Search for Physics beyond the Standard Model at CMS

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on behalf of the CMS Collaboration

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New physics at the TeV scale?

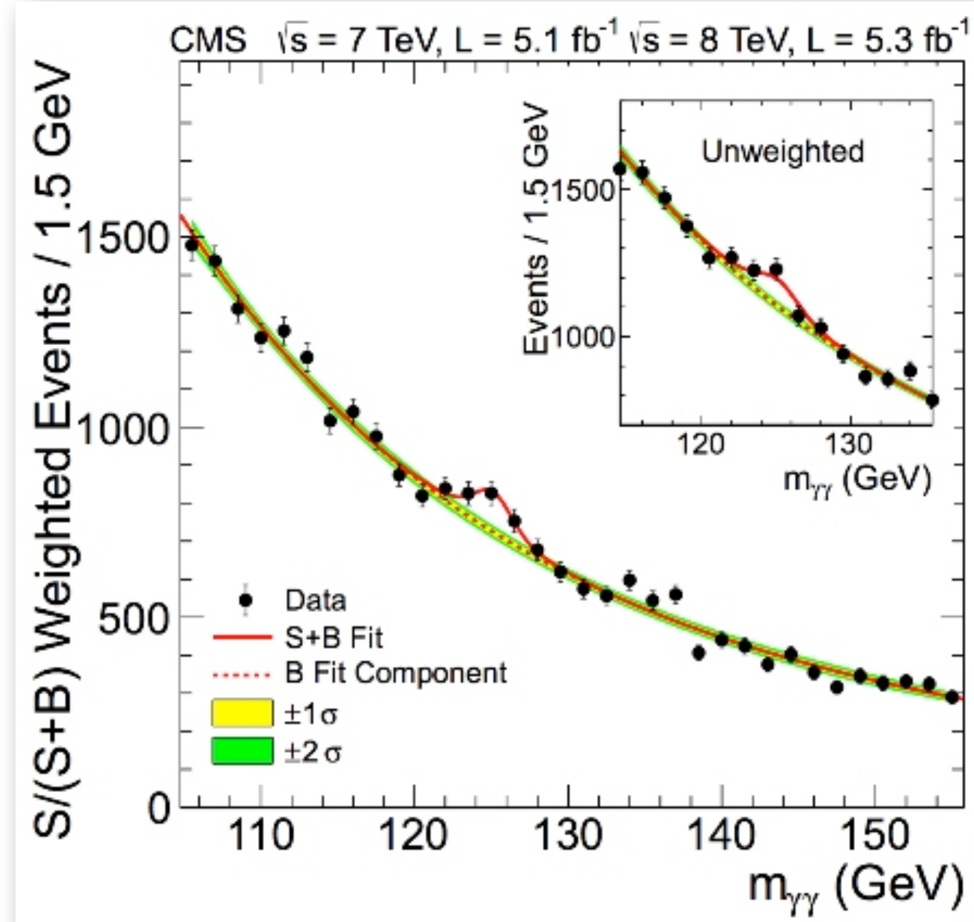
- A Higgs boson has been discovered

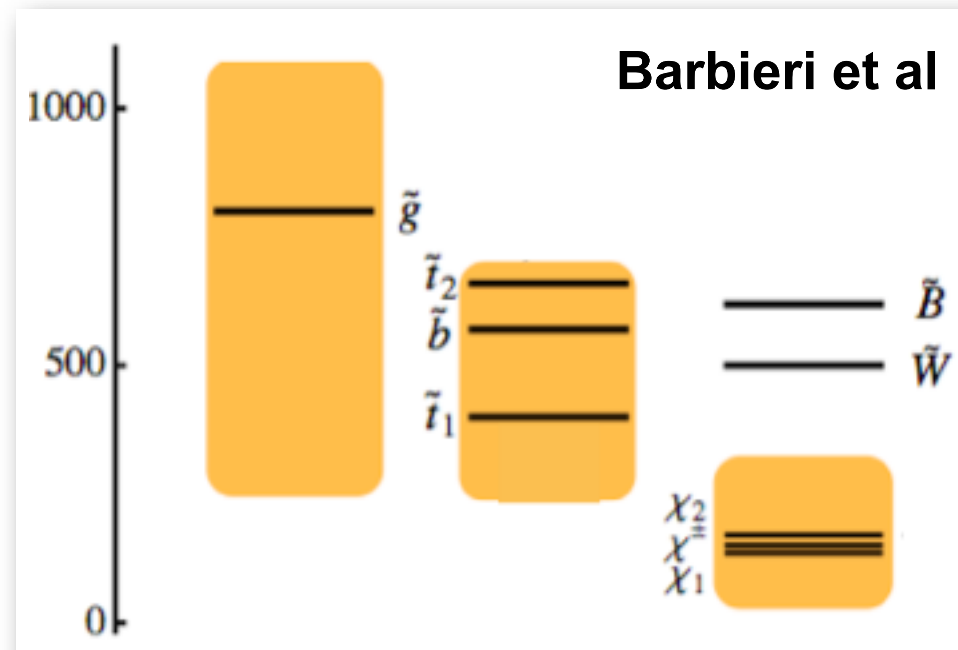
- If new physics has something to do with making the Higgs light, we expect it at the TeV scale...

- SUSY
  - Naturalness: gluino, 3rd gen. squark(s), $\chi^{\pm}\chi^{0}$ < ~1 TeV

- Extra dimensions (UED, ADD, RS)
  - TeV-scale objects from KK excitations

- Today, results from five searches
  - One with 12 fb^{-1}, four with ~20 fb^{-1} @ 8 TeV
  - Two SUSY hadronic searches with b-jets + MET
  - Dijet (Z′, G_{KK}) and dilepton (Z′) resonances
  - Lepton + MET final state (W'_{SSM}, W_{KK}, CI)





Inclusive search with α_T

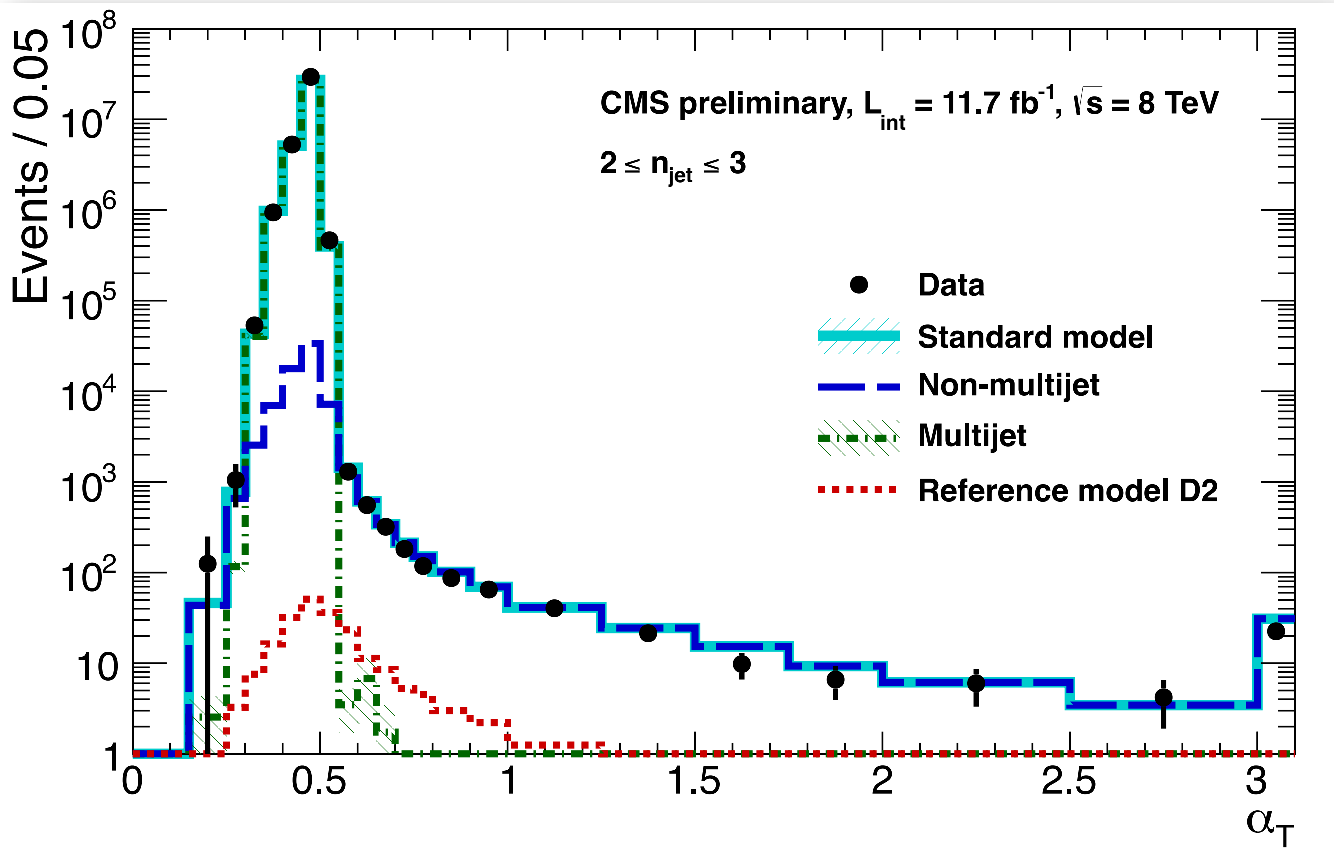
CMS-PAS-SUS-12-028

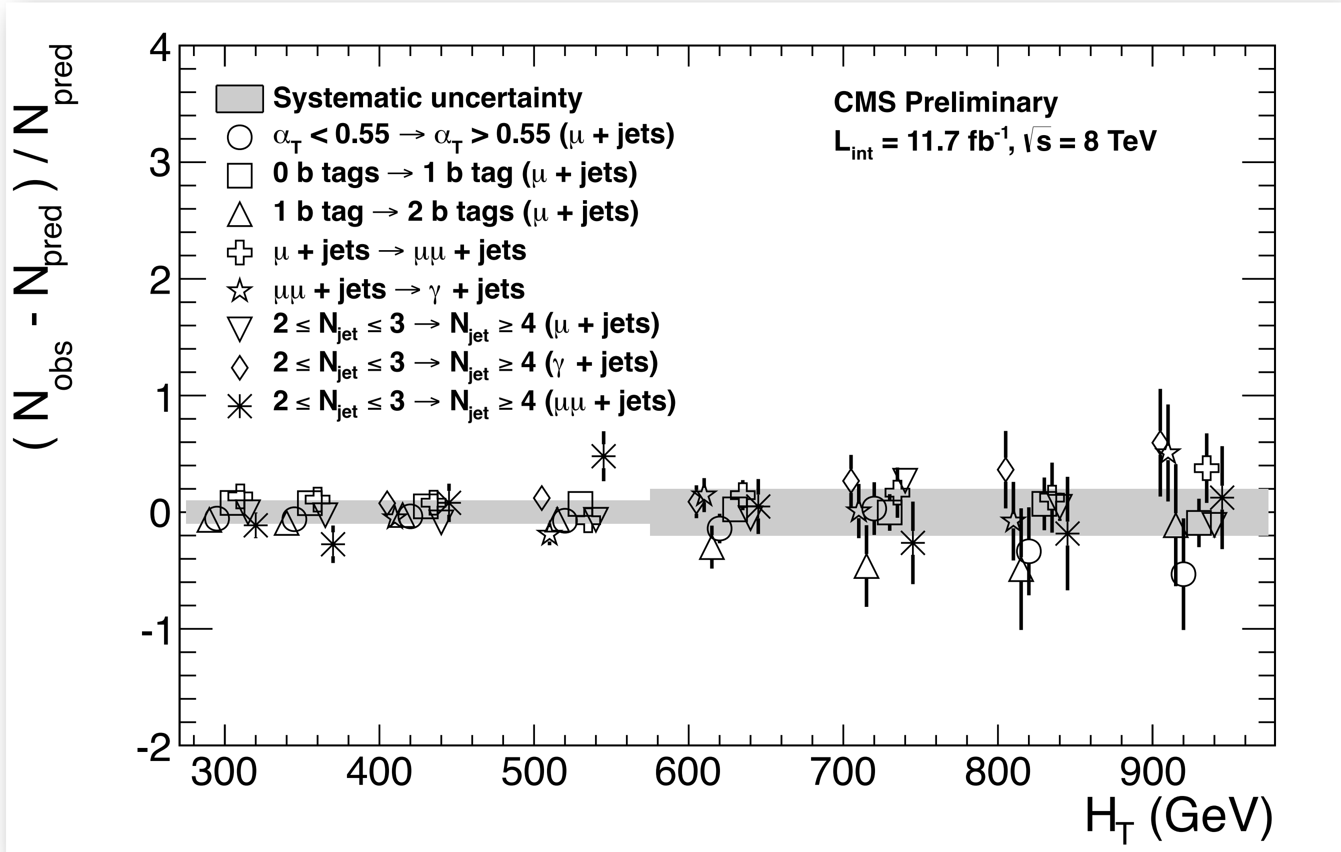
8 TeV, 11.7 fb^{-1}

- Hadronic final state: ≥2 jets with missing transverse energy
  - Events categorised according to **H_T** (>275 GeV), **N_{jet}** (2-3, ≥4), and **$N_{b\text{-}jet}$** (0,1,2,3,≥4)
- Negligible QCD due to α_T variable
  - Robust, discovery-orientated, for LHC start-up
  - Use jets only (eg, use $\not{H}_T$ as estimator of MET)
- Main backgrounds: tt, W+jets, Z(→vv)+jets
  - Data yields in 3 (kinematically-similar) control samples + transfer factors (ratios) from MC
  - Background systematic uncertainties (10-30%) from multiple closure tests in data

Dijet **Multijet**

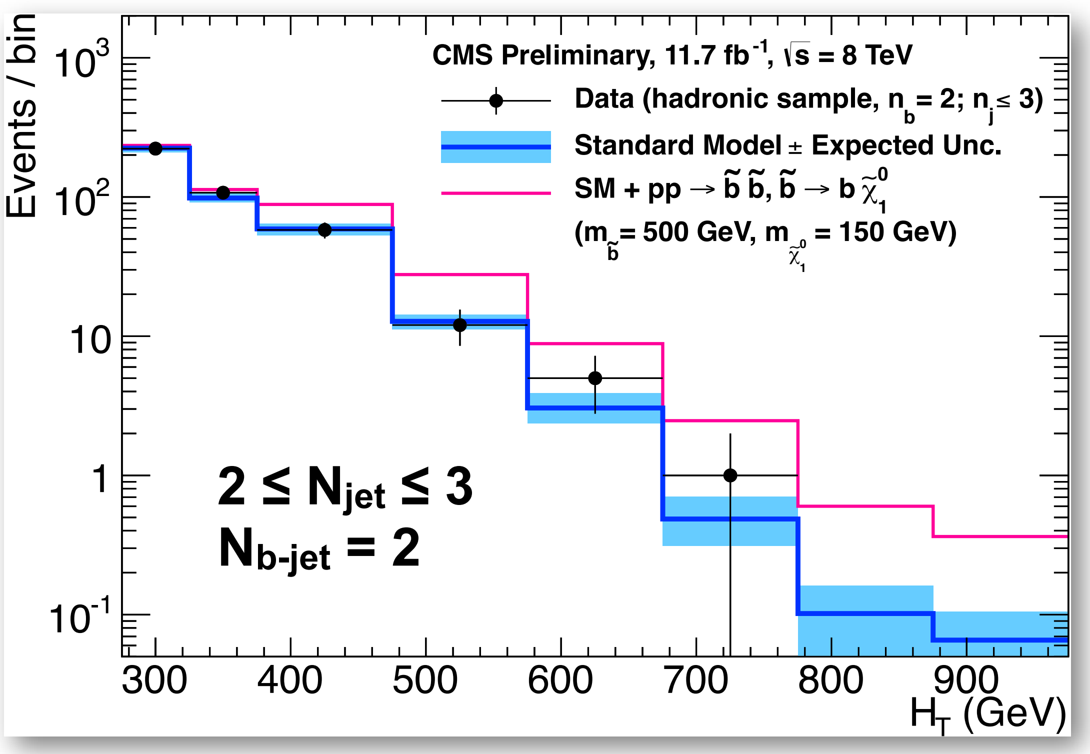
$$\alpha_T = \frac{E_T^{j_2}}{M_T} \qquad = \frac{1}{2} \times \frac{1 - (\Delta H_T / H_T)}{\sqrt{1 - (\not{H}_T / H_T)^2}}$$



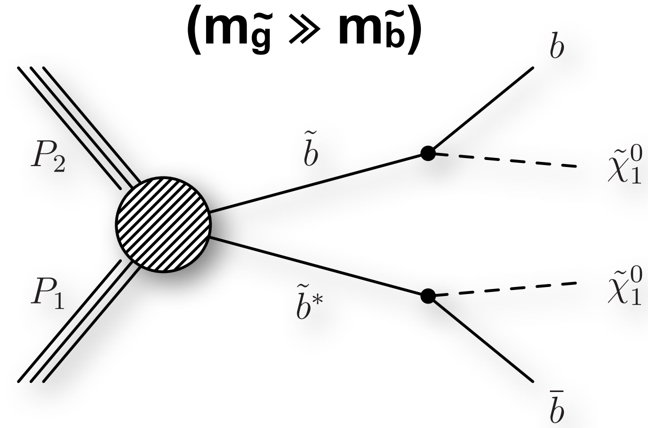


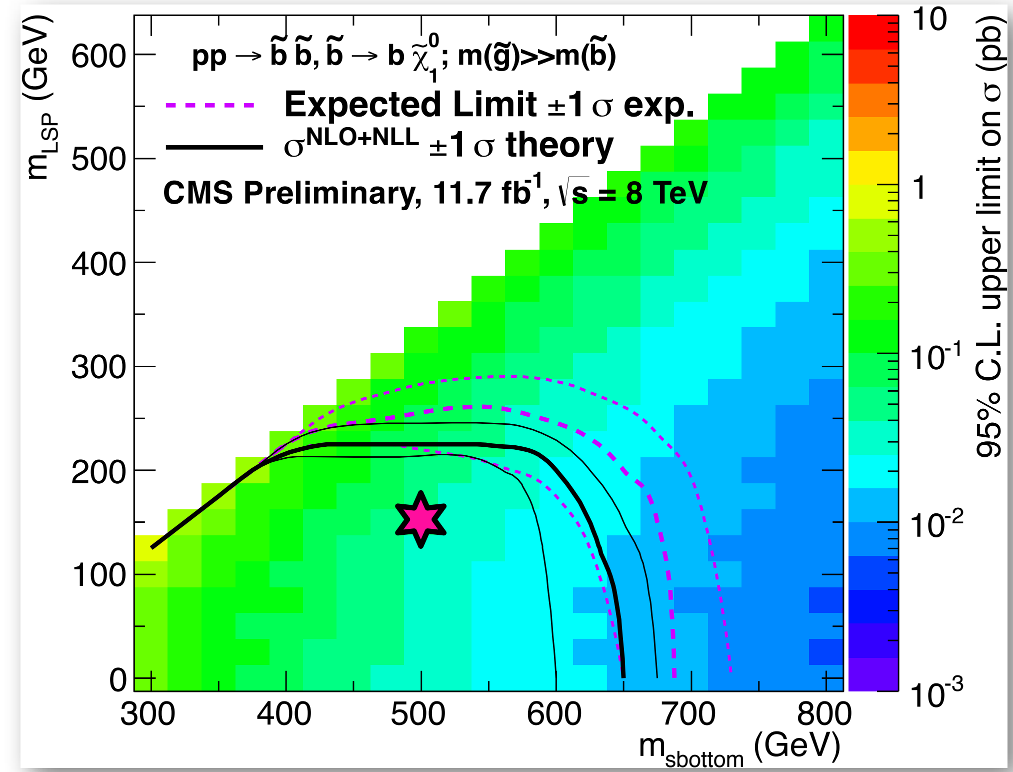
α_T: direct/gluino-mediated production of $\tilde{b}$

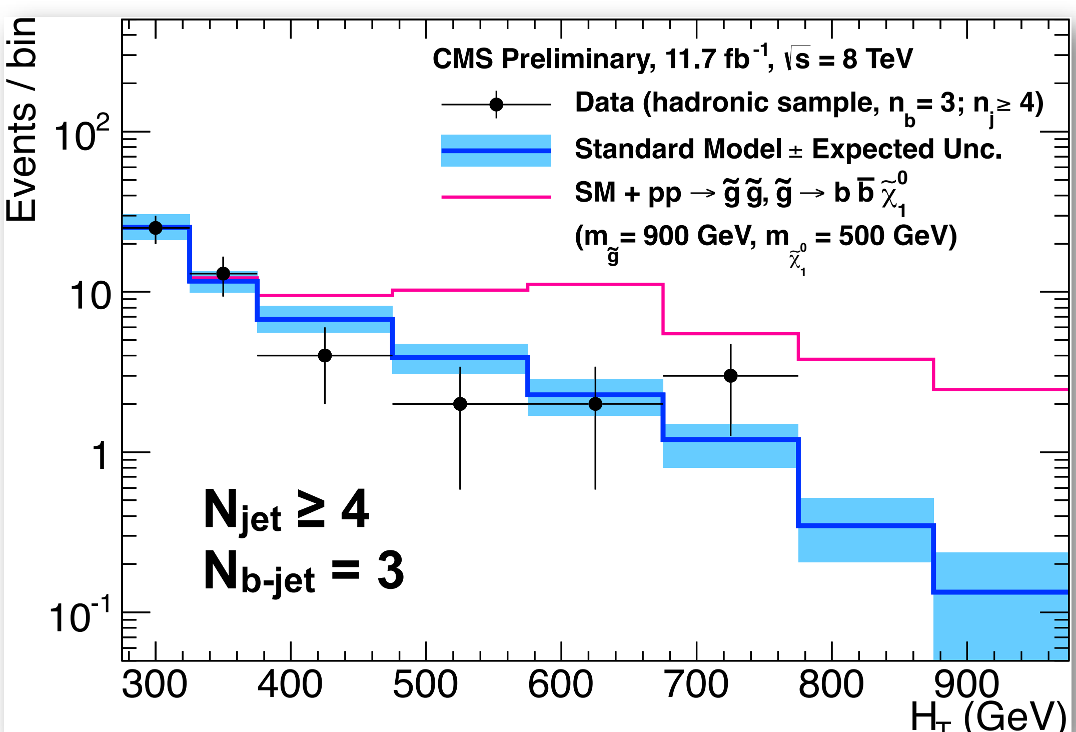
- Data compatible with bkgd.-only hypothesis in all event categories
- Limits with simplified models: individual topologies, kinematics depend on masses



