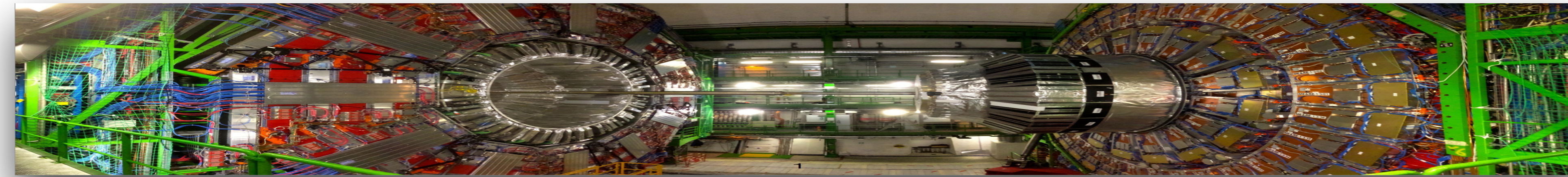


Exotic Physics

Michael Sigamani
on behalf of the CMS collaboration

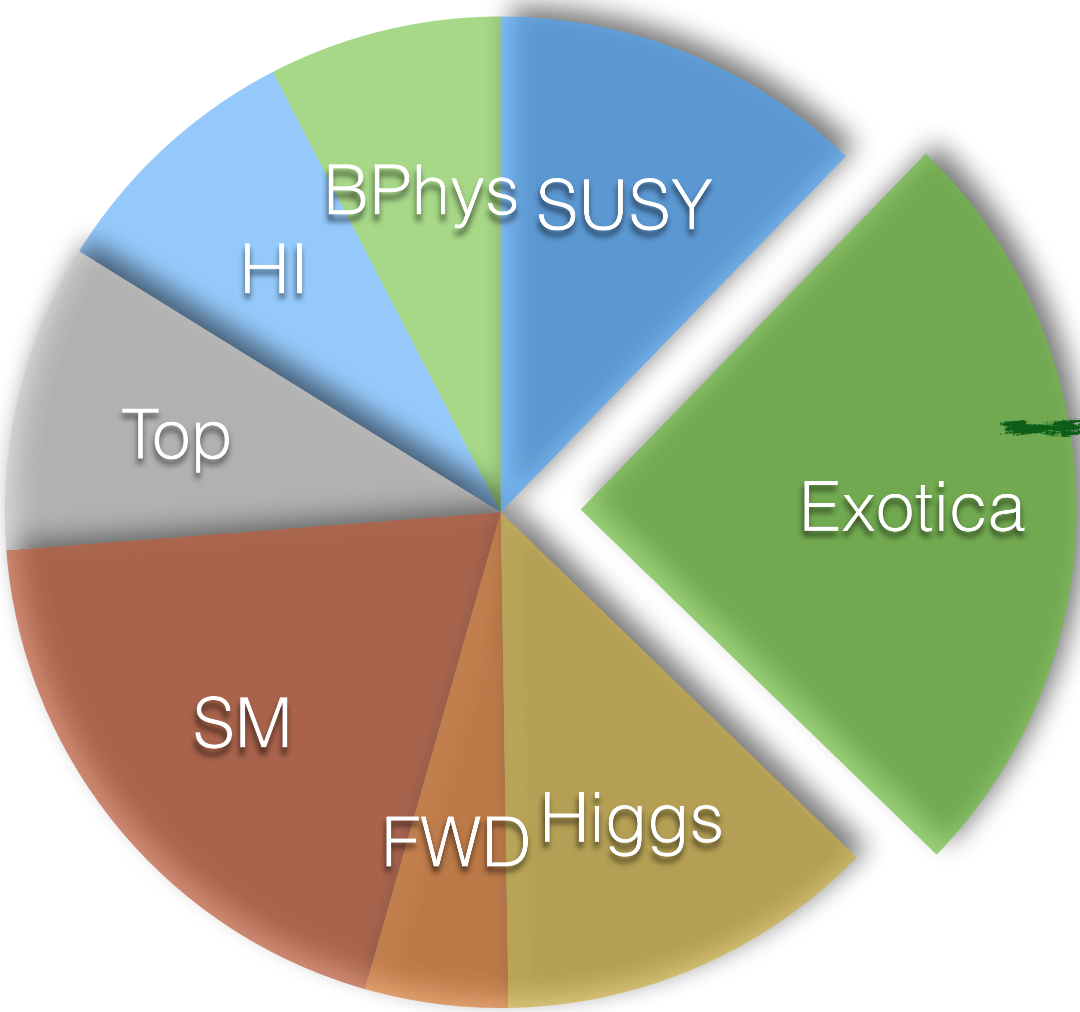
LISHEP

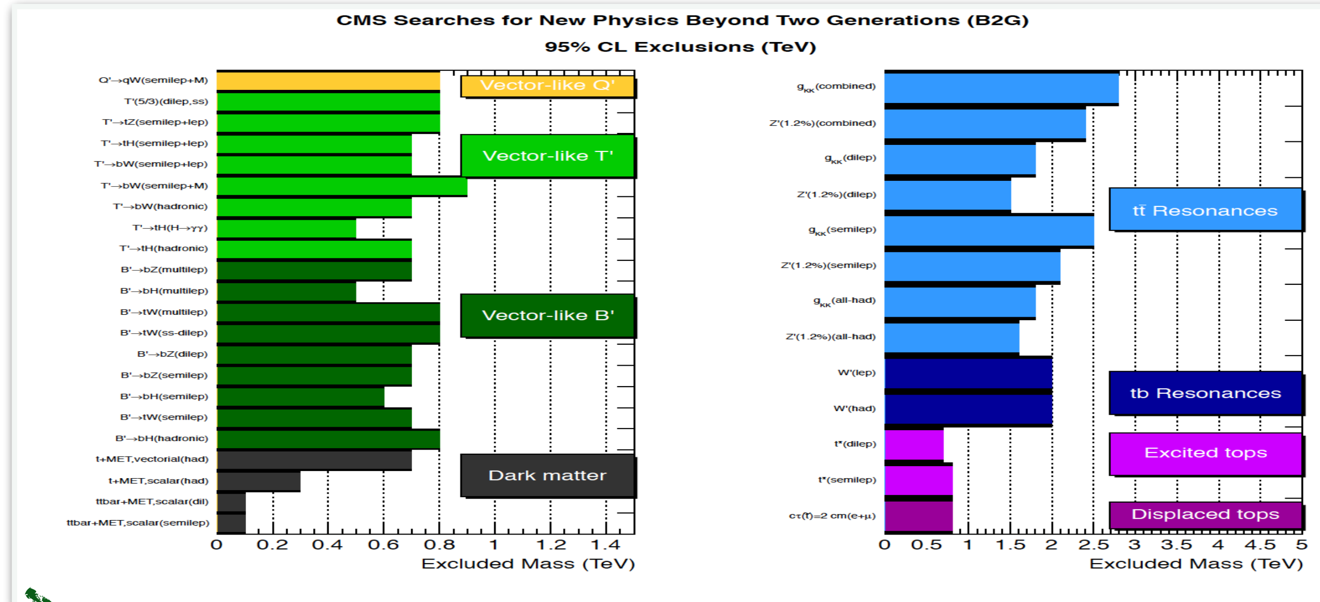
Universidade Estadual de Amazonas, Brazil (August 4th 2015)

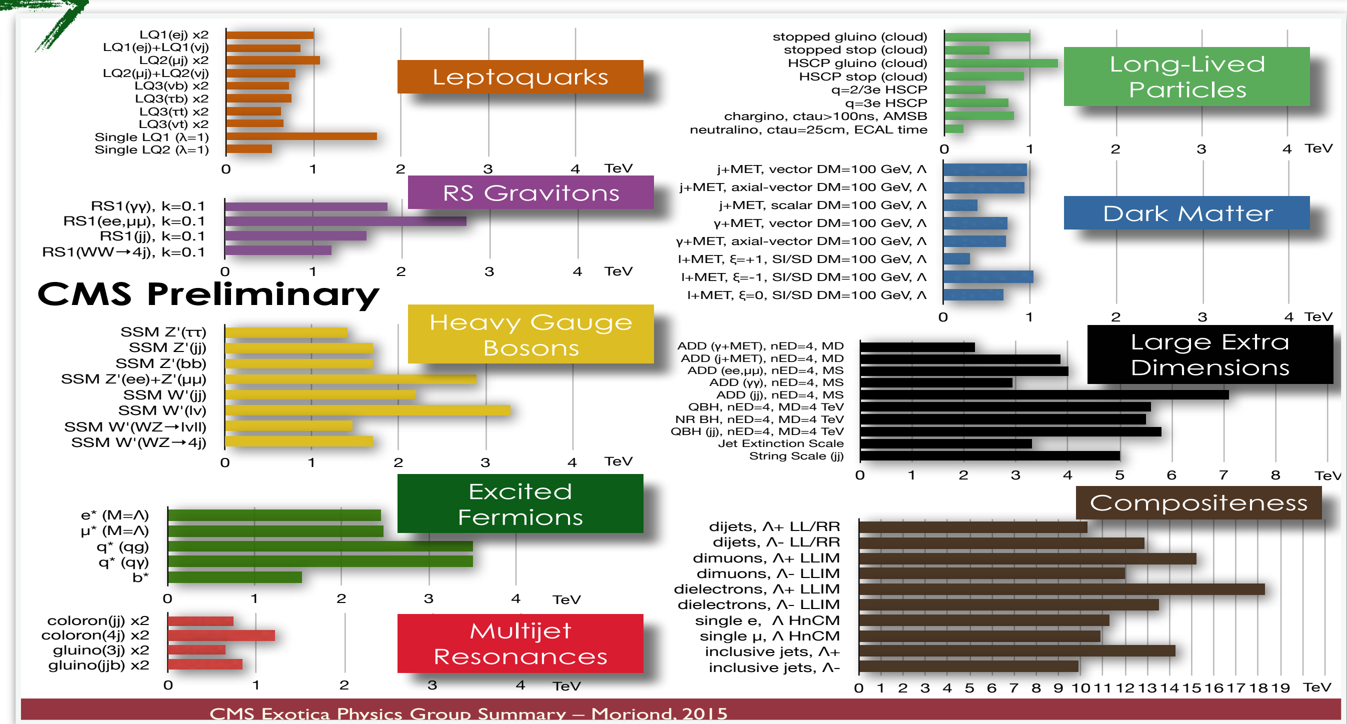
Introduction

- **The Standard Model has been successful at explaining the data, but is not without it's well documented shortcomings:**
  - Where did all the antimatter go?
  - Dark Matter?
  - Hierarchy problem (low mass Higgs motivates new physics at the TeV scale)
- **'Exotica' covers the full range of new phenomena searches and generally no set map or guide (i.e SUSY or Higgs)**
- **A variety of models:** Little Higgs/Composite Higgs, HVT, SUSY, MSSM, RS models, extra dimensions etc.
- **Yield a variety of particles:** Dark matter candidates, sparticles, Vector-like quarks, Excited Quarks, gravitons, leptoquarks etc.
- **With a variety of signatures:** Displaced objects, heavy resonances, boosted topologies etc.

Exotica at CMS



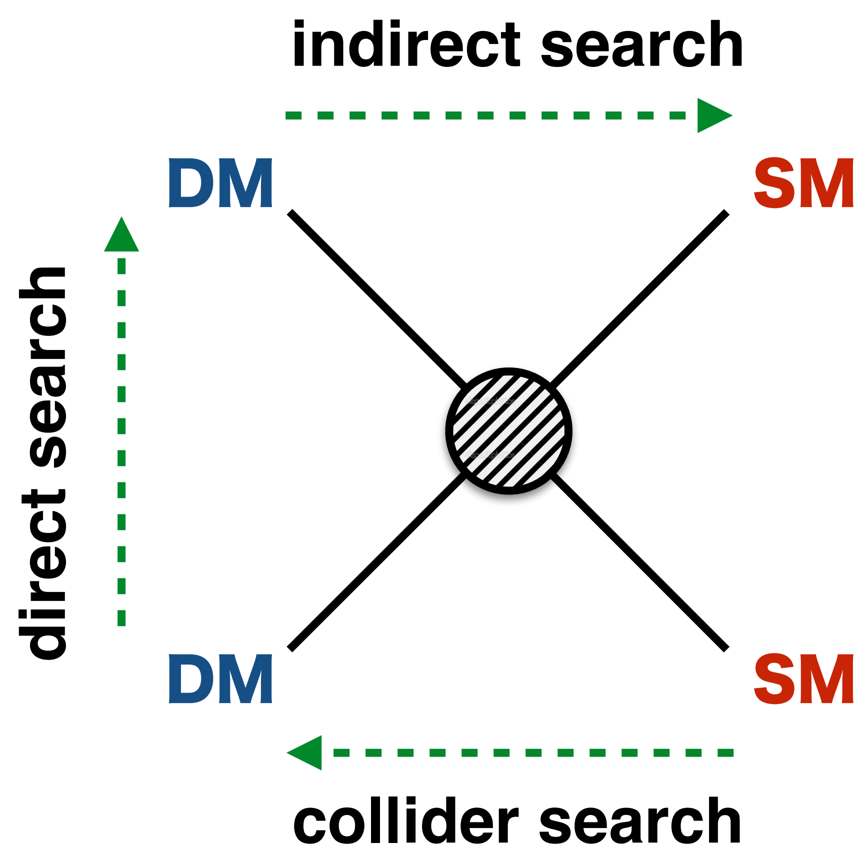


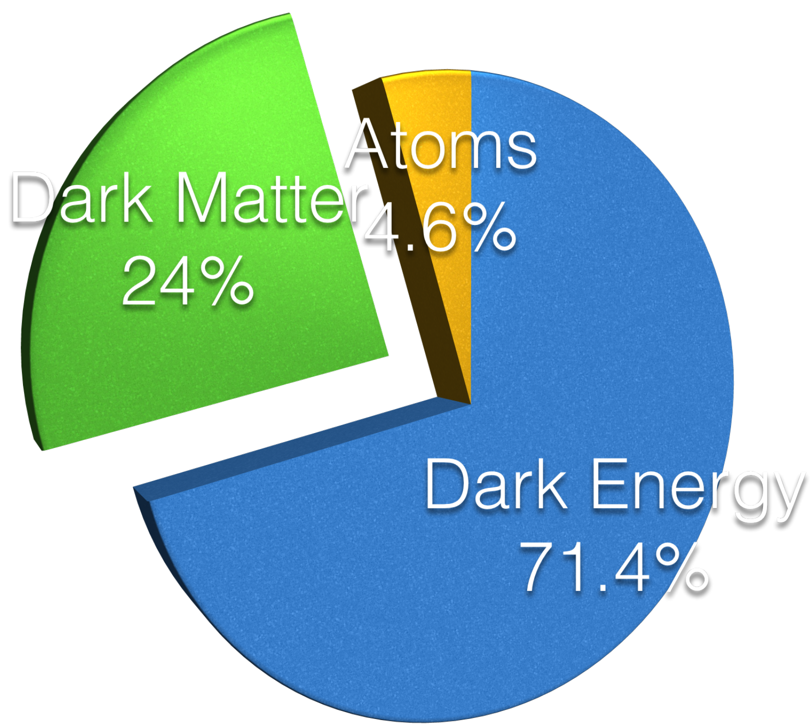


- **No significant evidence for new physics at Run 1 (click me)**
- **However, a few interesting small excesses here and there**

Dark matter

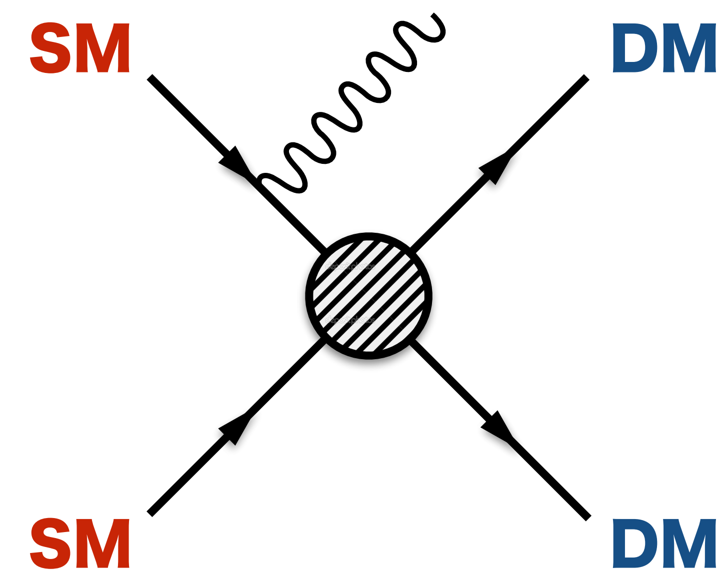
- **Search for dark matter at the LHC:**
  - Production of dark matter particles
  - Weakly interacting: no direct detection
- **LHC approach is complementary to direct and indirect searches**
  - Fermi-LAT, LUX etc.
- **Low mass region not accessible to direct detection experiments:**
  - Limited by threshold effects, backgrounds etc.
  - Less sensitive to spin-dependent couplings



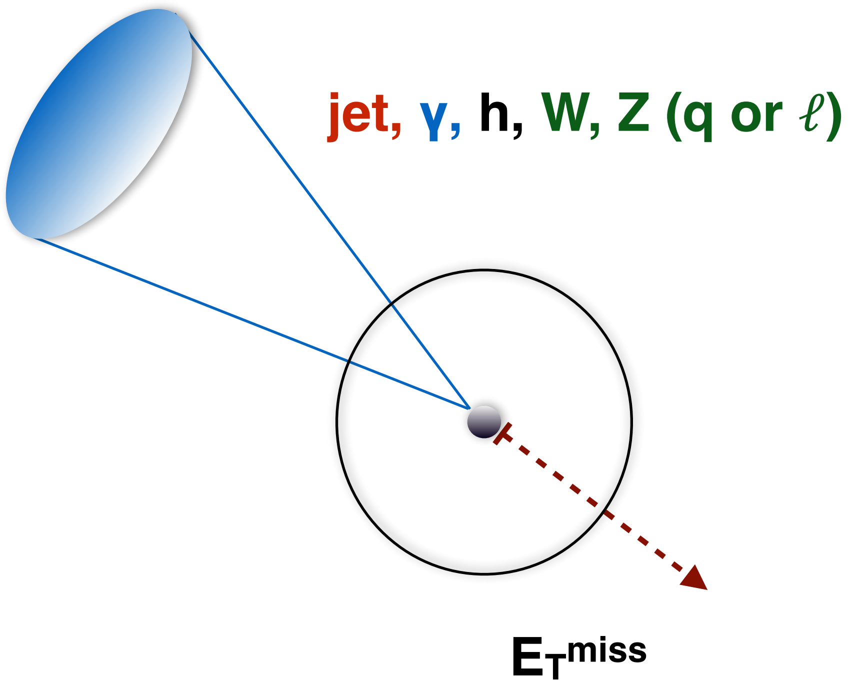


Dark matter at the LHC

- **Search for particle X recoiling against dark matter (X=photon, jet, W, Z, Higgs)**
  - Gives X recoiling against E_T^{miss}
- **Different interpretations:** Effective Lagrangians → Simplified Models → True Models (SUSY)
  - Standardised agreement for Run 2: http://arxiv.org/abs/1507.00966
- **'ISR tagging' now becoming an established technique for all new physics searches (not just DM)**
- Could also have corroborated evidence from SUSY decay chains, or discovery of new mediator in dijet or dilepton final states



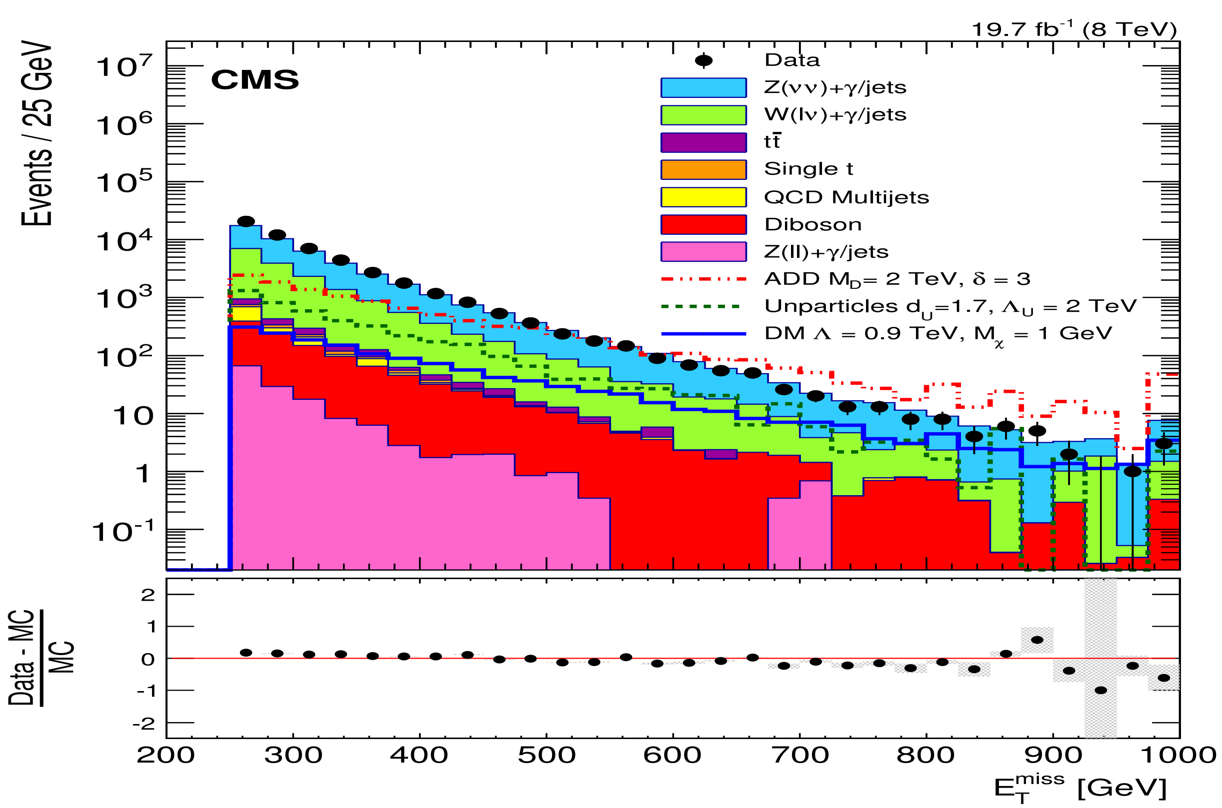
collider search

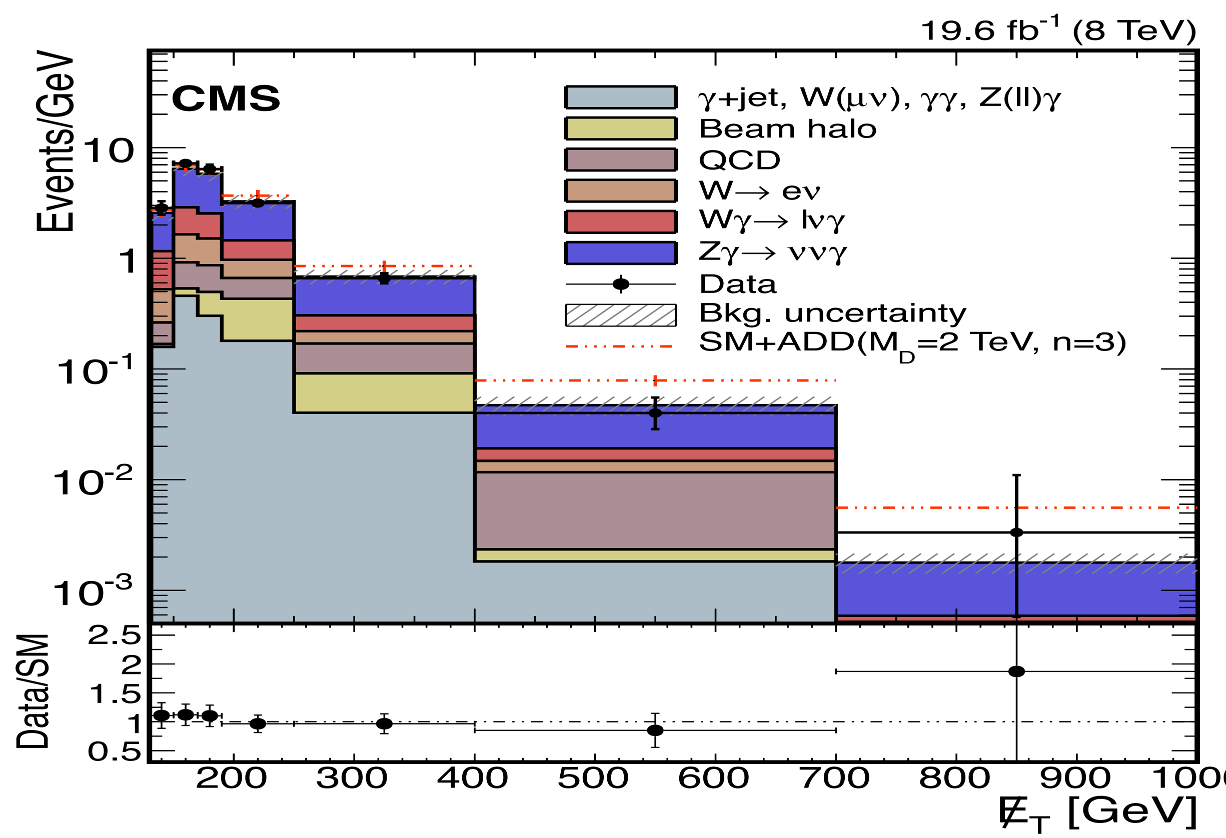


Monojets and monophotons

[arXiv:1408.3583](), [arXiv:1410.8812]()

