

Recent Results on Searches Beyond the Standard Model From the LHC

PING TAN - University of Iowa

on behalf of
ATLAS/CMS Collaborations

46th Annual Fermilab User Meeting, Jun. 12-13, 2013



Scope

SUSY + Exotica

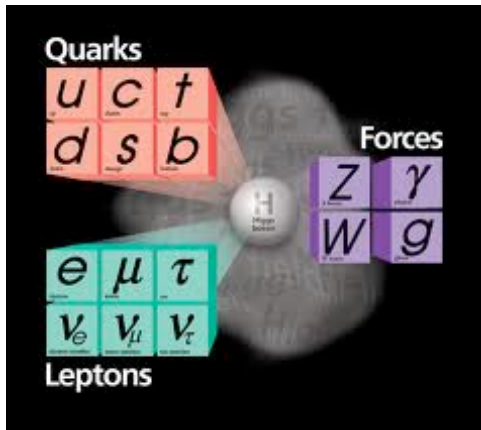
: expanded into 6 plenary talks + ~ 25 parallel talks in the recent LHCP conference

Sorry if your favorite subject is missed here. **Focus on latest new results with full 2012 data!**

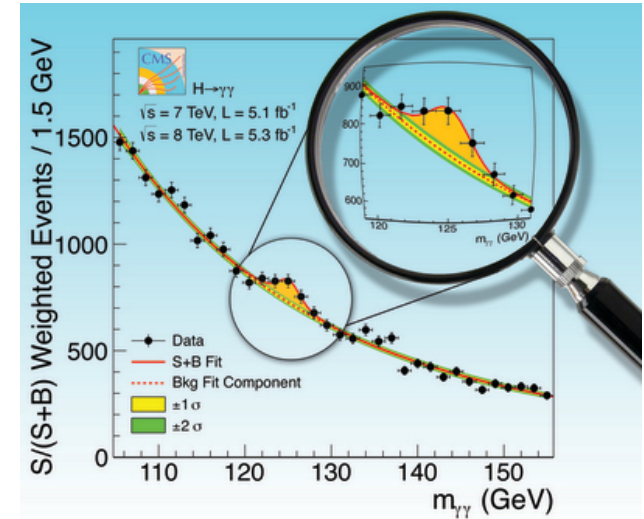


We Had a Boson

- ◆ Last July's discovery completes the SM.
- ◆ Properties of the new boson is very much SM Higgs-like:
more in **Jaco Konigsberg's** talk, "LHC Higgs"
- ◆ A triumph of the SM.



- ◆ 4-D space-time
- ◆ $SU(3)_c \times SU(2)_L \times U(1)_Y$
- ◆ EWSB: Higgs mechanism
- ◆ 3 generations of quarks/leptons

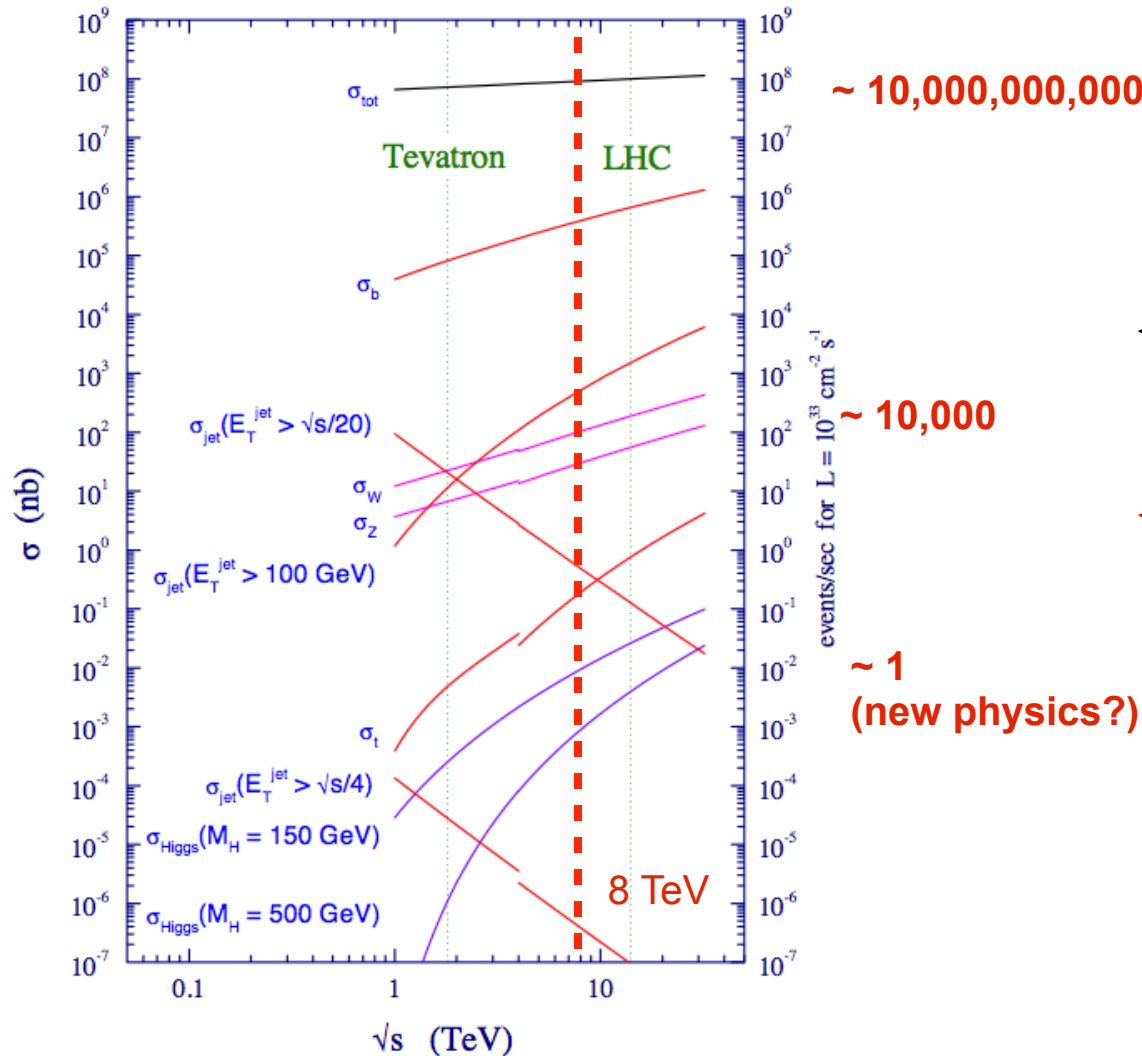


- ◆ **Most compelling experimental evidence for Beyond-the-SM physics:**
SM only accounts for ~4% of Universe
- ◆ Many extensions of SM:
SUSY,
Extra-dimensions,
fourth-generation,
lepto-quarks,
black-holes,
hidden-valley, ...
- ◆ Many predicted experimental signature have been extensively searched for at LHC



SM - “the Giant’s Shoulder”

proton - (anti)proton cross sections



2012 CMS data: $\sim 25 \text{ fb}^{-1}$

$\sim 100 \text{ M W}(\mu\nu)$
 $\sim 6 \text{ M Z}(\mu\mu)$
 $\sim 100 \text{ K ttbar}(\mu\nu + \text{jets})$

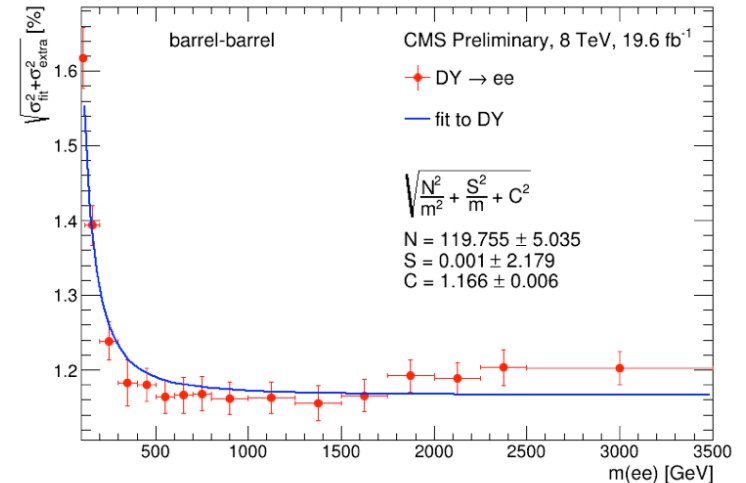
- ◆ Extensive SM program to provide solid ground: details in Joao Guimaraes da Costa's talk, “SM at LHC”,
- ◆ Theoretical input is vital.





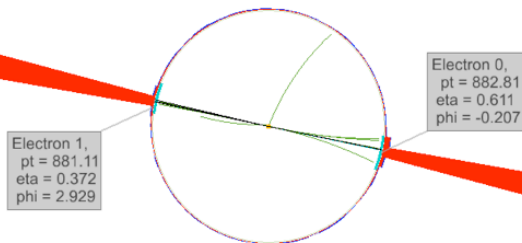
Narrow Dilepton Resonances

- Well motivated in theory;
 Z'_{SSM} , superstring inspired- Z'_ψ (E(6) model), RS-Graviton
- Demonstrated discovery potential: J/ψ , Y , Z**
- Utilize best strength of the detectors.

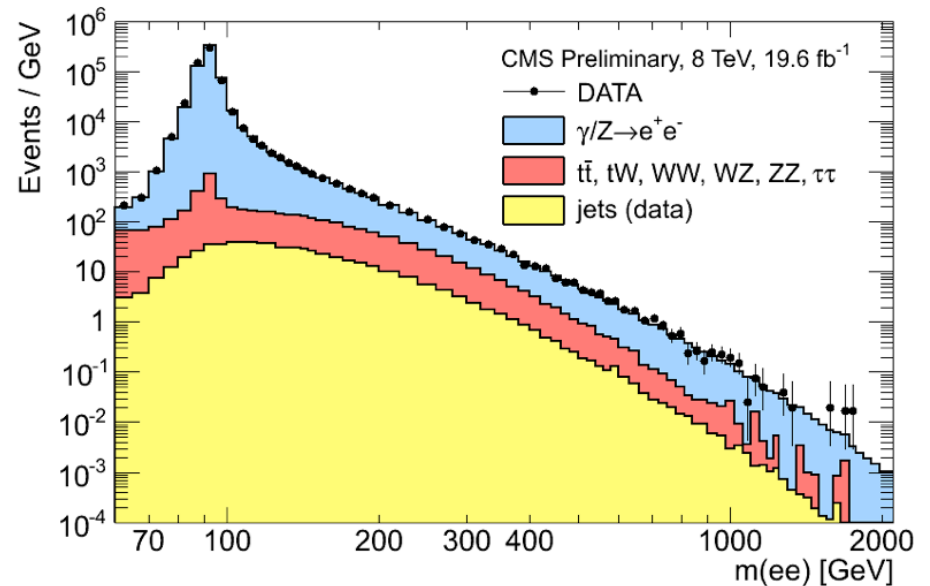


CMS Experiment at LHC, CERN
 Data recorded: Sun Jul 15 03:34:01 2012 CEST
 Run/Event: 198969 / 1188478742
 Lumi section: 1021

$m_{ee} = 1776 \text{ GeV}$



CMS-PAS-EXO-12-061

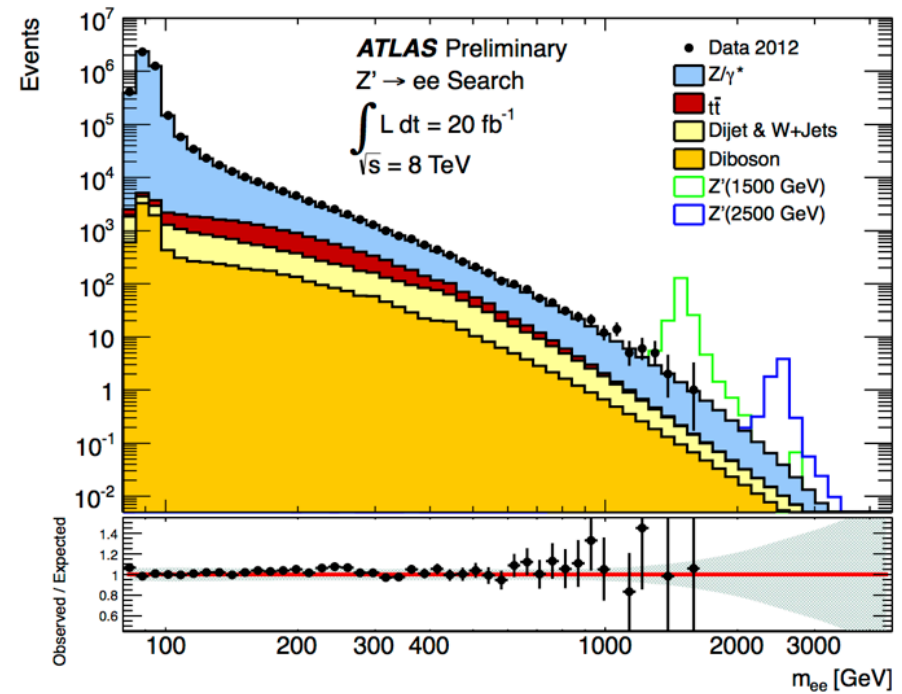
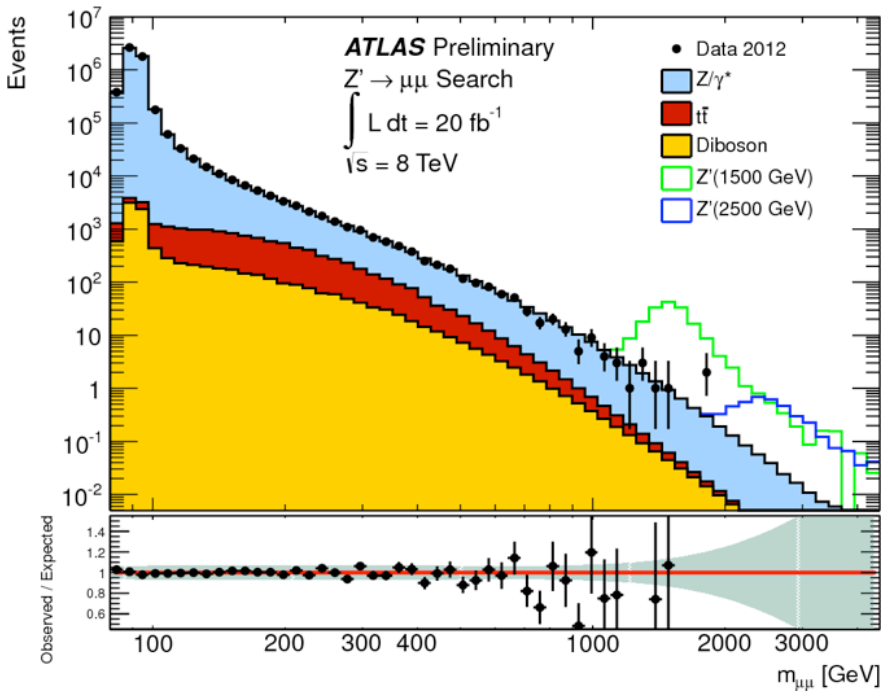




Narrow Dilepton Resonances (Cont.)

- ◆ No sign of any “excess”, either.
- ◆ Good cross check against each other (very critical in presence of a signal)

ATLAS-CONF-2013-037

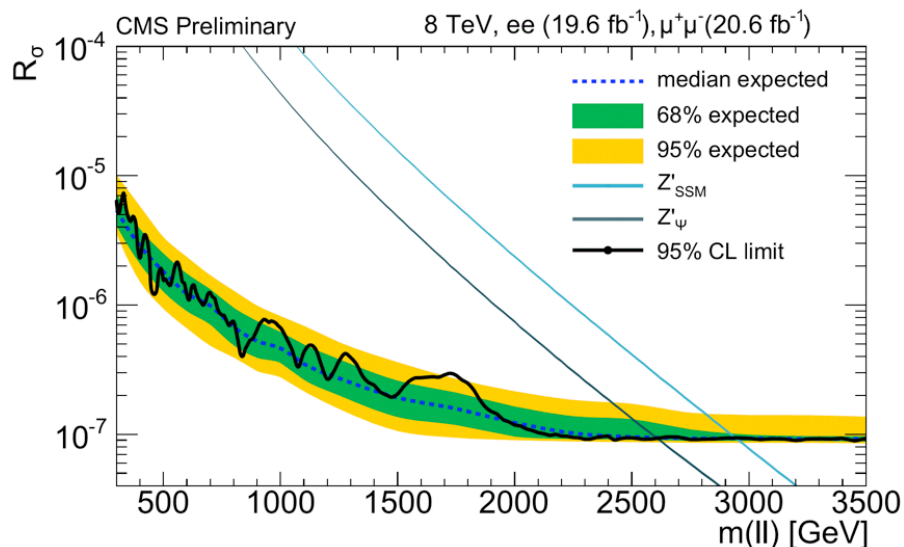




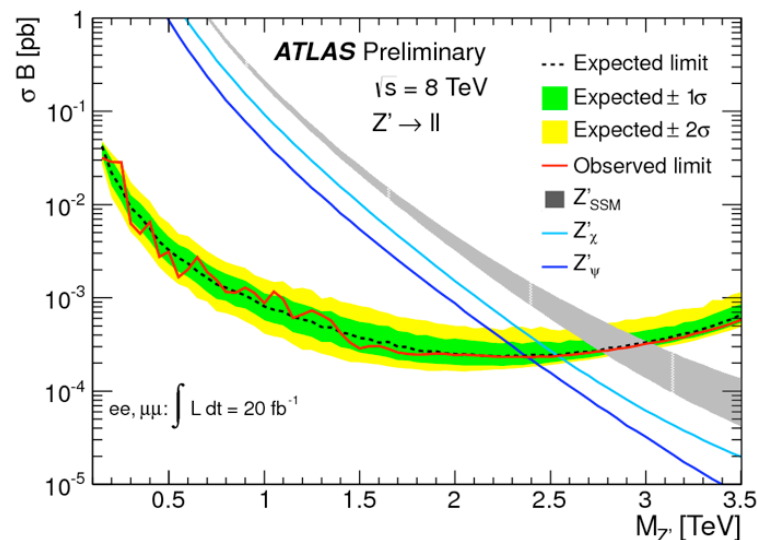
Narrow Dilepton Resonances - Interpretation

