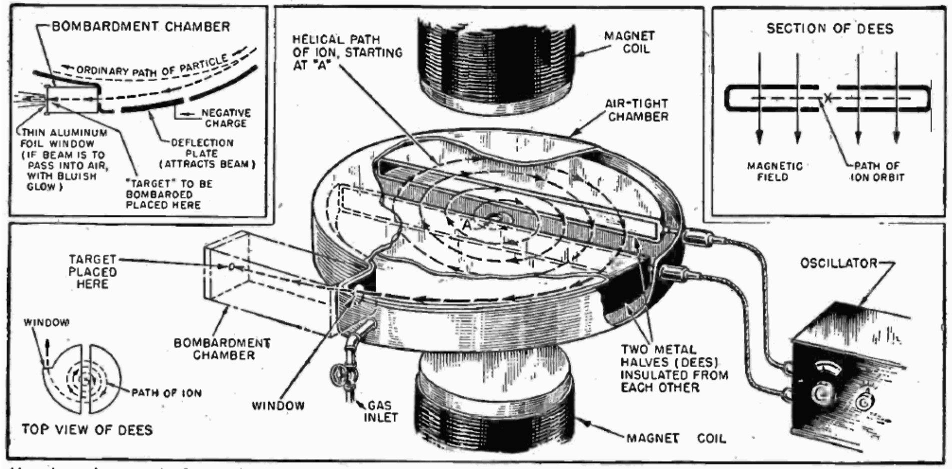
The Piper at the Gates of Dome: Probing Low-Mass New Physics with the CMS Scouting and Parking Pipelines

Andre Frankenthal (Princeton University)

Fermilab Wine & Cheese Seminar

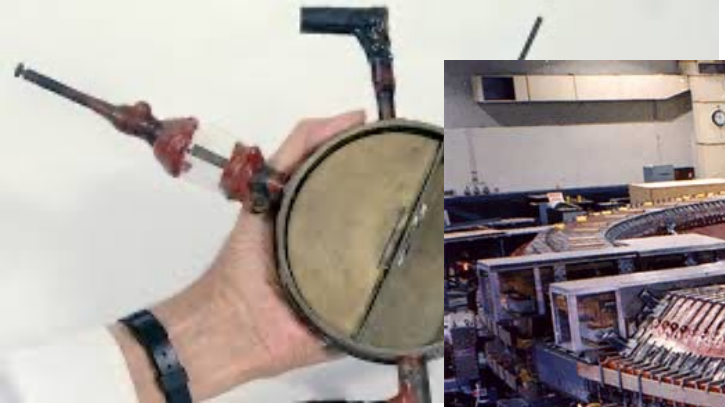
July 28th, 2023

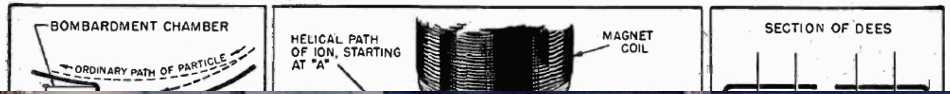
The evolution of particle accelerators



Ernst Lawrence’s first cyclotron, 1929 (Berkeley). Proton energy: ~ 1 MeV

The evolution of particle accelerators





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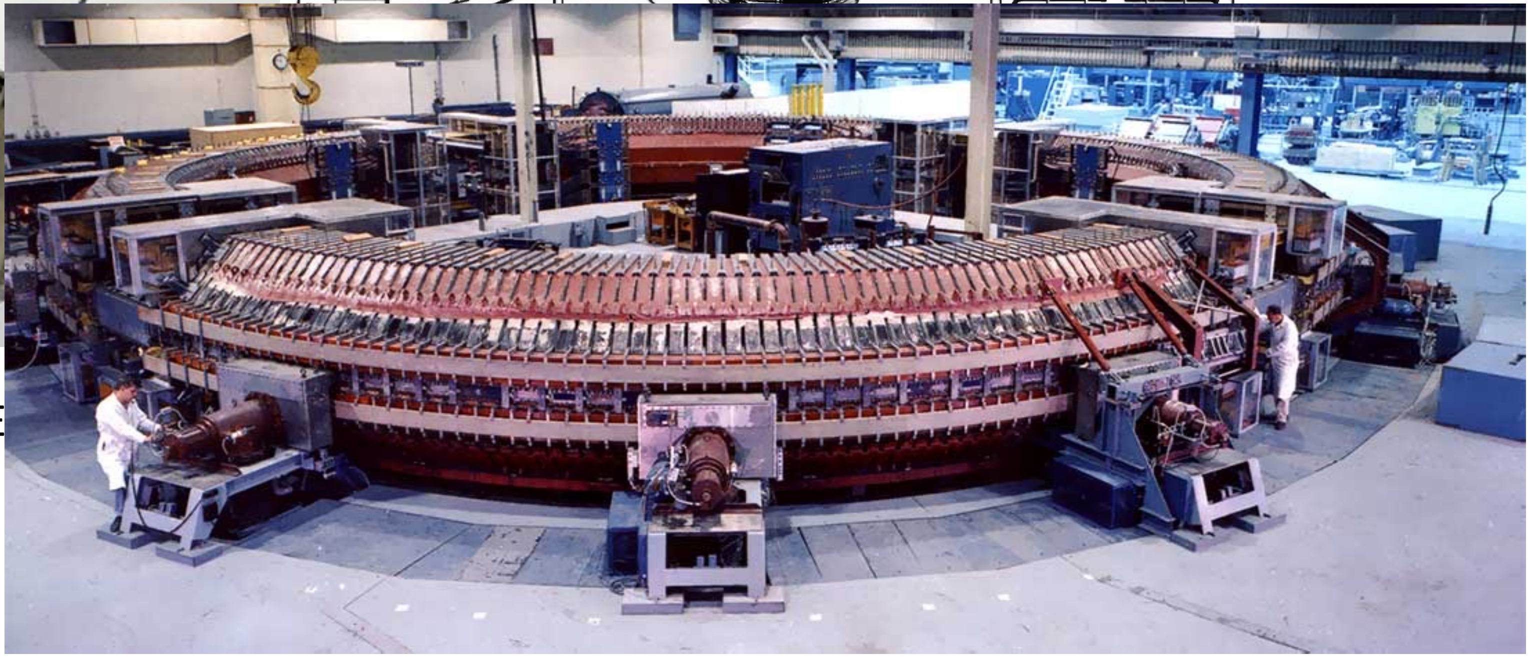
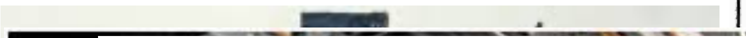
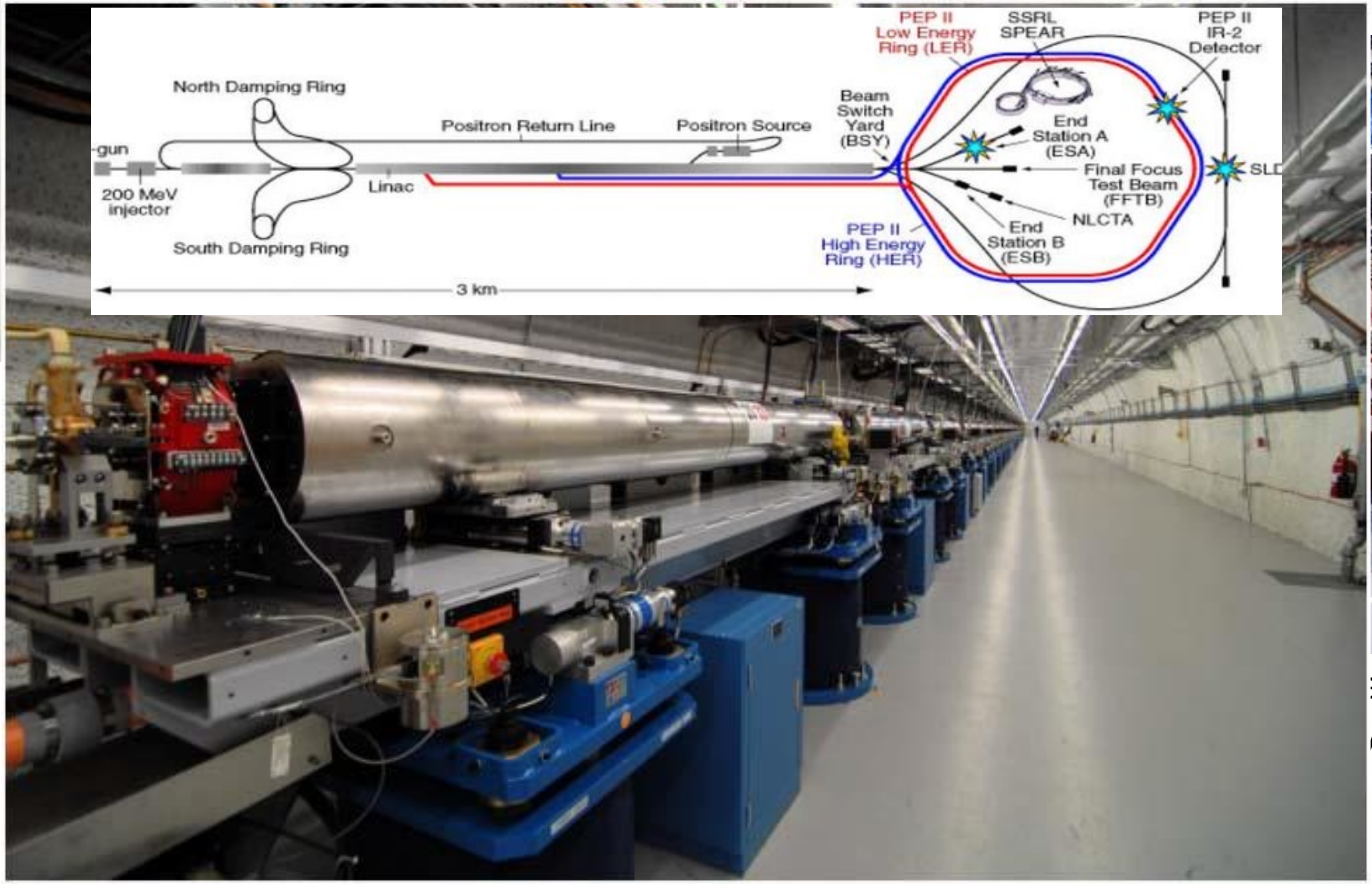
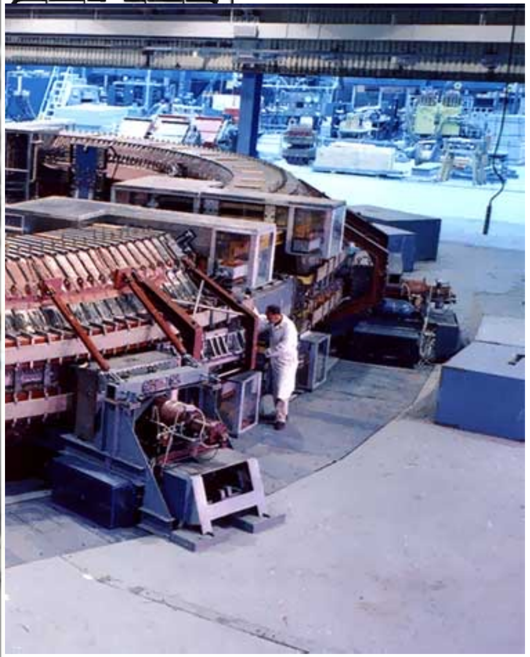


Cosmotron, the first proton synchrotron accelerator, 1953
(Brookhaven National Lab). Energy: 3.3 GeV

The evolution of particle accelerators





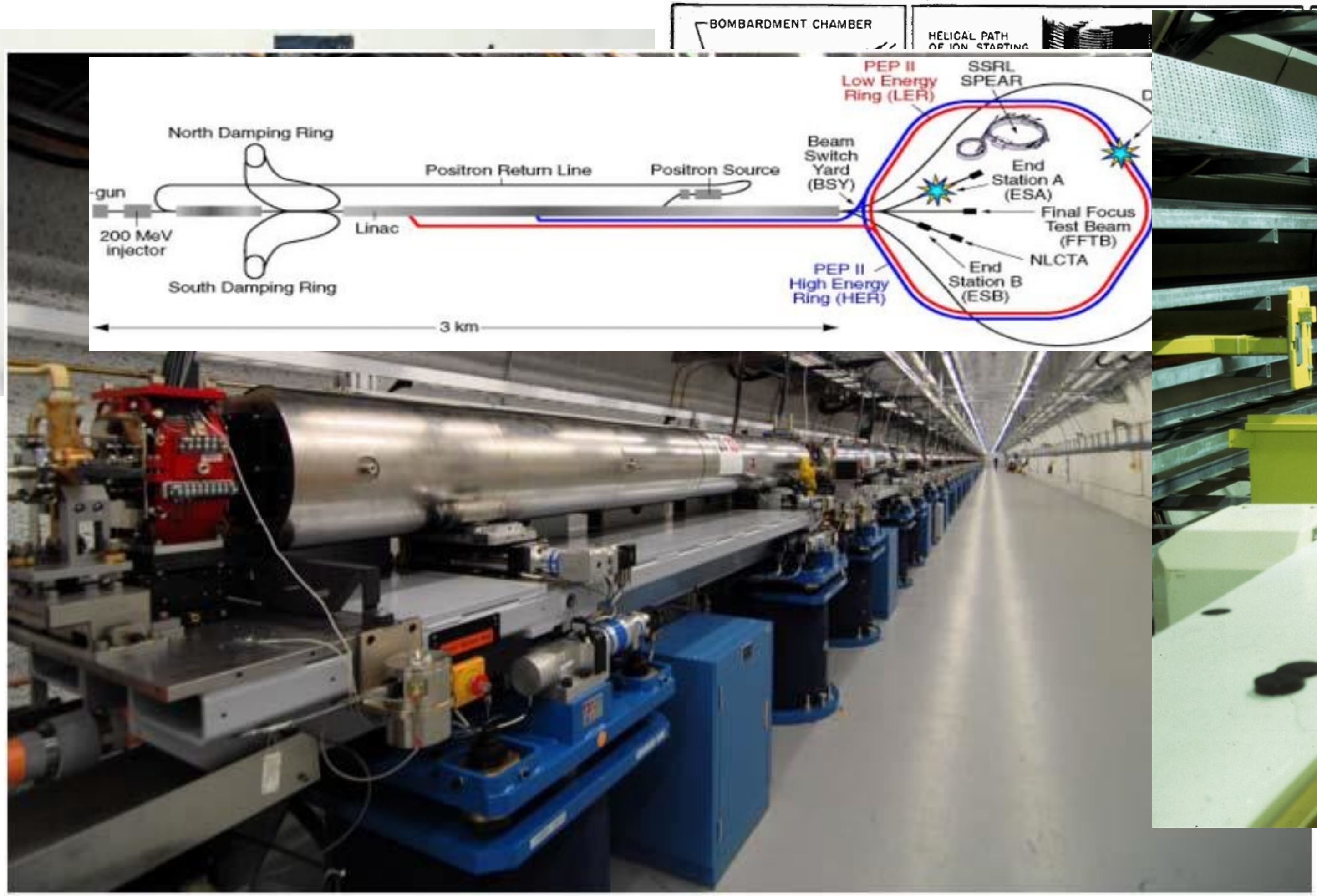


accelerator, 1953

: 3.3 GeV

Stanford Linear Accelerator, 1966 (SLAC). Electron energy: 50 GeV

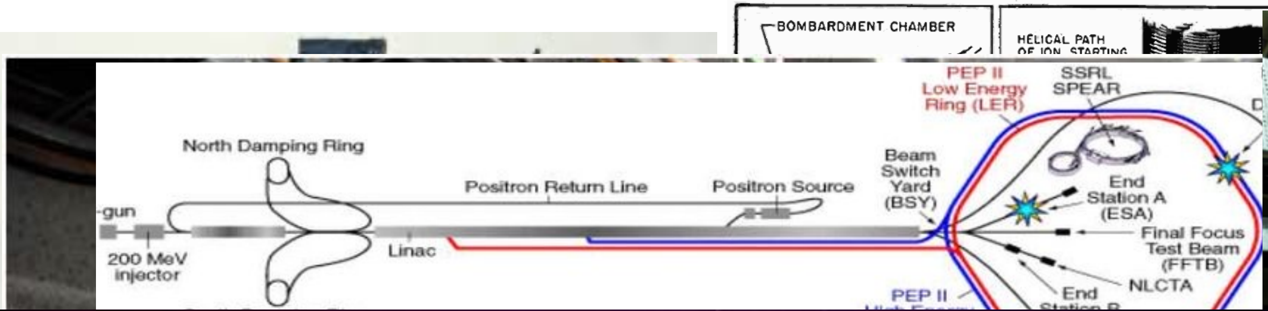
The evolution of particle accelerators

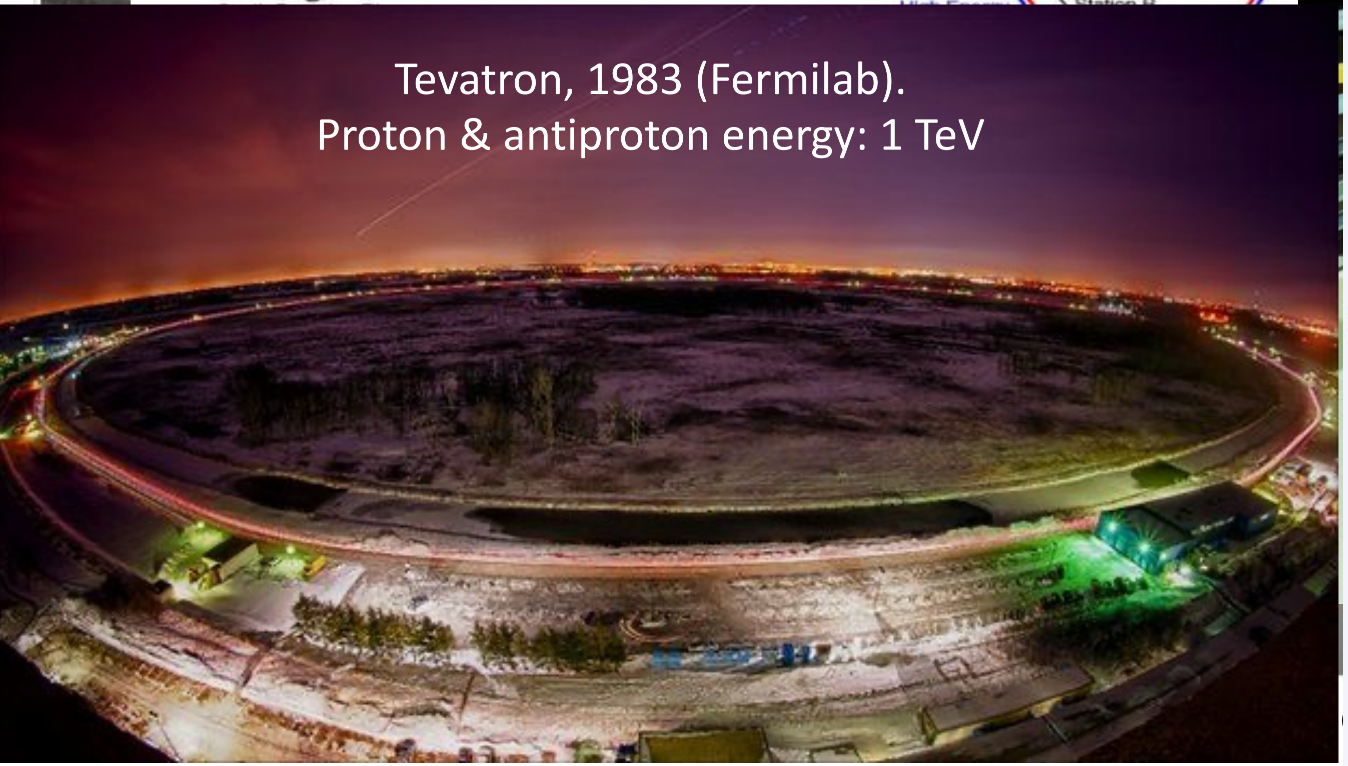


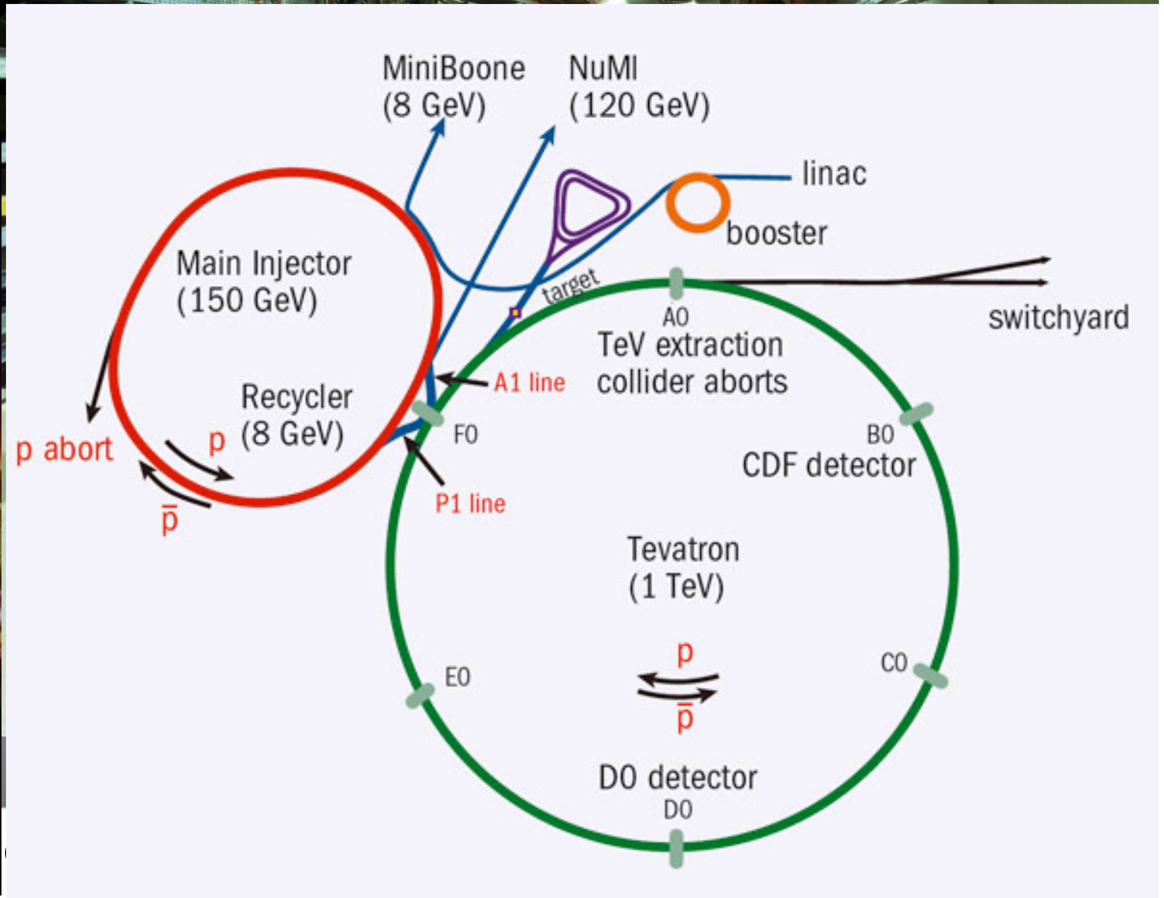
Stanford Linear Accelerator, 1966 (SLAC). Electron energy: 50 GeV

Large Electron Positron Collider, 1989 (CERN).
Electron & positron energy: 209 GeV

The evolution of particle accelerators







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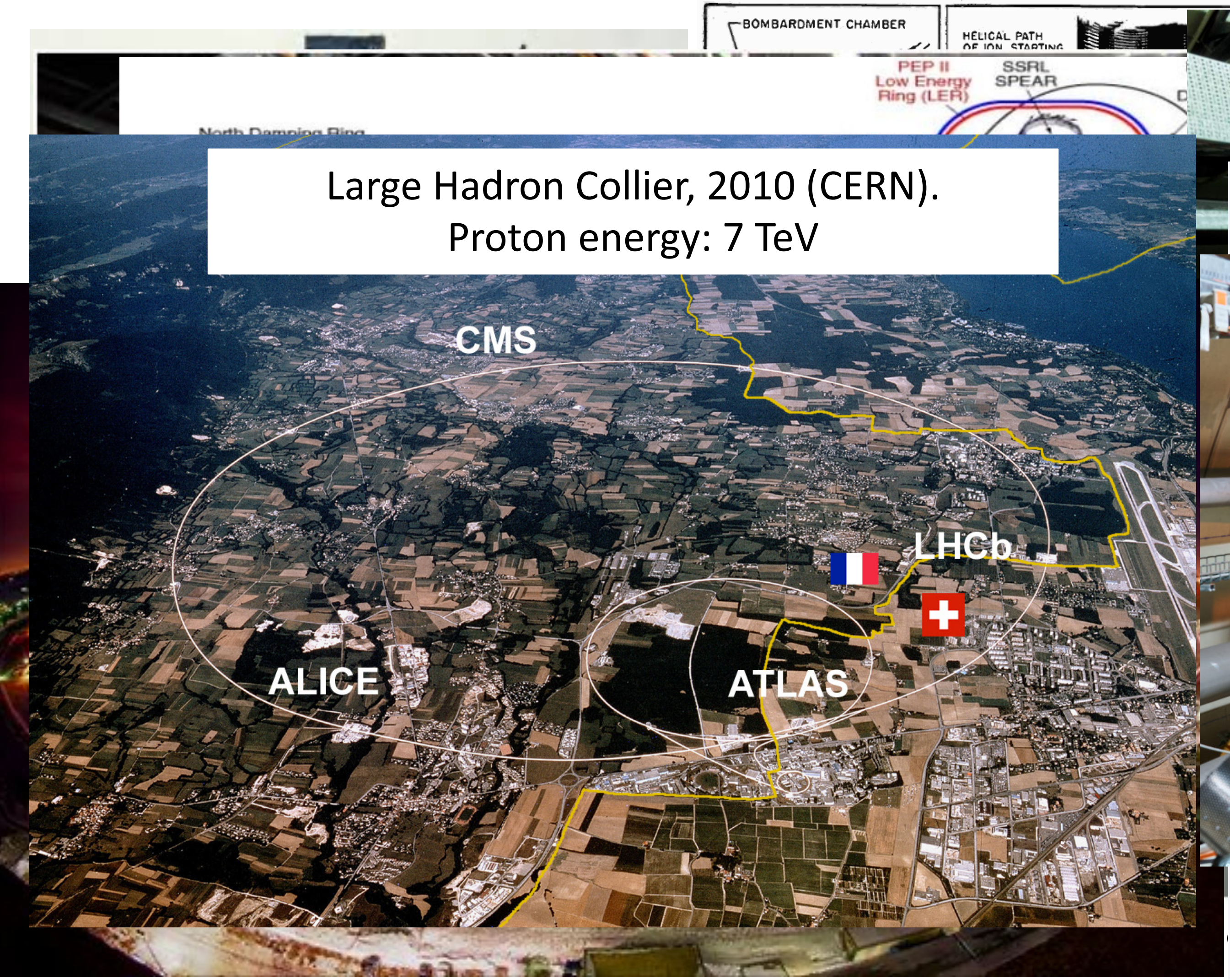
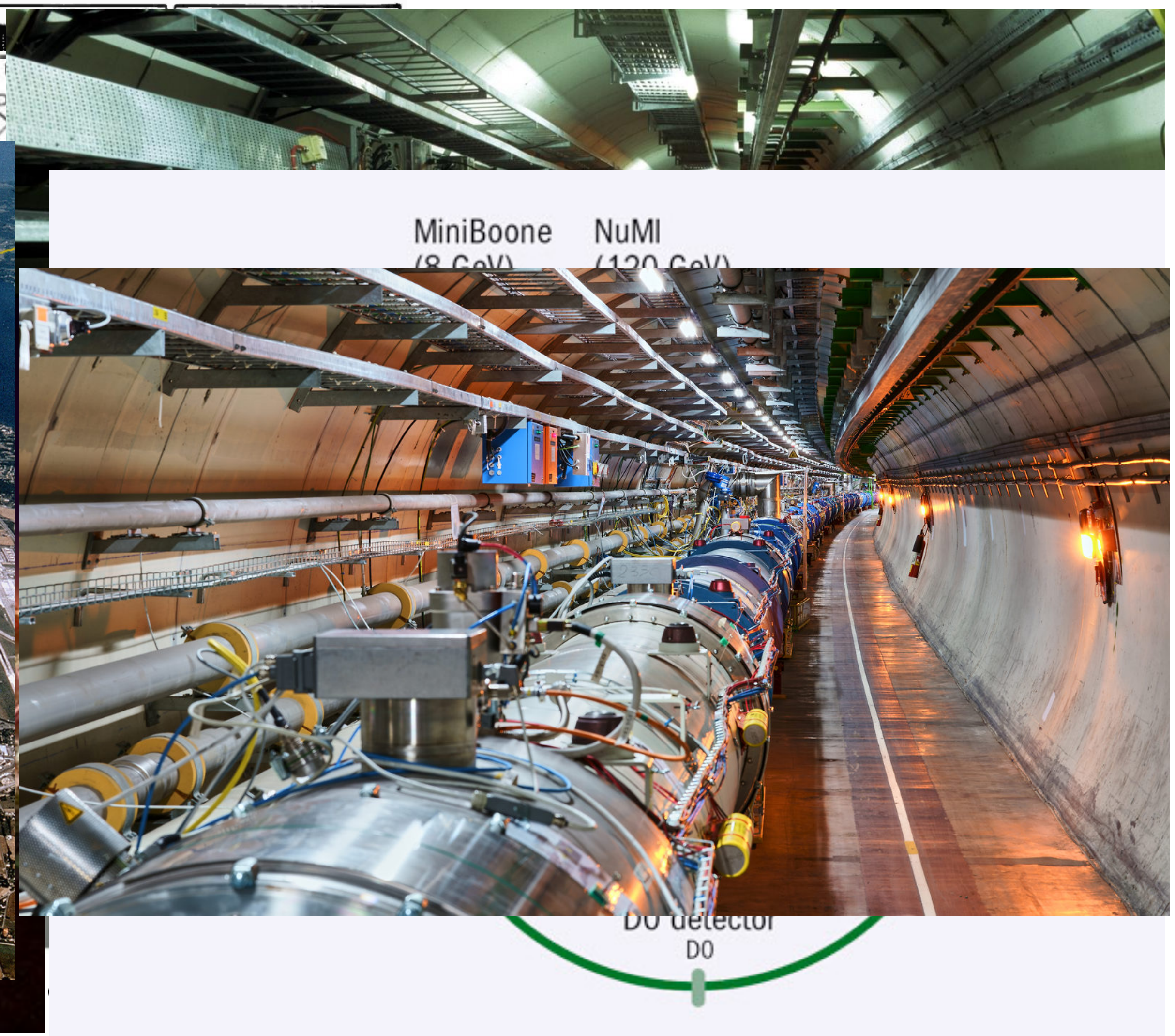
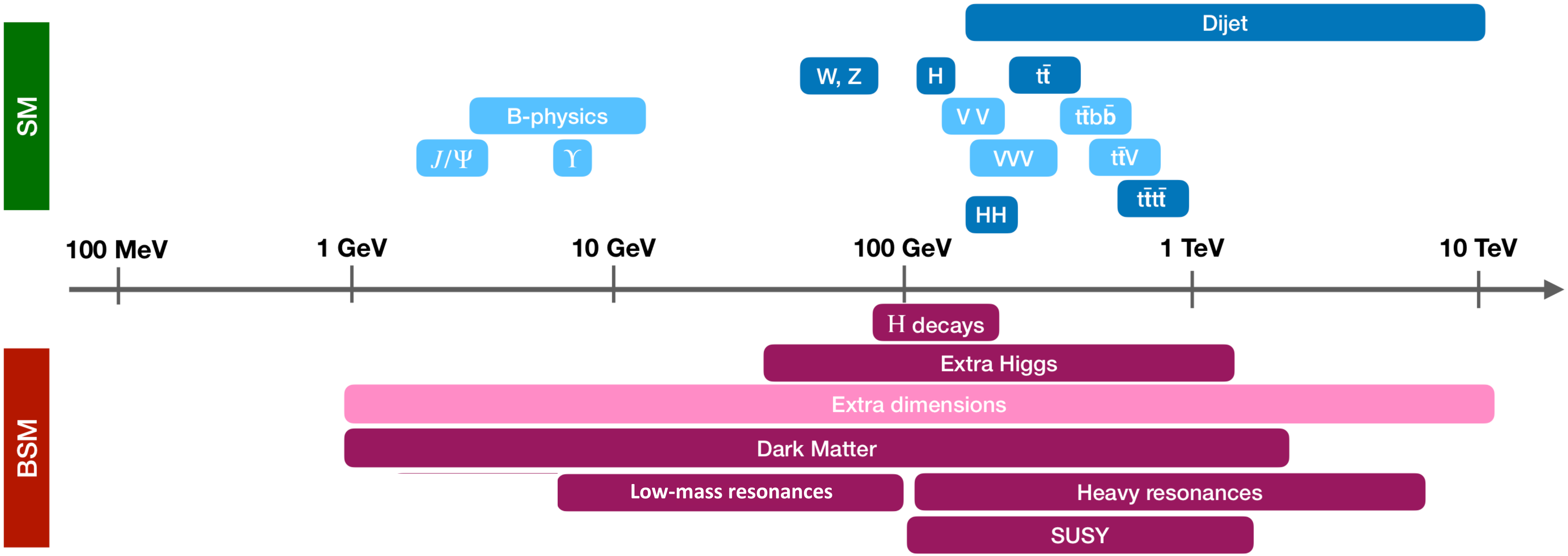


