CMS Scouting And Dark Matter Searches

Jakob Salfeld-Nebgen

April 8th, 2021

Intro

- Initially CMS Scouting and Parking came as a “siblings”:
  - Scout for new signatures, reconstruct parked data once new signature found
    - CMS Scouting introduced 2011
- Active development and further improvements over the years
  - Included additional Level-1 triggers and good reconstruction quality (Particle Flow)
- Basic concept: reconstruct events in High-Level Trigger compute farm instead of offline computing resources
  - Improves greatly BSM phase-space coverage and is cheaper (less resources)
- ATLAS and LHCb have similar workflows (Trigger-Level Analysis, Turbostream)
- This gives access to as much as 100 times higher rates at the LHC multipurpose experiments with thresholds applied at the Level-1 trigger rather than High-level trigger
- For Run 3 and Phase 2 these concepts become important to increase discovery potential and overcome the constantly increasing luminosity doubling time

A Note on Dark Matter

- **Direct searches for dark matter involve missing transverse energy signatures in the pp collisions**
- **Theories explaining dark matter usually involve additional particles, and the coupling to the SM is established via a mediator**
  - **==> Can generically look for visible decay signatures of mediators**
    - **There is obviously a large theory space suggesting many signatures**
- **Portal Framework covers many phenomenological consequences and possibilities; can be used as a guideline what signatures to explore experimentally at low masses**

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DS}} + \mathcal{L}_{\mathrm{Portal}}$$

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Sterile Neutrino, N	$y_N L H N$

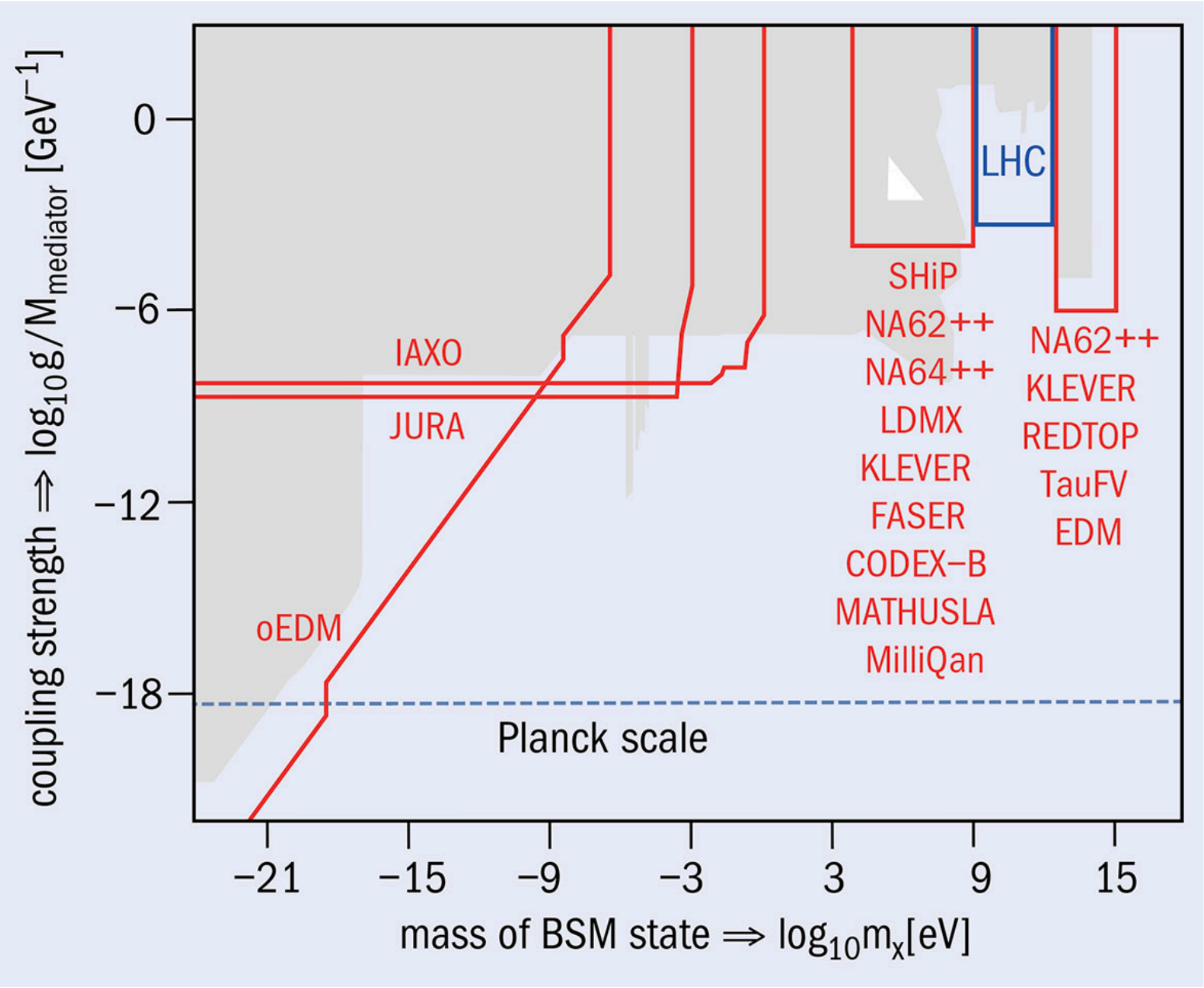
Dark Sectors Workshop

FIPs

PBC (BSM report)

Scouting Physics Potential

- **The light BSM phenomenology is well developed for experiments other than the LHC**
- **Will need effort to map out physics potential of low-pT physics with multipurpose detector at LHC**



LHC sensitivity for M>10 GeV exclusive for many BSM theories.

Multipurpose experiments also competitive for some models in O(0.1 - 10) GeV range

Dark Sectors Workshop

FIPs

PBC (BSM report)

CMS Scouting Run 2

L1-Trigger

Scouting Path	L1 trigger requirements
Muon CaloScouting	$2\mu, p_T > 15/7$ GeV $3\mu, p_T > 5/3/3$ GeV 2μ, OS, $p_T > 4.5$ GeV, $\lvert\eta\rvert < 2$, $7 < m(2\mu) < 18$ GeV 2μ, OS, $p_T > 0$ GeV, $\lvert\eta\rvert < 1.5, \Delta R < 1.4$ 2μ, OS, $p_T > 4.5$ GeV, $\lvert\eta\rvert < 2.5, \Delta R < 1.2$
H_T Calo/PF-Scouting	1 jet, $p_T > 180$ GeV 2 jets, $p_T > 30$ GeV, $\lvert\eta\rvert < 2.5$, $m(2j) > 300$ GeV, $\Delta\eta < 1.5$ $H_T > 360$ GeV

Loose Cuts at HLT

Scouting Path	Selection	Rate [kHz]	Proc. Time [ms]
Muon Calo-Scouting (2017–2018)	(2μ, $p_T > 3$ GeV)	2.7	350
H_T Calo–Scouting (2016–2018)	($H_T > 250$ GeV)	3	160
H_T PF–Scouting (2016–2018)	($H_T > 410$ GeV)	0.7	1200

Scouting Datasets

Scouting Dataset	# events	dataset size	average size per event
Muon Calo–Scouting (2017–2018)	14.4 B	56 TB	3.9 kB
H_T Calo–Scouting (2016–2018)	37.7 B	78 TB	2.1 kB
H_T PF–Scouting (2016–2018)	7.7 B	66 TB	8.6 kB

Event Content

- **CMS Scouting event content differed for the scouting triggers**

PF-Scouting

Calo-Scouting

1-10 kB per event

Physics Object	Event Content
Event based	ρ (average energy density) PF/Calo MET p_T, ϕ
Calo Jets ($p_T > 20$ GeV, $\lvert\eta\rvert < 3$)	p_T, η, ϕ, m Hadronic energy-fraction in HB, HE, HF EM energy-fraction in EB, EE, HF jet-area (AK4)
PF Jets [25] ($p_T > 20$ GeV, $\lvert\eta\rvert < 3$)	p_T, η, ϕ, m π^0, π^+, e, γ, μ sum of energies π^0, π^+, e, γ, μ multiplicities index in PF-Candidate collection
PF Candidates [25] ($p_T > 0.6$ GeV))	p_T, η, ϕ, m pdgId, index in vertex collection
Verices (also displaced dimuon)	x, y, z, δx, δy, δz # tracks, ndof, χ^2
Tracks around Muons	p_T, η, ϕ, charge dz, dxy, λ, q/p, diagonal of covariance matrix
Muons [29]	p_T, η, ϕ, m, charge track: ndof, χ^2, dz, dxy, λ, q/p relative isolation: (ΔR <0.3) ECAL, HCAL, Tracks ID: # SiPixel hits, # SiStrip hits, # muon chamber hits
Electrons [27]	p_T, η, ϕ, m, charge relative isolation: (ΔR <0.3) ECAL, HCAL, Tracks ID: H/E, $\sigma_{i\eta i\eta}$, dxy, dz, $(\frac{1}{E} - \frac{1}{p})$, missing hits, $\Delta\phi_{\text{in}}$, $\Delta\eta_{\text{in}}$
Photons [27]	p_T, η, ϕ, m, charge relative isolation: (ΔR <0.3) ECAL, HCAL ID: H/E, $\sigma_{i\eta i\eta}$

CMS Scouting Analyses

- **For now 7 published results based on CMS Scouting program**
  - **More analyses in the pipeline, datasets can be explored further**

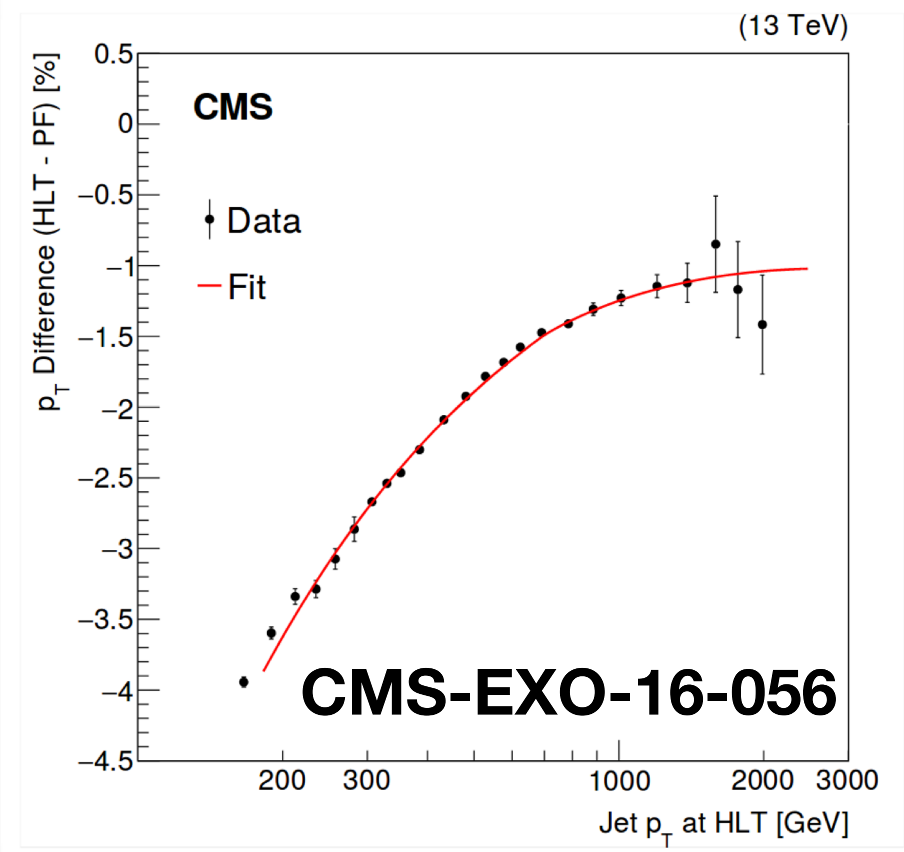
identifier	Title
EXO-11-094	Search for Narrow Resonances using the Dijet Mass Spectrum in pp Collisions at sqrt s of 7 TeV
EXO-14-005	Search for narrow resonances in dijet final states at 8 TeV using data scouting
EXO-16-032	Search for dijet resonances in proton-proton collisions at sqrt(s) = 13 TeV and constraints on dark matter and other models
EXO-16-056	Search for narrow and broad dijet resonances in proton-proton collisions at 13 TeV and constraints on dark matter mediators and other new particles
EXO-17-030	Search for pair-produced three-jet resonances in proton-proton collisions at 13 TeV
EXO-19-004	Search for dijet resonances using events with three jets in proton-proton collisions at 13 TeV
EXO-19-018	Search for a narrow resonance lighter than 200 GeV decaying to a pair of muons in proton-proton collisions at 13 TeV

