Searches of Physics Beyond the Standard Model

Khristian Kotov

Searches of Physics Beyond the Standard Model at the LHC

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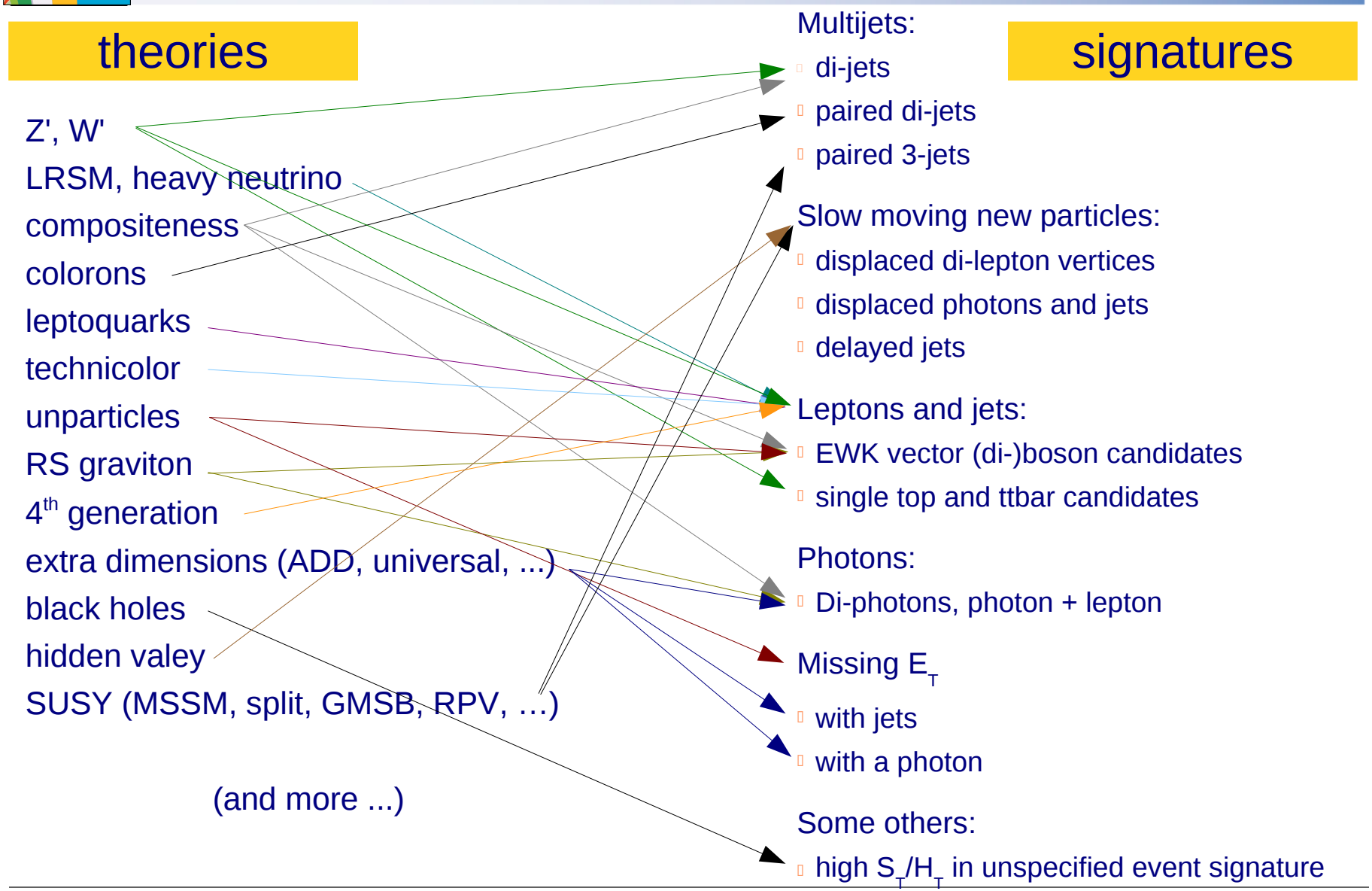
Searches of Physics Beyond the Standard Model with CMS detector at the LHC

Khristian Kotov
(on behalf of CMS collaboration)

Focus of this seminar

- Quick introduction to the CMS physics objects (reconstruction, resolution, uncertainties):
  - jets
  - leptons
  - photons
  - missing E_T
- Emphasis on the analysis specific techniques and redefined physics objects
- Some of recent physics results from competing CMS and ATLAS analyses:
  - di-jets searches
  - lepton tagged searches
  - displaced (and delayed) photon
  - simple signatures with missing E_T
- No SUSY contour plots
- Unless explicitly stated, CMS context is used

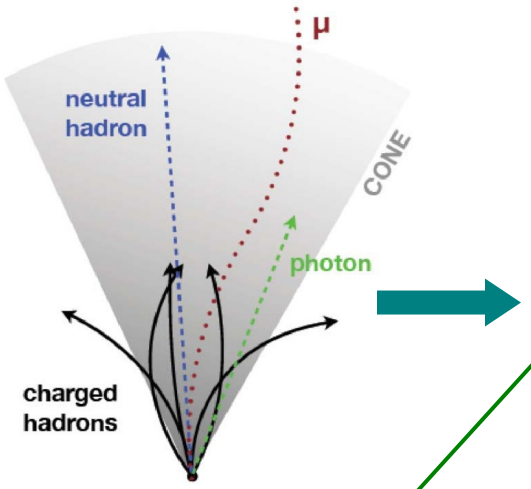
Physics Beyond the Standard Model



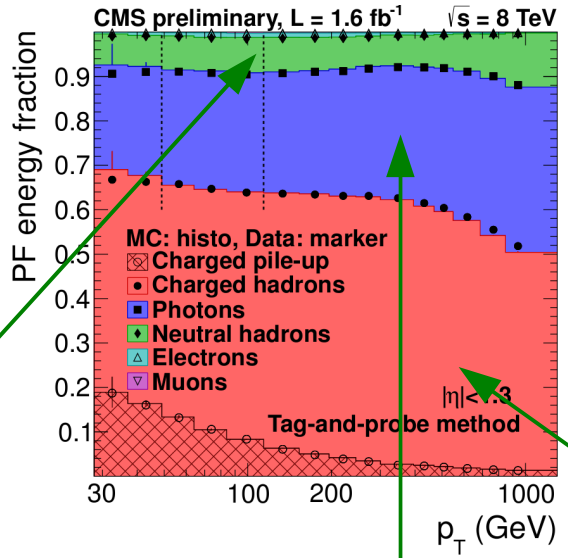
some analyses with jets

Physics objects: jets

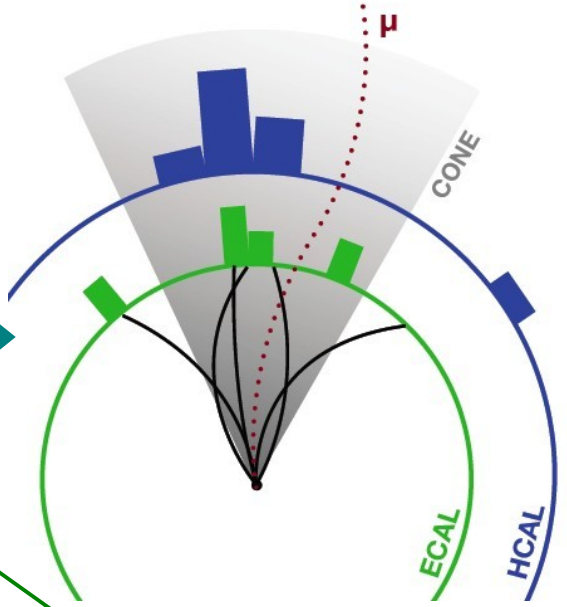
Jet:

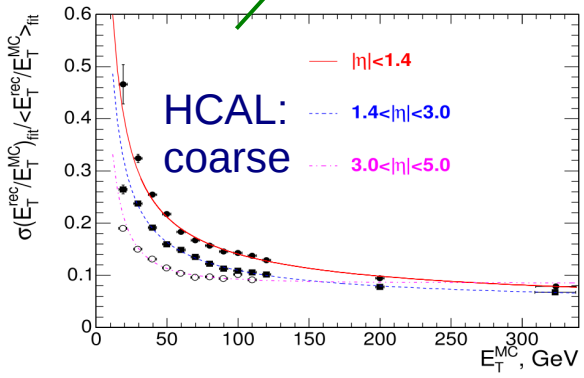


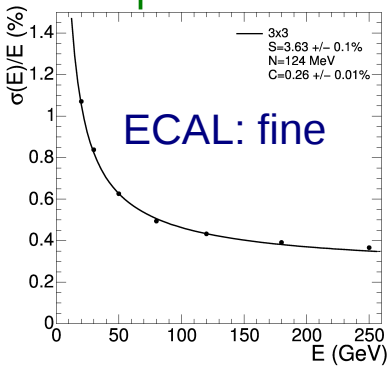
Jet composition:

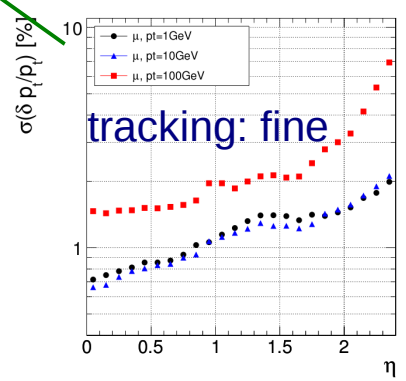


Deposits in subdetectors:







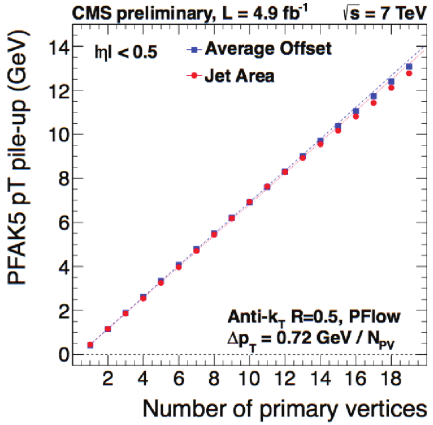


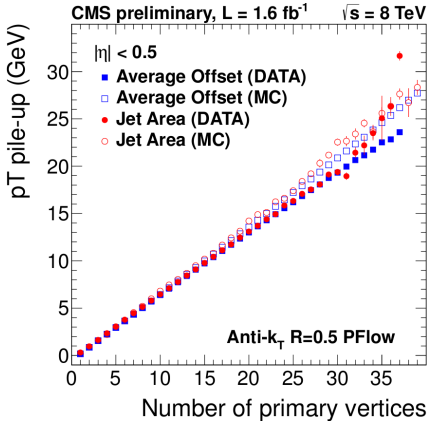
Particle Flow reconstruction takes advantage of best information available to construct a jet

