Search for known and unknown particles in all-muon final states with the CMS scouting data

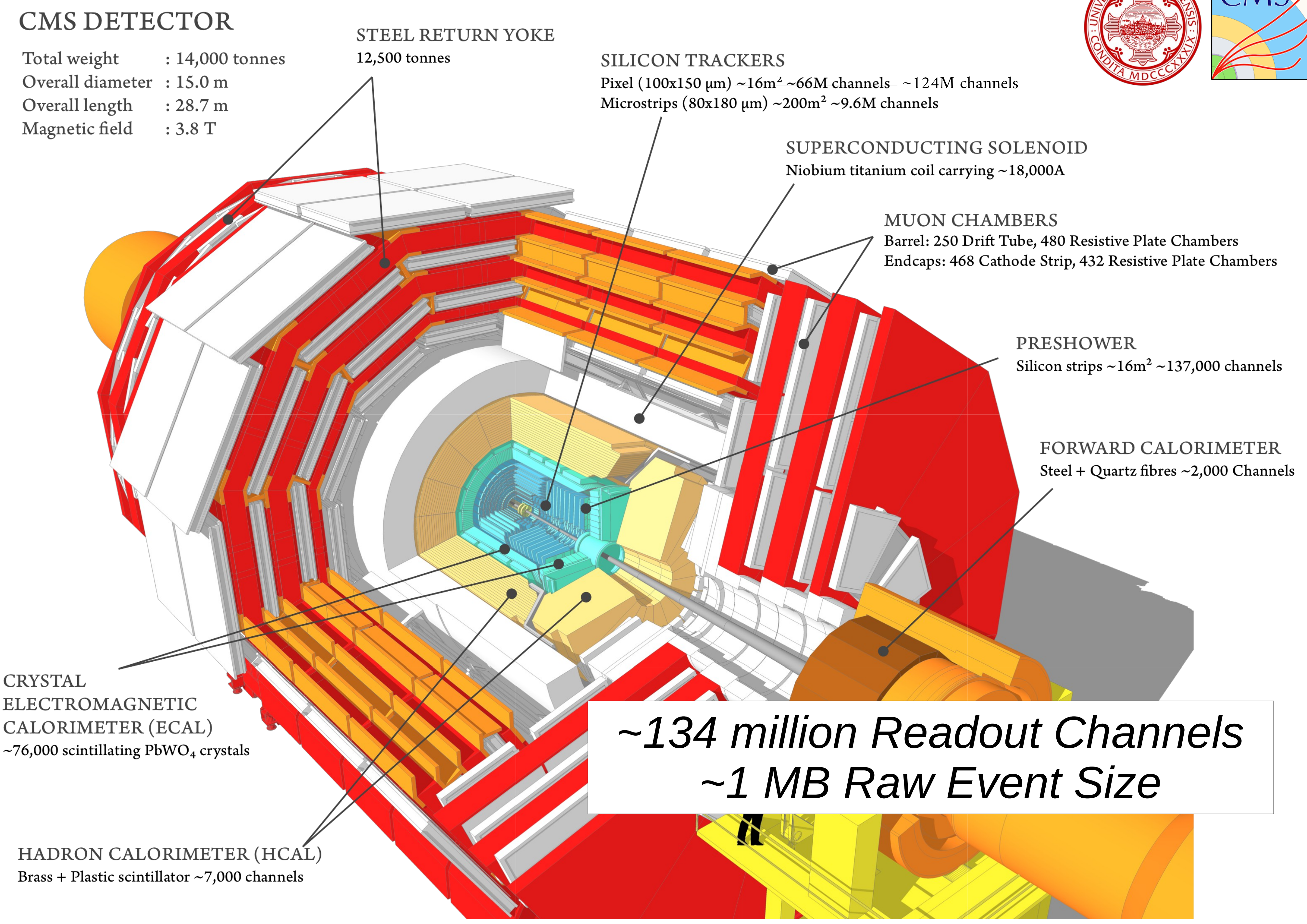
David Sperka
(Boston University)

On Behalf of the CMS Collaboration

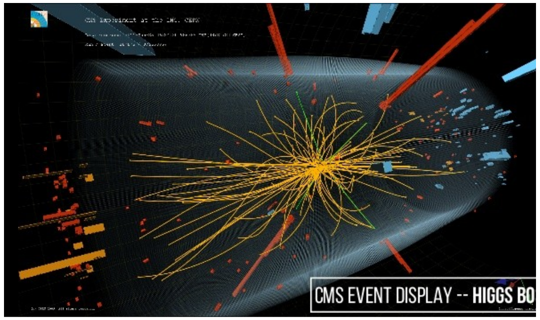
CERN LPCC Seminar
Feb. 28th, 2023

Outline

- **CMS Detector and Trigger System**
- **The "Data Scouting" strategy**
- **Searches for known and unknown particles**
  - Observation of $\eta \rightarrow 4\mu$ decay (*CMS-BPH-22-003*)
  - Search for $X \rightarrow \mu^+\mu^-$ resonances (*CMS-EXO-21-005*)
- **Scouting Plans for LHC Run 3 and Beyond**
- **Conclusions**


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~~~16m² ~66M channels~~ ~124M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels
~134 million Readout Channels
~1 MB Raw Event Size

CMS Trigger System



~40 MHz

CMS Trigger System

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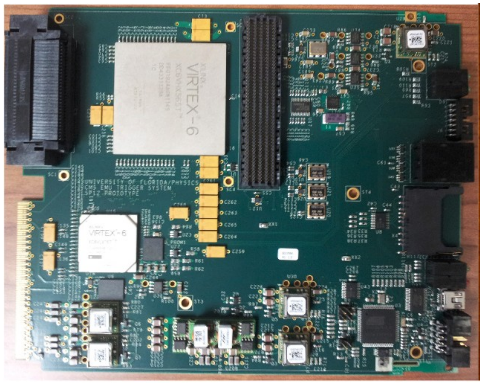
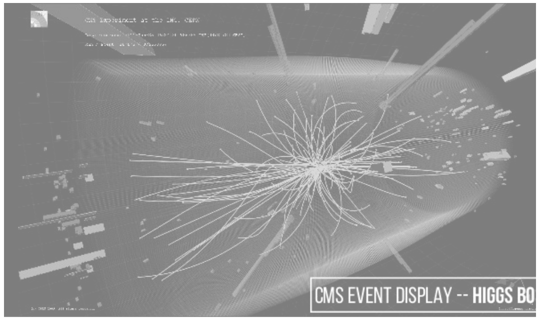


Level 1 Trigger (L1)

~100 KHz **(Hard Limit)**

3.2 μs **(Hard Limit)**

CMS Trigger System



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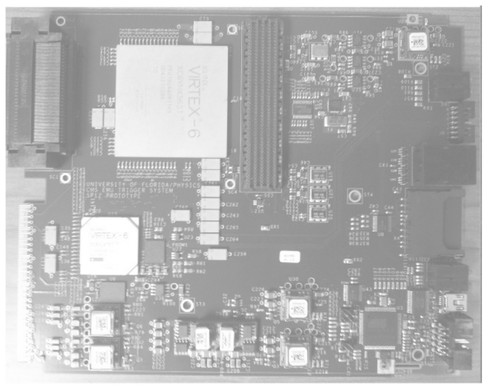

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3.2 μs ***(Hard Limit)***

High Level Trigger (HLT)

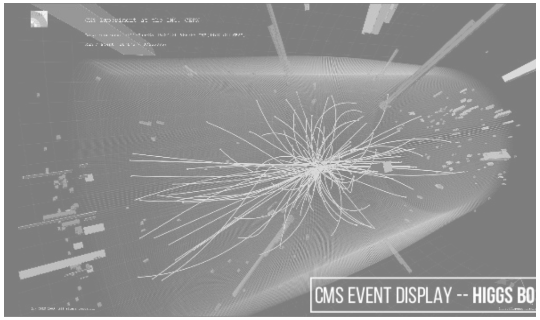
~5 GB/s ***(Hard Limit)***

~0.5 s ***(Hard Limit)***

~1.5 KHz ***(Soft Limit)***

CMS Trigger System

How can we maximize the physics output, working within these constraints?



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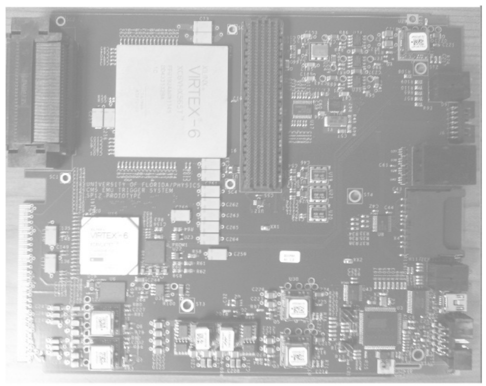

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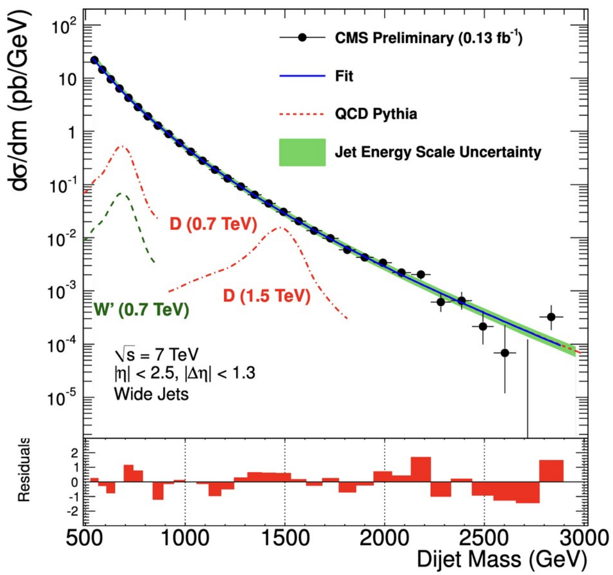
CMS "Data Scouting"

First employed for Dijet searches by CMS in LHC Run 1 (end of 2011)



JHEP 01 (2013) 013

PRL 117 (2016) 031802

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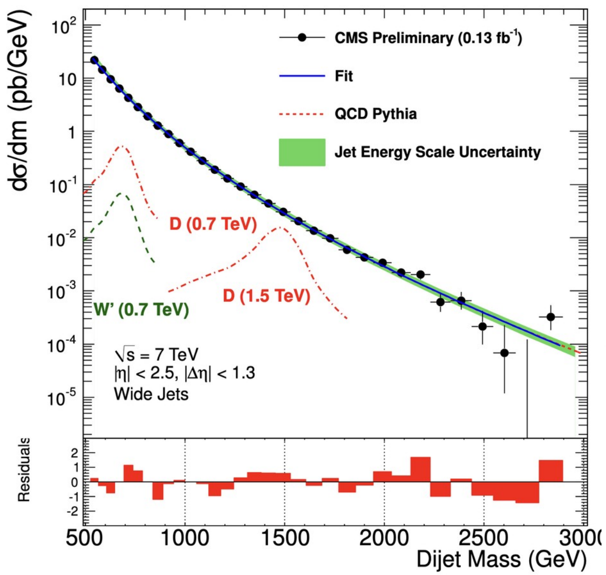

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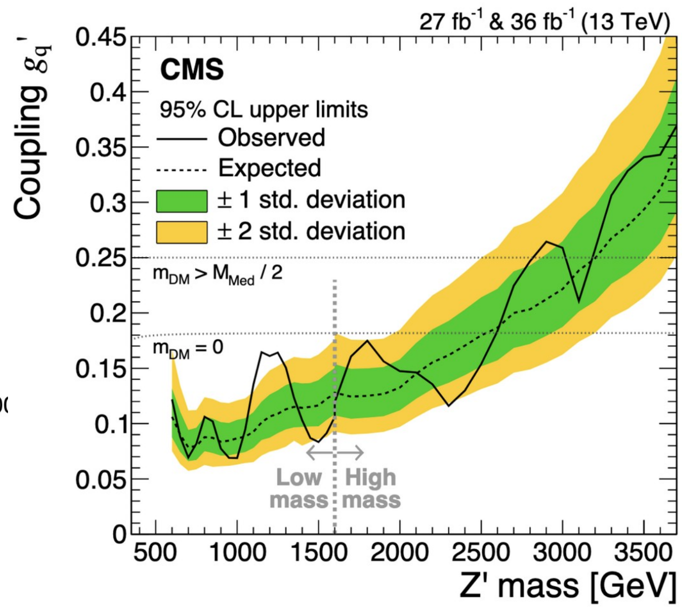
Used for a variety of hadronic resonances searches in 2012 and LHC Run 2



[PLB 769 (2017) 520](#)

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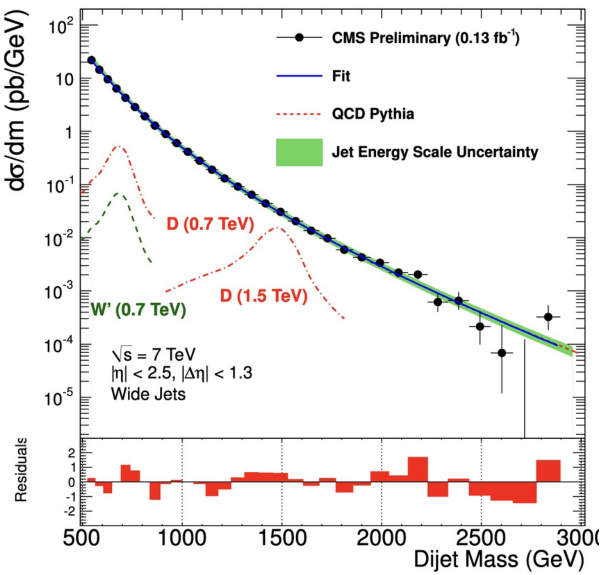

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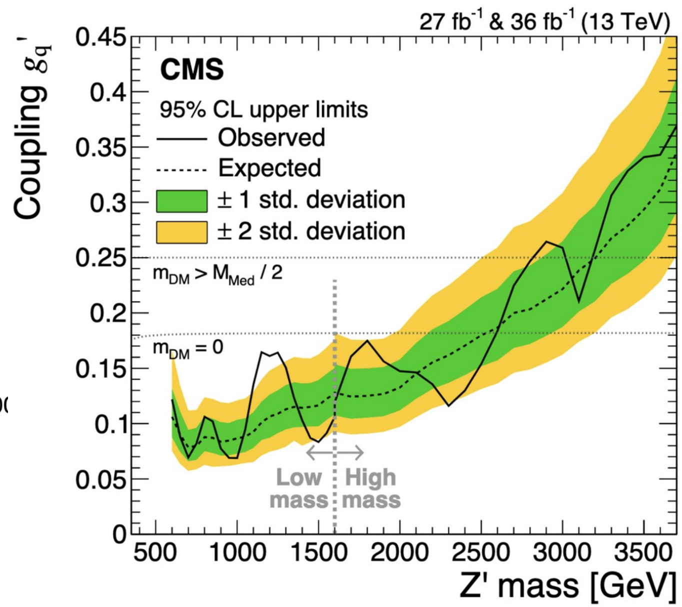

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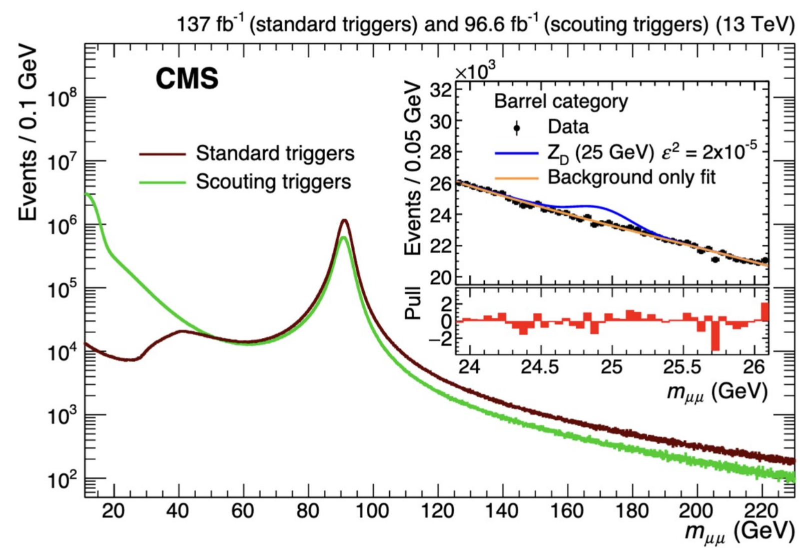
Fully commissioned for multi-muon final states in 2017 and 2018



[PLB 805 (2020) 135448](#)

[JHEP 04 (2022) 062](#)

CMS Muon Scouting

- Four main Level-1 dimuon triggers feed the HLT
  - Using dimuon topological requirements ($m_{\mu\mu}$, $\Delta r_{\mu\mu}$) to reduce the rate (~4 KHz)

L1 path	p_T [GeV]	$\lvert\eta\rvert$	ΔR	$m_{\mu\mu}$ [GeV]	Charge
#1	$> 4,4.5$	–	< 1.2	–	OS
#2	–	< 1.5	< 1.4	–	OS
#3	$> 15/7$	–	–	–	–
#4	> 4.5	< 2.0	–	7–18	OS

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- "Standard" dimuon analysis:
  - Apply filters at HLT, save the full event content for thorough offline analysis

Table 2: LHC Fill 7334 (23. Oct. 2018, $\mathcal{L} \approx 1.5 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$).

Data stream	Rate [Hz]	Event Size	Bandwidth (MB/s)
Muons	420	0.86 MB	360
Jets/HT	345	0.87 MB	300
Scouting Muons	4580	8.9 KB	40
Scouting Jets/HT	1380	14.8 KB	20

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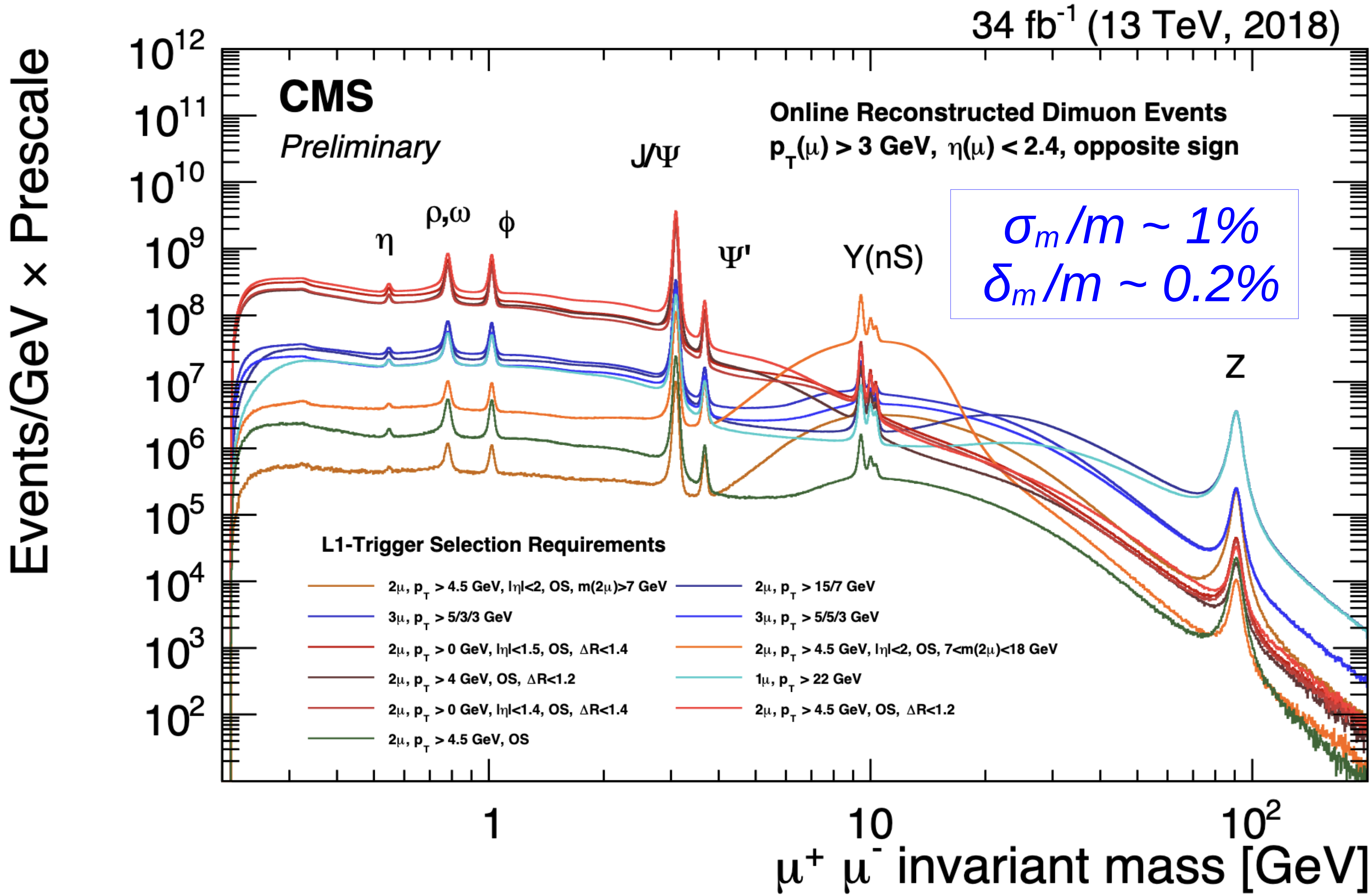
- "Scouting" dimuon analysis:
  - Minimal filters applied at HLT (p_T>3 GeV), save limited information (one shot reconstruction)

