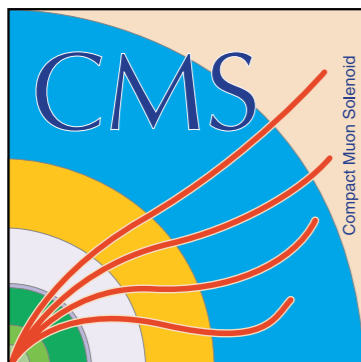


Higgs and Beyond
June 7th, 2013

Searches for Exotics with Other (than Jet!) Signature at the LHC

Koji Terashi
(ICEPP, University of Tokyo)

on behalf of the ATLAS and CMS Collaborations



“Other” Signature?

Thought about what “signatures other than jets” are currently considered in ATLAS and CMS

Maybe worthwhile going over the list of signatures (including jets) that both collaborations are looking into to find new physics

... and new physics scenarios that each signature is connected to



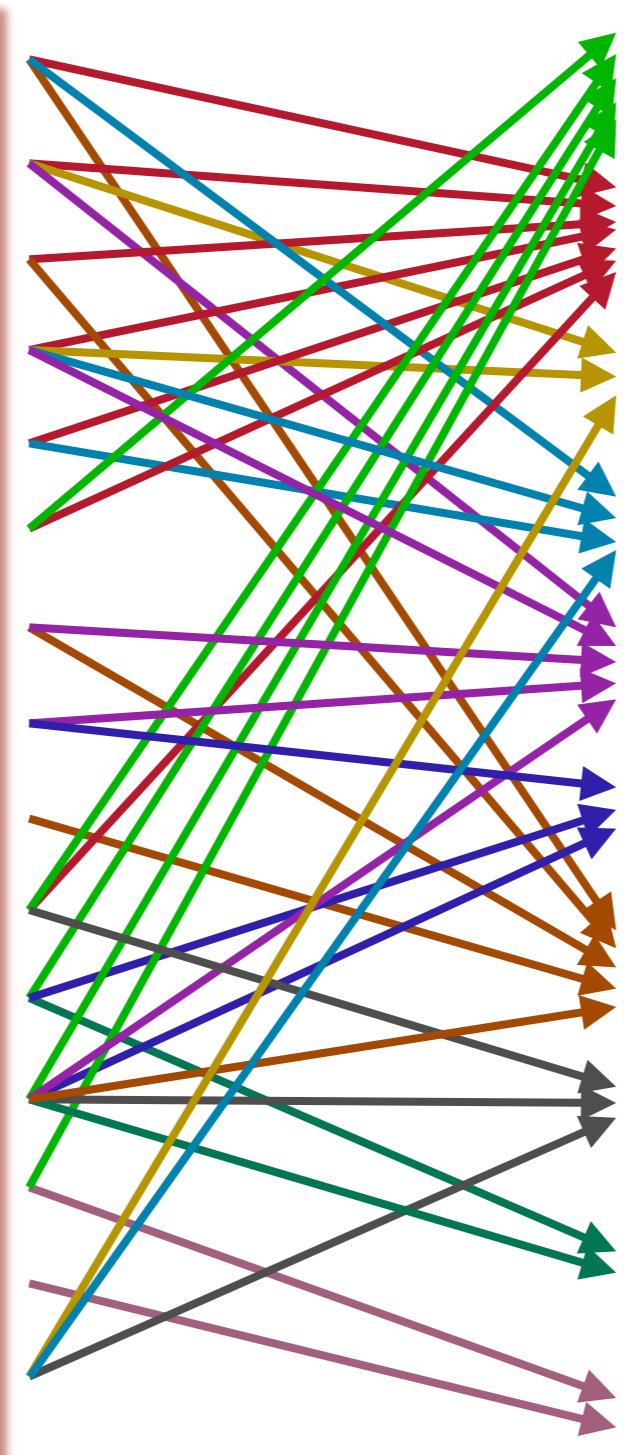
Just my personal view...

“Main” Signatures

Personal “illustrative” view

Final States

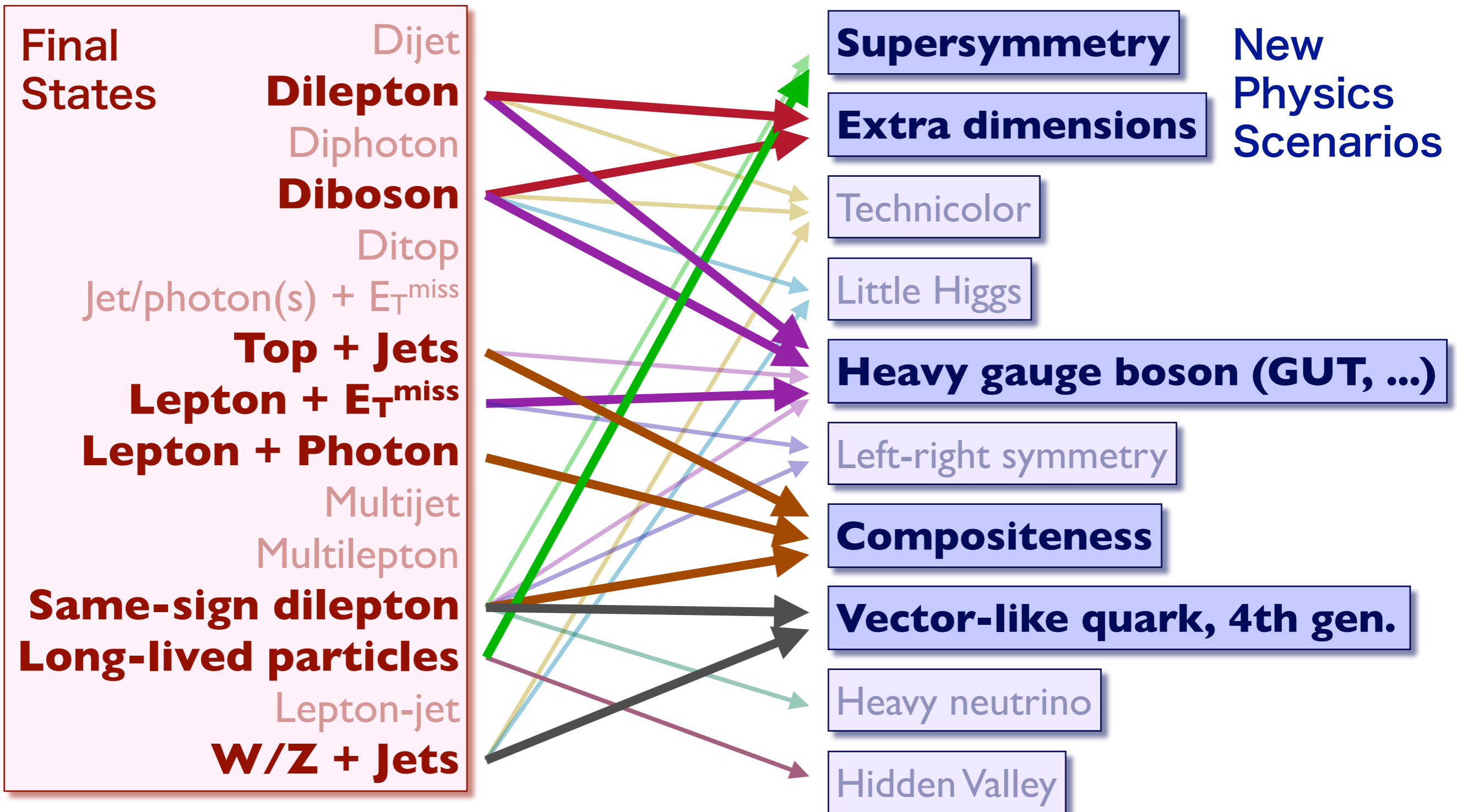
- Dijet
- Dilepton
- Diphoton
- Diboson
- Ditop
- Jet/Photon(s) + E_T^{miss}
- Top + Jets
- Lepton + E_T^{miss}
- Lepton + Photon
- Multijet
- Multilepton
- Same-sign dilepton
- Long-lived particles
- Lepton-jet
- W/Z + Jets
- and many more...



- New Physics Scenarios
- Supersymmetry
 - Extra dimensions
 - Technicolor
 - Little Higgs
 - Heavy gauge boson (GUT, ...)
 - Left-right symmetry
 - Compositeness
 - Vector-like quark, 4th gen.
 - Heavy neutrino
 - Hidden Valley

Cover as many signatures as possible

Goal in this Talk

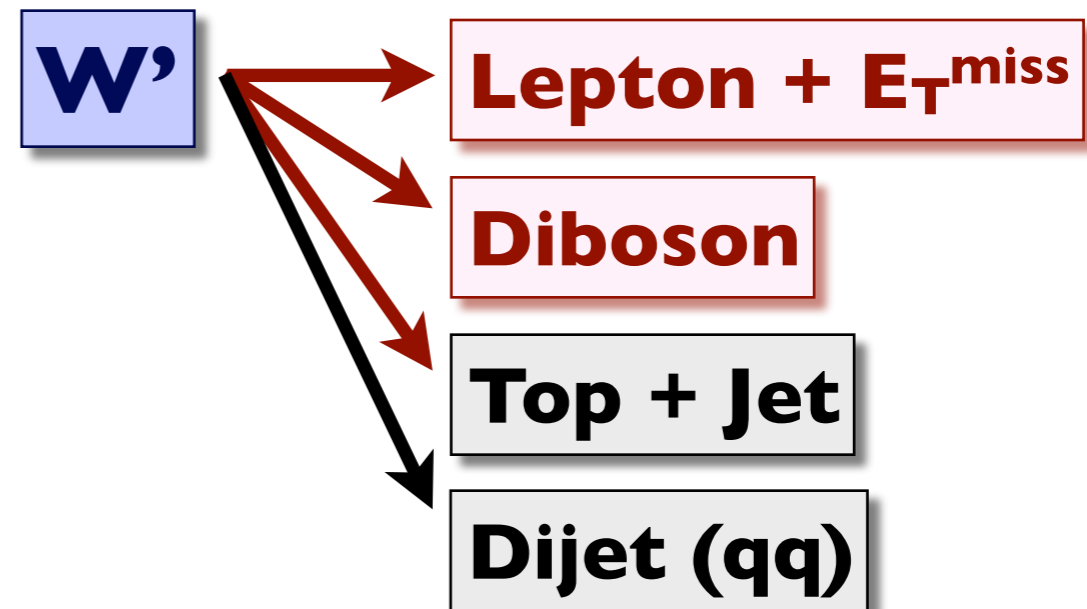
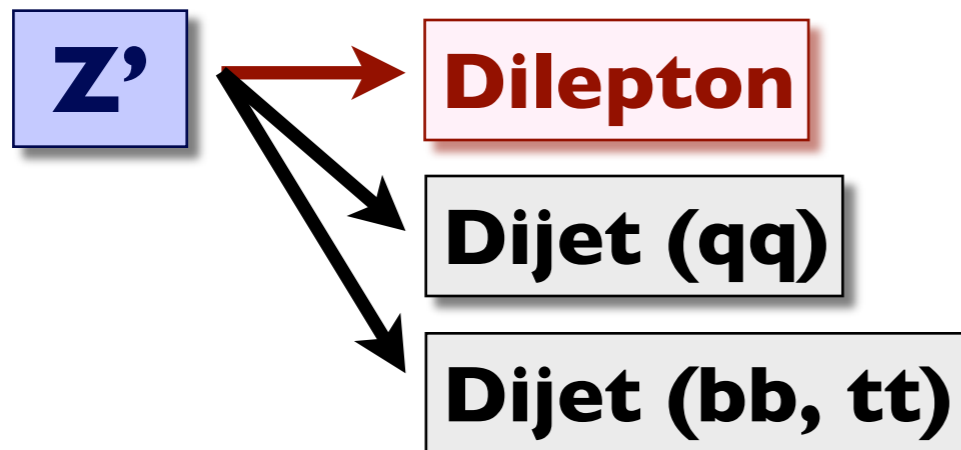


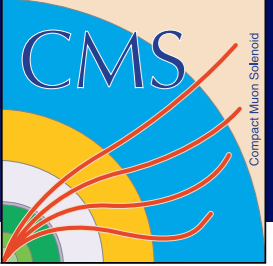
Review latest results for these 5 topics from searches in given final states

New Heavy W'/Z' Boson

Heavy gauge boson

- ▶ Extension to SM gauge symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$
 - $U(1)'$: neutral (Z') gauge boson
 - $SU(2)'$: charged (W') and neutral (Z') gauge bosons
- ▶ SM embedded within a larger gauge symmetry group: GUT-E6, $SO(10)$, ...
 - Charged (W') and neutral (Z') gauge bosons

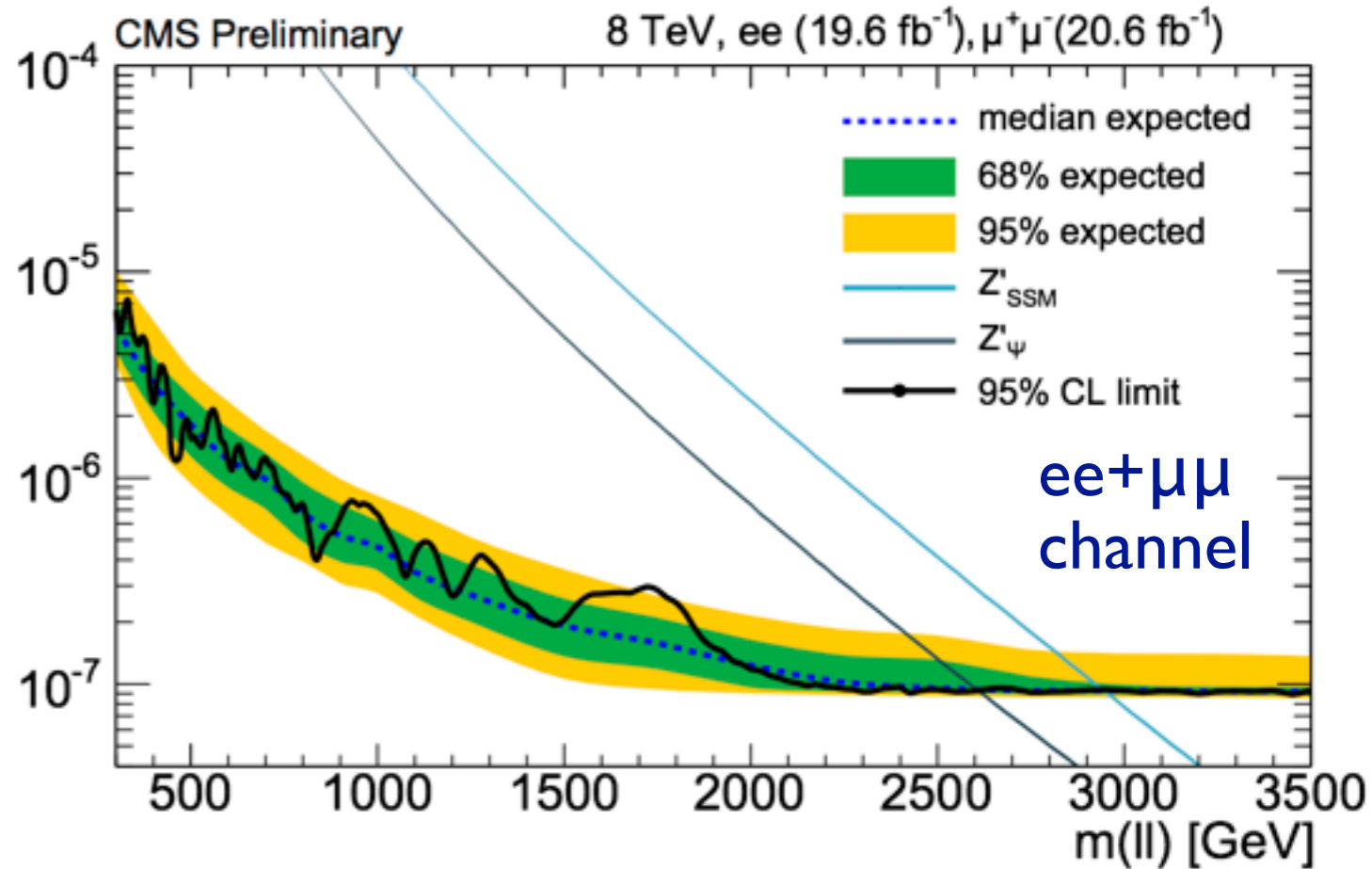
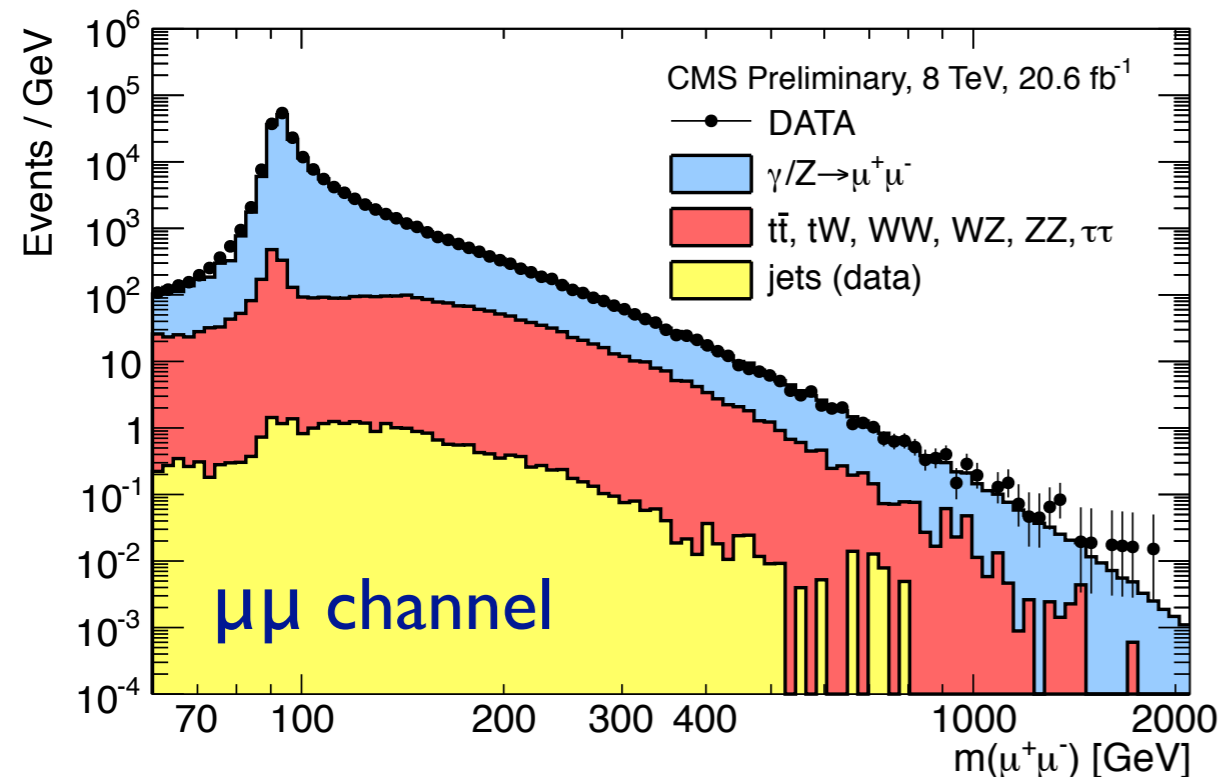
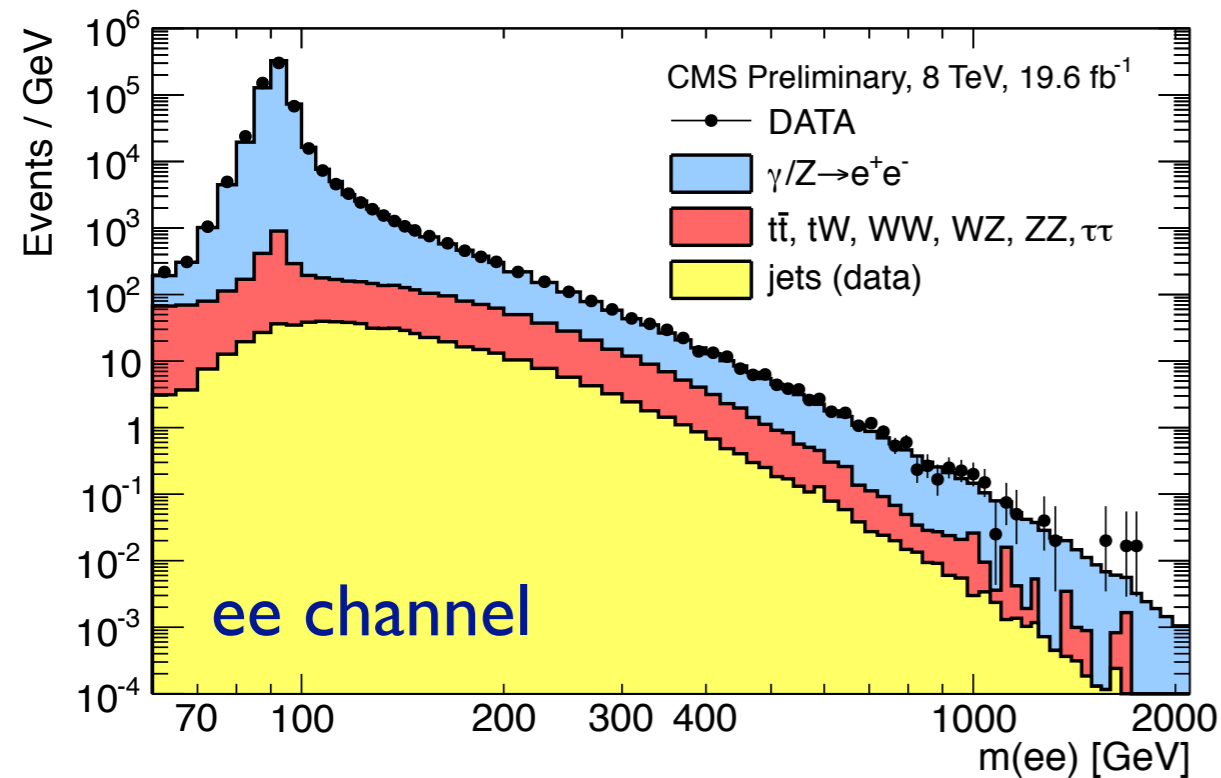




