A Search for BSM Light Bosons Decaying to Muon Pairs

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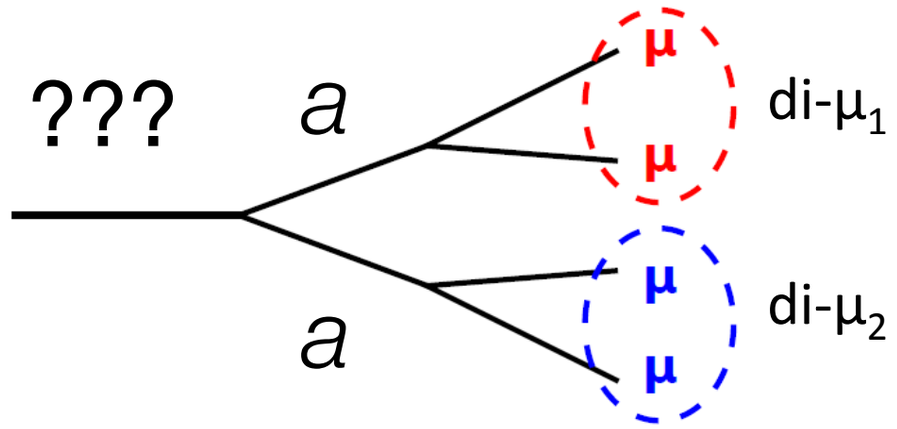
Physics Motivation

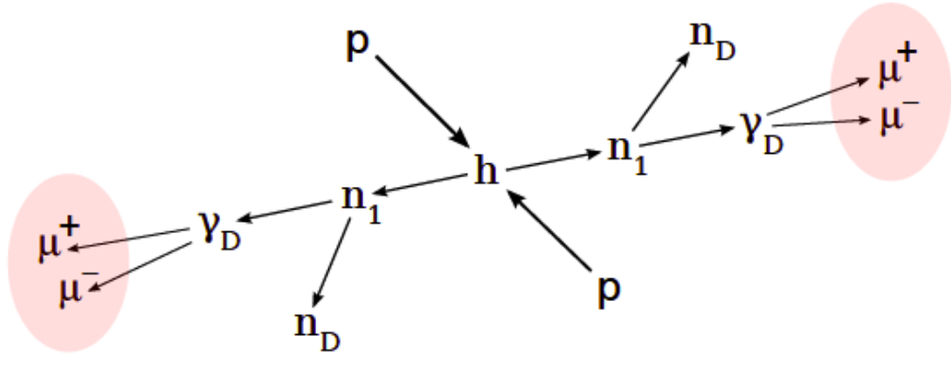
- We look for a new light boson "*a*"
- Signature is
  $??? \rightarrow 2a + X \rightarrow 2\mu + 2\mu + X$
  - signature is only dependent on muon pairs
  - open to many models/signatures



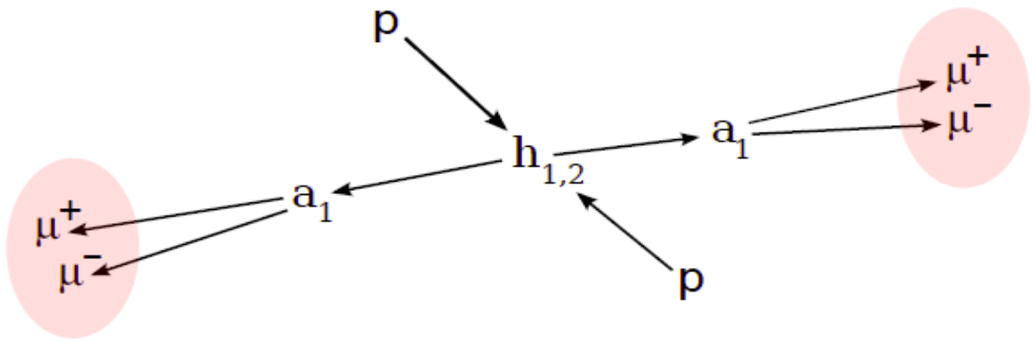
- Exciting possibilities: $h \rightarrow ??? \rightarrow 2a + X \rightarrow 2\mu + 2\mu + X$

Benchmark Models

- Dark SUSY
  - can have 125 GeV Higgs
  - Higgs decays to lightest 'visible' neutralino (n_1)
  - n_1 decays to dark photon (γ_D) and light hidden neutralino (n_D)
  - γ_D decays to $\mu\mu$
  - dark photon is possibly long-lived

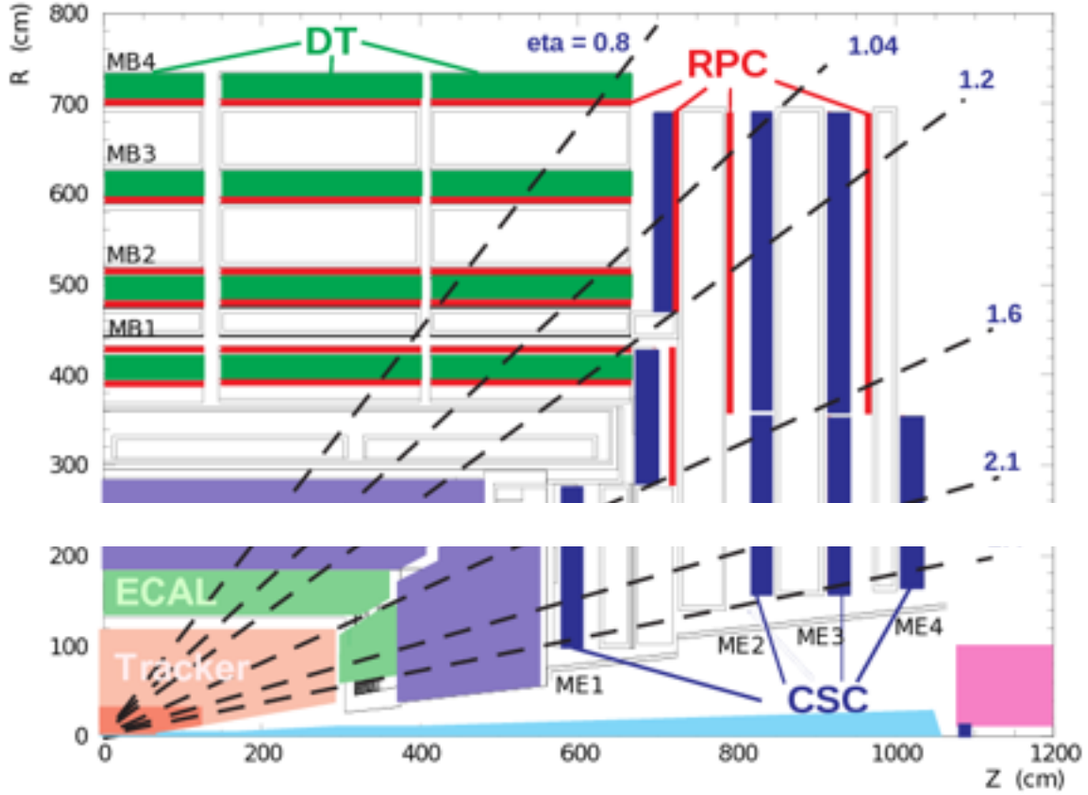


- NMSSM
  - predicts multiple CP-even Higgs ($h_{1,2,3}$)
    - $h_{1,2}$ could be consistent with 125 GeV Higgs
  - also predicts CP-odd Higgs (a_1, a_2)
    - could couple to SM leptons
  - can see decay of $h_{1,2}$ to a_1 to $\mu\mu$



Event Selection

- Trigger on ≥ 2 muons, p_T >17 GeV and p_T > 8 GeV
- Require ≥ 4 muons ID'd with Particle Flow algorithm [1]
  - must be either the Tracker or Global algorithms
  - 1 muon in the barrel (|η| < 0.9) with p_T > 17 GeV
  - 3 muons in the barrel or endcaps (|η| < 2.4) with p_T > 8 GeV



Longitudinal diagram of CMS detector [2]

