Experimental BSM Physics

Lecture 1 of 3

CERN-FERMILAB
HADRON COLLIDER PHYSICS
Summer School

Greg Landsberg

BROWN

18th HCPSS

CERN, August 25, 2023

Outline

- ***Why Search for BSM Physics?***
- ***The Hierarchy Problem***
- ***Some Search Methods***
  - ***Cut-and-count vs. MVA***
  - ***Model-independent Searches***
  - ***Look-Elsewhere Effect***
- ***Searches for SUSY***
  - ***Designer Variables***
- ***Exotica Searches***
  - ***Bump Hunt***
  - ***Long-Lived Particles***
  - ***Dark-Matter Searches***

Preamble

- Searches are a vast landscape, and you already have heard an excellent theoretical introduction by Tim Cohen, so I'll try to complement his views with an experimental perspective on this subject
- I apologize for not being able to cover all the various aspects of BSM searches, but I'd be happy to try answering your specific questions during the lectures and in the Discussion Sessions

A Few Words About Myself

- I am an experimentalist, working 100% in the CMS experiment at the LHC since 2006
  - A CMS Exotica Group Convener 2009-2010 and the CMS Physics Coordinator 2012-2013
  - Previously I've spend a decade working in the D0 experiment at the Fermilab Tevatron, where I received my Ph.D.
  - And even earlier, as an undergraduate, I worked in a fixed-target experiment doing meson spectroscopy
- I've started as a collider physicist doing EW measurements - $W\gamma$ and $Z\gamma$ production and limits on anomalous triple gauge boson couplings
- Soon after my Ph.D, I've switched to searches, including Leptoquarks, Extra Dimensions, Long-Lived Particles, other Exotica, SUSY, and Higgs
- Lately, I've been also working on flavor anomalies as a window on new physics
- I've done some phenomenological work, most notably the original proposal to search for black holes at the LHC

What I'll Cover

- Searches for BSM physics are really numerous
- For example, in CMS they are organized within three physics groups: SUSY (SUS), Exotica (EXO), and Beyond SM particles decaying into top quarks or 2 Higgs or gauge bosons (B2G)
  - While "bread-and-butter" Exotica searches (W′, Z′, extra dimensions, LQs, etc.) are winding down, a lot of attention is shifting to searches with b and t quarks, τ leptons, as well as searches in the Lorentz-boosted topologies, and searches for long-lived particles
  - SUSY searches moved toward "natural" SUSY models and Higgs production in the SUSY decay chains
  - Rare Higgs decays complement the landscape
- In these lectures, I'll highlight some of these recent results
- Will mostly use CMS analyses as examples - in the majority of the cases ATLAS has very similar results
  - I chose CMS simply because I know these analyses in more detail, but I'll mainly focus on the methods used in these searches, which are common to both ATLAS and CMS (and to a certain extent - LHCb)

Motivation

MOTIVATION

Some people need more than others...

As Confucius Once Said...

... about SUSY searches in the XXI century?..

It's very hard to find a black cat ...

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... in a dark room ... ... about SUSY searches in the XXI century?..

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As Confucius Once Said…

… in a dark room … **… about SUSY searches in the XXI century?..**

It’s very hard to find a black cat …

… especially if he is not there…

Why Motivate Yourselves?

- Searching for new physics is not for the weak at heart:
  - Some 10^3 searches have been carried out by the ATLAS and CMS experiments so far, and all but one (Higgs discovery) came empty-handed
  - A likelihood for any given search to find something interesting is therefore close to zero…
  - … yet, the only way to find something is to keep looking!
- It's much more fun to do a search analysis if you are motivated
  - …not [just] by your advisor, but by the physics you are doing!
- Remember, every search is a potential discovery, and only if it fails, it becomes a limit setting exercise
- *"Pier is a disappointed bridge"* - James Joyce
  - Set out to build bridges, not piers!