Monojet event selection	Monophoton event selection
$E_T^{miss} > 250$ GeV	$E_T^{miss} > 140$ GeV
Jet_1: $p_T > 110$ GeV, $\|\eta\| < 2.4$	Photon: $p_T > 145$ GeV, $\|\eta\| < 1.44$
Lepton veto	Lepton veto
Topological cuts to reduce QCD, e.g. $\Delta\phi(jet_1, jet_2) < 2.5$	Topological cuts to reduce γ+jet, e.g. $\Delta\phi(E_T^{miss}, \gamma) > 2$

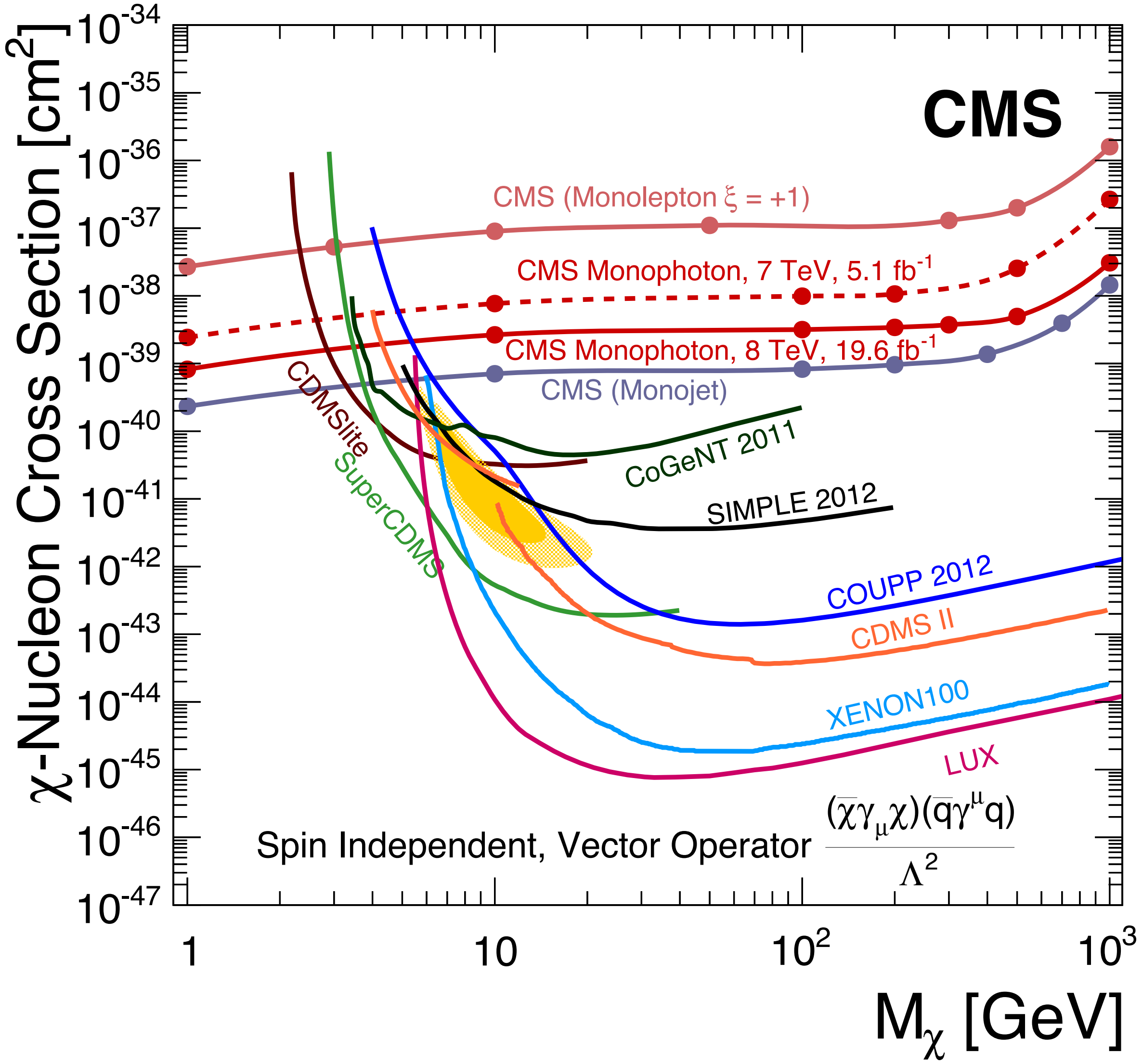




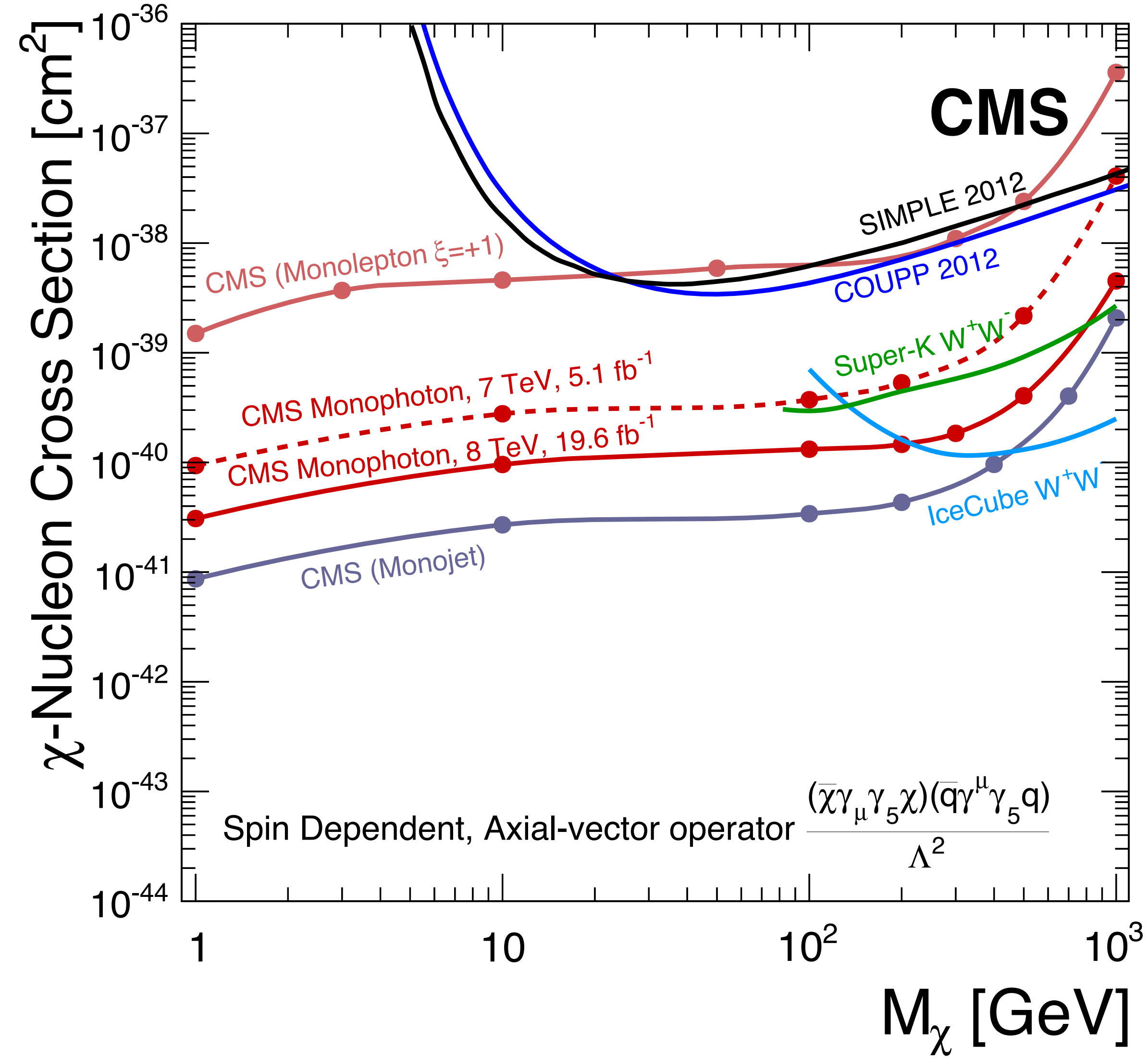
Comparison with direct detection

- More sensitivity wrt. direct searches at low mass
- More sensitivity wrt. direct searches in spin dependant scenario (right plot)

(a) Vector mediator

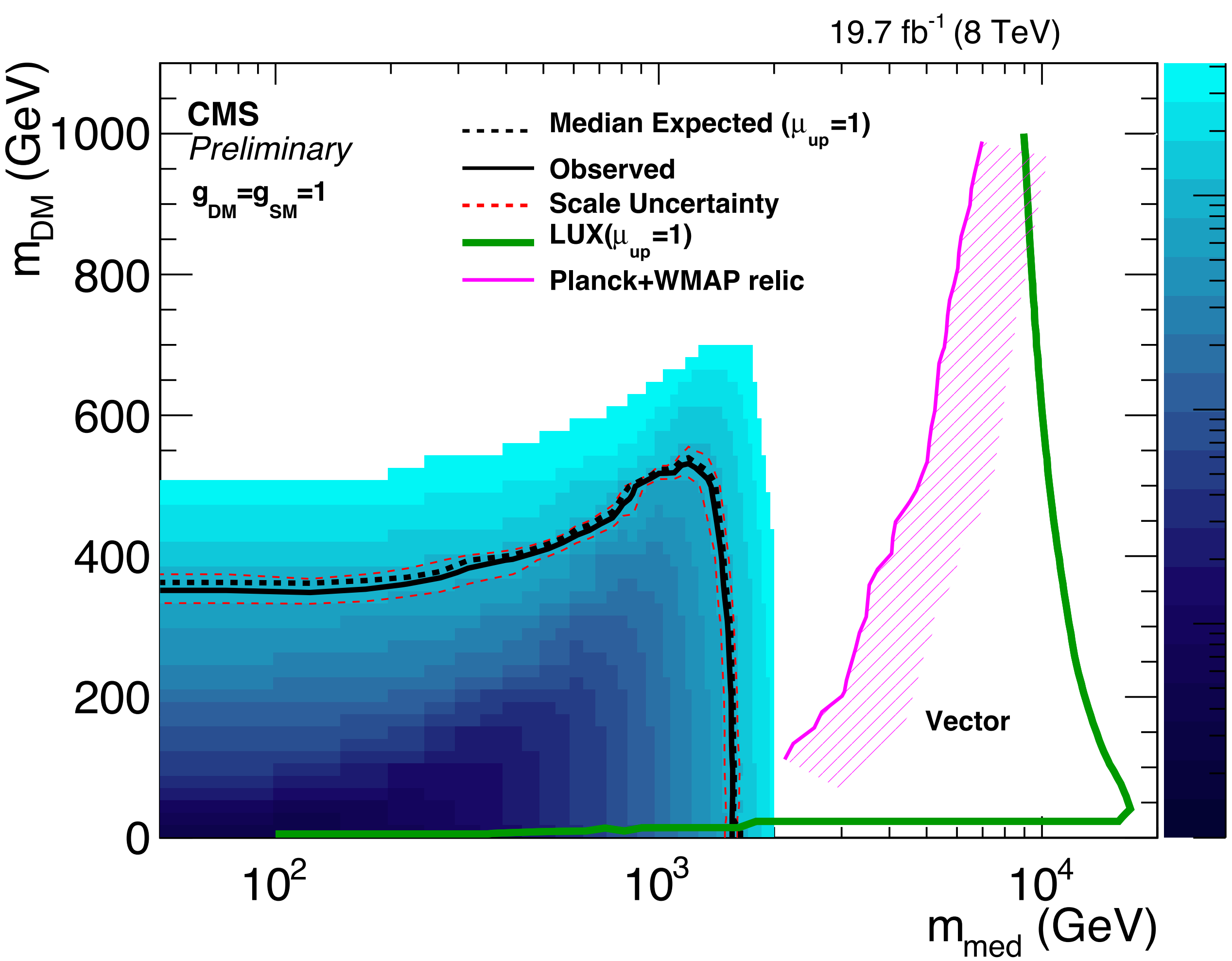


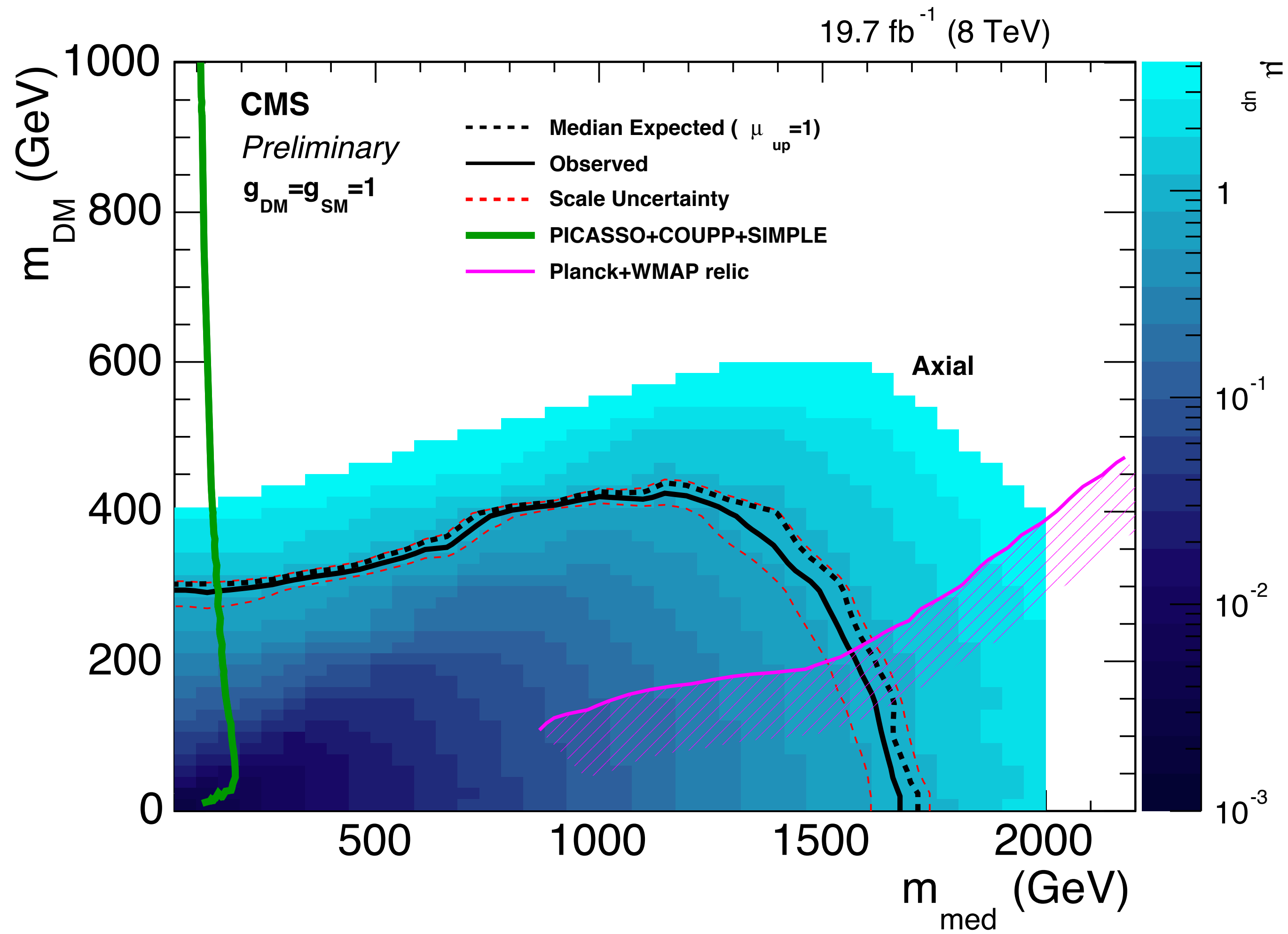
(b) Axial vector mediator



Comparison with direct detection

CMS-PAS-EXO12055



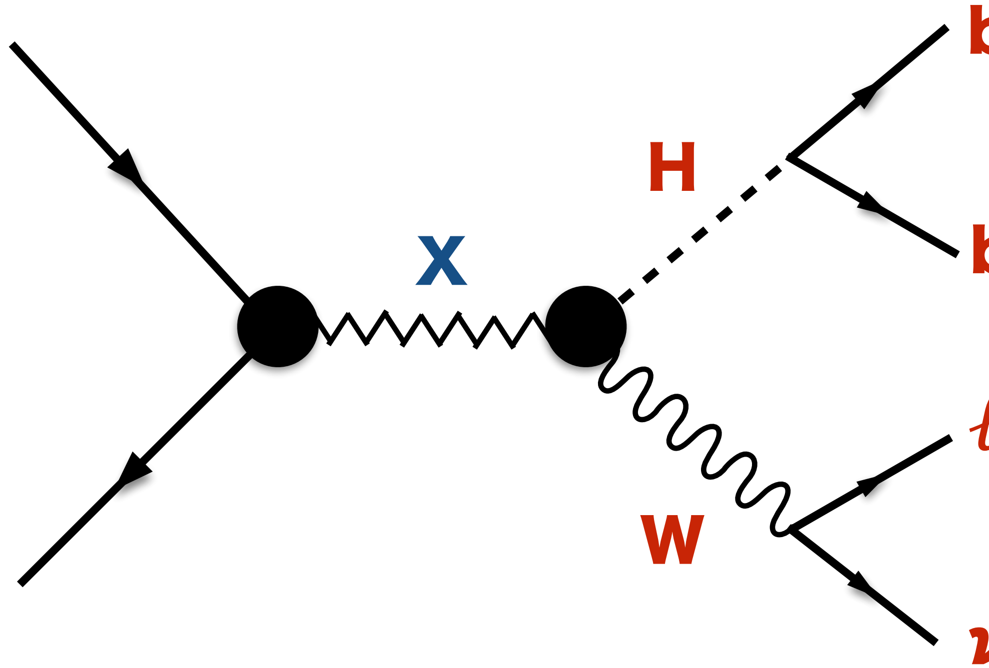


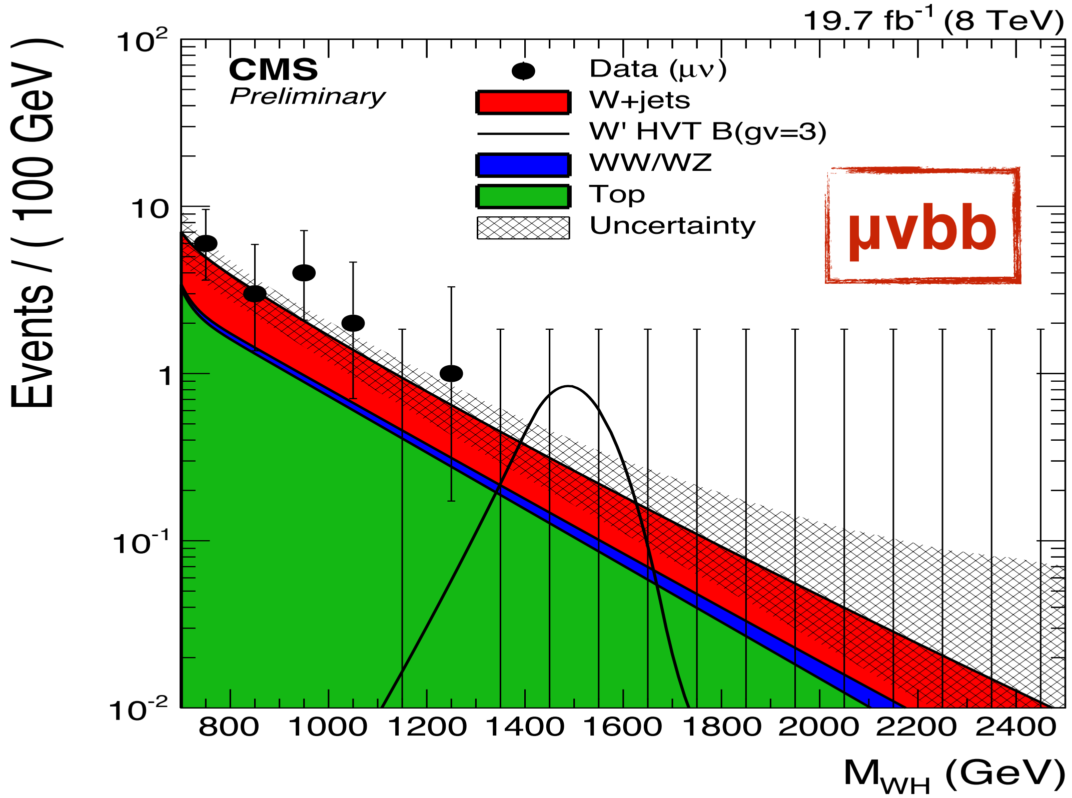
- Latest monojet + hadronic mono-V search
- Take advantage of boosted topologies
- Factor 20-50 improvement with respect to previous results
- **Interpret in the context of simplified models**

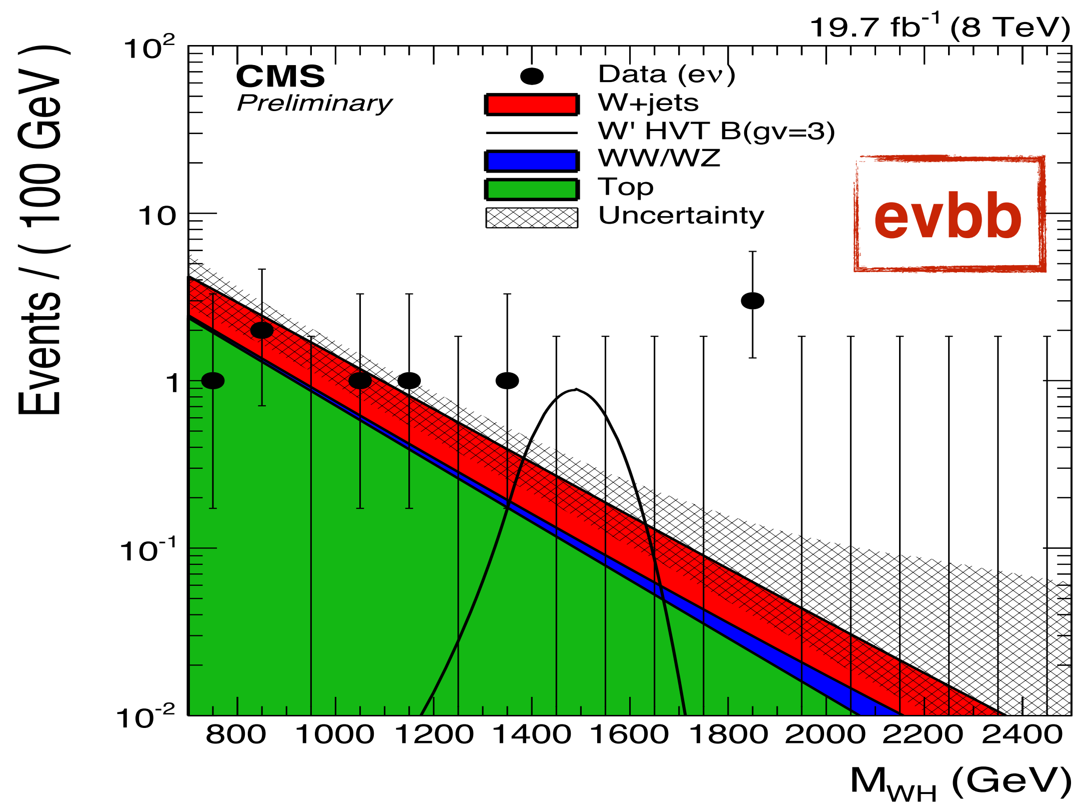
Boosted WH resonance (semileptonic)

CMS-PAS-EXO14010

- **Boosted signatures:** Important as we get sensitive to higher masses
- **Signal benchmarks:** Heavy Vector Triplet (HVT), Little Higgs, heavy resonances (W')
- Small excess in the evbb channel (not confirmed in μvbb channel)



