Signatures of complex hidden sectors at FCC

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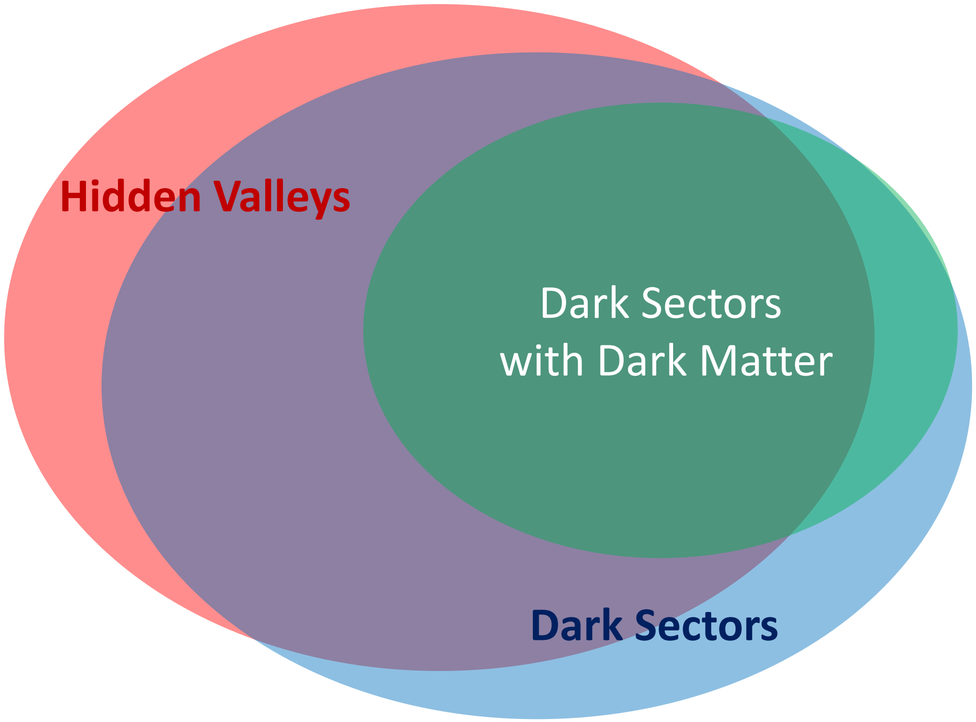
FCC BSM 9/22

Caveats:

- I'm no longer really in this field
  - *Though I'm still addressing some unfinished business*
- I wouldn't bet my house that the physics I'm describing exists
  - *The analogous caveat applies to all the other speakers at this workshop.*
- I haven't worked on FCC at all
  - *Yes, I'm too old… but also…*
- I'm not convinced that further FCC studies actually further FCC
  - *vs. doing more LHC analyses with significant discovery potential*
- I'm still getting over covid ☹

The Official Topic for Today:

- **Complex hidden sectors:**
  - Hidden Valleys/Dark Sectors: “HV/DS”
    - Self-interacting particles with no SM gauge charges
    - Mediator that may be neutral, or charged under both sectors



Depends on how you define “dark sector”: does that mean it includes “dark matter”?

The Point of the HV Scenario (et al.)

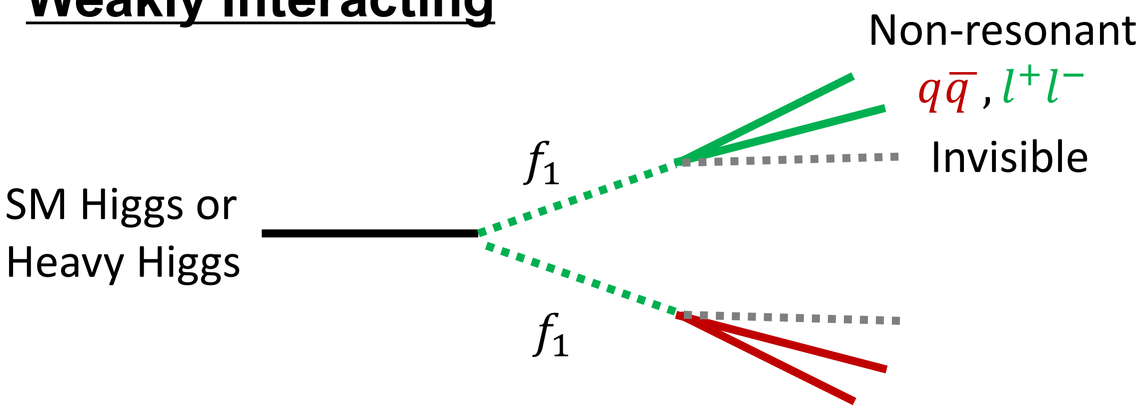
The Signatures LHC Was Preparing For

The Point of the HV Scenario (et al.)

The Effect of HV & Other Novel BSM

A Smattering of HV/DS Examples

Weakly Interacting

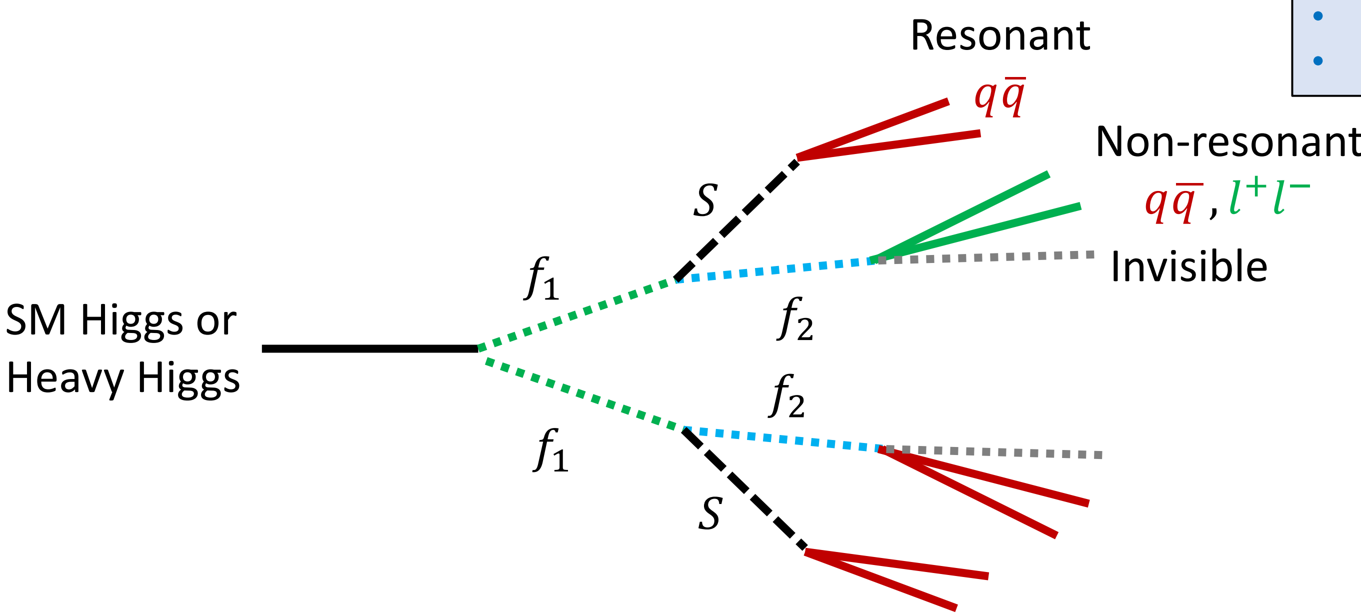


General Predictions:

- New SM-neutral particles
- Some decay to SM
  - Often resonant
- Multiplicity may be high
- May cluster in odd ways

Variants:

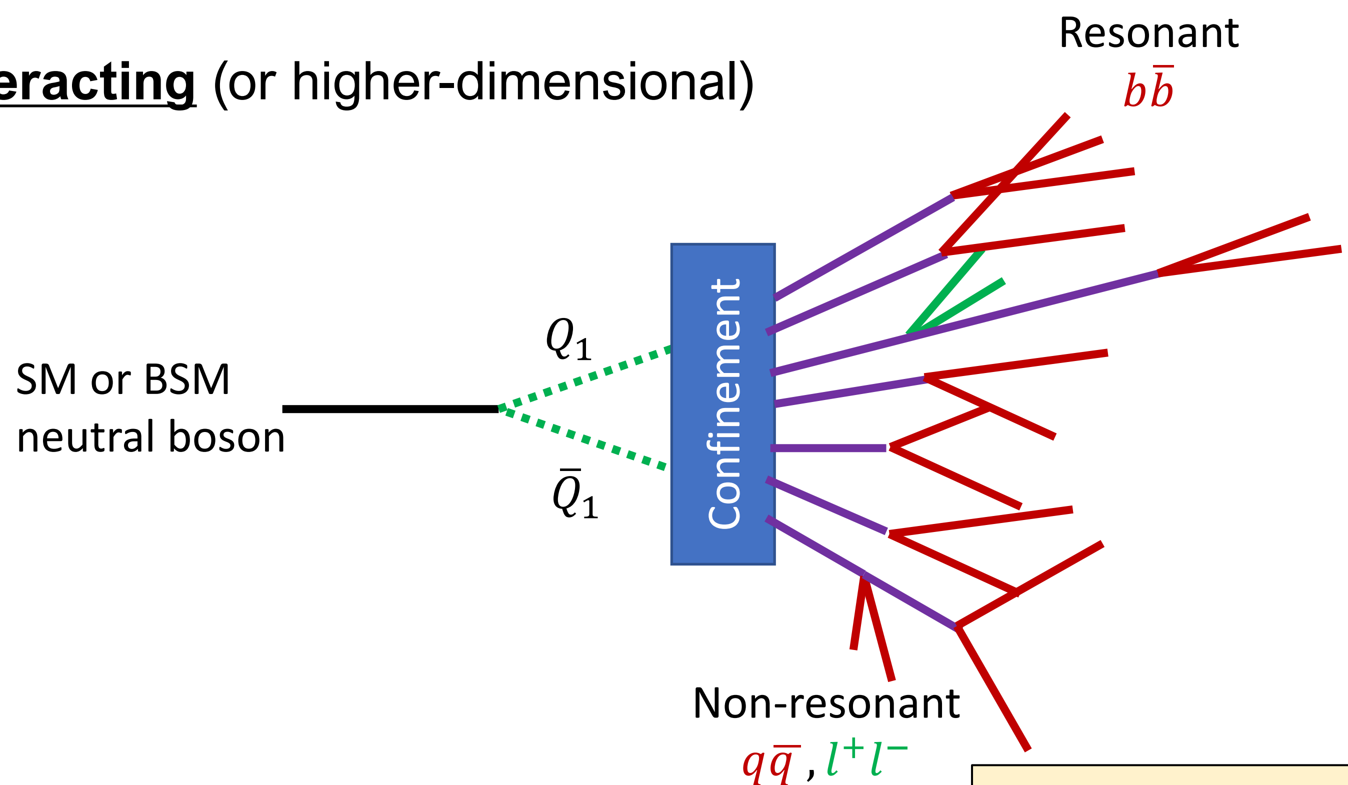
- Vertices may be displaced
- Jets may merge
- Leptons may be very soft
- Leptons may not be isolated



A Few HV/DS Examples

Cf. Verhaaren talk

Strongly Interacting (or higher-dimensional)



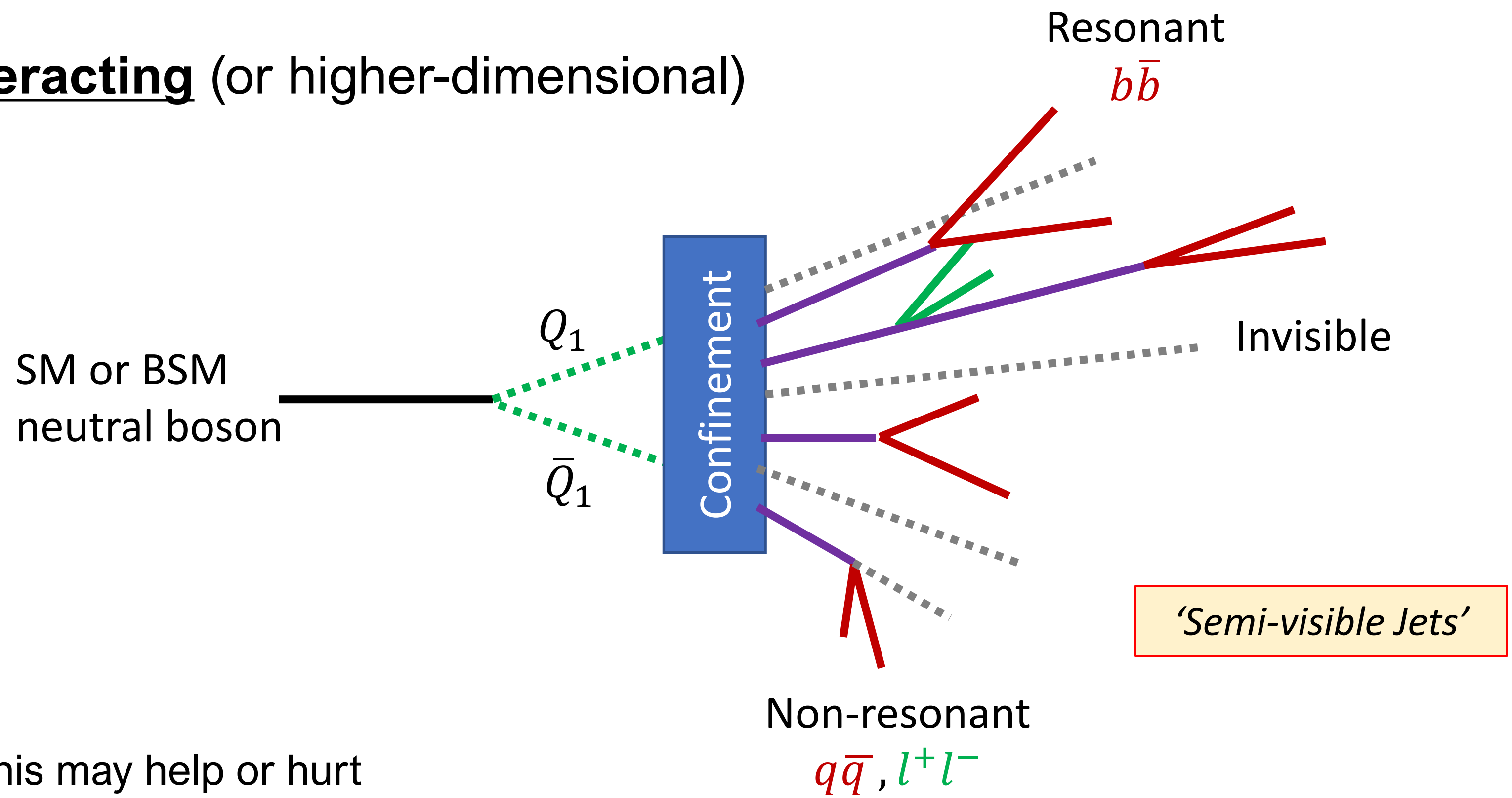
- Much like QCD, hidden sector may have
  - Its own hadrons
  - Produced in jets (or not)
  - Produced with high multiplicity (or not)
  - Produced with displaced vertices (or not)

