First observation of $\eta \to 4\mu$ decay with the CMS detector

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CMS Compact Muon Solenoid

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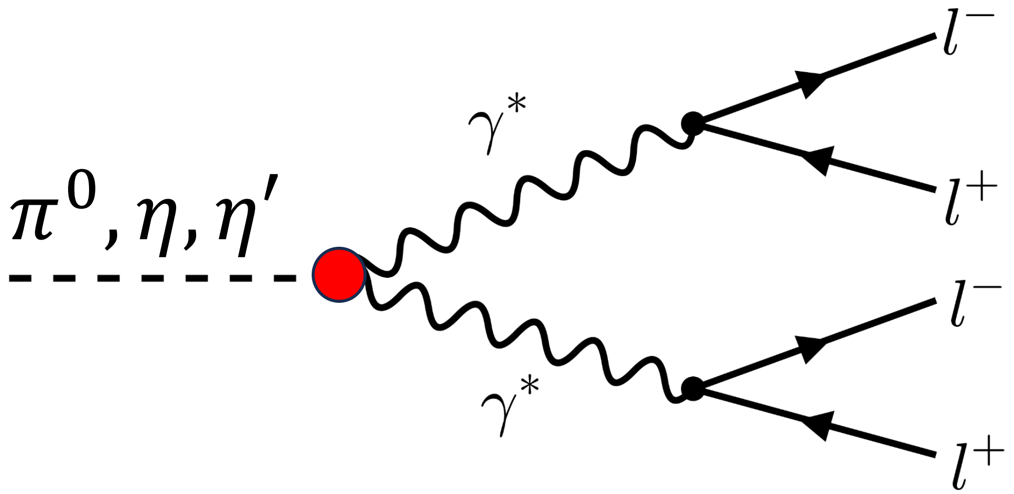
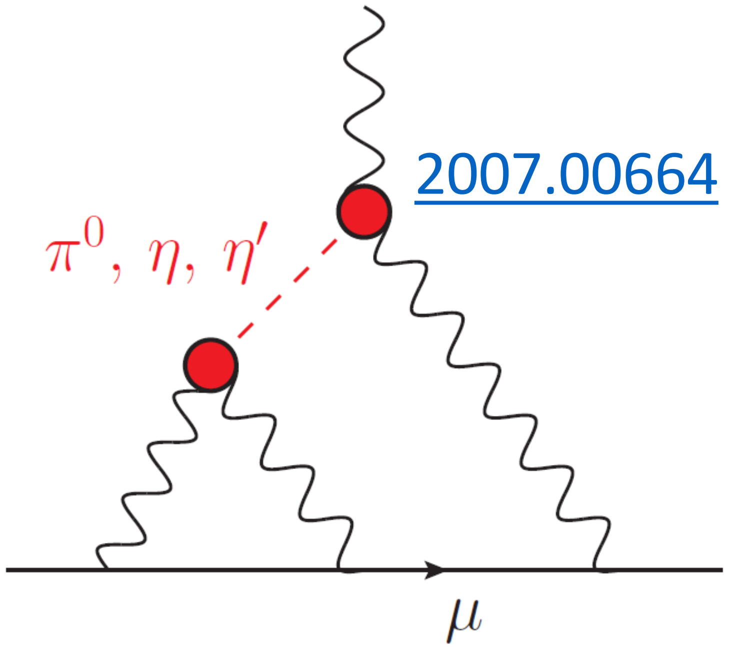
Physics motivations

η DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Charged modes		
Γ_{14}	$\mu^+\mu^-$	$(5.8 \pm 0.8) \times 10^{-6}$	
Γ_{15}	$2e^+2e^-$	$(2.40 \pm 0.22) \times 10^{-5}$	
Γ_{16}	$\pi^+\pi^-e^+e^-(\gamma)$	$(2.68 \pm 0.11) \times 10^{-4}$	
Γ_{17}	$e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	CL=90%
Γ_{18}	$2\mu^+2\mu^-$	$< 3.6 \times 10^{-4}$	CL=90%

PDG 2022



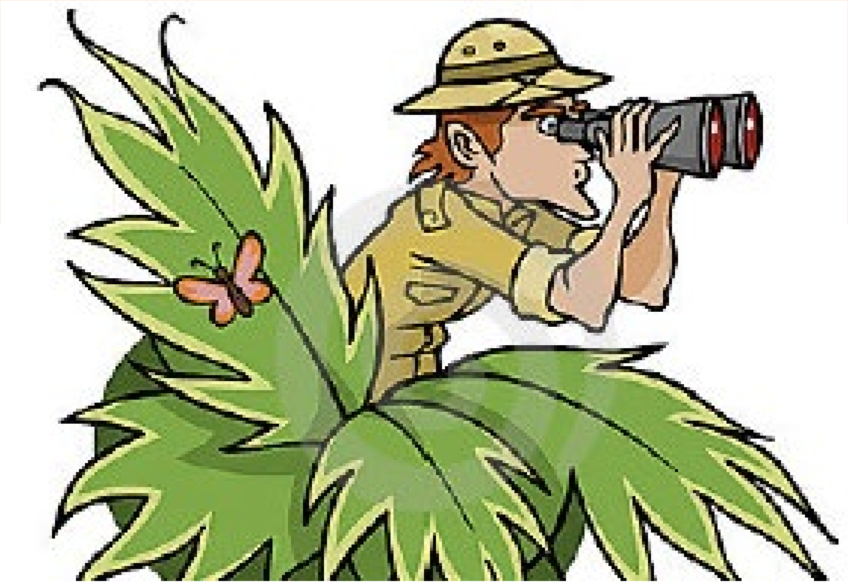
- Precision measurements of radiative decays and transitions of π^0, η, η' mesons provide inputs necessary to characterize many processes. The key quantities for these processes are the Transition Form Factors (TFFs).
- The TFFs affect the quantum corrections to $(g-2)_\mu$, the anomalous magnetic moment of the muon.
- These mesons contribute to the hadronic light-by-light-scattering in $(g-2)_\mu$
  - Shown diagramatically in figure, where the TFFs enter via the red vertices.