Dilepton : $Z' \rightarrow ll$

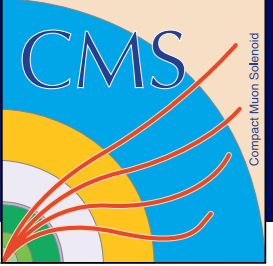
CMS PAS EXO-12-061

2 isolated leptons $p_T^{\text{electron(muon)}} > 35(45)$ GeV



- Drell-Yan background estimated with POWHEG (NLO)
- Total simulated background scaled to data at Z-peak ($60 < M_{ll} < 120$ GeV)
- Limits set on

$$R_{\sigma} = \frac{\sigma(pp \rightarrow Z' + X \rightarrow ll + X)}{\sigma(pp \rightarrow Z + X \rightarrow ll + X)}$$

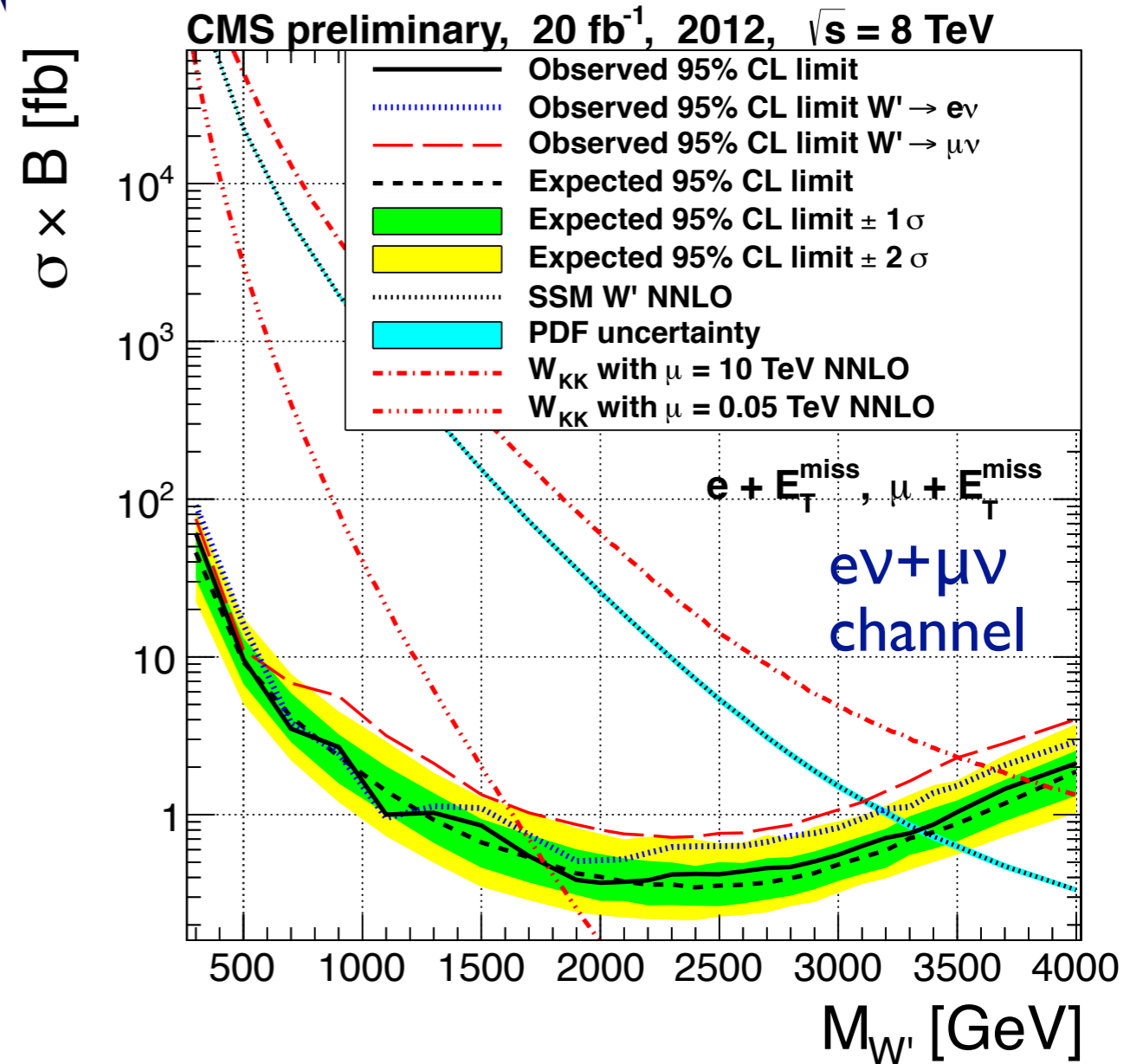
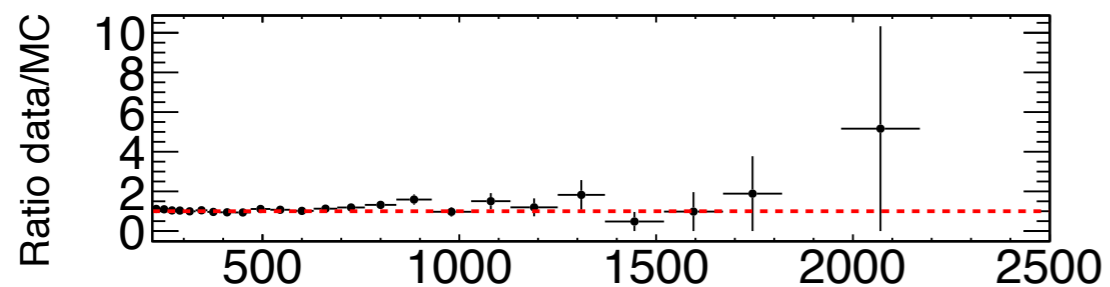
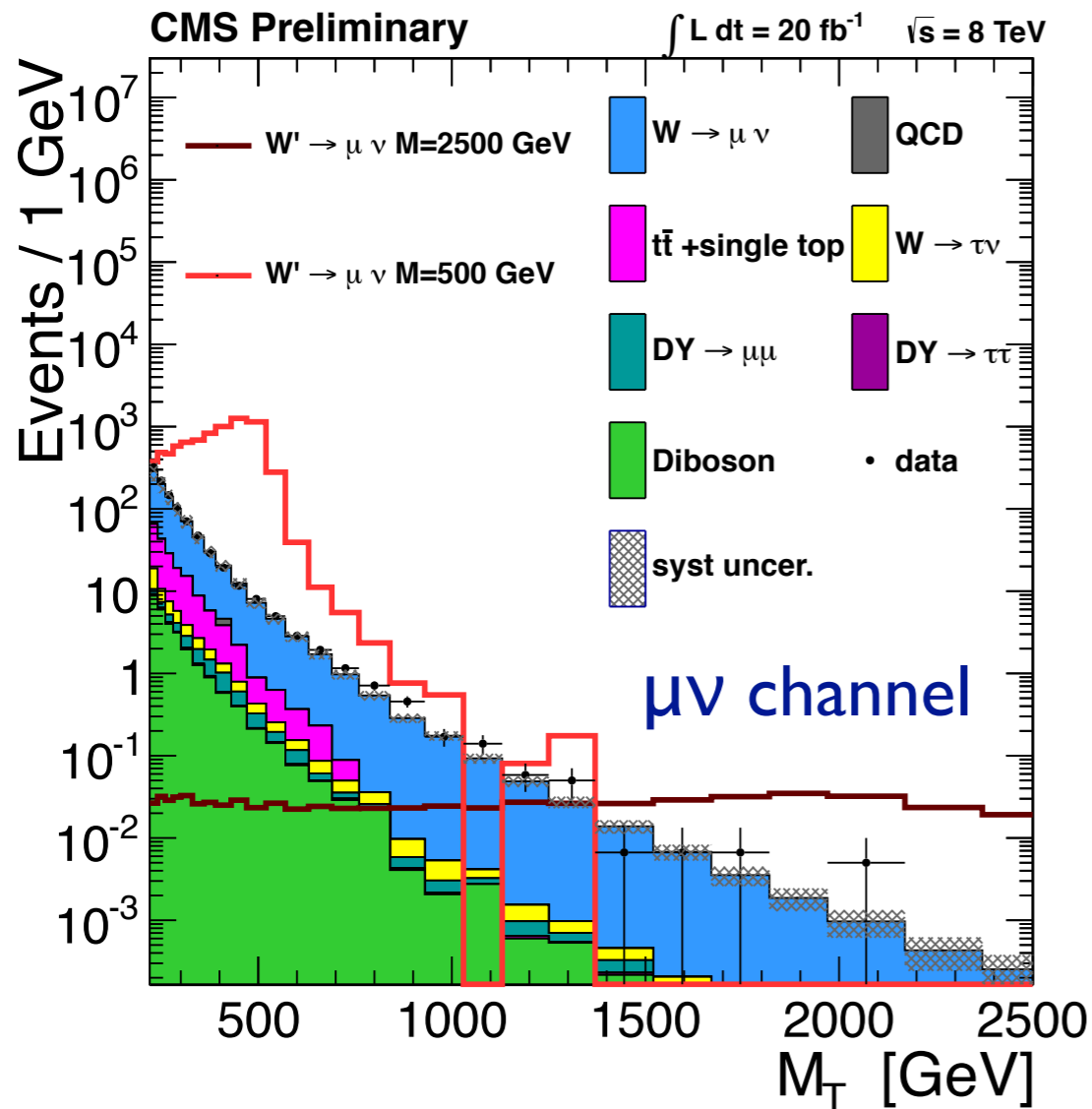


Lepton + E_T^{miss} : $W' \rightarrow l\nu$

CMS PAS EXO-12-060

$W' \rightarrow l\nu$ selection

- ▶ 1 electron(muon) $p_T > 100(45)$ GeV
- ▶ $0.4 < p_T^{\text{lepton}}/E_T^{\text{miss}} < 1.5$
- ▶ $\Delta\Phi(\text{lepton}, E_T^{\text{miss}}) > 0.8\pi$



- ▶ SM $W \rightarrow l\nu$ background (PYTHIA, NLO QCD corrected) extended to high M_T using fit
- ▶ Considering left-handed W' interfering with SM W (not shown)

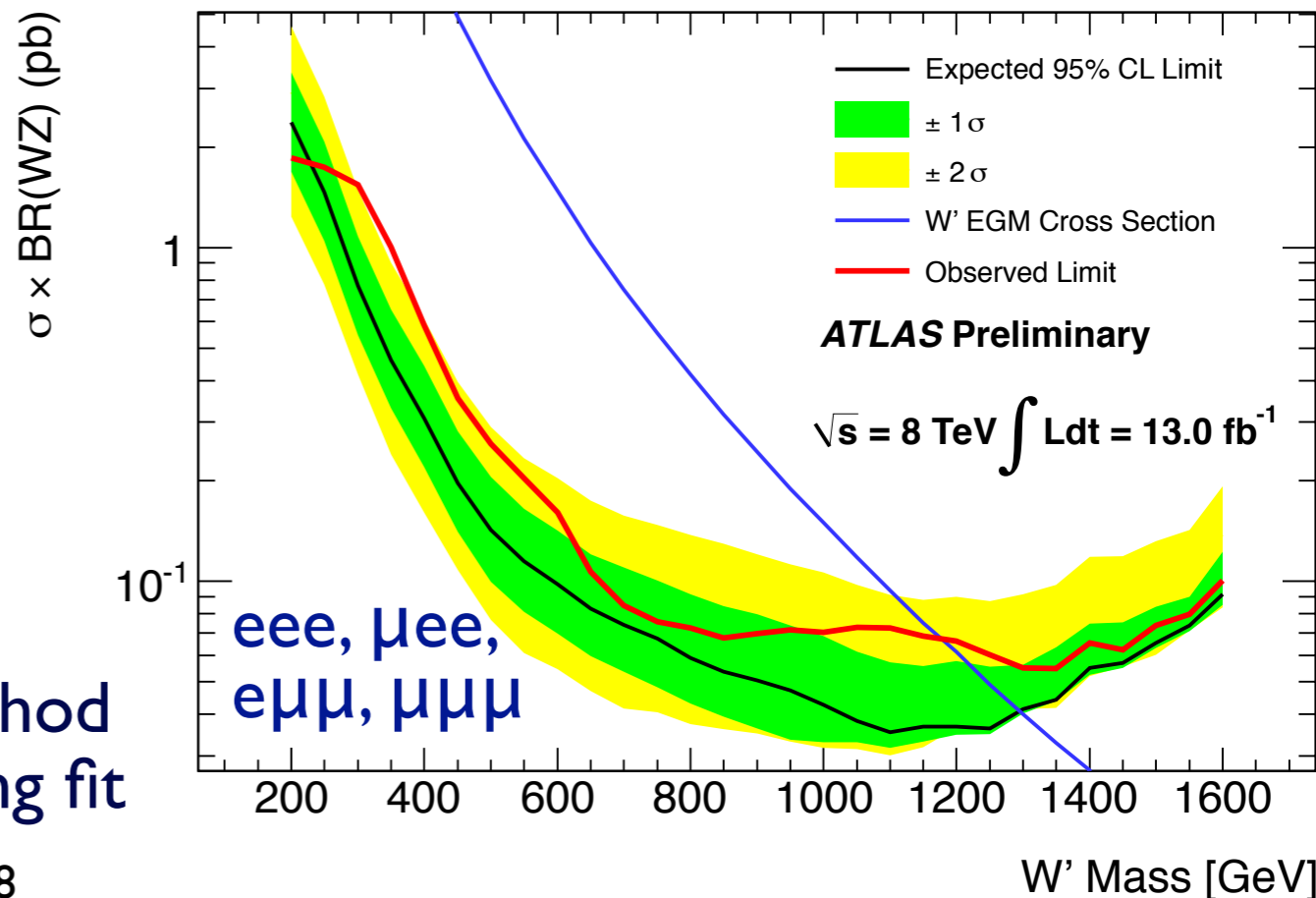
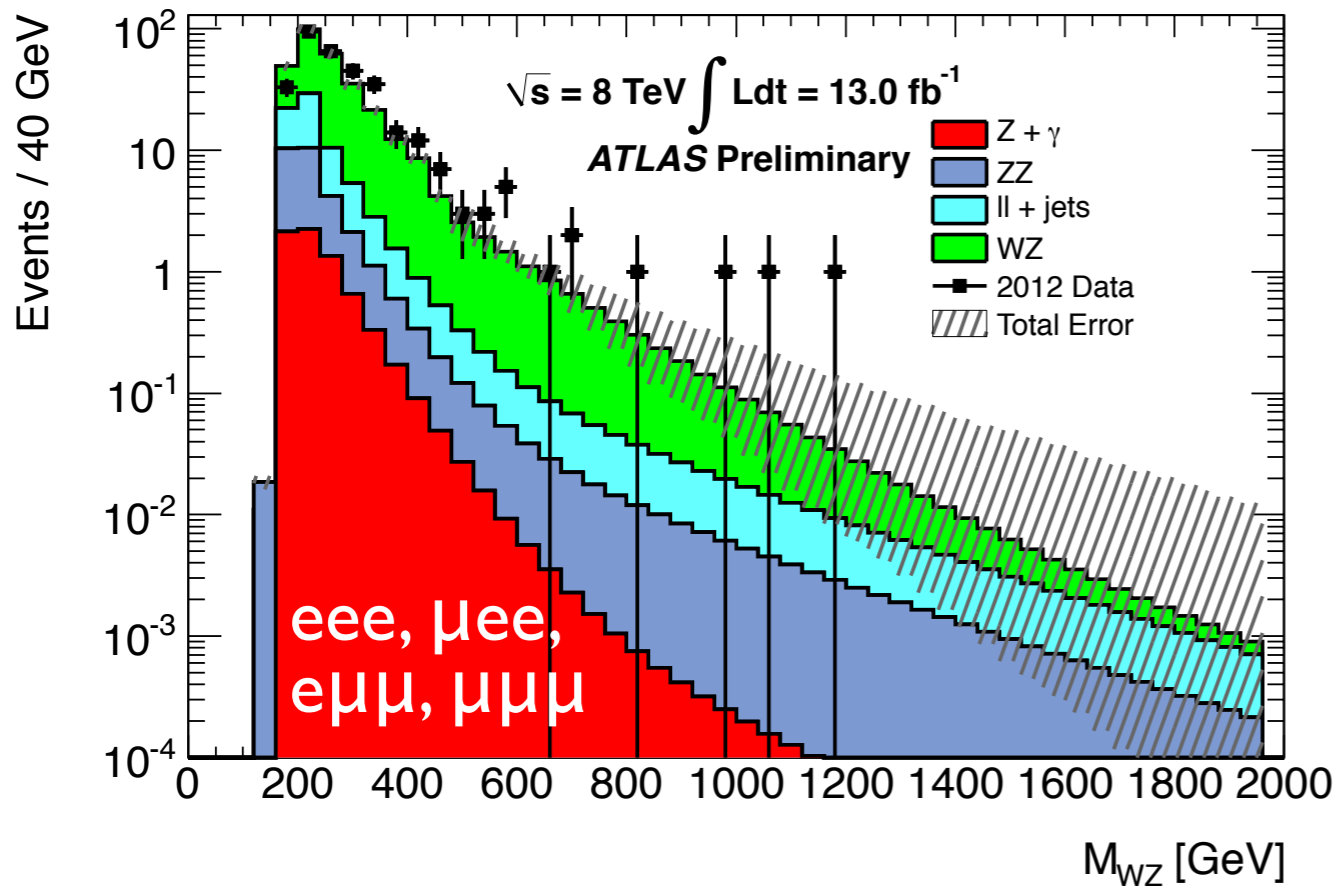
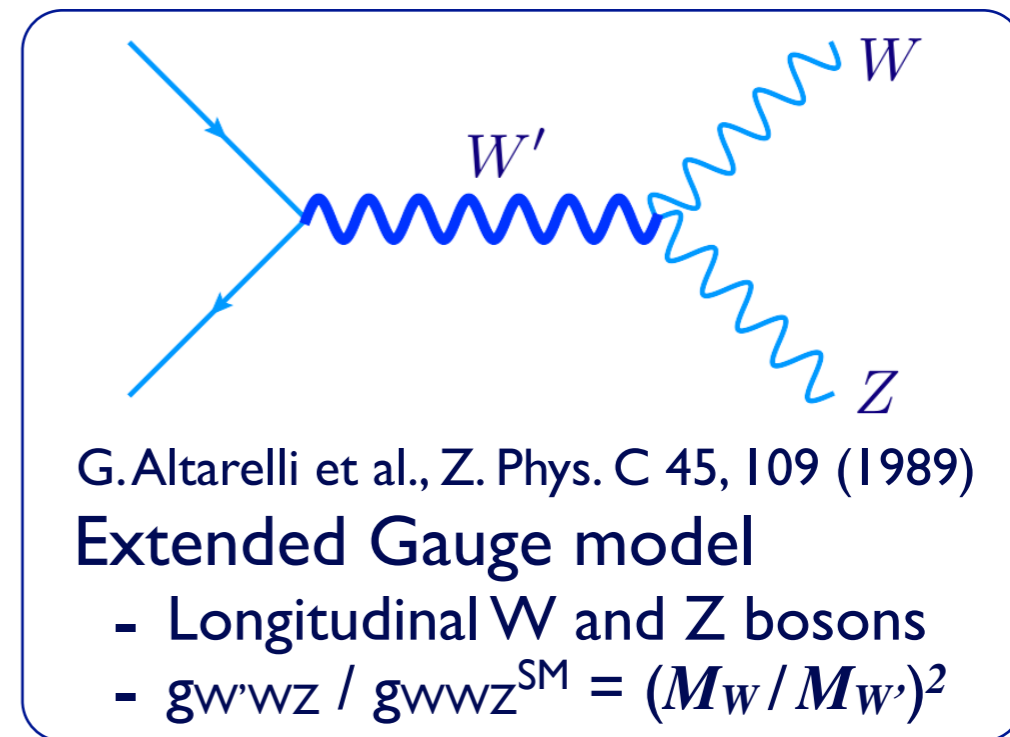


