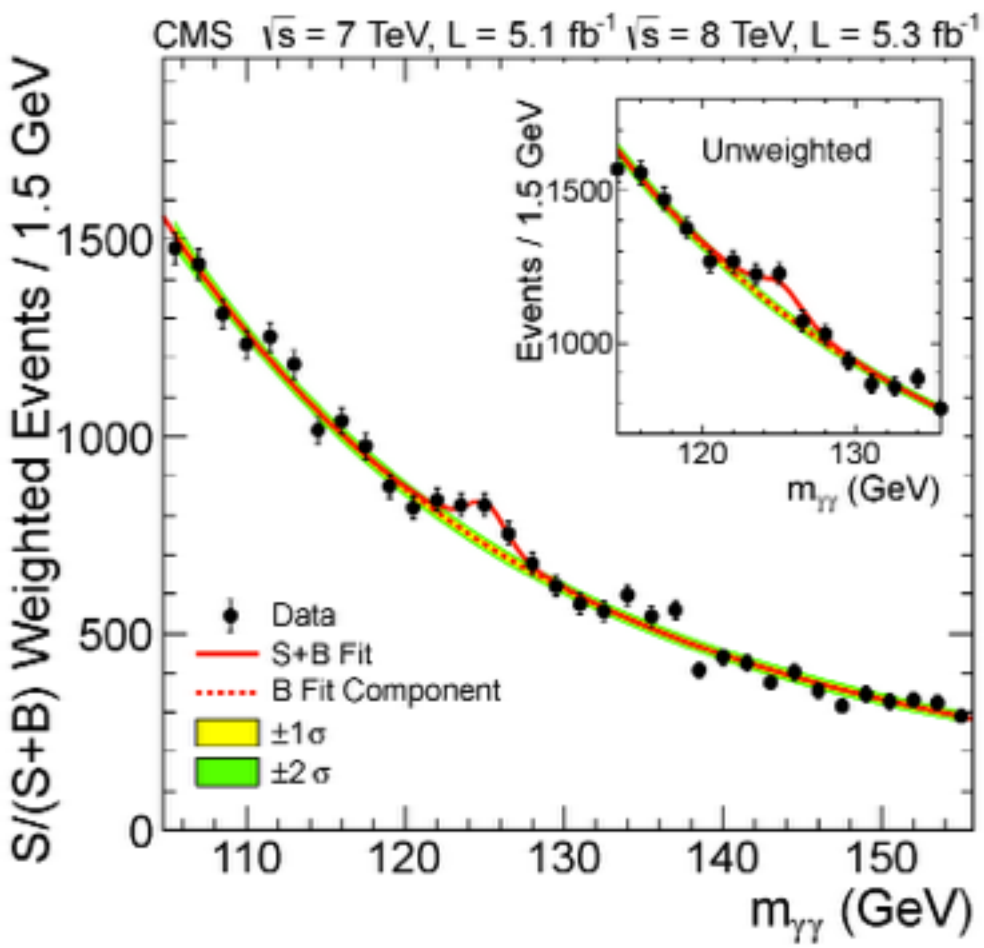
Search for non-SM Higgs Boson Decays to Boosted Dimuons at the LHC

A. Castaneda

On behalf of the CMS collaboration

Motivation

- http://dx.doi.org/10.1016/j.physletb.2012.08.021



- **Recent observation of a Higgs-like boson with a mass near 125 GeV/c^2**
- **The fundamental question: Is this the actual SM Higgs boson particle? Two approaches**

"Standard" searches

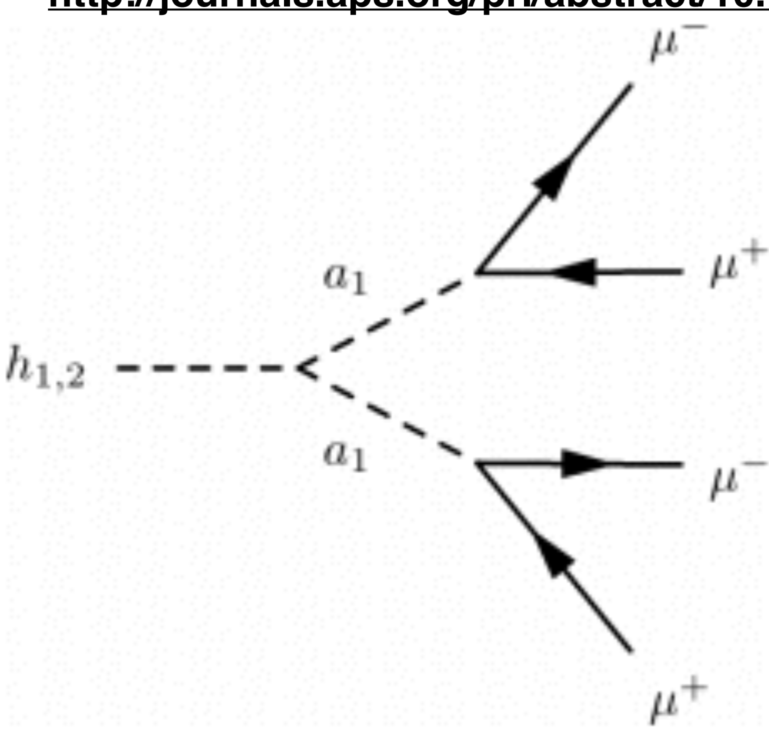
- **Precise comparison of Higgs rates in allowed SM final states to exclude non-SM scenarios**
- **It requires a lot more data than the actual dataset (20fb^{-1}), it can easily take years to reach some conclusion**

"Exotic" searches

- **Exotic Higgs decays based on well motivated extensions to the SM**
- **Searches can be sensitive even with the actual dataset (20fb^{-1})**
- **If signal is not observed strong limits can be set on that signature**

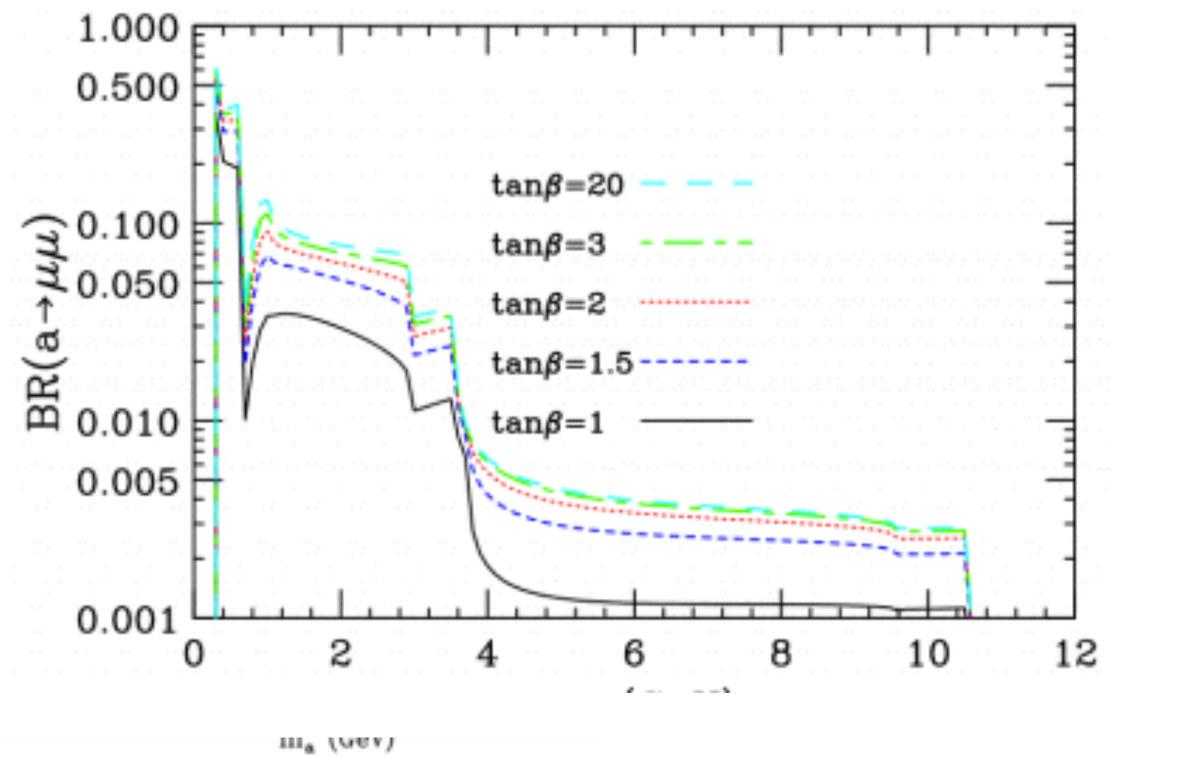
First scenario: Light Higgs Boson (NMSSM)

- NMSSM: well motivated extension of MSSM
- NMSSM Higgs sector:
  - 3 CP-even states ($h_{1,2,3}$)
  - 2 CP-odd states ($a_{1,2}$)
  - 2 charged Higgs states
- SM-like Higgs boson can be either the lightest or the 2nd-lightest CP-even scalar (h_1 or h_2)
- $h_{1,2}$ decaying to a new light boson a_1
- Previous searches with same signature in D0 (limited by Tevatron Higgs production)
  - http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.103.061801



2 low mass boosted dimuons in final state

$$h_{1,2} \to 2a_1 \to \mu^+\mu^-\mu^+\mu^-$$



- Phys. Rev. D 81, 075003 (2010): significant structures on the left figure due to variations in $\mathcal{B}(a_1 \to gg)$

