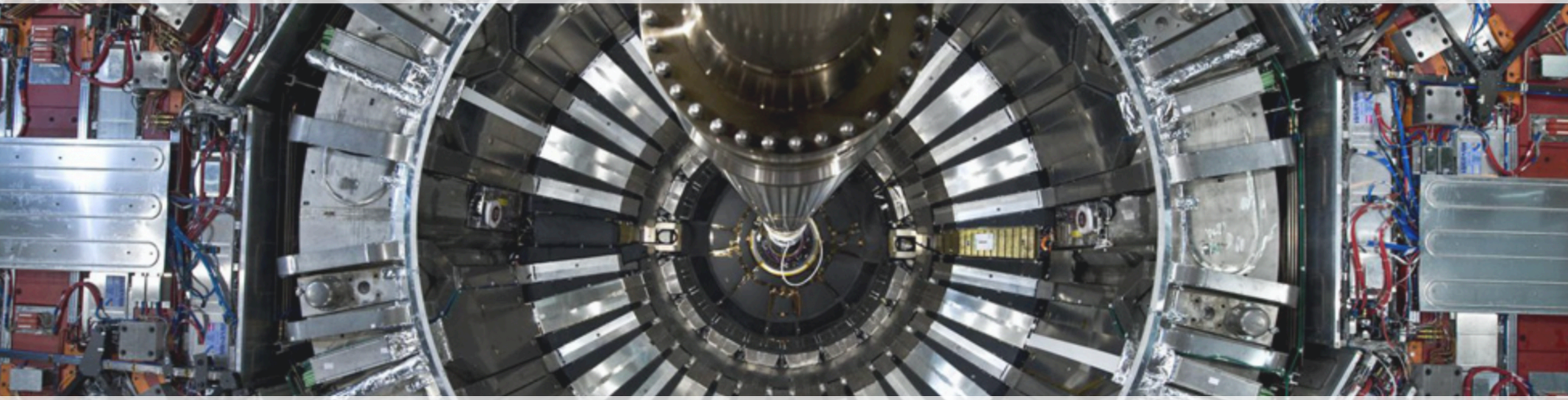
Vector-Portal to The Dark Sector

A Dark Matter Search at the LHC

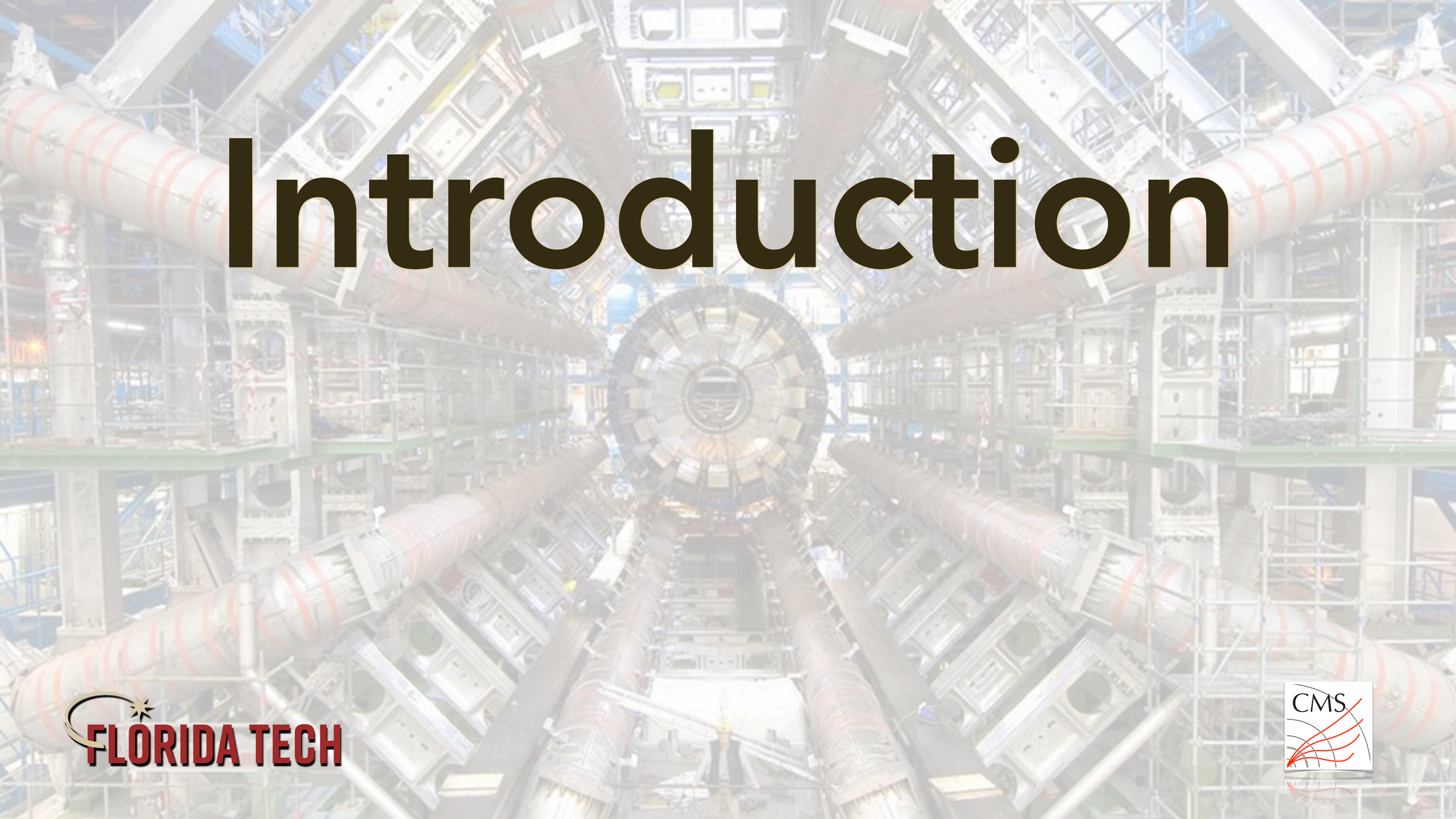


Mehdi Rahmani

Sep 3rd, 2022

CIPANP 2022

Introduction



The Dark Matter

Dark Matter Models at CMS

- Higgs and Z Boson Portals
- Effective Field Theories and Simplified Models
- Supersymmetric Models and Other Complete Theories
- Long-Lived Particle Models
- Dark Interactions and Dark Sectors

Dark matter searches at CMS and ATLAS
D Perez Adan - 2022

The Dark Matter

Simplified Models

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Simplified Models

Run I CMS searches

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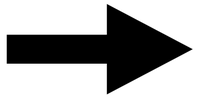
Simplified Models

Run I CMS searches 

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Simplified Models

Run I CMS searches → Effective field theories (EFTs)

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Simplified Models

Run I CMS searches → Effective field theories (EFTs)

Run II CMS searches

The Dark Matter

Simplified Models

Run I CMS searches → Effective field theories (EFTs)

Run II CMS searches →

The Dark Matter

Simplified Models

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Run II CMS searches →

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Simplified Models

Run I CMS searches → Effective field theories (EFTs)

Run II CMS searches →

- Energies exceed the EFT cut-off energy scale.
- Deviating mono-X reactions kinematics from ETF prediction
- The mediator may also produce qualitatively different signals

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Simplified Models

Run I CMS searches → Effective field theories (EFTs)

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Solution

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Simplified Models

Run I CMS searches → Effective field theories (EFTs)

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The Dark Matter

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Solution → Simplified Models

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Simplified Searches

Dark Matter

vector mediator ($qq\bar{q}$), $g_{\mathrm{q}} = 0.25, g_{\mathrm{DM}} = 1, m_{\chi} = 1$ GeV

vector mediator ($\ell\ell\bar{\ell}$), $g_q = 0.1, g_{DM} = 1, g_{\ell} = 0.01, m_{\chi} > 1$ TeV

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(axial)-vector mediator ($\ell\bar{\ell}$), $g_q = 0.1, g_{DM} = 1, g_{\ell} = 0.1, m_{\chi} > m_{med}/2$

scalar mediator ($+t/t\bar{t}$), $g_{\mathrm{q}} = 1, g_{\mathrm{DM}} = 1, m_{\chi} = 1$ GeV

scalar mediator (fermion portal), $\lambda_{\mathrm{u}} = 1, m_{\chi} = 1$ GeV

pseudoscalar mediator ($+j/V$), $g_{\mathrm{q}} = 1, g_{\mathrm{DM}} = 1, m_{\chi} = 1$ GeV

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complex sc. med. (dark QCD), $m_{\pi_{\mathrm{DK}}} = 5$ GeV, $c\tau_{\mathrm{X_{DK}}} = 25$ mm

Z′ mediator (dark QCD), $m_{\mathrm{dark}} = 20$ GeV, $r_{\mathrm{inv}} = 0.3$, $\alpha_{\mathrm{dark}} = \alpha_{\mathrm{dark}}^{\mathrm{peak}}$

Baryonic Z′, $g_{\mathrm{q}} = 0.25, g_{\mathrm{DM}} = 1, m_{\chi} = 1$ GeV

$\mathrm{Z}' - 2\mathrm{HDM}, g_{\mathrm{Z}'} = 0.8, g_{\mathrm{DM}} = 1, tan\beta = 1, m_{\chi} = 100$ GeV

Leptoquark mediator, $\beta = 1$, $B = 0.1$, $\Delta_{\chi,DM} = 0.1$, $800 < M_{LQ} < 1500$ GeV

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Simplified Searches

Dark Matter

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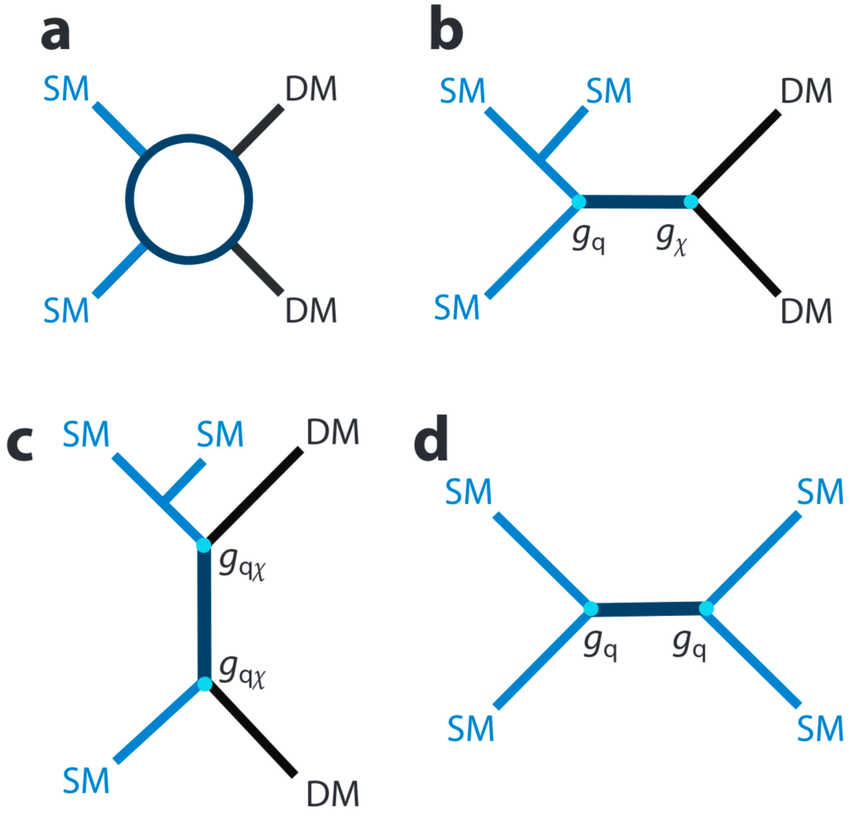

Dark matter searches at colliders
A Boveia, C Doglioni

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Simplified Searches

Dark Matter

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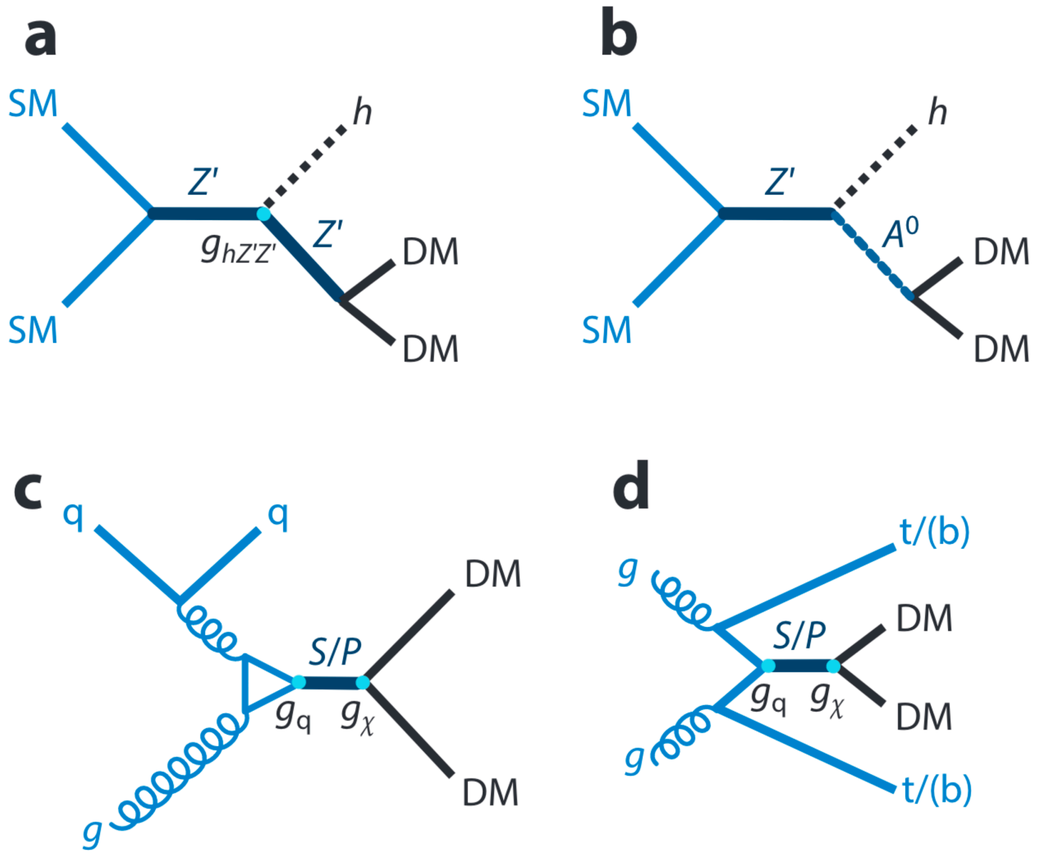

Dark matter searches at colliders
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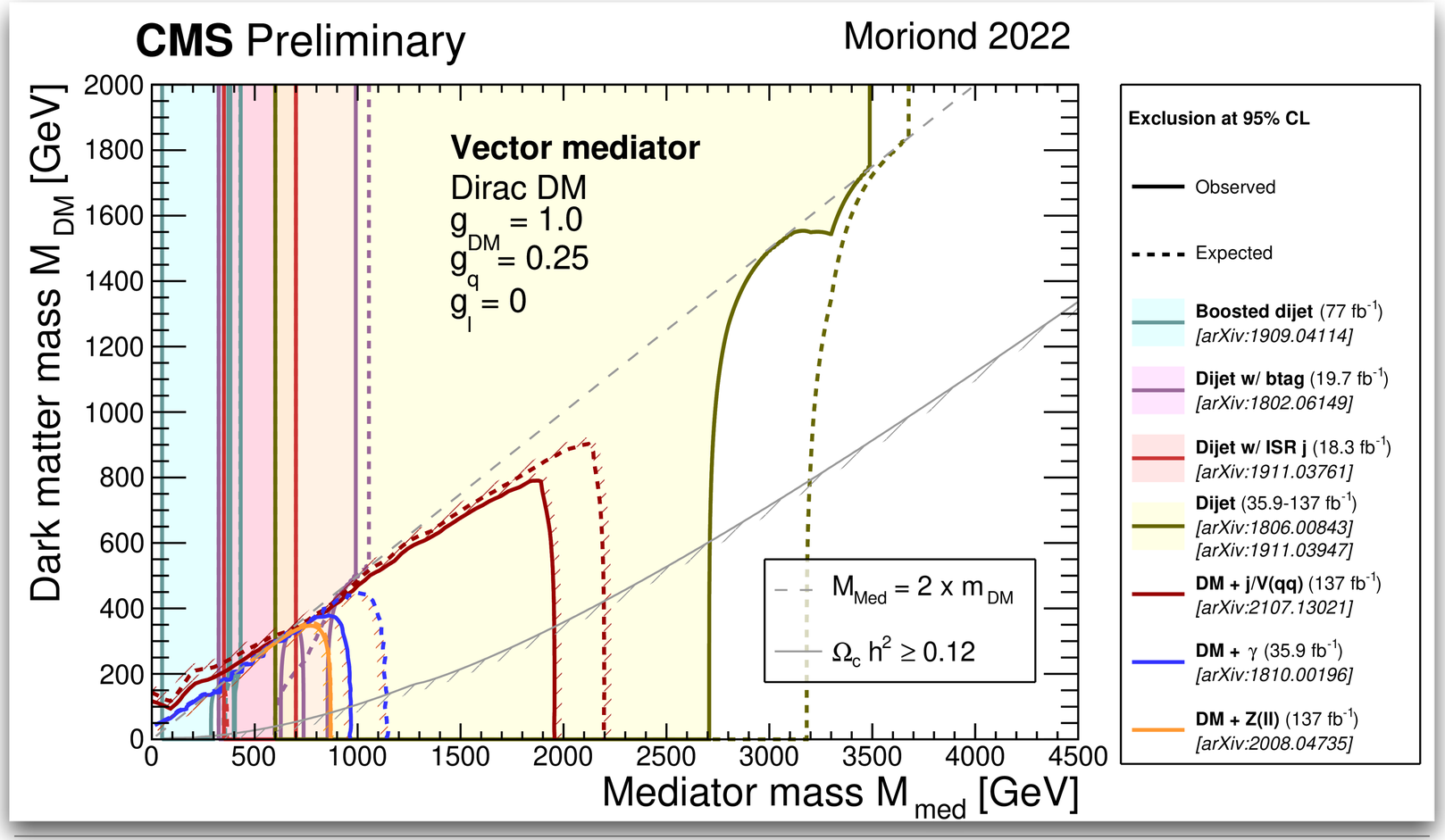
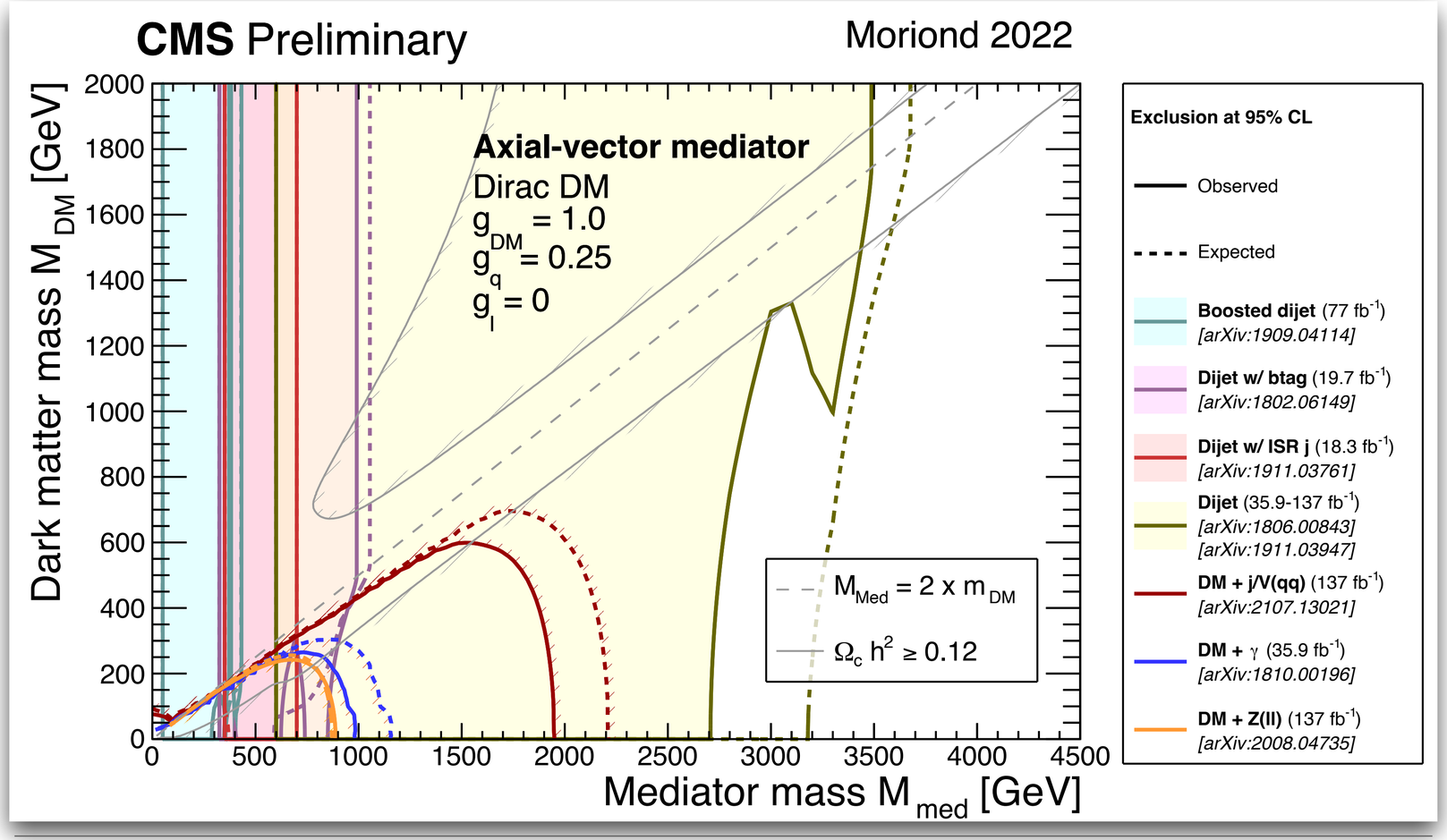
CMS Searches Summery Plots



95% CL observed and expected exclusion regions in m_{Med}-m_{DM} plane for di-jet searches and different MET based DM searches from CMS in the lepto-phobic vector model

The Dark Matter

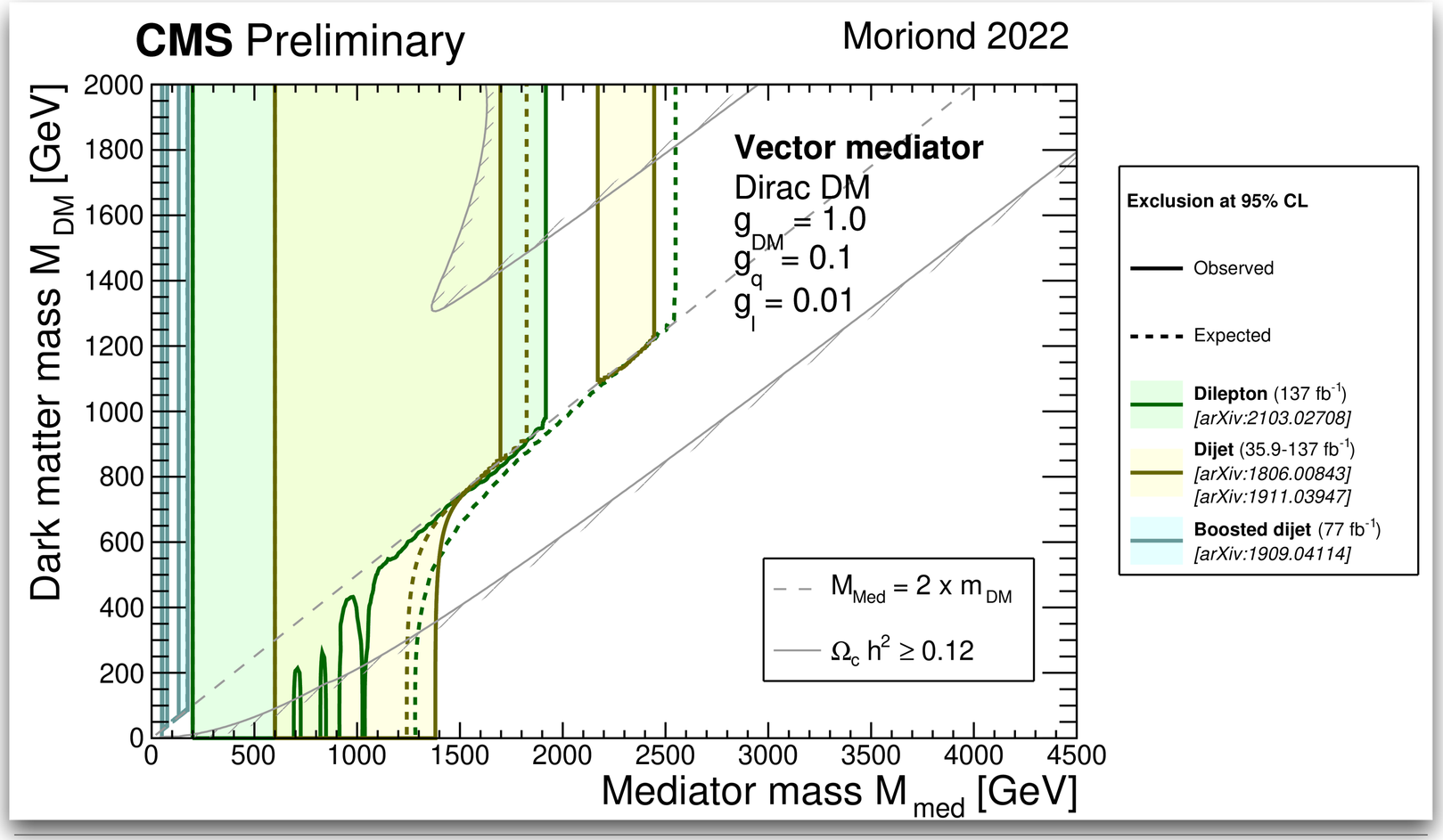
CMS Searches Summery Plots



95% CL observed and expected exclusion regions in m_{Med}-m_{DM} plane for di-jet searches and different MET based DM searches from CMS in the lepto-phobic Axial-vector model

The Dark Matter

CMS Searches Summery Plots



95% CL observed and expected exclusion regions in m_{Med}-m_{DM} plane for di-jet and di-lepton searches from CMS in the Vector model

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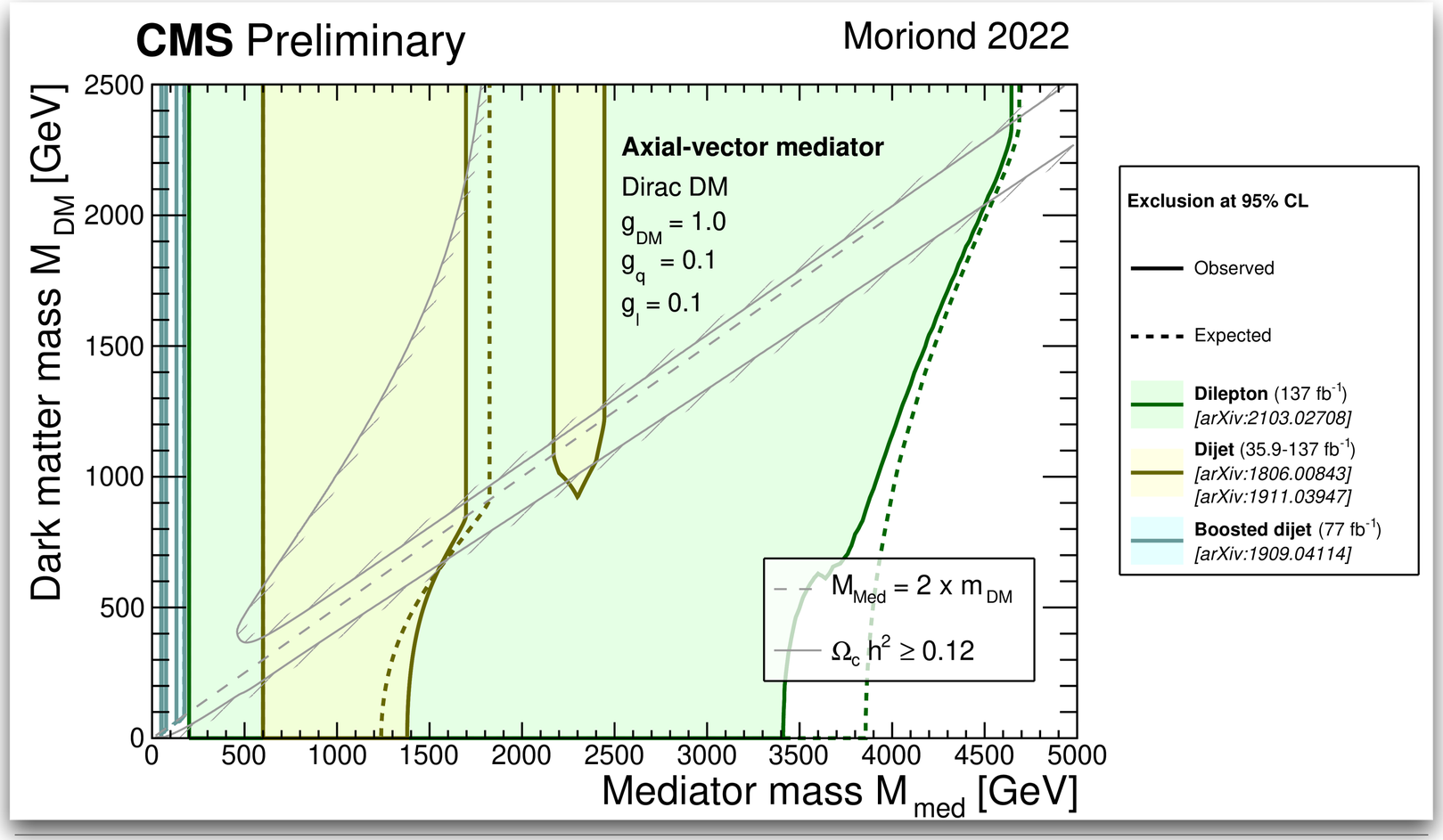
CMS Searches Summery Plots



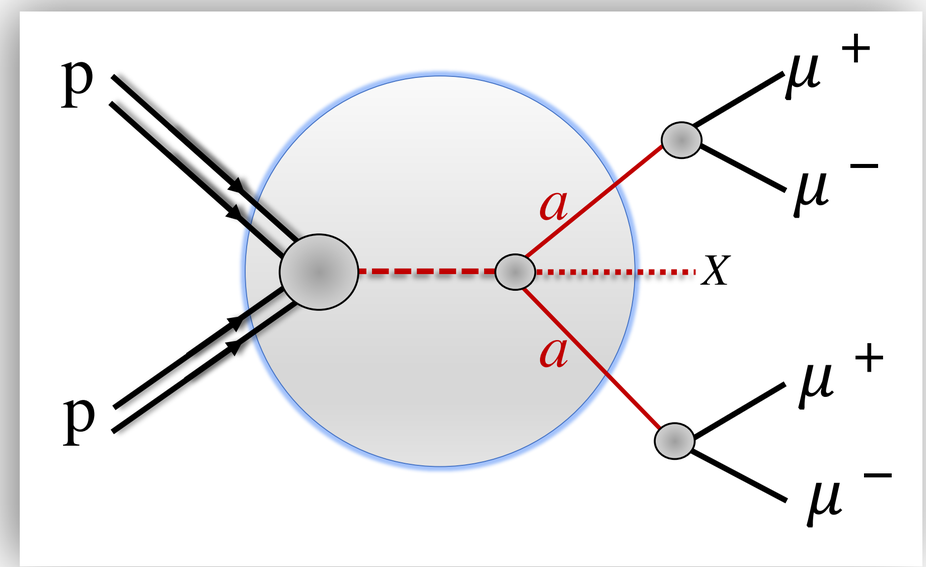
95% CL observed and expected exclusion regions in m_{Med}-m_{DM} plane for di-jet and di-lepton searches from CMS in the Axial-vector model.

Model-Independent Analysis
&
Vector-Portal Interpretation

The Dark Matter

Model-independent Analysis

- We explored the pair production of new bosons at the LHC in collaboration with research groups from Texas A&M, Rice University, and University of Sonora.
- Our analysis presents a search for **new light bosons** decaying **into muon pairs**, corresponding to an integrated luminosity of $59.8\ fb^{-1}$ at the center-of-mass 13 TeV energy , recorded during **2018** at the CMS.
- The parameter space probed is for the **mass of the mediator**



Schematic example of the pp interaction that produces a pair of new bosons of which each decays into a muon pair. The grey circle indicate the dark sector inter- actions. The X particle is to signify any excess processes other than the four lepton final state.

The Dark Matter | The Vector Portal

- DM resides in a dark sector (charged under a dark symmetry group).
- This new sector communicates with SM sector through a weak portal
- Spin 1-Vector portal where a dark gauge boson interacts with an SM gauge boson through **kinetic mixing**

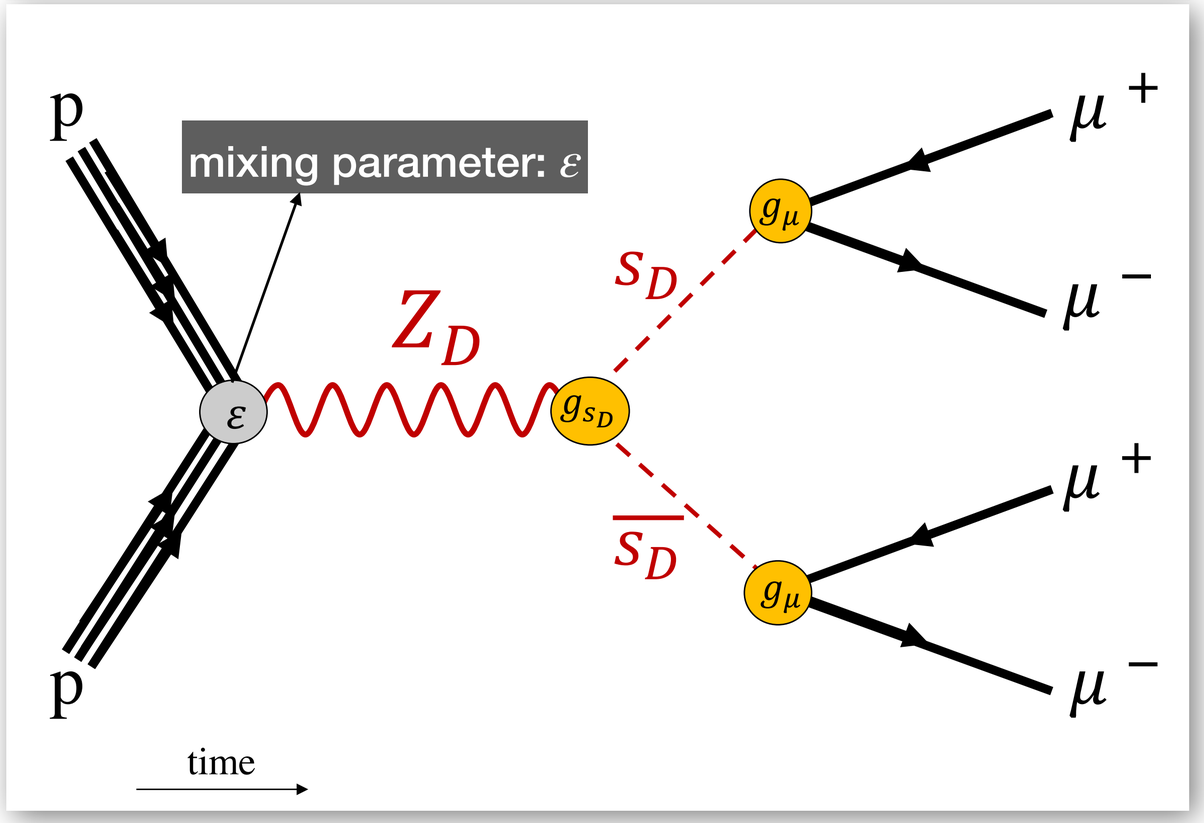
$$\mathscr{L} = -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}B'^{\mu\nu}B'_{\mu\nu} - \varepsilon B^{\mu\nu}B'_{\mu\nu}$$

- $B^{\mu\nu}$ is the SM electromagnetic field tensor
- $B'^{\mu\nu}$ The field tensor in the dark sector
- ε is the kinetic mixing parameter

The Dark Matter

Vector portal & Scalars

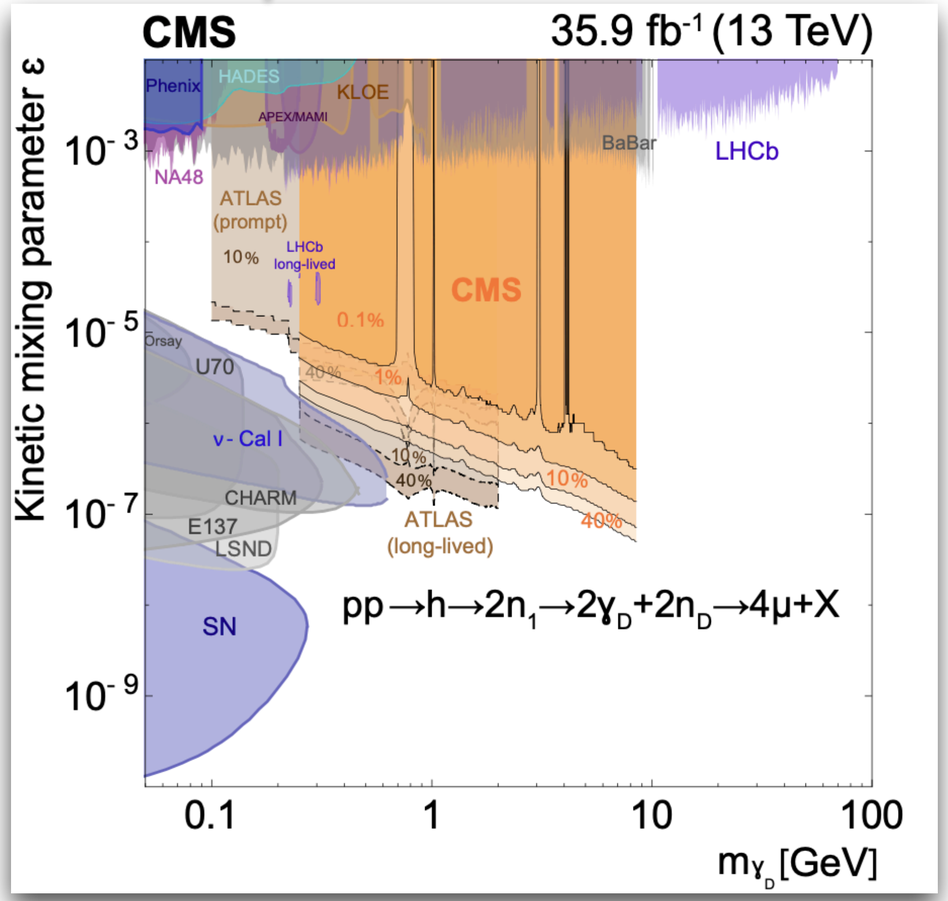
$$pp \rightarrow Z_D \rightarrow s_D\overline{s_D} \rightarrow \mu^+\mu^-\mu^+\mu^-$$



Z_D decays into a pair of scalar dark matter particles which then each subsequently decay into two oppositely charged muons.

The Dark Matter

Vector Mediator Summary Plot



The 90% CL upper limits (black solid curves) on the dark vector mediator in the plane of parameters m_{γ/Z_D} and ε are shown. The limits shown in light orange correspond to dataset recorded by CMS during the 2016 era.

A search for pair production of new light bosons decaying into muons in proton-proton collisions at 13 TeV
2019

Samples & Selection

2018 Analysis

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CMS

Samples | Monte-Carlo Simulation

MC Simulation

Simulation Process	Description
Model Implementation	Feynrules
Hard Scattering Simulation	amc@nlo v2.6.5
Parton showering	PYTHIA 8
Hadronization, detector response, & reconstruction	CMSSW 10 2 X

2018 Data

Dataset Labels	Number of Events
/DoubleMuon/Run2018A-17Sep2018-v2/ MINIAOD	75 499 908
/DoubleMuon/Run2018B-17Sep2018-v1/ MINIAOD	35 057 758
/DoubleMuon/Run2018C-17Sep2018-v1/ MINIAOD	34 565 869
/DoubleMuon/Run2018D-PromptReco-v2/ MINIAOD	169 225 355
Total	314 348 890

Analysis | Trigger and Muon Selection

Trigger Paths
HLT_DoubleL2Mu23NoVtx_2Cha
HLT_Mu18_Mu9_SameSign
HLT_TrkMu12_DoubleTrkMu5NoFiltersNoVtx,
HLT_TripleMu_12_10_5

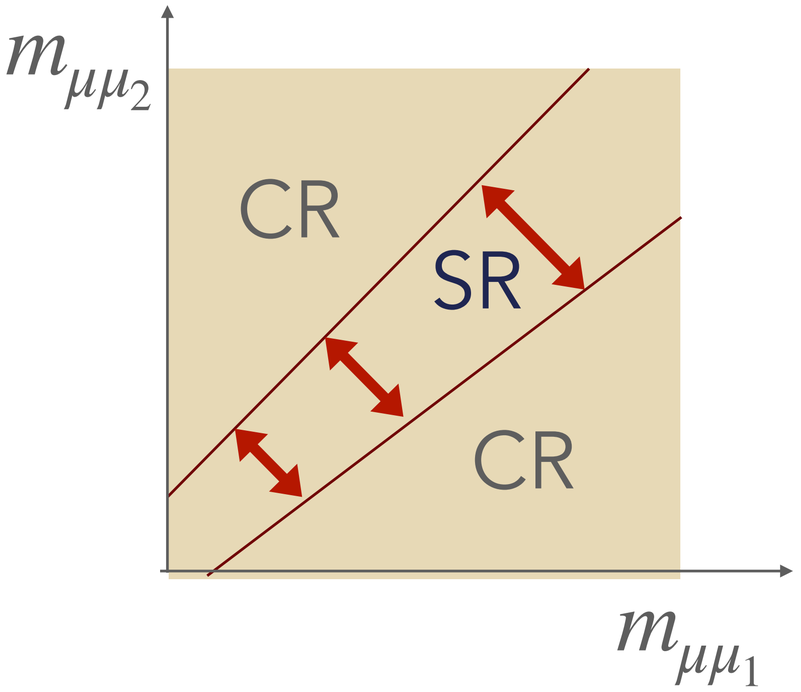
Muon selection
slimmedMuons in MiniAOD
PF Loose muon (>=3) + standalone-only (SA) muon (>=1)
Two muons: p_T >24 GeV, letal < 2
Four muons: p_T >8 GeV, letal < 2.4

Mass Window

Defining Control and Signal Regions

Since the muon pairs are produced from supposedly the same bosons with consistent masses, the invariant mass of muon pairs should be consistent as well.

$$m_1 - m_2 = f(\frac{m_1 + m_2}{2})$$



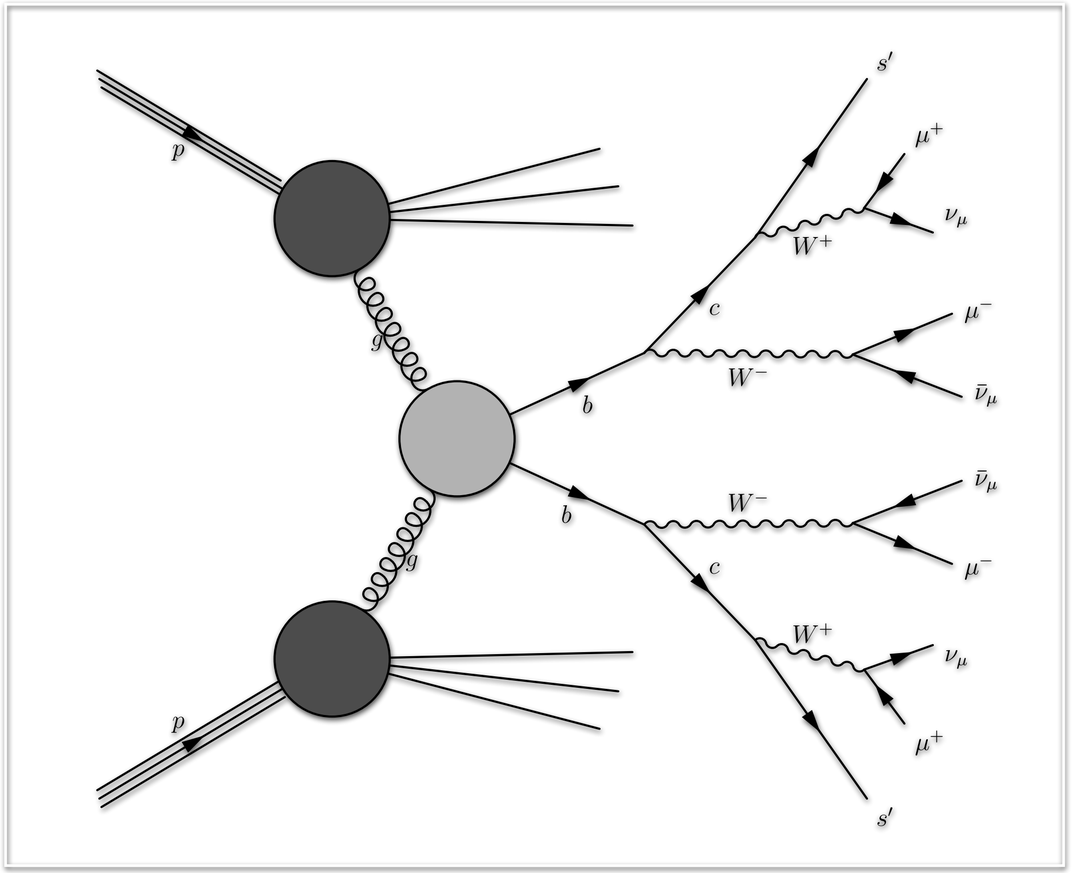
Background Estimation

Publication Status

- We have a CADI line with AN and draft paper based on Run II 2018 data with dimuon trigger w/o VTX constraints:
- CADI: HIG-21-004
- Pre-approval talk: Feb 16 , 2021
- Unblinded results: Apr 28 , 2021
- Twiki: HIG21004Run2
- 2017 data is being analyzed to be combined with 2018 results

Background | Below Upsilon (Υ) Resonances (0.25-9 GeV)

- QCD multi-jet processes, especially contributions from $b\overline{b}$
- Double semi-leptonic decay or decay via resonances
  $\eta, \omega, \phi, J/\psi(1S), \psi(2S)$
- Data driven (2018 DoubleMuon)

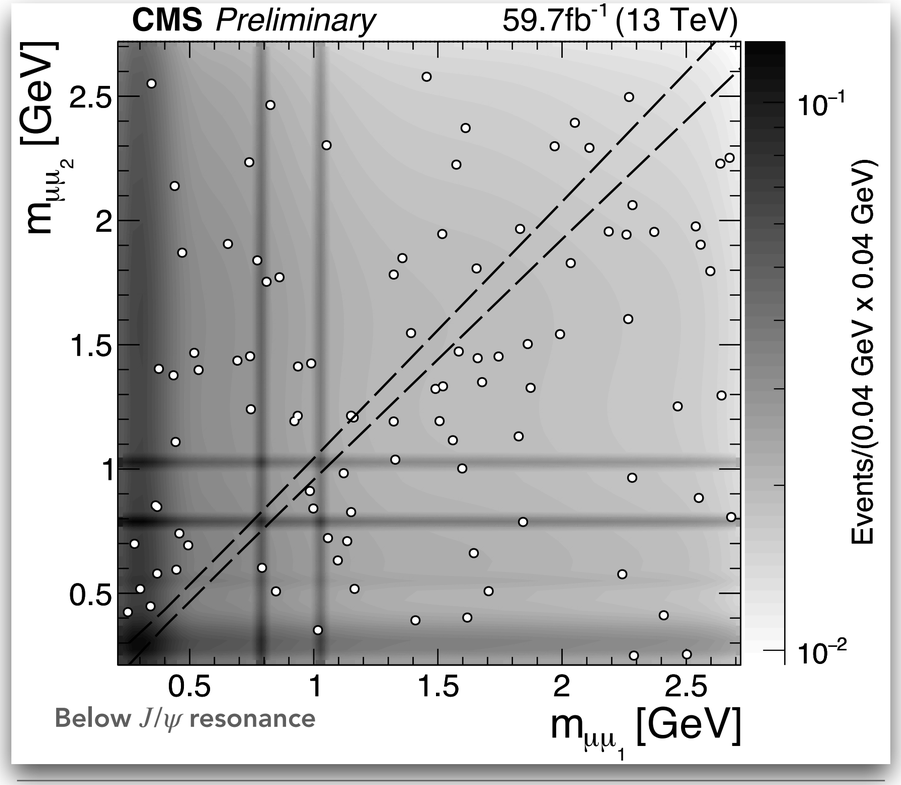


Double semi-leptonic $b\overline{b}$ decays

Background

Below Upsilon (ϒ) Resonances (0.25-9 GeV)

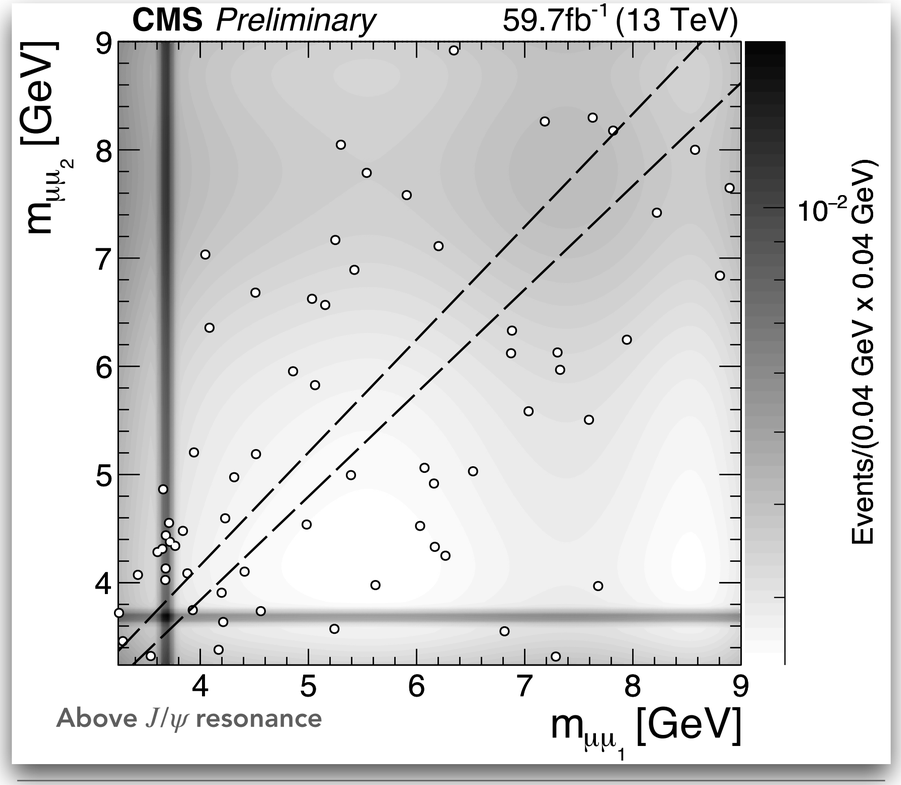
Work in progress



2D QCD background template + data at the CR

- 2D template integral SR/CR = 0.043/0.969
- 2-dimu events at CR: 98 (SR remain blinded)
- Estimated BKG events at SR: 4.34 +/- 0.44 (stat.)

Work in progress

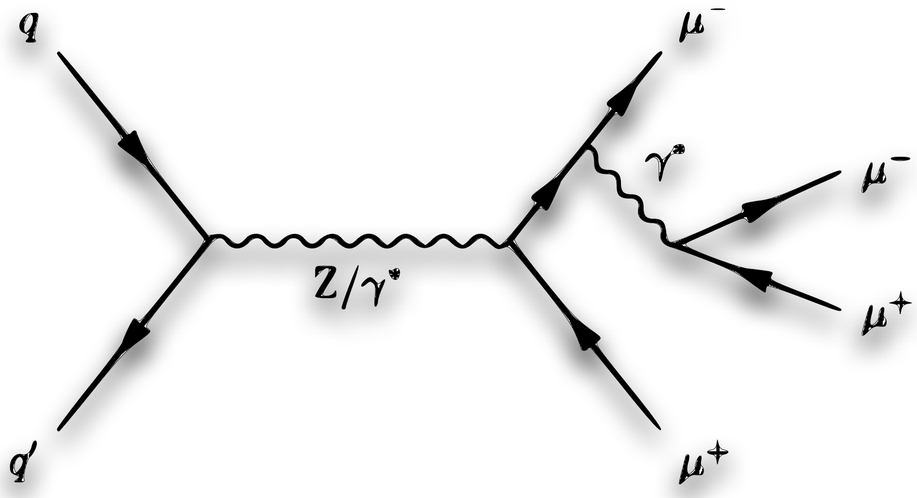


2D QCD background template + data at the CR

- 2D template integral SR/CR = 0.035/0.965
- 2-dimu events at CR: 66 (SR remain blinded)
- Estimated BKG events at SR: 6.16 +/- 0.76 (stat.)

Background | Above Upsilon (Υ) Resonances (11-60 GeV)

- QED radiated high-energy photons produces muon pairs
- Each muon is then paired with Drell-Yan (DY) single muons which mimics our di-muon signal
- Reject the events with QED background

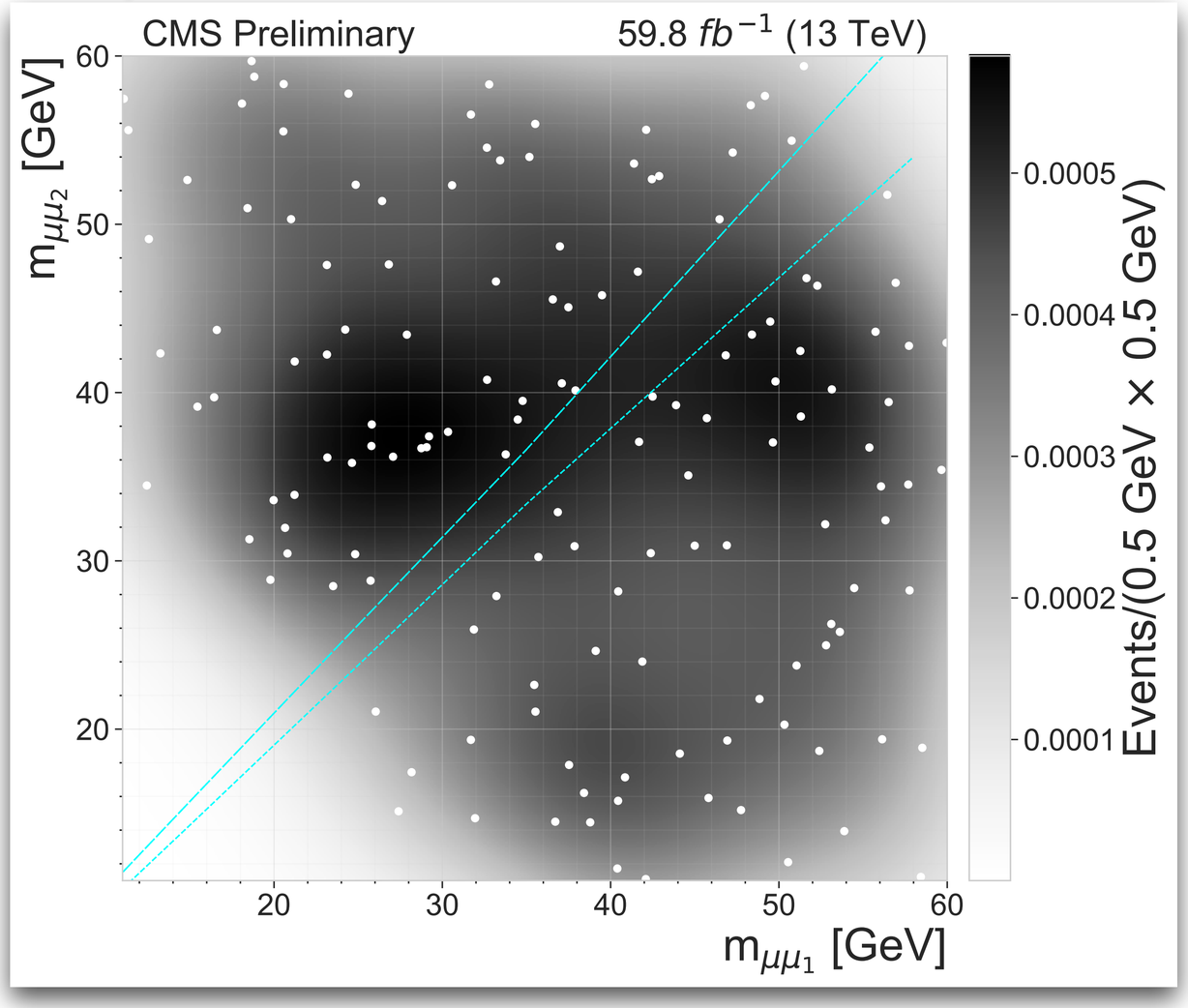


The Feynman diagram for QED radiation in DY process. The pairing of the muon decaying in the DY with muon decaying from the QED radiation mimics our signal

Background

Above Upsilon (Υ) Resonances (11-60 GeV)

Work in progress



Expected events in SR: 12.28 ± 2.01

Expected Limits

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CMS

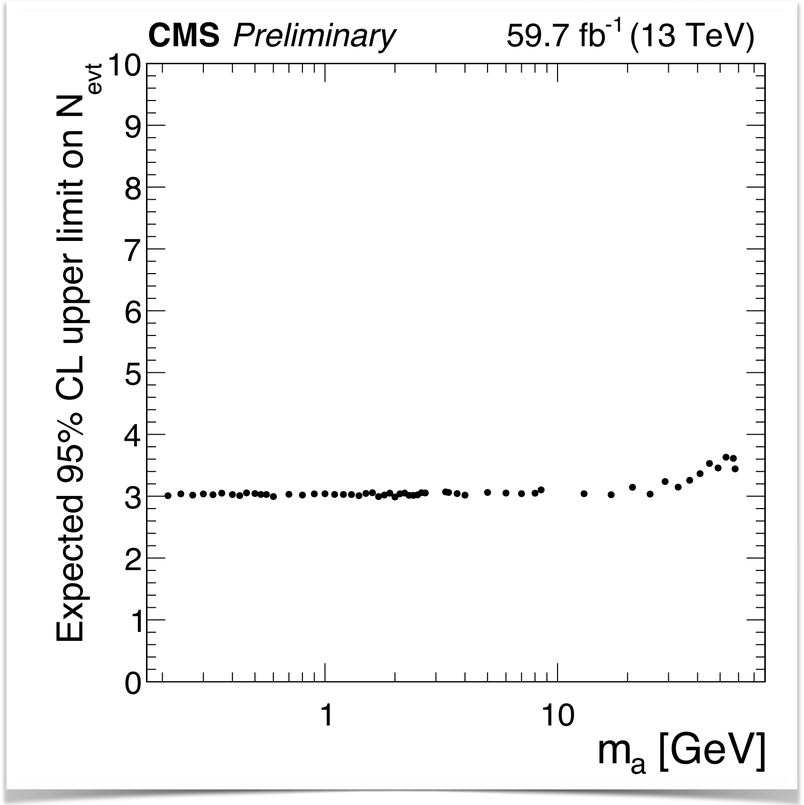
Expected Limits | Kinetic Mixing Parameter

$$\sigma(pp \to Z_D)\mathcal{B}(Z_D \to s_D\overline{s_D})\mathcal{B}^2(s_D \to \mu^+\mu^-) \times \alpha_{gen} \leq \frac{N_{\mu\mu}}{L \times r}$$

$N_{\mu\mu}$: 95% CL upper limit on the number of events

$$\mathscr{L} = 59.7\ fb^{-1},\ r = SF_{\epsilon_{Full}} \times \epsilon^{MC}_{Full}/\alpha_{Gen}$$

Close to zero background analysis: **expected 95%** CL upper limit is ~3 events at each mass point



Expected Limits | Kinetic Mixing Parameter

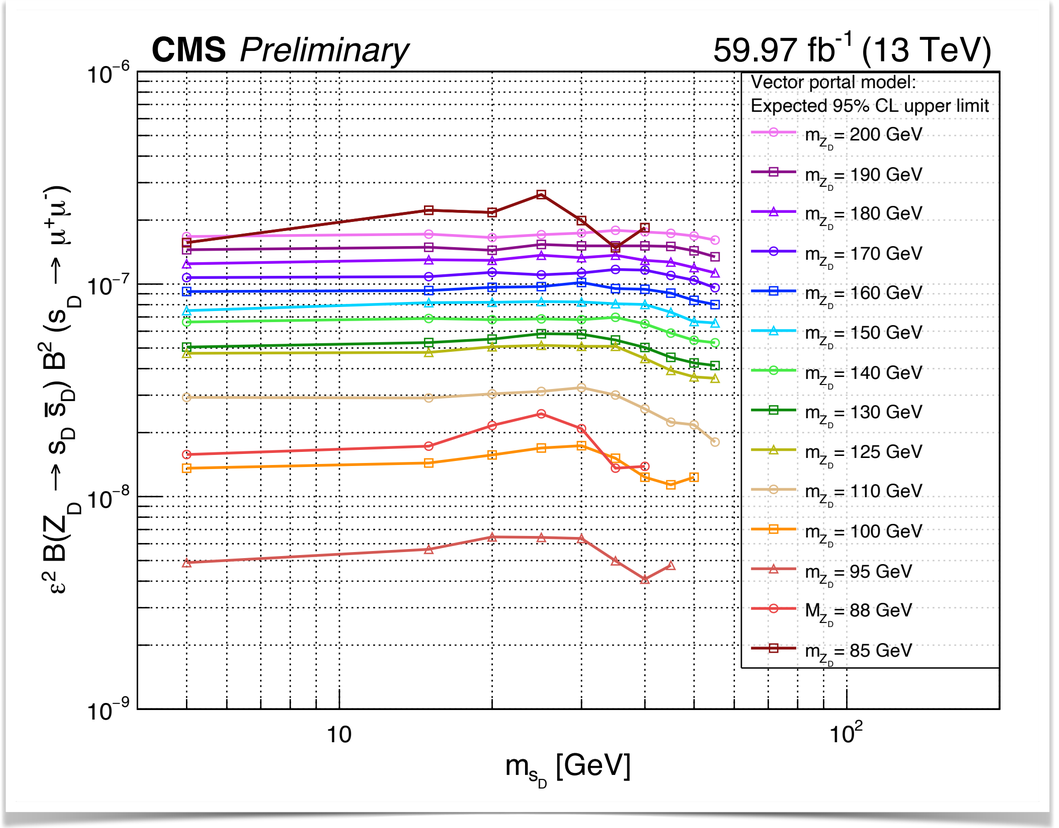
The expected 95% CL upper limits function of the **dark scalar mass** m_{s_D} and the **dark vector boson mass** m_{Z_D}

By translating the production cross-section to ε^2, we set **95% CL limit on**:

$$\varepsilon^2 \mathcal{B}(Z_D \to s_D \overline{s_D}) \mathcal{B}^2(s_D \to \mu^+ \mu^-)$$

The limit curves **exhibit a structure with an increase and a dip** as the s_D mass

approaches the kinematic limit of $m_{Z_D}/2$.



Combination With 2017

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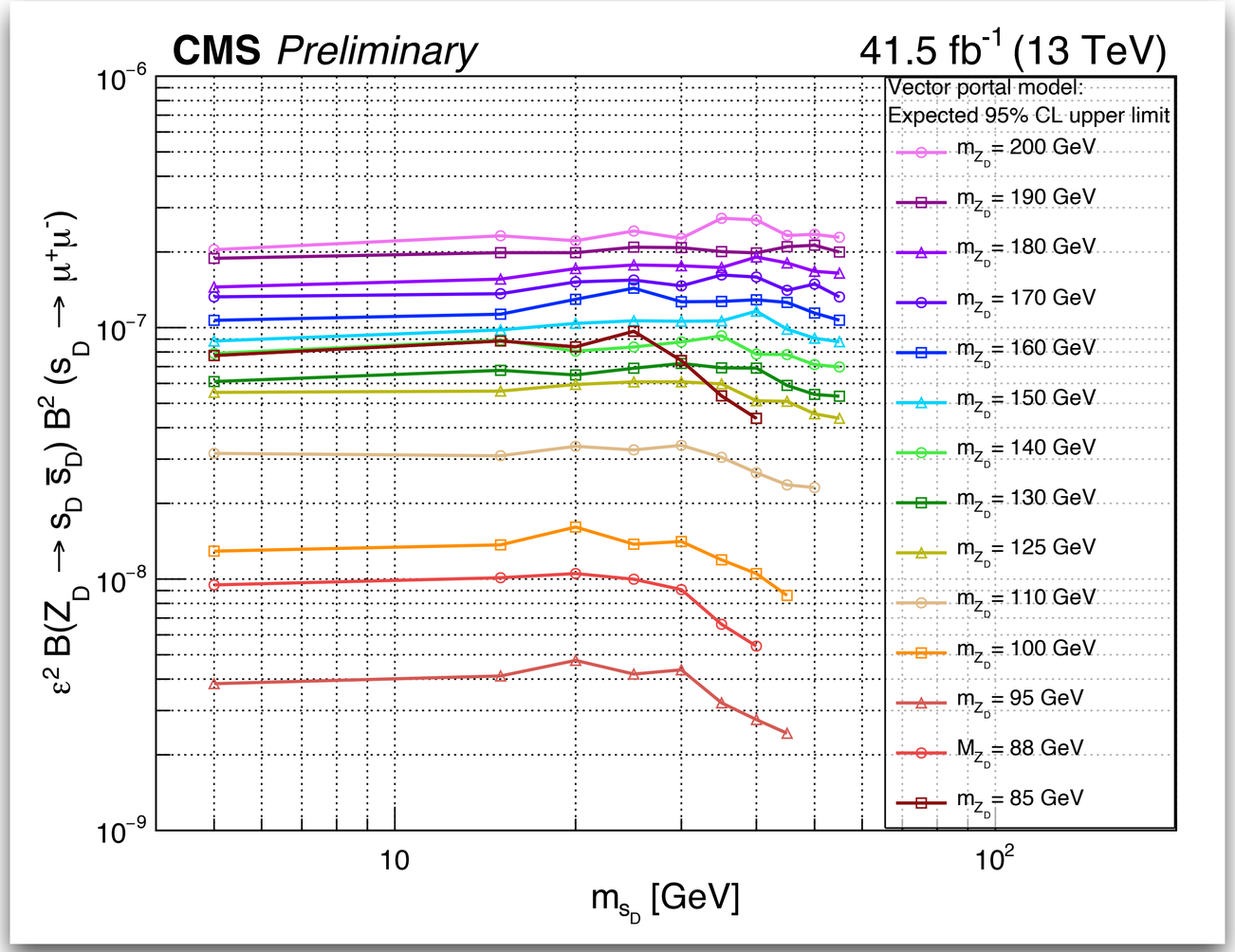
CMS

Expected Limits

Expected Limits - 2017

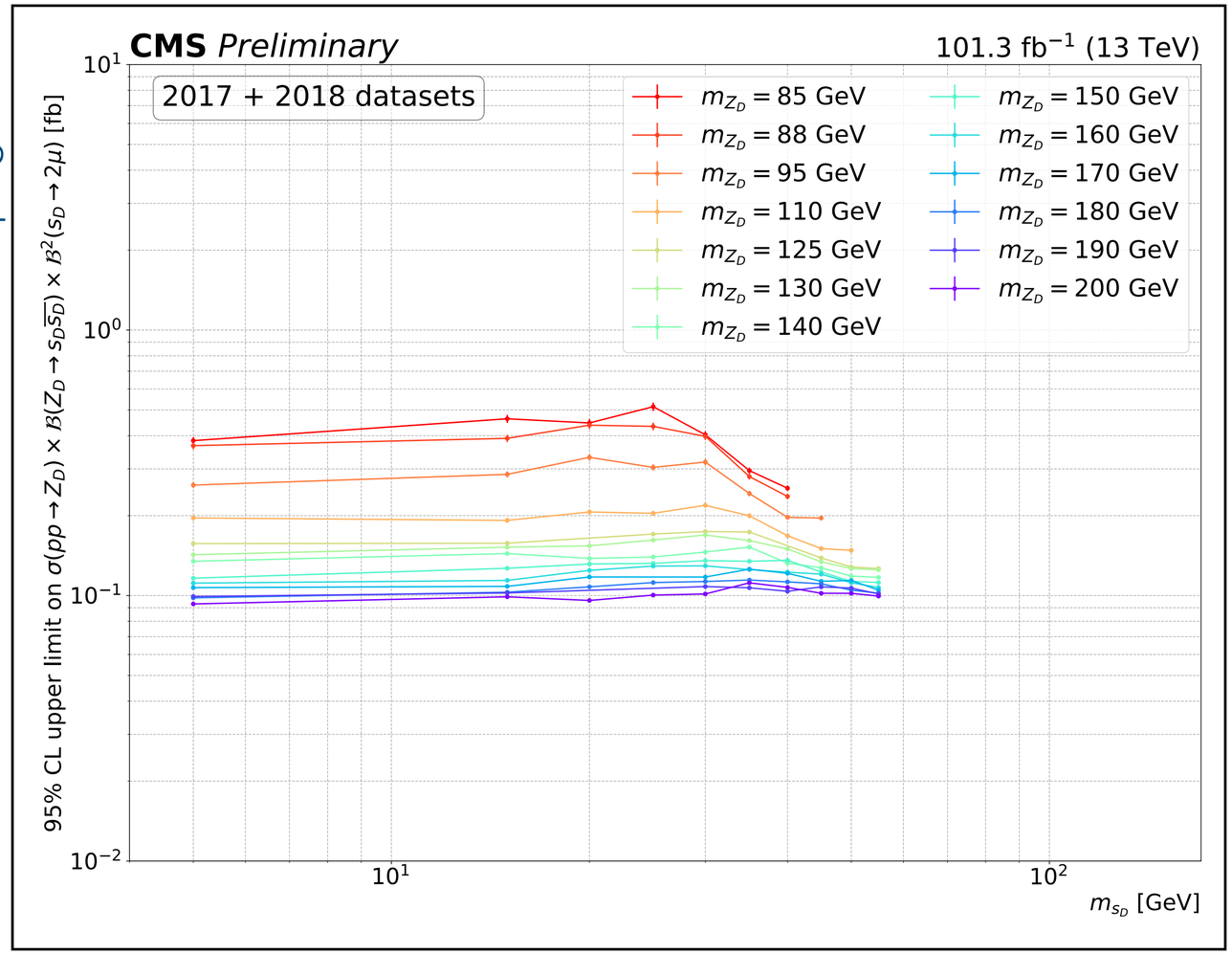
Work in progress



Expected Limits

Expected Limits - 2017 + 2018

Work in progress



Summary

- A **vector-portal model** is introduced as a **benchmark** dark matter model:

  $pp \rightarrow Z_D \rightarrow s_D\overline{s_D} \rightarrow 4\mu$

- Model independent **upper limits** on kinetic mixing parameter, cross-section branching ratio and acceptance **are set**.

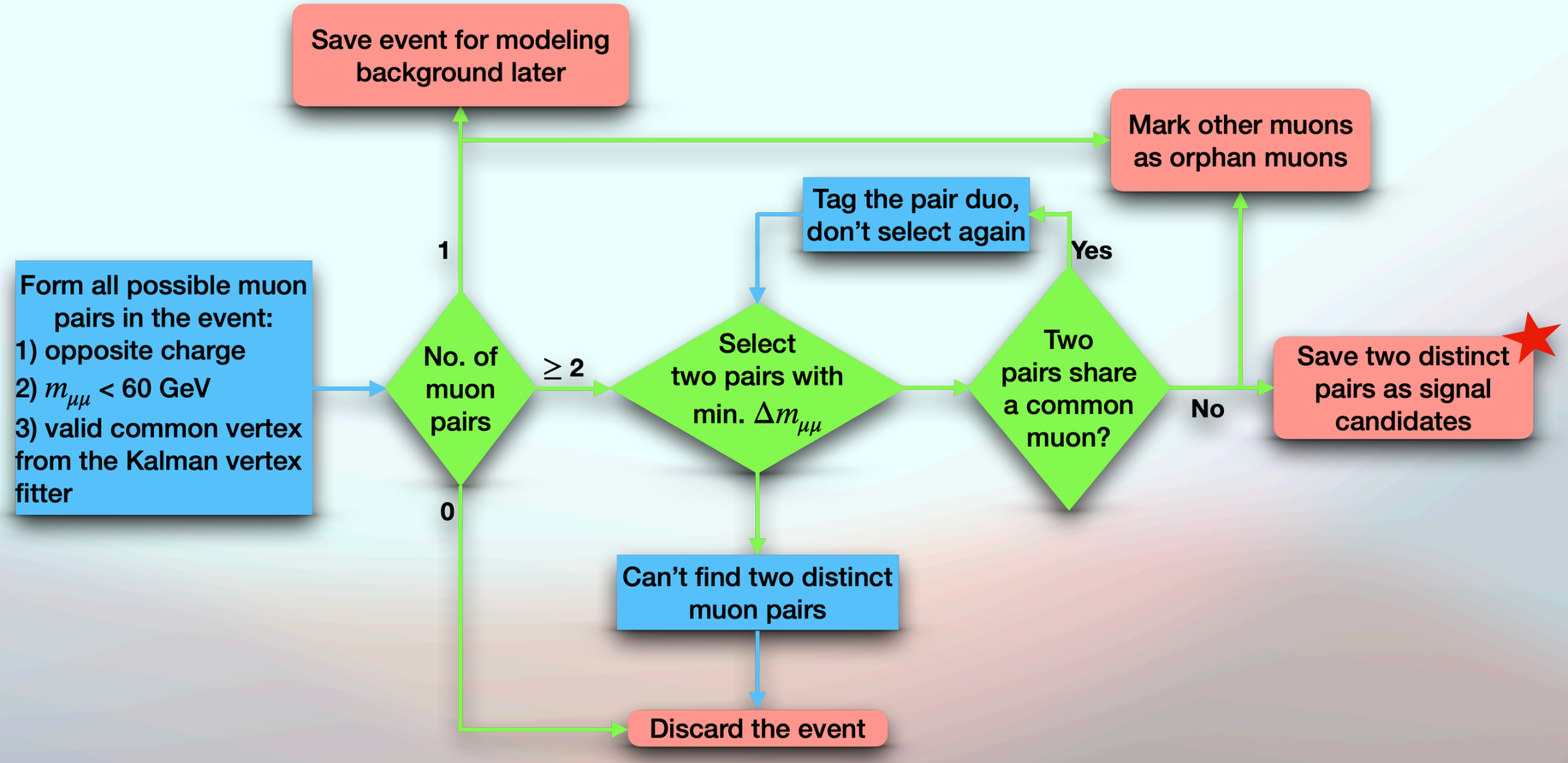
- The **2018 data** from CMS is **analyzed**.

- We are **adding 2017 data** to the analysis to improve the background modeling.

Backups

Analysis

Muon Pairing



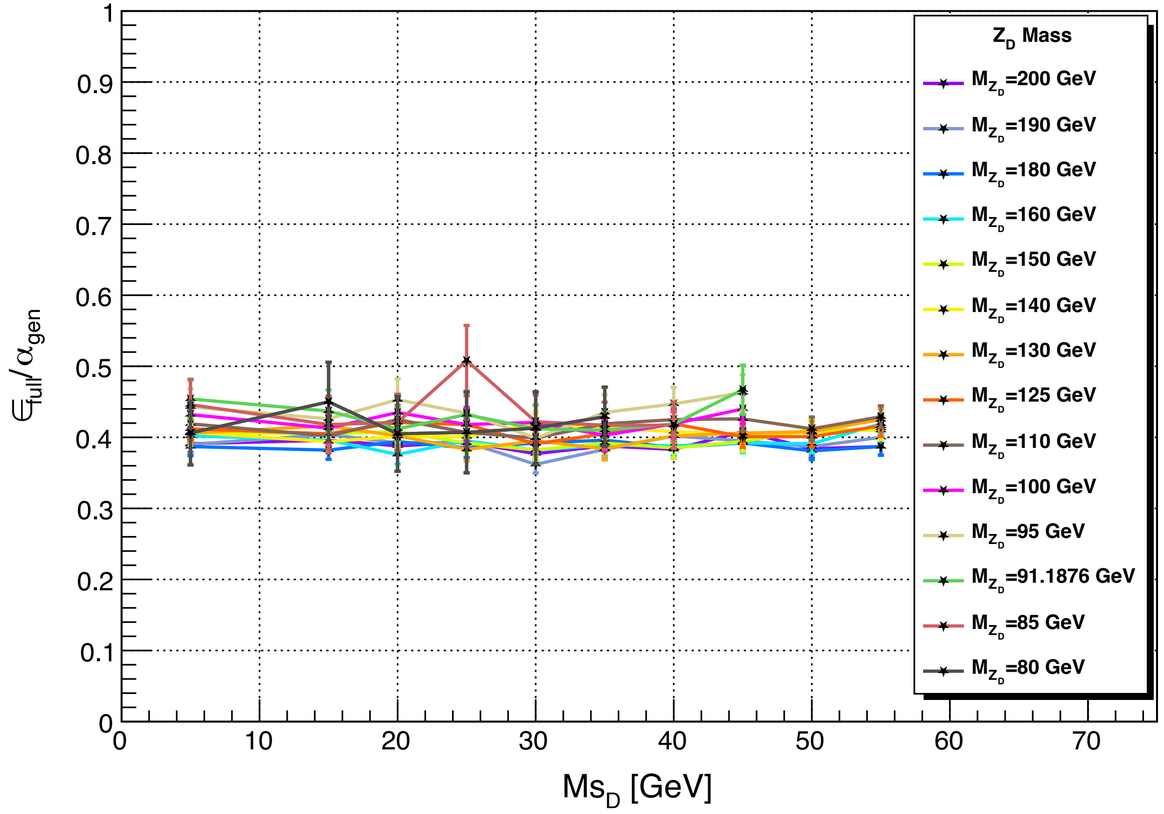
Analysis

High Level Selection

Selection	Description
Pixel Hit	Valid pixel hit for at least one muon in the muon pair: $L_{xy} < 16$ cm, $L_Z < 51.6$ cm
Dimuon Vertex	Fit dimuon vertex of each muon pair using KalmanVertexFitter, $P\mu\mu > P(L_{xy}, f(\Delta R), N_{SA}-\mu)$
Mass Window	Two signal dimuon required to have consistent invariant mass

Perfomance

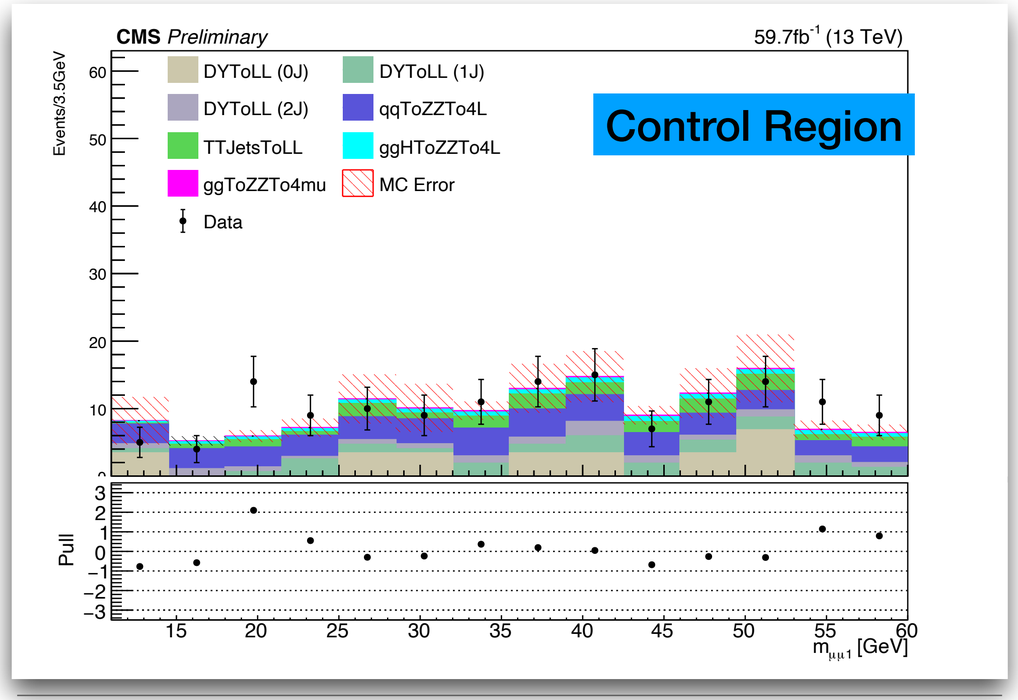
Generator v.s. Reco Efficiency



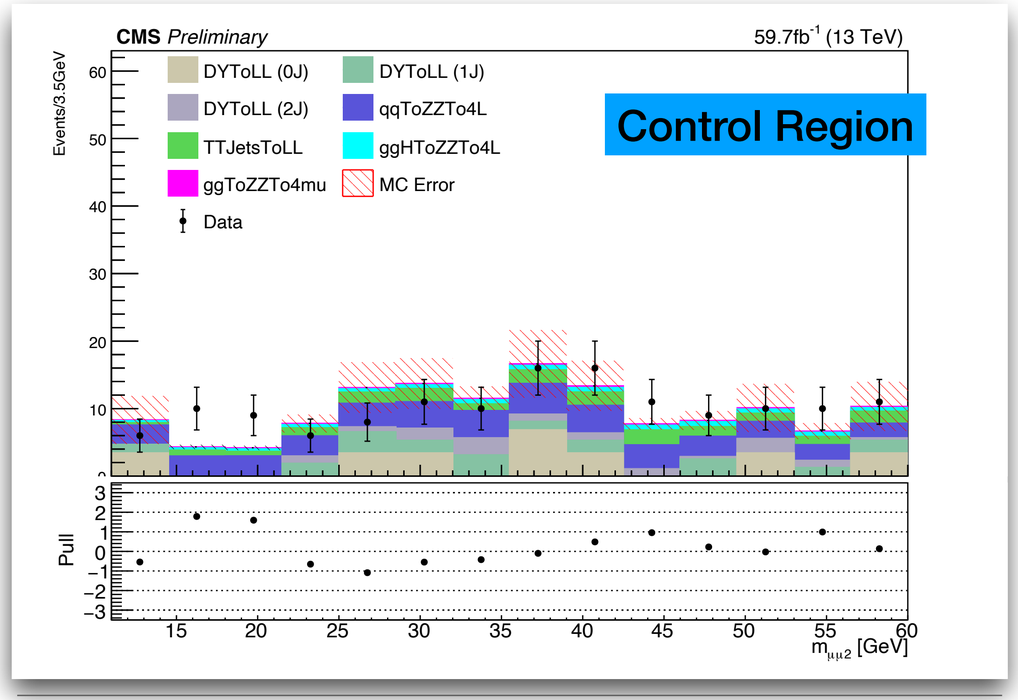
Total selection efficiency over generator level selection acceptance, $\epsilon_{Full}/\alpha_{gen}$ as a function of the s_D mass for various Z_D masses in the vector portal model. The KM parameter, ε, is 10^{-2}.

Background

Above Upsilon (Υ) Resonances (11-60 GeV) - Signal Region



MC simulation compared with the data in control region for muon pair 1.



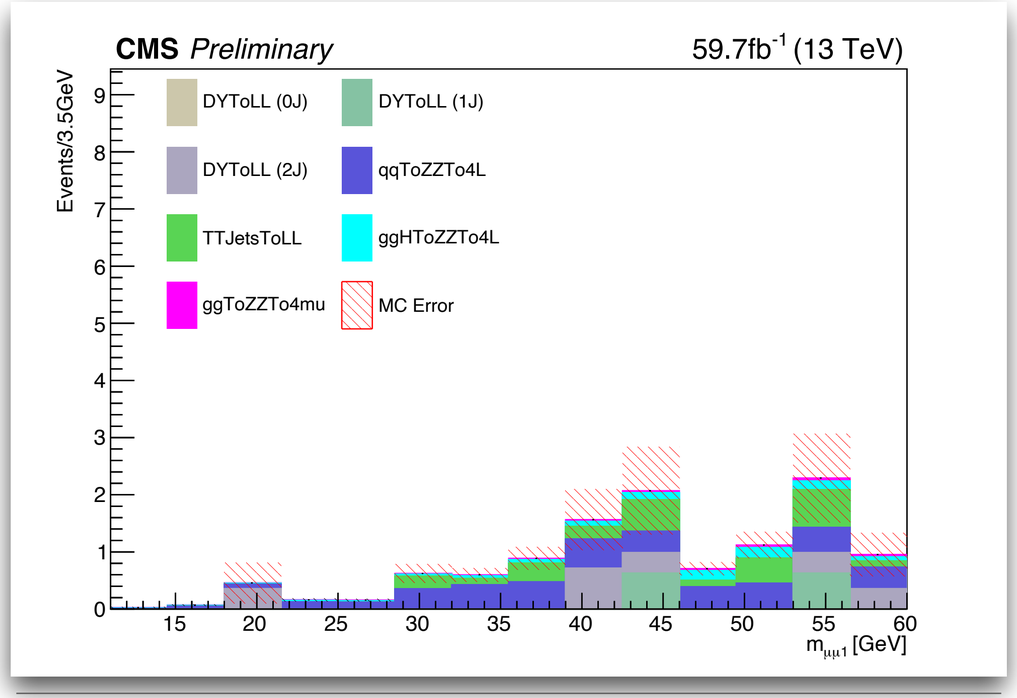
MC simulation compared with the data in control region for muon pair 2.

Good agreement between data and MC in control region

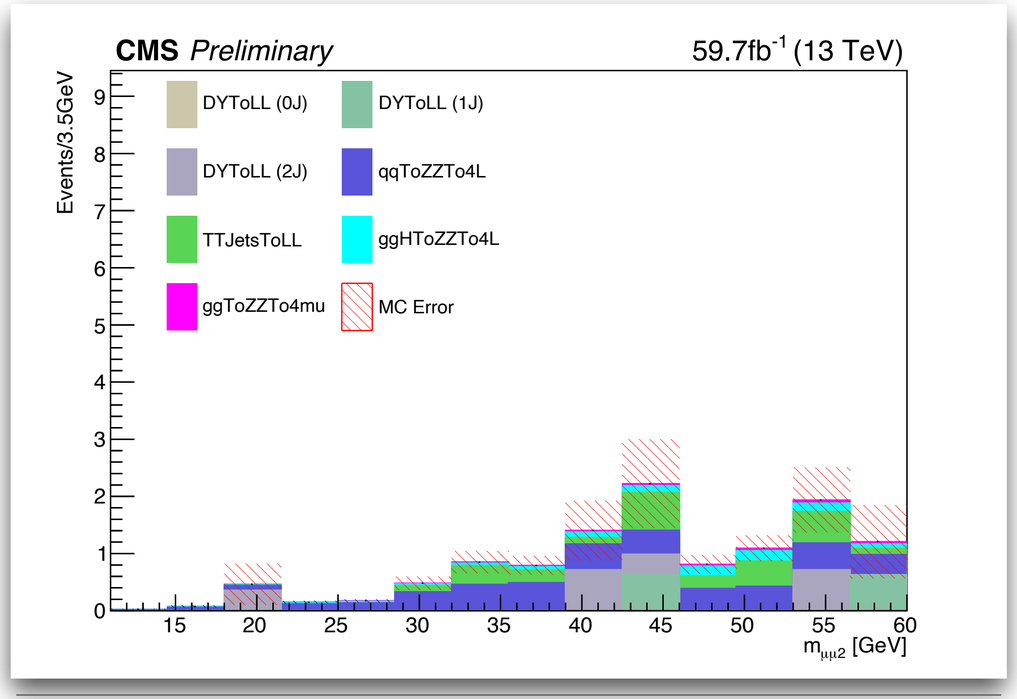
$$\frac{data}{MC} = 1.05 \pm 0.12$$

Background

Above Upsilon (Υ) Resonances (11-60 GeV) - Signal Region



MC simulation in signal region for muon pair 1.



MC simulation in signal region for muon pair 2.

Estimated number of background events in the SR

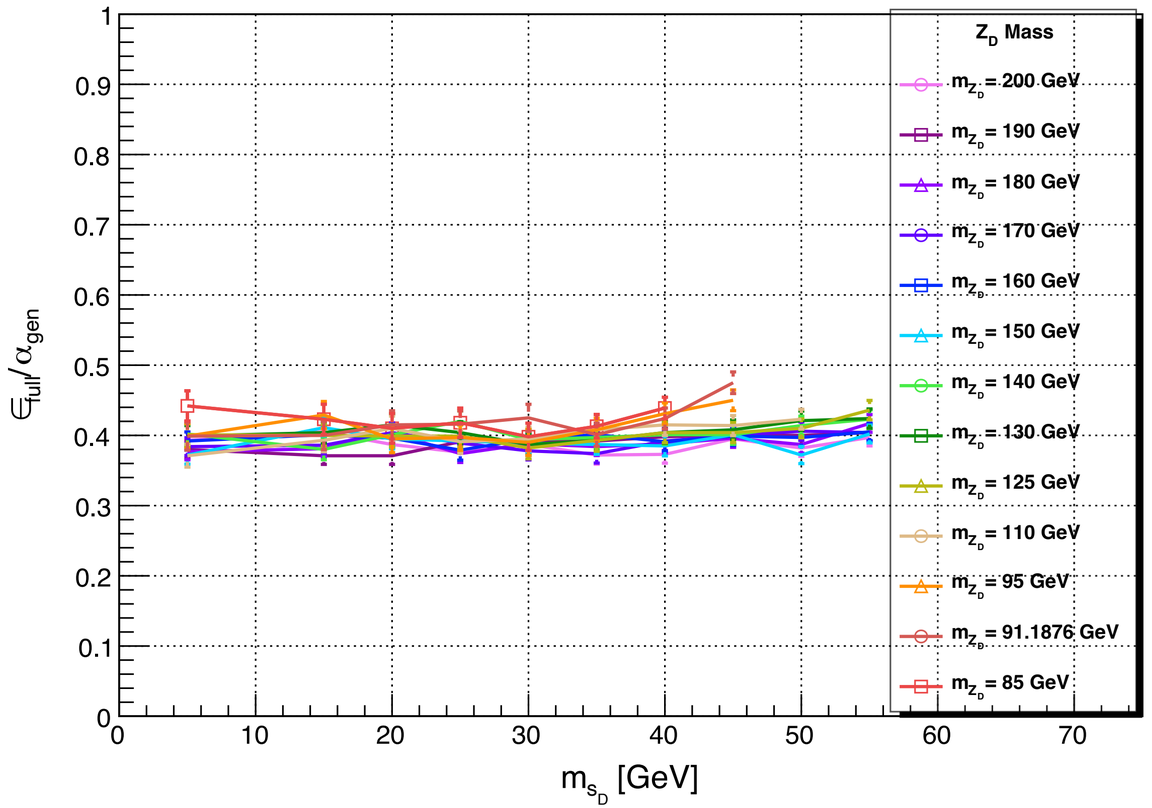
$SR : 12.28 \pm 2.01$

2017 Analysis

Model-Independence Performance

Total selection efficiency over generator level selection acceptance, $\epsilon_{Full}/\alpha_{gen}$ as a function of the s_D mass for various Z_D masses in the vector portal model.

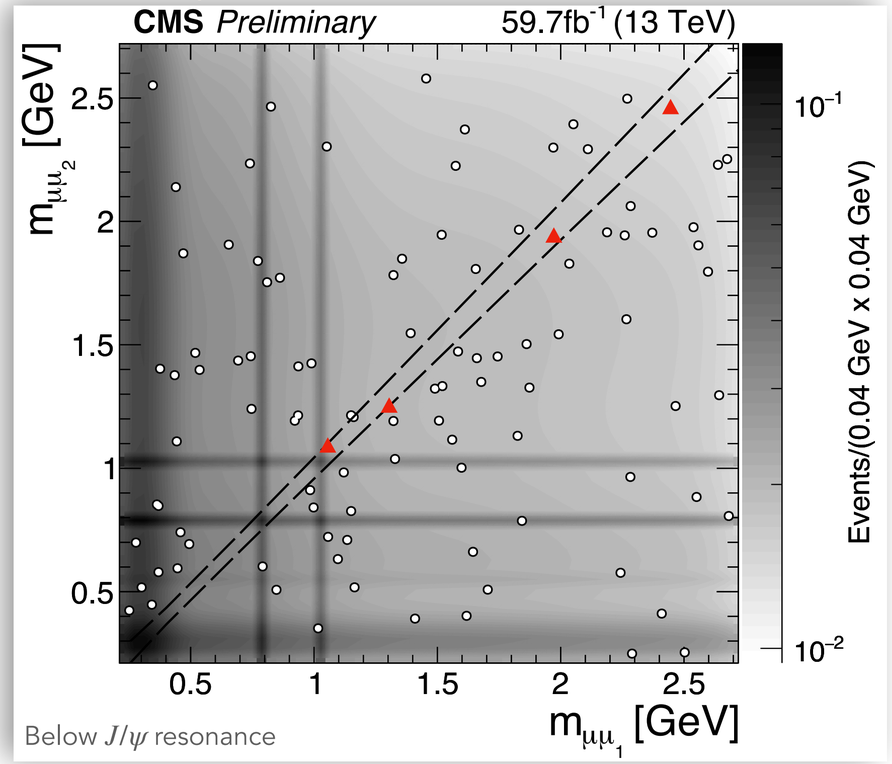
KM parameter, ε, is 10^{-2}



Unblinded Results

Below Upsilon (ϒ) Background

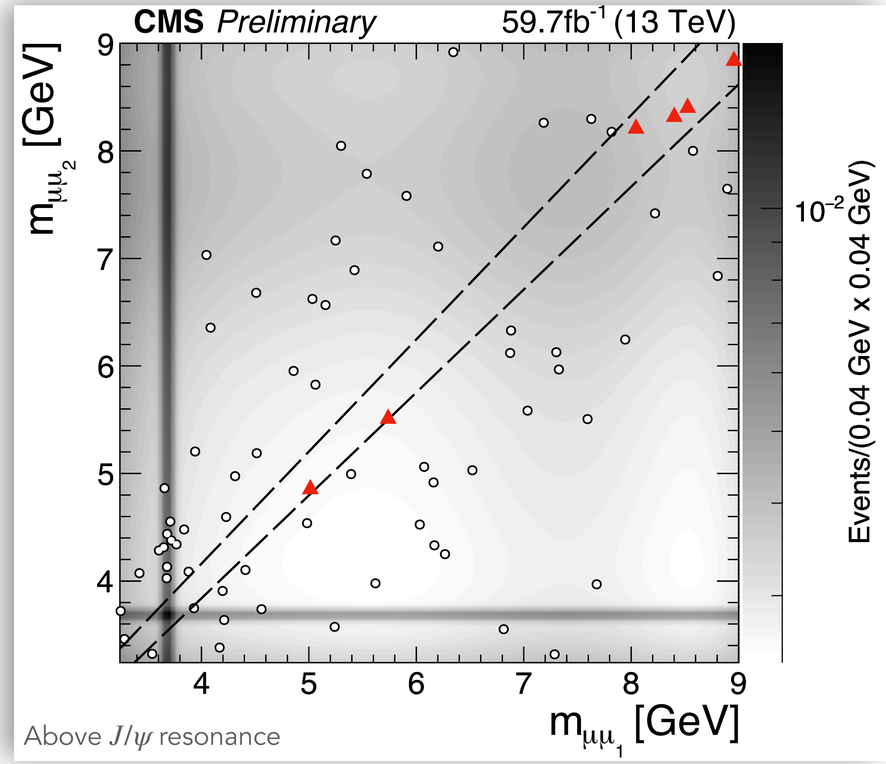
Work in progress



$4.34 \pm 0.44(stat.) \pm 0.18(sys.)$

Observed: 4 Events

Work in progress



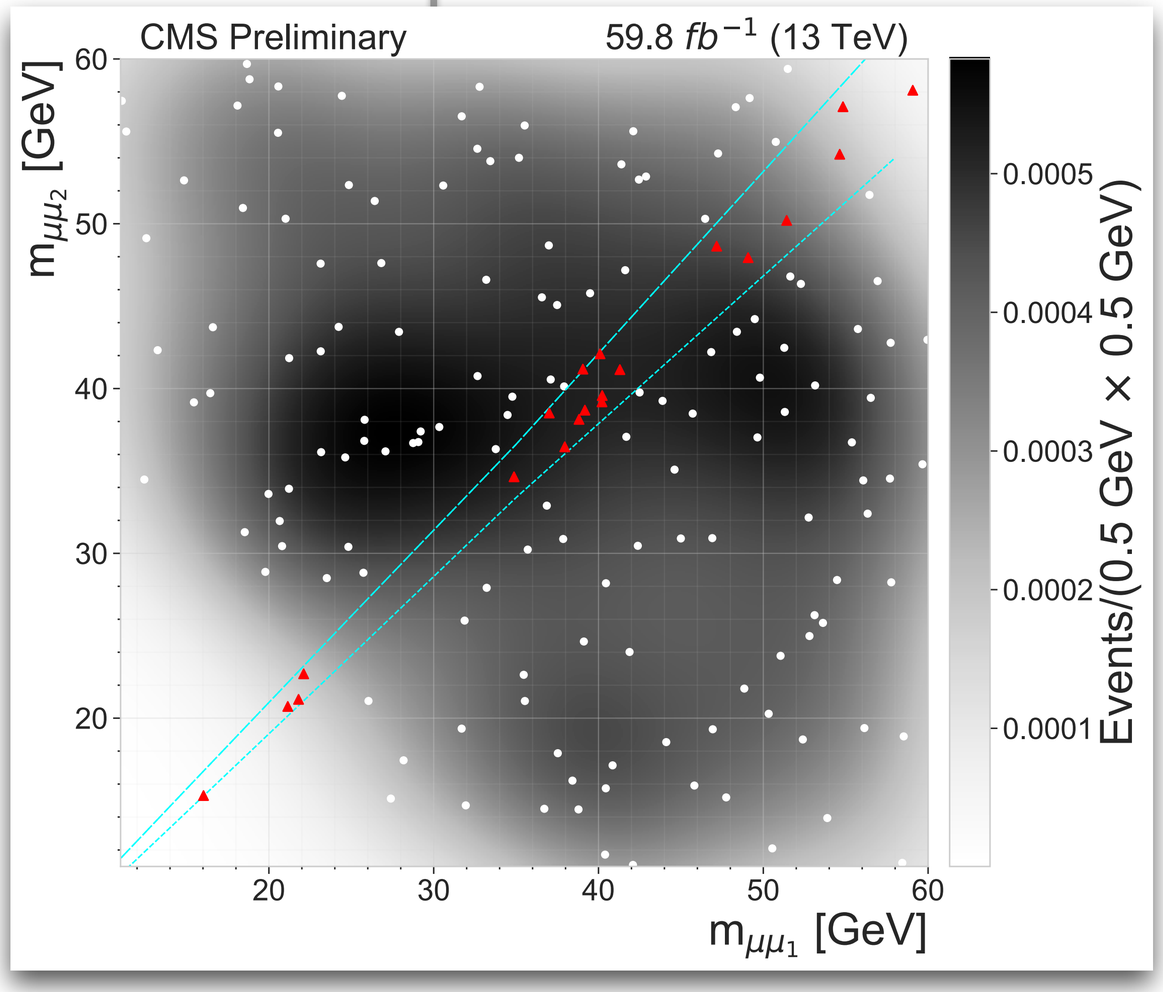
$6.16 \pm 0.76(stat.) \pm 0.09(sys.)$

Observed: 6 Events

Unblinded Results

Above Upsilon (Υ) Background

Work in progress



Work in progress

SR : 12.28 ± 2.01 events

Observed: 20 Events

Results

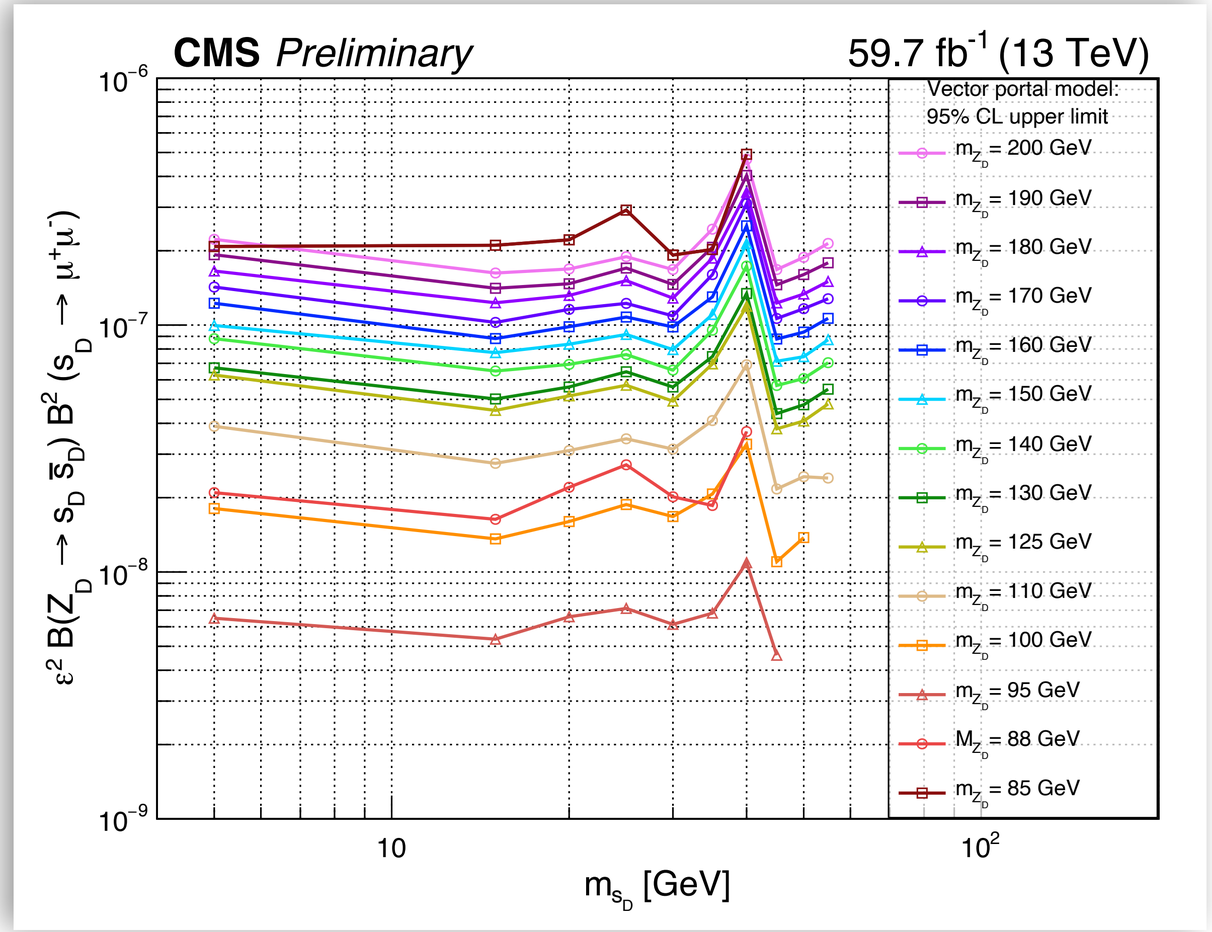
FLORIDA TECH

CMS

Unblinded Results

Observed Limits

The **observed 95%** CL upper limits function of the dark scalar mass m_{s_D} and the dark vector boson mass m_{Z_D}

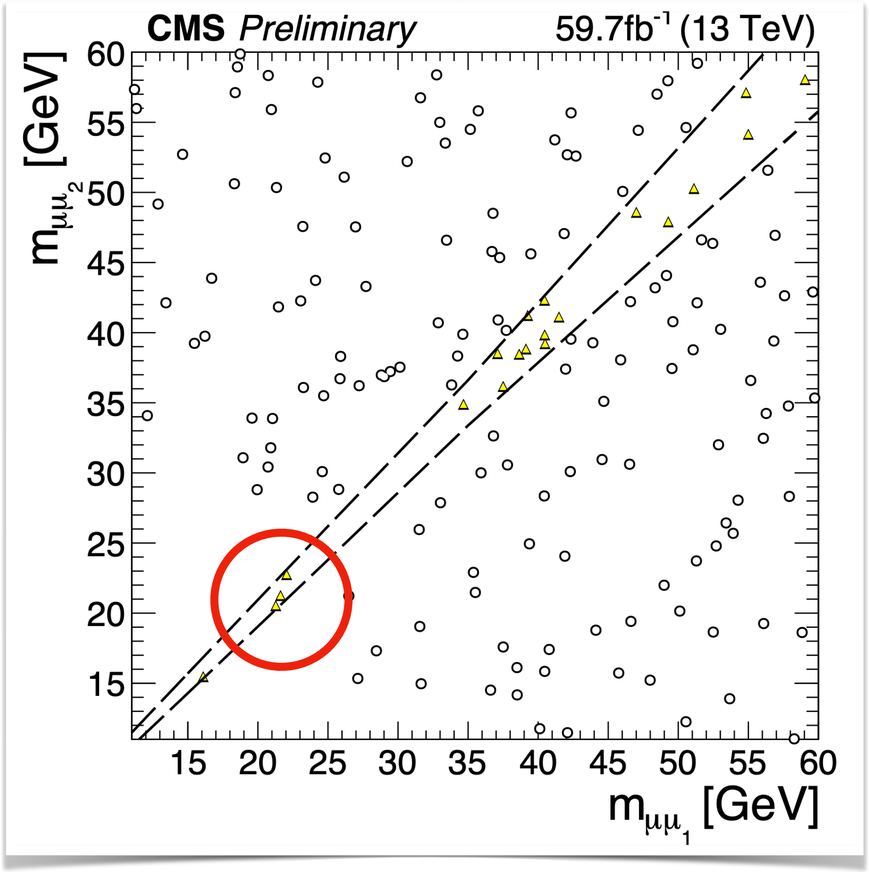


Work in progress

Unblinded Results

2018 Conclusion

- In 20-25 GeV region we observe 3 events
- The expected number of events in the said region is ~0.31
- This observation lead our research to explore the addition of 2017 CMS data to the our analysis



Work in progress

Combination With 2017

FLORIDA TECH

CMS

2017 Analysis | Tigger Paths and Selections

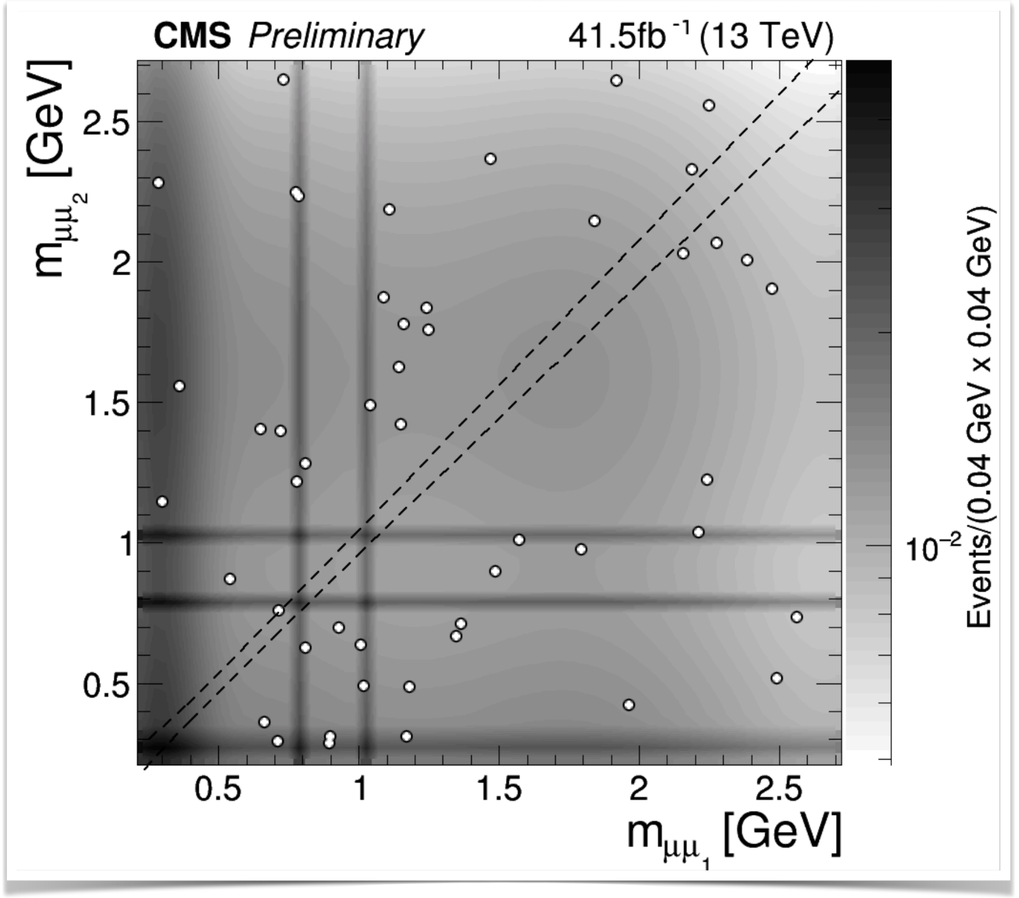
Trigger Paths
HLT_Mu23_Mu12
HLT_Mu18_Mu9_SameSign
HLT_TrkMu12_DoubleTrkMu5NoFiltersNoVtx
HLT_TripleMu_12_10_5

Muon selection
slimmedMuons in MiniAOD
4 PF Loose muon
Two muons: p_T >13 GeV, letal < 2
Four muons: p_T >8 GeV, letal < 2.4

Dataset Labels	Number of
/DoubleMuon/Run2017B-31Mar2018-v1/	14 501 767
/DoubleMuon/Run2017C-31Mar2018-v1/	49 636 525
/DoubleMuon/Run2017D-31Mar2018-v1/	23 075 733
/DoubleMuon/Run2017E-31Mar2018-v1/	51 589 091
/DoubleMuon/Run2017F-31Mar2018-v1/	79 756 560
Total	218 559 676

2017 Analysis | Background: Below Υ Resonances

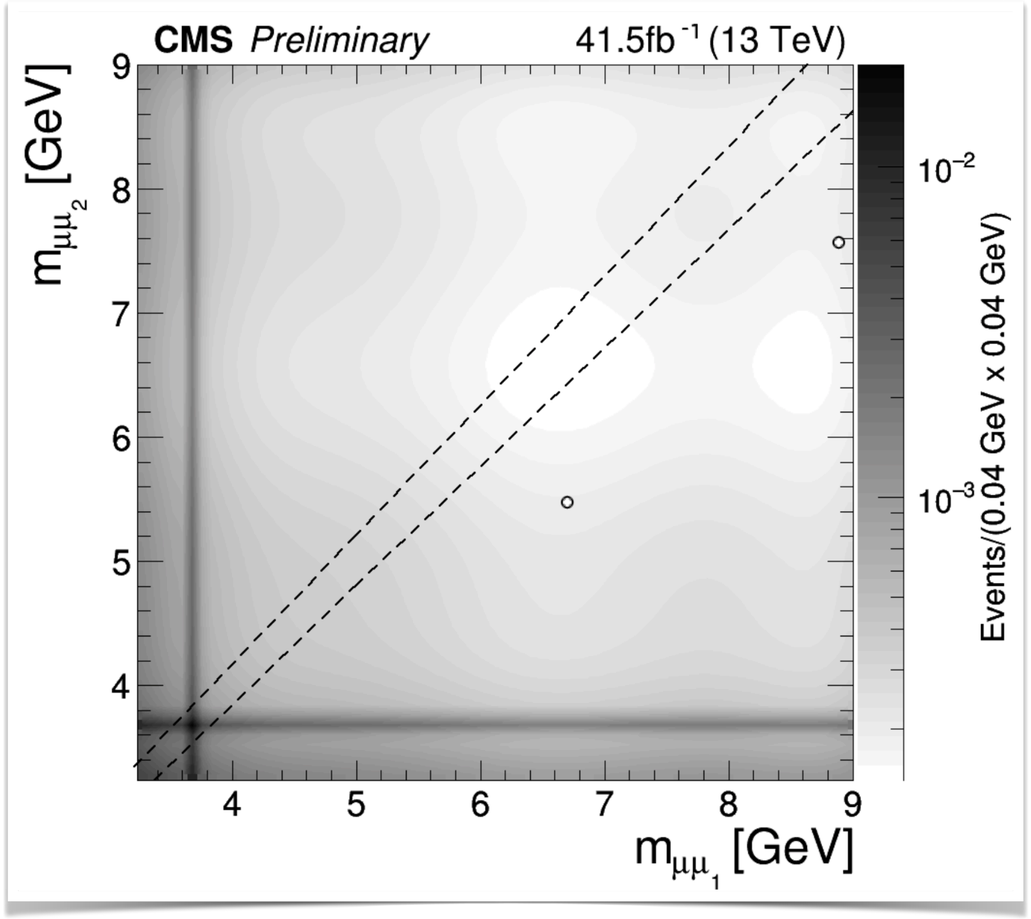
- 2D template integral SR/CR = 0.044/0.964
- 2-dimu events at CR: 49 (SR remain blinded)
- Estimated BKG events at SR: 2.26 +/- 0.32



Work in progress

2017 Analysis | Background: Below ϒ Resonances

- 2D template integral SR/CR = 0.087/0.918
- 2-dimu events at CR: 2 (SR remain blinded)
- Estimated BKG events at SR: 0.19 +/- 0.13

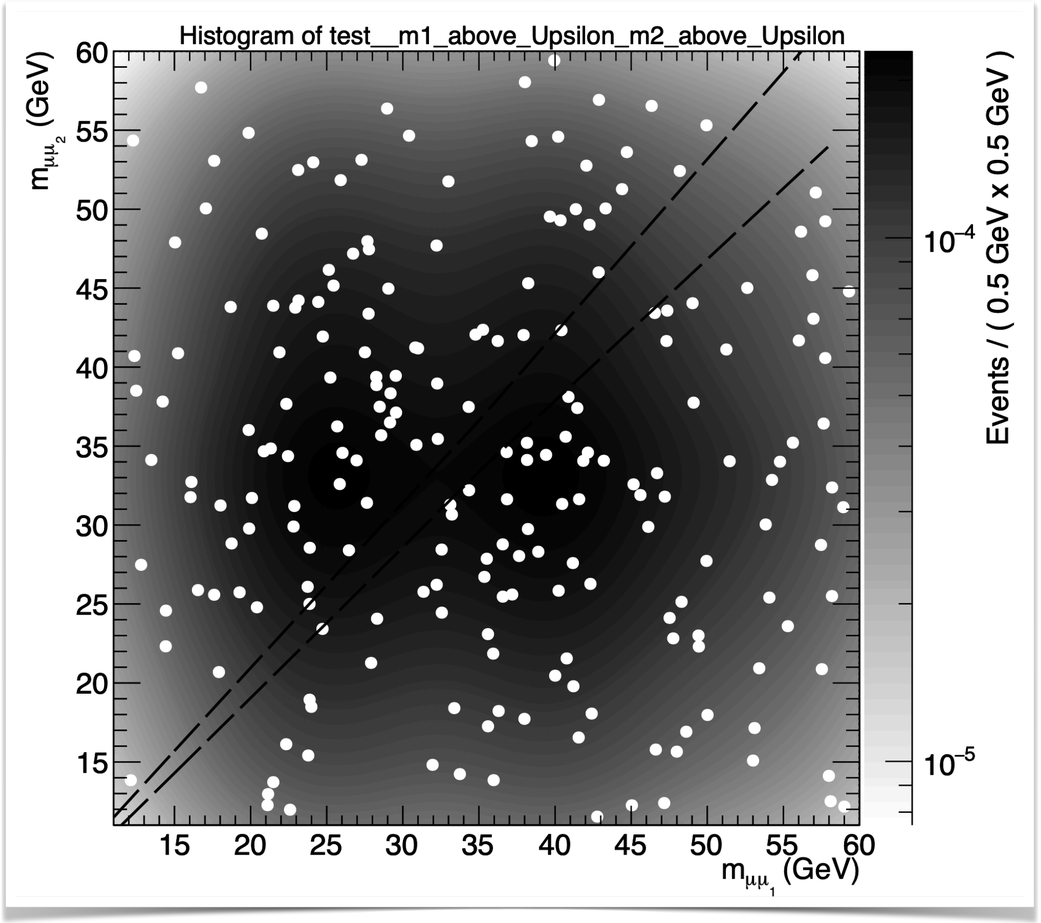


Work in progress

2017 Analysis

Background: Above Υ Resonances

- 2D template integral SR/CR = 0.082/0.918
- 2-dimu events at CR: 212 (SR remain blinded)
- Estimated BKG events at SR: 18.97 +/- 1.3



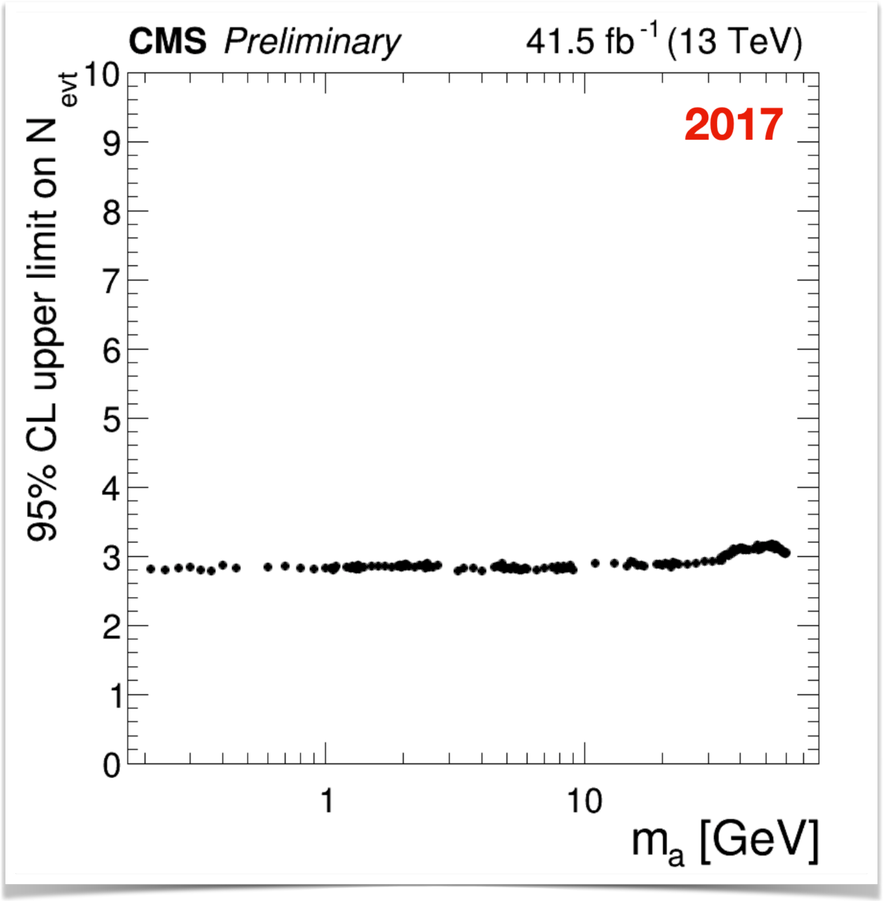
Work in progress

2017 Analysis | Summary

Expected model independent 95% CL upper limit on the number of events.

The analysis remains approximately **near zero background** analysis

The results to be **combined with 2018 and 2016** results using the Higgs combine tool



Work in progress

Summary

- A **model independent analysis** for $pp \rightarrow 2a \rightarrow 4\mu$ is represented

- A **vector-portal model** is introduced as a **benchmark** dark matter model: $pp \rightarrow Z_D \rightarrow s_D\overline{s_D} \rightarrow 4\mu$

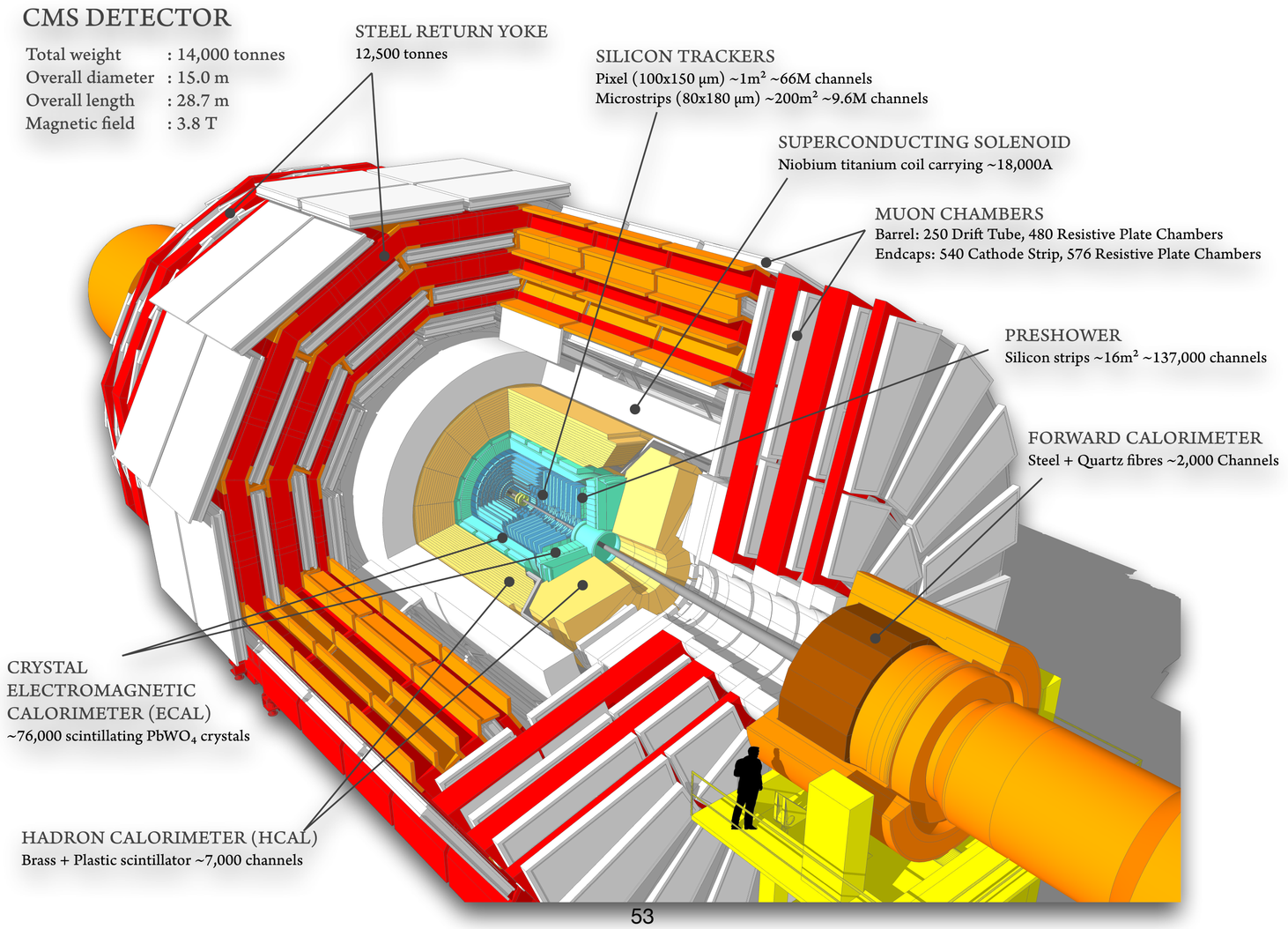
- Model independent **upper limits** on kinetic mixing parameter, cross-section branching ratio and acceptance **are set**.

- The **2018 data** from CMS is **analyzed**.

- We are **adding 2017 data** to the analysis to improve the background modeling.

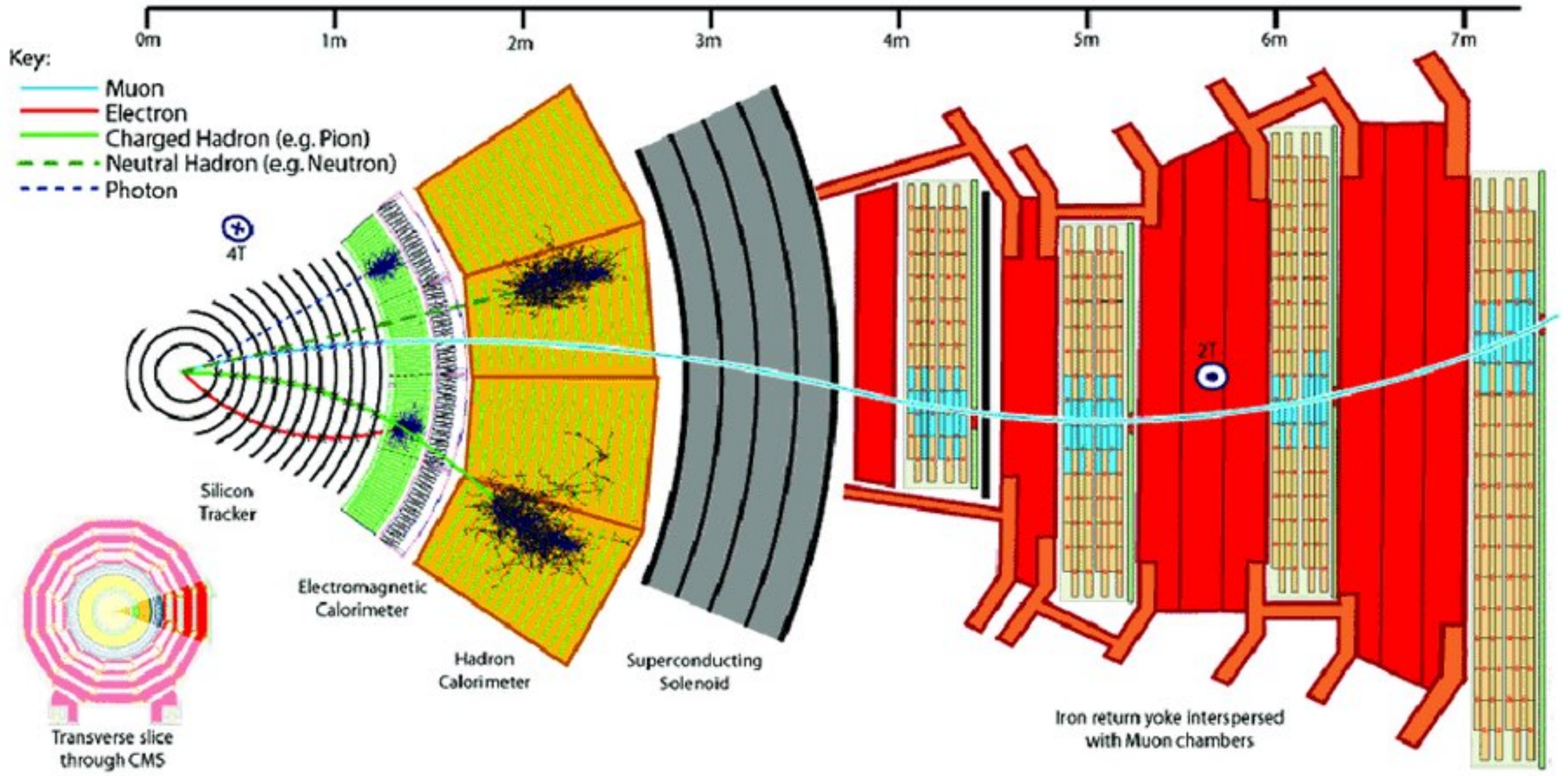
The Experimental Apparatus

CMS Illustration



The Experimental Apparatus

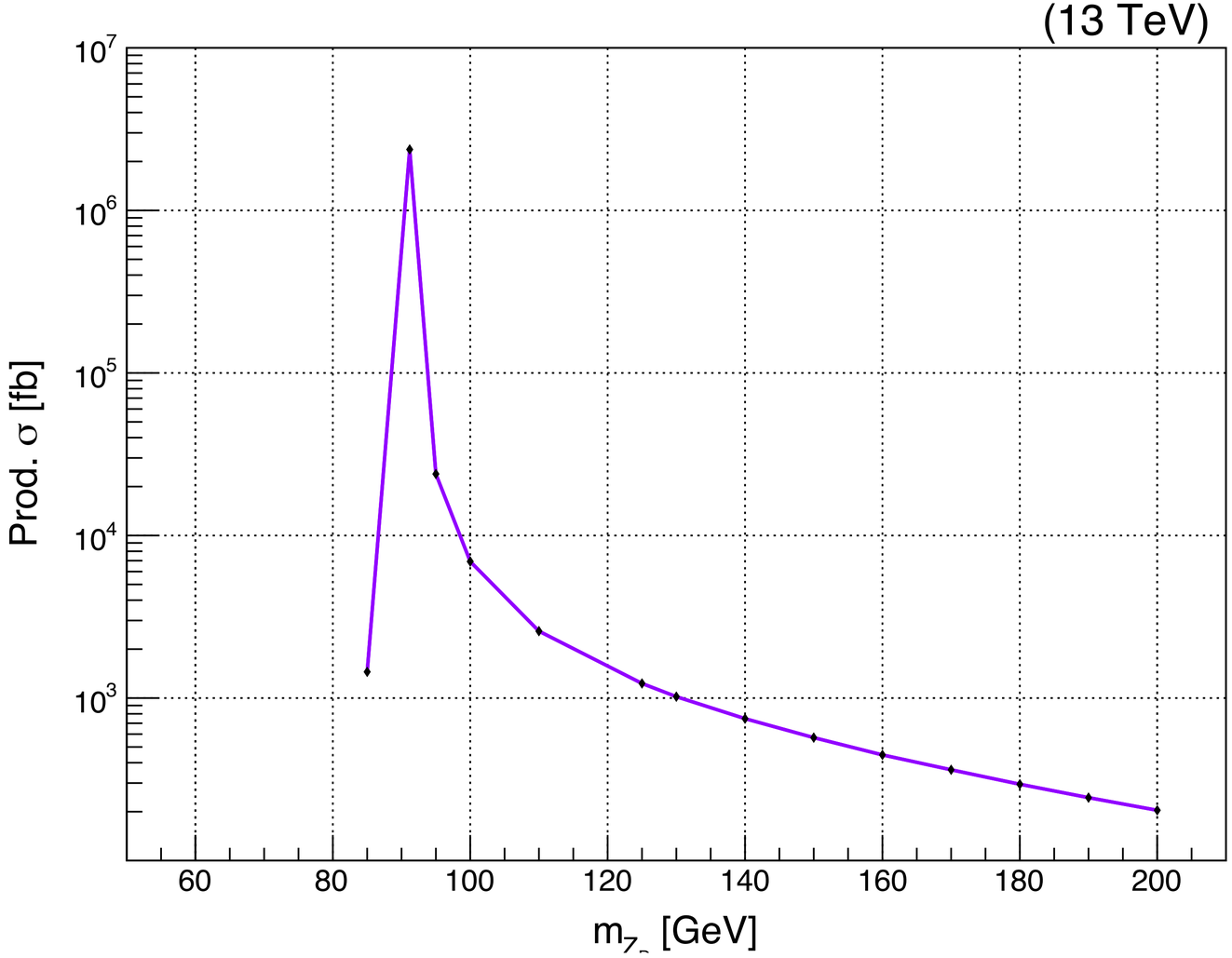
Bending Muons



Hard Process | Kinematics of the Model

A scan of production cross-section for

varying mass of Z_D.



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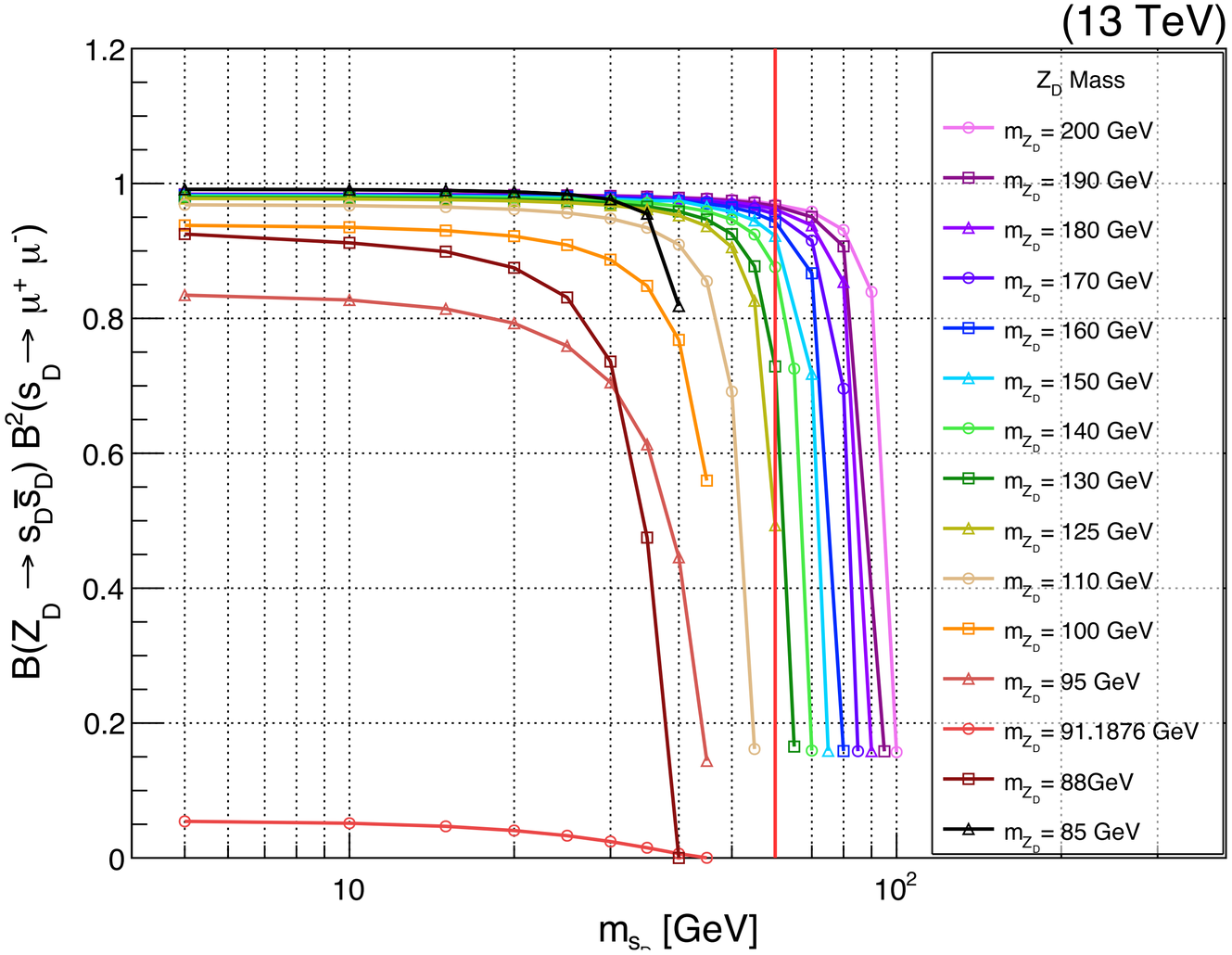

Hard Process | Kinematics of the Model

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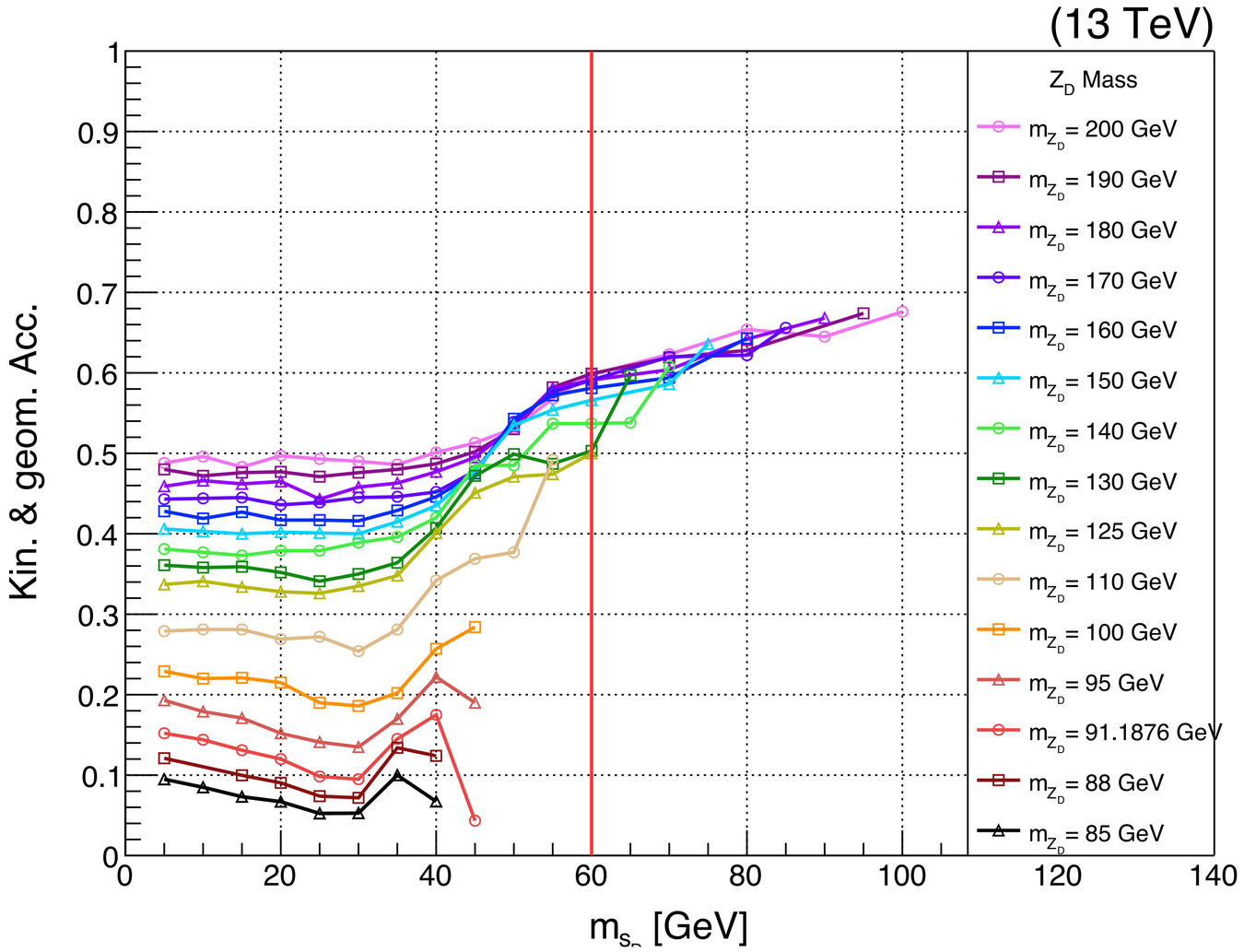
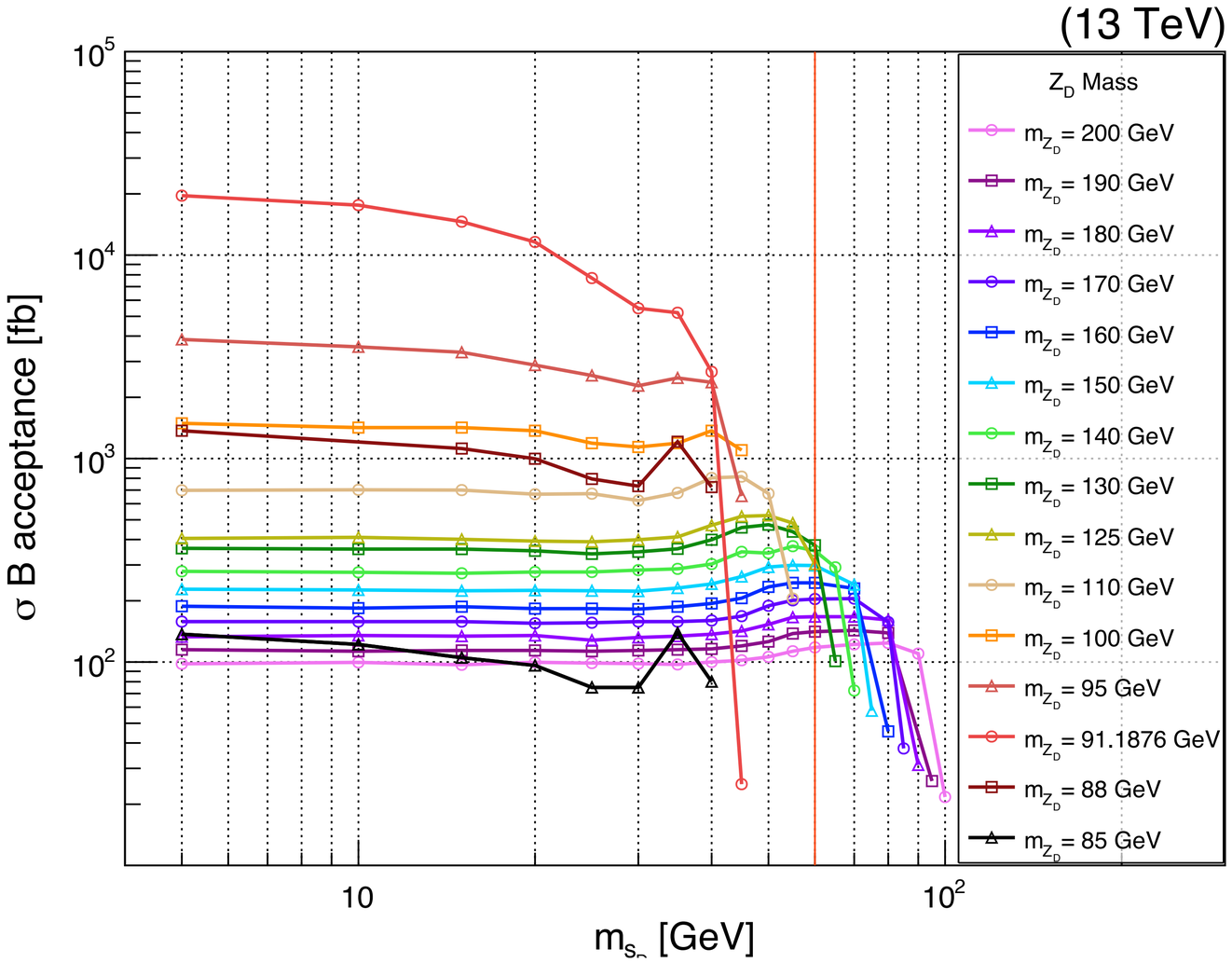


Hard Process | Kinematics of the Model

A scan of production cross-section for

varying mass of Z_D.



Model-Independence Performance

Generator v.s. Reco

Model independent ratio: $\epsilon_{Full}/\alpha_{Gen}$

- α_{Gen} : generator level acceptance
  - 4 gen-muons p_T and η selection + fiducial cuts
- ϵ_{Full}: full analysis efficiency
  - 4 reco-muons p_T and η selection + fiducial cuts+ full selection

Constant $\epsilon_{Full}/\alpha_{Gen}$ indicates model performance is independent of its parameters

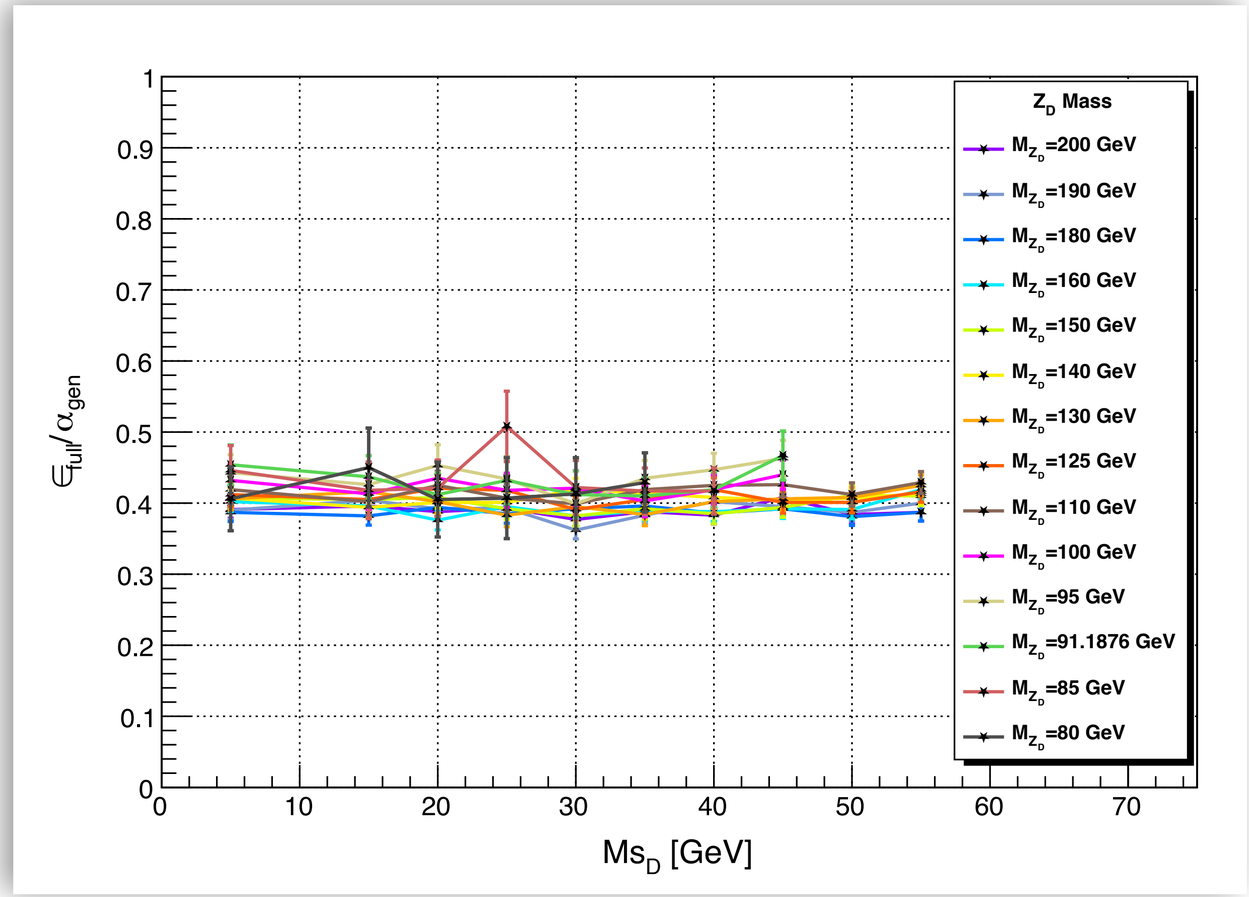
Average $\epsilon_{Full}/\alpha_{Gen}$ = 0.418 is consistent with other benchmark models

Model-Independence

Generator v.s. Reco

Total selection efficiency over generator level selection acceptance, $\epsilon_{Full}/\alpha_{gen}$ as a function of the $s_D$mass for various Z_D masses in the vector portal model.

The KM parameter, ε, is 10^{-2}.



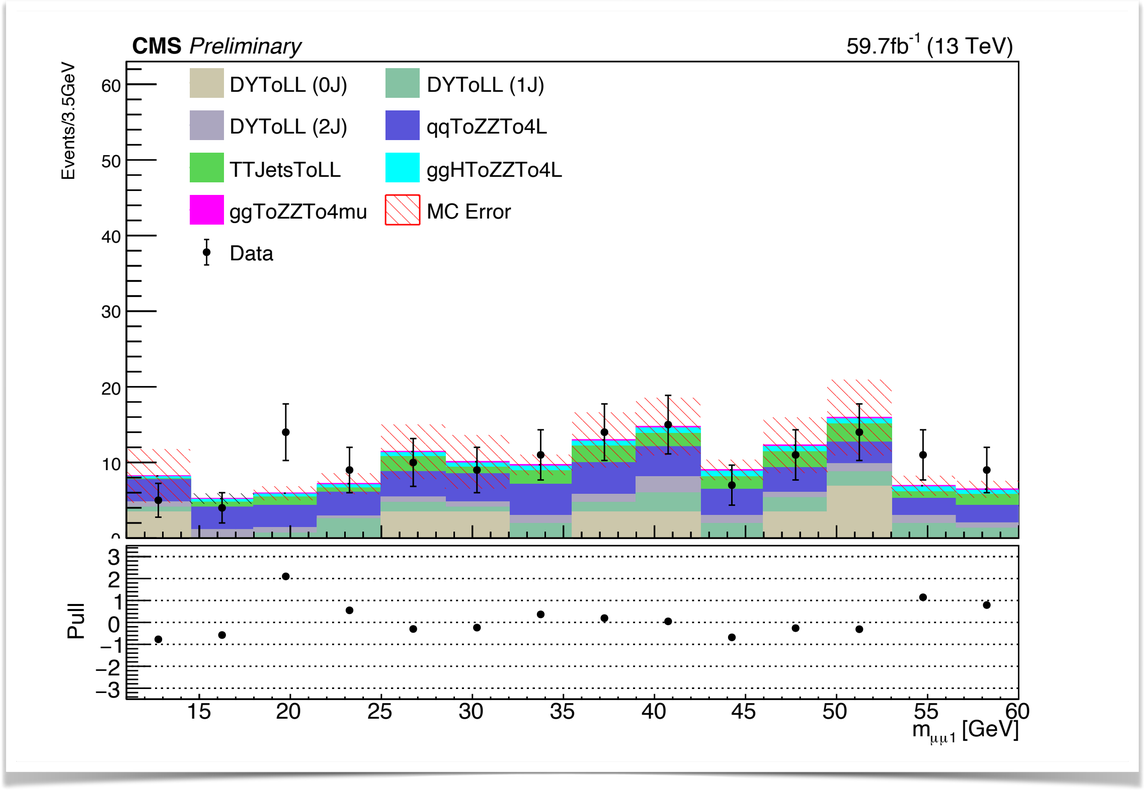
Background Estimation

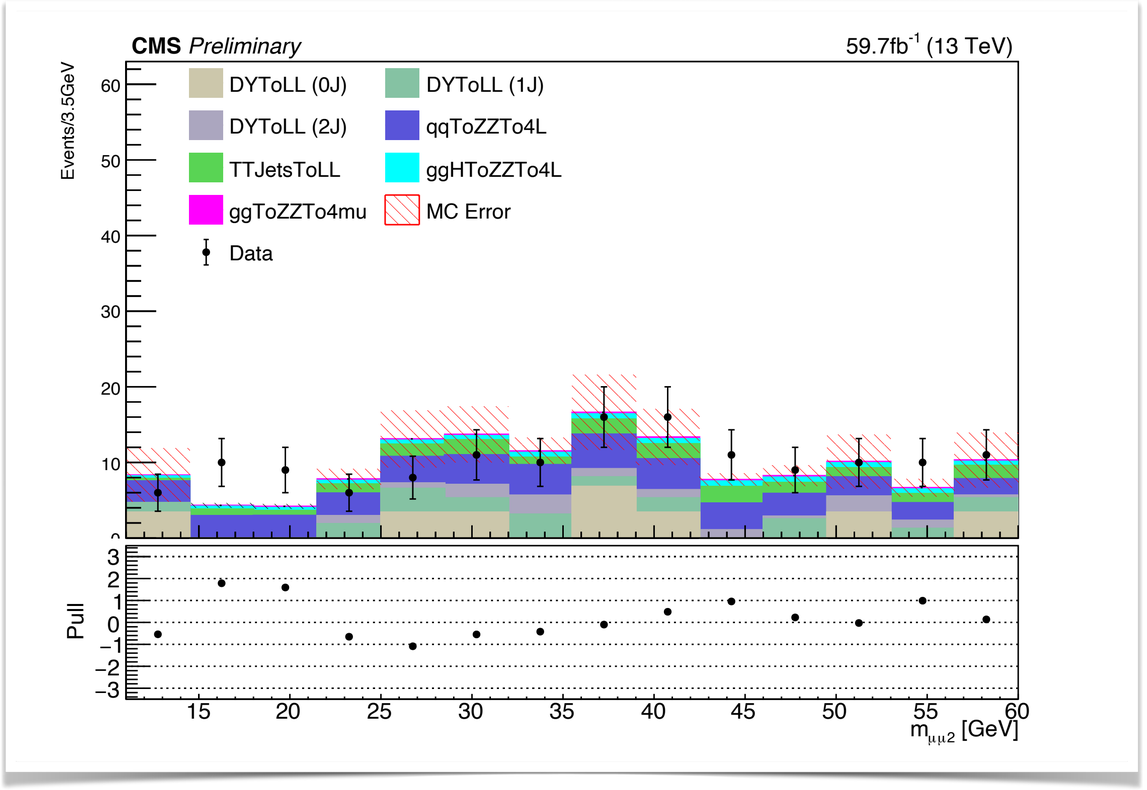
Below Upsilon (Υ) Resonances (0.25-9 GeV)

- Dominated by QCD multi-jet processes, especially contributions from $b\bar{b}$
- Double semi-leptonic decay or decay via resonances ($\eta, \omega, \phi, J/\psi(1S), \psi(2S)$)
- Data driven (2018 DoubleMuon): because, MC for QCD processes are limited
- Construct 2D background templates, based on 1D MC distributions and fitting them -> $f(m_{\mu\mu_1}) \otimes f(m_{\mu\mu_2})$. (See **App. B**)
- Estimate the number of background events in the signal region

Background Estimation

Above Upsilon (ϒ) Resonances (11-60 GeV) - Control Region

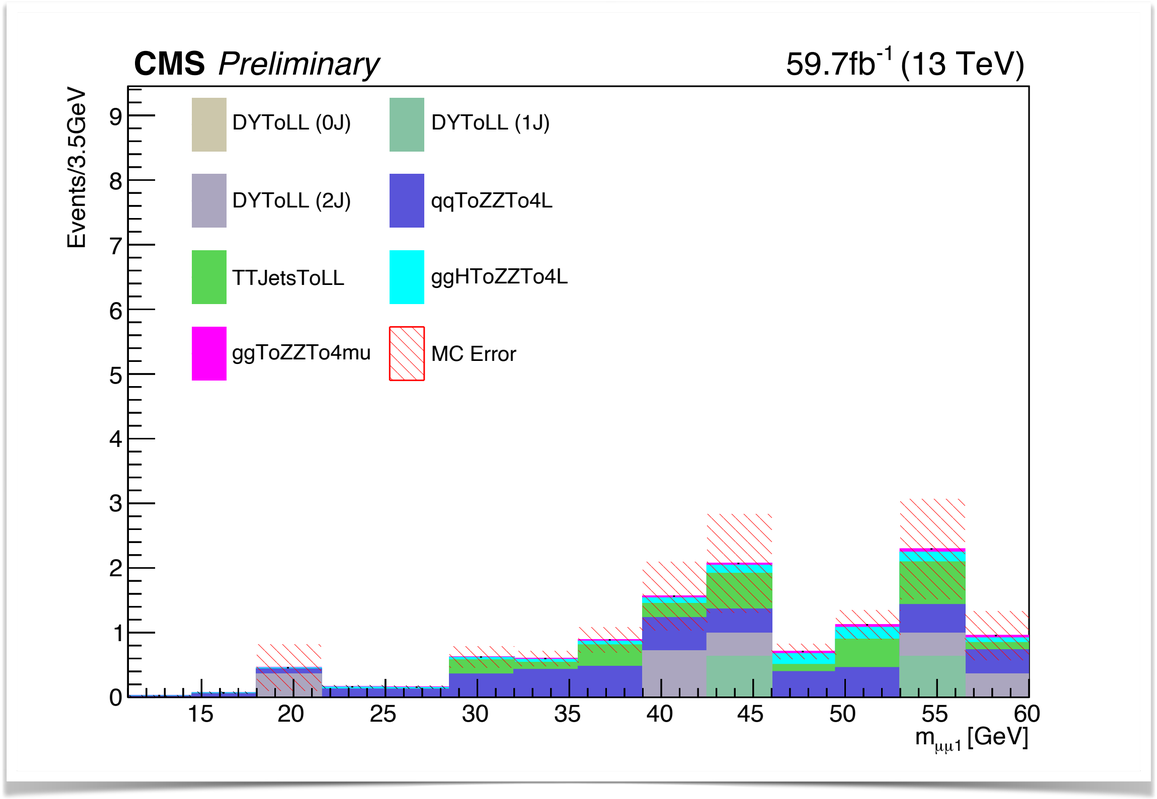


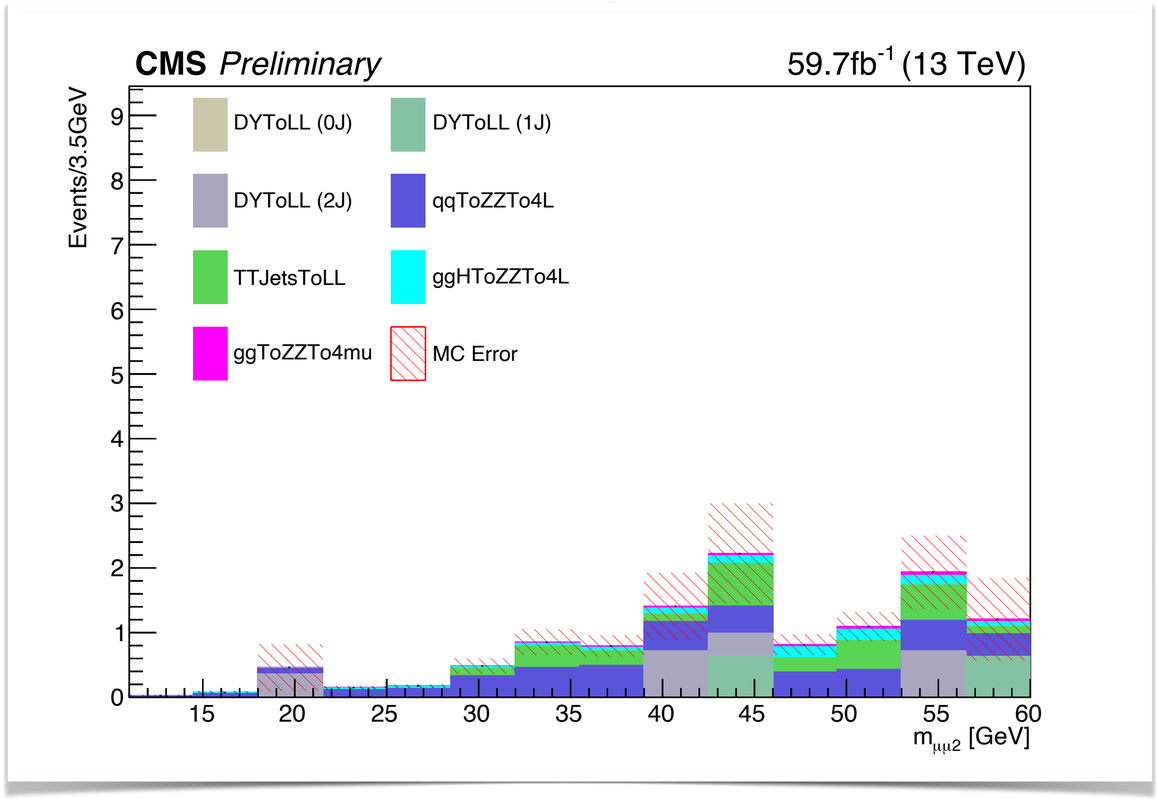


Good agreement between data and MC in control region.

Background Estimation

Above Upsilon (Υ) Resonances (11-60 GeV) - Signal Region





Estimated number of background events = $SR : 12.28 \pm 2.01$