Trigger Level Analysis in CMS During Run 2 and Beyond

HOW2019

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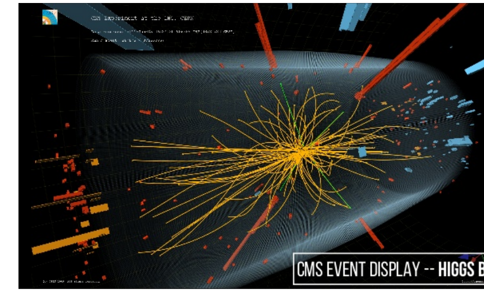
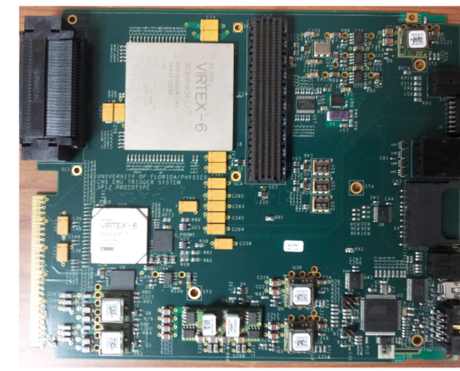
On behalf of the CMS collaboration

CMS Trigger System

- CMS has a two level trigger system to select the interesting collision events
  - ➔ Level 1 (L1) trigger: algorithms running on FPGA in custom electronics boards
    - Coarse information, no tracking information
    - Hard limits on latency (on-detector buffer size) and total accept rate (readout electronics design)
  - ➔ High Level Trigger (HLT): algorithms running on commercial CPUs
    - Full readout of the CMS detector, including the tracker
    - Hard limit on latency (CPU power) and total bandwidth (transfer data from online file system to storage)
    - *No hard limit on the total rate*

~30 MHz





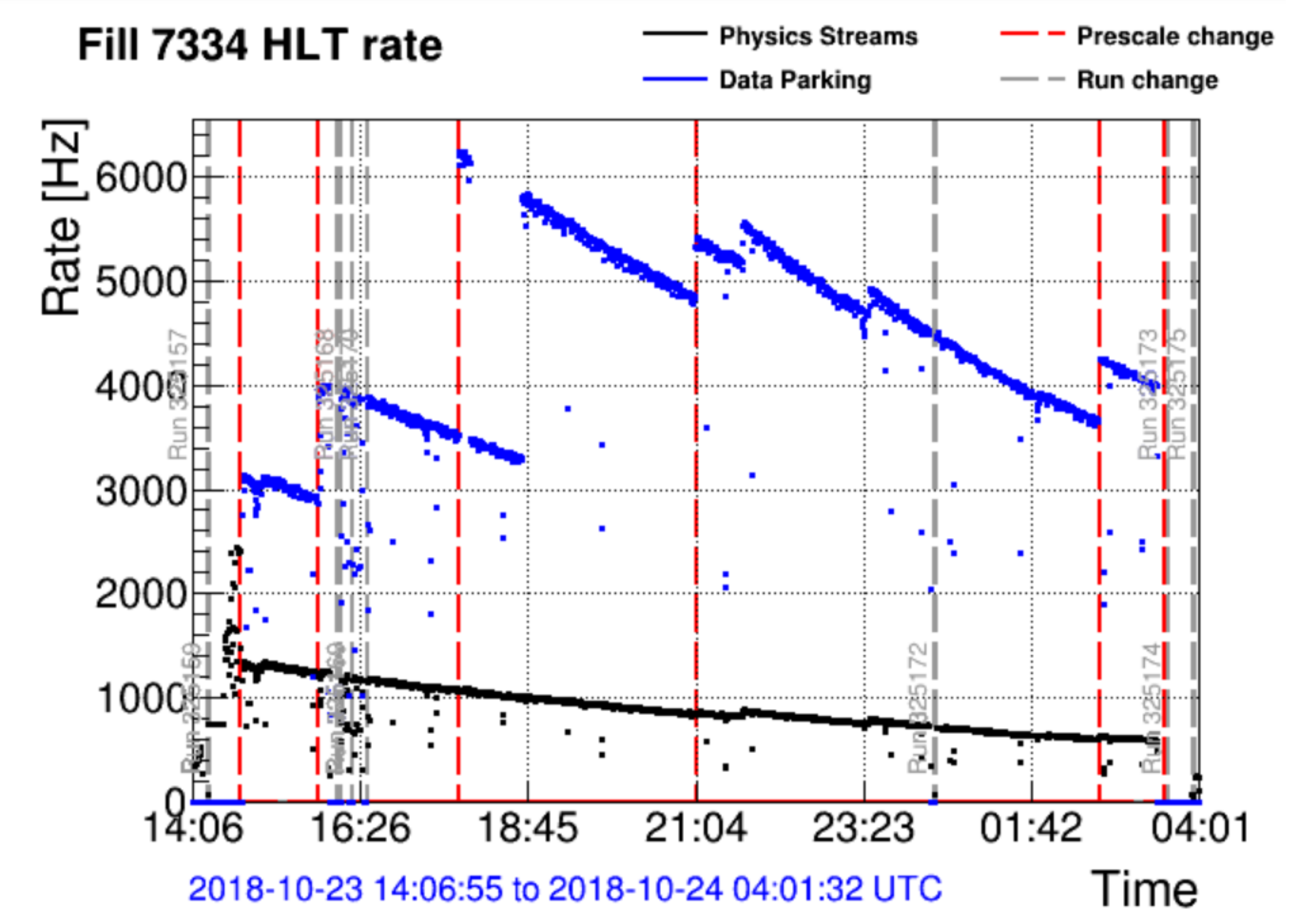
~100 KHz

~1 KHz

~3 GB/s

CMS "Data Parking"

- We can take a lot more than 1 KHz of data, e.g. in 2018 for BPH
  - ➔ If you are fine with waiting longer to have it fully reconstructed
  - ➔ Not the main point of this talk, focus on another strategy...



CMS "Data Scouting"

- Traditional trigger algorithms usually require high p_T particles to reduce the event rate, and then readout the full event information
- Need to reduce the event size to collect events at a higher rate
  - ➔ Physics objects produced by the HLT as the final objects
    - CaloScouting (vertices, muons, calo based jets and MET),

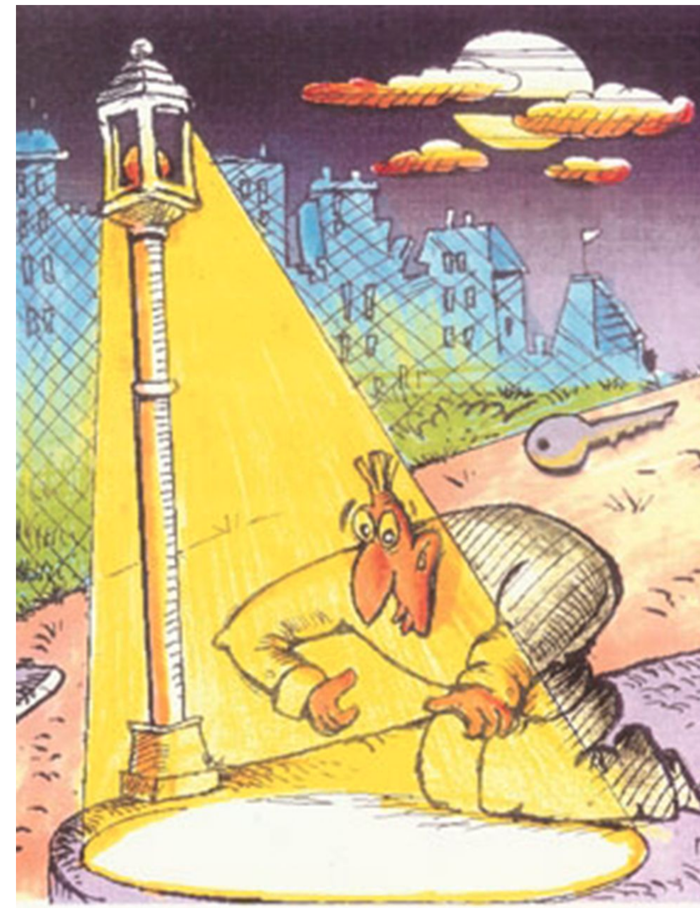
      → limited by L1 rate
    - PF Scouting (vertices, PF muons, PF jets and MET, PF cands.),
      → limited by HLT CPU time

Stream	Rate (Hz)	Event Size	Bandwidth (MB/s)
PhysicsMuons	420	0.86 MB	360
PhysicsHadronsTaus	345	0.87 MB	300
ScoutingCaloMuon	4580	8.9 KB	40
ScoutingPF	1380	14.8 KB	20

Selected CMS stream rate, event size, and bandwidth at the beginning of LHC Fill 7334 (23 Oct. 2018, $L \approx 1.5 \times 10^{34} cm^{-2} s^{-1}$)

Why go to lower p_T ?