Real Motivation: the Hierarchy Problem

Large Hierarchies Tend to Collapse…

SM: 10^{-34}
fine-tuning

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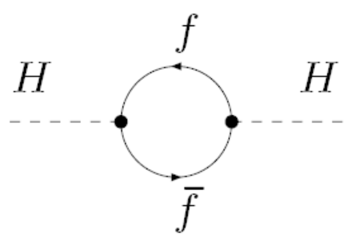
The Hierarchy Problem

- As Tim has explained earlier, Higgs boson **mass receives corrections from fermionic loops**:



- The **size of corrections is ~ to the UV cutoff (Λ) squared**:

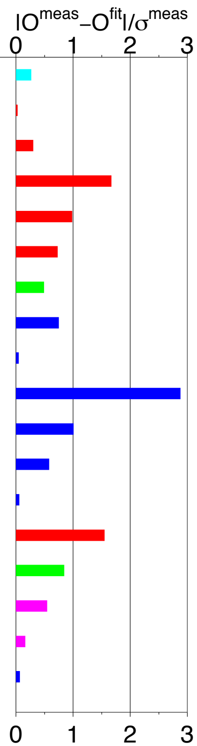
$$\Delta M_H^2 = \frac{\lambda_f^2}{4\pi^2}(\Lambda^2 + M_H^2) + \ldots$$

- In order **for the Higgs boson mass to be finite, a fine tuning** (cancellation) of various loops **is required to a precision ~$(M_H/\Lambda)^2$** ~ 10^{-34} for Λ ~ M_{Pl}
- This is known as a "hierarchy problem" stemming from a large hierarchy between the electroweak symmetry breaking and Planck scales, and it requires new physics at Λ ~ 1-10 TeV
- *The discovery of the Higgs boson with the mass of 125 GeV in 2012 made the hierarchy problem a reality, not just a theoretical concept!*
  - *The hierarchy problem is essentially only 11 years old!*

Standard Model: Beauty & the Beast

Beauty…

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2012

Standard Model: Beauty & the Beast

Beauty… and the Beast

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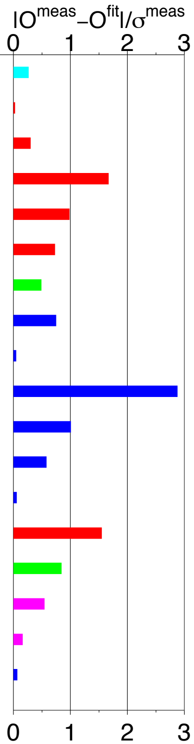

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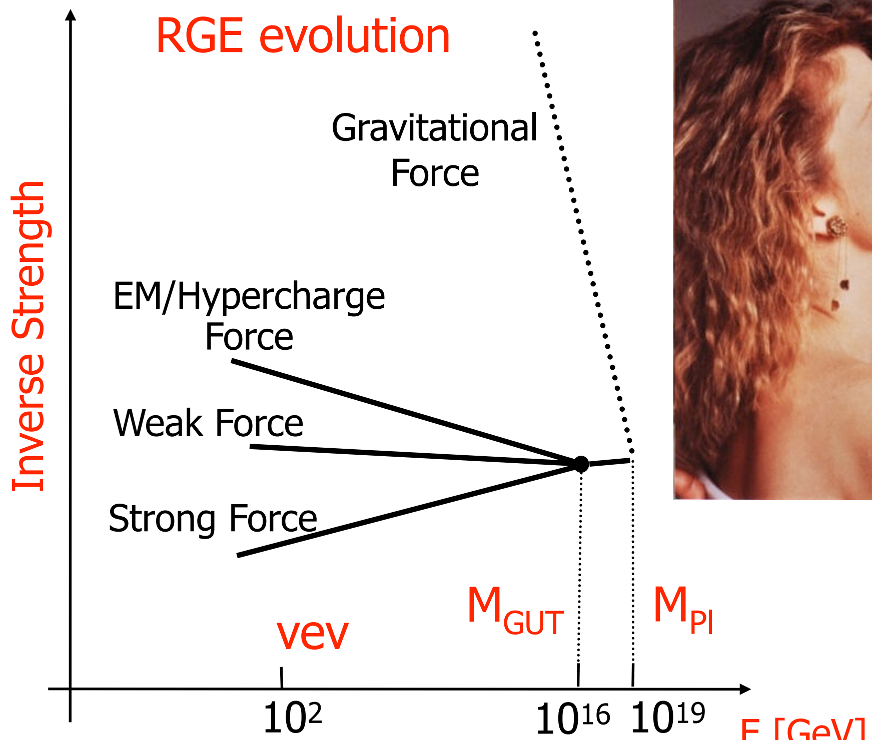