Kinematic quantities	ID variables	Track / Vertex
$p_T^\mu, \eta^\mu, \phi^\mu$	Ecal, Hcal, Track Iso.	$q/p, \lambda, \phi, d_{sz}$
$p_T^{track}, \eta^{track}, \phi^{track}$	#pixel, #strip, #muon hits	$\sigma_{q/p}, \sigma_\lambda, \sigma_\phi, \sigma_{d_{sz}}$
d_{xy}, d_z	#stations, #tracker layers	$\mu\mu$ vertex x, y, z
$\sigma_{d_{xy}}, \sigma_{d_z}$	χ^2, #d.o.f., i_{vertex}	$\mu\mu$ vertex $\sigma_x, \sigma_y, \sigma_z$

Dimuon Mass Distribution



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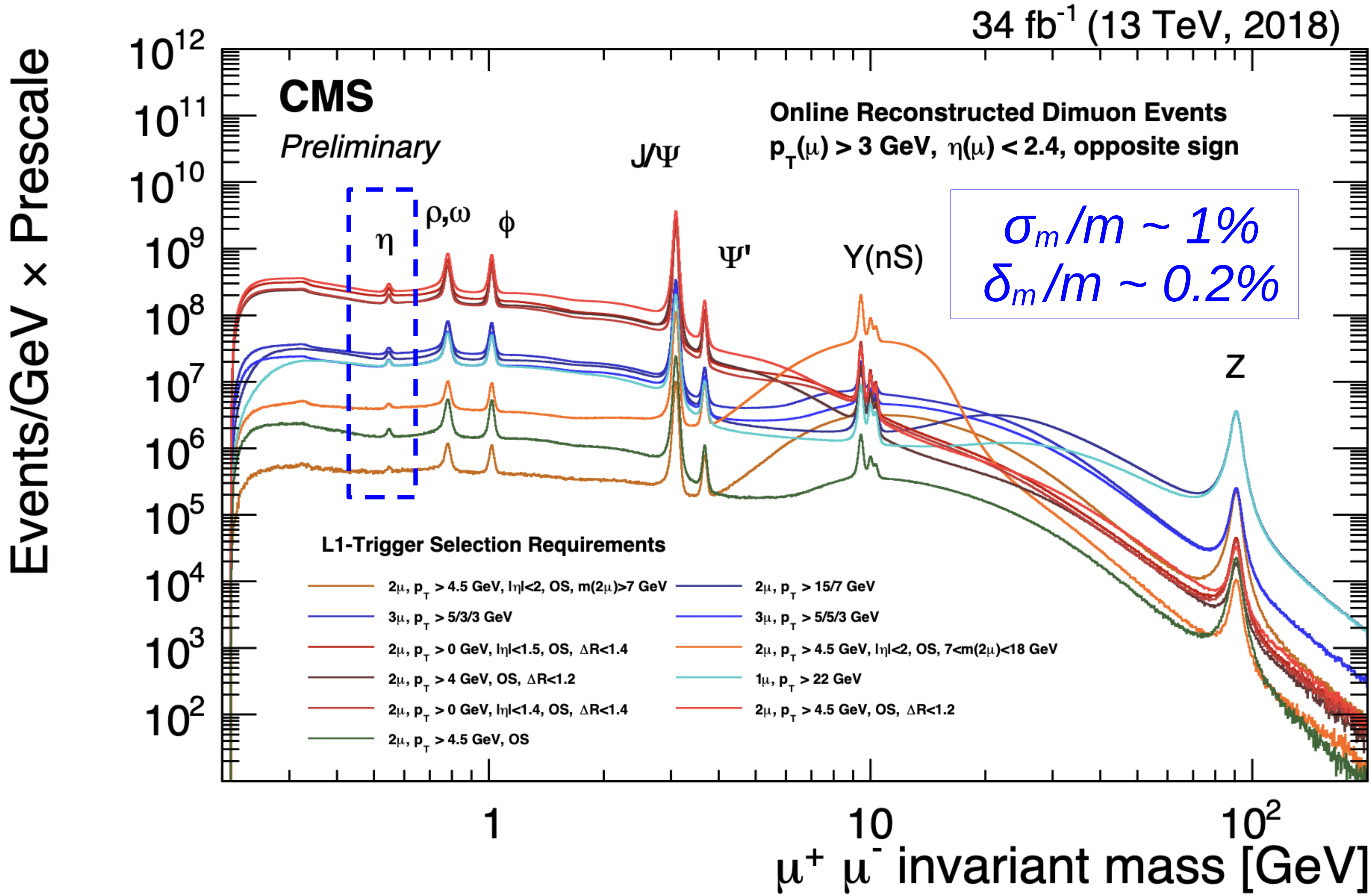
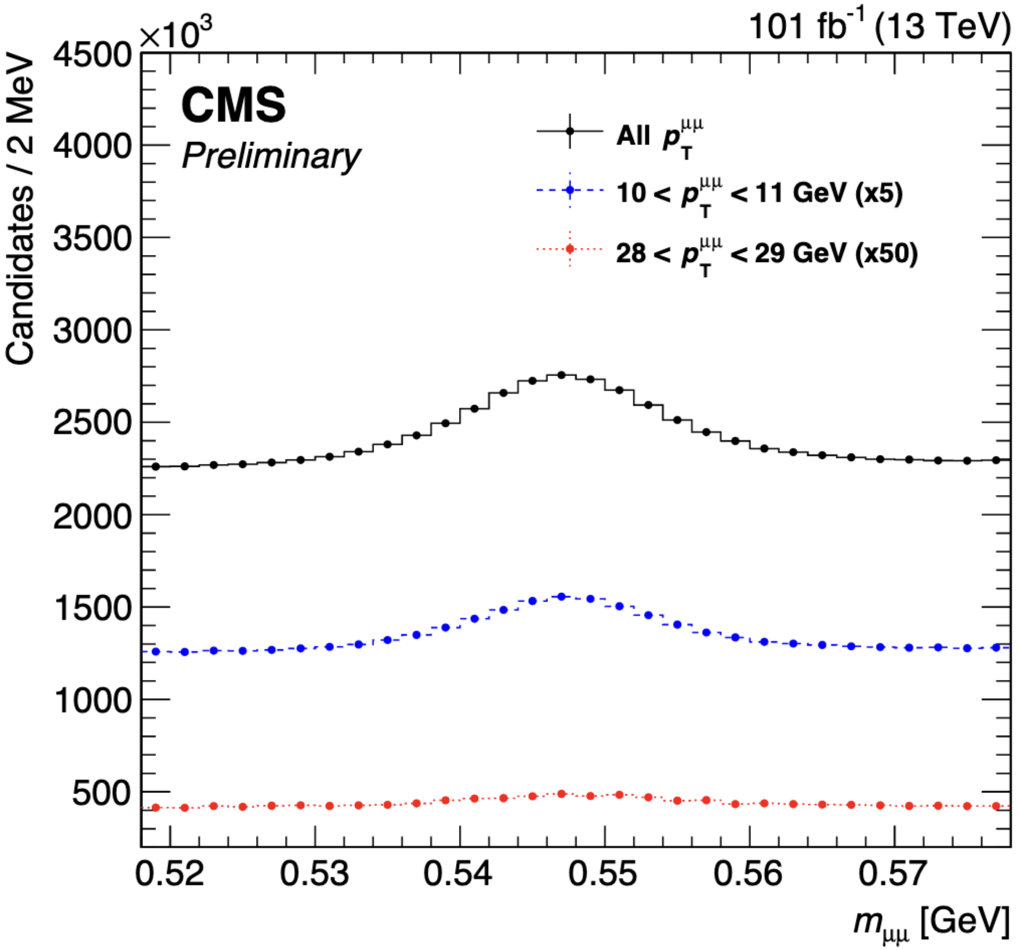


The LHC as an η factory

- The η meson is copiously produced in high energy pp collisions at the LHC
- Require opposite sign muon pair consistent with production from a common vertex



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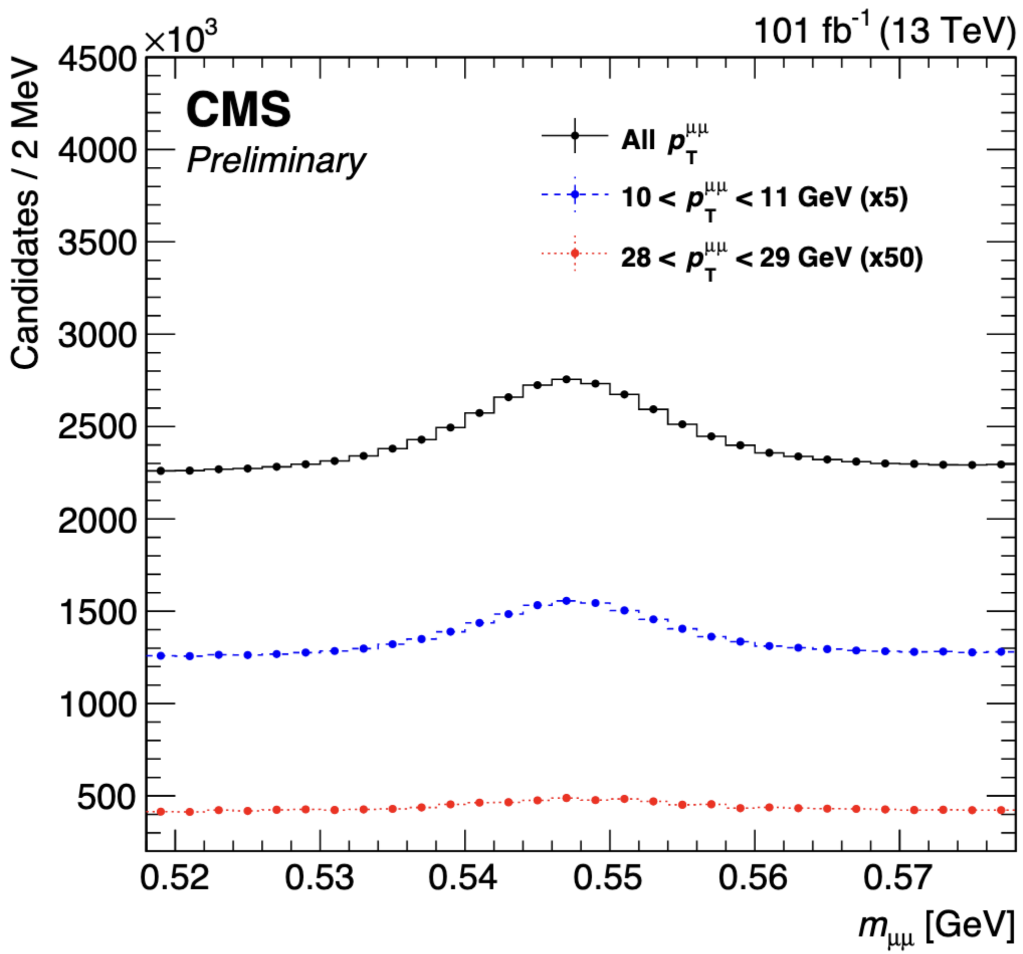
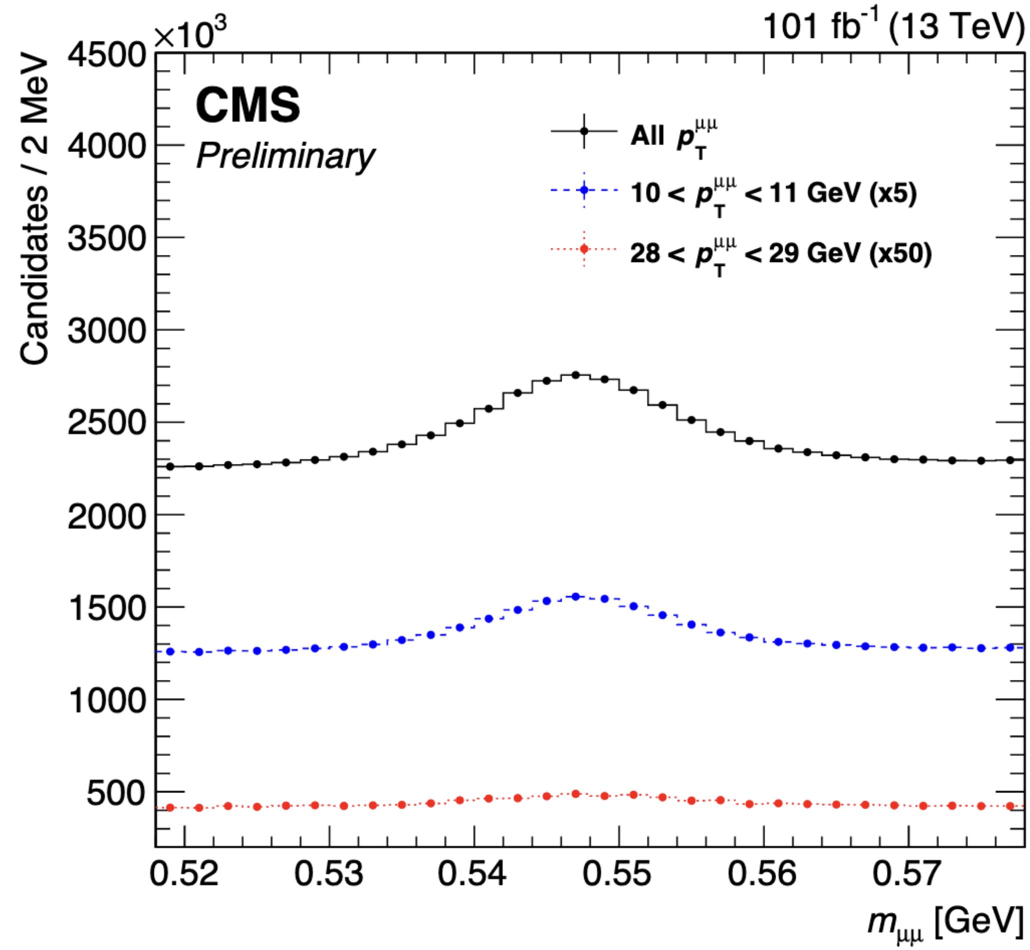
- Require opposite sign muon pair consistent with production from a common vertex
- Fit the η peak in the inclusive dimuon spectrum to extract the number of η→μμ events
  - ~4.5 x 10^{6} η→μμ events
  - B(η→μμ) ≈ 5.8 x 10^{-6}
  - Access to ~10^{12} η mesons



The LHC as an η factory

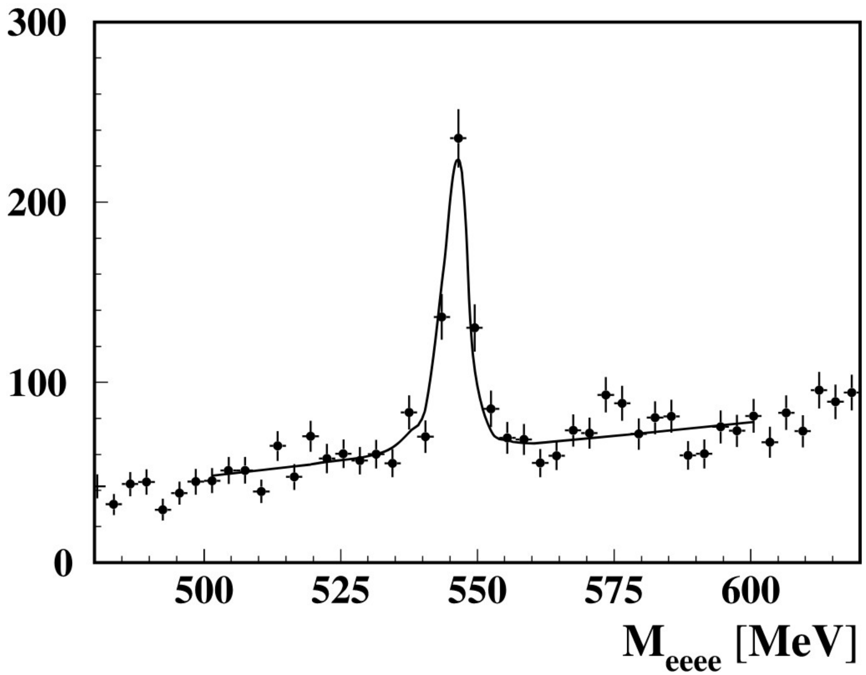
- The η meson is copiously produced in high energy pp collisions at the LHC
- Require opposite sign muon pair consistent with production from a common vertex
- Fit the η peak in the inclusive dimuon spectrum to extract the number of $\eta\to\mu\mu$ events
    - $\sim 4.5 \times 10^{6}$ $\eta\to\mu\mu$ events
    - $B(\eta\to\mu\mu) \approx 5.8 \times 10^{-6}$
    - Access to $\sim 10^{12}$ η mesons
- Can use the dimuon scouting data set to search for rare η meson decays!



The LHC as an η factory

- To put this number in context, CMS produces a number of η mesons much greater than KLOE experiment at DAΦNE, and comparable to the proposed REDTOP experiment at Fermilab

Observation of $\eta \to e^+e^-e^+e^-$ at KLOE (2011)
~7 x 10^7 η mesons



PLB 702 (2011) 324

Proposed REDTOP experiment at Fermilab
~10^{12}-10^{14} η mesons/year

https://redtop.fnal.gov/

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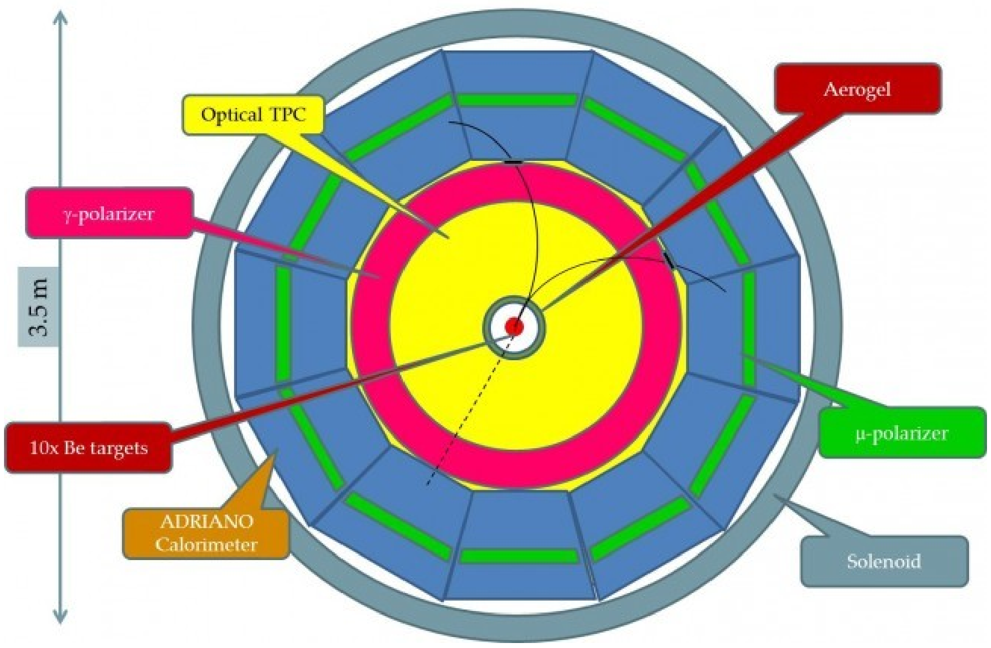

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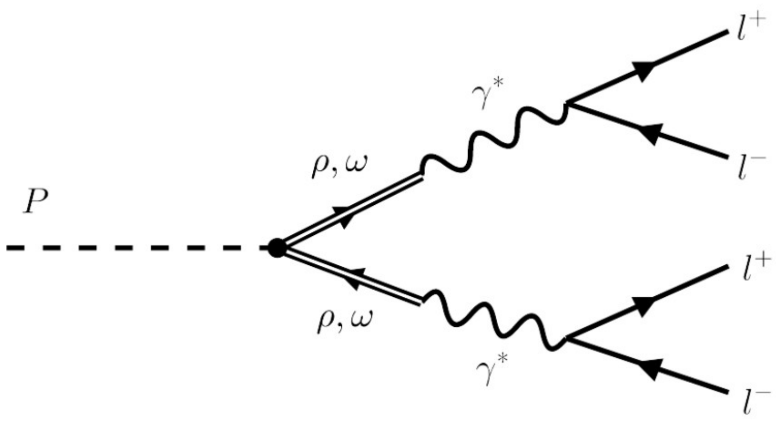
Rare Radiative Decays

- Leptonic radiative decays of the η/η’ meson are an interesting target
  - $\eta \to \mu^+\mu^-\mu^+\mu^-$ and $\eta \to \mu^+\mu^-e^+e^-$ are yet to be observed
  - $\eta' \to e^+e^-e^+e^-$ decay only recently observed at BESIII *PRD 105 (2022) 112010*
  - B(2e2μ)~2.4×10^{-6} , B(4μ)~4×10^{-9} in SM *arxiv:1511.04916*



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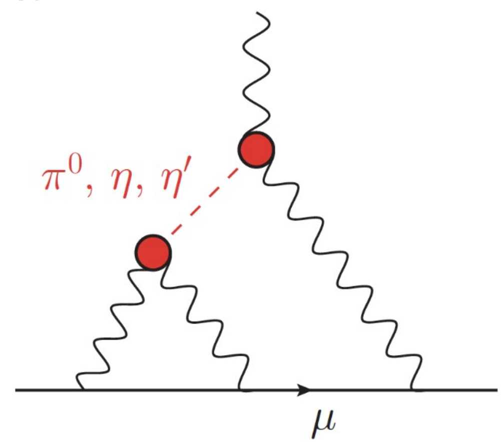
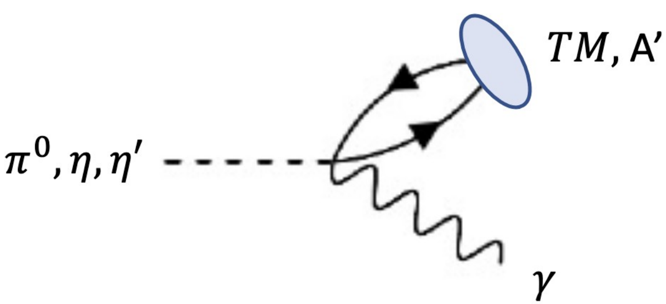
  - $B(2e2\mu) \sim 2.4\times10^{-6}$, $B(4\mu) \sim 4\times10^{-9}$ in SM *arxiv:1511.04916*

