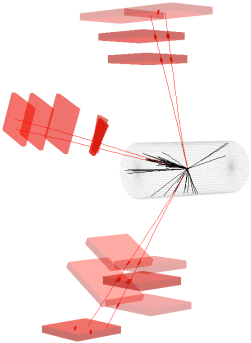
# Search for Dimuon Resonances in "Lepton Jets"

*Jim Pivarski*
Alexei Safonov
Aysen Tatarinov

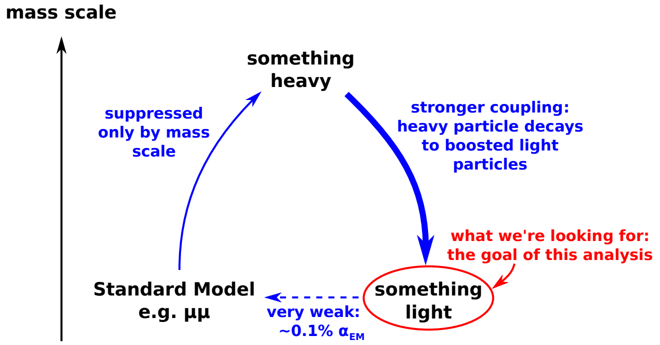
*Texas A&M University*

8 March, 2011



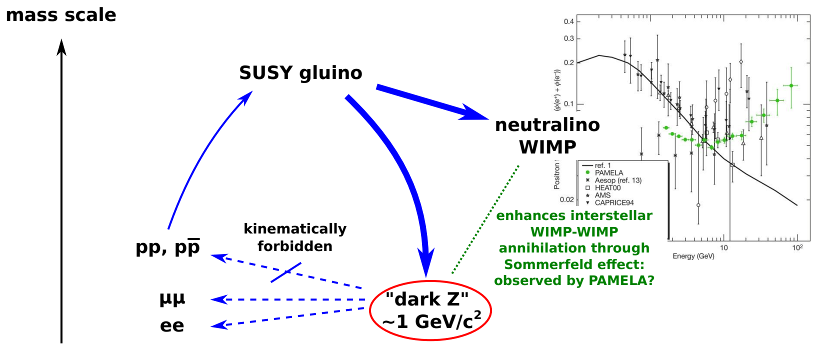
# Sketch of the basic goal





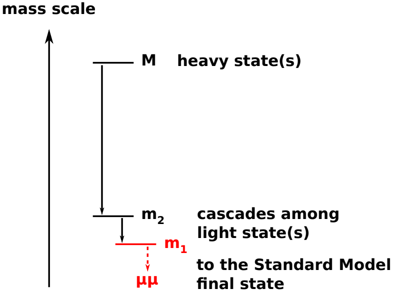

- Hidden-valley picture: predicts new low-mass, high-momentum particles decaying to Standard Model pairs like $\mu\mu$
- We want to maximize our sensitivity to "something like this"
  - strike a balance between accepting theoretical guidance and producing a general result

# Motivation from PAMELA result

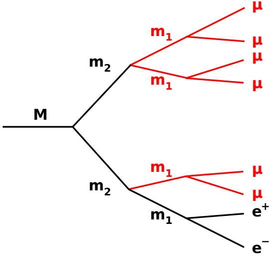



- Sub-class motivated by PAMELA positron excess
  - the "something light" is a long-range force between WIMPs
  - unobserved antiproton excess is kinematically forbidden
- Would appear in $pp$ collisions as high-$\vec{p}$, low-mass $Z/\gamma$-like objects

| Theoretical guidance | Experimental method |
|---|---|
| couplings within the hidden sector (dark matter, NMSSM Higgs, etc.) are stronger than couplings to the Standard Model, so only the lightest hidden particle ($m_1$) decays visibly | search for one new low-mass particle |



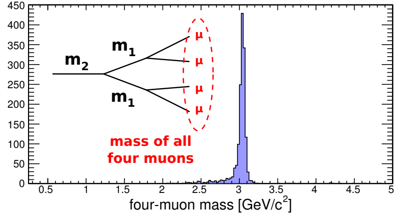

| Theoretical guidance | Experimental method |
|---|---|
| assume no fine splittings ($M_2 - M_1 \gg m$), such that some low-mass $m_i$ is on-shell | search for $m_1$ or $m_2$ resonance peak |

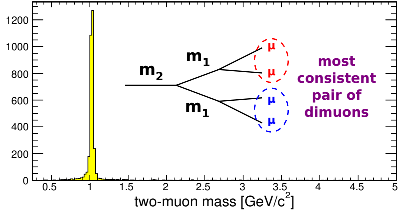
| Theoretical guidance | Experimental method |
| --- | --- |
| several $m_1$ may appear per event, and their decay products may overlap<br>cascades of low-mass particles would be collimated by a high-momentum boost | identify well-separated groups with a clustering algorithm |
|  | |
| $\mathcal{B}(m_1 \to \mu\mu)$ is likely to be high (DY-like if $m_1$ mixes with $\gamma$, $\sim$20% if Higgs-like, ...)<br>but non-$\mu\mu$ decays would also happen, so $m_1 \to \mu\mu$ could overlap electrons/pions | look for dimuons, but neither require nor exclude other particles (e.g. do not apply an isolation cut) |

# Overview of the method (3/5)



| Theoretical guidance | Experimental method |
|---|---|
| narrow groups of four or more muons come from cascades like $m_2 \to m_1 m_1$ with both $m_1 \to \mu\mu$ | resolve combinatorics within each group by finding the most consistent combination of dimuon masses ($a$ and $b$ such that $m_a \approx m_b$) |