General Predictions:
- New SM-neutral particles
- Some decay to SM
  - Often resonant
- Multiplicity may be high
- May cluster in odd ...

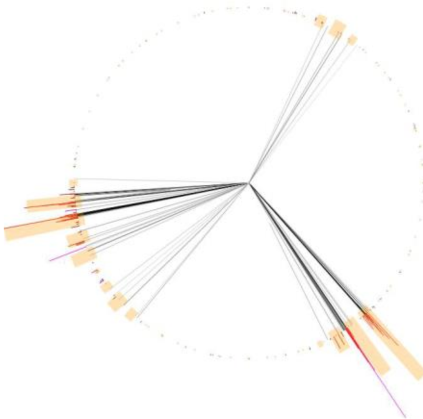
SAME – BUT MORE EXTREME!

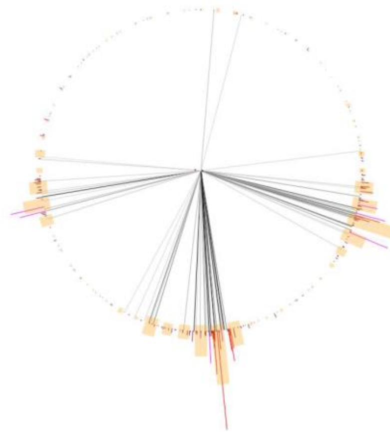
A Few HV/DS Examples

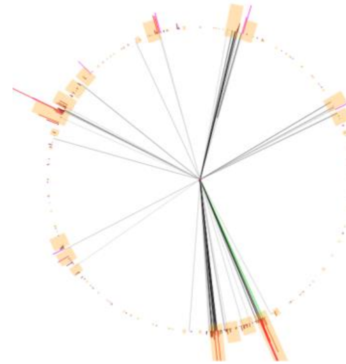
Strongly Interacting (or higher-dimensional)

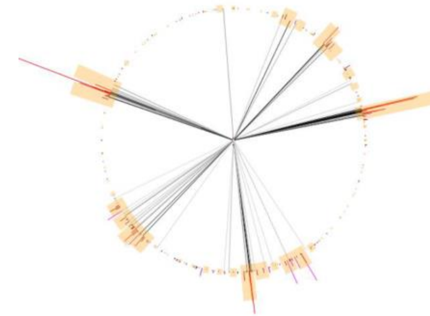


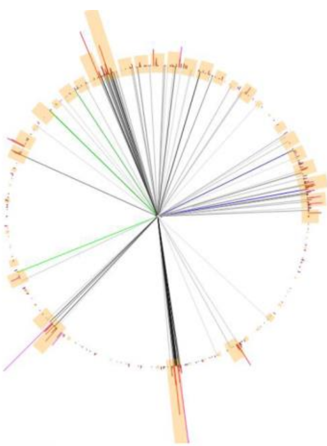
- If MET, this may help or hurt
  - Something easy to cut on
  - But signature less dramatic, so higher background

