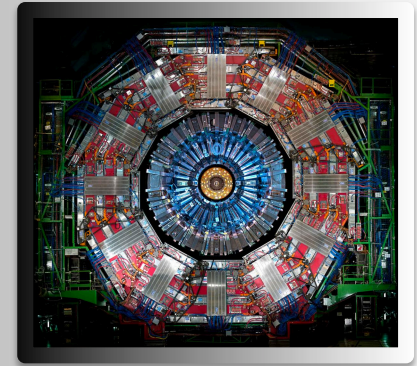


Highlights of Beyond the Standard Model searches in the CMS detector



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Standard Model and Beyond



**SFOF PTF: 5th Symposium of the Division for
Physics of Fundamental Interactions
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Beyond the Standard Model

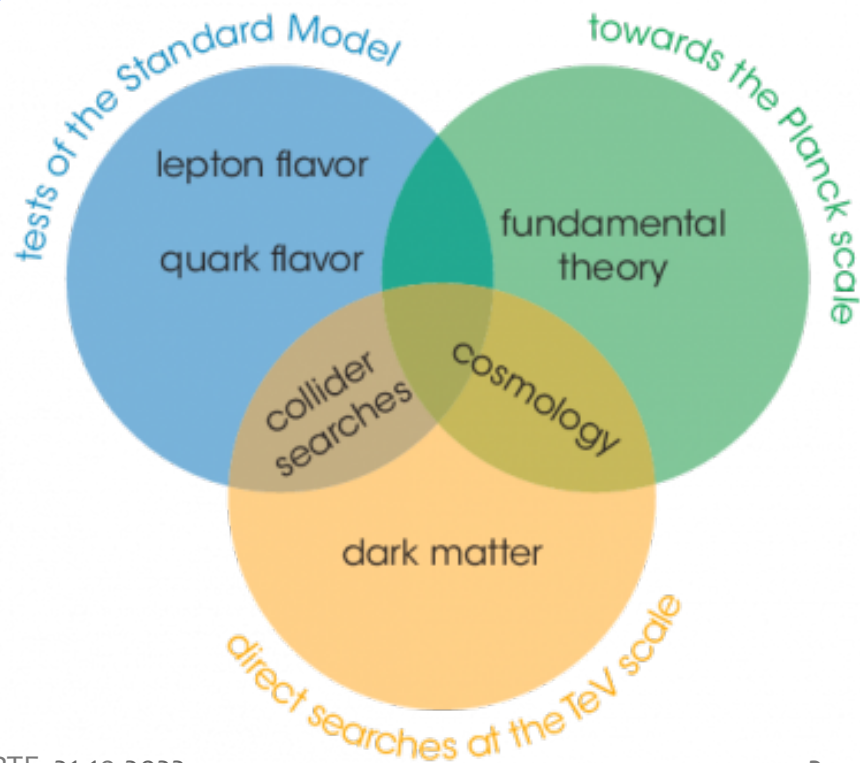
- CMS has a very **rich program** for searching for a wide range of BSM signals
 - *At this talk, only **several highlights** from the full **LHC Run 2 (~140/fb)** data*

■ The Standard Model:

- the most **rigorous theory** of the Nature of particle physics
- **incredibly precise** and accurate in its **predictions**
- **Higgs boson (very SM-like)** has been found!

■ But what about?

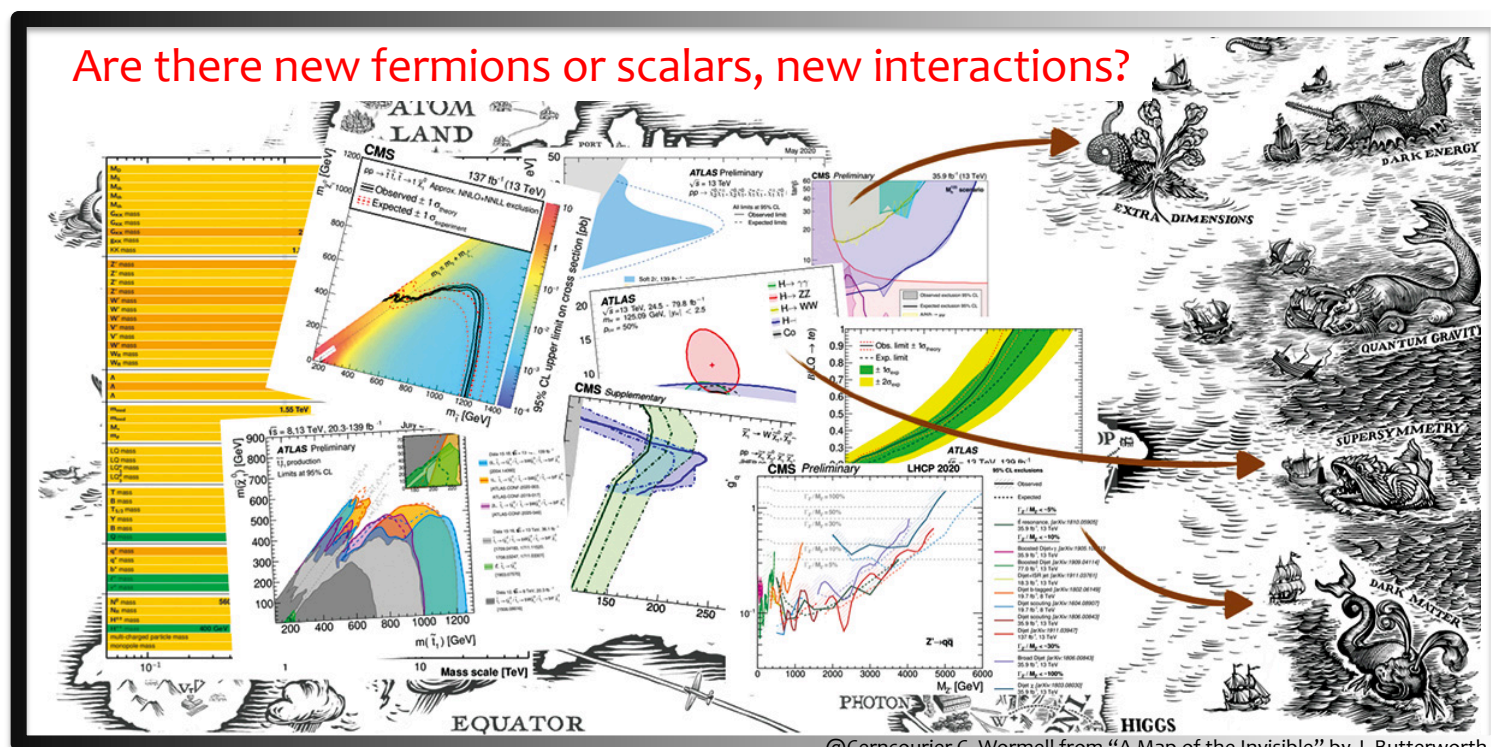
- **Dark matter** candidate...
- **Matter/antimatter asymmetry...**
- **Neutrino masses....**
- **Hierarchy** problem, **force unification...**





Experimental search recipe

- LHC continues its operating providing quality big data, Run 3 ongoing!
 - 13 years of data taking 😊
 - 10 years since the **Higgs boson** discovery!
 - Dozens of **exclusion limits** only...
 - No hints for New Physics... **NO SUSY!**
- Where New Physics is hiding ?





