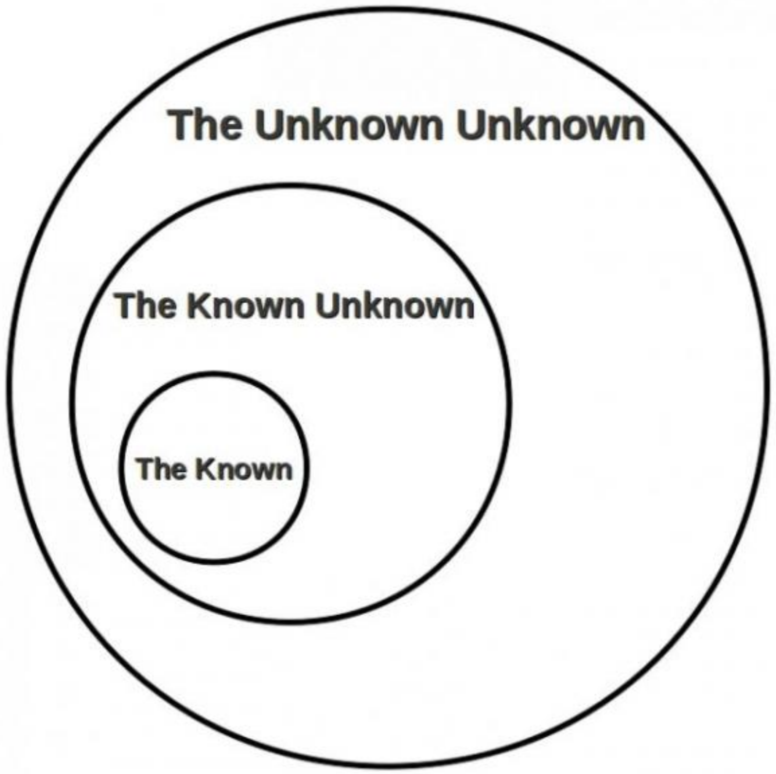
ML in (LHC) Experiments



Deep Thinking
vs
Deep Learning

Deepak Kar
deepak.kar@cern.ch

Who am I?


Gainesville, FL, USA
2003-2008
Glasgow, UK
2012-2014
Dresden, Germany
2009-2011
Calcutta, India
till 2003
Geneva, Switzerland
2011-2012
Johannesburg, SA
2015 -

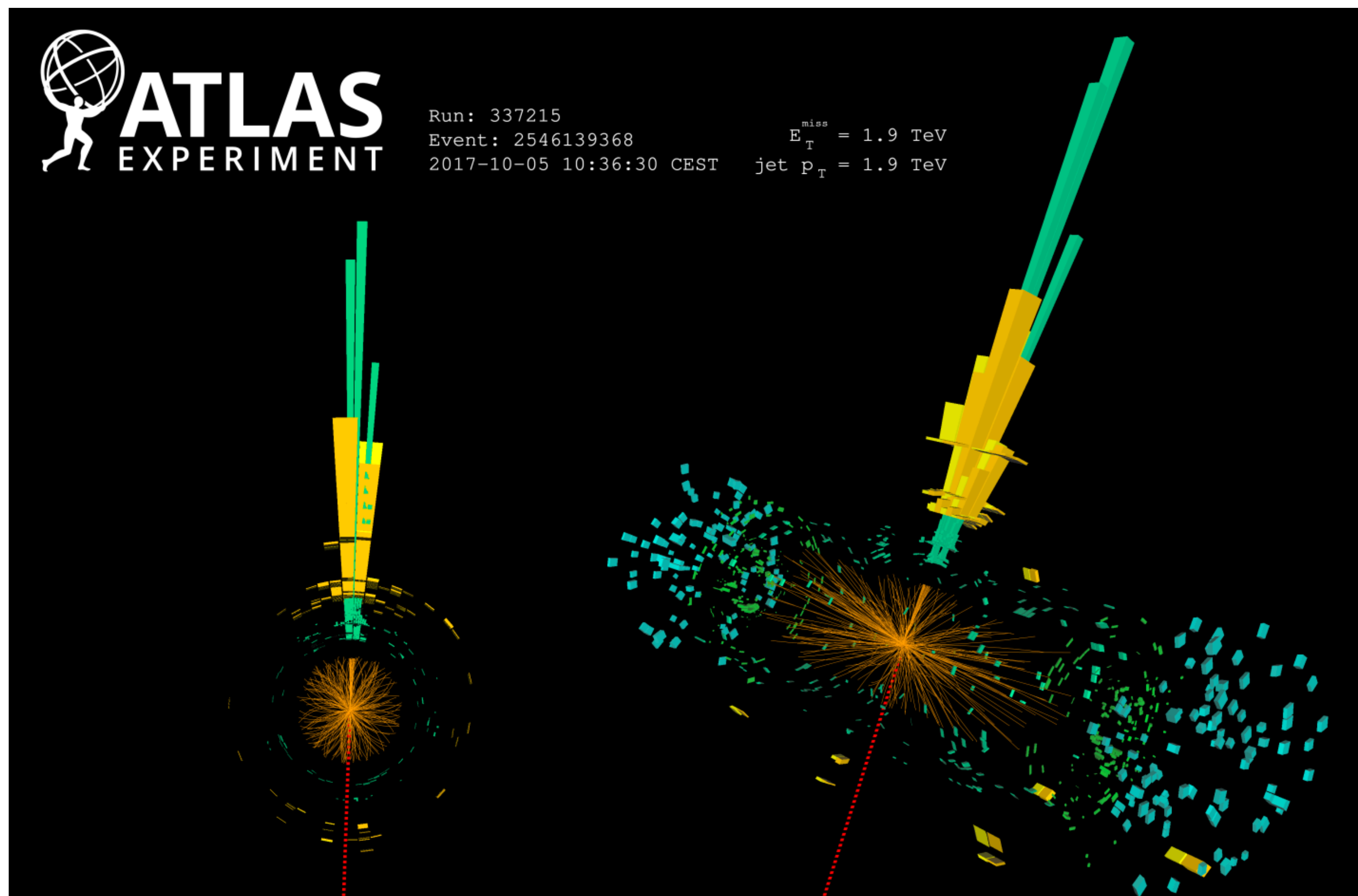
Semi-visible jets Se

Why this is novel?

So far, almost all dark matter searches in colliders are for WIMPs

So called mono-X signatures, X being any SM particle or object.

Large MET on one side!

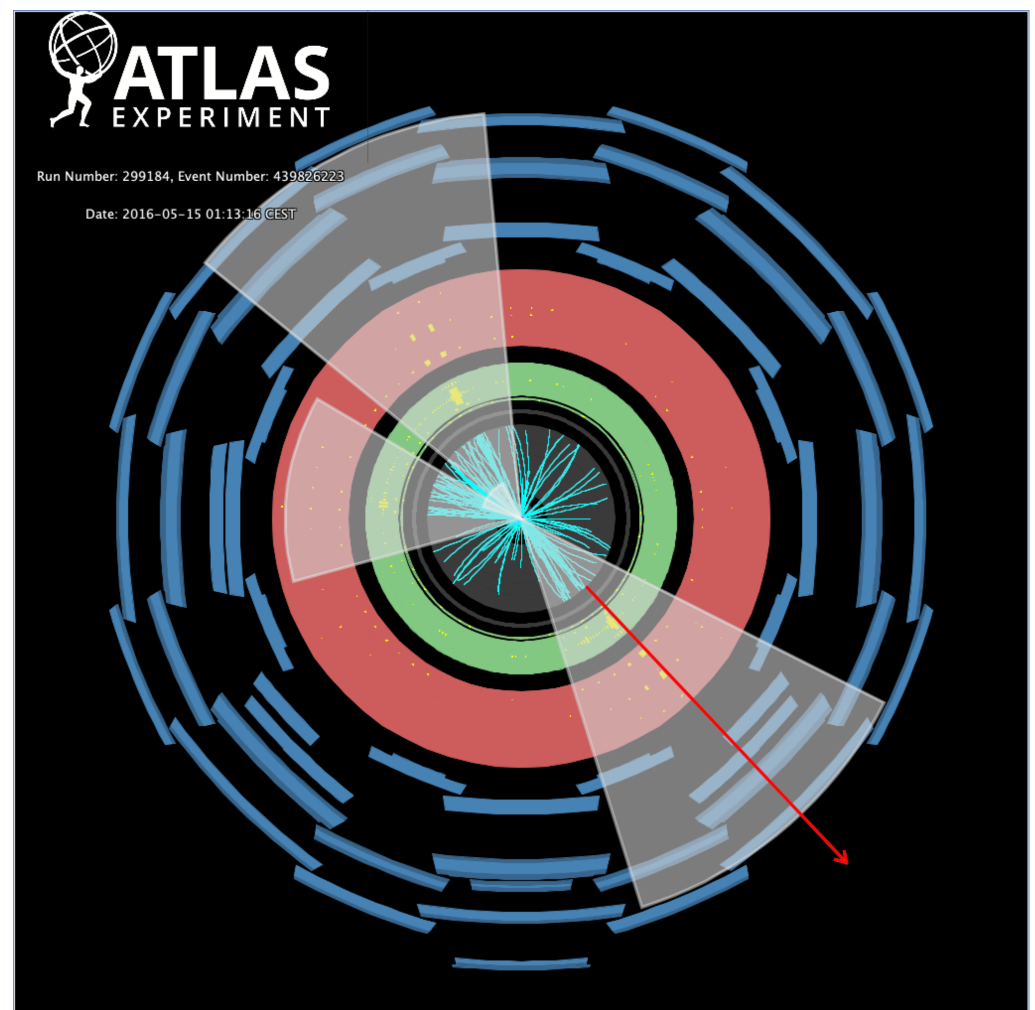


Semi-visible jets Se

Why this is novel?

So far, almost all dark matter searches in colliders are for WIMPs

We are looking for SIMPs, where the dark sector is considered A replica of QCD

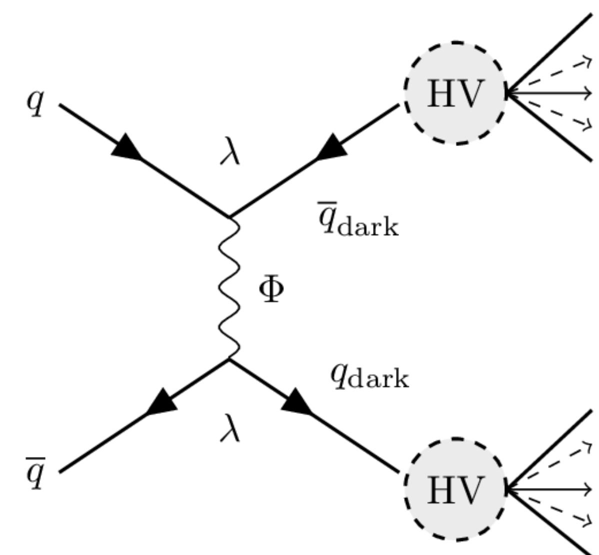


Semi-visible jets Search

Strongly interacting dark sector: bifundamental mediator acts as a portal!

Ratio of the rate of stable dark hadrons over the total number of hadrons in the event is termed R_{inv}

Simulated in Pythia Hidden Valley Module



Results in jets interpersed with dark hadrons, with missing transverse momentum direction aligned with one of the SVJs in leading order. Not so for events with extra jets and large boost.

Events with two central jets, MET trigger, leading jet p_T > 250 GeV, H_T > 600 GeV, MET 600 > GeV, jet closest to MET with $\Delta\Phi$<2

Define: SR (muon veto), and three CRs, 1L, 1L1B, $2L_5$ (with muons and b-tagged jets)

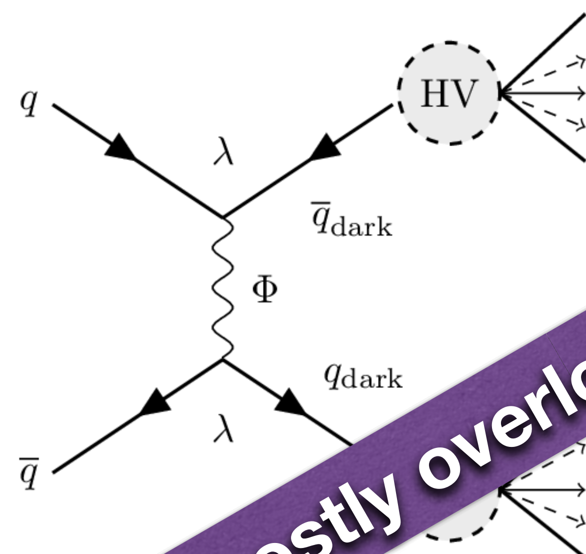
Semi-visible jets Search

Unique collider topology - mostly overlooked in searches!

Strongly interacting dark sector: bifundamental mediator acts as a portal!

Ratio of the rate of stable dark hadrons over the total numbe of hadrons in the is term inv

Si ulated in Pythia Hidden Valley Module



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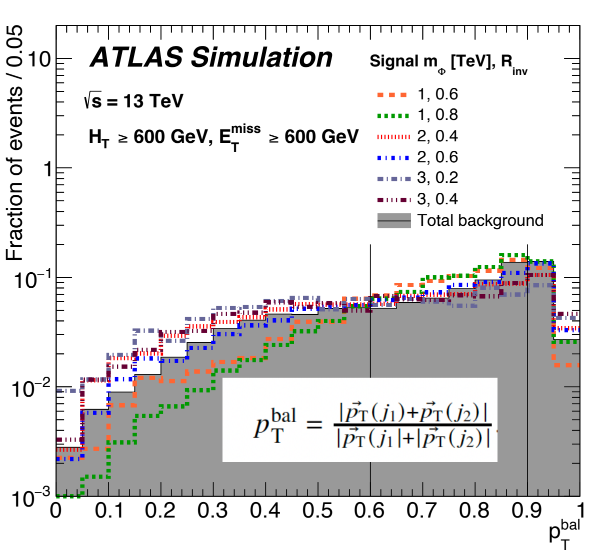
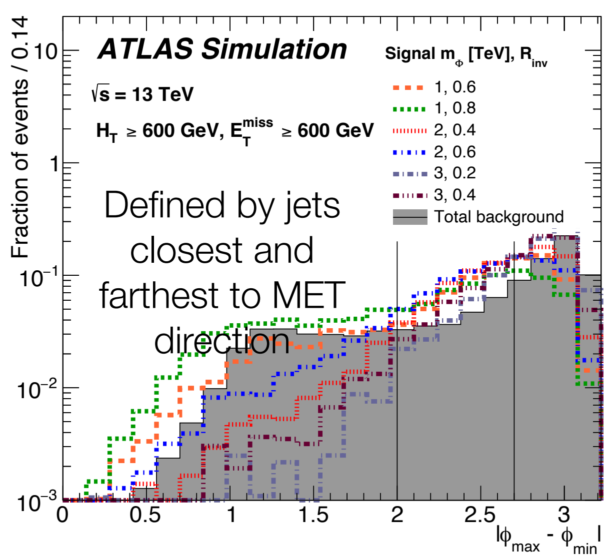
Define: SR (muon veto), and three CRs, 1L, 1L1B, $2L_6$ (with muons and b-tagged jets)

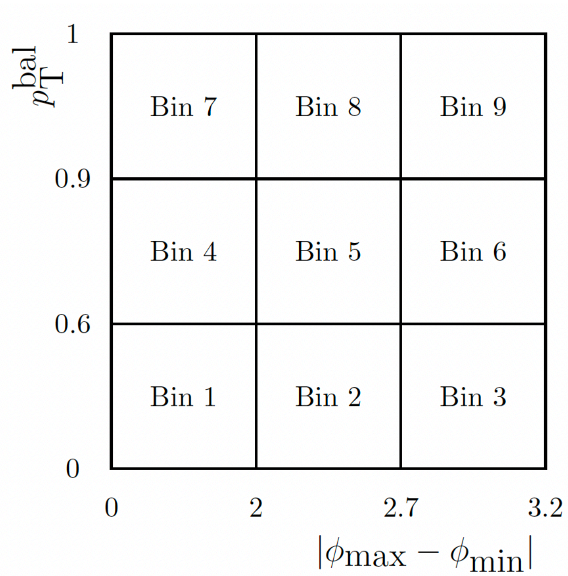
Background Estimate

Two sensitive observables:

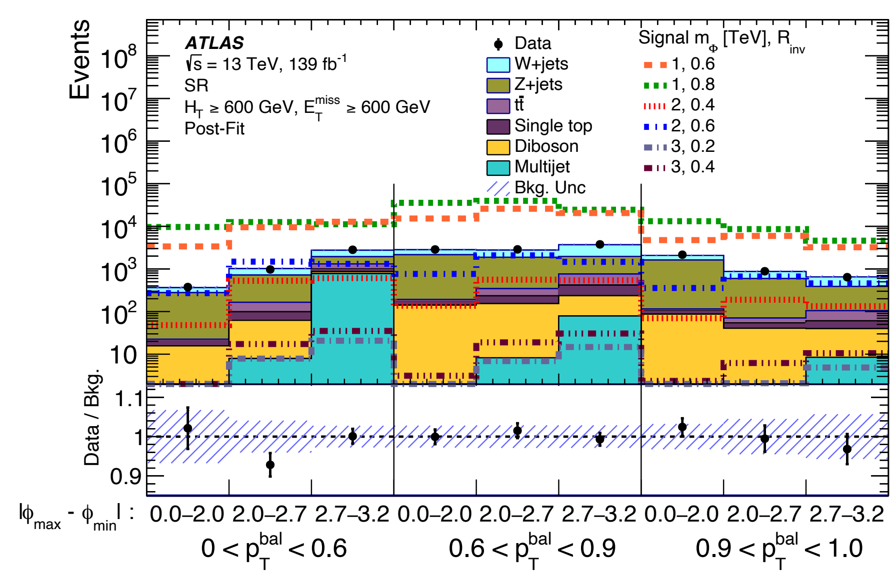




Used to Form a 9-bin grid, with yields in each bin treated as observables:



Partially data-driven method, simultaneously fit SR and three CRs to obtain scale factors for each bg process:

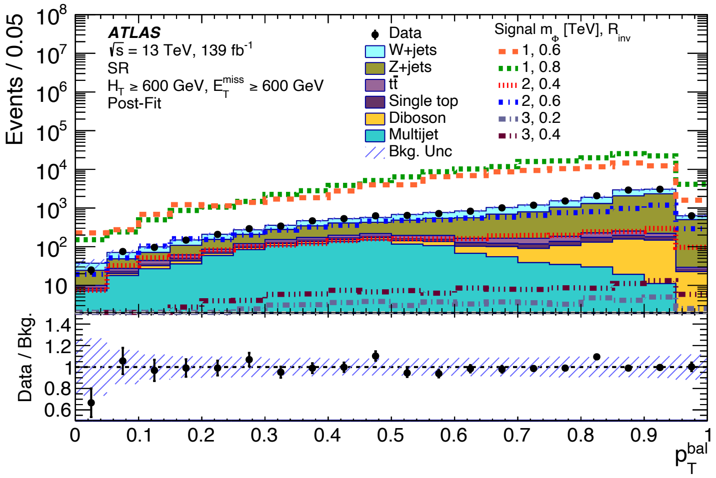


Process	k^{SF}
Z+jets	1.18 ± 0.05
W+jets	1.09 ± 0.04
Top processes	0.64 ± 0.04
Multijet	1.10 ± 0.04

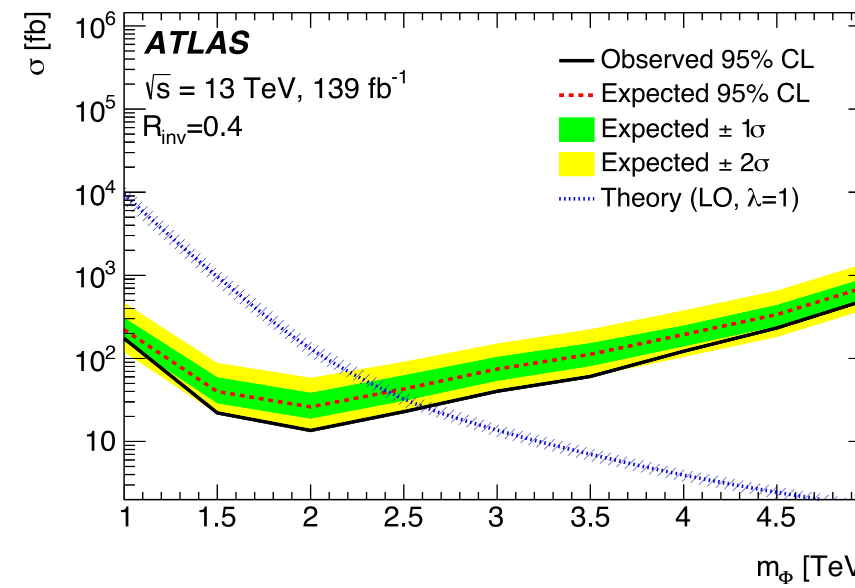
Multijet reweighed in using a dedicated VR given by MET within 250 to 300 GeV, then fitted

Absence of signal, good post-fit agreement :(

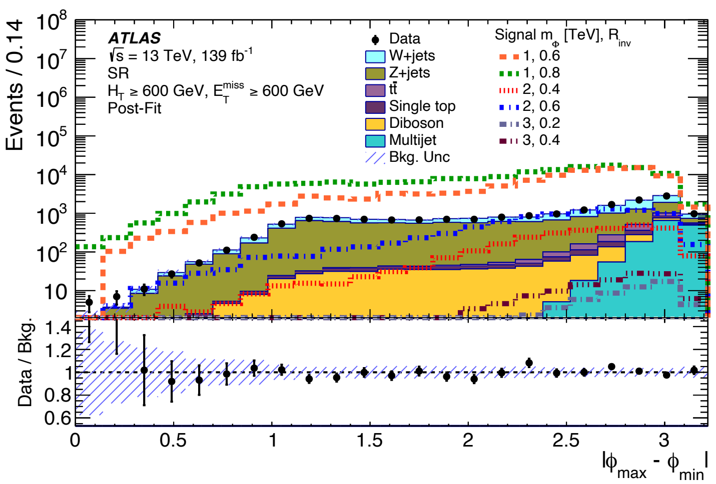
Results



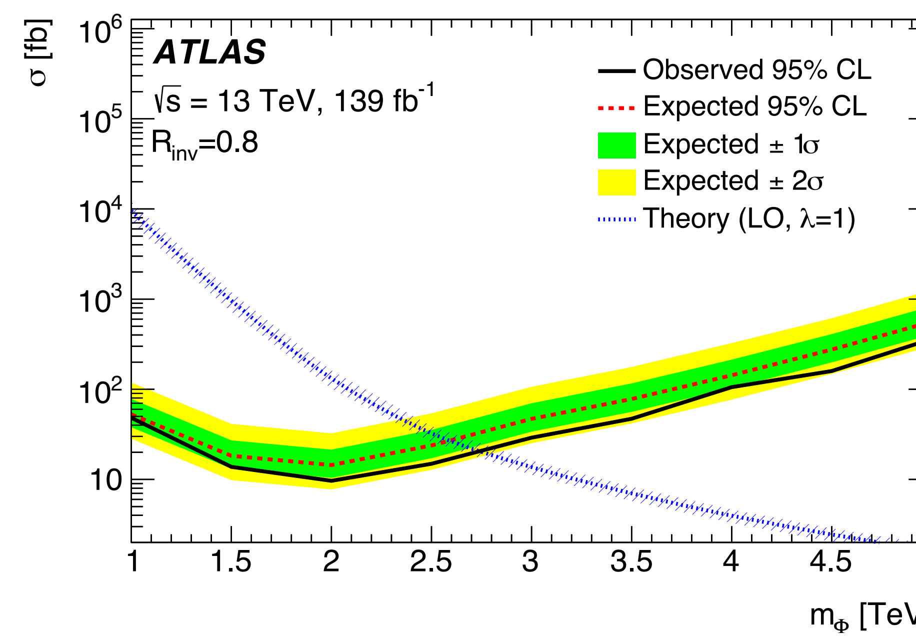
Excellent agreement between data and background prediction