The new light boson a_1 couples weakly to SM particles with a substantial Br to muons if:

$$2m_\mu < m_{a_1} < 2m_\tau$$

Second scenario: Dark-SUSY

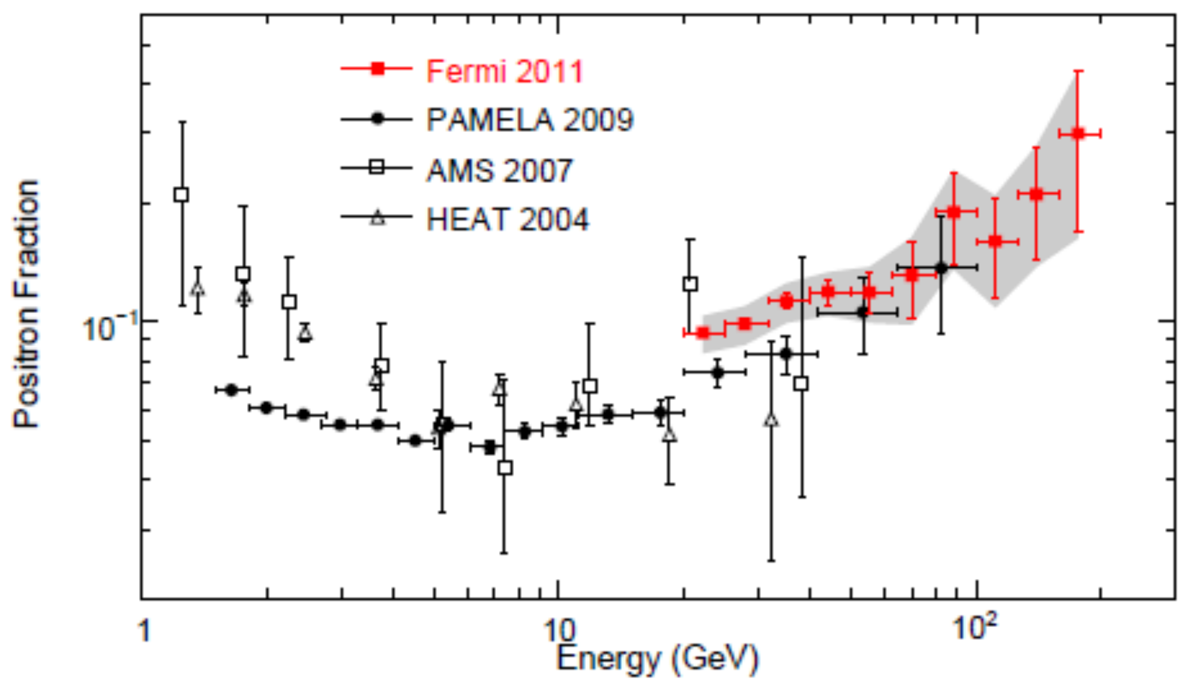


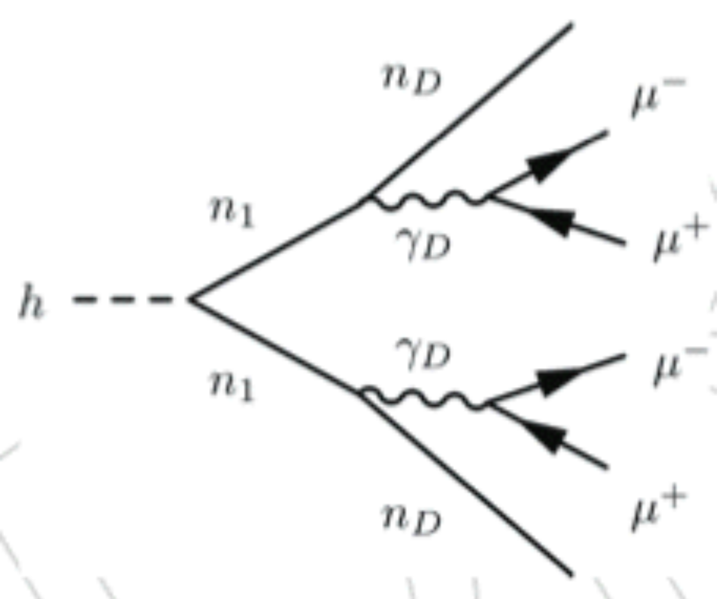
FIG. 5: Positron fraction measured by the Fermi LAT and by other experiments [10, 14, 35]. The Fermi statistical uncertainty is shown with error bars and the total (statistical plus systematic uncertainty) is shown as a shaded band.

- Dark-SUSY models motivated by the excess in positron spectra observed by satellite experiments
- One explanation is the annihilation of WIMPs, with dark-photon as the mediator.
- In MSSM Dark photon production from the decay of the lightest visible supersymmetric particles (LVSPs)

