Search for Dark Showers at Collider

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LPC Future DM@LHC Workshop

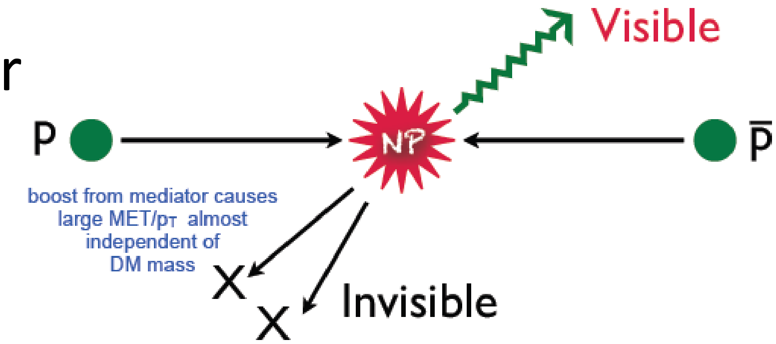
July 27, 2017

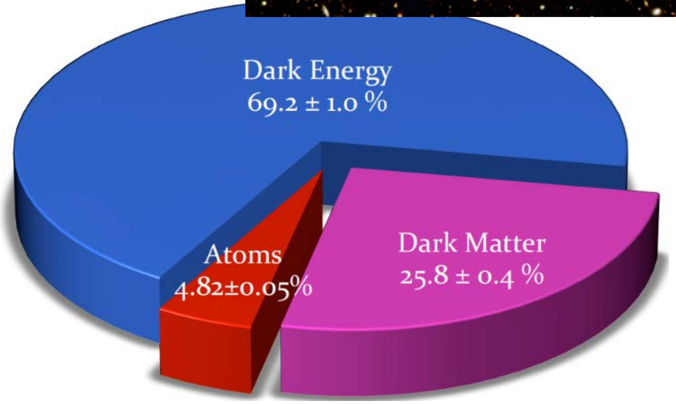
Outline

- Theory motivation
- Collider production
- Collider searches
- Experimental challenges
- Prospects with HL-LHC upgrade

Motivation: Current Constraints

- Conventional collider searches for dark matter has focused on the WIMP paradigm
  - assuming one type of dark matter particle
  - stringent constraints; no discovery of WIMPs* yet!
- Astrophysics observations suggest dark matter self-interactions
- Energy density of dark matter ~ 5x baryons: not accidental? → asymmetric dark matter

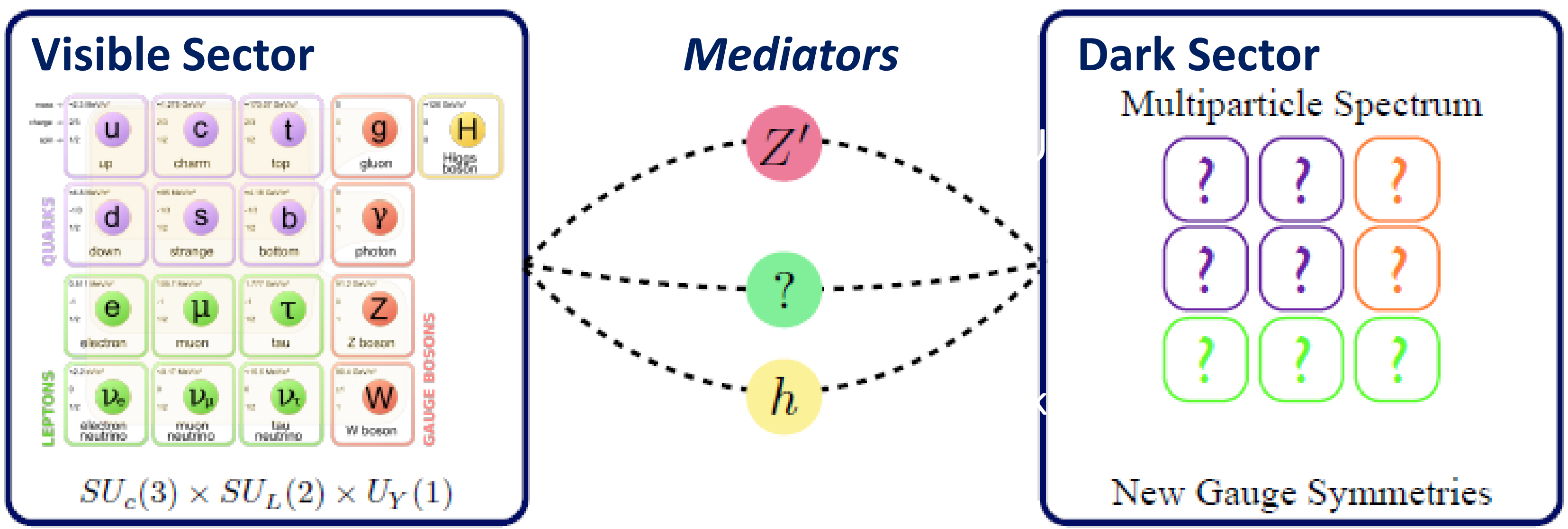




* Outside of Congress

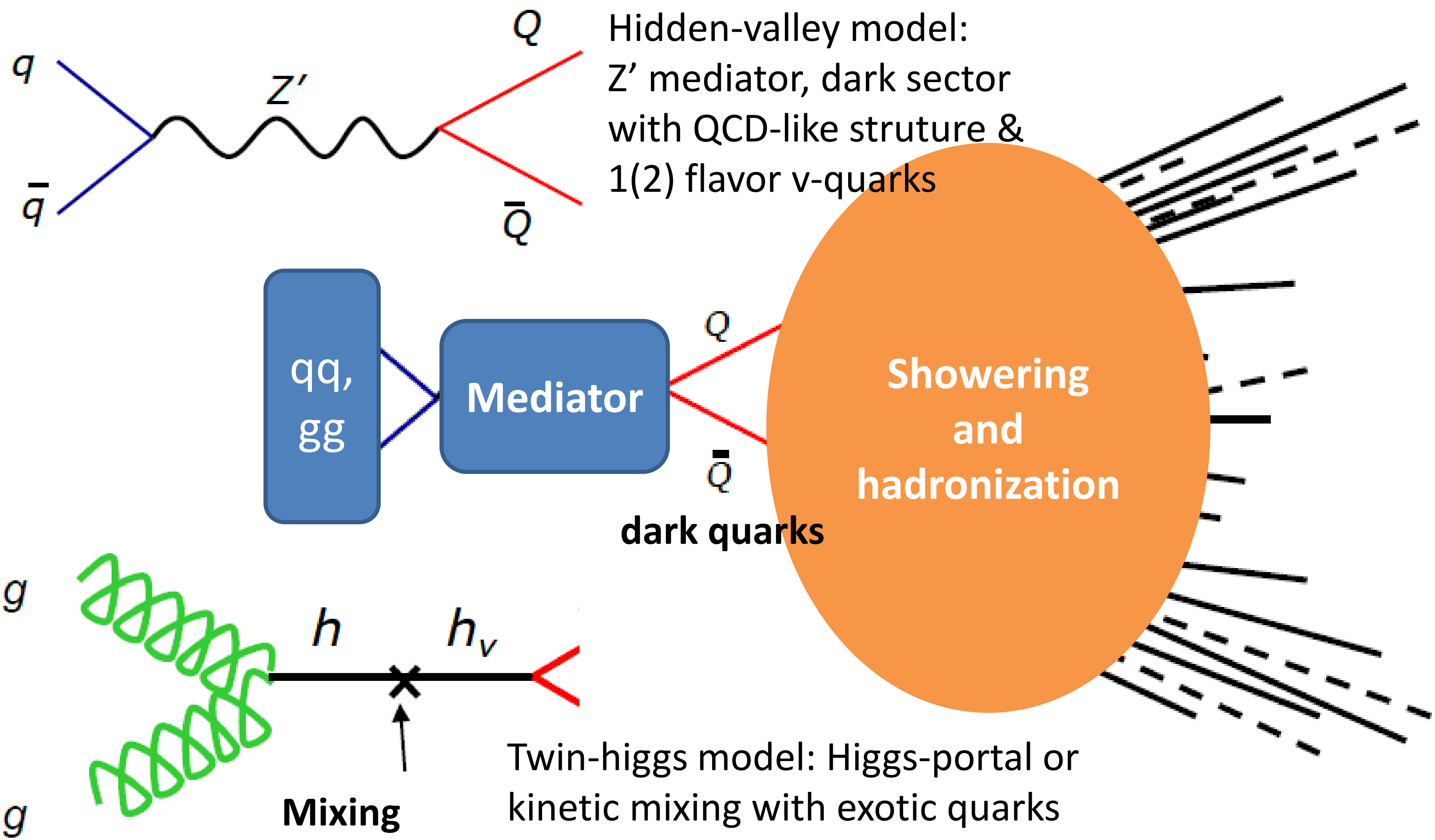
Motivation: Dark Sector

- If instead of one type of dark matter particle, there is a more complex dark sector with structures similar to the visible sector
- Extend the SM gauge symmetries to new hidden symmetry with new hidden particles
  - SM particles neutral under hidden symmetry
  - mediator (Z', Higgs, ...) between the visible and dark sectors



Dark Shower: Collider Production

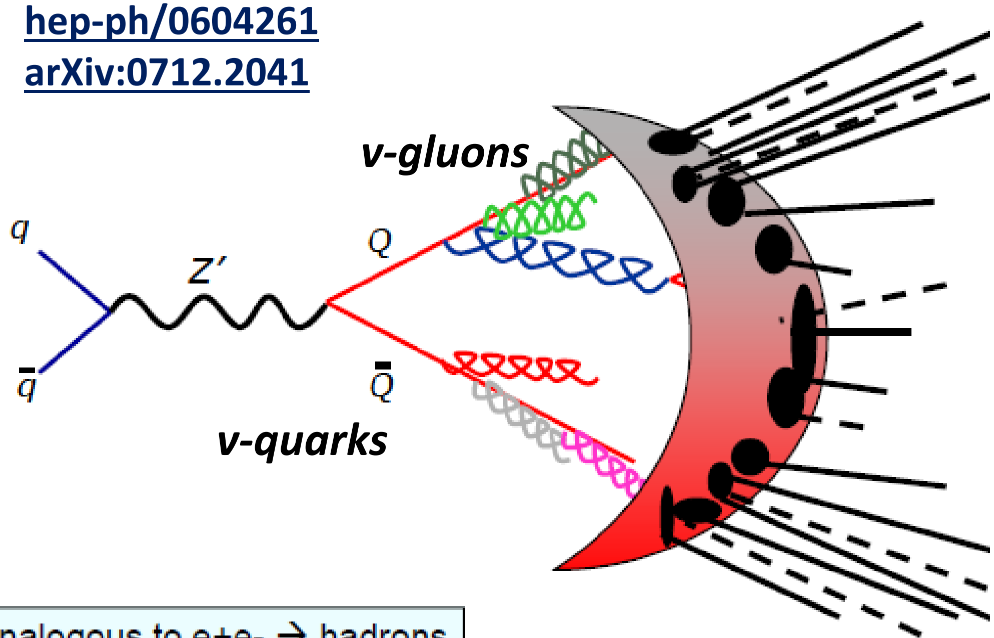
Hidden-valley model:
Z' mediator, dark sector with QCD-like struture & 1(2) flavor v-quarks



Twin-higgs model: Higgs-portal or kinetic mixing with exotic quarks

Example: Hidden Valley

hep-ph/0604261
arXiv:0712.2041



Analogous to e+e- → hadrons

The v(alley)-hadrons decay immediately to v-mesons and the lightest v-baryons:

