Searches for Lepton Jets at CMS

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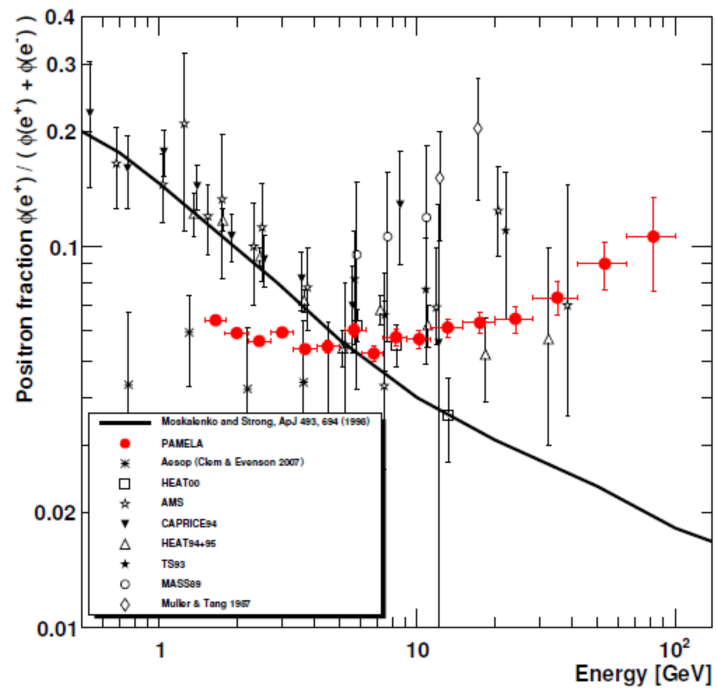
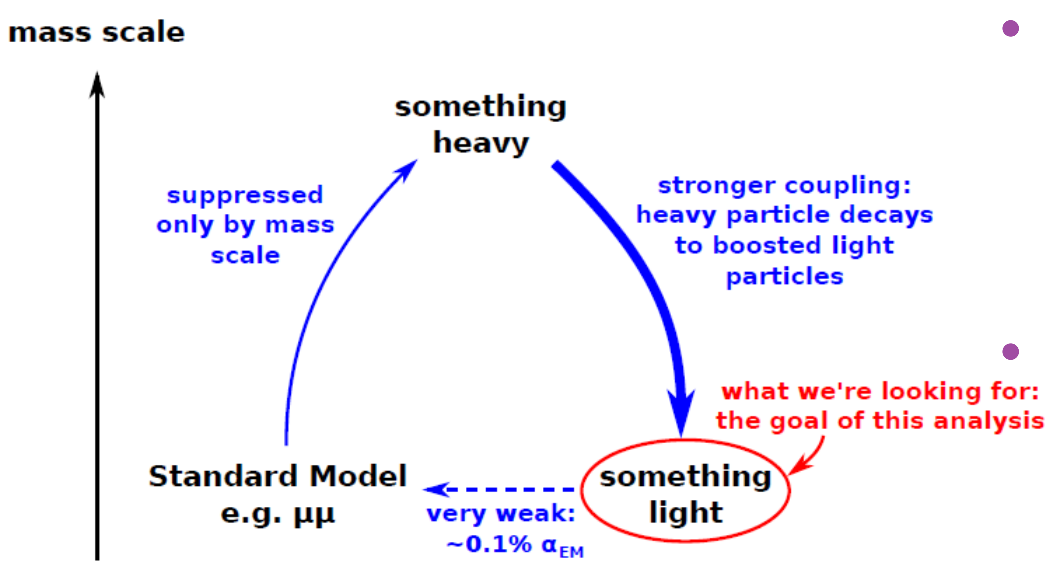
Motivation

- Excesses in cosmic ray data (e.g. Pamela)
  - ▫ Can be suggestive of dark matter annihilation in galactic halo
    - If SUSY, need a new "light dark boson" to get such large cross-section (Sommerfeld enhancement)
  - ▫ M~O(1 GeV), weakly couples to SM
- Fine tuning problems in SUSY
  - ▫ A new singlet field (NMSSM)
    - Solves the "μ-problem"
    - CP-odd higgs = new light boson
- Both suggest a new light boson weakly coupling to SM
  - ▫ Besides, it can just be there



Experimental Searches

- Use brute force to make them directly:
  - Either $ee \to \gamma^{dark}$ or $ee \to Y \to a_1\gamma$
    - But weak coupling means small cross section, need very high luminosity
- High energy colliders:
  - Make the heavy stuff that likes decaying to these



- They have to eventually decay to SM particles
  - So sit back and enjoy the show
- Decay modes:
  - $e/\mu/\pi$ pairs for γ^{dark}
  - $b/\mu/\tau$ for NMSSM a_1