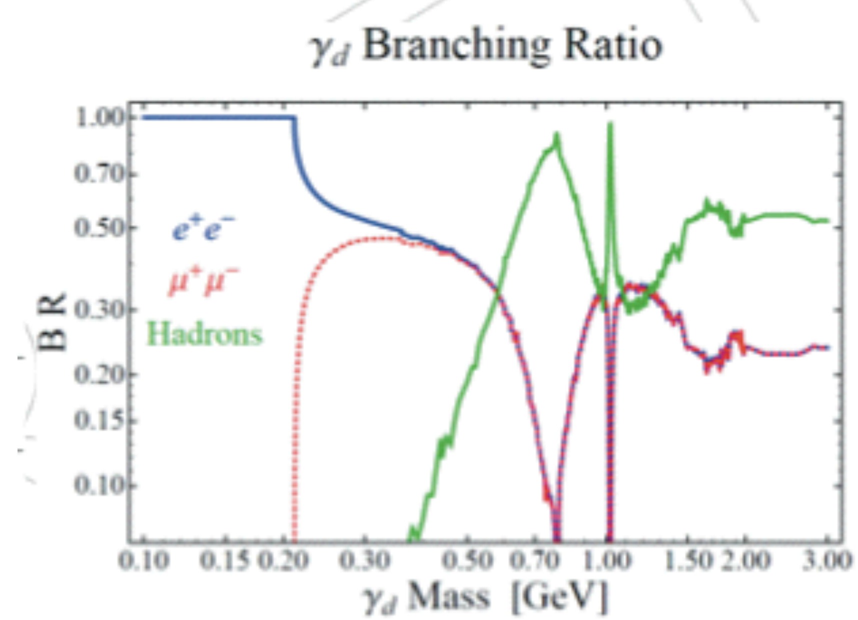
$$n_1 \rightarrow n_d \gamma_d$$

- If the Higgs boson has a substantial Br

$$h \rightarrow n_1 n_1$$

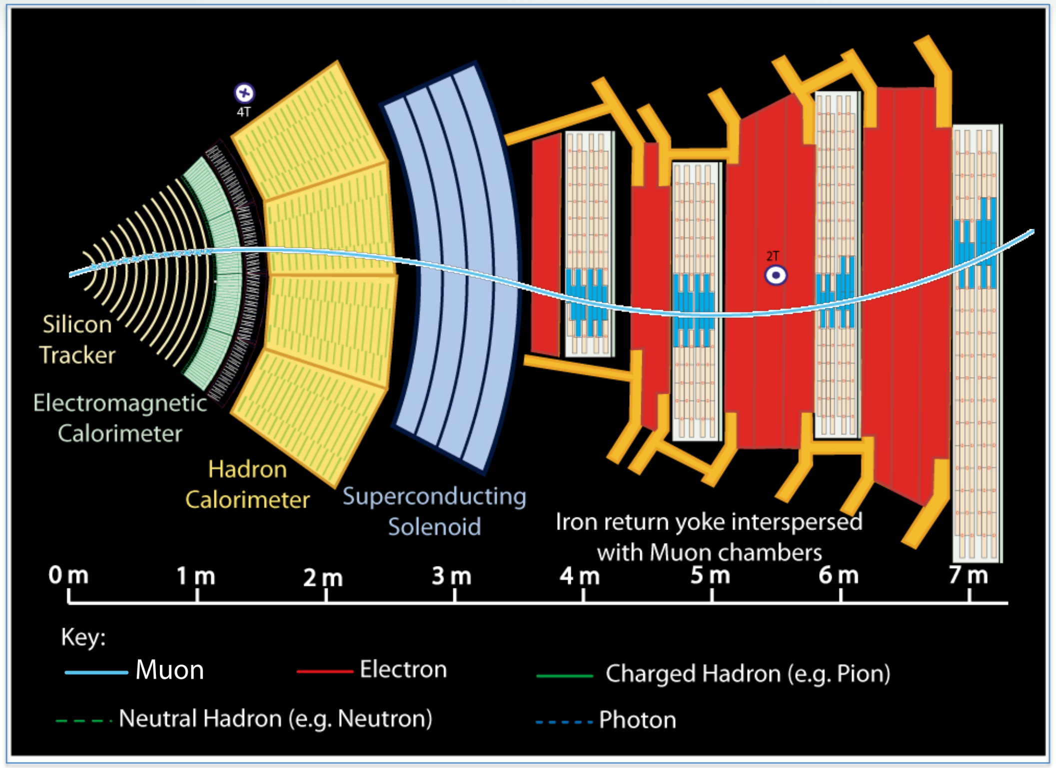


2 low mass boosted dimuons in final state

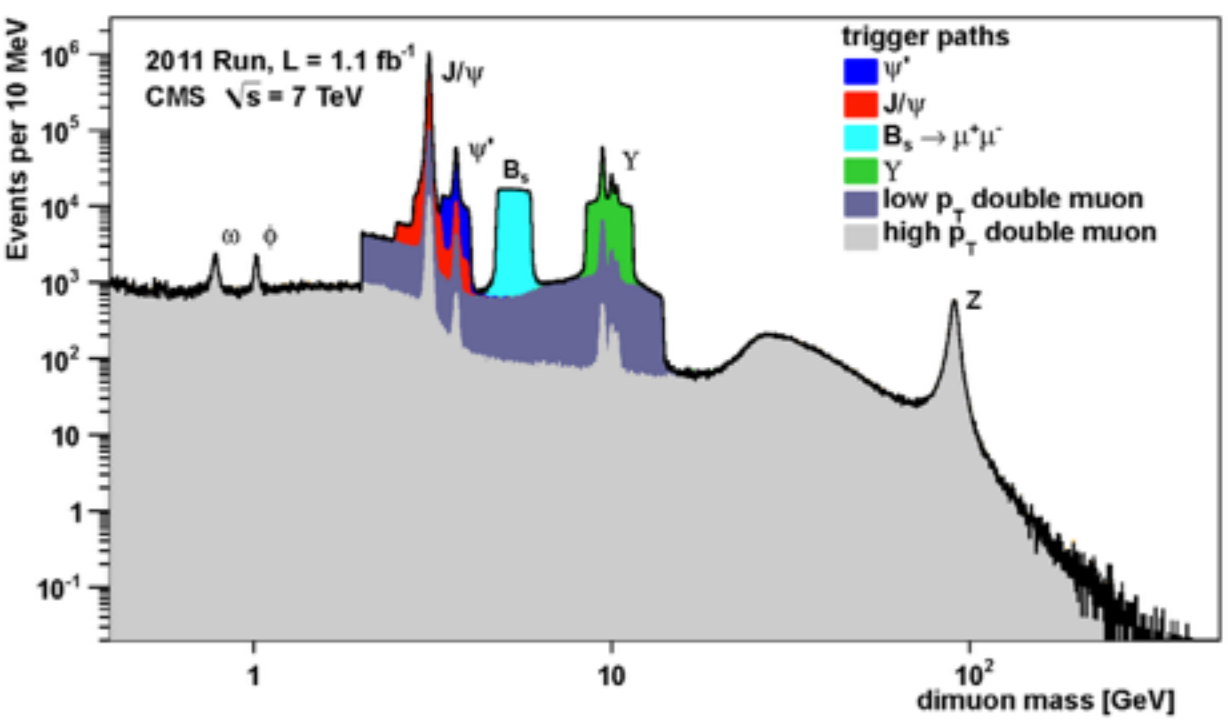


Dark-photon with substantial Br to muons

CMS muon identification



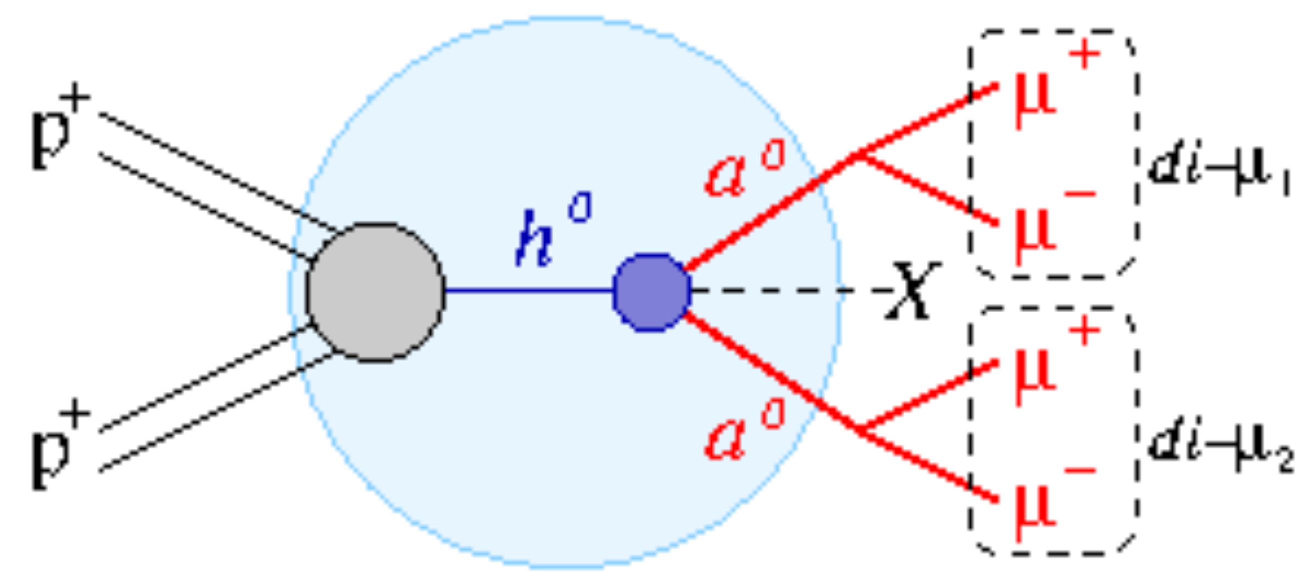
- Muons are a common signature for new physics searches (including the Higgs boson)
- Hardly interact with matter, Muon chambers located at the edge of the experiment
- Three type of gaseous detector technology: RPCs, CSCs, DTs



- CMS has excellent capabilities for the reconstruction of low mass dimuon resonances (such as the J/Psi particle)
- New light bosons (if they exist) will appear as a resonance in the dimuon mass spectrum (in events with 2 dimuons)

Analysis selection

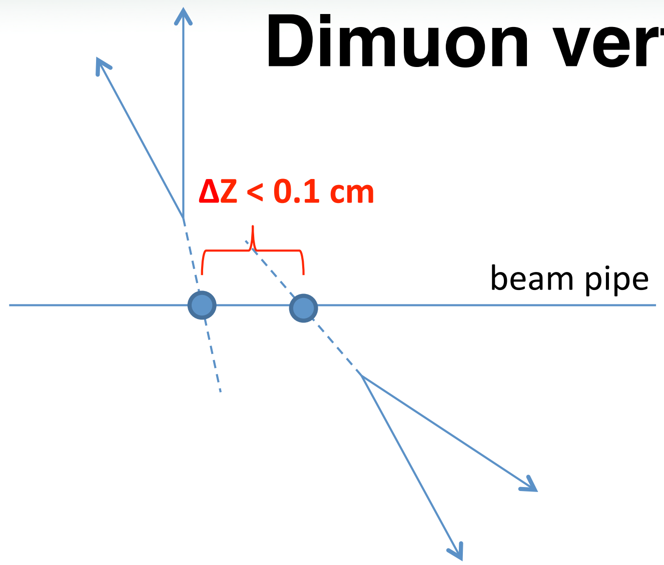
Initial selection

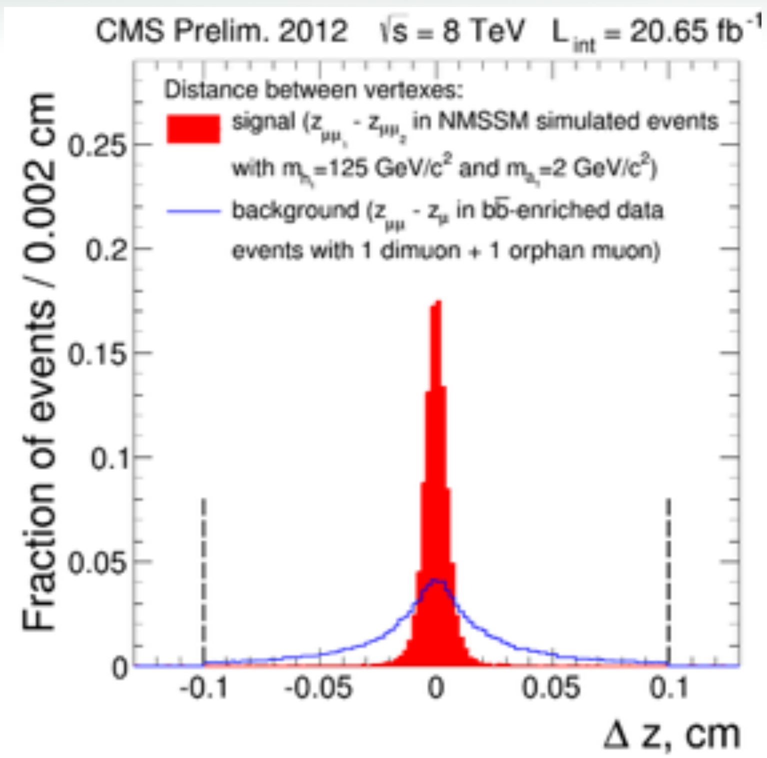


- Trigger: HLT_Mu17_Mu8
- At least one primary vertex
  - With at least 4 tracks
  - Global Z coordinate within 24cm w.r.t. beam spot
- Muon candidates:
  - At least 4 candidates: Reconstructed by CMS Particle Flow (PF) algorithm
- Clustering of nearby muons into pairs of opposite charge dimuons
  - Based on vertex probability and mass consistency
- Events with exactly 2 dimuons
  - Not limit on number of unpaired muons (orphans)

Dimuon requirements

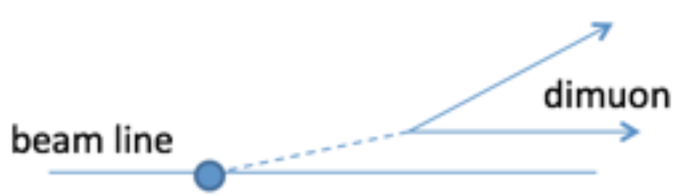
Dimuon vertex

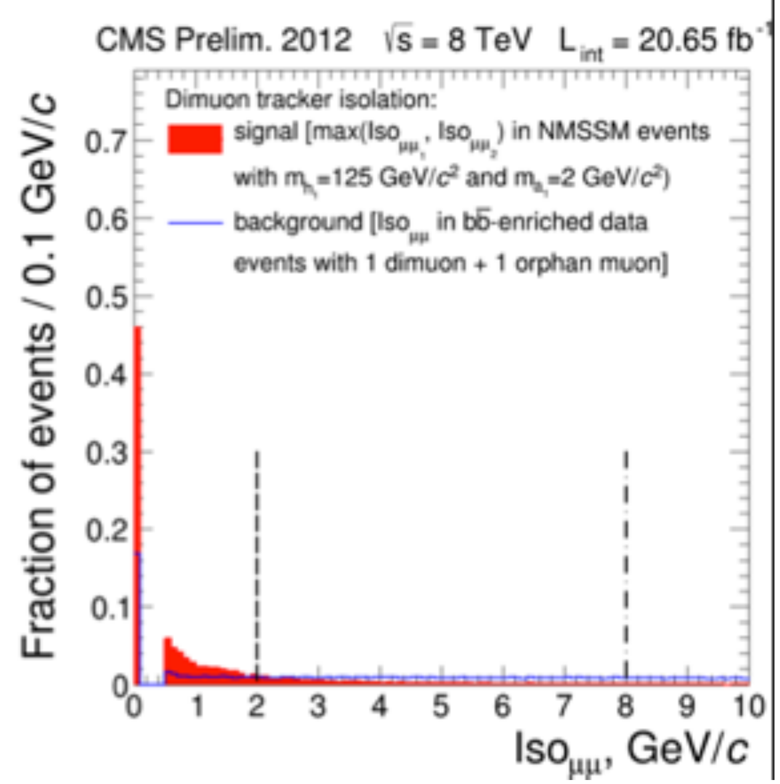




- If dimuons were originated from the light boson should have a common vertex point
- Dimuon vertex extrapolated to the beam line and requiring a distance between dimuons of less than 0.1cm

Dimuon isolation





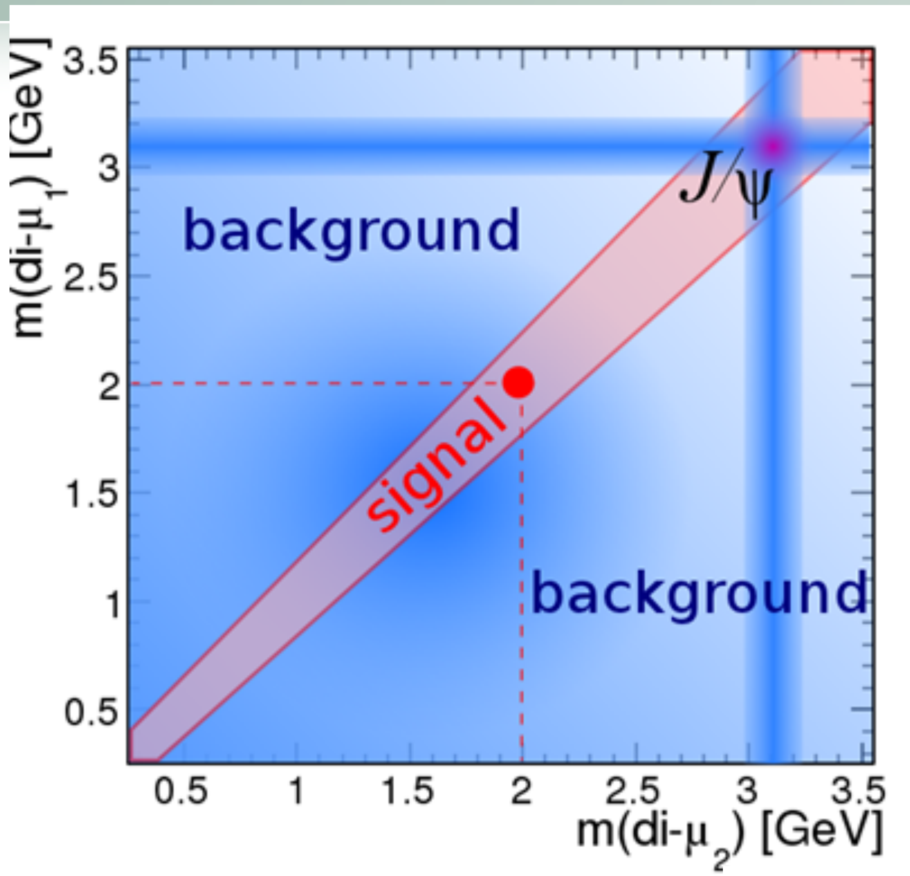
- Signal dimuons with very little extra activity around them
- Dimuon isolation less than 0.2 GeV

$$Iso_{\mu\mu} = \sum tracks/p_{T_{\mu\mu}} < 2GeV$$

Track selection:

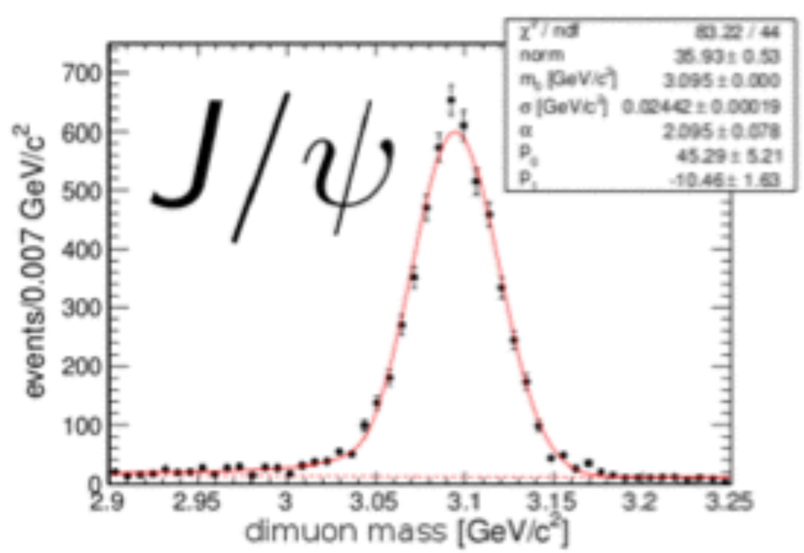
- $p_T > 5$ GeV
- ΔR(tracks,dimuon)<0.4
- $|Z_{track} - Z_{dimuon}|<0.1$cm
- tracks corresponding to muons used to form dimuons excluded

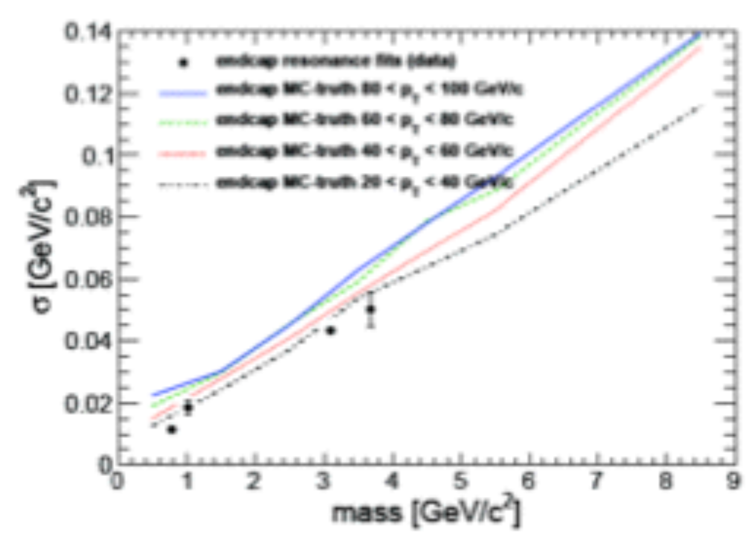
Signal Region: Dimuon masses



- Dimuon masses within 5 resolutions
$$|m_{\mu\mu_1} - m_{\mu\mu_2}| < 5\sigma$$
- Signal events located in the diagonal
- SM background spread all around the 2D space
- Off-diagonal can be used as a control region for Bkg extrapolation

✓ Study of detector resolution measured using low-mass SM resonances in data decaying to pair of muons — ω, φ, J/ψ, ψ′





$\sigma(m) = 0.026 + 0.013 \cdot m$

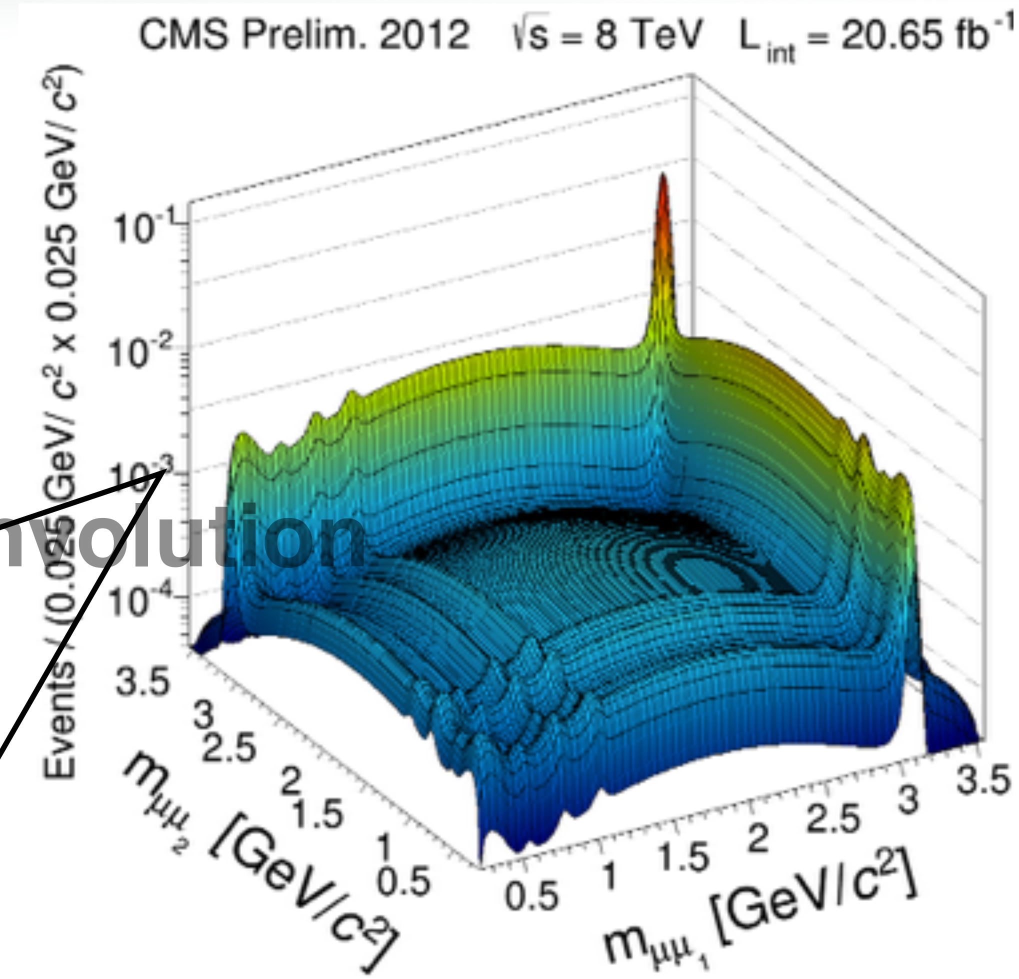
Standard Model Backgrounds

The background contribution from SM to a signature with two light dimuons after final selections:

- **bb:**
  - Both b-quarks decay to dimuons + X via double semileptonic decays + resonances (eg. ρ,ϕ,J/psi)
  - Data-driven technique to estimate the shape and contribution into the signal region
- **Prompt double J/Psi:**
  - Estimation using MC simulation and normalized with data
- **pp->4μ**
  - Estimated using MC simulation (COMPHEP)
  - Expected number of events in signal region < 0.15±0.03

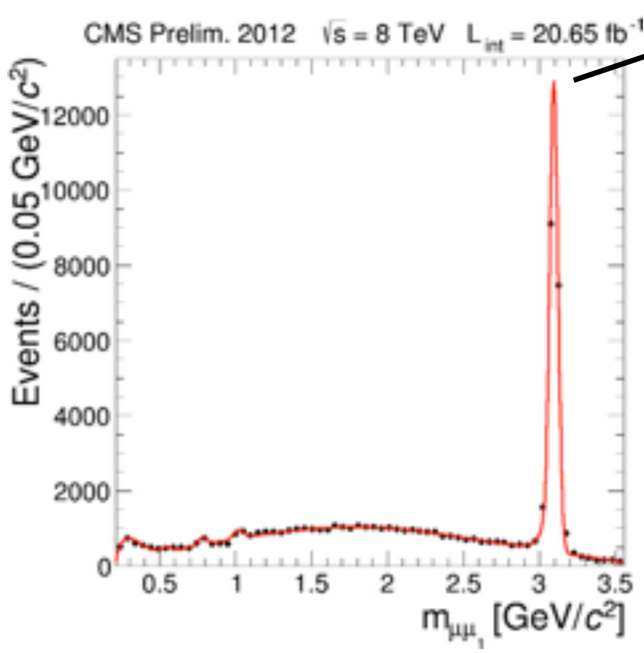
bb background modeling

- **Background enriched sample:**
  - **Exactly 1 dimuon + 1 orphan muon**
  - **Sample heavily dominated by bb events**
  - **1D invariant mass depends on the muon pT composition of the dimuon: with one high-pT muon ($N_{17,8}$), or with two high pT muons ($N_{17,17}$)**
  - **2D distribution after convolution of 1D**

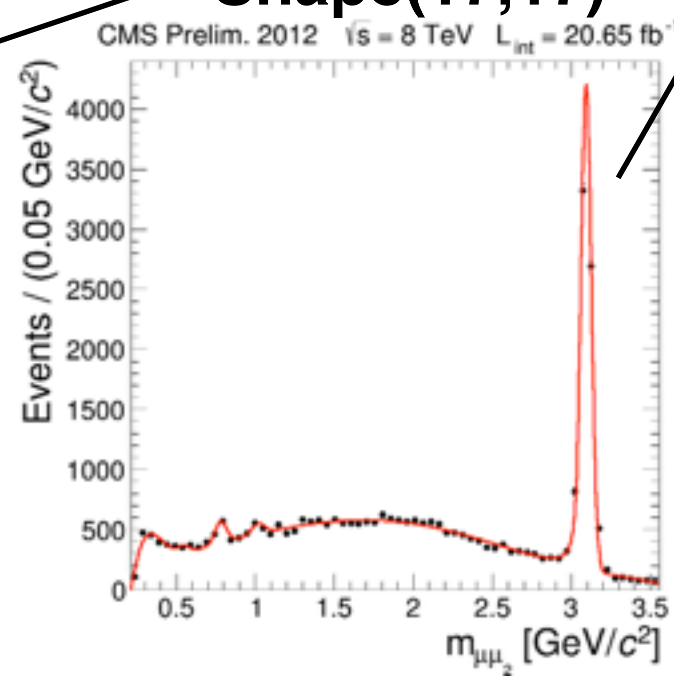


Convolution

Shape(17,8)