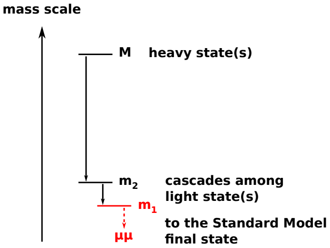



# Overview of the method (4/5)



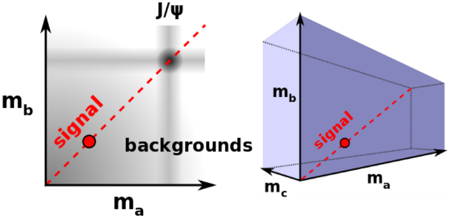
## Theoretical guidance

only the lightest hidden state decays to muon pairs, so only one new mass




## Experimental method

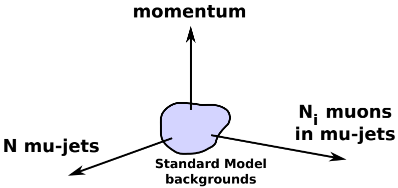
in the dimuon mass-dimuon mass plane, signal is a peak on the $m_a \approx m_b$ diagonal, background is diffuse




determine signal and background yields from a simultaneous fit, where the "side-band" is the non-diagonal part

shape of fit function derived from similar datasets

| Theoretical guidance | Experimental method |
|---|---|
| cross-section $\lesssim \mathcal{O}(\text{pb})$ | design search regions to exclude backgrounds rather than seek any particular topology |
| many topologies possible; typically high-momentum and/or high muon multiplicity | |




divide momentum and multiplicity space into non-overlapping signal regions, excluding low-momentum, low multiplicity

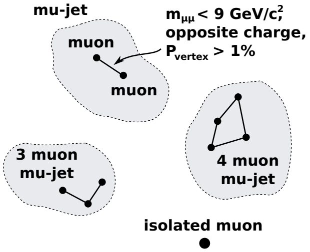
(listed on next page)

# Event selection/signal regions



All signal events must have:

- at least one $p_T > 15$ GeV/$c$, $|\eta| < 0.9$ muon
- HLT_Mu15 or equivalent
- at least one cluster of muons ("mu-jet")




Specific signal regions:

| name | description | min mu-jet $p_T$ |
|---|---|---|
| $R_2^1$ | high-$p_T$ dimuon | 80 GeV/$c$ |
| $R_4^1$ | four nearby muons | 30 GeV/$c$ |
| $R_{22}^2$ | two separate dimuons | 20, 10 GeV/$c$ |
| $R_{5+}^N$ | high multiplicity | same as above |

$R^N_{n_1 \cdots n_N}$ has $N$ mu-jets, $n_i$ muons in mu-jet $i$

no cuts on the number of isolated muons

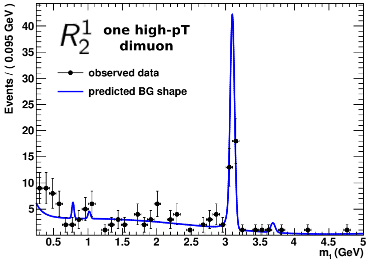
$R_3^1$ is not signal

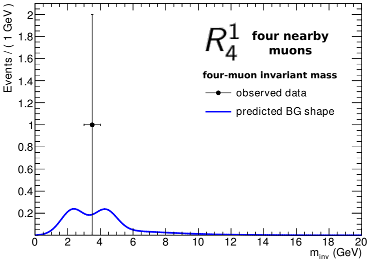
$R^{2+}_{\ldots 3 \ldots}$ is signal

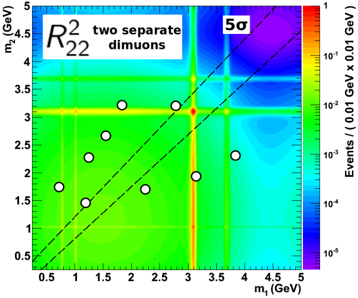
Muon cuts: TrackerMuon $p_T > 5$ GeV/$c$, $|\eta| < 2.4$, arbitrated seg. $\geq 2$, tracker hits $\geq 8$, $\chi^2/N_{\text{dof}} < 4$

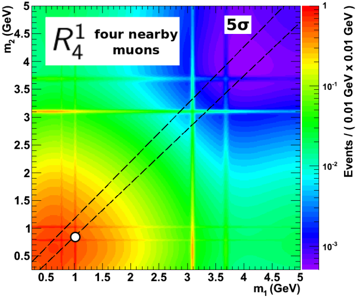
# Yields with background PDFs

Zero events in $R^N_{5+}$, nothing on-diagonal in any 2-D region

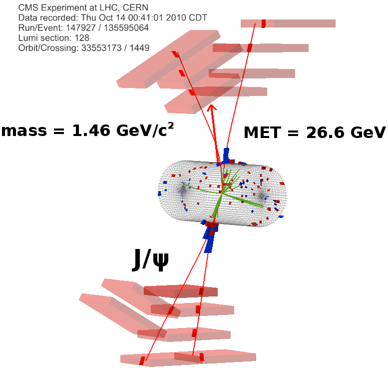


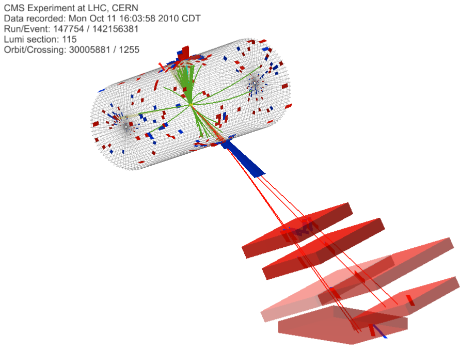



$R^2_{22}$: two separate dimuons
(sample event)




$R^1_4$: four nearby muons
(only event)

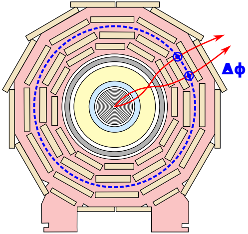


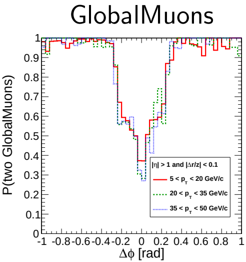
# Outline for the rest of this talk

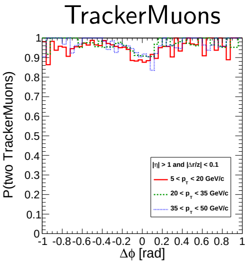
- Muon and trigger selection, efficiency
- Modeling the signal shape
- Analysis of background physics
- Modeling the background shapes
- Fits and model-independent results
- Benchmark models and model-dependent results

# Muon selection, trigger selection, and efficiencies

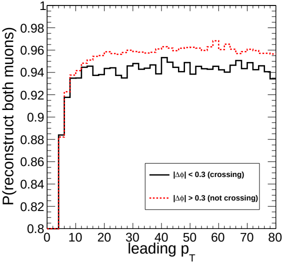
StandAloneMuons, and hence GlobalMuons, are inefficient when crossing:

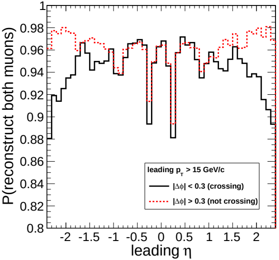



Efficiency of reconstructing *dimuon* with TrackerMuons + analysis cuts:




black: crossing in muon system

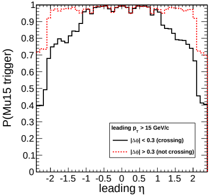
red: not crossing

# Trigger efficiency

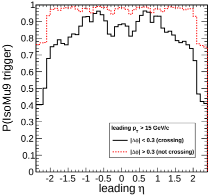


Trigger efficiencies are strongly dependent on whether muons cross in the muon system, with the exception of single-muon unisolated barrel trigger (middle of left plot)

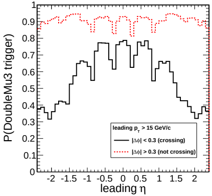
single-muon (HLT_Mu15)




single-muon isolated (HLT_IsoMu9)




double-muon (HLT_DoubleMu3)



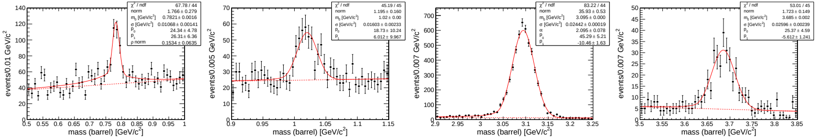

black: crossing in muon system

red: not crossing

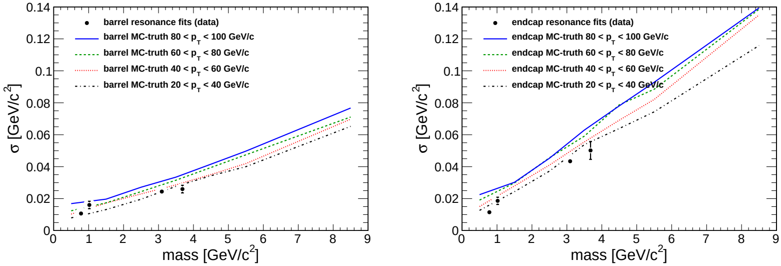
Accepting endcap-triggered events would introduce a strong efficiency dependence on dimuon kinematics; therefore, we require at least one $|\eta| < 0.9$ muon above trigger threshold ($p_T > 15$ GeV$/c$)

# Modeling the signal shape

A hidden-sector particle must, by definition, have a narrow width, so use narrow Standard Model resonances to determine detector resolution

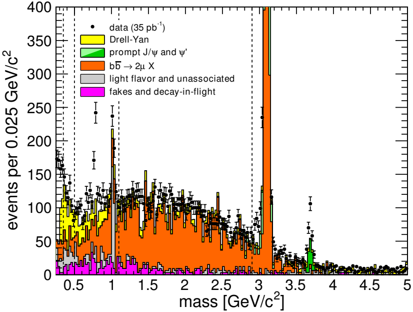



These resonances are on the lowest-$p_T$ edge of our desired range: determine $p_T$-scaling (and fill in gaps between masses) with Monte Carlo



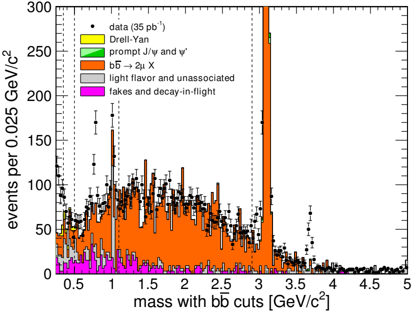
# Analysis of background physics

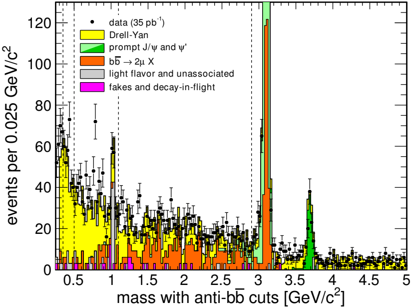
# Physics of dimuon backgrounds

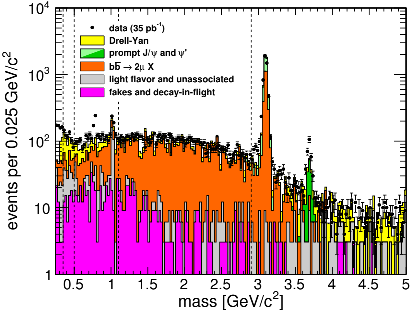



Data/MC comparison study to understand all background sources

- diagnostic tool: $b\bar{b}$ cuts $=$ $Iso > 4.5$ GeV$/c$ or $L_{xy} > 2$ mm
- "low-mass rise" now understood to be Drell-Yan (though MC is incomplete)

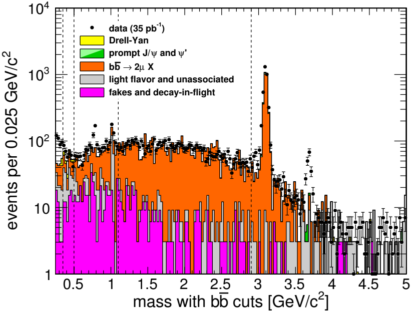


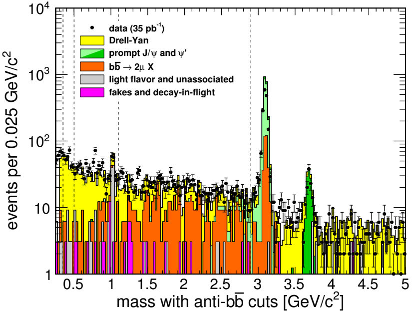






Data/MC comparison study to understand all background sources

- diagnostic tool: $b\bar{b}$ cuts = $Iso > 4.5$ GeV$/c$ or $L_{xy} > 2$ mm
- "low-mass rise" now understood to be Drell-Yan (though MC is incomplete)



