Triggering Soft Bombs at the LHC[‡]

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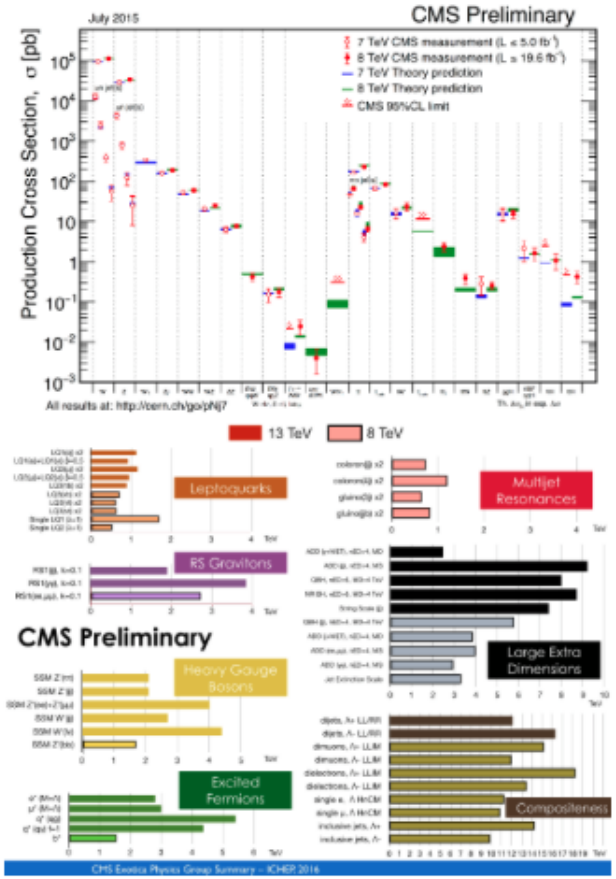
February 2017

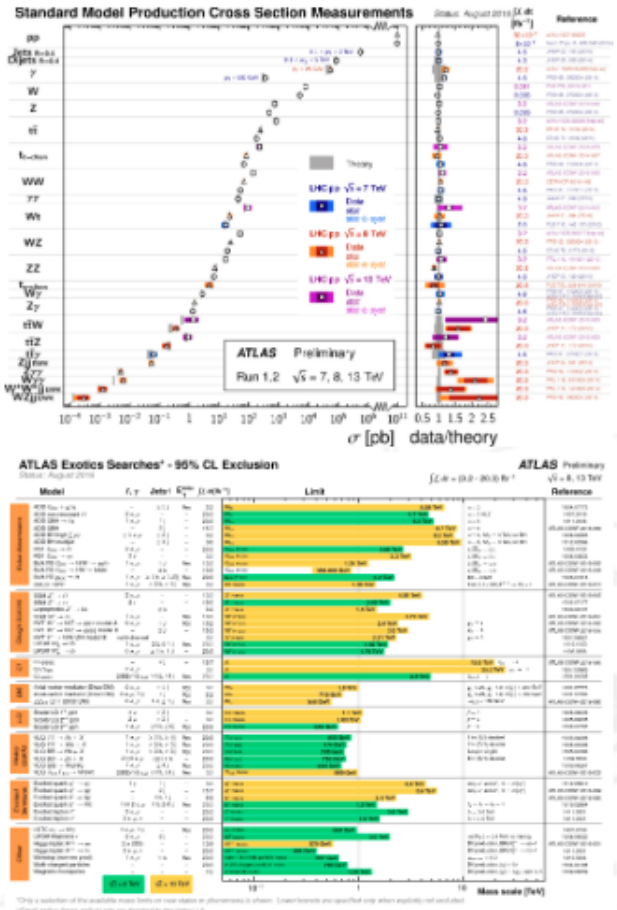
Based on: 1612.00850 (S. Knapen, S. Pagan Griso, M. Papucci & DR)

[‡]Or: How I learned to stop worrying and love the soft bomb

Status

Huge number of exotica search channels: so far only limits!





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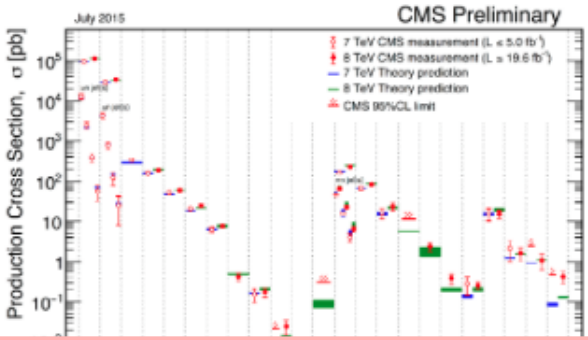
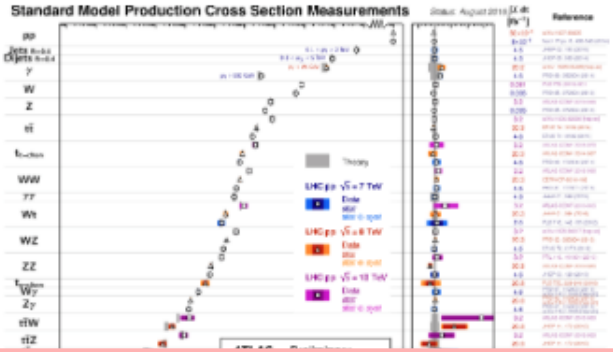
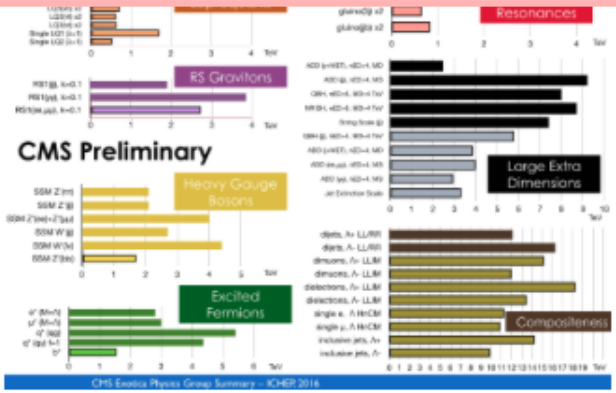
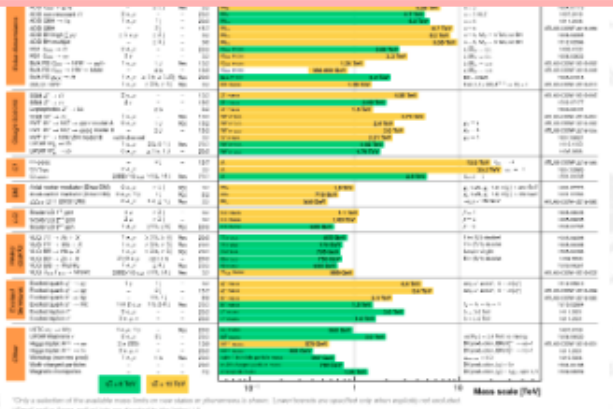




How else can we/ should we dig deeper?