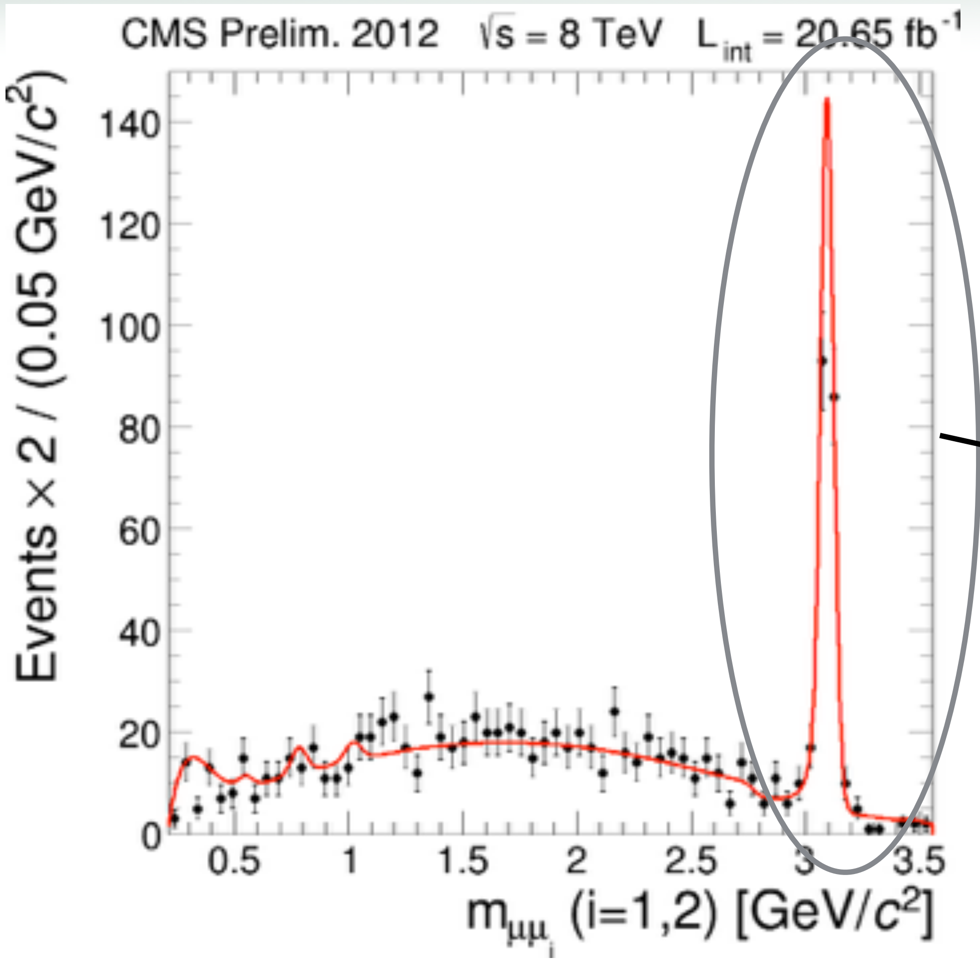
Shape(17,17)



Proper normalization

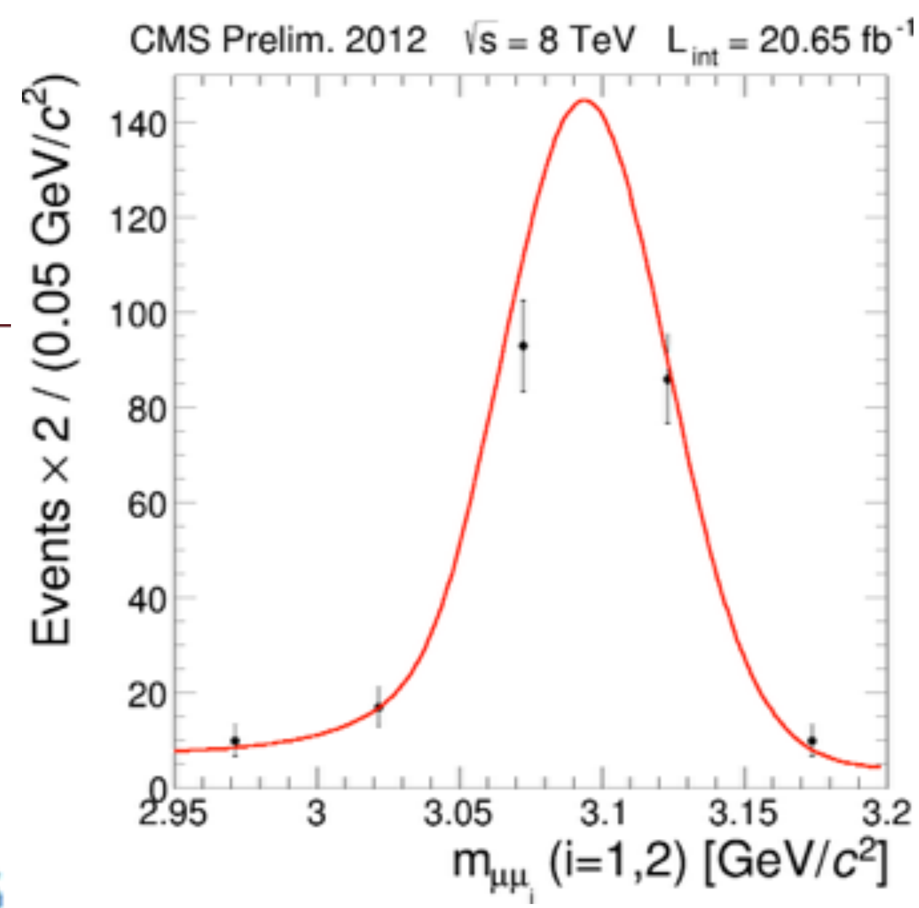
$$S(m_1, m_2) = \frac{N_{17,8}}{N_{17,8} + N_{17,17}} \cdot [S_{17}(m_1) \times S_8(m_2)] + \frac{N_{17,17}}{N_{17,8} + N_{17,17}} \cdot [S_{17}(m_1) \times S_{17}(m_2)] \, .$$

Validation of bbbar shape



✓ Switch to a signal-like sample

- use two dimuon data sample with the standard selections
- drop isolation requirements on both dimuons
- exclude diagonal part (could be signal there!)

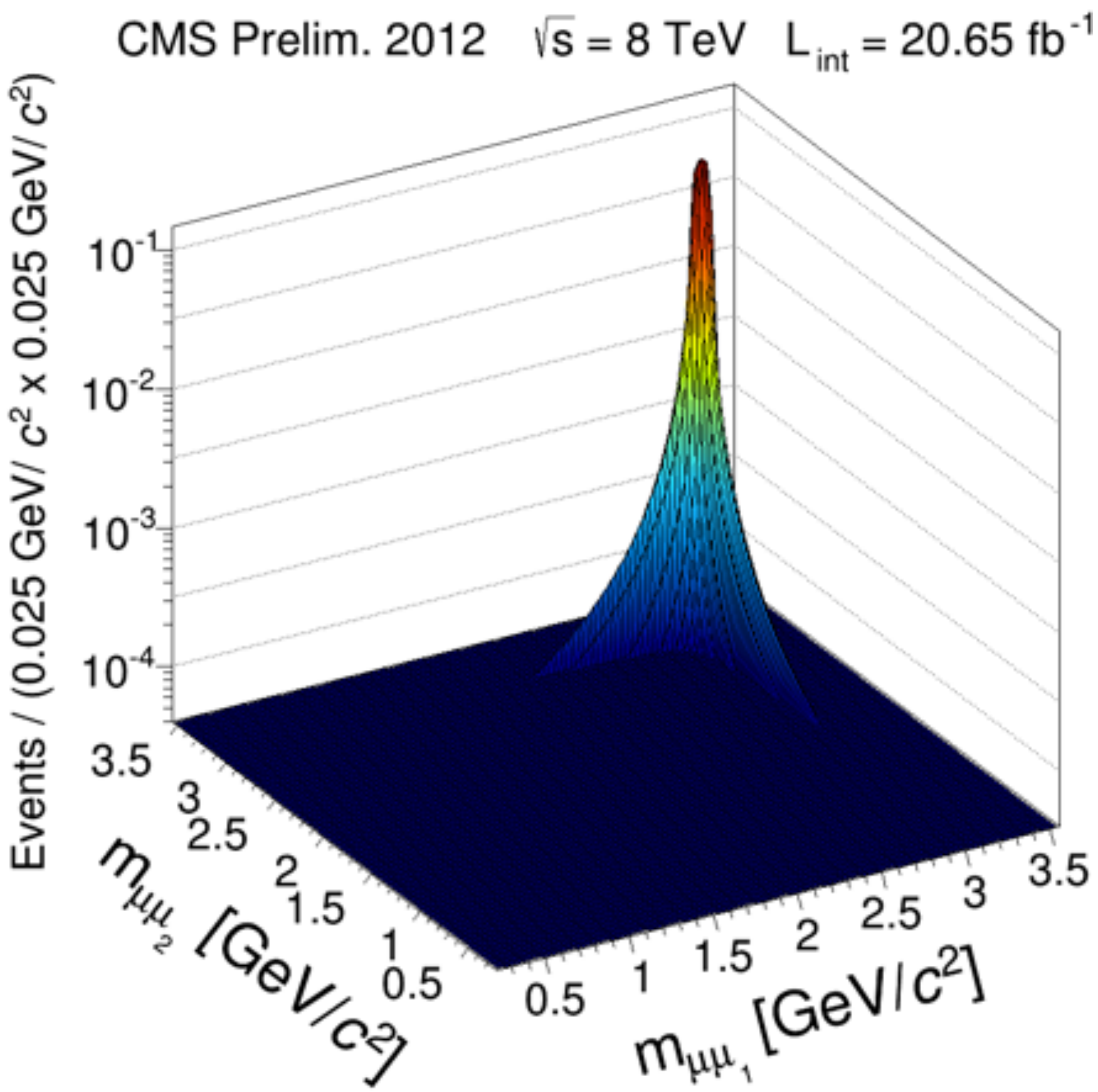


✓ Normalization of the J/psi peak in control sample

- 118.6 events predicted from fit (area below red curve between 2.95 and 3.20 GeV divided by 2)
- 108 events observed in data (area below solid dots histogram between 2.95 and 3.20 GeV divided by 2)
- Significance is 1.0 sigma

