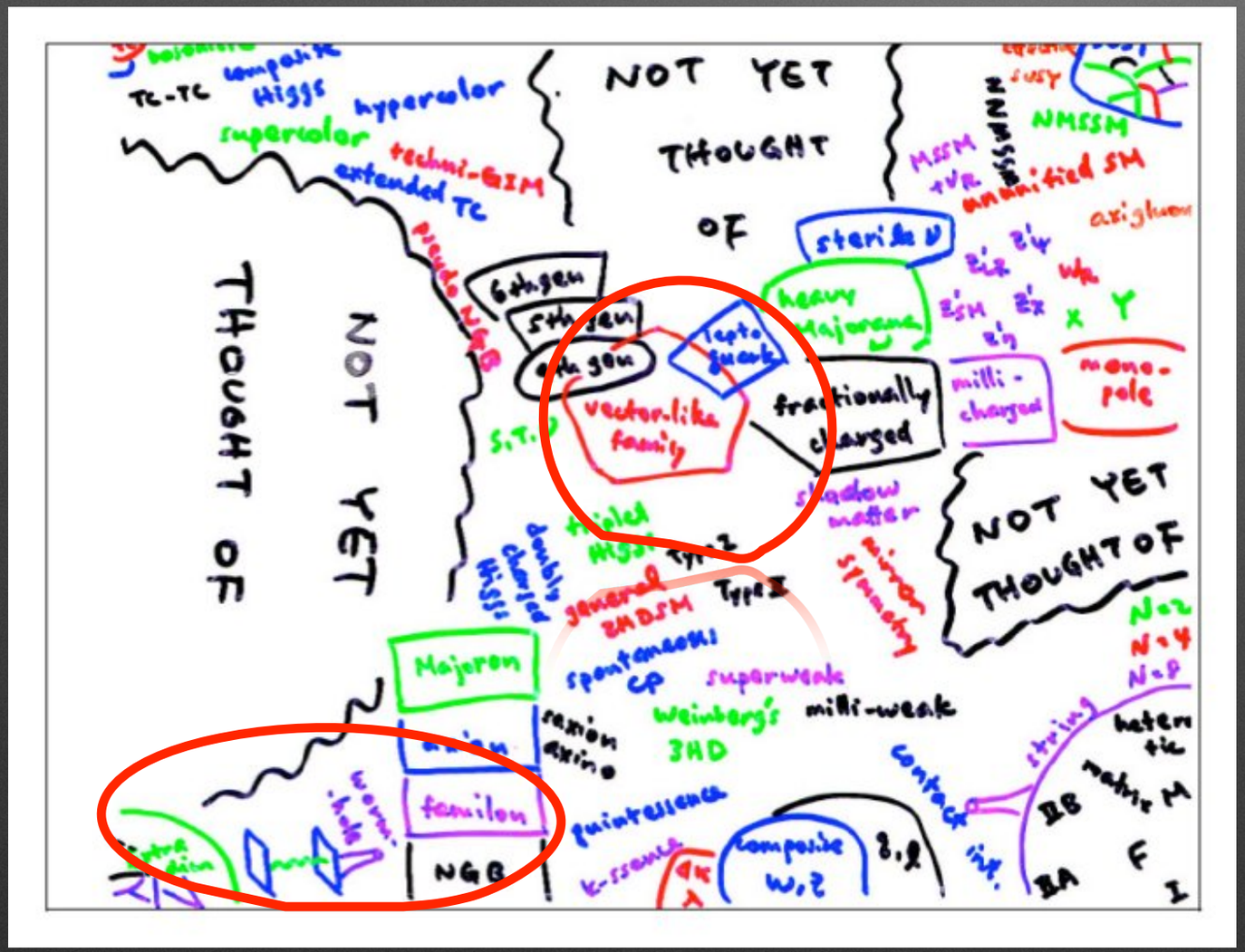
Non-SUSY Results from CMS

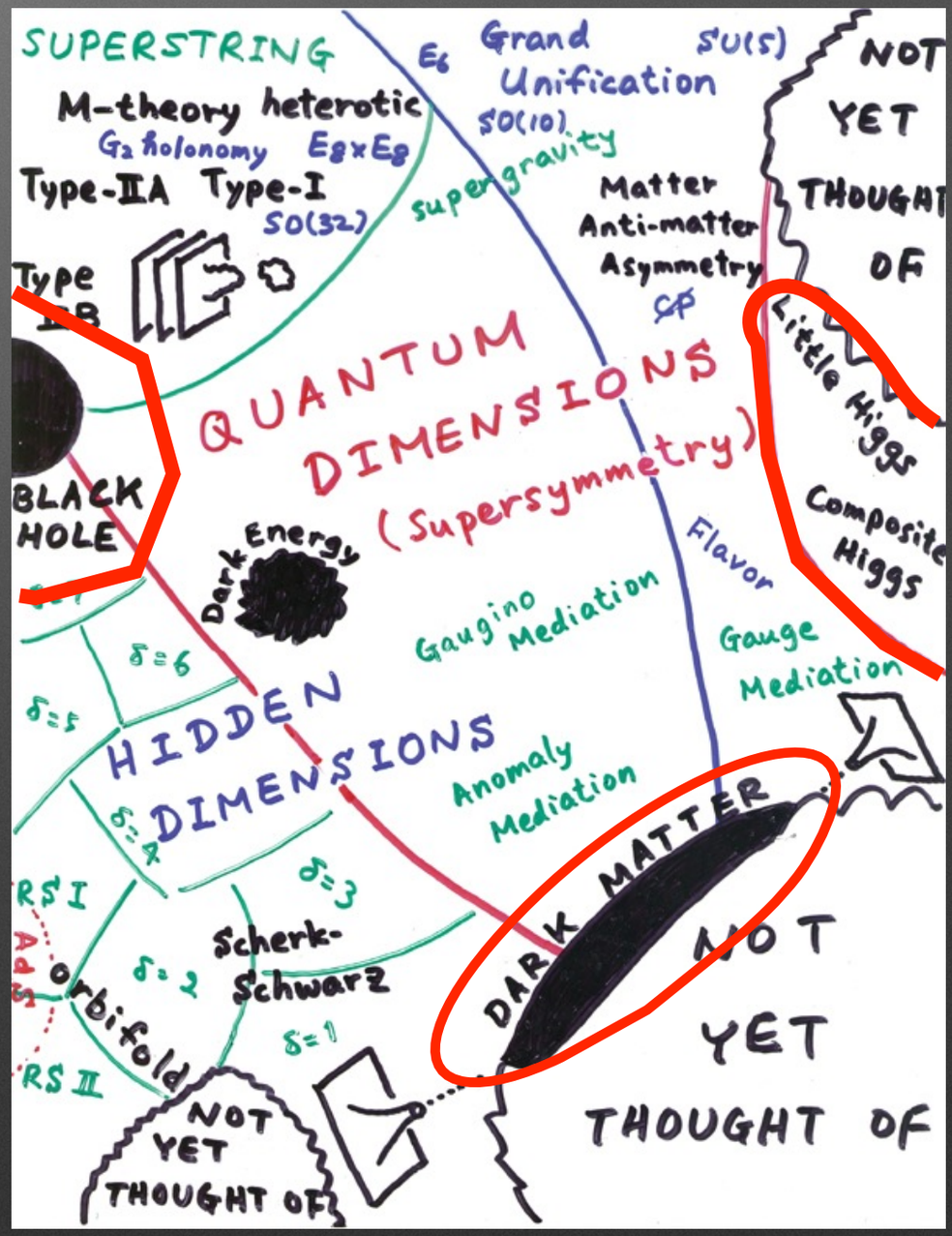
SUSY2014: The 22nd International Conference on Supersymmetry
and Unification of Fundamental Interactions
21 - 26 July 2014, Manchester, England

Sadia Khalil on behalf of CMS Collaboration

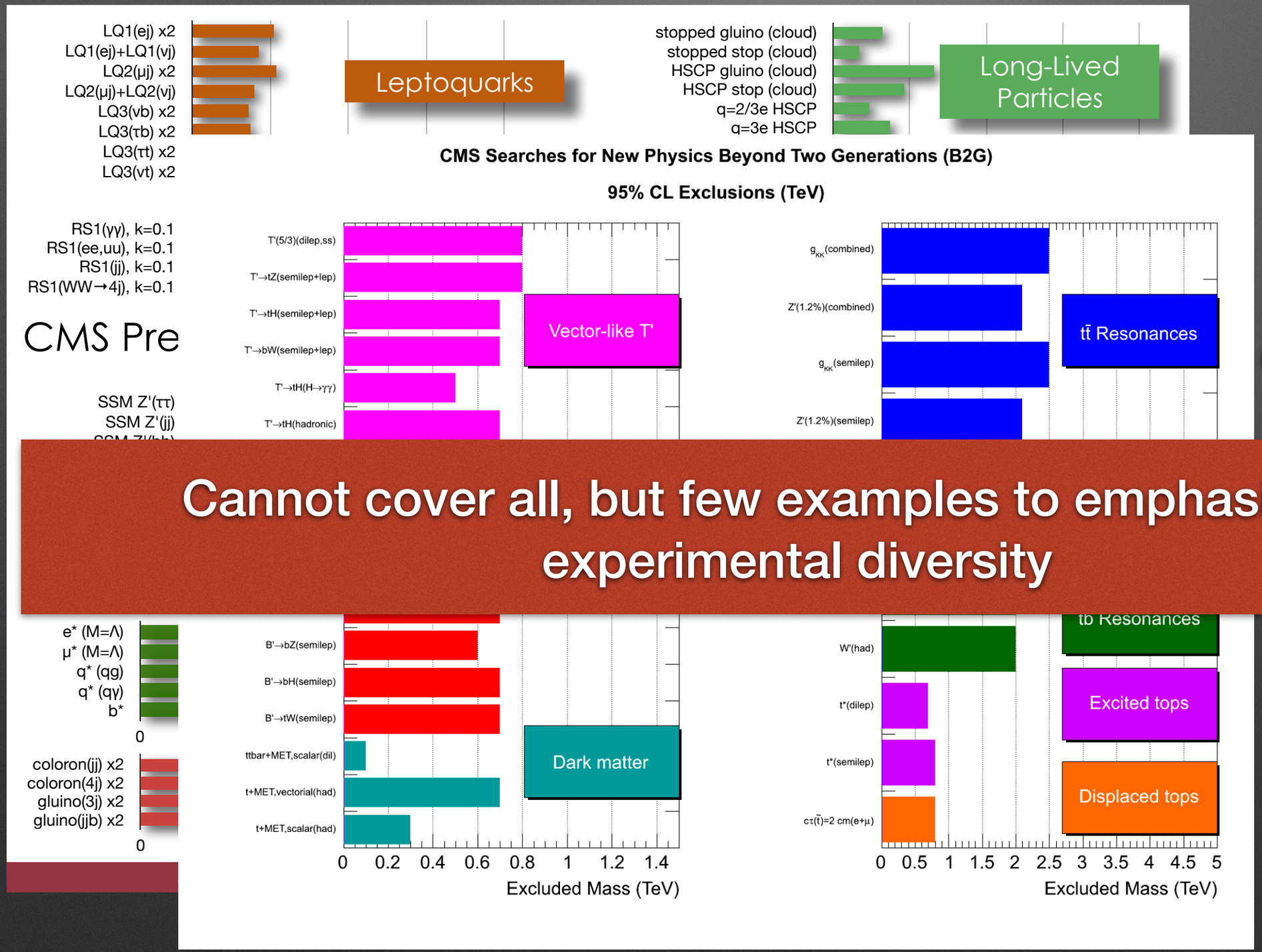
Theorist Maps

Hitoshi Murayama





Vast variety of NP Searches



CMS Pre

CMS Exotics:

- 10 pub + 18 PAS

ons:

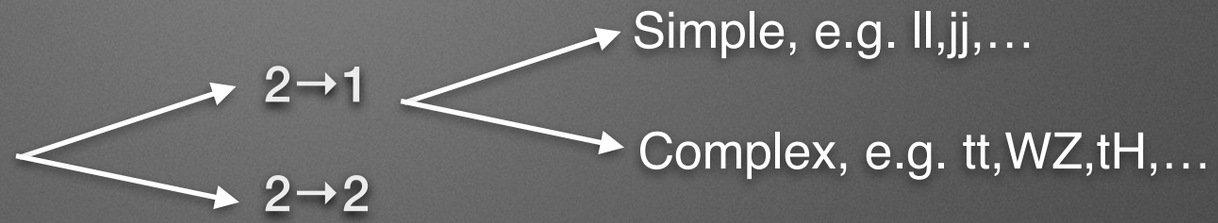
- 6 pub + 14 PAS

Cannot cover all, but few examples to emphasize the experimental diversity

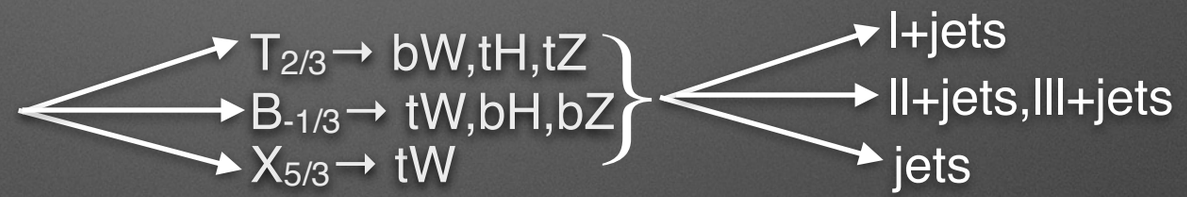
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

