IFAE - Trieste
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BSM Searches @ ATLAS and CMS

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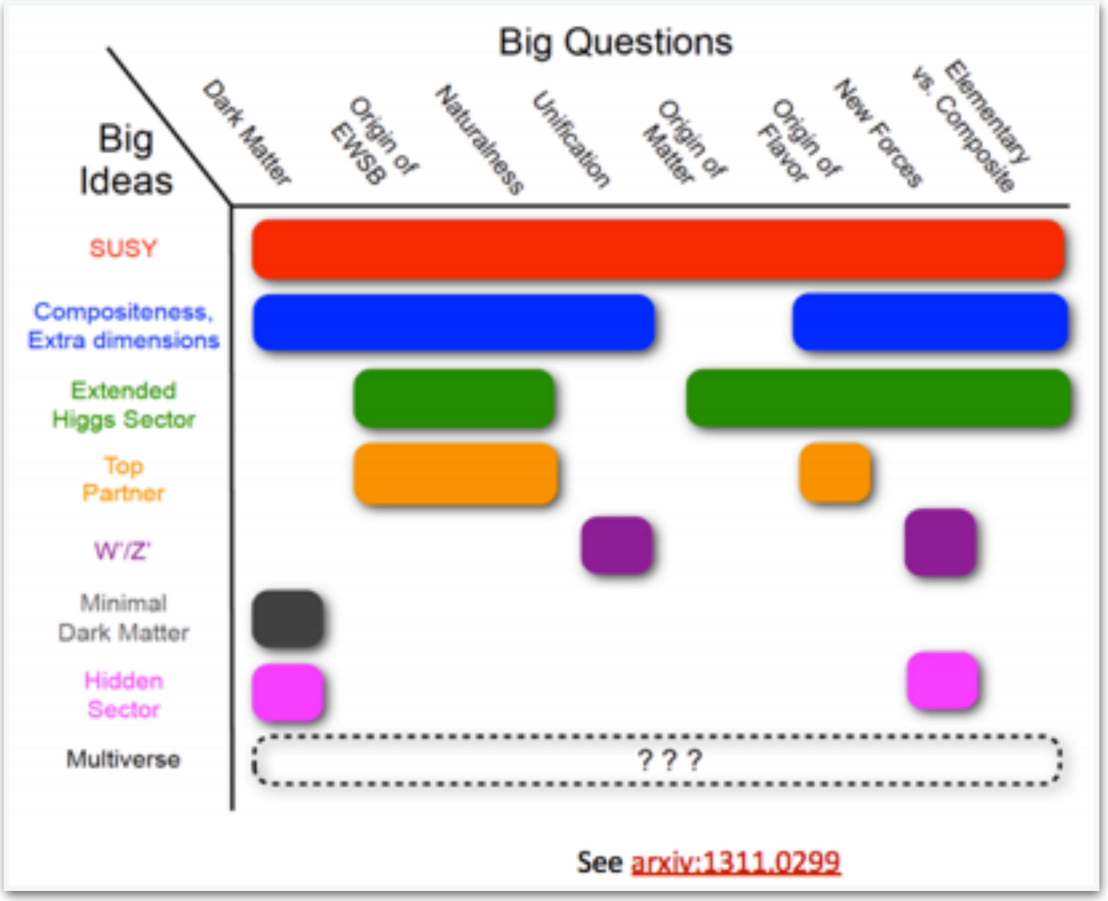
Introduction

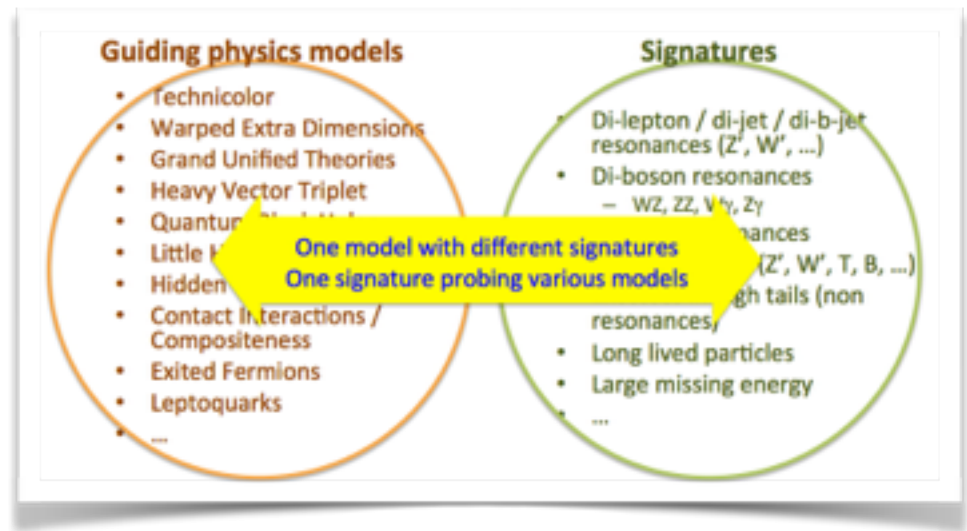
- The experimental results beautiful fit in Standard Model (SM) framework…
- …but some mysteries are still opened and need physics beyond the SM to be solved!



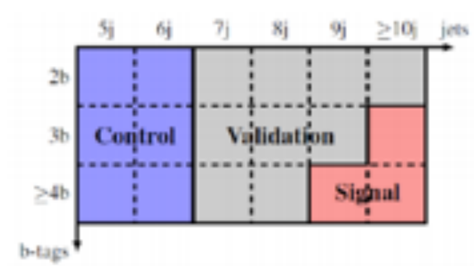
- This presentation will not cover all the ideas or address all the question. Apologies if your favorite analysis will not be shown!
  - Other talks will report results for Narrow and Heavy Resonances, Composites Neutrinos and Dark Matter searches.
  - The presentation will consider final state topologies with:
    - **di-jets**
    - **jets+MET**
    - **disappearing tracks**
    - **long-lived particles**

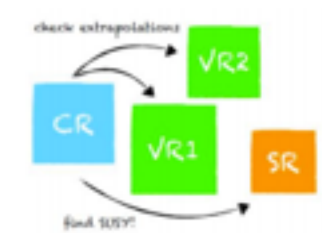
Direct BSM Searches

What is needed to perform searches for BSM phenomena?



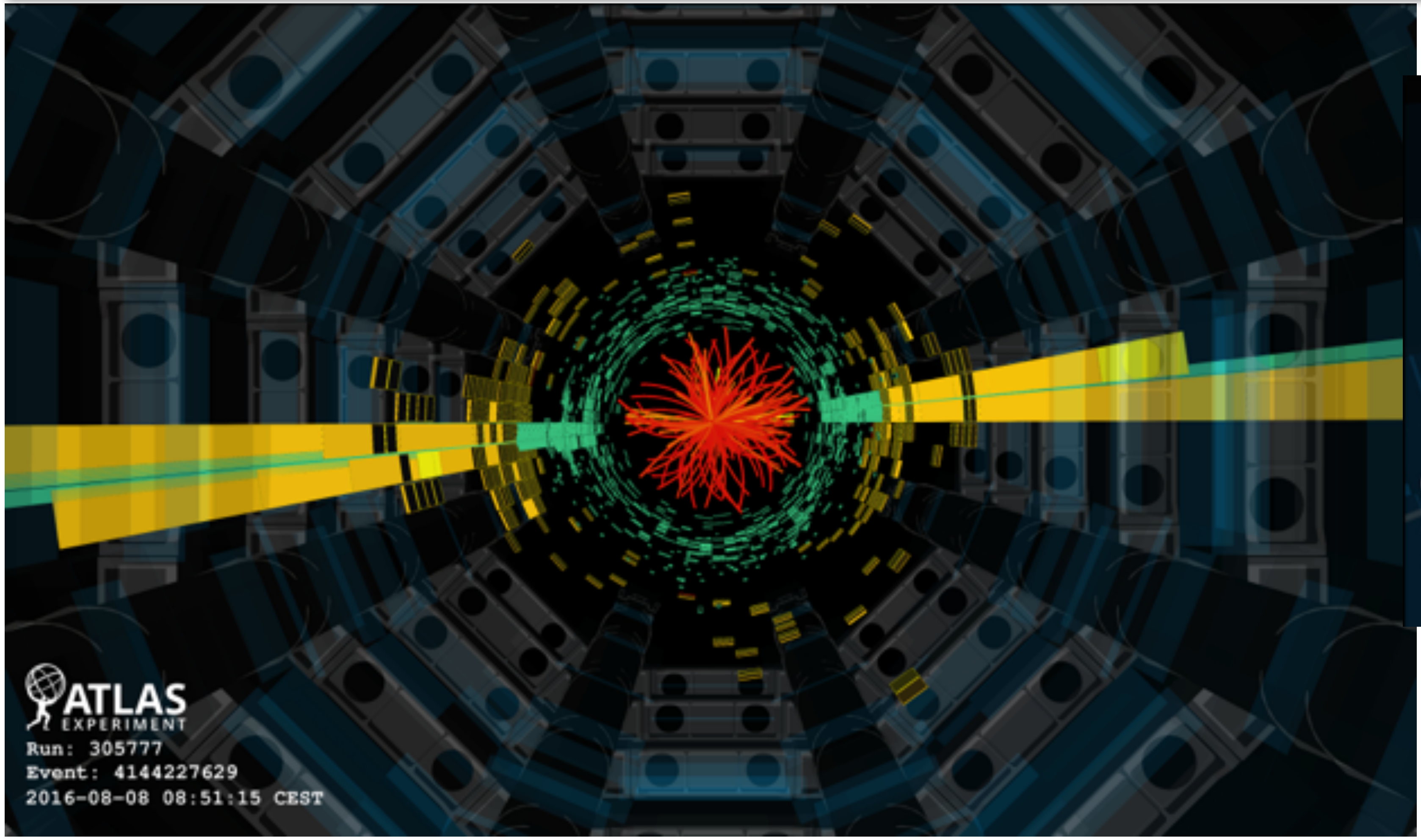
- **A choice of a search topology** (several topologies for one model and vice versa).
- **Trigger**: high level HLT (software) but not forgetting level one L1 (instrumental).
- **Physics objects** (jet, ET miss, leptons, photon): definition, performance, validation, time stability etc. It is done for all analyses, but **some searches need custom objects** (long-lived, monopoles …).
- A **choice of signal sensitive variables** (at least two).
  - Definition of one (or several) Signal enriched Regions SR (both criteria satisfied).
  - What rest form Control Regions CR in which at least one criterion is not satisfied.
  - Use data driven methods to find out and validate transfer factors from CR to SR to obtain a data driven estimate of background level in the SR (including background systematics – not explained here), however, while data driven methods are preferred, sometimes it is necessary to use MC to estimate the level of background.
  - It could be more complicated if "shape analysis" is used instead of "counting experiment".

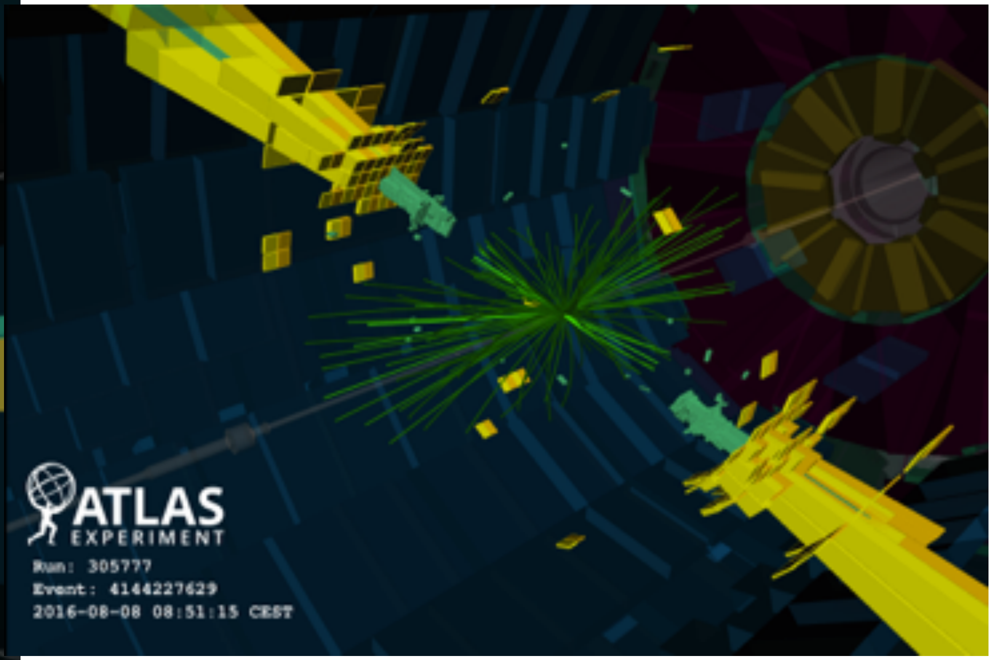




- **Claim discovery if statistically significant excess is found or, if not, interpret the result in term of constraints on selected models.**

A visualization of the highest-mass dijet event, (Event 4144227629, Run 305777)





New Physics with di-jets and multi-jets

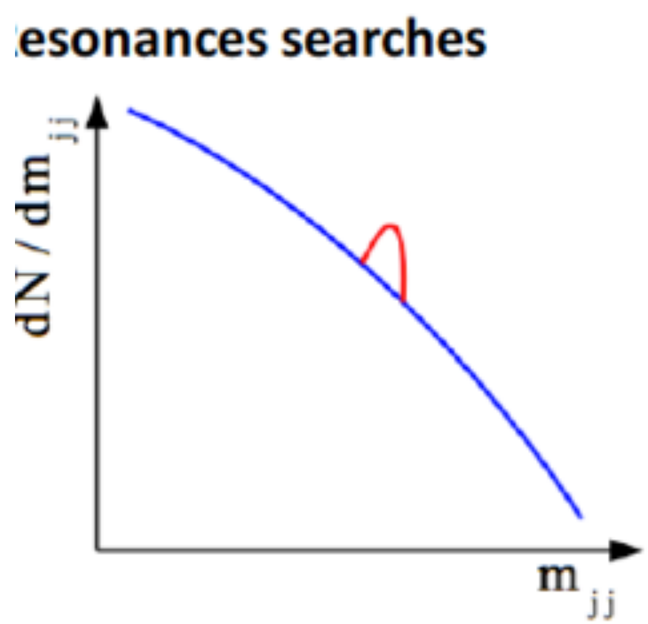
CMS di-jet : CMS-EXO-15-009 and CMS-EXO-16-056
ATLAS di-jet : arXiv:1703.09127

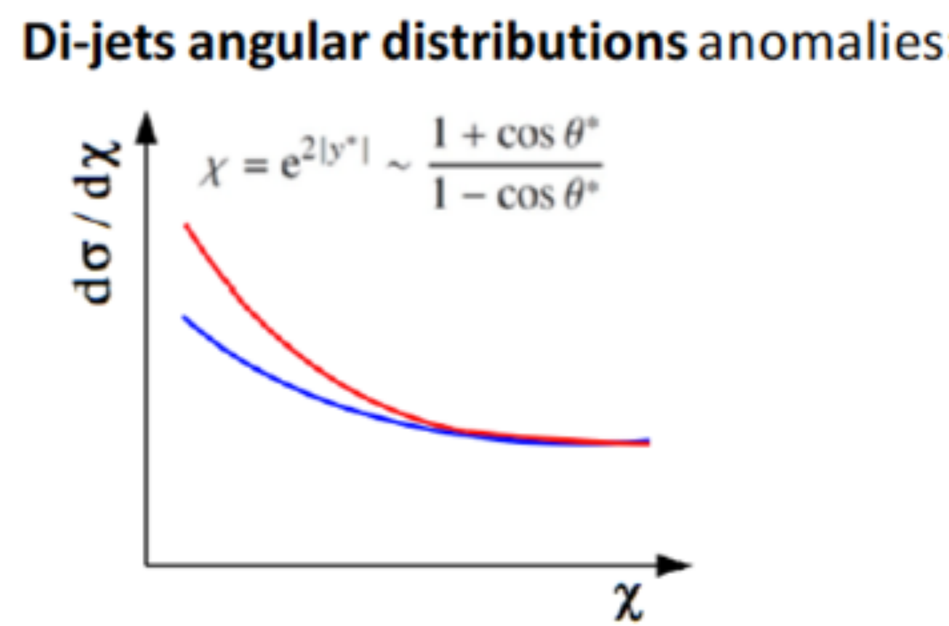
CMS multijet+MET : CMS-SUS-15-004

New phenomena in di-jets

ATLAS CMS

Sensitive to a broad class of new phenomena





Resonant search : localised excess in mjj

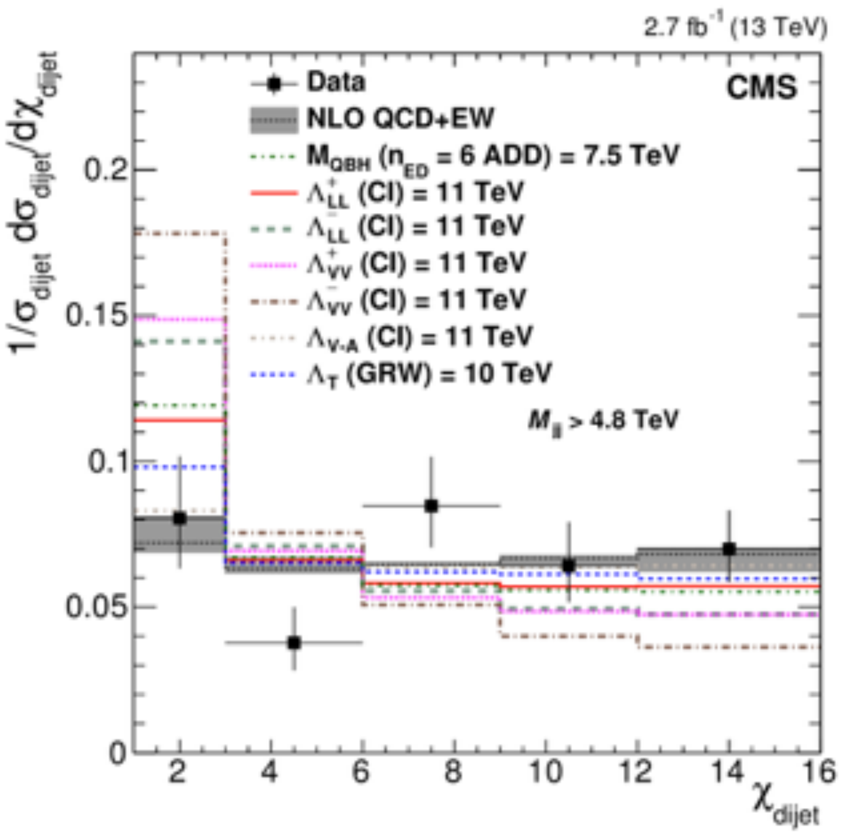
Non-resonant : QCD angular distribution flatter than BSM

ATLAS and CMS Common approach:
Event Selection: single jet trigger, rapidity and di-jets mass cut
Background: QCD described by MC, normalized to data in each mjj bin
Dominant Uncertainty: Jet energy scale (exp) and renormalization/factorization scales (theory)

Di-jets angular distribution anomalies

ATLAS CMS

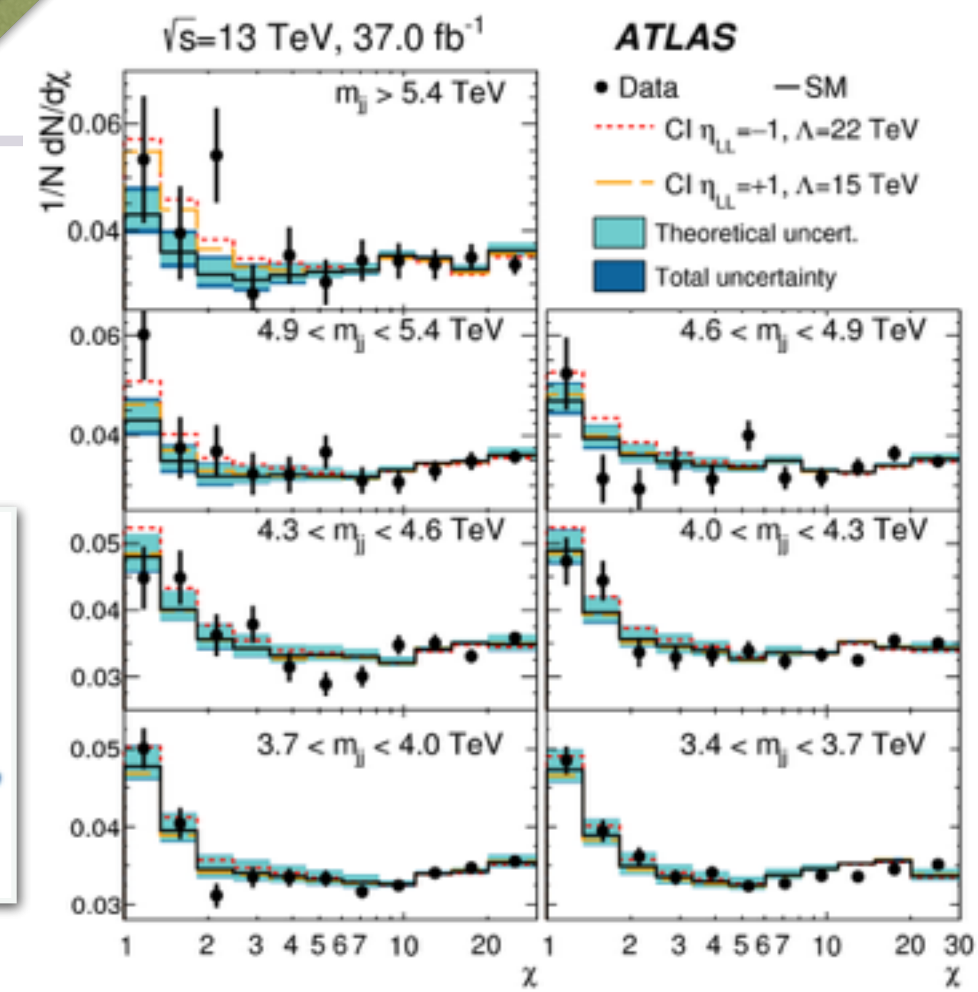
$$\chi = e^{y^*} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



- Reference model : **contact interaction with compositeness scale Λ**

$$L_{qq} = \frac{2\pi}{\Lambda^2}[\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_R\gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_L\gamma_\mu q_L)],$$

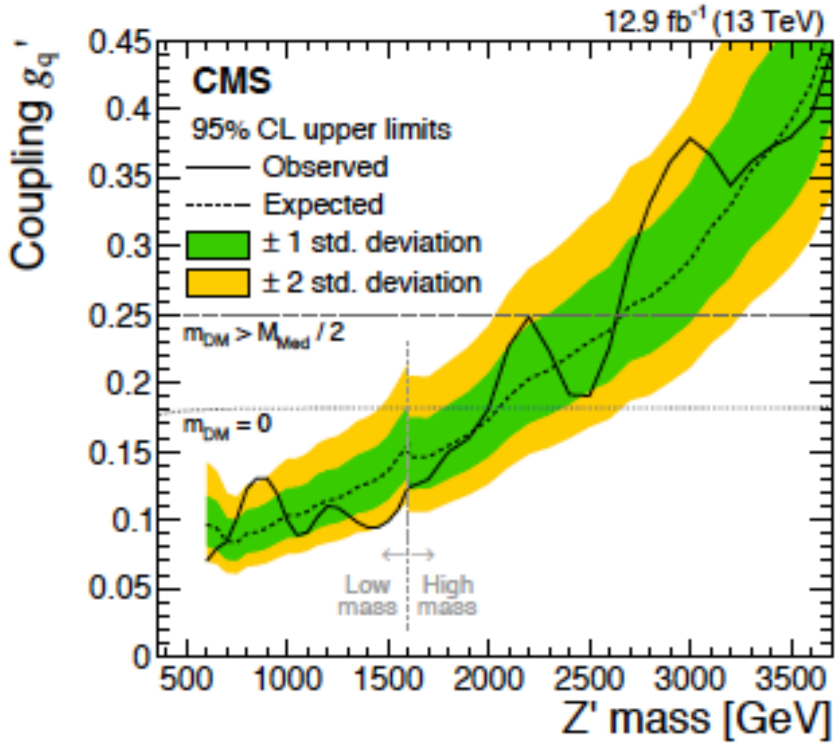
$$\eta_{LL} = \pm 1,\ \eta_{RR} = \eta_{RRL} = 0$$