Diboson : $W' \rightarrow WZ (\rightarrow l\nu ll)$

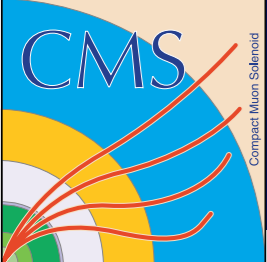
ATLAS-CONF-2013-015

$W' \rightarrow WZ \rightarrow l\nu ll$ selection

- ▶ Exactly 3 leptons $p_T > 25$ GeV
- ▶ At least one pair of $|M_{ll} - M_Z| < 20$ GeV
- ▶ $E_T^{\text{miss}} > 25$ GeV, $M_T^{W'} < 100$ GeV
- ▶ $\Delta y(W,Z) < 1.8$, $\Delta \phi(W,Z) > 2.6$



- ▶ SM WZ background (POWHEG NLO) checked in control region
- ▶ Z+jets, ttbar estimated by data-driven method
- ▶ Background extrapolated to high M_{WZ} using fit



Dilepton : ADD

Large extra dimensions

Arkani-Hamed, Dimopoulos, Dvali

- ▶ Compactified flat extra space (size R)
 - ▶ All SM particles on a brane
 - ▶ Gravity propagated through the bulk
 - ▶ Fundamental Planck scale $M_D \sim \text{TeV}$
- \Rightarrow 4-dim. Planck scale $M_{Pl}^2 \sim R^n M_D^{n+2}$

➡ Main LHC signal : jet/ γ + E_T^{miss} , jj/ll excess

ll excess search

2 isolated leptons

$p_T^{\text{electron(muon)}} > 36(45) \text{ GeV}$

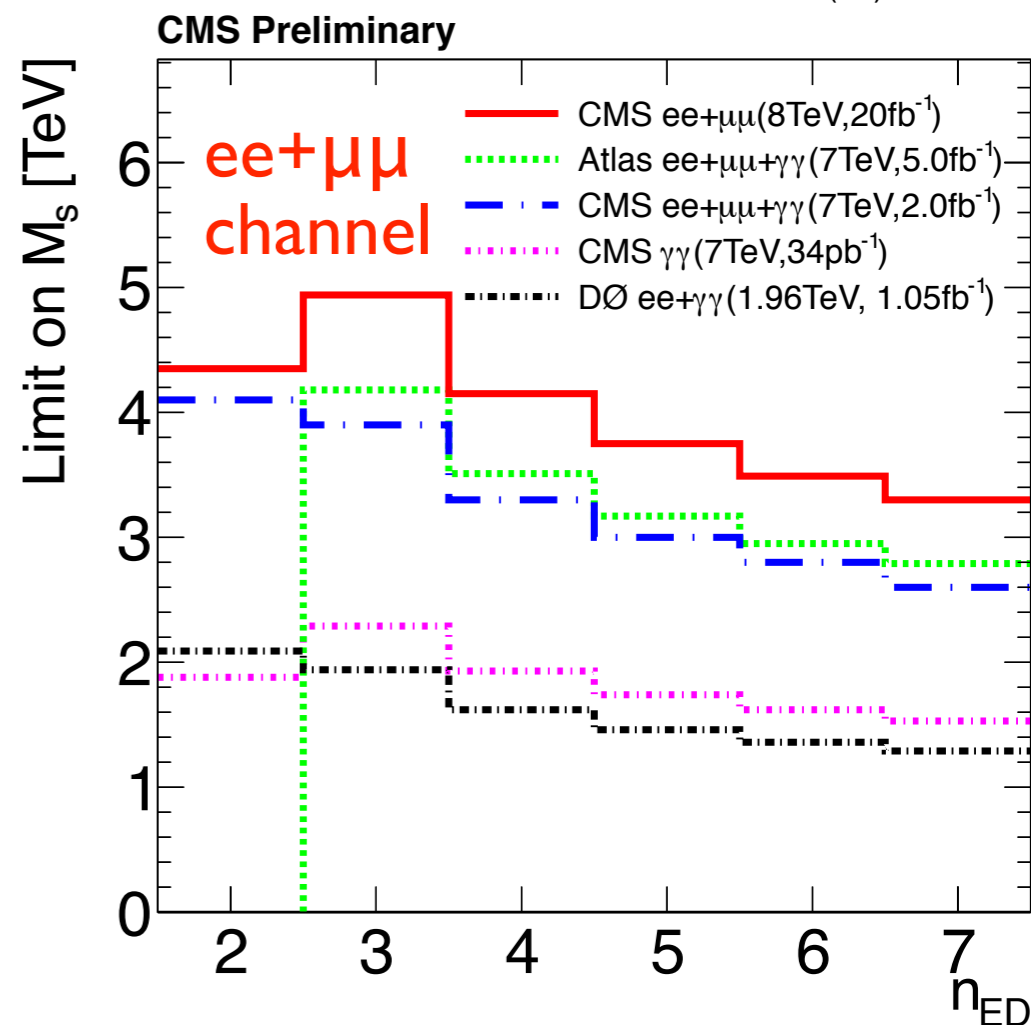
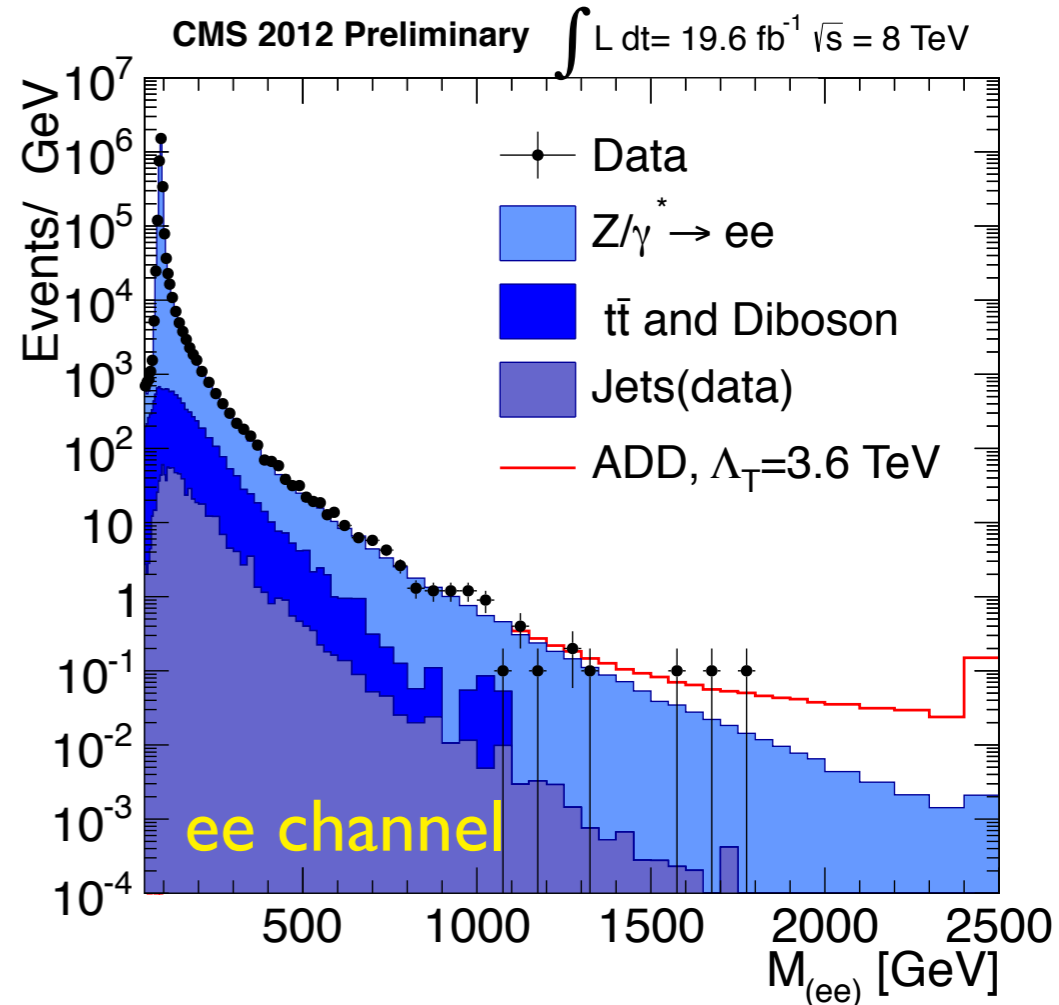
➔ Set limits on theory cut-off M_s ($\sim M_D$)

CMS PAS EXO-12-027

CMS PAS EXO-12-031

ee channel

Mass [TeV]	Data	Background
0.6-0.9	249	232 ± 35
0.9-1.3	41	36 ± 6
1.3-1.8	4	4.8 ± 0.7
>1.8	0	0.6 ± 0.1





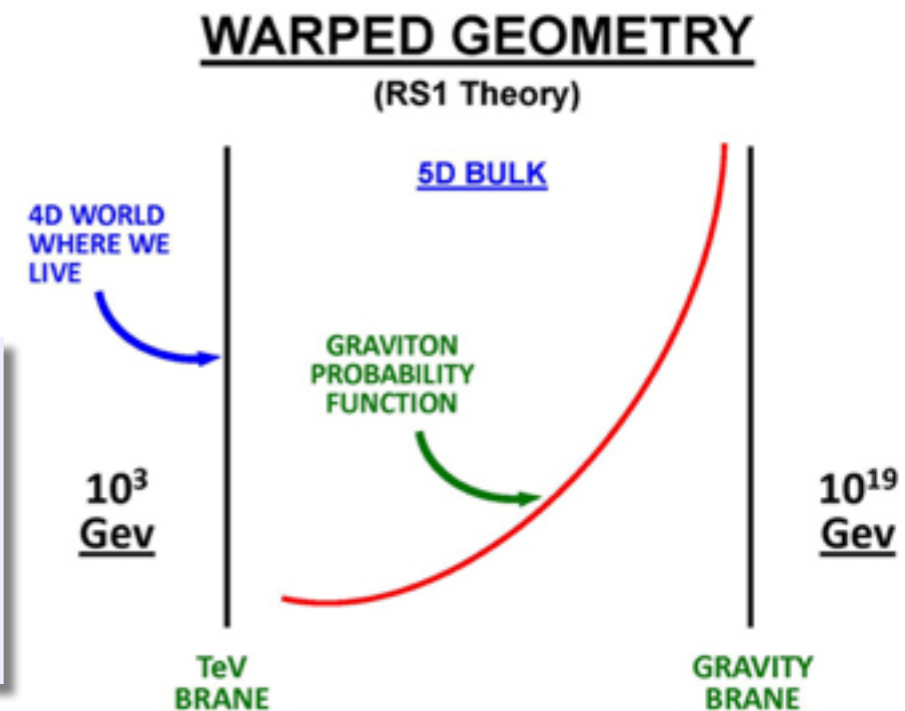
Dilepton : RS

Warped extra dimensions

Randall,
Sundrum

- ▶ 5D universe bounded by two branes
- ▶ All SM particles localized on TeV-brane
- ▶ 5th dim. highly curved with a warp factor = $\exp(-kr\pi)$
- ▶ Planck mass \rightarrow EW mass if $kr \approx 12$ (hierarchy problem)

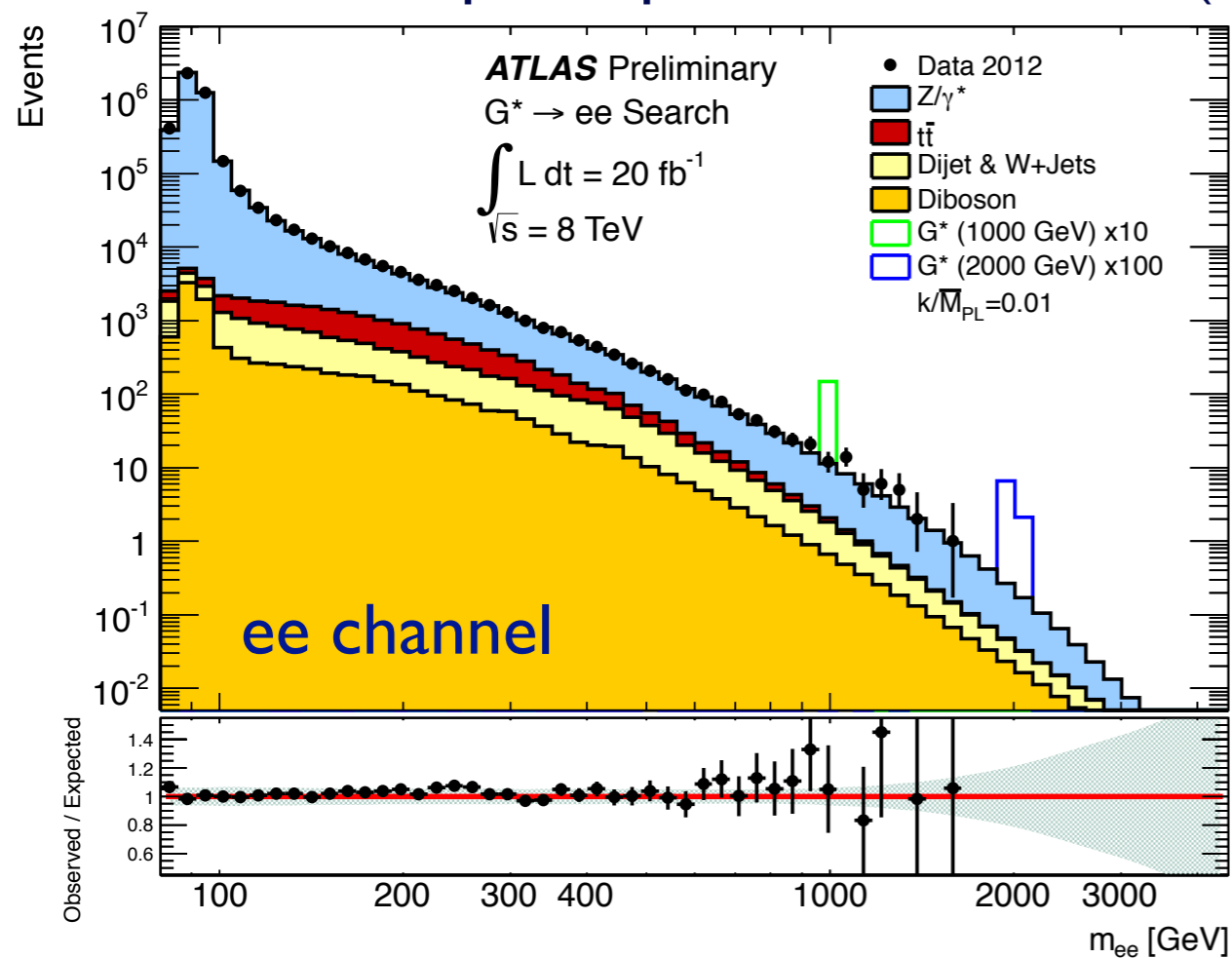
▶ Main LHC signal : $\ell\ell/\gamma\gamma$ resonance



