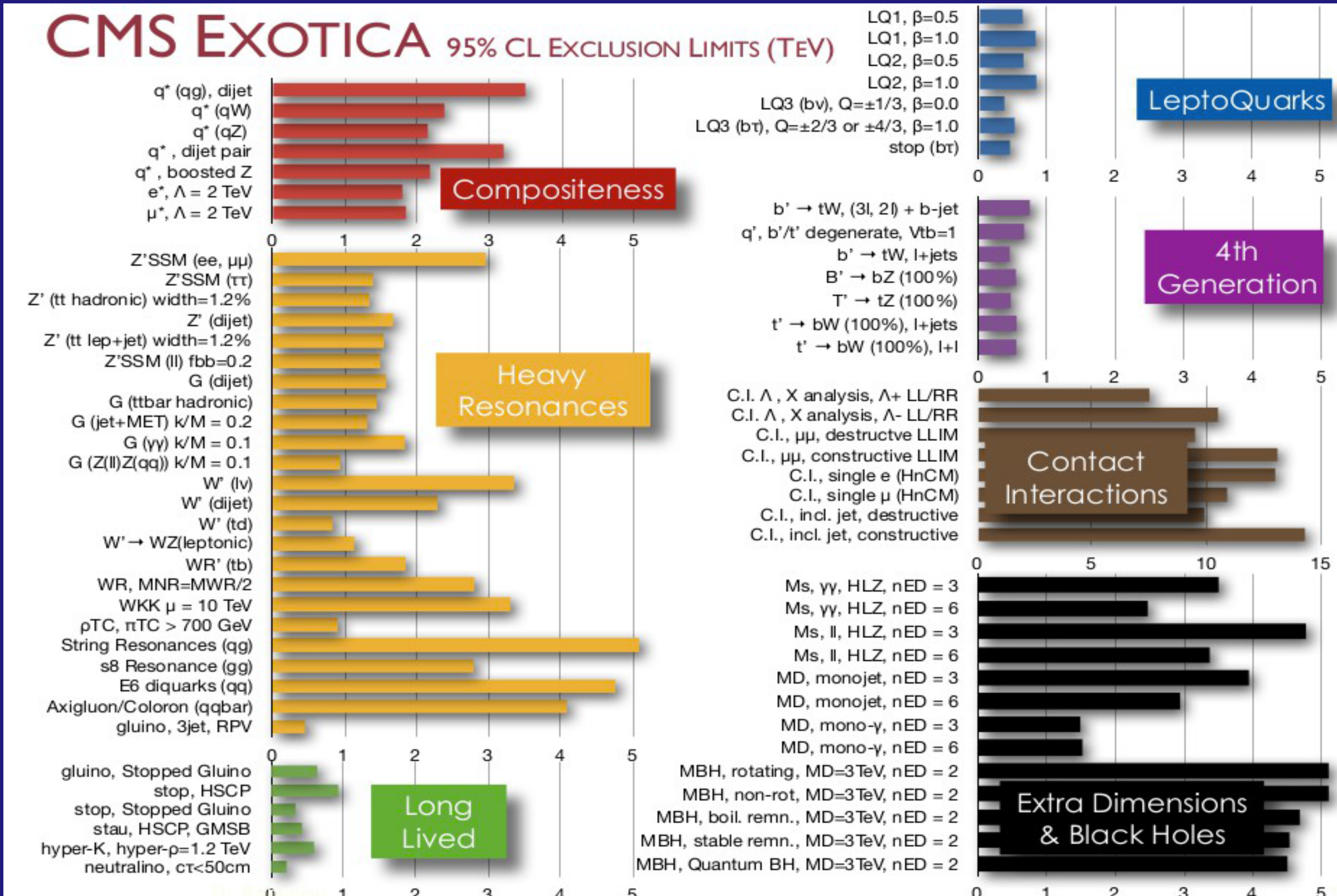
First CMS limits on gluino fully hadronizing into gluino balls (f=100%)