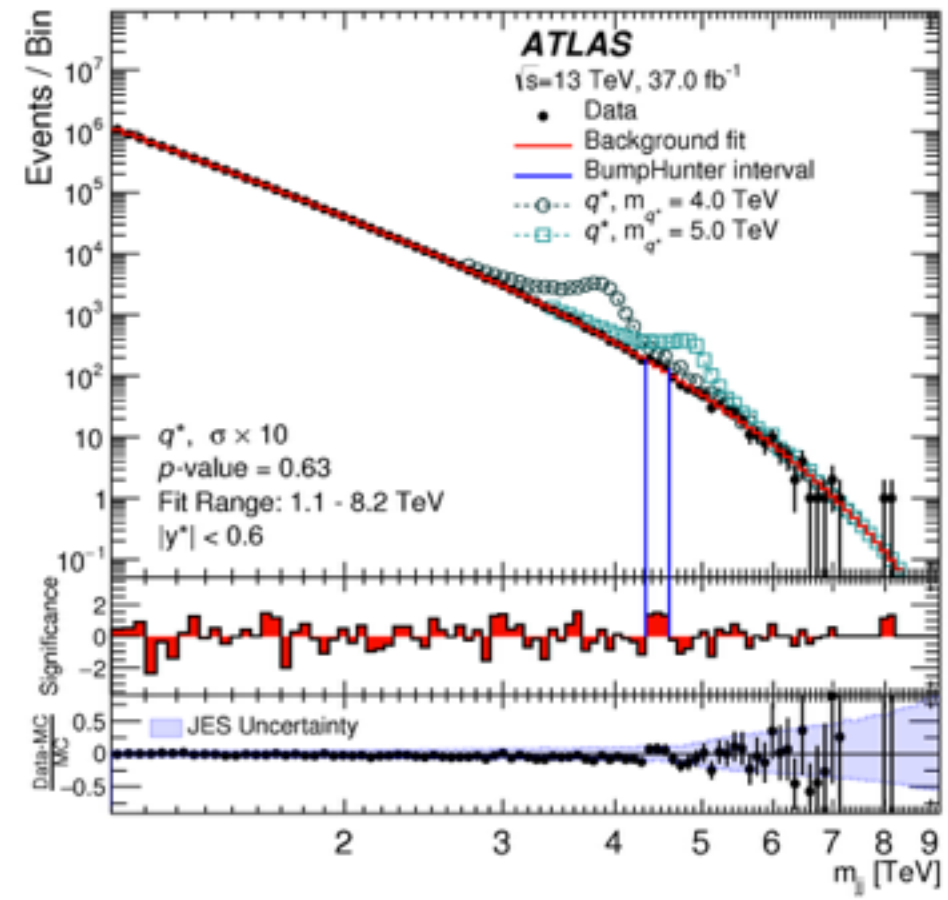
Exclusion Limits	CMS
Contact Interaction Constructive	<14.7 TeV
Contact Interaction Destructive	<11.5 TeV
QBH	<7.8 TeV <5.3 TeV
Virtual Graviton AHDD Model	<7.9 TeV <11.2 TeV

Exclusion Limits	ATLAS
Contact Interaction	<21.8 TeV <13.1
Excited quarks	<6.0 TeV
QBH	<8.9 TeV
Z' W'	<2.9 TeV <3.4 TeV

Di-Jets resonance search



- No bump seen
- Limits on cross sections/ couplings as a function of mass
- Limits on specific benchmark models
- **See also the talk of M. Vanadia**



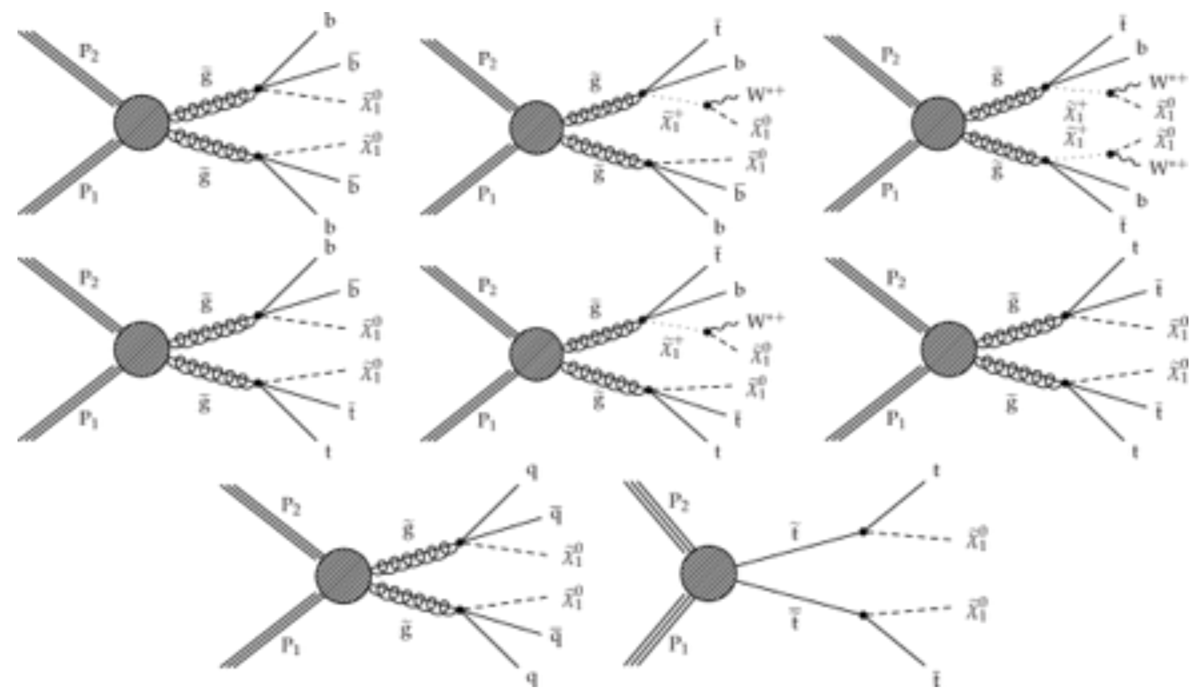
Model	Final state	Limit [TeV] Obs.	Exp.
String	qg	7.4	7.4
Scalar diquark	qq	6.9	6.8
Axigluon/coloron	$q\bar{q}$	5.5	5.6
Excited quark	qg	5.4	5.4
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.0	3.3
W′	$q\bar{q}$	2.7	3.1
Z′	$q\bar{q}$	2.1*	2.3
DM mediator (m_{DM} = 1GeV)	$q\bar{q}$	2.0	2.0
RS graviton	$q\bar{q}$, gg	1.9	1.8

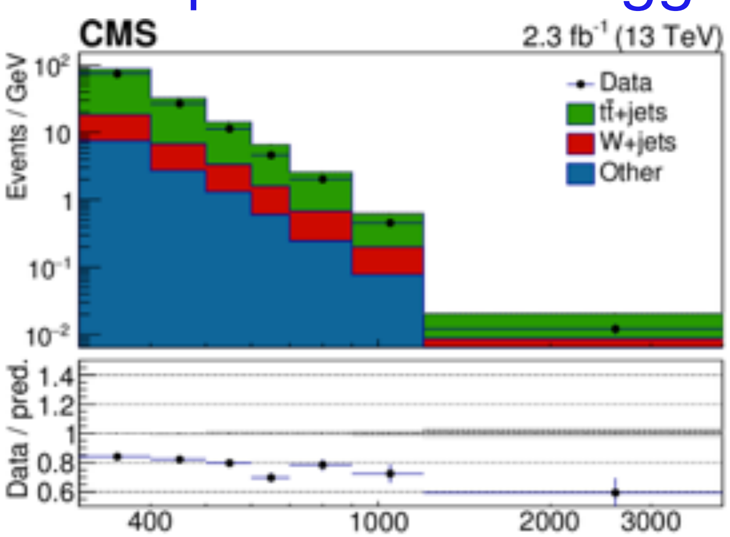
95 %CL exclusion limit		
Model	Observed	Expected
Quantum Black Hole, ADD	8.9 TeV	8.9 TeV
Excited quark	6.0 TeV	5.8 TeV
W'	3.7 TeV	3.7 TeV
W*	3.4 TeV, 3.8-3.9 TeV	3.6 TeV

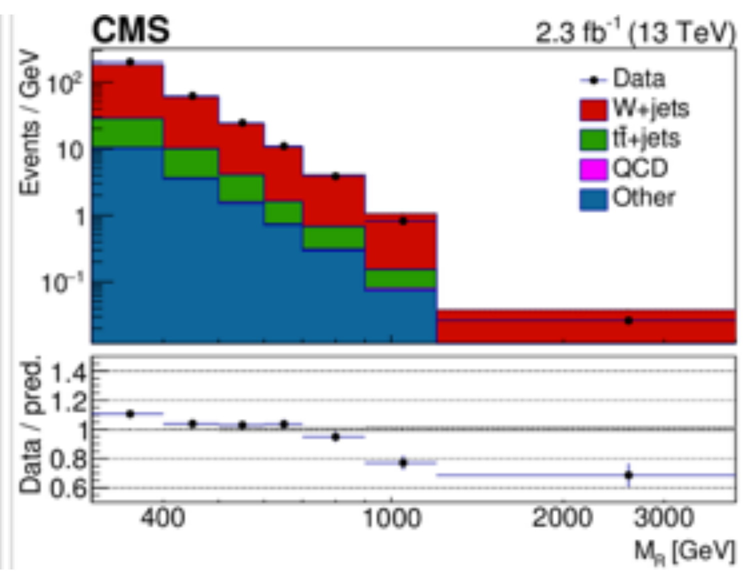
CMS-SUS-15-004
Phys. Rev. D 95, 012003

Multi Jets Final State

- **Inclusive search for supersymmetry (sensitive to a broad class of gluino and squark decay modes)**
- 4 or more jets (strong production)
- MET from undetected stable neutralino
- Search categories defined by number of leptons and b-tagged jets







$$M_R \equiv \sqrt{(|\vec{p}^{j_1}| + |\vec{p}^{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2},$$

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{p}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}},$$

$$R \equiv \frac{M_T^R}{M_R}.$$

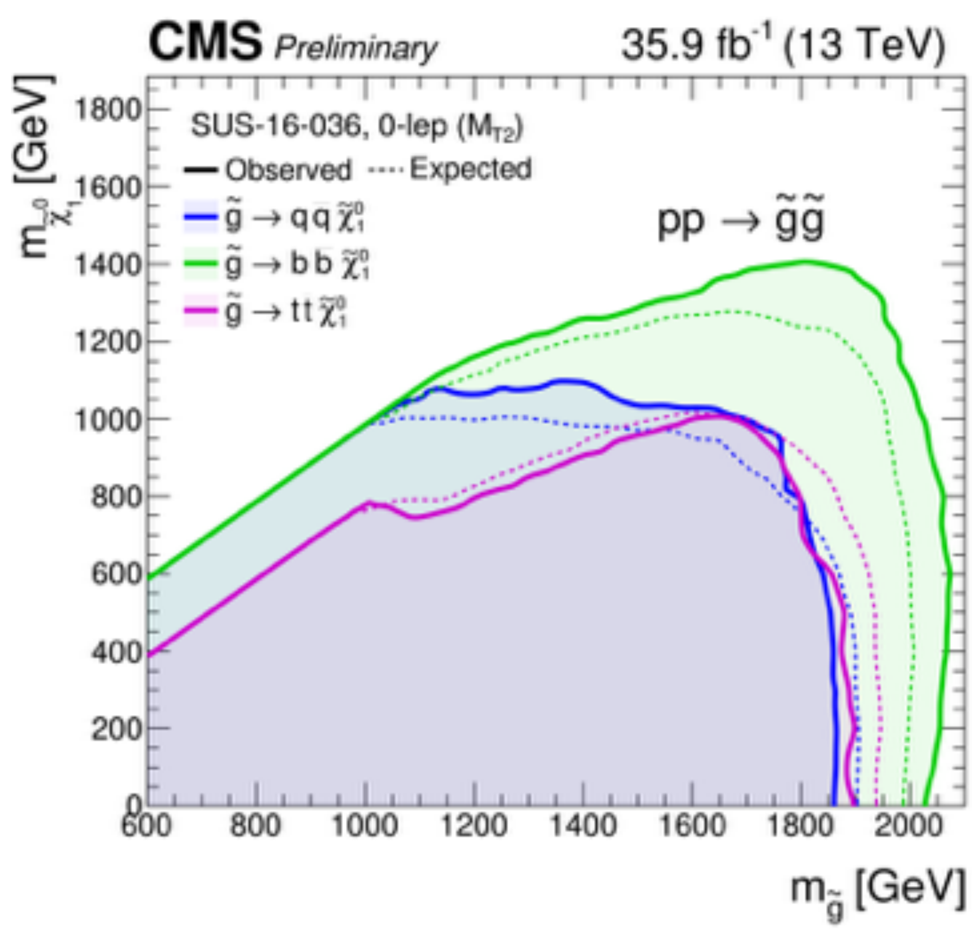
- **3 Categories:**
  1. **multi jets**
  2. **muon + jets**
  3. **electron + jets**
- **Using of Razor Variables: M_R and R**

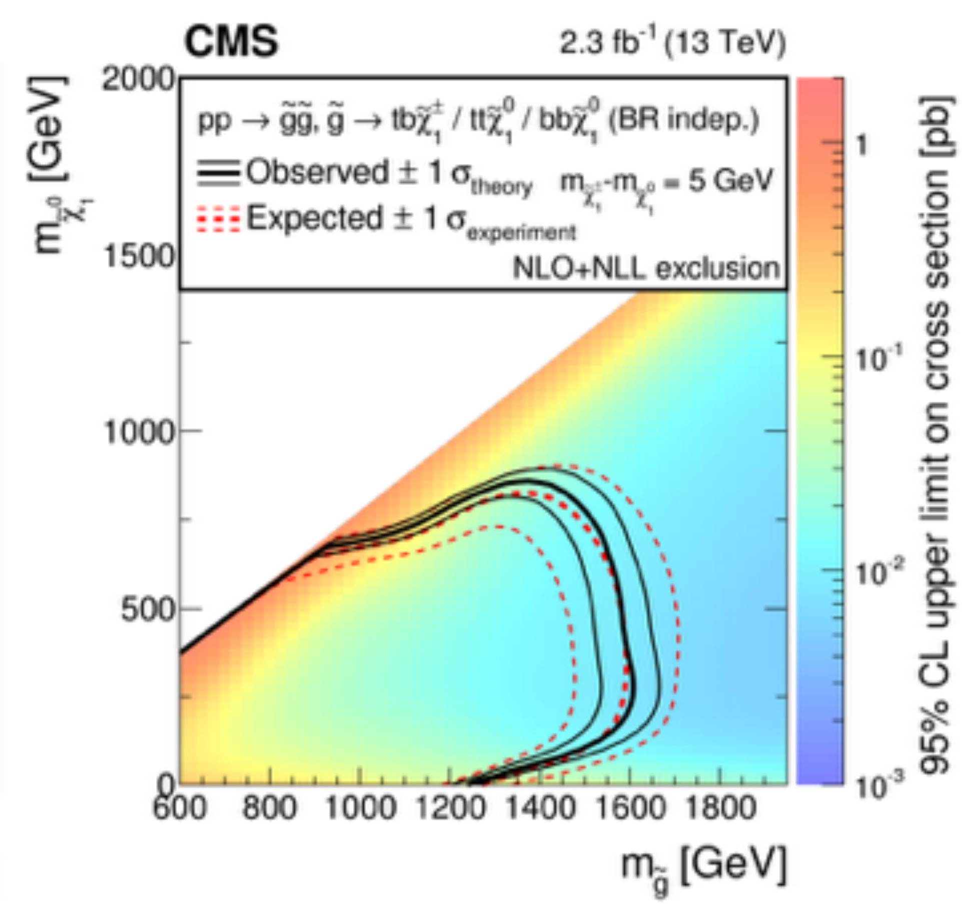
The main background processes in the search regions considered are W+jets, Z(vv)+jets, tt, and QCD multijet.

Results

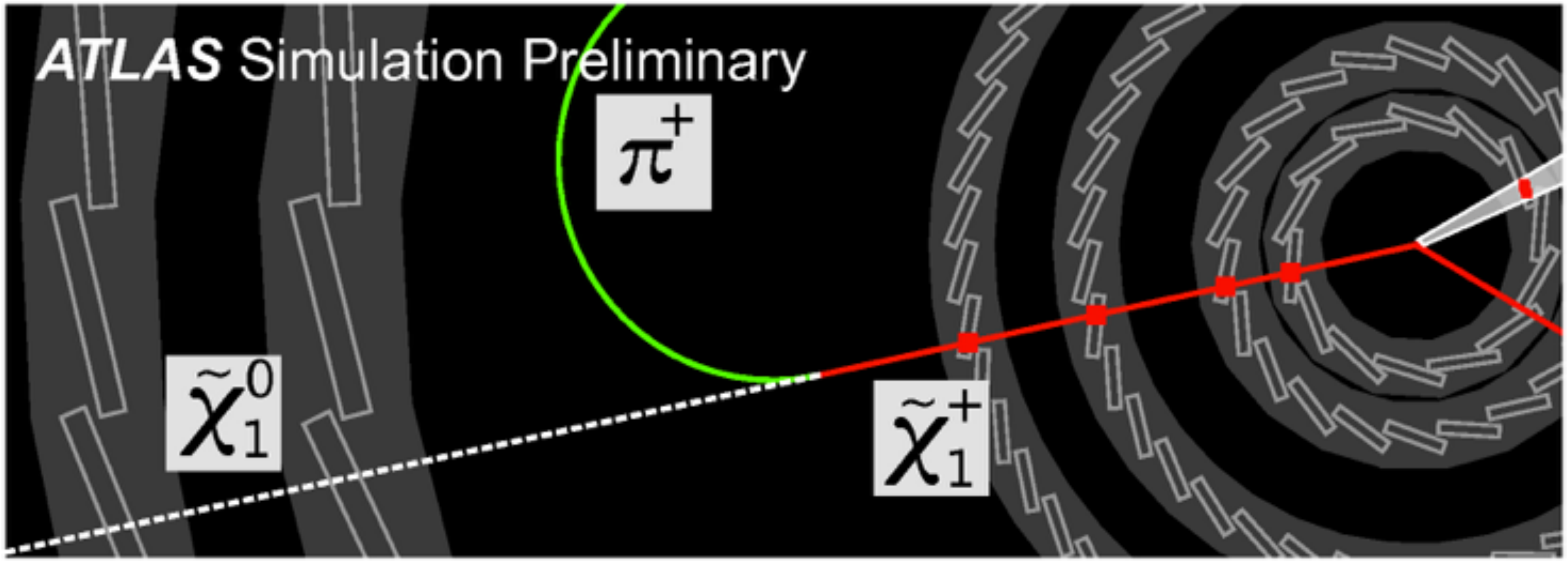
- **No significant excess - limits placed on gluino and top squark masses in a variety of decay modes**
- **Preliminary results with 36 fb^{-1} extend limits up to ~ 2 TeV in gluino mass and ~1 TeV in top squark mass for light neutralinos**
- **Many more results available ! See**

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults





Long-Lived Particle
Displaced objects



ATLAS-CONF-2016-042

CMS-EXO-15-010 ; CERN-EP/2016-204

ATLAS-CONF-2016-103

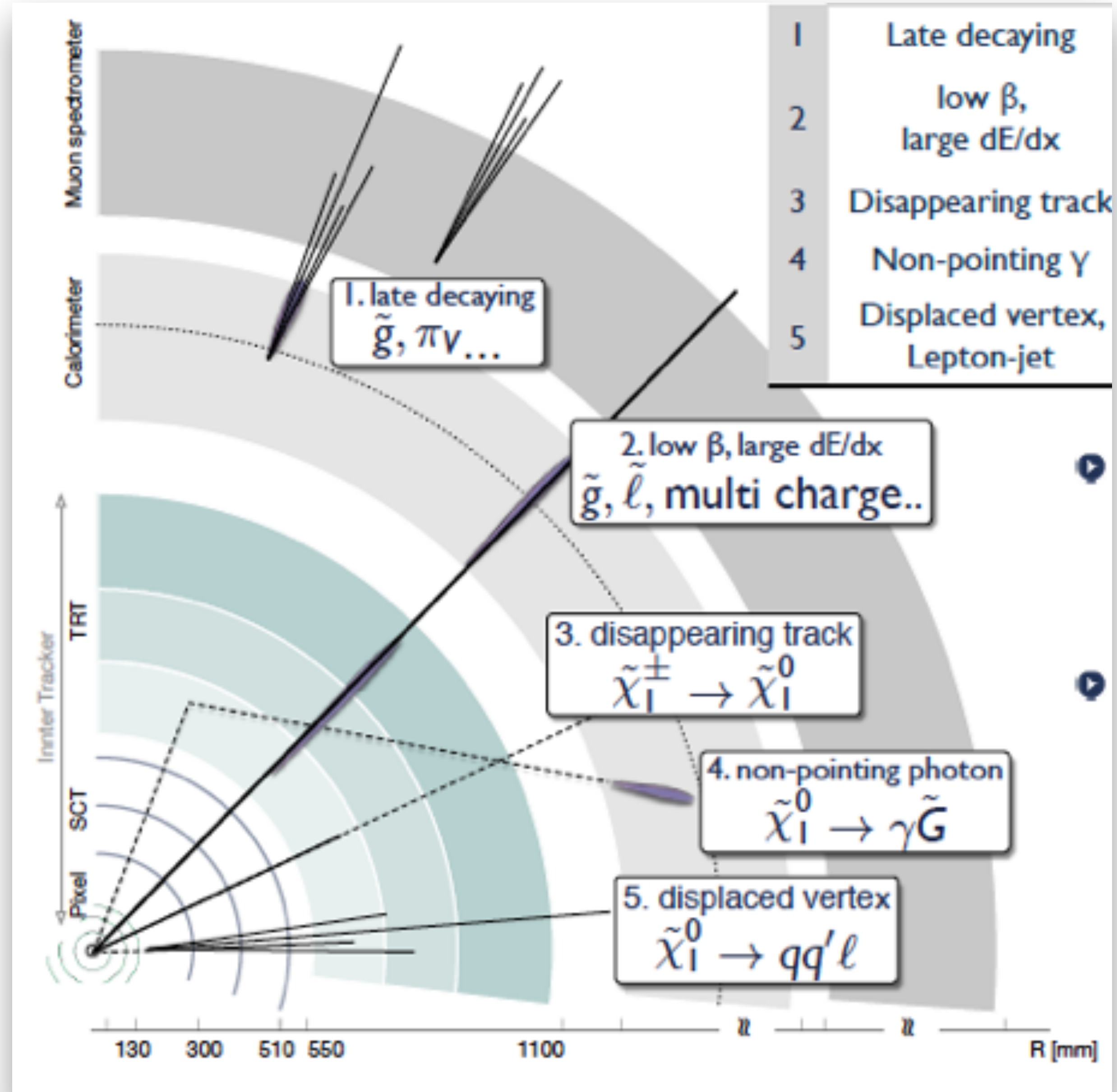
Long-Lived Particles

Several new physics models could give raise to new, massive particles with long-lifetime.

