Beyond Standard Model Searches at CMS

Andrew Ivanov
Kansas State University
On behalf of the CMS Collaboration

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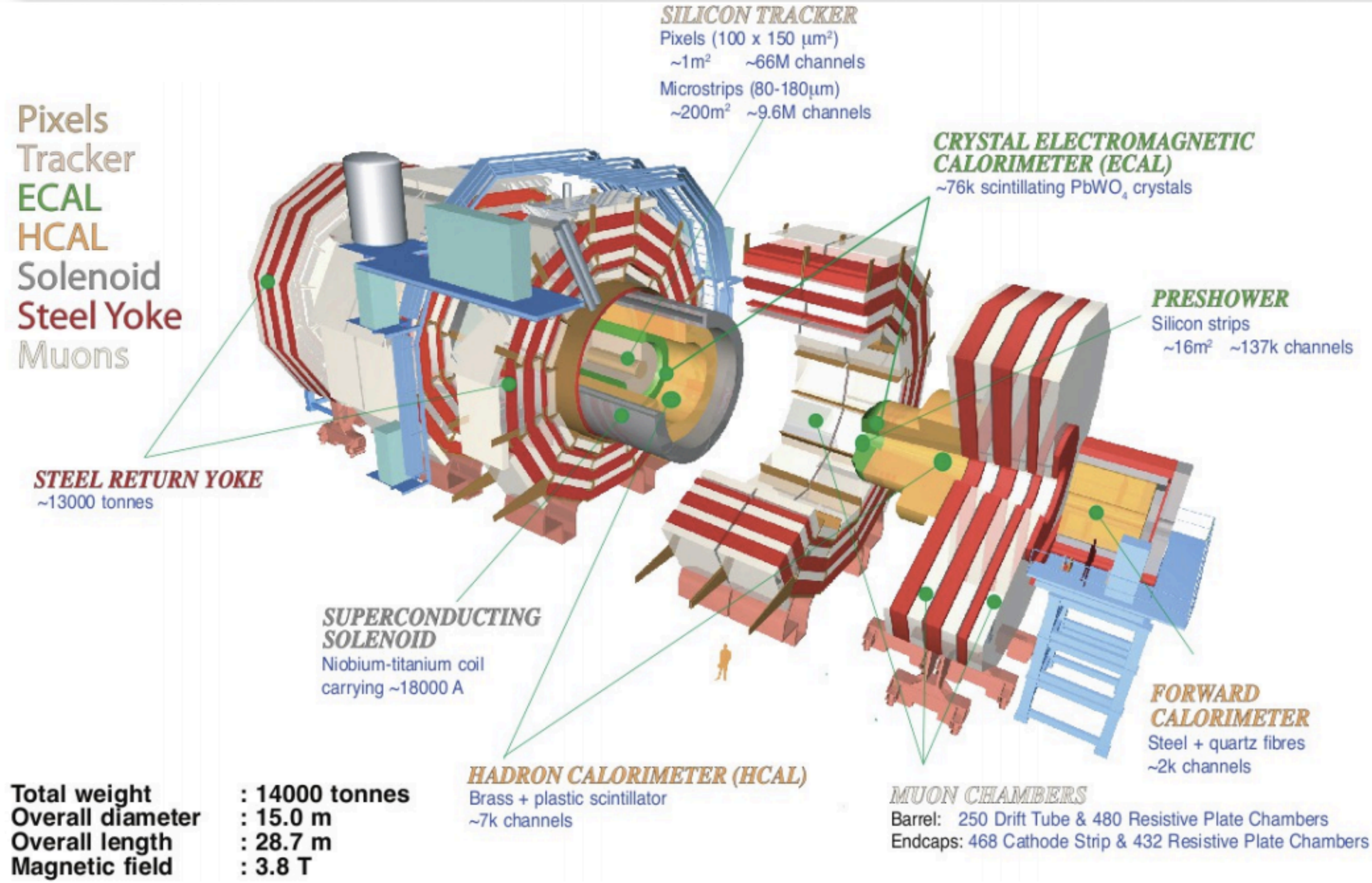
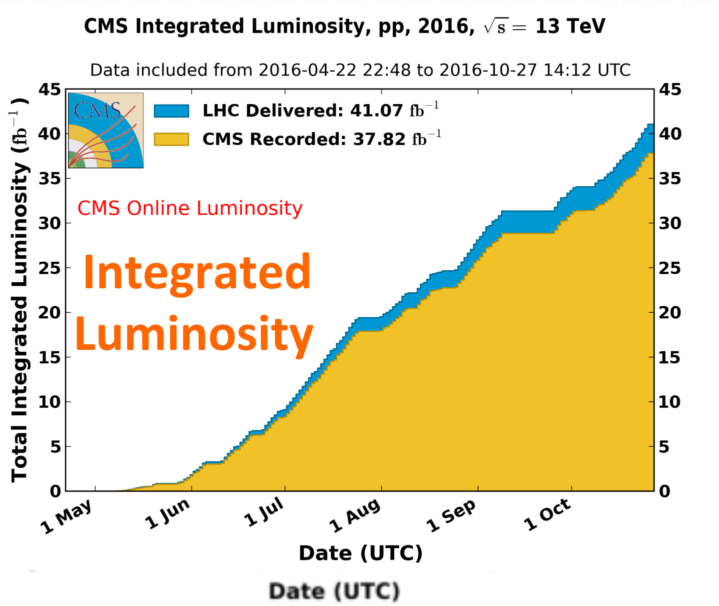
CMS Detector



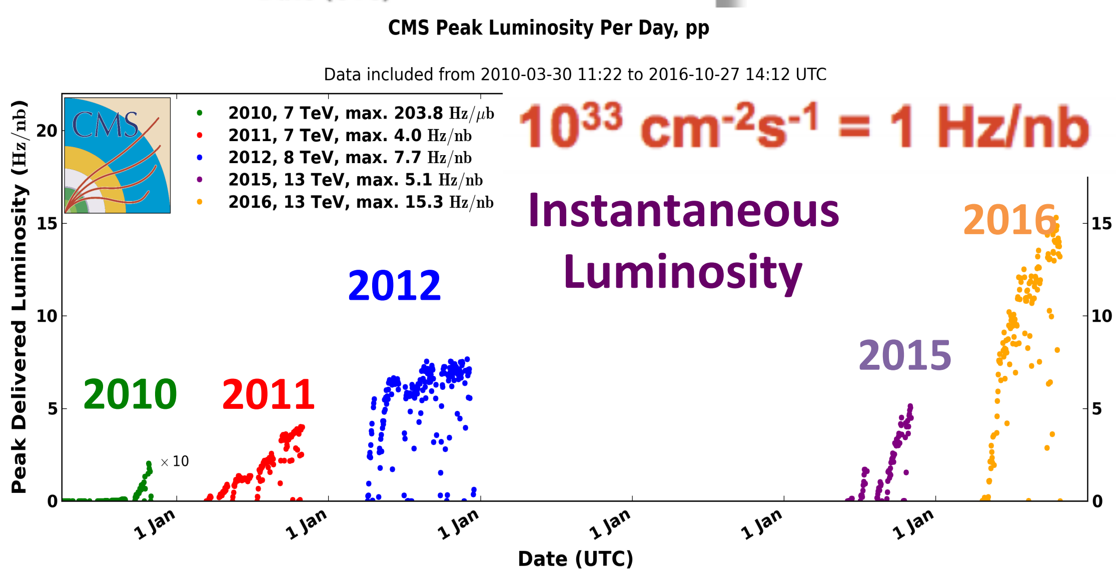
CMS Collaboration

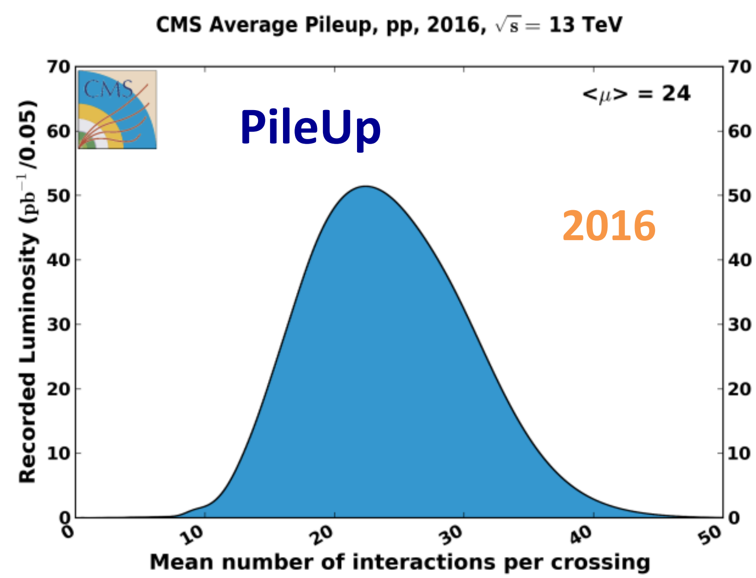
- ~3900 collaborators
  - ~1800 physicists
  - ~900 students
  - ~900 engineers
  - ~300 technicians
- From 43 countries

LHC Run 2 @ 13 TeV

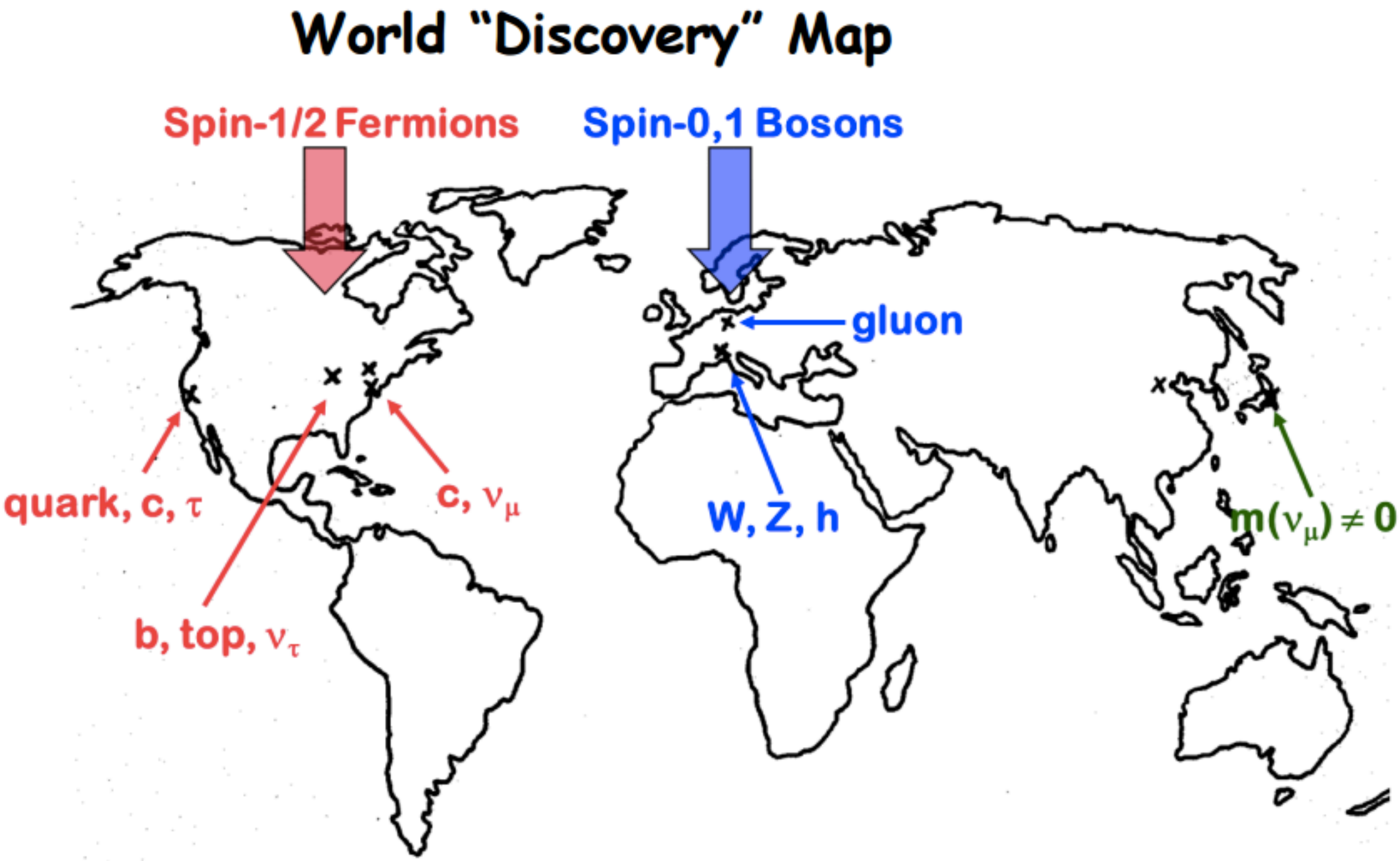


- Run 2 Dataset
  - 2015: ~3 /fb
  - 2016: ~38 /fb,
- Excellent detector performance
- High data-taking efficiency
  - ~ 92% of delivered data are recorded
  - ~ 92.5% if those are certified and used for physics analyses





We are Up for Discoveries ..



New Physics Searches Landscape

Exploring a New 13 TeV Energy Domain …

<u>Outline of my talk:</u>

Resonances

Di-photon, Di-V
Di-Jet, etc

Vector-like Fermions

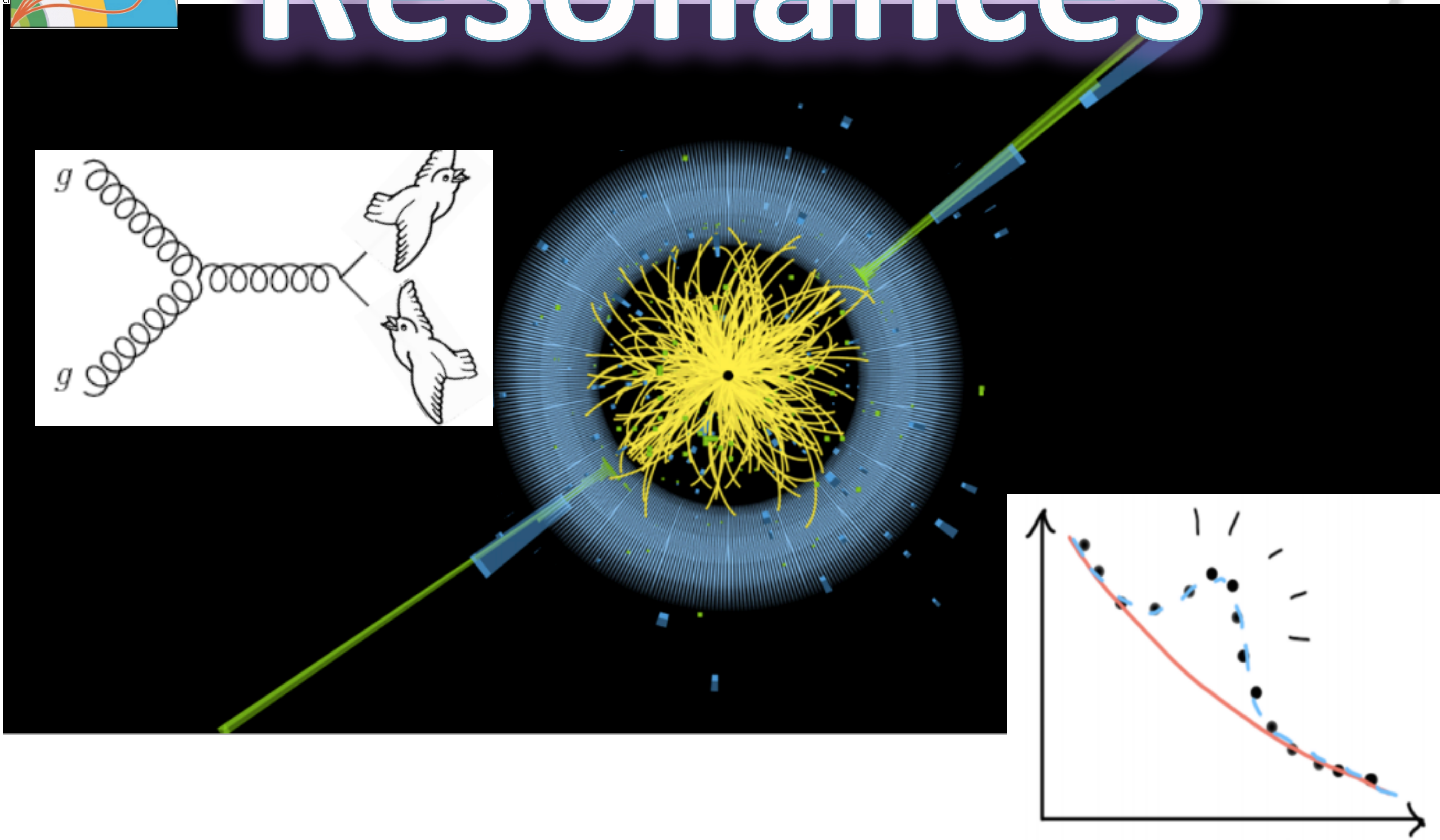
SUSY

Dark Matter

Mono-Jet
Mono-V

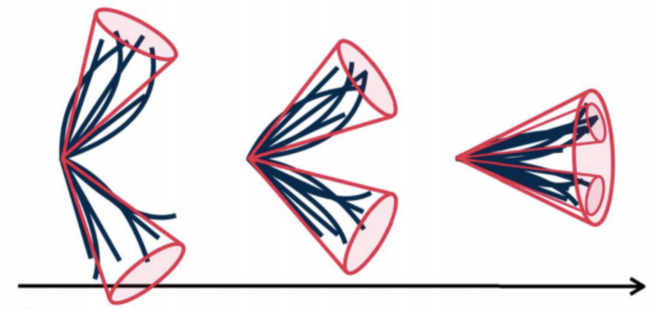
Leave no stone unturned …

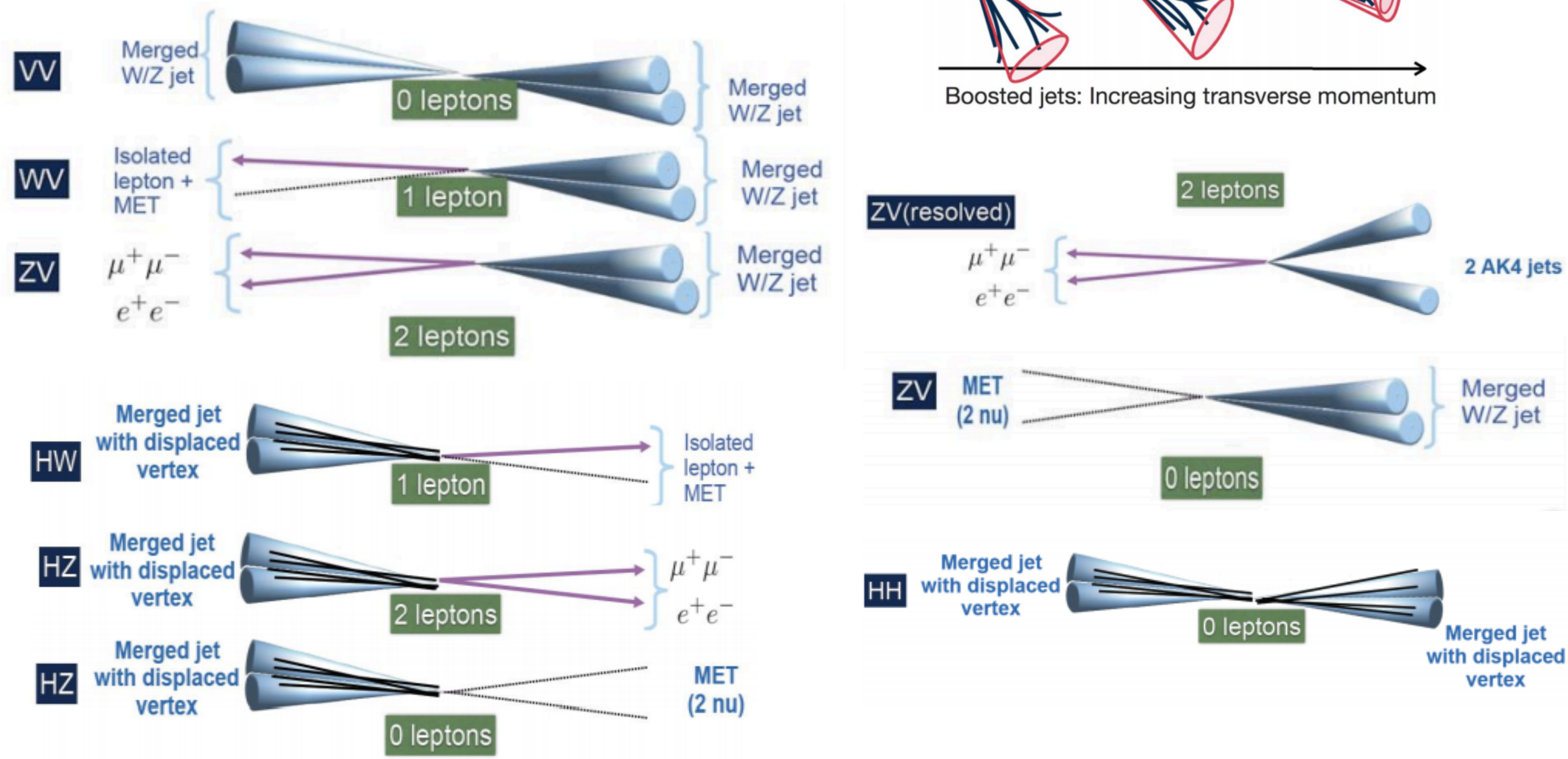
Resonances



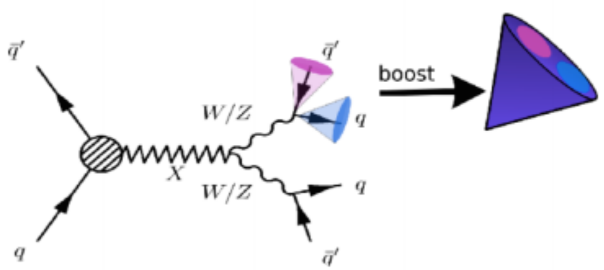
Di-Boson Resonances

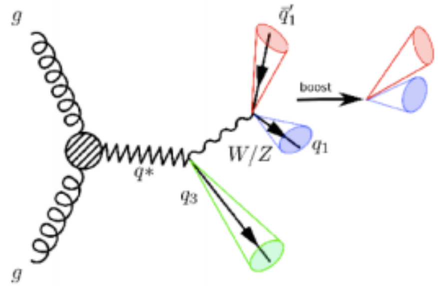
- Tag boosted W, Z and H-bosons using jet substructure algorithms



