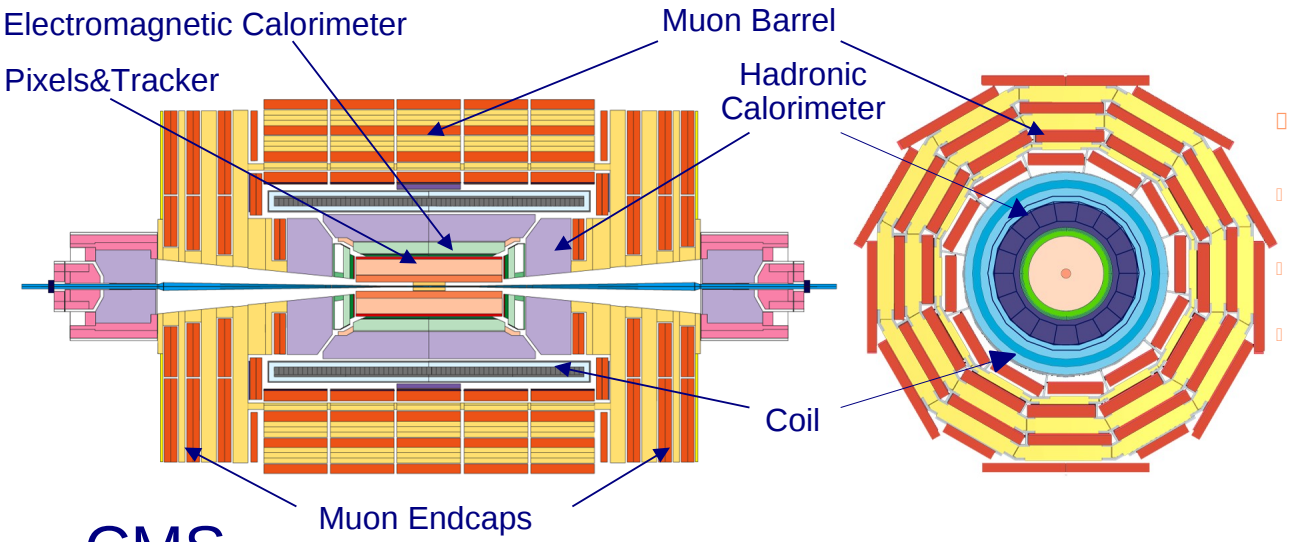
Searches of Exotic Physics at LHC

Khristian Kotov
on behalf of CMS and ATLAS collaborations

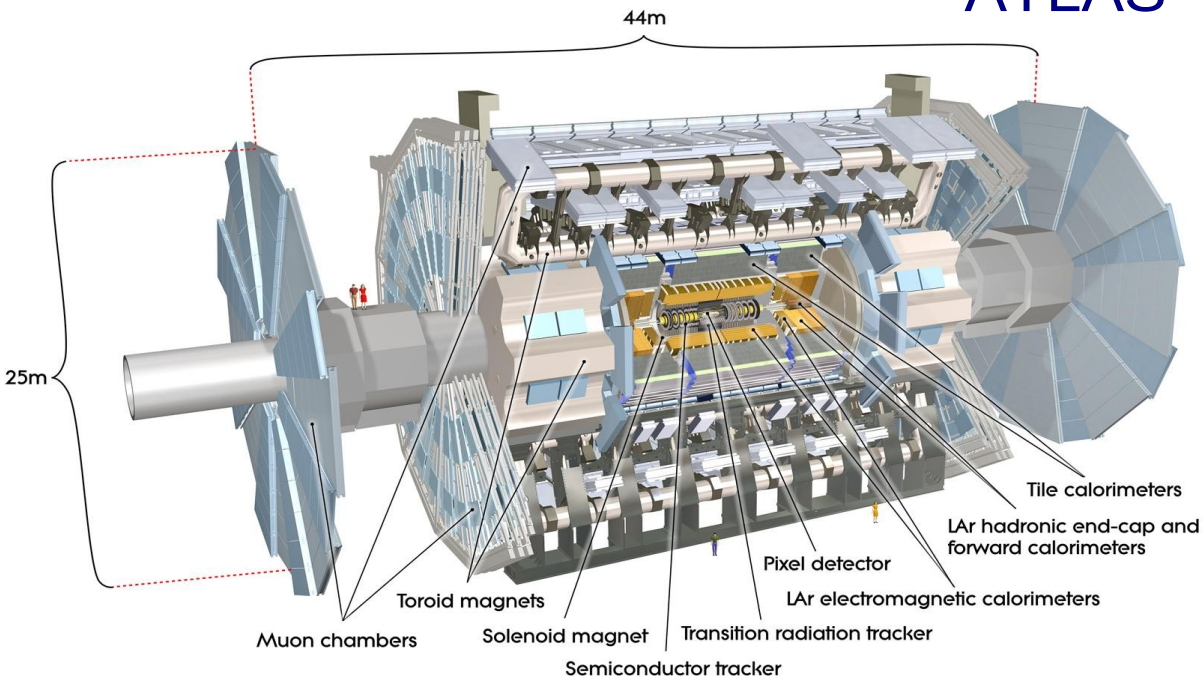
CMS and ATLAS detectors at LHC



CMS

- tracker: $\sigma(p_T)/p_T \sim 1.5 \cdot 10^{-4}\ p_T + .005$
- ECal: $\sigma_E/E \sim 3\%/\sqrt{E[GeV]} \oplus 0.5\%$
- HCal: $\sigma_E/E \sim 100\%/\sqrt{E[GeV]} \oplus 5\%$
- trk+Mu: 1%@50GeV–10%@1TeV

ATLAS

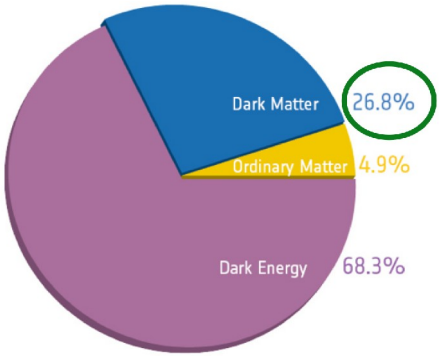


- tracker: $\sigma(p_T)/p_T \sim 5 \cdot 10^{-4}\ p_T + 0.01$
- ECal: $\sigma_E/E \sim 10\%/\sqrt{E[GeV]} \oplus 0.7\%$
- HCal: $\sigma_E/E \sim 50\%/\sqrt{E[GeV]} \oplus 3\%$
- trk+Mu: 2%@50GeV–10%@1TeV

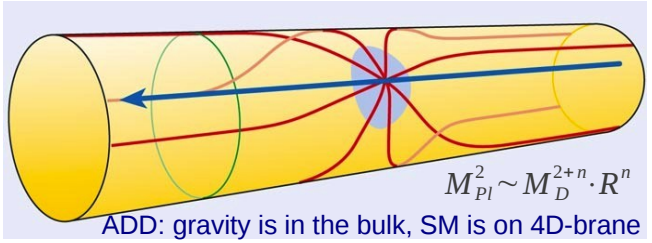
Exotic searches

Addressing some of the open questions beyond the Standard Model:

- Dark Matter (e.g. new species of particles):
  - cosmological evidences (galaxy rotations, lensing, CMB, …)
  - hints from direct (CDMS) and indirect (AMS) searches (more in backup)
  - prominent high $\not{E}_T$ signature for collider searches



- Hierarchies (e.g. addressed by theories of extra dimensions):
  - large gap between M_{PL} (gravity) and M_{EWK} (electroweak) scales requires fine tuning of the Higgs boson mass
  - smallness of neutrino masses vs. masses of other SM particles
  - can be searched for in $\not{E}_T$ signatures (e.g. escaping graviton)



ADD: gravity is in the bulk, SM is on 4D-brane

- Grand Unification Theories (e.g. superstring-inspired E6)
  - predict new heavy gauge bosons
  - search for SM-like Z' and W' resonances in di-lepton and di-jet events

No SUSY in this talk, see Fedor's talk for that

Two worlds

theories

Z', W'
LRSM, heavy neutrino
compositeness
colorons
leptoquarks
technicolor
unparticles
RS graviton
4th generation
extra dimensions (ADD, universal, ...)
black holes
hidden valey
SUSY (MSSM, split, GMSB, RPV, …)

(and more ...)

experiment

Multijets:
- di-jets
- paired di-jets
- paired 3-jets

Slow moving new particles:
- displaced di-lepton vertices
- displaced photons and jets
- delayed jets

Leptons and jets:
- EWK vector (di-)boson candidates
- single top and ttbar candidates

Photons:
- Di-photons, photon + lepton

Missing E_T
- with jets
- with a photon

Some others:
- high S_T/H_T in unspecified event signature

Outline

Searches for exotic physics in 2012 data (up to ~20 fb^{-1}) by ATLAS & CMS:

Searches for new resonances (and enhancements in spectra):

- leptonic searches:
  - di-lepton invariant mass
  - hunt for W' candidate
- di-jet searches:
  - narrow di-jets resonances
  - narrow bb- and bg- resonances
- new physics with enhanced coupling with 3rd generation quarks:
  - resonant and non resonant ttbar production
  - narrow t+b resonances
  - pair produced resonances decaying to a top quark and jet

Searches for Extra Dimensions and Dark Matter:

- Monojet search

Searches for long-lived particles

Leptonic searches

New heavy gauge bosons (Z' and W'):

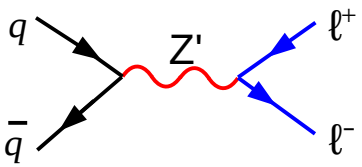
- Split Universal Extra Dimensions: Kaluza-Klein towers of the Standard Model bosons
- Grand Unification Models: superstring-inspired E6 Z'_{ψ}

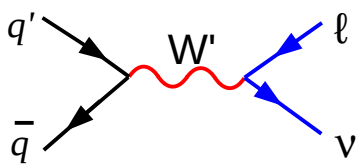
Large Extra Dimensions:

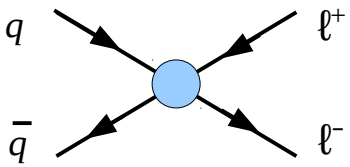
- ADD graviton exchange boosting the high mass tail of the di-lepton production

Compositeness:

- Four-fermion interaction $qq \to \ell\ell$ and $qq' \to \ell\nu$



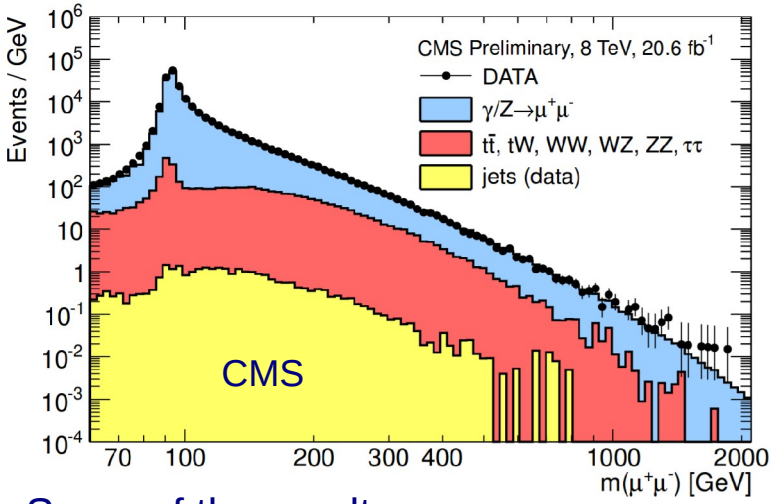


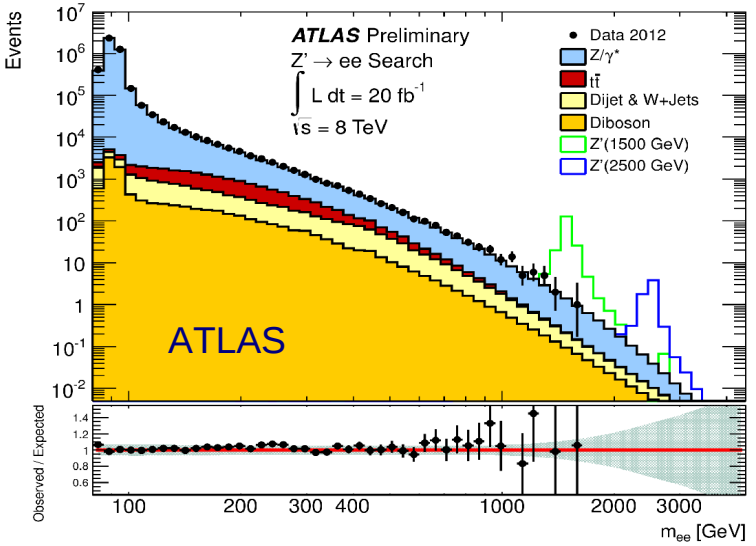


Di-lepton resonances

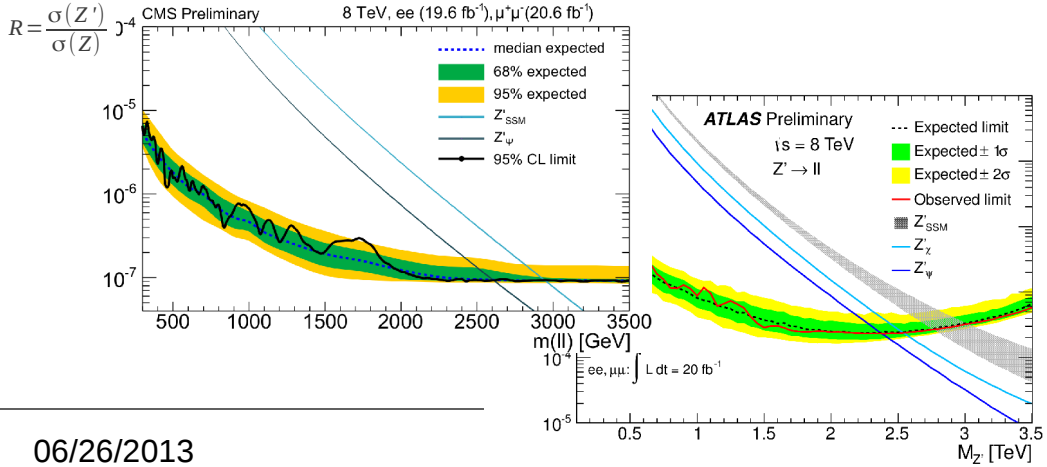
CMS-EXO-12-061 and ATLAS-CONF-2013-017: bump hunt for a $Z' \to \ell^+\ell^-$

- simple clean signature of 2 high p_T isolated leptons
- data-driven backgrounds using $e^{\pm}\mu^{\mp}$ (tt, VV,...), $e^{\pm}\mu^{\pm}$ (W+jets, multi-jets), inverse isolation (di-jets), …





Some of the results:

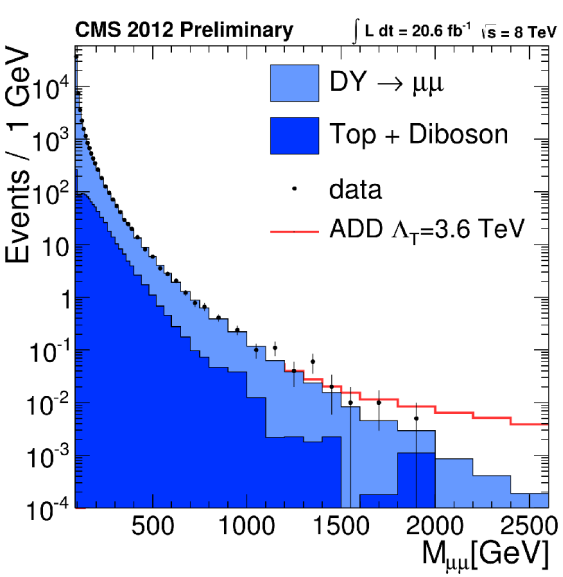


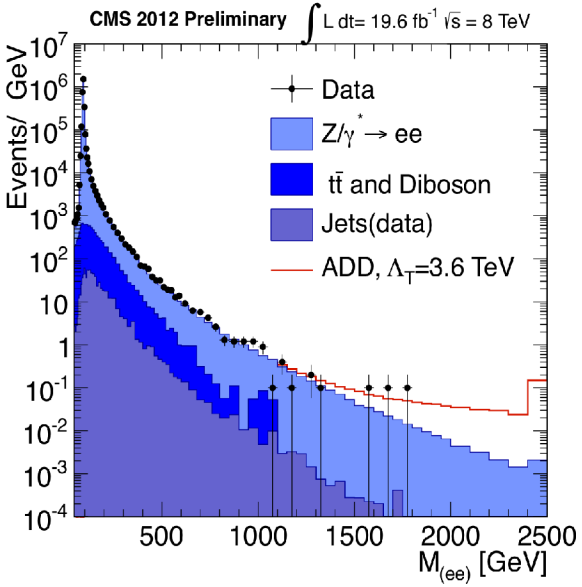
model	CMS	ATLAS
$m(Z'_{SSM})$	2.96	2.86
$m(Z'_{\psi})$	2.60	2.38

Search for excess in ℓℓ mass spectrum

CMS-EXO-12-027 And CMS-EXO-12-031:

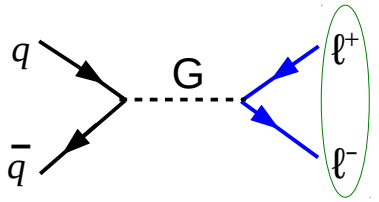
- selection and data-driven backgrounds as in previous CMS-EXO-12-061
- look for broad excess and interpret it within ADD extra dimensions





$\mu\mu$, $\mathcal{L}$ = 20.6 fb^{-1}			
Mass region [TeV]	N_{obs}	Background expectation	Signal exp. Λ_T = 3.6 TeV
Control regions			
0.12–0.20	$8.20 \cdot 10^4$	$(7.96 \pm 0.64) \cdot 10^4$	
0.20–0.40	$1.92 \cdot 10^4$	$(1.87 \pm 0.15) \cdot 10^4$	
0.40–0.60	$1.42 \cdot 10^3$	$(1.45 \pm 0.14) \cdot 10^3$	
0.60–0.90	287	282±32	
0.90–1.30	49	44.5±6.6	
1.30–1.80	11	5.74±1.16	3.38
Signal region			
> 1.80	1	0.73±0.21	6.04