- the v-baryon is stable: DM candidate!
- two out of the three v-mesons (dark pions) are stable
- the charge neutral v-pion decays: for O(10)GeV v-pion, primarily to b-quarks with lifetime:

$$\Gamma_{\pi_v \to b\bar{b}} \sim 6 \times 10^9 \ \mathrm{sec}^{-1} \frac{f_{\pi_v}^2 m_{\pi_v}^5}{(20 \ \mathrm{GeV})^7} \left(\frac{10 \ \mathrm{TeV}}{m_{Z'}/g'} \right)^4$$

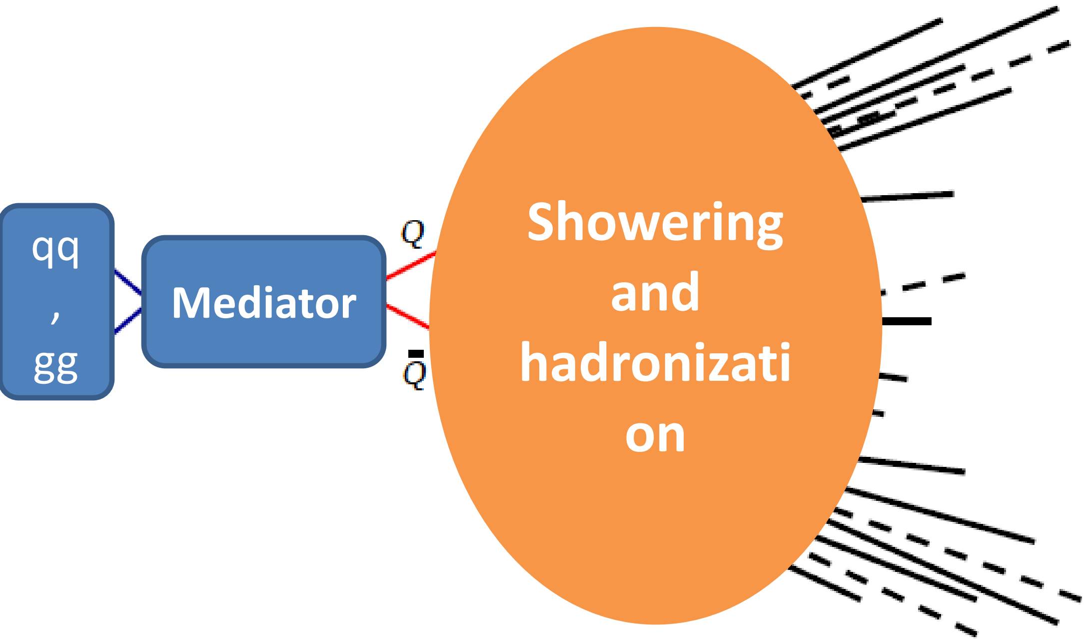
New Z′ from U(1)′

Standard Model SU(3)xSU(2)xU(1)

Hidden Valley v-QCD with 2 (or 3) light v-quarks

Lifetime can be long and largely dependent on ~free parameters → consider lifetime a FREE parameter!

Dark Shower: Collider Signature



Depending on the underlying model and the mass of the new particles, the final state holds extremely rich collider phenomenology:

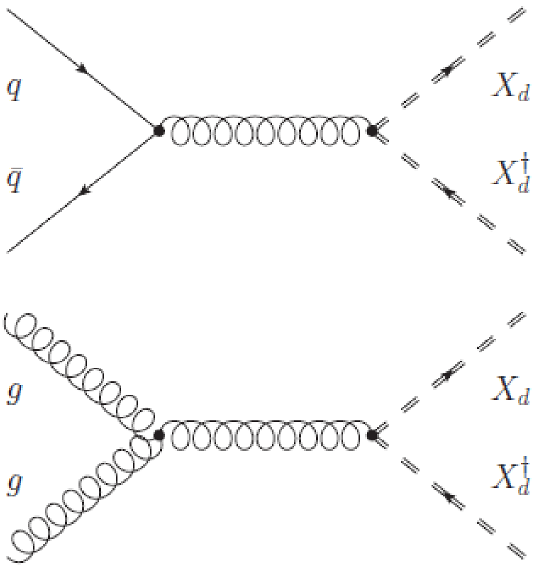
- hadronic/leptons/photons/…
- Multiplicity high/low
- Boost/not boosted
- Lifetime/ displacement

→ exciting & challenging for experimentalists!

Lifetime: considered as FREE parameter

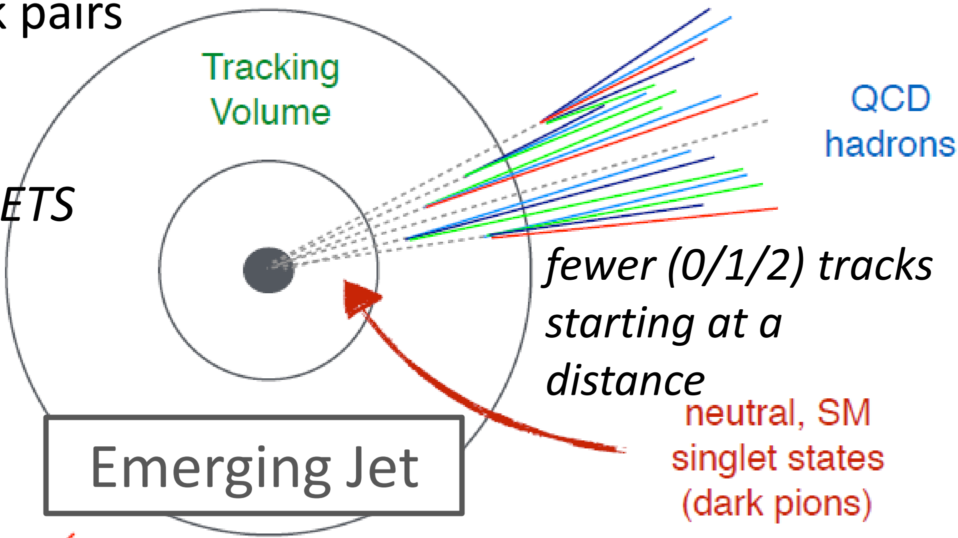
- very low lifetimes → prompt: hadronic exotic searches (resonant & non-resonant)
- very high lifetimes → escape detector: prompt SUSY and dark matter searches
- this talk focus on displacement within detector

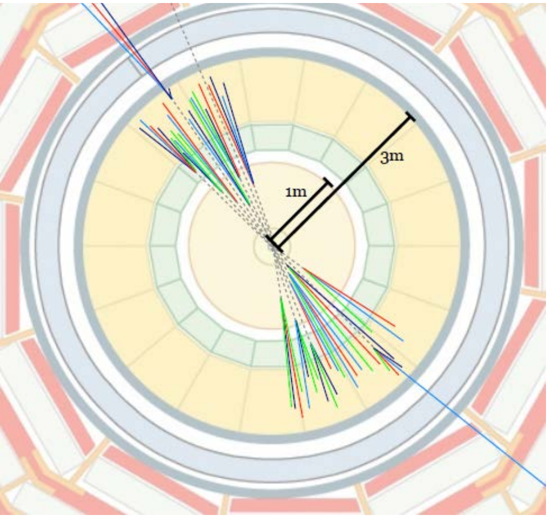
Final State: Emerging Jets

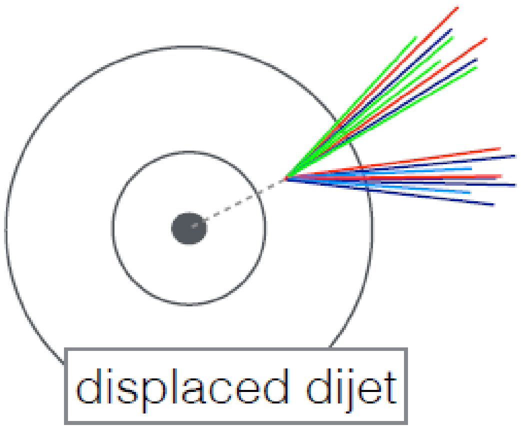


Pair production of heavy bi-fundamental scalars, each decay to quark-dark quark pairs
→
two QCD jets;
two *EMERGING JETS*

arXiv:1502.05409





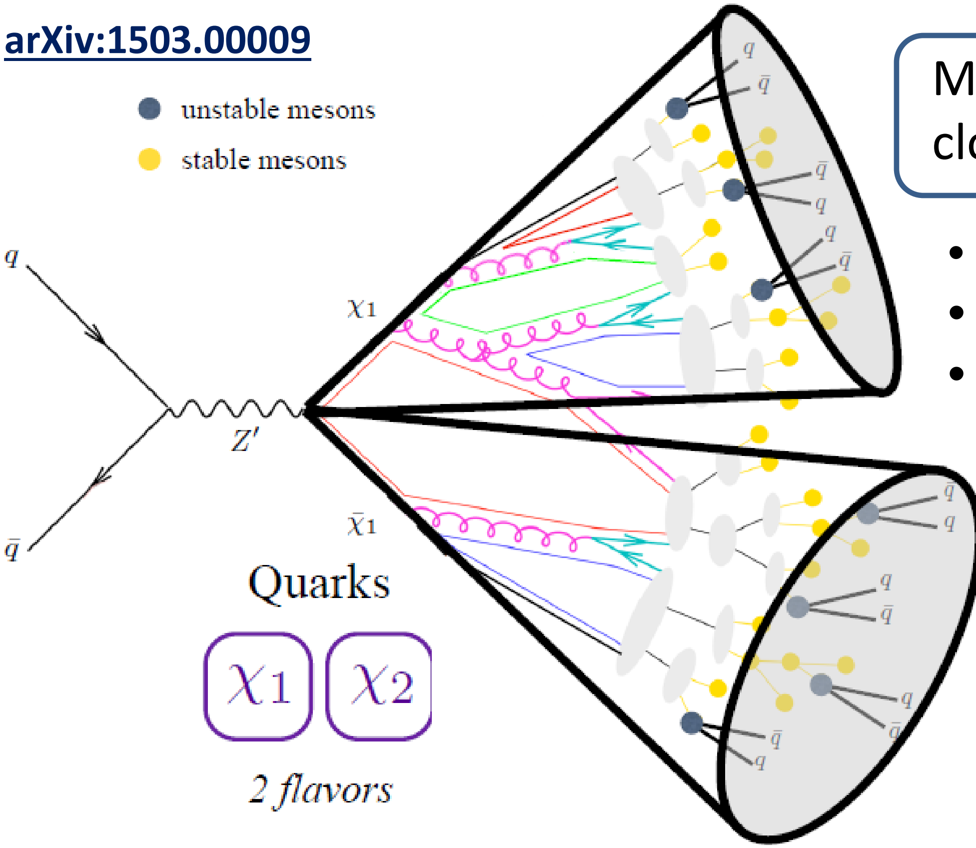


Different from displaced dijets:

- lower jet mass
- lower track multiplicity from multiple vertices
- multiple displaced vertices inside same cone