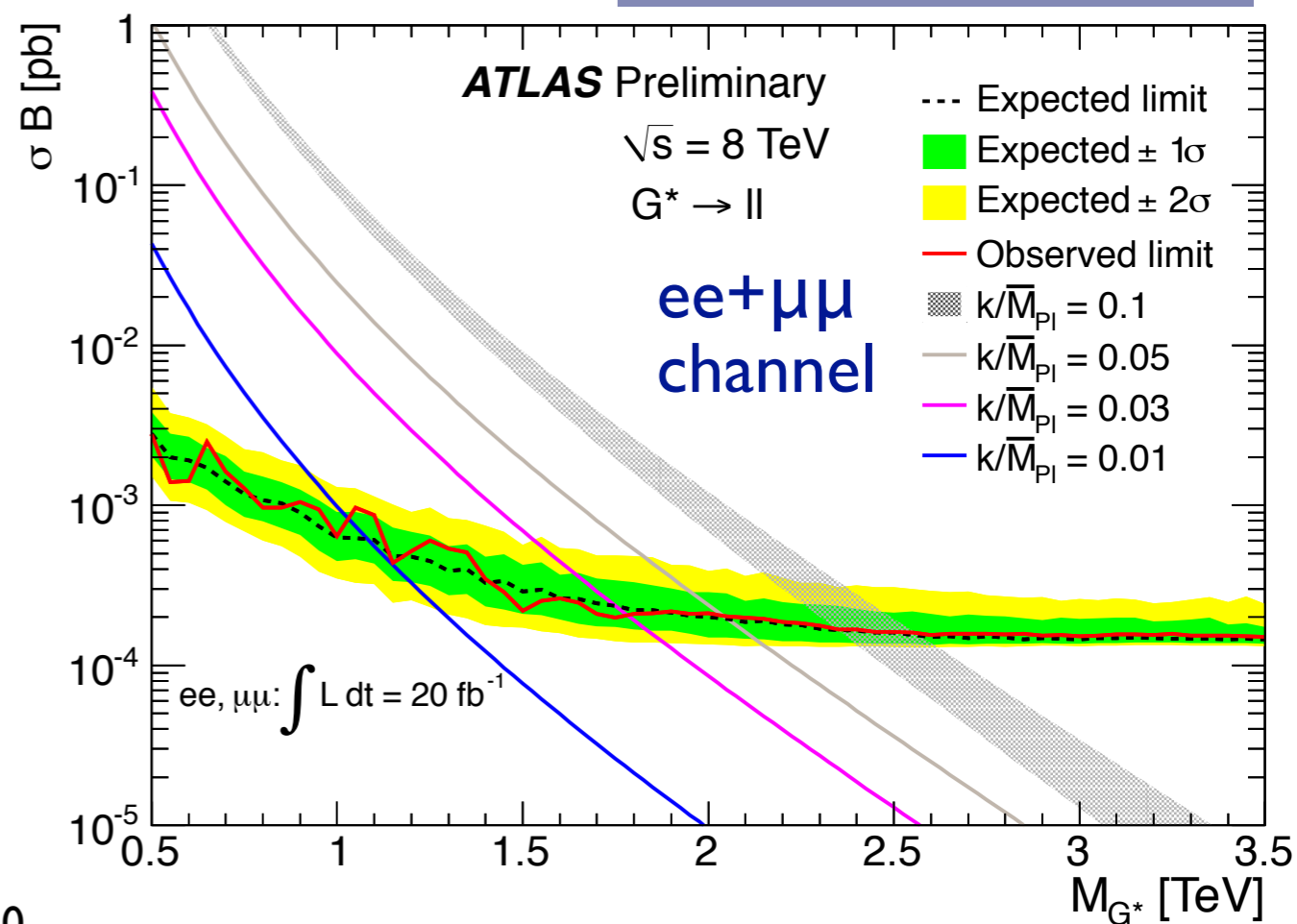
$\ell\ell$ resonance search

2 isolated leptons $p_T^{\text{electron(muon)}} > 40, 30(25)$ GeV

ATLAS-CONF-2013-017



10



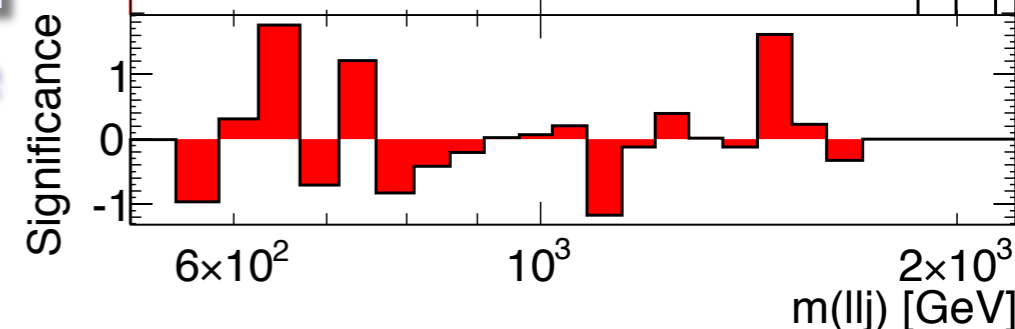
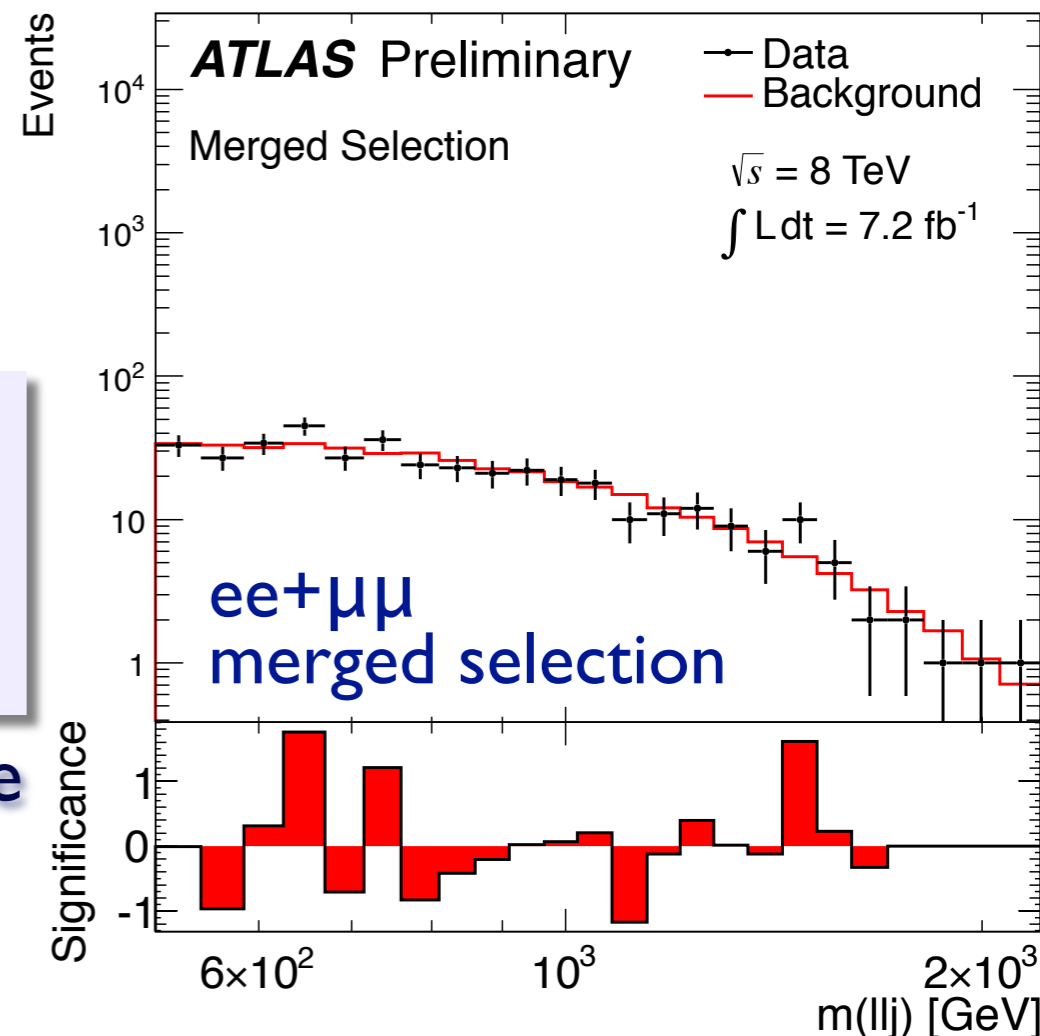


Diboson : Bulk RS

Bulk Randall-Sundrum

- ▶ All SM particles in the bulk of extra dimension
- ▶ Higgs and heavier particles localized near TeV-brane
- ▶ Lighter particles near Planck-brane
→ weak coupling (gauge/flavor hierarchy)

➡ Main LHC signal : $tt/WW/ZZ$ resonance



ZZ → llqq selection

ATLAS-CONF-2012-150

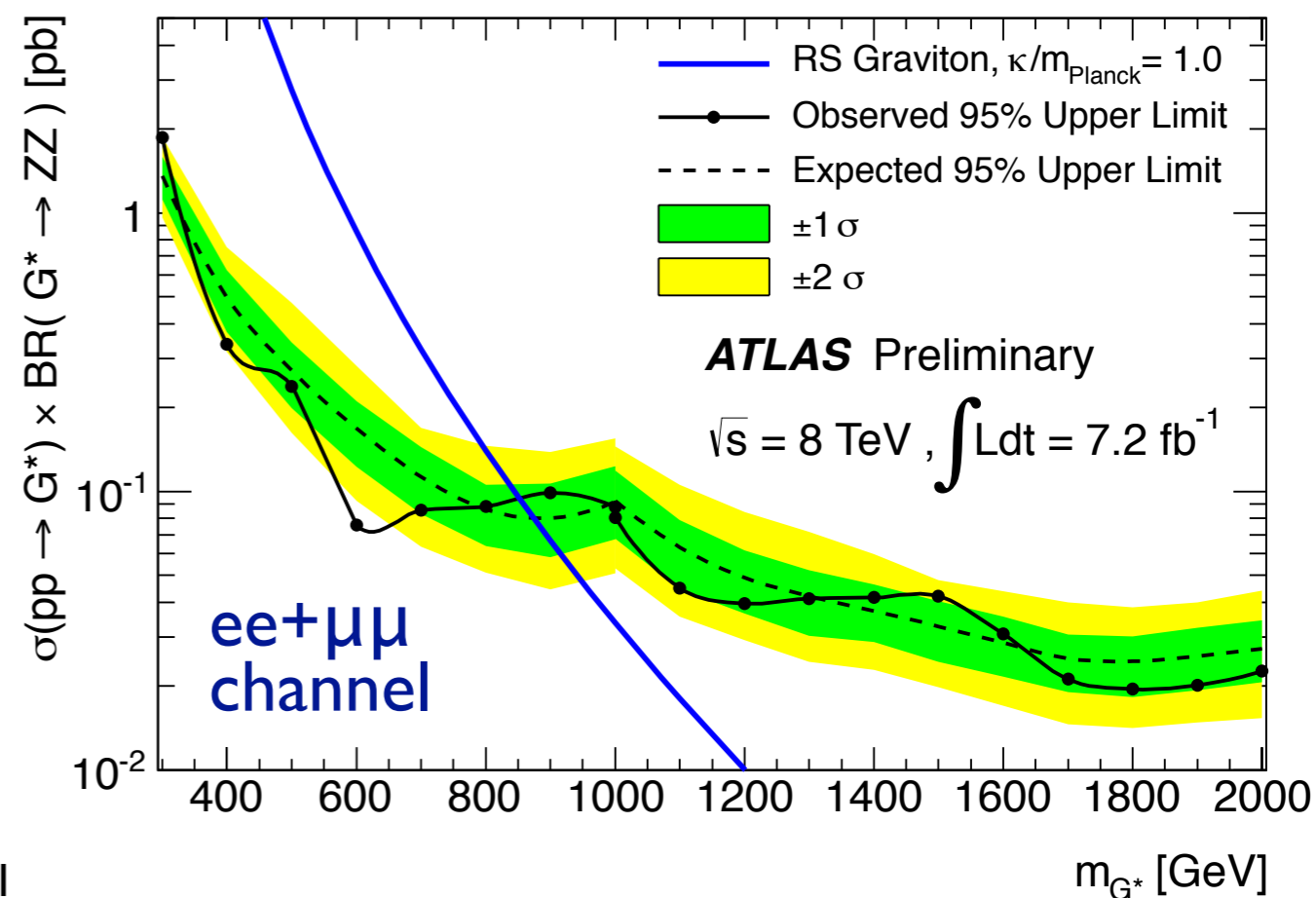
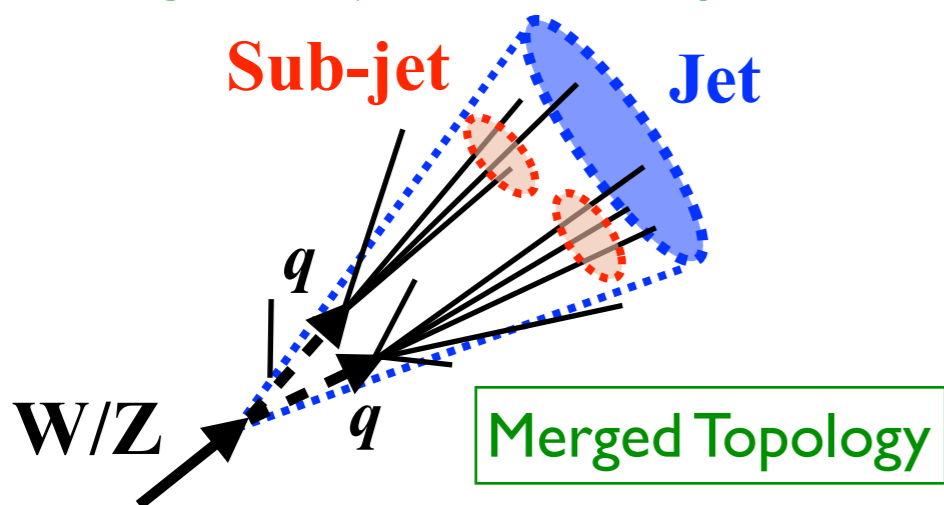
2 OS leptons $p_T > 25, 20$ GeV

Dilepton mass $|M_{ll} - M_Z| < 25$ GeV

Dilepton $p_T > 50, 200$ GeV

Two $Z \rightarrow qq$ selections

- ▶ Resolved : $65 < M_{jj} < 115$ GeV, $\Delta\Phi_{jj} < 1.6$
- ▶ Merged : $M_{jet} > 40$ GeV, $p_T^{jet} > 200$ GeV



Top/Bottom Partner

Vector-like quark, 4th gen.

Large Higgs mass correction in Standard Model

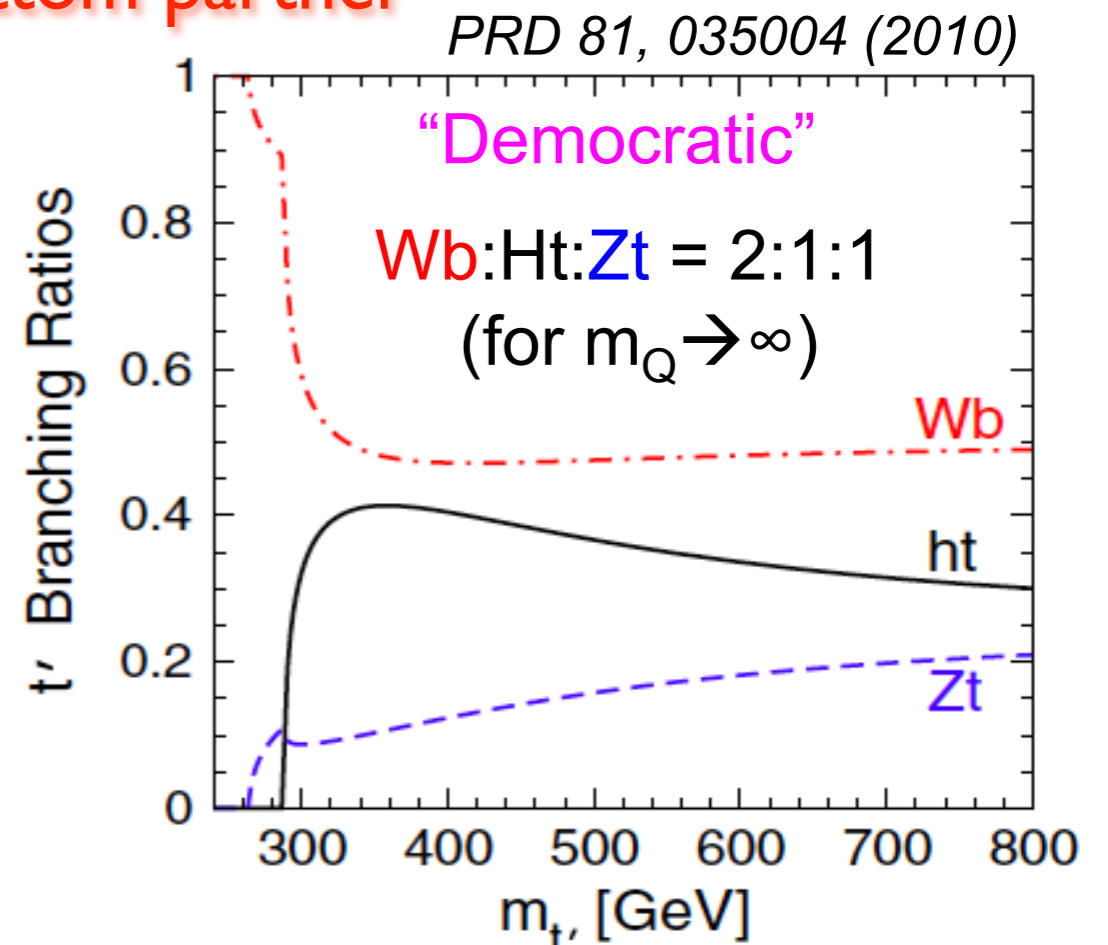
$$\Delta = \frac{\delta_{UV} m_H^2}{m_H^2} \gtrsim \left(\frac{\Lambda_{UV}}{400 \text{ GeV}} \right)^2 \sim 10^{27} \quad \text{if new physics scale } (\Lambda_{UV}) \text{ is at } \sim 10^{16} \text{ GeV}$$

→ “Fine tuning” (Naturalness problem)

$\Lambda_{UV} \sim \text{TeV}$ to have moderate tuning ⇒ Need “top” partners with $m \sim \Lambda_{UV}$

- ▶ Natural SUSY → Light scalar top/bottom
- ▶ Natural Non-SUSY → Fermionic top/bottom partner

- ▶ Important to cover different final states
- ▶ Branching fractions of top/bottom partner (t'/b') depend on model (mass, weak-isospin)



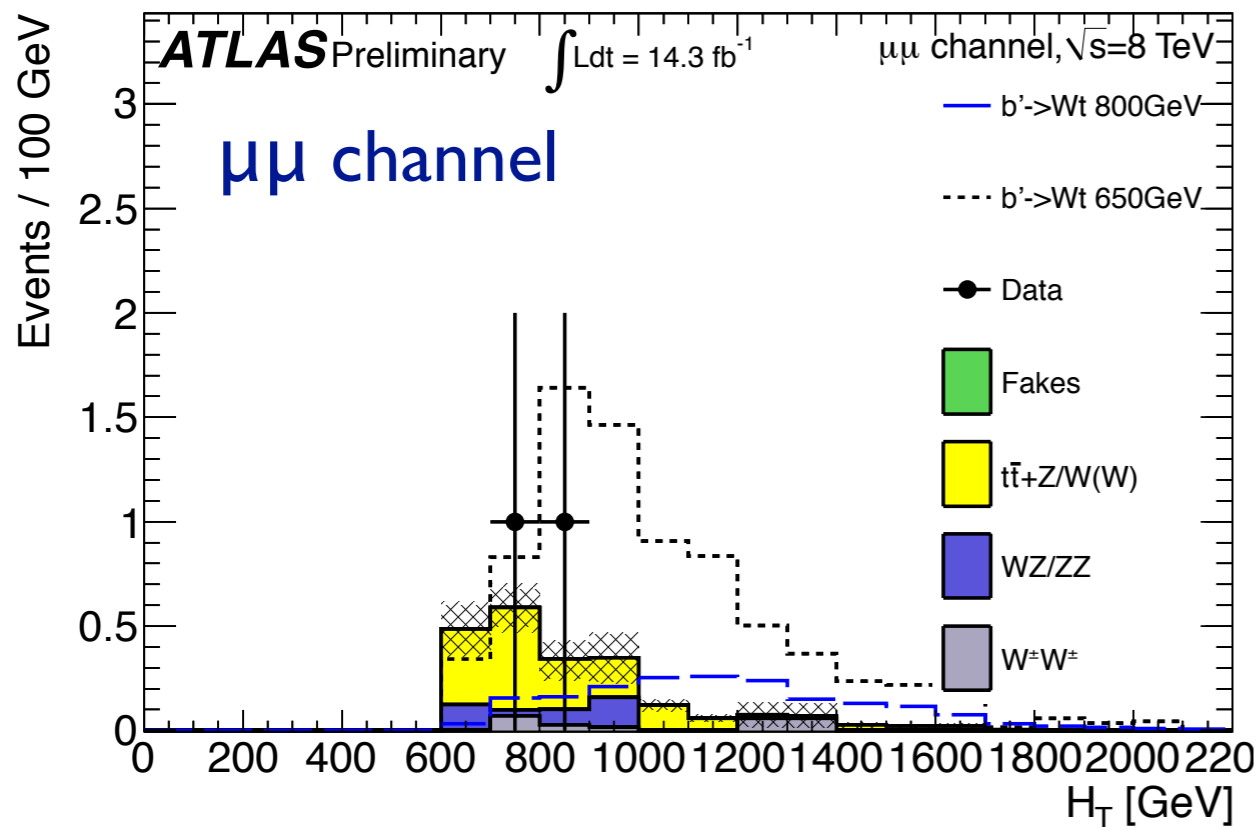


SS Dilepton : b'/t'

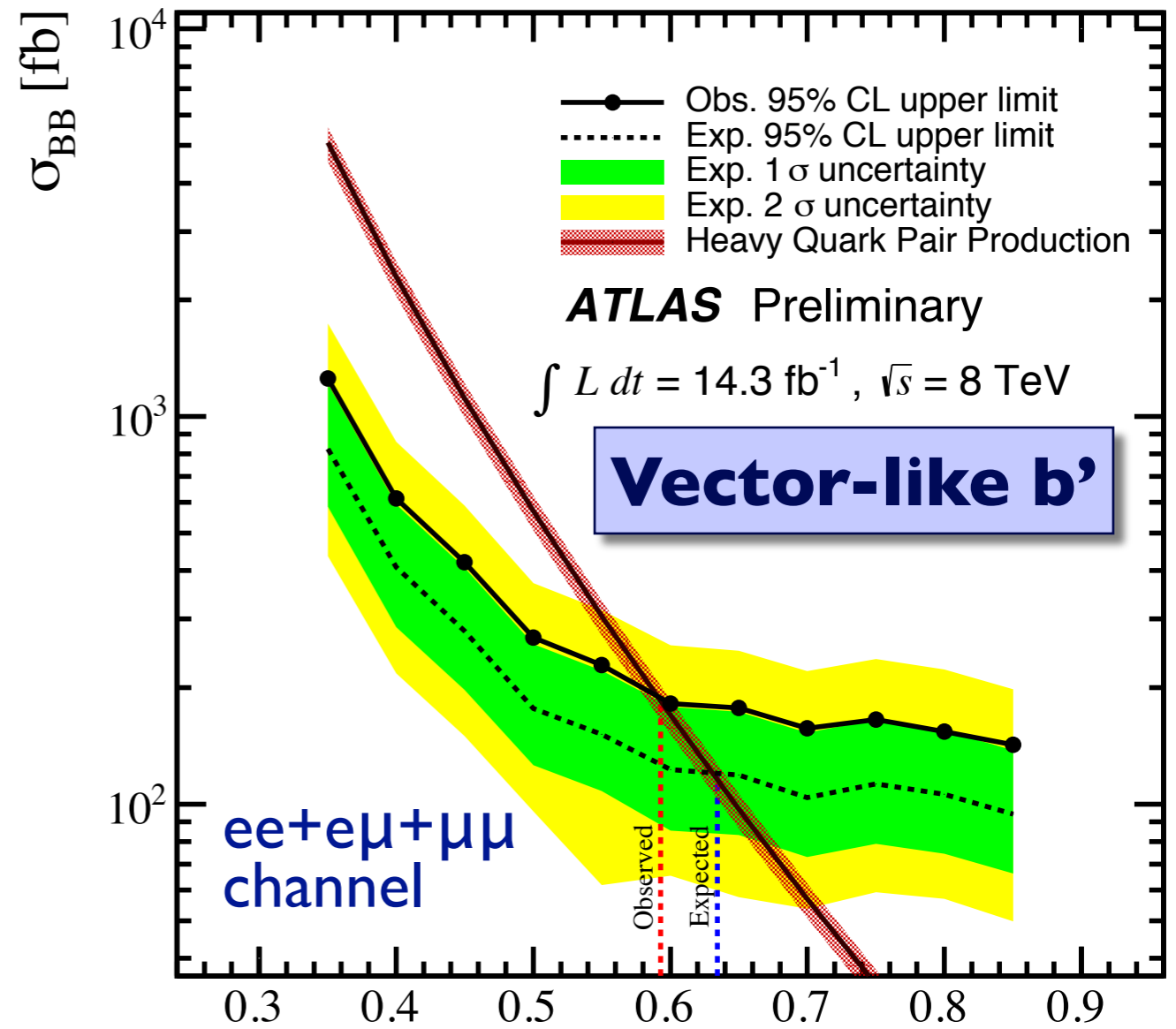
ATLAS-CONF-2013-051

$b' \rightarrow Wt/t' \rightarrow Zt, Ht$ SS dilepton selection

- ▶ 2 same-sign leptons $p_T > 25$ GeV
- ▶ ≥ 2 jets $p_T > 25$ GeV (≥ 1 or ≥ 2 b-tag)
- ▶ $E_T^{\text{miss}} > 40$ GeV
- ▶ SF pair : $M_{ll} > 15$ GeV, $|M_{ll} - M_Z| > 10$ GeV
- ▶ $H_T = \sum p_T^{\text{lepton, jet}} > 550-650$ GeV