Large Hadron Collier, 2010 (CERN).
Proton energy: 7 TeV



LHC can access a vast range of mass scales

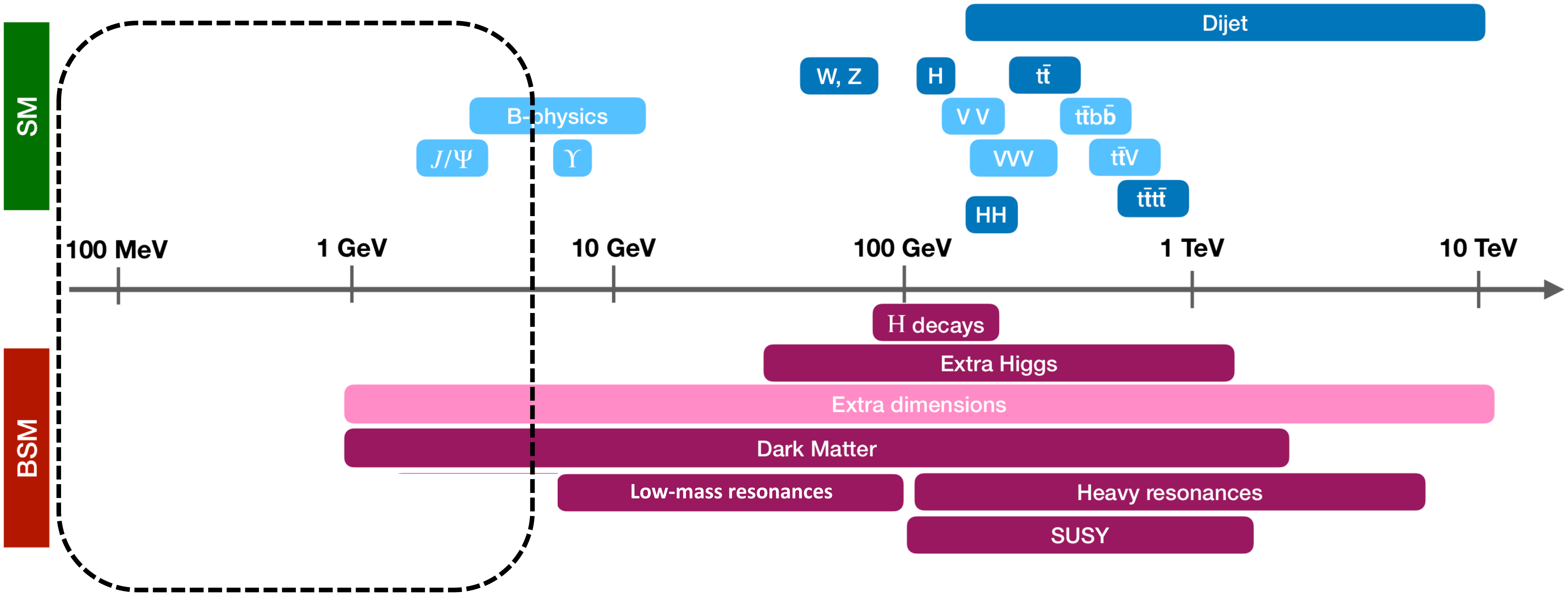
An example from the CMS experiment



Adapted from Nadja Strobbe

But there's plenty of room at the bottom!

An example from the CMS experiment



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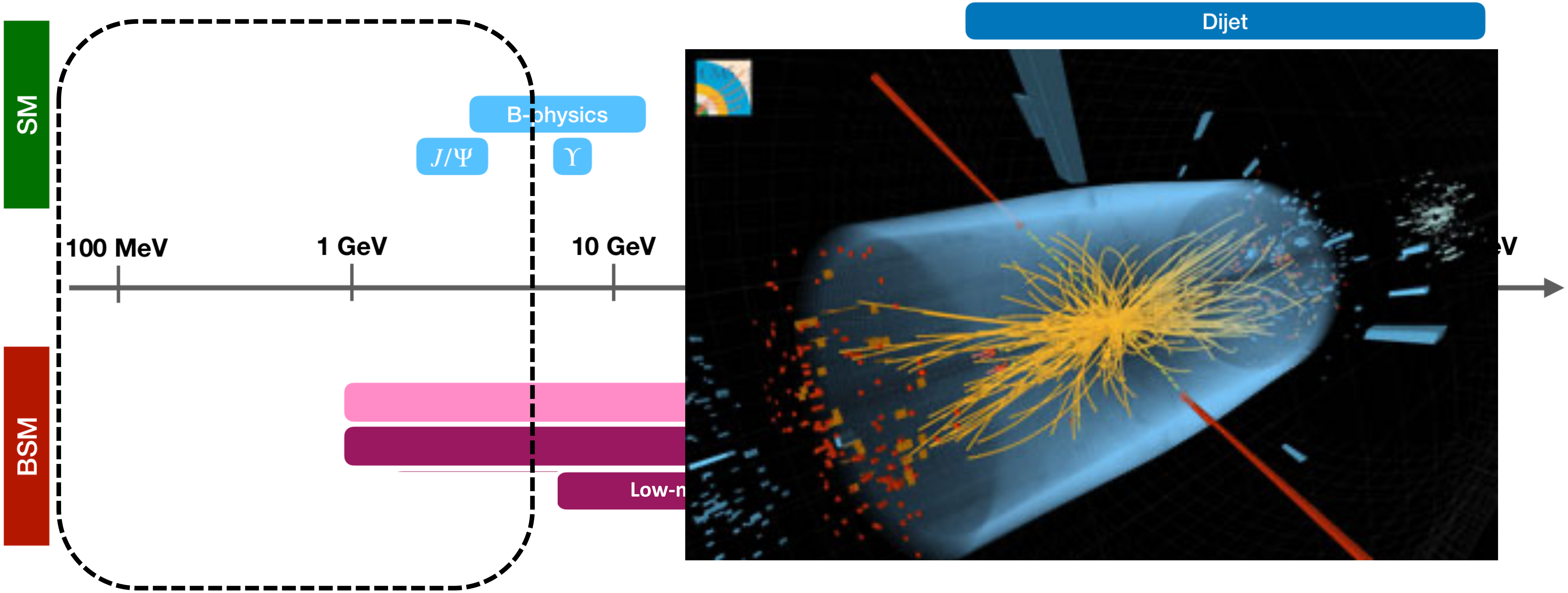

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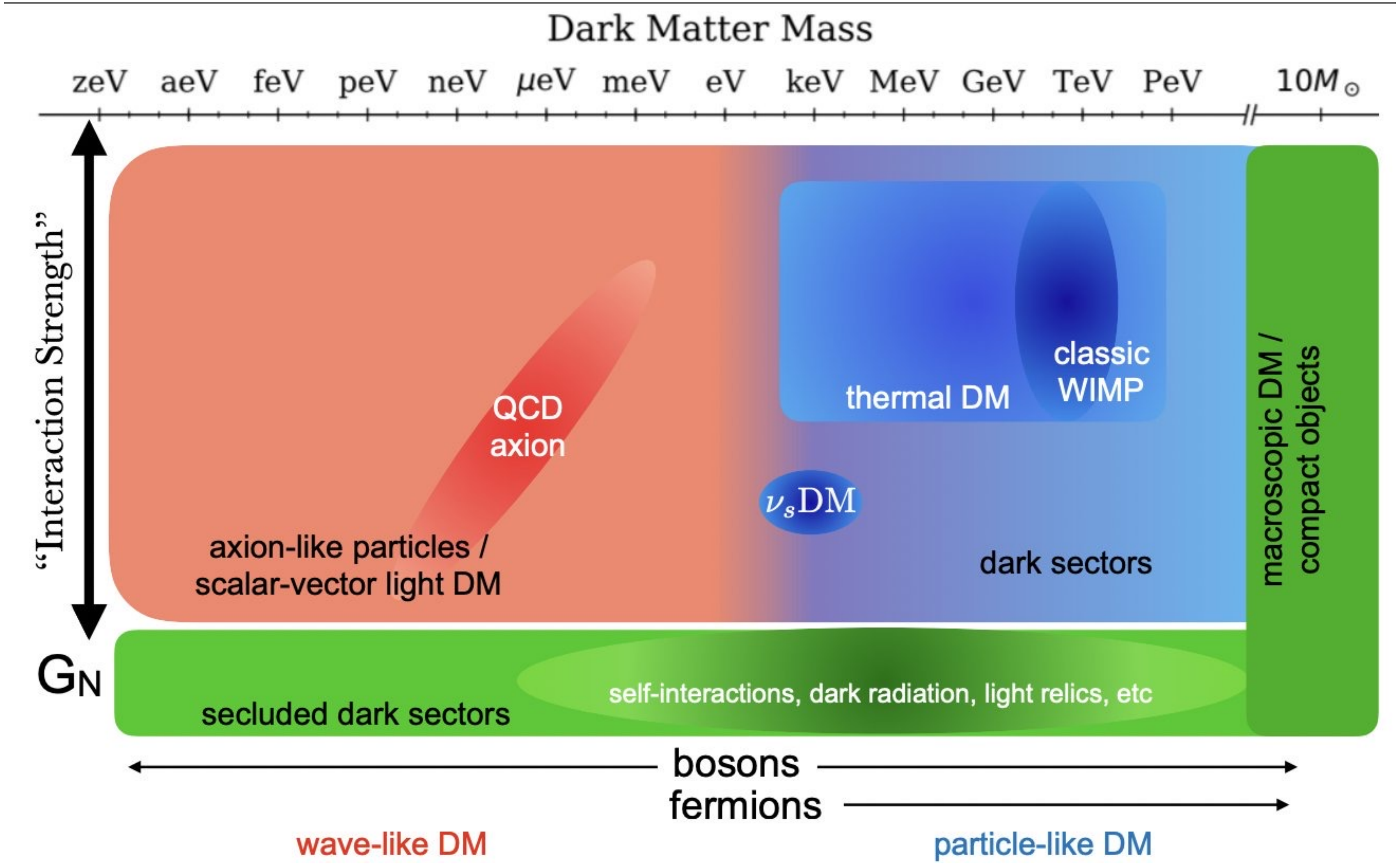
What new physics could exist at "low mass"?



Snowmass 2021

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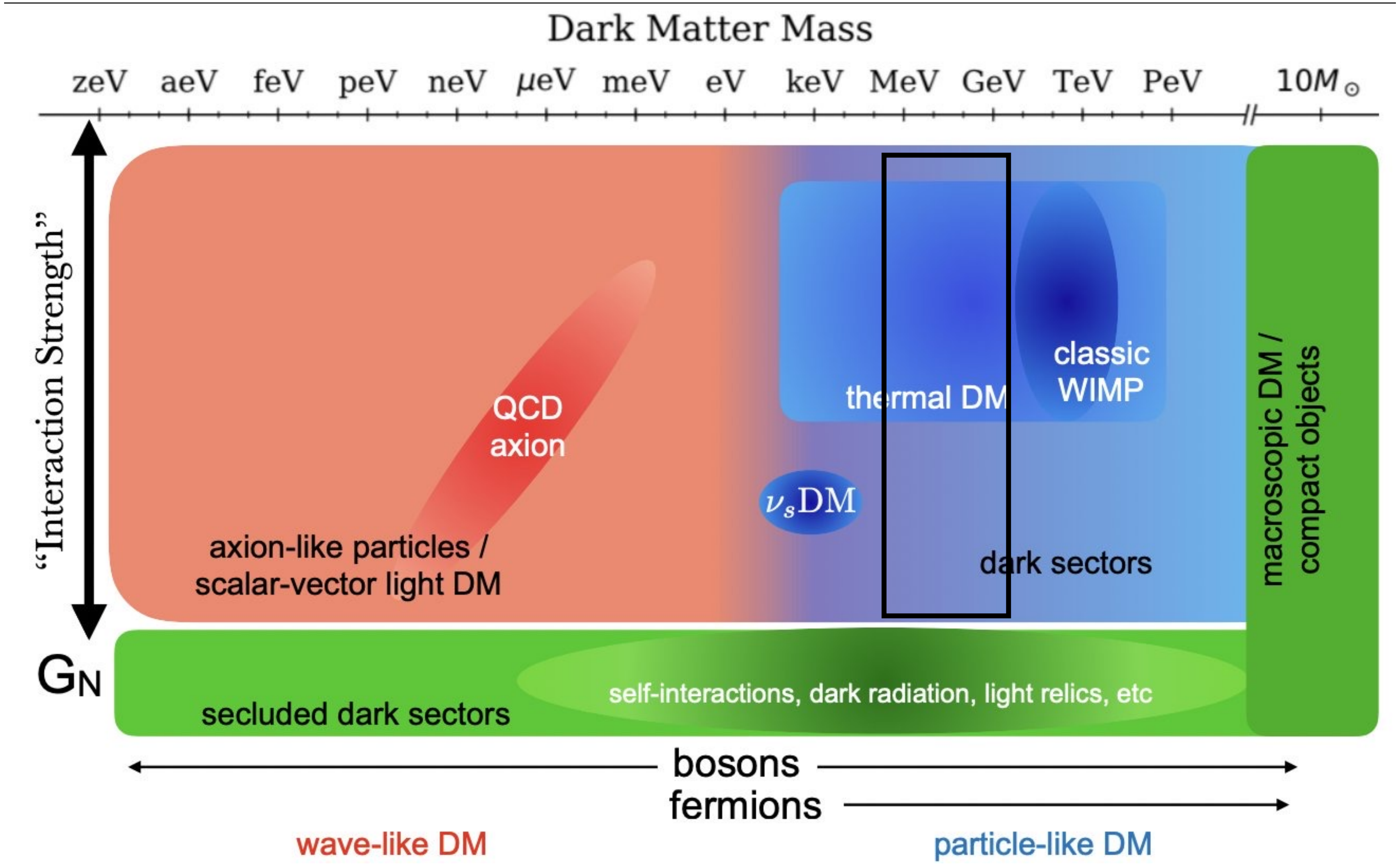


[Snowmass 2021]

A complex dark sector and the dark photon

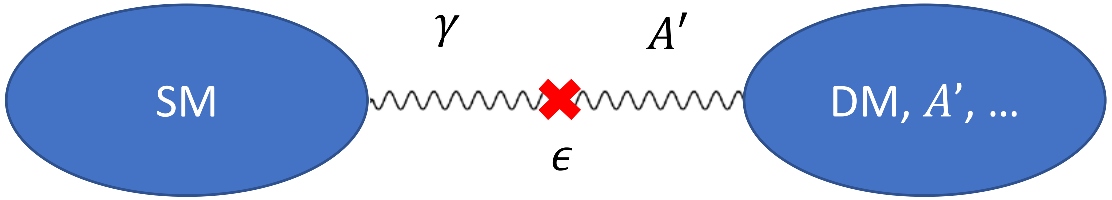
- Dark matter could belong to a complex dark sector
- Simple extension of the standard model (SM) is the **dark photon (A')**:
  - A’ is the gauge boson of a new symmetry, $U(1)_D$, similar to photon in SM
  - Only dark matter (not SM) is charged under this gauge symmetry
  - A “bridge” to the dark sector is permitted via special γ-A' mixing:
  - This additional term in the Lagrangian creates an EM-A’ coupling:
  - Finally, mass is allowed via symmetry breaking:

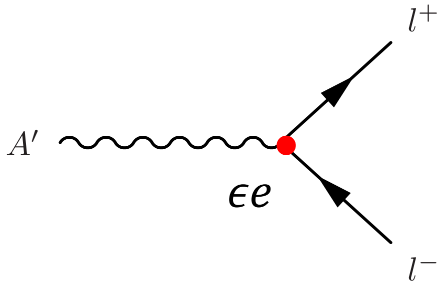
$$-\epsilon F'_{\mu\nu} B^{\mu\nu}$$

$$+\epsilon e A'^{\mu} J^{EM}_{\mu}$$

$$+\frac{1}{2} m^2_{A'} A'^{\mu} A'_{\mu}$$

Holstom, PLB 166 (1986) 196

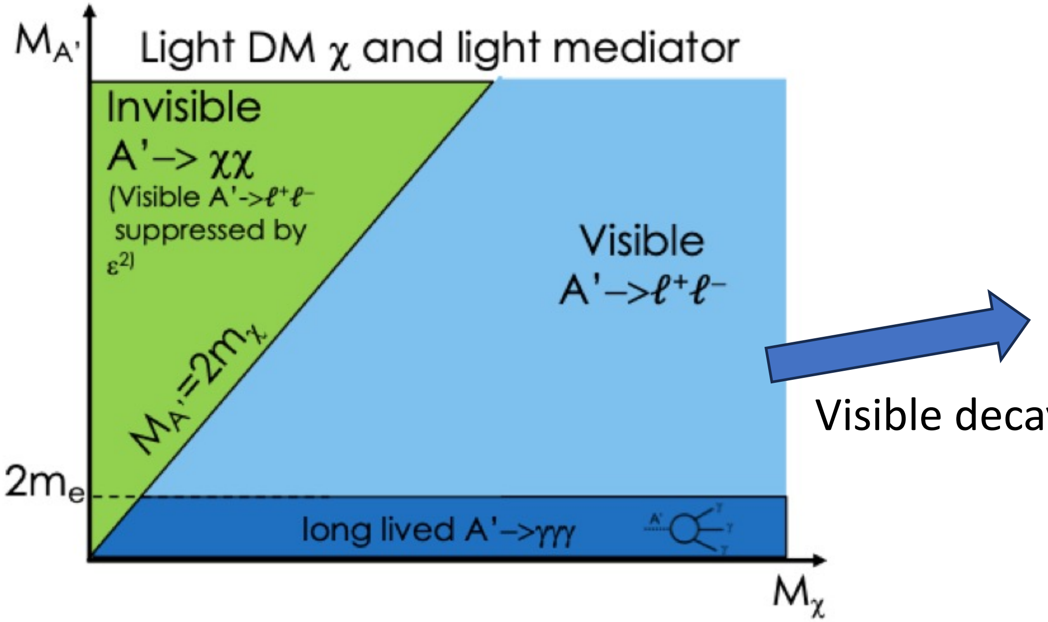




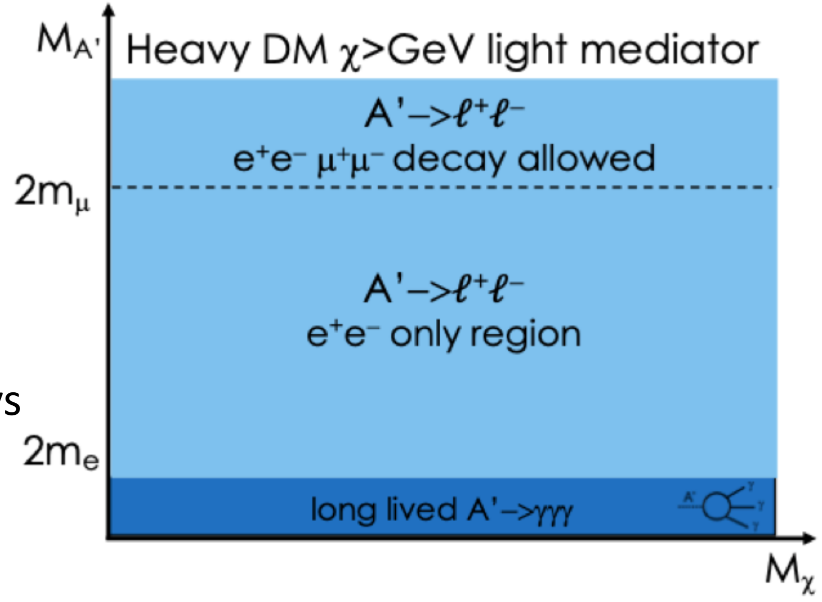
Searches for the dark photon

I. Oceano

Invisible decay



Visible decays



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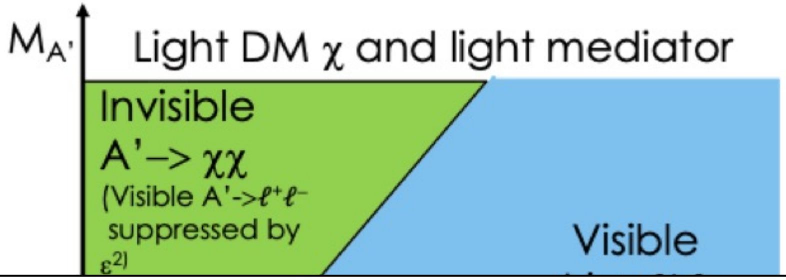