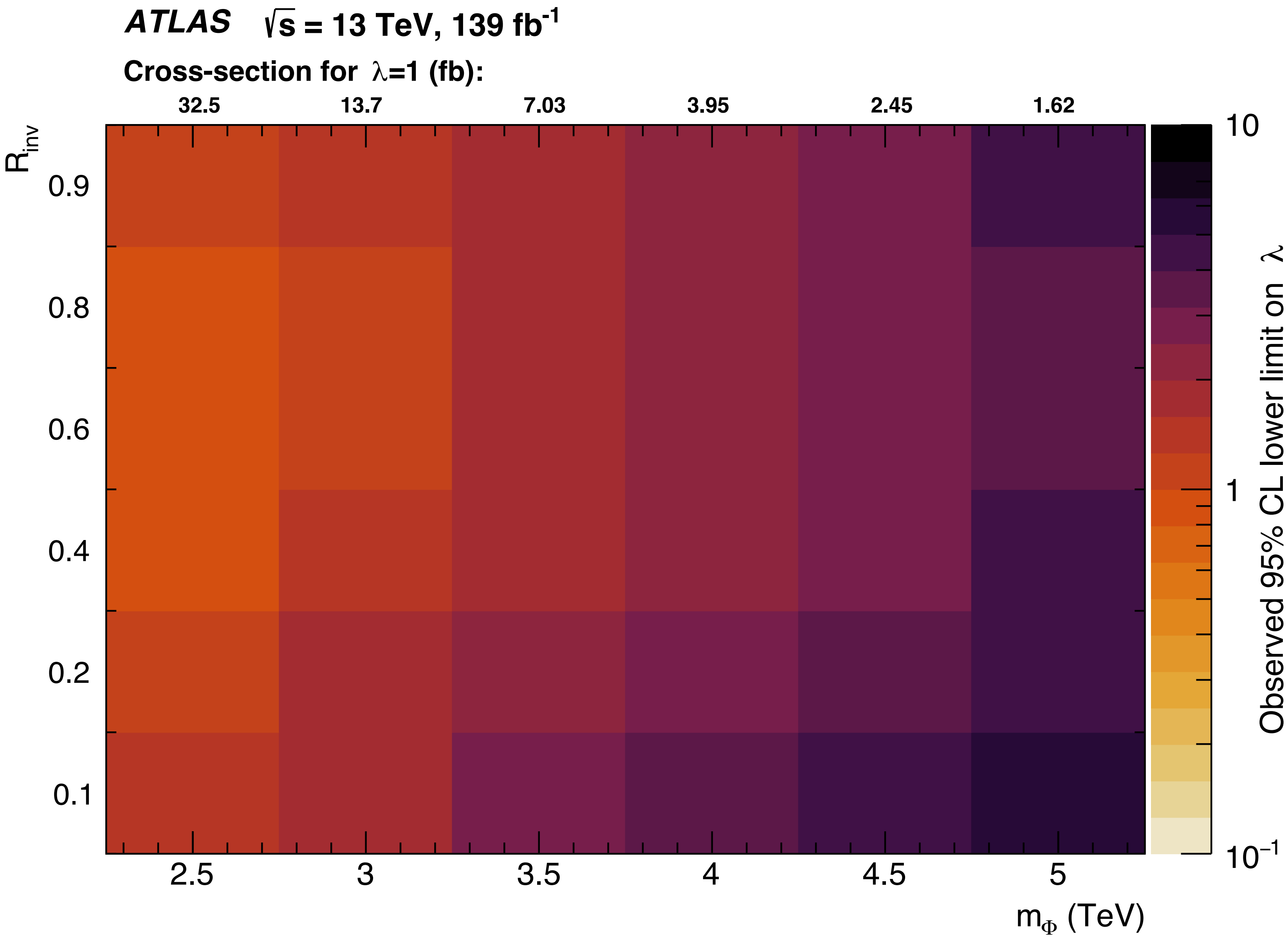
Limits on mediator mass separately for each $\boldsymbol{R}_{\text{inv}}$

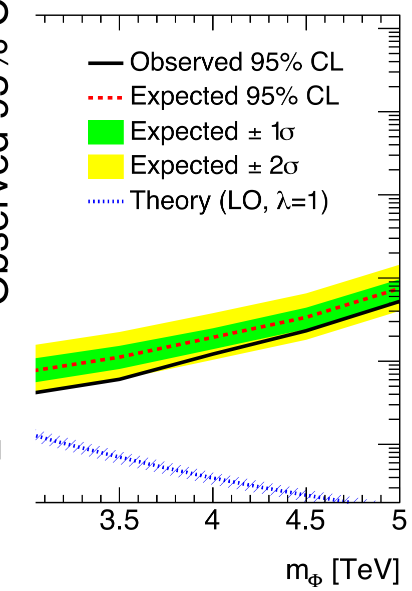


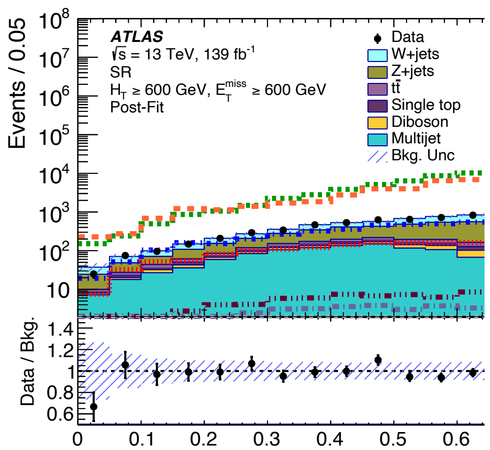
For mediator mass of 2.5 TeV or higher can also express the limits in terms of the q-q_d-$\boldsymbol{\phi}$ vertex coupling strength λ, with the XS scaling as λ^4

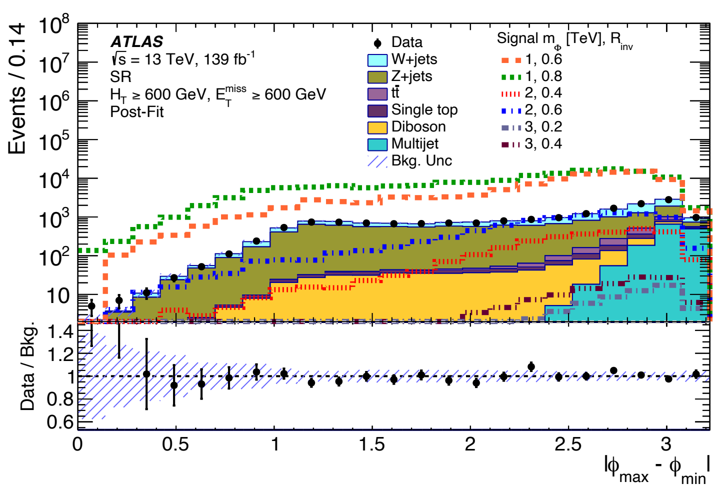


R









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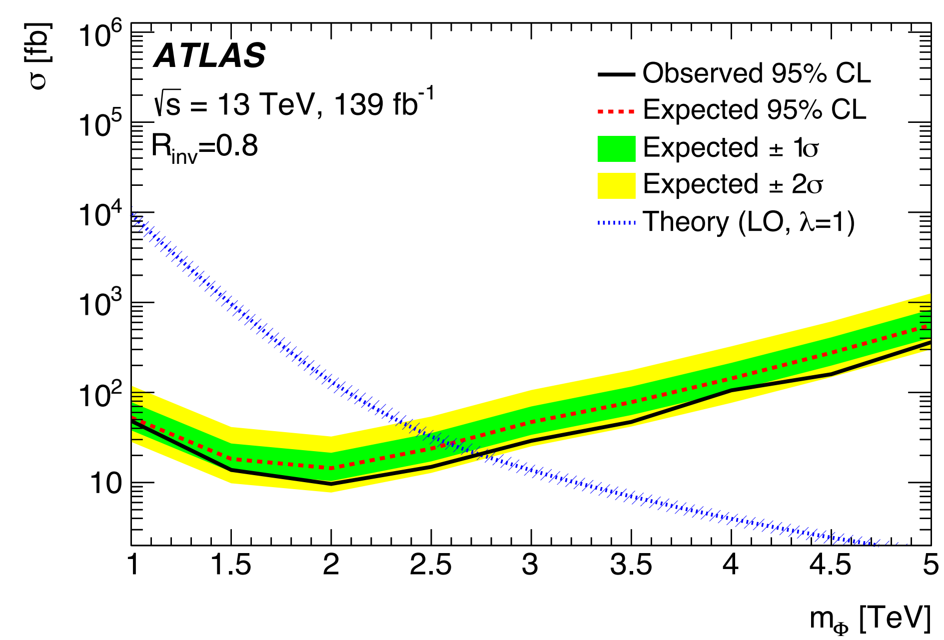

Session 1:
Setting the Scene/Objects

Poll

When was “Machine Learning” first used in (experimental) Particle Physics?

- A. Duh, during the Higgs boson discovery.
- B. Must be at Tevatron, say mid-2000’s, its always the Americans.
- C. Before I was born. Like way before that.

Poll

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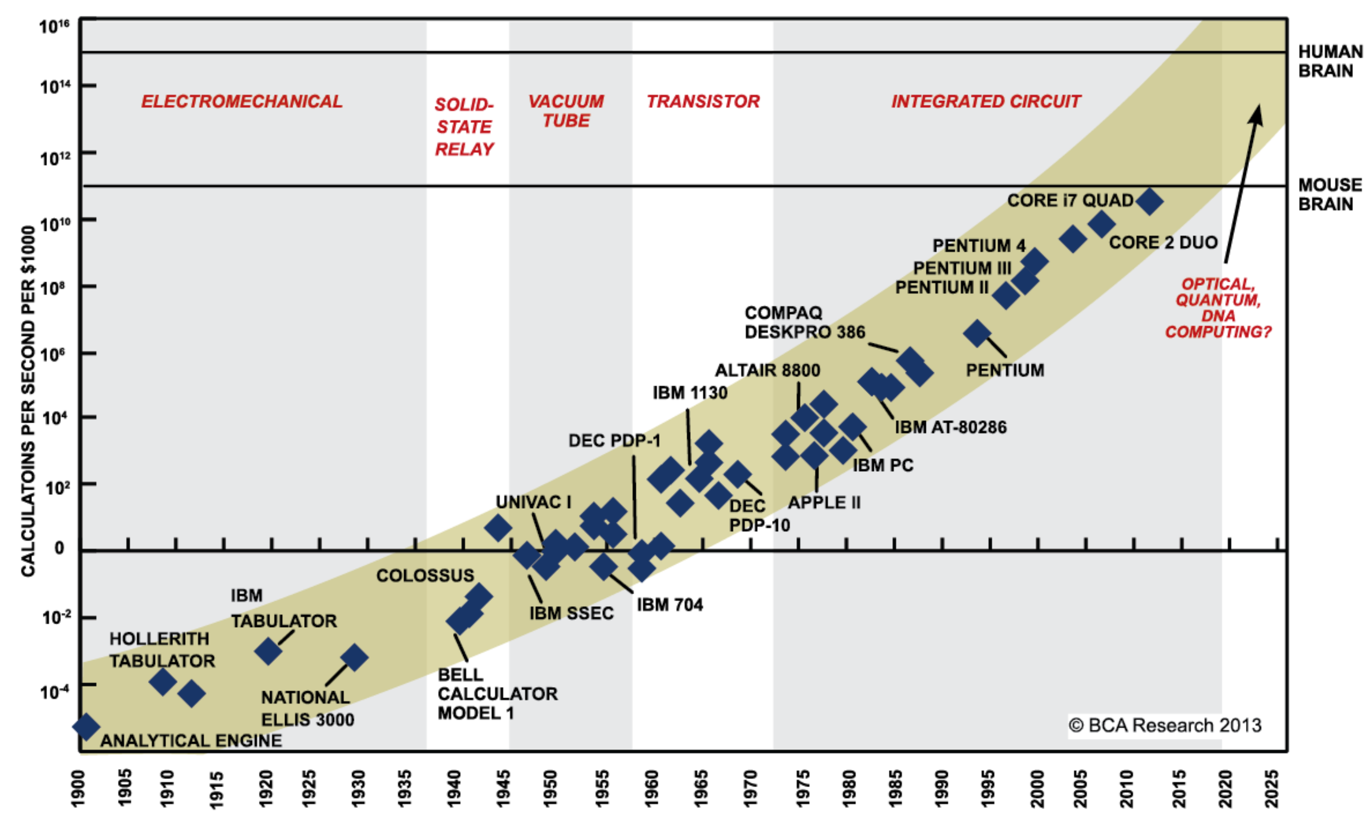
- **C. Before I was born. Like way before that.**

Machine Learning: Prologue

Moore's law: the number of transistors that can be packed into a given unit of space will roughly double every two years.

=

computing power tends to approximately double every two years



SOURCE: RAY KURZWEIL, "THE SINGULARITY IS NEAR: WHEN HUMANS TRANSCEND BIOLOGY", P.67, *THE VIKING PRESS*, 2006. DATAPOINTS BETWEEN 2000 AND 2012 REPRESENT BCA ESTIMATES.

But ...

Search for the neutral Higgs bosons of the MSSM in e^+e^- collisions at $\sqrt{s}$ from 130 to 172 GeV

The ALEPH Collaboration*)

20 June 1997

Abstract

The process $e^+e^- \rightarrow hA$ is used to search for the Higgs bosons of the Minimal Super-
symmetric Standard M
is performed in the da
energies between 130 a
events are found in eit
of 0.91 events from all S
this results in a 95% C
$\tan\beta > 1$.

3.2 b tagging neural network

Six variables which discriminate between b jets and light quark jets are combined using neural networks to tag b quark jets. The first two variables are lifetime-based; the third is based

3

on the transverse momentum of identified leptons and the last three are based on jet-shape properties. The quantities used are as follows:

1. $\mathcal{P}_{\mathrm{jet}}$: probability of the jet being a light quark (uds) jet based upon impact parameters of tracks in the jet, similar to that described in Ref. [9] with modifications for the new VDET;
2. $\Delta\chi^2_{\mathrm{svx}}$: the χ^2 difference between fitting tracks in the jet both to secondary and primary vertices compared to assuming all tracks come from the interaction point. This is based upon a secondary vertex pattern recognition algorithm which searches for displaced

The network architecture is multilayer feed-forward, consisting of four layers and is based upon the JETNET 3.4 package [12]. Detailed descriptions of theoretical aspects of neural networks are available elsewhere [13]. The neural network was trained, with the backward propagation method, using b and non-b jets in radiative returns to the Z from a sample of 400,000 Monte Carlo $q\bar{q}$ events generated at a centre-of-mass energy of 161 GeV. Radiative returns to the Z were used because the jets in such events are produced in a kinematic configuration similar to that of the signal; this was preferred to training the network using simulated signal events in order to reduce the associated systematic error in the signal efficiency.

Digging Deeper ...

LU TP 93-29
CERN-TH.7135/94
December 1993

JETNET 3.0 – A Versatile Artificial Neural Network Package

Carsten Peterson and Thorsteinn Rögnvaldsson

Department of Theoretical Physics, University of Lund,
Sölvegatan 14 A, S-223 62 Lund, Sweden

Leif Lönnblad

1993 CERN SCHOOL OF COMPUTING

Scuola Superiore G. Reiss Romoli, L'Aquila, Italy
12-25 September 1993

Neural Networks

S.R.Amendolia
University of Sassari and INFN of Pisa, Italy

Abstract

An introductory treatment of the subject of Neural Networks will be given. Topics covered will mostly be relevant for the use of Neural Networks in High Energy Physics, especially for triggering, and examples will be given of this application.

1. Basics of Neural Networks

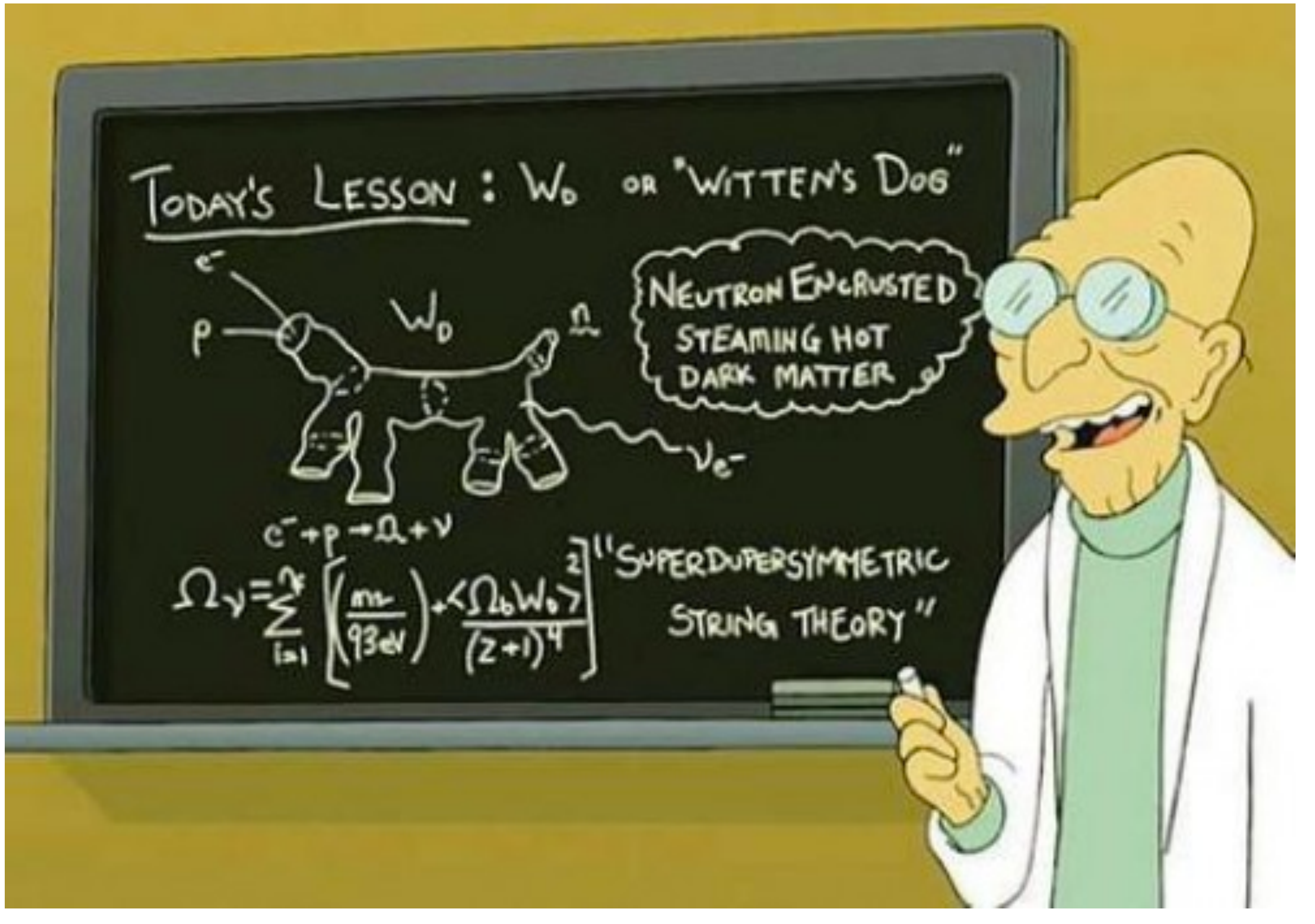
1.1 Introduction

There exist many papers and books on the subject of Neural Networks in the literature, and this cannot be an attempt at making a better or more comprehensive treatment. We send to the relevant references [1,2,3,4,5]. The difficulty in this work, compared to

CERN's Know-How

- Particle physicists were among the first to use machine learning (ML
- First AI HENP seminar in 1990
- Already in 2010, the CMS and LHCb experiments successfully introd
  system
- Higgs boson discovery earlier than expected (2012), also with help of ML

What you do/want to do?



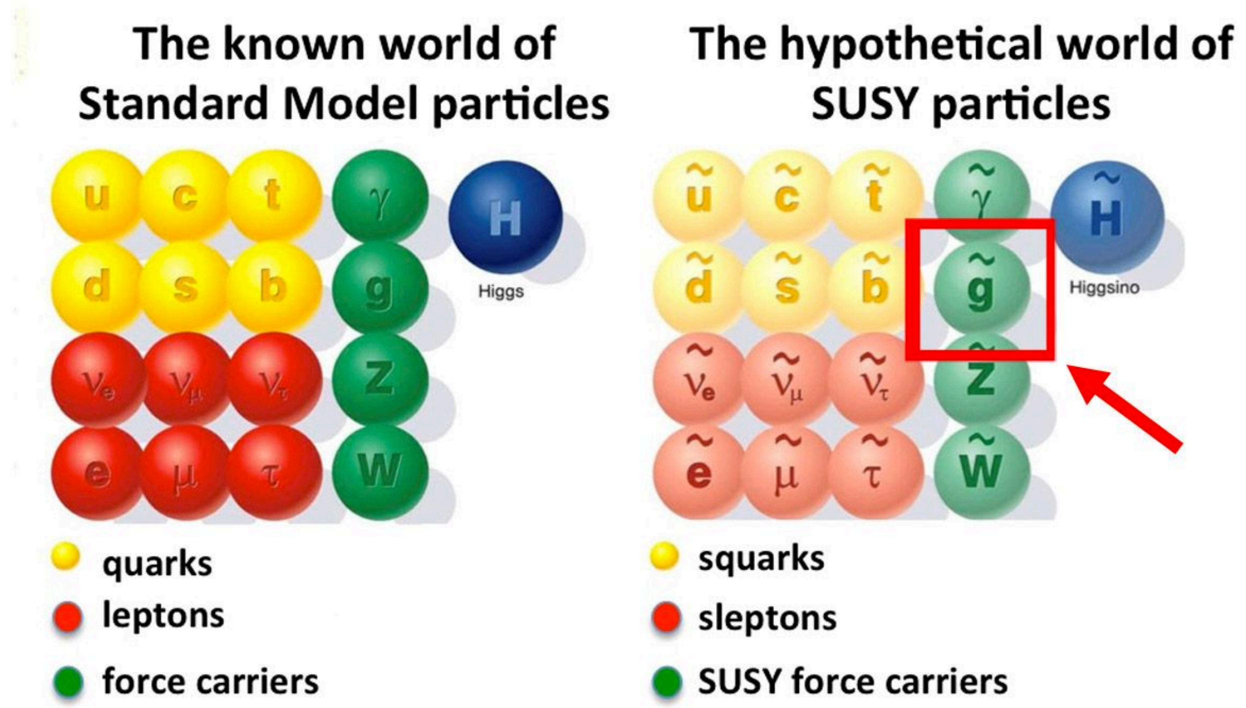
What we do/want to do

Steps from a model/calculation to experimental (non) observation

Searches: two broad (overlapping) categories …

Theoretical model driven

- SUSY
- UED incl QBH
- Compositeness
- LRSM



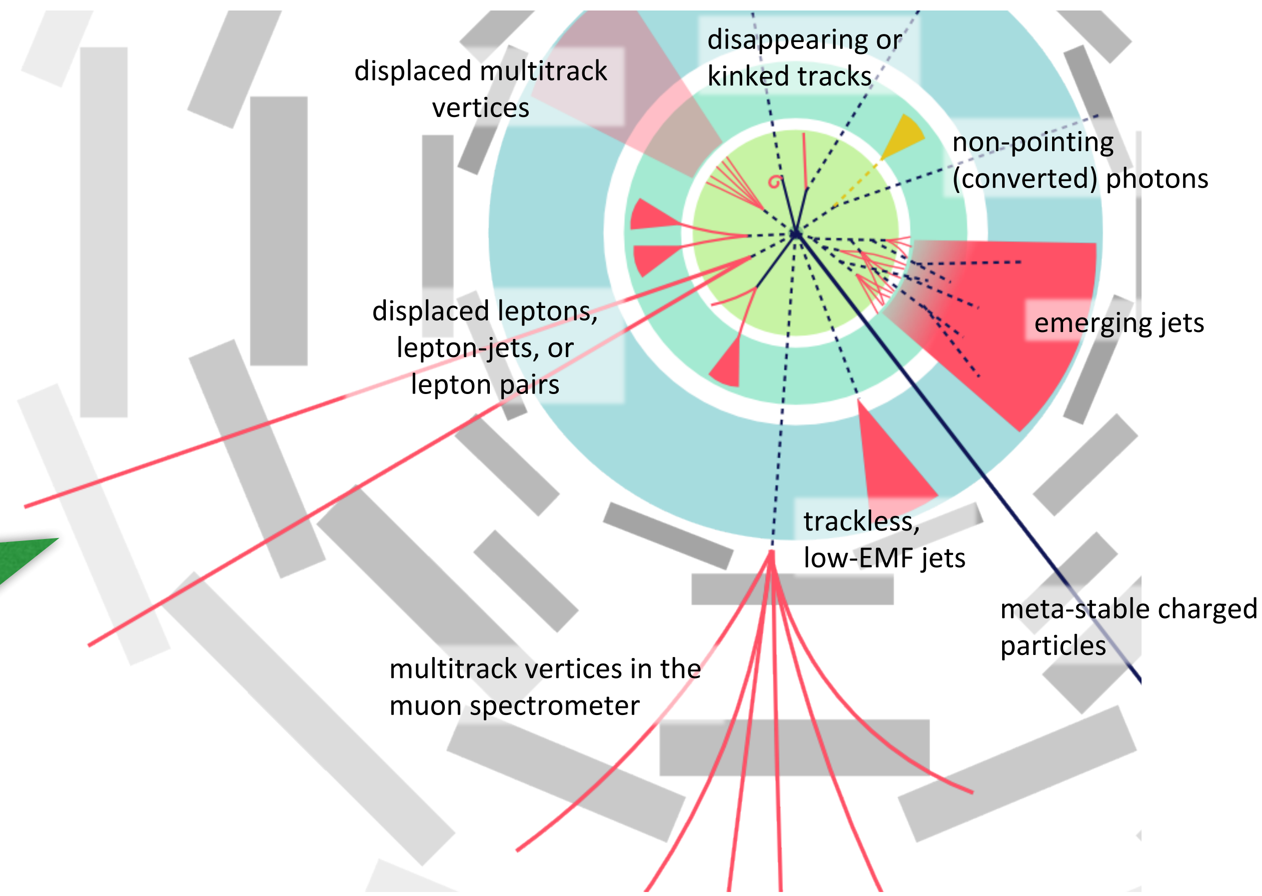
We can only exclude based on what our detectors see!