- ◆ Bayesian approach.
- ◆ CMS: set limit on a ratio, $\sigma \times \text{BF}(Z')/\sigma \times \text{BF}(Z)$;
- ◆ Take home upper-limits (depending on models):
e.g. $Z'_{\text{SSM}} < 2.86 \text{ TeV} (@95\% \text{ C.L.})$, ATLAS
 $< 2.96 \text{ TeV} (@95\% \text{ C.L.})$, CMS

ATLAS: set limit on $\sigma \times \text{BF}(Z')$



CMS-PAS-EXO-12-061



ATLAS-CONF-2013-037

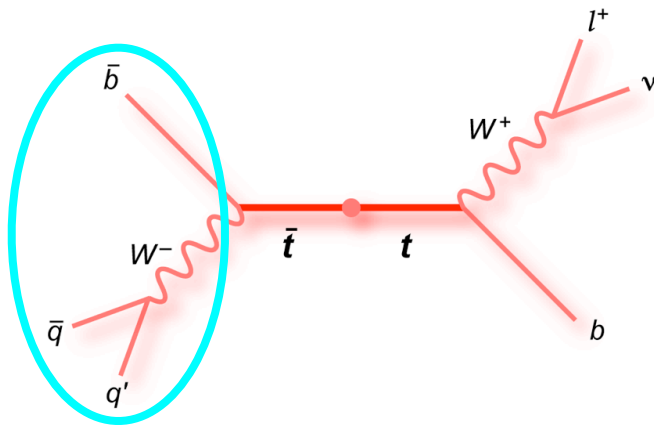
- ◆ More model-specific interpretation: Randall-Sundrum graviton, (e.g. ATLAS-CONF-2013-037)



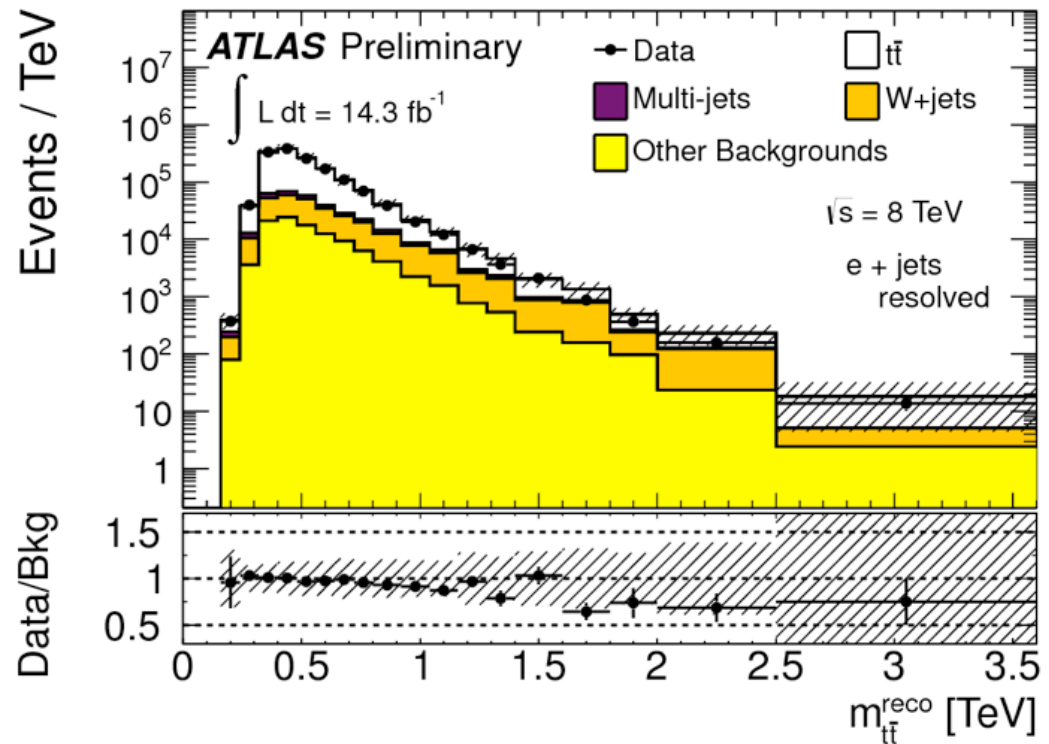
Top Quark

- ◆ Well studied since its discovery in 1995 by Tevatron experiments.
- ◆ **Large Yukawa couplings, mass, lifetime, ...**
 - **Unique opportunity to couple to new physics: top partners, $W'(tb)$, $t\bar{t}$ resonances**
 - **enriched in 3rd-generation SUSY searches**
- ◆ Reconstructed $t\bar{t}$ invariant mass in **$e+4\text{jets} + \text{MET}$**

resolved: W-b well separated



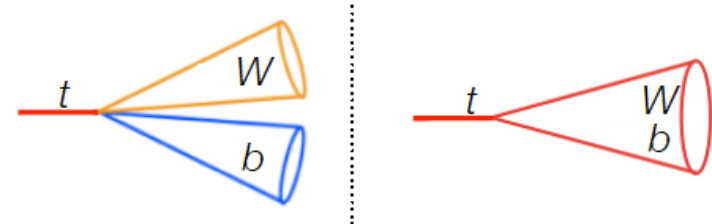
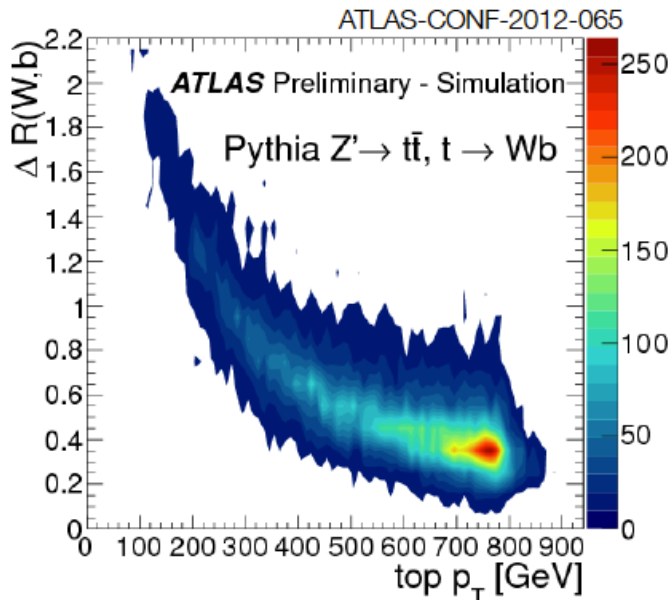
0 lepton: + 6 jets, “all hadronic”
1 lepton: + 4 jets+MET
 2 lepton: + 2 (b)-jets+MET



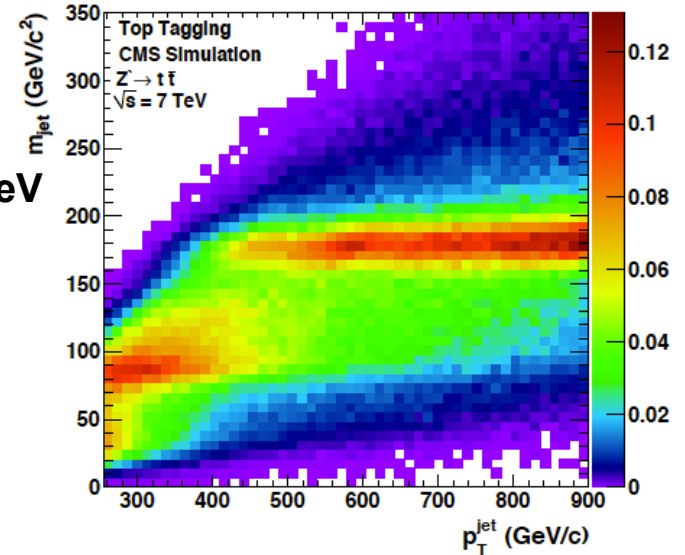


Top Tagger - a Novel Technique

- ◆ Tops could be heavily boosted at LHC: top-color Z' decays, Kaluza-Klein gluon excitations,



top:
 $p_T > 400-500$ GeV

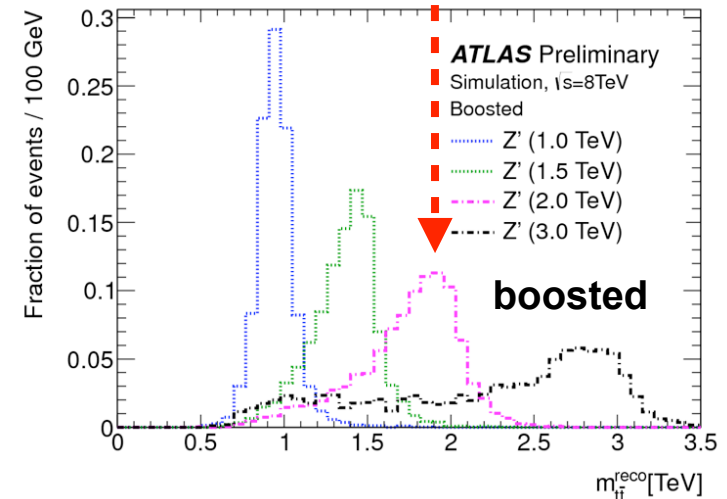
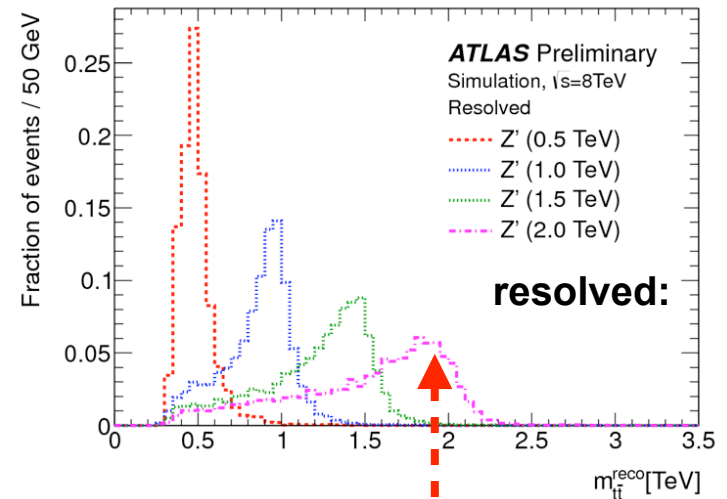
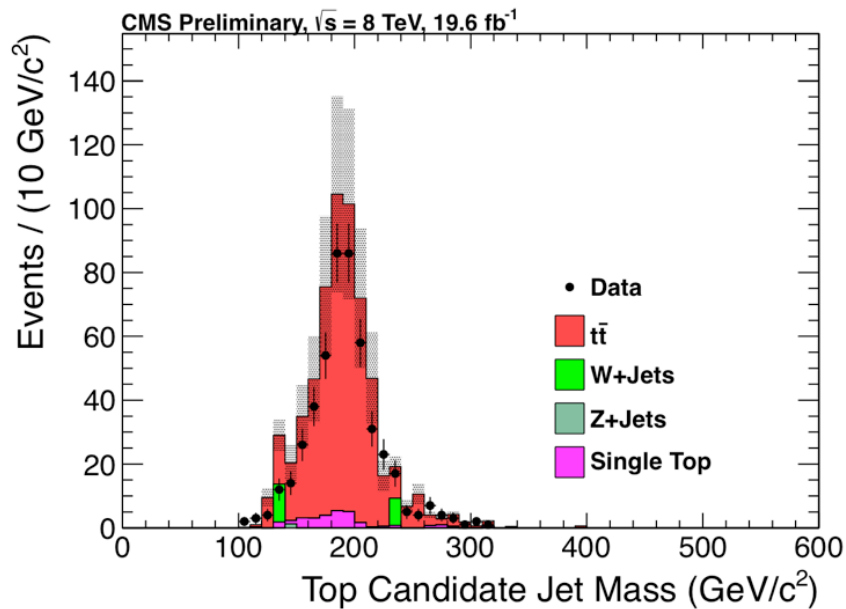
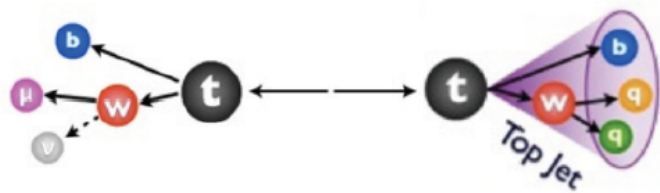


- ◆ Utilize jet substructure to tag “top”-jet
- ◆ ATLAS, (ATLAS-CONF-12-065)
Plehn, Spannowsky, Takeuchi, arxiv: 111.5034
- ◆ CMS,
Kaplan, Rehermann, Schwartz, Tweedie, PRL 101/142001 (2008)



Top Tagger - a Novel Technique (cont.)

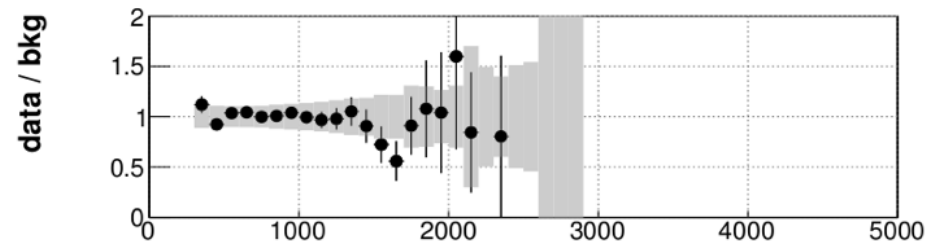
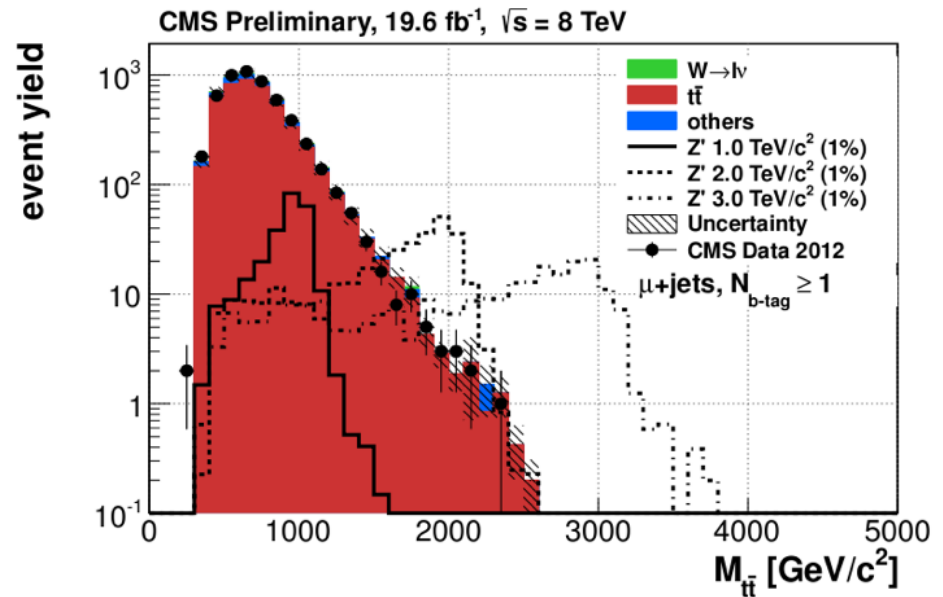
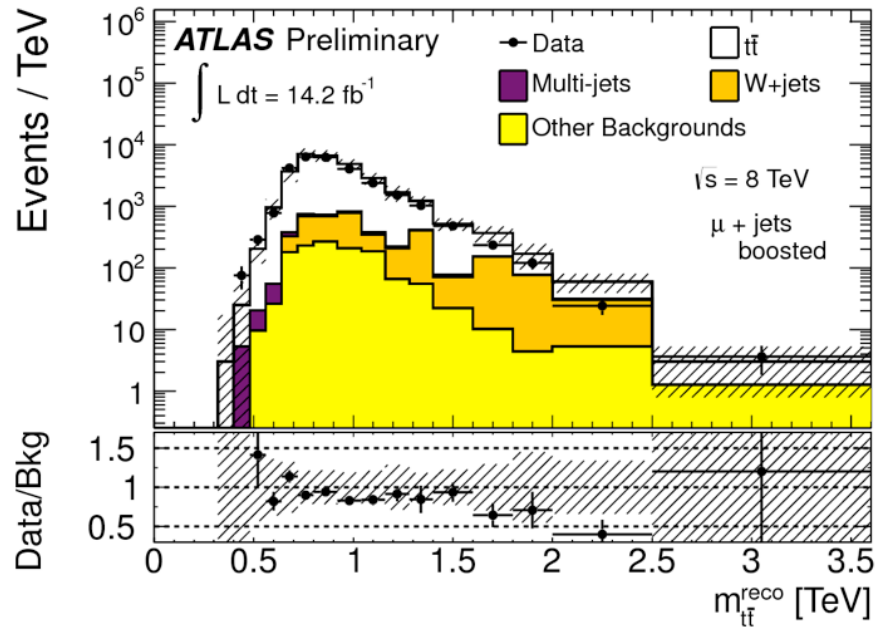
- ◆ “top” jet reconstruction (“top” tagger) can enhance kinematic reach
- ◆ Validate in leptons+jets sample,
- ◆ $> \sim 2$ TeV $Z' \rightarrow t\bar{t}$: significantly gain from boosted tops





ttbar Invariant Mass Spectrum - Boosted

- ◆ Combined with “resolved”(or “threshold”) distributions to improve sensitivities.
- ◆ “Resolved” (or “threshold”) ttbar: top daughters are well-separated/no “top” jet reconstruction involved.