Outline

- Introduction
- Resonances



- Vector-like quarks

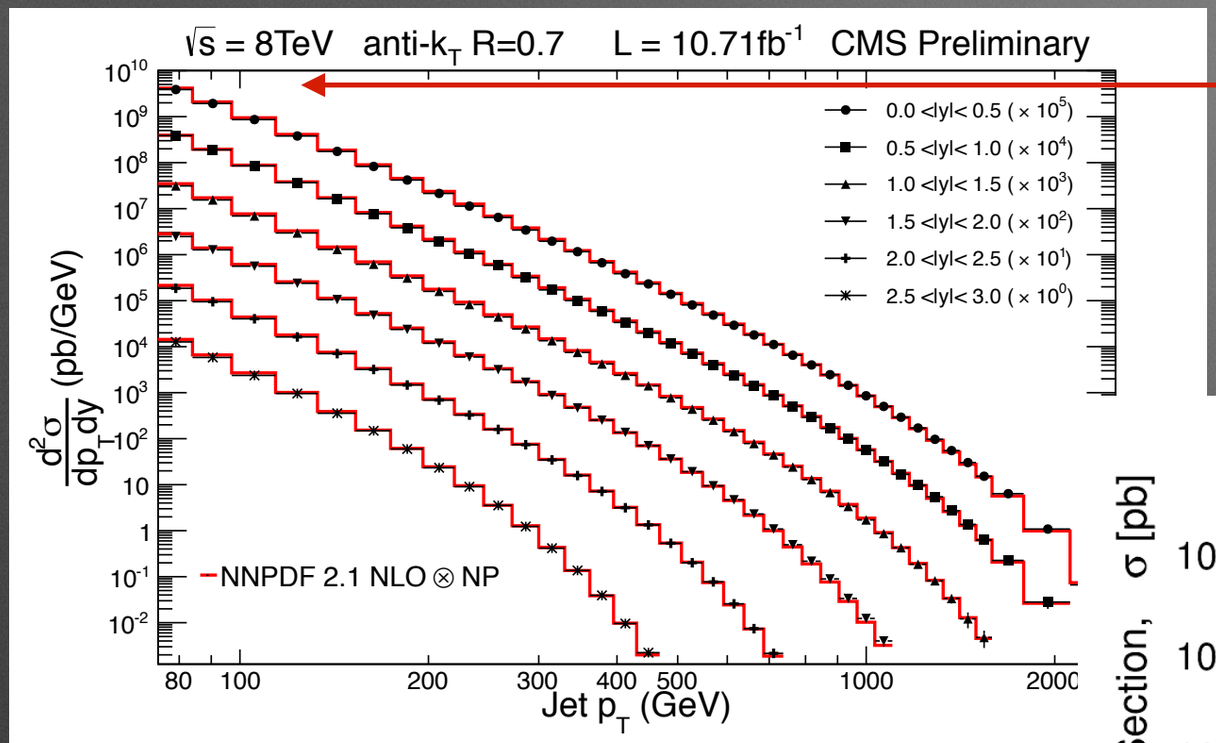


- Leptoquarks

- Dark Matter

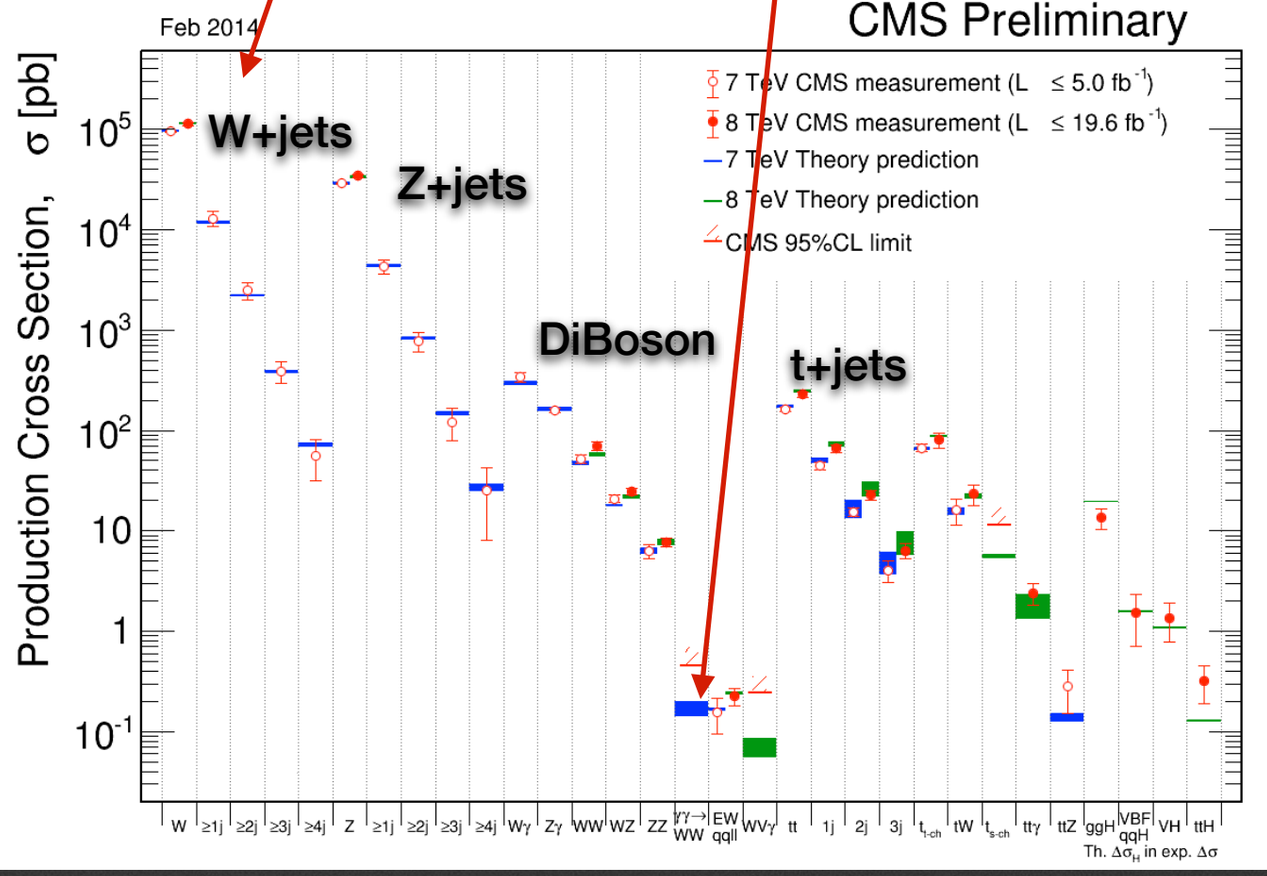
- Long lived particles

Standard Model backgrounds



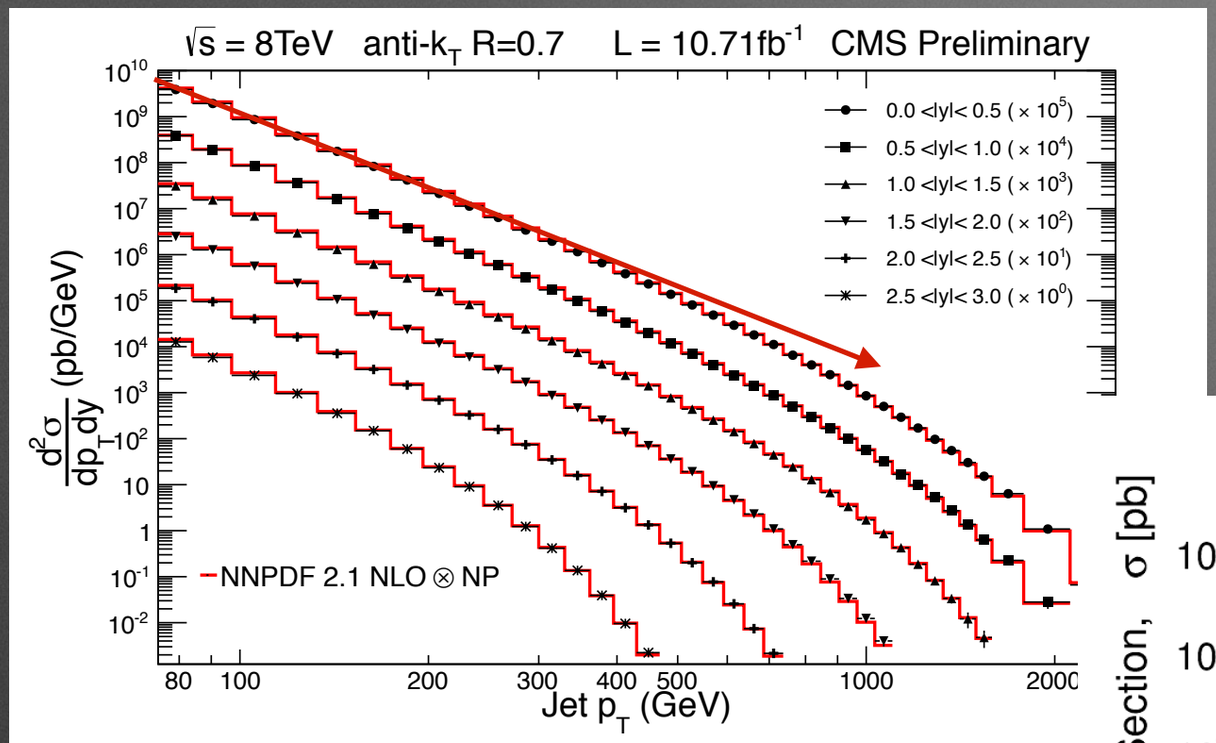
1-lepton + MET cross section~ x10^5 smaller than all hadronic

dilepton same-sign + MET cross section~ x10^{12} smaller than all hadronic

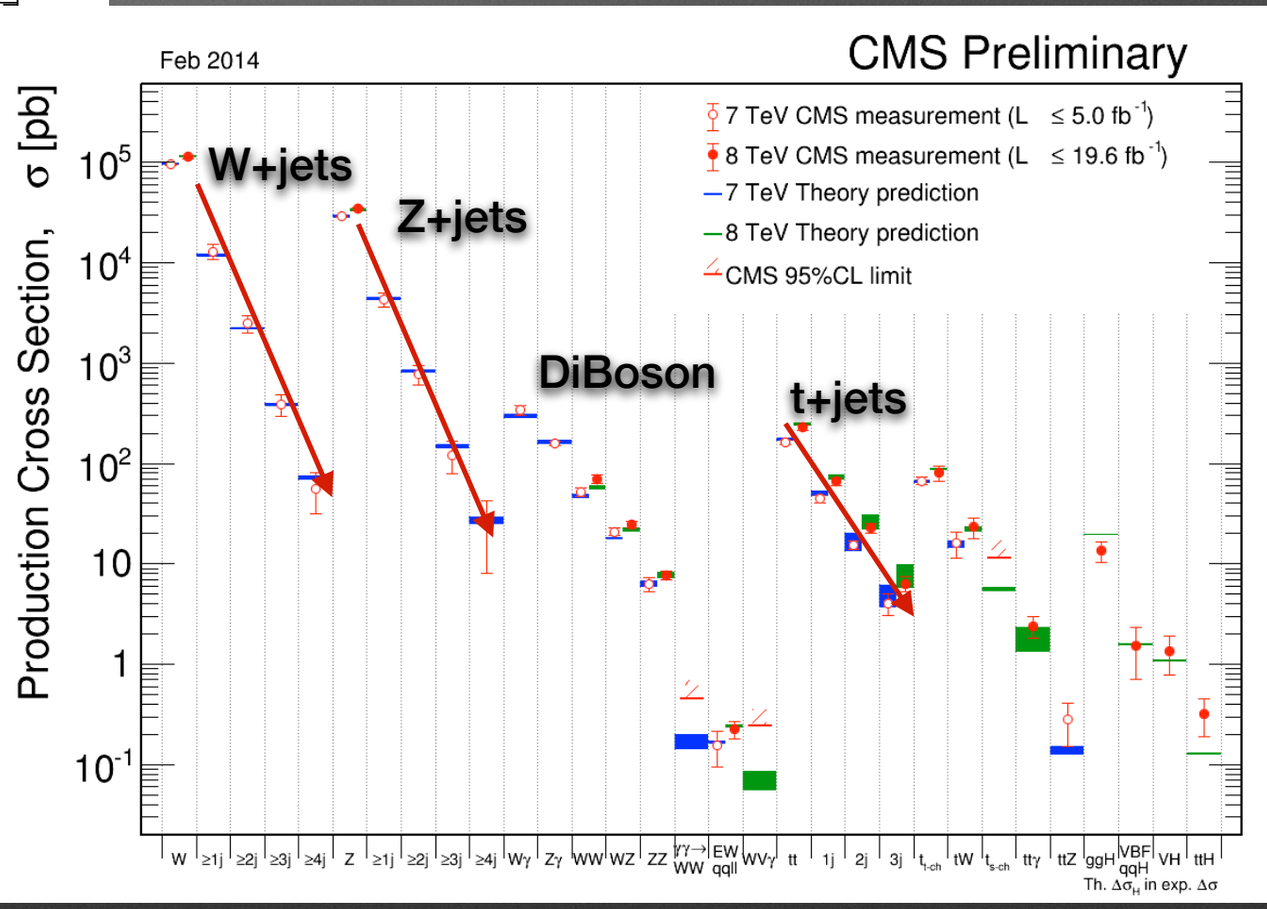


- Leptons, Jets, MET, W, Z, t,… are excellent probes for BSM Physics

Standard Model backgrounds



Cross section decrease exponentially with jet pT and # of jets



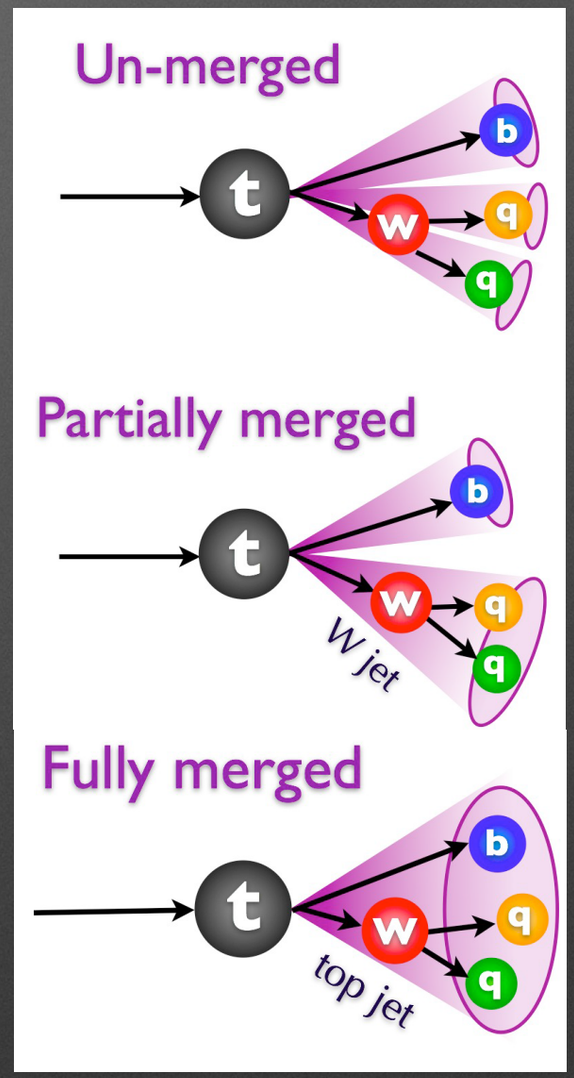
- Define:
- $H_T = \sum p_T$ of Jets
- $S_T = \sum p_T$ of Jets + MET + $\sum p_T$ of Leptons
- M_T = Transverse mass

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi_{\ell\nu})}$$

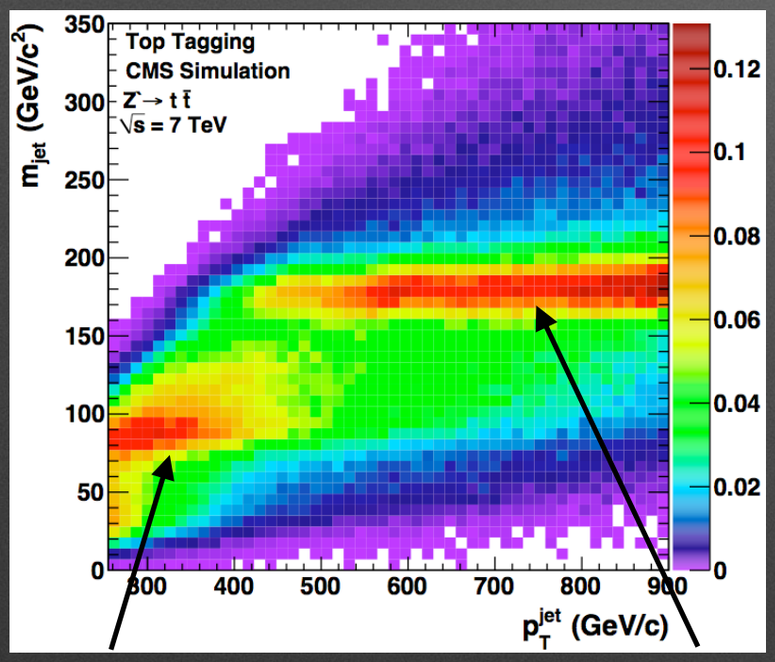
Jet Substructure

- The New Physics searches often imply to look for massive objects
  - boosted decay products => merged jets

$$\Delta R_{qq}^{\min} \approx \Delta\theta_{qq}^{\min} \approx 2\frac{M_V}{p_{T,V}}$$

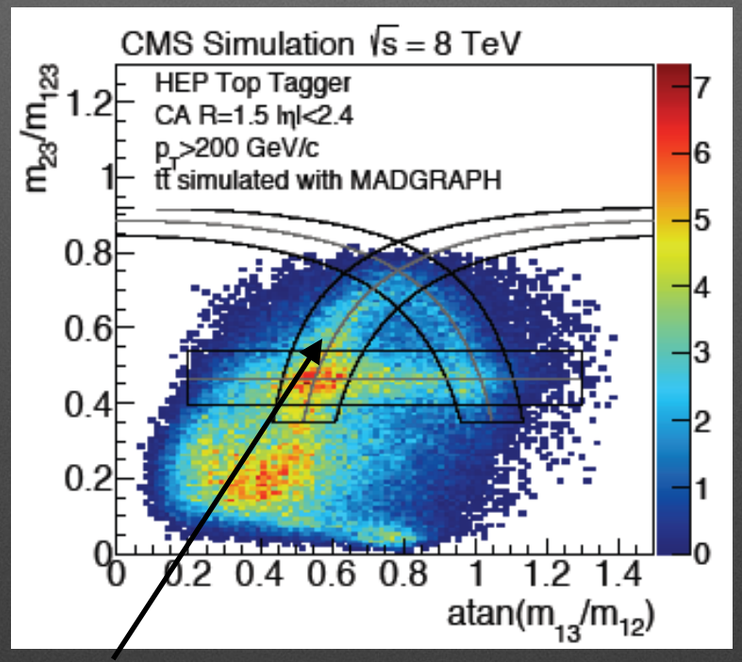


Example: Z′ →tt, t′ →tW



merged
W decay
products

Example: t′ →tH



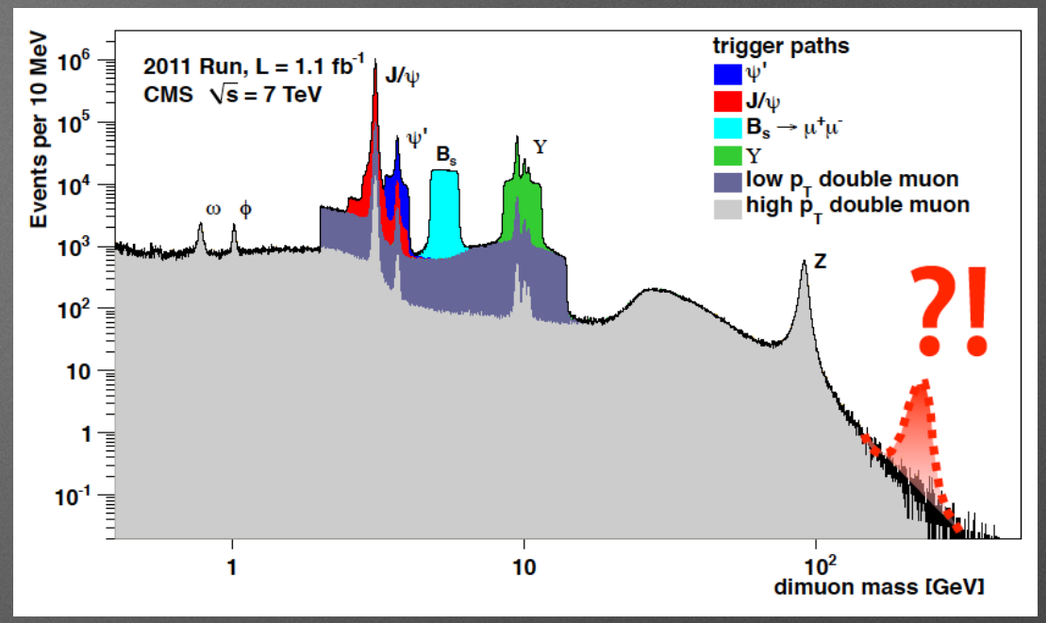
merged
top decay
products

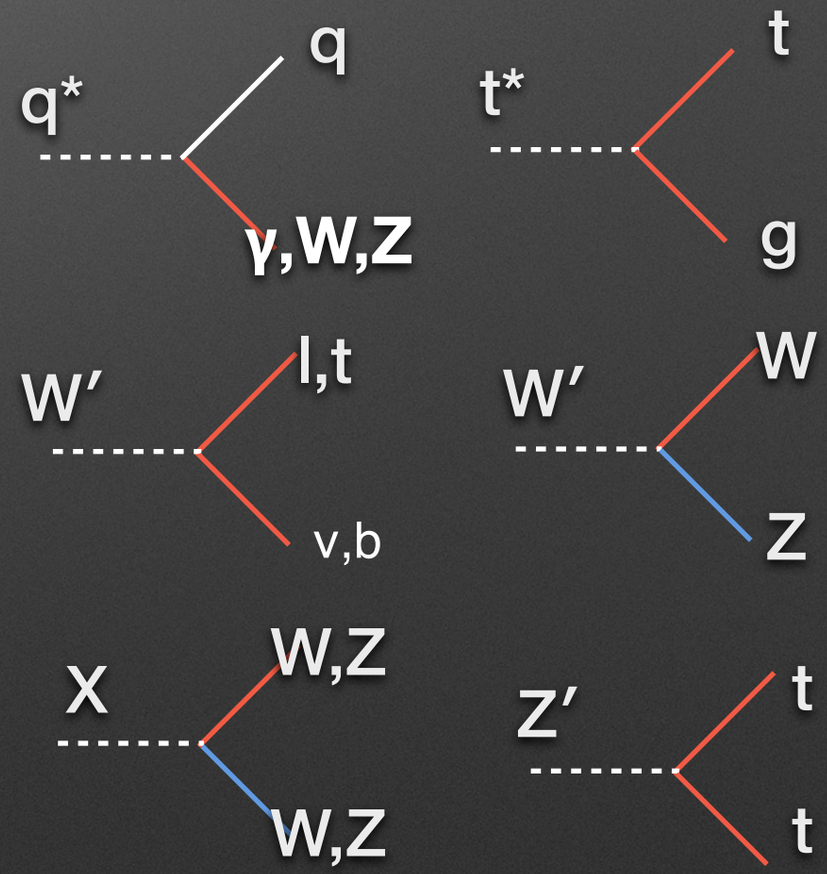
- Standard jet reconstruction with Anti-kt clustering algorithm, distance parameter 0.5 (ak5)
- Use fat jets tagging algorithms developed for Cambridge/Aachen jet clustering algorithm, with distance parameter 0.8 (CA8), 1.5 (Hep top tagger)

See details by Zeynep Demiragli and Rebekka HOEING at Alternate theory sessions

Resonances

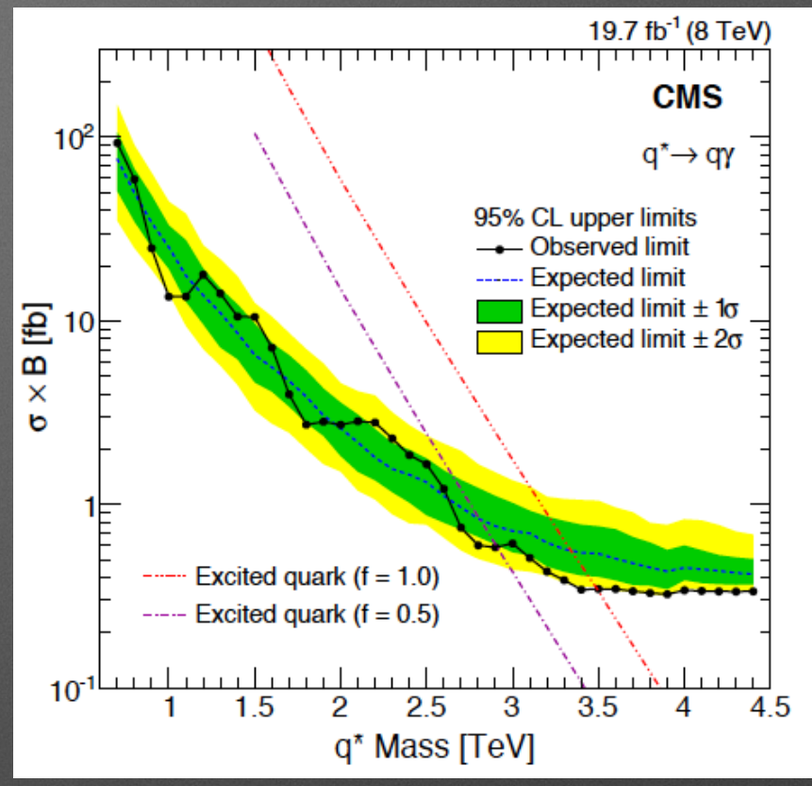
- Powerful, model-independent probe to new physics
  - Simple Strategy: Reconstruct invariant mass and look for “bump”
  - Bump at $m_{ff} > m_Z$ or m_H ➡ New Physics!
- Top quark resonances in BSM Models
  - Extended gauge sectors: Z′, W′ and G′ bosons
  - Complex Strategy: Use boosted techniques to identify t, W, Z, H along with b and reconstruct the resonance mass