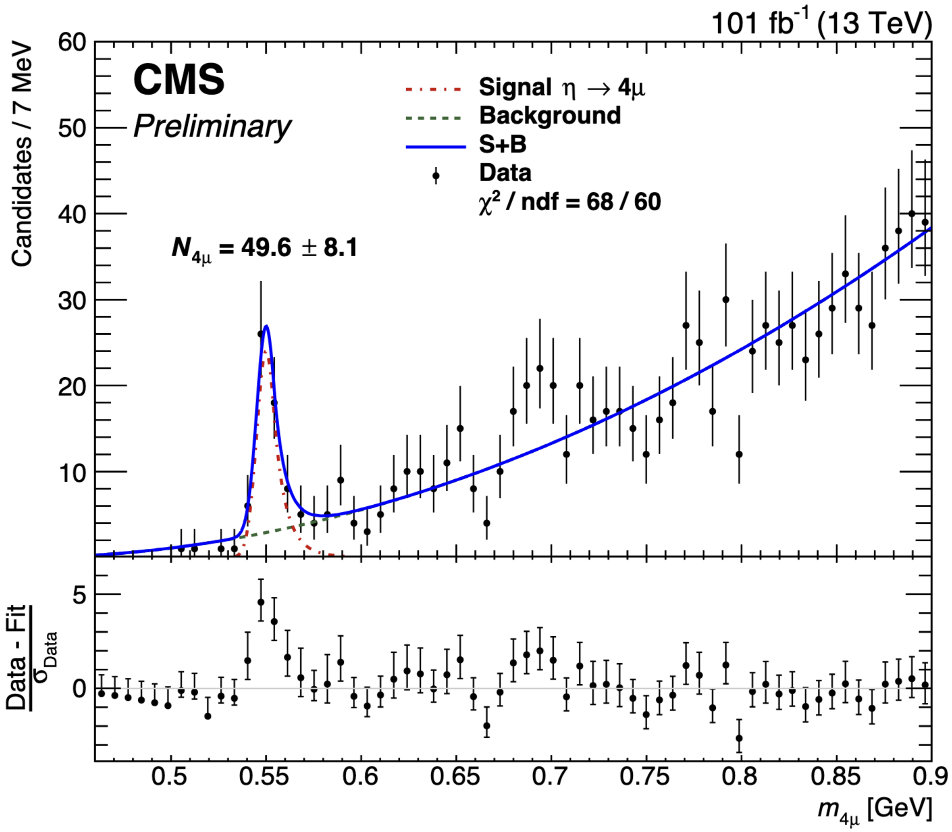
- Measuring the rare η meson branching ratios is important for several reasons
  - Tests low energy QCD calculations which contributes to the hadronic light-by-light component of the $(g-2)_\mu$
  - Sensitive to the presence of BSM physics (light mediators, True Muonium) *arxiv:2007.00664*





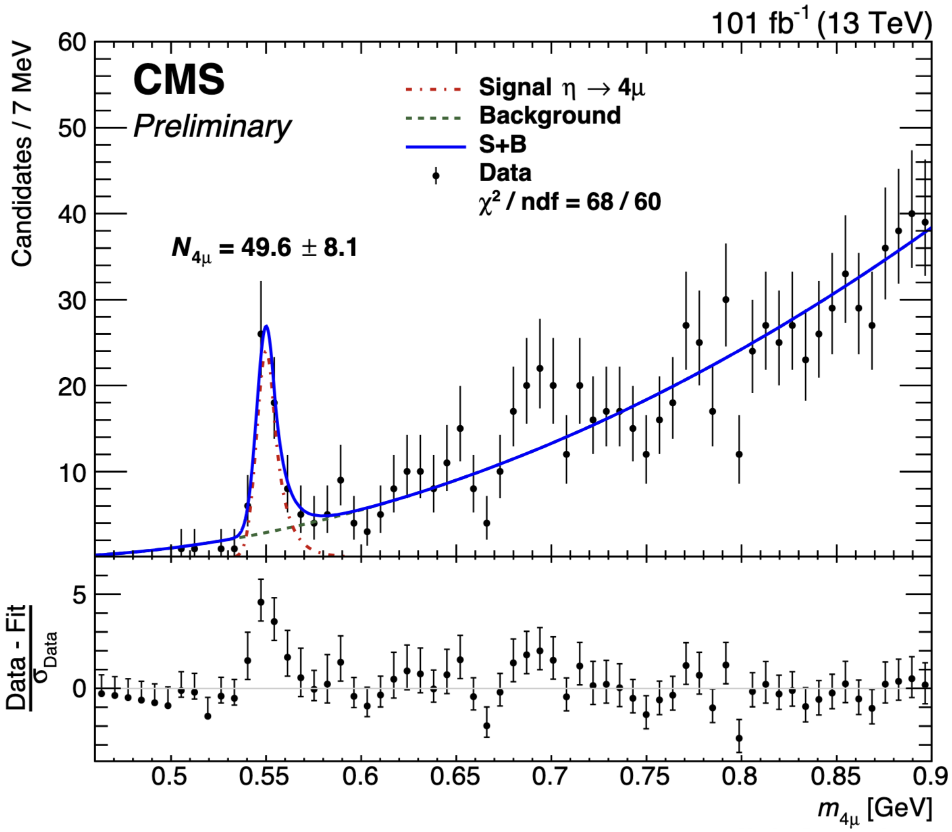
Observation of η→4μ

- Look for events with 4 muons and zero net charge, consistent with production from a common vertex
    - Clear peak observed at the η mass



Observation of η→4μ

- Look for events with 4 muons and zero net charge, consistent with production from a common vertex
  - Clear peak observed at the η mass
- Fit the distribution to a peaking signal and a threshold background shape
  - Signal: Crystal ball function
  - Background: $f(m_{4\mu}) = (m_{4\mu} - 4m_{\mu})^{\beta}$



Observation of $\eta \to 4\mu$

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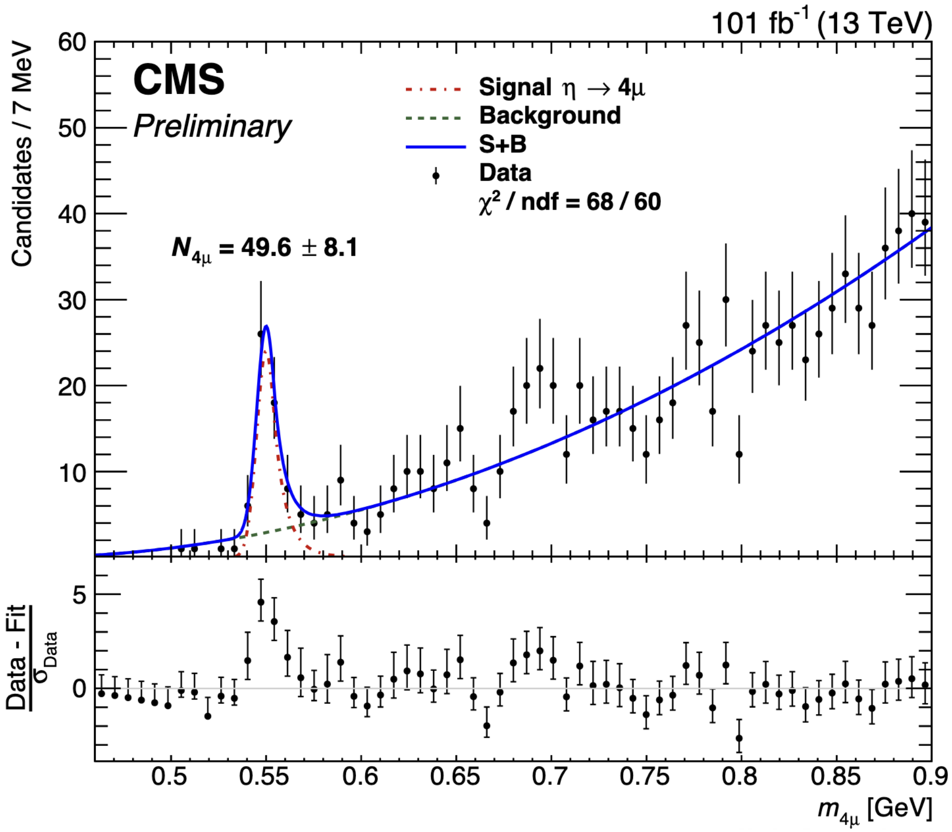
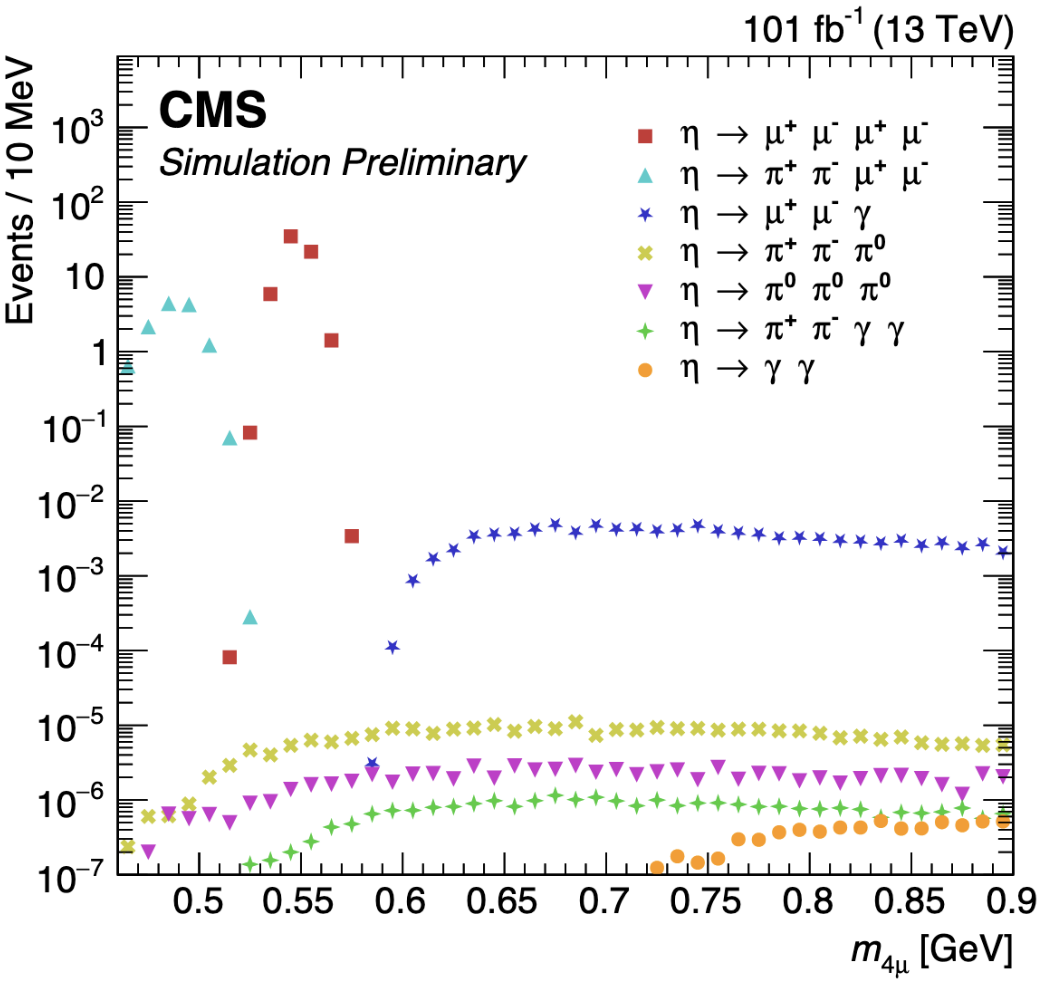


Significance of the signal well in excess of 5σ

First observation of $\eta \to 4\mu$!!!

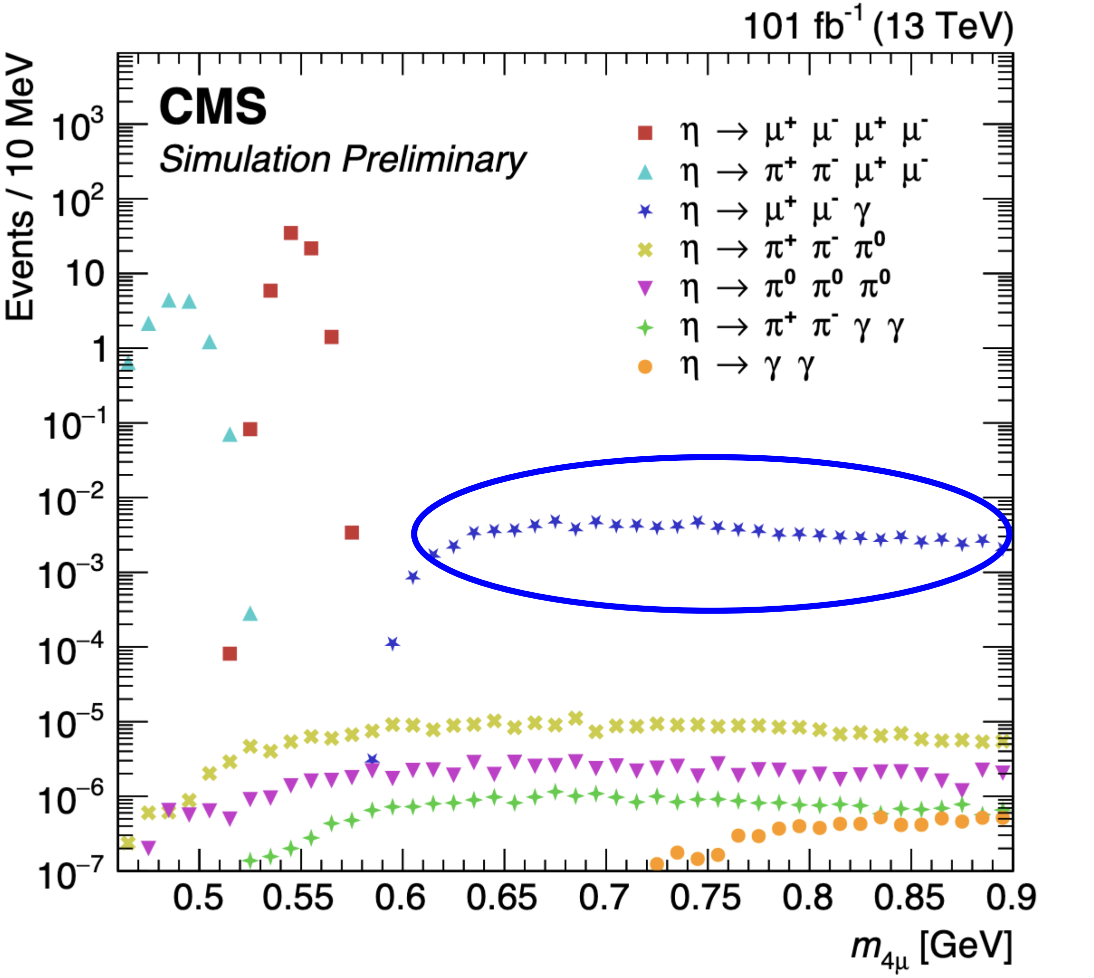
Peaking Backgrounds

- Cross check performed to check for possibility of rare η decay backgrounds using simulated samples



Peaking Backgrounds

- Cross check performed to check for possibility of rare η decay backgrounds using simulated samples
  - η→μ⁺μ⁻γ with γ conversion in material non-peaking and shifted to higher $m(4_\mu)$



Peaking Backgrounds

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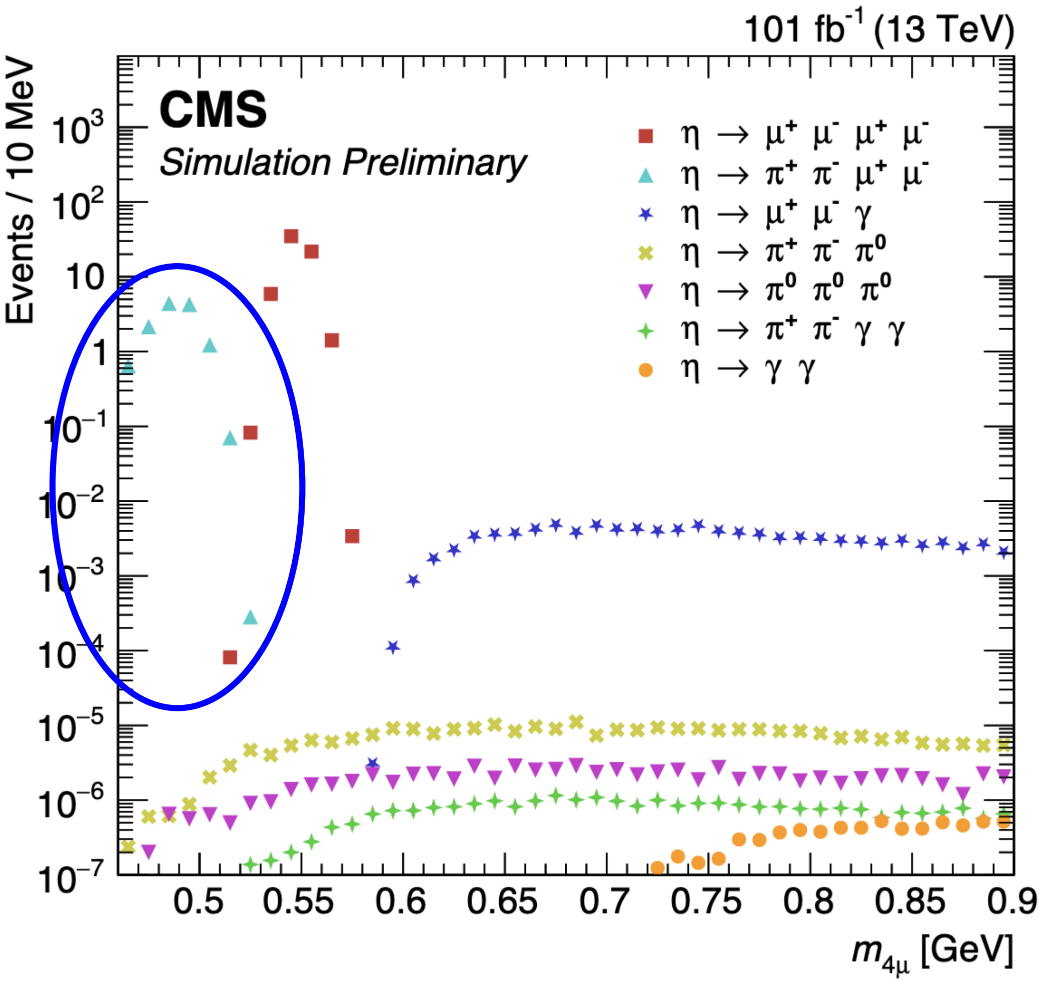
  - $\eta \to \mu^+\mu^-\gamma$ with γ conversion in material non-peaking and shifted to higher $m(4_\mu)$
  - $\eta \to \pi^+\pi^-\mu^+\mu^-$ with $\pi \to \mu$ fake shifted to lower mass due to wrong mass hypothesis
    - Rate shown is for current experimental upper limit $B(\eta \to \pi^+\pi^-\mu^+\mu^-) < 1.6\text{x}10^{-4}$
    - SM Prediction $6.5\text{x}10^{-9}$