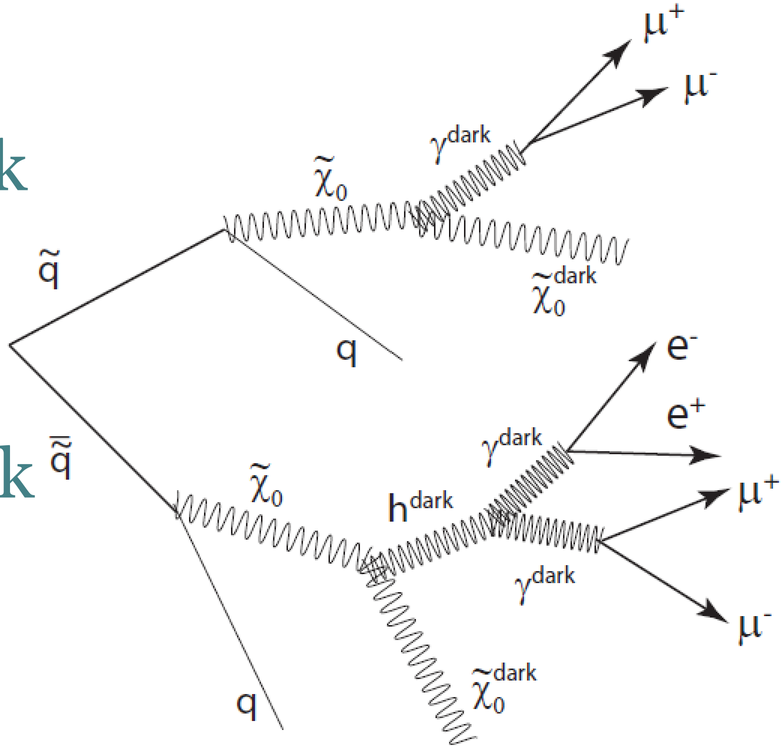
Focus on muons for now, they are easier

Potential Signatures

- Broad range of possible signatures:
  - NMSSM-like
    - A pair of isolated bosons from e.g. $gg \to h \to a_1 a_1$
  - Dark SUSY: more variety depending on details
    - Strength of coupling inside the dark sector
      - Strong: showers of dark photons (and dark higgses decaying to pairs of dark photons) at the end of MSSM cascades
      - Weak: less dark photons
    - Complexity of the dark sector
      - An hierarchy of states with cascade decays within dark sector
  - Decay Channels:
    - Higgs-like (NMSSM), photon-like or who knows
    - "Lepton jets" can be a mix of muon/electron/etc pairs

Benchmark Models

- MSSM with squarks/ gluinos accessible by LHC:
  - MSSM LSP is 400 GeV neutralino decaying to dark neutralino (300 GeV) and light γ^{dark}/h^{dark}
  - MSSM LSP is squark decaying to q and light dark fermion and γ^{dark}/h^{dark}
- NMSSM higgs:
  - $pp \rightarrow h_1 \rightarrow a_1 a_1$
    - $m(a_1) < 2m(\tau)$, $m(h1) \sim 100$ GeV
      - Moderate boost ($\gamma \sim 50/3$)

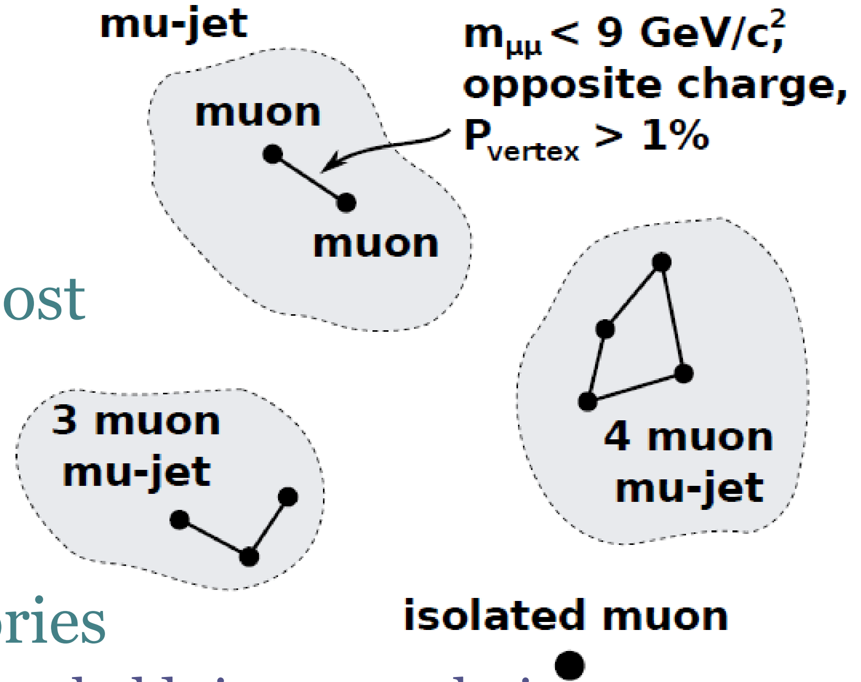


Analysis Strategy

- Desires:
  - Sensitivity to many kinds of new physics
    - Standalone light bosons or whole showers
  - Results (easily?) interpretable in other models
- Implementation:
  - Identify muon candidates
  - Cluster nearby muons into "muon jets"
  - Categorize events by topology R^{N}_{klm}
    - N is the number of muon jets
    - k, l, m – number of muons in jets # 1, 2, 3
  - Do not use:
    - Isolation (there could be electrons, pions, taus nearby)
    - Missing energy or extra jet requirements (to not loose NMSSM Higgs)