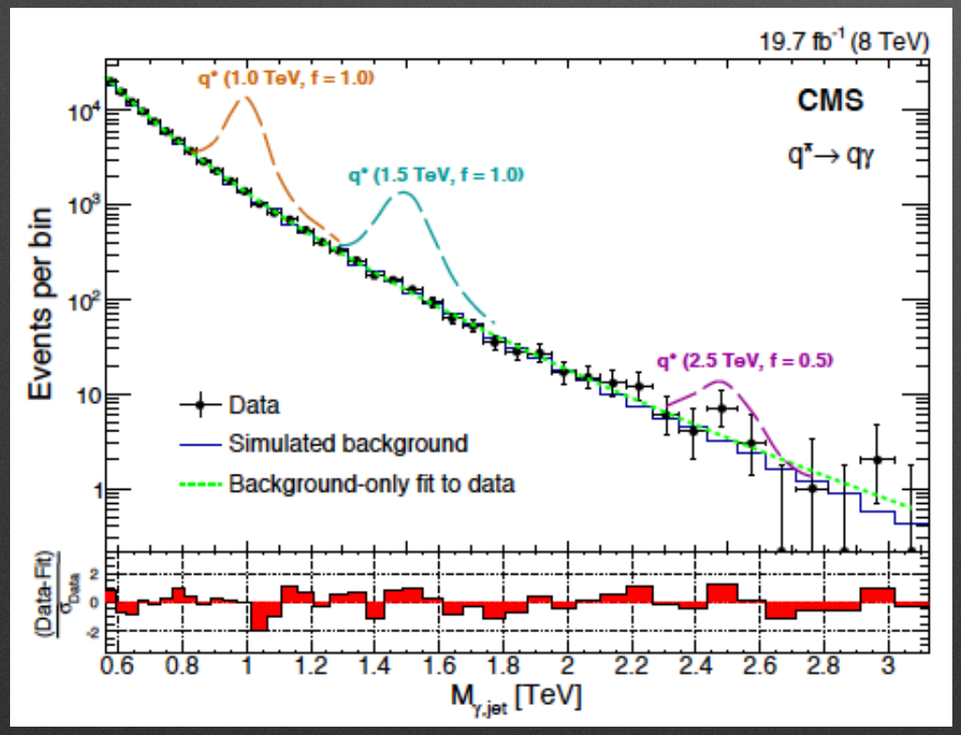


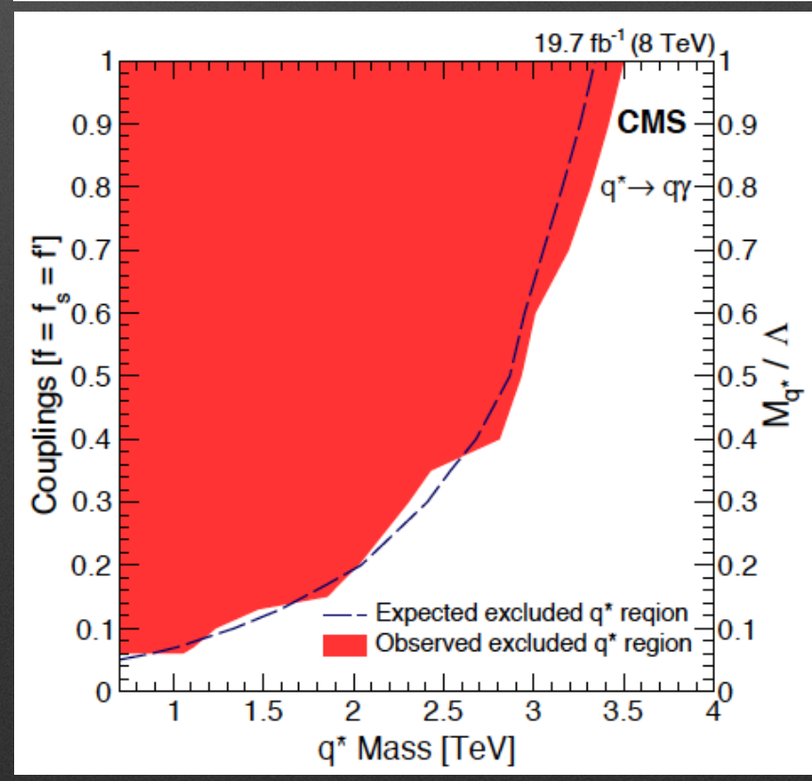


$q^* \rightarrow q + \gamma$ NEW!

- First CMS γ+jet resonance search with full 8 TeV data [arXiv:1406.5171, submitted to PLB]
  - Interpretations for excited quarks with varied coupling strength
- Photon+Jets:
  - ≥1 photon + ≥1 jet: p_T >170 GeV
  - ΔR(γ, jet) > 0.5
  - Δη(γ, jet) < 2.0, Δφ(γ, jet) > 1.5





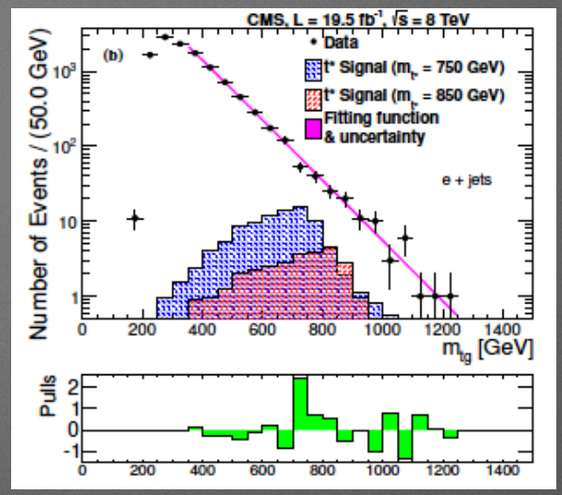


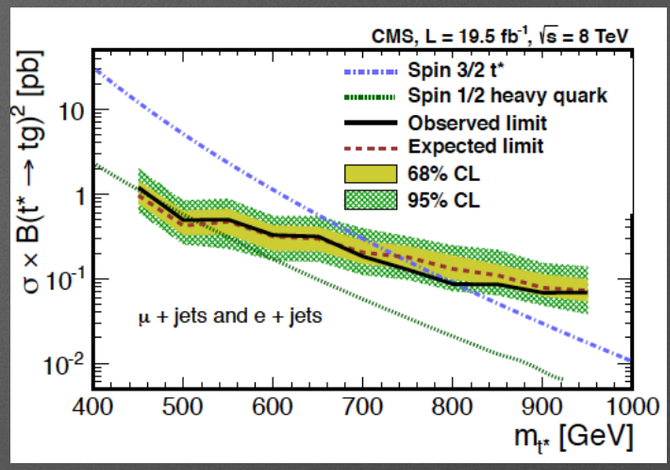
- Exclude masses below 3.5 TeV at 95% C.L for unit couplings to their SM partners

$t^* \rightarrow t + g$

[JHEP 06, 125 (2014)]

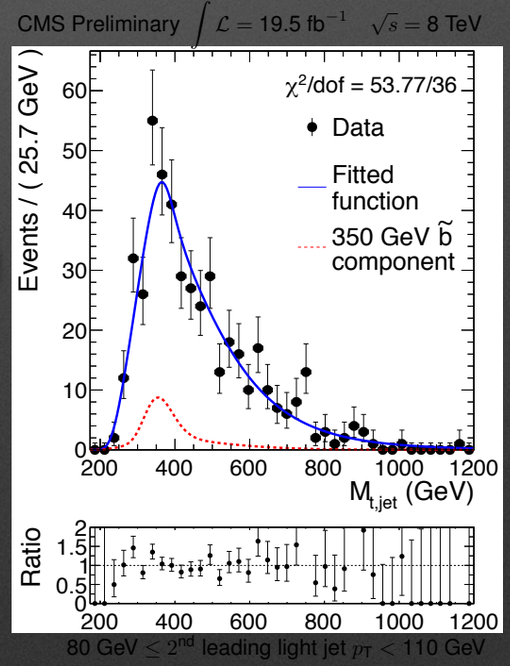
- Rich final state: tt + ≥ 2 jets
  - Do not reply on simulate of SM bkg
- Lepton+jets channel:
  - isolated lepton, ≥ 6 jets, ≥ 1 b-jet
  - mass reconstruction: M_{t+g}=m(lvbg)=m(qqbg)
  - background: fit to mass spectrum

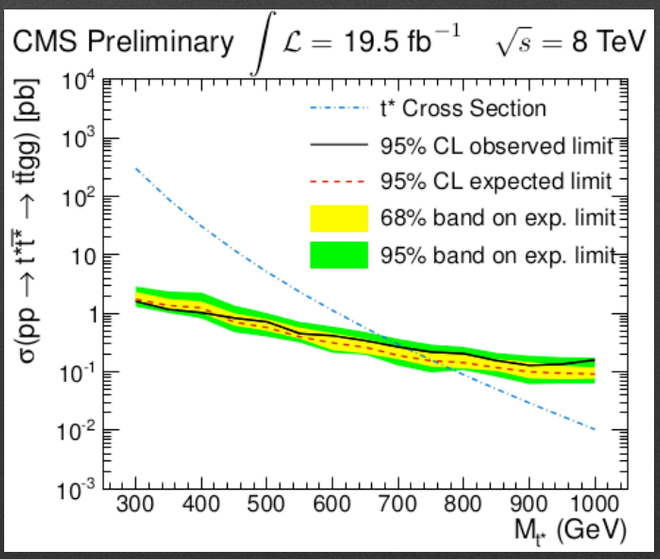




- Dilepton+jets channel:
  - 2 b-jets, 2 light-jets
    - fit background using jet p_T spectrum
- Exclusion limits:
  - l+jets: Exclude spin 3/2 t* resonances below 790 GeV (738 GeV expected)
  - dilepton: 717 GeV (754 GeV expected)

B2G-12-008

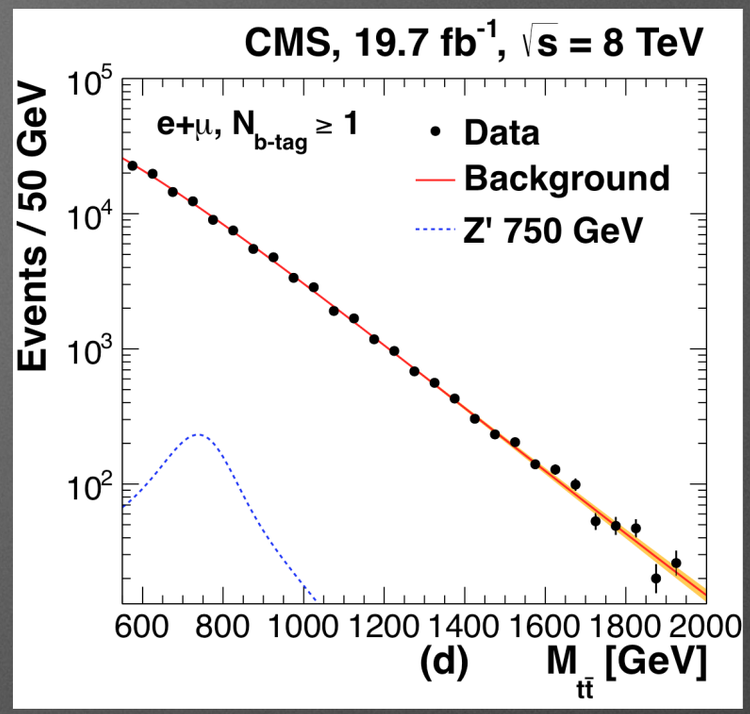


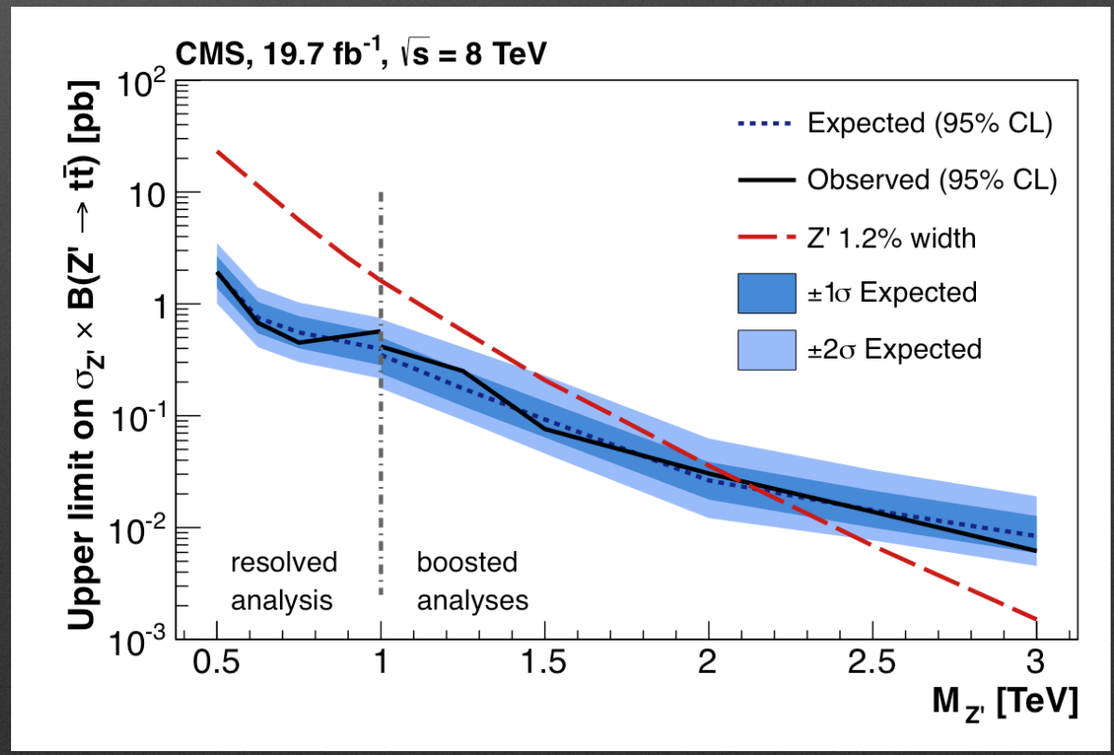


Z′→tt

[PRL 111, 211804 (2013)]

- **Threshold lepton+jet analysis**
  - Analysis technique similar to tt cross section measurement
  - low sensitivity at high mass: merged final state objects
- **Boosted lepton+jet analysis**
  - Non-isolated lepton selection and $N_{Jets} \geq 2$
- **Boosted all-hadronic analysis**
  - Based on dijet topology
  - Resolve substructure of jets: require 2 top-tagged jets
- **Combined limits**
  - $Z' \rightarrow tt$ (1% width): $M_{Z'} < 2.1$ TeV
  - Kaluza-Klein gluons: $M_{g^*} < 2.5$ TeV

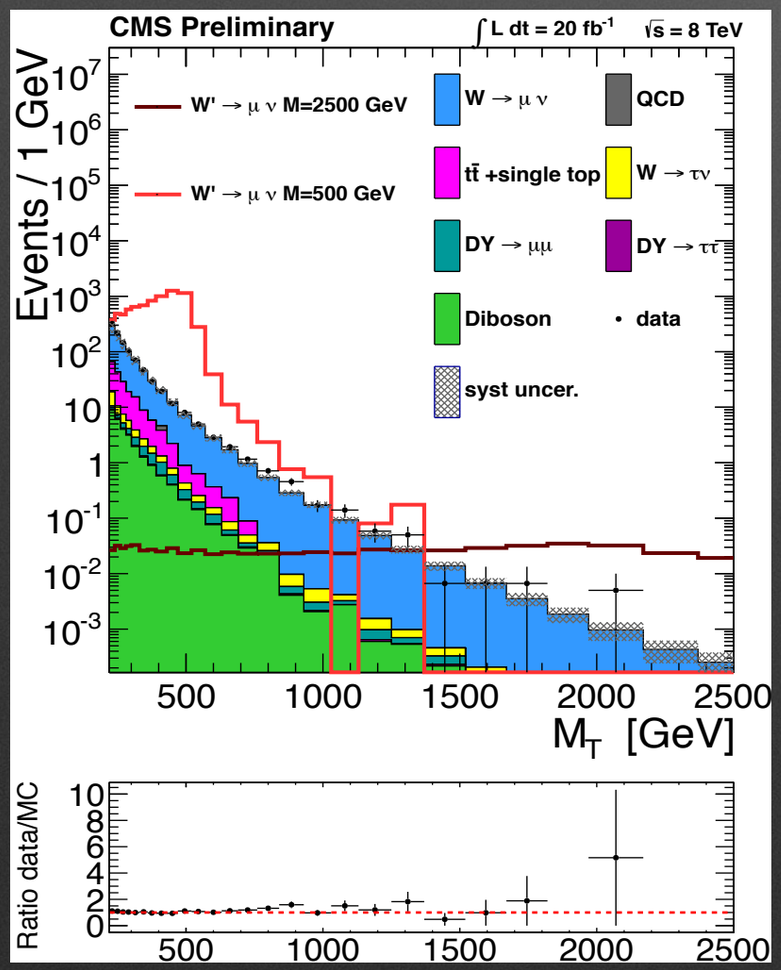


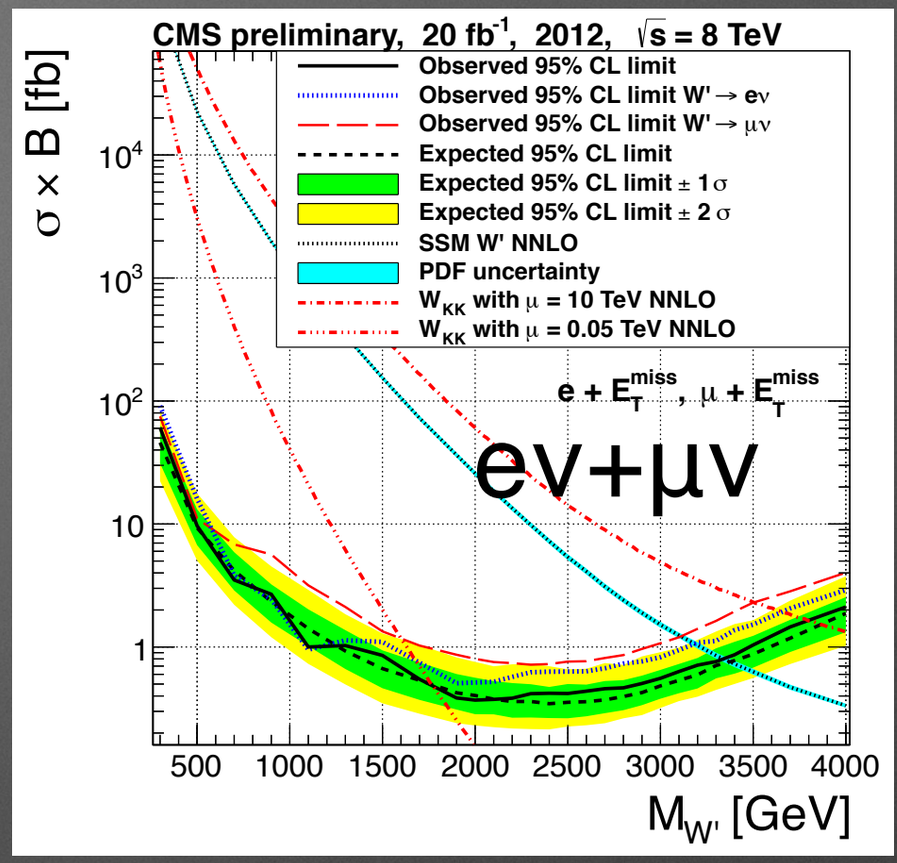


W′→l+ν

EXO-12-060

- **Lepton+MET**
  - lepton + jets selection:
    - 1 electron(muon) : p_T >100(45) GeV
    - 0.4 < lepton p_T/MET < 1.5
    - Δϕ(l,MET) > 0.8π
  - Look for Jacobian-Peak in M_T