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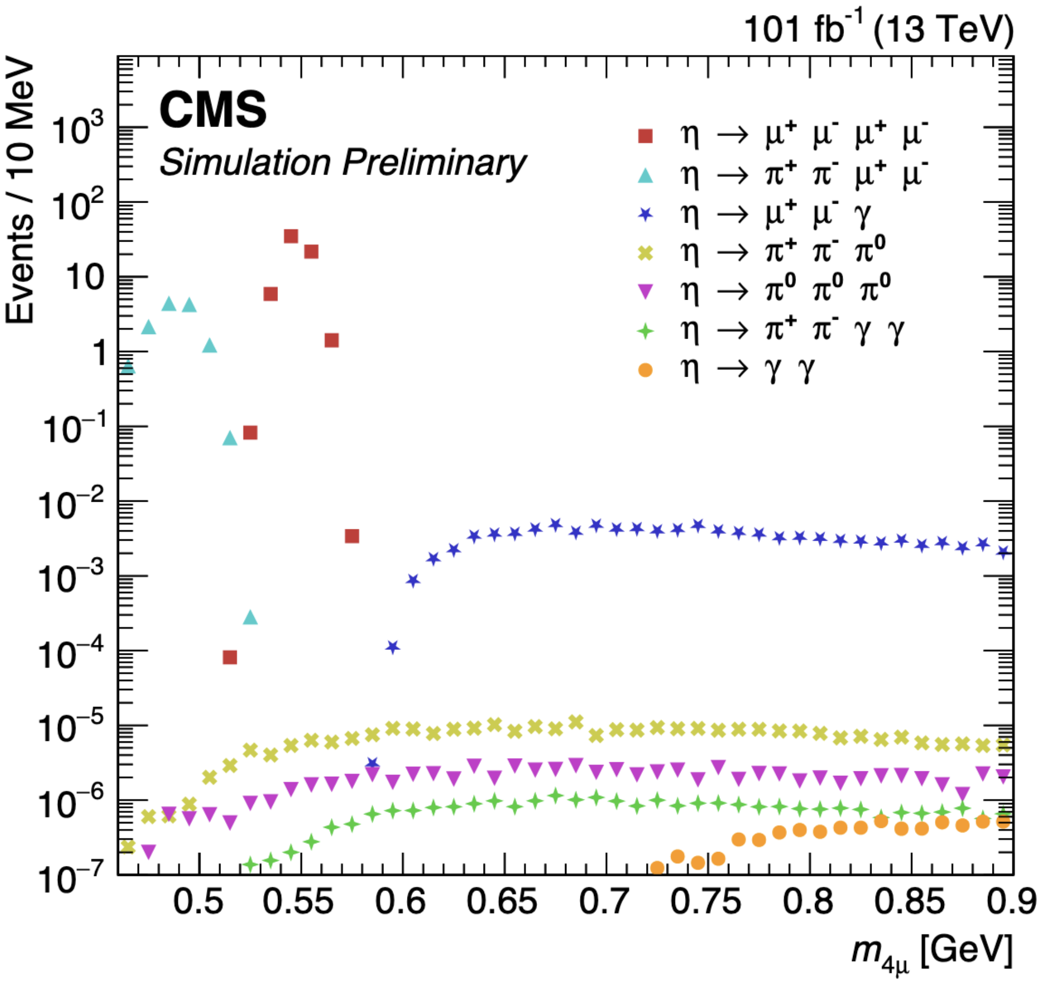
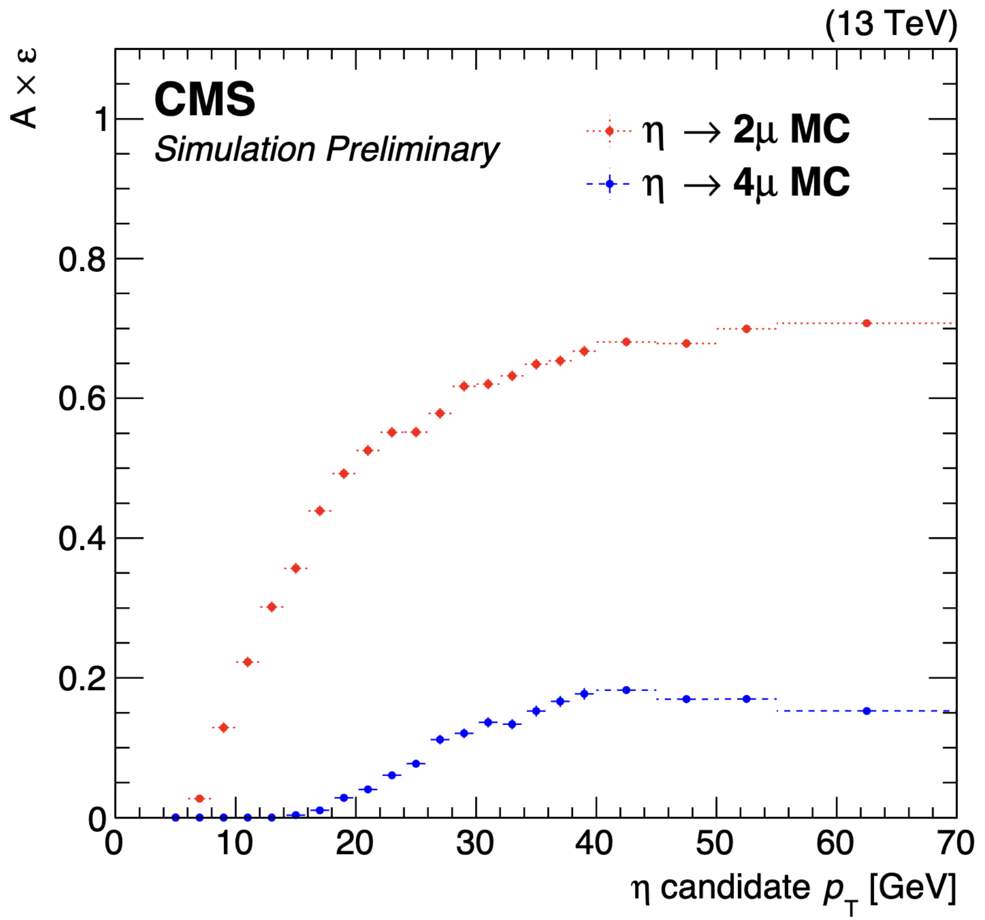
    - Rate shown is for current experimental upper limit $B(\eta \to \pi^+\pi^-\mu^+\mu^-) < 1.6 \times 10^{-4}$
    - SM Prediction 6.5×10^{-9}
- No possibility of significant peaking background component



Branching Ratio Strategy

- Measure the η→4μ branching ratio relative to η→2μ

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}}$$



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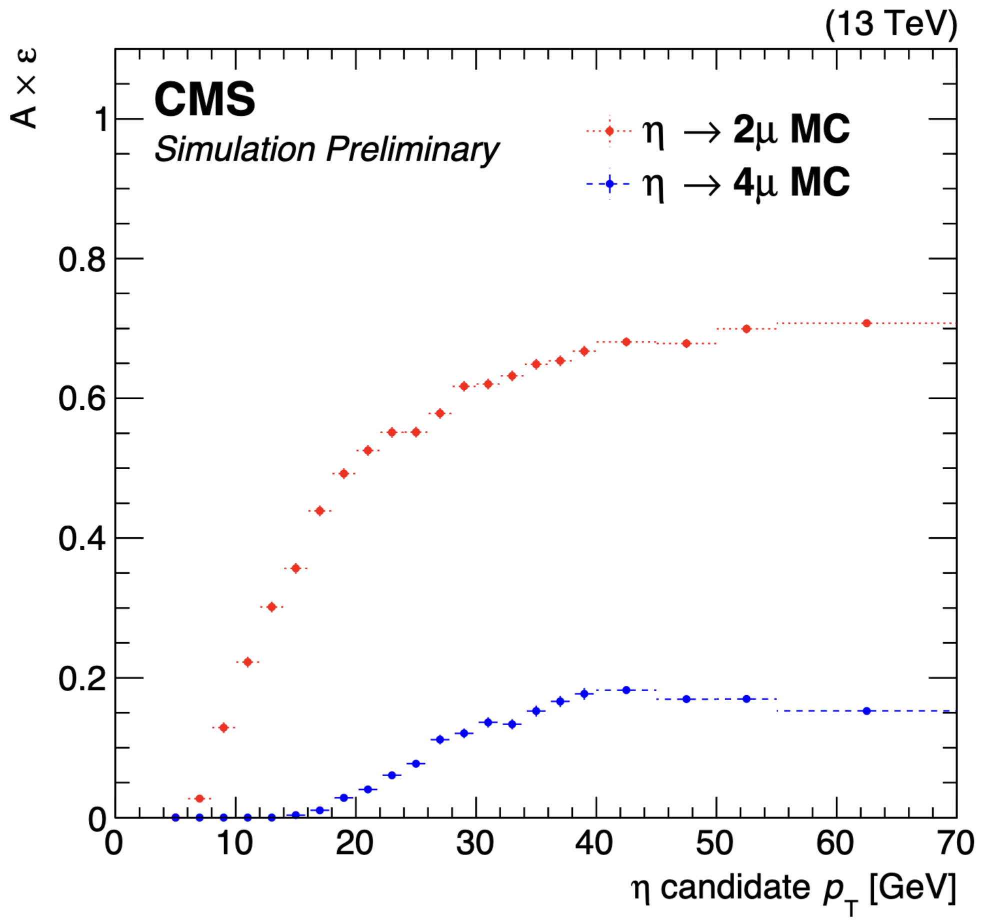

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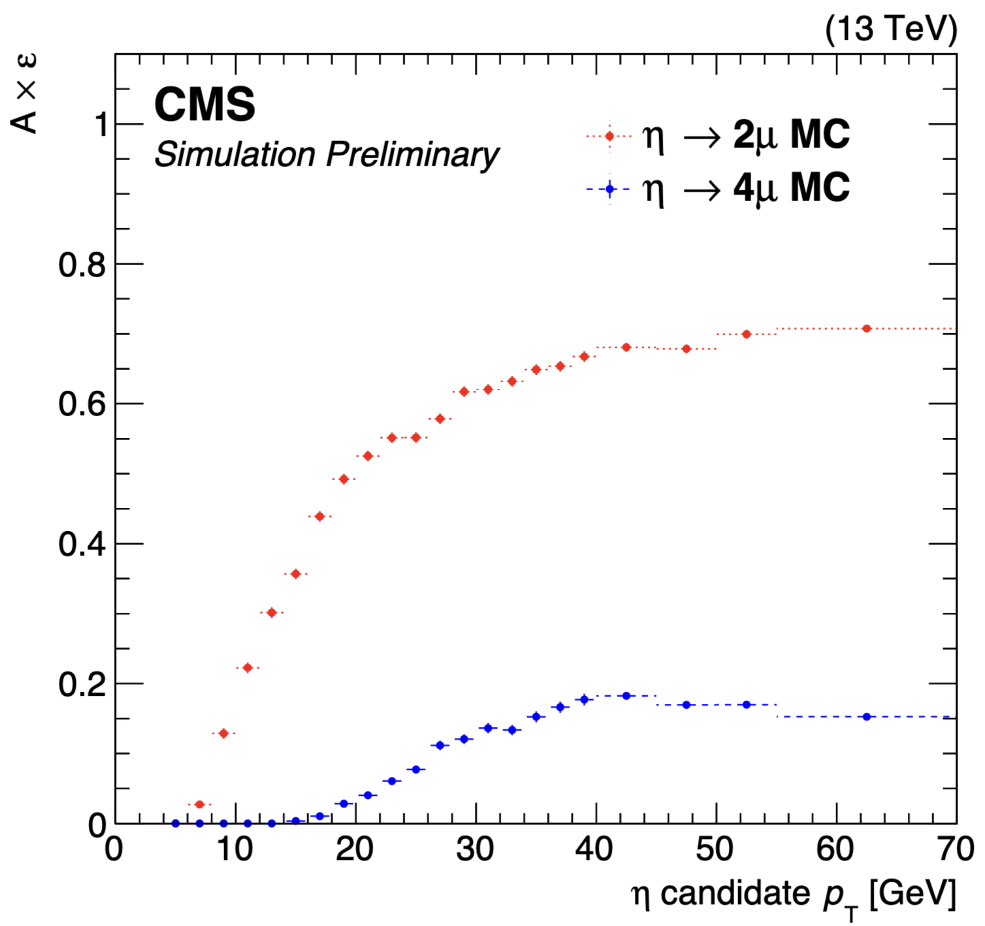
- The ratio of acceptance x eff. $A_{4\mu}$ / $A_{2\mu}$ determined from simulation (PLUTO generator) *arxiv:0708.2382*



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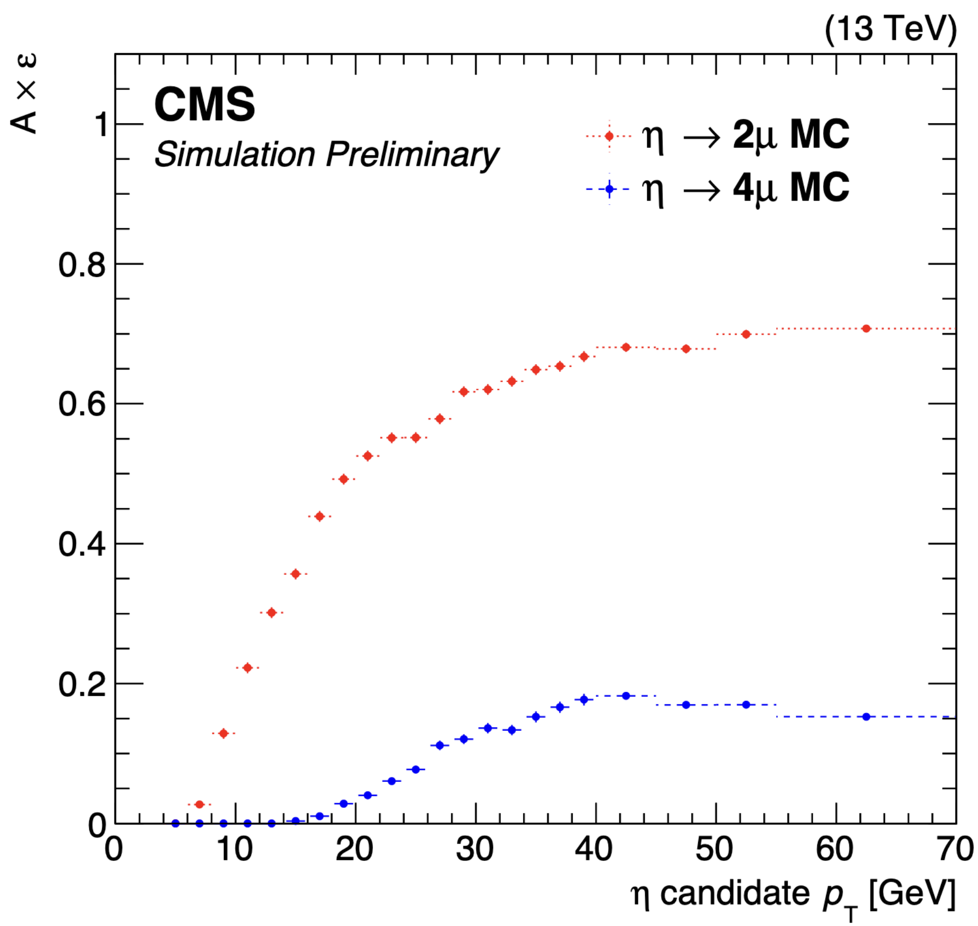
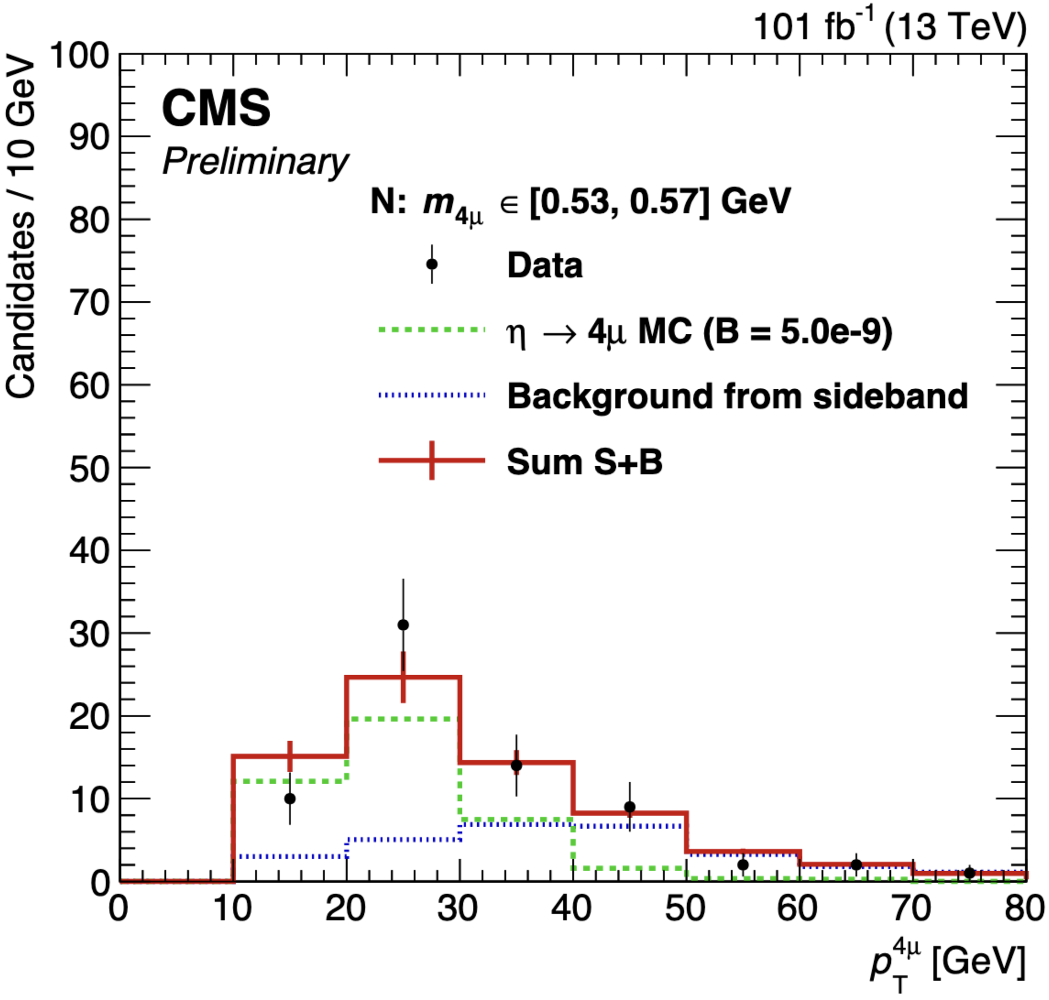


- η→2μ Axε driven by L1 trigger acceptance
- η→4μ Axε lower due to reconstruction requirements

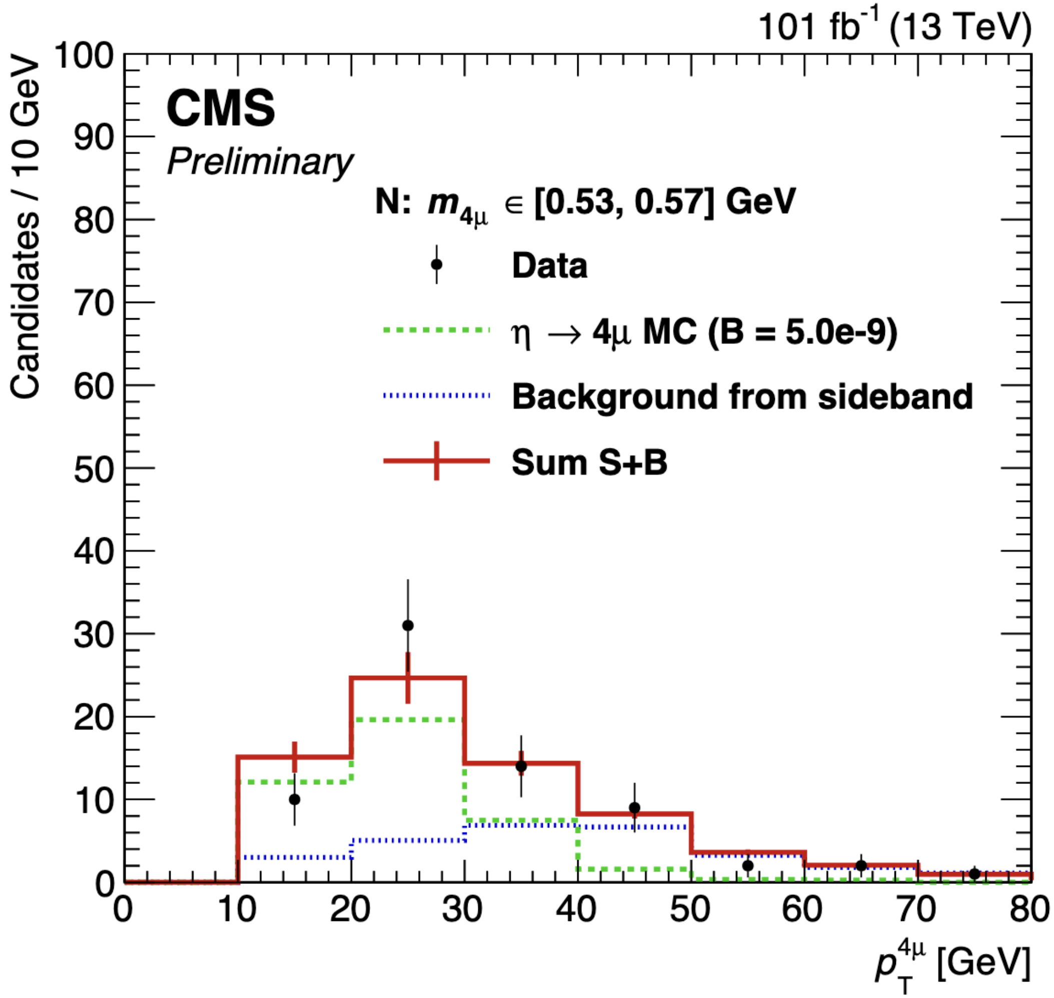
B(η→4μ) Uncertainties

- η→4μ differential event rate as a function of p_T in excellent agreement with the simulation