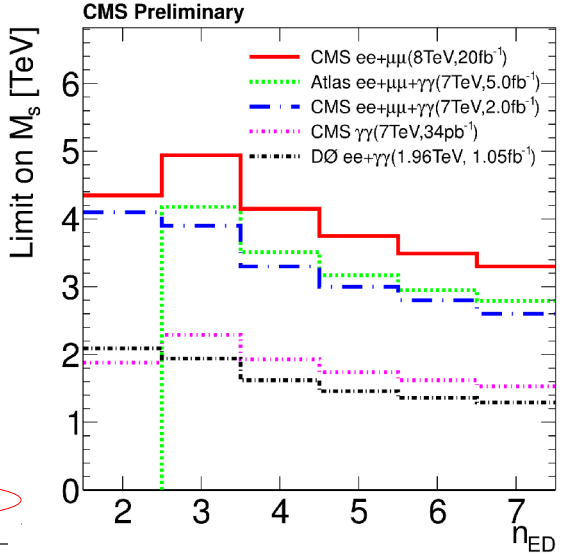
ee, $\mathcal{L}$ = 19.6 fb^{-1}			
Mass region [TeV]	N_{obs}	Background expectation	Signal exp. Λ_T = 3.6 TeV
Control regions			
0.12–0.40	85851	82497 ±12374	
0.40–0.60	1251	1131±169	
0.60–0.90	249	232 ±35	
0.90–1.30	41	36 ±6	
1.30–1.80	4	4.75 ±0.70	3.70
Signal region			
> 1.80	0	0.64±0.10	6.90



same di-lepton signature

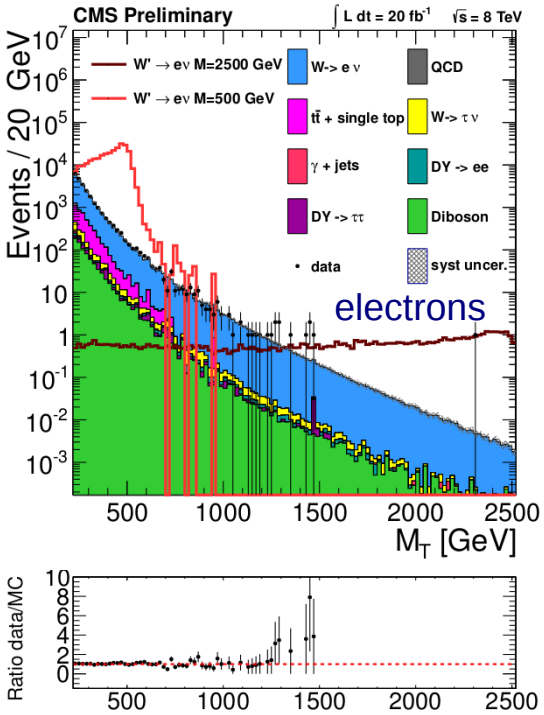
Results

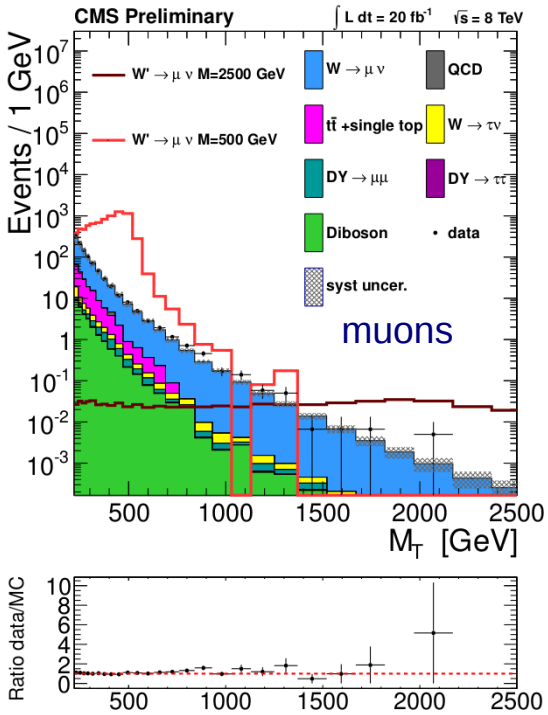
(limits on ADD fundamental scale):

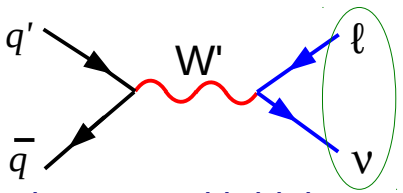


Search for W' → ℓ ν̄

CMS-EXO-12-060: search for excess over extrapolated SM bg. in $M_T = \sqrt{2\, p_T^l\, E_T^{miss} (1 - \cos \Delta \varphi_{l,\nu})}$

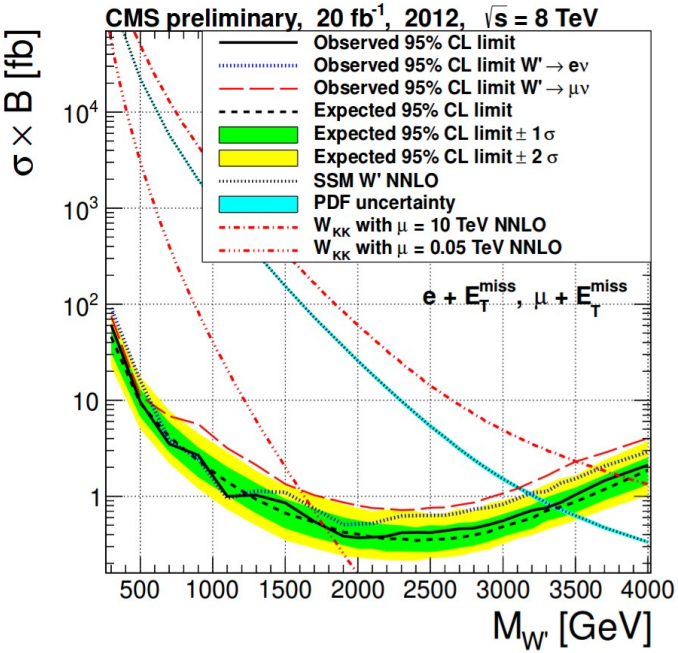






signature with high p_T lepton and missing energy

Results:



Limits:

Model	Channel	Observed limit	Expected limit
SSM	combined	$m_{W'} < 3.35$TeV	$m_{W'} < 3.40$TeV
SSMO	combined	$m_{W'} < 3.60$TeV	$m_{W'} < 3.60$TeV
SSMS	combined	$m_{W'} < 3.10$TeV	$m_{W'} < 3.20$TeV
W^2_{KK}	μ=0.05 TeV, combined	$m_{W^2_{KK}} < 1.7$TeV	$m_{W^2_{KK}} < 1.7$TeV
W^2_{KK}	μ=10.0 TeV, combined	$m_{W^2_{KK}} < 3.7$TeV	$m_{W^2_{KK}} < 3.6$TeV
HNC CI	e	$\Lambda < 13.0$ TeV	$\Lambda < 13.3$ TeV
HNC CI	μ	$\Lambda < 10.9$ TeV	$\Lambda < 12.2$ TeV

Destructive interf.

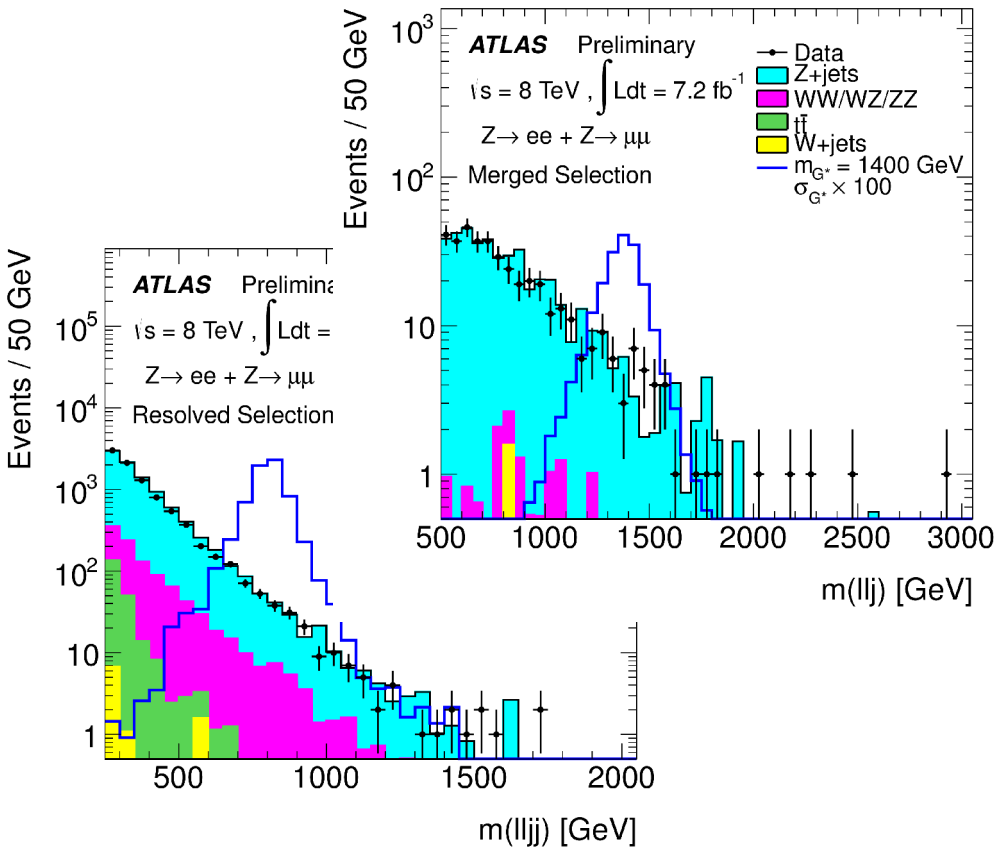
Constructive interf.

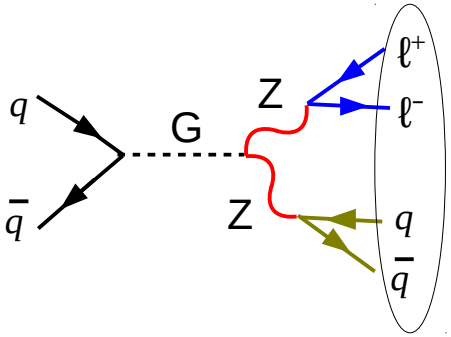
Split-UED

Contact interaction

Search for VV resonances (1)

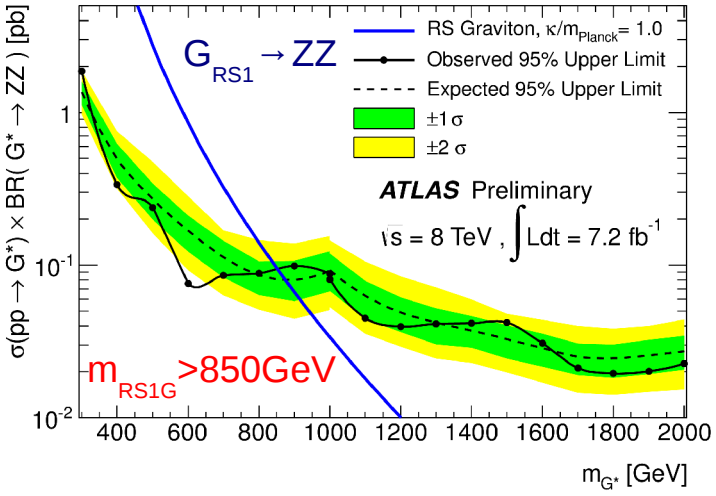
ATLAS-CONF-2012-150: search for ZZ resonances





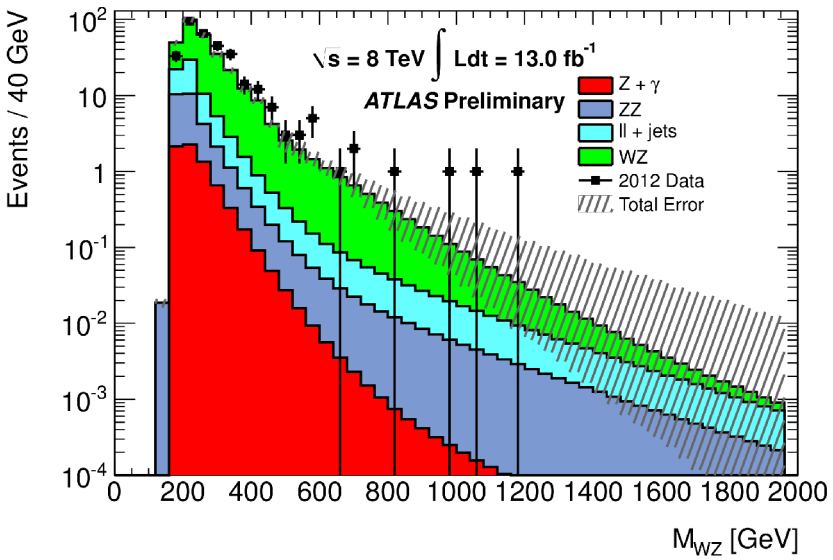
event signature of 2 ℓ + 2 jets /1 fat jet

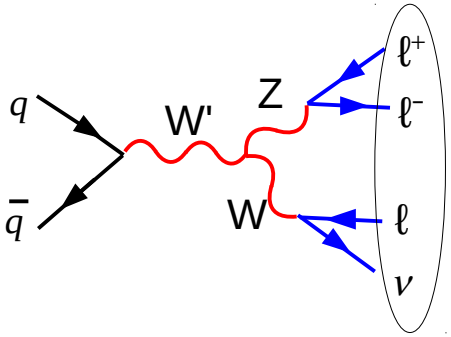
Some of the limits:



Search for VV resonances (2)

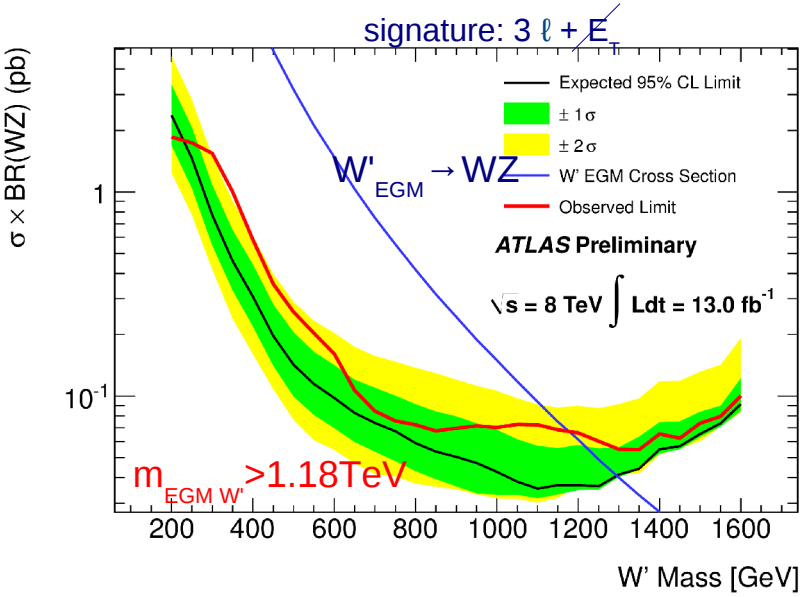
ATLAS-CONF-2013-015: search for WZ resonances:





event signature of 3 ℓ + missing energy

signature: 3 ℓ + $\not{E}_T$



di-jet searches

New heavy gauge bosons:

- Z' and W' decaying hadronically

Randall-Sandrum extra dimensions:

- RS graviton decaying to qq and gg

Compositeness:

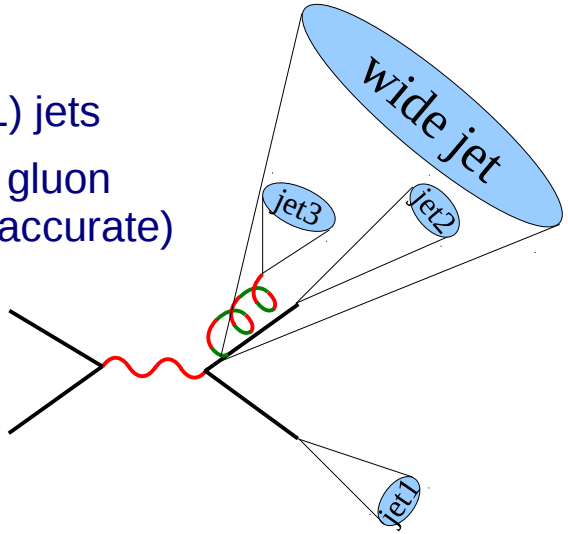
- Four-fermion interaction $qq \rightarrow qq$

Excited quarks:

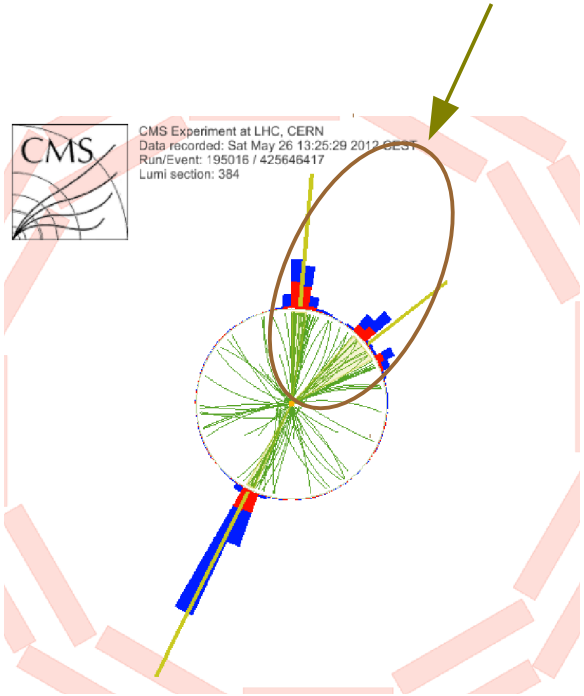
- $q^* \rightarrow qg$

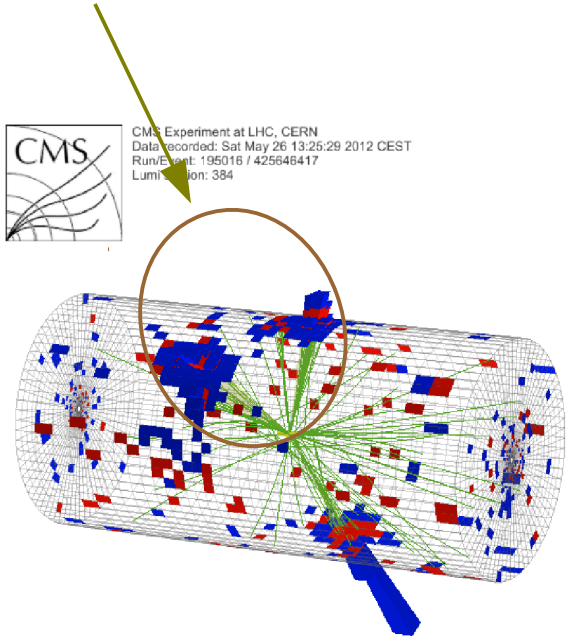
Recombination of radiation

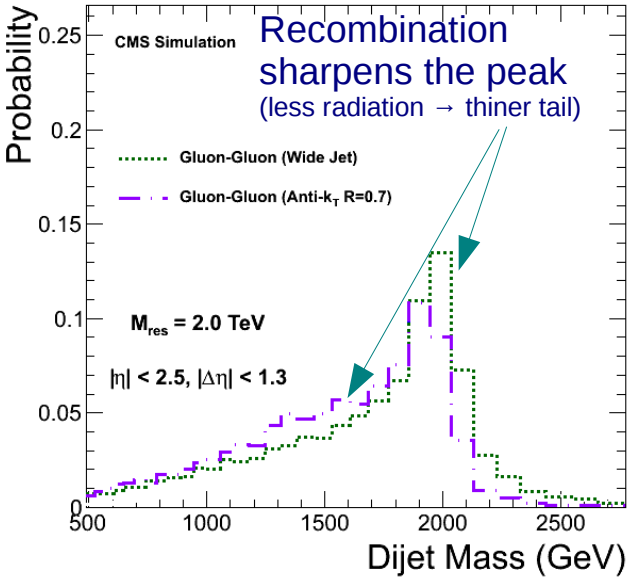
- Use standard calibrated jets (p_T>30 GeV, anti-k_T in ΔR=0.5)
- Take leading jets and sum with lorentz vector of nearby (ΔR<1.1) jets
- This technique helps to recover some resolution for gluon jet as gluon tend to radiate more often than quark (still, quark jets are more accurate)