Jet resolution

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

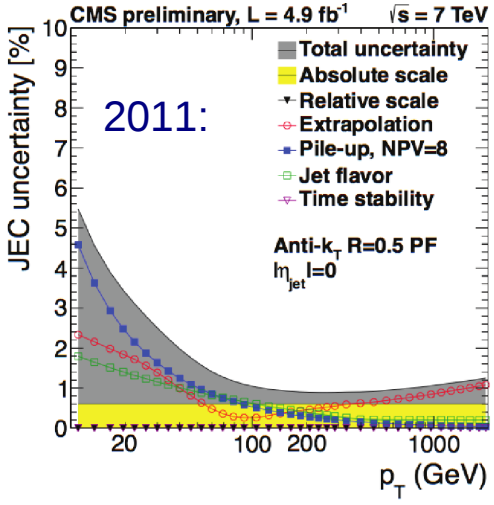
- offset expected pile-up deposits within jet area:
- relative (spatial-η) calibration:
  using di-jet balance correct jet response for arbitrary η wrt. jet response in the central region
- absolute (energy scale) calibration:
  using Z/γ + jet event balance set the absolute jet response scale using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

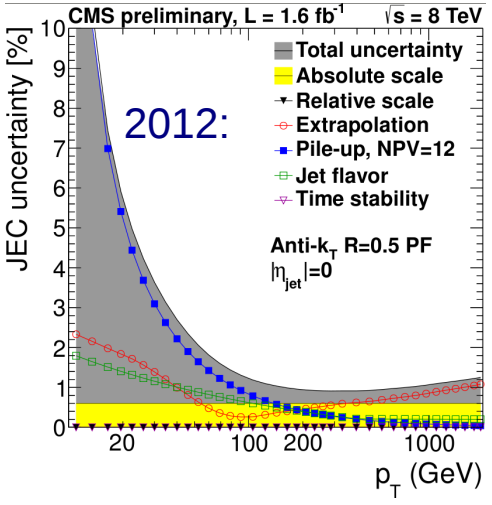




Resulting jet energy uncertainty:

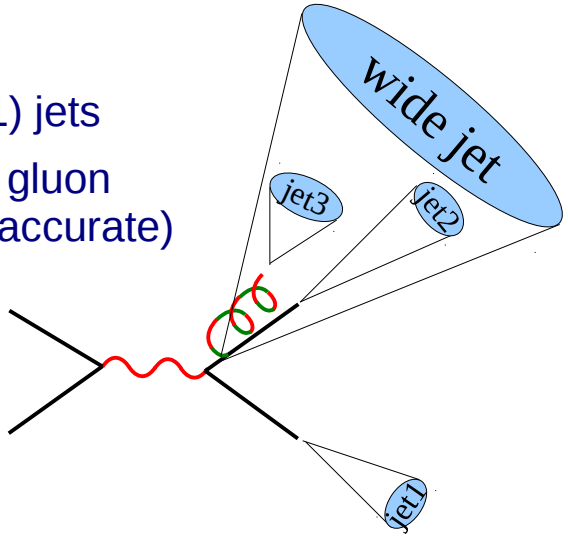
- jet energy scale is known at ~2%



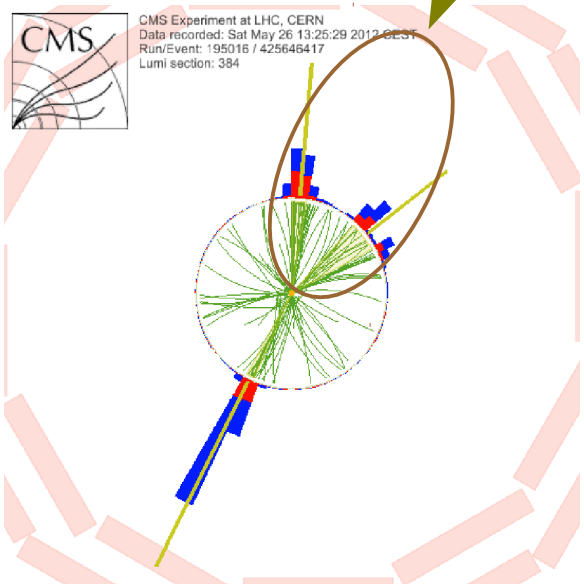


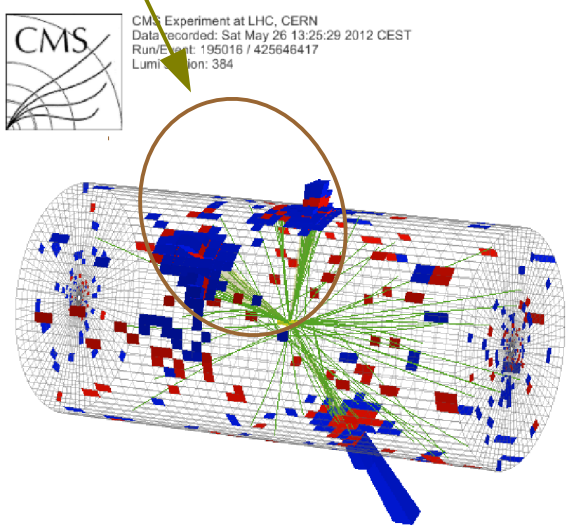
Recombination of radiation

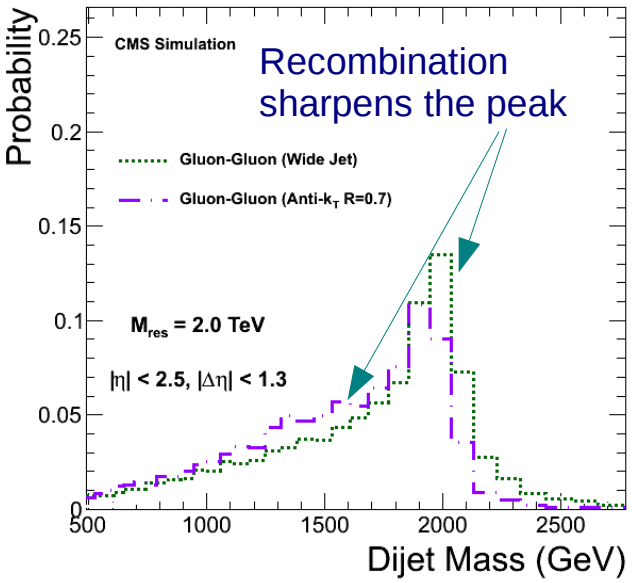
- Use standard calibrated jets (p_T>30 GeV, anti-k_T in ΔR=0.5)
- Take leading jets and sum with lorentz vector of nearby (ΔR<1.1) jets
- This technique helps to recover some resolution for gluon jet as gluon tend to radiate more often than quark (still, quark jets are more accurate)



example event with close jets merged to a wide jet





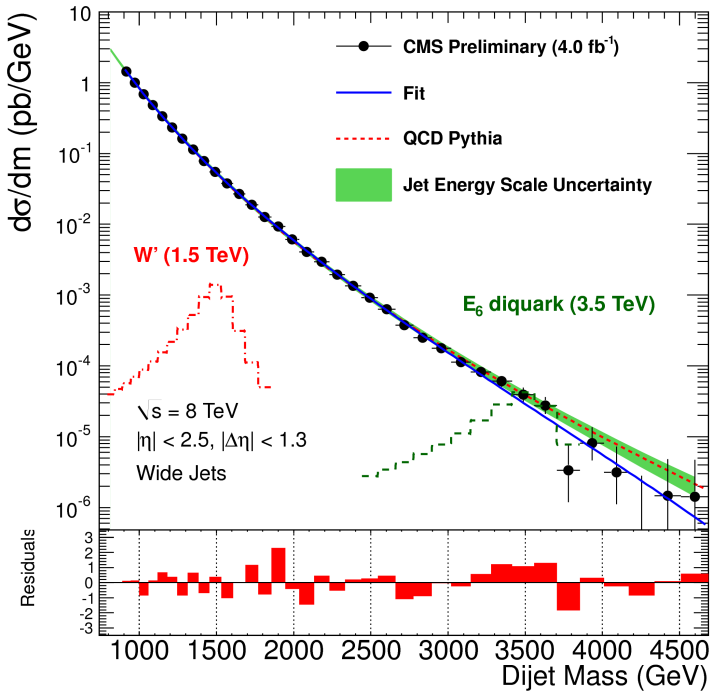


Analyses of di-jet invariant mass

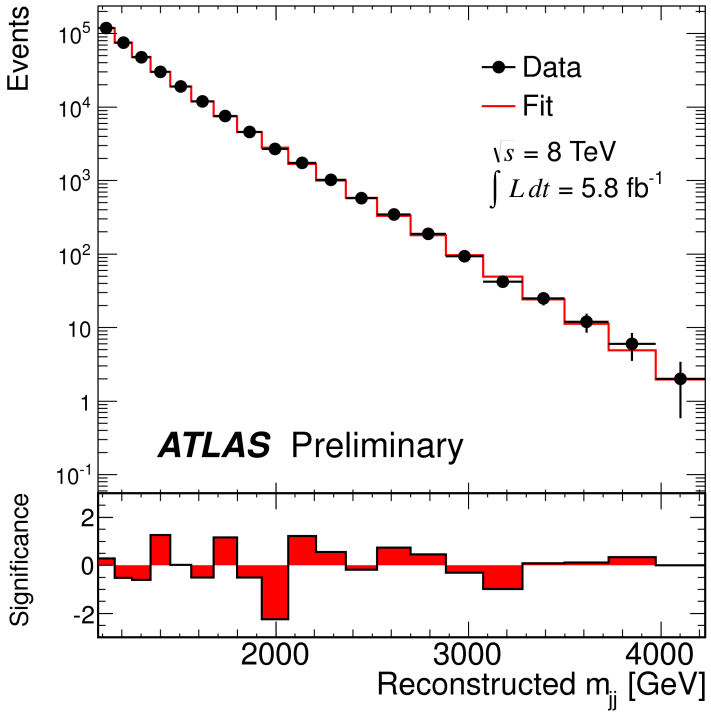
Bump hunt: resonances in smoothly falling invariant mass spectrum