- ▶ Charge misidentification, fake lepton background estimated from data
- ▶ Real SS dilepton events (ttV , diboson) estimated from MC

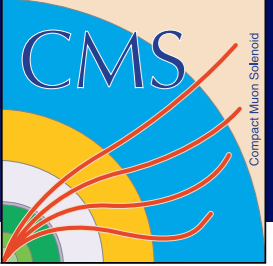


SU(2) singlet b' (500-650 GeV)

Wt	Zb	Ht
42-45%	31-29%	27-26%

Limits also set for VLQ t'

m_B [TeV]

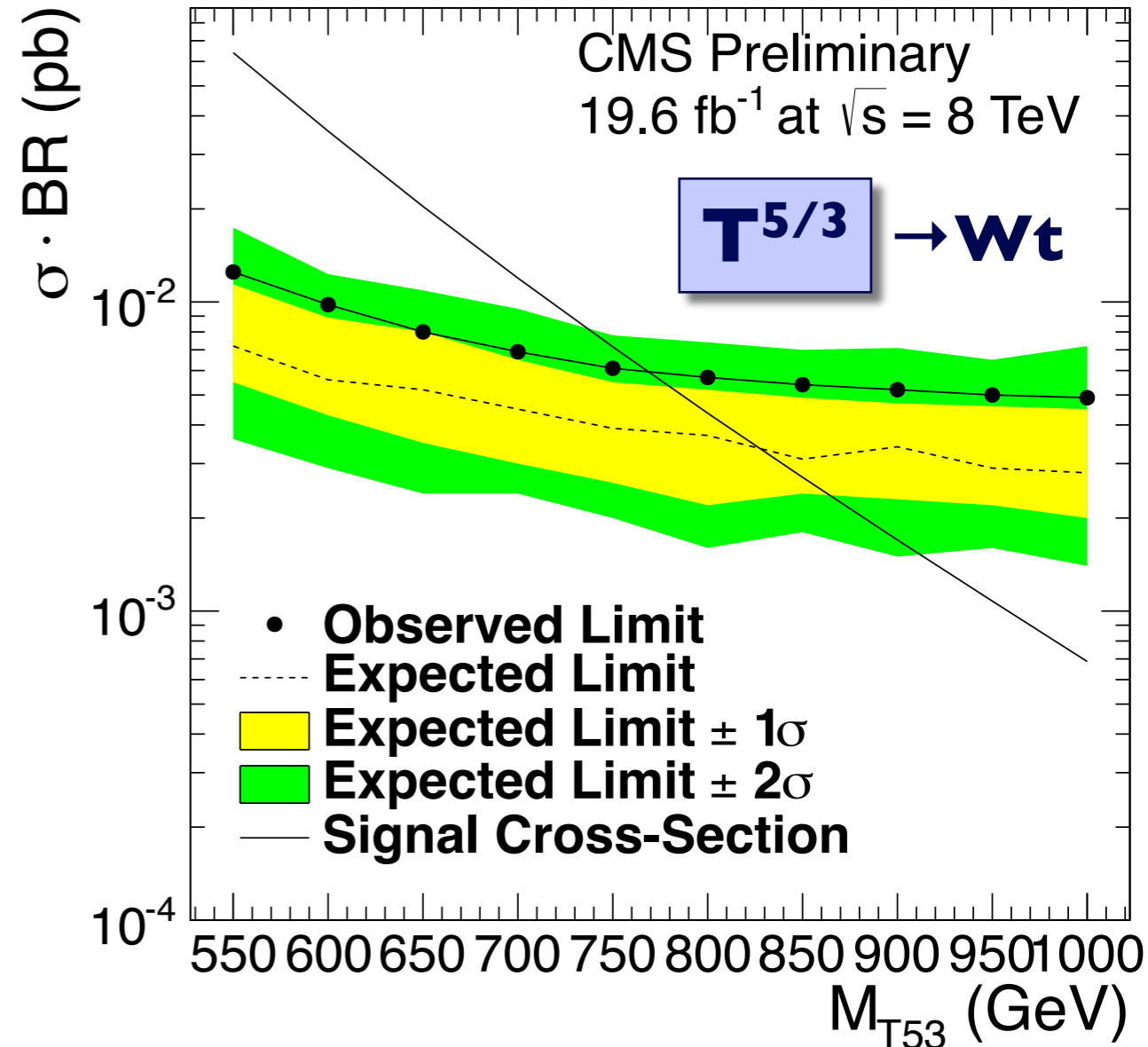
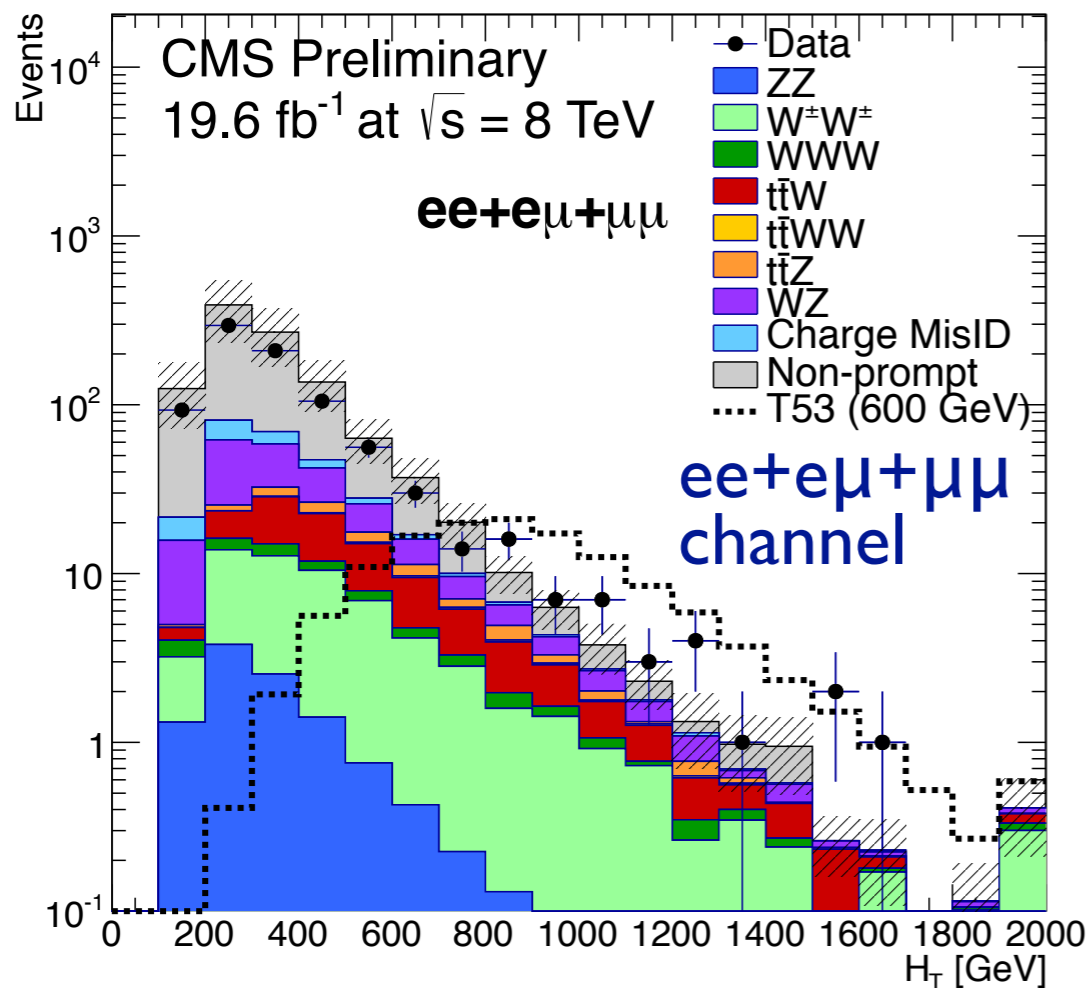


SS Dilepton : $T^{5/3}$

CMS PAS EXO-12-012

$T^{5/3}T^{5/3} \rightarrow Wt(\rightarrow l^\pm \nu l^\pm \nu b)Wt(\rightarrow \text{inclusive})$ selection

- ▶ 2 same-sign leptons $p_T > 30$ GeV
- ▶ SF pair : $M_{ll} > 20$ GeV, $|M_{ll} - M_Z| > 15$ GeV
- ▶ Presence of hadronic Top-jet, W-jet, other jets
- ▶ $HT = \sum p_T^{\text{lepton, jet}} > 900$ GeV



Similar background composition to ATLAS SS dilepton analysis

- Charge misidentification, fake lepton from data
- Real SS events (ttV, diboson) from MC

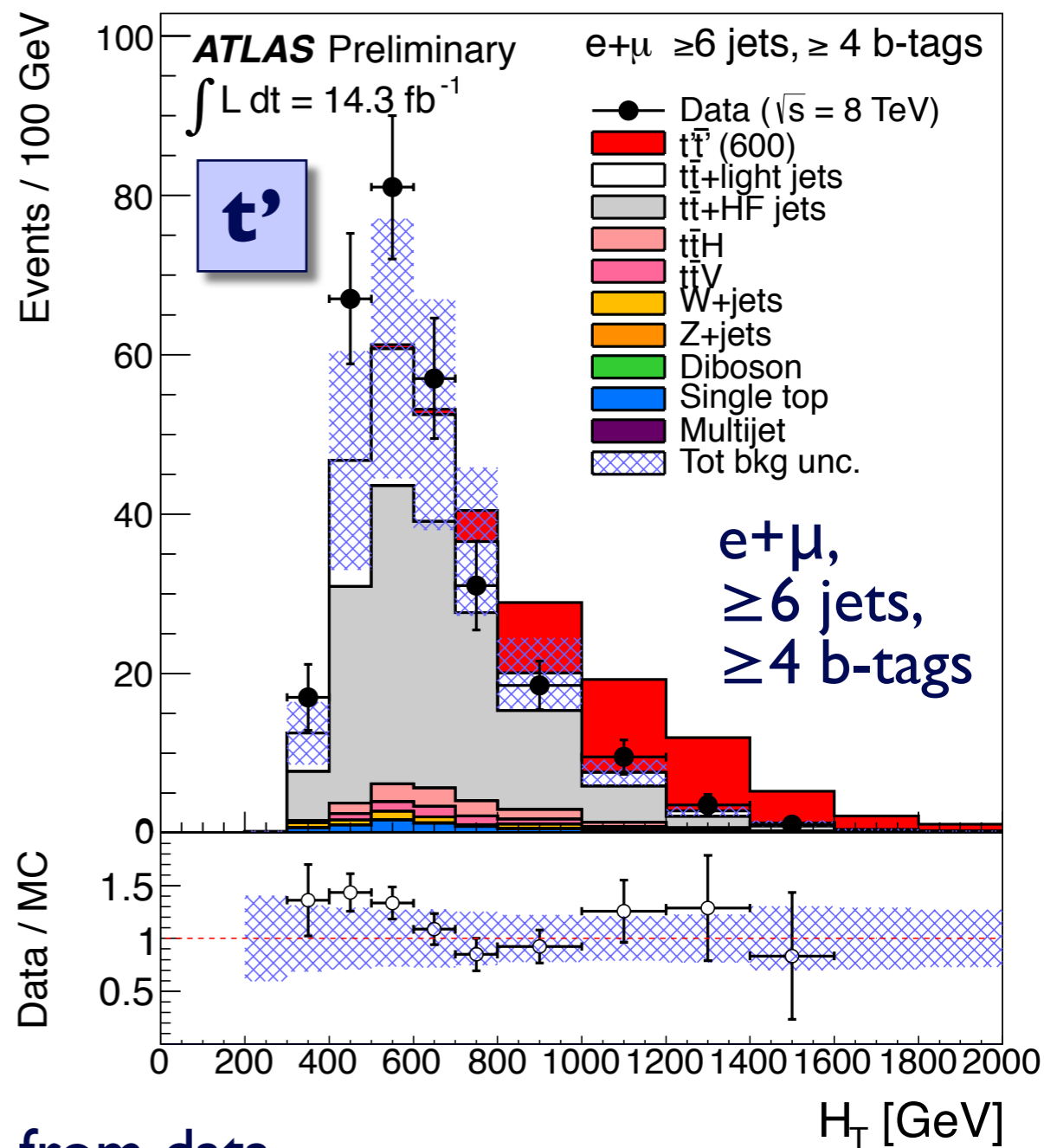
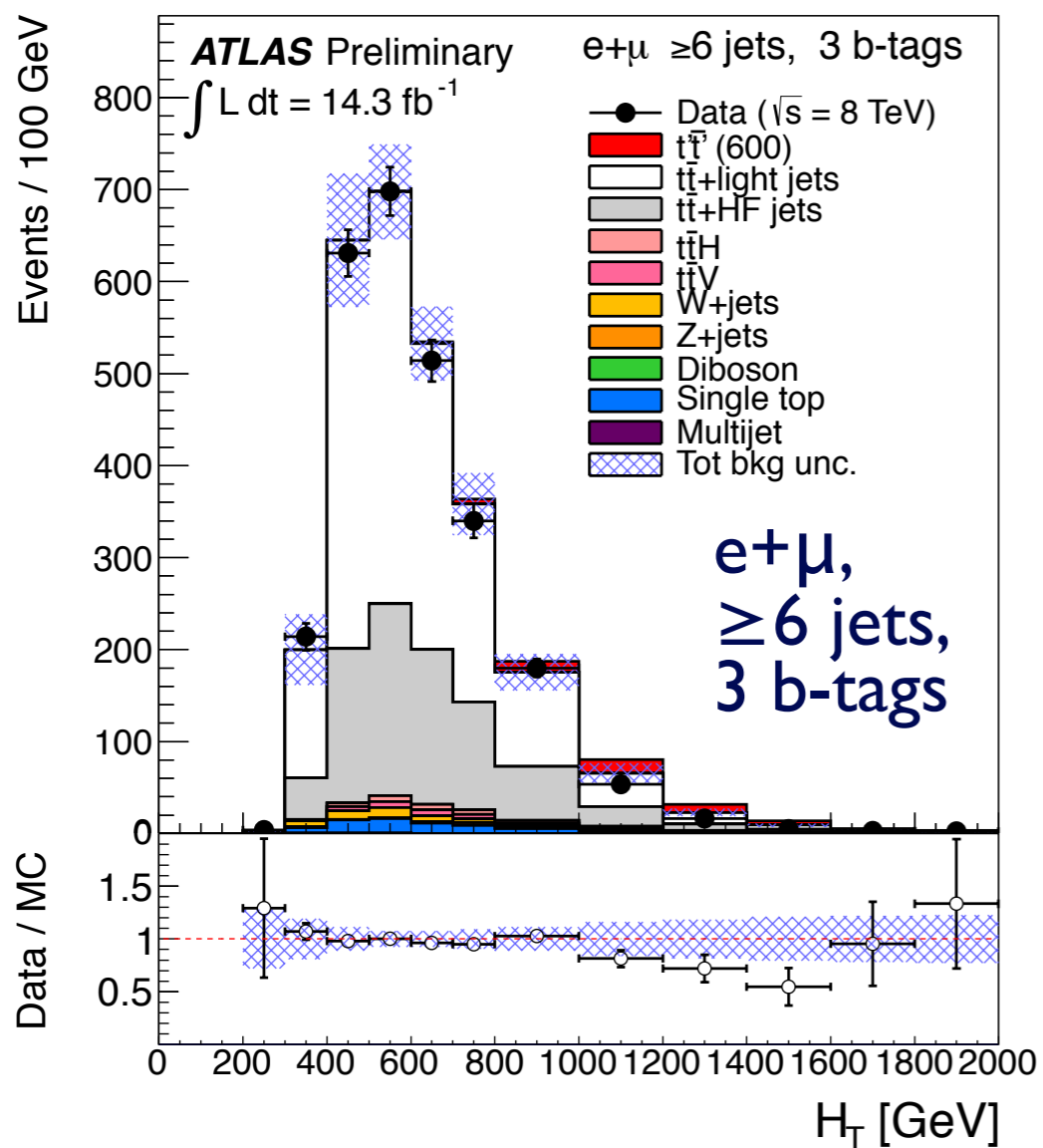


Ht+X : t'

t't' → H(→bb)t(→lvb)+X selection (sensitive to ZtZt, ZtWb with Z→bb)

- ▶ 1 lepton $p_T > 25$ GeV, ≥ 4 jets $p_T > 25$ GeV
- ▶ $E_T^{\text{miss}} > 20$ GeV, $E_T^{\text{miss}} + M_T^{\text{lv}} > 60$ GeV
- ▶ 2, 3, ≥ 4 b-tags