- SUSY with small couplings, mass splittings, strong virtuality in decay
- Higgs decay to hidden-sector neutral particles

Experimentally very diverse, depending on particles' properties:

- Slow particles : ionization, time of flight
- Displaced decays, disappearing tracks
- High lepton multiplicity (lepton-jets)



ATLAS-CONF-2017-017

Disappearing Tracks

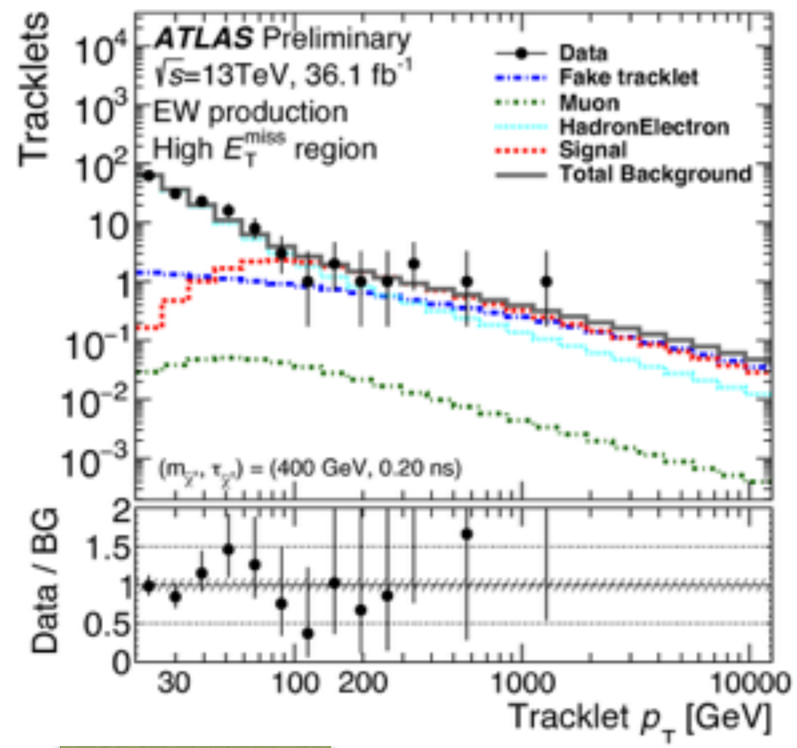
Long-lived charginos in AMSB model

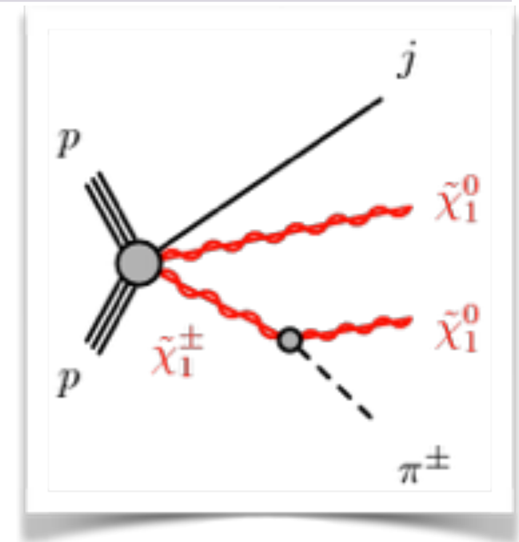
- For Wino LSP expected lifetime of ~0.2ns -> 6cm
- **Search for a disappearing track in the inner detector**

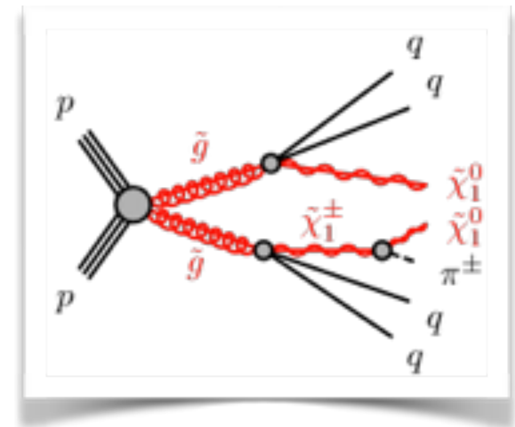
Event Selection

- Two selections defined for **weak** (direct) and strong (gluino) production.
- Backgrounds estimated by a simultaneous fit to the tracklet pT distribution
- pT templates are built for each background category
- typically using CR with standard tracks smeared for a tracklet resolution function

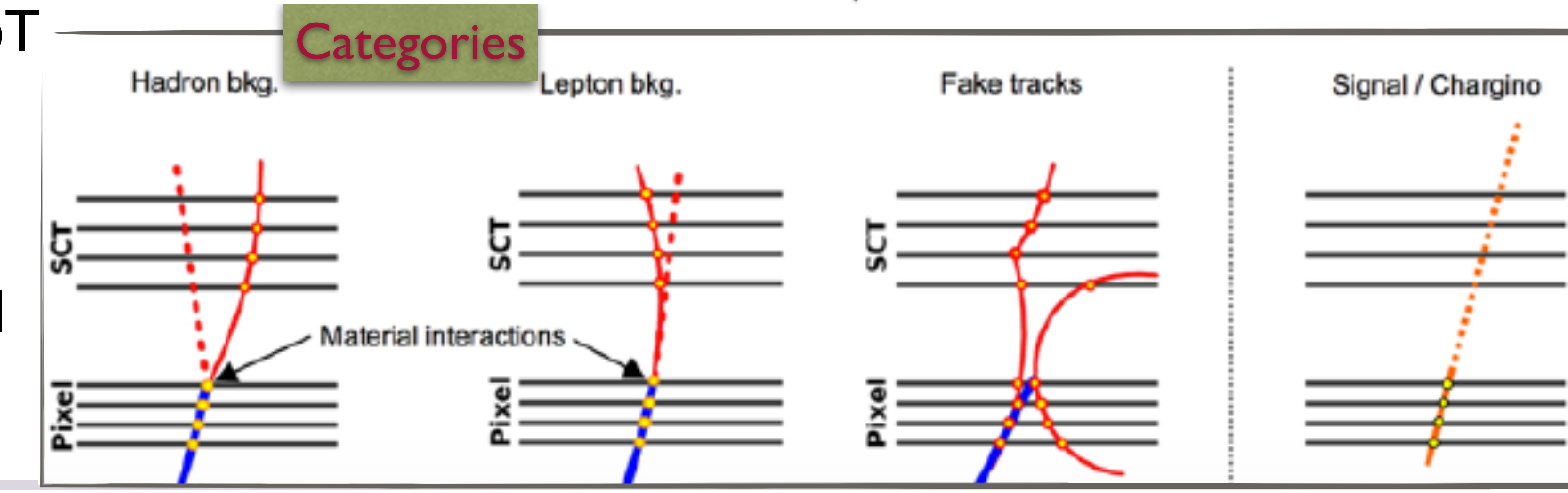
Hight MET, direct selection







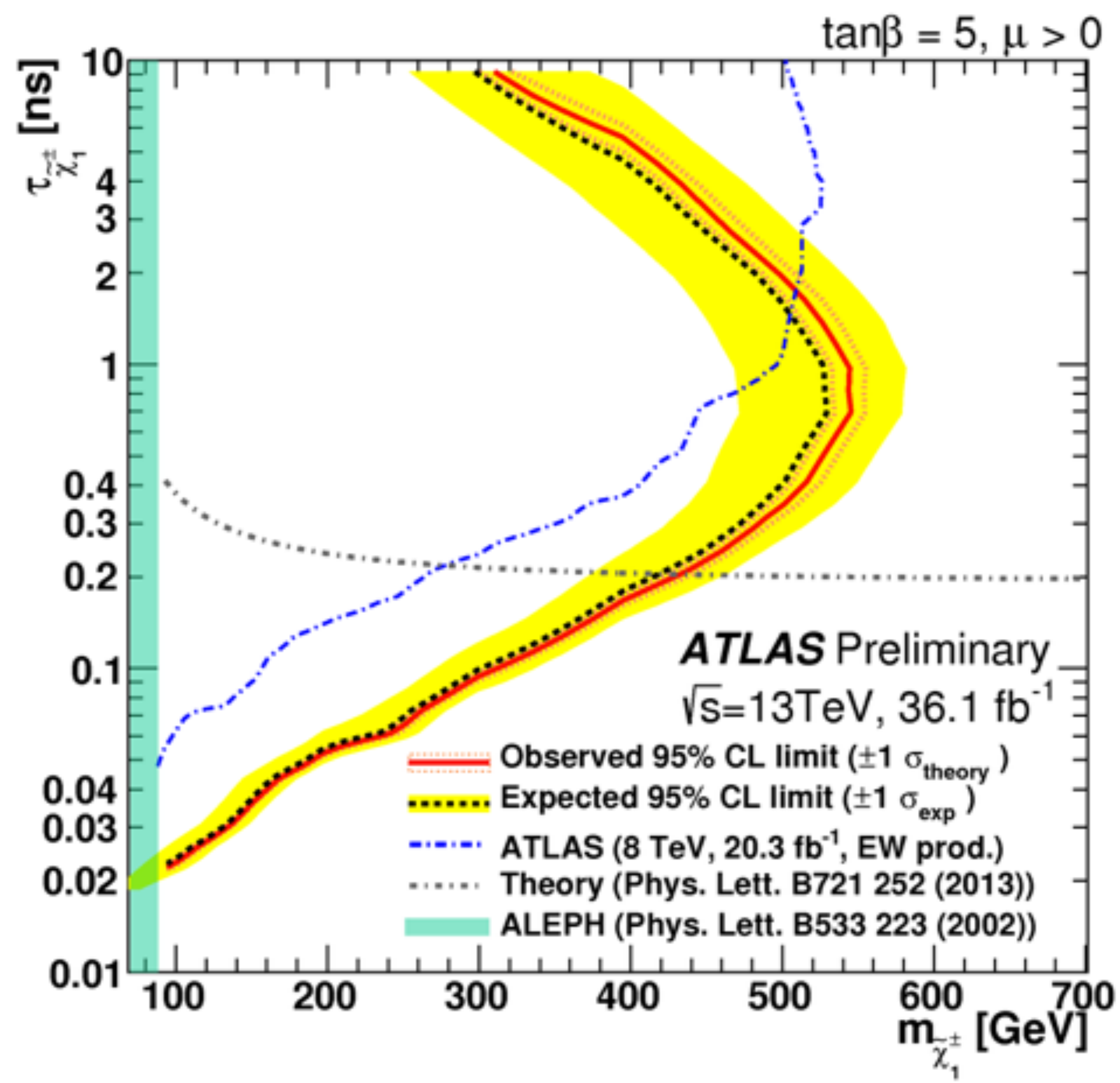
Categories



Results

No significant excess is observed

- Chargino mass in reference model excluded up to 430 GeV
- strong production limits in backup

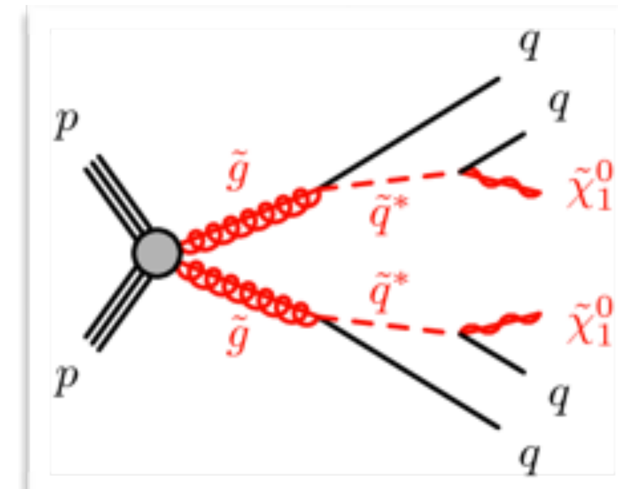


electroweak production channel in terms of the lifetimes and the masses of chargino

Displaced Vertices with MET

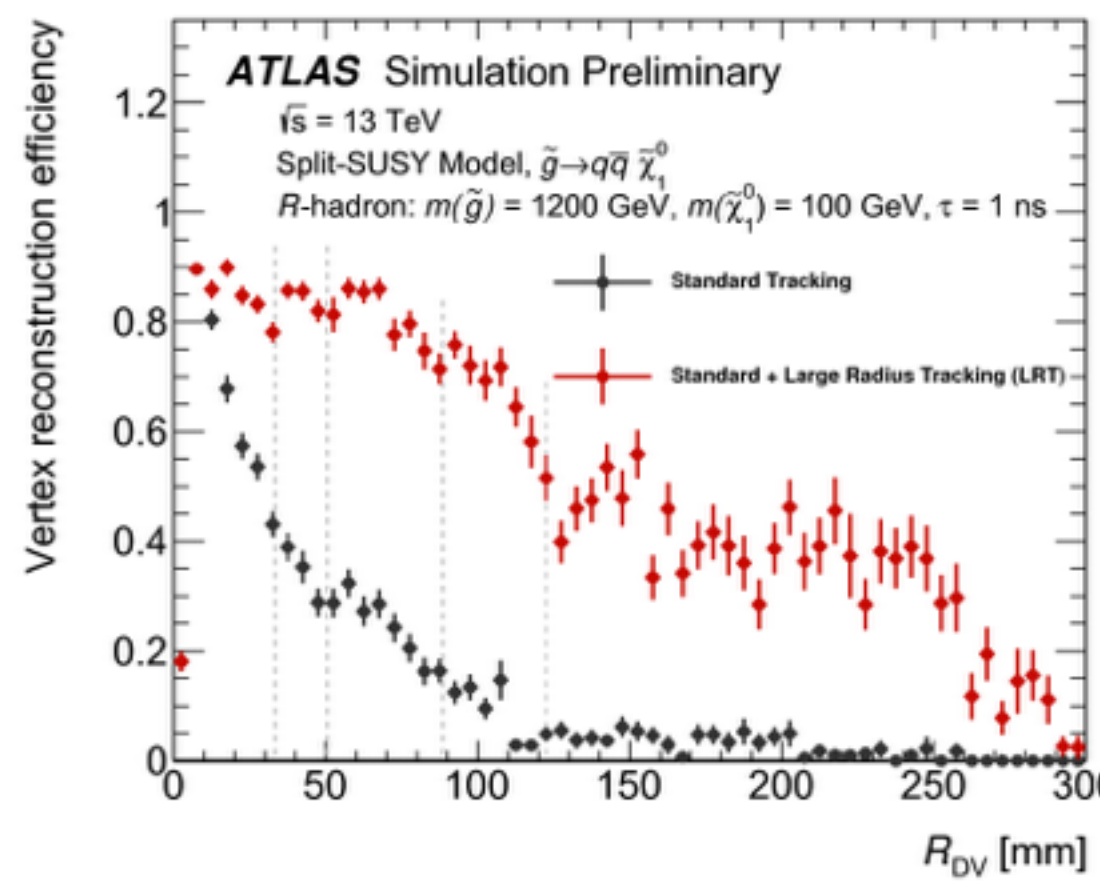
Search for displaced vertices decaying into the Inner Detector

- Predicted in few models of R-parity violation or split-SUSY
- Benchmark signal: gluino hadronizing into an R-hadron
- **Signature**: Displaced vertices + MET



Event Selection

- Rerun track and vertex reconstruction
- Backgrounds are instrumental and estimated from data
- High track multiplicity hadronic interactions
- DV in regions with high material density vetoed
- The remaining contribution extrapolated from low-mass vertexes
- Merged DV with low track multiplicity obtained by mixing vertices from different events
- Random large-angle track crossing are estimated by adding random tracks to an N-1 track template



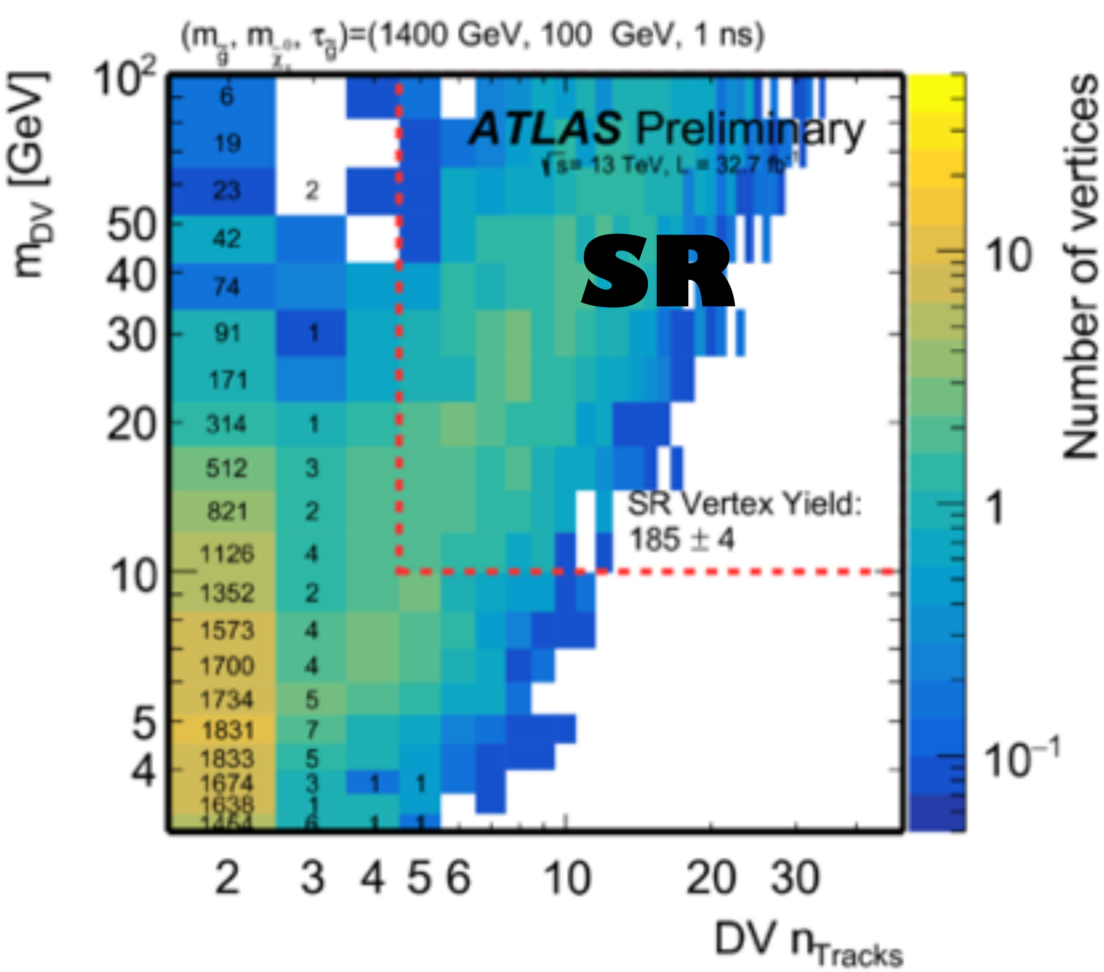
ATLAS-CONF-2017-026

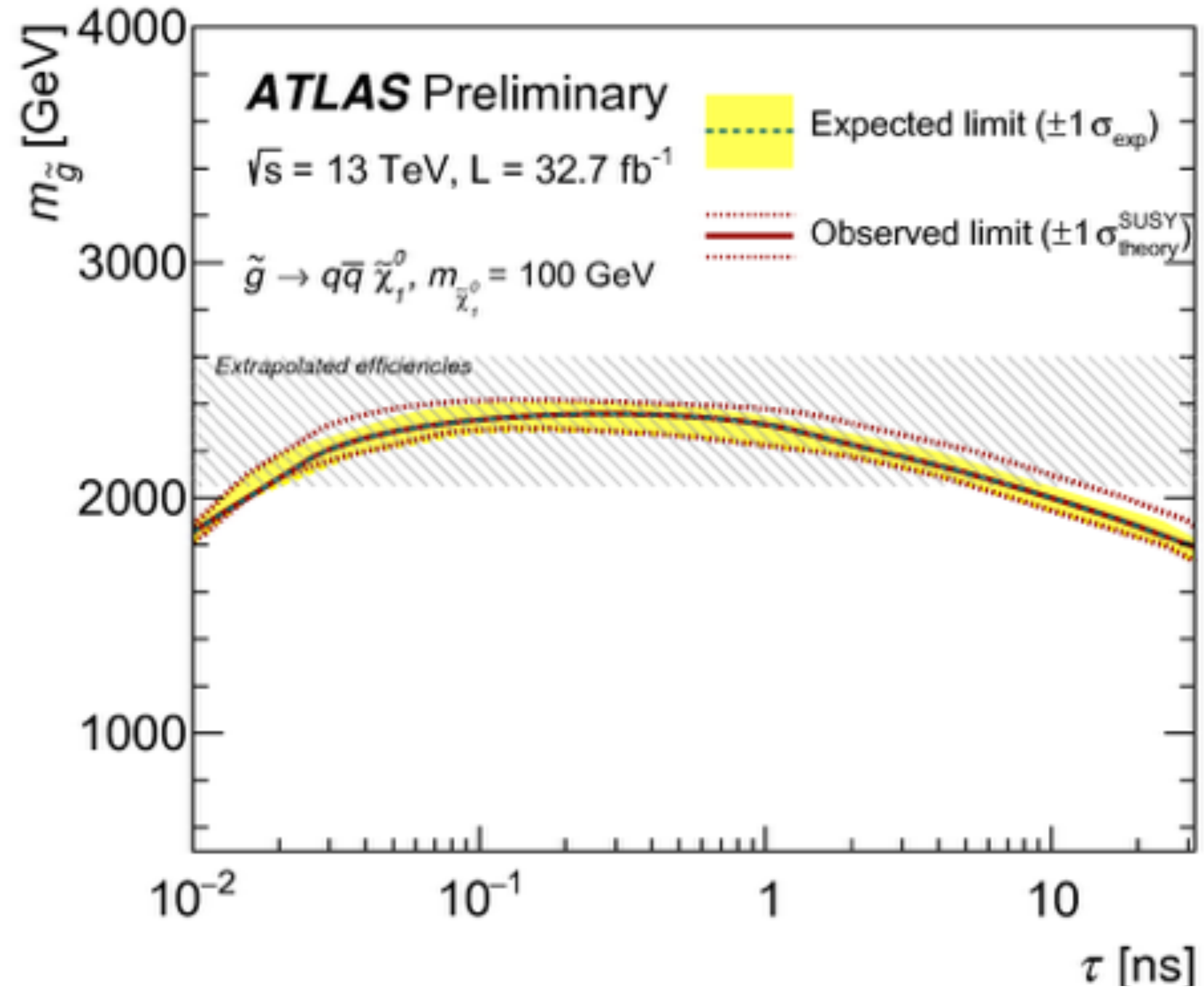
Results

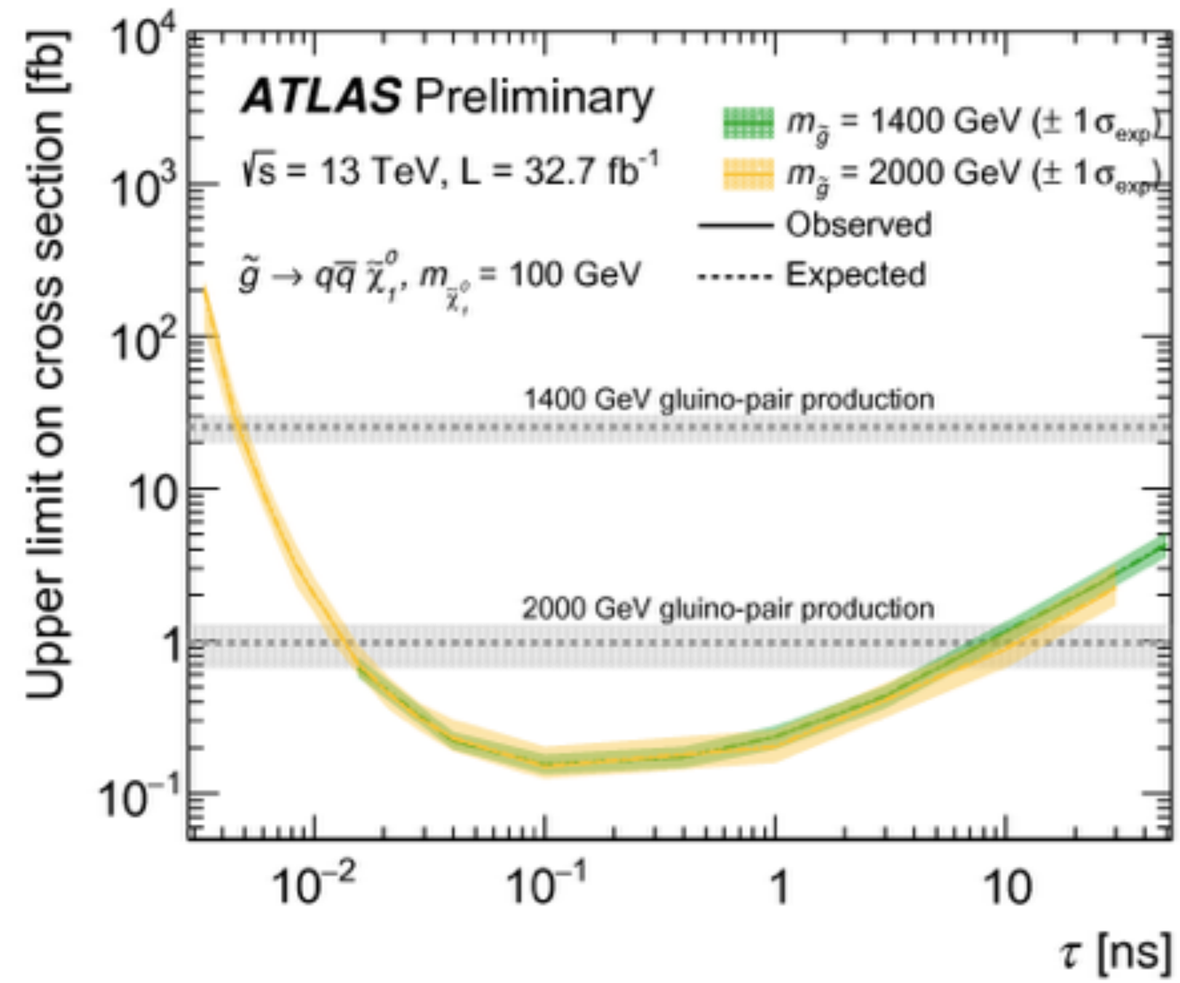
Bkg. estimate is validated in a number of signal depleted regions.
No event is observed in the SR, compatible with the bkg. expectation of 0.2±0.2 events.