- m_{jj} > 0.8 – 1.0 TeV (due to trigger and selection) + a dedicated push down to 0.6 TeV (CMS)
- data driven background shape from fit to: $d\sigma/dm = P_0(1-m/\sqrt{s})(m/\sqrt{s})^{P_2+P_3\ln(m/\sqrt{s})}$
- most important uncertainty is due to JES ~ 2%(CMS) – 4(ATLAS)%

CMS-EXO-12-016:



ATLAS-EXOT-2012-88:

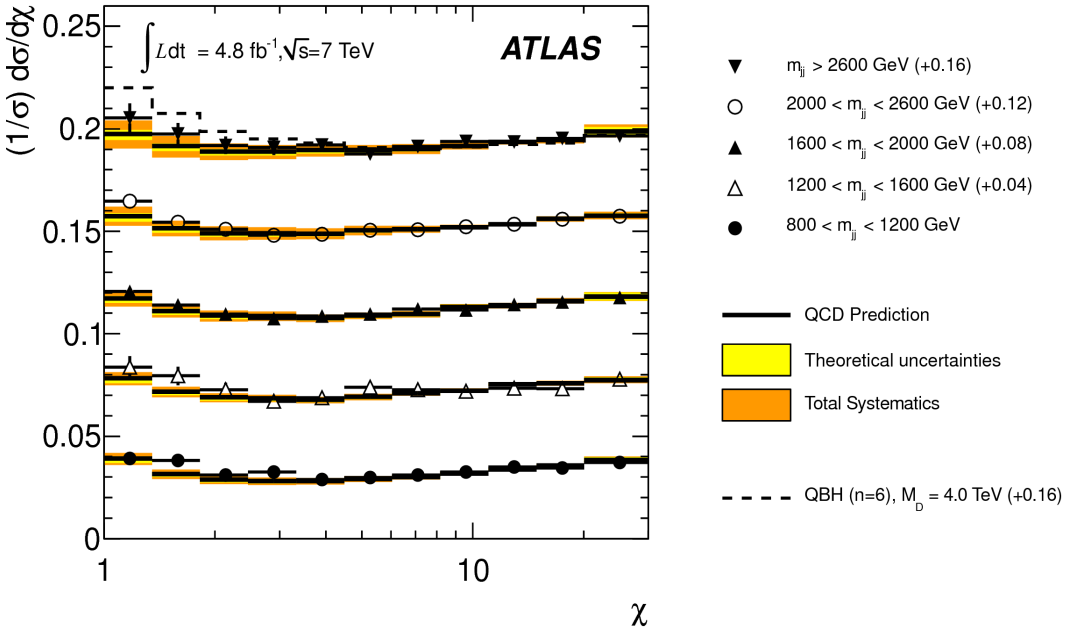


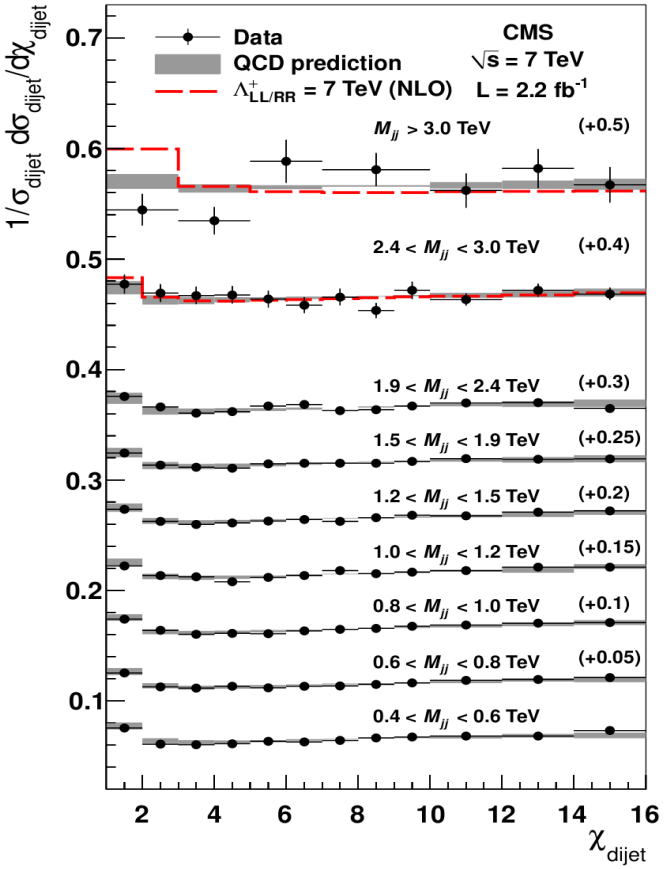
Angular analyses with di-jets

Angular analysis: deviation from highly forward (in CM frame) QCD di-jet signature

- construct $\chi=\exp(|y_1-y_2|)$: flat for QCD and peaks at 0 for more isotropic new physics decays
- in several (coarse) mass bins plot the $1/\sigma\ d\sigma/d\chi$ shape
- uncertainties due to JES, PDF, and luminosity are greatly reduced in the ratio

ATLAS-EXOT-2011-21 and CMS-EXO-11-017:





Some results from analyses with di-jets

- 2011, 7 TeV run:

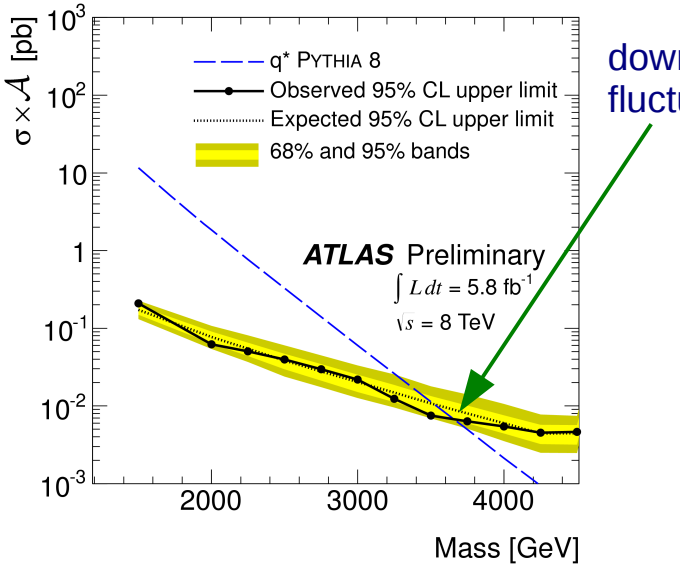
observed limits	excited quarks	compositeness	SSM W'	color octet s8
ATLAS 7TeV	m_{q^*}>2.83 TeV*	Λ>7.6 TeV	$m_{W'}$> 1.86 TeV	m_{s8}> 1.86 TeV*
CMS 7TeV	m_{q^*}>3.27 TeV*	Λ^{+}_{LL}>7.5 TeV	$m_{W'}$> 1.9 TeV**	m_{s8}> 2.07 TeV*

* the expected limits are close, but in observation CMS got luckier with downward data fluctuations

** because of data fluctuation CMS doesn't exclude W' mass windows of [0.69–0.82] and [0.96–1.0] TeV

- In 2012, 8 TeV run: we can compare q* limits:

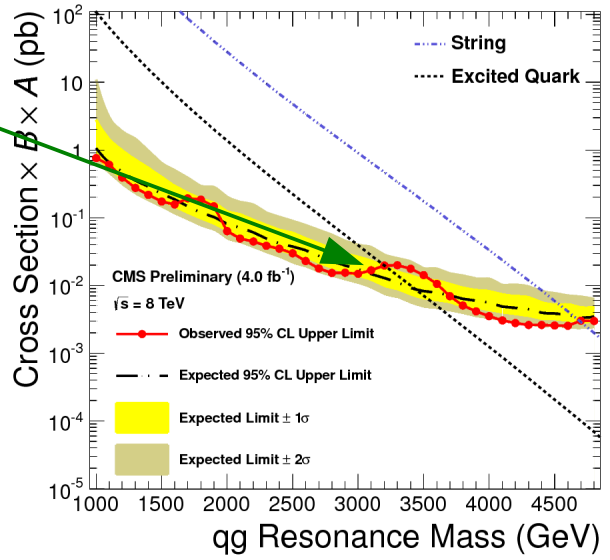
ATLAS: m_{q^*}>3.66 TeV (~3.5TeV with CMS' theory curve):



downward fluctuation

upward fluctuation

CMS: m_{q^*}>3.19 TeV:



some analyses with electrons and muons

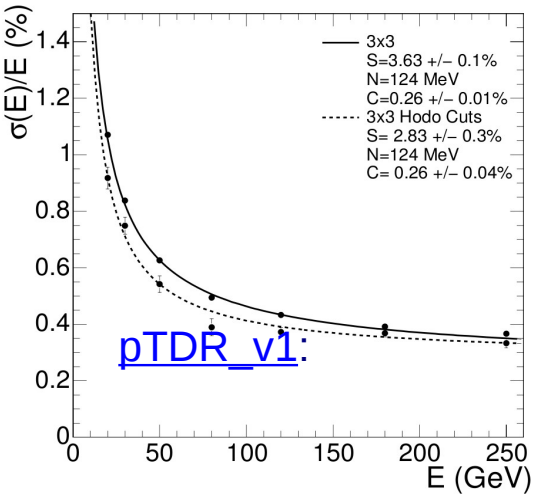
Physics objects: electrons and muons

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:

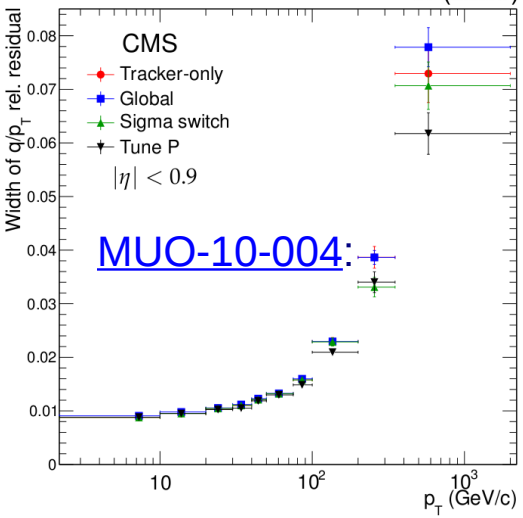
  (2012: $\delta p^e_T/p^e_T = \delta m_Z/m_Z$ = 1-2.6 GeV / 91GeV ~ 1-3% tr1%)



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:

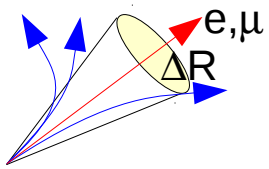
  (for electrons resolution flattens; for muons it degrades with p_T)



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)



Analyses with leptons

New heavy bosons (e.g. Z', W'):

- EXO-12-015: $pp \to Z' \to \ell^+\ell^-$
- EXO-12-001: $pp \to W' \to tb \to \ell^\pm$ + 2j($\geq$1b) + met
- EXO-11-031: $pp \to Z' \to \tau\tau$
- EXO-11-092, EXO-11-093: $pp \to Z' \to ttbar \to \ell$ + 2j + X
- EXO-11-041: $pp \to W'/a_{TC}/\rho_{TC} \to WZ \to \ell^+\ell^-\ell^\pm$ + met
- EXO-11-081: $pp \to W'/G_{RS} \to VZ \to \ell^+\ell^-$ + 2j
- EXO-11-056: $pp \to tW' \to ttd \to \ell^\pm$ + 5j($\geq$1b) + met

Typically analysis techniques:

- finding $p_z(\nu)$ from kinematic fit: $m(\ell+met)=m_W$
- jet assignment: $m(j+j)=m_W$, $m(\ell+met+b)=m_t$
- data driven EWK and ttbar background estimate
- Results: cut-and-count or shape analysis

4th generation quarks:

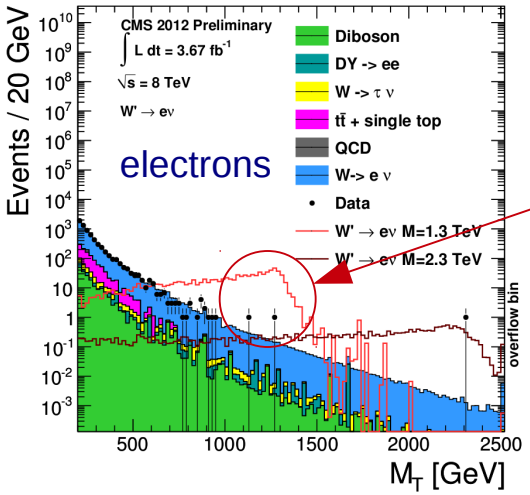
- EXO-11-005: $pp \to T'T' \to tZ\ tZ \to bWZ\ bWZ \to \ell^+\ell^-\ell^\pm$ + 2j + X
- EXO-11-050: $pp \to t't' \to bW\ bW \to b\ell\nu\ b\ell\nu \to \ell^+\ell^-$ + 2b + met
- EXO-11-099: $pp \to t't' \to bW\ bW \to b\ell\nu\ bqq \to \ell^\pm$ + 4j($\geq$1b) + met
- EXO-11-036: $pp \to b'b' \to tW\ tW \to bWW\ bWW \to \ell^\pm\ell^\pm$ + 4j + X , $\ell^+\ell^-\ell^\pm$ + 2j + X
- EXO-11-098: $pp \to q'q', q'q \to \ell^\pm$ + 1b + met + X , $\ell^\pm\ell^\pm$ + X , $\ell^+\ell^-\ell^\pm$ + X

Some other analyses with leptons:

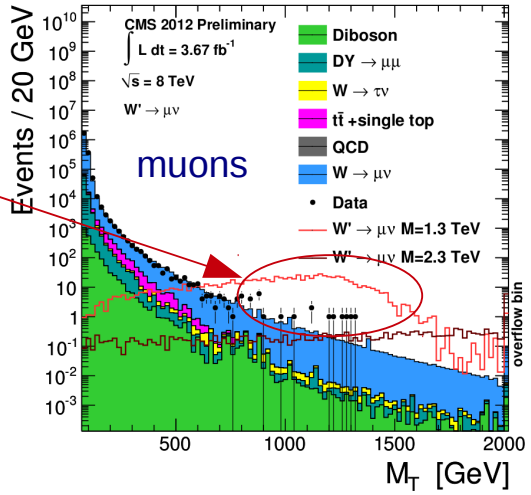
- heavy neutrino: EXO-12-017: $pp \to W_R \to \ell\ N_\ell \to \ell^+\ell^-\ W_R \to \ell^+\ell^-$ 2j
- displaced leptons: EXO-11-101: $pp \to H^0 \to 2a \to \ell^+\ell^-\ \ell^+\ell^-$ (EXO-12-012)

Example: search for W' → ℓ ν̄

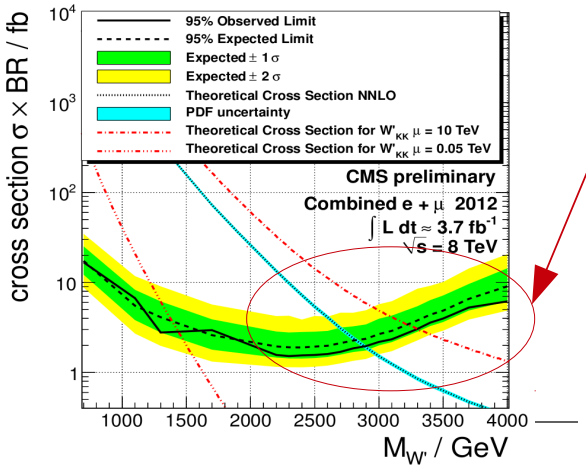
- The key observable: $M_T = \sqrt{2\, p_T^l\, E_T^{miss}\,(1-\cos\Delta\phi_{l,\nu})}$
- Some selection cuts: $p_T^l > 40(\mu), 85(e)\,GeV$, CMS: $\Delta\phi_{l,\nu} > 0.8\pi$, $0.4 < p_T^l / E_T^{miss} < 1.5$, ATLAS: $E_T^{miss} > 85\,GeV$
- Results: cut-and-count using MC; CMS normalizes MC bg. to a data sideband, ATLAS to $\sigma^{\text{NNLO MC}} \times \mathscr{L}$)

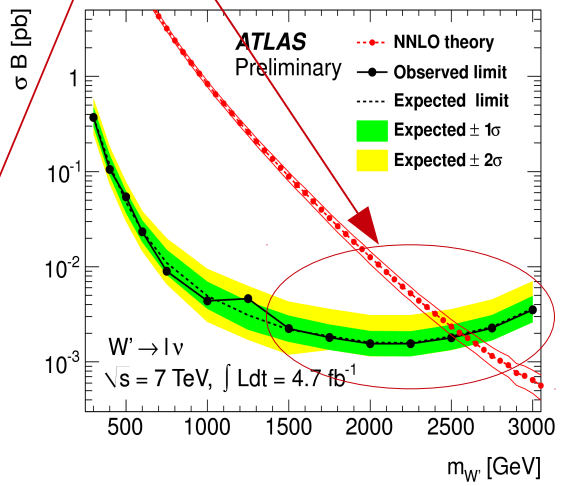


note difference in resolution for e and μ



note evidence of degrading signal efficiency on the limit: high mass W' produced off-shell is likelier to give soft $\ell^{\pm}$



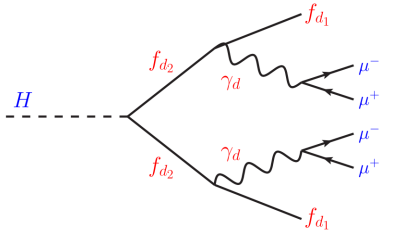


Result:

- ATLAS: m(W')>2.55 TeV
- CMS: m(W')>2.85 TeV

Example: multi-muon events

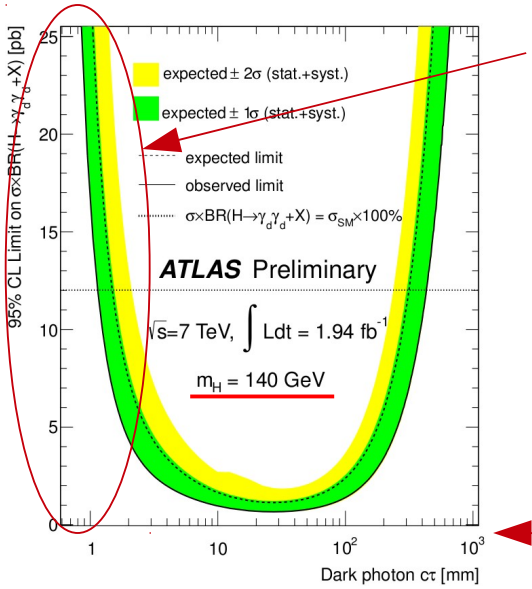
Model: new light ($2m_\mu < m_{\gamma d} < 2m_\tau$) boson $\gamma_d \to \mu^+\mu^-$, pair-produced in decays: $H \to \gamma_d\,\gamma_d + X$:



Search for 2 collinear di-muon pairs; suppress multijet ($K,\pi,\omega,\rho,\phi,J/\psi$), $b\bar{b}$, and cosmics:

- CMS-EXO-12-012 (search for 2 $\mu^+\mu^-$ pairs originating from the interaction point):
  - select: di-μ trigger (p_T^{μ}>17,8 GeV); $m_{\mu\mu}$<5GeV, common origin, $|m^1_{\mu\mu} - m^2_{\mu\mu}|$<~0.1GeV, $\mathrm{TrkIso}^{\mu\mu}$<3GeV
- ATLAS-EXOT-2011-12 (search for 2 $\mu^+\mu^-$ displaced and not reco'ed in the tracker due to finite γ_d lifetime):
  - select: 3-sa-μ trigger (ε^{sig}~0.3); $\Delta R_{\mu\mu}$<0.2, $|\Delta\phi_{\mu\mu 1\mu\mu 2}|$>2, $\mathrm{CaloIso}^{\mu\mu}$<0.5GeV, "tracker veto" (Σp_T^{ID}<3GeV)