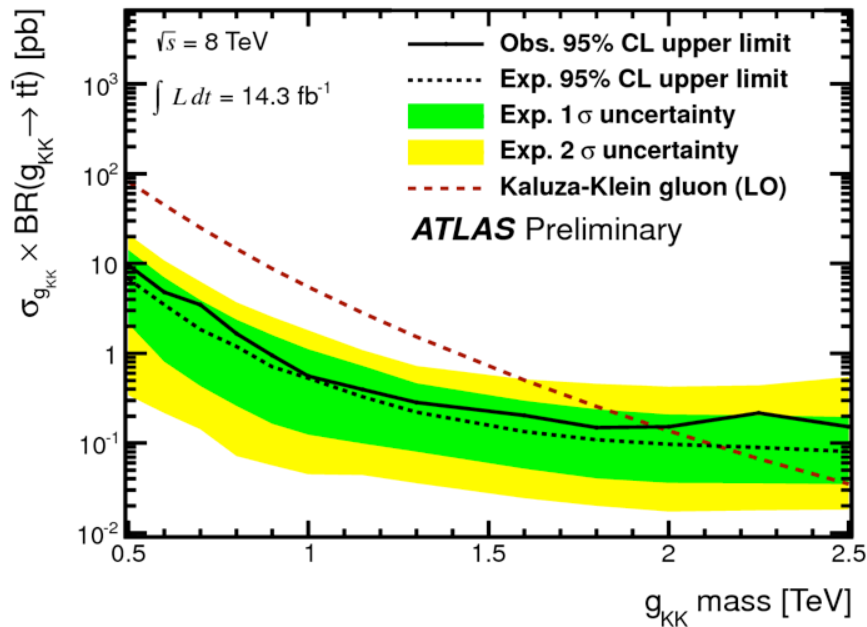




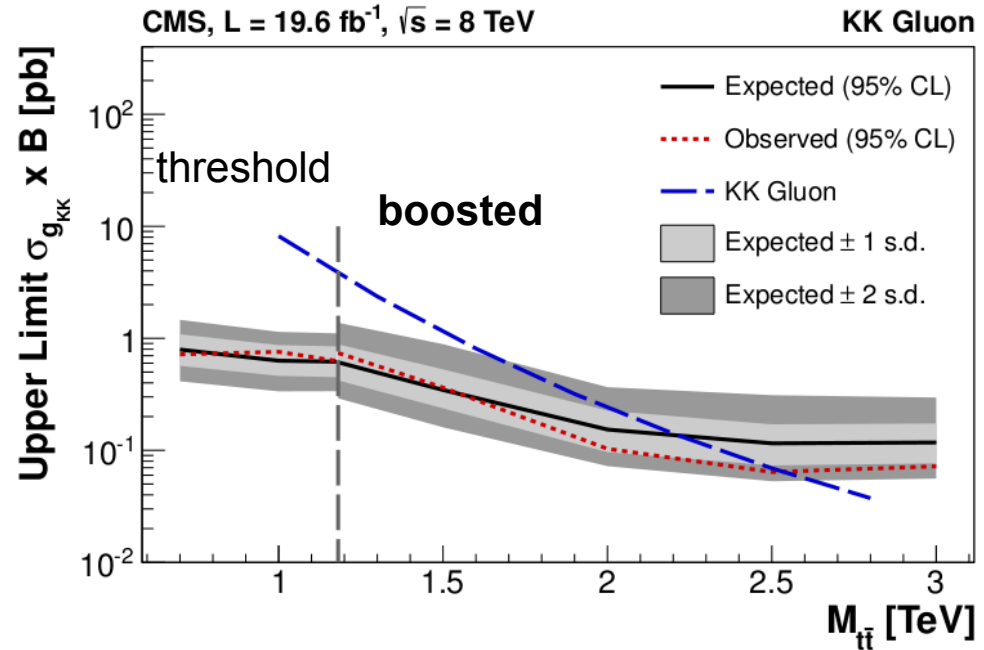
Interpretation of Results

- ◆ No “excess” has been observed. Model-dependent limits are set.
- ◆ **ATLAS: KK gluon <2.0 TeV (@ 95% C.L.)**
- ◆ **CMS: <2.5 TeV (@ 95% C.L.)**
(difference largely due to different dataset)
- ◆ More model-specific limits in public analysis summary (or conference note)

ATLAS-CONF-2013-052



CMS-PAS-B2G-12-006

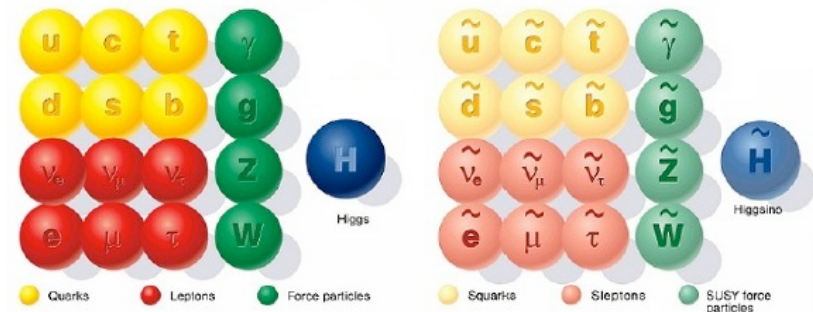




SUSY

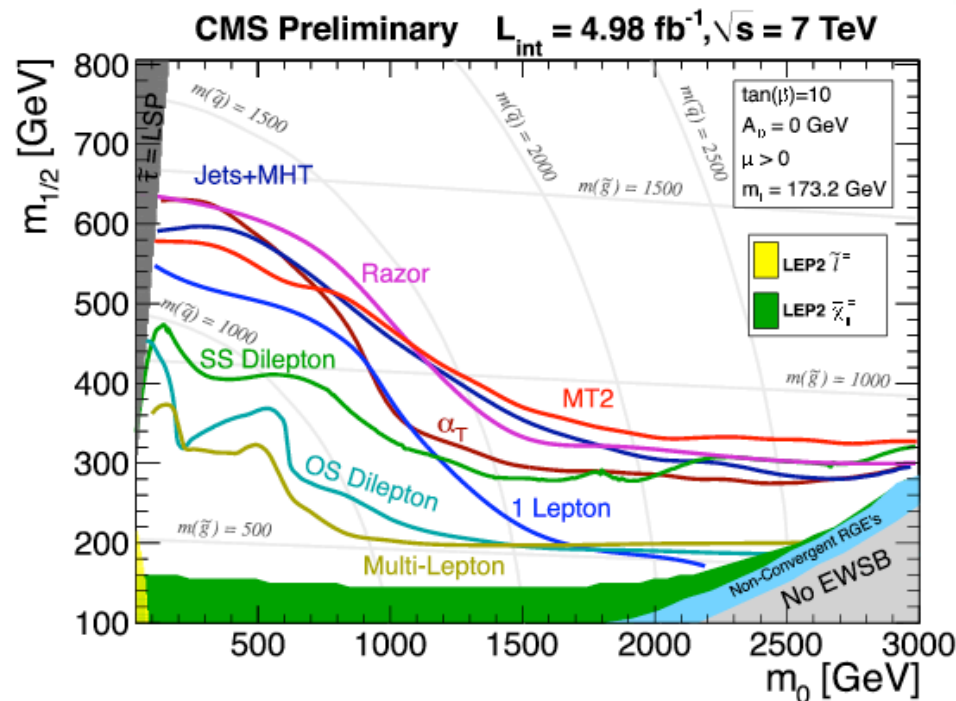
- ◆ Beautiful idea, strong implication, a zoo of new “SUSY” particles, ...
- ◆ **A whole set of striking experimental signatures**
- ◆ **Theoretical input is very critical:**
- ◆ Large phase space has been explored at 7 TeV LHC run, e.g. CMSSM

SUPERSYMMETRY



Standard particles

SUSY particles



m_0 : scalar particle mass at GUT scale

$m_{1/2}$: gauginos mass at GUT scale

Similar constraints by
ATLAS



SUSY (cont.)

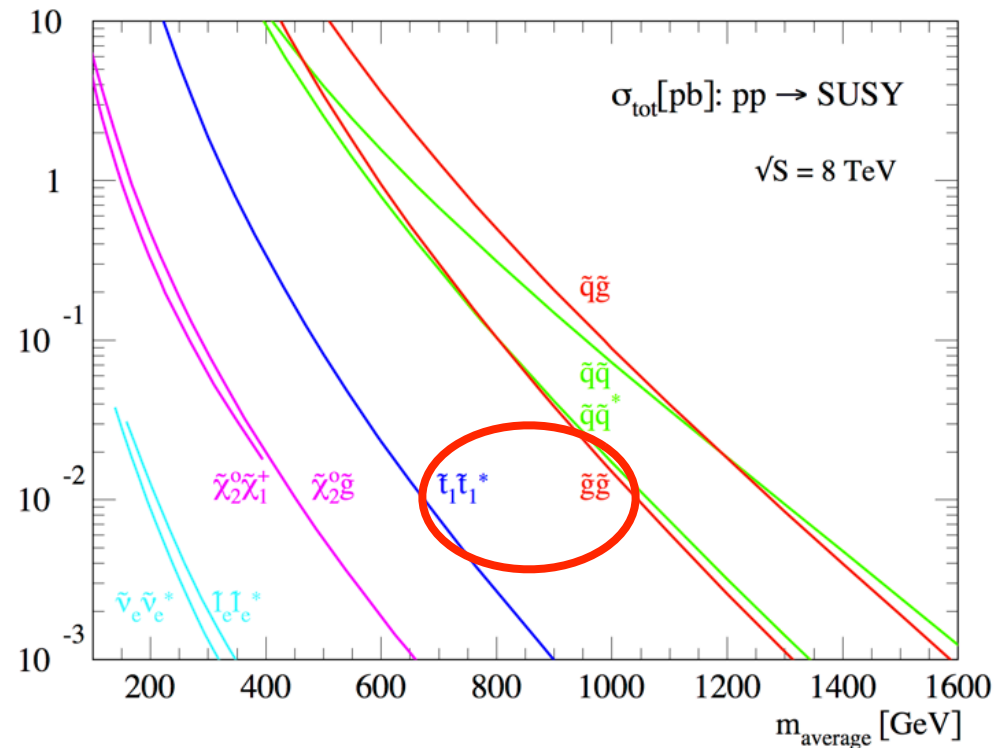
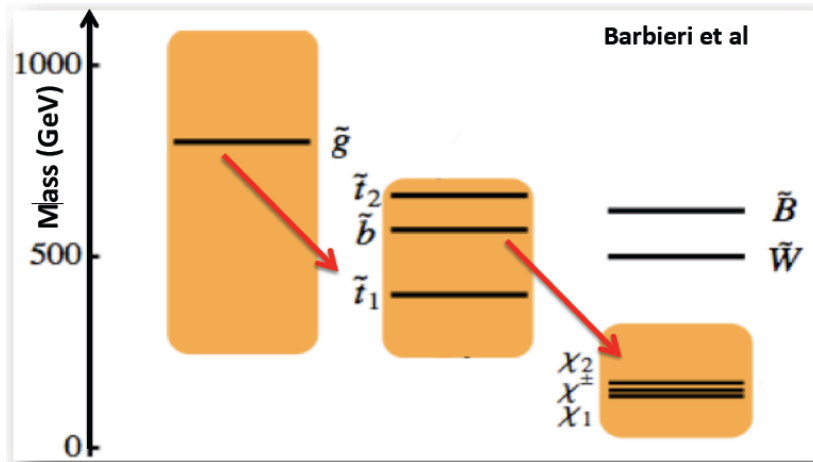
Signature-based → Model-specific searches:

focus on R-parity violating SUSYs, (low MET region) [SM particle: $R=1$; SUSY particles: $R=-1$]

“Natural” SUSY with

relatively light gluinos/3rd-generation squarks, (confront to discovery of the Higgs boson)

...

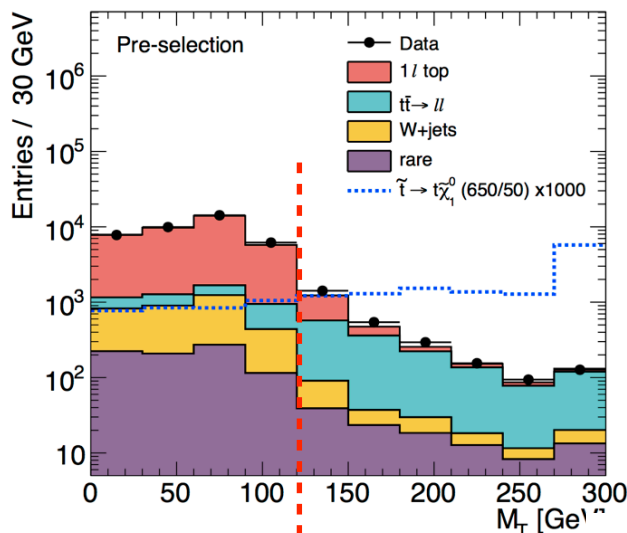
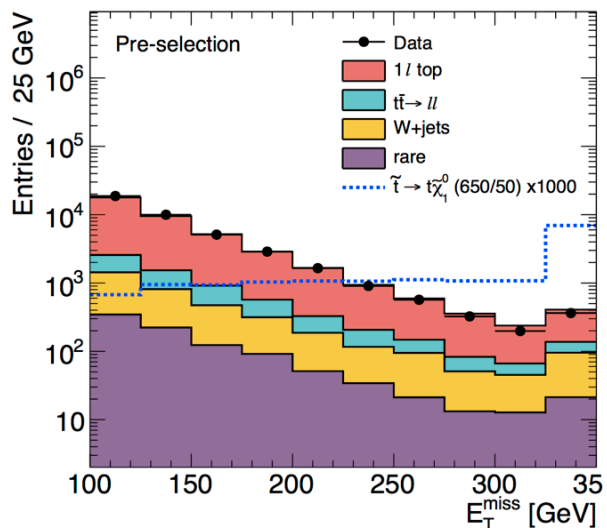
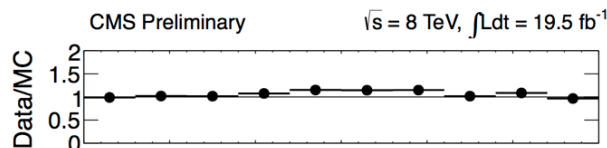
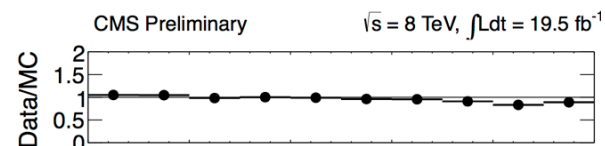
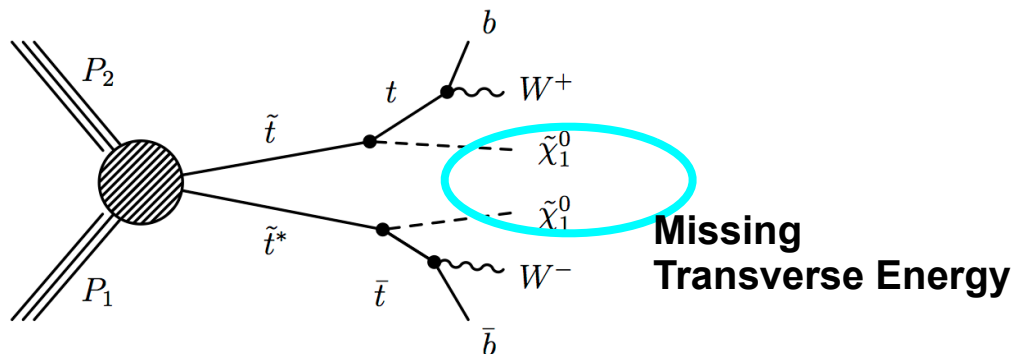




Searches for Direct Stop Pair Production

- ◆ Similar final state as $t\bar{t}$ production.
- ◆ Latest result in “lepton + 4 jets + MET” final state

**CMS-
SUS-13-011**



- ◆ Differ from $t\bar{t}$: larger transverse mass

- ◆ Additional sensitivity by combining other kinematic variables, into Boosted Decision Tree output.

- ◆ Cut & count on BDT output

$$m_T > 120 \text{ GeV} \quad m_T = \sqrt{2 p_T(l) p_T(\nu) \{1 - \cos[\phi(l) - \phi(\nu)]\}}$$

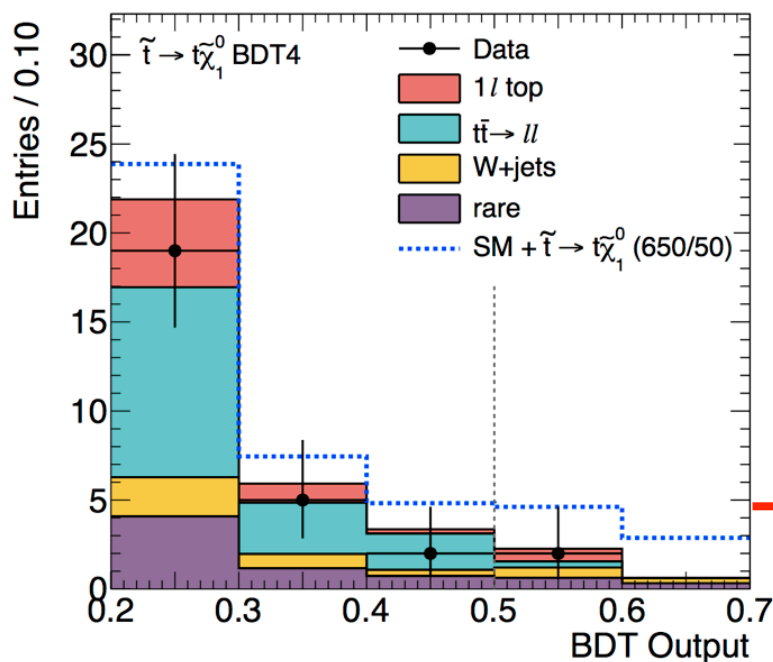
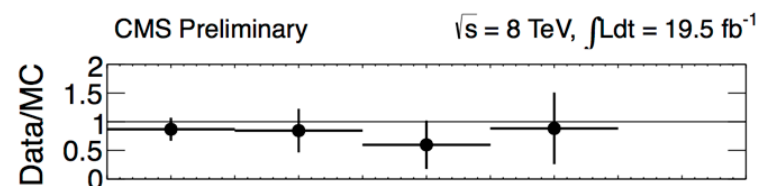


Searches for Direct Stop Pair Production (Cont.)