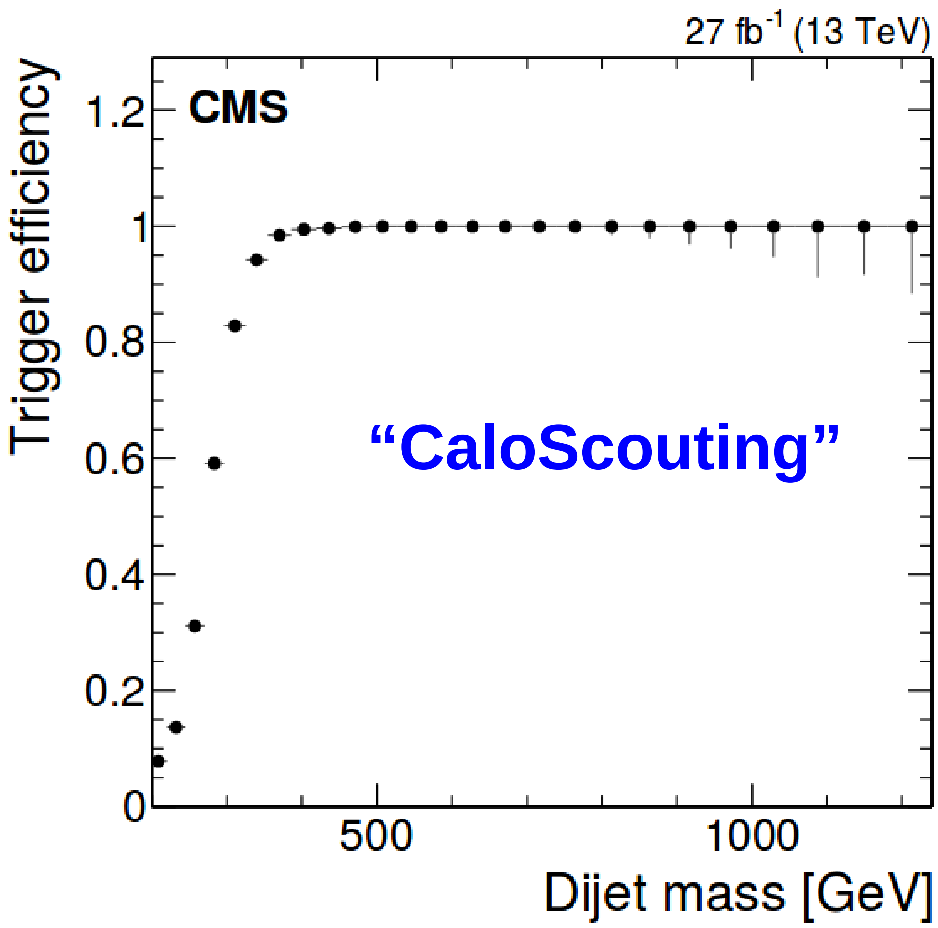
- We expected to find new physics at the TeV scale, but haven’t found it so far
- Eventually we will have diminishing returns on looking at very high p_T at the LHC
- The LHC experiments are the only active collider experiments which can do direct searches for new physics above ~12 GeV, maybe we have missed something
- Several BSM models do not prefer any specific mass scale, just need weaker couplings for lower masses
  - ➔ Dark matter / Dark sectors...
  - ➔ Axion like particles...
  - ➔ Models for flavor anomalies...

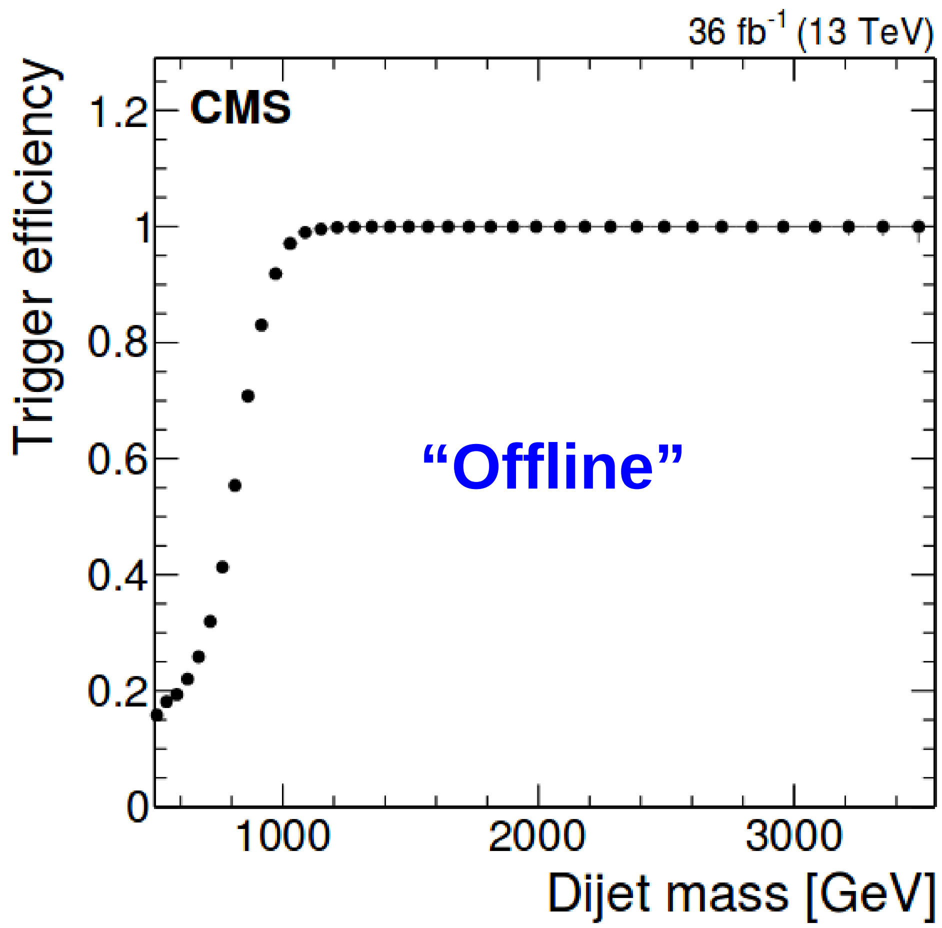


Low Mass Dijet Search

CMS-EXO-16-056

- Search for dijet resonances using the **CaloScouting** stream
- The scouting trigger is fully efficiency for a dijet mass of 490 GeV
  - ➔ Almost 500 GeV lower than the the traditional trigger