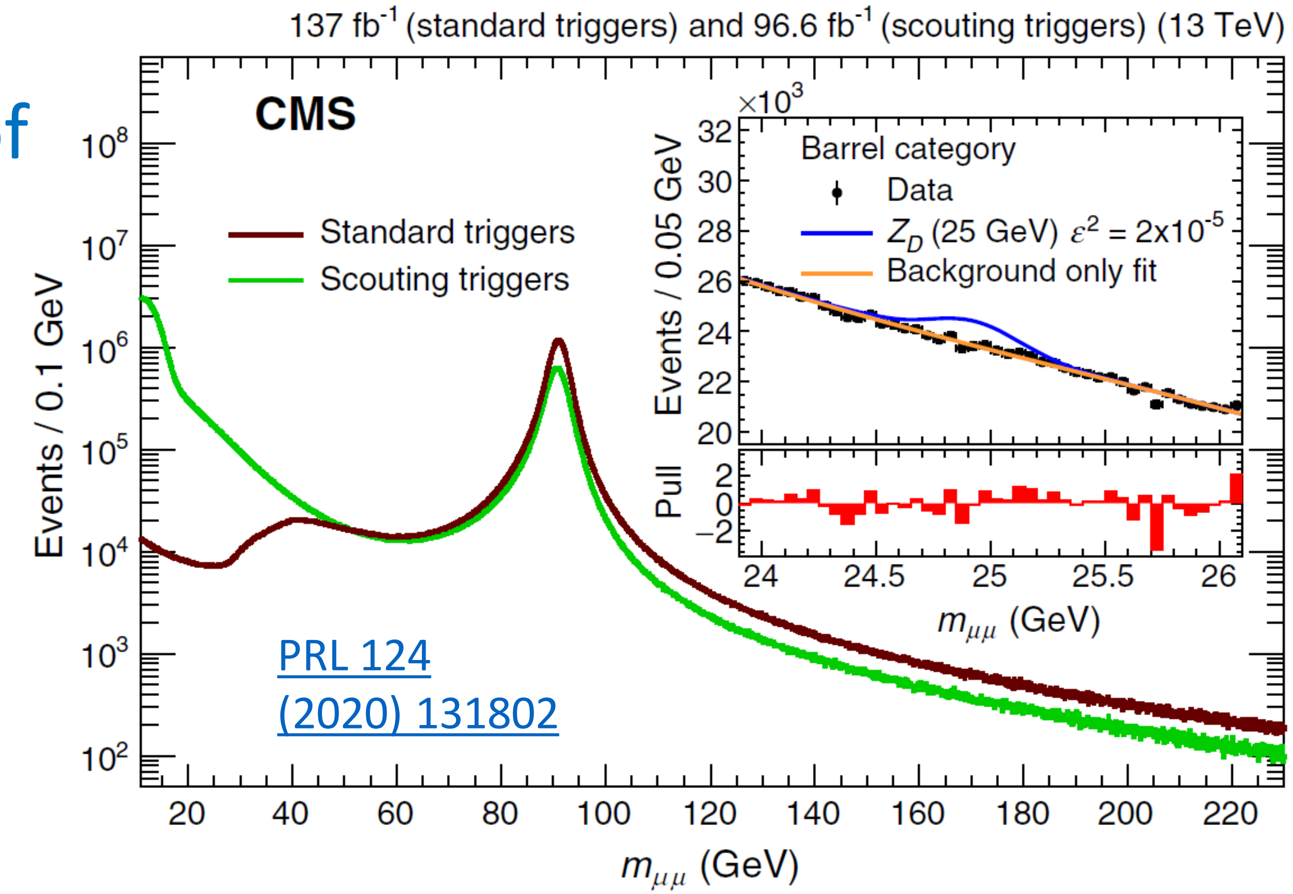
Datasets and triggers

- Data collected with a double muon trigger ($\int \mathcal{L}dt = 101\ fb^{-1}$) in 2017 and 2018 at $\sqrt{s} = 13\ TeV$
  - HLT: DST_DoubleMu3_noVtx_CaloScouting_v*
    - Two muons with $p_T > 3\ GeV$
    - No mass cut (low mass resonances)
    - No vertex displacement cuts (efficient up to $\sim 10\ cm$ displacement)
  - L1:
    - L1_DoubleMu4p5er2p0_SQ_OS_Mass7to18
    - L1_DoubleMu_15_7
    - L1_DoubleMu4(p5)_SQ_OS_dR_Max1p2 in 2017 (2018)
    - L1_DoubleMu0er1p5_SQ_OS_dR_Max1p4
- The data are saved in scouting datasets, i.e. only HLT objects are retained

Scouting @ CMS



- The maximum event rate collected by CMS ($\sim 1\ kHz$) is defined by the total rate of data that can be transferred and stored (and processed) by CMS, not the actual number of events.
- The technique of data scouting consists of reducing the amount of information stored per event in exchange for a higher event rate
  - E.g: store only the calo jets, muons and vertices reconstructed during High Level Trigger online processing. NO raw data from CMS detector ⇒ no offline reconstruction