$M_{GUT} \sim M_{Pl} \gg vev$

Standard Model: Beauty & the Beast

- **Physics beyond the SM may get rid of the beast while preserving SM's natural beauty!**

Beauty… and the Beast

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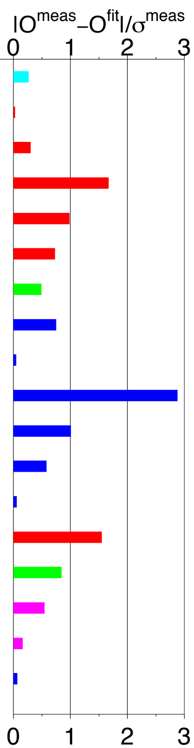

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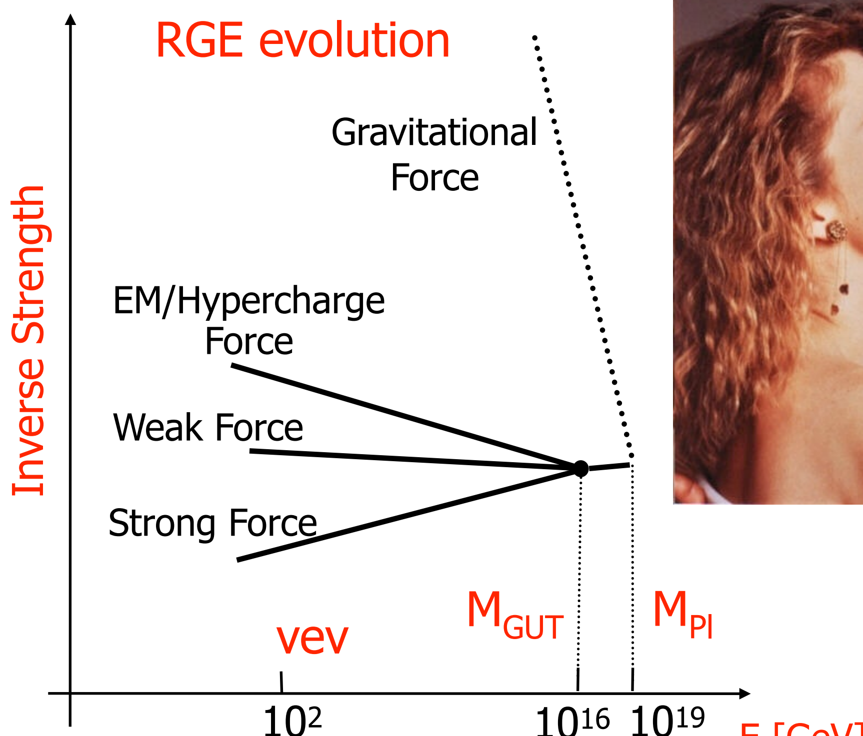

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- Nevertheless: beware of the *anthropic principle*
  - Properties of the universe are so special because we happen to exist and be able to ask these very questions
  - Is it time to give up science for philosophy? – So far we've been able to explain the universe entirely with science!

Beyond the Standard Model

Beyond the Standard Model

- Apart from the naturalness argument:
  - Standard Model accommodates, but does not explain:
    - EWSB
    - CP-violation
    - Fermion masses (i.e., the values of the Yukawa couplings to the Higgs field)
  - It doesn't provide natural explanation for the:
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- Logical conclusion:
  - Standard model is an effective theory – a low-energy approximation of a more complete theory, which ultimately explains the above phenomena
  - This new theory must take off at a scale of ~1 TeV to avoid significant amount of fine tuning
  - Four classes of solutions:
    - Ensure automatic cancellation of divergencies (SUSY/Little Higgs/Twin Higgs)
    - Eliminate fundamental scalar and/or introduce intermediate scale Λ ~ 1 TeV (Technicolor/Higgsless models) - basically dead now
    - Reduce the highest physics scale to ~1 TeV (Extra Dimensions) - severely constrained
    - Dynamically create EWSB scale starting from the Planck scale (Relaxion, Nnaturalness)