M_{Gluino} > 1322 GeV, M_{Stop} > 935 GeV

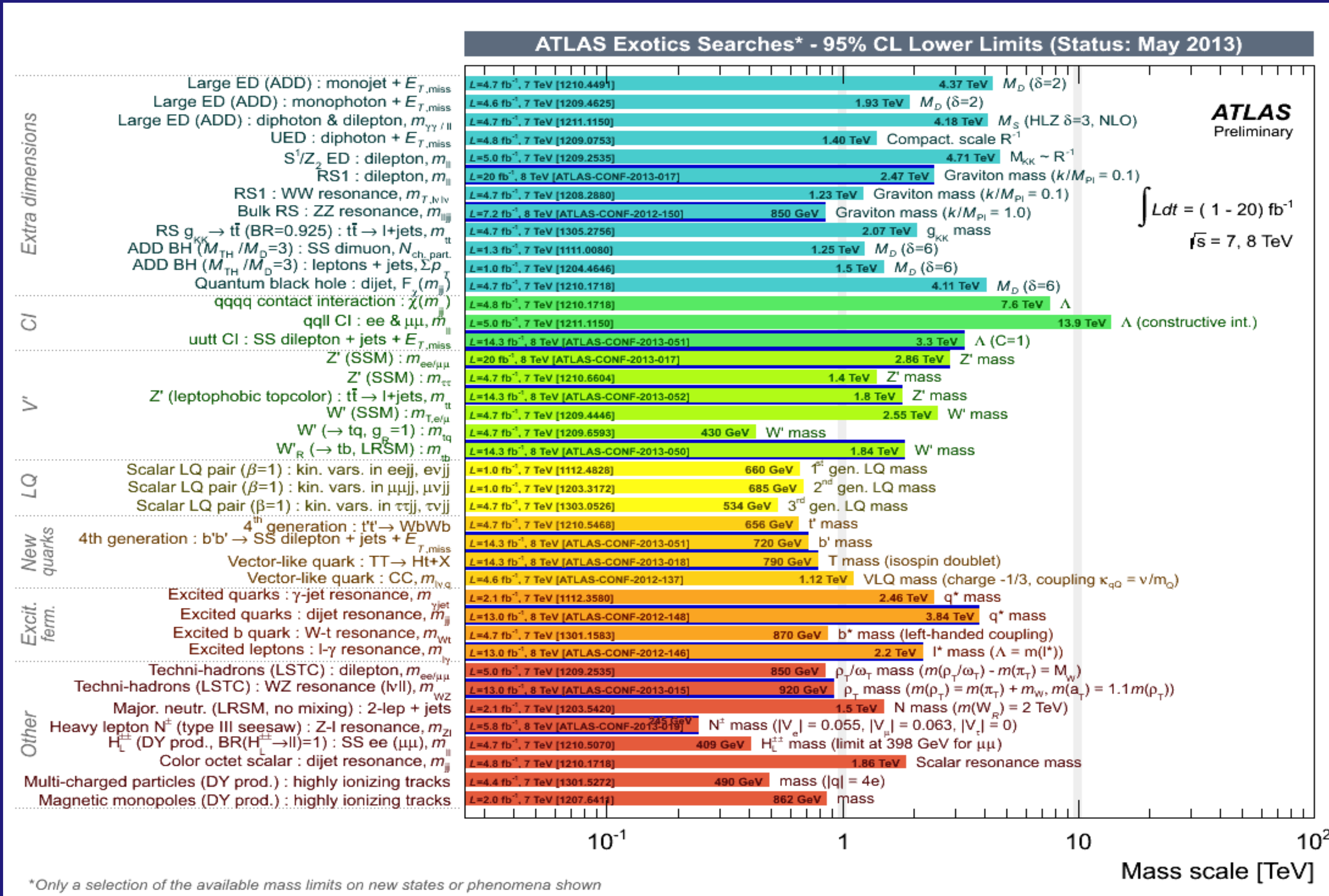
Review of New Physics Searches



Review of New Physics Searches



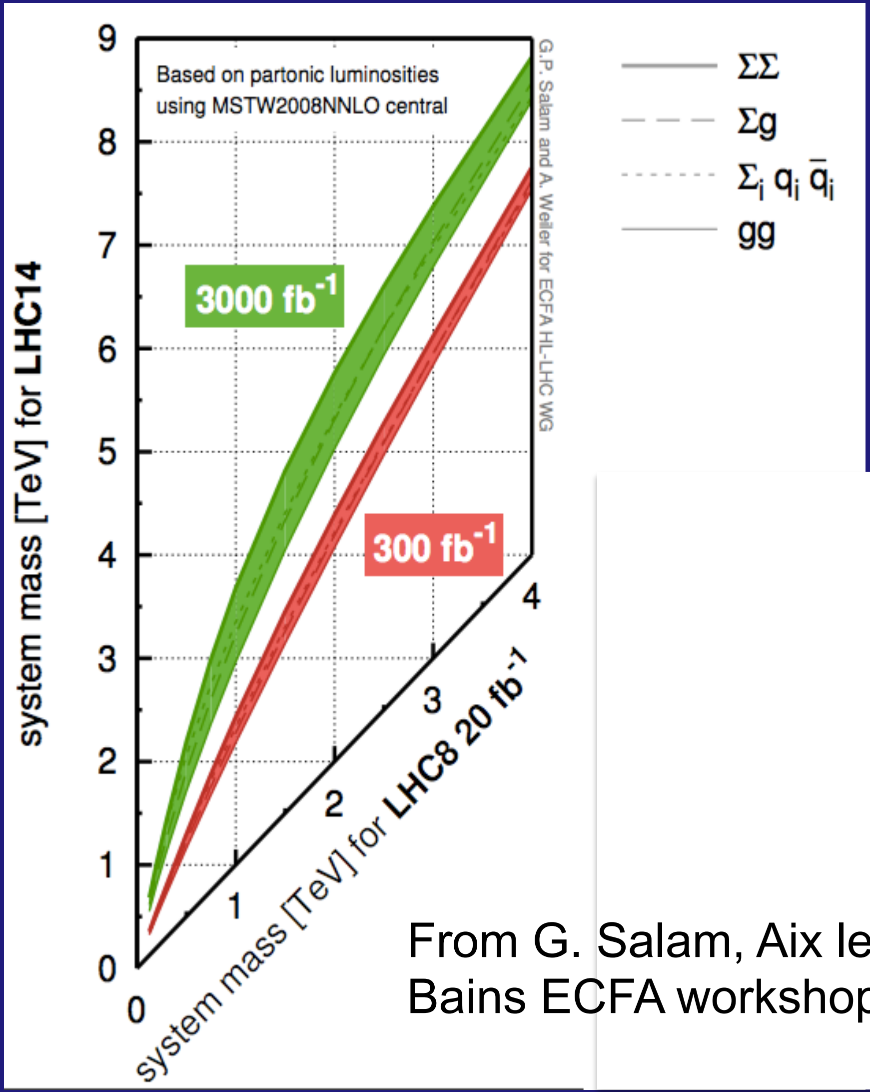
Review of New Physics Searches



Summary of New Physics Searches

- Searches for the physics beyond standard model has been performed in many channels in ATLAS and CMS.
- No signal of new physics observed in data yet.
- Most stringent limits to date has been put on the models across the broad phase space.
- But, its not over yet!

Searches : Future at LHC

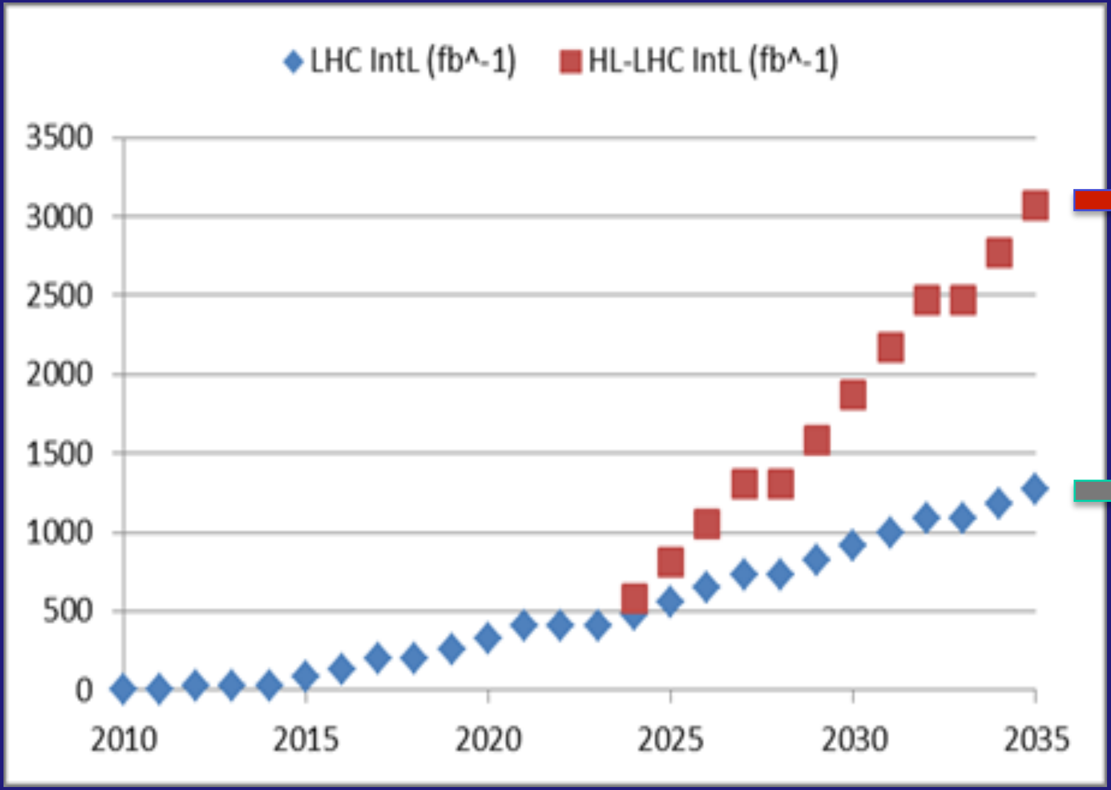


From G. Salam, Aix les Bains ECFA workshop

Reach of 14 TeV for new physics particle 'mass' (from parton luminosities ratios wrt to 8 TeV and for different integrated lumi)
Reality might be more difficult…but analysis will get smarter

The search is on!

