Experimental BSM Physics

Lecture 3 of 3



Greg Landsberg





CERN, August 26, 2023



Exotica Searches

- HCPSS 2020 \odot Search for Exotics @ the LH Greg Landsberg

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Slide



The Where

- Given that the LHC has reached its ultimate energy, looking for heavy particles is a game of a diminishing return - it will take many years to discover something in this regime, if we haven't seen a hint so far
 - * No more low-hanging fruit!
- The focus shifts to much more complicated signatures, which haven't been exploited thus far, as well as significantly more sophisticated analyses than we pursued during the earlier years
 - Doubling time has doubled since Run 2; it is now about three years



★ Compatible with a "lifetime" of a graduate student in an LHC experiment, allowing for a well-designed and sophisticated analysis rather than a "luminosity chase"

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Shift of the Paradigm

- At first, we were looking at the highest masses, which opened up due to the record-high machine energy
- These are low-background searches, but only sensitive to large couplings
- Last few years marked a shift in the paradigm: we are going for high-background, experimentally challenging searches for low couplings and low masses, and often long lifetimes - something that earlier machines may have missed!





New Tools for the New Paradigm

- Use of new triggers not available earlier in the LHC running
 - \star A variety of triggers optimized for long-lived particles
 - ★ Trigger-level analysis (TLA), aka data scouting ATLAS and CMS, and triggerless design with real-time alignment and calibration (LHCb)

* Extensive use of GPU in the trigger

- ★ ISR-based triggers with jet substructure and massdecorrelated subjet taggers
- ★ Data parking
- Novel approaches with machine learning (ML) techniques: weakly supervised and unsupervised ML
- In what follows I'll illustrate these concepts using a mix of older analyses, where the techniques were established, and new results





$0.1 < d_0 < 0.3$ mm control regions

- Data agree well w/ expectations in 3 signal regions corresponding to different dimuon threshold masses
- The new result bridges the prompt searches $(d_0 < 0.3 \text{ mm})$ and the dimuon LLP analysis $(0.3 \text{ cm} < d_0 < 300 \text{ cm})$

Set of Regions	Expected N_H^{bkg}	Observed N_H^{data}	Threshold $m_{\mu^+\mu^-}$	Additional cut
1	2.1 ± 0.8	1	200 GeV	-
2	12.5 ± 5.2	7	140 GeV	-
3	17.2 ± 7.4	14	125 GeV	$\Delta R_{\mu^+\mu^-} > 3$ rad.

ATLAS <u>arXiv:2305.02005</u>

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Search for Disp

- Displaced jets are expected in many weakly coupled new physics models, e.g., RPV SUSY, Twin Higgs, split SUSY
- New ATLAS search in multijet final states, using dedicates track and displaced vertes (DV) reconstruction algorithms to be sensitive to particle with lifetimes up to ~10 ns
 - ★ DVs are vetoed in the areas with large amount of detector material
- Events are recorded using a multijet trigger
- Backgrounds estimated using control samples with a DV not correlated with a jet
- Limit are set in a variety of models, including strong RPV SUSY production





Classical Dijet Search

- Pursued at every hadron machine at every new energy
 - ★ Each, ATLAS and CMS, has over a dozen of these searches conducted over the last decade!
- Classical "bump-hunt" analysis, i.e., a search for bumps on top of a smoothly falling background spectrum
 - ★ Important not to "sculpt" the background with the selections!
- Usually done with very simple selections, e.g. one cosθ*, which, together with the invariant mass fully describes the dijet system





Bump Hunt Technique

- Many searches are looking for a relatively narrow resonance on top of smoothly falling background
 - ★ Examples include dijet resonances, VV resonances, and many more
- In this case, one does not have to rely on simulation to understand the background, but instead use the locality of the excess and estimate the background from signal sidebands
 - This technique has been used for years in meson spectroscopy
- This type of searches is known as "bump hunt"
- There are several approaches typically used in such searches



