Search for Pair Production of New Light Bosons Decaying into Boosted Dimuons: $h \rightarrow 2a + X \rightarrow 4\mu + X$

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CMS

TEXAS A&M UNIVERSITY

TEXAS A&M UNIVERSITY at QATAR

2015 Mitchell Workshop on Collider and Dark Matter Physics

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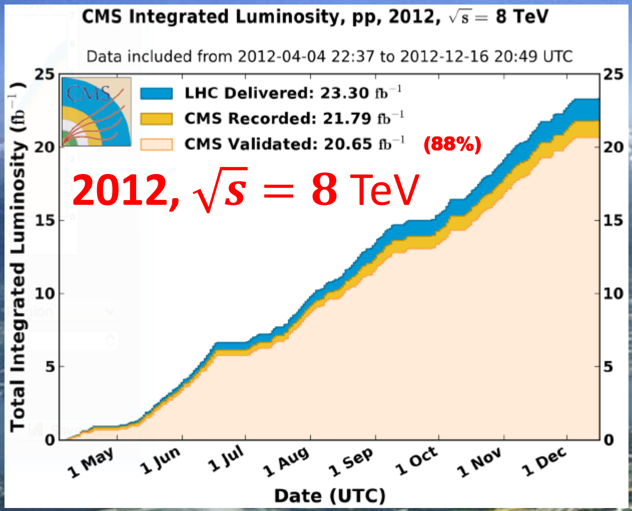
Friday, 22 May 2015

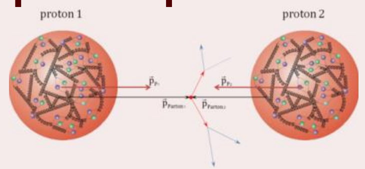
Large Hadron Collider (LHC)



Analysis presented in this talk:

- $L < 20.7\ fb^{-1}$ at $\sqrt{s} = 8$ TeV in 2012

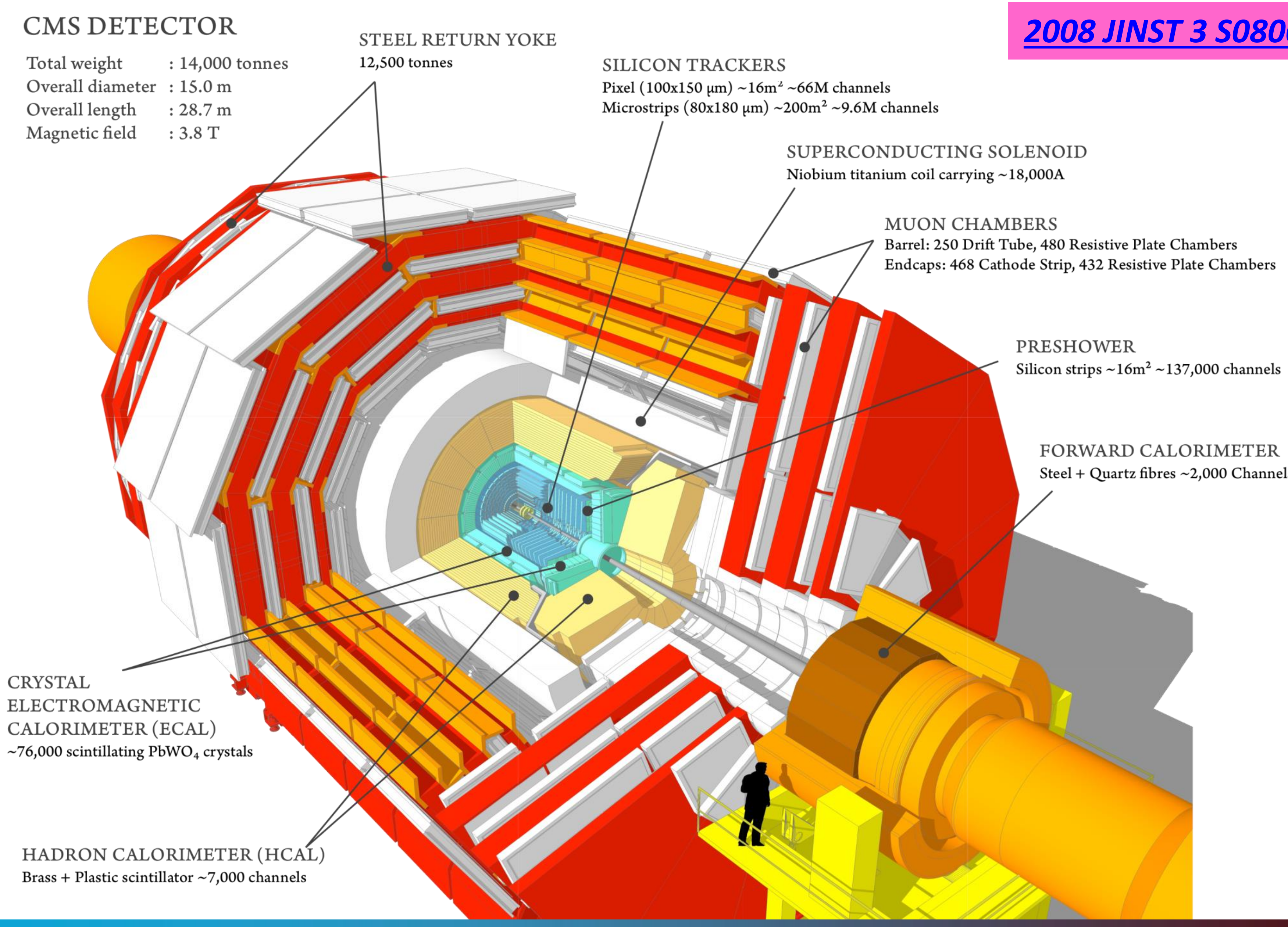
LHC: proton-proton collider



*No results from Heavy-ions collisions in this talk

CMS Experiment

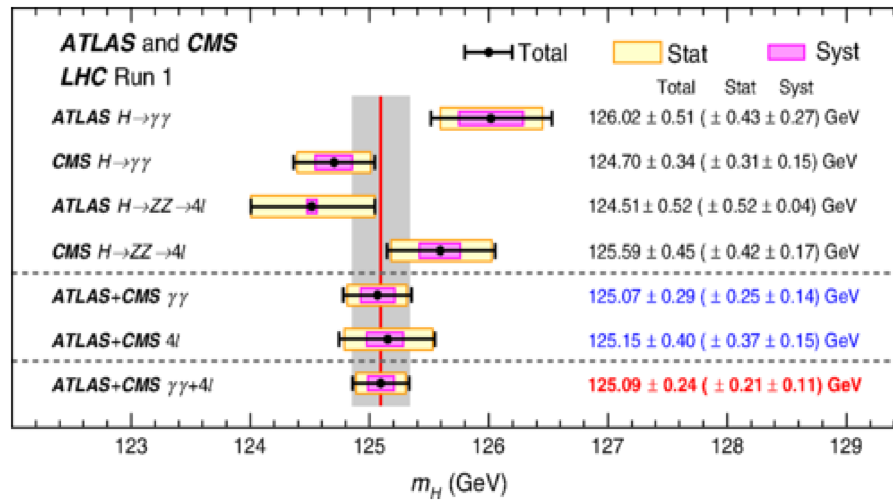
[2008 JINST 3 S08004]

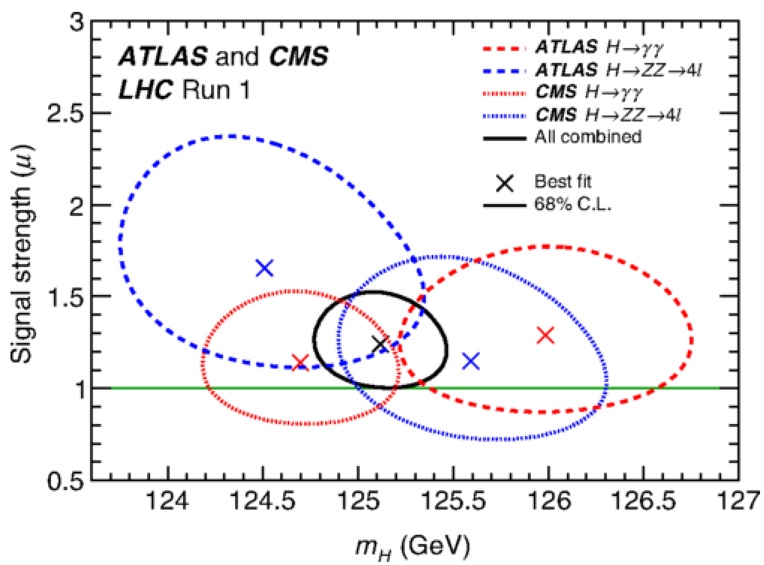


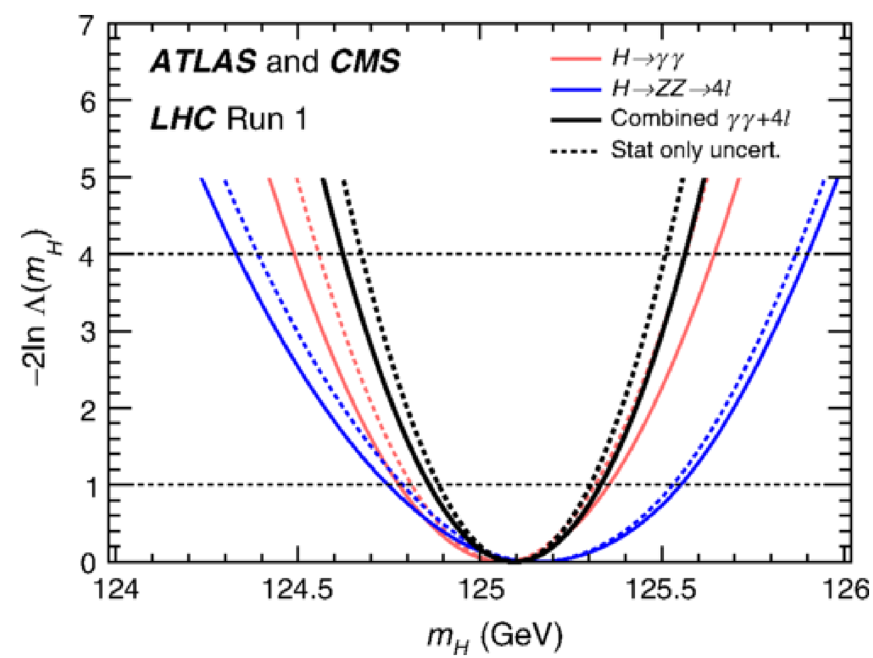
Search for h: ATLAS and CMS Combined Results

PhysRevLett.114.191803

- ✓ Combined measurement
  - mass from $h \to \gamma\gamma$ and $h \to ZZ \to 4l$ analyses
  - $m_h = 125.09^{\pm 0.11(syst)}_{\pm 0.21(stat)}$GeV
- ✓ Consistency with SM
  - $\mu = \frac{\sigma_{expt} \times BF_{expt}}{\sigma_{SM} \times BF_{SM}} = 1.24^{+0.18}_{-0.16}$







Non-SM Higgs

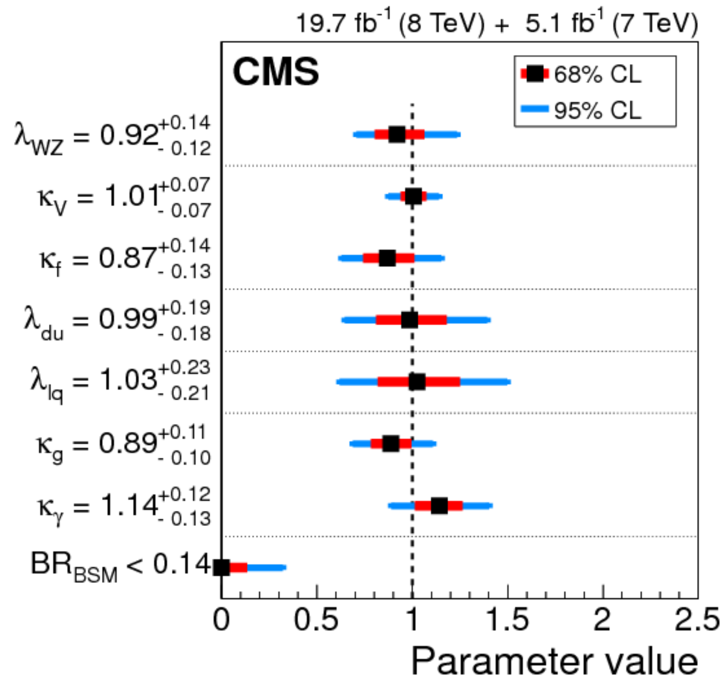
✓ Next question after discovery: **Is it SM Higgs?**

1. Answer by precise measurements of its couplings and branching ratios
   - may take many years requiring $\sim 100\ fb^{-1}$
   - current combination of the CMS results sets the limits at 95% C.L.:

$$0 \leq BR_{BSM} \leq 0.32$$

2. Answer by direct search for non-SM Higgs decays
   - In case of observation: non-SM Higgs!
   - In case of no signal: restrict broad class of non-SM scenarios

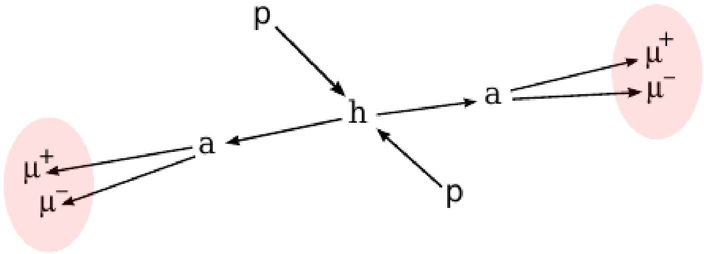
arXiv:1412.8662 [hep-ex]



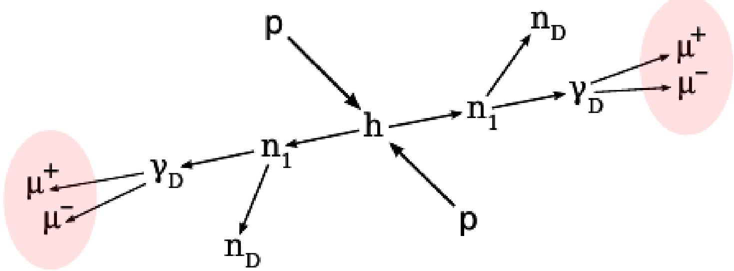
✓ Searches for non-SM decays are very important!