Searches : Future at LHC



HL-LHC

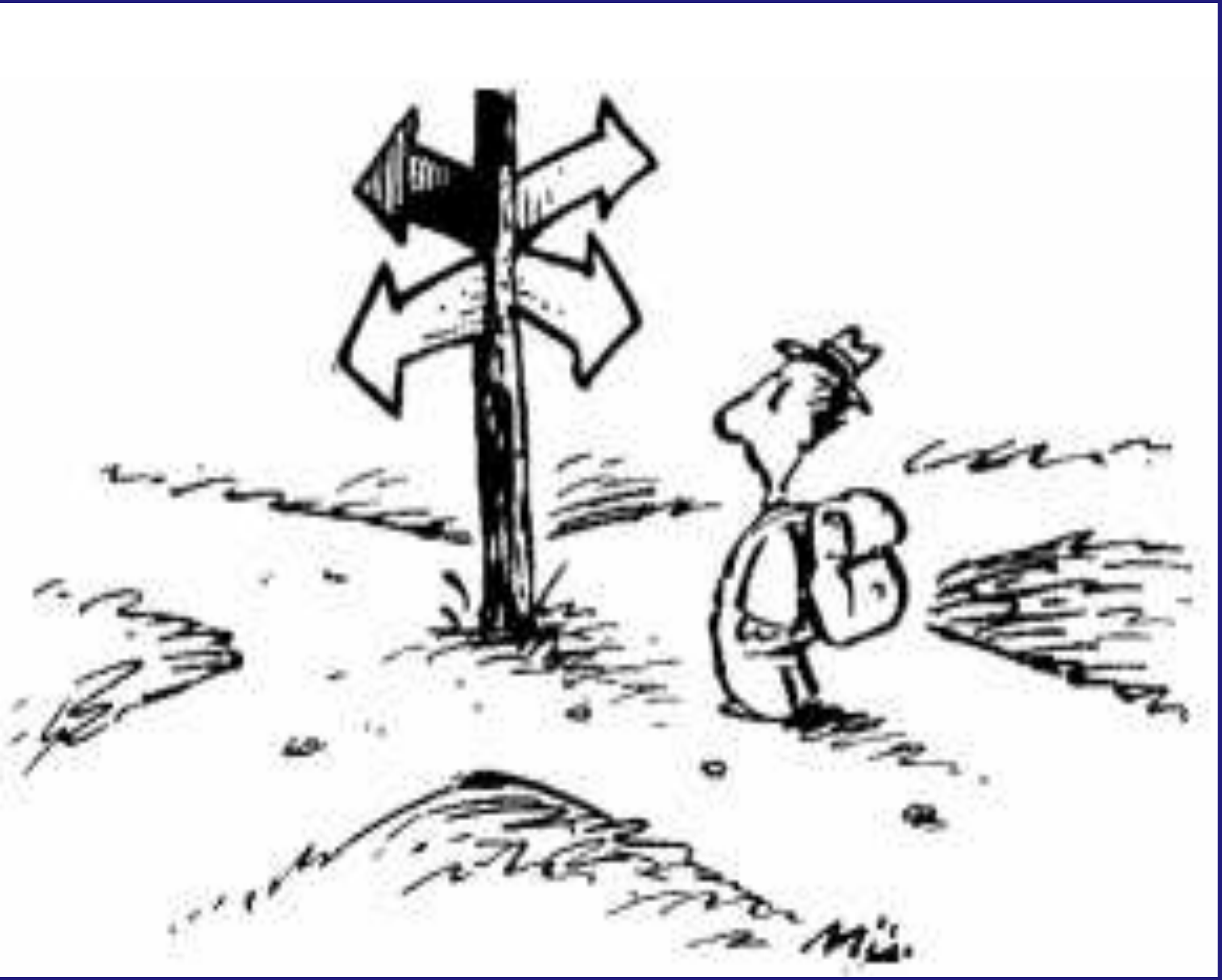
Almost a factor 3

By continuous performance improvement and consolidation

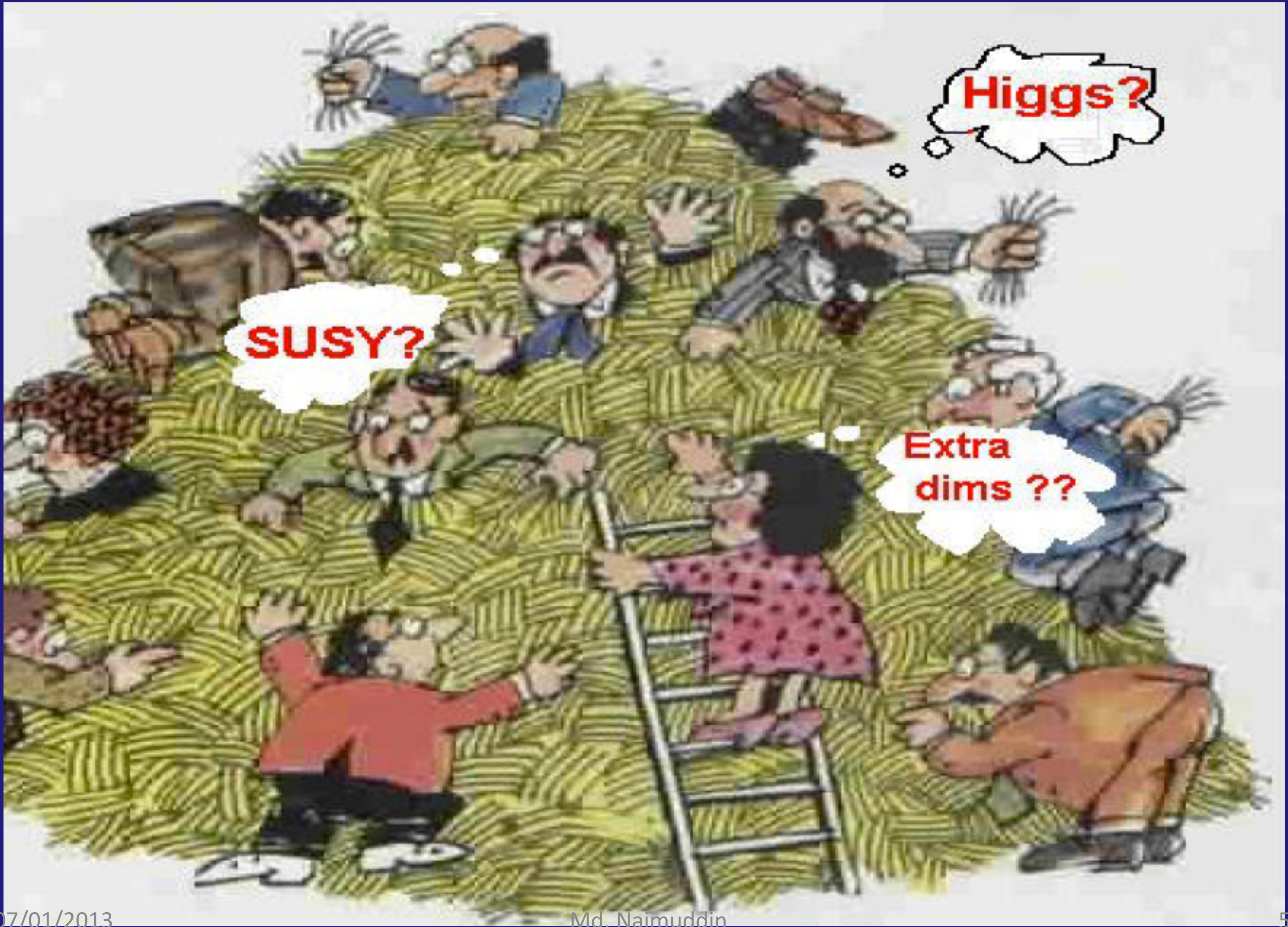
High Luminosity LHC is approved!

Theoretical Landscape

How to choose? Which Model?



How to choose? Which Model?



Model Independent Approach

- SM and data comparison: Instead of starting with a model in sight, a simple comparison can be made just by counting the number of events in data and SM prediction across all the possible topologies.
- A simple statistical method like Kolmogorov-Smirnov test can also be applied to the data and MC histograms for comparison.
- Analyzing and understanding the discrepancy: This is the most interesting, challenging and fun part – Model building based on the discrepancy.

Successfully implemented in CDF and D0 experiments

Implemented for 2010 CMS data, 2011+2012 data analysis is ongoing.

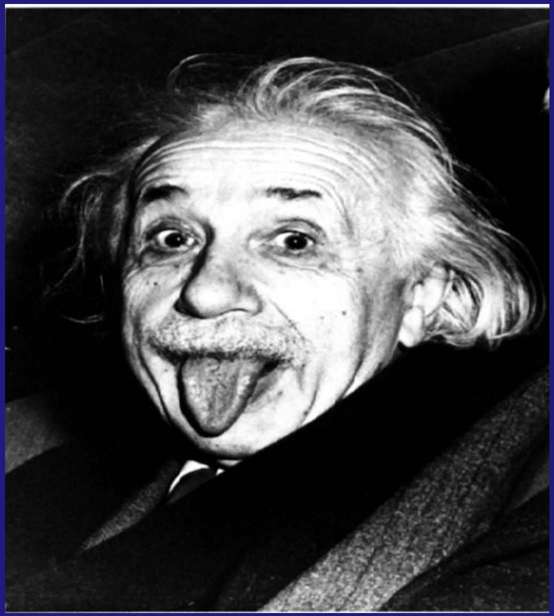
Interpreting the Excess

Would need to qualitatively and quantitatively describe any excess observed in data.

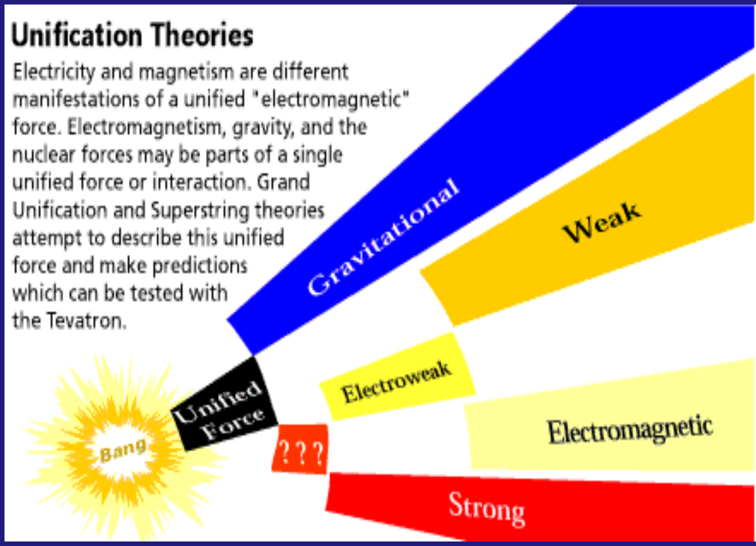
- Once the discrepancy is found, next is to interpret it.
- Need to have a model building tool.
- You make a model and compare that with the observed discrepancy.
- If model fit then go for party, otherwise make more models.

"There's really no need for confusion. Page 95, section 33, paragraph L clearly explains ..."

What are we going to find?



I don't know!