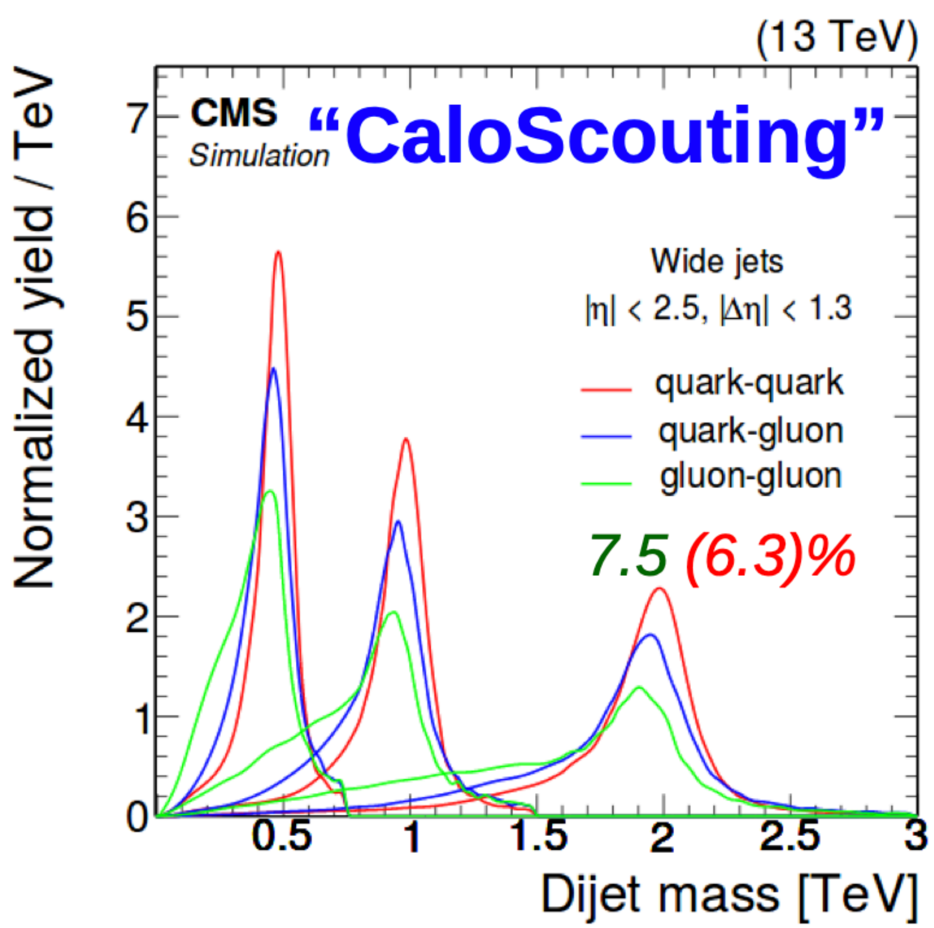
- **And 2 technical notes**

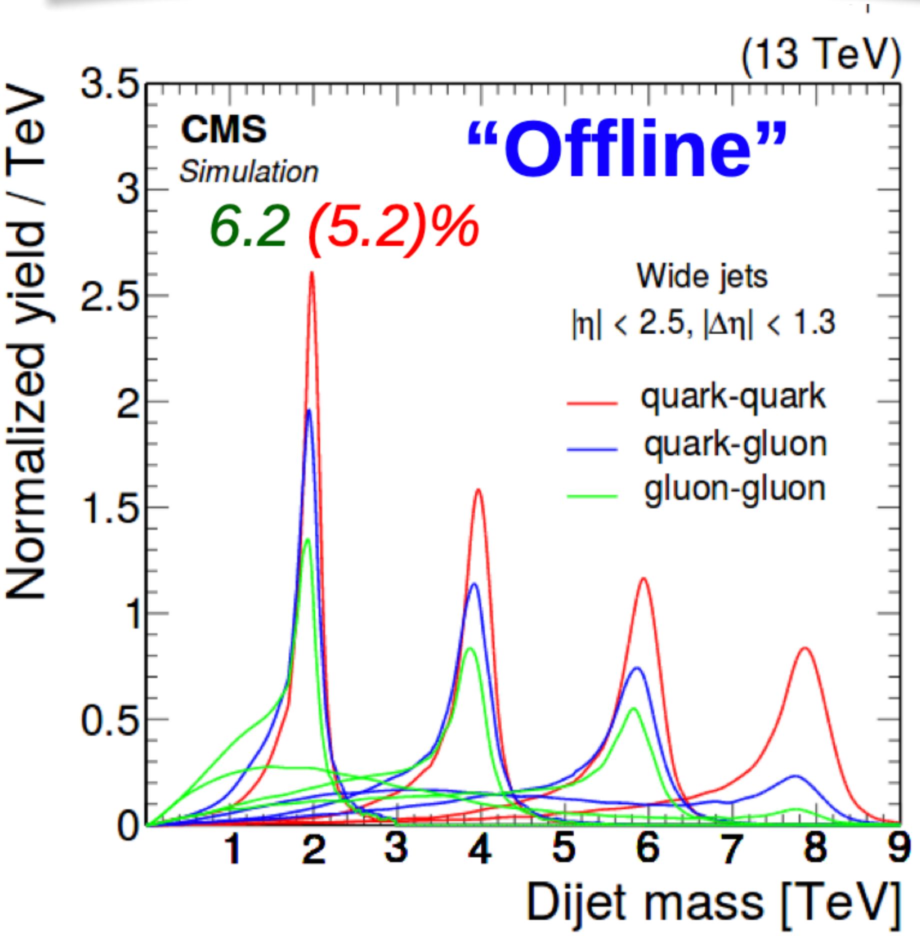
identifier	Title
DP-2012-022	Data Parking and Data Scouting at the CMS Experiment
DP-2018-055	HLT Dimuon Invariant Mass Distributions in 2017 and 2018

Inclusive Di-Jet Resonance

- **Jet energy scale of Scouting calorimeter jets to offline reconstructed jet**
  - **Dedicated Calibration Stream**
- **For resonances at 2 TeV, the detector resolution is ~20% worse in Scouting (Calo-Jets)**

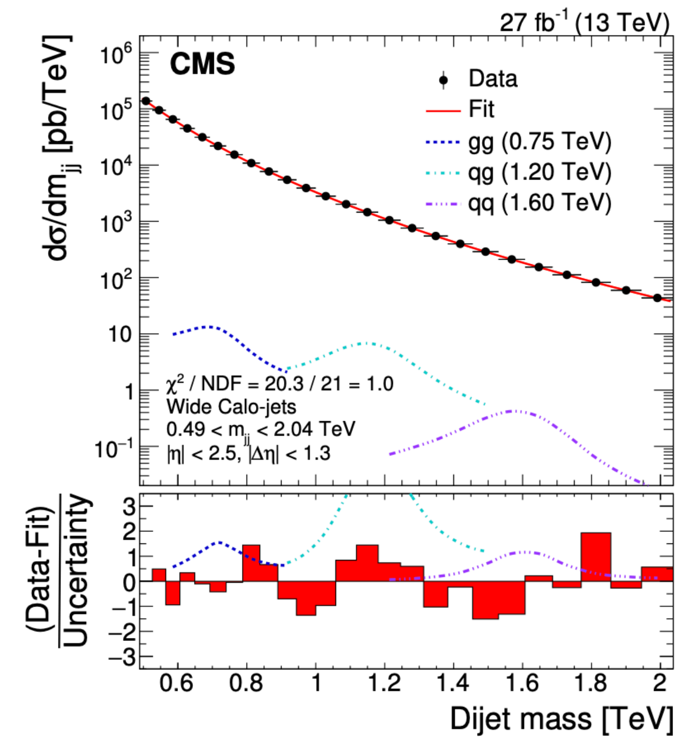


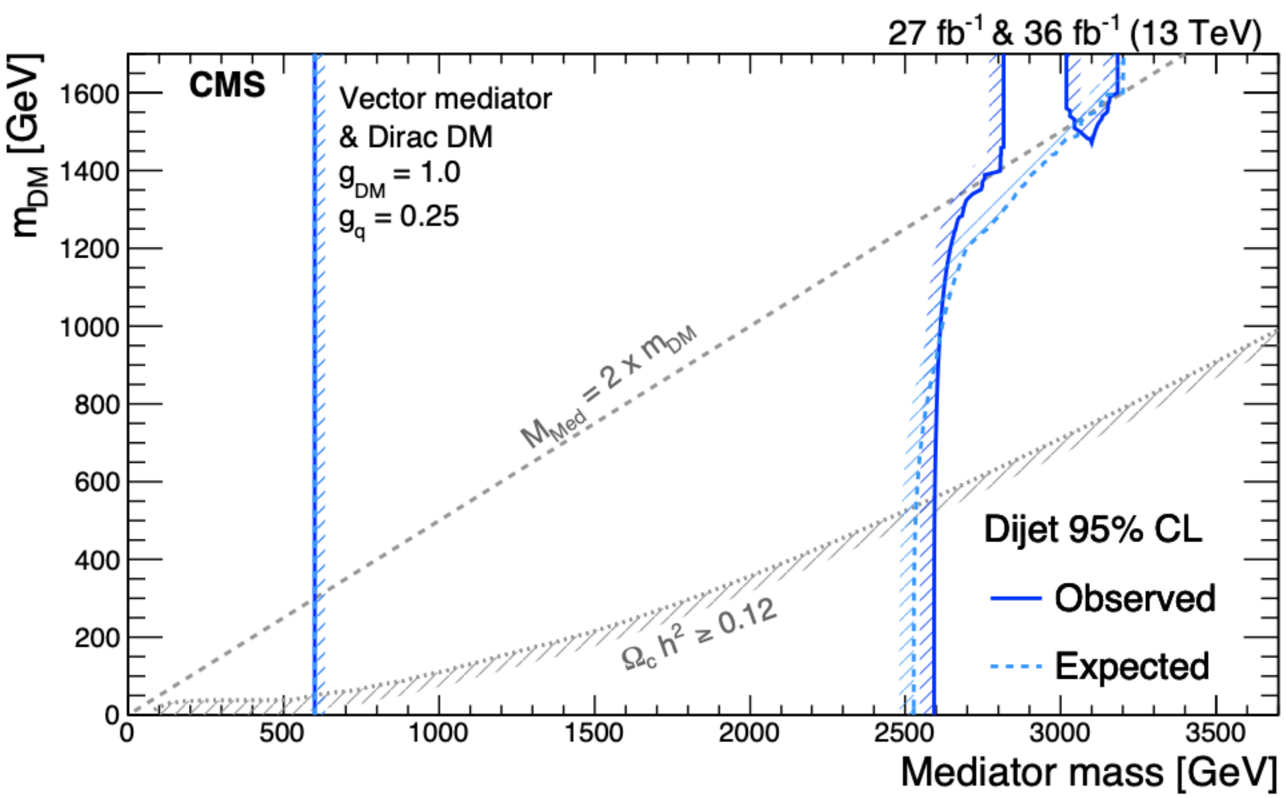


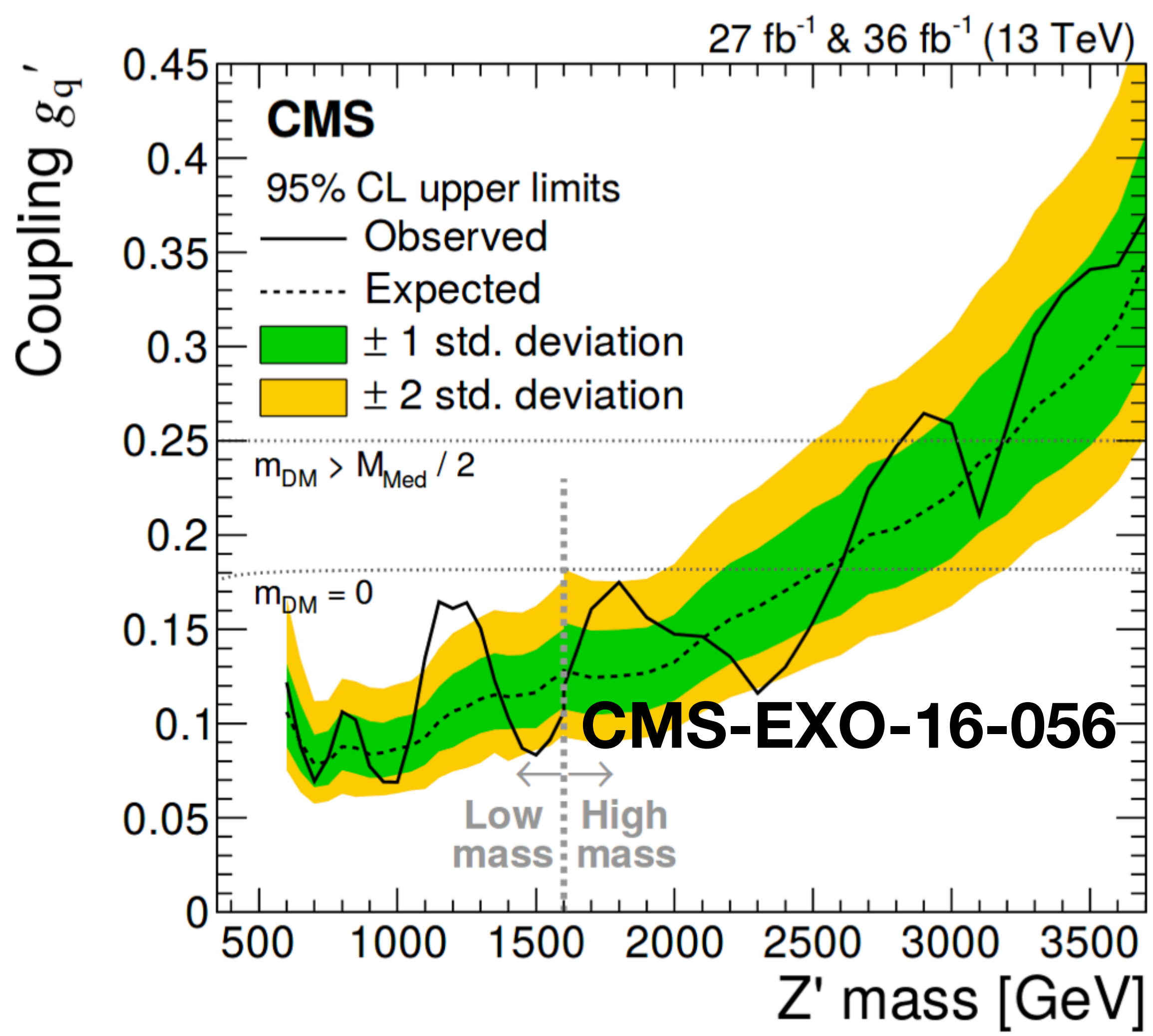


Inclusive Di-Jet Resonance

- Dijet mass spectrum is fitted with analytic function to extract knowledge about any signs for a resonance
  - Projections into the dark matter mass vs mediator plane performed
- Full Run 2 analyses in progress