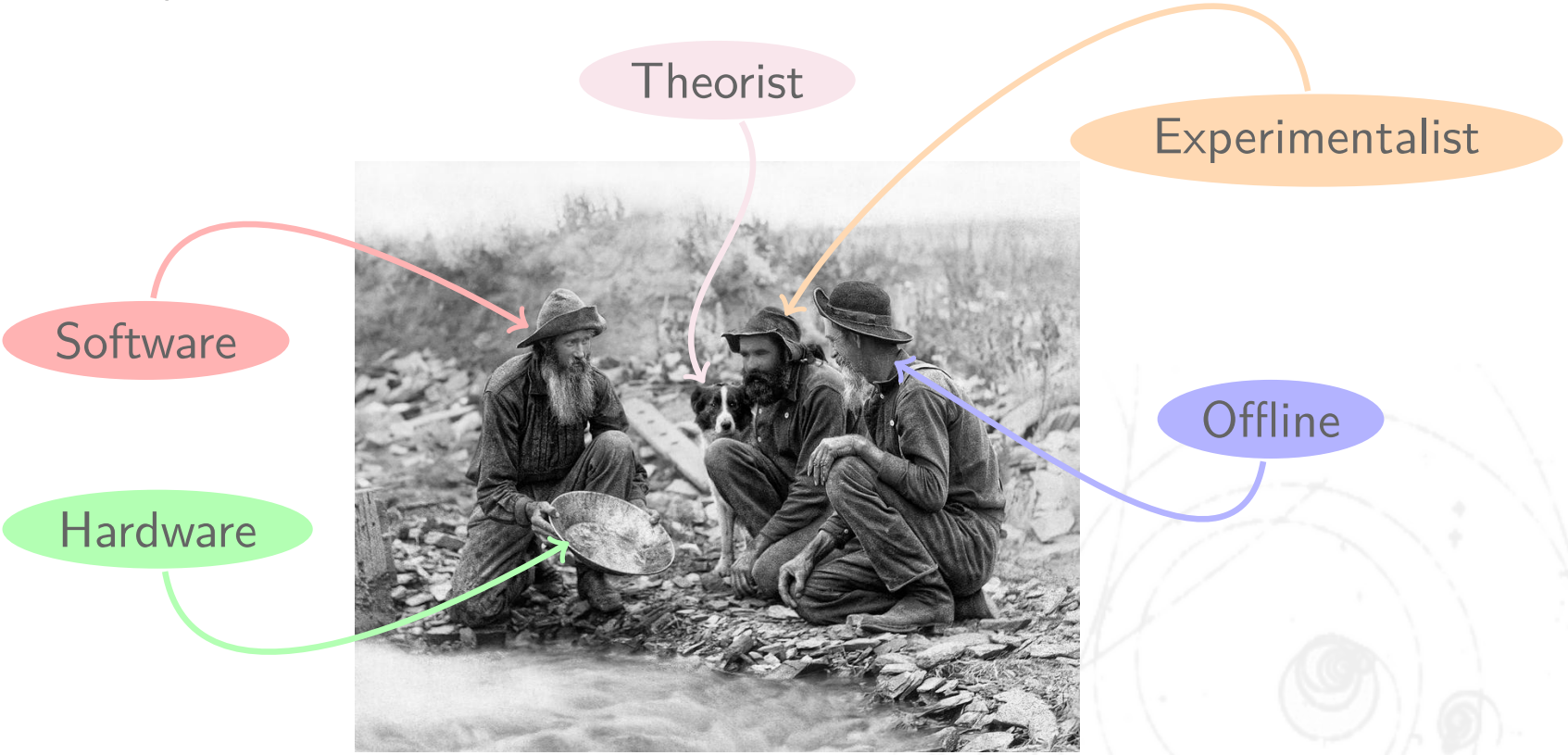




Triggers

Hard to find specks of gold in a huge river of data! Some strategies:

- Reading tape: Look for exotica in events that pass(ed) current triggers.
- (Partially) online: E.g. data scouting. Need to decide on them a priori!



Holes must be patched before the ship sails!

Question for Right Now

Are there signals that would be missed with current trigger paths, but could be seen relatively easily with a practicable online trigger strategy?

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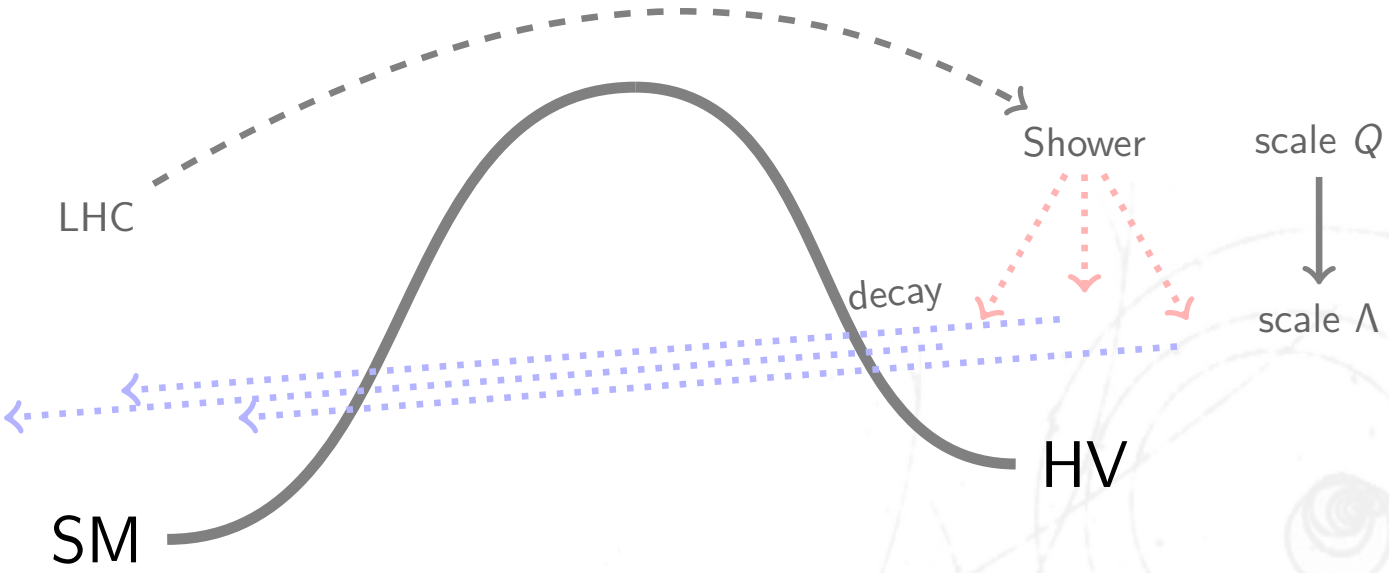
Are there signals that would be missed with current trigger paths, but could be seen relatively easily with a practicable online trigger strategy?