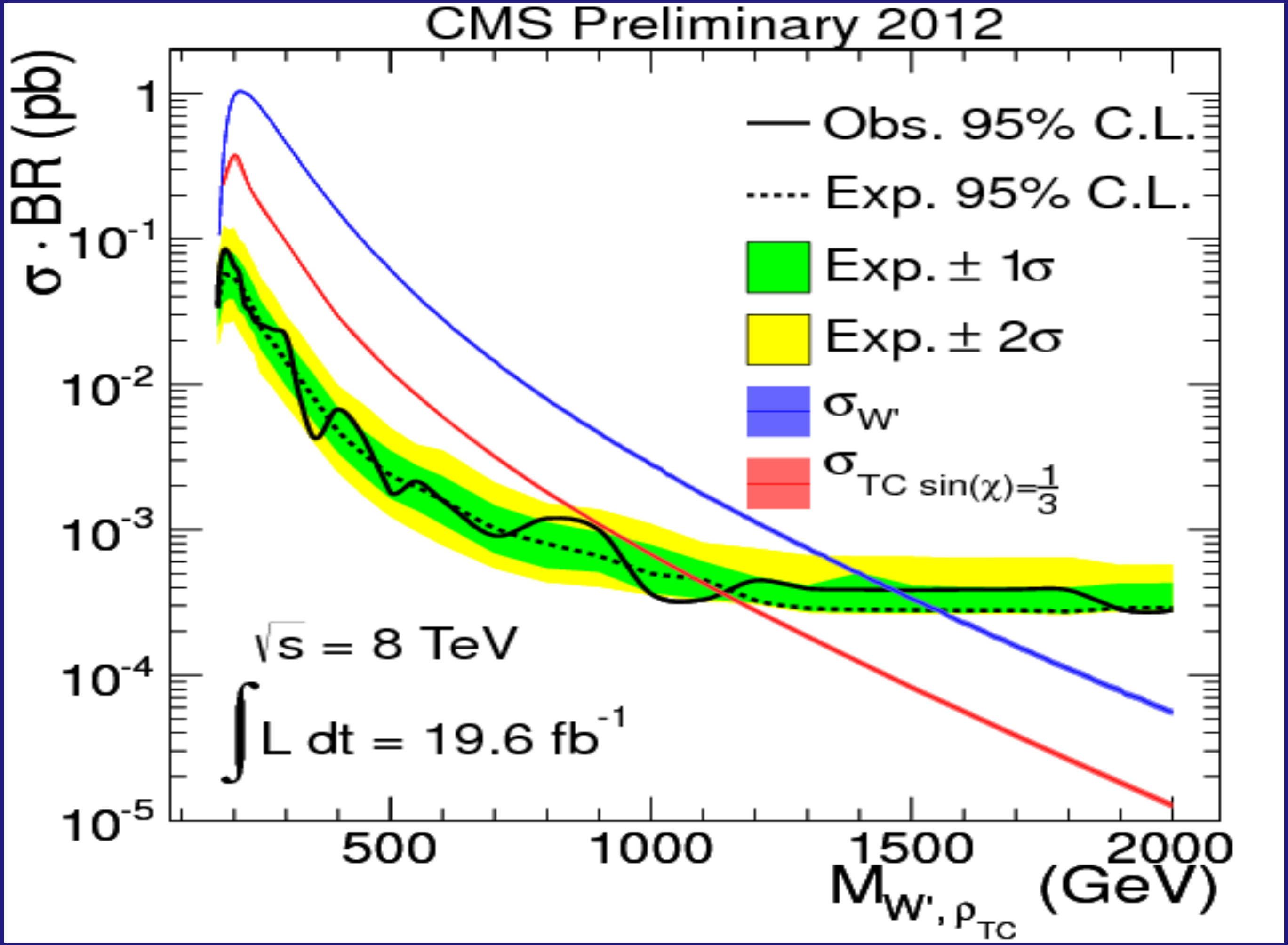
Supersymmetry, Higgs, Technicolor, compositeness, something unexpected?

13/14 TeV LHC run might throw up surprises …. we need to be patient and ready.

"What is now proved was once only imagined" - William Blake

THANK YOU!

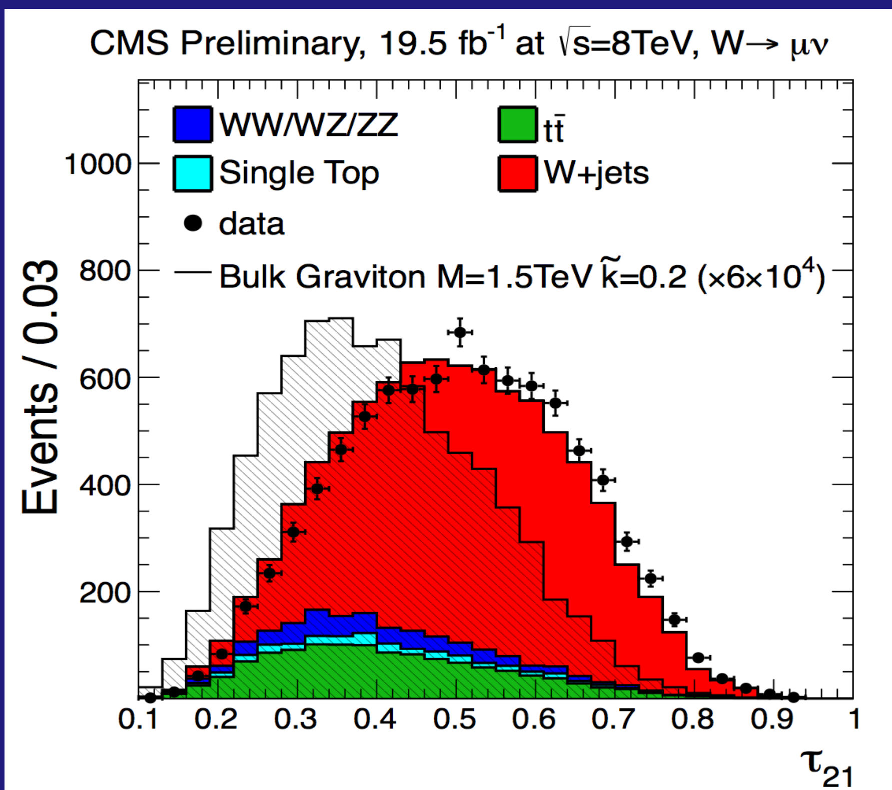
Searches – W' ➔WZ➔ 3l+MET

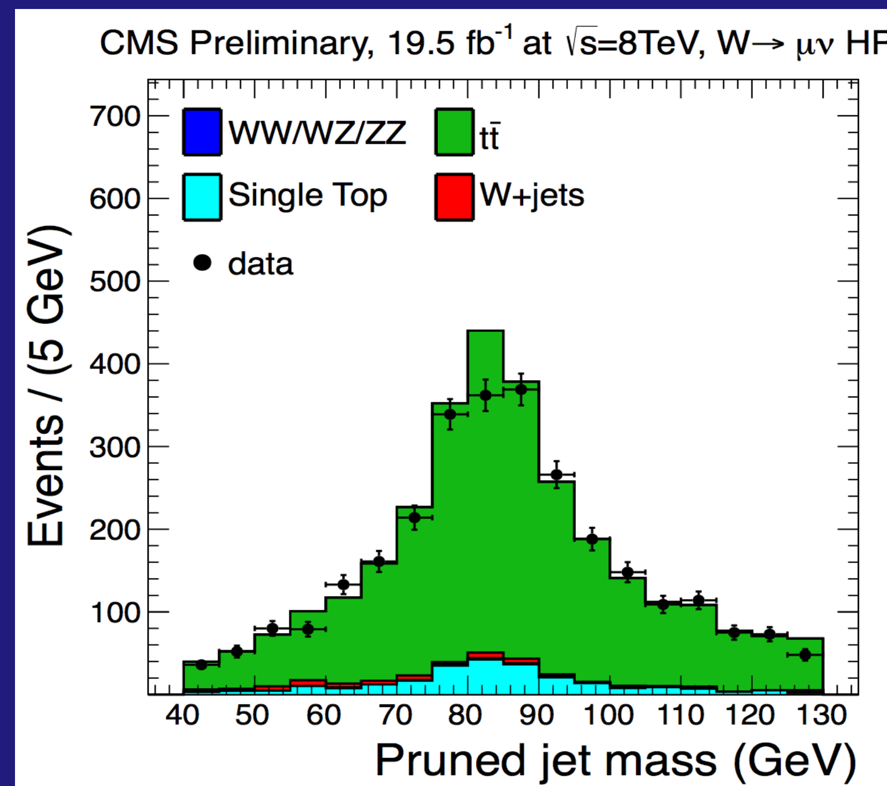


Searches – Semileptonic WW resonance

Dominant W+jets backgrounds data-driven

- Side-band region M_{jet}=[40,65] GeV
- W signal region M_{jet}=[65,105] GeV
- W+jets: M_{WW} obtained from scaled M_{jet} sidebands