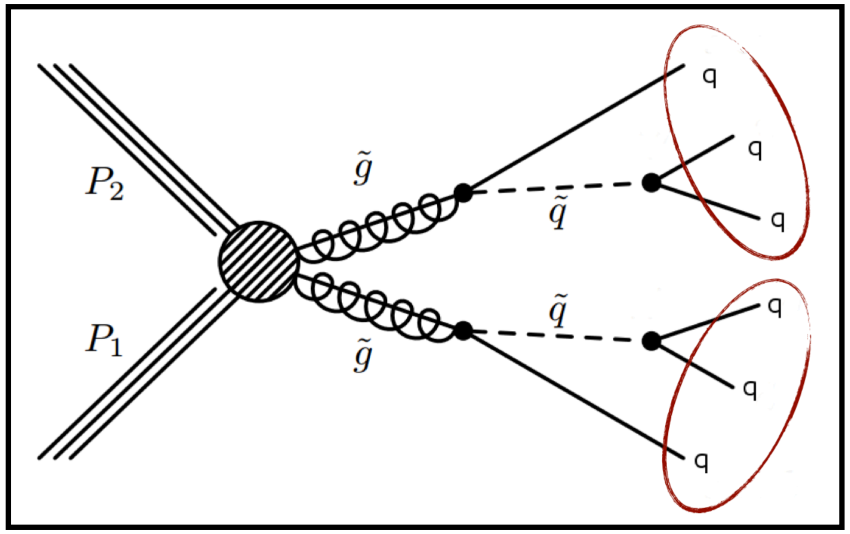




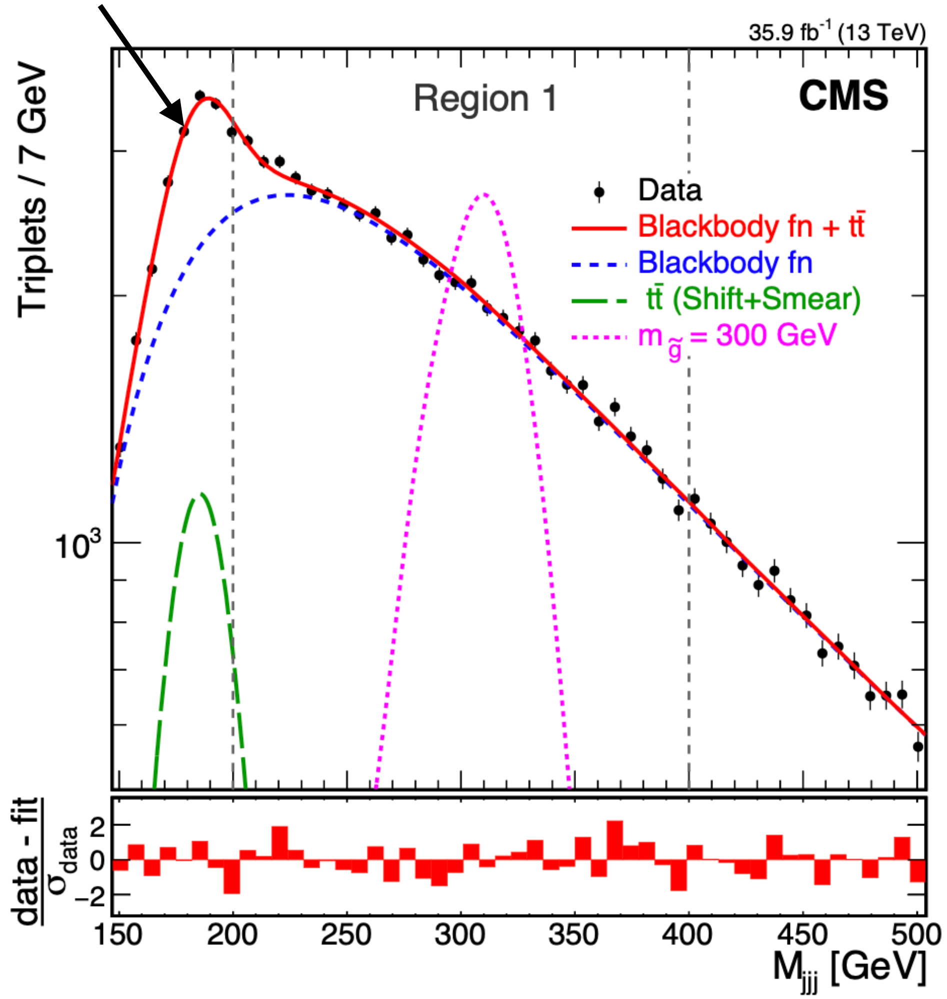
Particle Flow Scouting

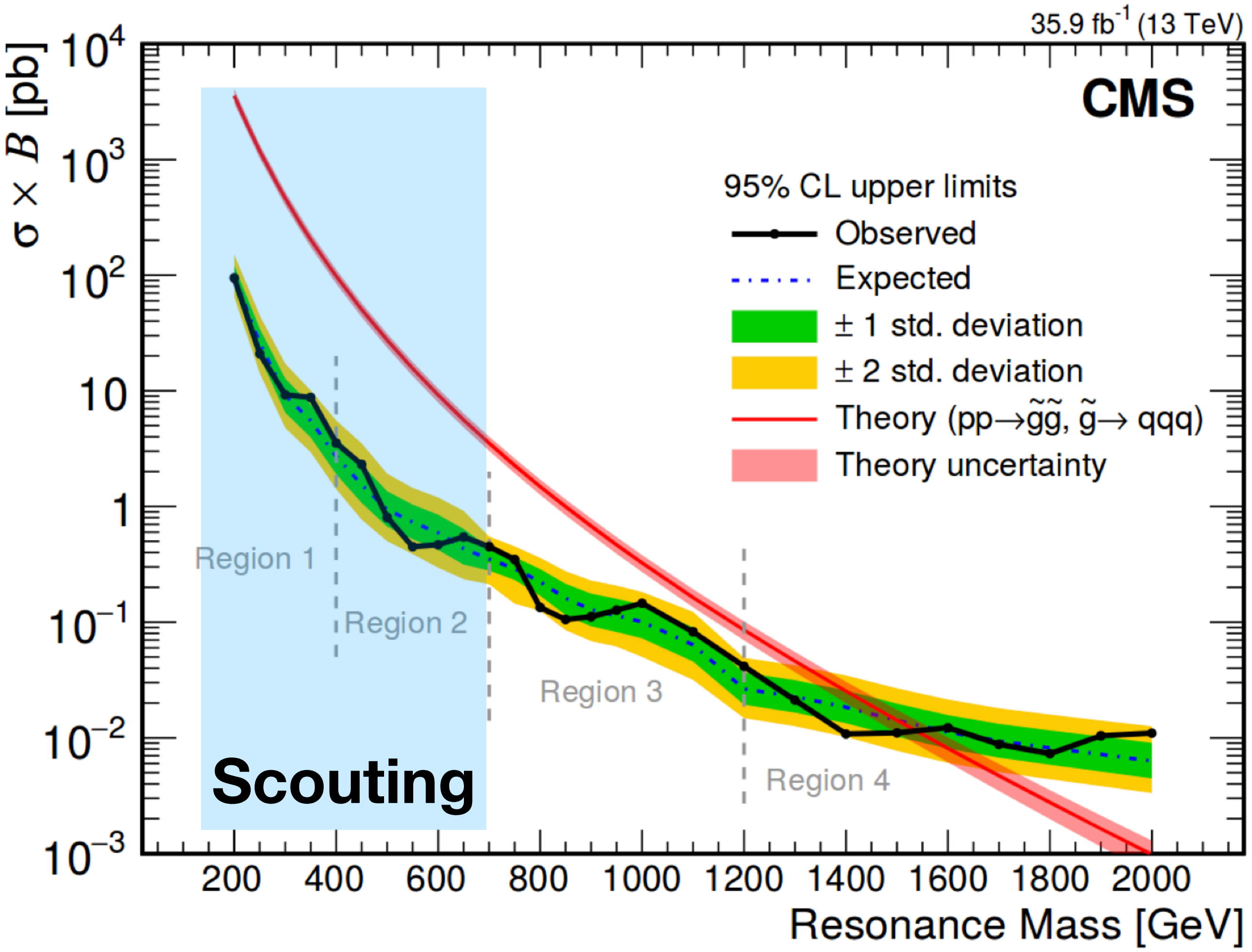
CMS-EXO-17-030

- A search for pair produced tri-jet resonances as e.g. predicted by Supersymmetric Models
- Full Run 2 dataset being analysed
  - Detailed jet substructure studies being performed



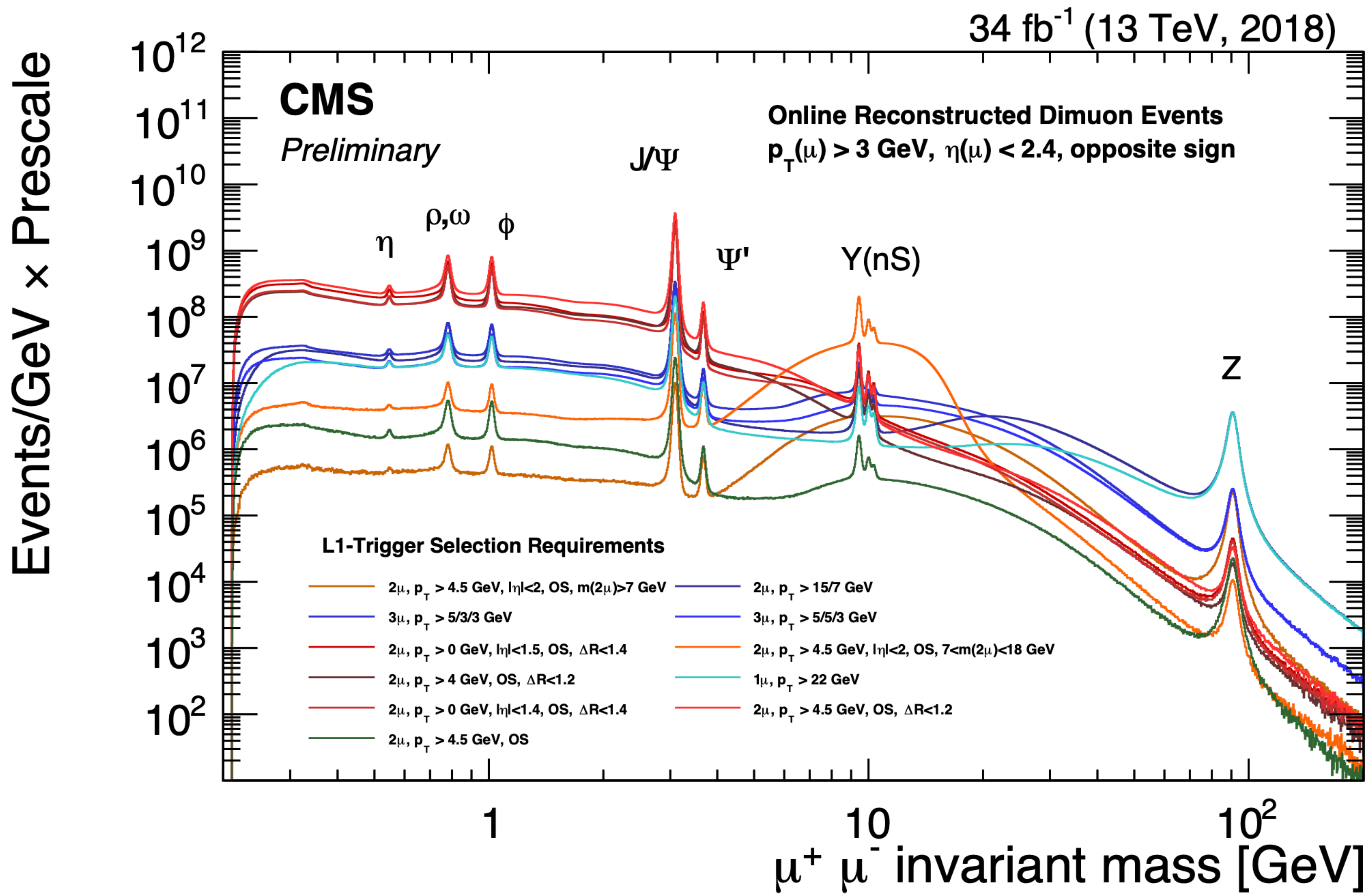
Top quark mass





Leptonic Mediator Decays

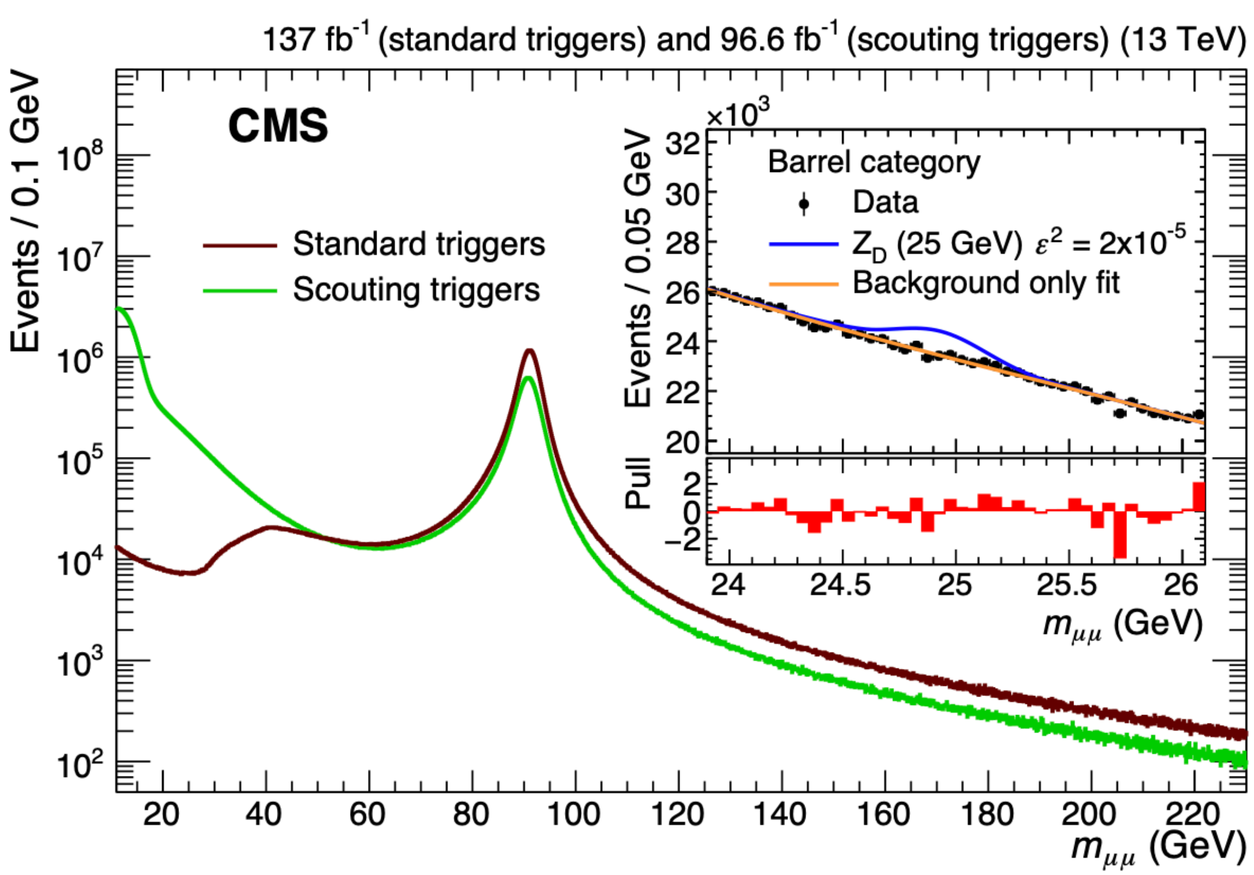
Invariant mass spectrum per L1-Trigger as collected with Scouting