Non-SM Higgs Decay to Two Light Bosons

- We explore non-SM decay modes of the Higgs boson (h), which include production of two new light bosons (a), that can decay to pairs of muons (dimuons): $h \rightarrow 2a + X \rightarrow 4\mu + X$
  - Analysis is designed to minimize dependence on the details of specific models
  - Complementary to direct SM Higgs searches
- Two specific scenarios as benchmark models:
  - Next-to-Minimal Supersymmetric Standard Model (NMSSM)



  - SUSY with hidden sector (Dark SUSY)



- Results of the analysis:
  - Recipe for simple future interpretations using other models with similar signature
  - Limits on the production rate, examples for benchmark models

Benchmark Model: NMSSM

✓ NMSSM — well motivated minimal extension of MSSM

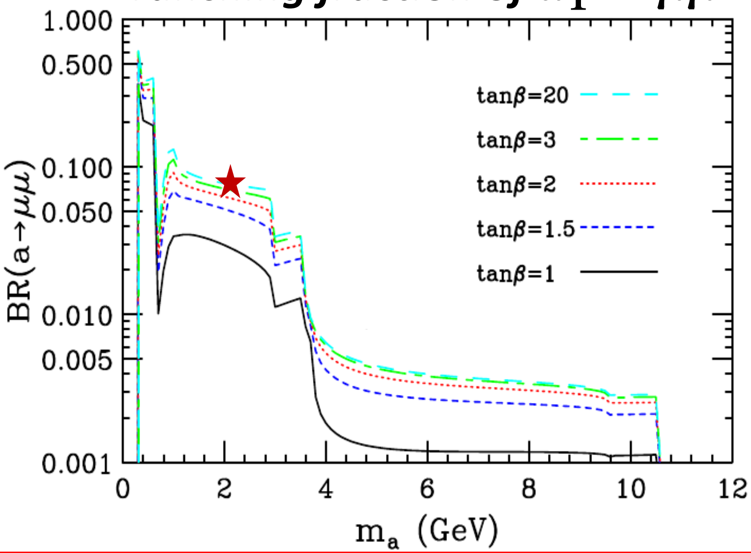
- Modified superpotential with a singlet: $\mu H_u H_d \rightarrow \lambda S H_u H_d + \frac{1}{3}\kappa S^3$
- Requires less fine tuning and solves μ-problem:
  - μ is generated by singlet field VEV and naturally has EW scale
- More complex Higgs sector:3 CP−even: $h_{1,2,3}$, 2 CP-odd: $a_{1,2}$

✓ In this analysis we explore signature

- $h_{1,2} \rightarrow 2a_1 \rightarrow 4\mu$
- $0.25 < m_{a_1} < 3.55$ GeV
  $(2m_\mu \lesssim m_{a_1} \lesssim 2m_\tau)$

PhysRevD.81.075003

Branching fraction of $a_1 \rightarrow \mu\mu$



✓ Typical branching

- $Br(a_1 \rightarrow \mu^+\mu^-) \approx 7.7\%$
  at $m_{a_1} \approx 2$ GeV and $\tan\beta = 20$

✓ Benchmark Higgs masses

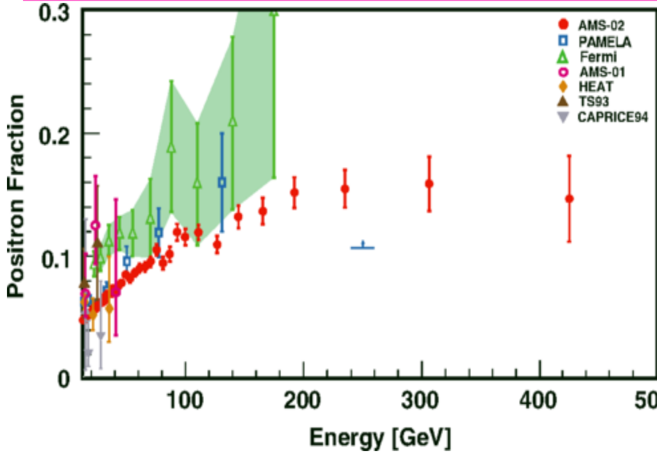
- $90 \lesssim m_{h_1} \lesssim 125$ GeV
- $125 \lesssim m_{h_2}$

significant structures on figure are due to variations in B(a1 → gg) when ma1 crosses internal quark loop thresholds

Benchmark Model: Dark SUSY

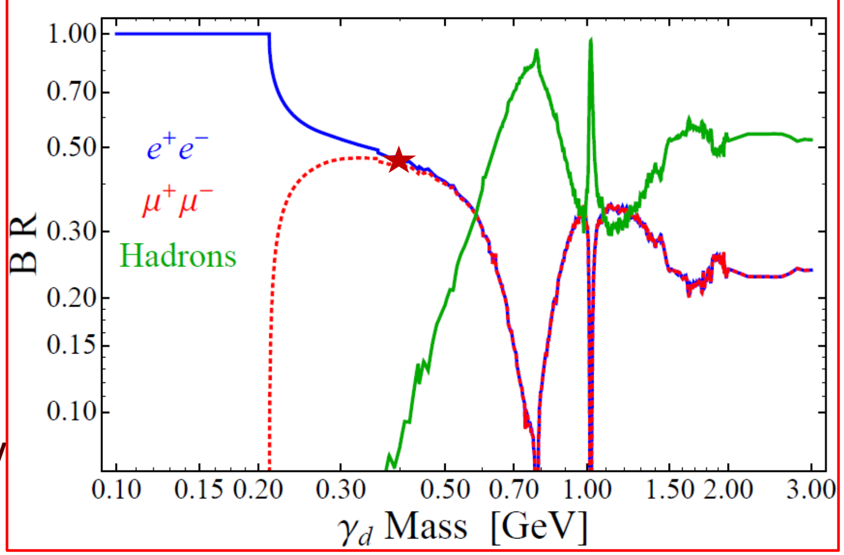
- ✓ SUSY model with hidden sector $U(1)_D$
  - New γ_D (light dark boson) weakly couples to SM via kinetic mixing with photon
    - Depending on the value ε of the kinetic mixing, the γ_D may also be long-lived
  - Satellite experiments rising positron fraction towards high energy: γ_D mediates an attractive long-distance force between slow WIMPs
- ✓ In this analysis we explore signature
  - $h \rightarrow 2n_1 \rightarrow 2n_D + 2\gamma_D \rightarrow 2n_D + 4\mu$
  - $0.25 < m_{\gamma_D} < 2$ GeV
    $(2m_\mu \lesssim m_{\gamma_D} \lesssim 2m_p)$
- ✓ Maximum branching
  - $Br(\gamma_D \rightarrow \mu^+\mu^-) \approx 45\%$ at $m_{\gamma_D} \approx 0.4\ GeV$
- ✓ Benchmark masses
  - $m_h = 125$ GeV, $m_{n_1} = 10$ GeV, $m_{n_D} = 1$ GeV

AMS: PhysRevLett.113.121101



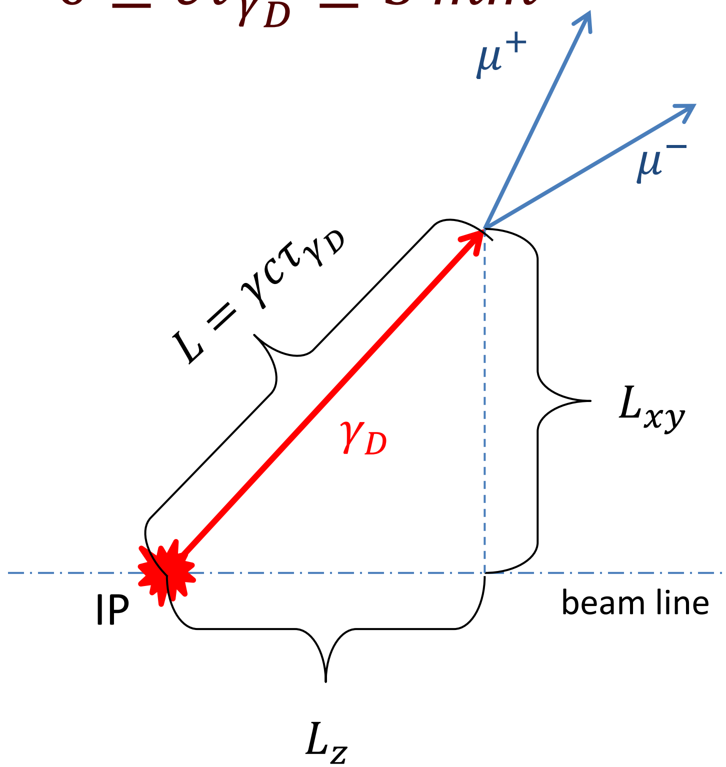
JHEP05(2010)077

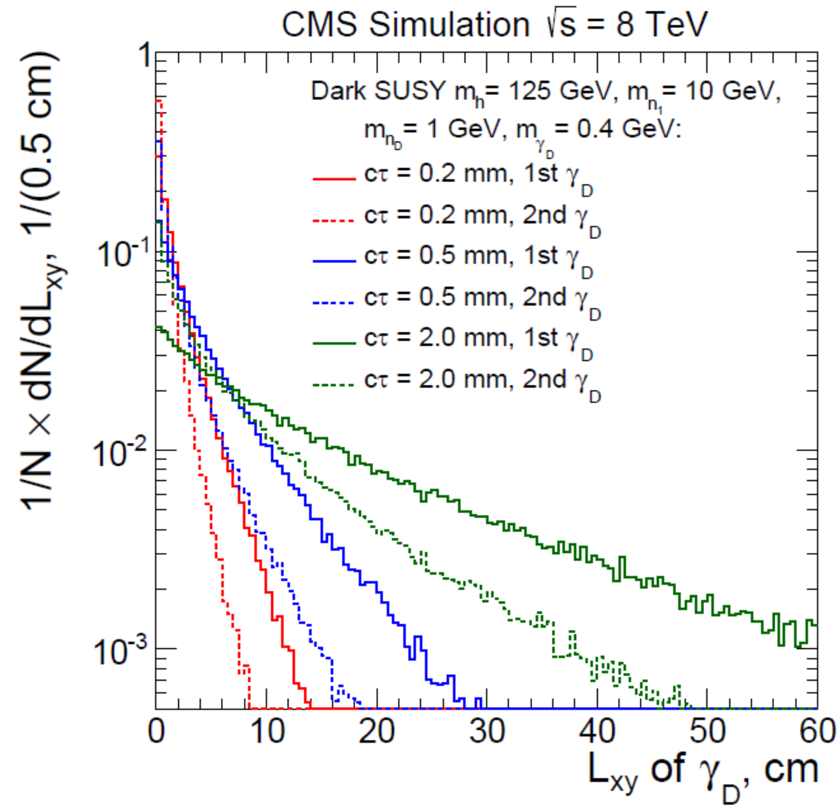
Branching fraction of $\gamma_D \rightarrow \mu\mu$



Dark SUSY with $c\tau_{\gamma_D} > 0$

- ✓ The γ_D may also be long-lived depending on the value ε of the kinetic mixing: $c\tau_{\gamma_D} \sim \varepsilon^{-2}$
- ✓ Simulated benchmark Dark SUSY samples
  - $0 \leq c\tau_{\gamma_D} \leq 5\,mm$

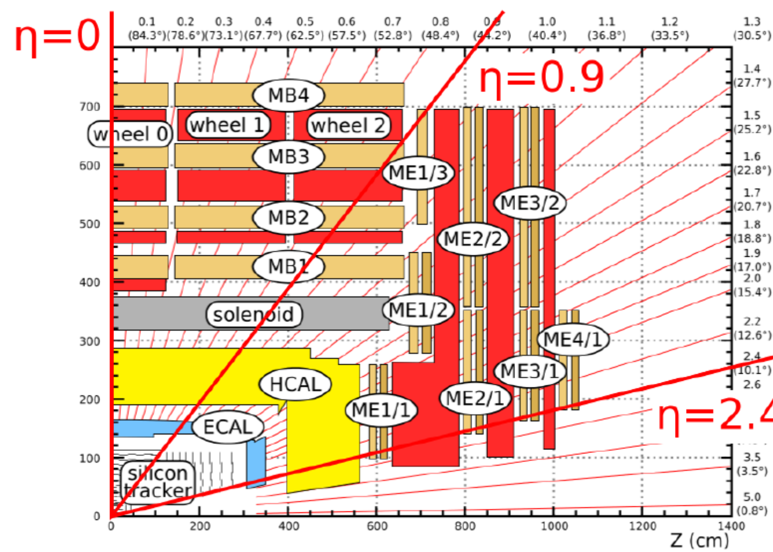


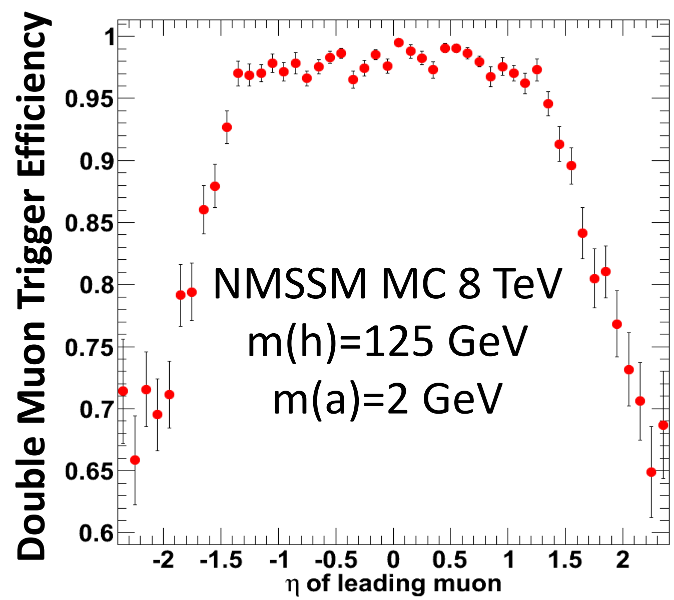


$$L_{xy}(m_{\gamma_D}, c\tau_{\gamma_D}) = \gamma c\tau_{\gamma_D} \frac{p_T}{p} = \frac{E}{m_{\gamma_D}}\, c\tau_{\gamma_D} \frac{p_T}{p}$$