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Scouting in this analysis

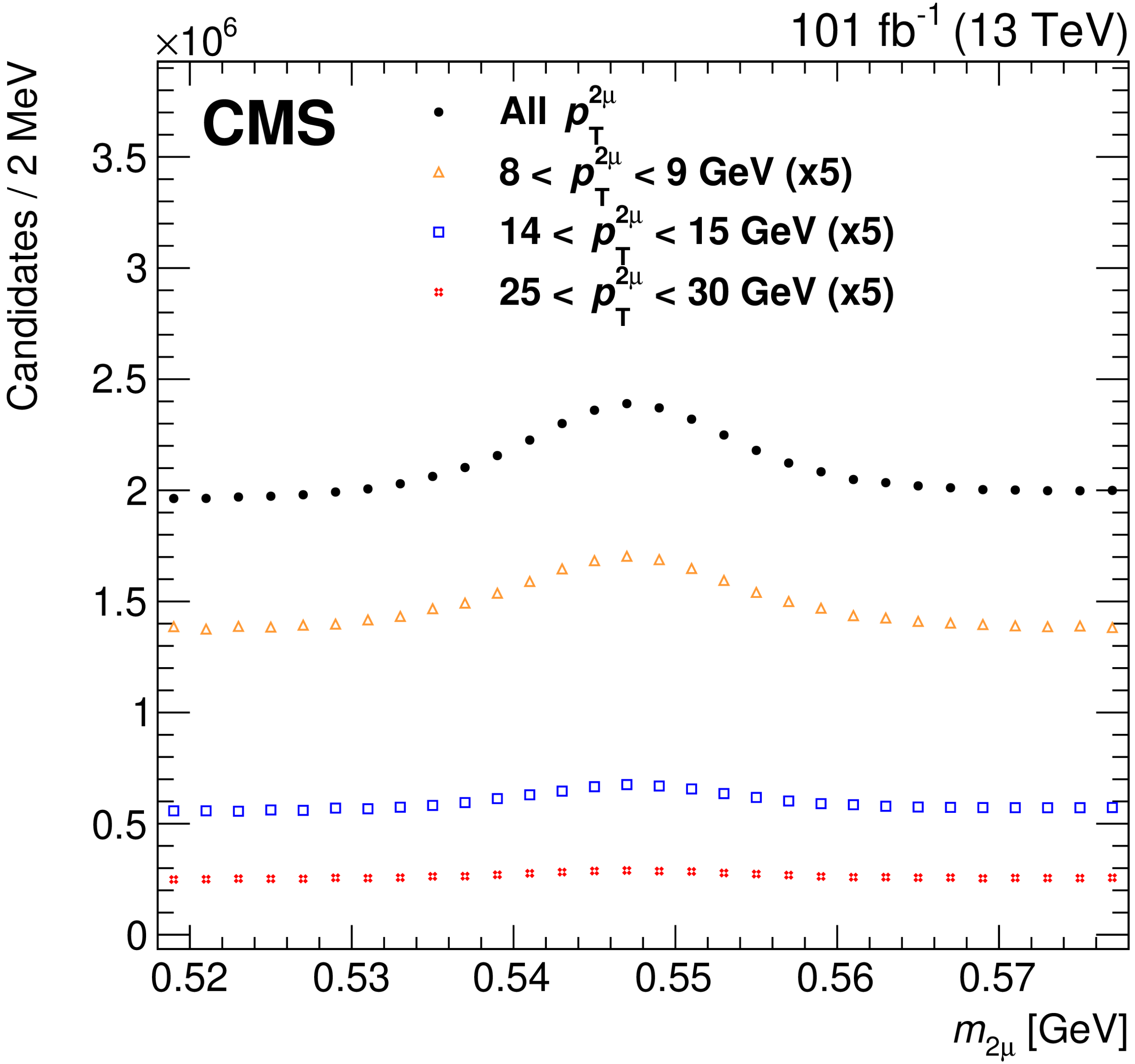
- By reducing the event size by a factor of roughly 1000, very low-pT muon triggers reaching close to $m_{\mu\mu} \gtrsim 0.2\ GeV$ can be designed that still remain within a reasonable rate of around 3 kHz
  - Event size is about 1.5 kB
- The main objects used for this analysis are the ScoutingMuon and ScoutingVertex HLT collections

Further event selections require:

- 4 (or 2) muons with $p_T > 3\ GeV$ ($p_T > 3.5\ GeV$ in the barrel) and $|\eta| < 2.4$.
- muons must be associated w/ a reconstructed vertex which is $< 1\ cm$ from the beam spot in the xy plane

η production at the LHC

- The η meson is copiously produced in pp scattering at the LHC
- Clearly visible peak in the $\mu\mu$ invariant mass spectrum in scouting dataset
- Fitting gives about 4.5M $\eta \rightarrow \mu\mu$ in this dataset
- Assuming a (pdg) $B(\eta \rightarrow \mu\mu) = 5.8(0.8) \times 10^{-6}$ this implies there are a lot of ηs produced in CMS $(\sim 10^{12})$
- $B^{theory}(\eta \rightarrow \mu\mu\mu\mu) \sim 4 \times 10^{-9} \rightarrow$ it should be in the reach of CMS



Analysis strategy

The goal is to measure the

$$BR(\eta \to 4\mu) \coloneqq B_{4\mu}$$

The relation btw the number of $\eta \to 4\mu$ events observed, $N_{4\mu}$, and $B_{4\mu}$ is

$$N_{4\mu} = \int \mathcal{L}dt \cdot \sigma_{pp\to\eta} \cdot B_{4\mu} \cdot A_{4\mu}$$

Where:

- $\int \mathcal{L}dt \cdot \sigma_{pp\to\eta}$ is the total number of ηs produced in CMS
- $A_{4\mu}$ is the CMS acceptance to $\eta \to 4\mu$

Analysis strategy

Using a reference channel $\eta \rightarrow 2\mu$ to measure $B_{4\mu}$ removes the need to measure $\int \mathcal{L}dt \cdot \sigma_{pp\rightarrow\eta}$ and reduces the uncertainties on $A_{4\mu}$. Binning in p_T and $|y|$ of the reconstructed meson:

$$N_{4\mu} = \sum_{i,j} N_{4\mu}^{i,j} = \int \mathcal{L}dt \cdot \sigma_{pp\rightarrow\eta} \cdot B_{4\mu} \cdot \sum_{i,j} A_{4\mu}^{i,j}$$

$$N_{2\mu} = \sum_{i,j} N_{2\mu}^{i,j} = \int \mathcal{L}dt \cdot \sigma_{pp\rightarrow\eta} \cdot B_{2\mu} \cdot \sum_{i,j} A_{2\mu}^{i,j}$$

- Taking the ratio bin-by-bin and summing over the bins

$$N_{4\mu}^{i,j} = N_{2\mu}^{i,j} \cdot \frac{B_{4\mu}}{B_{2\mu}} \cdot \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}} \Rightarrow B_{4\mu} = B_{2\mu} \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}}$$

Experimental BR from PDG

$\eta \rightarrow 4\mu$ in scouting data (101 fb^{-1})

$\eta \rightarrow 2\mu$ in scouting data (101 fb^{-1})