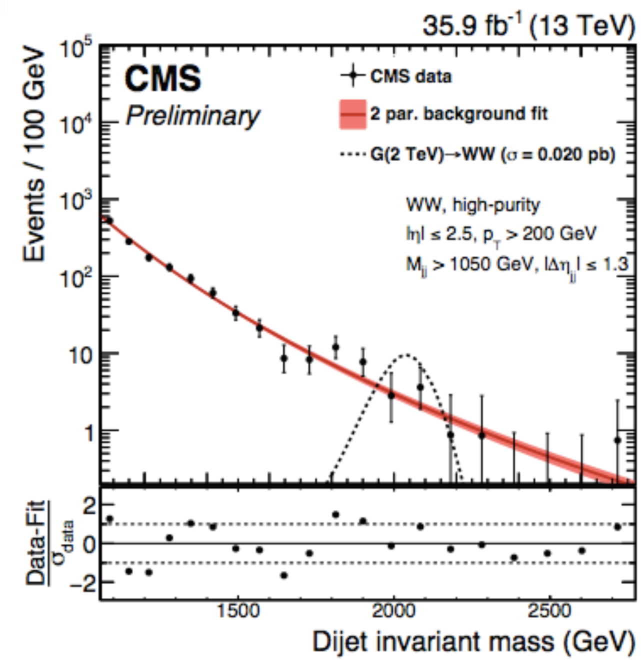


Resonant V(qq)V(qq)



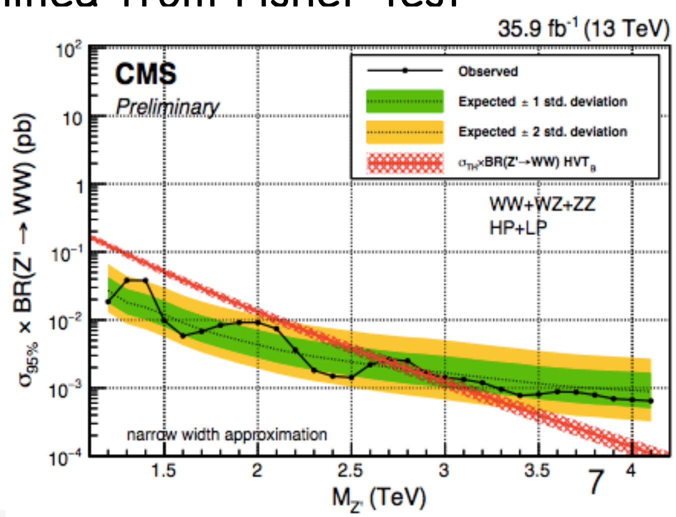


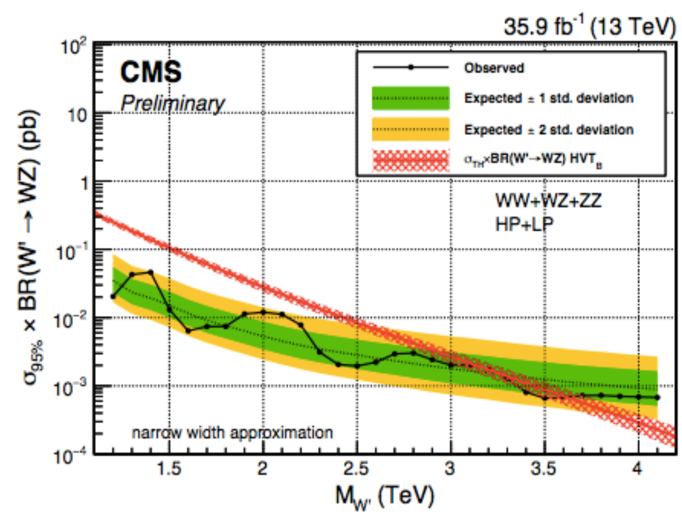
- All-hadronic resonance search with double (VV) or single (qV) V-tag
- Categorize events based on V-jet mass: W=[65,85], Z=[85,105]; high/low-purity τ_{21} < 0.35 or [0.35,0.75]
- Backgrounds: multi-jet, ttbar, V+jets
- Fit the data spectrum with power law functions
- # of parameters determined from Fisher test



$M_{Z'}$ > 2.7 TeV
$M_{W'}$ > 3.6 TeV
@ 95 % C.L.

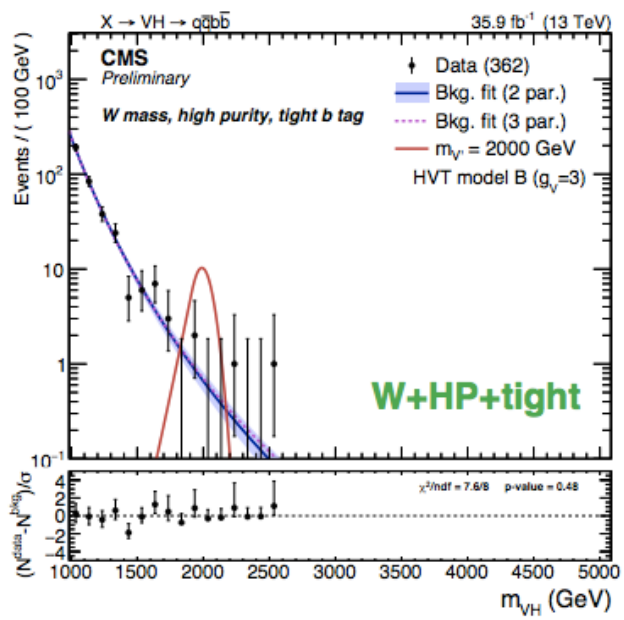
CMS-PAS-B2G-17-001

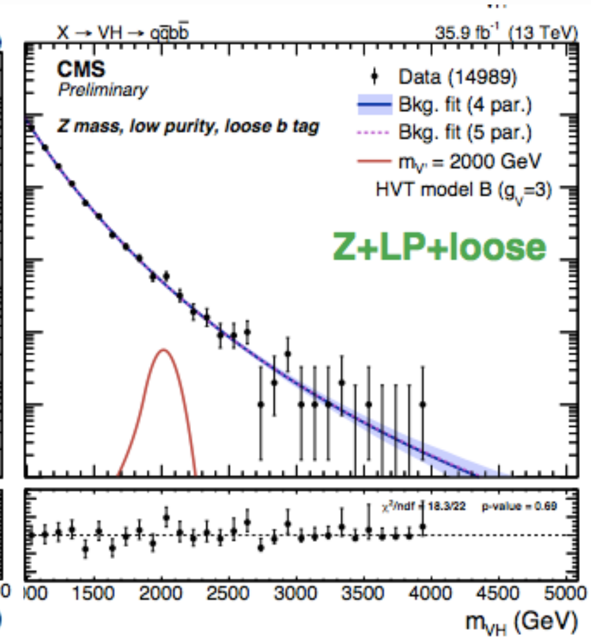




Resonant V(qq)H(bb)

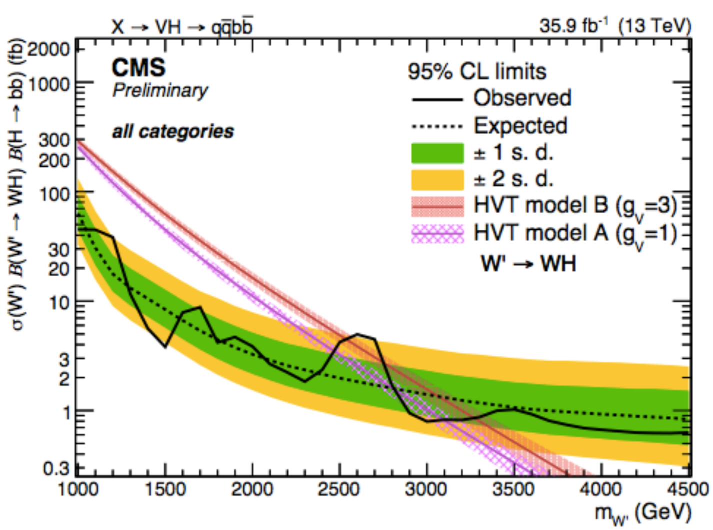
- Similar to VV resonance search, but with dedicated identification of H with sub-jet b-tagging
- Additional categorization: H[105,135]; and tight/loose H-jet b-tag > 0.9 or [0.3, 0.9]
- Backgrounds: multi-jet, ttbar, V+jets
- Fit the data spectrum with power law functions
- # of parameters determined from Fisher test

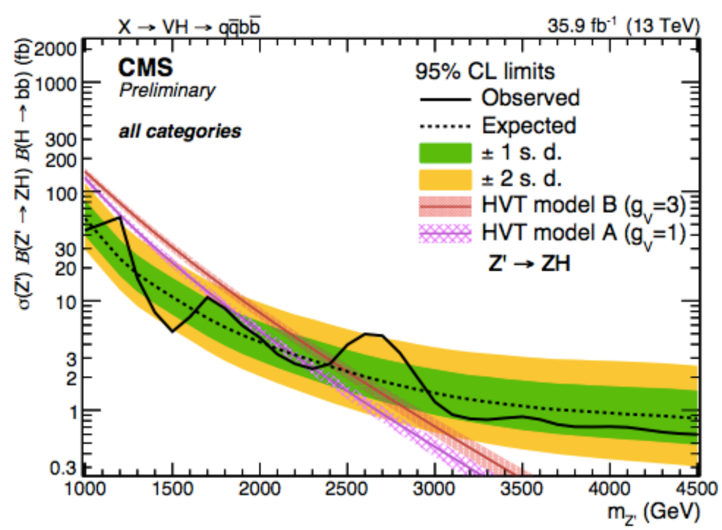




$M_{Z'}$ > 2.4 TeV
$M_{W'}$ > 3.3 TeV
@ 95 % C.L.

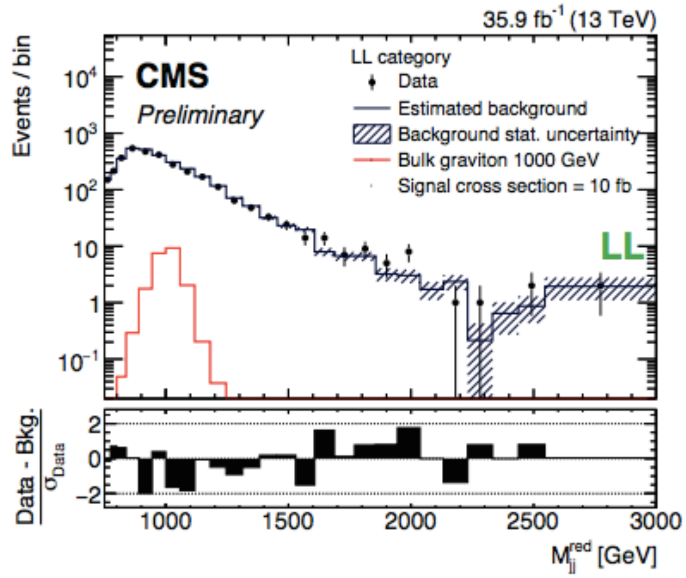
CMS-PAS-B2G-17-002

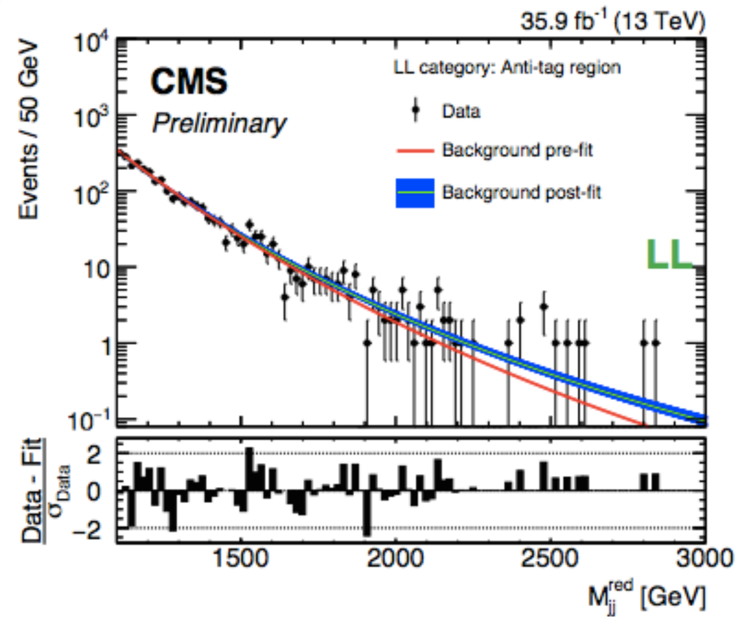




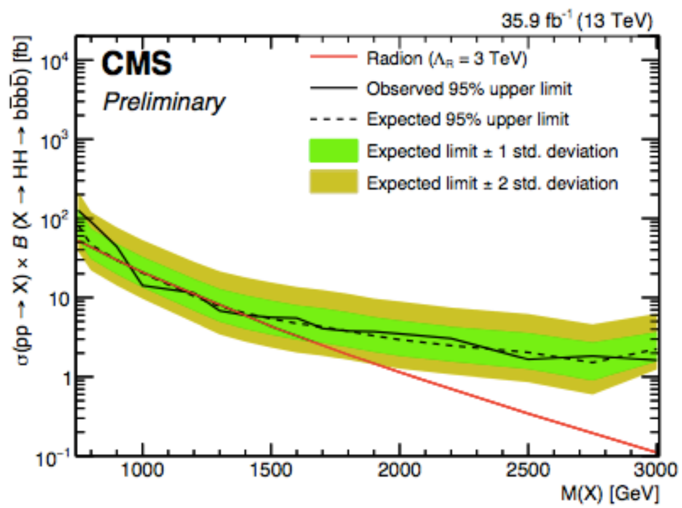
Resonant H(bb)H(bb)

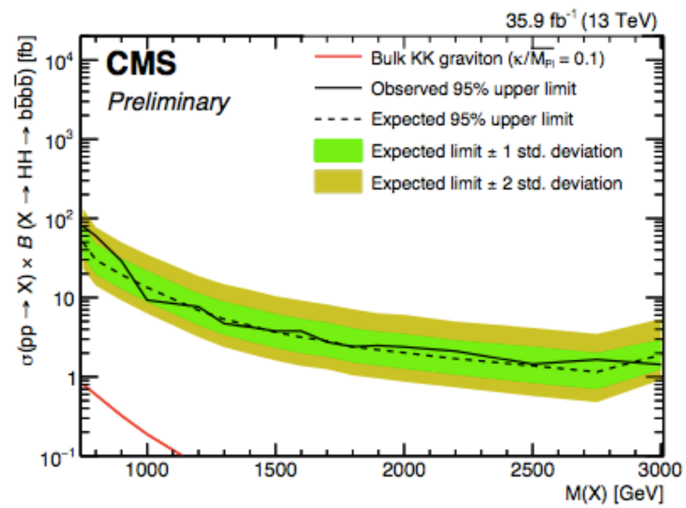
- H-jet tagging
- Dedicated low-mass and high-mass searches
- Background normalization based on several sidebands by inverting jet soft drop mass and double b-tag discriminator





$M_{Z'}$ > 2.4 TeV
$M_{W'}$ > 3.3 TeV
@ 95 % C.L.

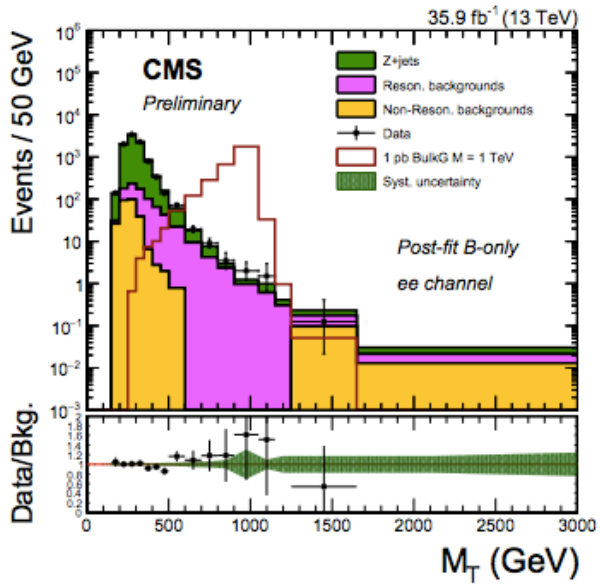


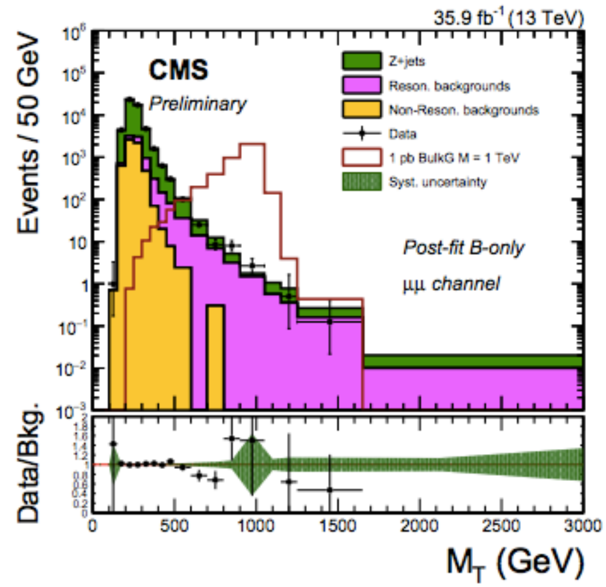


CMS-PAS-B2G-16-026

Resonant Z(ll)Z(νν)

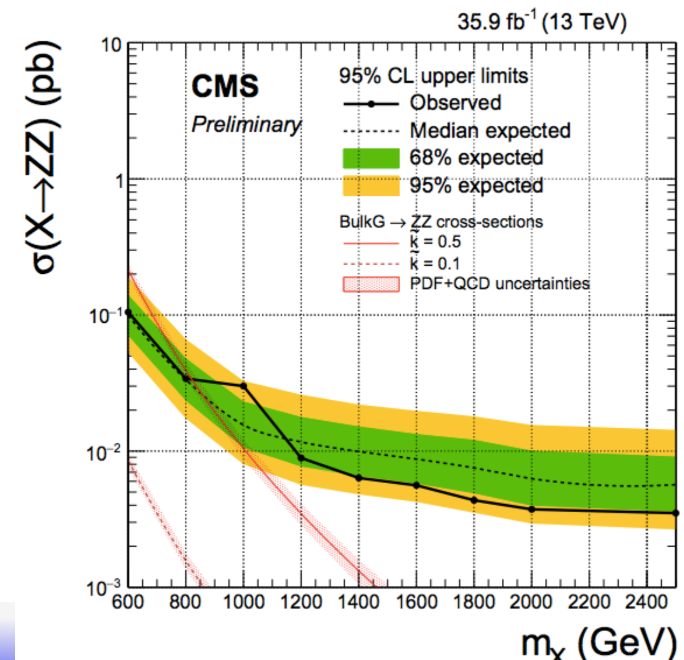
- Event signature: resonant di-lepton +MET
- Use transverse mass mT as the observable to separate signal over background





$$M_T^2 = \left[\sqrt{p_{T,ll}^2 + M_{ll}^2} + \sqrt{(E_T^{miss})^2 + M_{ll}^2}\right]^2 - \left[\vec{p}_{T,ll} + \vec{E}_T^{miss}\right]^2$$

- Backgrounds: Z+jets (data-driven using γ +jets); resonant WZ, ttZ (MC); non-resonant WW, ttbar (data-driven using eμ events)

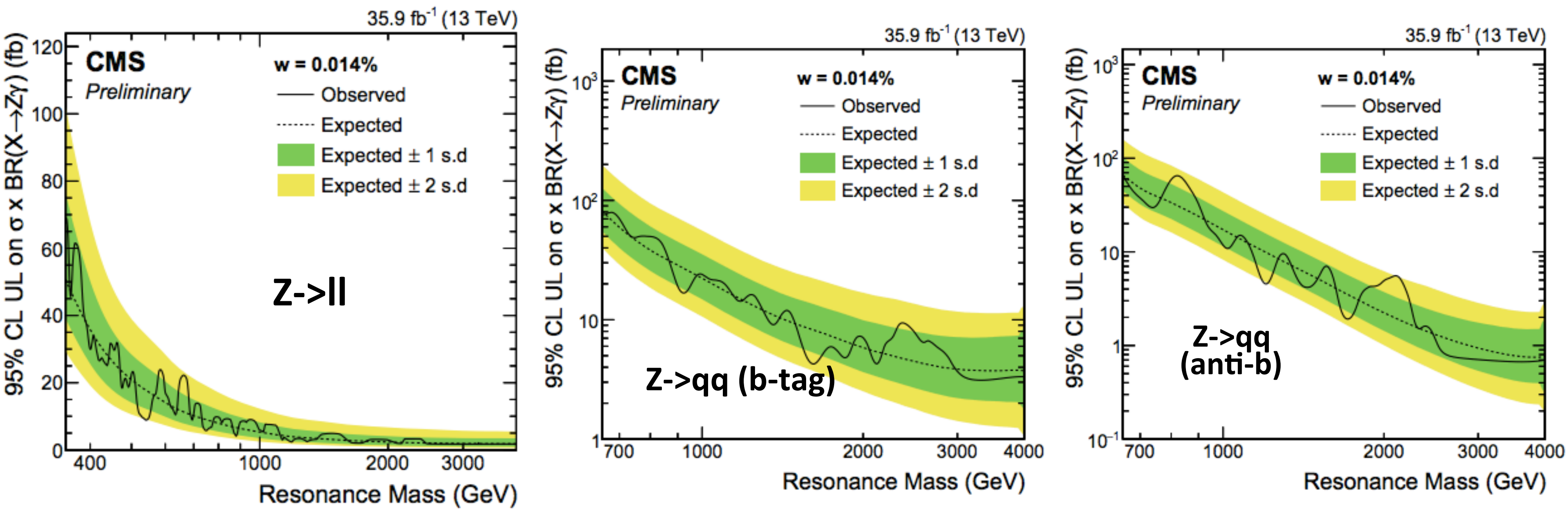


CMS-PAS-B2G-16-023

Search for Zγ Resonance

- Complementary to a possible γγ resonance
- Leptonic search Z(ll)γ at low masses
- Boosted hadronic search Z(qq) γ at using b-tag info and jet substructire at high masses