Yes. Can look for very high multiplicity soft events – 'soft bombs' – by looking for high density band of hits on the innermost layer of the tracker. Seeded by L1 jet, E_T^{miss}, or lepton triggers implies effficiency of $\sim 10\%$ for bomb mass few 100 GeV.

Hidden Valley Motivation

[Strassler, Zurek: hep-ph/0604261, 0605193, 0607160 and others]

- SM-HV mediator much heavier than HV mass gap, plus a low scale HV-SM portal.
- Often a high multiplicity of SM final states
- Applications in DM theories, neutral naturalness, ...



Can be hard to see; need special triggers

Soft Bombs

We'll focus on a particularly egregious scenario: Quasi-conformal, strongly-coupled HV from Q to Λ

[Strassler: 0801.0629; Hatta, Matsuo: 0804.4733; Hofman, Maldacena: 0803.1467]

- Large 't-Hooft coupling $\lambda \sim g^2 N \gg 1$: large angle emission
- Quasi-conformal dynamics: maximally efficient showering down to Λ
- Leads to $\sim$ spherically symmetric event, with multiplicity scaling linearly

$$\langle n(Q) \rangle \sim \left(\frac{Q}{\Lambda} \right)^{1+1/\sqrt{\lambda}}$$

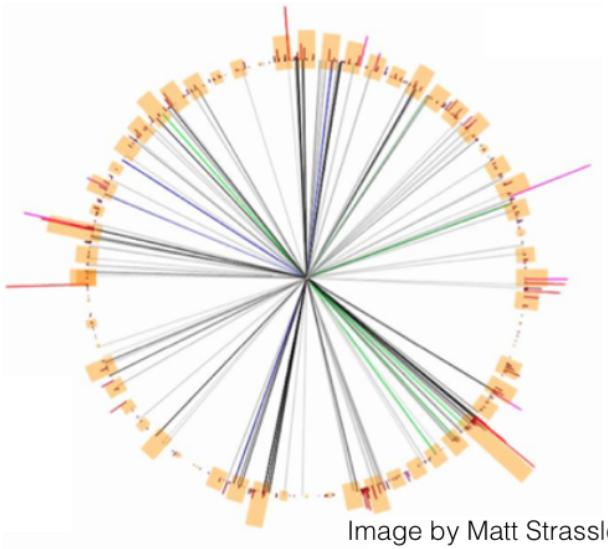


Image by Matt Strassler

High multiplicity of soft particles

Event resembles pile-up

Passes minimum bias triggers with very low efficiency

Soft Bombs

Let's add a few simplifying details, and try to maximise triggering difficulty!

- Assume one species ϕ in HV low-lying spectrum.
- Thermal p_T distribution, temperature $T \sim m_\phi \sim \Lambda$.
  Hatta, Matsuo: 0804.4733

$$f(\boldsymbol{p}) \sim \frac{\boldsymbol{p}^2}{m_\phi^2} e^{-\sqrt{m_\phi^2+\boldsymbol{p}^2}/T}$$

  p_T spectrum controlled by $T \sim \Lambda$, not hard scale Q!
- Assume prompt $\phi \to 4$ SM μ's, e's. Typical of on-shell KM mediator $\phi \to 2(Z' \to \ell\ell)$

  No intrinsic missing stuff
- Push lepton p_T down to LHC observation thresholds for leptons (a few 100 MeV), implies

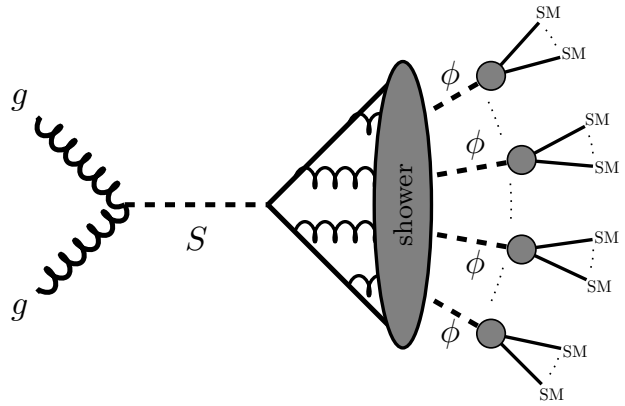
$$m_\phi \sim \Lambda \sim 1\,\text{GeV}\,.$$

  Dialing Q up or down changes multiplicity, but not p_T spectrum

Soft Bomb Production

Many different possible production portals. Representative case:

- Single resonant production from gluon fusion $gg \to S \to N\phi$



Choose some concrete benchmarks

$$m_S = 750\,\text{GeV} \qquad \text{or} \qquad 400\,\text{GeV}\,.$$

- Also consider Higgs bomb $S = h$, with GF, VBF or VH.

  Some model building challenges from tadpoles generated by EWSB etc.

  Could consider double bomb production, too ($SSH^\dagger H + S\mathcal{O}_{\text{HV}}$)

General Atlas* Triggering Strategy

- Use existing L1 triggers to pass L1: $1j$, $3j$, $4j$, E_T^{miss}, 1γ etc
- At software level, count hits on the IBL. Look for overdensities of hits for BG rejection rate $\sim 10^{-3}$–10^{-4}, for total event rate $\sim$ Hz.
- Offline, can use time-expensive track reconstruction to identify PV and set limits (or find!) bombs.

*We'll focus on Atlas; conclusions for CMS should be similar

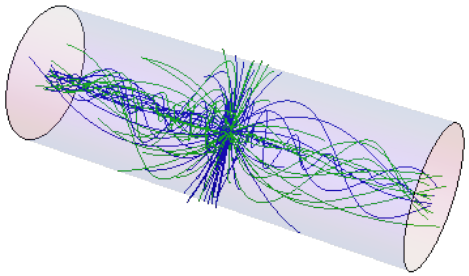
L1 Trigger

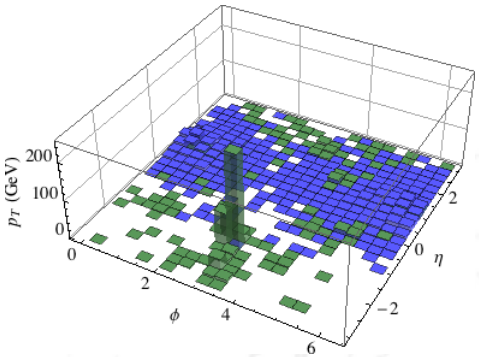
No tracking is available at L1. But,

Gluon fusion production: Can look for an ISR jet.

And, there's more:

- Even though ϕ decays are prompt, leptons are so soft, many 'loopers', that don't reach the calos. With moderate boosts, this produces calo E_T^{miss}.