ATLAS-CONF-2013-018



▶ Estimate multijet and W+jets backgrounds from data

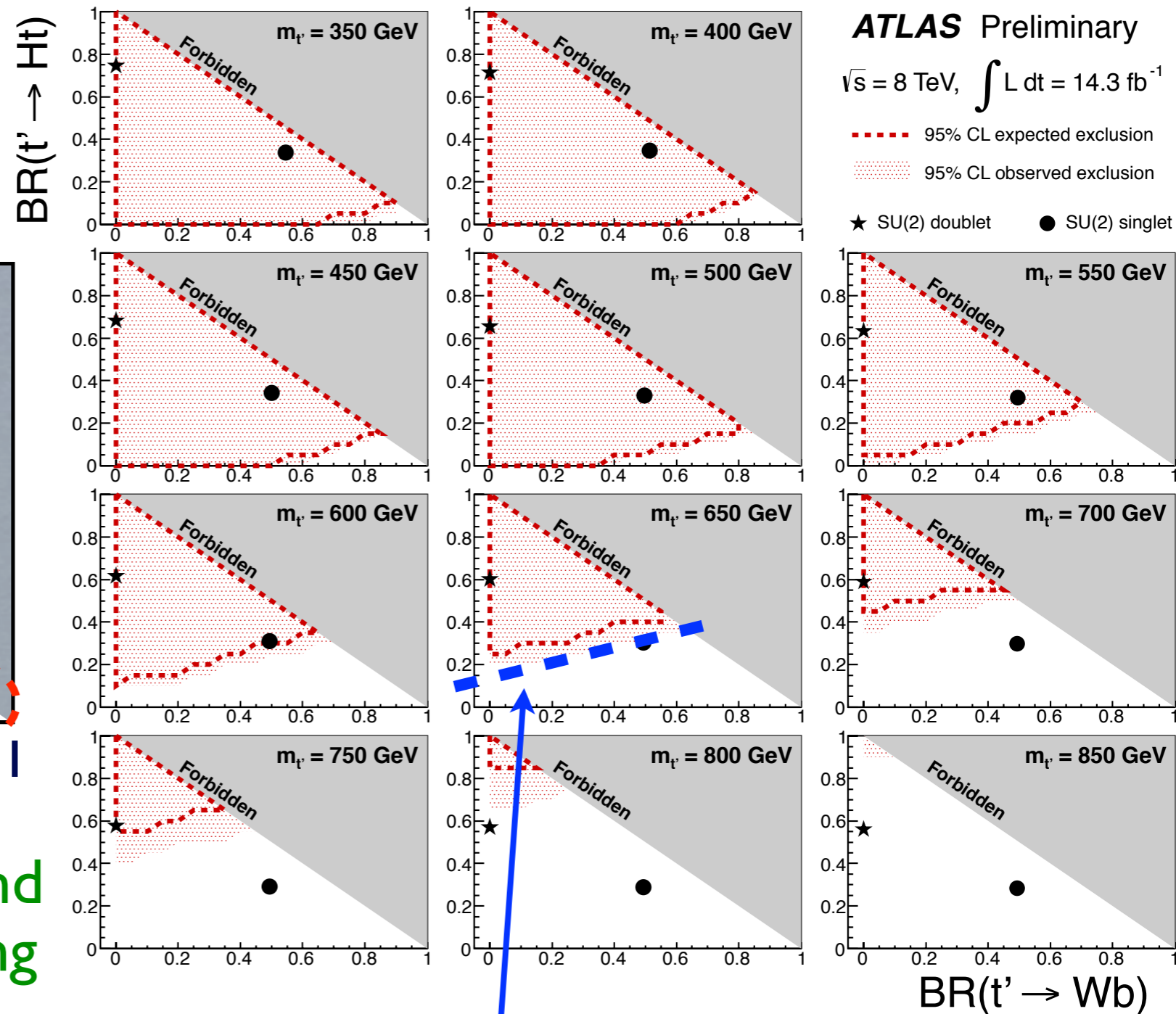
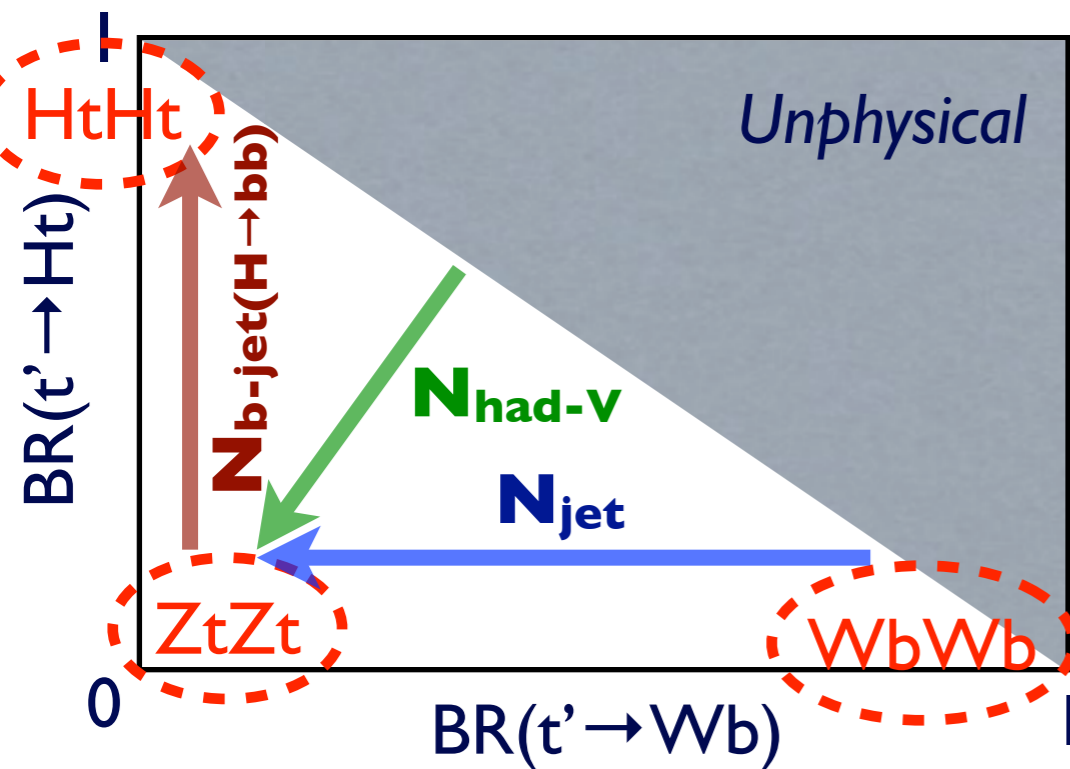
▶ $H_T = \sum p_T^{\text{lepton, jet}} + E_T^{\text{miss}} < 700 \text{ GeV}$ used to determine $t\bar{t}$ +HF/ $t\bar{t}$ +LF jet normalization



Ht+X : t'

ATLAS-CONF-2013-018

Comprehensive approach to cover branching fraction space



ATLAS Preliminary

$\sqrt{s} = 8 \text{ TeV}, \int L dt = 14.3 \text{ fb}^{-1}$

--- 95% CL expected exclusion

... 95% CL observed exclusion

★ SU(2) doublet ● SU(2) singlet

t' with mass up to ~650 GeV excluded for $BR(t' \rightarrow Ht) \sim 0.3$

Dedicated searches for Wb and Zt corners at 8 TeV are coming soon!!

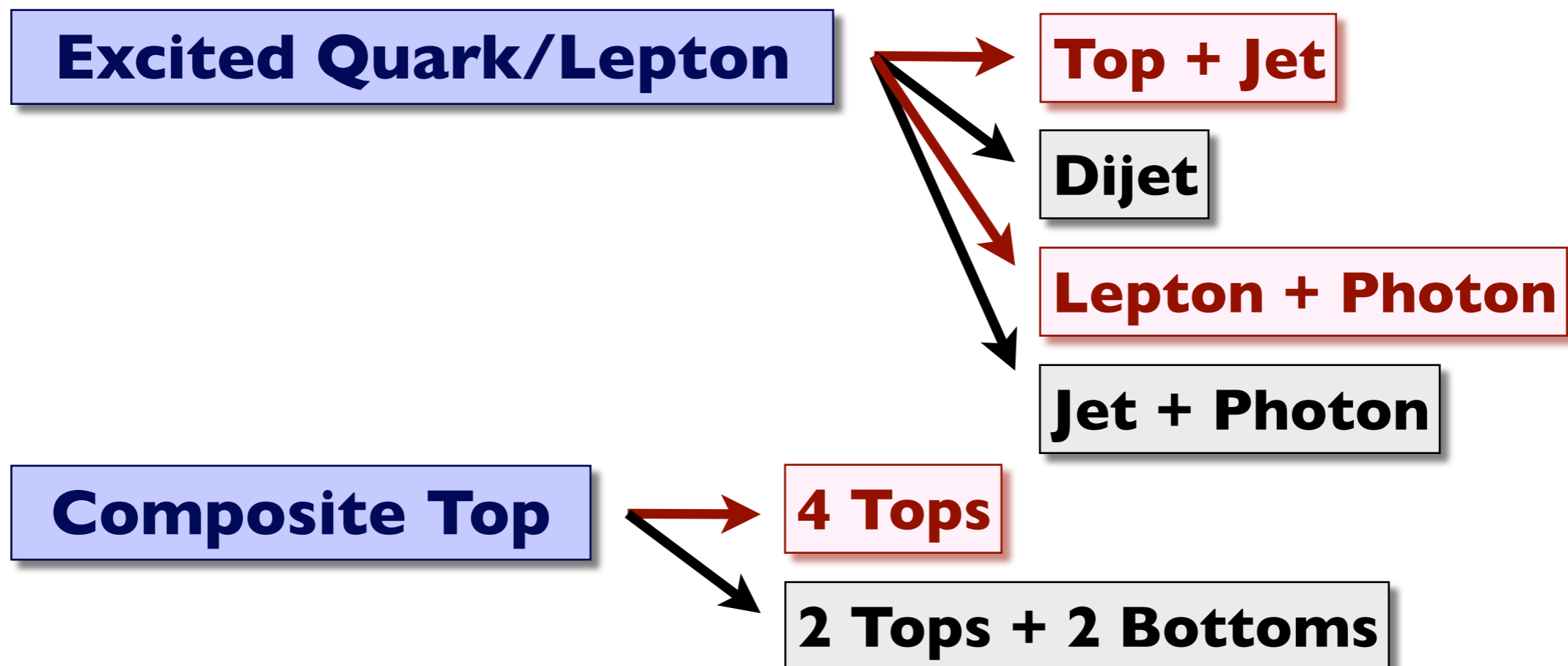
Compositeness

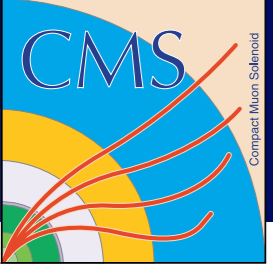
Compositeness

Observed mass hierarchy in the quark and lepton sectors
→ “Composite” objects built from fundamental constituents?

Compositeness scale Λ (constituents binding energy)

$\sqrt{s} \ll \Lambda \rightarrow$ 4-fermion contact interaction



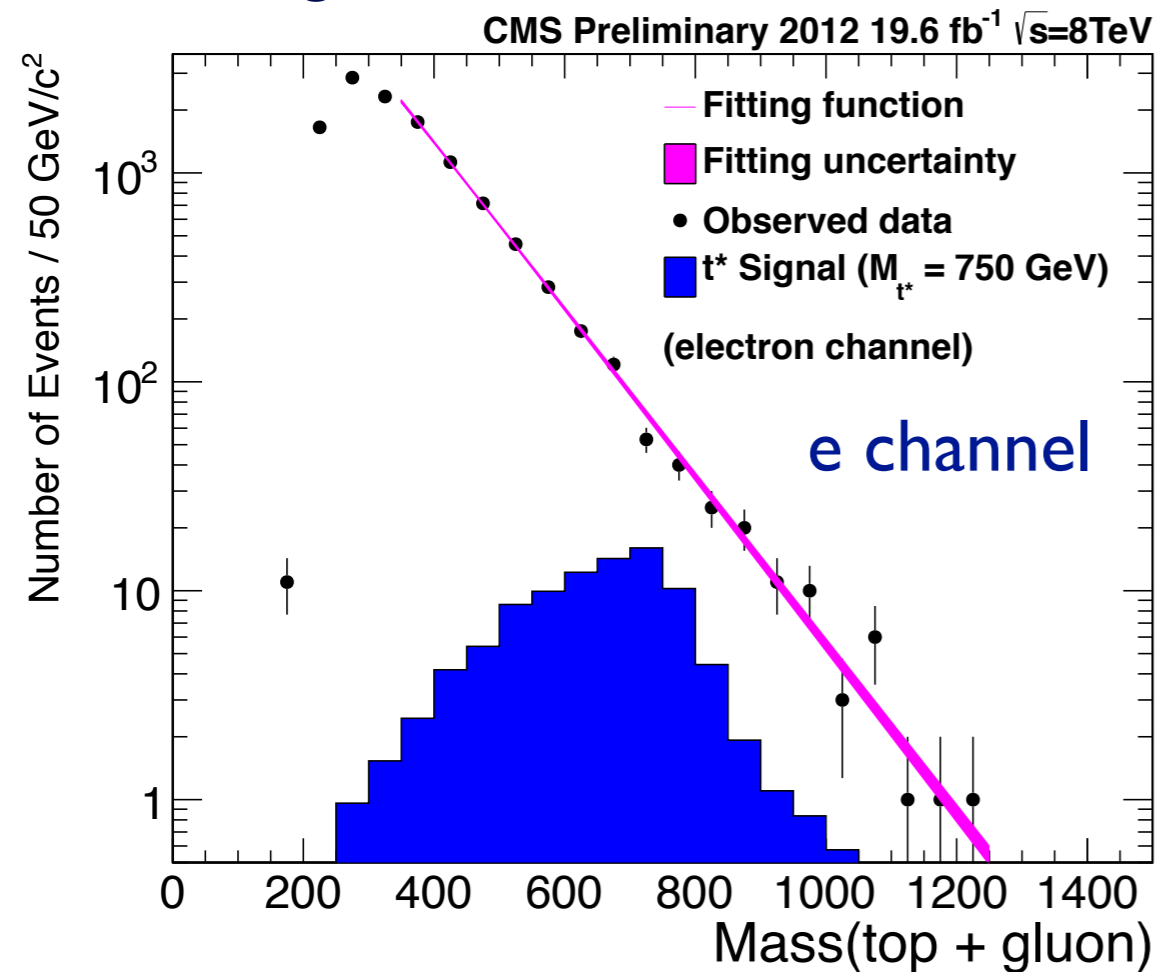


Top+Jet : Excited Top

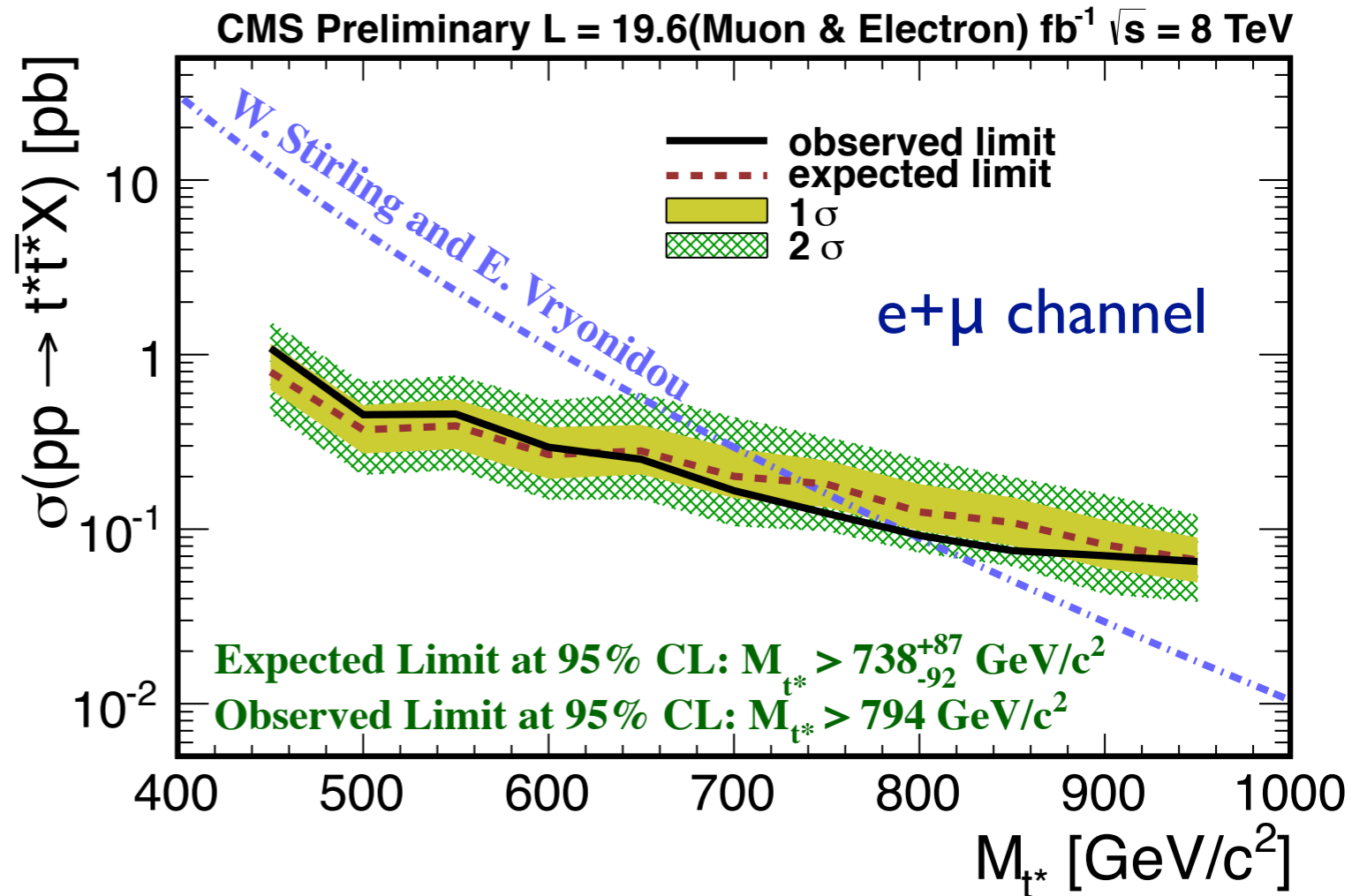
CMS PAS EXO-12-014

$t^*t^* \rightarrow t(\rightarrow l\nu b)g + t(\rightarrow \text{inclusive})g$ selection

- ▶ 1 lepton $p_{T}^{\text{electron(muon)}} > 30(26)$ GeV
- ▶ ≥ 6 jets $p_{T}^{\text{jet1,2,3(4,5,6)}} > 35-55(30)$ GeV
- ▶ ≥ 1 b-tag



- ▶ Neutrino p_z from two equal top masses
- ▶ Determine jet assignment by kinematic fit for measured momenta using W , top and t^* mass constraints



Maximum likelihood fit to reconstructed t^* mass using signal prediction and background modeling given by $f(x) = \frac{a}{1 + e^{\frac{x-b}{c}}}$

t^* mass limit set on spin-3/2 RS model



SS Dilepton : Composite Top

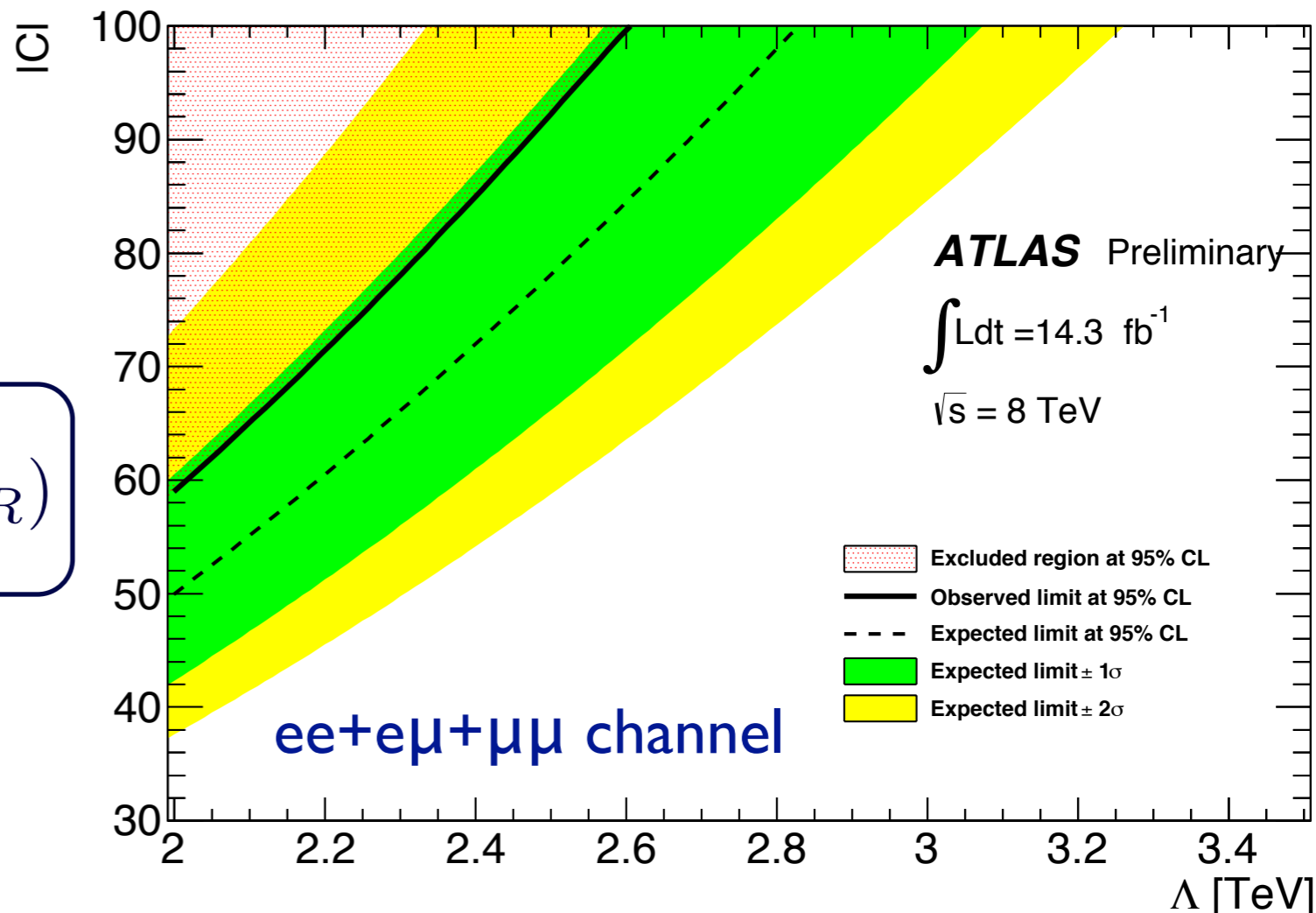
Same selections as b'/t' SS dilepton

- ▶ ≥ 2 b-tag
- ▶ $H_T = \sum p_T^{\text{lepton,jet}} > 650$ GeV

4-top production via 4-fermion contact interaction

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{C}{\Lambda^2} (t_R \gamma^\mu t_R) (t_R \gamma_\mu t_R)$$

ATLAS-CONF-2013-051



Model	$\sigma(\text{tttt})$ [fb]		$ C /\Lambda^2$ [TeV ⁻²]
	Expected	Observed	Observed
SM	43-89	85	-
Contact Interaction	29-61	59	15