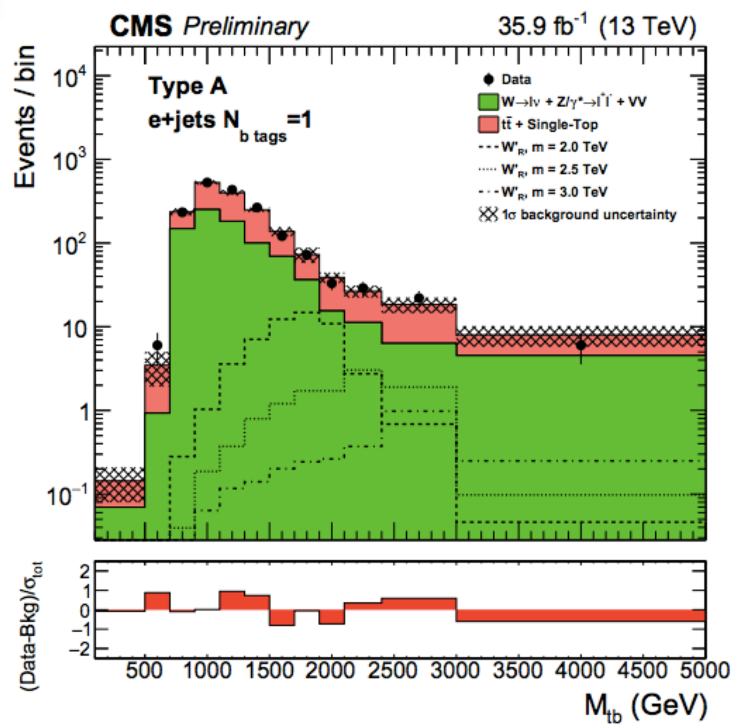
CMS-PAS-EXO-17-005

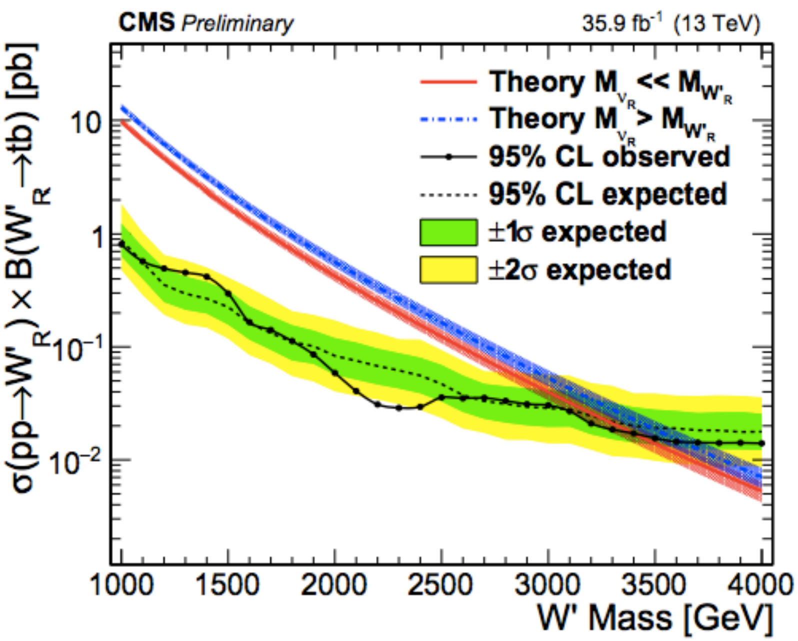


CMS-PAS-B2G-17-010

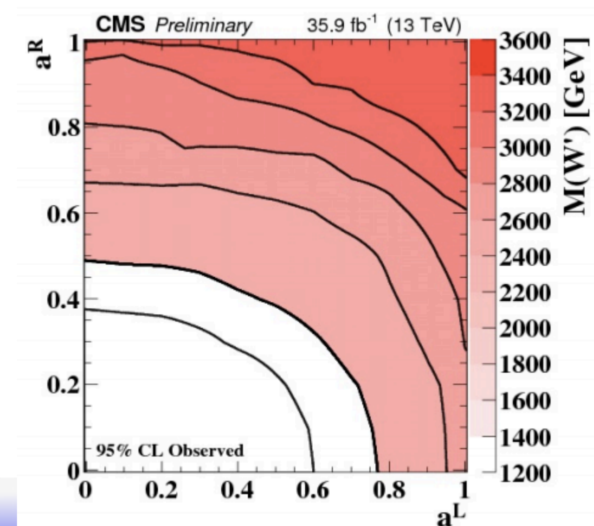
W'->tb in l+jets state

- In many BSM scenarios heavy W' has enhanced couplings to 3rd generation quarks
- Split event into 8 event categories, based on e, μ, b=1,2, kinematical A,B with large/smaler high-top p_T
- W' mass is reconstructed using lepton, MET and 2 highest-p_T jets





$M_{W'}$ > 3.4/3.6 TeV @ 95 % C.L.

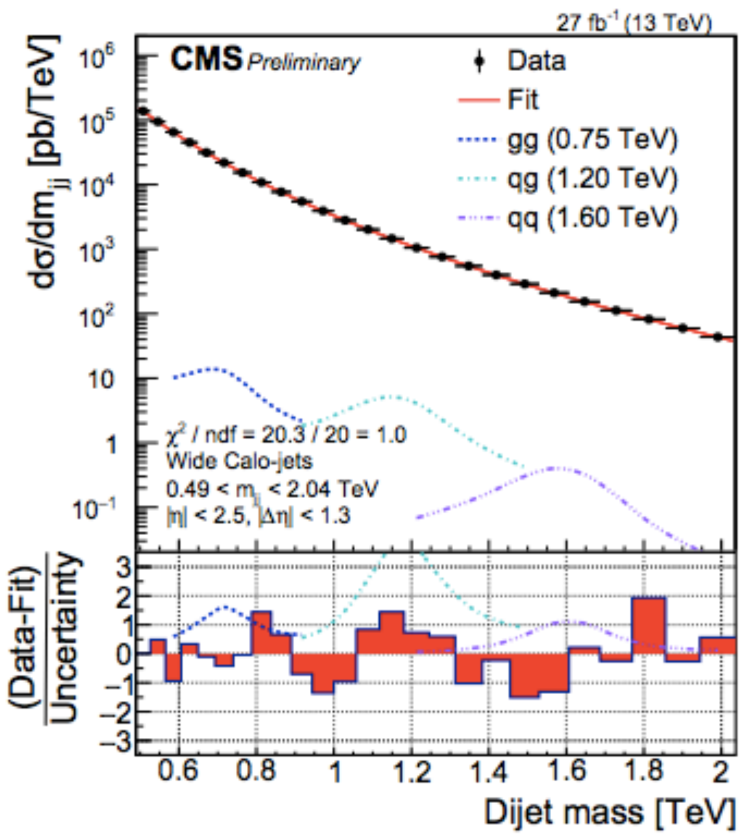


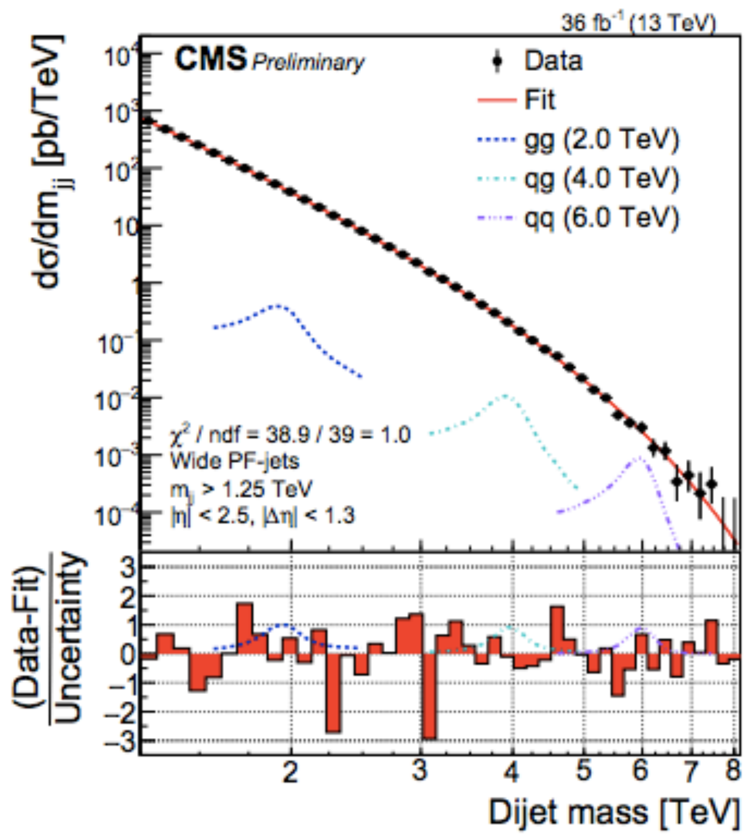
Search for Di-Jet Resonances

CMS-PAS-EXO-16-056

- Any resonance coupling to quarks/ gluons.
- Strong production -> high rate, high mass reach
- Dedicated low-mass and high-mass searches
- Data scouting at low-masses: low trigger threshold by storing reduced info

Fit to line-shapes of detector resolution gaussians convoluted with theoretical BW shapes





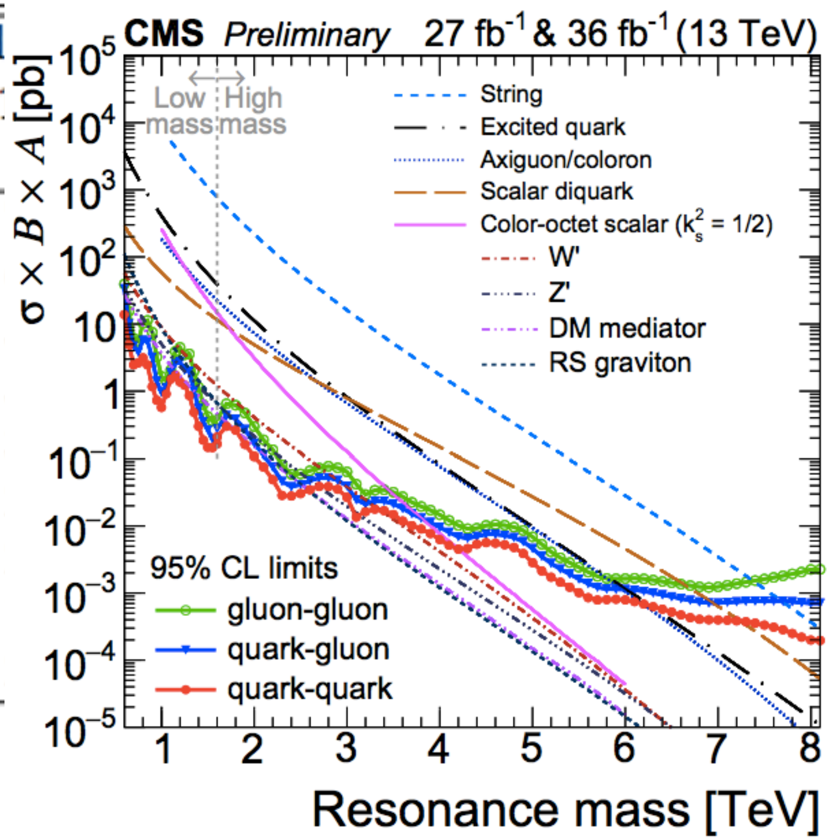
Di-Jet Interpretations

- Predicted by BSM models: axigluons, colorons, W′/Z′ bosons, color octet scalars, string resonances, RS, etc.

CMS-PAS-EXO-16-056

Model	Final State	Observed 36 fb^{-1} 13 TeV
String	qg	7.7 (7.7)
Scalar diquark	qq	7.2 (7.4)
Axigluon/coloron	$q\bar{q}$	6.1 (6.0)
Excited quark	qg	6.0 (5.8)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)
W′	$q\bar{q}$	3.3 (3.6)
Z′	$q\bar{q}$	2.7 (2.9)
RS Graviton ($k/M_{PL} = 0.1$)	$q\bar{q}$, gg	1.7 (2.1)
DM Mediator ($m_{DM} = 1$ GeV)	$q\bar{q}$	2.6 (2.5)

Up to 7.7 TeV

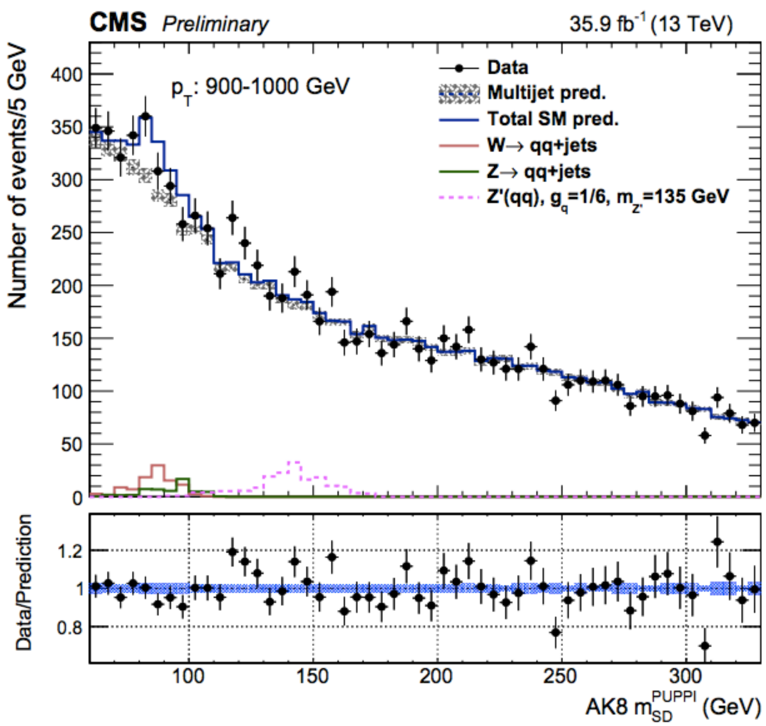


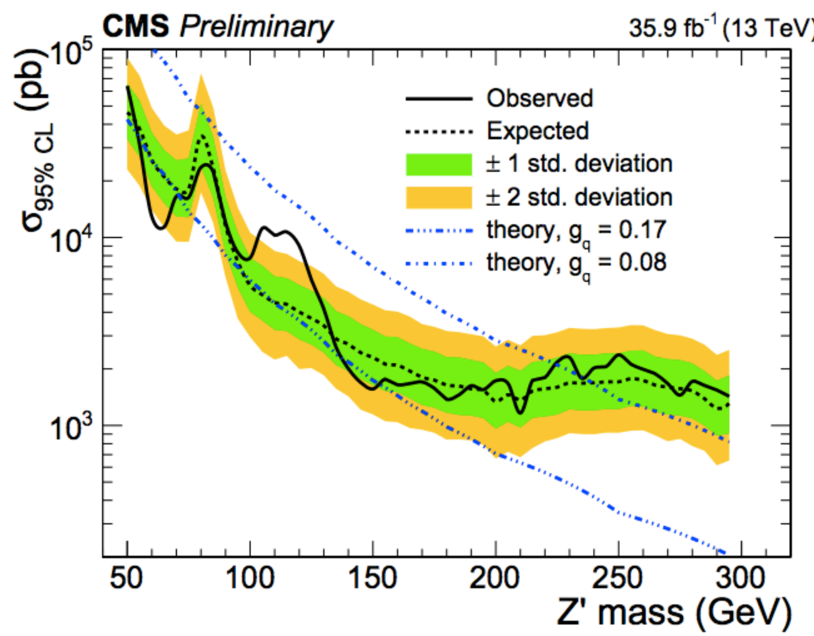
Low-mass Di-Jet Search

CMS-PAS-EXO-17-001

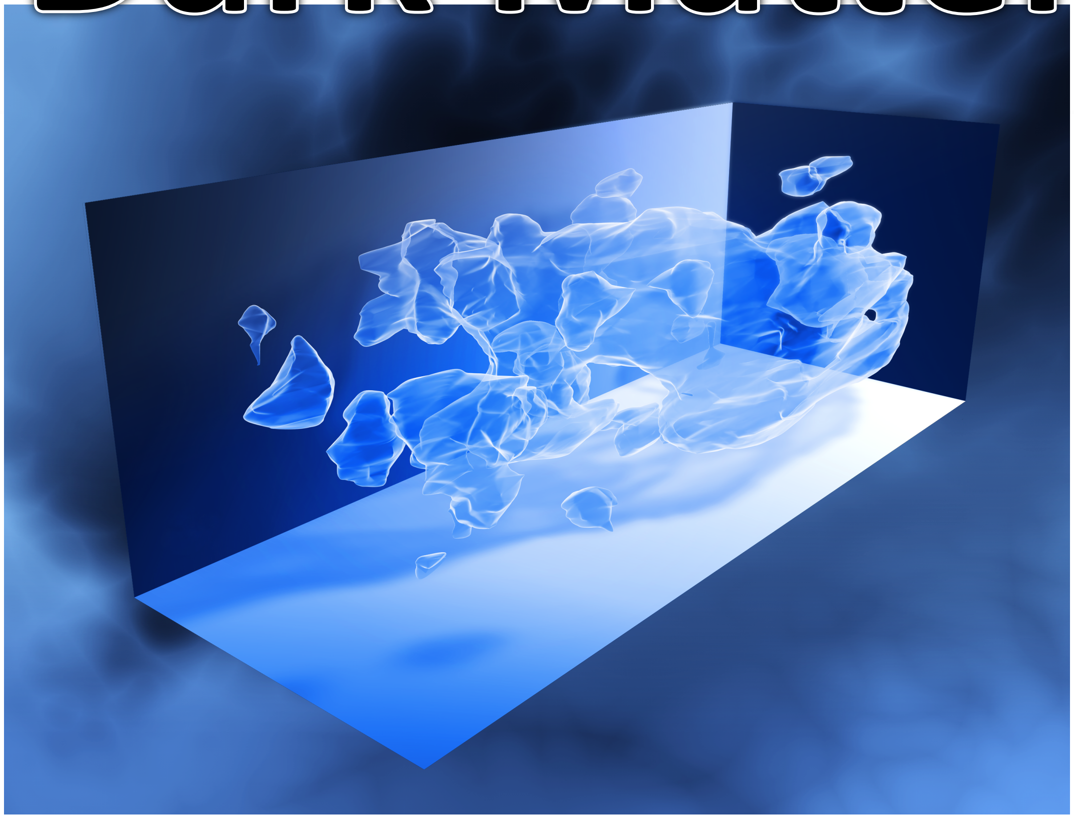
- Search for resonance produced at high-p_T with decay products merged into a single jet
- Event signature: 2-prong jet +ISR jet
- Trigger on H_T or high-p_T jet with $m_{trimmed}$>30-50 GeV
- Multi-jet background is estimated from control region

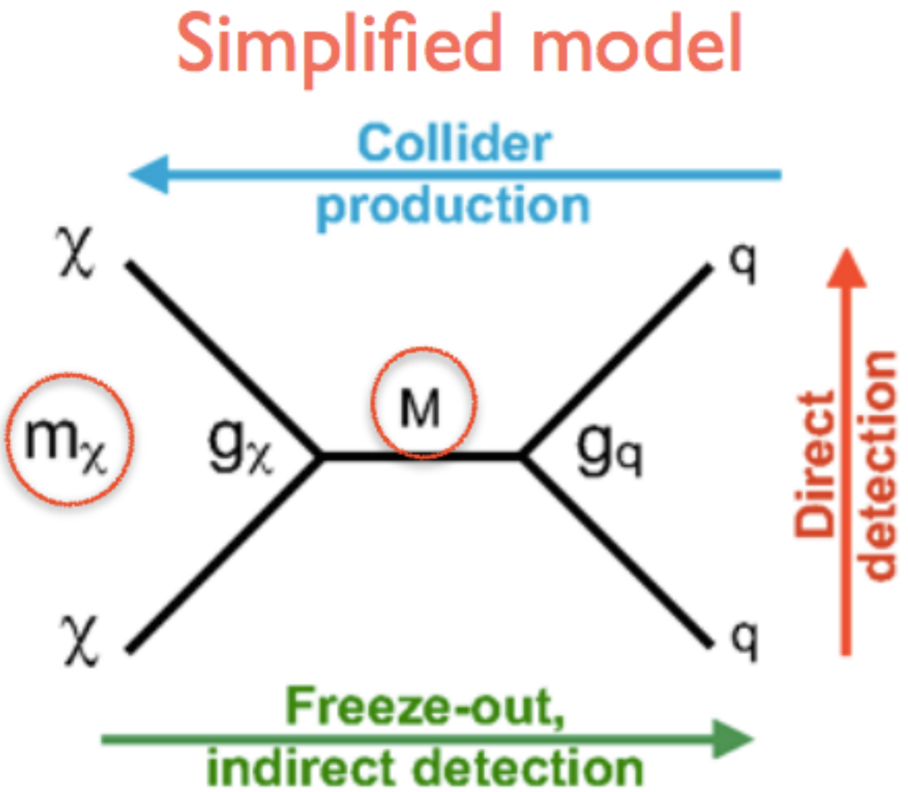
Maximum local p-value (2.9σ) corresponds to m(Z') = 115 GeV, global p-value = 2.2σ





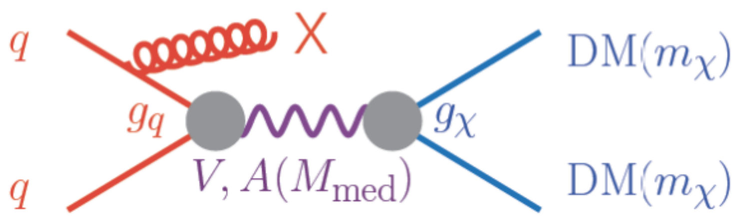
Dark Matter

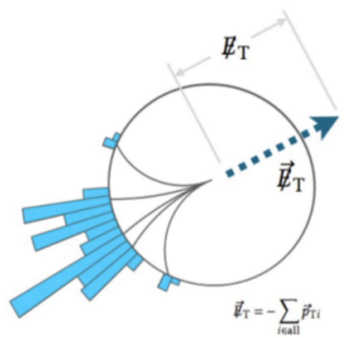


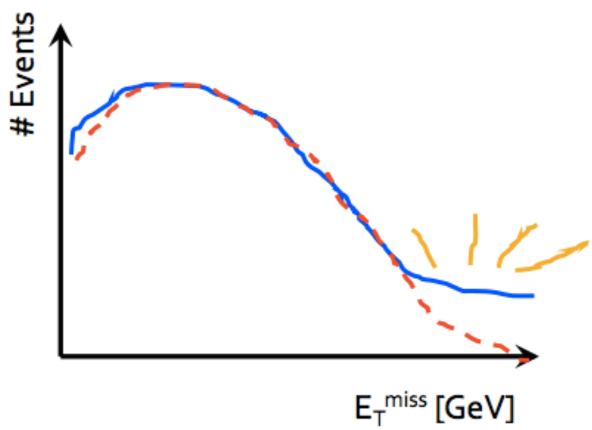


- Interpretation within Simplified models
- Four parameters: DM mass, Mediator mass, SM and DM couplings
- Couplings chose to keep the mediator width/mass below ~10%