Search Methods

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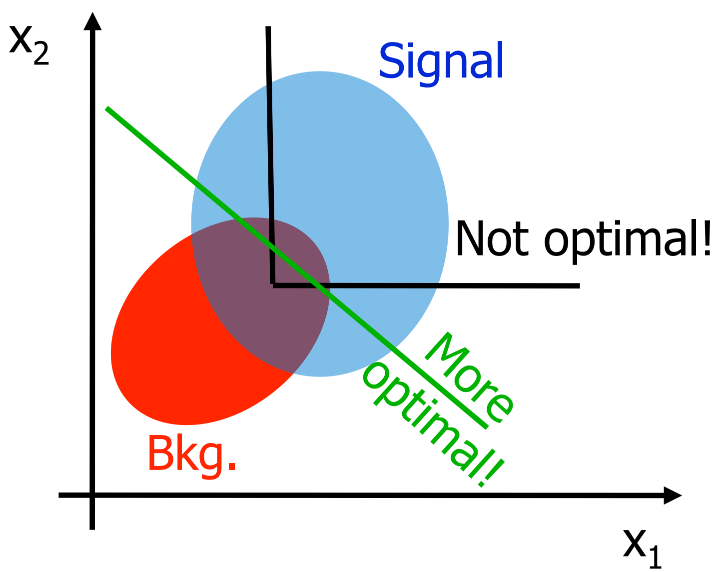
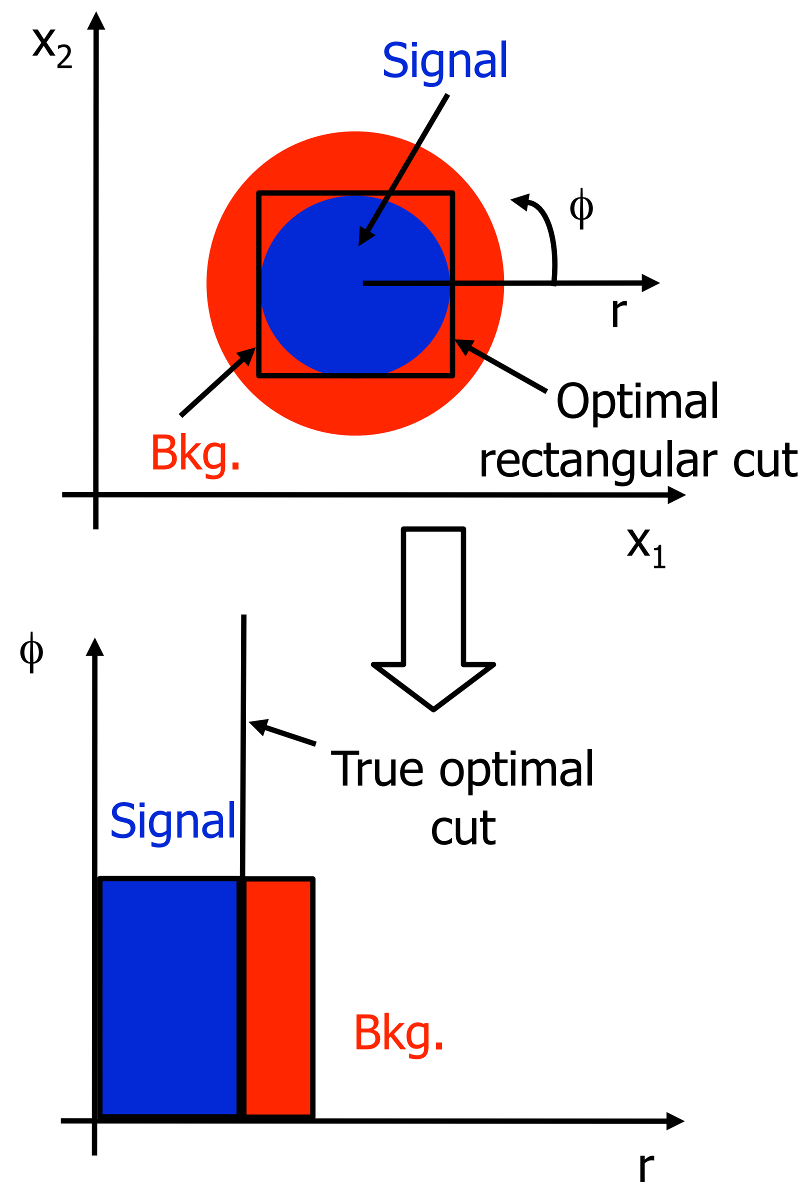
Search Concept