example event with close jets merged to a wide jet

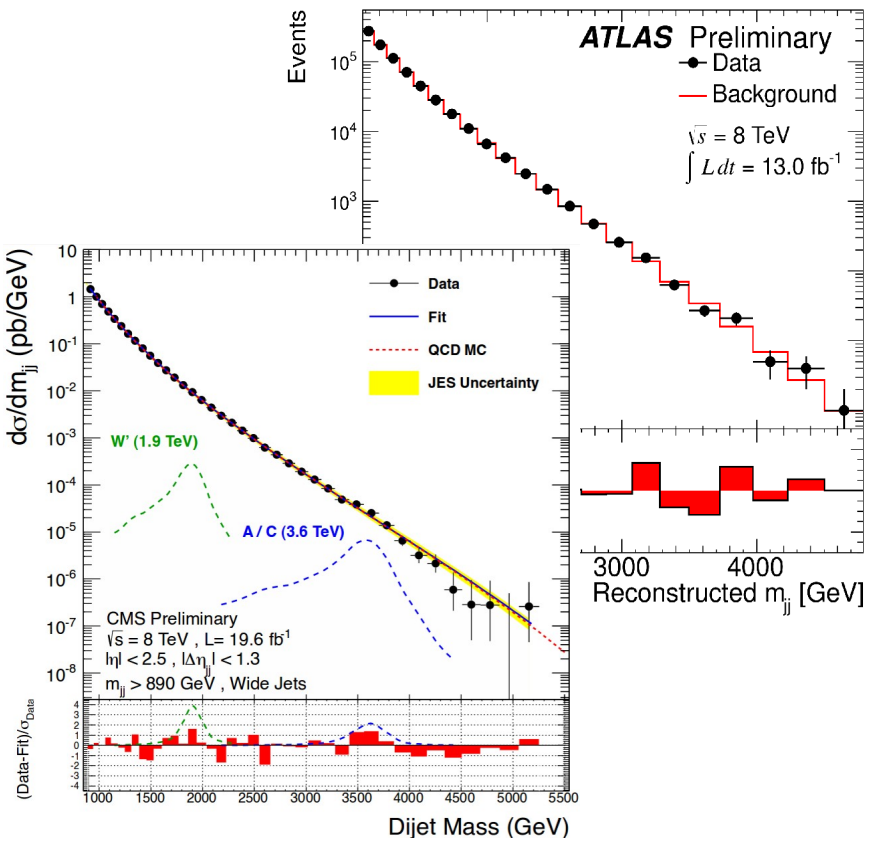


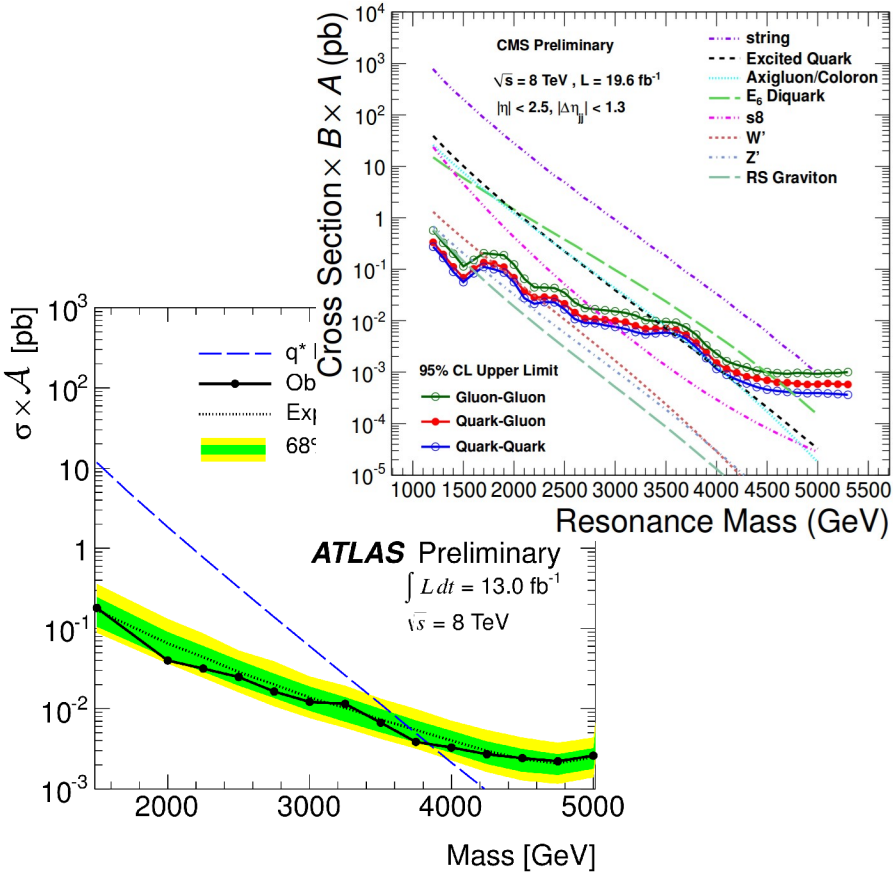




Narrow di-jet resonances

CMS-EXO-12-059, ATLAS-CONF-2012-148: hunt for a bump in smooth di-jet mass spectrum





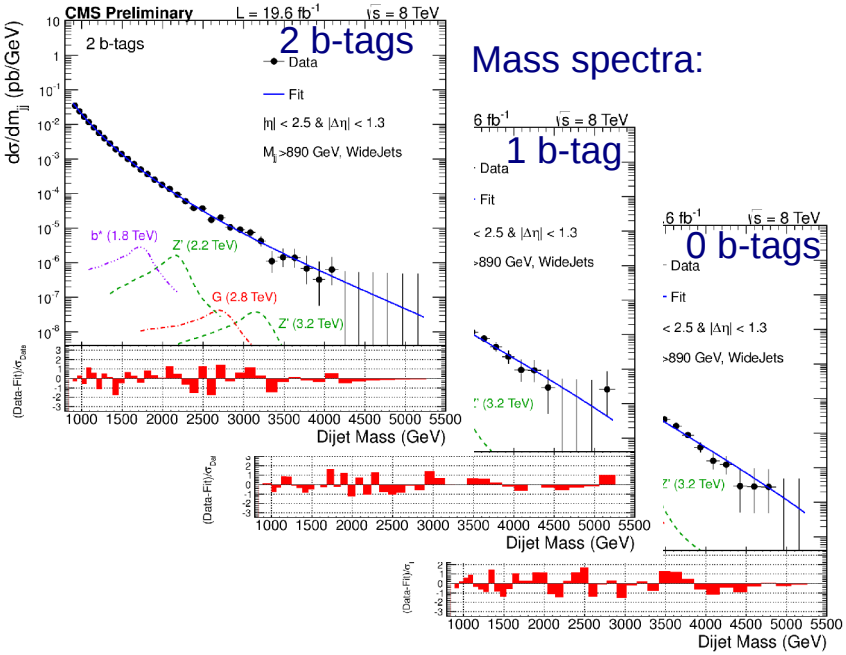
Some limits:

model	excited quarks	RS graviton	SSM W'/Z'	color octet s8
observed limit (TeV)	m_{q^*} >3.5$_{CMS}$/3.84$_{ATLAS}$	m_{RSg} > 1.58	$m_{V'}$ > 2.29 / 1.68	m_{s8} > 2.79

Narrow $b\bar{b}$ and bg resonances

CMS-EXO-12-023: hunt for a bump in di-jet mass spectrum with b-tags (helps to mitigate QCD)

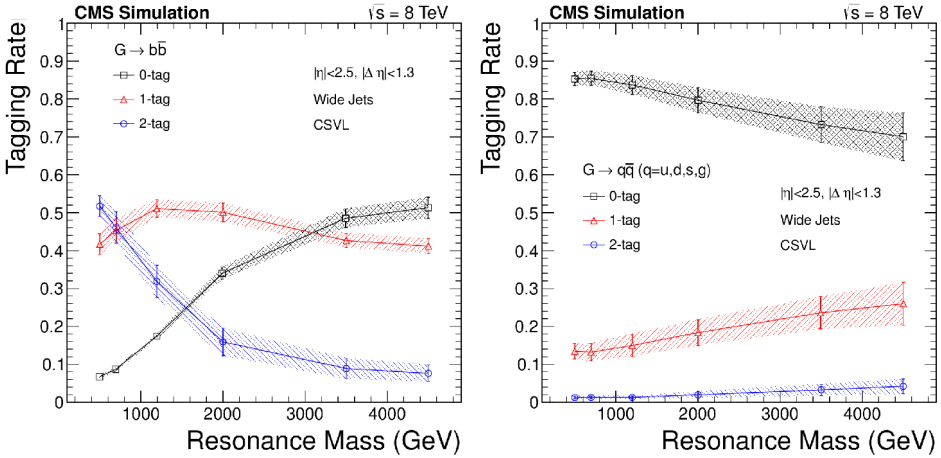
Mass spectra:



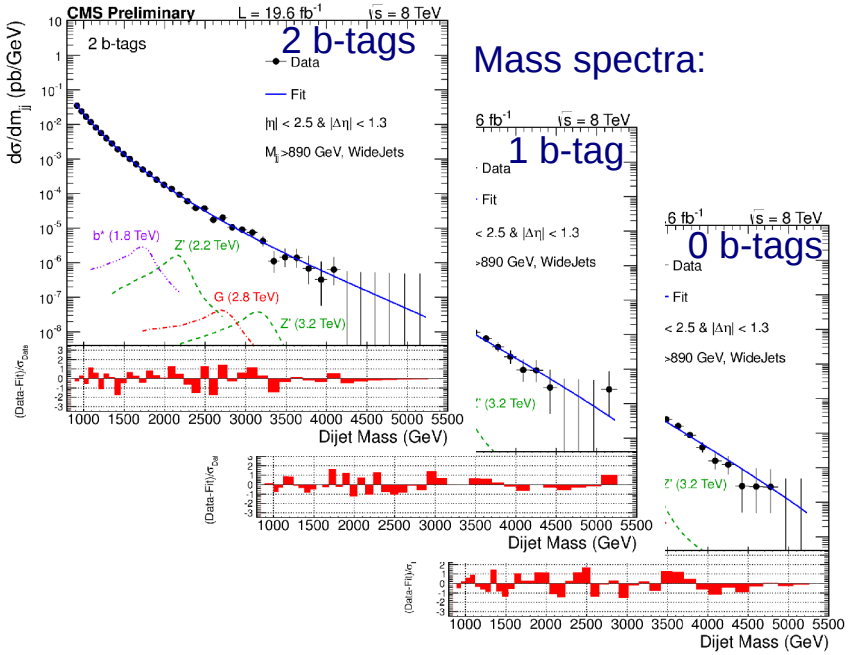
Narrow $b\bar{b}$ and bg resonances

CMS-EXO-12-023: hunt for a bump in di-jet mass spectrum with b-tags (helps to mitigate QCD)

b-tagging efficiencies and mistag rates:



Mass spectra:



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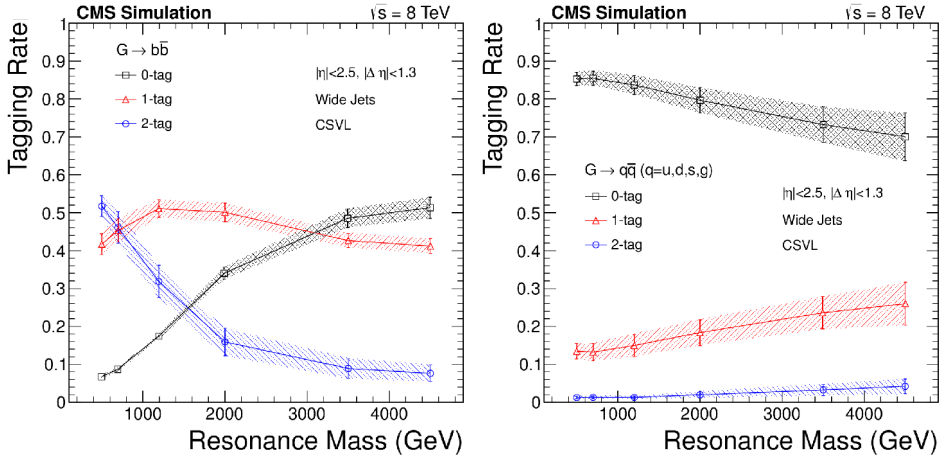

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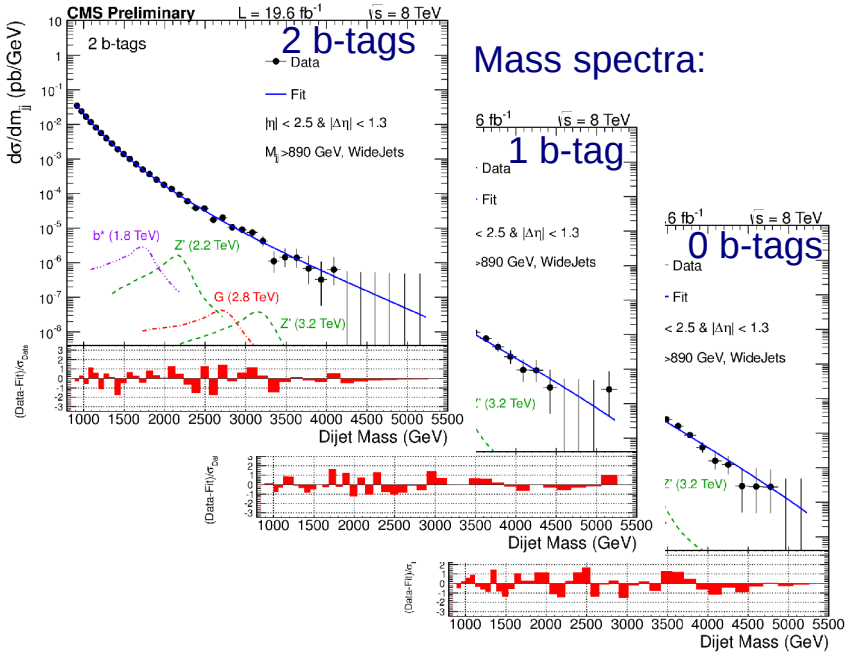
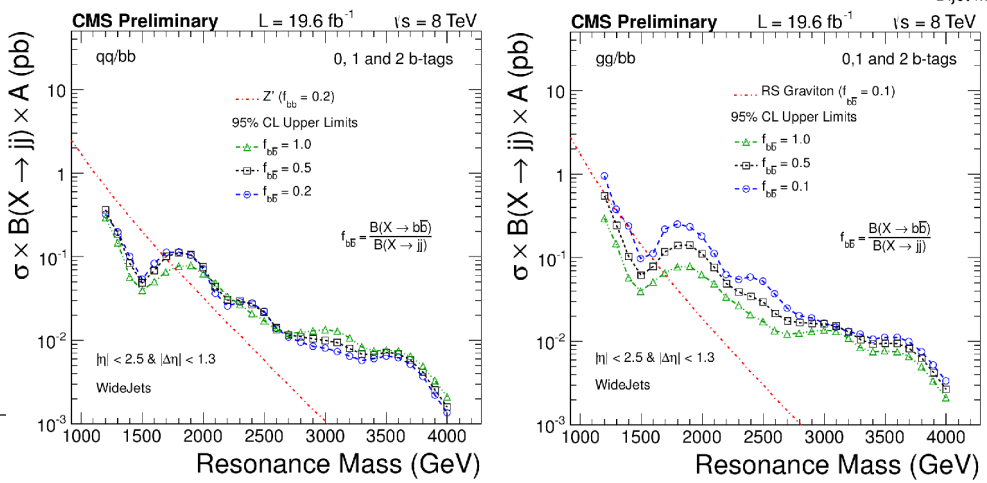


Results (quark jets have better resolution than gluon jets):

- Z'→qq̄: $m_{Z'}$>1.68 TeV for branching f_{bb}=0.2
- graviton$_{RS}$→gg/bb: m_{RS}>1.57 TeV at f_{bb}=0.1
- compositeness: b*→bg, m_{b^*}>1.54 TeV



Physics with top quark

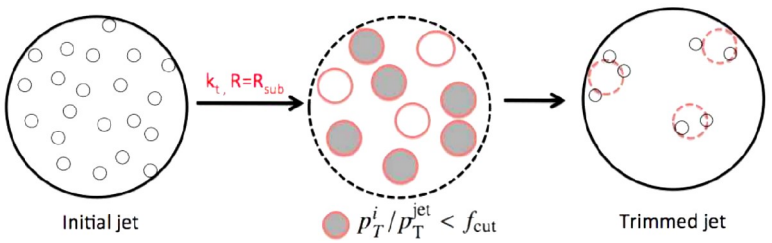
The Z'→tt and W'→tb searches are well-motivated by many models of new physics, predicting new particles with enhanced couplings to the 3rd generation quarks:

- SUSY and little Higgs theories, addressing fine tuning of Higgs boson mass
- colorons and axigluons models in which a pseudoscalar Higgs boson couples to top quark
- models with extra dimensions such as Kaluza-Klein excitations of SM gluons and gravitons

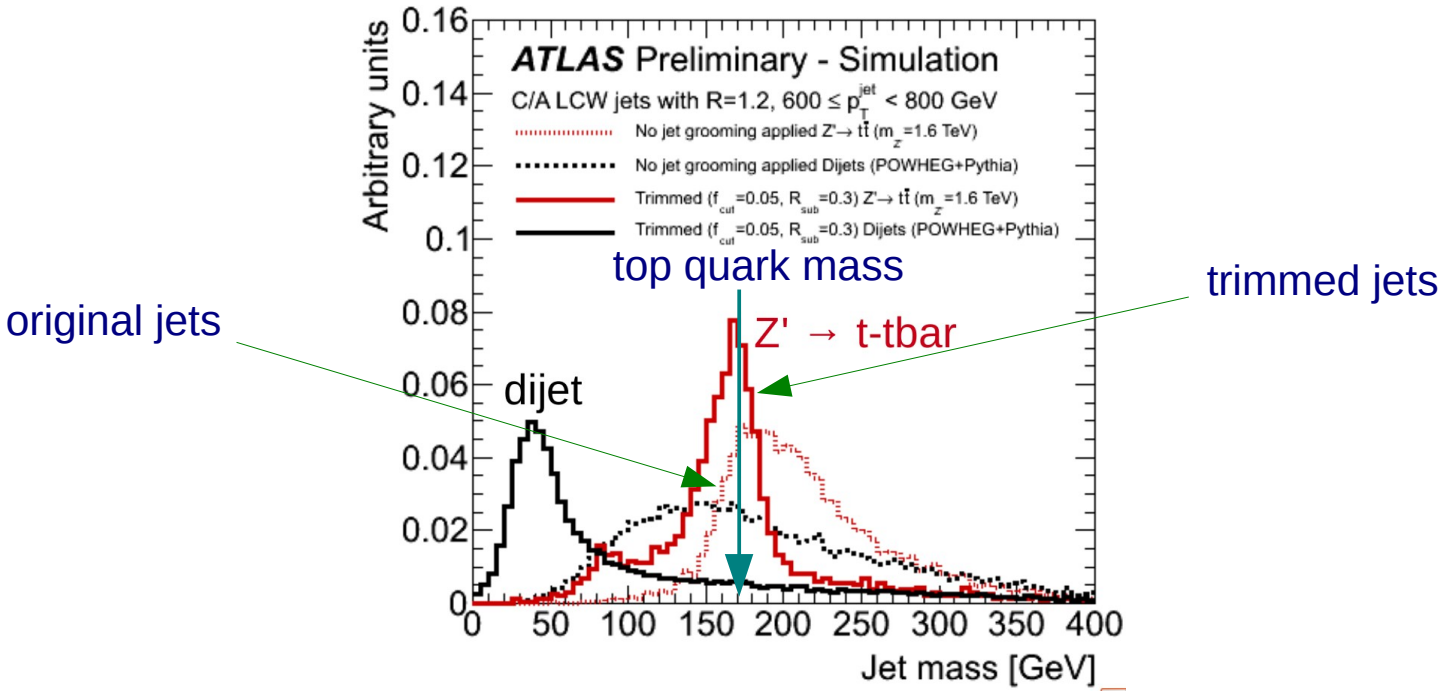
The t*→tg search is motivated by the compositeness theories

Top jet substructure

- Reconstruct “fat” jet with large cone (e.g. use Cambridge-Aachen clustering with R≥0.8 cone)
- Run jet pruning/trimming: remove low p_T & large angle particles (i.e. pile-up, underlying event, …)
  - $\frac{min(p_T^i, p_T^j)}{p_T^{i+j}} < z_{cut}$, $\Delta R_{ij} > \alpha \times \frac{m^J}{p_T^J}$, z_{cut}~0.1, α~0.5