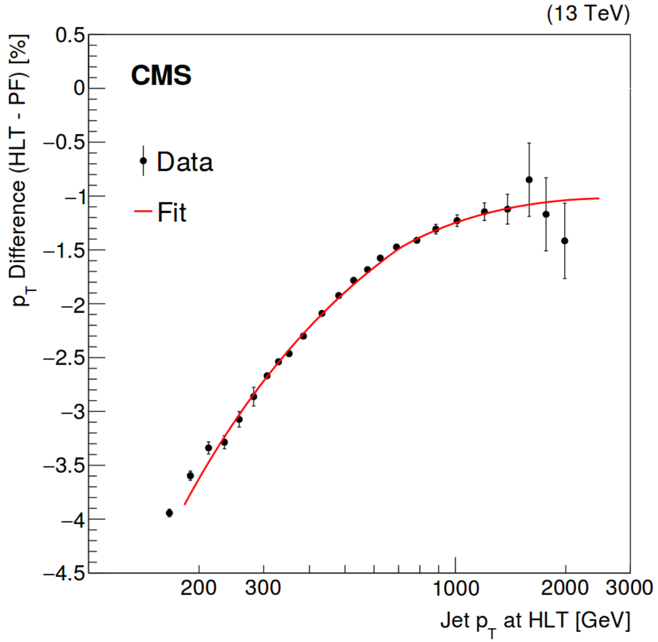


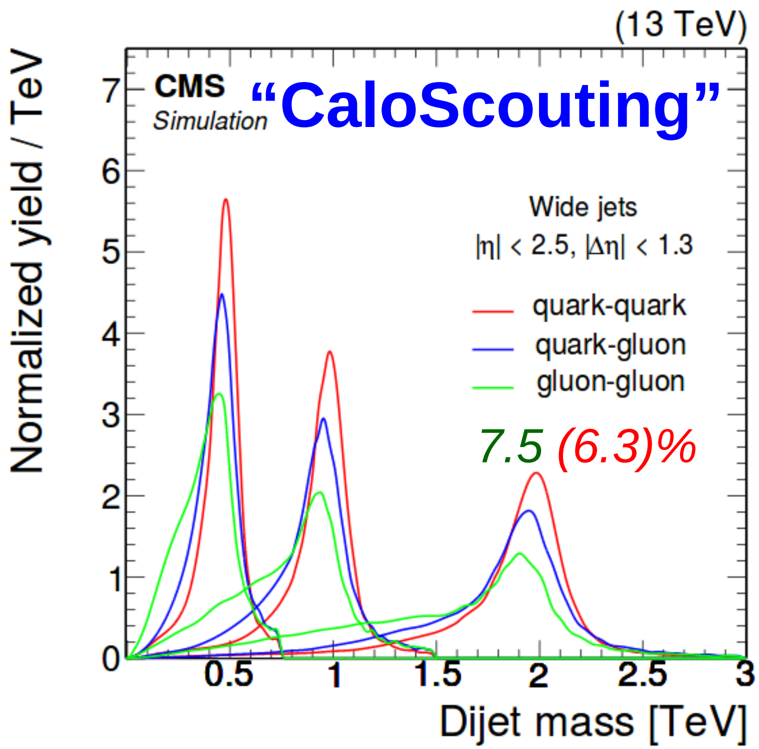


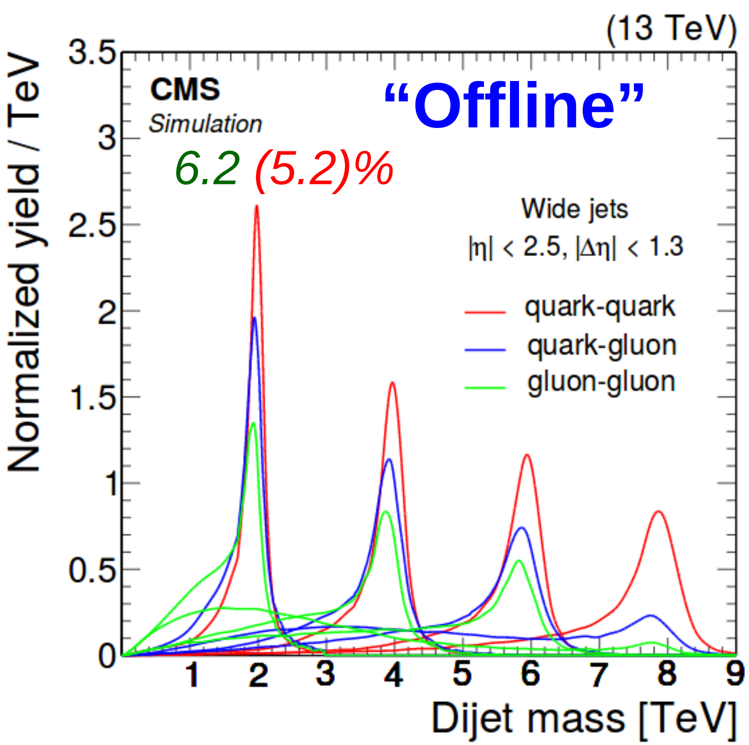
Low Mass Dijet Search

CMS-EXO-16-056

- Spatially close jets are combined into "wide jets" to build the dijet mass
- "Scouting" jets are calibrated to give the same response as the "offline" jets using di-jet balancing technique
- Resolution about ~18% worse in scouting for a dijet mass of 2 TeV







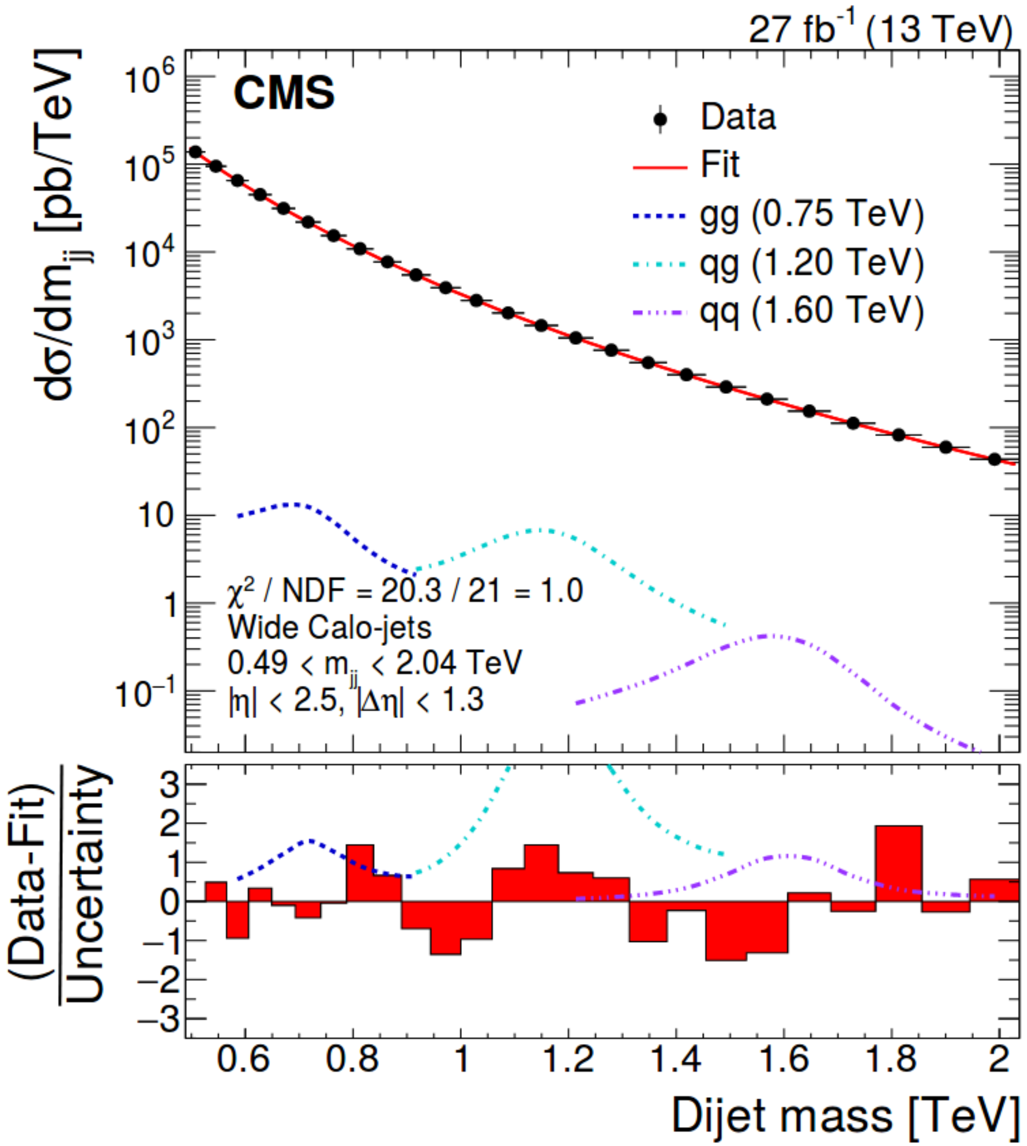
Low Mass Dijet Search

CMS-EXO-16-056

- The low dijet mass spectrum is fit with a 5 parameter function motivated by QCD calculations:

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)+P_4\ln^2(x)}}$$

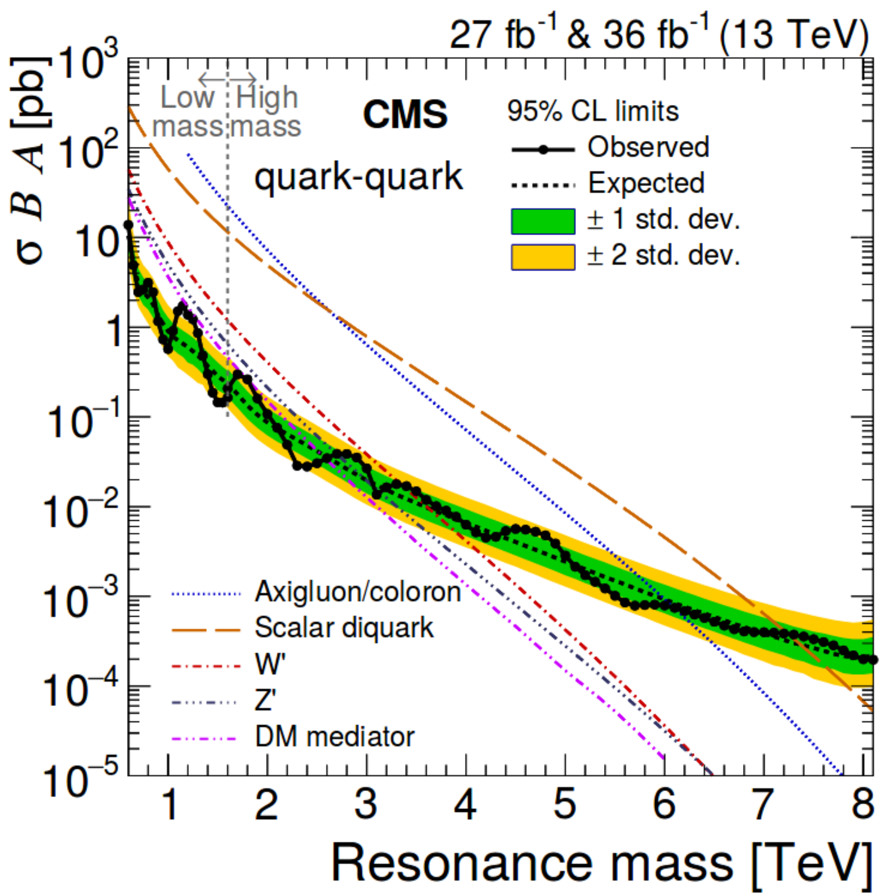
- Dominant sources of uncertainty are similar to the offline analysis:
  - Jet energy scale and resolution
  - Luminosity
  - Acceptance
  - Background shape

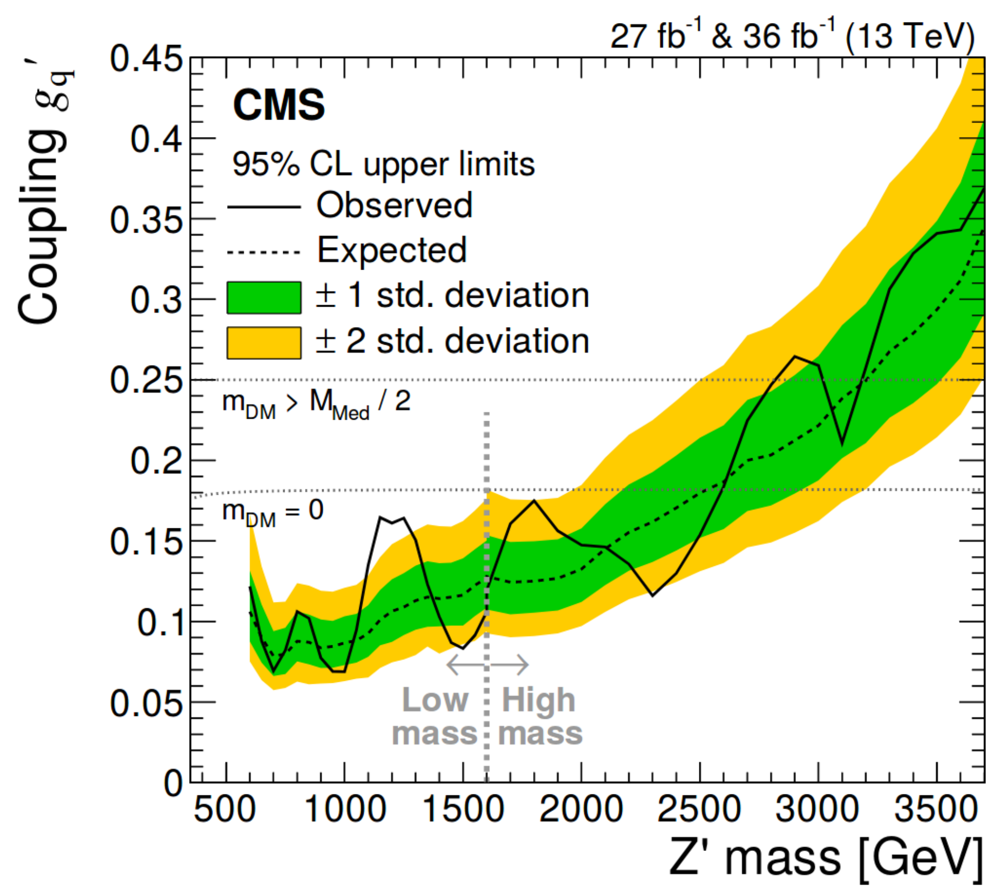


Low Mass Dijet Search

CMS-EXO-16-056

- No evidence of a new resonance, constraints are placed on a wide variety of new physics models
  - ➔ Scouting analysis pushing the limit on the coupling strength, which is essentially a free parameter in many models

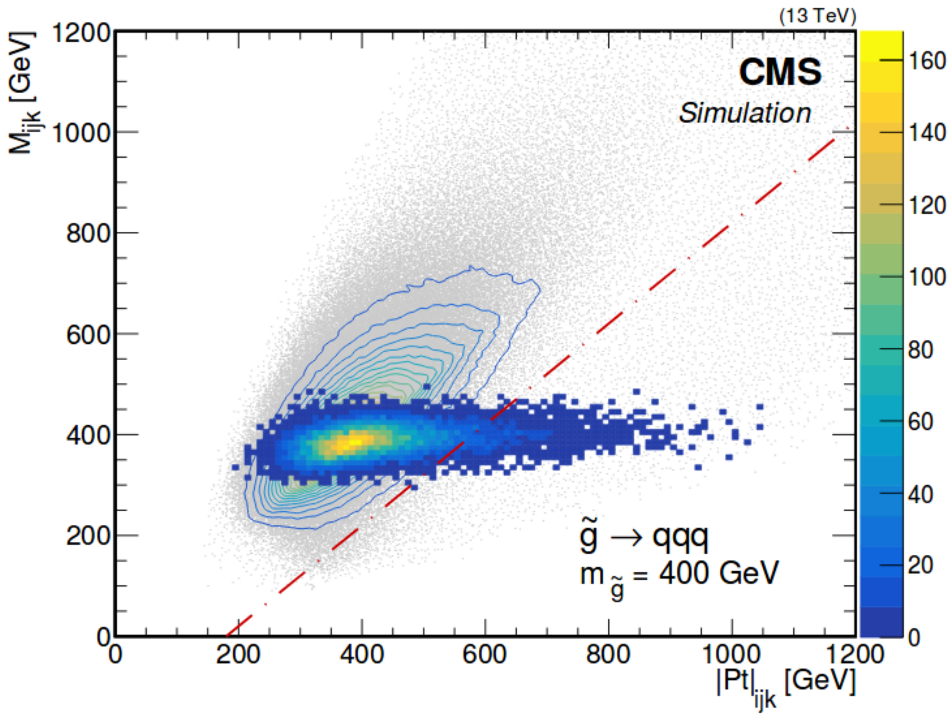




Three-jet Resonance Search

CMS-EXO-17-030

- BSM models such as heavy color octets and RPV SUSY predict a pair produced resonance decaying to 3 jets
  - Offline analysis using an HT requirement of 900 GeV using jets with p_T > 50 GeV, at least 6 jets
  - **PF Scouting** analysis uses an HT requirement of 650 GeV using jets with p_T > 40 GeV, at least 6 jets
    - PF needed to reduce combinatoric background from pileup
- Additional selections are applied to reduce QCD background