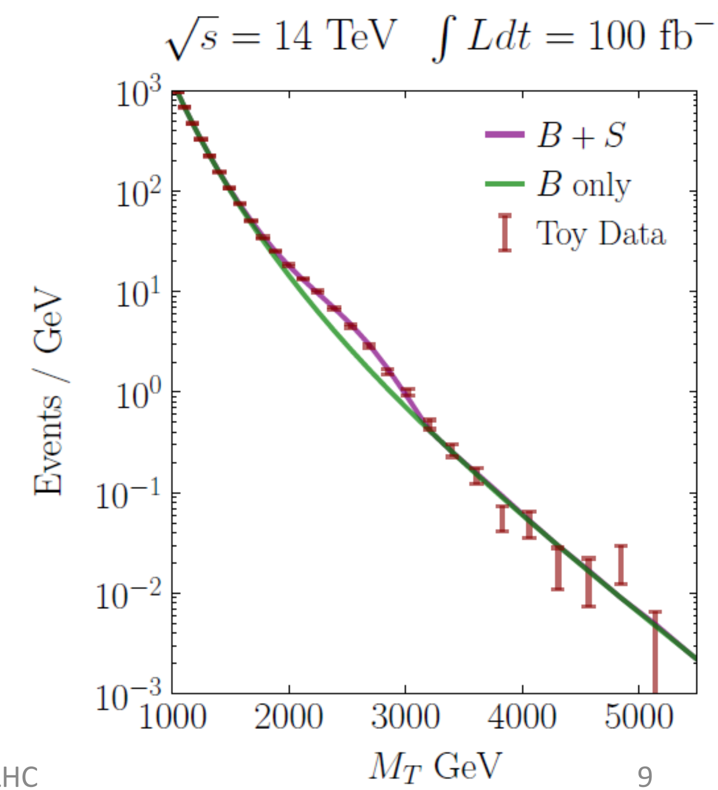
Final State: Semi-visible Jets

arXiv:1503.00009



Multijet + E_t^{miss} , where one of the jets is closely aligned with the direction of E_t^{miss}

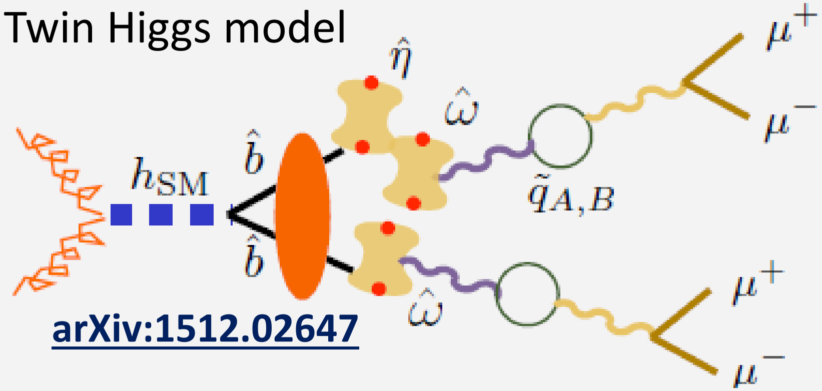
- Large-R jets with pT aligned with E_t^{miss}
- E_t^{miss} /M_T > 0.15; isolated lepton veto
- Fit transverse mass→ resonance bump hunt



- A TeV-scale, leptophobic gauge boson portal
- Dark sector with a QCD-like structure.
- Showering from the dark quark observed as a hadronic jet that also contains invisible particles

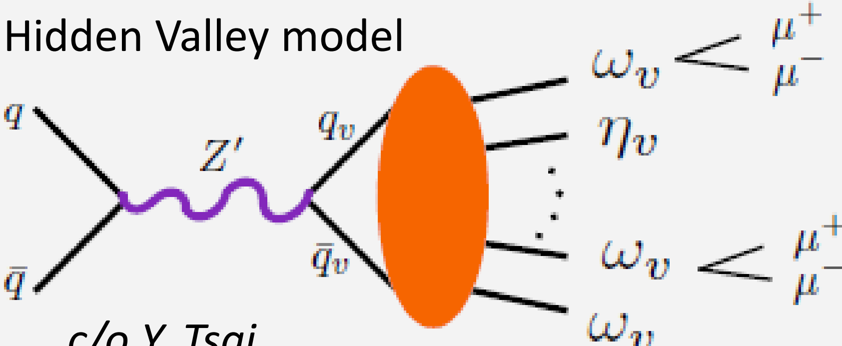
Final State: Displaced Muons

Twin Higgs model



arXiv:1512.02647

Hidden Valley model

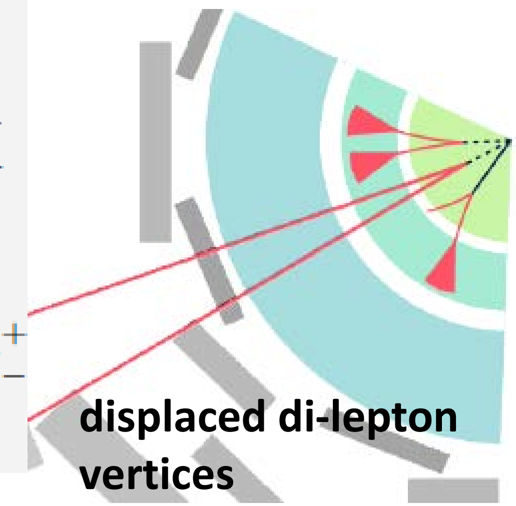


c/o Y. Tsai

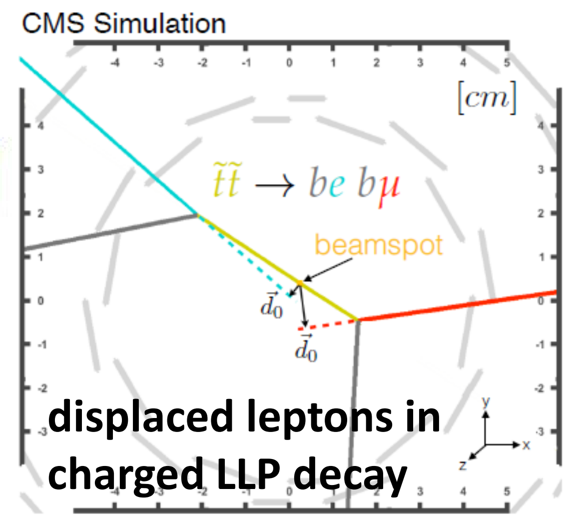
The light dark mesons can also decay to muon pairs with varying displacement.

ATLAS & CMS have conducted various searches for displaced muons in other models.

- <u>decays inside the inner tracker</u>



displaced di-lepton vertices

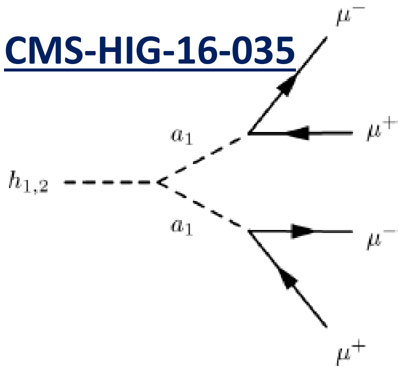


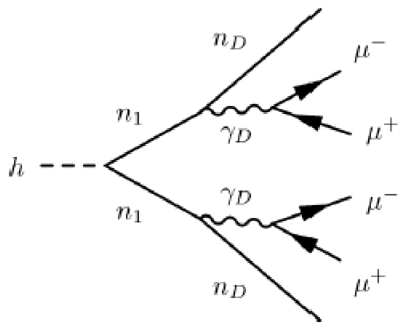
displaced leptons in charged LLP decay

- <u>decays outside inner tracker</u>: →more susceptible to cosmic ray background
    - e.g. dimuon vertex outside tracker (CMS), lepton-jets(ATLAS)
- displaced muons difficult to trigger: dedicated triggers developed for analysis
- these triggers often too hard on muon pT for a dark shower topology

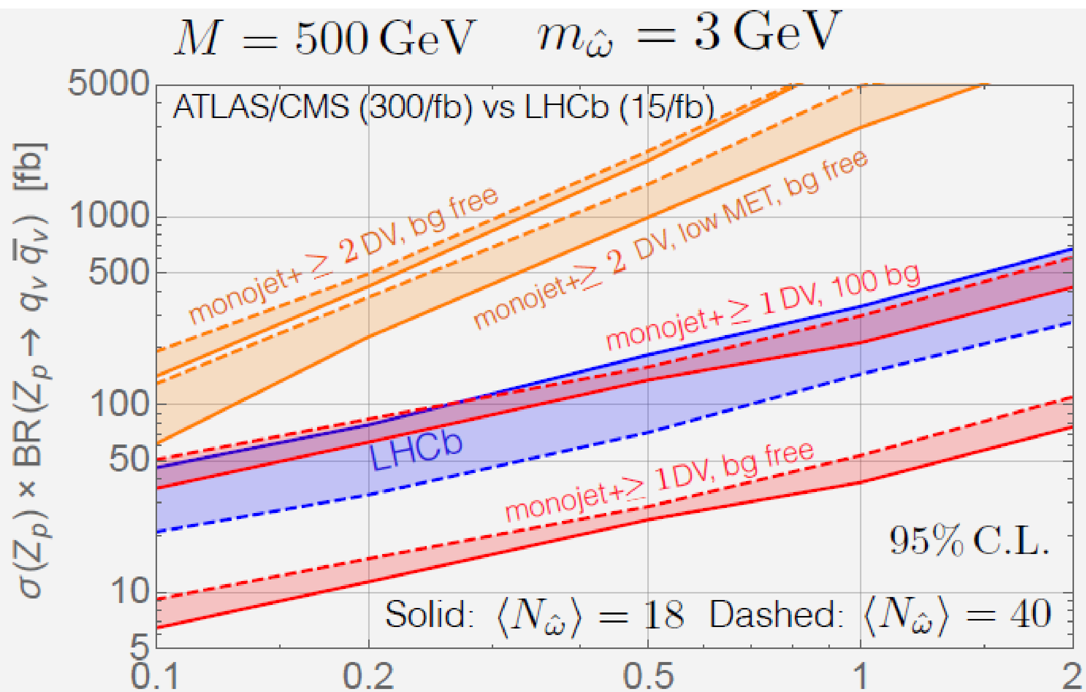
Displaced Muons: Sensitivity Projection

CMS-HIG-16-035



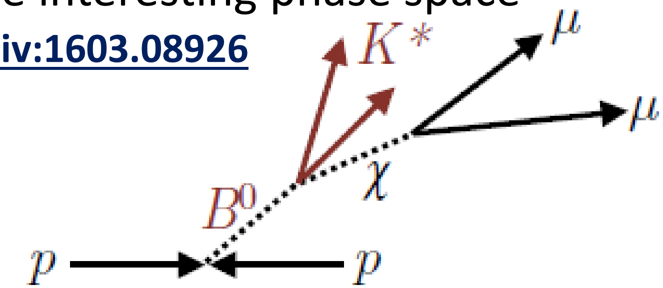


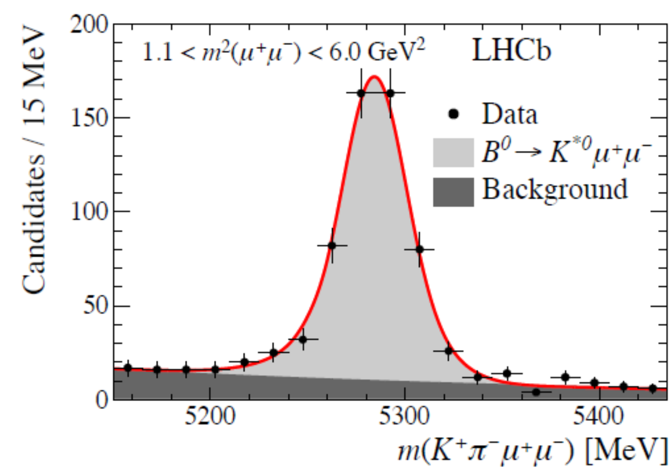
- CMS light boson search used a tri-muon trigger with lower pT thresholds
- Can also consider triggering on E_t^{miss} and/or ISR jet (see theory projection)
- LHCb has unique capabilities to cover some of the interesting phase space