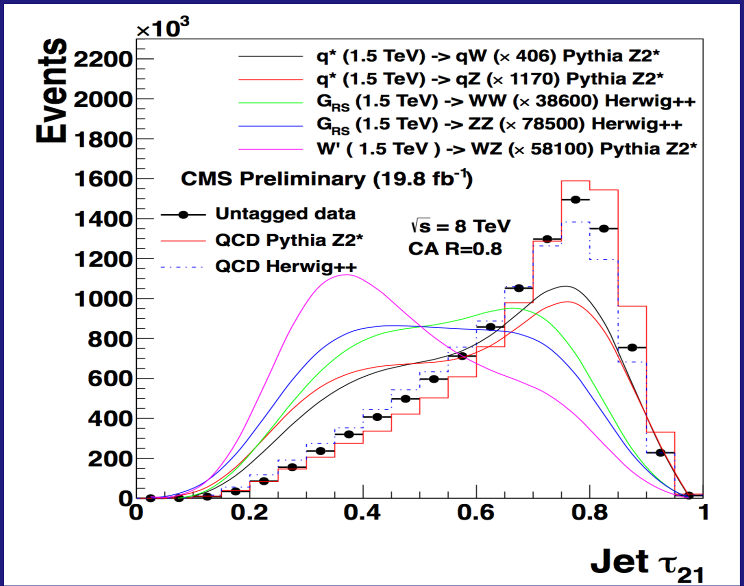




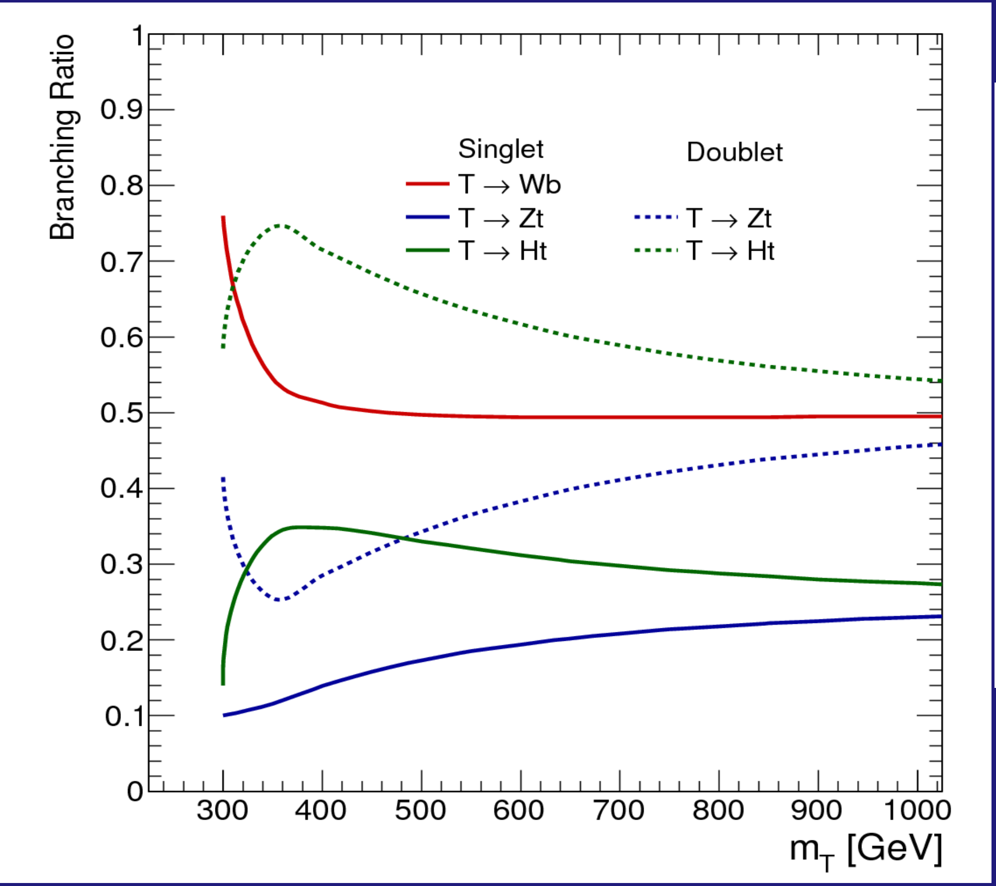
Searches – WW / ZZ / WZ in dijets

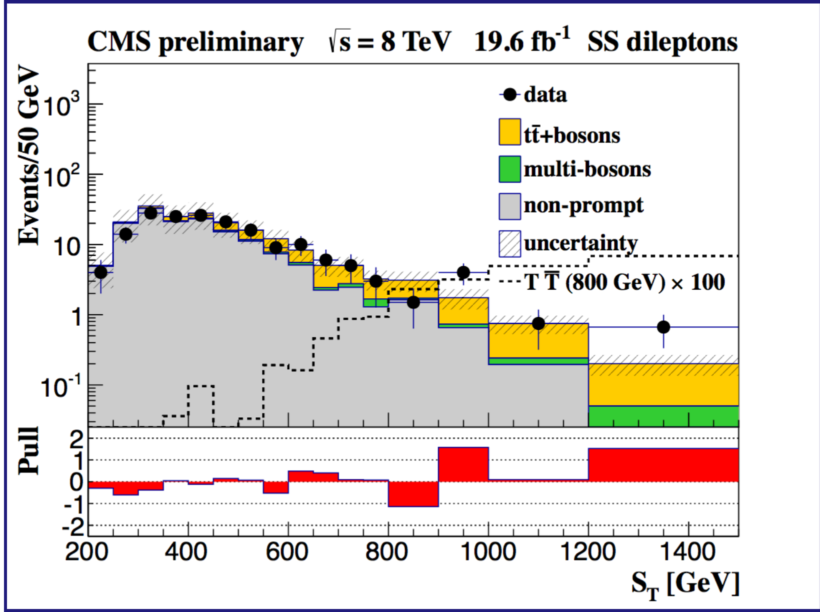
Each jet is required to pass the "W/Z-tagger"

- pruned jet mass: $70 < M_{jet} < 100$ GeV/c^2
- N-subjettiness (same as previous): $\tau_{21} < 0.5$ for high purity, and $0.5 < \tau_{21} < 0.75$ for low



Searches – Vector Like T′→ tZ/tH/bW



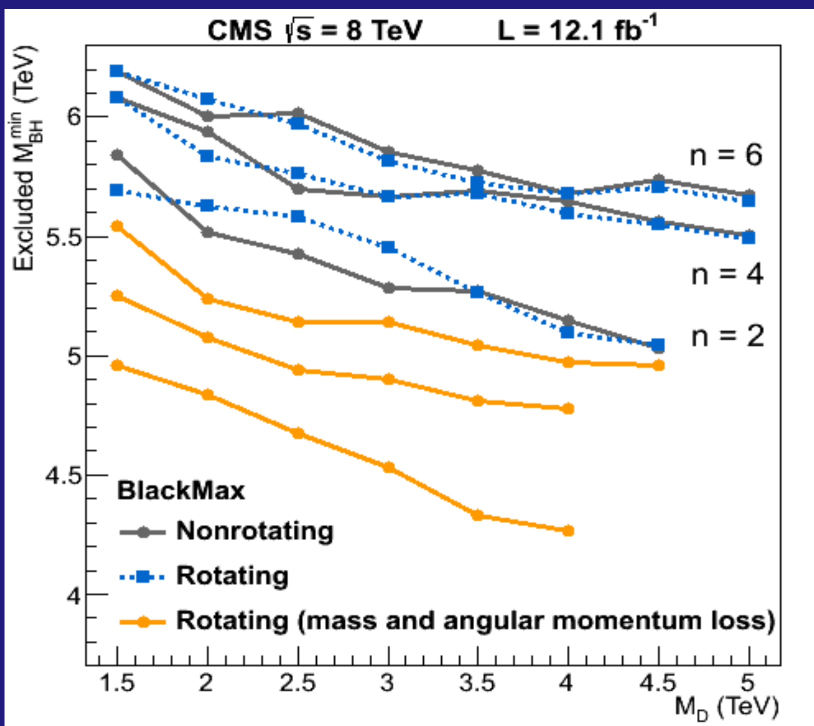


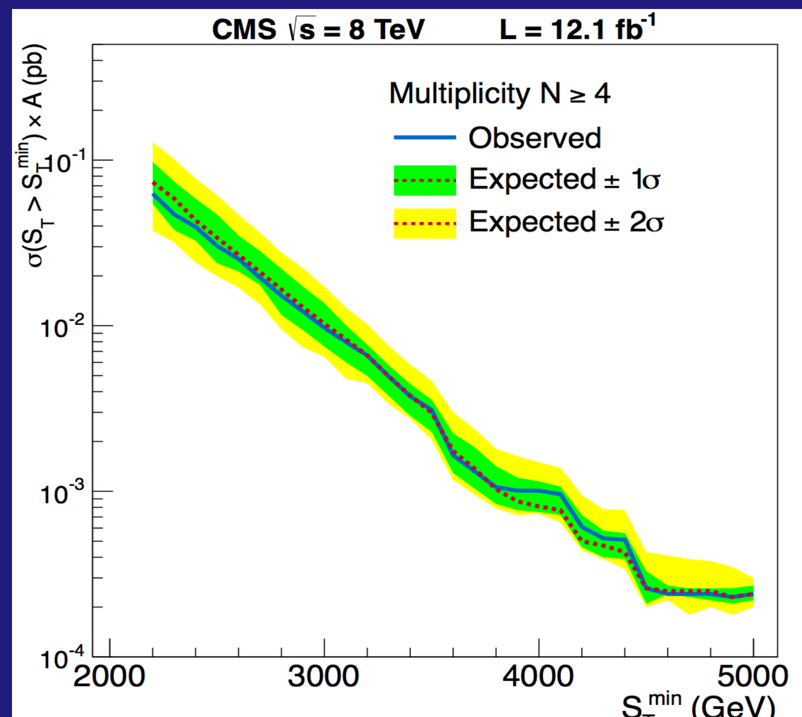
Branching ratios for T decay as a function of m_T as computed with Protos in the weak-isospin singlet and doublet scenarios.