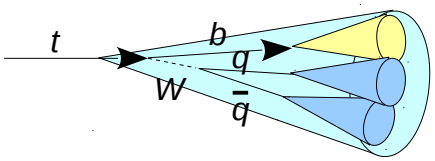


- Reconstruct mass of the resulting jet:
  - $m_{jet}^2 = (\Sigma_i E_i)^2 - (\Sigma_i p_i)^2$



$t\bar{t}$ resonances (1)

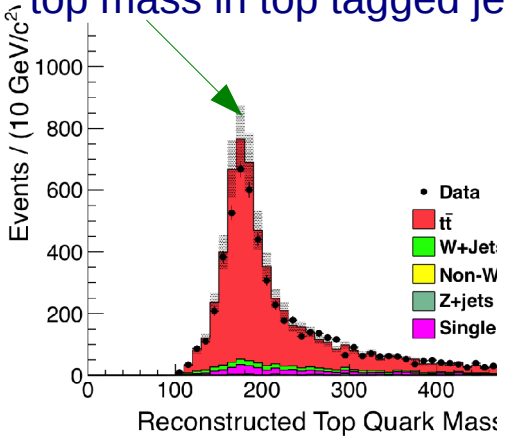
CMS-B2G-12-005, a search for $t\bar{t}$ resonances in events with ≥2 top-tagged jets:

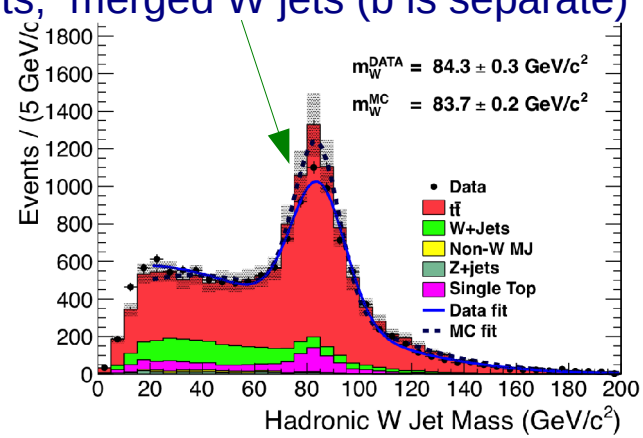


top-tagged jet (p_T>400 GeV/c):

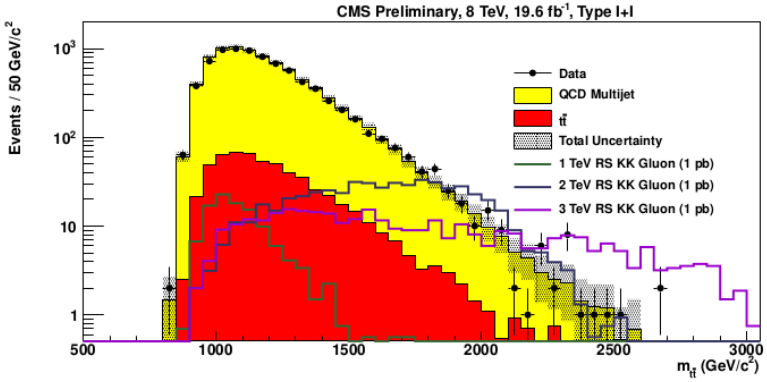
- find ≥3 subjets (reverse CA)
- 140 < m_{jet}(GeV/c^2) < 250
- $m^{min}_{2\ subjets}$ > 50 GeV/c^2

top mass in top tagged jets; merged W jets (b is separate)





Invariant mass of 2 top-tagged jets:



Results (exclusions):

- Topcolor Z': $M_{Z'}$>2.35 TeV ($\Gamma_{Z'}/M_{Z'}$=10%)
- Randall-Sandrum KK gluon: $M_{RS\ KK}$>1.8 TeV
- limit on generic enhancement in M_{tt} spectrum excludes everything that predicts more than 1.79 × SM expectation for M_{tt}>1TeV/c^2

$t\bar{t}$ resonances (2)

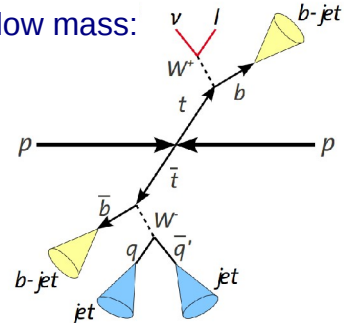
CMS-B2G-12-006, ATLAS-CONF-2013-052: searches for $t\bar{t}$ resonances in ℓ + jets channel:

- light resonances: 1 e/μ + ≥ 4 jets + $\not{E}_T$
- heavy resonances: 1 e/μ + ≥ 2 (merged) jets + $\not{E}_T$

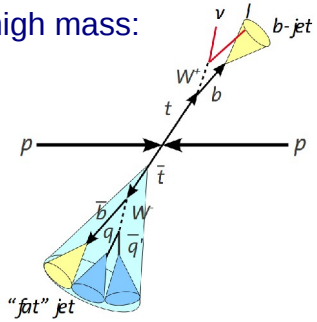
Fully and partically data-driven backgrounds (e.g. W+jets and $t\bar{t}$)

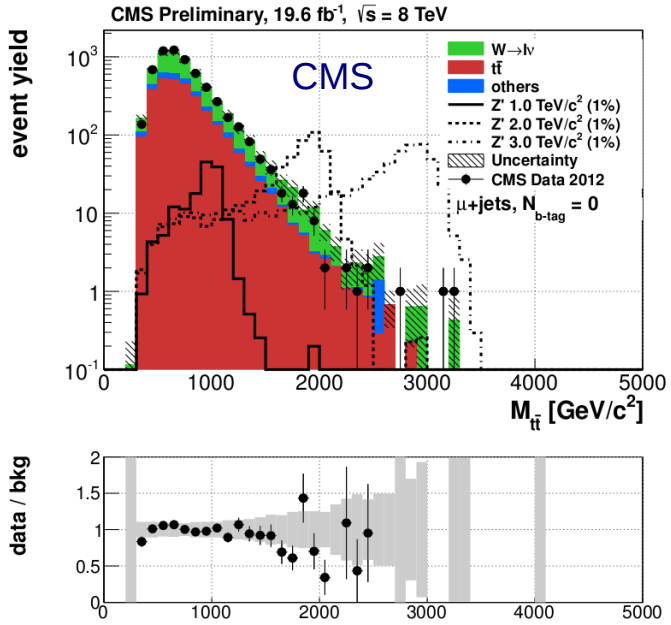
ATLAS is also using top-tagging for the hadronic "fat" jet

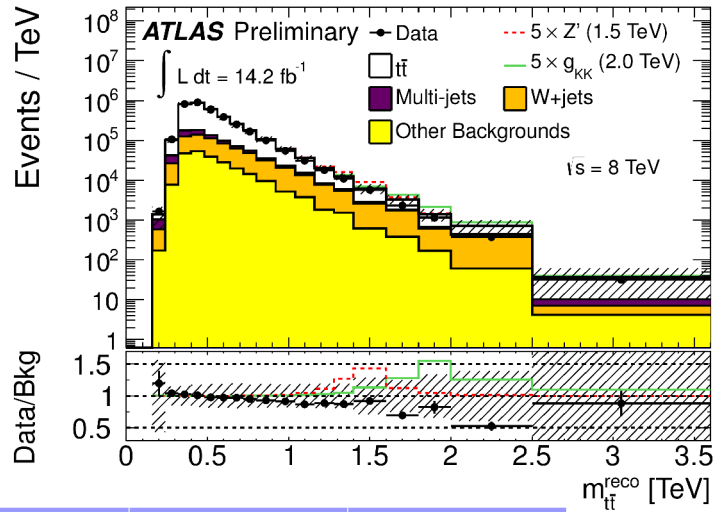
low mass:



high mass:







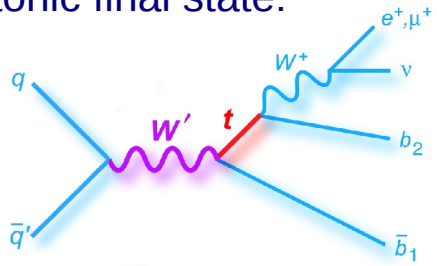
Results (exclusions on mass in TeV):

model	CMS	ATLAS
$m(Z'_{topcolor})$	$>2.10_{\Gamma=1.2\%}$	$>1.8_{\Gamma=3\%}$
$m(gluon_{RS})$	>2.54	>2.0

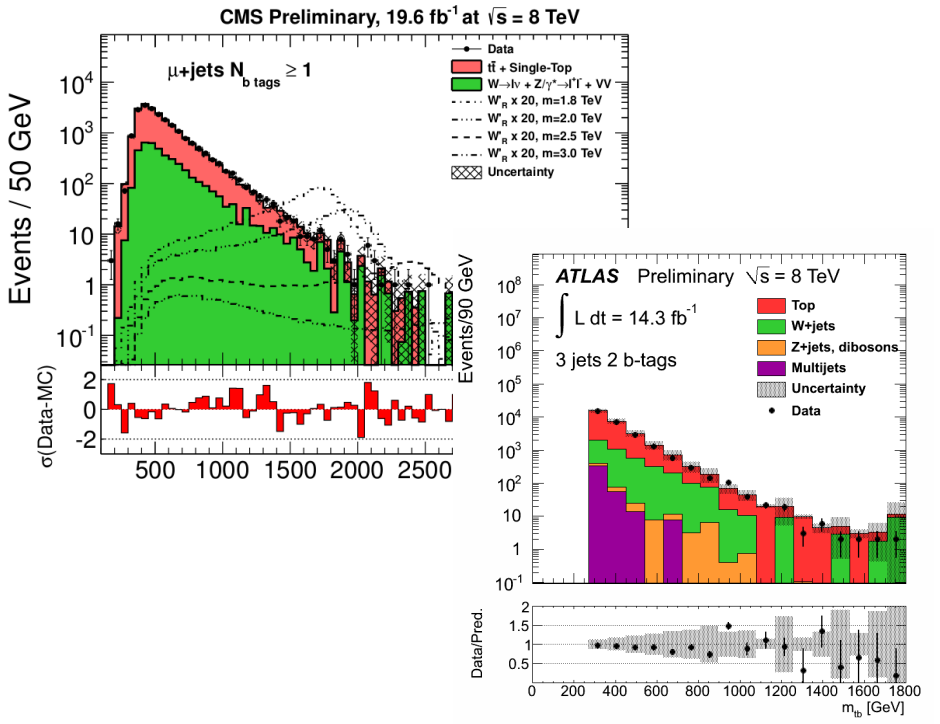
t+b resonances

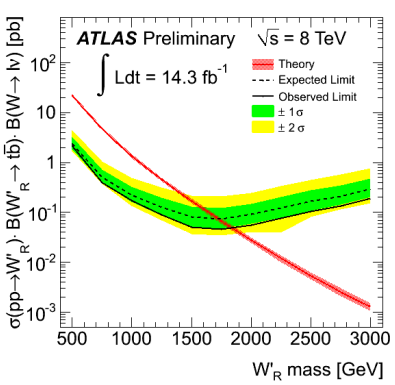
CMS-B2G-12-010, ATLAS-CONF-2013-050: search for a W'→tb in leptonic final state:

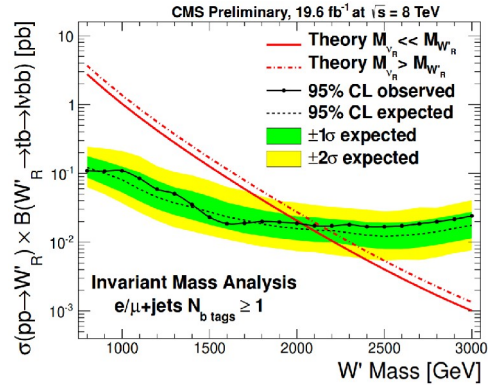
- look for events with: 1 isolated e or μ + ≥2 jets + ≥1 b-tag + $\not{E}_T$ (+M_T)
- reconstruct top quark using m(jet+ℓ+ν) = m_{top} (first find p^{ν}_z from m(ℓ+ν) = m_W)
- check spectrum of m(top + another jet) for deviations from SM predictions:



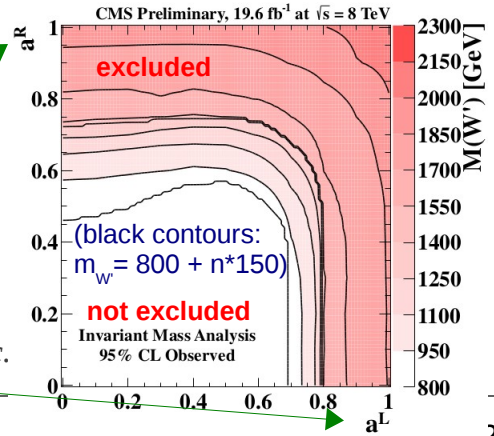
Results: M(W'$_R$) > 2.03$_{CMS}$ / 1.84$_{ATLAS}$ TeV:







$$\mathcal{L} = \frac{V_{ij}^{CKM}}{2\sqrt{2}} \frac{e}{\sin\theta_W} \bar{f}_i \left(a^R (1+\gamma^5) + a^L (1-\gamma^5) \right) W'^{\mu} f_j + H.c.$$

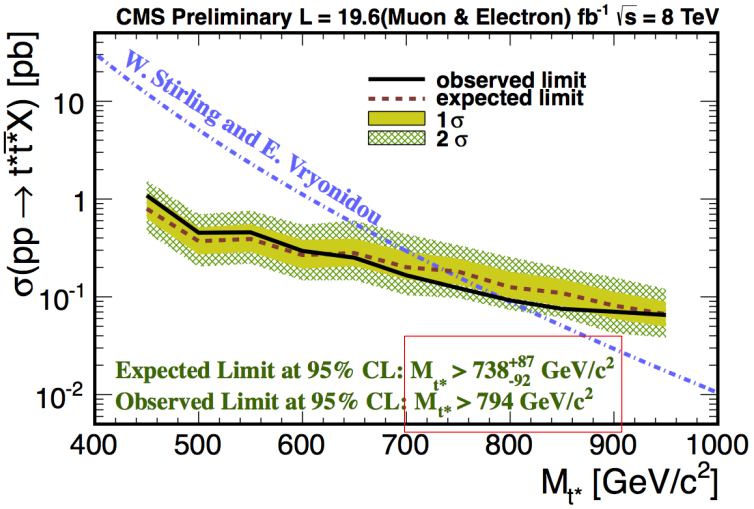


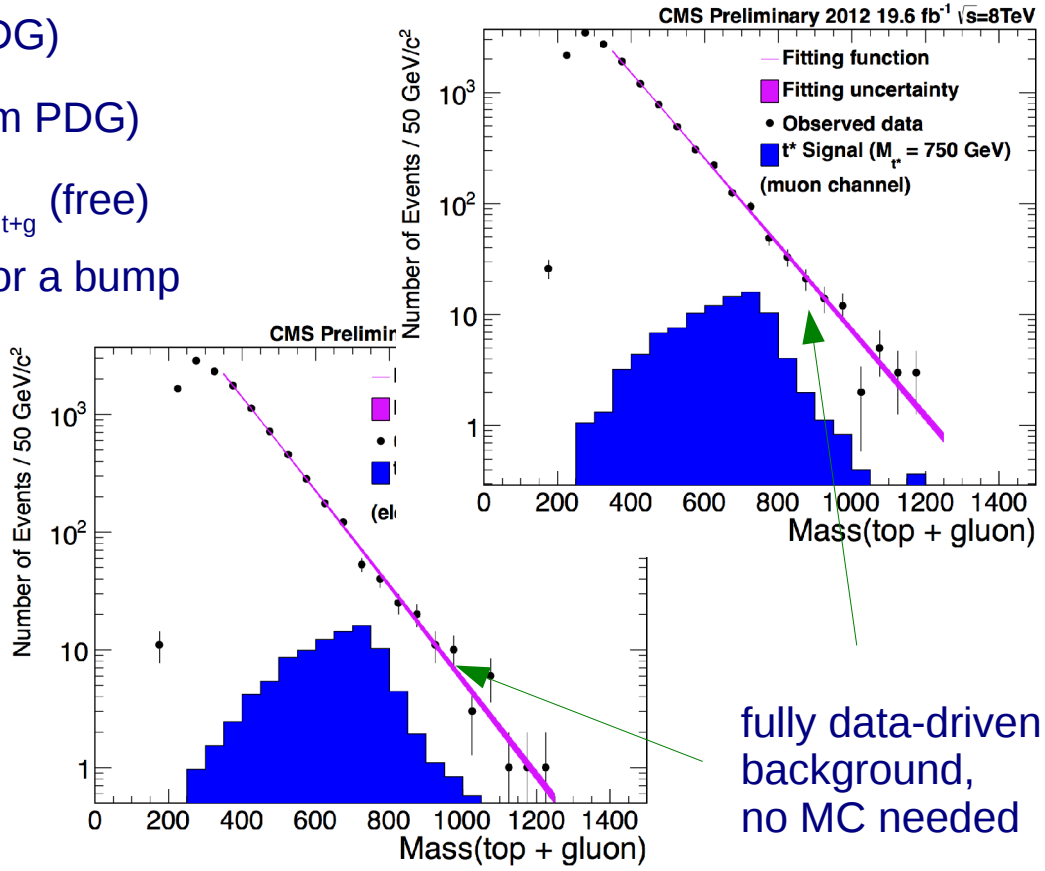
t+j resonances (1)

CMS-B2G-12-014, search for a pair produced excited top quark (t*) in leptonic final state

- signal signature: $pp \to t^*\bar{t}^* \to tg\,\bar{t}g \to$ isolated e or μ + ≥6 jets + ≥1 b-tag
- construct $t^*\bar{t}^* \to (\ell\nu bg)(q\bar{q}bg)$ event using kinematic reconstruction:
  - $m(\ell+\nu) = m(q+\bar{q}) = M_W$ (from PDG)
  - $m(\ell+\nu+b) = m(q+\bar{q}+b) = M_t$ (from PDG)
  - $m(\ell+\nu+b+g) = m(q+\bar{q}+b+g) = M_{t+g}$ (free)
- fit the M_{t+g} spectra in data and look for a bump

Results:





fully data-driven background, no MC needed

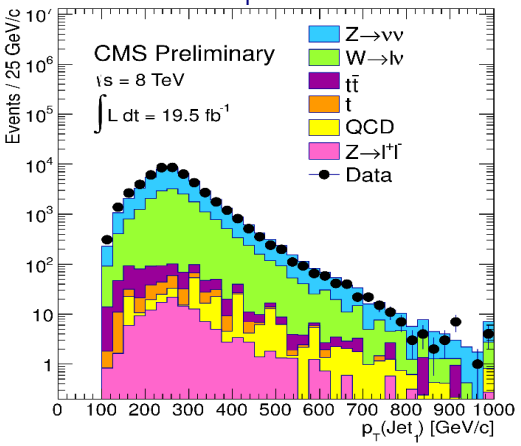
Searches for Extra Dimensions and Dark Matter (large $\not{E}_T$ signatures)

Monojets

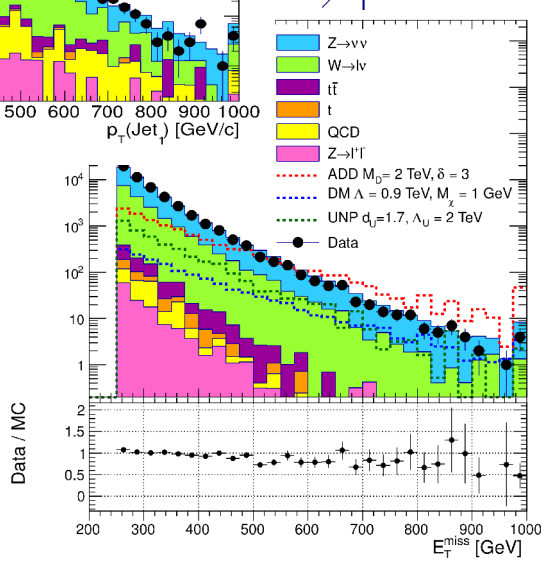
CMS-EXO-12-048, ATLAS-CONF-2012-147: excess of high $\not{E}_T$ events with 1 or 2 high p_T jets