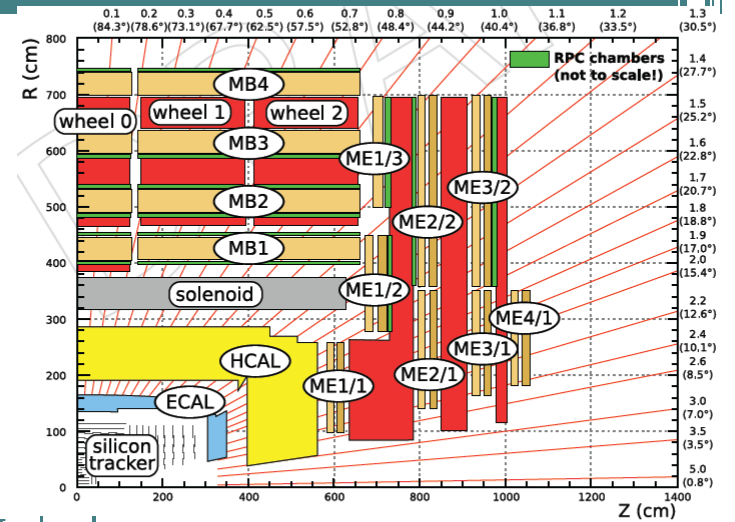
Clustering Muons into Jets

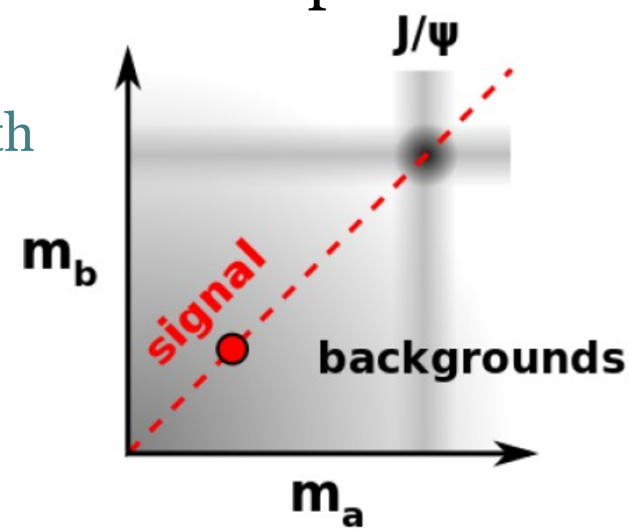
- Add a new muon (μ_{i+1}) to the jet if the jet contains another muon (μ_i) and if:
  - $Q(\mu_i) \times Q(\mu_{i+1}) = -1$
  - Common vertex Probability(μ_i, μ_{i+1})>1%
  - $m(\mu_i, \mu_{i+1}) < 9$ GeV
  - Ignore single muons
- Advantages:
  - Efficient independent of boost
  - Insensitive to pile-up
  - Mass cut can be dialed for optimal distribution of backgrounds among categories
    - 9 GeV is in-sync with muon thresholds in our analysis

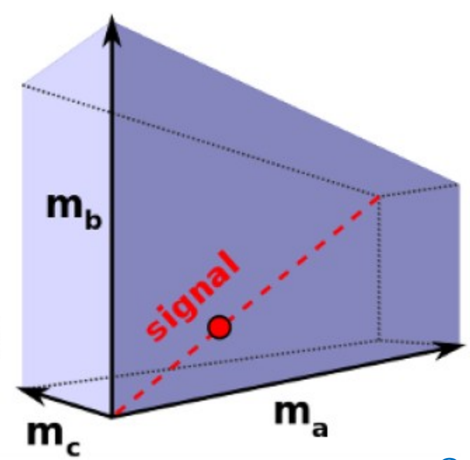


Selections

- Data:
  - 35 pb^{-1} of 2010 LHC data
  - Inclusive muon trigger p_T>15 GeV
- Offline:
  - Require at least 1 muon with p_T>15 GeV, $|\eta|$<0.9
  - Identify all other muons with p_T>5 GeV, $|\eta|$<2.4
  - Reconstruct muon jets and categorize
- Target the case with new bosons produced on-shell:
  - Consider all pairings of muons and pick one with most consistent mass
  - Plot pair masses
  - Signal will be on the diagonal



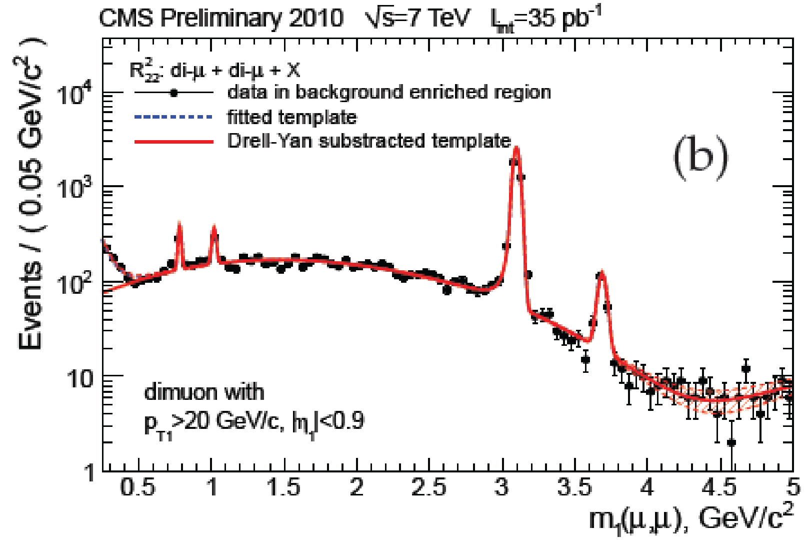




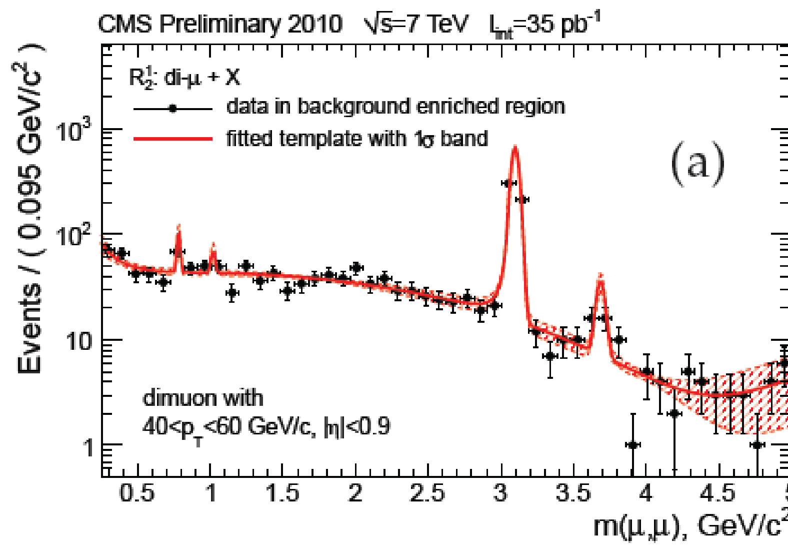
Dimuon Spectrum

- Topology R^1_2
  - "One muon jet with two muons"
- Spectrum and its composition very well understood
  - Good agreement with simulation
    - Modulo some well understood features
      - Some missing resonances, low mass Drell Yan

