Emerging Jets signatures of a composite Dark Sector in the CMS detector … and other long-lived states

A. Belloni

University of Maryland

New Physics with Displaced Vertices

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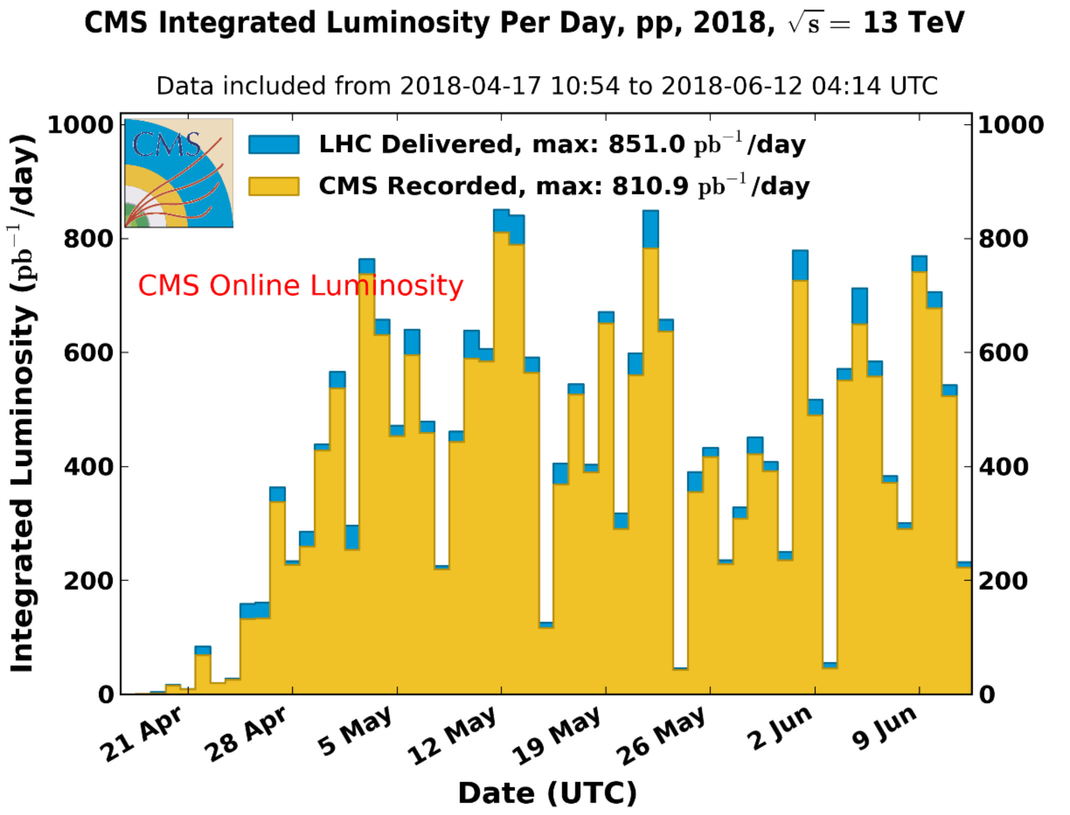
National Tsing Hua University

Motivations

- Standard Model so far has withstood all challenges from precision measurements
  - Alas, no new physics yet, but wealth of data available to search for exotic signatures
- Search for Long-Lived Particles is well motivated theoretically
  - Small couplings; phase-space suppressions; conserved (or nearly conserved) symmetries
- Spectacular signatures are possible, requiring a different way to look at experimental data
  - Dedicated tools needed to exploit key ingredients: displacement, timing, material interactions



About 0.5/fb collected per day in 2018
Expect 150/fb by end of year; 300/fb by 2023

A Wealth of Unusual Signatures

- Three major classes of signatures
  - Displaced objects
  - Disappearing/kinked tracks
  - Heavy stable charged particles (HSCP)
- Focus on displaced vertices (and more)
  - Could encompass displaced dijet, lepton, dilepton, conversion
- Executive summary of talk
  - Review of most recent CMS results pertaining long-lived states (with focus on displaced objects)
  - Presentation of emerging-jet analysis
    - First dedicated search in BSSW dark-QCD model

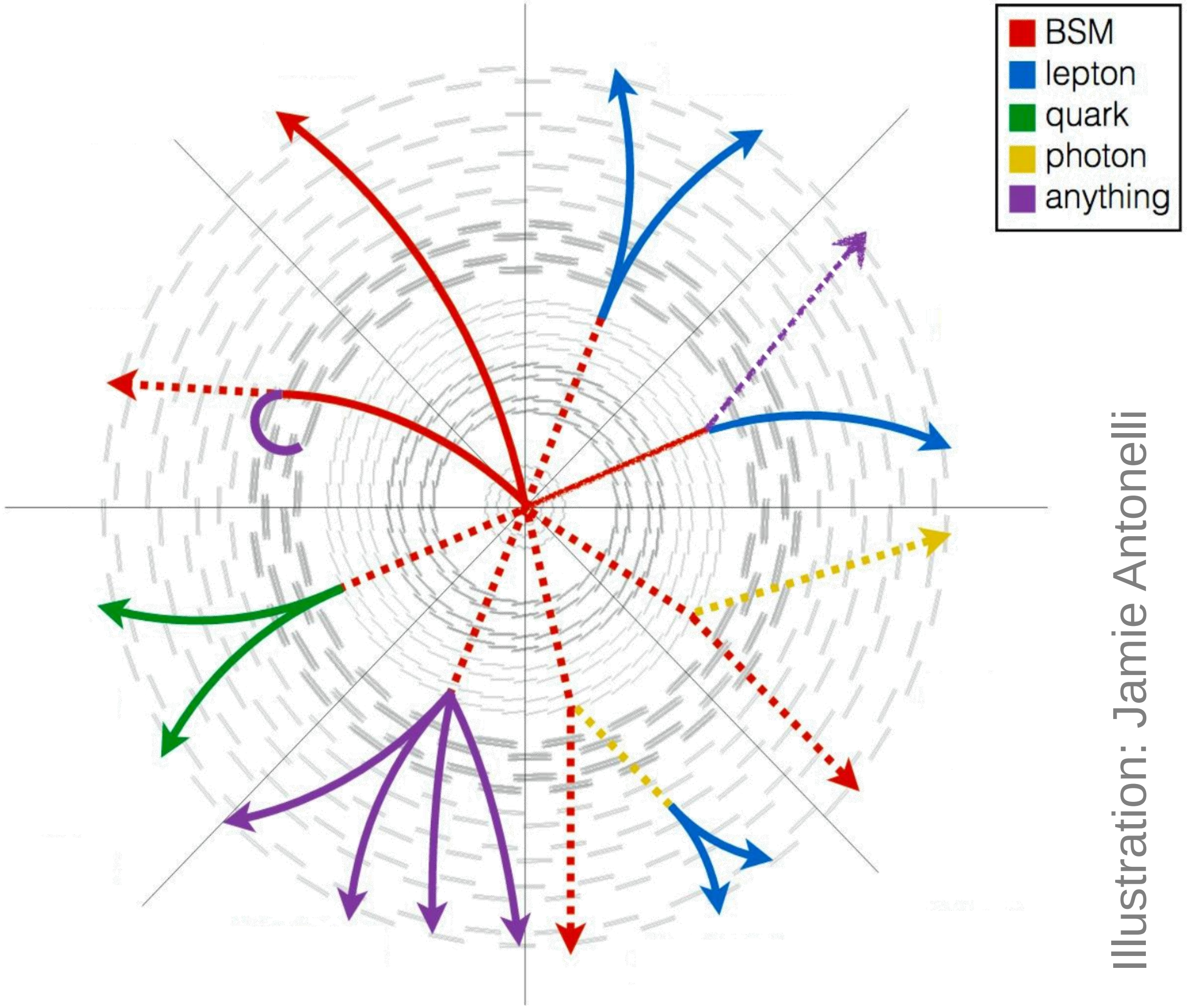


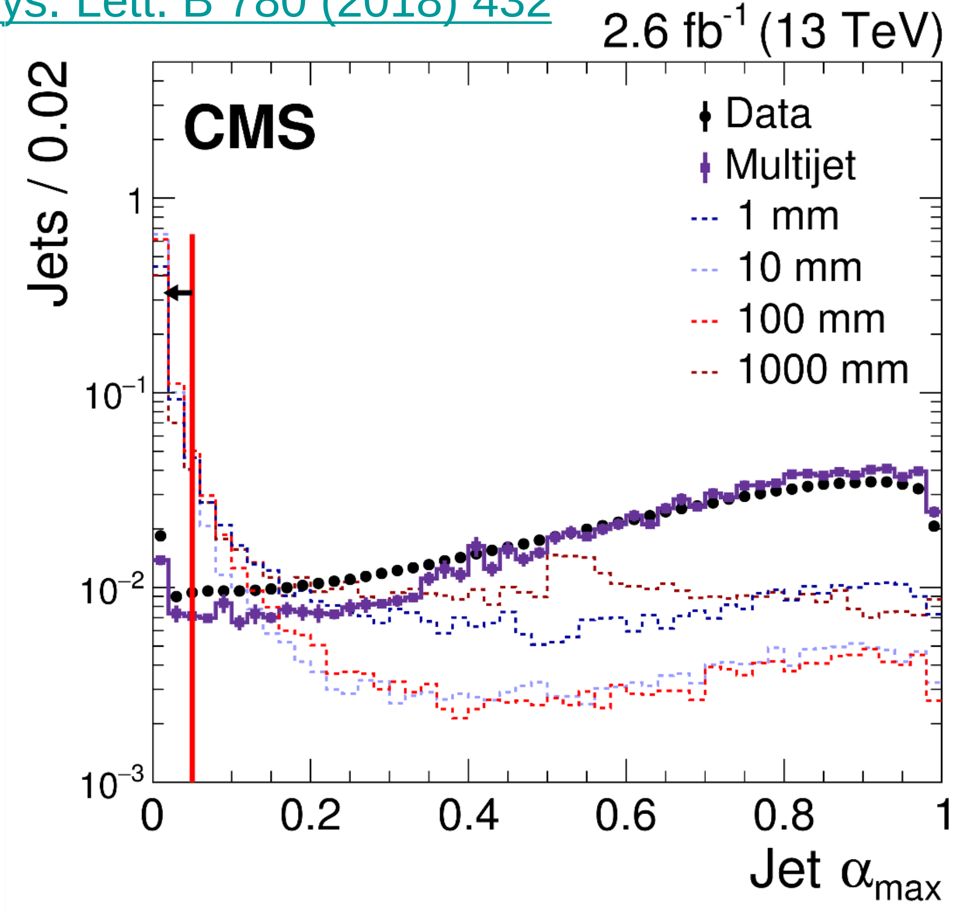
Illustration: Jamie Antonelli

Apologies for presenting again the same signature summary…

Inclusive Displaced Jets (1)

- Search for long-lived particles using customized topological triggers
  – Require jets with no more than two associated prompt tracks, and at least one track with impact parameter significance larger than 5
- Three criteria to tag displacement
  – Compatibility with primary vertex, jet tracks impact parameter significance, emission angle
- Consider displaced jet multiplicity to set limits on new particles decaying within 1mm to 1m from primary vertex
  – A general approach that allows to cover a variety of event topologies (including leptons), without requiring the explicit reconstruction of a displaced vertex