Analysis Strategy: Select Events with Muons

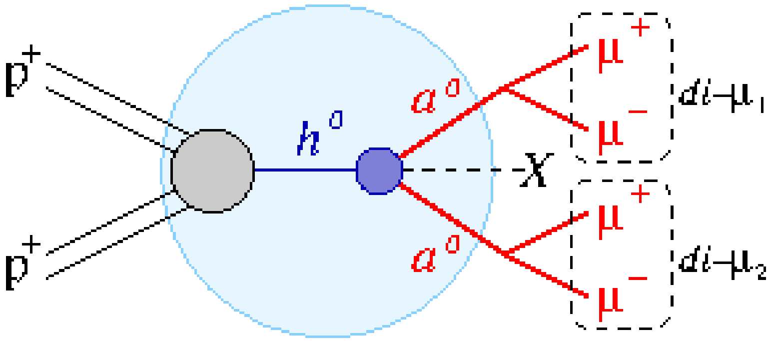
- ✓ Data: 20.7 fb^{-1} of 2012 LHC data
- ✓ Inclusive double muon trigger
  - $p_{T1} > 17$ GeV, $p_{T2} > 8$ GeV
- ✓ Identify muon candidates
  - Particle-flow muon reconstruction algorithm (maintains high efficiency for close by muons)
- ✓ We require at least 4 muons
  - $p_T > 8$ GeV, $|\eta| < 0.9$, good track quality
- ✓ Additionally, at least one muon is required
  - to be in the barrel region $|\eta| < 0.9$
  - have $p_T > 17$ GeV
  - this requirement ensures that the trigger efficiency is high, flat and model independent





Analysis Strategy: Build Dimuons

✓ Cluster nearby muons into pairs of opposite charge muons with low invariant mass



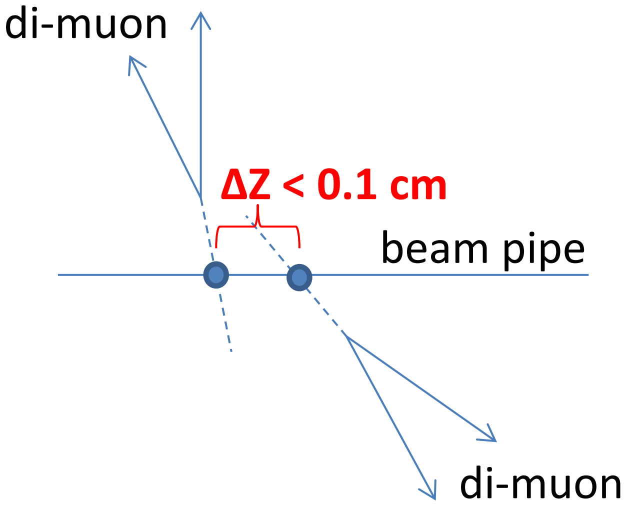
- $m_{\mu\mu} < 5\ GeV$
- good common vertex or $\Delta R_{\mu\mu} < 0.01$
- call them *dimuons*

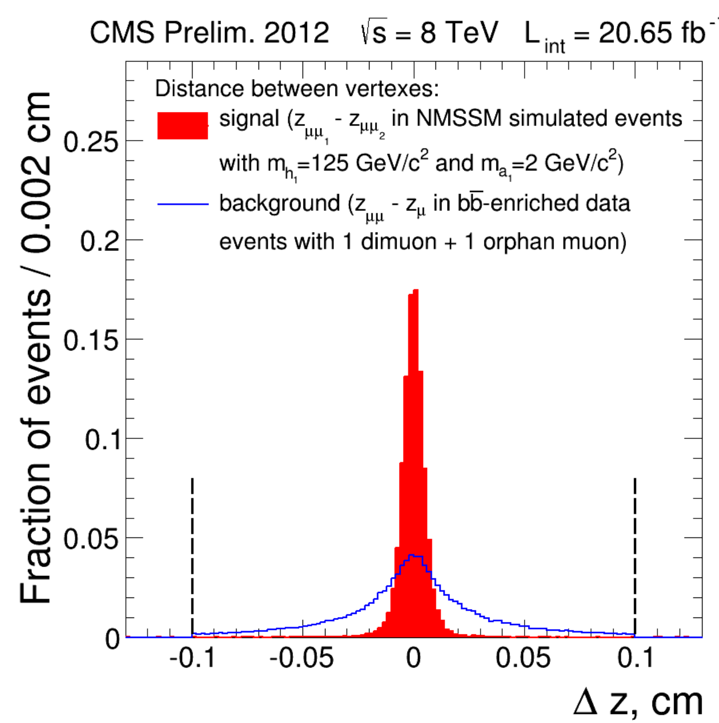
✓ Select events with exactly 2 distinct dimuons

- reconstruct dimuon vertices and require dimuons to be produced in the same pp collision
- no limit on the number of unpaired muons (call them *orphans*)

Analysis Strategy: Dimuons' Vertexes

- ✓ We require that the two dimuons are originating from the same pp collision: $\Delta Z = |z_{\mu\mu 1} - z_{\mu\mu 2}| < 0.1$ cm
  - assuming that each dimuon is a decay product of a new light boson, we reconstruct $z_{\mu\mu}$
    - z coordinate of the boson trajectory at the point of the closest approach to the beam line
  - also essential for the proper definition of isolation, use the same 0.1 cm in the isolation requirement (see next page)
- ✓ Loose and safe requirement
  - Assuming highly luminous region is ~15 cm, for 30 pile-up collisions "average distance" between them ~0.5 cm

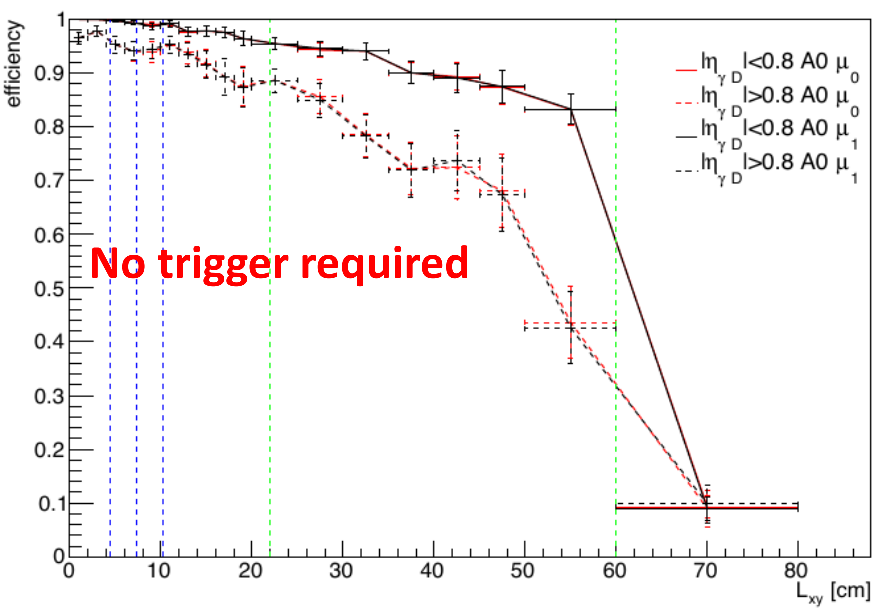


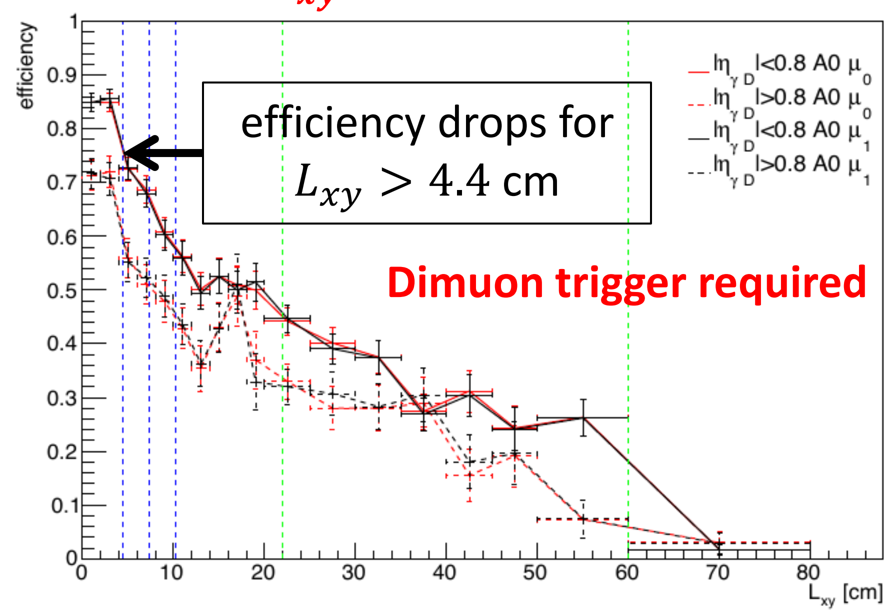


Analysis Strategy: Fiducial Volume

- ✓ Effective fiducial volume of the analysis in (L_{xy}, L_z) space
  - at GEN level requirement: $L_{xy} < 4.4$ cm and $L_z < 34.5$ cm
    - corresponding to the distance from the center of the detector to the first layer in the pixel barrel (PXB) and the pixel endcap (PXF) respectively.
  - at RECO level requirement: a hit in the first pixel layer for at least one muon in each dimuon
- ✓ Main motivation for such fiducial constraint is trigger inefficiency outside first layer of pixel (barrel and endcaps)
  - Outside this region results become model dependent
- ✓ New displaced muon trigger for Run2 analysis to increase fiducial region

Muon reconstruction efficiencies vs L_{xy}



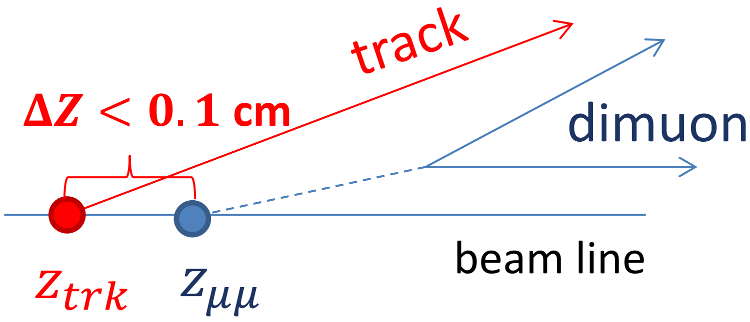


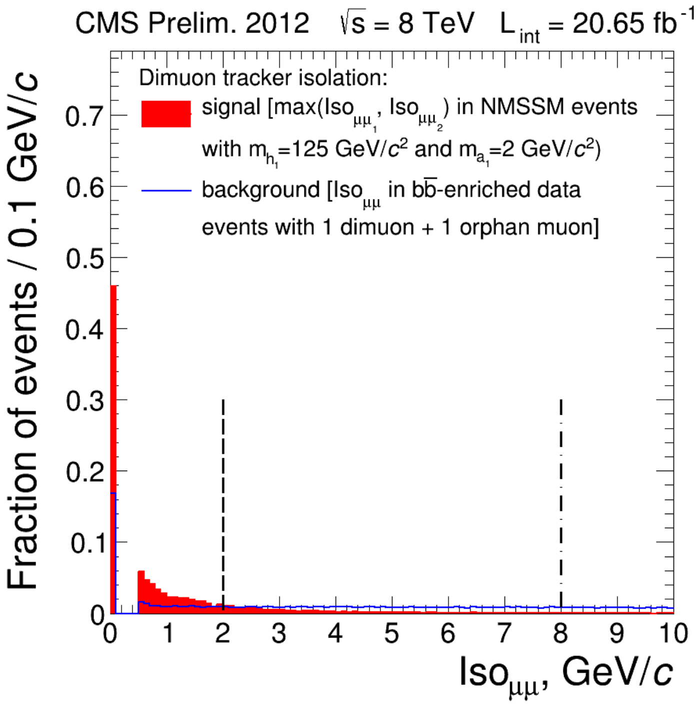
Analysis Strategy: Dimuons' Isolation

- ✓ To suppress one of the main background sources, $b\bar{b}$ events, we require each dimuon to be isolated:

$$Iso = \sum_{tracks} p_{\mathrm{T}} < 2\text{ GeV}$$

- ✓ Dimuon isolation Iso is sum over tracks in the silicon tracker with:
  - $p_T > 0.5$ GeV
  - $\Delta R(trk, \mu\mu) < 0.4$
  - $|z_{trk} - z_{\mu\mu}| < 0.1$ cm
  - muons forming dimuon excluded
- ✓ We use absolute isolation
  - Relative isolation introduces unnecessary p_T-dependence that leads to model-dependency
- ✓ Isolation requirement reduces background by a factor of 50, while we loose only 20% of signal