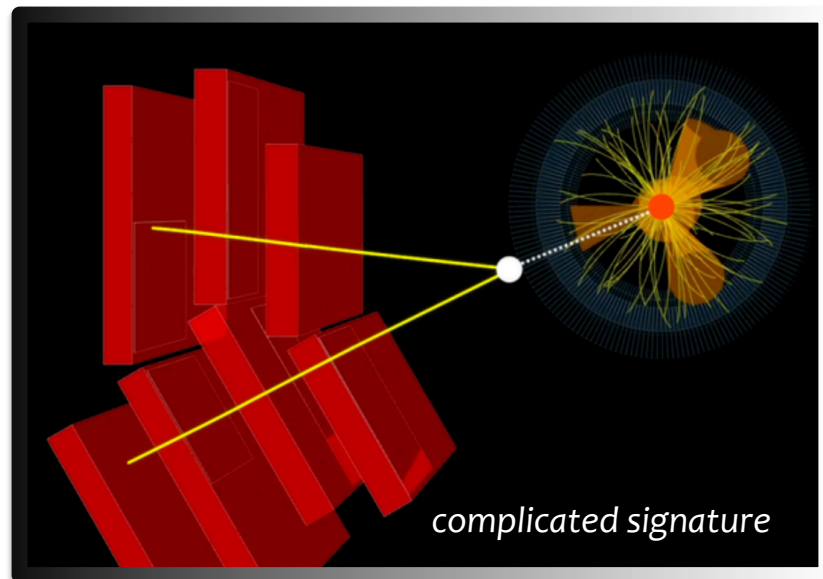
Experimental search recipe

- To continue searches we may need to change the approach since we are almost on the limit of **high mass reach** with simplified models:

- Shift to more **complicated signatures**
 - Shift to **low masses** and **small couplings**
 - Go towards **long lifetimes**
- Can new particles live in *hidden sectors* or be *long-lived*?

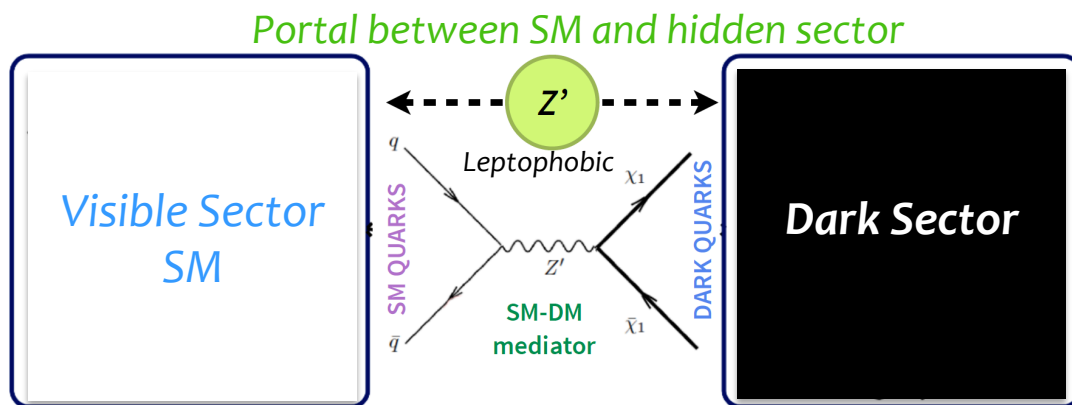
- **Apply New Tools:**

- Use of **new triggers** not available earlier in the LHC running
 - Triggers optimized for **long-lived particles**
 - Triggers based **initial state radiation** and **jet sub-structure** and **tagging**
 - **Data scouting** use for trigger level analysis
- Novel approaches with **machine learning** (BDT, NN, DNN etc) techniques

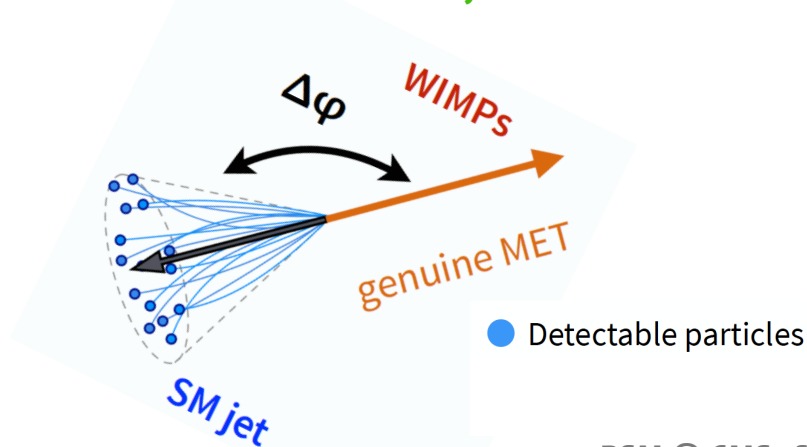


Elaborate search for complicated BSM scenario

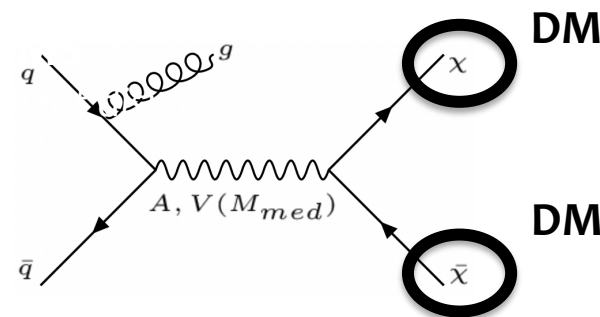
- Search for resonant production of strongly coupled Dark Matter (DM)



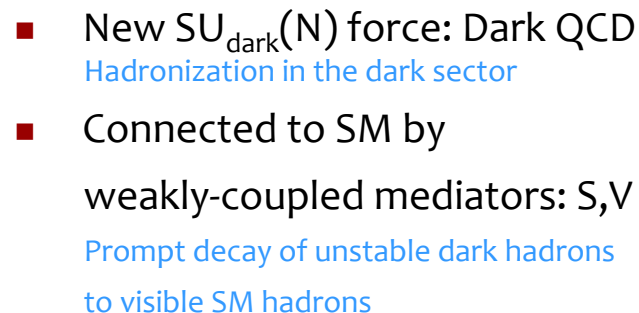
- Generic simple signature of DM (WIMPs)
missing (transverse) momentum (MET)
and back-to-back SM object



Jet from the
initial state radiation (ISR)

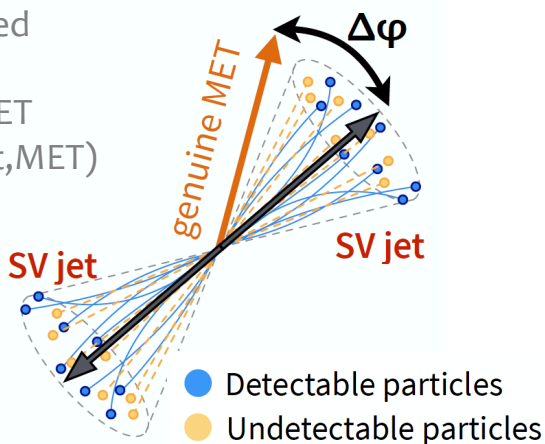


- Search for **resonant production** of **strongly coupled dark matter**

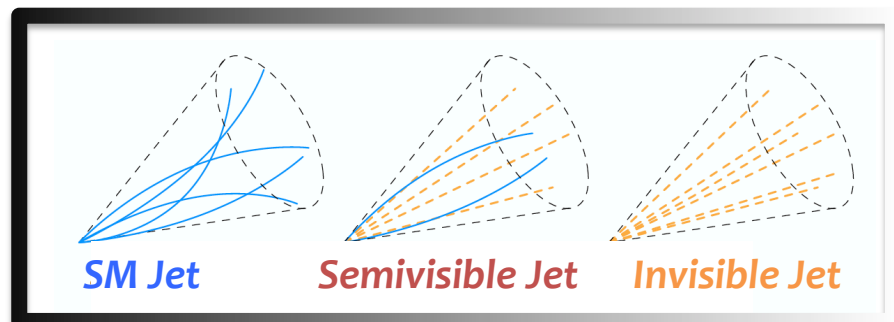


- **Signature** with **semivisible jets (SVJets)** and non-SM behavior

Moderate MET
low $\Delta\varphi_{\text{min}}(\text{jet}, \text{MET})$



- Stable **dark hadrons** remain **invisible**
 - Can be considered as **DM candidates**