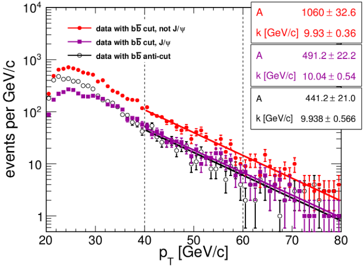
# Modeling the background shapes

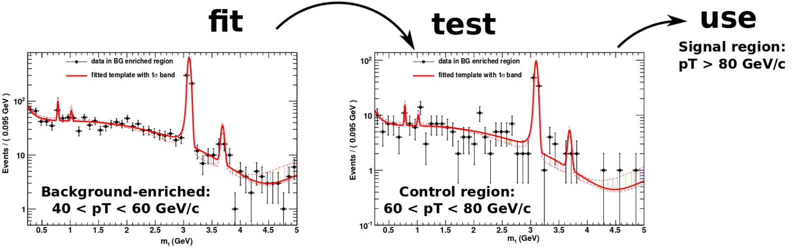
# Background shape of $R_2^1$



Different physics sources contribute to each signal region, so the background shape templates must be individually constructed

- For $R_2^1$: note that the prompt and isolated, $b\bar{b}$-like, and $J/\psi$ components all scale as $\exp(-p_T/10\text{ GeV})$ above 40 GeV/$c$
- Derive shape from high-statistics low-$p_T$ data, test in medium-$p_T$, and use in high-$p_T$ signal search

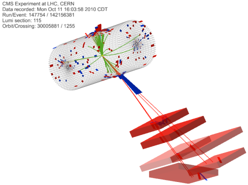


# Background shape of $R_4^1$



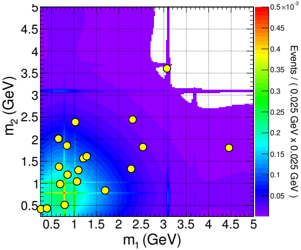
## For $R_4^1$: four nearby muons

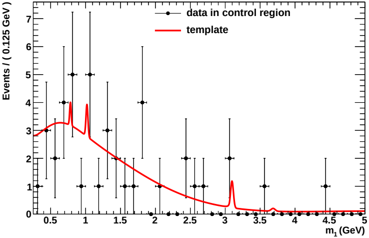



- Dominant Standard Model backgrounds: decays-in-flight and misreconstruction (fakes)
- Simulate fake muons by putting non-muon tracks into mu-jets:

| Background-enriched | Control | Signal Region |
|---|---|---|
| 2 muons, 2 tracks | 3 muons, 1 track | 4 muons |

- Plots of control region with template shape overlaid:

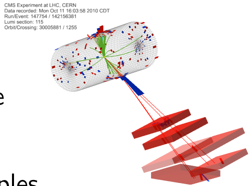


# $R_4^1$ four-muon mass shape



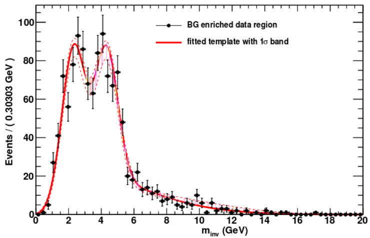
## Still $R_4^1$: four nearby muons



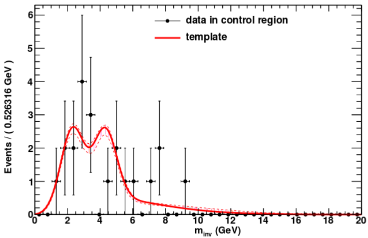

Considering the case of $m_2 \to m_1 m_1 \to 4\mu$ with $m_1$ off-shell but $m_2$ on-shell, we prepare a template for the four-muon mass

- background-enriched, control, and signal samples are the same as on the previous page
- four-muon mass has a two-peak structure: second peak is $J/\psi$

background-enriched fit

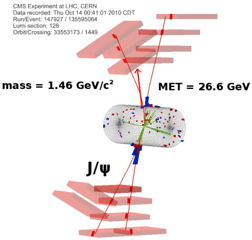



control sample test



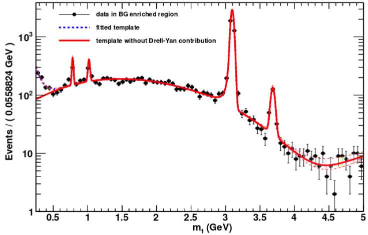
# Background shape of $R^2_{22}$

## For $R^2_{22}$: two separate dimuons

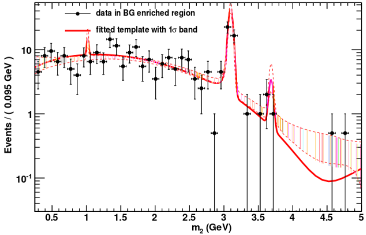



- Dominant Standard Model backgrounds: $b\bar{b}$ with both $b$-quarks producing $\mu\mu X$ by double-semileptonic decay, resonances, etc.
- Assume that each $b$-quark decays independently and construct 2-D distribution from Cartesian product of 1-D $b \to \mu\mu X$ distributions
- Complication: requiring a $p_T > 15$ GeV/$c$ trigger muon changes the distribution; need templates for both cases

template for dimuon with trigger




template for any dimuon

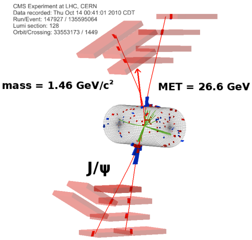


# Background shape of $R^2_{22}$



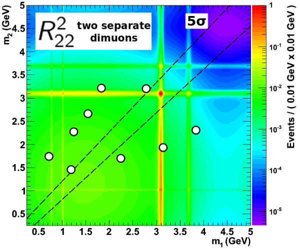
## For $R^2_{22}$: two separate dimuons

- Dominant Standard Model backgrounds: $b\bar{b}$ with both $b$-quarks producing $\mu\mu X$ by double-semileptonic decay, resonances, etc.
- Assume that each $b$-quark decays independently and construct 2-D distribution from Cartesian product of 1-D $b \to \mu\mu X$ distributions

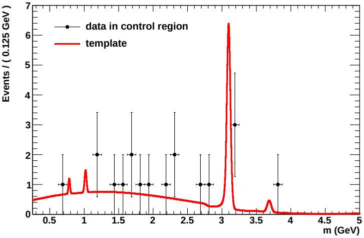



- Complication: requiring a $p_T > 15$ GeV/$c$ trigger muon changes the distribution; need templates for both cases

control (non-diagonal signal region)