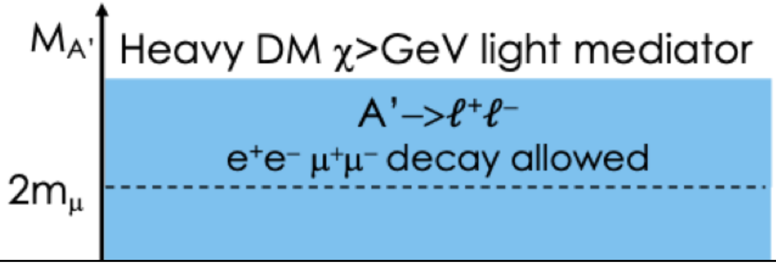

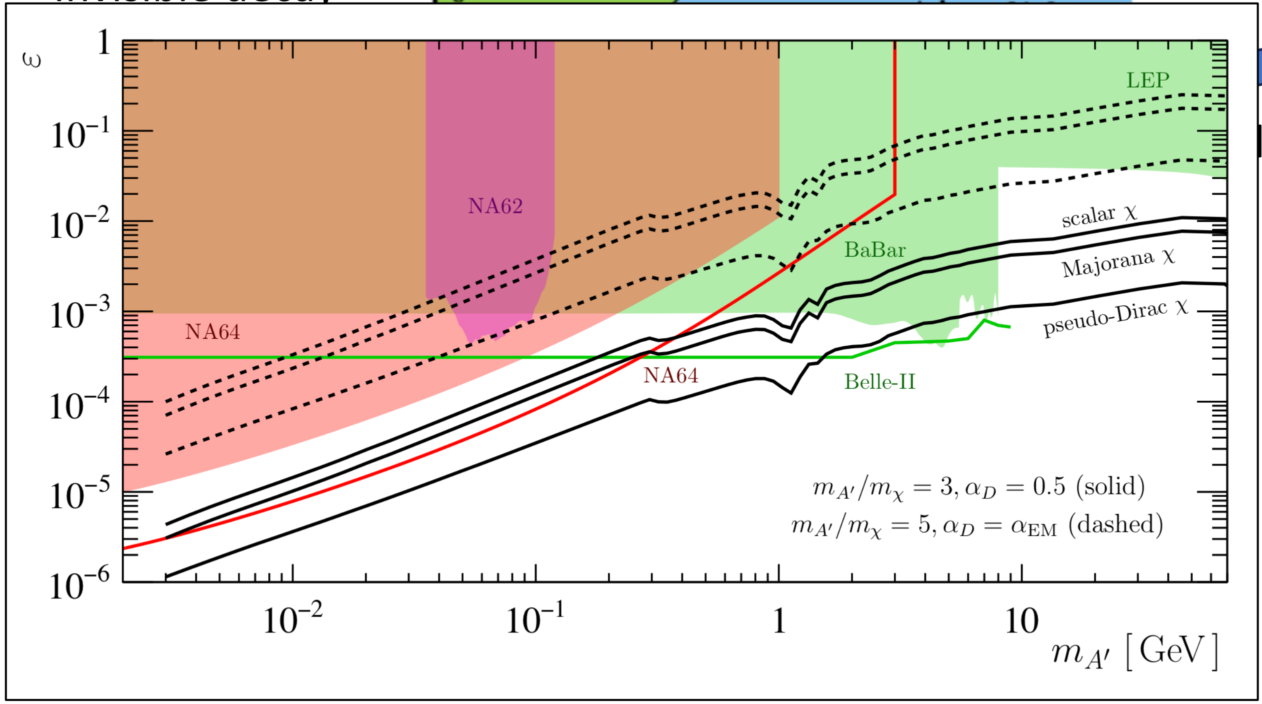

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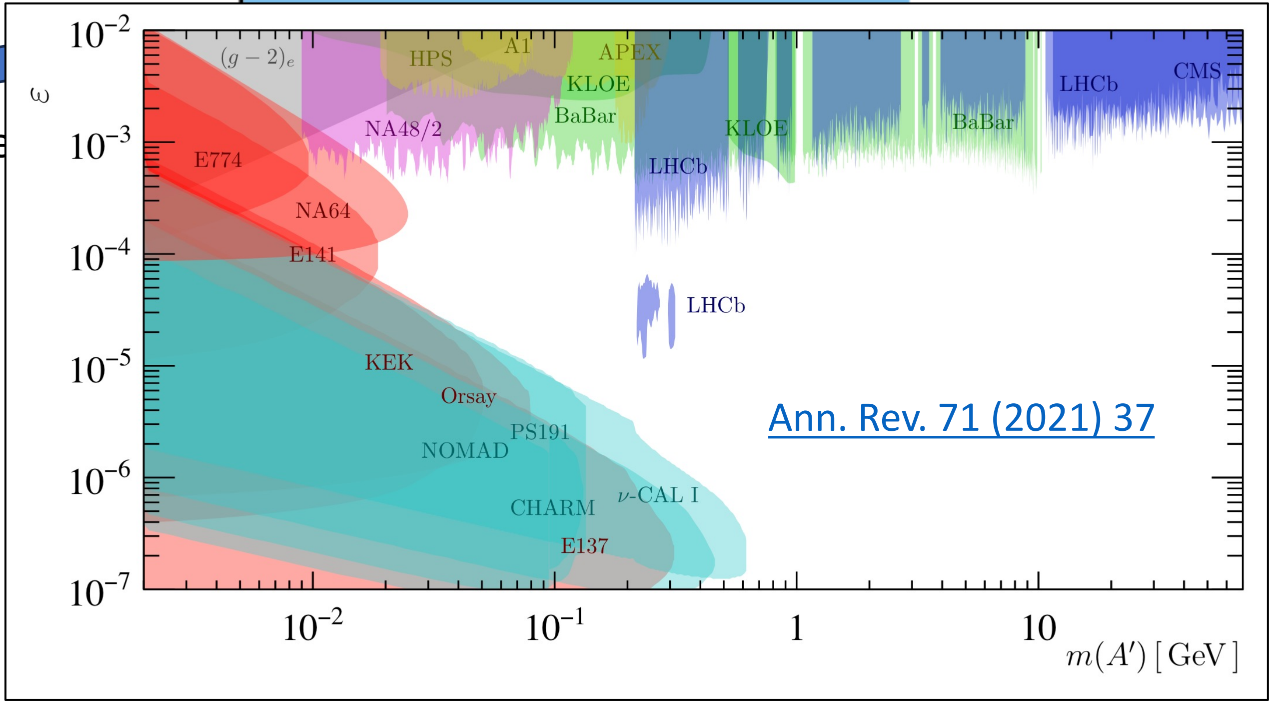
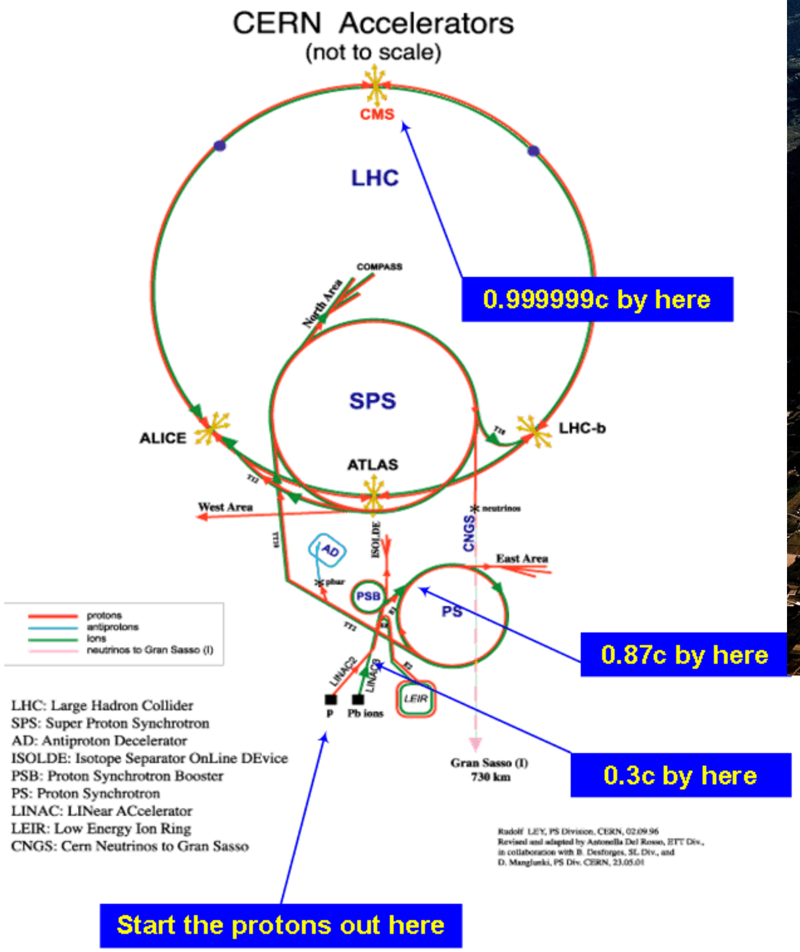
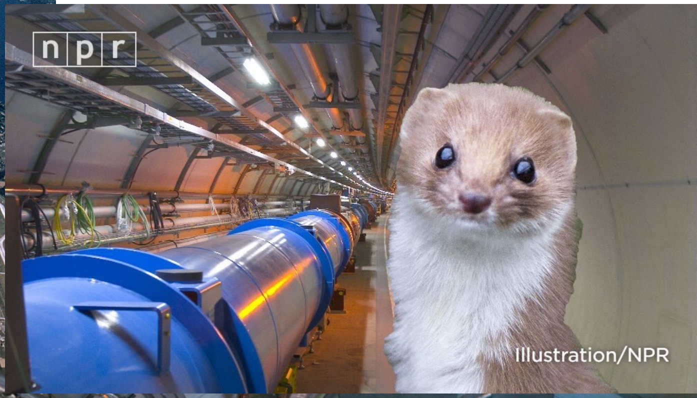
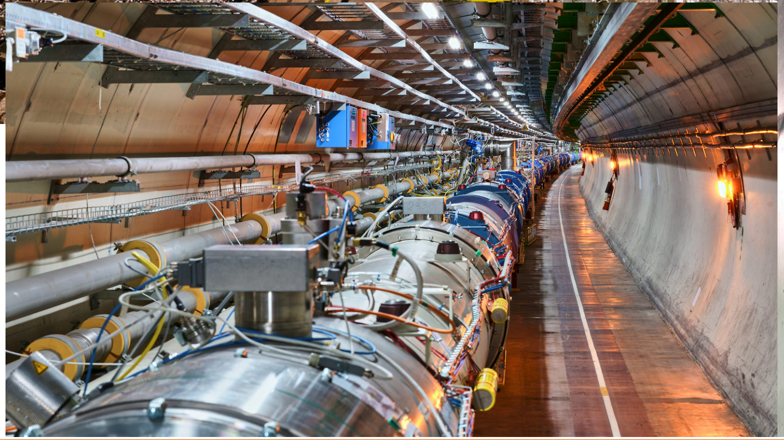


Visible decays

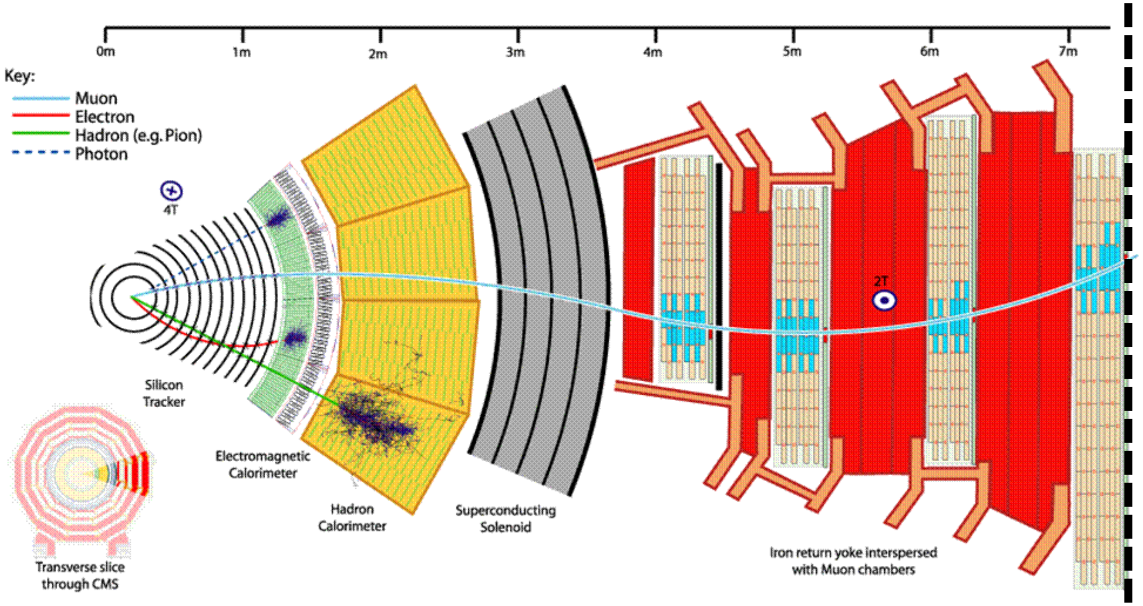
The Large Hadron Collider



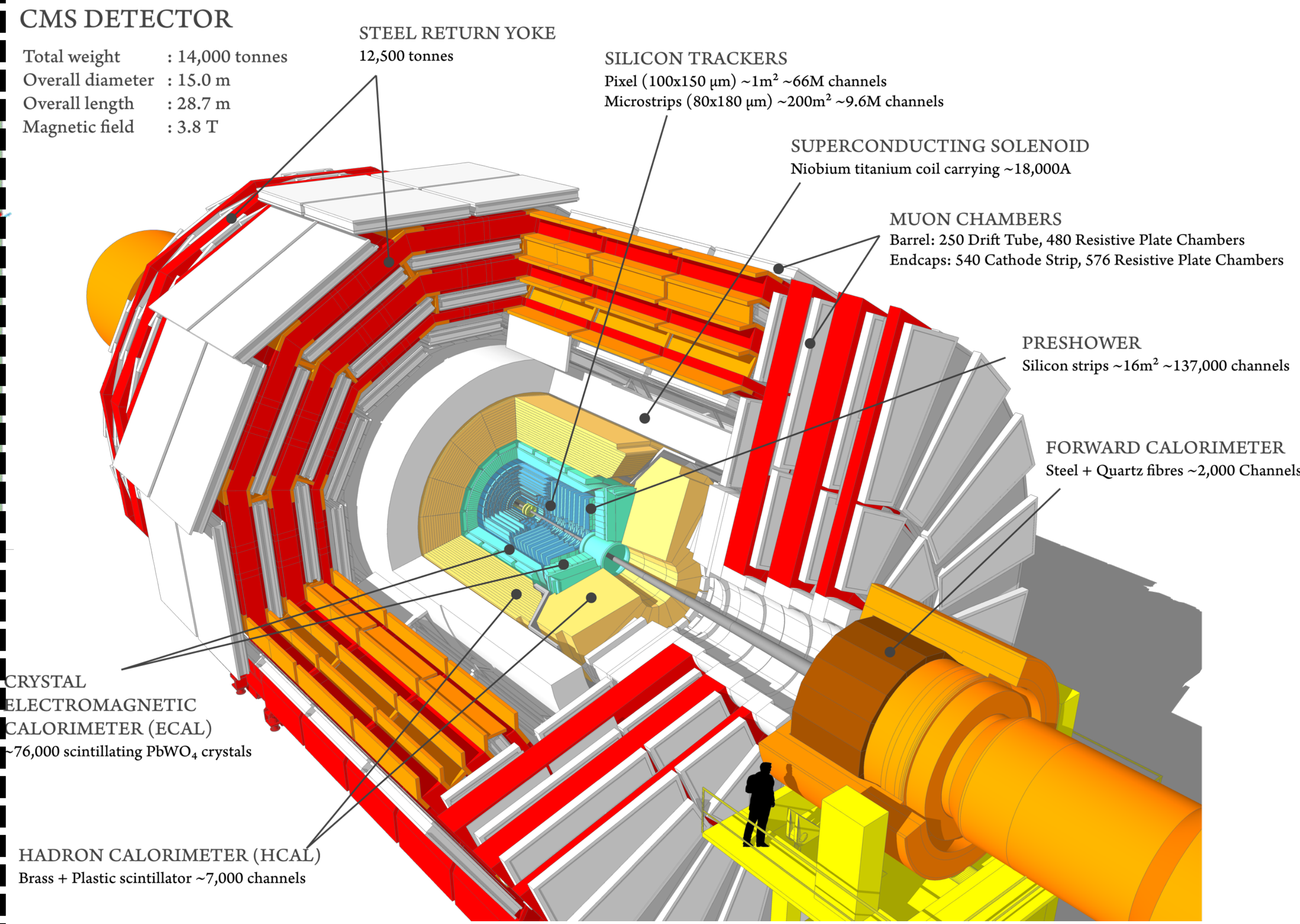




Compact Muon Solenoid (CMS)

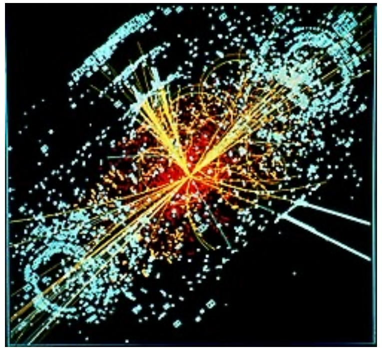


- General-purpose detector
- Two trackers, two calorimeters
- Muon detectors in the outer layers
- Up to 4T magnetic field
- "Compact" relative to ATLAS



The CMS trigger system

- LHC collides proton bunches with a rate of 40 MHz (every 25 ns)
- → Impossible to store every single collision event
- CMS developed a two-tier trigger system to cope:
  - Hardware-based (Level-1 or **L1**)
  - Software-based (High-level trigger or **HLT**)



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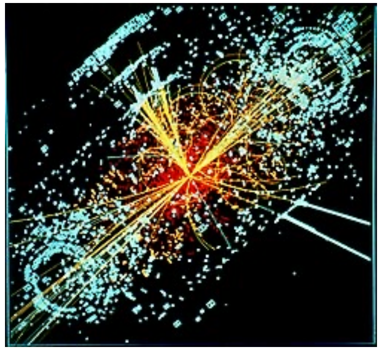

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L1

Rate: **100 kHz** (hard limit)
Latency: 3.2 μs (hard limit)

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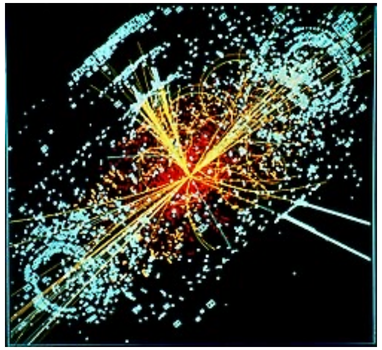

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L1

Rate: **100 kHz** (hard limit)
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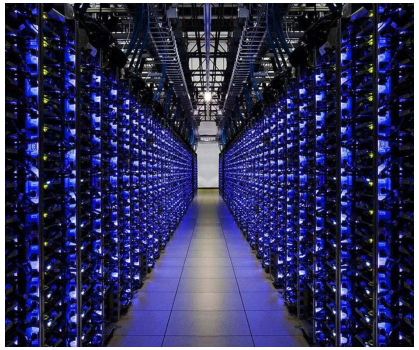
HLT

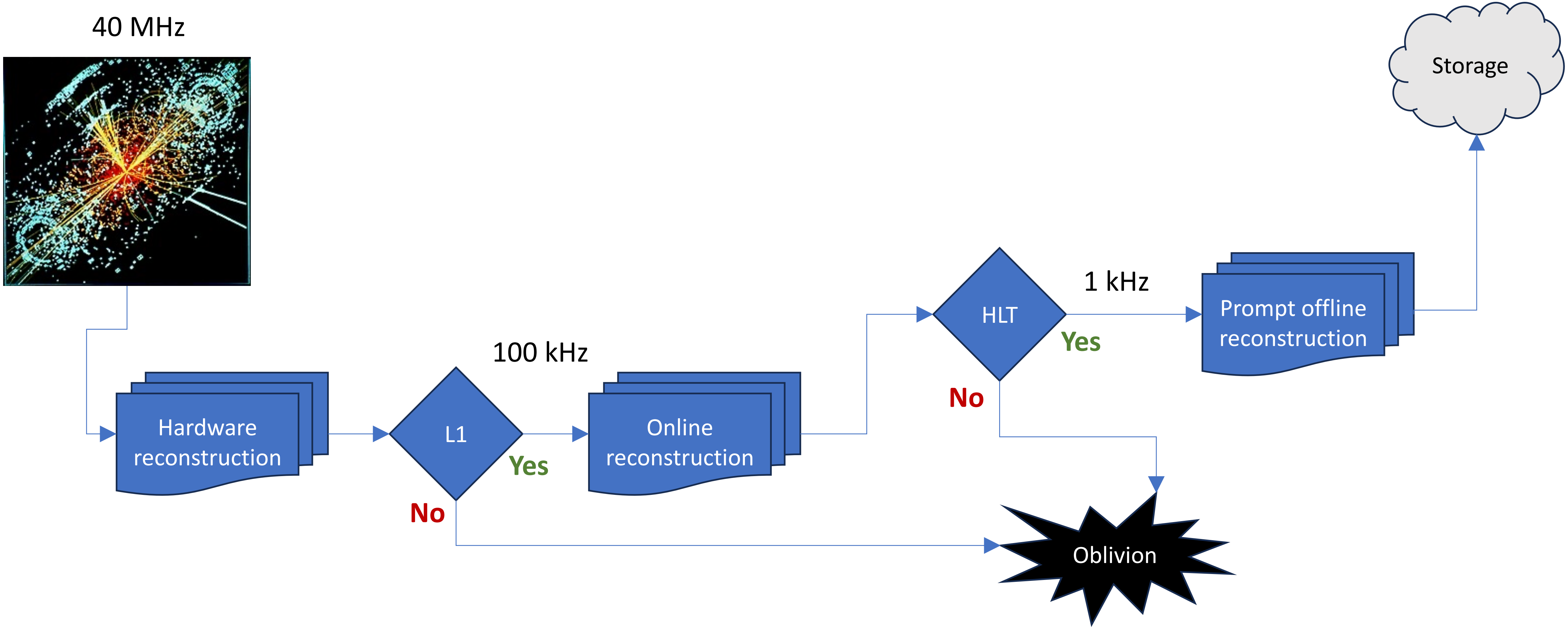


Rate: **1 kHz** (soft limit)
Latency: 500 ms (hard limit)
Data BW: 5 GB/s (hard limit)

Doing more with less: scouting & parking

- The need for a trigger system limits experimental sensitivity to rare processes involving low mass particles
  - → Momentum thresholds too high to efficiently accept events featuring decays of such particles
- CMS has developed strategies to boost acceptance to such processes:
  - **Data scouting**: Limit information saved per event in exchange for more events
  - **Data parking**: Save (or park) more raw events in storage, only reconstructing later when there is CPU available
- Initially devised as “siblings”: first scout for new signatures, then reconstruct parked data once found
  - But active development over the years offered further improvements to pipelines

The scouting and parking pipelines



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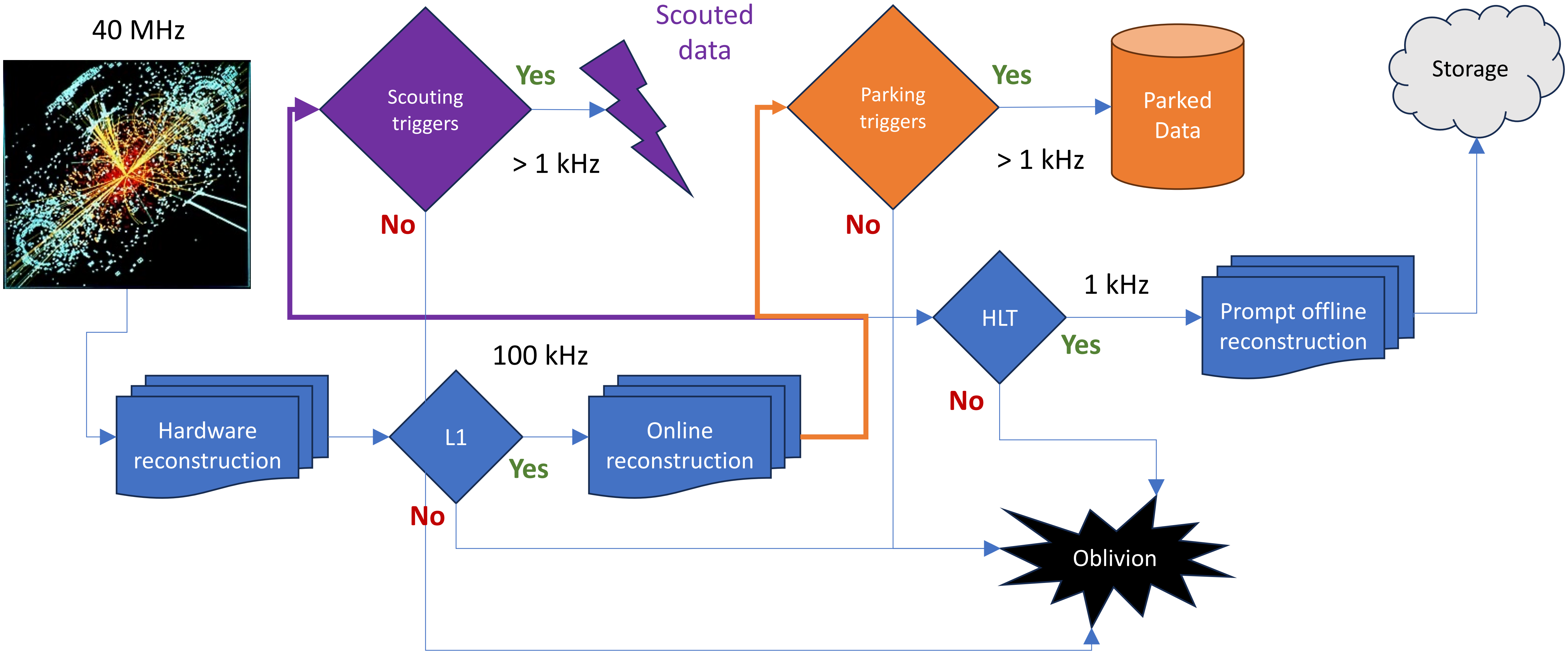
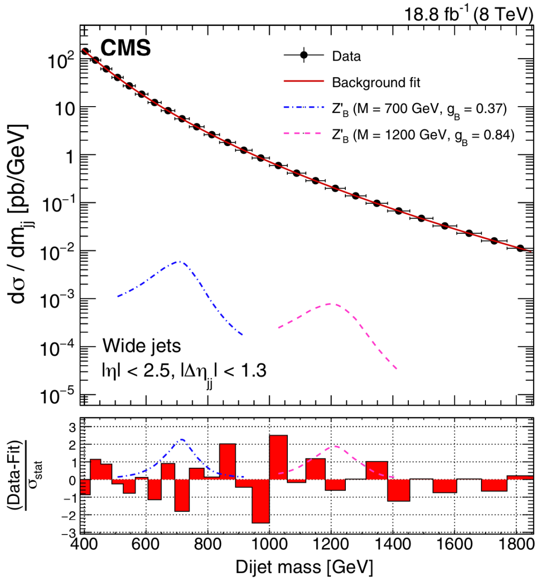


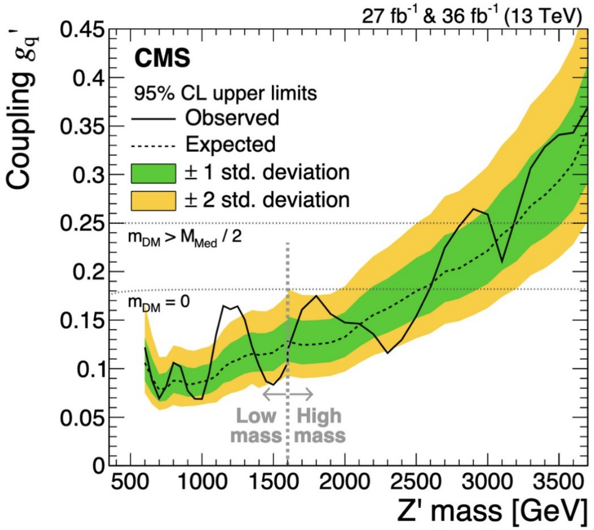
A brief history of CMS scouting & parking



First developed for dijet searches in 2011 (Run 1)

[JHEP 01 (2013) 013](#)
[PRL 117 (2016) 031802](#)

Scouting

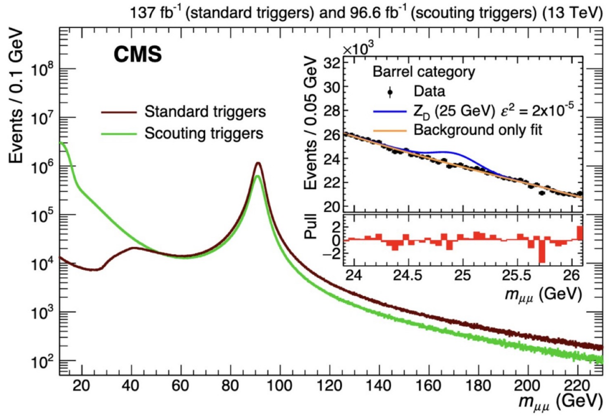


Used for several hadronic resonance searches in 2012 (Run 1) and Run 2

[PLB 769 (2017) 520](#)
[JHEP 08 (2018) 130](#)
[PRD 99 (2019) 012010](#)
[PLB 805 (2020) 135448](#)

Multi-muon scouting first developed in 2017 and 2018

[PLB 805 (2020) 135448](#)
[JHEP 04 (2022) 062](#)



Parking first developed in 2012, reconstructed during LHC 2013 shutdown. Used by several Higgs exotic searches

[JHEP 05 (2014) 104](#)
[JHEP 10 (2014) 160](#)
[PLB 753 (2016) 363](#)
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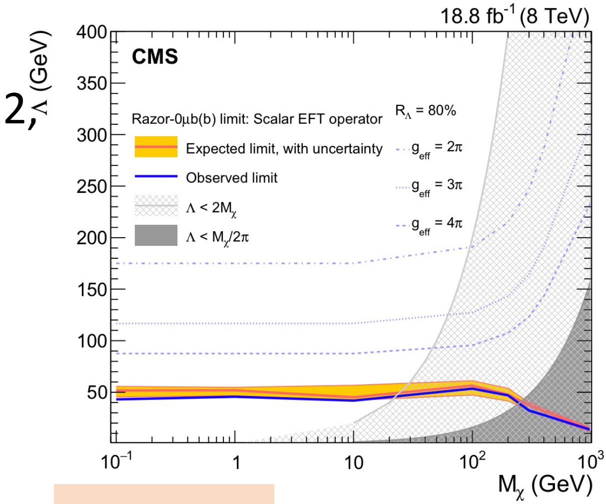
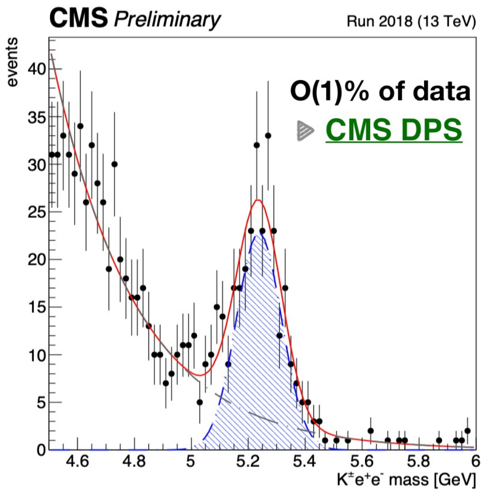


Parking

"B-parking" developed in 2018 to collect B meson leptonic decays for R(K) studies



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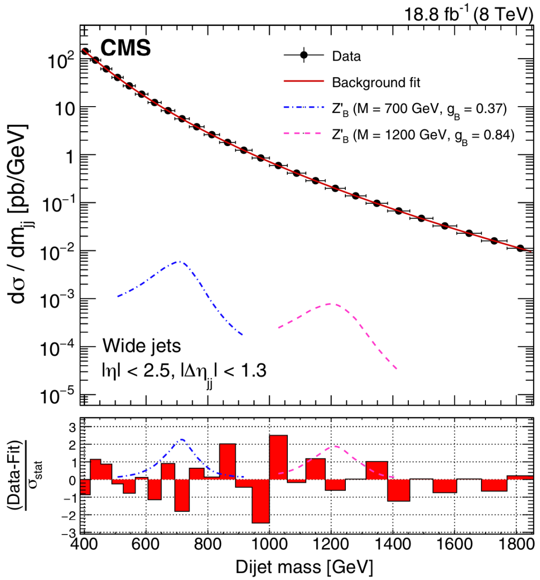

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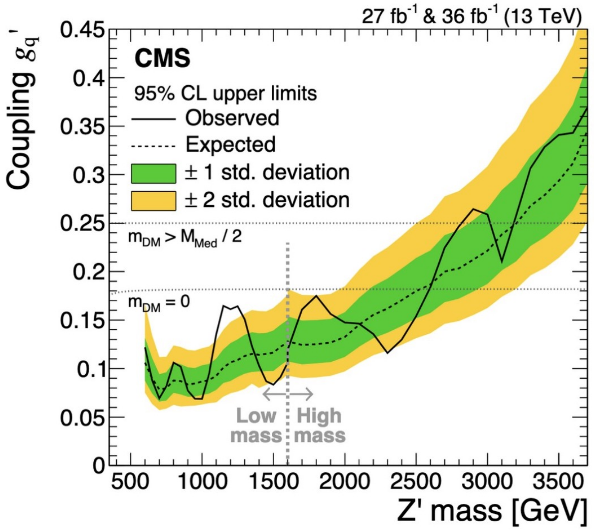