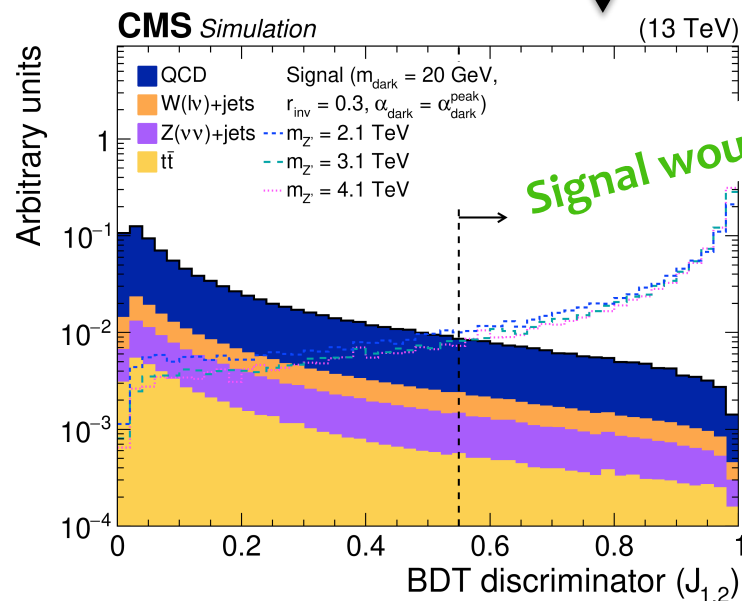
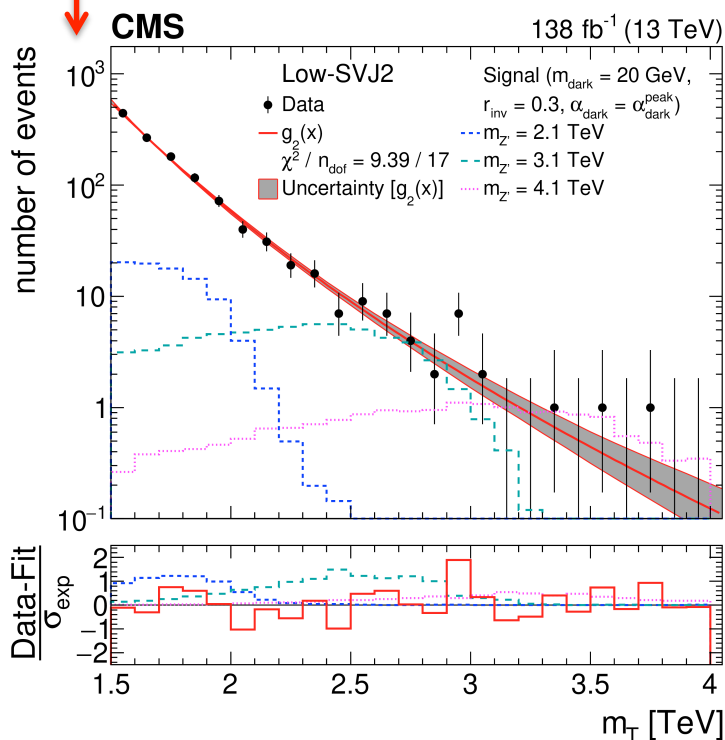




Dark QCD – semivisible jets

Analysis strategy:

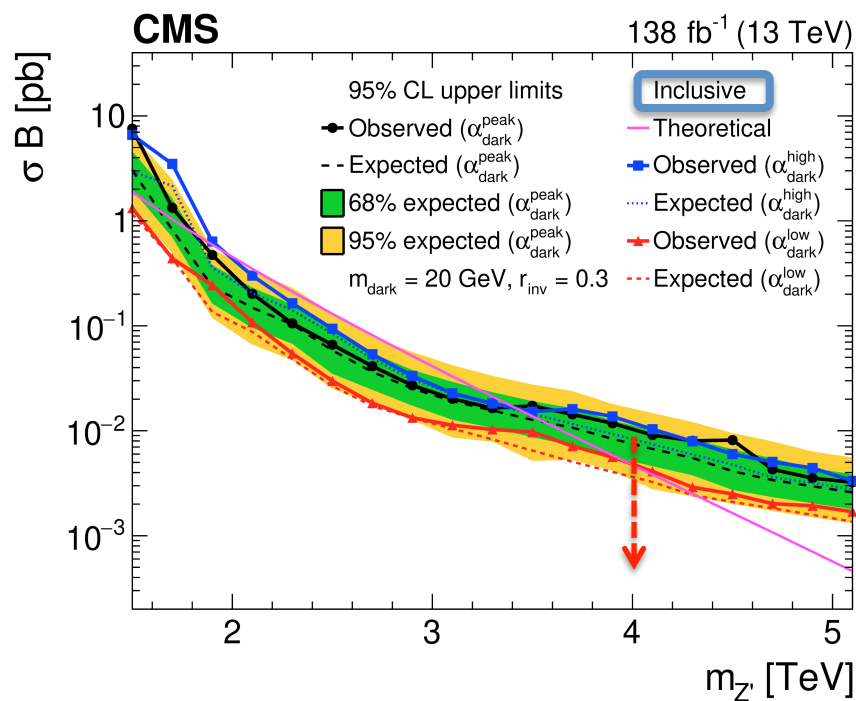
- Resonance dijet search: 2 jets with $p_T > 200$ GeV and $|\eta| < 2.4$
- Discrimination variable: **transverse mass** m_T of dijet system and MET
- QCD background rejected with cut on $R_T = \text{MET}/m_T > 0.15$
- Bkg normalization extracted in fit
- **Jet-level BDT** with dedicated SVJ tagger reduces bkg by $\sim O(100)$



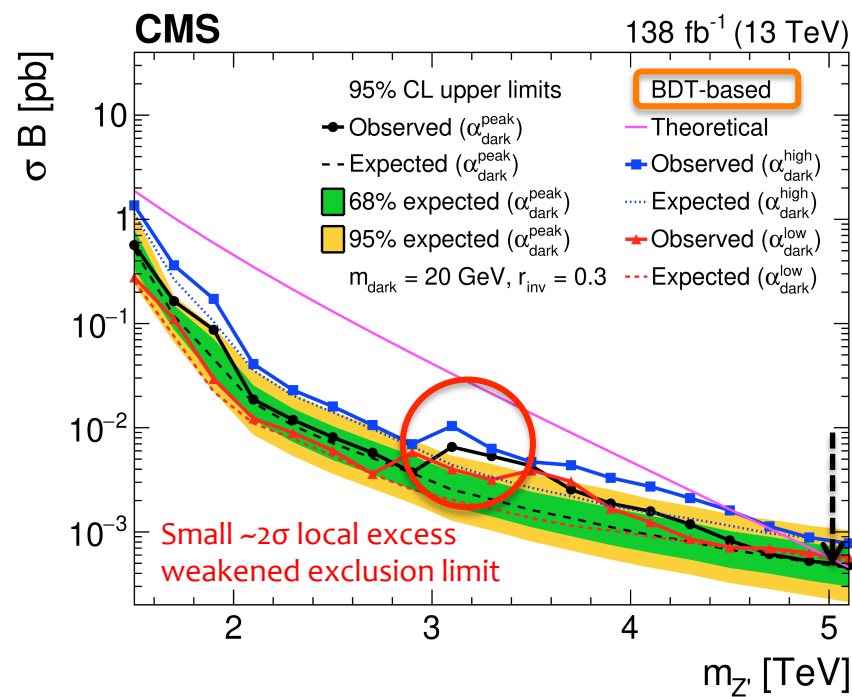


Dark QCD – results

- No structure (\sim resonance peak) in the SVJ dijet transverse mass spectra is observed
- Present results for two conditions:
 - **Inclusive**, signal-independent cut-based approach (*most conservative*), $R_T = \text{MET}/m_T > 0.15$
 - **BDT-based**, improved by almost a factor 10 (*most aggressive*), $R_T > 0.15 + \text{BDT}$