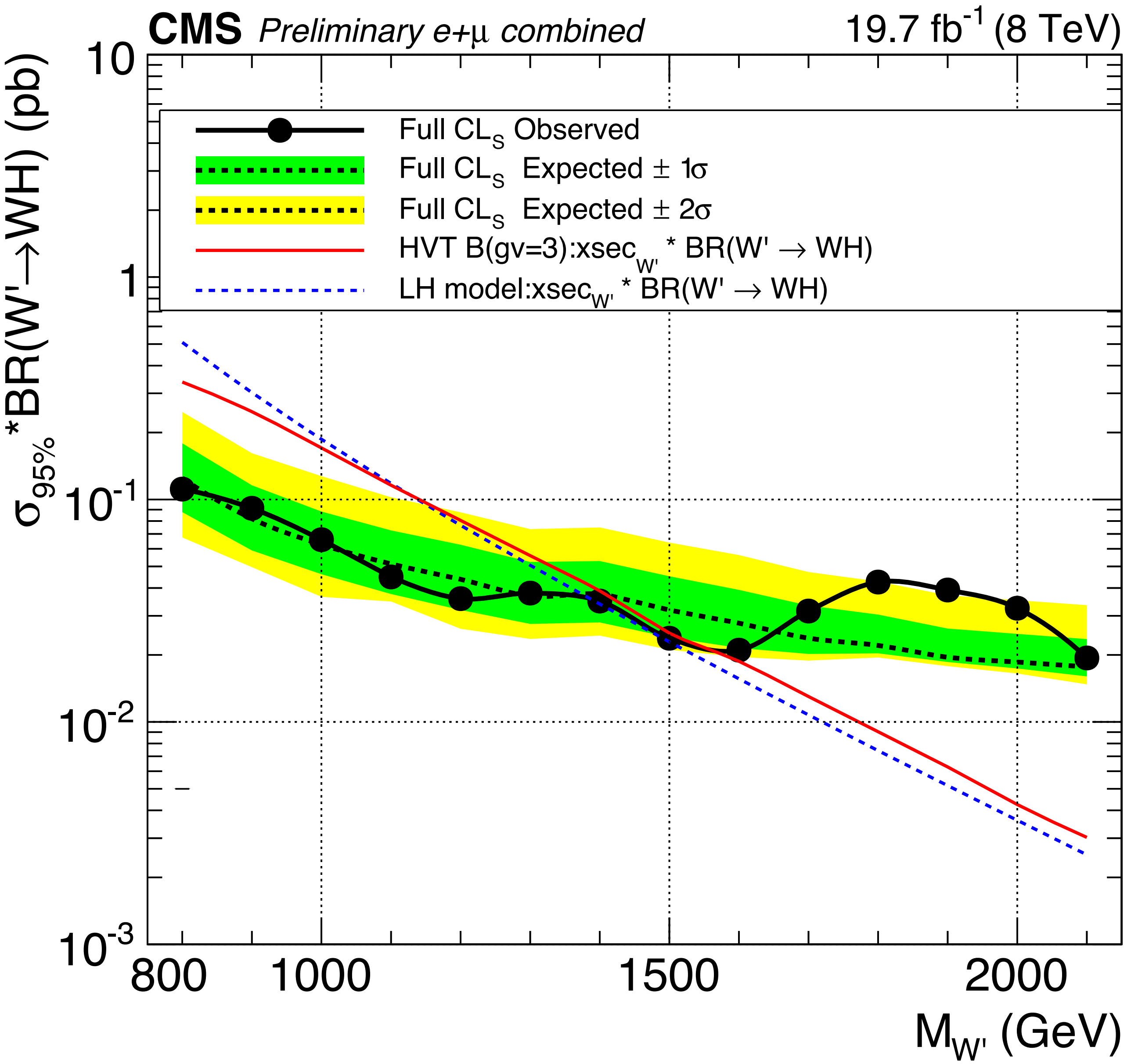




Boosted WH resonance (semileptonic)

CMS-PAS-EXO14010

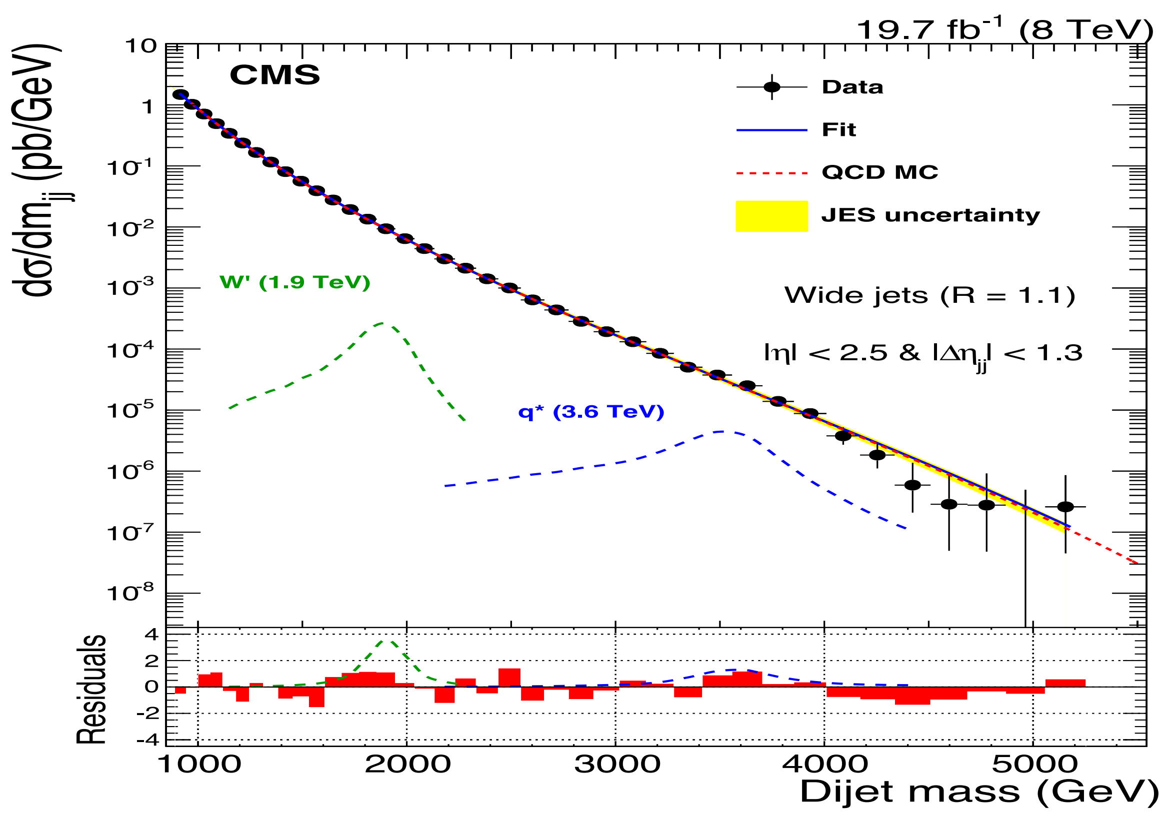
- Novel pruned jet mass and sub/fat jet b-tagging employed: BTV-13-001
- Assume natural width of resonance is much smaller than experimental resolution
- **Other related analyses:**
  - arXiv:1502.04994: X → ZH (γγ+bb)
  - PAS-HIG-13-032: X → HH (γγ+bb)
  - arXiv:1506.01443: X → VH (had.)
  - arXiv:1405.1994: X → VV (had.)
  - arXiv:1405.3447: X → WW (semilep.)

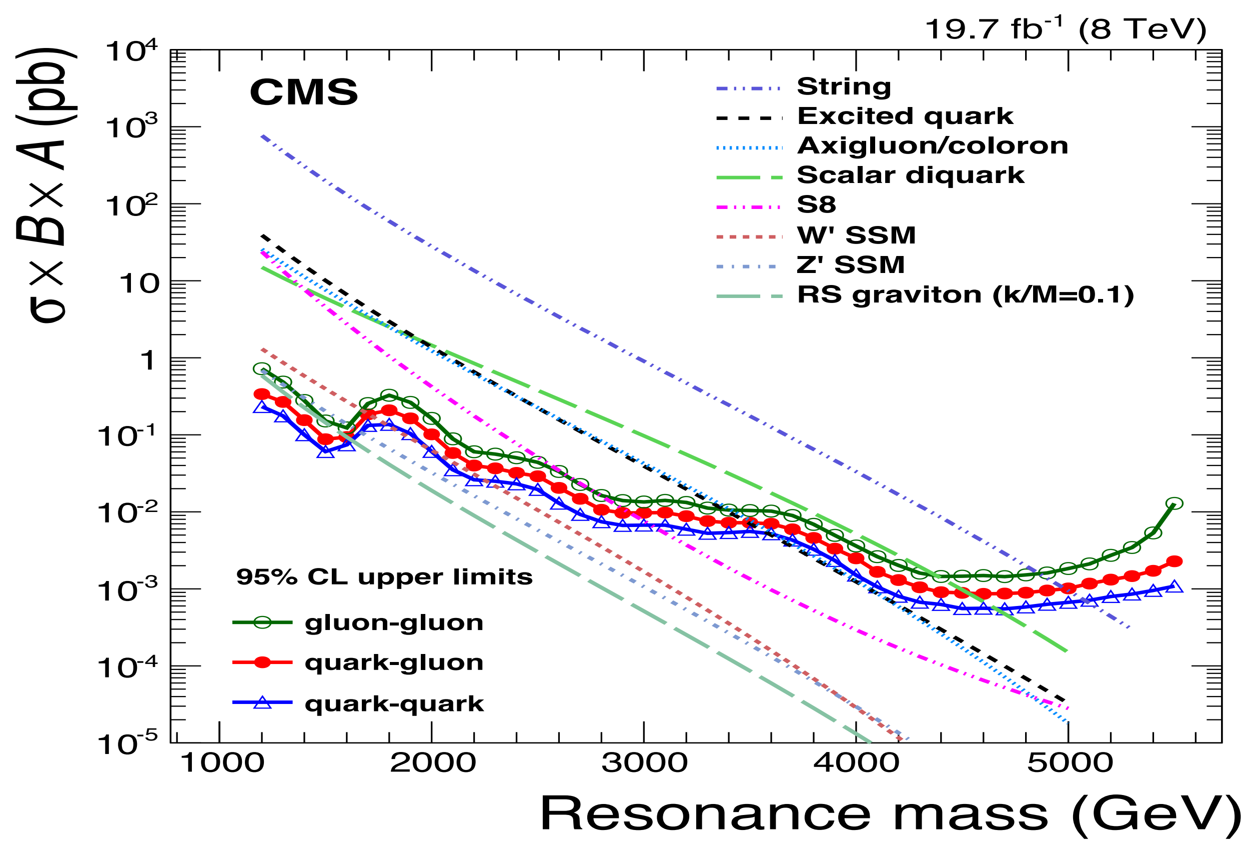


Search for dijet resonances

arXiv:1501.04198

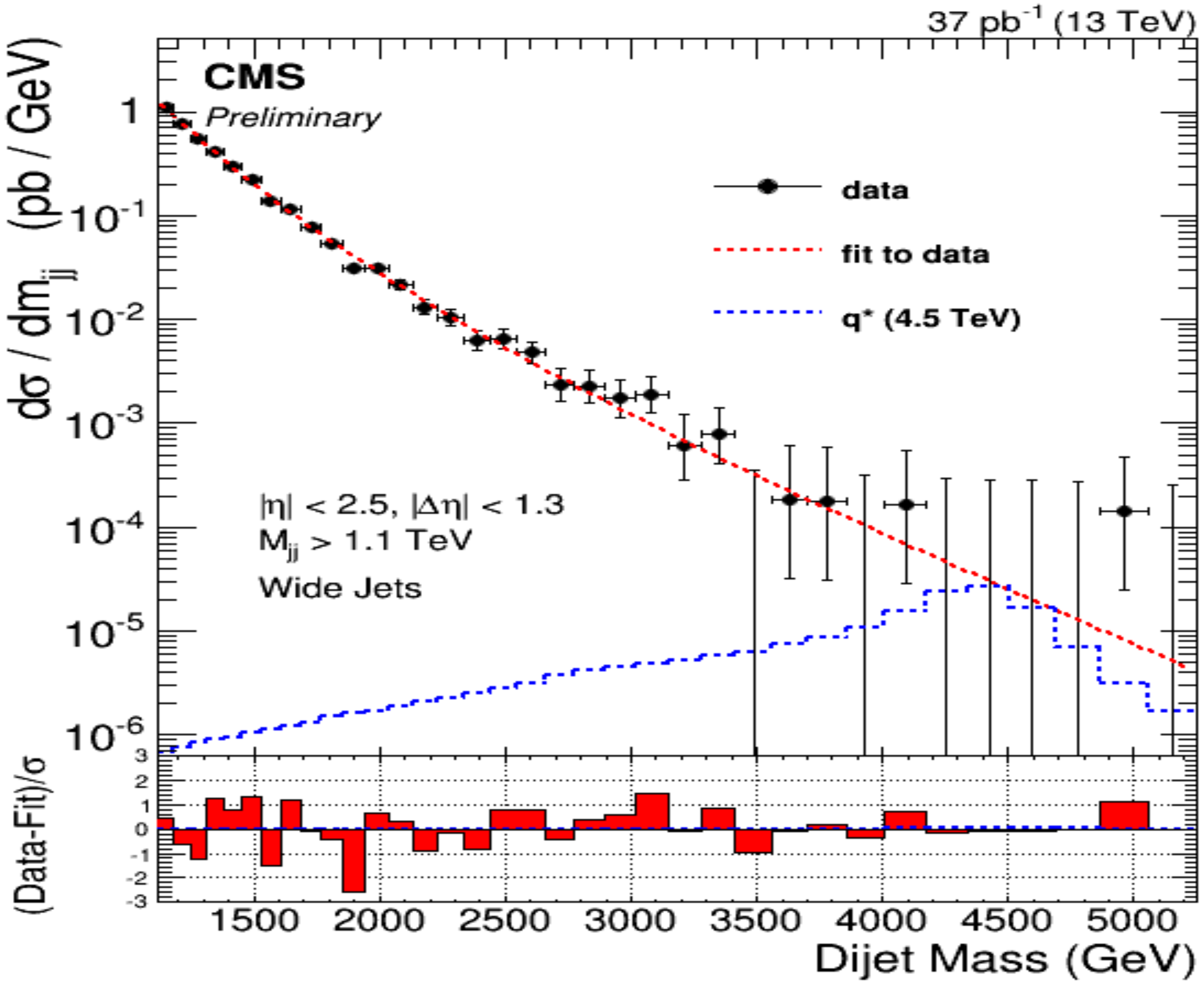
- **Search for dijet resonance on a smoothly falling mass spectrum**
  - Leading jet mass: m_{jj} > 0.9 – 1 TeV from trigger and other constraints
- Background estimated from smooth functional fit to data:
  $d\sigma/dm_{jj} = P0(1-x)^{P1}/x^{P2+P3\ln(x)}$
- Major player in terms of new physics models addressed
  (also set limits on wide resonances)





Search for dijet resonances (13 TeV)

- **Preliminary 13 TeV results shown at EPS**
- Same technique as 7 and 8 TeV to estimate bkg. (fit to data)
- No significant evidence for any dijet resonances in first 37 pb^{-1}



We expect to exceed the sensitivity of the 8 TeV analyses only for narrow resonances with masses greater than about 5 TeV.

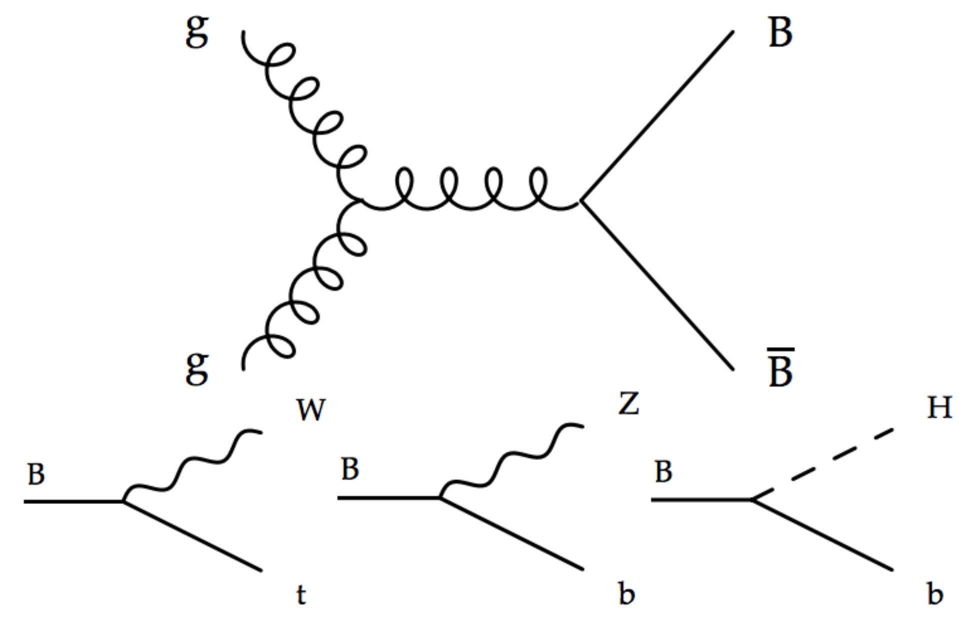
Event selection

Jet_1: p_T > 60 GeV, $|\eta|$ < 2.5
Jet_1: p_T > 30 GeV, $|\eta|$ < 2.5
$|\Delta\eta_{jj}|$ < 1.3
M_{jj} > 1.1 TeV

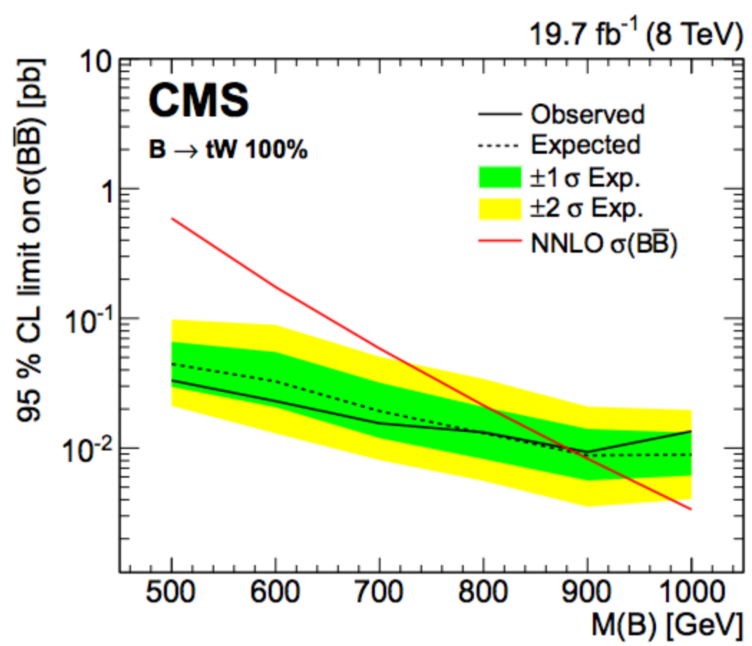
Search for B' → b + W/Z/Higgs (comb.)

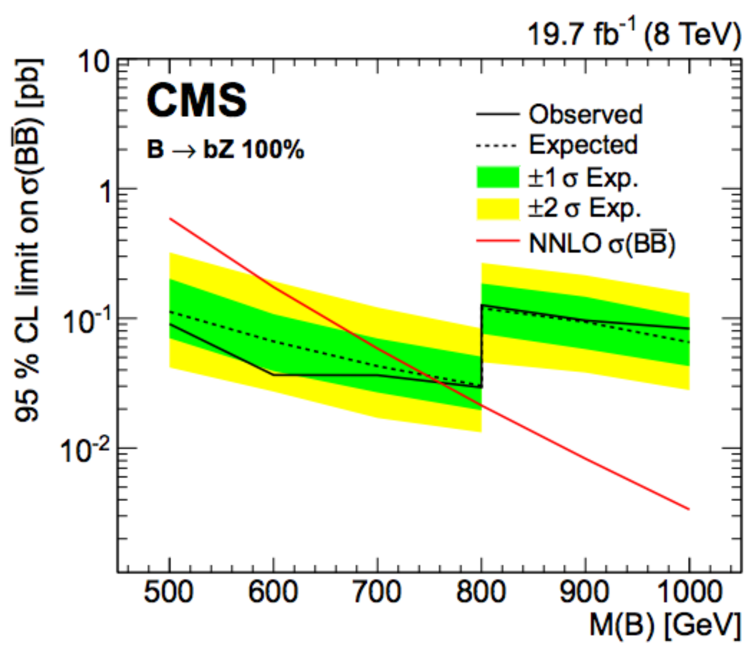
arXiv:1507.07129

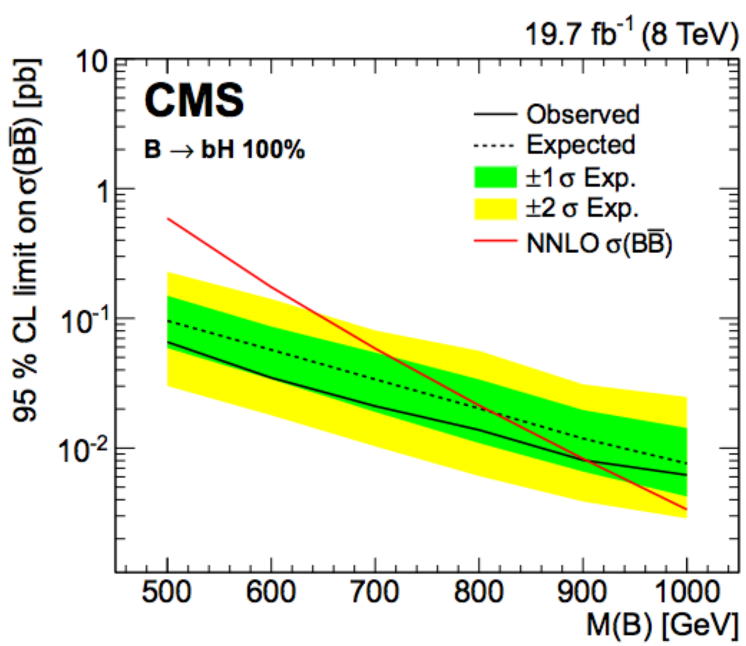
- **Search for pair of heavy vector-like B' quarks decaying into Higgs + b**
- Five sub-analyses combined to give a stronger more coherent limit
- B(B → tW) + B(B → bZ) + B(B → bH) = 1.0
- Scan over the entire phase space of B' in steps of 0.1 for each decay mode
- Step in bZ limit due to 2 analysis channels which do not contribute to the combination



- **Limit below is combination of five channels:** single lepton+jets, opposite-signed dilepton+ jets, same-signed dilepton + jets, multileptons + jets, and all-hadronic with boosted Higgs tagging (dominating contribution)