- Generally, one searches for a specific signal S in a sample composed of a potential signal and background B
- Classical hypothesis testing statistical problem, which is usually solved using maximum likelihood method (as will be explained in Wouter's lectures)
  - Various possible treatment of systematic uncertainties: profiling, integration, etc.
- Search analyses typically deal with the $S \ll B$ situation, which requires analysis *optimization*
  - Various optimization figures of merit (FOM) are used, e.g., Gaussian significance S/sqrt(S+B), modified Gaussian significance taking into account systematics $S/\mathrm{sqrt}(S+B+\delta B^2)$, Punzi significance, etc.
  - For low-background cases, important to use Poisson significance, which is usually done by maximizing the expected signal significance
  - N.B. Beware optimizing for the best limit: what's the point of doing a search when you are venturing to set a limit *a priori*?
    - While in the Gaussian case, the discovery and limit based optimizations give the same optimal cuts, this is no longer true for the Poisson case!

Simple Analysis Methods

- **Straight (rectangular) cuts are not always a good idea, despite simplicity**
  - **Requires careful choice of variables, often hard to find a priori**
  - **May result in non-optimal cuts for correlated variables!**





Multivariate Analysis Techniques (MVA)

✦Random Grid Search:

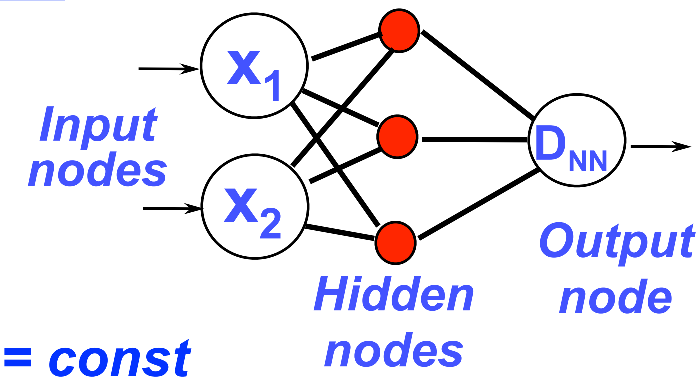
- Use kinematic parameters of MC events for signal, and MC or data events for backgrounds in order to find the optimal cuts, given chosen optimization criterion

✦Neural Nets/Boosted Decision Trees:

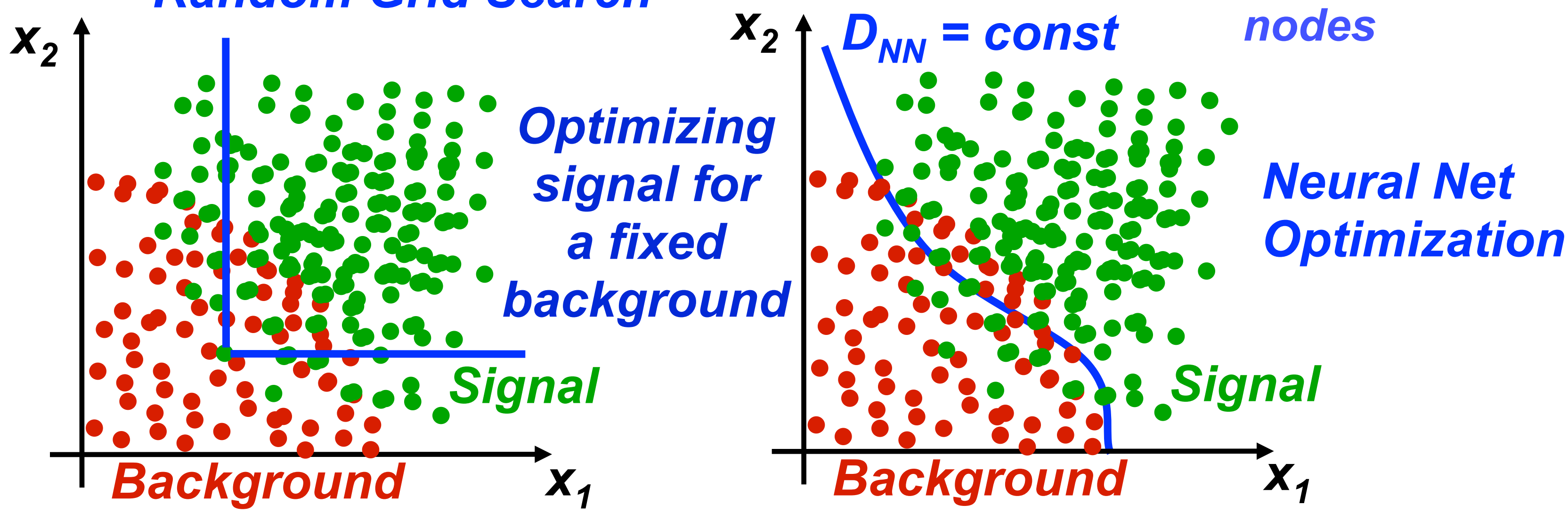
- Train a net on a mixture of signal MC and background, so that the output D ≈ 1 for signal and D ≈ 0 for background