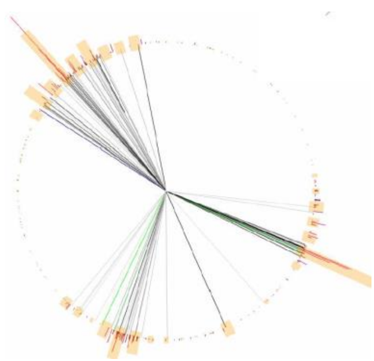


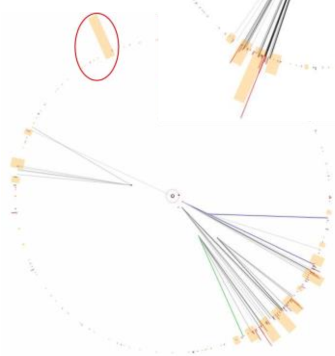


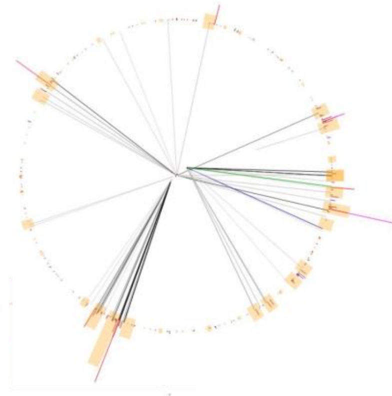










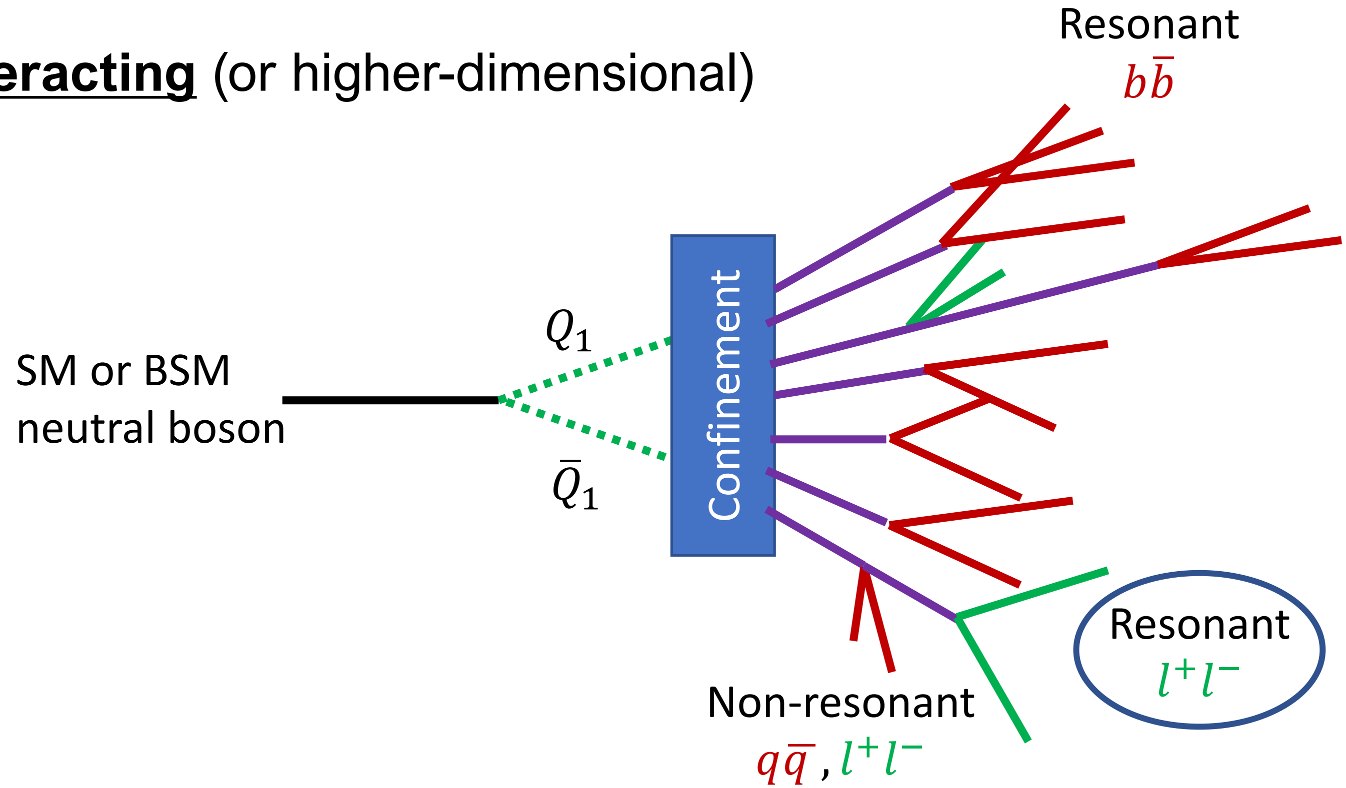


Some crude event displays

MJS 2008

A Few HV/DS Examples

Strongly Interacting (or higher-dimensional)



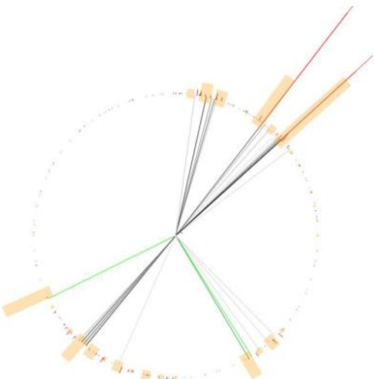
- Resonant decays to dileptons or diphotons always help
- But these leptons/photons may not be isolated!

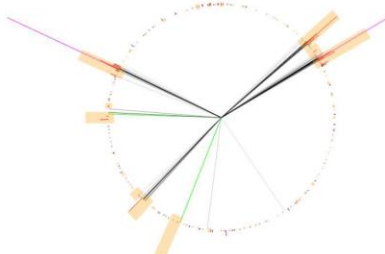
Lepton pairs

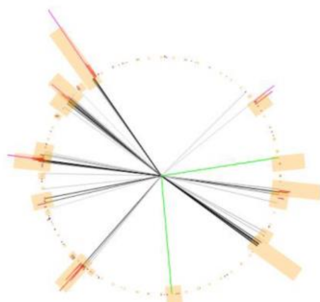
Han, Si, Zurek, MJS [0712.2041](0712.2041)

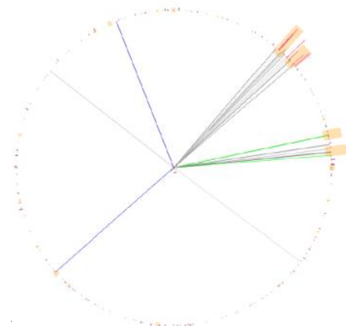
Leptons (green lines)

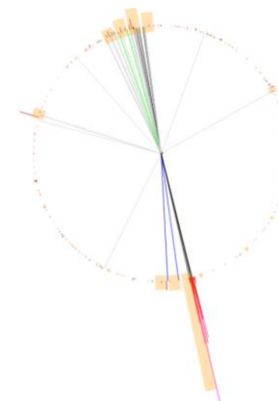
- within a complex event
- often non-isolated

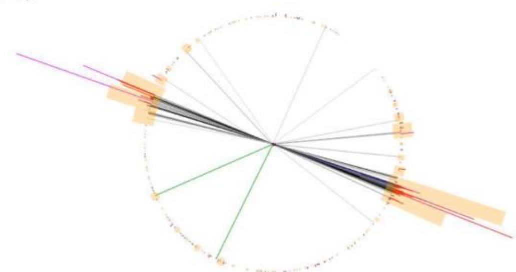












Some crude event displays
MJS 2008

HV/DS Predictions – The Question

- Huge range of other examples with qualitatively different details
- Yet there are general HV/DS predictions:

  - *New neutral particles decaying*
    - *resonantly to SM particles*
    - *non-resonantly to SM particles + MET*
    - *possibly with displaced vertices*
  - *Their masses may be very low*
  - *They may be produced*
    - *in abundance,*
    - *possibly clustered*
    - *with angular distribution that's jetty, spherical, something between*
  - *Their decay products may not be isolated*

  - *Quirks of all sorts [ultramicro-, micro-, meso-, macro-scopic]*

FCC and Blind Spots

Blind Spots and Biases

- FCC-CDR executive summary – 8 pages; what does it say?

Direct searches for new physics

At the upper end of the mass range, the reach for the direct observation of new particles will be driven by the FCC-hh. The extension with respect to the LHC will scale like the energy increase, namely by a factor of 5 to 7, depending on the process. The CDR detector parameters have been selected to guarantee the necessary performance up to the highest particle momenta and jet energies required by discovery of new particles with masses up to several tens of TeV. Examples of discovery reach for the production of several types of new particles, as obtained in dedicated detector simulation studies, are shown in Fig. S.5. They include Z' gauge bosons carrying new weak forces and decaying to various SM particles, excited quarks Q^*, and massive gravitons G_{RS} present in theories with extra dimensions. Other standard scenarios for new physics, such as supersymmetry or composite Higgs models, will likewise see the high-mass discovery reach greatly increased. The top scalar partners will be discovered up to masses of close to 10 TeV, gluinos up to 20 TeV, and vector resonances in composite Higgs models up to masses close to 40 TeV. The direct discovery potential of FCC is not confined to the highest masses. In addition to the dark matter examples given before, volume 1 of the FCC CDR documents the broad, and in most cases unique, reach for less-than-weakly coupled particles, ranging from heavy sterile neutrinos (see Fig. S.5, right) down to the see-saw limit in a part of parameter space favorable for generating the baryon asymmetry of the Universe, to axions and dark photons.

The FCC has a broad, and in most cases unique, reach for less-than-weakly coupled particles. The Z running of FCC-ee is particularly fertile for such discoveries.

Blind Spots and Biases

- FCC-CDR executive summary – 8 pages; what does it say?

High Mass Particles are for Serious Physicists

Direct searches for new physics

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Low Mass Particles…

WELL…

Blind Spots and Biases

Inertia?