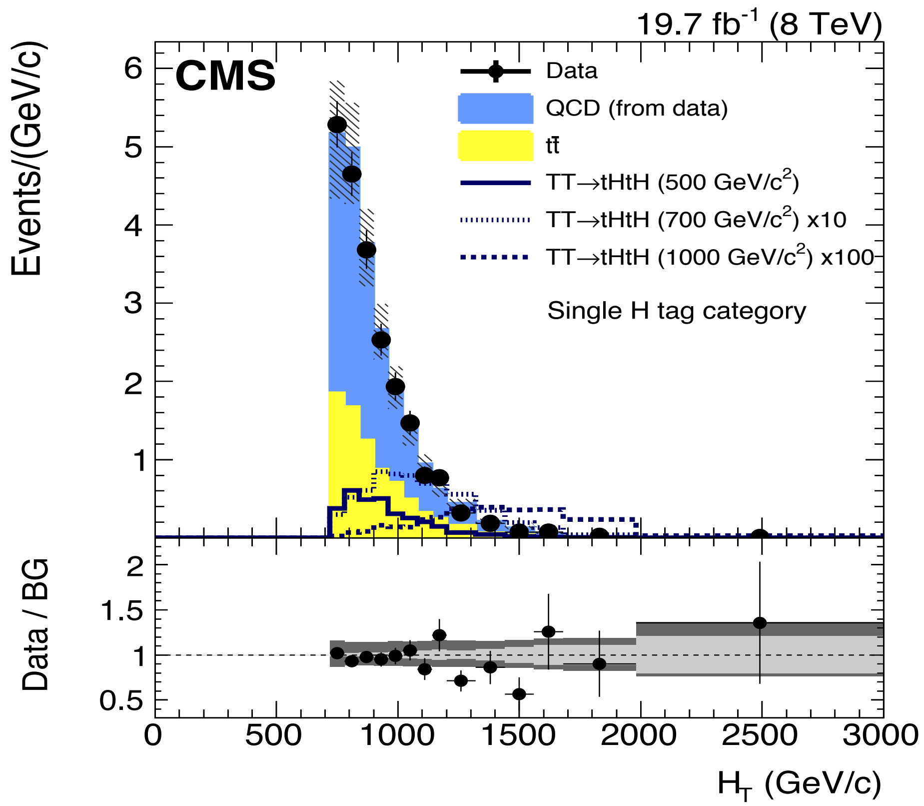


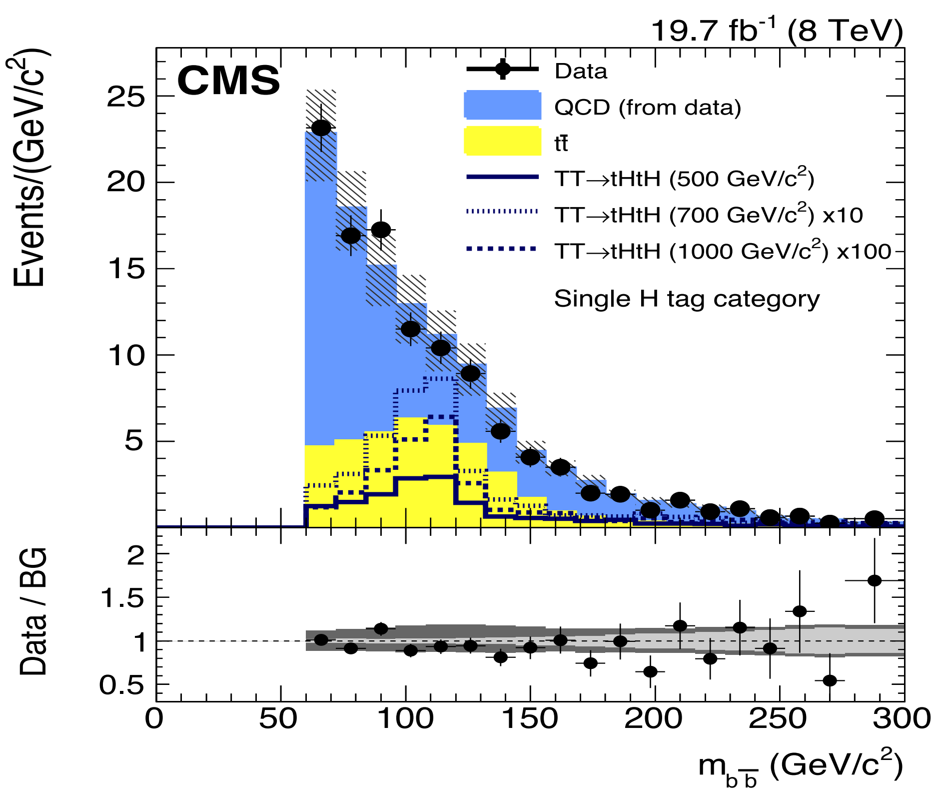




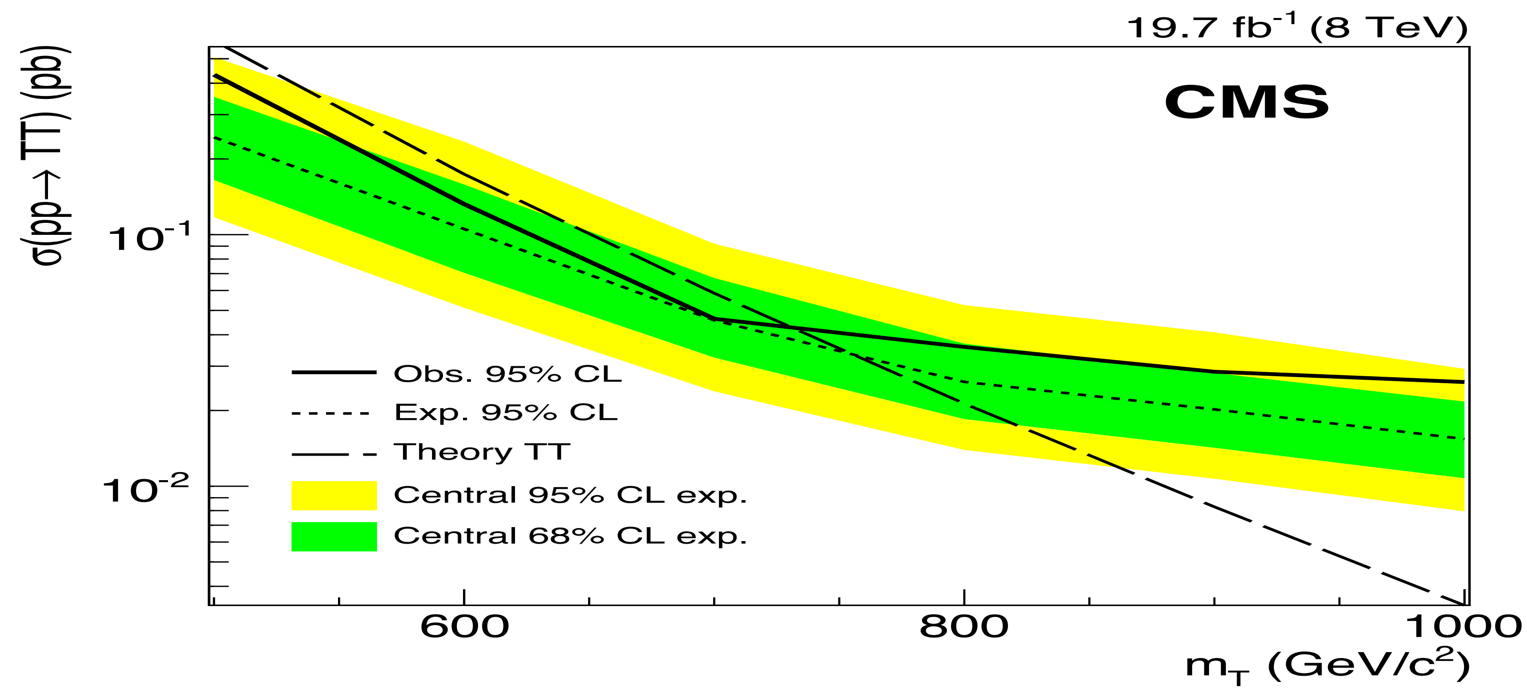
Search for T’ → top + Higgs

arXiv:1503.01952



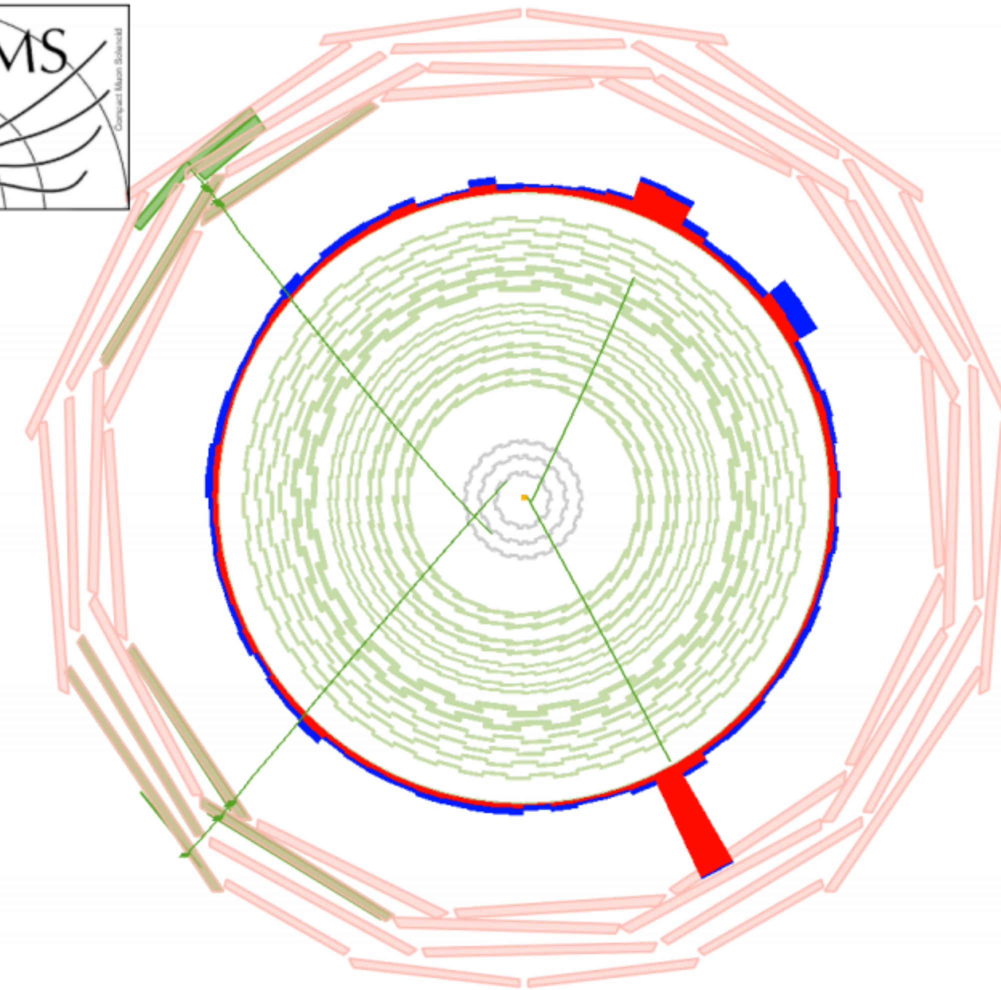


- **Search for pair of heavy vector-like T’ quarks decaying into Higgs + top**
- Top decays via bW (all hadronic final state), and Higgs→bb̄. Also, methods applied to resolve the substructure of merged jets
- Background fit on likelihood discriminant based on H_T and m_H
- Stay tuned for similar T'→ bW, T'→ tH and T’ → tZ combination



Long-lived searches

- **Definition:** Search for events where particles are produced and/or decay at a significant distance from the primary interaction.
- **Predicted by a wide variety of theoretical models:** Hidden valley, weakly RPV SUSY, split SUSY with long-lived gluinos, Z' decays, little Higgs, etc.
- **Generally signature-based searches**
- Typically very small SM backgrounds due to the significant lifetime
- Standard triggers & reconstruction are not optimal for these objects
- **Important since most SUSY searches only target prompt decays ($d_0 \lesssim$ mm)**

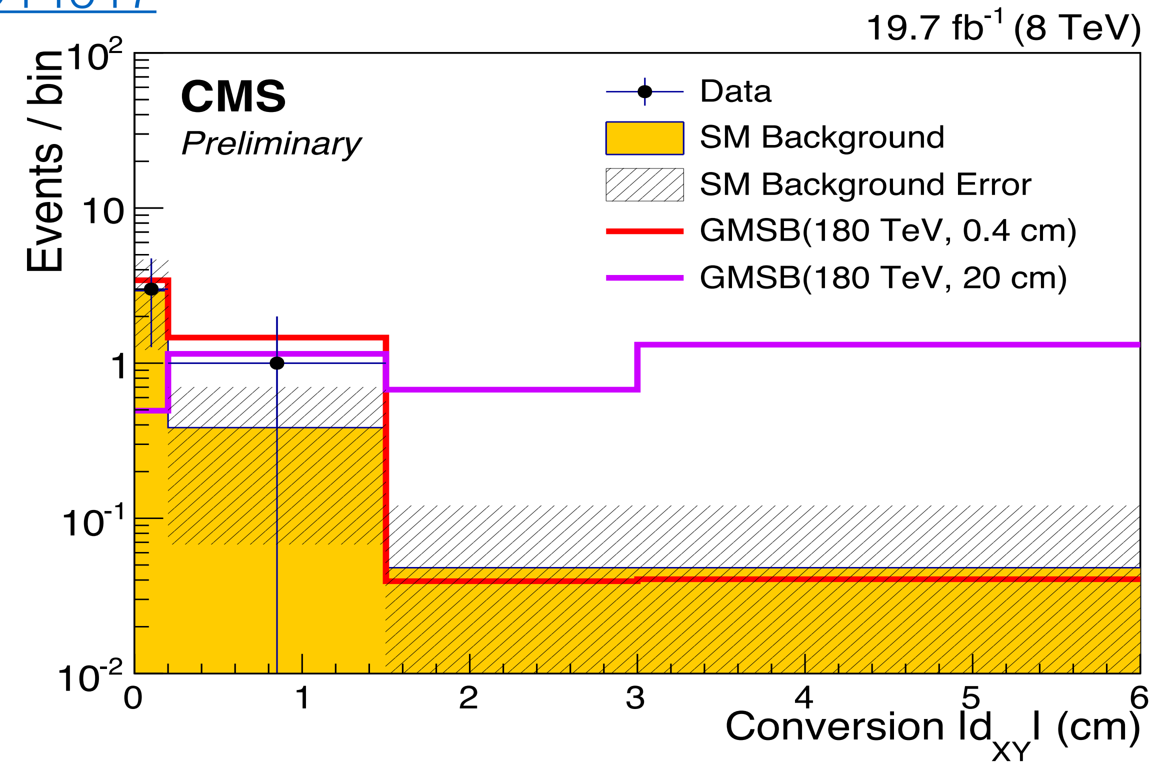


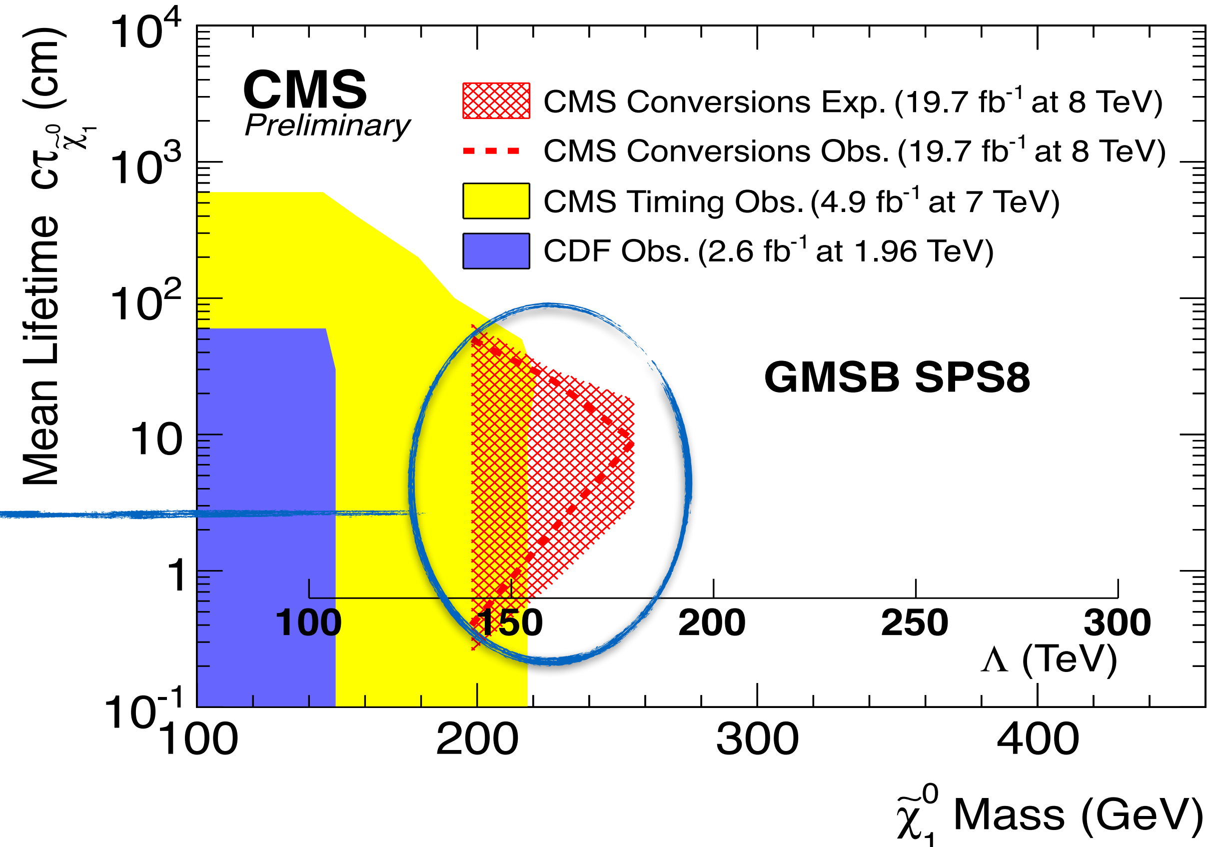
Simulated displaced leptons event at CMS

Displaced photons (conversions)

CMS-PAS-EXO14017

- **Search for a displaced photon using conversions ($\gamma \rightarrow e^+ e^-$)**
- **Signal benchmarks:** GMSB model
  - Two free parameters Λ and $c\tau_{\tilde{\chi}0}$
- **Discriminating variable:** Transverse impact parameter (d_{XY}) of converted γ
- **Main background:** γ + jet (use data est.)
- **Sensitive to neutralino lifetimes between $0.01\text{ ns} < \tau_{\tilde{\chi}0} < 1\text{ ns}$**
- Complimentary to ECAL timing based search
- Typically less sensitive wrt. ECAL timing method due to conversion reconstruction efficiency, but targets targets small ctau region well



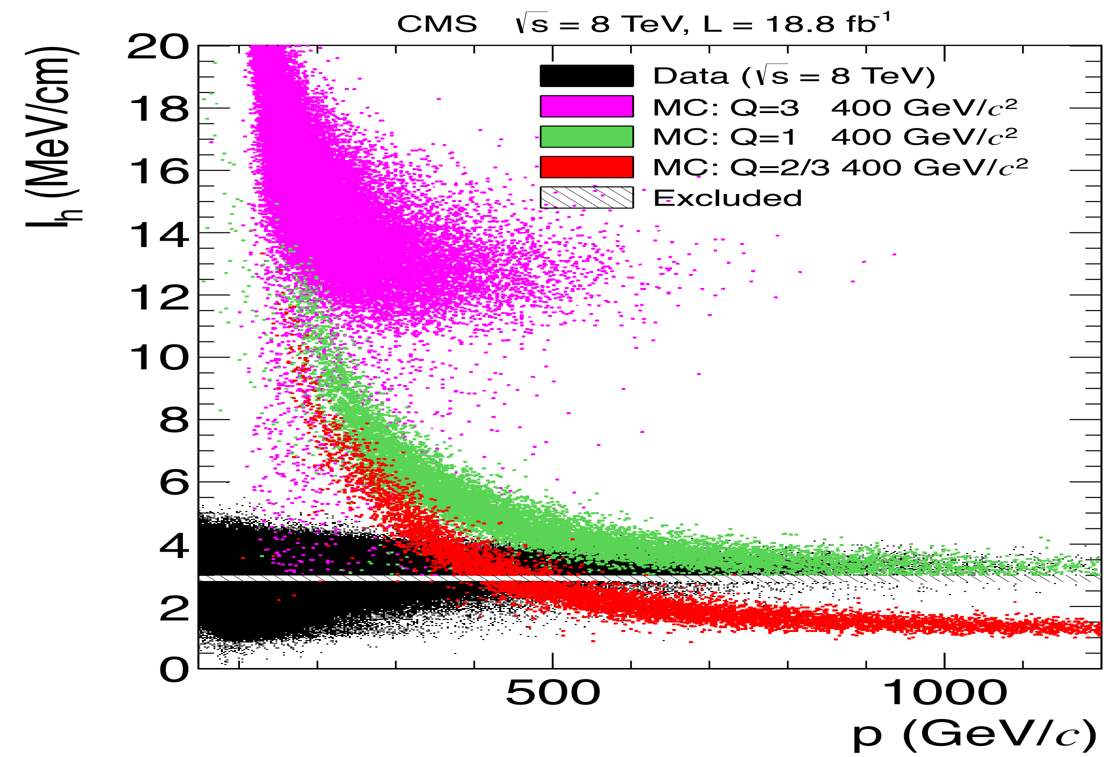


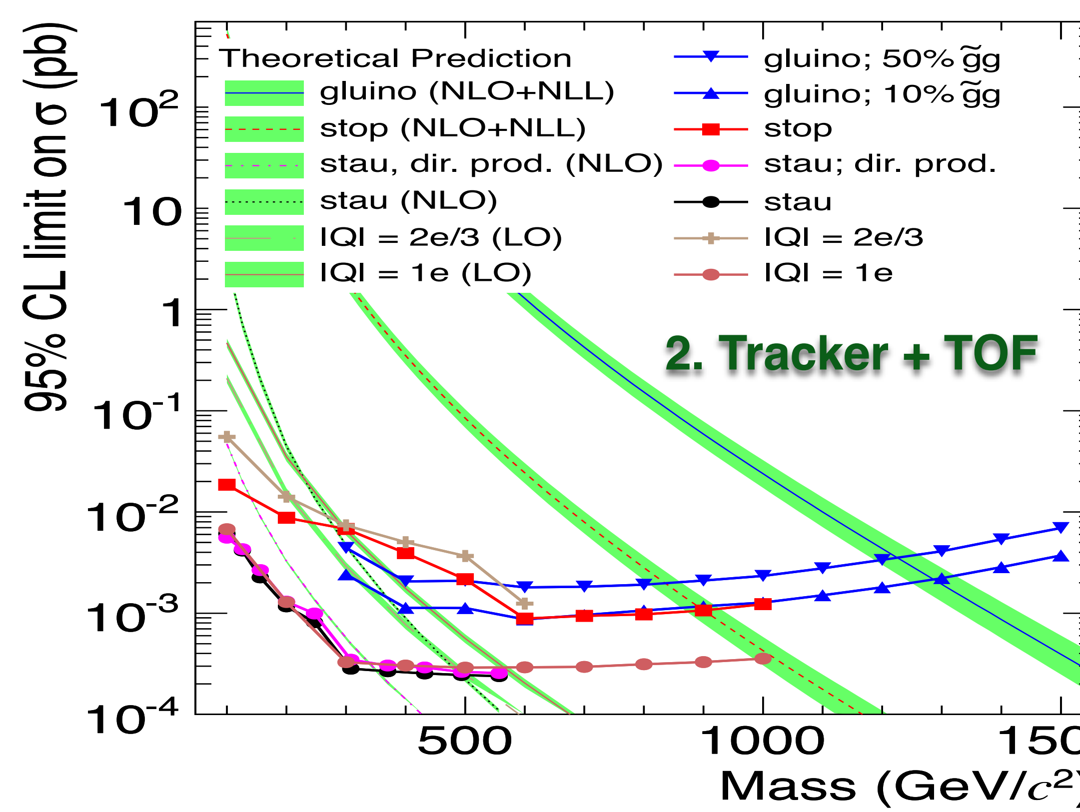
Heavy stable charged particles

arXiv:1305.0491

- **Search for particles with long lifetimes (> few ns), v < c, and possibly |Q| ≠ 1e**
- **Signal benchmarks:** Models with Gluinos, stop, DY-like $\tilde{\tau}_1$ production, |Q| < 1e, |Q| > 1e
- **Discriminating variables:** dE/dx in tracker (right), time-of-flight (TOF) to muon system
- **Five sub-analyses:** table below
- **Backgrounds:** SM particles with energy / timing/ p_T mis-measurement

	pT (GeV)	$I_{as}^{(\prime)}$	1/β	Mass (GeV)
1. Tracker only	> 70	> 0.4	-	> 0 …. 500
2. Tracker + TOF	> 70	> 0.125	> 1.225	> 0 …. 300
3. Muon only	> 230	-	> 1.4	-
4. IQI > 1e	-	> 0.5	> 1.2	-
5. IQI < 1e	> 125	> 0.275*		-