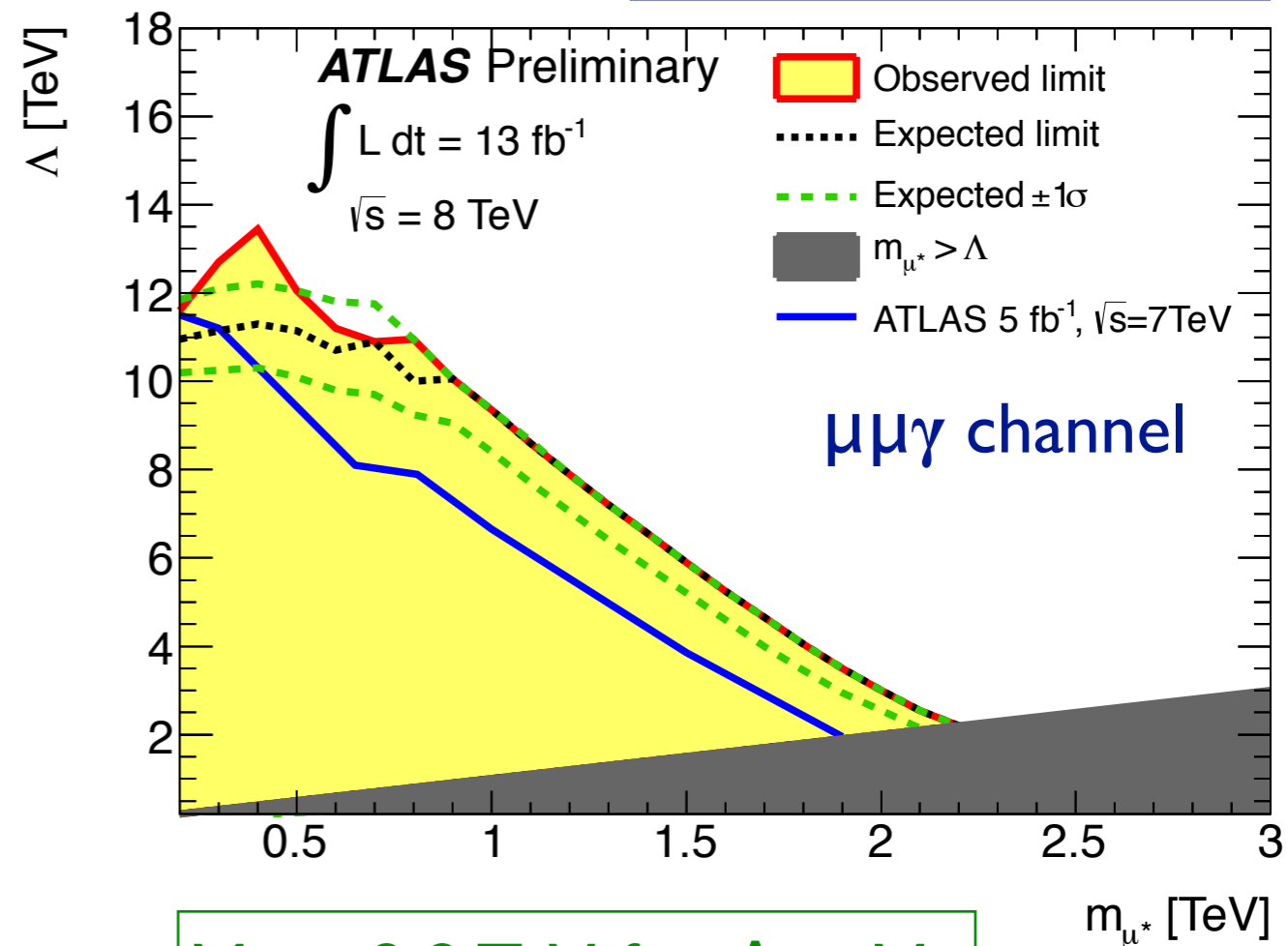
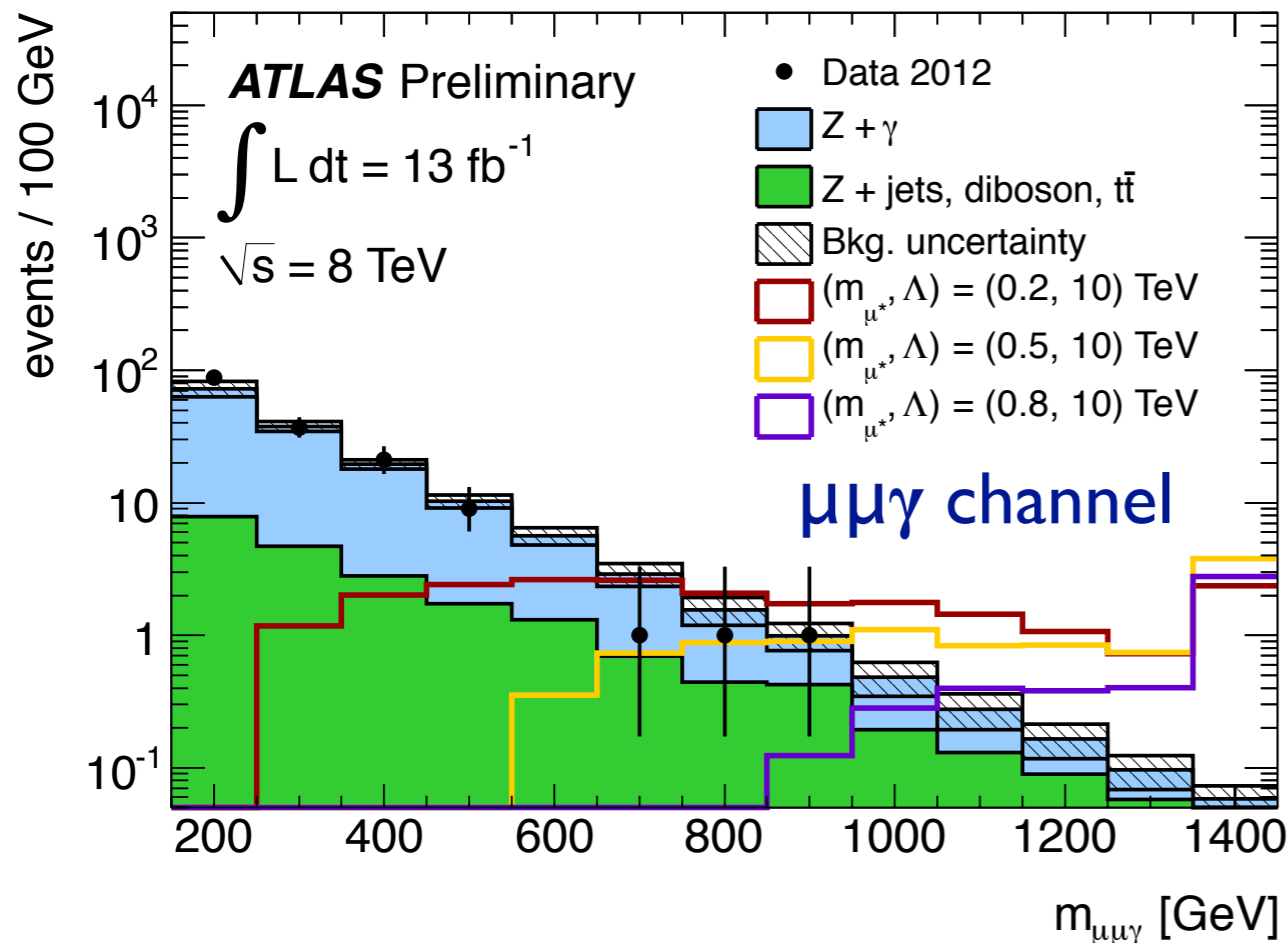


Lepton+Photon : Excited Lepton

ATLAS-CONF-2012-146

$l^* \rightarrow ll\gamma$ selection

- ▶ 2 leptons $p_T^{\text{electron(muon)}} > 40, 30$ (25,25) GeV
- ▶ ≥ 1 photon $p_T > 30$ GeV
- ▶ $\Delta R(\text{lepton}, \gamma) > 0.7$
- ▶ $M_{ll} > 110$ GeV
- ▶ $M_{ll\gamma} > M_{l^*} + 150$ GeV (for $M_{l^*} < 900$ GeV)
> 1050 GeV (for $M_{l^*} > 900$ GeV)



$M_{l^*} > 2.2$ TeV for $\Lambda = M_{l^*}$
for both $e e \gamma$ and $\mu \mu \gamma$

- ▶ Z+ γ background from SHERPA (normalization checked with NLO MCFM)
- ▶ Z+jets background from MC with data-driven normalization

Long-lived Particle

Supersymmetry

Motivation

- ▶ Gauge-mediated SUSY breaking : Stau NLSP (meta)stable in detector
- ▶ Split SUSY (very large m_0) : Gluino \rightarrow R-hadron
- ▶ Exotic multiply/fractionally charged states

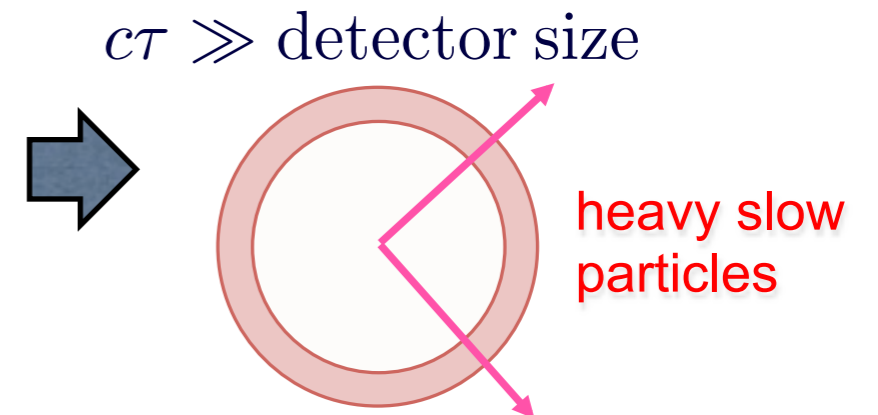
$$\beta < 1$$

Signatures

Heavy stable charged particles (HSCP)

\rightarrow GMSB Stau, R-hadron

- ▶ Energy loss dE/dx in silicon detectors
- ▶ Time-of-flight information in muon spectrometers

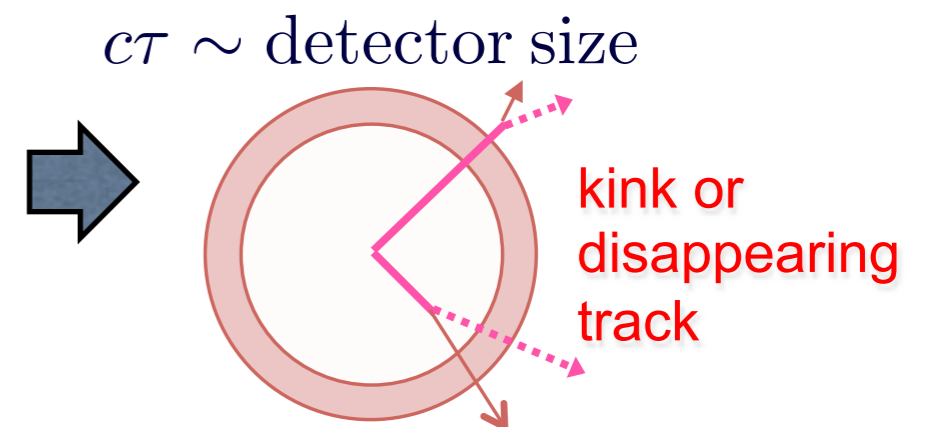


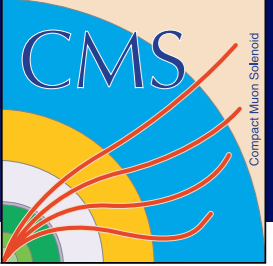
arXiv:1305.0491 Submitted to JHEP

Long-lived/Metastable charged particles

\rightarrow GMSB Stau, AMSB chargino

- ▶ Decay in flight (kink/disappearing track)

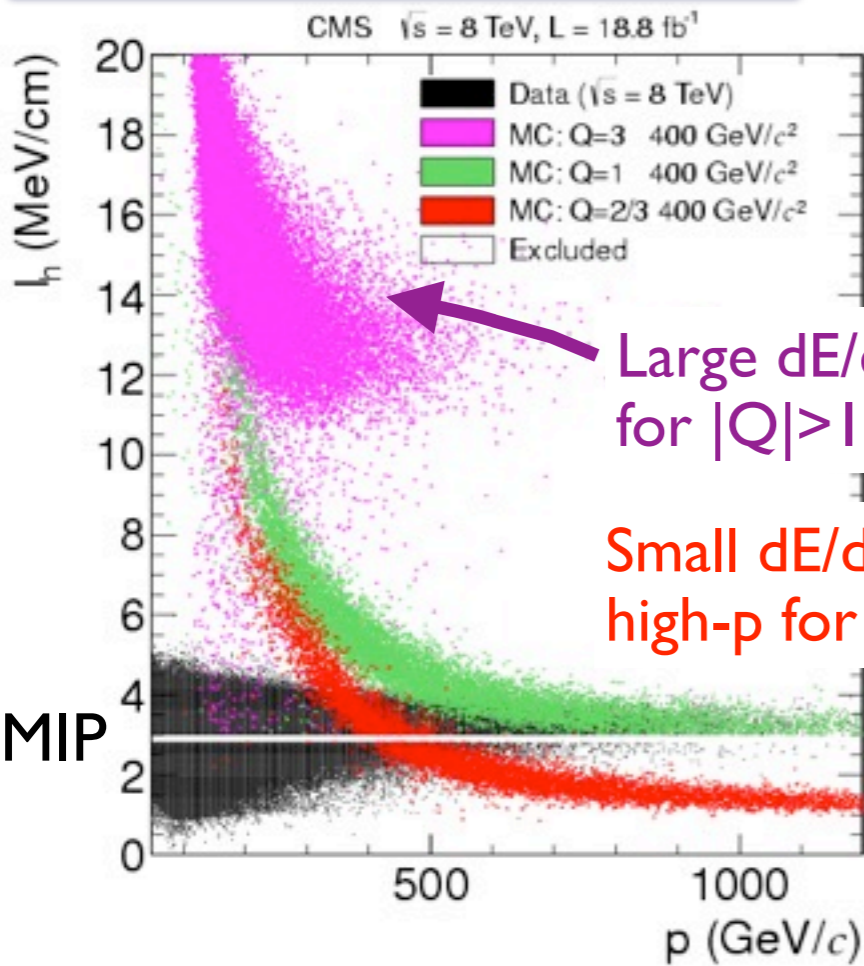




dE/dx and TOF Measurements

dE/dx in Silicon Tracker

→ Measure momentum → Determine mass and dE/dx

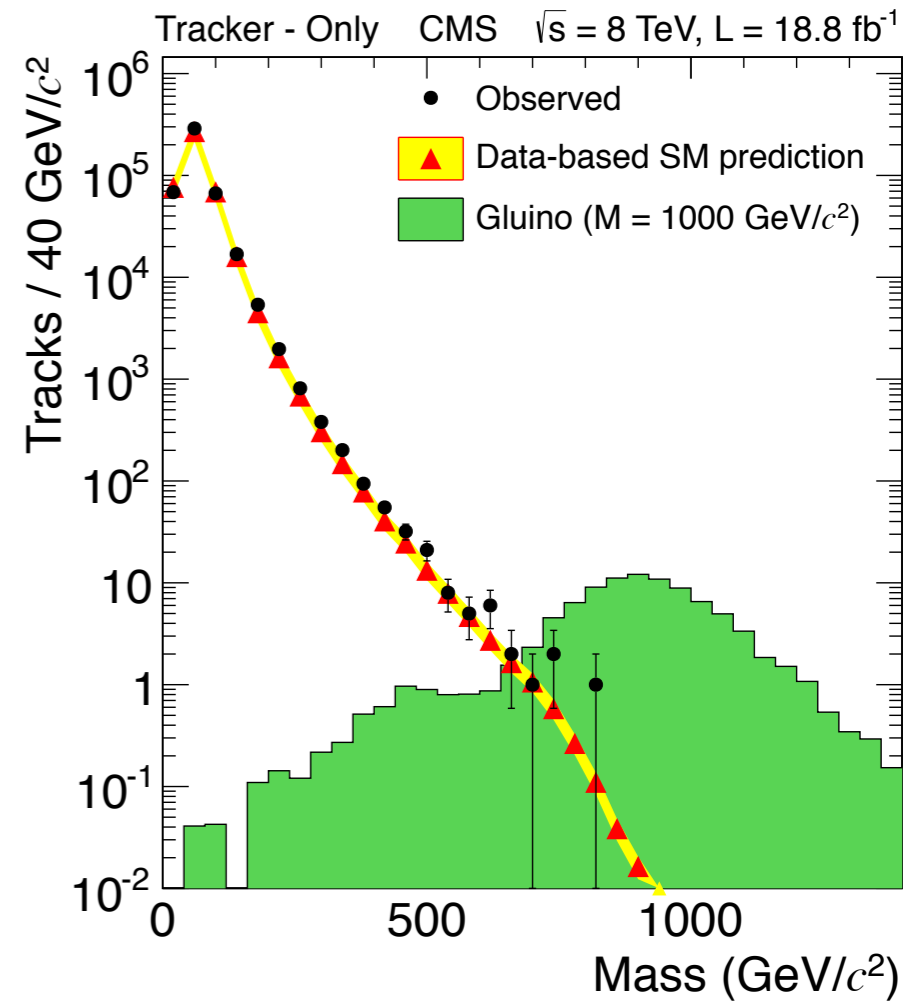


Ionization energy loss (Bethe-Bloch)

$$I_h \sim dE/dx \sim 1/\beta^2$$

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

K and C determined from protons in data



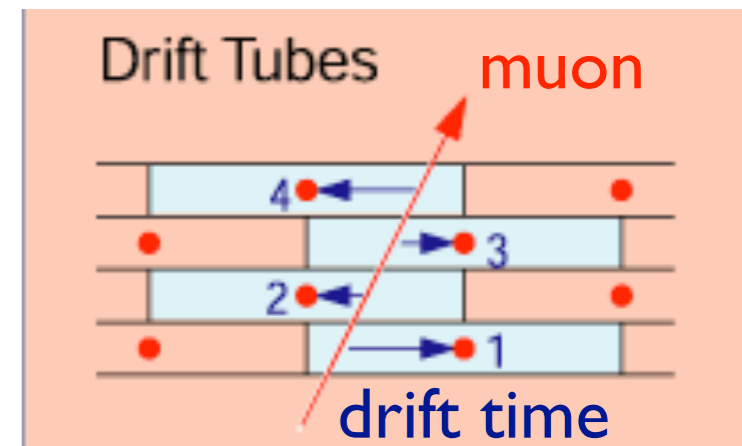
Time-of-flight in Muon Chamber

β determined from time difference δ_t of hit relative to $\beta \approx 1$ particle

$$1/\beta = 1 + \frac{c\delta_t}{L}$$

L : flight distance from IP

$\beta < 1 \rightarrow$ "longer" drift time
 $\rightarrow \delta_t$ measured as residual of straight line fit ($\beta = 1$ assumed) to hits

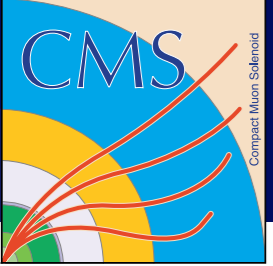


Selections : HSCP

Various combinations of silicon and muon detectors and optimized selections to cover a wide range of signals

- *R-hadron : charge exchange through detector interaction (charged \leftrightarrow neutral)*
- *different amounts of ionization loss (singly, fractionally, multiply charged)*
- *different thresholds for reconstructed mass*