B(η→4μ) Uncertainties

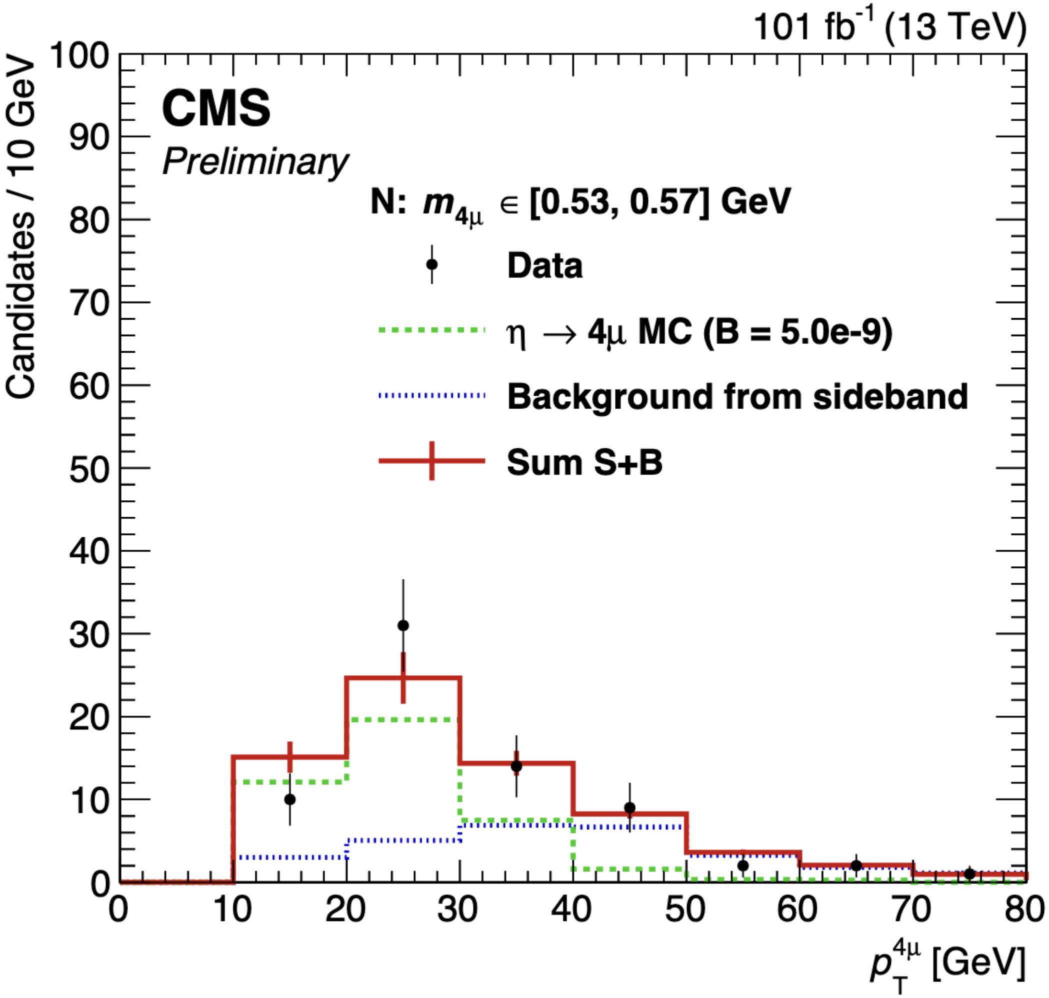
- η→4μ differential event rate as a function of p_T in excellent agreement with the simulation
- Residual uncertainty due to the imperfect knowledge of Axε for η→2μ and η→4μ
  - Accounts for threshold effects and η→2μ efficiency differences between data and MC (in total ~13%)



B(η→4μ) Uncertainties

- η→4μ differential event rate as a function of p_T in excellent agreement with the simulation
- Residual uncertainty due to the imperfect knowledge of Axε for η→2μ and η→4μ
  - Accounts for threshold effects and η→2μ efficiency differences between data and MC (in total ~13%)
- Uncertainty in normalization mode branching ratio (~14%)

$$\mathcal{B}(\eta \to 2\mu) = (5.8 \pm 0.8) \times 10^{-6}$$



B(η→4μ) Measurement

- B(η→4μ)/B(η→2μ) is extracted summing over all p_T / |η| bins:

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \left(0.9 \pm 0.1\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst})\right) \times 10^{-3}$$

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- Using the world average B(η→2μ), B(η→4μ) is measured for the first time:

$$\mathcal{B}(\eta \to 4\mu) = (5.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.7\,(\mathcal{B})) \times 10^{-9}$$

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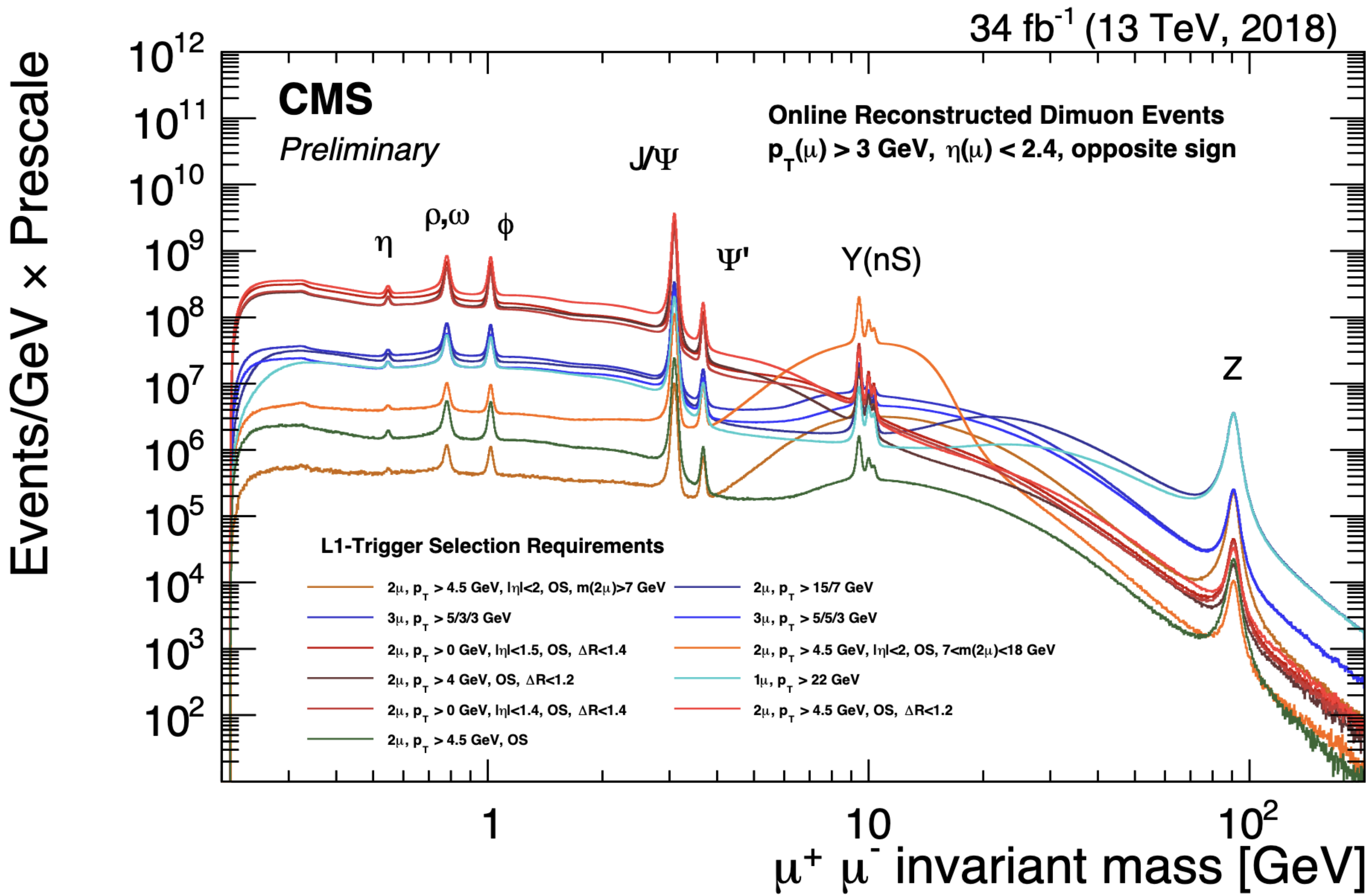
- In agreement, within uncertainties, with the SM prediction:

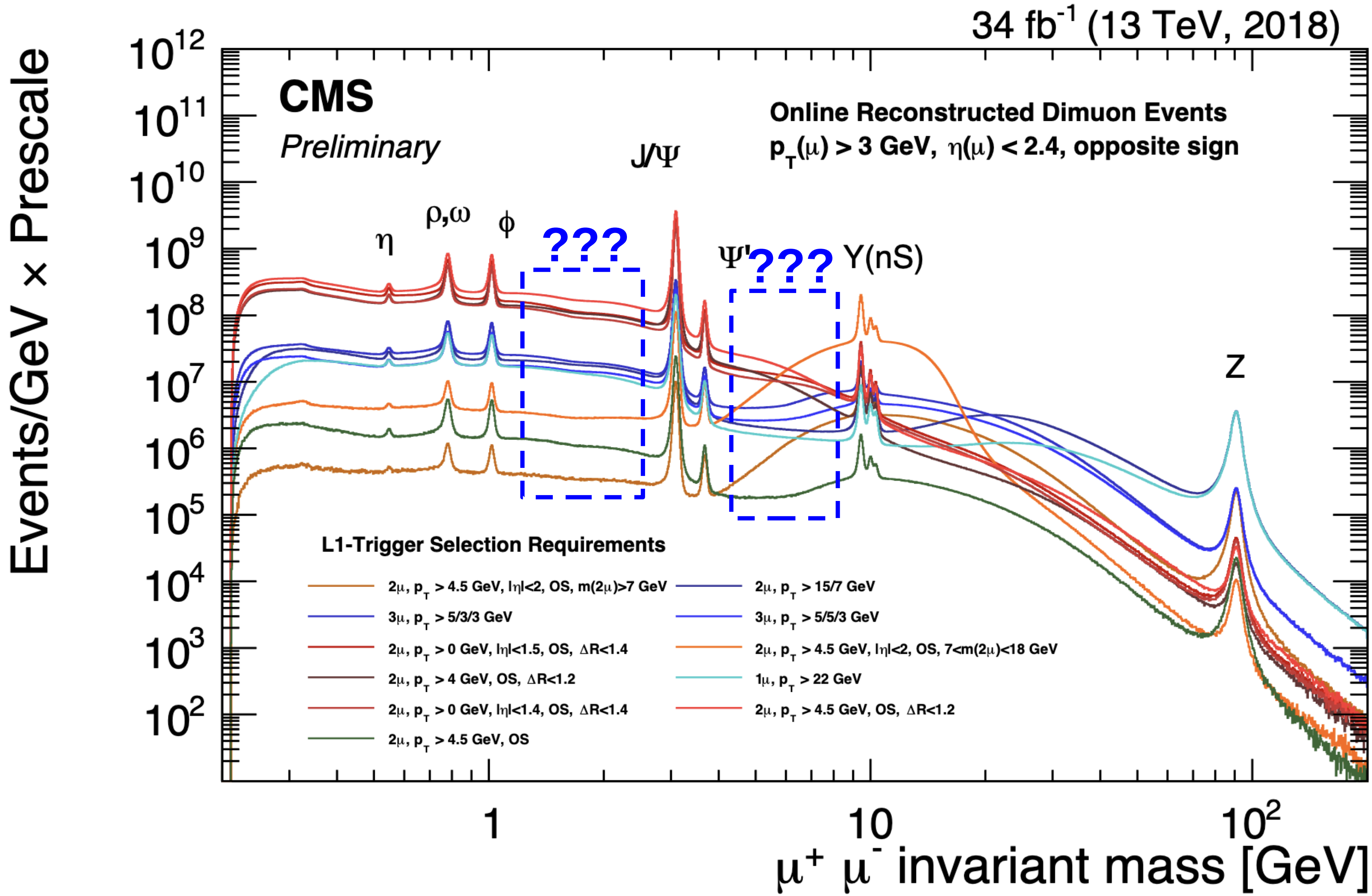
$$(3.98 \pm 0.15) \times 10^{-9}$$

arxiv:1511.04916

Search for Unknown Resonances

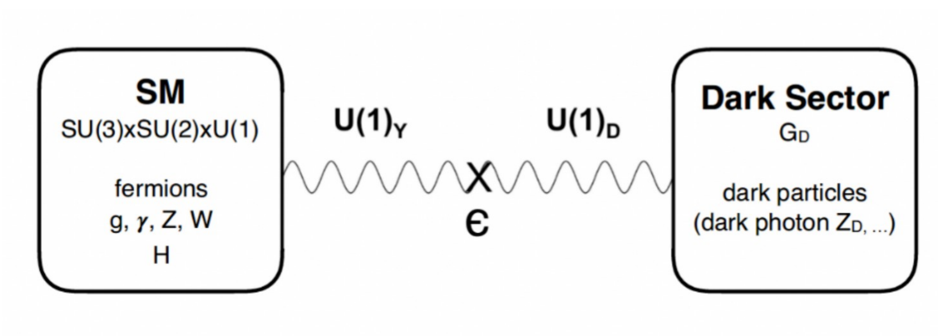


Search for Unknown Resonances

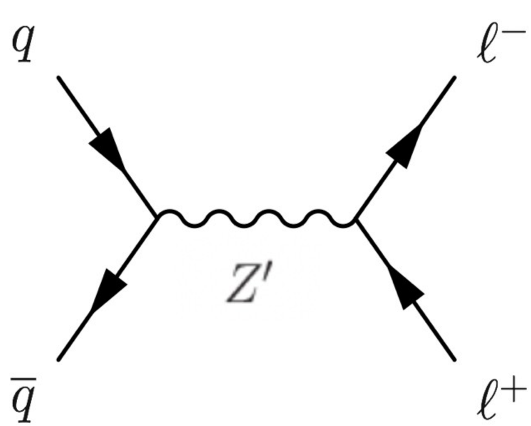


Why the GeV Scale?

- New states at the GeV scale are motivated from several perspectives
  - Vector portal interaction in thermal dark matter models
  - New scalar or vector coupling to muons could help explain $(g\text{-}2)_\mu$



$$\mathcal{L} \supset -\frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$



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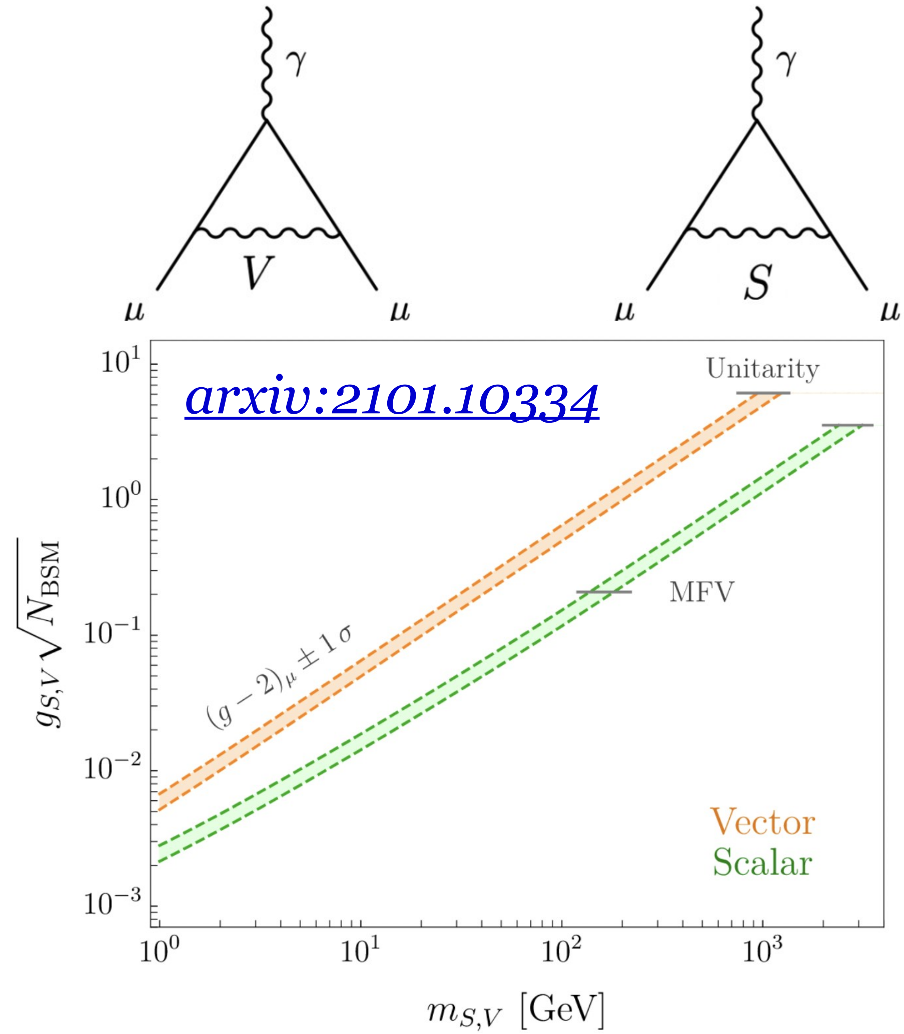
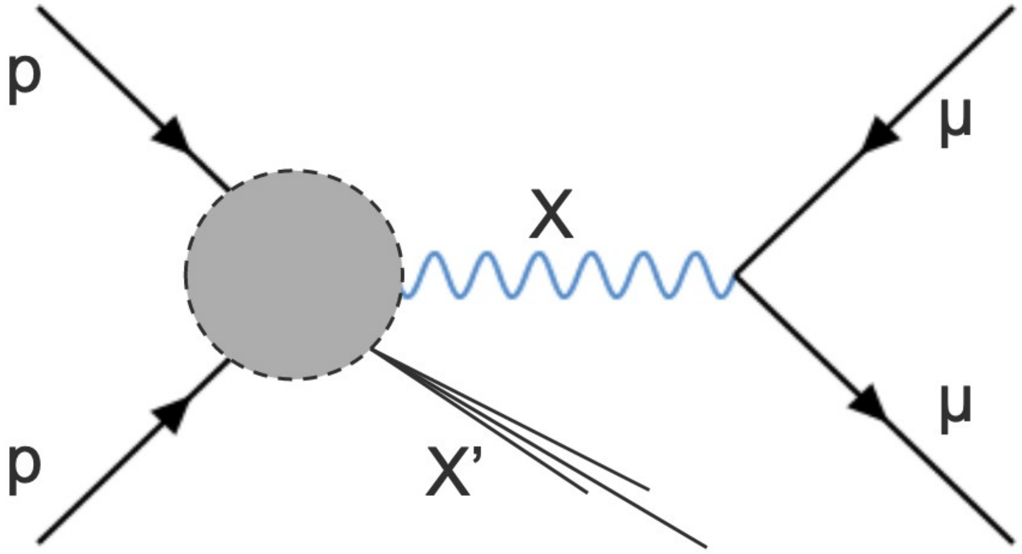


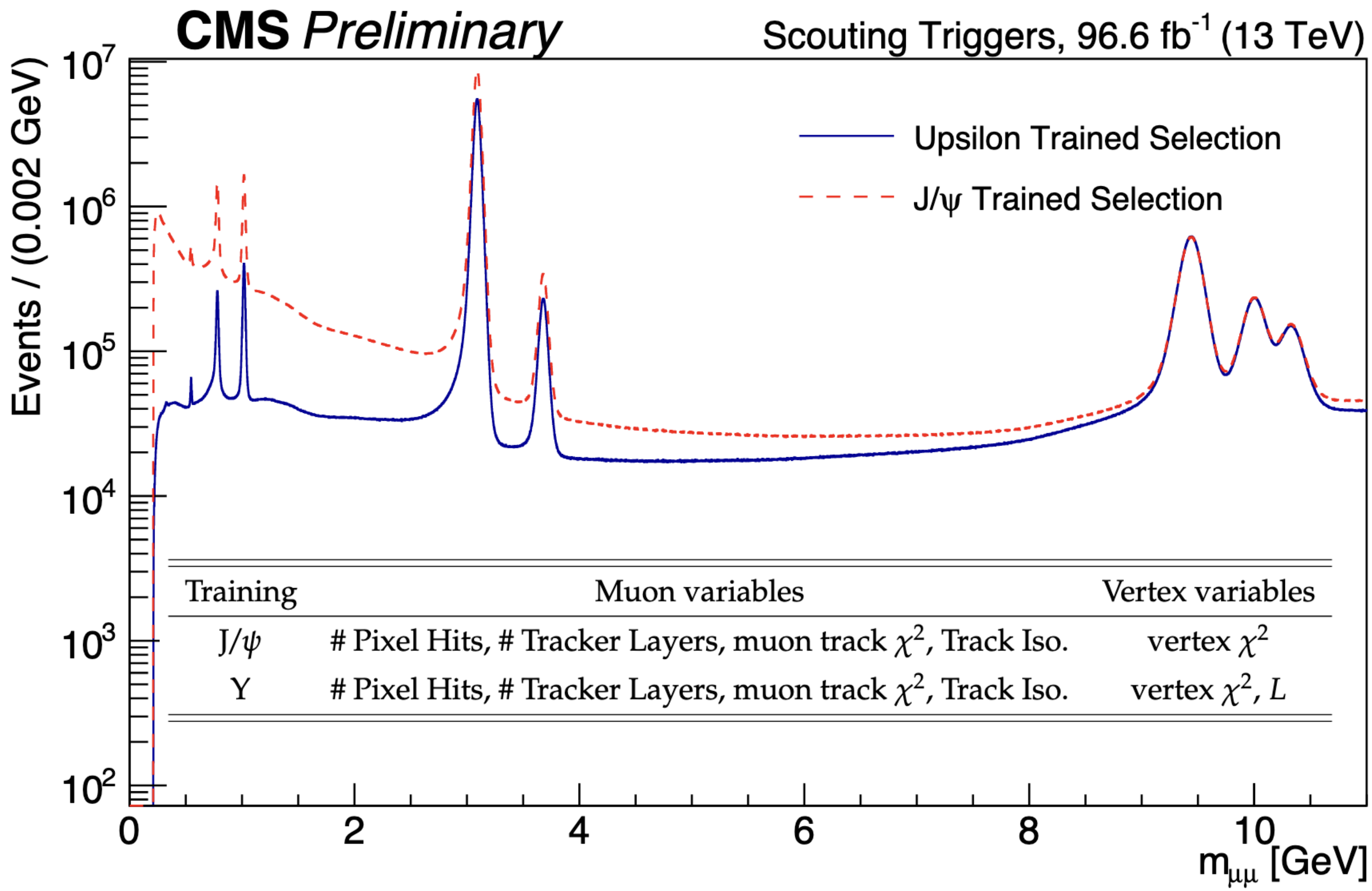
Analysis Strategy

- Bump hunt on the dimuon mass using analytical signal and bkg. pdfs
- Multivariate identification to suppress misidentified muons
- Define a simple fiducial volume (2 muons with $p_T^{\mu} > 4$ GeV and $|\eta|<1.9$)
- Data driven measurement of trigger and reconstruction efficiency
- Measure integrated luminosity, set model independent limit on $\sigma \times B \times \alpha$
- Compute $\sigma \times B \times \alpha$ in specific models to set limits on model parameters