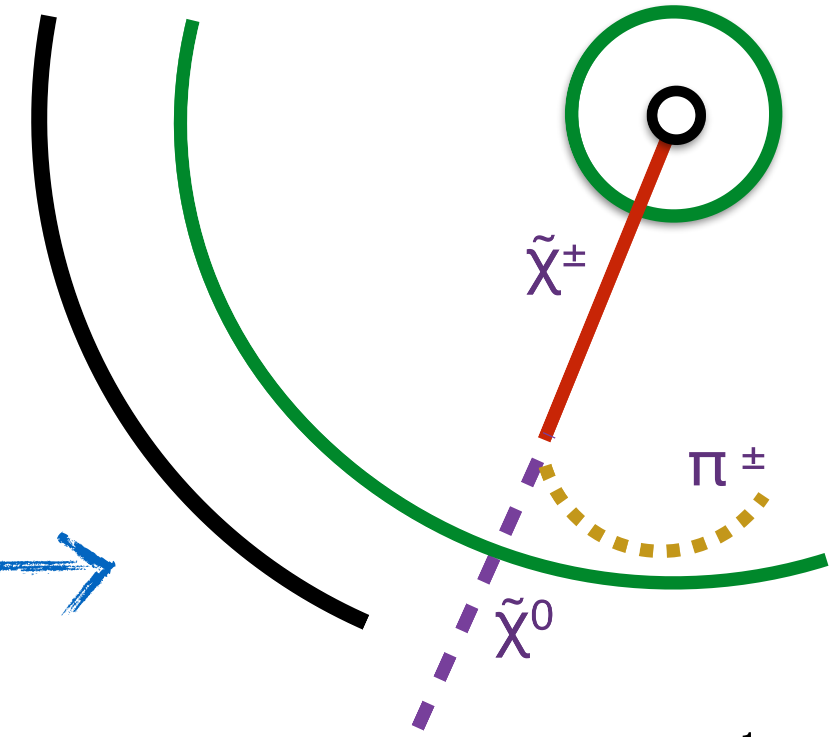


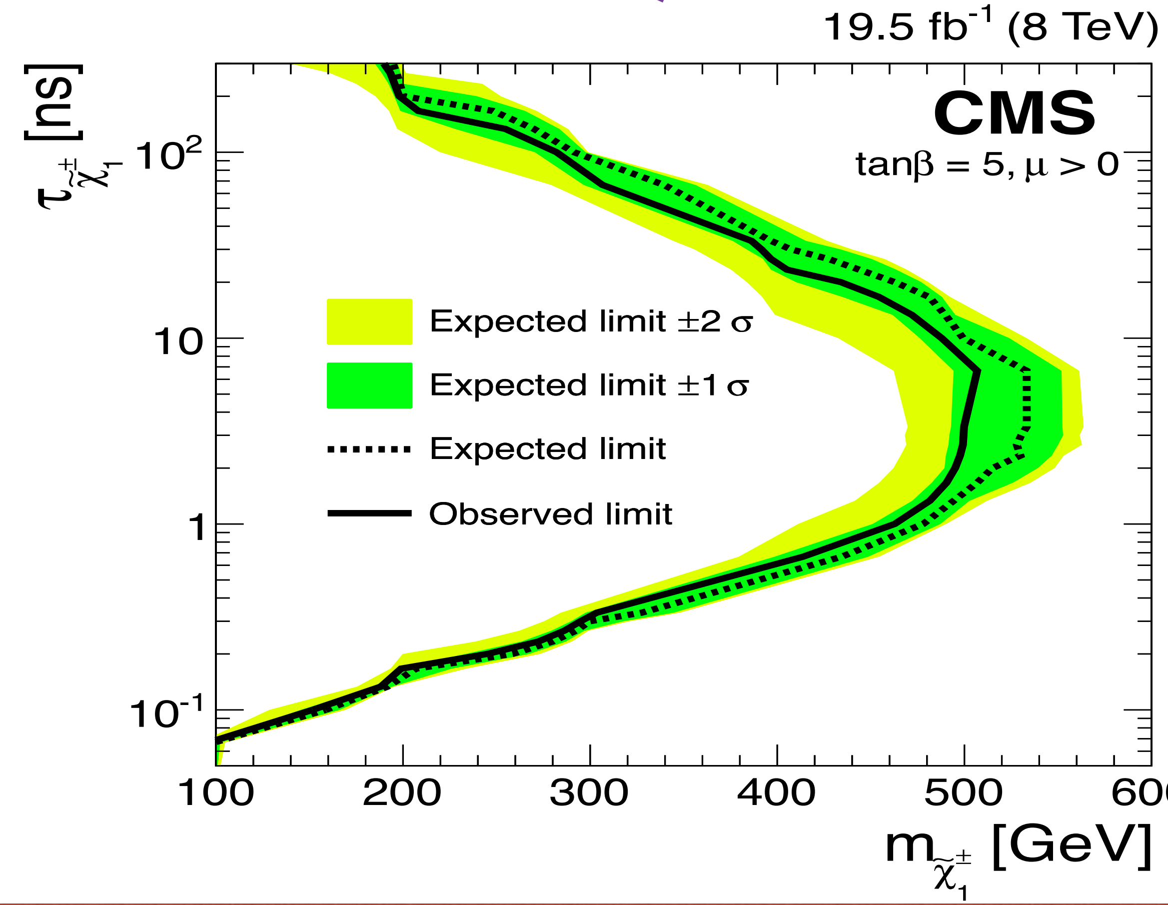


Disappearing tracks

arXiv:1411.6006

- **Search for long-lived charged particles decaying in tracker (disappearing track)**
- **Signal benchmark:** AMSB model
  - Small mass splitting between $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^{0}$ (leads to non-zero $\tilde{\chi}^{\pm}$ lifetime)
  - π tracks too soft to be reco. in tracker
  - Analysis is sensitivity to intermediate $\tilde{\chi}^{\pm}$ lifetimes (decays in tracker)
- **Key selection criteria:** Num. missing outer hits ≥ 3, associated calorimeter energy < 10 GeV
- **Backgrounds:** SM particles with unidentified leptons, mis-reconstructed p_T, fake tracks





Summary

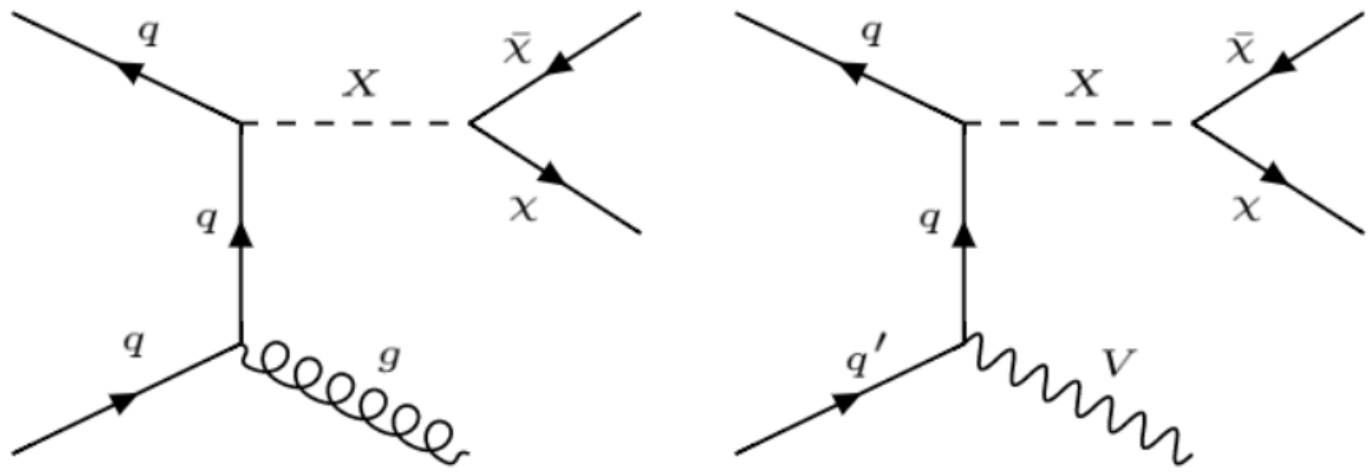
- **No significant evidence for new exotic physics in Run1 at CMS**
- **Many interesting new directions in exotic searches, with efforts to:**
  - Search for dark matter at the LHC in a very comprehensive manner (both experimental and theoretical)
  - Searches for final states with boosted decays looked at in Run1 —> Will become more important for Run 2
  - Search for long-lived decays thoroughly covered are important topologies (not just left-overs from prompt SUSY phase space)
- **The energy increase of Run 2 could lead to early discoveries**
- **Will surpass the Run 1 sensitivity soon in most exotic searches → Hope we go in the direction of discovery instead of upper-limits!**

“If you wish to make an apple pie from scratch,
you must first invent the universe.”

– *Carl Sagan*

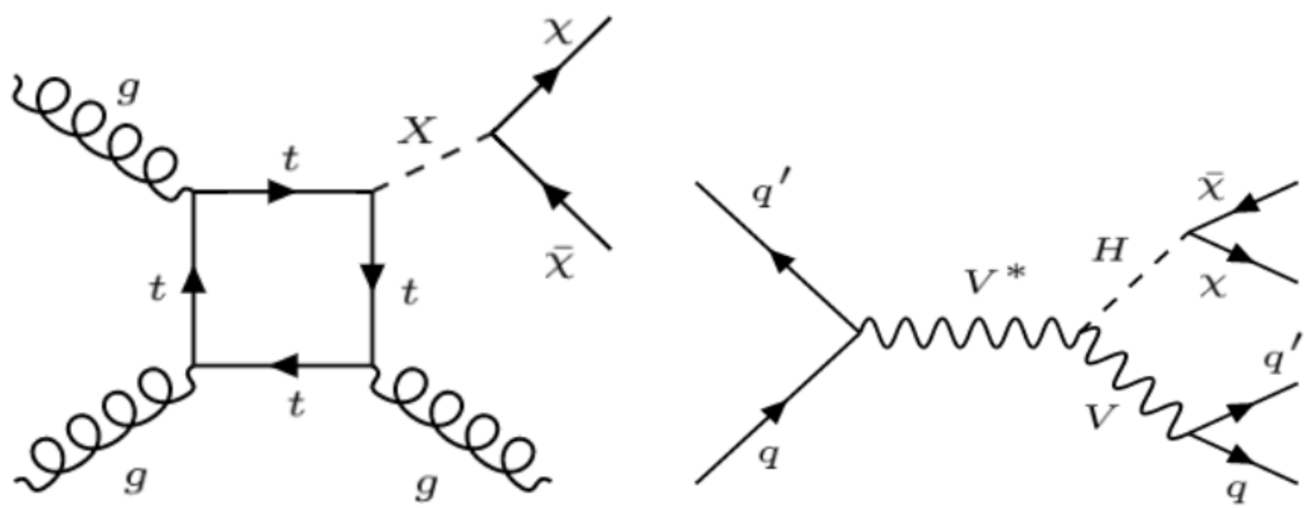
Dark matter from monoV/jet

CMS-PAS-EXO12055 (click me)



(a) (b)

Figure 1: Diagrams for the monojet (a) and mono-V (b) processes with a spin-1 mediator.

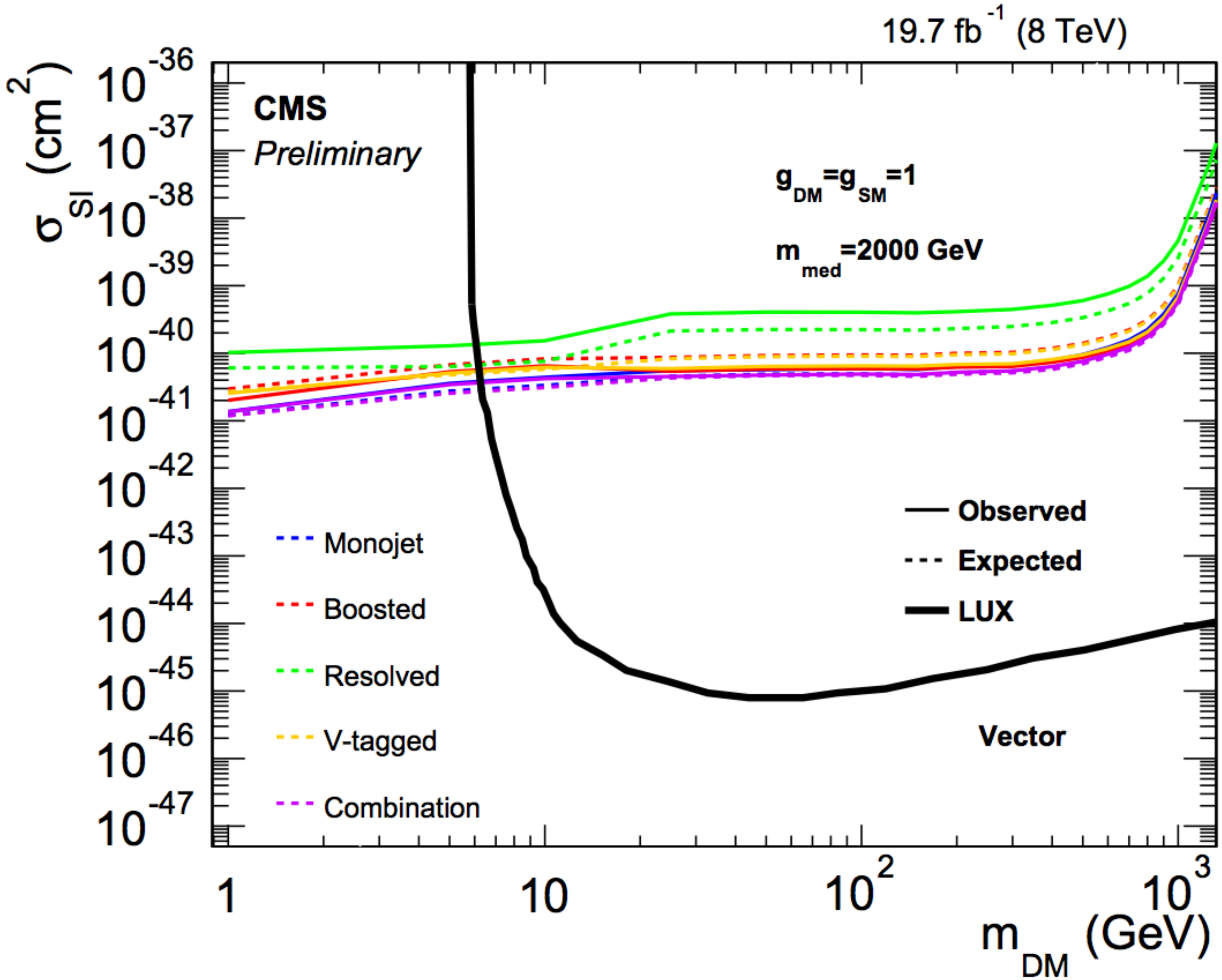


(a) (b)

Figure 2: Diagrams for production of the monojet (a) and mono-V signature through Higgs-strahlung (b), through a scalar mediator.

Dark matter from monoV/jet

CMS-PAS-EXO12055 (click me)



Dark matter forum

- We can produce these points :

m_χ / GeV	M_{med} / GeV									
1	10	20	50	100	200	300	500	1000	2000	10000
10	10	15	50	100						10000
50	10		50	95	200	300				10000
150	10				200	295	500	1000		10000
500	10						500	995	2000	10000
1000	10							1000	1995	10000

- And scan these guys :

Mono-jet : Vector/AxialScalar/Pseudoscalar

Mono-X : Vector/Axial/Scalar/Pseudoscalar

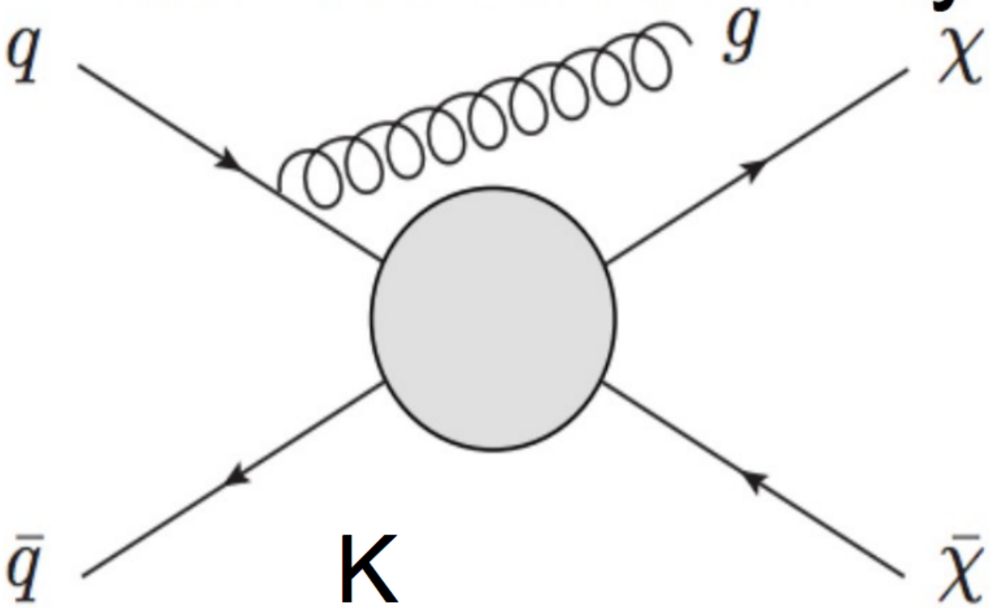
- X=W,Z,H,γ,j,l

Top/bs : Scalar/Pseudoscalar

Mono-top/b : Flavor Changing signatures

EFT vs simplified models

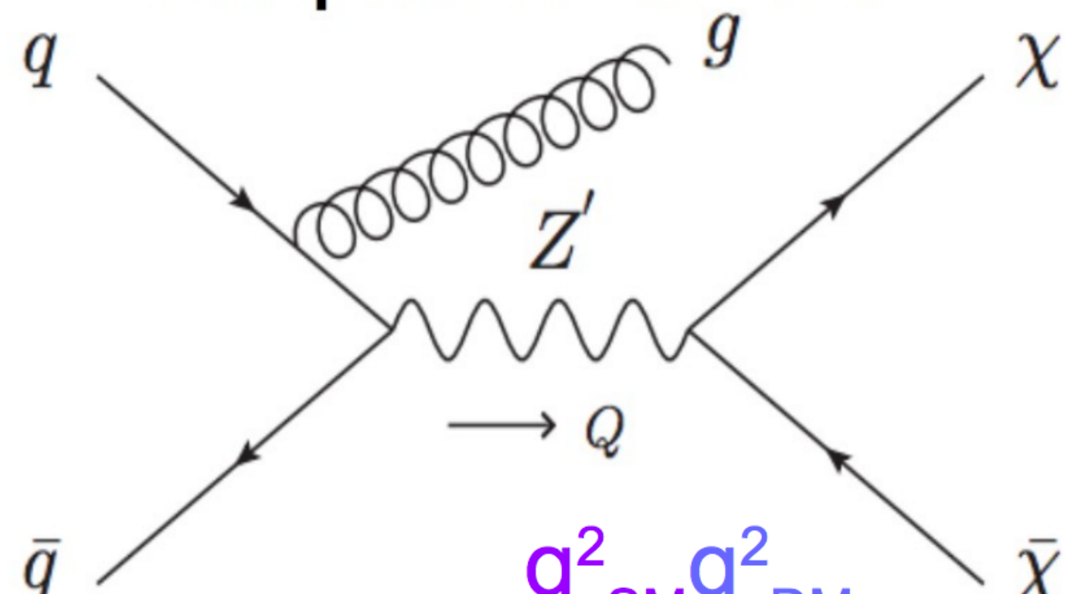
Effective field theory



$$\sigma = \frac{K}{\Lambda^4}$$

One free parameter

Simplified model



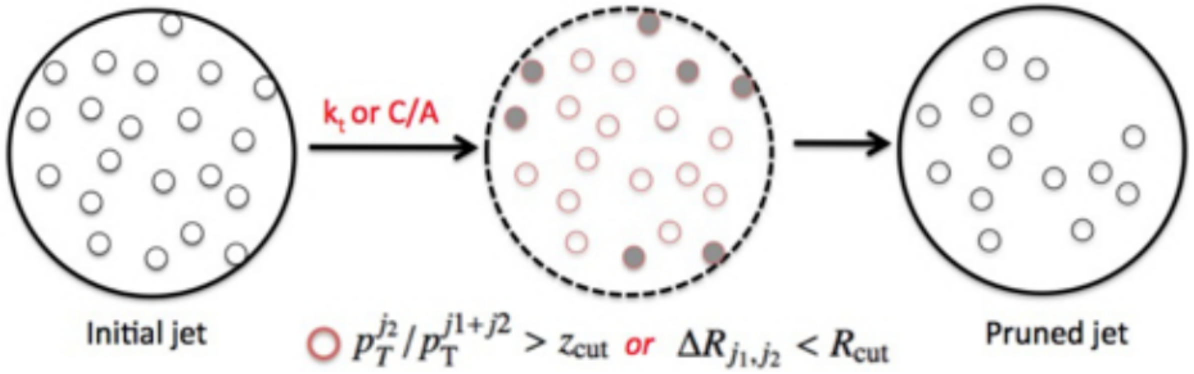
$$\sigma = K' \frac{g^2_{SM} g^2_{DM}}{M^4 \Gamma_{med}}$$

4 free parameters

- M = mediator mass
- Γ = mediator width
- g_{SM} = coupling to SM
- g_{DM} = coupling to DM

Jet substructure techniques

- Pruning: cut softer or wider constituents during jet reconstruction [arXiv:0912.0033]



- N-subjettiness: [arXiv:1101.2268]
  - Measure to what degree a jet can be considered to be composed of N-subjets
  - Force a jet algorithm to produce N subjets
  - The N-subjettiness characterizes how close to these jets the p_T is distributed

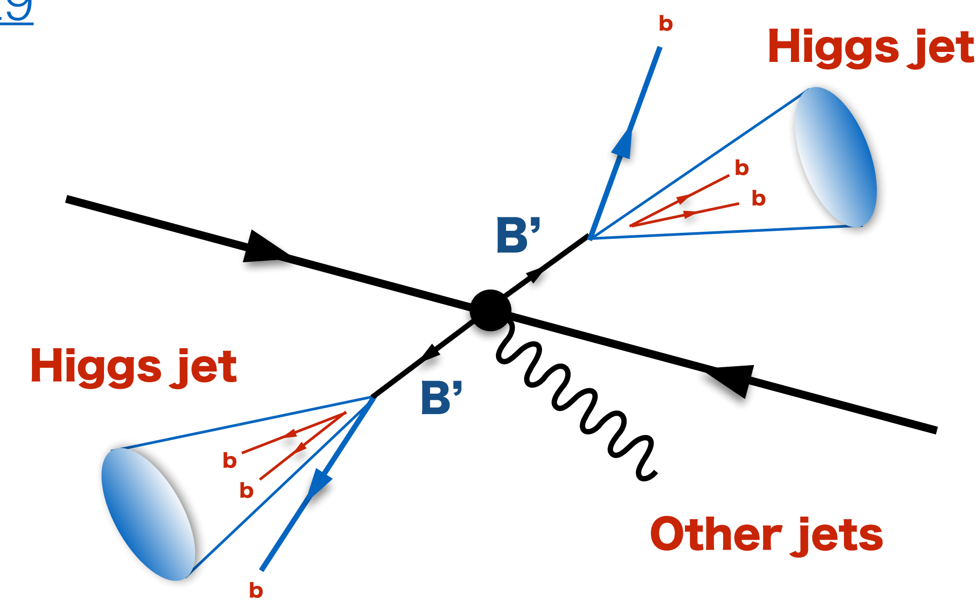
$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k} \min\{\Delta R_{1.k}, \Delta R_{2.k}, ..., \Delta R_{N.k}\}$$

- Q-jets: [arXiv:1201:1914]
  - Instead of clustering according to d_{ij} (as in CA), cluster at each algorithm step *randomly* according to a probability distribution of $P = \exp(-\alpha d_{ij})$
  - Get a probability distribution for the jet substructure instead of just one quantity
  - Discriminator: volatility (~RMS) of the jet mass

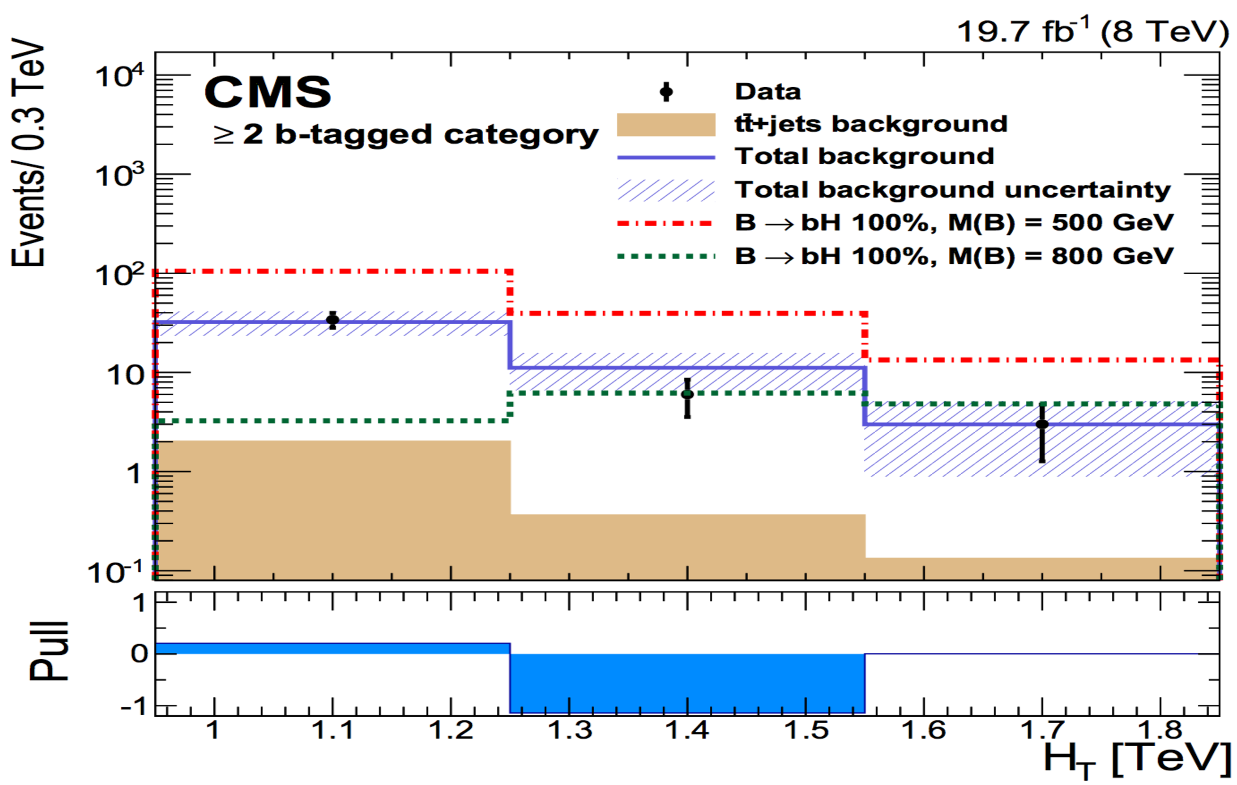
Search for B’ → b + Higgs (had)