c/o Y. Tsai

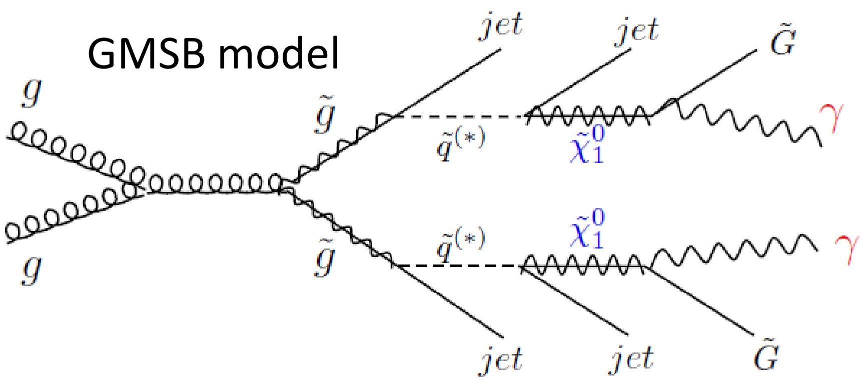
arXiv:1603.08926





Dark Shower: Displaced Photons

GMSB model

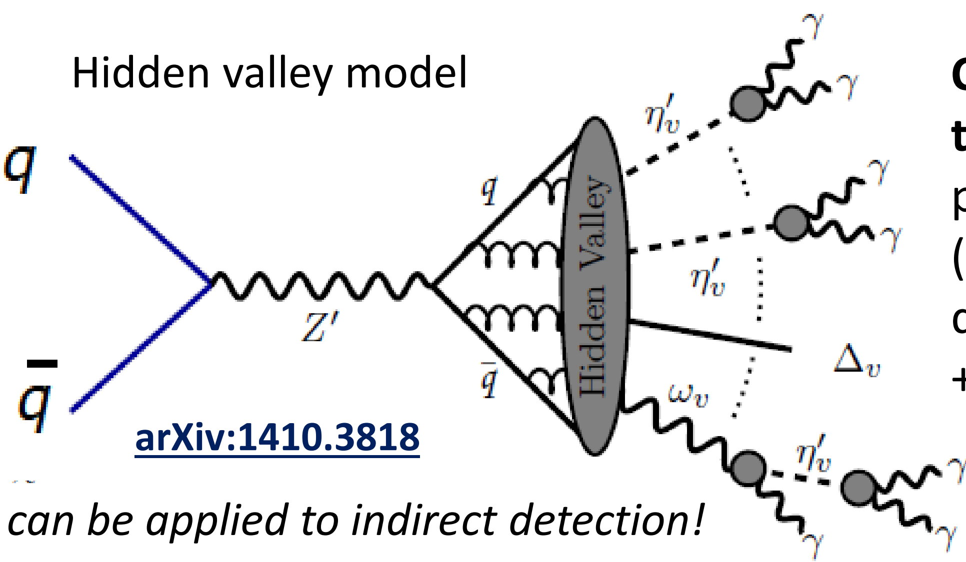


<u>ATLAS & CMS ECALs have very different designs</u>
→ different capabilities w.r.t. displaced photons

- ATLAS, liquid argon segmented in depth → additional Z info → non-pointing&delayed
- CMS, lead tungstate crystals → delayed in time + some shower shape info

Prior displaced photon searches on ATLAS&CMS focused on the GMSB model: very different topology!

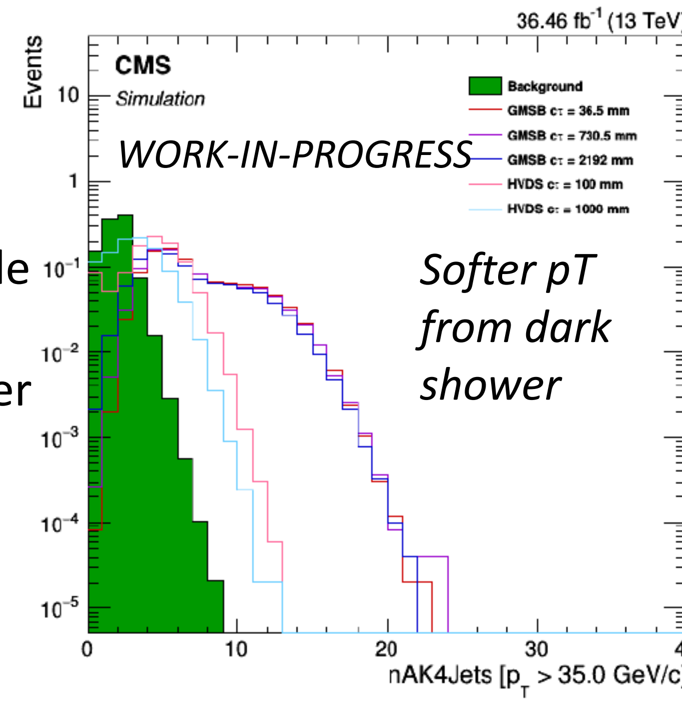
Hidden valley model



arXiv:1410.3818

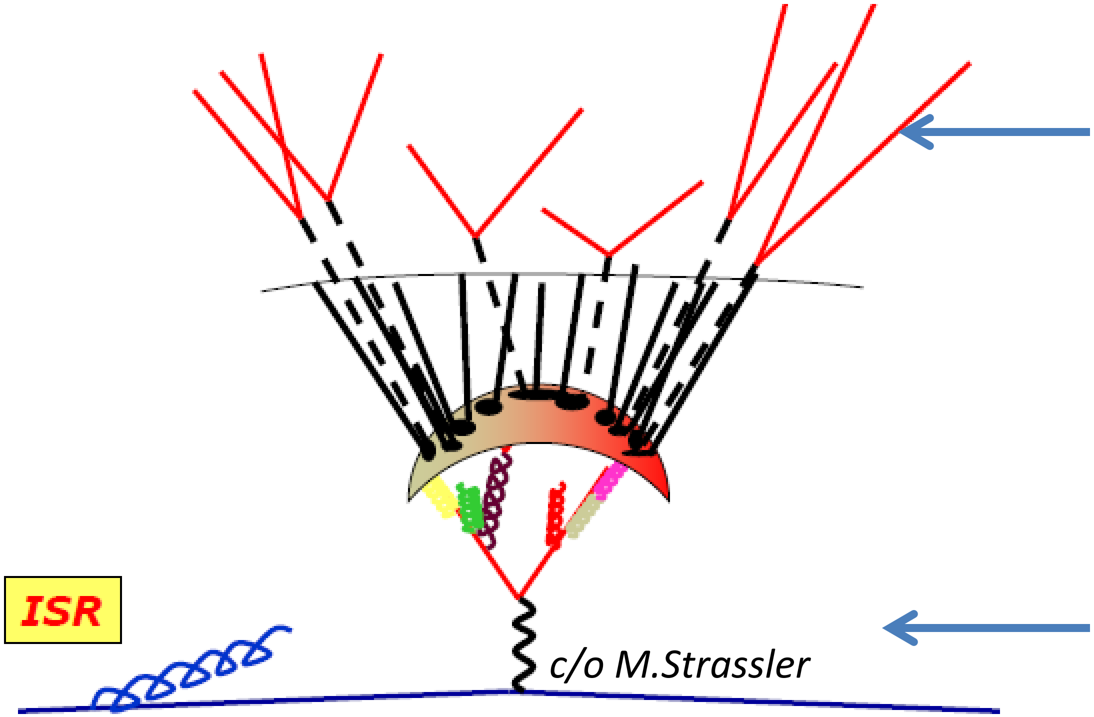
can be applied to indirect detection!

CMS Run2 trigger: single photon+HT (also consider diphoton +mass)



Softer pT from dark shower

Challenge: Trigger



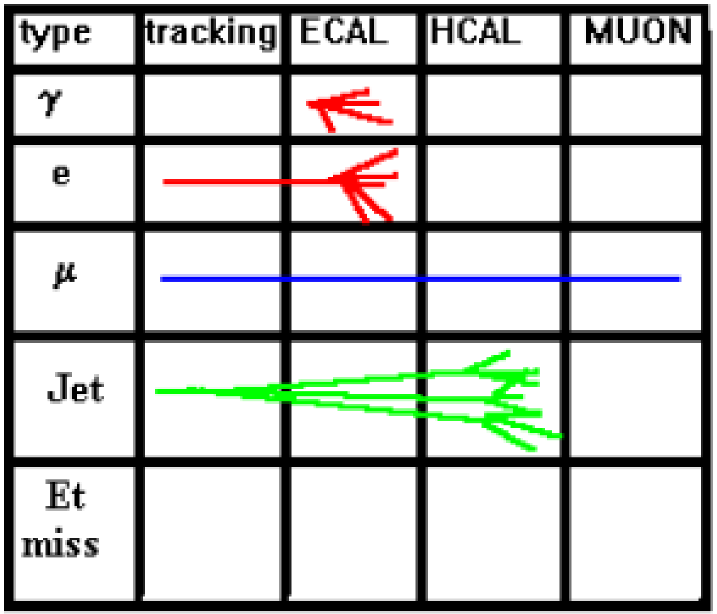
Trigger strategy B:
trigger on the decay final products (back to SM particles), e.g. jets, leptons, photons

<u>The two strategies can be combined in cross-triggers!</u>

Trigger strategy A:
trigger on the new heavy particle(s) (e.g. HT) and/or its production process (e.g. ISR)

Dark shower process poses unique challenges for the trigger:
- the multitude and mass of new particles → more but softer final objects, esp. μ, γ
- the displacement of the decay inside the detector affects the efficiency of prompt triggers → ability to design displaced triggers?

Challenge: Object Reconstruction



Dark showers pose unique challenges for object reconstruction:

<u>For long-lived particles in general:</u>

- Decaying later in the detector → info from earlier subdetector (e.g. tracker) unavailable
- Increased vulnerability to background e.g. calorimeter noise, cosmic rays etc.
- Conventional reconstruction methods to remove noise etc. often remove our signals

<u>For dark showers in particular:</u>

- High multiplicity and broad range of lifetimes: how to #CatchThemAll?
- Isolation: displaced objects can be collimated with other displaced or prompt objects
- Vertexing: Fewer tracks with displacement; poor (non-) isolation
- Jet reconstruction:
  - jets from dark showers have different energy distribution in calorimeters and/or track info; likely to fail conventional jet ID