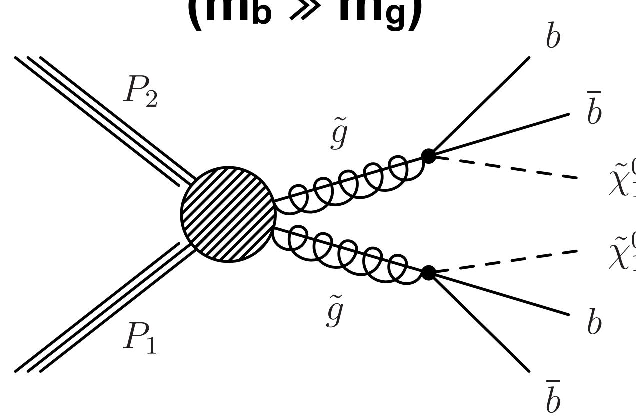
Direct production of bottom squarks ($m_{\tilde{g}} \gg m_{\tilde{b}}$)

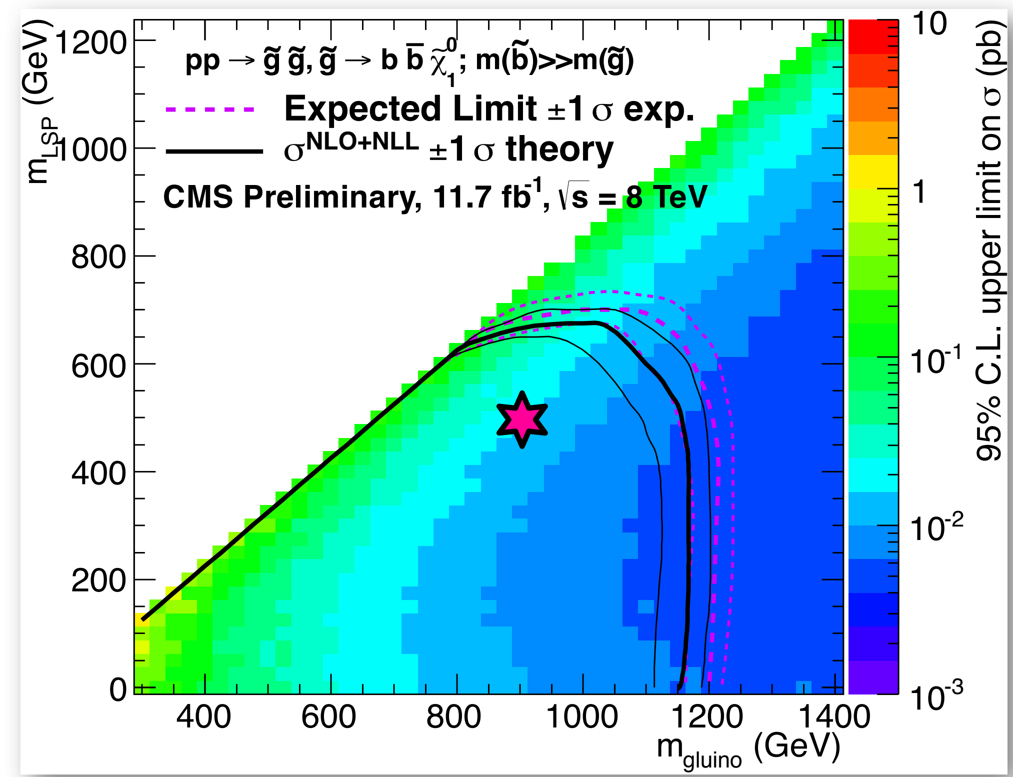






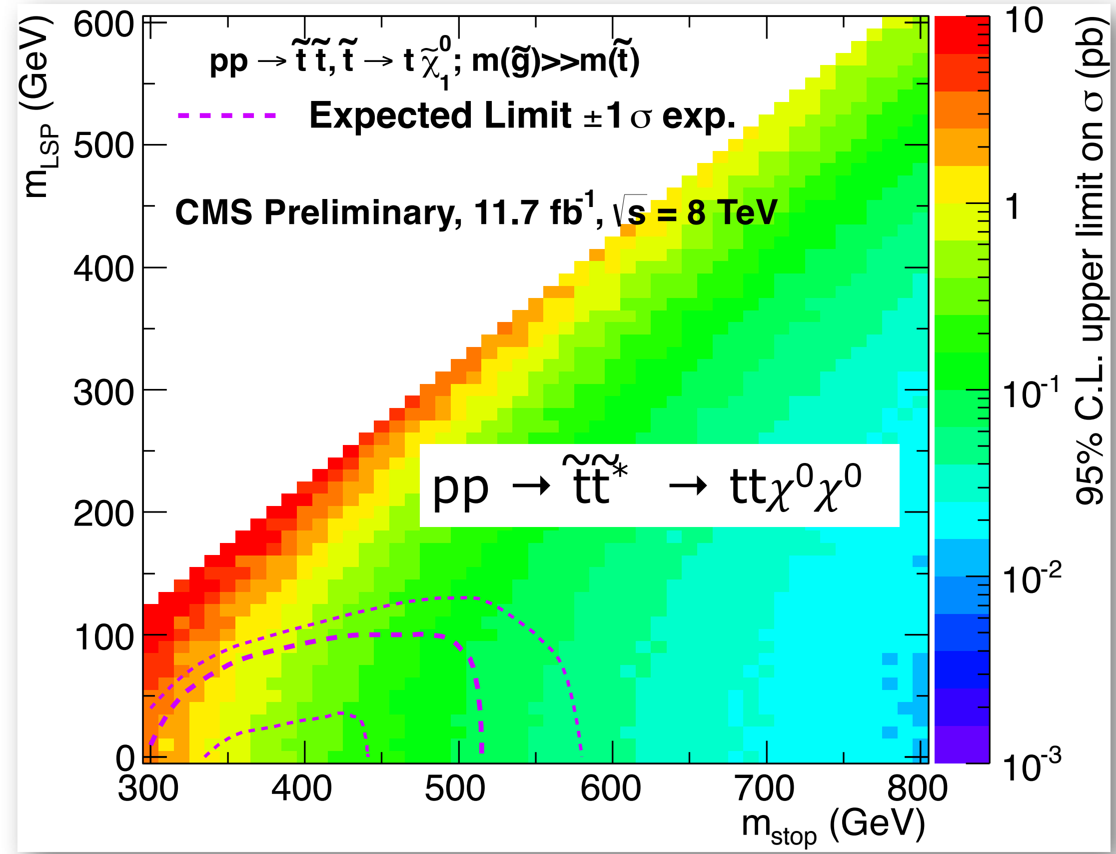
Gluino-mediated production of bottom squarks ($m_{\tilde{b}} \gg m_{\tilde{g}}$)





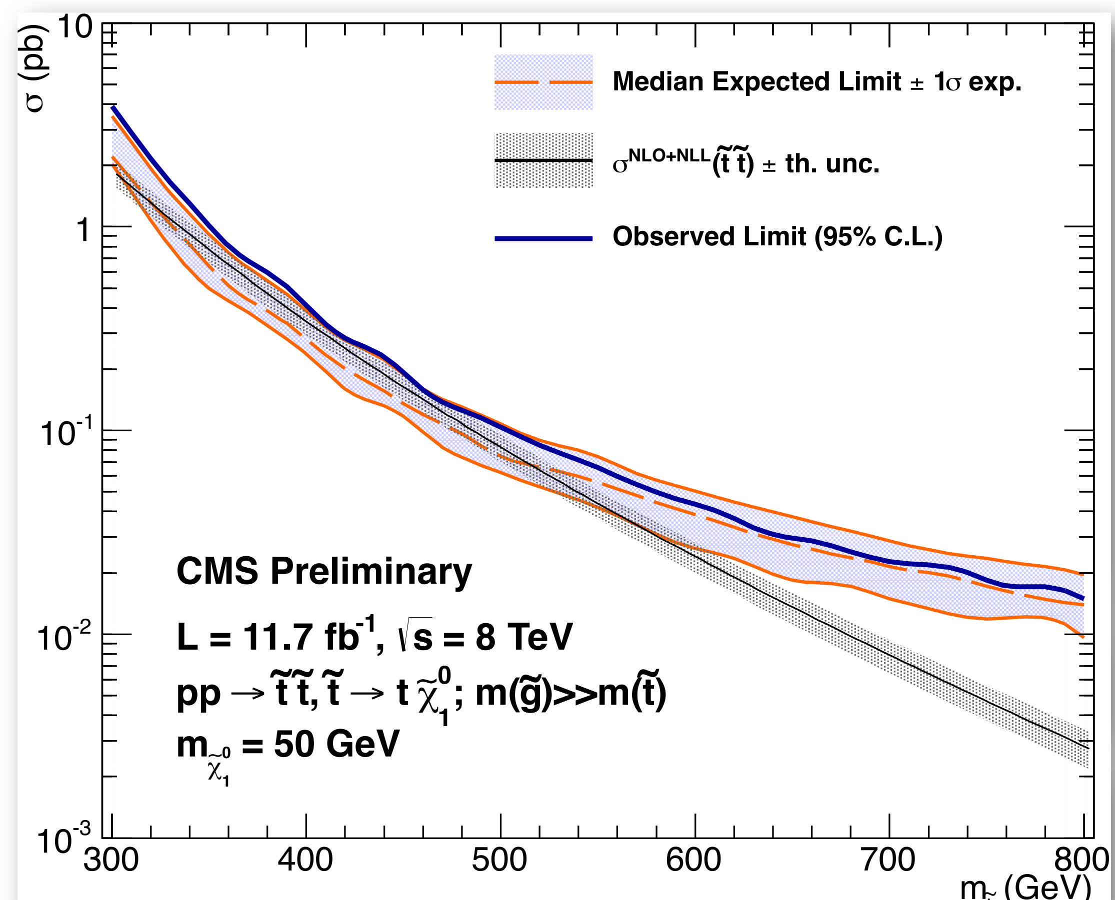
α_T: direct production of $\tilde{t}$ (and other models)

- No observed exclusion for direct $\tilde{t}$ production
  - Expect to exclude [320,500] for m_{LSP} = 50 GeV
  - Yet to update to full 20 fb^{-1} and parked data
- Currently, interpretations in 6 simplified models
  - Direct / gluino-mediated pair-production of $\tilde{q}$, $\tilde{b}$, $\tilde{t}$
- Expected limits improve w.r.t. 7 TeV by ~200 GeV



Observed (expected) limits on parent sparticle and LSP masses

	Model	m_{parent}	m_{LSP}
Direct production	$pp \to \tilde{q}\tilde{q}^* \to qq\chi^0\chi^0$	775 (850)	325 (350)
	$pp \to \tilde{b}\tilde{b}^* \to bb\chi^0\chi^0$	600 (675)	200 (250)
	$pp \to \tilde{t}\tilde{t}^* \to tt\chi^0\chi^0$	- (520)	- (100)
Gluino-mediated	$pp \to \tilde{g}\tilde{g} \to qqqq\chi^0\chi^0$	950 (1050)	450 (550)
	$pp \to \tilde{g}\tilde{g} \to bbbb\chi^0\chi^0$	1125 (1200)	650 (700)
	$pp \to \tilde{g}\tilde{g} \to tttt\chi^0\chi^0$	950 (1075)	325 (375)



Multiple b-jets + MET search

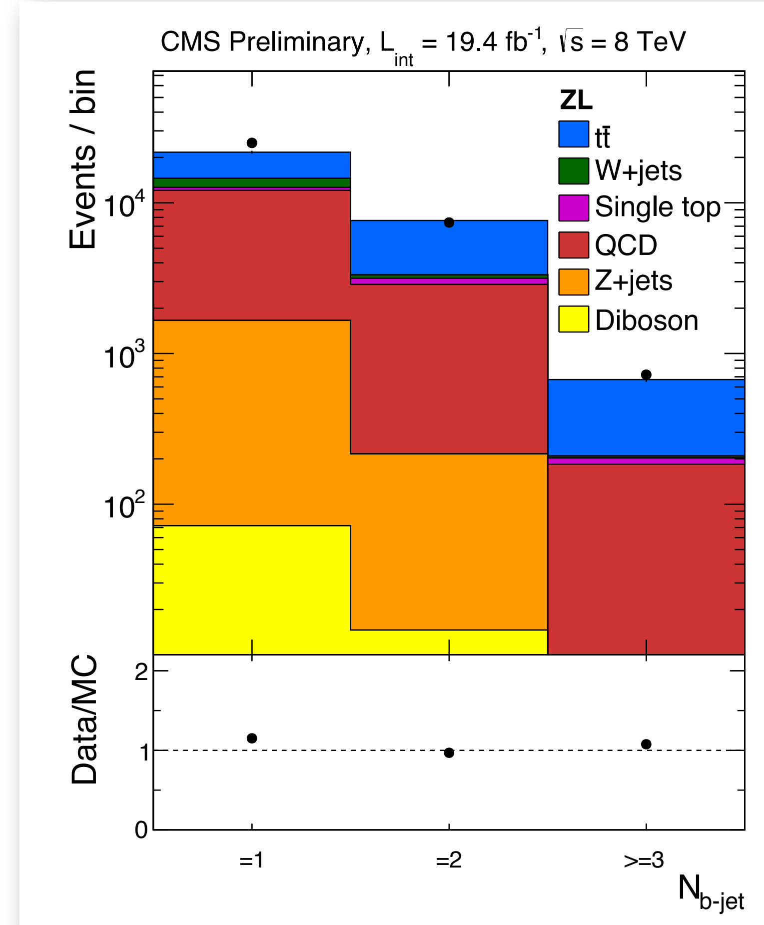
CMS-PAS-SUS-12-024

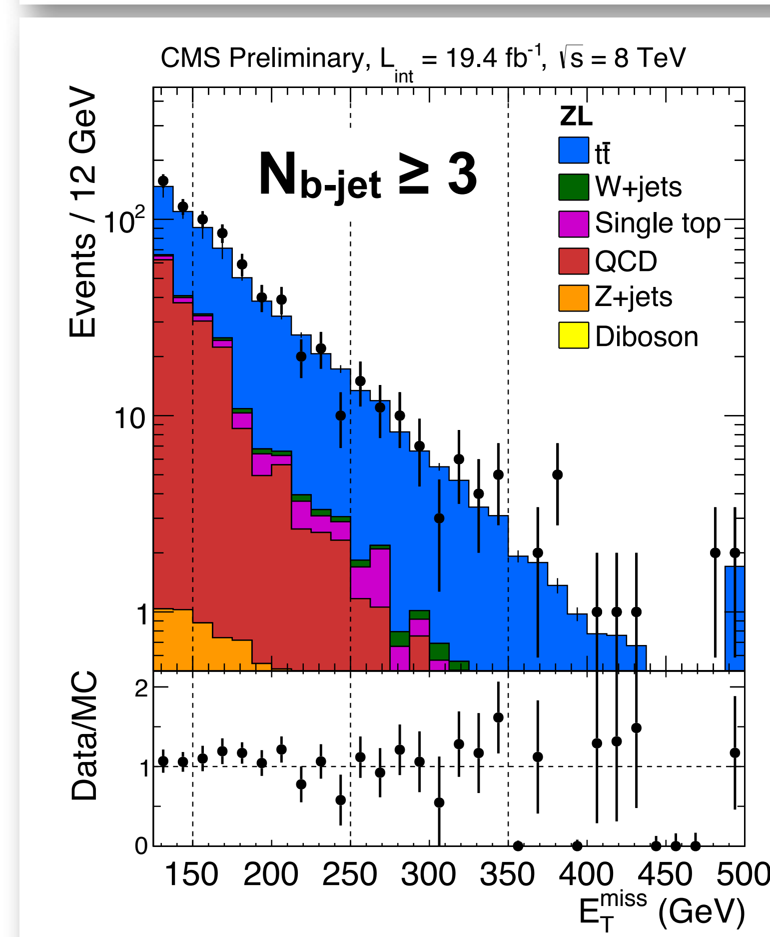
8 TeV, 19.4 fb^{-1}

- Target gluino-mediated pair-production of b or t squarks
  - hadronic final state: ≥3 jets, ≥1 b-jets + MET
  - Candidate events categorised by $\mathbf{H_T}$, **MET**, and $\mathbf{N_{b\text{-}jet}}$

- Event selection
  - Trigger based on H_T and MET ($\varepsilon > 90\%$)
  - Physics objects from particle flow algorithm
  - Veto events with isolated leptons and single tracks
  - Jets: pT > 50 GeV (2^{nd} jet: pT > 70 GeV), $|\eta| < 2.4$
  - $H_T > 500$ GeV, MET > 125 GeV
  - $\Delta\varphi^{min} > 0.4$ to suppress QCD

- Backgrounds estimated from data control samples
  - tt, top, W+jets: e/μ+jets sample (low M_T, to suppress signal)
  - QCD multijets: invert $\Delta\varphi^{min}$ requirement
  - $Z \rightarrow \nu\nu$ + jets: use Zee and Zμμ samples
  - Kinematically-similar control samples, binned identically to SR
  - Estimate: 3D shape from data + normalisation + MC scale factors



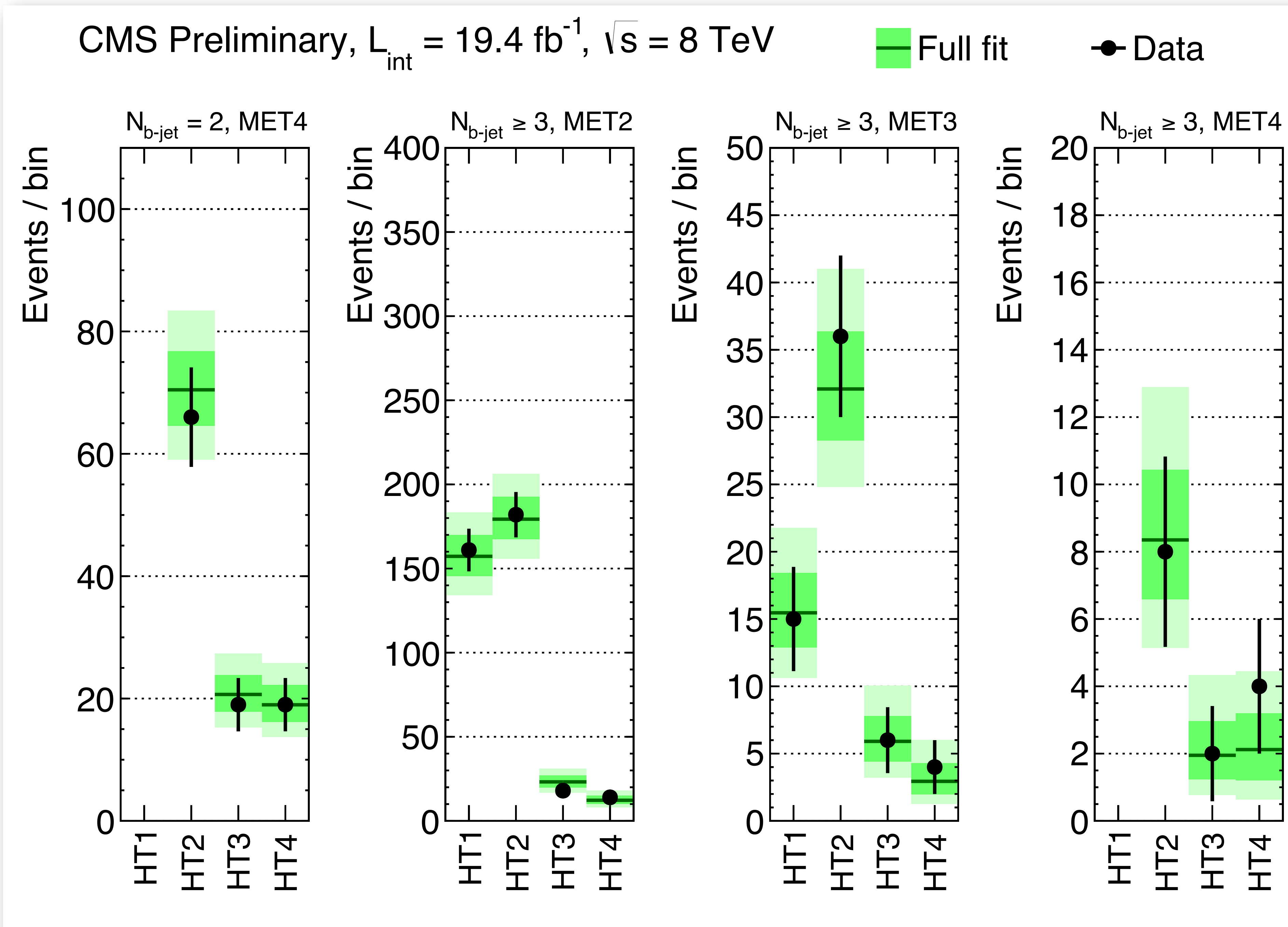


Result of fit with SM-only hypothesis

- Binned likelihood fit performed simultaneously over all H_T, MET, $N_{b\text{-jet}}$ bins in signal and control regions