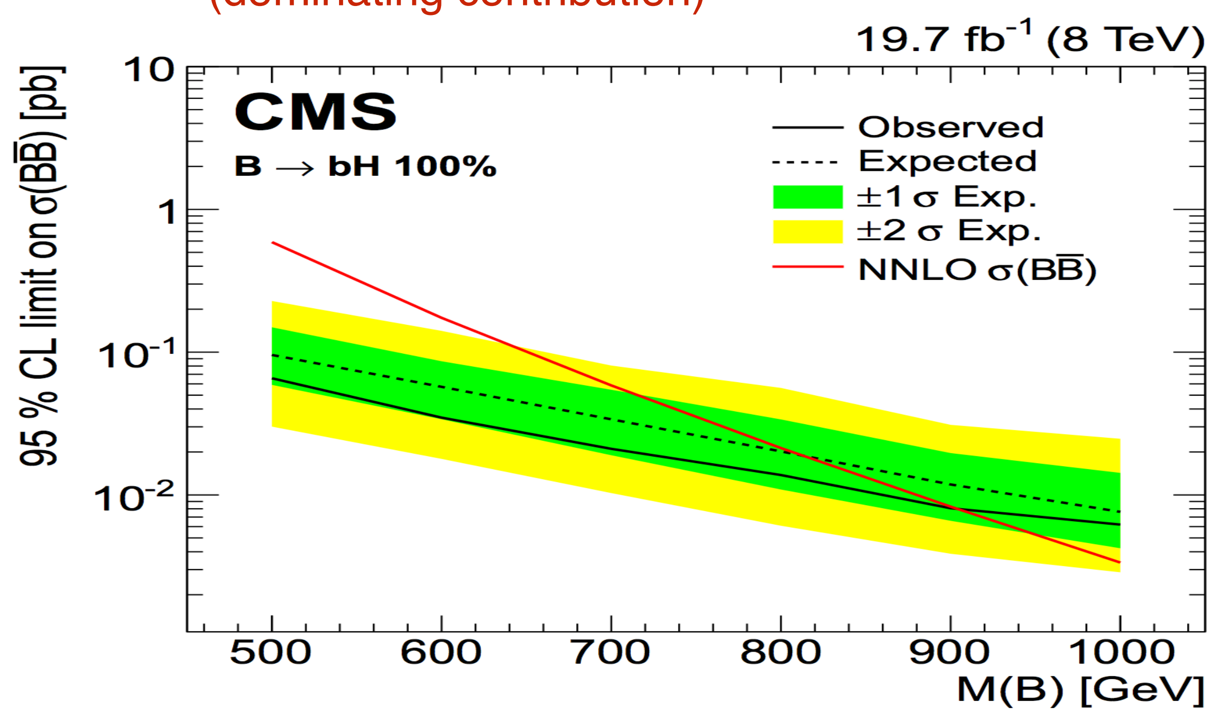
arXiv:1507.07129

- **Search for pair of heavy vector-like B’ quarks decaying into Higgs + b**
- Novel boosted b-tagging approach for H → bb reconstruction (require ≥ 1 fat jet)
- Good suppression of QCD wrt. jet substructures using this method
- 2 signal regions (1b and >2b) binned in H_T

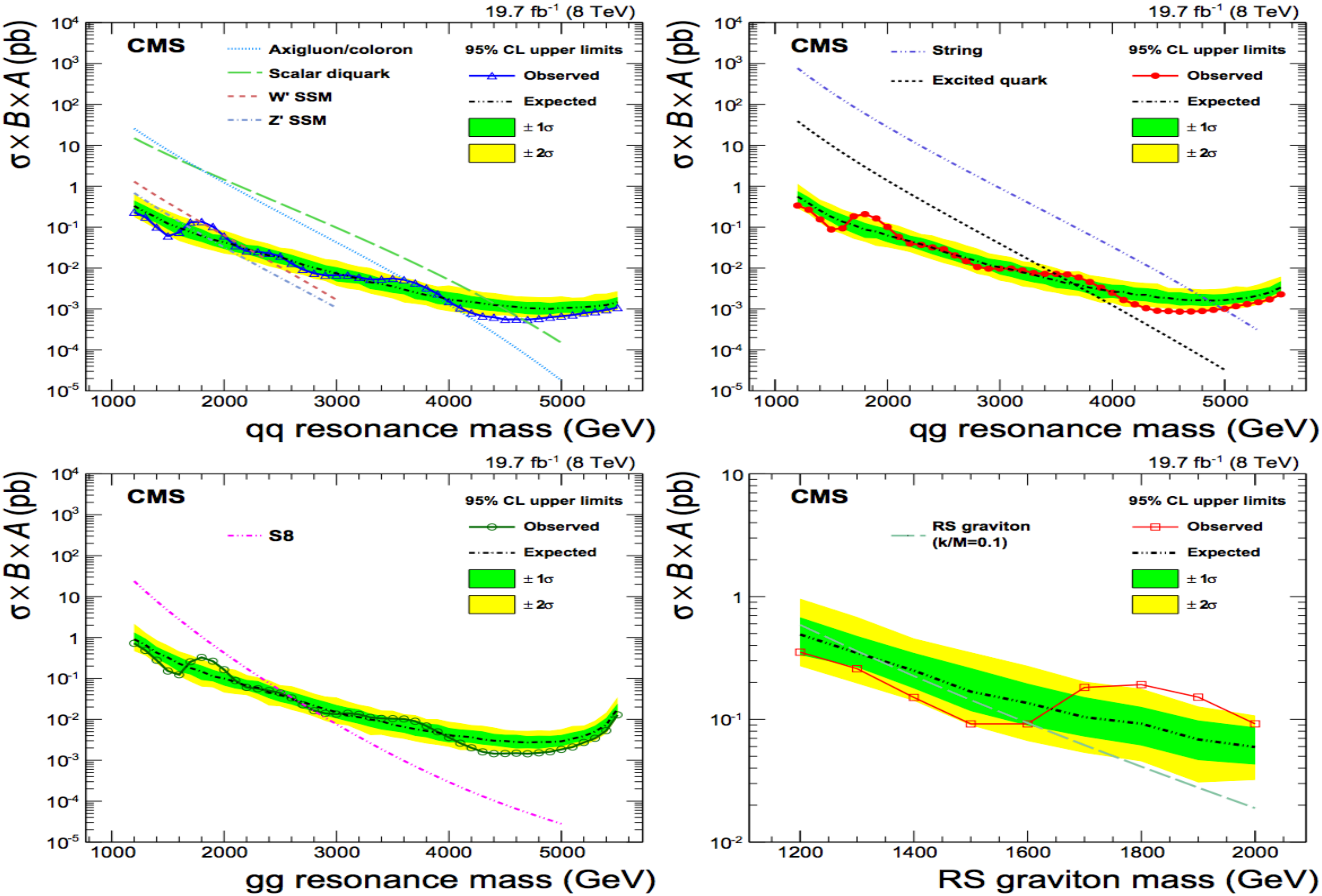


- **Limit below is combination of five channels:** single lepton+jets, opposite-signed dilepton+ jets, same-signed dilepton + jets, multileptons + jets, and all-hadronic with boosted Higgs tagging (dominating contribution)





Dijet

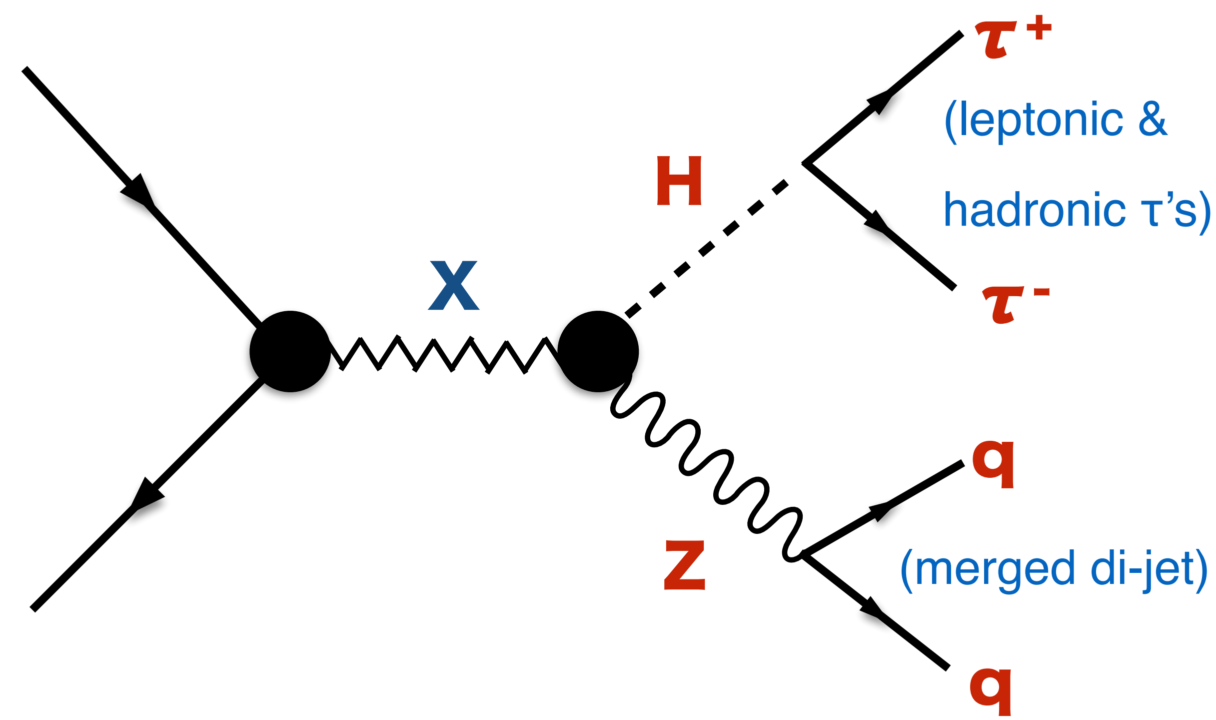


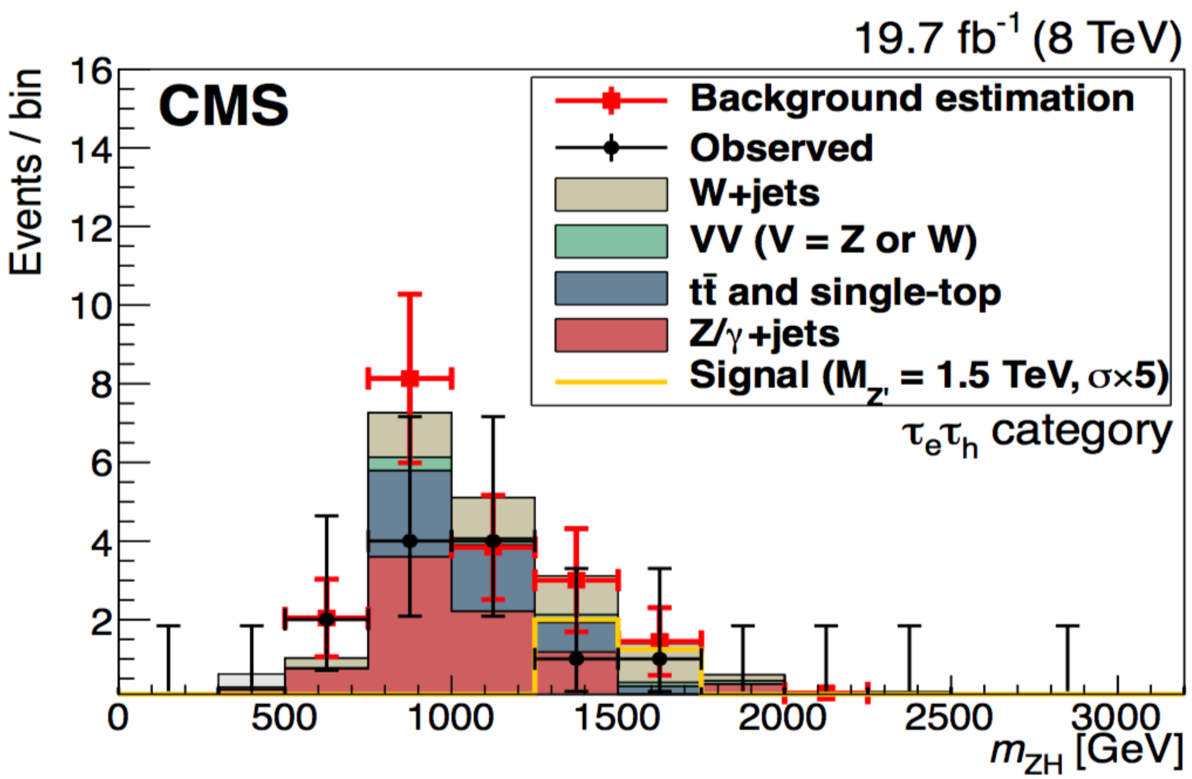
19.7 fb^{-1} (8 TeV)
CMS
Axigluon/coloron
Scalar diquark
W' SSM
Z' SSM
95% CL upper limits
Observed
Expected
± 1σ
± 2σ
σ×B×A (pb)
qq resonance mass (GeV)
19.7 fb^{-1} (8 TeV)
CMS
String
Excited quark
95% CL upper limits
Observed
Expected
± 1σ
± 2σ
σ×B×A (pb)
qg resonance mass (GeV)
19.7 fb^{-1} (8 TeV)
CMS
S8
95% CL upper limits
Observed
Expected
± 1σ
± 2σ
σ×B×A (pb)
gg resonance mass (GeV)
19.7 fb^{-1} (8 TeV)
CMS
RS graviton (k/M=0.1)
95% CL upper limits
Observed
Expected
± 1σ
± 2σ
σ×B×A (pb)
RS graviton mass (GeV)

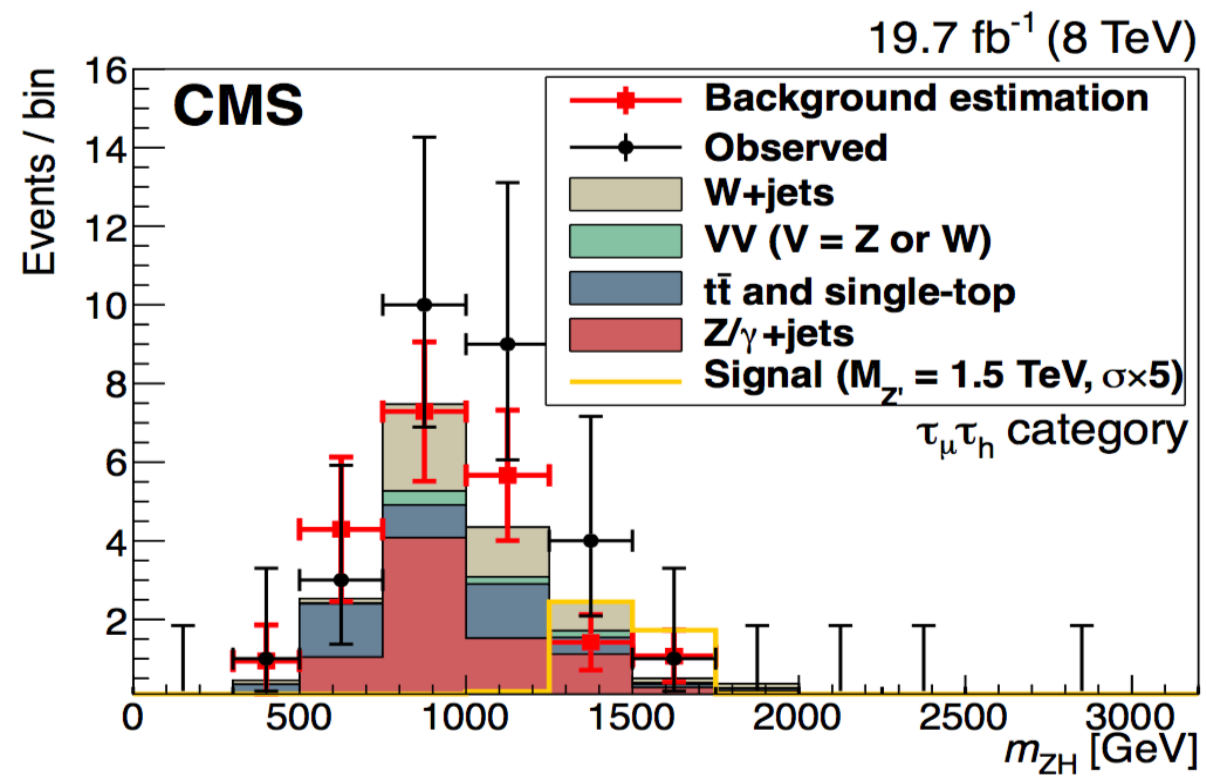
Boosted ZH resonance

arXiv:1502.04994 (click me)

- **Search for a massive (0.8—2.5 TeV) narrow resonance decaying to Z and H bosons**
- **Signal benchmarks:** HVT, Composite Higgs, heavy resonances (Z')
- **Discriminating variable:** ZH inv. mass



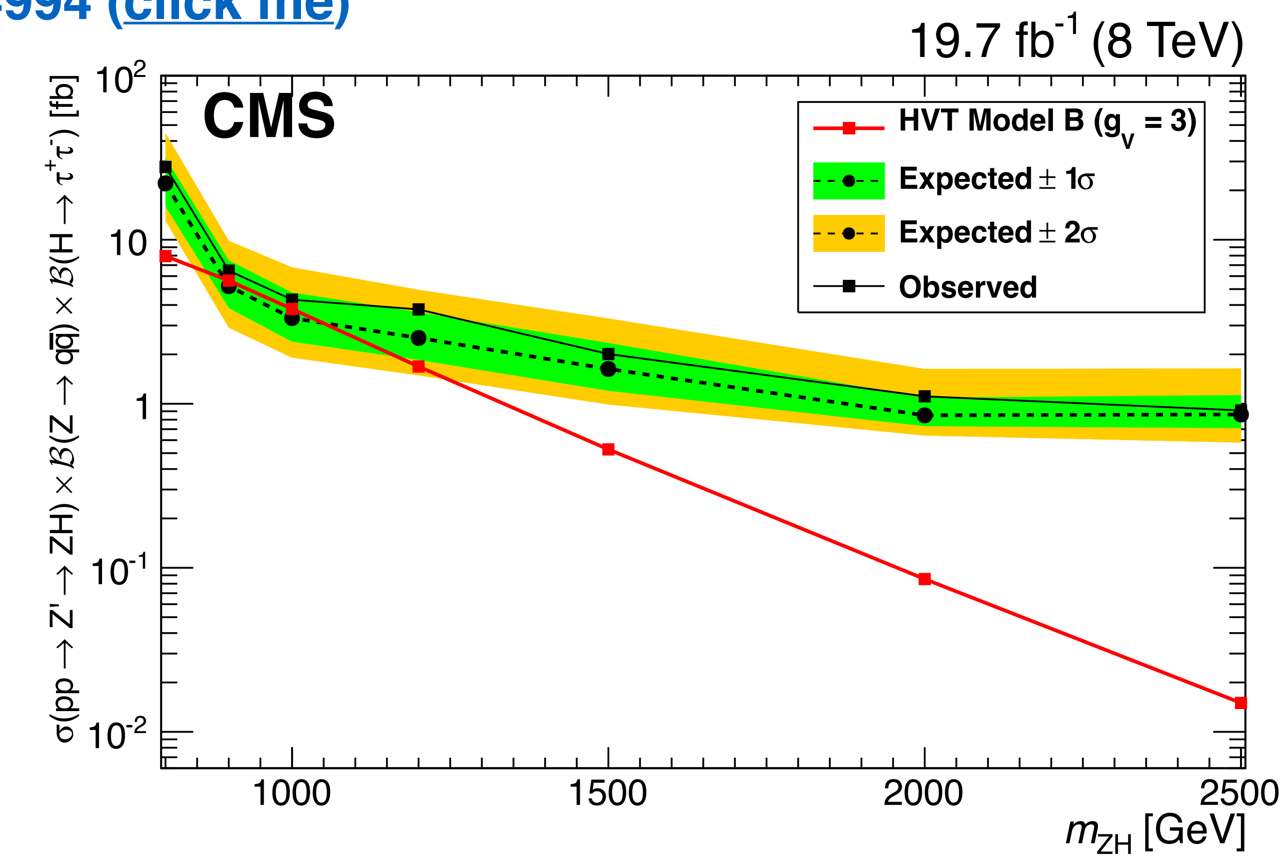


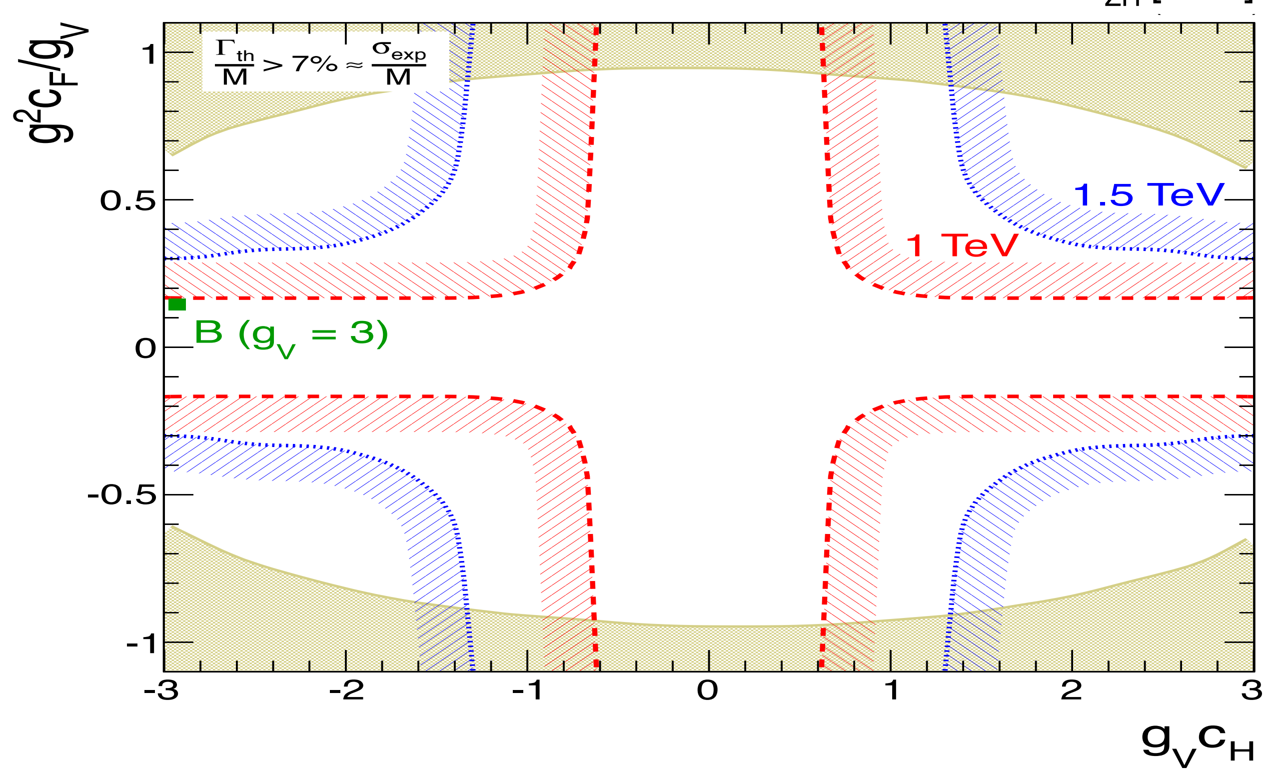


Boosted ZH resonance

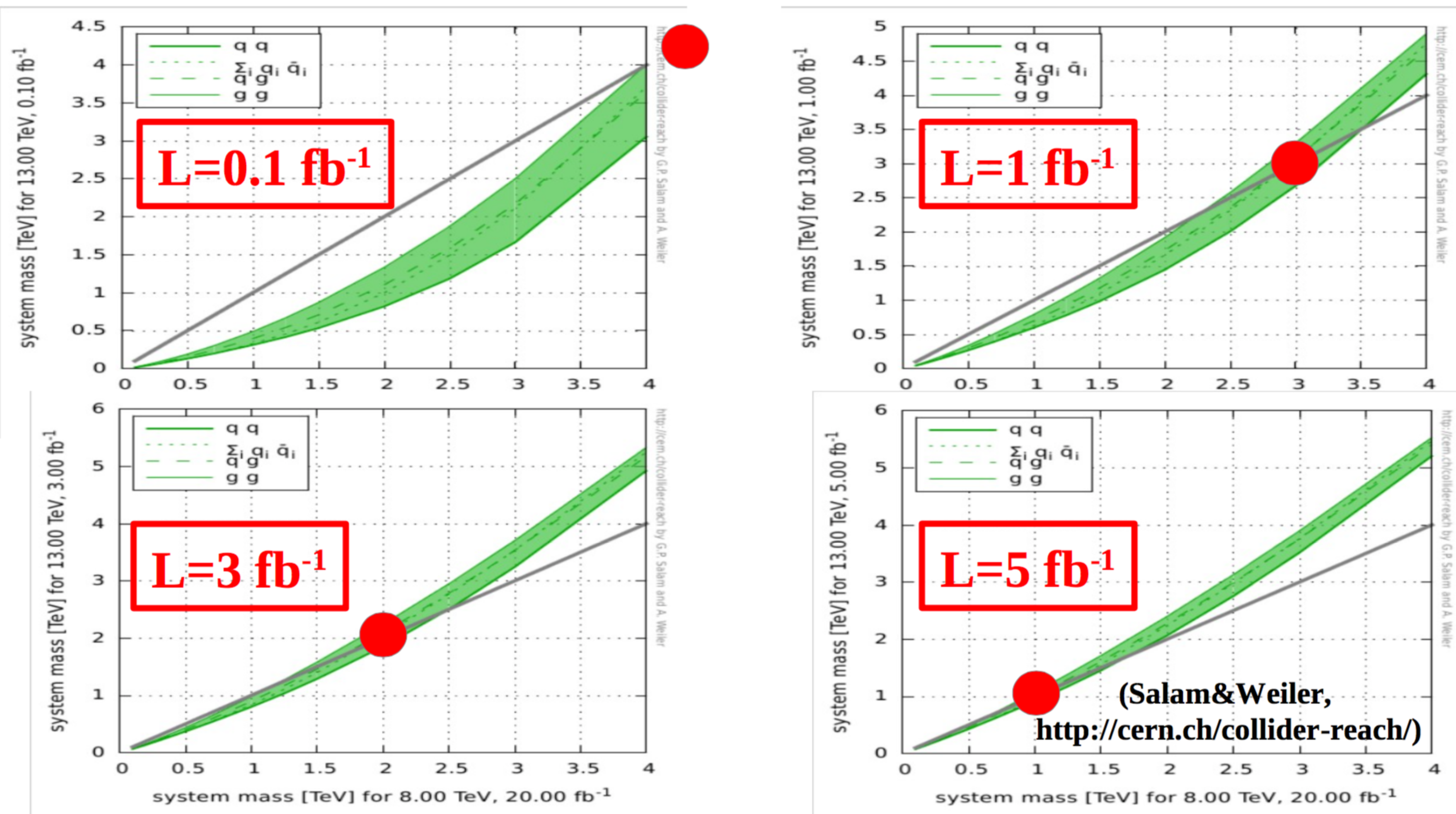
arXiv:1502.04994 (click me)