- **Interference with SM W boson**
  - No interference: SSM W’
  - Constructive: Coupling of W’ has OS to coupling of W to f_L (SSMO)
  - Destructive: Coupling of W’ has SS to coupling of W to f_L (SSMS)

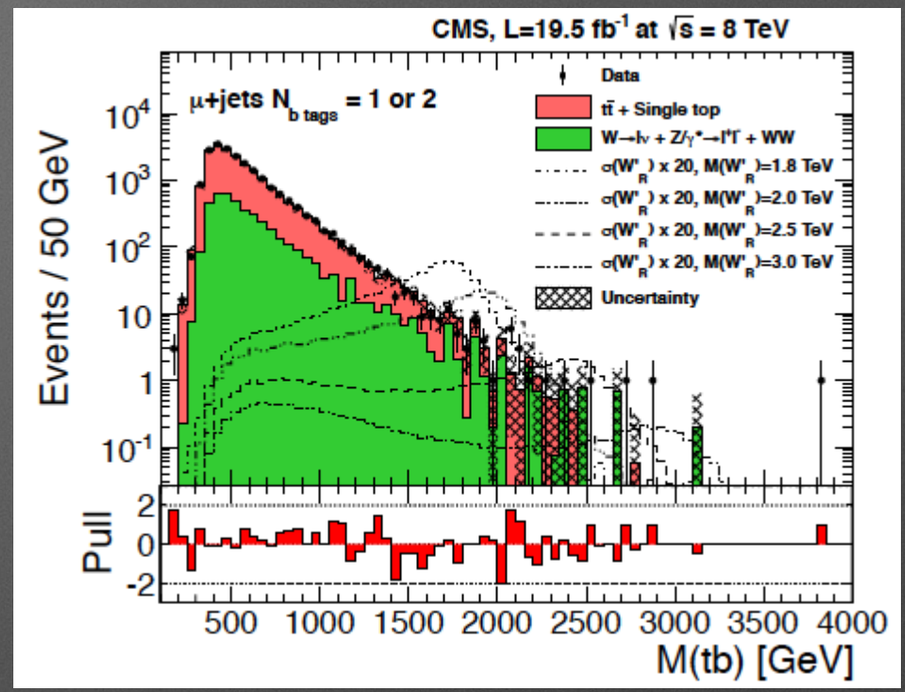
95% CL lower mass limit (in TeV)

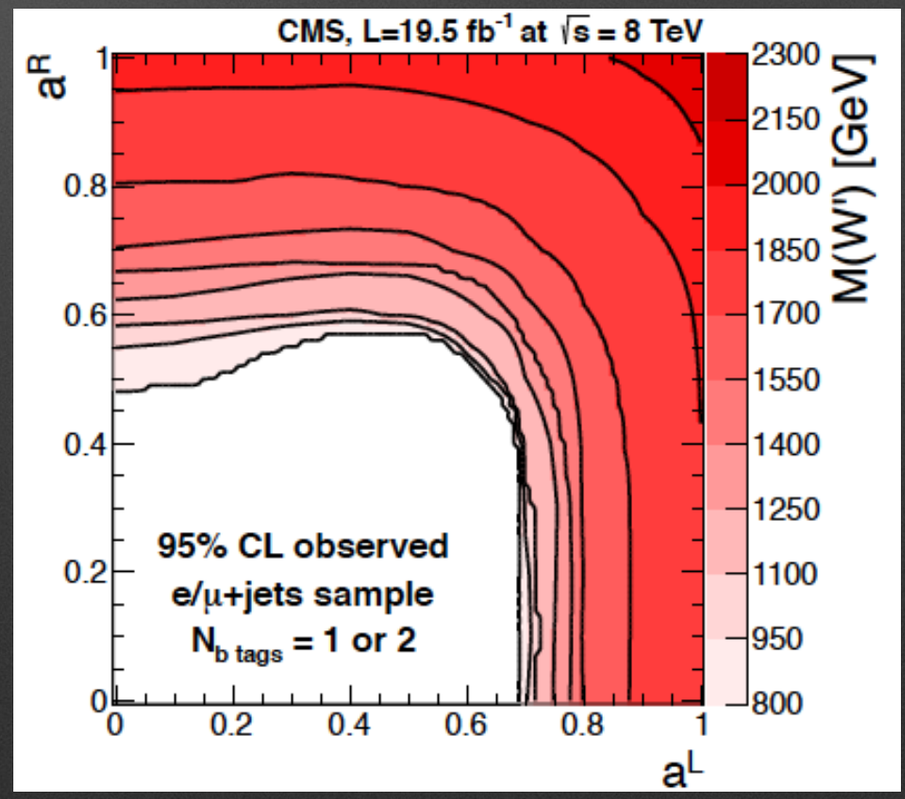
MODEL	OBS	EXP
W'_{SSM}	3.35	3.40
W’	3.60(3.10)	3.60(3.20)

W′→t+b

[JHEP 05,108(2014)]

- **Semi-leptonic analysis** t→W+b→(lν)+b
  - lepton + jets selection:
    - One isolated lepton (e, μ), $P_T > 50$ GeV
    - 2 jets: $P_{T1,2} > 120, 40$ GeV, at least one b-tag
  - Background reduction:
    - $P_{Ttop} > 85$ GeV
    - $130 < m_{top} < 210$ GeV
  - Exclusion limits:
    - $M(W'_R) > 2.03$ TeV (2.09 TeV expected) at 95% C.L.
    - Limits for left- and right-handed couplings

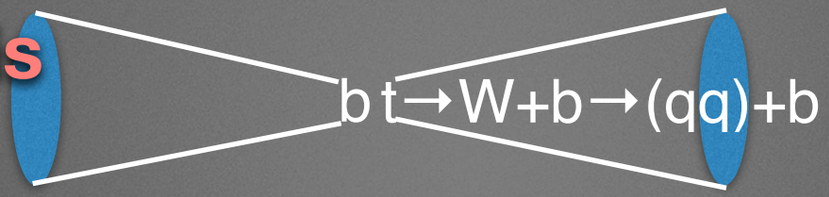




W′→t+b NEW!

B2G-12-009

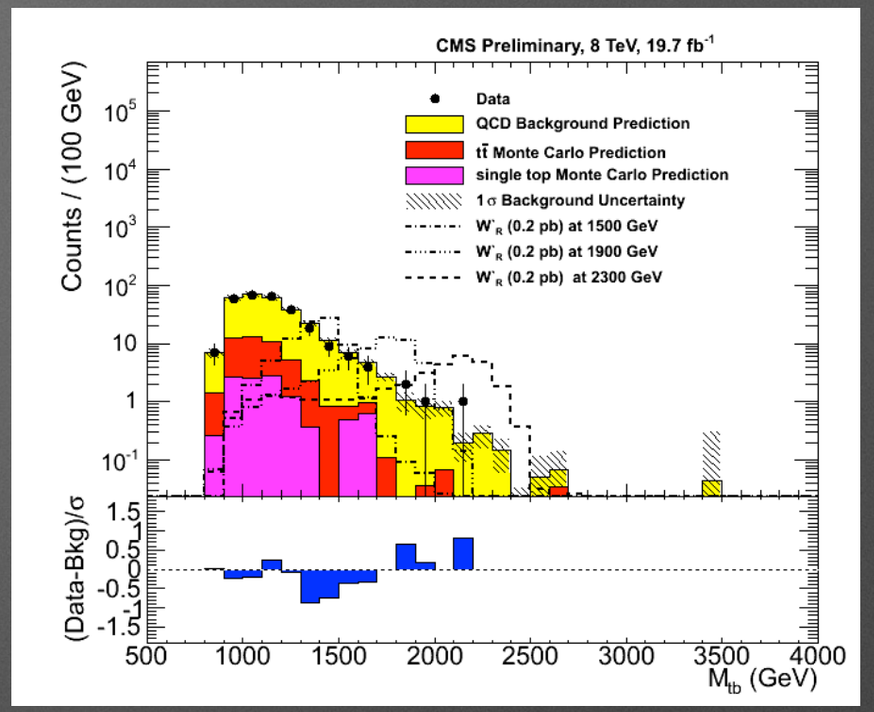
- **All Hadronic analysis**

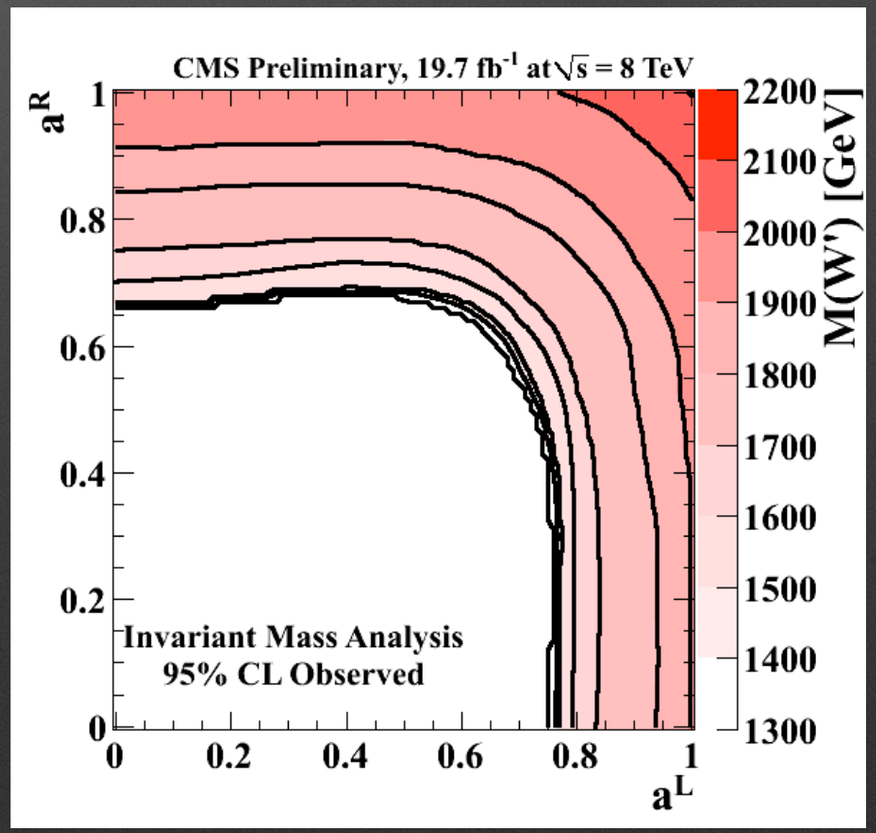


  - Top Candidate jet:
    - P_T > 450 GeV with CMS top-tagging algo
    - N-subjettiness
    - Subjet b-tagging

    } inverted to define control regions with similar kinematics

  - b candidate jet:
    - P_T> 370 GeV using CSVM b-tagging algo
    - m < 70 GeV
  - $|\Delta y|_{tb}$ < 1.6
  - Exclusion limits:
    - M(W'$_R$) > 2.00 TeV (1.99 TeV expected) at 95% C.L.
    - Limits for left- and right-handed couplings

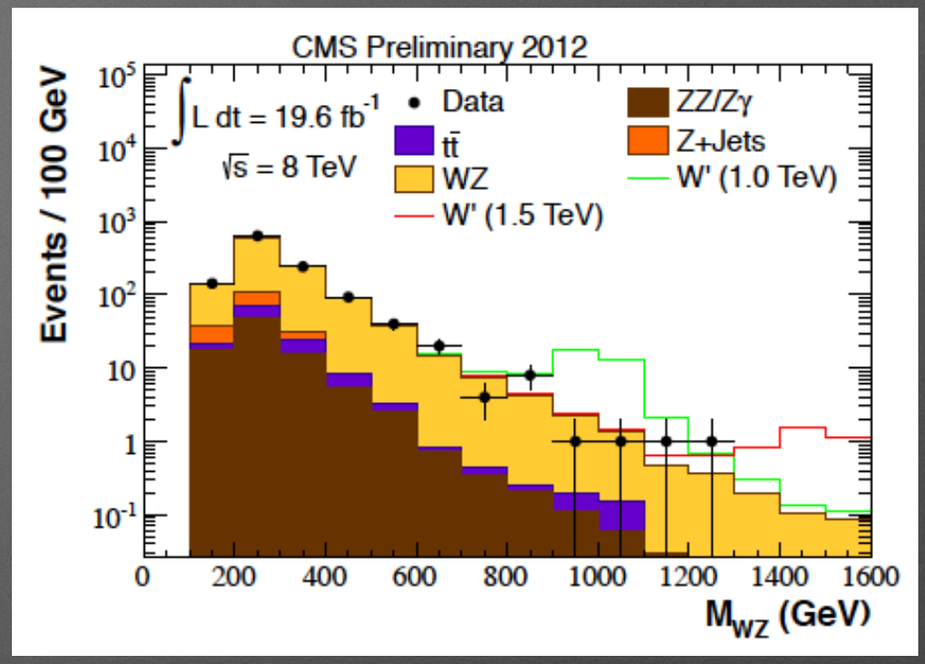


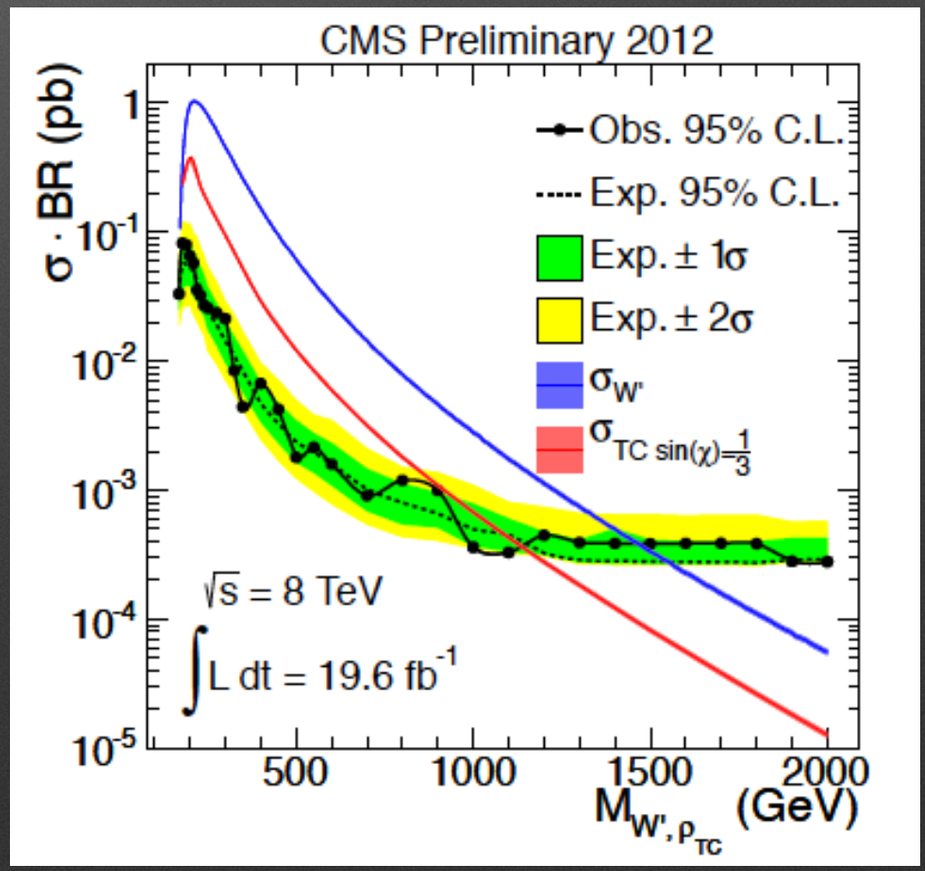


W′→WZ→lνll

EXO-12-025

- **Fully leptonic final state**
  - Select Z and W candidates
    - 4 final states: eνμμ, eνee, μνee, μνμμ
  - Background Reduction:
    - M_{3l} >120 GeV: Events close to Z mass
    - ΔR(W, Z) > 0.3: W from converted photons
  - Search for bump in M_{WZ} spectrum
    - Neutrino p_z from W mass constraint, optimize L_T = Σ p_T (l) and M_{WZ} for each mass hypothesis
  - Exclusion limits:
    - M(W′) are excluded for range [170, 1450] GeV
    - Low-scale technicolor models with the chosen parameters $M(\pi_{TC})$ = 3/4 $M(\rho_{TC})$- 25 GeV
      - Exclude ρ_{TC} for range [170, 1125] GeV





Vector-like quarks

- Top Partners cancels the top loop divergence in m_H and are light in all Natural Theories

See details by **Rebekka HOEING** at Alternate theory session on Tue, July 22nd

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{125\ \text{GeV}}{m_H}\right)^2 \left(\frac{M_P}{400\ \text{GeV}}\right)^2$$

- **Light Higgs** plus **Low Tuning** need **light Partners**

SUSY	**X-dim, Little Higgs, Composite Higgs…**
bosonic partners(stops)	fermionic partners

http://arxiv.org/abs/1205.0013
http://arxiv.org/abs/1211.5663

- What is “vector-like” about them?
- Charged current:
  - SM chiral quarks:
  - VLQ:

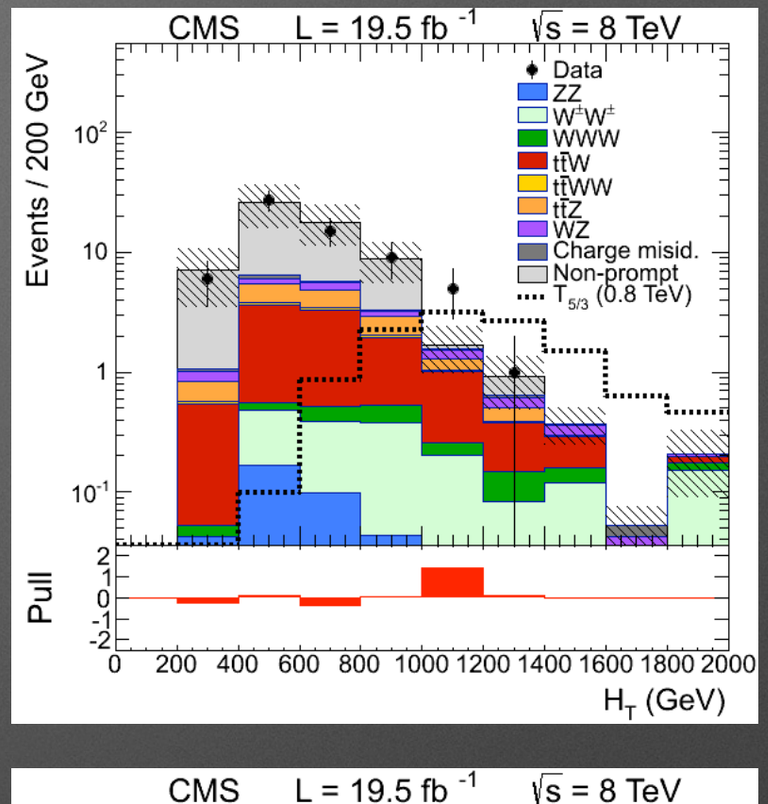
$$J^{\mu+} = J_L^{\mu+} = \bar{u}\gamma^\mu(1-\gamma^5)d = V - A$$

