Search for beyond the Standard Model Higgs boson decaying to a pair of new light bosons in boosted dimuon final states

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on behalf of the CMS Collaboration

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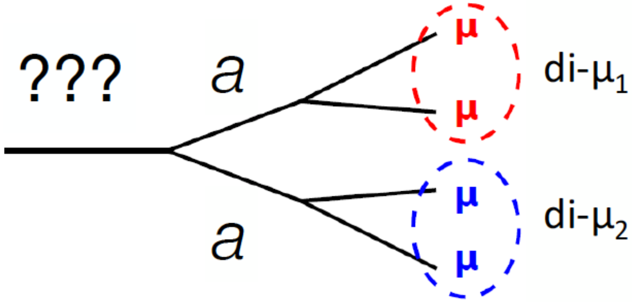
Overview

- Physics motivation
- Benchmark models
- The CMS detector at the LHC
- Datasets
- Event selection
- Standard model backgrounds
- Model independent results
  - Interpretation in benchmark scenarios: dark SUSY & NMSSM
- Conclusions & outlook

Physics motivation

- Search for non-SM Higgs boson which decays to new light bosons
  - $h \rightarrow 2a + X \rightarrow 4\mu + X$

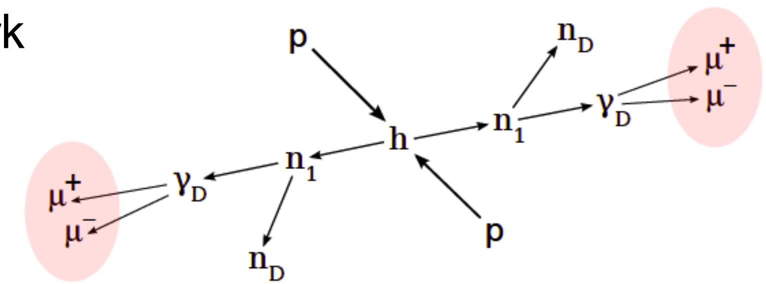


- Analysis is designed to be model independent
  - Can be used for a wide range of beyond the standard model scenarios for new light bosons, with boosted dimuons in event topology

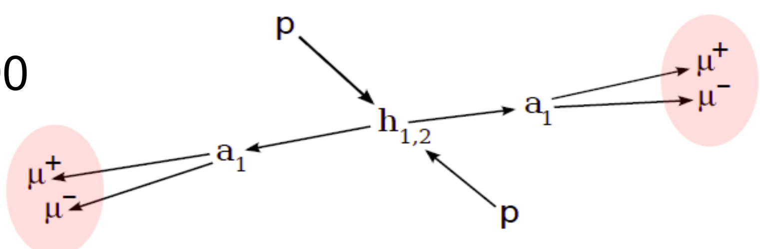
- We consider two BSM scenarios:
  - SUSY + dark sector (dark SUSY)
  - Next-to-minimal supersymmetric standard model (NMSSM)

Benchmark models

- Dark SUSY: Model a simplified dark sector $U(1)_D$ in SUSY
  - 125 GeV Higgs decays to lightest SUSY particle n_1 (neutralino)
  - n_1 decays to dark photon γ_D and a light dark neutralino n_D
  - Kinetic mixing between γ and γ_D
    - γ_D can decay to pair of muons (dimuon)
    - If γ_D is long-lived: displaced muons w.r.t IP
  - $m(\gamma_D)$ between 0.25 and 8.5 GeV
  - $m(n_1)$ = 10 GeV, $m(n_D)$ = 1 GeV

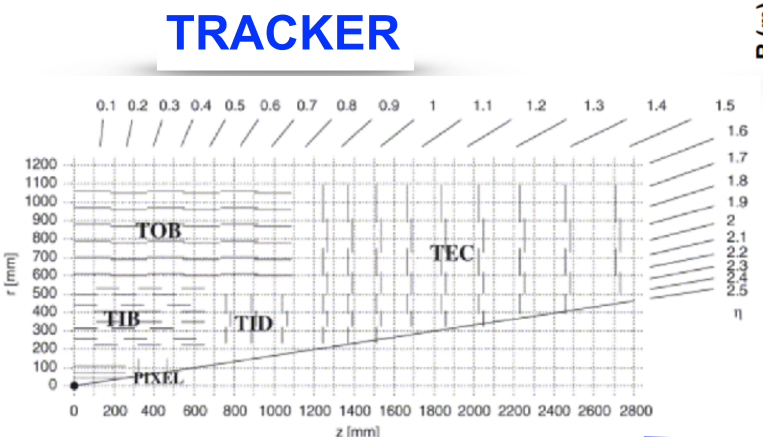


- NMSSM: we consider the model
  - CP-even Higgs $h_{1,2}$ with masses between 90 and 150 GeV
    - 125 GeV $h_{1,2}$ is the SM Higgs boson
  - CP-odd Higgs a_1 which decays to 2 muons
    - Masses between 0.25 and 3.55 GeV

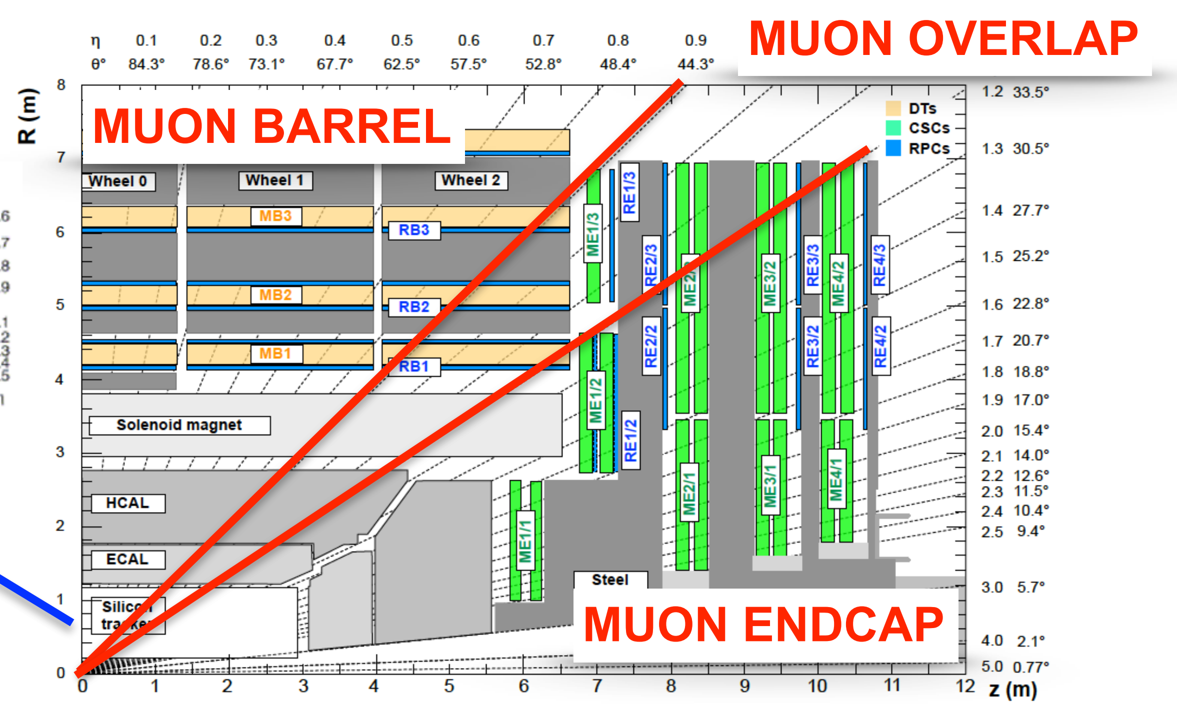


The CMS detector at the LHC

- Multi-purpose detector at LHC
- Excellent muon detection and reconstruction abilities
- This analysis uses information from tracker + muon system

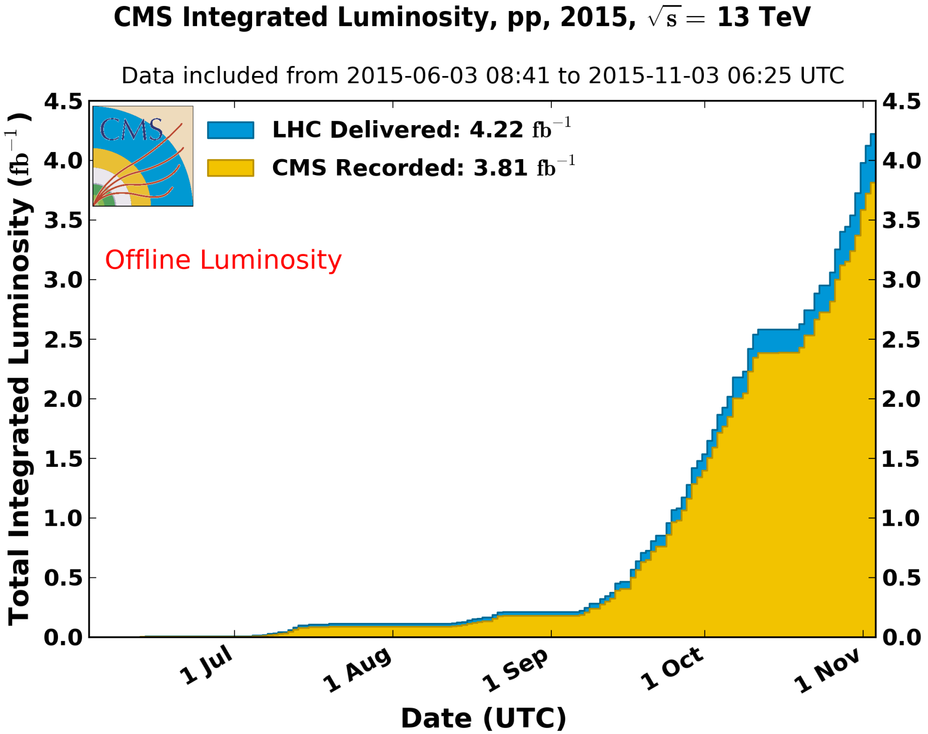


$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



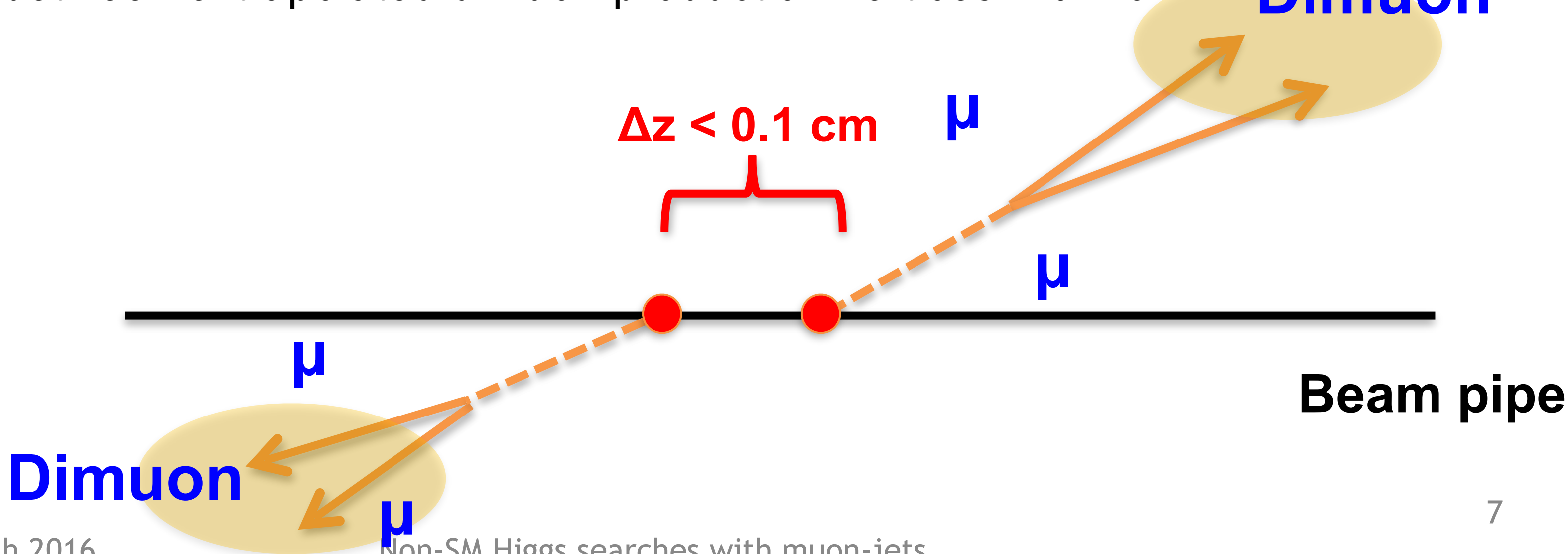
Datasets

- 2010: 35 pb^{-1} @ 7TeV 10.1007/JHEP07(2011)098
- 2011: 5.3 fb^{-1} @ 7TeV 10.1016/j.physletb.2013.09.009
- 2012: 20.7 fb^{-1} @ 8TeV 10.1016/j.physletb.2015.10.067
- **2015: 2.8 fb^{-1} @ 13TeV (2015): recently completed - This talk**
- 2016: analysis on 13TeV (2016) has started



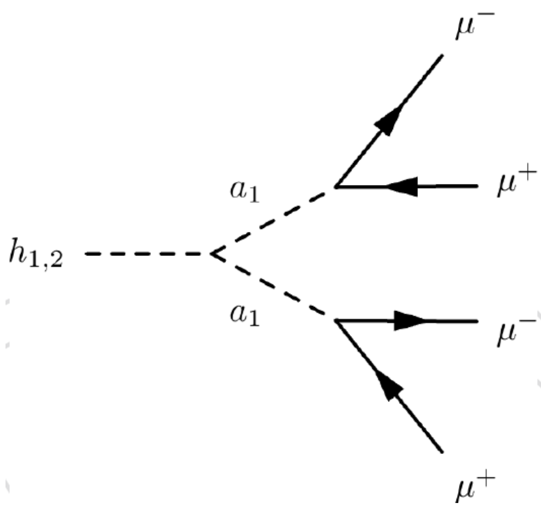
Event selection

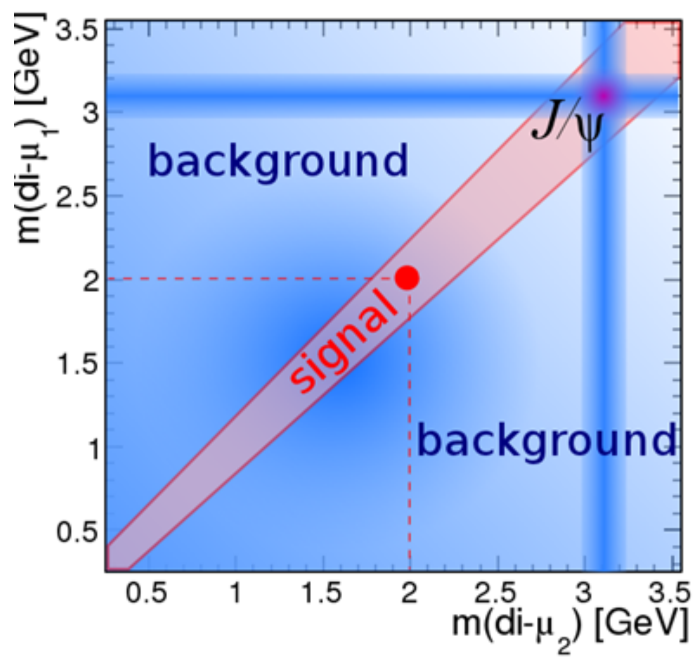
- **New in this analysis!** Online selection is done with a non-isolated triple-muon trigger
  - Requires at least 3μ, 1 with p_T > 15 GeV and 2 with p_T > 5 GeV
- Offline selection: 4μ with 8 GeV in |η| < 2.4, 1μ with 17 GeV in |η| < 0.9
- Nearby muons are clustered into dimuons if m(μμ) < 9 GeV and they satisfy either
  - Dimuon vertex from Kalman filter has vertex probability $P_{vertex}(\mu\mu) > 1\%$
  - $\Delta R(\mu\mu)<0.01$
- Require events with exactly 2 dimuons
  - No limit on number of unpaired muons
- Distance between extrapolated dimuon production vertices < 0.1 cm



Dimuon mass constraint

- Dimuons are produced in decay of same type of new light bosons



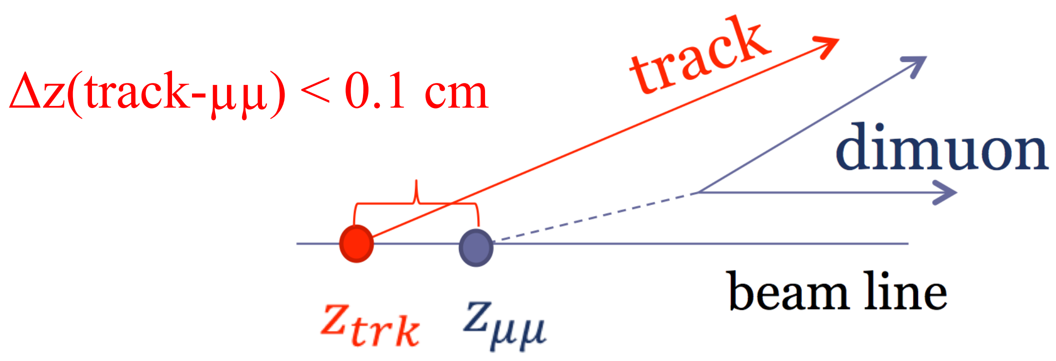


- Dimuon masses must be compatible
  – Diagonal mass corridor
    – $|m_{\mu\mu 1} - m_{\mu\mu 2}|$ < 5 x mass resolution
  – Use light SM resonances (ρ, ω, ϕ, J/ψ) to study mass resolution

Dimuon isolation

- Require low activity around dimuons
  - Select tracks with $p_T > 0.5$ GeV within $\Delta R<0.4$ and $\Delta z(\text{track-}\mu\mu) < 0.1$ cm
  - Tracks forming the dimuon are excluded
  - Require the total isolation < 2 GeV

$$Iso_{\mu\mu} = \sum_{tracks} p_T(track) < 2\,GeV$$

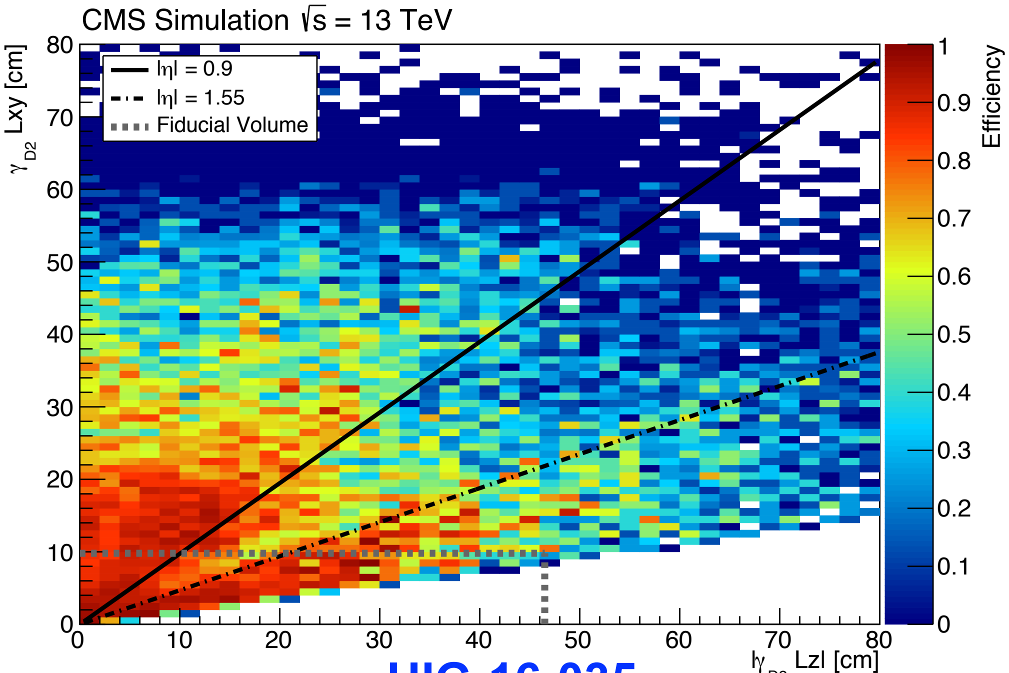


Fiducial search region

- Performance of online and offline muon reconstruction algorithms degrades with displacement due to
  - Fewer hits in tracker
  - Vertex that does not point back to IP
- These inefficiencies can introduce a model dependency in the analysis

- To mitigate this, we construct a fiducial region around the IP
  - Distance along z-axis between IP and dimuon vertex: $L_z <$ 46.5 cm (second pixel endcap)
  - Radial distance between IP and dimuon vertex: $L_{xy} <$ 9.8 cm (third pixel barrel)

- Plot shows $m(\gamma_D) = 0.25$ GeV (including all lifetimes)



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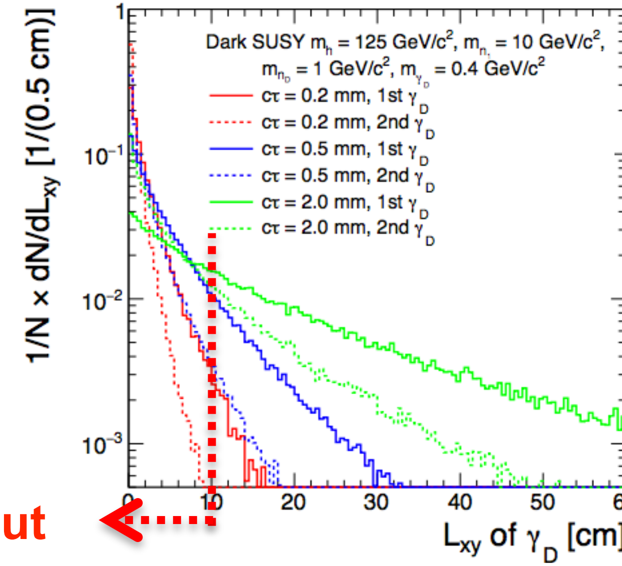
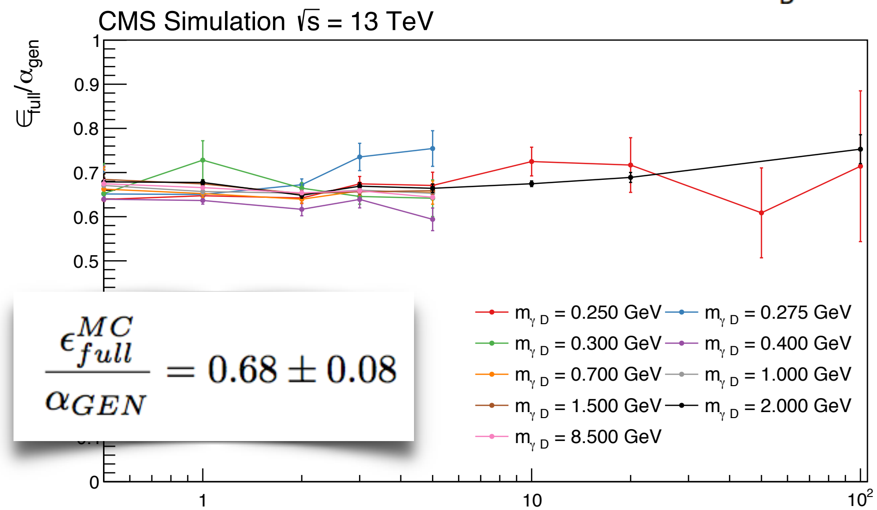
Efficiency over acceptance

- Even with L_{xy} < 9.8 cm, we are sensitive to various dark SUSY models

- The important quantity is ϵ/α:
  → Ratio of the number of events with 2 reconstructed dimuons (after full selection over the number of events with 2 generated light bosons (within fiducial volume)

- Flat ϵ/α: **0.68 ± 0.08**
  – Allows easy reinterpretation of the results in context of other models





$$\frac{\epsilon^{MC}_{full}}{\alpha_{GEN}} = 0.68 \pm 0.08$$

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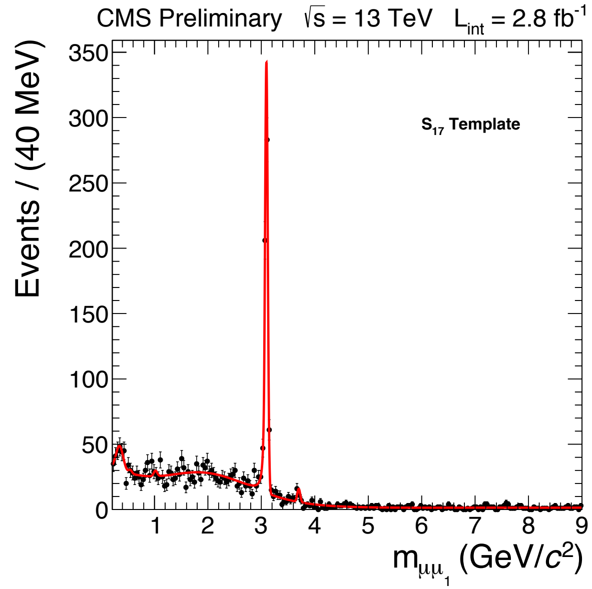
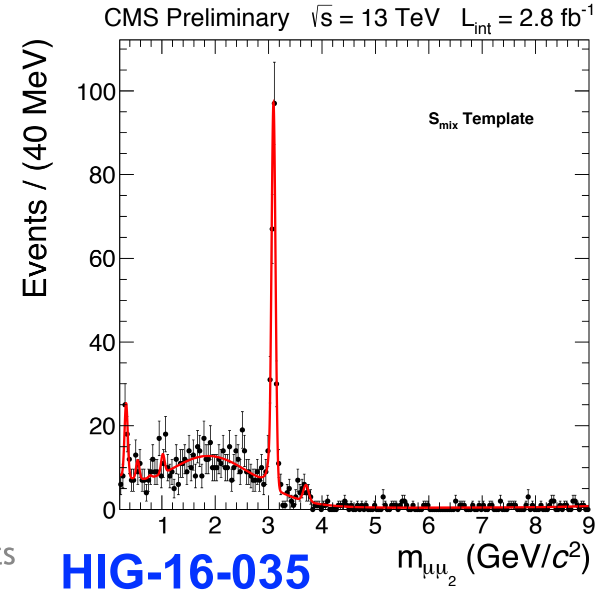
Background: QCD $pp \to b\bar{b} \to 4\mu$

- Both b quarks decay into a pair of muons, via semi-leptonic decay of b-quark and daughter c-quark, or via resonances (ρ, ω, ϕ, J/ψ)

- Determine from data
- Control sample: select events with exactly 1 dimuon and exactly 1 orphan muon (3μ)
  - Same trigger and similar offline selections
- Construct a 2 1D templates
  - The distributions are fit with sum of analytic functions:
    - Bulk shape is Bernstein polynomial
    - ρ, ω and ϕ resonances are modeled by Gaussian
    - J/ψ is modeled with Crystal ball function
- 2D template from cartesian product
- Scale the template; expected contribution in signal region: **$0.68^{+0.54}_{-0.32}$** events





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Background: QCD $pp \to$ *prompt* $2J/\psi \to 4\mu$

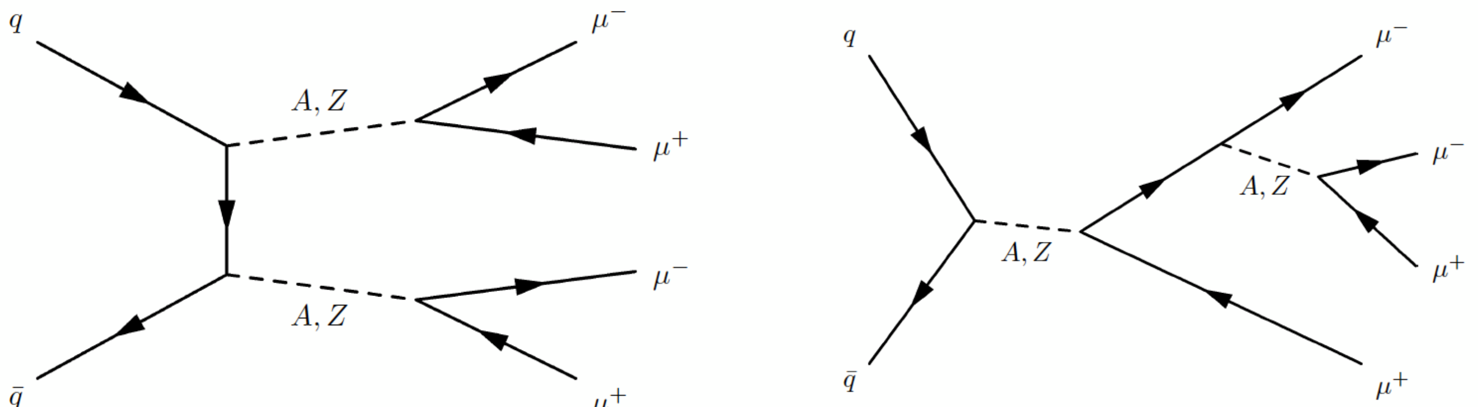
- Two sources of prompt J/ψ
  - Single Parton Scattering (SPS)
  - Double Parton Scattering (DPS)

- Method:
  - Select sample subset: 2.8 GeV ≤ m($\mu\mu$) ≤ 3.3 GeV
  - Separate the prompt from non-prompt contribution with the ABCD method
  - Fit SPS/DPS MC templates to prompt sample
  - Apply signal selection criteria to prompt sample

- Expected contribution in signal region:
  - SPS + DPS : **0.064 ± 0.020** events

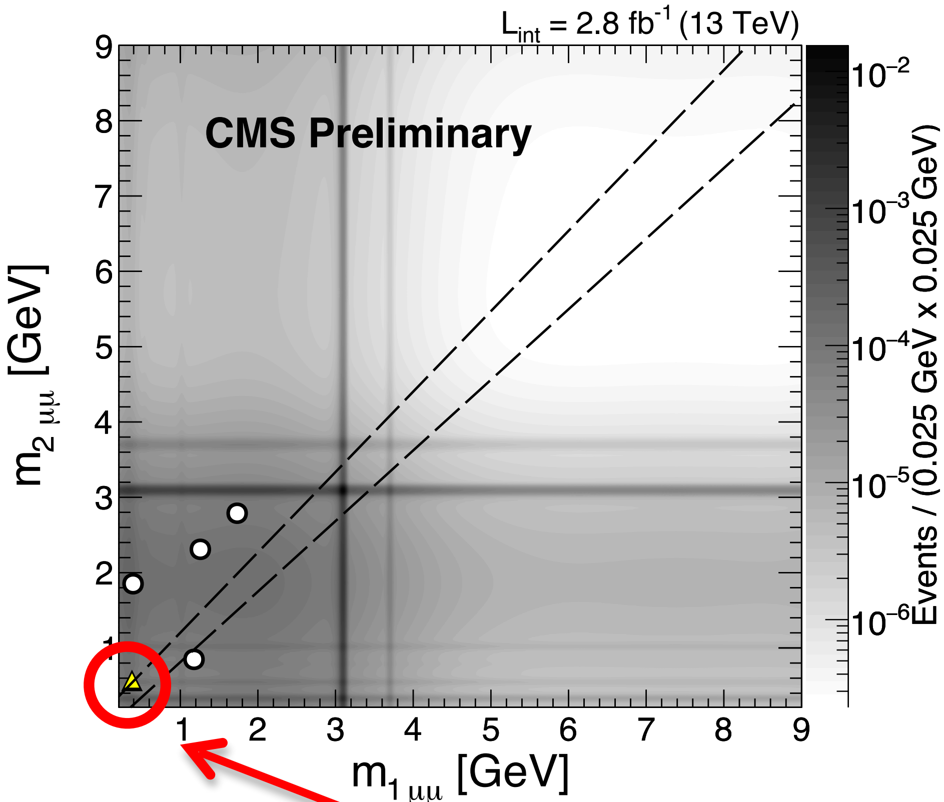
Background: EWK *pp* → *4μ*

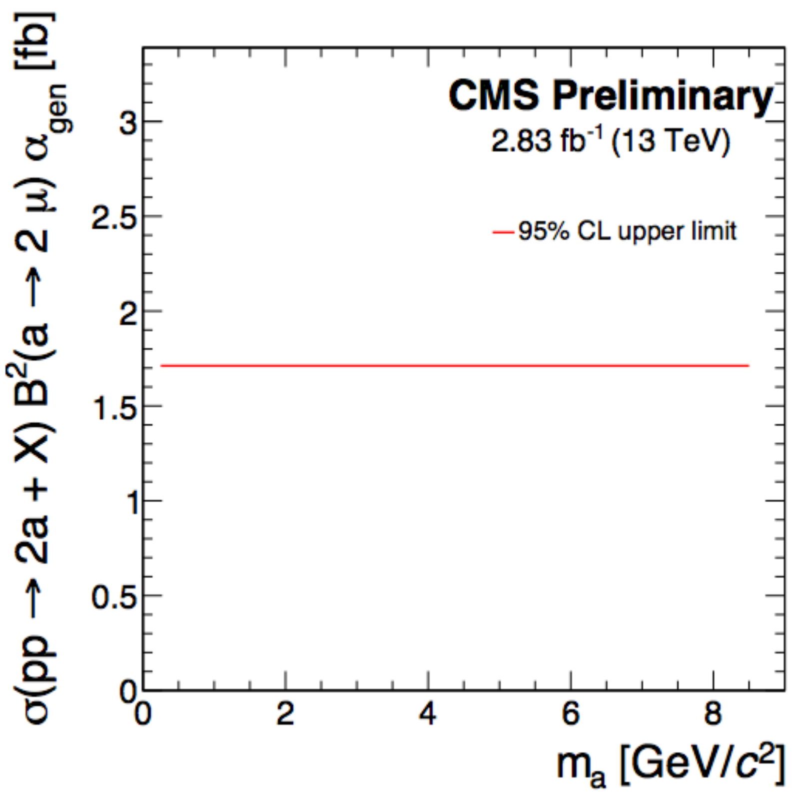
- Model the electroweak contribution to *pp* → *4μ* in MC simulation
  - Include the processes *qq* → *ZZ* → *4μ* (left) and *qq* → *Z* → *2μ*, with 2nd Z radiation (right)
  - Other processes are considered negligible
  - 0.036 ± 0.008 events over entire 2D mass plane
    - Expected contribution in signal region is **negligible**



Results

- After full event selection only one event survives in 2015 dataset
- Compatible with SM expectation: **0.74 ± 0.34 (stat.) ± 0.15 (syst.)**
- Model independent limit on σ(pp → 2a + X) x B^2(a → 2μ) x α_{GEN}





This is the one event that passed the full selection

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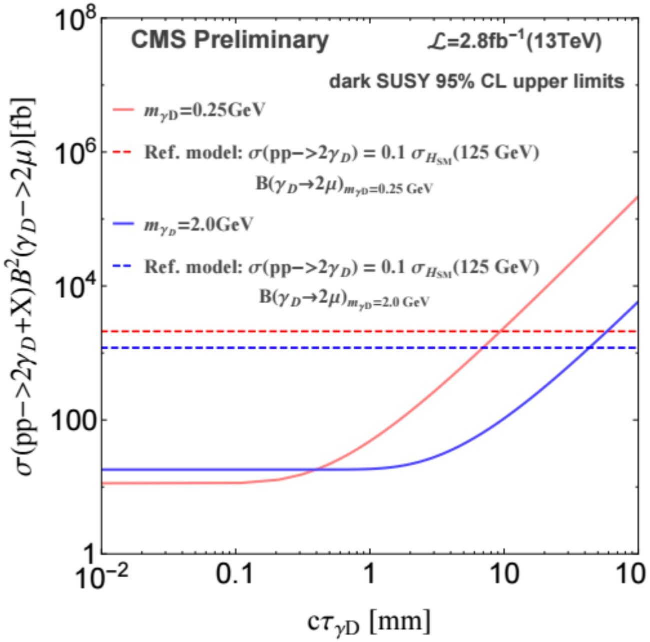
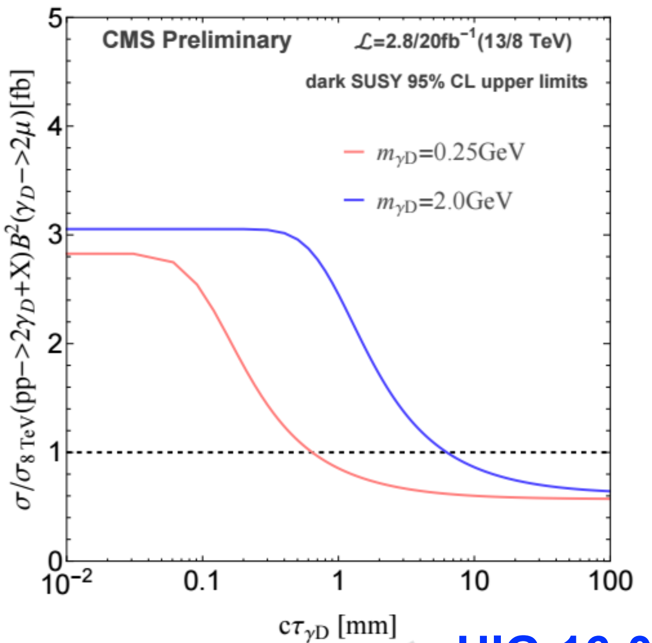
Benchmark scenario: dark SUSY

- Translate model independents limits into limits vs cτ (displacement)
  - Left: limits are compared to the predicted rate (dashed lines) obtained using a simplified scenario with $\sigma(pp \rightarrow 2\gamma_D) = 0.1 \times \sigma_{SM}$ (125 GeV) and $B(\gamma_D \rightarrow 2\mu)$ for 0.25 and 2 GeV mass points
  - Right: Comparison with 8 TeV results shows an improvement at intermediate/high cτ due to the enlarged fiducial region





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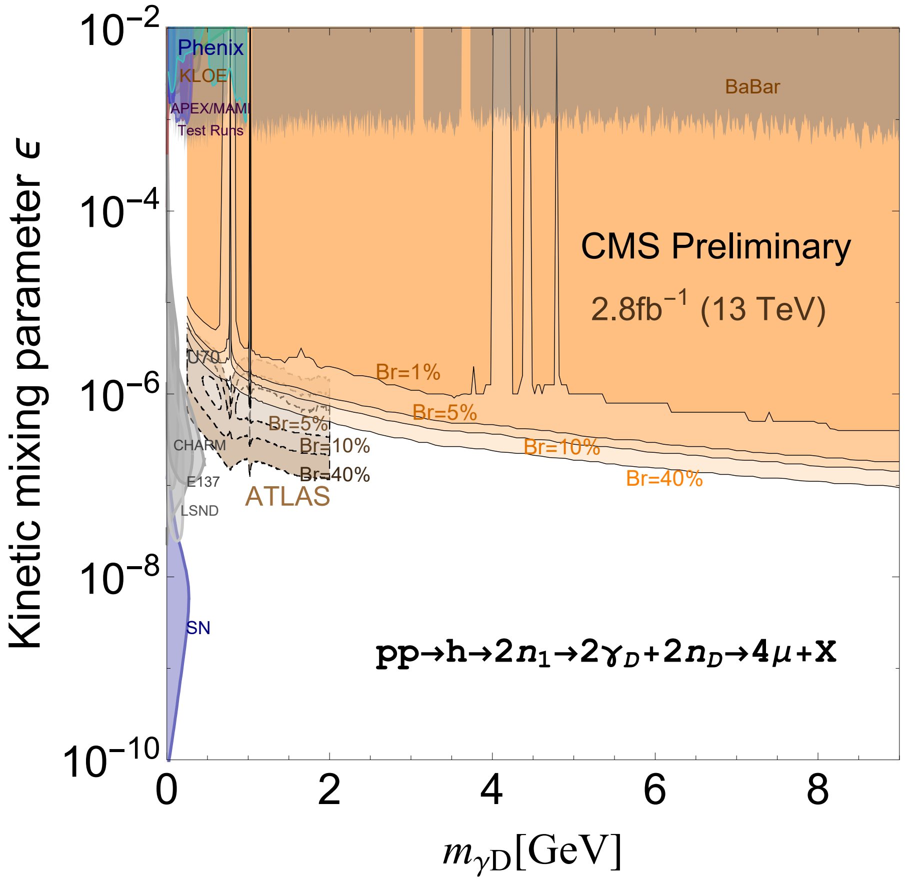
Benchmark scenario: dark SUSY

- **95% CL upper limits (black solid curves) on σ(pp→h→2γ_D + X) x B^2(h→2 γ_D + X) in plane of dark photon mass (m(γ_D)) and kinetic mixing parameter (ε)**
- Exclusion limits from other experiments shown as well
- Colored contours represent different values of B(h → 2 γ_D + X) in the range 0.1% to 40%



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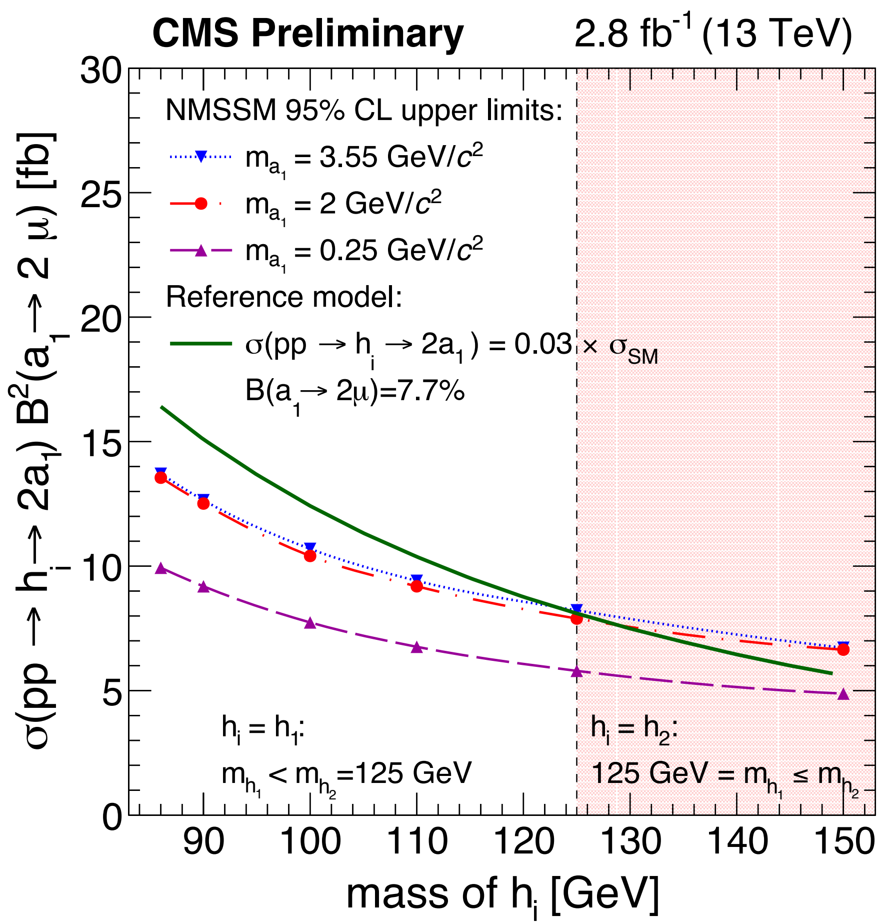
Benchmark scenario: NMSSM

- **95% CL upper limits as function of m_h on $\sigma(pp \rightarrow h_{1,2} \rightarrow 2a_1) \times B^2(a_1 \rightarrow 2\mu)$**
- Assume one of the two CP-even Higgs is LHC Higgs boson, then the other one is lighter or heavier
  - $\tan\beta = 20$
- Invisible BSM fraction (3%) was tuned such that model cross section intersects with blue line at 125 GeV
  - Much less than most recent CMS +ATLAS 95% CL upper limit (34%) JHEP 08 (2016) 045
- $B(a_1 \rightarrow 2\mu) = 7.7\%$ from theory
- Limit at each mass point is calculated as if **only source of signal events is CP-even Higgs** boson with corresponding mass



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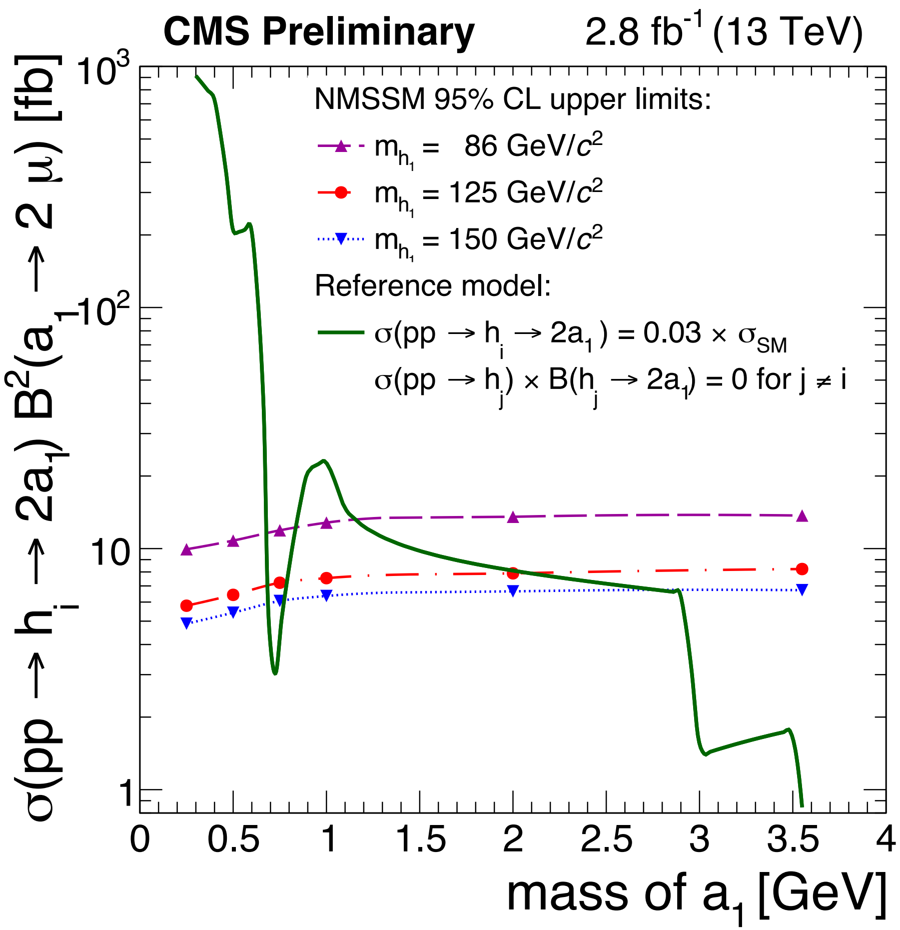
Benchmark scenario: NMSSM

- **95% CL upper limits as function of $m(a_1)$ on $\sigma(pp \rightarrow h_{1,2} \rightarrow 2a_1) \times B^2(a_1 \rightarrow 2\mu)$**
- Experimental limits (dashed curves) are compared to simple reference model (solid curve) on previous slide



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Conclusions & outlook

- A search for new light bosons decaying to prompt or displaced dimuons was presented
- 1 event observed in 2.8 fb^{-1} of 13 TeV Run-2 data consistent with SM expectation
  - 95% C.L. model independent limit is set
- Results can be used to set limits on a various models with same signature
- Interpreted in the context of 2 benchmark scenarios:
  - dark SUSY and NMSSM
- Analysis is being continued on 2016 Run-2 dataset

Backup slides

Kinetic mixing parameter

- Ctau is related to kinetic mixing parameter in following way:

$$c\tau_{\gamma_D}(\epsilon, m_{\gamma_D})[mm] = \frac{1.97 \cdot 10^{-13}[GeV \cdot mm]}{\epsilon^2} \times f(m_{\gamma_D})[GeV^{-1}],$$

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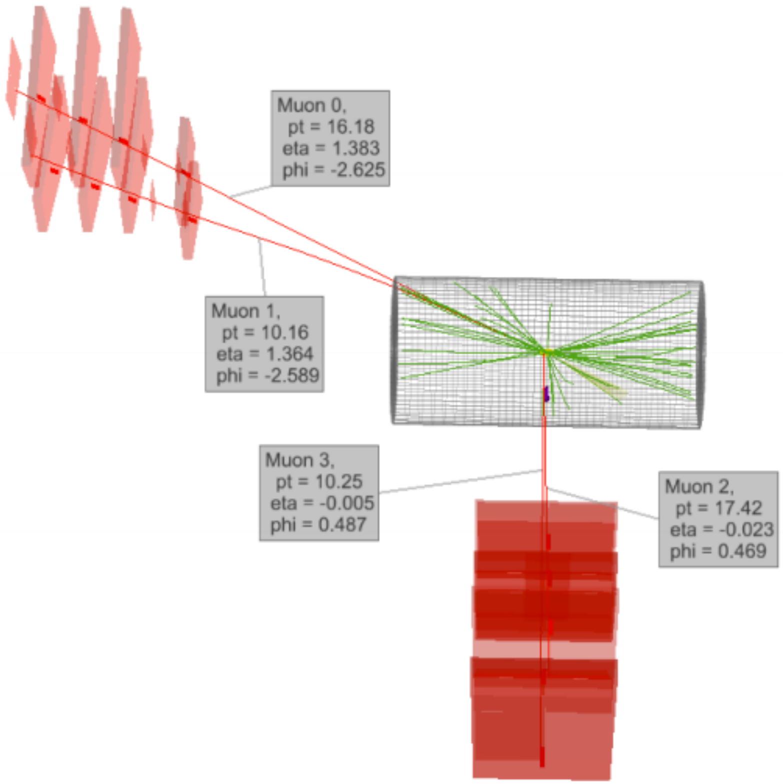
Event display



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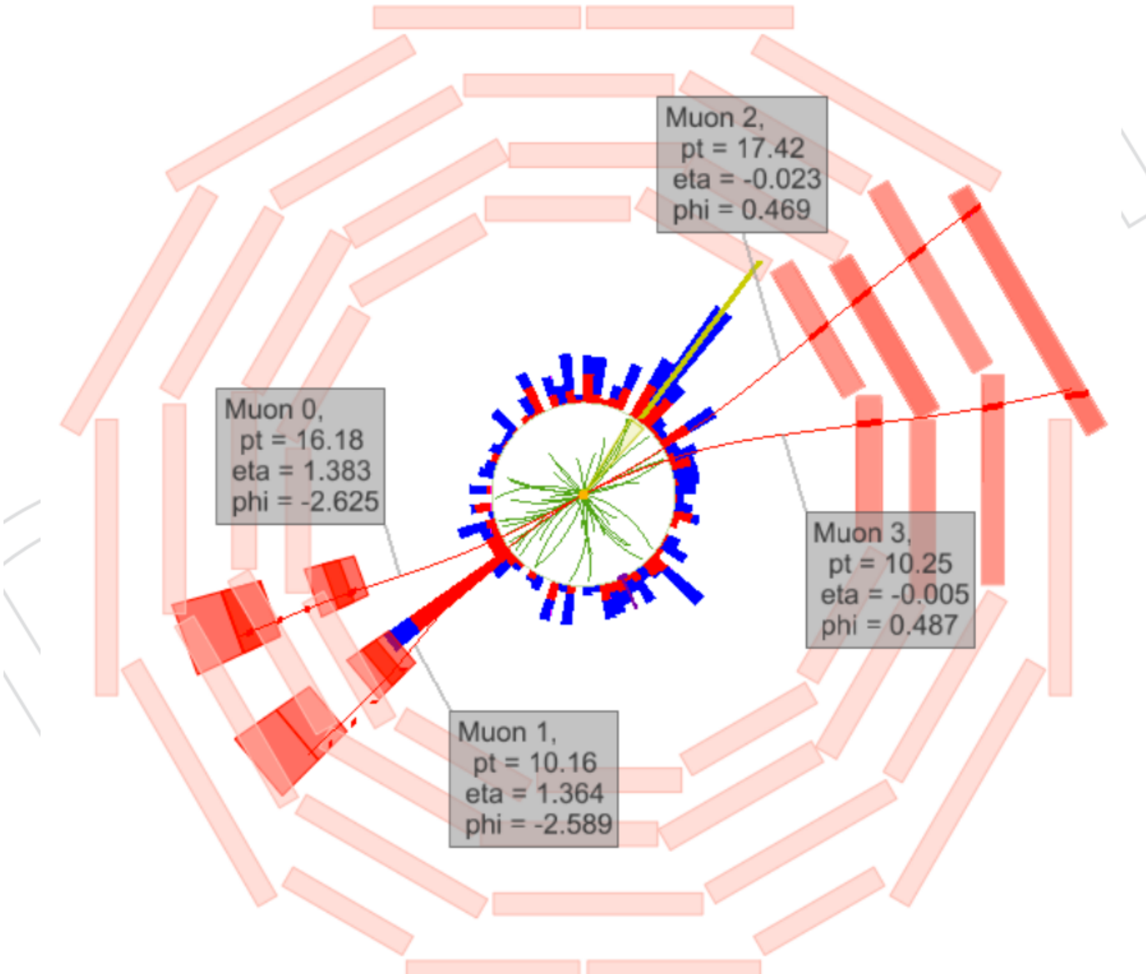
Event display

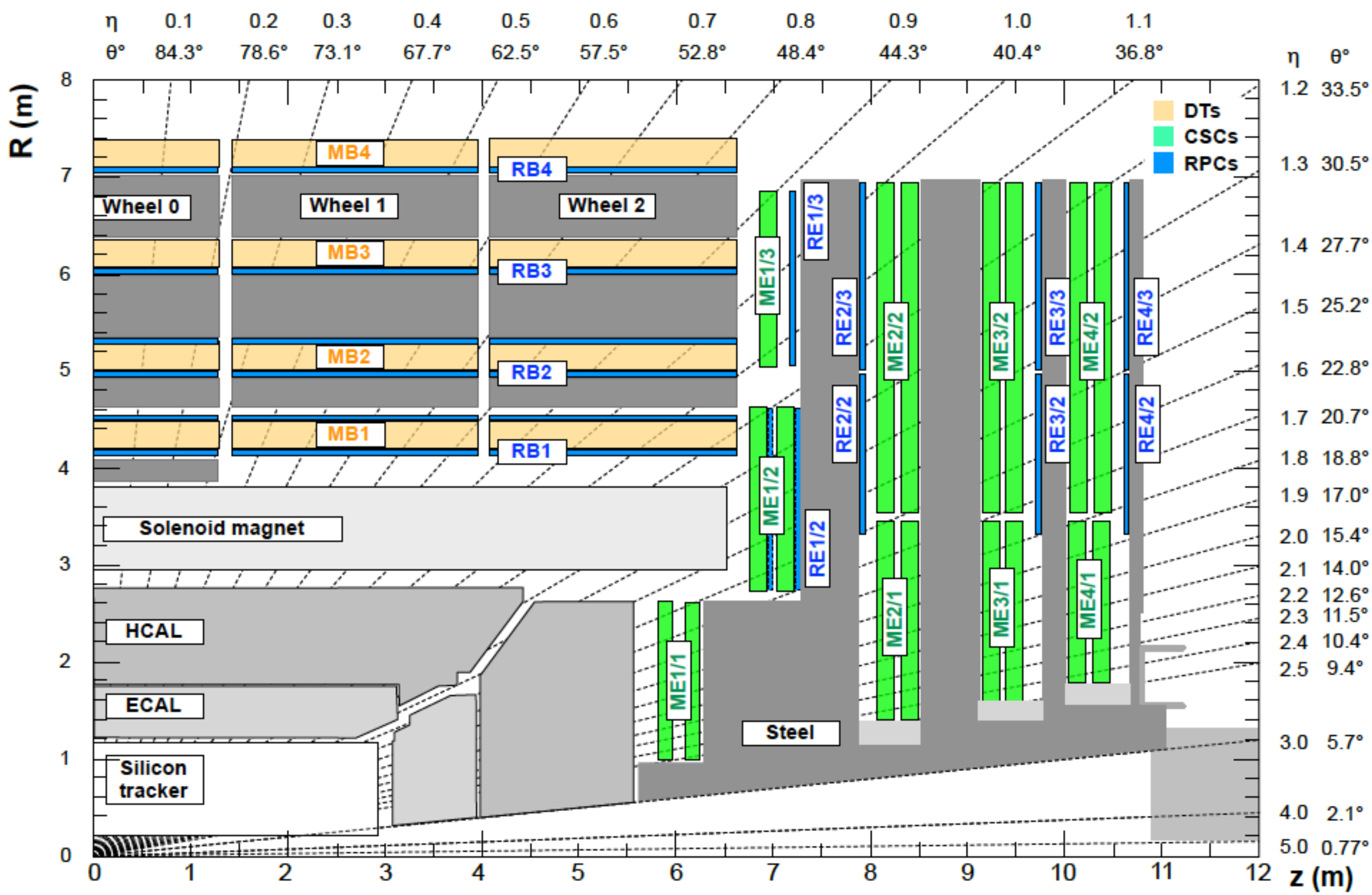


Systematic uncertainties

Table 9: Summary of the magnitude of systematic uncertainties.

Source of uncertainties	Error, %
Integrated luminosity	2.7%
Muon HLT	3%
Muon ID	$4 \times 1\%$
Muon tracking	$4 \times 0.2\%$
Di-muon isolation	$2 \times 1\%$
Overlapping in Tracker	$2 \times 1.2\%$
Overlapping in Muon System	$2 \times 1.3\%$
Pile-up	1.6%
Dimuons mass consistency	1.5%
NNLO Higgs p_T re-weighting	2.0%
PDF+α_s	3.0%
Total	11.1%

CMS in Run-2



η
θ°
0.1
84.3°
0.2
78.6°
0.3
73.1°
0.4
67.7°
0.5
62.5°
0.6
57.5°
0.7
52.8°
0.8
48.4°
0.9
44.3°
1.0
40.4°
1.1
36.8°
1.2 33.5°
1.3 30.5°
1.4 27.7°
1.5 25.2°
1.6 22.8°
1.7 20.7°
1.8 18.8°
1.9 17.0°
2.0 15.4°
2.1 14.0°
2.2 12.6°
2.3 11.5°
2.4 10.4°
2.5 9.4°
3.0 5.7°
4.0 2.1°
5.0 0.77°
R (m)
z (m)
DTs
CSCs
RPCs
MB4
MB3
MB2
MB1
RB4
RB3
RB2
RB1
Wheel 0
Wheel 1
Wheel 2
Solenoid magnet
HCAL
ECAL
Silicon tracker
Steel
ME1/1
ME1/2
ME1/3
RE1/2
RE1/3
ME2/1
ME2/2
RE2/2
RE2/3
ME3/1
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RE3/2
RE3/3
ME4/1
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RE4/2
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