Challenge: Background Estimation

Nature's fault

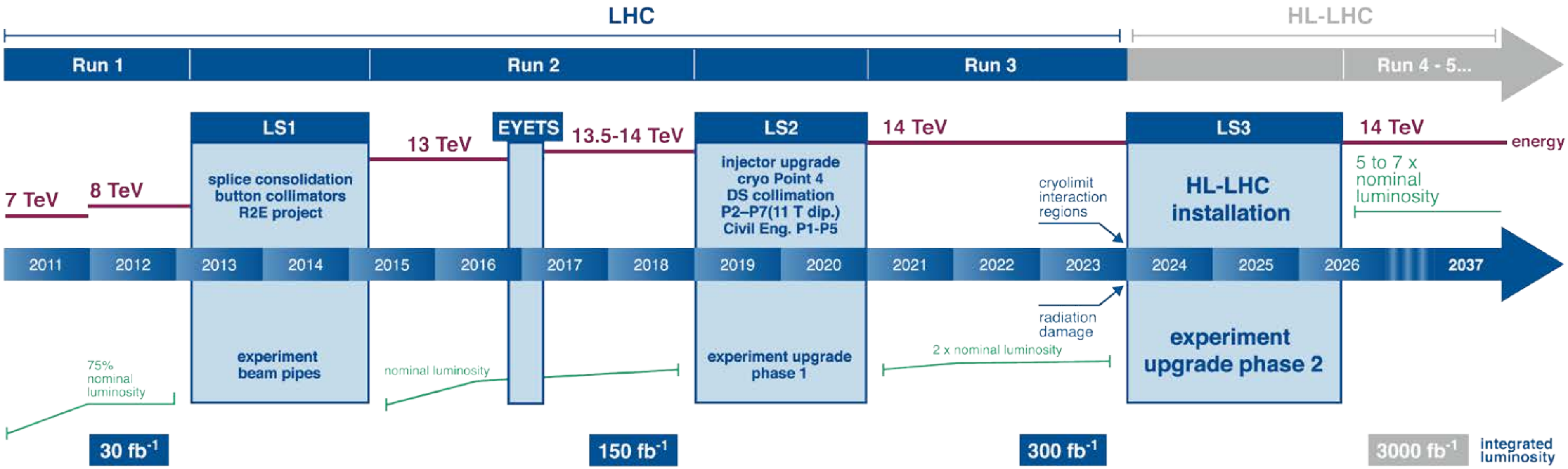
- Particles created at detector center
  - long-lived particles in the SM: simulation + data-driven
  - effects from pile-up
- Particles created inside detector volume
  - photon conversions
  - nuclear interactions …
- Particles created outside of detector
  - cosmic muons, beam halos …

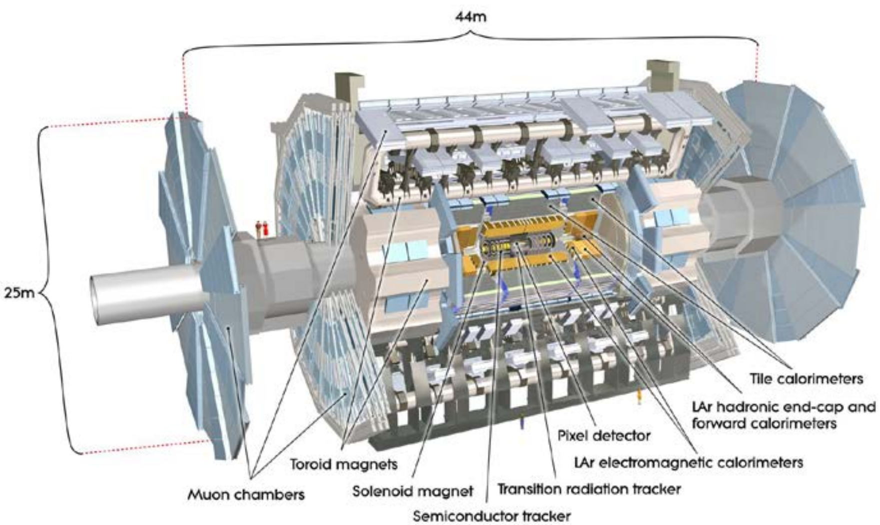
Our fault

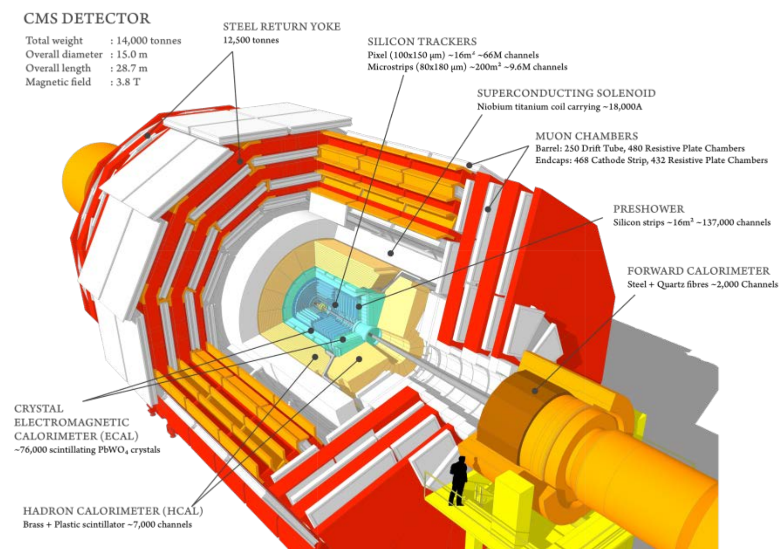
- Imperfect hardware
  - ECAL timing resolution ~O(ns)
    - limits delayed photons
  - tracking resolution ~O (10μm)
    - limits displaced track/vertex
- Imperfect software
  - software is always imperfect
  - algorithms often designed with prompt objects in mind

Sources of background in LLP searches often only relevant to LLP searches and less understood

Dark Shower: Prospects@HL-LHC





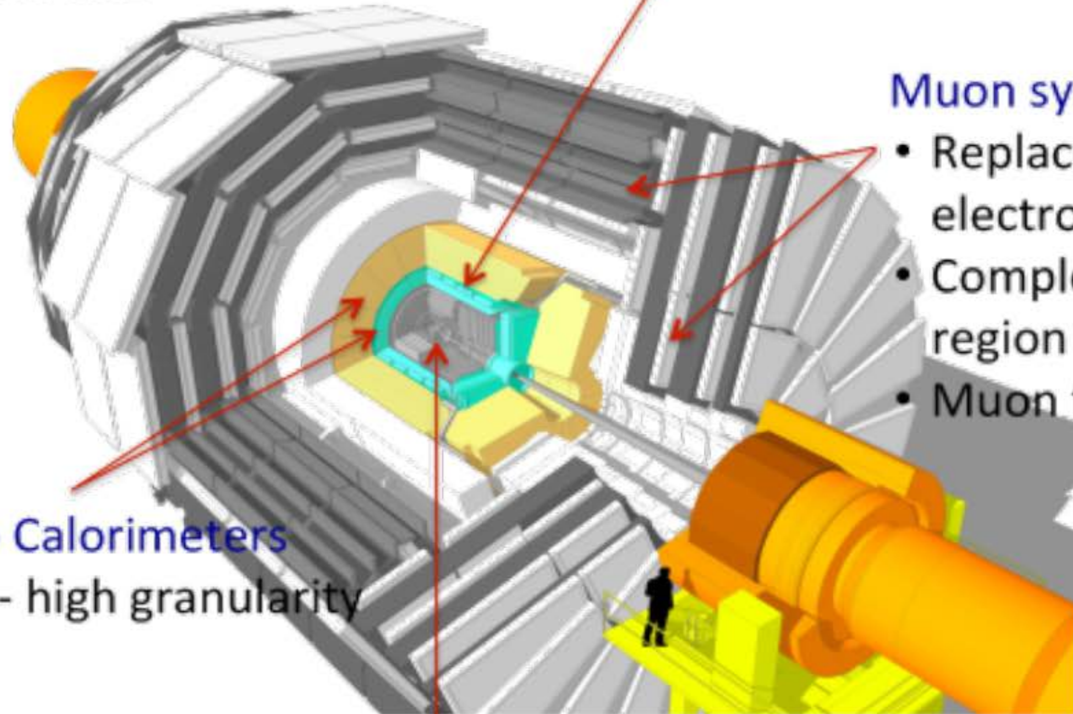


The CMS Detector Upgrade @ HL-LHC

Trigger/HLT/DAQ
- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output ≃7.5 kHz

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8°)

Muon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

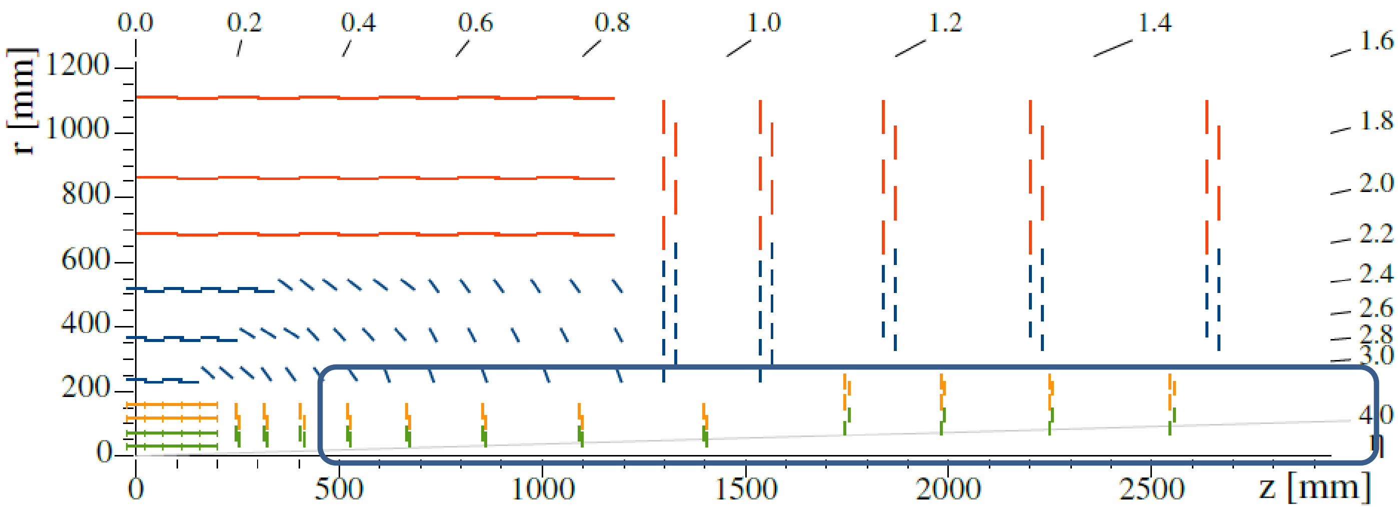


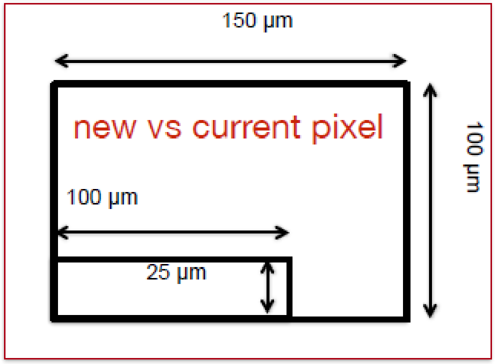
Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

+Timing layer?