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Sideband Subtraction

- Works best if the background can be approximated by a linear function over the range of order of the resonance width
 - ★ Often the case even for exponential or power-law backgrounds, as they can be approximated by a linear function over narrow enough range (basically, keeping the first term of the Taylor series)
- The simplest approach is to define the signal window of the width Γ and two sidebands: lower and upper, each of the width Γ/2
 - The sidebands could be either immediately adjacent to the signal window or slightly offset from it to minimize the signal contamination
 - ★ In this case, the background prediction under the peak is equal to the sum of the observed data in both sideband regions
 - The accuracy of the method is 1/sqrt(N_{SB})
 - Consequently, increasing the width of the sidebands improves the background prediction precision
 - ★ In reality this is often limited by the non-linearity of the background far away from the peak
- In a typical search, one slides the windows across the desired mass range





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- A fancy version of the sideband subtraction is the *sPlot* technique [Pivk, Le Diberder, <u>NIM A 555 (2005) 356</u>] often used in flavor physics [<u>TSPlot</u> class in Root]
- Calculates per-event weights (sWeights) for n classes of events using a discriminating variable x, which allows to get distribution in a control variable y for each of the class, with the relative statistical uncertainty of sqrt(1/Nn)

* Crucial: x and y must be statistically independent (hence uncorrelated!)

- Simplest example: n = 2 (signal and background), but works for any n (e.g., a signal and several background sources)
- Example of use: study of the $B_s \rightarrow \chi_{c1}(3872)\pi^+\pi^-$ decay with $\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-$
 - ***** Discriminating variable: total invariant mass $J/\psi \pi^+\pi^-\pi^+\pi^-$
 - **★** Control variable: $\pi^+\pi^-$ invariant mass for the pions accompanying χ_{c1} (3872)





Bump Hunt: Global Fit

- An alternative is to use the entire spectrum to predict the background
 - \star This maximizes the statistical power of the background prediction
 - ★ Widely used in ATLAS/CMS for bump searches in dijet and VV channels
- This is based on the fact that the background cross section falls rapidly, as a power law, mainly due to the effects of the PDFs
- Allows to parameterize the entire spectrum with a reasonably simple function that depends only on a few parameters and encapsulates the effect of PDFs
- Given that the signals we are looking for are fairly small, the presence of such signal in the data won't affect the fit over a broad range of masses
- For any hypothesized resonance mass, compare a fit to the background-only and S+B hypotheses, to extract the signal and quantify its significance or to set a limit on its strength



Empirical Functions

A number of empirical functions have been used in LHC searches: x = m/sqrt(s)

CMSBH (from previous CMS BH searches) [link] $f_{cmsBH1}(x) = \frac{p_0(1+x)^{p_1}}{x^{p_2\log x}}$

$$f_{cmsBH2}(x) = \frac{p_0(1+x)^{p_1}}{x^{p_3+p_2\log x}}$$

"ATLAS" (from Zgamma search) [link]

$$f_{ATLAS1}(x) = \frac{p_0(1 - x^{1/3})^{p_1}}{x^{p_2}}$$

$$f_{ATLAS2}(x) = \frac{p_0(1 - x^{1/3})^{p_1}}{x^{p_2 + p_3 \log^2(x)}}$$
"UA2" (from UA2 dijet search) [link]

$$f_{UA2_1}(x) = p_0 x^{p_1} e^{p_2 x}$$

$$f_{UA2_2}(x) = p_0 x^{p_1} e^{p_2 x + p_3 x^2}$$

Standard dijet [link]

$$f_{dijet1}(x) = \frac{p_0(1-x)^{p_1}}{x^{p_2}}$$

$$f_{dijet2}(x) = \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\log(x)}}$$

$$f_{dijet3}(x) = \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\log(x)+p_4\log^2(x)}}$$