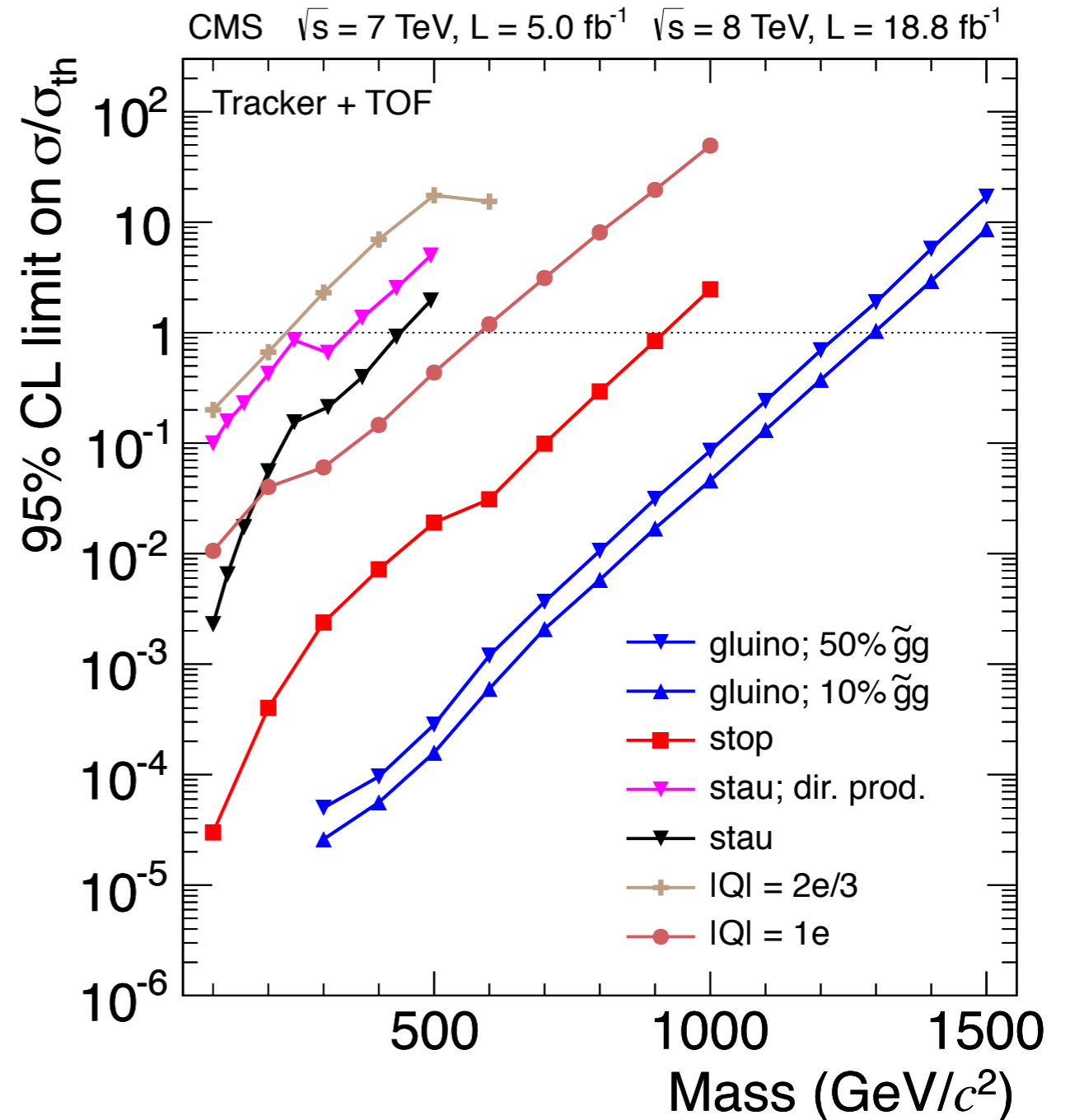
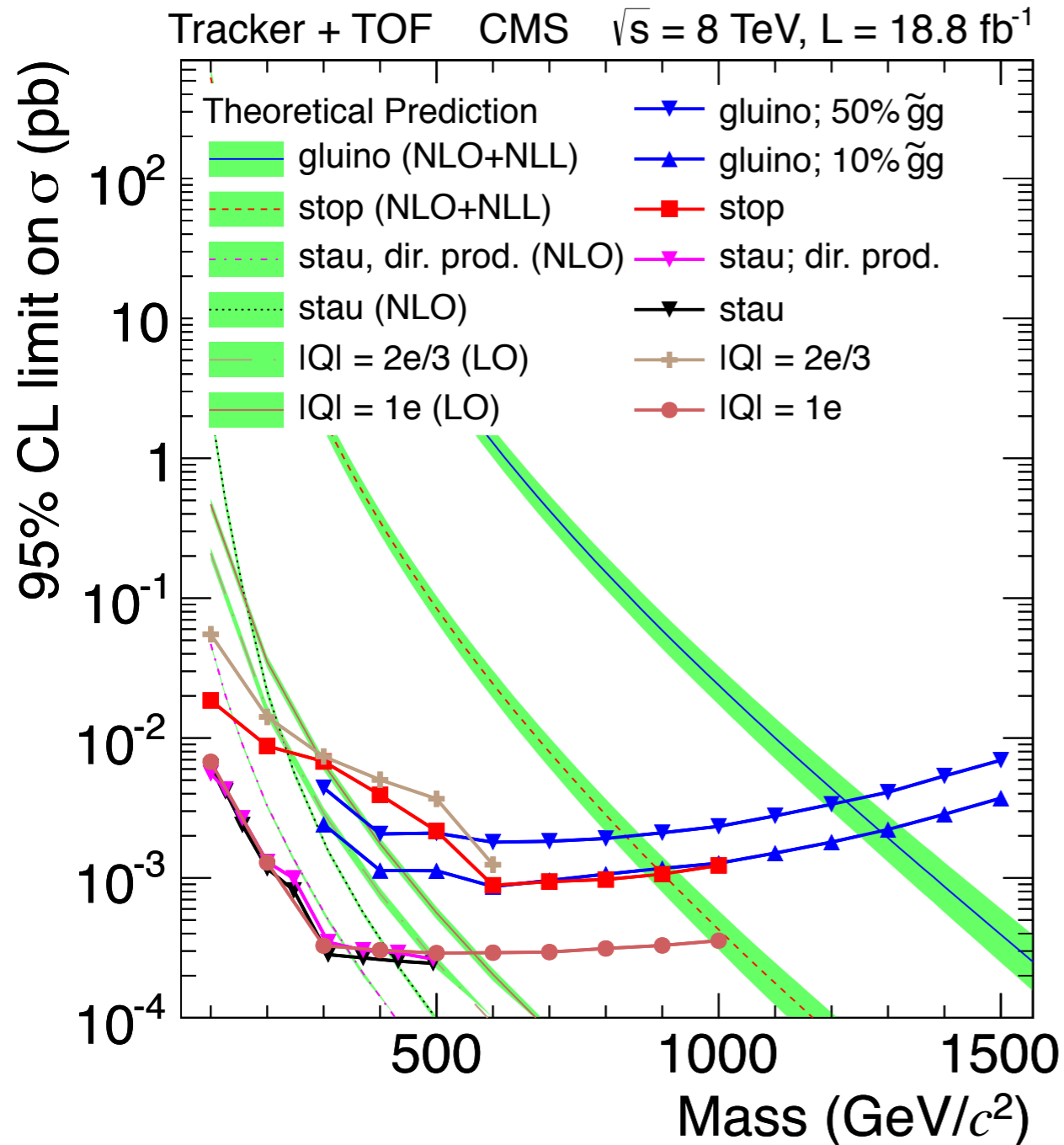
HSCP charge	Signature	Selection Cuts				Model
		p_T [GeV]	dE/dx	β	Mass [GeV]	
$ Q = 1e$	Tracker+TOF	>70	small	small	>0-300	GMSB stau
	Tracker only	>70	large	-	>0-400	Gluino R-hadron Stop R-hadron
	TOF only	>230	-	very small	-	Gluino R-hadron
$ Q < 1e$	Tracker only	>125	medium	-	-	Fractionally charged state
$ Q > 1e$	Tracker+TOF	-	very large	small	-	Multiply charged state



Results : HSCP

arXiv:1305.0491

Cross section and mass limits from Tracker+TOF measurements





Baryon Number Violating Top

- ▶ Baryon number violation (BNV) : indication to new physics (SUSY, GUT, ...)
- ▶ Probing BNV in top-quark decay motivated by
 - Good identification of top events
 - Access to BNV at the quark level (before hadronization)
 - BNV at $\sim O(\text{TeV})$ energy scale

CMS PAS B2G-12-023

Analysis strategy

- Look for BNV decay in tt events with a top \rightarrow all-had decay
- Enhance possible BNV decays of **$top \rightarrow bc\mu$** or **$top \rightarrow bue$**
- Fix tt and Wt normalization using data in baseline selection
- Likelihood fits to data after tight selection with signal (BNV BR as a parameter) and background hypotheses

Tight selection

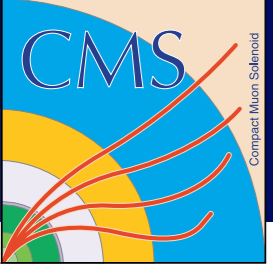
Baseline selection

- ▶ 1 lepton $p_T^{\text{electron(muon)}} > 30(25)$ GeV
- ▶ ≥ 5 jets $p_T > 30-70$ GeV (≥ 1 b-tag)

- ▶ $E_T^{\text{miss}} < 20$ GeV

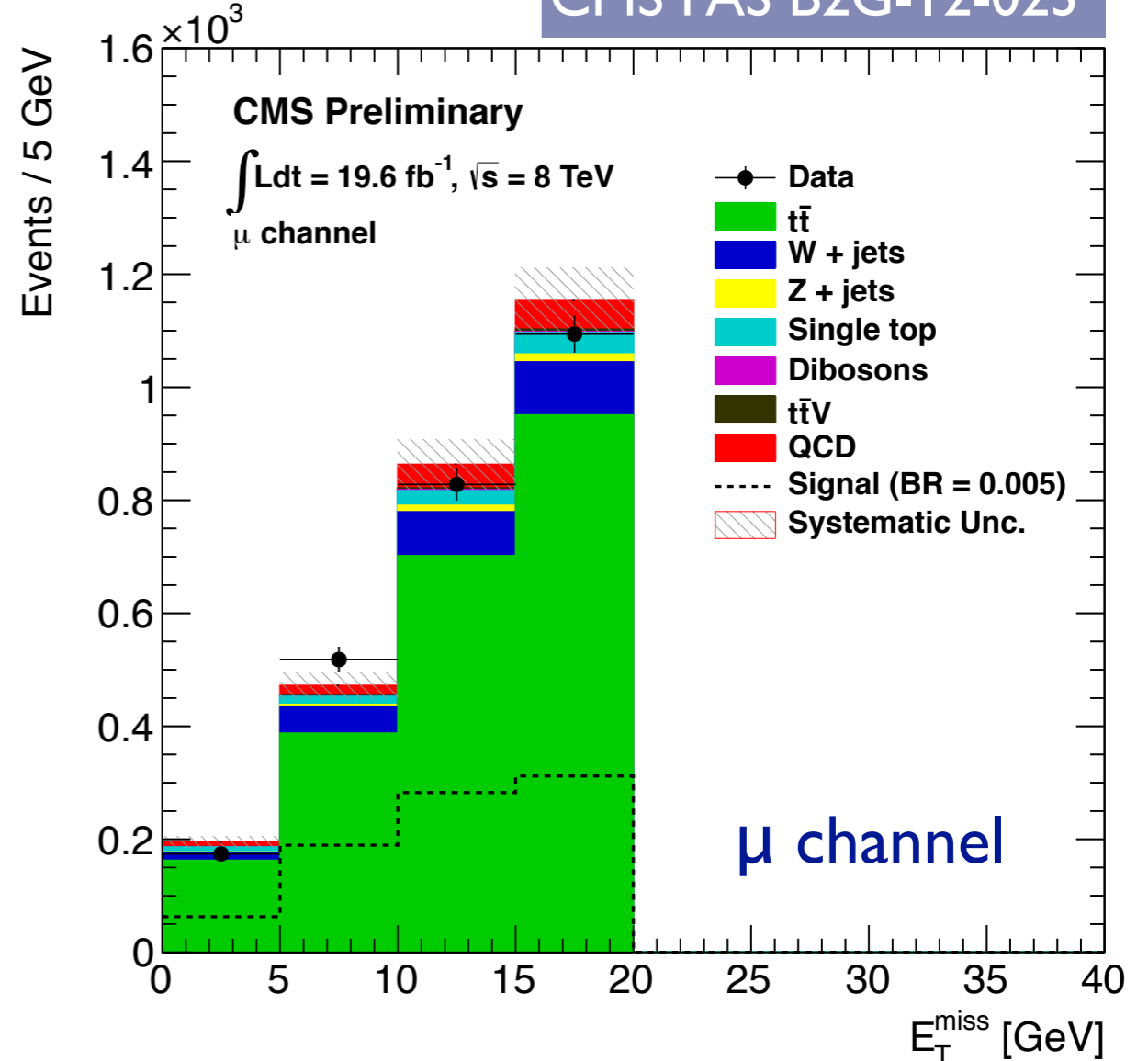
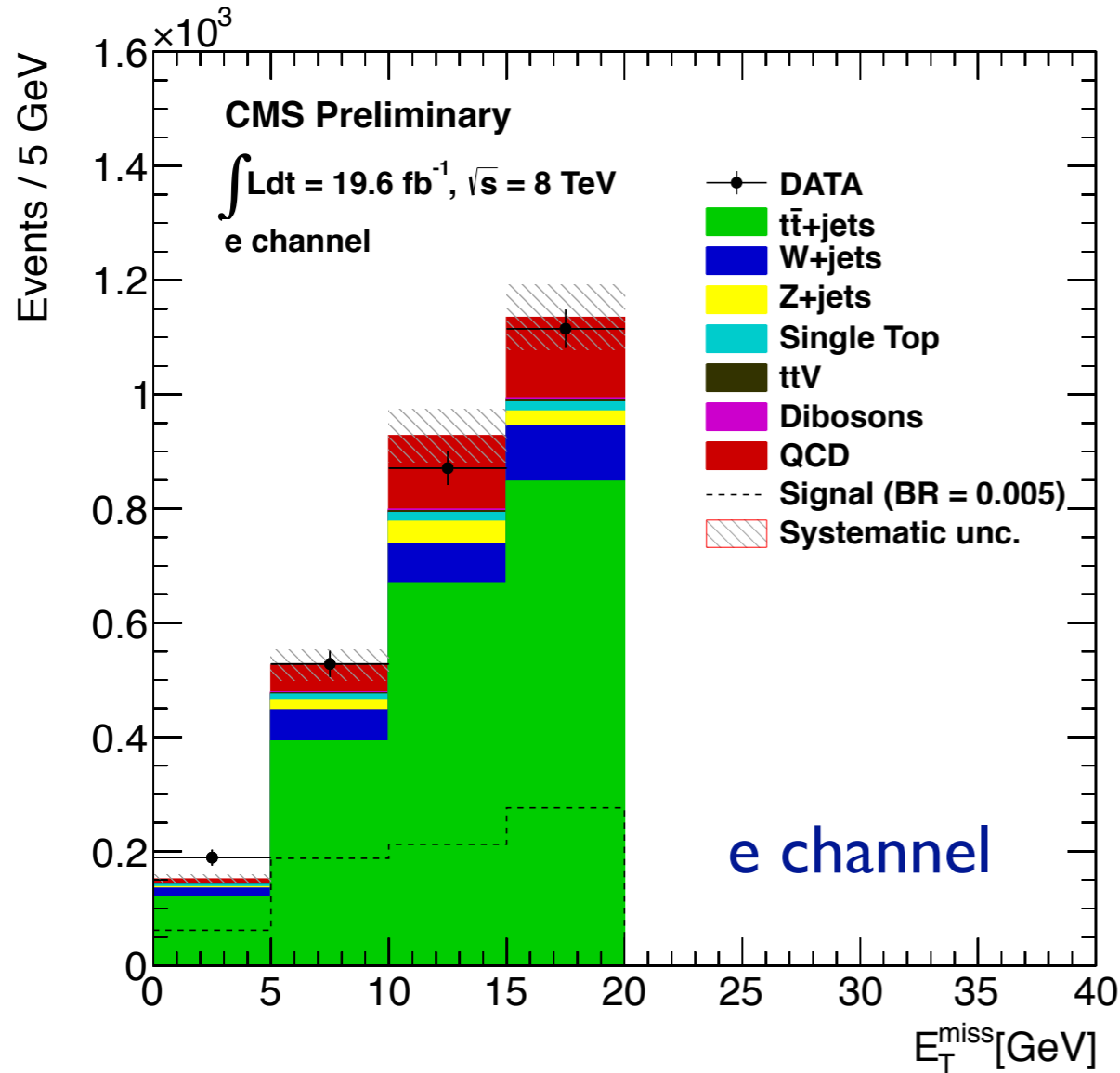
- ▶ Compatibility with SM-BNV ttbar decay

$$\chi^2 = \sum_i \frac{(x_i - \bar{x}_i)^2}{\sigma_i^2} \rightarrow \chi_{\text{min}}^2 < 20$$



Baryon Number Violating Top

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Branching fraction limits for BNV decay of top quarks into 1 lepton + 2 jets

	95%CL Obs. Limit	95%CL Exp. Limit	68%CL Exp. Limit Range
Muon	0.0016	0.0029	[0.0017, 0.0042]
Electron	0.0017	0.0031	[0.0018, 0.0045]
Combined	0.0015	0.0029	[0.0016, 0.0042]

Summary

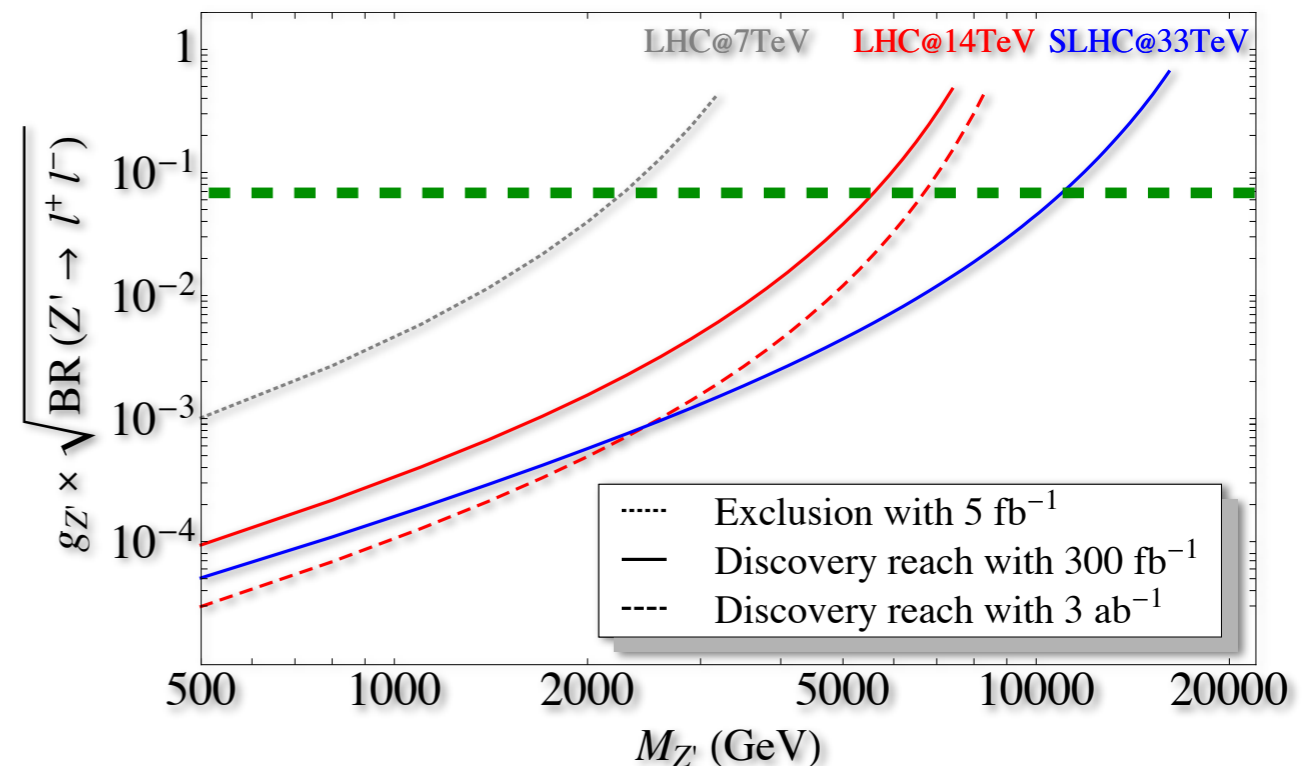
Review latest results on non-jet based signature searches for

- ▶ Heavy gauge bosons : dilepton, lepton+ E_T^{miss} , diboson
- ▶ Extra dimensions : dilepton, diboson
- ▶ Fermionic top/bottom partners : same-sign dilepton, lepton+ E_T^{miss} +jets
- ▶ Compositeness : semi-leptonic top+jet, same-sign dilepton, lepton+photon
- ▶ Supersymmetry : long-lived particles
- ▶ Baryon number violation : lepton+jets

No indication of new physics yet, but...

Still many to come from full data analysis at 8 TeV and more exciting 13/14 TeV run at 2015!!

Era of Tera-scale physics



Z'_{SSM} discovery sensitivity
~5.5TeV at 14TeV (300 fb^{-1})