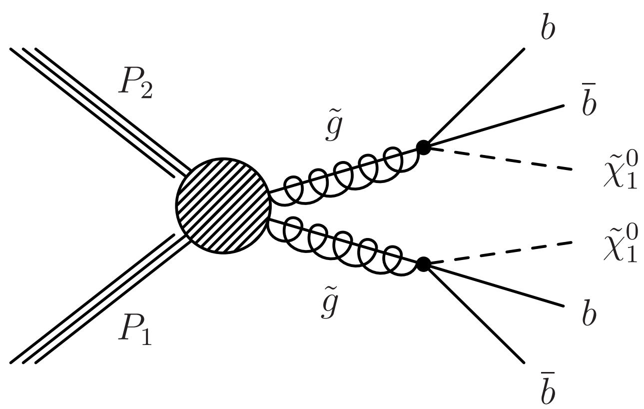
- No significant excess in data

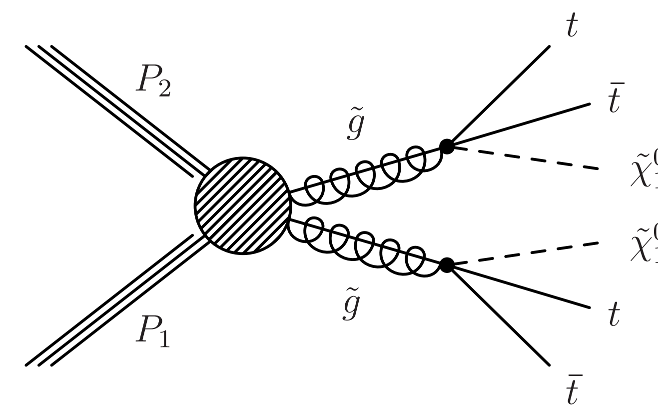
Events with $N_{b\text{-jet}} \geq 3$

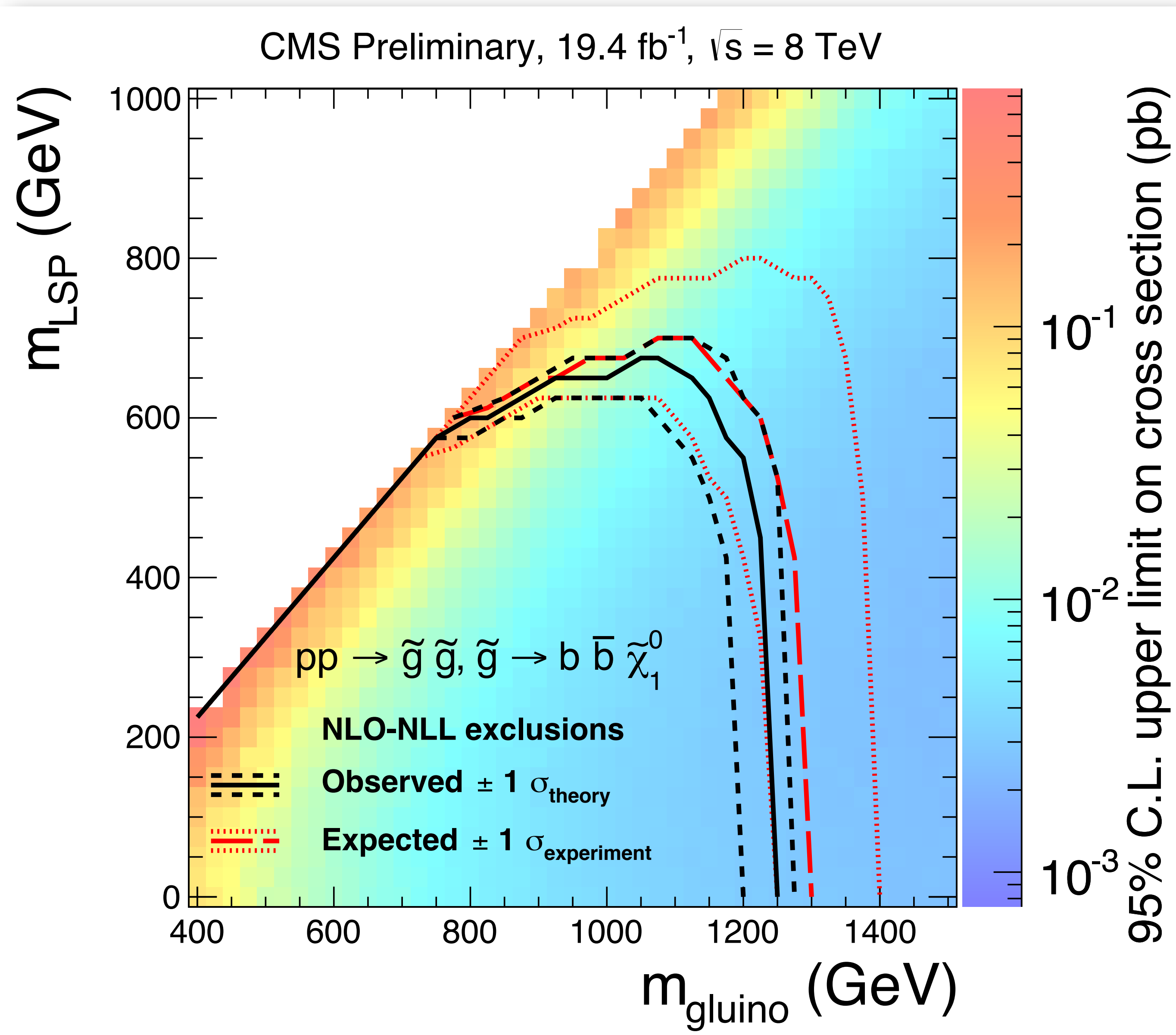


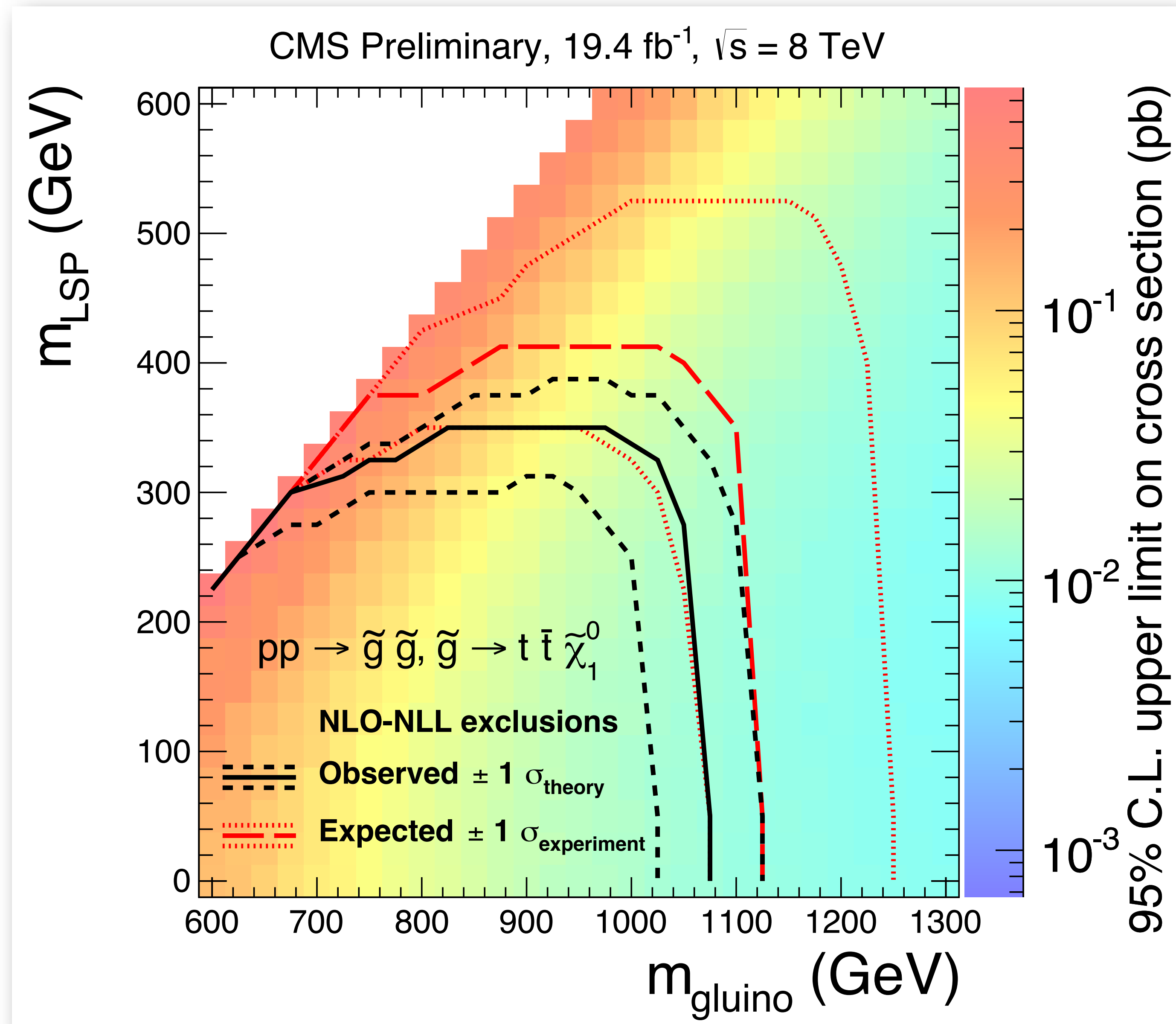
Gluino-mediated production of $\tilde{t}$ or $\tilde{b}$

- Limit of **m_{gluino} >1200 (1025) GeV** at low m_{LSP} for 4b (4t) final state







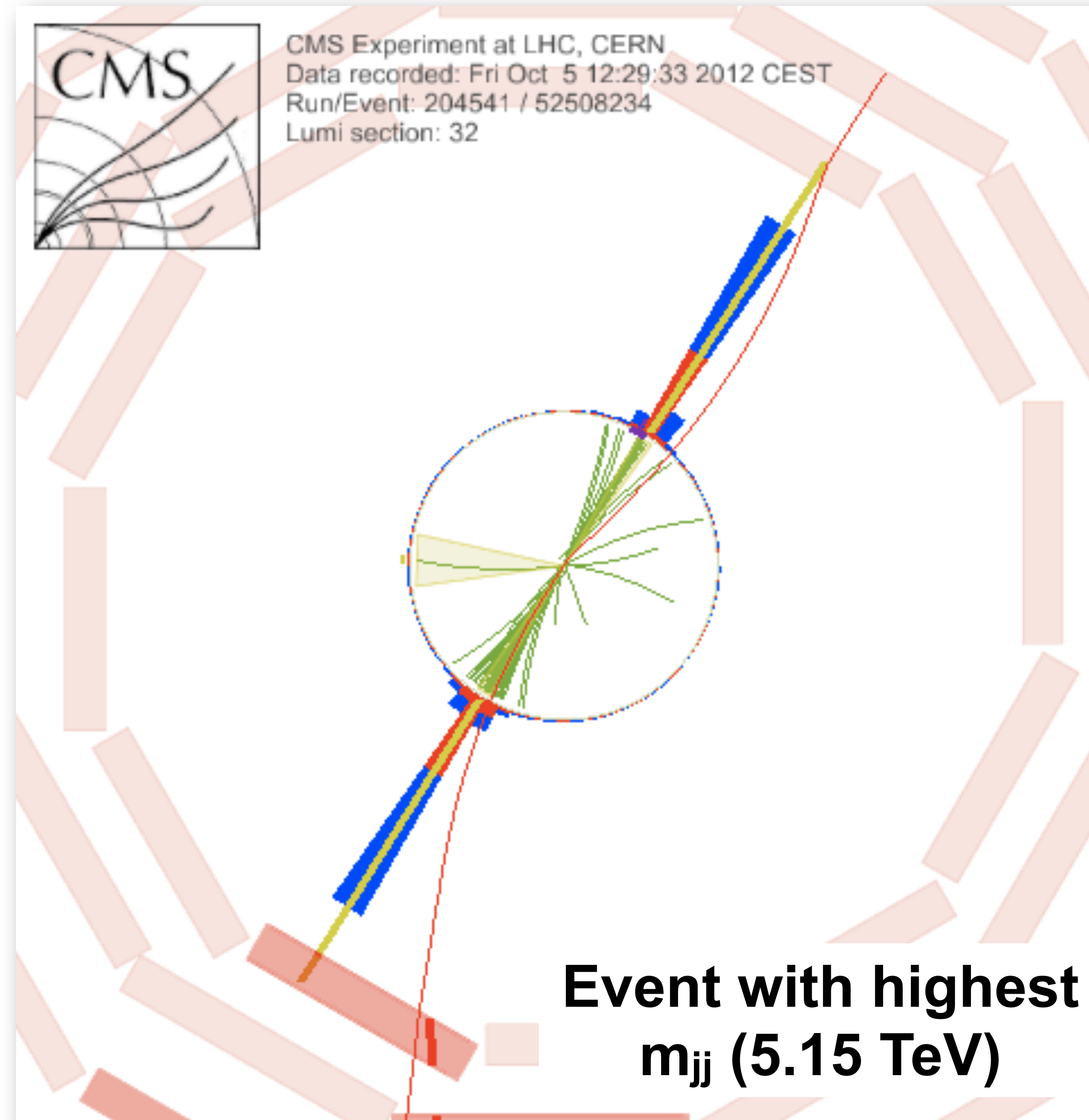


Dijet resonance search

CMS-PAS-EXO-12-059

8 TeV, 19.7 fb^{-1}

- Many models predict existence of new massive objects that couple to q or g
  - Study dijet mass spectrum to look for narrow resonances on falling background
- High-level (software) trigger
  - Loose jet requirements at L1
  - Use particle flow to reconstruct jets
  - Anti-k_T ($\Delta R = 0.5$), $p_T > 40$ GeV, $|\eta| < 2.5$
  - $H_T > 650$ GeV or $m_{jj} > 750$ GeV ($\varepsilon \sim 100\%$)
- Event reconstruction
  - Cluster with anti-k_T algo with $\Delta R = 0.5$
  - Jets: $p_T > 30$ GeV, $|\eta| < 2.5$, ID requirements
  - Jet energy scale corrections (eg, pileup effects)
- Event selection
  - "**Wide jets**" (reduce sensitivity to gluon radiation)
  - Add FSR jets to nearest of 2 leading jets ($\Delta R = 1.1$)
  - $|\Delta\eta_{jj}| < 1.4$ (suppress QCD t-channel contributions)
  - $m_{jj} > 890$ GeV



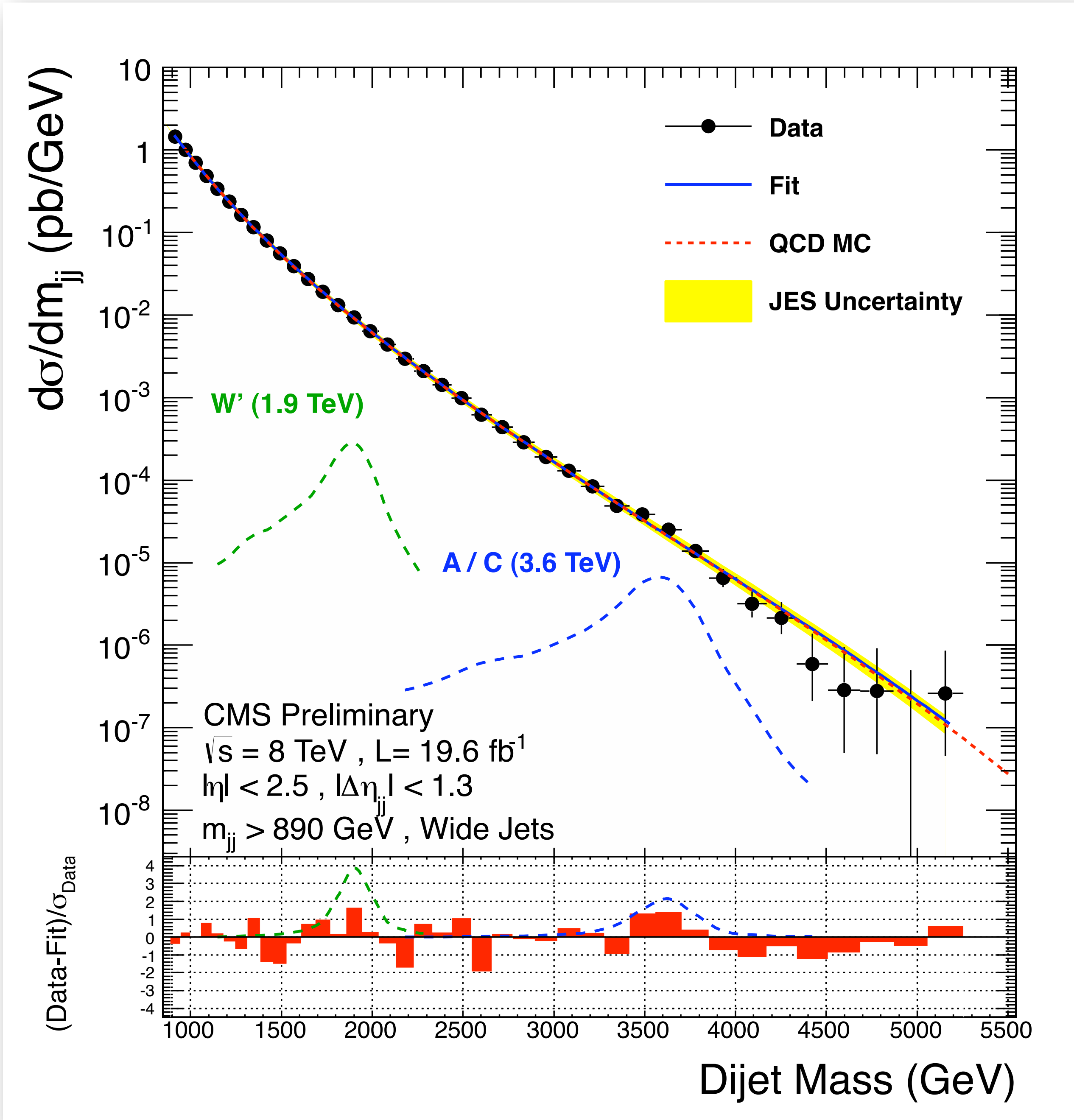
Event with highest m_{jj} (5.15 TeV)

Dijet mass spectrum

- Fit to data using following 4-parameter function:
  - Allows for smooth variations but not localised excesses
- Data well described by the fit, no statistically significant outliers
  - χ^2 = 30.65 (35 d.o.f.)