$$p_T^{\mu\mu} > 20\ GeV$$



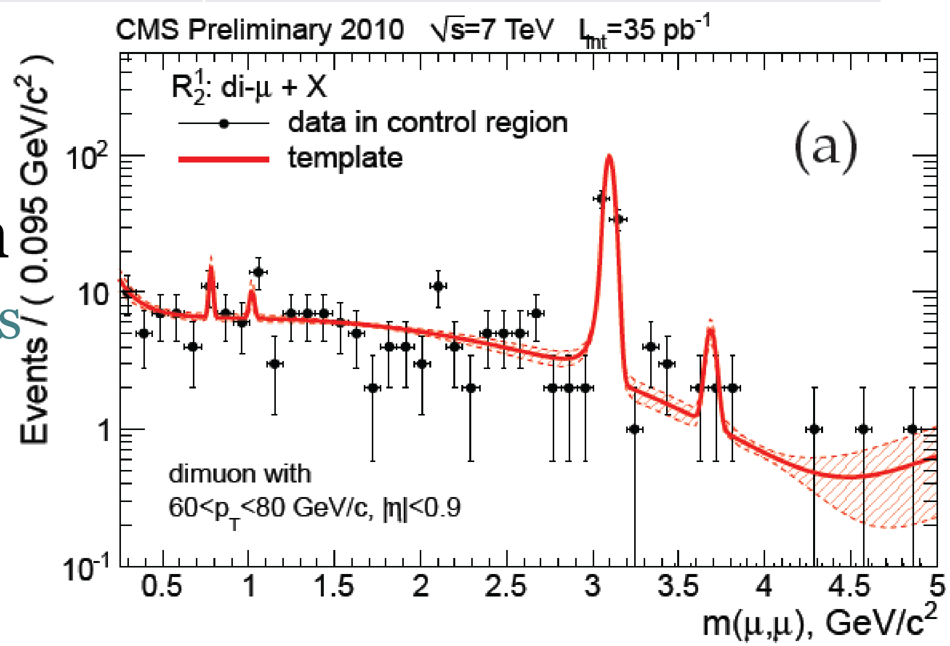
$$40 < p_T^{\mu\mu} < 60\ GeV$$



Topologies and Backgrounds

name	description	Lead μ-Jet p_T	Backgrounds
R^1_2	Single dimuon+X	>80 GeV/c	2μ's from a b-jet, Drell Yan
R^1_4	Single quadmuon+X	no explicit cut	2μ's from a b-jet + 2 fakes
R^2_{22}	Two dimuons+X	no explicit cut	bb-bar+X, 2μ's from each b
R^N_{5+}	All other categories	no explicit cut	Rare, from bb-bar+X/fakes

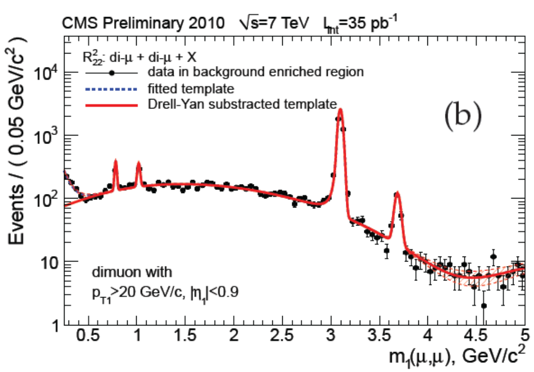
- Apply p_T cut on "single dimuon" category or else backgrounds are too high
  - At p_T>80 GeV, backgrounds are reduced to O(1evt) per pb^{-1} of luminosity in windows of m(μμ)
    - Ballpark of the expected signal cross section



$$60 < p_T^{\mu\mu} < 80 \ GeV$$

Background Modeling

- Fairly elaborate and fully data driven procedure
  - Use templates to build multidimensional distributions predicting background shapes
    - Non-diagonal side-band data is fit for normalization
- One example: the "two dimuons" topology
  - 2D distribution (m_1,m_2) is built as a Cartesian product of 1D distributions for "trigger" and "non-trigger" dimuons



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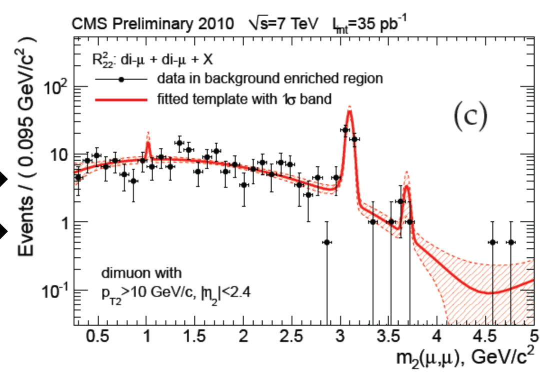