Phys. Lett. B 780 (2018) 432

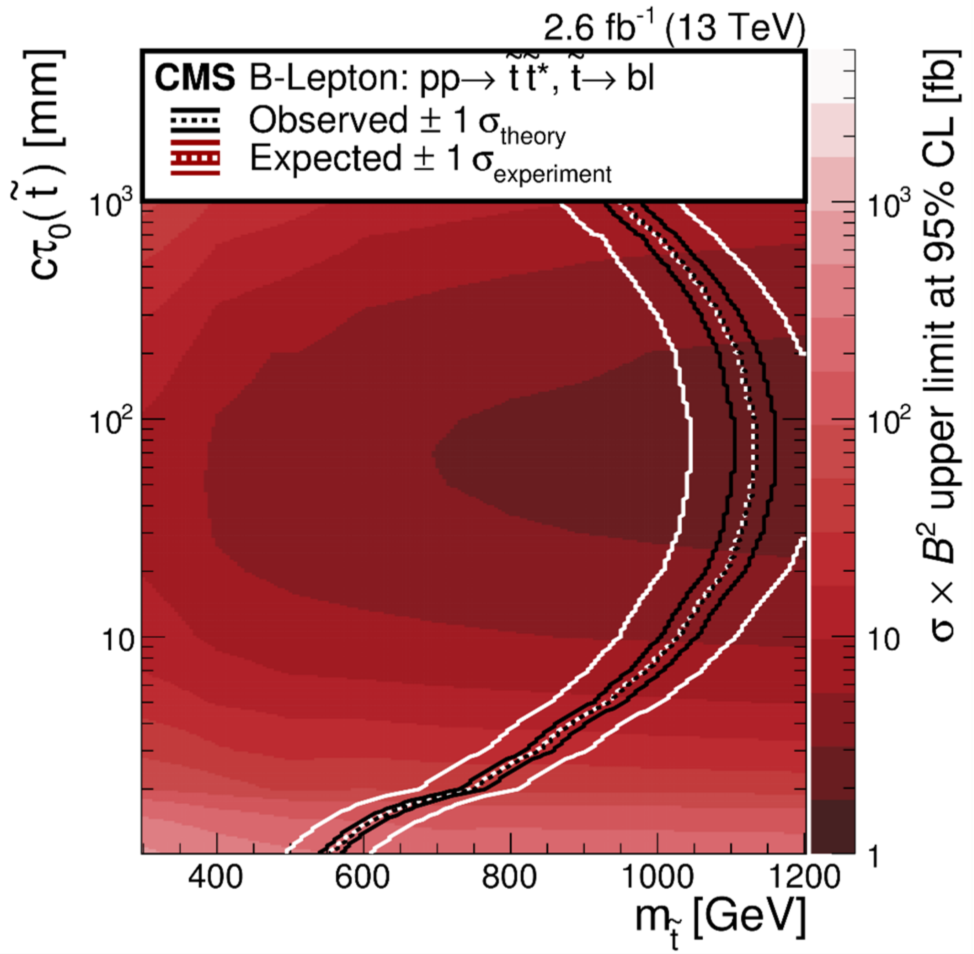


α_{max} : p_T-weighed fraction of prompt tracks associated with jet

Inclusive Displaced Jets (2)

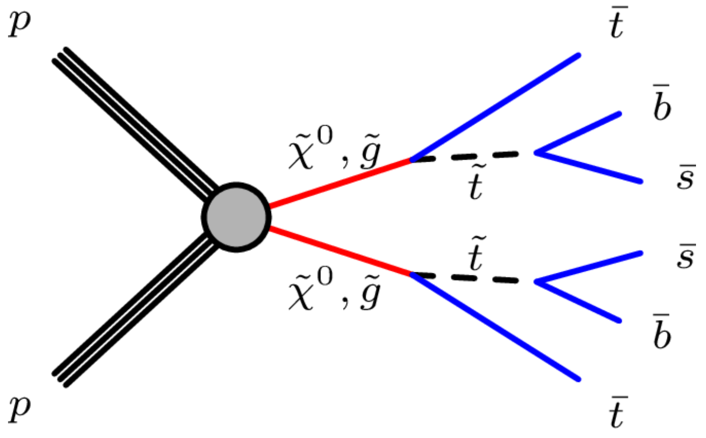
Phys. Lett. B 780 (2018) 432

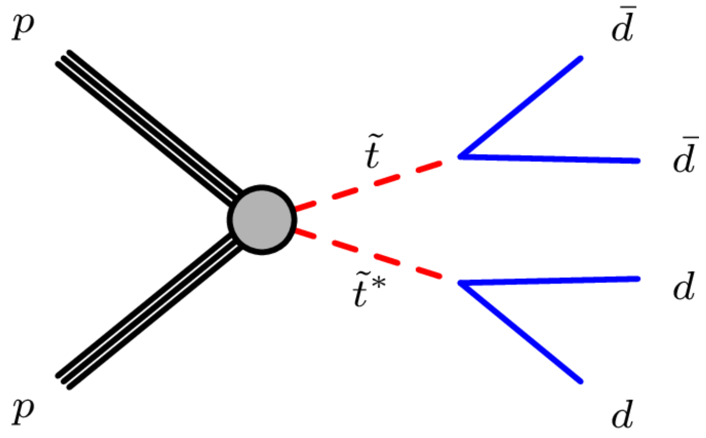
- Observed 1 event with exactly two tagged jets, and no events with at least three tagged jets
  - No excess observed, results consistent with expectations
- Exclusion limits set on various models
  - Scalar neutral particle decaying to di-jet
  - RPV stop decaying to b quark + lepton
    - Also separately by lepton flavor
- RPV stop cross section limit translated into mass exclusion bound, assuming equal lepton branching fractions
  - Exclude stop mass between 550 and 1130GeV, currently most stringent bound for top squarks with $c\tau$ larger than 3mm

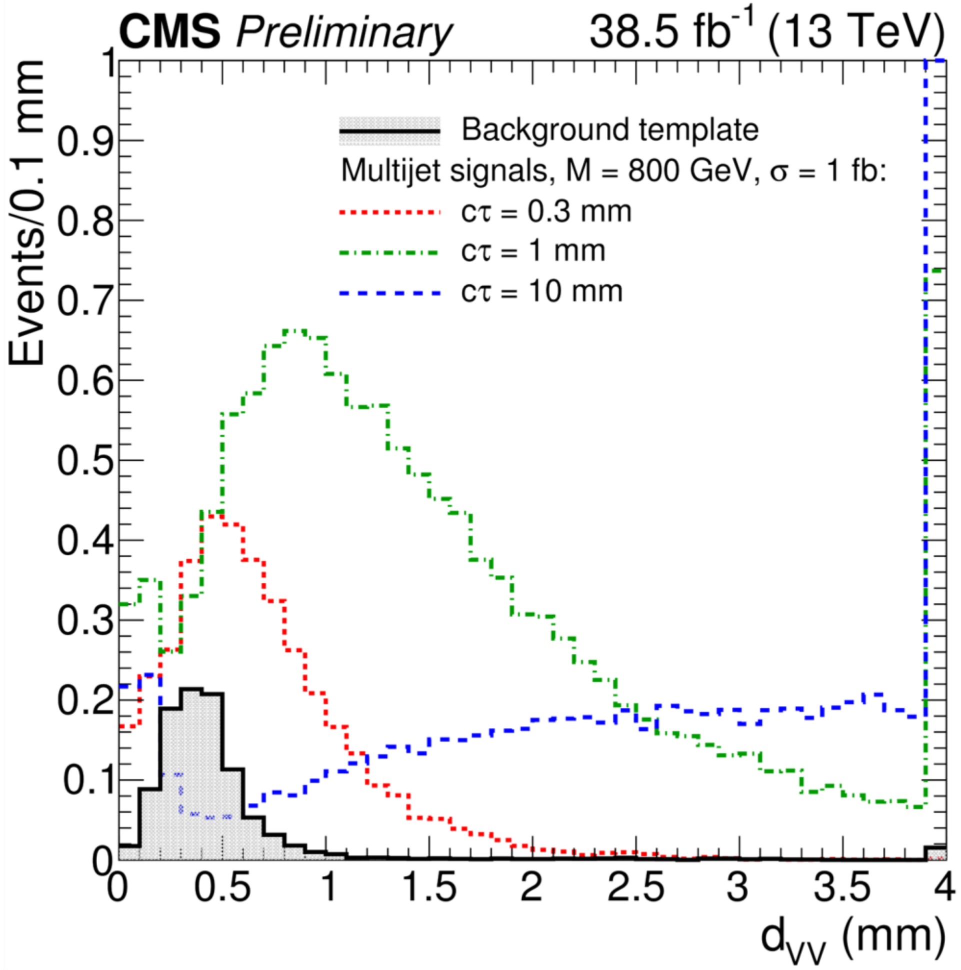


Displaced Vertices (1)

CMS-PAS-EXO-17-018



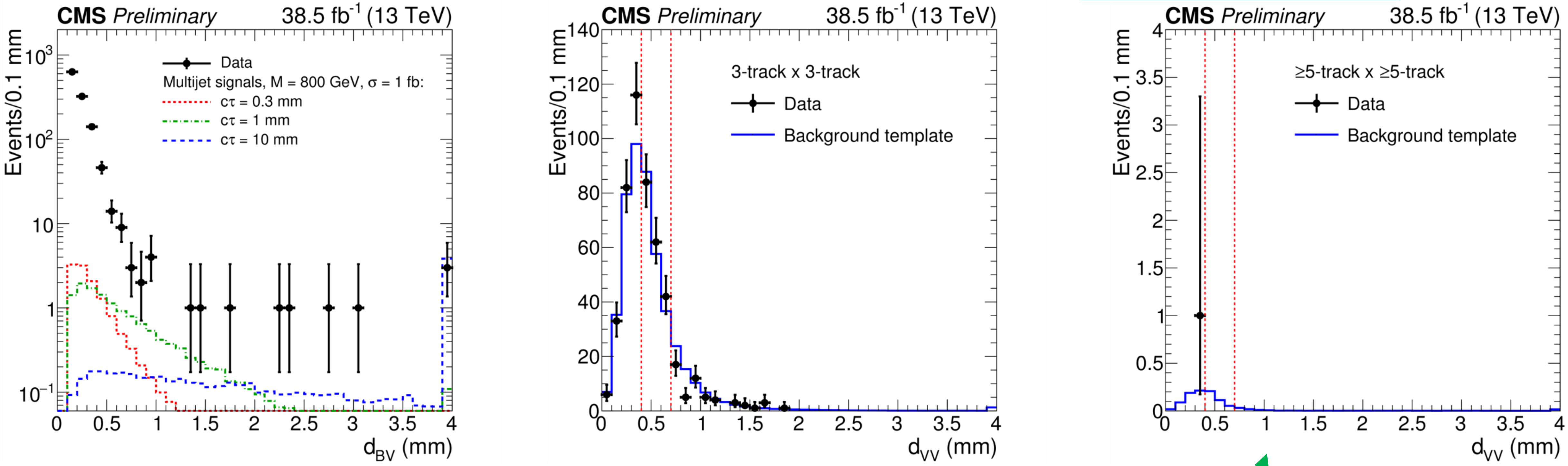




- Search for pair-produced long-lived particles decaying to multiple jets
  - Signal events characterized by presence of two displaced vertices with large number of tracks
- Candidate signal events tagged using transverse displacement between vertex pairs
  - Fit performed in three bins of d_{VV}
- Specifically addressed two benchmark models
  - Multi-jet: minimal flavor-violating RPV SUSY, neutralino or gluino long-lived LSP
  - Di-jet: pair-produced long-lived top squark in RPV SUSY