Phenomenological model/signature driven

- DM/WIMP: mono-*everything*

+ SIMP!

- Dark Photon
- Extended Higgs sector: 2HDM
- 4th generator quarks/top partners
- Leptoquarks
- Heavy W' or Z'
- Diboson resonances
- LFV
- LLP

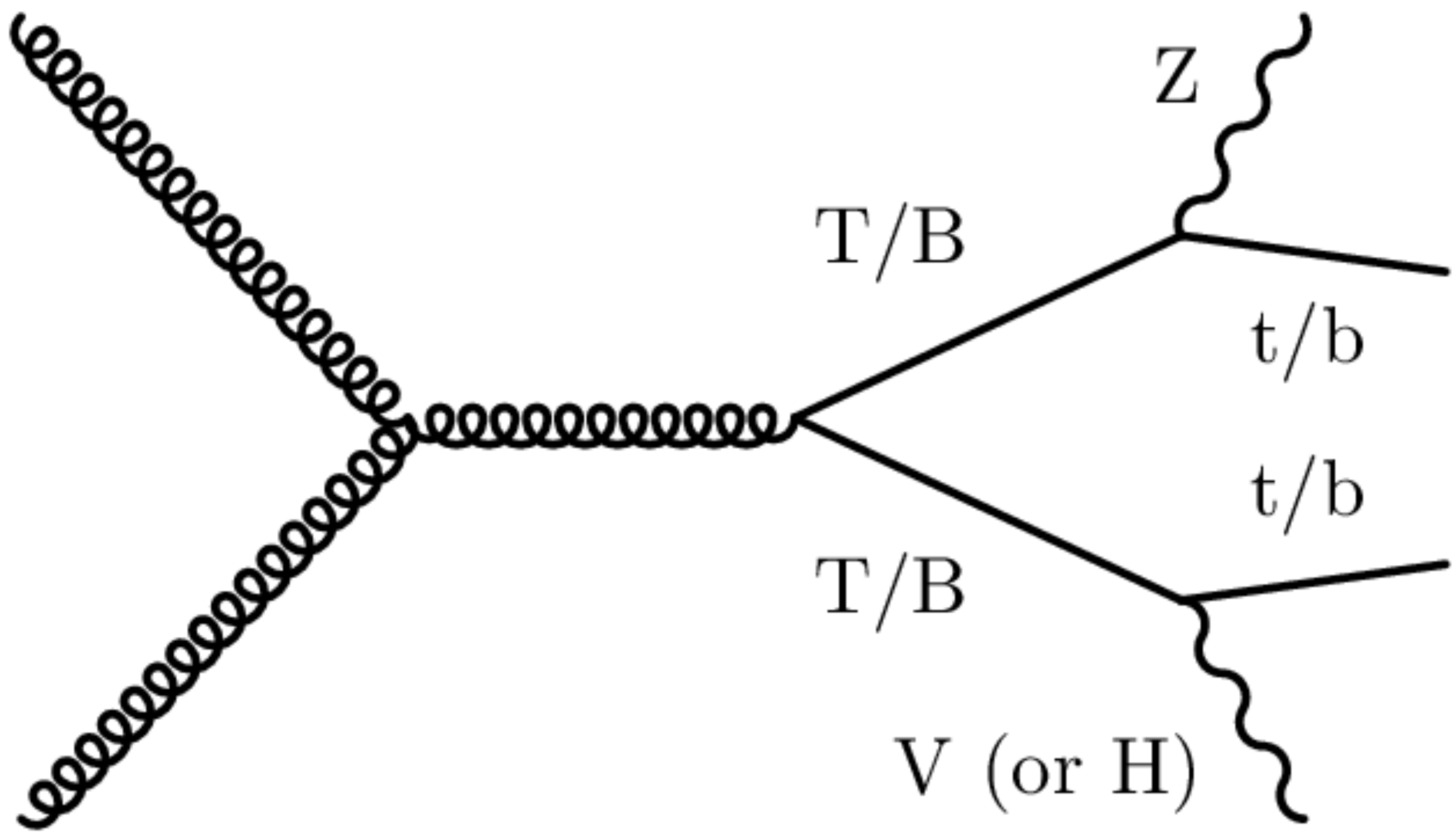


Let's start with an example:

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2018-58/

Search for:

Pair production of VLQs

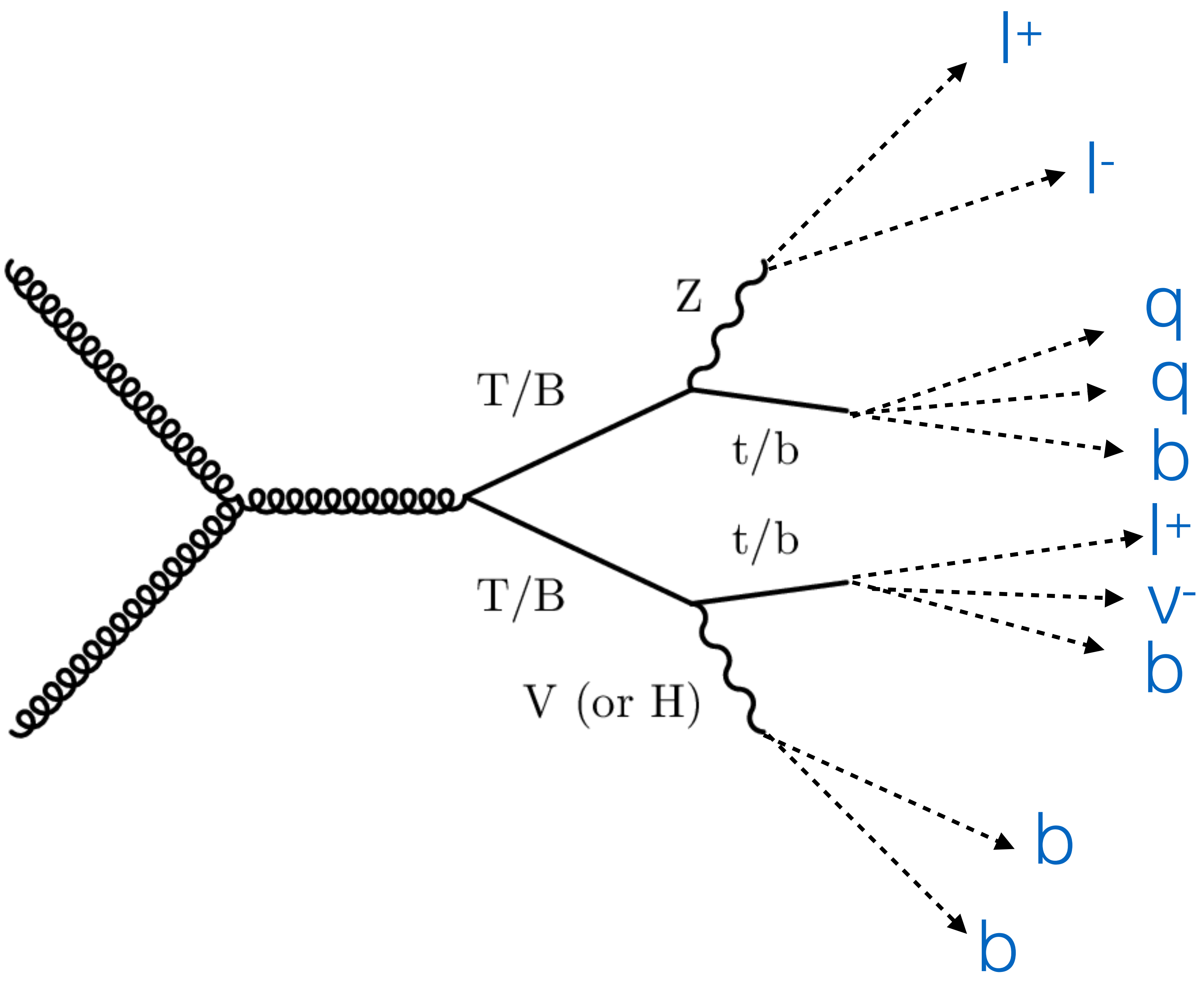


Question: what would we see in the detector?

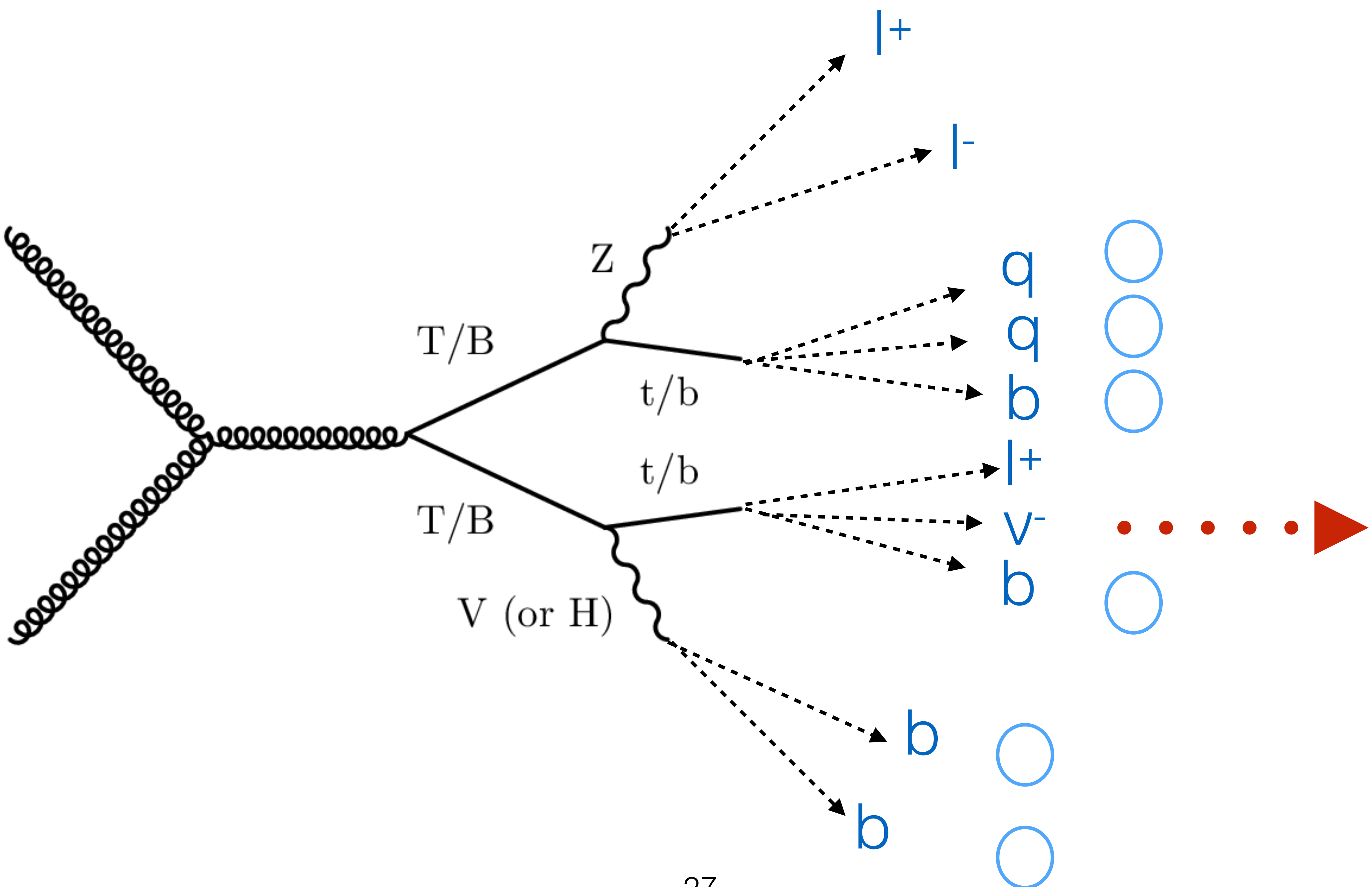
What you see is not what you have!

- We don't get what is coming out of the collisions.
- Finite lifetime of particles, decays before reaching the detector.
- Detectors have finite resolution, less than perfect response and efficiency.

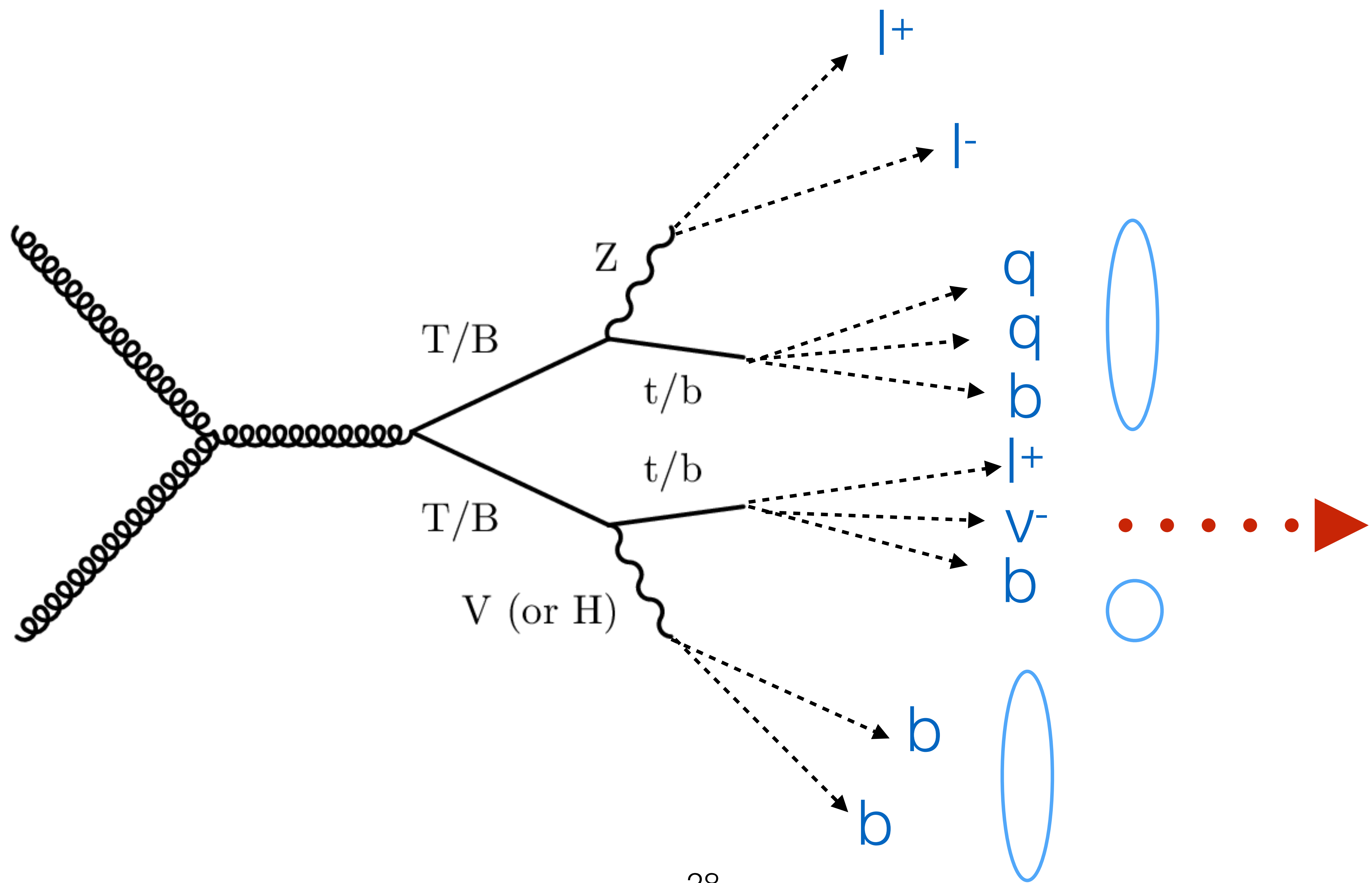
Decays:



Decays: Detector Objects



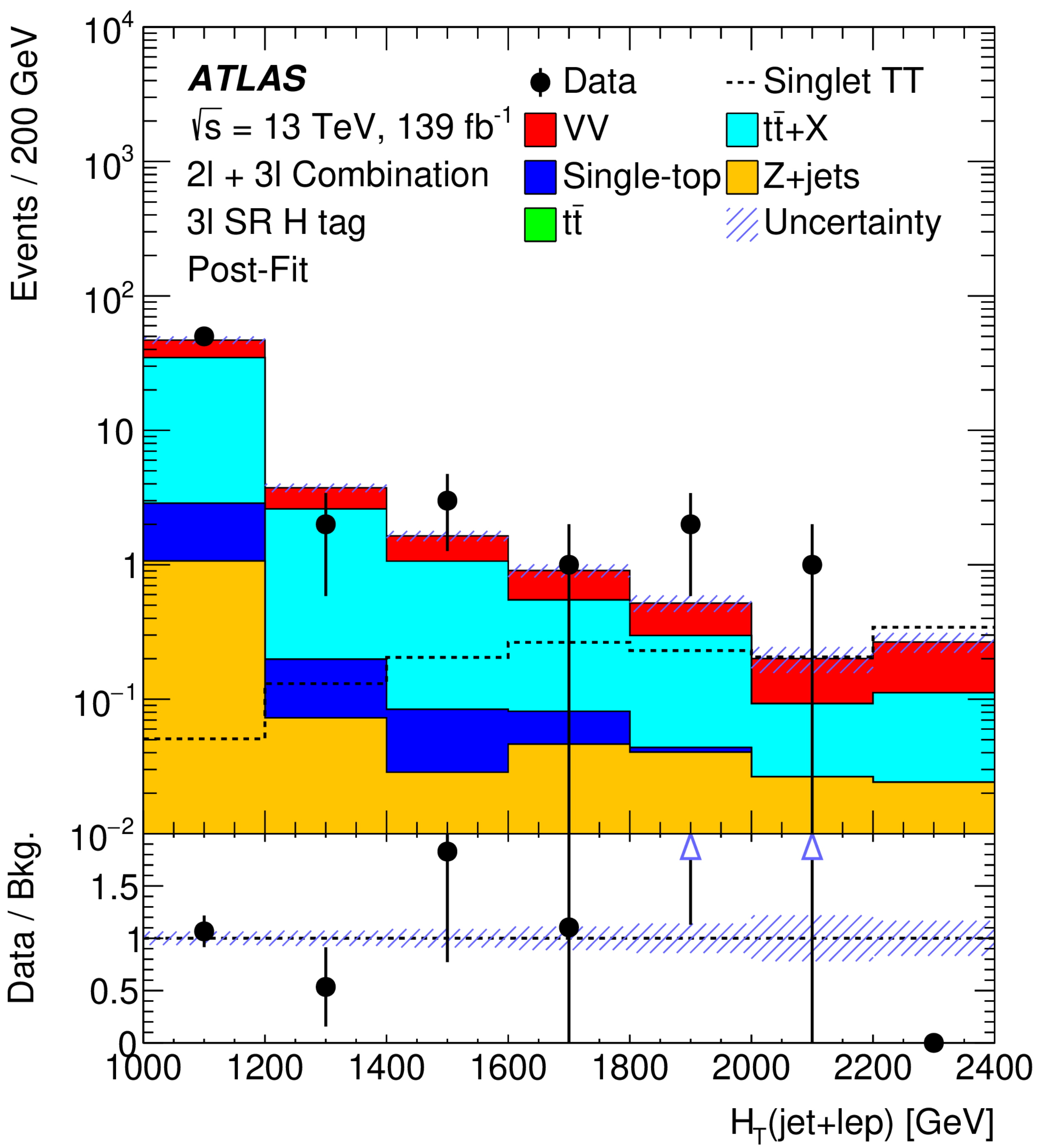
Decays: Detector Objects



Details

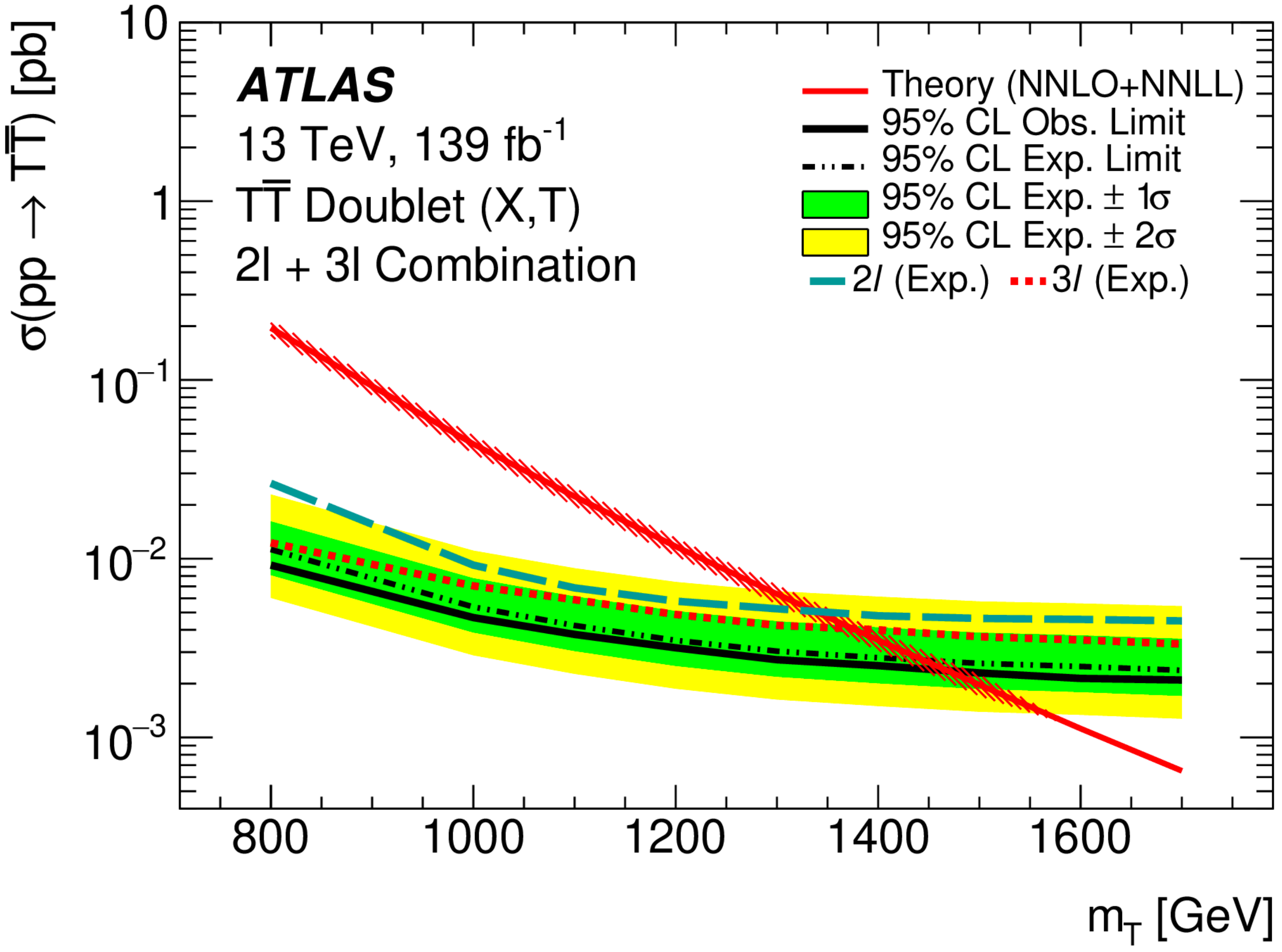
Preselection	≥ 2 central jets at least two SF leptons with $p_T > 28$ GeV at least one pair of OS-SF leptons $\lvert m(\ell\ell) - m_Z \rvert < 10$ GeV					
Channel definitions	2ℓ $= 2\ell$ $p_T(\ell\ell) > 300$ GeV $H_T(\text{jet}) + E_T^{\text{miss}} > 920$ GeV				3ℓ $\geq 3\ell$ $p_T(\ell\ell) > 200$ GeV $H_T(\text{jet}+\text{lep}) > 300$ GeV	
Region definitions	$1b$ SR	$2b$ SR	$1b$ CR	$2b$ CR	SR	VV CR
	$H_T(\text{jet}) + E_T^{\text{miss}} > 1380$ GeV		$H_T(\text{jet}) + E_T^{\text{miss}} < 1380$ GeV		–	–
	$= 1$ b-jet	≥ 2 b-jet	$= 1$ b-jet	≥ 2 b-jet	≥ 1 b-jet	$= 0$ b-jet
MCBOT categories	7	7	–	–	5	–
Fitted variable	$m(Zb_1)$	$m(Zb_2)$	$H_T(\text{jet}) + E_T^{\text{miss}}$		$H_T(\text{jet}+\text{lep})$	

From this:



Construct observables,
Signal and Control regions,
estimate background…

From this:



Discover or set limits: When signature of a new model is not found, the model is excluded up to a certain parameter value

Presented in terms of 95% confidence level, which the associated probability of that observation being correct 95% of the time. In other words, if the measurement is made repeatedly on independent datasets, the measured value will be obtained at least 95% of the time.