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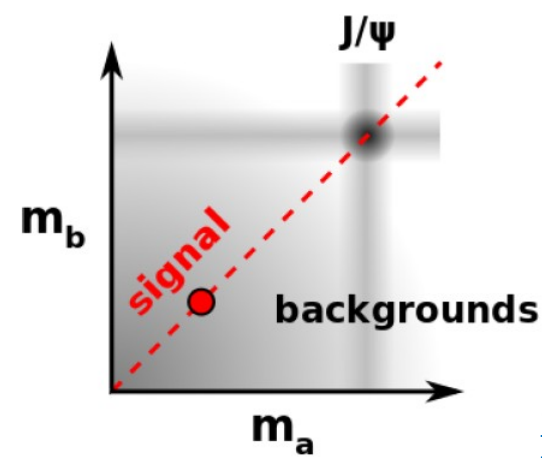
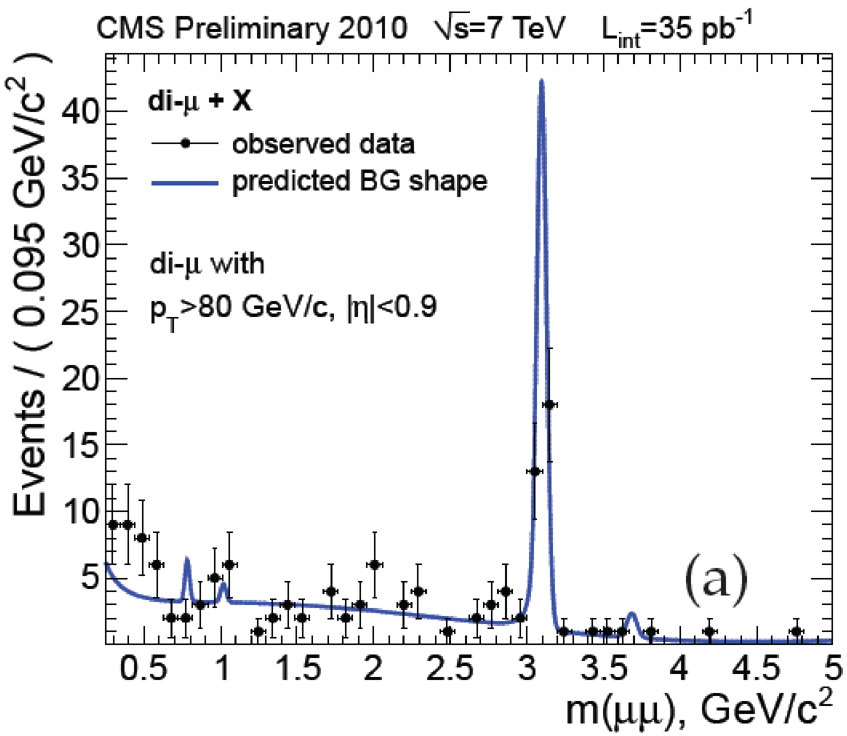


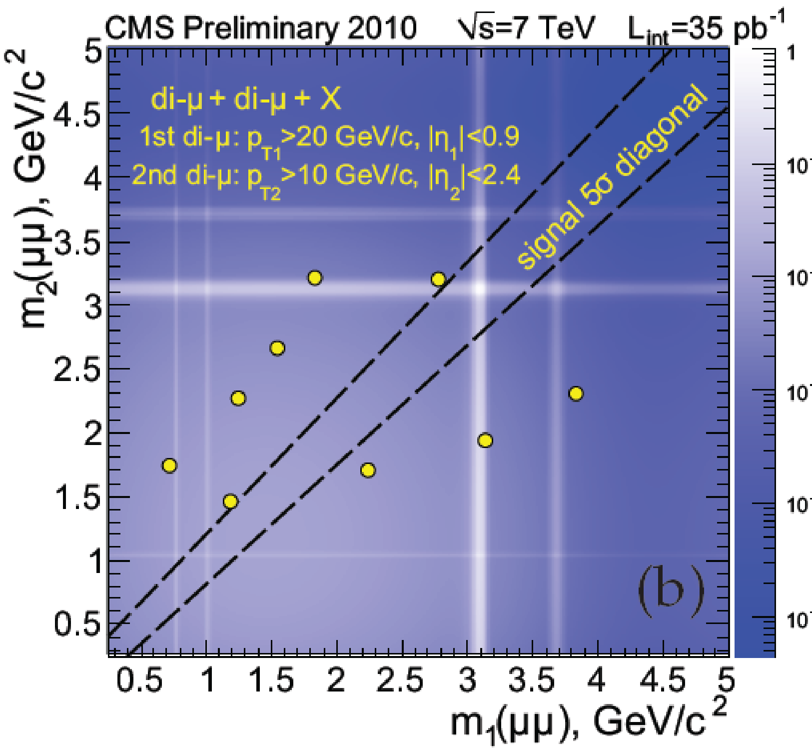
Signal Efficiencies

- Muon system:
  - Dominant factor for $p_T(\mu\mu)<150$ GeV, $\varepsilon\sim92$-95%
    - Losses due to non-instrumented gaps and muon overlaps in the muon system (endcap)
- Tracking:
  - Important for high momentum dimuons
    - Losses when tracks have large overlap of hits in the tracker
    - $m(\mu\mu)\sim0.4$-0.6: $\varepsilon\sim85/75\%$ at $p_T(\mu\mu)=250/350$ GeV
    - Elsewhere $\varepsilon\sim95/85\%$ at $p_T(\mu\mu)=250/350$ GeV
- Mass resolution (for $p_T(\mu\mu)<200$ GeV):
  - $\sigma(m, p_T) \sim 0.011\ \text{GeV}+0.0065\ m+10^{-4}\ p_T$ (barrel)
  - $\sigma(m, p_T) \sim 0.011\ \text{GeV}+0.0130\ m+10^{-4}\ p_T$ (endcap)
- High multiplicity muon jet efficiency ~factorizes into efficiencies of finding dimuons in it

Data in Signal Regions -1

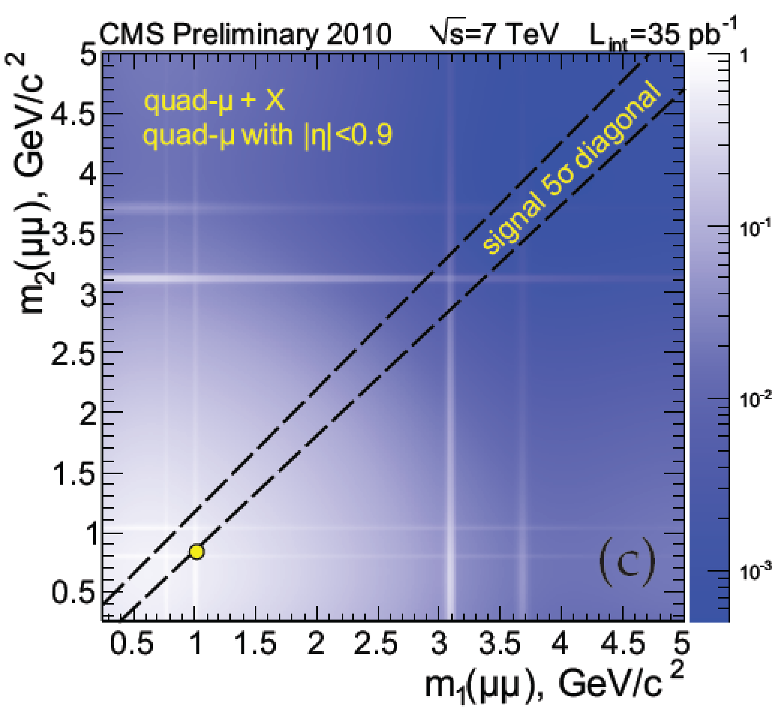
- Single dimuon+X: narrow bump would indicate signal
- The two-dimuon+X (right): zero diagonal events
  - Background normalization assumes that new resonances are produced on-shell