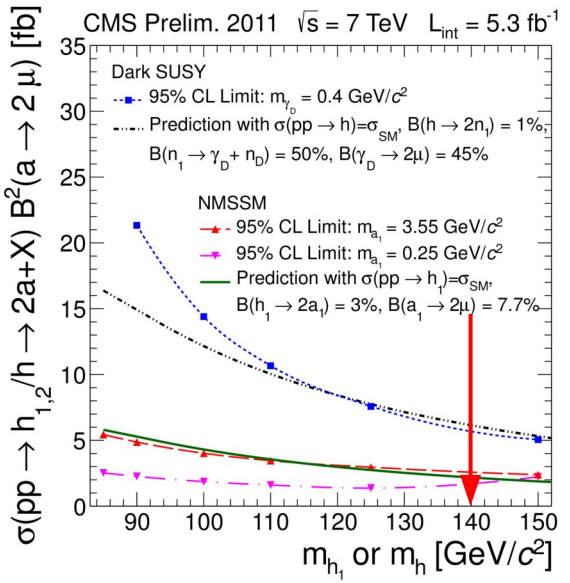
Results are complementary: CMS probes different parameter space of the same theory (i.e. short γ_d lifetime)



- note the "tracker veto" impact
- putting the m_h=140 GeV benchmarks from two results on γ_d together:
  Short lived: $\sigma \times \mathrm{Br}(h \to \gamma_d\gamma_d) < 35$ fb
  Long lived: $10^{-3} < c\tau(m) < 0.43$, $\sigma \times \mathrm{Br} < 12$ pb

(though, note slightly difference in kinematics: $m^{CMS}_{fd2,1}$=10,1 GeV vs. $m^{ATLAS}_{fd2,1}$=5,2 GeV)

(don't forget the γ~50 factor if compare it to the detector size)



Example: multi-muon events

Model: ne

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- CMS-EX
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- ATLAS-
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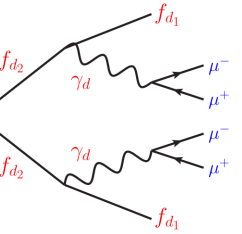
Results a



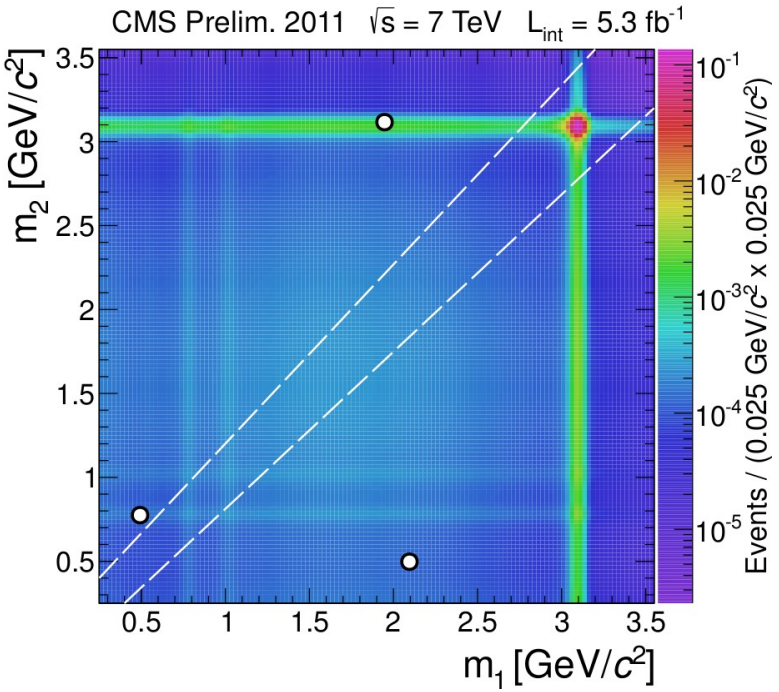
Iso$^{\mu\mu}$<3GeV

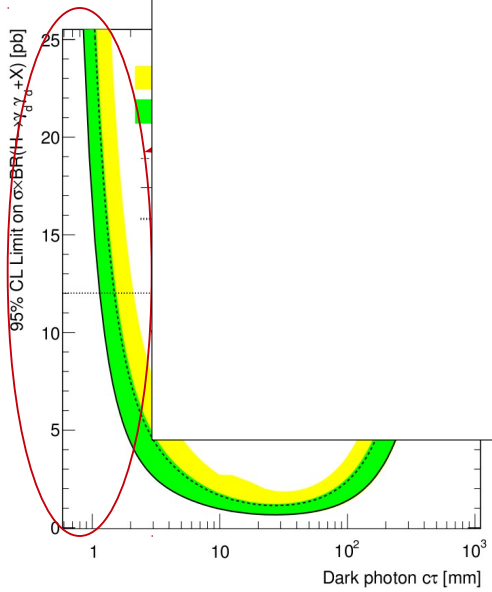
γ_d lifetime):

p_T^{ID}<3GeV)

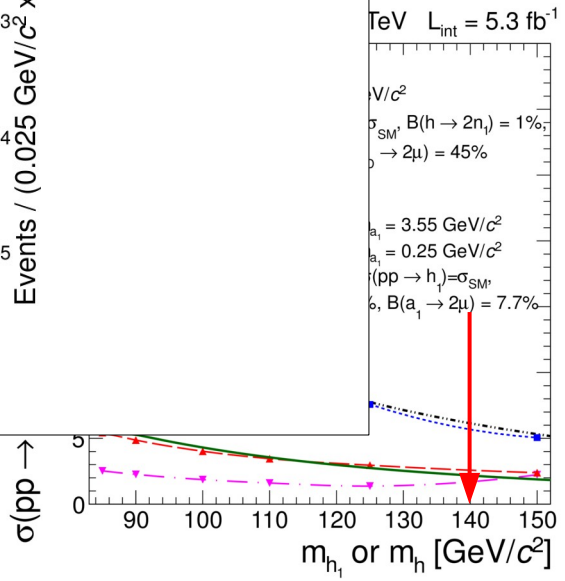
t γ_d lifetime)

CMS: assumption that di-muon pairs should have the same mass and the corresponding diagonal cut allows to cut bulk of background:



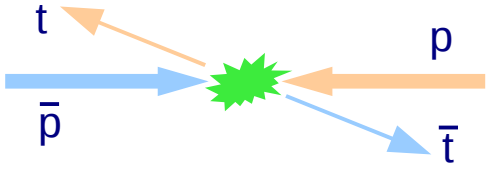


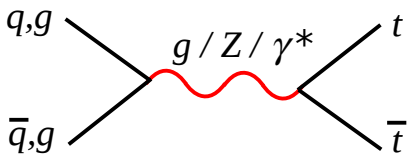
(don't forget the γ~50 factor if compare it to the detector size)



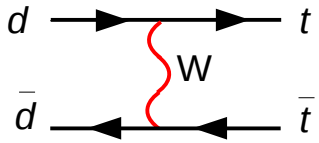
Example: search with $t\bar{t}$+jet signature

- Motivation: CDF and D0 ttbar forward-backward asymmetry puzzle: top (anti-top) prefers to fly along to the proton (anti-proton) direction more ofter than one could find with SM calculation:





(one of the FB symmetric contributions)

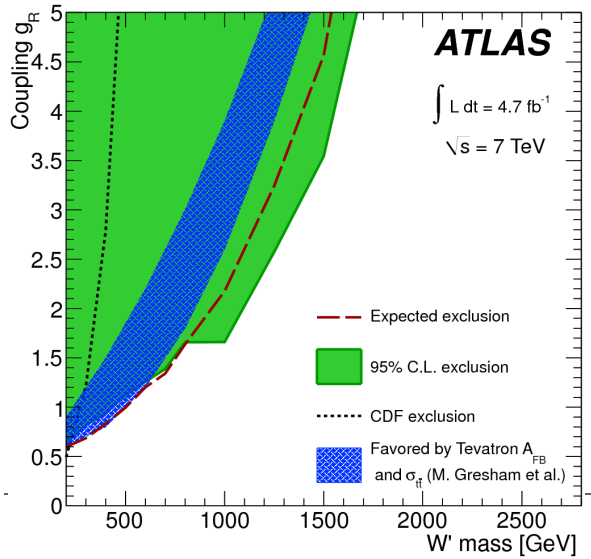


(FB asymmetric contribution)

- A model with additional W' fixes the A_{FB} puzzle while keeping production $\sigma(t\bar{t})$ within its uncertainties

The search is aimed at the raise in $t\bar{t}$+1j production rate due to the contributions with new W'

- selection (aimed at semileptonically decaying ttbar): $\ell^{\pm}$ + ≥5j (≥1b) + ν (soft MET cut at 20 GeV)
- kinematic fit: minimizes likelihood against $p_z(\nu)$ and jet-to-top assignment with m_W and m_t constraints

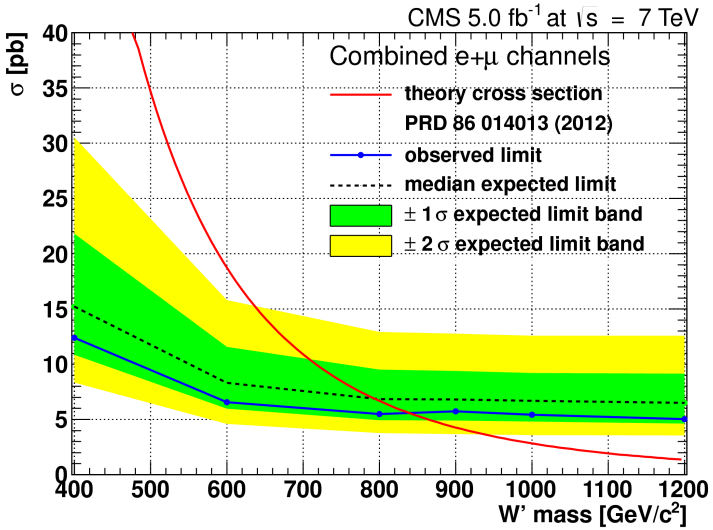


Results for g_R=2 coupling:

ATLAS: $m_{W'} > 1.1$ TeV

CMS: $m_{W'} > 0.84$ TeV

(this analysis is similar to some other 4th generation analyses on CMS)