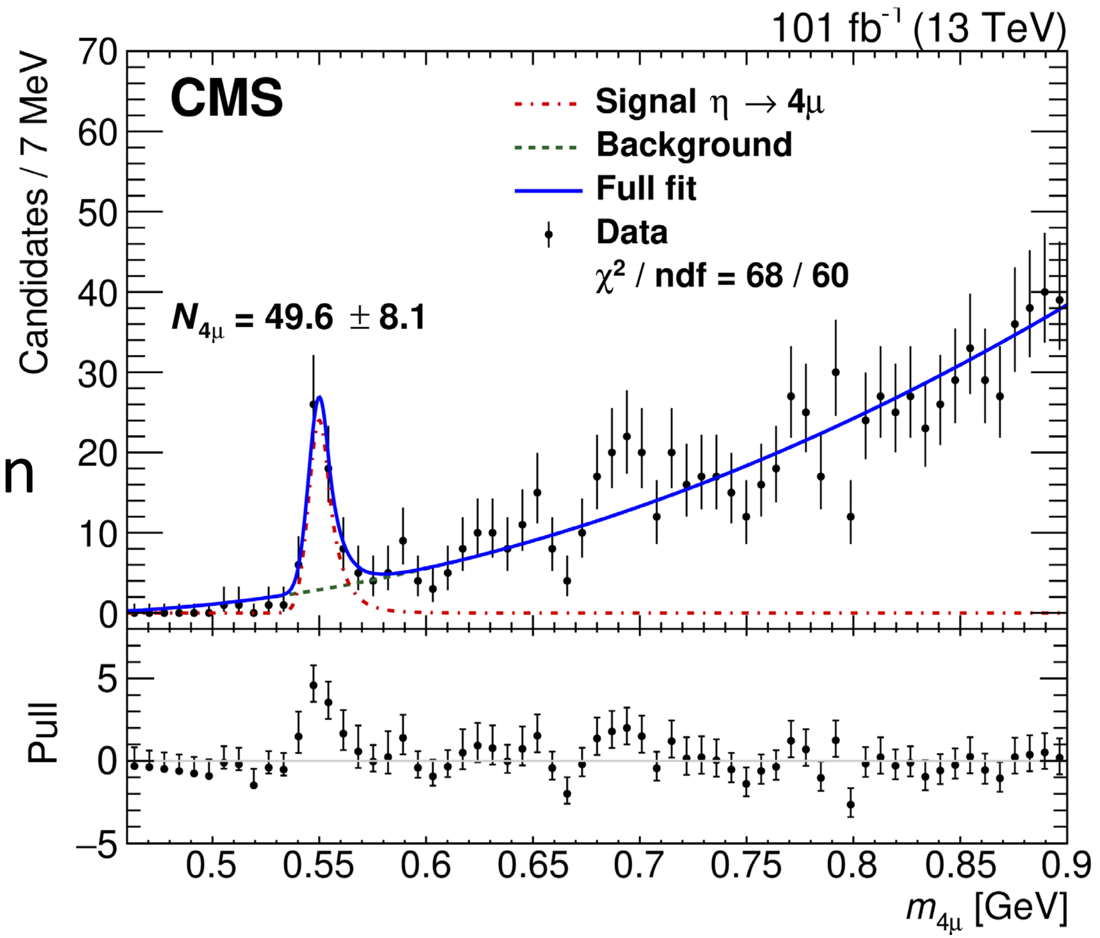
CMS acceptance to $\eta \rightarrow 4\mu$ in $p_T$and $|y|$ bins)

CMS acceptance to $\eta \rightarrow 2\mu$ in $p_T$and $|y|$ bins)

Extracting $N_{4\mu}$ signal

$$B_{2\mu} \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}}$$

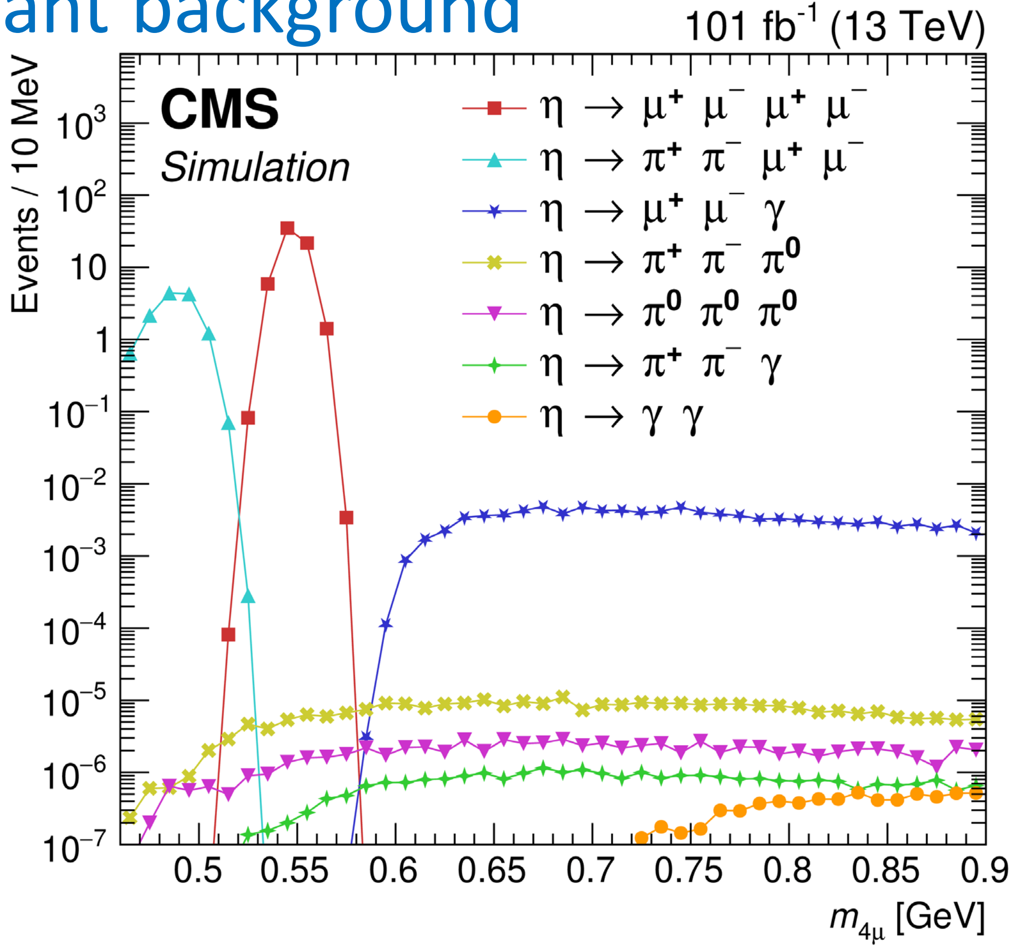
- After applying the 4-muon selection a peak is clearly seen at $m_{4\mu} \sim 0.55\ GeV$
  - Require all 4 muons to be compatible with production at the beam spot and have $\sum_{i=1}^{4} q_{\mu_i} = 0$
- Signal model:
  - Crystal-Ball (CB) only (data); CB + Gaussian (MC)
  - all of the CB parameters except for the signal normalization are fixed from MC
- Background model:
  - $f(x) = \alpha(x - 4m_\mu)^\beta$ (data)