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Today: 2 more muon scouting results

Multi-muon scouting first developed in 2017 and 2018

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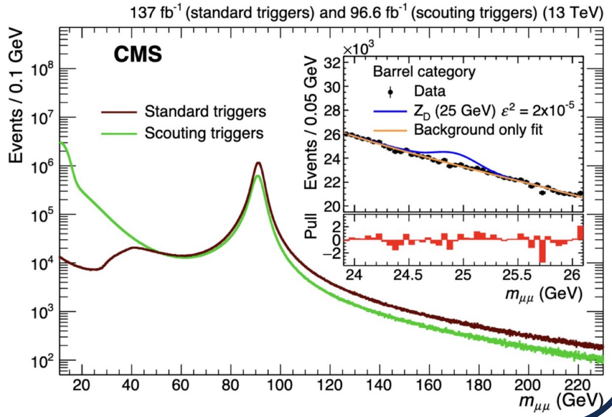

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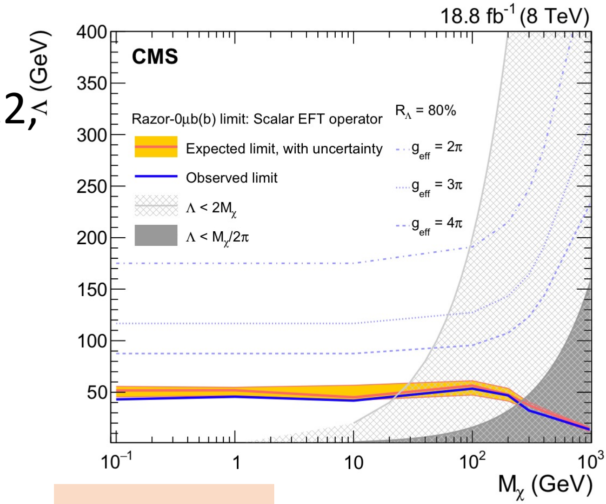

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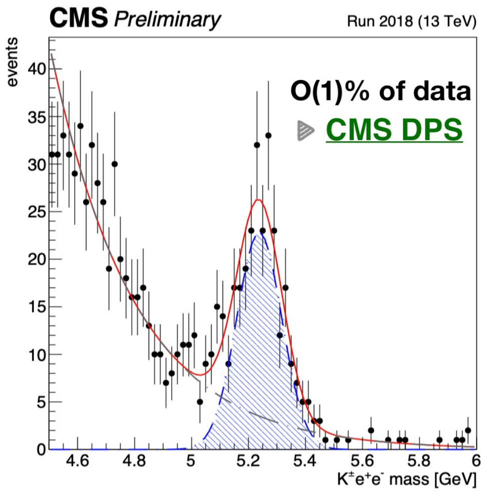
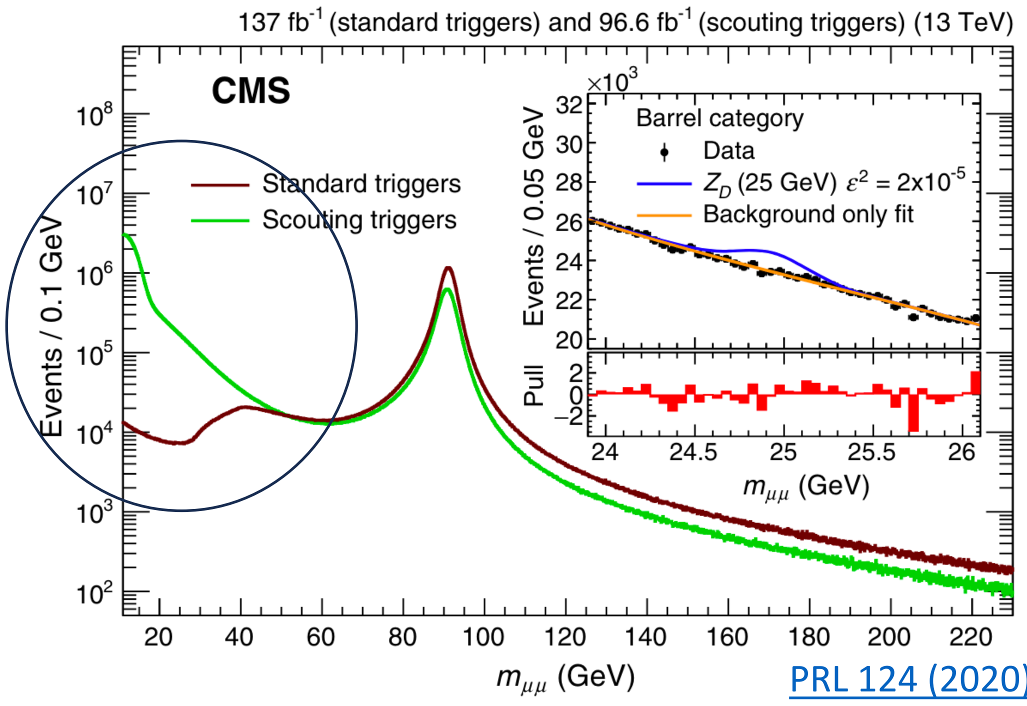


The muon scouting dataset

- Scouting exchanges complete event information for higher trigger rates
  - Only save muon objects per event
  - Trigger rates up to 60x higher
- Dimuon momentum thresholds substantially reduced
  - **(17, 8) GeV → (3, 3) GeV**

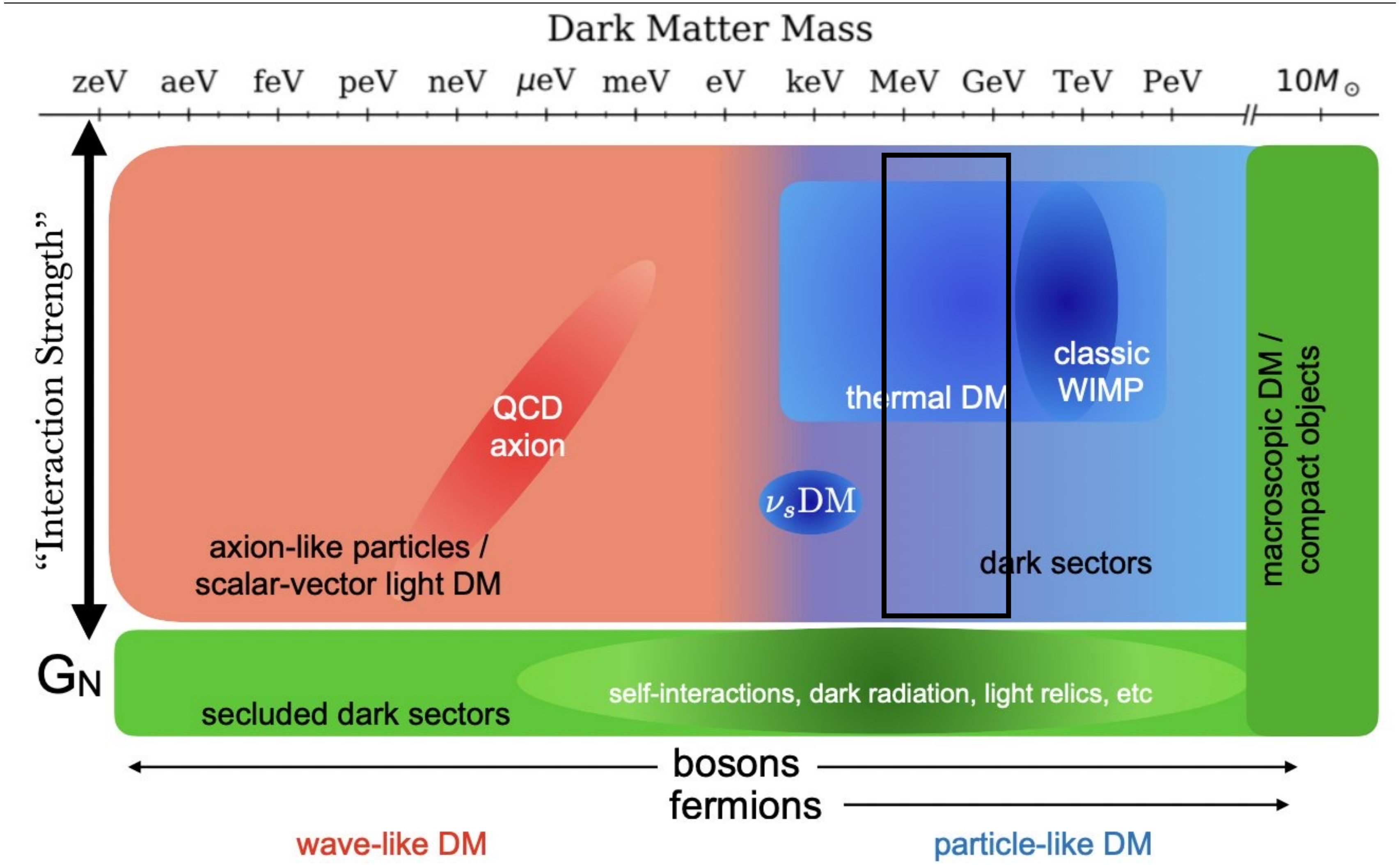


PRL 124 (2020) 131802

Muon scouting triggers in 2017 & 2018:
- **At least two muons with p_T > 3 GeV**
- **No mass cut (low mass resonances)**
- No displacement cuts (Up to ~ 10 cm displacement)

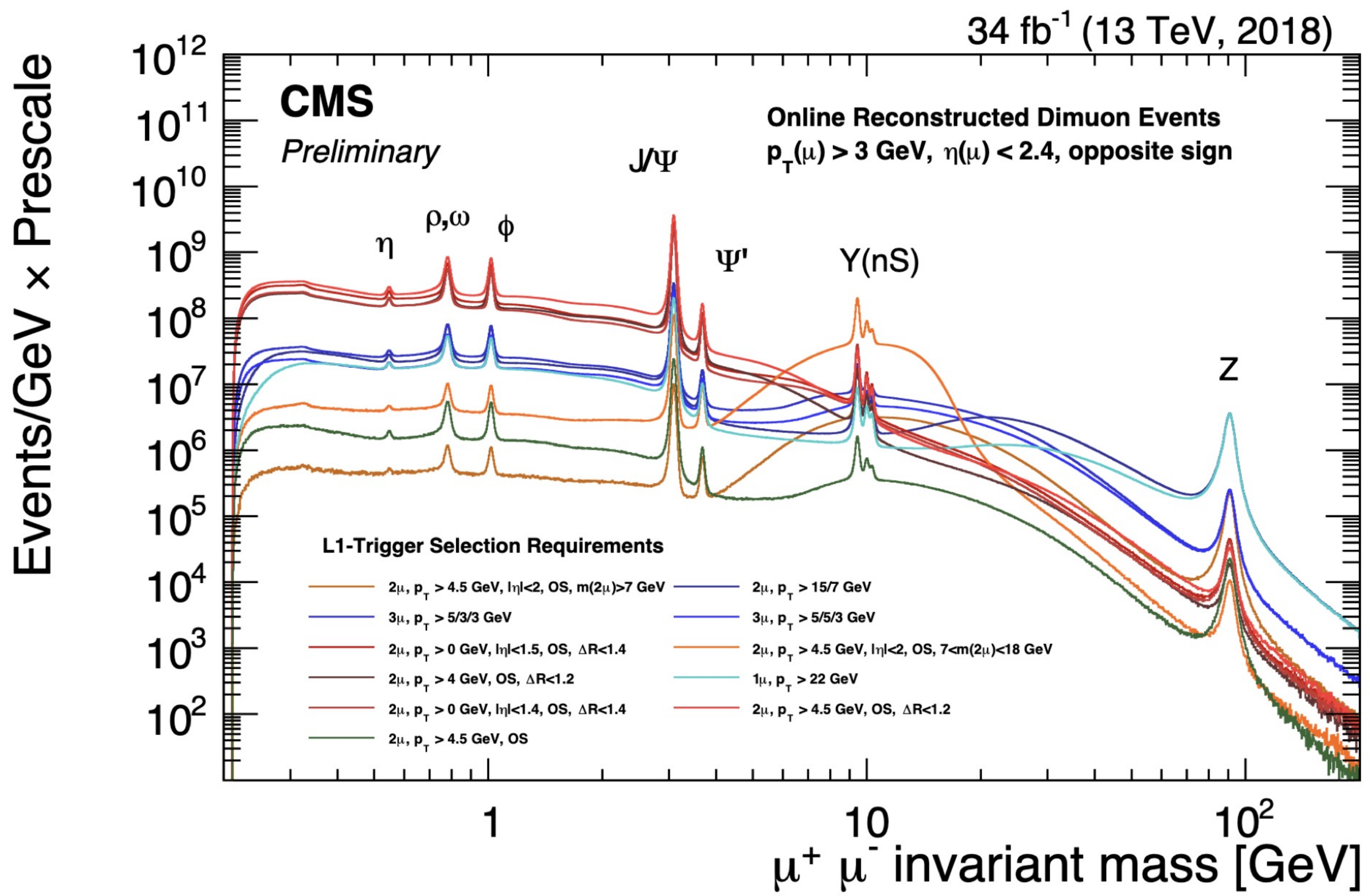
Data stream	Rate [Hz]	Event size	Bandwidth [MB/S]
Muons	**420**	0.86 MB	360
Scouting Muons	**4580**	8.9 KB	40

What new physics could exist at "low mass"?



Snowmass 2021

Dimuon mass spectrum with scouting



- Most important L1 selections:

L1 path	p_{T} [GeV]	$\lvert\eta\rvert$	ΔR	$m_{2\mu}$ [GeV]	Charge
#1	>4.0 (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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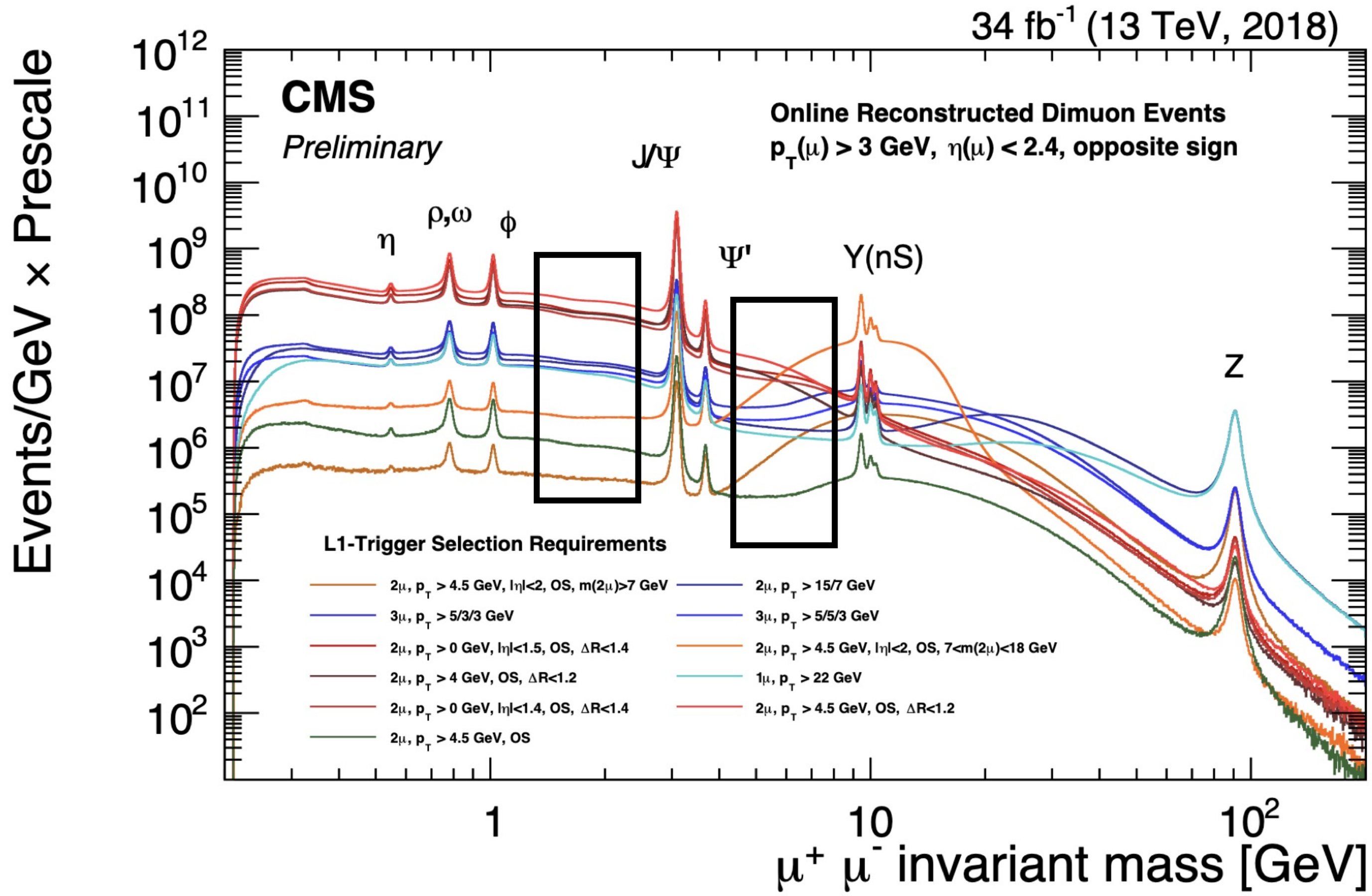

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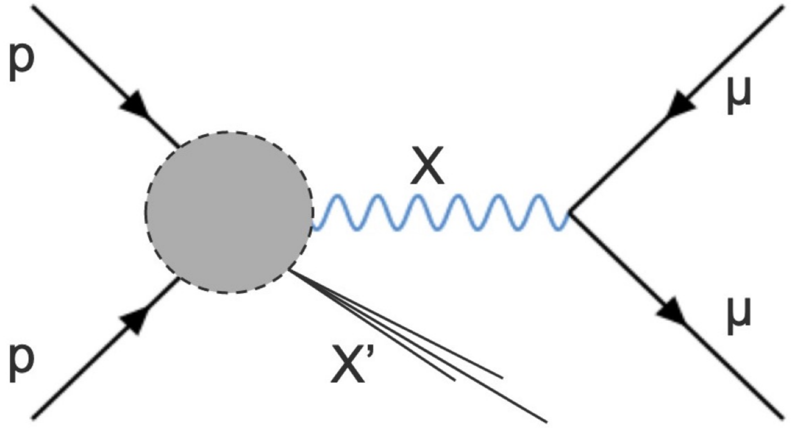
#2	–	< 1.5	< 1.4	–	OS
#3	>15, >7	–	–	–	–
#4	>4.5	< 2.0	–	7–18	OS

- Can we use this neat spectrum to search for new physics with low masses?

Scouting for dark photons

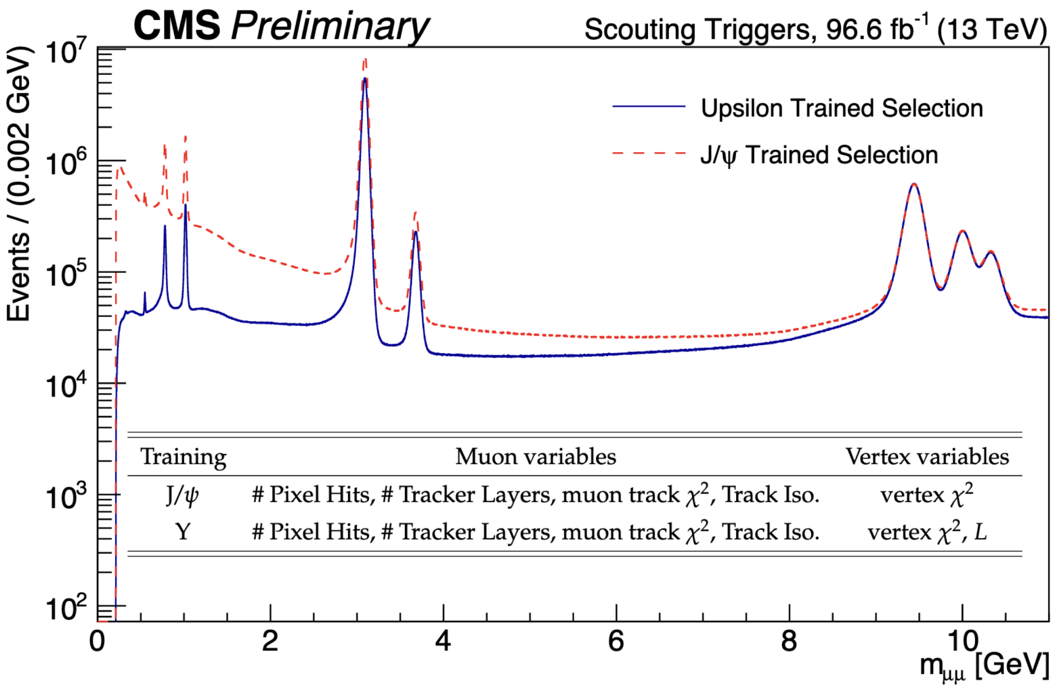
CMS PAS EXO-21-005

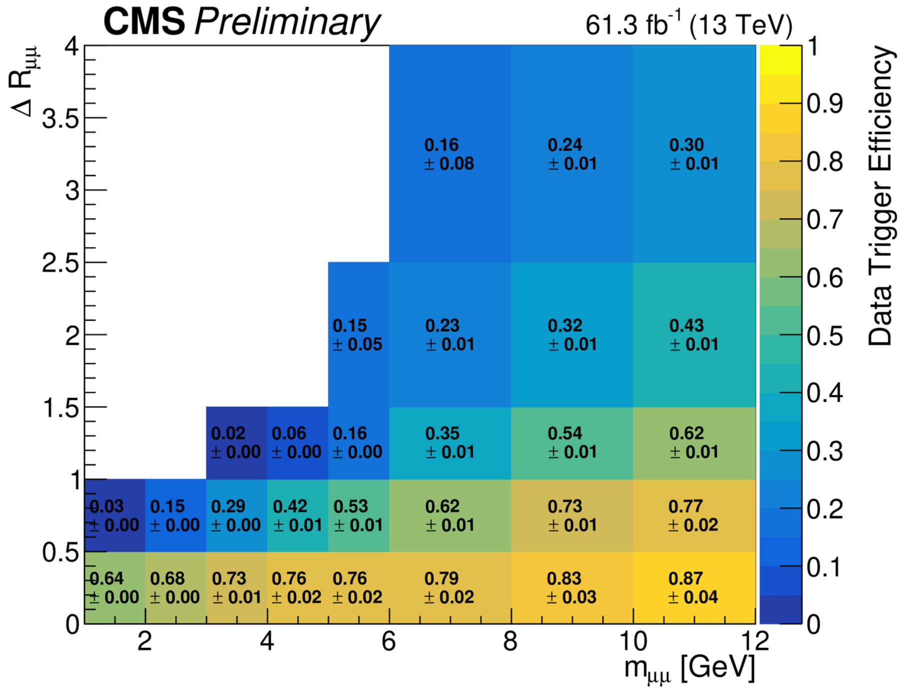
- Analysis goal and basic strategy:
  - Search for dimuon resonances in a model-independent and general way
  - Look for a bump hunt in the dimuon mass spectrum
- Define custom set of muon identification (ID) criteria to suppress backgrounds
- Measure trigger and reconstruction efficiencies with data-driven methods
- Derive model-independent limit as a function of $\sigma \cdot B \cdot A$
- Then compute above terms for specific models



Trigger and muon ID & efficiencies

- Measure trigger and ID efficiencies in data & MC to derive uncertainties
- Use BDT for ID, trained on Υ and J/ψ: OS → signal, SS → background
- Derived uncertainties: 2-20% (trigger), 4-20% (ID)

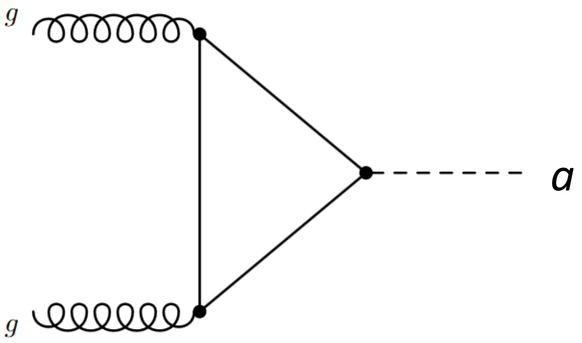




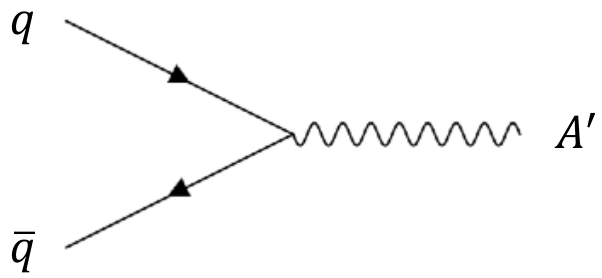
Event categories

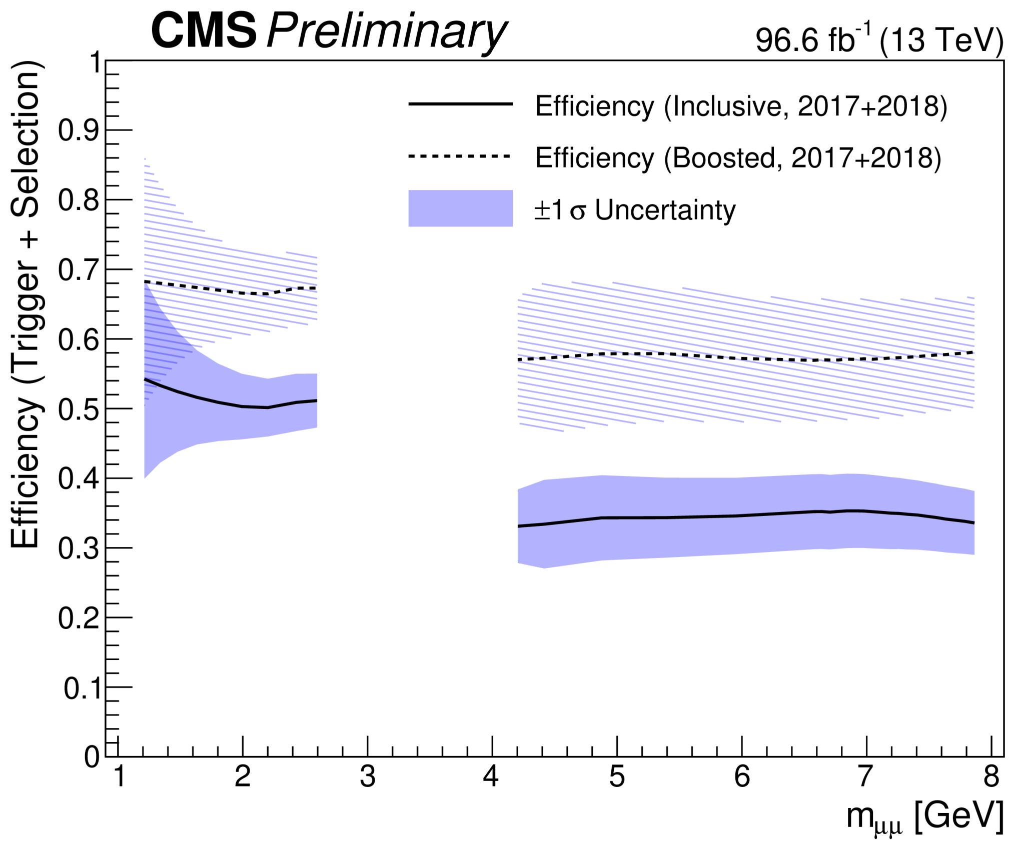
- Two event categories to better target different production mechanisms:
  - Boosted (gluon-gluon fusion): $p_T^{\mu\mu}$ > 20 (35) GeV for $m_{\mu\mu}$ > 4.2 (< 2.6) GeV
  - Inclusive (Drell-Yan): no $p_T^{\mu\mu}$ cut
- Also have maximum displacement cut to focus on prompt production

Boosted
Gluon-gluon fusion



Inclusive
Drell-Yan





Signal model and largest excess

- Model signal shape from fits to SM resonances
  - Double Crystal-Ball + Gaussian
  - Assign 20% uncertainty on resolution

- Largest excess observed at $m_{\mu\mu}$ = 2.41 GeV in the boosted category
  - 3.2 σ local, 1.3 σ global significances
  - LHCb observes 3.1 σ local excess at 2.42 GeV in one event category
  - To be watched