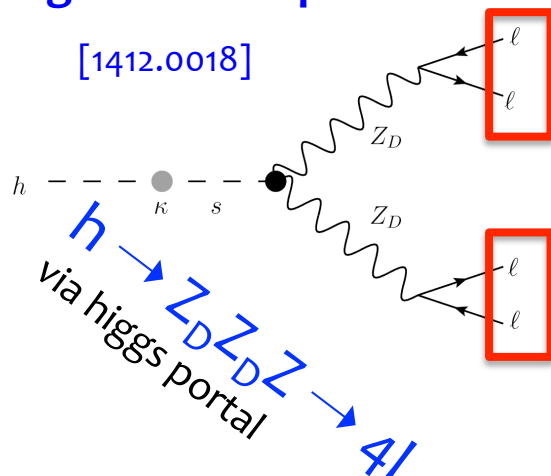
Inclusive analysis excludes the mediator masses in range **$1.5 < m_{Z'} < 4.0 \text{ TeV}$**



When the BDT is employed to identify each jet in the dijet system as semivisible, the mediator mass exclusion increases to **5.1 TeV**

Long-lived- low mass displaced di-muons

Higgs boson decays to a pair of **long-lived dark photons**



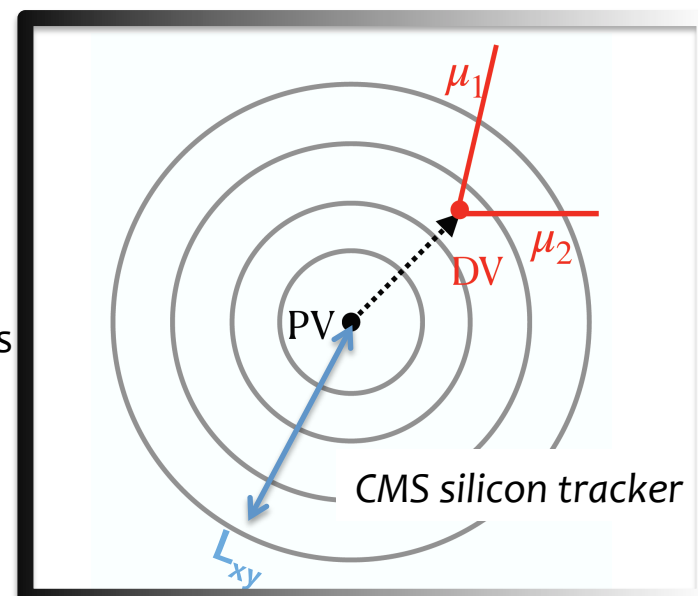
Dark Photons Z_D : $0.5 \text{ GeV} \leq m(Z_D) \leq 50 \text{ GeV}$
 $0.1 \text{ mm} \leq c\tau_0(Z_D) \lesssim 1 \text{ m}$

■ **Signature:** very low mass displaced dimuons

- At least 2 opposite sign muons ($p_T > 3 \text{ GeV}$, $|\eta| < 2.4$)
 - with masses **down to $\sim 2m_\mu$**
 - with **displaces vertex (DV)** **shifted (L_{xy})** up to 11 cm

Search conditioned by **high rate triggers (scouting)**:

- CMS newly use for the analysis
- Allow sensitivities to **otherwise inaccessible low-mass** events
- Bypass the high-level trigger (HLT) thresholds by directly sending HLT objects to disk instead of saving raw data
- Reduced event info compared to offline reconstructed objects

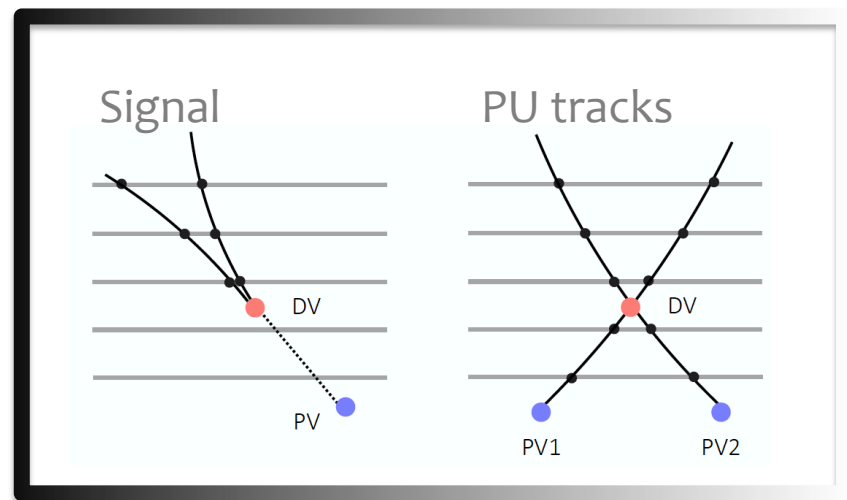




Displaced di-muon search

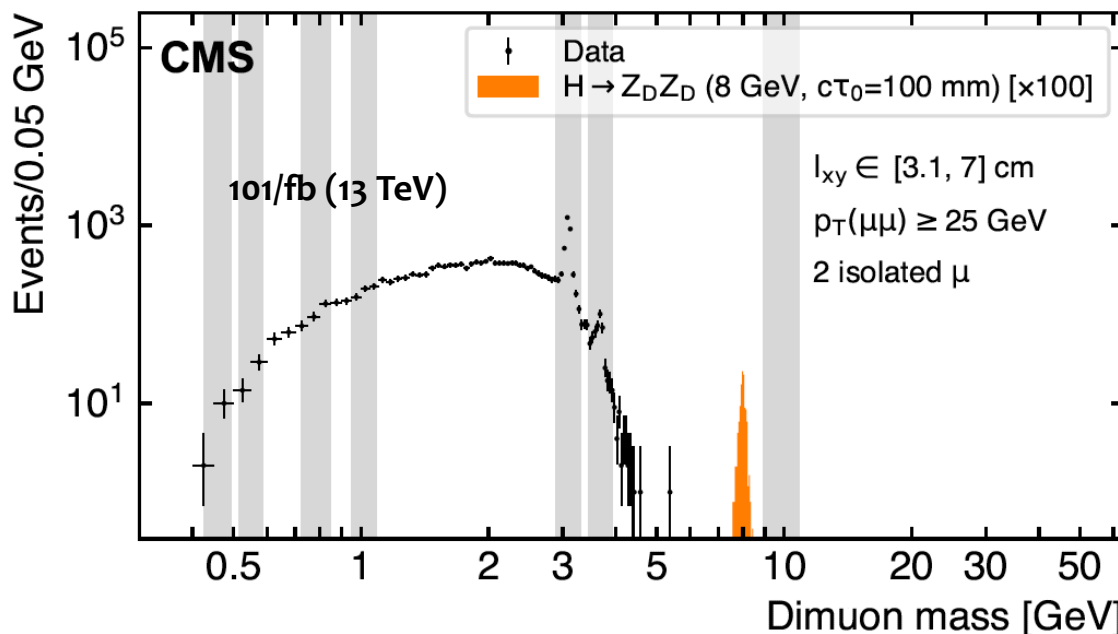
Strategy:

- Search for a **narrow peak** in dimuon invariant mass spectrum
 - SM resonances are masked ($\pm 5\sigma_{\text{res.}}$ window) for the result



Background:

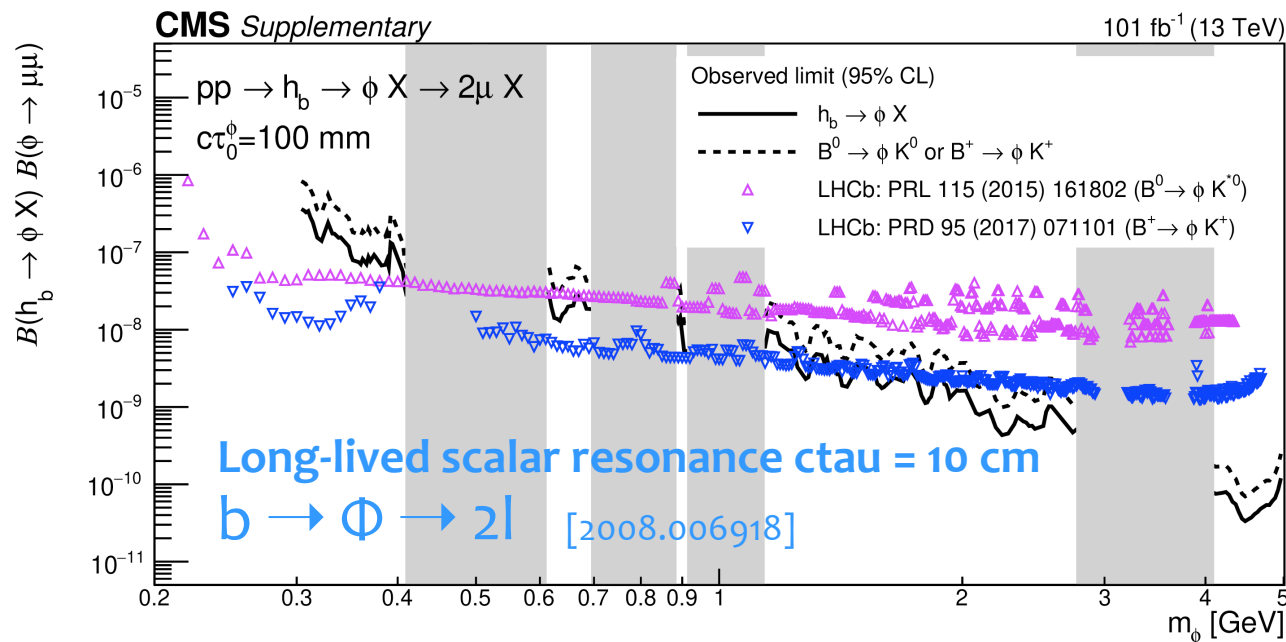
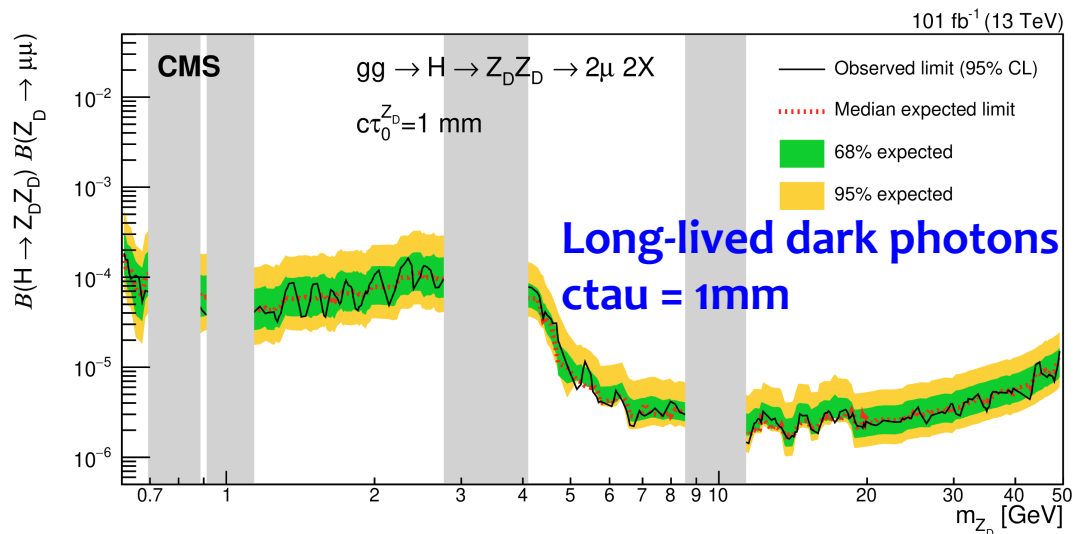
- controlled with a set of kinematical cuts
- estimated directly from data
- Events are **categorized in bins** of muon isolation ($2,1,0$ iso- μ) di-mu momentum $p_T(\mu\mu)$ and displacement l_{xy}





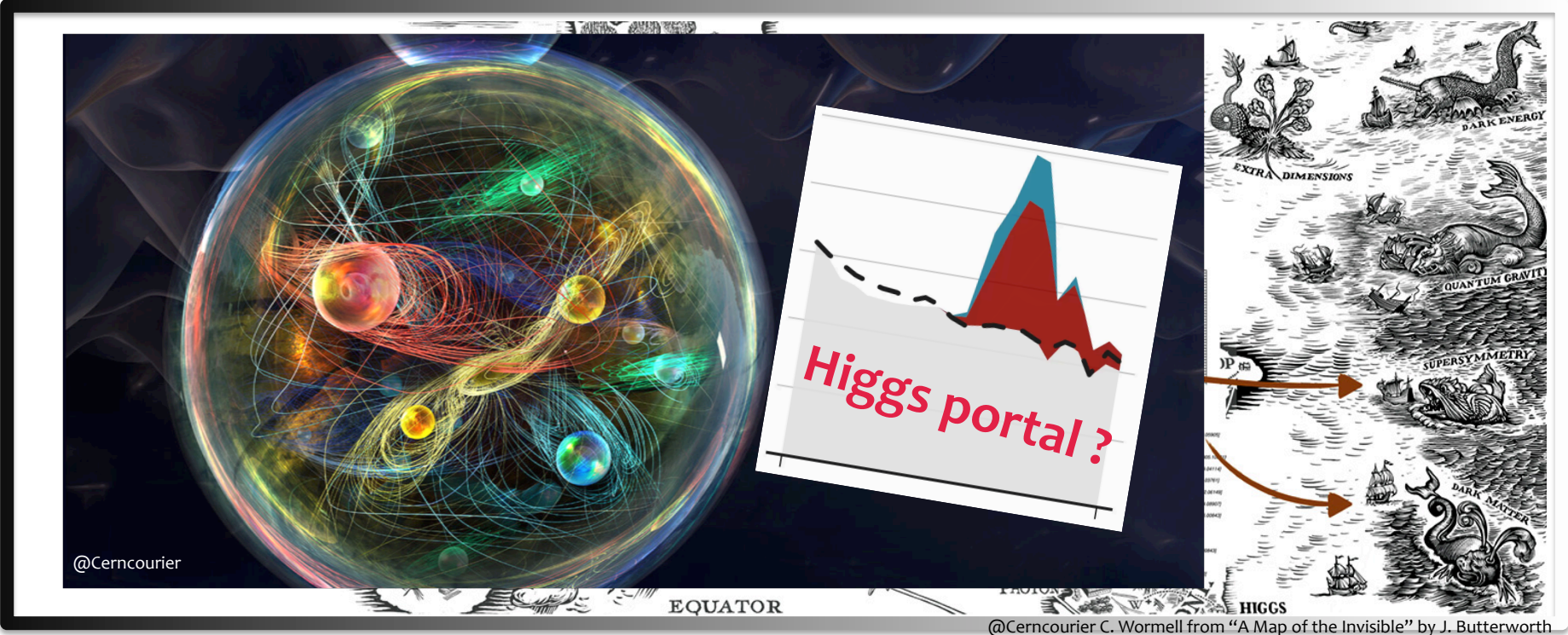
Displaced di-muon – results

- No significant excess is observed
- The CMS most stringent constraints to date in a wide range of signal **low-mass** and lifetime hypotheses



- CMS reached sensitivity comparable with LHCb especially at higher mass and higher lifetime

Where New Physics is hiding ?