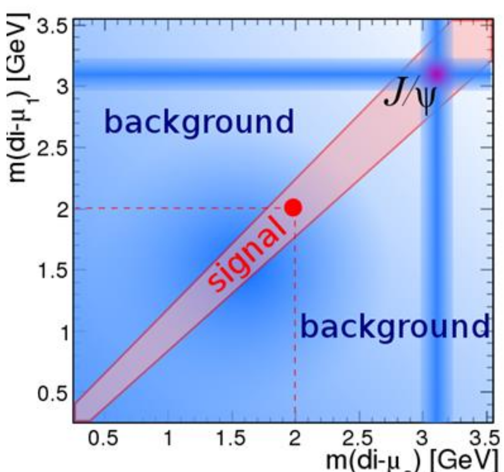
Analysis Strategy: Diagonal Signal Region

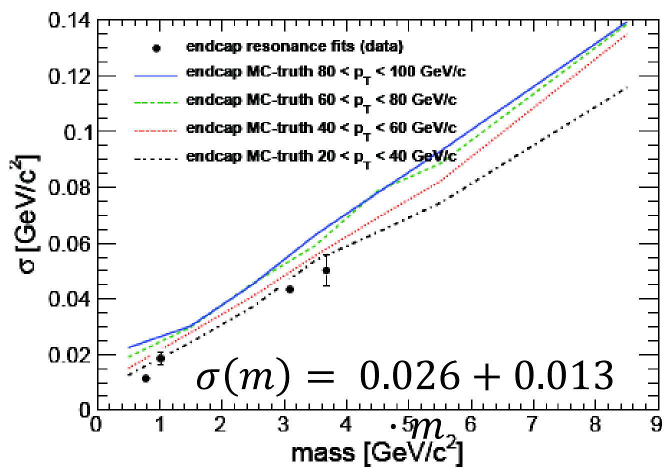
✓ We search for events with 2 dimuons which are produced in decays of the same type of new light bosons

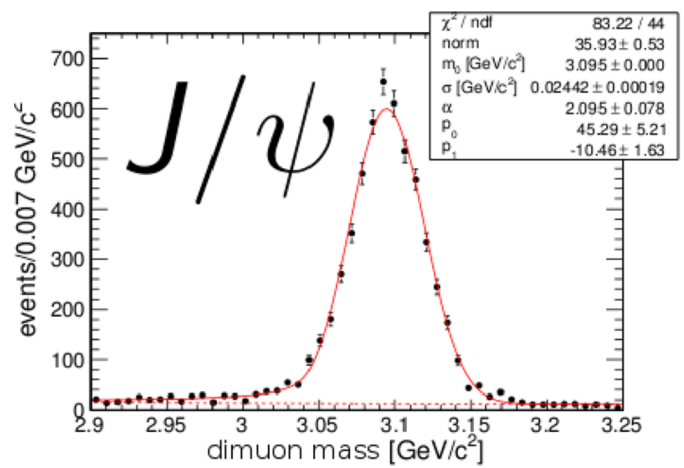
- $m_{\mu\mu}$ is a good variable for getting limits on m_a
  - for relevant example compare with MET and m_{LSP} in SUSY searches
- The masses of the two dimuons should be consistent with each other within five detector resolutions:

$$\left|m_{\mu\mu1} - m_{\mu\mu2}\right| < 5\sigma = \; 0.13 + 0.065 \cdot (m_{\mu\mu1} + m_{\mu\mu2})/2$$

- Detector resolution studied using low-mass SM resonances in data decaying to pair of muons — ω, φ, J/ψ, ψ’







Signal Selection Efficiency

✓ The analysis selection requirements are designed to keep ratio $r = \frac{\epsilon_{\text{data}}}{\alpha_{\text{gen}}}$ varying only weakly

NMSSM

m_{h_1} [GeV]	90	125	125
m_{a_1} [GeV]	2	0.5	3.55
ϵ_{sim} [%]	11.0 ± 0.1	21.1 ± 0.1	17.3 ± 0.1
α_{gen} [%]	15.9 ± 0.1	32.0 ± 0.1	26.3 ± 0.1
$\epsilon_{\text{sim}}/\alpha_{\text{gen}}$	0.69 ± 0.01	0.66 ± 0.01	0.66 ± 0.01

Dark SUSY

m_{γ_D} [GeV]	0.25			1.0		
$c\tau_{\gamma_D}$ [mm]	0	0.5	2	0	0.5	2
ϵ_{sim} [%]	8.85 ± 0.12	1.76 ± 0.05	0.23 ± 0.03	6.13 ± 0.23	4.73 ± 0.07	1.15 ± 0.04
α_{gen} [%]	14.32 ± 0.14	2.7 ± 0.06	0.31 ± 0.03	8.89 ± 0.28	6.98 ± 0.09	1.68 ± 0.05
$\epsilon_{\text{sim}}/\alpha_{\text{gen}}$	0.62 ± 0.01	0.65 ± 0.02	0.74 ± 0.13	0.69 ± 0.03	0.68 ± 0.01	0.68 ± 0.03

$$r = \frac{\epsilon_{data}}{\alpha_{gen}} = \frac{\epsilon_{data}}{\epsilon_{sim}} \times \frac{\epsilon_{sim}}{\alpha_{gen}} = 0.63 \pm 0.07$$

✓ This allows us to provide the simple model independent recipe for 95% CL upper limit depending only on α_{gen}

- applies to models with the same signature

SM Backgrounds

- The background contribution from the SM to a signature with two light dimuons after final selections:
  - $b\bar{b}$
    - both b-quarks decay to dimuons + X via double semileptonic decays or resonances, e.g. ω, ρ, ϕ, J/ψ
    - expected number of events in signal region: 2.0 ± 0.7
  - prompt double J/ψ
    - two prompt J/ψ's can be produced in double parton scattering (DPS) or single parton scattering (SPS)
    - expected number of events in signal region: 0.05 ± 0.03
  - $pp \rightarrow 4\mu$
    - estimated with MC simulation (COMPHEP)
    - expected number of events in signal region: 0.15 ± 0.03
- Total expected number of SM background events in signal region is 2.2 ± 0.7

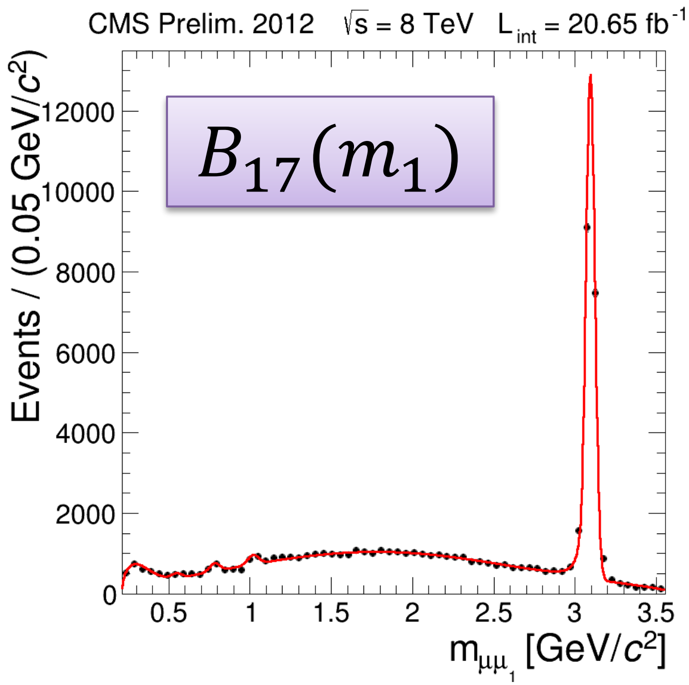
Modeling of the $b\bar{b}$ Background Shape (1)

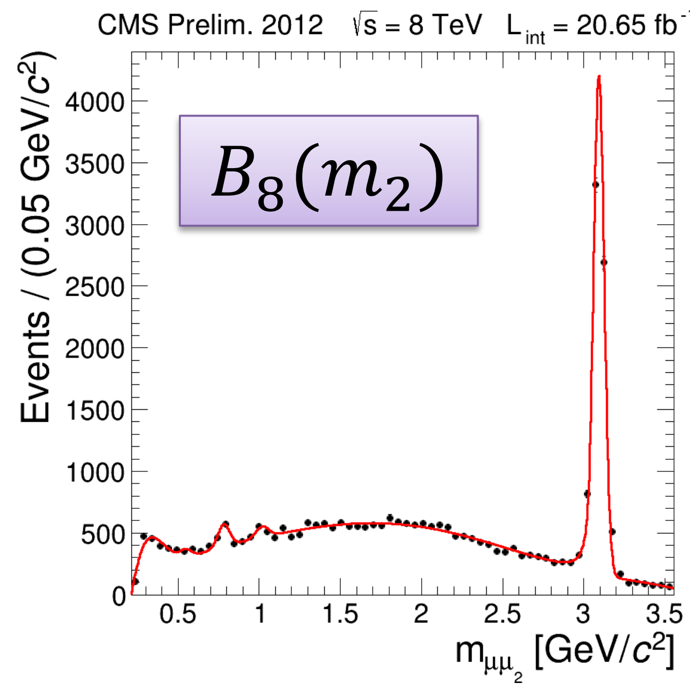
- Background contribution from $b\bar{b}$ events modeled by 2D template $B_{b\bar{b}}(m_1, m_2)$
  - m_1 refers to the dimuon containing a muon with $p_T > 17$ GeV and |η| < 0.9
  - if both dimuons have such muons, m_1 and m_2 labels assigned randomly
- The shape of the dimuon invariant mass distribution depends on p_T thresholds used to select muons and whether muons are in the barrel or in the endcap
  - Need to measure shapes independently for each of two dimuons
  - The shapes are measured using orthogonal sample of $b\bar{b}$ events with exactly one dimuon and one orphan muon
- As each b-quark fragments independently, 2D template is constructed as a Cartesian product of 1D templates of both dimuon invariant mass distributions

$$B_{b\bar{b}}(m_1, m_2) = B_{17}(\mathrm{m}_1) \text{ x } B_8(\mathrm{m}_2)$$

Modeling of the $b\bar{b}$ Background Shape (2)

- ✓ Background templates obtained from events with exactly one dimuon and one orphan muon
  - no isolation requirement applied



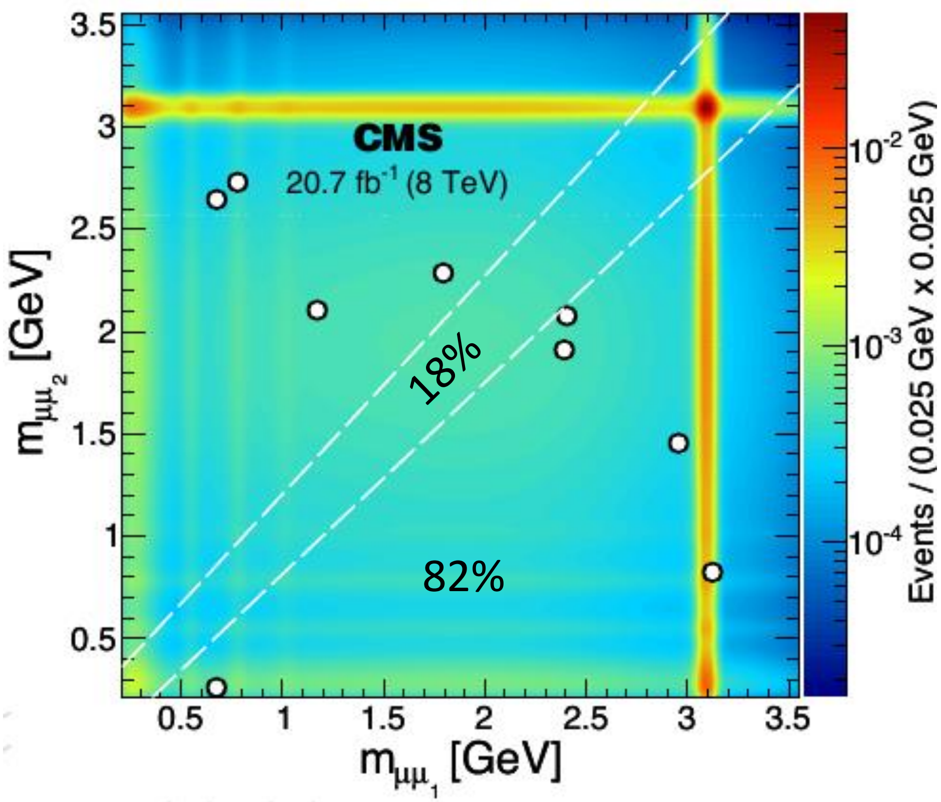


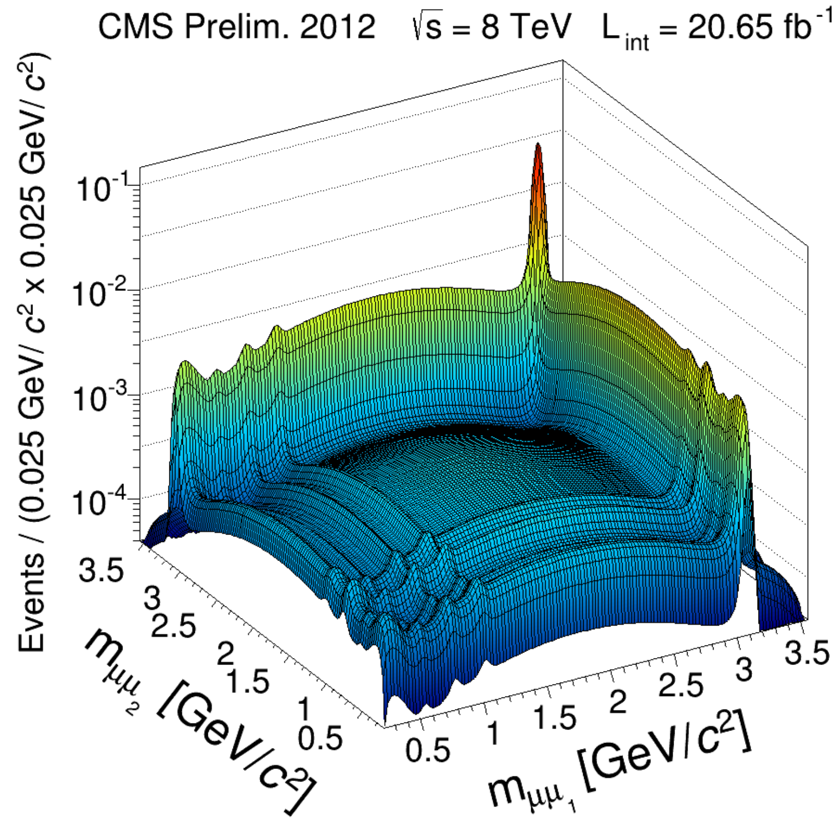
- ✓ Background shapes are fitted with analytical functions:
  - resonances ρ, ω, η, ϕ fitted with Gauss; J/ψ – with Crystal Ball
  - bulk shape is series of Bernstein polynomial
- ✓ Once 1D shapes are constructed, the 2D template is fixed