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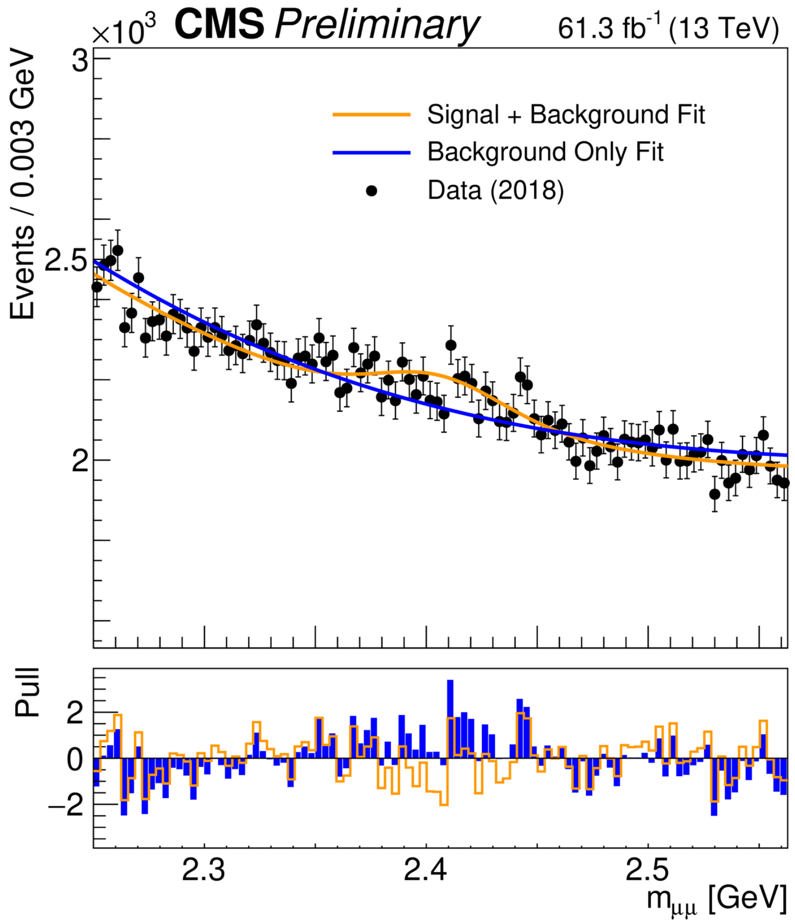
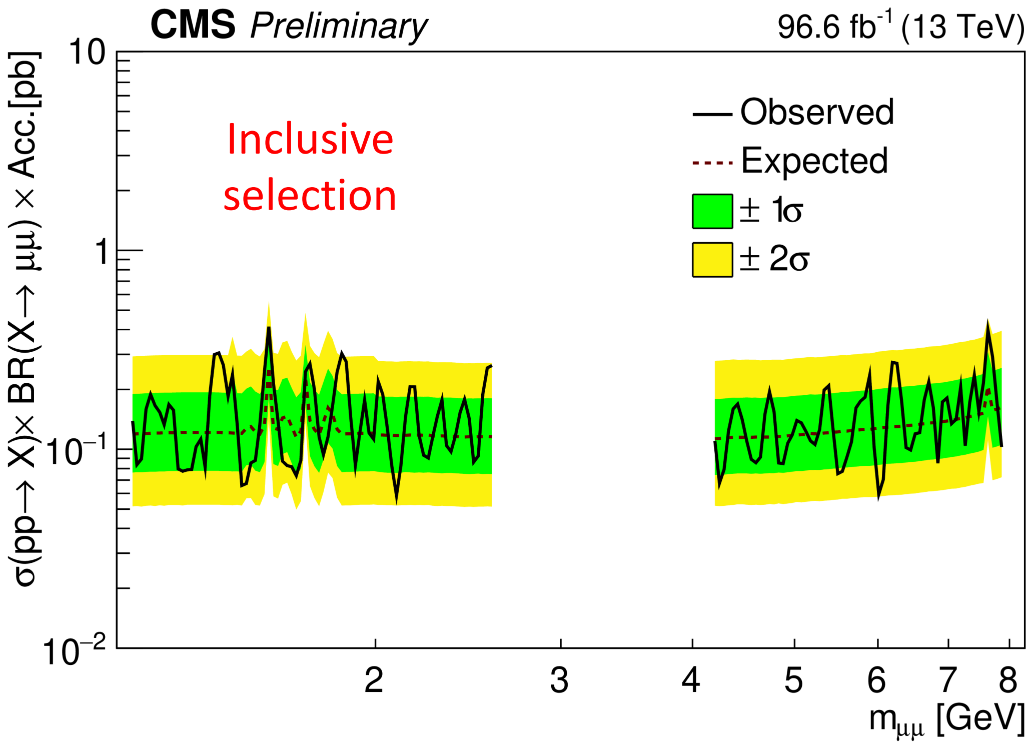
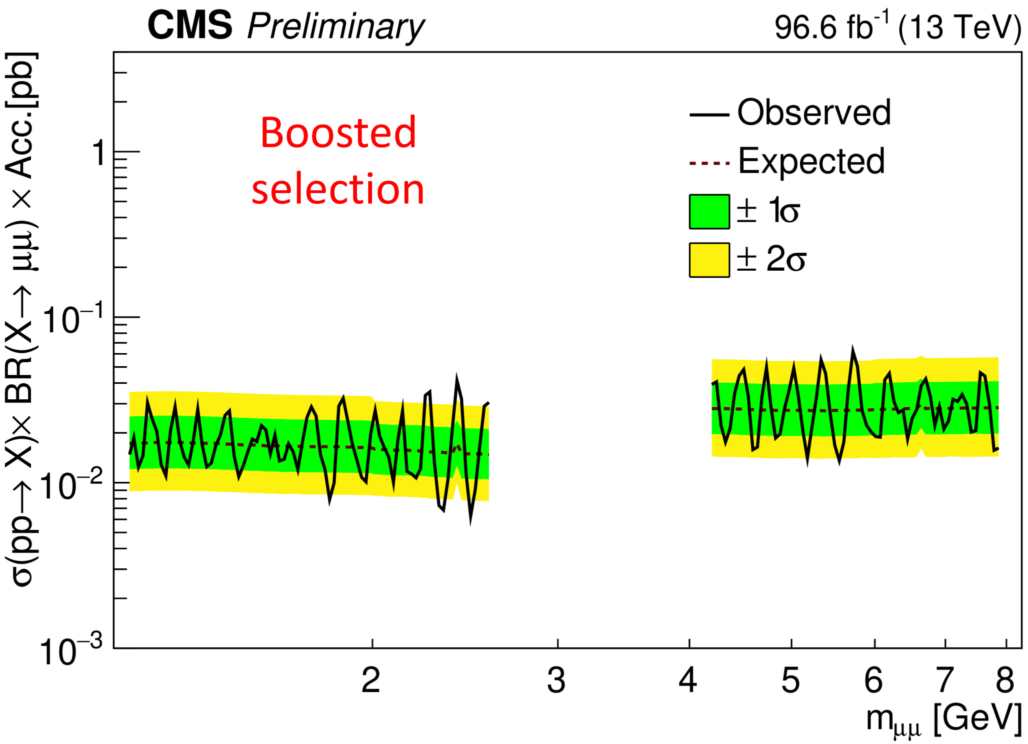


Model-independent limits

- Limits derived for $\sigma \cdot B \cdot A$
- Includes experimental uncertainties (no theory dependence)

CMS PAS EXO-21-005

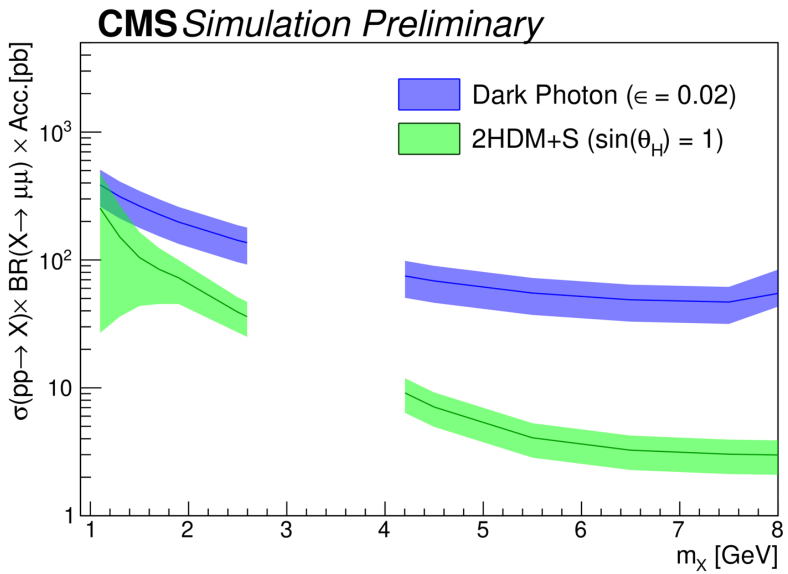




Model-dependent limits

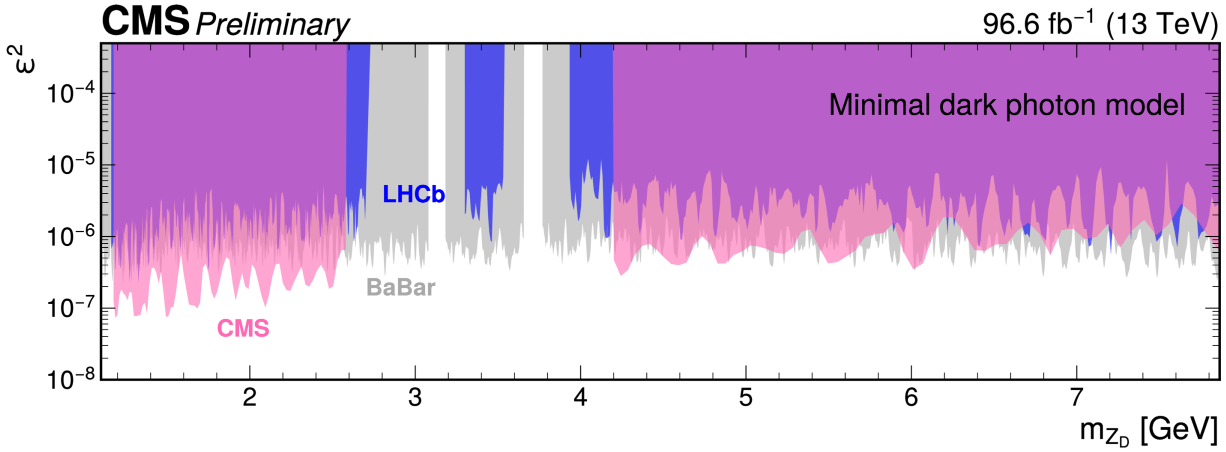
[CMS PAS EXO-21-005]

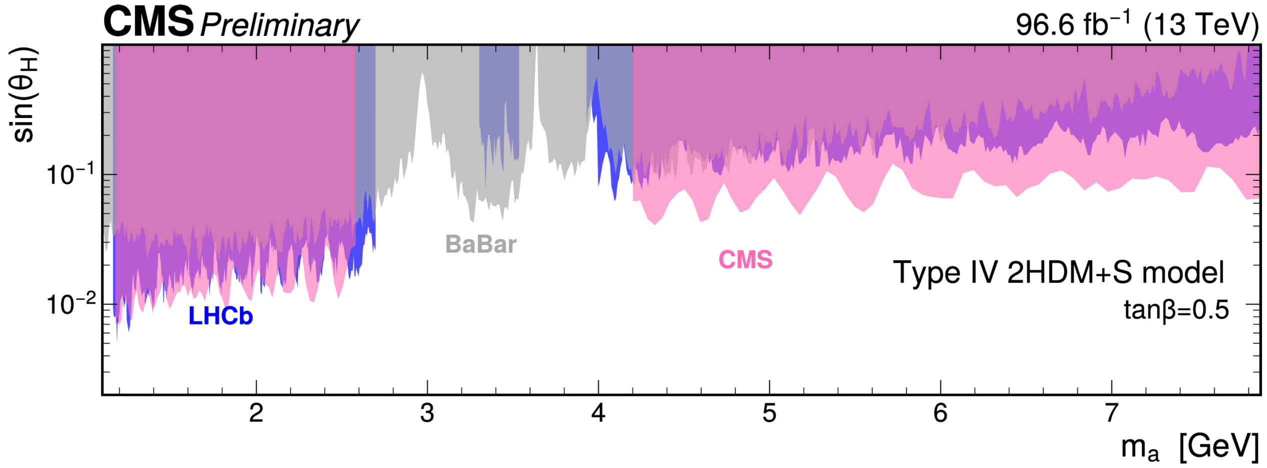
- Compute production $\sigma \cdot B \cdot A$ for models and derive model-dependent limits
- In addition to dark photon model, consider also 2-Higgs Doublet Model + Scalar (2HDM+S):



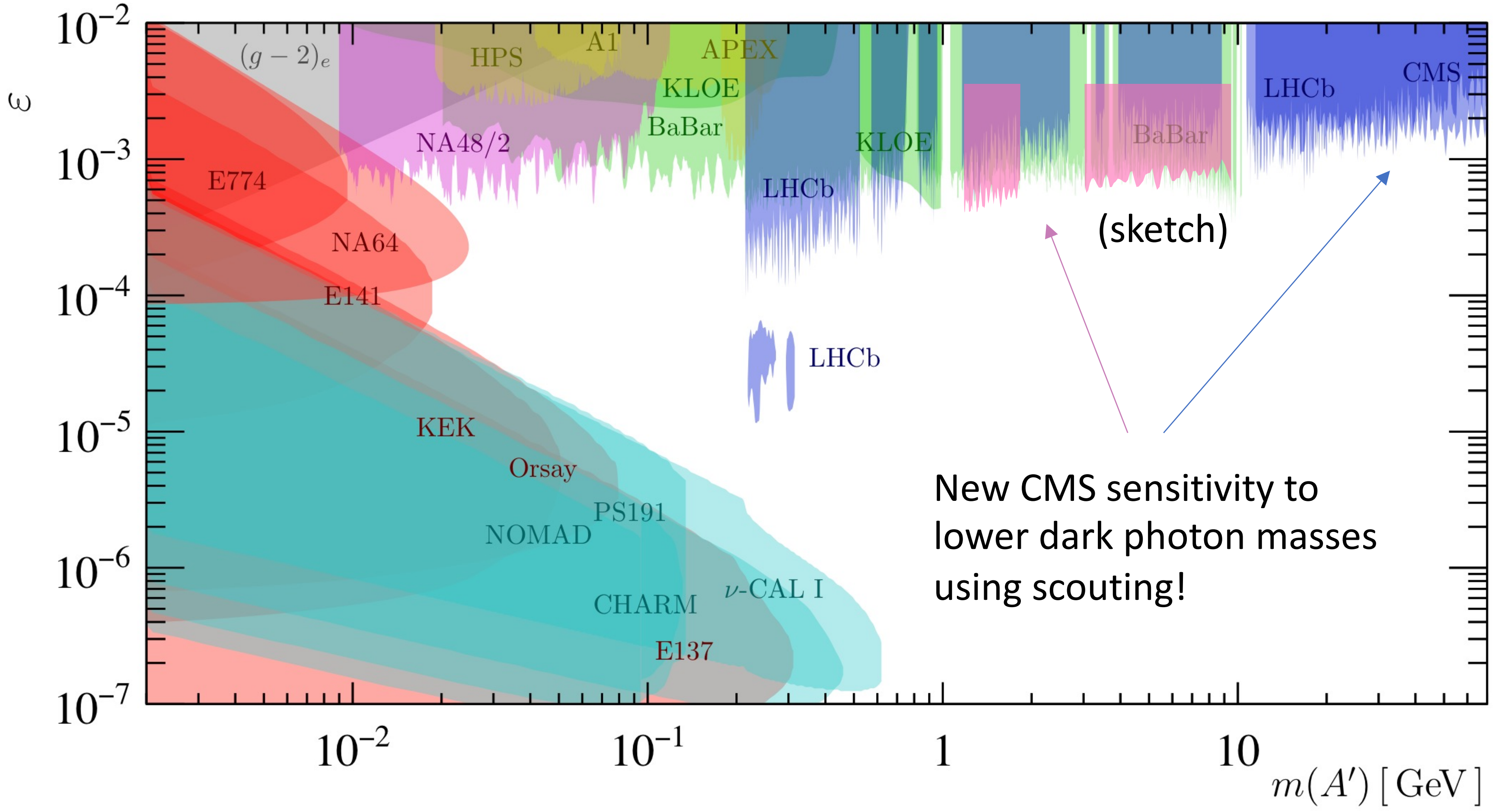
$$\sigma_{pp\to A'} \cdot \epsilon^2 \cdot B \cdot A = \sigma_{\text{limit}}$$

$$\sigma_{pp\to a} \cdot \sin^2(\theta_H) \cdot B \cdot A = \sigma_{\text{limit}}$$





“Updated” dark photon map



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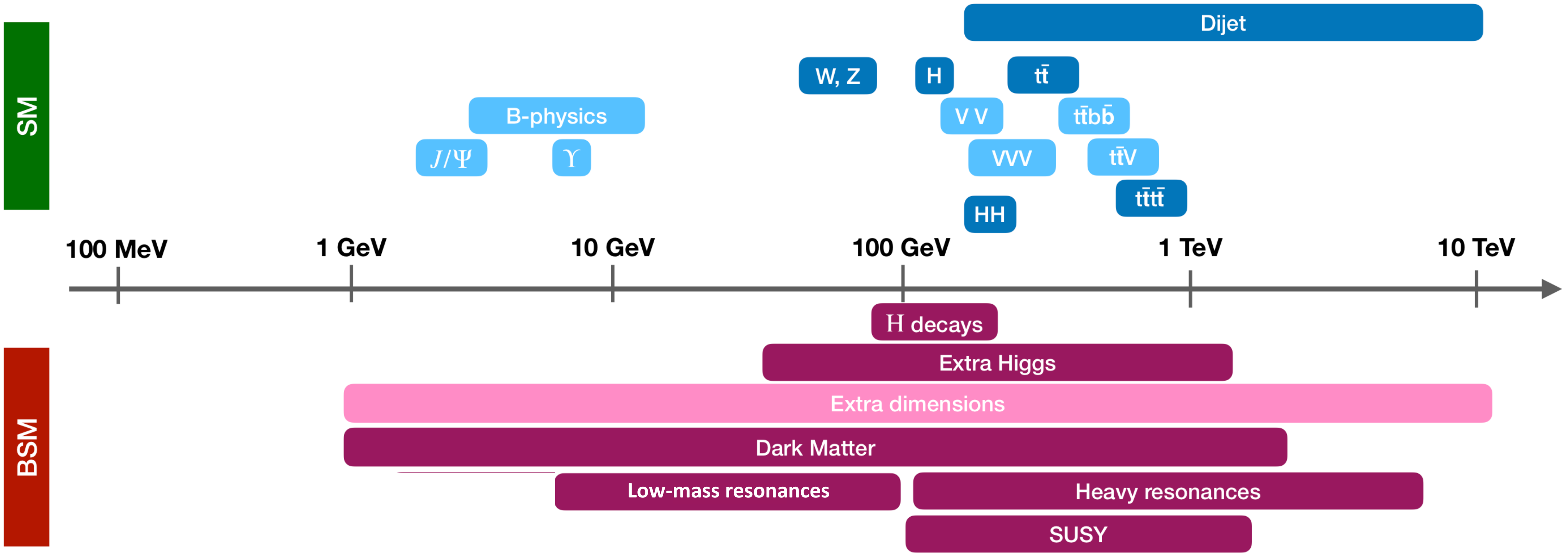
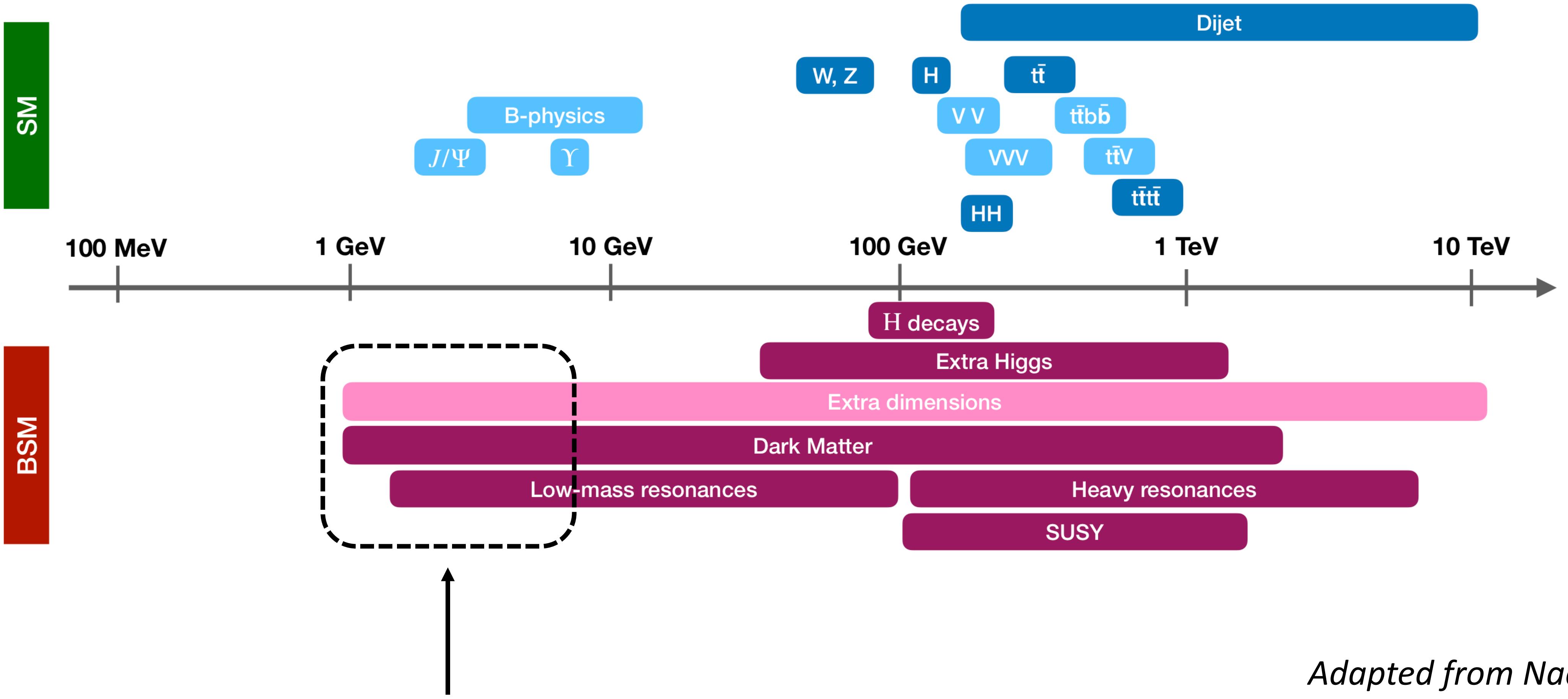
LHC can access a vast range of mass scales



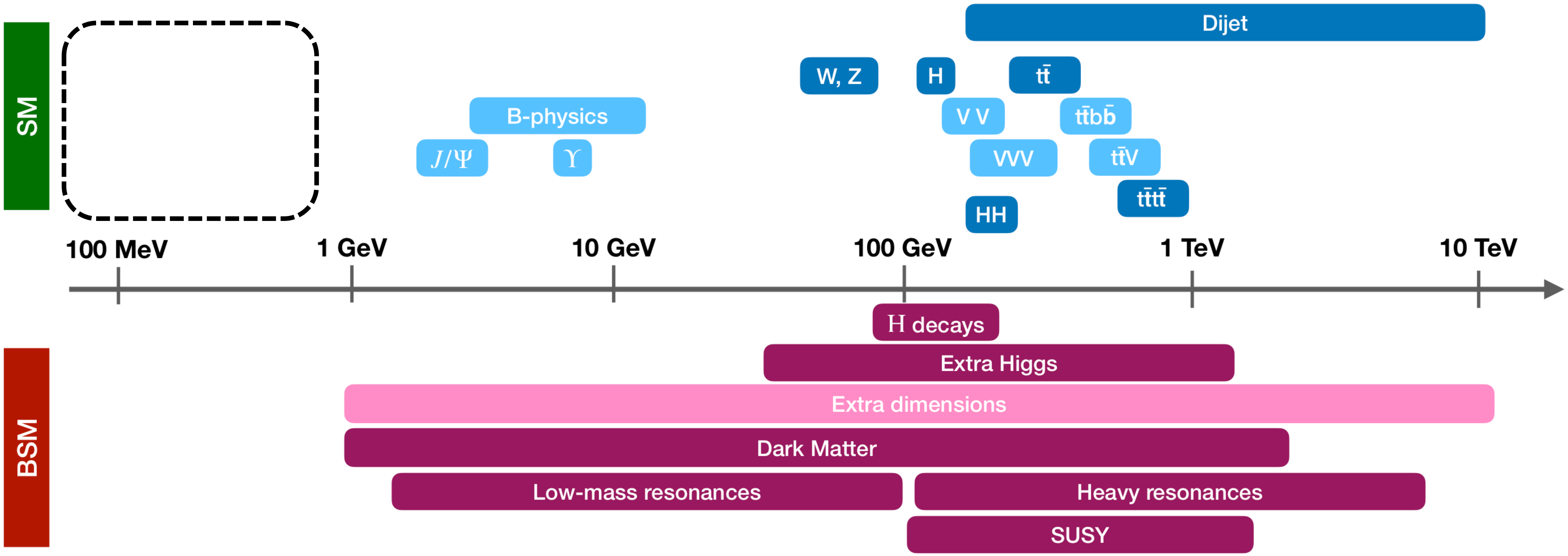
Adapted from Nadja Strobbe

LHC can access a vast range of mass scales



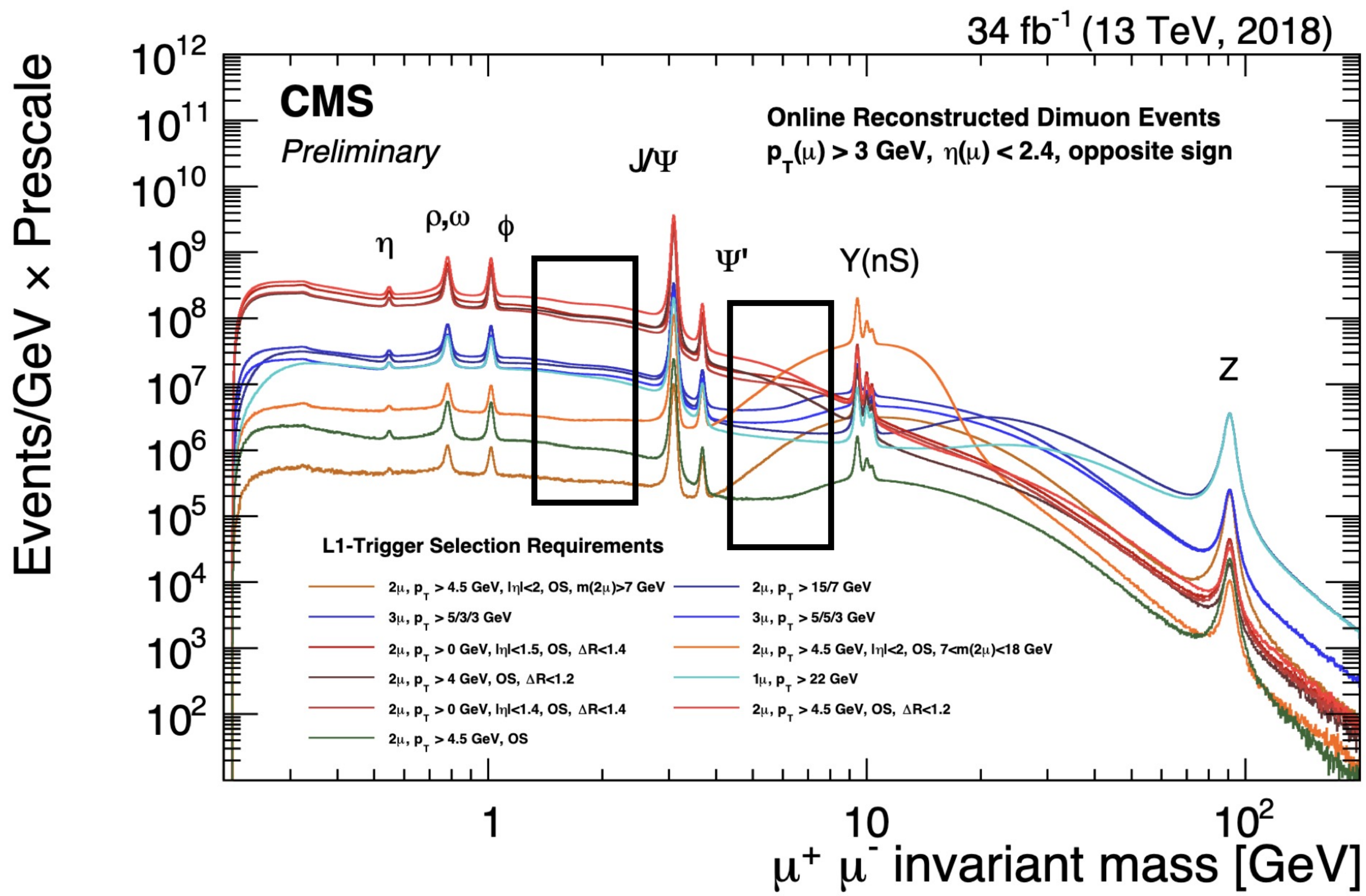
Adapted from Nadja Strobbe

Can we go even lower in mass?