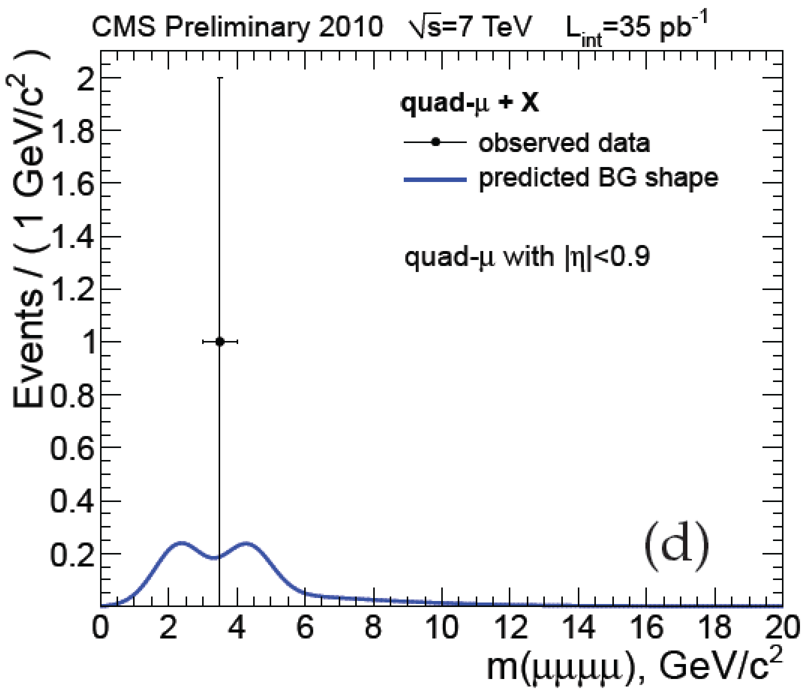




Data in Signal Regions -2

- Quadmuon +X: zero diagonal events
  - Background normalization assumes that new resonances are produced on-shell
    - If produced off-shell, signal can be off-diagonal
    - Can also look at the 4μ mass (search for $h^{dark} \rightarrow \gamma^{dark}\gamma^{dark}$)