Components of a limit plot

- Expected line: from MC simulation (SM), usually using same luminosity as data. The 1 and 2 σ bands are from MC uncertainty. (Brazil plot!)

- Observed line: from data, actual number of events seen, with statistical uncertainties. It is expected to stay within the expected bands if the simulation is accurate.

- Theory line: calculated from new model, often with associated systematic uncertainties.

Interpreting a limit plot

- As long as the expected and observed lines are below the theory prediction, the conclusion is no evidence of the new particle is seen. By this argument, the expected and observed limits are respectively 5.1 and 5.2 TeV, from where the theory prediction line intersects the expected and observed lines. If at any point, the observed line goes beyond the expected brazil-bands, that may indicate data contains more events than SM predicts. However, the threshold for an observation is 3σ and a discovery is 5σ. Only in the region where observed is higher than the theory line, and beyond the statistically allowed deviations from expected, this particular new model can be confirmed.

An Aside: Why Limits?

We all want to find new physics.

An Aside: Why Limits?

We all want to find new physics.

But out of 100 new physics models, at least 99 are wrong, possibly all 100 are!

So null results also tell us a lot.

And techniques/methods developed can help in a future discovery!

Recap:

- Reconstruct objects from detector information
- Decide on sensitive observables for the specific final state we are interested in
- Estimate (SM) background
- Look for new physics/*measure at particle level*

One collision == EVENT

Outcome of the collisions is probablistic, no exhaustive list of possibilities!

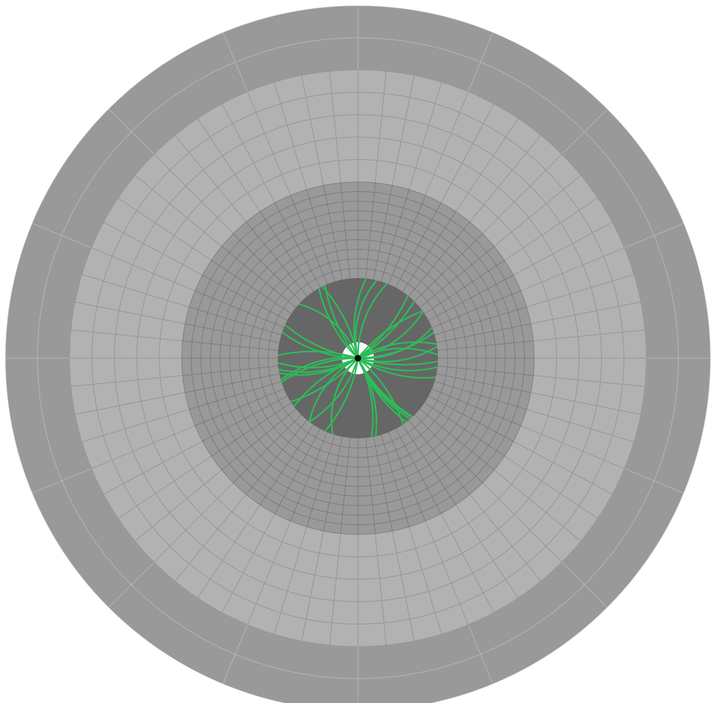
Cross section: how often a particular process occurs, measured as an effective area the target particle presents to projectile particles.

Actual number for a process:

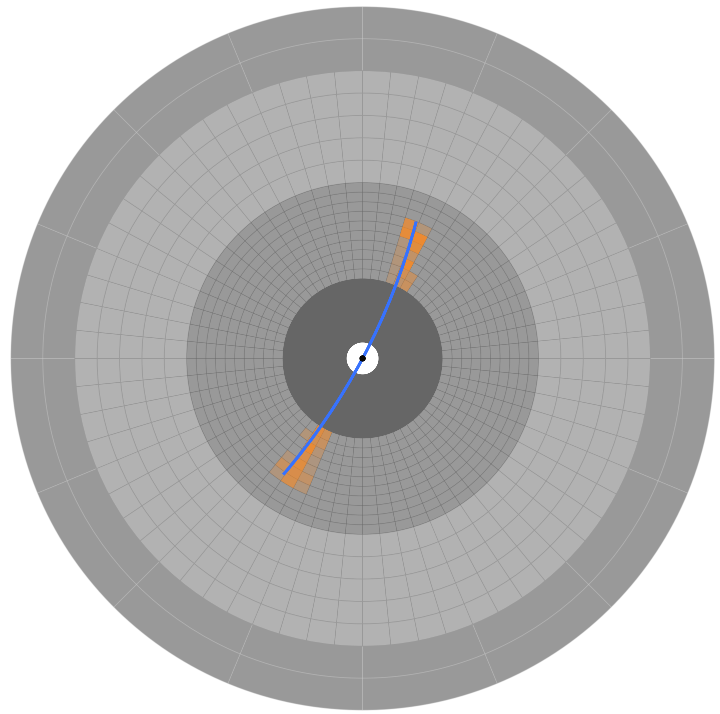
$$N_{process} = \sigma_{process} \int L dt$$

Luminosity measured in units of 1/area

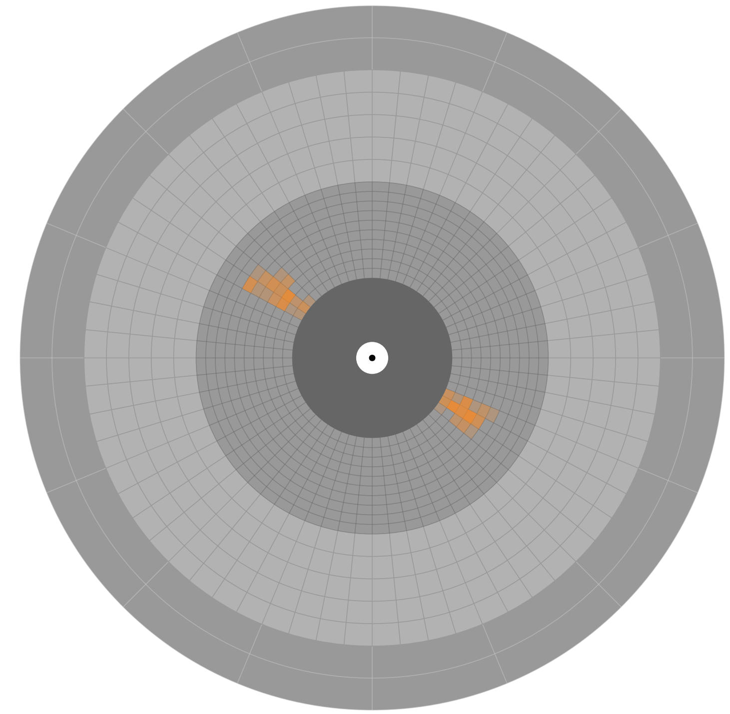
Objects from Collisions



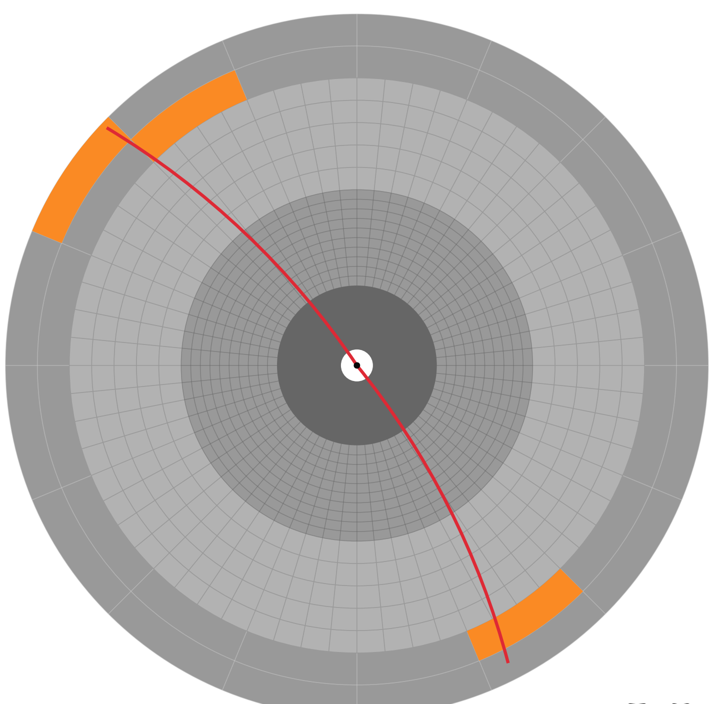
Charged particles



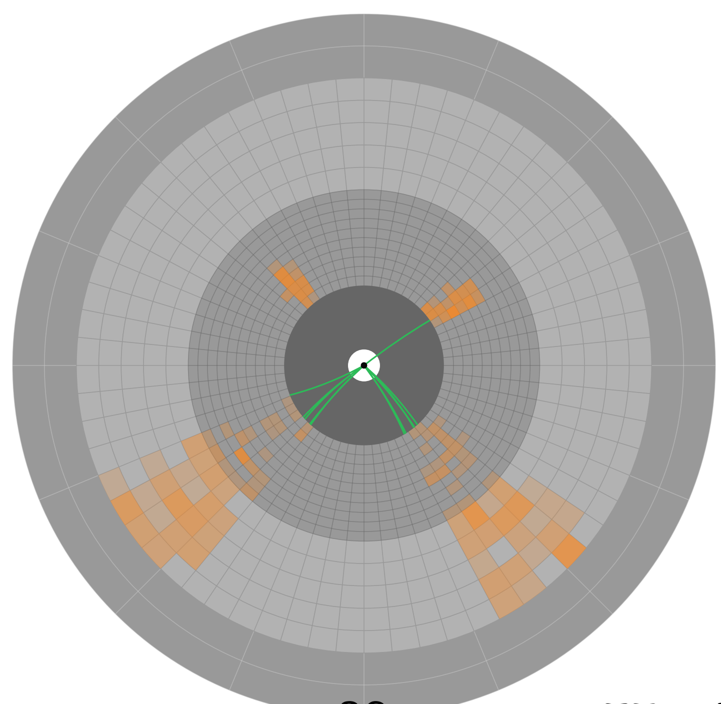
Electrons



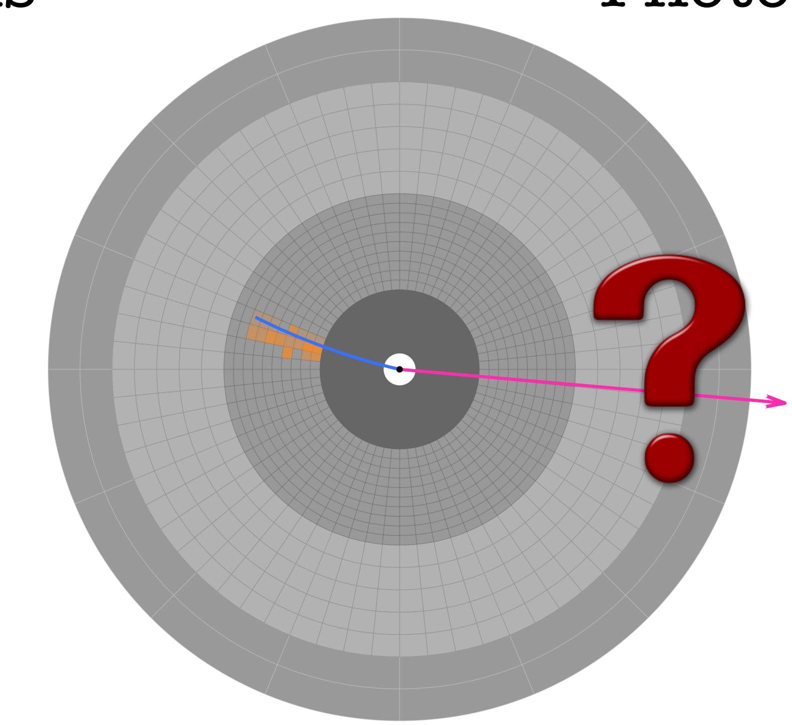
Photons



Muons



Hadrons



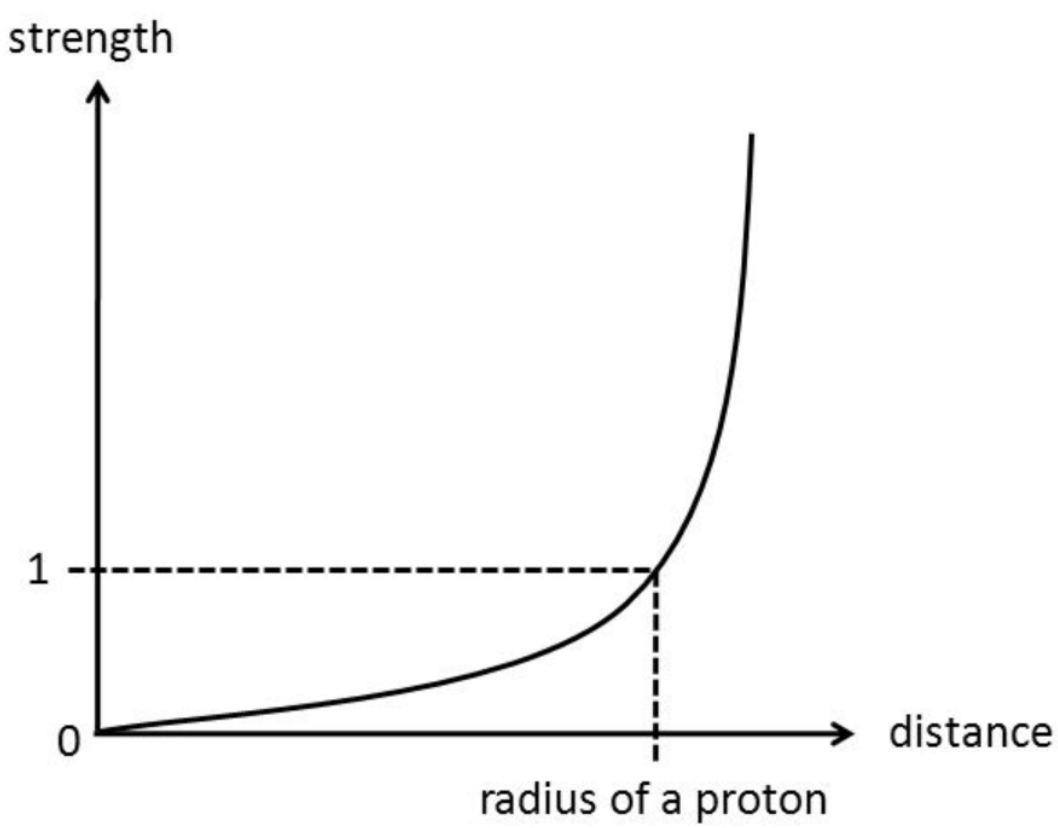
Neutrinos

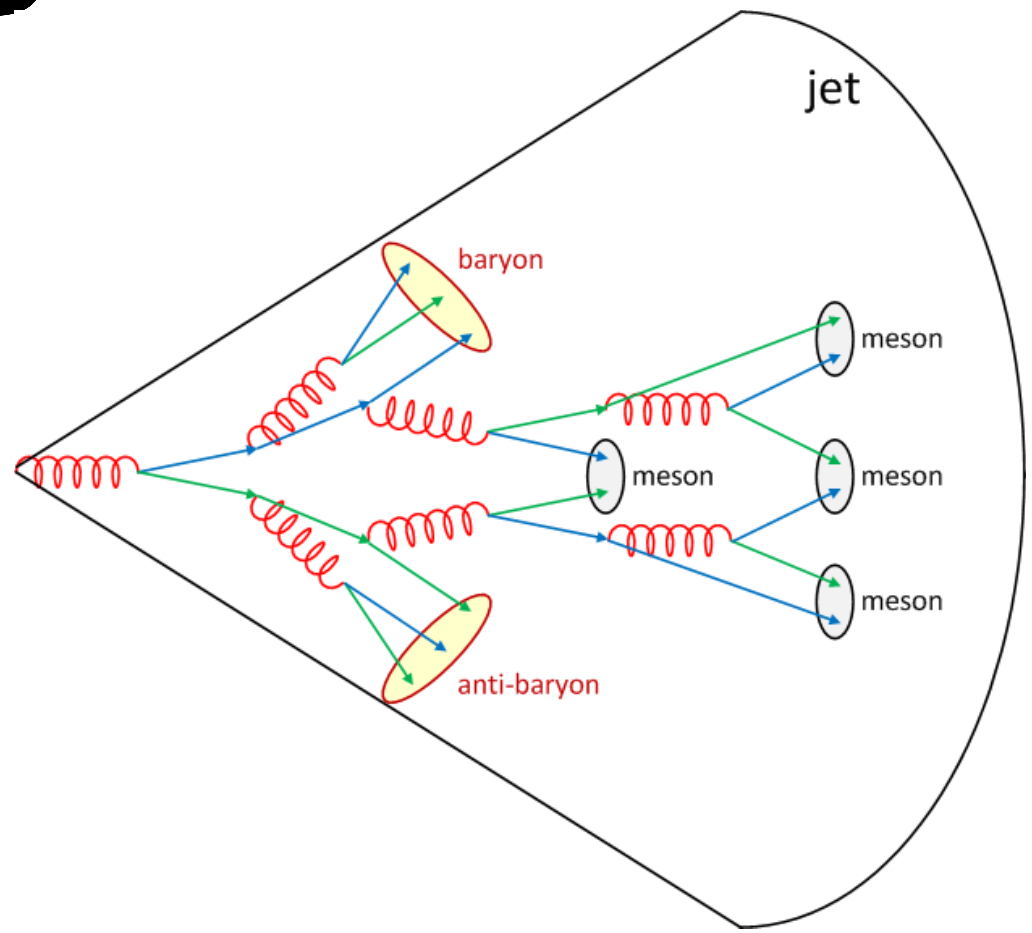
Missing (Transverse) Energy

- Do not interact with the detector
- Imbalance of p_T
- Can be signs of new physics as well!

Only invisible SM particles are the neutrinos.
DM, SUSY particles have not been seen yet!

Jets

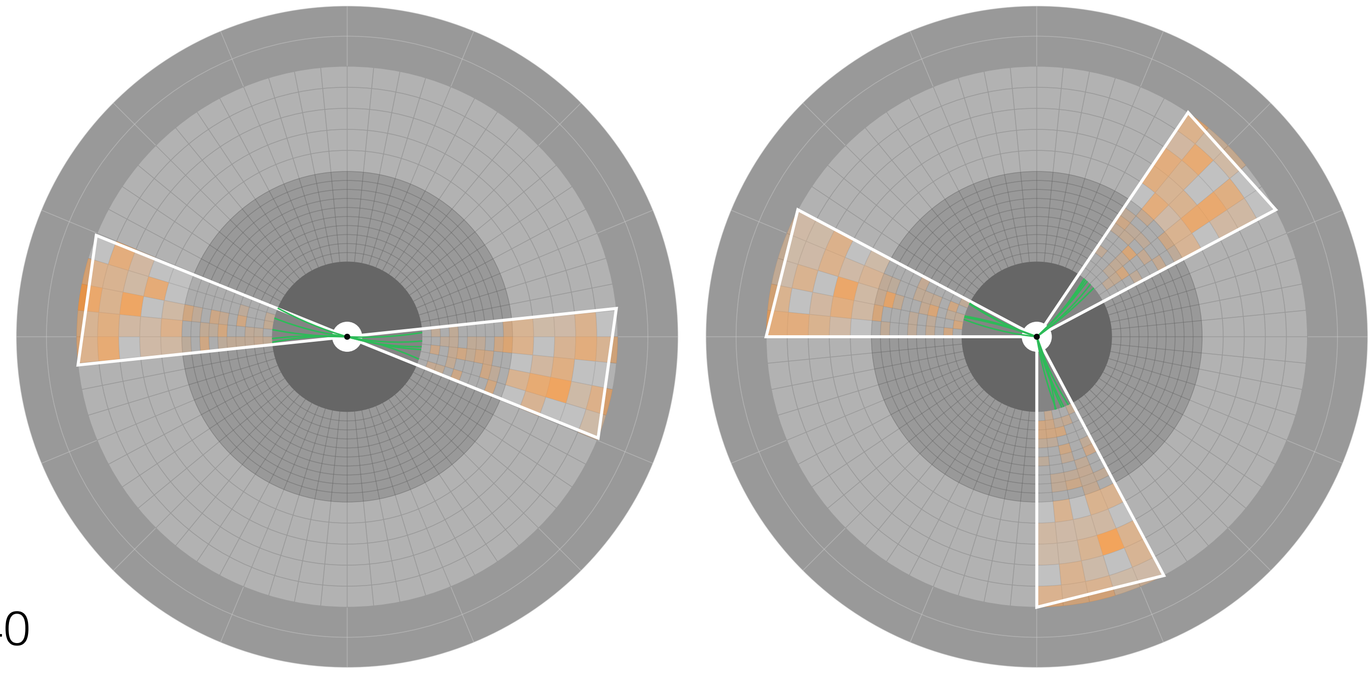


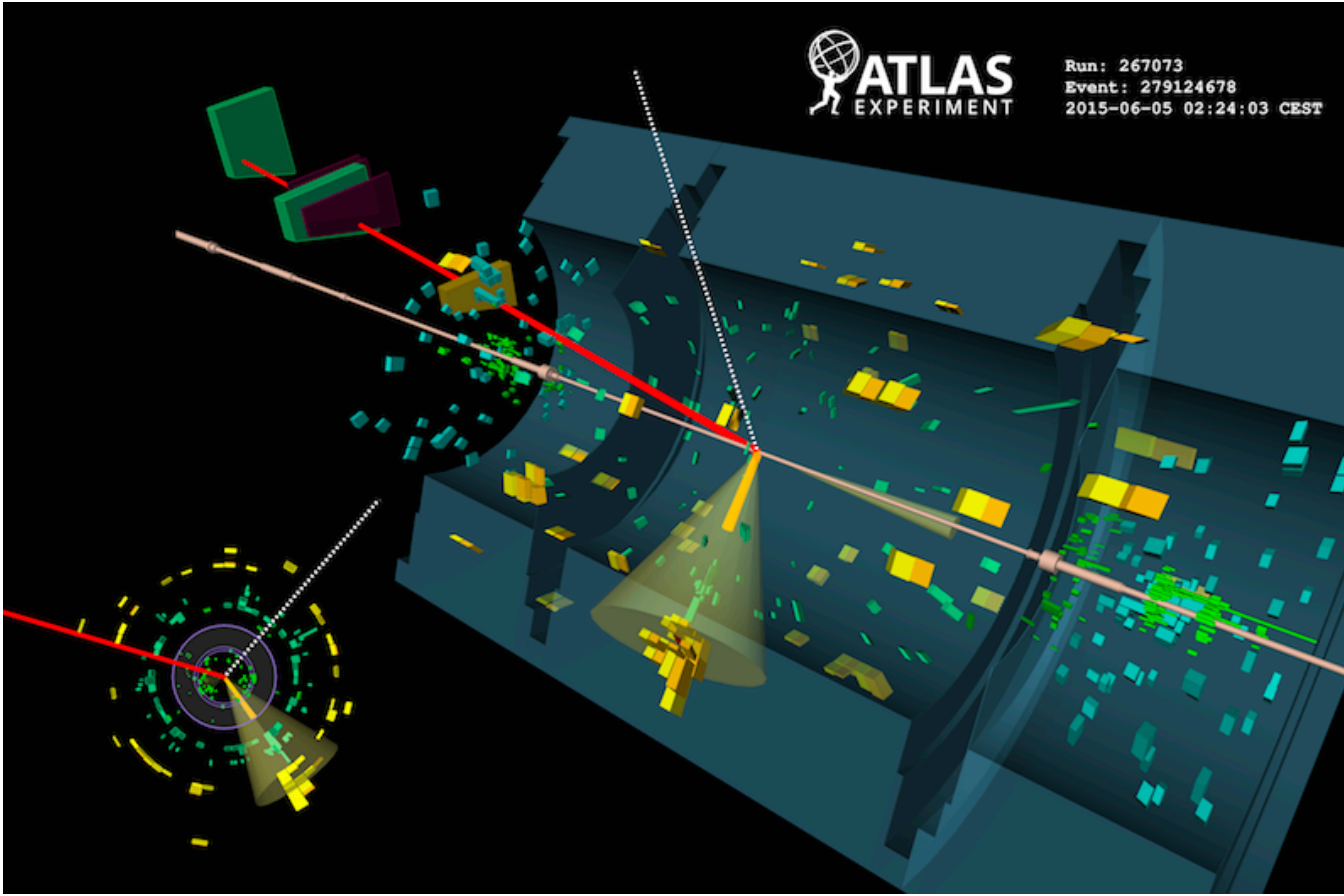


Strong interaction works like a rubber band!