Example: search with $t\bar{t}$+jet signature

- Motivation: CDF and D0 ttbar forward-backward asymmetry puzzle: top (anti-top) prefers to fly along to the pro

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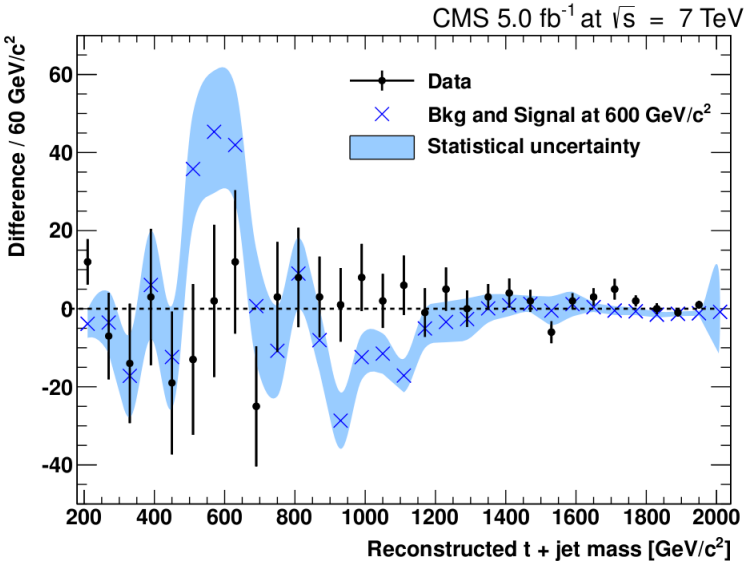
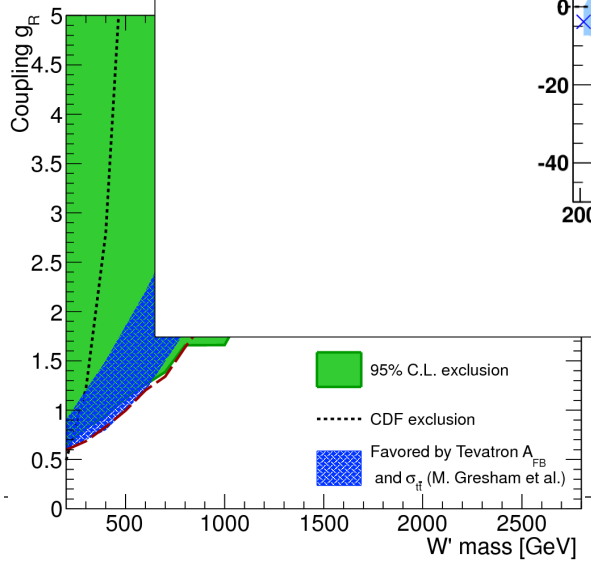
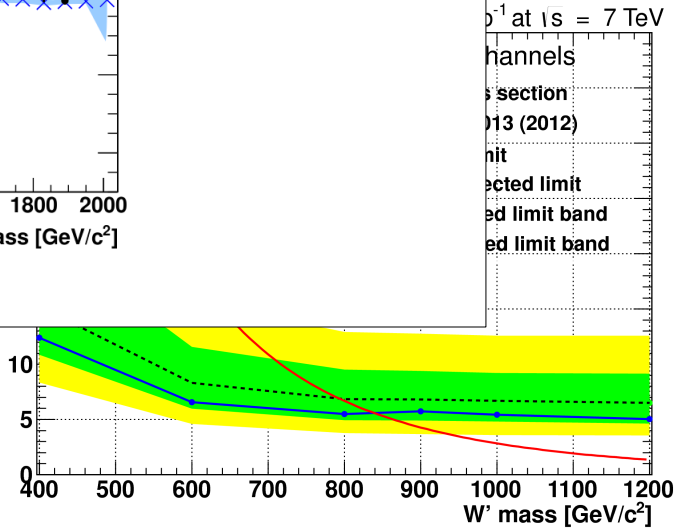
An interesting analysis technique has been proposed to make use of charge asymmetry of W' production:

- only 15% of pp produced W' are positively charged and 85% are W'^{-}
- W' may be better seen in invariant mass of t^{-} + jet compared to t^{+} + jet:





some other 4th generation analyses on CMS)



some analyses with photons

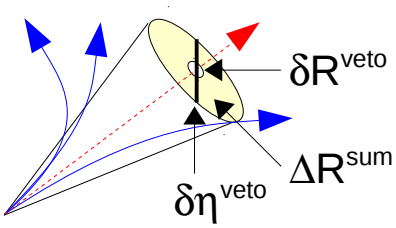
Physics object: photon

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)

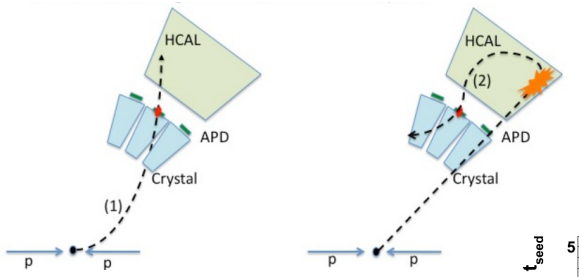


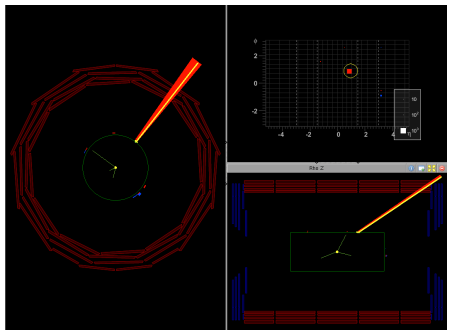
CMS features:

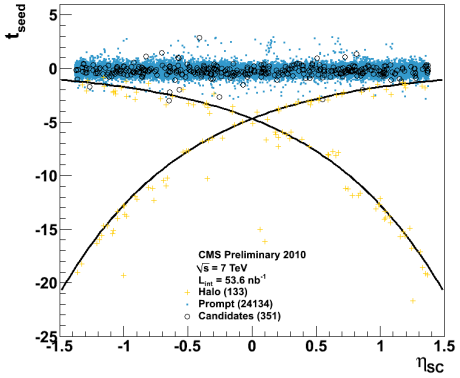
- very fast ECAL: 80% of light within 25ns (<1ns time resolution for impact time!)
- relatively high material budget: ~1X_0 before ECAL (brem and conversion: $e \rightarrow e\gamma$ and $\gamma \rightarrow e^+e^-$)

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)



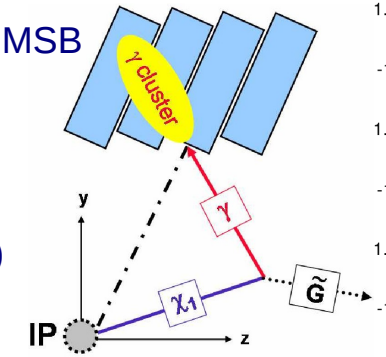


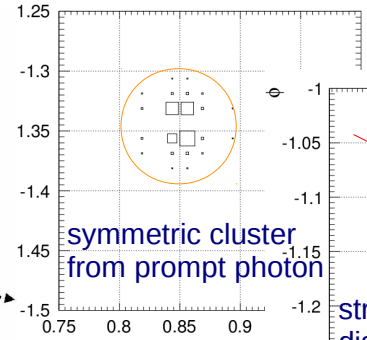


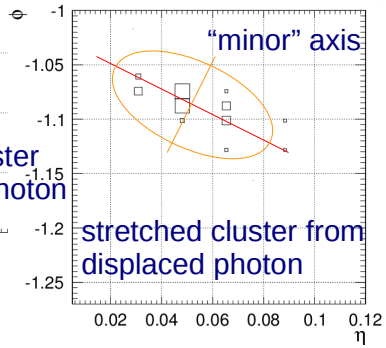
Displaced and delayed photon

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

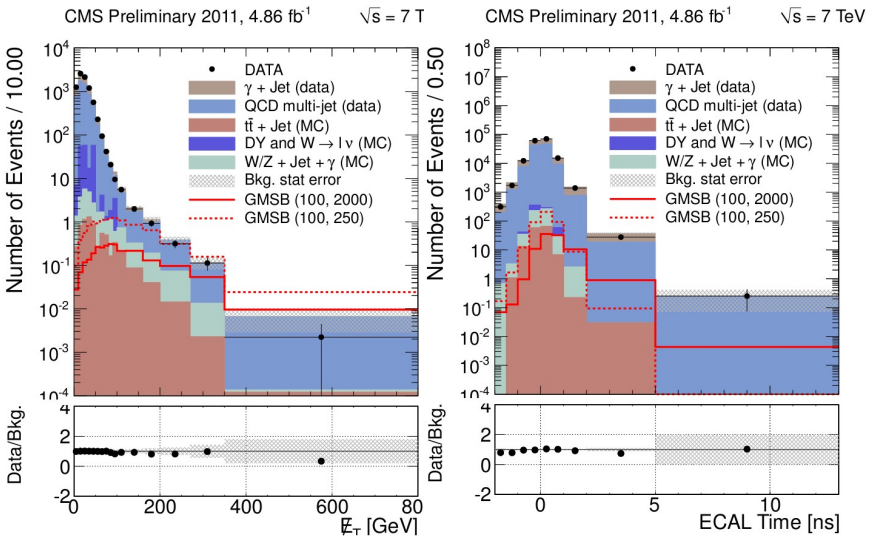
- single photon trigger (sharp turn-on, ε~100%)
- energetic photon in barrel (p^{γ}_T>100 GeV, $|\eta^{\gamma}|$<1.4)
- Iso_{ECAL}, Iso_{HCAL}, Iso_{Trk} (<5%, 5%, 10% E^{γ}_T; 2.4 GeV)
- e/γ-like cluster shape projected on “minor” axis
- no ±3ns window, EMu halo veto, spikes cleaning, ...