Displaced Vertices (2)

CMS-PAS-EXO-17-018



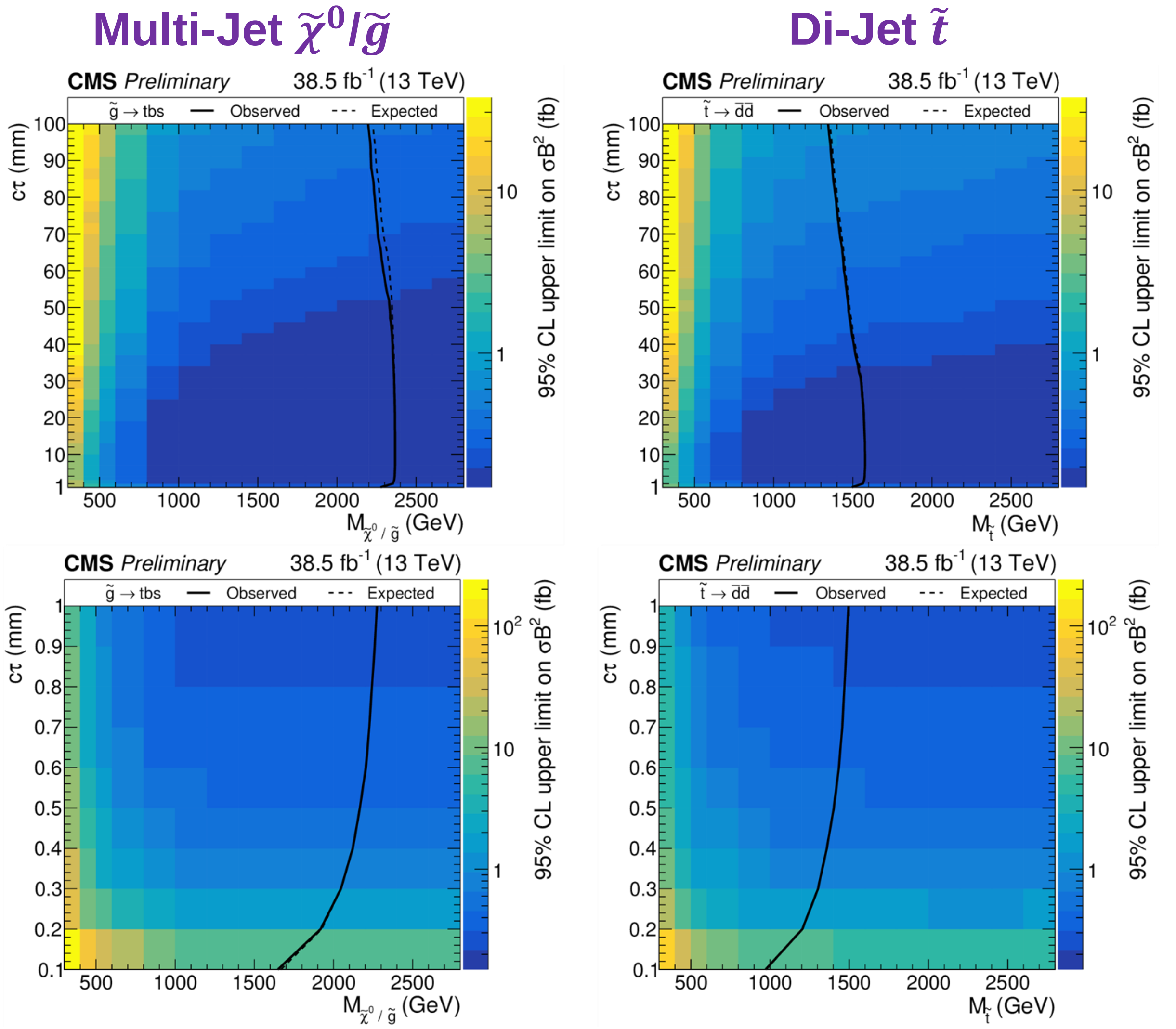
Limits on production cross sections of new states extracted from this plot

- One vertex pair selected per event
  - Highest track multiplicity, then max vertex mass
- Template fit of d_{VV} distributions
  - Background template built from 1-vertex data events
    - Ingredients: d_{BV} (transverse vertex-beam distance) and $\Delta\phi_{JJ}$ (azimuthal angle between jet pairs)

Displaced Vertices (3)

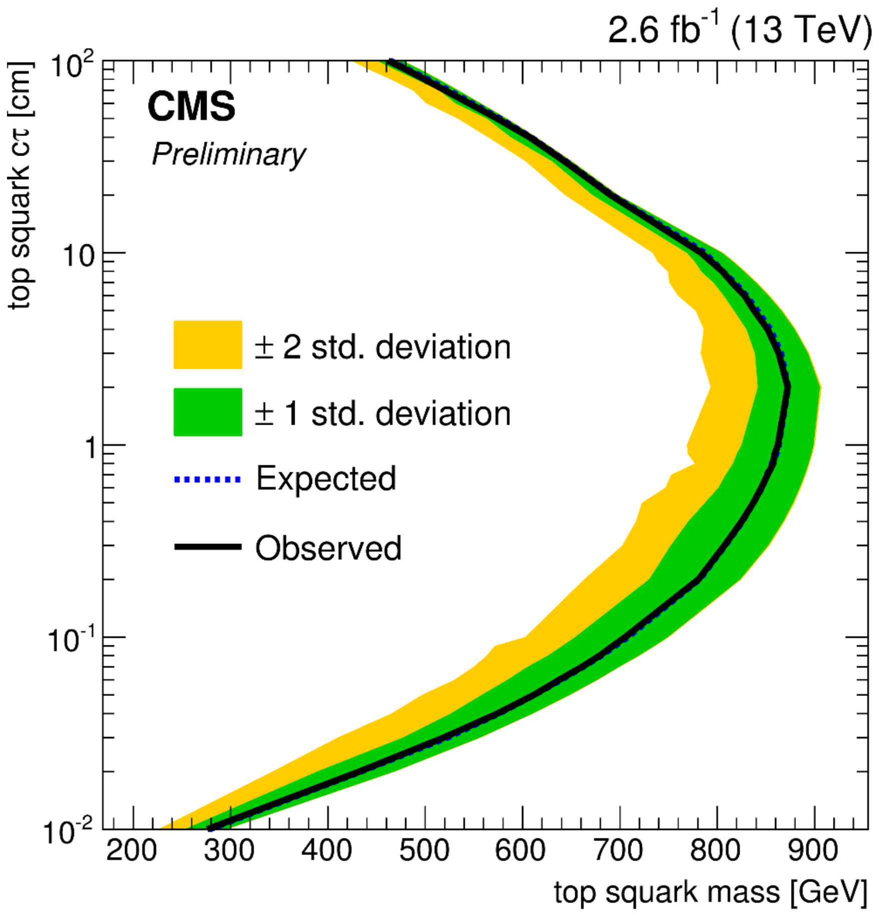
CMS-PAS-EXO-17-018

- No excess yield above the prediction from standard model processes is observed
  - Excluded cross section times branching fraction squared above approximately 0.3fb for long-lived particles with mass between 800 and 2600GeV and mean proper decay length between 1 and 40mm
- Specific interpretation in RPV SUSY sets limits to gluino and top squark masses
  - Excluded gluino masses below 2200GeV and top squark masses below 1400GeV, for mean proper decay lengths between 0.6 and 80mm
- Results relevant also to other models with long-lived states decaying to final states with multiple tracks
  - Improved technique, in addition to larger statistics and increase in center-of-mass energy, tighten the constraints set with the 8TeV data sample



Displaced Leptons (1)

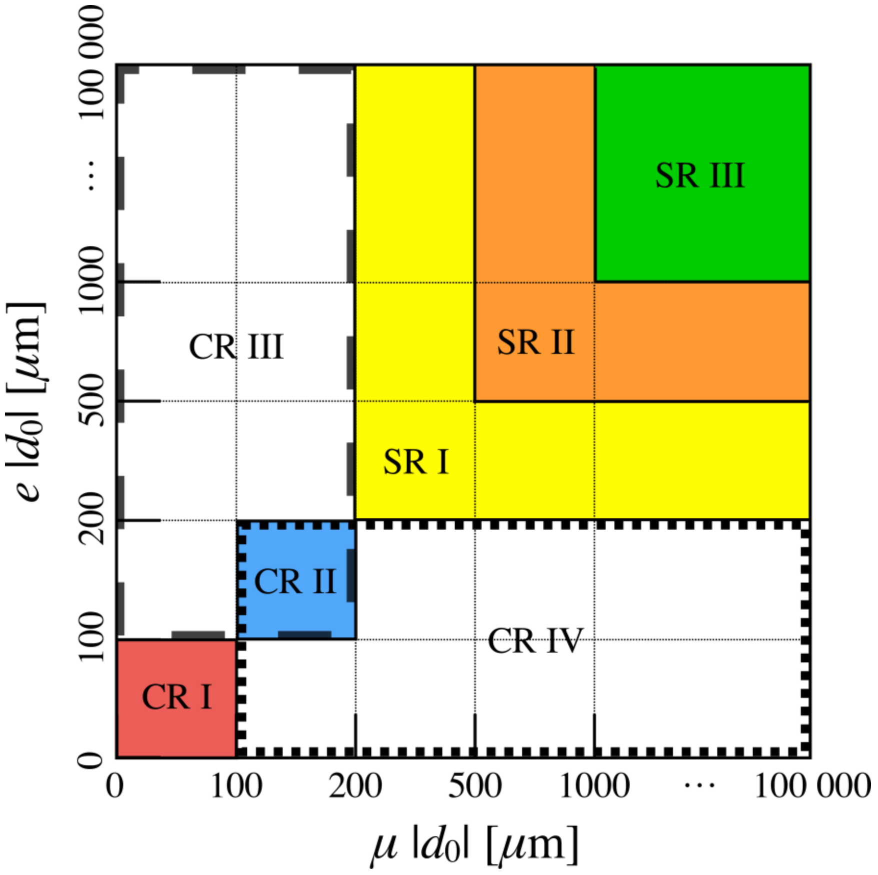
CMS-PAS-EXO-16-022



- Search for pair production of long-lived top squarks, decaying to electron+b and muon+b
  - Displaced SUSY with RPV top squark decay
- Event selection exclusively focused on displaced leptons from different vertices
  - Not relying on hadronic activity and/or E_T^{miss} allows analysis to maintain sensitivity to models with lepton displacements up to 10cm
- Three search regions investigated
  - Lepton $|IP_{2D}|$>0.2, 0.5, 1mm
- No excess observed: excluded stop with mass smaller than 870GeV, with proper decay length equal to 2cm
  - Most stringent limit to date on Displaced SUSY model with RPV-decaying top squark