Muon Identification

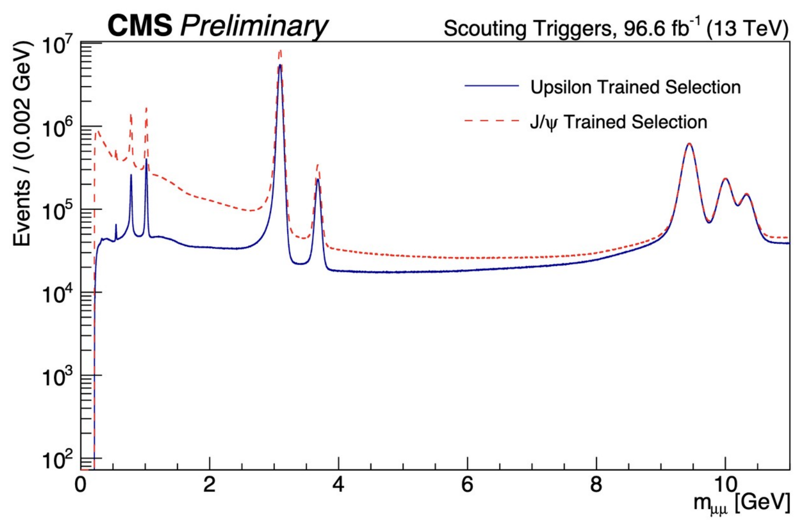
- Target prompt production, require transverse displacement L<0.2cm
- Data-driven BDT: OS J/Ψ and Υ events as signal, SS events as background
  - Υ training optimal for higher mass, J/Ψ training for low mass/boosted



Training	Muon variables	Vertex variables
J/ψ	# Pixel Hits, # Tracker Layers, muon track χ^2, Track Iso.	vertex χ^2
Υ	# Pixel Hits, # Tracker Layers, muon track χ^2, Track Iso.	vertex χ^2, L

Efficiency Measurement

- BDT ID efficiency measured in data using tag and probe method on J/Ψ and Υ
    - Uncertainty in ID eff. from data sample and data/MC diff. (4-20%)



- Trigger efficiency for dimuon events within fiducial volume is measured using an unbiased sample of standard e/γ events
    - Dependent on $m_{\mu\mu}$ and $\Delta r_{\mu\mu}$
    - Difference between data and simulation and taken as uncertainty (up to 20%)

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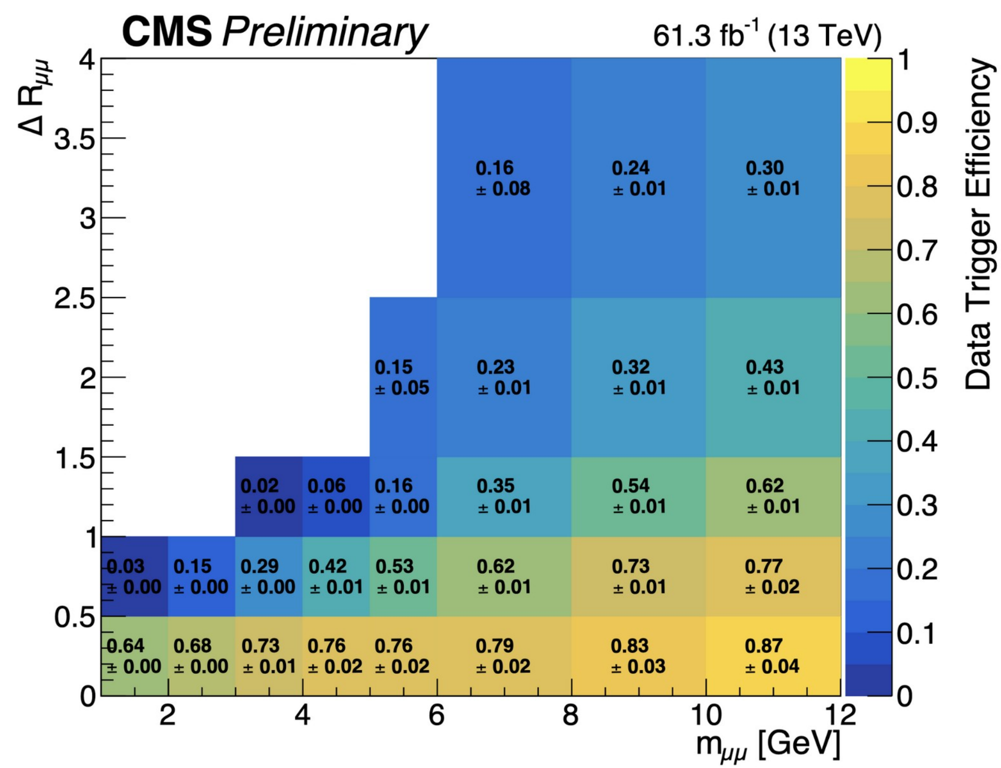
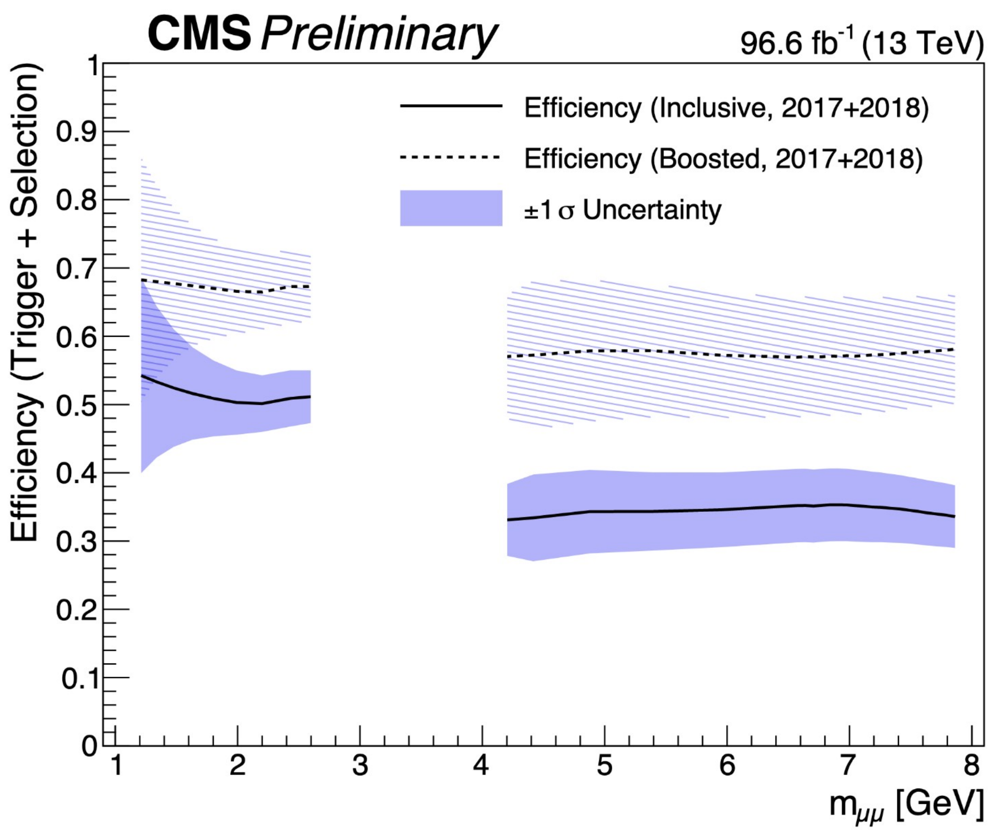


Event Categorization

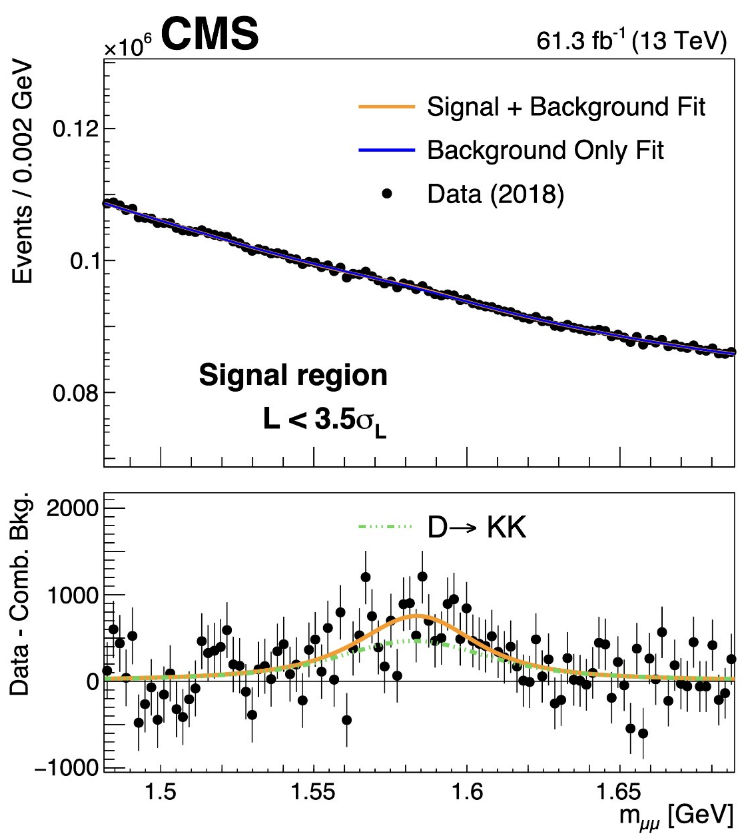
- Two signal categories targeting inclusive and boosted production
  - Optimal for different production mechanisms (e.g. DY or ggF)
- For high mass inclusive category, additional requirement L<0.015cm
- For inclusive low mass and boosted categories vertex resolution degrades so instead cut on displacement significance

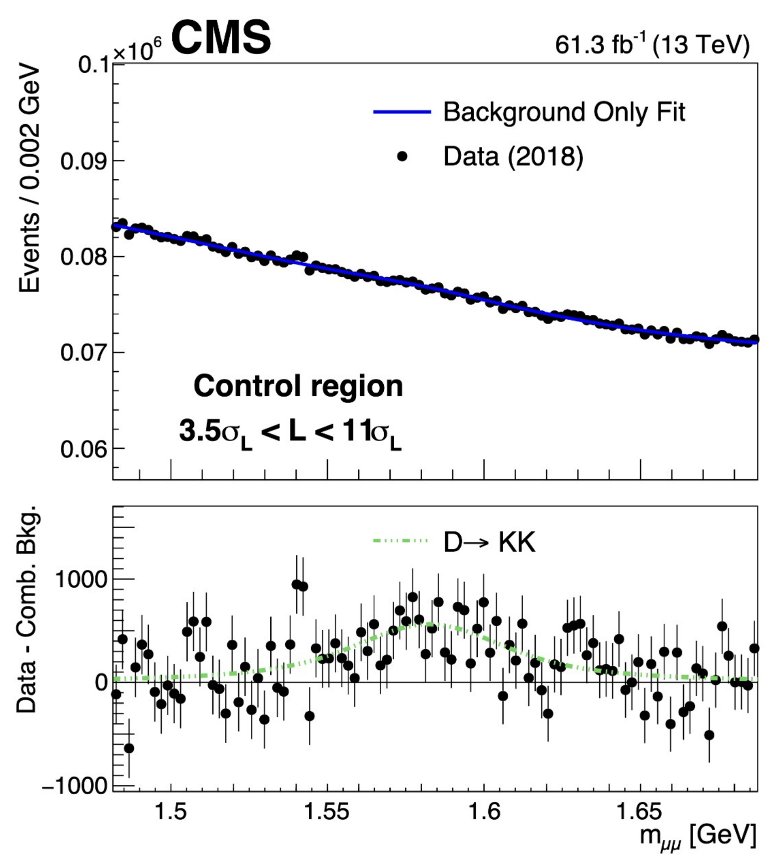


Preselection	$L < 0.2\,\mathrm{cm}$, $\lvert\eta^{\mu}\rvert < 1.9$, OS			
Category	Inclusive		Boosted	
Mass Range	$m_{\mu\mu} < 2.6\,\mathrm{GeV}$	$m_{\mu\mu} > 4.2\,\mathrm{GeV}$	$m_{\mu\mu} < 2.6\,\mathrm{GeV}$	$m_{\mu\mu} > 4.2\,\mathrm{GeV}$
p_T^{μ}	$> 4\,\mathrm{GeV}$		$> 5\,\mathrm{GeV}$	
BDT ID	J/ψ ID > -0.1	Υ ID > 0.0	J/ψ ID > -0.1	
Vertex	$\sigma_L < 3.5L$	$L < 0.015\,\mathrm{cm}$	$\sigma_L < 3.5L$	
$p_T^{\mu\mu}$	–	–	$> 35\,\mathrm{GeV}$	$> 20\,\mathrm{GeV}$

Background Modeling

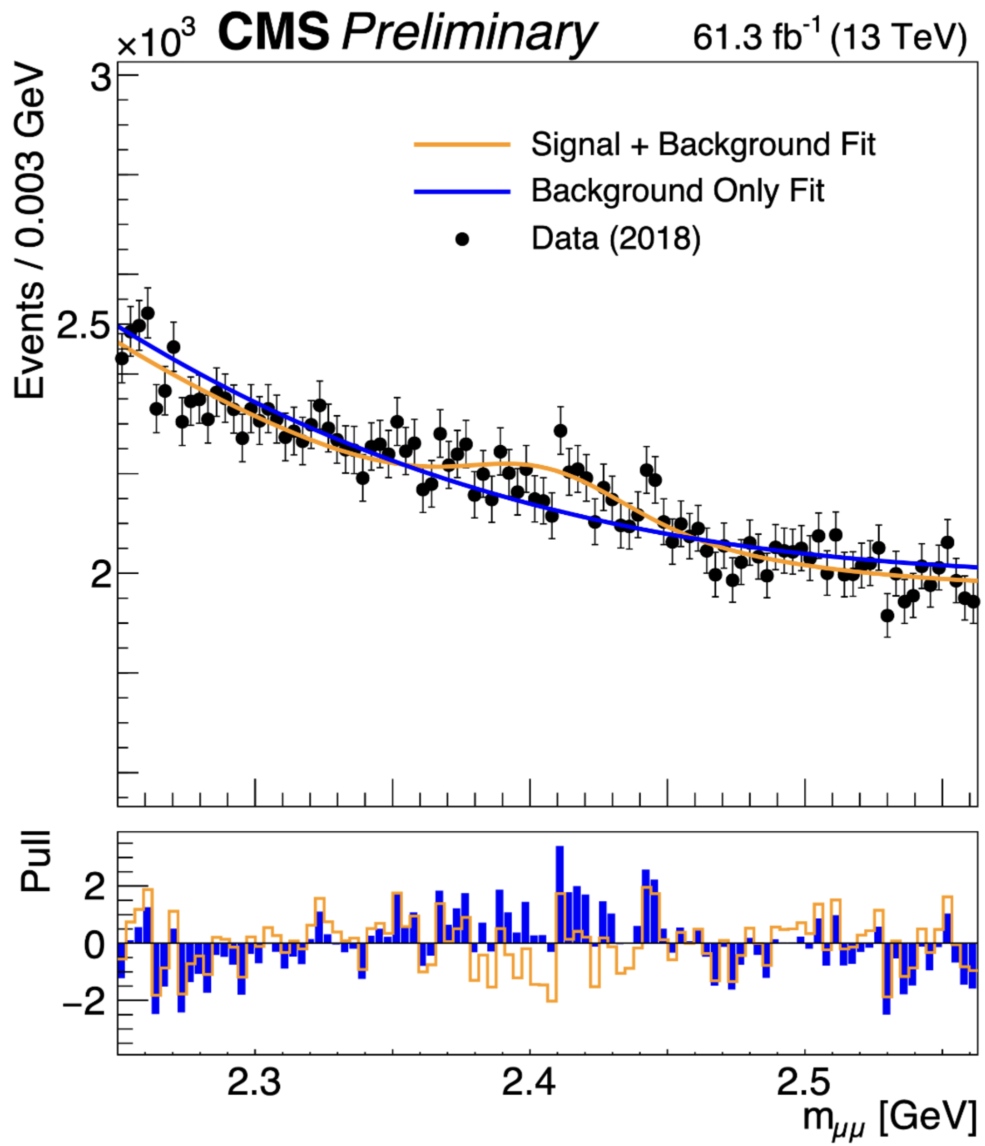
- Combinatorial background is modeled using 4^{th} order Bernstein polynomial (checked with toy datasets to have negligible bias)
- Peaking backgrounds ($D_0 \to KK, K\pi$) estimated from control regions with inverted L/σ_L cuts (transfer factors estimated from simulation)
  - Uncertainty on transfer factors 20-25% estimated using J/Ψ data/MC





Signal Model and Largest Excess

- Signal modeled from fits to SM resonances
  - Double Crystal Ball + Gaussian
  - 20% uncertainty on resolution



Signal Model and Largest Excess

- Signal modeled from fits to SM resonances
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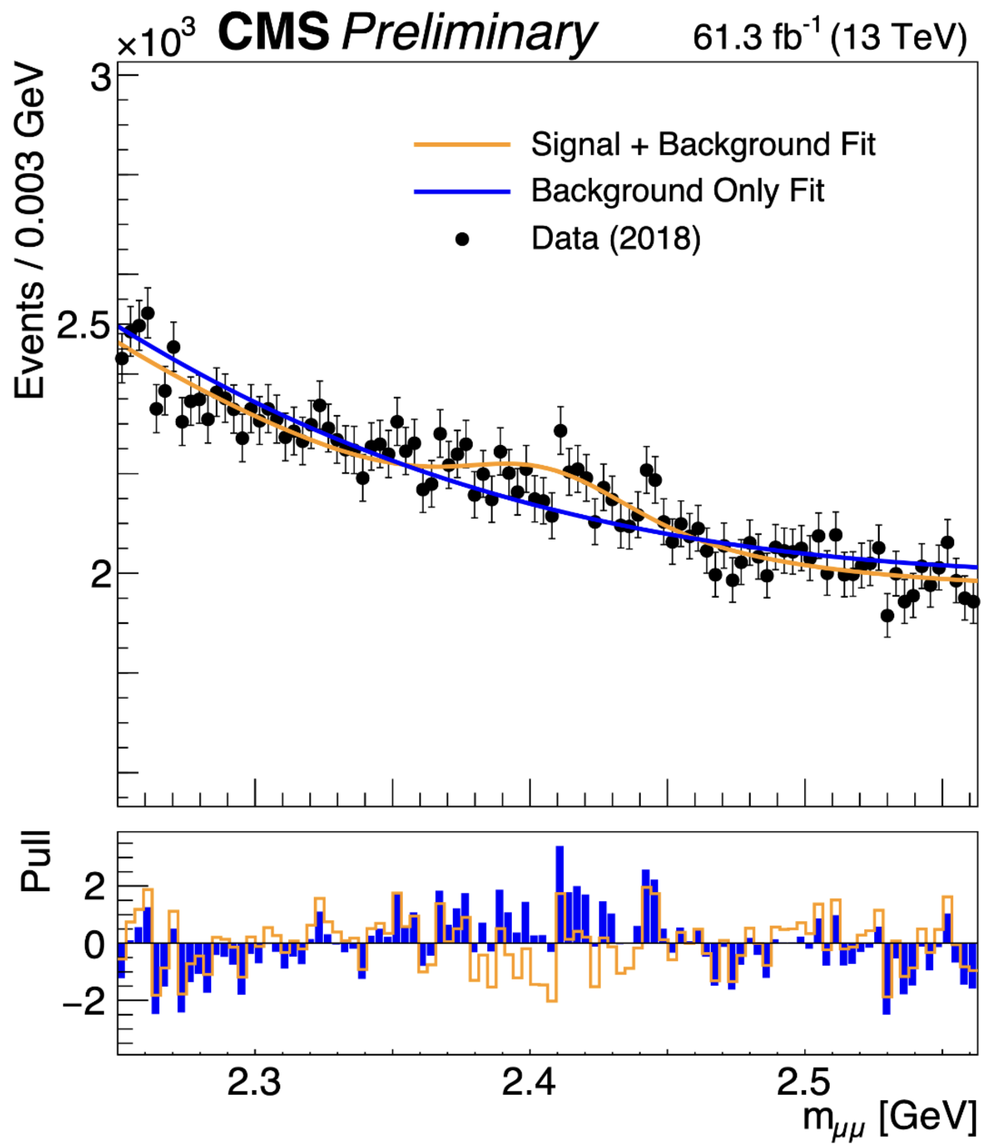
- The mass hypothesis with the largest local significance comes at 2.41 GeV in the boosted category
  - 3.2σ local significance, 1.3σ global significance