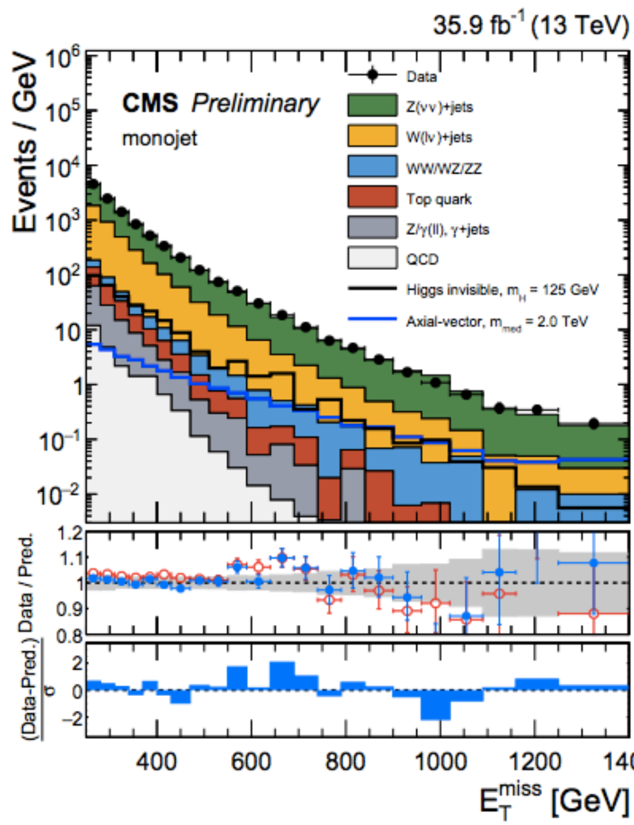
Mono-X Searches

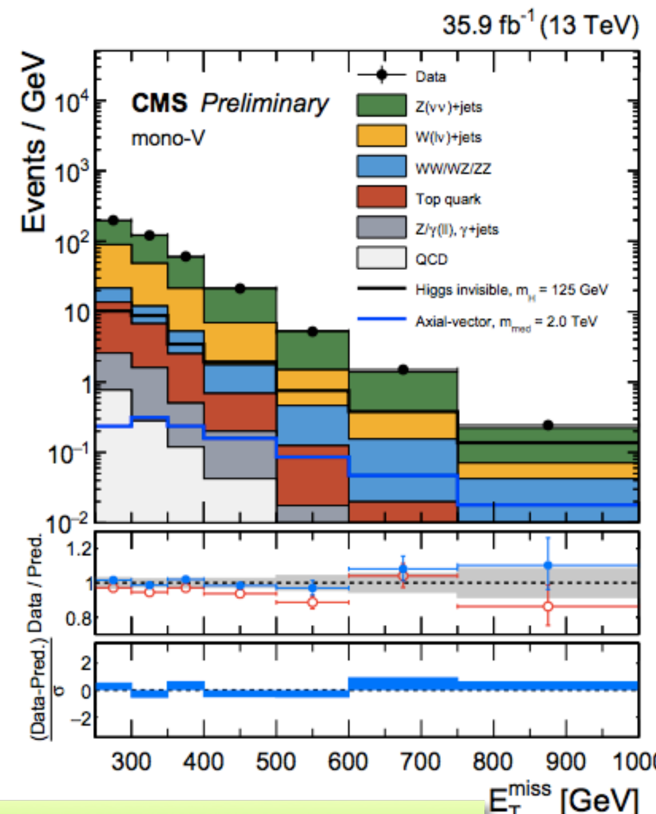






- Trigger on Initial State Radiation
- Search for mono-object recoiling against MET
- Main backgrounds: Z(νν)+jets, W(lν)+jets (lost lepton)
- Background estimation using control regions: ll+jets, γ+jets, l+jets

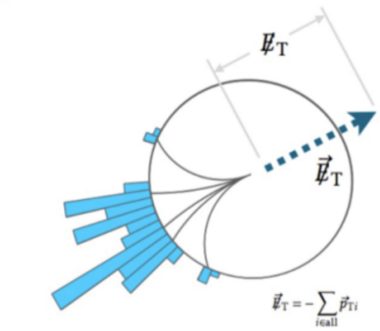




CMS-PAS-EXO-16-048

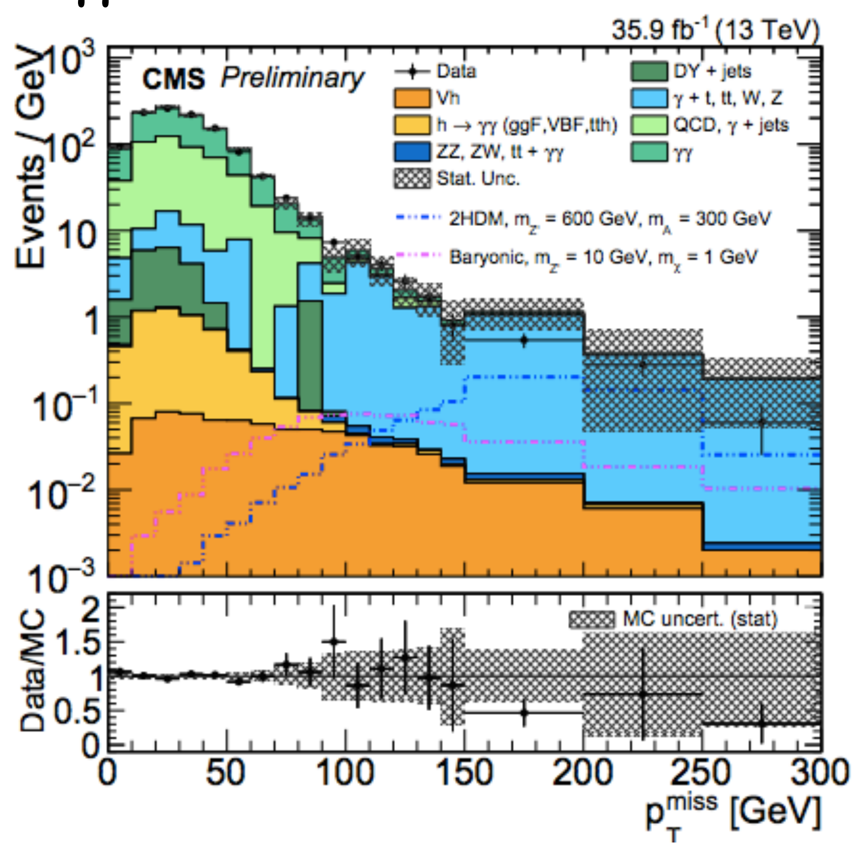
Mono-X Searches

- Search for mono-object recoiling against MET

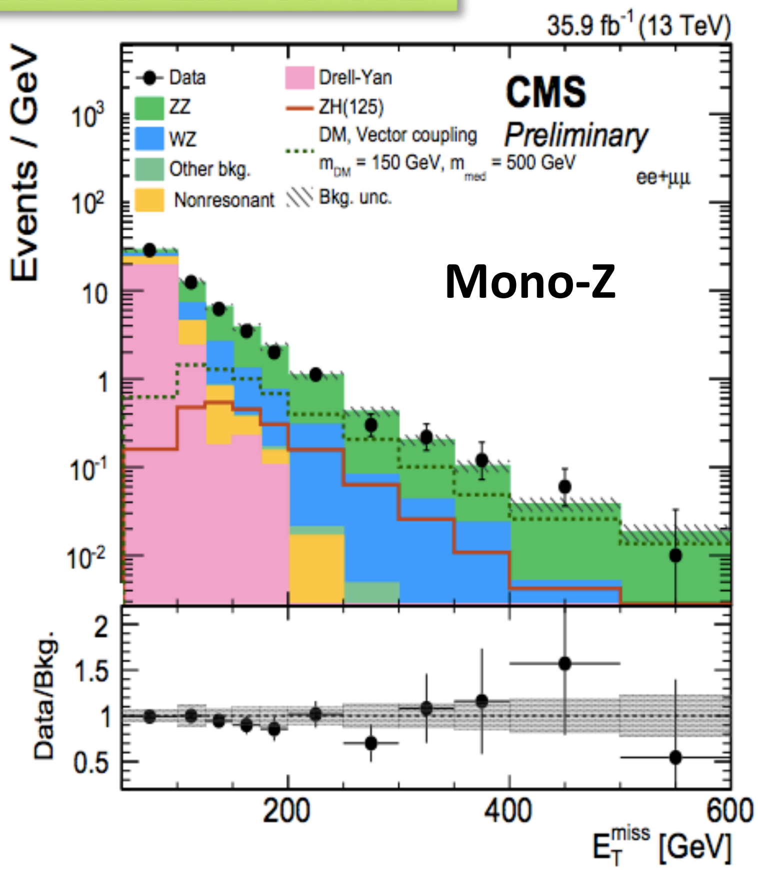


CMS-PAS-EXO-16-054

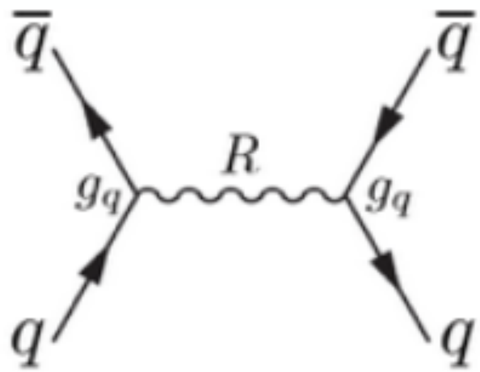
Mono-H-γγ



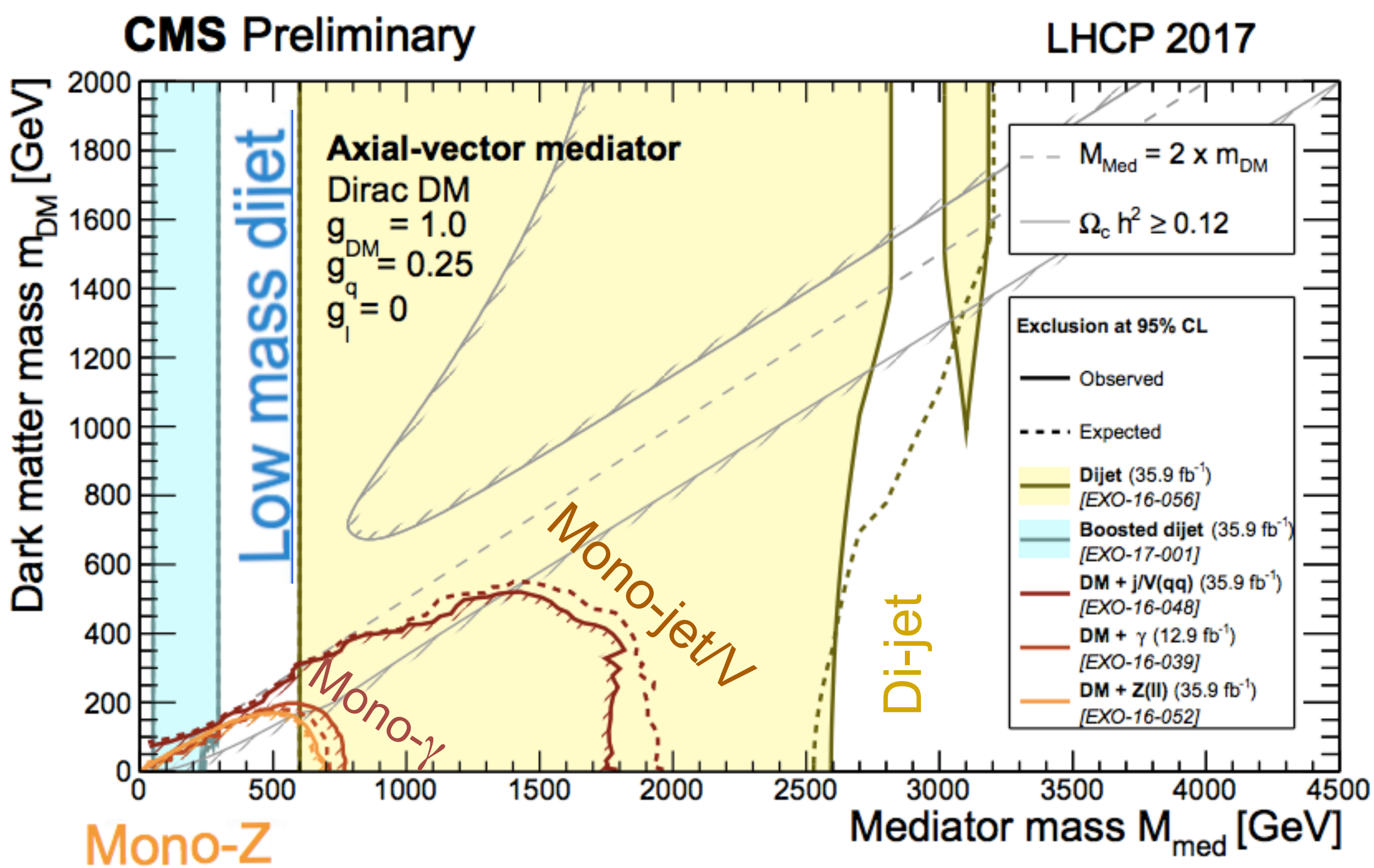
CMS-PAS-EXO-16-052



Searching for Mediator



- Recycle di-jet searches

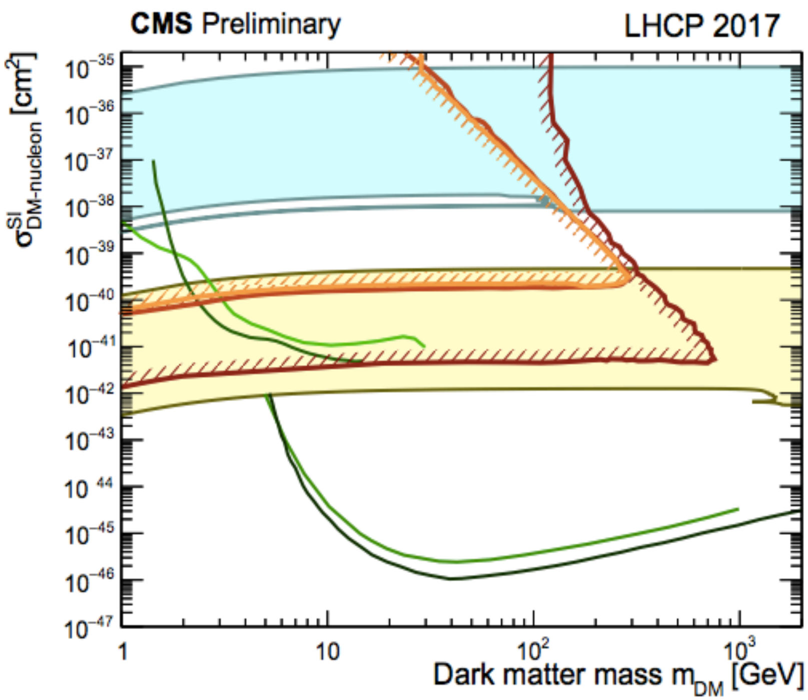


- DM exclusions up to ~500 GeV
- Vector mediator up to ~2000 GeV

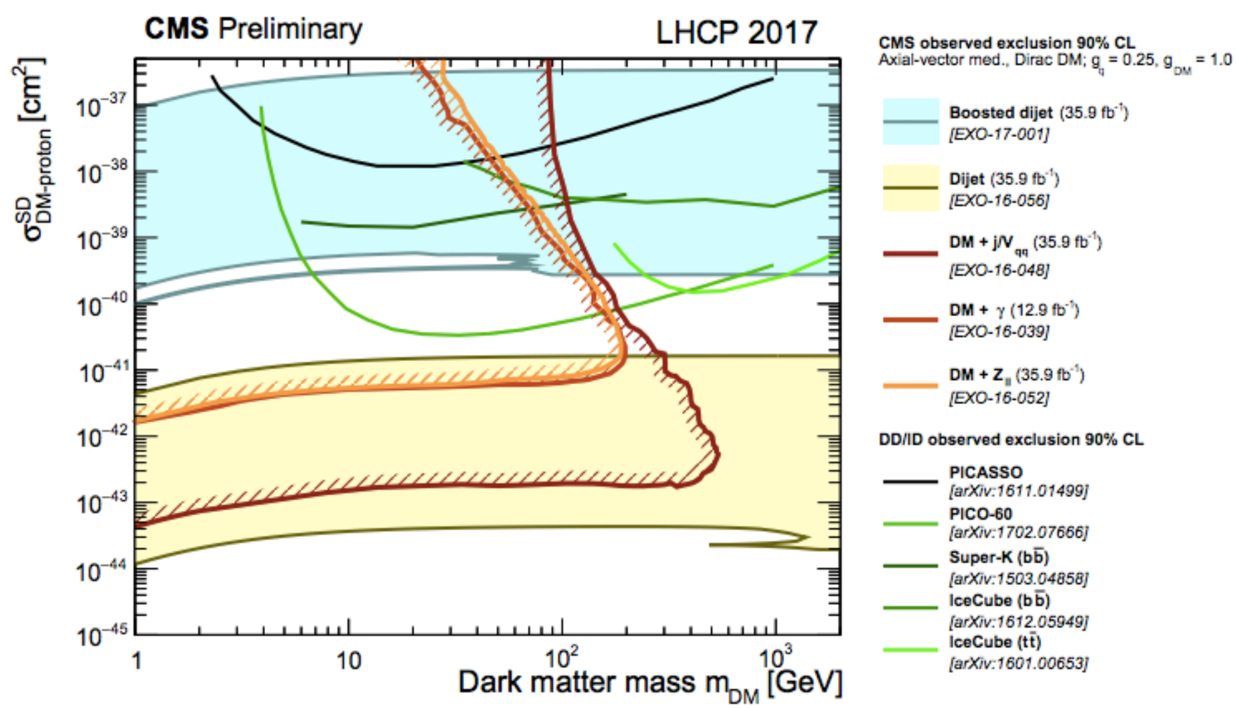
Dark Matter Summary

- Comparison with direct detection limits as a function of DM-nucleon scattering cross section
- Collider constraints are more stringent at low dark matter masses and spin-dependent cross sections

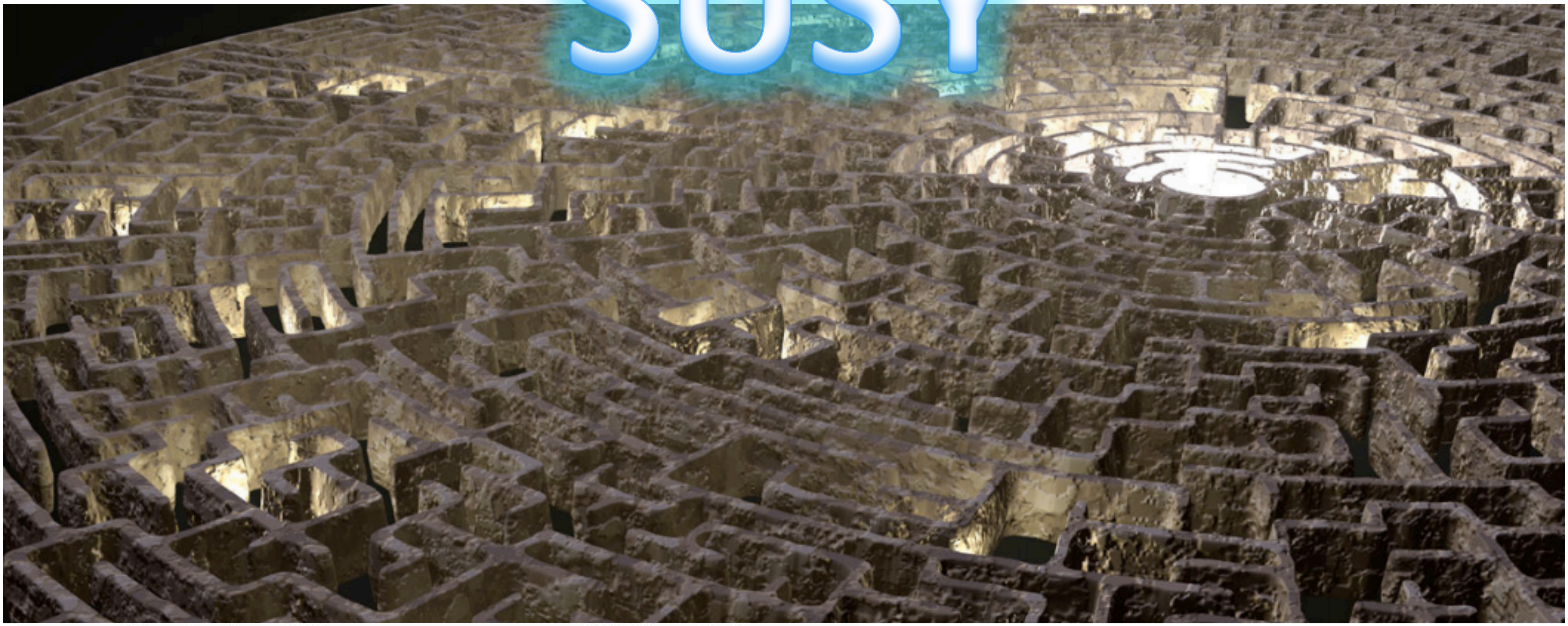
Vector

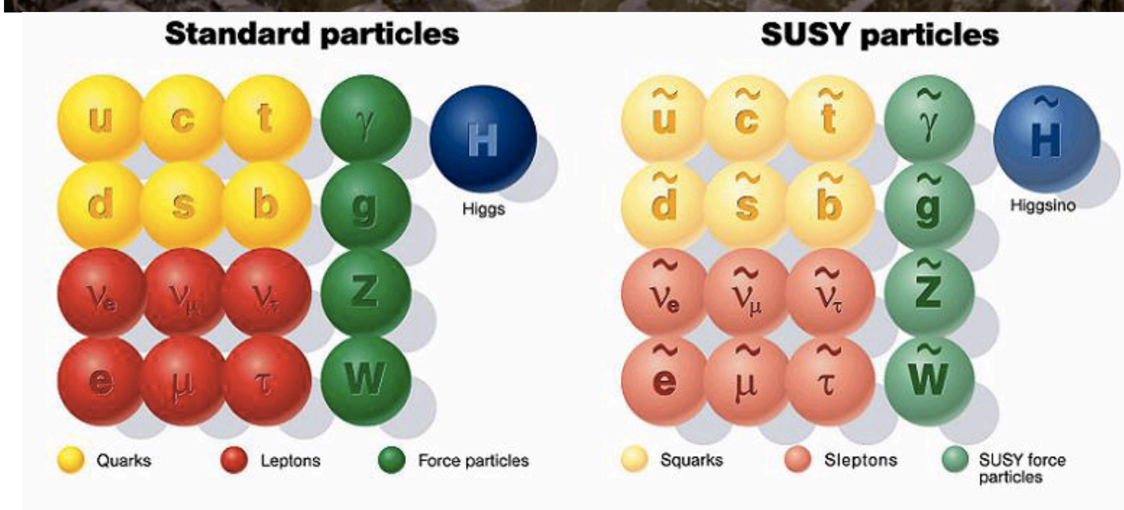


Axial-vector



SUSY



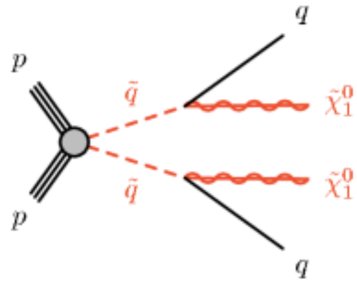


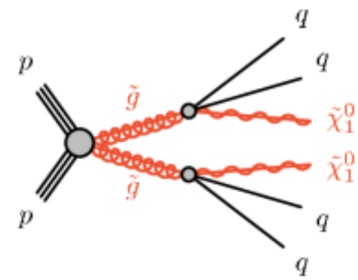
- SUSY is around the corner
- Which one?