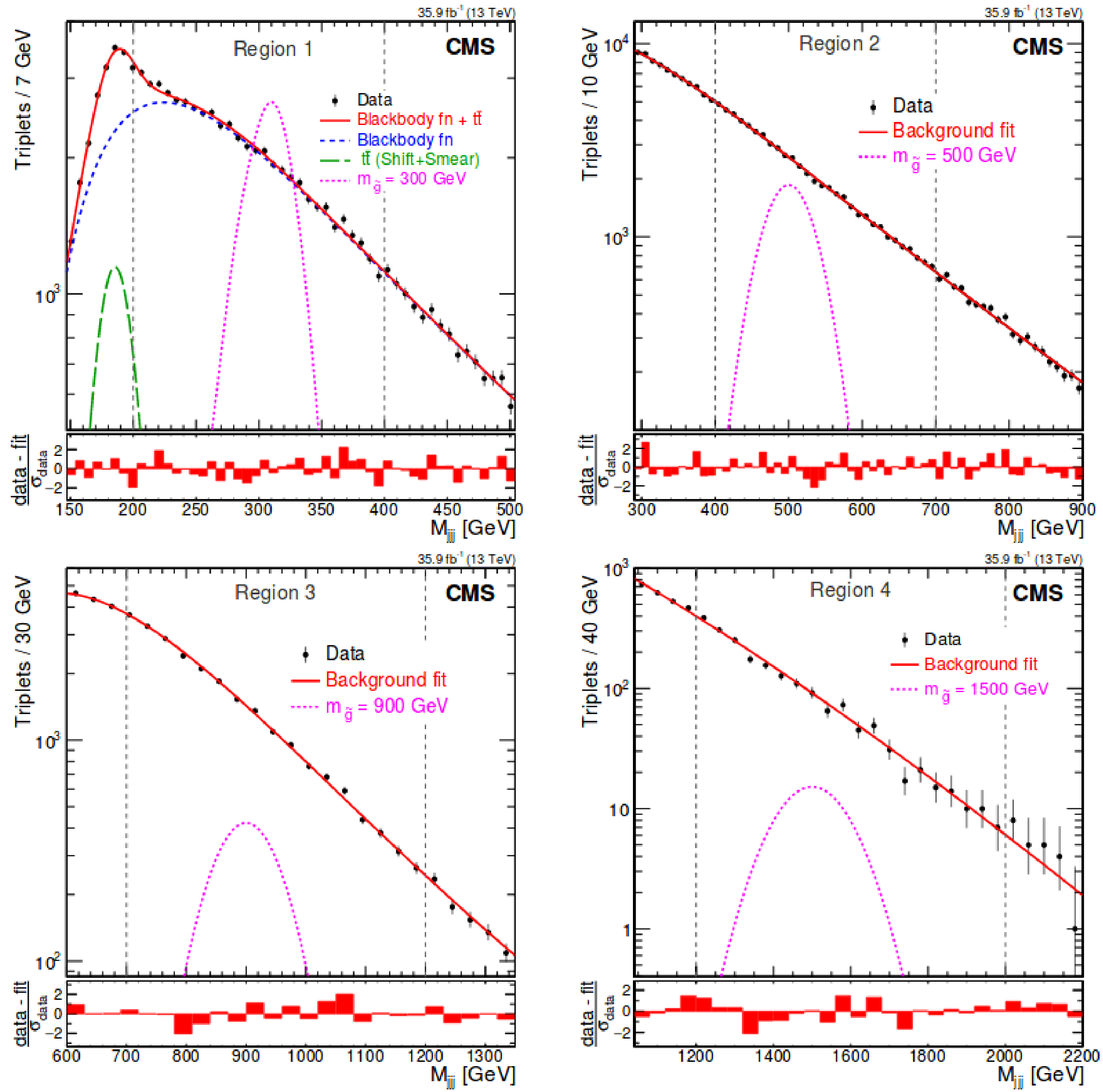
$$m_{ijk} < |p_T|_{ijk} - \Delta$$

Region	Gluino mass range	Jet p_T	H_T	sixth jet p_T	$D^2_{[(6,3)+(3,2)]}$	A_m	Δ	$D^2_{[3,2]}$
1	200–400 GeV	>30 GeV	>650 GeV	>40 GeV	<1.25	<0.25	>250 GeV	<0.05
2	400–700 GeV	>30 GeV	>650 GeV	>50 GeV	<1.00	<0.175	>180 GeV	<0.175
3	700–1200 GeV	>50 GeV	>900 GeV	>125 GeV	<0.9	<0.15	>20 GeV	<0.2
4	1200–2000 GeV	>50 GeV	>900 GeV	>175 GeV	<0.75	<0.15	>-120 GeV	<0.25

Three-jet Resonance Search

CMS-EXO-17-030

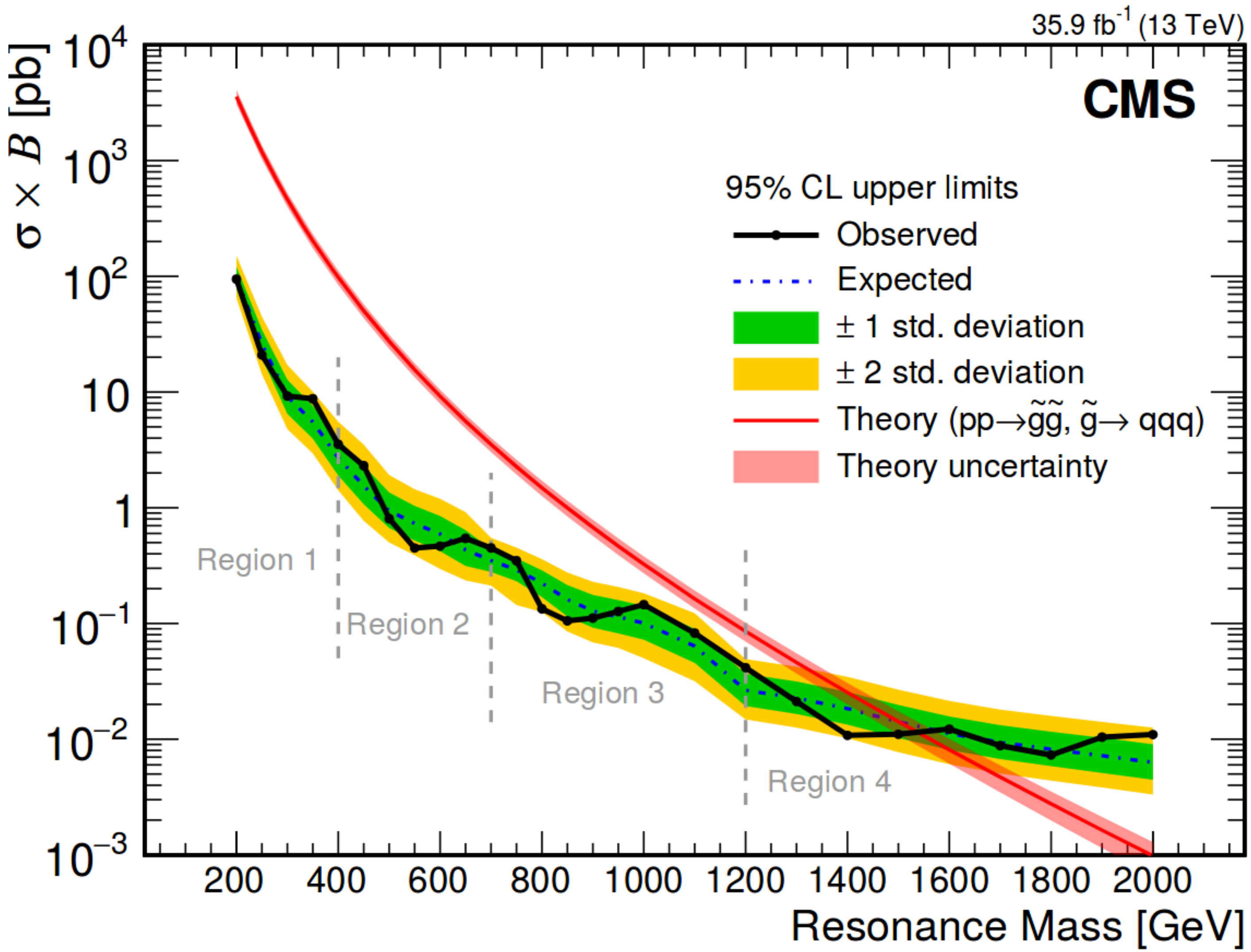
- QCD background dominates for high mass regions, but top pair production is also considered in the lowest mass region
- Scale and resolution corrections are derived from the all hadronic top quark decays and used to correct the gluino simulation



Three-jet Resonance Search

CMS-EXO-17-030

- No significant excess observed, results interpreted in the context of gluino pair production with RPV decay