✦Artificial neural nets approximate the way brain works via numerically solving set of non-linear ODE's

✦Implemented in major stat packages, e.g., TMVA in Root

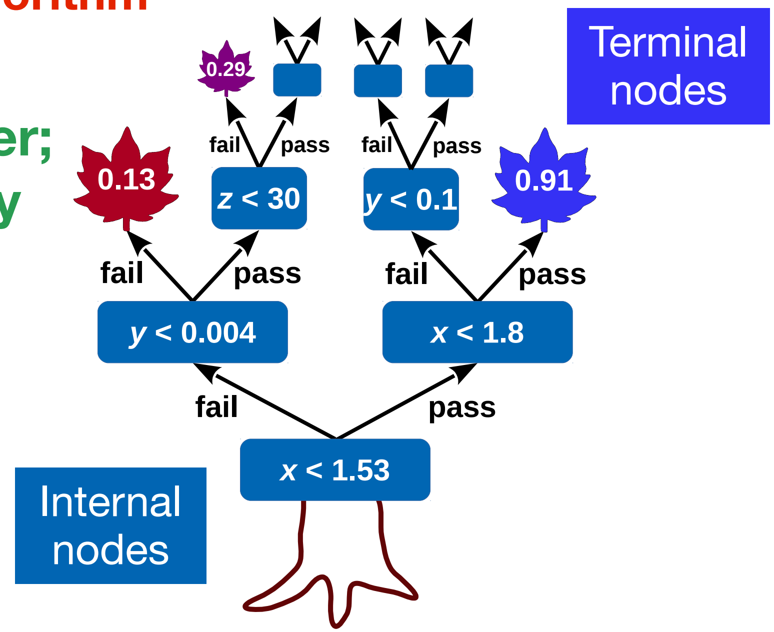


Random Grid Search



Boosted Decision Trees

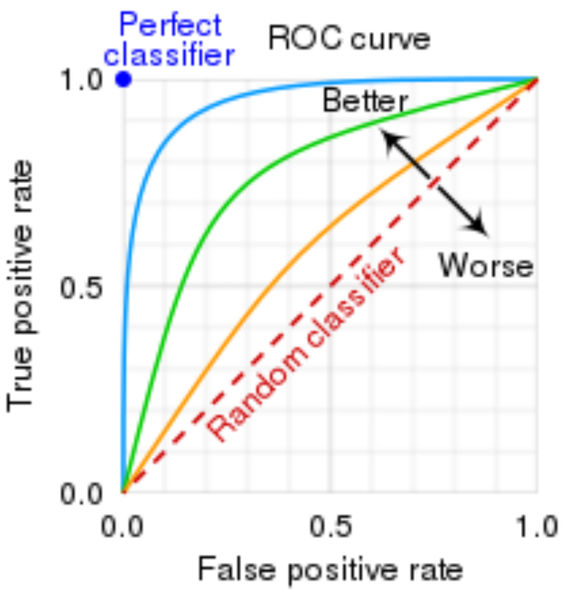
- BDTs are based on recursive binary trees:
  - Sort data in each input variable
  - For each variable find an optimal split value
  - For the next node, select the variable and the split value that gives best separation
  - If no improvement in separation can be achieved by further splitting, make the node a terminal node and exit the algorithm
  - Apply the above steps recursively
- In reality, a single tree is a weak classifier; boost the performance by creating many trees (random forest) and weight them according to the separation power
- In the training of each tree use some new events and some events misclassified by a previous tree
- XGBoost is a powerful boosting library for decision trees