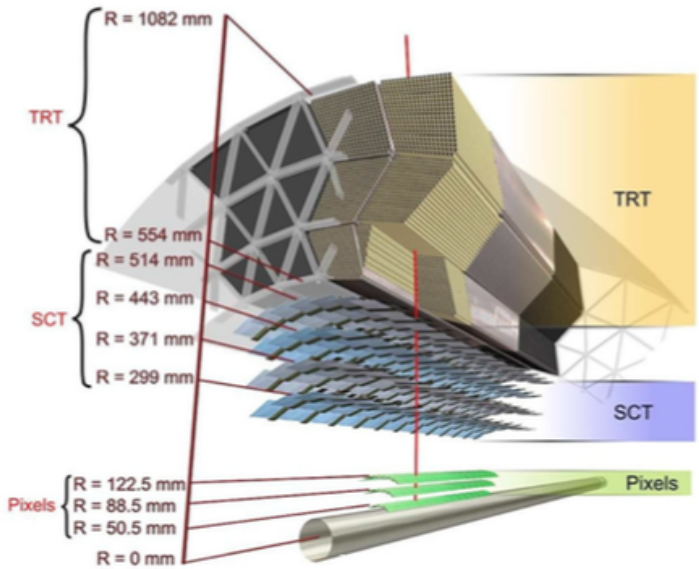


- Muons are generally soft too: muon triggers are inefficient. But contribute to calo MET.
- For Higgs bomb, have associated jet (VBF) or muon (VH).

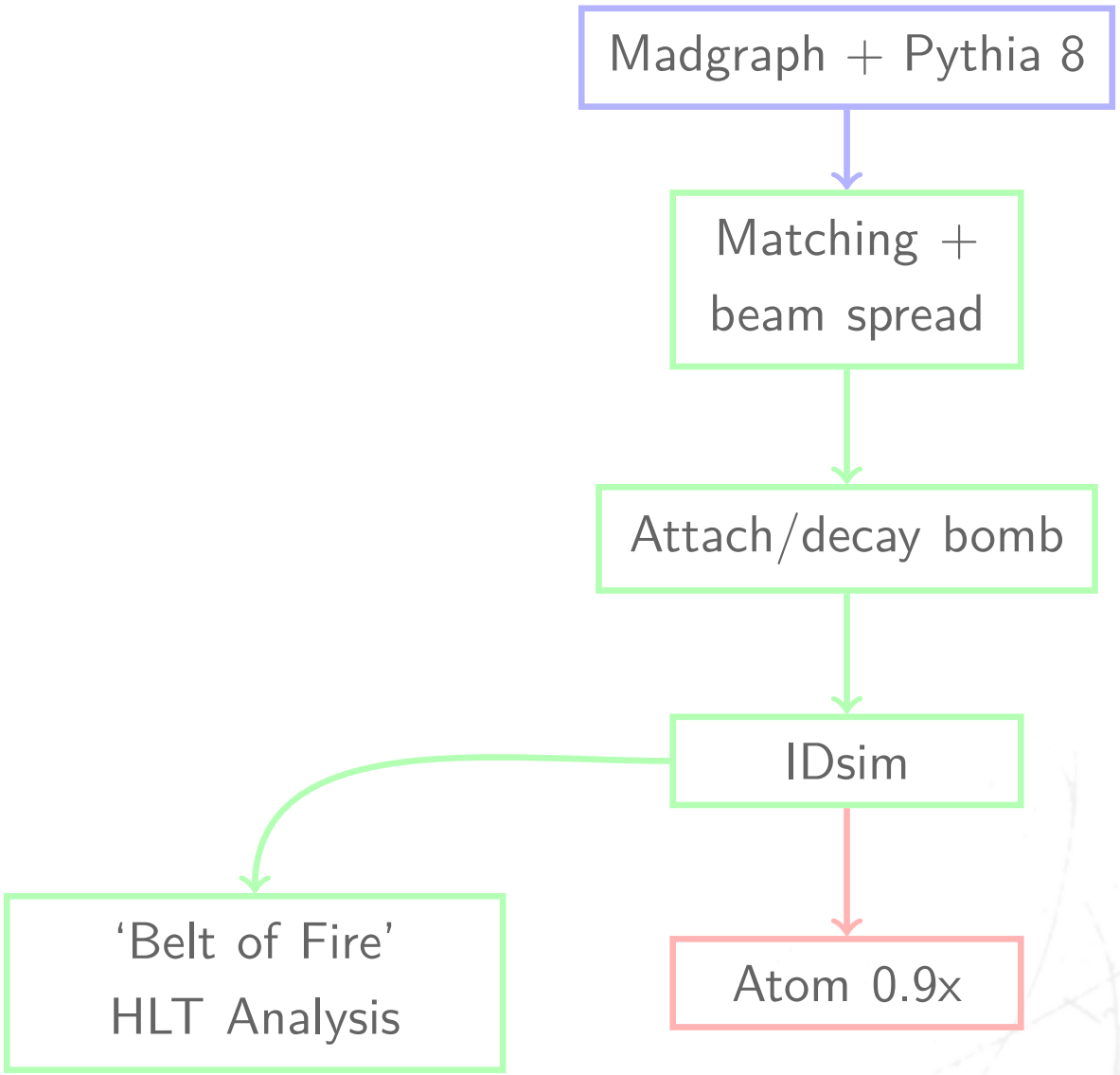
IDsim

To get a sense of the possible L1 efficiencies, use a semi-faithful homebrewed Inner Detector simulator

- Includes ionization and bremsstrahlung photons
- Models ID elements as infinitely thin with finite radiation length
- Ionization modelled by Bethe-Bloch
- Neglect clustering effects: single 'hit' = single 'cluster'
- Included components:
  - pipe, and IBL
  - 3 pixel barrels, 3 pixel wheels
  - services
  - 4 SCT barrels, 9 SCT wheels
  - (4) TRT barrels, 4 TRT wheels
  - ECAL barrel, ECAL wheels



Pipeline



Generate $gg \to S$

$0j$ and $1j$ samples

Matched $0 + 1j$ sample

Pile-up $\langle\mu\rangle = 50$

beam spot $\sim 45\,\text{mm}$

Thermal soft bomb $\to$ SM Truth Level

Propagate to IBL/Ecal

Apply L1 analysis

Incl. turn-on, isolation, clustering

Pipeline

Madgraph + Pythia 8

Generate $gg \to S$

samples

$1j$ sample

$\langle \quad \rangle = 50$

$\sim 45\,\text{mm}$

omb $\to$ SM

Level

IBL/Ecal

And then several months of:

'Belt of Fire'
HLT Analysis

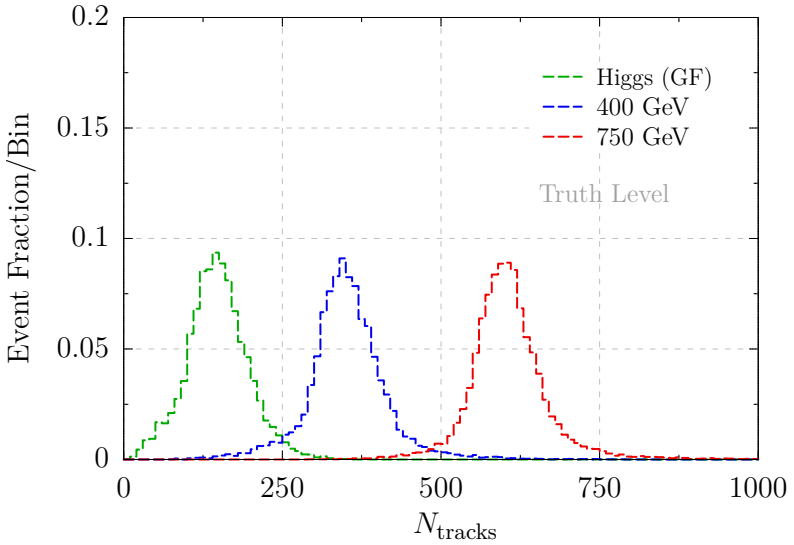
Atom 0.9x

Apply L1 analysis

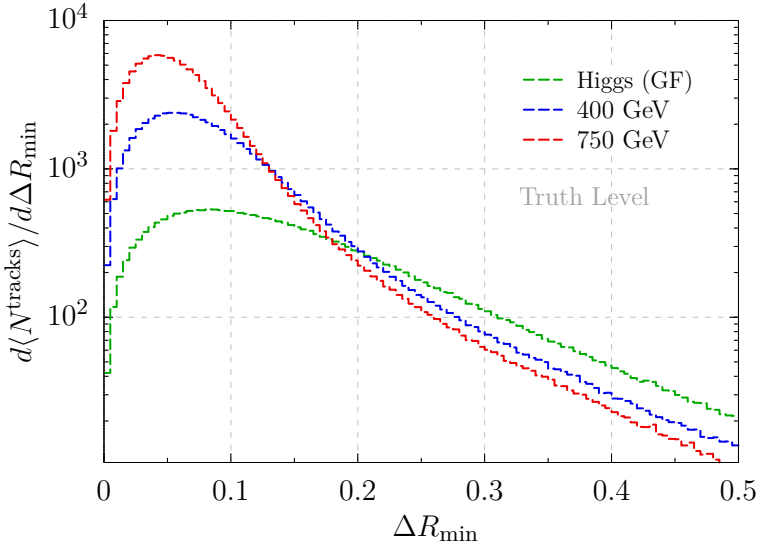
Incl. turn-on, isolation, clustering

L1 Analysis

Track ($p_T > 400\,\text{MeV}$) multiplicity scales linearly



Min ΔR sufficient for offline tracking



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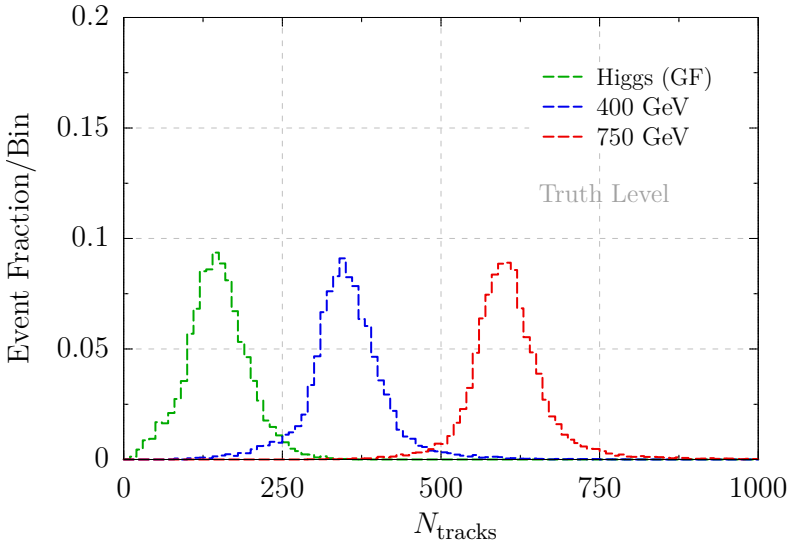

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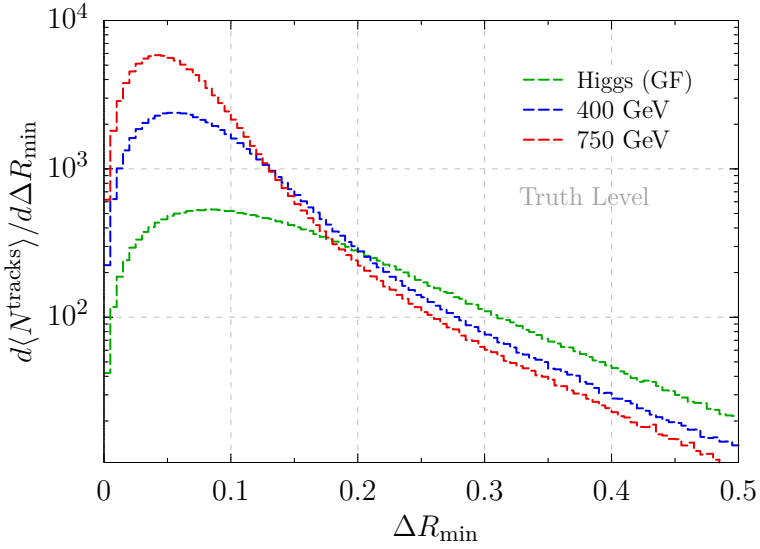
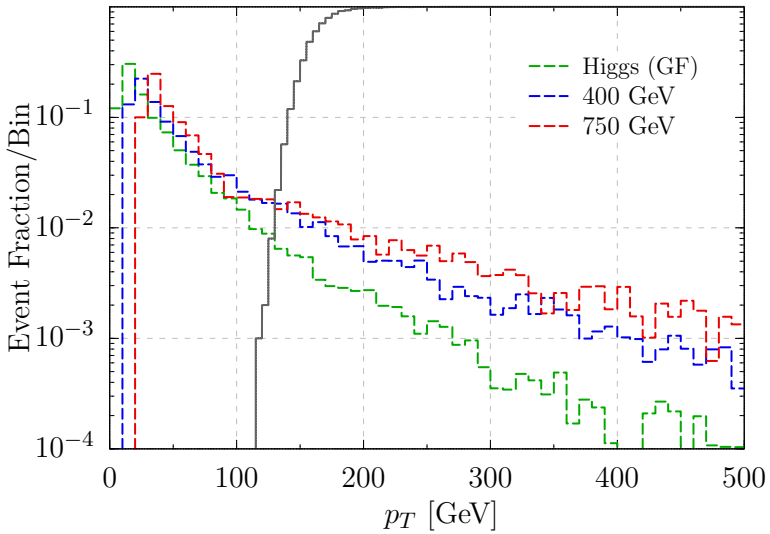
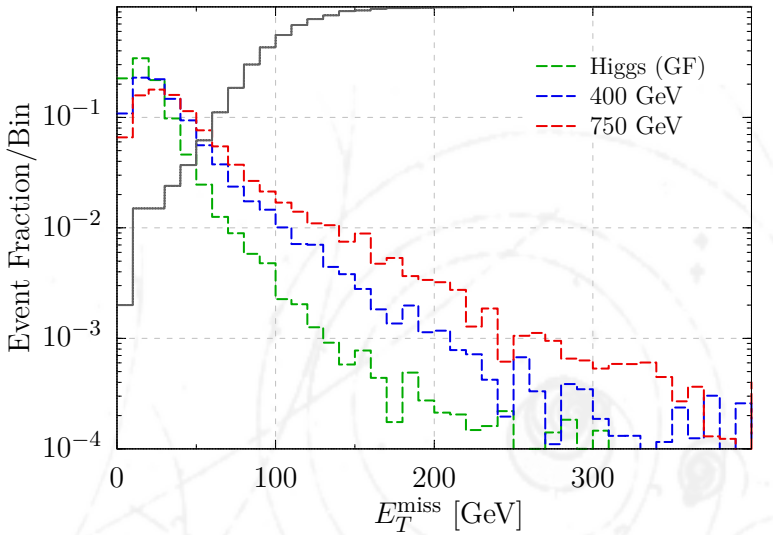