Motivation for Low Mass Dimuon Search

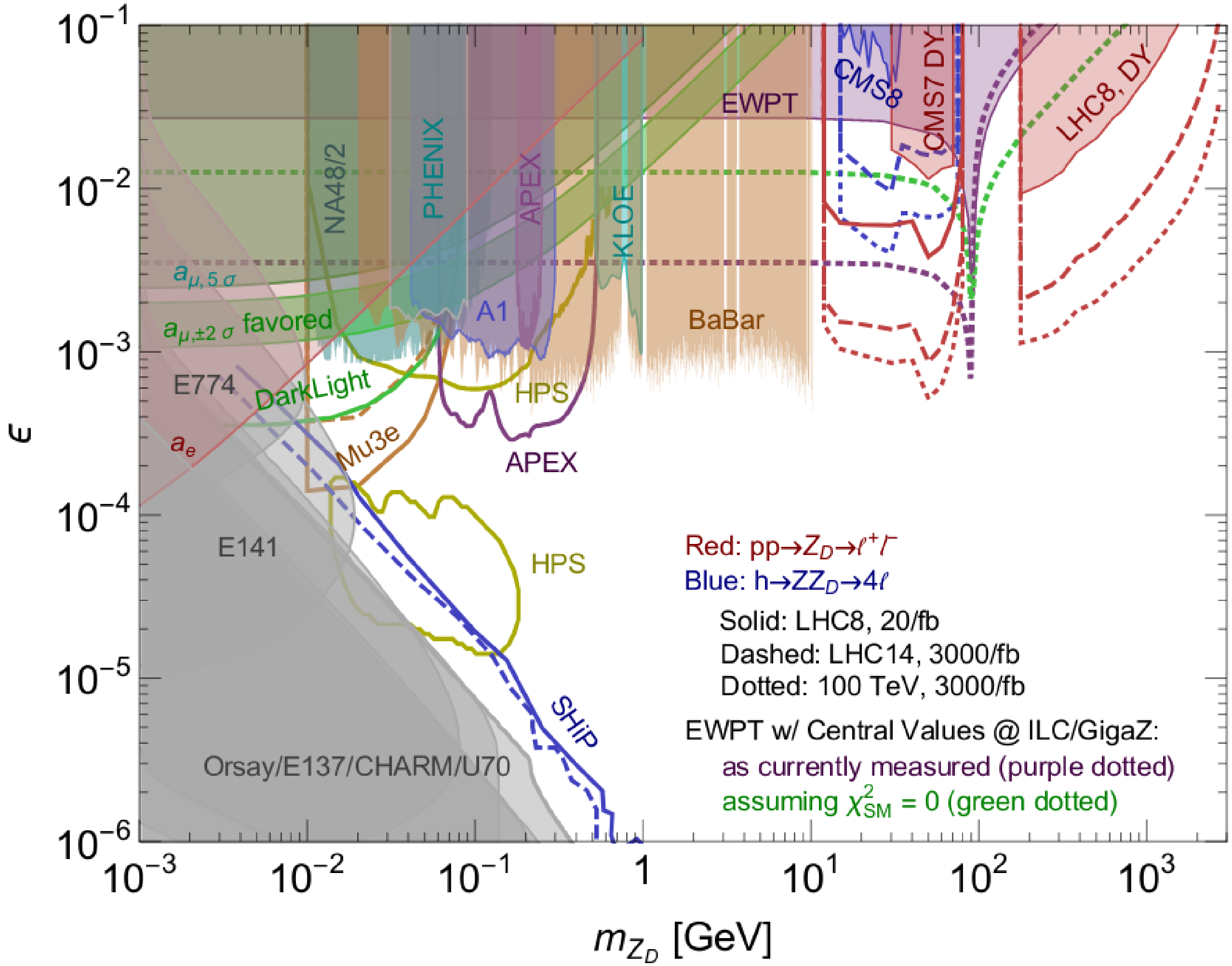
- “Dark photons” arise in many models with hidden sectors

- Rich experimental program covering many order of magnitude in mass and coupling strength

- Couple to electromagnetic charge, dimuon final state promising at colliders

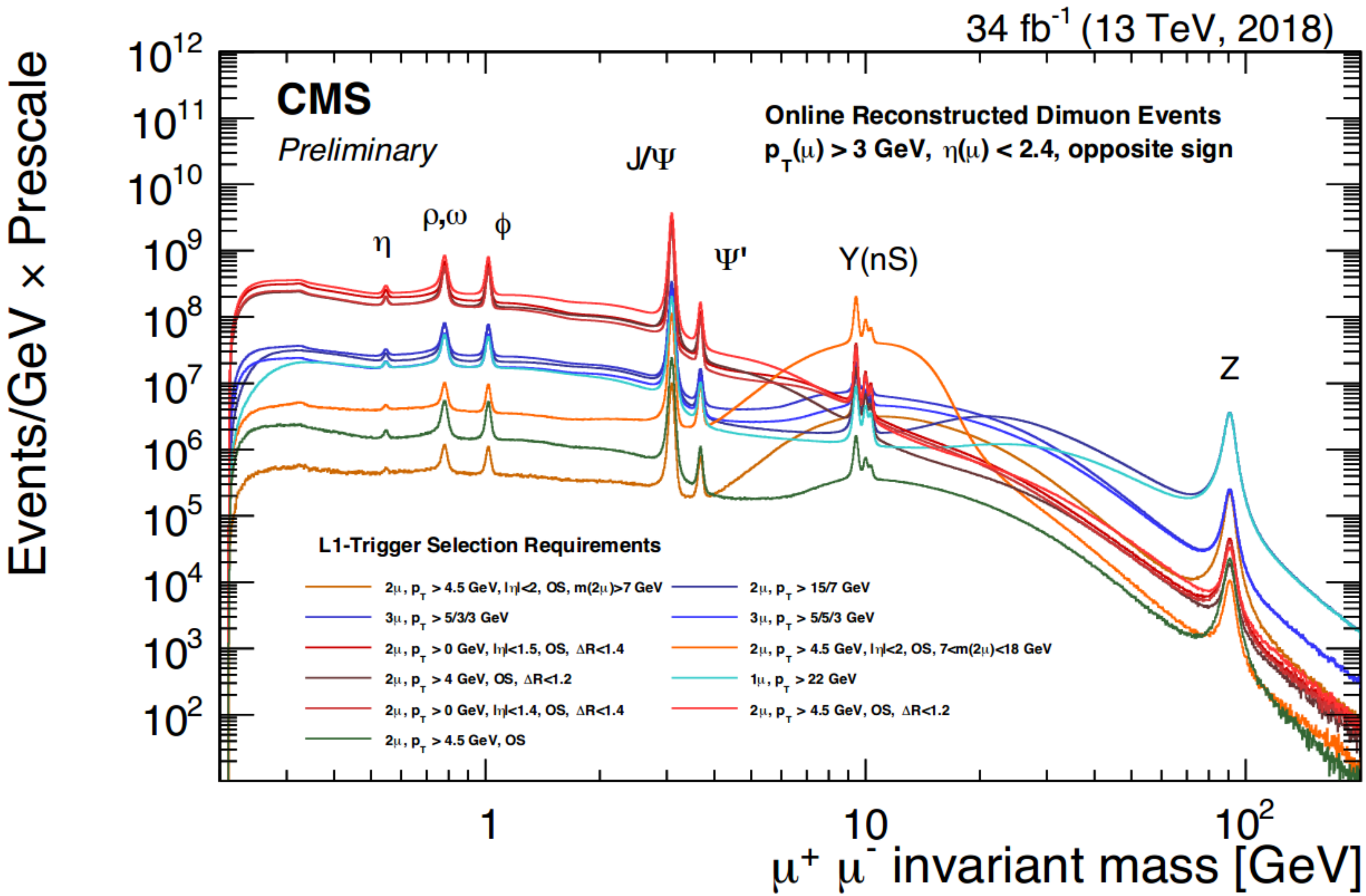
  → Standard dimuon thresholds are 17/8 GeV at HLT

arxiv:1412.0018



Scouting Dimuon Mass Distribution

- CMS collected dimuon events using a collection of L1 muon triggers, and minimal requirements at the HLT level:



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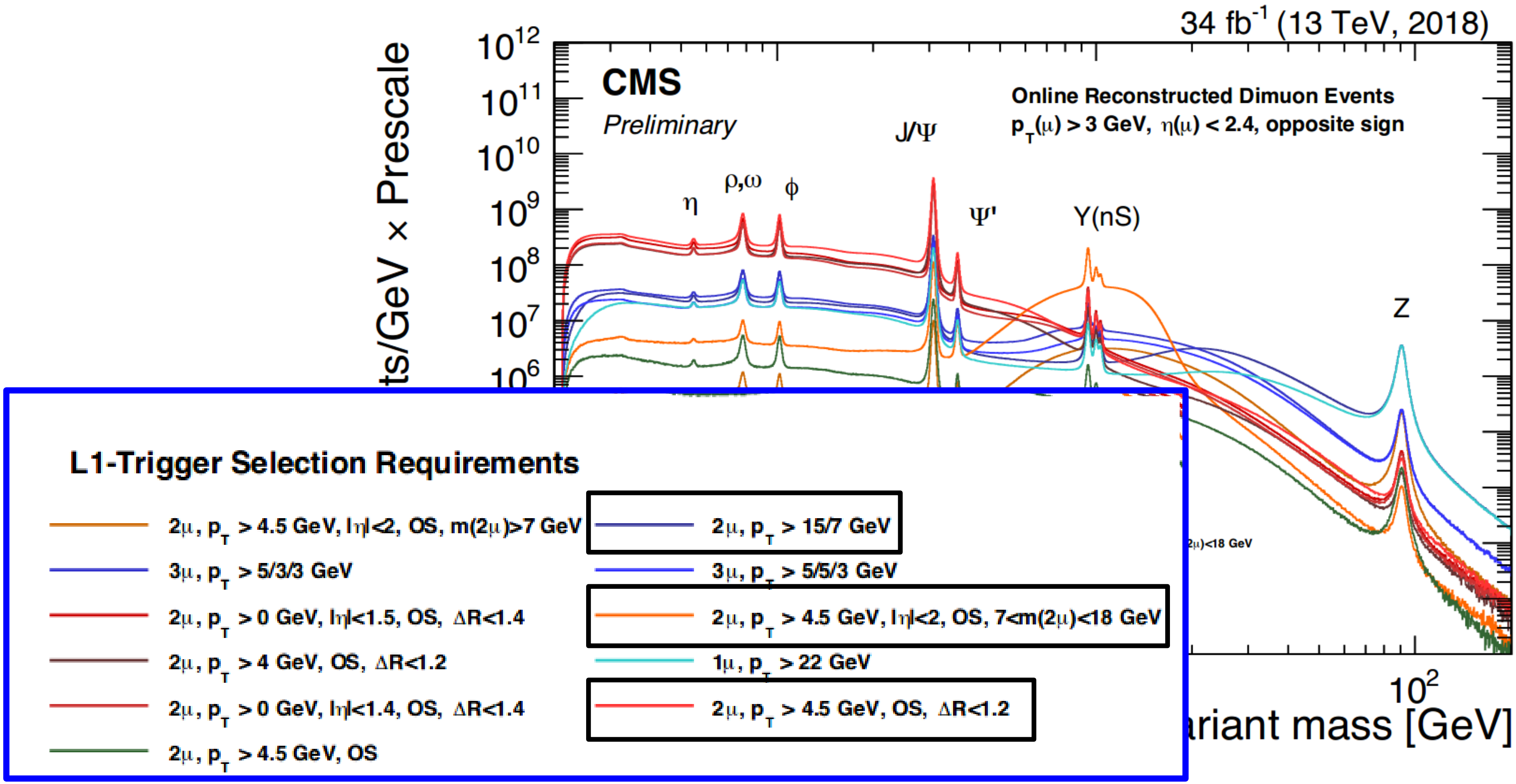
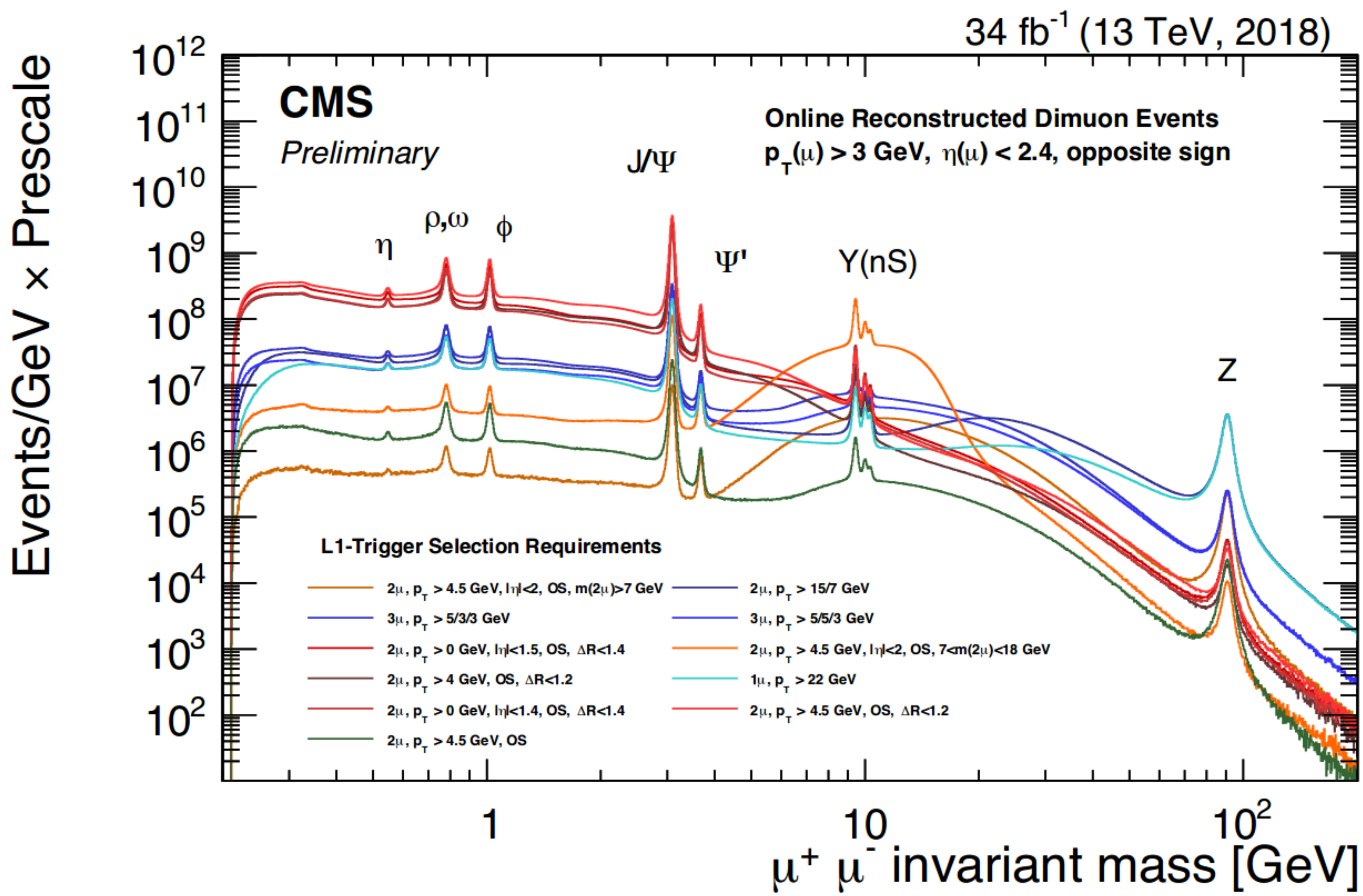


Scouting Dimuon Mass Distribution

- CMS collected dimuon events using a collection of L1 muon triggers, and minimal requirements at the HLT level:

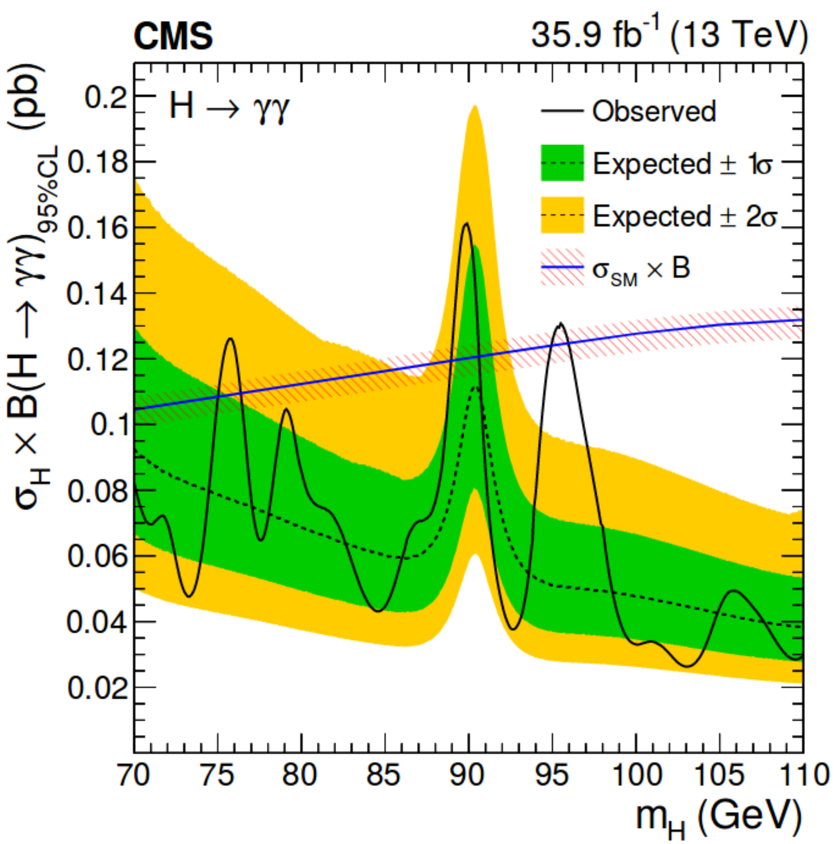
- Expect to achieve “Scouting Advantage” around m(X) ~ 35 GeV

- Finalizing efficiency measurements, background estimation, and statistical analysis...