Limits are set as on gluino R-hadrons as a function of masses and lifetime

For a lifetime of 1ns gluino masses up to 2.2 TeV are excluded

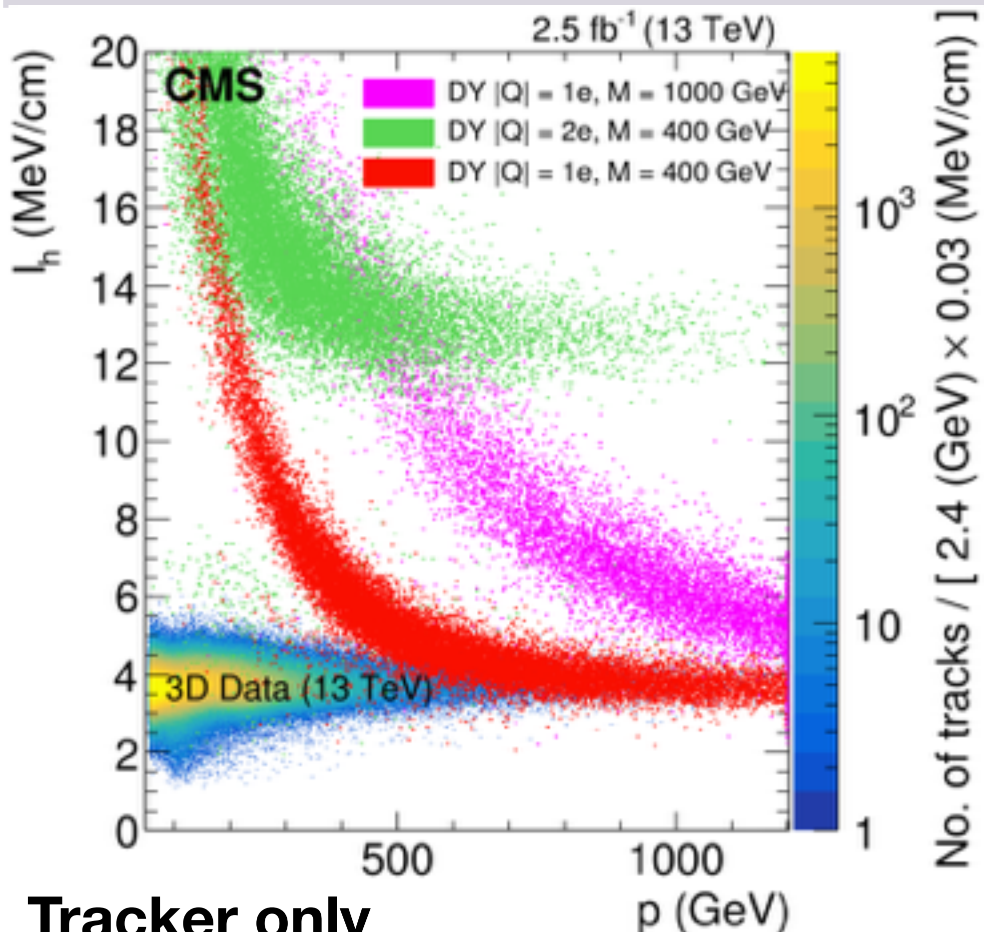






CMS-EXO-15-010 ; CERN-EP/2016-204

Heavy Stable Charged Particles (HSCP)



- Search for heavy stable charged particles produced in proton-proton collisions at $\sqrt{s}$= 13 TeV using the CMS detector.
  - Two complementary analyses were performed: using **only the tracker** and using both the **tracker and the muon system**.

Tracker only
- Sensitive to any HSCP produced prompt
- Uses dE/dX in tracker to separate signal from BKG

Muon Only
- Sensitive to any HSCP crossing muon detector
- Uses TOF to separate signal from BKG

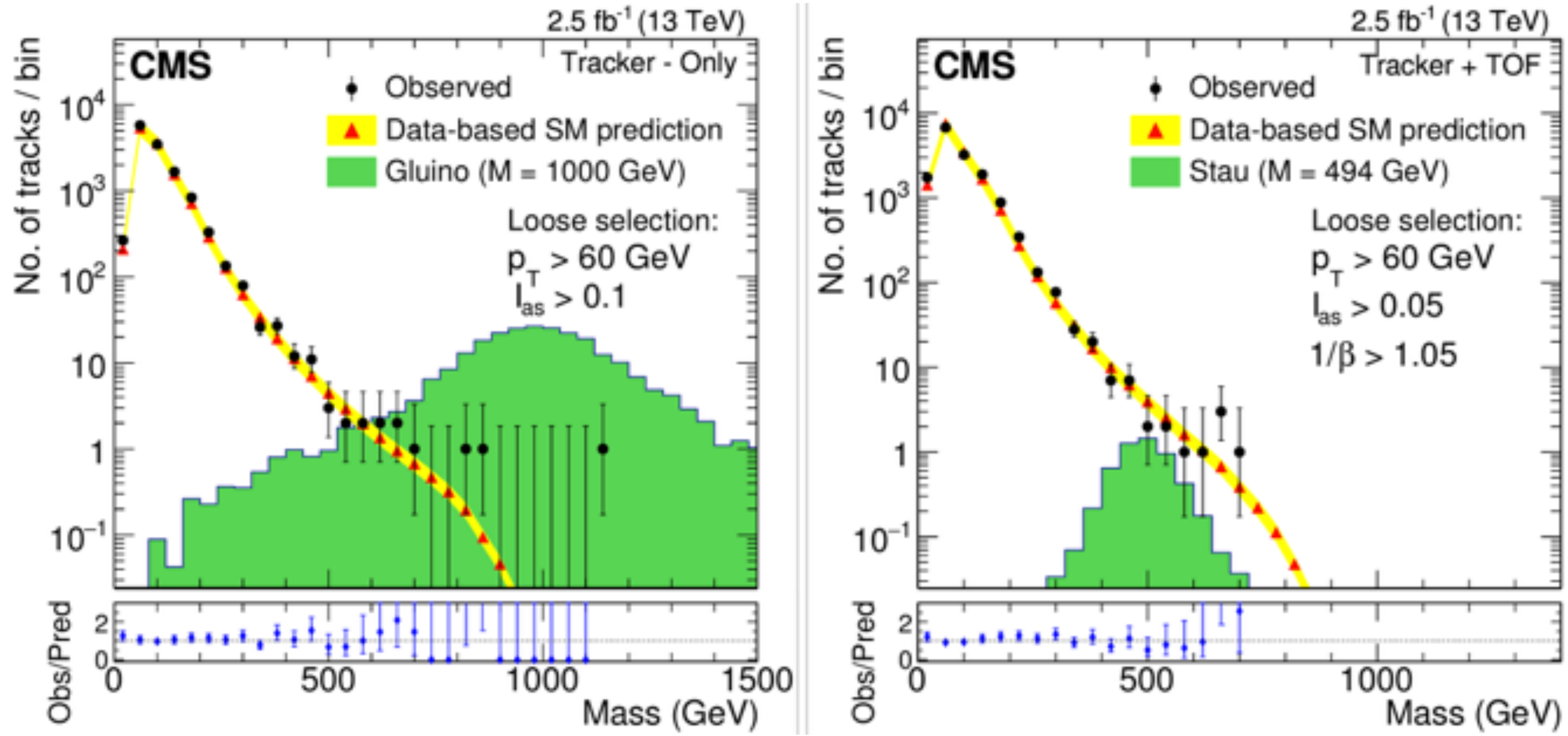
Tracker+TOF
- uses both (for HSCP crossing the detector)

	Selection requirements				Numbers of events $\sqrt{s}=13$ TeV	
	p_T (GeV)	I_{as}	$1/\beta$	Mass (GeV)	Pred.	Obs.
tracker-only	>65	>0.3	—	>0	28.7 ± 6.0	24
				>100	20.7 ± 4.4	15
				>200	3.8 ± 0.8	2
				>300	0.82 ± 0.18	0
				>400	0.25 ± 0.05	0
tracker+TOF	>65	>0.175	>1.250	>0	18.2 ± 3.7	14
				>100	5.4 ± 1.1	4
				>200	0.90 ± 0.19	0
				>300	0.06 ± 0.04	0

CMS-EXO-15-010 ; CERN-EP/2016-204

Analysis Selection

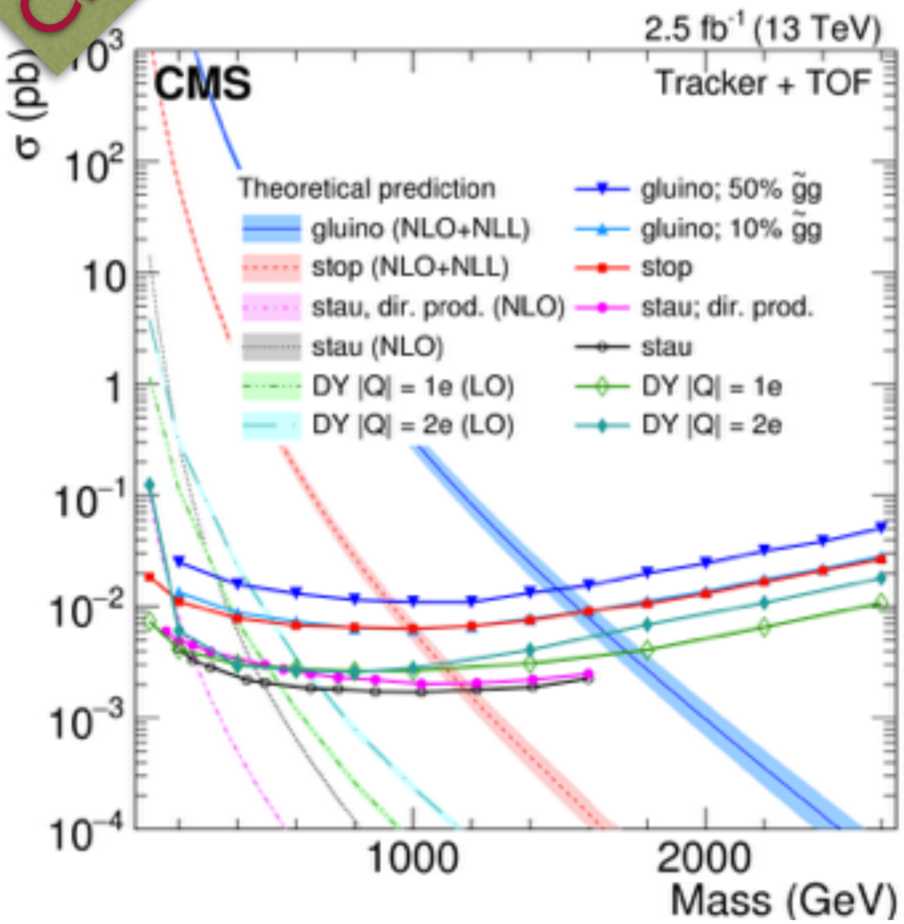
- **Selection**: muon and E_T^{Miss} Trigger.
  - Muon P_T > 50 GeV and E_T^{Miss} >170 GeV)
  - Quality on the tracks to reject SM background

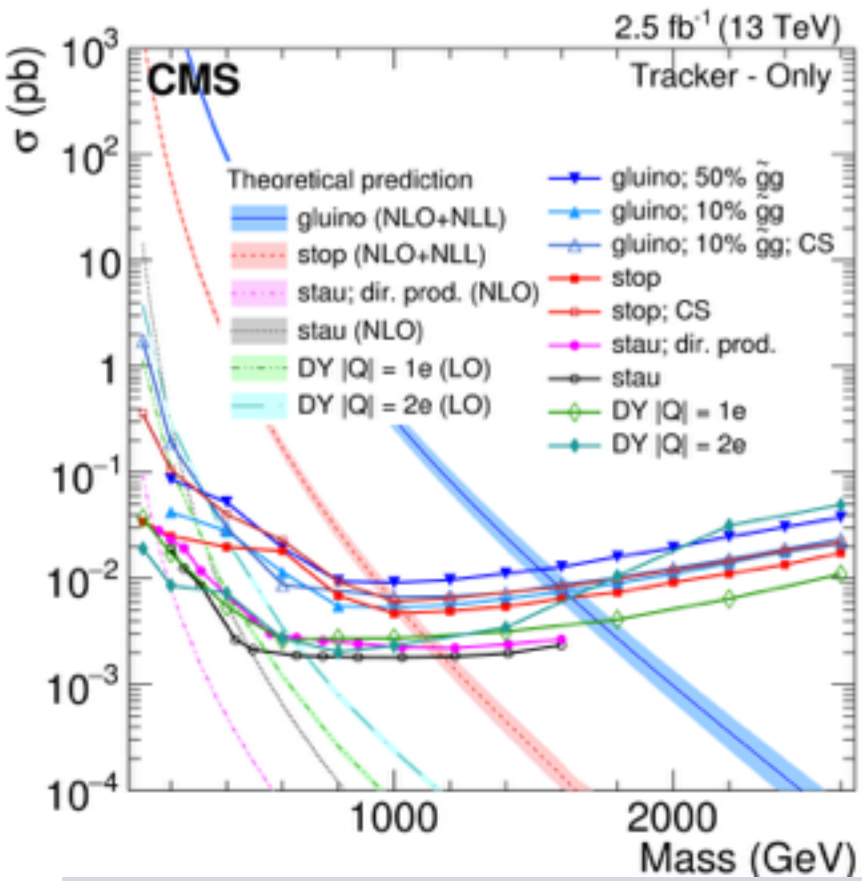


- For the reconstructed track, information about **dE/dx** can be gained from measurements of ionisation deposited in layers of the pixel and silicon tracker.
- **The time of flight to the muon system** can be used to discriminate between particles travelling at near the speed of light and slower candidate.

Source of systematic uncertainty	Relative uncertainty (%)	
Signal acceptance	*tracker-only*	*tracker+TOF*
- Trigger efficiency	13	13
- Track momentum scale	<20	<20
- Track reconstruction	<2	<2
- Ionization energy loss	<15	<15
- HIP background effect	<3	<4
- Time-of-flight	—	<5
- Muon reconstruction	—	2
- Pileup	<1	<1
Tot. uncert. in signal acceptance	<20	<25
Collision background uncert.	20	20
Luminosity uncertainty	2.7	2.7

Results of the HSCP





- **Results of the HSCP search as the cross section upper limits at 95% CL for various signal models**
- **Set mass limits for long-lived gluinos, top squarks, tau sleptons, and multiply charged particles**

Model	analysis used	$\sqrt{s} = 7+8$ TeV	$\sqrt{s} = 13$ TeV
Gluino $f = 0.1$	*tracker-only*	$M > 1320$ GeV	$M > 1610$ GeV
	tracker+TOF	$M > 1290$ GeV	$M > 1580$ GeV
Gluino $f = 0.1$ CS	*tracker-only*	$M > 1230$ GeV	$M > 1580$ GeV
Gluino $f = 0.5$	*tracker-only*	$M > 1250$ GeV	$M > 1520$ GeV
	tracker+TOF	$M > 1220$ GeV	$M > 1490$ GeV
Gluino $f = 0.5$ CS	*tracker-only*	$M > 1150$ GeV	$M > 1540$ GeV
Top squark	*tracker-only*	$M > 930$ GeV	$M > 1040$ GeV
	tracker+TOF	$M > 910$ GeV	$M > 990$ GeV
Top squark CS	*tracker-only*	$M > 810$ GeV	$M > 1000$ GeV
GMSB tau slepton	*tracker+TOF*	$M > 430$ GeV	$M > 490$ GeV
	tracker-only	$M > 389$ GeV	$M > 480$ GeV
Pair prod. tau slepton	*tracker+TOF*	$M > 330$ GeV	$M > 240$ GeV
	tracker-only	$M > 180$ GeV	—
DY $\lvert Q \rvert = 1e$	*tracker-only*	$M > 640$ GeV	$M > 510$ GeV
	tracker+TOF	$M > 650$ GeV	$M > 550$ GeV
DY $\lvert Q \rvert = 2e$	*multiply charged*	$M > 720$ GeV	—
	tracker-only	$M > 520$ GeV	$M > 680$ GeV
	tracker+TOF	$M > 520$ GeV	$M > 660$ GeV

ATLAS

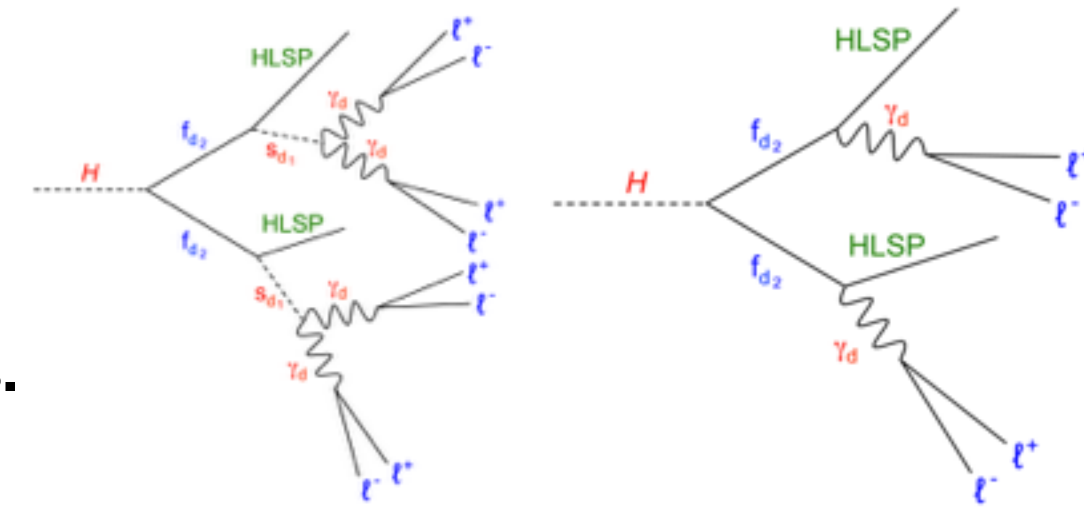
ATLAS-CONF-2016-042

Displaced Leptonic Jets (LJ)

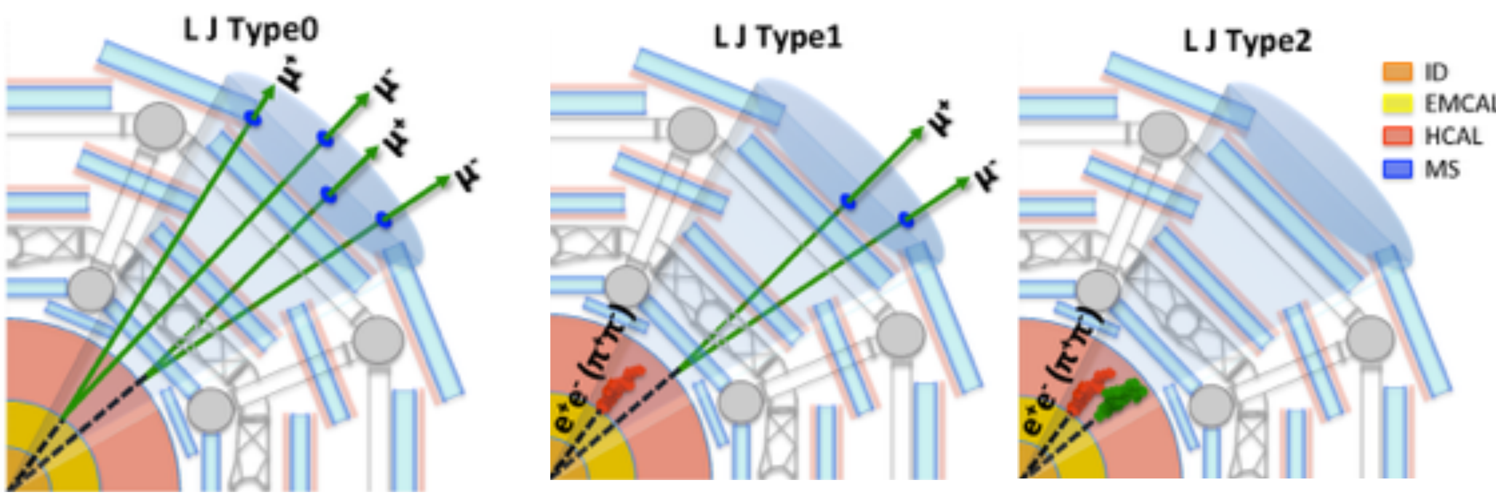
Search for long-lived neutral particles decaying into **collimated jets of light leptons and mesons, so-called "lepton-jets".**

Benchmark models predicting Higgs boson or heavy scalar particle decays to neutral long-lived particles (dark photons $\gamma_d\gamma_d$), which in turn produce lepton-jets.

The dark photons and two LJs are expected to be produced back-to-back in the azimuthal plane.

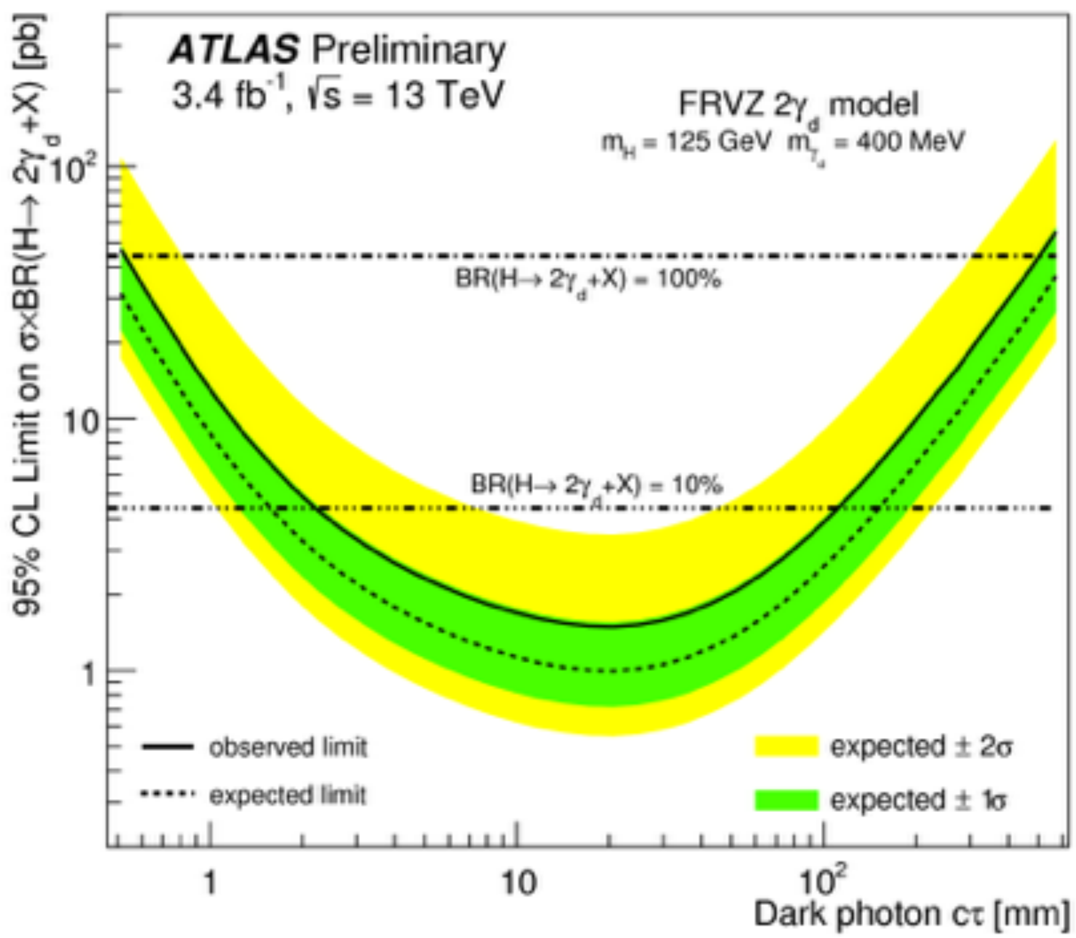


Three Topologies:
Type0 LJ is composed of only muons.
Type1 LJ is composed of muons and a jet.
Type2 LJ is composed of only jets.