SUSY Signatures

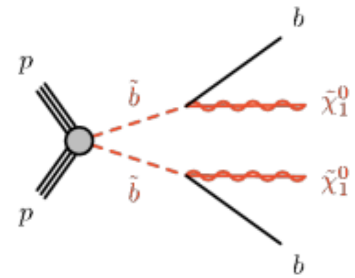
- **Simplified model interpretations (BR=1, 2D-parameter scan)**

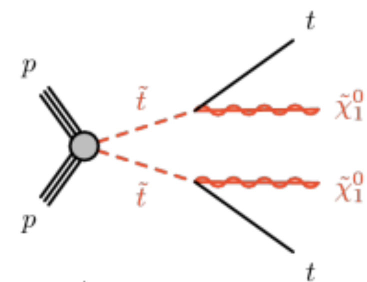
- Squark and gluino production
  - Strong production
  - High cross section
  - Jets and missing E_T



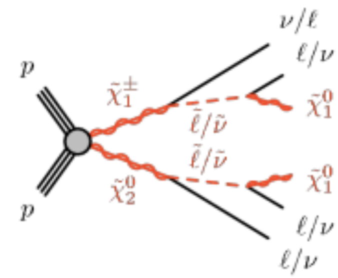


- 3^{rd} generation squarks
  - Lower cross section
  - B-tagging

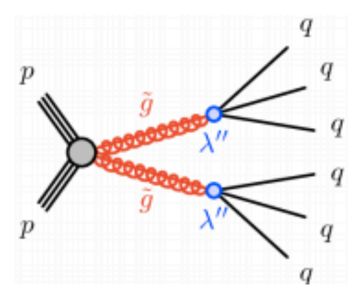




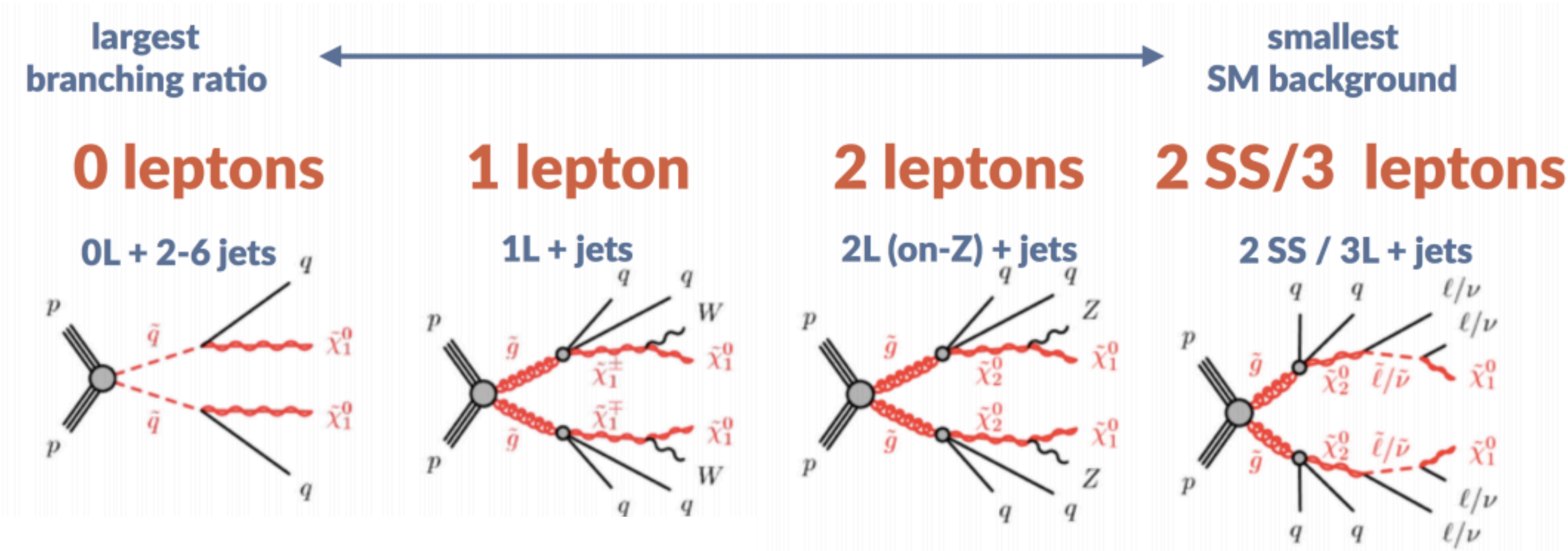
- Electroweak production
  - Low cross section, mass scale
  - Multi-lepton with missing E_T



- R-parity violating scenarios
  - No missing E_T, jets (and leptons)
  - High jet multiplicity, resonances



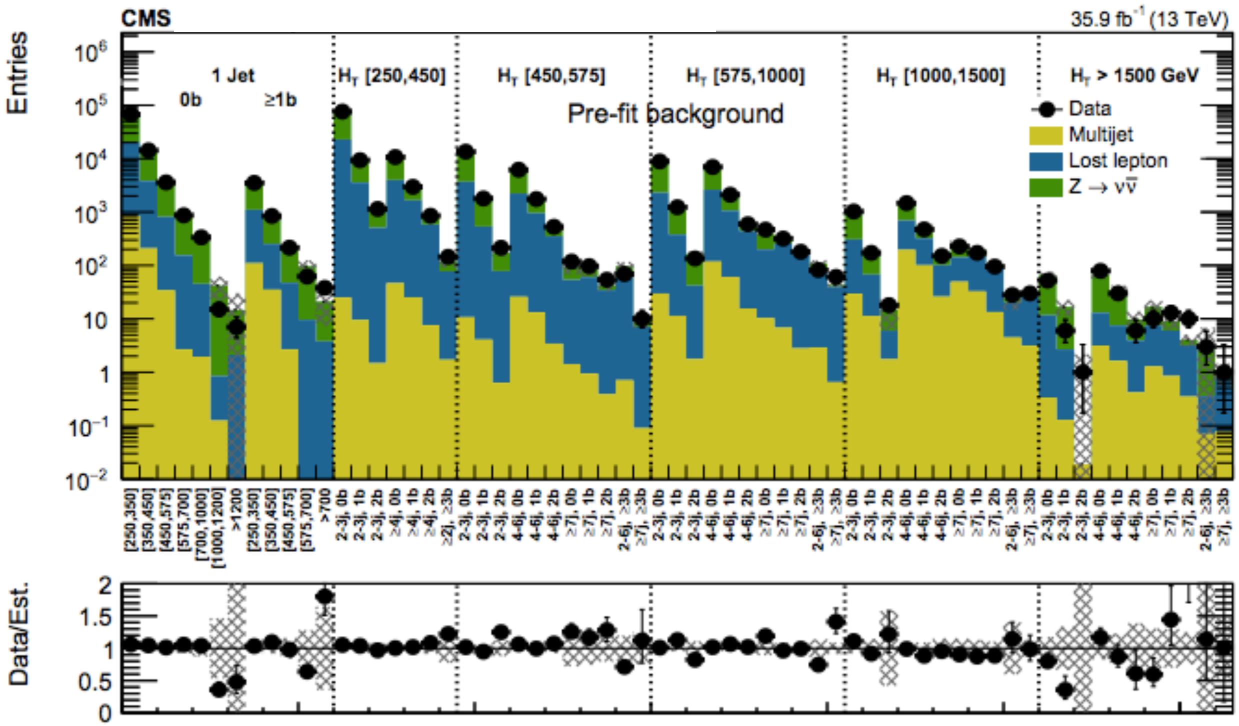
SUSY Signatures

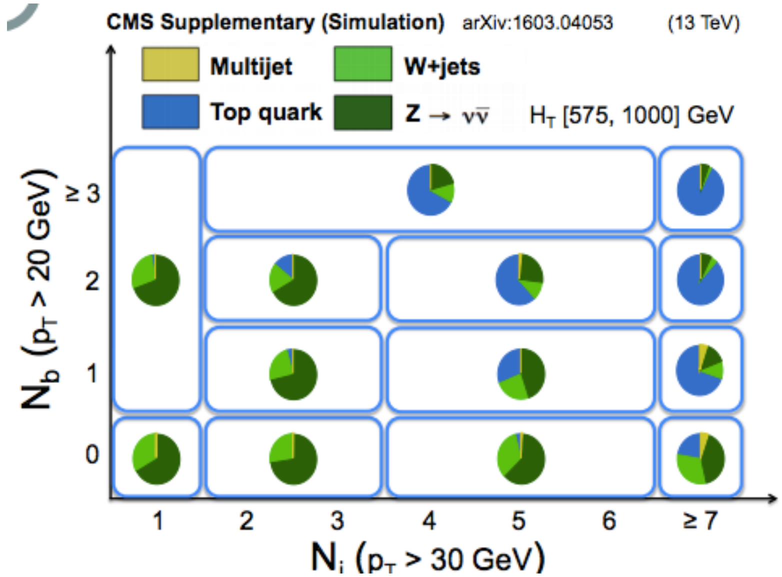


- Various signal regions to cover large range of models

Search for SUSY in Jets+MET

CMS-PAS-SUS-16-036
arXiv:1705.04650





$$M_{T2} = \min_{\vec{p}_T^{\,\mathrm{miss}\,X(1)} + \vec{p}_T^{\,\mathrm{miss}\,X(2)} = \vec{p}_T^{\,\mathrm{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

- Each region is further binned based on H_T and M_{T2}

- Backgrounds are grouped by features and estimated from control regions: Z->νν, lost lepton, QCD

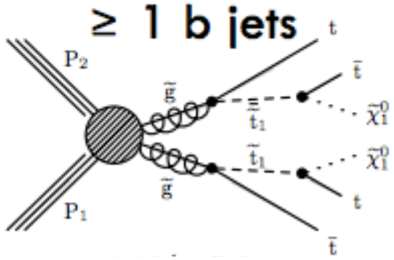
Search for SUSY in lepton+jets

CMS-PAS-SUS-16-037
arXiv: 1705.04673

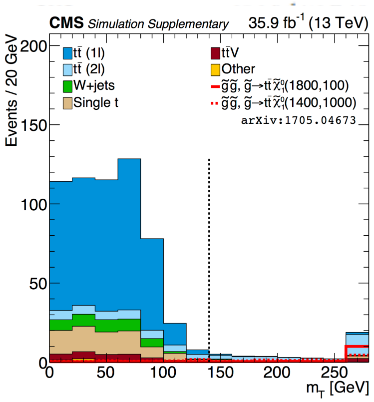
CMS-PAS-SUS-16-042

MJ + M_T + n(b)Jets

≥ 1 b jets

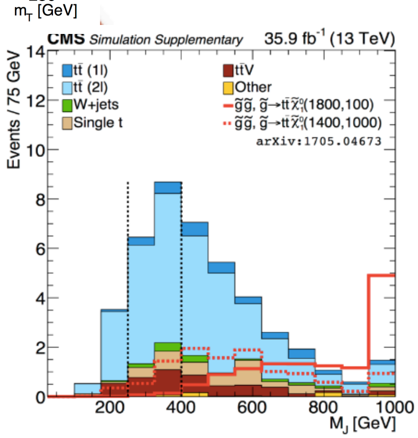


Main discriminating variables:
m_T (l, MET) and MJ



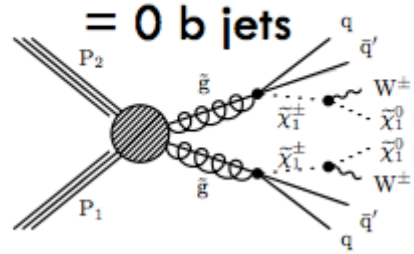
Small radius R=0.4 jets + lepton are clustered into R=1.4 jets

mJ = mass of large radius jets

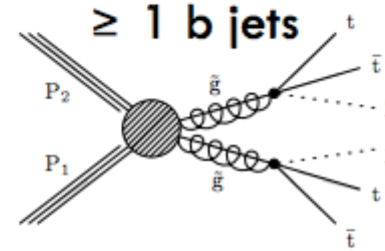


Δϕ+ H_T + L_T + n(b)Jets

= 0 b jets

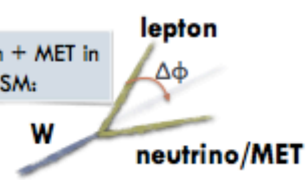


≥ 1 b jets

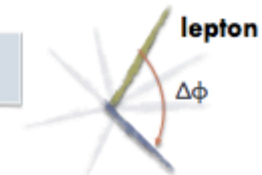


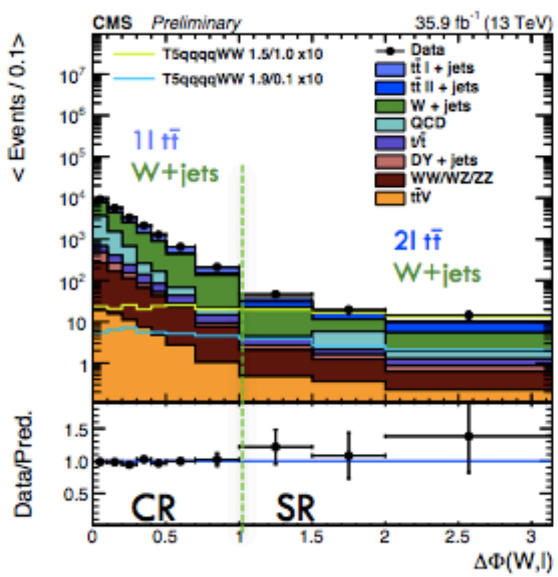
Main discriminating variable: Δϕ(W,l)

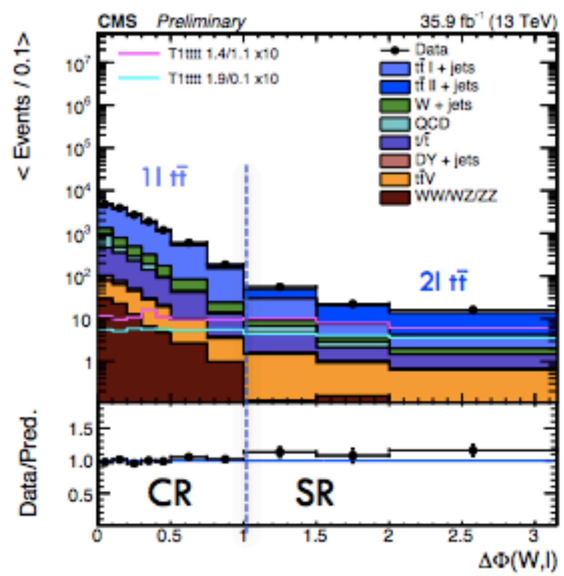
Lepton + MET in SM:



Lepton + MET with SUSY:





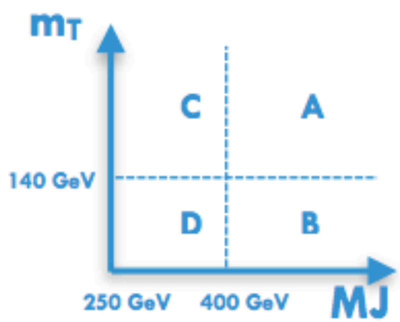


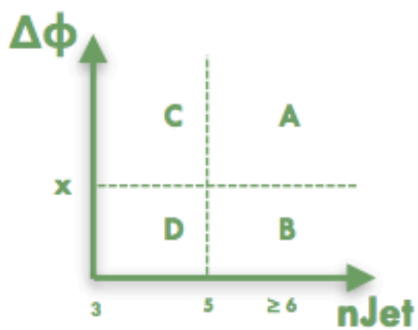
Search for SUSY in lepton+jets

CMS-PAS-SUS-16-037
arXiv: 1705.04673

CMS-PAS-SUS-16-042

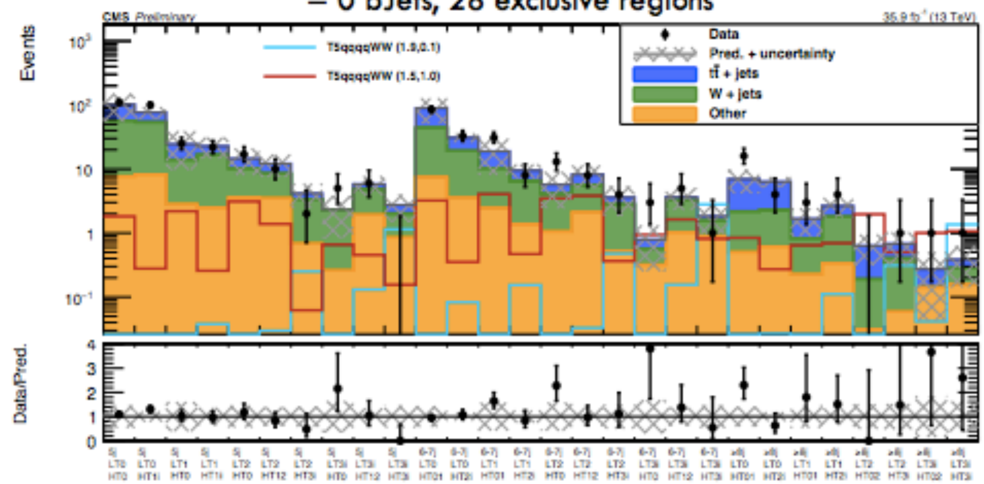
- Data driven background estimates based on control regions (ABCD)