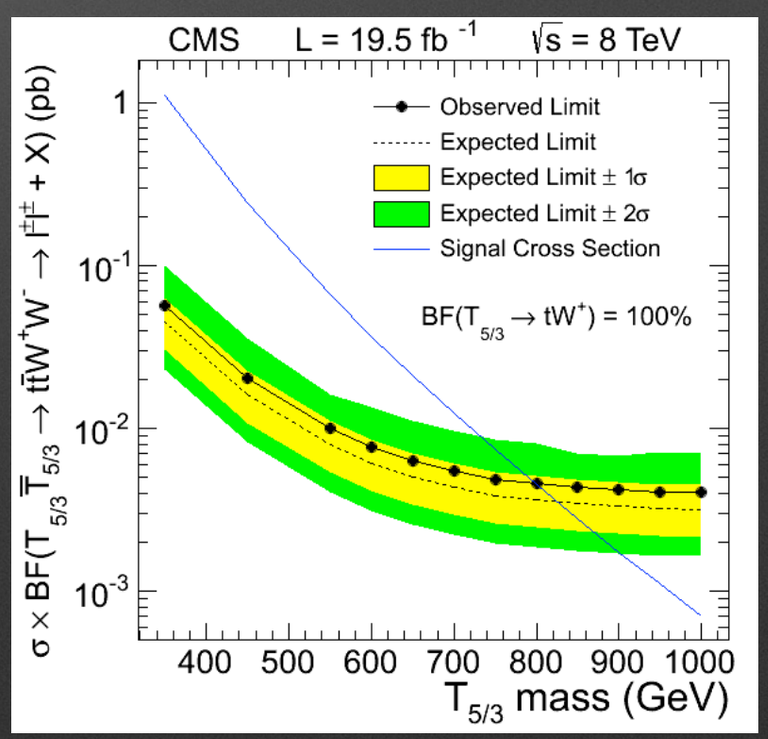
$$J^{\mu+} = J_L^{\mu+} + J_R^{\mu+} = \bar{u}\gamma^\mu d = V$$

$T_{5/3} \rightarrow t+W$

[PRL 112, 171801 (2014)]

- **Same Sign dilepton**
  - ee, eμ, μμ channels
  - Background reduction: Vetos Quarkonia, Dilepton and Trilepton Z boson
  - Possibility to have merged jets at high mass
  - Count constituents, taking into account subjets from W- and top-jets: $N_C \geq 7$
  - Reconstruct $M_{T5/3}$ for $H_T > 900$ GeV
  - Exclusion limits
  - $M_{T5/3} < 800$ GeV (830 GeV expected)

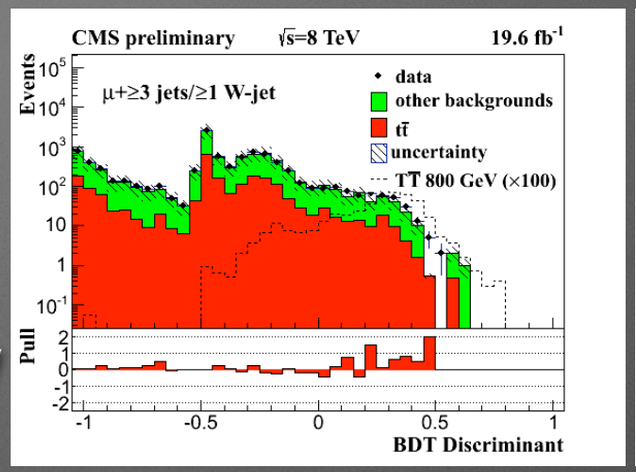


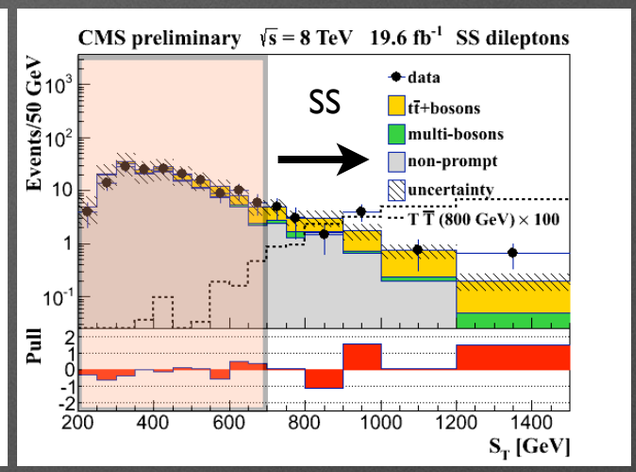


T→bW, tZ, tH

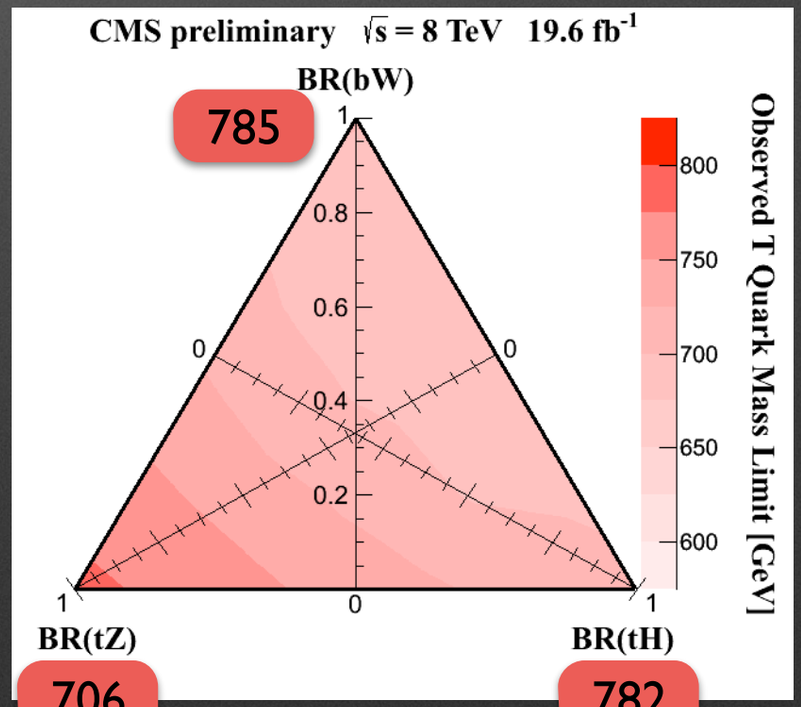
[PLB 279, 149 (2014)]

- **Inclusive lepton**
  - Single-lepton channel
    - Hadronic W-tag and top-tagging
    - optimized for best overall sensitivity
    - BDT trained with BR of 0.50 : 0.25 : 0.25 = bW : tZ : tH





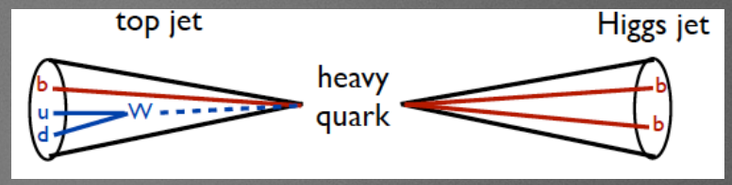
- **Multi-lepton channel**
  - Binned likelihood fir for 12 different channels in high ST regions
  - Categories: OS dilepton (On/Off Z), SS dilepton and Trileptons
- **Exclusion limits**
  - A mass bound of [687, 782] GeV is set at 95% CL for all possible BR



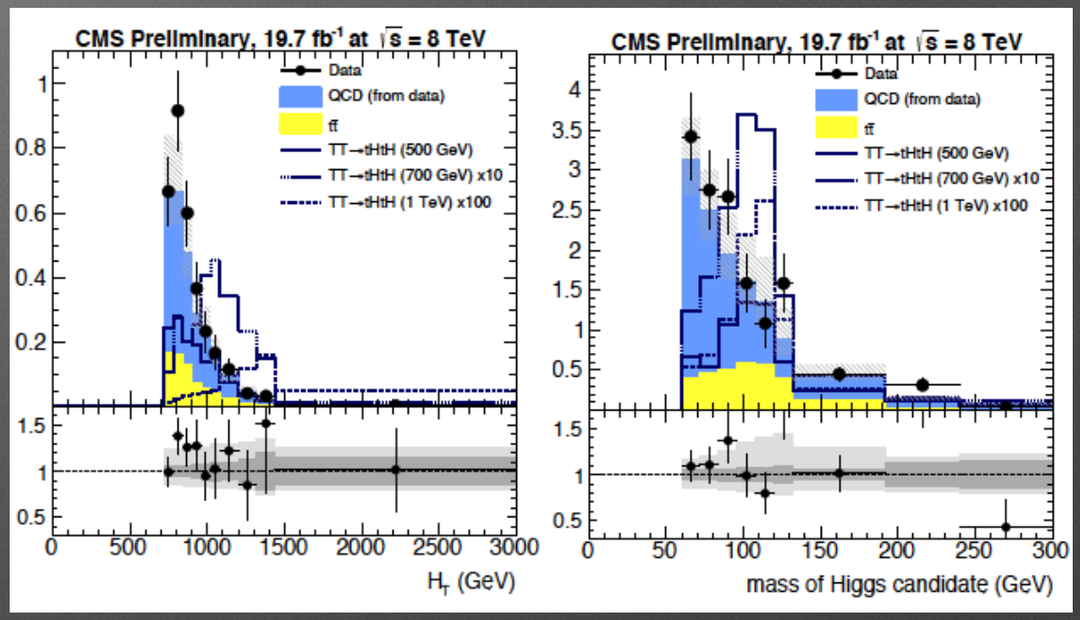
T→bW, tZ, tH NEW!

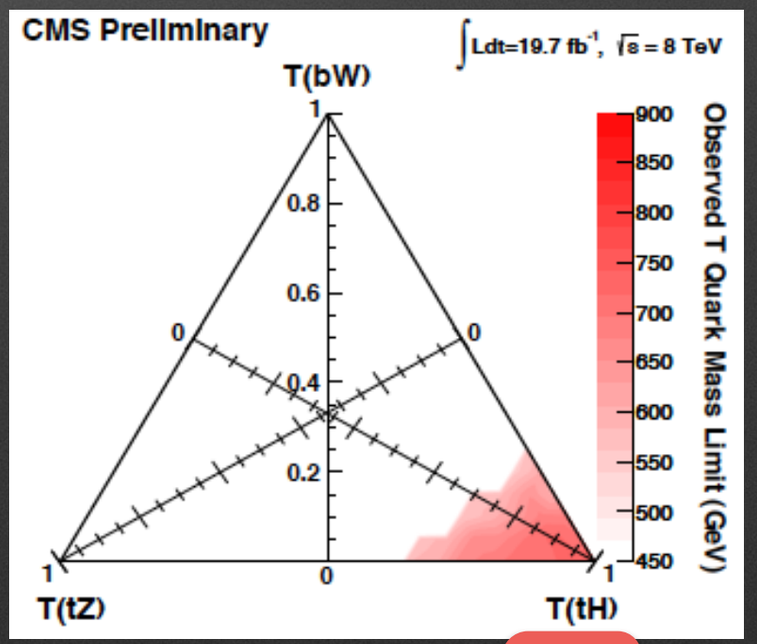
B2G-14-002

- **All hadronic analysis in tH, H→bb channel**



  - Special substructure analysis using subject b-tagging
    - 1 HEP top-tagger jet and 1 or 2 H→bb jets
  - H_T>720 GeV, subjets in H_T have p_T>150 GeV
  - In addition to double b-tagging, require m_H>60 GeV
  - Exclusion limits
  - A mass bound of [687, 782] GeV is set at 95% CL for all possible BR





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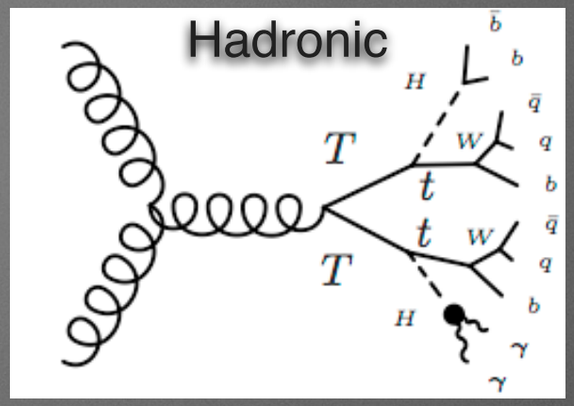
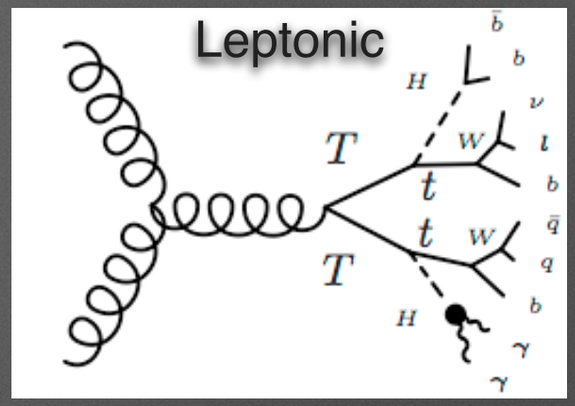
T→bW, tZ, tH NEW!

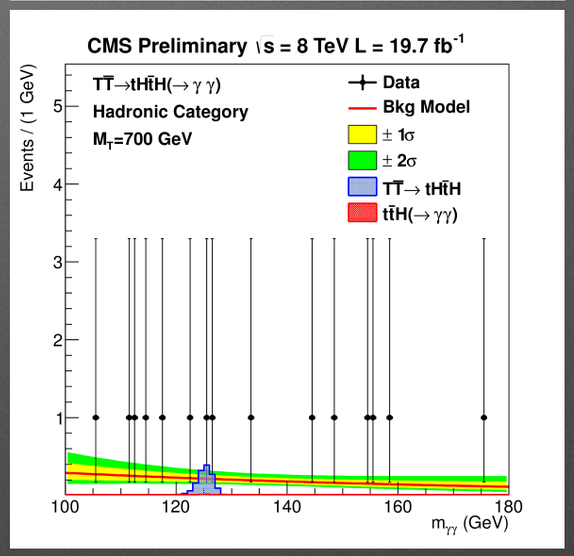
B2G-14-003

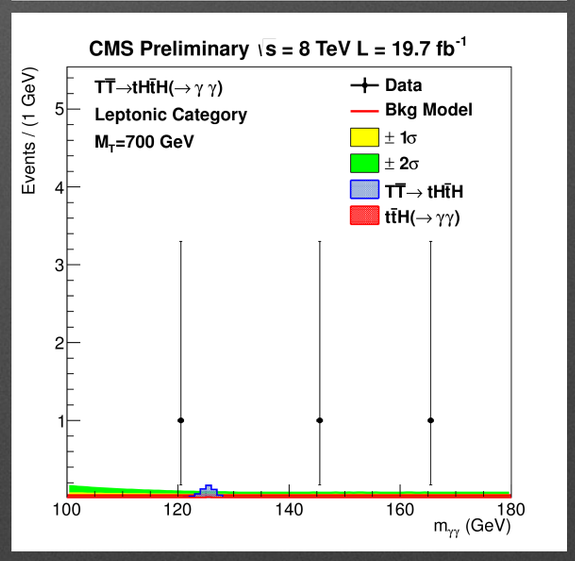
- **Hadronic and leptonic analysis in tH, H→γγ channel**
  - Event Selection

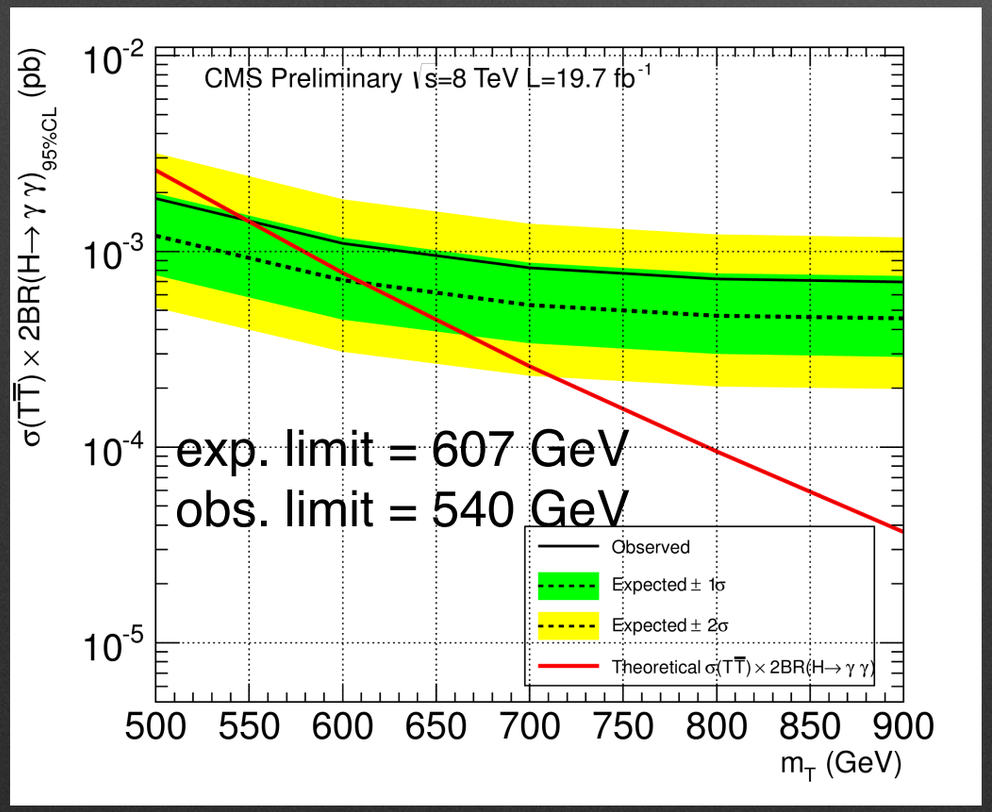
Variable	Hadronic channel	Leptonic channel
$p_T^{lead\ photon}$	$> \frac{3}{4} m_{\gamma\gamma}$ GeV	$> \frac{1}{2} m_{\gamma\gamma}$ GeV
$p_T^{sublead\ photon}$	35 GeV	25 GeV
n_{jets}	≥ 2	≥ 2
H_T	≥ 1000 GeV	≥ 770 GeV
leptons	0	≥ 1
b tags	≥ 1	-











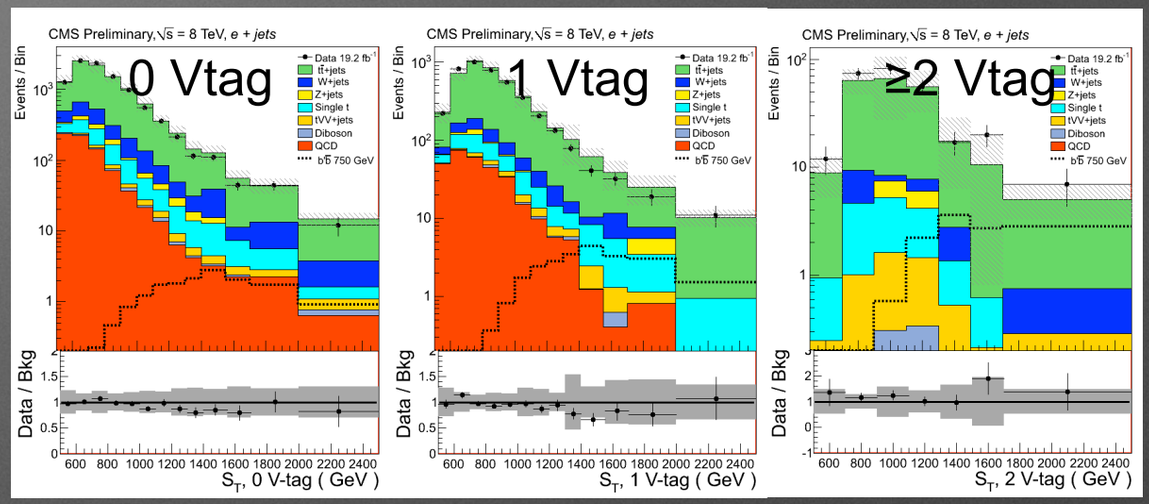
- Strategy: Exploit the **narrow resonance** of H→γγ, by fitting the peak in Mγγ distribution and $S_T > 1$ TeV
- Search is limited by statistics, yet a very powerful analysis for Run 2