Hardest jet p_T distribution flattens out



E_T^{miss} drops exponentially

L1 Efficiencies

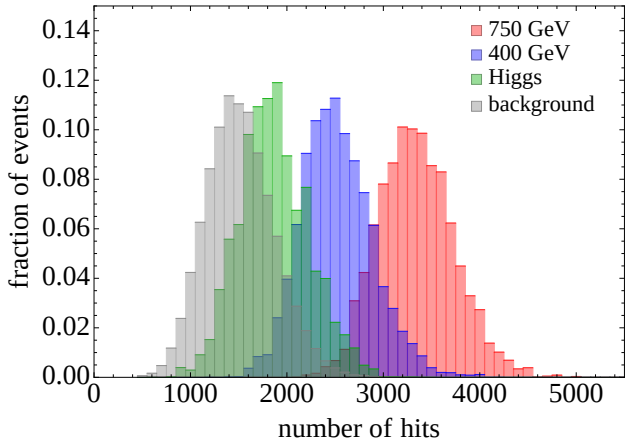
	Higgs (VH)	Higgs (VBF)	Higgs (GF)	400 GeV (GF)	750 GeV (GF)
1j ($p_T > 100$ GeV)	0.057 ± 0.002	0.107 ± 0.003	0.034 ± 0.001	0.104 ± 0.002	0.169 ± 0.002
3j ($p_T > 40$ GeV)	0.026 ± 0.001	0.045 ± 0.002	$< 1\%$	$< 1\%$	0.019 ± 0.001
4j ($p_T > 20$ GeV)	0.019 ± 0.001	0.034 ± 0.002	$< 1\%$	0.016 ± 0.001	0.052 ± 0.002
$E_T^{\text{miss}} > 50$ GeV	0.088 ± 0.002	0.063 ± 0.001	0.030 ± 0.001	0.077 ± 0.001	0.136 ± 0.002
$1\gamma/e$ ($E_T > 20$ GeV)	0.045 ± 0.002	0.011 ± 0.001	$< 1\%$	$< 1\%$	$< 1\%$
1μ ($p_T > 20$ GeV)	0.073 ± 0.002	0.011 ± 0.001	$< 1\%$	$< 1\%$	$< 1\%$
Combined	0.224 ± 0.003	0.162 ± 0.003	0.055 ± 0.001	0.140 ± 0.002	0.217 ± 0.002
$\sigma_{pp \to h+X} \times \epsilon_{\text{comb}}$ (pb)	0.50	0.60	2.39	–	–

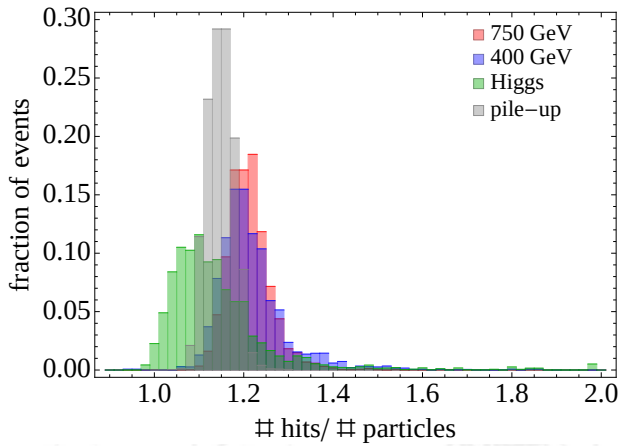
- L1 efficiencies of $\mathcal{O}(15\%)$ are possible!
- For Higgs, VH channel could be competitive (more soon)

What about the High Level Trigger?

Hit Counting

- Passing the HLT trigger thresholds is hard
  Need to separate events from pile-up and Z + jets/dijets BG.
- With $\mathcal{O}(1000)$ tracks, tracking is not feasible online.
- But, we could count hits on the tracking surfaces.
- Focus on the IBL: Least geometric spread, more stuff reaches it



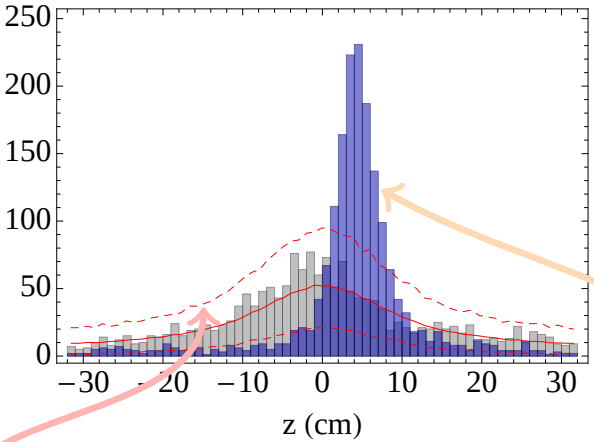


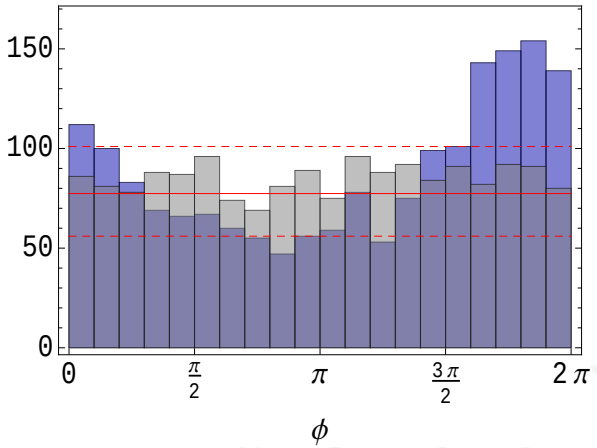
- Fairly good BG discrimination already, but large systematics.
  Can we do better?

Soft Bomb Geometry

Hit distribution from the soft bomb looks quite different to pile-up!

- Not symmetric longitudinally, and much narrower!
- Boosts alter ϕ distribution





$\langle \mu \rangle = 50$

beam spot 45 mm

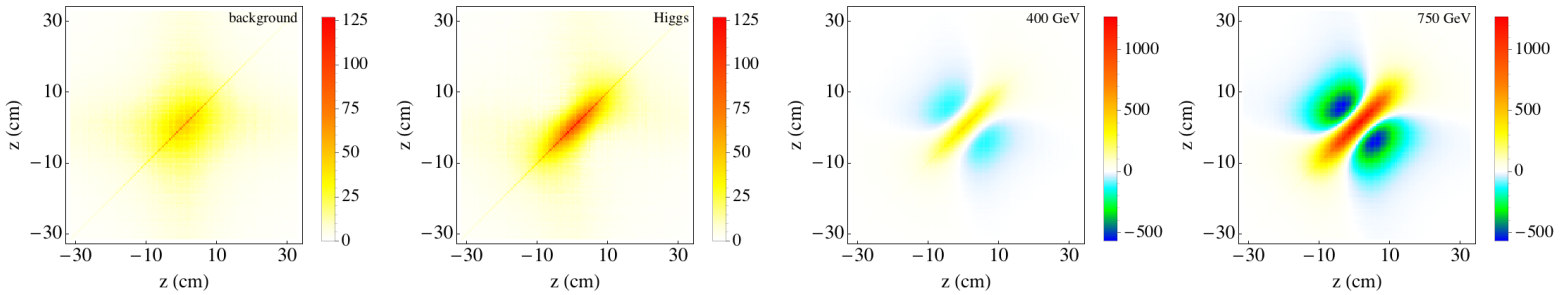
'Belt of Fire'
750 GeV

Discriminants

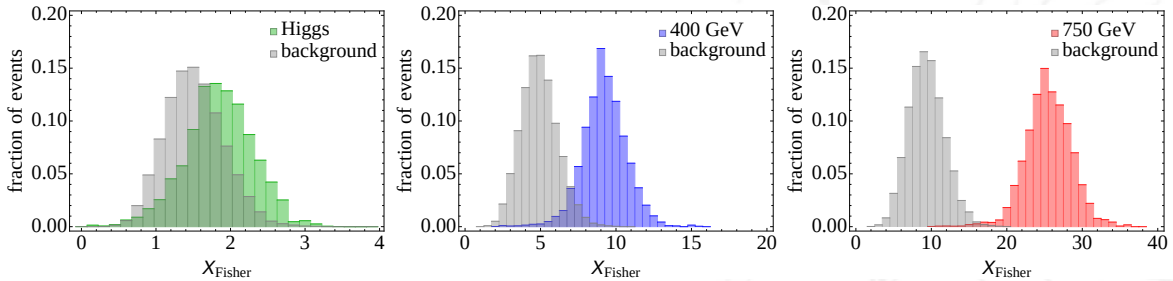
Try a Fisher discriminant:

$$X_{\text{fisher}} = (\vec{\mu}_S - \vec{\mu}_B) \cdot (\Sigma_S + \Sigma_B)^{-1} \cdot \vec{x}$$

Discrimination is mainly driven by correlation matrices



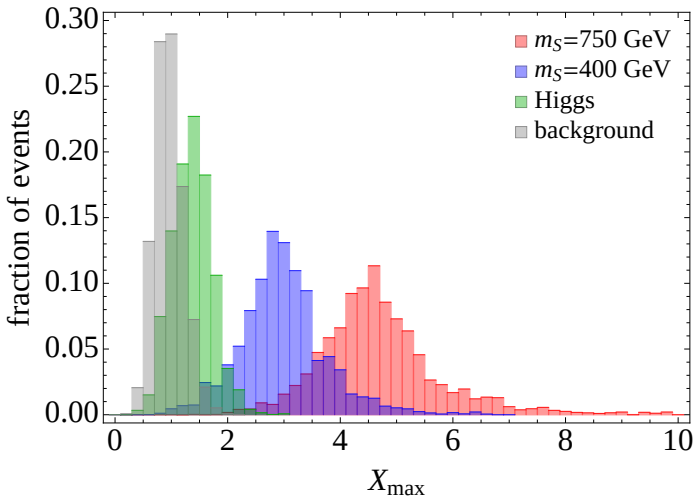
Reasonably good discrimination, but variable is mass-dependent



Peak Discriminant

Or, design a mass-independent version. In an interval around the maximum bin, define

$$X_{\text{max}} = \frac{\text{observed hit frequency}}{\text{expected background hit frequency}}.$$



	Maximum Bin			
	BG rejection: 10^{-3}		BG rejection: 10^{-4}	
	$X_{\text{max}}^{\text{thres.}}$	ϵ	$X_{\text{max}}^{\text{thres.}}$	ϵ
750 GeV	1.99	1.00	2.19	1.00
400 GeV	1.99	0.93	2.19	0.90
Higgs	1.99	0.063	2.19	0.027

- Excellent discrimination for the 750 and 400 GeV benchmarks.
- Reasonable for Higgs. For Higgs VH production, muon trigger is reasonably efficient at HLT. Can compensate for lower production cross-section.

Summary of Channels

Sensitivity and reach at 300 fb^{-1}, for 10^{-3} BG rejection rate:

	750 GeV	400 GeV	Higgs (all)	Higgs (VH)
ϵ_{L1}	0.22	0.14	0.071	0.073
ϵ_{HLT}	1.00	0.93	0.06	0.83
$\epsilon_{\text{L1+HLT}}$	0.22	0.13	0.004	0.06
$\sigma_{pp\to h+X} \times \epsilon_{\text{L1+HLT}}$ (pb)	/	/	0.21 pb	0.14 pb
sensitivity (300 fb^{-1})	0.045 fb	0.078 fb	$\text{BR}_{h\to\mathcal{B}} < 4.8 \times 10^{-5}$	$\text{BR}_{h\to\mathcal{B}} < 7.1 \times 10^{-5}$

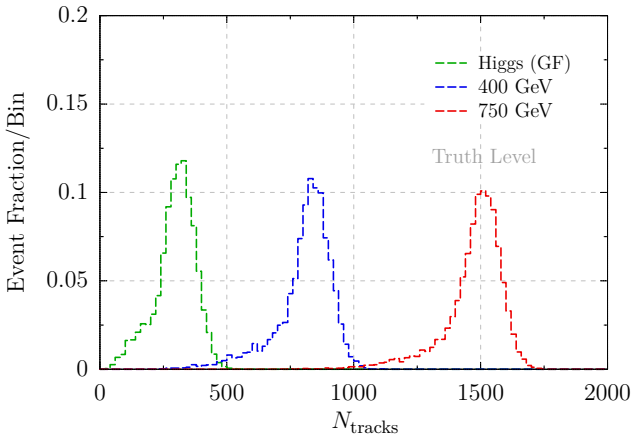
- Overall trigger efficiencies of $\sim$ 15–20% for few 100 GeV benchmarks! What was maximally hard for traditional triggers to see, becomes easy with an online strategy.
- For Higgs bomb, belt of fire is competitive with VH trigger path. Both set tight BR constraints
- There are more handles we have not used: ϕ distribution; PV vs max bin (for online tracking)

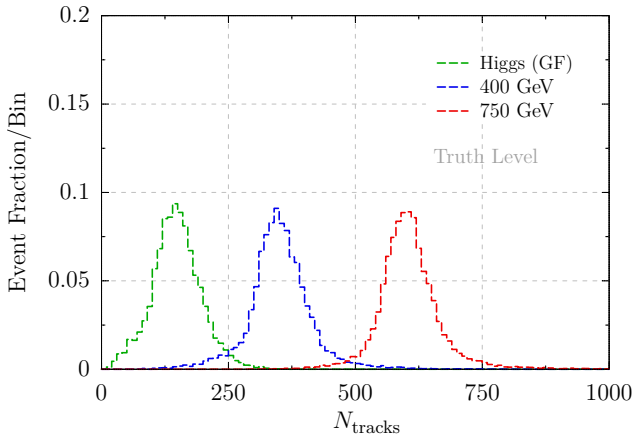
Summary

- If we want to use partially online searches to supplement LHC reach, we need to be thinking about strategies now!
- Hidden Valleys may produce high multiplicity soft events – soft bombs – that would not pass present or future triggers.
- As a proof of concept, L1 + belt of fire technique can search for few 100 GeV soft bombs with $\mathcal{O}(10\%)$ efficiencies.

Thank you!

Tracks


Higgs (GF)
400 GeV
750 GeV
Truth Level
Event Fraction/Bin
N_{tracks}


Higgs (GF)
400 GeV
750 GeV
Truth Level
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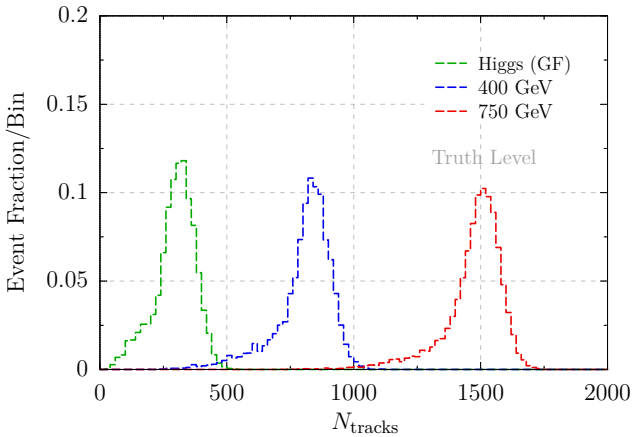
N_{tracks}


Higgs (GF)
400 GeV
750 GeV
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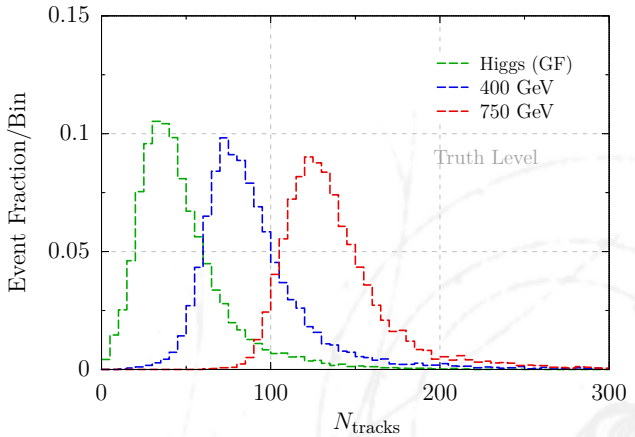
Higgs (GF)
400 GeV
750 GeV
Truth Level
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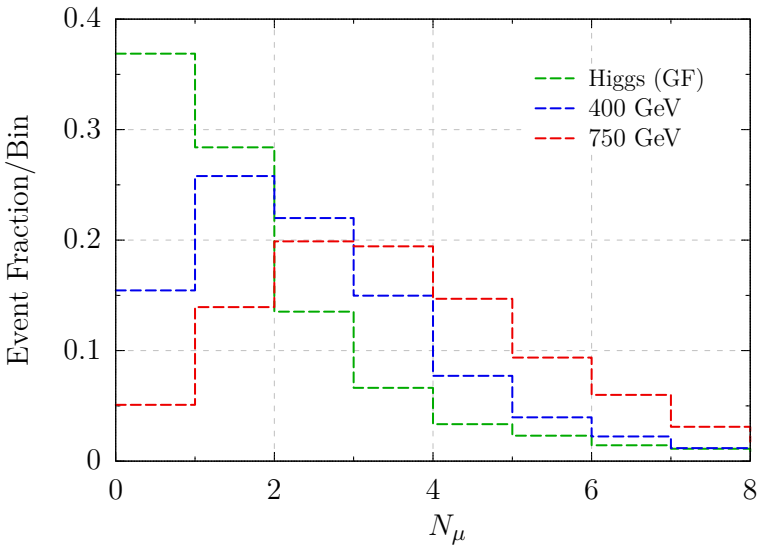
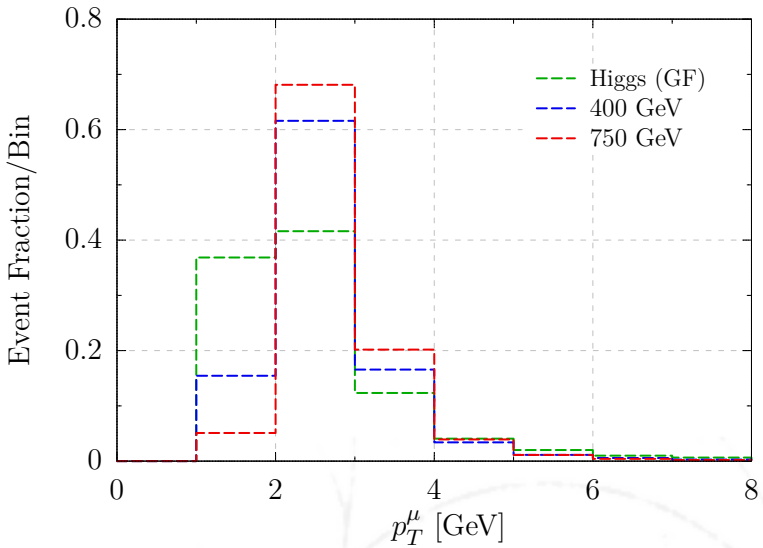
Muons


Higgs (GF)
400 GeV
750 GeV
Event Fraction/Bin
N_μ
0
0.1
0.2
0.3
0.4
0
2
4
6
8


Higgs (GF)
400 GeV
750 GeV
Event Fraction/Bin
p_T^μ [GeV]
0
0.2
0.4
0.6
0.8
0
2
4
6
8