No free quarks/gluons!

Collected in jets!

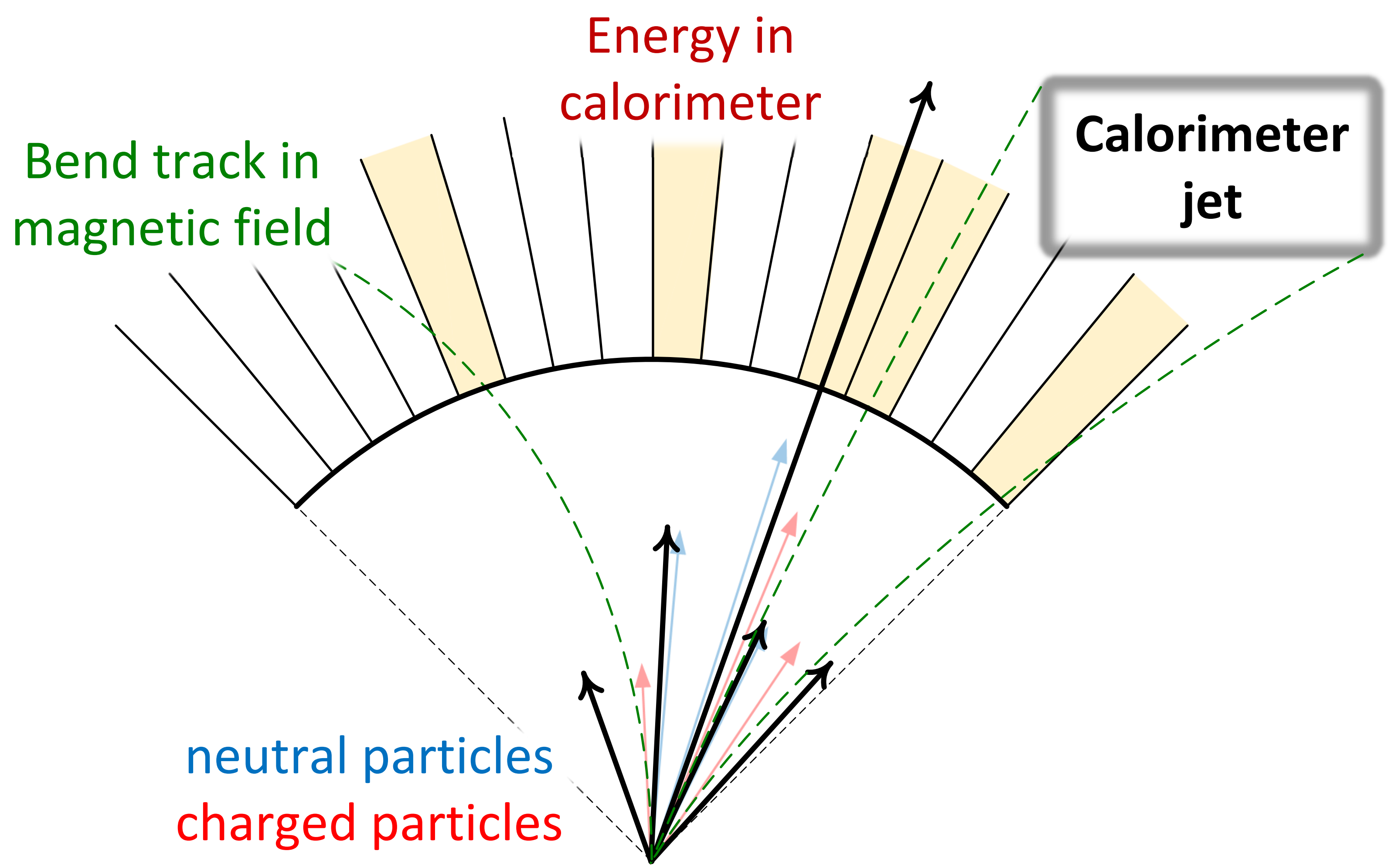



ATLAS
EXPERIMENT
Run: 267073
Event: 279124678
2015-06-05 02:24:03 CEST

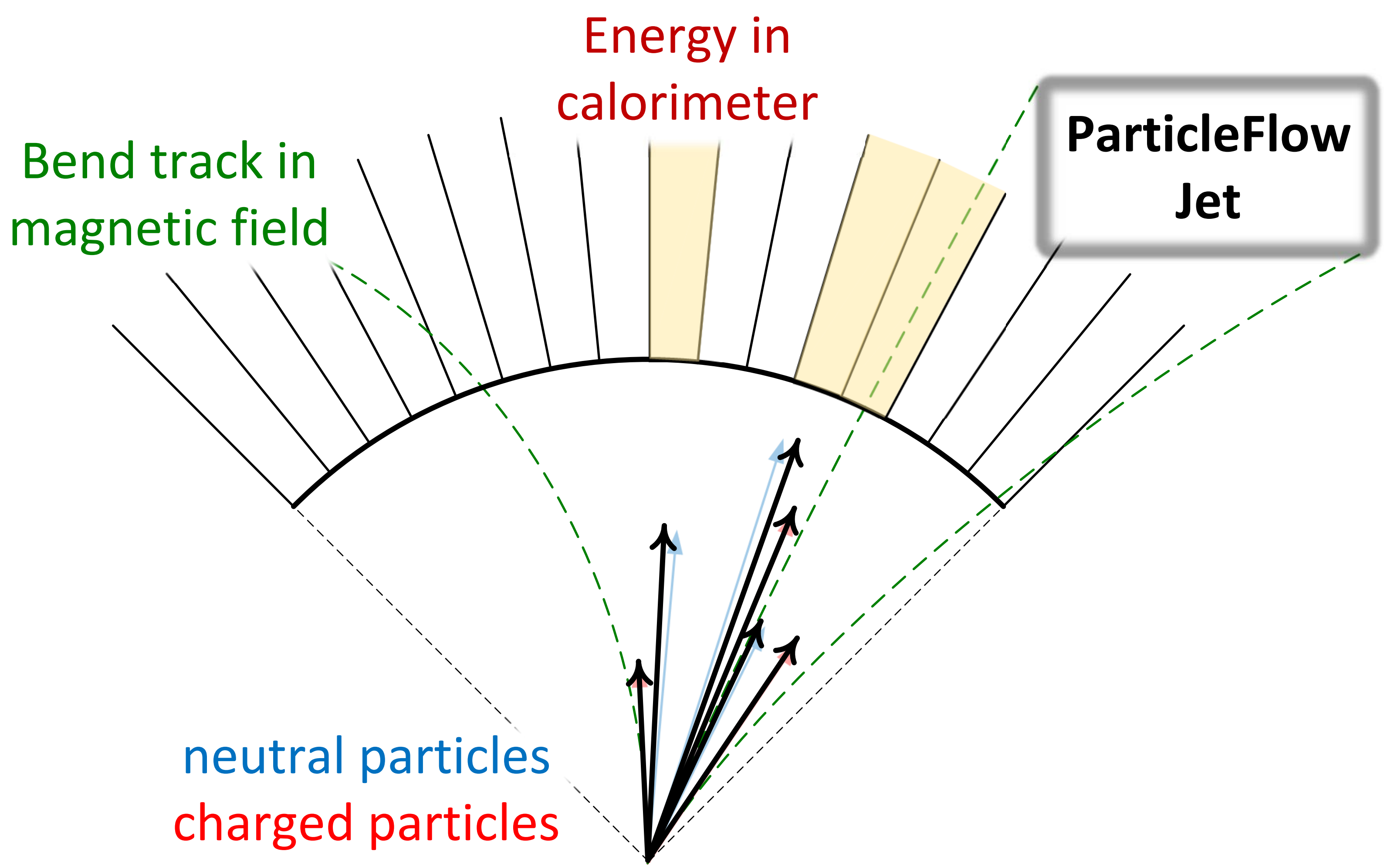
Jet Making

- Defined by input objects, combination algorithm, and the radius.
- Usual algorithm in LHC experiments: anti-k_t algorithm, which combines inputs in momentum-space, starting with *hardest* inputs.
- Algorithms need to be theoretically robust!

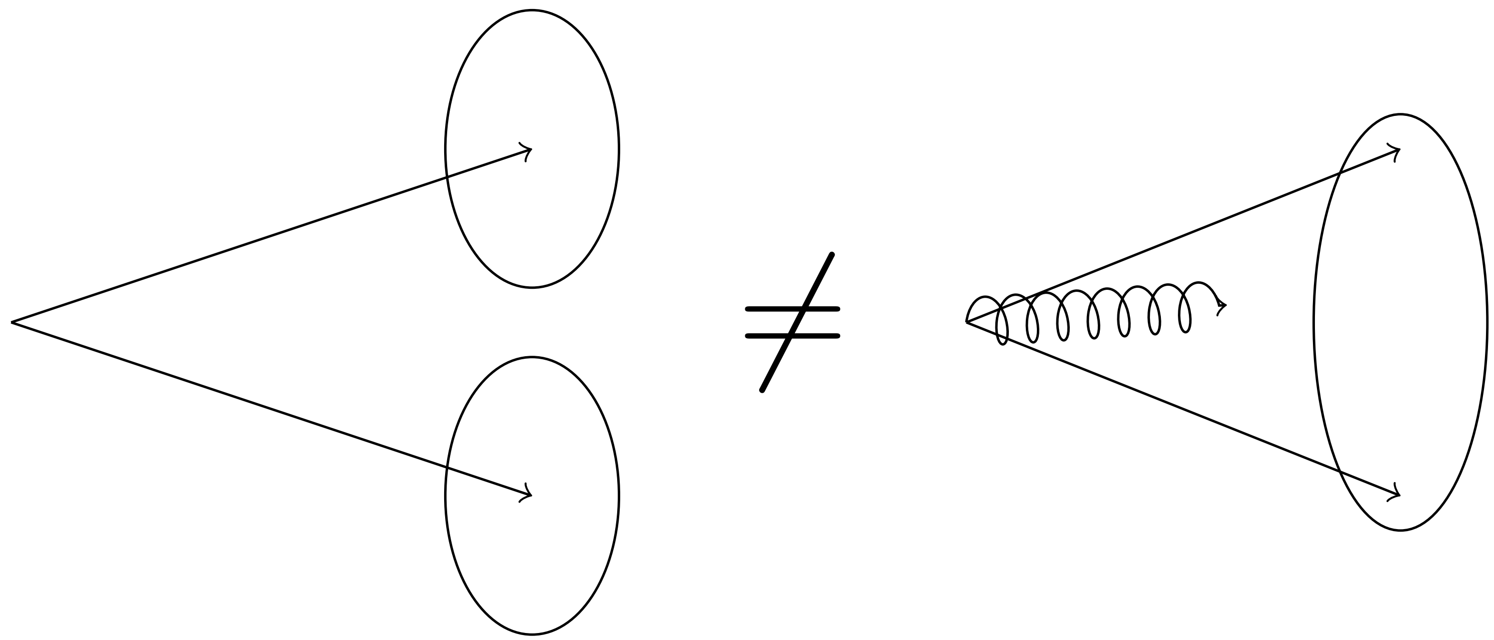
Calorimeter Objects



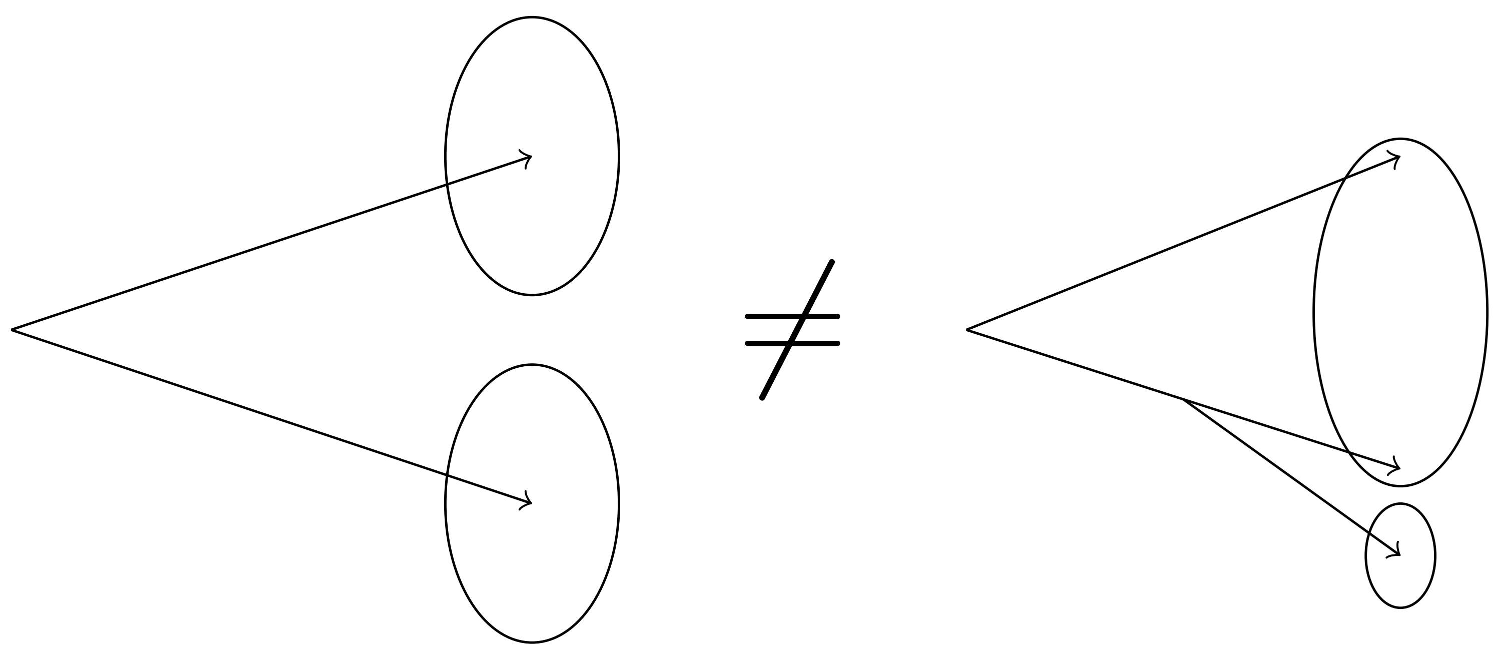
ParticleFlow Objects



IRC Safety



Infrared safety



Collinear safety

Jet making

Bottom Up

- Sequential recombination algorithms (momentum space): iteratively pairwise combination of the inputs till a minimum inter-jet distance is reached.

Top Down

- Cone algorithms (coordinate space): Collect all inputs within a cone such that the cone axis is the vector sum of momenta in it.

Jet making

Distance between two input objects

Distance between each input object and beam

$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta y^2 + \Delta\phi^2}{R^2}; \quad d_{iB} = k_{ti}^{2p}; \quad p = \begin{cases} 1 & k_t \\ 0 & \text{Cambridge/Aachen} \\ -1 & \text{anti-}k_t \end{cases}$$

Intrinsic transverse momentum

Fixed “radius” parameter

- Find the smallest of all $\{d_{ij}, d_{iB}\}$
- If this is one of the d_{ij} values, inputs i and j are merged.
- If it is one of the d_{iB} values, i^{th} input is considered a jet.
- Continue till all inputs are merged into jets.

Jet making

Distance between two input objects

Distance between each input object and beam

$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2}; \quad d_{iB} = k_{ti}^{2p}; \quad p = \begin{cases} 1 & k_t \\ 0 & \text{Cambridge/Aachen} \\ -1 & \text{anti-}k_t \end{cases}$$

Intrinsic transverse momentum

Fixed “radius” parameter

- Find the smallest of all $\{d_{ij}, d_{iB}\}$

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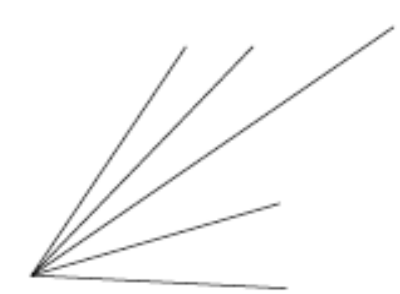
Intrinsic transverse momentum — Fixed “radius” parameter

- Find the smallest of all $\{d_{ij}, d_{iB}\}$
- If this is one of the d_{ij} values, inputs i and j are merged.



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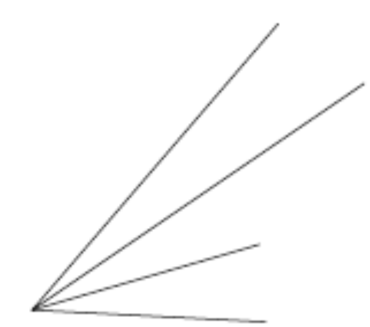
- If it is one of the d_{iB} values, i^{th} input is considered a jet.
- Continue till all inputs are merged into jets.



Jet making

Distance between two input objects

Distance between each input object and beam

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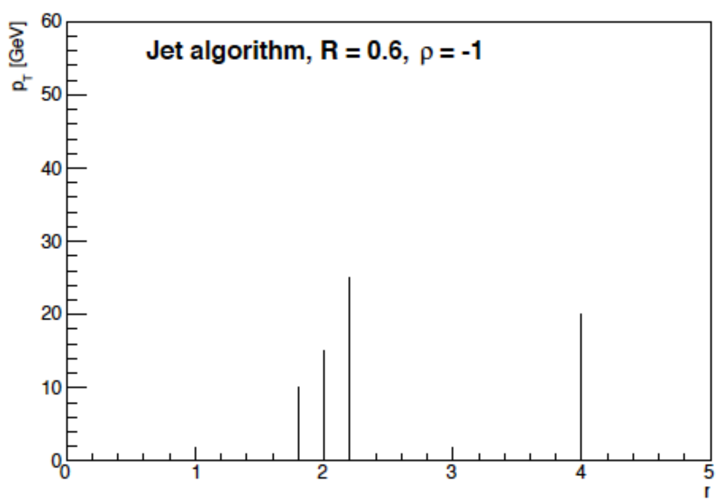
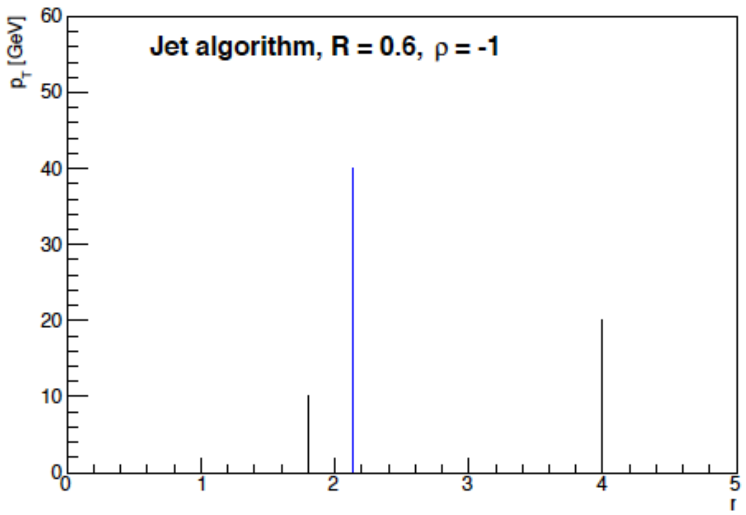
Step 1



d_{ij}	1	2	3	4
1	-	0.00049	0.00071	0.03361
2	0.00049	-	0.00018	0.02778
3	0.00071	0.00018	-	0.01440
4	0.03361	0.02778	0.01440	-
d_{iB}	0.01000	0.00444	0.00160	0.0025

(a) We have 4 input objects as shown. The smaller value is indicated, which dictates 2 and 3 should be merged. The merged p_T will be 40 GeV, and the position is determined by the p_T-weighted average: $(2*15+2.2*25)/40 = 2.13$.

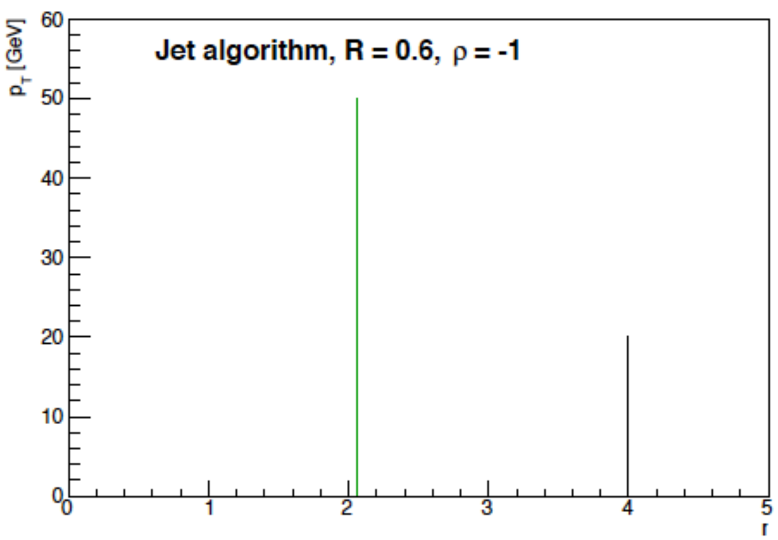
Step 2



d_{ij}	1	23	4
1	-	0.00019	0.03361
23	0.00019	-	0.00607
4	0.03361	0.00607	-
d_{iB}	0.00444	0.00063	0.00250

(b) At this step, we indicate the merged input from previous step by 23. The distances indicate that inputs 1 and 23 should be merged. The merged p_T will be 50 GeV, and the position will be determined by the p_T-weighted average: $(1.8 * 10 + 2.13 * 40)/50 = 2.06$.