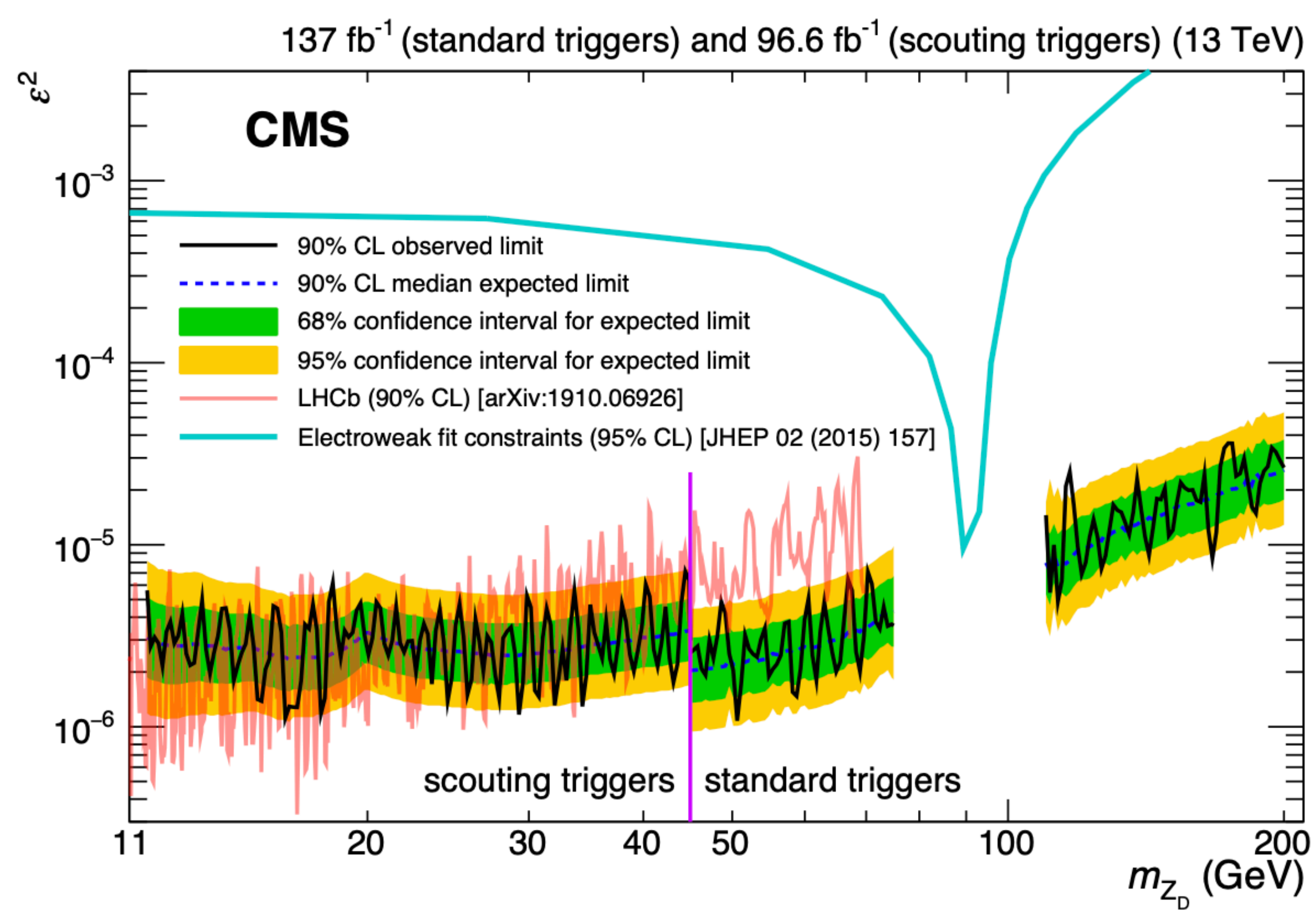


CMS DP-2018/055

CMS Dark Photon Search

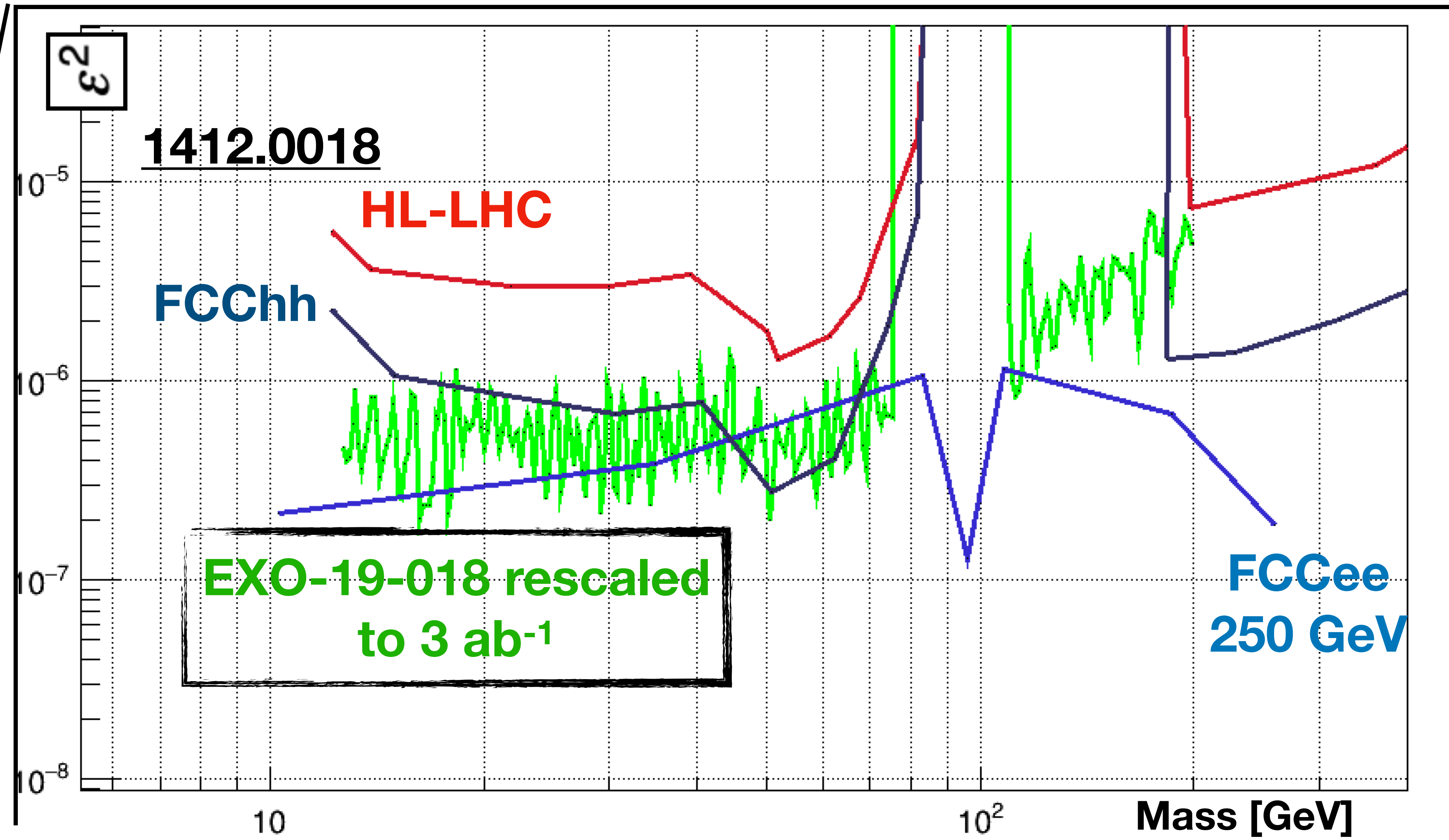
- **CMS performed a search for a narrow dimuon resonance at 13 TeV**
  - **~ 100 fb-1 was collected with the Scouting trigger**
- **The dimuon invariant resolution is 1-2%, depending on pseudo rapidity**
  - **In Scouting, the resolution is roughly 10% worse, impact on sensitivity ~3%**
- **Interpreted in Dark Photon model, cross section scales with ε²**



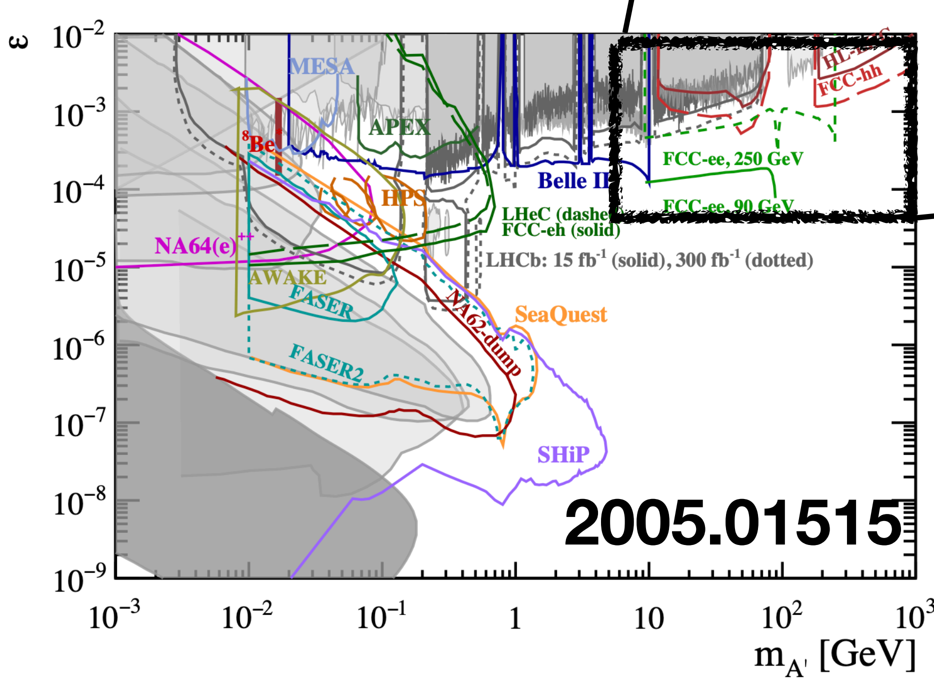


High-Mass Future Projections

Anticipated reach is largely out-performed



Also check EU Strategy for Particle Physics document
1910.11775



Can improve analyses techniques, sensitivity reaches projections for colliders a couple of decades away

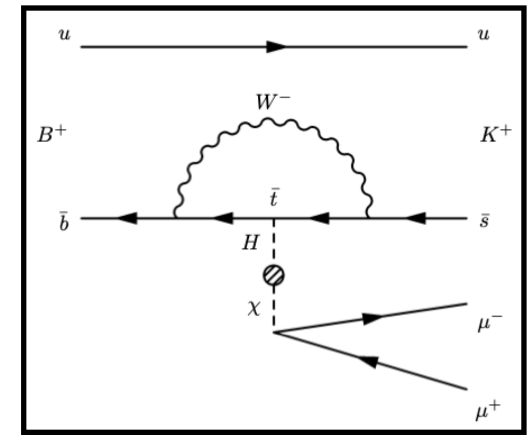
Low Mass Dimuon Scouting

Exploitation of mass below 10 GeV not yet published

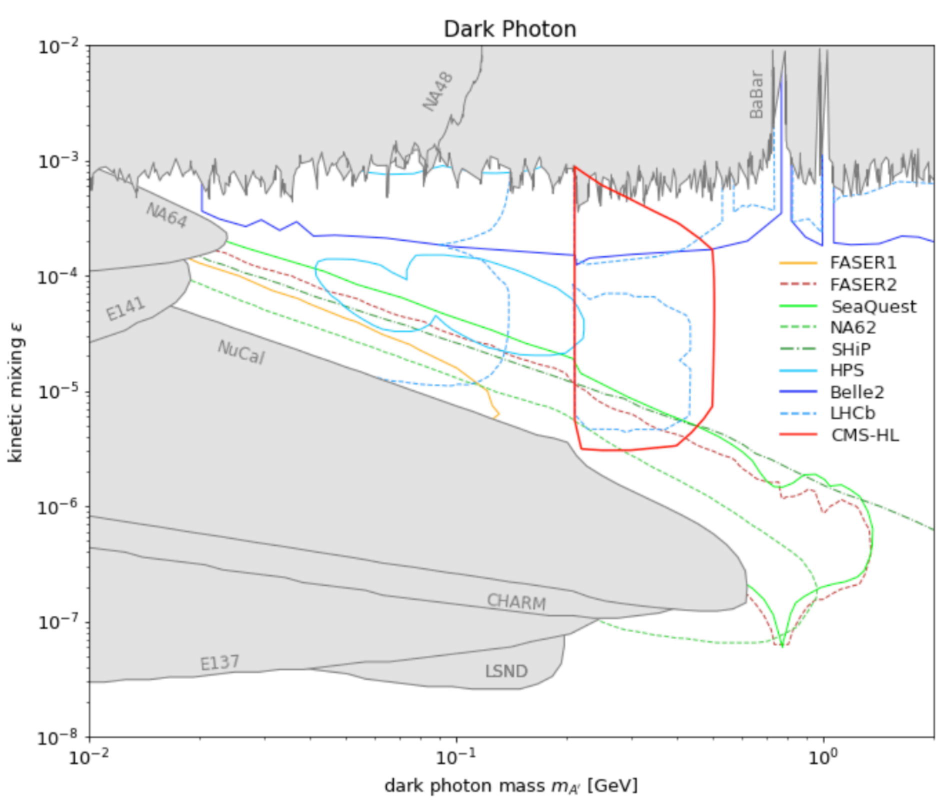
Expect good sensitivity in particular for displaced (< 10cm) dimuon decays