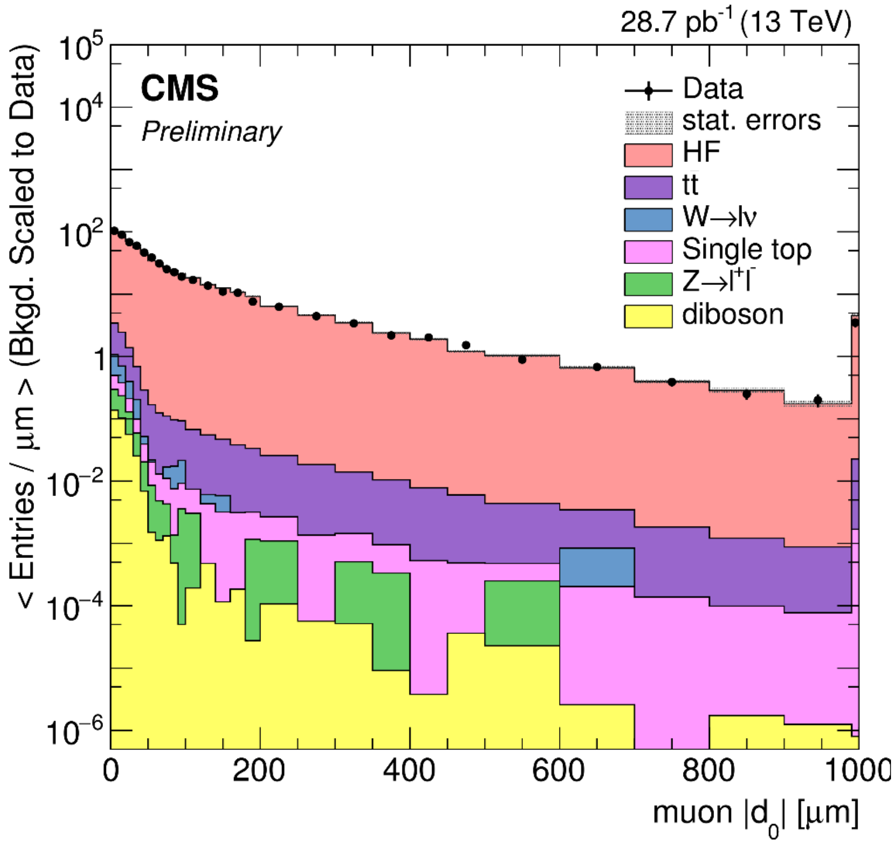
Displaced Leptons (2)

CMS-PAS-EXO-16-022



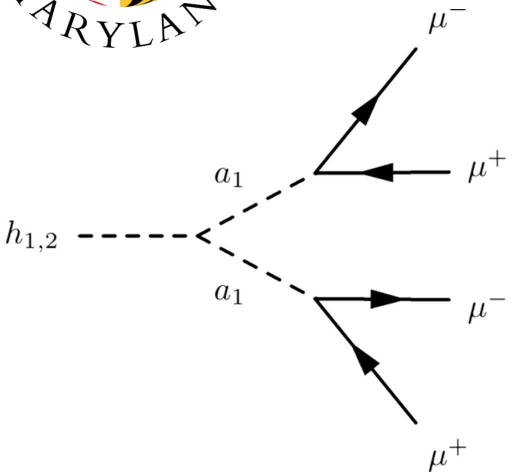
Three exclusive signal regions and four control region defined by lepton impact parameters

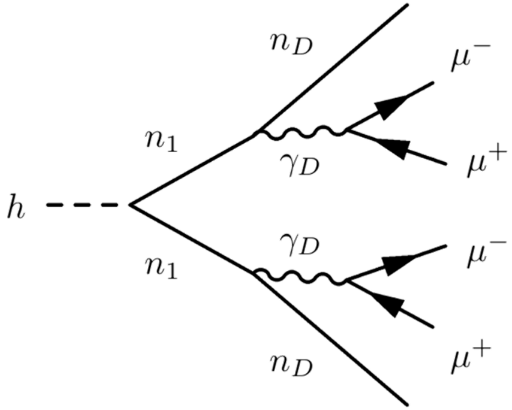
Muon+heavy-flavor jet control region $|d_0(\mu)|$ used to model heavy-flavor background in signal region

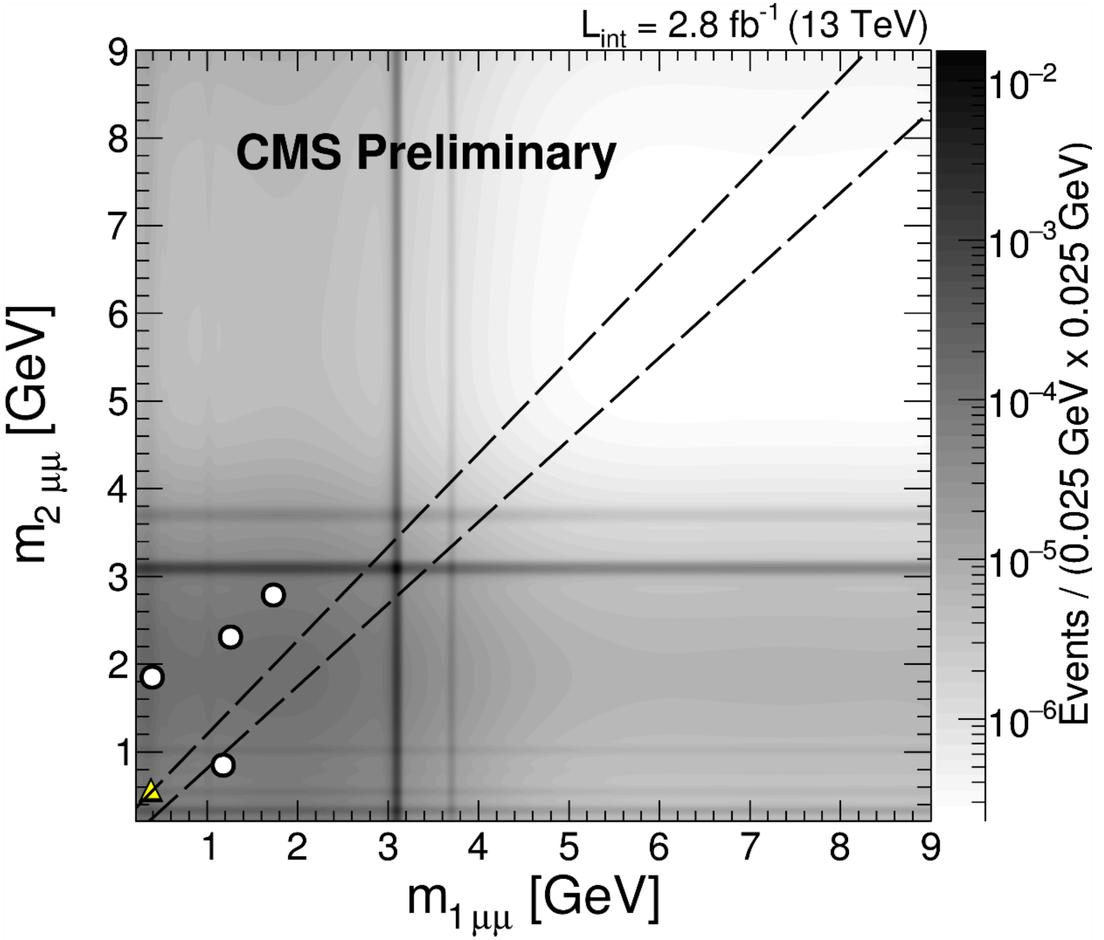


Displaced Di-Muon Pairs (1)

CMS-PAS-HIG-16-035







One event in signal region (△)

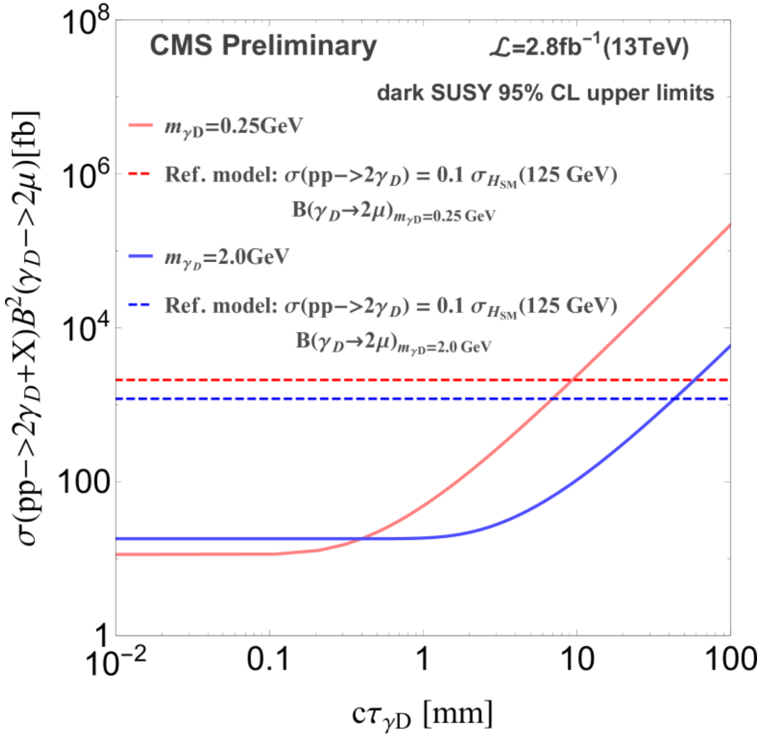
- Search for displaced di-muon pairs from decay of long-lived light boson, with mass between 0.25 and 8.5GeV
  - Benchmark models: next-to-minimal SUSY and SUSY with a hidden sector (dark SUSY)
- Require di-muon pairs to have the same mass
  - Investigate displaced decays up to 9.8cm on transverse plane, and 46.5cm along z axis

Displaced Di-Muon Pairs (2)

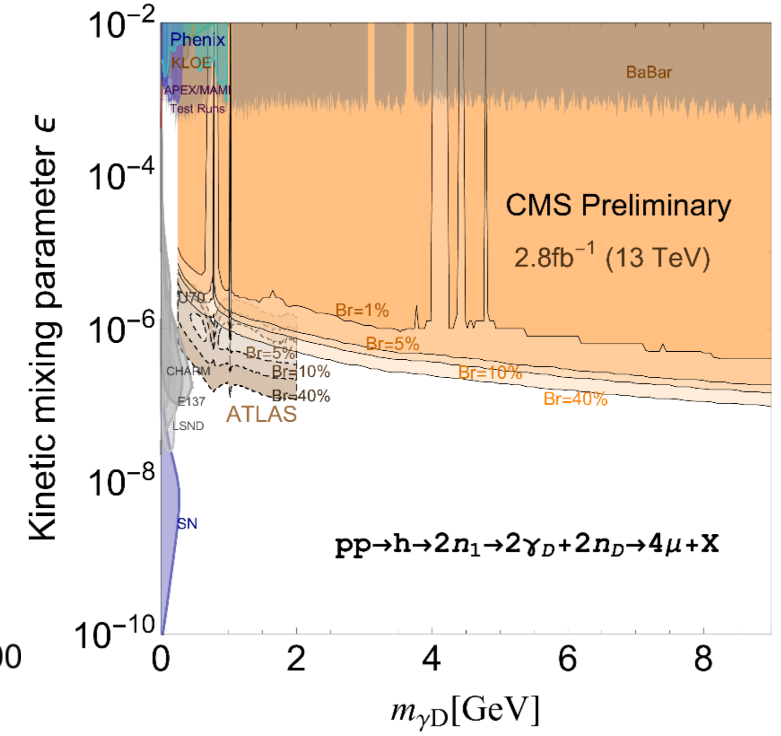
CMS-PAS-HIG-16-035

- Focus (personal choice) on dark-SUSY model
  - Results on NMSSM interpretation reported in public note
- Model-independent limit of 1.7fb on $\sigma(pp \rightarrow 2a + X) \cdot BR(a \rightarrow \mu\mu)$
  - Re-interpreted in $c\tau(\gamma_D)$-dependent cross-section limit in Dark-SUSY scenario
- Excluded large parameter space in (ϵ, m_{γ_D}) plane previously unconstrained
  - Dark photon lifetime directly related to kinetic mixing parameter ϵ and dark photon mass