Coadou, arXiv:2206.09645

ROC Curves

- **Performance of an MVA algorithm is often characterized by a *ROC (Receiver Operating Characteristic) curve***
  - **The term originated during WWII as a way to identify enemy objects on the battlefield using radars**
  - **Used to compare the performance of various algorithms and to set working points, e.g., at a given true positive rate (efficiency) or a fixed false positive rate (misidentification)**
  - **The algorithm with larger *area under curve* (AUC) performs better**
    - **AUC = 0.5 - random classifier**
    - **AUC = 1 - perfect classifier**
    - **Good algorithms typically have AUC > 0.9**

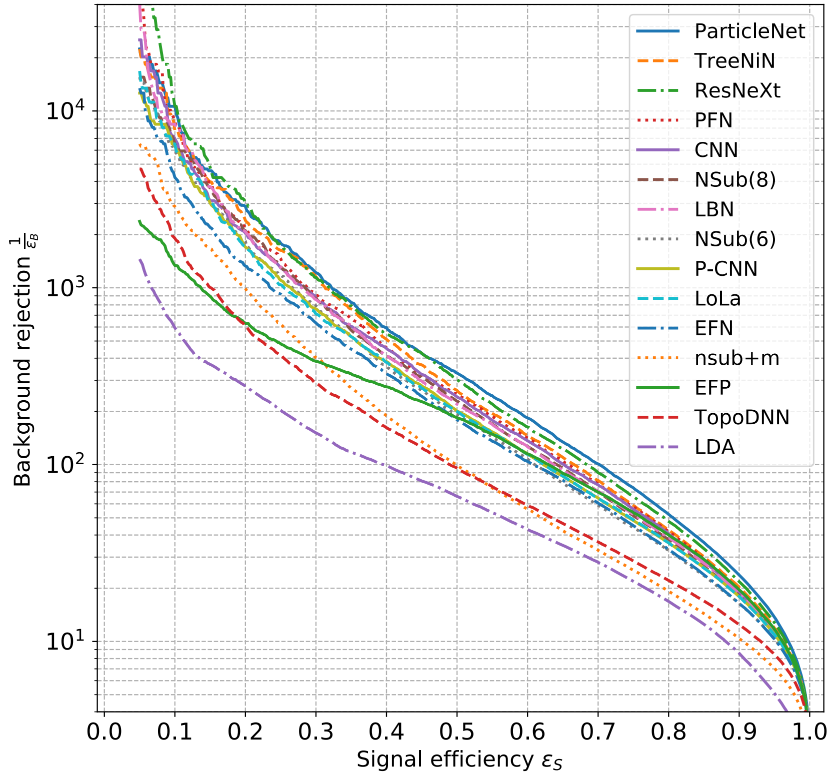


Deep Learning

- Advances in CPU and GPU allowed to take ANNs to a quantitatively new level, Deep Neural Networks
- They contain large number of hidden layers, resulting in billions (or sometimes trillions) nodes, thus allowing for a qualitative improvement in performance
  - N.B. Human brain contains 80 billion neurons and 150 trillion synapses
- DNNs are a very popular tool these days, both in everyday life (ChatGPT) and particle physics
  - ChatGPT 4 contains 170 trillion parameters - more than the human brain!
- Basic idea: minimize the so-called loss function over a set of parameters, using a non-linear function (NN)