Models investigated in 1902.04222 where ATLAS/CMS could have an edge

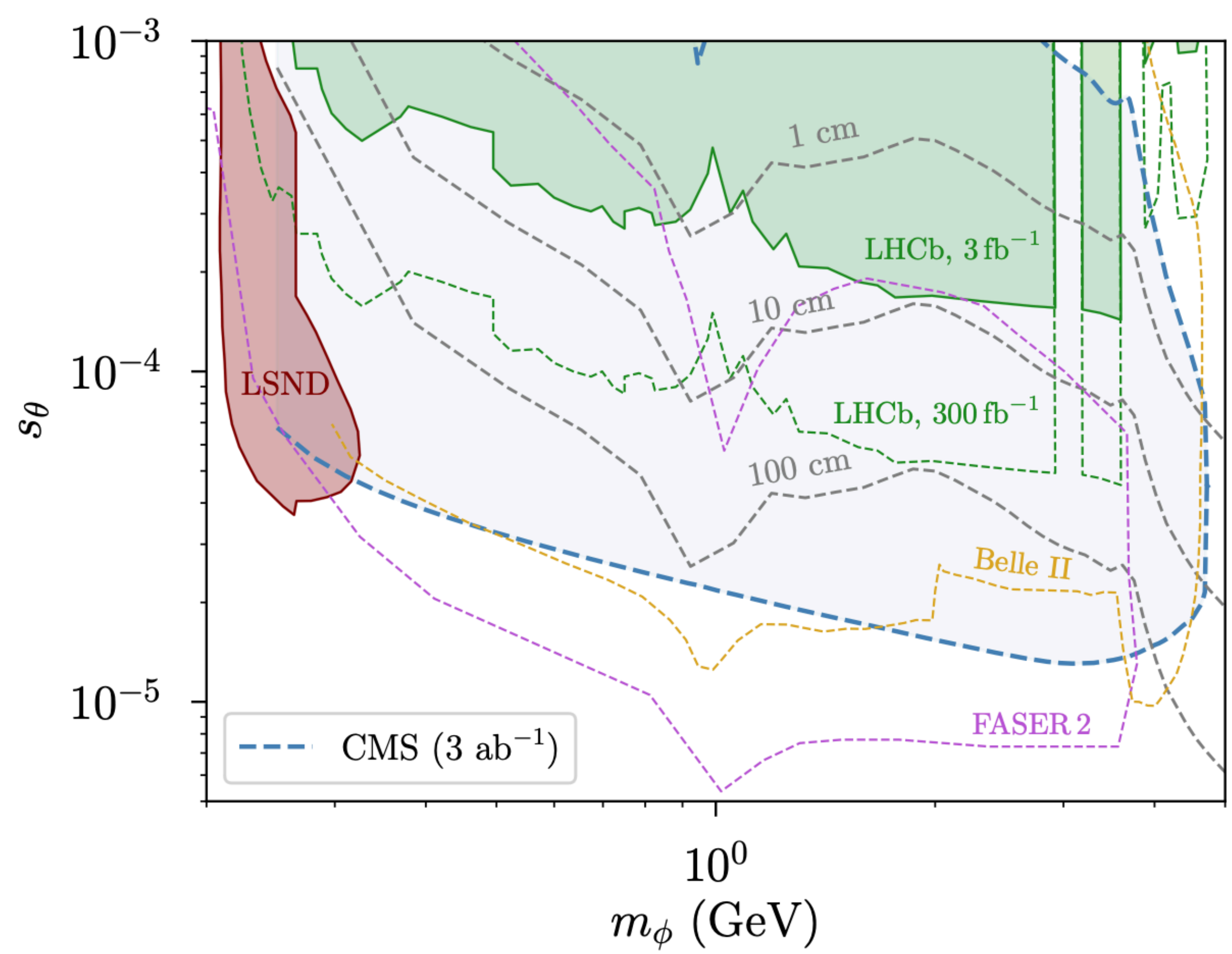
$$\theta = \frac{\mu v}{m_h^2 - m_S^2}$$



$$\eta \rightarrow \gamma A \rightarrow \gamma \mu \mu$$



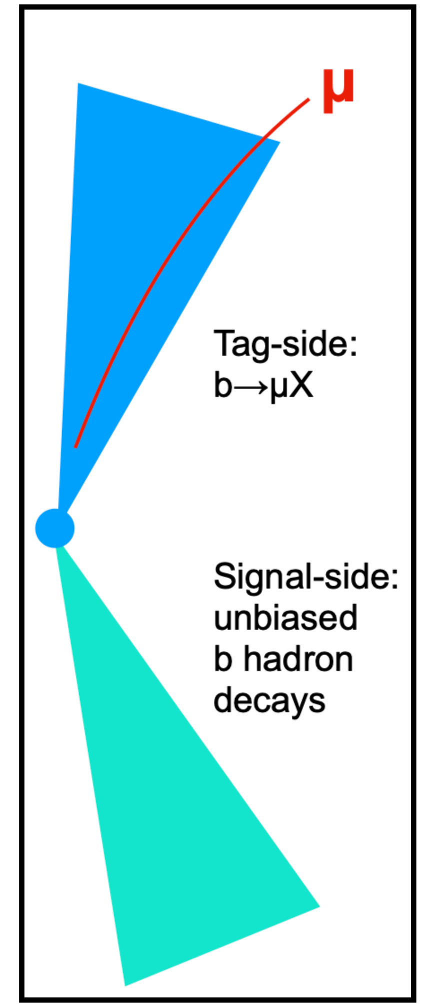
Unpublished, optimistic estimate, assuming 0 background



arxiv:2008.06918

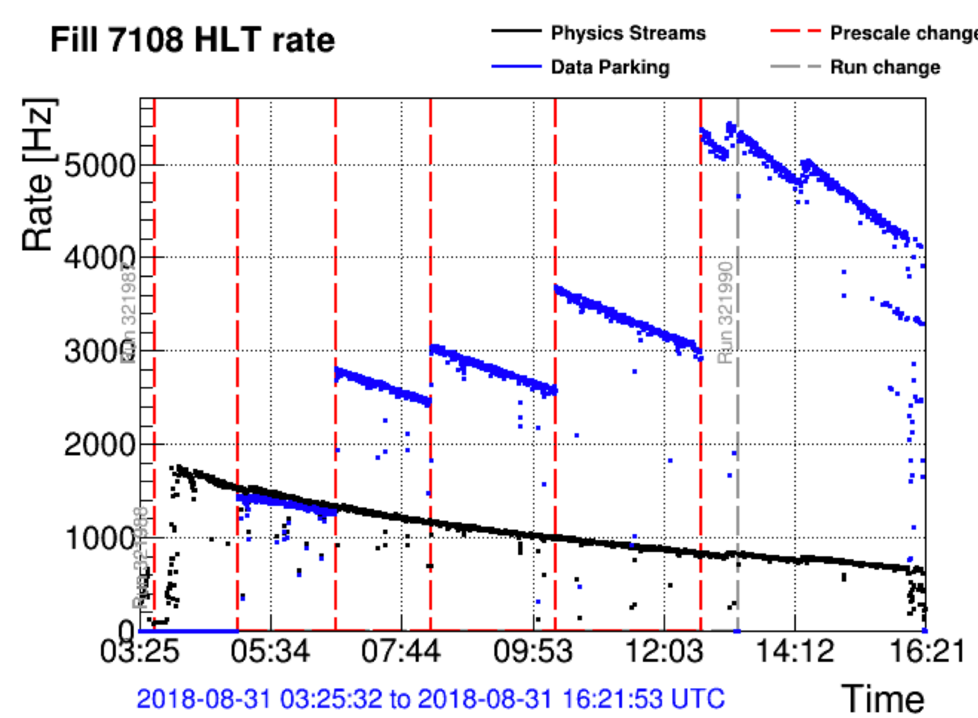
CMS B-Parking 1

- **Run-2 (2018) B-Parking: more data targeting studies of b-meson decays**
  - **Keep the full RAW event content, park and reconstruct data once resources are available**
  - **Information: R. Bainbridge, CMS DPS**
- **Main target: B->K$^{(*)}$ll**
- **Full RAW CMS detector readout is stored and reconstructed**



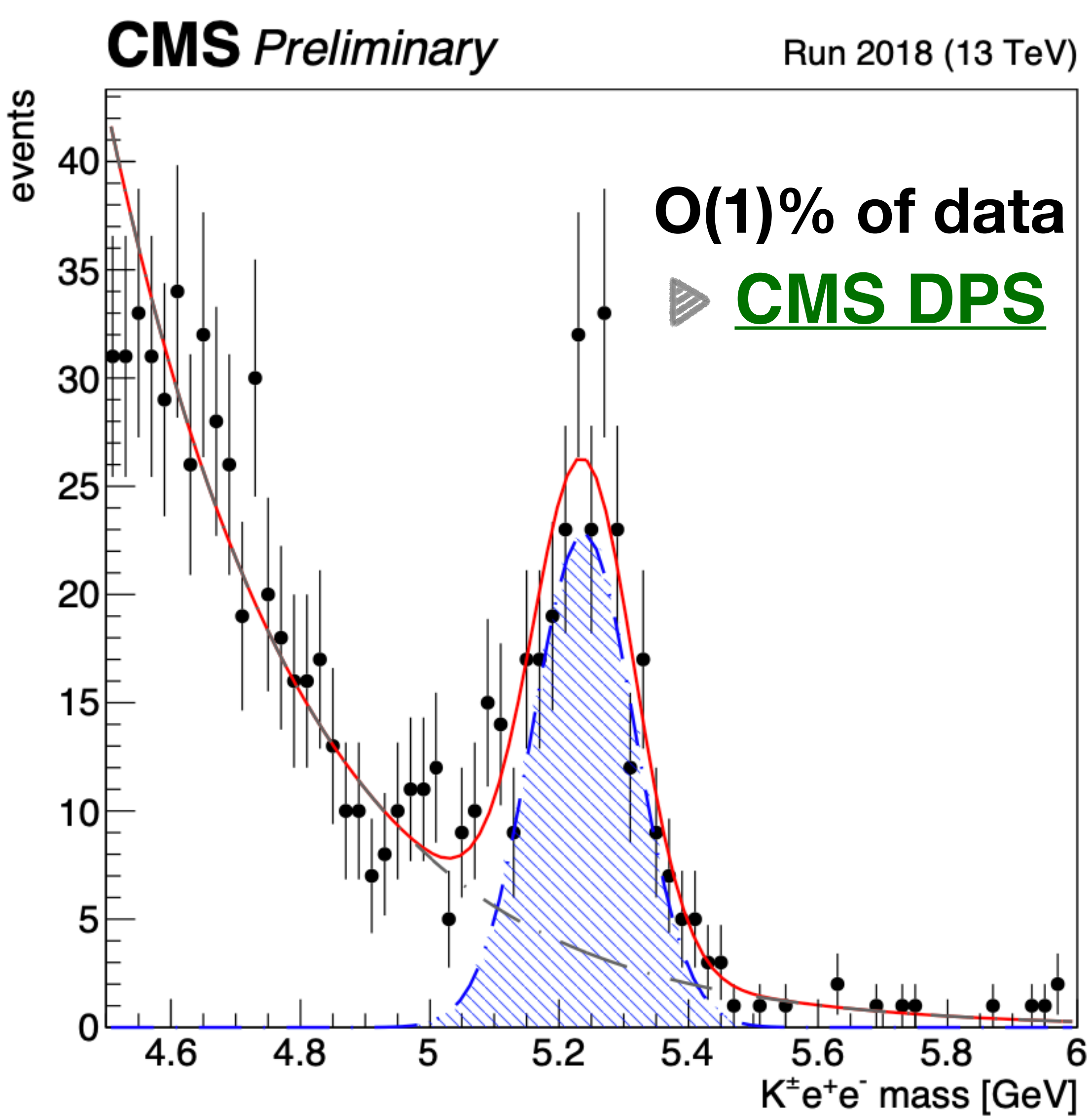
Trigger on this

Settings	Peak $\mathcal{L}_{inst}$ [10^{34} cm^{-2} s^{-1}]	L1 μ p_T threshold [GeV]	HLT μ p_T threshold [GeV]	HLT μ IP_{sig} threshold	Trigger purity [%]	Peak rate [kHz]
1	1.7	12	12	6	92	1.5
2	1.5	10	9	6	87	2.8
3	1.3	9	9	5	86	3.0
4	1.1	8	8	5	83	3.7
5	0.9	7	7	4	59	5.4