Event Selection

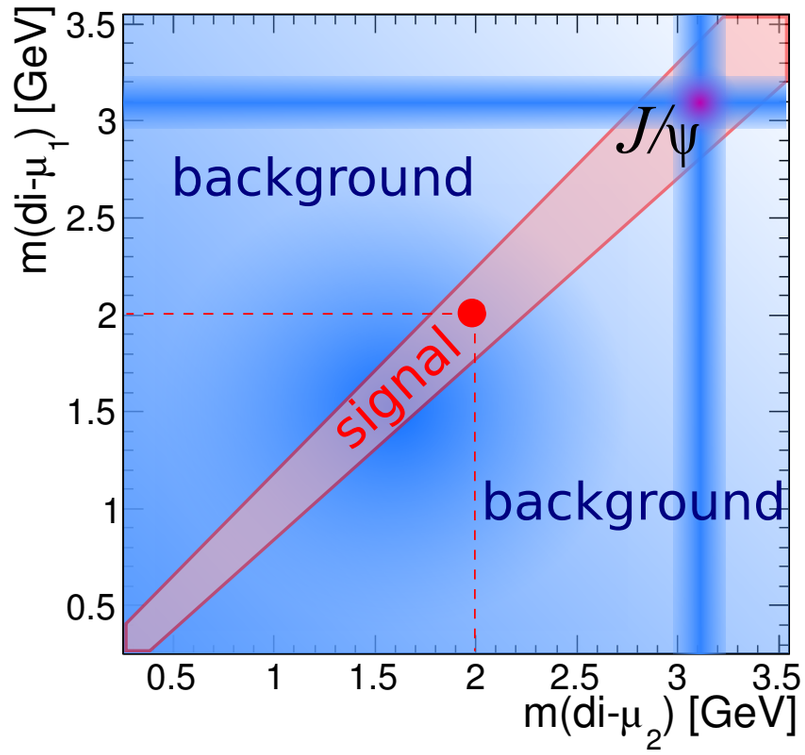
- Group into muon pairs
  - opposite charge
  - tracker tracks have vertex probability > 1% or $\Delta R(\mu^+\mu^-) < 0.01$
  - invariant mass of pair < 2 GeV

- Define dimuons
  - look for muon pairs that do not have any muons in common with other muon pairs
  - classify pairs as “dimuons”
  - note: unpaired muons / muon pairs with muons in common are allowed in event

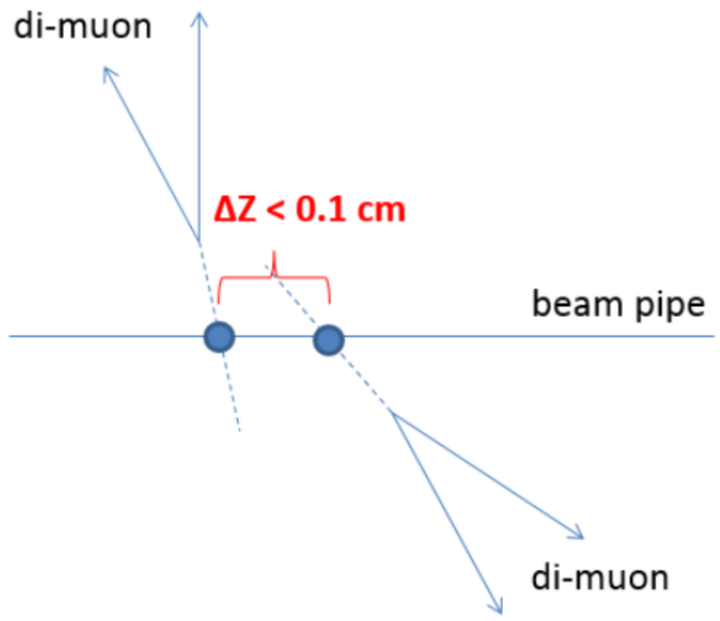
Offline Selection

Dimuons have the same parent particle type, therefore:

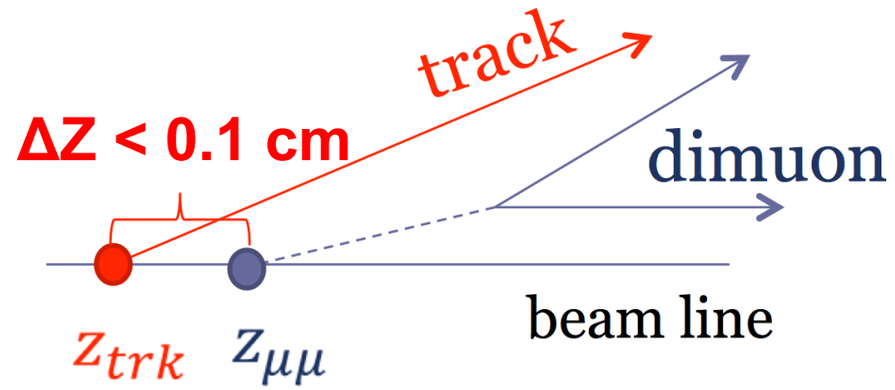
- Same invariant mass
  - criteria based on detector resolution
  - $|\Delta m_{\mu\mu}| < (0.13 + 0.065(m_{\mu\mu 1} + m_{\mu\mu 2})/2)$
  - 5x resolution of $m_{\mu\mu}$ measurement
  - also defines the signal region



- Common vertex
  - $\Delta z = |z_{\mu\mu 1} - z_{\mu\mu 2}| < 0.1$ cm



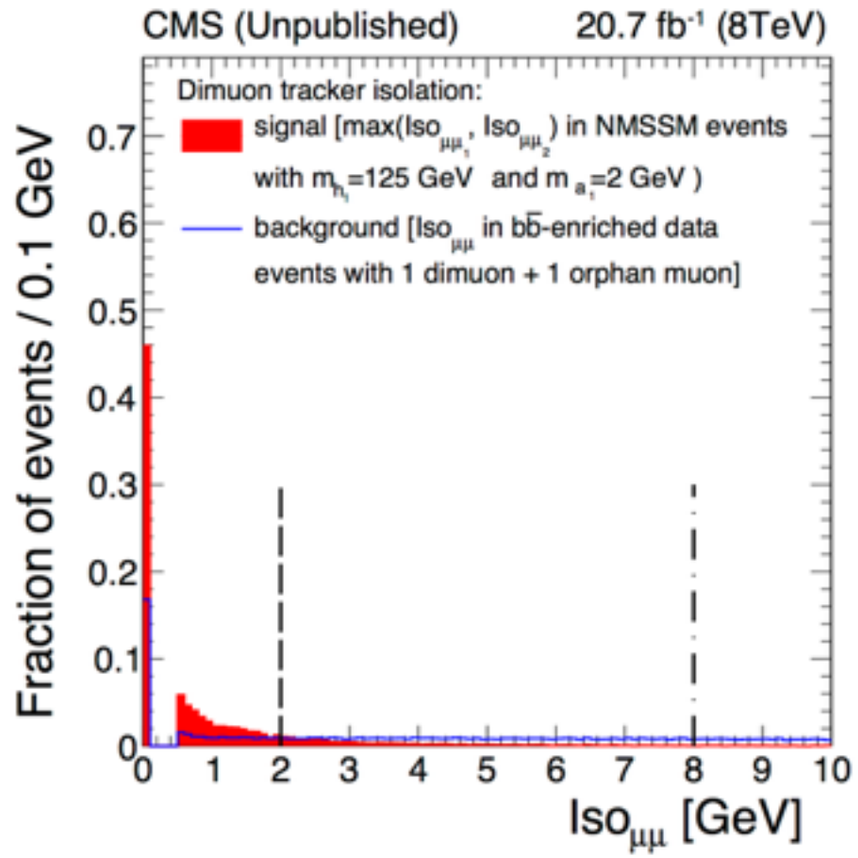
Offline Selection



- Isolation cut

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

- sums over all reconstructed tracks
  - p_T(tracks) > 0.5 GeV
  - ΔR(track, $\mu\mu$) < 0.4
  - $|z_{track} - z_{\mu\mu}| < 0.1$ cm
  - tracks forming dimuon are excluded



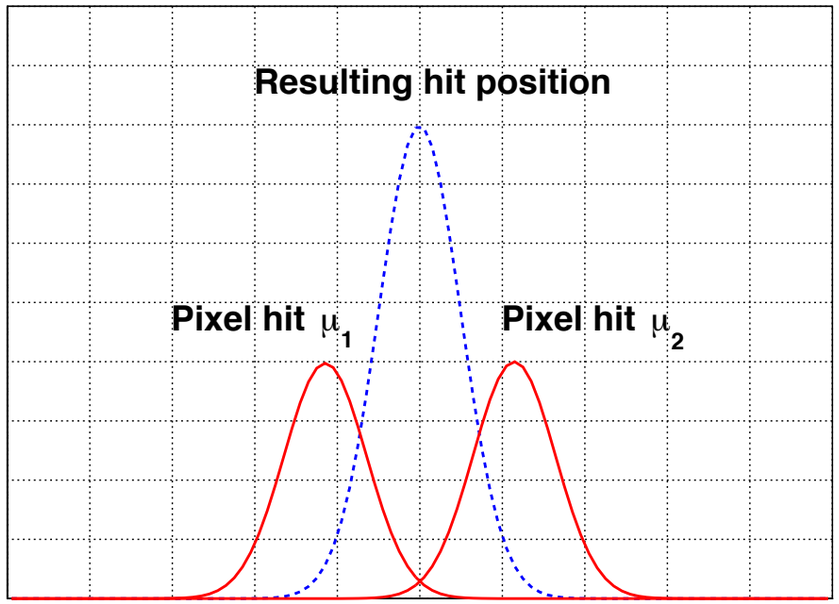
Histogram from Ref [3]

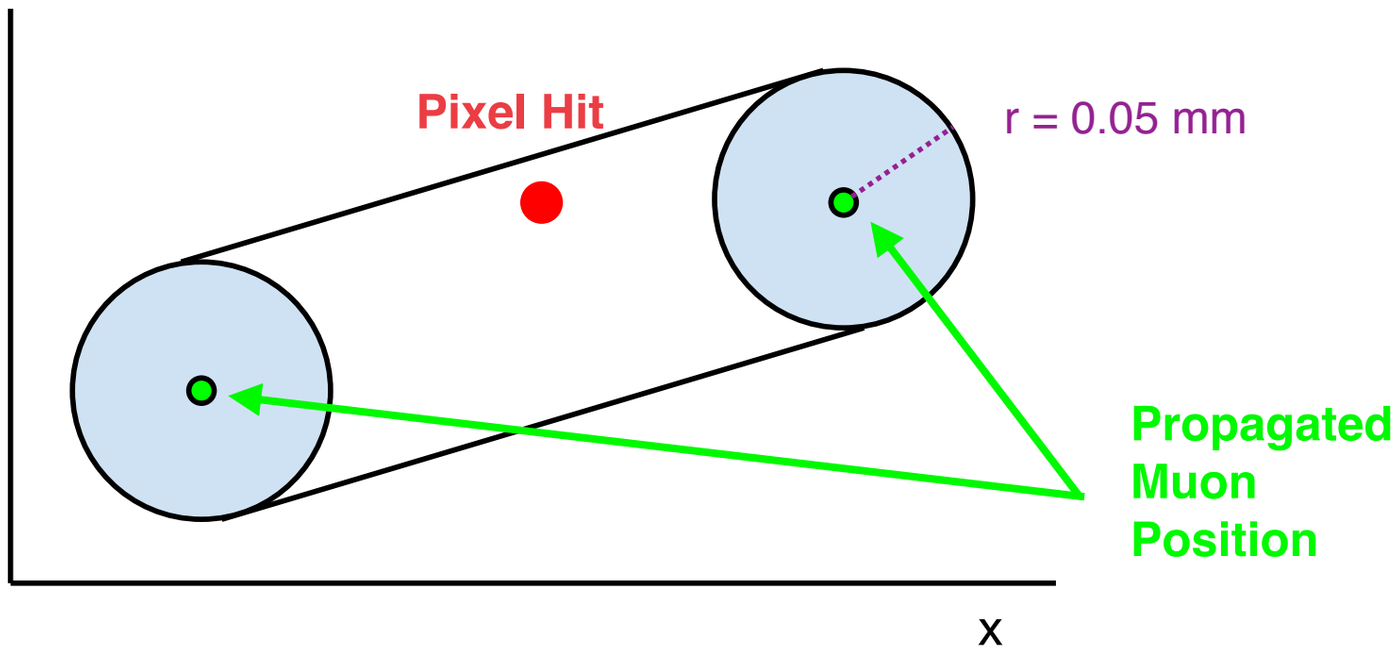
Vertex Finding

- Vertex finding is critical
  - required for selecting muon pairs
  - needed for valid dimuons
- Vertex finding is also challenging
  - muons can have small separation & nearly parallel tracks
  - dimuons are highly boosted
  - long displacement from IP if new boson is long-lived
- Vertex finding techniques
  - initial attempt with Kalman fitter to find a dimuon vertex
  - if Kalman fails:
    - use point of muon tracks' distance of closest approach as the dimuon's vertex
    - recalculate the dimuon's kinematics
  - improvement seen for low-mass dimuons

Pixel Hit Recovery

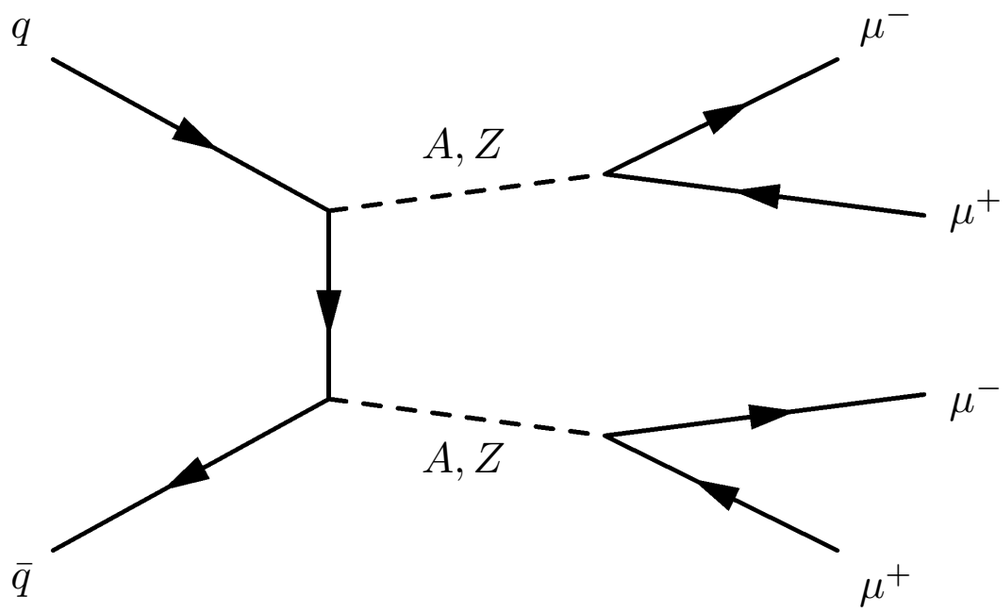
- Lost events with dimuons
  - fiducial volume extends to first pixel layer
  - two spatially close, parallel track muons may create a single pixel hit
  - the single pixel hit might not be assigned to either muon
  - the event, without muon with 1st pixel layer hit, is rejected

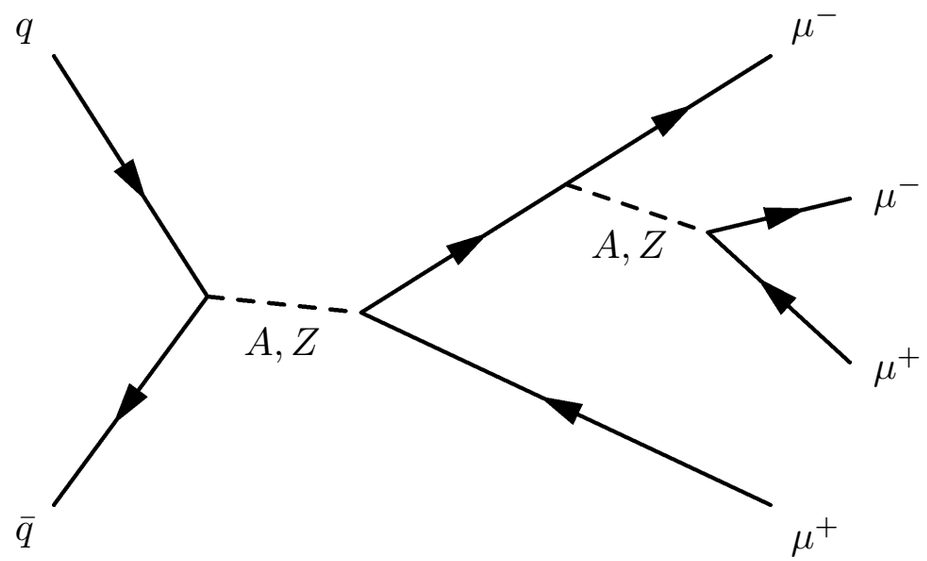




- Pixel hit recovery
  - use muon track trajectory info to propagate back to 1st pixel layer
  - define a 0.05 mm radius about the propagated muon position
  - look in circumscribed region areas for pixel hit, recover event if found

Background: EWK $pp \rightarrow 4\mu$

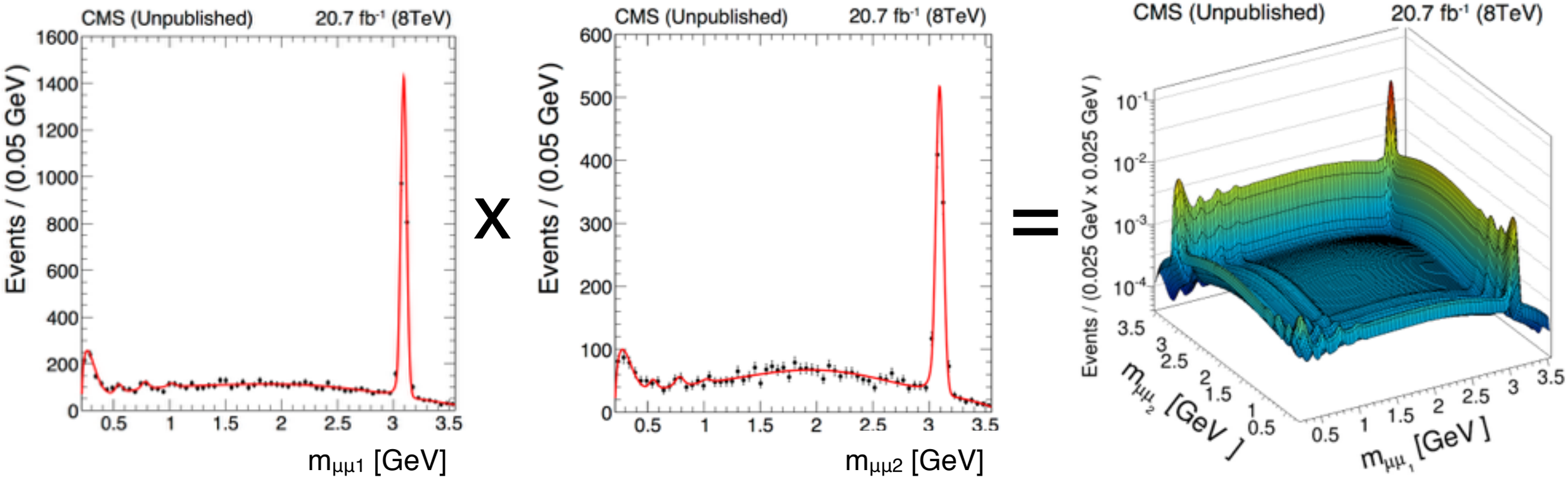




- Modeled electroweak $pp \rightarrow 4\mu$
  - included $qq \rightarrow ZZ \rightarrow 4\mu$ (left) and $qq \rightarrow Z \rightarrow 2\mu$ with 2nd Z (right)
  - other processes were negligible (<1 per million)
  - expected contribution in signal region < 0.15 ± 0.03 events

Background: QCD pp→bb̄→4μ

Make a template via Cartesian product:



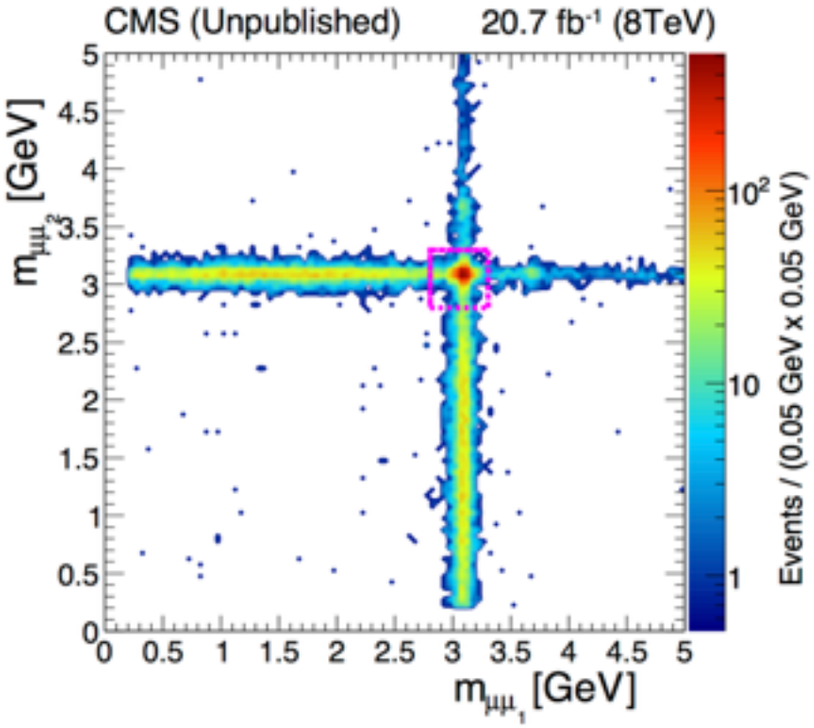
- Distributions fit with analytic functions
  - bulk shape is Bernstein polynomial
  - η, ω, and ϕ resonances are Gaussians
  - J/ψ is a Crystal Ball

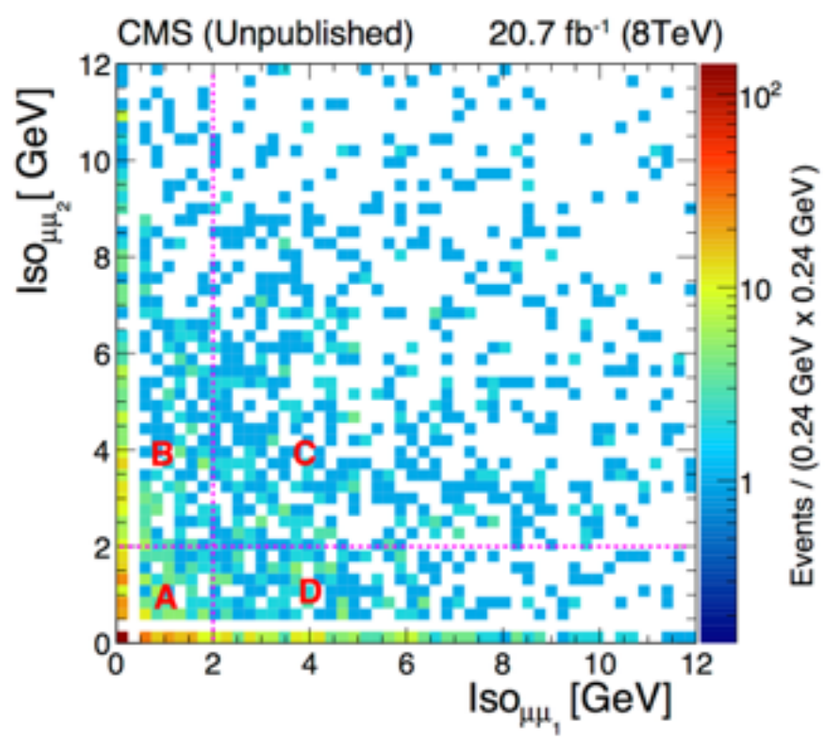
All figures from Ref [3]

- Scale template; signal region contribution is 2.0 ± 0.7 events

Background: QCD Prompt pp $\rightarrow 2J/\Psi \rightarrow 4\mu$

- Previous $b\bar{b}$ background elimination leaves prompt J/ψ
- Two sources of prompt J/ψ
  - Single Parton Scattering (SPS)
  - Double Parton Scattering (DPS)
- Methodology
  - select subset (2.8 GeV ≤ $m_{\mu\mu}$ ≤ 3.3 GeV)
  - separate prompt from non-prompt (ABCD method)
  - fit SPS/DPS MC templates to prompt sample
  - apply selection criteria to prompt samples
- Results
  - DPS: 0.008 ± 0.008 events
  - SPS: 0.050 ± 0.031 events





All figures from Ref [3]

Run I Result

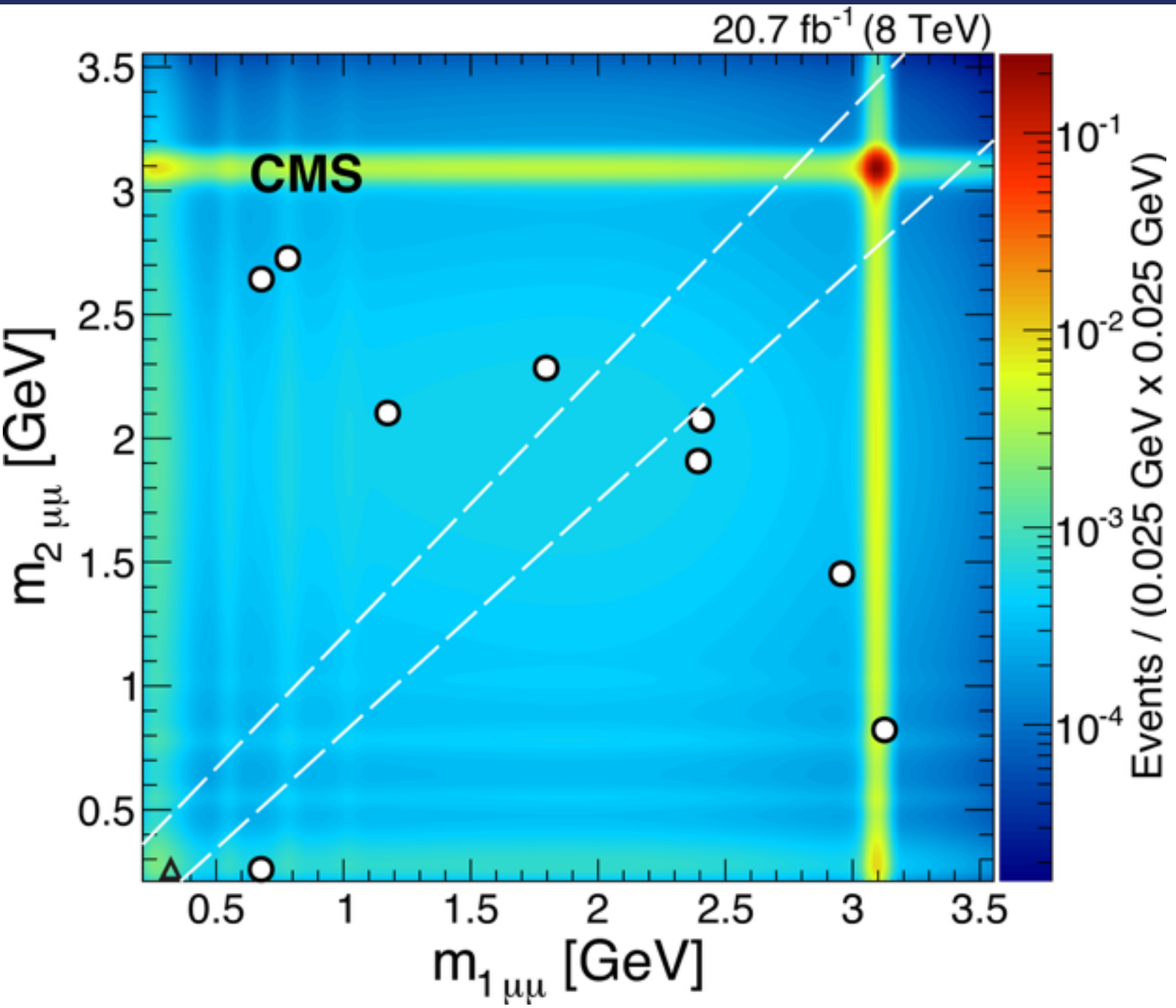
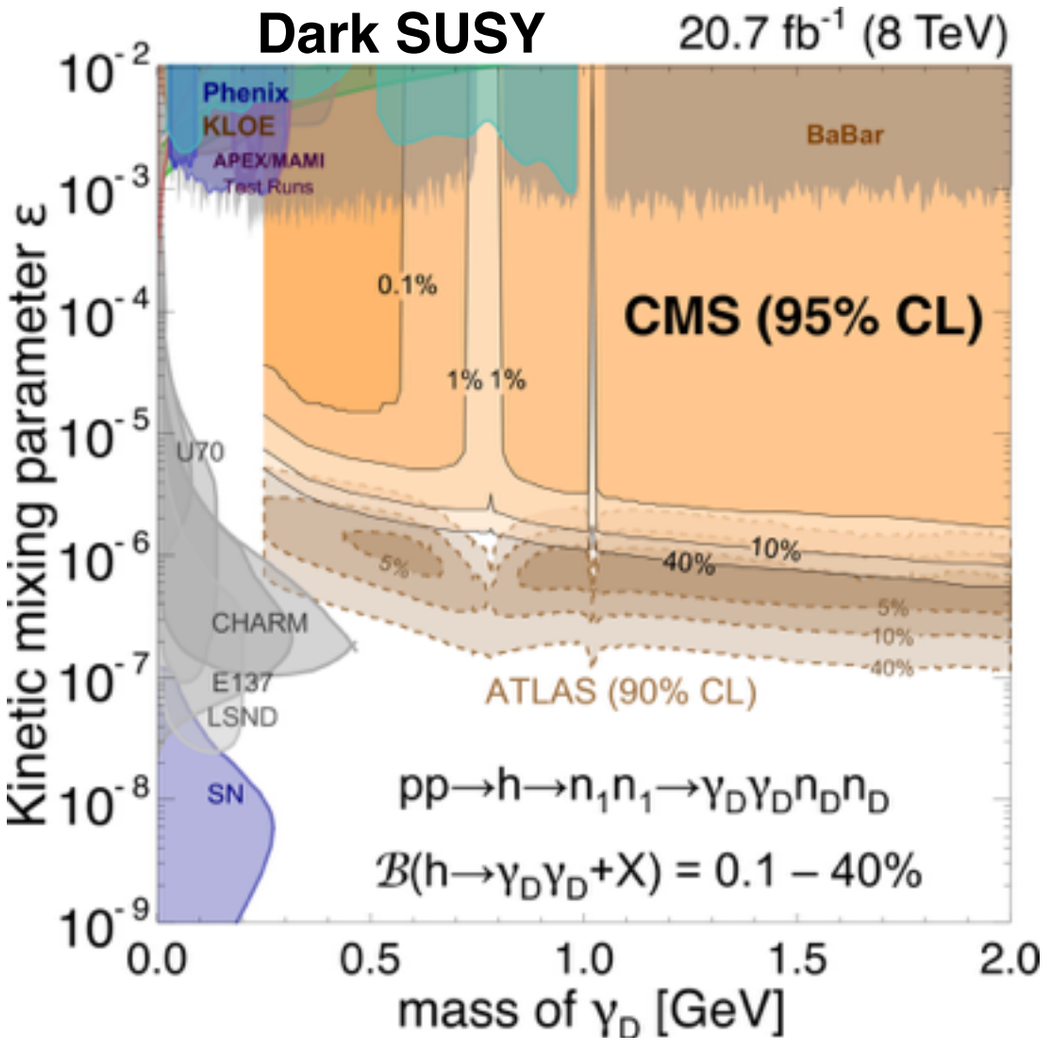
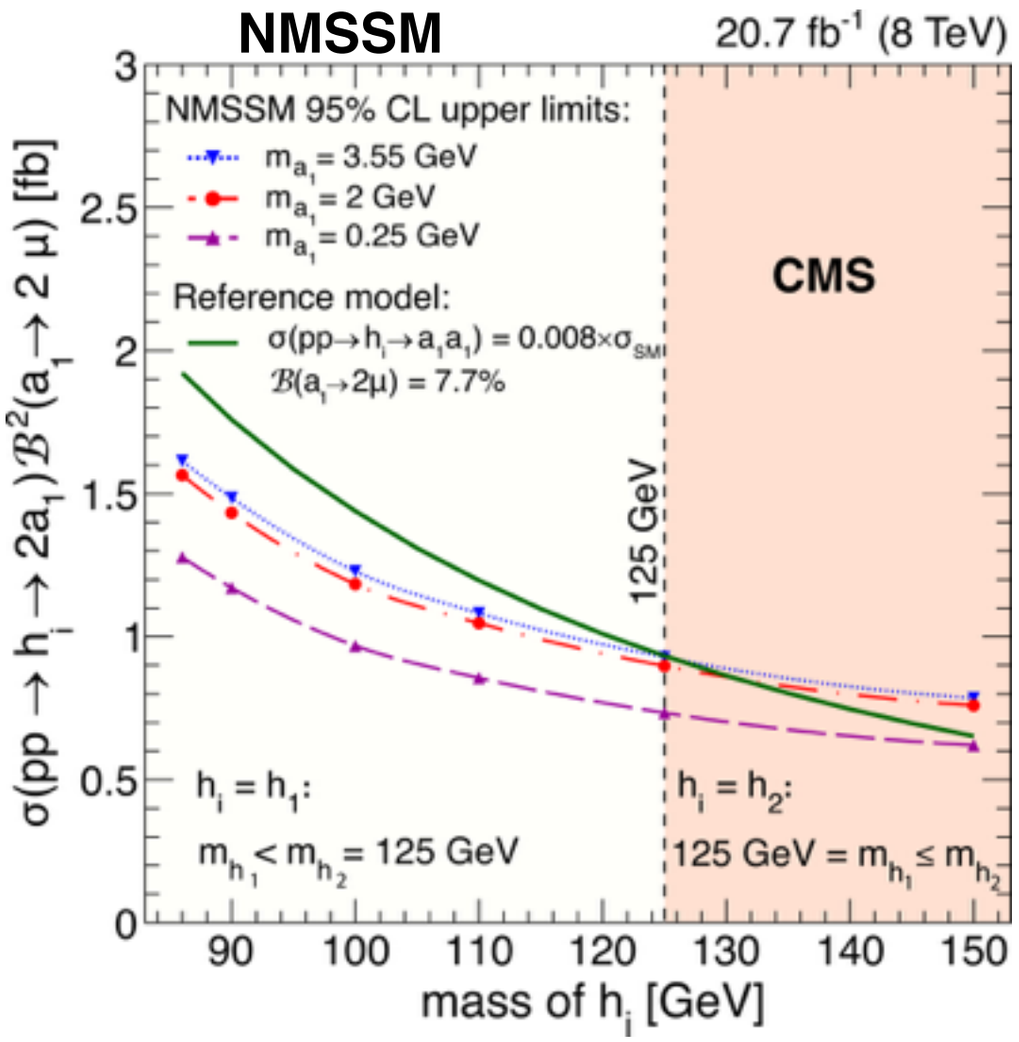


Figure from Ref [3]

- Total Background (EWK + J/ψ + $b\bar{b}$): 2.1 ± 0.7 events
- One event seen in signal region, consistent with no signal

Run I Result Interpretation





All figures from Ref [3]

- Dark SUSY
  - Areas covered by CMS and ATLAS are complementary
- NMSSM:
  - “conservative” upper limits for more general model parameters
  - plot for different relative masses of h_1, h_2; a_1

Conclusion

- Model-independent search has exciting opportunities for discovery and model elimination
- Number of events seen in Run I (8 TeV) consistent with no signal
- Run I results interpreted in the context of multiple models
- Running again on Run II (13 TeV) data in 2016

Cited References

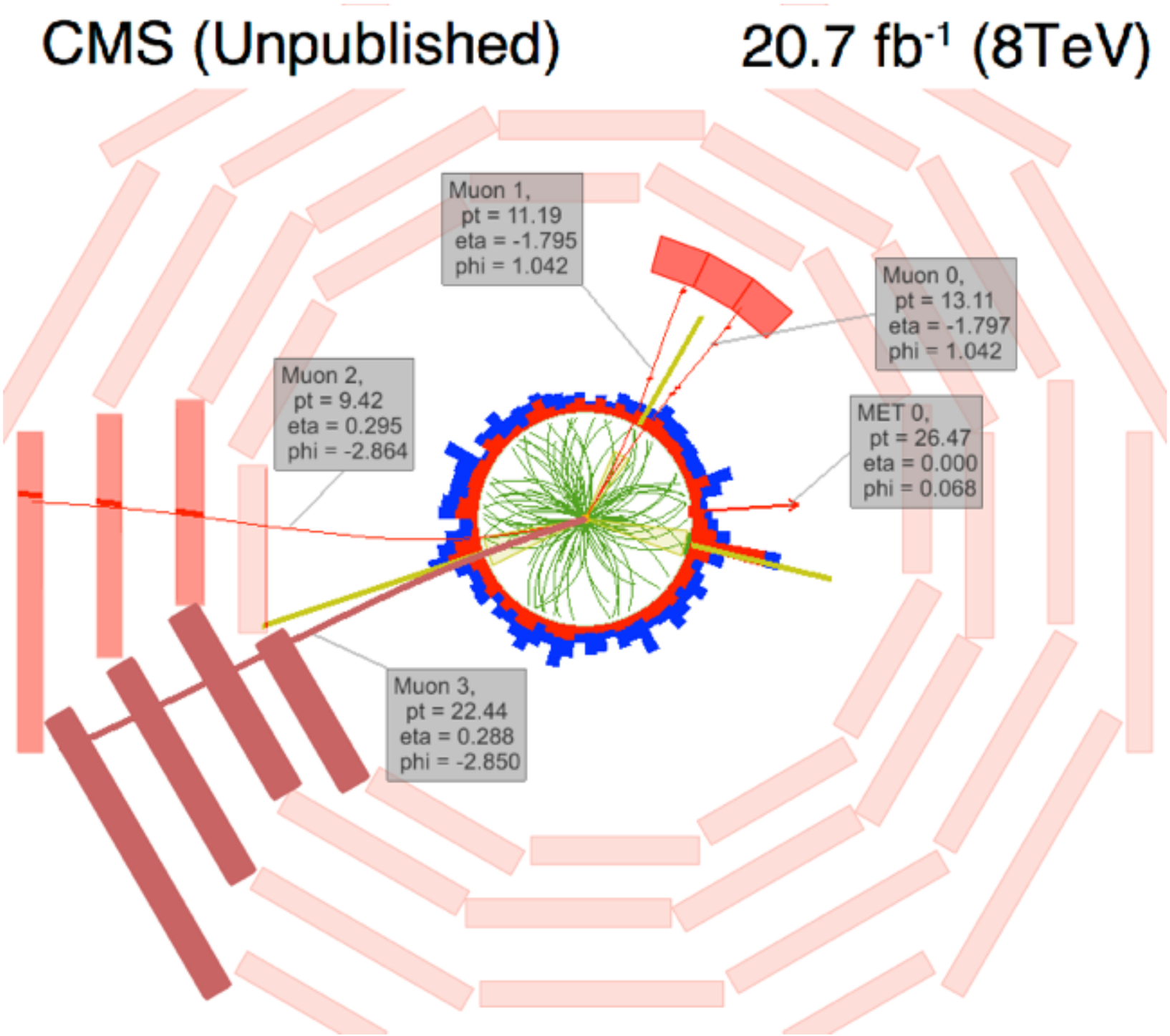
- [1] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at $\sqrt{s}$ = 7 TeV”, *JINST* **7** (2012) P10002, DOI:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071
- [2] CMS Collaboration, “CMS reconstruction improvement for the muon tracking by the RPC chambers”, DOI: 10.1088/1748-0221/8/03/T03001
- [3] CMS Collaboration, “A Search for New Light Bosons Decaying into Muon Pairs”, Phys. Lett. B 752 (2016) 146, arXiv:1506.00424 (2015)

BACKUP SLIDES

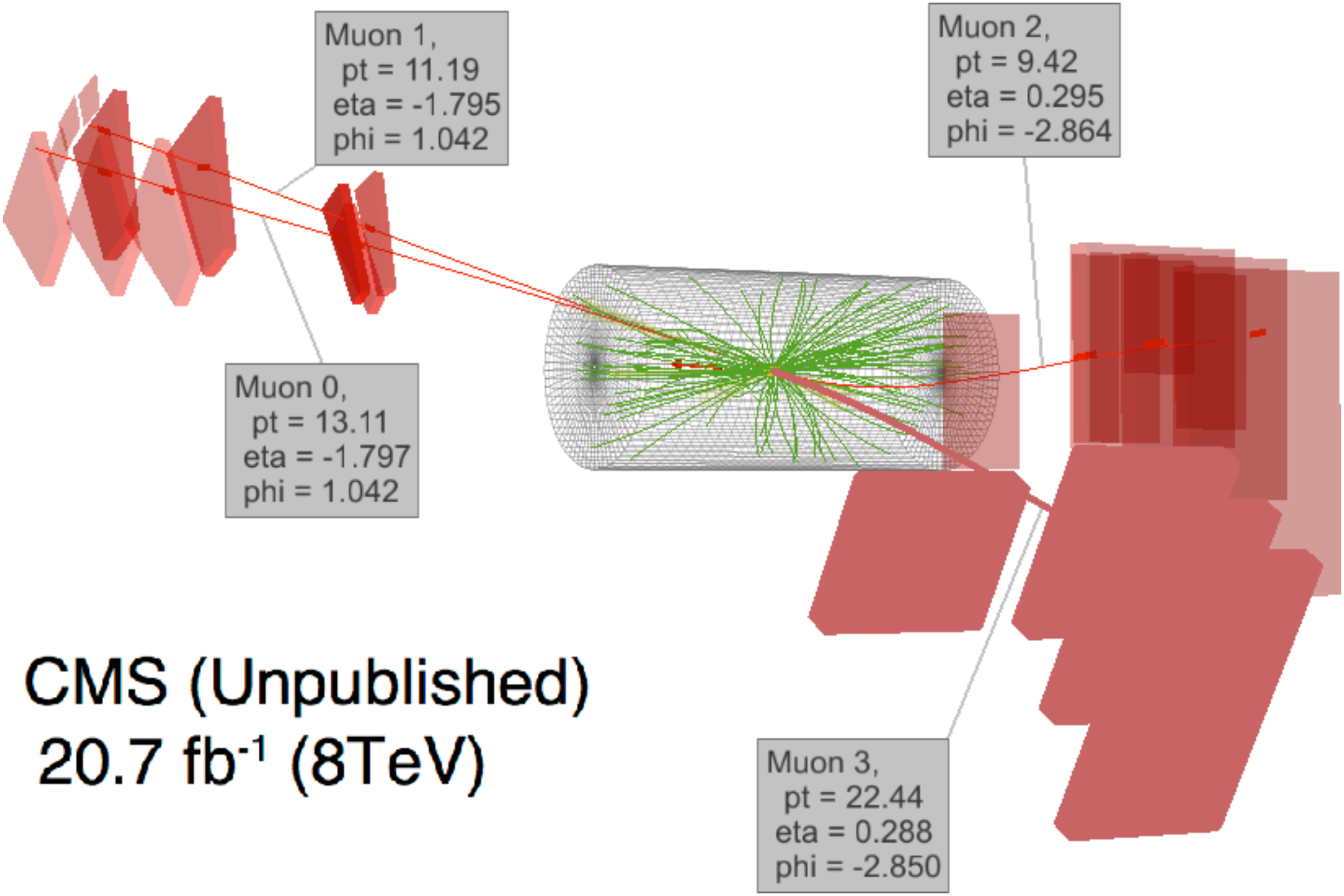
Other References

- Previous iterations of this analysis performed by this group
  - CMS Collaboration, “Search for light resonances decaying into pairs of muons as a signal of new physics”, JHEP 07 (2011) 098, doi:10.1007/JHEP07(2011)098, arXiv:1106.2375
  - CMS Collaboration, “Search for a non-standard-model Higgs boson decaying to a pair of new light bosons in four-muon final states”, arXiv:1210.7619. (2013)

Candidate Event



Candidate Event

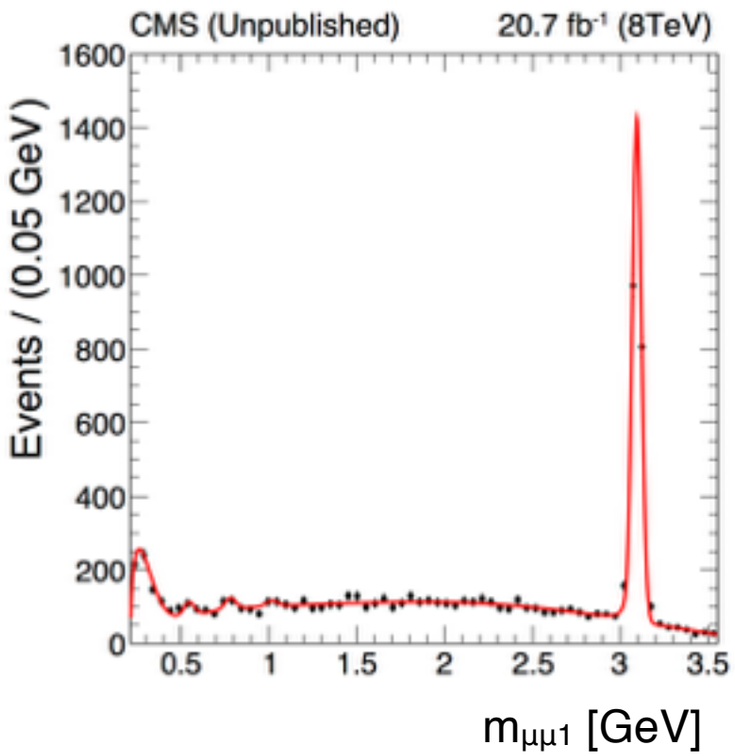


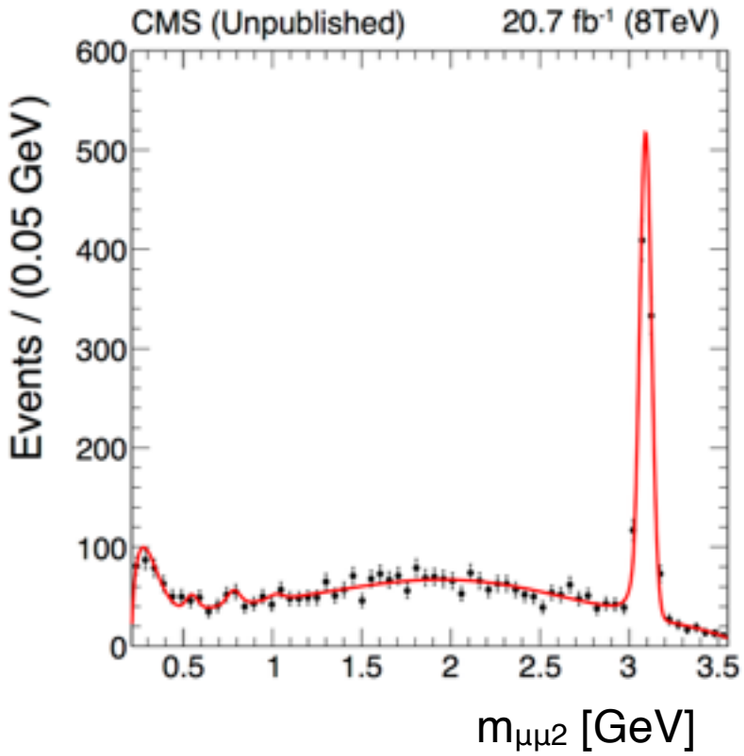
CMS (Unpublished)

20.7 fb^{-1} (8TeV)

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

- Selection criteria allows for two dimuon invariant mass distributions (shapes) based on p_T:
  - S_{17}: contains a high p_T muon (p_T >17 GeV) in barrel
  - S_8: does not contain a high p_T muon
- Two different 2D distributions contribute to the overall template
  - $S_{17}xS_8$ and $S_{17}xS_{17}$
  - Template = $F_1(N_{17,17}; N_{17,8})S_{17}xS_8 + F_2(N_{17,17}; N_{17,8})S_{17}xS_{17}$
- Can be factorized into S_{17}x"S_{MIX}"





Fit from data sample with 1 dimuon, 1 unpaired muon

Data from two dimuon sample sideband w/o isolation cut

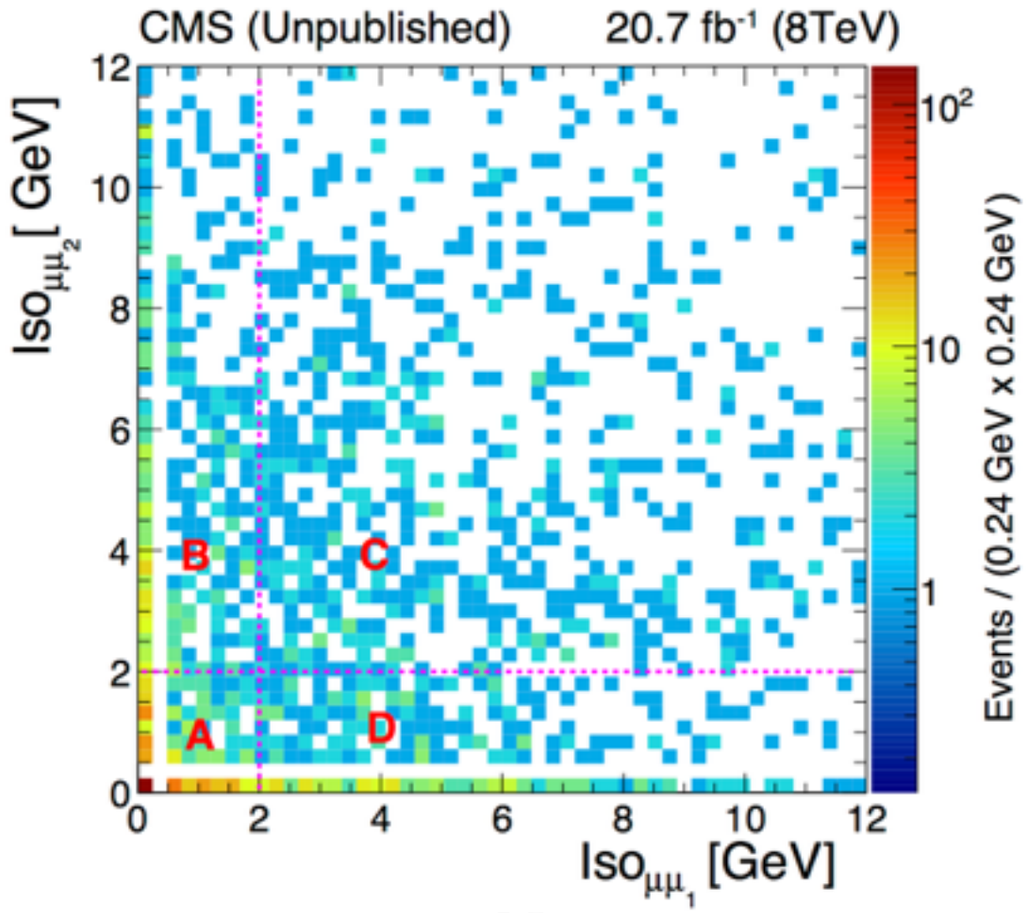
All figures from Ref [3]

Background: QCD Prompt pp →2J/Ψ→4μ

- Show isolation distribution of dimuon 1 and 2 are at most weakly correlated
- Divide distribution into A,B,C, and D regions where "A" satisfies the Iso < 2 GeV requirement
- Iso > 2 GeV region (BCD) is mostly *b*-decay J/ψ with little prompt contamination
- Use the following relations:

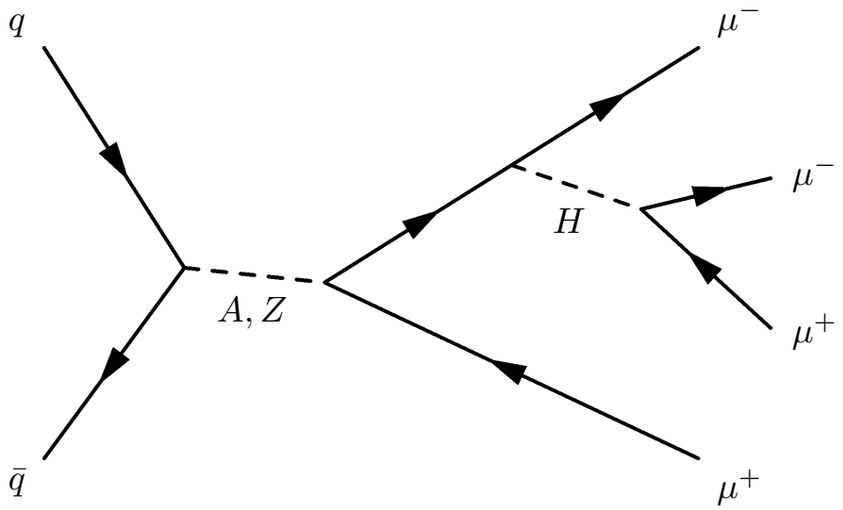
$$\frac{N_{A_{non-prompt}}}{N_B} \sim \frac{N_D}{N_C}$$

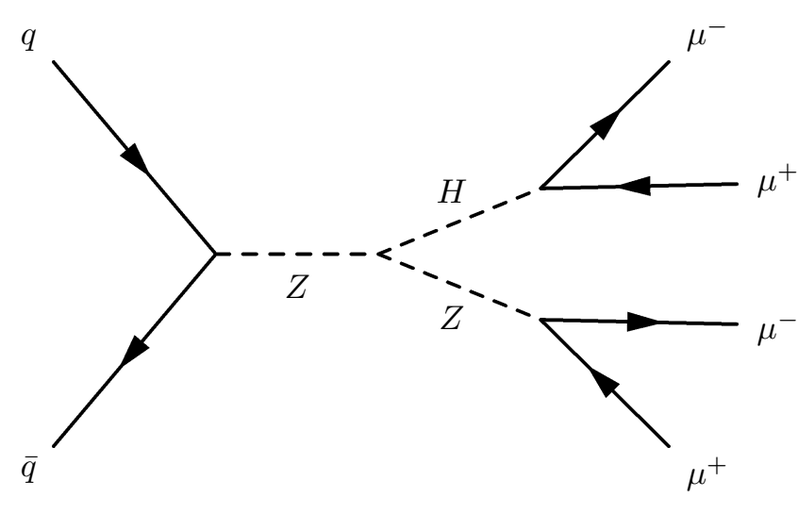
$$N_{A_{non-prompt}} \sim N_B \times \frac{N_D}{N_C}$$



$$N_{A_{prompt}} = N_A - N_{A_{non-prompt}} \sim N_A - N_B \times \frac{N_D}{N_C}$$

EWK Not Used





- EWK processes that mimic signal and were found to be negligible

Background: bb->4u QCD

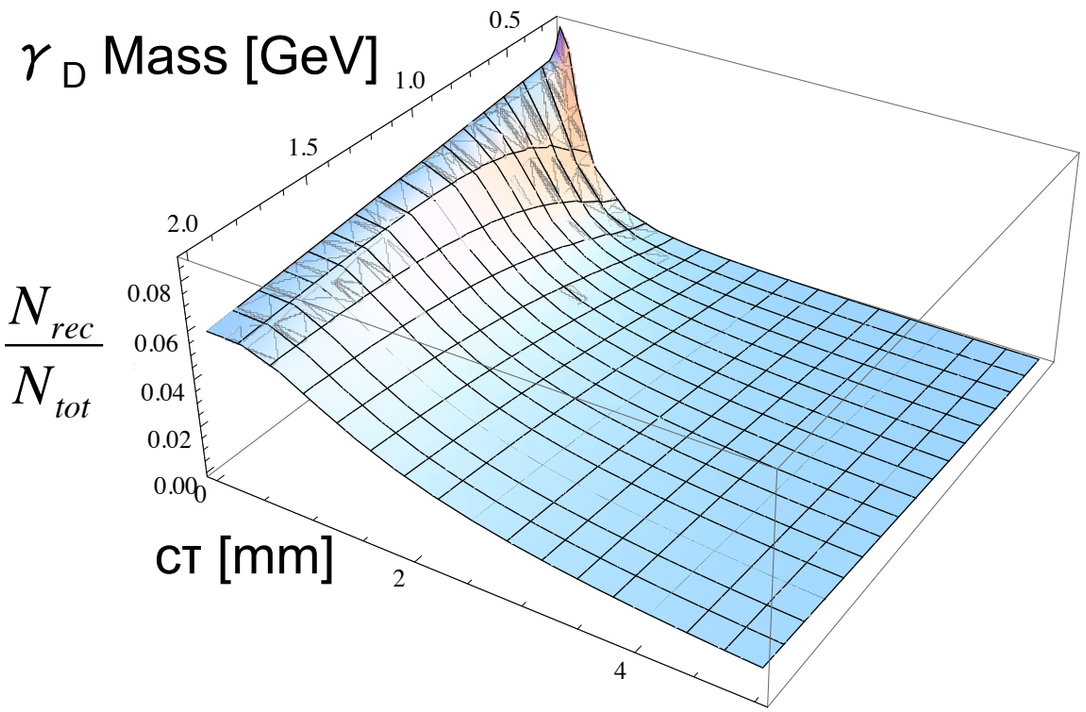
$$S(m_1, m_2) = \frac{N_{17,8}}{N_{17,8} + N_{17,17}} \cdot [S_{17}(m_1) \times S_8(m_2)] + \frac{N_{17,17}}{N_{17,8} + N_{17,17}} \cdot [S_{17}(m_1) \times S_{17}(m_2)]$$

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

$$S(m_1, m_2) = S_{17}(m_1) \times S_{mix}(m_2).$$

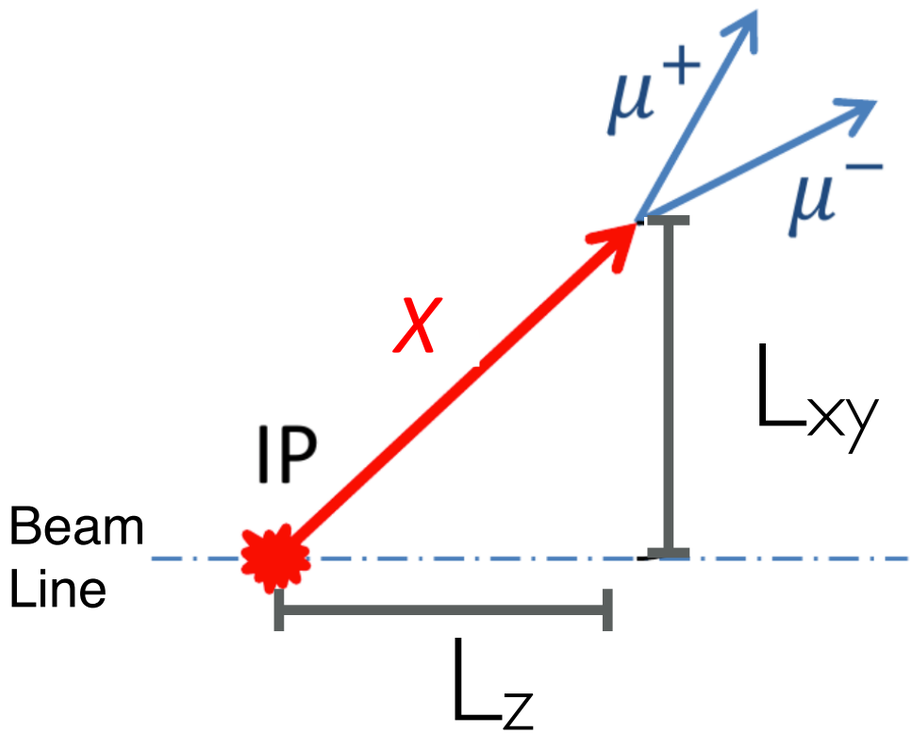
Efficiency Curves

$$\varepsilon_{rec} = \frac{N_{rec}}{N_{tot}}$$



- Apply all selection criteria, corrections, etc
- Create efficiency distribution
  - efficiency defined as (N_{RECO}/N_{tot})
  - is a function of mass and lifetime
  - assume smoothly varying function
- Can pass this into limit machinery

Fiducial Region Selection



- Want efficiency independent of decay vertex location
  - efficiency “high” and “flat”
  - non-uniformity of dimuon reconstruction efficiency would be complicated
- Solution: fiducial cut restricting to uniform region
  - currently set at $L_{xy} < 4.4$ cm, $L_z < 34.5$ cm
  - nearly matches 1st pixel layer
  - require RECO dimuon have 1st pixel layer hit; offline selection

Ratio Plot in Fiducial Region

- Examine ratio of GEN level acceptance RECO level acceptance as a function of $c\tau$
- Gen level acceptance (α_{gen})
  - 1 GEN mu $p_T > 17$ ($|\eta| < 0.9$)
  - 4 GEN mu $p_T > 8$ ($|\eta| < 2.4$)
  - GEN level fiducial cut
- Full analysis acceptance at RECO level (ε_{full})
  - 1 RECO mu $p_T > 17$ ($|\eta| < 0.9$)
  - 4 RECO mu $p_T > 8$ ($|\eta| < 2.4$)
  - GEN level fiducial cut
  - event and full offline selection

Vertex Finding

- Vertex finding is critical
  - required for selecting muon pairs
  - needed for valid dimuons
- Vertex finding is also challenging
  - muons can have small separation & nearly parallel tracks
  - dimuons are highly boosted
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- Vertex finding techniques
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  - improvement seen for low-mass dimuons