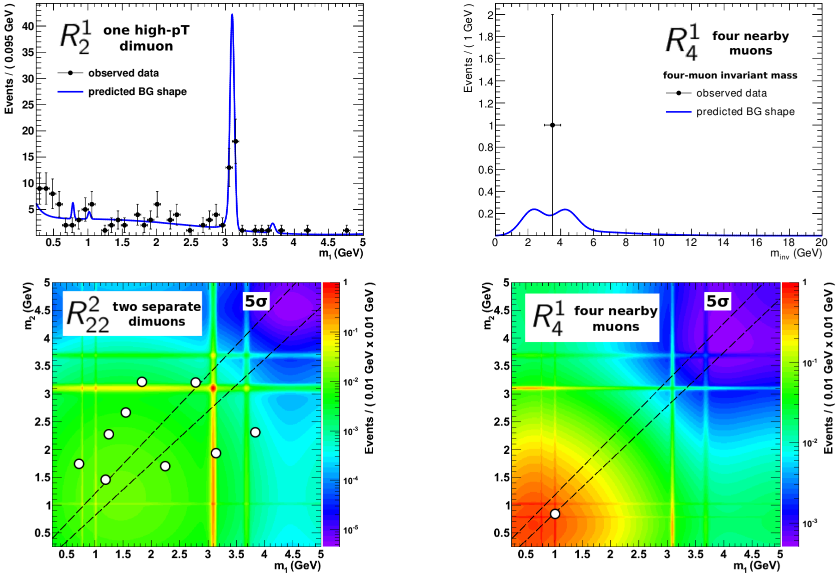

projection of control region



# Fitting technique and model-independent results

# Fits of signal regions (again)

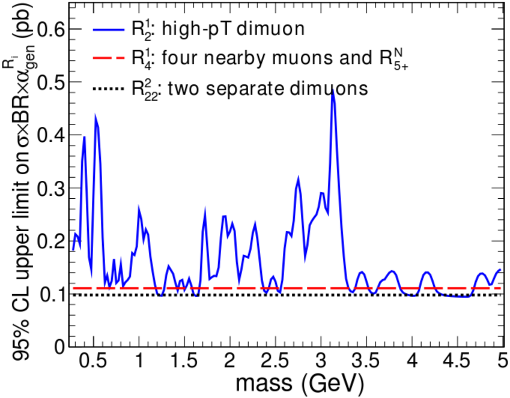
Zero events in $R^N_{5+}$, nothing on-diagonal in any 2-D region



# Model-independent limits

Upper limit on cross-section × branching fraction × acceptance, where acceptance must be supplied by the model in question

- acceptance = probability that an event satisfies basic $p_T$, $\eta$, mass, and multiplicity requirements of a given region $R_i$



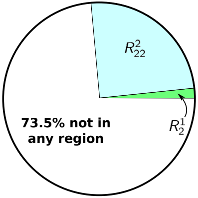
# Benchmark models and model-dependent results

# Benchmark model acceptances

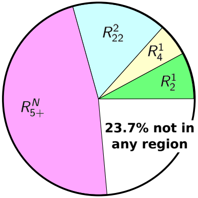
Calculate model-dependent limits from acceptances of each model into each signal region

- three sample models: one NMSSM Higgs and two dark matter
- depends strongly on $\mathcal{B}(\gamma_{\mathrm{dark}} \to \mu\mu)$ (assumed to be 100% here)

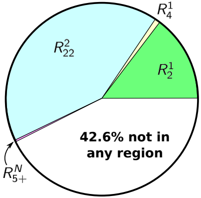
**NMSSM Higgs**
produce Higgs, decays to dimuons: $h_1 \to a_1 a_1$ with $a_1 \to \mu\mu$



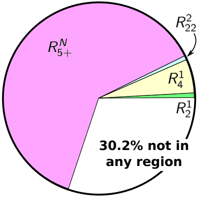

**MSSM + mixed**
produce gluino, mixed decays: $\gamma_{\mathrm{dark}} \to \mu\mu$ and $h_{\mathrm{dark}} \to \gamma_{\mathrm{d}}\gamma_{\mathrm{d}} \to 4\mu$




**MSSM + $\gamma_{\mathbf{dark}}$**
produce squark, decays to dimuons: $\gamma_{\mathrm{dark}} \to \mu\mu$



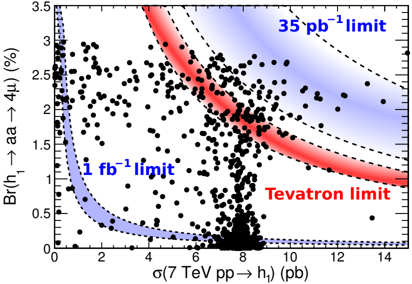

**MSSM + $h_{\mathbf{dark}}$**
produce squark, decays to quadmuons: $h_{\mathrm{dark}} \to \gamma_{\mathrm{d}}\gamma_{\mathrm{d}} \to 4\mu$

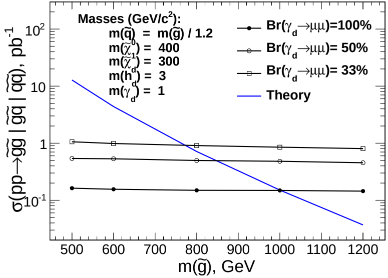


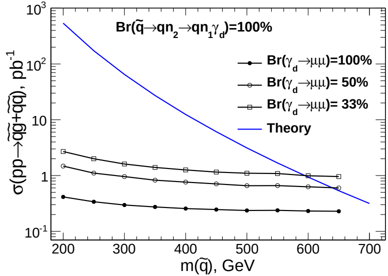
# Benchmark model limits

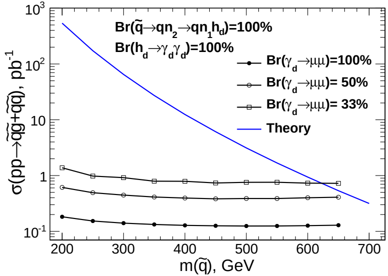


Same arrangement as previous page



# Systematic uncertainties

| | $R^1{}_2$ | $R^1{}_4$ | $R^2{}_{22}$ | $R^{1+}{}_{5+}$ (not all muons need to be found) |
|---|---|---|---|---|
| Muon eff | 1% | 2.3% | 4% | 4% |
| Tracking @ high pT<br>Pt=0-300 GeV assume mean of the group pt~150 GeV | 10% (m=0.25)<br>5% (m=0.5)<br>2% (m>1 GeV) | 2% | 20% (m=0.25)<br>10% (m=0.5)<br>4% (m>1 GeV | 20%<br>10%<br>4% (conserv. from $R^2{}_2$ |
| Luminosity | 4% | 4% | 4% | 4% |
| Signal/Bkg Shape Systematics | In the fit | In the fit | In the fit | In the fit |
| TOTAL: | 12% | 5% | 20% | 20% |
| Add for model independent results ONLY to account for efficiency variations vs m and pT. Assume mean of the group pt=150 GeV | 20% | 2% | 35% | 16% |