- Non-collision bg. (noise, beam halo, ...) is cut based on balance of jet's deposits in tracker and calorimeters
- Leading SM backgrounds, Z(→νν)+jets and W(→ℓν)+jets, are derived from data requiring muon

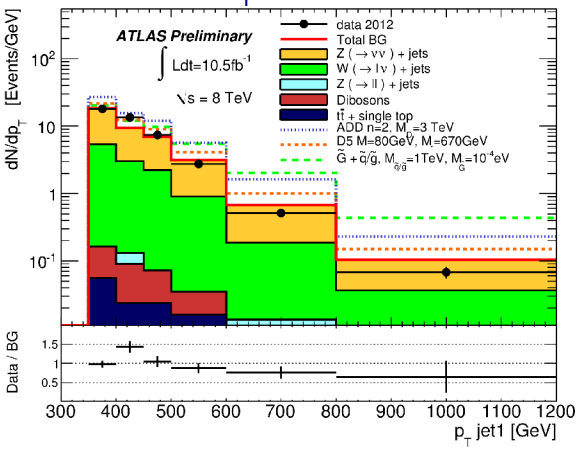
leading jet p_T:



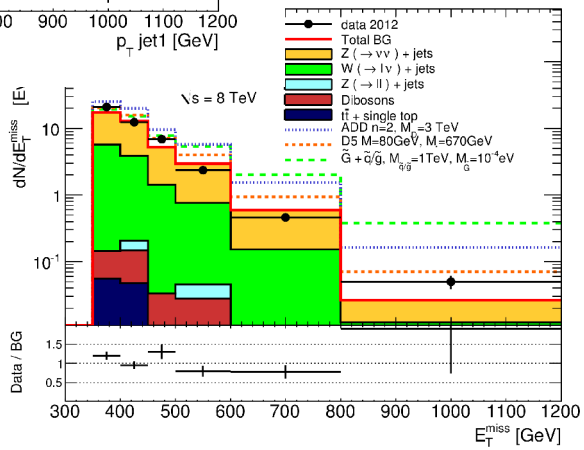
$\not{E}_T$:



leading jet p_T:

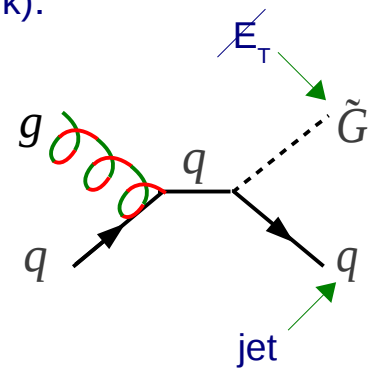


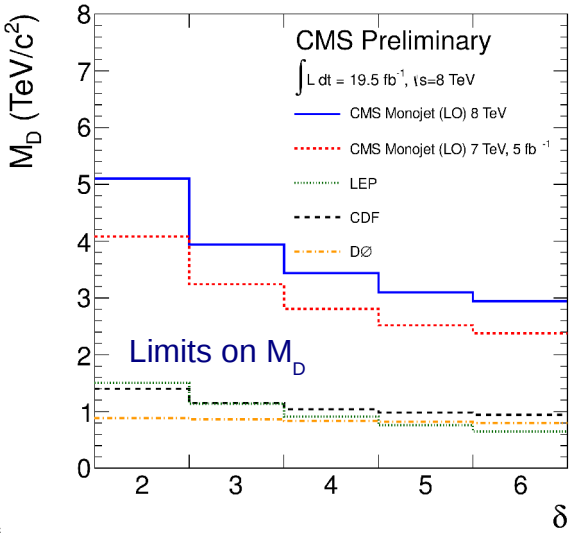
$\not{E}_T$:



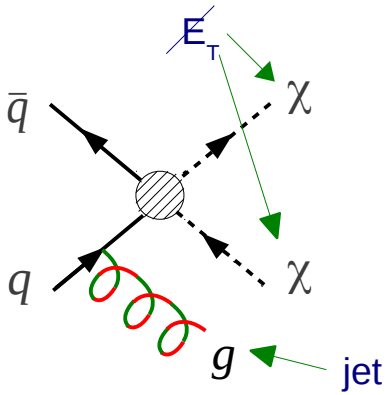
Interpretations for the monojet search

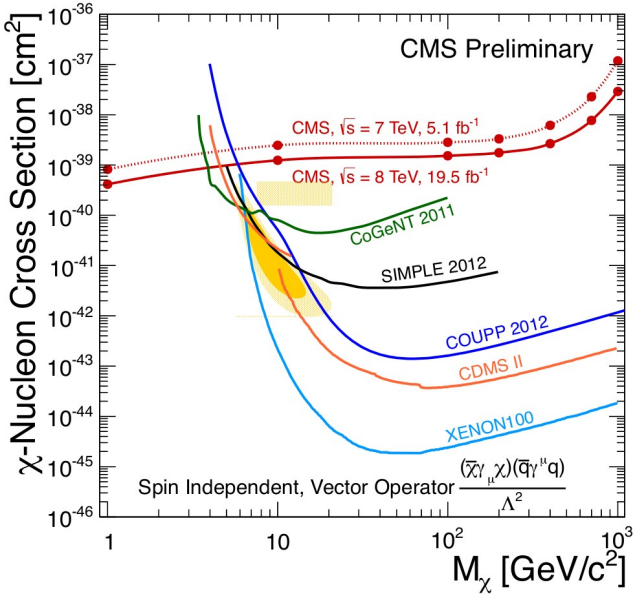
- Large Extra Dimensions (ADD framework):
  - $M_{Pl}^2 \sim M_D^{2+n} \cdot R^n$, where
    - M_{Pl} – 4D Plank mass,
    - n – # of extra dimensions,
    - R – size of extra dimensions,
    - M_D – fundamental Plank scale

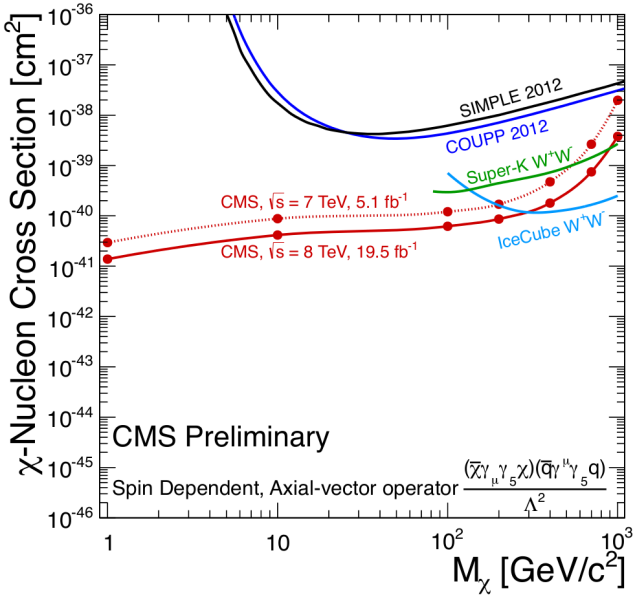




- Weakly Interacting Massive Particles:







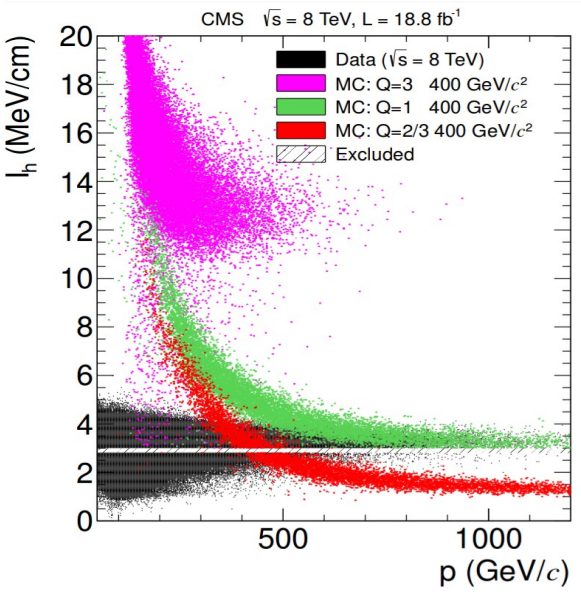
Search for long-lived particles

- Predicted by SUSY and Hidden Valley models
- Many search signatures (some CMS searches are progressing, but not all are yet public):
  - highly displaced vertices
  - highly ionizing (dE/dx)
  - slow (time-of-flight)
  - kinked tracks
  - disappearing tracks
  - highly out-of-time

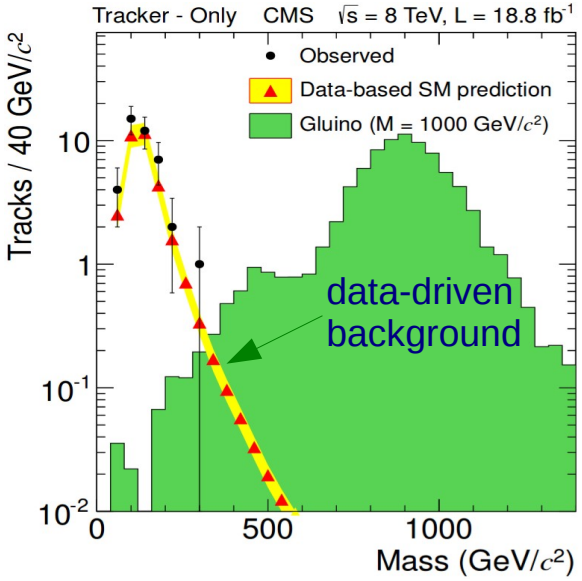
Long-lived charged particles

CMS-EXO-12-026: search for high *dE/dx* (tracker) and long time-of-flight (mu syst.) signatures:

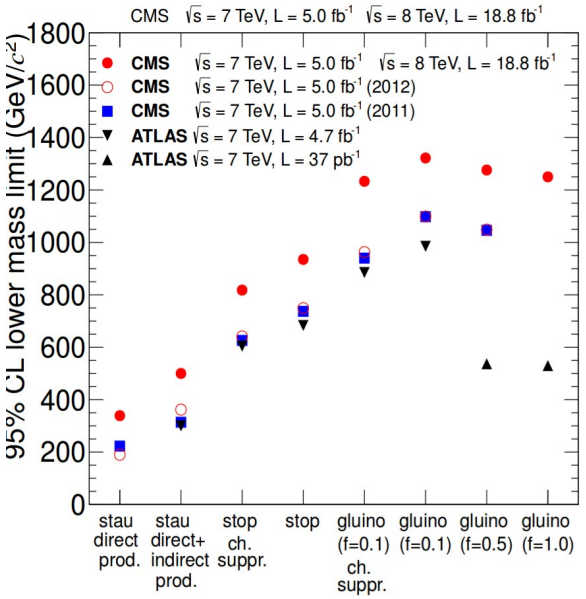
- slow heavy particles or high-charge-multiplicity particles



mass in plots calculated from *p* and *dE/dx* and assuming |*Q*| = 1*e* :



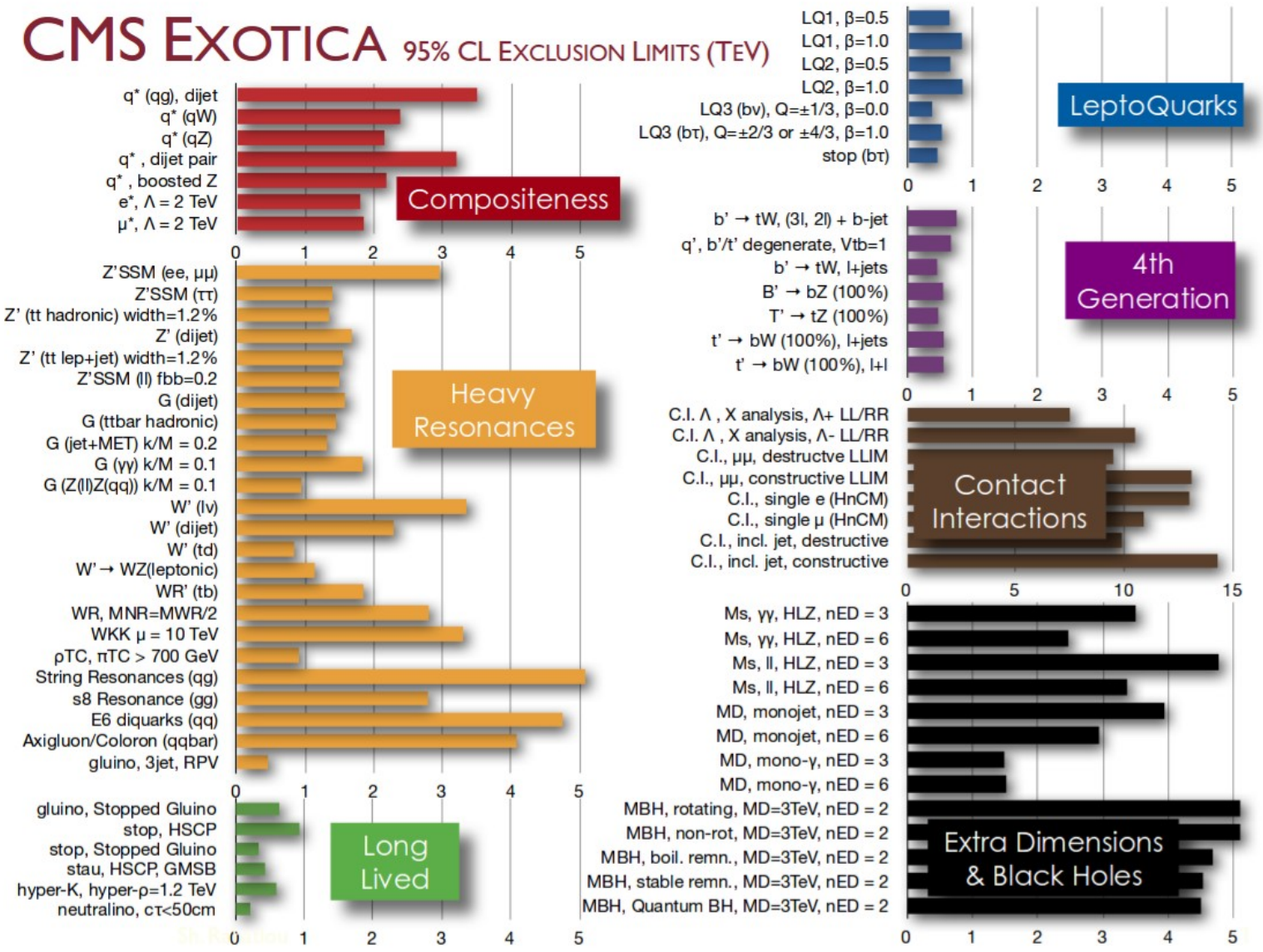
Some of the results:



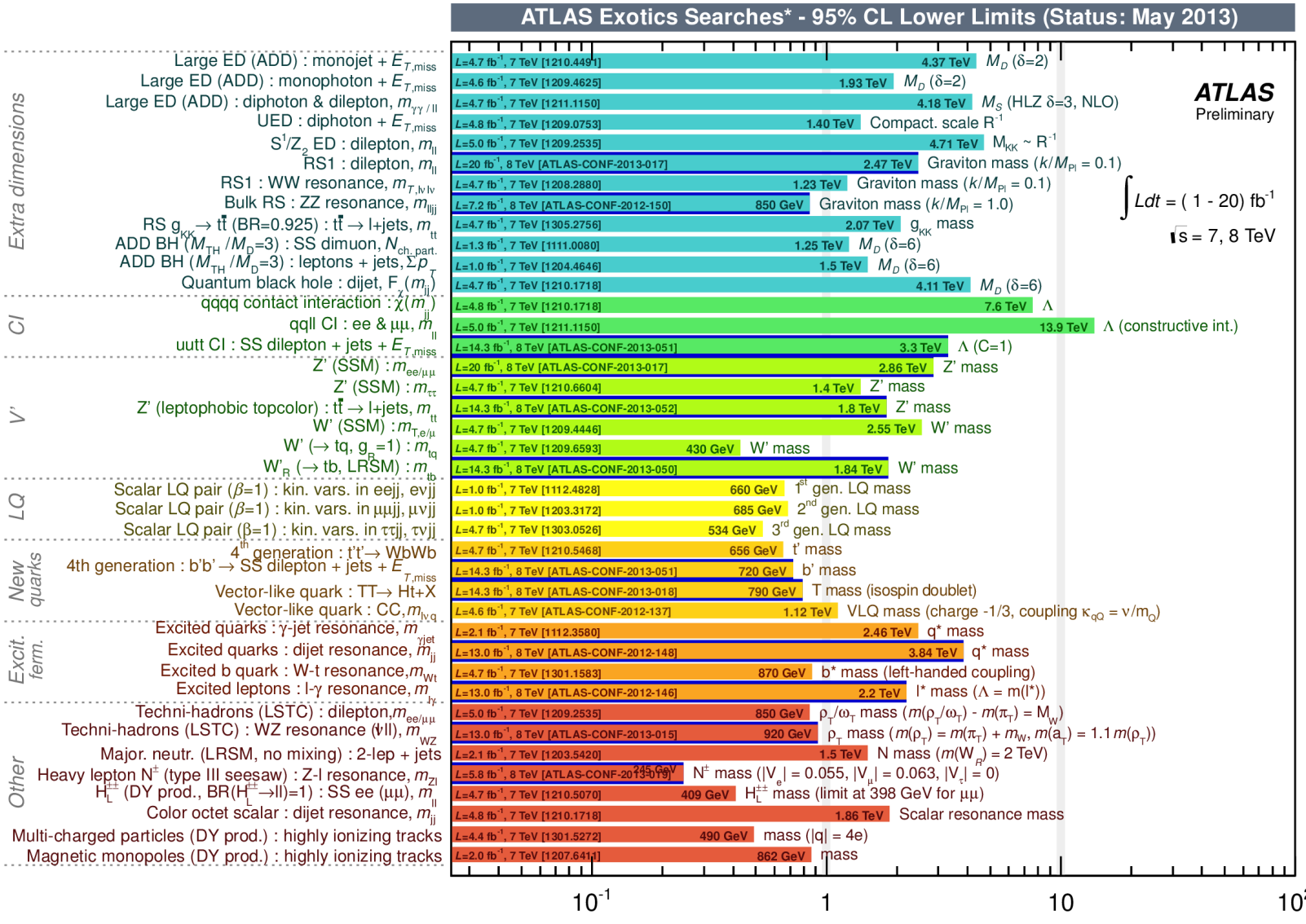
Summary

- Presented are several recent ATLAS & CMS searches for exotic physics with 2012 data
- No deviations from the Standard Model were found
- Some of the limits set on the new physics models:
  - RS KK gluon: M > ~2.5 TeV
  - SSM Z' / W': M > ~3 TeV
  - excited quarks: M > ~4 TeV
  - ADD extra dimensions: M_D > ~5 TeV ($n_{ED} \leq 3$)

Summary CMS


CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Compositeness
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lν)
W' (dijet)
W' (td)
W' → WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Heavy Resonances
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
Long Lived
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
LeptoQuarks
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
4th Generation
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Contact Interactions
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
Extra Dimensions & Black Holes