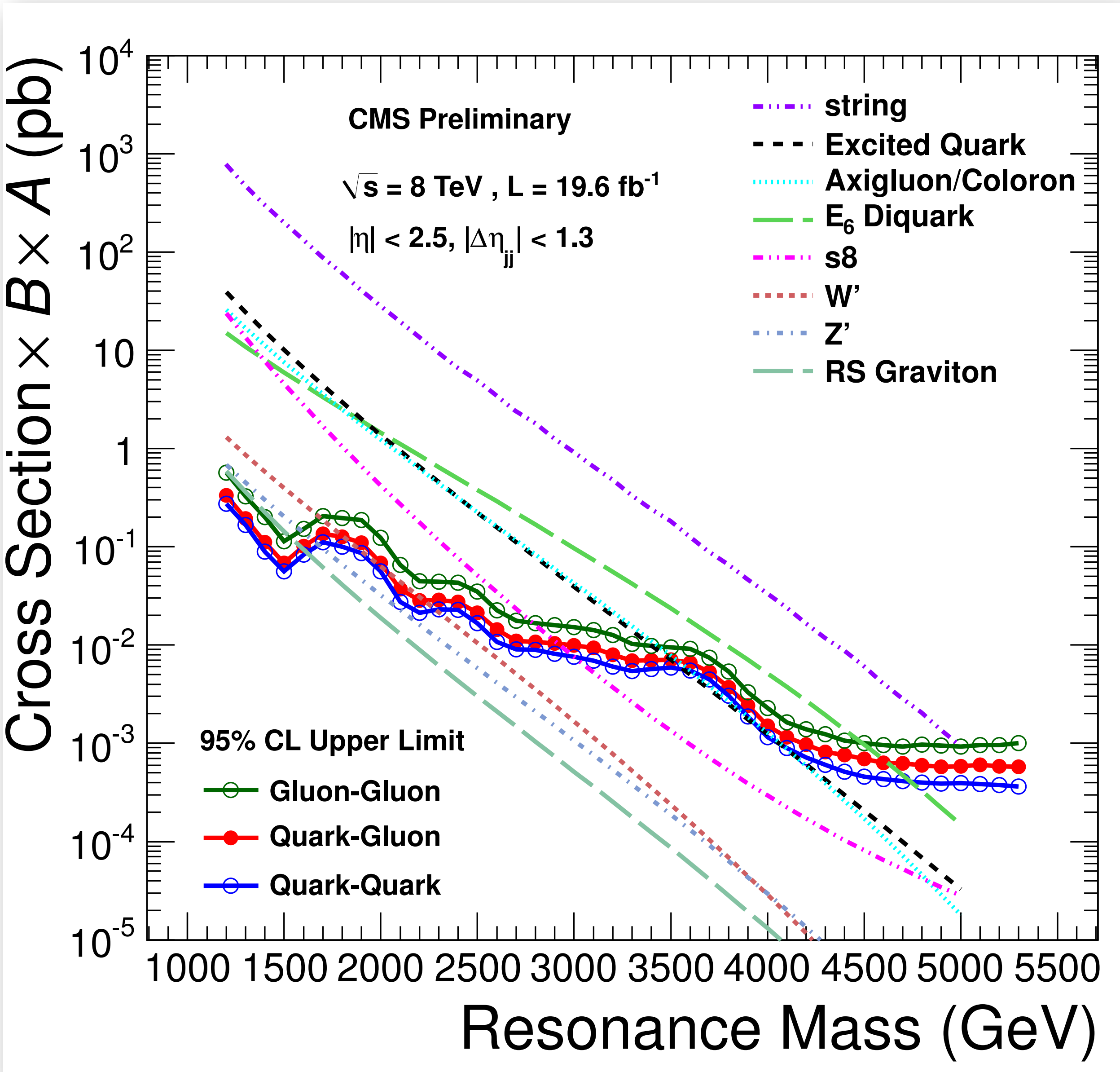
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

$$x = m_{jj}/\sqrt{s}$$



Model limits

- Dominant systematic uncertainties on signal, propagated through to m_{jj}:
  - –Jet energy scale (~1.5%) and resolution (~10%), lumi (4.4%)
  - –Variations of background parameters from best-fit values
- Model-independent cross-section upper limit on generic qq, qg, and gg final states
  - –Upper limit compared to various models to derive mass limits



Model	Final State	Obs. Mass Excl. [TeV]
String Resonance (S)	qg	[1.20,5.08]
Excited Quark (q^*)	qg	[1.20,3.50]
E_6 Diquark (D)	qq	[1.20,4.75]
Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.20,3.60] + [3.90,4.08]
Color Octet Scalar (s8)	gg	[1.20,2.79]
W′ Boson (W′)	$q\bar{q}$	[1.20,2.29]
Z′ Boson (Z′)	$q\bar{q}$	[1.20,1.68]
RS Graviton (G)	$q\bar{q}$+gg	[1.20,1.58]

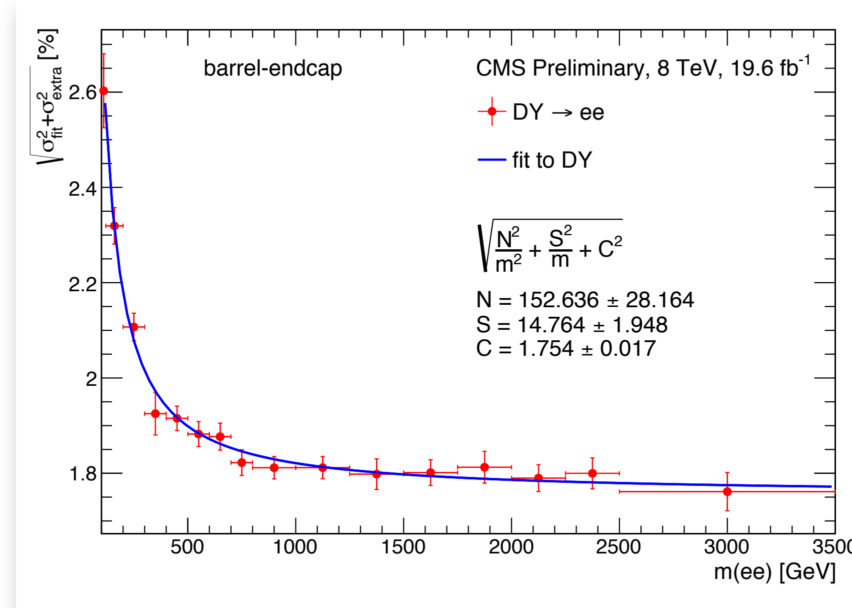
Z′ dilepton resonance

CMS-PAS-EXO-12-061

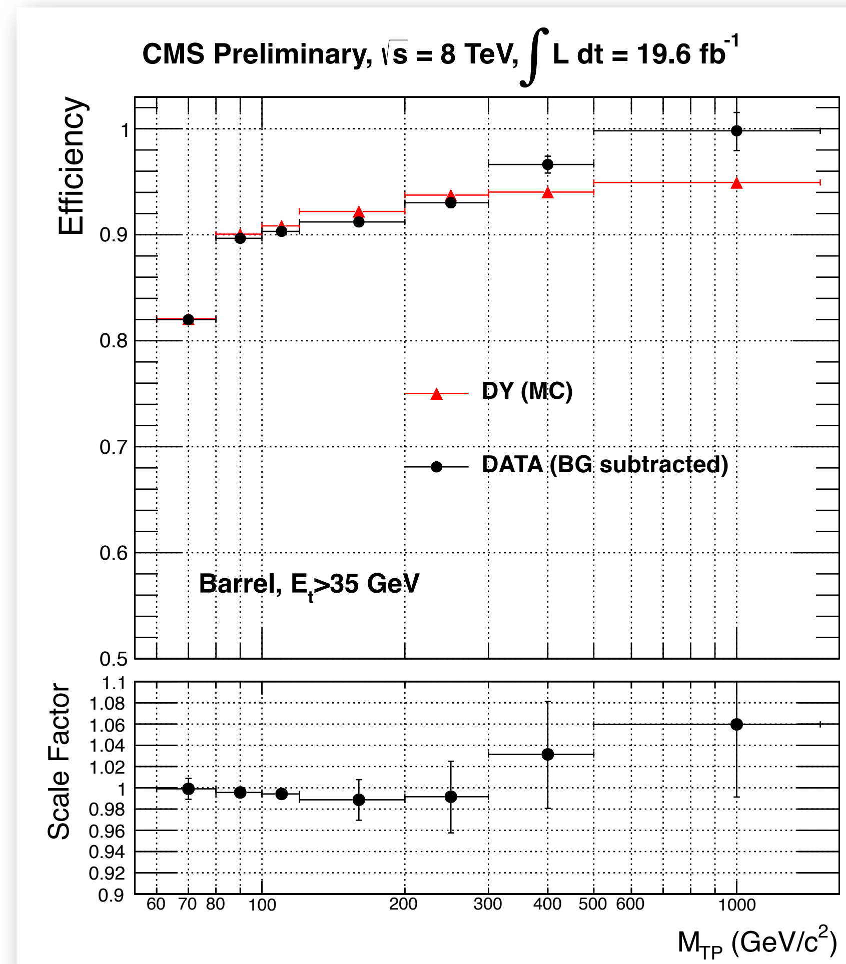
8 TeV, ~20 fb^{-1}

- Study dilepton mass spectrum to look for Z′ resonance
  - Peak on top of Drell-Yan continuum
- Event selection
  - Two isolated leptons: ee or $\mu^+\mu^-$
  - $m_{\ell\ell}$ > 300 GeV
  - A×ε (Z′ 1 TeV) = ~0.77 (μ), ~0.64 (e)
- Lepton identification, challenging at high energies
  - Require high efficiency/purity over 35 GeV → 1 TeV
  - Track p_T resolution worsens, pileup effects, etc...
  - ID is optimised for high-energy regime
- Checks on MC modelling of ID in $m_{\ell\ell} \sim m_Z$ control region
  - ID eff. corrected to data (also for 200 < $m_{\ell\ell}$ < 300)
  - Electron energy scale validated against data
  - m_{ee} resolution is corrected to data at Z peak

m_{ee} resolution from MC



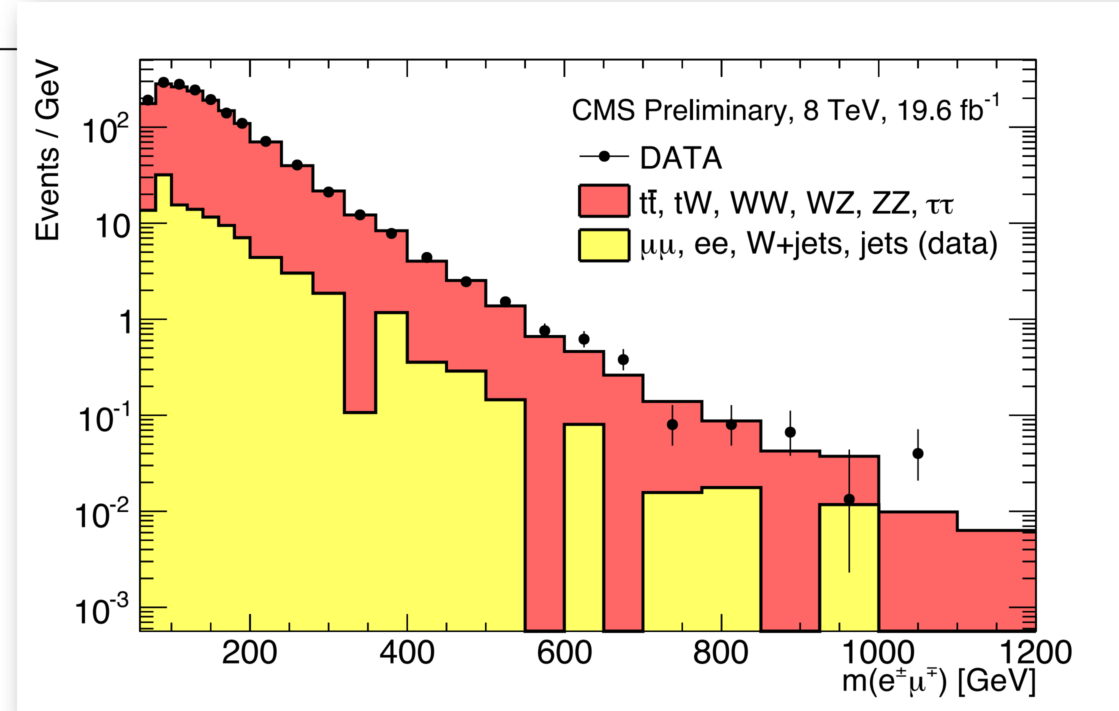
Data/MC ID efficiencies from T&P



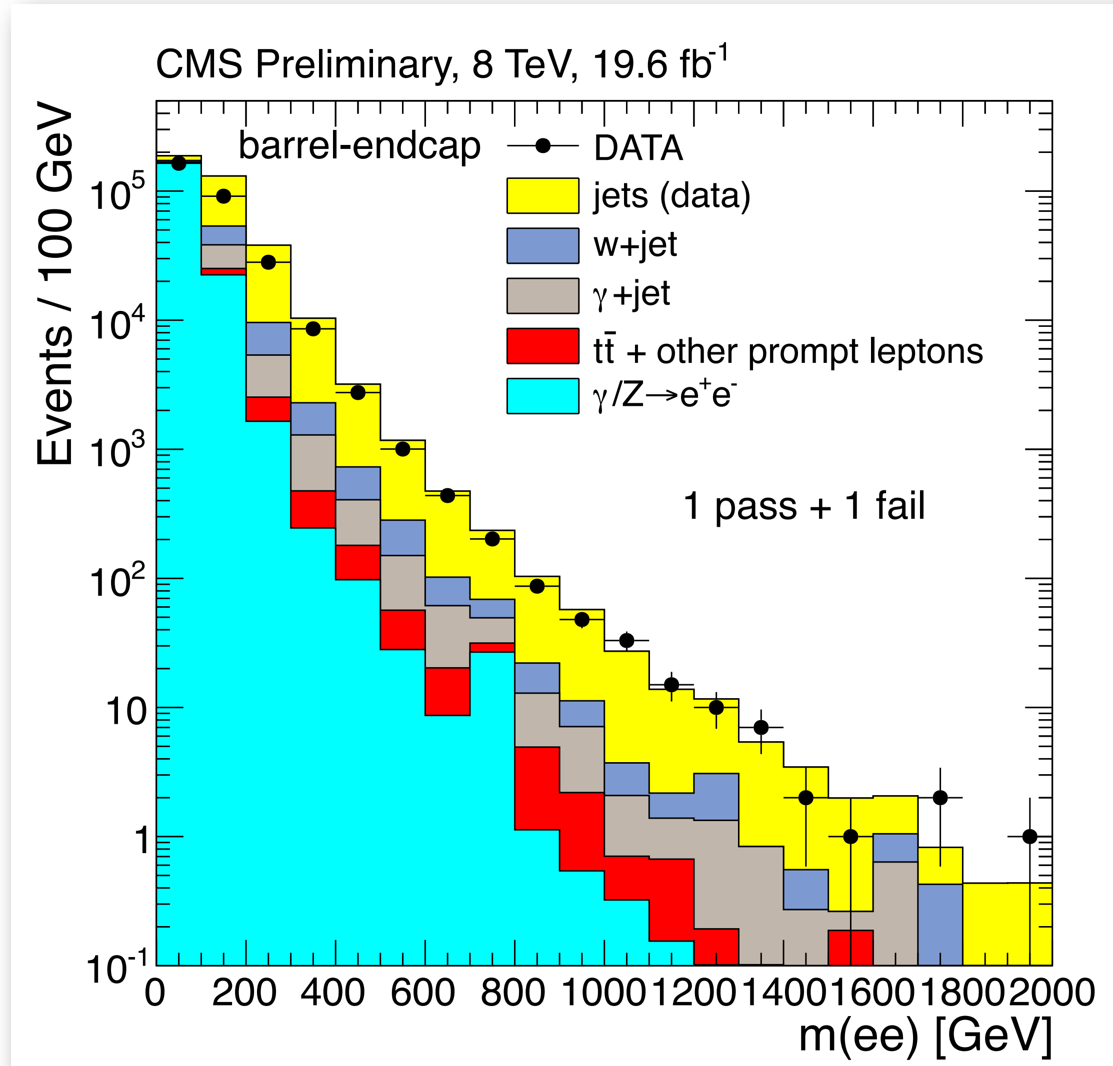
Backgrounds

- Background shapes taken from MC (except fakes)
  - Relative contributions defined by σ_{NLO}
  - Total normalised to data in $m_{\ell\ell} \sim m_Z$ sideband
- Irreducible Drell-Yan background dominates
  - 2-20% systematic (σ, PDF)
- Prompt lepton pairs: tt, tW, diboson, Z→ττ (~10%)
  - Estimated from MC
  - MC validation in $e^{\pm}\mu^{\mp}$ control sample
  - 7% systematic (σ_{tt})
- Jets faking electrons: V+jets, multijets (<5%)
  - Negligible effect for muons
  - Fake rate FR(p_T,η) measured in e+jets sample
  - FR/(1-FR) applied twice to ee events (both fail ID)
  - 40% systematic uncertainty
  - Validation in ee events with (1 pass / 1 fail)

$e^{\pm}\mu^{\mp}$ mass spectrum (MC validation)



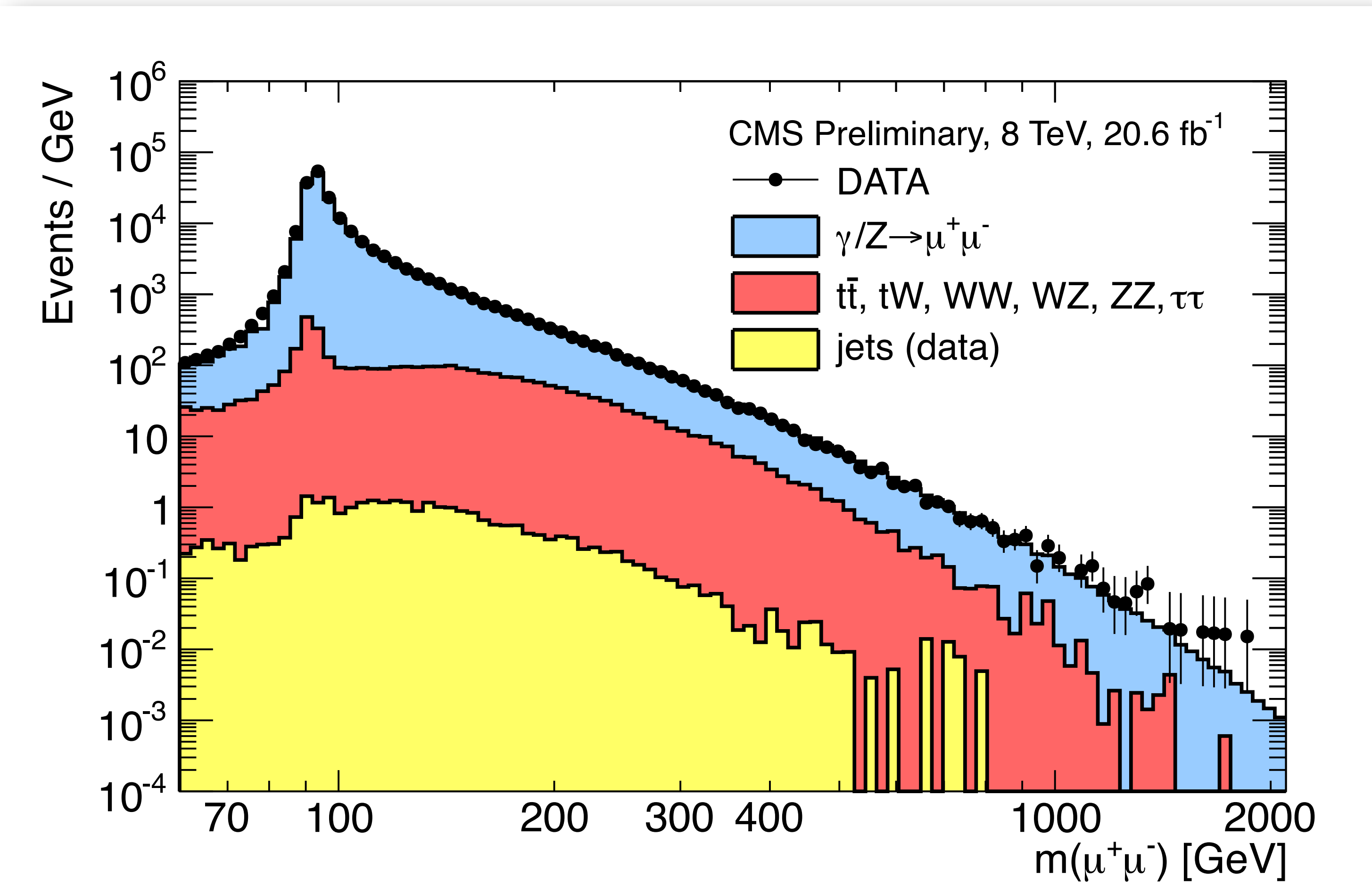
Jets background (validation)



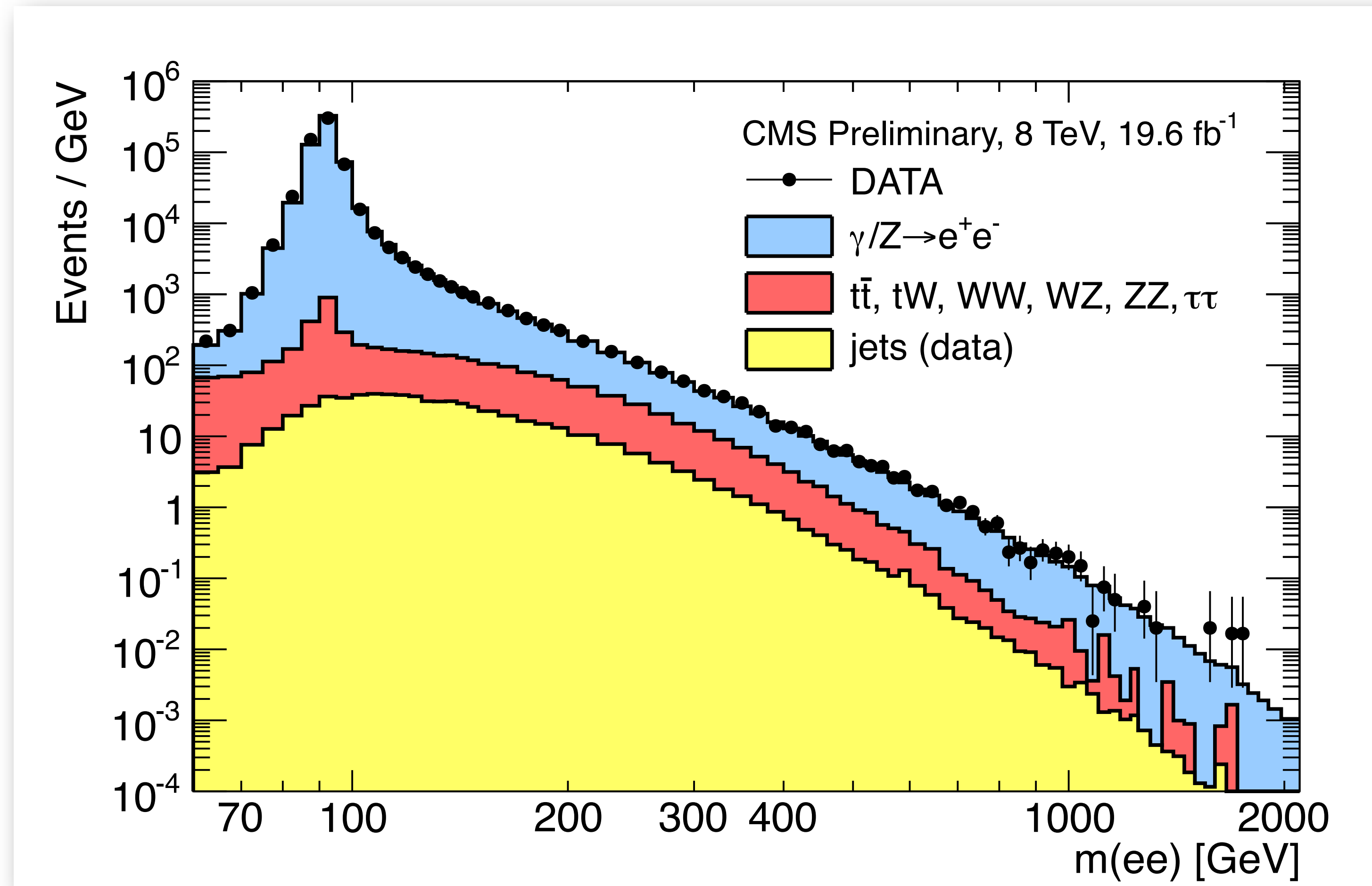
Dilepton mass distributions

- Consider three event categories: μμ, ee (barrel-barrel), ee (barrel-endcap)
- No significant deviations from background estimate
- Data/MC agreement over many orders of magnitude