Modeling of the $b\bar{b}$ Background Shape (3)

✓ Once 1D shapes are constructed, the 2D template is fixed

$$B_{b\bar{b}}(m_1, m_2) = B_{17}(\mathrm{m}_1) \times B_8(\mathrm{m}_2)$$



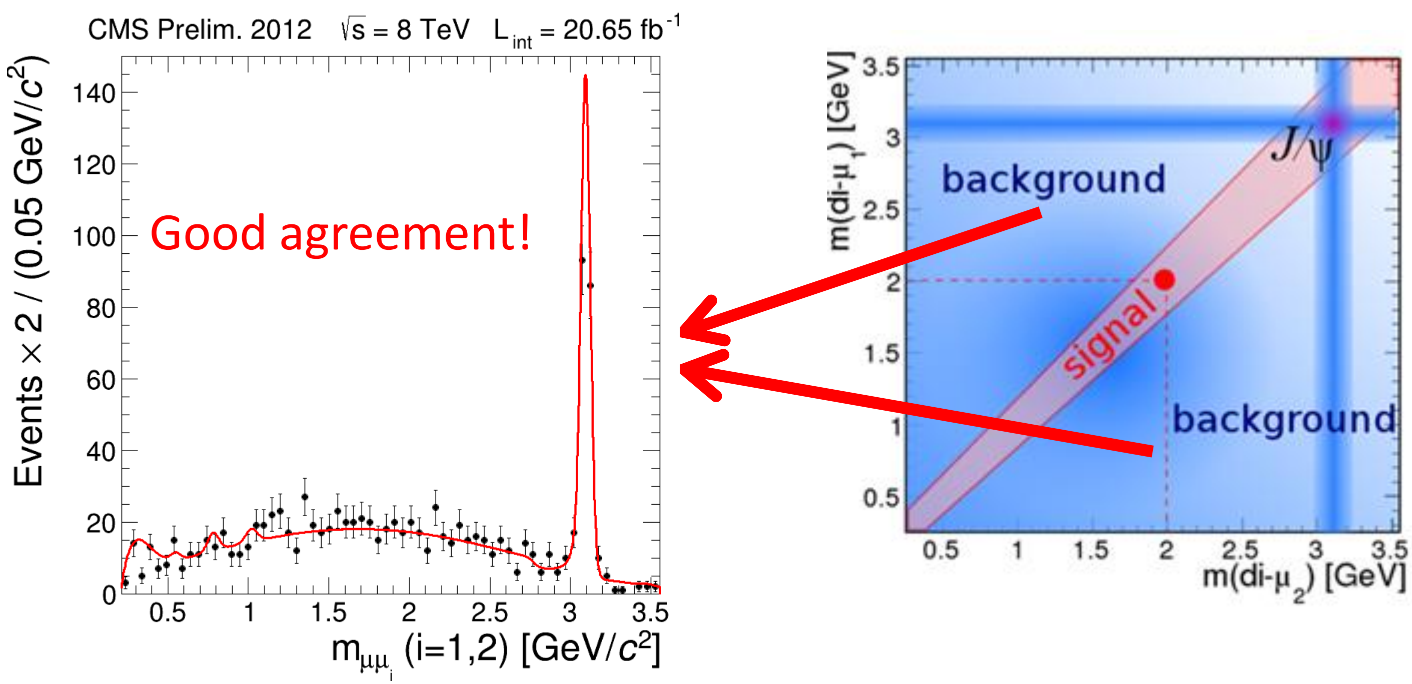


- 9 events observed in off-diagonal region used for template normalization: $(9 \pm \sqrt{9}) \times \frac{0.18}{0.82} = 2.0 \pm 0.7$ events

Validation of $b\bar{b}$ Background Shape

✓ Switch to a signal-like sample

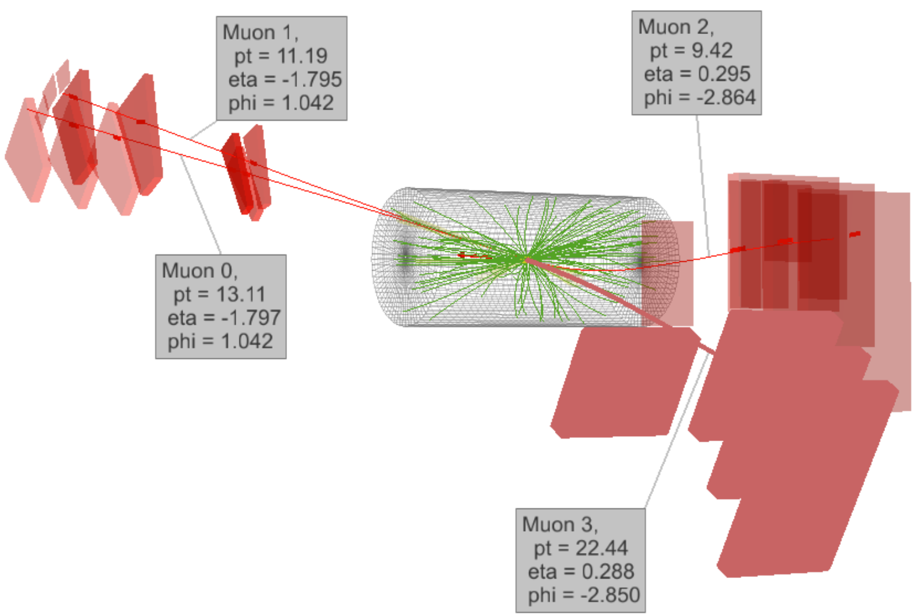
- use two dimuon data sample with the standard selections
- drop isolation requirements on both dimuons
- exclude diagonal part (could be signal there!)
- sum up projections on m_1 and m_2 axes (to have 1 plot instead of 2)
- compare these sums in data and in the template

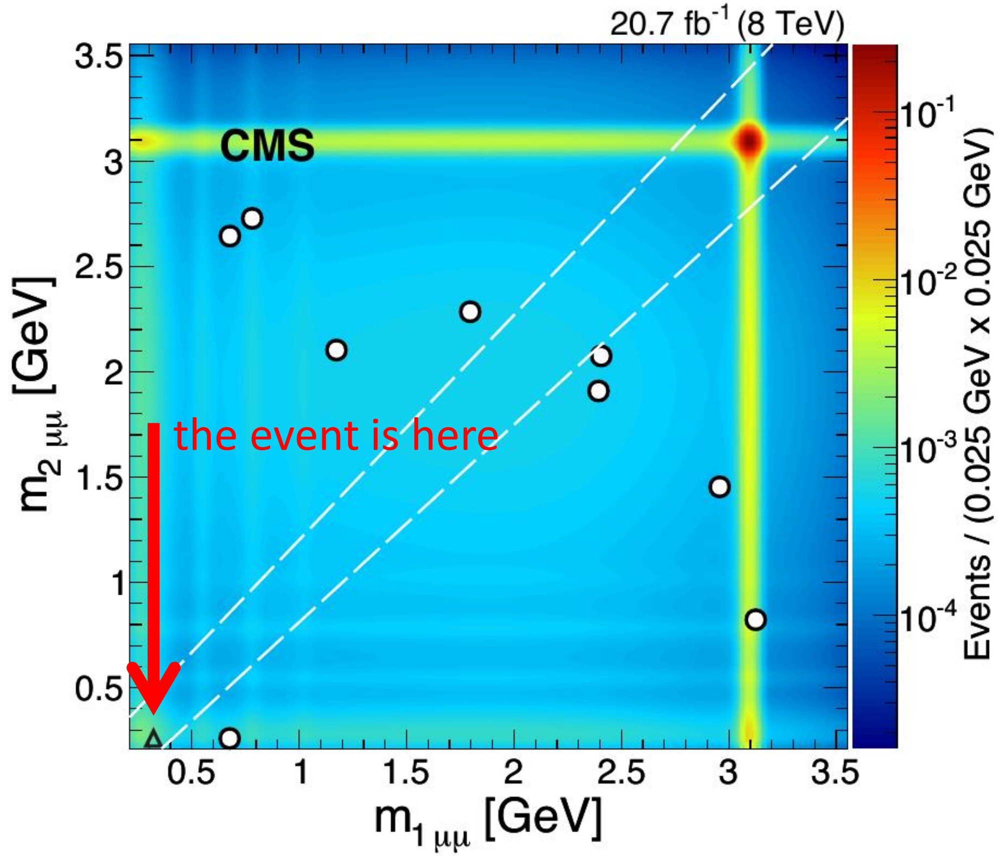


Diagonal Signal Region

✓ In the signal region: one event observed

Run #	Event #	mass of the triggered di-muon (GeV/c^2)	mass of the other di-muon (GeV/c^2)	isolation of the triggered di-muon (GeV/c)	isolation of the other di-muon (GeV/c)
202045	159896605	0.33	0.22	0.00	0.00



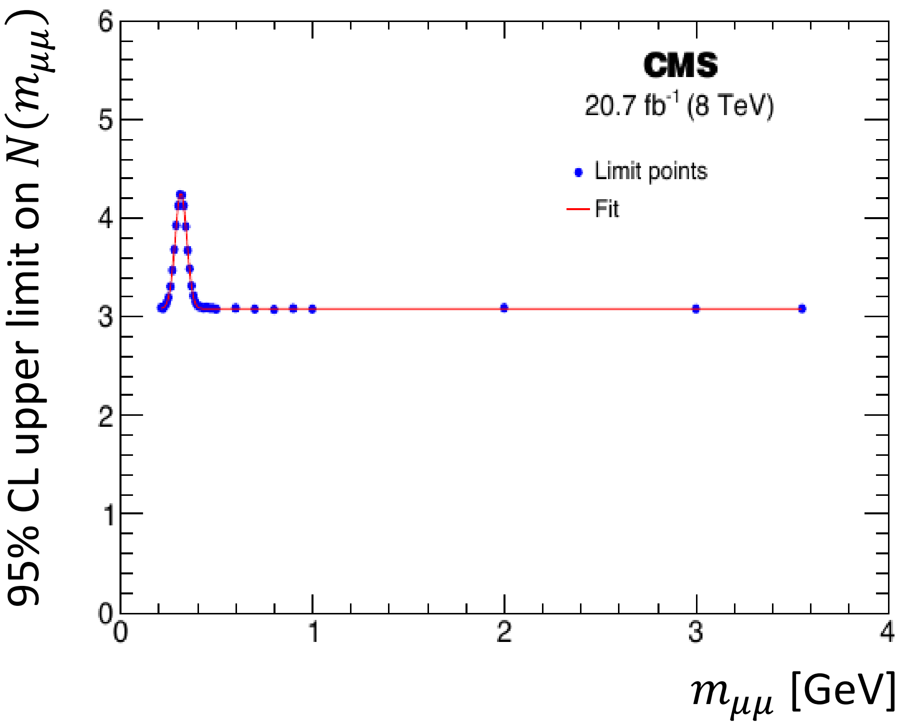


Model Independent Result (1)

✓ The result of the analysis is the 95% CL upper limit on the production rate calculated using CL_S approach:

$$\sigma(pp \to 2a + X) \times Br^2(a \to 2\mu) \times \epsilon_{data} \times L = N(m_{\mu\mu})$$

where ϵ_{data} - is event selection efficiency and $L = 20.7\ fb^{-1}$ - is integrated luminosity collected by CMS



The obtained limit as a function of dimuon mass $m_{\mu\mu}$ can be conveniently approximated as a constant everywhere except the vicinity of the observed event, where it follows a Gaussian distribution:

$$N(m_{\mu\mu}) \leq 3.1 + 1.2 \times \exp\left[-\frac{(m_{\mu\mu} - 0.32)^2}{2 \times 0.03^2}\right]$$

Model Independent Result (2)