Dark-SUSY interpretation



Cross-section limits
Dark photon masses:
0.25GeV and 2.0GeV

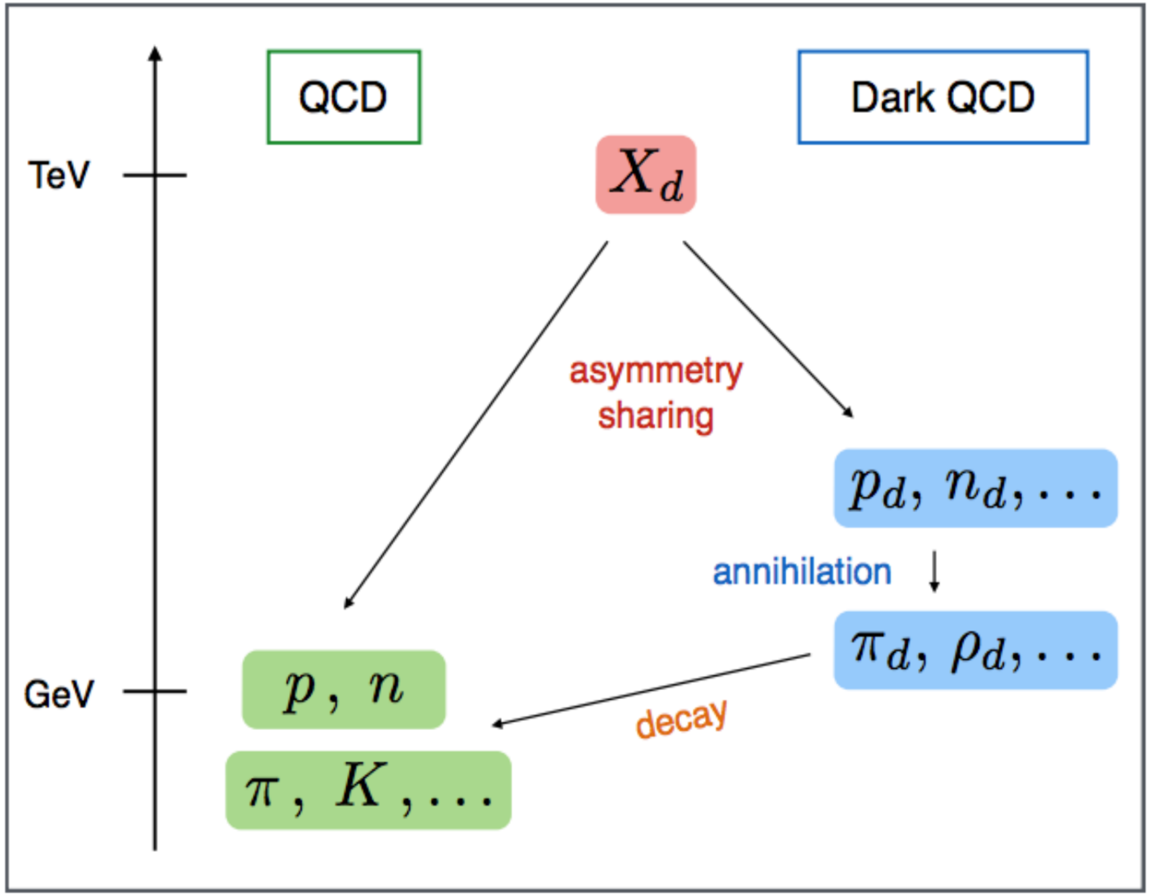


95% CL upper limits in (ϵ, m_{γ_D}) plane; m_{n_1}=10GeV, m_{n_D}=1GeV

Emerging Jets

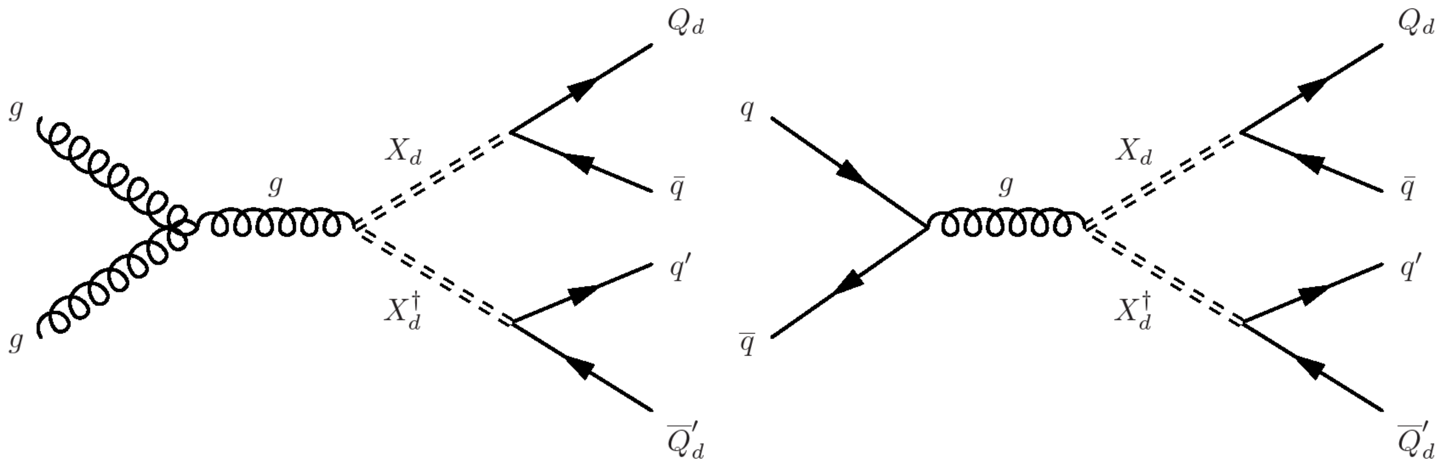
CMS-PAS-EXO-18-001

- Emerging jets represent the signature of a Dark-QCD model presented by Bai, Schwaller, Stolarski and Weiler
  - arxiv:1306.4676 and arxiv:1502.05409
  - DM candidate is the dark baryon
- The existence of a dark-QCD sector is posited, with a massive mediator that couples SM and dark quarks
  - The dark quarks hadronize into dark mesons, which then decay into SM jets via the mediator
- Dark mesons can have lifetimes from centimeters to meters
  - Analysis focus on jets produced within the CMS tracker



Model Parameters

- Dark force
  - SU(N) symmetry; seven dark colors
  - Confinement scale set equal to twice the dark pion mass
- Dark mediator X_d
  - Scalar, SU(3) color triplet
  - Fractional charge; Yukawa coupling to SM quark and dark quark
    - Satisfy restrictions from FCNC, neutral meson mixing, rare decays by assuming all couplings are negligible except for coupling to down quark
  - Mass of order TeV
- Dark mesons π_d and ρ_d
  - Mass of order 1-10GeV
  - Lifetime of order 1mm to 3m

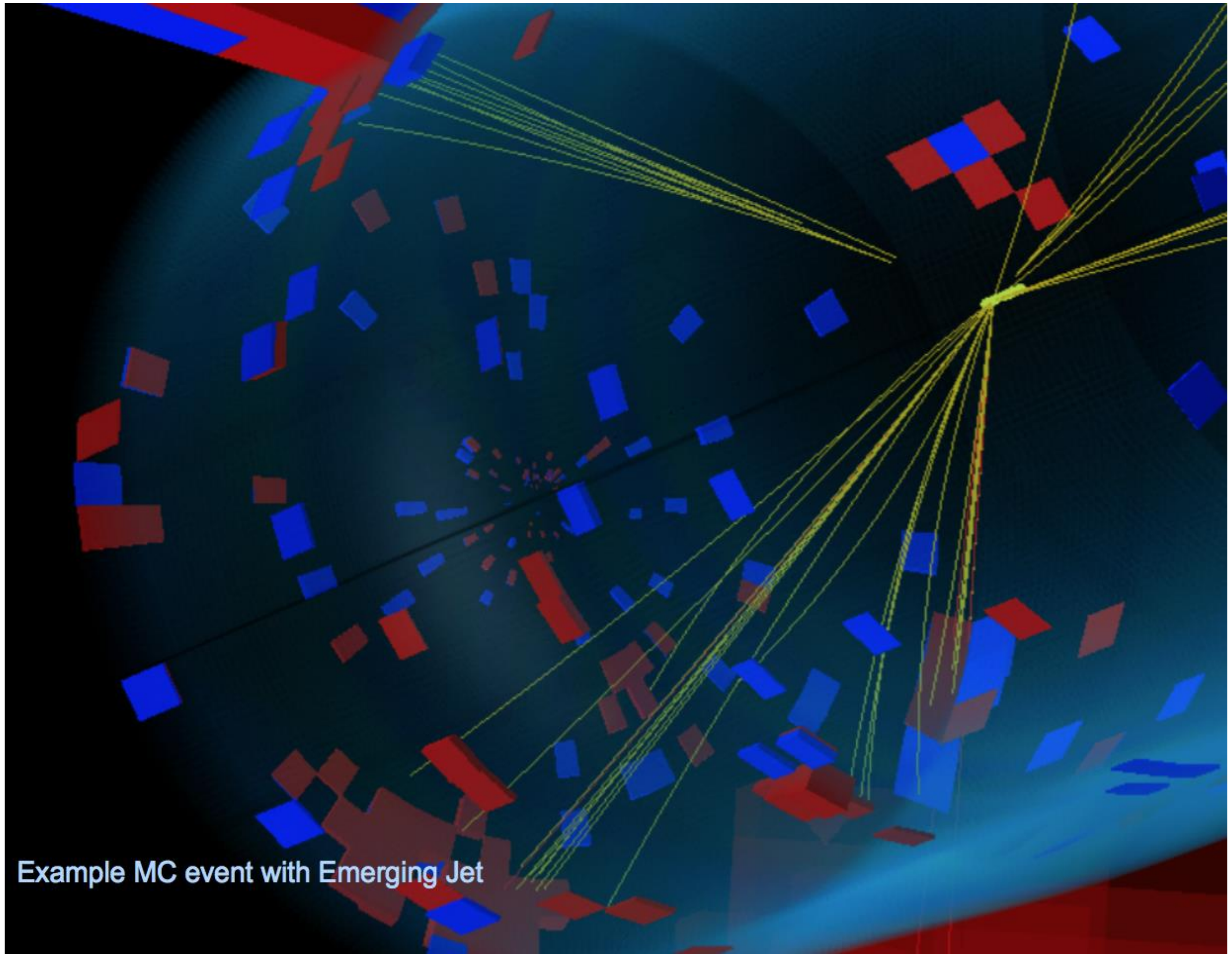


Highlights

- Mediator is QCD-colored ⇒ pair-produced via quark-antiquark or gluon fusion
- Mediator decays promptly to light QCD quark and dark quark ⇒ two prompt light jets
- Dark pions decay with sizeable lifetime ⇒ two emerging jets