μμ mass spectrum



(Combined) ee mass spectrum

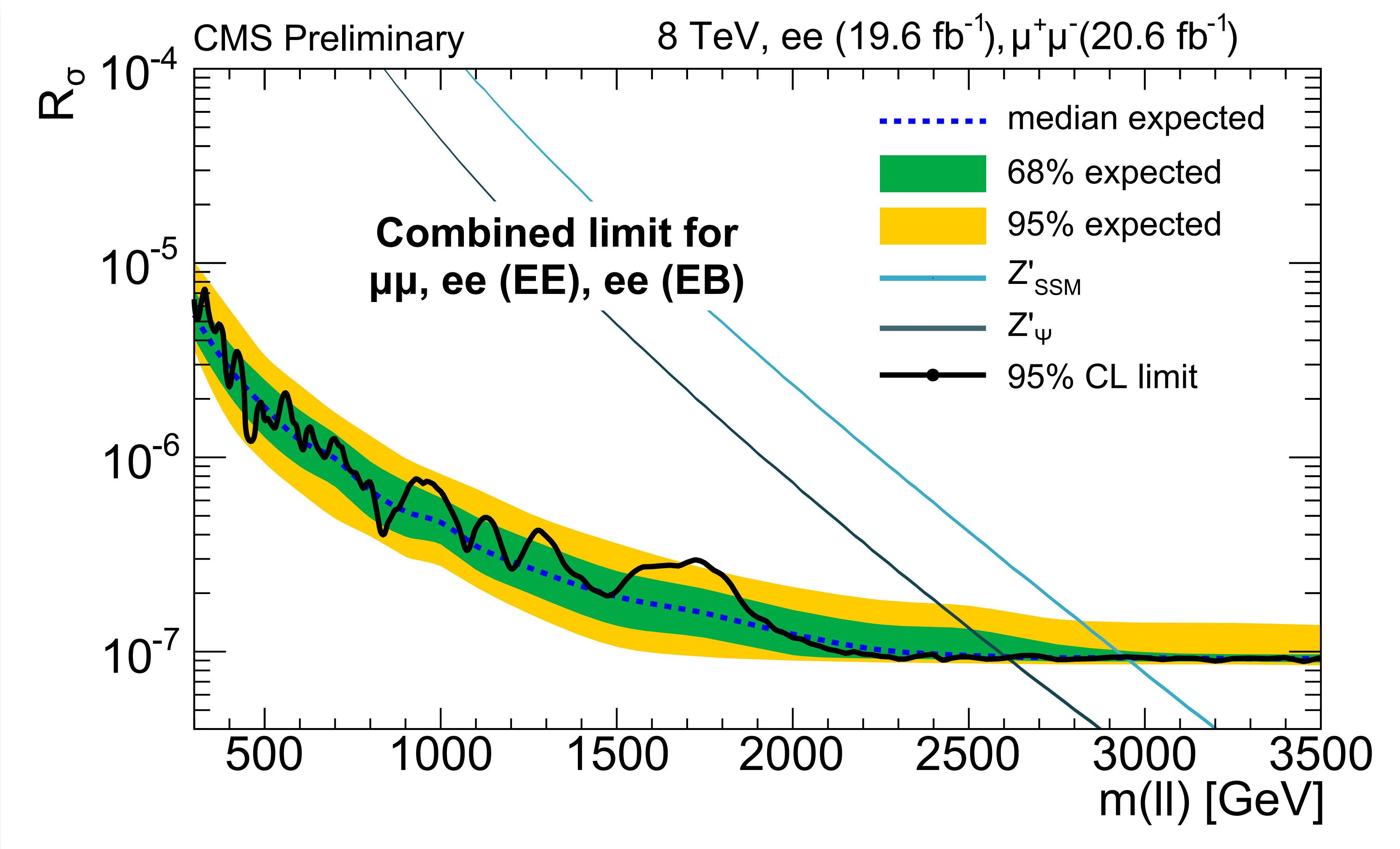


Limits on Z′ mass

- Upper limit on σ×*A*×ε for Z′ relative to SM Z:
  - Many systematic uncertainties cancel
  - *A*×ε (3-6%), background shape (2-20%)

$$R_\sigma = \frac{\sigma(pp \to Z' + X \to \ell\ell + X)}{\sigma(pp \to Z + X \to \ell\ell + X)}$$

- Mass limits:
  - SM-like couplings: **$m_{Z',SSM}$ > 2.96 TeV**
  - Superstring-inspired: **$m_{Z',\psi}$ > 2.6 TeV**



Lepton + E_T^{miss} ($W' \to \ell\nu$)

CMS-PAS-EXO-12-060

8 TeV, ~20 fb^{-1}

- Look for Jacobian peak on falling M_T distribution:
  - E_T^{miss} estimator from particle flow

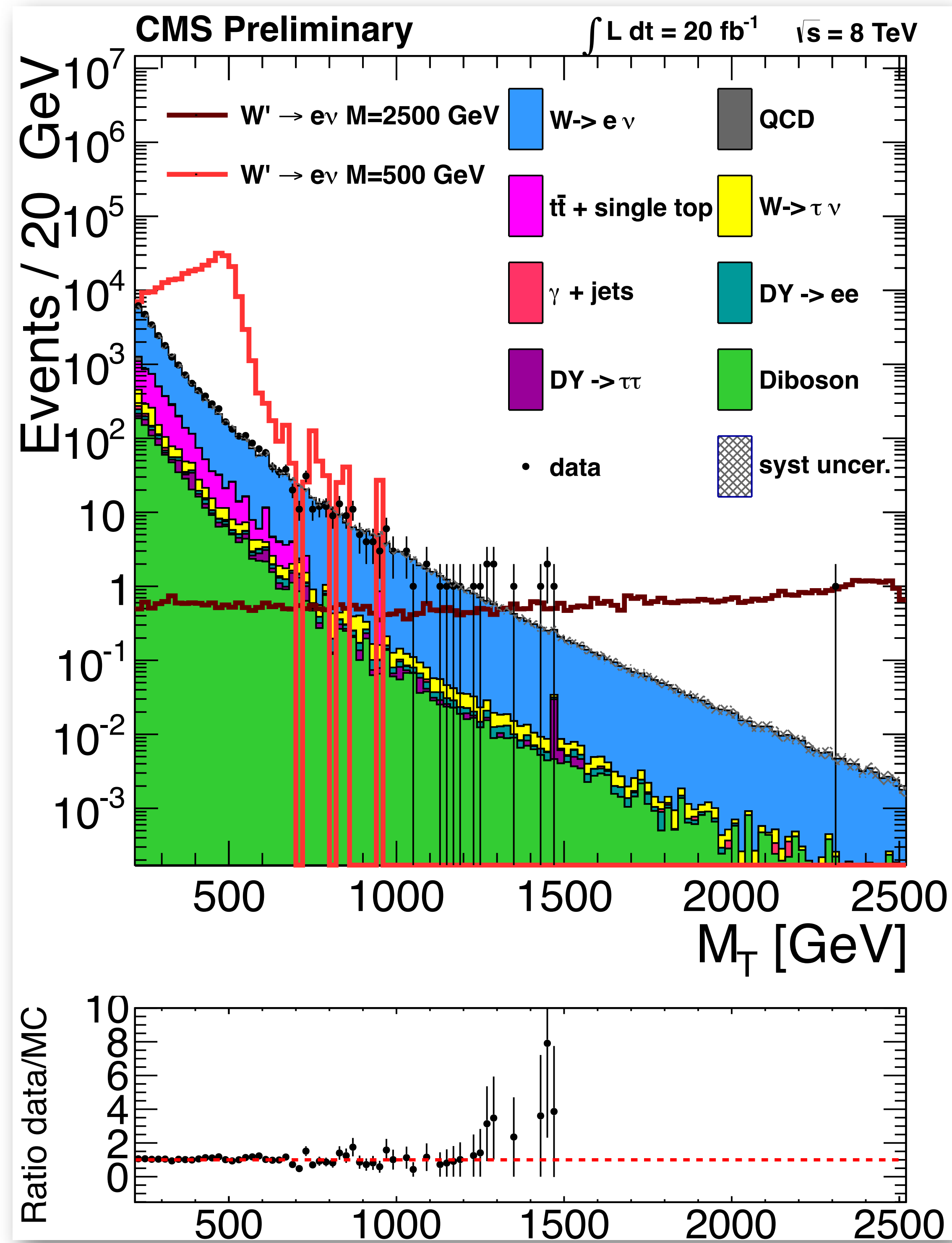
$$M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{miss} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

- Lepton (e,μ) identification
  - IDs optimised for high-energy regime
  - Muons: $p_T > 45$ GeV, $|\eta| < 2.1$, $\Delta p_T/p_T < 0.3$
  - Electrons: $E_T > 100$ GeV, $|\eta| < 2.5$
  - Lepton isolation corrected for PU effects

- Event selection
  - Exactly 1 isolated electron or muon
  - $0.4 < p_T/E_T^{miss} < 1.5$, $\Delta\phi_{\ell,\nu} > 0.8\pi$
  - $M_T > 300$ GeV
  - $A\times\varepsilon$ = ~0.67-0.75 for W′ masses of 1.0-2.5 TeV

- Dominant backgrounds
  - Off-peak high-M_T tail from SM W decays
  - Contributions from tt, single top, DY

Electron channel



Result for lepton+MET search

- Background prediction given by MC
  - Fit to MC with empirical function:

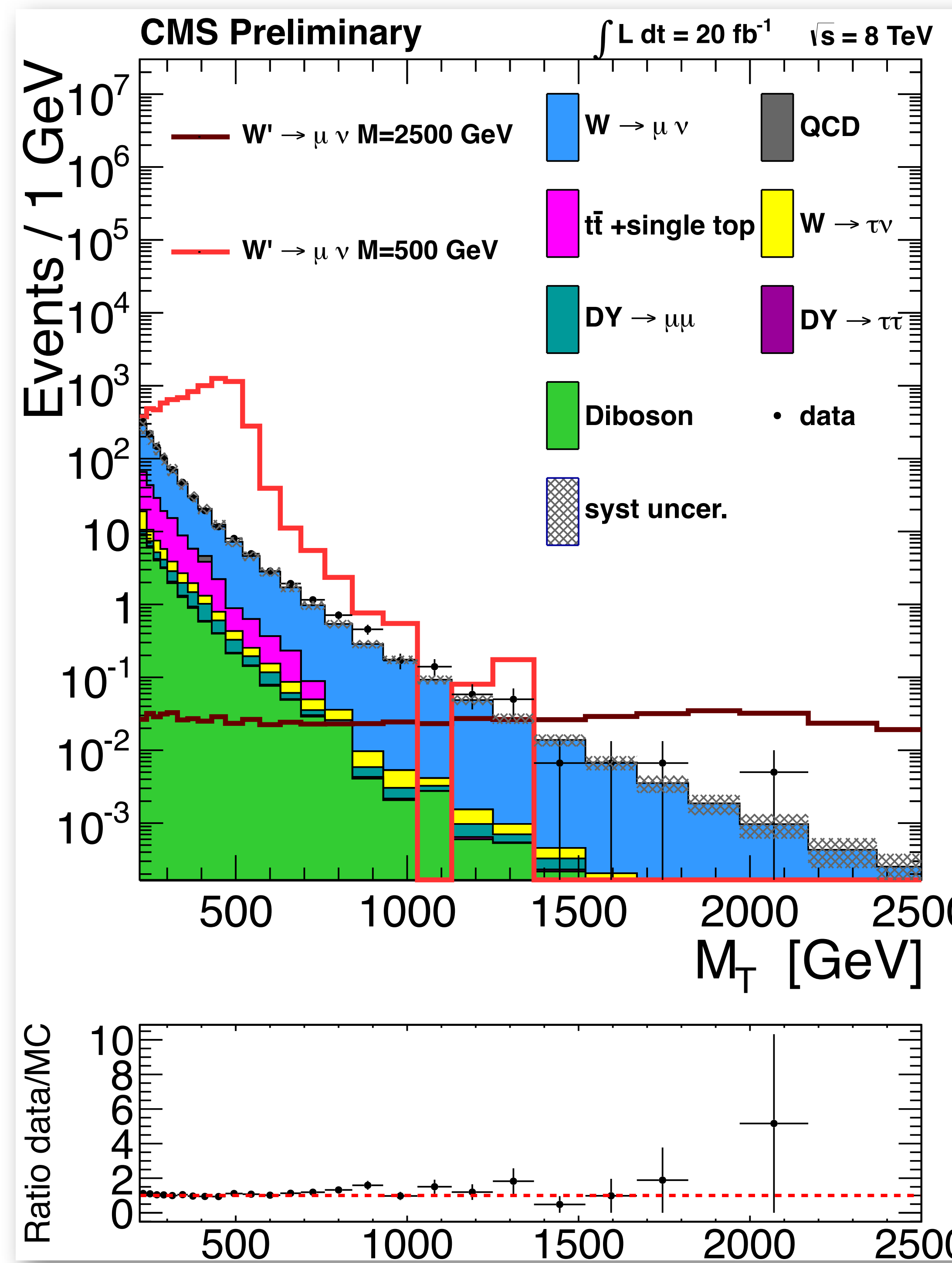
$$f(M_T) = \frac{a}{(M_T^3 + bM_T + c)^d}$$

- Systematic uncertainties
  - Electron E and muon ***p*** scale and resolution
  - E_T^{miss} scale and resolution also considered
  - Luminosity
  - All propagated to M_T spectrum and refit
  - Similar considerations for signal shapes

- No significant deviation from bkgd expectation

	$M_T > 1.0$ TeV	$M_T > 1.5$ TeV	$M_T > 2.0$ TeV
Muon channel			
Data	33	3	1
SM background	$26^{+4}_{-3.5}$	$2.27^{+0.62}_{-0.49}$	$0.33^{+0.15}_{-0.1}$
W', $M_{W'} = 2.5$ TeV	$47^{+5.4}_{-4.8}$	$35^{+4.9}_{-4.3}$	$20^{+4.8}_{-3.8}$
W', $M_{W'} = 3$ TeV	$9.9^{+1.5}_{-1.3}$	$7.4^{+1.3}_{-1.1}$	$5.15^{+1.2}_{-0.99}$
Electron channel			
Data	21	1	1
SM background	$25^{+0.99}_{-0.96}$	$1.989^{+0.088}_{-0.085}$	$0.223^{+0.012}_{-0.011}$
W', $M_{W'} = 2.5$ TeV	$49^{+1.1}_{-1.1}$	$38^{+0.92}_{-0.9}$	$23^{+0.71}_{-0.69}$
W', $M_{W'} = 3$ TeV	$10^{+0.24}_{-0.24}$	$7.72^{+0.2}_{-0.19}$	$5.68^{+0.16}_{-0.16}$

Muon channel

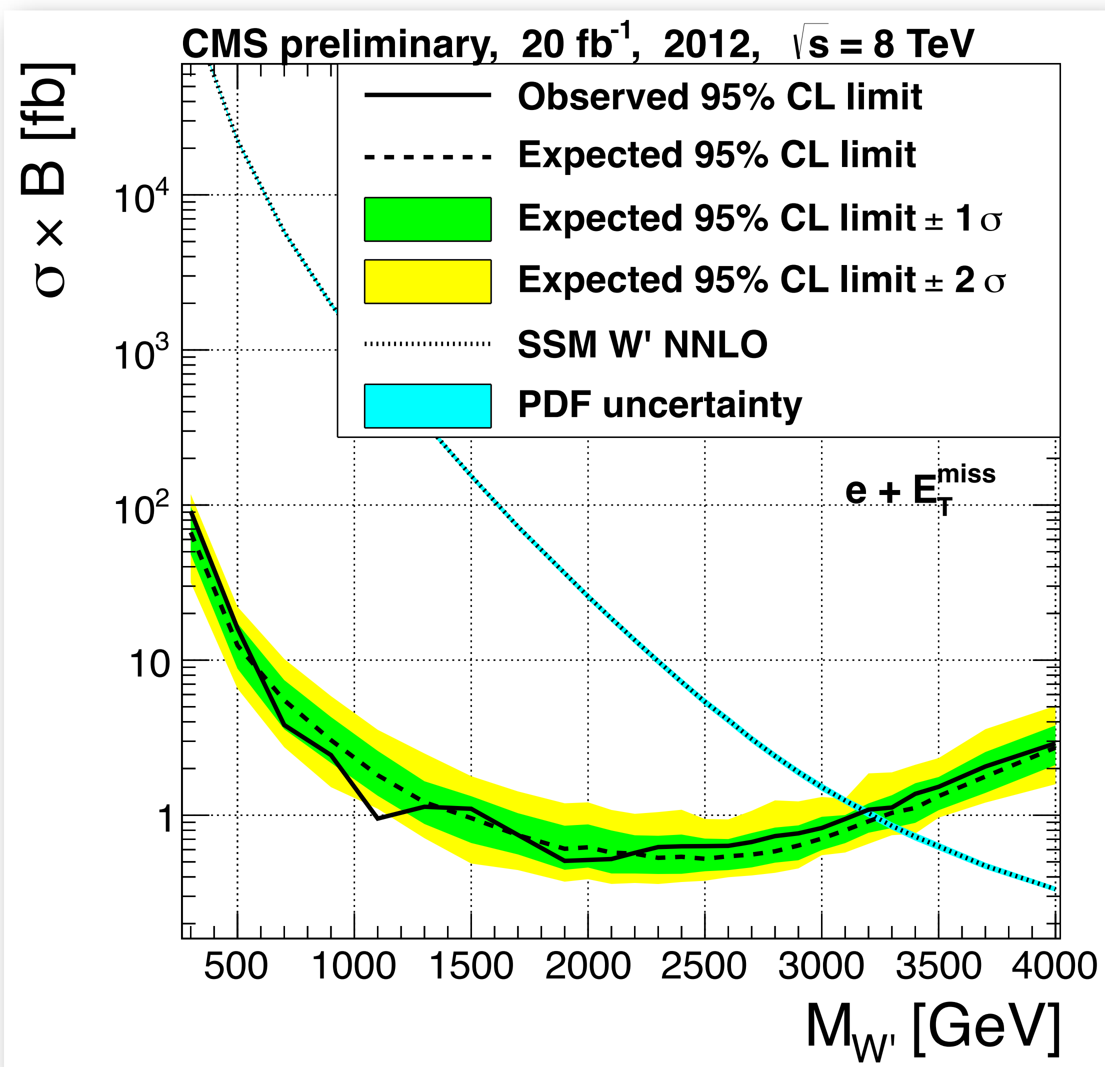


Limits for SSM W’

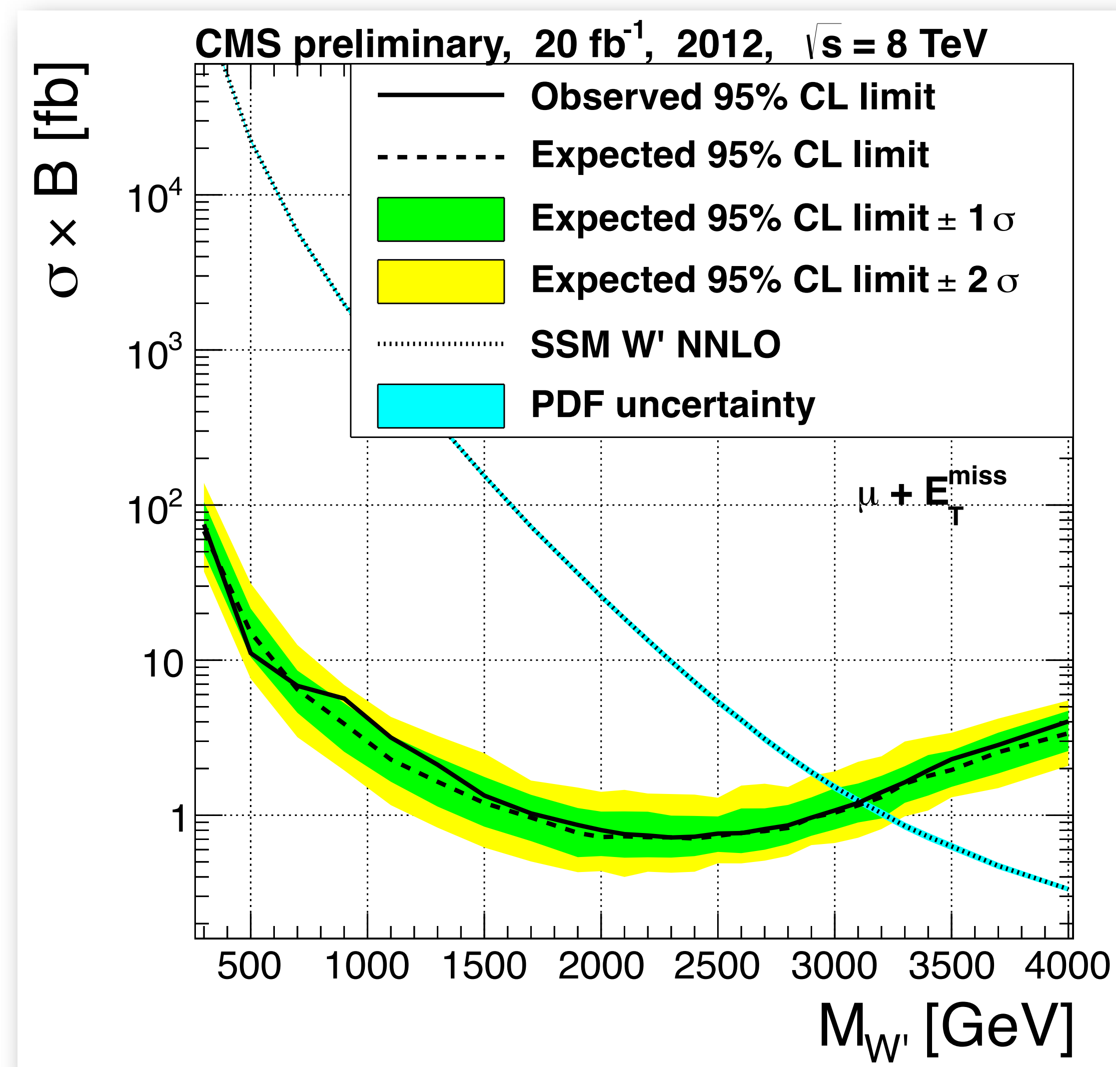
- W'_{SSM}: heavy copy of SM W, with SM-like BF and decay modes: benchmark model
  - Decay to tb considered in decay width, BF($\ell\nu$) ~8%
  - Assume no interference with SM W