✓ The generic model independent result is the 95% C.L. upper limit on the production rate

$$\sigma(pp \to 2a + X) \times Br^2(a \to 2\mu) \times \alpha_{gen} = \frac{N(m_{\mu\mu})}{L \times \bar{r}}$$

or

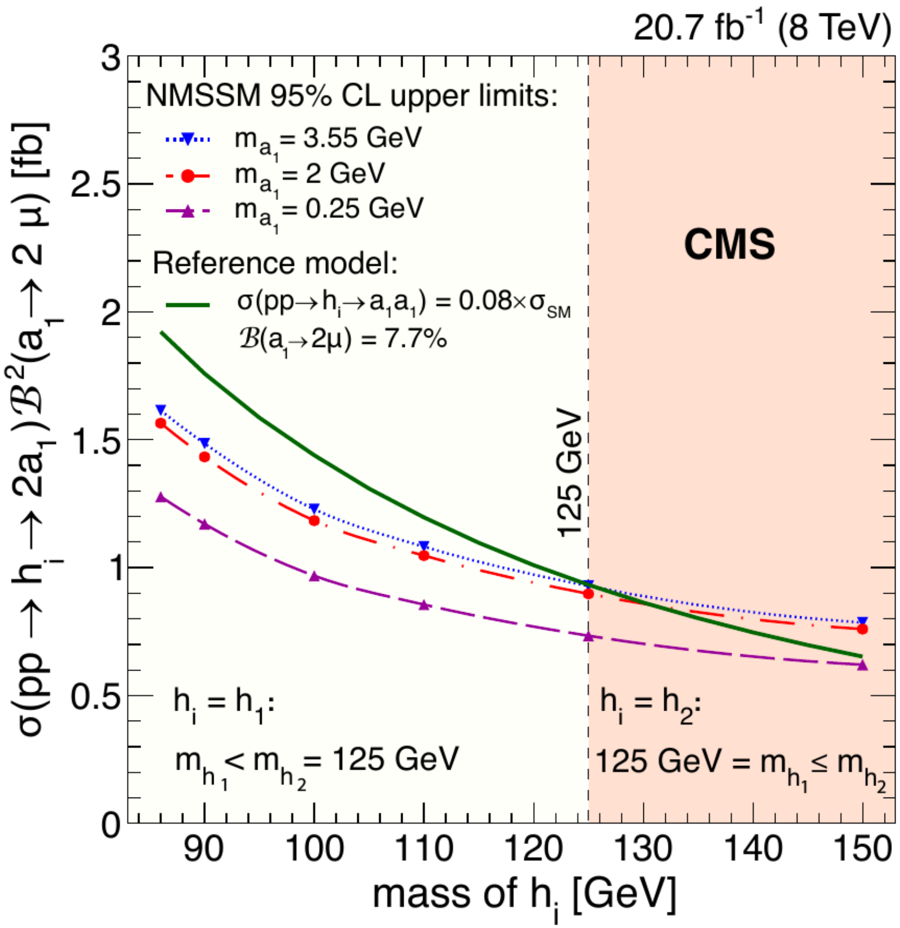
$$\sigma(pp \to 2a + X) \times Br^2(a \to 2\mu) \times \alpha_{gen} \leq 0.24 + 0.09 \times \exp\left[-\frac{(m_{\mu\mu} - 0.32)^2}{2 \times 0.03^2}\right]$$

- easily applicable to an arbitrary non-SM scenario predicting the similar signature
  - two muon pairs coming from light bosons of the same type
  - light boson mass $0.25 < m_a < 2$ GeV
  - light boson is typically isolated
  - light boson decays within $L_{xy} < 4.4$ cm and $L_z < 34.5$ cm
- α_{gen} is the geometric and kinematic acceptance calculated using generator level information only
- $\bar{r}$ is central value of the ratio $r = \epsilon_{data}/\alpha_{gen} = 0.63 \pm 0.07$ with data/MC scale factor (0.93 ± 0.07) included

Exclusion Limit: NMSSM

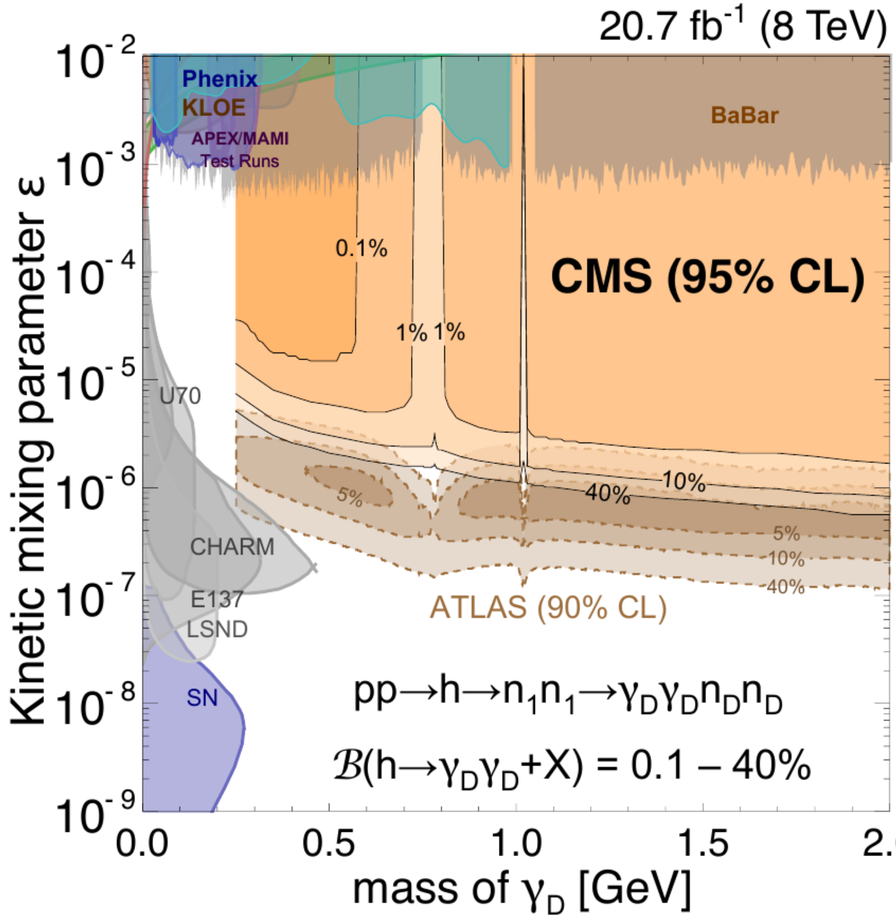
✓ 95% CL upper limit on the product of Higgs boson production cross section times branching fractions in NMSSM as a function of $h_{1/2}$ mass

- Masses: m_{a_1} = 0.25 GeV, 2 GeV and 3.55 GeV
- Two scenarios:
  1. $m_{h_1} < m_{h_2} = 125\ GeV$
  2. $125\ GeV = m_{h_1} \leq m_{h_2}$
- Simplified reference model:
  - $\sigma(pp \to h_{1/2} \to 2a_1) = 0.08\sigma_{SM}$
  - $B(a_1 \to \mu\mu) = 7.7\%$



Exclusion Limit: Dark SUSY

- ✓ 95% CL upper limit on the product of Higgs boson production cross section times branching fractions in dark SUSY as a function of γ_D mass and kinetic mixing parameter ε
  - Masses: $m_h = 125$ GeV, $m_{n_1} = 10$ GeV, $m_{n_D} = 1$ GeV
  - Branching fraction varies $B(h \to 2\gamma_D + X) = 0.1 - 40\%$
- ✓ Results are compared with complimentary search at ATLAS (90%CL limit JHEP11(2014)088), searches at a range of low energy e^+e^- colliders, fixed target experiments, and cosmological measurements



Conclusion

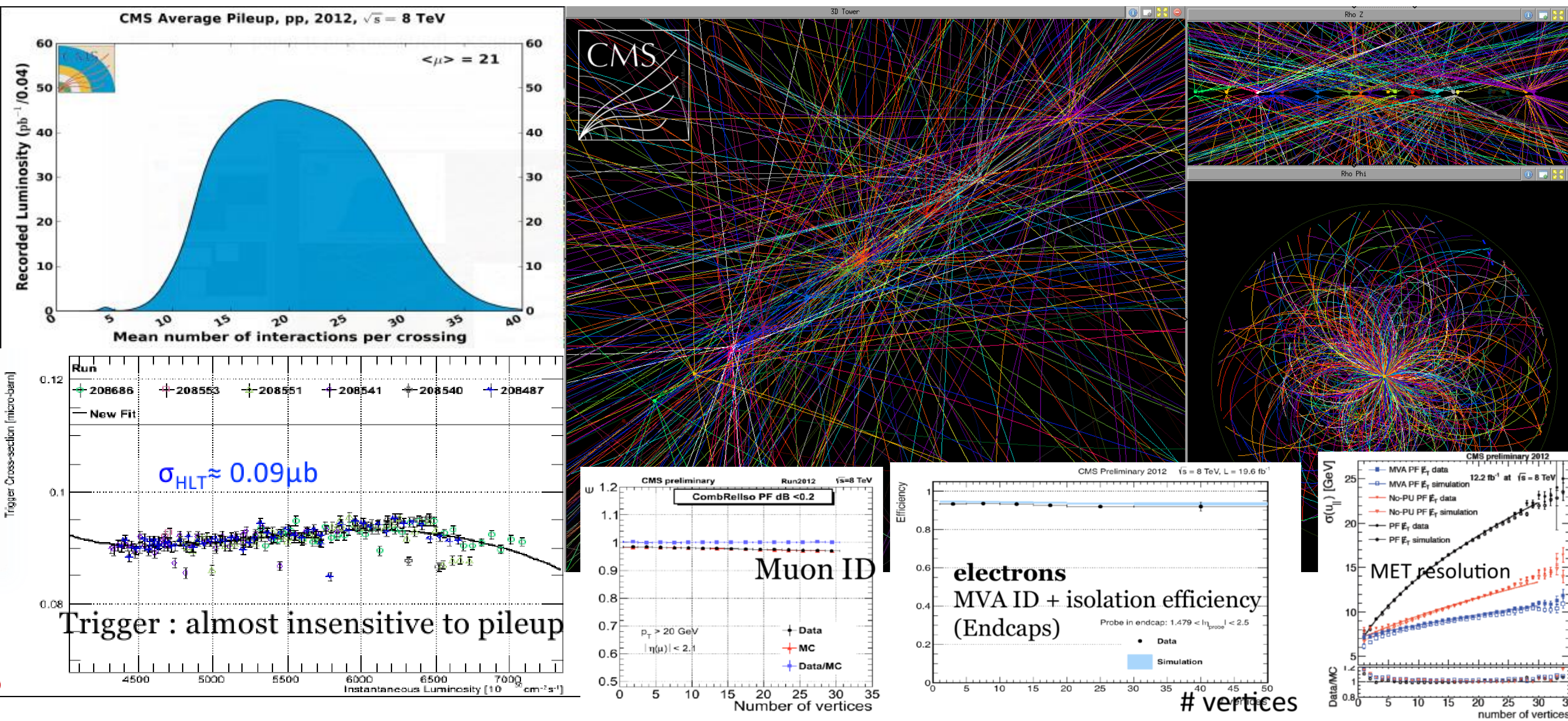
- ✓ The search for pairs of new light bosons, each of which decays into the $\mu^+\mu^-$ boosted final state is reported
  - Direct search for motivated non-SM Higgs boson decay
  - Explored mass range of new light boson: $2m_\mu < m_a < 2m_\tau$
  - Sensitivity range of new light boson lifetime: up to $c\tau_{\gamma_D} < 20\ mm$
  - One event in signal region observed with 20.7 fb^{-1} of data recorded by the CMS in 2012 at $\sqrt{s} = 8\ \mathrm{TeV}$
  - 95% CL model independent upper limit for signal rate is set
    - Results are applicable to a broad spectrum of non-SM scenarios predicting the analysis signature
    - Recipe is provided
  - Results are interpreted for two benchmark models
    - NMSSM and dark SUSY
- ✓ The paper with results is approved by CMS Collaboration and will appear at arXiv shortly
- ✓ The search will be continued in Run 2 with improved trigger

Backup

Pileup at $\sqrt{s} = 8$ TeV

✓ Multiple proton-proton interactions in one bunch crossing

- $\sim$21 interactions per crossing in 2012 at $\sqrt{s} = 8$ TeV
- trigger almost insensitive to pileup
- reconstruction of leptons and MET almost insensitive to pileup

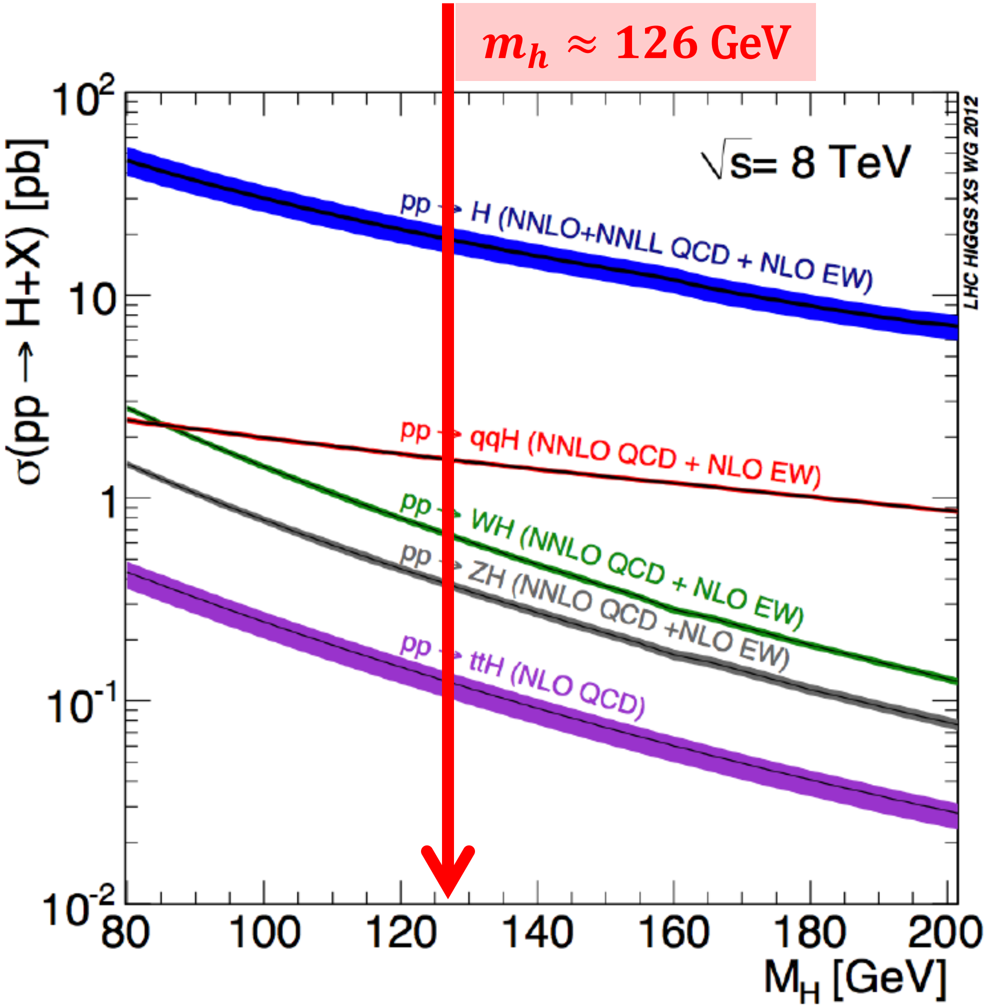


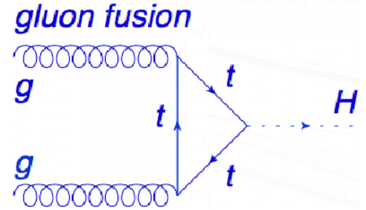
Higgs Production at LHC

✓ Cross section of the Higgs production in pp collisions at $\sqrt{s} = 8$ TeV is calculated with high precision