ATLAS BH (3 parameters variants of dijet2) [link] $f_{ATLASBH1}(x) = p_0(1-x)^{p_1}x^{p_2\log(x)}$ $f_{ATLASBH2}(x) = p_0(1-x)^{p_1}(1+x)^{p_2\log(x)}$ $f_{ATLASBH3}(x) = p_0(1-x)^{p_1}e^{p_2\log(x)}$ $f_{ATLASBH4}(x) = p_0(1-x^{1/3})^{p_1}x^{p_2\log(x)}$ $f_{ATLASBH5}(x) = p_0(1-x)^{p_1}x^{p_2x}$ $f_{ATLASBH6}(x) = p_0(1-x)^{p_1}(1+x)^{p_2x}$ 14



Examples of Global Fit

• Here are typical examples from CMS and ATLAS search for Hy resonances, with the Higgs boson reconstructed as a large-cone jet with substructure





Background Uncertainty

- In the global fit method, the background uncertainty is a statistical uncertainty in the fit, which is proportional to 1/sqrt(B), where the background is taken over the full range, which makes it much more accurate than in the SB method
 - ★ But how do we know that there is no additional systematic uncertainty related to and [arbitrary] choice of the fitting function?
 - \star This is achieved via *bias studies* that are done to answer two questions:
 - Can the background function create a signal-like structure in the lack of signal in data?
 - * Can the background function "fit away" the signal present in data?
 - ★ Typically for the families of functions describe above, the first bias is small, as the functions are fast falling by constructions, and typically do not have wiggles
 - ★ The second bias, nevertheless, can be significant, particularly at large masses, where there are just a few background events, and therefore there is a possibility that the background fit could adjust to fit away a small signal



Bias Studies

- The bias tests are done by generating pseudo-data sets with the statistical power similar to that in data using one particular function, and fitting it with other functions
 - \star Typically functions of several different families are used in the test
 - One first fits all the functions to be tested to data and fixes their parameters
 - * Then one uses these best fit functions to generate pseudo-data and fit these data with other functions
 - Bias studies are done with and without signal injection in order to answer the above two questions
 - ★ For the case of signal injection, one injects a signal with various masses and several strengths, e.g., at the expected 95% CL cross sections limit and five times this number
- One then plots the mean and the RMS of the extracted signal from a large number of pseudo-experiments to gauge whether there is a sizable bias present







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Going Lower in Mass

- The latest ATLAS dijet analysis started at masses of 1 TeV
 - This is because the jet rate at low masses becomes overwhelming and saturate the readout capability of the experiment

• Can something be done about that?

- ***** One can b tag jets at the trigger level, thus reducing the rate, which would allow to lower the trigger threshold
 - * Example: CMS di-b-jet search with Run 1 data, which was able for the first time to probe masses below the tt threshold
- ***** One can also explore reducing the event size to fit higher rate in the same bandwidth

- Bkgd) Bkgd

* Data scouting technique pioneered by CMS; now also used in ATLAS as the TLA (trigger-level analysis)

CMS PRL 120 (2018) 201801





Scouting Analysis

- The trigger/DAQ limitations are properly expressed in terms of the bandwidth, namely how many bits can the system send out from the detector in unit time
 - \star This is limited by various latencies and the number of available digital links
 - * The CMS DAQ system deals with a typical event size of 1 MB, and can write a few kHz of these events to tape, so the bandwidth is a few GB/s
- However, if one manages to reduce an event size to, e.g., 10 kB, one could run at a 100 kHz rate to tape, i.e., at a full CMS Level-1 trigger rate!
 - ★ This is precisely the idea: all the event reconstruction is done only at the HLT, and the reduced information about the event, e.g., about the jets, is written out in a special "scouting" data stream to enable a low-mass analysis
 - * These data are never re-reconstructed again, as there is not enough information, but could be used in a search analysis

• Why scouting?

- ★ It would be hard to claim a discovery based on this reduced data set, as very few cross-checks can be done in the case of an observed excess
- **★** Thus, we technically use these data to "scout ahead" for discoveries:
 - If an excess is seen in the scouting data, the idea is to change the triggers to write out full events in the region of an excess in the future running

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Dijet Scouting

 Here are a couple of examples of scouting analyses: dijet scouting and dimuon scouting, which allowed to significantly lower the mass reach, compared to standard triggers





Trijets as Dijet Proxies

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- Usually, initial-state radiation (ISR) creates difficulties at the LHC, as it pollutes final states we look for with extra jets

- However, it could also become our best friend:
 - ★ It gives the possibility to trigger on an event when everything else fails - perfect for low-mass final states
 - ★ Granted, one pays a price for an energetic ISR jet, but it's a good (and often only!) way to trigger
 - * Can also use ISR photons, but it's not as powerful, due to $\alpha_{\text{EM}} \ll \alpha_{\text{S}}$



Boost or Bust

- Typical trigger threshold on an ISR jet is ~500 GeV
- If we want to extend the dijet search to even lower masses than the scouting technique allov
 Small-radius jets | Large-radius jet



 $\gamma \sim p_T^{ISR}/m(Z')$; for m(Z') ~ 100 GeV, $\gamma \sim 5$, and $\alpha \sim 0.5$: reconstructed as a single jet



Jet Substructure Techniques

- In the past decade, we saw significant theoretical and experimental developments in identifying jet with substructure
- These involve several steps:
 - ★ Jet grooming removing soft, wide-angle radiation and pileup contributions that artificially increase the jet invariant mass
 - ★ Jet substructure determination how likely is that a largeradius jet consist of N subjets
 - ★ Jet mass measurement after grooming and determining that jet has a substructure, jet invariant mass becomes a powerful discriminant to look for resonances decaying into two jets
 - ★ Large-radius jet b tagging used to determine if a jet is consistent with having a b jet or b jets within it

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One of the proposed variables u_____t^{*} of jet is consistent with having N subjets is the "Nsubjettiness" variable:

 $\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \left\{ \Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k} \right\}$

- Here, the sum is over all particles in the jet, N is the number of subjets forced to be found by a jet clustering algorithm, e.g., exclusive k_T algorithm, and d₀ is a normalization coefficient
- A ratio τ₂/τ₁ shows how likely is that a jet has two subjets



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Jet Mass

- An important variable, which allows to distinguish merged signal jets from the tail of QCD jets
- Example: jet mass in boosted tt semileptonic events before (left) and after (right) the $\tau_2/\tau_1 < 0.5$ requirement



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Jet Mass at Higher Orders

- Generally, jet mass is a function of jet p_T
 - * This is due to large double-logarithms (Sudakov logs) coming from QCD higher-order corrections
- The proper scaling variable is $\rho = M^2/(p_T R)^2$, where R is the jet distance parameter
- Cross section do/dp exhibit a Sudakov peak at small values, which depends on the grooming algorithm
- Important to operate above Sudakov peak for stability against higher-order corrections
 - **★** E.g, for p_T = 500 GeV, M = 100 GeV, R = 0.8, ρ = 0.25² = 0.06 reasonably safe





Mass-Decorrelated Taggers

- Because the jet mass fundamentally depends on the jet p_T, requiring a large Lorentz boost of a resonance generally sculpts the mass spectrum
 - ★ Additional sculpting occurs when a jet substructure variable is used to ensure the 2-prong jet structure
- In order to avoid sculpting, one needs to decorrelate the mass and the substructure tagger performance, which can be achieved by using a mass-dependent requirement on the tagger output

★ The technique is known as mass-decorrelated tagging

- There are also alternative methods, such as use of adversarial neural nets to remove mass correlation
- Once one ensures that the mass spectrum is not biased, the rest of the analysis is "simple", particularly since one has W and Z bosons to ensure proper performance at ~100 GeV



Low Mass Dijet Analysis

- Put it all together to look for ISR-tagged dijet resonances
- Allows to lower the dijet mass reach to 50 GeV, as demonstrated with the W/Z peak observation in the dijet spectrum
- Goes well beyond the only available 30-year old UA2 limits in terms of mass reach and couplings (see next slide)!