B→tW, bZ, bH

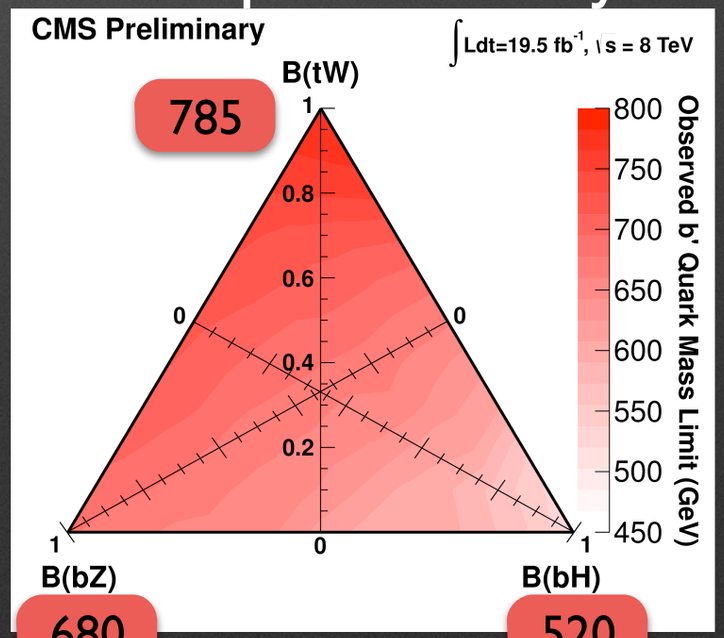
B2G-12-019, B2G-12-021, B2G-13-003

- **Single, di, and multi-lepton analyses**
  - lepton selection and high p_T jets
  - Extract limits from S_T or M_B variables
  - **Single-lepton:** classify events according to hadronic W-tag
  - **multi-leptons:** different search regions in SS and OS lepton pairs and S_T bins
  - **OS dilepton:** Reconstruct the B mass
  - **Exclusion limits**
    - Limits on B mass between 520-785 GeV

e/μ analysis



multi-leptons analysis



Leptoquarks

- New bosons that carry both lepton and baryon number are predicted by many BSM theories: GUTs, Composite models, Technicolor
- Dominant processes for LQ pair production at LHC
    - gluon-gluon fusion & quark-antiquark annihilation
- Exact properties (spin, weak isospin, electric charge) depend on specific model: direct searches at the LHC →Buchmuller-Ruckl-Wyler model (BRW)
    - interact with SM fermions through coupling λ
    - preserves baryon and lepton number
    - couple to a single chirality and generation of SM fermions at a time
- BR, β is generally unknown, but {ll,lv,vv} + qq maximally produced for β = 1, 0.5, and 0

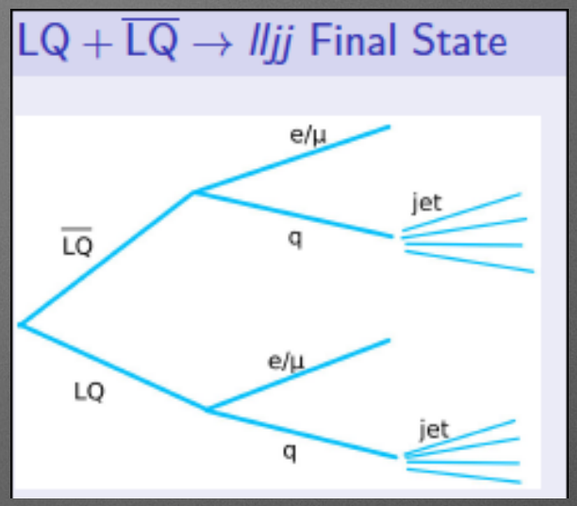
BR(LQ→lq) = β
BR(LQ→vq) = 1-β

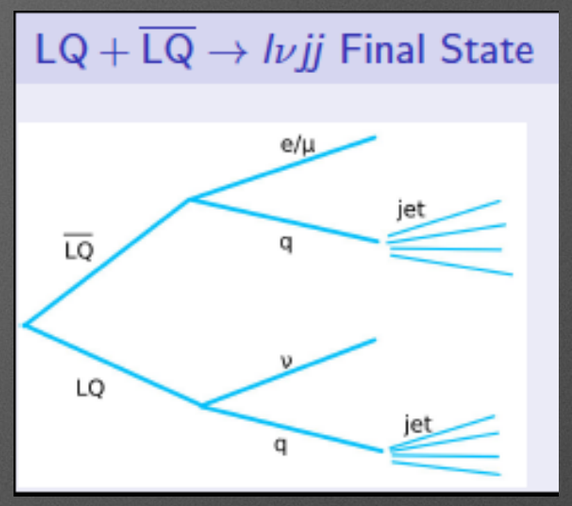
$LQ\bar{L}\bar{Q}$	β^2	$\beta(1-\beta)$	$(1-\beta)^2$
1st gen	$ee+jj$	$e\nu+jj$	n/a
2nd gen	$\mu\mu+jj$	$\mu\nu+jj$	n/a
3rd gen	$\tau\tau$+bb,tt	n/a	$\nu\nu$+bb,tt

LQ1 and LQ2 in lljj , lvjj NEW!

- lljj analysis: β = 1
  - M_{ll}, M_{lj}
  - $S_T^{ll} = p_T(l_1) + p_T(l_2) + p_T(j_1) + p_T(j_2)$
- lvjj analysis: β = 0.5
  - MET, M_{lj}
  - $S_T^{lv} = p_T(l) + MET + p_T(j_1) + p_T(j_2)$

EXO-12-041, EXO-12-042

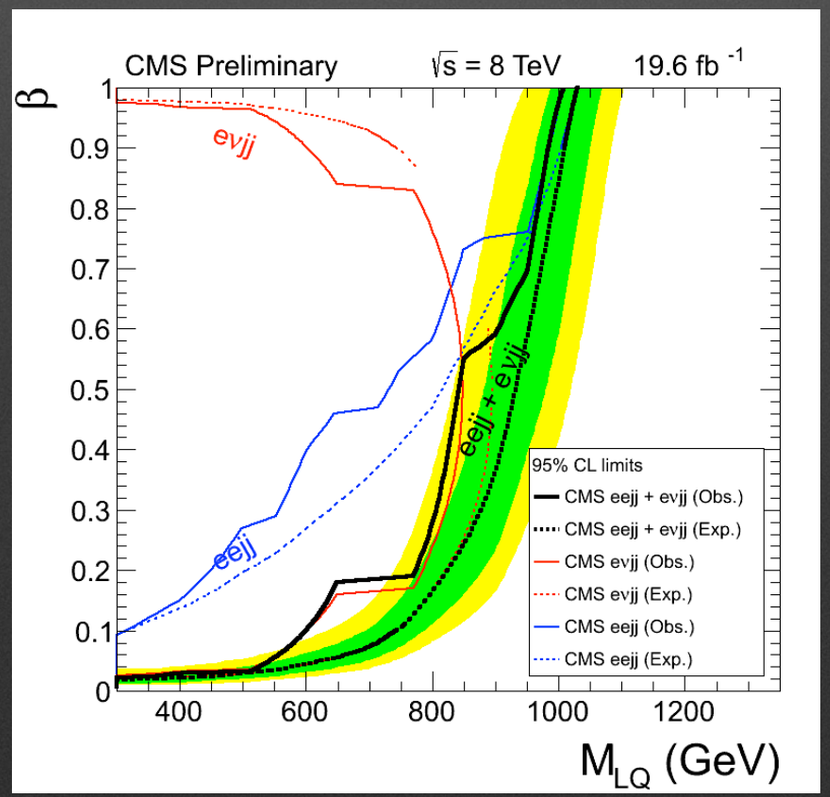


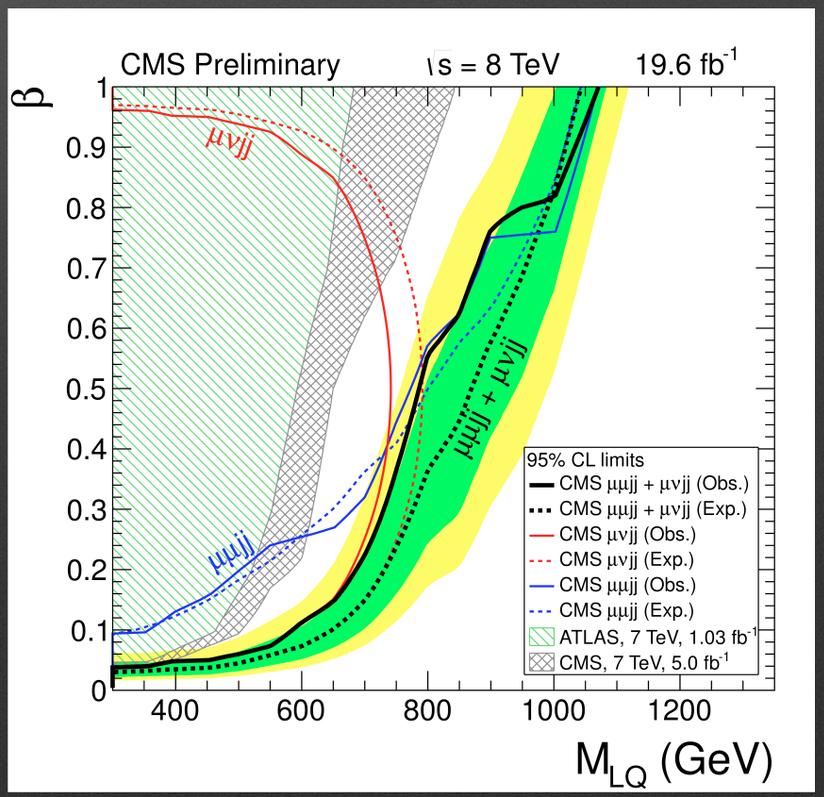


- Selections are optimized for each signal mass point including M_{lj} and S_T
- Exclusion limits

95% CL lower mass limit (in GeV)

	β = 1	β = 0.5
LQ1	830	640
LQ2	1070	785





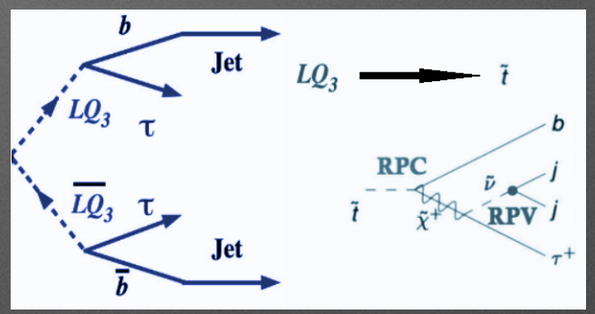
LQ3 and stop in ττbb

NEW!

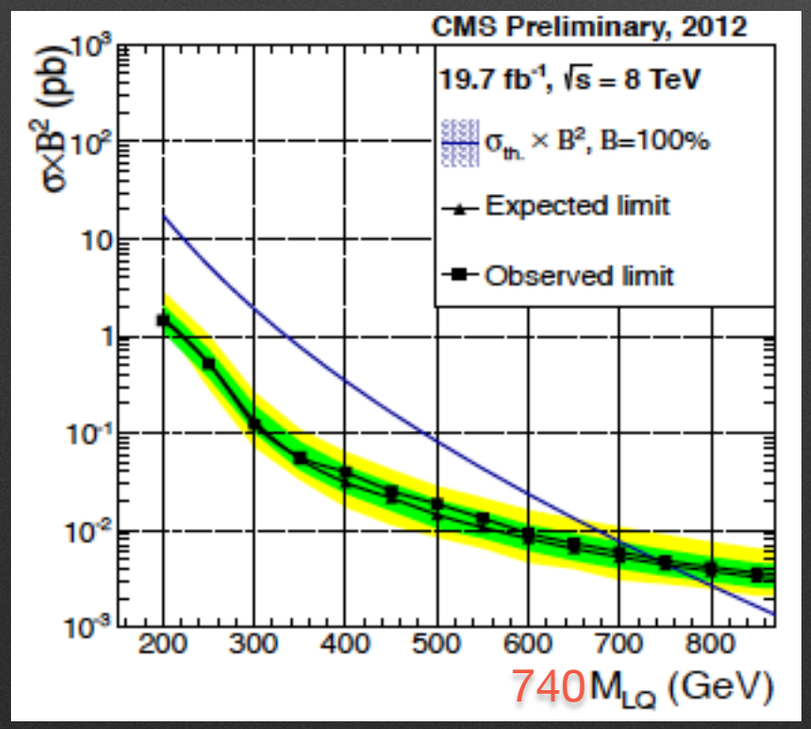
EXO-12-032

- Selection
  - Require one τ_l and one τ_h
  - e, μ: $p_T > 30$ GeV and veto 2nd lepton
  - τ_h: $p_T > 50$ GeV
- Strategy
  - $S_T = p_T(l) + p_T(\tau_h) + p_T(j) + p_T(b)$

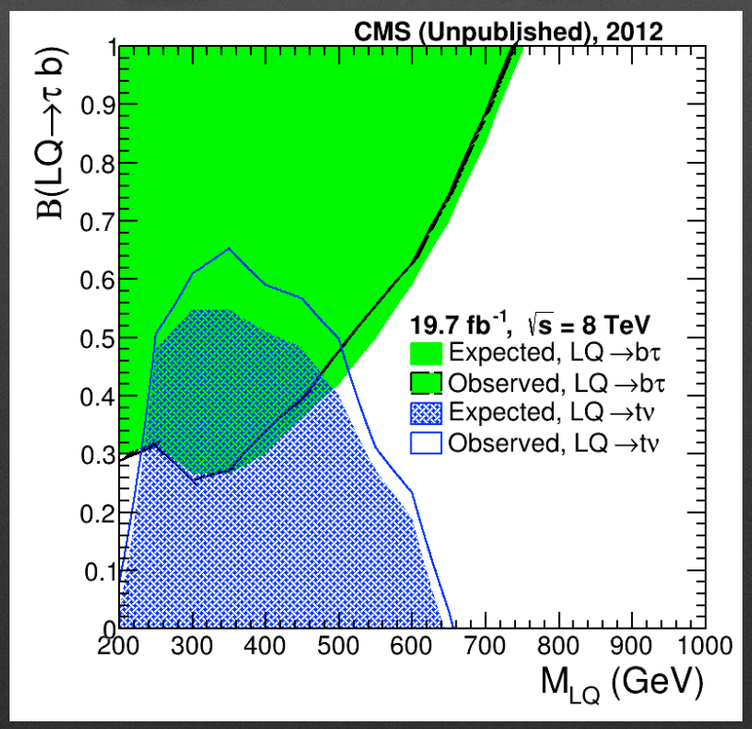
- LQ3 analysis
  - ≥ 2 jets, ≥ 1 b-jet, $M(\tau_h, j) > 250$ GeV
- Stop analysis
  - ≥ 5 jets, ≥ 1 b-jet



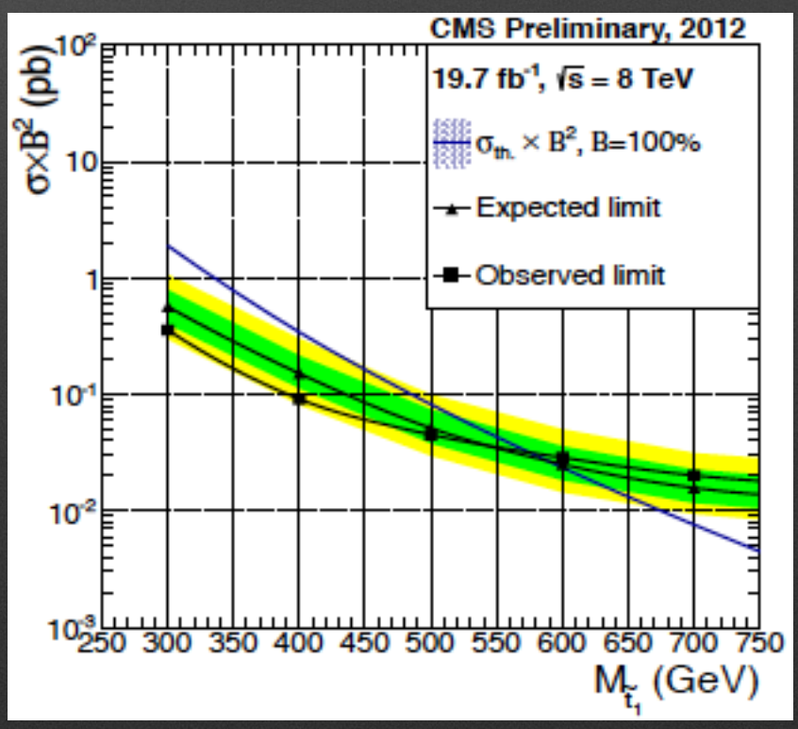
LQ3 < 740 GeV



LQ3→tν: SUS-13-011



$\tilde{t}$ < 576 GeV

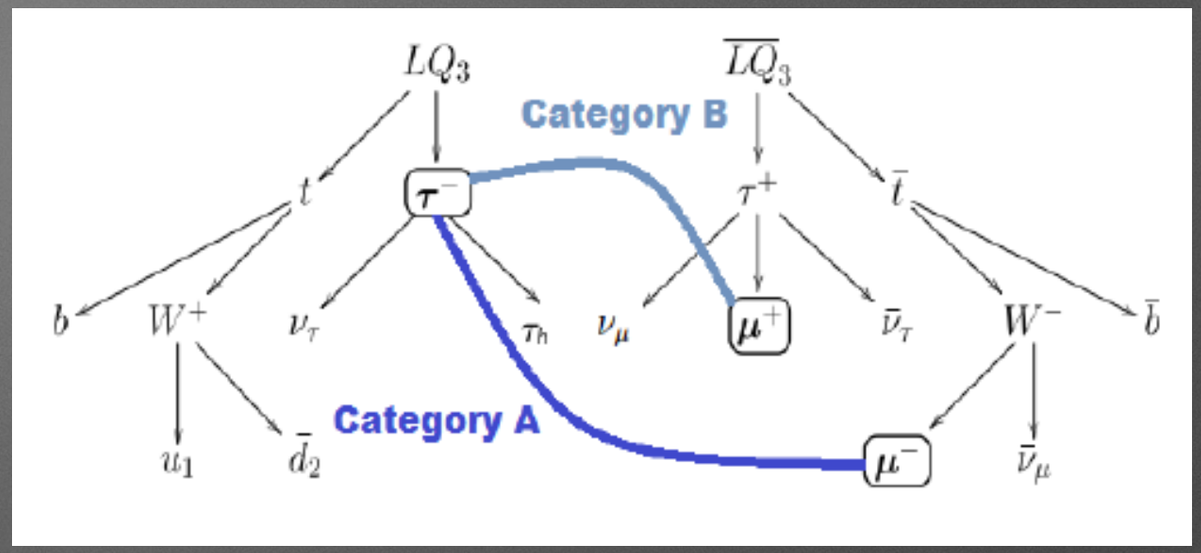


LQ3 in τττt

NEW!