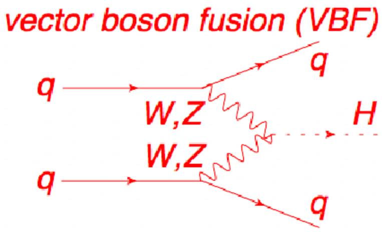
arXiv:1101.0593

$m_h \approx 126$ GeV

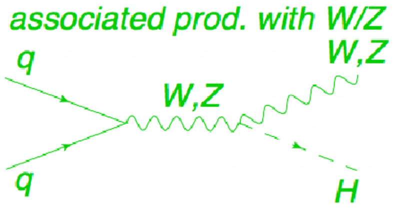




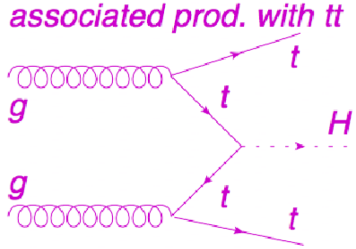
- Large uncertainty from QCD
- Probes fermion coupling
- Sensitive to BSM in loops



- Small uncertainty
- Probes W/Z coupling
- Tagged with forward jets



- Small uncertainty
- Access to W/Z coupling
- Tagged with W/Z lepton decay



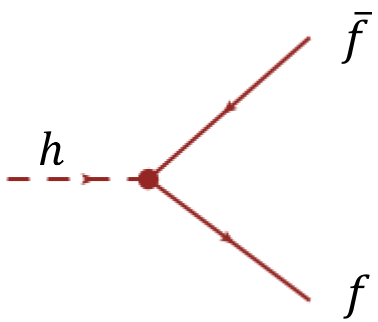
- Large uncertainty from QCD
- Probes top coupling
- Tagged with b-jets

Standard Model Higgs Decay Channels

✓ Five most sensitive channels studied

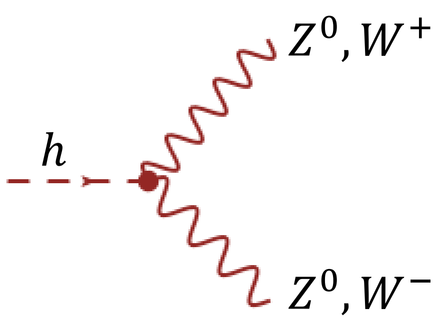
arXiv:1101.0593

- High yield: $h \to WW/\tau\bar{\tau}/b\bar{b}$
- High mass resolution: $h \to \gamma\gamma/ZZ$



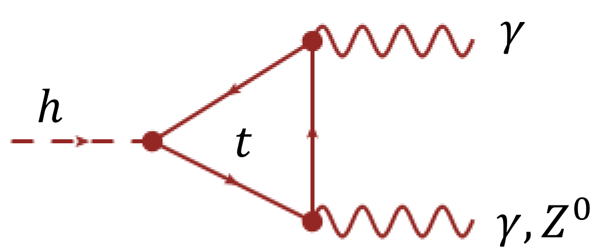
$h \xrightarrow{57\%} b\bar{b}$

$h \xrightarrow{6\%} \tau\bar{\tau}$

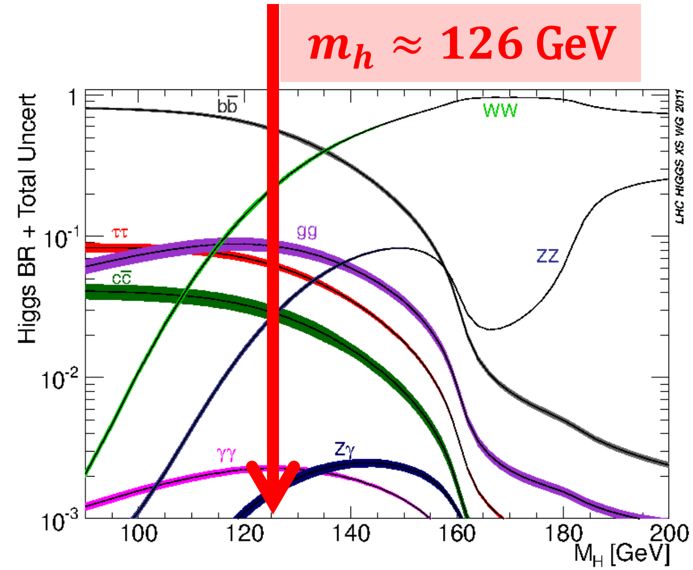


$h \xrightarrow{21\%} WW \to 2l + 2\nu$

$h \xrightarrow{3\%} ZZ \to 4l$ or $2l + 2\tau$



$h \xrightarrow{9\%} \gamma\gamma$



@ 125GeV	signature	S/B	Mass Resol.	N events in 20fb^{-1}	Good For
H→bb	two b-jets, Z or W, bb inv. mass	low O(0.1)	10%	~10^5 ~50 (sel)	couplings to fermions
H→ττ	had tau, leptons, MET	low O(0.1)	15%	~10^4 ~40 (sel)	couplings to fermions
H→WW	two leptons with opposite charge MET	medium O(1)	-	~10^3 ~120 (sel)	cross section, BR, couplings to V
H→γγ	two photons peak in inv. mass	low O(0.1)	2%	800 ~400 (sel)	H mass, couplings $K_V K_F$, discovery
H→ZZ	four leptons with right charge peaks in inv. mass (Z_1 and Higgs)	high >1	1-2%	40 ~12 (sel)	H mass, discovery

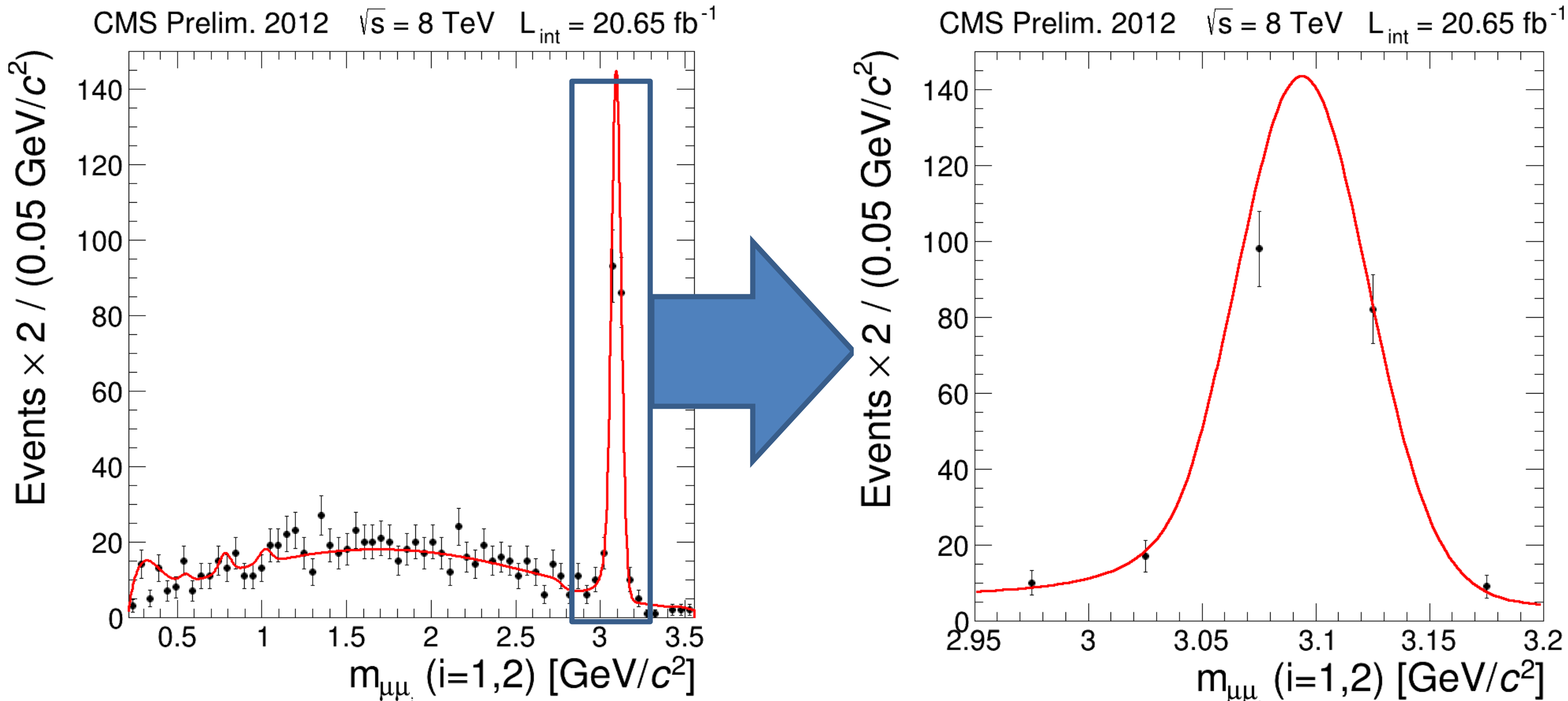
Benchmark Models Simulation

- All events in the benchmark signal samples are processed through a detailed simulation of the CMS detector based on Geant4 and are reconstructed with the same algorithms used for data analysis
  - ~100k events per sample
  - pile up included
- NMSSM
  - Pythia6 MSSM Model: gg $\rightarrow H^0_{MSSM} \rightarrow 2A^0_{MSSM} \rightarrow 4\mu$
    - $m(H^0_{MSSM}) = m(h_{NMSSM})$ within the range 90 - 150 GeV
    - $m(A^0_{MSSM}) = m(a_{NMSSM})$ within the range 0.25 – 3.55 GeV
- Dark SUSY
  - Madgraph4 SM Higgs production: gg $\rightarrow h^0_{SM}$
    - $m(h^0_{SM}) = m(h_{NMSSM})$ within the range 90 - 150 GeV
  - BRIDGE new model: $h^0 \rightarrow 2n_1 \rightarrow 2n_D + 2\gamma_D$
    - $m(n_1) = 10$ GeV, $m(n_D) = 1$ GeV and $m(\gamma_D) = 0.4$ GeV

Validation of $b\bar{b}$ Background Shape (2)

✓ 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: Good agreement!



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_{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 ΔR(μ^+, μ^-) < 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

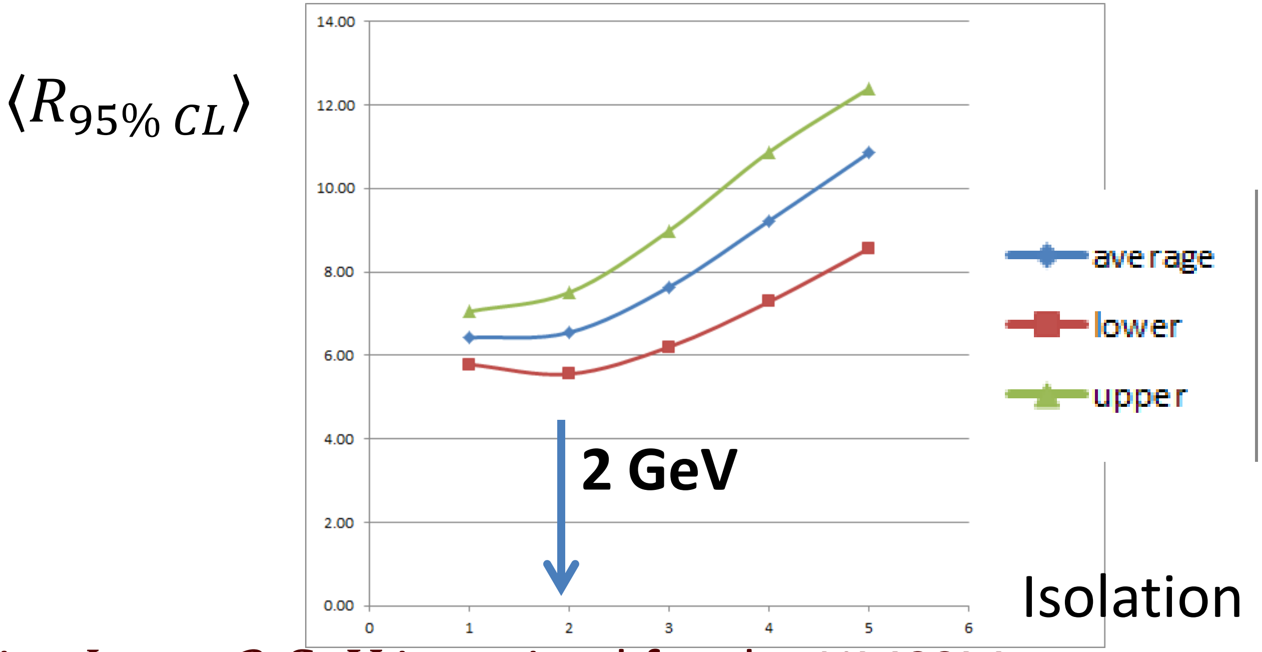
✓ Select events with exactly two dimuons not sharing any common muons