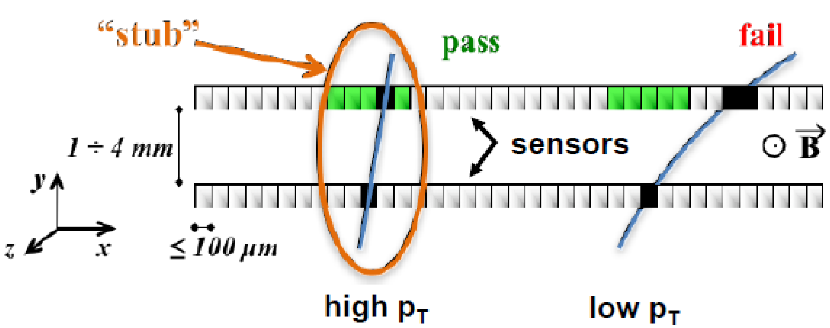
Replace Tracker
- Radiation tolerant; high granularity
- Extend $|\eta|$ coverage up to 4

HL-LHC Upgrade: Tracker



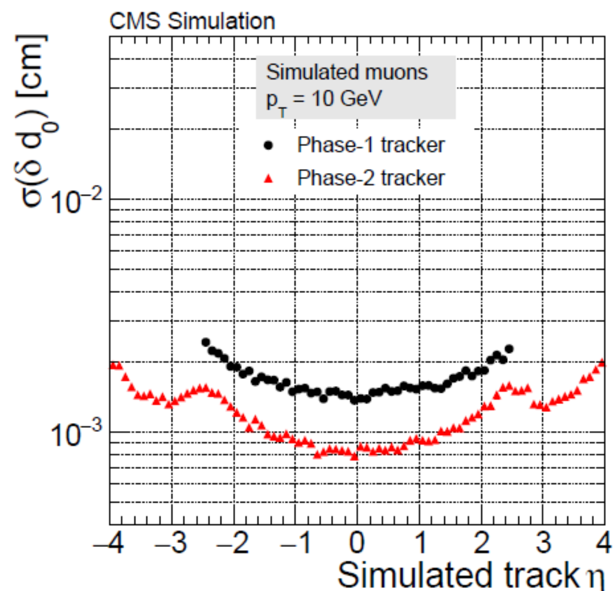


Extend coverage to |η|=4 with pixels 1/6 the size

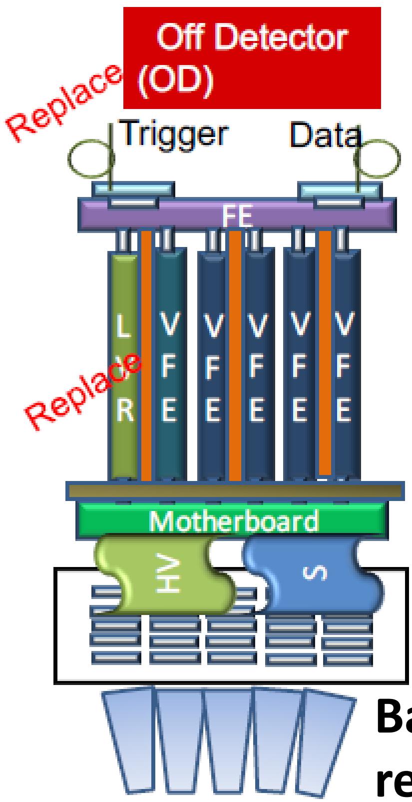


Outer tracker L1 track finding

*COMPLETELY new tracker at HL-LHC expected to deliver **better tracking** performance with extended **forward coverage***



HL-LHC Upgrade: Calorimetry

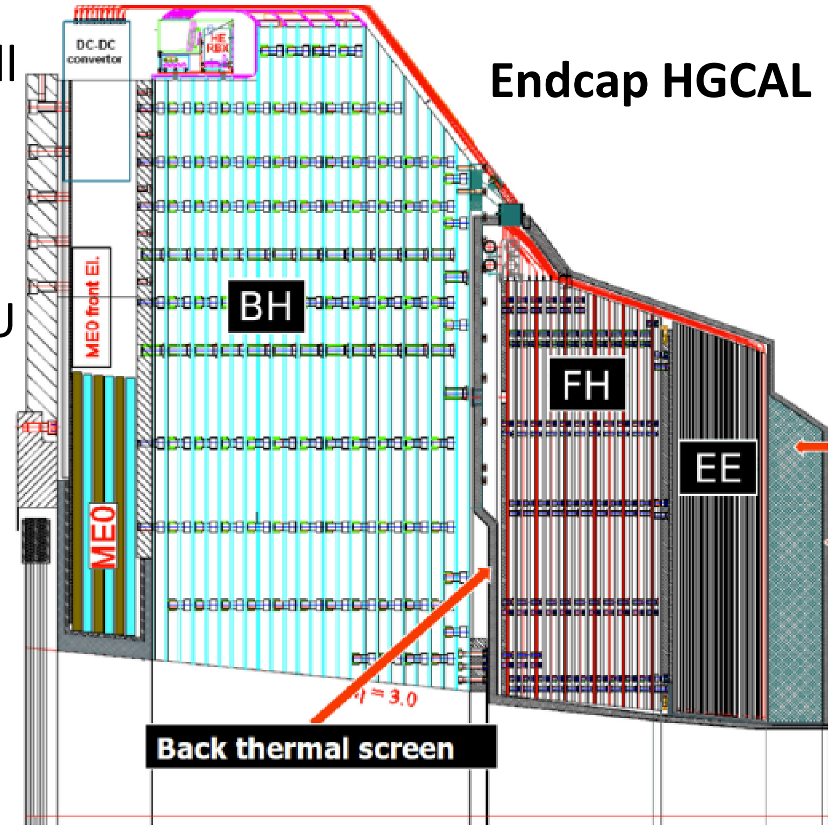


Barrel ECAL readout

The endcap calorimeter will be replaced with a silicon-based calorimeter:

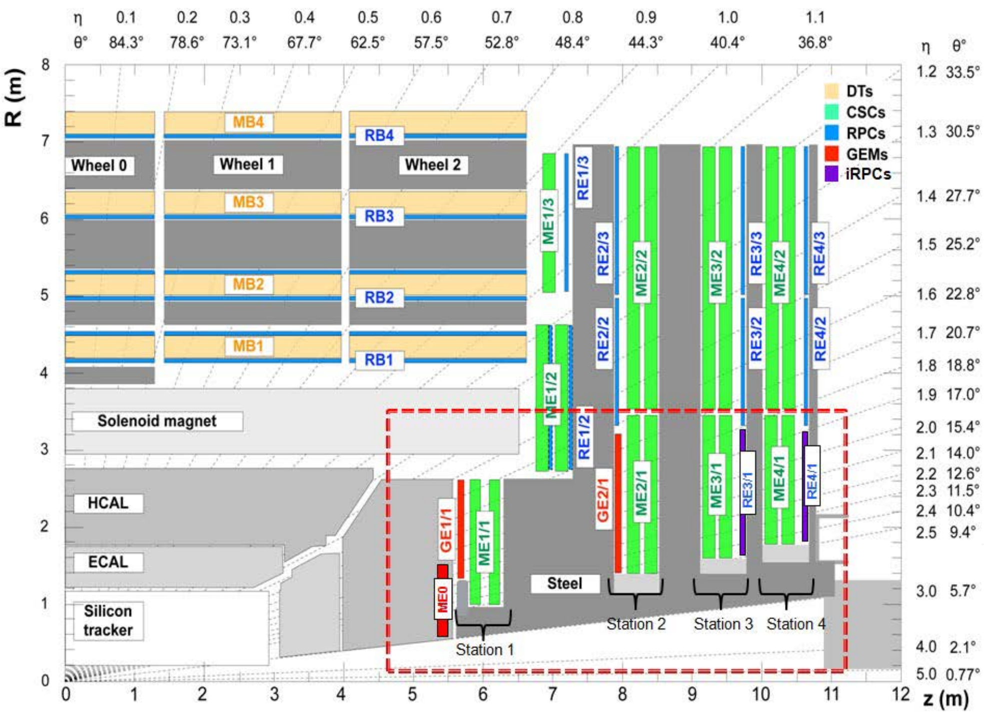
- high granularity and 3D imaging to help mitigate PU
- Fast signal collection (<10ns) and **fast timing capability (few tens of ps)**

Endcap HGCAL



- The crystals in the ECAL will be kept for duration of LHC
- The FE & BE electronics will be replaced for more precise timing, useful in both pile-up mitigation and new physics
- Target (hardware fundamental limit): **~30ps for E > ~30GeV** (1/10 of current limit)

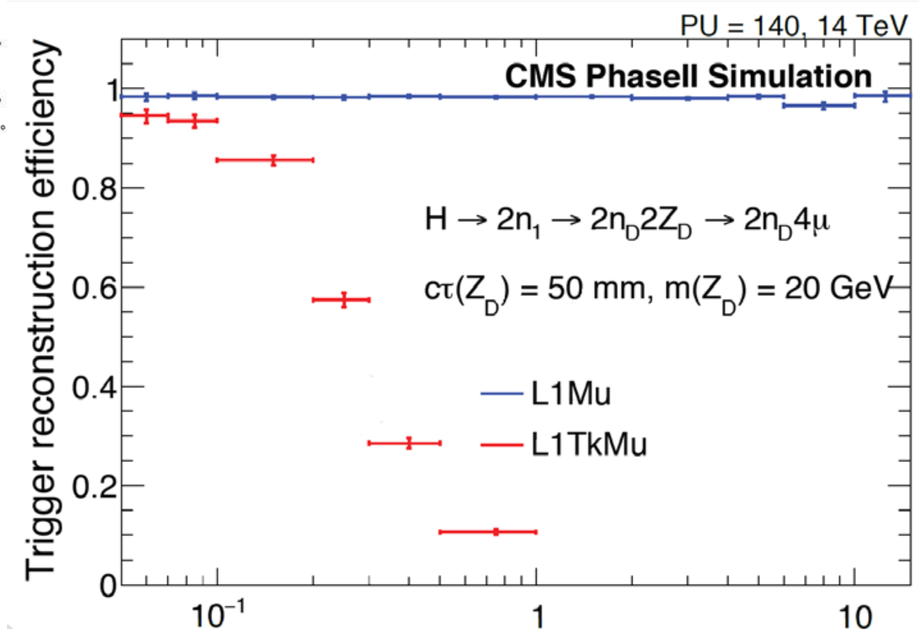
HL-LHC Upgrade: Muon System



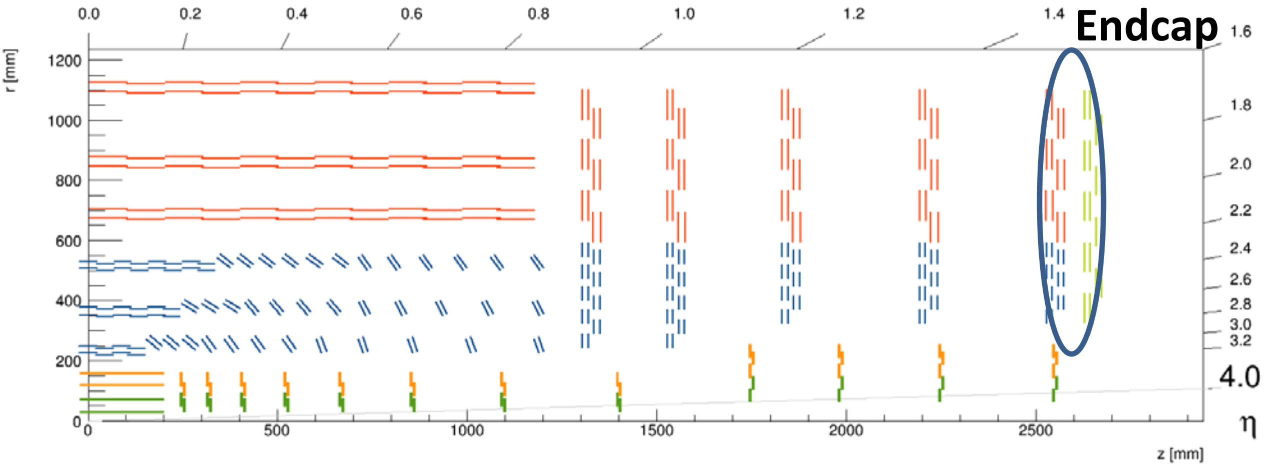
Muon system upgrade scope for HL-LHC:

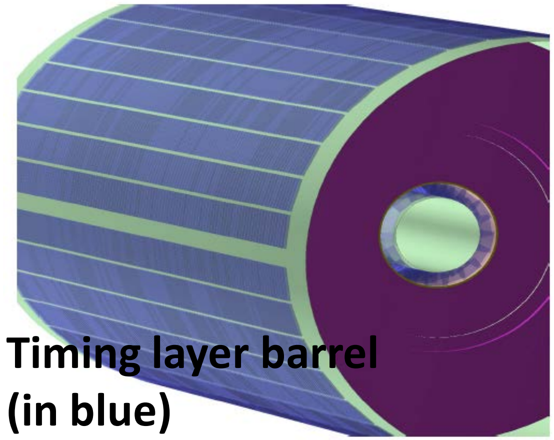
- Existing detectors:
  - upgrade barrel DT and endcap CSC electronics for 40MHz readout
- Extend forward coverage:
  - GEM & RPC detectors: $1.6<\eta<2.4$
  - ME0 (for trigger): $2.4< \eta<2.9$

- Broad trigger coverage is important to reduce trigger threshold for lower p_T muon pairs with dimuon trigger
- L1 track trigger is inefficient for tracks with dxy over a few mm
  - but can be utilized for track veto
- Forward region is very challenging!