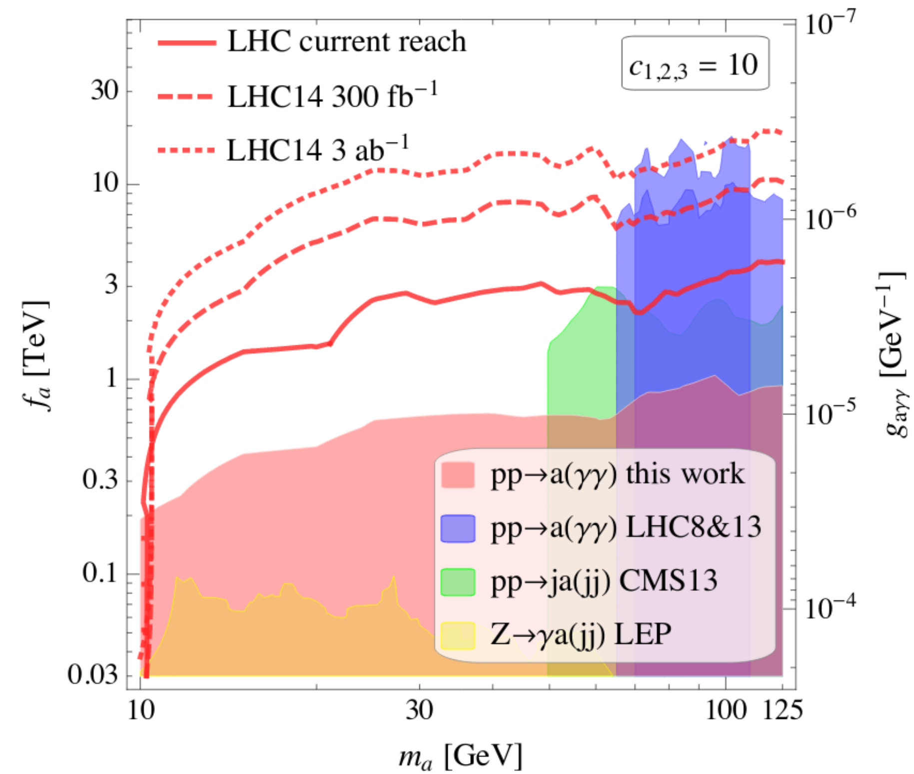


Possible Extensions for HLT Scouting

- For Run 3, plan to extend the coverage further to other final states
  - ➔ PF Scouting on all L1 events? ~400 ms / event, probably unrealistic…
- More realistic to target specific scenarios such as search diphoton resonances to look for low mass scalars or axion like particles
  - ➔ Double EG Thresholds 22 / 12 GeV (L1) and 30 / 18 GeV (HLT)



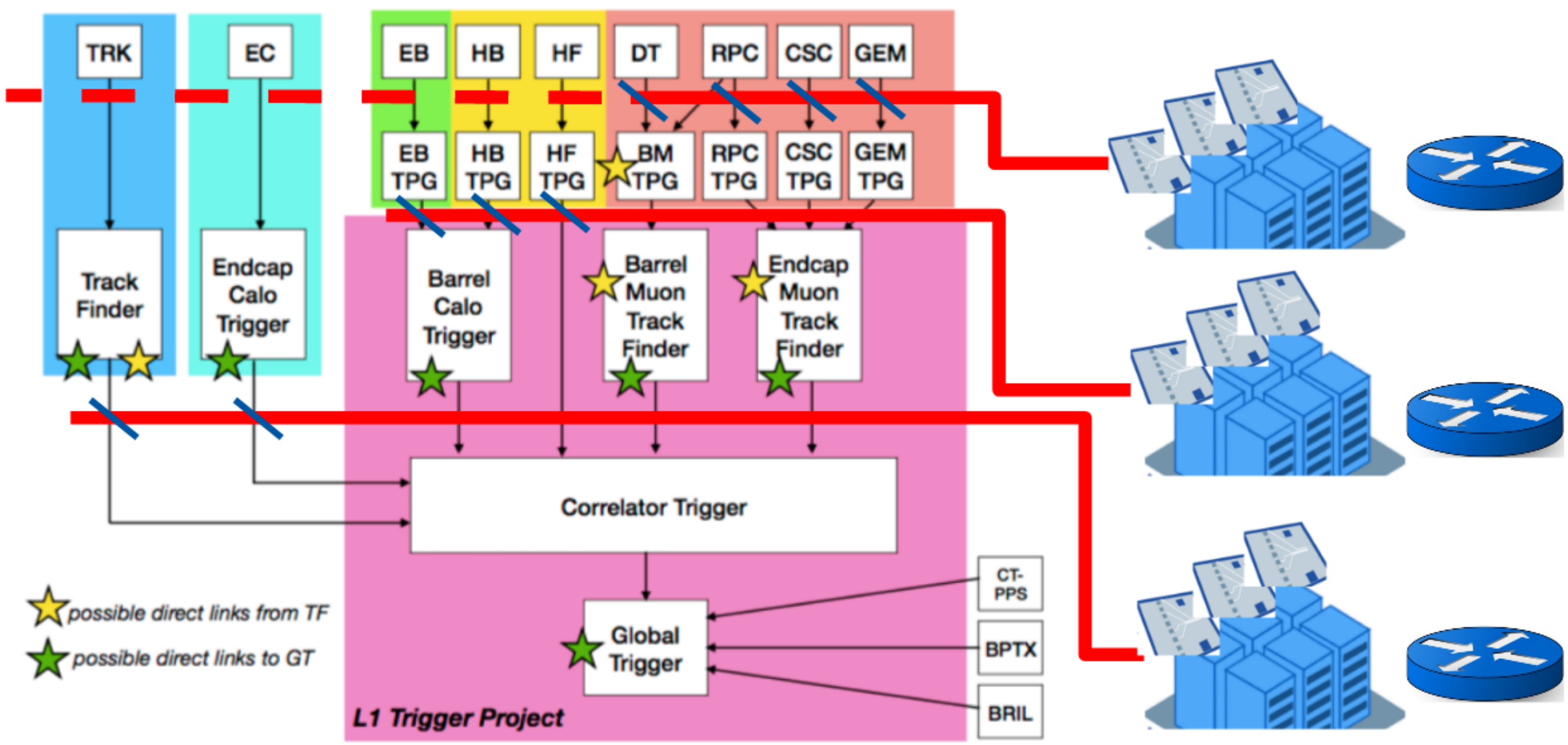
CMS-HIG-17-013



arxiv:1710.01743

Possible Extensions: 40 MHz Scouting

- For HL-LHC, CMS will incorporate tracking into the L1 trigger
  ➔ Muon momentum resolution comparable to today's HLT (few %)
- In addition, several detectors (Barrel Calorimeter, Barrel Muon chambers) will have streaming readout (full granularity for each BX)
- Demonstrator systems currently being developed (DT, uGMT)



Picture Credit: Emilio Meschi

Physics Case for 40 MHz Scouting ?

- Such a system would benefit analyses which are limited by the Level 1 Trigger rate budget, or possibly latency constraints
- And which do not suffer from resolution or background limitations
  - ➔ Not entirely trivial boundary conditions, since the upgraded trigger is very powerful
- Work ongoing to study in detail different signatures, but some being considered are:
  - ➔ Dark photons ($pp \to A \to \mu\mu$ or $D^* \to D^0 A, A \to \ell\ell$)
  - ➔ $H \to \Phi\gamma$, $\rho\gamma$
  - ➔ Low mass $W' \to \tau\nu$
  - ➔ Hidden sector hadronic physics

Summary

- **Data Scouting is by now a well established technique in CMS**
- **Several publications based on hadronic signatures, and first results in dimuon channel being finalized**
- **For Run 3 and HL-LHC, the program will be expanded creating new possibilities for discovery**