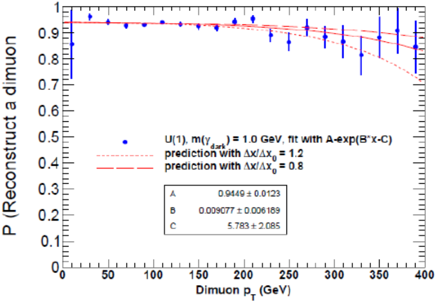
# Conclusions

- We present a complete search for cascade decays in a hidden sector decaying (at least partly) to $\mu\mu$, with either the lightest ($m_1$) or second lightest ($m_2$) state on-shell
- Reconstruction methods were chosen for uniform, predictable efficiencies and independence from signal kinematics
- Sources of backgrounds are understood using Monte Carlo
- Template shapes for signal and background fit well-tested in control samples
- Fit yields robust 0.1 pb limit on $\sigma \times \mathcal{B} \times \alpha$ for all all regions with more than one dimuon; 0.1–0.5 pb for one dimuon
- Demonstrated application with several benchmark models

# Backup

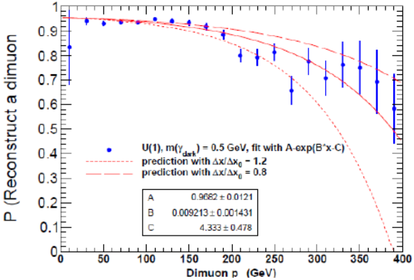
# Tracking Efficiency Systematics

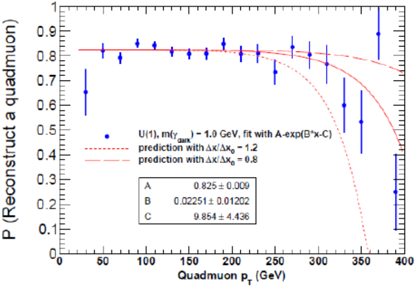
- Loss of efficiency happens if hits are merged more often in data then in MC due to incorrect cluster size in simulation
  - Either tracker hits or muon stubs (!)
- Distance between two tracks from $\gamma^D$ with mass *m* and momentum *p* at radius *R*:
  - $\Delta x \approx R^*m/p$, hits are merged until radius $\mathbf{R = p/m\,\Delta x^{min}}$
    - $\Delta x^{min}$ – minimum distance to resolve hits
- If cluster sizes are off in data, $\Delta x^{min}$ can be larger/smaller in data
  - Can adjust cluster sizes in simulation
    - E.g. $\mathbf{\Delta x^{min} \rightarrow 1.2\,\Delta x^{min}}$
  - Or can estimate the same effect by making tracks a little “closer”
    - Adjust momentum $p \rightarrow p/1.2$
    - Measure efficiency systematics by looking at dimuon efficiency at ±20% momentum



# Tracking Systematics Continued

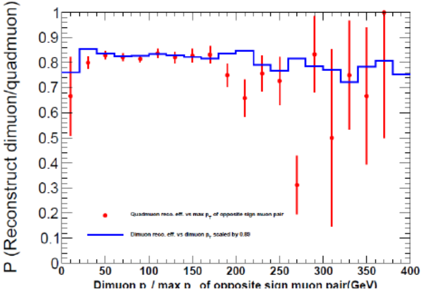
- The same method for different dimuon masses
- The same method for quadmuons:
  - Momentum of the dark shower is limited by the kinematics reach (200-300 GeV per cascade)
  - Higher multiplicity lepton jets have better average tracking efficiency b/c the same energy is divided between more tracks
    - Less collimation, better separation by the magnetic field for softer tracks

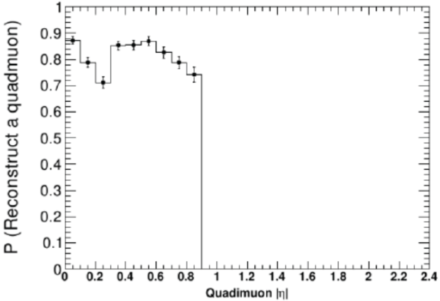


# More on Quadmuons

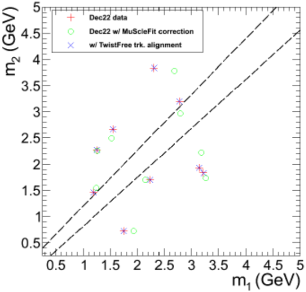
- Efficiency of reconstructing a quadmuon is driven by the efficiency to reconstruct the higher momentum dimuon within the quadmuon
  - But larger correlated inefficiency term from gaps between the DT wheels
    - Many muons near the gap reduces probability to find all four of them

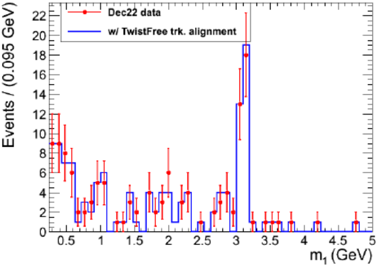


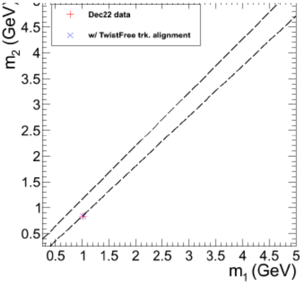



# Tracker Twist Studies

- MuscleFit corrections (suggested by ARCs) have shown large changes in reconstructed masses
  - E.g. severely degrading J/psi peak in the single dimuon region
  - Not what one expects from smooth twist effect
- Fully re-reconstruct events with new untwisted tracker geometry
  - Very consistent with the original results
  - MuscleFit corrections not applicable in this topology