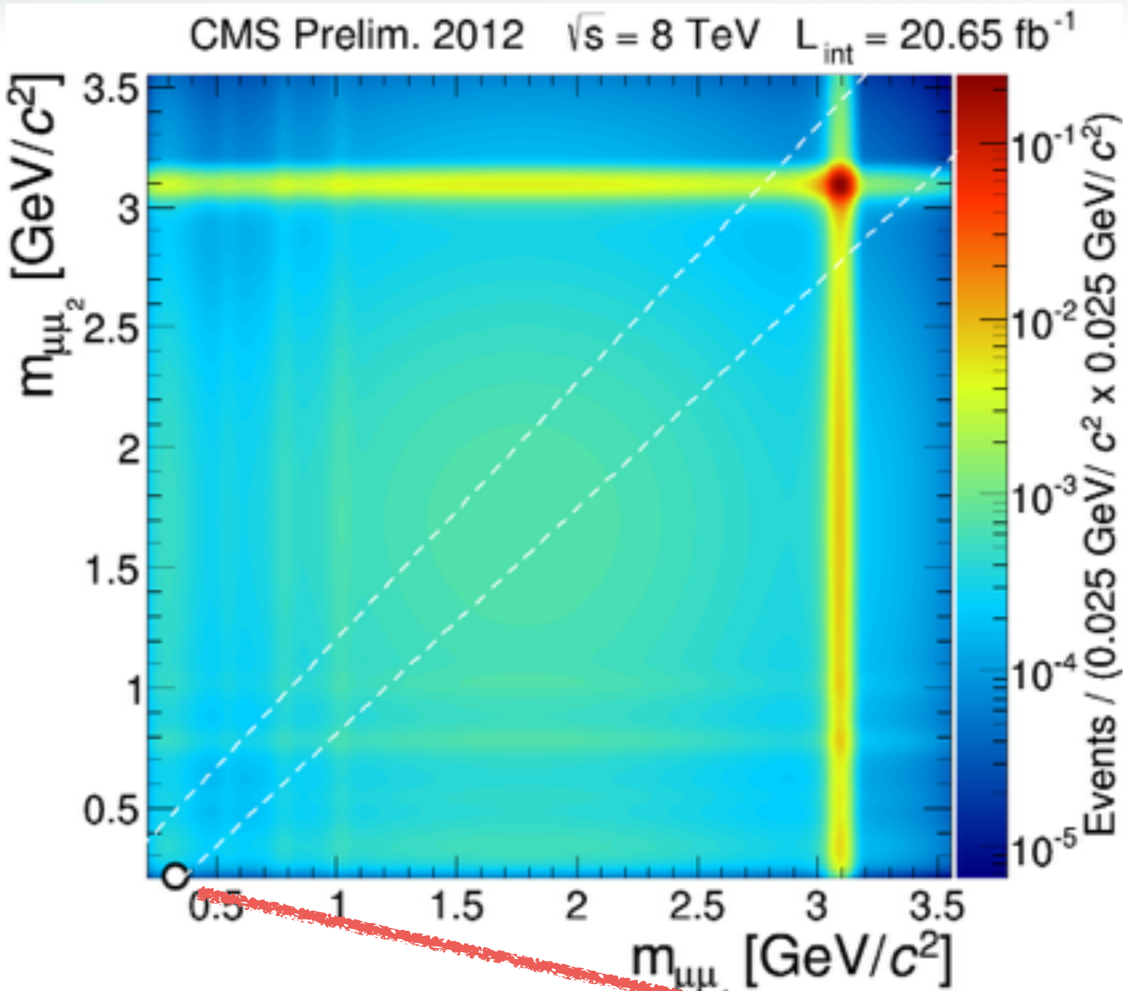
  - expected number of events in signal region: 1.8±0.6

Prompt J/psi and EW backgrounds

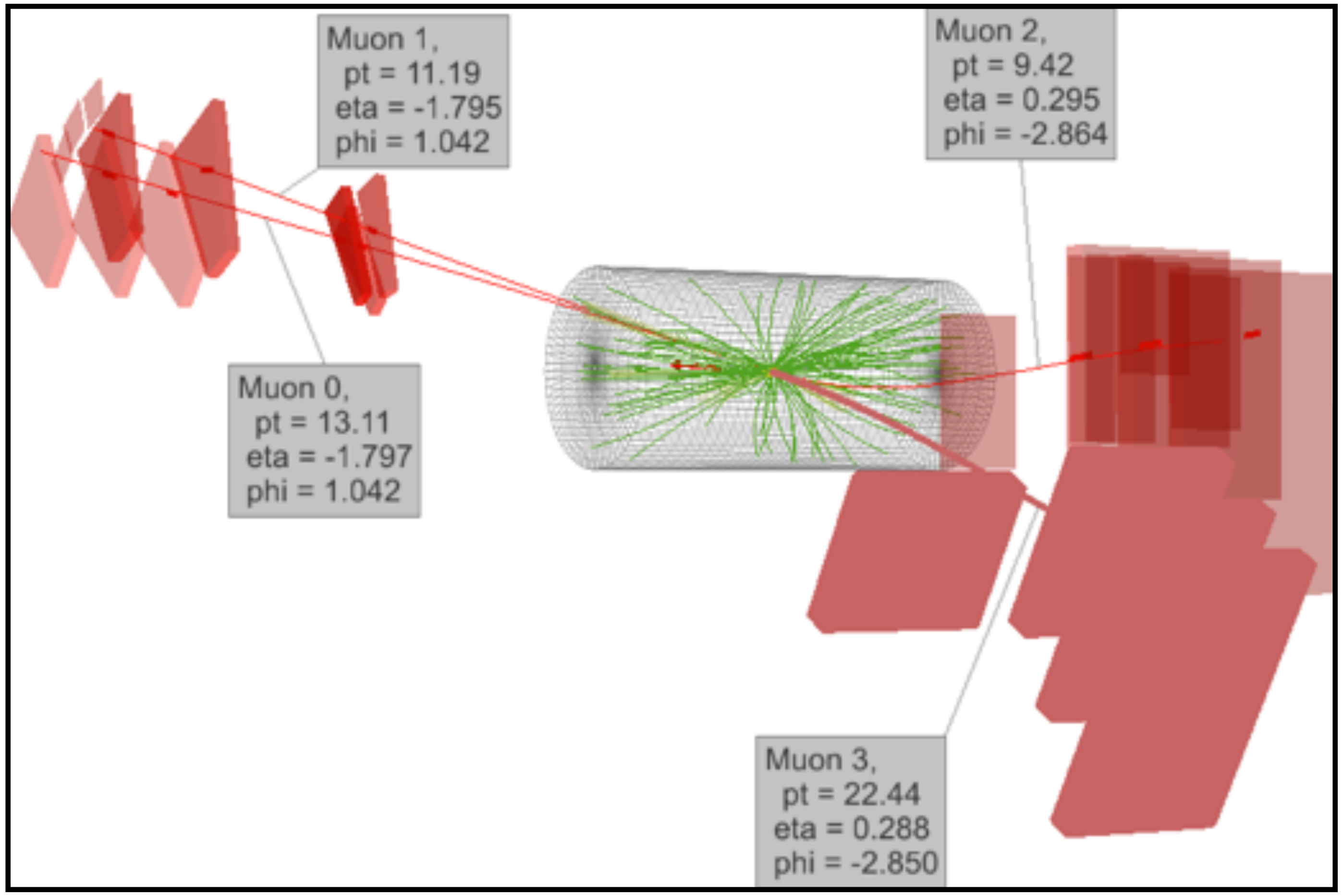


- Prompt double J/Psi contribution in signal region estimated using Monte Carlo information
- Normalization factor from data in double J/Psi control region
- Total contribution in signal region =2.0±2.0 events

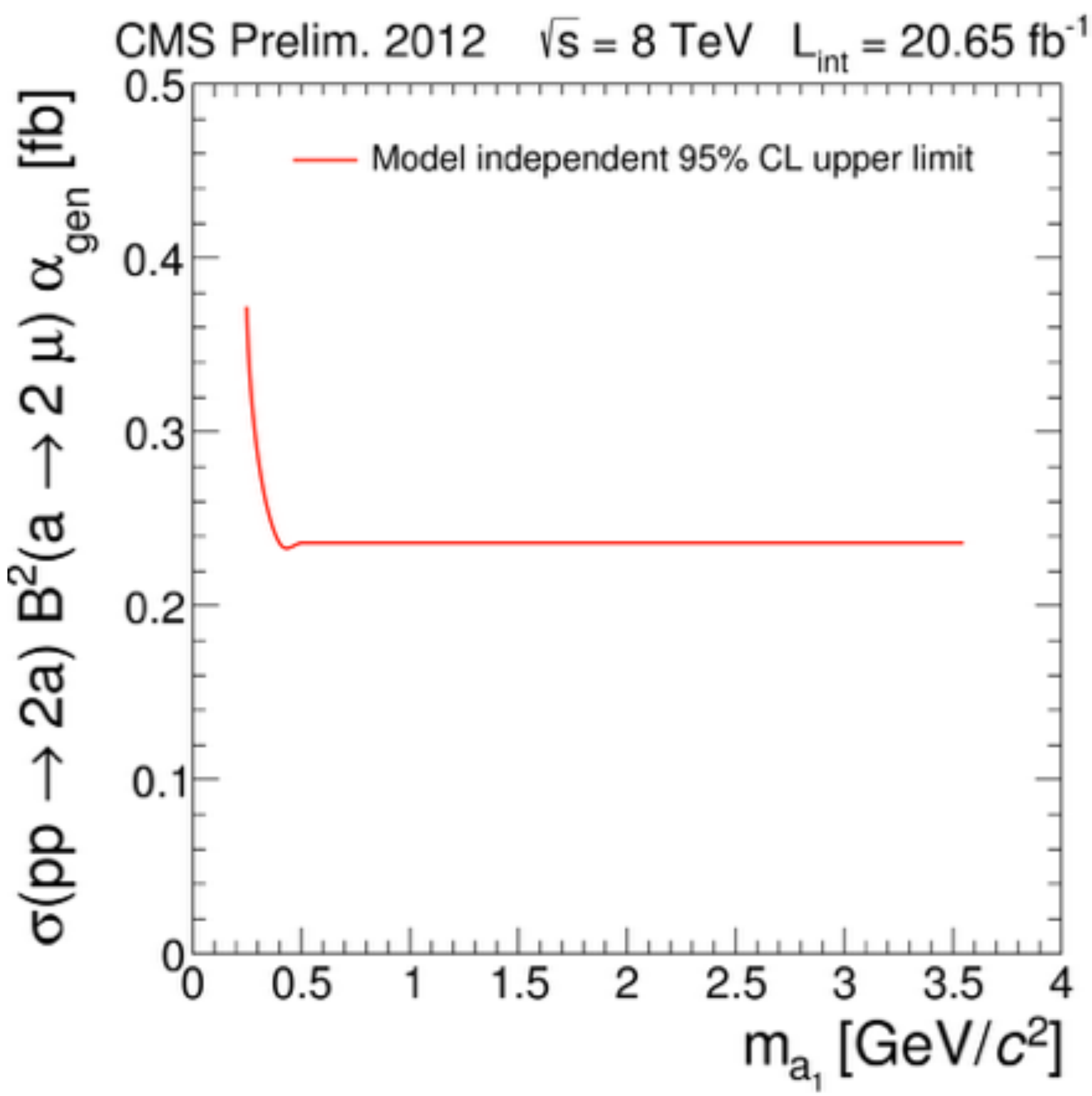
Event Yield



- After complete event selection only one event survived in data ($20fb^{-1}$)
- Consistent with SM expectation (3.8±2.1 events)