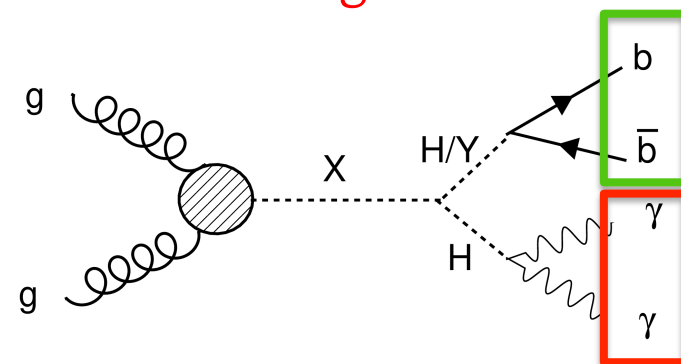
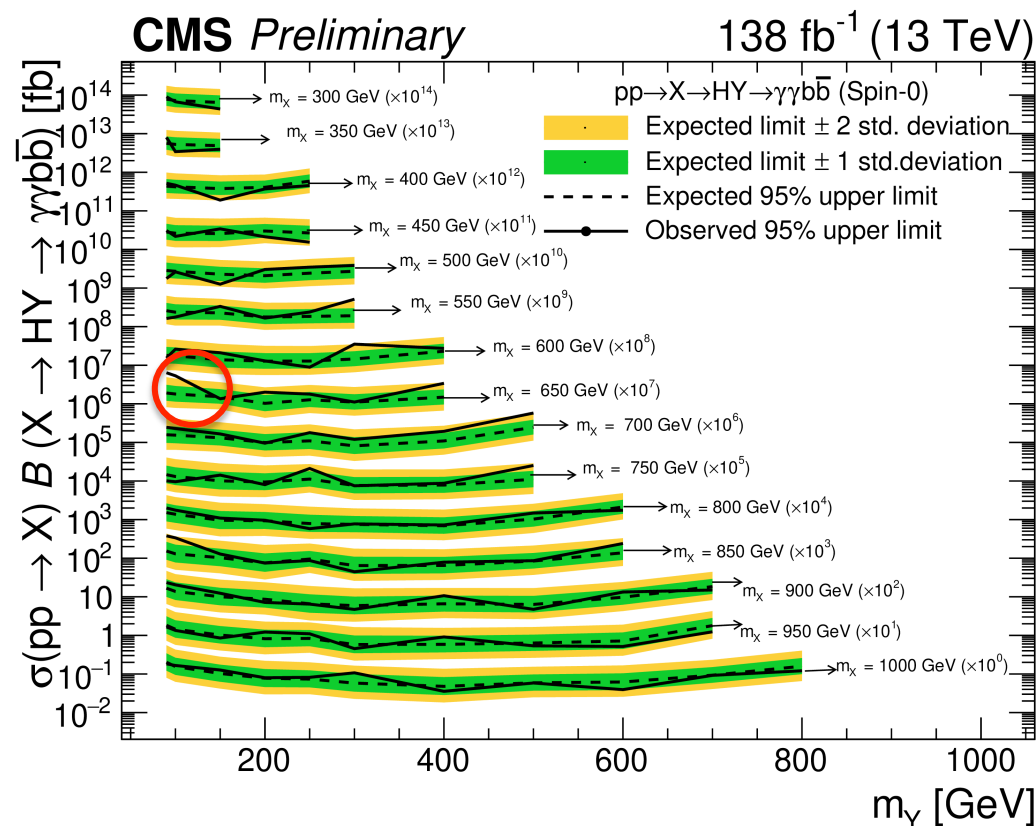
Any hints from LHC Run 2 ?



Run 2 excitements: H/Y (bb) H($\gamma\gamma$) search

- Search for **new resonances X** decaying to Higgs bosons $X \rightarrow H/Y$ (**bb**) $H(\gamma\gamma)$
- Several excesses but **the largest excess is 3.8σ local and 2.8σ global**

for $m_X = 650$ GeV and $m_Y = 90$ GeV:

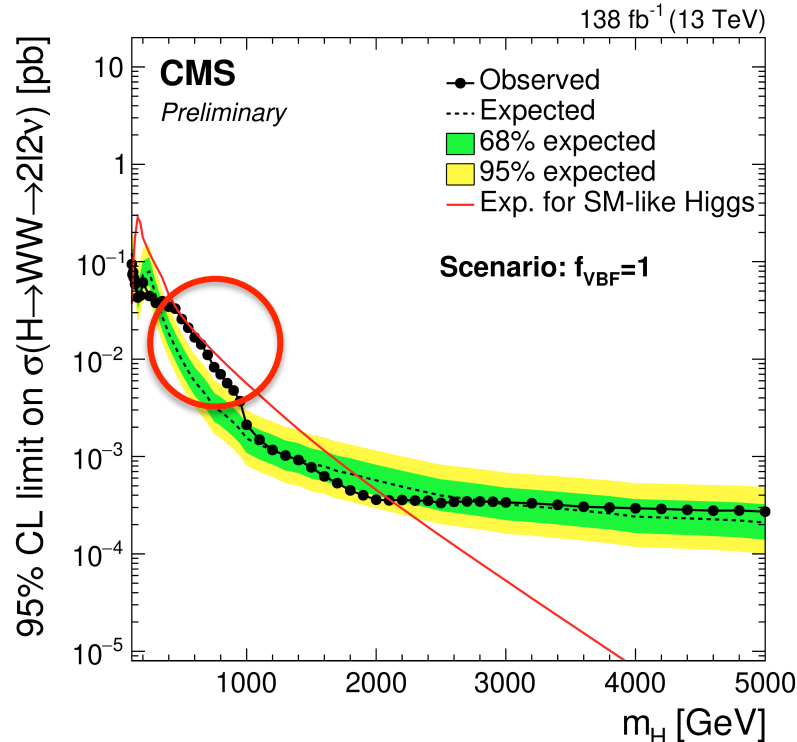
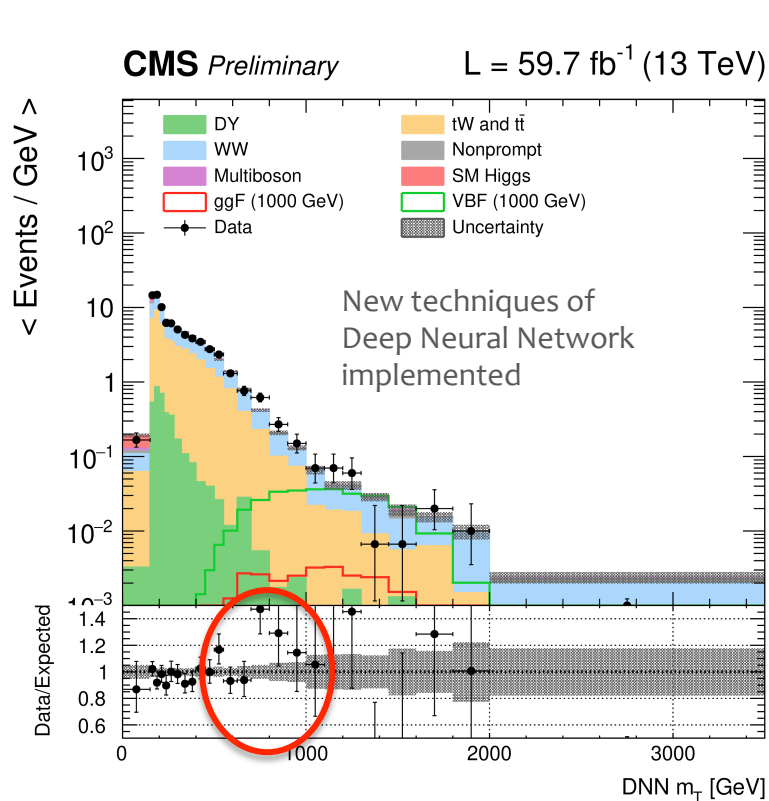