$N_{4\mu}$: Resonant backgrounds

Potential sources of peaking backgrounds might affect the estimation of $N_{4\mu}$ They consist of other η decay modes with $\pi \to \mu$ misidentification, $\gamma \to \mu\mu$ conversion. Studies of these modes with simplified MC simulations indicate that other η decay modes are not sources of resonant background

1. $\eta \to \pi\pi\mu\mu$: Largest potential contribution but has never been measured. Assumed $B = 1.6 \times 10^{-4}$, the experimental UL. Theoretical prediction is 7.5×10^{-9}. Plus, $\pi \to \mu$ mis-ID shifts the peak down considerably
2. $\eta \to \mu\mu\gamma$: Has been observed with $B = 3.1 \times 10^{-4}$, but $\gamma \to 2\mu$ conversion near nucleus imparts momentum to the dimuon and increases $m_{4\mu}$ overall
3. $\eta \to \pi^+\pi^-\pi^0$: Needs conversion plus two mis-IDs, with probability $\sim 10^{-13}$. Falls inside the signal region, but tiny contribution



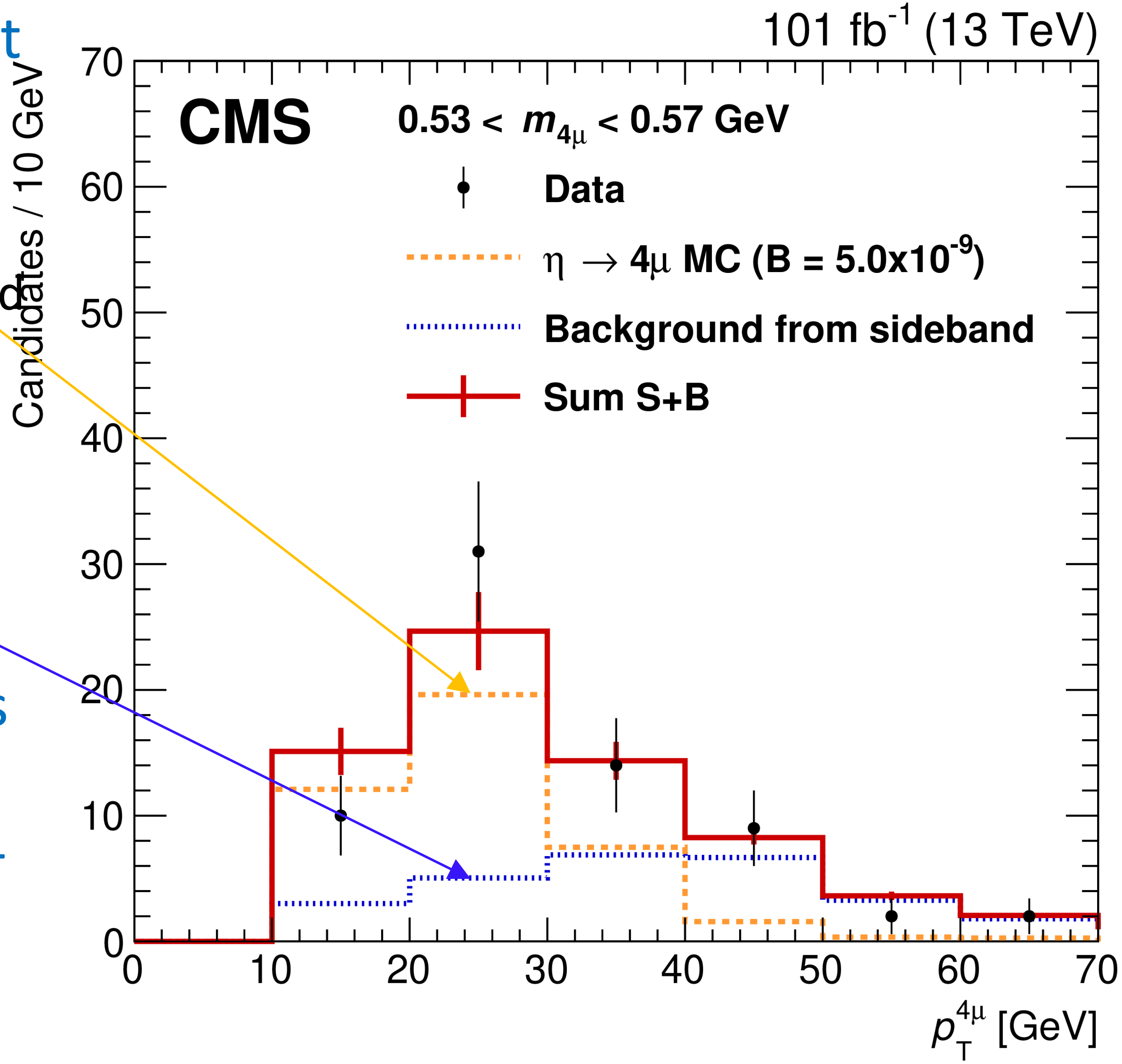
$N_{4\mu}$: Non resonant backgrounds

A continuous background contributes about ¼ of events in signal window

- $p_T^{4\mu}$ spectrum has distinct peak in signal vs. sideband window
- Inverting net charge cut reveals this background to be combinatorial

- Predicted $p_T^{4\mu}$ background shape extracted from the mass sideband, normalized to the background fit yield (dotted blue line)
- Sum of signal and background predictions (solid red line).

No indication of systematic issues with MC-estimated acceptance across the p_T range



Measuring $N_{2\mu}^{i,j}$

$$B_{2\mu} \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}}$$

Defined 32 bins in p_T in the range $7 - 70\ GeV$ and 2 bins in $|y|$

For each p_T and $|y|$ slice, $m_{2\mu}$ spectrum is fit with:

- Signal: double-Gaussian with common mean and different sigma at low-p_T, single Gaussian at higher p_T
- Background: Chebyshev polynomials