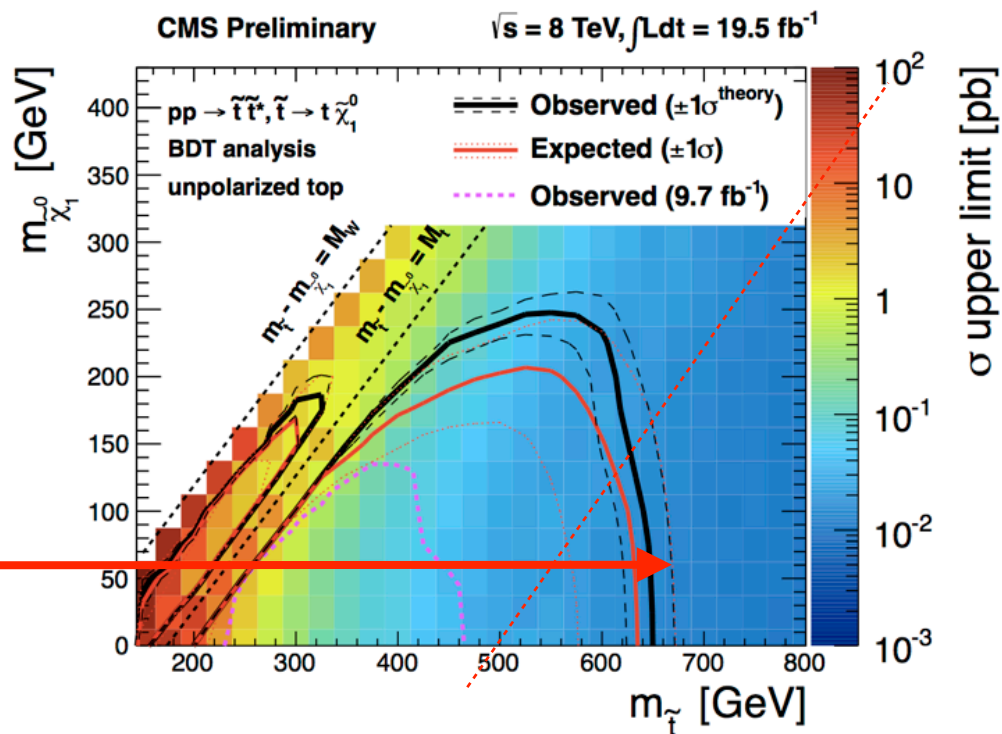
- ◆ BDTs are optimized to different regions of parameter space
- ◆ Polarization of tops can result in small variations of limits.

CMS-SUS-13-011

- ◆ Simplified Model Spectra: assume a single production and one decay channel with 100% BF



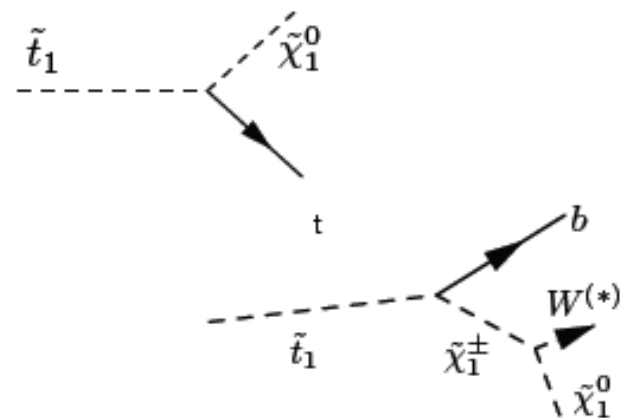
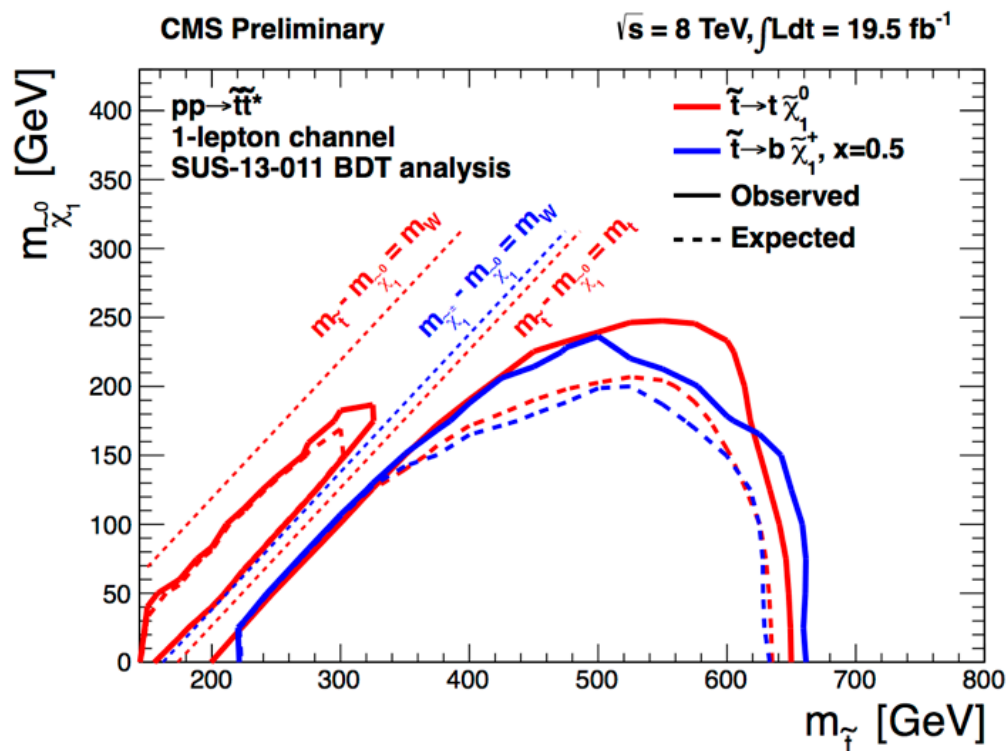
stop: $\sim 625 \text{ GeV}$
neutralino: $\sim 225 \text{ GeV}$,





Summary of Searches for Direct Stop Pair Production

- ◆ Different specific decay modes are explored to cover the whole phase space (each assumed 100% BF)
- ◆ More results are to come during summer (stay tuned)



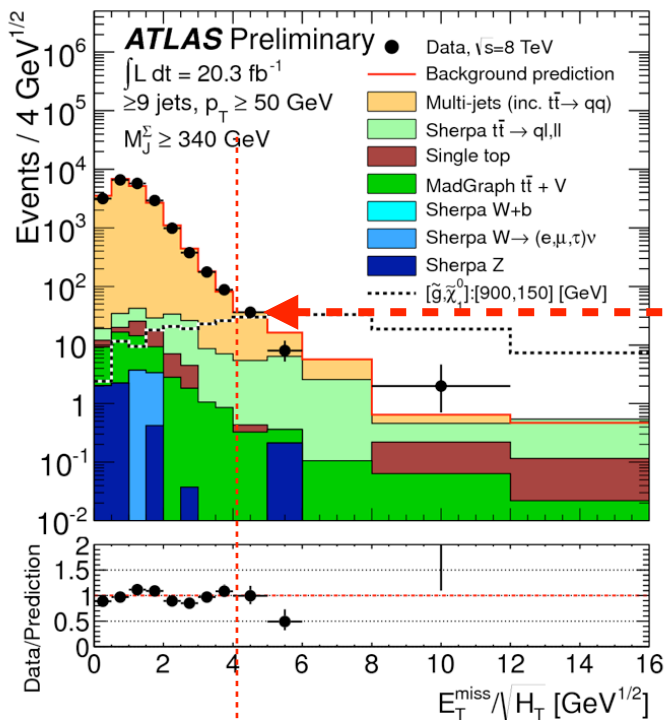
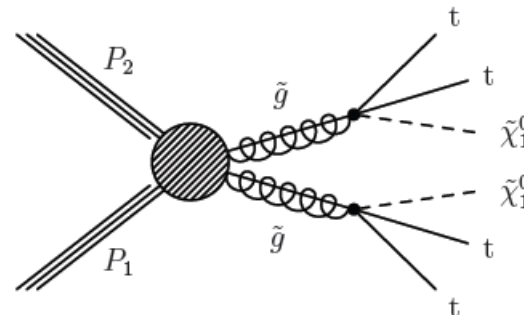
: 100% BF on each decay channel

CMS-SUS-13-011: 1 lepton + jets + MET



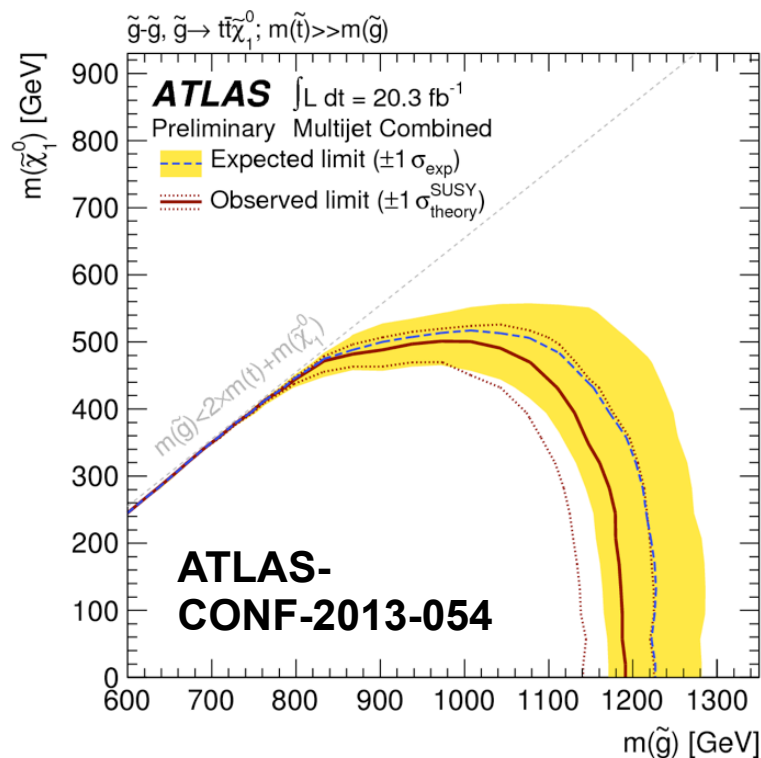
Gluino-mediated Stop Production - All Hadronic Final State

- ◆ 4 tops in the final state, very rich final state
- ◆ Explored 7-10 jets + MET
- ◆ 19 signal regions:
(jet multiplicity + flavor content/composite jet mass)



signal region

H_T :
 scalar sum of jets
 $p_T > 40 \text{ GeV}$,
 $|\eta| < 2.8$

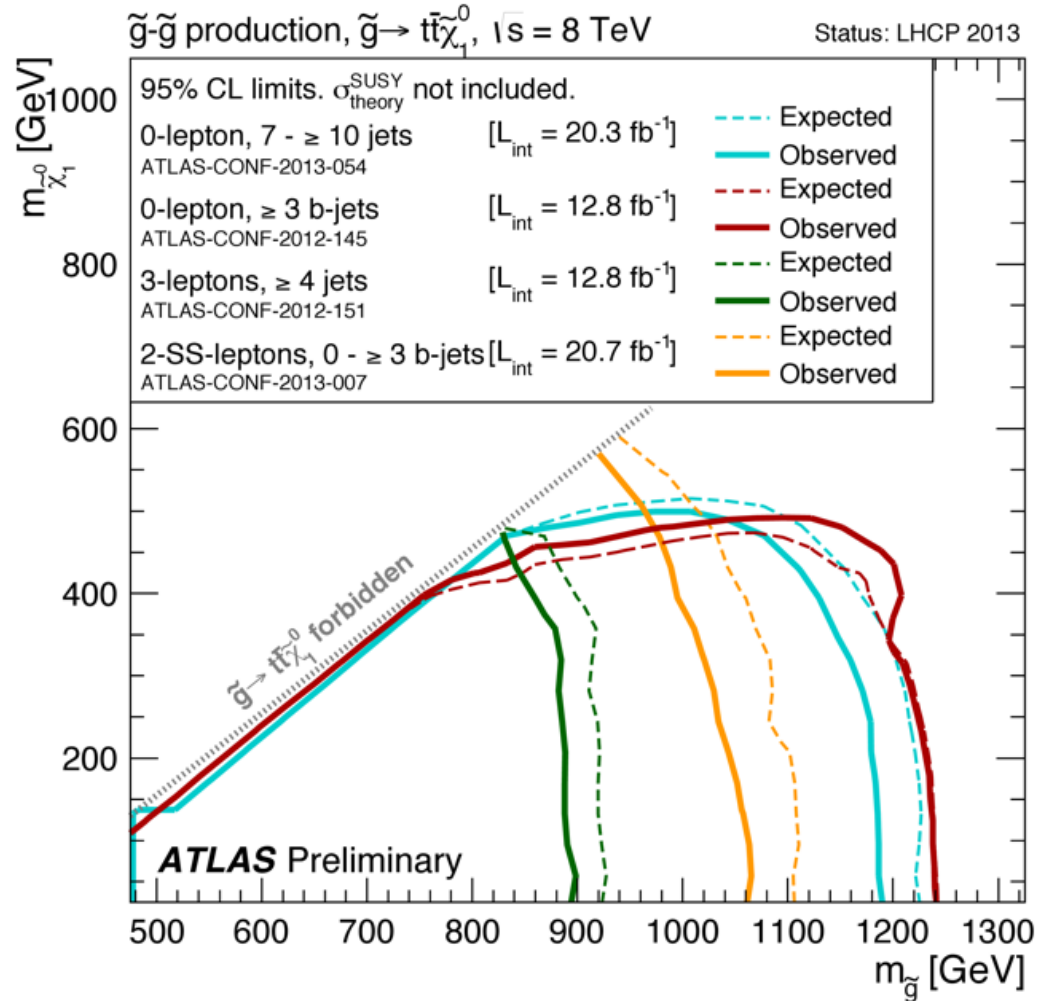
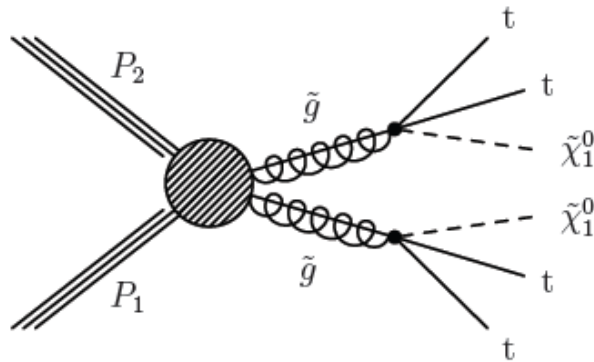




Summary of Gluino-mediated Stop Production

Combined mass reach:

- ◆ **Gluino:** up to ~1.2-1.3 TeV
- ◆ **Neutralino:** up to ~500-600 GeV





2 TeV

1 TeV

95% CL EXCLUSION LIMITS (TeV)



Heavy Resonances

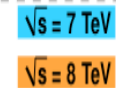
Long
Lived



Contact Interactions

Extra Dimensions & Black Holes

LHCP 2013



CMS Preliminary

For decays with intermediate mass,

$$m_{\text{intermediate}} = x \cdot m_{\text{mother}} + (1-x) \cdot m_{\text{so}}$$

*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit



Summary and Outlook

- ◆ **LHC experiments have been actively exploring the TeV scale in all different perspectives.**
excellent detector performance/high quality LHC data,
novel experimental techniques,
creative theoretical inputs, ...
- ◆ No BSM physics has been observed.
- ◆ **Nature could come up with surprise in current 7+8 TeV data**
- ◆ **Look forward to the coming LHC Run 2 at 13(or 14) TeV**
- ◆ **“Once in lifetime” opportunity to harvest the LHC data!**