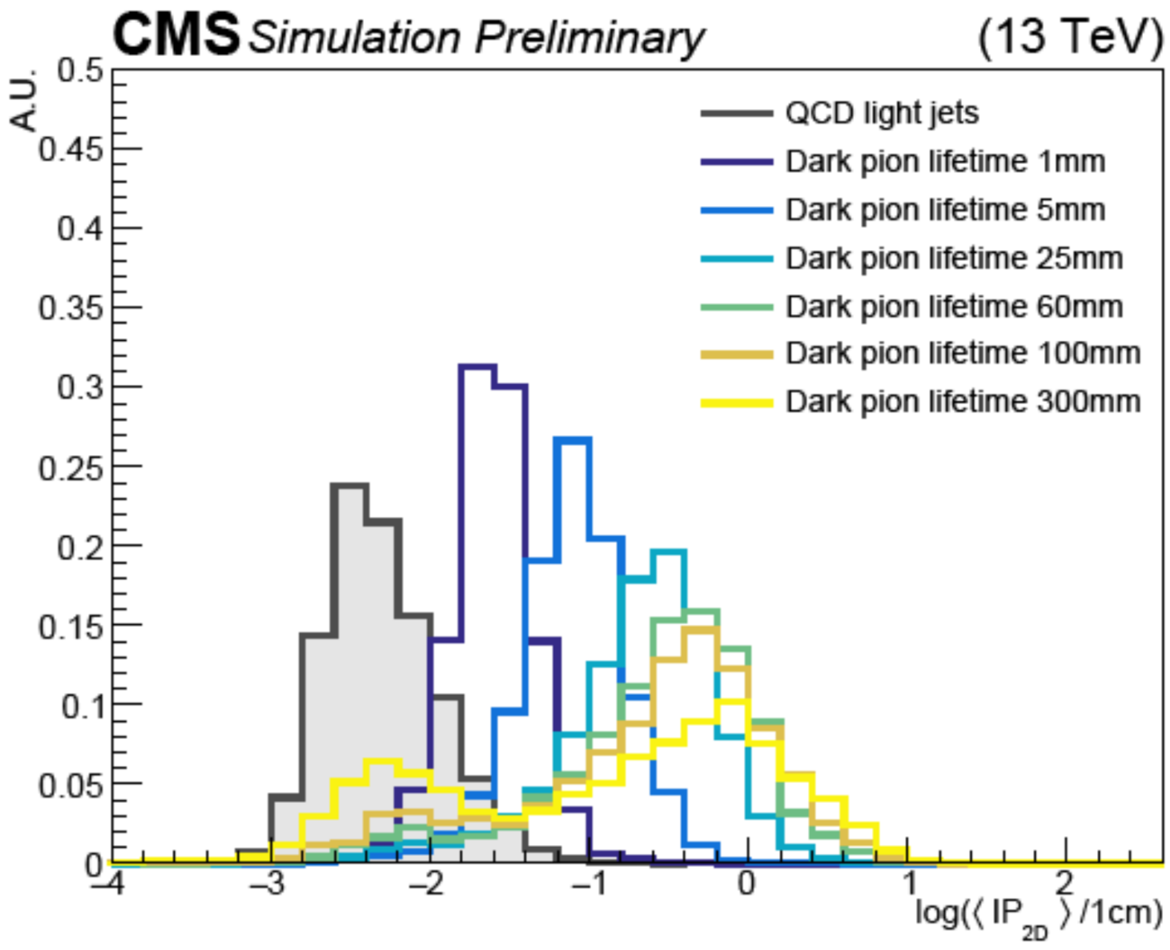
Striking Signature

- Two prompt jets + two emerging jets
  - Two heavy mediator produced: can use large event Q^2 to trigger events
- Investigated large range of model parameters
  - Mediator mass: 400-2000GeV
  - Dark pion mass: 1-10GeV
  - Dark pion lifetime: 1-1000mm
- Experimentally challenging
  - Short lifetime: SM displaced vertices (e.g., b quarks); mismeasurements
  - Long lifetime: low tracking efficiency



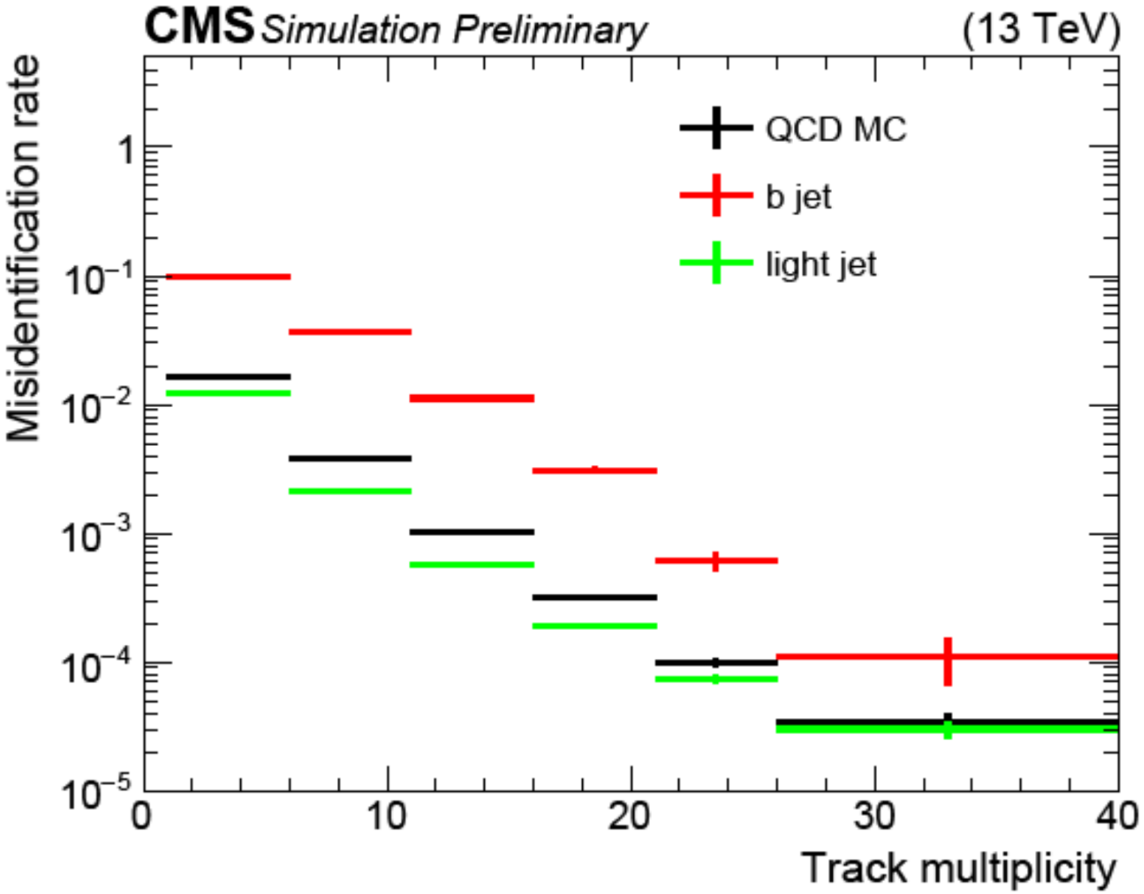
Quantifying Displacement

- Key ingredient in analysis is emerging-jet tagging
  - Need to define robust estimator of jet displacement, stable up to many cm from primary interaction vertex
- Four variables define different flavors of emerging-jet tagger
  - $\langle IP_{2D} \rangle$: median of unsigned transverse impact parameter of tracks associated to jet
  - $PU_{\delta z}$: distance between the z position of the primary vertex (PV) and of a track at its point of closest approach it
  - D_N: a 3D impact parameter significance, assuming a z resolution of 100µm
  - α_{3D}: the p_T-weighed fraction of tracks associated to a jet that are below a D_N threshold
- Final selection optimized for each grid point in model parameter space
  - An E_T^{miss} cut is added for long lifetimes, to compensate for the loss in tracking efficiency



Background Estimate

- The dominant background is QCD jet production
  - QCD jets can mimic the emerging-jet signature with a probability that depends on the flavor of the initiating parton and the jet track multiplicity
- A data-driven method is defined to estimate the background
  - Mimicking failures of tracking is not a job that Monte Carlo simulated events do well
- Determining the contribution of b quarks is critically important
  - They mostly come in pairs, and b hadrons do have a non-negligible lifetime



Misidentification rate for jets initiated by a b quark is one order of magnitude larger than for light-quark jets

Misidentification Rate Measurement

- The misidentification rates are measured in a signal-depleted data sample: γ+jet
  - They will then be applied to data samples with one or zero emerging-tagged jets
- A matrix method is designed to measure the misidentification rate for light and b jets in data
  - Two samples with a different fraction of b jets are selected by applying a cut on a b-tagging discriminator
- The misidentification rate, binned in track multiplicity, is applied to events in QCD-enhanced control regions
  - The misidentification rate is averaged using the fitted b-jet fraction in data

Measure fraction of b jets in samples 1 and 2 (b-enhanced and b-depleted) with template fit of b-tagging discriminator: f_{b1} and f_{b2}

→ Measure misidentification rate in samples 1 and 2 : ϵ_1 and ϵ_2

→ Invert the misidentification rate equation:

$$\begin{pmatrix}\epsilon_1\\ \epsilon_2\end{pmatrix} = \begin{pmatrix} f_{b1} & 1-f_{b1}\\ f_{b2} & 1-f_{b2}\end{pmatrix}\begin{pmatrix}\epsilon_b\\ \epsilon_l\end{pmatrix}$$

and obtain the rates for b and light jets: ϵ_b and ϵ_l

→ Calculate average misidentification rate in QCD-enhanced control region:

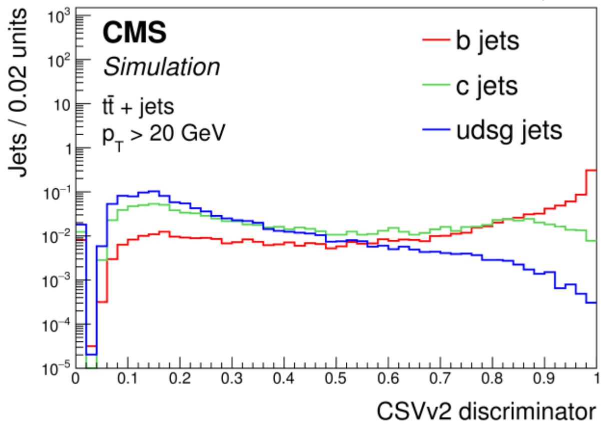
$$\epsilon_{f,CR} = f_{b,CR}\epsilon_b + (1-f_{b,CR})\epsilon_l$$