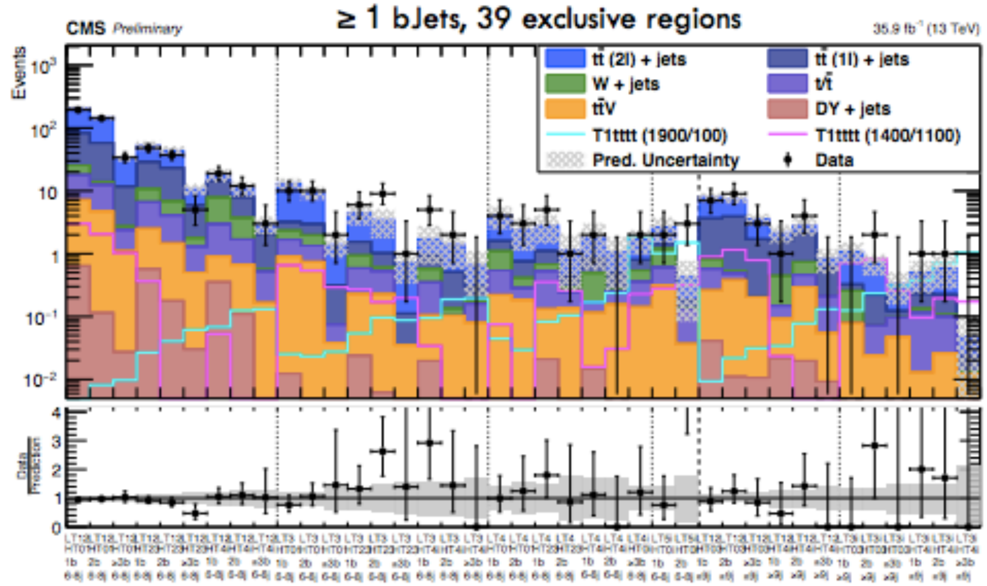


$\Delta\phi + H_T + L_T + n(b)Jets$

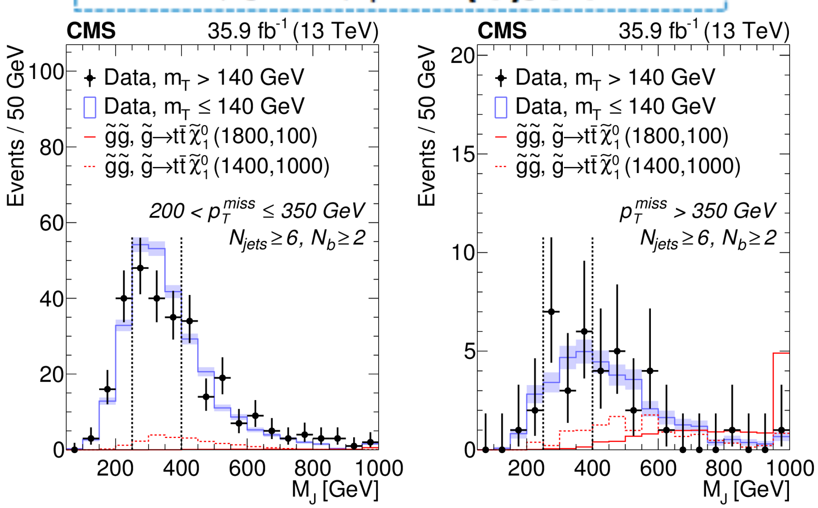
= 0 bJets, 28 exclusive regions



≥ 1 bJets, 39 exclusive regions

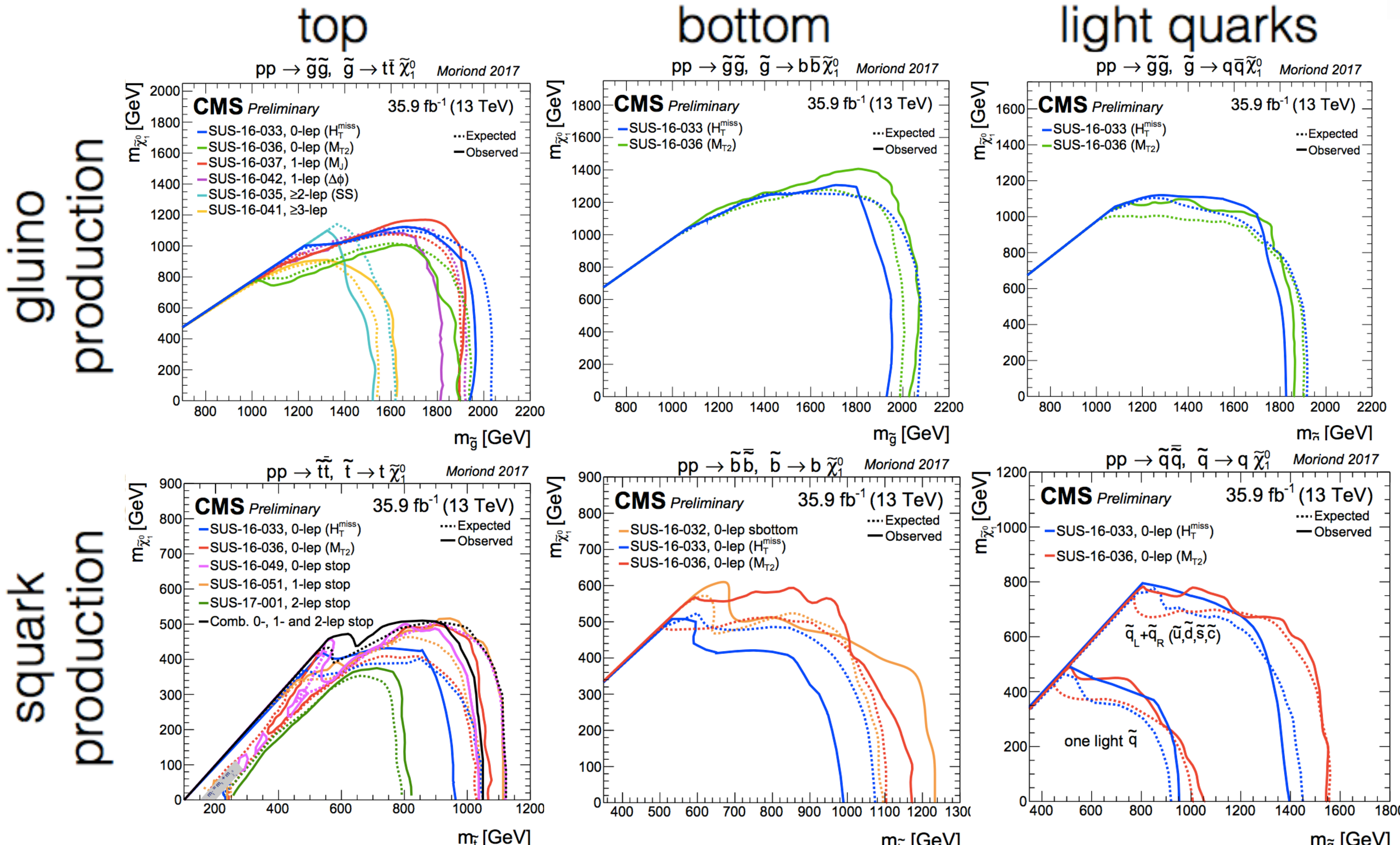


$MJ + M_T + n(b)Jets$



≥ 1 bJets, 18 exclusive regions

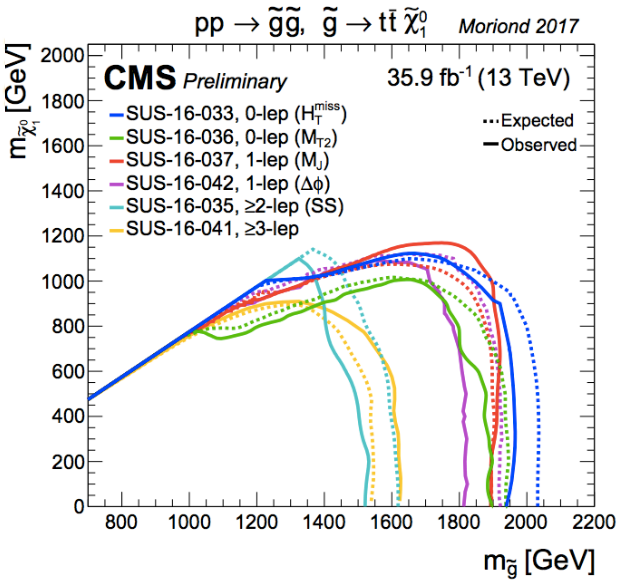
Strong Production Summary



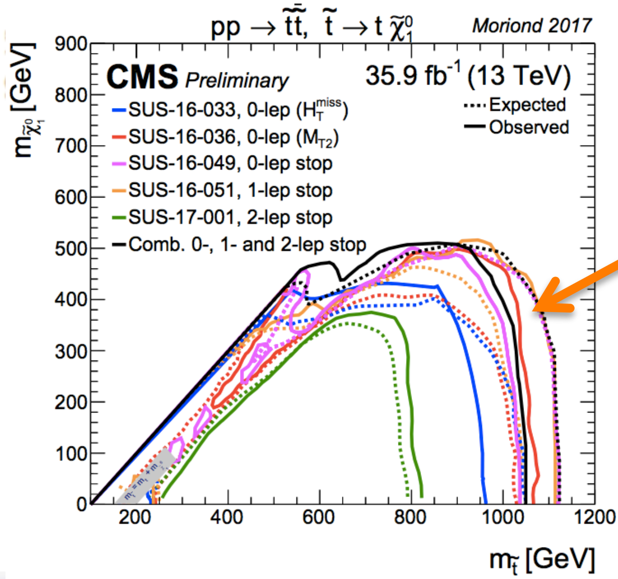
Stop Searches

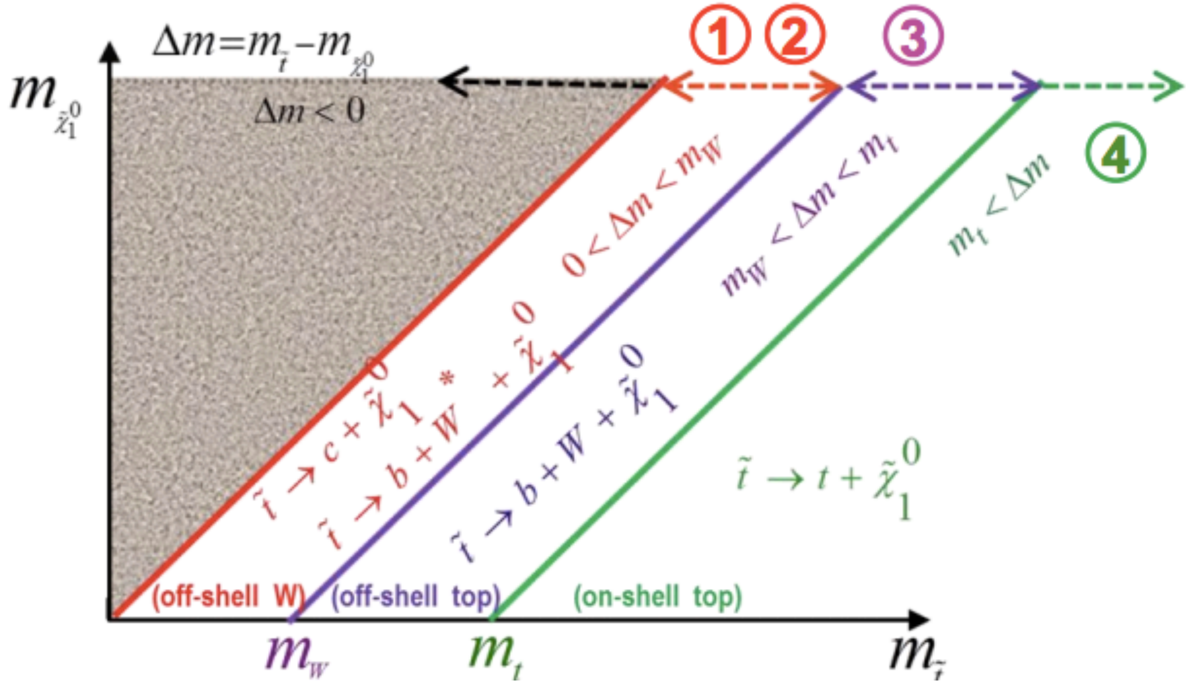
top

gluino production



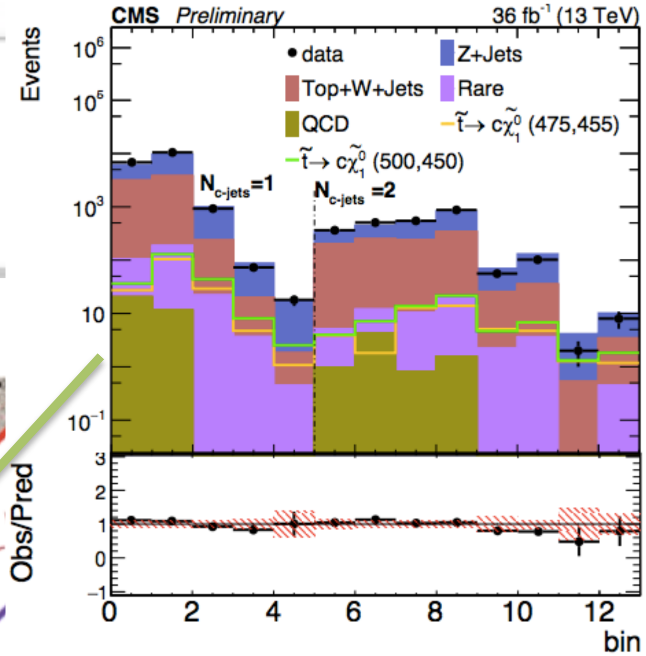
squark production



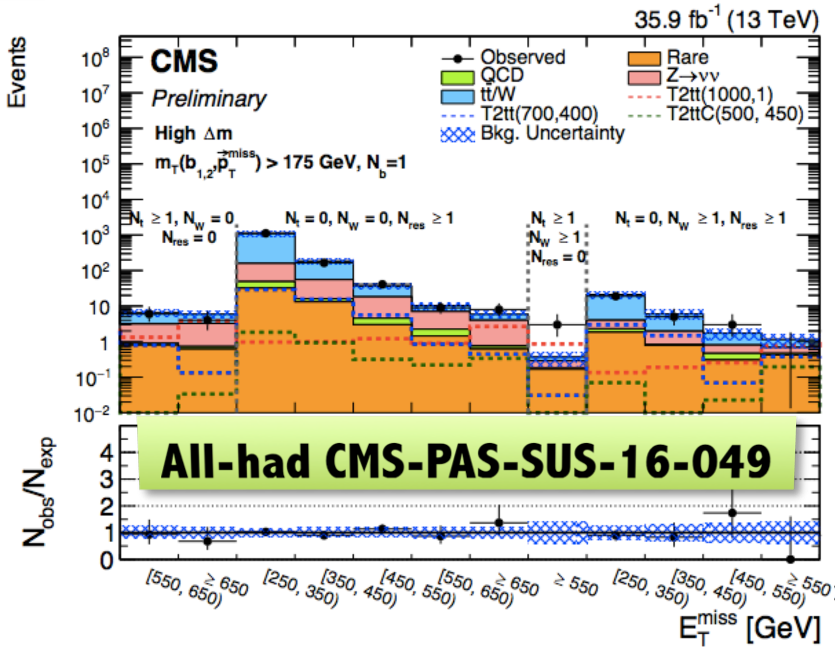


- Complex phase space structure

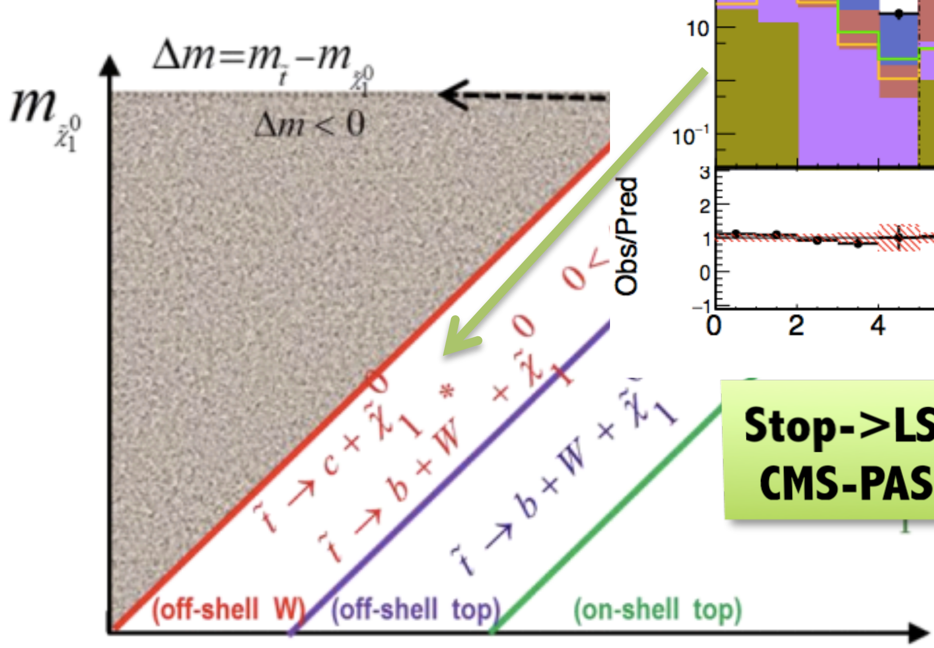
Stop Searches



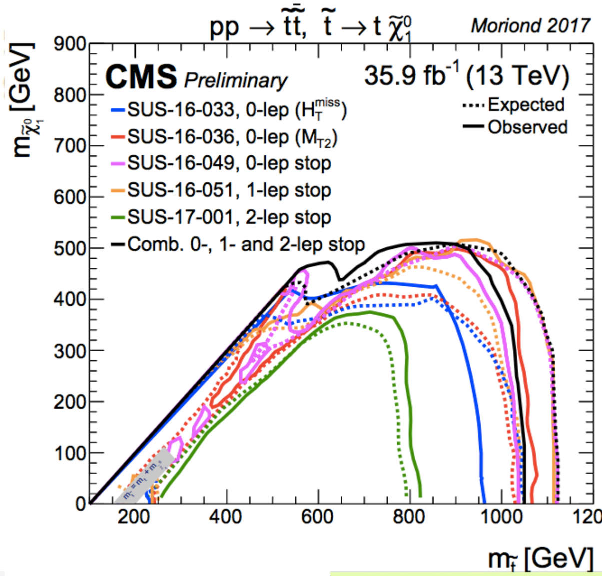
Stop->LSP+charm CMS-PAS-SUS-16-032

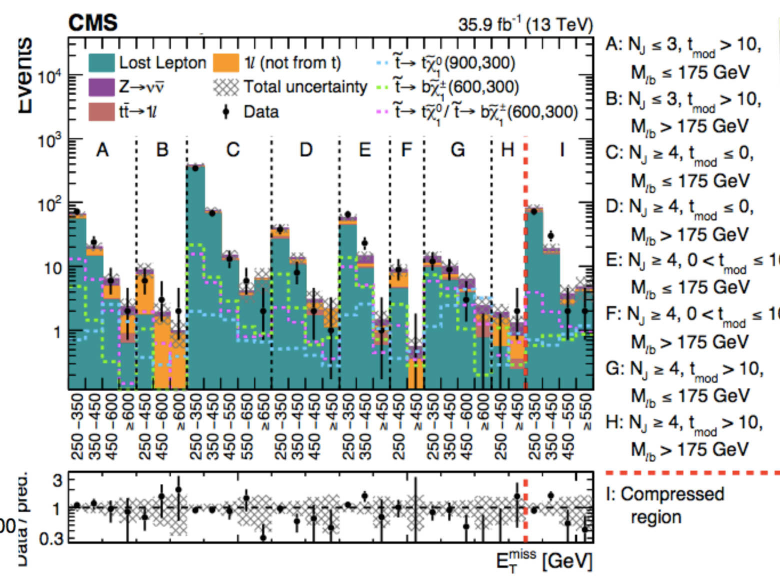


All-had CMS-PAS-SUS-16-049

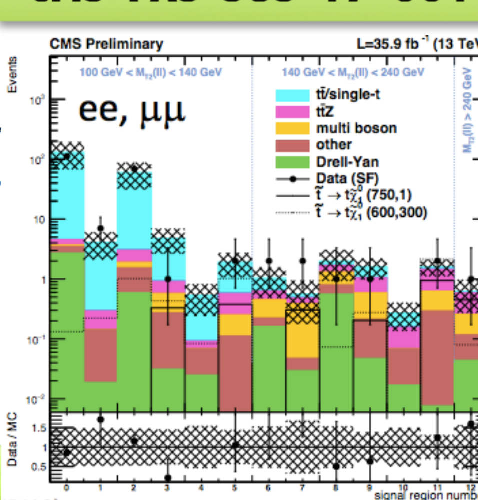


squark production





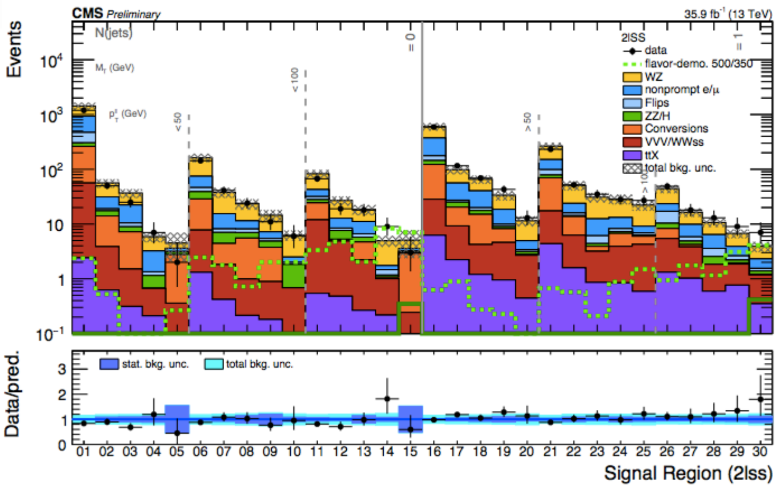
Dilepton CMS-PAS-SUS-17-001



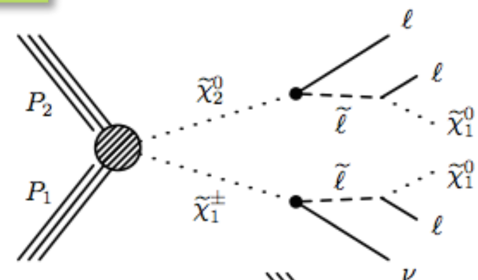
L+jets CMS-PAS-SUS-16-051, arXiv: 1706.04402

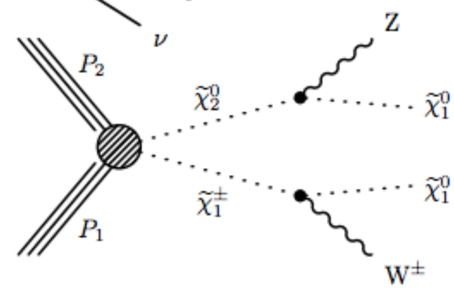
Electroweak Production

CMS-PAS-SUS-16-039



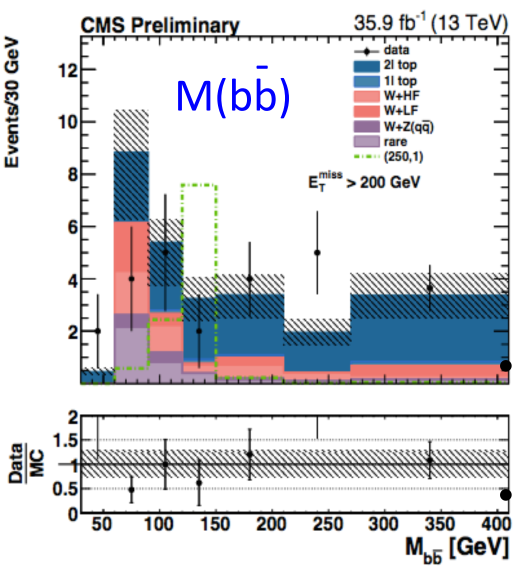
- 2l (SS and OS), 3,4l binned in m(ll), MET, M_T