- For >80 years: TeV scale from *n, μ* decay (Fermi theory)
- Now: No guarantee of new particles for next 12 orders of magnitude
  - *Pushing naturalness-based models ever upward = epicycles*
- Dark matter might be a clue toward weaker coupling. Or not.

This era is over. After LHC,

- ***Anything BSM is equally exotic.***
  - *Neither lower mass, feebly-coupling particles nor higher mass particles are likely*

FCC-ee: A **Discovery** Machine

Need to remind the old powerful people, repeatedly.

- It’s a very important argument for FCC! Don’t downplay it!
- Without it, why would other scientists or the public care about FCC-ee?

How to make the argument:

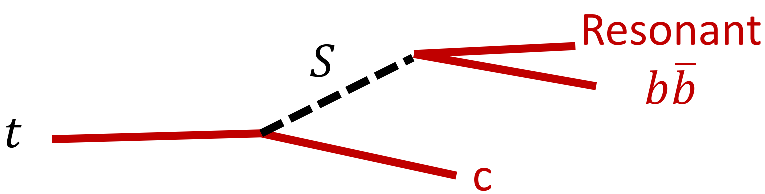
- *Precision is great!*
- *It requires high rate and/or low backgrounds*
- *And so do rare SM decays*
- *Oh, and also, so do rare BSM decays, even to entirely new, low-mass particles*
- *In fact, these BSM decays might not even be rare!*
    - *They can hide at LHC and be obvious at FCC-ee*

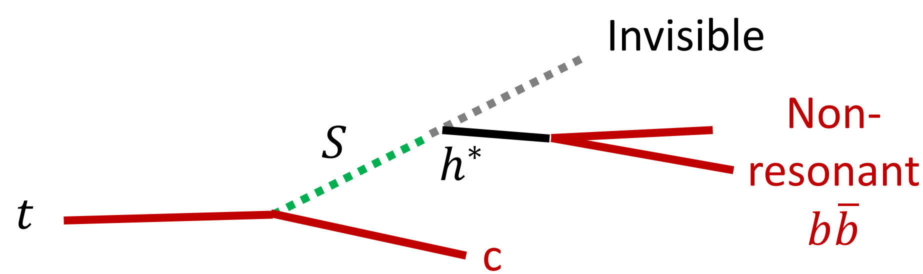
FCC-ee Discoveries in Non-SM Decays

- Higgs – CDR!
- Z – CDR!
- Top?!

  This is clearly a sociological blind spot at the LHC
    - Not even many theory papers! *[MJS 08,… Kong Lee & Park arXiv:1401.5020…]*

- FCC-ee can do this. But are we going to ***wait*** until FCC-ee?





- Not aware of systematic LHC search strategy for rare top decays
    - This is a crucial place to look for BSM
    - Trigger is not a problem; it's just too "exotic"

Don’t Build the Wrong Detectors

Only one way to miss BSM at FCC-ee: **build the wrong detectors**

LHC lessons – an example from long-lived particles:

- ATLAS, CMS were designed **against** LLPs with $c\tau\gamma > 2\ \mathrm{cm}$
- LHCb: mostly limited to decays in the VELO
- To correct this, many LHC detectors being designed now; but not optimized!!

FCC-ee? Few worries, but I would watch:

- Timing info?
- Readout?
  - “Altogether, the various contributions sum up to a data rate of about 1 TB/s. Reading out these data and sending them into an event builder would not be a challenge, but the data storage requires a large reduction. Because the noise and background hits are ltered out by the FPGA algorithm, the data rate induced by Z hadronic decays is reduced to 25 GB/s, for a total bandwidth of about 30 GB/s.”

FCC-hh and HV/DS

How can we possibly know!?

- Most LHC searches haven't been carried out
  - We don't know backgrounds or best methods! (often require data)

- LHC analyses have barely been studied by phenomenologists
  - Pythia improvements in 2022 open door to wider range of models
    - Cf. Snowmass proceedings

- The range of analyses that ought to be performed is huge

Example: 20 Straightforward Searches

Semi-Exclusive Drell-Yan

With and without lepton isolation!

Han, Si, Zurek, MJS 0712.2041, MJS 2009 talks

- Dileptons at high dilepton pT
- Dileptons + high MET
- Dileptons + high HT (summed jet pT)
- Dileptons + multiple jets
- Dileptons + multiple b-tagged jets

Each of these strategies reduces DY background while retaining a wide class of possible signals