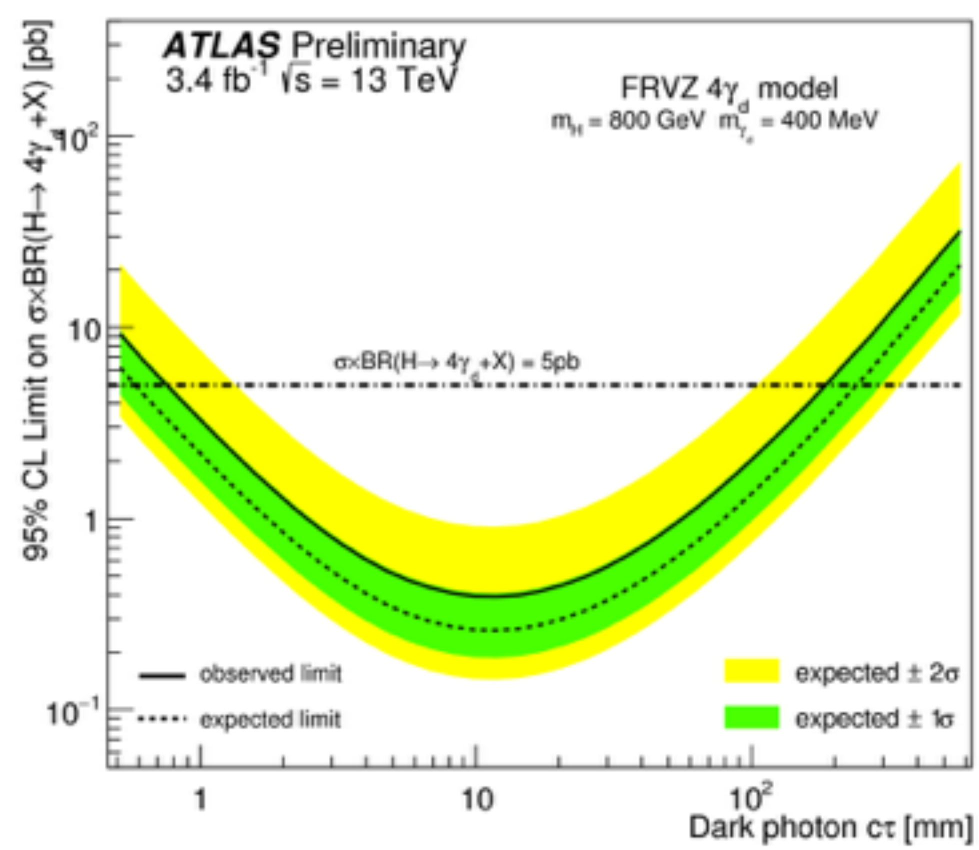


- **Selection**: dedicated trigger to select these states. Different selections depending on the LJ type.
  - **Collimated final-state particles difficult to reconstruct** (detector granularity)
  - **Tracks with displaced decay vertices difficult to reconstruct** (no primary vertex constraint)
- **Background**: Cosmics events (impact parameter and timing as discriminating variables), machine background, QCD jets (ABCD method)
- **Main Uncertainty**:Trigger, reconstruction efficiency

Limits on LJ searches



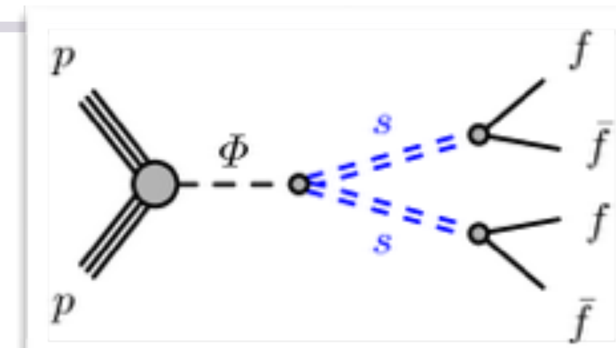
- The 95% upper limits on the σ×BR for the FRVZ 125 GeV Higgs and heavy scalar of 800 GeV.
  - Higgs → 2γd+X and Higgs → 4γd+X benchmark models as a function of the γ_d lifetime (c τ).

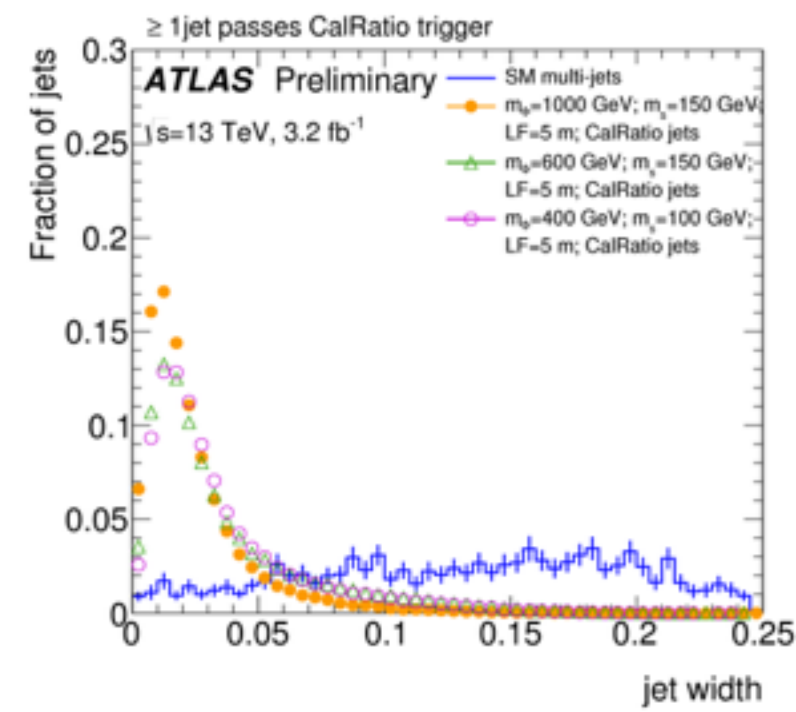


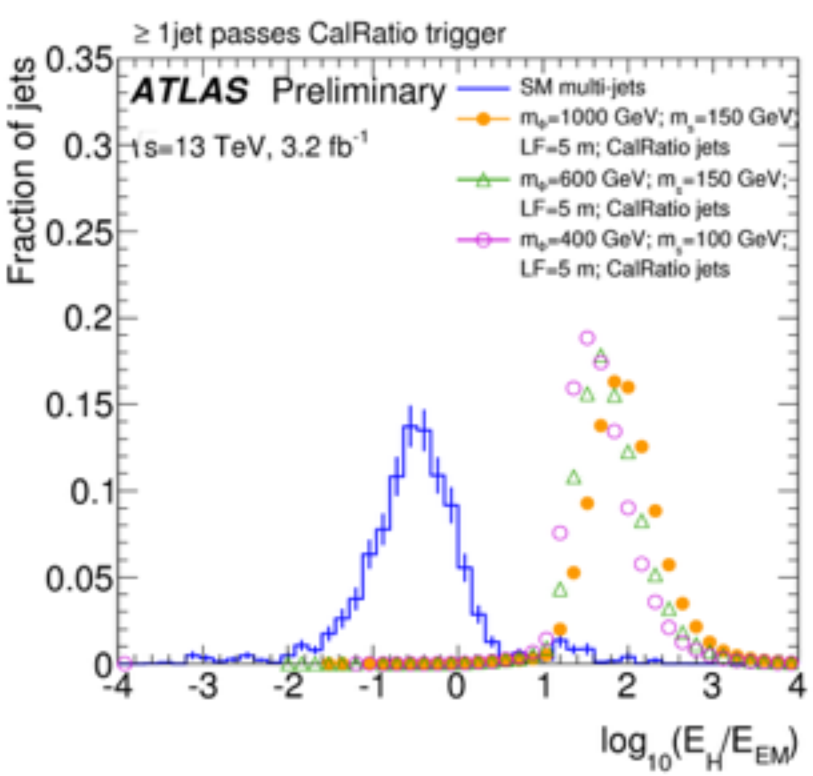
FRVZ model	m_H (GeV)	Excluded $c\tau$ [mm]
Higgs $\rightarrow 2\gamma_d + X$	125	$2.2 \leq c\tau \leq 111.3$
Higgs $\rightarrow 4\gamma_d + X$	800	$3.8 \leq c\tau \leq 163.0$
Higgs $\rightarrow 2\gamma_d + X$	125	$0.6 \leq c\tau \leq 63$
Higgs $\rightarrow 4\gamma_d + X$	800	$0.8 \leq c\tau \leq 186$

Displaced Jets Topology

- **Search for neutral, long-lived particles produced from heavy-scalar decays decaying into displaced fermions.**
- A schematic showing the $\Phi \rightarrow ss$ decay used as the benchmark model. Due to their Yukawa coupling with the Φ, the s decay primarily to heavy fermion pairs (Hidden Valley Models).
- This analysis explores signature, where **a neutral LLP decaying in the hadronic calorimeter.** This would yield to an atypical jet with no tracks in the inner tracker and would deposit no energy in the electromagnetic calorimeter



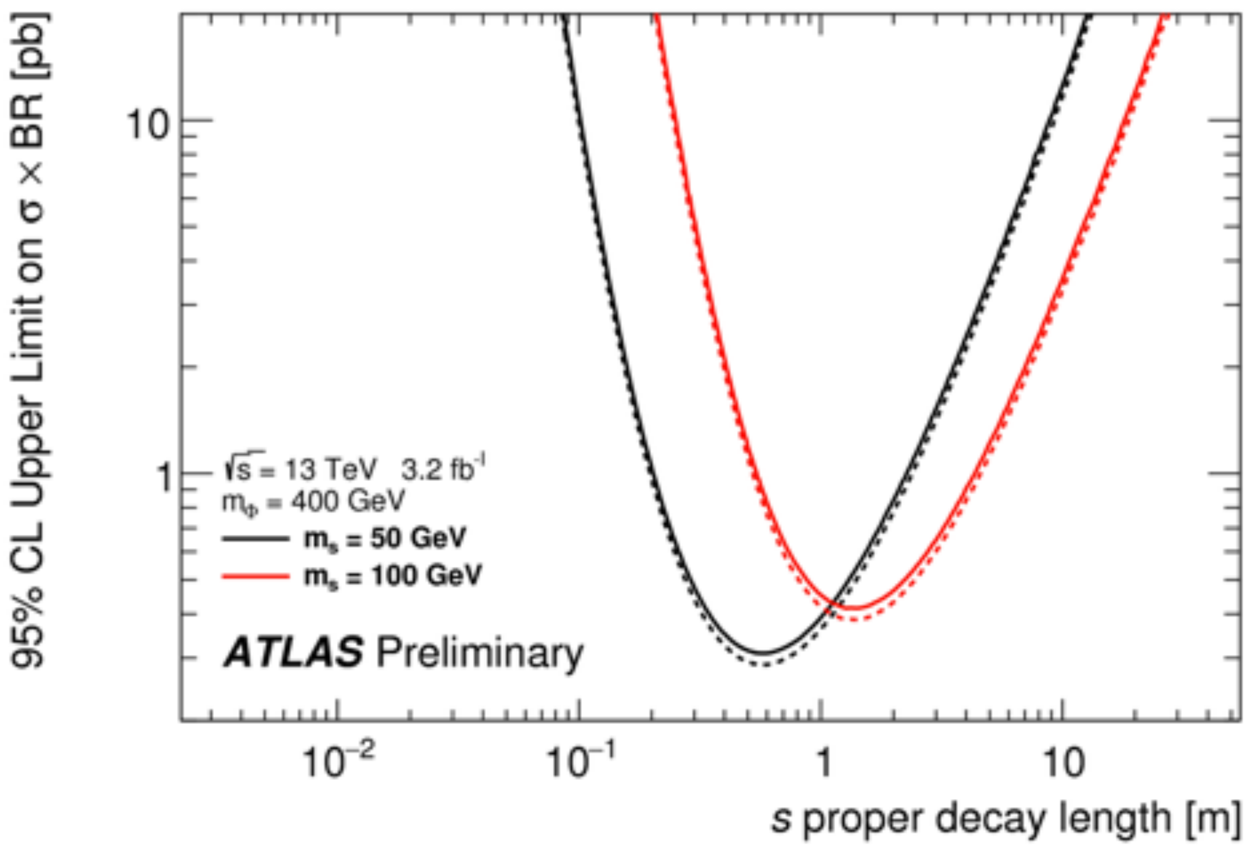


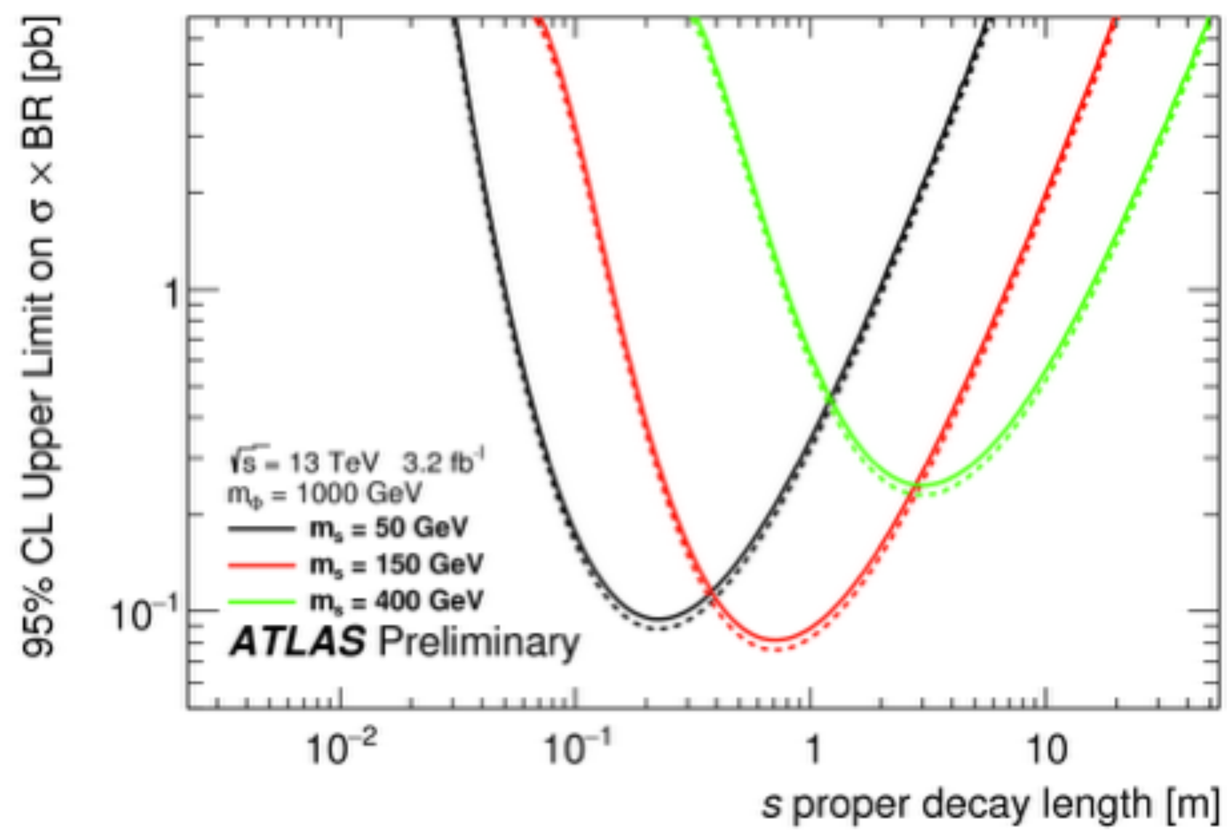


- **Dedicated trigger**
- **BDT to improve the identification of displaced jets.**
- **Background**: Cosmics events (impact parameter and timing as discriminating variables), machine background, QCD jets (ABCD method)
- **Main Uncertainty**: Trigger, JES

Excluding Limits

- The observed 95% CL upper limits on the σ × BR for the signal samples with different ϕ and s masses

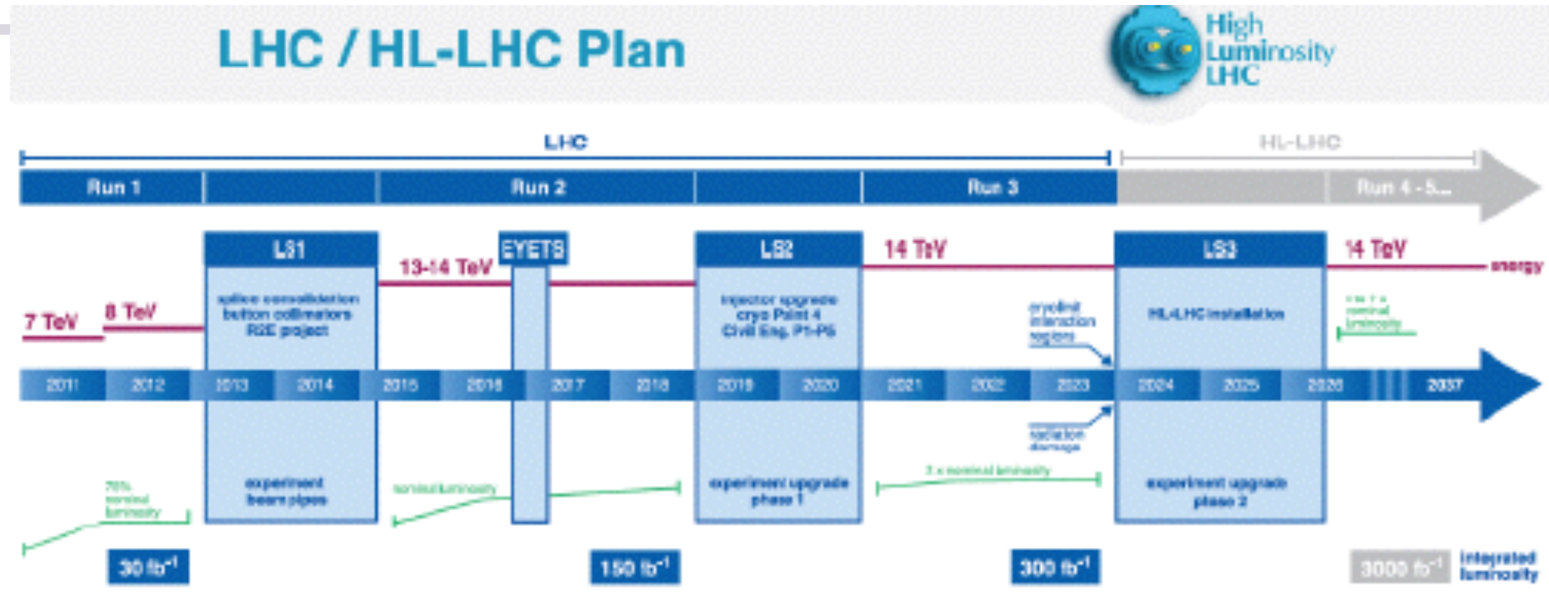




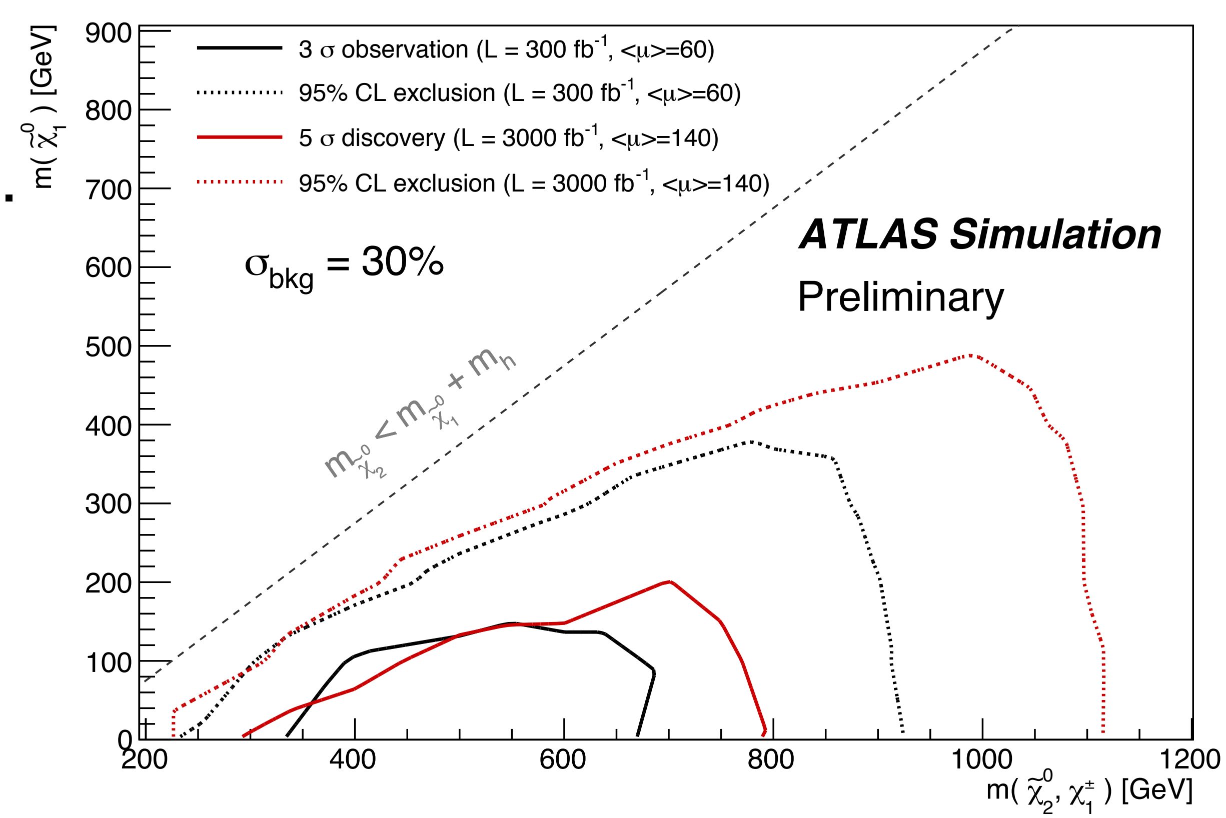
	$m_s = 50\ GeV$	$m_s = 100\ GeV$	$m_s = 150\ GeV$	$m_s = 400\ GeV$
	Decay length range excluded at 95% CL for $\sigma\times$ BR = 1 pb			
$m_\Phi = 400\ GeV$	(0.20, 2.4) m	(0.52, 4.6) m	–	–
$m_\Phi = 600\ GeV$	(0.09, 2.7) m	–	(0.38, 8.2) m	–
$m_\Phi = 1\ \text{TeV}$	(0.05, 2.0) m	–	(0.14, 7.2) m	(0.78, 16) m

A window to the Future: HL-LHC

The target integrated luminosity for the HL-LHC program is about 3000 fb^{-1}. An ultimate performance of the accelerator along with upgrade on the detector layout.



- **Scoping Document**: few BSM studies have been already explored at HL-LHC.
  - Search for **charginos and neutralinos** in final states with one lepton and two b-jets.
  - **Resonant Higgs boson pair** production in the $bb\bar{b}\bar{b}$ final state. Cross-section limit improved by a factor 2.
  - **Dijet resonance** searches:
    - q* from 4 TeV to 8 TeV
    - QBH from 5 TeV to 10 TeV
  - Soon long-lived particles results.