- **Backgrounds:**
  - Z+jets/W+jets, ttbar, single-top, ZZ, WW, QCD
- **Main source of systematic uncertainty:** MC stats. for signal efficiencies and bkg. estimation
- **7 signal regions** optimised for different mass assumptions for the resonance
- **Advanced reconstruction techniques used for boosted topology**
- Final state particles detected and reconstructed in small angular regions
- Can exclude xsecs between ~ 1 - 28 fb depending on mass of resonance

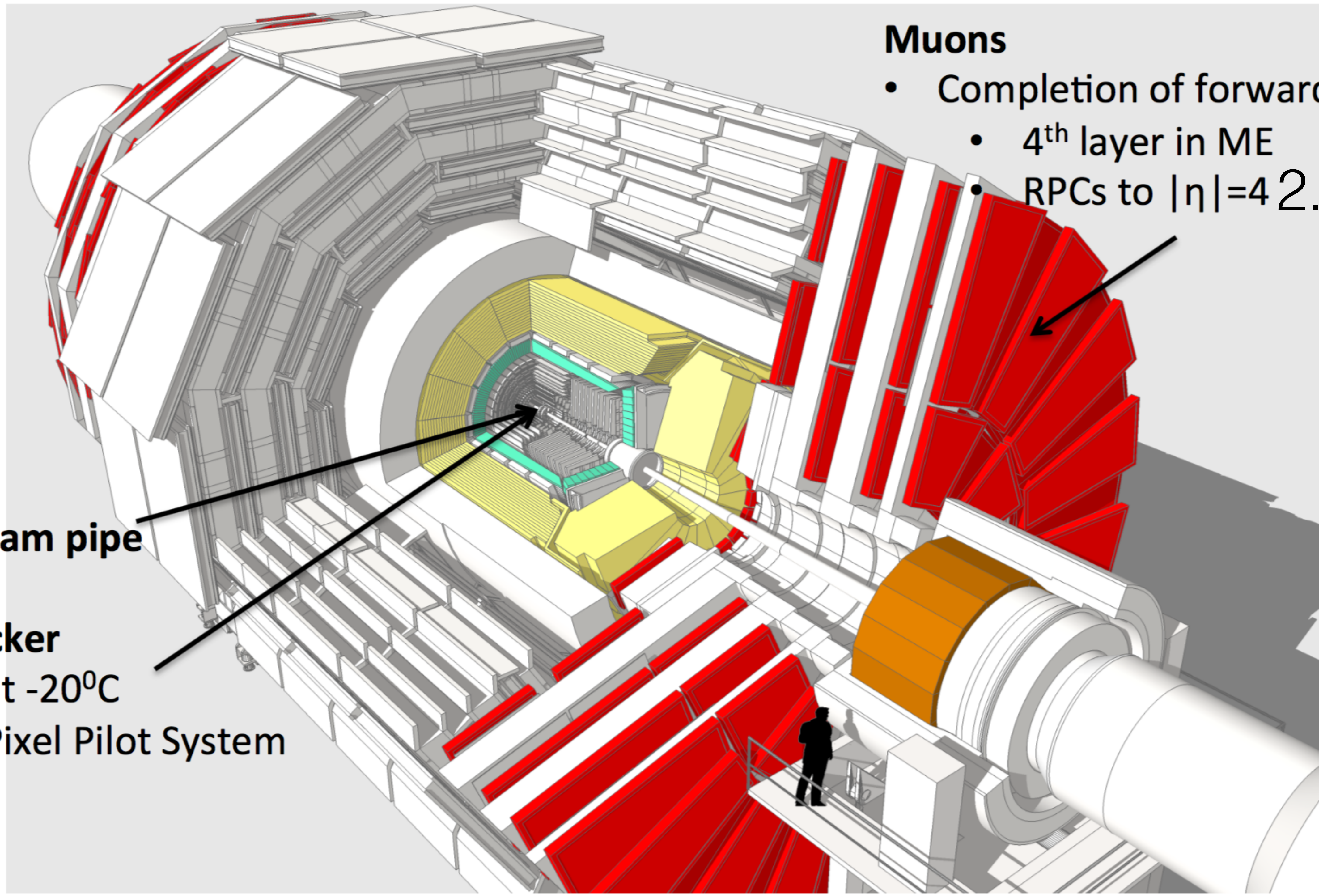




Resonances in Run 2



Detector improvements for Run 2



Muons
- Completion of forward detector
  - 4^{th} layer in ME
  - RPCs to $|\eta|$=4 2.4 max

New Beam pipe

Tracker
- at -20^{0}C
- Pixel Pilot System

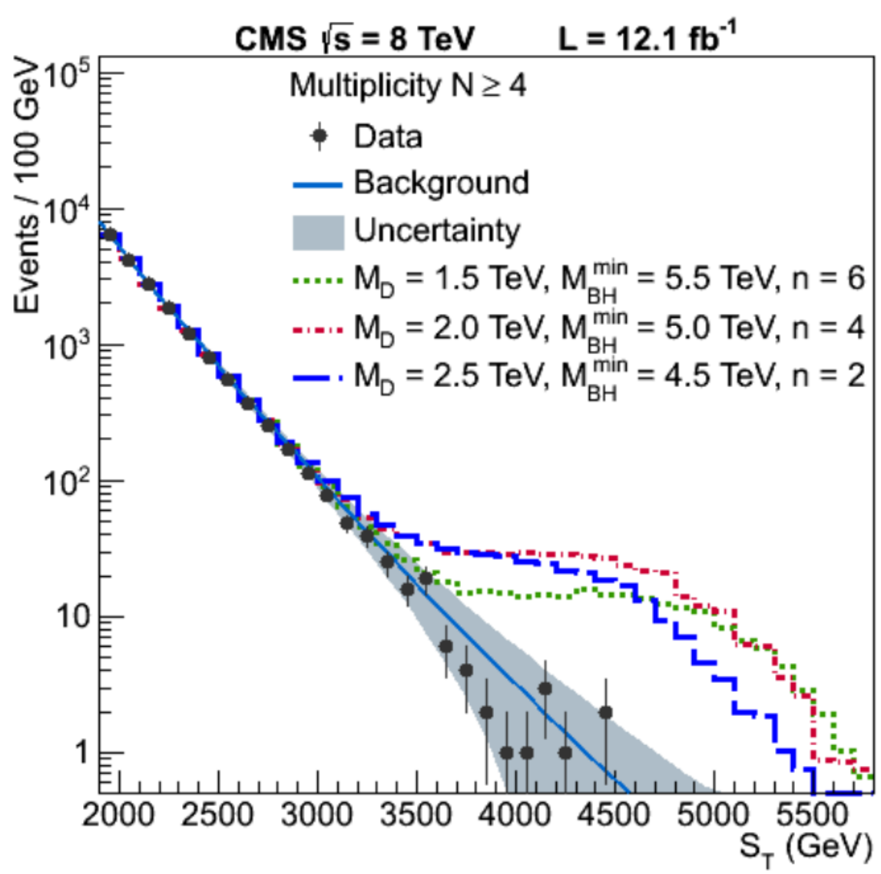
Black holes

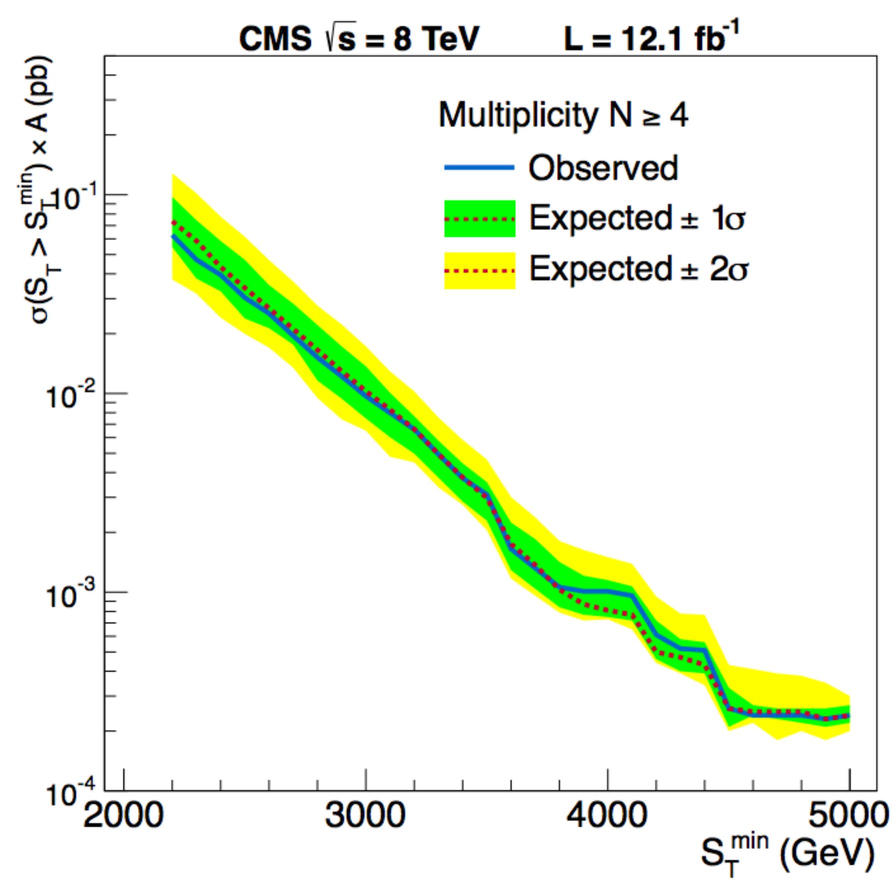
- Search for microscopic Black Holes in 12 fb^{-1} of 8 TeV data
  - Hypothetical BH would evaporate into many high-$p_{t.}$ objects
  - Estimate by S_T, the p_T sum of physics objects with p_T > 50 GeV
- Main background of QCD estimated by fit to n=2 distribution
  - Normalised for each multiplicity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

arXiv:1303.5338

$$S_T = \sum_{j,e,\mu,\gamma,MET}^{N} p_T$$

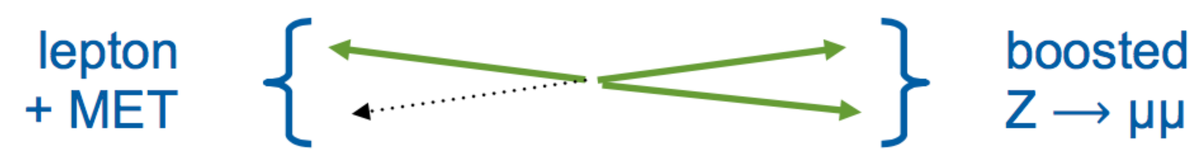
Black Hole limits around 5 TeV, also model-independent limits on high S_T



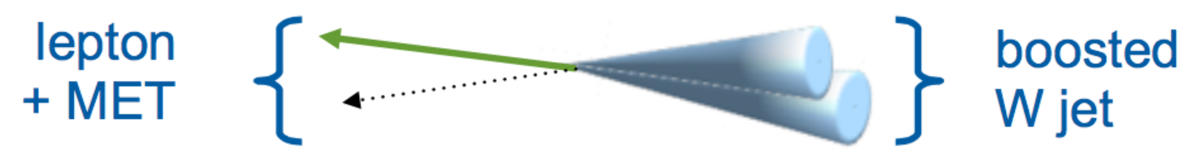


High-mass diboson resonant searches

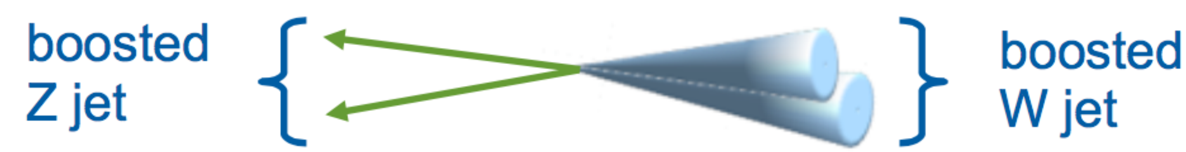
$W'/\rho_{TC} \longrightarrow WZ \longrightarrow 3l + MET$
[CMS EXO-12-025, ATLAS-CONF-2014-015]



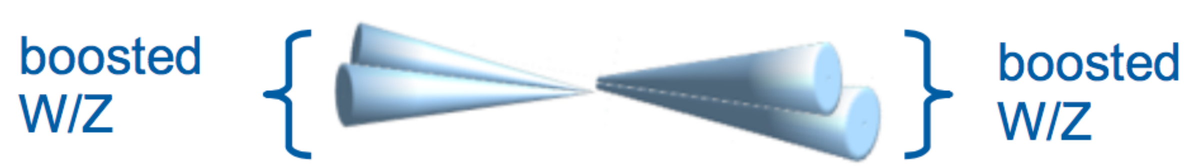
$G_{bulk} \longrightarrow WW \longrightarrow l + jet + MET$
[CMS arXiv:1405.3447, ATLAS-CONF-2013-074]



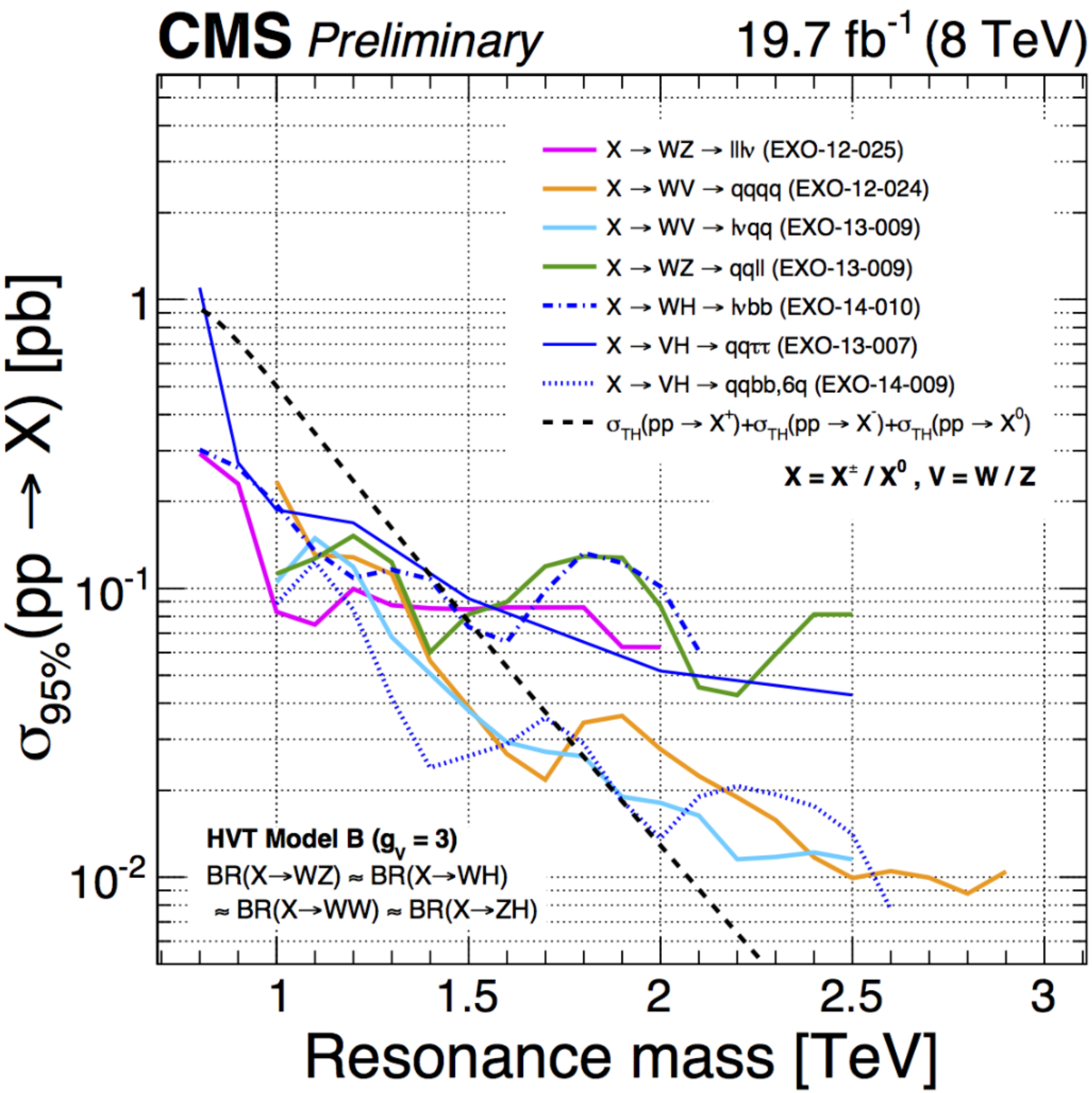
$G_{bulk} \longrightarrow ZZ \longrightarrow 2l + 2jets$
[CMS arXiv:1405.3447, ATLAS-CONF-2013-074]



$G_{RS} \longrightarrow WW/ZZ$ and $W' \longrightarrow WZ$
[CMS arXiv:1405.1994]



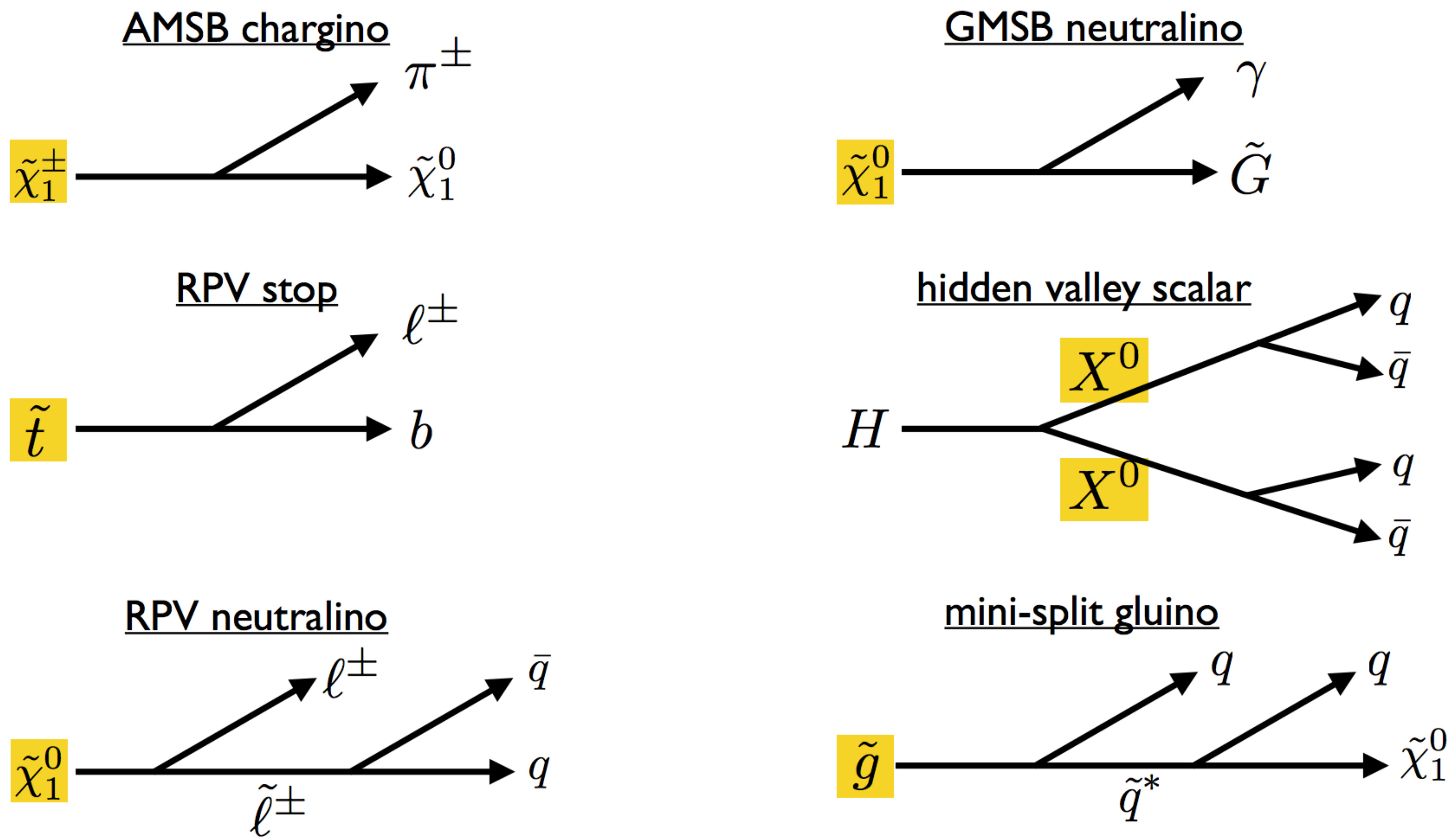
HVT analysis sensitivity comparison



- **Heavy Vector Triplet model B predicts predominantly the following spin-1 signals:** W' → WZ, W' → WH, Z' → WW, Z' → ZH mass(W') = mass(Z')
- **Roughly:** σ(pp → W' → WZ) = σ(pp → W' → WH) = 2σ(pp → Z' → WW) = 2σ(pp → Z' → ZH)
- **Sensitivity comparison plot including all WW, WZ, WH, ZH channels (but no combination)**
- **Why lnuqq more sensitive than lnubb?**
- 1. lnuqq sensitive to WW and WZ, lnubb only to WH a factor 1.5
- 2. combinatorics of WW → lnuqq leads to a factor 2 compared to WH → lnubb. A Total factor 3