Summary ATLAS

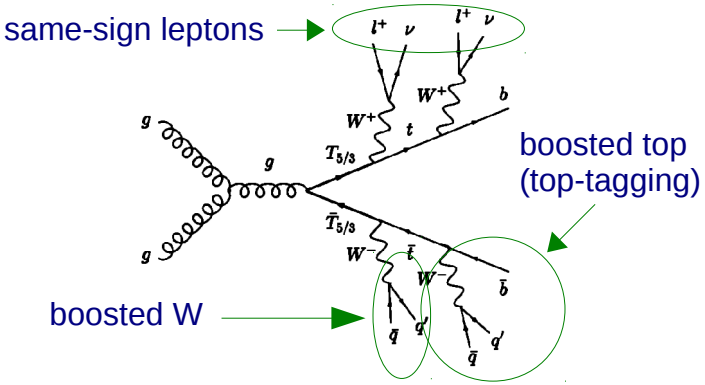


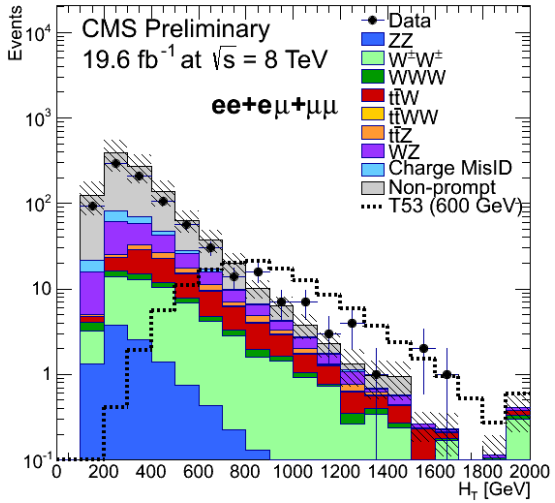
*Only a selection of the available mass limits on new states or phenomena shown

Backup

Analyses with same-sign leptons

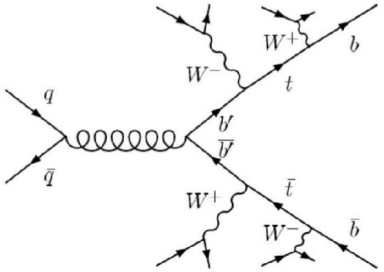
CMS-B2G-12-012: $T_{5/3}T_{5/3} \rightarrow tWtW \rightarrow 4W+2b$

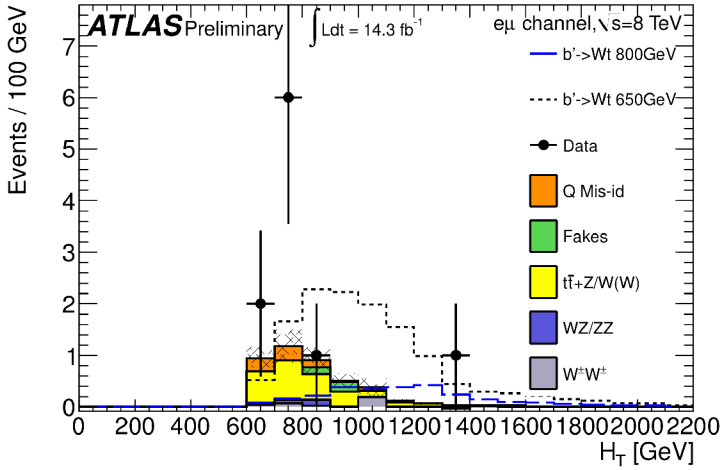




$m(T_{5/3}) > 770$ GeV

ATLAS-CONF-2013-051: $b'b' \rightarrow tWtW \rightarrow 4W+2b$





Assuming BR(b'→Wt) = 100%: $m(b') > 720$ GeV

Bibliography

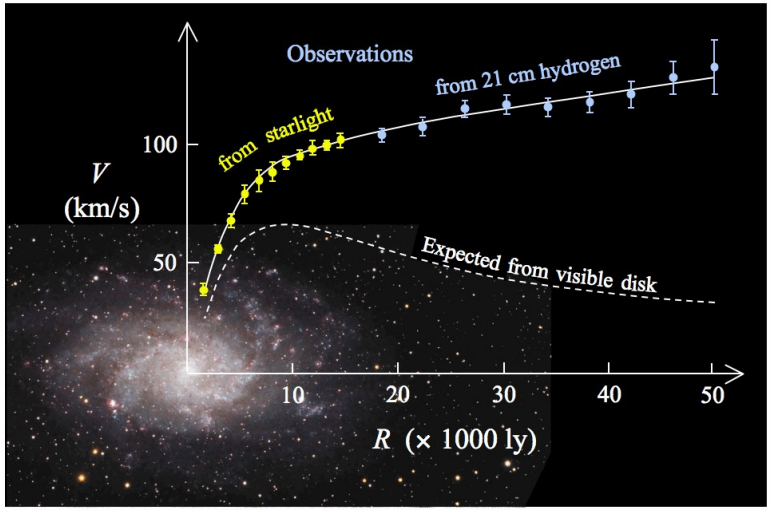
- Search for resonant t t-bar production in lepton+jets events in pp collisions at sqrt(s)=8 TeV, CMS PAS B2G-12-006
- Search for resonant t t-bar production in all hadronic events in pp collisions at sqrt(s)=8 TeV, CMS PAS B2G-12-005
- Search for narrow t+b resonances in the leptonic final state at sqrt(s) = 8 TeV, CMS PAS B2G-12-010
- Search for pair production of new physics resonances decaying to a top quark and jet in the lepton+jets decay channel, CMS PAS B2G-12-014
- Search for anomalous t t-bar production in the highly-boosted all-hadronic final state, 7 TeV, CMS PAS EXO-11-006 (superseded by CMS B2G-12-005)
- Search for Z' resonances decaying to ttbar in dilepton+jets final states in pp collisions at sqrt(s) = 7 TeV, CMS PAS TOP-11-010
- Search for resonant t t-bar production in lepton+jets events in pp collisions at sqrt(s)=7 TeV, CMS PAS TOP-12-017 (superseded by CMS B2G-12-006)
- Search for resonant WZ -> lnu ll production using sqrt(s) = 8 TeV pp collisions with ATLAS, ATLAS-CONF-2013-015
- Search for resonant ZZ production in the ZZ -> llqq channel with the ATLAS detector using 7.2 fb-1 of sqrt(s) = 8 TeV pp collision data, ATLAS-CONF-2012-150

Bibliography (2)

- Search for Narrow Resonances in Dilepton Mass Spectra in pp Collisions at √s = 8 TeV CMS PAS EXO-12-061
- Search for Large Extra Dimensions in Dimuon Events in pp Collisions at √s = 8 TeV CMS PAS EXO-12-027
- Search for Large Extra Spatial Dimensions in Dielectron Production with the CMS Detector CMS PAS EXO-12-031
- Search for new physics in the final states with a lepton and missing transverse energy at √s = 8 TeV, CMS PAS B2G-12-060
- Search for Narrow Resonances using the Dijet Mass Spectrum with 19.6 fb^{-1} of pp Collisions at √s = 8 TeV, CMS PAS EXO-12-059
- Search for Heavy Resonances Decaying into bb and bg Final States in pp Collisions at √s = 8 TeV, CMS PAS EXO-12-023
- Search for new physics in monojet events in pp collisions at sqrt(s) = 8 TeV, CMS PAS EXO-12-048
- Searches for Long-lived Charged Particles in pp Collisions at √s = 7 TeV and 8 TeV, CMS PAS EXO-12-026

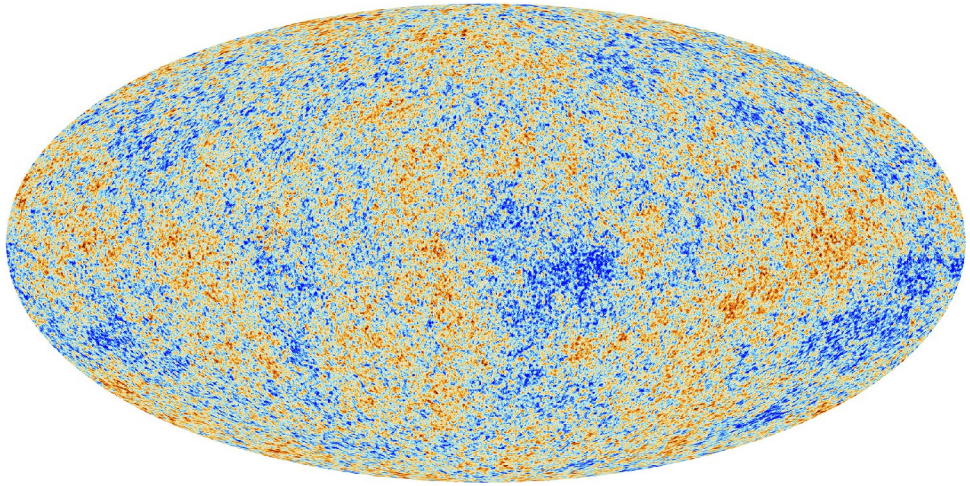
Dark Matter: indirect evidence

Galaxy rotation curves:

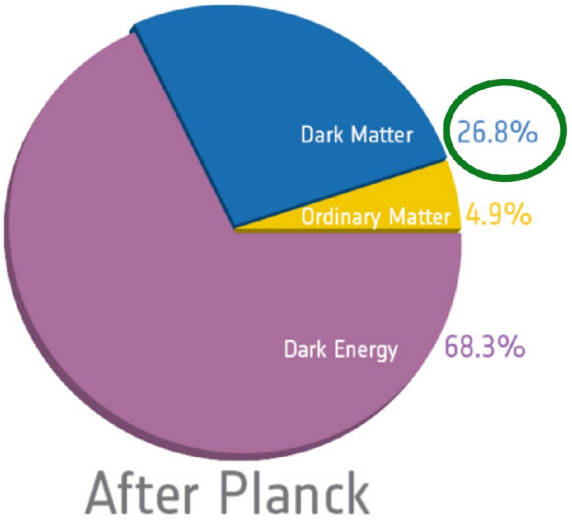


Gravitational lensing:

Cosmic microwave background:



fitting ΛCDM

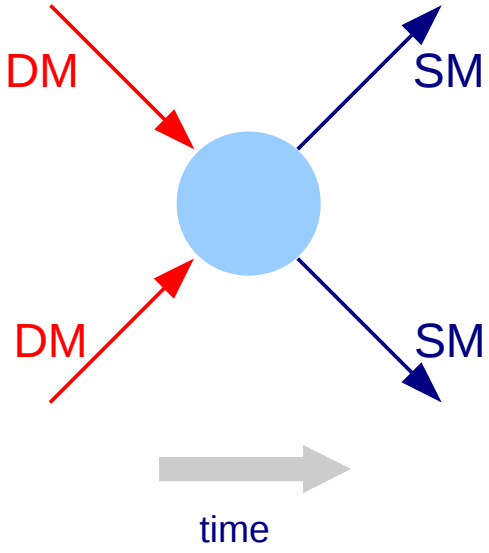


Dark Matter: candidates

- Weakly Interacting Massive Particles (WIMPs, in this talk)
  - **Weakly Interacting**: right relict abundance without fine-tuning
  - **Massive**: cold dark matter ($v \ll c \rightarrow$ won't smear large-scale structure of universe)
  - Side product of R-parity conserving SUSY
- Sterile neutrinos (not in this talk)
  - Neutrinos in Standard Model are left-handed; right-handed analog would be invisible
- Axions (not in this talk)
  - hypothetical $U_{PQ}(1)$ field solving strong CP problem (making QCD Lagrangian CP-invariant)

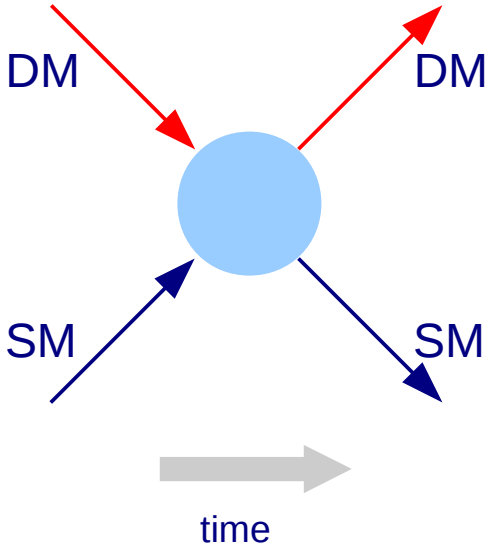
Dark Matter: searches

indirect detection:



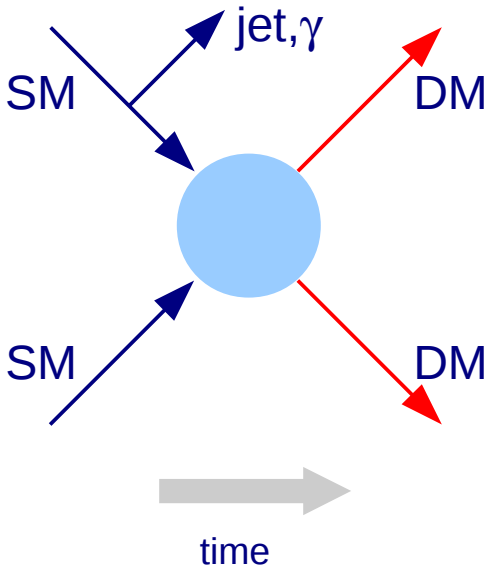
searches in space

direct detection:



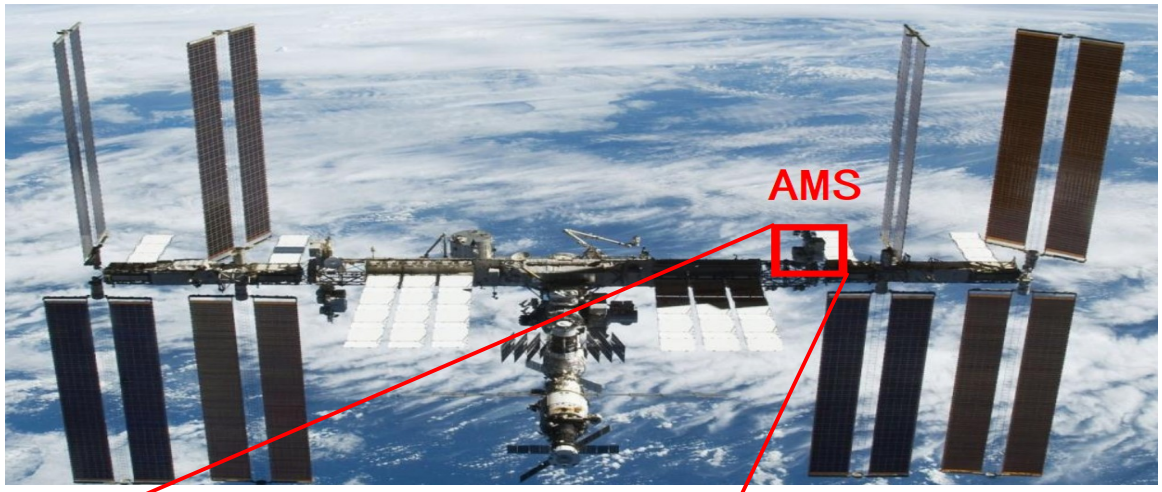
solid-state searches

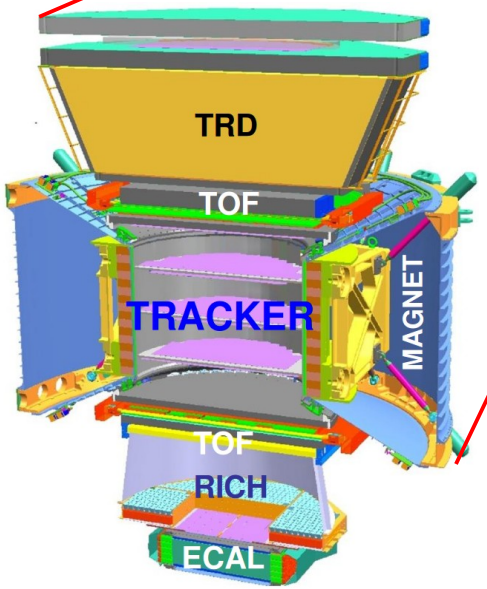
colliders:



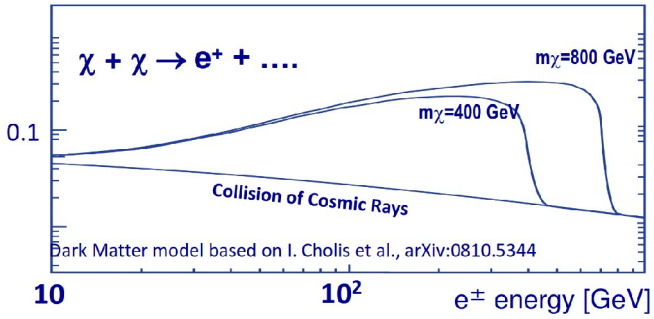
Mono-jet/-photon searches

Indirect searches: new AMS results

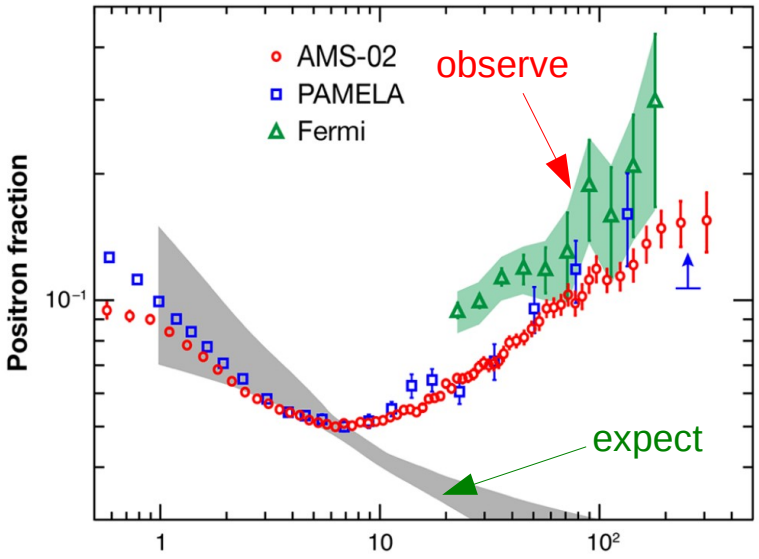




Model example:

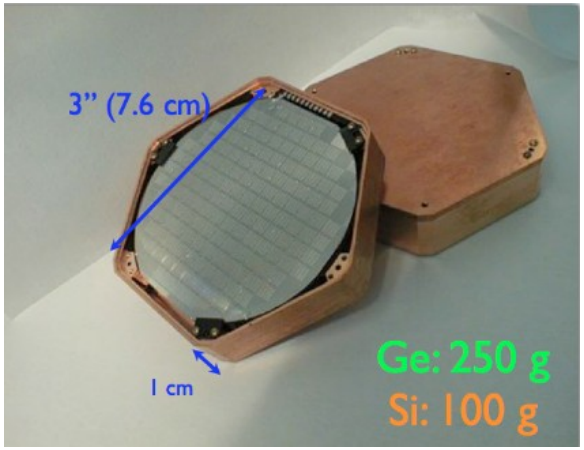


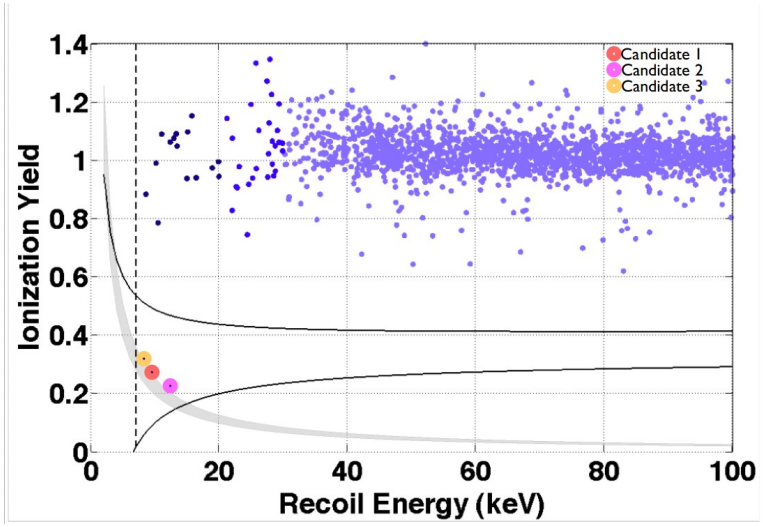
AMS confirms PAMELA and Fermi:

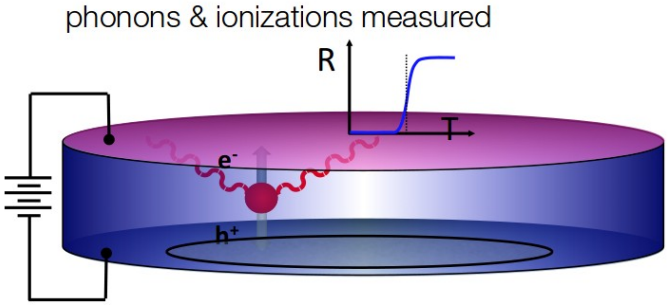


Very interesting results, but many puzzles remain (e.g. no excess of anti-protons)

Direct searches: hints from SuperCDMS







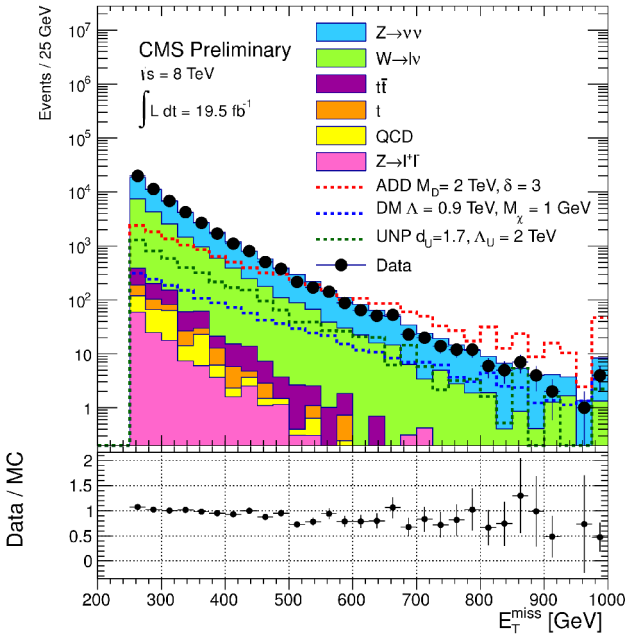
- 3 events in signal region at 140 kg-day exposure.
- Likelihood test favors WIMP+background at ~3σ
- The maximum likelihood occurs at m_{WIMP}= 8.6 GeV and $\sigma_{SI}=1.9\times10^{-41}$ cm^2

Monojets

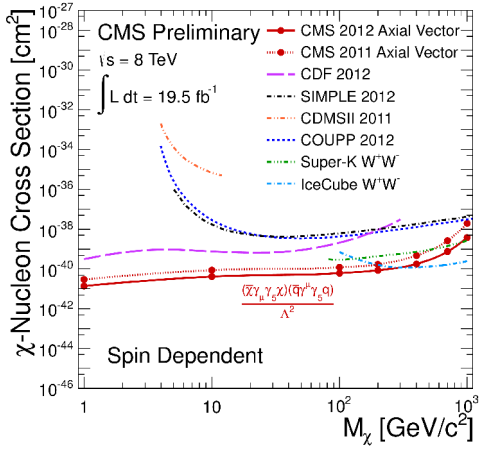
CMS-EXO-12-048, ATLAS-CONF-2012-147: excess of high $\not{E}_T$ events with 1 or 2 high p_T jets

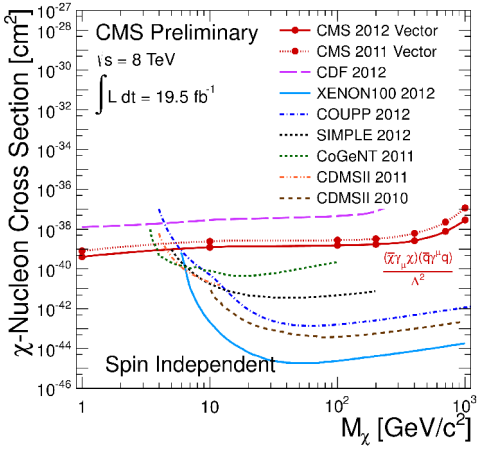
- Non-collision bg. (noise, beam halo, ...) is cut based on balance of jet's deposits in tracker and calorimeter
- Leading SM backgrounds, Z(→νν)+jets and W(→ℓν)+jets, are derived from data requiring extra muon:

$$N(Z\to\nu\bar{\nu}) = \frac{N(Z\to\mu\mu)-N(bg)}{A\times\epsilon}\cdot\frac{Br(Z\to\nu\bar{\nu})}{Br(Z\to\mu\mu)} \quad \text{and} \quad N(W\to lost\, l\,\bar{\nu}) = (1-A\times\epsilon)\cdot N_{total},\ N_{total} = \frac{N(W\to l\bar{\nu})-N(bg)}{A'\times\epsilon'}$$



Limits on WIMP pair production:

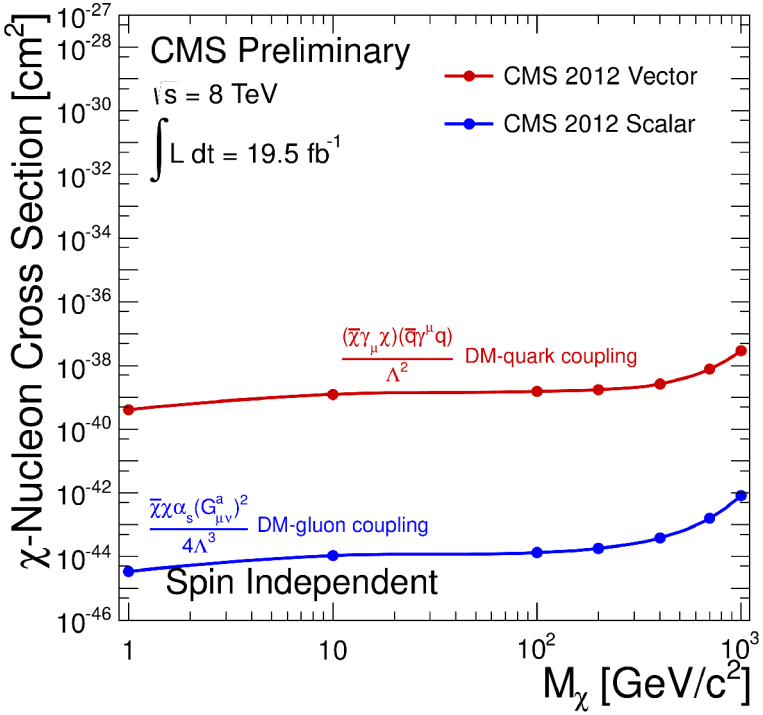


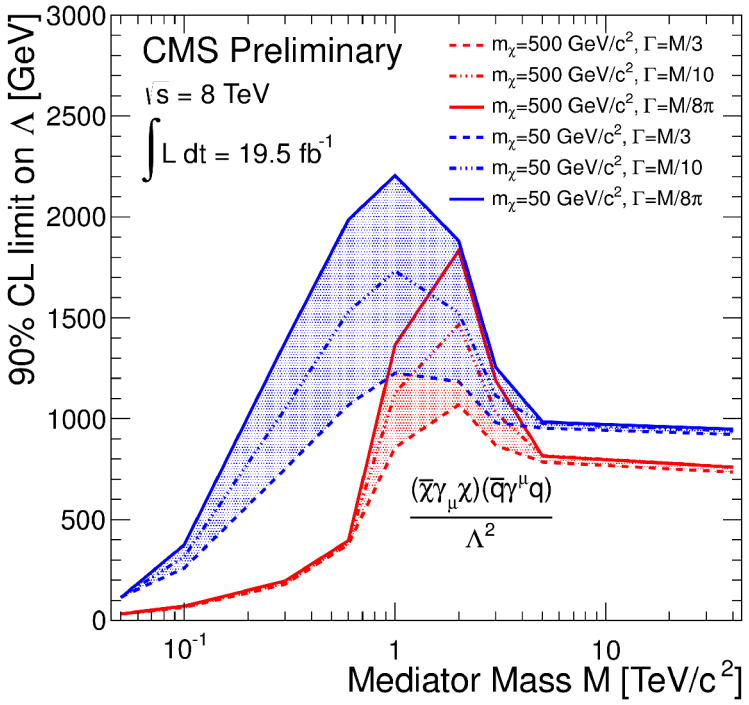


Limits on ADD fundamental scale M_D (TeV):

N^{dim}	2	3	4	5	6
LO	5.1	3.9	3.4	3.1	2.9
NLO	5.7	4.3	3.7	3.3	3.1

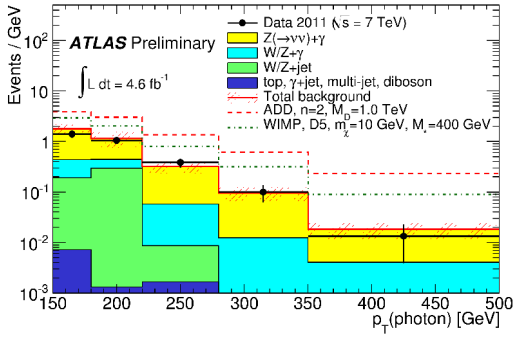
Dark matter in the monojet search



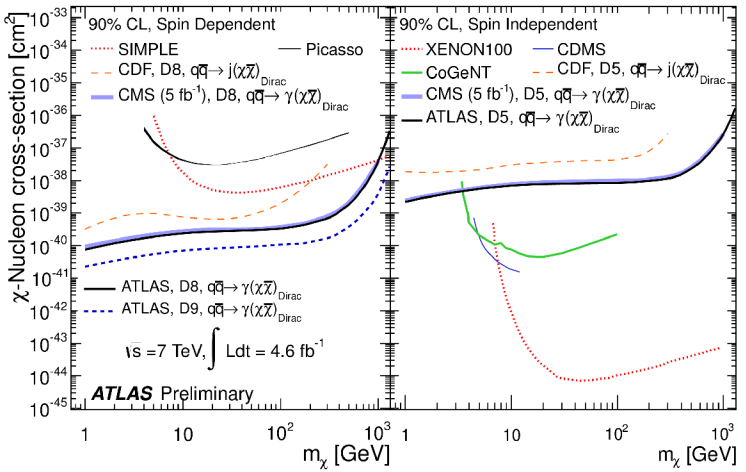


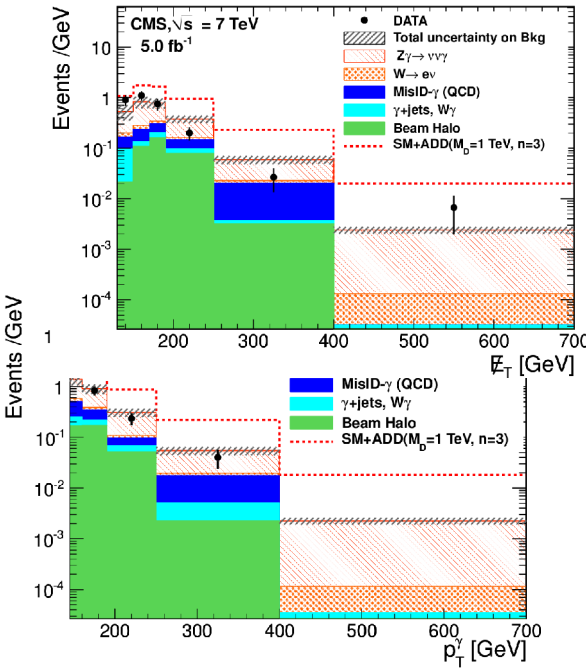
Monophoton search

- ATLAS-EXOT-2012-05 and CMS-EXO-11-096 analyses probe excess of high (>150-130GeV) $\not{E}_T$ events in association with a high (>~150GeV) p_T isolated photon, vetoing events with leptons
- Non-collision bg.: halo, cosmics, spikes, … (cut using shower shape, timing, veto on non-IP muons)
- Leading SM backgrounds: QCD (jet faking photons), $Z(\rightarrow \nu\nu)+\gamma$, $W(\rightarrow \ell\nu)/Z(\rightarrow \ell\ell)+\gamma$, all data driven (e.g. key distributions in control regions of enriched QCD by limiting MET, W/Z by selecting events with ℓ,...)



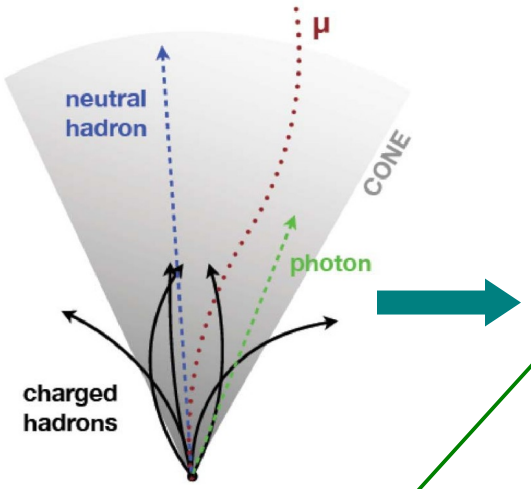
Results on paired WIMP production:



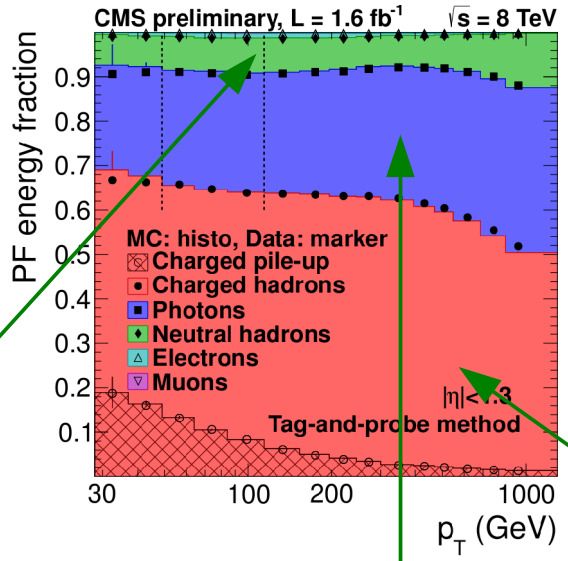


Physics objects: jets

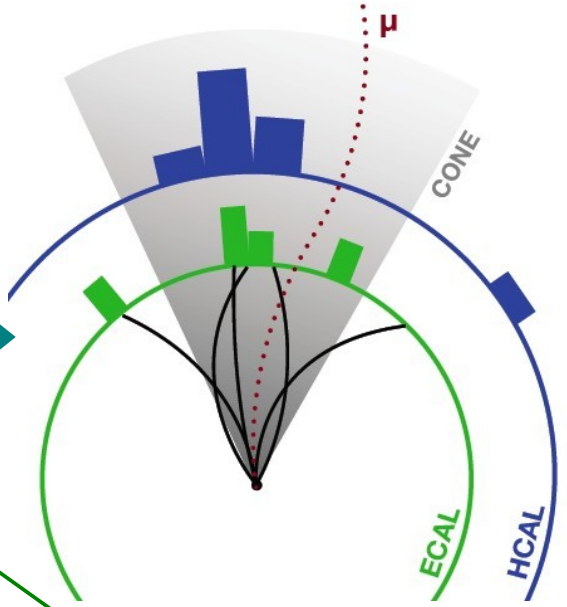
Jet:

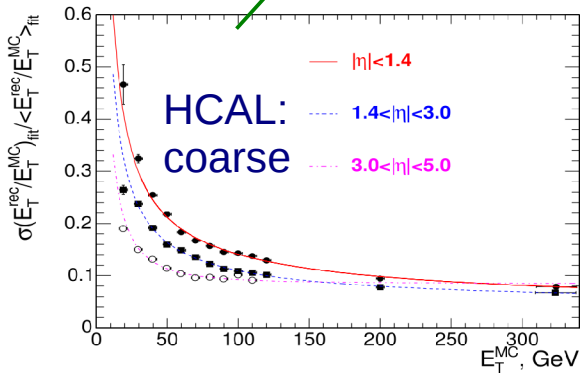


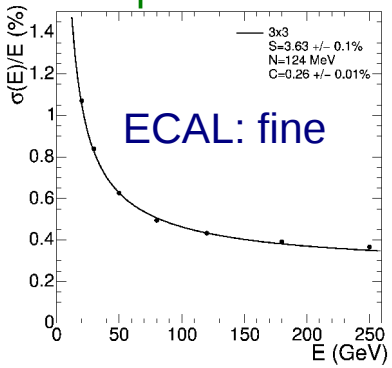
Jet composition:

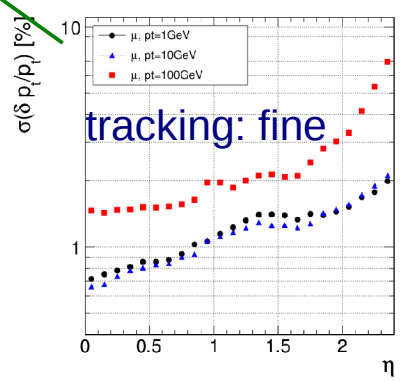


Deposits in subdetectors:







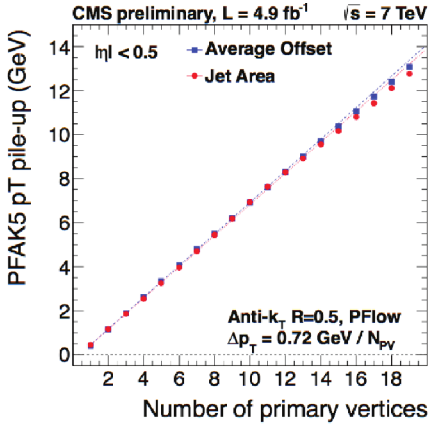


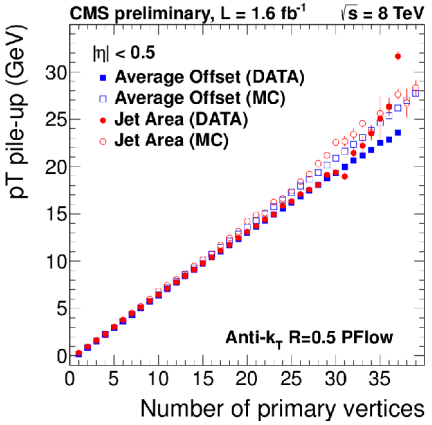
Particle Flow reconstruction takes advantage of best information available to construct a jet

Jet resolution

Offline jet energy calibration (same is used in ATLAS):

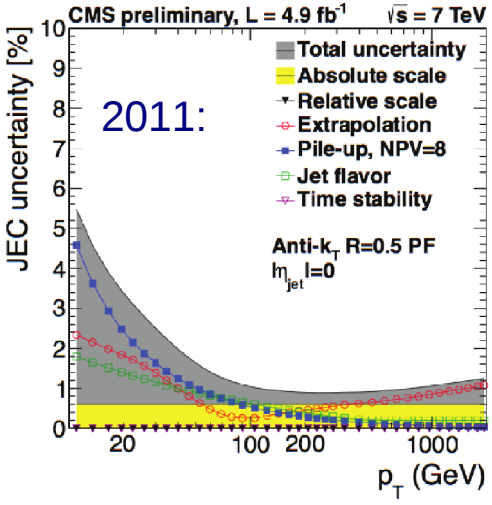
- offset expected pile-up deposits within jet area:
- relative (spatial-η) calibration:
  using di-jet balance correct jet response for arbitrary η wrt. jet response in the central region
- absolute (energy scale) calibration:
  using Z/γ + jet event balance set the absolute jet response scale using Z→ee/μμ p_T measurement