- MVA and BDT categorization applied
- The HH limits are compared with predictions in the warped extra dimensional model
- The HY limits are interpreted with the N-MSSM and the two-real-scalar-singlet model



Run 2 excitements: $H(WW)$ search

- Search for **new resonances X** produced in gluon-gluon (ggF) or vector-boson fusion (VBF) decaying to Higgs bosons $X \rightarrow H$ (**WW**) where **W** is fully leptonic final state (**$e\mu$, $\mu\mu$, ee**)
- Curiously, observed **excess** for $m_X = 650$ GeV is **3.8σ local and 2.6σ global**



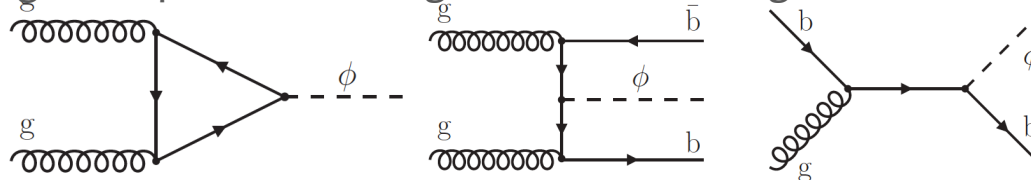
Exclusion limits are also derived on various two-higgs-doublet models and MSSM scenarios



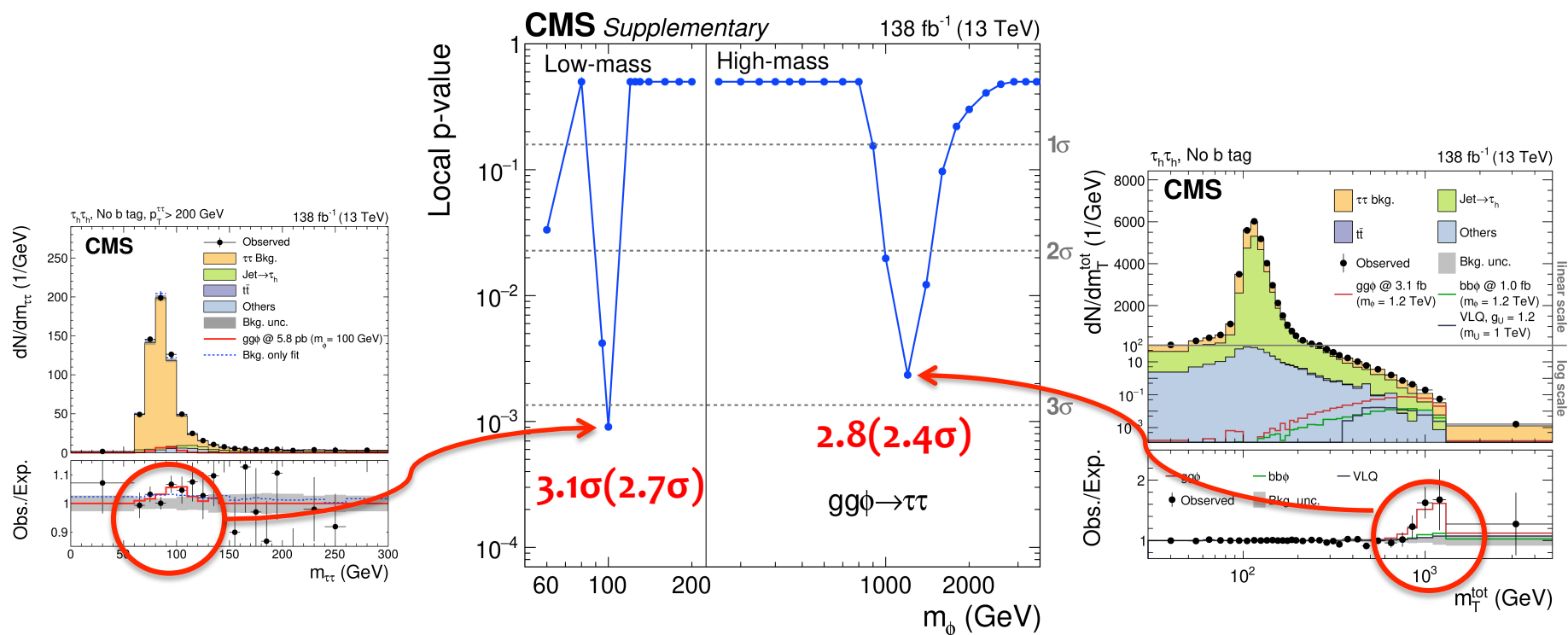
Run 2 excitements: $H(\tau\tau)$ search

- Search for MSSM Higgs bosons decaying into the $\tau\tau$ final state

Sophisticated background prediction using the " τ -embedding" method



- Two $\sim 3\sigma$ excesses are seen in the ditau mass distributions ~ 100 GeV and 1.2 TeV





BSM at CMS summary

- CMS experiment builds up a rich program of **BSM** searches:
 - Large variety of **signatures**:
 - Complex searches for hypothetical **resonances**
 - Signals with **heavy flavours**
 - **Higgs** giving light to **New Physics / dark sector / matter**
 - Distinctive signatures of **long-lived particle**optimized to be model independent for a wide range of model types
- Experimental techniques evolves to more **sophisticated approaches**
- Use of **machine learning** brings substantial improvements
- More improvements and analyses with **full Run 2** data expected while **new Run 3** data will be available soon
 - **There are several excesses in Run 2 data to cross check with Run 3**
Attention! There were false excitements already in the past (e.g.: 750GeV in $H(\gamma\gamma)$)



Thank you!

<http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO>

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV>

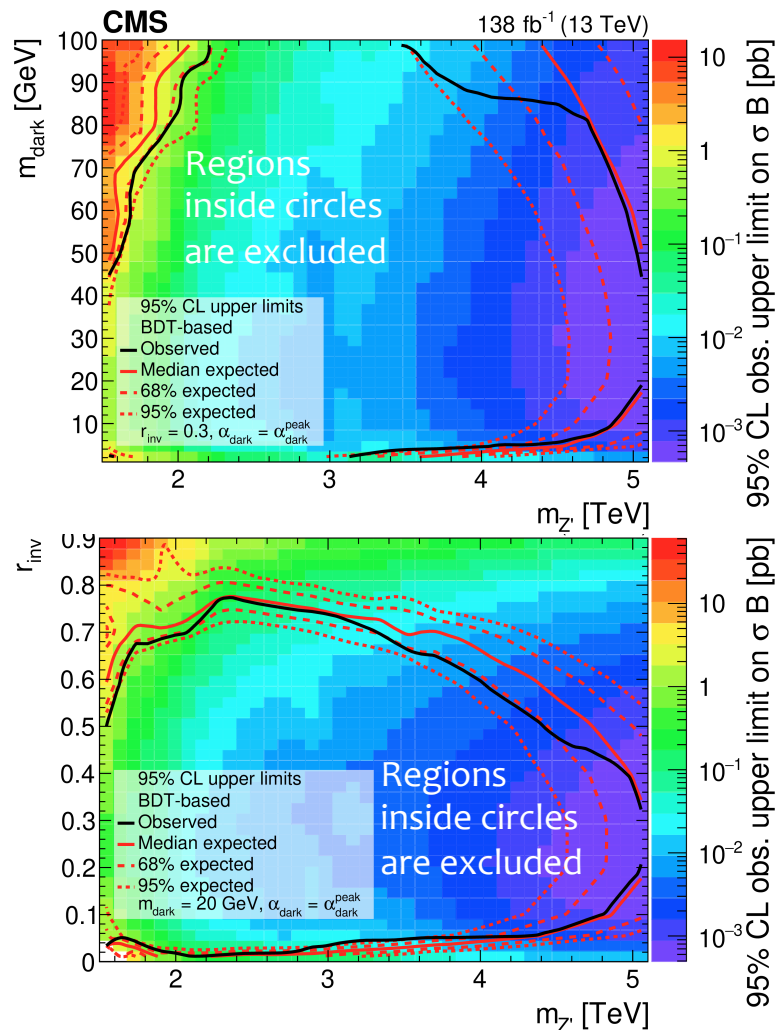
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Backup slides