- Exclude W'_{SSM} with masses below **3.20 TeV** (e) and **3.15 TeV** (μ)
- Combining the channels gives $m_{W'SSM}$ > **3.35 TeV** (c.f. 2.5 TeV for 5 fb^{-1} @ 7 TeV)

Electron channel



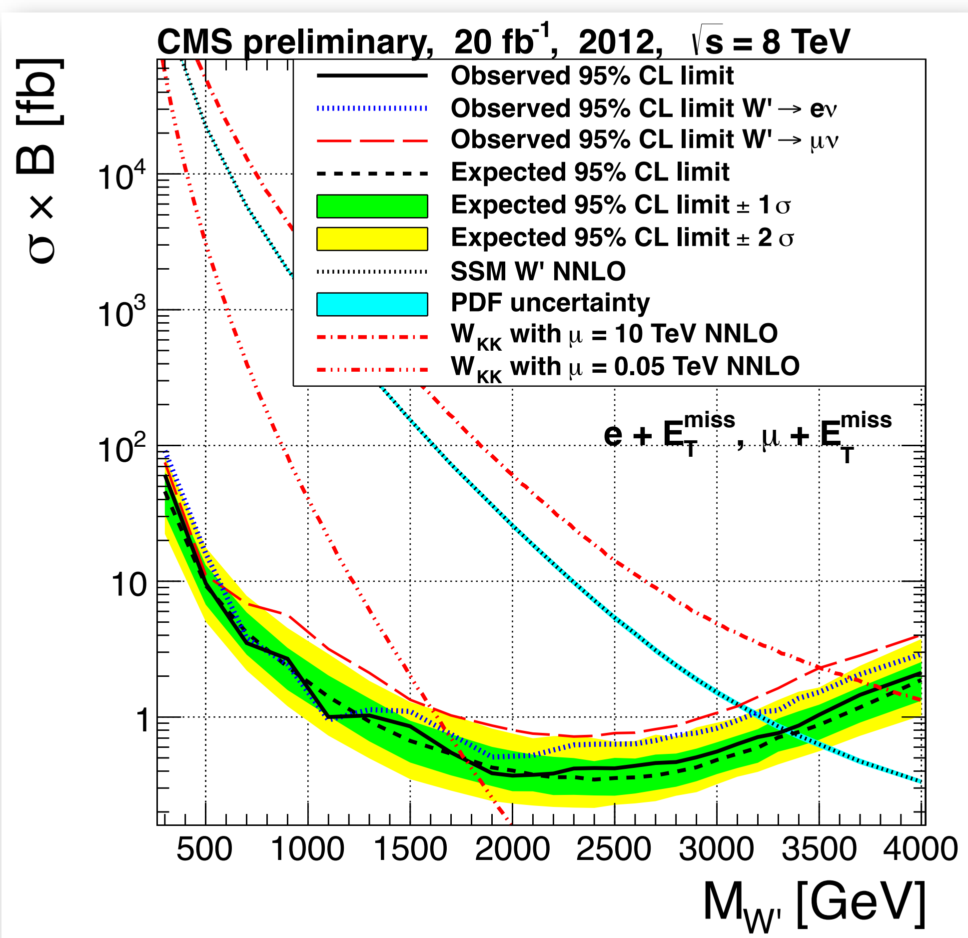
Muon channel



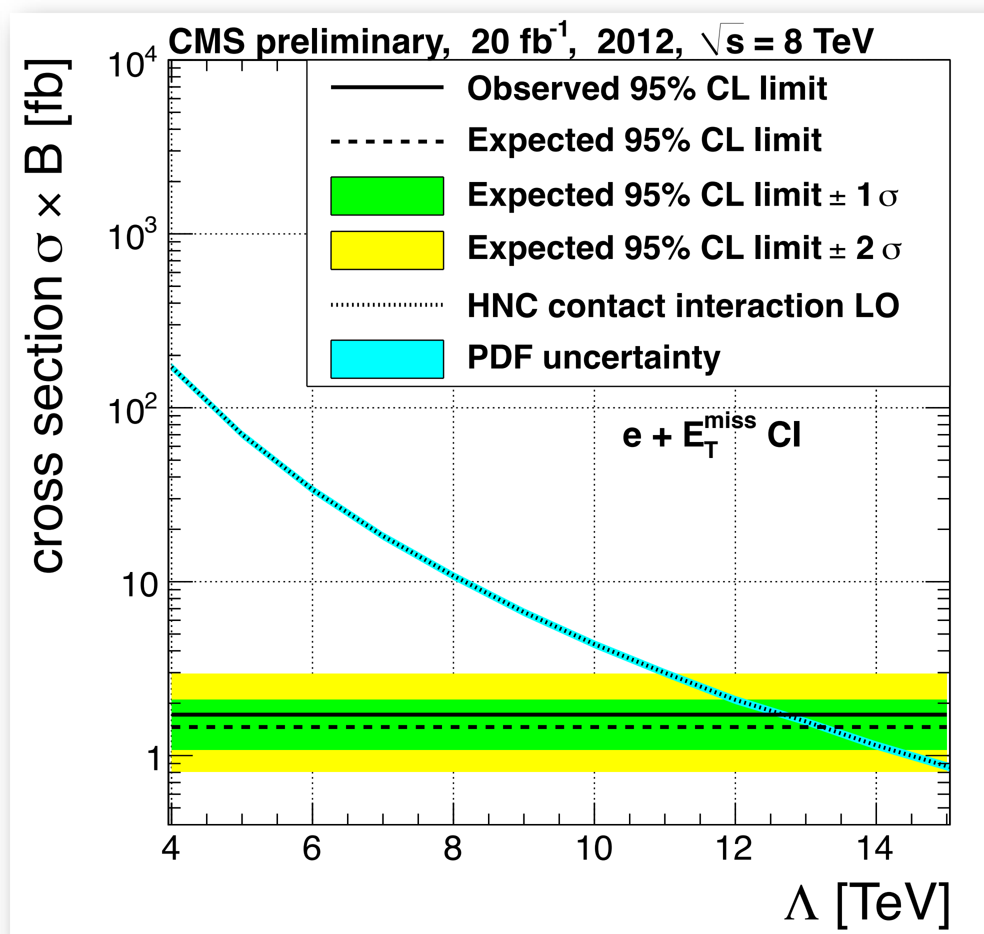
Lepton+MET search: further interpretations

- W′ with non-zero LH coupling leads to interference with SM W
  - Destructive (constructive) with same- (opposite-) sign coupling to fermions (quarks)
  - **m > 3.10 (3.60) TeV** for SSMS (SSMO)
- Split UED
  - Second Kaluza-Klein excitation (W^2_{KK}): **m > 1.7 (3.7) TeV** for μ = 0.05 (10) TeV
- Four-fermion contact interaction (Helicity-non-conserving model)
  - Binding energy scale Λ of **13.0 (10.9) TeV** in the electron (muon) channel

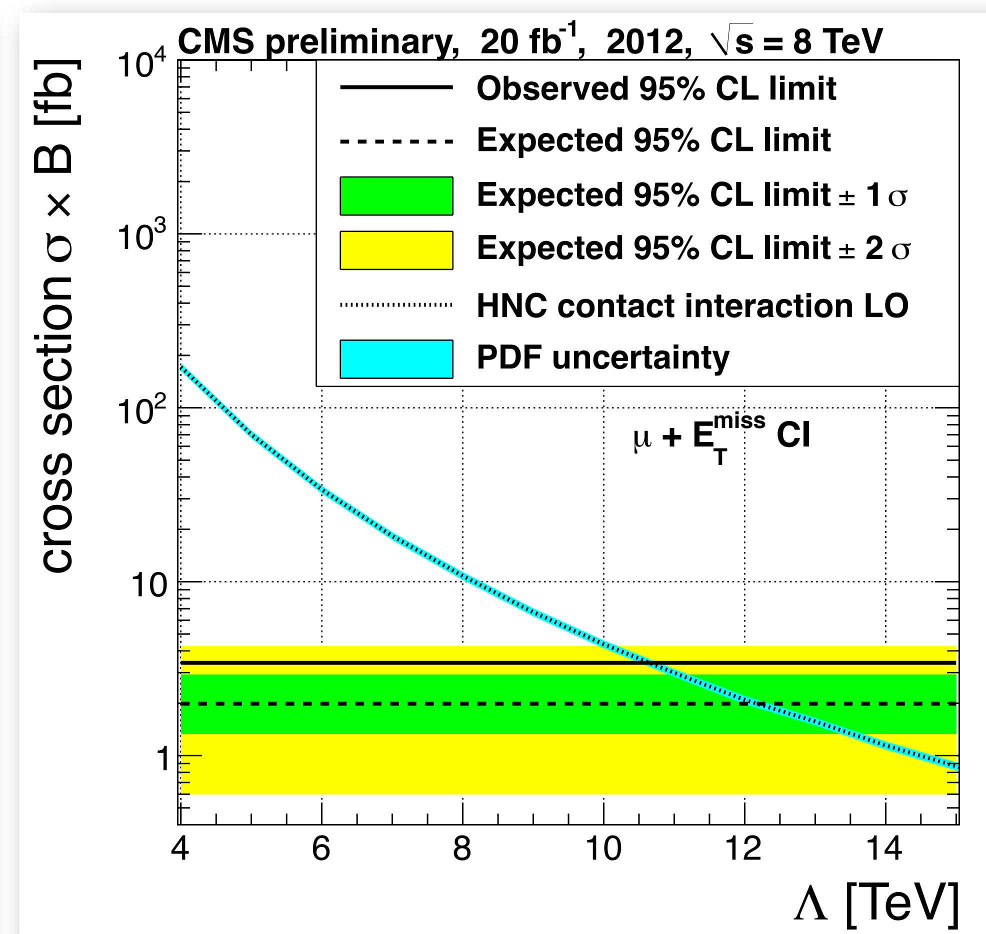
Split UED (combined channels)



CI (electron channel)



CI (muon channel)



Summary

- Analyses shown demonstrate sensitivity to TeV-scale objects

- However, new physics beyond the standard model has yet to appear

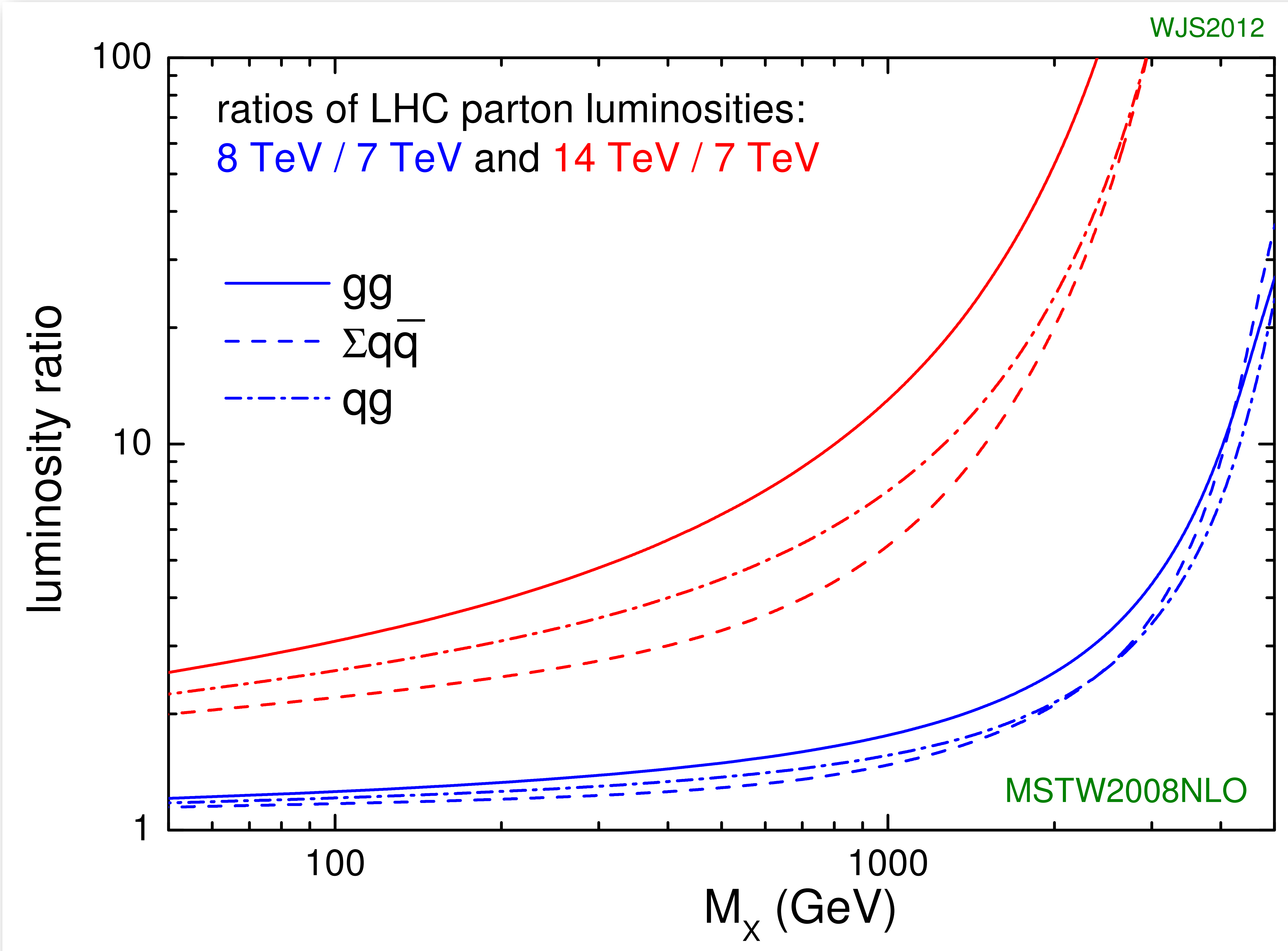
- There is still much to be learned from the 8 TeV dataset (plus parked data)

- Several preliminary results based on full 8 TeV dataset already available
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G (BSM via top)

- Many more new results to arrive in the next few weeks

- However, the LHC is a 14 TeV machine...

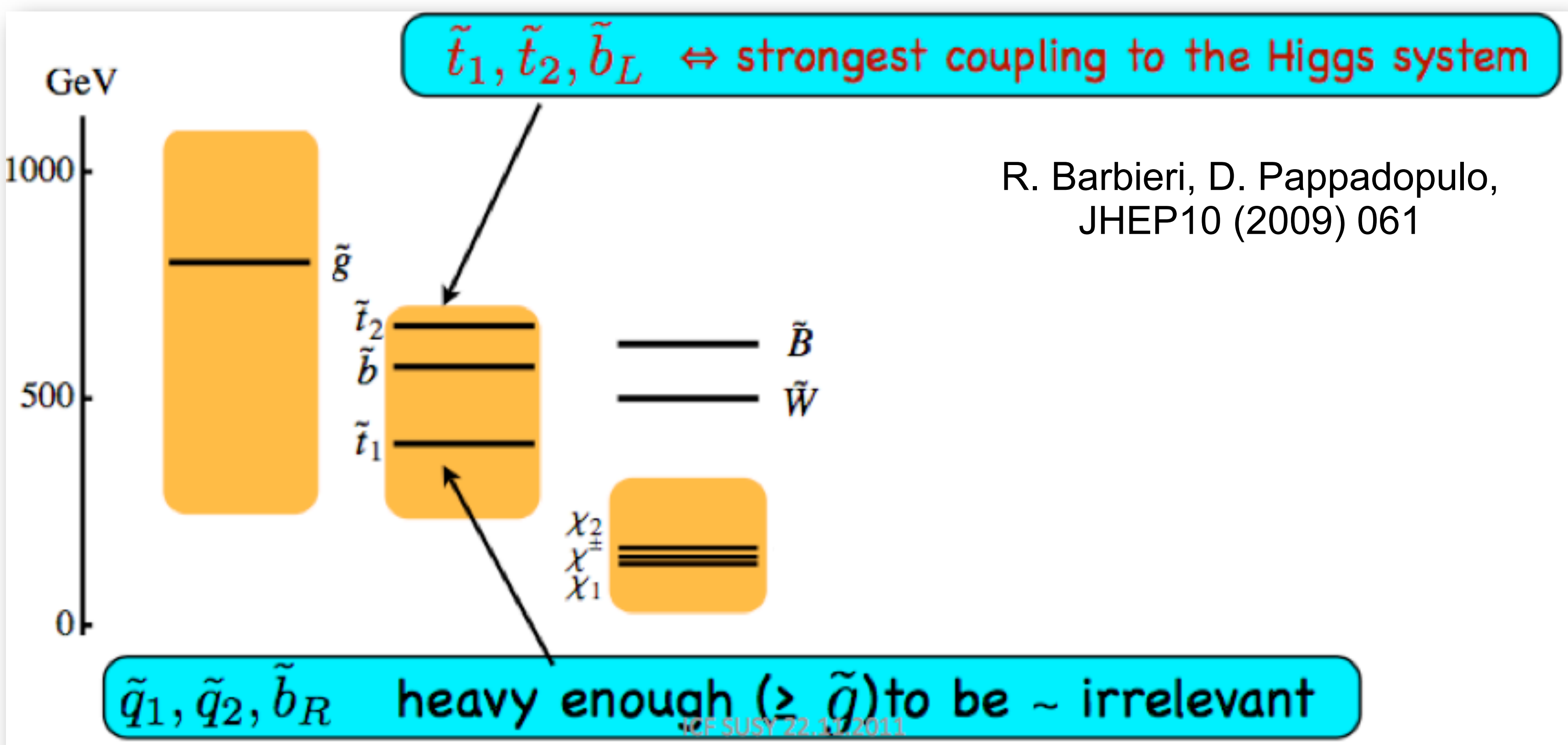
The real fun begins in 2015...