Amazing Tool for Particle ID

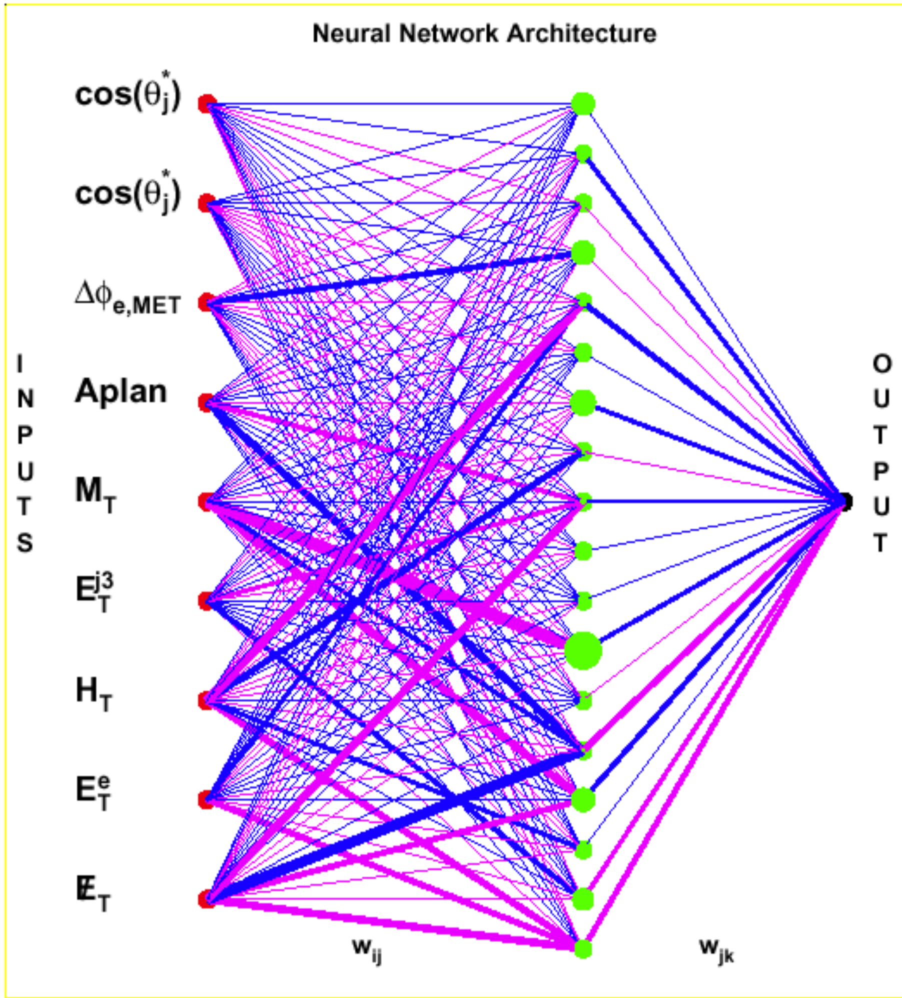
- e.g., ParticleNet - a deep graph network allowing to classify jets as t, b, c, q, g, etc.
- Deep learning based algorithms outperform dedicated taggers based on theoretical considerations
- Solved problem in particle physics; just requires further optimization and better training
- Well-understood performance, thanks to essentially infinite samples of different kinds of jets available both in MC and in data, allowing for efficient deep training and performance evaluation



Kasieczka et al., Sci. Post Phys. 7 (2019) 014

NN's: A Word of Caution

- It's very dangerous to use NNs (or other multivariate techniques) as black boxes
- Representative and large training samples are crucial, especially for deep neural networks
- Important to avoid overtraining and sculpting!
- Even complicated neural nets can be "opened" up
- Use of two-dimensional projections and other graphic tools to make sure that the NN acts reasonably
- More in Wouter's lectures



Use of DNNs in Analysis

- This is a much more debatable issue
- Unlike large training and test samples for particle ID purposes, there is only one reincarnation of the analysis
  - How do you know that a DNN hasn't picked on some artificial feature of the signal MC sample, e.g., due to a lack of higher-order corrections?
  - How do we know that the DNN is stable against small changes in the architecture?
  - Not so easy to prove that the performance is correct with simulation, especially if very large background rejection is required
- Shall be used with a lot of caution and cross checks to avoid false "discoveries"

An Example of a Poor Optimization

- A complicated search for hypothetical particles in a high-multiplicity final states in a model with several types of new particles
- Chose DNN to optimize signal against the dominant QCD background, with a lot of attention given to avoid the mass sculpting
  - Clearly optimized for a limit, not a discovery!
  - Surprise after the unblinding: a nearly 3σ excess, but no clue at what mass!
- Lesson learned: poor optimization of the analysis, not allowing to even design a dedicated analysis with future data
  - Excess is likely driven by the DNN features, but the way the analysis is done makes it very hard to cross-check the result by using simpler means

Plot from a real publication with identifiable information removed