- Analogously for for diphotons

NOTE: Inspired by but hardly specific to HV

As far as I know, never attempted at ATLAS/CMS, nor is anyone planning to

- *Please let me know if these were done privately/unpublished*

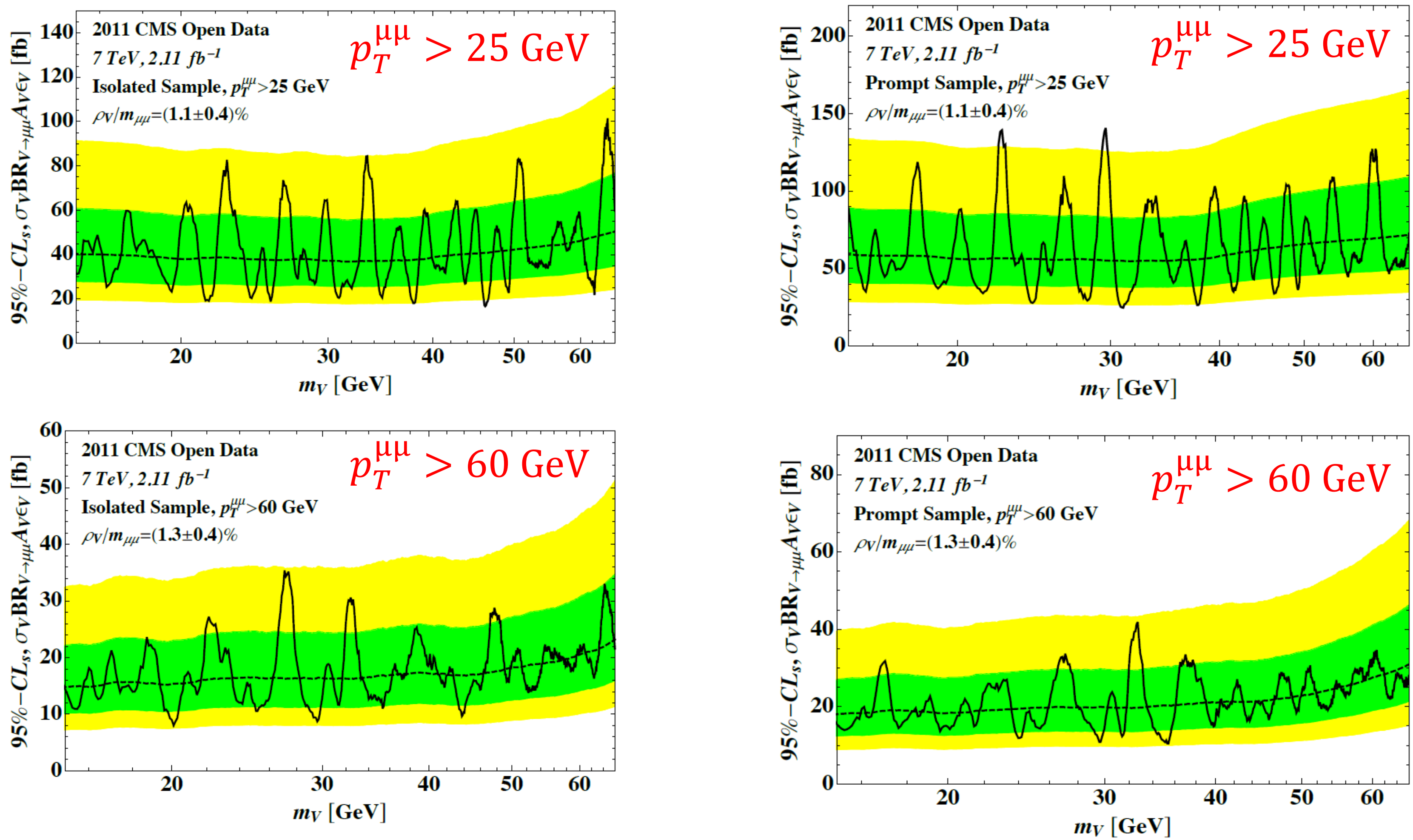
Limits on Dilepton Resonances

Cesarotti, Soreq, MJS, Thaler & Xue 2019

2 inv fb of 7 TeV CMS Open Data
Dimuon Trigger 13+8 GeV
Dimuon Cuts 15+10 GeV

Isolated

Prompt, not necessarily isolated



More Searches

Semi-Exclusive Drell-Yan

With and without lepton isolation!

Han, Si, Zurek, MJS 0712.2041, MJS before 2010

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- Dileptons + multiple b-tagged jets

Each of these strategies reduces DY background while retaining a wide class of possible signals

NOTE: Inspired by but hardly specific to HV

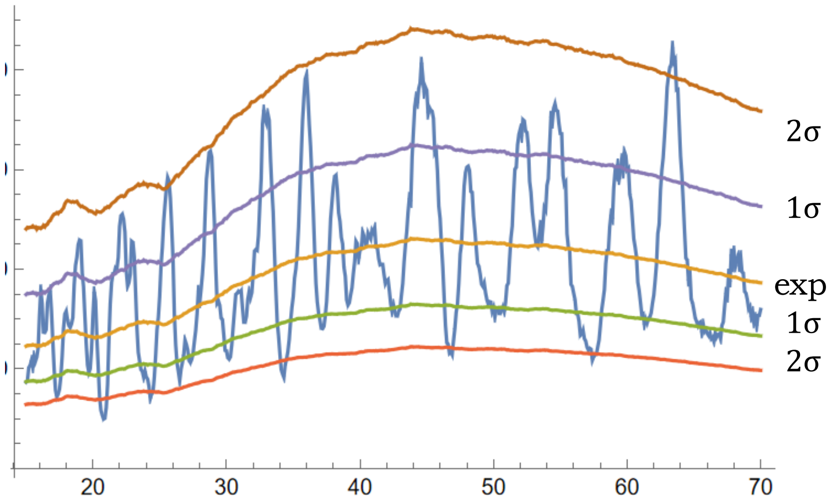
2020: With E. Metodiev, P. Komiske, J. Thaler, began work to do all of these on large fraction of 8 TeV 2012 CMS Open Data…

So easy that theorists can do it

Komiske, Metodiev, MJS, Thaler in limbo

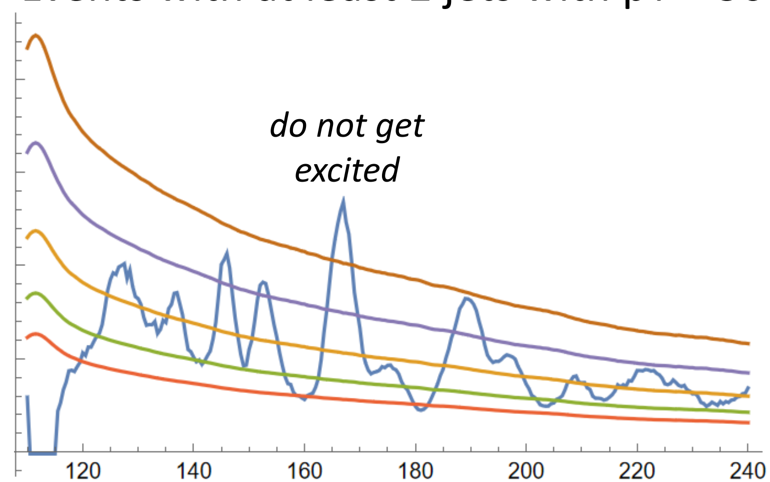
No isolation requirement on the muons

Events with at least 4 jets with pT > 50 GeV



dilepton resonance mass

Events with at least 2 jets with pT > 50 GeV



dilepton resonance mass

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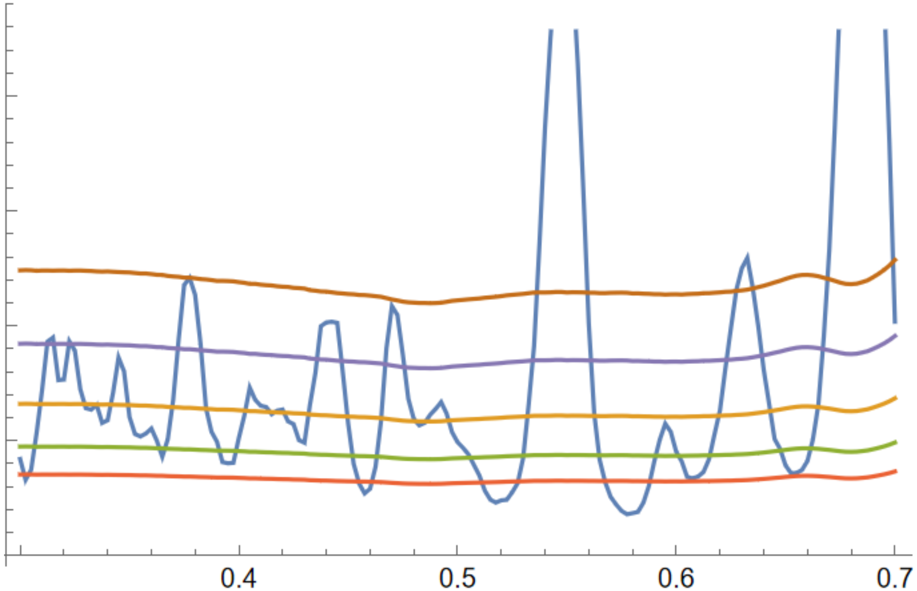