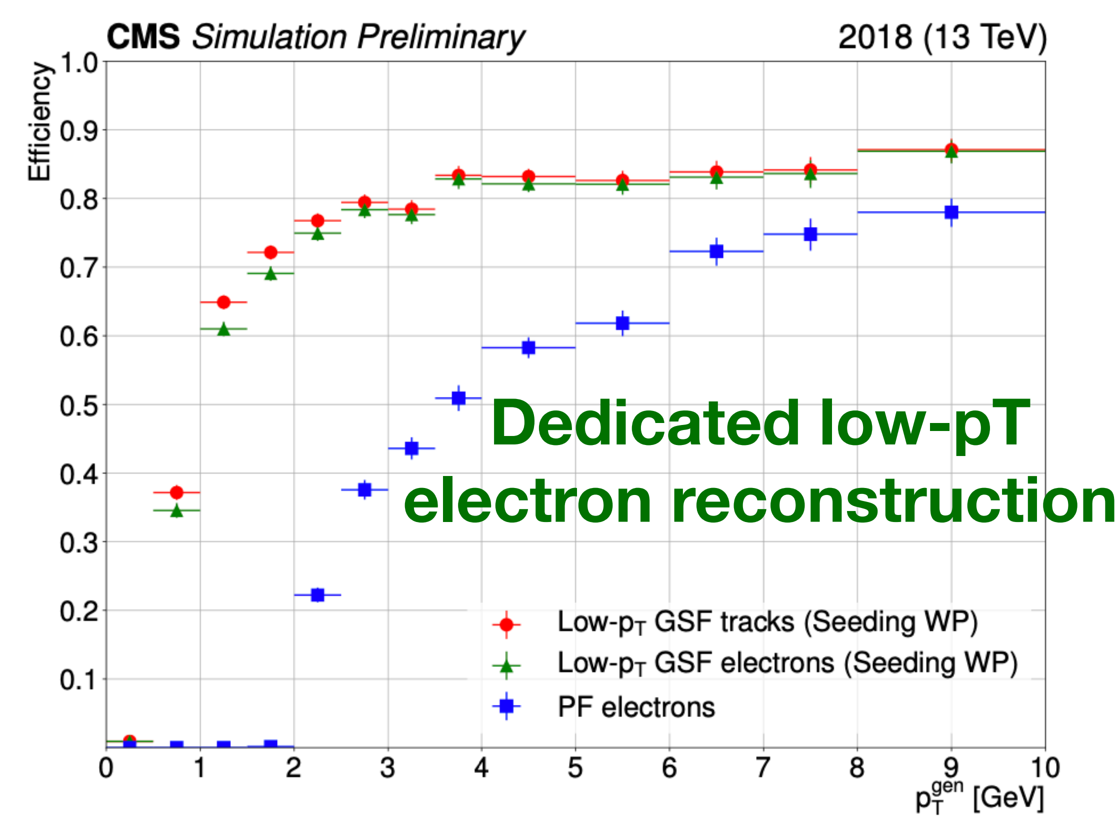
CMS B-Parking 2

- **Data exploration started**
  - **Expect first publication soon**
- **Dataset can find many applications also for BSM searches**



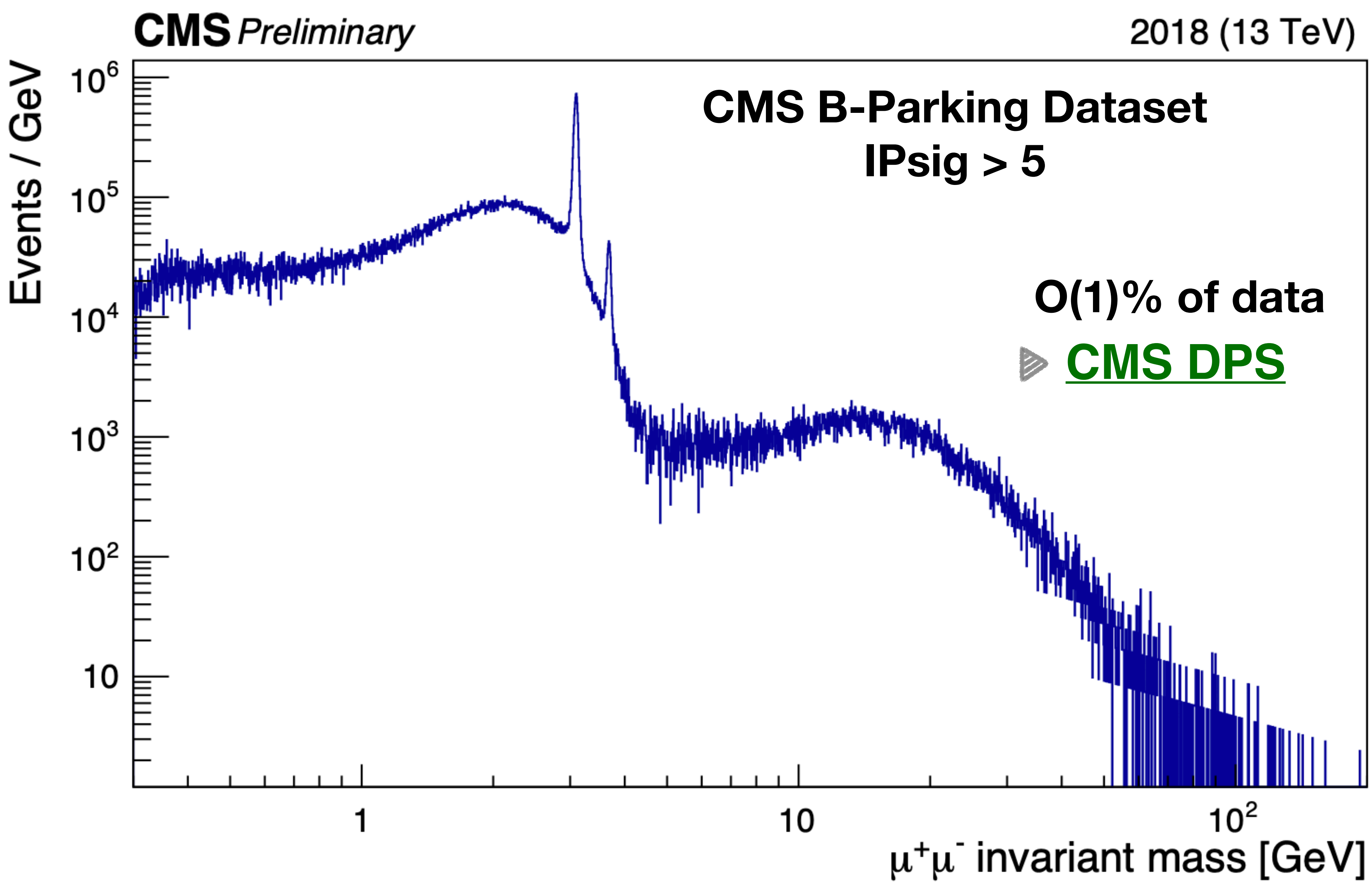
Expected yields

Mode	N_{2018}	f_B	$\mathcal{B}$
	Generic b hadrons		
B^0_{d}	4.0×10^9	0.4	1.0
$B^\pm$	4.0×10^9	0.4	1.0
B_{s}	1.2×10^9	0.1	1.0
b baryons	1.2×10^9	0.1	1.0
B_{c}	1.0×10^7	0.001	1.0
Total	1.0×10^{10}	1.0	1.0
	Events for R_K and R_{K^*} analyses		
$B^0 \to K^* \ell^+ \ell^-$	2600	0.4	6.6×10^{-7}
$B^\pm \to K^\pm \ell^+ \ell^-$	1800	0.4	4.5×10^{-7}



CMS B-Parking 3

- **B-Parking offers excellent search possibilities for displaced signatures too**
  - **Note: scouting also includes displaced dimuon signatures; to be compared**



Scouting in Run 3

For Run 3 2022 - 2024 could aim for high-rate O(10) kHz Particle Flow Scouting Stream with GPU accelerated reconstruction

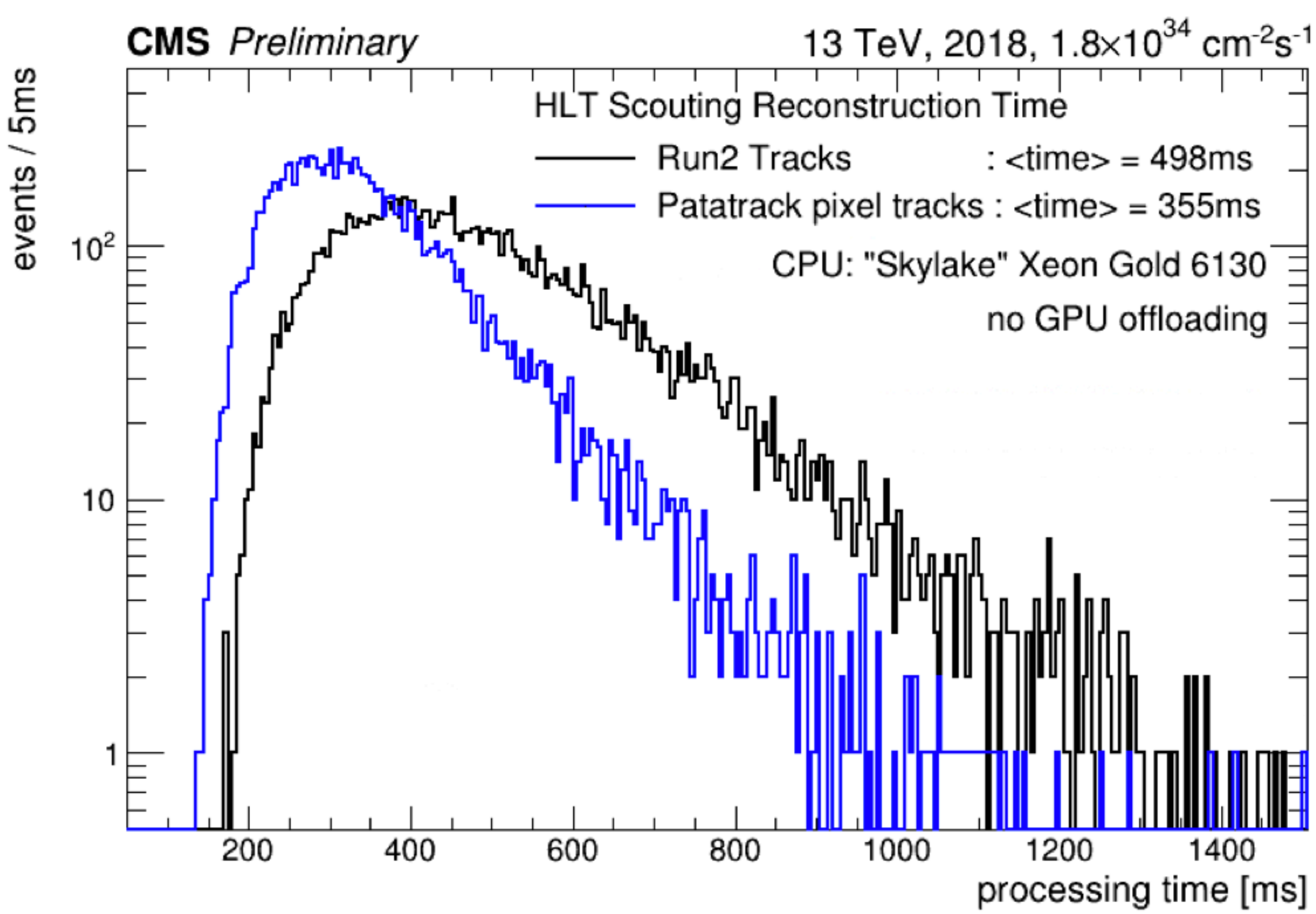
- Can also target recent model agnostic Bump Hunt search strategies ANODE, CWoLa arxiv:1708.02949 , arxiv:2001.04990 , auto encoders

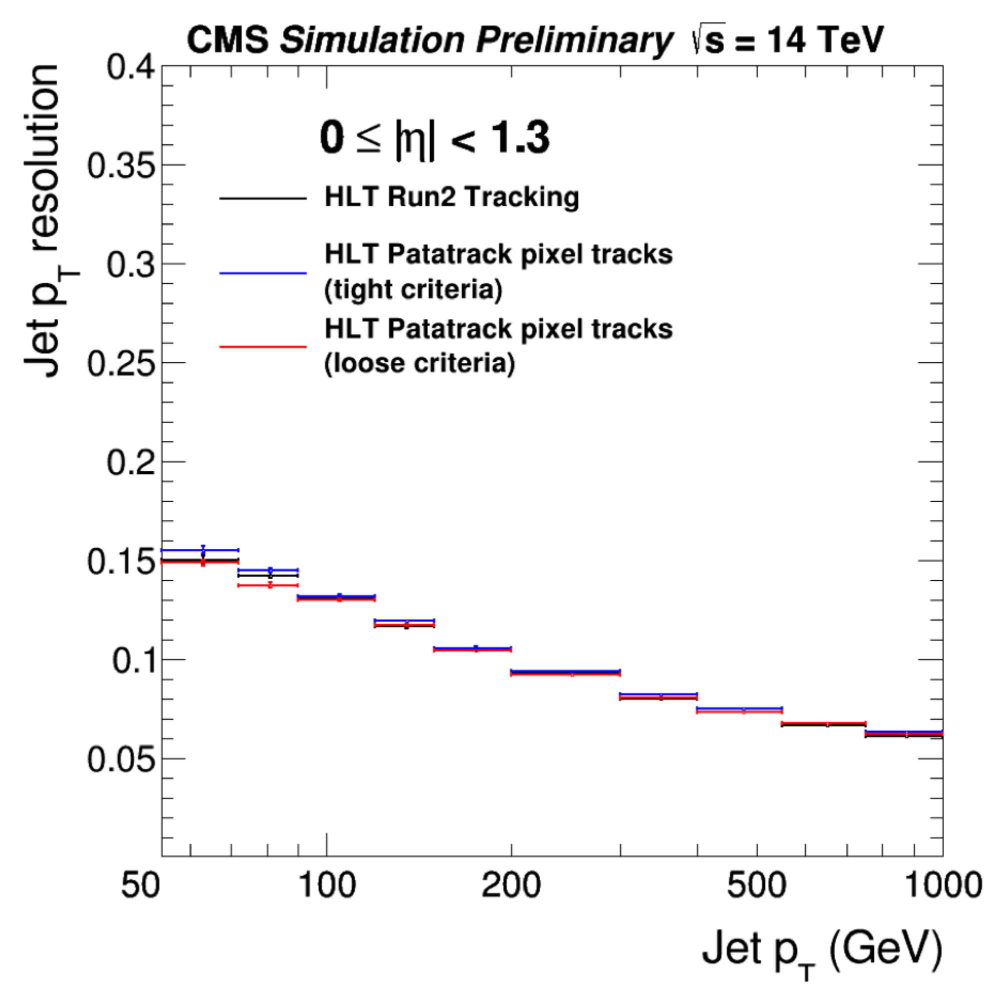
	HLT Threshold	L1 Threshold	L1[kHz]
(non) Isolated di-photon	pT>30/22, M>60GeV	pT>(25/12) 22/12 GeV (|eta|<2.5)	3
(non) Isolated di-muon	pT>17/8 GeV, M>3.8	pT>15/7 GeV or pT>0 + DR/M/Eta cuts	3
Single jet	pT>500 GeV	pT>180 GeV	1
HT	HT>1050 GeV	HT>360 GeV	3
(non) isolated photon	pT>(200) 110 GeV |eta|<1.476	pT>(60) [28+Iso+|eta|<2.1]	13
MET	MHT/MET > 200 GeV	Etmiss >100 GeV	1