Step 3

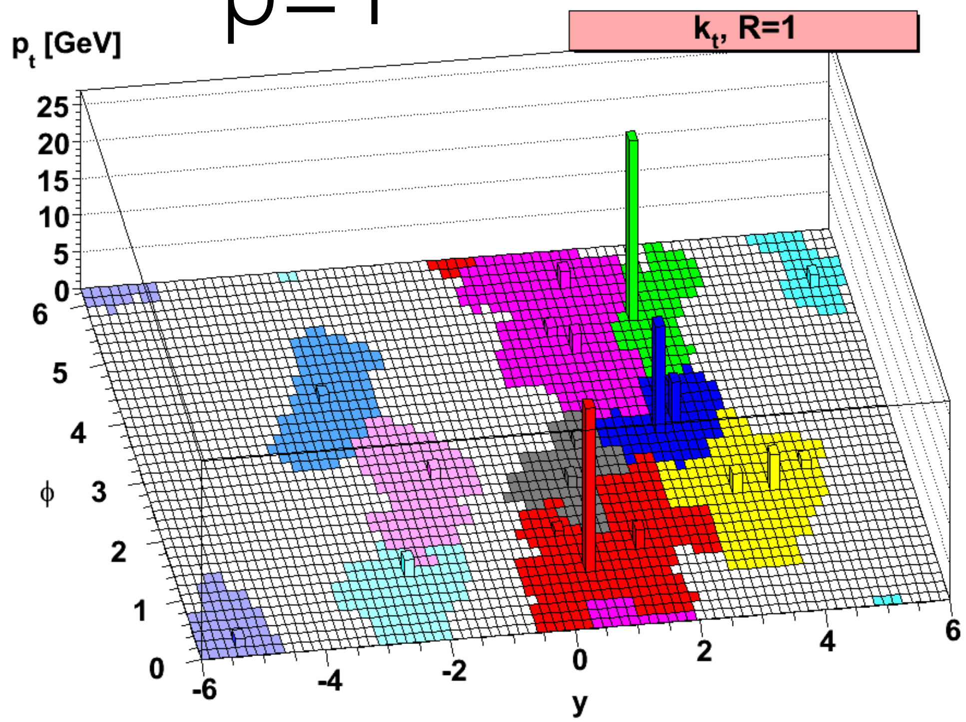


d_{ij}	123	4
123	-	0.00418
4	0.00418	-
d_{iB}	0.00040	0.00250

(c) At this step, we indicate the merged input from previous step by 123. The distances indicate the input 123 should be classified as a jet itself. Since that leaves input 4, that will be classified as a jet as well.

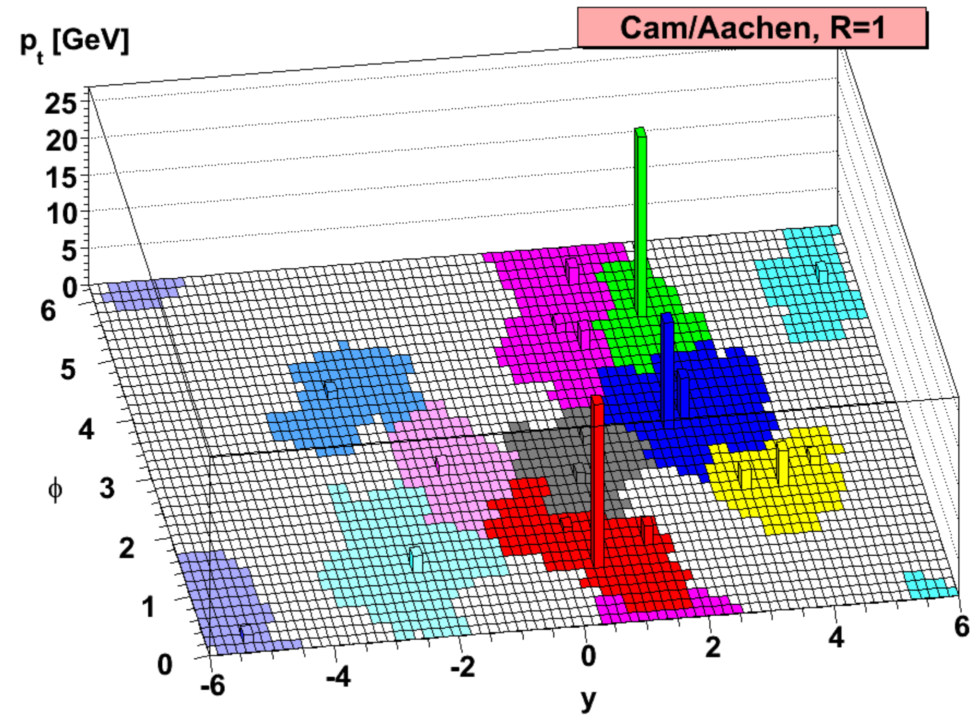
Finished product!

p=1



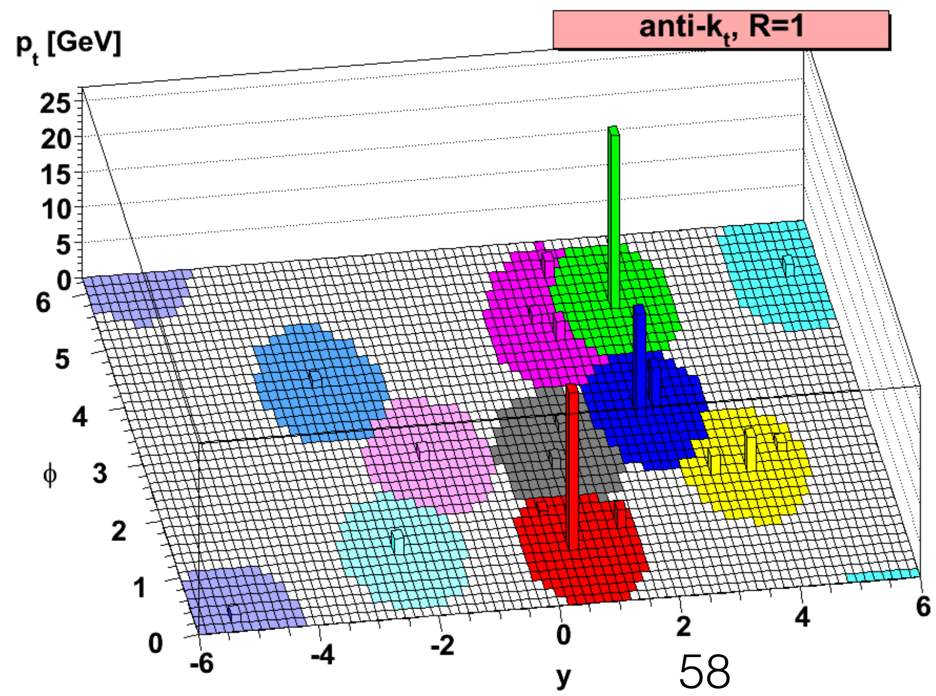
Irregularly shaped jets

p=0



Shape follow angular distribution of components

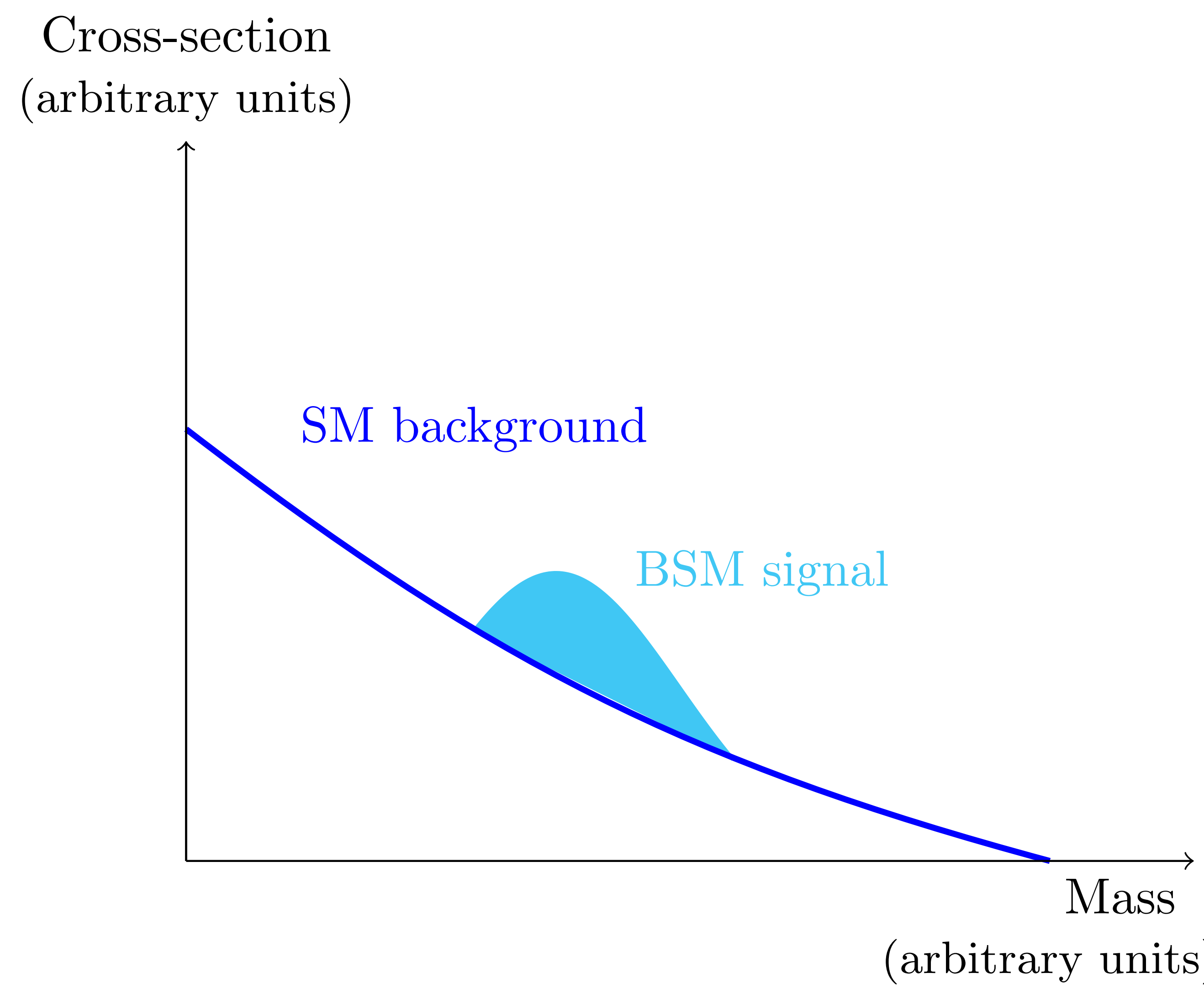
p=-1



Almost circularly shaped jets

Searches

- Resonance searches: bumphunting
- Cut and count
- Excess of MET: DM
- Signal strength



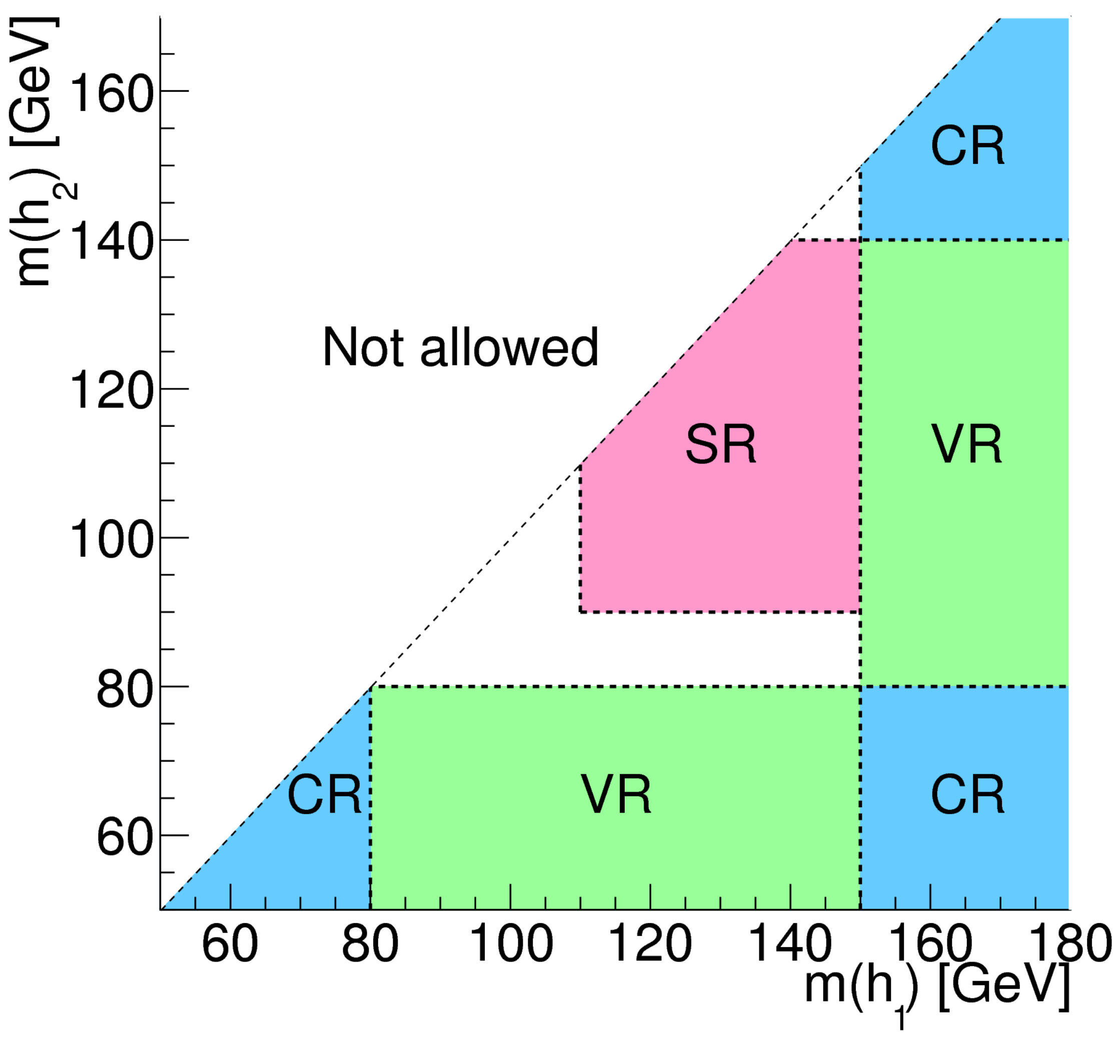
Types of backgrounds

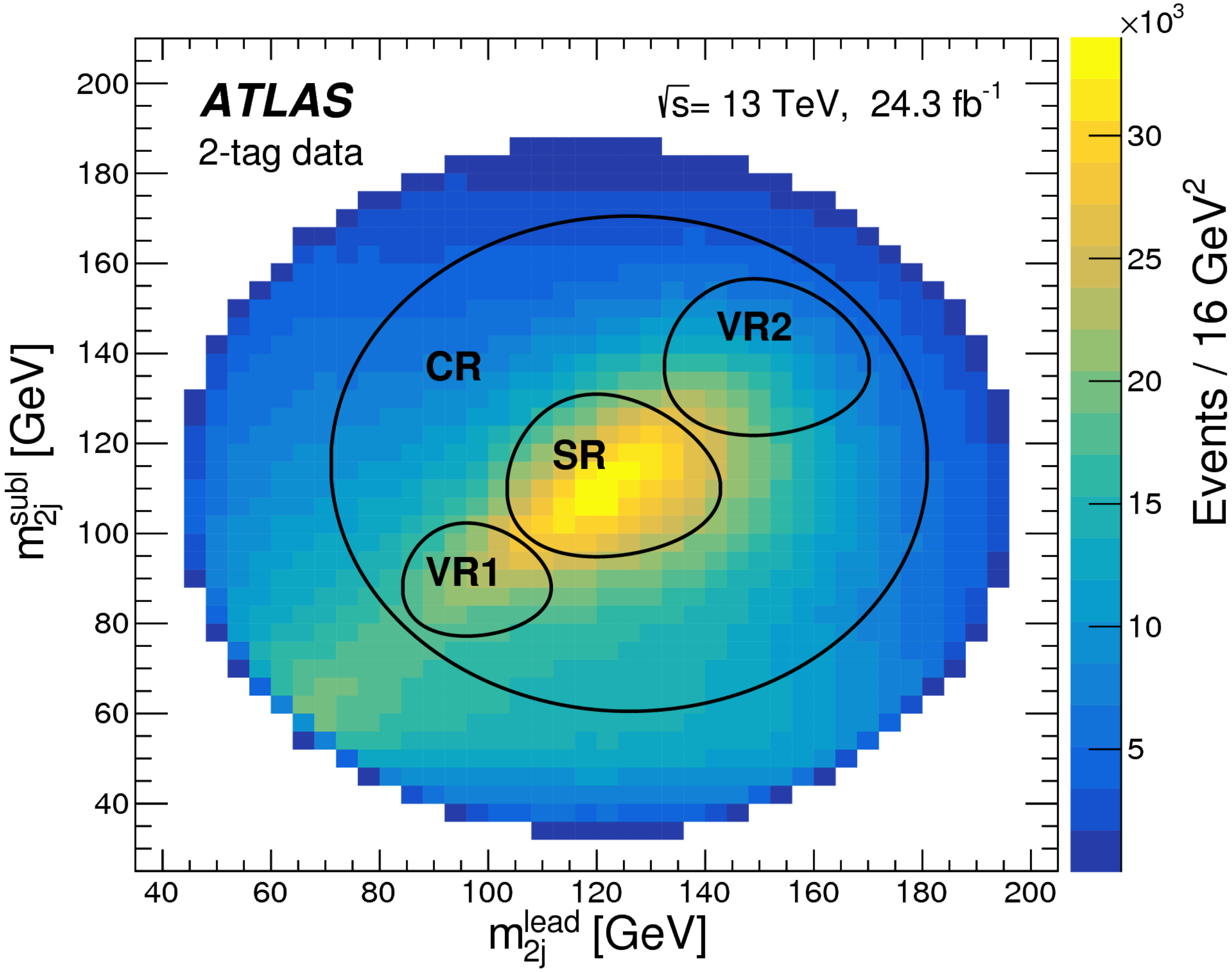
- Irreducible: same final state. SM ZZ for H to ZZ.
- Reducible: not the same final state, resulting from misreconstructed processes or misidentified objects. W(lnu)+jets for Z(ll)+jets.
- Combinatorial: random combination of objects looking like the signal. All hadronic ttbar.

Signal and control regions

- We apply selection *cuts* on the objects and event topology to maximise signal and minimise background.
- However, when searching for a new physics signal, we do not want to bias ourselves.
- So divide the events into signal region, where data is blinded when we fix analysis strategies, and control region by inverting one (or more signal cuts), where we can check data-MC agreement and estimate background contribution.
- Unblinded after cuts are optimised and **fixed.**

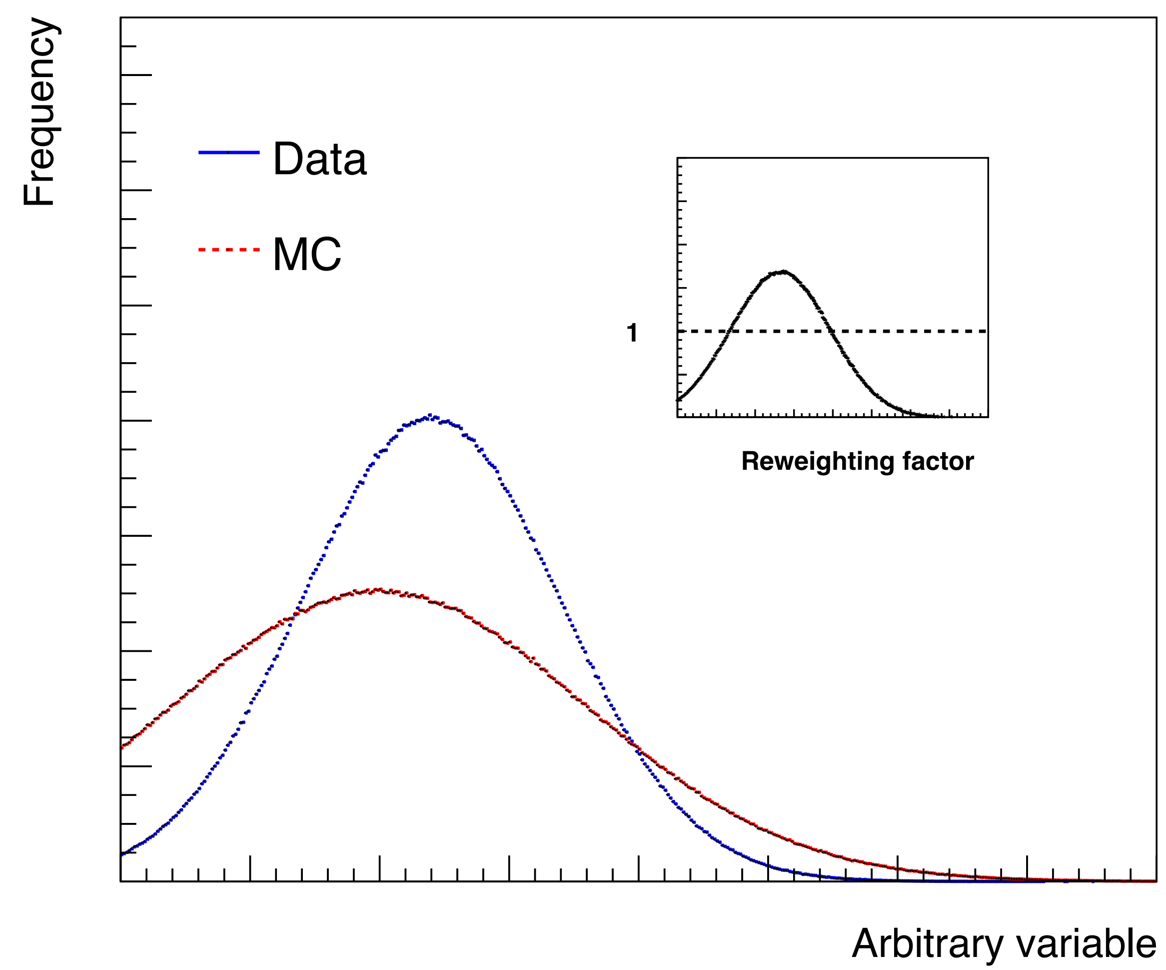
SR and CR


Not allowed
SR
VR
CR
VR
CR
CR
m(h2) [GeV]
m(h1) [GeV]


ATLAS
2-tag data
√s= 13 TeV, 24.3 fb-1
CR
VR2
SR
VR1
m2j subl [GeV]
m2j lead [GeV]
×10^3
Events / 16 GeV^2

Data-MC agreement in CR

- What if simulation does not describe the data in CR?
- Modelling?
- Calibration/efficiency estimates wrong?
- Reweight :-(

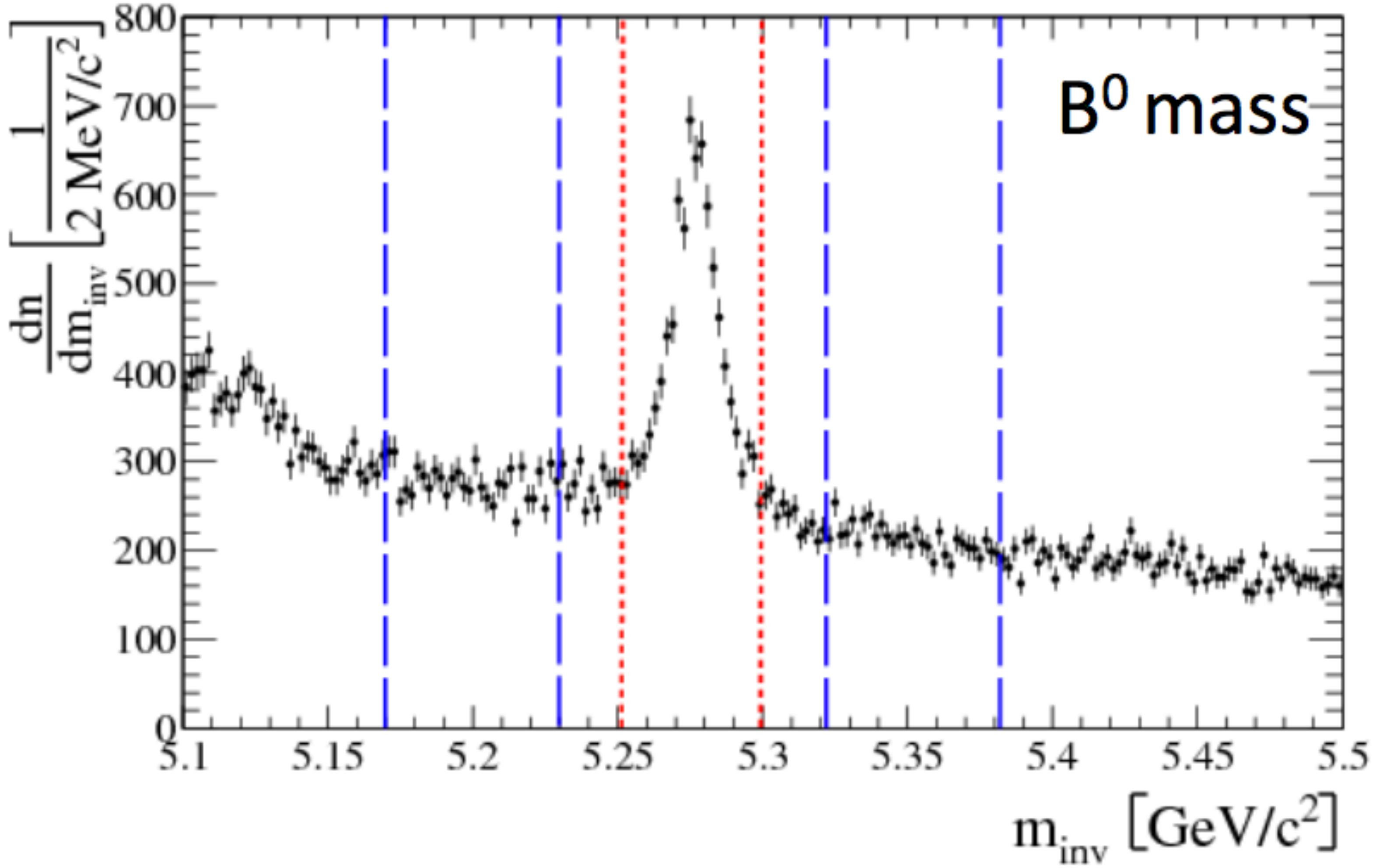


Estimate the backgrounds

Data and/or simulation driven

- Anti-selection/inversion of cuts
- Side-bands/shape extraction by fit
- ABCD method
- …

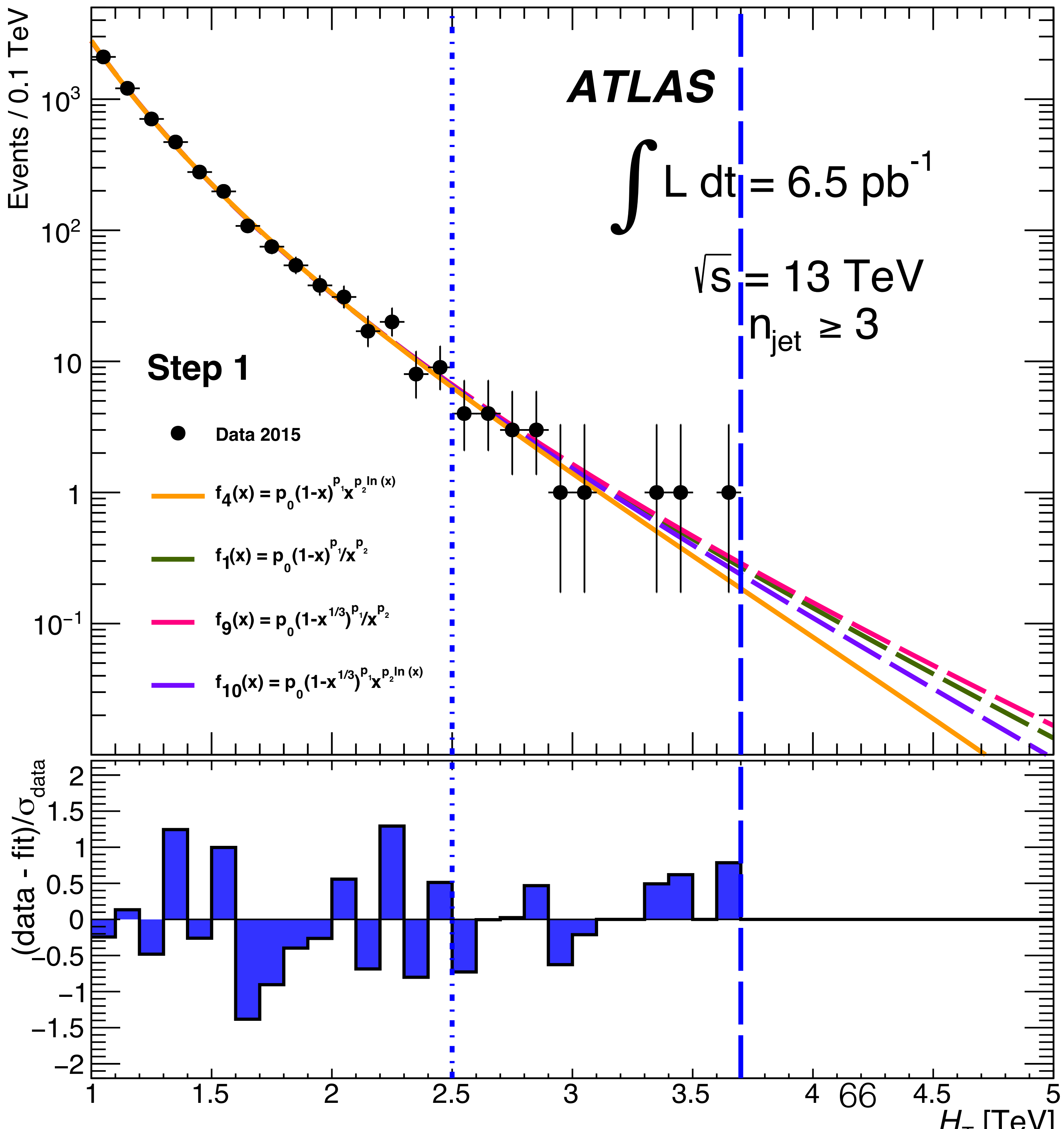
Sidebands



Estimate background under a resonance peak

With or without fitting

Sidebands

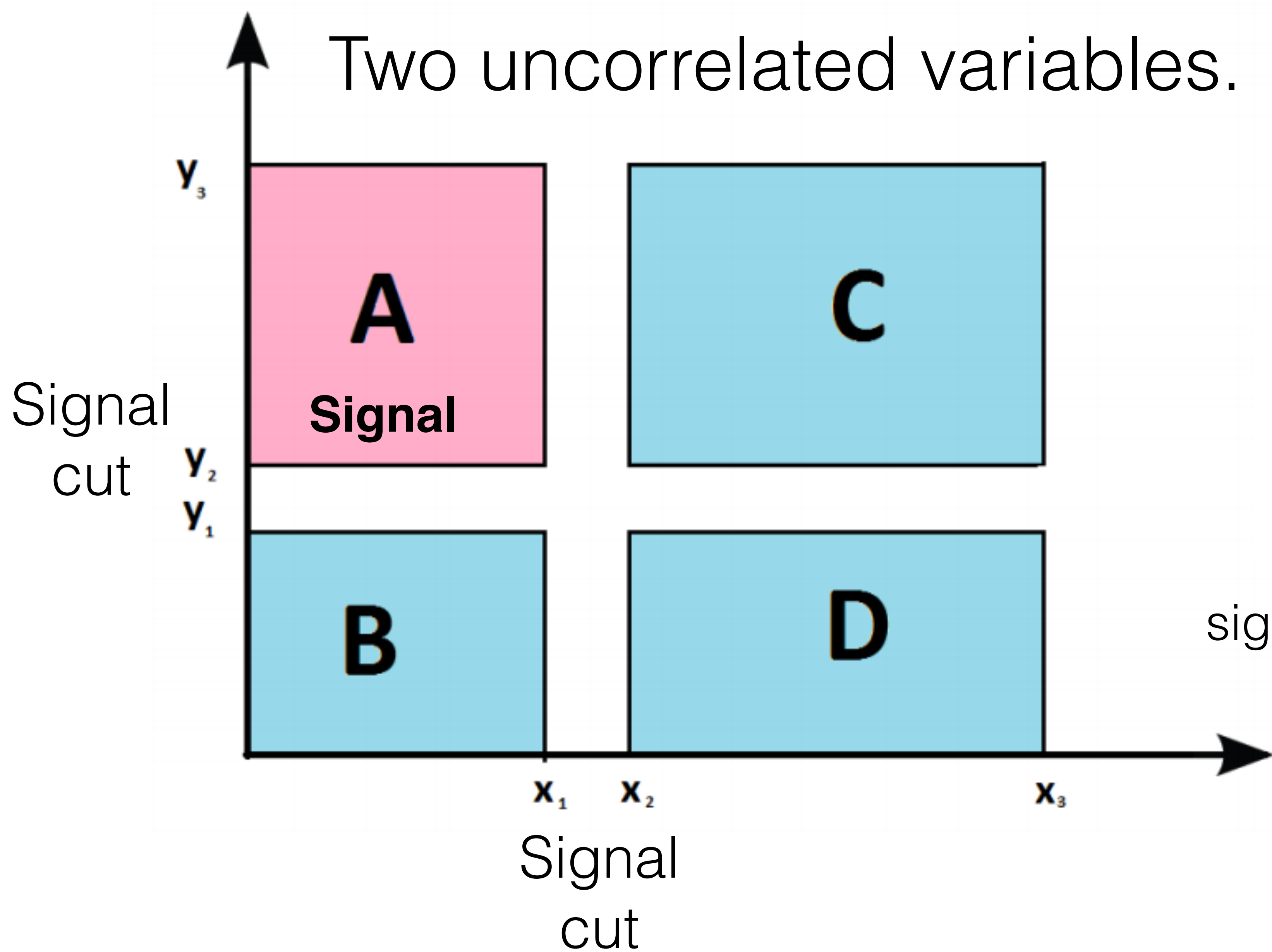


Estimate background under a resonance peak

With or without fitting

ABCD method

Two uncorrelated variables.



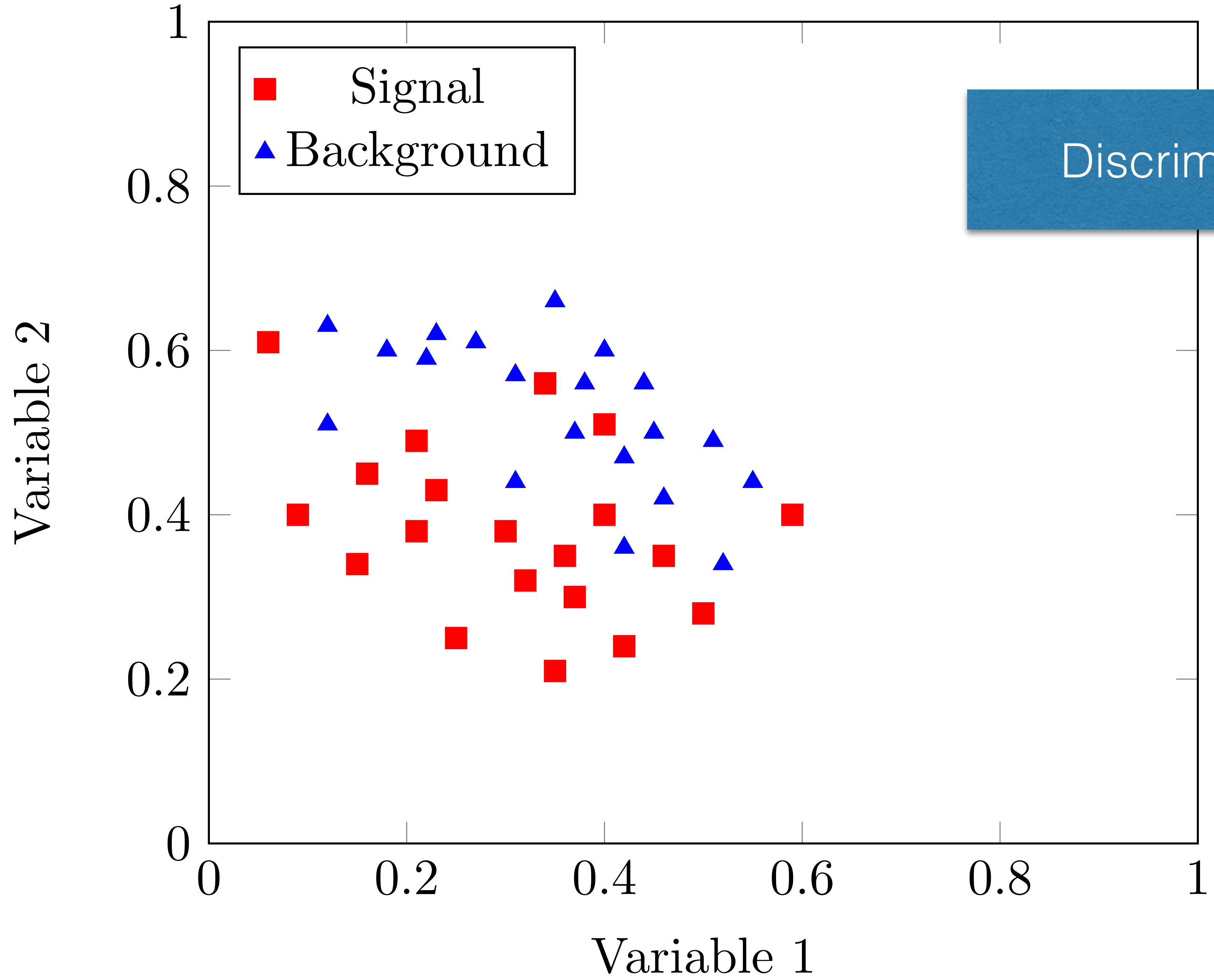
Estimate by:

$$N_A = \frac{N_B \times N_C}{N_D}$$

b.g in
signal region

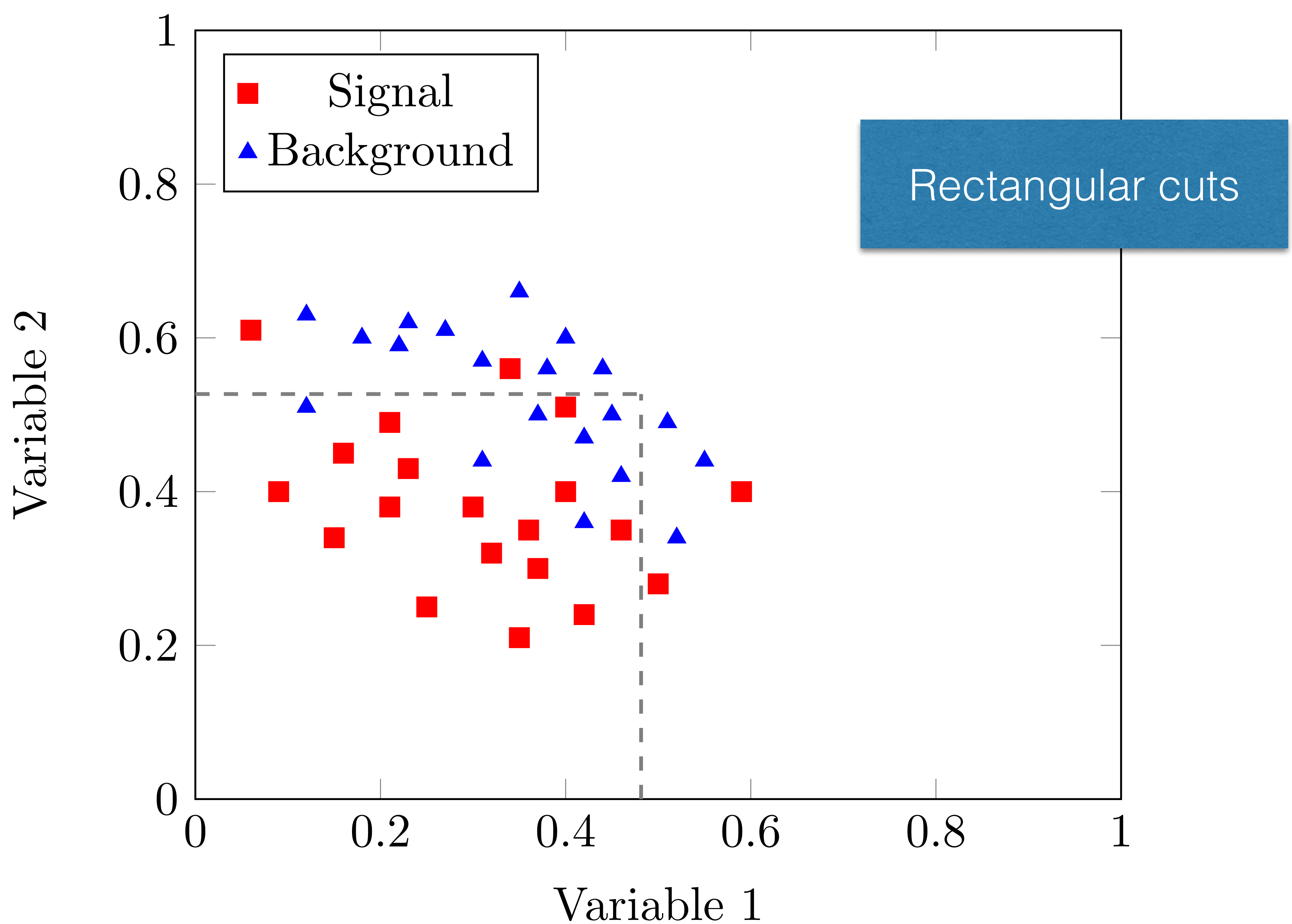
Use of ML in object reconstruction

Precursor: Multivariate analysis

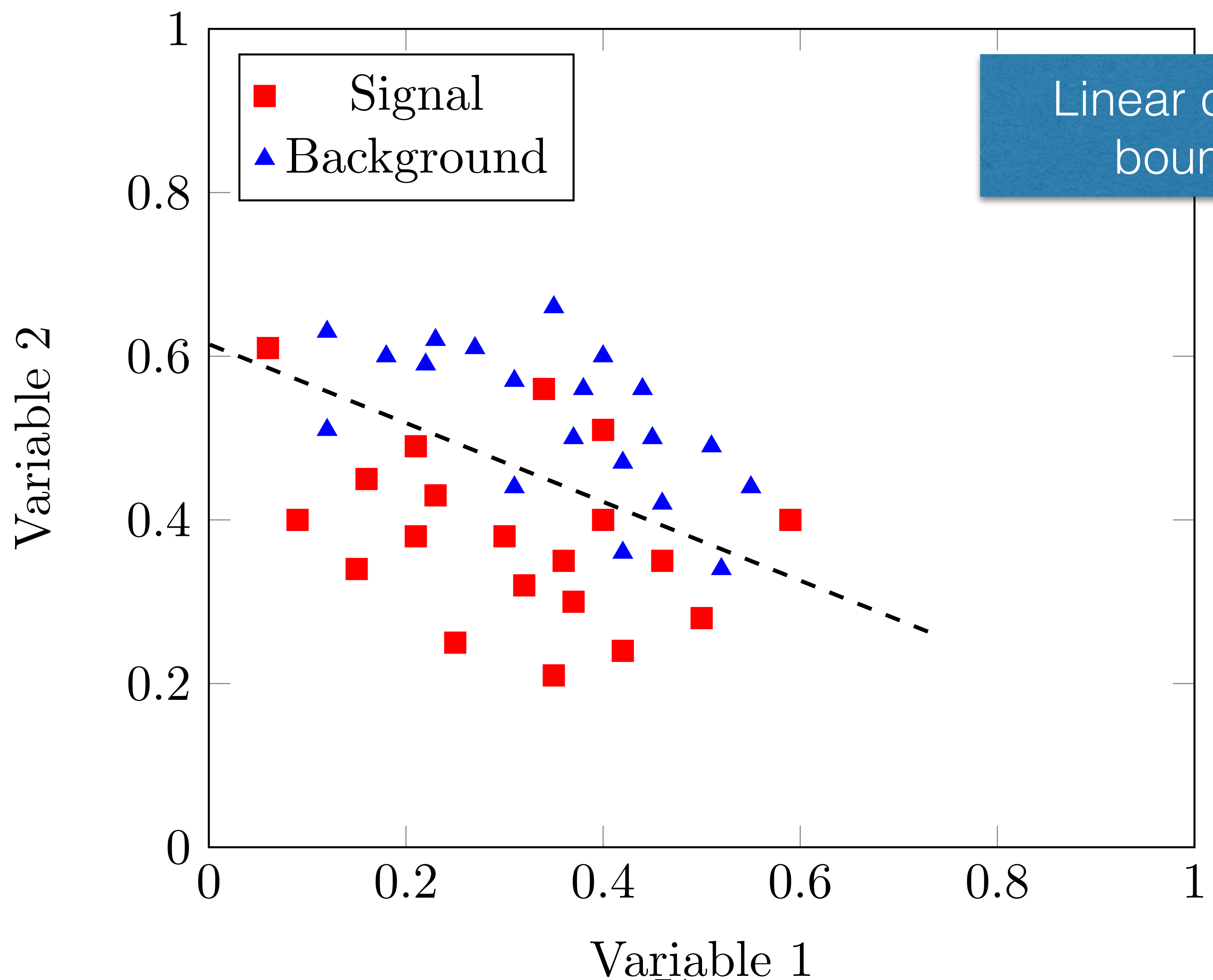


Discriminate!