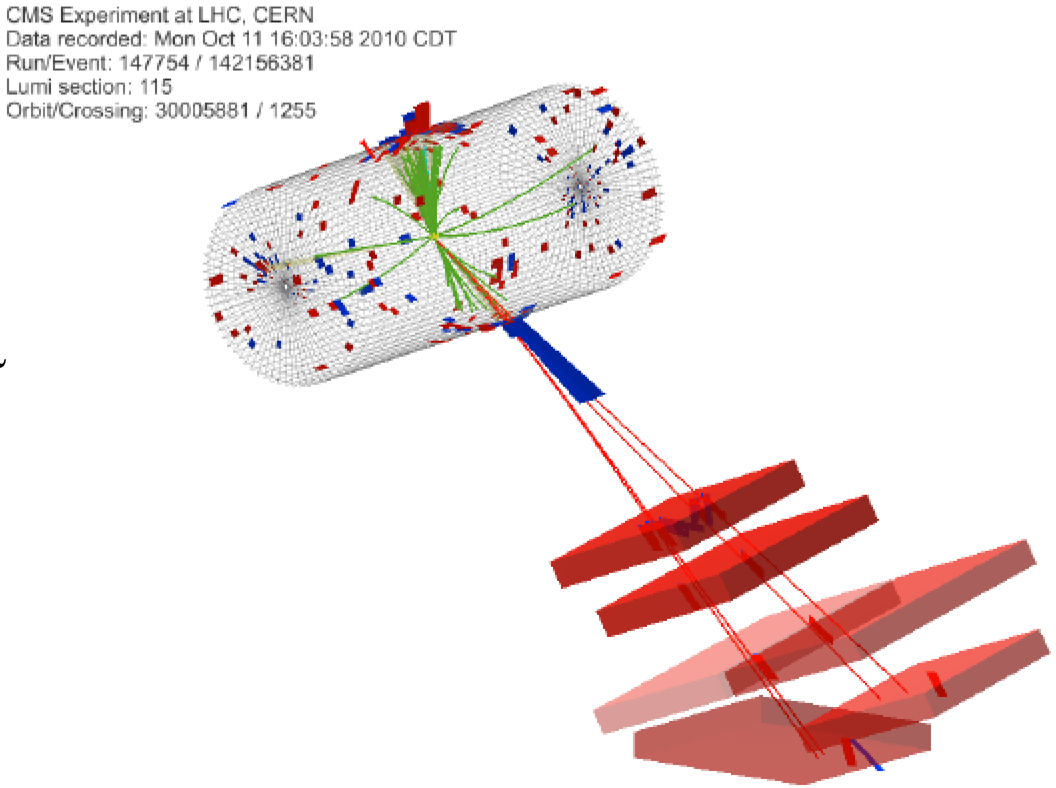


No data events in any of the higher multiplicity topologies

The Quadmuon Event

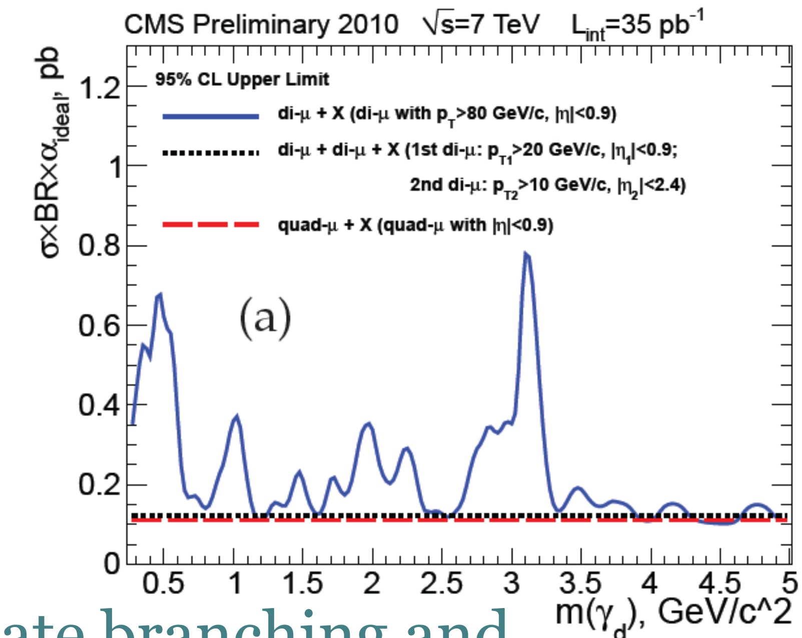
- Consistent with two true muons and two tracks misidentified as muons
- Likely a bb-bar event with $\phi \to \mu\mu$ in one of the b-jets

R_4^1: four nearby muons (only event)



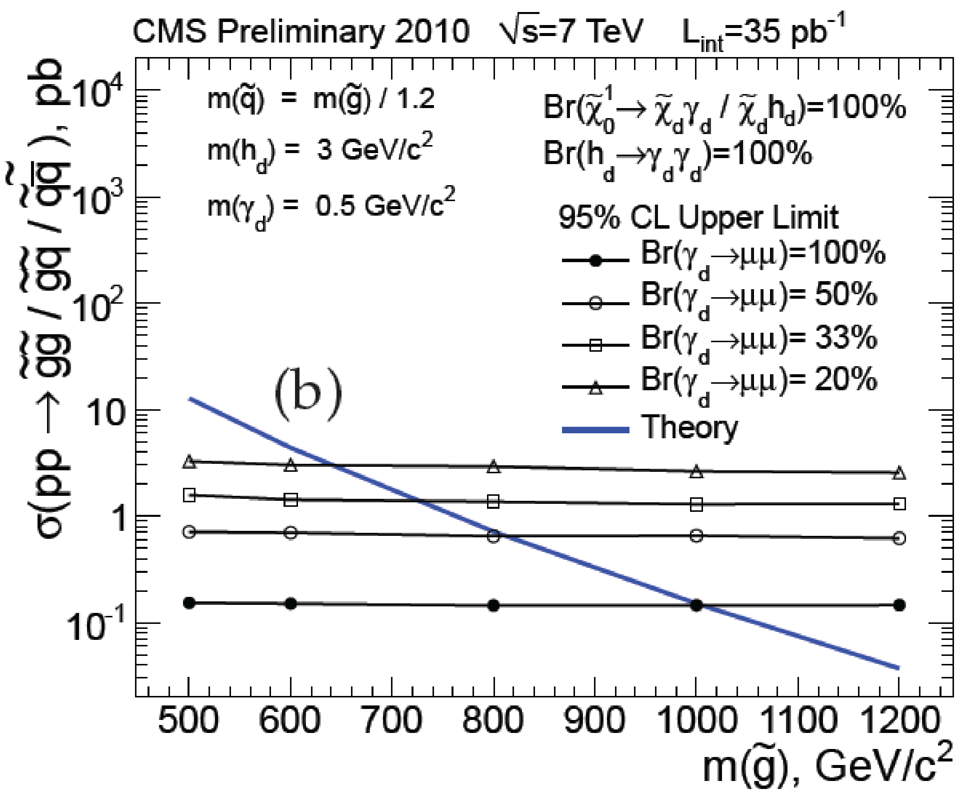
Model-Independent Interpretation

- Use three simplest topologies to set "conservative" model independent limits:
  - Dimuon+X
  - Two-dimuon+X
  - Quadmuon+X
- Limits of applicability:
  - Mean p_T(μ-jet)≤250GeV
- Instructions for future uses:
  - Follow analysis steps to calculate branching and acceptance for specific final state
  - Assuming an ideal detector and compare with the limit plot
    - Complex topologies can be reduced to one of these three