Signal MC simulation for $A_{4\mu}^{i,j}$ and $A_{\mathbf{2}\mu}^{i,j}$

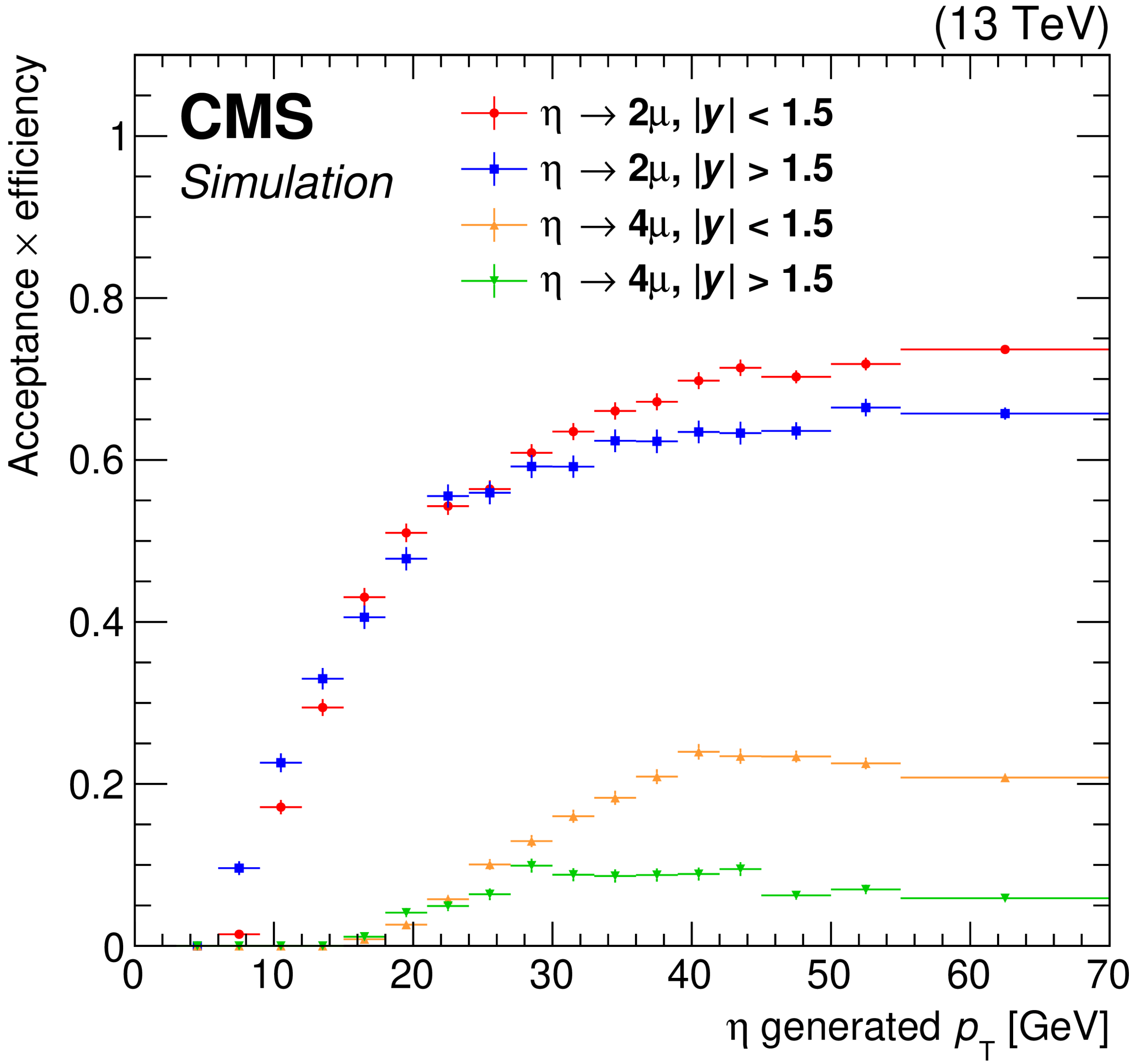
Simulated samples of rare η decays are generated at leading order with a custom workflow.

- Generator: PLUTO V6 to simulate the two- and four-muon decays of the η meson in its rest frame (vector meson dominance model). Subsequently, the η meson and its decay products are boosted to the laboratory frame
- fragmentation, parton shower, and hadronization: PYTHIA 8.230
- Simulation in CMS: GEANT4

$A_{4\mu}^{i,j}$ and $A_{2\mu}^{i,j}$ acceptances

$$B_{2\mu}\frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j}\frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}}$$

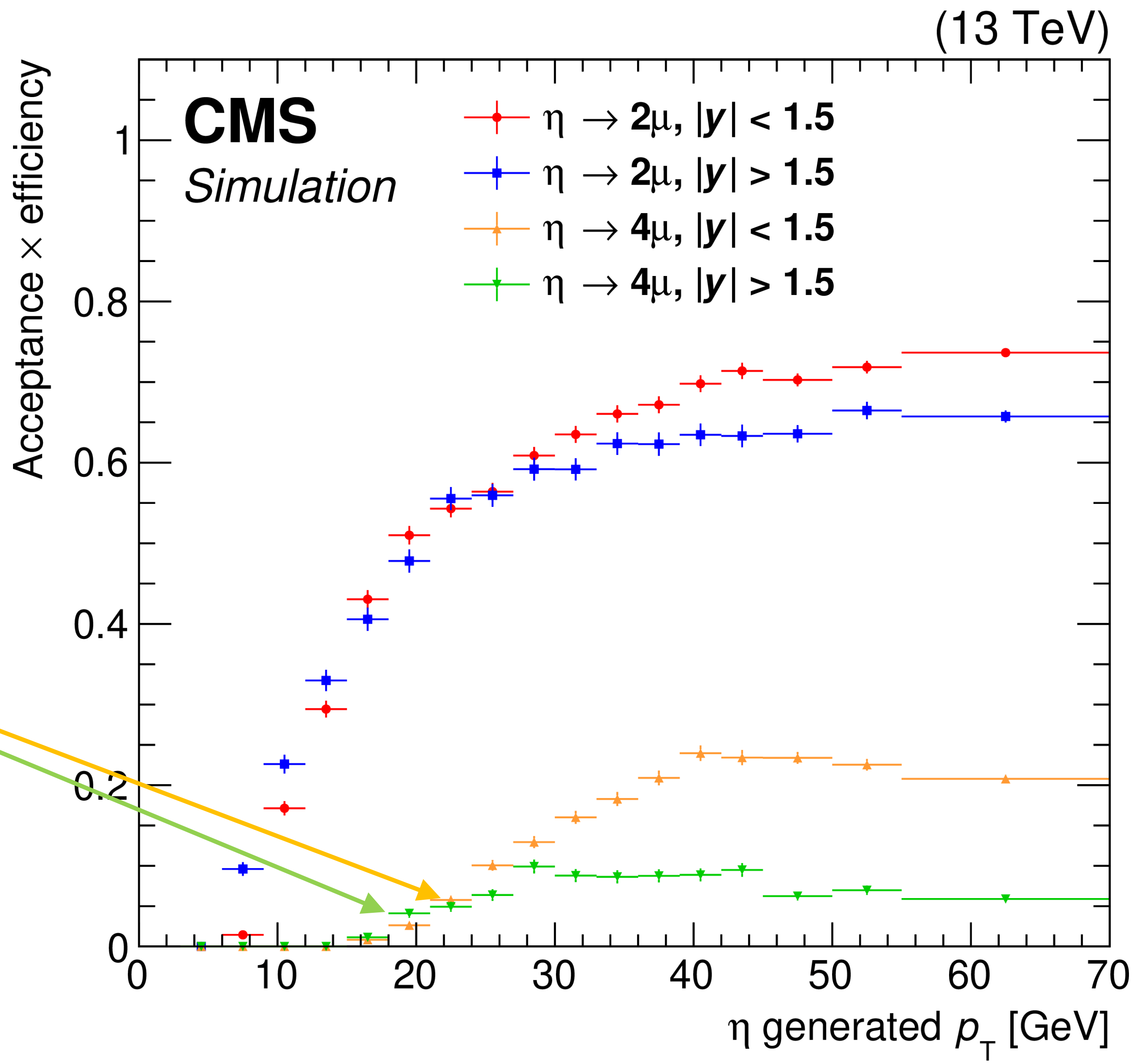
Simulated samples of $\eta \rightarrow 4\mu$ and $\eta \rightarrow 2\mu$ events are used to evaluate the total signal efficiencies $A_{4\mu}^{i,j}$ and $A_{2\mu}^{i,j}$, given by the product of detector geometric acceptance and reconstruction and selection efficiencies, as functions of p_T for two rapidity regions: $|y| < 1.5$ and $1.5 < |y| < 2.4$.