Model independent limit



- **Limit on the production rate**

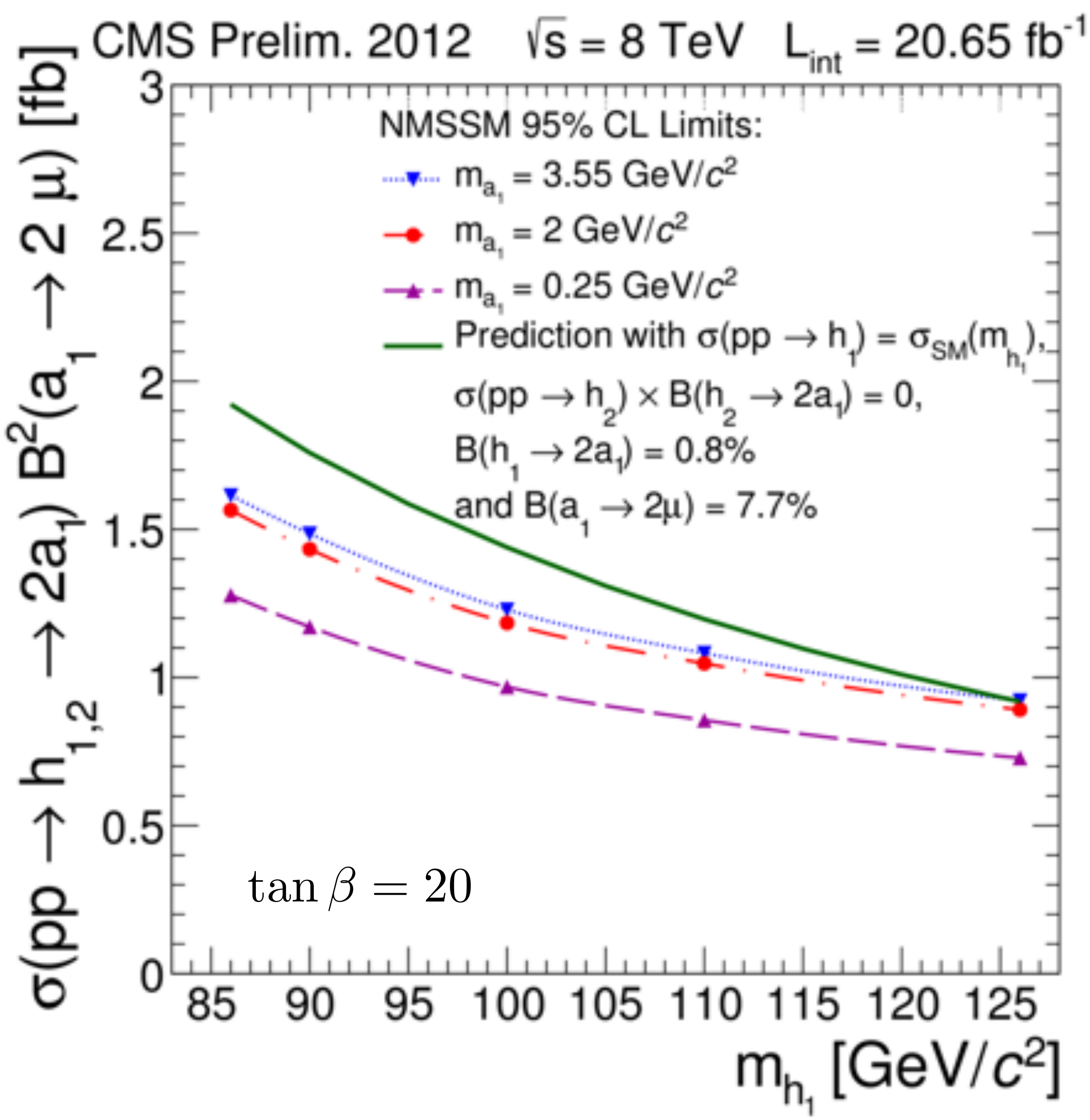
$$\sigma(pp \to 2a + X) \times B_r^2(a \to 2\mu)\alpha_{gen} < \frac{N}{Lumi \times \frac{\alpha_{full}}{\alpha_{gen}}}$$

α_{gen} **geometric and kinematic acceptance calculated using generator level information**

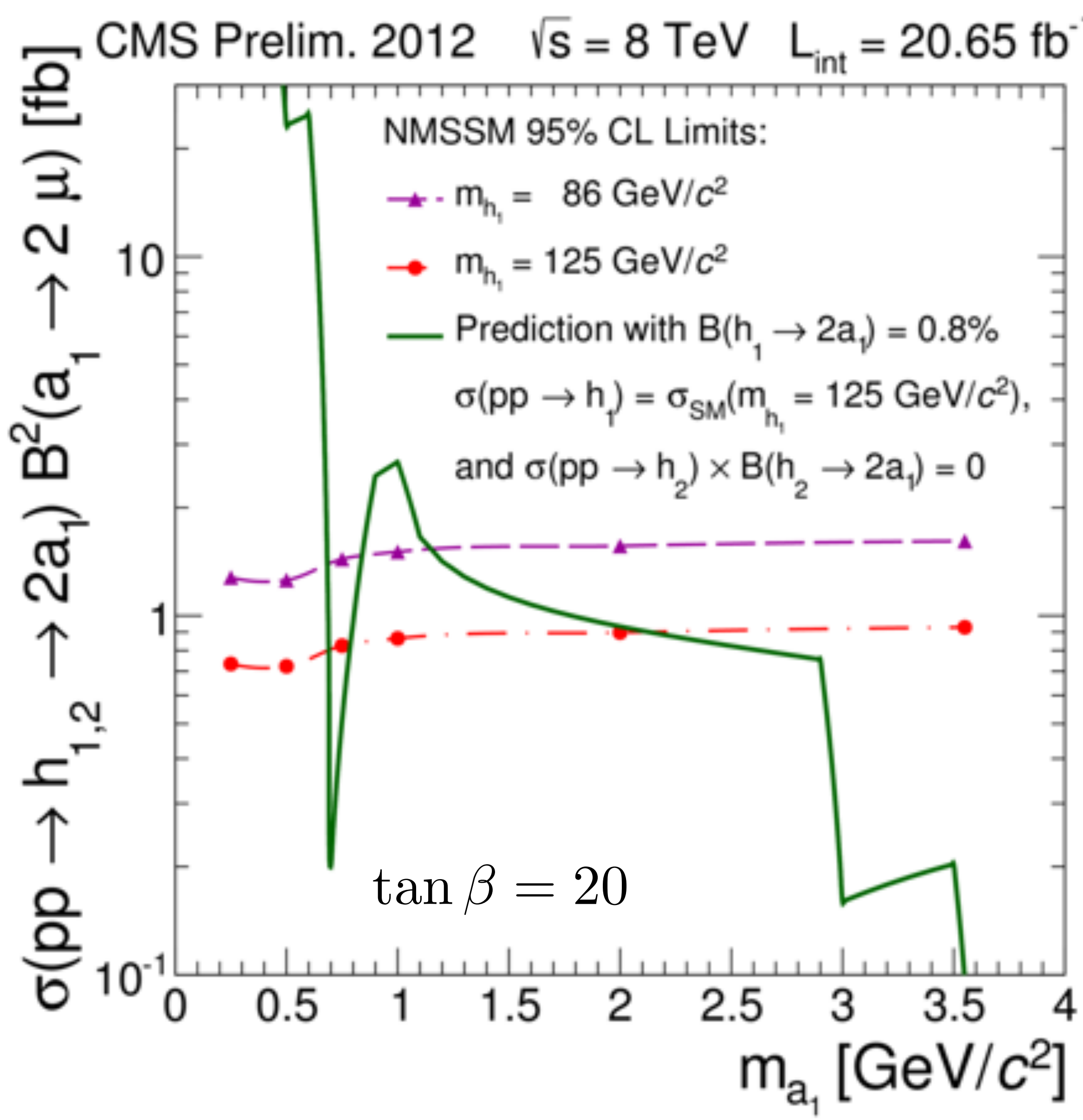
- **Ratio of full efficiency vs generator level remains constant (0.74), by using different benchmark samples**

Exclusion limits: NMSSM

- As a function of the Higgs boson mass

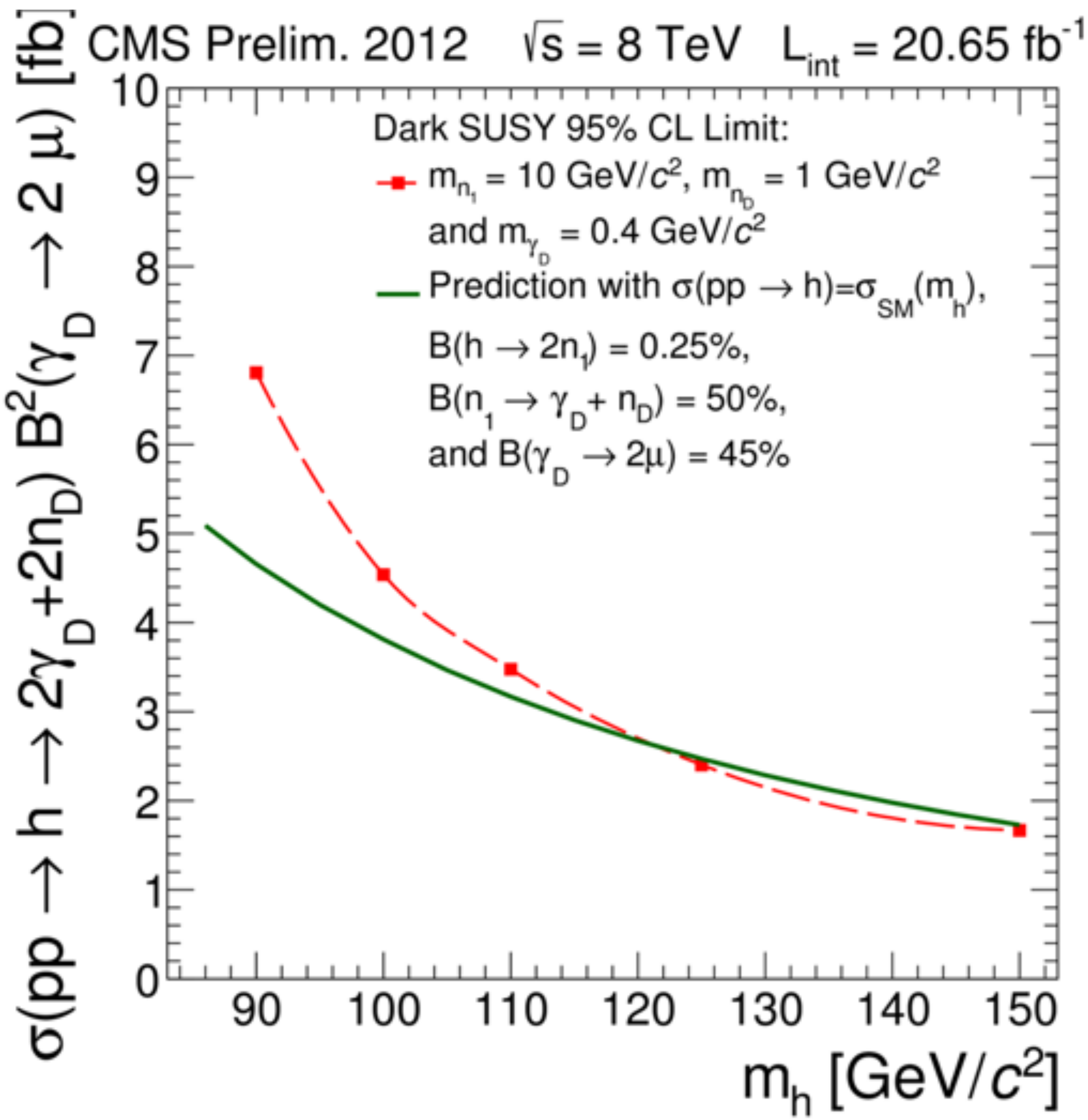


- As a function of the light boson mass



Exclusion limits: Dark-SUSY

- **As a function of the Higgs boson mass**



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Conclusions

✓ A search for non-SM Higgs boson decays to pairs of new light bosons was presented.