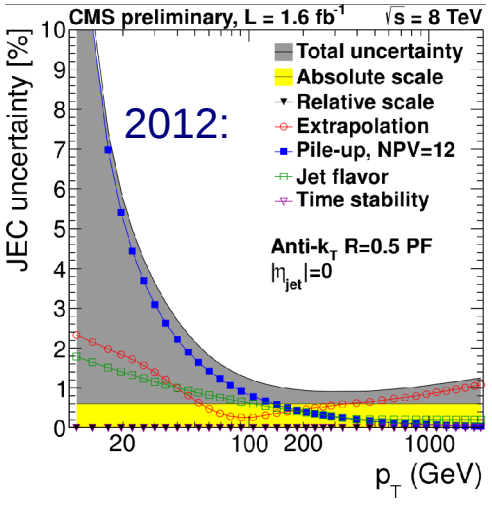




Resulting jet energy uncertainty:

- jet energy scale is known at ~2%





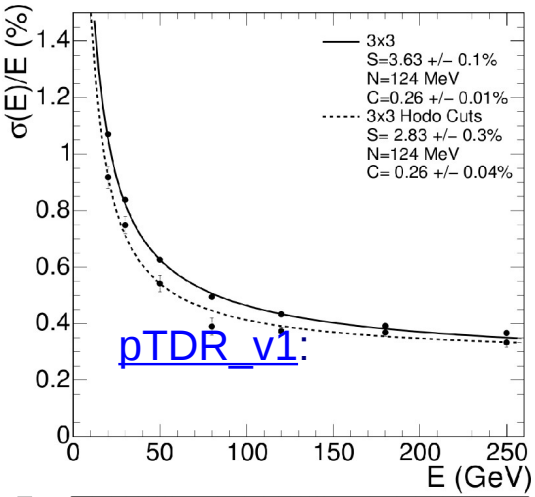
Physics objects: electrons and muons

Electron:

- essentially it is a track matched to an EM cluster with $E_{cal}/p_{trk} \sim 1$

  (current MVA ID scheme uses ~20 handles controlling matching, cluster shape, track quality, ...)
- p_T assignment: relies on ECAL energy resolution:

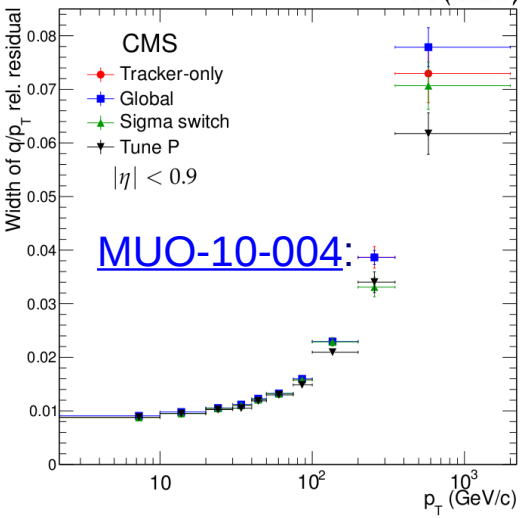
  (2012: $\delta p^e_T/p^e_T = \delta m_Z/m_Z$ = 1-2.6 GeV / 91GeV ~ 1-3% tr1%)



Muon:

- essentially this is a track matched to hit(s) in the muon system
- p_T assignment: tracker + muon hits for a really stiff tracks:

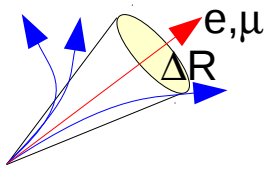
  (for electrons resolution flattens; for muons it degrades with p_T)



Lepton isolation (discriminating jets with leptons and prompt leptons):

- tracker: $Iso_{TRK} = \Sigma p^{trk}_T$, tracks of same vertex in cone $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$
- calorimeter: $Iso_{ECAL,HCAL} = \Sigma e_i$ corrected for the track's p_T and pile-up
- combined: $Iso_{comb} = \Sigma(\alpha\, Iso_{TRK} + \beta\, Iso_{ECAL} + \gamma\, Iso_{HCAL})$

  (often the choice of α, β, and γ is analysis dependent)



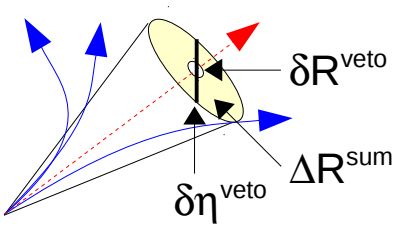
Physics object: photon

Prompt photon's signature:

- no trices in tracker
- clustered deposits in ECAL
- little (or no) deposits in HCAL

Basics of photon identification:

- $Iso_{TRK} = \Sigma p^{trk}_T$ in cone $0.04<\Delta R<0.4$
- $Iso_{ECAL} = \Sigma e_i$ in a similar size cone
- $Iso_{HCAL} = \Sigma e_i$ in cone $0.15<\Delta R<0.4$
- $H/E = E^{ECAL}/E^{HCAL}$ in cone $\Delta R<0.15$
- $\sigma_{i\eta i\eta}$ – cluster shape in η-projection (highly localized for e/γ)

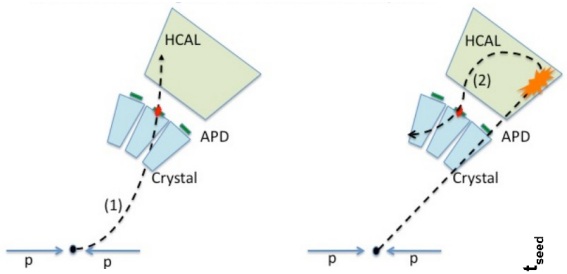


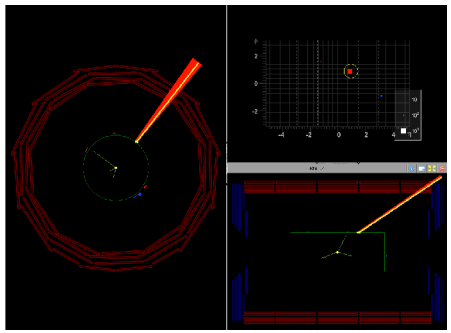
CMS features:

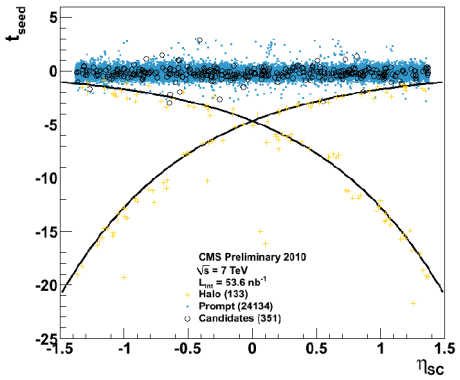
- very fast ECAL: 80% of light within 25ns (<1ns time resolution for impact time!)
- relatively high material budget: ~1X_0 before ECAL (brem and conversion: e → eγ and γ→e^+e^-)

Instrumental backgrounds:

- spikes – vetoed by shower shape and timing:
- cosmics – primary vertex requirement
- beam halo – vetoed by endcap muon chambers and time of impact (negative time)



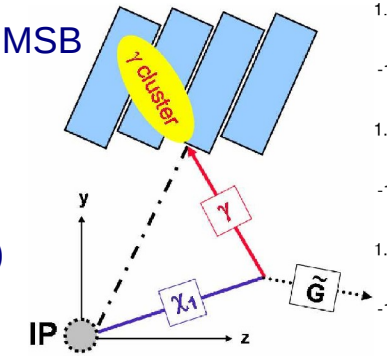


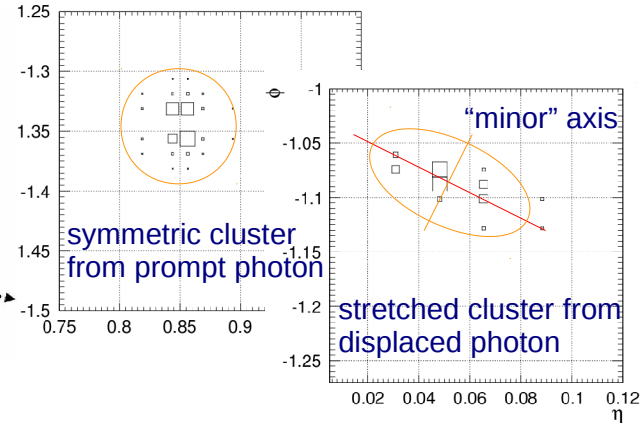


Displaced and delayed photon

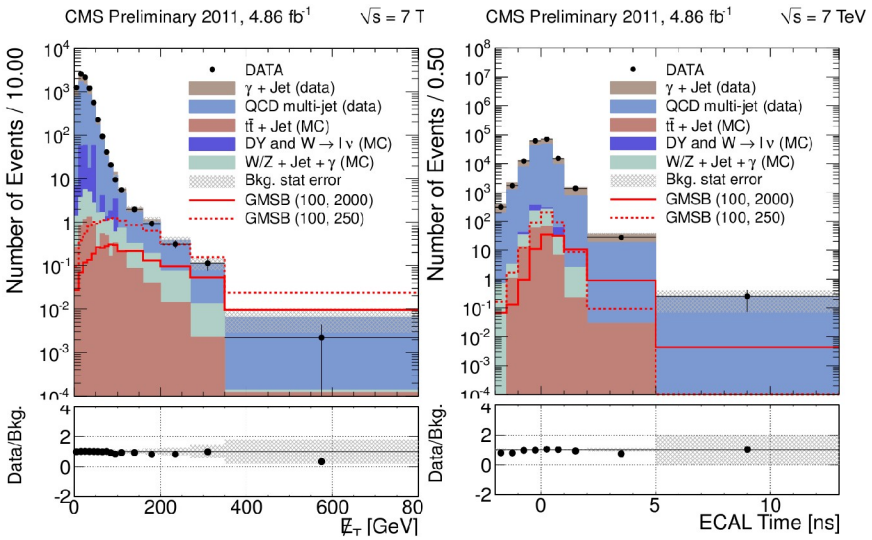
Selection: γ + 3 jets (p^{jet}_T>35 GeV) aimed at same GMSB

- single photon trigger (sharp turn-on, ε~100%)
- energetic photon in barrel (p^{γ}_T>100 GeV, $|\eta^{\gamma}|$<1.4)
- Iso_{ECAL}, Iso_{HCAL}, Iso_{Trk} (<5%, 5%, 10% E^{γ}_T; 2.4 GeV)
- e/γ-like cluster shape projected on “minor” axis
- no ±3ns window, EMu halo veto, spikes cleaning, ...



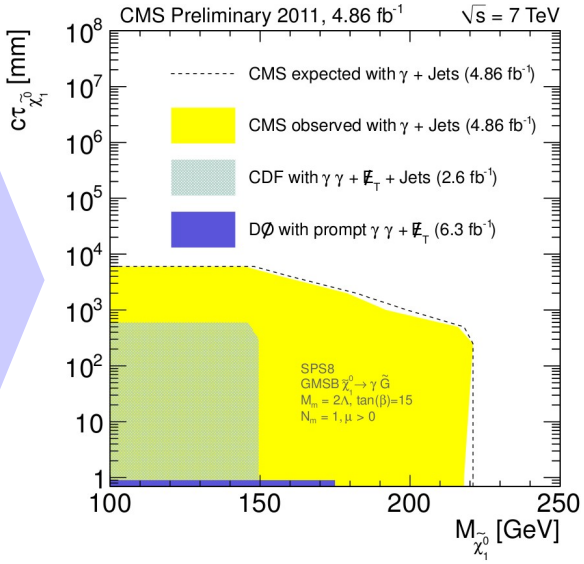


Main backgrounds: QCD and γ+jets; their shapes are taken from background enriched control data regions (made by relaxing isolation cuts for QCD or relaxing/inverting γ+jets specific cut: $\Delta R_{\gamma,jet} > 2/3$, $0.6 < p_T^{jet}/p_T^{\gamma} < 1.4$)



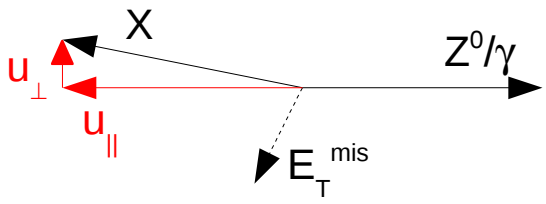
CMS-EXO-11-035:

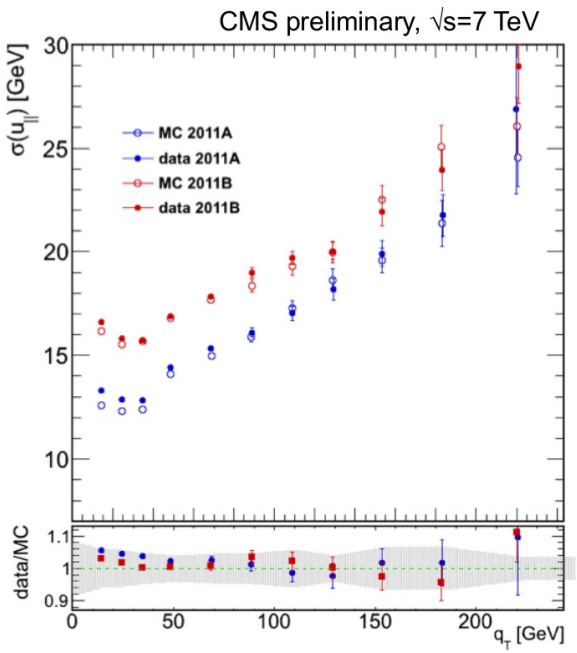
Simultaneous fit of $A \cdot PDF_{sig} + \Sigma C_i \cdot PDF_{bg,i}$ in the two views to the data

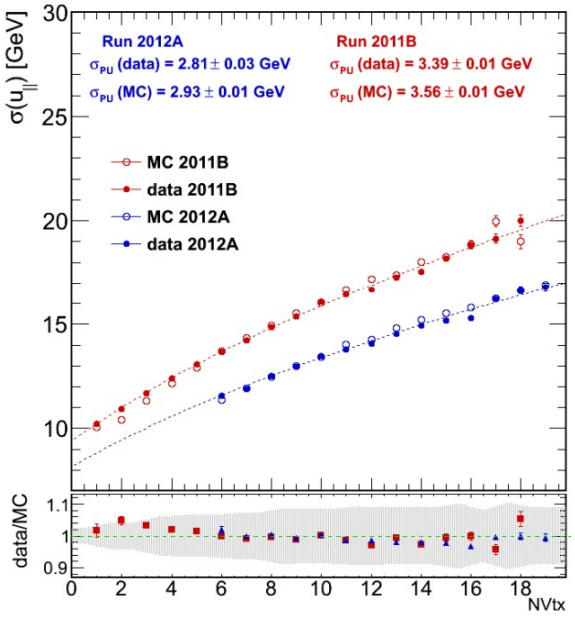


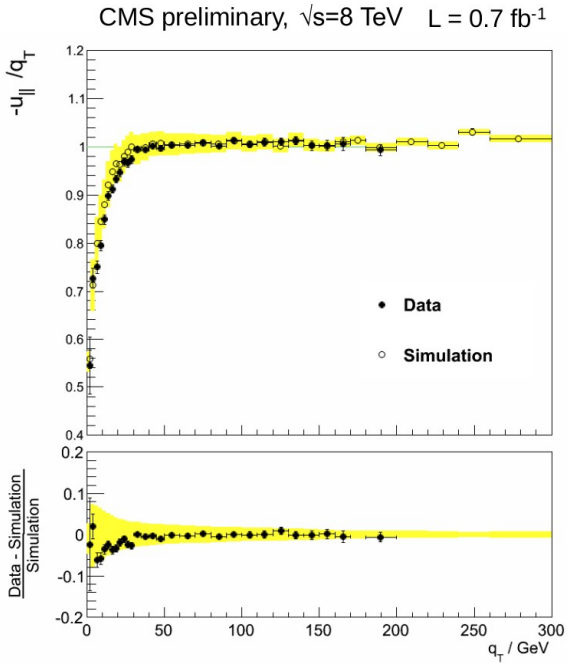
Physics object: missing E_T

- In CMS we use PF MET which is a negative of a vector sum of all momenta of PF particles
- Calibrated with standard SM candle: boosted Z/γ→μμ
  - MET scale is the average: $\langle u_{\parallel}/q_T \rangle$
  - MET resolution is RMS width: $\sigma(u_{\perp}), \sigma(-u_{\parallel}-q_T)$
- Various types of offline MET corrections, e.g.:
  - Type1: propagates jet energy correction: $\vec{E}_T^{corr} = \vec{E}_T^{raw} + \Sigma(\vec{p}_T^{calib} - \vec{p}_T^{raw})$
  - MET ϕ: correction for the shift in x-y plane, induced by calorimeter noise (strongly pile-up dependent)



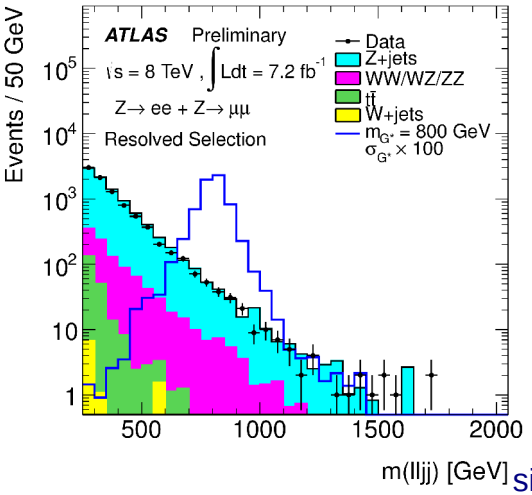


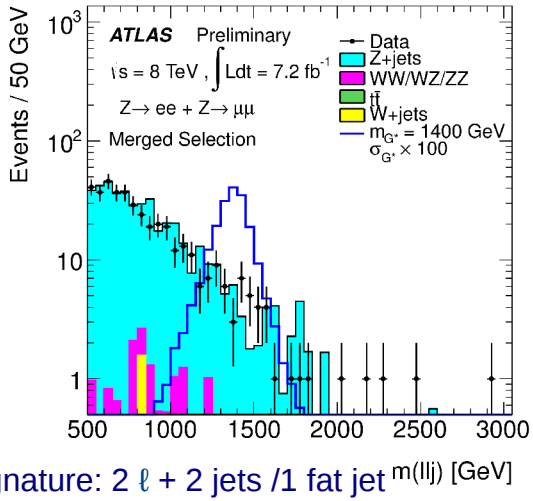




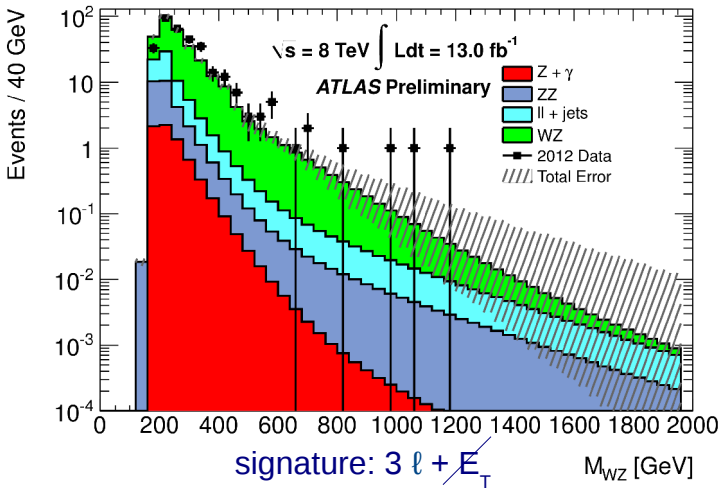
Search for VV resonances

ATLAS-CONF-2012-150, ATLAS-CONF-2013-015: searches for ZZ and WZ resonances:





signature: 2 ℓ + 2 jets /1 fat jet



signature: 3 ℓ + E_T

Some of the limits: