Search for inelastic dark matter with CMS

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On behalf of the CMS Collaboration

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arXiv: 2305.11649

Inelastic dark matter

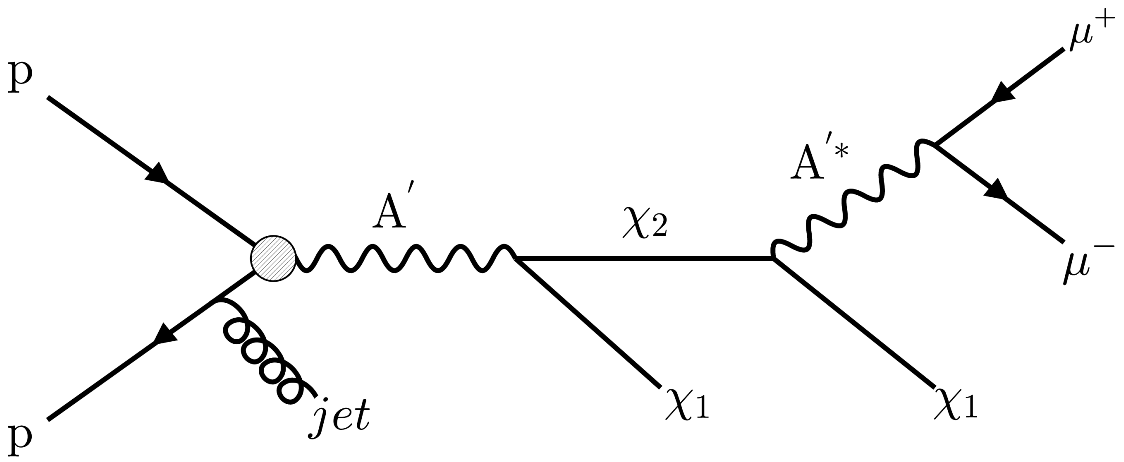
- Dark matter states χ_2 and χ_1 with near mass degeneracy
- Predominant inelastic (off-diagonal) coupling between χ_2 and χ_1
- → By adding small Majorana mass term

Smith & Weiner, PRD 64 (2001) 043502

$$\overline{\psi}\gamma_\mu\psi \simeq i(\overline{\chi}_1\overline{\sigma}_\mu\chi_2 - \overline{\chi}_2\overline{\sigma}_\mu\chi_1) + \frac{\delta}{2m}(\overline{\chi}_2\overline{\sigma}_\mu\chi_2 - \overline{\chi}_1\overline{\sigma}_\mu\chi_1).$$

Izaguirre, Krnjaic & Shuve, PRD 93 (2015) 063523

Vector current couples χ_2 to χ_1 since $\delta/m \ll 1$ with δ the mass splitting



- Kinetic mixing ϵ between γ, Z and dark photon A'
- Compatible with observed thermal-relic DM abundance

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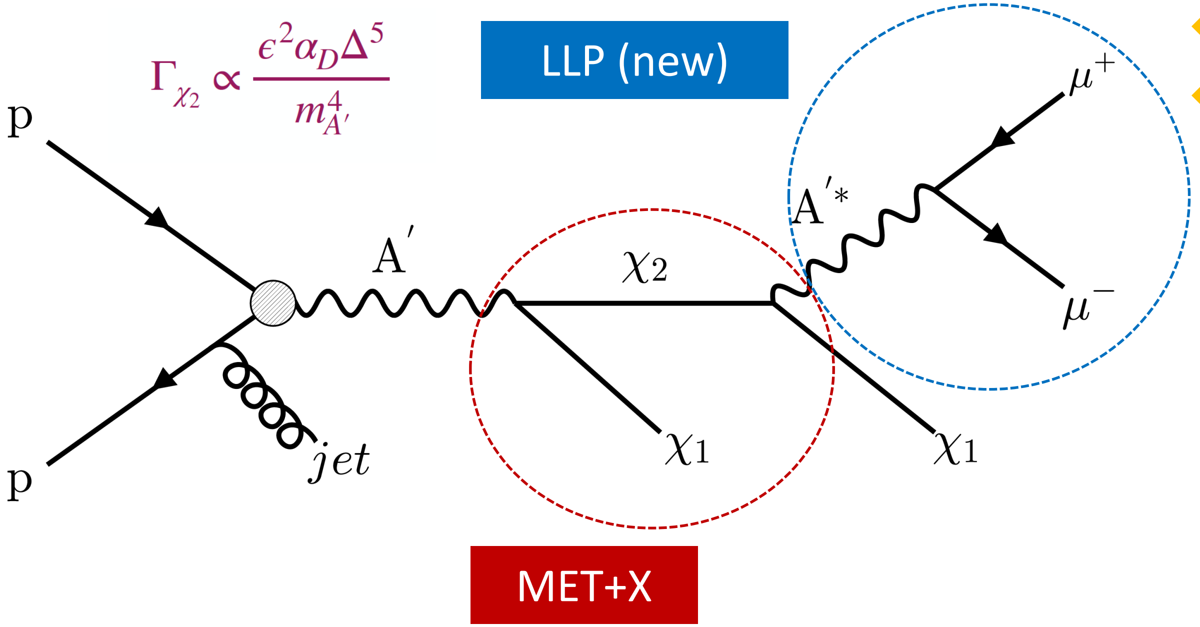

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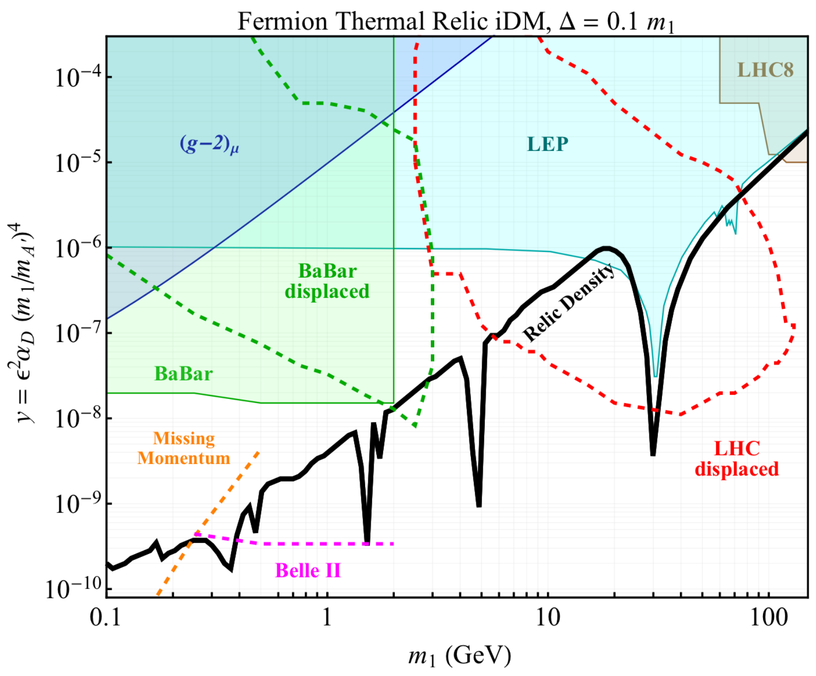
Parameter	Symbol	Values	Notes
χ_1 mass	m_1	3—80 GeV	Experiment reach and theory interest
χ_2-χ_1 mass splitting	Δ	{0.1, 0.4} m_1	
χ_2 lifetime	$c\tau$	1—1000 mm	
Dark photon mass	$m_{A'}$	3 m_1	$m_{A'} \gtrsim m_1 + m_2$
Dark sector α	α_D	{0.1, a_{EM}}	$\alpha_D \propto 1/\varepsilon^2$
Kinetic mixing	ε	Fixed by others	$\sigma_{prod} \propto \varepsilon^4$

Theory sensitivity projections

Izaguirre, Krnjaic & Shuve, PRD 93 (2015) 063523

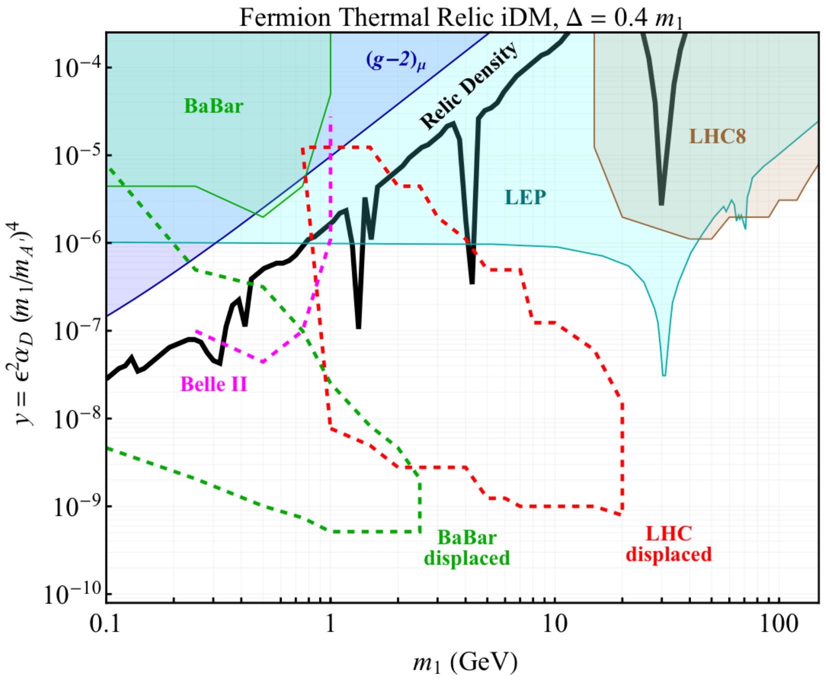
- Projected sensitivity from theory ("LHC displaced" curves)
- Lower y sensitivity for higher mass splittings, but thermal-relic DM curve also shifts up
- Lower mass sensitivity range limited by the ability to produce two muons

10% mass splitting

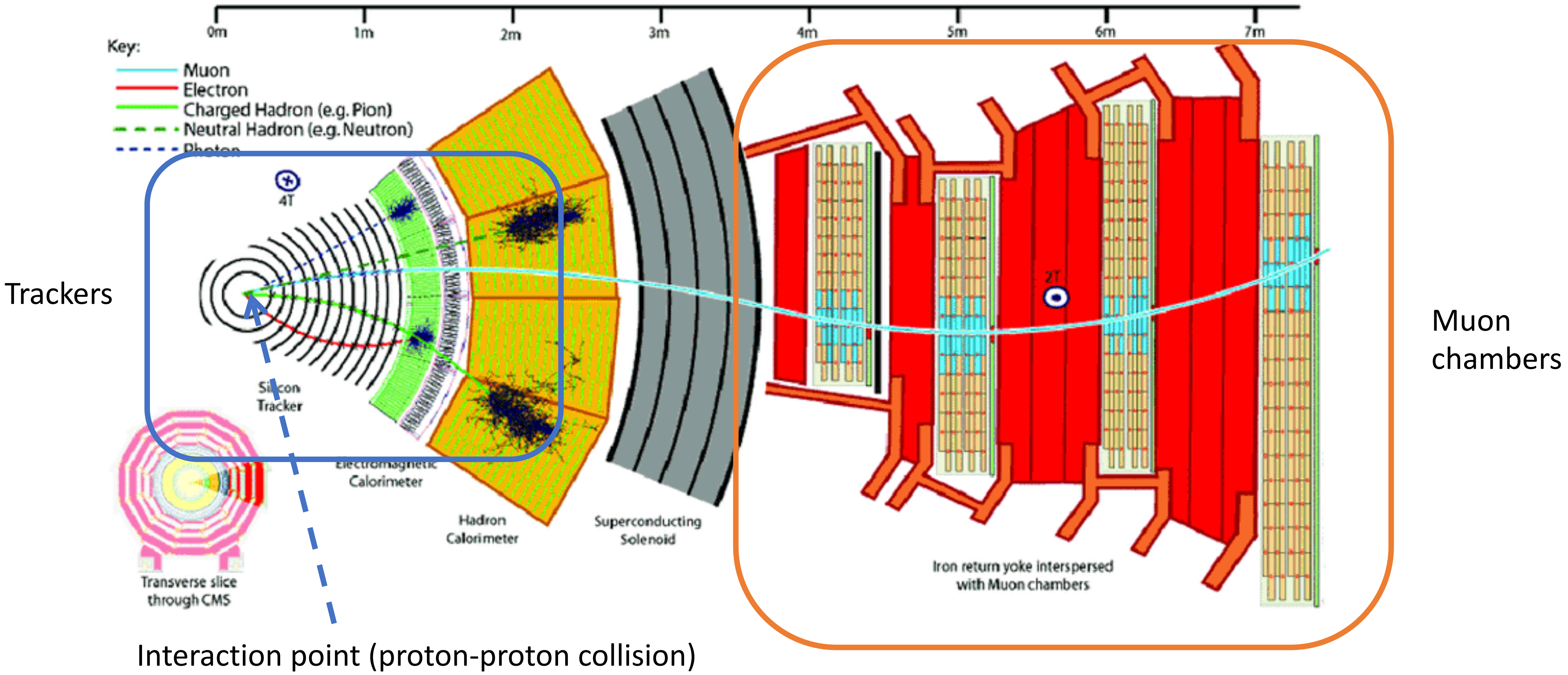


$$\sigma v \propto y \equiv \epsilon^2 \alpha_D \left(\frac{m_1}{m_{A'}} \right)^4$$

40% mass splitting

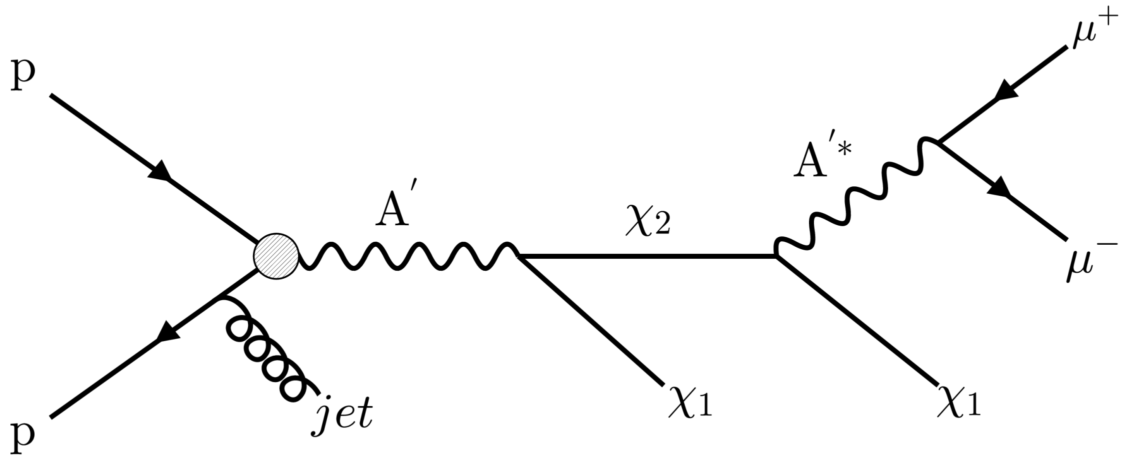


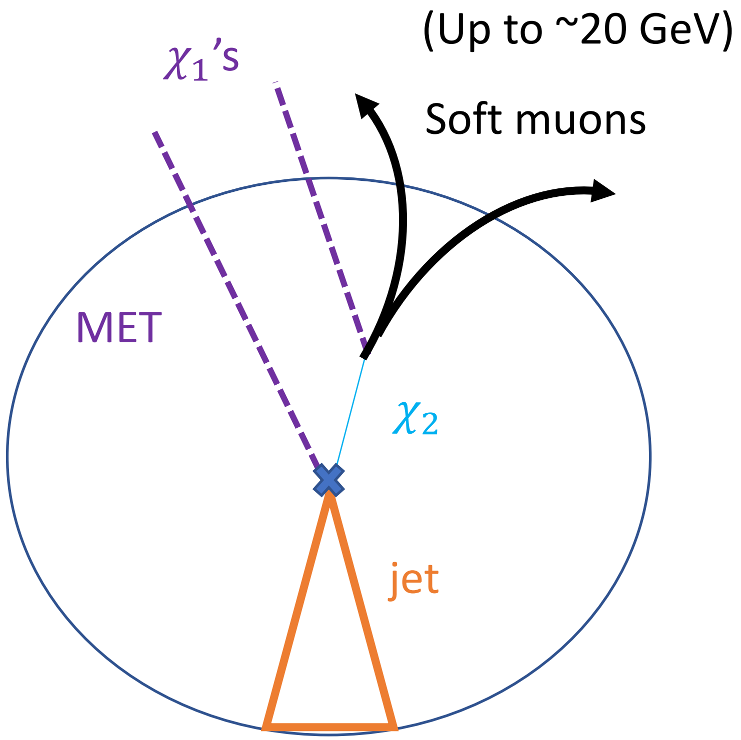
The CMS detector



Search for iDM with CMS in a nutshell

- Small mass difference (**compressed scenario**) → **soft decay products**
- Decay width of χ_2 proportional to Δ^5 and ε^2 → **LLP and displaced signatures**
- Production of two $\chi_1' s$ → **Significant MET activity**
- Soft decay muons → **Trigger using MET** with ISR jet

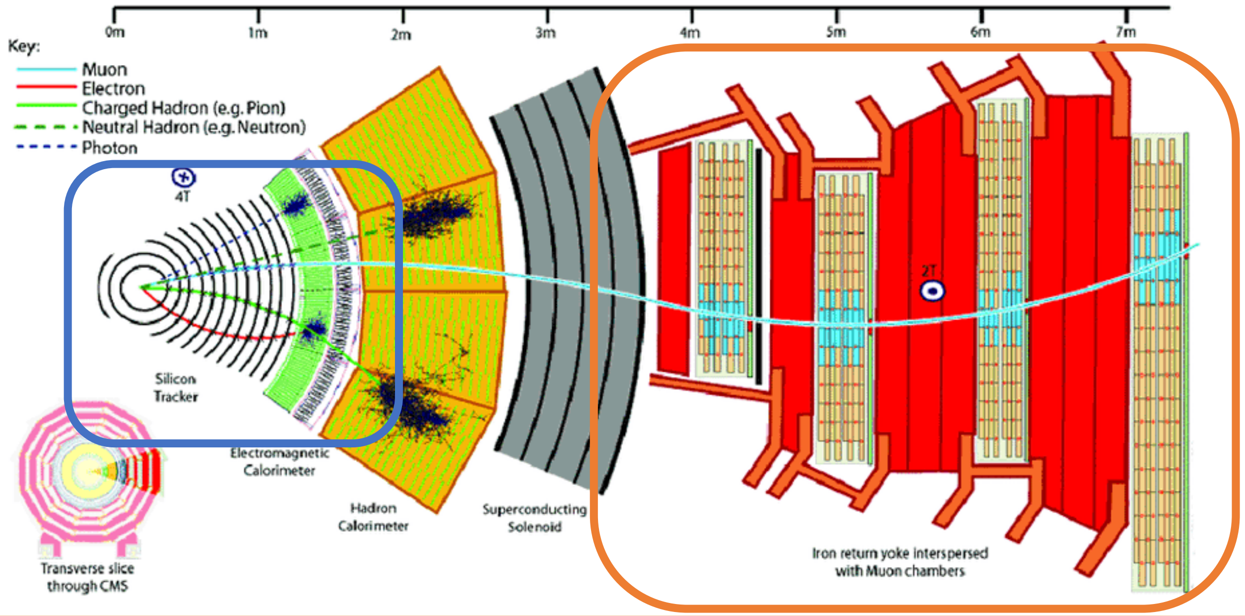


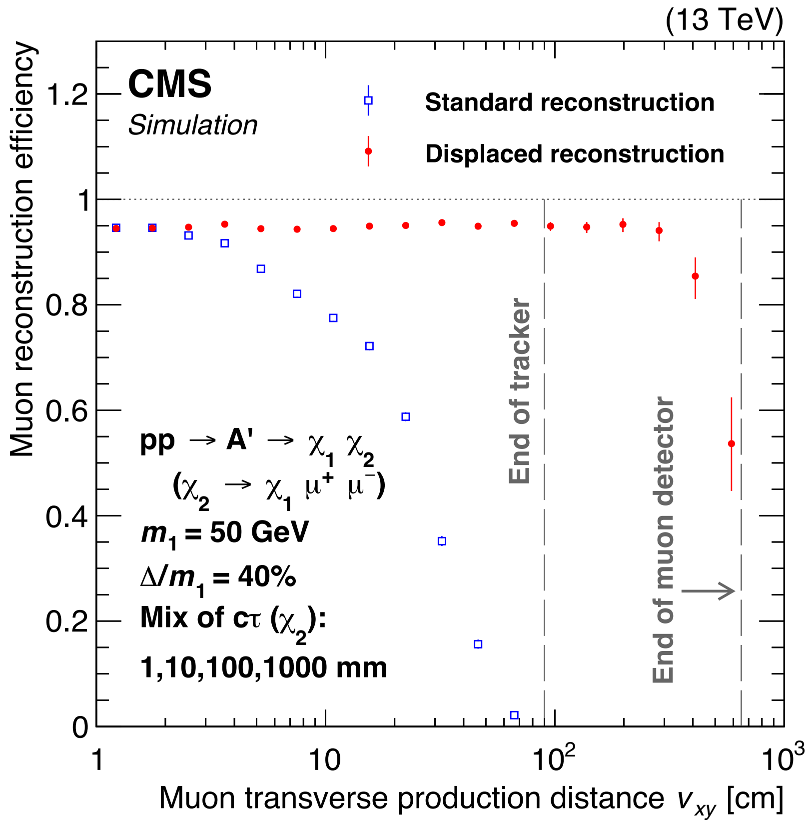


CMS transverse cross-section

Displaced muon reconstruction

- CMS has a dedicated displaced muon reconstruction (DSA):
  - Use only muon chamber hits
  - Rely on cosmic tracking seeds
  - No beam spot constraints on the fit
- High efficiency at large displacements from interaction point
- Trade-off is worse momentum and position resolution
- ➔ Prefer standard muon objects when they are available

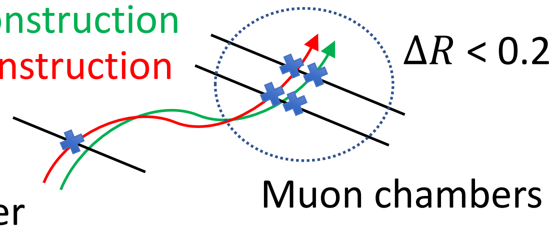


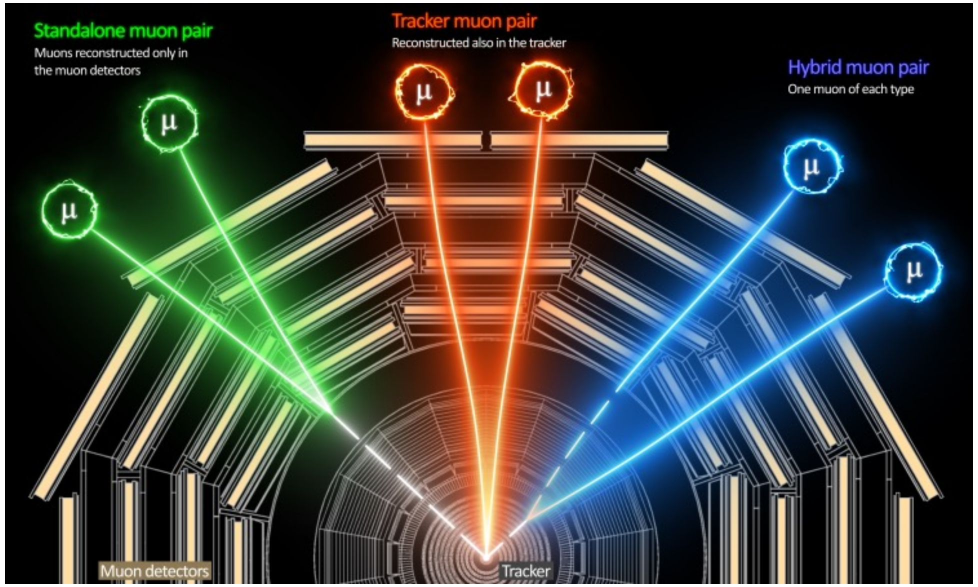


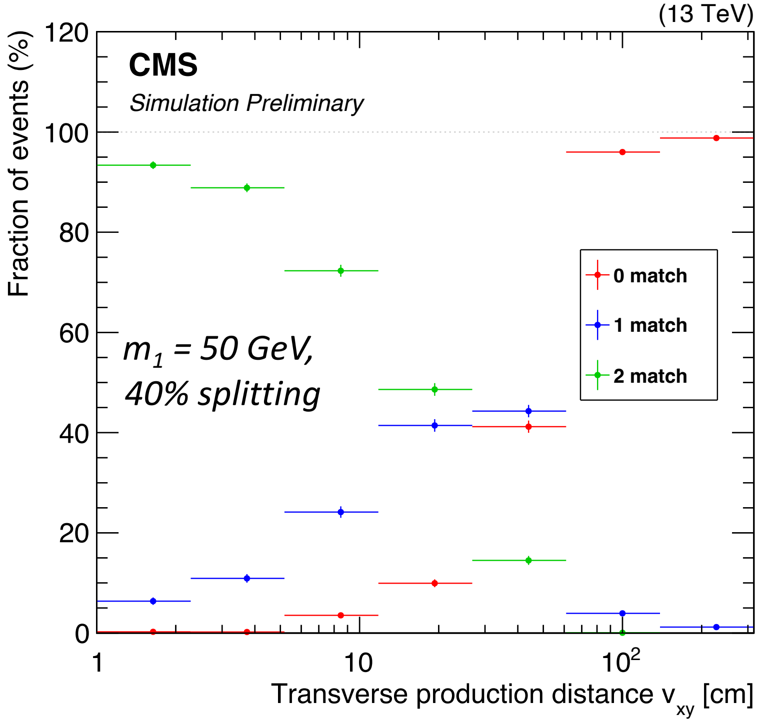
Muon reconstruction efficiency

Muon object matching

- Strategy:
  - Require 2 displaced muon objects as baseline
  - Look for geometric match between displaced and standard muons
  - Split events passing baseline into 3 categories: 0, 1, or 2 muons matched
- Benefits:
  - Maximize information (resolution)
  - SM backgrounds fall largely in 1- or 2-match categories
  - Improve signal discrimination in 0-match



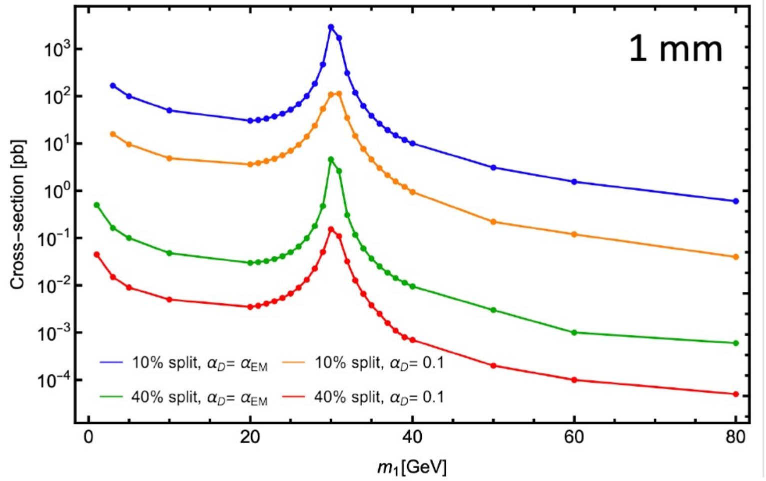


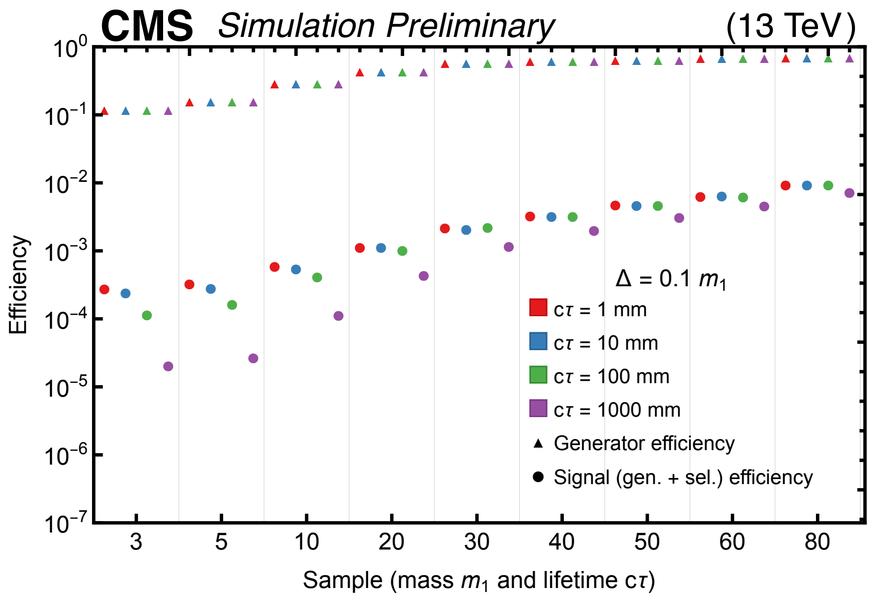


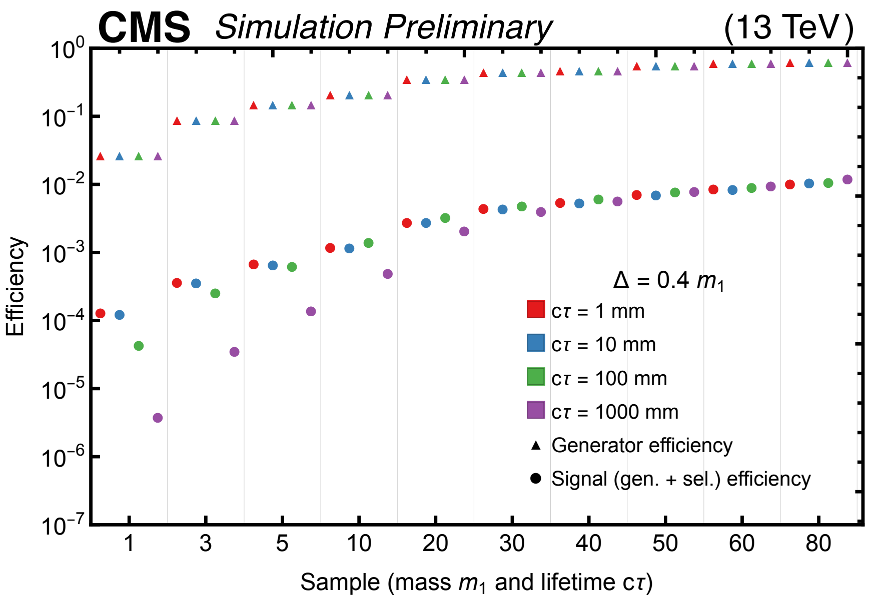
[Source](#)

Event selection and efficiencies

- Event selection designed to suppress major backgrounds (QCD, EW, top quark)
  - Relies on large MET (> 200 GeV), 1 or 2 jets with b quark veto, large separation between ISR jet and MET, at least two muons identified
- Efficiency can be quite low for low-mass signal (10^{-4} to a few percent)
- Compensated for by large production cross sections
- And aided by displaced muon reconstruction

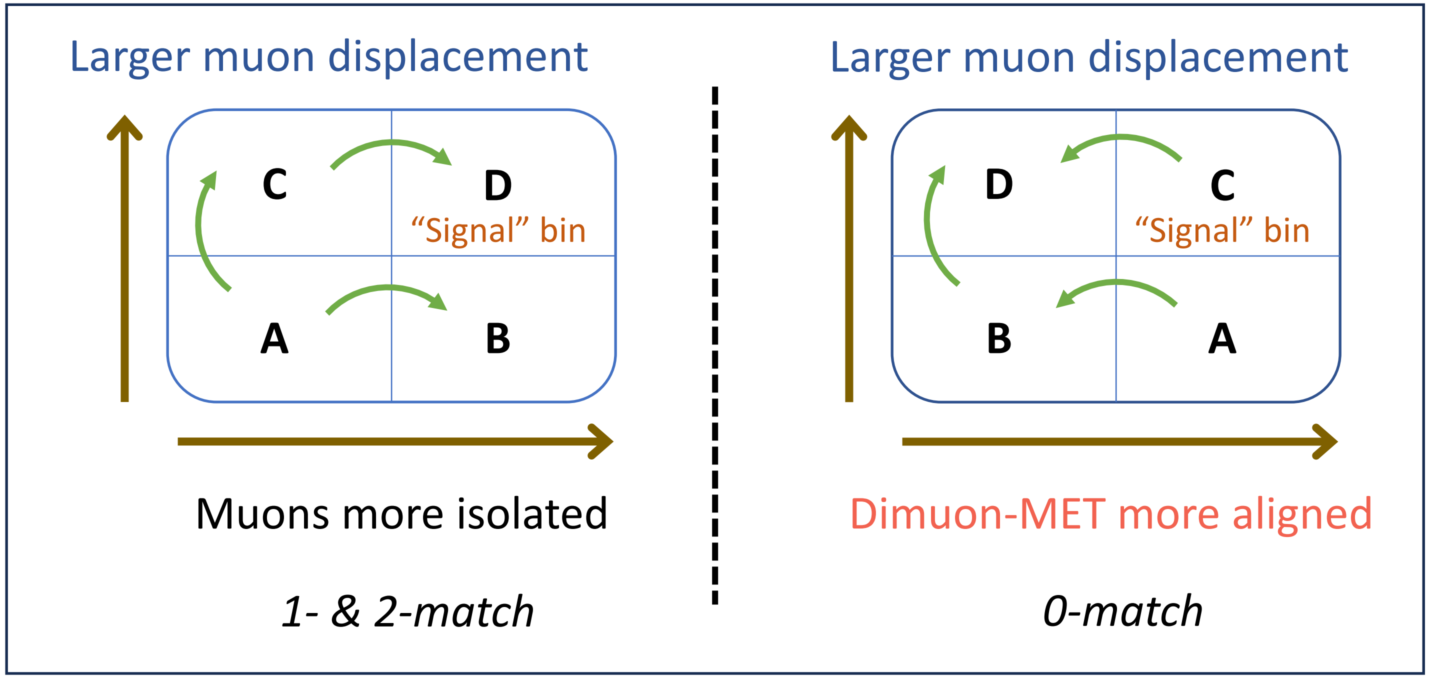


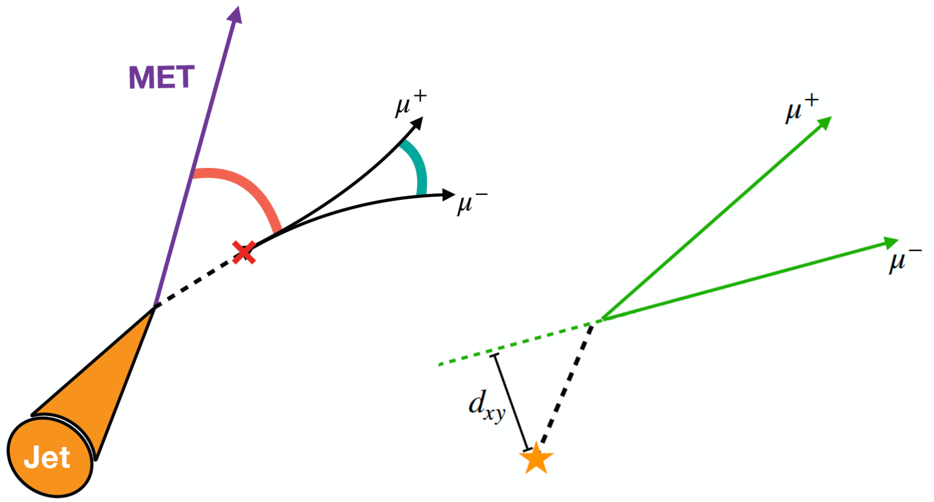




Signal extraction and background prediction

- Backgrounds have poor(er) MC modeling → predict yields from data itself
- Modified "ABCD" procedure to simultaneously fit signal and background yields
- Fit all three match categories together
- Use unique iDM topology to enhance sensitivity



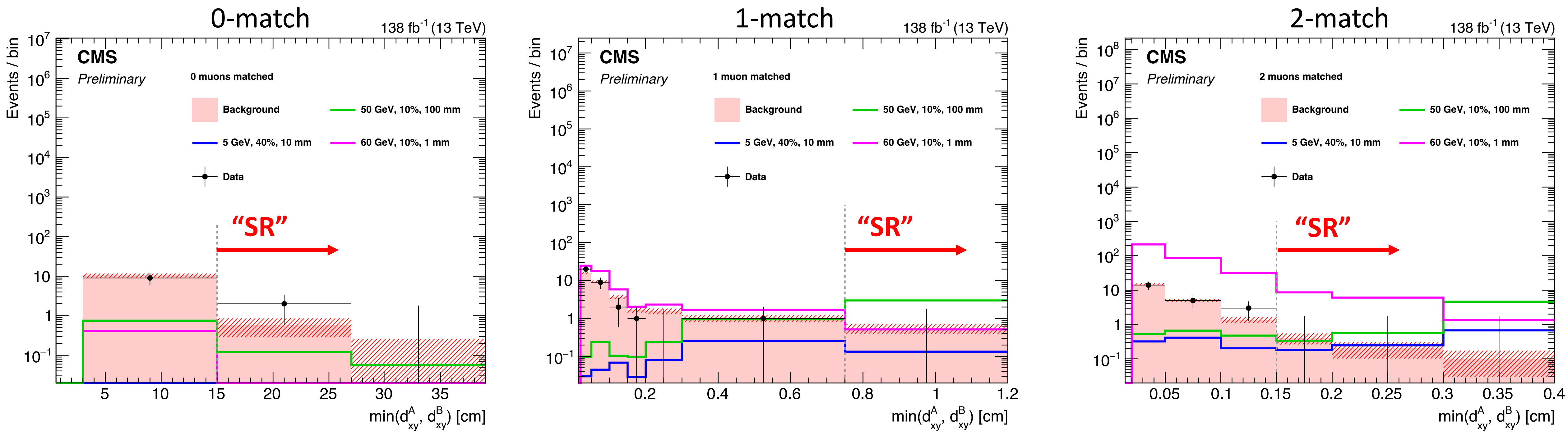


$\Delta\phi(\mathrm{MET}, \mu^+\mu^-) < 0.5$: dimuon-MET alignment

$\Delta R(\mu^+\mu^-) < 0.9$: dimuon alignment

$\min\left(d_{xy}^A, d_{xy}^B\right) > \{3, 0.02, 0.02\}$ cm: minimum impact parameter between both muons

Results

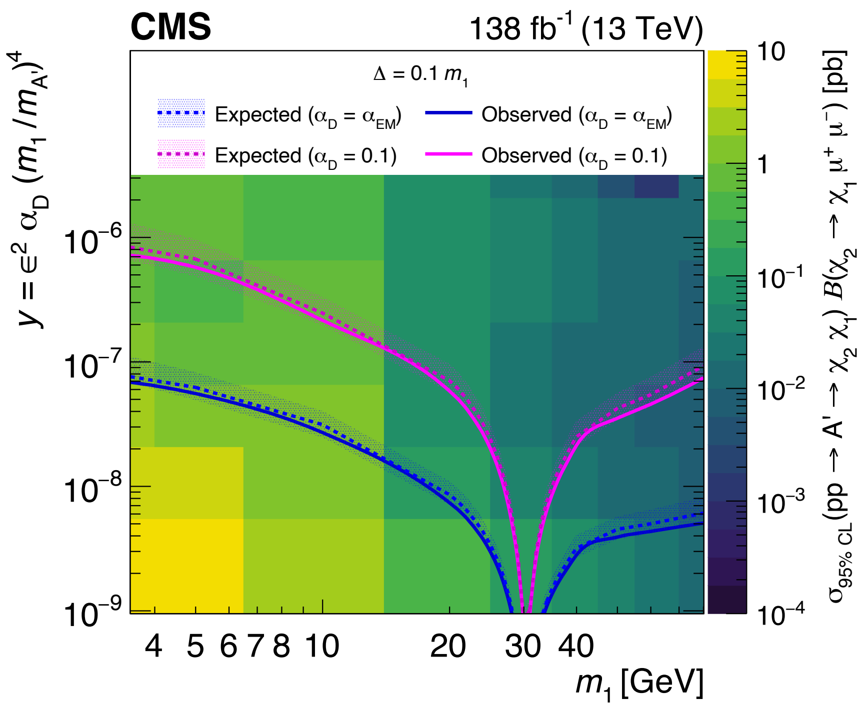


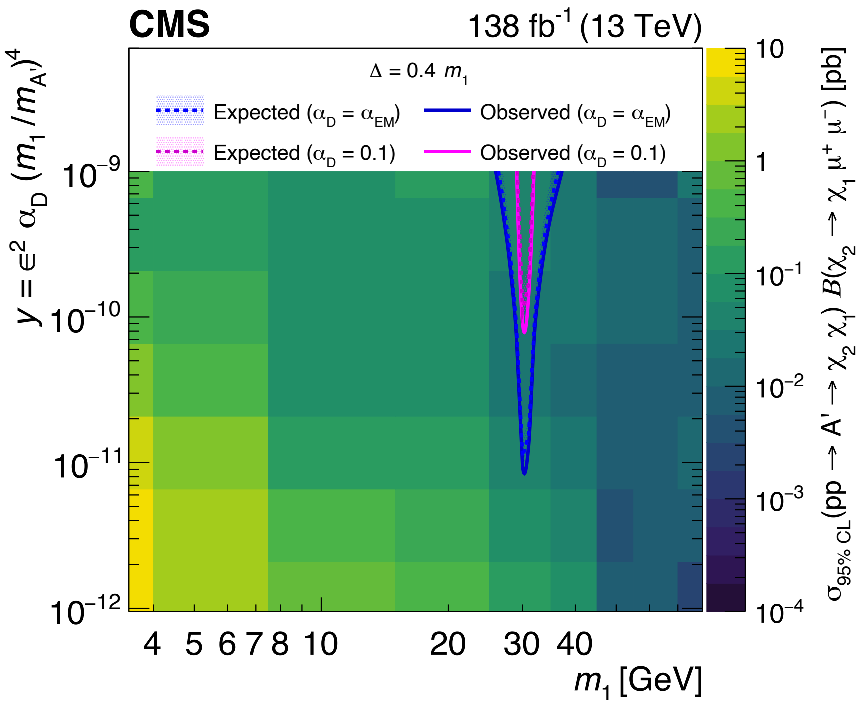
- No observed excess over the predicted background
- Can place upper limits on production cross section

	0-match	1-match	2-match
Predicted	1.2 ± 0.6	0.5 ± 0.2	0.5 ± 0.2
Observed	2	0	0

Observed limits on cross section

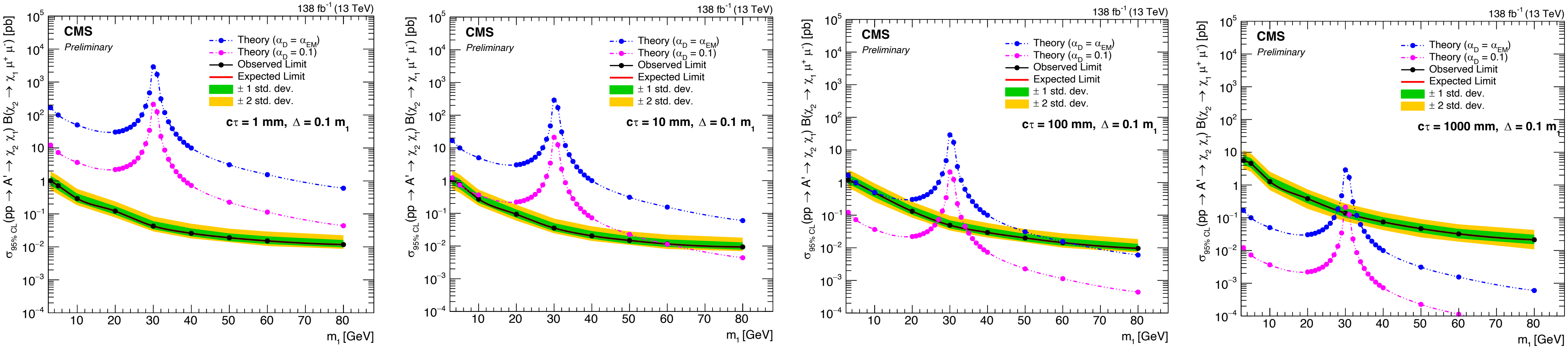
- Upper limits on $\sigma(pp \rightarrow A \rightarrow \chi_1\chi_2 \rightarrow \chi_1\chi_1\mu^+\mu^-)$ for 10% and 40% mass splitting scenarios
- Resonance enhancement around $m_1 = 30$ GeV ($m_{A'} = 90$ GeV $\approx m_Z$)
- First iDM parameter space exclusion at the LHC!
- (Comparison with theory in backup)





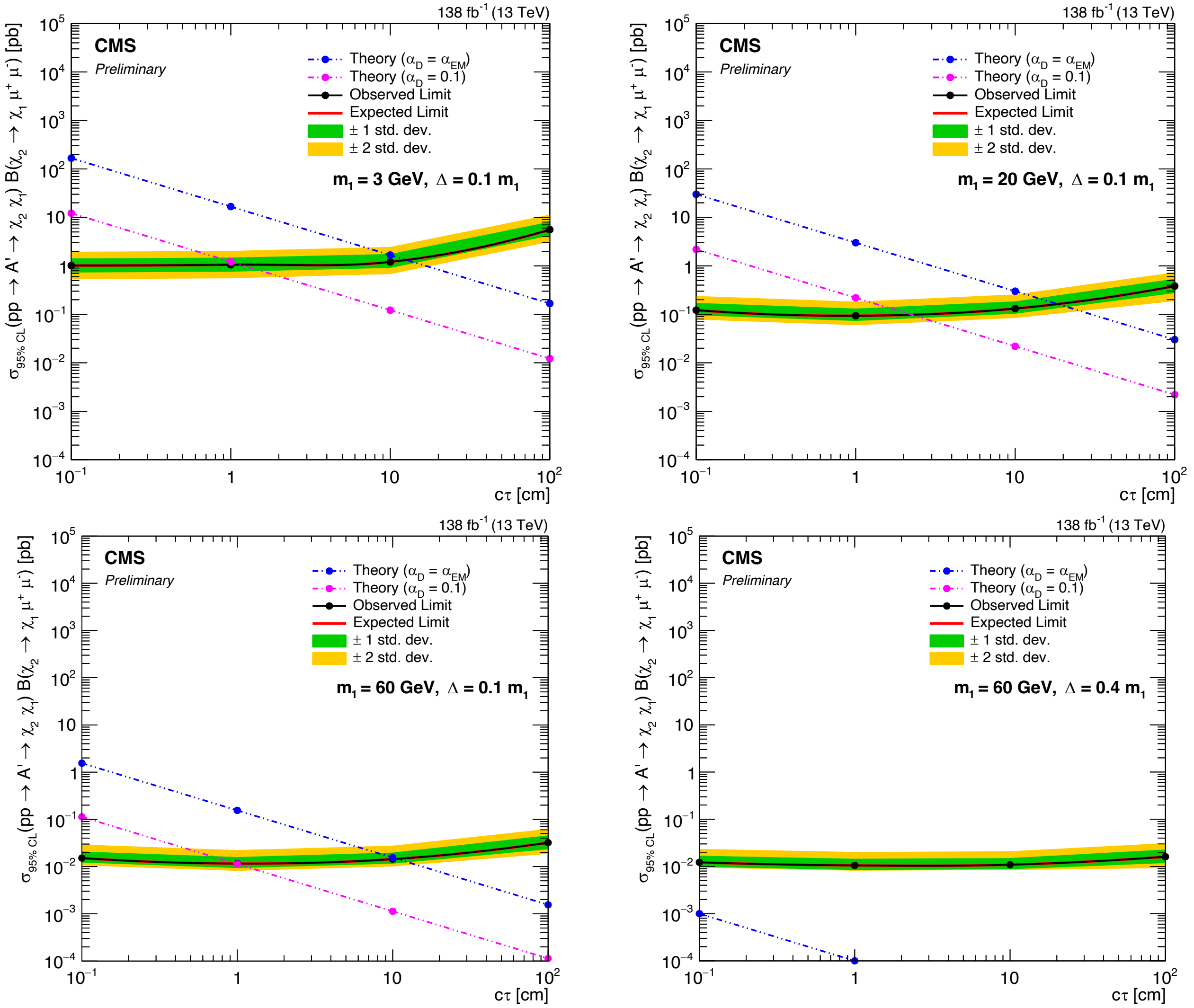
Limits vs. m_1 (10% splitting)

- Limits vs. m_1 for various lifetimes
- Cross section enhancement clearly visible at $m_1 = 30$ GeV
- High sensitivity to the 10% mass splitting scenario (40% splitting in backup)
- Higher experimental sensitivity to larger masses (more energetic muons)



Limits vs. $c\tau$

- Selection of 1D limits vs. proper lifetime for different masses
- Typical U-shaped curve with higher sensitivity to moderate lifetimes
  - Signal efficiency drops at high displacement
  - Backgrounds are more challenging at low displacement
- Production cross section inversely proportional to lifetime, mass splitting, and mass (apart from the Z resonant enhancement)



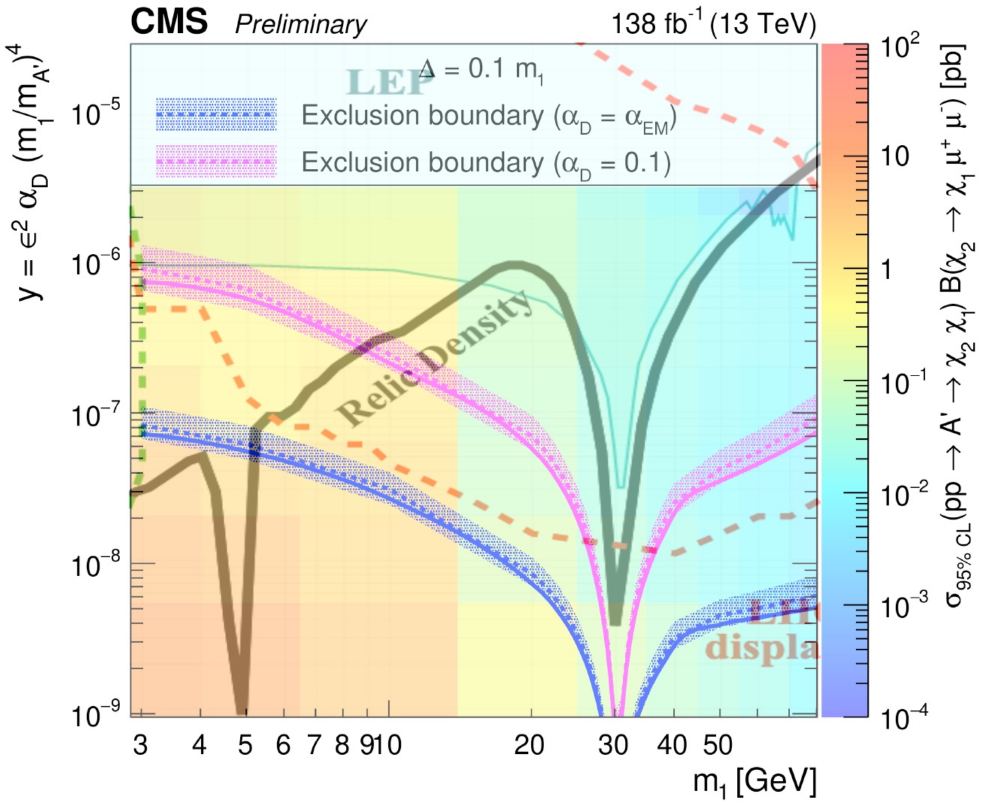
Conclusions

- Presented first dedicated collider search for inelastic dark matter
- Model is compatible with observed thermal-relic DM abundances
- Higher experimental sensitivity to lower mass splitting scenarios
- Signal efficiency enhanced with dedicated displaced muon reconstruction
  - Still quite low efficiencies for some signal hypotheses ($10^{-4} - 10^{-2}$)
  - Aided by large predicted iDM production cross sections
- Exclusion limits placed for 10% and 40% mass splitting scenarios
- Some future directions:
  - Study electron channel with dedicated low-p_T electron reconstruction
  - Study dedicated triggers for displaced compressed scenarios

Rough limit comparison with theory

[Izaguirre, Krnjaic & Shuve, PRD 93 (2015) 063523]

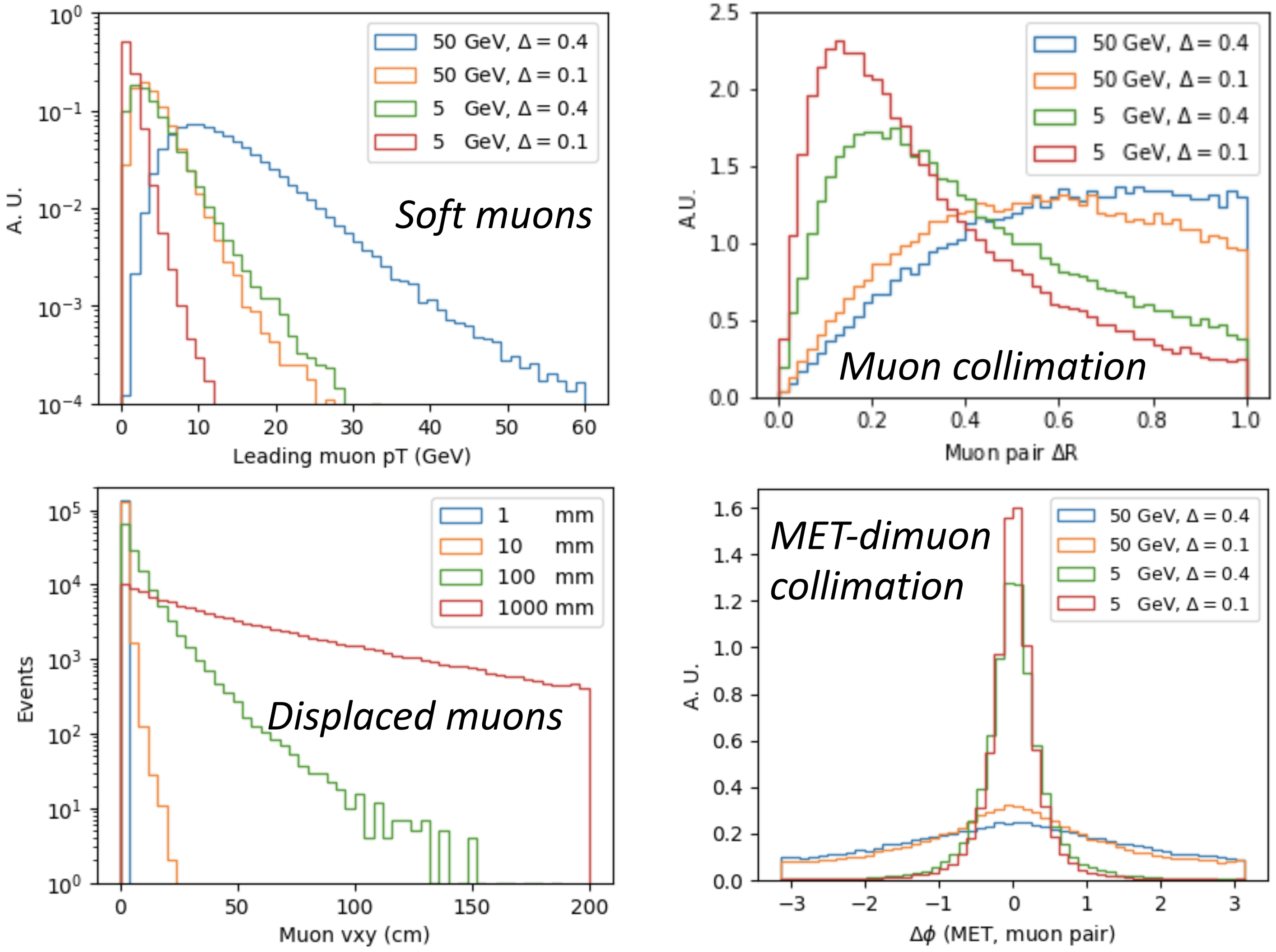
- Comparison between pink curve (experimental limit) and red dashed curve (theory projection) and black solid curve (DM relic density) with α_D = 0.1 and Δ = 0.1 m_1
- Theory projections assume 300 fb^{-1} of integrated luminosity, vs. ~140 fb^{-1} with Run 2 data
- No cross section enhancement from Z mixing considered in theory projection
- Regions of the relic density phase space are excluded



Signal kinematics

- Distinctive features:
  - Muons:
    - Displaced
    - Soft
    - Collimated
  - MET:
    - Significant
    - Collimated with muons
  - ISR jet:
    - Energetic
    - Opposite MET-dimuon system

Generator MC plots
(MG5 2.6.0 LO + Pythia 8)



Full event selection

- Event selection optimized with N-1 cuts using signal significance as metric (some examples in backup)

- **Jet & MET selection:**
  - Trigger on MET triggers
  - Offline MET > 200 GeV
  - 1 or 2 jets only
  - Leading jet p_T > 80 GeV, |η| < 2.4
  - Sub-leading jet p_T > 30 GeV
  - |Δϕ|(MET, leading jet) > 1.5
  - |Δϕ|(MET, sub-leading jet) > 0.75
  - No b-tagged jets

- **Dimuon selection:**
  - 2 ID'd dSA muons
  - $q_1 \mathrel{!}= q_2$
  - Vertex χ^2/dof < 4 (pick lowest)
  - dR(muons) < 0.9
  - 3D angle $\alpha > 2.8$ rad
  - |Δϕ|(MET, muons) < 0.5 (next slide)

- **dSA ID:**
  - Number of muon chambers > 1
  - Number of muon hits > 12
  - And > 18 if no CSC hits
  - Track χ^2/dof < 2.5
  - $\sigma(p_T)$ / p_T < 1.0
  - & p_T > 5 GeV, $|\eta|$ < 2.4

- **"PF" Loose ID:**
  - Muon is a PF muon
  - And muon is a Global Muon
  - & p_T > 5 GeV, $|\eta|$ < 2.4

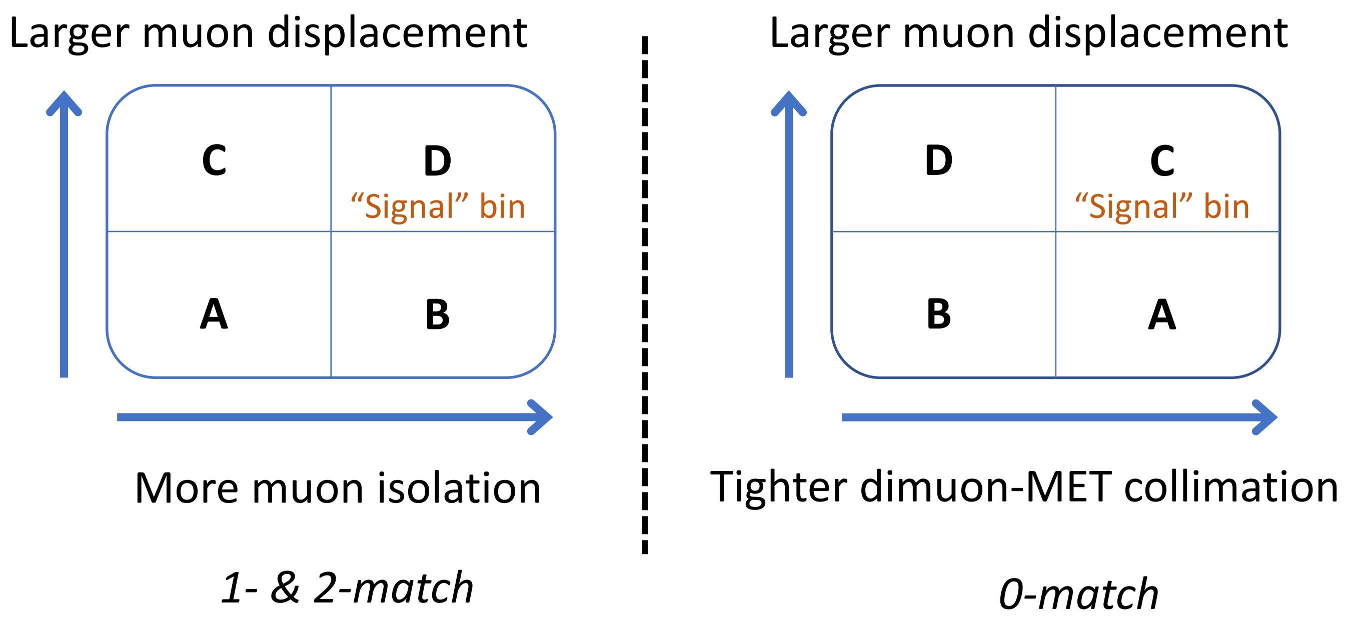
- **SR categorization:**
  - 0, 1, or 2 dSA matches with ID'd PF muons

Signal extraction and background prediction

- Backgrounds have poor(er) MC modeling, so predict from data itself
- Modified "ABCD" procedure to simultaneously fit signal and background yields
  - Useful if potential signal contamination in one or more ABCD bins:

$$
\begin{aligned}
N_A^{\text{obs}} &= N_A^{\text{bkg}} + \mu \times N_A^{\text{sig}} \\
N_B^{\text{obs}} &= N_A^{\text{bkg}} \times c_1 + \mu \times N_B^{\text{sig}} \\
N_C^{\text{obs}} &= N_A^{\text{bkg}} \times c_2 + \mu \times N_C^{\text{sig}} \\
N_D^{\text{obs}} &= N_A^{\text{bkg}} \times c_1 \times c_2 + \mu \times N_D^{\text{sig}}
\end{aligned}
$$

- Fit all three match categories together



- Validation of background prediction in signal-free multijet validation region
  - Require orthogonal cut: number of jets > 2
  - Good closure between prediction and observation in "signal-enriched" bin

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