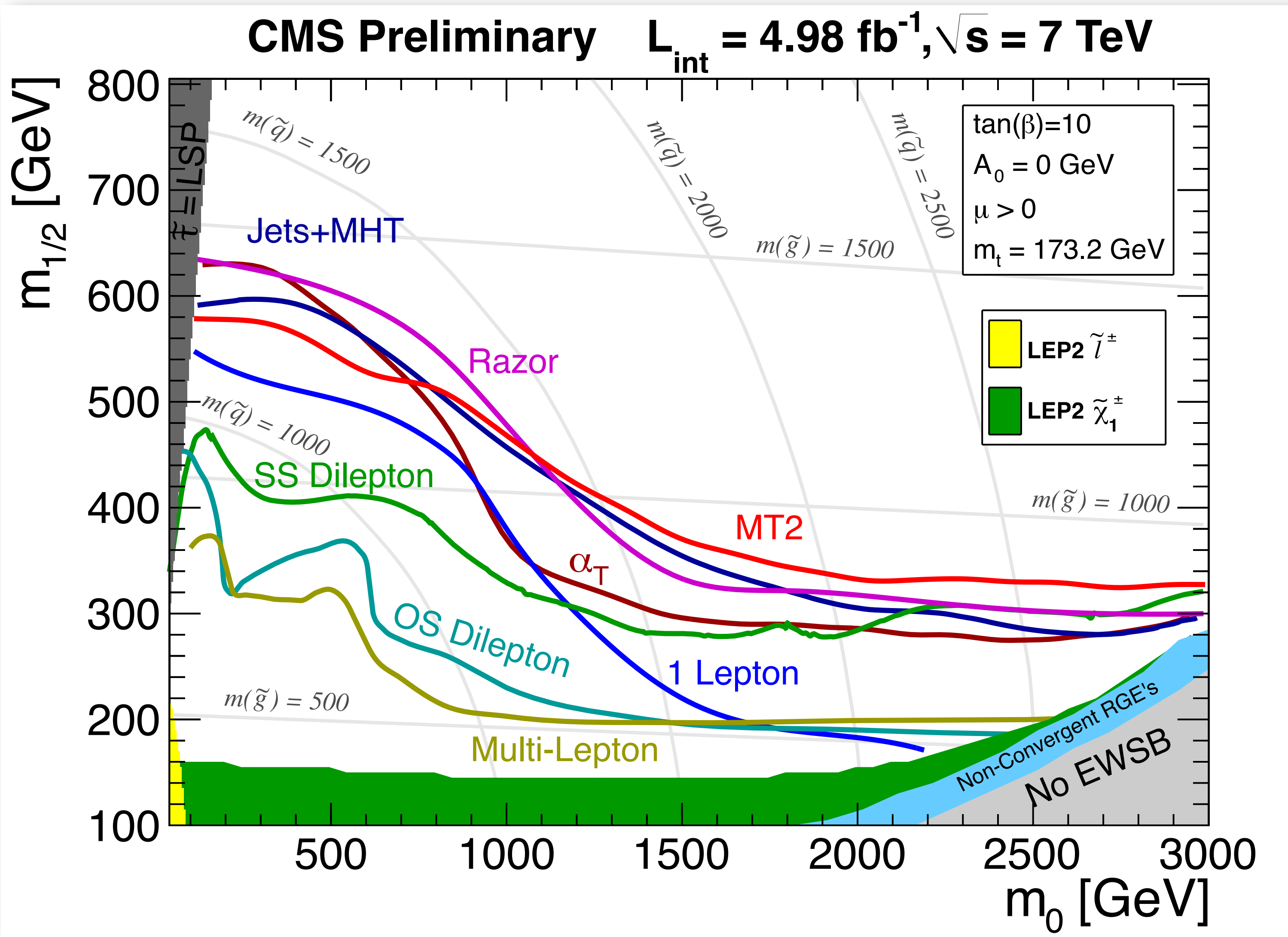
Backup slides

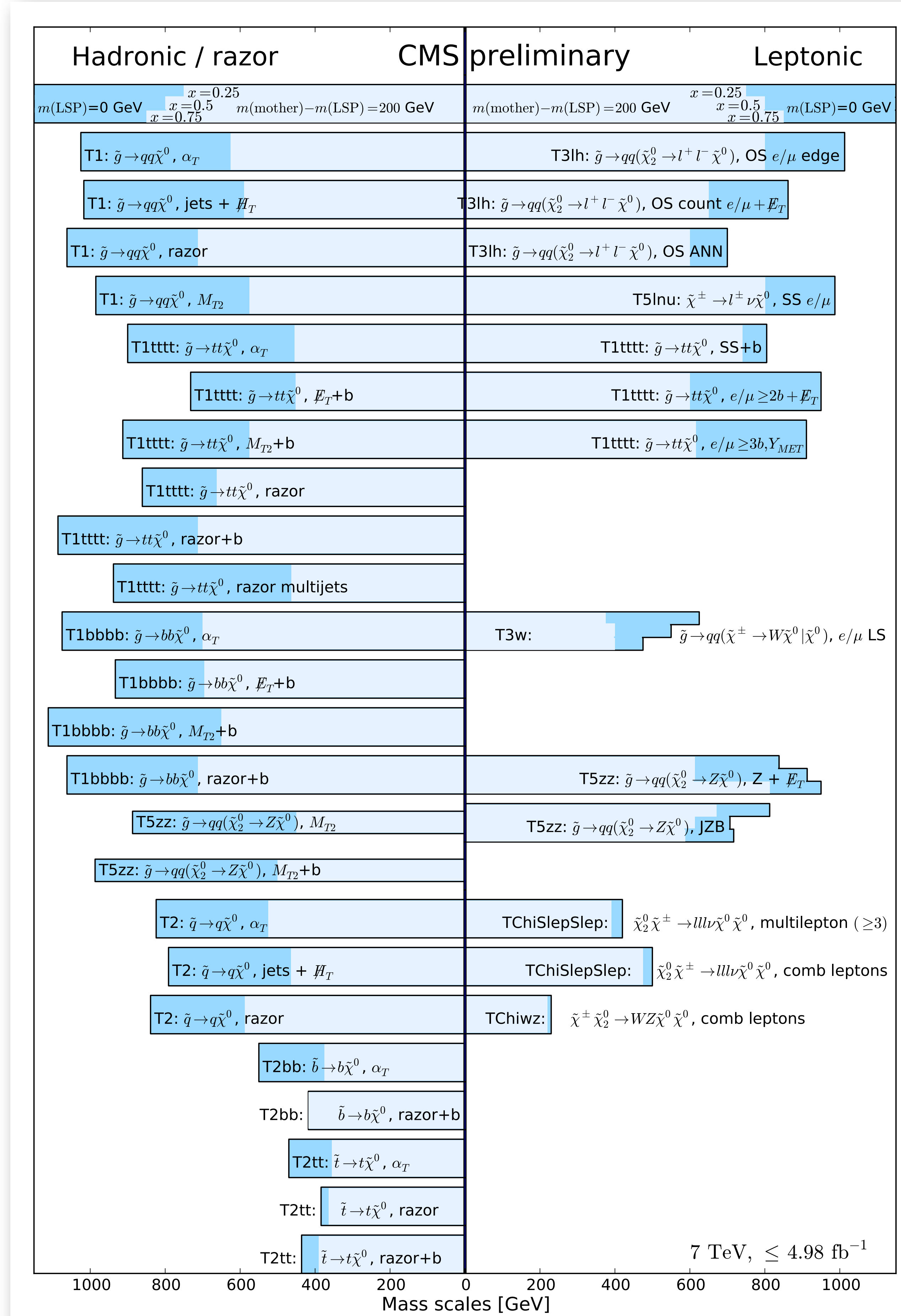
SUSY search strategies and naturalness

- Focus in 2010-11 was on model-independent, signature-based searches (0ℓ, 1ℓ, ...)
  - Data-driven methods for background estimation (now, appropriately, more reliant on MC)
- 7 TeV data disfavour constrained models (eg, CMSSM), so turn to natural SUSY?
  - Minimal spectrum required: gluino + $\tilde{t}$ + LSP $\Rightarrow$ **final states rich in b-jets**
- New focus (and huge effort) on analyses targeting specific models
  - eg, several new dedicated searches to maximise sensitivity to direct $\tilde{t}$ production
  - Alternatively, add b-jet identification to existing inclusive analyses (two examples today)

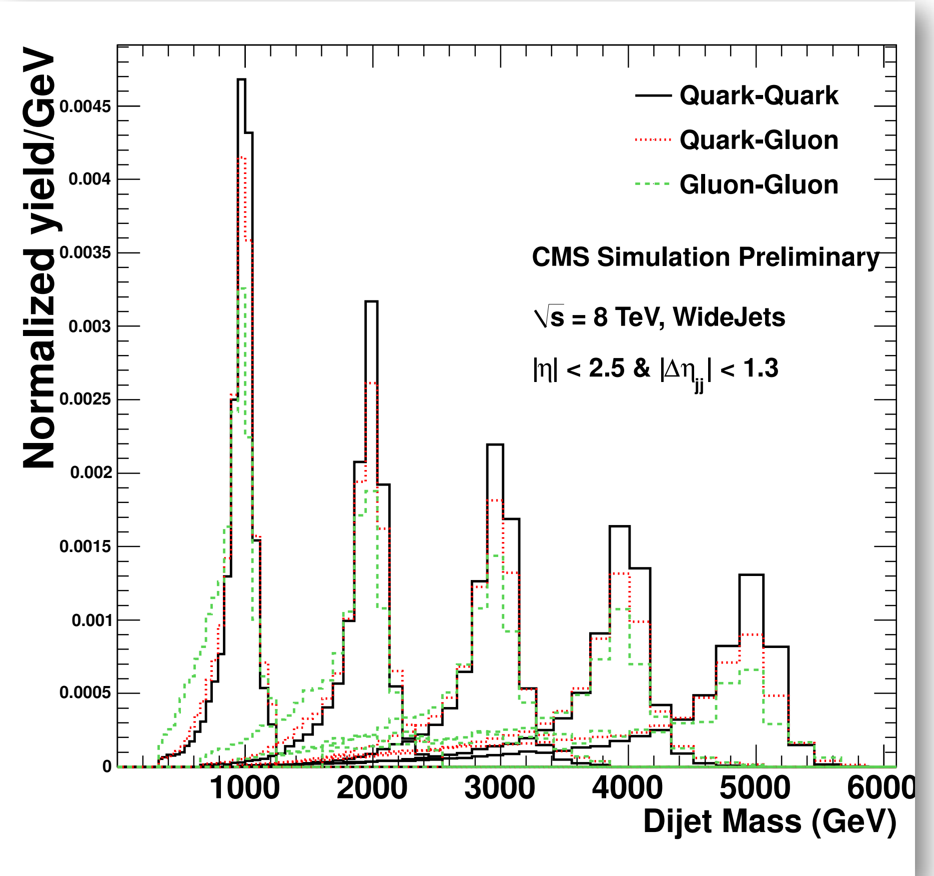


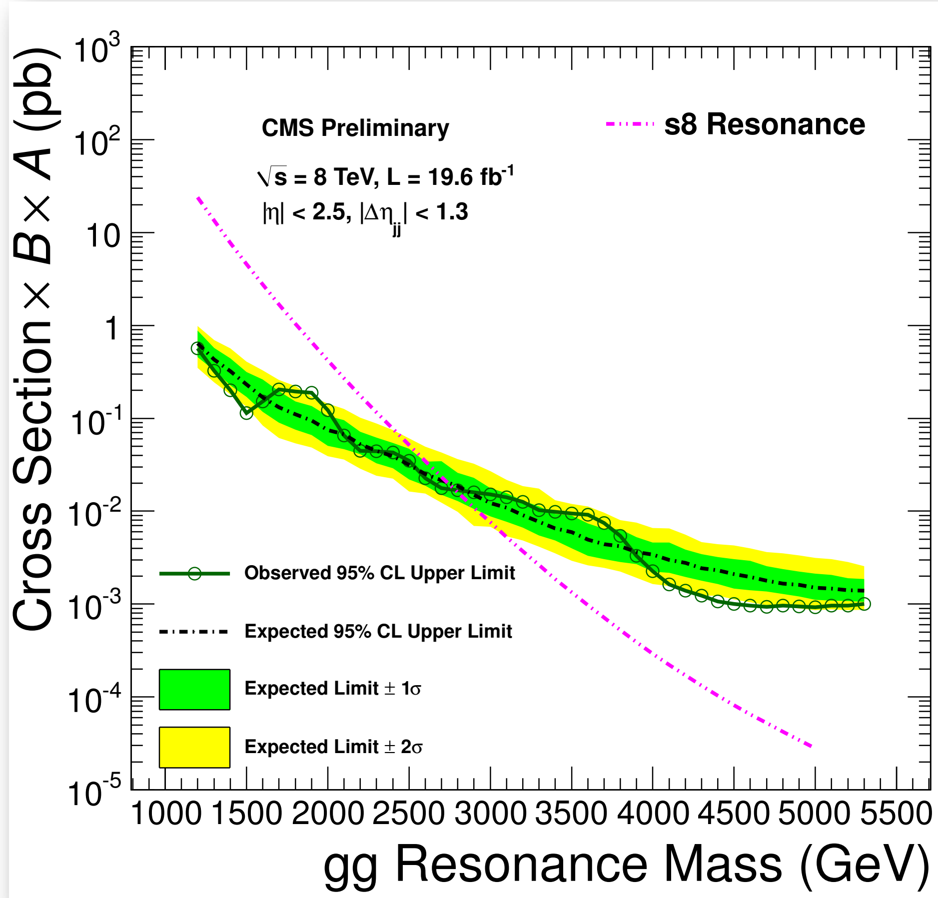
SUSY summary for 7 TeV dataset

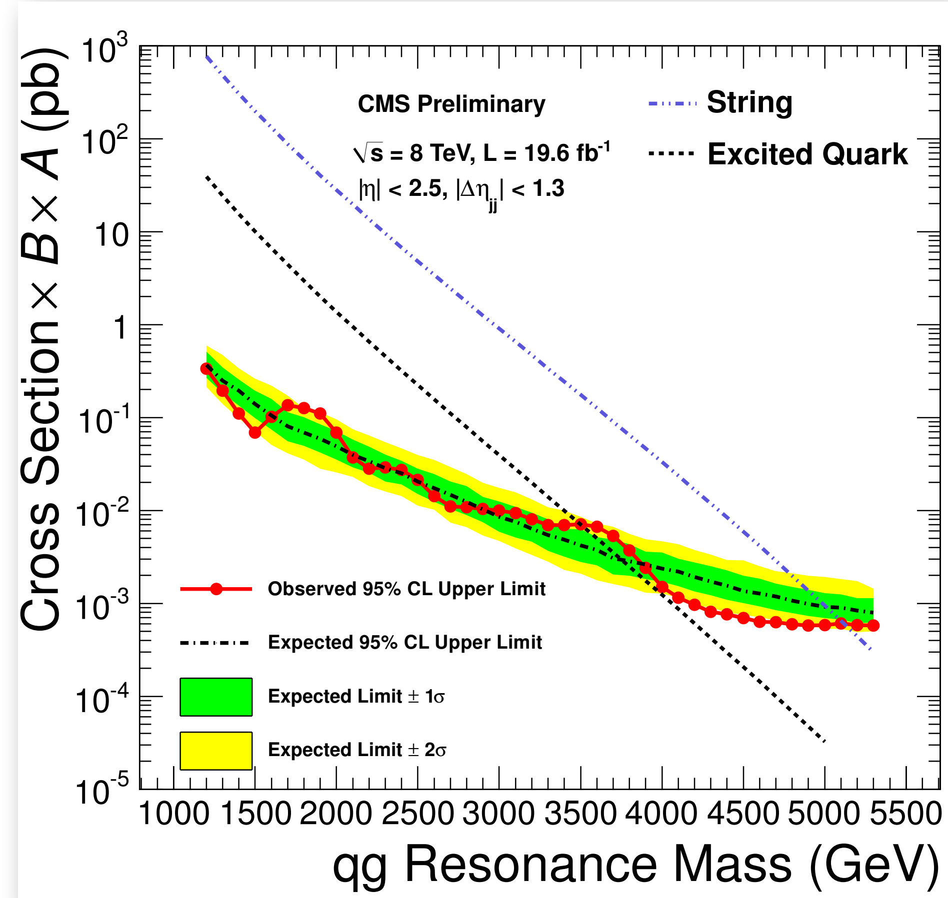




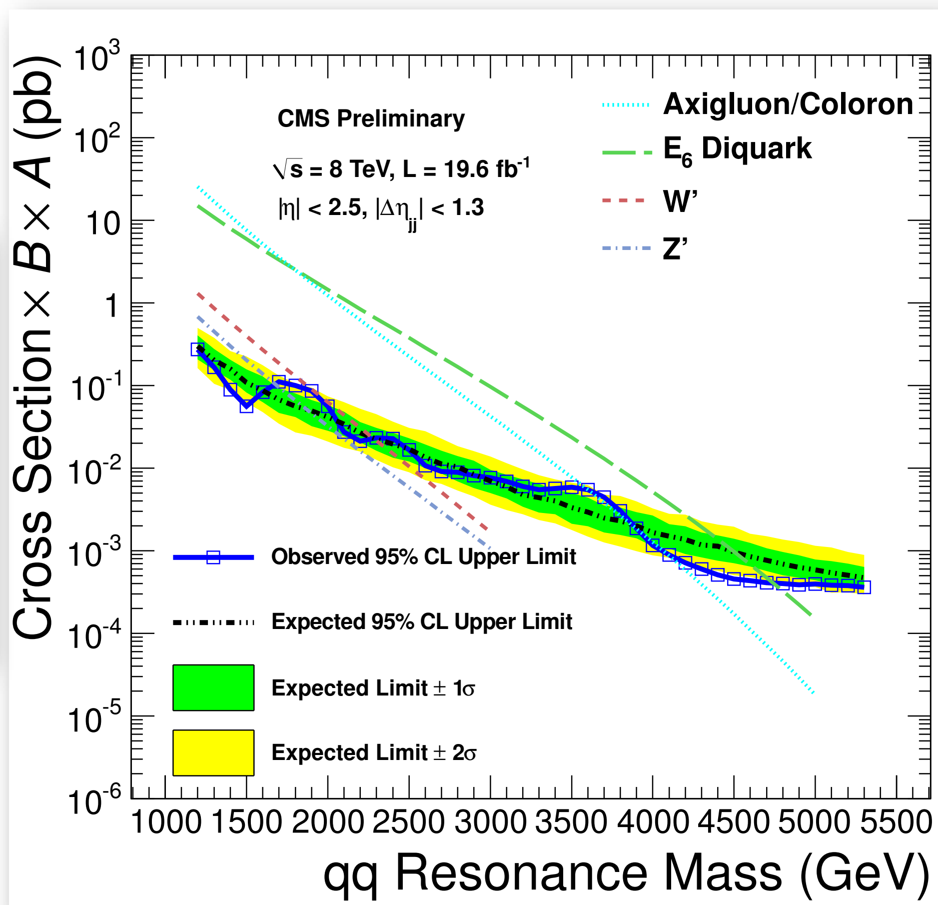
Dijet resonance: limits for qq, qg, gg

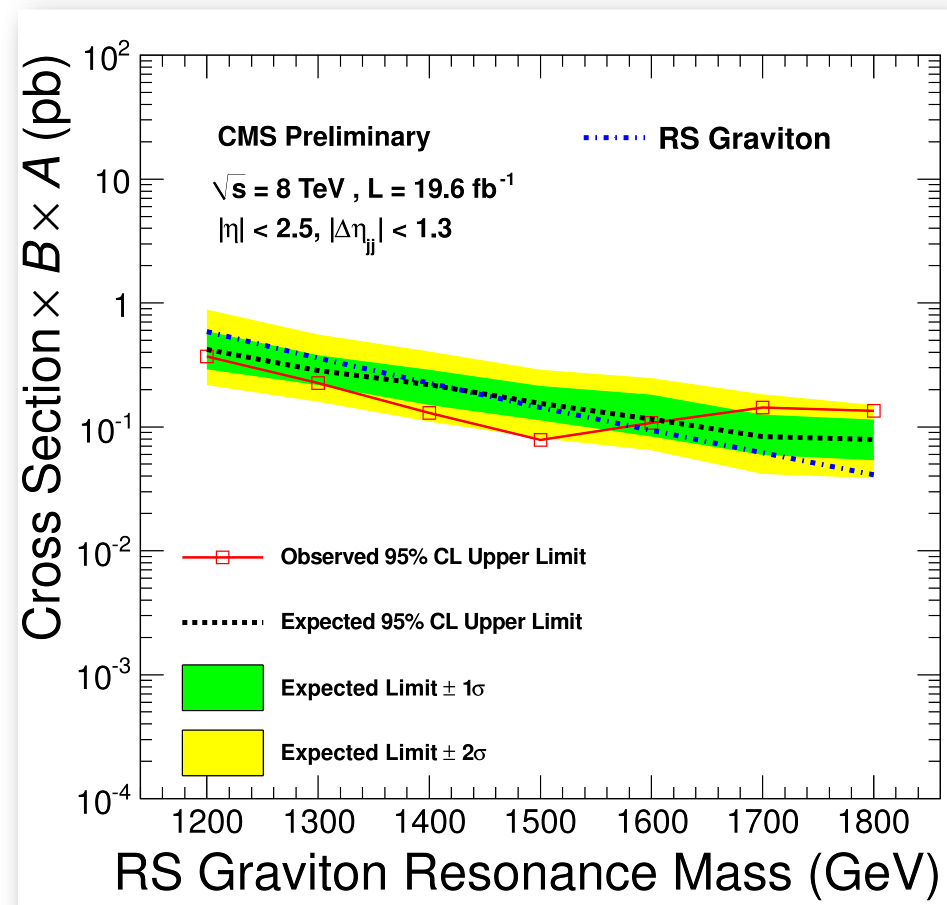






Model	Final State	Obs. Mass Excl. [TeV]
String Resonance (S)	qg	[1.20,5.08]
Excited Quark (q^*)	qg	[1.20,3.50]
E_6 Diquark (D)	qq	[1.20,4.75]
Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.20,3.60] + [3.90,4.08]
Color Octet Scalar (s8)	gg	[1.20,2.79]
W′ Boson (W′)	$q\bar{q}$	[1.20,2.29]
Z′ Boson (Z′)	$q\bar{q}$	[1.20,1.68]
RS Graviton (G)	$q\bar{q}$+gg	[1.20,1.58]



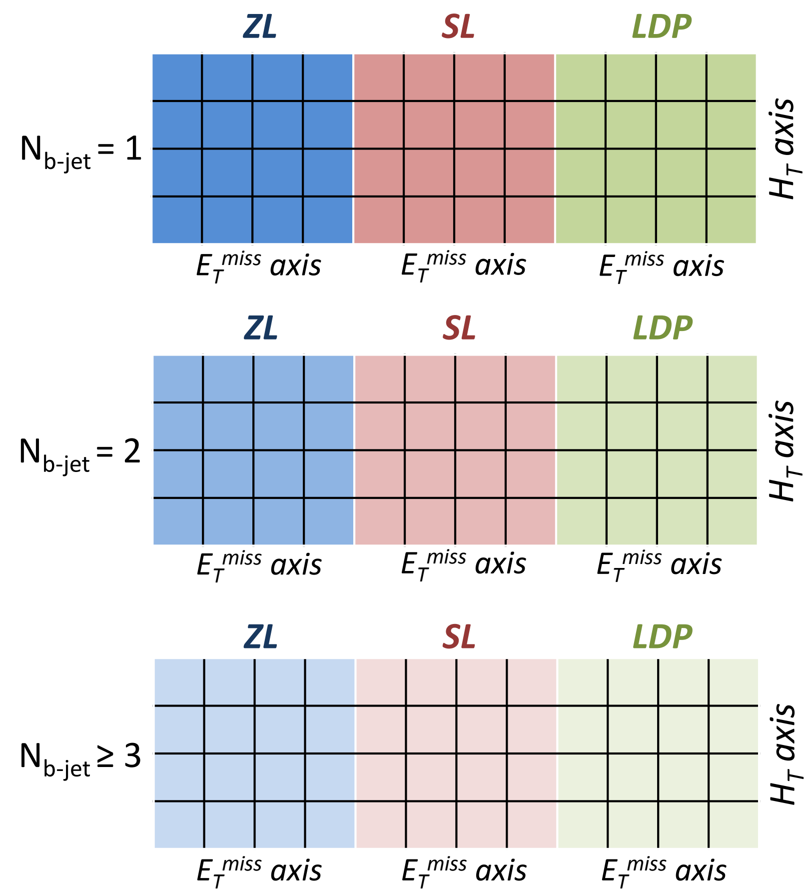


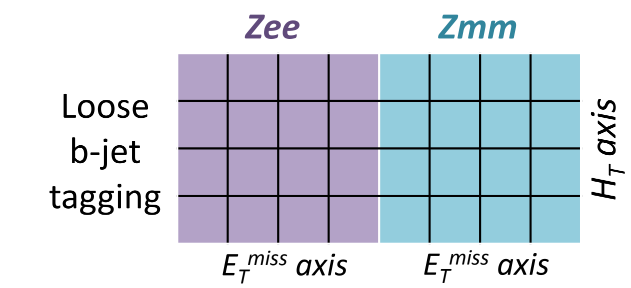
Multi b-jets + MET: background estimation