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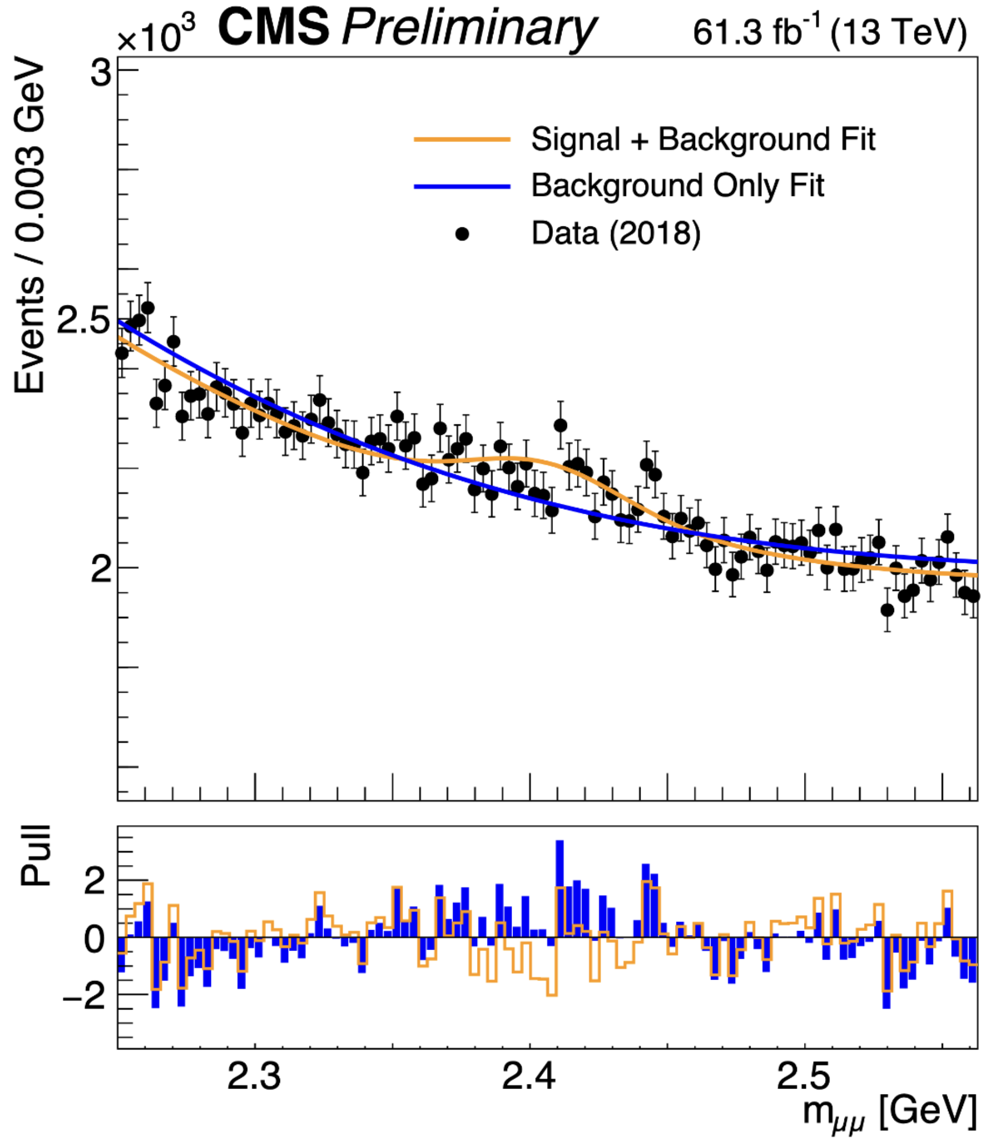
  - Double Crystal Ball + Gaussian
  - 20% uncertainty on resolution
- The mass hypothesis with the largest local significance comes at 2.41 GeV in the boosted category
  - 3.2σ local significance, 1.3σ global significance
  - Notably LHCb reports a 3.1σ local excess at 2.42 GeV in one event category (X+b, 10<p_T(X)<20 GeV)

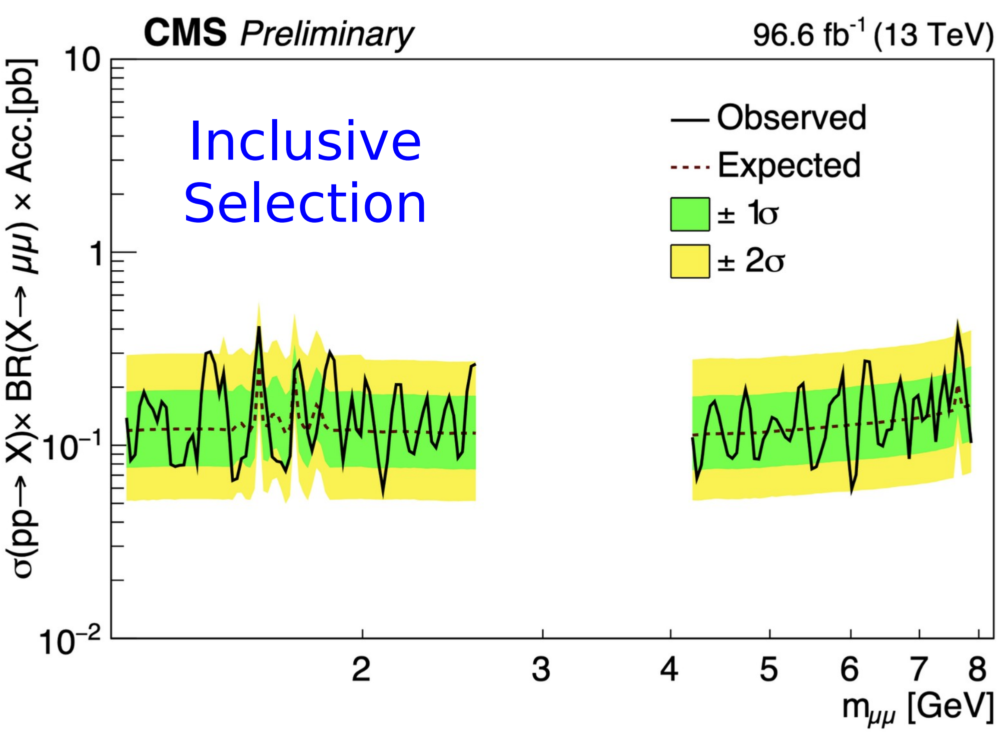
  [*JHEP 10 (2020) 156*]

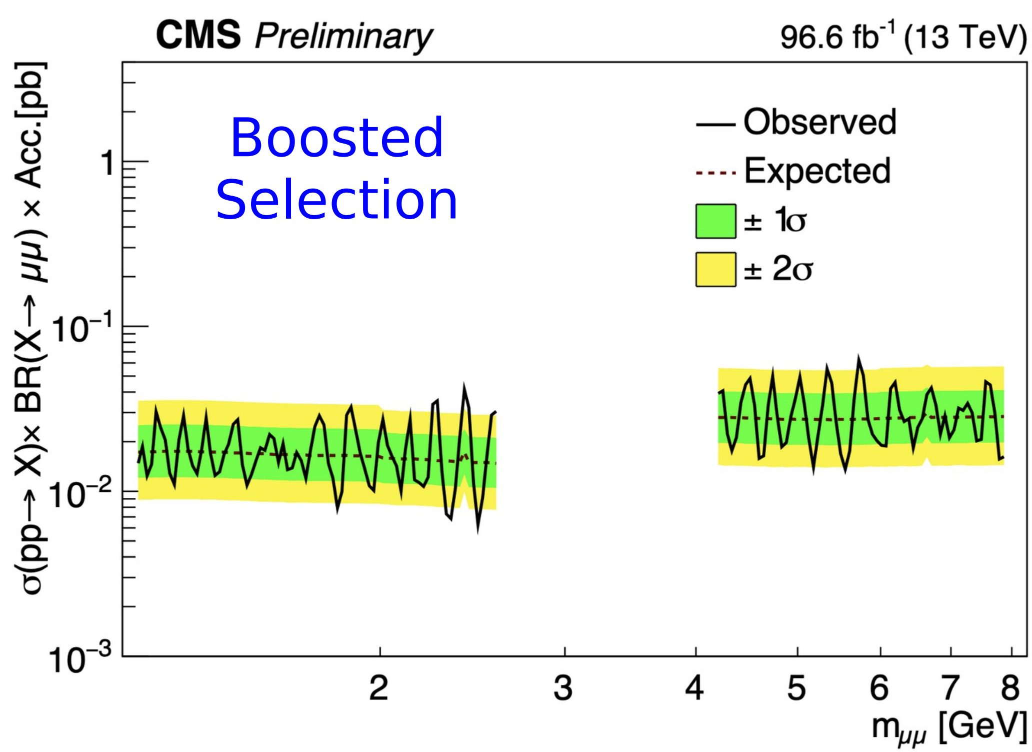


Model Independent Limit

- Main results are model independent limits on $\sigma \times B \times \alpha$ for the inclusive and boosted selections
- Limit calculation includes all experimental uncertainties

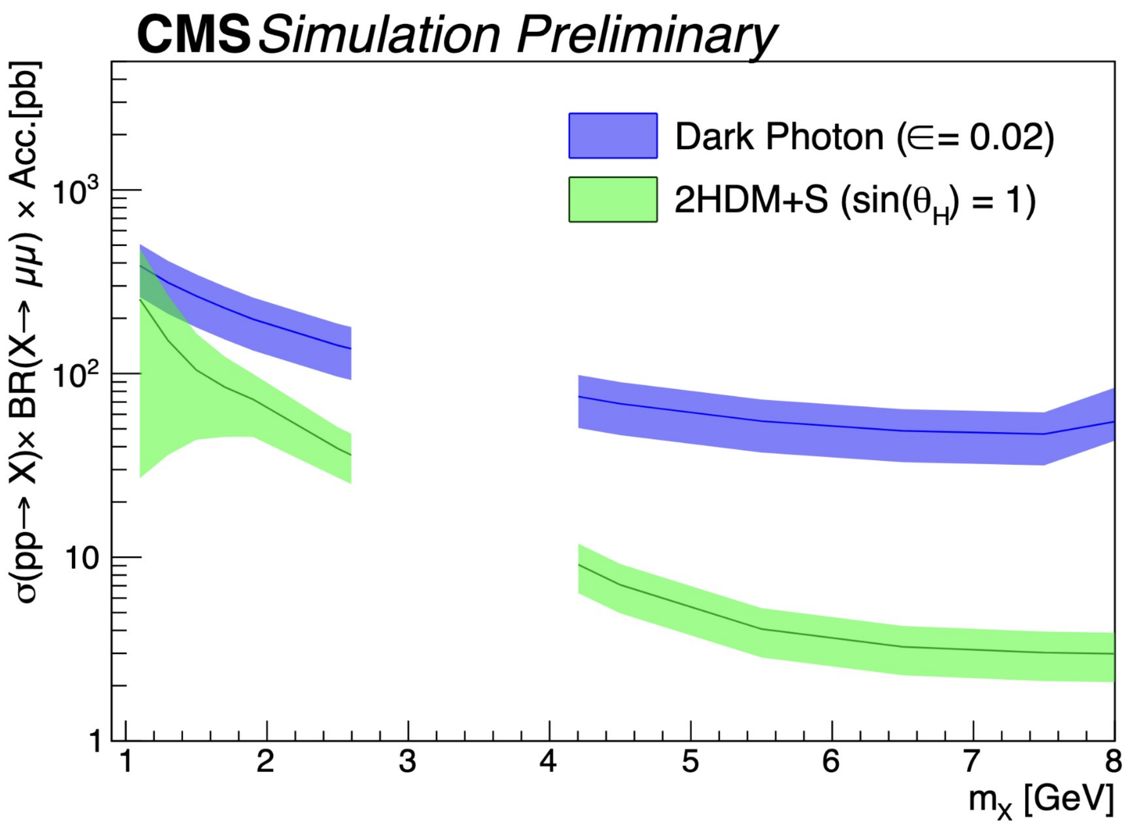
Effect	$m_{\mu^\pm\mu^\mp} < 2.6$ GeV	$m_{\mu^\pm\mu^\mp} > 4.2$ GeV
Integrated luminosity	2.3–2.5%	
Mass resolution	20%	
Trigger efficiency	1–20%	
Muon ID efficiency	4–9%	12–20%
Vertex selection	—	3%
Efficiency application	8%	4%
D meson normalization TFs	20–25%	—





Model Dependent Limits

- We choose two specific models to constrain model parameters
  - DY production of vector boson (dark photon)
  - Gluon fusion production of pseudoscalar (2HDM+S)
- Relies on theoretical calcuations of cross sections, branching ratio, and experimental acceptance



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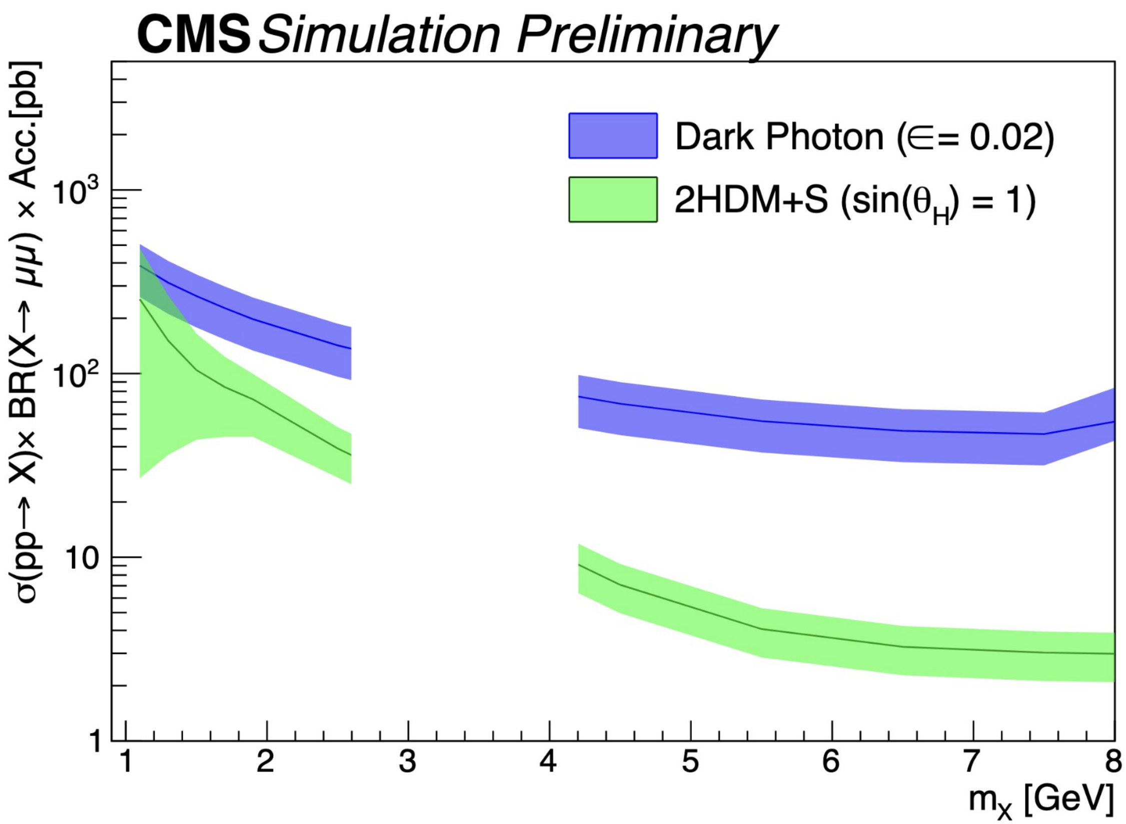

$$\sigma_{\mathrm{pp}\to\mathrm{Z_D}} \cdot \epsilon^2 \cdot \mathcal{B} \cdot A = \sigma_{\mathrm{limit}}$$

- Dark photon cross section and BR calculated with MadGraph
- NNLO corrections and acceptance from DYTurbo *EPJC 80 (2020) 251*

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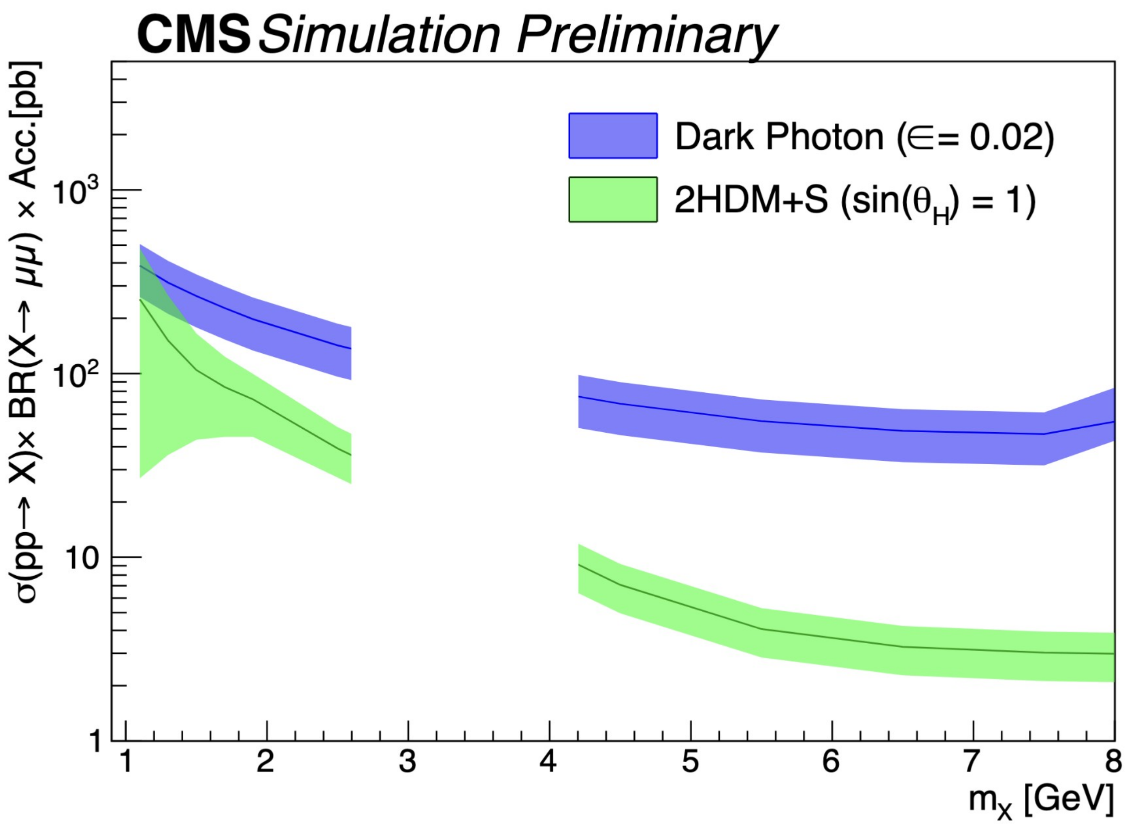

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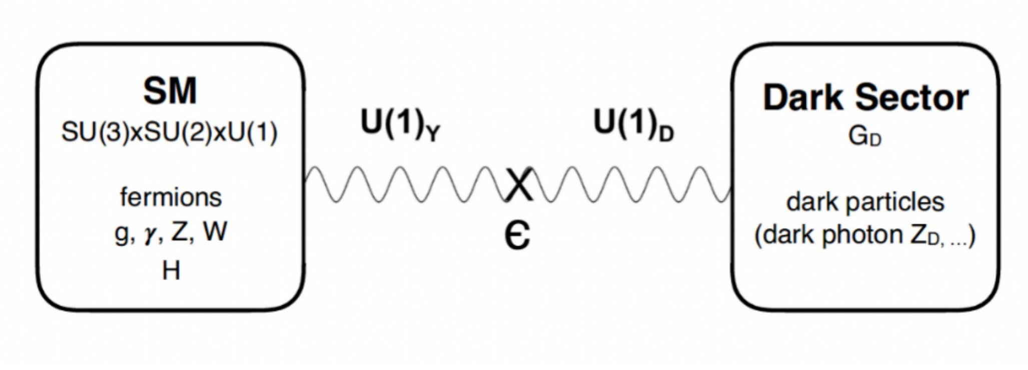
- Dark photon cross section and BR calculated with MadGraph
- NNLO corrections and acceptance from DYTurbo *EPJC 80 (2020) 251*

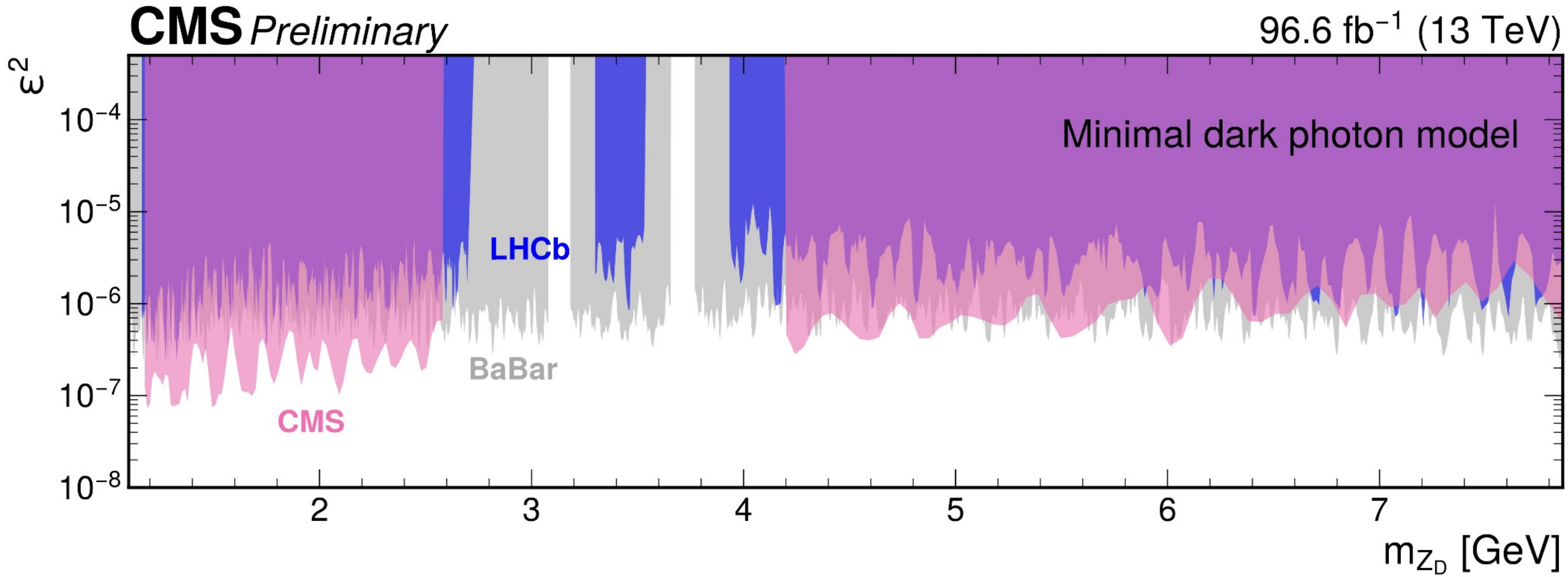
$$\sigma_{\mathrm{pp}\to a} \cdot \sin^2(\theta_{\mathrm{H}}) \cdot \mathcal{B} \cdot A = \sigma_{\mathrm{limit}}$$