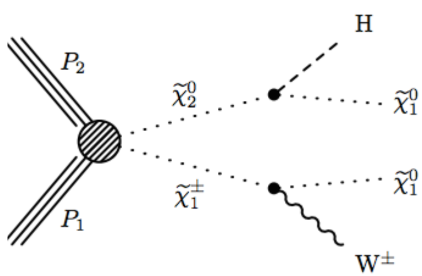




- On-Z OS dilepton pair + W->jj
- Expect signal at high-met tail

CMS-PAS-SUS-16-034

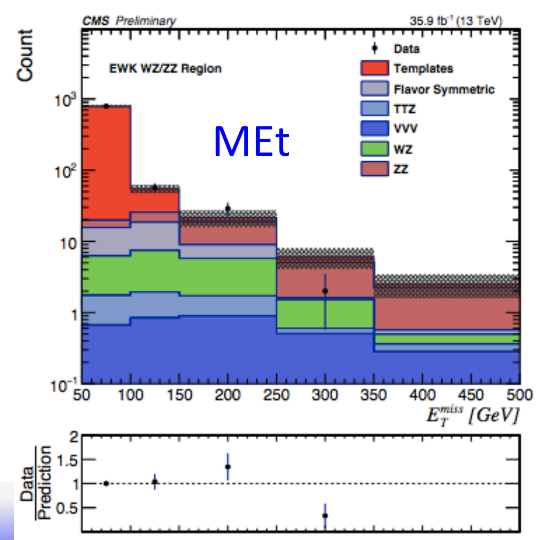


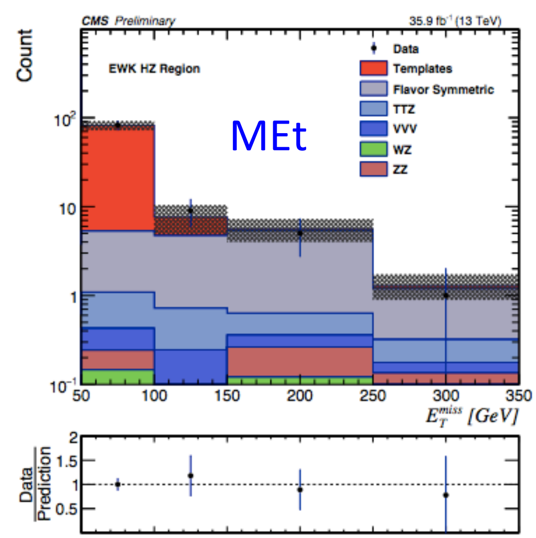


L+HF jets +high-met signature

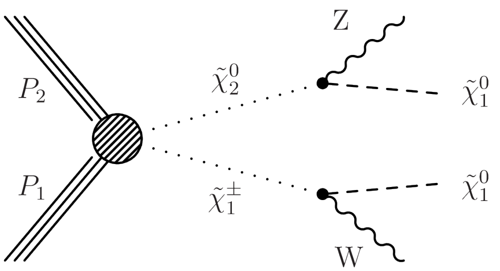
Search for mass peak in bbbar spectrum

CMS-PAS-SUS-16-043

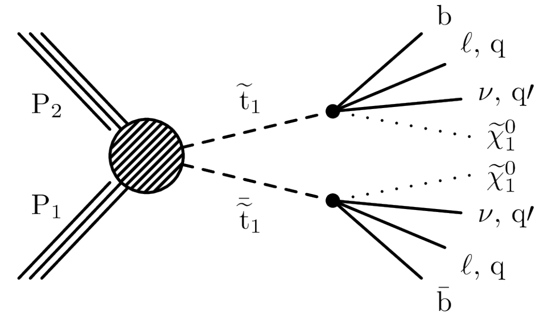


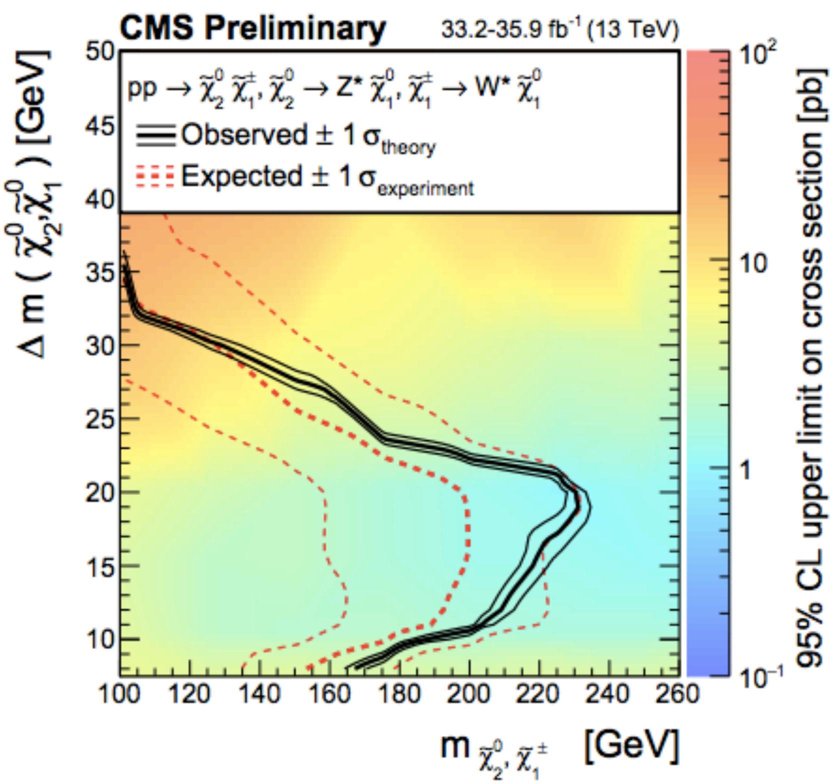


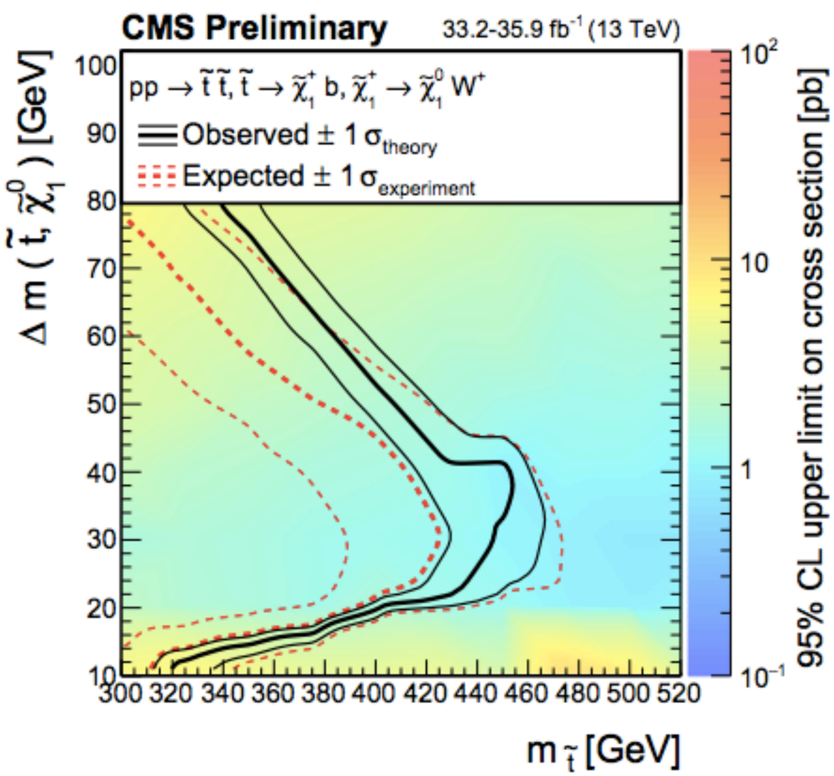
Compressed Spectra



- Soft leptons from small mass splitting
- Trigger on MET or MET+soft muon pair





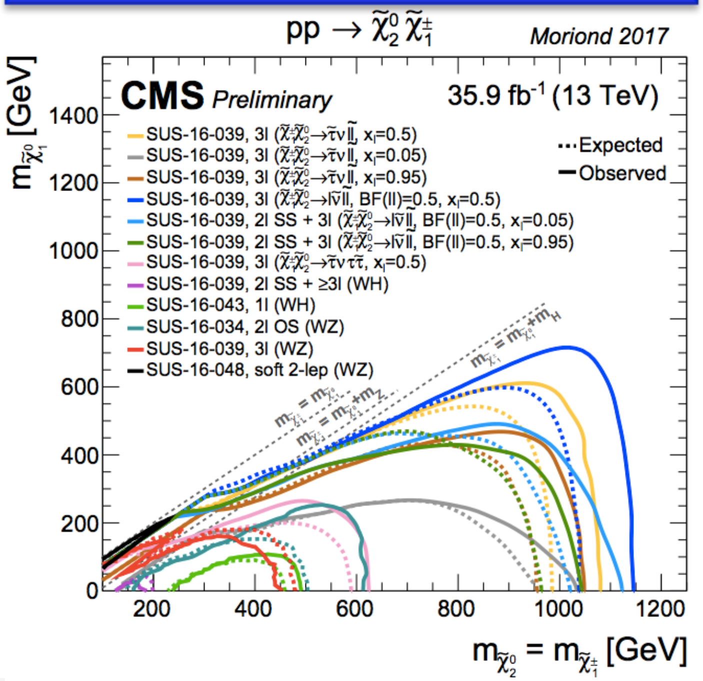


CMS-PAS-SUS-16-048

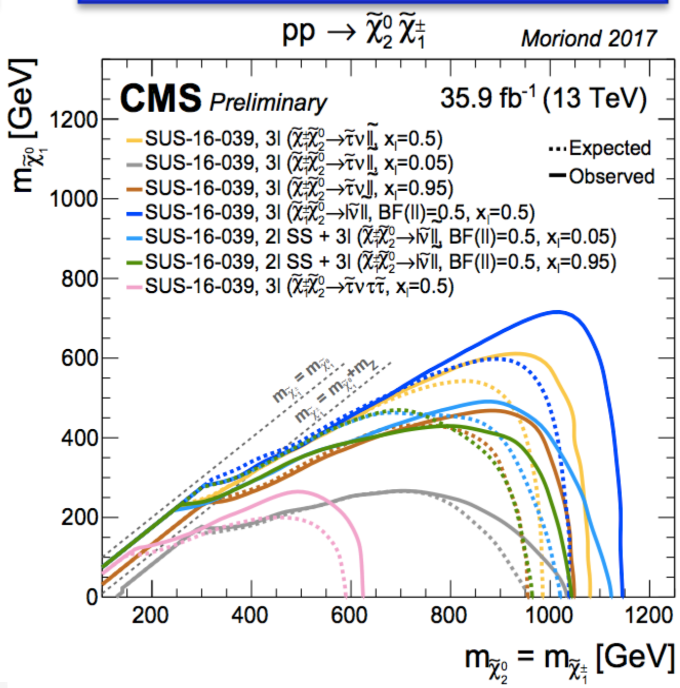
Electroweak Production Summary

- Over a hundred of different search regions dependent on # jets, b-tags, leptons, flavour, charge

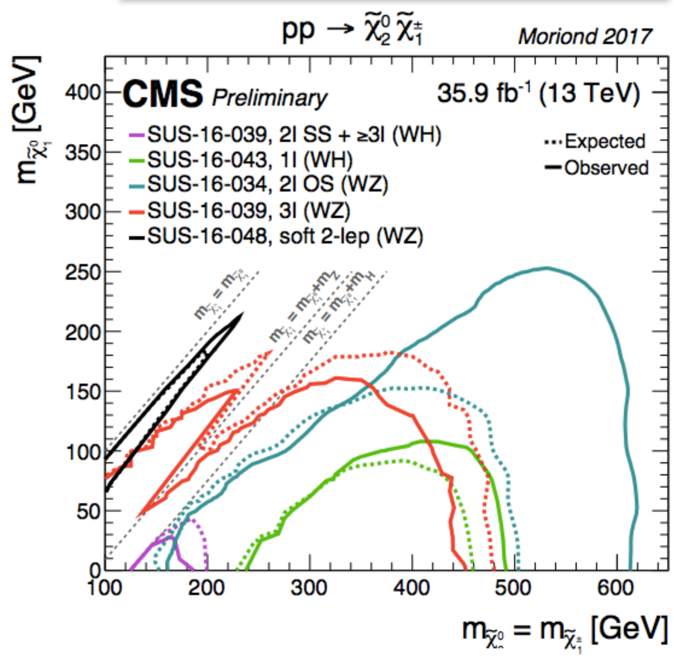
Chargino-neutralino production



with decays via sleptons

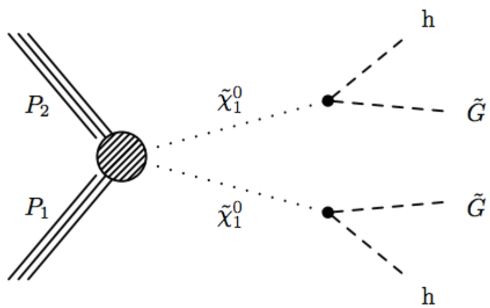


with decays via W/Z/H



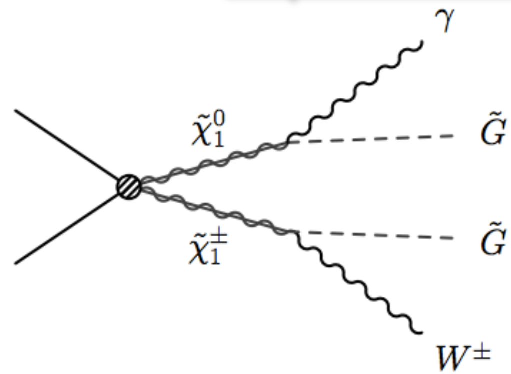
GMSB SUSY Searches

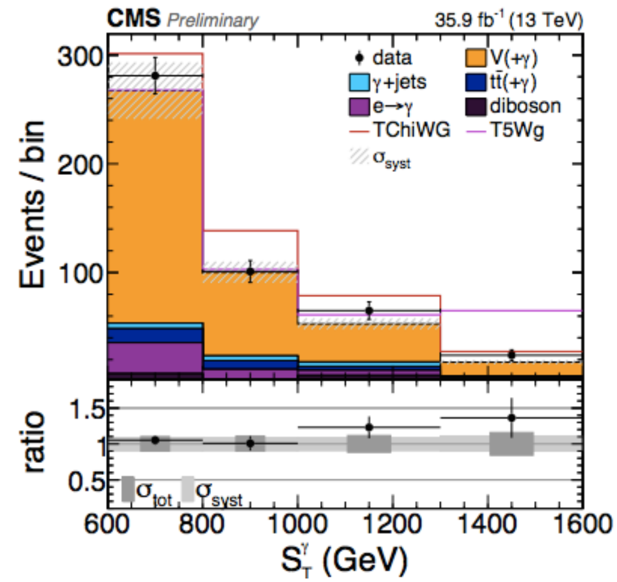
hh: CMS-PAS-SUS-16-044

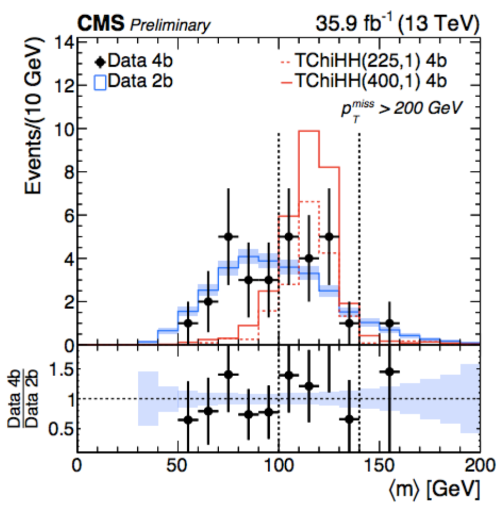


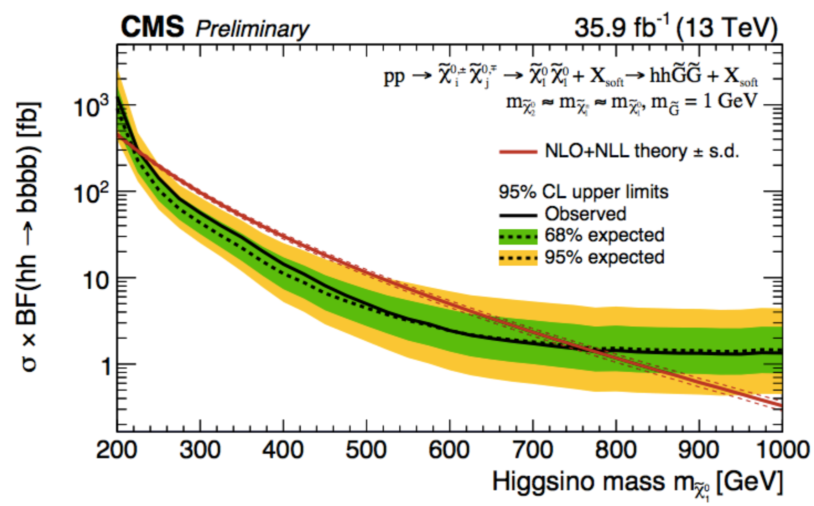
- Target higgsino production: Two H->bb
- Pairing is based in min $|m_{H1}-m_{H2}|$
- Use <m> = ½$(m_{H1}+m_{H2})$ as discriminating variable
- Estimate backgrounds in 2b regions, search in 3,4b

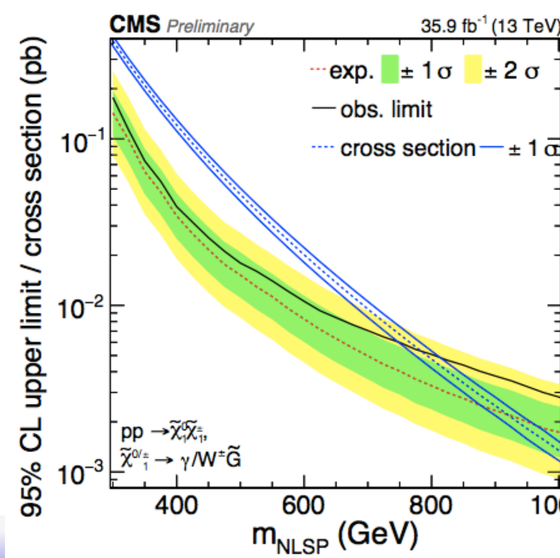
Wγ: CMS-PAS-SUS-16-046



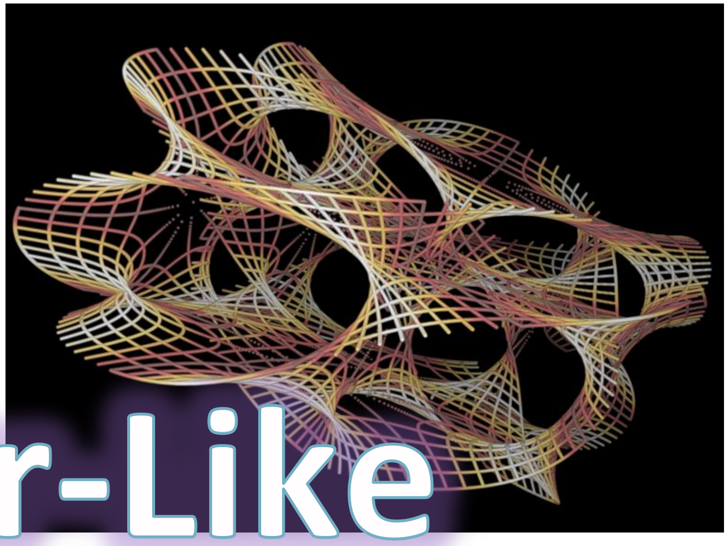


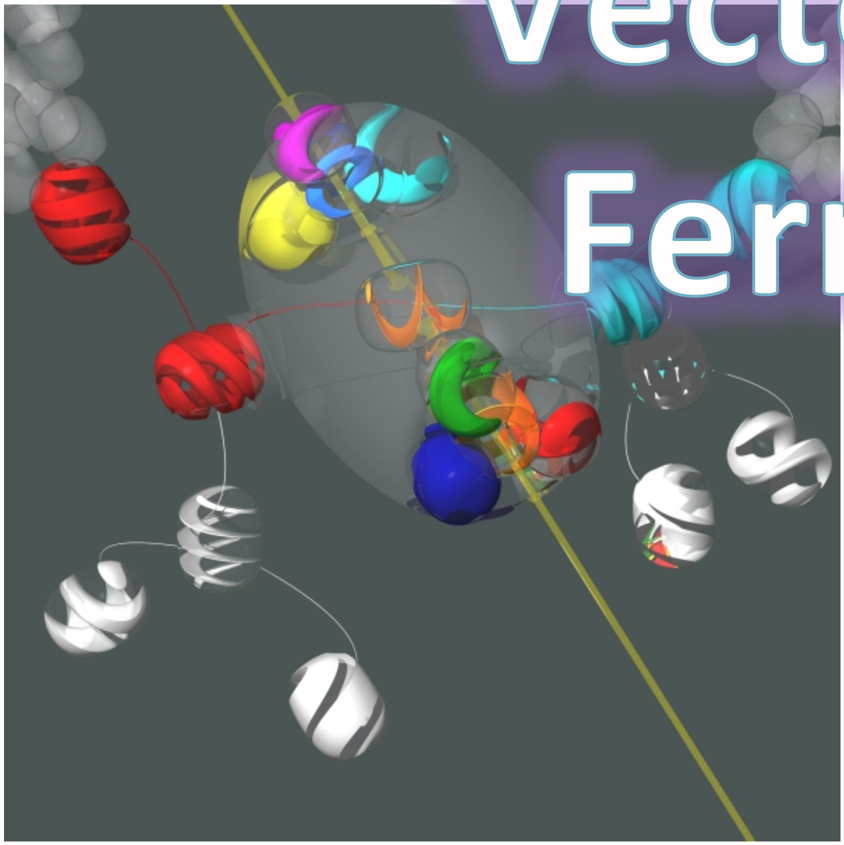






Vector-Like Fermions





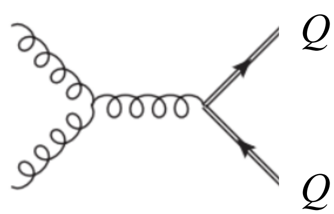
Vector-Like Quarks

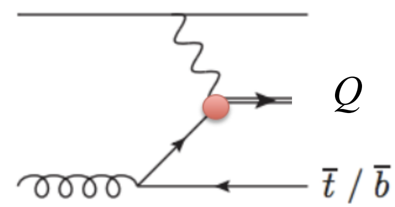
- Vector-like quarks are extra family of quarks with symmetric "vector-like" couplings to W,Z
- Both chiralities have the same representation under the electroweak group $SU(2)_L \times U(1)_Y$
- Pair-production, strong mechanism, model-independent
- Single production, electroweak, depends on the mixing with SM quarks

	SM	Singlets		Doublets			Triplets	
	$\binom{u}{d}\binom{c}{s}\binom{t}{b}$	(t')	(b')	$\binom{X}{t'}$	$\binom{t'}{b'}$	$\binom{b'}{Y}$	$\begin{pmatrix}X\\t'\\b'\end{pmatrix}$	$\begin{pmatrix}t'\\b'\\Y\end{pmatrix}$
$SU(2)_L$	2	1		2			3	
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3	-1/3	1/6	7/6	-5/6	2/3	-1/3

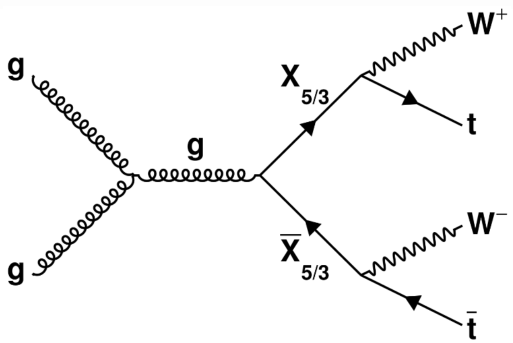
Minimal model: $SO(5) \times U(1)/SO(4) \times U(1)$

$$\mathbf{5}_{SO(5)} \to \mathbf{4}_{SO(4)} \oplus \mathbf{1}_{SO(4)} = (\mathbf{2}_{SU(2)_L}, \mathbf{2}_{SU(2)_R}) \oplus (\mathbf{1}, \mathbf{1})$$

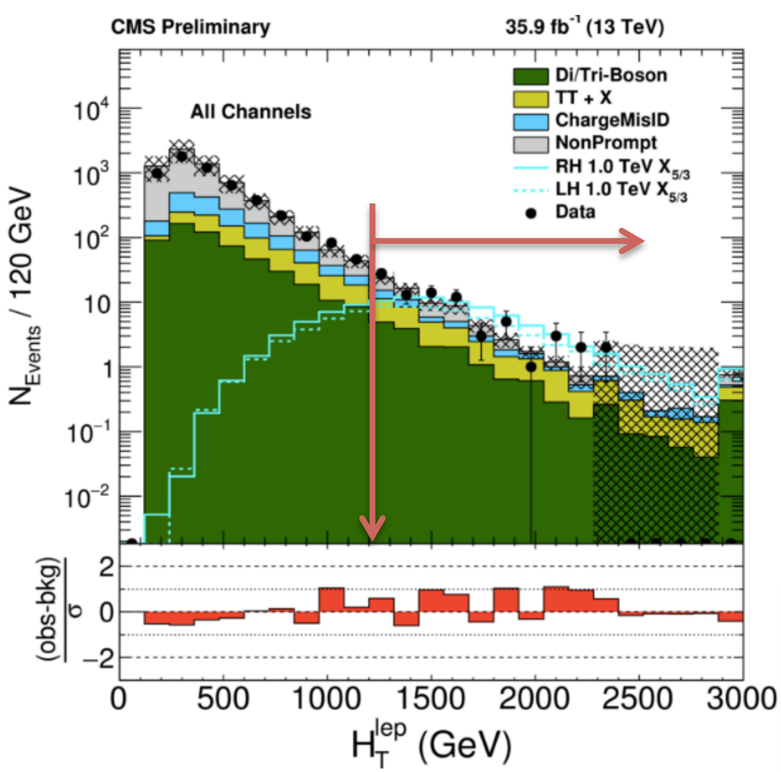


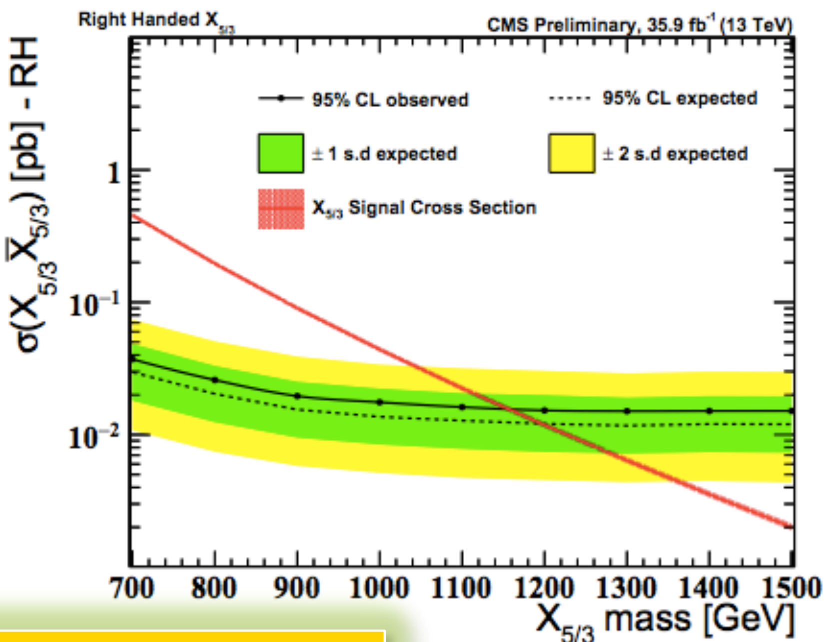


Pair B / $X^{5/3}$ in Same-Sign Di-leptons



- Signature: 2 same-sign charge leptons + jets OR 3 leptons + jets
- Determine lepton fake rates from lepton-depleted data samples
- Evaluate charge-misID rates using Z->ee events
- Use the matrix method to estimate backgrounds in the signal region
- Background estimate are validated in control regions, with signal region cuts inverted