Full list of L1 thresholds in backup

Scouting in Run 3

For Run 3 2022 - 2024 could aim for high-rate O(10) kHz Particle Flow Scouting Stream with GPU accelerated reconstruction



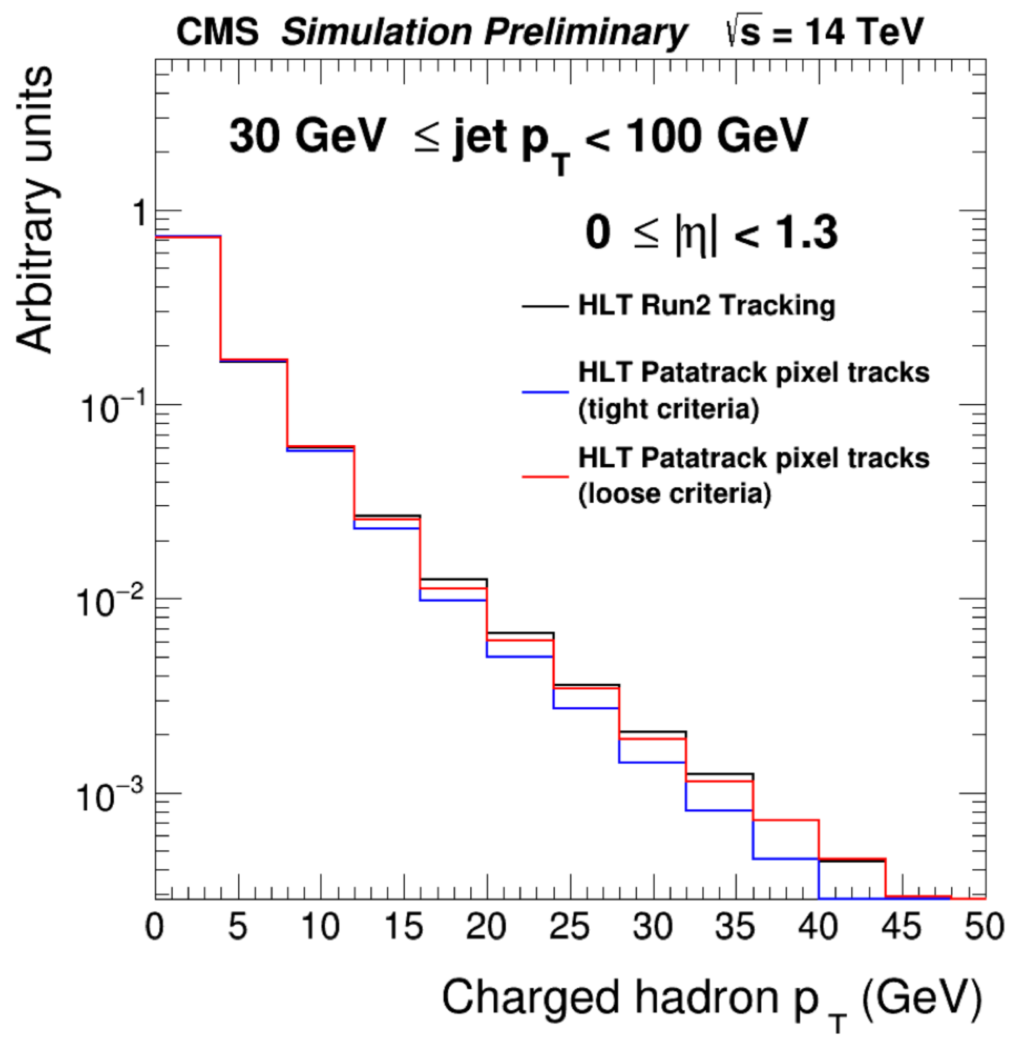


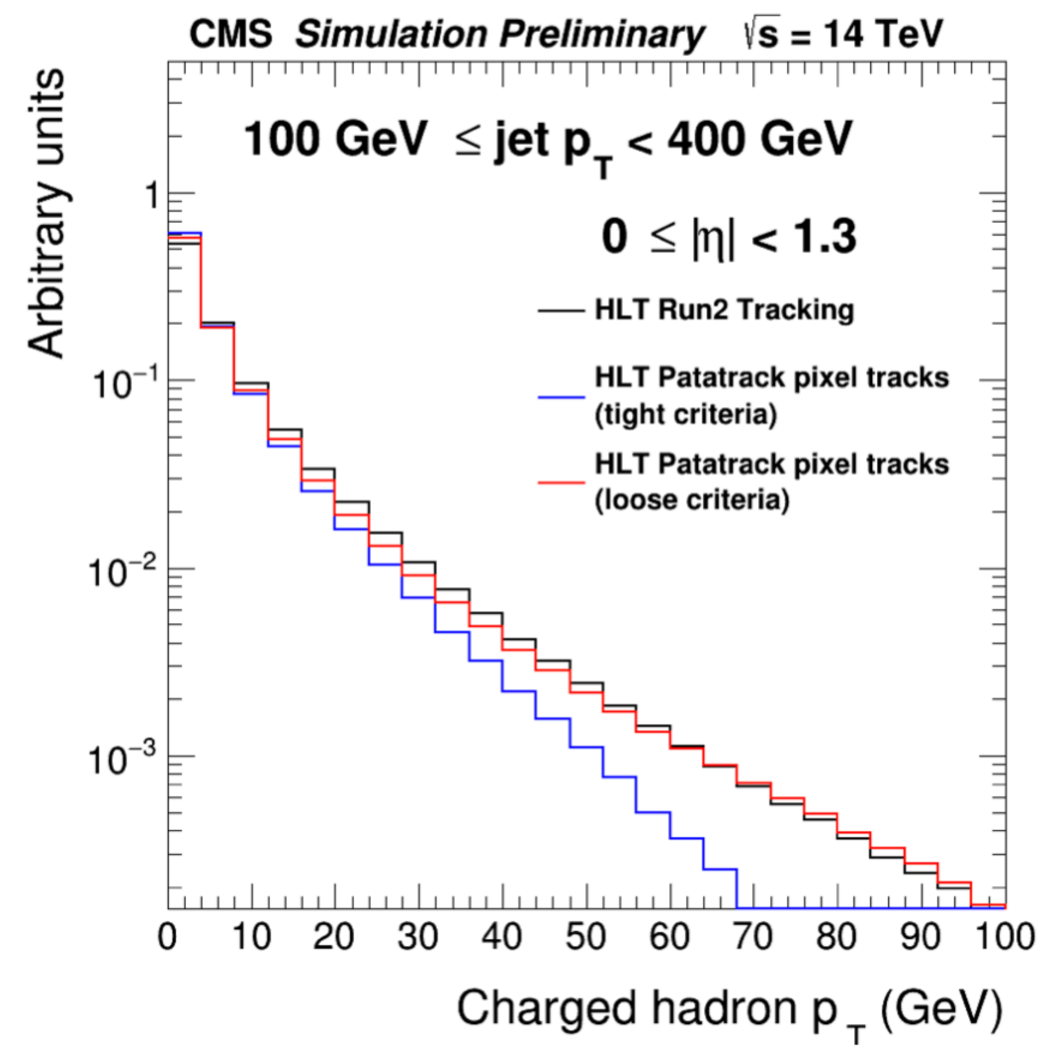
Pixel tracking was successfully ported to GPU, Particle Flow with pixel tracks developed, expect further speed up and Particle Flow porting to GPU

arxiv:2008.13461

Scouting in Run 3

- **Preliminary Particle Flow reconstruction using CMS patatrack pixel tracks results in good performance**

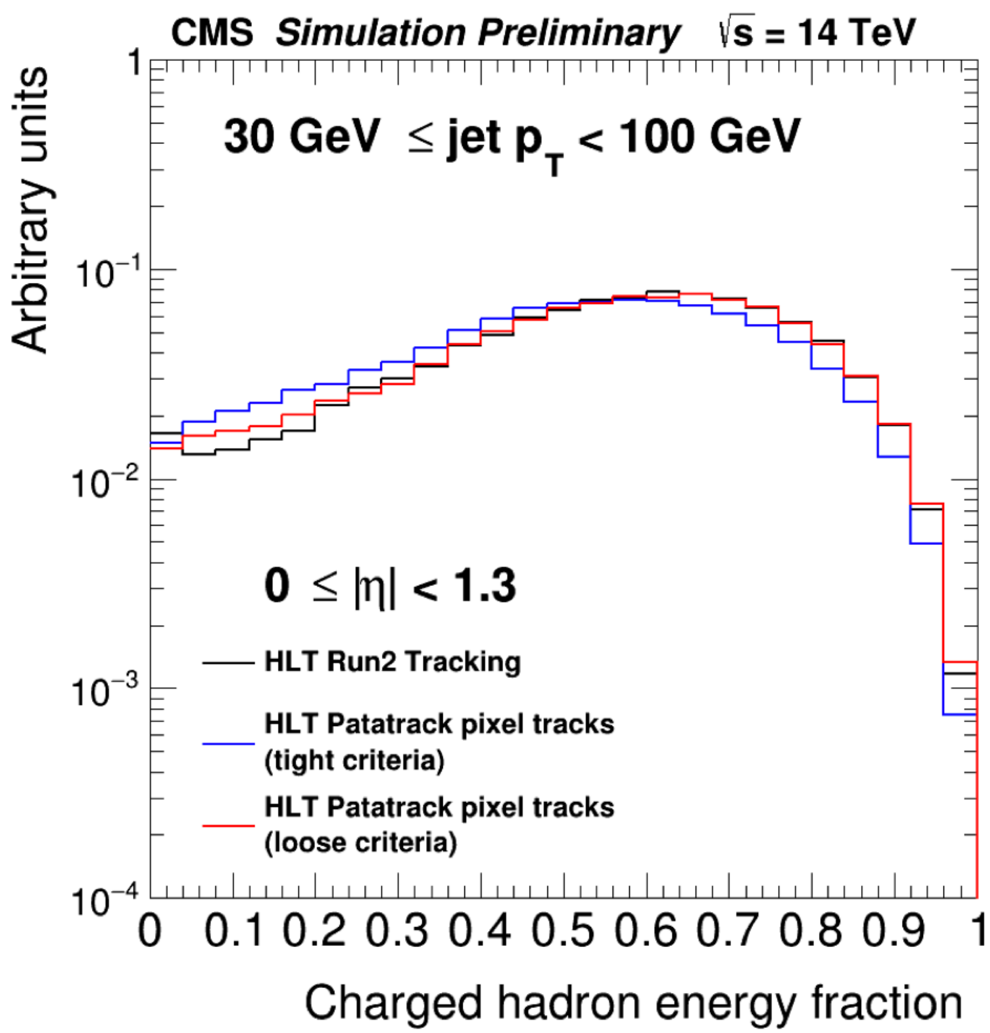


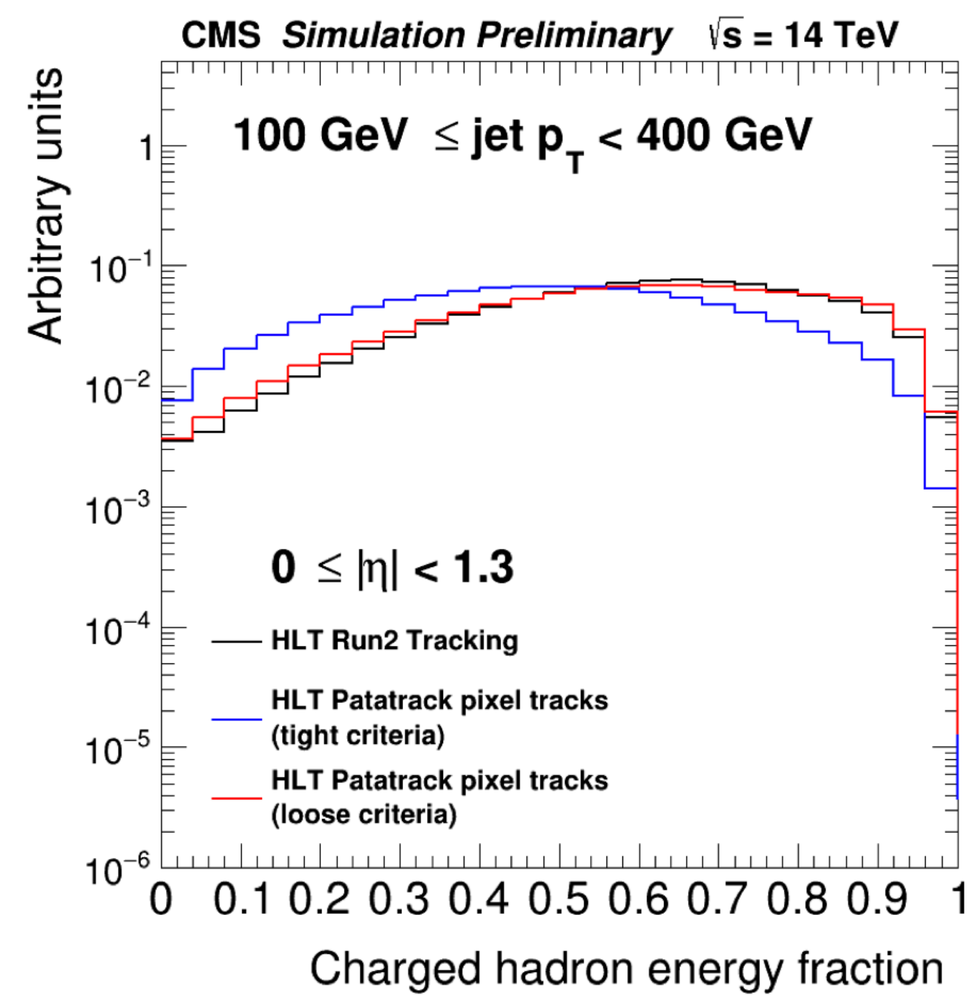


- **Further refinements ongoing, also dedicated checks resolving detailed jet substructure, flavour and tau tagging performance needed**