$A_{4\mu}^{i,j}$ and $A_{2\mu}^{i,j}$ acceptances

$A_{2\mu}^{i,j}$ is limited by the trigger efficiency, reaching a plateau of about 70%.

- $A_{4\mu}^{i,j}$ has a maximum value of about 25%/10% ($|y| < 1.5/|y| > 1.5$).
  - The low-p_T behavior is correlated to the minimum p_T of about 3.5 GeV required for a muon in the central region to reach the muon detectors.
  - The high-$p_T^{4\mu}$ drop off comes from the difficulty of reconstructing four muons with very small angular separation, owing to the boost of the parent η meson.



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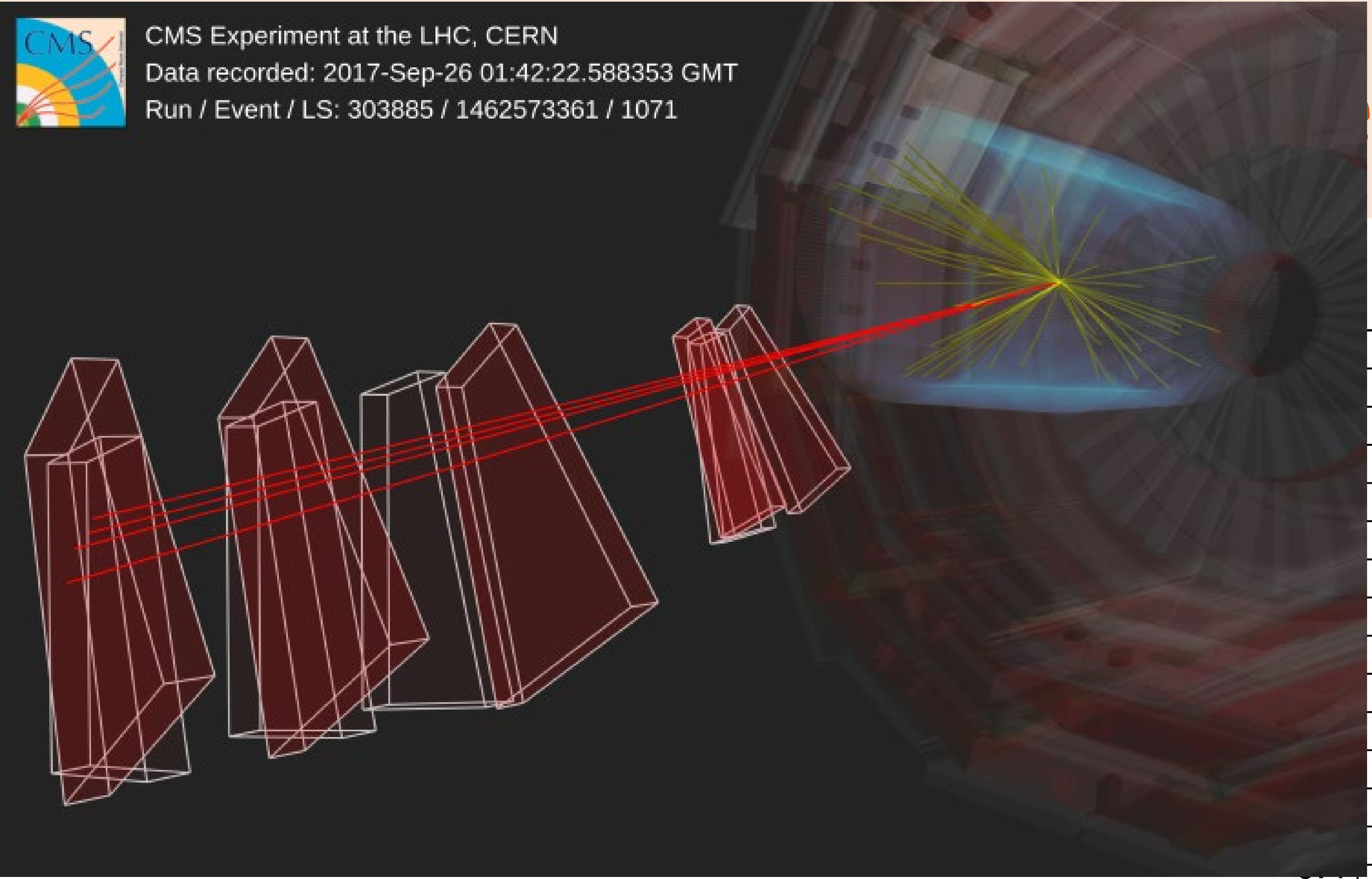