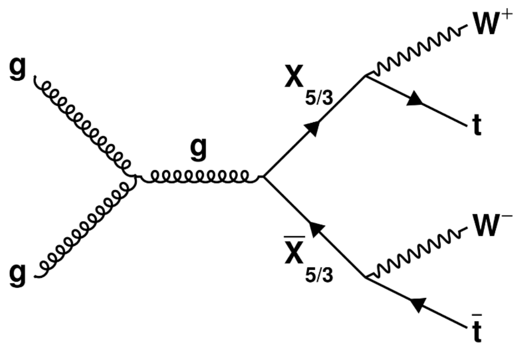




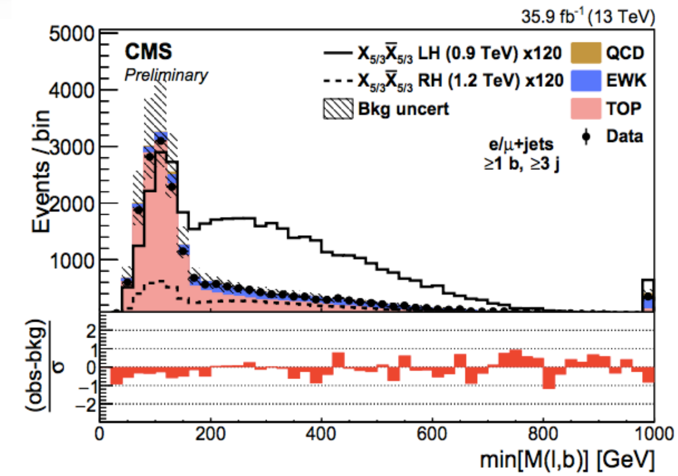
LH(singlet or triplet) / RH(doublet)
M_X > 1.15 TeV / 1.20 TeV
@ 95 % C.L.
BR (X→tW)= 100%

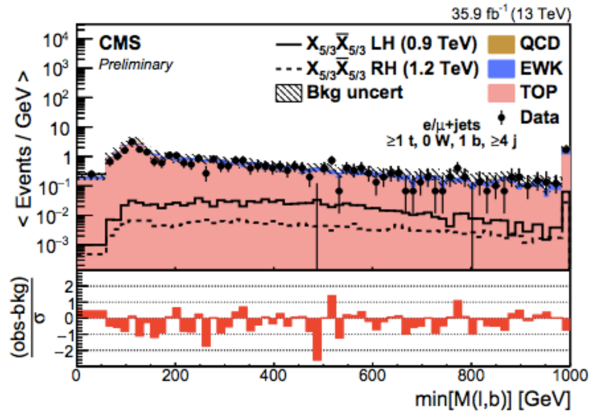
CMS-PAS-B2G-17-008

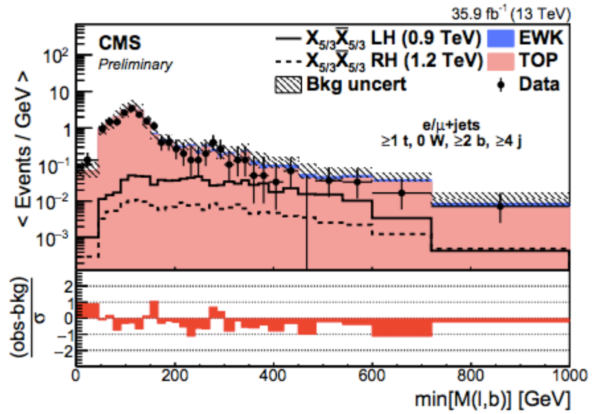
Pair $X^{5/3}$ in ℓ + jets

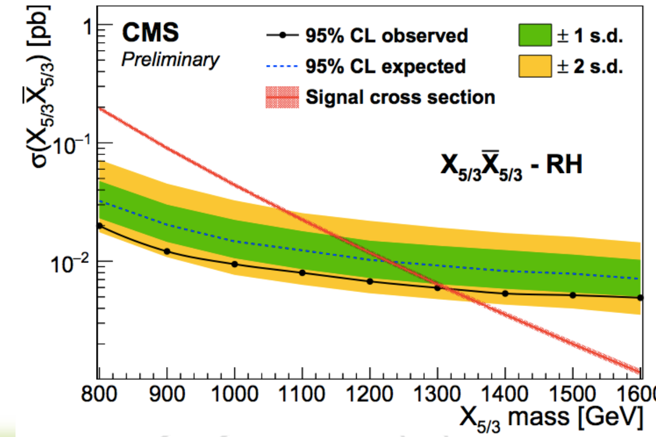


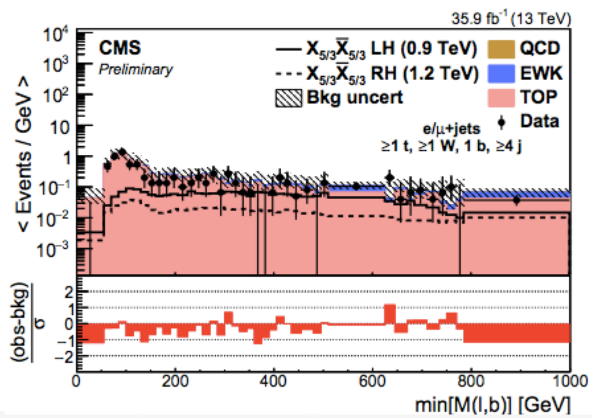
- Signature: l+jets, ≥ 1 b-tag
- Categorize events based on the # of W, t-tags
- Perform fit min M[l,b] variable
- Validate MC modeling in signal-depleted regions

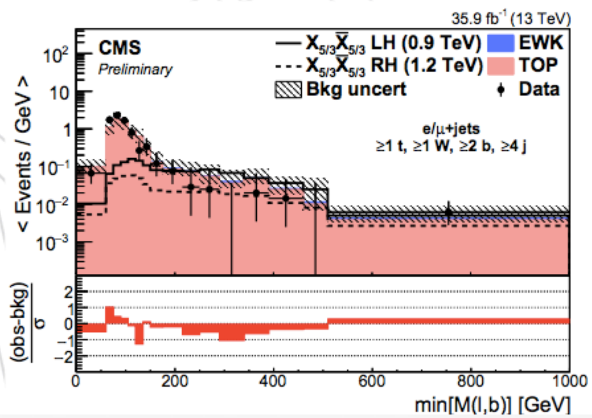








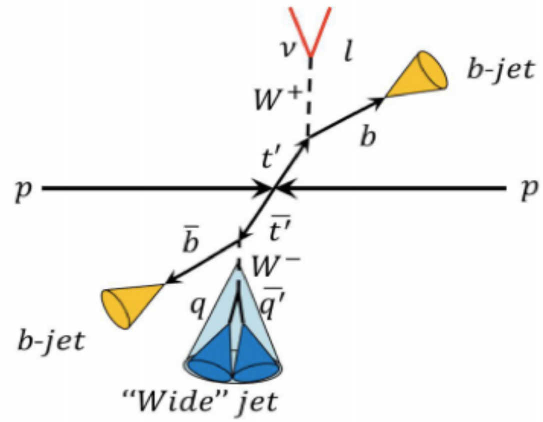


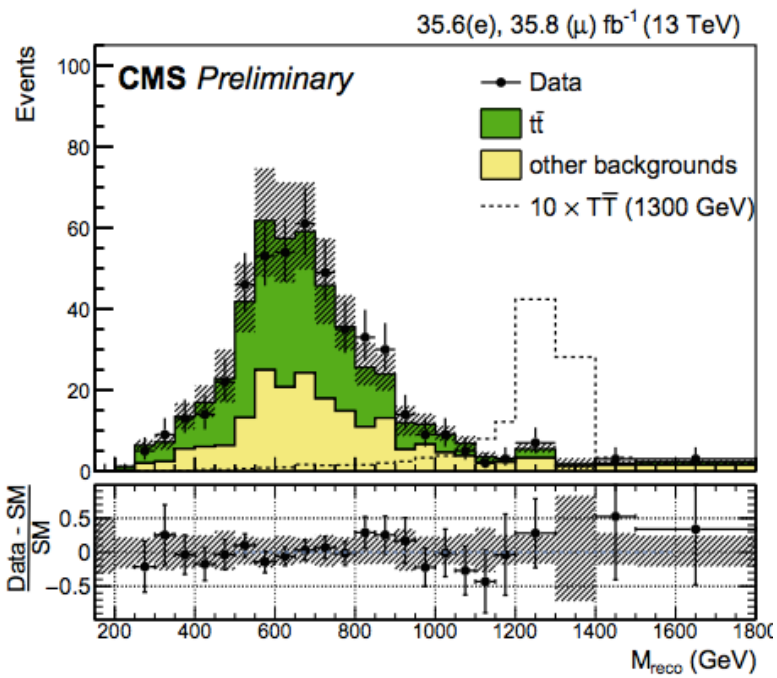


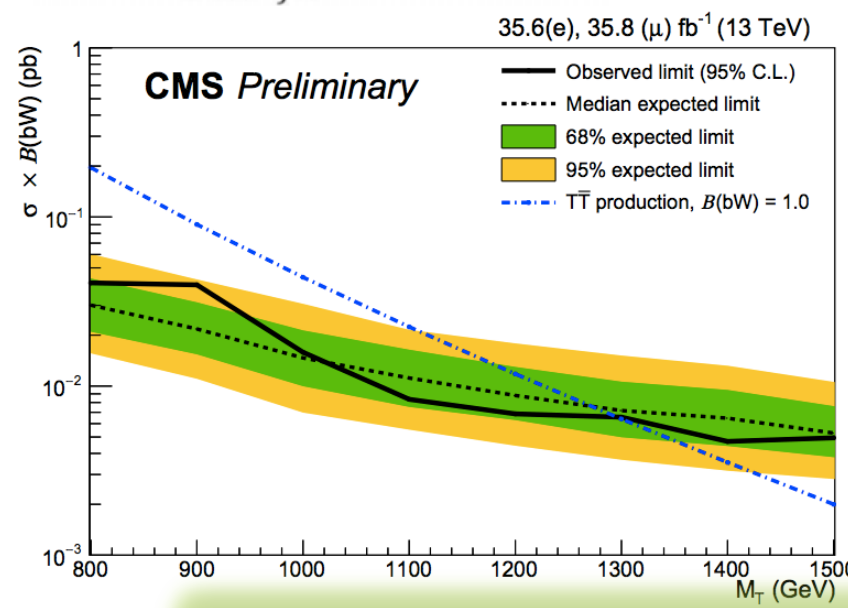
LH (singlet or triplet) / RH (doublet)
M_X > 1.30 TeV / 1.32 TeV
@ 95 % C.L.
BR (X→tW) = 100%

Pair T/Y$^{-4/3}$ in ℓ + jets

- Focus on bWbW decays
- Perform a kinematic fit identical to the one used in top quark mass measurement
- Highly boosted W bosons merge into single jets
- Use W-tag sub-jets for the fit input

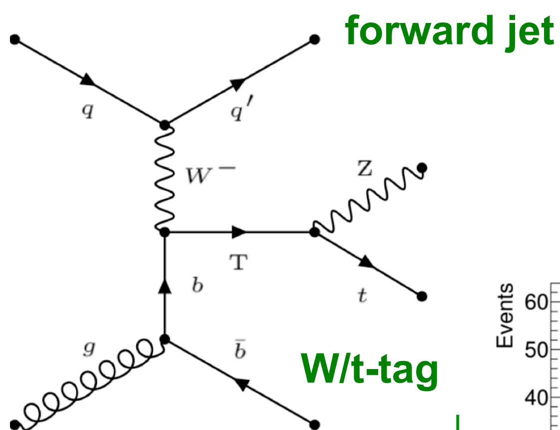




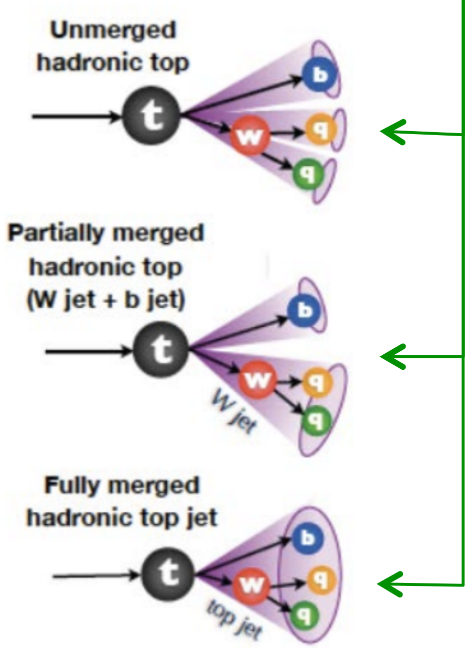


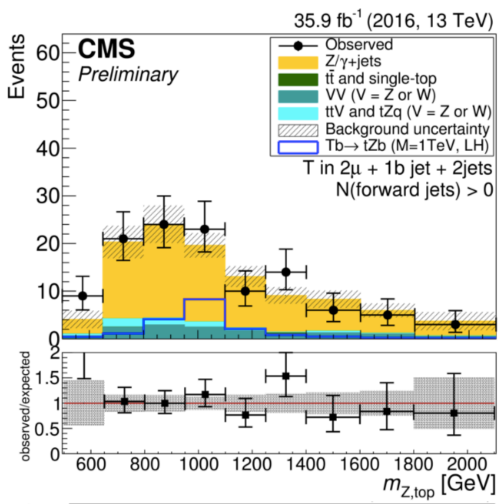
M_T > 1.3 TeV @ 95 % C.L.
BR (T→Wb) = 100%

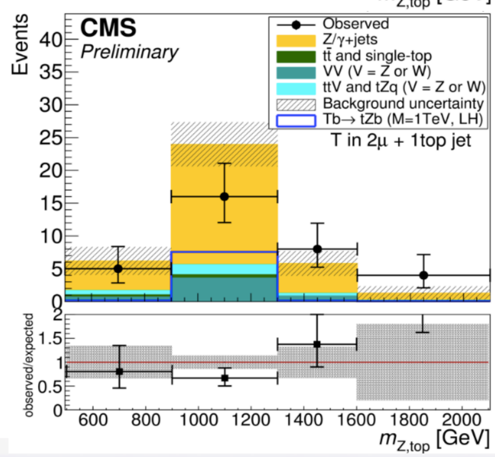
Single T->tZ

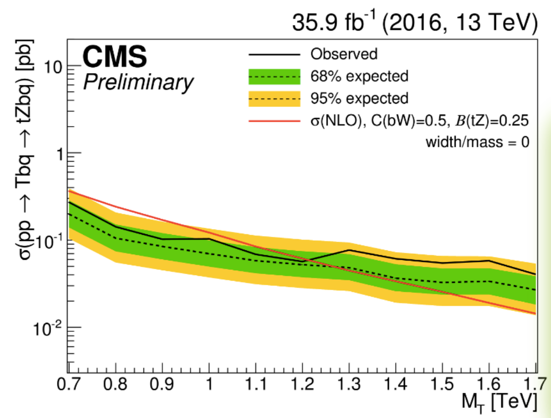


- Signature: Z->ee/μμ + jets, ≥ 1b-tag
- Categorize events based on # of W, t-tags and forward jets
- Reconstruct mass of the T quark as M(tZ)
- Data-driven backgrounds based on 0b-control region



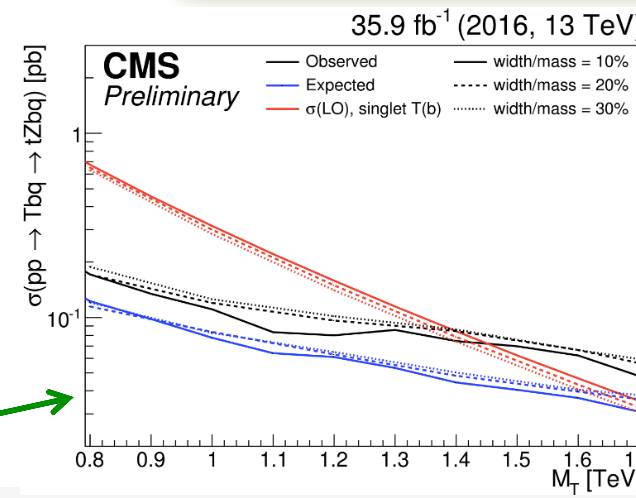




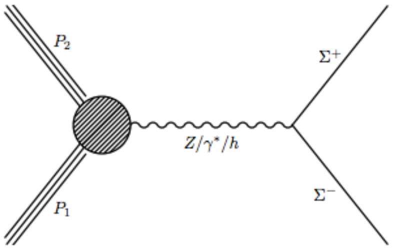


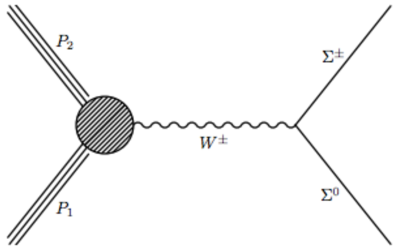
Singlet M_T > 1.2 TeV @ 95 % C.L.
C(bW) = 0.5
BR (T→tZ)= 25%

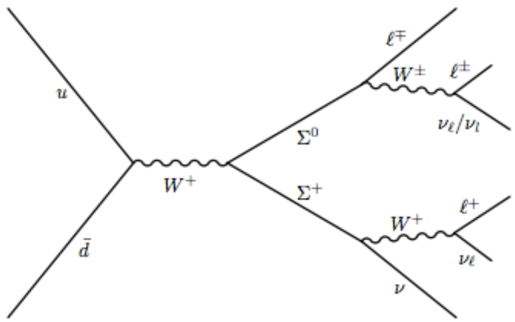
- Large couplings <-> large widths
- Similar limits for larger quark widths



Type-III See-saw mechanism



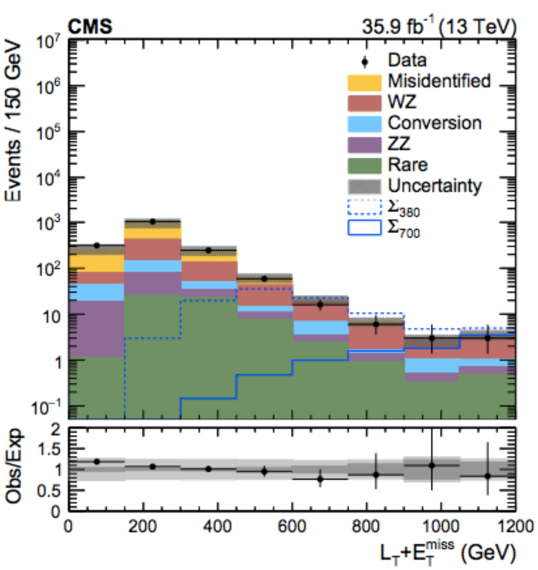


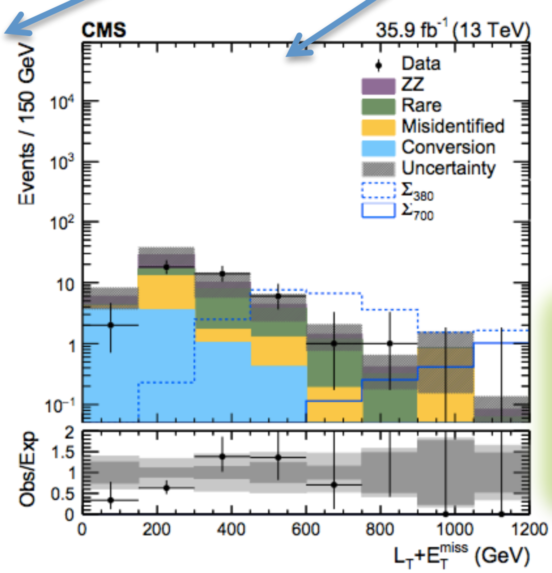


- $\Sigma^\pm \to W^\pm \nu$
- $\Sigma^\pm \to Z/H l^\pm$
- $\Sigma^0 \to W^\pm l^\pm$
- $\Sigma^0 \to Z/H \nu$

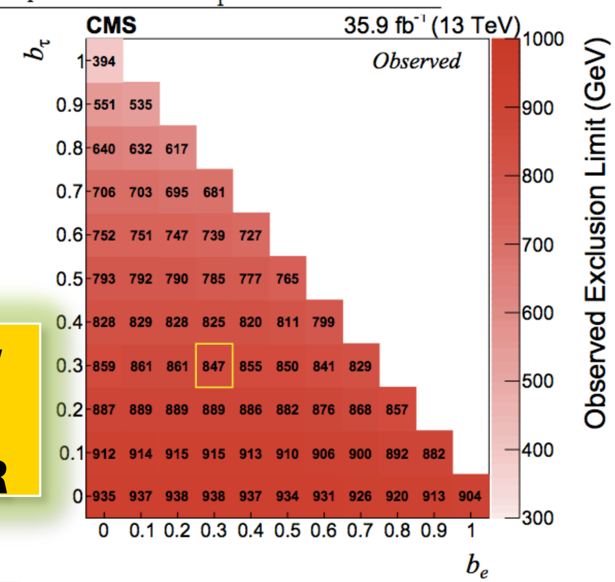
- Type III refers to heavy neutrino mass arising via mediation of massive fermion partners
- Search for electroweak production of exotic heavy leptons in multi-lepton final states
- Signal regions :

N_{leptons}	OSSF	Kinematic Variable	CR-veto
3	above-Z	$L_T + E_T^{\text{miss}}$	-
	below-Z	$L_T + E_T^{\text{miss}}$	$E_T^{\text{miss}} > 50\,\text{GeV}$
	none	$L_T + E_T^{\text{miss}}$	-
≥ 4	1 pair	$L_T + E_T^{\text{miss}}$	-
	2 pairs	$L_T + E_T^{\text{miss}}$	$E_T^{\text{miss}} > 50\,\text{GeV}$ if on-Z
3	on-Z	M_T	$E_T^{\text{miss}} > 100\,\text{GeV}$





M_Σ > 847 GeV
@ 95 % C.L.
Democratic BR



Conclusions

- CMS (and ATLAS) performed an exploration of new energy scale (13 TeV) using large pp collisions dataset (36 inv. fb) and large number of physics analyses in a multiple number of final states

- No evidence for new physics so far…

- LHC will continue taking data until the end of 2018, expecting to collect 3-4 times more data than used in analyses presented today
- Detector upgrades are underway to prepare for high-luminosity data-taking, with eventually 100x fold increase in statistics