Scouting in Run 3

- **Preliminary Particle Flow reconstruction using CMS patatrack pixel tracks results in good performance**





- **Further refinements ongoing, also dedicated checks resolving detailed jet substructure, flavour and tau tagging performance needed**

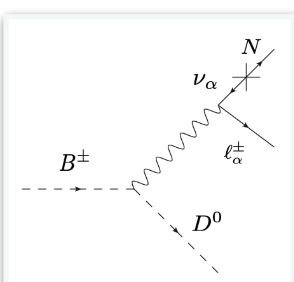
Scouting Physics Potential

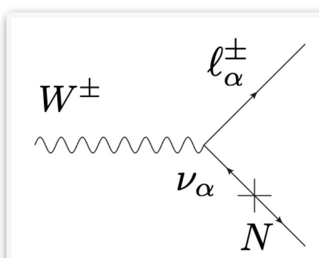
- **The light BSM phenomenology is well developed for experiments other than the LHC**
- **Will need effort to map out physics potential of low-pT physics with multipurpose detector at LHC**

Heavy Neutral Leptons

1504.02470 1604.06099

$$Z' \rightarrow NN$$





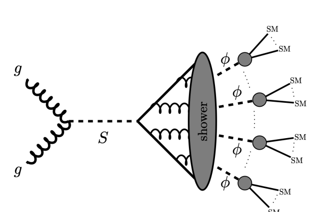
Inelastic DM

1810.01879 1508.03050

$$pp \rightarrow \chi_1\chi_2 \rightarrow 2\chi_1 Z'$$

SUEPs, Hidden Valley

1612.00850



True Muonium

1904.08458

$$\eta \rightarrow \gamma \mathcal{TM}$$

Boosted H->bb

2006.13251

LFV

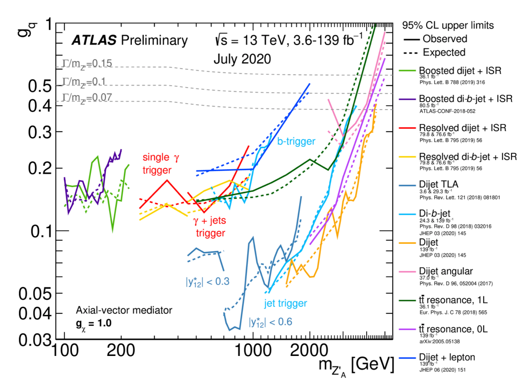
$$\tau \rightarrow 3\mu$$

2007.05658

Dark Showers Emerging Jets

2103.08620
2103.01238

ISR+Z'

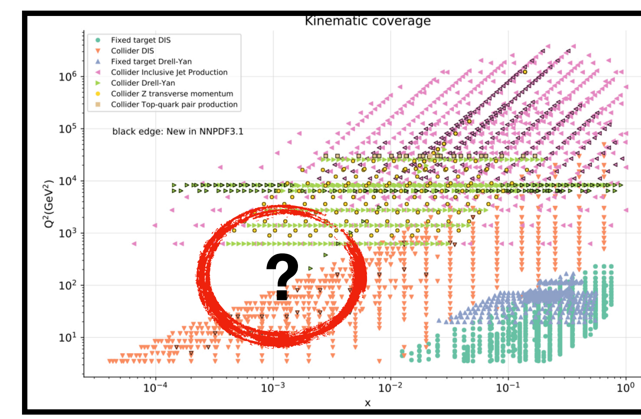


Extended Higgs Sectors

Stefanias talk yesterday

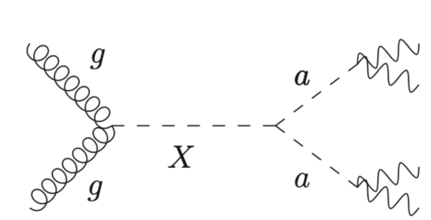
1802.02156

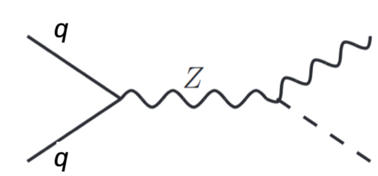
Drell Yan and PDFs



ALPs, Collimated photons

1808.10515 1708.00443





Summary

- **Scouting program offers discovery potential at the LHC beyond the √L-limitation for high mass searches in Run 3 and Phase 2**
  - **Gives in principle access to 100 kHz instead of 1-2 kHz**
- **CMS Parking data-taking program also greatly improved, target to run this scheme as well in Run 3**
- **Refined and accelerated reconstruction techniques using heterogenous computing architectures offer new possibilities for high-rate high-fidelity event reconstruction and thus new phase-space to explore**
  - **Active development happening in CMS Collaboration, target high-speed Particle Flow implementation for Run 3**
- **Note that for Phase 2, L1 scouting would enable access to full LHC collision rate, simplified tracking at 40 MHz would enable good-fidelity event reconstruction**
  - **Program will benefit from well defined use case and benchmark models**
- **Personal recommendation: Include/use Level-1 trigger thresholds (or even no thresholds at all) for phenomenological studies targeting low-mass/pT physics at LHC in the future**

Additional Material

L1 thresholds (CERN-EP-2020-065)

Table 2: List of the most used unprescaled Level-1 trigger algorithms (seeds) during Run 2 and their requirements.

Algorithm	Requirements (p_T, E_T, $m_{\mu\mu}$, and m_{jj} in GeV)
Muons	
Single μ	$p_T > 22$ & Tight quality
Double μ	$p_T > 15, 7$ & Medium quality
Double μ	$p_T > 15, 5$ & Tight quality
Double μ	$p_T > 8, 8$ & Tight quality
Double μ + mass	$p_T > 4.5$ & $\lvert\eta\rvert < 2.0$ & Tight quality & OS & $m_{\mu\mu} > 7$
Double μ + ΔR	$p_T > 4$ & Tight quality & OS & $\Delta R < 1.2$
Double μ + ΔR	$p_T > 0$ & $\lvert\eta\rvert < 1.5$ & Tight quality & OS & $\Delta R < 1.4$
Double μ + BX	$p_T > 0$ & $\lvert\eta\rvert < 1.4$ & Medium quality & Non-colliding BX
Triple μ	$p_T > 5, 3, 3$ & Medium quality
Triple μ	$p_T > 3, 3, 3$ & Tight quality
Triple μ + mass	$p_T > 5, 3.5, 2.5$ & Med. qual.; two μ OS & $p_T > 5, 2.5$ & $5 < m_{\mu\mu} < 17$
Triple μ + mass	Three μ any qual.; two μ & $p_T > 5, 3$ & Tight qual. & OS & $m_{\mu\mu} < 9$
Electrons / photons	(e/γ)
Single e/γ	$p_T > 60$
Single e/γ	$p_T > 36$ & $\lvert\eta\rvert < 2.5$
Single e/γ	$p_T > 28$ & $\lvert\eta\rvert < 2.5$ & Loose isolation
Double e/γ	$p_T > 25, 12$ & $\lvert\eta\rvert < 2.5$
Double e/γ	$p_T > 22, 12$ & $\lvert\eta\rvert < 2.5$ & Loose isolation
Triple e/γ	$p_T > 18, 17, 8$ & $\lvert\eta\rvert < 2.5$
Triple e/γ	$p_T > 16, 16, 16$ & $\lvert\eta\rvert < 2.5$
Tau leptons (τ)	
Single τ	$p_T > 120$ & $\lvert\eta\rvert < 2.1$
Double τ	$p_T > 32$ & $\lvert\eta\rvert < 2.1$ & Isolation
Jets	
Single jet	$p_T > 180$
Single jet + BX	$p_T > 43$ & $\lvert\eta\rvert < 2.5$ & Non-colliding BX
Double jet	$p_T > 150$ & $\lvert\eta\rvert < 2.5$
Double jet + $\Delta\eta$	$p_T > 112$ & $\lvert\eta\rvert < 2.3$ & $\Delta\eta < 1.6$
Double jet + mass	$p_T > 110, 35$; two jets $p_T > 35$ & $m_{jj} > 620$
Double jet + mass	$p_T > 30$ & $\lvert\eta\rvert < 2.5$ & $\Delta\eta < 1.5$ & $m_{jj} > 300$
Triple jet	$p_T > 95, 75, 65$; two jets $p_T > 75, 65$ & $\lvert\eta\rvert < 2.5$
Energy sums	
E_T^{miss}	$E_T^{miss} > 100$ (Vector sum of p_T of calorimeter deposits with $\lvert\eta\rvert < 5.0$)
H_T	$H_T > 360$ (Scalar sum of p_T of all jets with $p_T > 30$ and $\lvert\eta\rvert < 2.5$)
E_T	$E_T > 2000$ (Scalar sum of p_T of calorimeter deposits with $\lvert\eta\rvert < 5.0$)

Terms used
Tight quality: muons with hits in at least 3 different muon stations.
Medium quality: muons with hits in at least 2 different muon stations.
The "non-colliding BX" requirement selects beam-empty events.
$\Delta R \equiv ((\Delta\phi)^2 + (\Delta\eta)^2)^{1/2}$, and phi is the azimuthal angle in radians.
OS: Opposite Sign (of electric charge).
E_T: Scalar sum of p_T of calorimeter deposits.
H_T: Scalar sum of p_T of jets.
Isolation and loose isolation: The isolation requires an upper limit on the transverse cal-

Table 3: List of the most used cross object unprescaled Level-1 trigger algorithms (seeds) during Run 2 and their corresponding requirements.

Algorithm	Requirements (p_T, E_T, $m_{\mu\mu}$, and m_{jj} in GeV)
Two objects	
Single μ + Single e/γ	$p_T(\mu) > 20$ & Tight quality(μ) & $p_T(e/\gamma) > 10$ & $\lvert\eta(e/\gamma)\rvert < 2.5$
Single μ + Single e/γ	$p_T(\mu) > 7$ & Tight quality(μ) & $p_T(e/\gamma) > 20$ & $\lvert\eta(e/\gamma)\rvert < 2.5$
Single μ + Single τ	$p_T(\mu) > 18$ & $\lvert\eta(\mu)\rvert < 2.1$ & Tight quality(μ) & $p_T(\tau) > 24$ & $\lvert\eta(\tau)\rvert < 2.1$
Single μ + H_T	$p_T(\mu) > 6$ & Tight quality(μ) & $H_T > 240$
Single e/γ + Single τ	$p_T(e/\gamma) > 22$ & $\lvert\eta(e/\gamma)\rvert < 2.1$ & Loose isolation(e/γ) & $p_T(\tau) > 26$ & $\lvert\eta(\tau)\rvert < 2.1$ & Isolation(τ) & $\Delta R > 0.3$
Single e/γ + Single jet	$p_T(e/\gamma) > 28$ & $\lvert\eta(e/\gamma)\rvert < 2.1$ & Loose isolation(e/γ) & p_T(jet) > 34 & $\lvert\eta$(jet)$\rvert < 2.5$ & $\Delta R > 0.3$
Single e/γ + H_T	$p_T(e/\gamma) > 26$ & $\lvert\eta(e/\gamma)\rvert < 2.1$ & Loose isolation(e/γ) & $H_T > 100$
Single τ + E_T^{miss}	$p_T(\tau) > 40$ & $\lvert\eta(\tau)\rvert < 2.1$ & $E_T^{miss} > 90$
Single jet + E_T^{miss}	p_T(jet) > 140 & $\lvert\eta$(jet)$\rvert < 2.5$ & $E_T^{miss} > 80$
Three objects	
Single μ Double jet + ΔR	$p_T(\mu) > 12$ & $\lvert\eta(\mu)\rvert < 2.3$ & Tight quality(μ) & p_T(jet) > 40 & $\Delta\eta$(jet,jet) < 1.6 & $\lvert\eta$(jet)$\rvert < 2.3$ & $\Delta R(\mu,$jet$) < 0.4$
Single μ + Single jet + E_T^{miss}	$p_T(\mu) > 3$ & $\lvert\eta(\mu)\rvert < 1.5$ & Tight quality (μ) & p_T(jet) > 100 & $\lvert\eta$(jet)$\rvert < 2.5$ & $E_T^{miss} > 40$
Double μ + H_T	$p_T(\mu) > 3$ & Tight quality(μ) & $H_T > 220$
Double μ + Single jet + ΔR	$p_T(\mu) > 0$ & Medium quality(μ) & $\Delta R(\mu,\mu) < 1.6$ & p_T(jet) > 90 & $\lvert\eta$(jet)$\rvert < 2.5$ & $\Delta R(\mu,$jet$) < 0.8$
Double μ + Single e/γ	$p_T(\mu) > 5$ & Tight quality(μ) & $p_T(e/\gamma) > 9$ & $\lvert\eta(e/\gamma)\rvert < 2.5$
Double e/γ + Single μ	$p_T(e/\gamma) > 12$ & $\lvert\eta(e/\gamma)\rvert < 2.5$ & $p_T(\mu) > 6$ & Tight quality(μ)
Double e/γ + H_T	$p_T(e/\gamma) > 8$ & $\lvert\eta(e/\gamma)\rvert < 2.5$ & $H_T > 300$
Four objects	
Double μ + Double e/γ	$p_T(\mu) > 3$ & Medium quality(μ) & OS(μ) & $p_T(e/\gamma) > 7.5$
Double μ + Double e/γ	$p_T(\mu) > 5$ & Medium quality(μ) & OS(μ) & $p_T(e/\gamma) > 3$
Five objects	
Double μ + E_T^{miss} + Single jet OR Double jet	$p_T(\mu) > 3$ & Tight quality(μ) & $E_T^{miss} > 50$ & (p_T(jet) > 60 & $\lvert\eta$(jet)$\rvert < 2.5$) OR (p_T(jet) > 40 & $\lvert\eta$(jet)$\rvert < 2.5$)
H_T + Quad jet	$H_T > 320$ & p_T(jet) $> 70, 55, 40, 40$ & $\lvert\eta$(jet)$\rvert < 2.4$