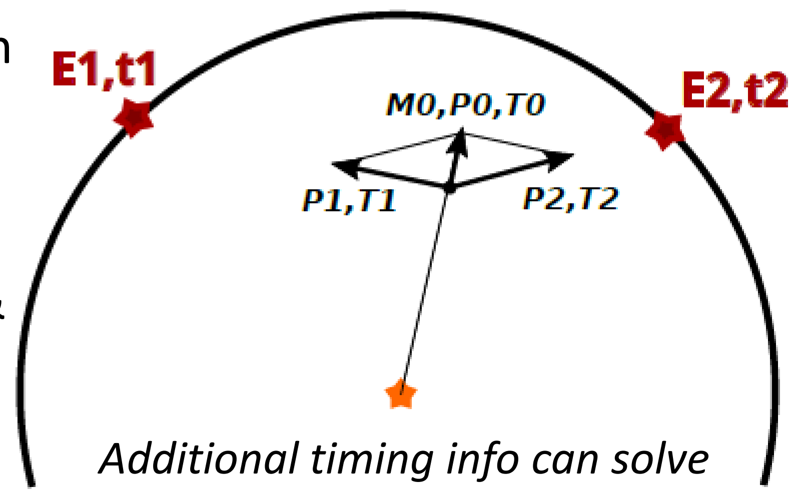


HL-LHC Upgrade: Fast Timing





- Calorimeter upgrades (ECAL electronics + HGCAL) will provide precise (a few 10s of ps) timing for high energy photons in barrel and high energy hadrons/photons in endcap
- Additional timing layer (outside tracker volume) can provide precision timing for charged hadrons & converted photons down to a few GeV.
- Traditional 3D vertex fit can upgrade to a 4D fit
  - PU suppression; vertexing; isolation; …
  - Could significantly expand scope for LLP search



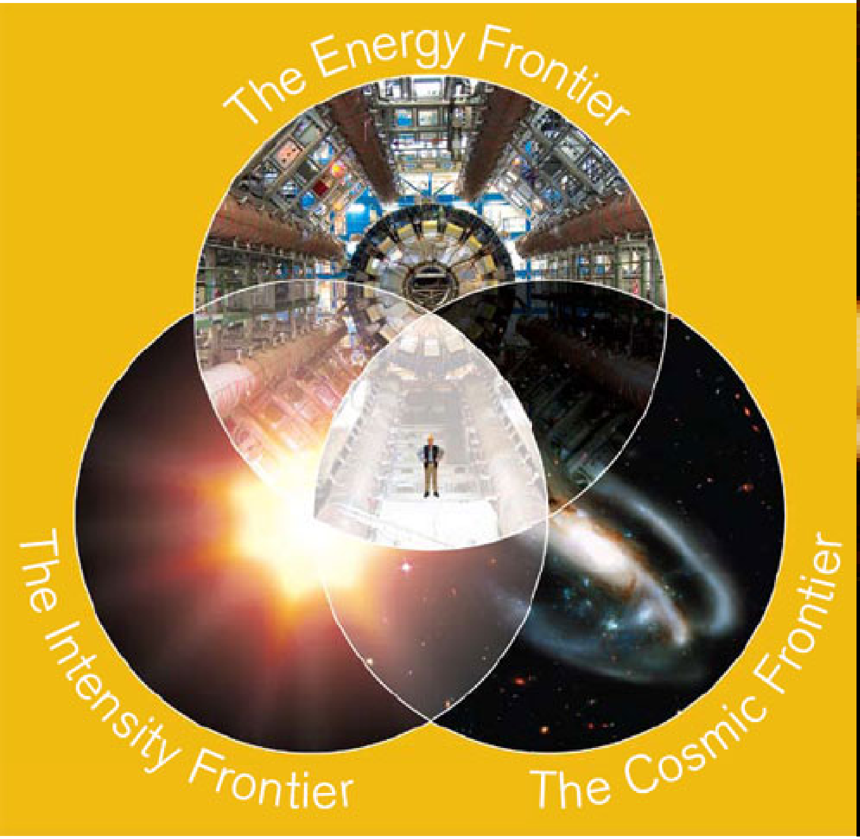
Additional timing info can solve secondary vertex for a long-lived neutral particle decay

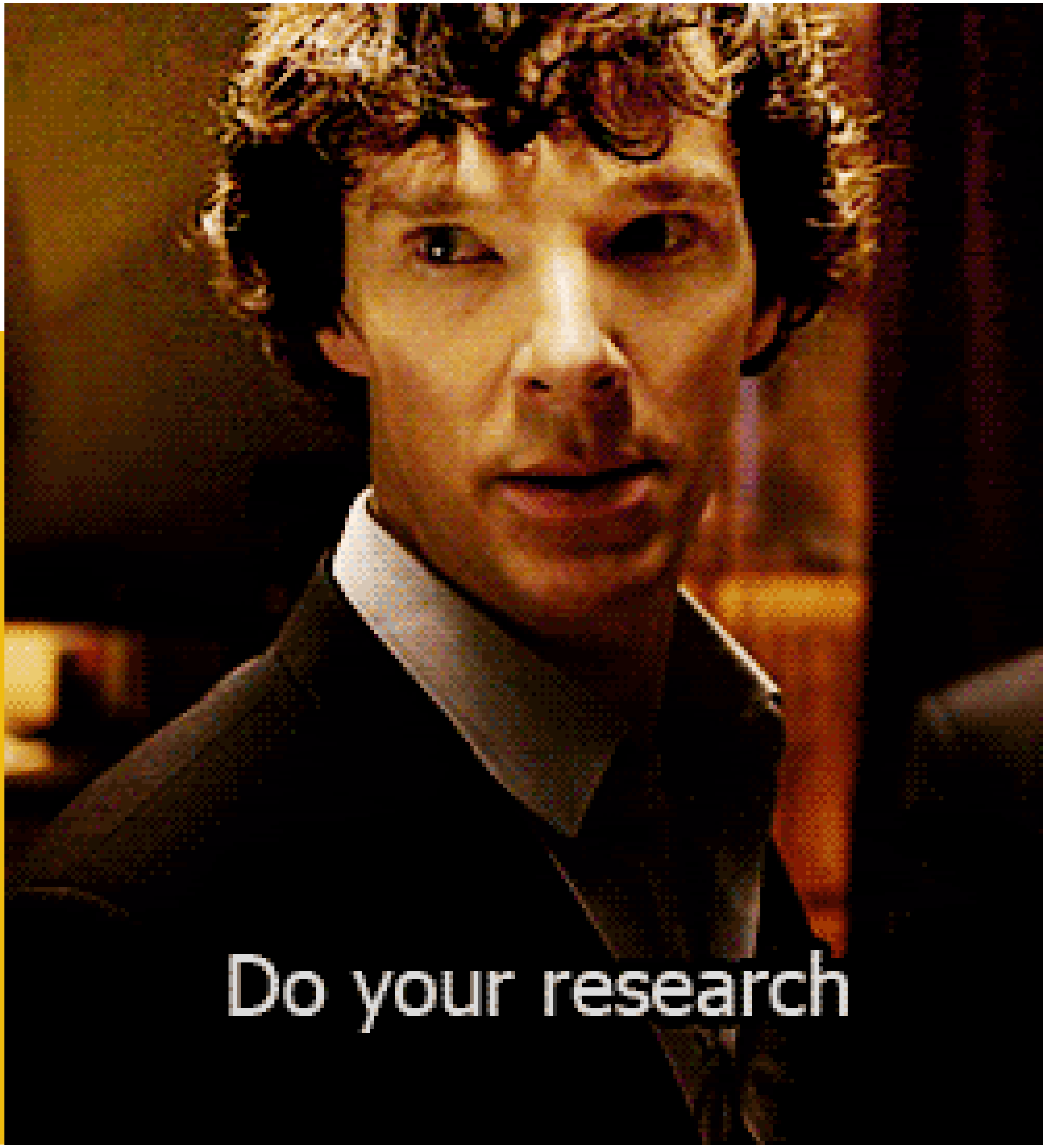
Conclusions and Outlook

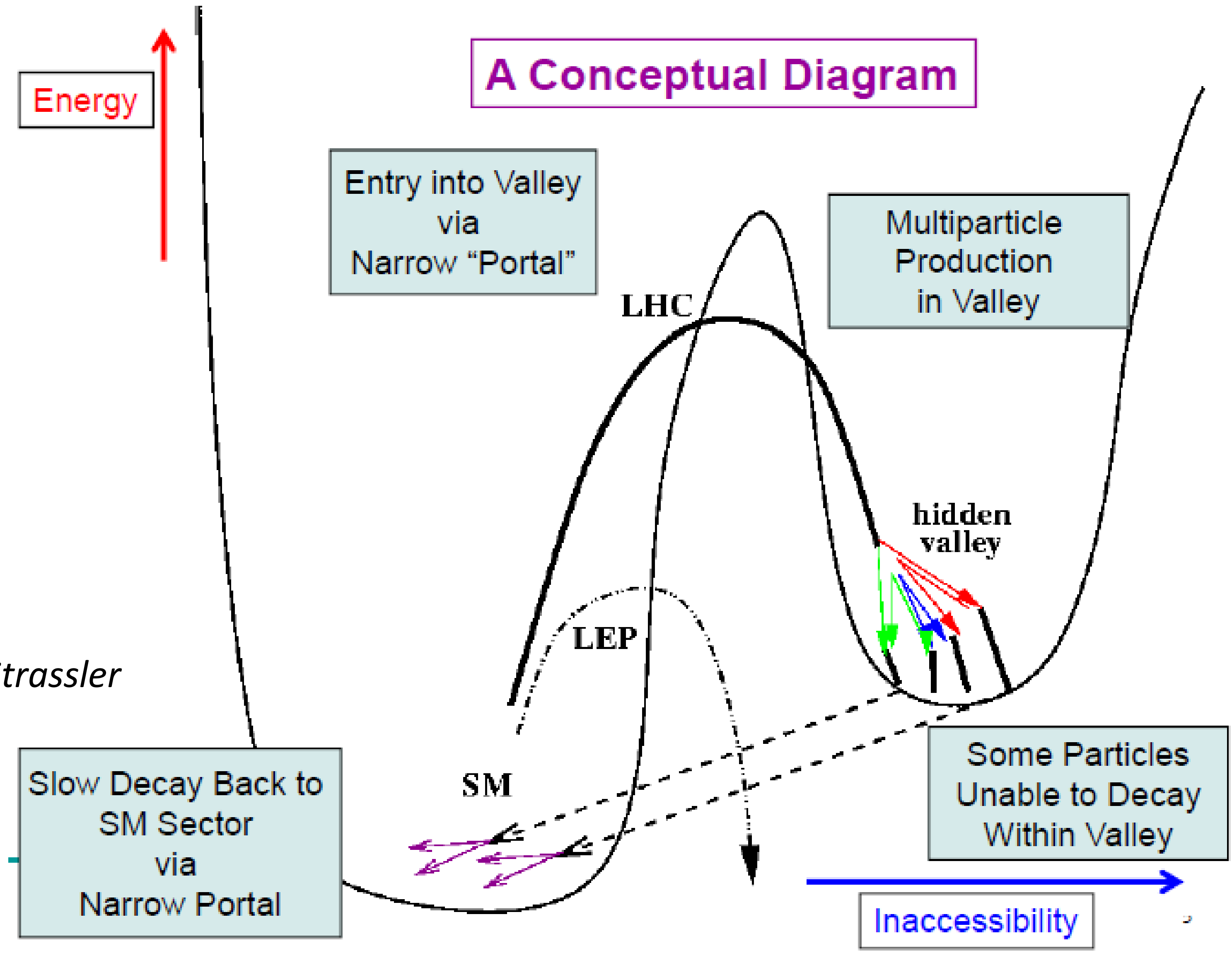
- A QCD-like dark sector is well-motivated in many BSM physics scenarios, in particular dark matter and naturalness
- A dark shower provides rich collider phenominology; broad ranges of decay time and decay products
  - jets (displaced, emerging, semivisible, …), displaced muons/photons…
  - higher multiplicity, softer pT
- Existing LLP searches can shed light on some models/final states; dedicated searches are being designed/carried out at LHC Run2
  - unique challenges in trigger, reconstruction, background estimation
  - sensitivity vs inclusivity
- Detector and trigger upgrades bring tantalizing prospects of future dark shower searches at HL-LHC