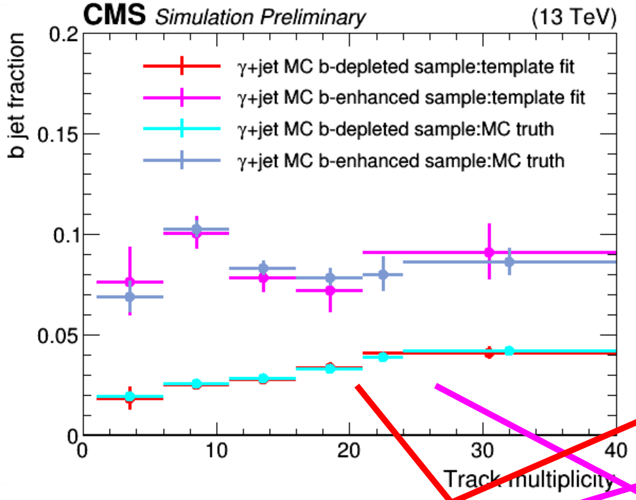
and apply to each jet in control region with correct combinatorial factor ✓

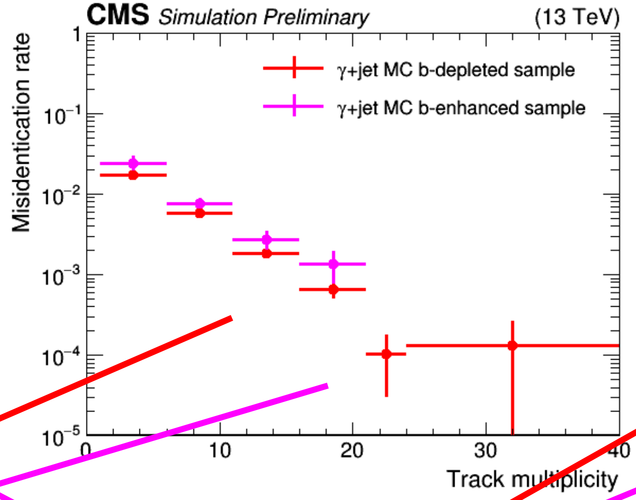
A Pictorial View

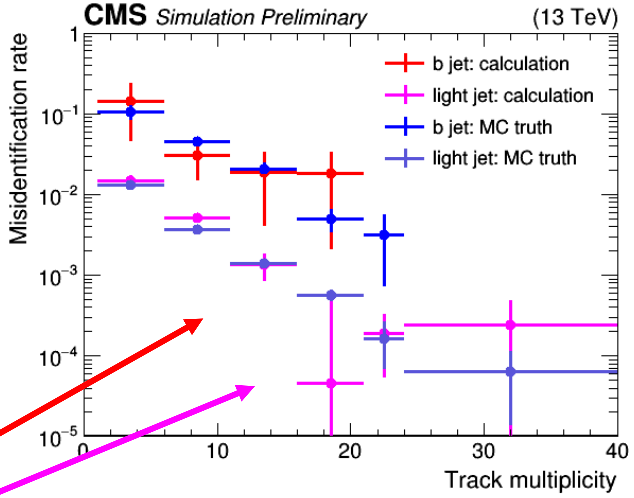
CSVv2 template fit in bins of track multiplicity → Obtain b fraction in independent samples → Measure misid. rate in independent samples → Invert rate matrix and calculate misid. rate of b and light jets

[JINST 13 (2018) P05011]



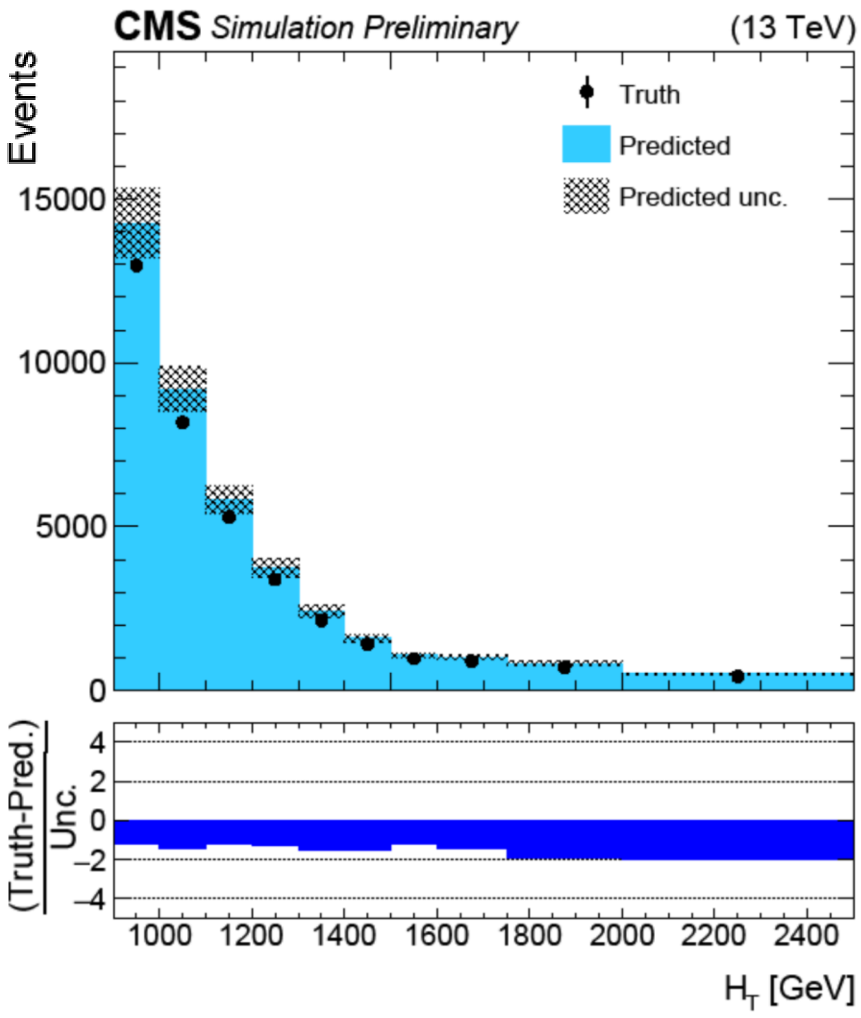




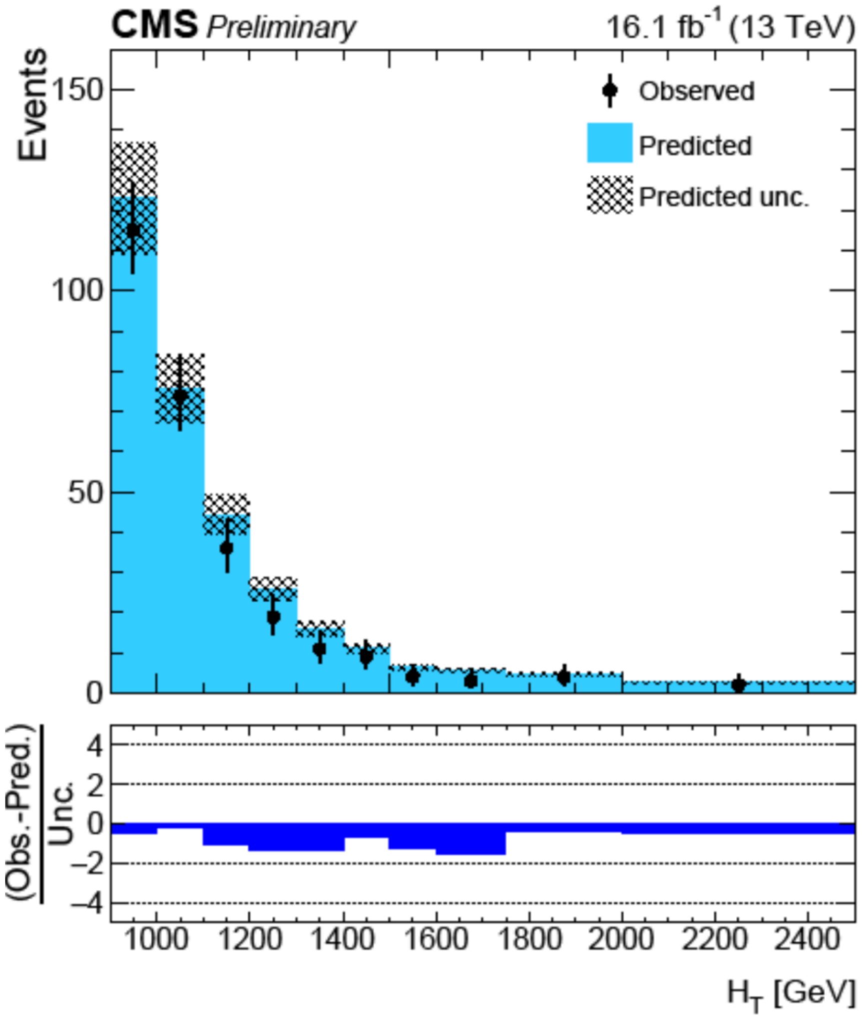


$$\begin{pmatrix} \epsilon_1 \\ \epsilon_2 \end{pmatrix} = \begin{pmatrix} f_{b1} & 1 - f_{b1} \\ f_{b2} & 1 - f_{b2} \end{pmatrix} \begin{pmatrix} \epsilon_b \\ \epsilon_l \end{pmatrix}$$