Searches – Black Holes

No excess of events above expected backgrounds observed

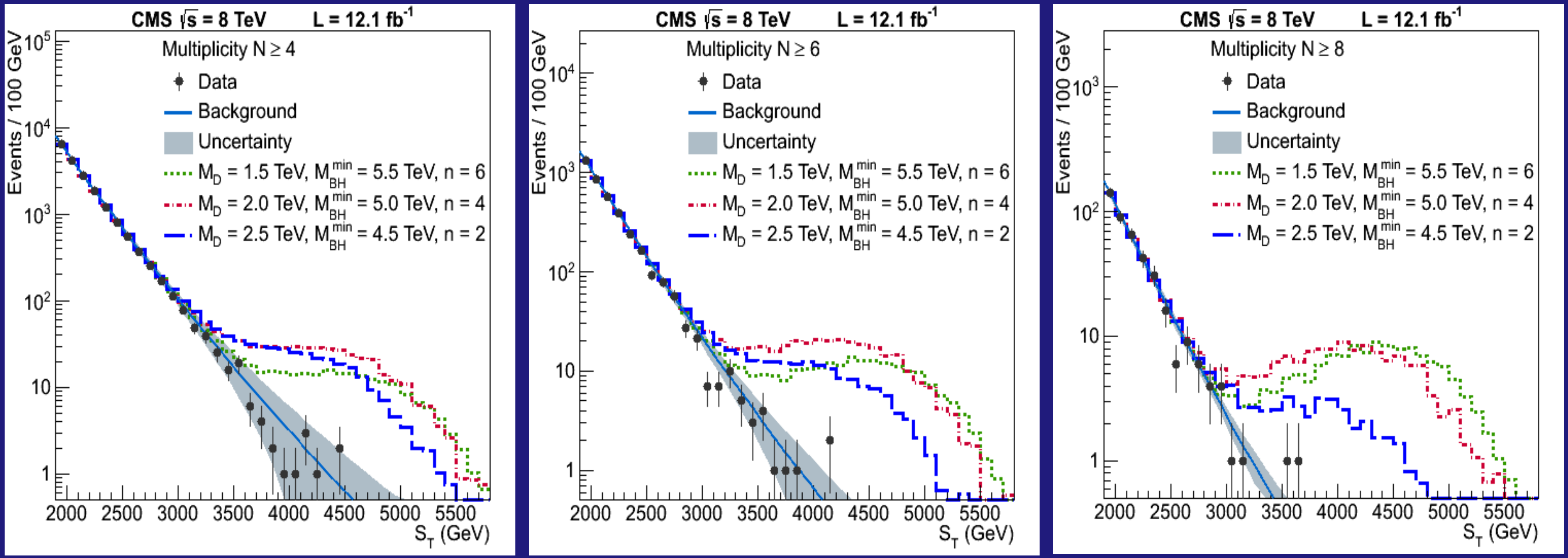
- Limits on ADD parameter M_D assuming specific BH models (Charybdis, BlackMax, ...)
- Model-specific limits on semiclassical BH masses in the 4.3 – 6.2 TeV range



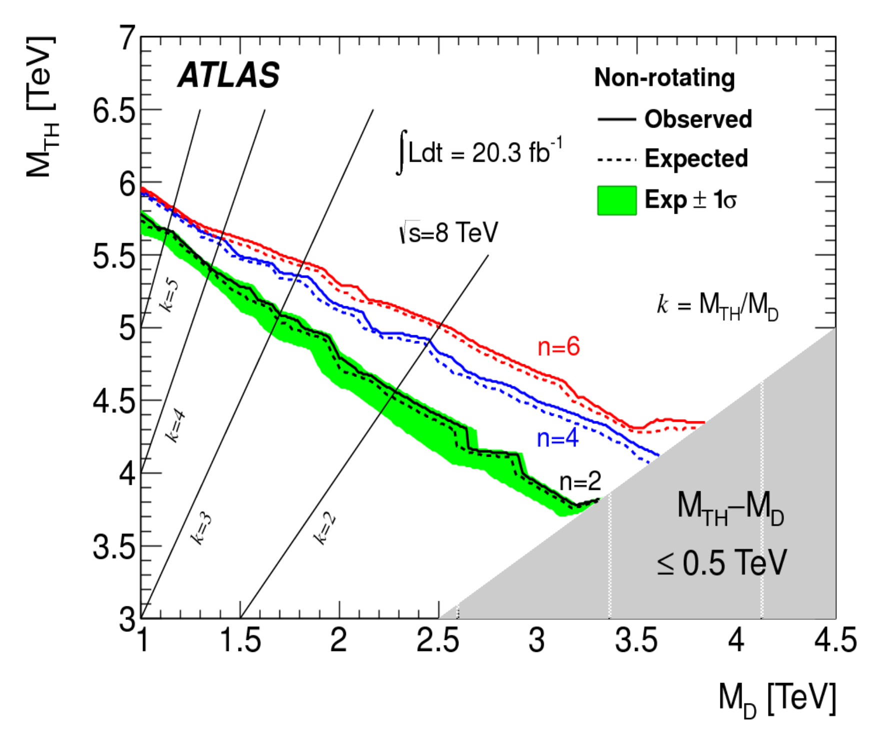


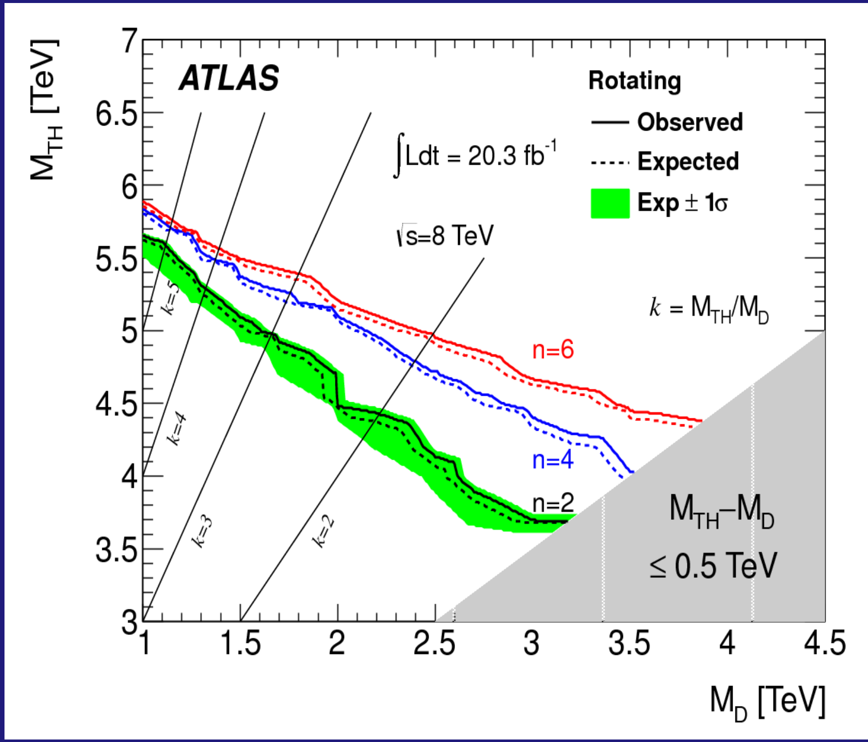
Searches – Black Holes

- Search for microscopic Black Holes in 12 fb^{-1} of 8 TeV data
  - Hypothetical BH would evaporate into many high-p_t objects
  - Estimate by S_T, the p_T sum of physics objects with $p_T > 50$ GeV
- Main background of QCD estimated by fit to n=2 distribution
  - Normalised for each multiplicity bin separately at S_T = 1.8–2.2 TeV
  - Model-independent limits vs S_T and multiplicity



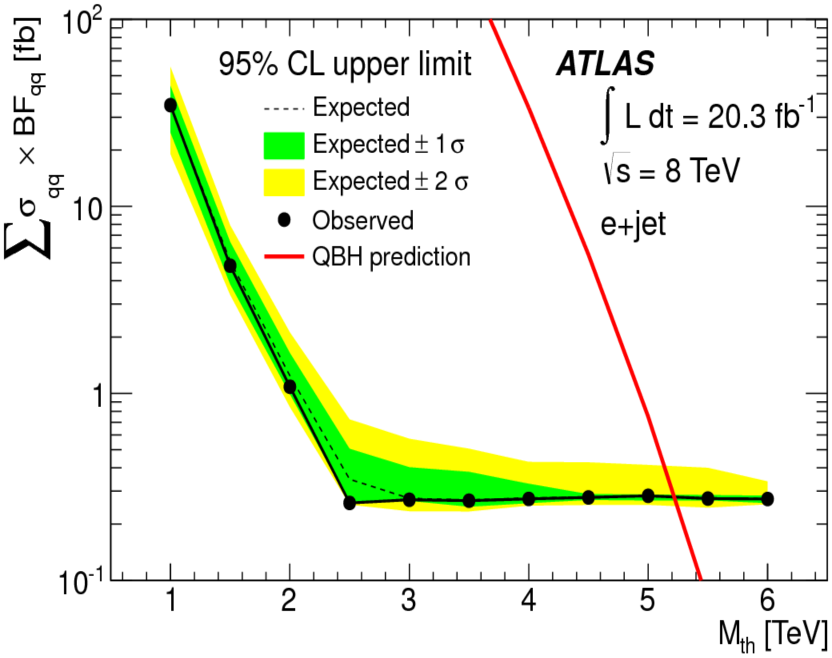
Searches – Black Holes





The 95% CL exclusion contours for rotating black holes in models with n = 2, 4, and 6. The dashed lines show the expected exclusion contour, the solid lines show the observed exclusion contour. The regions below the contours are excluded by this analysis. The 1σ uncertainty on the expected limit for n = 2 is shown as a band. Lines of constant slope k = MTH/MD = 2, 3, 4, and 5 are also shown. Only slopes kgg 1 correspond to physical models.

Searches – Black Holes



Similar limit for mu+jet

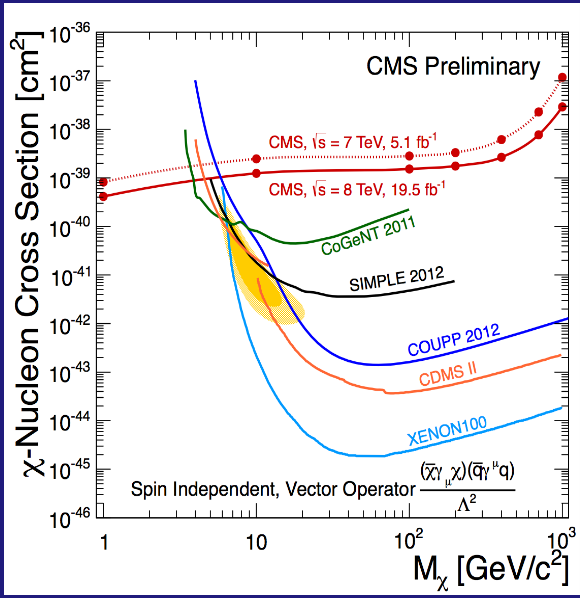
The 95% CL upper limits on $\Sigma\, \sigma_{qq} \times BF_{qq}$ for QBHs decaying to an electron and a jet, as a function of M_{th}, assuming $M_D = M_{th}$ and n = 6 ADD extra dimensions. The limits take into account statistical and systematic uncertainties. Points along the solid black line indicate the mass of the signal where the limit is computed. Also shown are the ± 1 σ and ± 2 σ bands indicating the underlying distribution of possible limit outcomes under the background-only hypothesis. The predicted cross section for QBHs is shown as the solid curve.

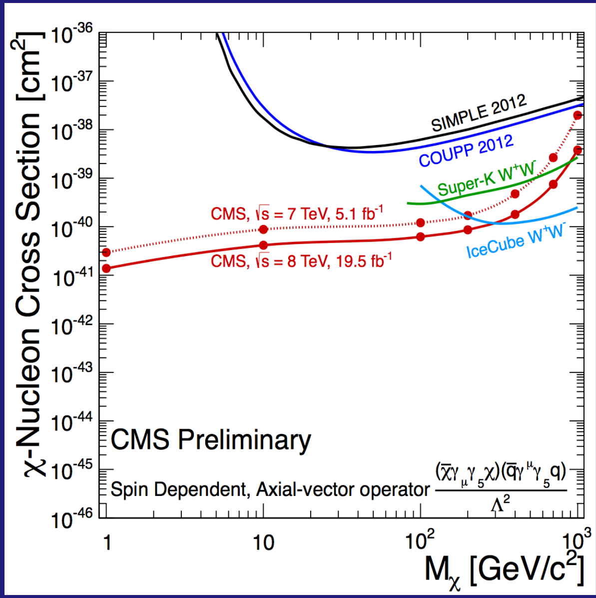
Searches – Dark Matter with monojets

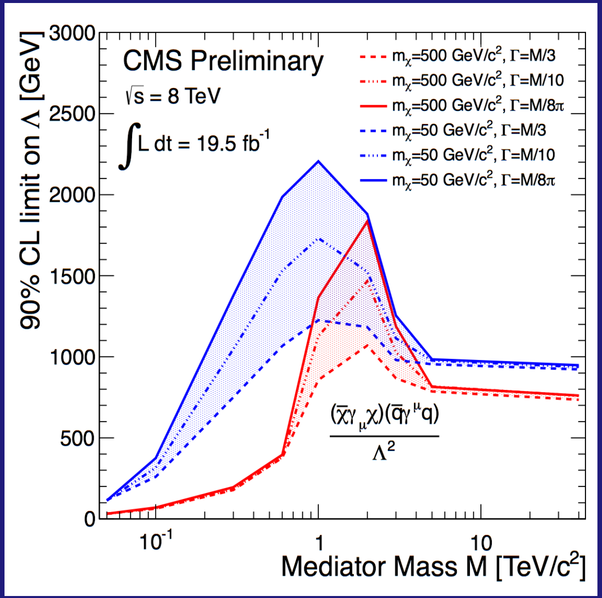
Pair-production of DM (χ) characterized by a contact interaction effective theory

Derived limits then compared to direct-detection experiments

ATLAS & CMS results similar for 7 TeV data, improved with 8 TeV

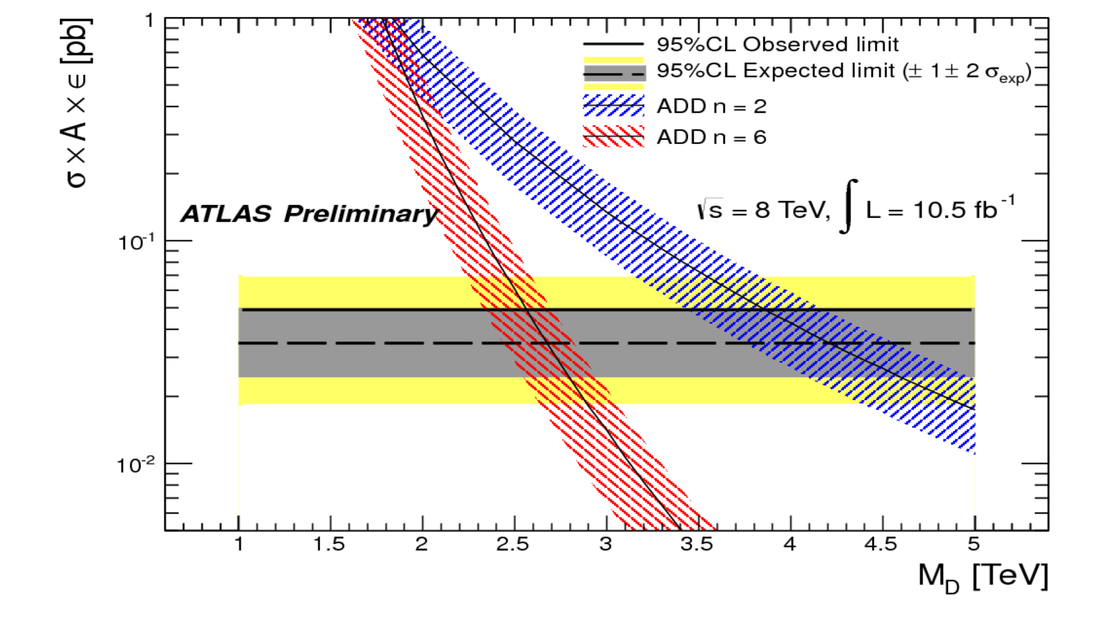






Starting to extend simple contact interaction scenario to new operators, scan over mediator mass, new models

Searches – ADD from Monojets



M_D (ADD) at LO 95% CL limits	Lumi. [fb^{-1}]	δ=3 Exp. [TeV]	δ=3 Obs. [TeV]	δ=6 Exp. [TeV]	δ=6 Obs. [TeV]
CMS Monophoton	5.0	1.53	1.55	1.55	1.57
ATLAS Monophoton	4.6	1.65	1.74	1.75	1.87
CMS Monojet	5.0	3.06	3.24	2.28	2.38
ATLAS Monojet	4.7	3.22	3.32	2.45	2.51

Searches – Long Lived

Many extension of SM predict heavy long lived (stable) charged particle HSCP
–Ex: in GMSB, with LSP = gravitino, NLSP = L.L. gluino/stop/stau
–A colored NLSP can form an R-hadron, lead to interesting events
•Signature
–Candidates with dE/dx losses ≠ MIP
–Candidates with large Time-of-Flight w.r.t. IP
•Analysis:
–Variables:
•$I\hbar$?is the energy loss dE/dx as measured with the Silicon Tracker
•Ias ?a S.C.vM uses dE/dx & compares with MIP
•1/b uses Muon sys's timing info w.r.t. IP
•pT the transverse momentum
–Five different analysis strategies employed
–Use an ABCD method to separate signal from background
•HSCPs with |Q| < 1e: tracker only is used. Here we use *pT* and select tracks with dE/dx less than expected for |Q| = 1e.
•HSCPs with |Q| > 1e: tracker + Muon use *pT* , dE/dx and TOF optimized for large dE/dx than expected for |Q| = 1e
•HSCPs with |Q| = 1e: 3 analyses that either use tracker or the muon system alone, or both systems together. For these analyses the track *pT* , the *Ias* and/or TOF is used to discriminate btw bkg and signal

Searches – Long Lived

stau benchmark model:

|Q=e| in GMSB (SPS7)

$e/3 \leq |Q| \leq 8e$ pair production (neutral under $SU(2)_L$)

gluino (spit SUSY) or stop (large gluino masses limit) benchmark

form R-hadrons containing a massive parton,

uncertainty from hadronization (fraction of gluino balls?) and charge flipping

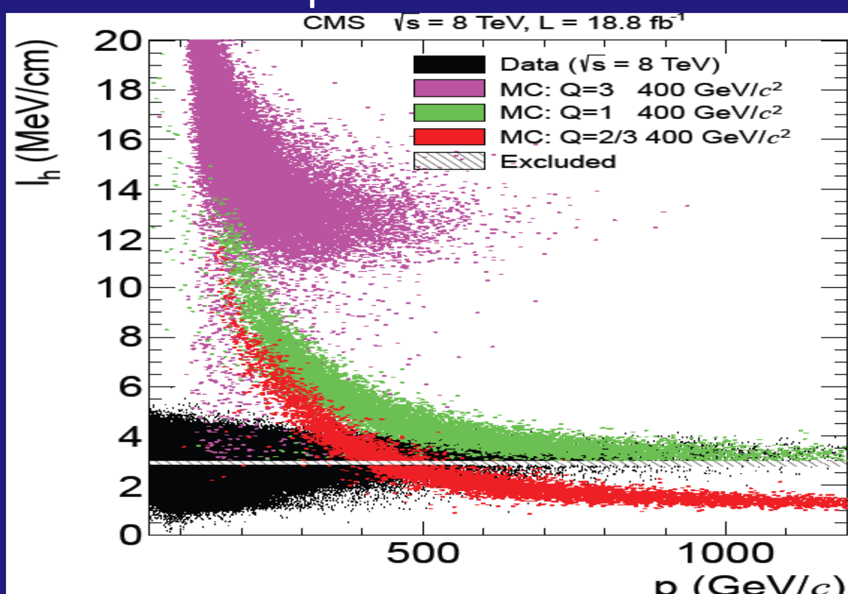
electric charge can change while interacting with the detector

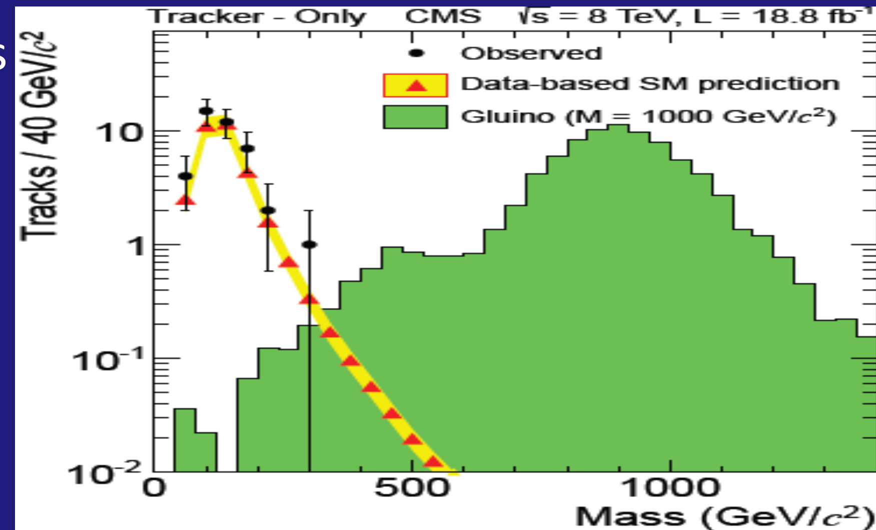
Searches - HSCP

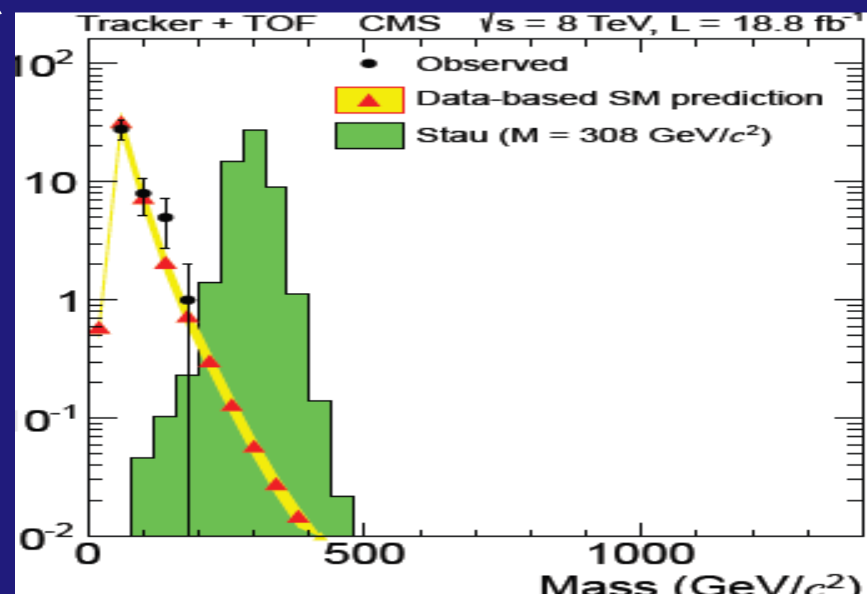
ABCD-technique; p_T, dE/dx and $1/\beta$ variables

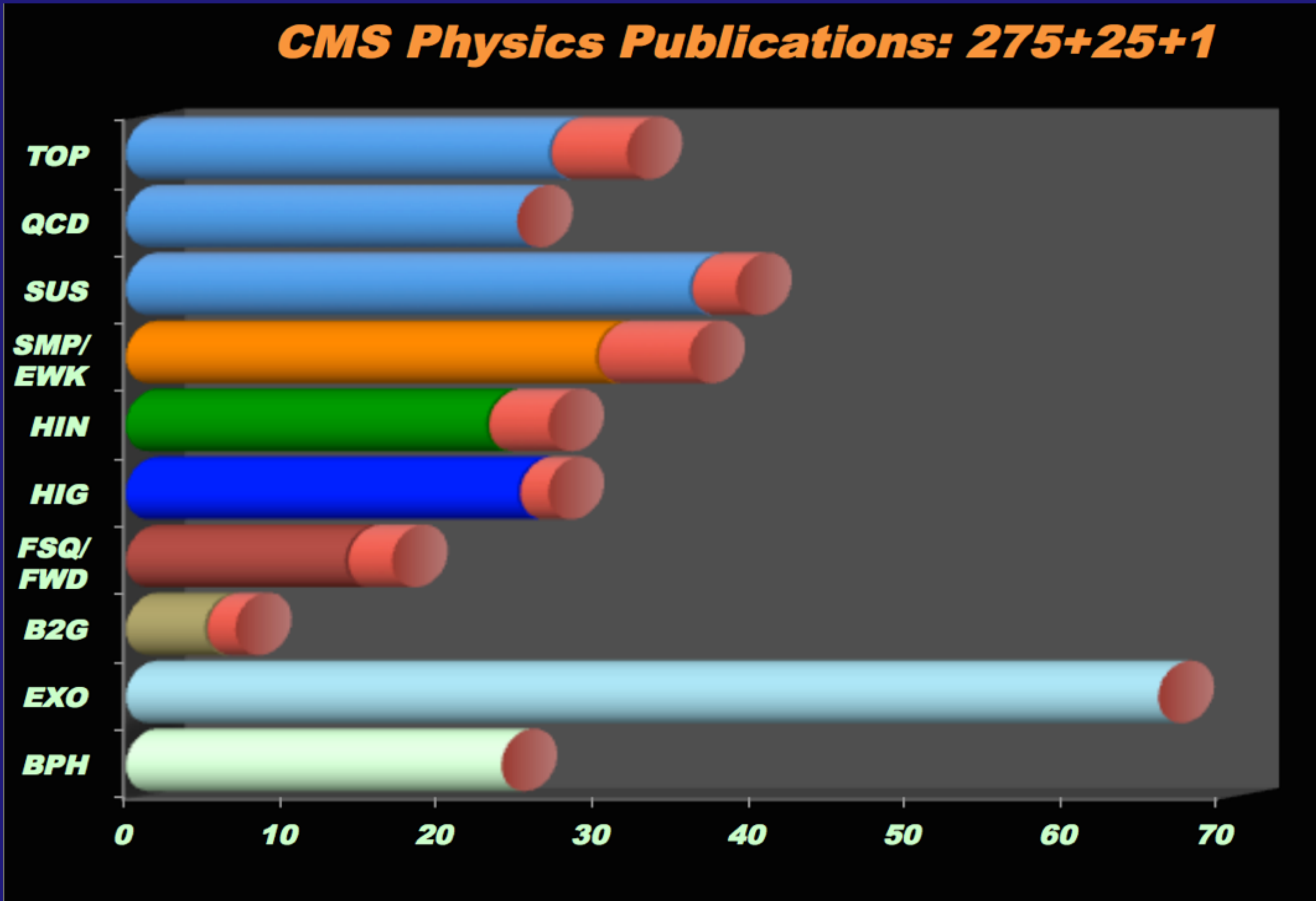
Tk-Only	p_T +dE/dx
Tk+TOF	p_T +dE/dx +$1/\beta$
Mu-Only	p_T +$1/\beta$
multi. charged	dE/dx +$1/\beta$
frac. charged	p_T +dE/dx

Tk and Tk+TOF: predict the mass from dE/dx








CMS Physics Publications: 275+25+1
TOP
QCD
SUS
SMP/ EWK
HIN
HIG
FSQ/ FWD
B2G
EXO
BPH
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10
20
30
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