- no restriction on number of ungrouped (“orphan”) muons

Dimuon Isolation Optimization

✓ The analysis value of the dimuon isolation $Iso < 2\ \text{GeV}$ is compared to several alternatives

- Signal acceptance efficiencies are calculated with MC sample
  - NMSSM with $m_{h_1} = 125\ GeV,\ m_{a_1} = 2\ GeV$
- Background efficiencies are evaluated per dimuon with background enriched data sample (1dimuon + 1orphan) and recalculated per event
- Average weighted 95% C.L. upper limit on the rate of signal events within 0.25 < m < 3.55 GeV is calculated to test different values of the isolation



- Choice $Iso < 2\ \text{GeV}$ is optimal for the NMSSM

Average weighted 95% C.L. upper limit

✓ $R_{95\%\ C.L.}$ – average weighted expected 95% C.L. upper limit on the rate of signal events is used to test optimal values of the analysis requirements (e.g. dimuon isolation or signal region width)

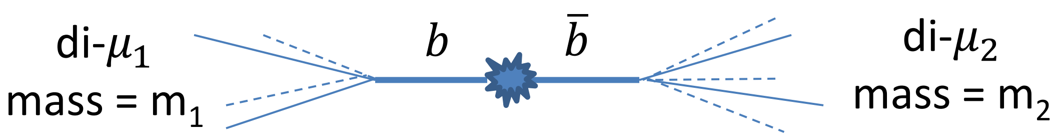
- assumes a counting experiment
- Input #1: ϵ_S - signal acceptance efficiency of the requirement
- Input #2: ν_B - expected background rate in the signal region after the requirement is applied

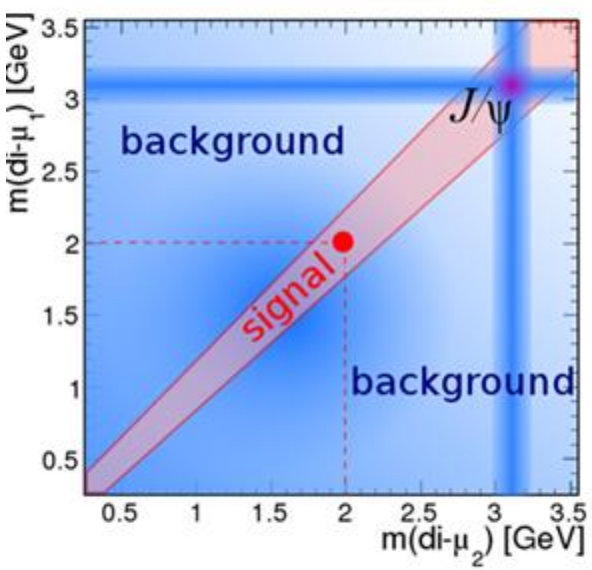
$$R_{95\%\ C.L.} = 1/\epsilon_S \times [3 \times P(N=0,\nu_B) + 4.74 \times P(N=1,\nu_B) + 6.3 \times P(N \geq 2,\nu_B)]$$

This expression is a slight simplification of the true limit calculation where the numerical factors are the Bayesian upper 95% C.L. exclusions in terms of the rate of signal events for experiments with observed 0, 1 and 2 events, which are weighted by the Poisson probabilities to observe 0, 1, or 2 and more events

Modeling of the $b\bar{b}$ Background Shape (1)

- ✓ Each b-quark in background events decays independently
- ✓ Naively, we can measure 1D mass background template B for one b-quark
- ✓ 2D mass background template can be modeled as Cartesian product of 2 di-muons mass distributions: $\mathrm{B}(\mathrm{m}_1) \times B(m_2)$





Modeling of the $b\bar{b}$ Background Shape (2)

- ✓ However, invariant mass shape of dimuon candidates in b-bbar events depends on pt tresholds of its muons
- ✓ At least one of the di-muons required to have barrel muon with pt > 17 GeV, while the second not:
  - "high pt" di-muon --- contains barrel muon with pt > 17 GeV
  - "low pt" di-muon --- doesn't contain it
- ✓ All events may have:
  - one "high pt" di-muon and one "low pt" di-muon
    - m_1 = mass of "high pt" di-muon
    - m_2 = mass of "low pt" di-muon
  - two "high pt" di-muons
    - masses of di-muons randomly assigned to m_1 and m_2
- ✓ No isolation requirement on dimuons applied

Modeling of the $b\bar{b}$ Background Shape (3)

$B(m_1, m_2)$ — 2D background shape

B_{17} — 1D shape of "high pt" di-muon

B_8 — 1D shape of "low pt" di-muon

$N_{17,8}$ — number of events with one "high pt" di-muon and one "low pt" di-muon

$N_{17,17}$ — number of events with two "high pt" di-muons

$$B(m_1, m_2) \sim N_{17,8} \cdot [B_{17}(m_1) \times B_8(m_2)] + N_{17,17} \cdot [B_{17}(m_1) \times B_{17}(m_2)]$$

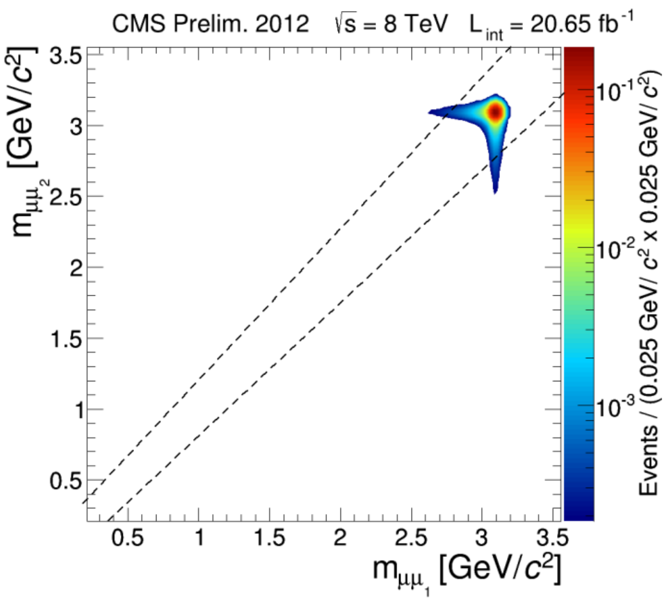
Events with one "high pt" di-muon and one "low pt" di-muon

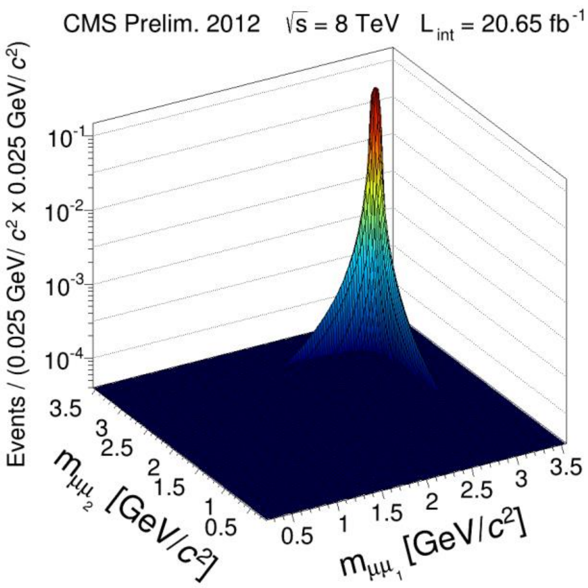
Events with two "high pt" di-muons

$$B(m_1, m_2) \sim B_{17}(m_1) \times B_{mix}(m_2)$$

Prompt Double J/ψ Background

- ✓ 2D Crystal Ball shape is used to model the prompt double J/ψ background





- ✓ Approximately 1500 events in the region of low invariant mass of the two J/ψ candidates were used for template normalization: 2.0 ± 2.0 events
  - MC samples were used to extrapolate normalization factor from low-p_T (control) to high-p_T (analysis) regions

Systematic Uncertainties

- Table of systematic uncertainties

Source of uncertainty	Error, %
Lumi	2.6%
Muon HLT	1.5%
Muon ID	$4 \times 1\%$
Muon tracking	$4 \times 0.2\%$
Overlapping in tracker	$2 \times 1.2\%$
Overlaping in muon system	$2 \times 1.3\%$
Dimuon mass consistency	1.5%
Theory (PDF+α_S) (not included in model independent)	3%
Total	**7%**

- Uncertainties on backgrounds:
  - $b\bar{b} = 2.0 \pm 0.7$
    - estimation is fully data driven ; normalized to off-diagonal region in $(m_{\mu\mu_1}, m_{\mu\mu_2})$ plane
  - prompt 2 J/ψ = $0.050 \pm 0.031(SPS) + 0.008 \pm 0.008(DPS)$= 0.058 ± 0.032
    - shape is data driven
    - for normalization data events from background enriched area scaled to signal region using MC. Uncertainty on the scale factor is 20%
    - two contributions: SPS – single parton scattering and DPS – double parton scattering
  - EWK $pp \rightarrow 4\mu$ = 0.15 ± 0.03 (stat)
    - estimation is based on MC: 7% systematic uncertainty as in signal applied

Model Independent Results (2011 data)

✓ The result of the analysis is the 95% C.L. upper limit on the production rate

$$\sigma(pp \to 2a + X) \times Br^2(a \to 2\mu) \times \epsilon_{full} < \frac{3}{\mathcal{L}}$$

Zero events observed in signal region

where ϵ_{full} - is event selection efficiency

✓ The analysis selection requirements are designed to keep ratio $r = \frac{\epsilon_{full}}{\alpha_{gen}} = 0.74 \pm 0.05$ constant

the ratio was checked with NMSSM and Dark SUSY MC

- α_{gen} is the geometric and kinematic acceptance calculated using generator level information only
- flatness of the ratio is checked for several benchmark samples

✓ The generic model independent result:

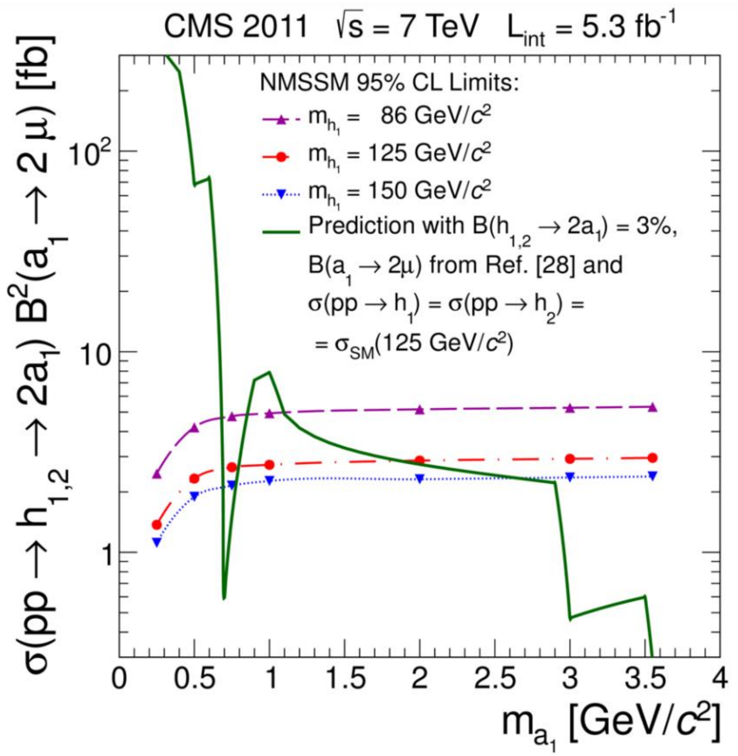
Limit with 2011 data

$$\sigma(pp \to 2a + X) \times Br^2(a \to 2\mu) \times \alpha_{gen} < \frac{3}{\mathcal{L} \cdot r} = 0.77 \text{ fb}$$

- easily applicable to an arbitrary non-SM scenario predicting the signature of two boosted isolated dimuons with consistent masses

NMSSM Exclusion Limits (2011 data)

✓ 95% CL Upper limit on the Higgs boson production in NMSSM as function of Higgs boson a_1 mass for a few masses of h



- $\sigma(pp \to \boldsymbol{h_1} \to 2a_1) \times \mathcal{B}^2(\mathrm{a}_1 \to 2\mu) \times \alpha(\boldsymbol{m_{h_1}}, m_{a_1}) +$
  $\sigma(pp \to \boldsymbol{h_2} \to 2a_1) \times \mathcal{B}^2(\mathrm{a}_1 \to 2\mu) \times \alpha(\boldsymbol{m_{h_2}}, m_{a_1}) < 3/\mathcal{L}$
- Since $\alpha(\boldsymbol{m_{h_1}}, m_{a_1}) < \alpha(\boldsymbol{m_{h_2}}, m_{a_1})$, we use $\alpha(\boldsymbol{m_{h_1}}, m_{a_1})$ to set conservative limit on

$$\sigma(pp \to h_{1,2} \to 2a_1) \times \mathcal{B}^2(\mathrm{a}_1 \to 2\mu) < 3/\mathcal{L}/\ \alpha(\boldsymbol{m_{h_1}}, m_{a_1})$$

NMSSM and Dark SUSY Exclusion Limits (2011 data)

✓ Set 95% CL Upper limit on the Higgs boson production in NMSSM and SUSY with hidden sector as functions of h_1 or h Higgs boson mass

- NMSSM:
  - $m(a_1) = 2m_\tau$
  - $m(a_1) = 0.25$ GeV
- NMSSM prediction:
  - $\sigma(h_1) = \sigma(h_{SM})$
  - $Br(h_1 \to 2a_1) = 3\%$
  - $Br(a_1 \to 2\mu) = 7.7\%$
- Dark SUSY: $m(\gamma_D) = 0.4$ GeV
- Dark SUSY prediction:
  - $\sigma(h) = \sigma(h_{SM})$
  - $Br(h \to 2n_1) = 1\%$
  - $Br(n \to n_D + \gamma_D) = 50\%$
  - $Br(\gamma_D \to 2\mu) = 45\%$