Adapted from Nadja Strobbe

Dimuon mass spectrum with scouting

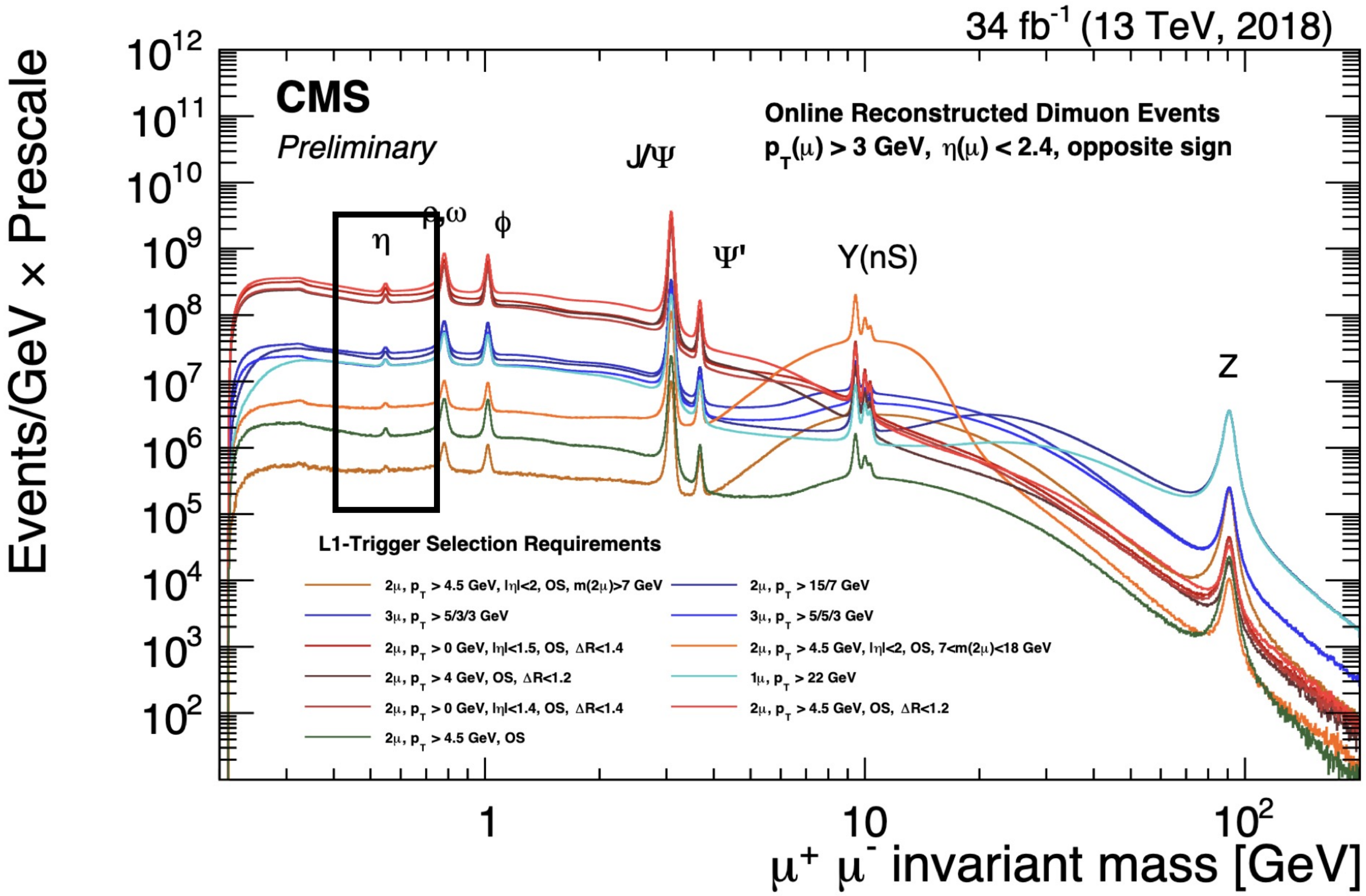


- Most important L1 selections:

L1 path	p_T [GeV]	$\lvert\eta\rvert$	ΔR	$m_{2\mu}$ [GeV]	Charge
#1	>4.0 (4.5)	–	<1.2	–	OS
#2	–	< 1.5	< 1.4	–	OS
#3	>15, >7	–	–	–	–
#4	>4.5	< 2.0	–	7–18	OS

- Can we use this neat spectrum to search for new physics with low masses?

Dimuon mass spectrum with scouting



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#3	>15, >7	–	–	–	–
#4	>4.5	< 2.0	–	7–18	OS

- Can we use this neat spectrum to search for new physics with low masses?

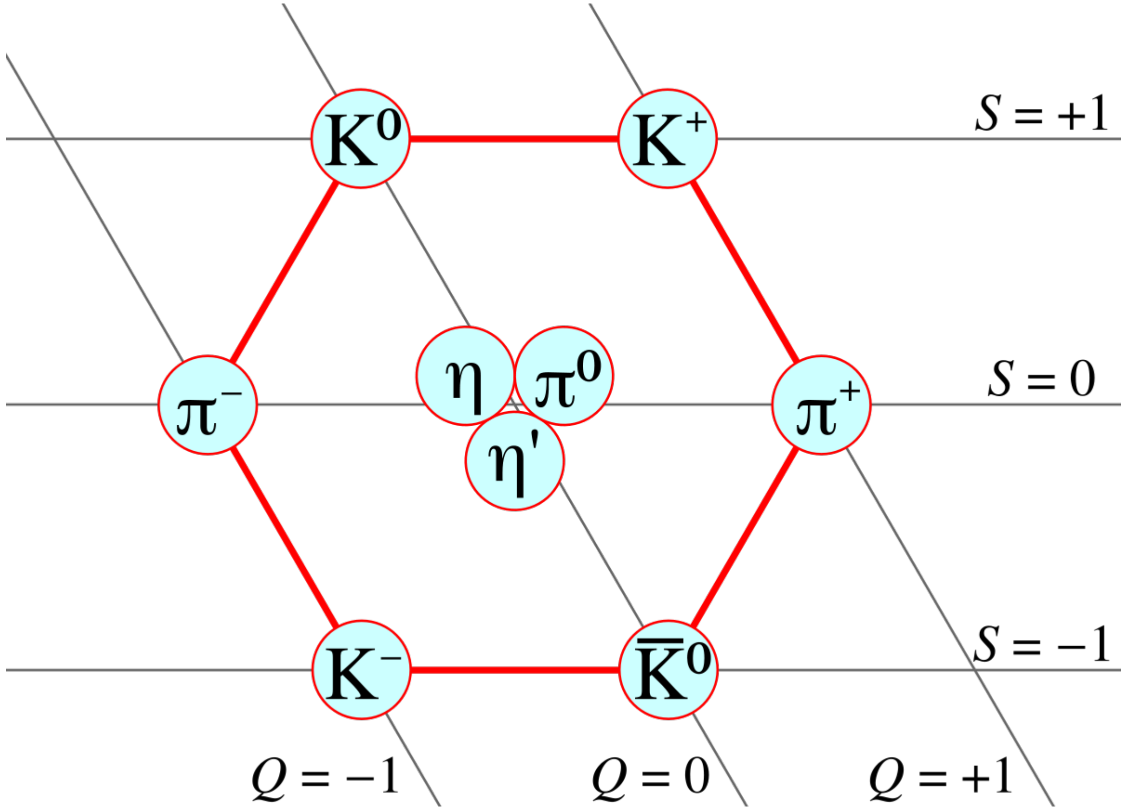
The η and η' mesons

- Neutral pseudoscalars like π^0
- S = Q = I = J = L = 0 → $I^G(J^{PC}) = 0^+(0^{-+})$
- Mixing of all light quark states:

$$\eta = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

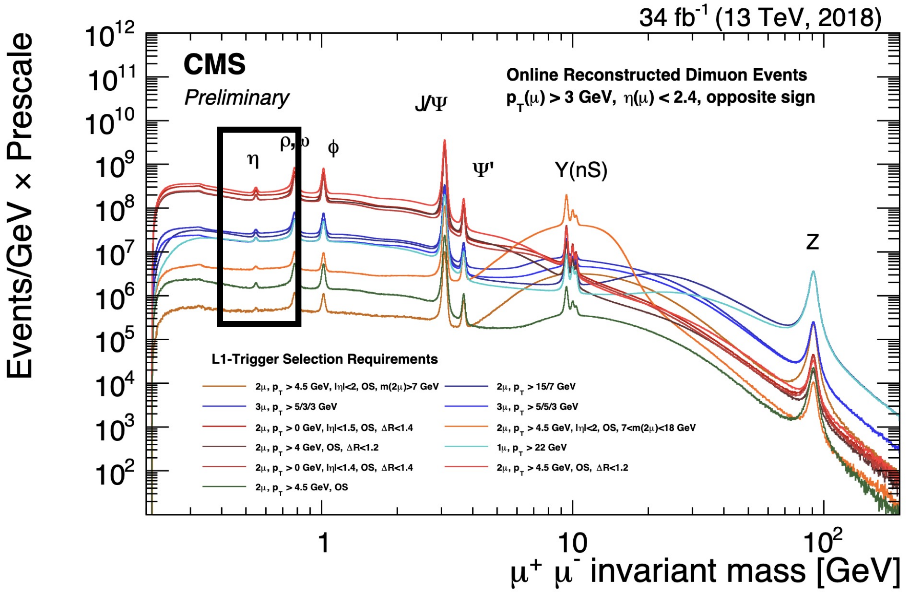
$$\eta' = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$

- Masses / widths:
  - η : 547.9 MeV / 0.0013 MeV
  - η': 957.8 MeV / 0.2 MeV
- Mixing angle estimated at 11.5%



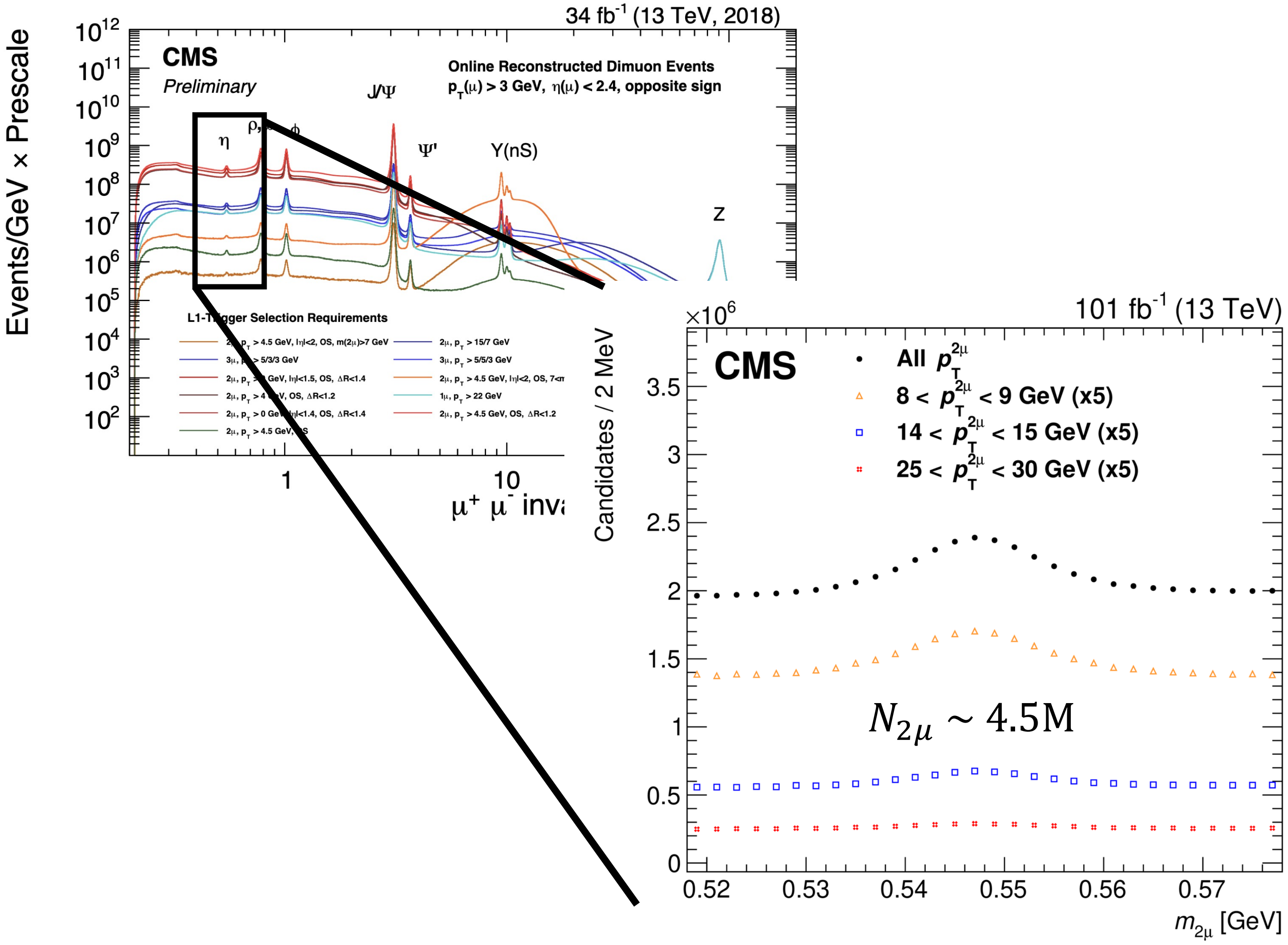
η production at the LHC

- The η meson is copiously produced in pp scattering at the LHC
- Clearly visible peak in the dimuon invariant mass spectrum with scouting dataset



η production at the LHC

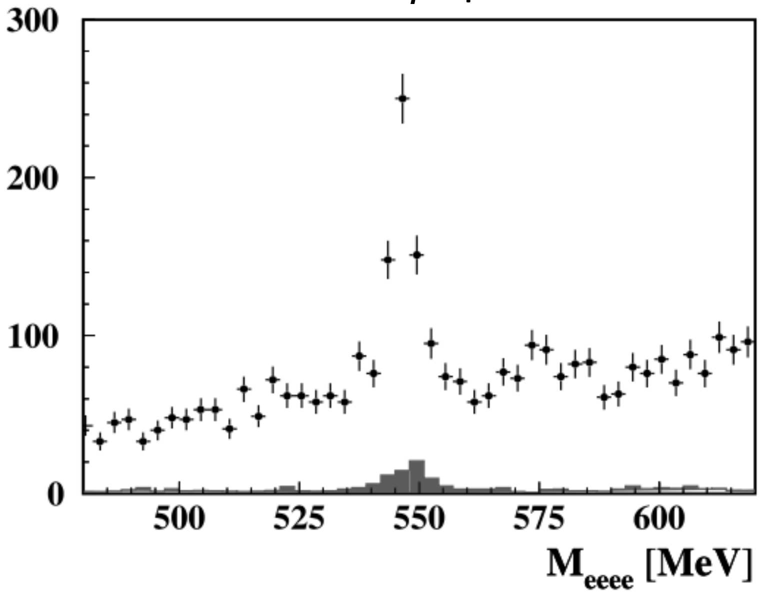
- The η meson is copiously produced in pp scattering at the LHC
- Clearly visible peak in the dimuon invariant mass spectrum with scouting dataset
- Fitting gives about 4.5M $\eta \rightarrow \mu\mu$ in this dataset
- B($\eta \rightarrow \mu\mu$) = $5.8(0.8)\times10^{-6}$, so there are a lot of $\eta's$ ($\sim10^{12}$)



Some context

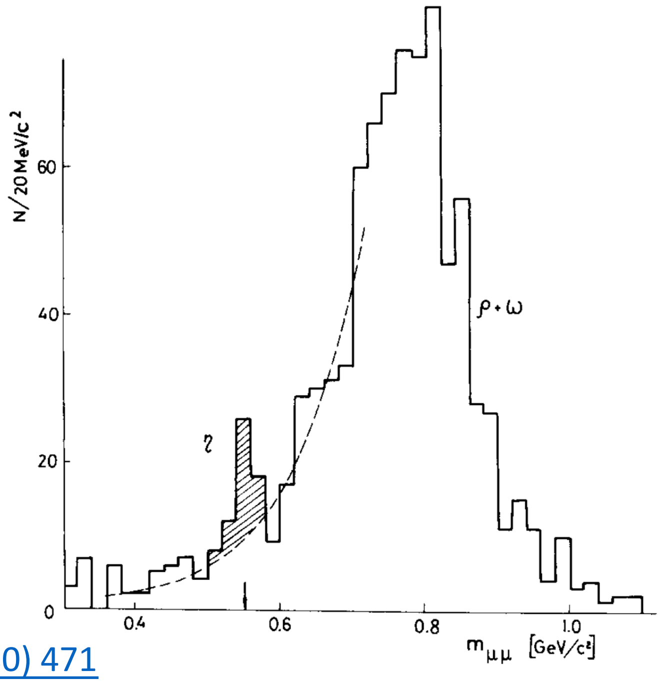
- CMS is competitive with several past, current and planned experiments dedicated to light meson physics:

KLOE $\eta \rightarrow 4e$ observation (2011)
$\sim 5 \times 10^7$ η's produced



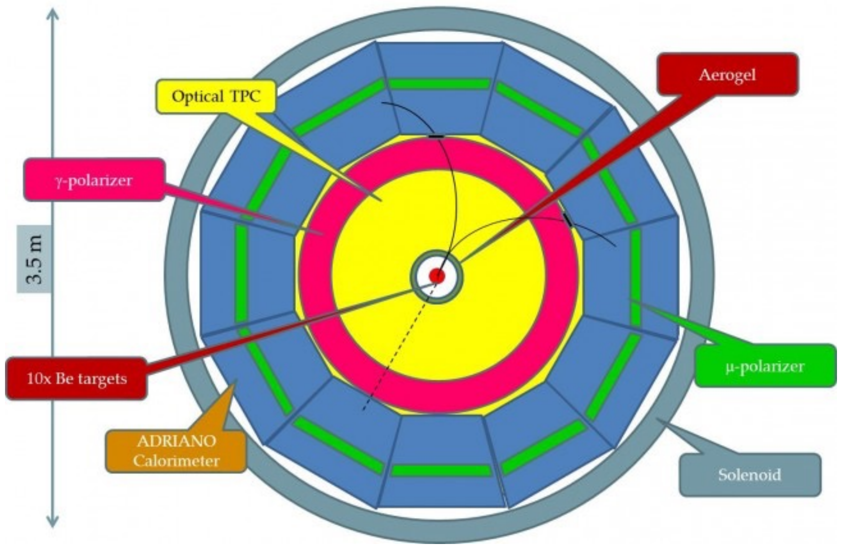
[PLB 702 (2011) 324](PLB 702 (2011) 324)

SEPR $\eta \rightarrow 2\mu$ observation (1980)
$\sim 2 \times 10^7$ η's produced



PLB 97 (1980) 471

REDTOP experiment at Fermilab
$\sim 10^{13}$ η's / year proposed



https://redtop.fnal.gov

Rare radiative decays of the η meson

- This huge η sample makes one contemplate the study of rare η decays

PDG

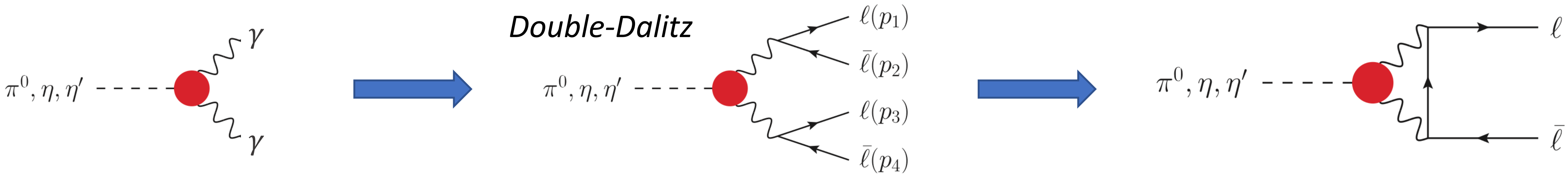
Charged modes

Γ_8	charged modes	(27.89 ± 0.29) %	S=1.2
Γ_9	$\pi^+ \pi^- \pi^0$	(22.92 ± 0.28) %	S=1.2
Γ_{10}	$\pi^+ \pi^- \gamma$	(4.22 ± 0.08) %	S=1.1
Γ_{11}	$e^+ e^- \gamma$	$(6.9 \pm 0.4) \times 10^{-3}$	S=1.3
Γ_{12}	$\mu^+ \mu^- \gamma$	$(3.1 \pm 0.4) \times 10^{-4}$	
Γ_{13}	$e^+ e^-$	$< 7 \times 10^{-7}$	CL=90%
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%

Never observed directly, predictions: $B_{4\mu} \sim 4 \times 10^{-9}$ and $B_{2\mu 2e} \sim 2.4 \times 10^{-6}$

Rare radiative decays of the η meson

- This huge η sample makes one contemplate the study of rare η decays
- Rich phenomenological motivation exists in the literature



- Refine η-η' mixing angle and transition form factors $F_{\eta\gamma\gamma}(q_1^2, q_2^2)$ for $q_1, q_2 \neq 0$:

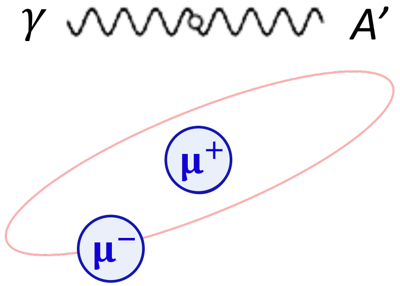
$$F_{\eta\gamma\gamma} = \frac{1}{4\sqrt{3}\cos(\theta_8 - \theta_0)\pi^2}\left[\frac{\cos\theta_0}{F_8} - \frac{2\sqrt{2}\sin\theta_8}{F_0}\right]$$

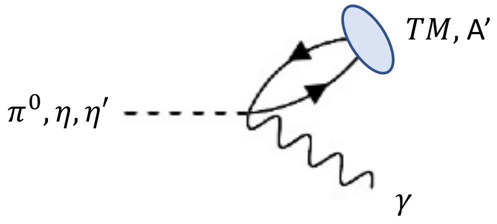
2007.00664

Eur. Phys. J. C (2015) 75:414

- Search for new SM and BSM states:

Dark photon / X17 2009.05578



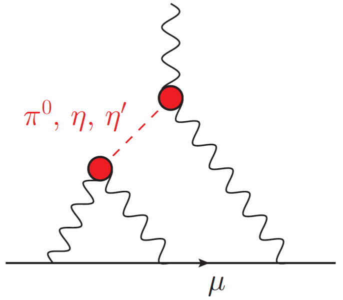


True Muonium (TM)

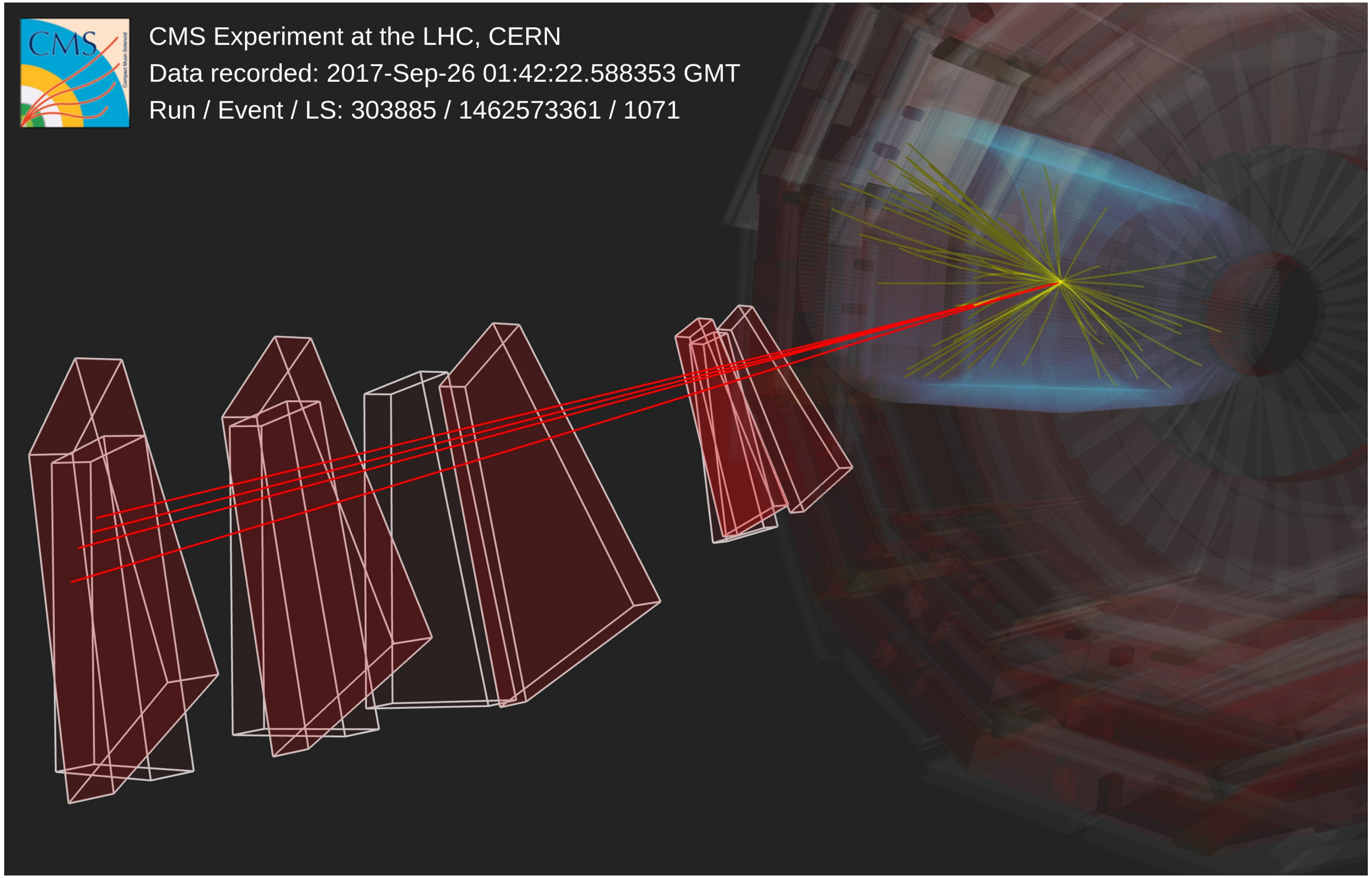
PRD 100 (2019) 053003

- Measure hadronic contribution to light-by-light scattering, relevant to the muon g-2:

2007.00664

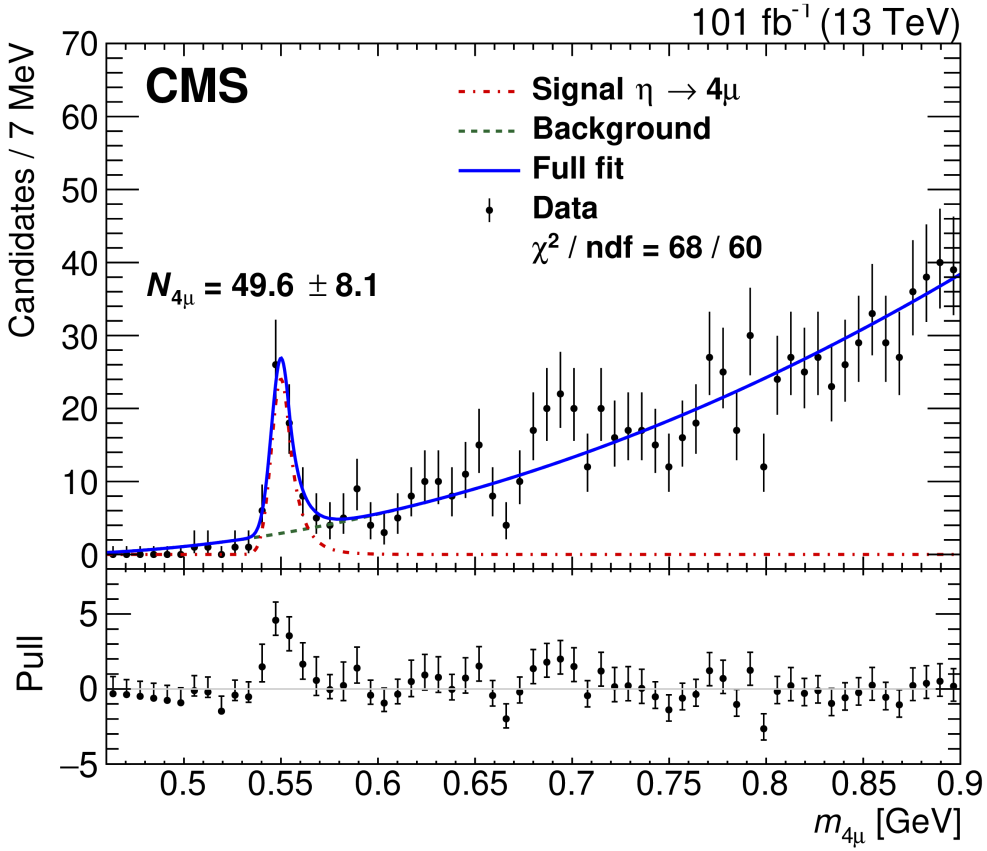


A candidate $\eta \rightarrow 4\mu$ decay!