Conclusions

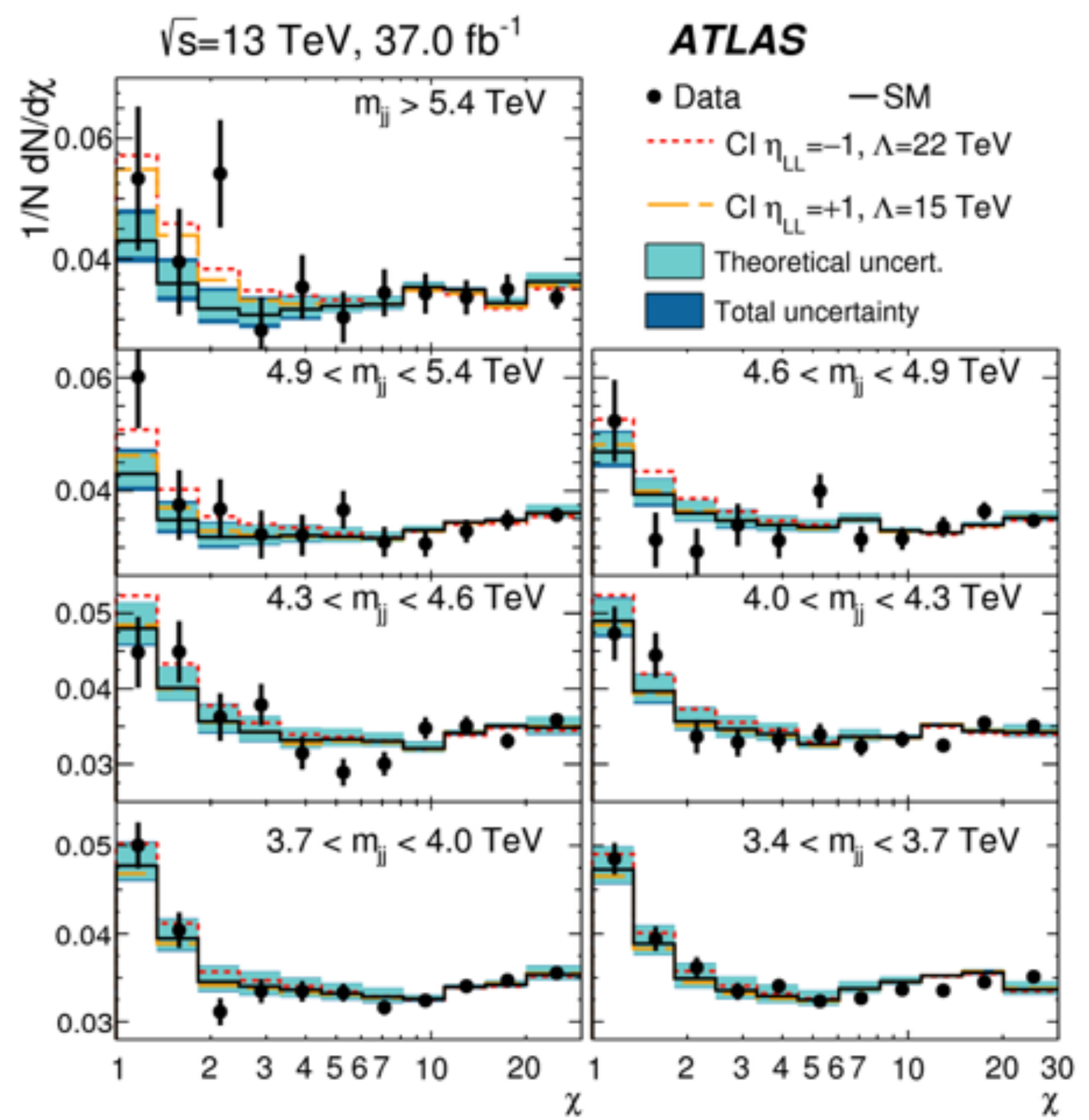
- **Presented new results using the full 13 TeV dataset collected so far**
  - Large increase in sensitivity from the Run 1 results
  - But no significant deviation observed yet
- **Di-jets and multi jets final states:**
  - limits on resonances masses between 3.4 and 8.9 TeV
  - contact interactions scale $\Lambda > 13$ - 29 TeV
  - limits of gluinos masses.
- **Disappearing Tracks**
  - a lifetime of 1ns gluino masses up to 2.2 TeV are excluded.
  - strong production reaching 1.4 (1.1) TeV in chargino mass for lifetimes of 1.0 (0.2) ns
- **HSMP states:**
  - Set mass limits for long-lived gluinos, top squarks, tau sleptons, and multiply charged particles
- **Displaced jets and lepton-jets final states (new results by summer):**
  - limits on the $\sigma \times$ BR for the signal different mediator masses and life time of gamma dark (exclusion up to few meters from interaction point)

- **Exploitation of the 13 TeV dataset has just started, can still hope for surprises**

BACK UP

Di-jets angular distribution

- **Di-jets final states: looking at the angular distribution.**
- **Event Selection:** single jet trigger, rapidity and di-jets mass cut
  - Single jet trigger $p_T > 380$ GeV,
  - $p_{T\mathrm{lead(sub)}} > 440(60)$ GeV
  - $y^* < 1.7$, $y_B < 1.1$, $m_{jj} > 2.5$ TeV,
  - y_B semi-sum of rapidities
- **Background**: QCD described by MC, normalized to data in each mjj bin
- **Dominant Uncertainty:** Jet energy scale (exp) and renormalization/ factorization scales (theory)



$$L_{qq} = \frac{2\pi}{\Lambda^2}\left[\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_R\gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_L\gamma_\mu q_L)\right],$$

$$\eta_{LL} = \pm 1,\ \eta_{RR} = \eta_{RRL} = 0$$

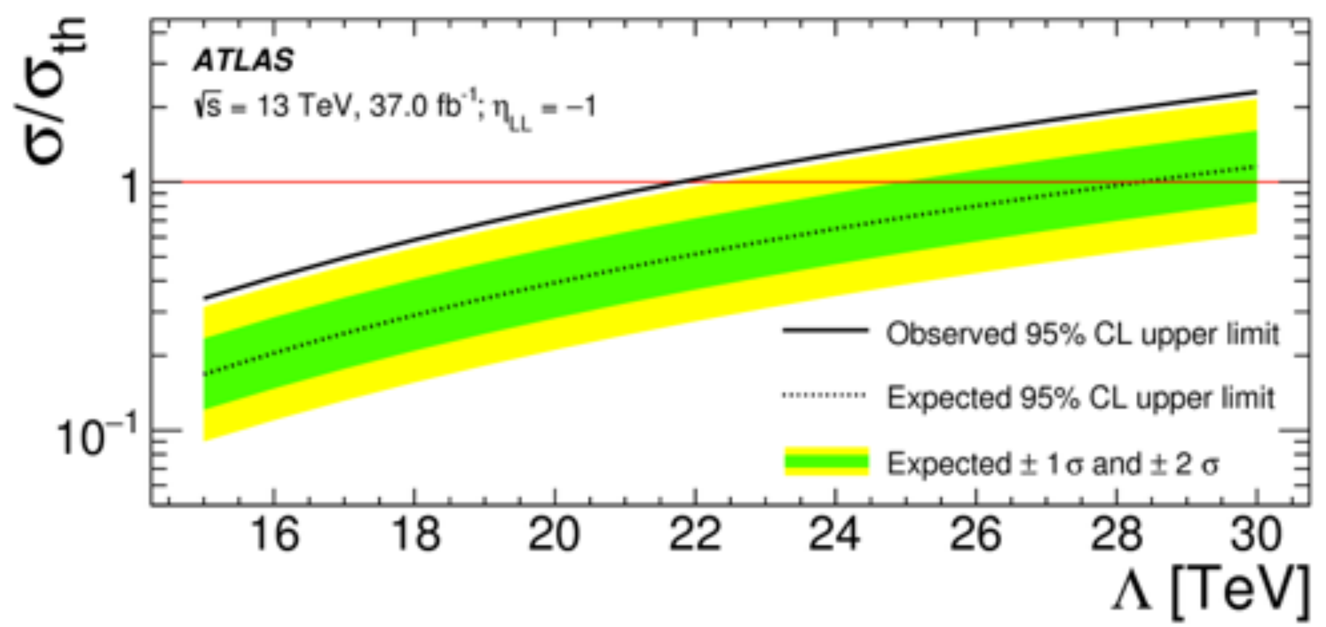
Contact Interaction Model

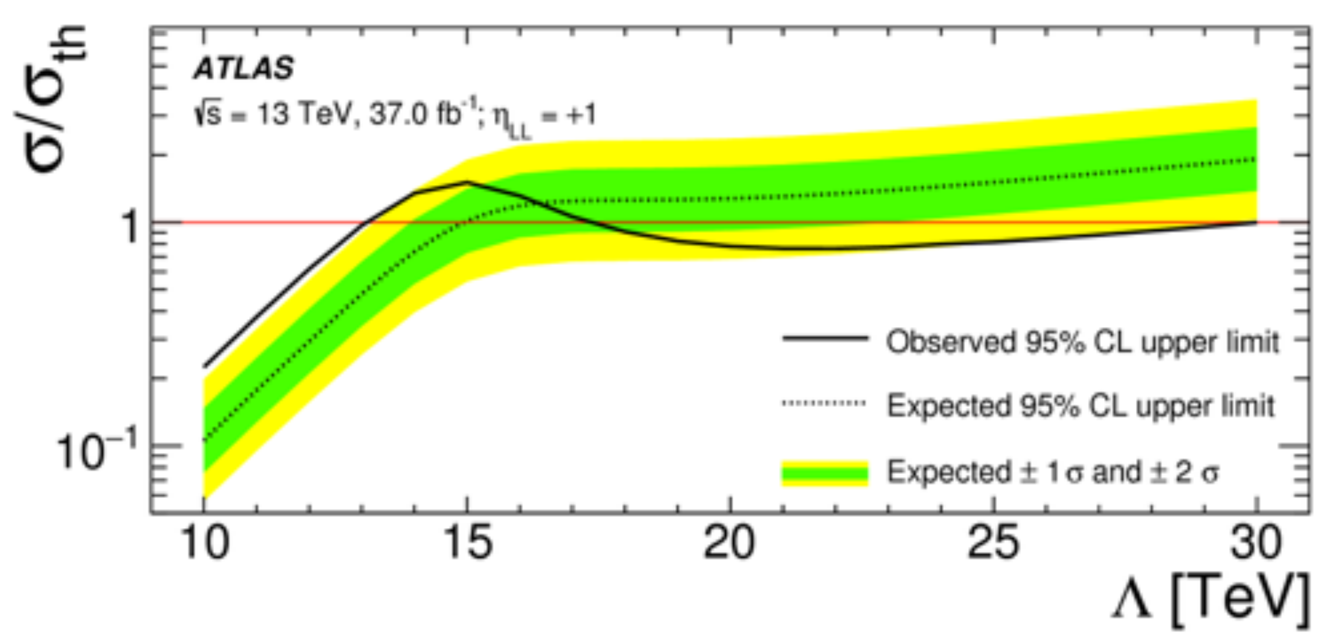
$$\chi = e^{y^*} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

Exclusion Limit on Contact interactions

- Ratio σ/σth of the observed and expected 95% CL upper limits on the cross-section in the contact interaction model to the predicted cross-section as a function of the compositeness scale Λ
  - for constructive (top) and destructive (bottom) interference with QCD processes

Model	95% CL exclusion limit	
	Observed	Expected
Quantum black hole	8.9 TeV	8.9 TeV
W'	3.6 TeV	3.7 TeV
W^*	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
Excited quark	6.0 TeV	5.8 TeV
Z' ($g_q = 0.1$)	2.1 TeV	2.1 TeV
Z' ($g_q = 0.2$)	2.9 TeV	3.3 TeV
Contact interaction ($\eta_{LL} = -1$)	21.8 TeV	28.3 TeV
Contact interaction ($\eta_{LL} = +1$)	13.1 TeV 17.4 TeV – 29.5 TeV	15.0 TeV

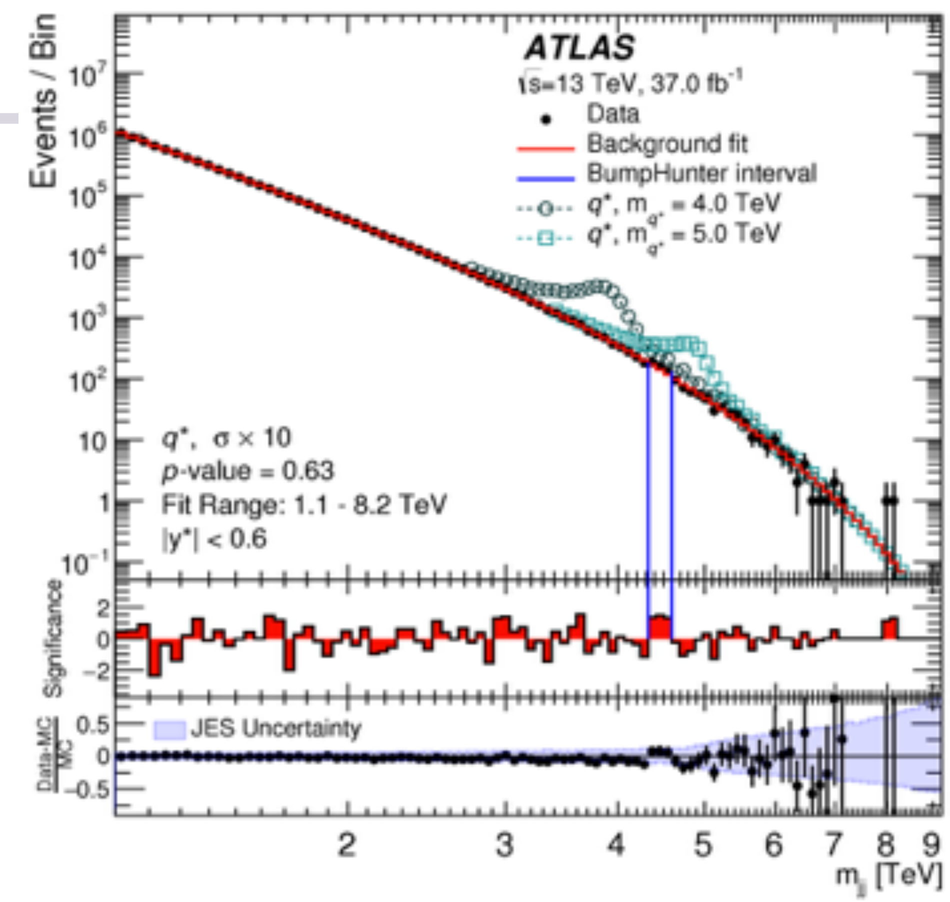


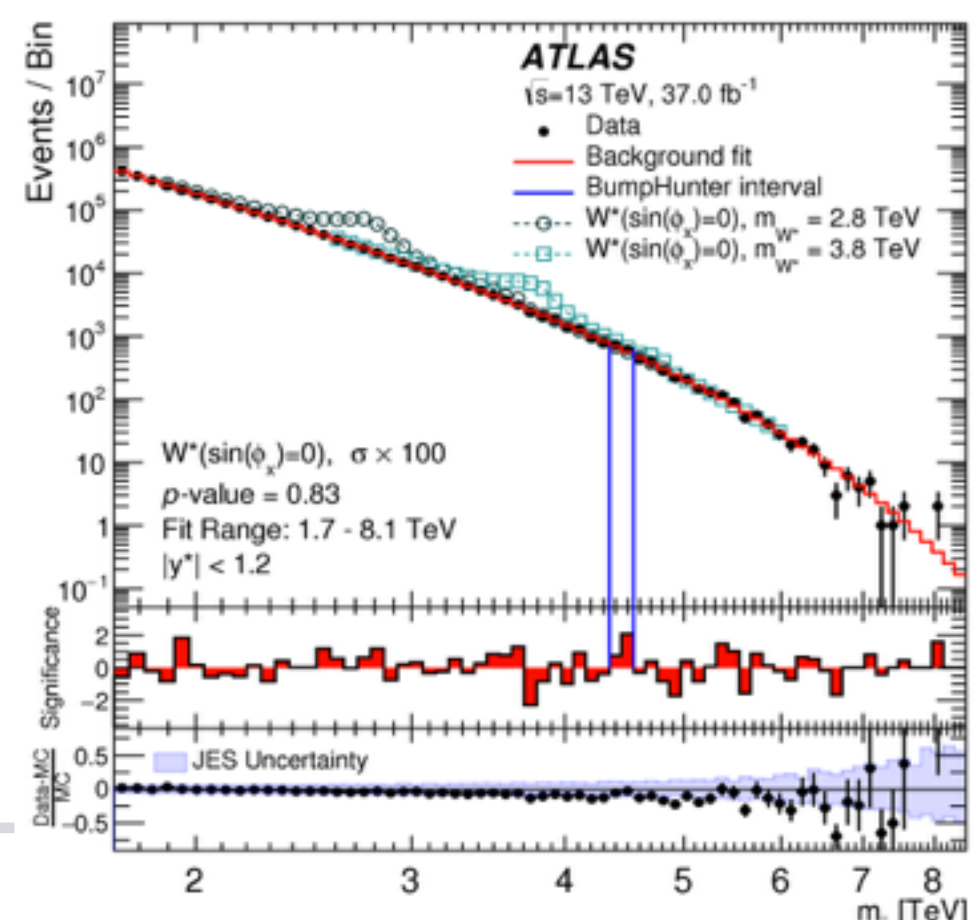


Negative (positive) interference of signal model $\eta_{LL} = +1(-1)$ with SM QCD

Resonance in di-jets

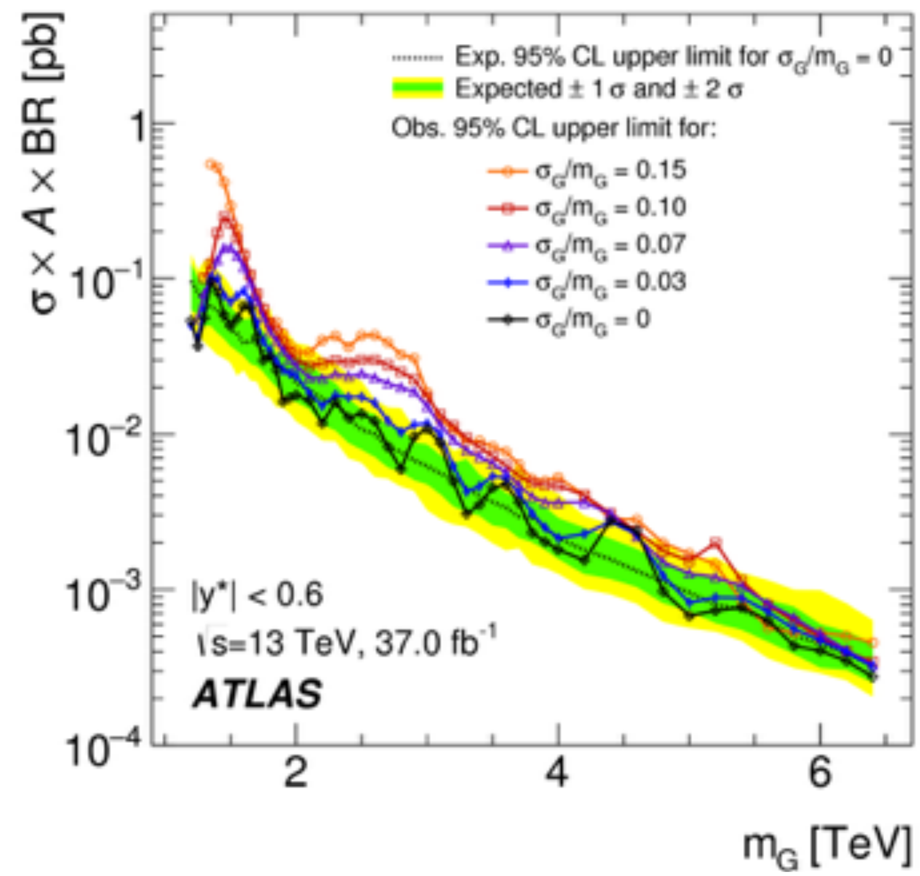
- **Di-jets final states: looking at the invariant mass.**
  - **Event Selection**
    - Single jet trigger pT > 380 GeV
    - $p_{T\ lead(sub)} > 440\ (60)$ GeV
    - To suppress t-channel scattering:
      - $y^* < 0.6(1.2)$, $y^* = |\ y_{lead} - y_{sublead}\ |\ /\ 2$
      - $m_{jj} > 1.1(1.7)$ TeV (for W*)
      - fully efficient trigger selection
  - **Smooth QCD background from a Sliding Window Fit**
  - **BumpHunter algorithm to scan for excesses**
    - Most discrepant interval: 4326 – 4595 GeV
    - global significance of 0.63 (0.83 for W*)





Results: Resonance di-jets

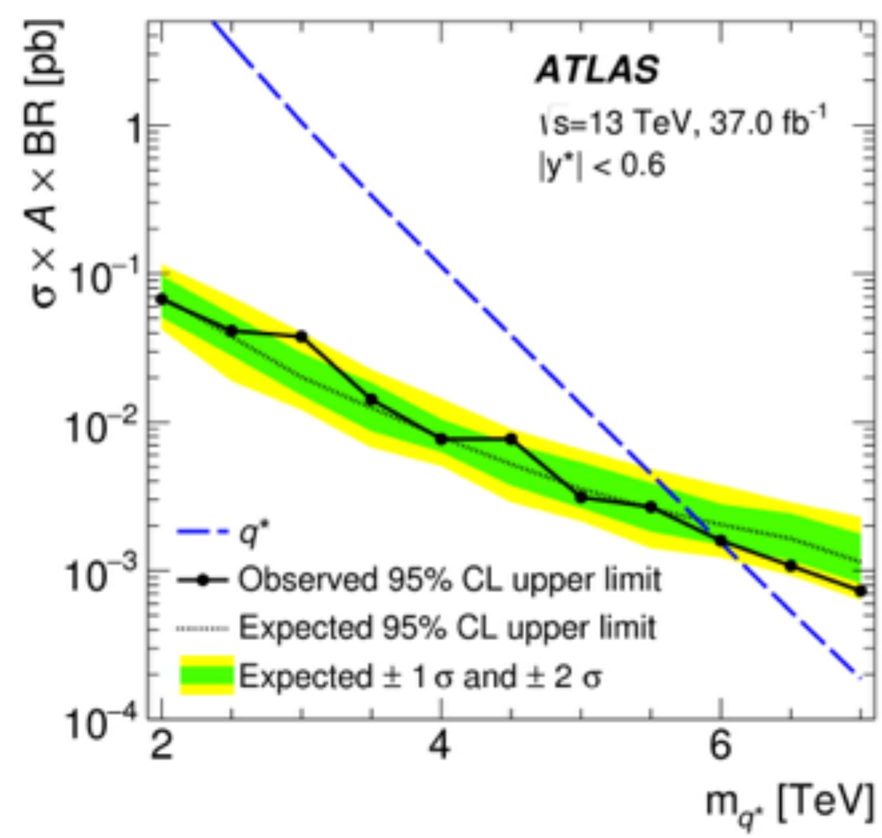
95 %CL exclusion limit		
Model	Observed	Expected
Quantum Black Hole, ADD	8.9 TeV	8.9 TeV
Excited quark	6.0 TeV	5.8 TeV
W’	3.7 TeV	3.7 TeV
W*	3.4 TeV, 3.8-3.9 TeV	3.6 TeV



Improved limits from 7% to 40% wrt analysis based on 3.2 fb^{-1}

Limits on generic Gaussian signals can be re-interpreted with various signal models

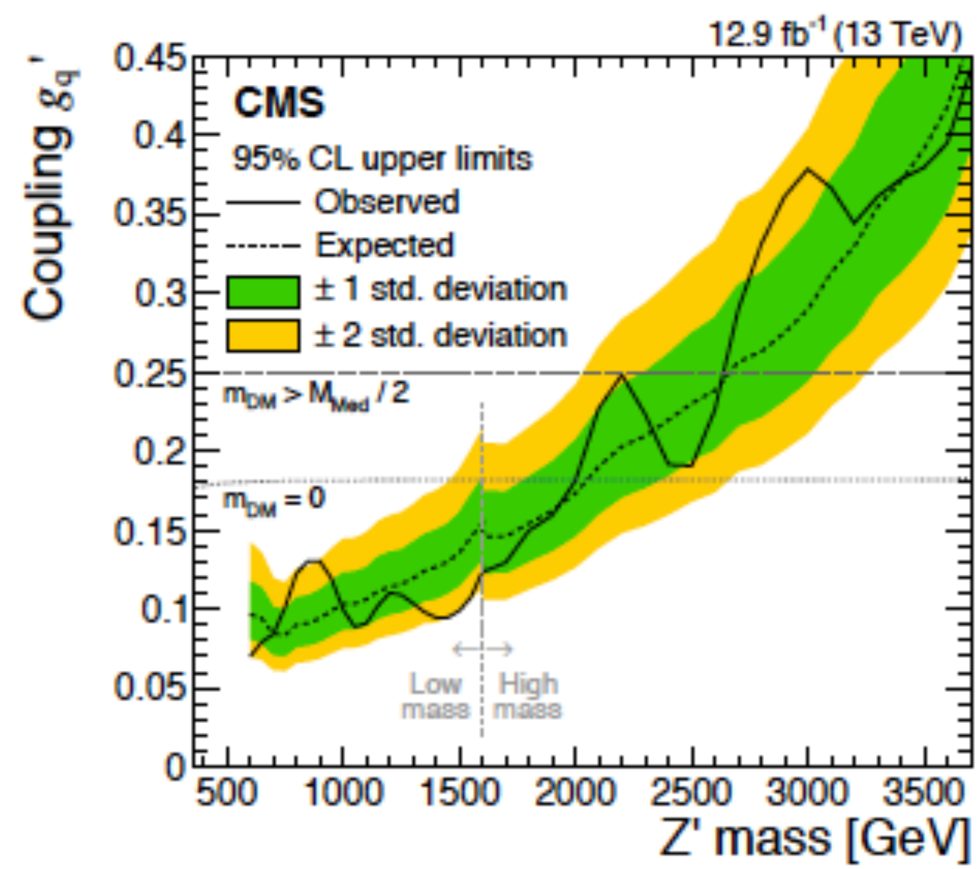
- MC-based folding methods to factorize physics & detector effects
- Excluded at 95% CL effective cross-sections from 20–50 fb at m_G < 2 TeV to 0.2-0.4 fb for m_G>6 TeV