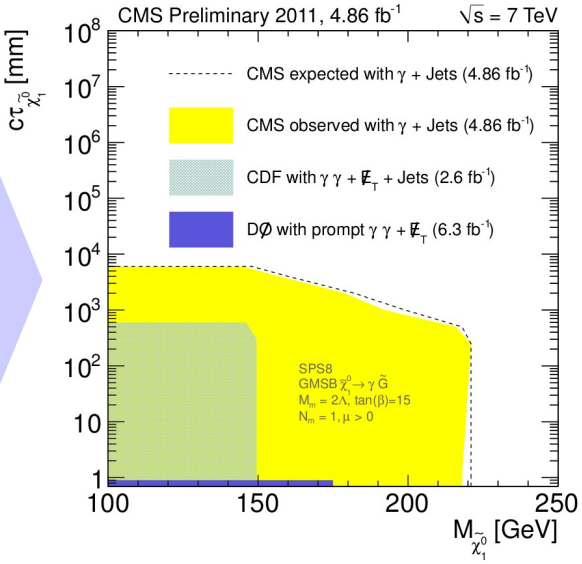


Main backgrounds: QCD and γ+jets; their shapes are taken from background enriched control data regions (made by relaxing isolation cuts for QCD or relaxing/inverting γ+jets specific cut: $\Delta R_{\gamma,jet} > 2/3,\ \ 0.6 < p_T^{jet}/p_T^{\gamma} < 1.4$)



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

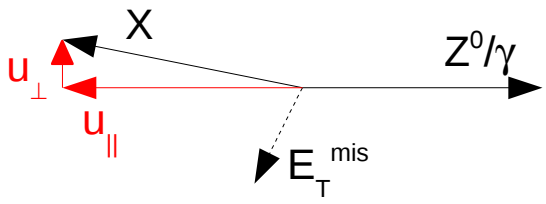


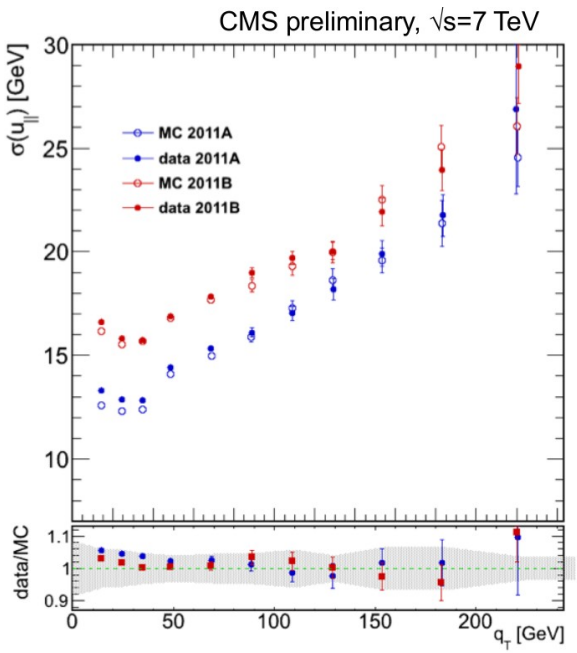
some analyses with missing E_T

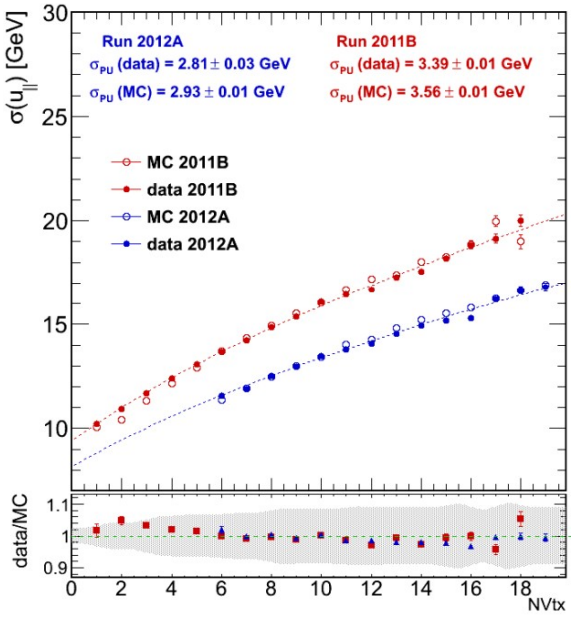
(candidate for dark matter)

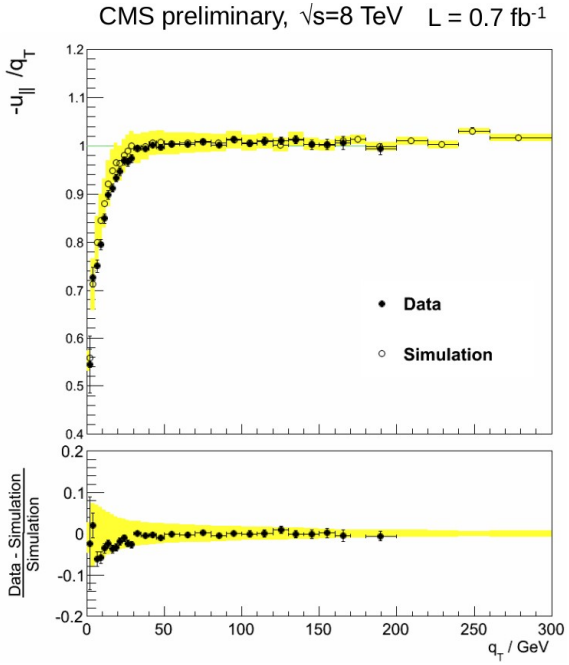
Physics object: missing E_T

- 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 $Z/\gamma \rightarrow \mu\mu$
  - 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)





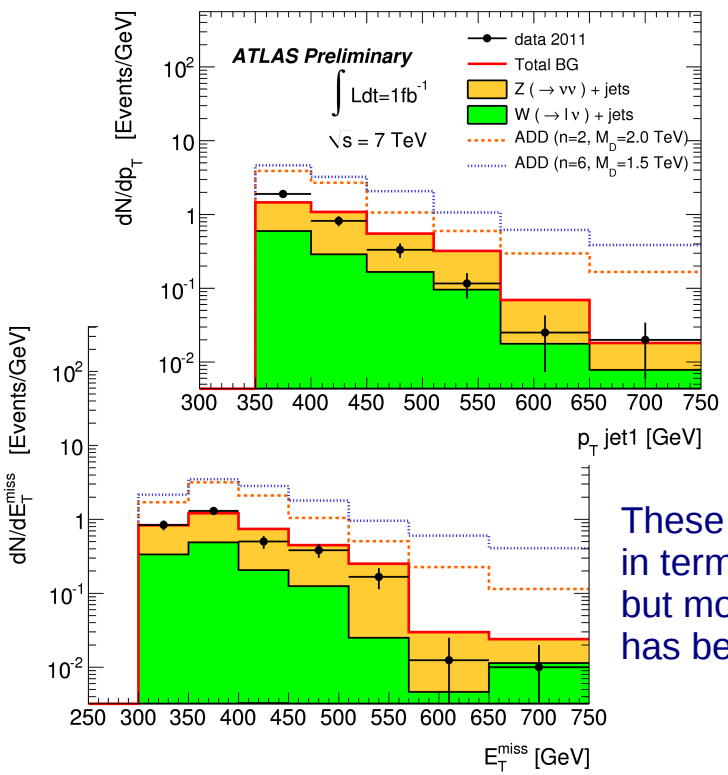




Monojet search

- ATLAS-CONF-2011-096 and CMS-EXO-11-059 analyses probe excess of high (>0.1-0.4TeV) $\not{E}_T$ events in association with =1 high p_T jet (ATLAS) or 1 or 2 high p_T jets (CMS), vetoing events with leptons
- Non-collision bg. (noise, beam halo, ...) is cut based on balance of jet's deposits in tracker and calorimeter
- Leading SM backgrounds, $Z(\rightarrow \nu\nu)$+jets and $W(\rightarrow \ell\nu)$+jets, are derived from data with all but lepton veto cuts:

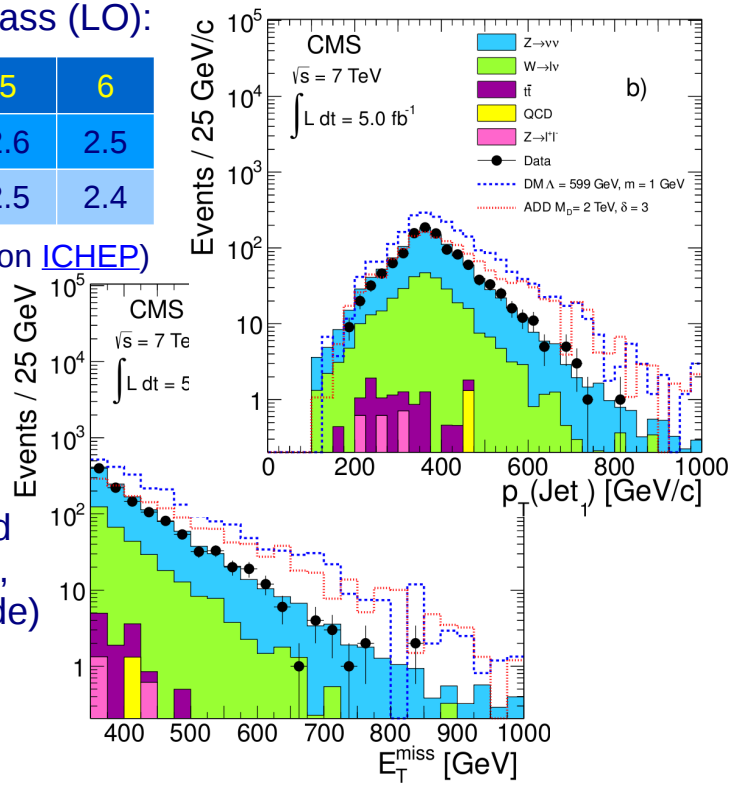
$$N(Z\rightarrow \nu\bar{\nu}) = \frac{N(Z\rightarrow \mu\mu) - N(bg)}{A\times\epsilon}\cdot\frac{Br(Z\rightarrow \nu\bar{\nu})}{Br(Z\rightarrow \mu\mu)} \quad \text{and} \quad N(W\rightarrow lost\, l\bar{\nu}) = (1-A\times\epsilon)\cdot N_{total}, \quad N_{total} = \frac{N(W\rightarrow l\bar{\nu}) -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



Limits on ADD graviton mass (LO):