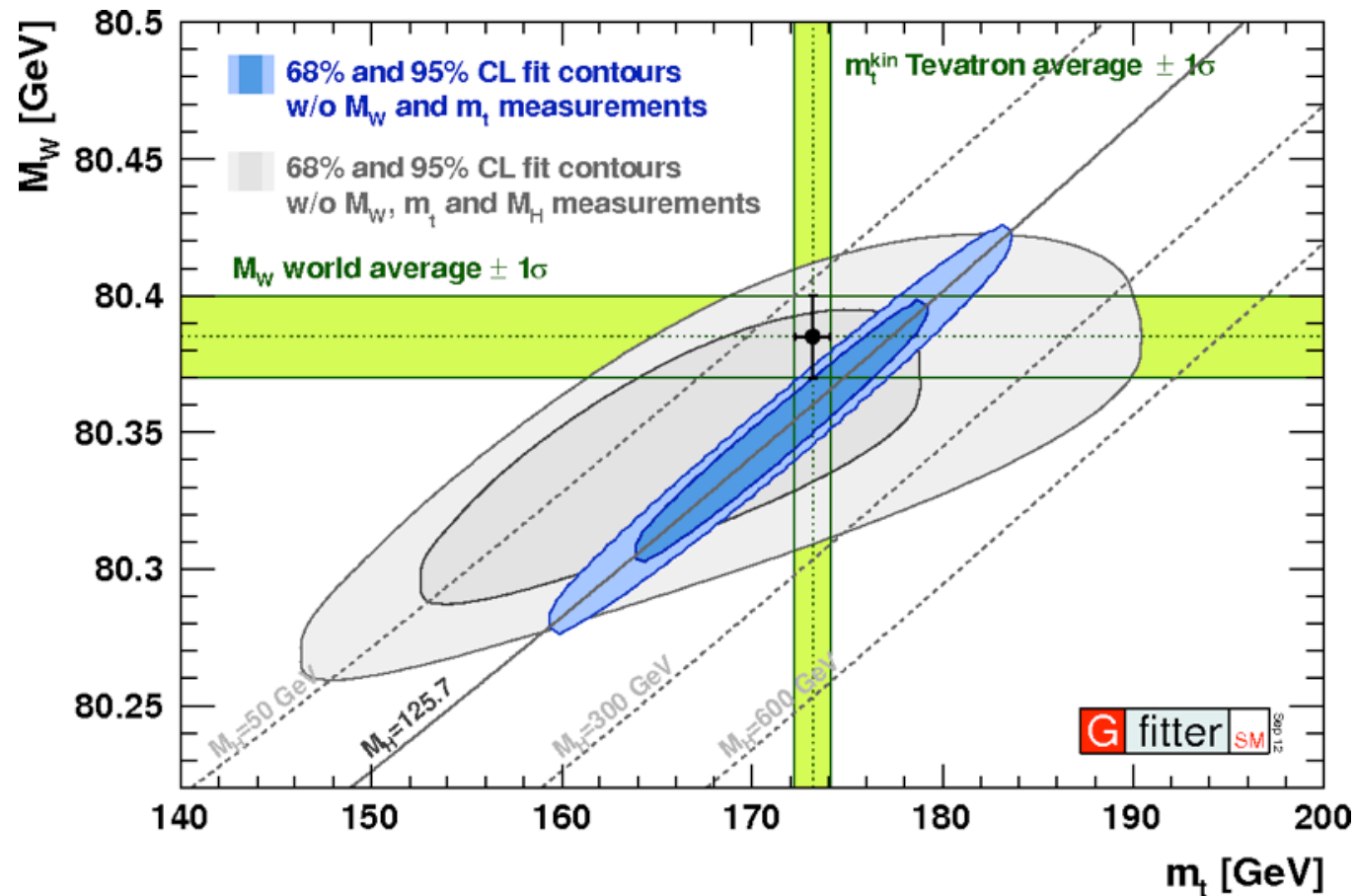


Backup



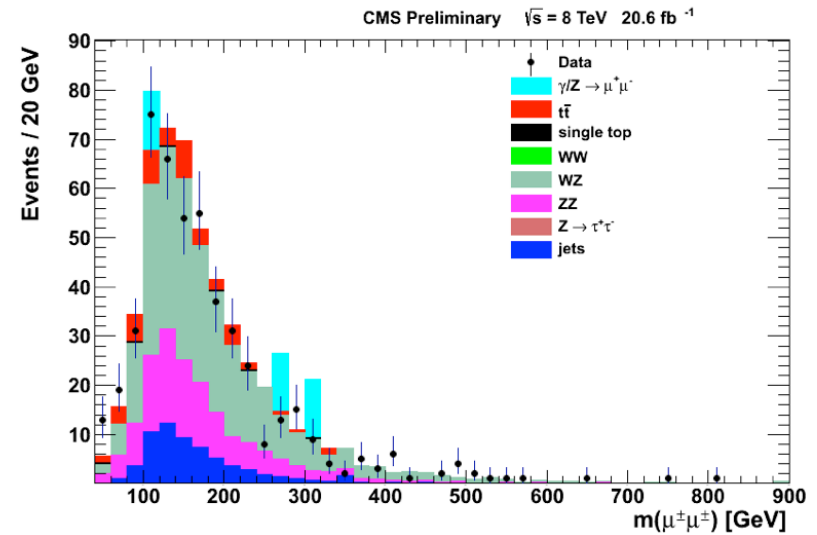
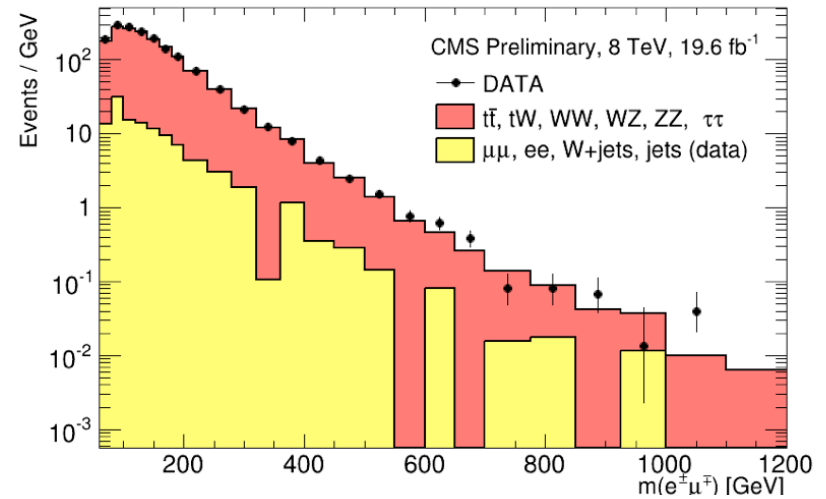
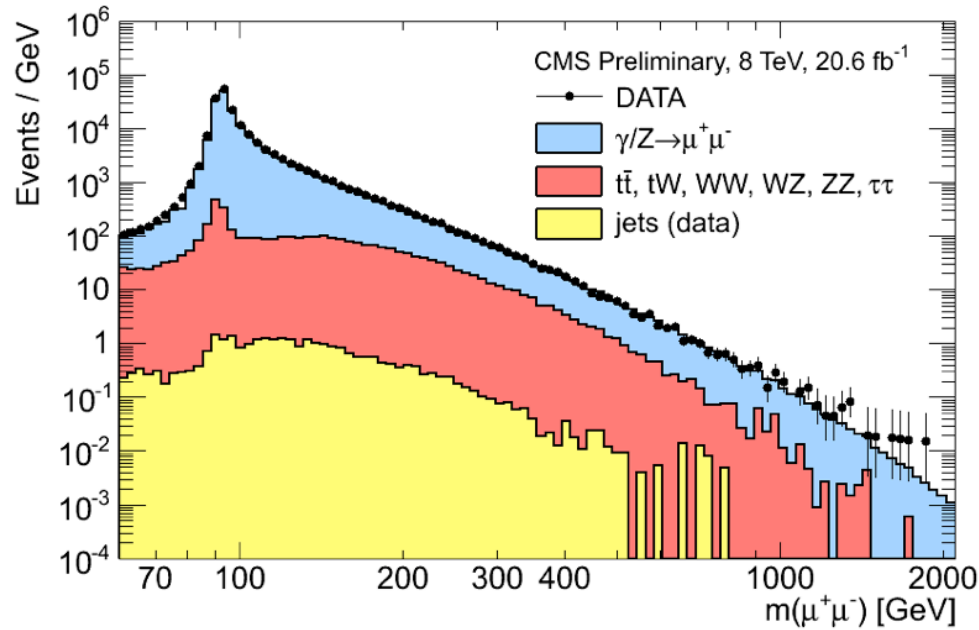
We Had a Boson

- ◆ Global electro-weak fit to check consistence of the SM,



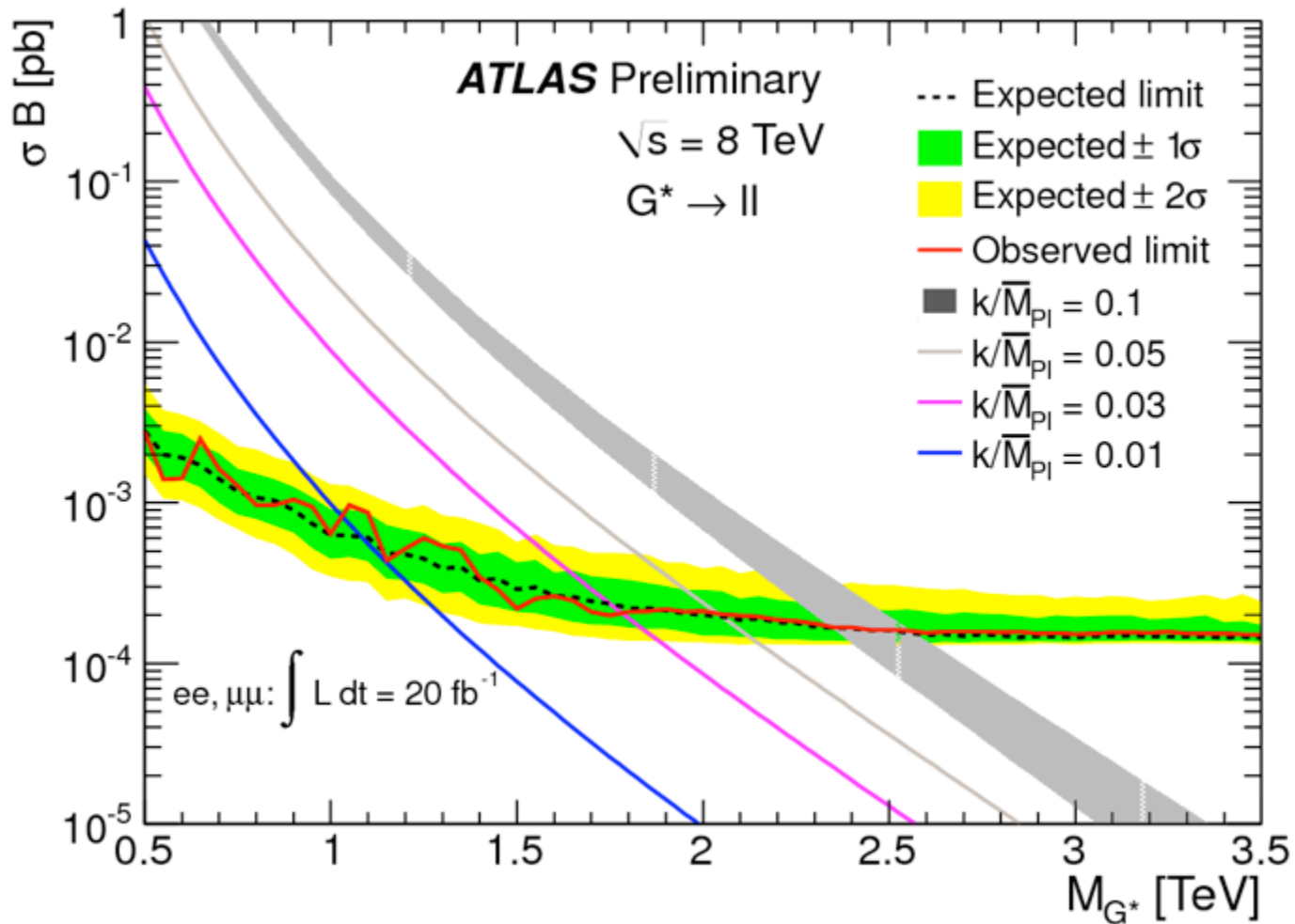


CMS-PAS-EXO-13-061





ATLAS-CONF-2013-017

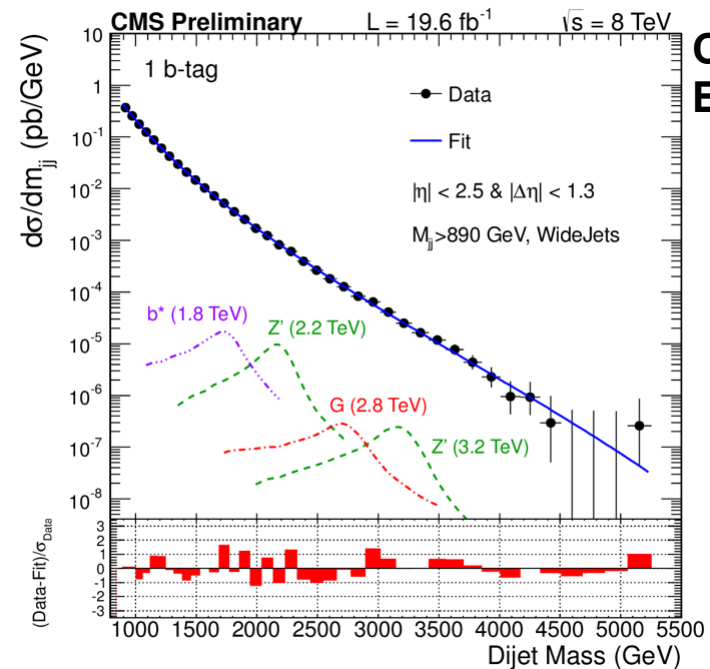
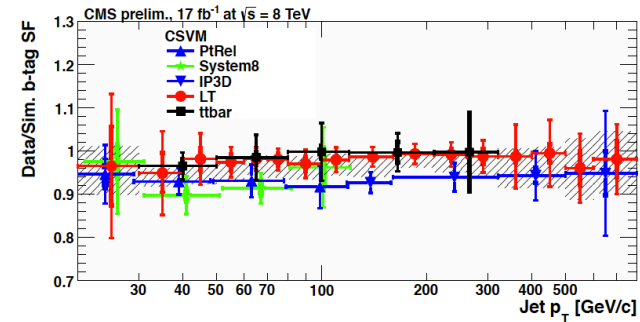
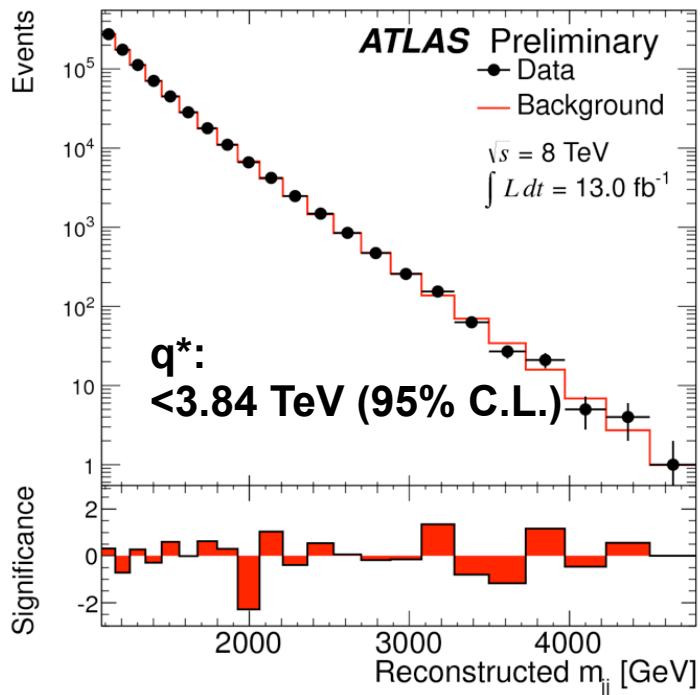




Dijet Resonances

- ◆ ATLAS di-jet searches used up to 13 fb^{-1}
- ◆ **Interesting extension of CMS dijet searches: tagging b-jets with p_T up to 0.8 TeV**
- ◆ A whole literature of multi-jet resonance searches.

ATLAS-CONF-12-148

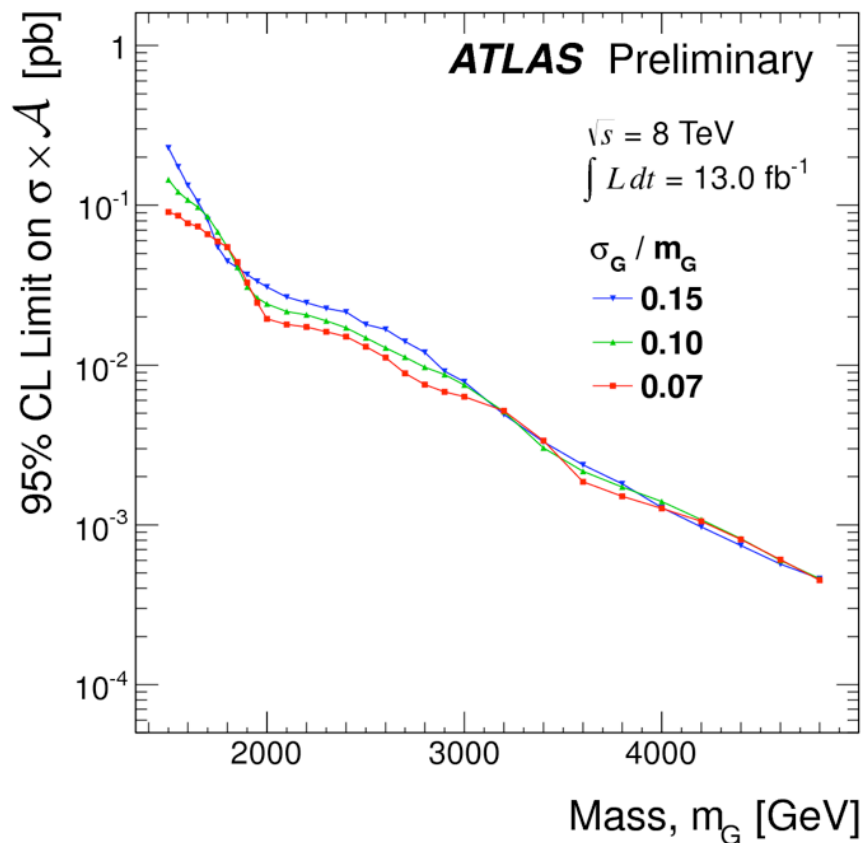
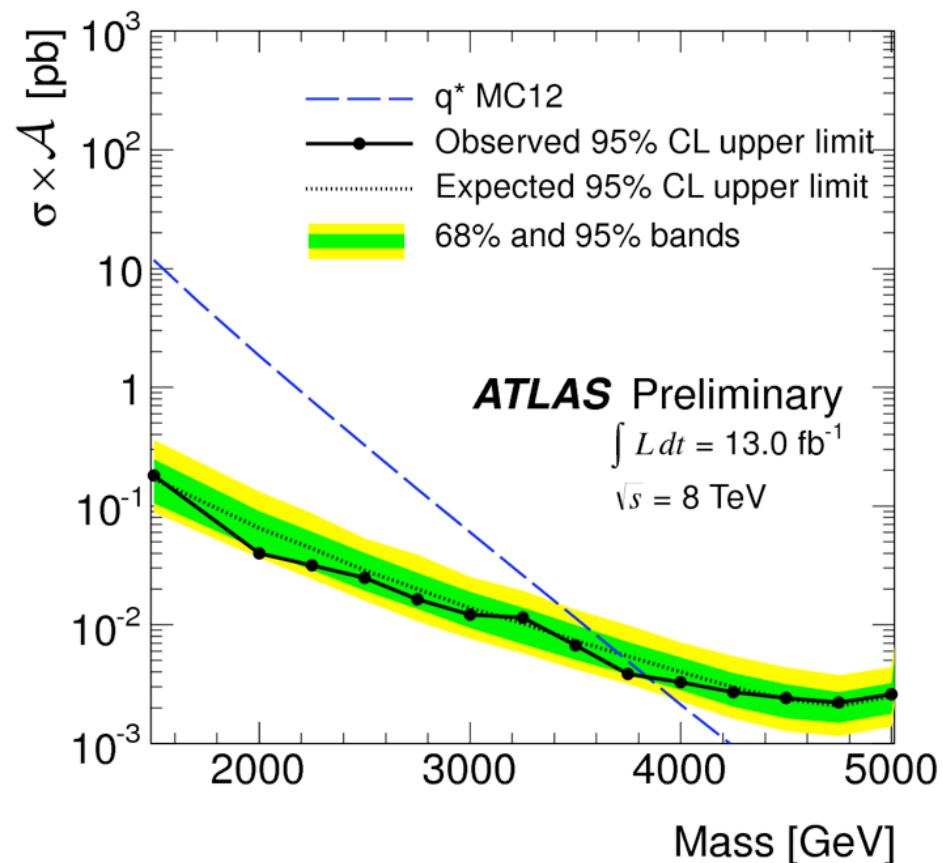