"One of the major outstanding questions in designing a search program for displaced objects is how to design a simple and flexible basis of models for showering dark sectors." – Jessie Shelton

THANK YOU!


The Energy Frontier
The Intensity Frontier
The Cosmic Frontier

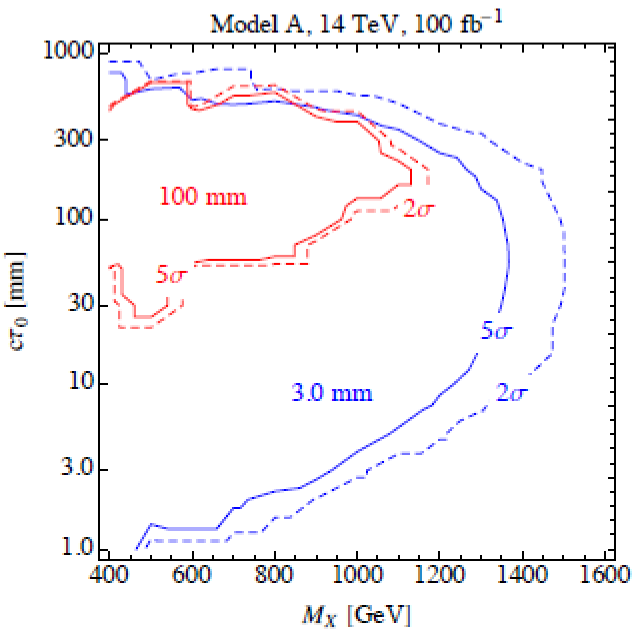

Do your research

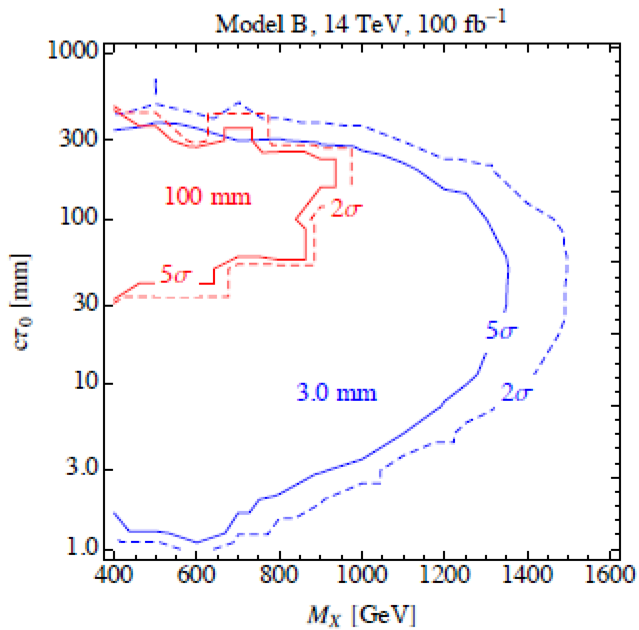


c/o M.Strassler

Emerging Jets: Sensitivity Projection

c/o P. Schwaller

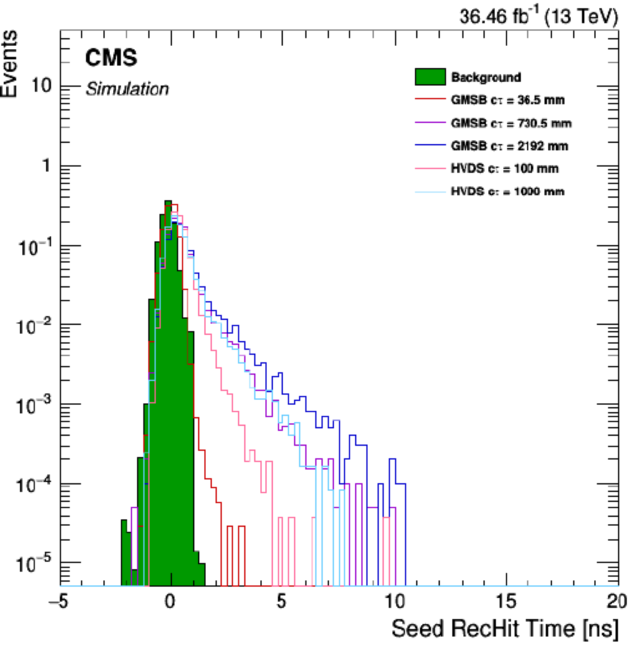


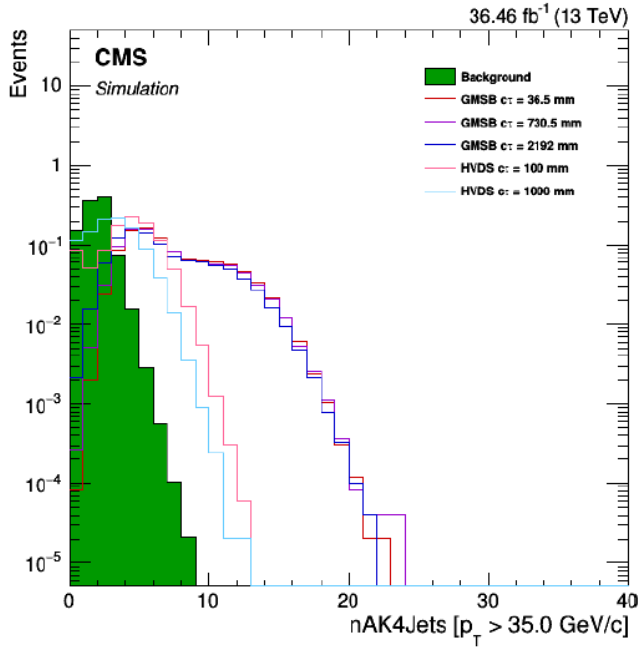


- Pair production of 1 TeV bi-fundamental scalars
- Trigger on 4 HCAL jets $p_T > 200$ GeV
- Require one or two "emerging jets:" Jets with at most 0/1/2 tracks originating from a distance $r < r_{\text{cut}}$

	Model A	Model B
Λ_d	10 GeV	4 GeV
m_V	20 GeV	8 GeV
m_{π_d}	5 GeV	2 GeV
$c\tau_{\pi_d}$	150 mm	5 mm

Displaced Photons: Search Strategy





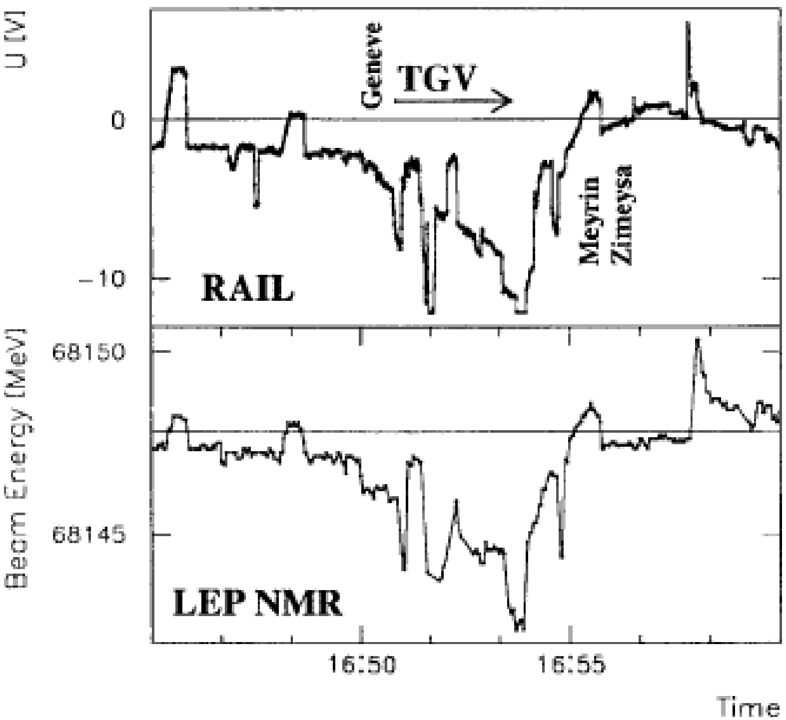
c/o K.McDermott

- Develop a dedicated, unprescaled HLT path based on **photon p_T**, **cluster shape**, **isolation**, and a cross trigger with HT

- Do not want to filter on MET as analysis result ultimately a 2D fit to the timing plus MET
  New path baseline configuration:
  HLT_DisplacedPhoton60_R9Id90_CaloIdL_IsoL_PFHT350_v
  HLT_Photon42_*_Photon25_*_Mass15_v*

bulletin

Week Monday 27 Novembre | no 48/95 | Semaine du lundi 27 novembre



Recordings of the potential difference, U, between the rails and the Earth (top) compared with the magnetic field inside one of LEP's dipole magnets, given in units of beam energy equivalent, MeV.

A strange disturbance was noticed in LEP in June 1995. A bizarre pattern in the bending magnetic field was detected for the first time thanks to new Nuclear Magnetic Resonance, NMR, probes recently installed in LEP. Small energy changes in the beam caused head scratching amongst the LEP energy team.

This disturbance always appeared at regular times, with peaks in the morning at 8 am, then from 11 am to 1pm, and later in the afternoon between 6 pm and 7 pm. Whereas between midnight and 4 in the morning things were completely calm. A bottle of champagne was offered to anyone who could solve the mystery.

LEP, due to its large size, is a very sensitive machine, its beam energy can be affected by many parameters during running. Already, it has been shown that phenomena such as the moon's orbit and the water level in Lac Leman have to be taken into consideration to understand LEP's energy behaviour. This new disturbance, however, is smaller than either of these effects, at a level of under 5 MeV.

The change of magnetic field was found to be caused by small electrical currents flowing along the beam pipe. The energy calibration working group decided to consult the Swiss and French electricity companies, EOS and EDF. After some thinking, M. Fleury of EOS suggested that the disturbance could be due to known effects related to electrical trains, winning himself a bottle of champagne.