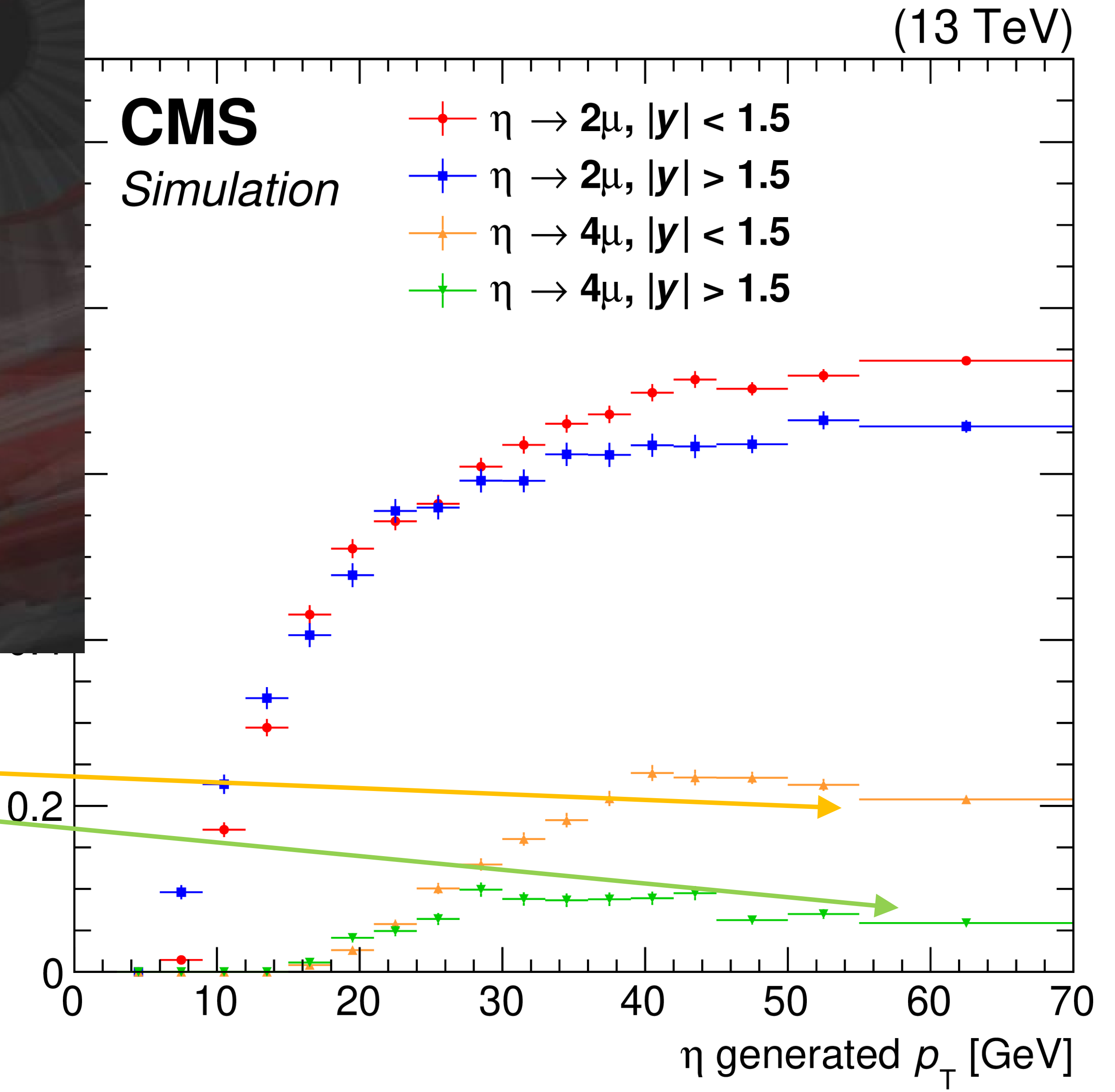

- The high-$p_T^{4\mu}$ drop off comes from the difficulty of reconstructing four muons with very small angular separation, owing to the boost of the parent η meson.

Analysis uncertainties

$$B_{2\mu} \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}}$$

- $B_{2\mu}$: 14% from PDG
- $N_{4\mu}$: 16% statistical from the signal fit
- $N_{2\mu}^{i,j}$: negligible statistical uncertainty
- Uncertainties on $A_{4\mu}^{i,j}$ and $A_{2\mu}^{i,j}$: arise from incomplete knowledge of the efficiencies evaluated by simulation.

$A_{4\mu}^{i,j}$ and $A_{2\mu}^{i,j}$ systematic uncertainties

Systematic uncertainties on $A_{4\mu}^{i,j}$ and $A_{2\mu}^{i,j}$ can be subdivided into three parts:

1. on the track p_T threshold, 9.0%;
2. on the trigger turn-on p_T threshold, 8.4%;
3. on the efficiency plateau, 3.2%.

- Parts (1.) and (2.) are caused by imperfect modeling of the turn-on behavior of the single-muon reconstruction efficiency observed in data. They are estimated by varying the thresholds in simulation and measuring the corresponding variation of the relative $N_{4\mu}$ yield.
- The uncertainty on (3.) is determined by measuring the trigger efficiency in data with an unbiased sample of events collected with electron triggers.

Other uncertainties

- A subdominant source of systematic uncertainty is attributed to the choice of fit model used to extract the signal yield in both $\eta \to 4\mu$ and $\eta \to 2\mu$ channels.
- This uncertainty is assessed by testing several alternative signal and background models, and determining the variation in signal yield, resulting in a value of 6.6%.
- Overall, we estimate the total systematic uncertainty in the measurement of the ratio of branching fractions

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

to be 14%, adding all contributions in quadrature.

Conclusions

- The branching fraction of the $\eta \to 4\mu$ decay is measured relative to the $\eta \to 2\mu$ decay, yielding a ratio of branching fractions of

$$\frac{B_{4\mu}}{B_{2\mu}} = [0.86 \pm 0.14(stat) \pm 0.12(syst)] \times 10^{-3}$$

- Using the world average branching fraction value for the normalization channel, the branching fraction of the four-muon decay channel is

$$B_{4\mu} = \left[5.0 \pm 0.8(stat) \pm 0.7(syst) \pm 0.7\left(B_{2\mu}\right)\right] \times 10^{-9}$$

In agreement with the theoretical prediction of

$$B_{4\mu}^{th} = (3.98 \pm 0.15) \times 10^{-9}$$