N^{dim}	2	3	4	5	6
ATL*	4.2	3.3	2.9	2.6	2.5
CMS	4.1	3.2	2.8	2.5	2.4

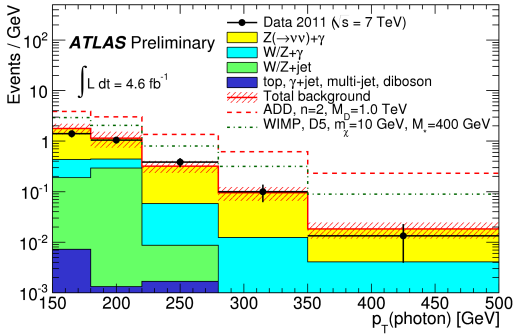
(*ATLAS 4.6fb^{-1} result, shown on ICHEP)

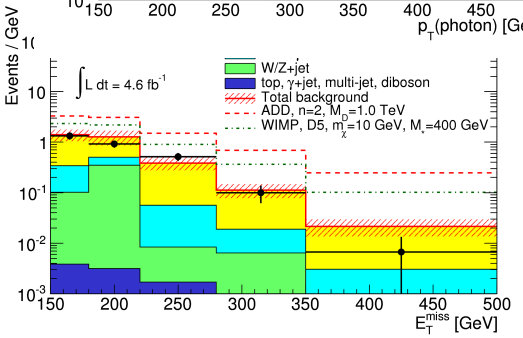


These results are also interpreted in terms of WIMP pair production, but monophoton search (next slide) has better sensitivity to WIMPs

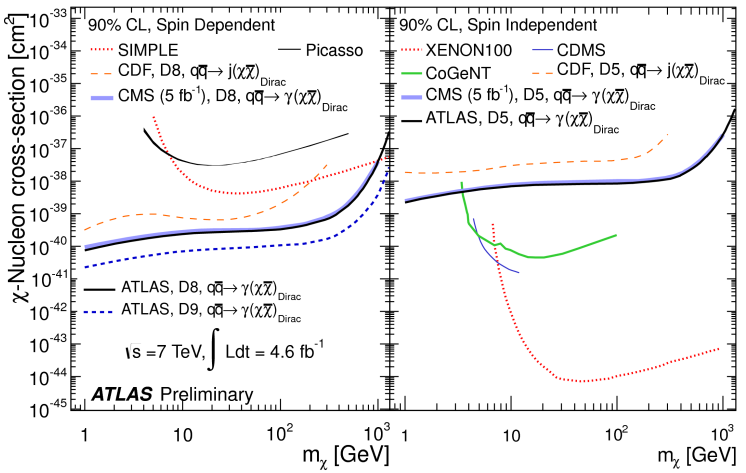
Monophoton search

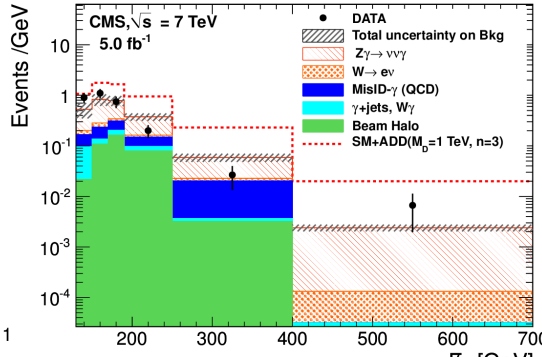
- ATLAS-EXOT-2012-05 and CMS-EXO-11-096 analyses probe excess of high (>150-130GeV) $\not{E}_T$ events in association with a high (>~150GeV) p_T isolated photon, vetoing events with leptons
- Non-collision bg.: halo, cosmics, spikes, … (cut using shower shape, timing, veto on non-IP muons)
- Leading 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,...)

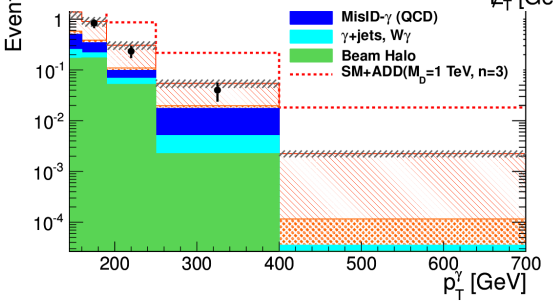




Results on paired WIMP production:







Monotop search

This is work in progress (no official results are available yet)

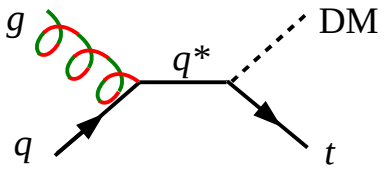
Contributors:

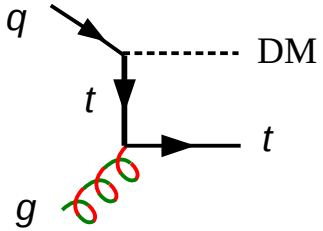
- CNRS/Strasbourg: Jeremy Andrea, Benjamin Fuks, Eric Conte, Jean-Laurent Agram
- OSU: Khristian Kotov, Christopher Hill, Stan Durkin

Motivation:

- Signature driven search with an effective theory ([1], [2]), which can be reinterpreted within several different new physics scenarios (e.g. UED, SUSY, FCNC)
- Complements monojet and monophoton searches for the Dark Matter candidate

  (an independent model, no competition on the ADD or WIMPs)
- Current monotop limits are set with CDF search is m_{DM}>125 GeV/c^2 (a different model, though)





Signatures:

- hadronic top decay: $pp \to t + \not{E}_T \to bW + \not{E}_T \to bjj + \not{E}_T$
- leptonic top decay: $pp \to t + \not{E}_T \to bW + \not{E}_T \to b\,l\,\nu + \not{E}_T$

Backgrounds: ttbar, VV, single top (can be taken from MC), Z+jets, W+jets, QCD (better be data-driven)

Selection: b-jet + [lepton / 2 jets] + MET

Summary

- Several event signatures are summarized in context of exotic searches
- Currently no deviation from the Standard Model are observed
  - no compositeness below Λ~7.5 TeV
  - excited quarks are heavier than ~3.3 TeV
  - 4^{th} generation is heavier than 0.6-0.7 TeV
  - new heavy gauge bosons (e.g. SSM W',Z') are heavier than 2.5 – 3 TeV
- Nevertheless, specific analysis techniques taking advantage of the CMS detector design as well as the developments of the standard HEP methods aimed at the exotic signatures make many analyses an interesting playground

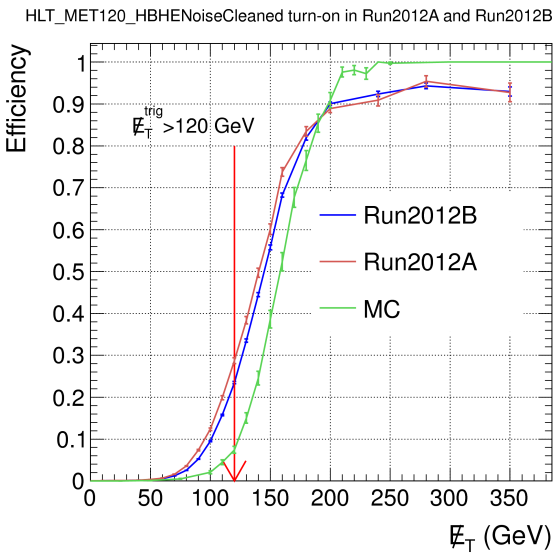
Backup

Monotop selection and backgrounds

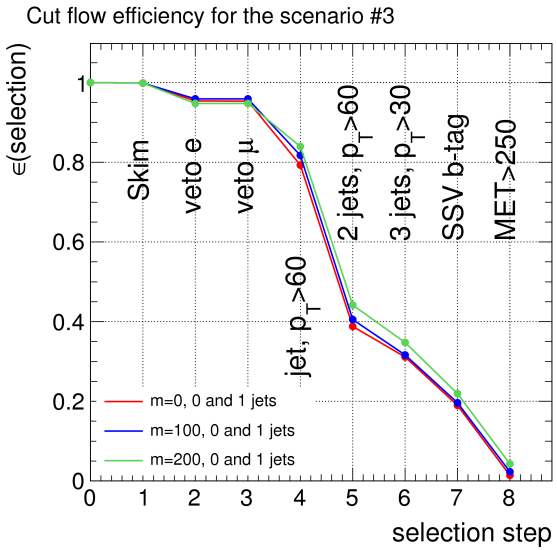
Event selection for: $pp \to t + \not{E}_T \to bW + \not{E}_T \to bjj + \not{E}_T$

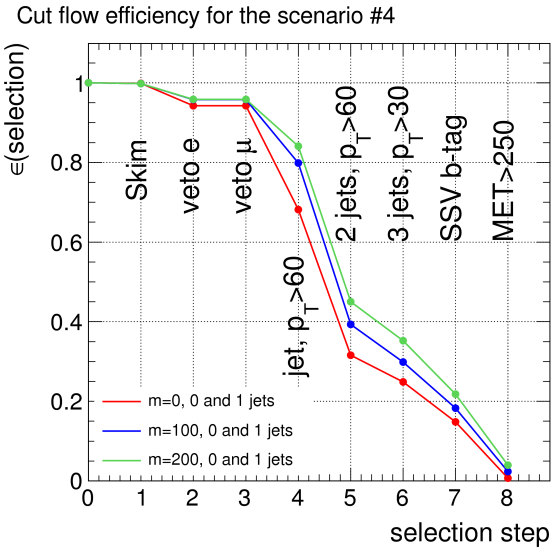
- MET driven: HLT_MET120 + $\not{E}_T$>250 GeV + 3 jets: p_T>60,60,30 GeV (≥1b-tag)
- Jet driven: HLT_QuadJet + 4 jets: p_T>80,60,40,20 GeV (≥1b-tag) + $\not{E}_T$>X GeV (study is in progress)

Slow MET trigger turn-on justifies high offline MET cut:



Signal efficiency is ~1-3% (mostly due to hard MET cut):





Backgrounds:

- ttbar (leading) ~1K events; comparable to yield in scenario #3 for m_{DM}< 100 GeV and #4 for m_{DM}< 400 GeV
- Z+jets + W+jets + single top yield additional ~0.5K events, QCD doesn't survive MET cut

We need to complete study of uncertainties and start writing the note