e.g., b^* : $\notin [1.34, 1.54] \text{ TeV (95\% C.L.)}$

CMS-PAS-
EXO-12-023

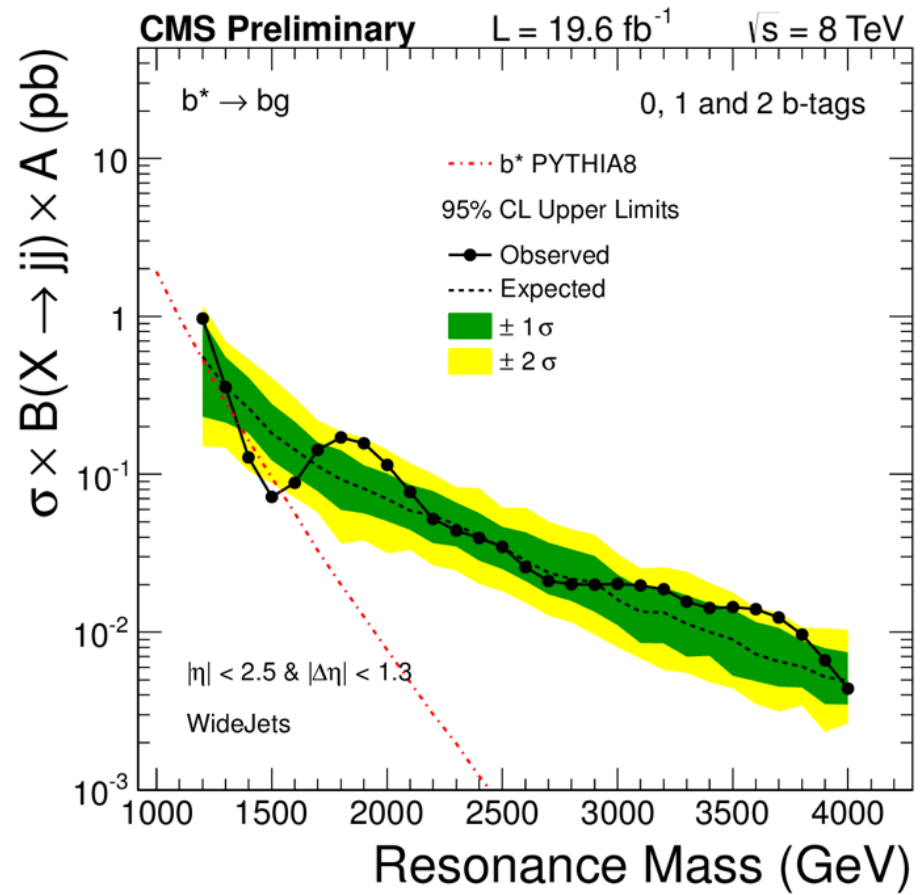
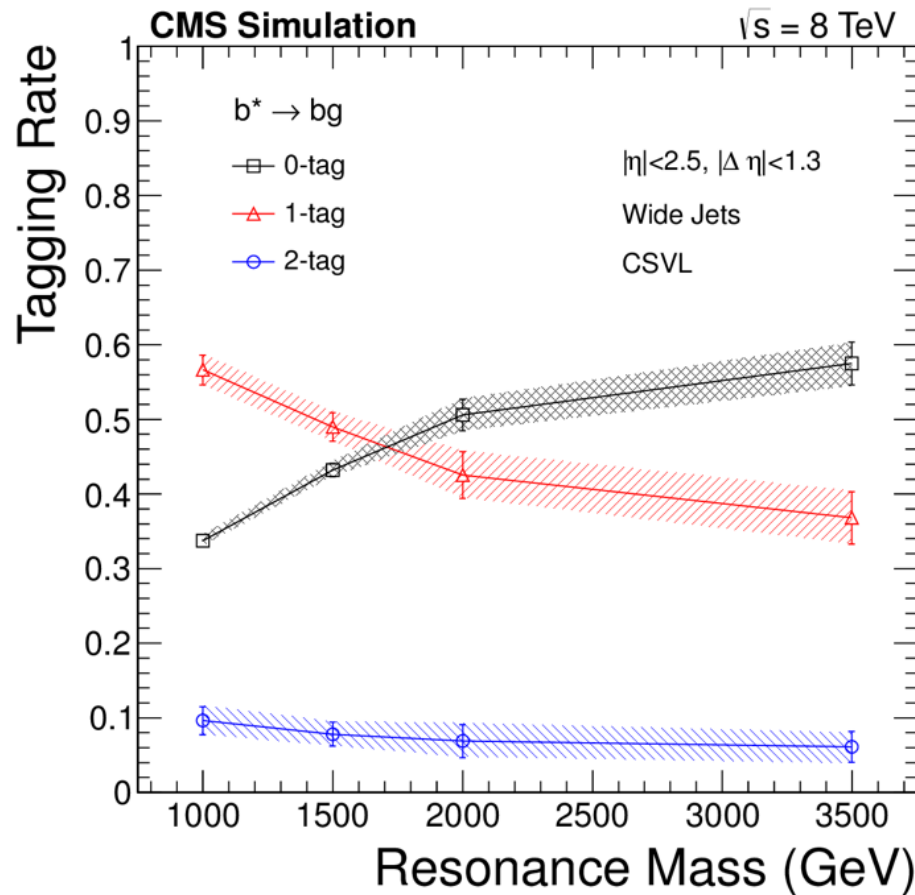


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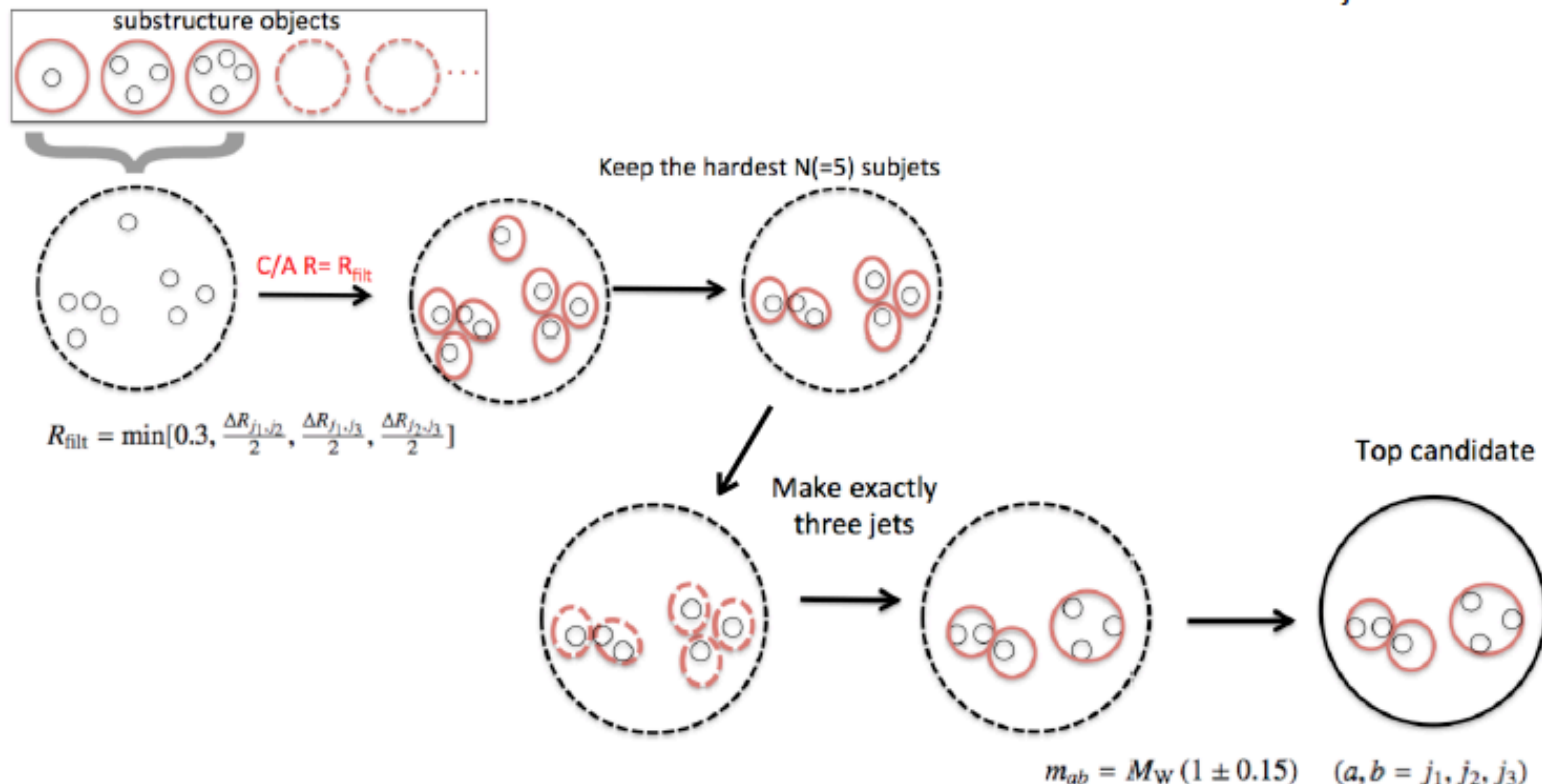




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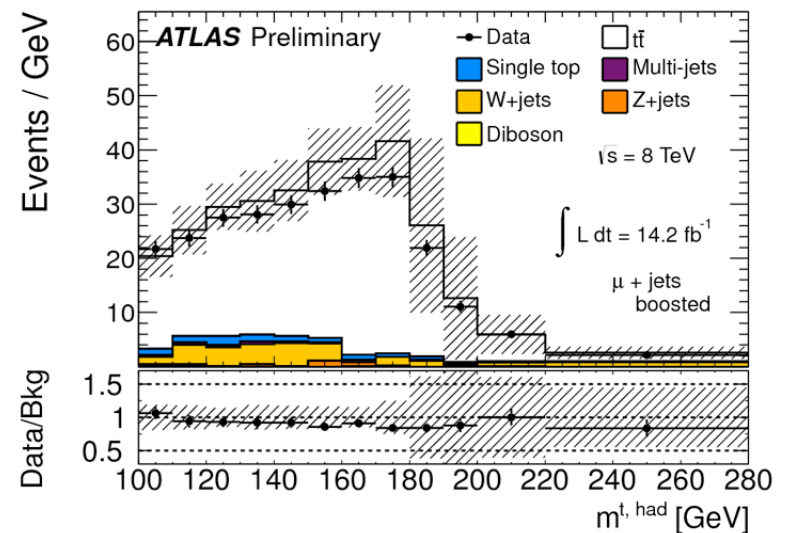
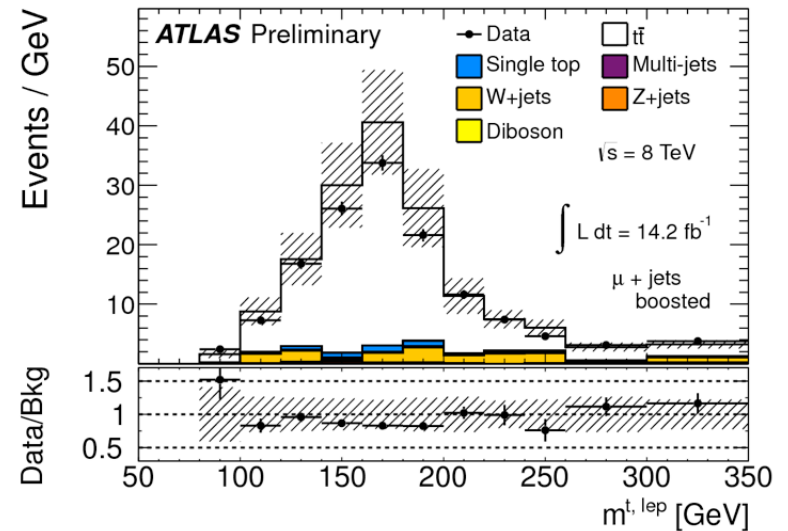
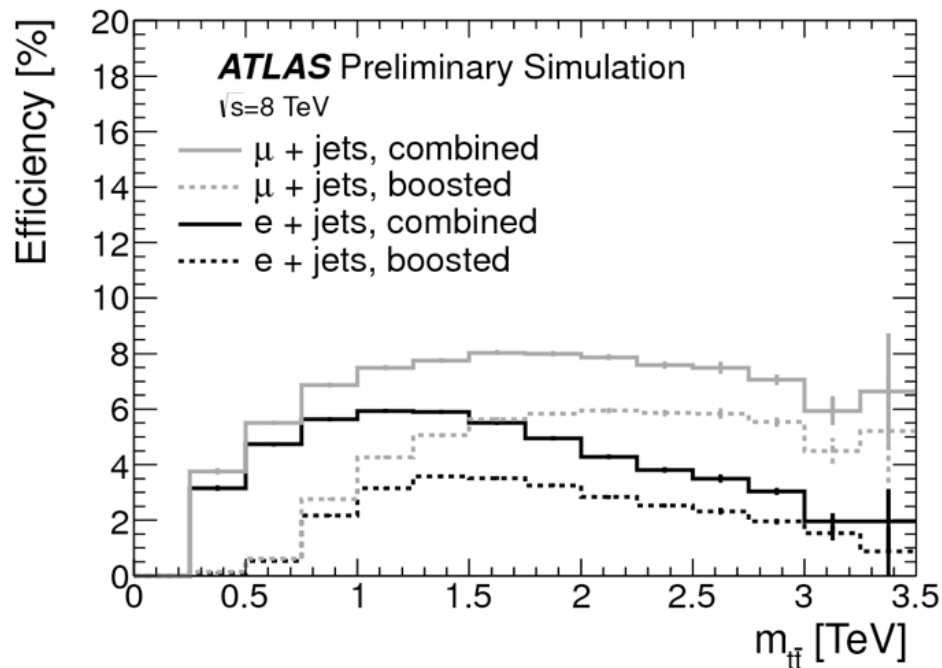


- ▶ ATLAS has extensively studied and optimized the HEPTopTagger
 - ▶ Plehn, Spannowsky, Takeuchi, arXiv:1111.5034
- ▶ HEPTopTagger reclusters the large-R jet using a smaller distance parameter
 - ▶ Removes soft, wide-angle radiation
- ▶ Left with 3 decay products of top quark reconstructed as subjects



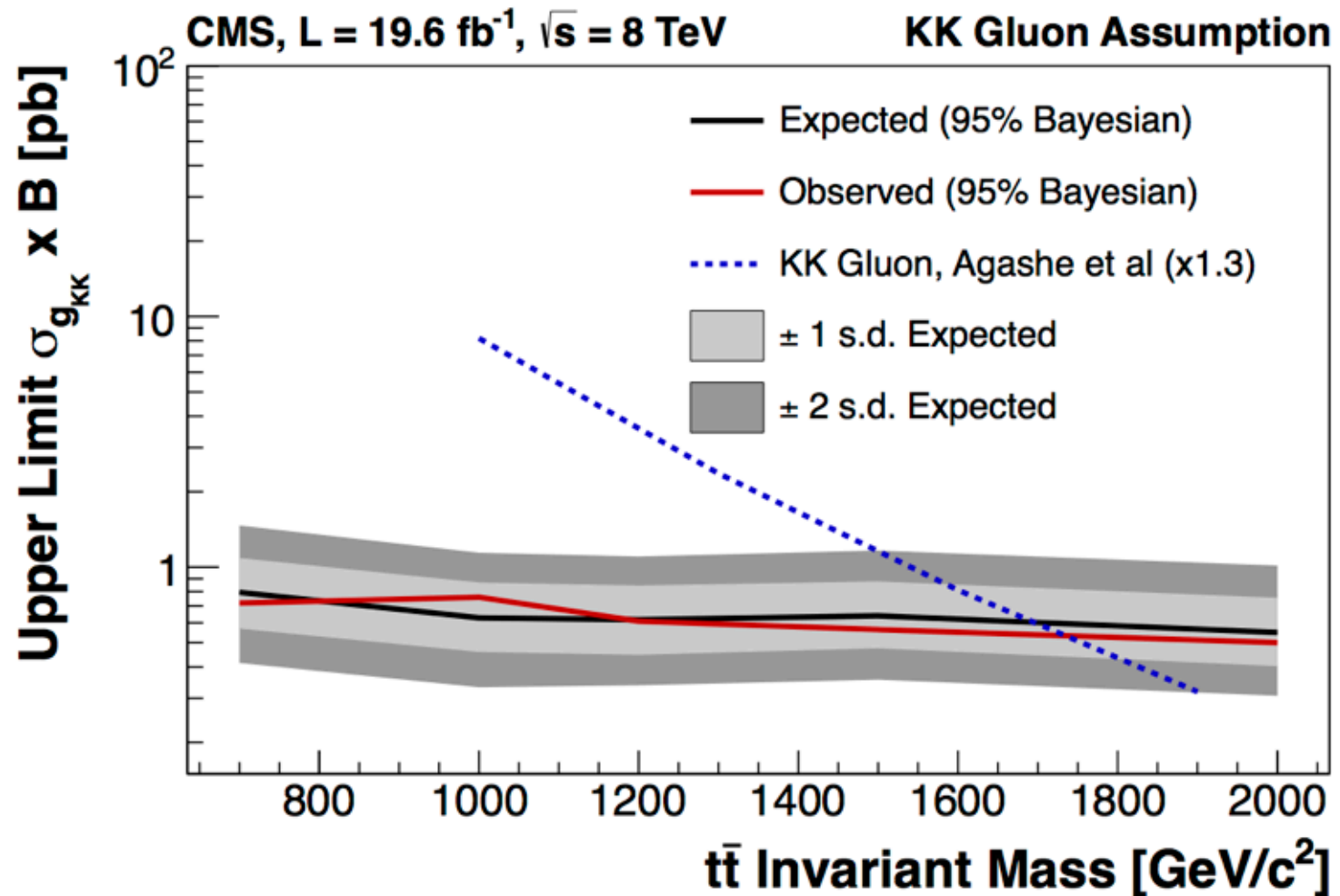


ATLAS-CONF-2013-052



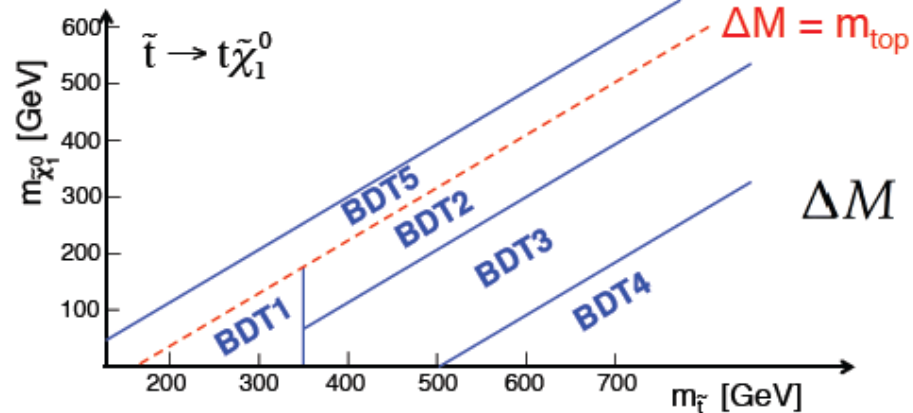
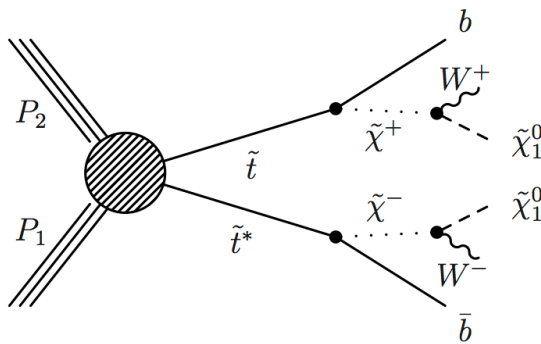
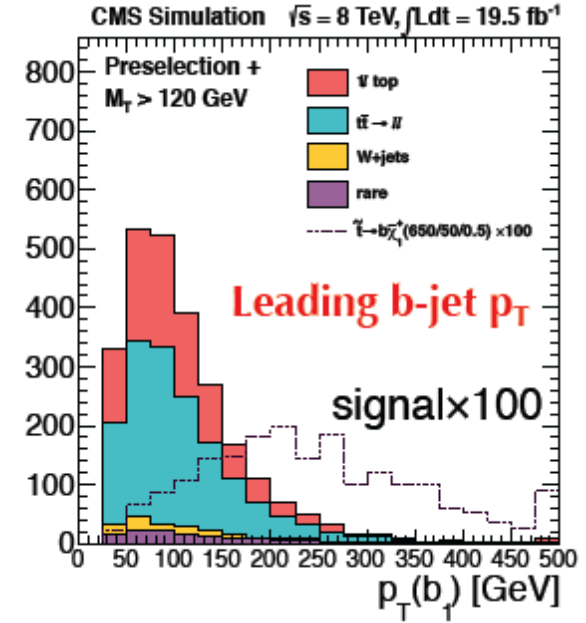
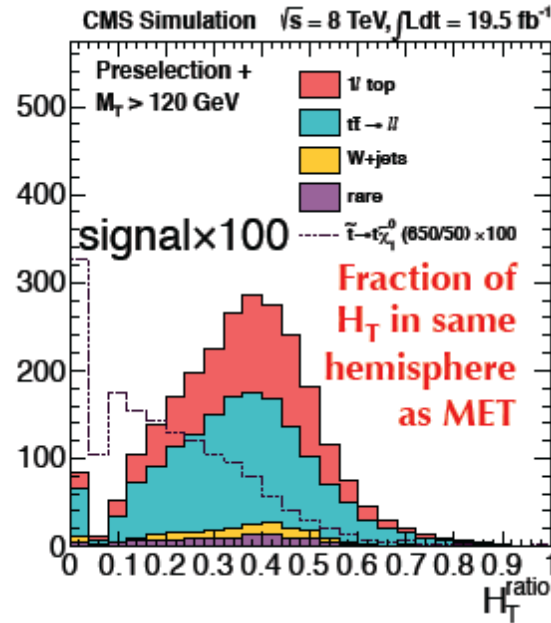
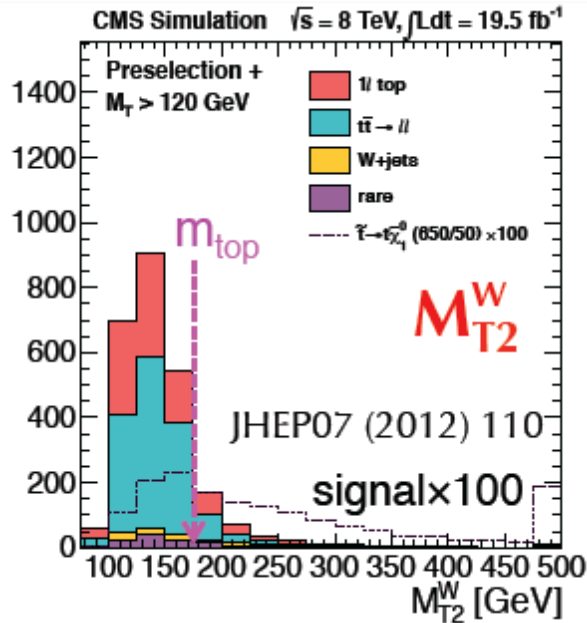


CMS-PAS-B2G-12-006



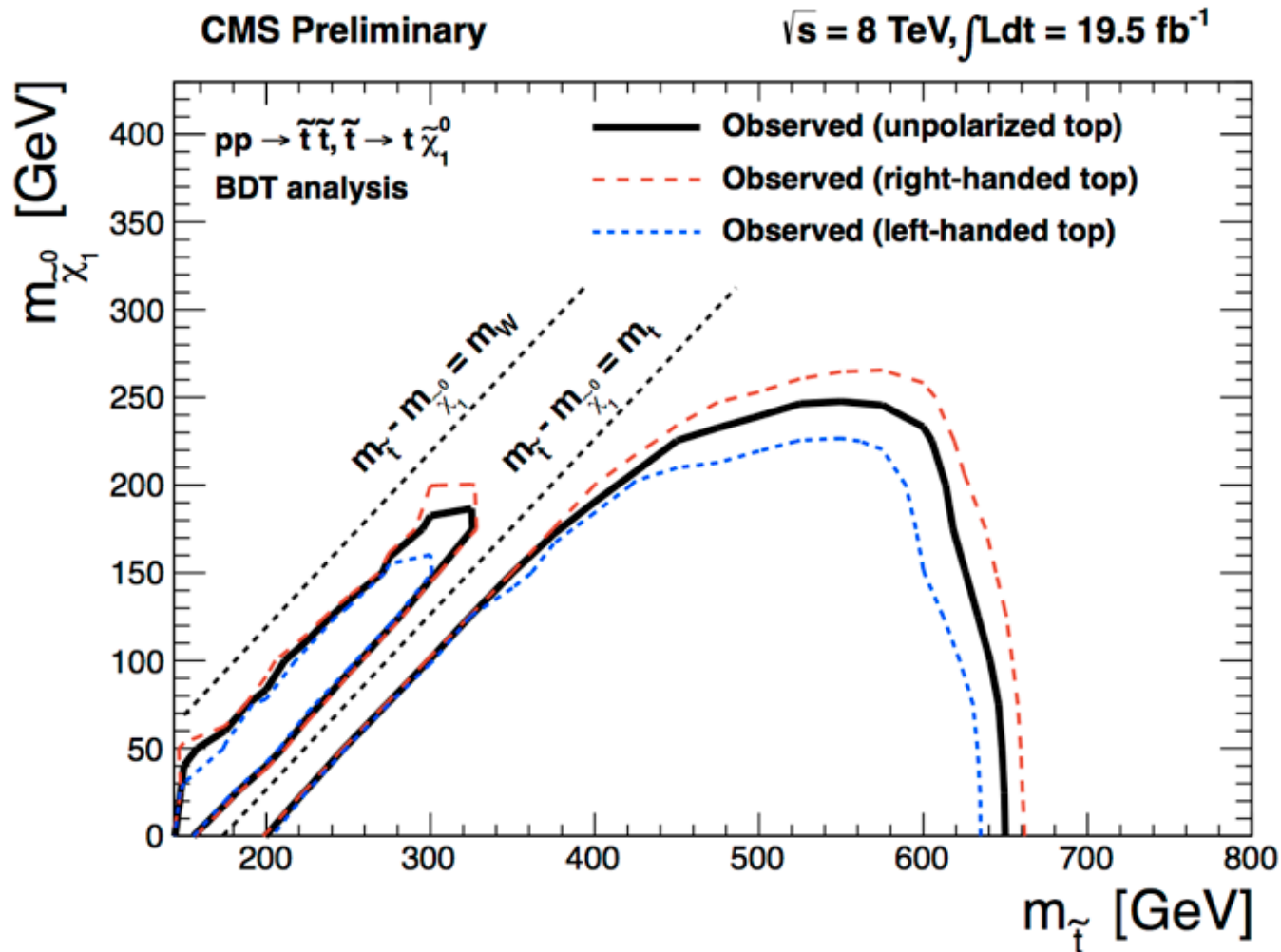


CMS-PAS-SUS-13-011





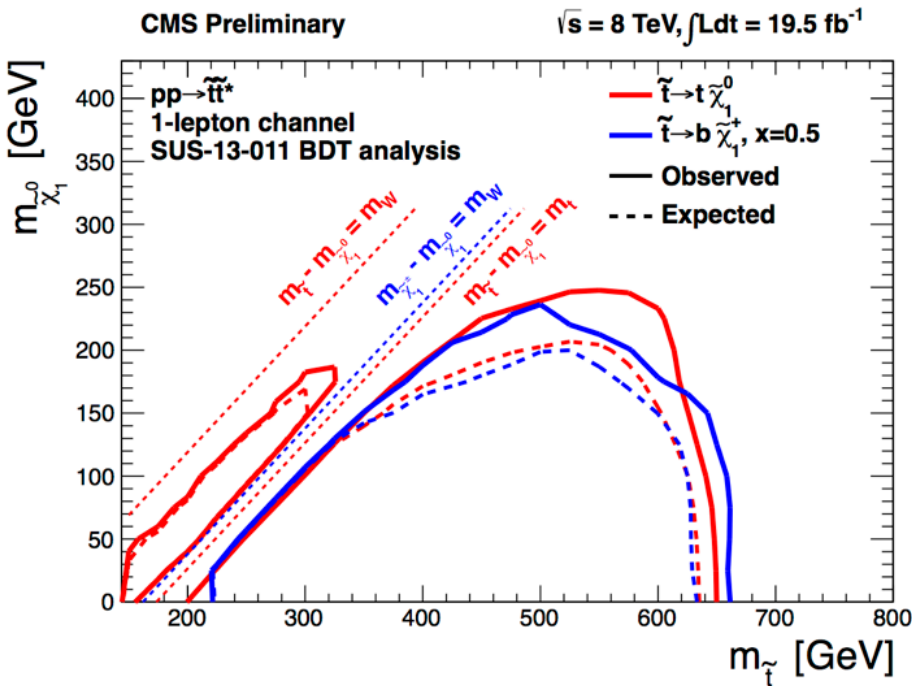
CMS-PAS-SUS-2013-011





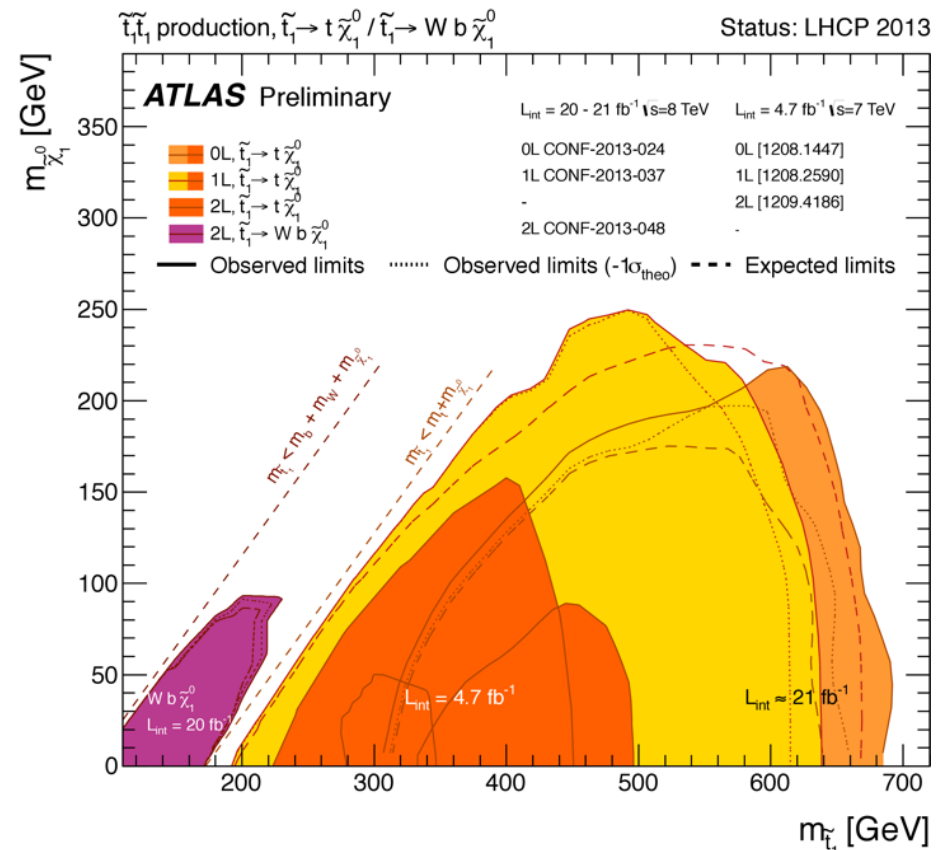
Summary of Searches for Direct Stop Pair Production

- ◆ Different specific decay modes are explored to cover the whole phase space (each assumed 100% BF)
- ◆ More results are to come during summer (stay tuned)



CMS-SUS-13-011: 1 lepton + jets + MET

University of Iowa

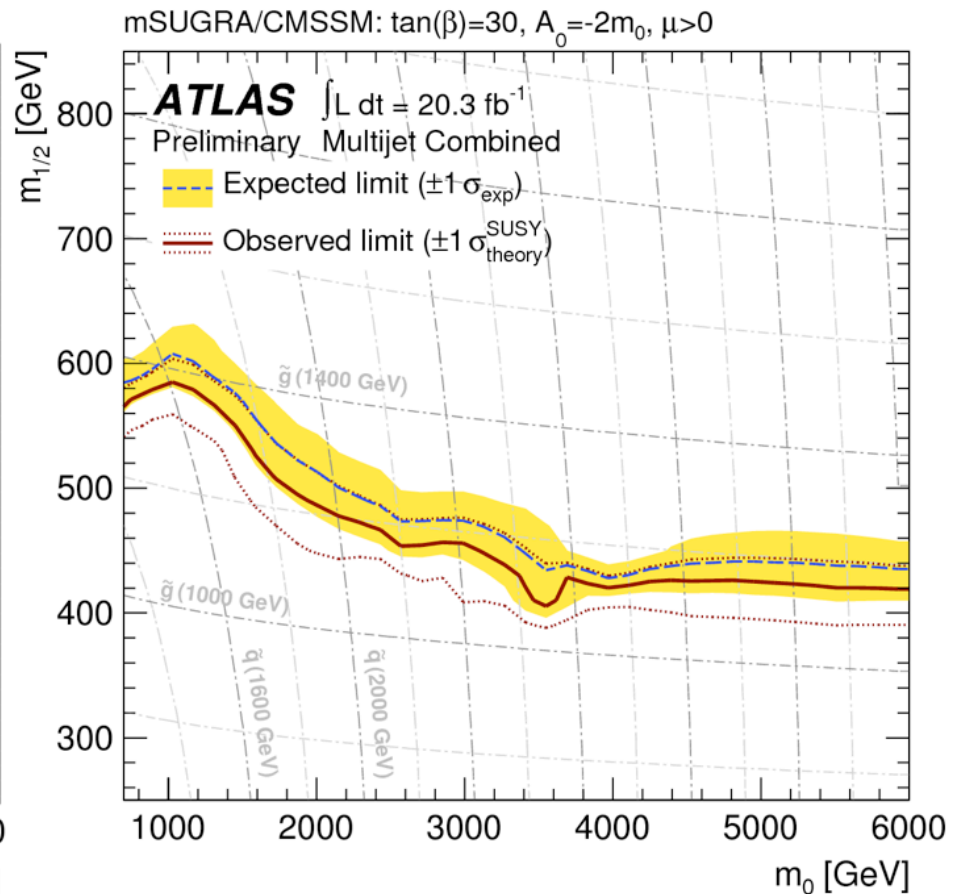
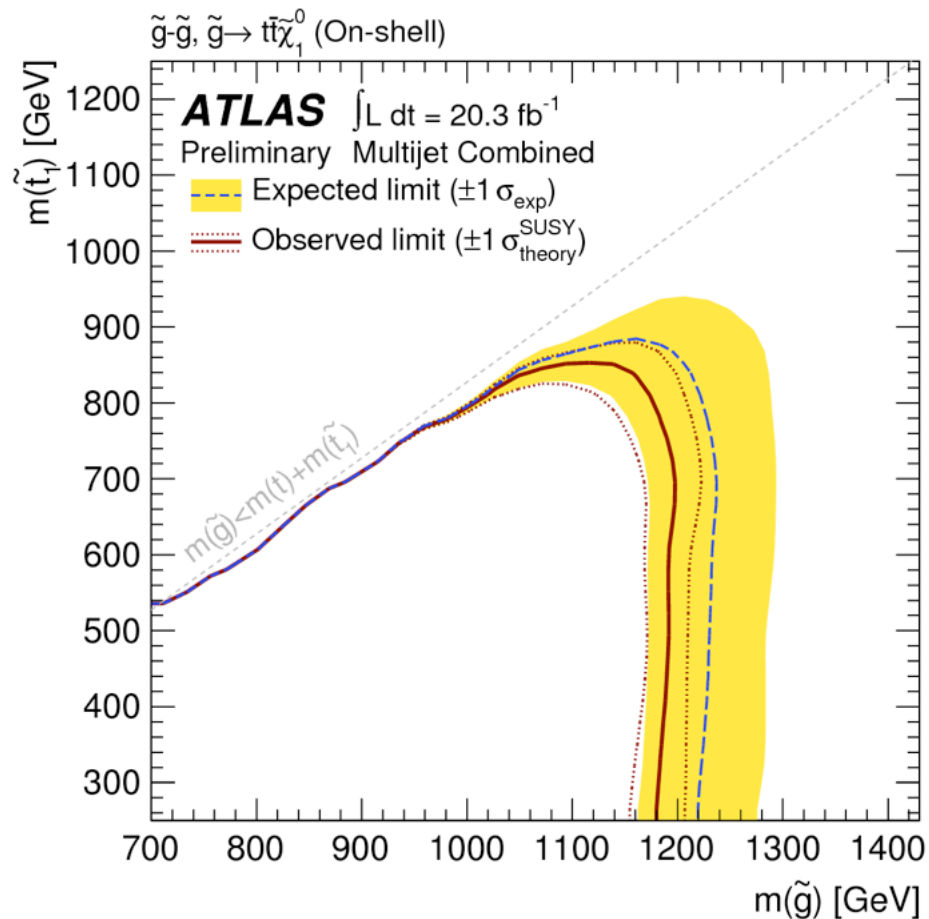


ATLAS: (0-2) leptons + jets + MET

Ping Tan



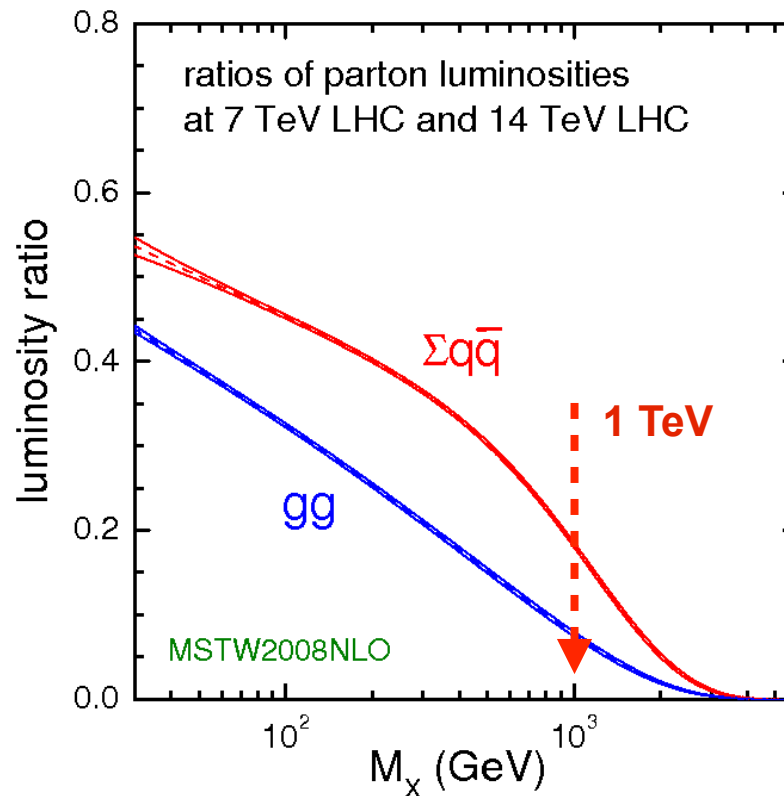
ATLAS-CONF-2013-054





Looking Beyond

- ◆ **There are many ongoing analyses with the 8 TeV (and even in 7 TeV) LHC data:**
e.g., “parked” CMS data is largely un-explored
- ◆ The newly discovered Higgs boson opens a completely new door for BSM physics.
- ◆ LHC Run 2



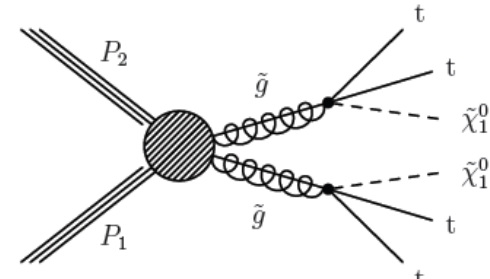
J. Stirling et. al,
PDF4LHC



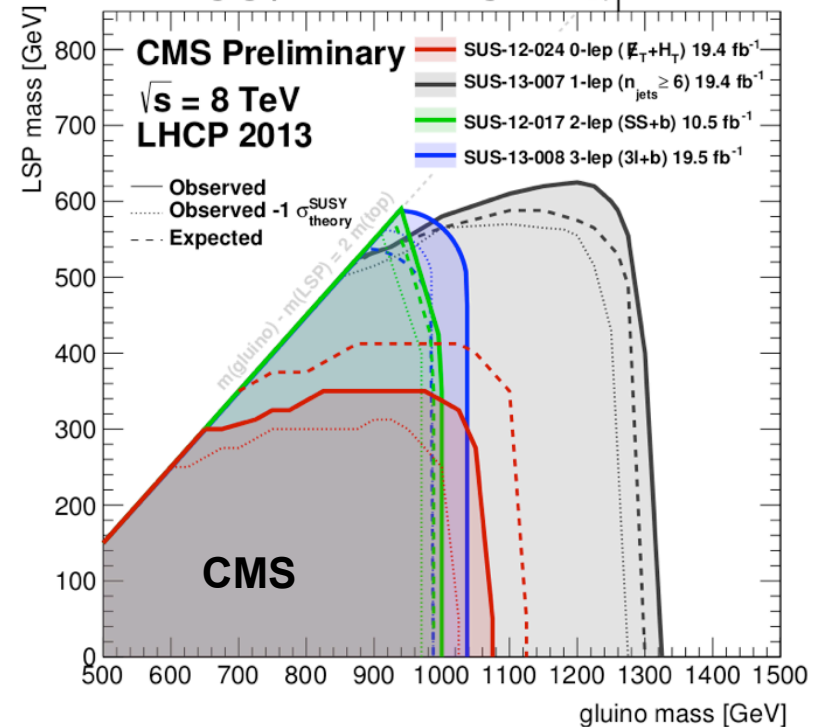
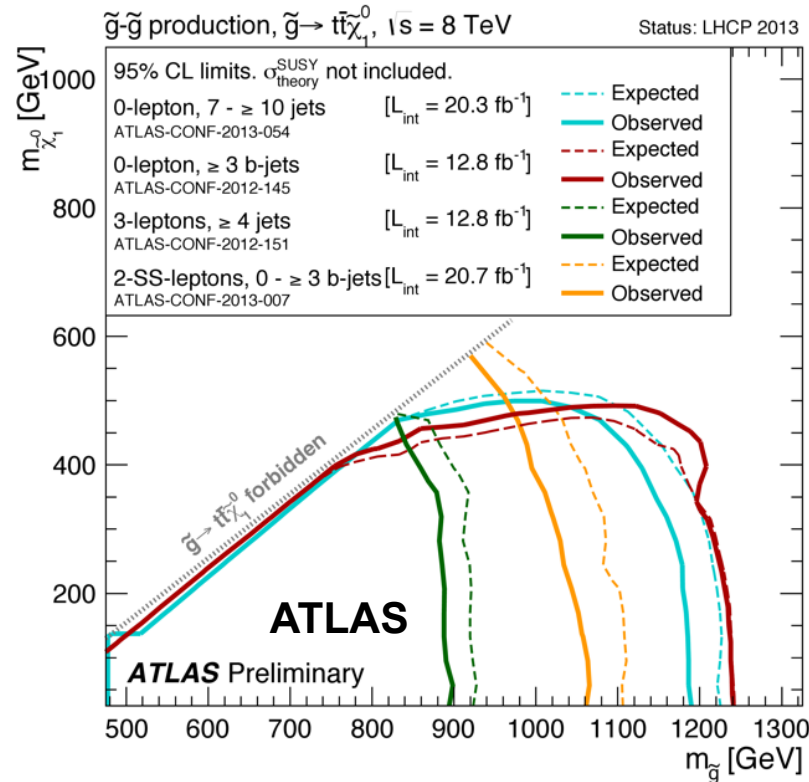
Summary of Gluino-mediated Stop Production

Combined mass reach:

- ◆ **Gluino:** up to ~1.2-1.3 TeV
- ◆ **Neutralino:** up to ~500-600 GeV
- ◆ Different analyses/datasets; exclusion is similar



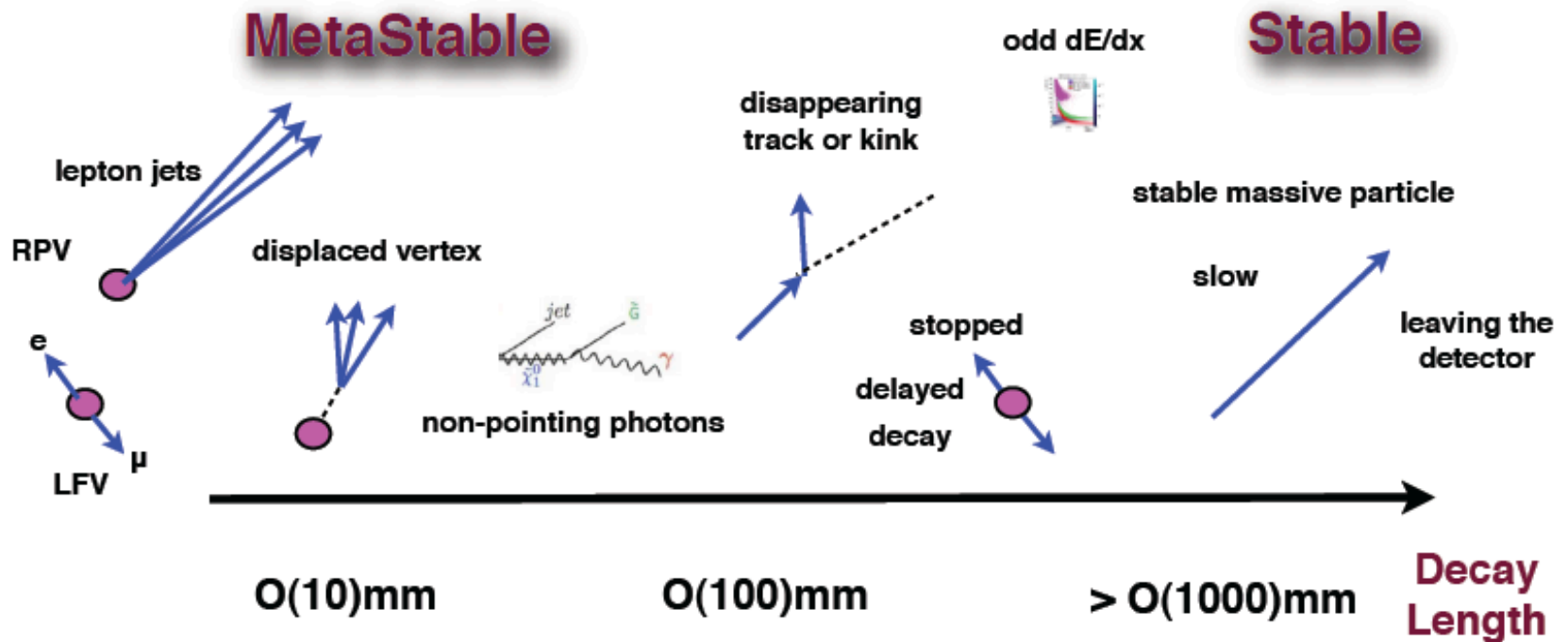
$\tilde{g}\text{-}\tilde{g}$ production, $\tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^0$





HSCP (SMP) and Other Unusual Signatures

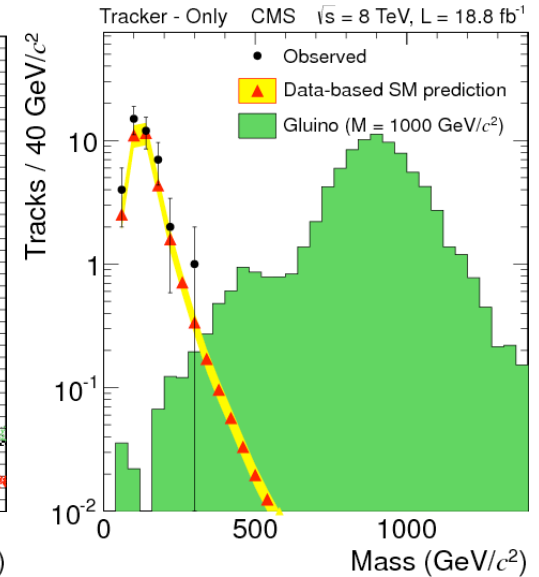
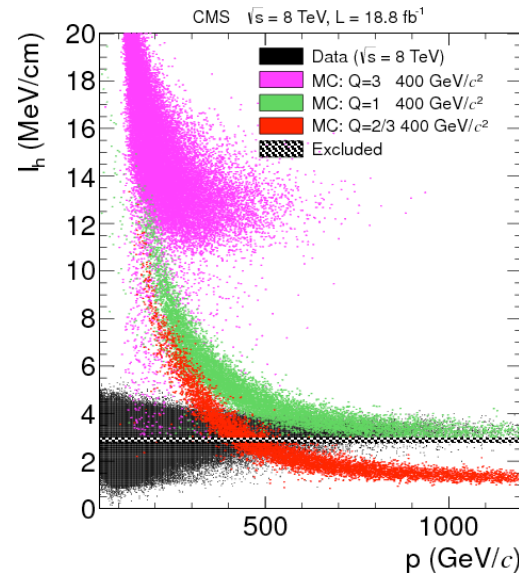
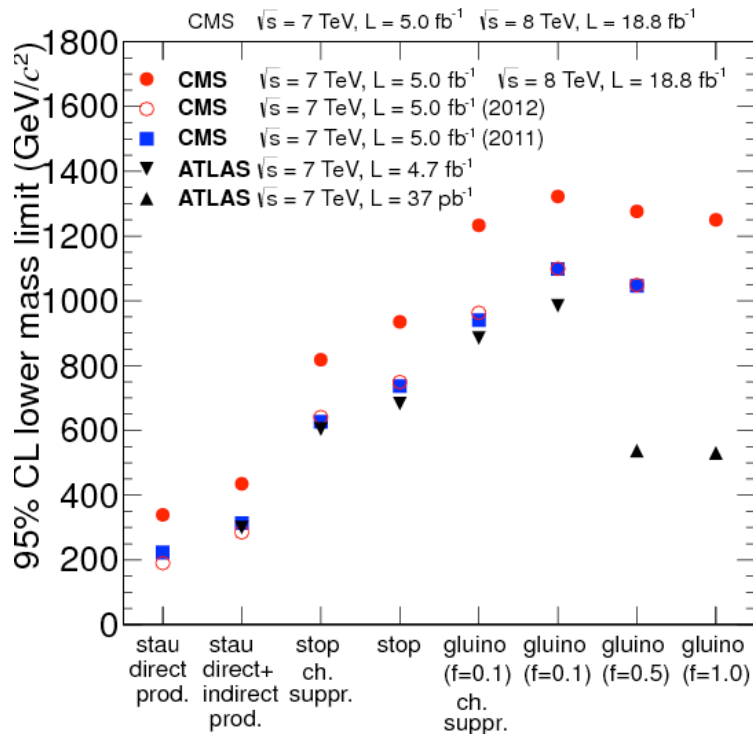
- ◆ A whole set of exotic experimental signatures:
Heavy stable charged particle (HSCP)/Stable massive particles (SMP),
Displaced fermions/jets/vertices/
non-pointing photons,
lepton-jets, ...
- ◆ Theoretical motivations: R-parity conserved SUSY, extra-dimension with KK-parity.





Latest Result - HSCP/SMP

- ◆ Charged heavy particle with $\beta < 1$; special care in reconstruction
- ◆ β reconstruction
dE/dx (silicon tracker),
Time-of-Flight with muon system



$$I_h = \left(\frac{1}{N} \sum c_i^{-2} \right)^{-1/2},$$

$$I_h = K \frac{m^2}{p^2} + C,$$

[arxiv: hep-ex/1305.0491](https://arxiv.org/abs/hep-ex/1305.0491) (submitted to JHEP)

stop: $\sim 0.8\text{-}0.9 \text{ GeV}$

gluino: $\sim 1.2\text{-}1.3 \text{ TeV}$, depending on models