dilepton resonance mass

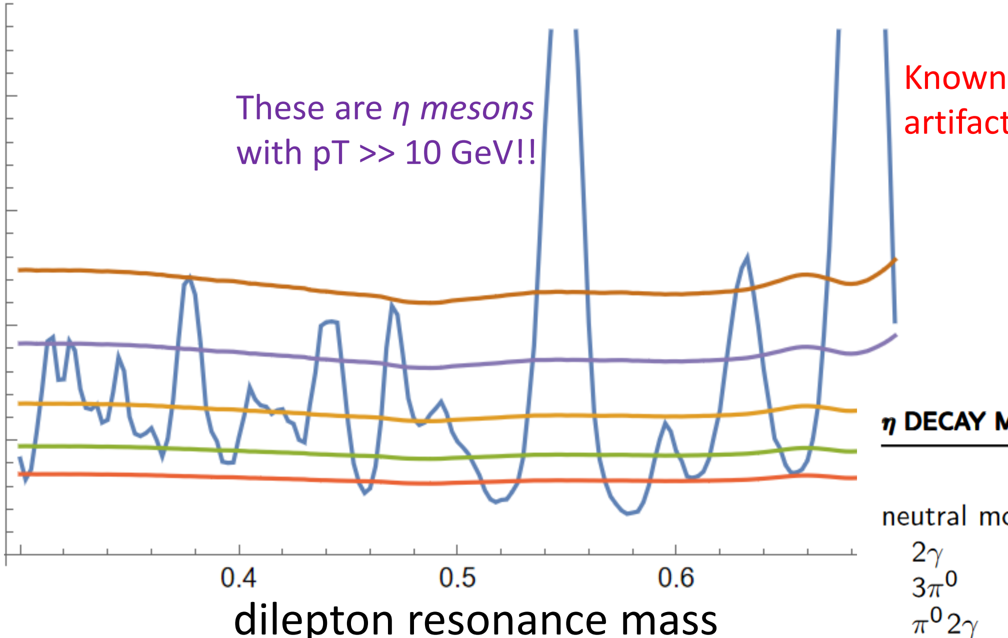
No isolation requirement on the muons

Found the eta, in non-iso leptons

Komiske, Metodiev, MJS, Thaler in limbo

No isolation requirement on the muons

Events with at least 2 jets with pT > 50 GeV



η DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Neutral modes			
neutral modes	(72.12 ± 0.34) %	S=1.2	–
2γ	(39.41 ± 0.20) %	S=1.1	274
$3\pi^0$	(32.68 ± 0.23) %	S=1.1	179
$\pi^0 2\gamma$	$(2.56\pm0.22)\times10^{-4}$		257
$2\pi^0 2\gamma$	$< 1.2 \times10^{-3}$	CL=90%	238
4γ	$< 2.8 \times10^{-4}$	CL=90%	274
invisible	$< 1.0 \times10^{-4}$	CL=90%	–
Charged modes			
charged modes	(27.89 ± 0.29) %	S=1.2	–
$\pi^+\pi^-\pi^0$	(22.92 ± 0.28) %	S=1.2	174
$\pi^+\pi^-\gamma$	(4.22 ± 0.08) %	S=1.1	236
$e^+e^-\gamma$	$(6.9\pm0.4)\times10^{-3}$	S=1.3	274
$\mu^+\mu^-\gamma$	$(3.1\pm0.4)\times10^{-4}$		253
e^+e^-	$< 7 \times10^{-7}$	CL=90%	274
$\mu^+\mu^-$	$(5.8\pm0.8)\times10^{-6}$		253

HV/DS Predictions – The Question

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- Yet there are general HV/DS predictions:

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    - *resonantly to SM particles*
    - *non-resonantly to SM particles + MET*
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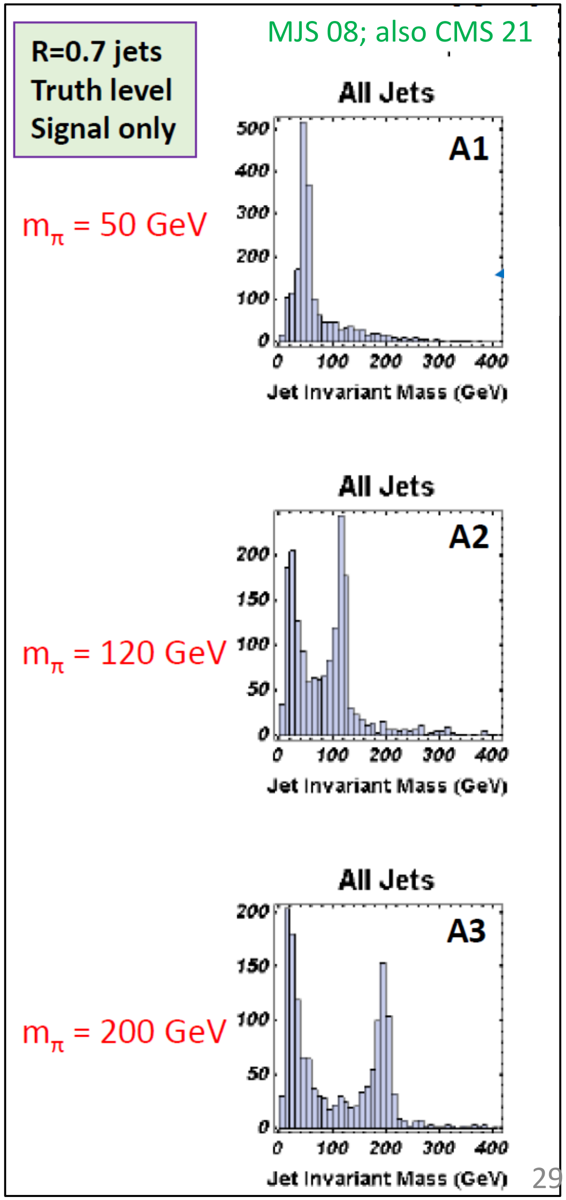
    - *with angular distribution that's jetty, spherical, something between*
  - *Their decay products may not be isolated*

  - *Quirks of all sorts [ultramicro-, micro-, meso-, macro-scopic]*

- Question: **what detector(s) would cover all of these possibilities?**

FCC-hh: Mass Resolution

- Dilepton mass resolution obvious
  - dark photons, etc., even below 1 GeV!!
- Diphoton mass resolution
  - How far down will the design allow?
- Dijet mass resolution also
  - Not used in recent CMS/ATLAS “semi-visible jet searches”
  - – but should be! Cf. Zurich Workshop https://indico.cern.ch/event/1133166/
  - Bias will be to assure resolution only to m_W
  - – but need to push **well below** m_W
- More generally: Jet Substructure



FCC-hh trigger

As we have seen time and time again at LHC:

- What is viewed as "exotic" gets the least personnel and least trigger study
  - History: ATLAS ROI trigger structure, CMS L1 jet triggers, trigger limitations from beam halo backgrounds; prevented certain searches at LHC Run 1 that are now limited by high pileup

Every effort should be made to prevent this from happening at FCC-hh.

CDR:

first muon stations at $r = 650\,\mathrm{cm}$ for the peak luminosity. The additional rate from punch-through still has to be evaluated, but it is clear that the charged particle count rate of about $500\,\mathrm{Hz/cm^2}$ due to high energy photons will dominate the rate in the muon system. The total rate of muons above a given threshold inside an acceptance of $|\eta| < 2.5$ is shown in Figure 7.20b, together with the muon rate from W, Z, t decays only. The total muon rate is above 20 MHz for a p_T threshold of 10 GeV/c and a single muon trigger with this threshold will therefore not provide any selectivity. However, the rate of muons from W, Z, t always stays below 100 kHz for any threshold. Since muons from c and b decays are always accompanied by jets, the determination of muon isolation at the first trigger level is a key item for useful selectivity.