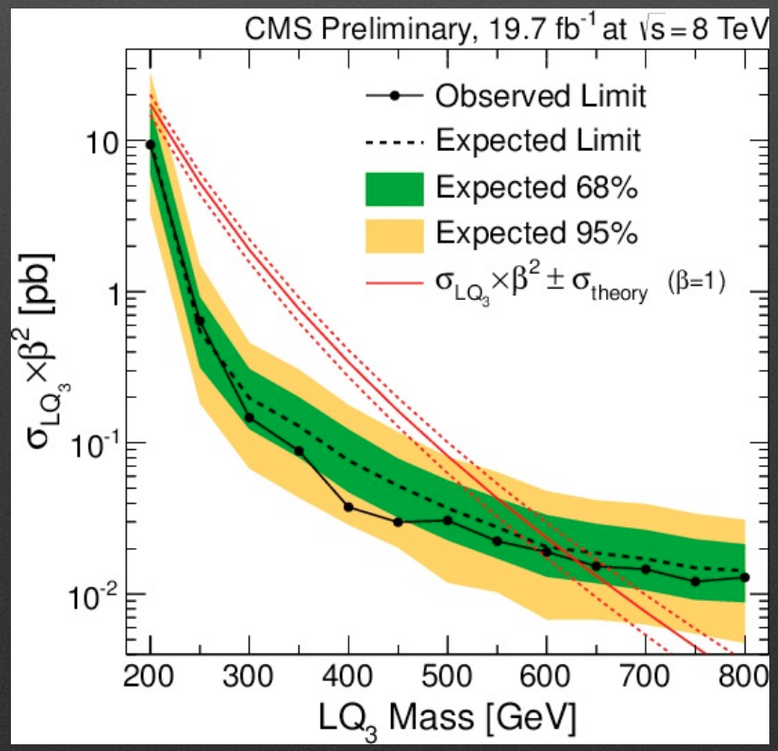
EXO-13-010

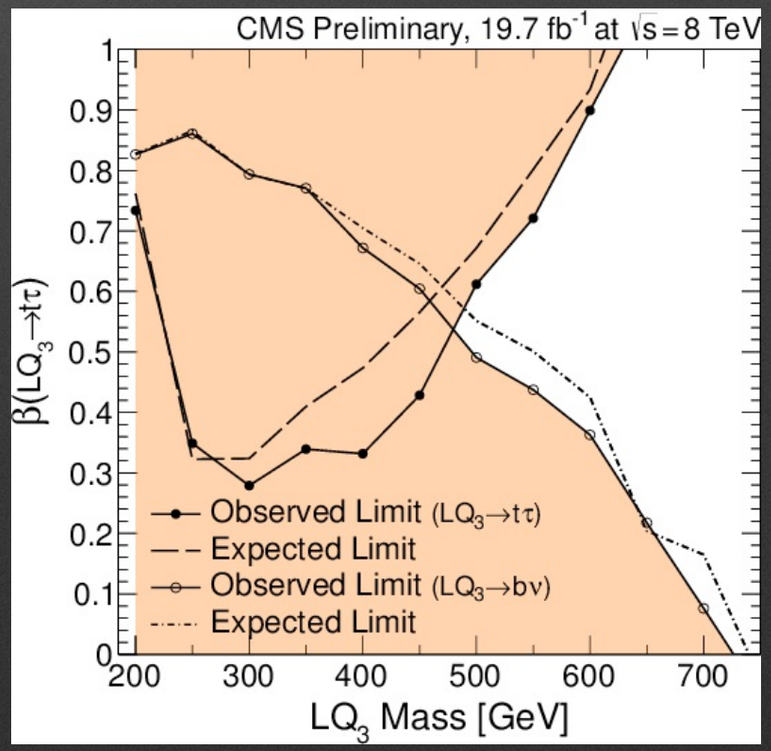
- Category A
  - Require one μ and one tight τ_h with same sign
  - ≥ 2 jets, $S_T > 400$ GeV
- Category B
  - Require one one μ and one loose τ_h
  - ≥ 3 jets, $S_T > 400$ GeV, MET > 50 GeV
  - Veto evt of category A
- Selections are optimized for each signal mass point for $p_T(\tau_h)$ and S_T



95% CL lower mass limit (in GeV)

	GeV
LQ	634 (β
LQ	724(β =0)

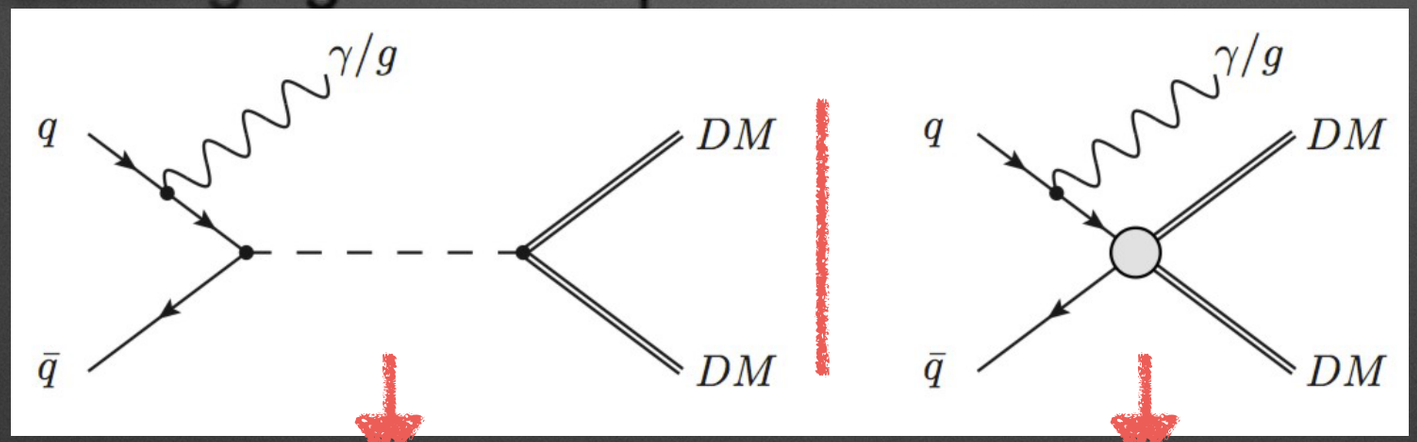


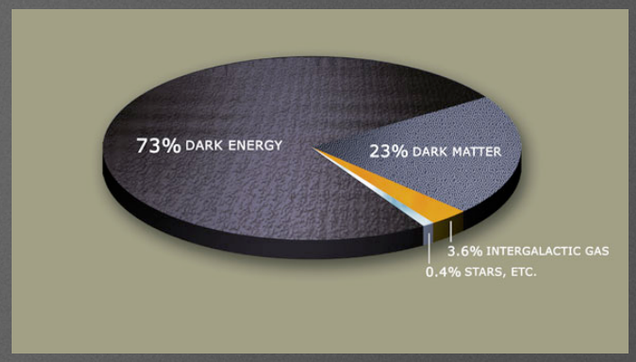


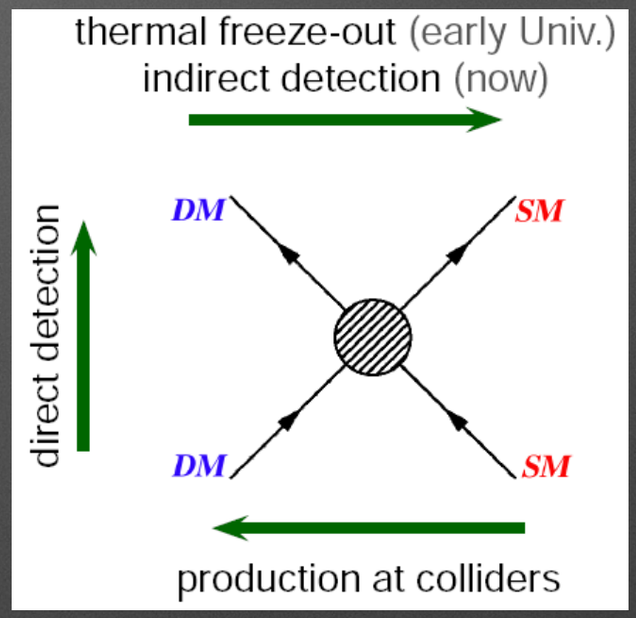
See details by **Bhawana Gomber** in Particle Cosmology session on Monday, Jul 21st

Dark Matter

- Strong astrophysical evidences for the existence of DM
- No unambiguous direct detection so far
- Production at colliders
  - DM produced in cascade decays from heavier new states: SUSY, Higgs portal
  - Pair production: higher-order diagrams provide probe recoiling against DM pair







- Simplified Models: Only SM + DM sector
  - Mediator and interactions specified explicitly
  - More parameter space to scan

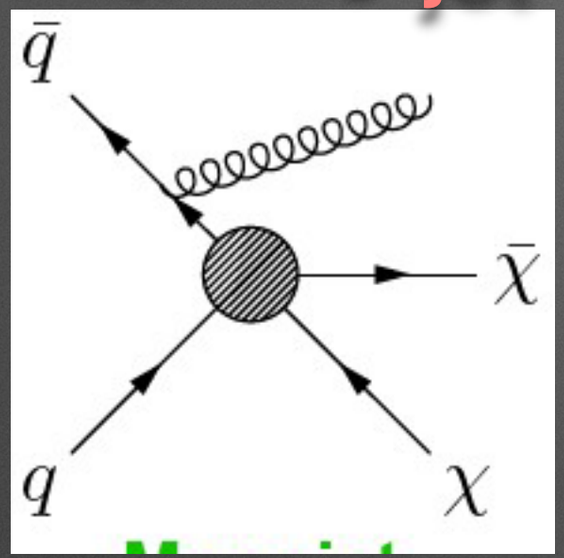
- Effective Theories: Collapse SM-DM interaction in effective 4-point operator
  - Parameters: m_{DM}, EFT scale $\Lambda = M_* = \frac{M}{\sqrt{g_\chi g_q}}$
  - Translate to DM-nucleon cross-section

$$\sigma(\chi N \to \chi N) \sim \frac{g_q^2 g_\chi^2}{M^4} \mu_{\chi N}^2$$

Mono-X Searches

EXO-12-048, EXO-12-047, EXO-13-004

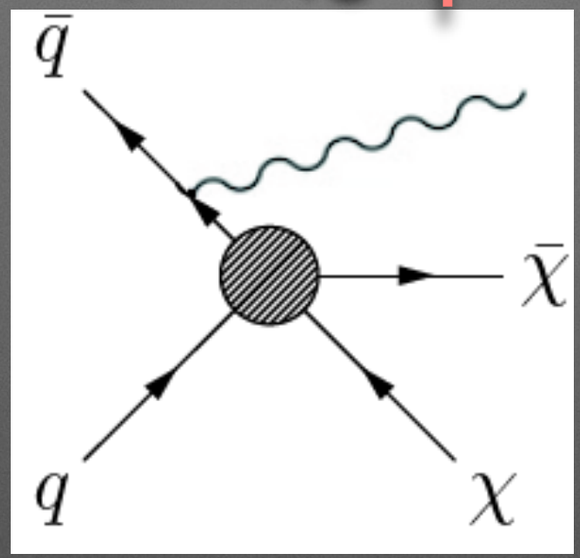
• Mono-jet



- Large MET from DM recoils against a jet/γ from QCD ISR

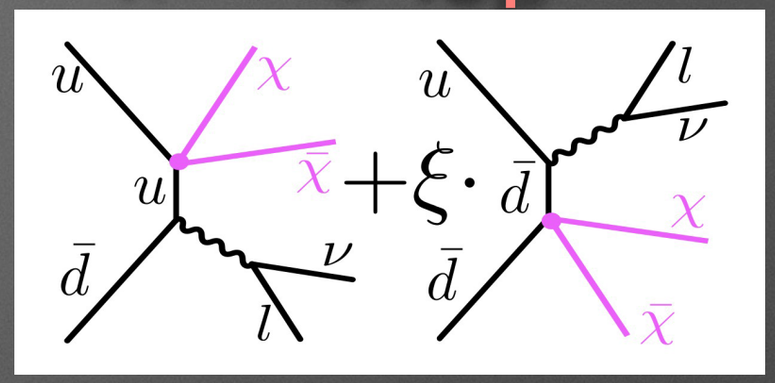
- MET > 250 GeV
- 1 central jet p_T > 110 GeV
- lepton Veto
- Bkg: Z→νν and W→lν from Z→μμ

• Mono-γ



- MET > 140 GeV
- γ p_T > 145 GeV
- Veto: lepton and hadronic activity
- Bkg: Z(→νν) γ, W(→lν) γ, W→eν, QCD, beam halo

• Mono-lep

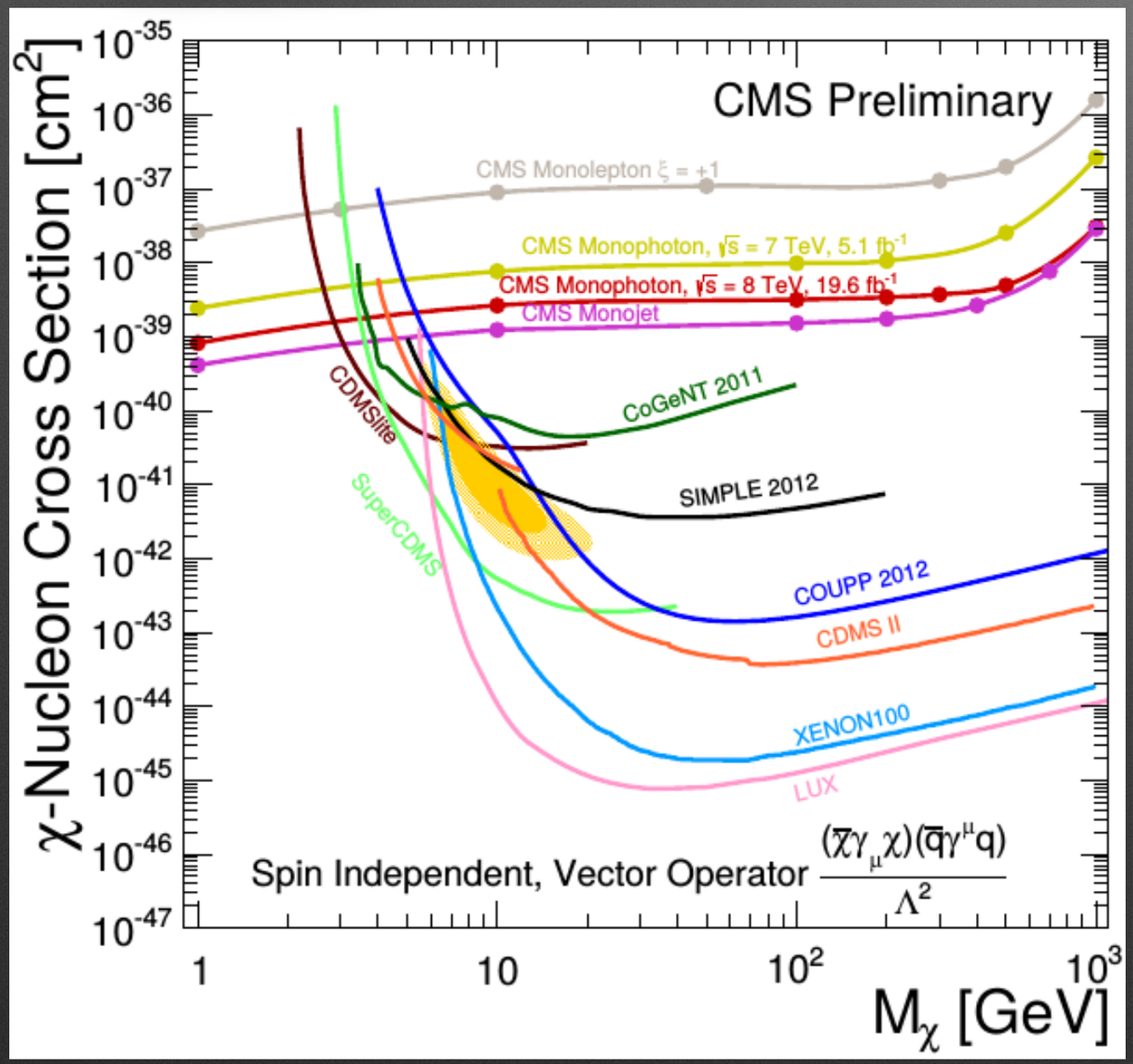


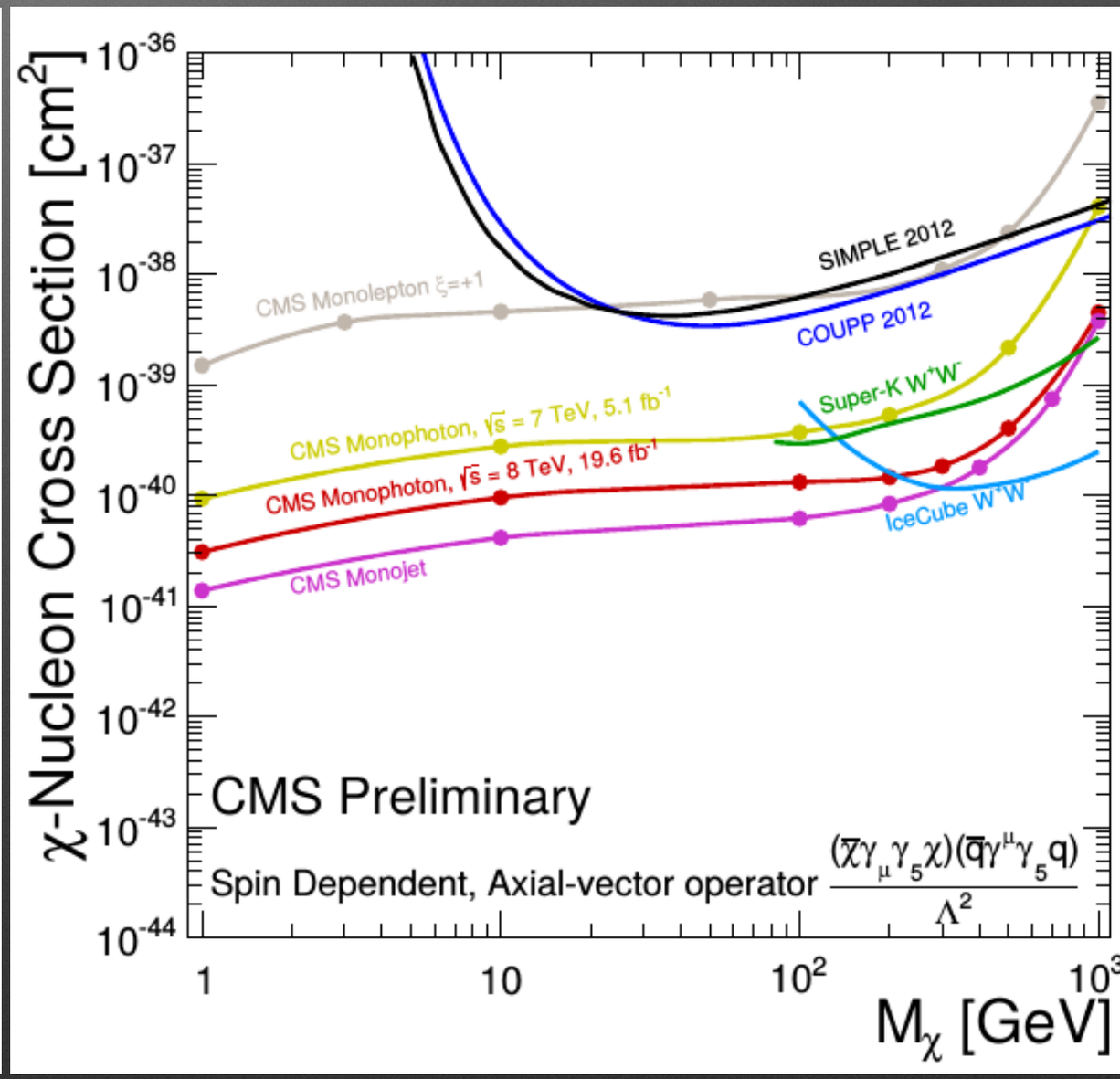
- DM pair produced along with a recoiling W boson
- Interference is destructive if coupling is the same
  - $uu \rightarrow \chi^0 \chi^0 = dd \rightarrow \chi^0 \chi^0$

- p_T (e / μ) > 100 / 45 GeV
- 0.4 < lepton p_T/MET < 1.5
- Δφ(e/μ, MET) > 0.8 π
- Bkg: W(→ ℓ ν)

Mono-X Searches

- Limits are set on EFT scale Λ using effective operators at 95%CL ⇒ limits on elastic DM-nucleon cross section versus DM mass
- Complementary, unique, coverage at low mass and strong sensitivity for spin-dependent interactions