✓ A final state with two low mass dimuons was considered

✓ After the events selection one event was observed (20.65fb^{-1} of data) consistent with SM expectation

✓ Two benchmark scenarios were explored: NMSSM and Dark-SUSY

✓ Results are applicable to a broad spectrum of non-SM scenarios predicting the same signature

✓ Stronger limits compared with the previous version (2011 dataset)

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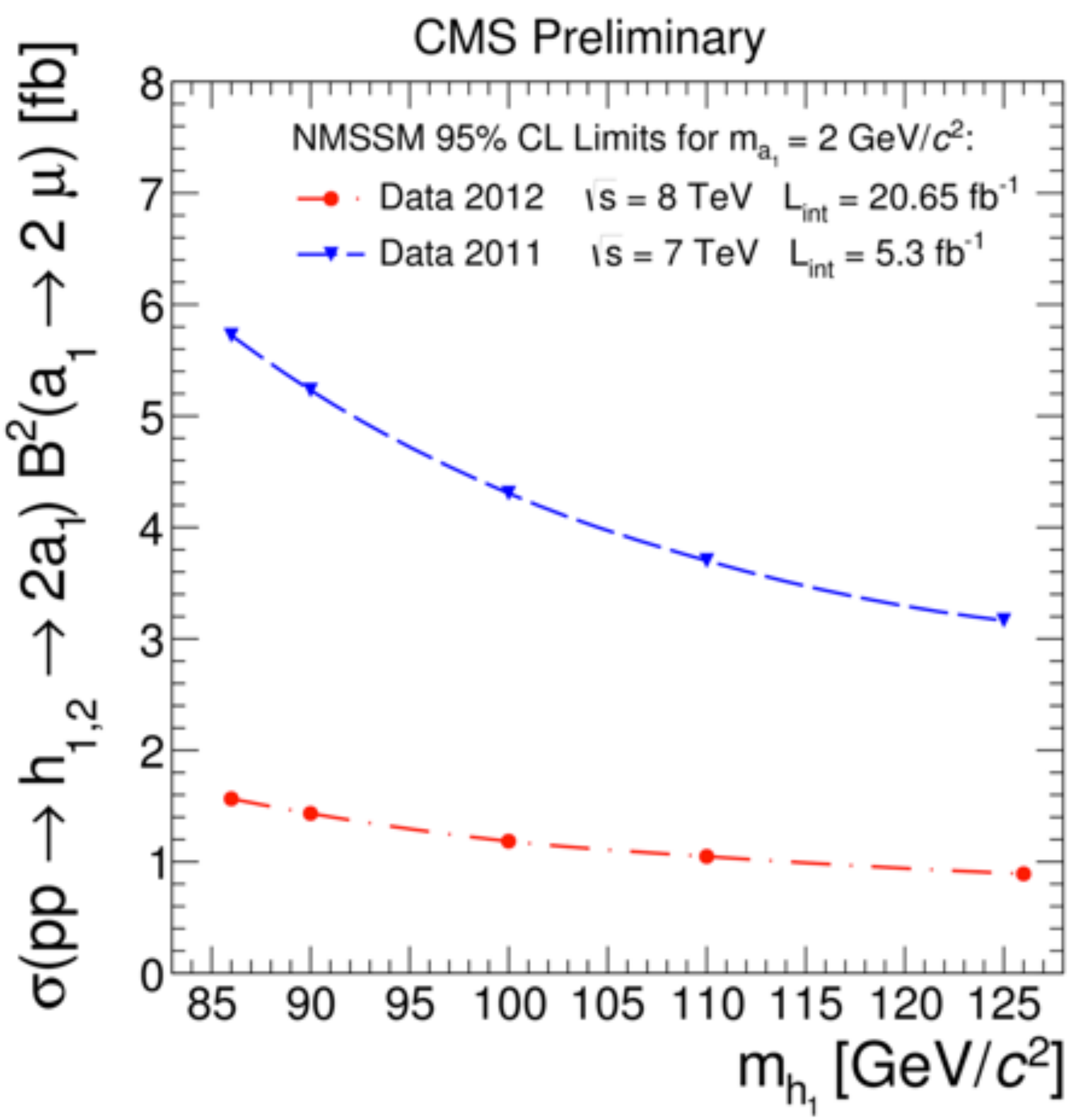
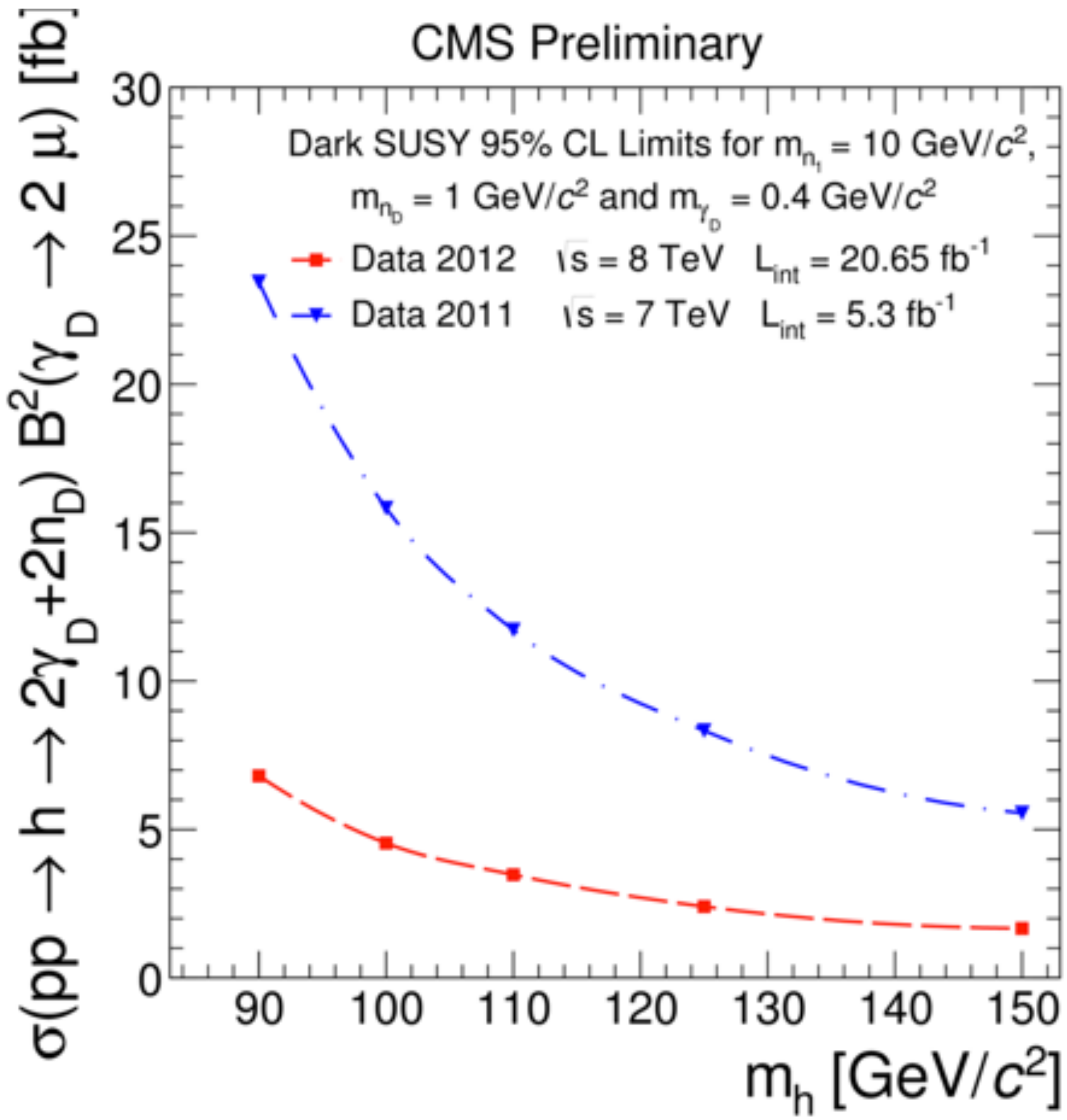
Backup

Improvements w.r.t. 2011 data

- **NMSSM scenario**



- **Dark-SUSY scenario**



Clustering Muons into Dimuons

- Group oppositely charged muons into dimuons:
  - **if** their pairwise invariant mass $m_{\mu\mu} < 5$ GeV **and**
  - **either** the fit of two muon tracks for a common vertex has the probability $P_{\mathrm{vertex}} > 1\%$
    - this vertex is not required to match any primary vertex of the event or any vertex of another dimuon
  - **or** two muon tracks satisfy $\Delta R(\mu^{+}, \mu^{-}) < 0.01$
    - compensates for reduced efficiency of common vertex probability requirement for dimuons with very low mass ($m_{\mu\mu} \sim 2m_{\mu}$), in which muons tracks are nearly parallel to each other
- Any muon may be shared between several dimuons
- Select events with exactly two dimuons not sharing any common muons
  - no restriction on number of ungrouped ("orphan") muons

Performance of the PF Muons

- ✓ Stage 1: analysis requires at least 4 muons with p_T>8 GeV
  - At least one of them must have p_T>17 GeV and be in the barrel
- ✓ Stage 2: form dimuons, apply isolations on dimuons and require the two dimuon masses to be compatible
- ✓ Compare ratio a_{RECO}/a_{GEN}=(reco level efficiency for steps 1+2) / (generator level efficiency for step 1 only)
  - It is important to keep this ratio flat to make results interpretable

NMSSM MC Samples		$\epsilon_{full} / a_{gen}$ (%)	
m_h (GeV)	m_a (GeV)	PF muon ID	private muon ID
125	0.25	**66.4±0.4**	**74.3±0.3**
125	2	**69.3±0.7**	**72.6±0.3**
125	3.5	**68.2±0.7**	**72.7±0.3**

- ✓ PF “loose” muons and “private” tracker muons has similar performance