- Gluon fusion cross section from HIGLU *arxiv:hep-ph/9510347*, BR from Haisch et. al. *JHEP 03 (2018) 178*
- Acceptance from MadGraph and Pythia

Dark Photon Interpretation

- Limits on kinetic mixing parameter ε^2 in dark photon model extracted from the inclusive category limits



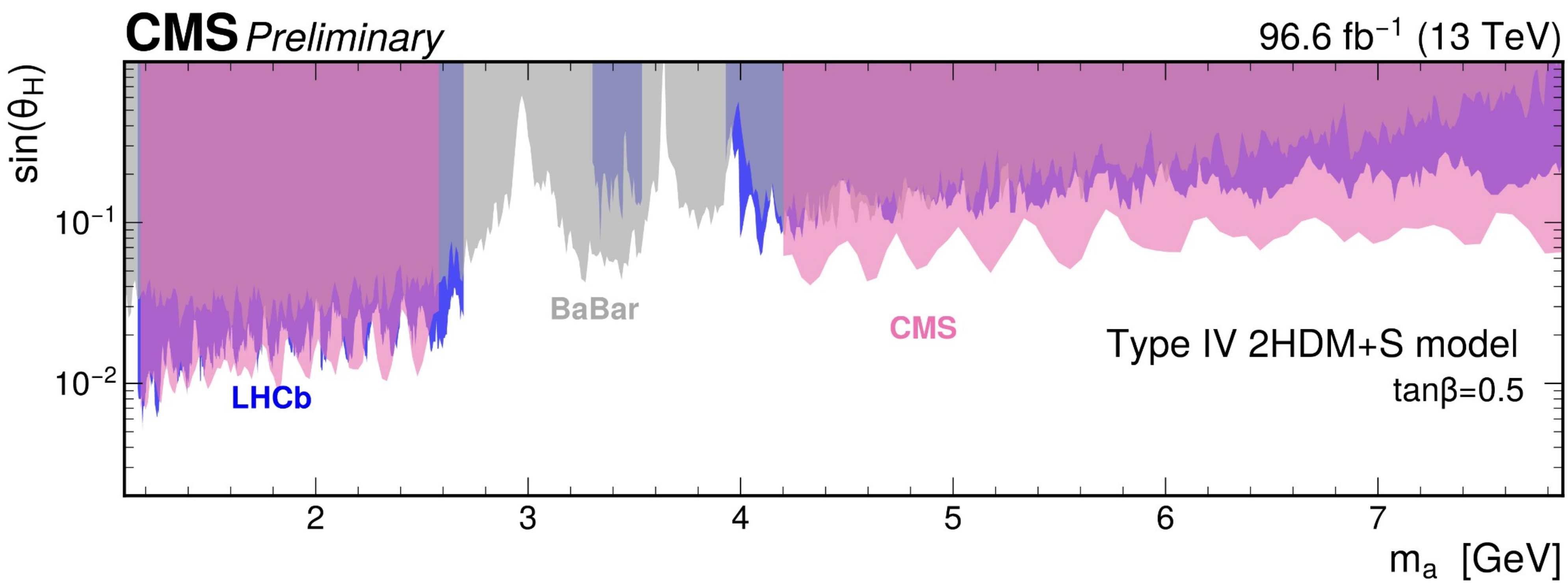


2HDM+S Interpretation

- Limits on mixing angle sin(Θ_H) in Type-IV 2HDM+S model (tanβ=0.5) extracted from the boosted category limits

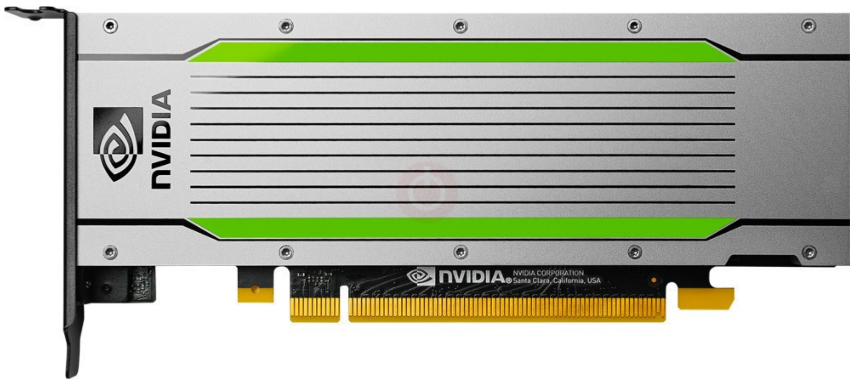
$$\mathcal{L} \supset -\sum_f \frac{y_f}{\sqrt{2}}\, i\xi_f^{\mathrm{M}}\, \bar{f}\gamma_5 f\, a$$

type	I	II	III	IV
up-type quarks	s_θ/t_β	s_θ/t_β	s_θ/t_β	s_θ/t_β
down-type quarks	$-s_\theta/t_\beta$	$s_\theta t_\beta$	$-s_\theta/t_\beta$	$s_\theta t_\beta$
charged leptons	$-s_\theta/t_\beta$	$s_\theta t_\beta$	$s_\theta t_\beta$	$-s_\theta/t_\beta$



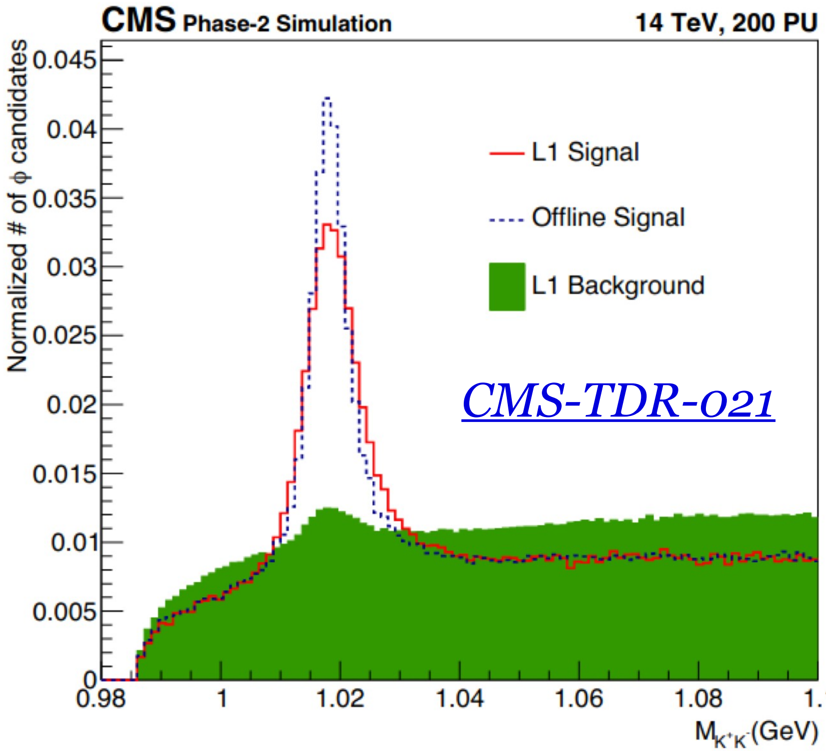
Data Scouting in Run 3

- **Bottleneck #1: HLT speed**
  - Accelerate pixel tracking and calorimeter reco. w/ GPUs
  - Running HLT Scouting in Run 3 at ~30 KHz, 350 MB/s



- **Bottleneck #2: Event Content**
  - Reconstruct and store more information (e.g. electrons, photons) in smaller data format (~6 kB after compression)

- **Final Bottleneck: L1 rate**
  - For HL-LHC, L1 trigger will have much better resolution, opportunity for scouting at L1



Summary

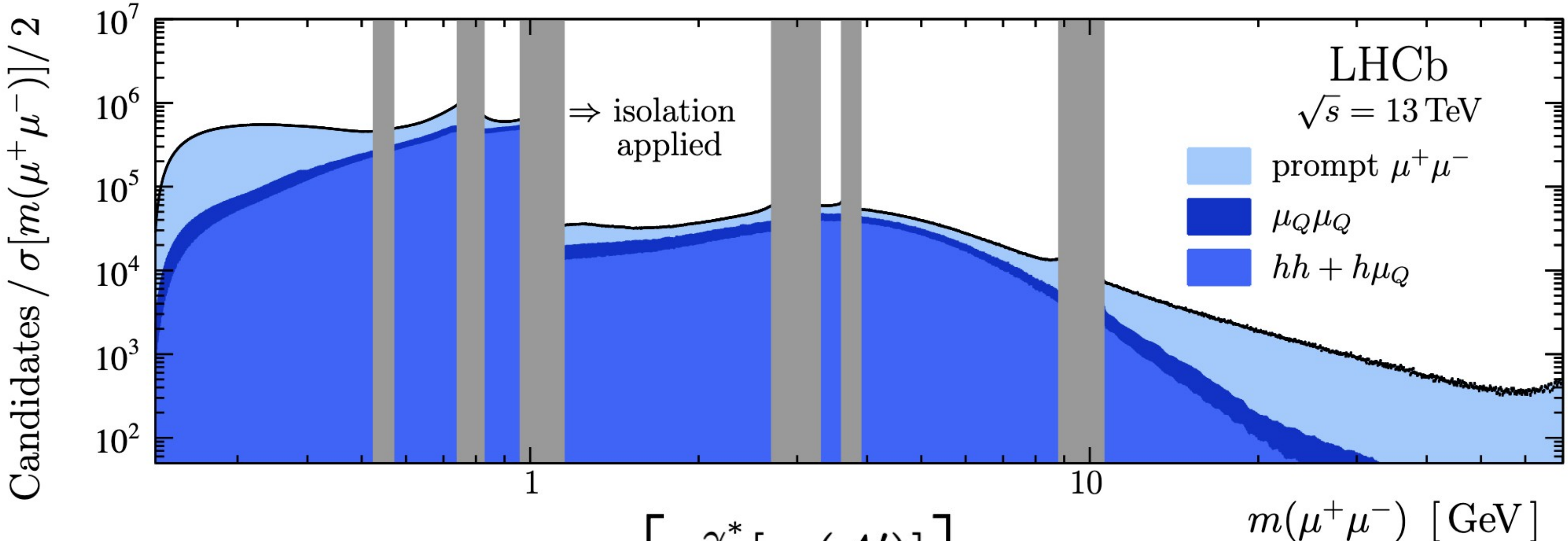
- **Data Scouting is a powerful frameworks for performing otherwise impossible searches and measurements**
- **CMS has further exploited the dimuon scouting stream**
  - First ever observation of the rare $\eta \rightarrow 4\mu$ decay
  - Impressive sensitivity to dark photon and scalar resonances at the GeV scale
- **LHC Run 3 will be extremely interesting!!!**

Backup

LHCb Dark Photon Search

- The mechanism is the same for γ* and dark photon production
- Estimate non-prompt γ* bkg. using SS sample, subtract from observation
- Ratio between the observed γ* yield and signal yield proportional to ε^2
- Does not use theory cross sections, detector efficiency, or luminosity

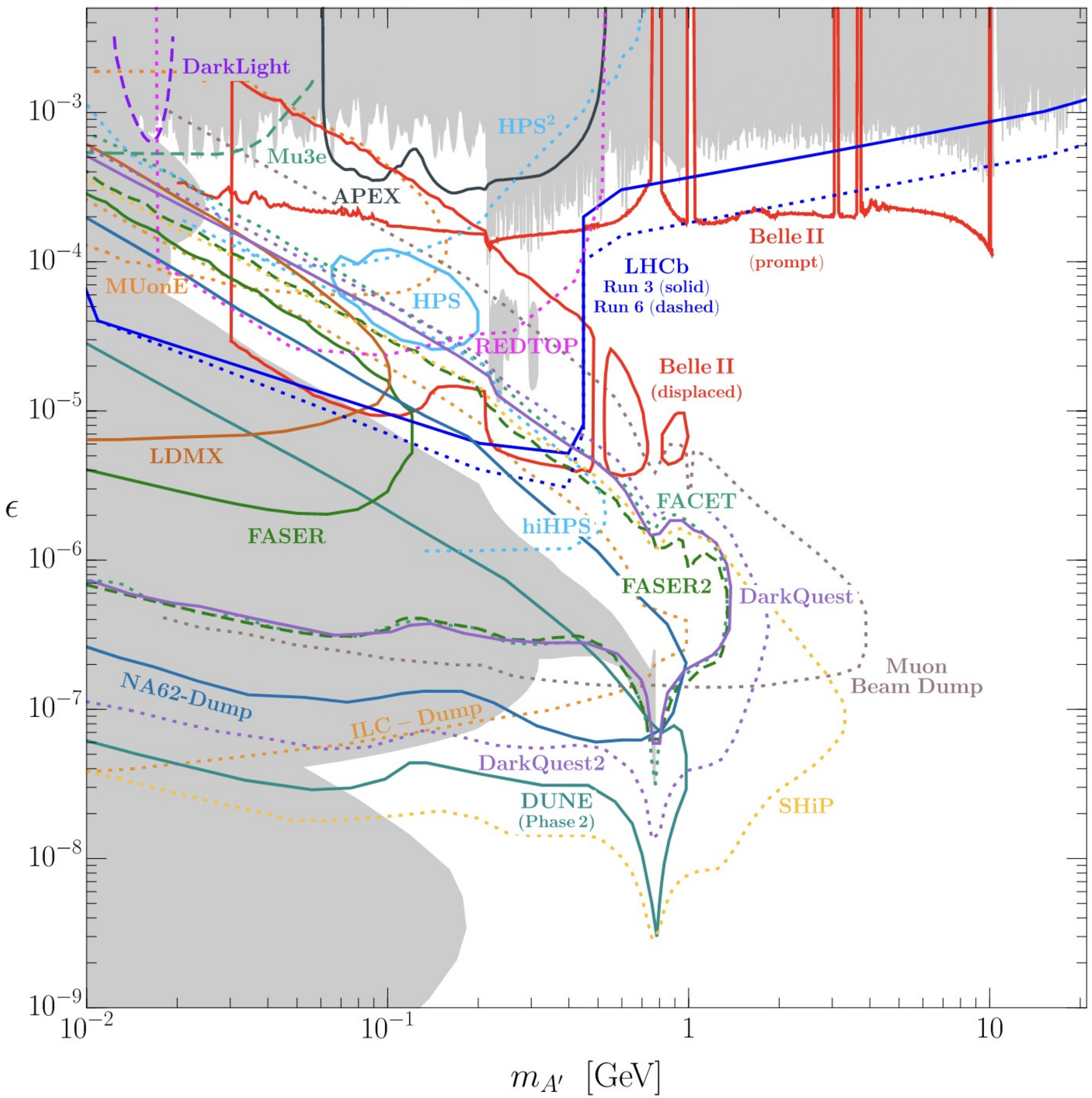
Phys. Rev. Lett. 124 (2020) 041801



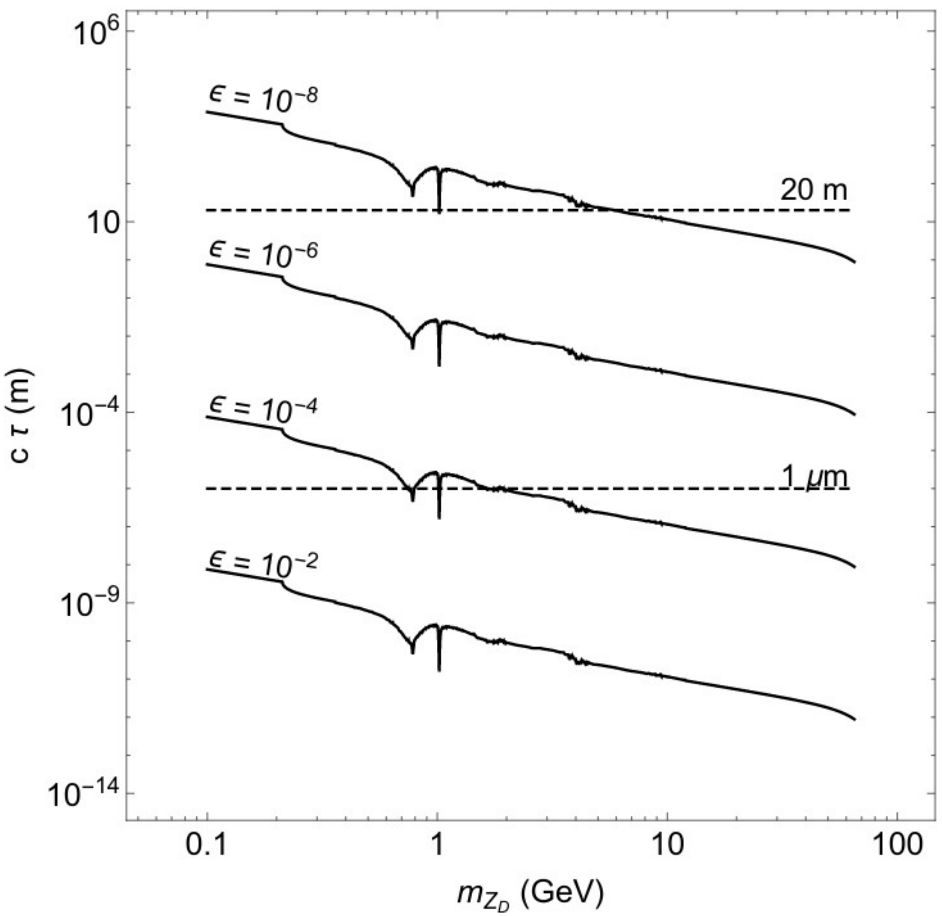
$$n_{\rm ex}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\rm ob}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]$$

Sensitivity Projections

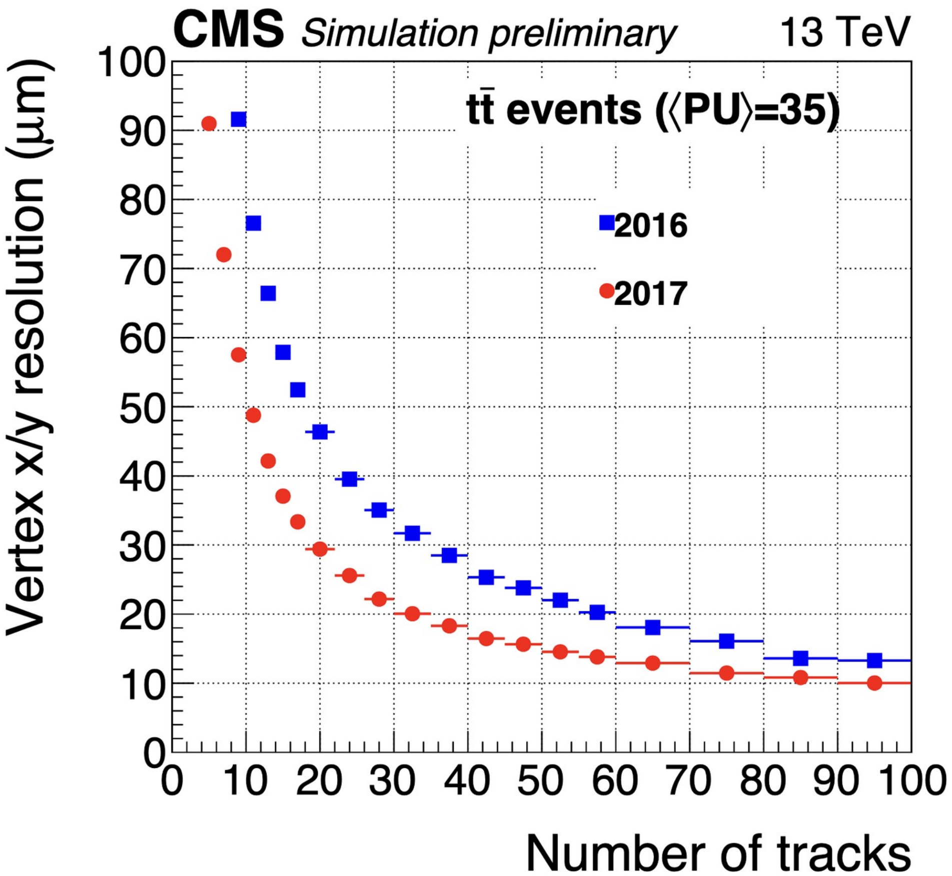
arxiv:2207.06905



Dark Photon Lifetime



[JHEP 02 (2015) 157]



[CMS Tracking POG Performance Plots For 2017 with Phase I pixel detector]

L1 Trigger Upgrade

[JINST 12 (2017) P12019](#)