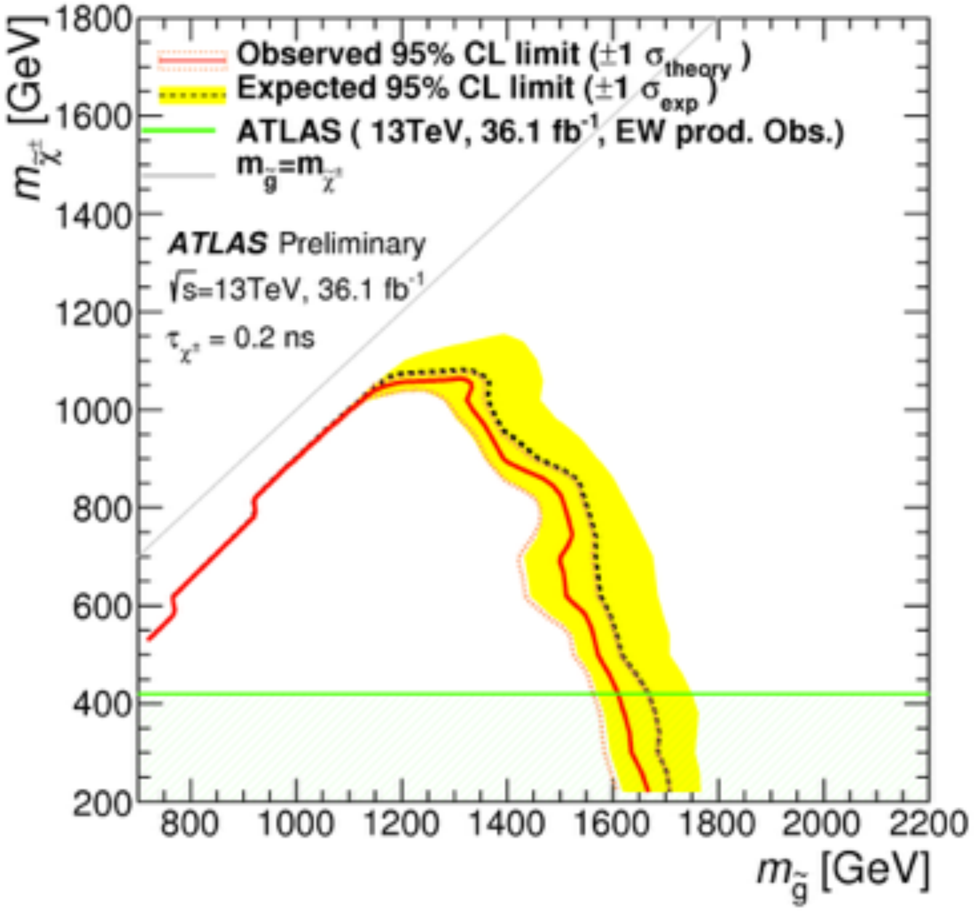
Results: Search in di-jets @ CMS

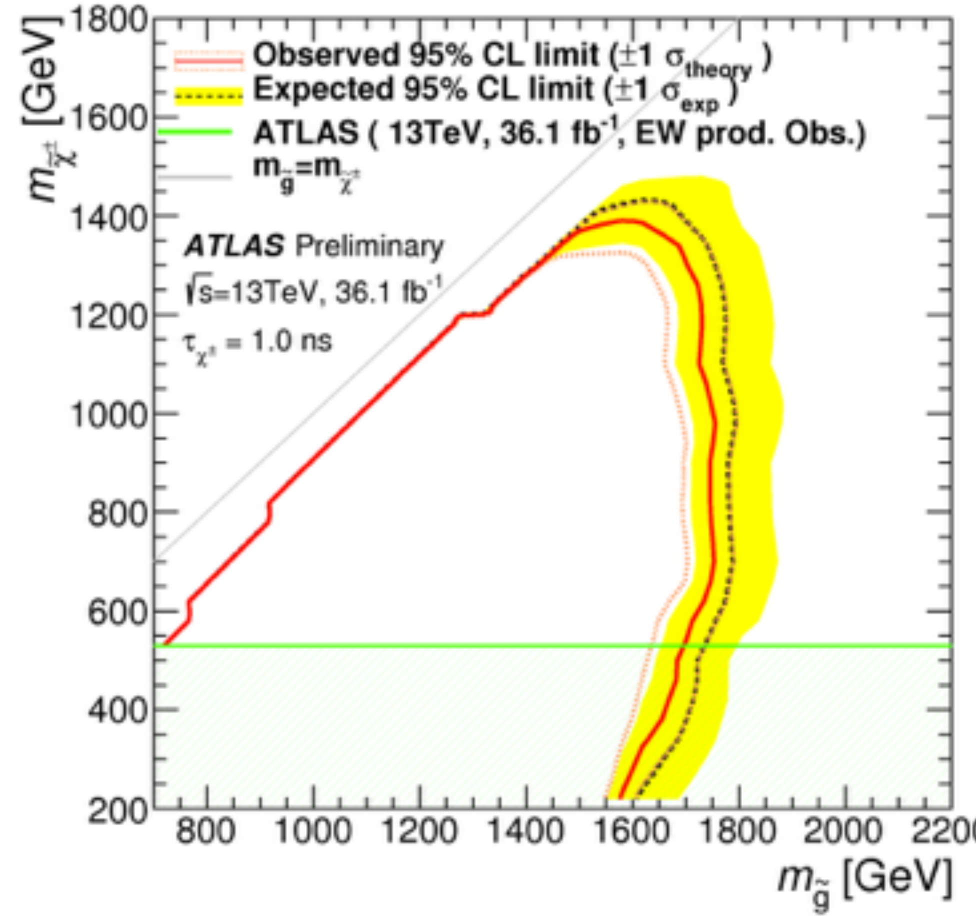
- The dijet mass spectrum is used from wide jets, including the background parameterisation, and the dijet resonance shapes to **set limits on the production of new particles decaying to the parton pairs qq (or qq), qg, and gg.**
- A separate limit is determined for each final state (qq, qg, and gg) because of the dependence of the dijet resonance shape on the types of the two final-state partons.
- **The dominant sources of systematic uncertainty are the jet energy scale and resolution**, integrated luminosity, and the estimation of background.

Model	Final state	Limit [TeV] Obs.	Exp.
String	qg	7.4	7.4
Scalar diquark	qq	6.9	6.8
Axigluon/coloron	$q\bar{q}$	5.5	5.6
Excited quark	qg	5.4	5.4
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.0	3.3
W′	$q\bar{q}$	2.7	3.1
Z′	$q\bar{q}$	2.1*	2.3
DM mediator ($m_{DM} = 1$GeV)	$q\bar{q}$	2.0	2.0
RS graviton	$q\bar{q}$, gg	1.9	1.8

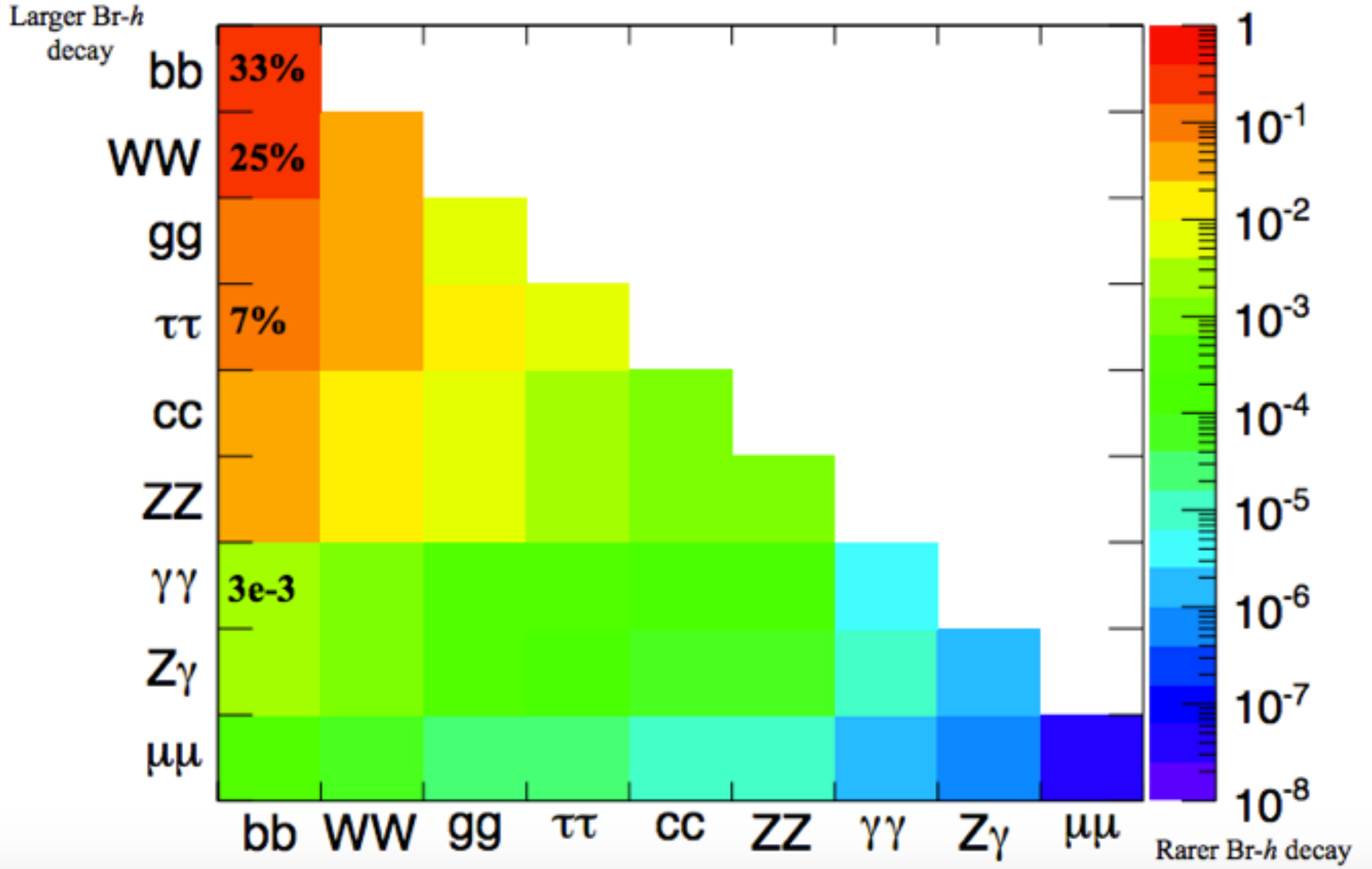


DISAPPEARING TRACK STRONG PRODUCTION LIMITS





strong production channel in terms
of the gluino and chargino masses



Di-Higgs Searches

ATLAS-CONF-2016-049

ATLAS-CONF-2016-004

ATLAS-CONF-2016-071

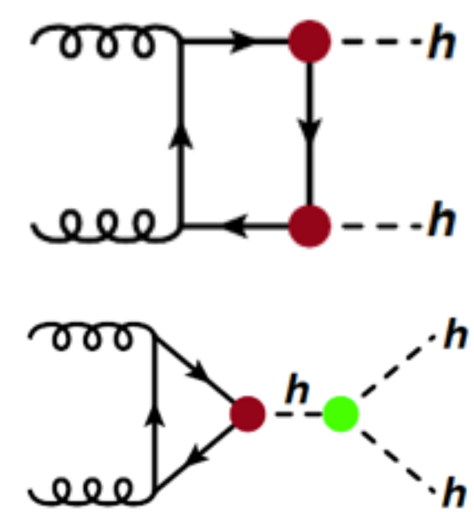
Di-Higgs Production

SM Higgs pair production is small, large increase in BSM Higgs scenarios
Models: RS-Graviton, heavy Higgs of 2HDM

Non-Resonant Higgs boson pair production:

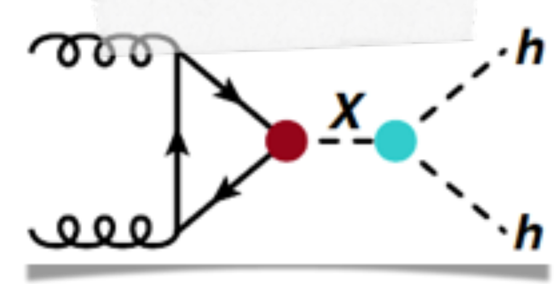
The SM predicts leading-order production modes for Higgs boson pairs through a heavy-quark loop via Yukawa-type interactions and the Higgs self-coupling at tree-level (self-interaction). This production cross section is extremely small within the SM, any significant enhancement would indicate physics beyond the SM.

- g_{HHH} is related to fundamental SM parameters: $g_{HHH} = 3m^2_H = 6\lambda v$ (following PDG scheme $V(\phi) = m^2\phi\phi^+ + \lambda(\phi\phi^+)^2$)



Resonant Higgs boson pair production:

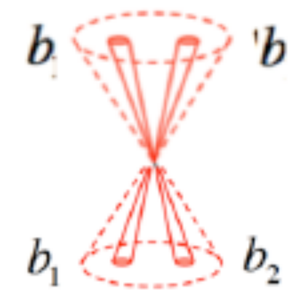
BSM Higgs boson pair production could proceed through changes in the SM Higgs couplings or through an intermediate resonance X. BSM can potentially enhance the production rate and alter the event kinematics, for example 2HDM, SUSY, electroweak singlet, GUT.

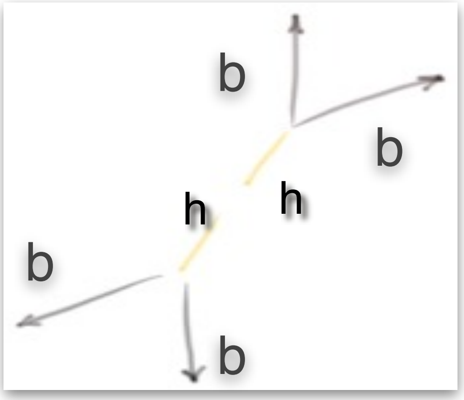


Di-Higgs Final States

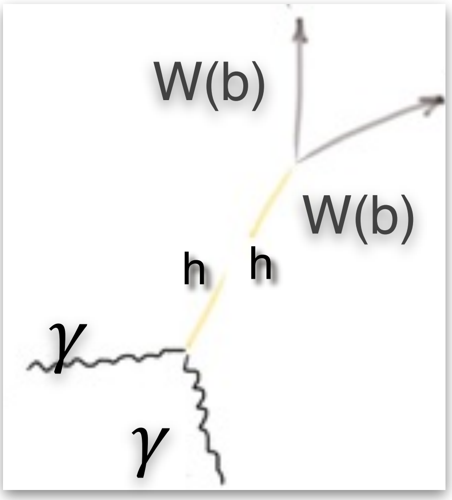
bbbb: ATLAS-CONF-2016-049 - 13.3 fb-1 data at 13 TeV

- **The final state of interest consists of four b-quarks.**
- Results on on-resonant and resonant production (300 and 3000 GeV)
- Boosted and resolved category
- Signal regions with 2, 3, 4 b-tags



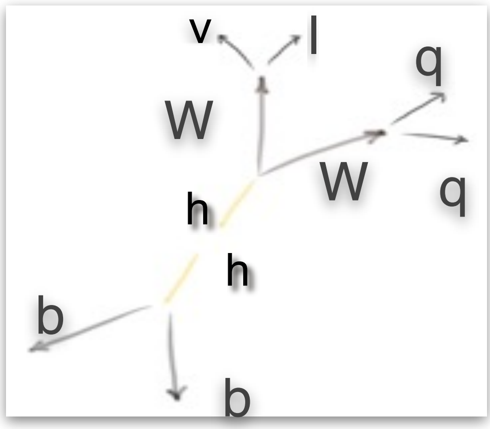


- $\gamma\gamma$**bb**: ATLAS-CONF-2016-004 - 3.2 fb-1 data at 13 TeV
  - **The final state: two isolated photons, accompanied by two jets, both identified as containing a b-hadron decay (b-jet).**
  - Results on non-resonant and resonant production (275 and 400GeV)



$\gamma\gamma$**WW***: ATLAS-CONF-2016-071 - 13.3 fb-1 data at 13 TeV

- **The final state: two photons, two jets and one charged lepton.**
- Results on non-resonant and resonant production (250 and 500 GeV)



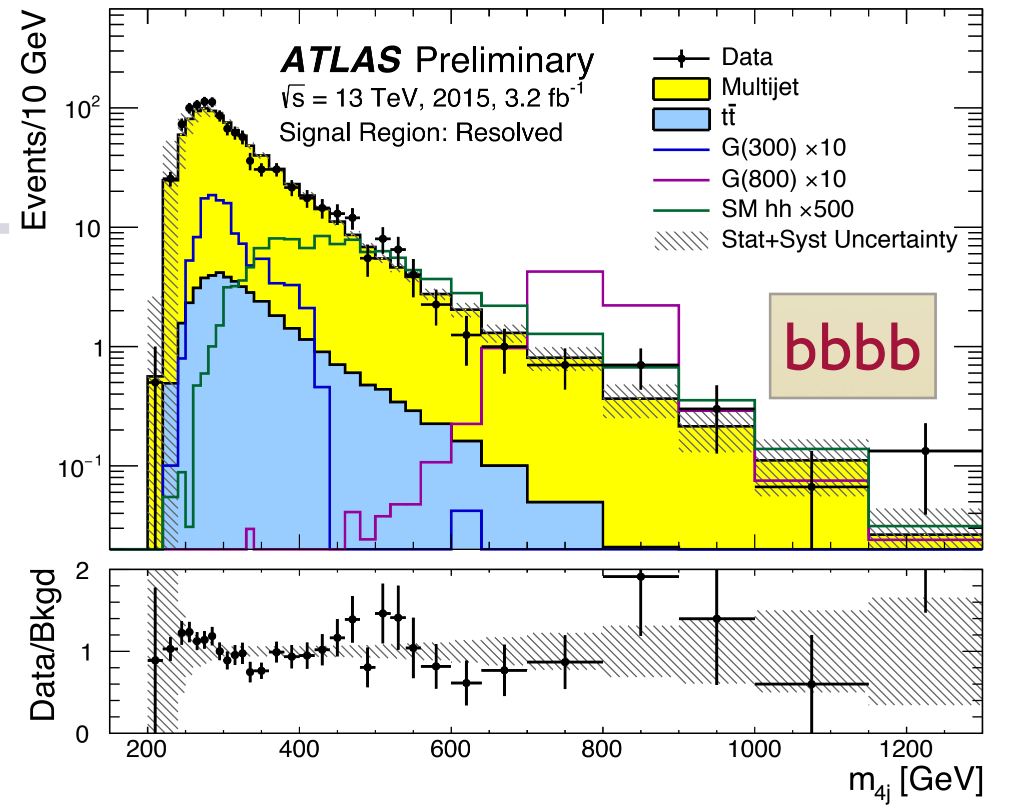
Di-Higgs Results @13 TeV

ATLAS

bbbb

Non-Resonant: pp→ hh→bbbb < 330 fb

Resonant: 2 fb < pp→ G^{*}_{KK}→ hh→bbbb < 1000fb
360 (380) < Mx < 860 (910) GeV obs (exp)

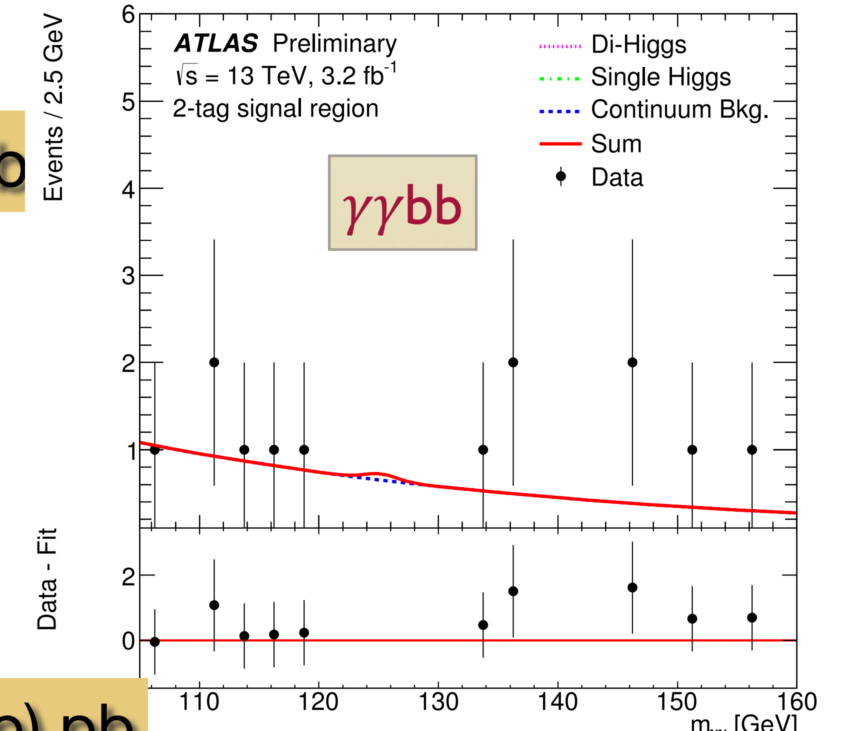


Explored in HL-LHC

$\gamma\gamma$bb

Non-Resonant: pp→ hh→$\gamma\gamma$bb < 3.9 obs (5.4 exp) pb

Resonant: 7 (7.5) < pp→ X→ hh→$\gamma\gamma$bb < 4 (4.4) pb [obs (exp)]
275 < Mx < 400 GeV



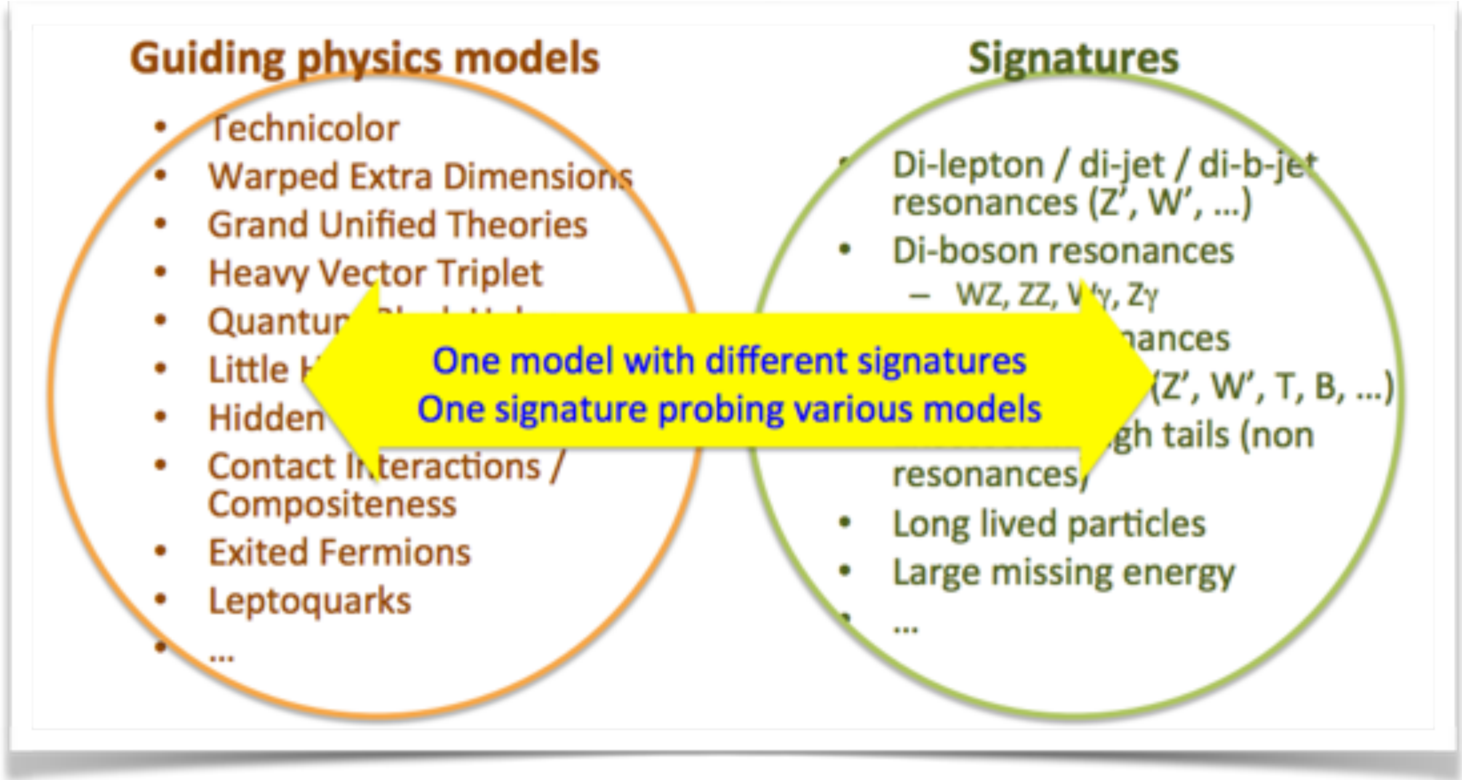
$\gamma\gamma$WW

Non-Resonant: pp→ hh→$\gamma\gamma$WW < 25.0 obs (12.9 exp) pb

Resonant: 47.7 (24.3) < pp→ X→ hh→$\gamma\gamma$WW< 24.7 (12.7) pb [obs (exp)]
260 < Mx < 500 GeV