- **Single lepton sample**
  - **–tt, single top, W+jets**
  - –Invert e/μ veto
  - –M_T < 150 GeV (suppress signal)
- **LDP control sample**
  - **–QCD multijets**
  - –Invert $\Delta\varphi^{min}$ cut
- **Zee, Zμμ** control sample
  - **–Z(→νν) + jets**
  - –Two leptons within Z mass window
  - –Loose b-tag requirements

Event sample legend

ZL = Zero Lepton; signal sample	*SL* = Single Lepton; top & W+jets control sample	*LDP* = low $\Delta\hat{\phi}_{min}$; QCD control sample	*Zee* = Z → e⁺e⁻; Z to $\nu\bar{\nu}$ control sample	*Zmm* = Z → μ⁺μ⁻; Z to $\nu\bar{\nu}$ control sample





bin	H_T (GeV)	E_T^{miss} (GeV)
bin 1	400 – 500	125 – 150
bin 2	500 – 800	150 – 250
bin 3	800 – 1000	250 – 350
bin 4	> 1000	> 350

Example: single lepton control sample (tt, single top, W+jets backgrounds in bin i,j,k)

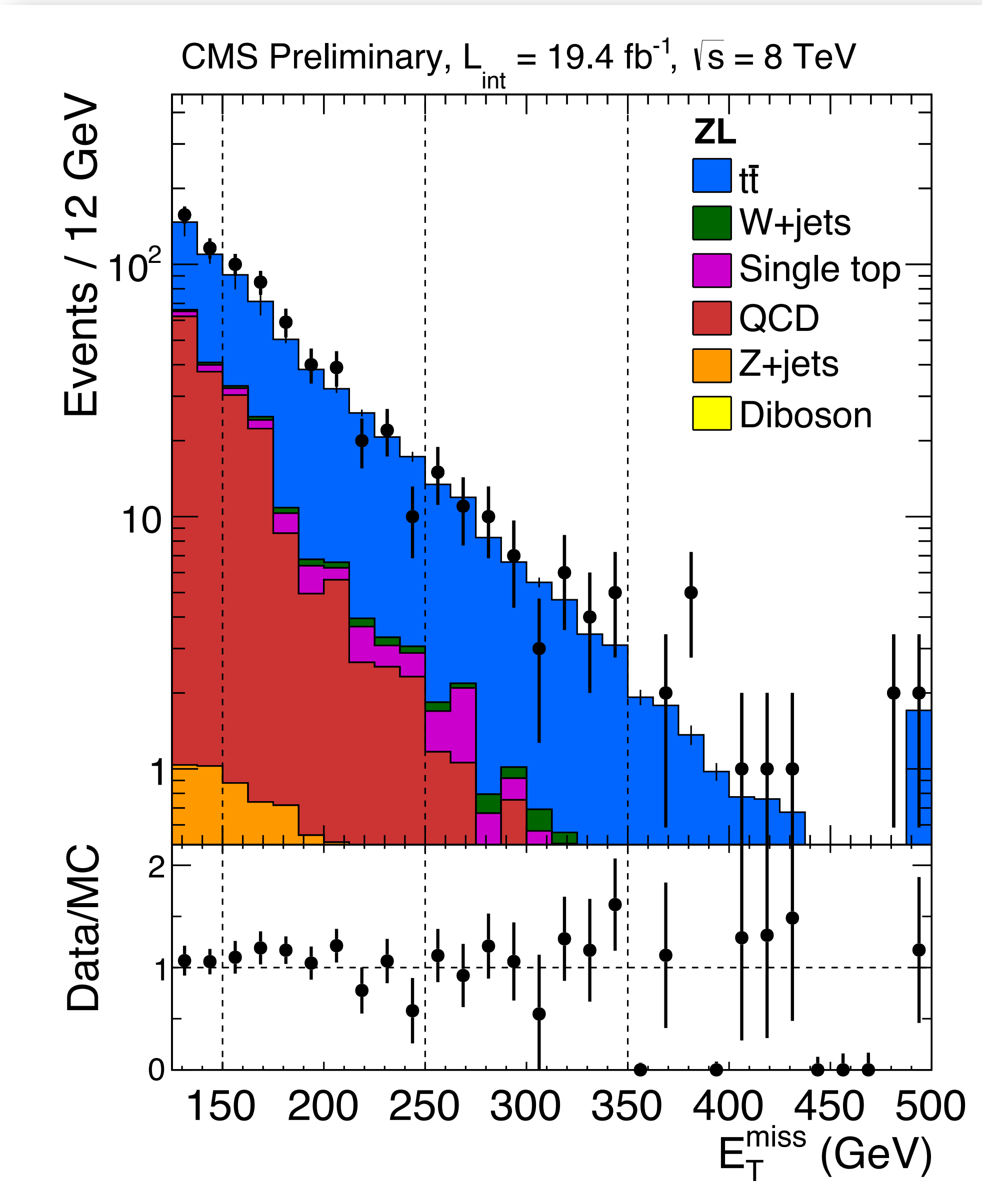
$$\mu^{ttWj}_{ZL;i,j,k} = S^{ttWj}_{i,j,k} \cdot R^{ttWj}_{ZL/SL} \cdot \mu^{ttWj}_{SL;i,j,k}$$

Yield in bin i,j,k of control sample — **Overall normalisation (unconstrained nuisance)** — **Bin-by-bin scale factor (nuisance parameters with log- normal priors)**

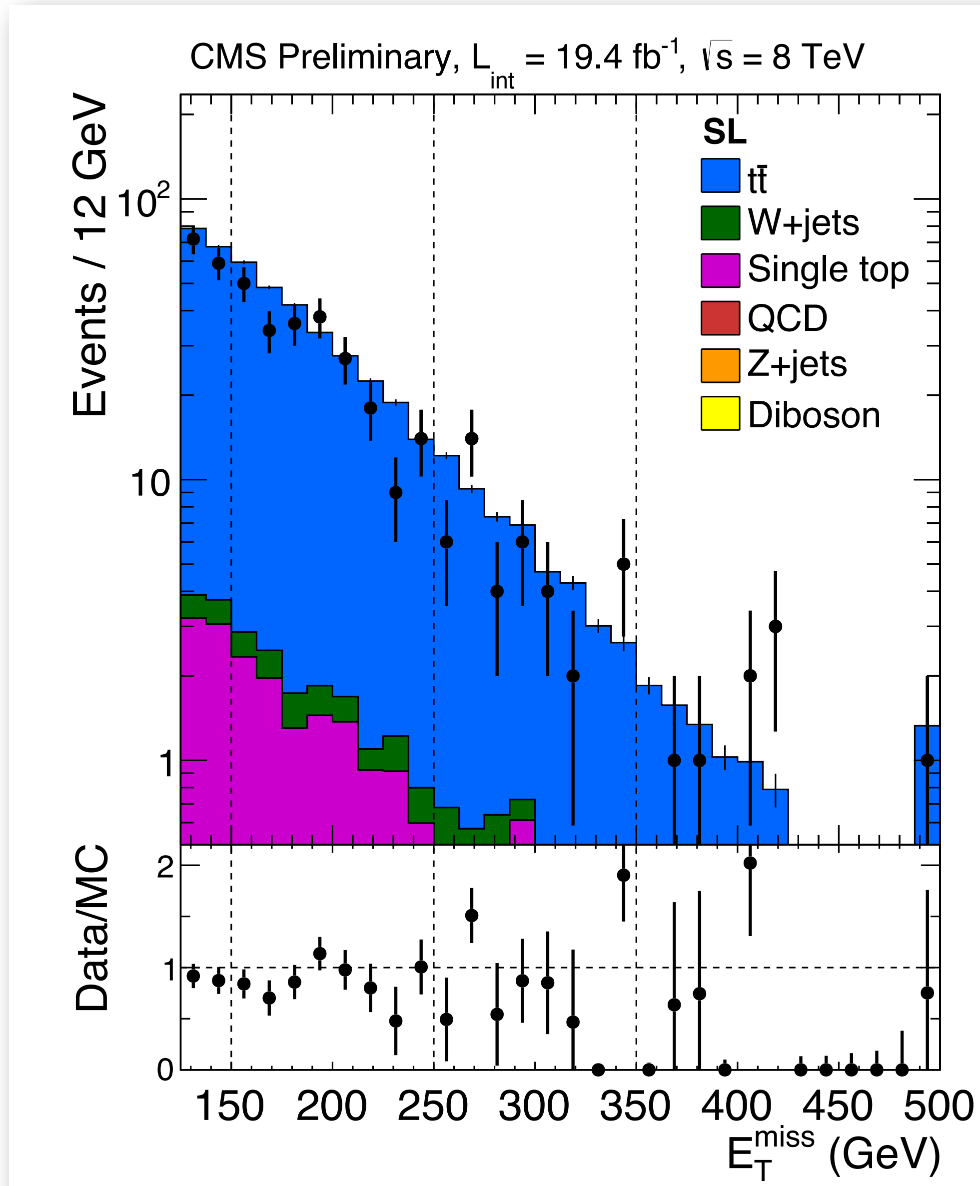
Multiple b-jets + MET: example distributions

- Plots for illustration only (MC only used for scale factor corrections)
- All distributions for $N_{b\text{-jet}} \geq 3$

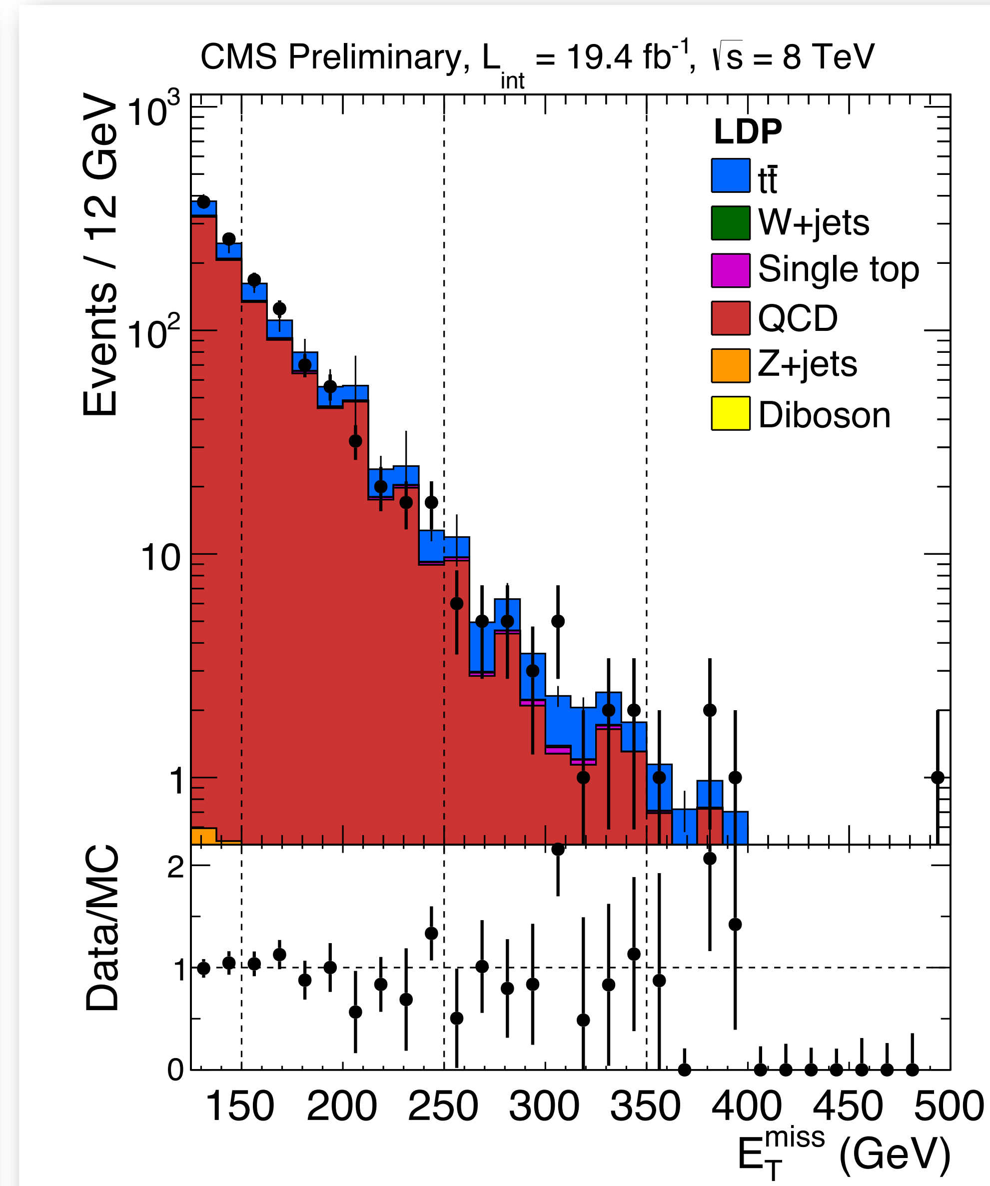
Signal region



Single lepton control region (tt, single top, W+jets)

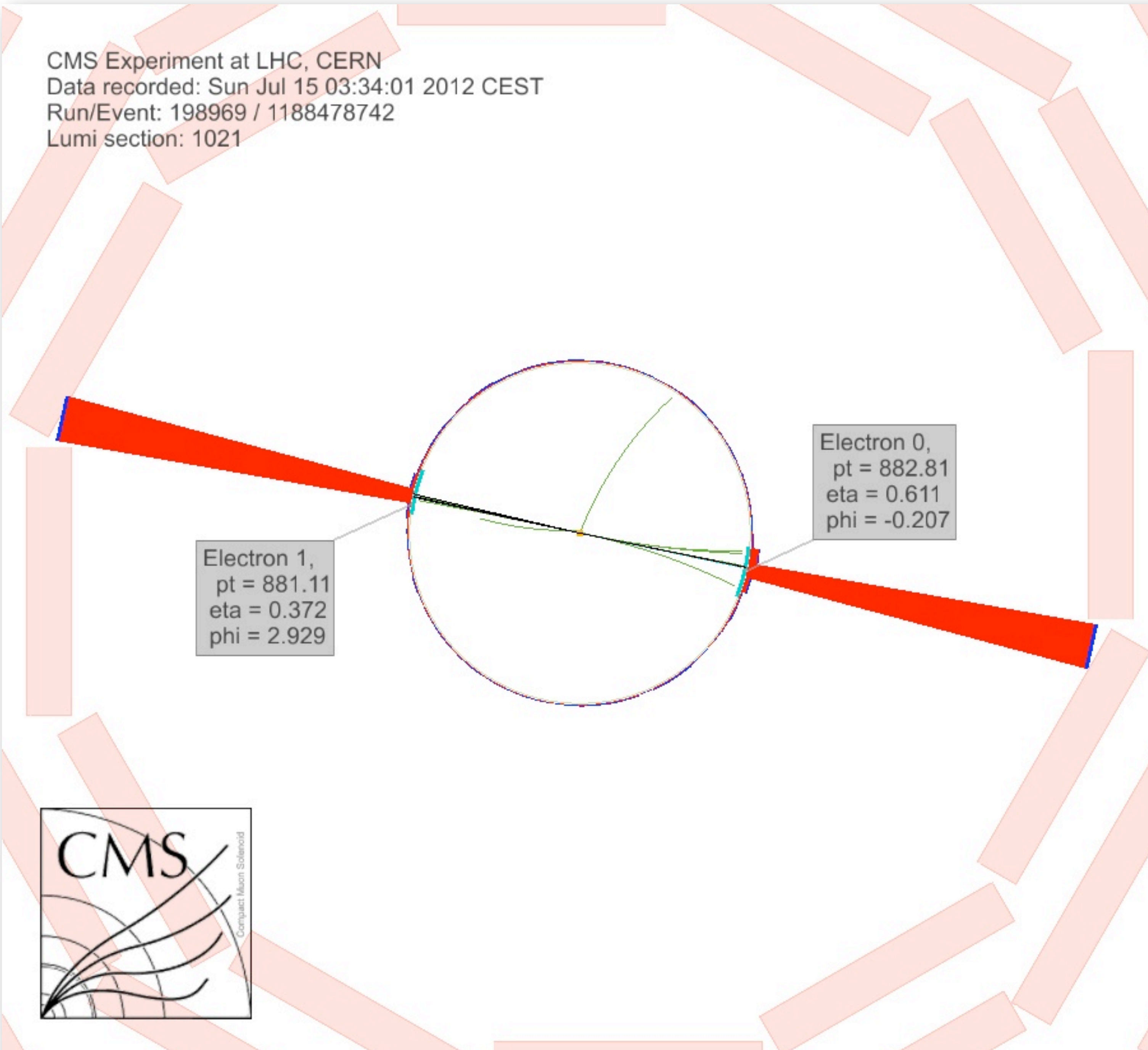


Low Δφ control region (QCD multijets)

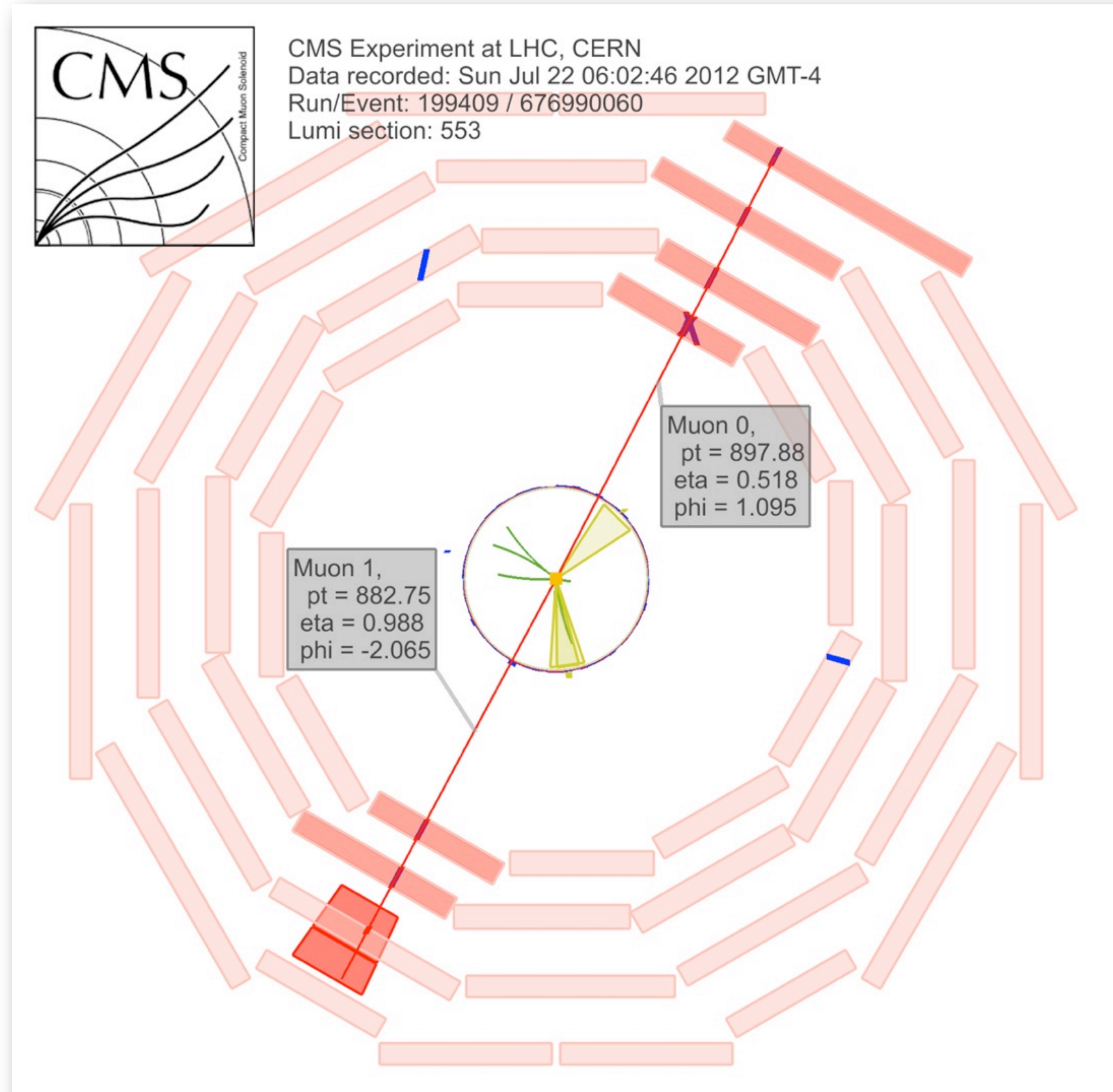


High $m_{\ell\ell}$ events

Event with highest m_{ee} (1.78 TeV)



Event with highest $m_{\mu\mu}$ (1.82 TeV)



W’ signal shapes