Precursor: Multivariate analysis

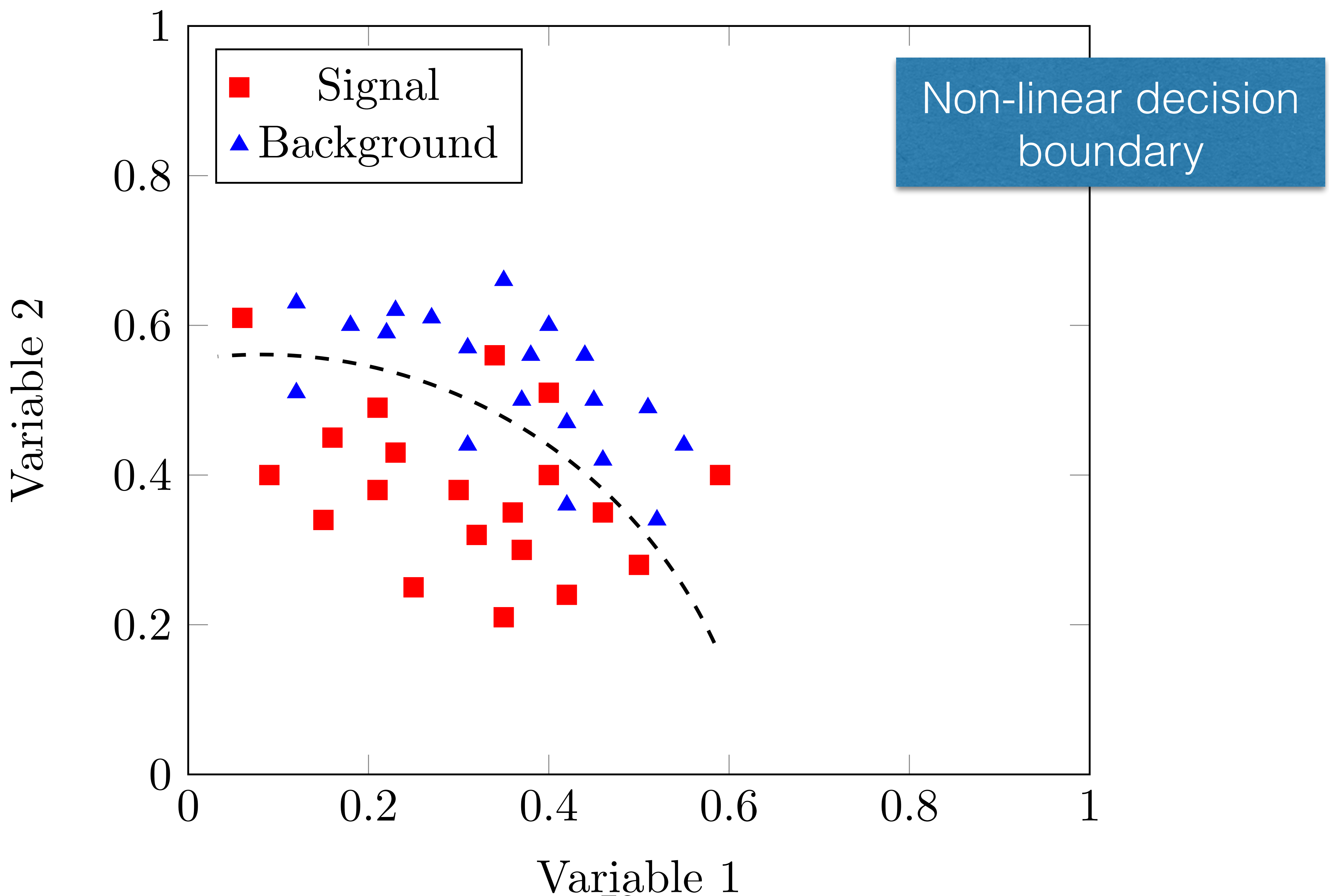


Precursor: Multivariate analysis



Linear decision boundary

Precursor: Multivariate analysis



Challenge:

Find the optimal decision boundary in N-dimension!

MVA

- N variables used in classification: feature variables
- Correlation reduces dimensionality
- N dimensional constant surface —> mapping to a single discriminating variable
- Actual cut on the variable, as before!

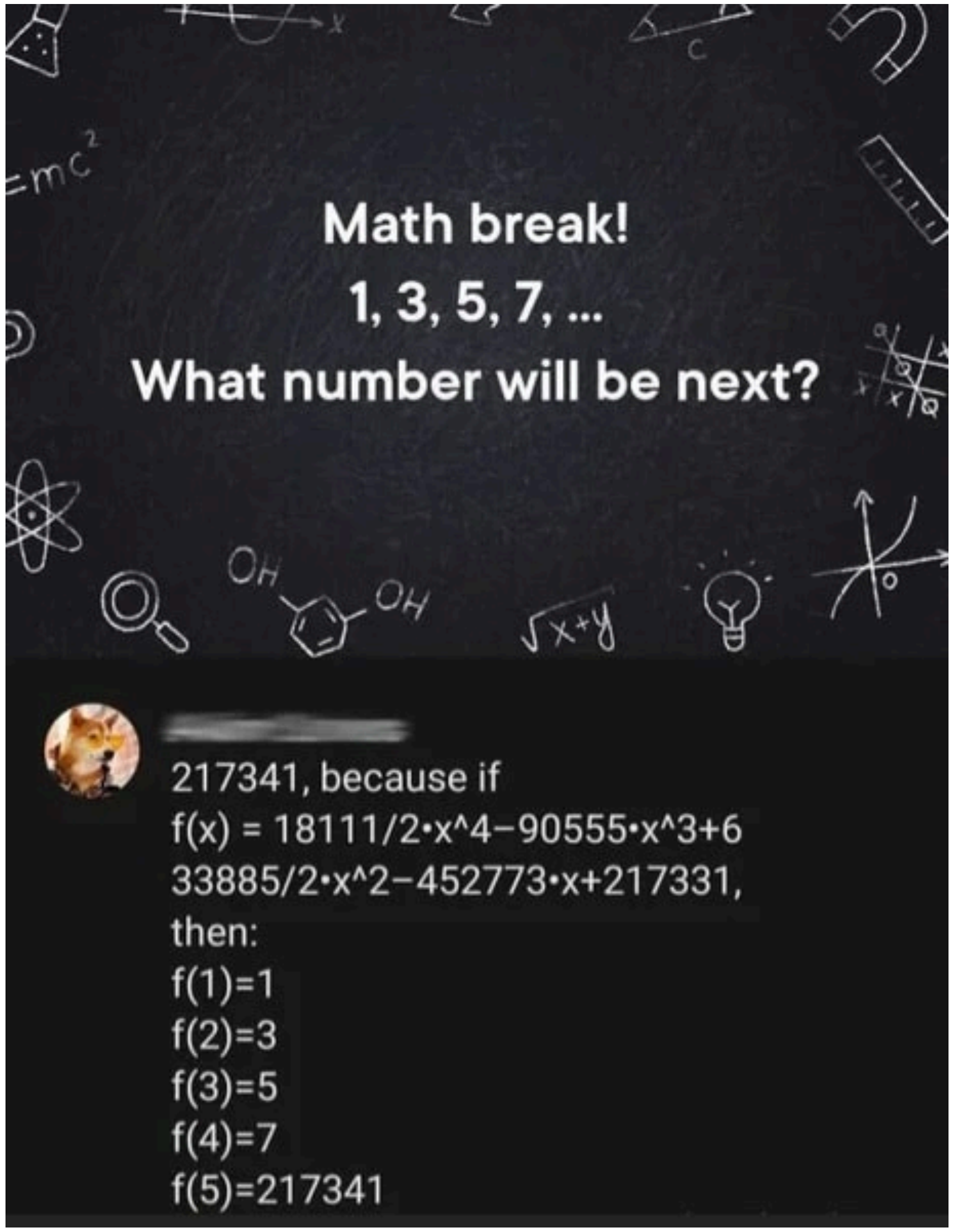
Preprocessing

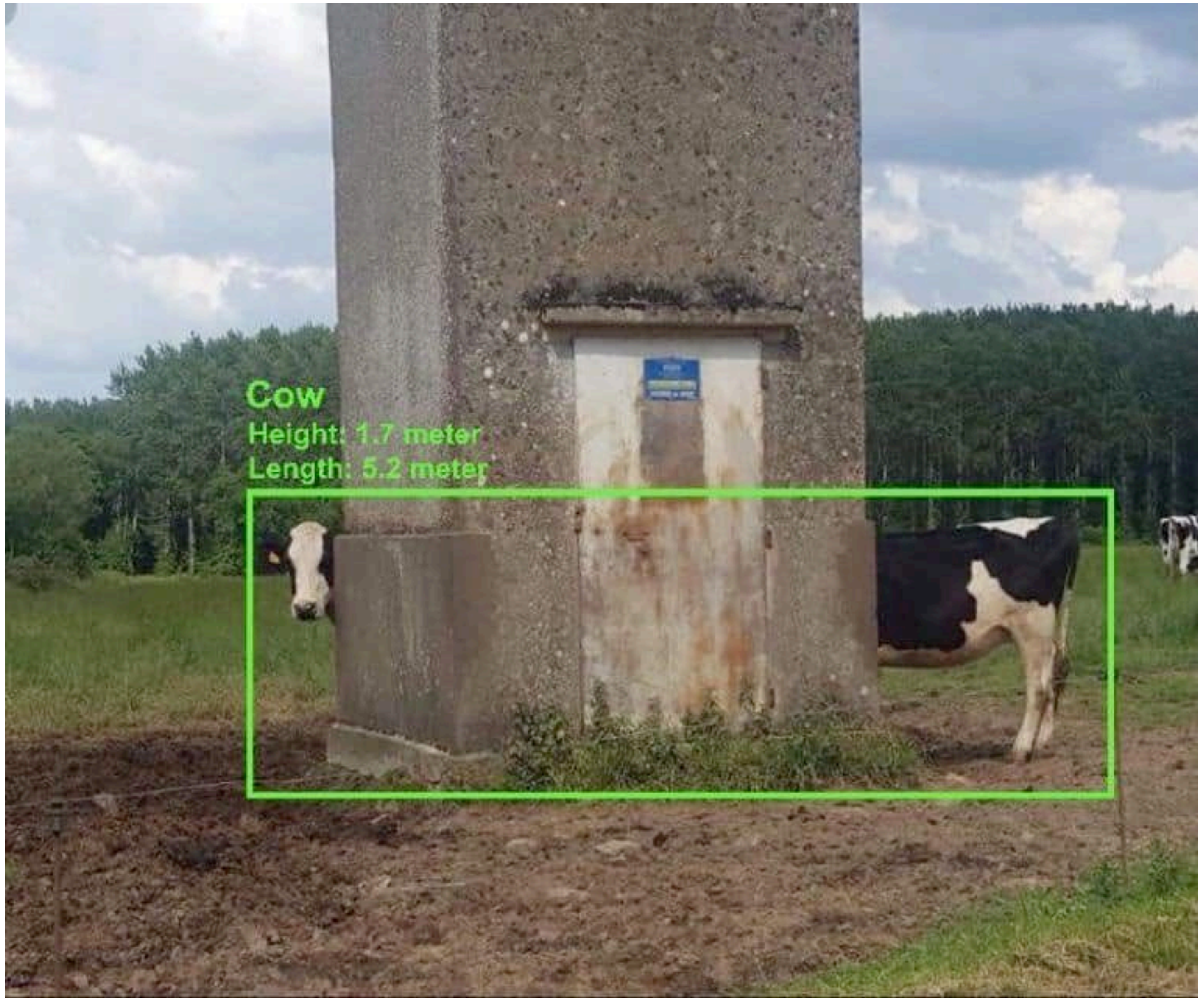
- Combine or transform the variables to bring out physical features —> called feature extraction
- Example: W-boson transverse mass, scaling by sqrt(s),

Machine Learning

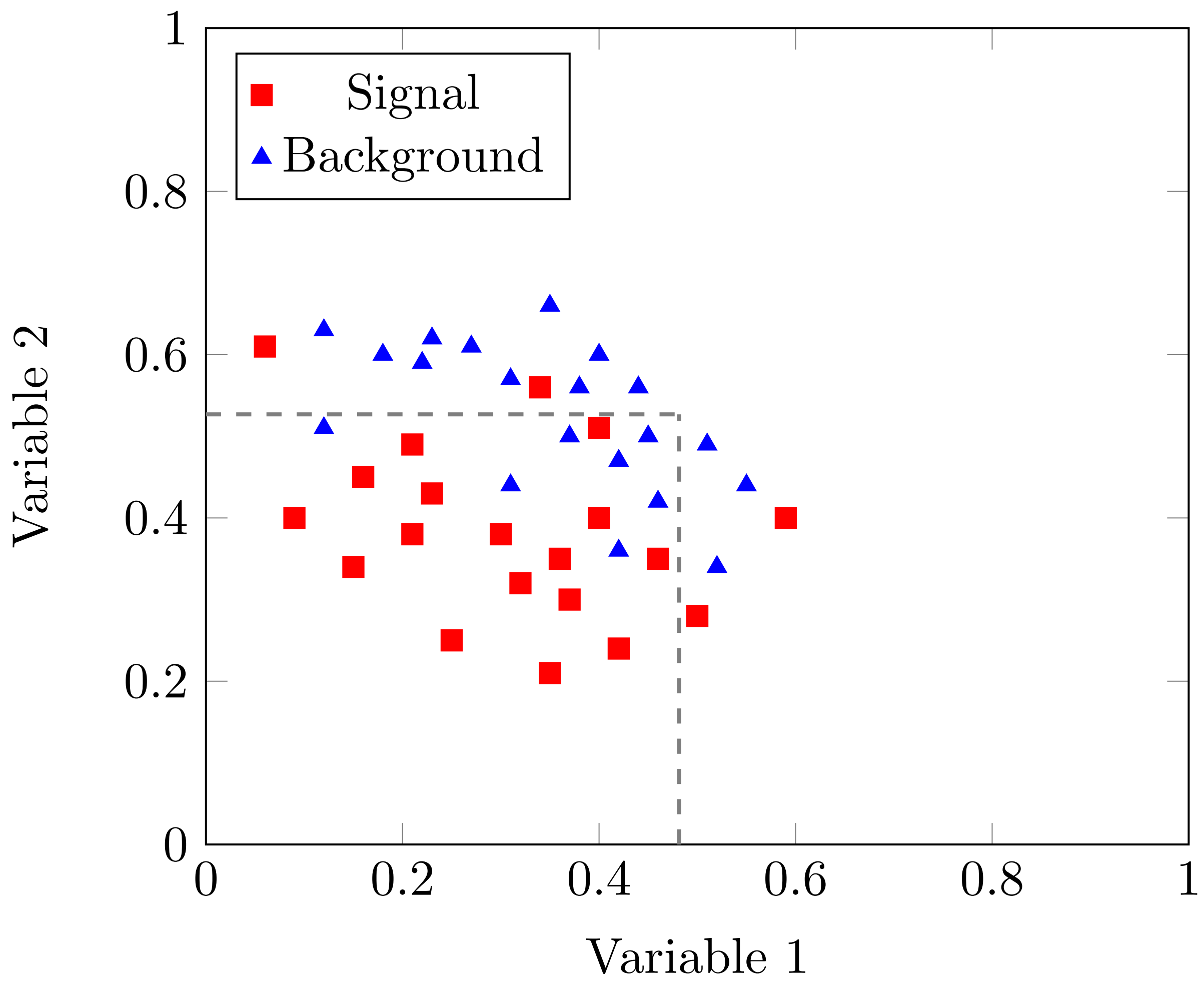
- Algorithmically find this decision boundary based on *data* (without explicitly programmed)
- Learning: represent the data by an approximate functional form (whether or not such a form exists is immaterial) between input variables x and output variables y
- Use that predict behaviour of future similar datasets from x' to y'.

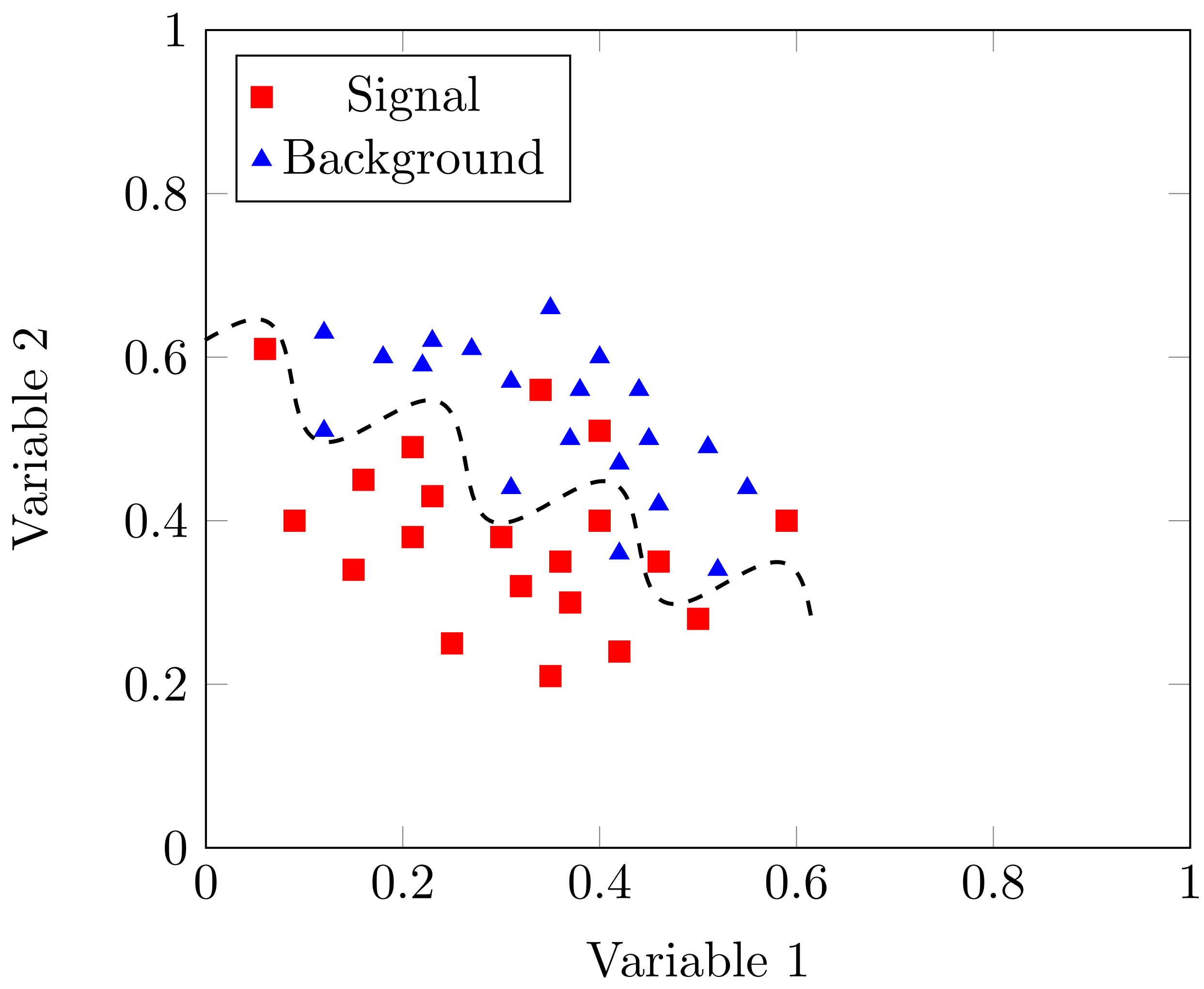
But!


Math break!
1, 3, 5, 7, ...
What number will be next?
217341, because if
f(x) = 18111/2·x^4−90555·x^3+6
33885/2·x^2−452773·x+217331,
then:
f(1)=1
f(2)=3
f(3)=5
f(4)=7
f(5)=217341


Cow
Height: 1.7 meter
Length: 5.2 meter

Underfitting and Overfitting





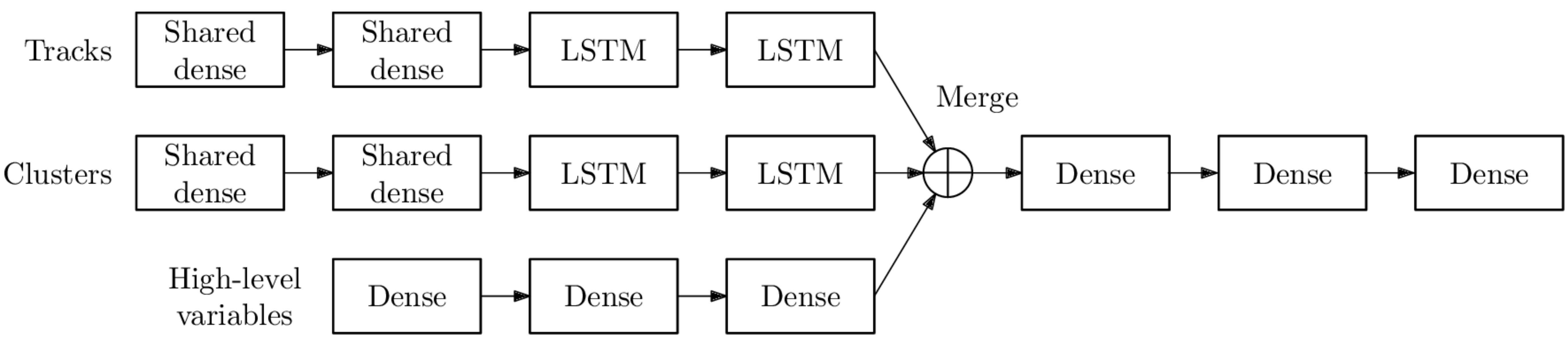
Back to the Objects

Quiz

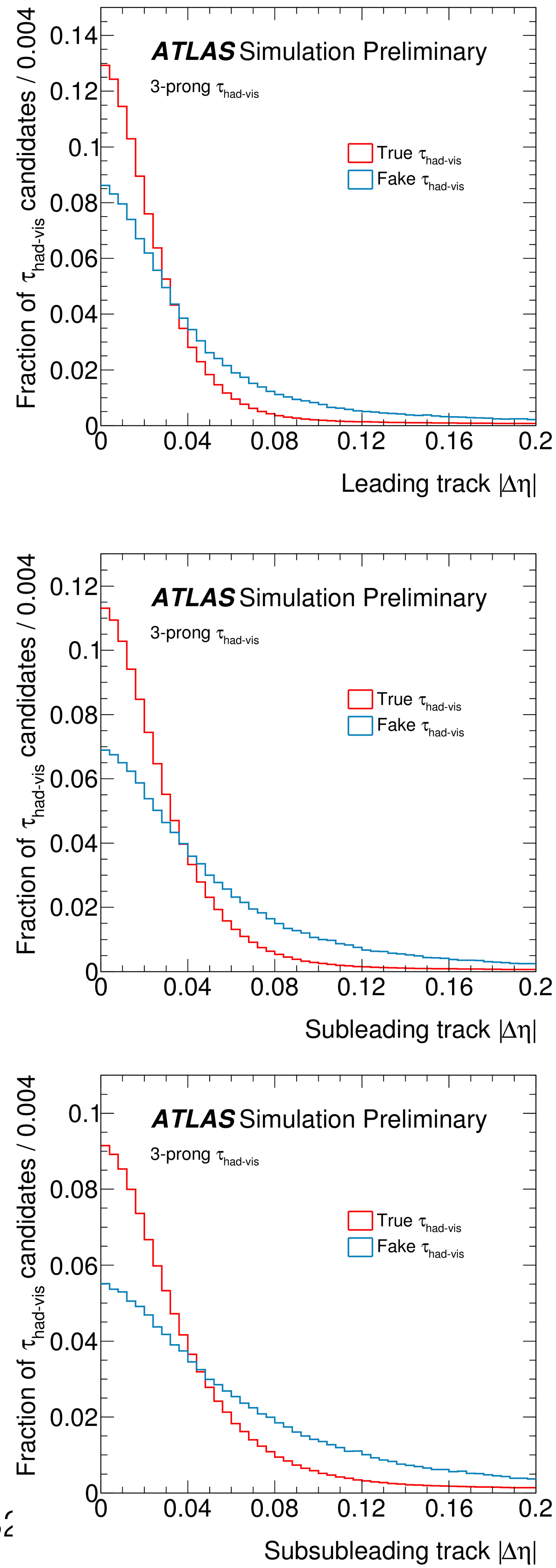
Why the (hadronic) decay of tau contain only odd number of charged particles tracks?

Example: ATLAS hadronic tau reconstruction

- The challenge: discriminating non-tau jets
- Use a RNN
- Trained sep for 1/3 prongs using simulated samples



	Observable	1-prong	3-prong
Track inputs	$p_T^{\text{seed jet}}$	●	●
	p_T^{track}	●	●
	$\Delta\eta^{\text{track}}$	●	●
	$\Delta\phi^{\text{track}}$	●	●
	$\lvert d_0^{\text{track}}\rvert$	●	●
	$\lvert z_0^{\text{track}} \sin\theta\rvert$	●	●
	$N_{\text{IBL hits}}$	●	●
	$N_{\text{Pixel hits}}$	●	●
	$N_{\text{SCT hits}}$	●	●
Cluster inputs	$p_T^{\text{jet seed}}$	●	●
	E_T^{cluster}	●	●
	$\Delta\eta^{\text{cluster}}$	●	●
	$\Delta\phi^{\text{cluster}}$	●	●
	λ_{cluster}	●	●
	$\langle\lambda^2_{\text{cluster}}\rangle$	●	●
	$\langle r^2_{\text{cluster}}\rangle$	●	●
High-level inputs	$p_T^{\text{uncalibrated}}$	●	●
	f_{cent}	●	●
	$f^{-1}_{\text{leadtrack}}$	●	●
	ΔR_{max}	●	●
	$\lvert S_{\text{leadtrack}}\rvert$	●	
	S_T^{flight}		●
	$f_{\text{iso}}^{\text{track}}$	●	●
	$f_{\text{track}}^{\text{EM}}$	●	●
	$p_T^{\text{EM+track}}/p_T$	●	●
	$m^{\text{EM+track}}$	●	●
	m^{track}		●



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