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Using Photon ISR

 One could go to even lower masses if one uses photon ISR, where triggers are available at significantly lower p_T than for the jet ISR
 ★ That allowed to probe amazingly small masses - down to 10 GeV!





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Mono-mania or LHC as a Dark Matter Factory



Dark Matter Landscape

Dark Sector Candidates, Anomalies, and Search Techniques



Dark Matter Landscape



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Known Unknowns

- While the true origin of DM is unknown, several things about DM are well understood
- Assuming that DM has particle origin we know that:
 - ★ It has to be a neutral particle
 - ***** It's unlikely that it carries color (strong interactions)
 - ***** It must be stable on a cosmological timescale
 - ***** It must have the right abundance, which sets constraints on its decay channels, couplings, and mass
 - * For example, ordinary neutrinos can't be a sole source of DM, despite having mass
 - * In order to get the right abundance, DM usually should be able to interact with the SM particles, which is achieved via a "mediator" particle coupled to both SM species and DM



Make It, R



Dark Matter Production at the LHC





Monojets: the Classics

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Slide



Monojet Searches

- Monojet analysis is a classical search for a number of new physics phenomena
 - ★ Smoking gun signature for supersymmetry, large extra dimensions, dark matter production, ...
 - ★ Was pursued since early 1980s
- The signature is deceptively simple, yet it's not
 - ★ Backgrounds from instrumental effects
 - ★ Irreducible Z(vv)+jet background
 - ★ Reducible backgrounds from jet mismeasurements and W+jets with a lost lepton
- Number of techniques have been developed since the first search by UA1, resulting in an incorrect claim of an excess
- State-of-the-art theoretical predictions of major backgrounds



Fast-Forward 30 Years

State-of-the-art analyses, which employ multiple \bigcirc control regions and the latest theory calculations of **NLO EW and QCD corrections to V+jets production**





A Monojet Event



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ATLAS



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How is this Analysis Done?

- This analysis is a classic example of simultaneous use of the signal region (SR) and control regions (CRs) to optimally constrain the background, which mainly comes from W(lv)+jet with a lost lepton or Z(vv)+jet
 - Connect CR1/2 with the W(lv)+jet w/ a lost lepton background via MC transfer factor
 - Connect CR3/4 with the Z(vv)+jet background via branching fraction/ acceptance from simulation
 - ★ Connect CR5 with CR3/4 via acceptance/mass effects via simulation
- Do simultaneous fit to S+B hypothesis in SR and B-only hypothesis in the CR1-5, which allows to constrain the background shape and absolute rate





DM Interpretation

Present the limits in terms of constraints on the mediator vs. DM particle masses for fixed value of couplings

★ Convention: $g_q = 0.25$; $g_{DM} = 1$

CMS JHEP 11 (2021) 153

Vector mediators

ATLAS PRD 103 (2021) 112006

Axial-vector mediators



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Complementarity w/ DD

Collider experiments competitive w/ direct detection \bigcirc ones in the SD case (axial-vector mediator) up to mDM ~ 500 GeV and in the SI case (vector mediator) for very light **DM** ($m_{DM} < 5 \text{ GeV}$)





Complementarity w/ ID

- For a pseudoscalar mediator, the nucleon scattering cross section is velocity suppressed because of this factor in the matrix element: $\mathcal{M} \sim (\vec{v}_f \vec{v}_i) \cdot \vec{\sigma}_n$
- Given v ~ 10⁻³, the sensitivity of DD experiments vanishes
- The collider results can be compared w/ ID experiments and are competitive for DM masses below ~150 GeV



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Dark_Matter_Summary_plots



Conclusions

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I hope these lectures gave you some ideas and inspiration on how to do searches, and what are the important techniques and topics being pursued at the LHC!



Thank You!