# Clustering algorithm



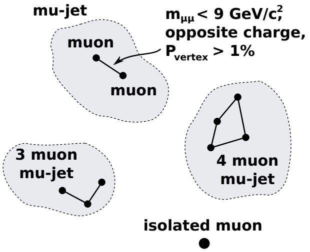
- If two muons satisfy

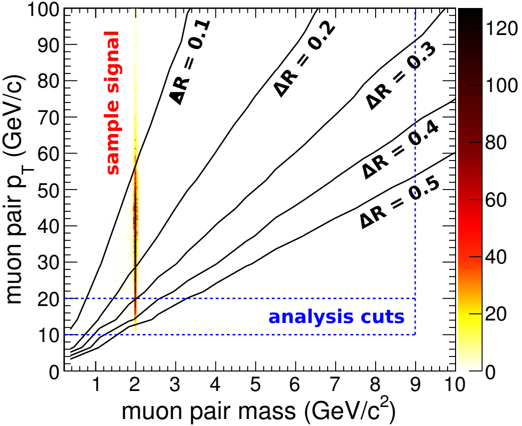
$$\Big( (\text{mass} < 9\ \text{GeV}/c^2 \text{ and } P_{\text{vertex}} > 1\%) \text{ or } \Delta R < 0.01 \Big) \text{ and opposite charge}$$

  then they are "close" to one another
- Each mu-jet is a connected subgraph of "close" muons
- There is *no* order dependence at all in the clustering process

Test of the algorithm on background Monte Carlo: $b\bar{b}$ with each $b \to 2\mu X$. The algorithm should not merge the muons from different $b$ quarks.

| Clustering threshold | two mu-jets | one mu-jet |
|---|---|---|
| mass $< 5$ GeV/$c^2$ | 6015 | 6 |
| mass $< 9$ GeV/$c^2$ | 6019 | 6 |
| mass $< 15$ GeV/$c^2$ | 5870 | 172 |

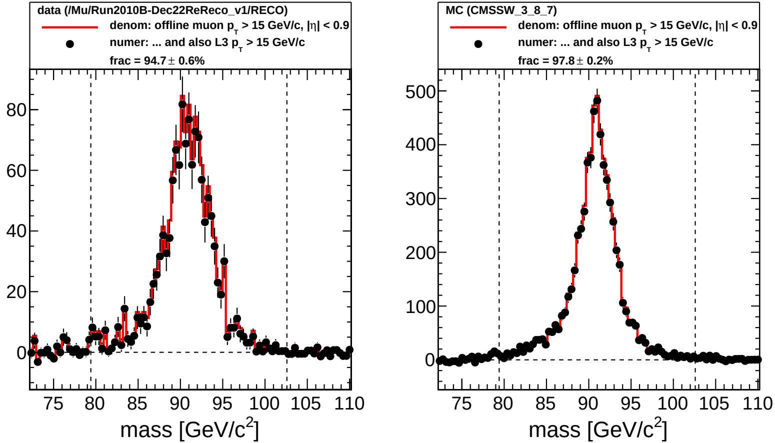





Note: $\Delta R$ presented here is the *average* $\Delta R$ in each mass, $p_T$ bin (not necessarily the most probable value)

# Trigger tag-and-probe

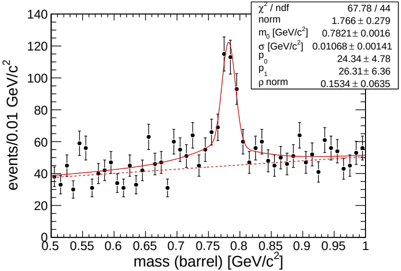


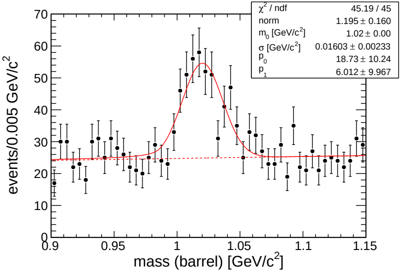


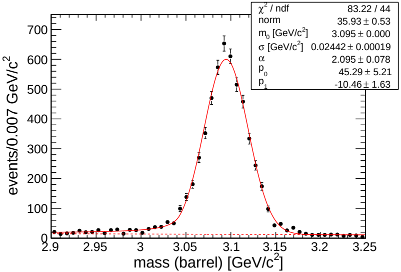

- We refer to $t\bar{t}$ cross-section group for tag-and-probe trigger efficiencies
- However, we performed a basic $Z \to \mu\mu$ tag-and-probe study with our own data samples to verify
  - using exactly the data sample/release and exactly the MC release as in analysis