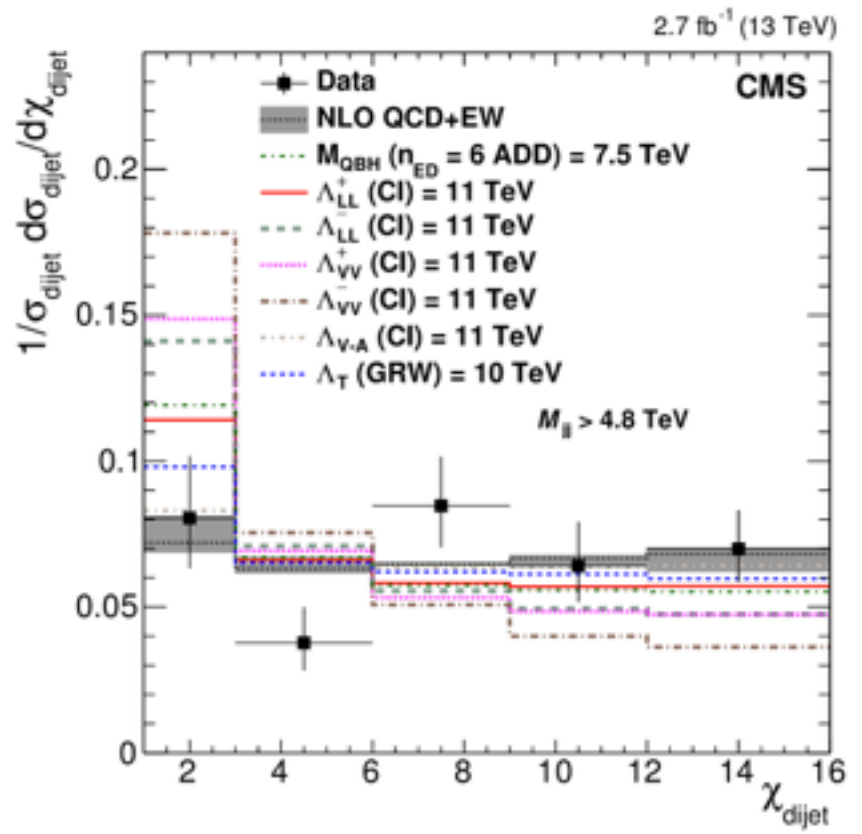
Exploring New Physics

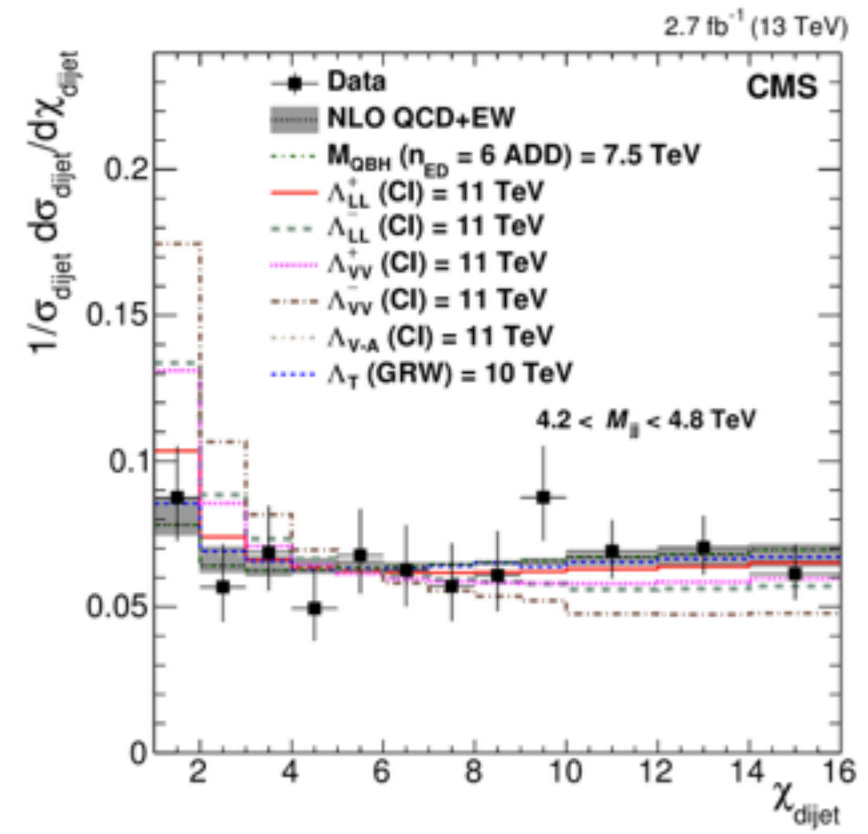
- **Strategy for new physics searches** (for example, in the case of Higgs boson):
  - **Indirectly**, ***by looking for non-standard properties*** of light Higgs (spin, CP, couplings…)
  - **Directly**, ***by explicit search for BSM objects***
    - additional Higgs bosons (neutral and charged, decays to SM particles,..)
    - Higgs boson decays to BSM states (light scalar resonances, invisible decays,..)
- **In the case of direct searches, define selection based on signal signatures/ acceptance and background kinematics**
- **Comparisons provided for specific models, but usually possible to constrain additional models**



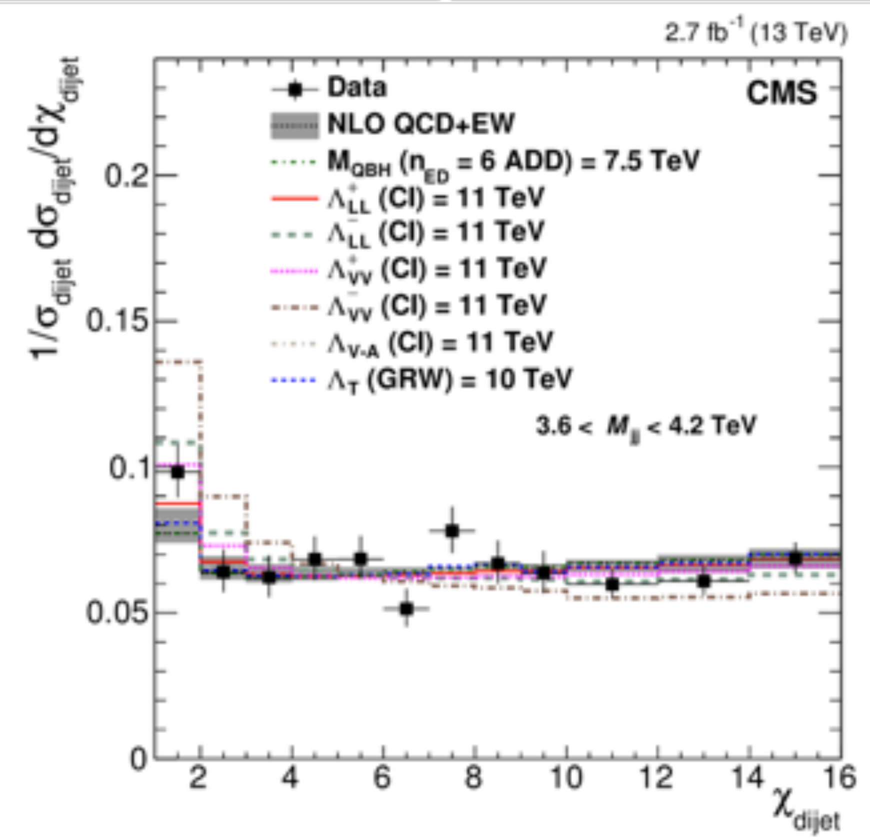
CMS-EXO-15-009 ; CERN-EP-2017-047

Di-jets angular distribution

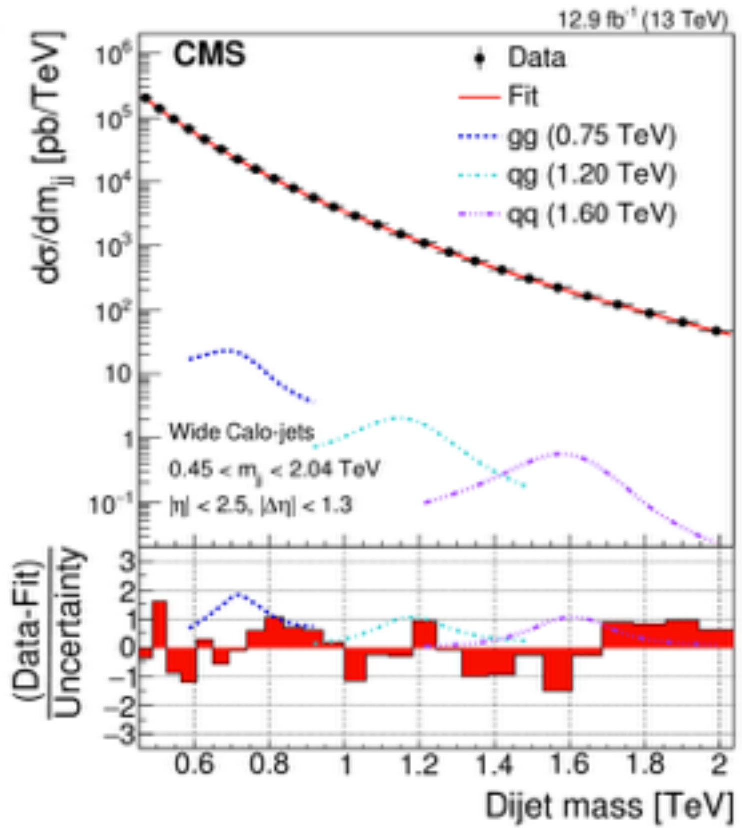


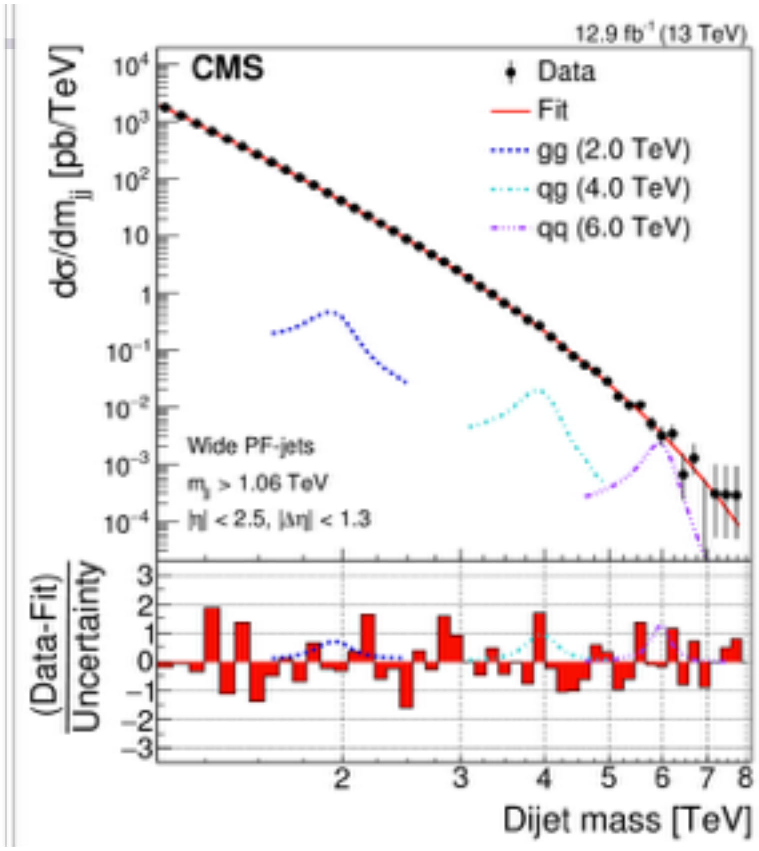


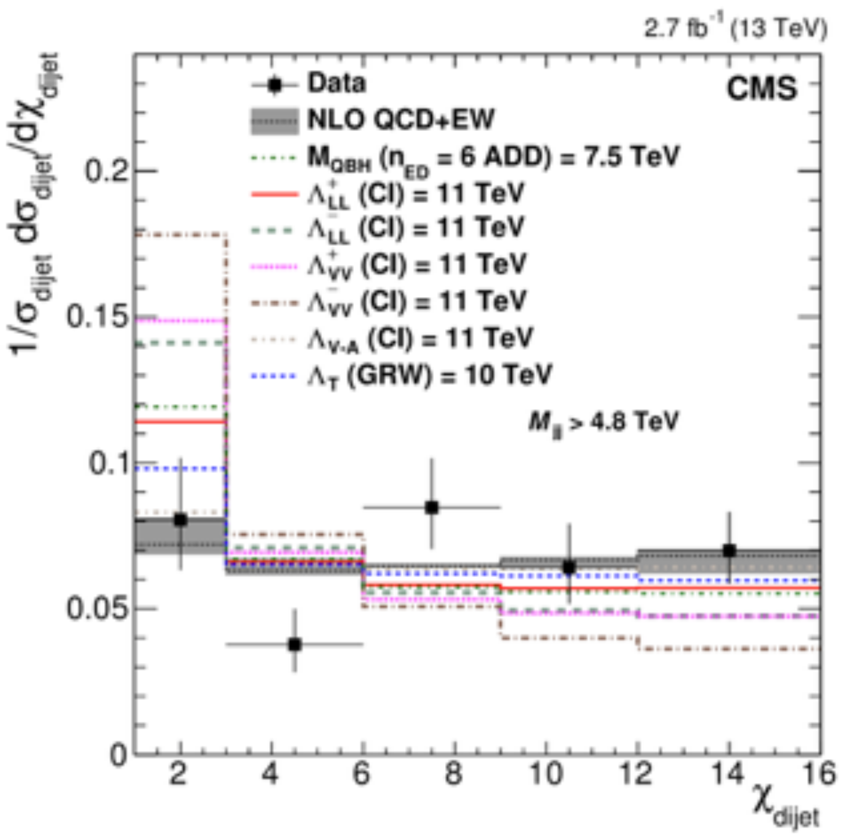
Uncertainty	$1.9 < M_{jj} < 2.4$ TeV	$M_{jj} > 4.8$ TeV
Statistical	1.1%	26%
Jet energy scale	2.2%	3.6%
Jet energy resolution (core)	0.4%	1.1%
Jet energy resolution (tails)	0.6%	0.5%
Unfolding, modelling	0.1%	0.8%
Unfolding, detector simulation	0.3%	0.8%
Pileup	0.2%	0.2%
Total experimental	2.6%	26%
NLO QCD scale	$^{+7.9\%}_{-2.8\%}$	$^{+13\%}_{-4.9\%}$
PDF (CT14 eigenvectors)	0.15%	0.4%
Nonperturbative effects	<1%	<1%
Total theoretical	$^{+7.9\%}_{-2.8\%}$	$^{+13\%}_{-4.9\%}$



Di-jets Analysis Results in CMS





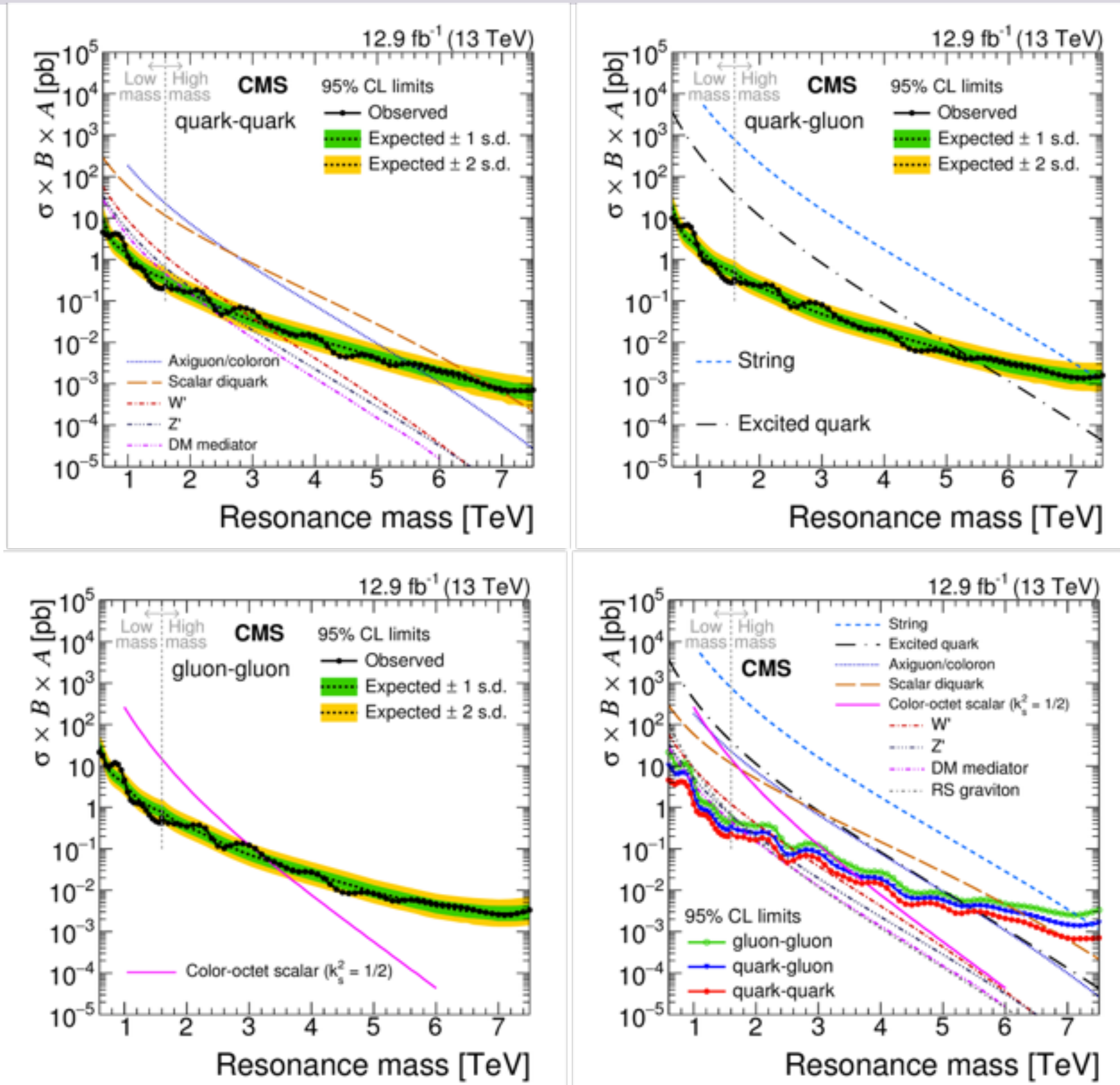


Model	Observed lower limit (TeV)	Expected lower limit (TeV)
$\Lambda^{+}_{LL/RR}$ (NLO)	11.5	12.1±1.2
$\Lambda^{-}_{LL/RR}$ (NLO)	14.7	17.3±3.4
Λ^{+}_{VV} (NLO)	13.3	13.9±1.2
Λ^{-}_{VV} (NLO)	18.6	22.2±5.4
Λ^{+}_{AA} (NLO)	13.3	13.9±1.2
Λ^{-}_{AA} (NLO)	18.6	22.1±5.1
$\Lambda^{+}_{(V-A)}$ (NLO)	8.4	9.5±1.6
$\Lambda^{-}_{(V-A)}$ (NLO)	8.4	9.5±1.7
ADD Λ_T (GRW)	9.4	9.8±1.2
ADD M_S (HLZ) $n_{ED} = 2$	10.1	10.6±1.3
ADD M_S (HLZ) $n_{ED} = 3$	11.2	11.7±1.4
ADD M_S (HLZ) $n_{ED} = 4$	9.4	9.8±1.2
ADD M_S (HLZ) $n_{ED} = 5$	8.5	8.9±1.1
ADD M_S (HLZ) $n_{ED} = 6$	7.9	8.2±1.0
$n_{ED} = 6$ ADD QBH M_{QBH}	7.8	7.7±0.3
$n_{ED} = 1$ RS QBH M_{QBH}	5.3	5.3±0.4

CMS-EXO-15-009 ; CERN-EP-2017-047

Results on di-jets resonance

- The observed 95% CL upper limits on the product of the cross section, branching fraction, and acceptance.
- Limits are compared to string resonances, excited quarks, axigluons, colorons, scalar diquarks , color-octet scalars, new gauge bosons W+′W+′ and Z′Z′ , dark matter mediators for m_{DM}=m_{DM}= 1 GeV, and RS gravitons.



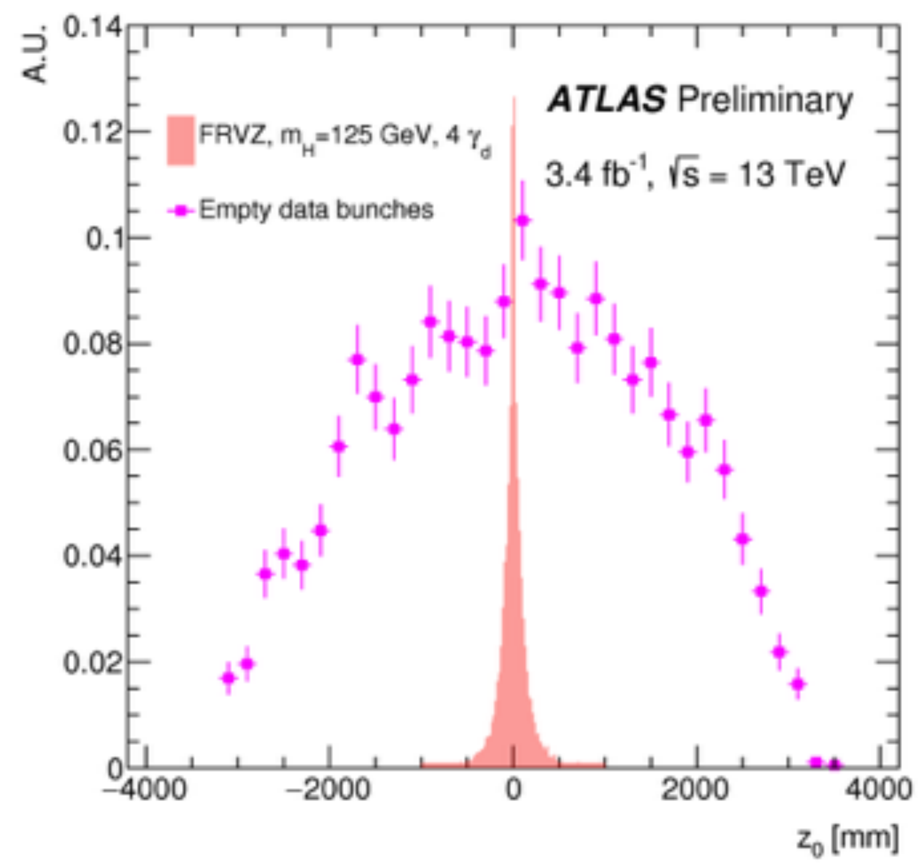
Displaced Jets: Full Cut Flow

Requirement	Data main	SM multi-jets MC	$m_\phi = 600\ GeV$; $m_s = 150\ GeV$	Data BIB	Data cosmic rays
Events passing the trigger	548600 ± 740	404000 ± 27000	25.7%	100%	100%
≥ 2 clean jets	421800 ± 650	197000 ± 19000	22.1%	38.3%	21%
$\mathrm{jet}_{1,2}^{\mathrm{CalRatio}}$ clean	23860 ± 150	900 ± 440	7.21%	6.67%	7.28%
$\Delta\phi > 0.75$	17590 ± 130	600 ± 350	6.85%	0.86%	3.38%
$-3 < \mathrm{time} < 15$	16180 ± 130	600 ± 350	6.84%	0.35%	1.10%
$H_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}} < 0.3$	14880 ± 120	600 ± 350	6.09%	0.30%	0.25%
$\sum \Delta\mathrm{R}_{\mathrm{min}} > 0.5$	9500 ± 97	500 ± 330	6.08%	0.14%	0.25%
BDT value($\mathrm{jet}_1^{\mathrm{CalRatio}}$) > 0.2	8190 ± 91	500 ± 330	5.95%	0.09%	0.25%
BDT value($\mathrm{jet}_2^{\mathrm{CalRatio}}$) > -0.2	4890 ± 70	300 ± 260	5.93%	0.06%	0.25%
$p_{\mathrm{T},1} > 150\ GeV$	330 ± 18	0 ± 0	5.31%	0.005%	0%
$p_{\mathrm{T},2} > 120\ GeV$	110 ± 10	0 ± 0	4.27%	0.001%	0%
region A:					
$\sum \Delta\mathrm{R}_{\mathrm{min}} > 1.5$	60 ± 8.0	0 ± 0	3.73%	0%	0%
$\sum \mathrm{BDT} > 0.15$	24 ± 4.9	0 ± 0	3.57%	0%	0%

Mass Point (GeV, GeV)	JES (%)	JES EMF (%)	JER (%)	Trigger (%)	Pile-up (%)	Luminosity (%)
(400,150)	3.3	14	0.43	2.3	4.0	2.1
(600,150)	1.5	5.4	0.40	1.5	0.56	2.1
(1000,150)	0.51	1.8	0.05	1.0	2.0	2.1

Signal Event: topology and selection

- **Selection**: dedicated trigger to select these states. Different selections depending on the LJ type.
  - **Collimated final-state particles difficult to reconstruct** (detector granularity)
  - **Tracks with displaced decay vertices difficult to reconstruct** (no primary vertex constraint)



- **Background**: Cosmics events (impact parameter and timing as discriminating variables), machine background, QCD jets (ABCD method)

- **Main Uncertainty**:Trigger, reconstruction efficiency

LJ type	Selection requirement	Requirement description
Type 0/1	z_0 limits	an impact parameter $\lvert z_0 \rvert$ < 280 mm for both muons of the LJ
Type 1/2	jet timing Δt_{Calo}	remove jets outside the ± 4 ns time window
Type2	tile-gap scint.	max energy in tile-gap scintillators ≤ 10% of the jet energy
Type2	EM fraction	EM fraction of the jet < 0.1
Type2	jet width	$W < 0.058$
Type2	JVT	JVT variable ≤ 0.56
Type2	BIB	use BIB tagging to remove fake jets from beam-halo muons
Type 0/1	no-CB	all muons of the LJ to be non-combined (“no-CB”)

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Event Selection

- **Selection**: dedicated trigger to select displaced decays. BDT to improve the identification of the two displaced jets.
  - Cut on $\mathrm{Log}_{10}(E_{Had}/E_{Em})$
  - Isolation wrt inner tracks
  - Cuts on Jet pt
- **Background**: Cosmics events (impact parameter and timing as discriminating variables), machine background BIB, QCD jets (ABCD method)
- **Main Uncertainty**: Trigger, JES