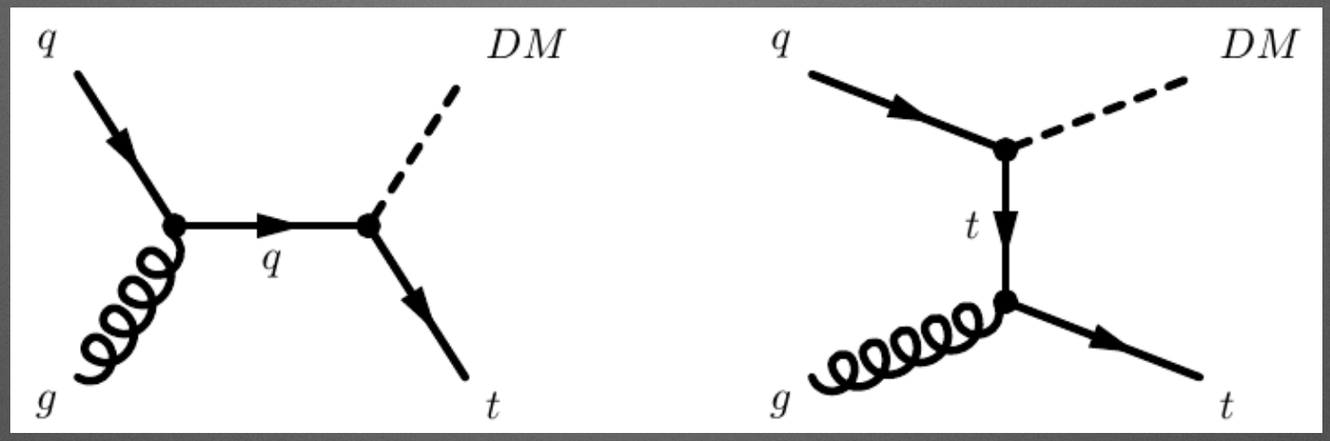


Mono-top Search

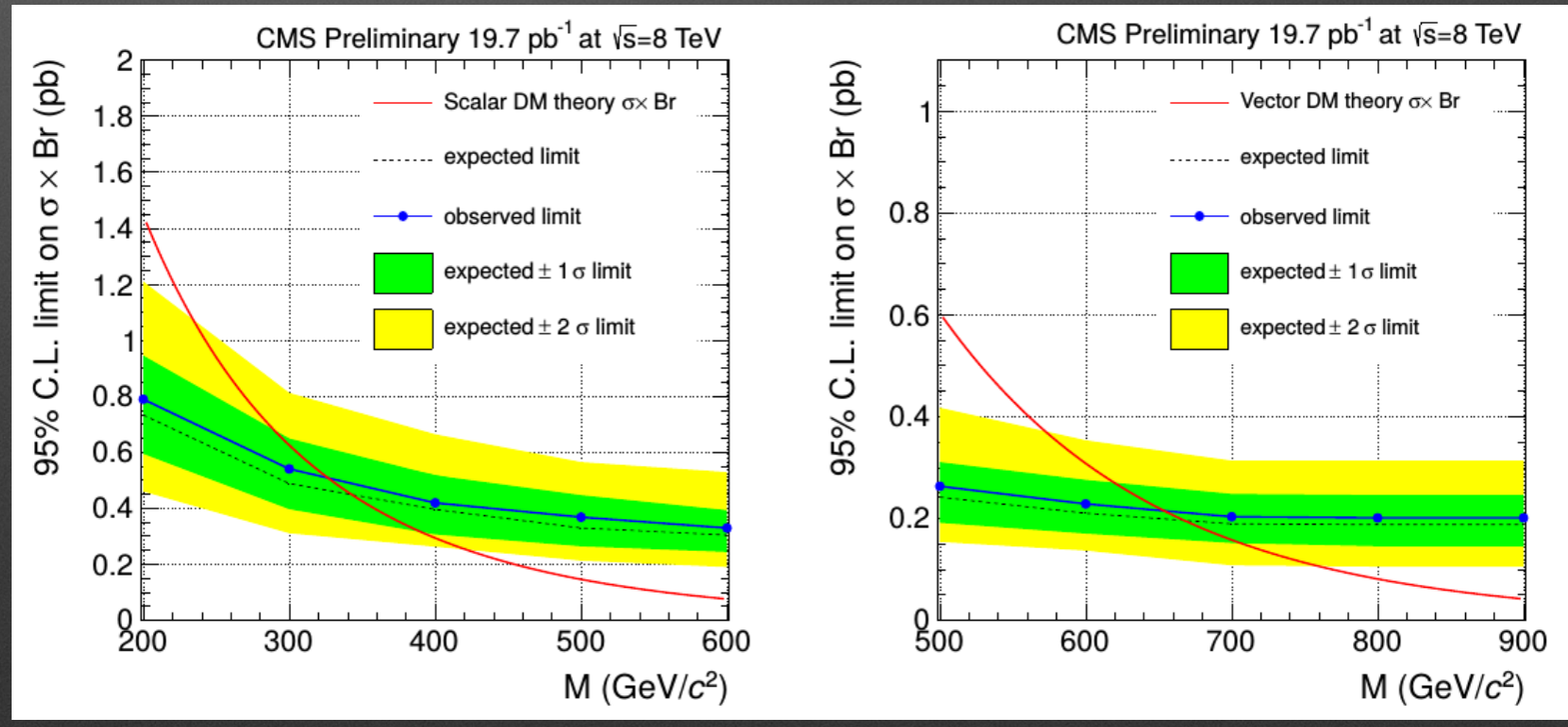
NEW!

B2G-12-022

- DM preferentially couples to heavy quarks through FCNC diagrams



- Selection
  - ≥ 3 jets, ≥ 1b-jet
  - MET > 350 GeV
  - Veto leptons
- Exclusion limit
  - Scalar DM < 327 GeV
  - Vector DM < 655 GeV

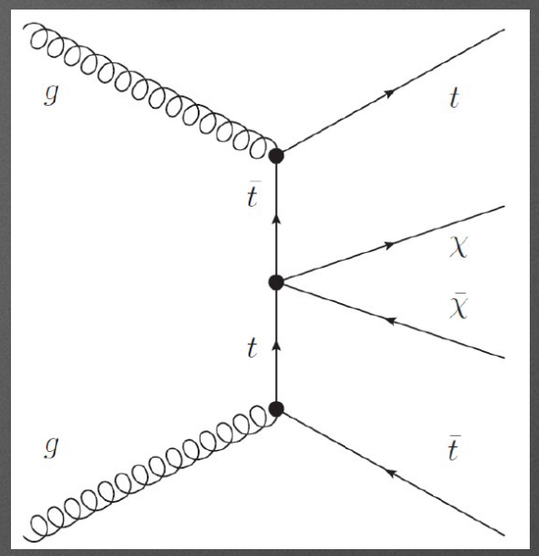


Di-top +MET Search

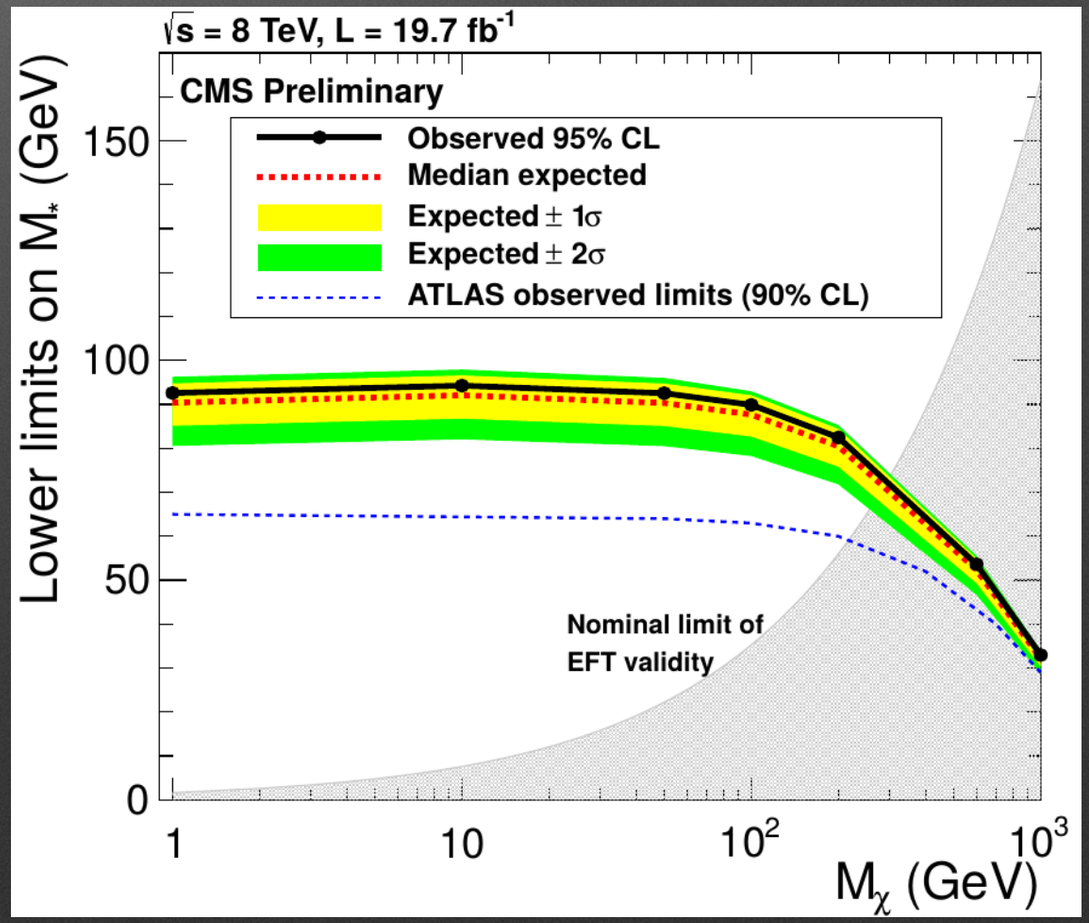
NEW!

B2G-13-004

- EFT scalar interaction least constrained $\mathrm{L_{int}} = \frac{m_q}{M_*^3}\bar{q}q\bar{\chi}\chi$
  - quark mass dependence top → coupling enhanced



- Selection
  - 2 electrons/muons
  - ≥ 2 jets
  - MET > 320 GeV
  - Veto leptons
  - Selections on scalar sums of leptons and jets, and lepton opening angle
- Exclusion limit
  - $\sigma > 0.09\ (0.24)$ pb excluded for $m_{DM} = 50\ (1000)$ GeV at 95% CL

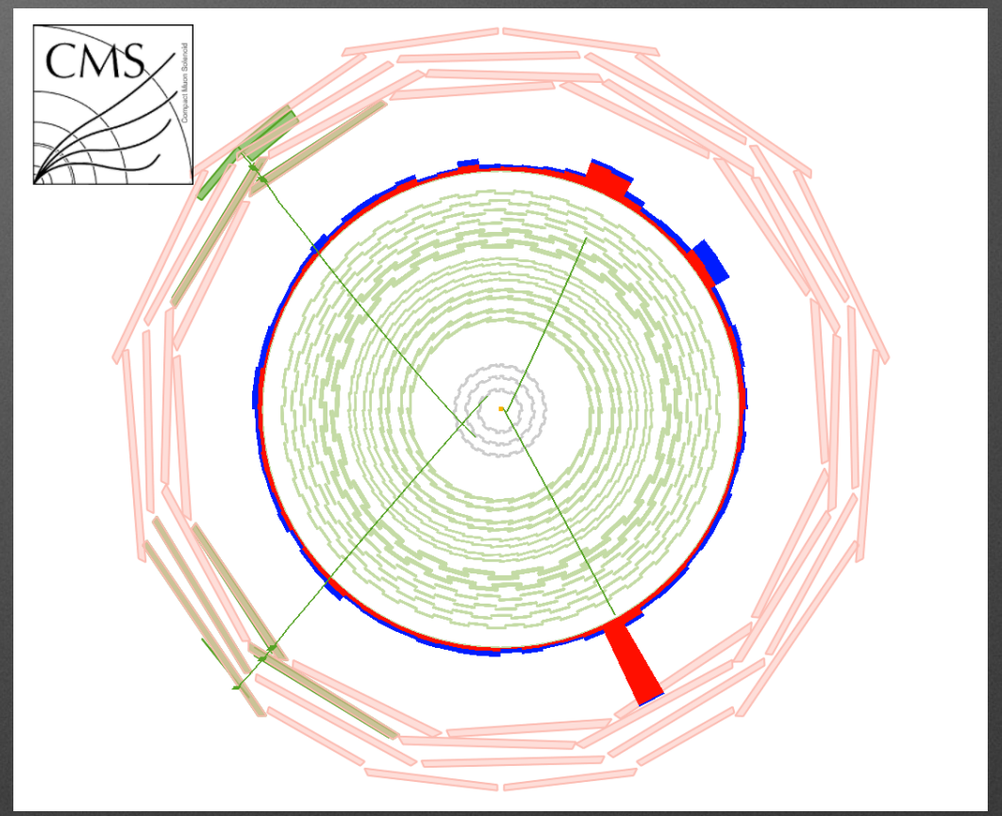


Long lived particles

- Searches for events where particles are produced or decay at a significant distance from the primary interaction
  - ⇒ Models: Hidden valley, weakly RPV

    SUSY, split SUSY with long-lived gluinos, Z' decays, little Higgs
- Small SM bkgs due to significant lifetime
- Standard triggers & reconstruction are **not optimal** for these objects
  - ⇒ a large amount of work is necessary

    to develop custom selections

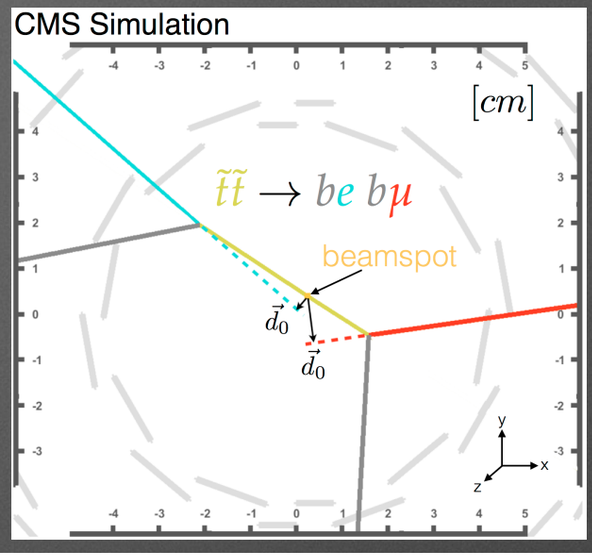


simulated displaced lepton event

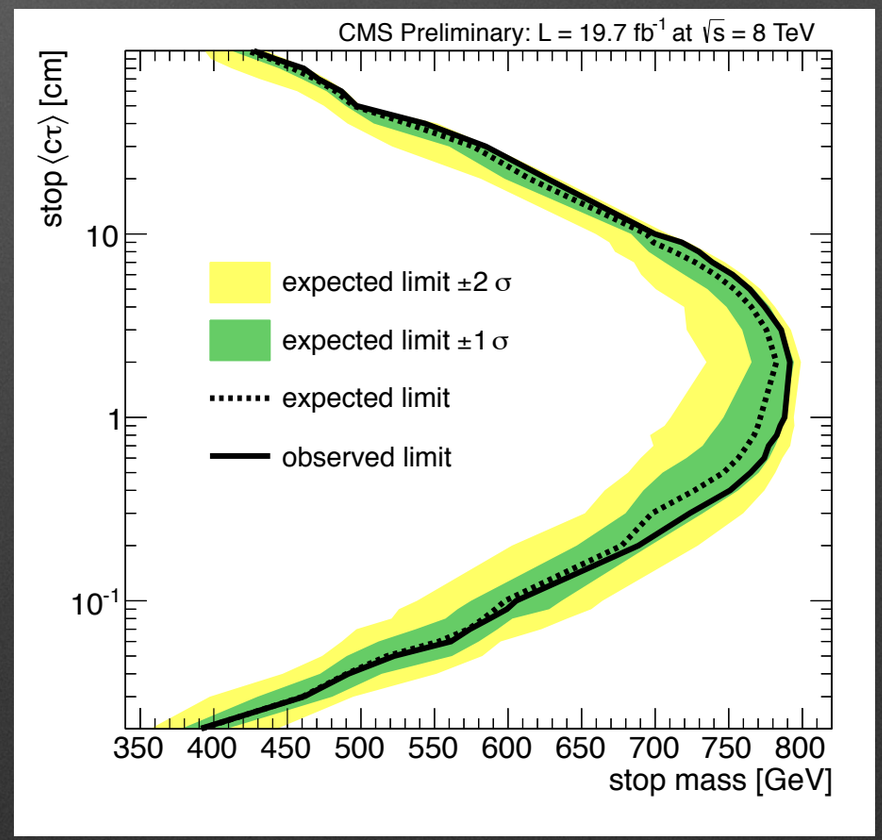
Displaced Dilepton: e, μ NEW!

B2G-12-024

- Model:
  - $\tilde{t}\,\tilde{t} \rightarrow bl\,bl$ with lifetimes ($c\tau \sim 100\mu m$ - 2 cm)
- Selection:
  - OS and isolated e and μ with no common vertex
  - Control regions: SS & non-isolated regions to derive QCD background estimate
  - Validation regions: control regions with smaller d0



Event Source	$0.02\text{ cm} < \lvert d_0\rvert < 0.05\text{ cm}$	$0.05\text{ cm} < \lvert d_0\rvert < 0.1\text{ cm}$	$\lvert d_0\rvert > 0.1\text{ cm}$
Total expected background	$18.0 \pm 0.5 \pm 3.8$	$1.01 \pm 0.06 \pm 0.30$	$0.051 \pm 0.015 \pm 0.010$
Observation	19	0	0
$pp \rightarrow \tilde{t}_1\tilde{t}_1^*$			
$M = 500$ GeV, $\langle c\tau \rangle = 1$ mm	$30.1 \pm 0.7 \pm 1.1$	$6.54 \pm 0.34 \pm 0.24$	$1.34 \pm 0.15 \pm 0.05$
$M = 500$ GeV, $\langle c\tau \rangle = 1$ cm	$35.3 \pm 0.8 \pm 1.3$	$30.3 \pm 0.7 \pm 1.1$	$51.3 \pm 1.0 \pm 1.9$
$M = 500$ GeV, $\langle c\tau \rangle = 10$ cm	$4.73 \pm 0.30 \pm 0.17$	$5.57 \pm 0.32 \pm 0.20$	$26.27 \pm 0.70 \pm 0.93$



- Best results at $c\tau \sim 2$ cm with exclusion of $m(\tilde{t}) < 790$ GeV at 95% CL

Summary and Conclusion

- We looked all over the place ….
  - Singly produced resonances up to ~ 5 TeV
  - Pair produced new particles up to ~ 1.5 TeV
  - Vast diversity of signatures
- No new physics found anywhere we looked
  - Lots of progress in exploring difficult regions of parameter space with complicated/boosted final states
  - Devil's in the details ⇒ many places left to hide!
- Let's do it all over again next few years a higher energy and larger luminosity !!!

Backup

Samples and Uncertainties

- **Generators:**
  - Background samples
    - Ttbar/Single t : MadGraph/POWHEG + PYTHIA 6 (Z2*)
    - W/Z+jets, ttW, ttZ : MadGraph + PYTHIA
    - WW/WZ/ZZ, ttH : PYTHIA
  - Signal samples
    - MadGraph/COMPHEP interfaced with PYTHIA
- **Triggers:**
  - Single lepton/dilepton, Lepton+3 central PFjets, H_T
  - All efficiencies studied on MC and data, selection tuned to be on the plateau
- **Systematics:**
  - All HLT, reconstruction and selection efficiencies and data/MC differences
  - Luminosity (4.4%)
  - JES (~5% eta and p_T dependent), JER
  - When rely on MC : factorization and renormalisation scale, jet-parton matching scale, dedicated systematic samples
  - When estimation from data: Uncertainties of the methods, data/MC, closure tests
  - Analysis specific

Black Hole Search

arXive: 1303.5338

- **Selection:**
  - γ, e, μ and jets $p_T > 50$ GeV
  - Sum p_T of final state products:

$$S_T = \Sigma p_T^l + p_T^\gamma + \Sigma p_T^{jet} + E_T^{miss}$$

- **Categorize into number jets:**
  - Shown here are the two extremes:
    - inclusive N ≥ 2 (top)
    - inclusive N ≥ 10 (bottom).
- **Exclusion limits:**
  - Masses below 4.3 to 6.2 TeV are excluded, depending on model assumptions