Model Specific Limits -1

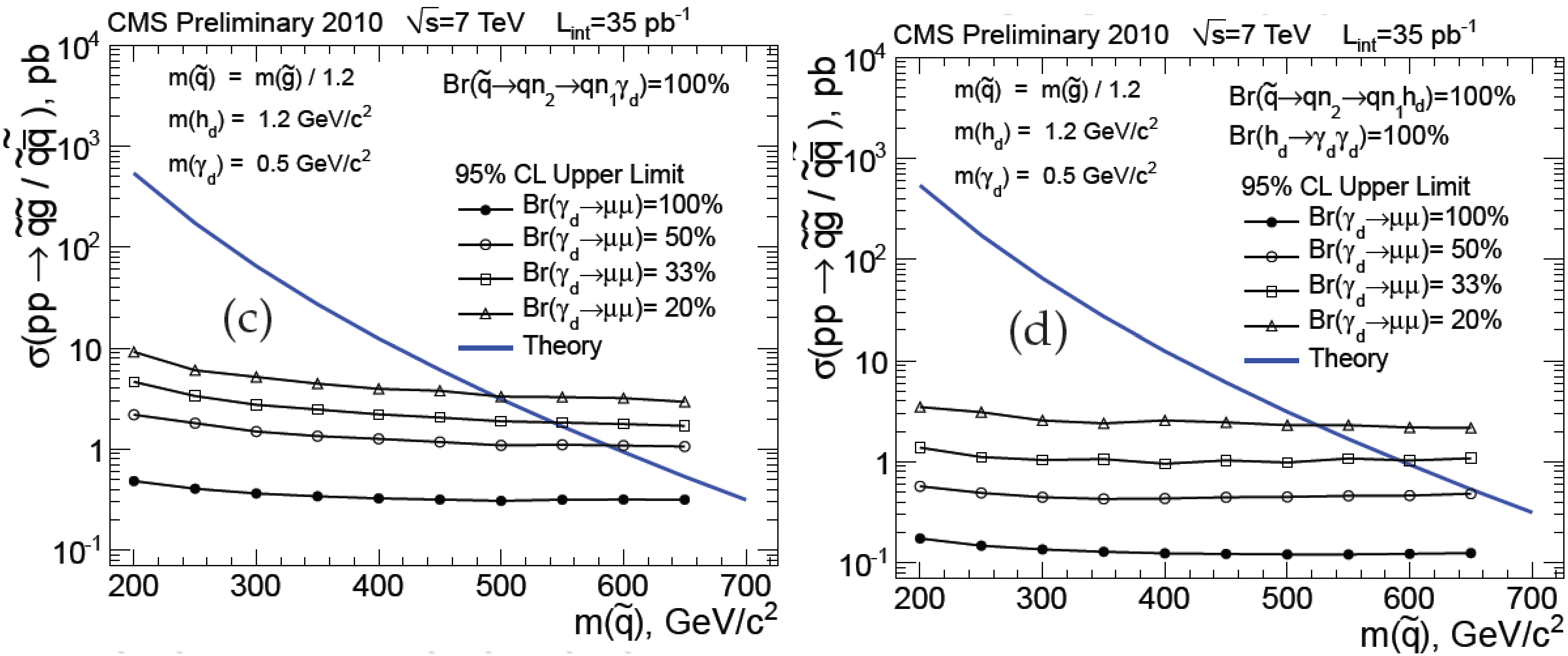
Theory reference: Y. Bai and Z. Han, Phys. Rev. Lett. 103 (2009) 051801.



- MSSM neutralino decays to a heavy stable dark neutralino and γ^{dark}/h^{dark} $(h^{dark} \rightarrow \gamma^{dark}\gamma^{dark})$

Model Specific Limits - 2

Theory reference: J. T. Ruderman et al., JHEP 04 (2009) 014.



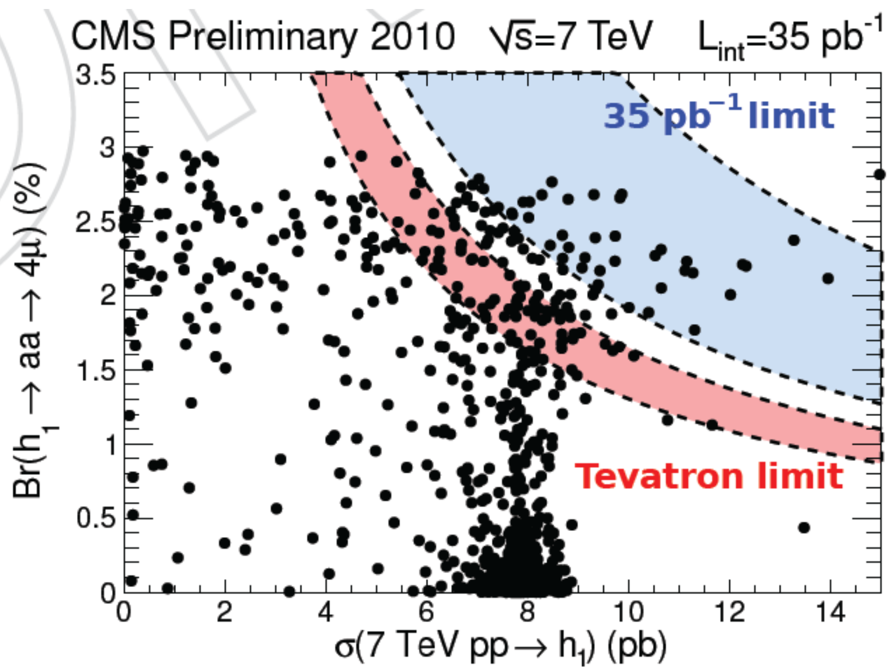
- MSSM LSP is a squark decaying to a quark, light dark fermion and either γ^{dark} (left) or h^{dark} (right)

Y. Bai and Z. Han, "Measuring the Dark Force at the LHC", Phys. Rev. Lett. 103 (2009) 051801.

NMSSM Higgs Limits

Following Belyaev, Pivarski, A.S. et al., Phys. Rev. D 81 (2010) 075021.

- Limits derived using two-dimuon topology
  - Scan over NMSSM parameter space for $m(a_1)<2m_\tau$
    - WMAP and LEP constraints applied
  - Limits are blurred due to varying acceptance as function of $m(h_1)$ and $m(a_1)$
    - Not yet competitive with the Tevatron, need ~100 pb^{-1} to overtake



Summary

- First LHC analysis targeting final states with lepton jets has been completed
- No discovery, but new ground in sensitivity to SUSY models with light squarks and gluinos
  - Complementary to Tevatron searches sensitive to SUSY with light charginos
- Results allow a quazi model independent interpretation for future phenomenological use
- NMSSM Higgs search with light CP-odd Higgses is gaining ground and will surpass the Tevatron sensitivity when the data already on tape is analyzed
- New results with an order of magnitude more data are to come over the summer