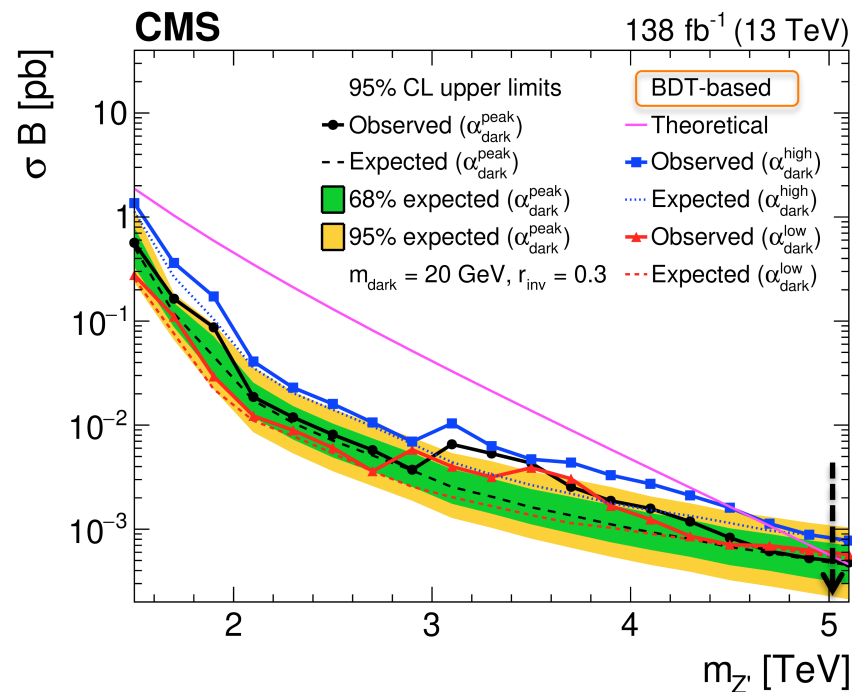
Dark QCD – BTD limits

- **BDT-based**, improved by almost a factor 10 (*most aggressive*), $R_T > 0.15$ + BDT



Assuming the Z' boson has a universal coupling of 0.25 to the SM quarks:

- $1.5 < m_{Z'} < 5 \text{ TeV}$ excluded for $r_{\text{inv}} = 0.3$
- $0.02 < r_{\text{inv}} < 0.77$ excluded for $m_{\text{dark}} = 20 \text{ GeV}$



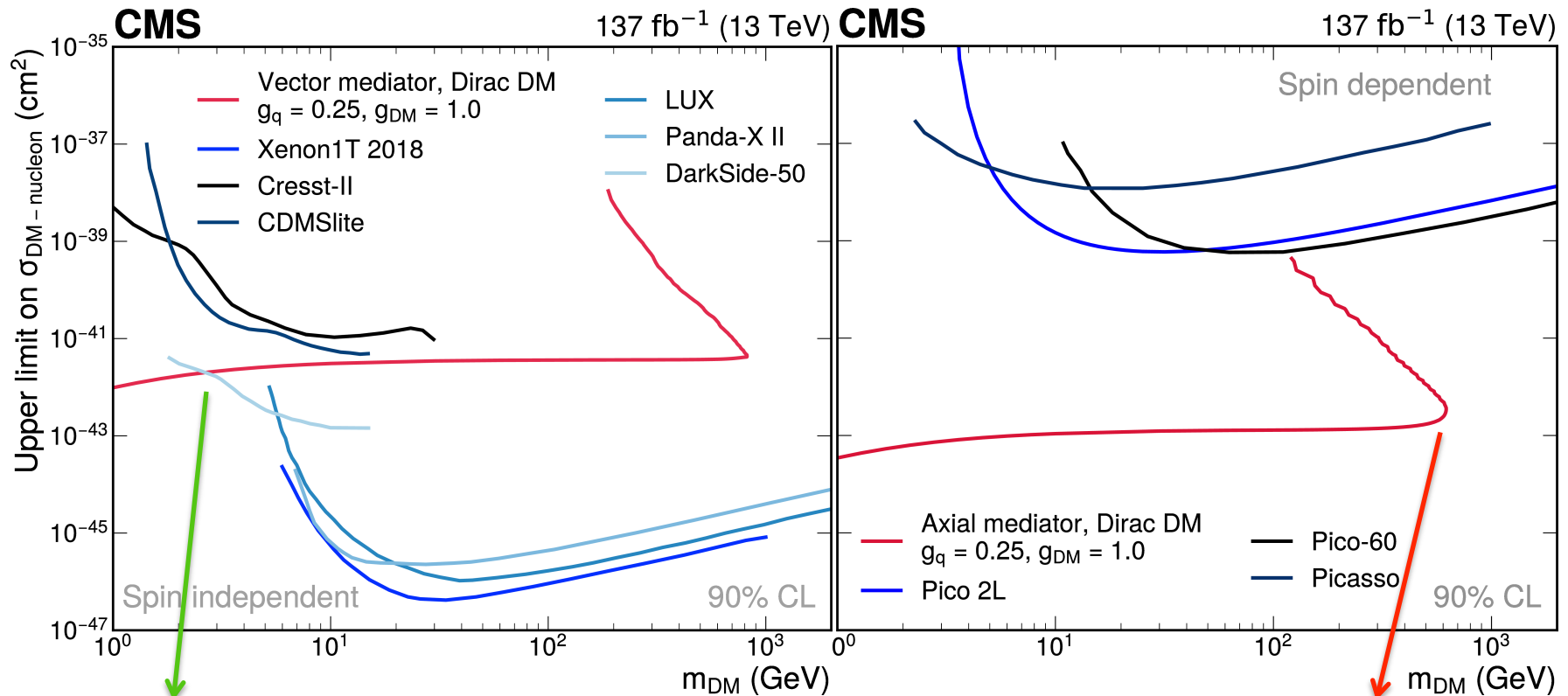
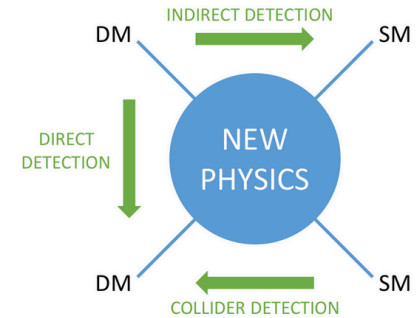
- Small excess around $m_{Z'} \sim 3.5 \text{ TeV}$ w/ small $\sim 2\sigma$ local significance weakened exclusion limit

These limits exclude a wide range of strongly coupled hidden sector models for the first time



Dark Matter: Mono-Jet results

- Limits are set on DM particle production in the context of **Simplified Models** for spin-1 **Vector (Axial) Mediator**
- Comparison to **direct detection (DD)** experiments



CMS compatible with DD at low mass

CMS competitive with DD up to 600 GeV



Run 2 excitements: LQ3 search

- Search for a third-generation leptoquark (LQ3) in non-resonant $\tau\tau$ and b -quark final state
- B-tagger: DeepCVS: DNN extension of combined secondary vertex algo
- Discriminators: S_T^{MET} (scalar sum of $p_T \tau_1 \tau_2 b\text{-jet} + \text{MET}$) and angular separation between two tau jet
- **3.4σ local excess** for non-resonant production at large LQ3 masses and couplings; no excess is seen for resonant production