$m_{4\mu}$ in the scouting data

- Peak clearly seen at 0.548 GeV
- $> 10\sigma$ statistical significance



Branching fraction measurement

- Use reference channel $\eta \rightarrow \mu\mu$ to measure target channel $\eta \rightarrow \mu\mu\mu\mu$
- B$(\eta \rightarrow 2\mu) = (5.8 \pm 0.8)\times 10^{-6}$, a precision of 13.8%
- Also need to measure the CMS acceptance to decays in simulation

Extracted from data

Extracted from MC

Experimental input

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

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

CMS acceptance to $\eta \rightarrow 4\mu$ in bins of p_T and η

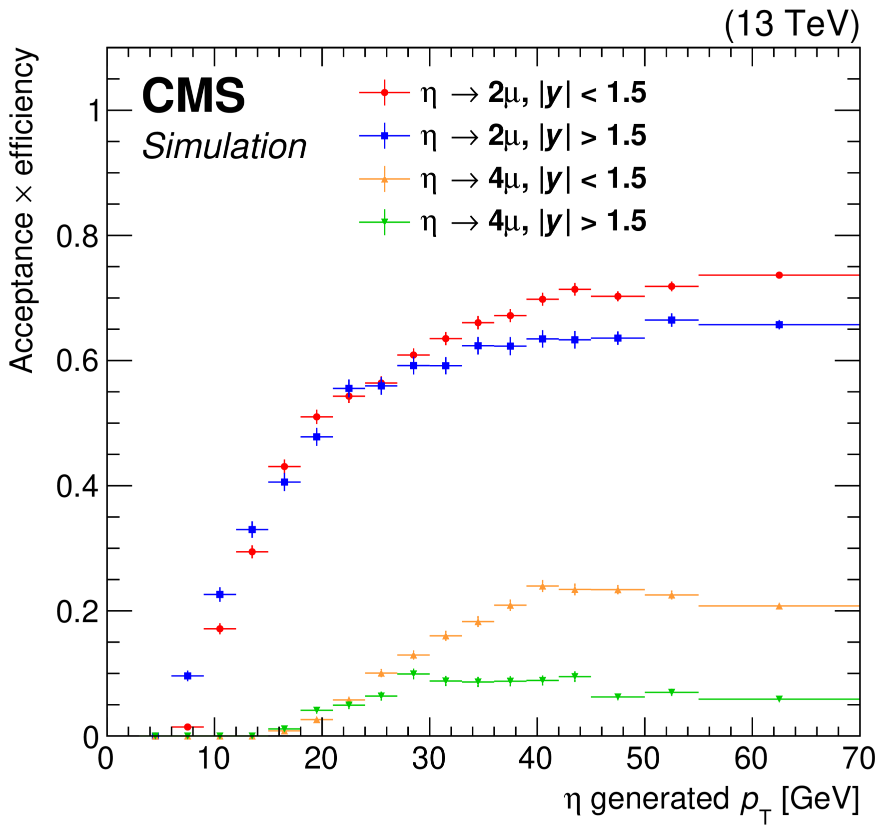
Experimental input

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

CMS acceptance to $\eta \rightarrow 2\mu$ in bins of p_T and η

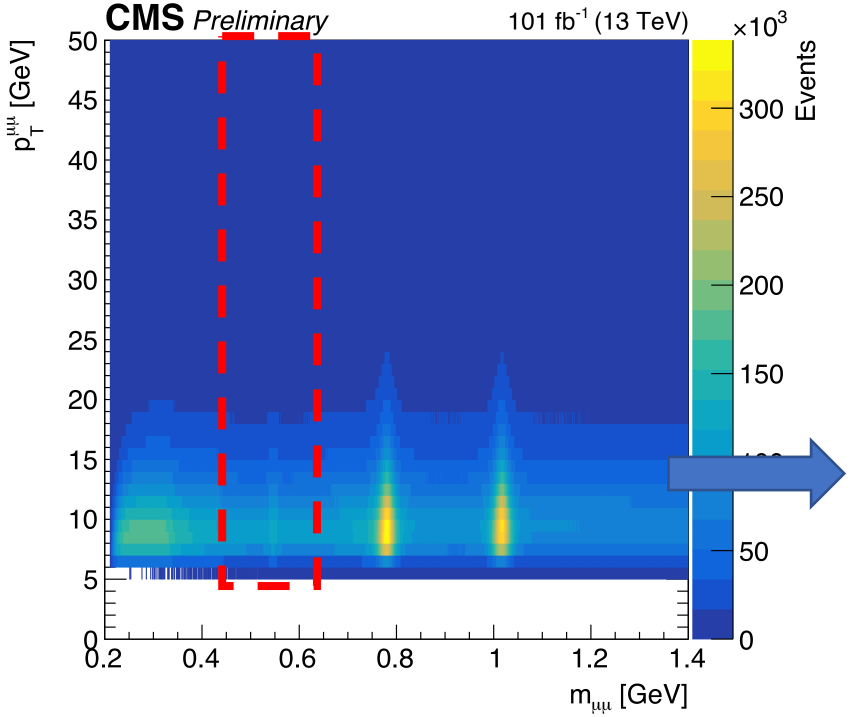
$A_{4\mu}^{i,j}$ and $A_{2\mu}^{i,j}$ acceptances

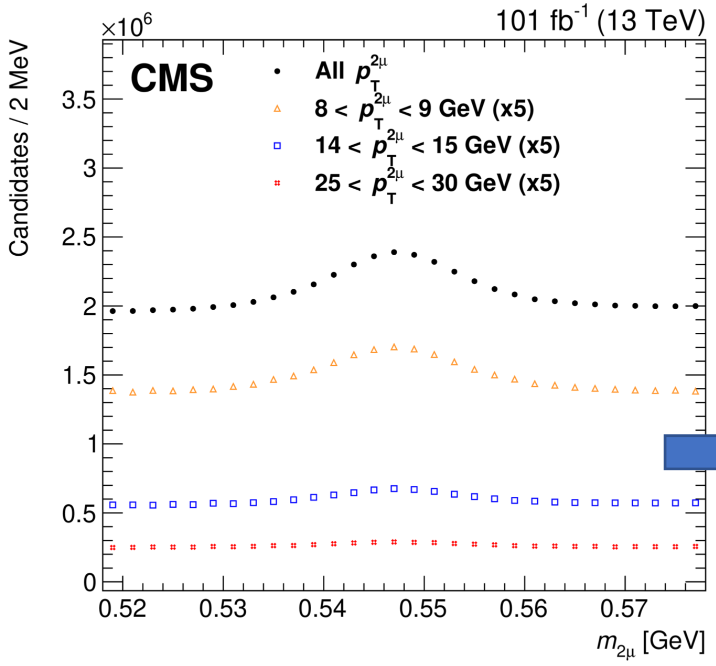
- Measured from MC simulation with $\sim 1k$ events per GeV of p_T
- Acceptance: all muons are compatible with beam spot and at least one vertex in the event
- Mostly limited by scouting trigger efficiency in 2μ channel, and by reconstruction efficiency of all four muons in 4μ channel
- Acceptance goes to zero around $p_T^{2\mu} \sim 8$ GeV and $p_T^{4\mu} \sim 14$ GeV

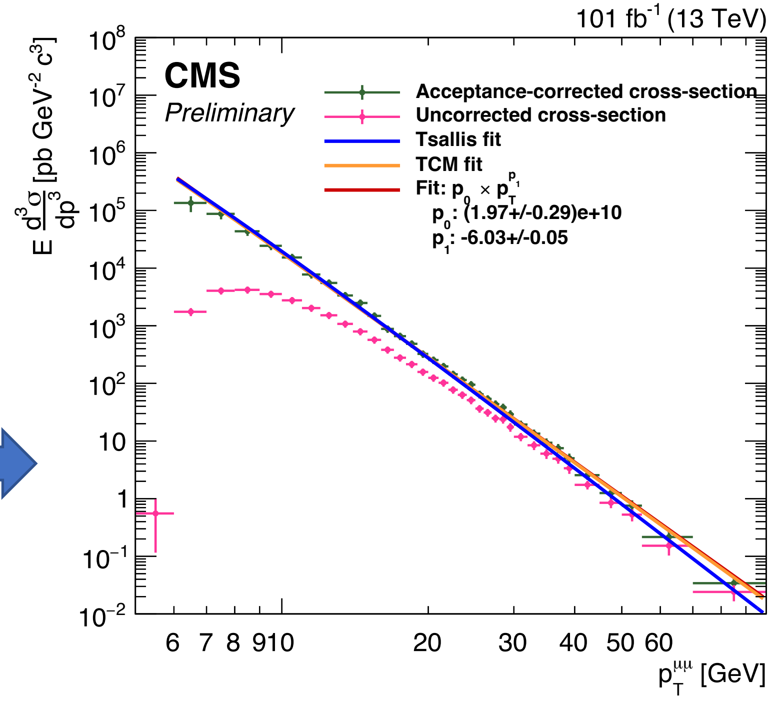


$N_{2\mu}^{i,j}$ signal extraction

- Extract $N_{2\mu}^{i,j}$ and derive $d\sigma/dp_T$ of the η from fits of $m_{\mu\mu}$ spectrum per $p_T^{\mu\mu}$ bin
- Agreement with ALICE measurement (done to $p_T^{\mu\mu} \sim 40$ GeV only) is robust after accounting for acceptance



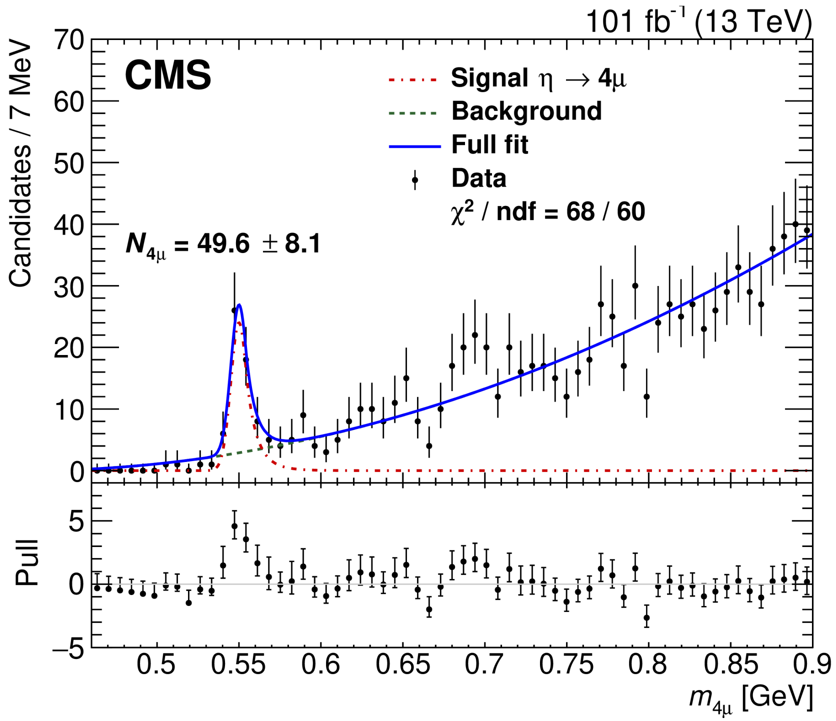




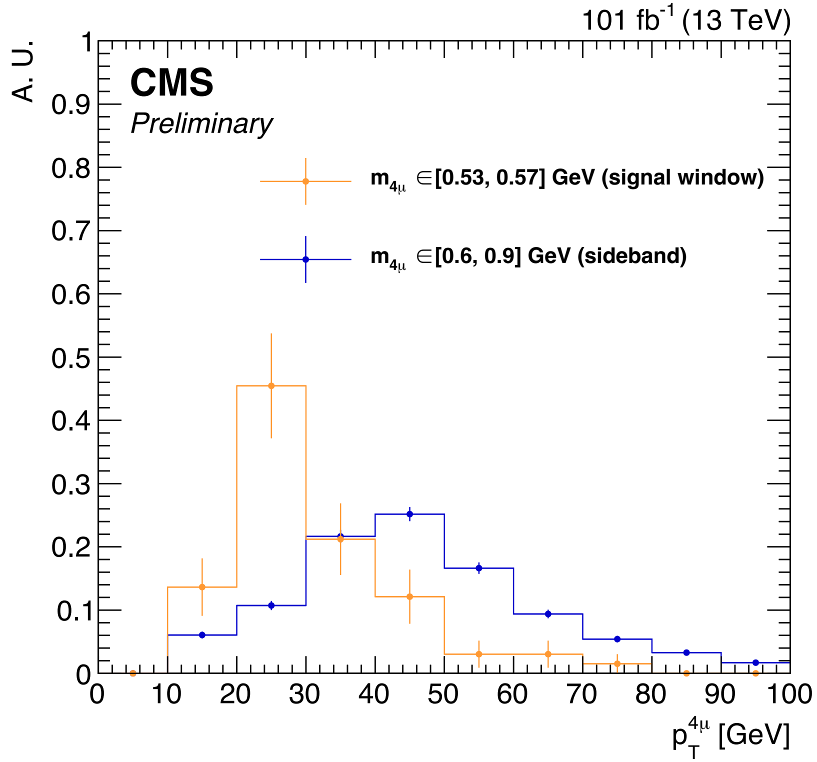
Eur. Phys. J. C 78 (2018) 263

$N_{4\mu}$ signal and non-resonant background

- Fit $m_{4\mu}$ spectrum to extract signal ($N_{4\mu} = 50$) and bkg. (17) yields
- Use sideband (0.6–0.9 GeV) and signal MC to study $p_T^{4\mu}$ spectrum



signal window sideband

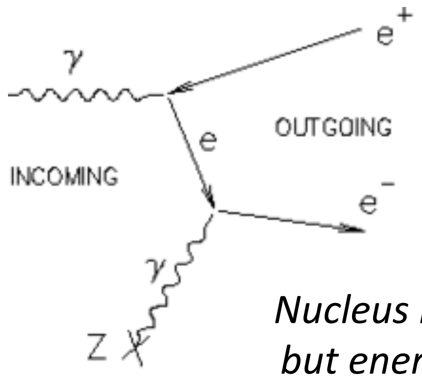


Resonant backgrounds

- Studied several other decay modes as potential resonant backgrounds
  - Via toy MC simulations reproducing approximate expected kinematics
- Conclusion: no other modes can mimic the observed peak

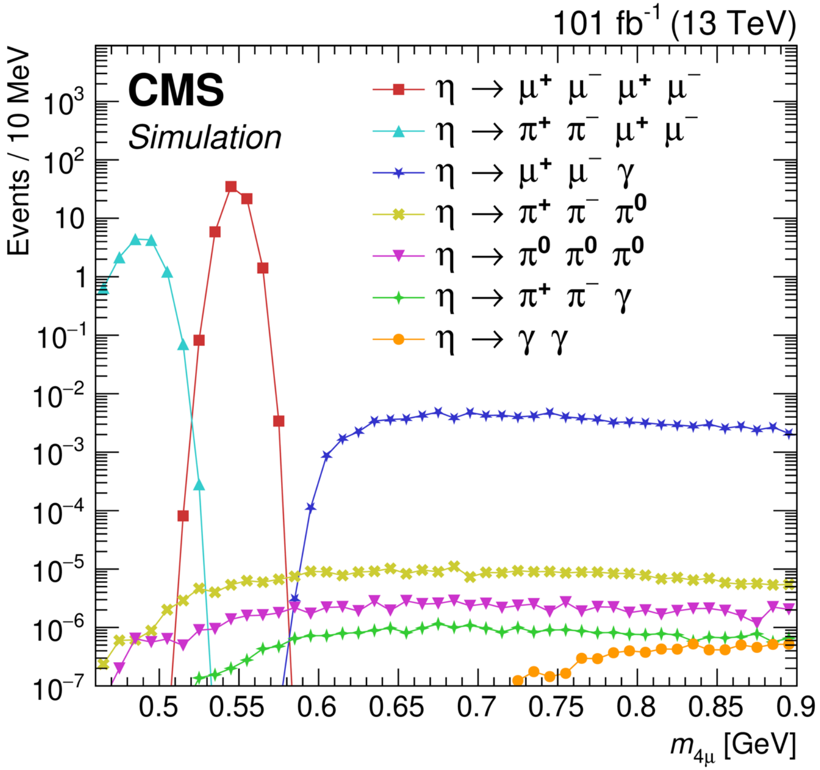
Photon conversions:

$M_\gamma = 0$

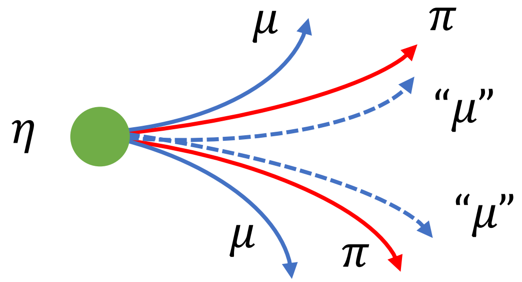


$M_{\mu\mu} > 2m_\mu$

Nucleus imparts p_T kick, but energy is conserved



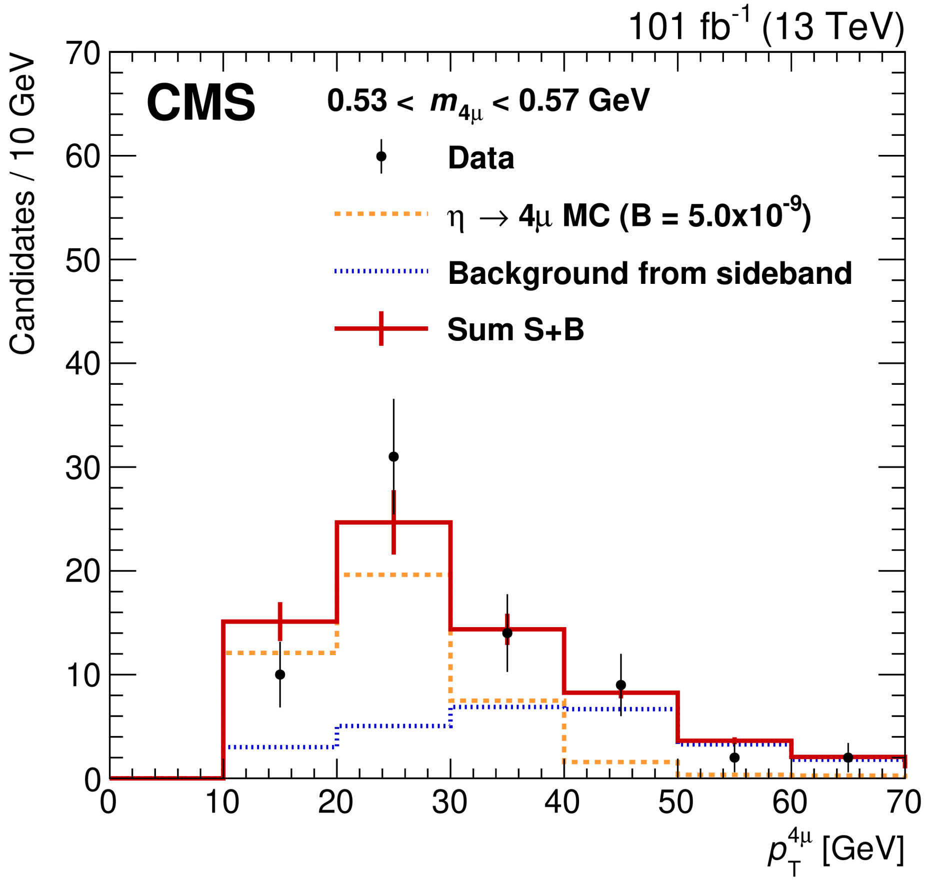
Pion misidentification:



Mass peak shifts by ~40 MeV for each mis-ID'd pion

Non-resonant background and $p_T^{4\mu}$

- Can use sideband p_T spectrum in data and signal MC to predict yields in signal region
- Very good agreement between data and MC → no indication of systematic issues with MC-estimated acceptance across the p_T range



Uncertainties

- Uncertainties are roughly balanced between statistical (14.9%), systematic (14.3%) and on $\mathrm{B}(\eta \rightarrow 2\mu)$ (13.8%)
- Main systematic uncertainties:
  - Imperfect knowledge of the acceptance curves from simulation
  - Different fit model choices when extracting the yields
- Relative uncertainty estimate on $\mathrm{B}(\eta \rightarrow 4\mu)/\mathrm{B}(\eta \rightarrow 2\mu)$ is **22%**
- Absolute uncertainty estimate on $\mathrm{B}(\eta \rightarrow 4\mu)$ is **26%**
- (Details in backup)

Branching fraction measurement

- Relative branching fraction:

$$\frac{B(\eta \to 4\mu)}{B(\eta \to 2\mu)} = \left(0.86 \pm 0.14\,(\text{stat.}) \pm 0.12\,(\text{syst.})\right)\times 10^{-3} = (0.9 \pm 0.1)\times 10^{-3}$$

- Absolute branching fraction:

$$\text{B}(\eta \to 4\mu) = \left(5.0 \pm 0.8\,(\text{stat.}) \pm 0.7\,(\text{syst.}) \pm 0.7\,(\text{B}_{2\mu})\right)\times 10^{-9}$$

arXiv:2305.04904 (accepted by PRL)

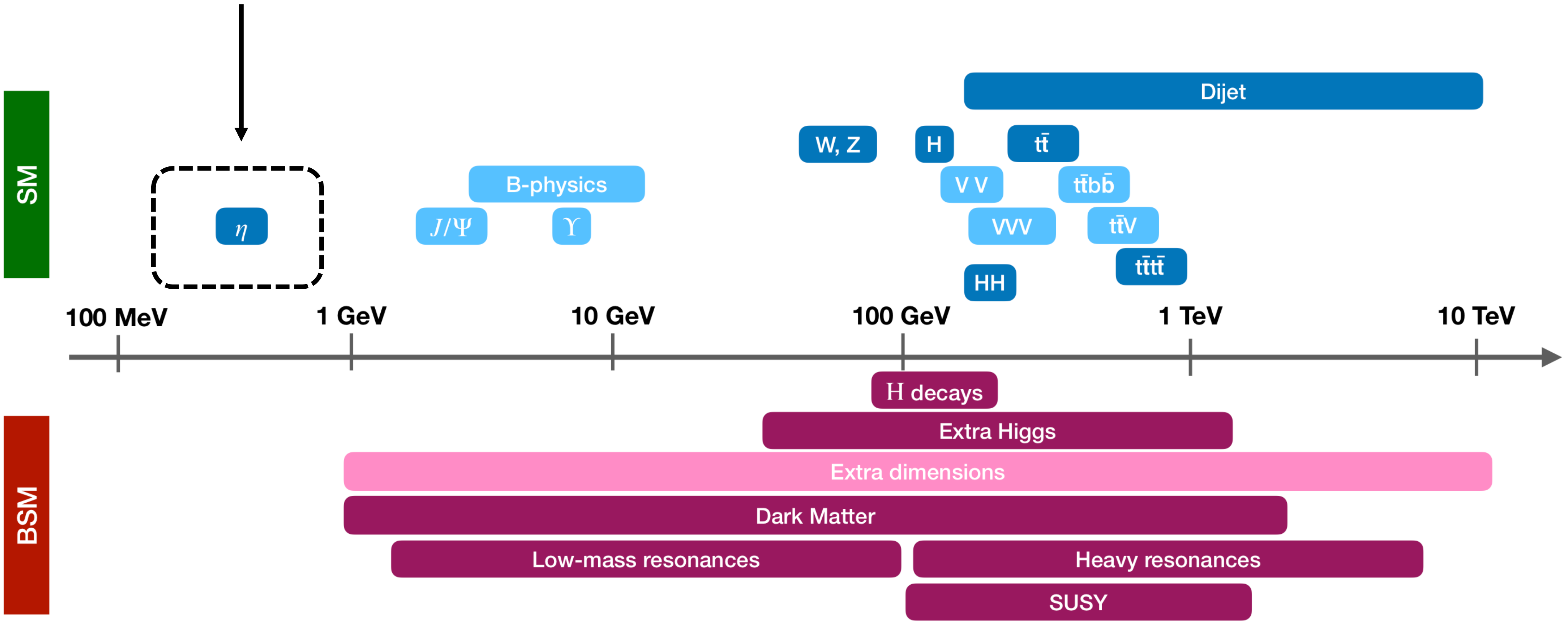
$$\boldsymbol{B(\eta \to 4\mu) = (5.0 \pm 1.3)\times 10^{-9}}$$

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

Chin. Phys. C 42 (2018) 023109

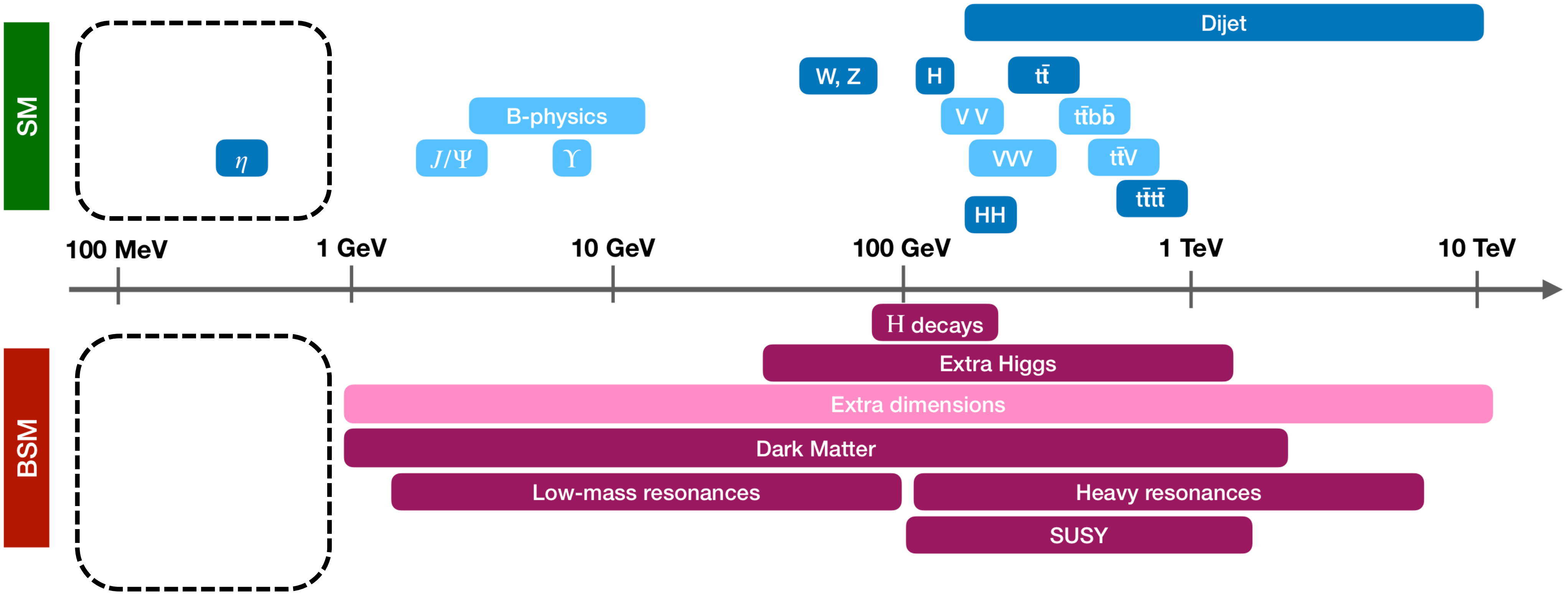
- Represents an improvement of **over 5 orders of magnitude** over previous measurement: $B(\eta \to 4\mu) < 3.1\times 10^{-4}$

CMS is sensitive to low-mass physics!



Adapted from Nadja Strobbe

But could we go **even** lower in mass??