Summary

- For HV/DS
  - FCC-ee is excellent discovery machine for HV/DS at h, Z
    - Need attention to detectors, just to be sure
    - Should also think about rare top decays to HV/DS
  - FCC-hh cannot be optimized for HV/DS because LHC hasn't been yet
    - LHC effort is increasingly urgent
      - **NEED MORE SEARCHES!**
    - FCC-hh HV/DS studies may be premature
    - Focus needs to be on trigger and detector design
      - Need to avoid capabilities being designed away
  - Pros and Cons of detectors with complementary capabilities?

Additional Slides

Qualitatively Different Detectors?

Another eternal question: how different should the various detectors be?

- Not an accident that ATLAS and CMS do equally well on many things
  - Optimized on Higgs, then SUSY
- LHCb does very well on what it was optimized for

- At FCC-ee, and especially FCC-hh, should we have different detectors with quite different capabilities, perhaps
  - One for precision SM
  - One for LLPs, weird tracks and low-mass resonances
  - One for high-energy signals
  - Etc.

cf. CLD vs IDEA

- We're certainly seeing the need/opportunity for this at LHC!

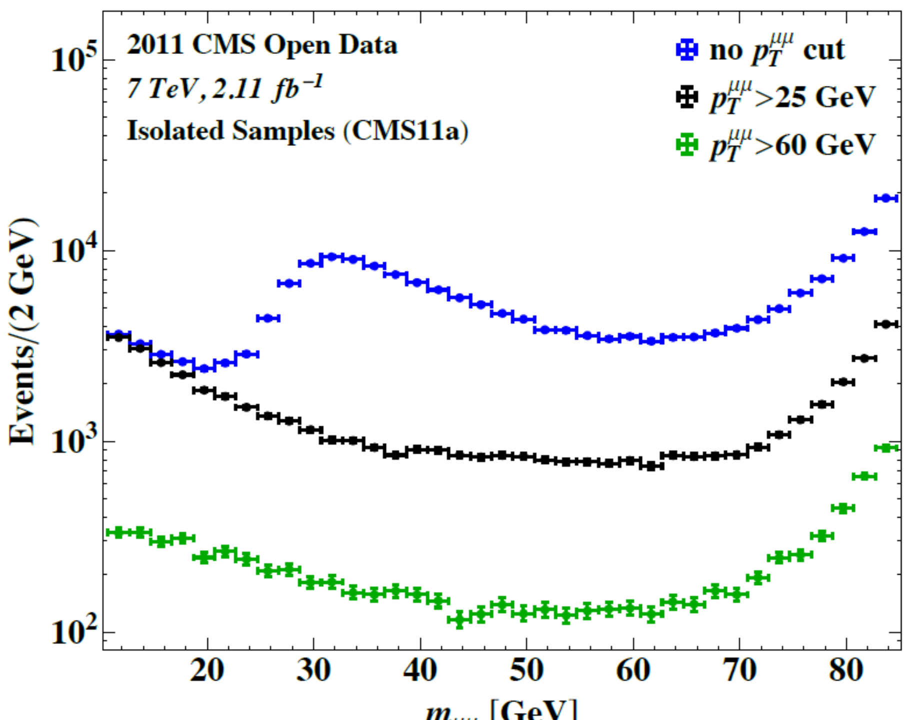
Example of What Is Possible

Cesarotti, Soreq, MJS, Thaler & Xue 2019

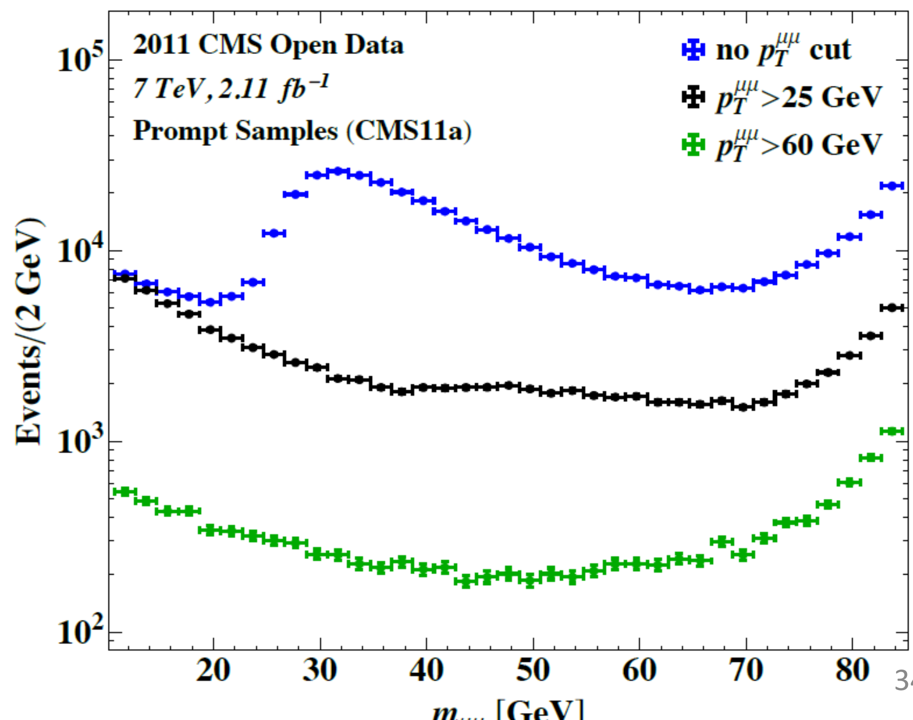
- Open Data Analysis
  - based on studies from 2006-2010
  - cf my talks at ATLAS 2010, CMS 2010
- Take **first 2 inv fb of 2011 CMS data**
  - Look for a moderate-pT dimuon pair (not necessarily isolated)

2 inv fb of 7 TeV data
Dimuon Trigger 13+8 GeV
Dimuon Cuts 15+10 GeV

Isolated



Prompt, not necessarily isolated



Detector Requirements: FCC-ee

Maybe at FCC-ee, low backgrounds ➔ doesn't matter so much?

- But surely would love to have
  - Extremely good dilepton, diphoton mass resolution even at low mass
    - HV/DS: identifying resonance is often easiest discovery channel
  - Extremely good timing and/or clean tracking to pick up LLPs
    - Of all sorts! None should be completely undetectable
  - Ability to pick out electrons/photons near jets
    - Not important in SM, but important here!
  - High granularity particle flow
    - HV/DS: to observe substructure in jets with high precision
    - Measure dijet masses with reasonable resolution

- Same issues arise, but worse, at FCC-hh
  - Higher backgrounds
  - Higher energies

Lessons From LHC

We got lucky!

- The Higgs could have eluded us if ~100% of its decays were BSM
  - Only case carefully studied pre-LHC: Higgs → invisible.

- But Higgs could have gone to some of these other channels

- LHC would have had great difficulty
  - In some cases, difficulty exacerbated by detector design

- Other new particles (e.g. 2nd Higgs, Z', RH neutrinos) may also elude us
  - Need to assure FCC detector designs reflect the physical possibilities
    - Should not be shaped by purely sociological effects
      - No one theorist should have too much influence
      - No one theory should have too much influence