Long-lived searches

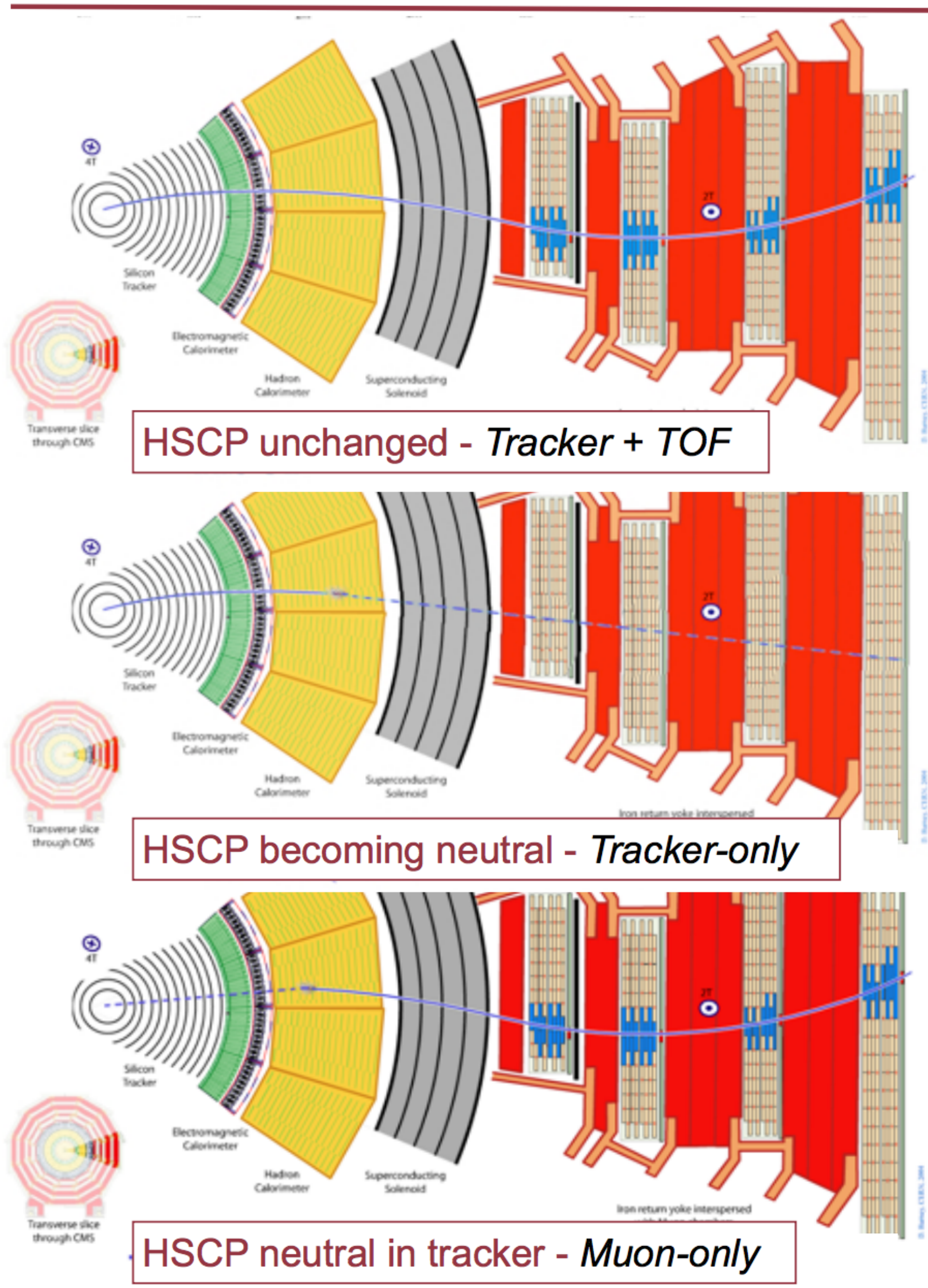
- Various mechanisms could lead to long lifetimes
- Long lived particle highlighted in yellow

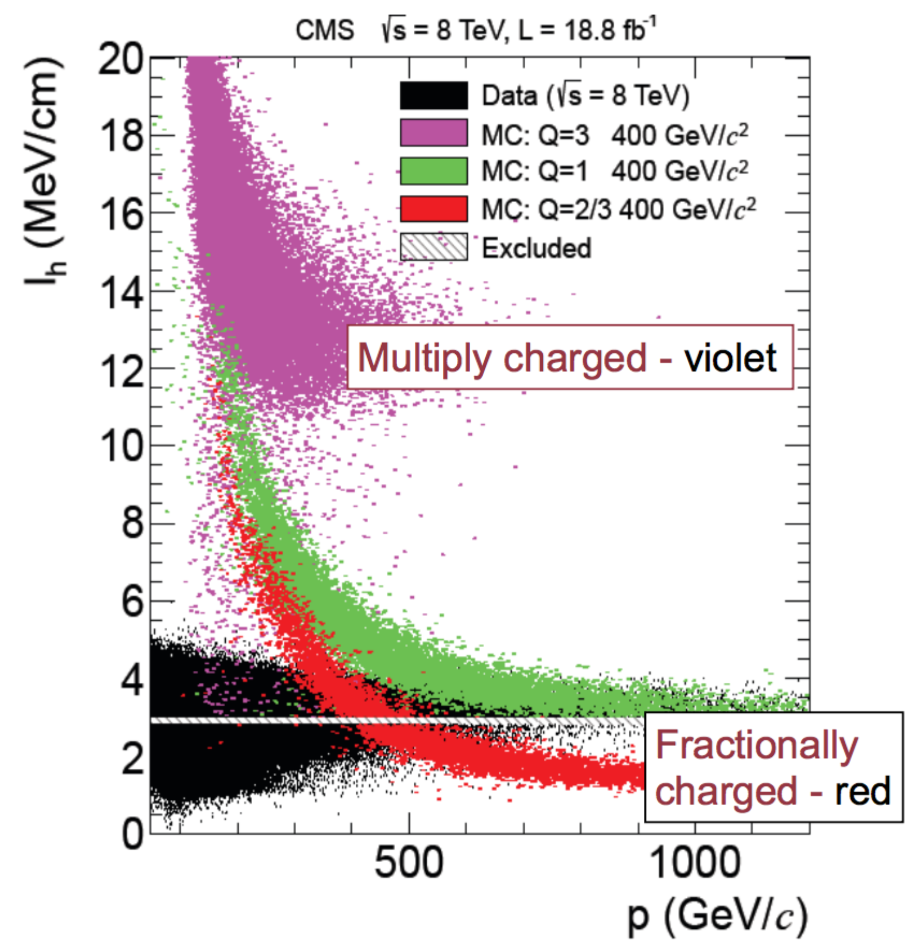


Q=1 HSCP

Q≠1 HSCP

[CMS EXO-12-026]





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

$$dE/dx \cong K\frac{m^2}{p^2} + C$$

- Track p_T : inner tracker transverse momentum
- Muon $1/\beta$: measured by muon system
- Track I_{as} : incompatibility of the track energy loss w.r.t MIP expected dE/dx

HSCP reinterpretation

arXiv:1305.0491 (click me)

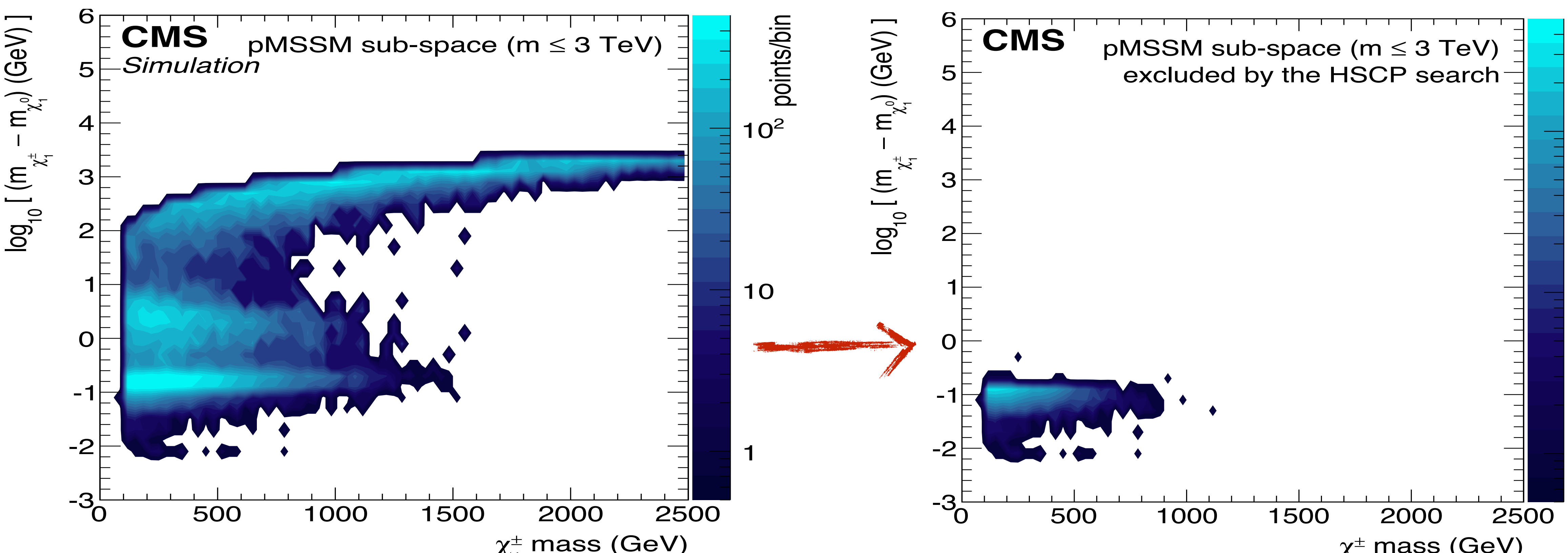
i. **Goal:** Allow assess to CMS sensitivity to any model predicting long-lived lepton-like particles

ii. **Technique:** measure the efficiency for these particles as a function of β and η in bins of p_T ; then you just need the predicted kinematics from the model

iii. Can reinterpret these results in the context of the pMSSM (for e.g.)

pMSSM points expected at the LHC

excluded by this analysis

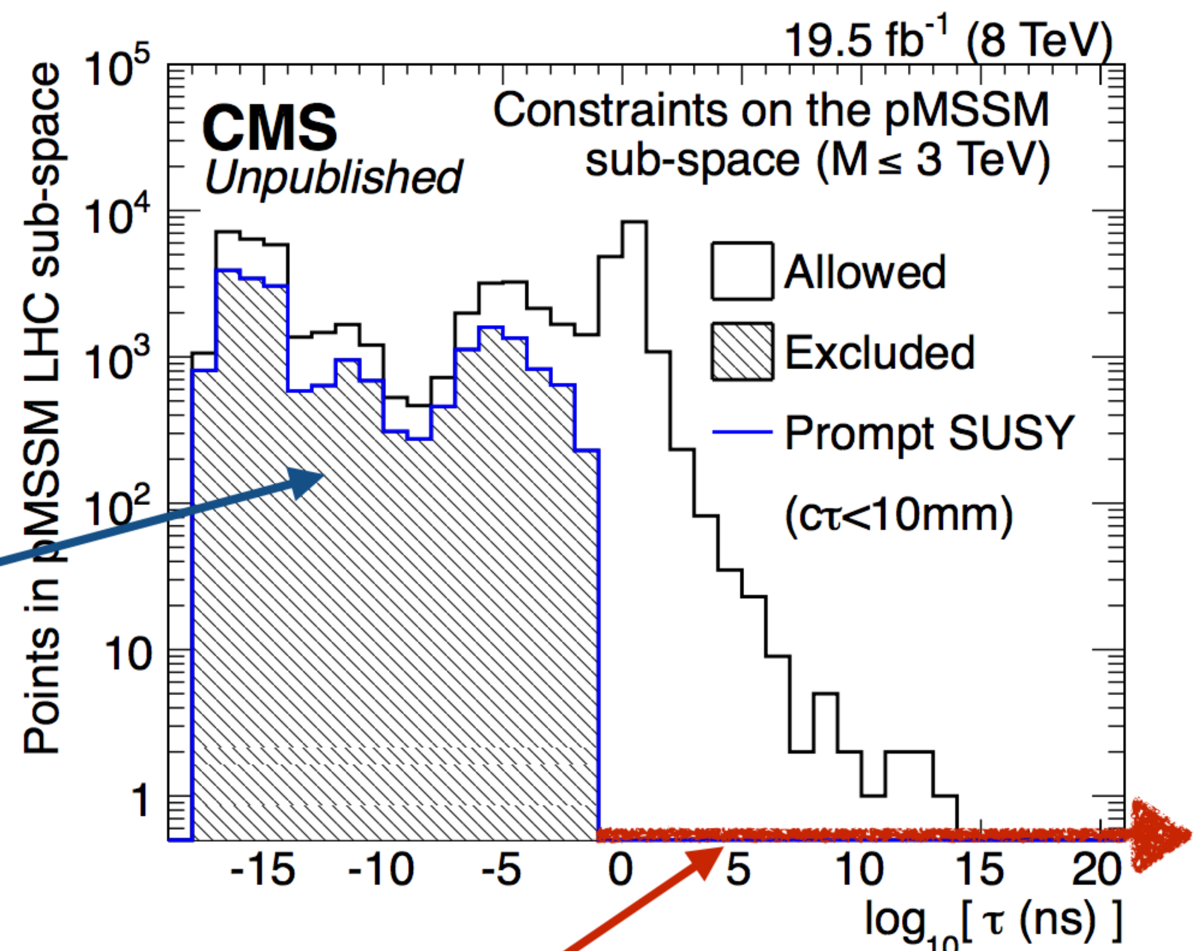


Long-lived particles in pMSSM

Large parameter space available for particles with long lifetimes.

Each entry is a point in 19-D pMSSM parameter space.

Most SUSY searches target prompt decays, d_0 ~< mm.



27% of pMSSM points have NLSP (chargino) with cτ > 1 cm.

Displaced dijets

arXiv:1411.6530 (click me)

Benchmarks:

i. Neutral long-lived spin-0 boson X, with H → XX, X → qq

ii. Long-lived $\tilde{\chi}^0$ produced from squark decay ($\tilde{q} \rightarrow q\tilde{\chi}^0$) then $\tilde{\chi}^0 \rightarrow qq\mu$

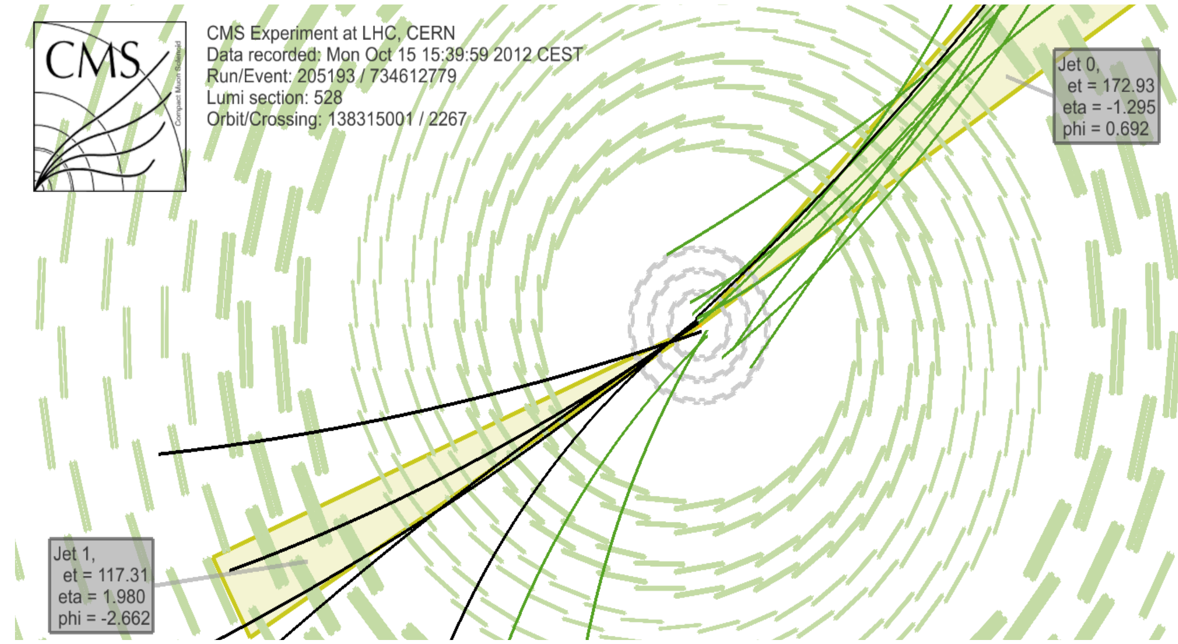
iv. Look for pair of high-momentum jets forming a vertex (decay length L_{xy} ~20 cm)

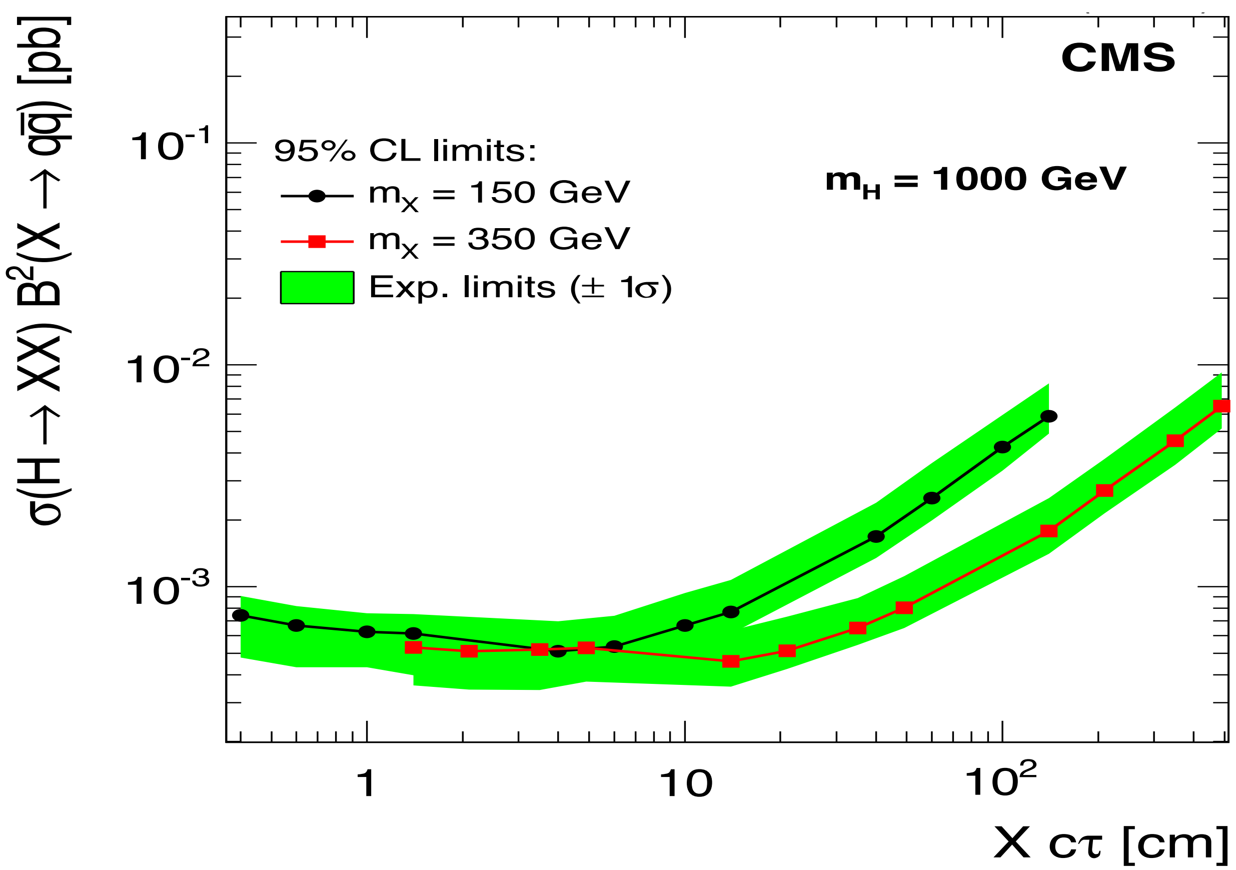
v. Identify displaced jets by requiring:

vi. few prompt tracks in jet, high fraction of energy in jet carried by, displaced tracks, clustering-based discriminant

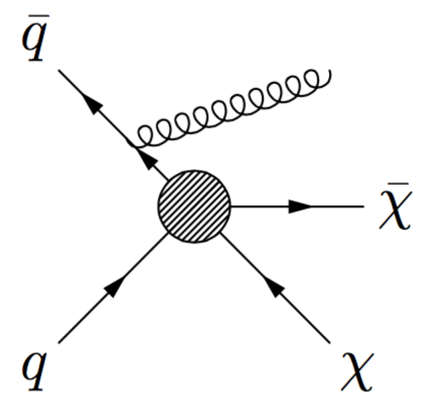
vii. Two sets of selection criteria optimised for smaller/larger L_{xy} values

viii. Clean channel (small SM backgrounds)

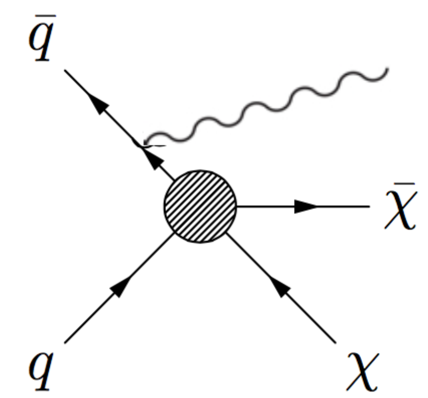




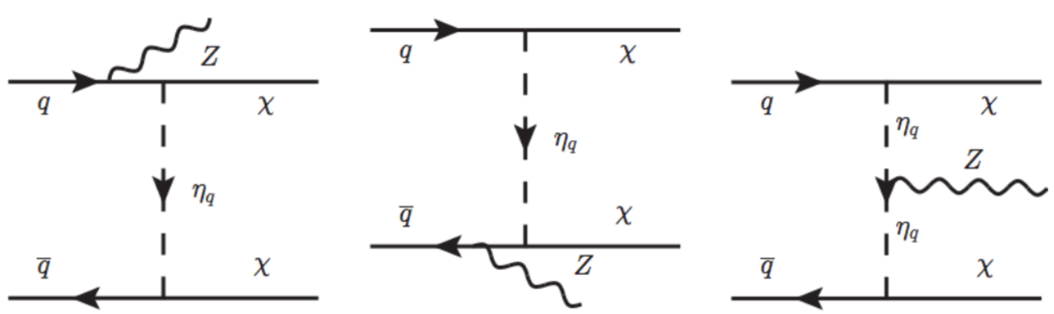
Mono



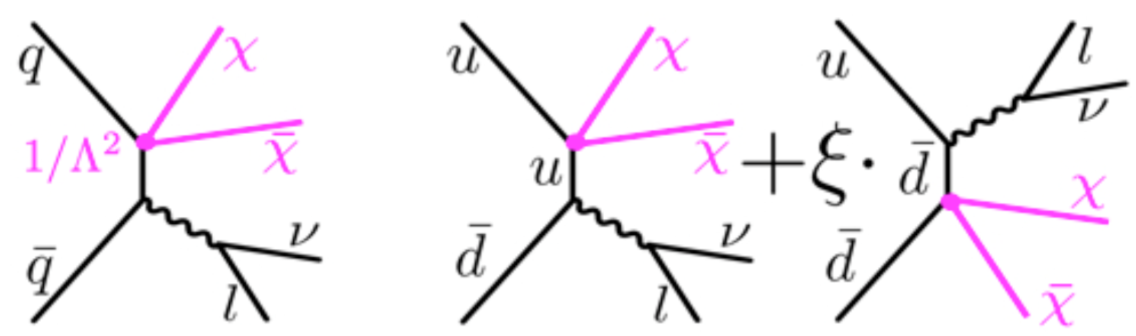
Monojet



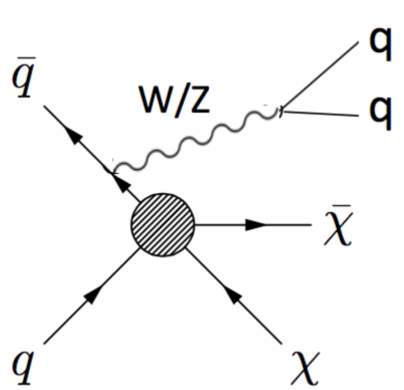
Monophoton



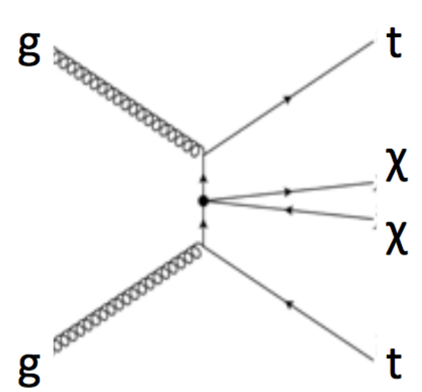
MonoZ



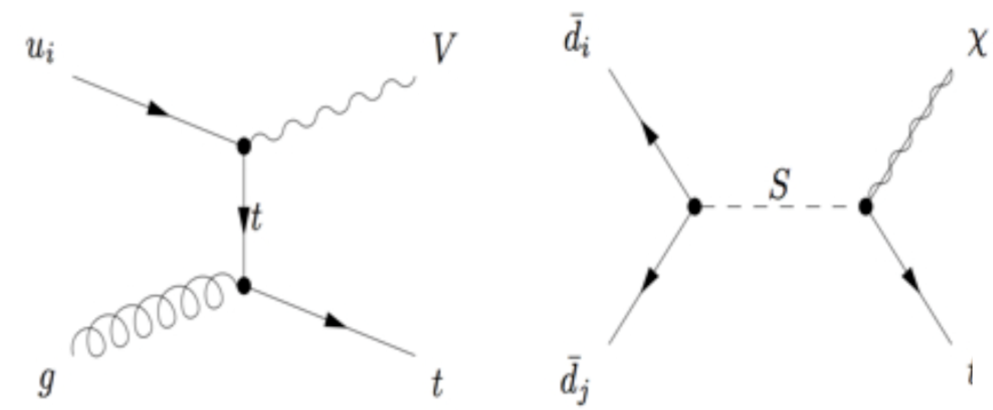
MonoW (Monolepton)



MonoW/Z (hadronic)



ttbar DM



MonoTop