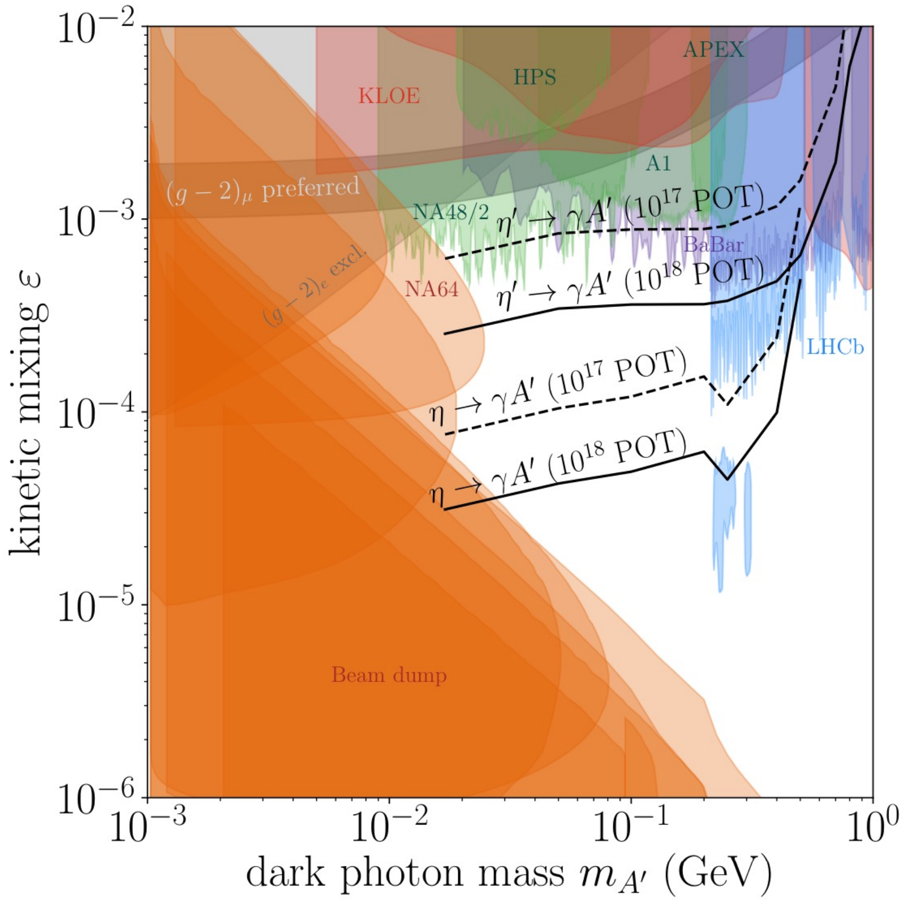
Adapted from Nadja Strobbe

Scouting in Run 3 and beyond

- Several improvements in scouting for Run 3 (2022 – present):
  - **HLT speed**:
    - Accelerate pixel tracking and calorimeter reconstruction with GPUs
    - Running overall HLT scouting reconstruction in Run 3 at **~ 30 kHz** (350 MB/s)
  - **Event content**:
    - Reconstruct and store more information per event, while keeping size stable
    - Now include in Run 3 **electrons** and **photons**, and possibility of **missing transverse momentum**
    - Event size remains small (~ 6 KB after compressions)
  - **L1 rate**:
    - For HL-LHC (Run 4, ~ 2028), L1 trigger will feature much improved resolution
    - → Opportunity for L1 scouting at close to full LHC rate!

Search for dark photons with the η

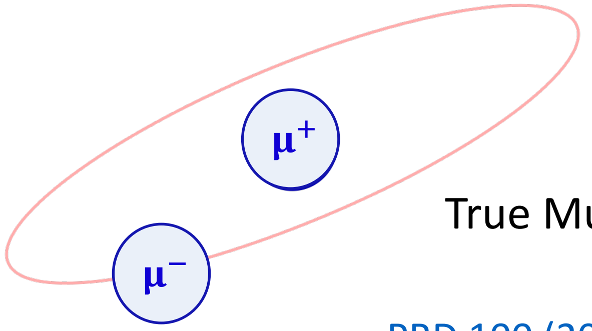
- Proposed REDTOP experiment at Fermilab (10^{18} POT) or CERN (10^{17} POT) is sensitive to dark photons
- Each scenario corresponds to about 10^{13} (10^{12}) η / year
- CMS has about 5×10^{12} η in 2 years of Run 2 scouting ($100\ \mathrm{fb}^{-1}$)
  - We are an η factory!
- Challenge in Run 3 is to reconstruct $A'\rightarrow e^+e^-$ and the photon in $\eta\rightarrow\gamma A'$ with scouting or parking to reach below $m_A' \sim 200$ MeV
- But $m_{A'} > 200$ MeV may be feasible with current setup



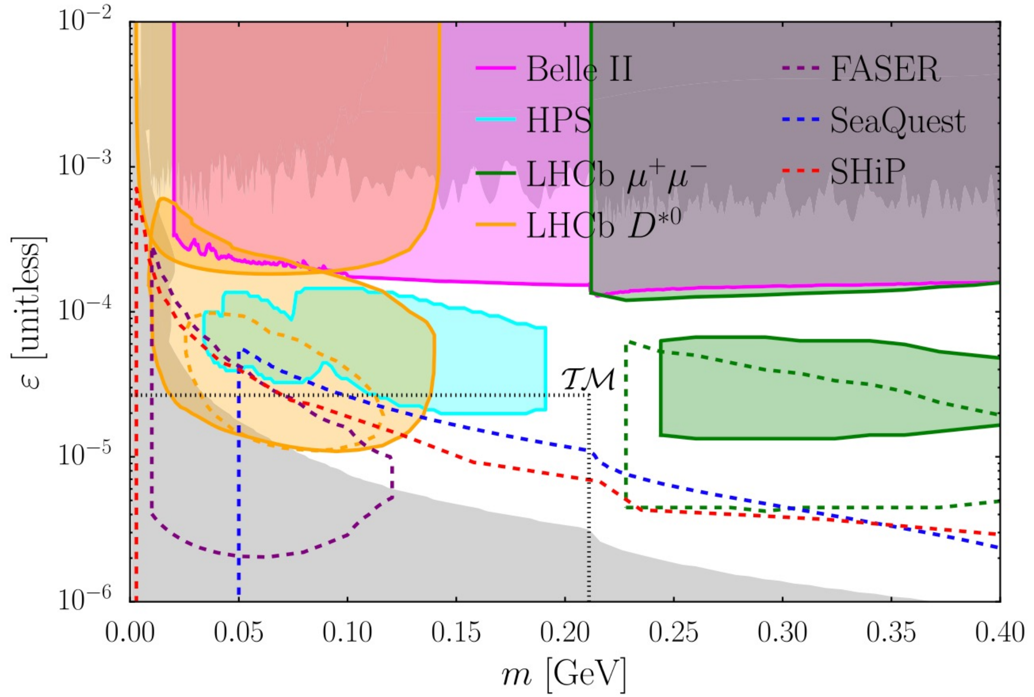
arXiv:2203.07651

Search for True Muonium ™

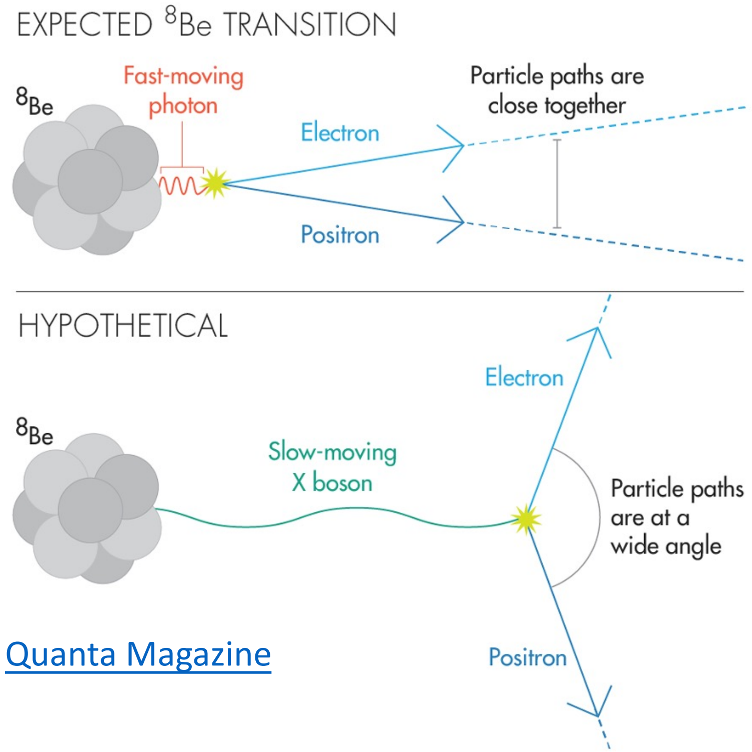
- True muonium is a bound state of two muons, never observed (unlike muonium, a μe bound state)
- Predicted branching ratio of $\eta \to \gamma\, TM$ is $\sim 10^{-10}$-10^{-9}
- Main decay mode is e^+e^-, but also dissociates to two muons in material
- Use displaced ee vertex (with material veto) to isolate signal, plus photon
- Might be possible in CMS with B-parking dataset (see projected LHCb limits)



PRD 100 (2019) 053003

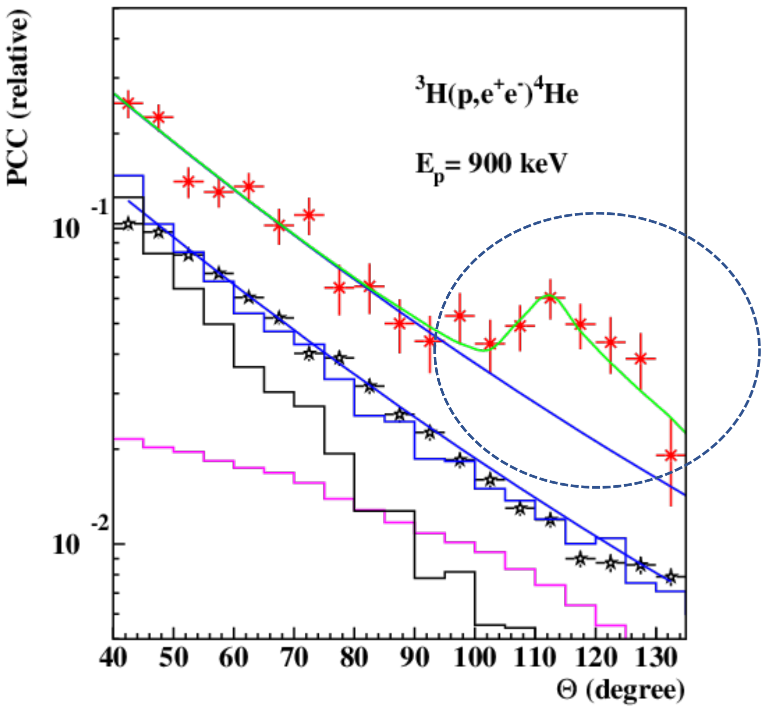


X17 search and resonant production

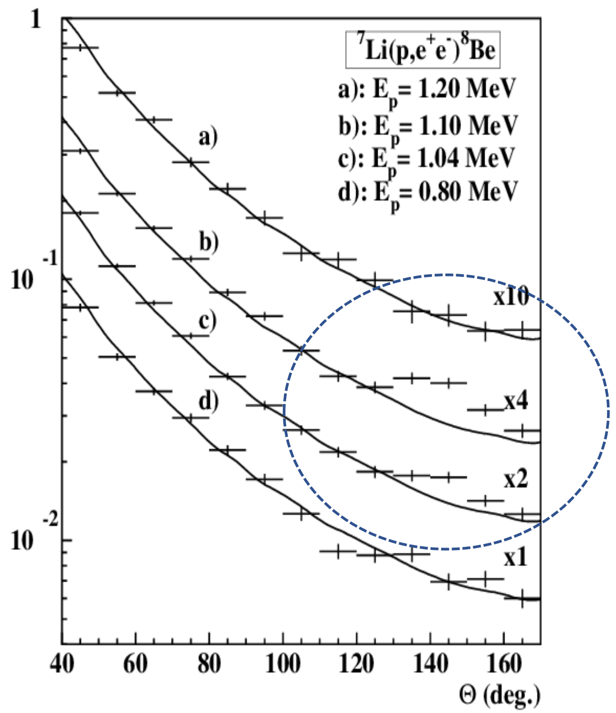


Quanta Magazine

Krasznahorkay et al, PRC 104 (2021) 44003



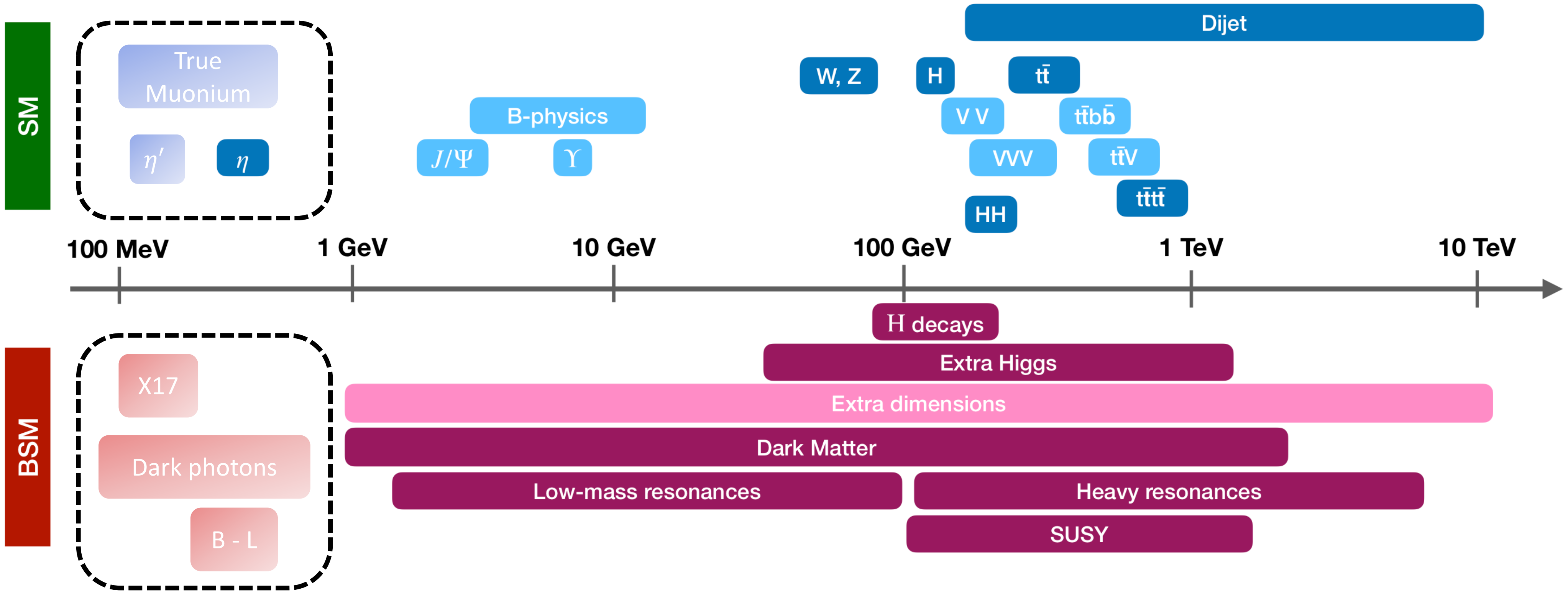
Krasznahorkay et al, PRL 116 (2016) 042501



- Recent results indicate anomalous excesses in ^{4}He and ^{8}Be atomic measurements of internal pair creation
- A possible explanation is the existence of a new proto-phobic boson with 16.7 MeV mass (X17)
- Could potentially look for $\eta \rightarrow \gamma\ X17 \rightarrow \gamma ee$ but will depend on electron acceptance

Feng et al, PRL 117 (2016) 078103

To be continued…



Adapted from Nadja Strobbe

Conclusions

- There's plenty of interesting physics at "low" masses!
- High-energy and **high-intensity** accelerators allow us to probe promising new physics scenarios also at these low masses
- Complex dark sectors could feature an array of light particles hidden from view, such as the dark photon and X17
- The data scouting and parking techniques employed by CMS are promising avenues to gain experimental sensitivity to rare and low-mass phenomena
- Two scouting results shown today: $\boldsymbol{\eta \to 4\mu}$ and **search for** $\boldsymbol{A'}$
- Stay tuned for more updates in this area soon!

Backup slides

Summary of uncertainties

- Absolute uncertainty estimate on $\mathrm{B}(\eta \to 4\mu)$ is **25.7%**
- Relative uncertainty estimate on $\mathrm{B}(\eta \to 4\mu)/\mathrm{B}(\eta \to 2\mu)$ is **21.7%**

Line	Source	Value (%)
1	Track p_{T} threshold	9.0
2	Trigger p_{T} threshold	8.4
3	Efficiency plateau	3.2
4	Fit signal model, $N_{4\mu}$	3.4
5	Fit background model, $N_{4\mu}$	4.2
6	Fit signal and background models, $N^{i}_{2\mu}$	3.8
7	Total systematic uncertainty	14.3
8	Statistical uncertainty	16.3
9	Total relative uncertainty	21.7
10	Uncertainty in $B(\eta \to 2\mu)$	13.8
11	Total absolute uncertainty	25.7

Extracting $N_{2\mu}^{i,j}$ signal

- Slice the spectrum into bins of p_T & η, then fit the invariant mass distribution $m_{\mu\mu}$ to obtain the $\eta \to 2\mu$ yield per p_T & η bins
- Fit MC signal first to obtain guidance on parameters
- Signal model in MC:
  - Double-Gaussian
- Sig. & bkg. models in data vary by p_T:

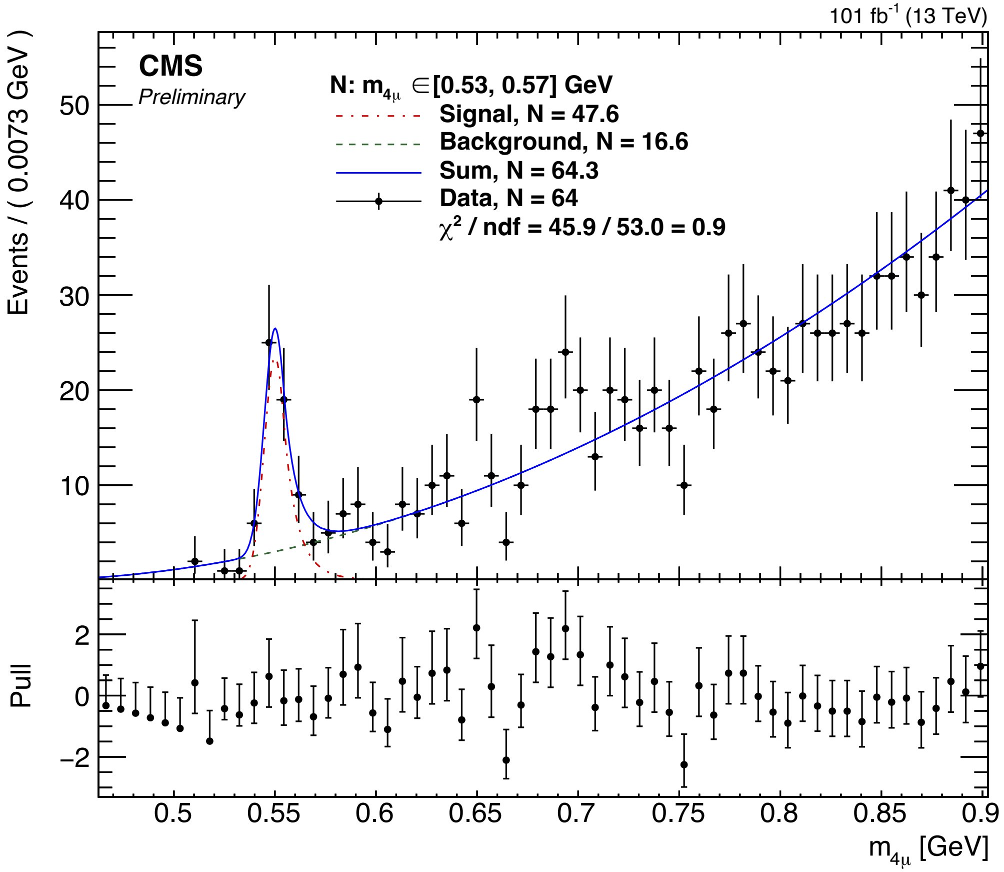
Table 3: Fit functions used in the 2-μ fits for various p_T ranges.

p_T range	Signal function	Background function
$(6, 8)$ GeV	Double-Gaussian (floating ratios)	Chebychev-3
$(8, 16)$ GeV	Double-Gaussian (fixed ratios)	Chebychev-3
$(16, 28)$ GeV	Single-Gaussian	Chebychev-3
$(28, 100)$ GeV	Single-Gaussian	Chebychev-2

Extracting $N_{4\mu}$ signal

- Fit MC signal first to fix parameters
- Signal model:
  - Crystal-Ball (CB) only (data); CB + Gaussian (MC)
  - Fix N_{CB} and α_{CB} from MC, float m_{CB} and s_{CB}
- Background model:
  - $f(x) = (x - 4m_\mu)^\beta$ (data)

Parameter	Best-fit value in MC	Best-fit value in data
β	–	1.97 ± 0.11
m_0	0.550 ± 0.0004	0.550 ± 0.001 GeV
σ	0.0049 ± 0.0004	0.0053 ± 0.0008 GeV
α	-0.83 ± 0.10	fixed (-0.83)
N	8.1 ± 9.3	fixed (10)
$\mathcal{N}_{sig}$	–	49.9 ± 8.4
$\mathcal{N}_{bkg}$	–	906.1 ± 30.5



Resonant background studies

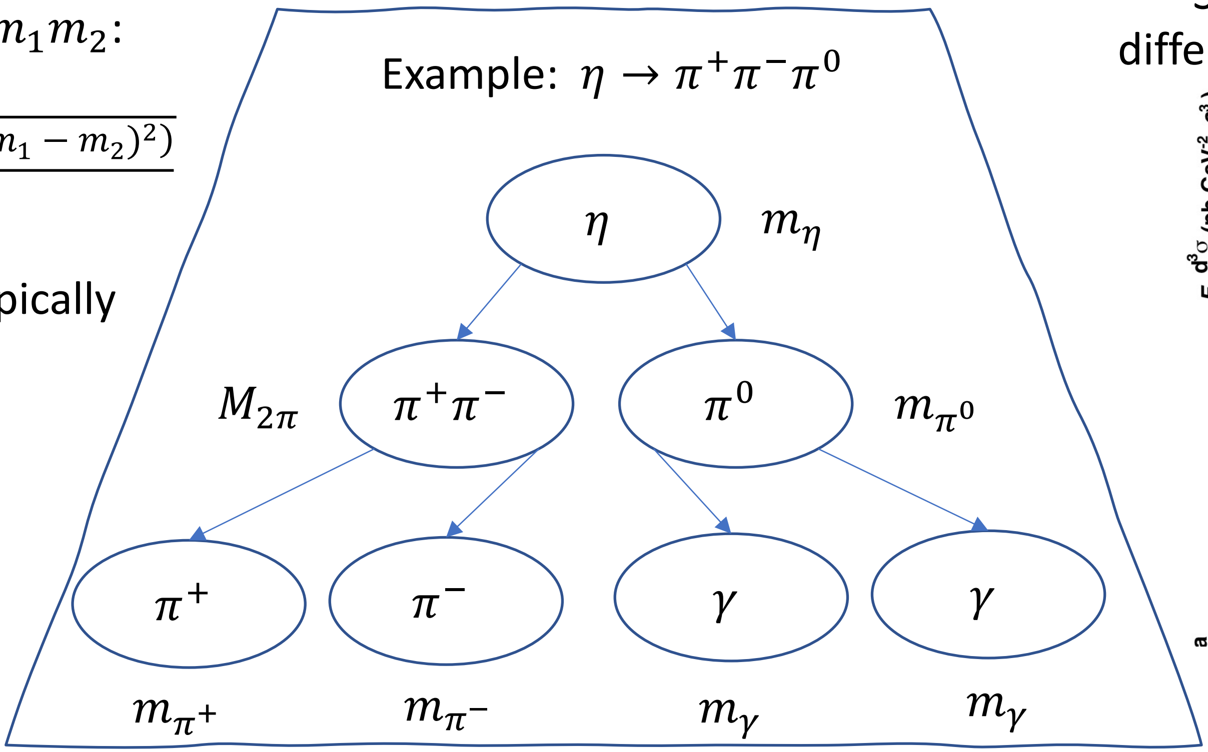
- Potential sources of peaking backgrounds consist of other η decay modes with $\pi \to \mu$ misidentification, $\gamma \to \mu\mu$ conversion, or both
- Comprehensive study of these modes with toy MC simulations

Two-body decay chains of $M \to m_1 m_2$:

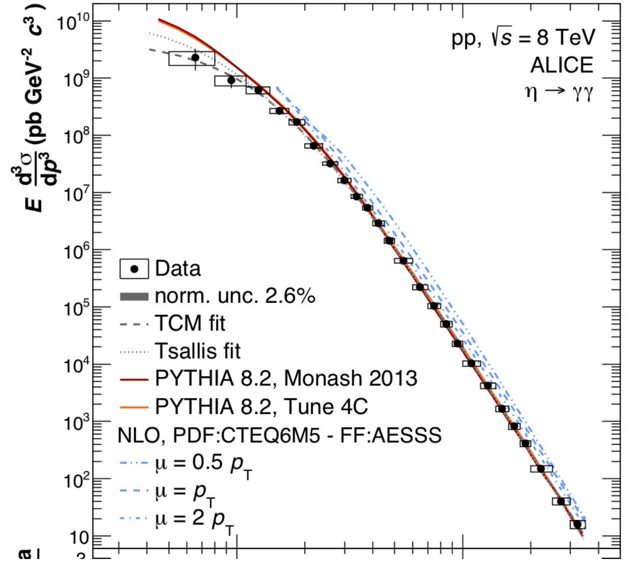
$$|p_1| = |p_2| = \frac{\sqrt{(M^2 - (m_1 + m_2)^2)(M^2 - (m_1 - m_2)^2)}}{2M}$$

Assume decay products are isotropically distributed in M's rest frame

Assume uniform dimass (M) distributions in 3- or 4-body systems and smear by 1.1%



Sample η p_T from measured differential production cross-section



Resonant background studies

Branching fractions:

- $\eta \to 3\pi^0$: 32.7%
- $\eta \to \pi\pi\pi^0$: 22.9%
- $\eta \to \pi\pi\gamma$: 4.22%
- $\eta \to \pi\pi\mu\mu$: $< 1.6 \times 10^{-4}$
- $\eta \to \mu\mu\gamma$: 3.1×10^{-4}

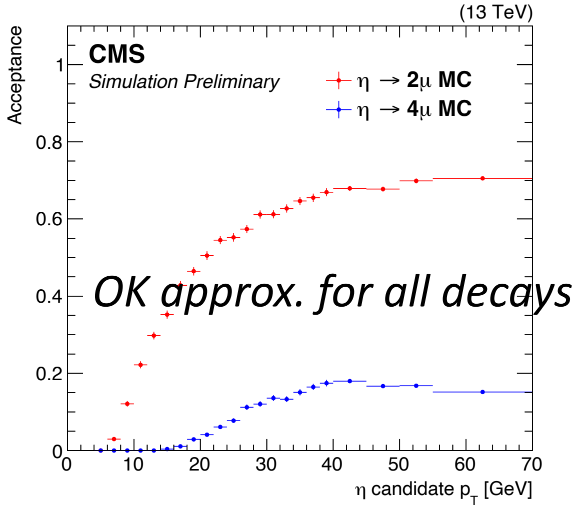
Event weighing

$$w = \sigma\, \mathcal{L}\, B\, A\, f_{ID}\, f_{conv}$$

$$f_{ID} = 0.0015^2 = 2.25 \times 10^{-6}$$

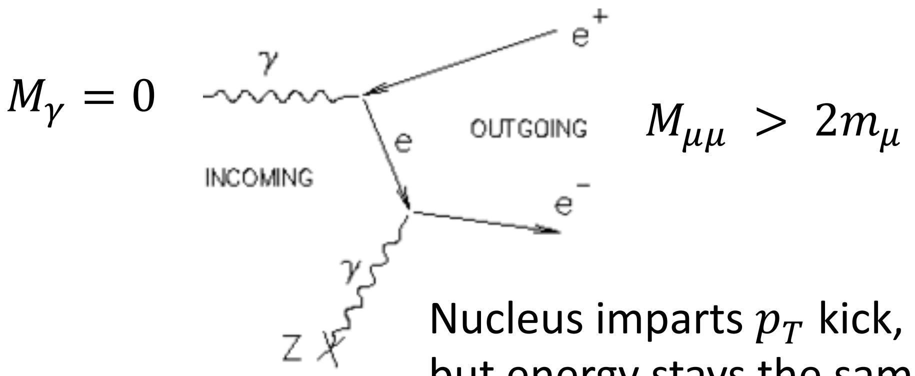
Assume conversions after first pixel layer are fully suppressed with vertex requirement

Layer thickness: 0.3 mm / $\sin(\theta)$



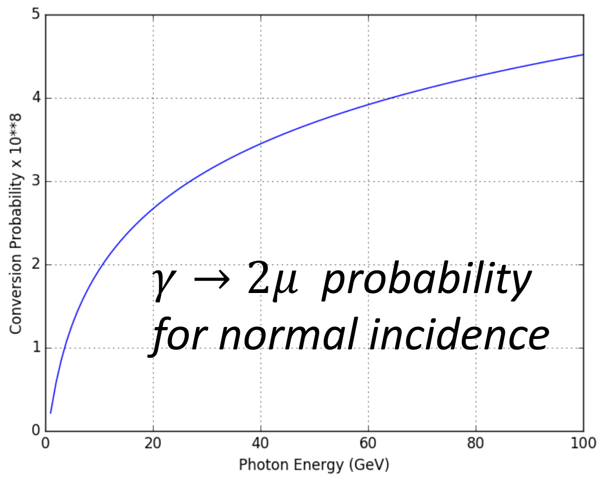
Acceptance vs. p_T

Photon conversions:



Nucleus imparts p_T kick, but energy stays the same

θ: polar angle of muon



But there’s plenty of room at the bottom!

1-100 GeV mass range