Closure Test

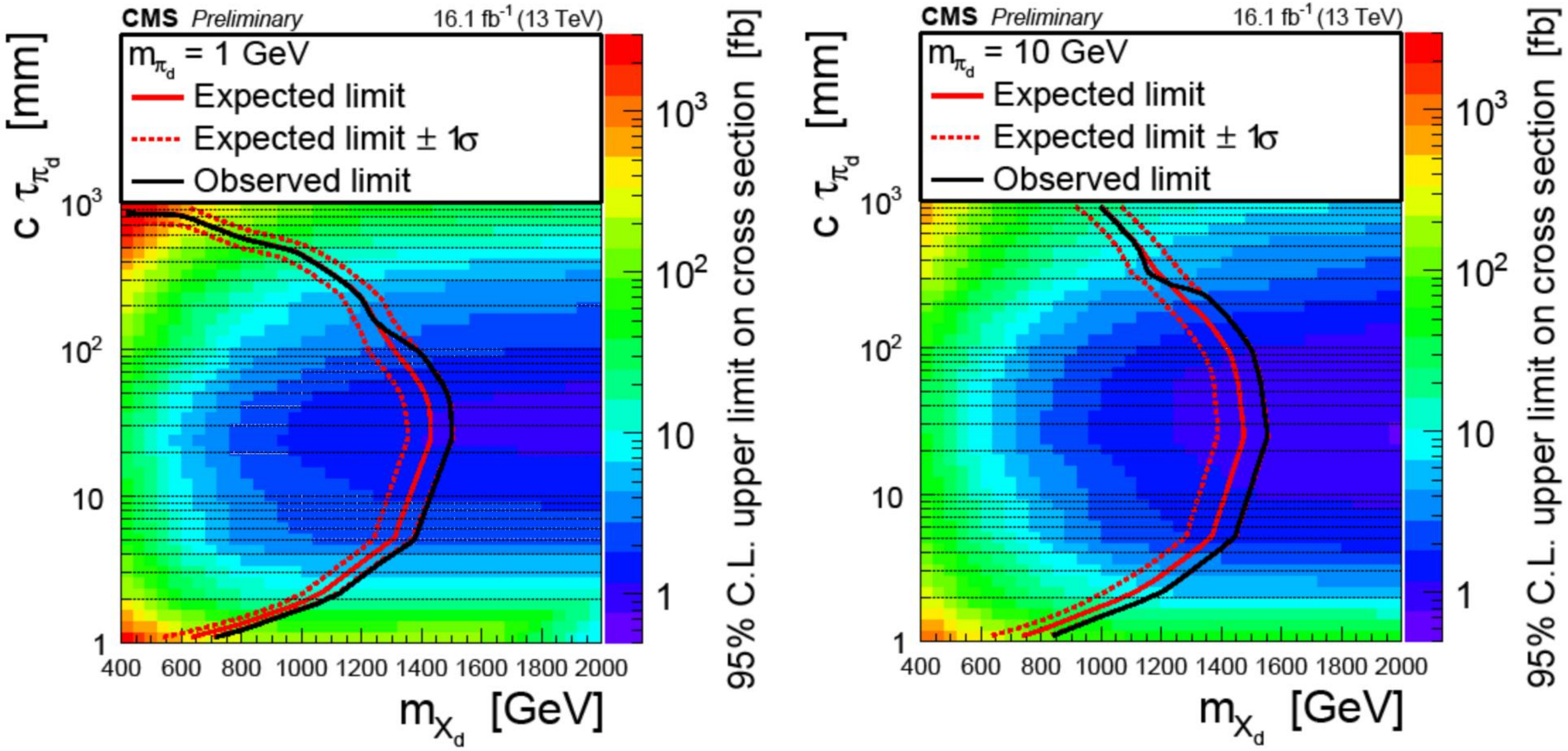


- The method devised to estimate the QCD background is verified with a closure test
  - (Left) comparison between prediction and truth, using QCD simulated events, in 1-tag sample
  - (Right) comparison between measurement in 2-tag data control region and prediction obtained using 1-tag data control region
- Agreement within estimated uncertainties between prediction and truth/measurement
  - Successfully checked agreement as a function of jet p_T, track multiplicity, and m(jj) in 1- and 2-tag samples



CMS-PAS-EXO-18-001

Setting Limits



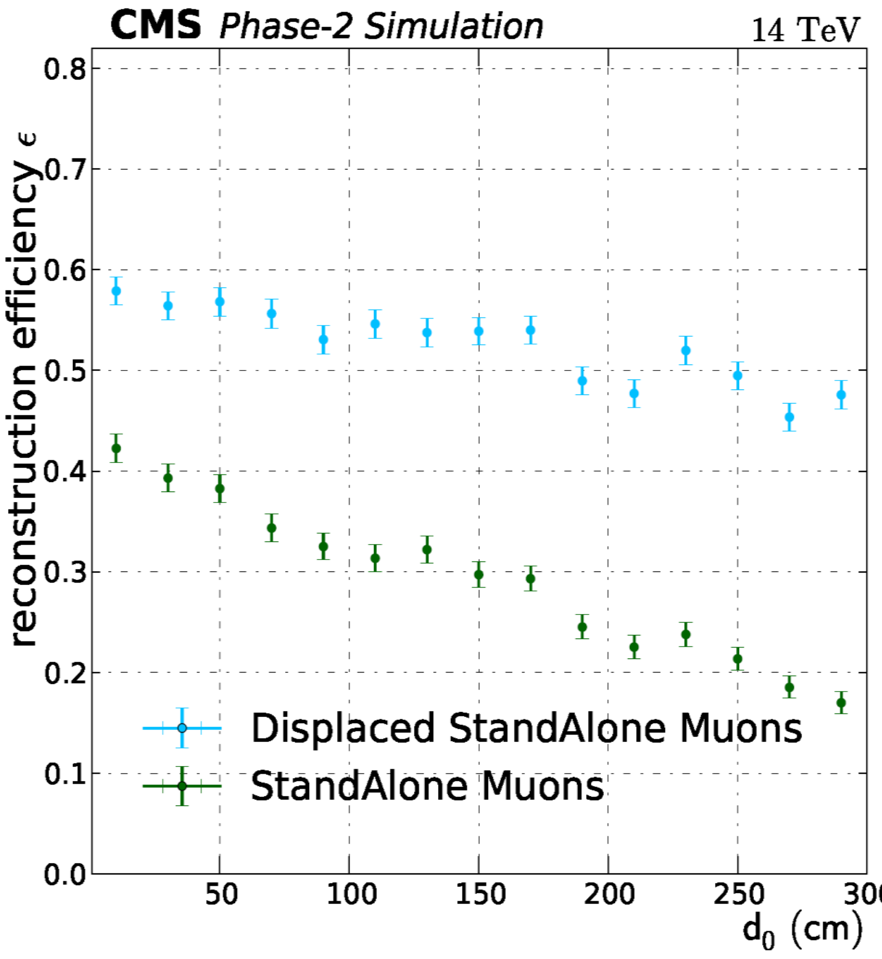
- No excess observed over SM expectations
  - Excluded mediator masses in the 400 to 1250GeV range, for dark-pion decay lengths in the 5 to 225mm range; limits set with dark-pion masses of 1, 2, 5, and 10GeV
- First dedicated search for emerging jets in BSSW model at the LHC

More LLP Results…

- Disappearing / kinked tracks
  - Search for disappearing tracks as a signature of new long-lived particles in proton-proton collisions at sqrt(s)=13TeV, arXiv:1804.07321, submitted to JHEP
- Heavy Stable Charged Particles (HSCP)
  - Search for heavy stable charged particles with 12.9fb^{-1} of 2016 data, CMS-PAS-EXO-16-063
- Stopped exotic LLP
  - Search for decays of stopped exotic long-lived particles produced in proton-proton collisions at sqrt(s)=13TeV, JHEP 05 (2018) 127
- Leptoquarks in Displaced RPV SUSY
  - Search for pair-production of first generation scalar leptoquarks in pp collisions at sqrt(s)=13TeV with 2.6fb^{-1}, CMS-PAS-EXO-16-043
- Re-interpretation of prompt searches in LLP scenario
  - Search for natural and split supersymmetry in proton-proton collisions at sqrt(s)=13TeV in final states with jets and missing transverse momentum, JHEP 05 (2018) 025
  - Search for pair production of second generation leptoquarks at sqrt(s)=13TeV, CMS-PAS-EXO-17-003

A Peek at CMS @ HL-LHC

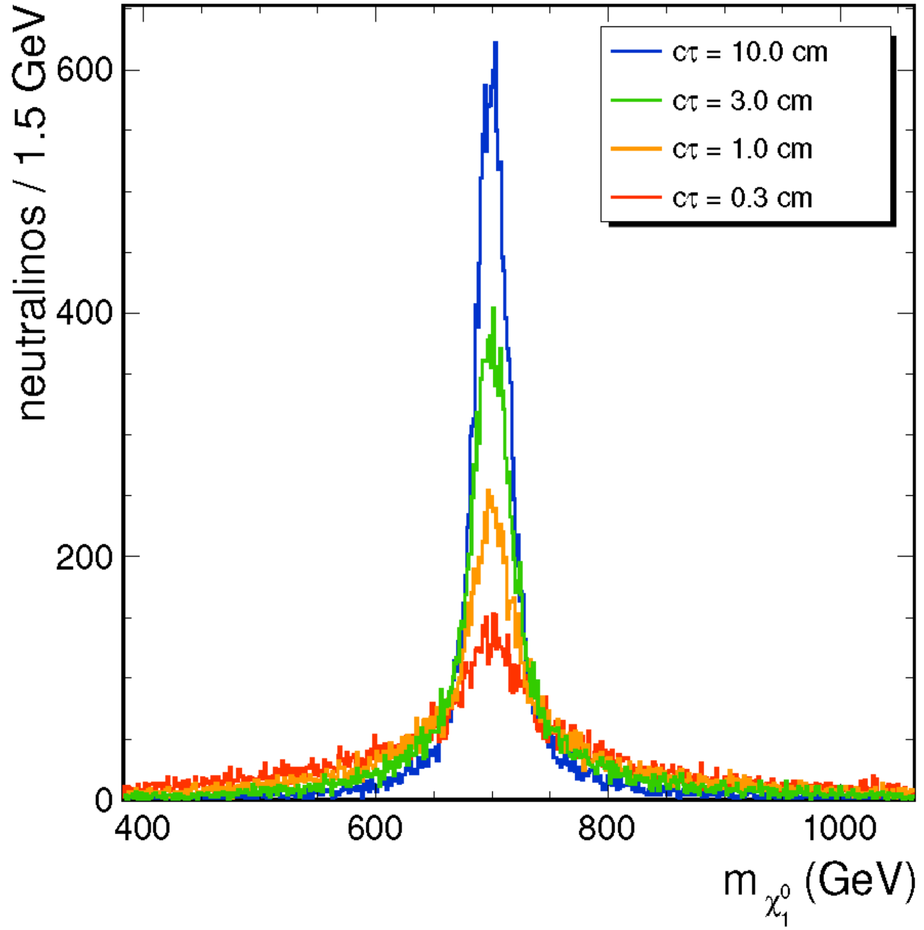
- High-Luminosity LHC runs
  - 2026-2035 run period
  - Expect to collect 4.5/ab
- Significant upgrades planned for all CMS detectors
  - Address radiation damage, and increase in trigger latency and data rates
  - Extension of detector coverage to improve particle identification
  - New detectors to help cope with increased number of concurrent collisions (pileup)
- Personal choice of two topics
  - Muon upgrade CERN-LHCC-2017-012
  - MIP Timing detector CERN-LHCC-2017-027



Additional muon layers in forward region allow for fit without PV constraint

Impact of Timing Measurement

- The MIP Timing Detector (MTD) is expected to provide vertex timing with 30ps resolution
  - Allows for 4-dimensional reconstruction of vertices, reducing impact of pileup
    - Vertex density in HL-LHC will be 2/mm, vs. 0.3/mm in current run; expect on average ~200 pp interactions per bunch crossing
- Timing information also allows for the definition of new variables
  - Can measure time-of-flight of long-lived particle between primary and secondary vertices, and reconstruct its mass from energy and momentum measurement of decay products
- Benchmark analysis: long-lived neutralino in GMSB
  - Neutralino produced in top squark decay; decays to Z boson and massless gravitino



Peaking variable made available by MTD

Summary

- Important motivations to searches for displaced-object signatures
  - E.g., complement traditional E_T^{miss}+X searches for DM candidates
- Challenging analyses in which we look outside usual comfort zone
  - Vertex reconstruction far from beamline; disappearing or kinked tracks; non-pointing objects
- Excellent detectors (and smart analyzers) allow for investigation of exotic final states
  - Alas, no sign of new physics beyond the SM, but stringent limits on many SM extensions
- Exciting times ahead, with a O(10) expected increase in data size by 2023
  - Moreover, CMS upgrades for HL-LHC will add capabilities that promise to play an important role in extending current reach

Additional Material

The Importance of Timing

- Precise timing information adds a new dimension to vertex reconstruction
  - Promises ability to distinguish individual pp interactions that occur within a bunch crossing
- Numbers of interest
  - Average number of pp interactions per bunch crossing at HL-LHC: 200
  - Time-spread among pp interactions: 150ps
  - Luminous region along beam: ~4.5cm RMS
  - Vertex density in HL-LHC: 2mm^{-1}
    - LHC: 0.3mm^{-1}
- While HGC provides timing info with 50ps resolution per cell, proposals are advanced for detectors that specifically measure track timing
  - ATLAS: High-Granularity Timing Detector (HGTD)
  - CMS: MIP Timing Detector (MTD)