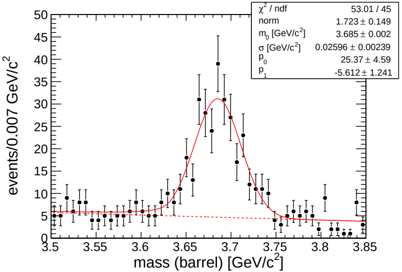
# Resonance fits: barrel





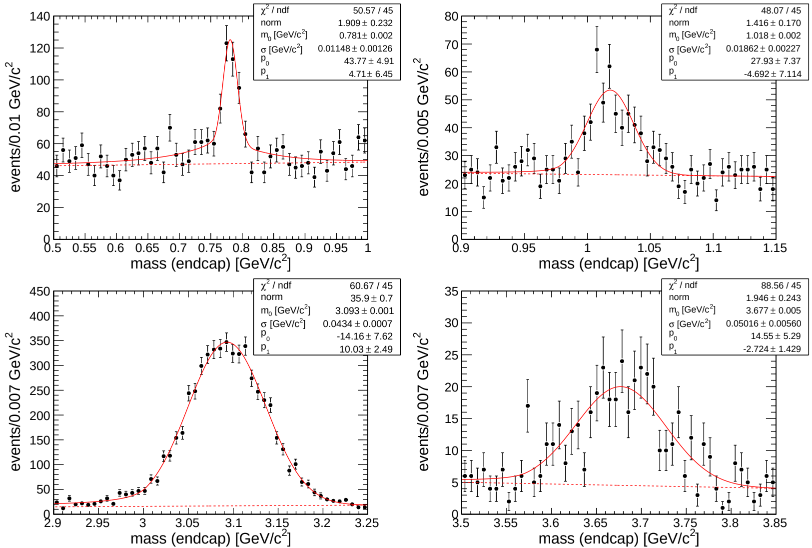



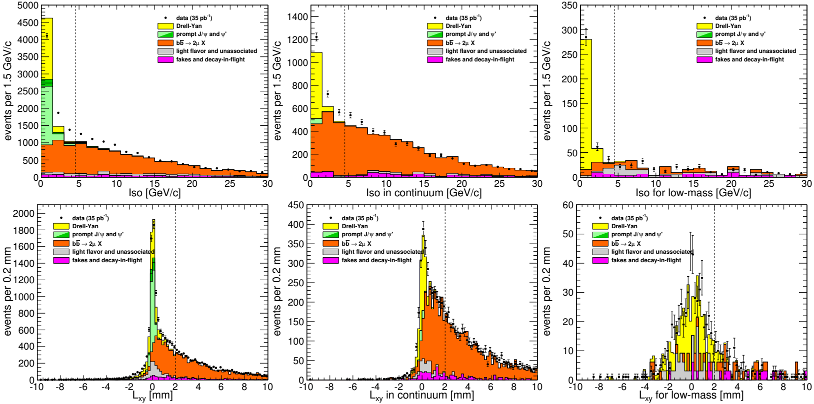



# Resonance fits: endcap

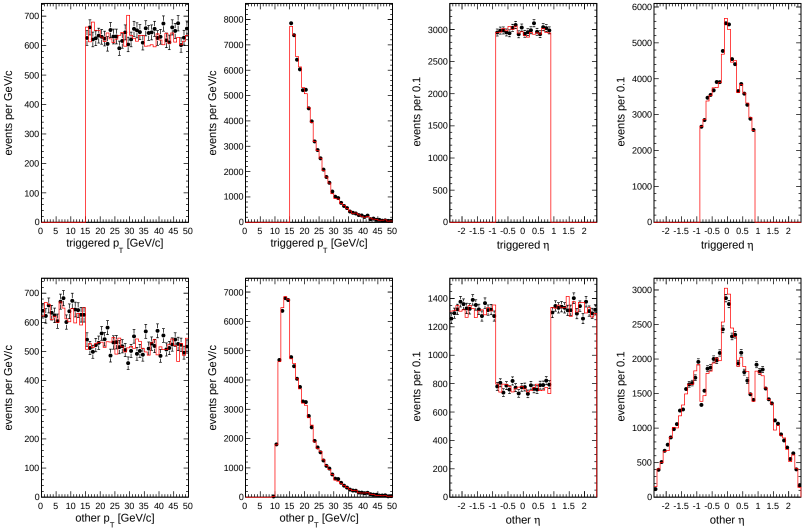




# *Iso* and $L_{xy}$ of dimuons

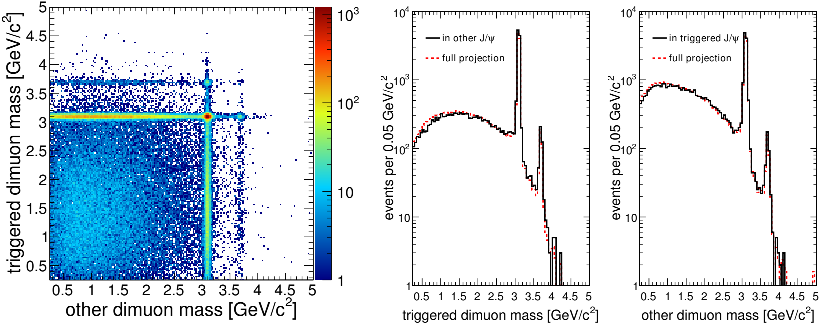


# Labelling in $R^1_{22}$ (MC)



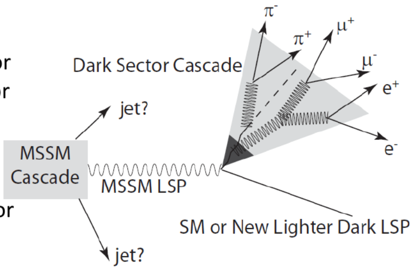
# Factorizability of $R^1_{22}$ (MC)





# Realistic model

- Phenomenology:
  - MSSM LSP decays to a dark sector cascade plus either SM particle or something else
    - e.g. new (heavy) dark matter particle
  - The cascade always ends in one or more dark photons and possibly something stable (or long living)
    - The "typical" number of dark photons is extremely dependent on assumptions (couplings and complexity of the dark sector)
  - Dark photon decays like a photon
    - Although possible to modify couplings, e.g. only couple to leptons



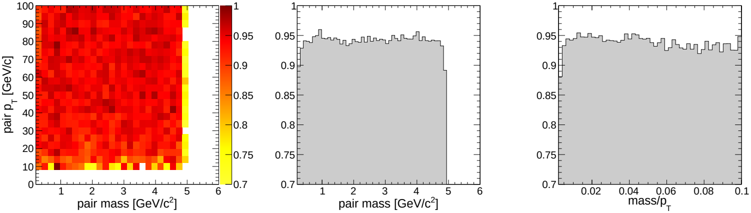

- Conclusion: expect muon pairs mixed with electron pairs
  - At all costs <u>avoid isolation</u>, instead rely on categorization to cope with backgrounds

# Full-chain dimuon efficiency

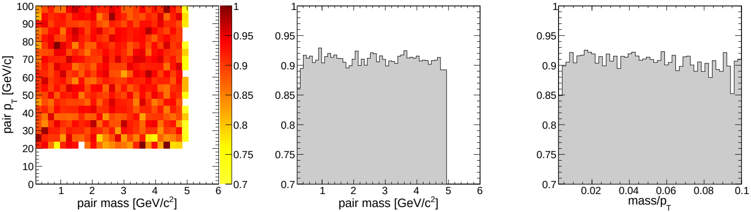


The probability to reconstruct, cluster, and trigger on a mu-jet is only weakly dependent on the mass and opening angle $\Delta\varphi \sim \text{mass}/p_T$

- Reconstructing a two-muon mu-jet ($p_T > 10$ GeV/$c$, $|\eta| < 2.4$):



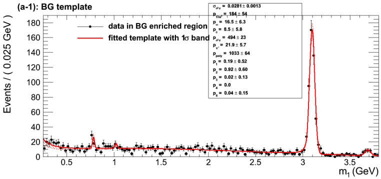

- Triggering *and* reconstructing ($p_T > 20$ GeV/$c$, $|\eta| < 0.9$):



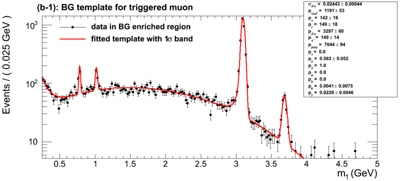
# Templates with many bins



$R_2^1$




$R_{22}^2$ with trigger muon




$R_2^1$ single high-$p_T$ dimuon shape template: