

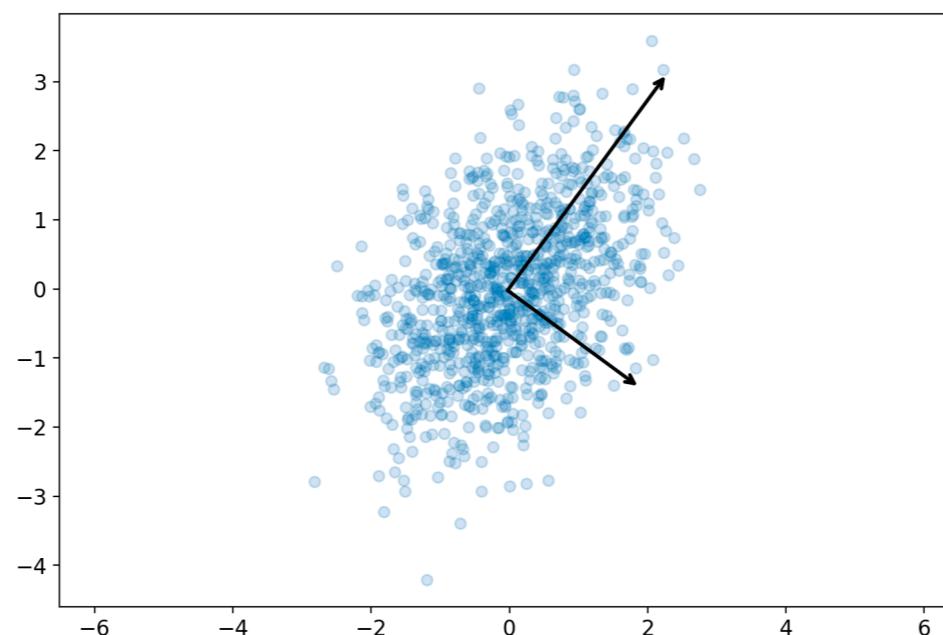


Lecture 8

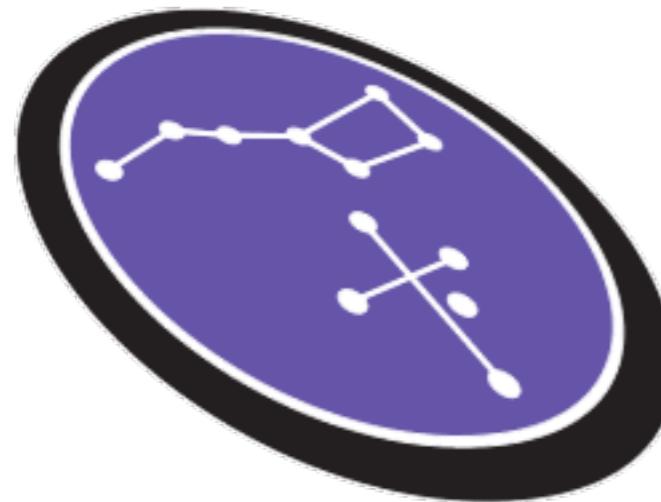
Understanding Jets

Principal Component Analysis

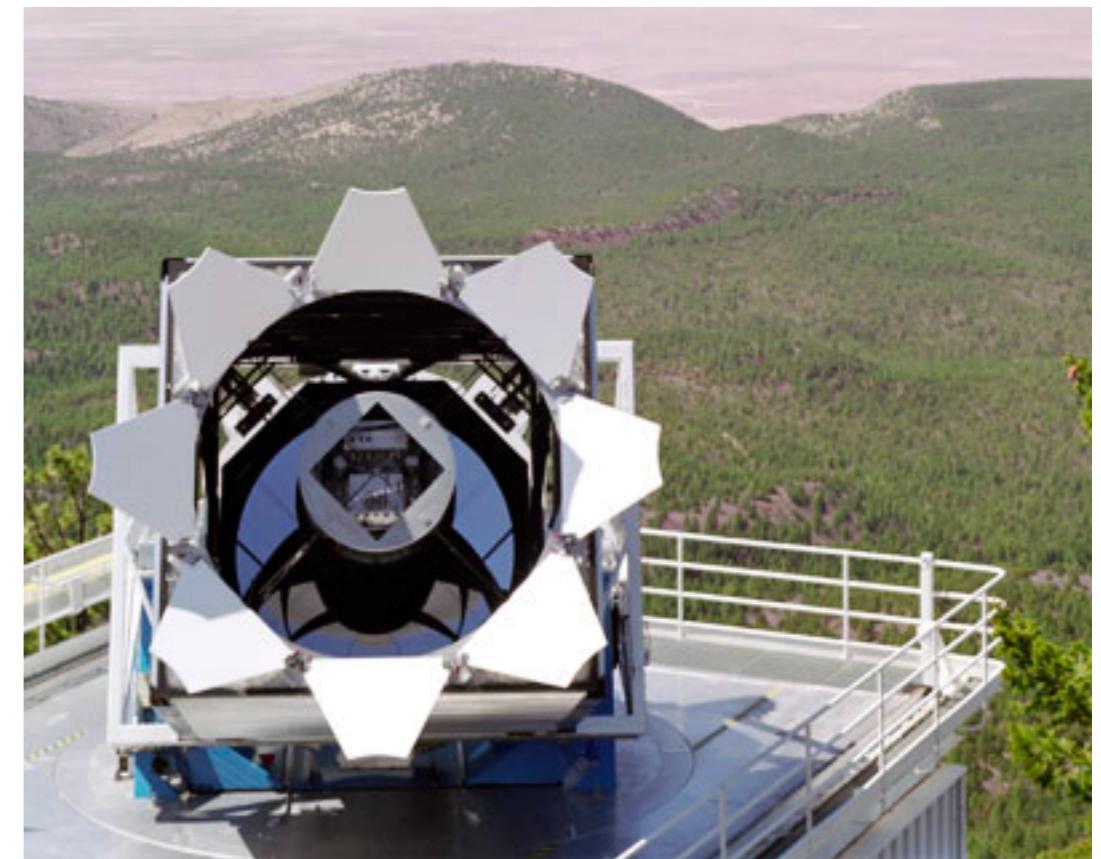
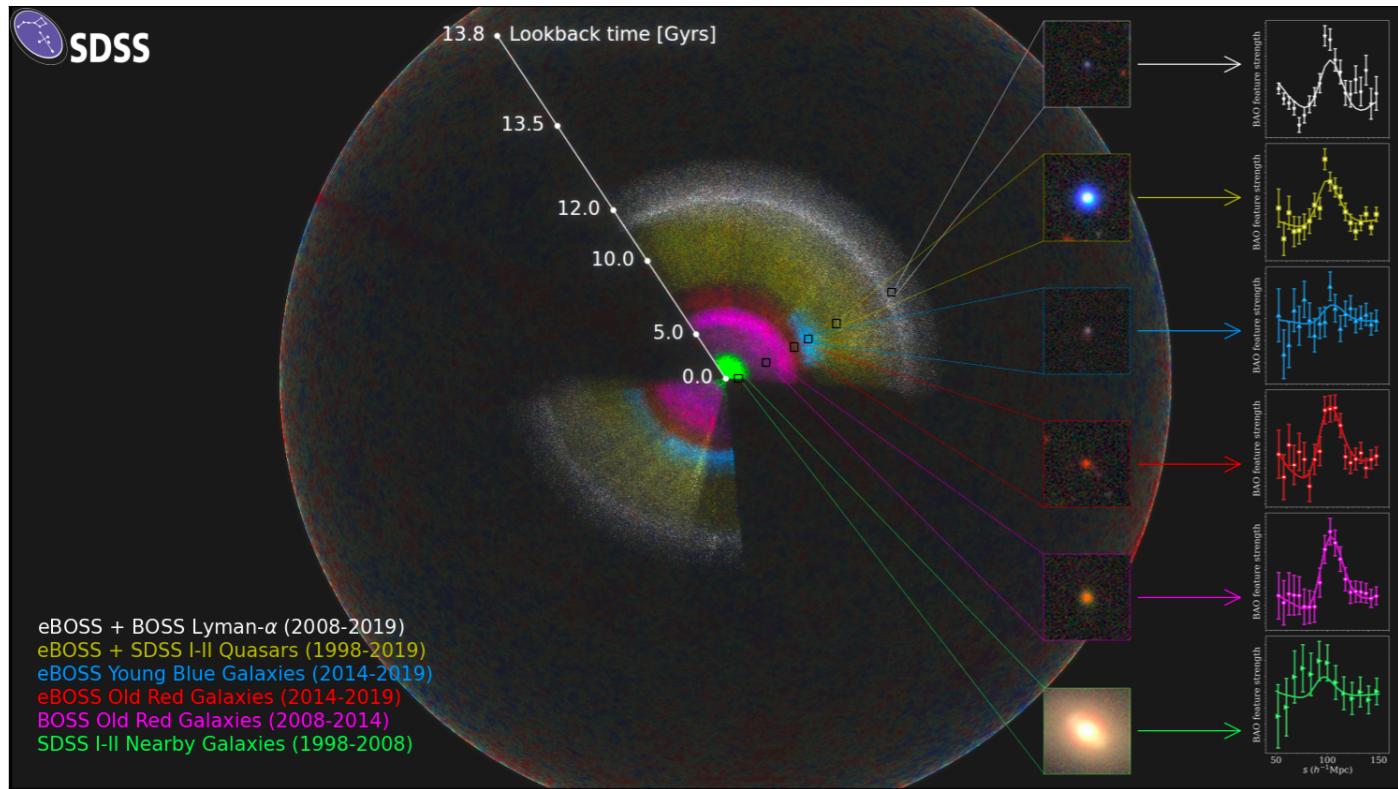
- Just taking the Eigen-vectors/values of an n-d space
 - Sorted by Eigenvalues, which give rank
 - Number of Eigenvalues above threshold is dimension



SDSS



SDSS

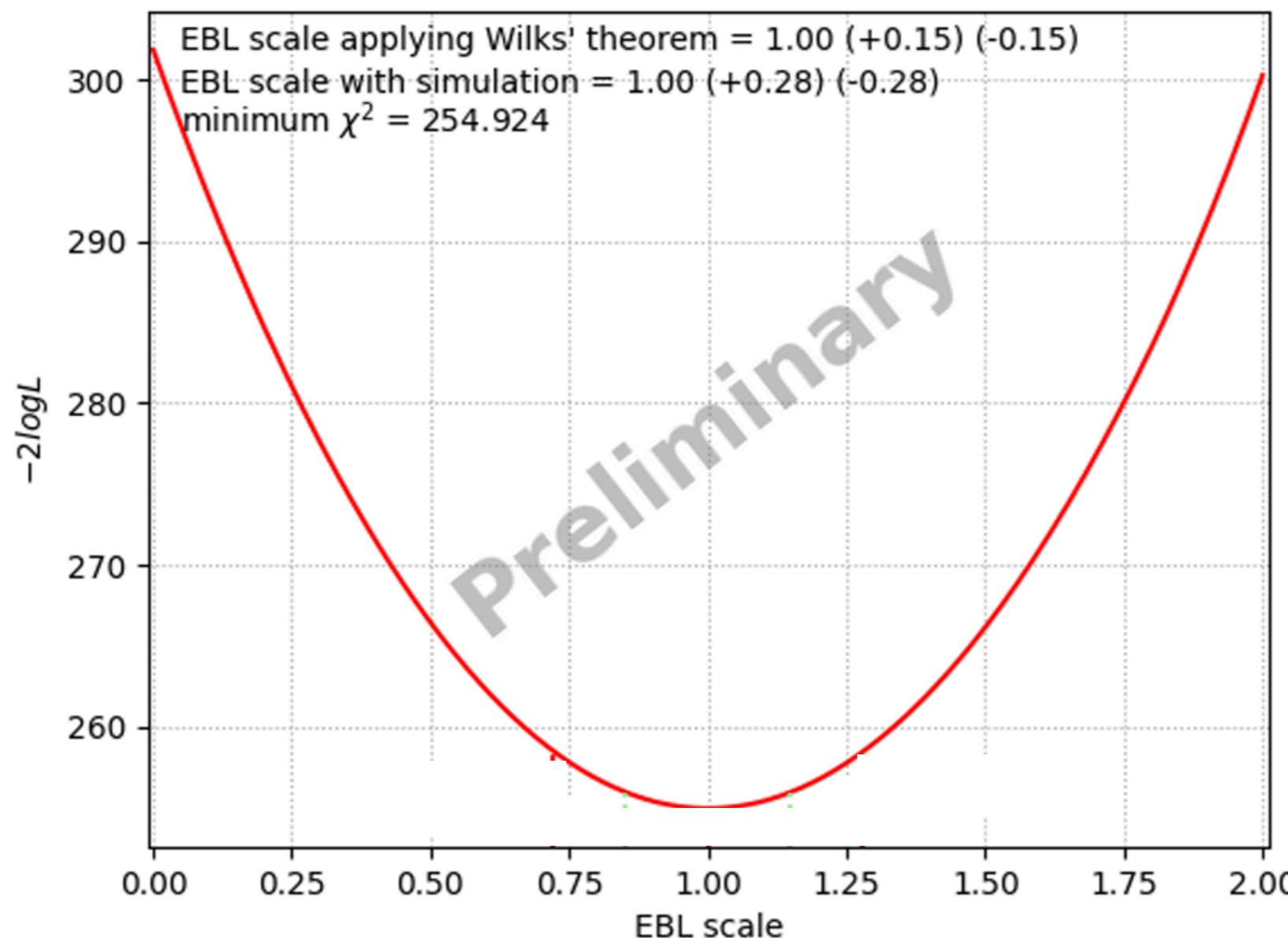


Fitting Checklist

- When I fit a function:
 - I minimize Log likelihood (usually approxed by chi2)
 - When I fit does the fit converge
 - Check the final chi2 value
 - ▶ Chi2/NDOF should be close to 1
 - ▶ Chi2 p-value should be good (5%-95%)
 - Look at the parameters
 - ▶ Do my uncertainties make sense? (Too small/large)
 - Are parameters moving far away from expected?
 - ▶ Should I do a 2D scan of the parameters?
 - How do I want to express my results?

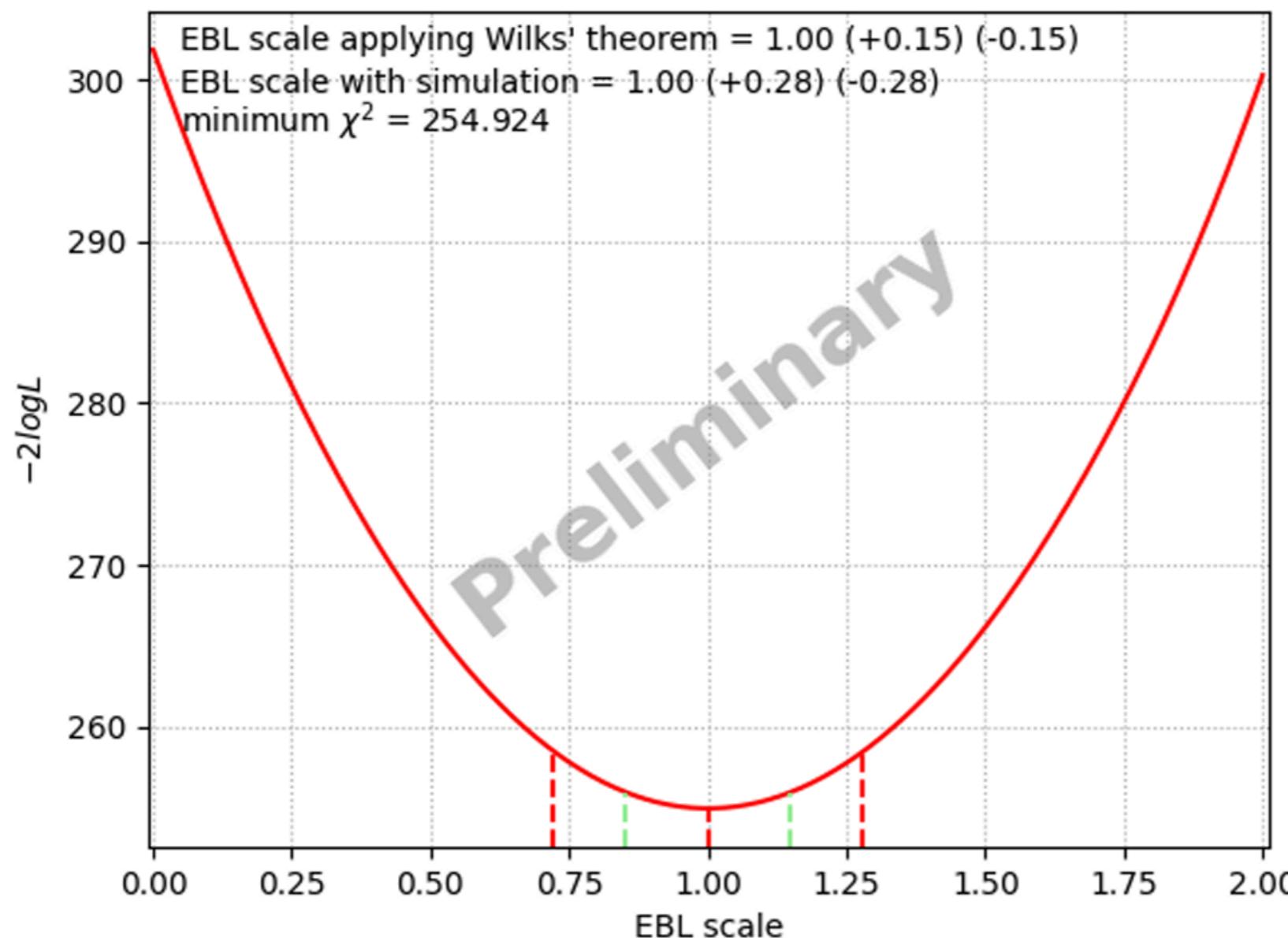
Recap

- For a minimization along 1D what is the best fit and minima?

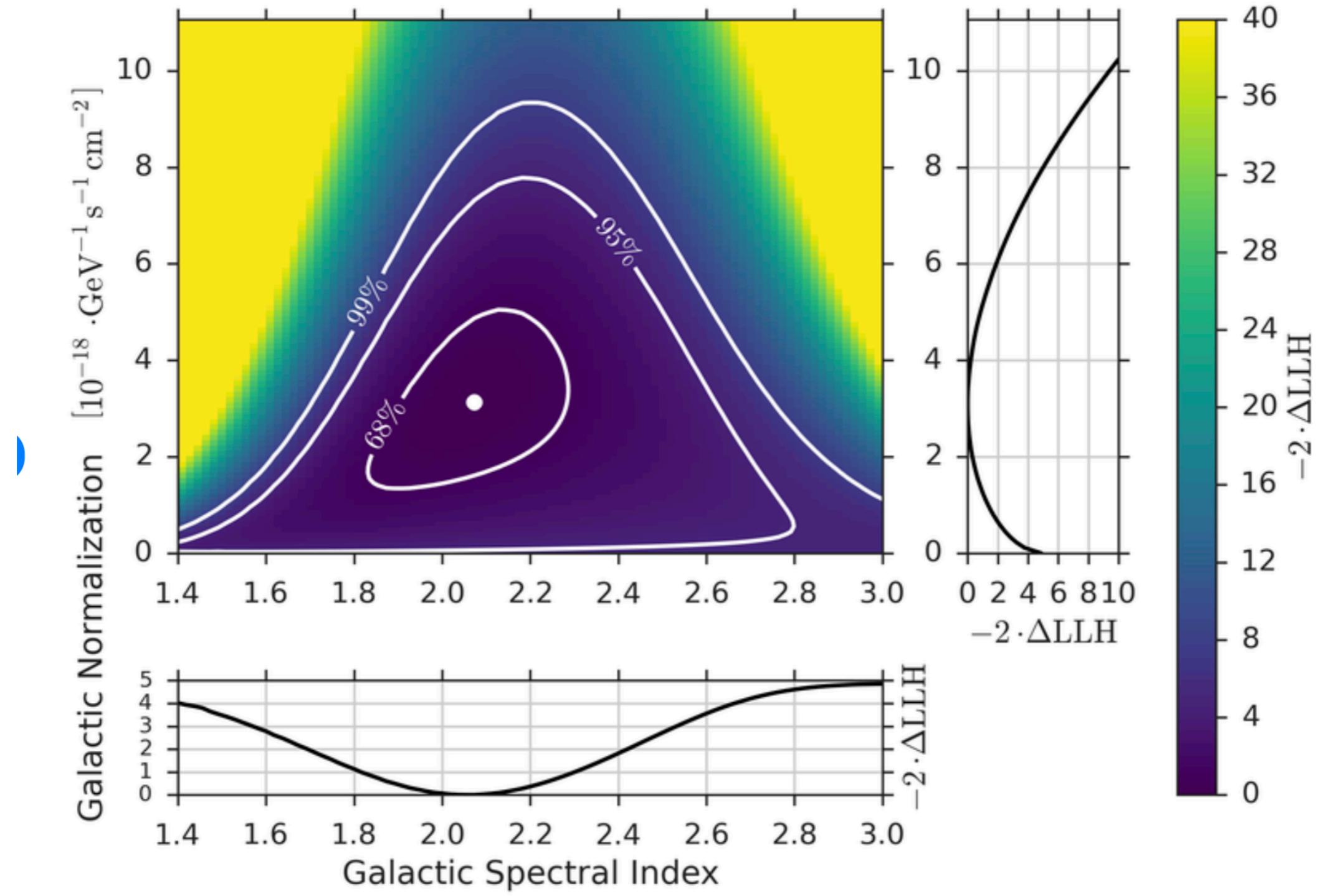


Recap

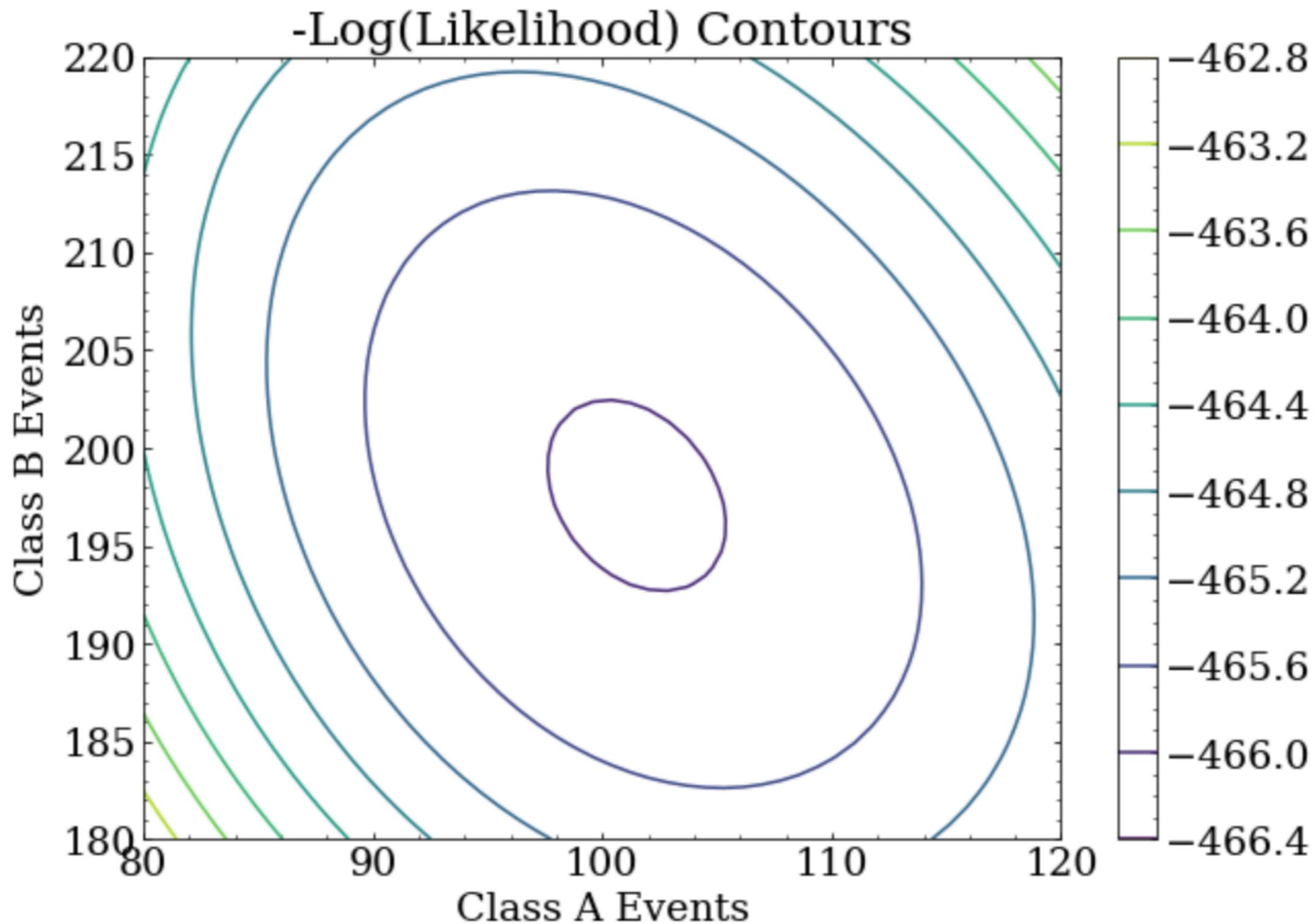
- Chi-2 of 1 Degree of freedom for a 1D profile



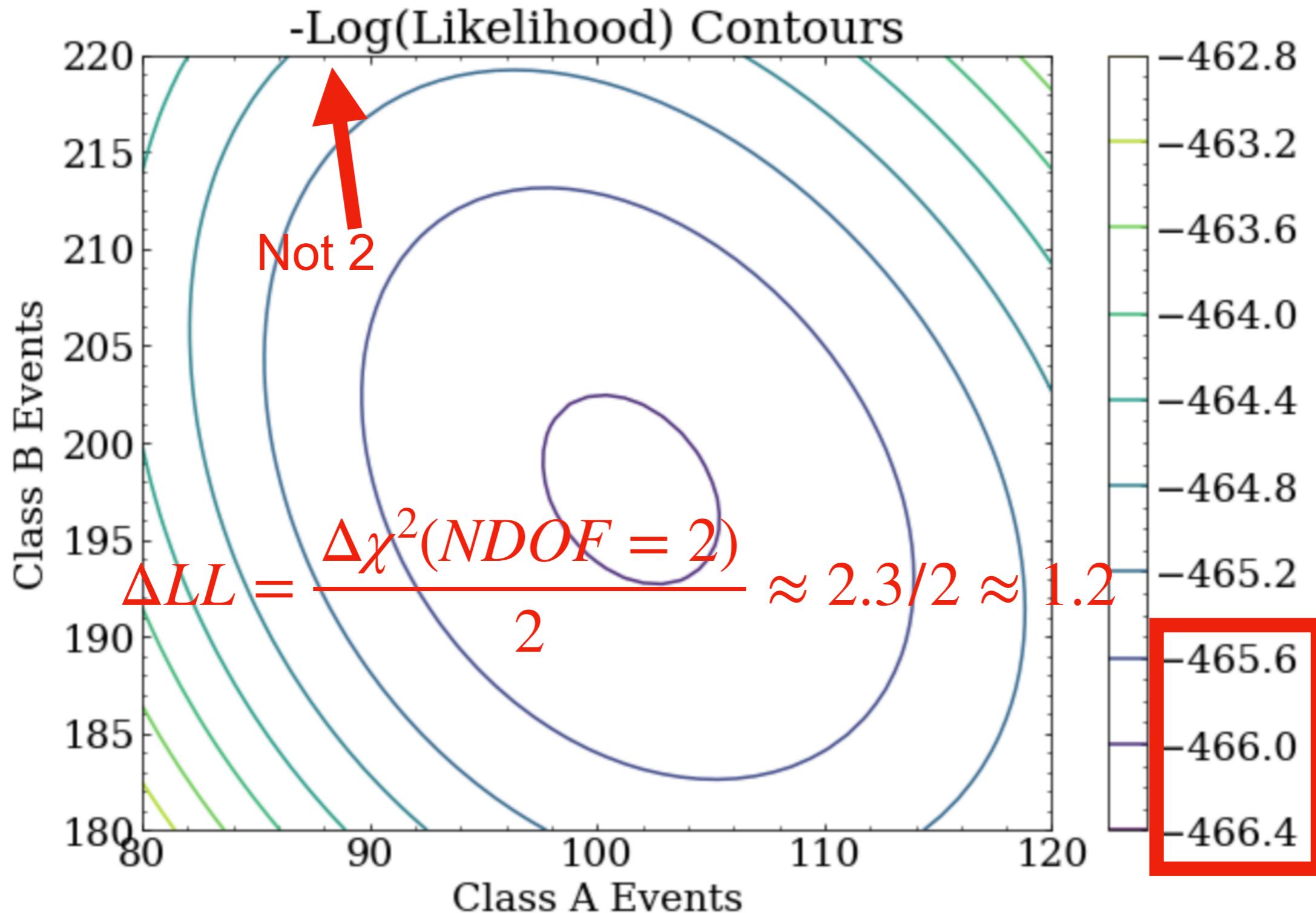
1D and 2D



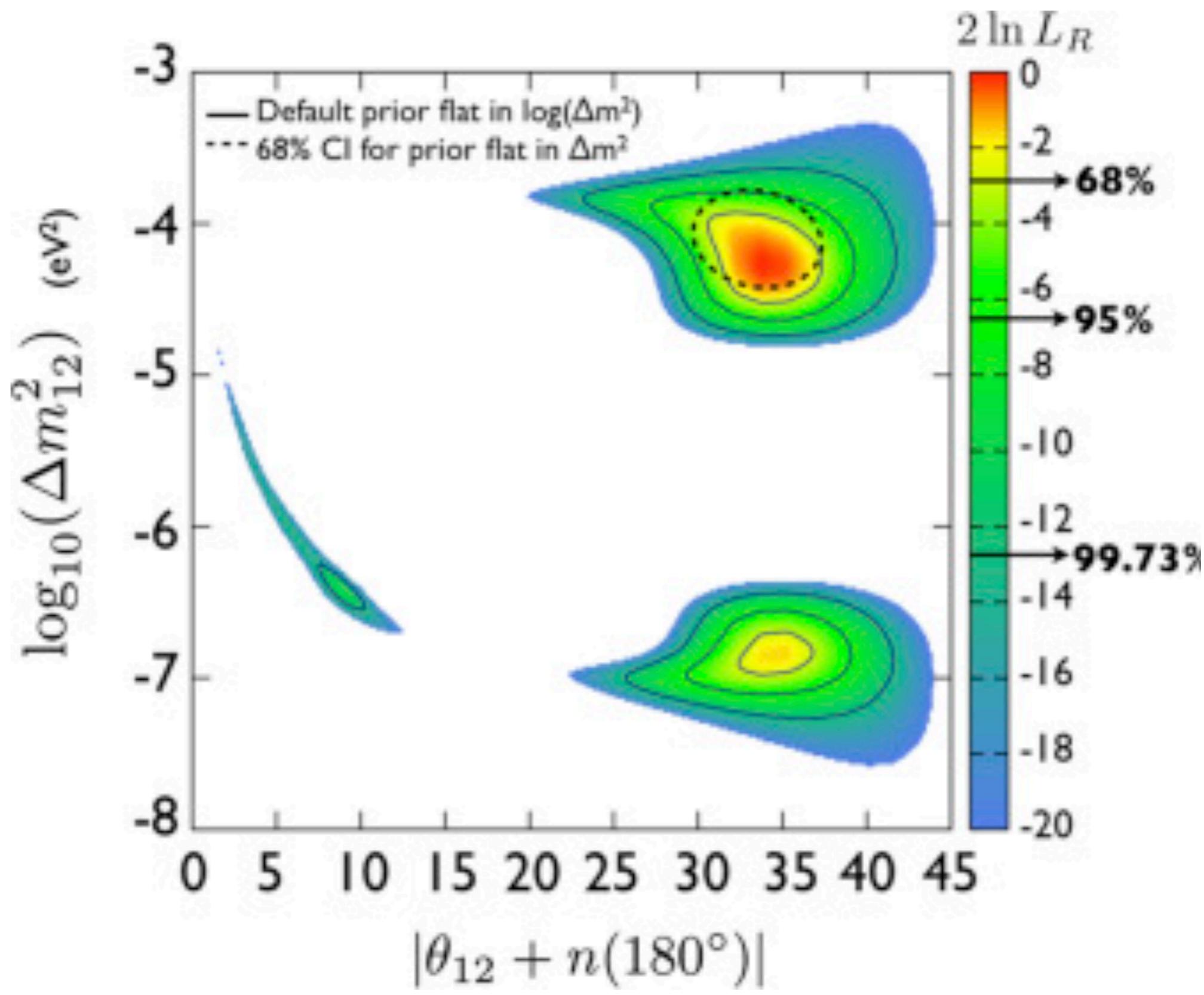
Which line for a 2D



Which line for a 2D

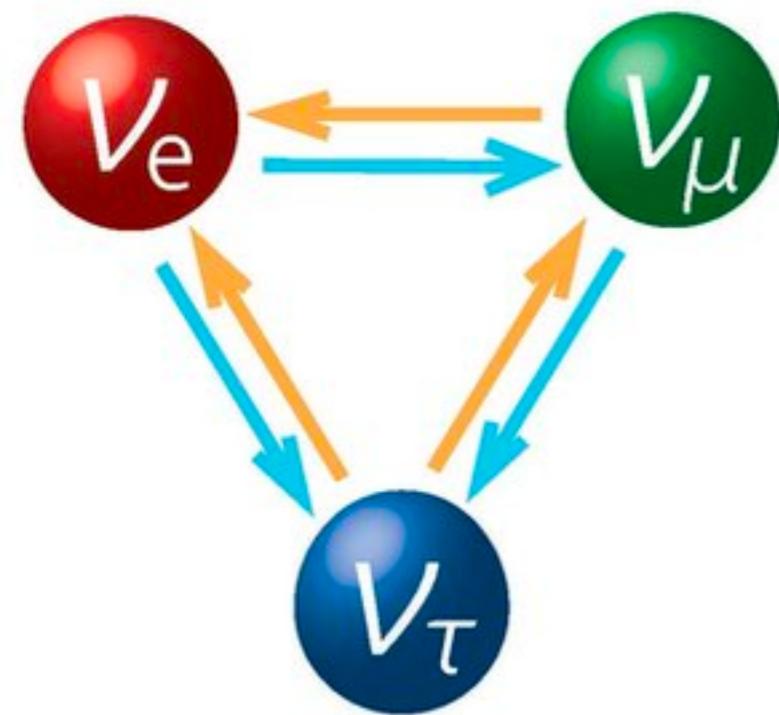


<https://www.sciencedirect.com/science/article/pii/S0168900214013953>



Fitting Checklist

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Neutrinos oscillate into other neutrinos

Nobel Prize

The Nobel Prize in Physics 2015

Takaaki Kajita
Arthur B. McDonald

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Takaaki Kajita

Prize share: 1/2



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Prize share: 1/2

- Nobel prize was recently awarded for neutrino oscillations
 - This is a second award on neutrino properties

Neutrino Mixing

Particle
Eigenstates

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \quad s_{ij} \equiv \sin \theta_{ij}, \quad c_{ij} \equiv \cos \theta_{ij}$$

$$| \nu_\alpha \rangle = \sum_{i=1}^3 U_{\alpha i}^* | \nu_i \rangle$$

Mass
Eigenstates

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrino Mixing

$$P_{\alpha \rightarrow \beta} = | < \nu_\beta(t) | \nu_\alpha(t) > |^2$$

$$= \left(\sum_{j=1}^3 U_{\beta j} U_{\alpha j}^* e^{-i \frac{m_j L}{2E}} \right) \left(\sum_{i=1}^3 U_{\beta i}^* U_{\alpha i} e^{i \frac{m_j L}{2E}} \right)$$

As we evolve over time the particle eigenstates oscillate through the mass states

$$P_{\alpha \rightarrow \beta} = \delta_{\alpha \beta} - 4 \sum_{i>j} \Re[U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*] \sin^2 \left(\frac{\Delta m_{ij}^2}{4E} L \right)$$

$$+ 2 \sum_{i>j} \Im[U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*] \sin^2 \left(\frac{\Delta m_{ij}^2}{2E} L \right)$$

Neutrino Mixing

Master Formula

$$P_{\mu \rightarrow \mu} \simeq 1 - 4s_{23}^2 c_{23}^2 (s_{12}^2 + c_{12}^2) \sin^2 \left(\frac{1.27 \Delta m_{atm.}^2}{E} L \right)$$

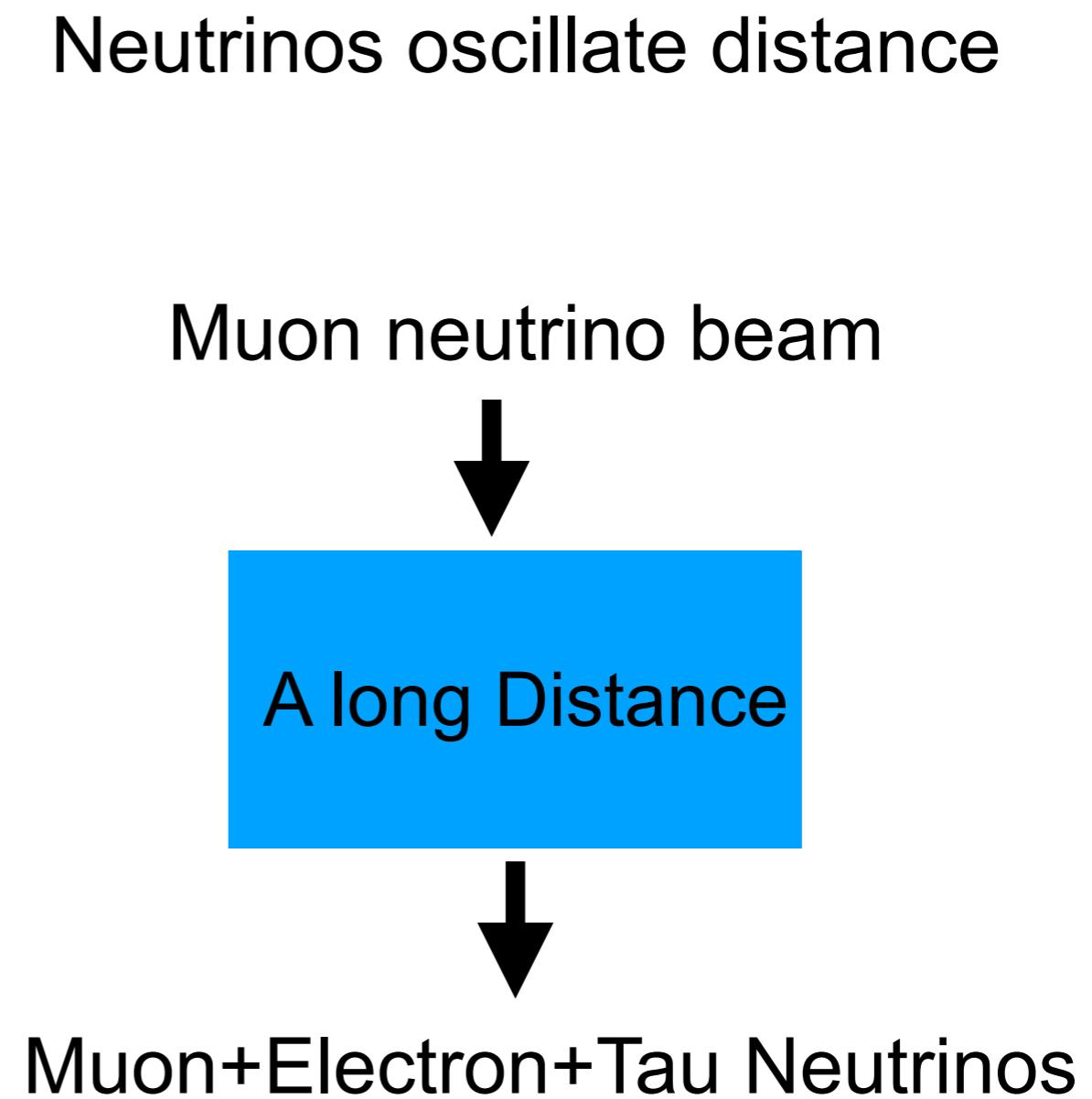
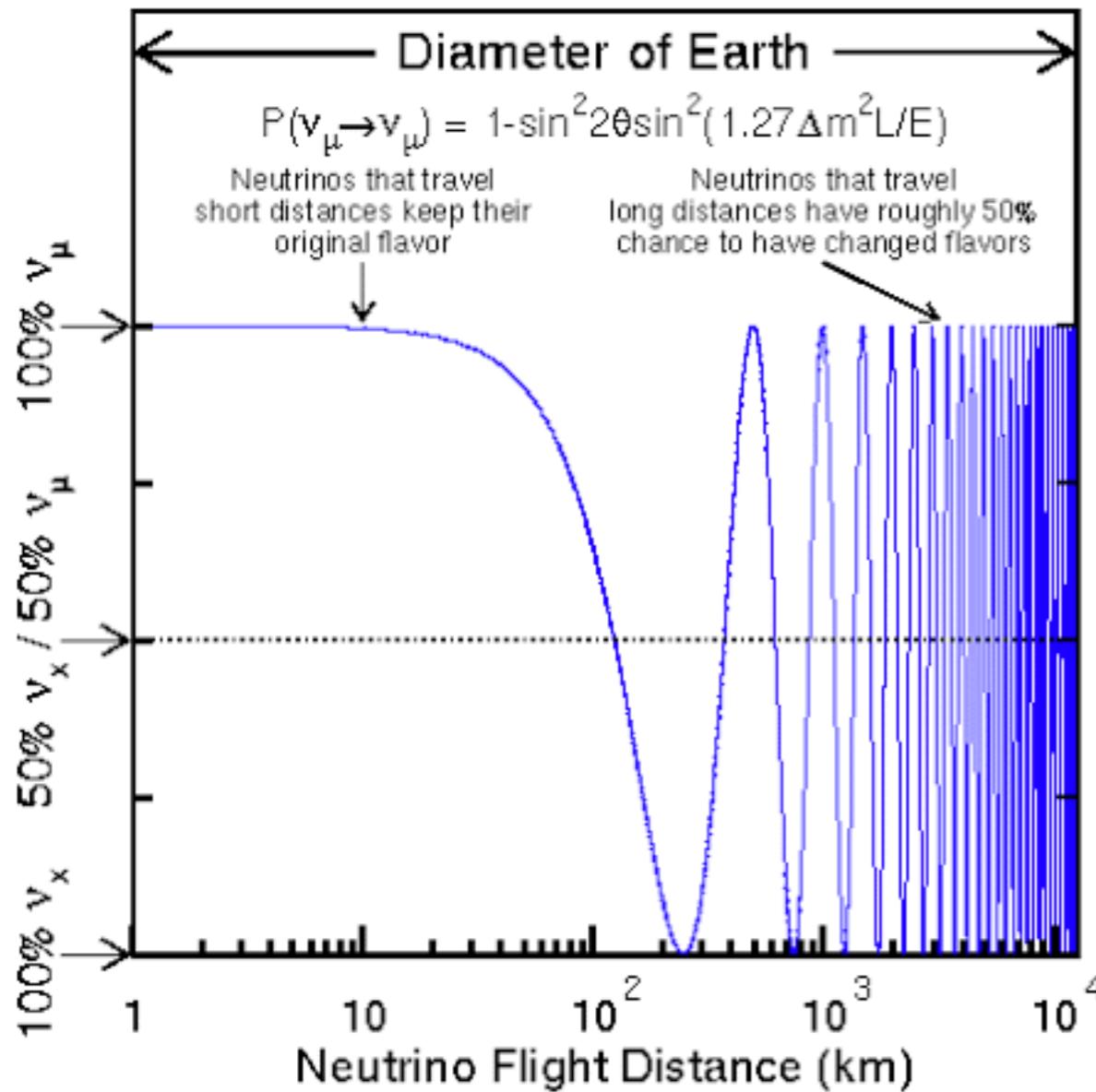
$$\simeq 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{1.27 \Delta m_{atm.}^2}{E} L \right),$$

As we evolve over time the particle eigenstates oscillate through the mass states

$$P_{\alpha \rightarrow \beta} = \delta_{\alpha \beta} - 4 \sum_{i>j} \Re[U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*] \sin^2 \left(\frac{\Delta m_{ij}^2}{4E} L \right)$$

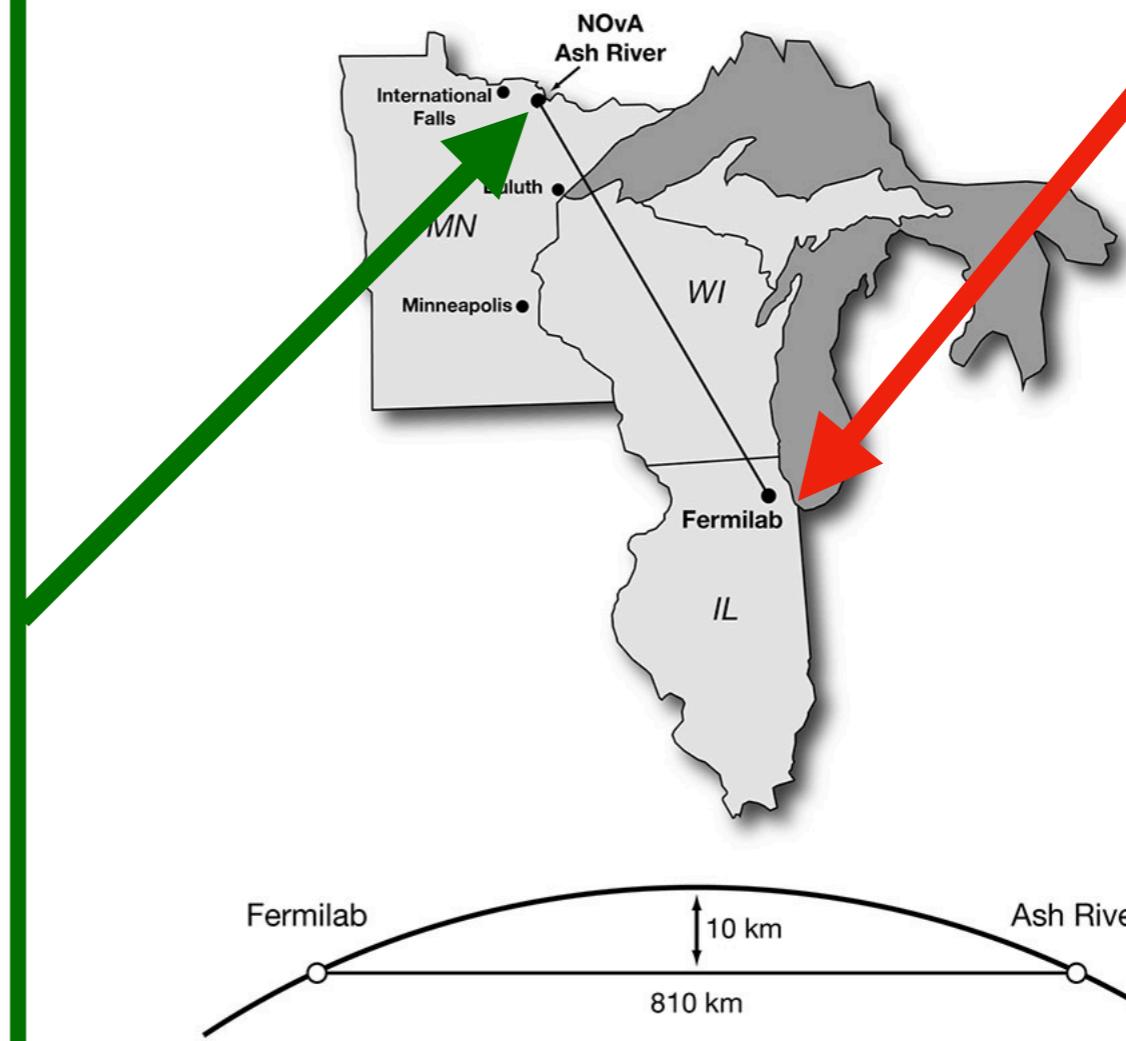
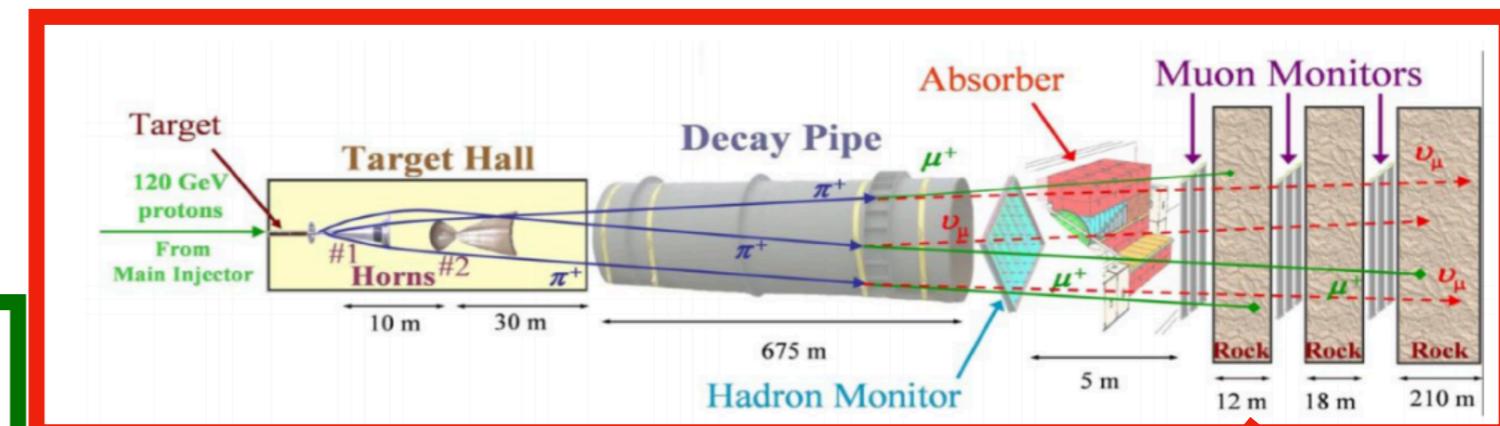
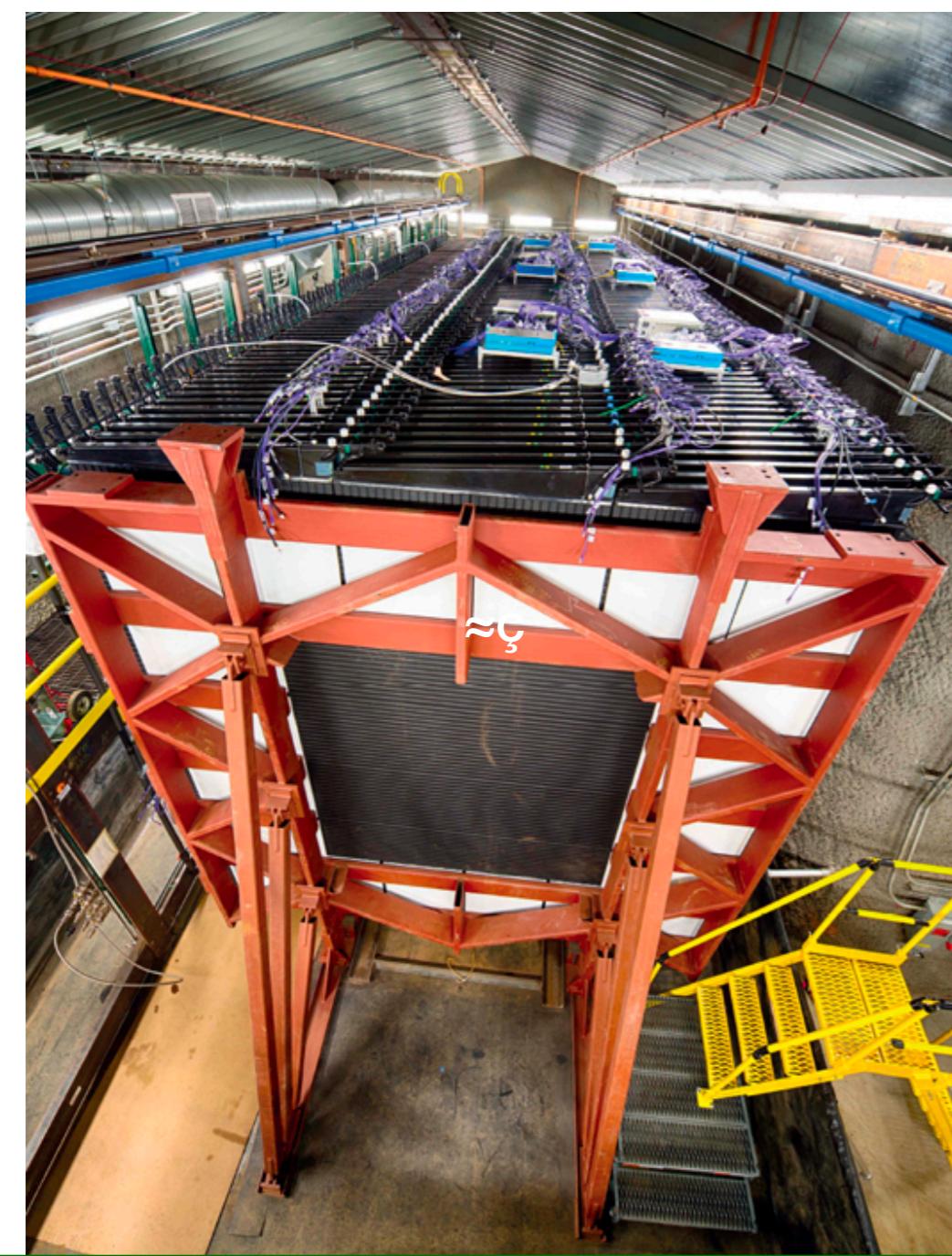
$$+ 2 \sum_{i>j} \Im[U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*] \sin^2 \left(\frac{\Delta m_{ij}^2}{2E} L \right)$$

Observing Oscillations

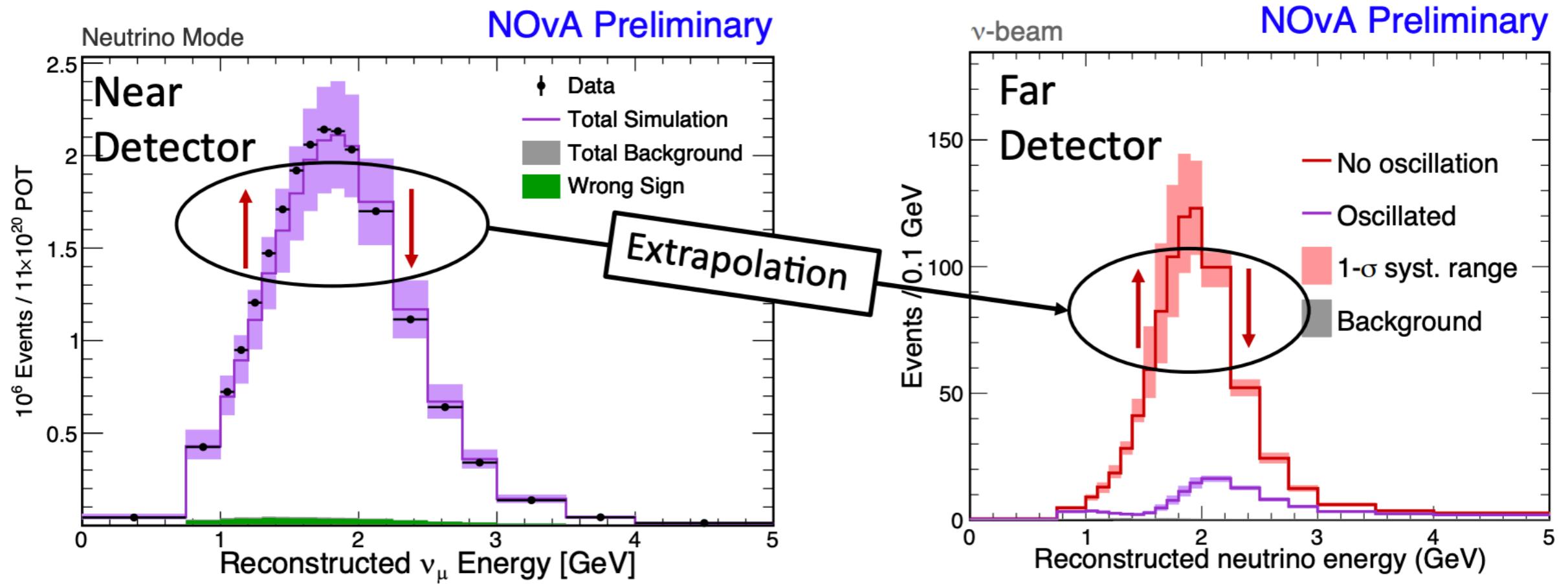


NOvA Detector

Neutrino Beam
From Fermilab (Near Chicago)
To Minnesota (Near Canada)

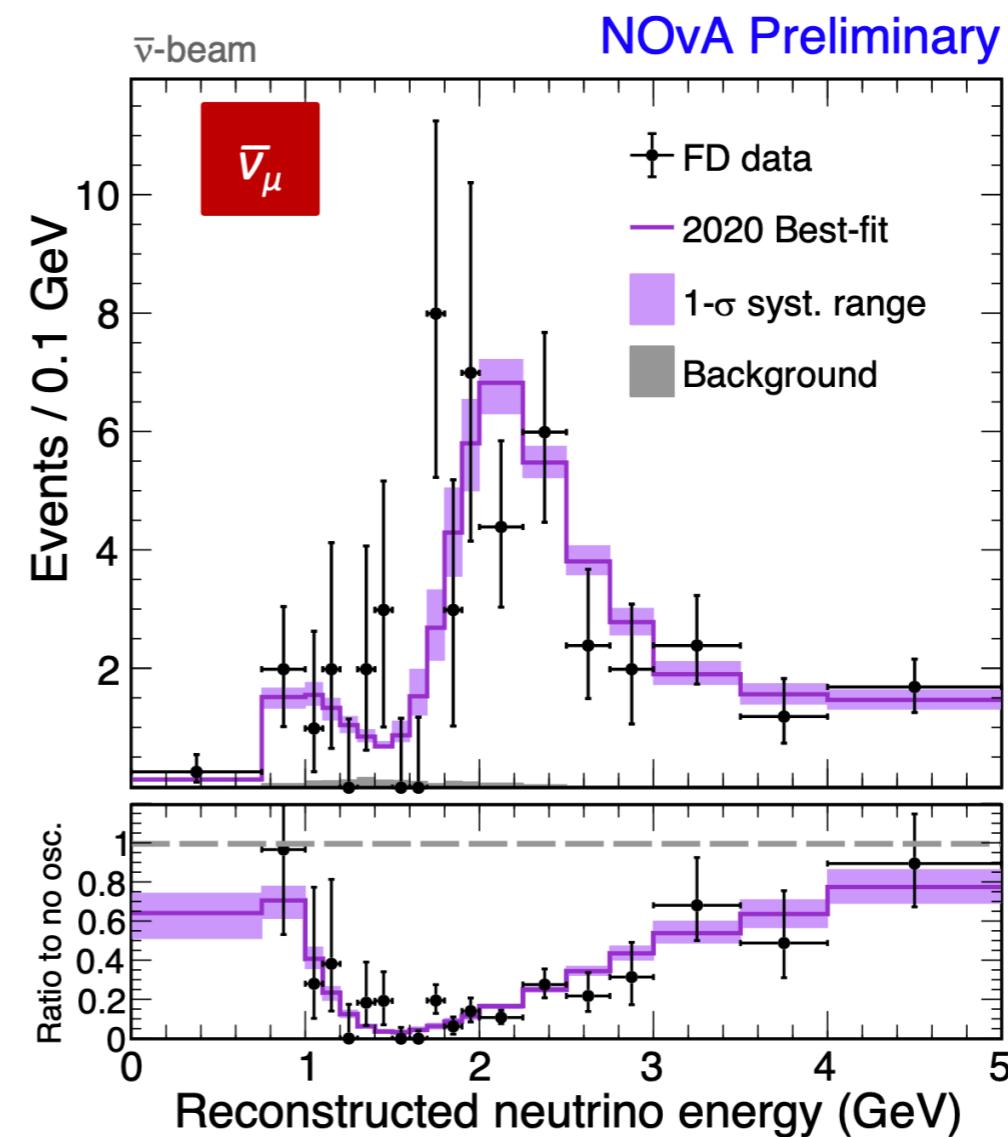
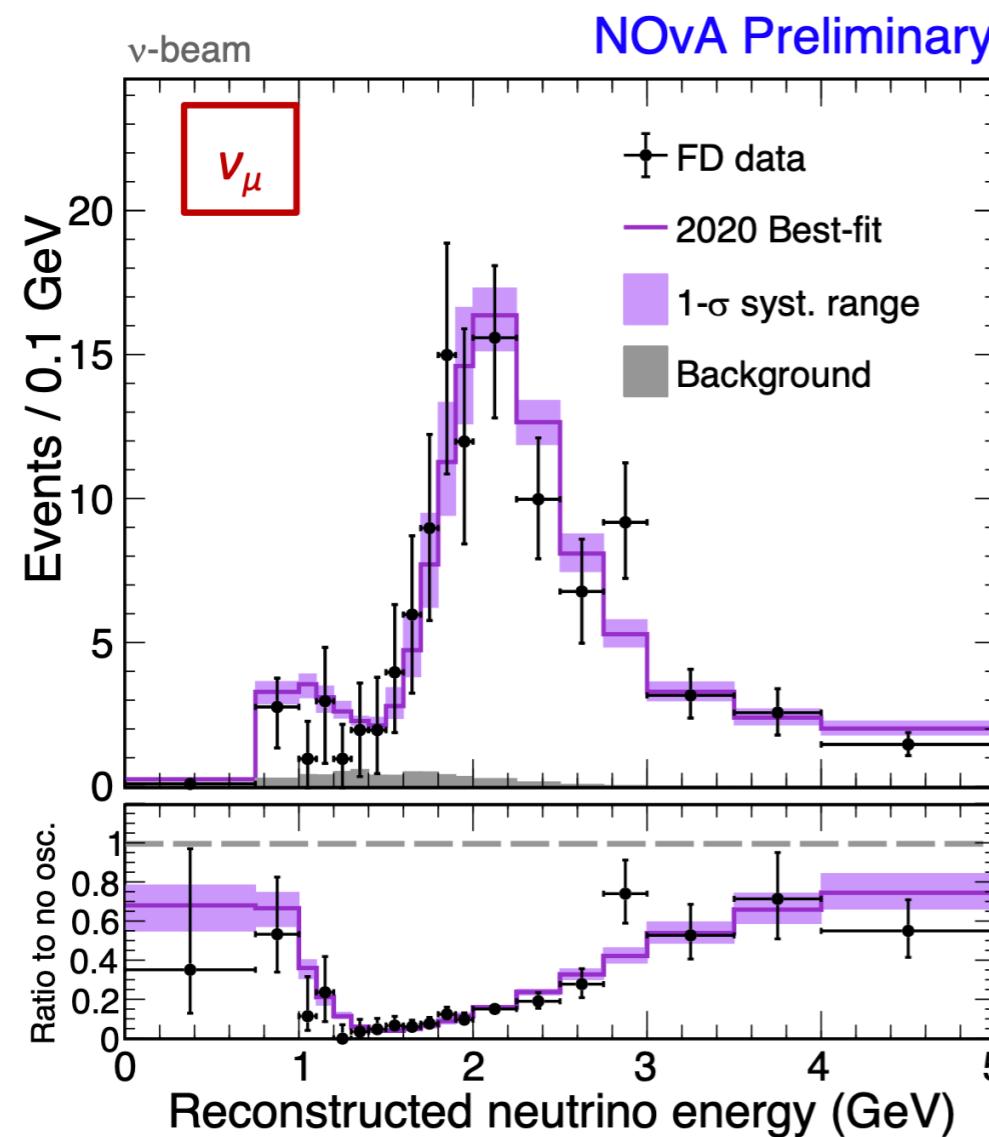


NOvA Data



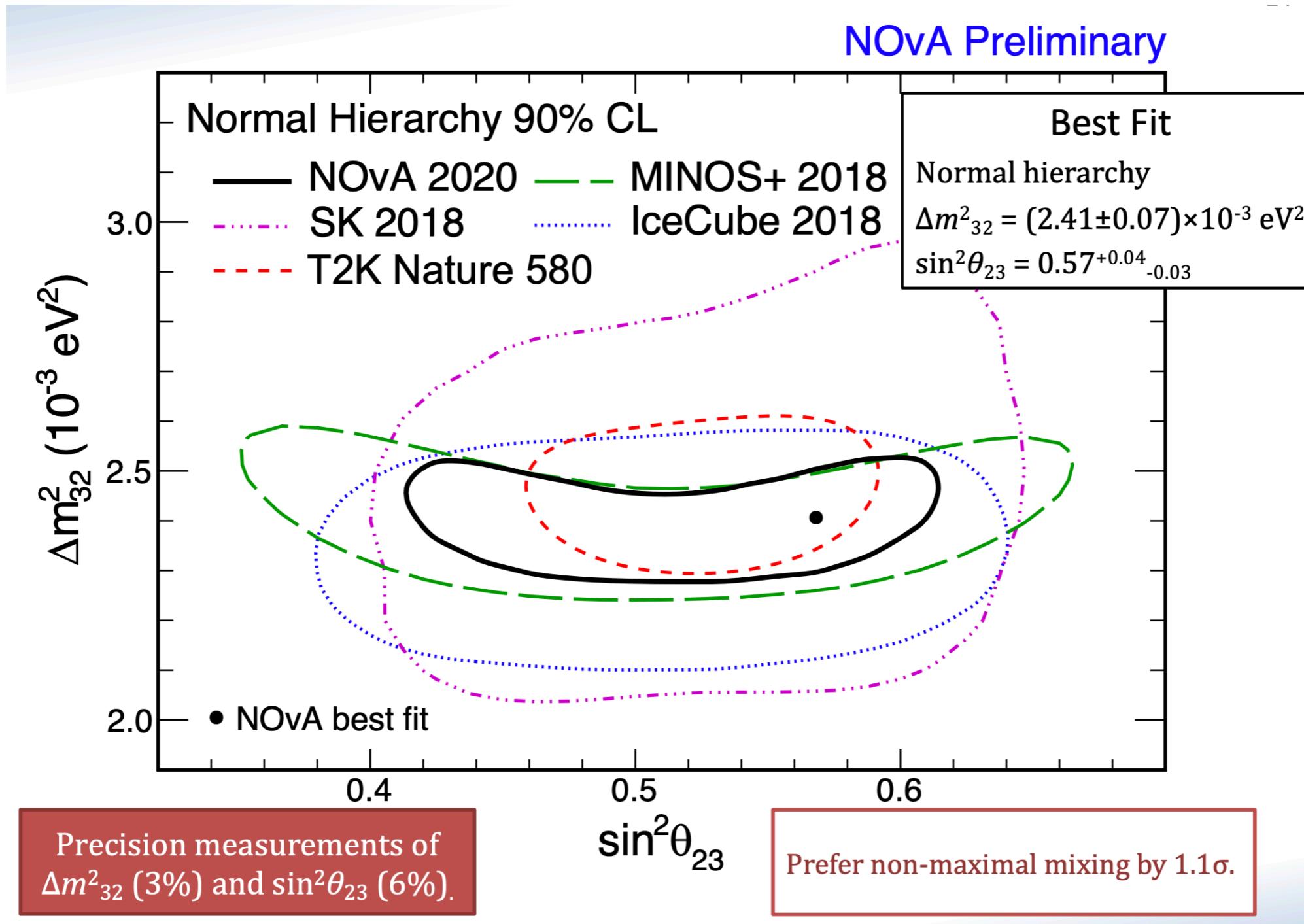
- With the input detector we can predict the output dist
 - In this way we predict it without any oscillations
 - The oscillation depends on our formula

NOvA Data



- With the input detector we can predict the output dist
-

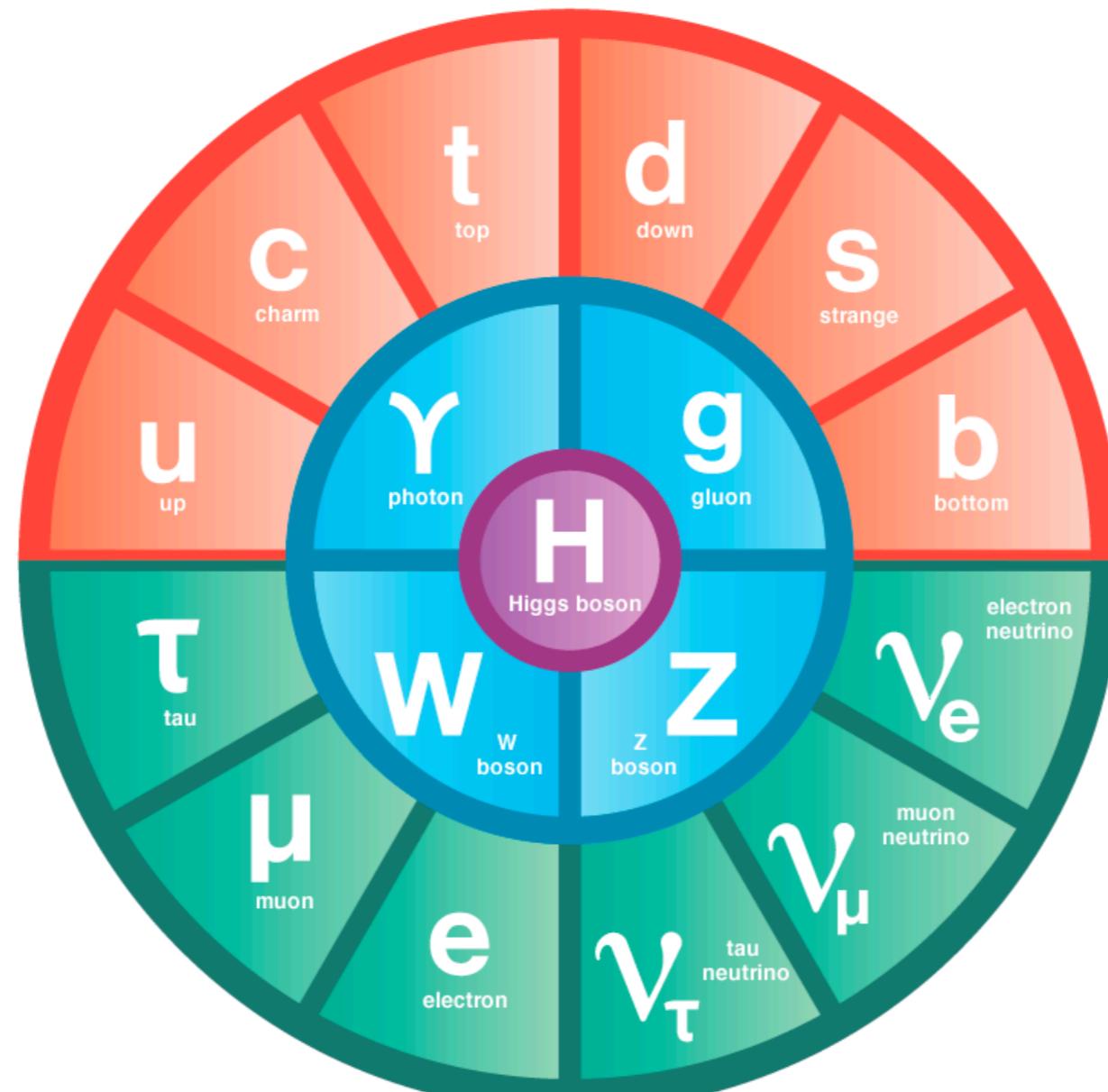
NOvA Result



- From those plots: Lets look at those results

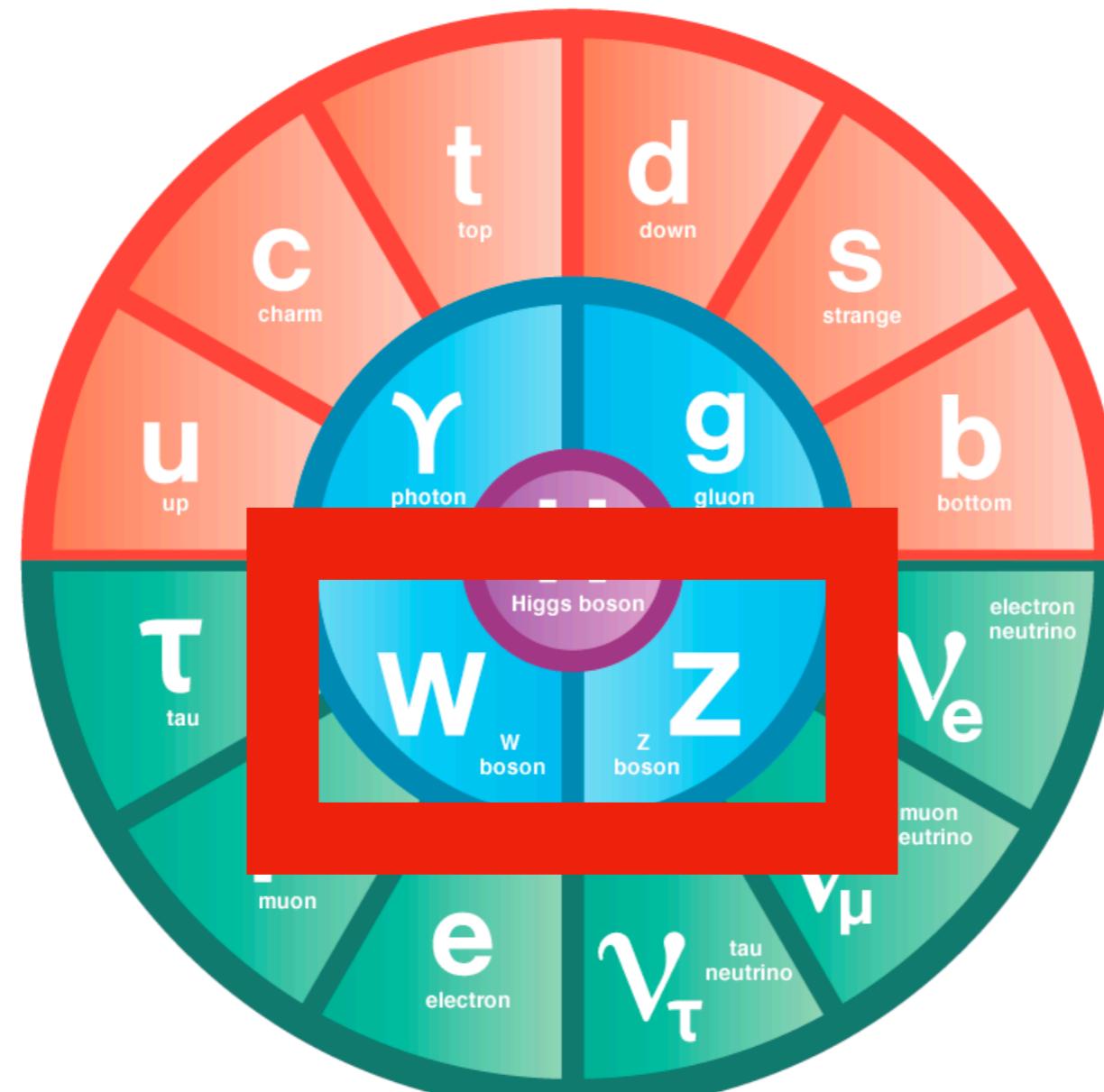
Laboratory

- The challenge of this lab is to fin the W and Z boson



Laboratory

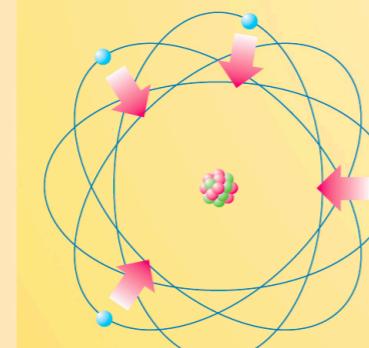
- The challenge of this lab is to fin the W and Z boson
 - These are the particles that cover the Weak Boson Interaction



Fundamental Forces

The Four Fundamental Forces of Nature

Electro-magnetism



Weak Interaction



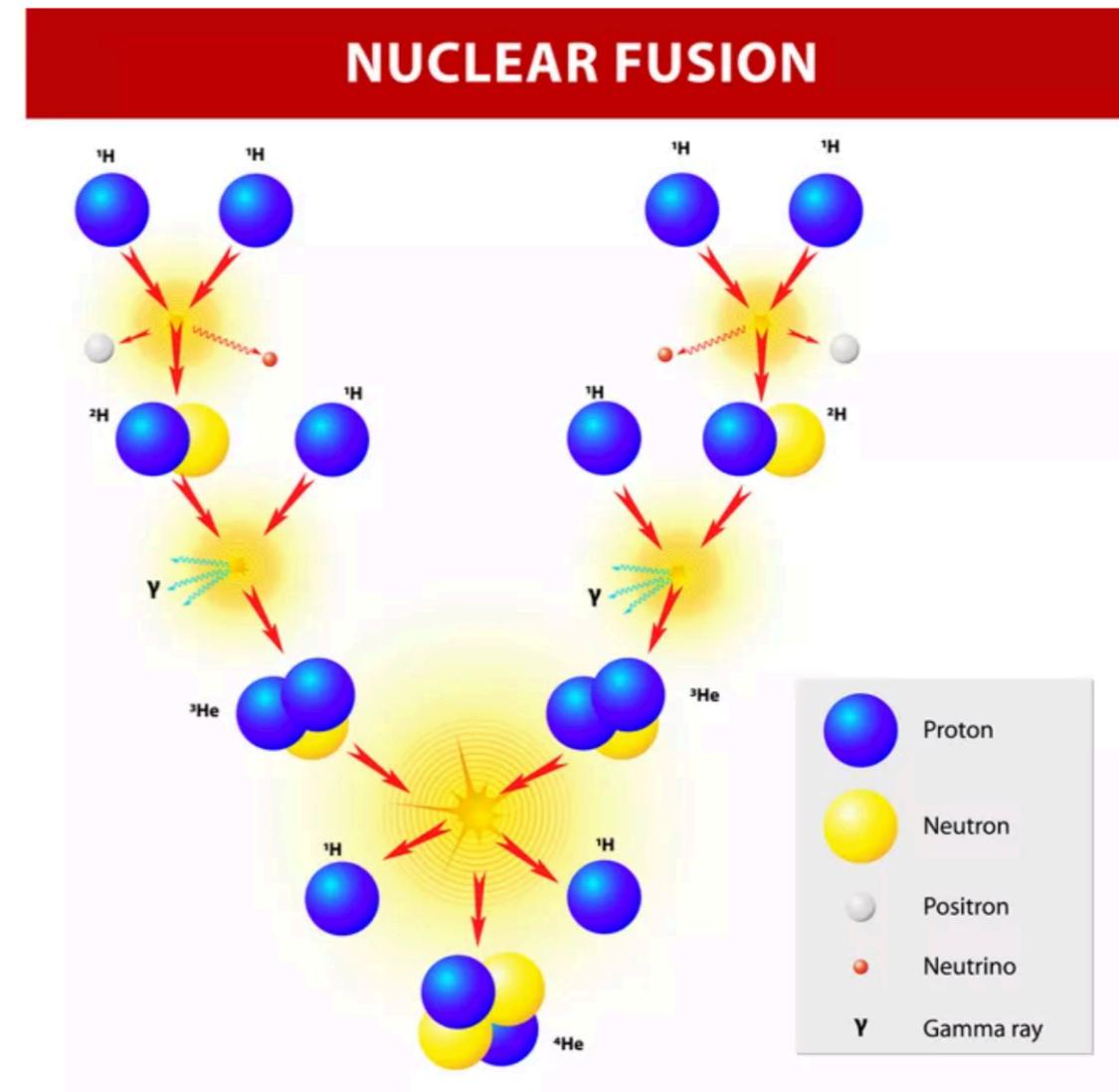
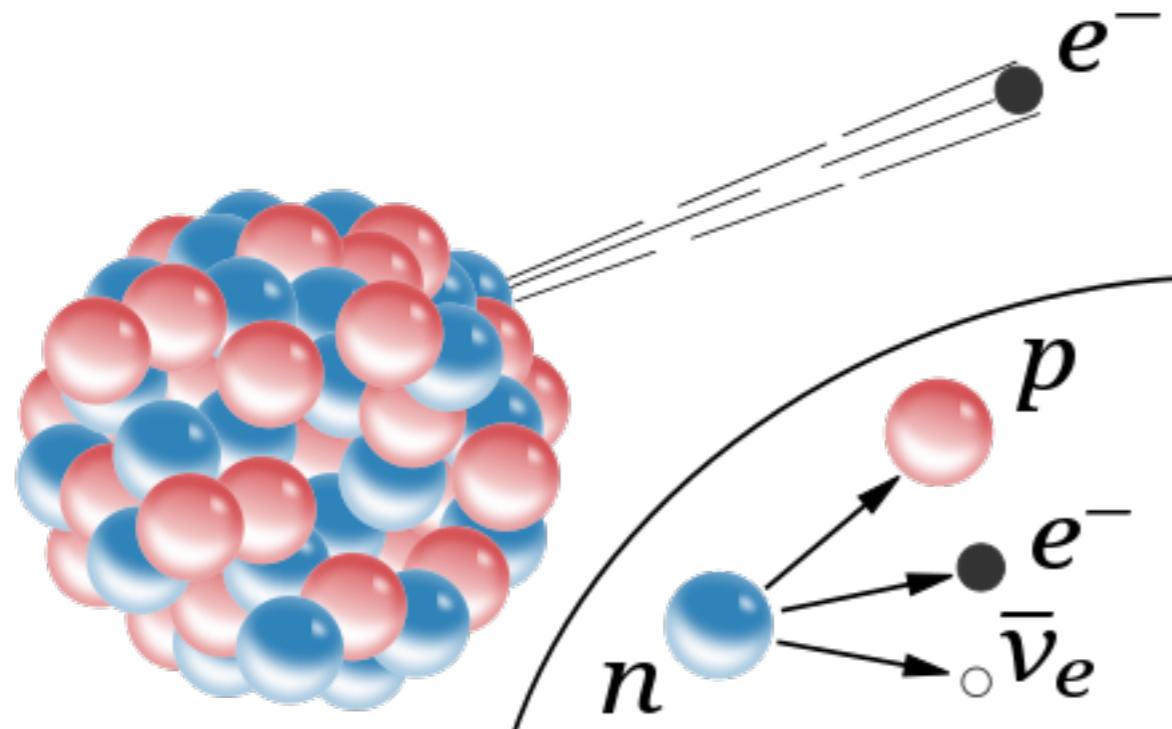
Strong Interaction



Gravitation

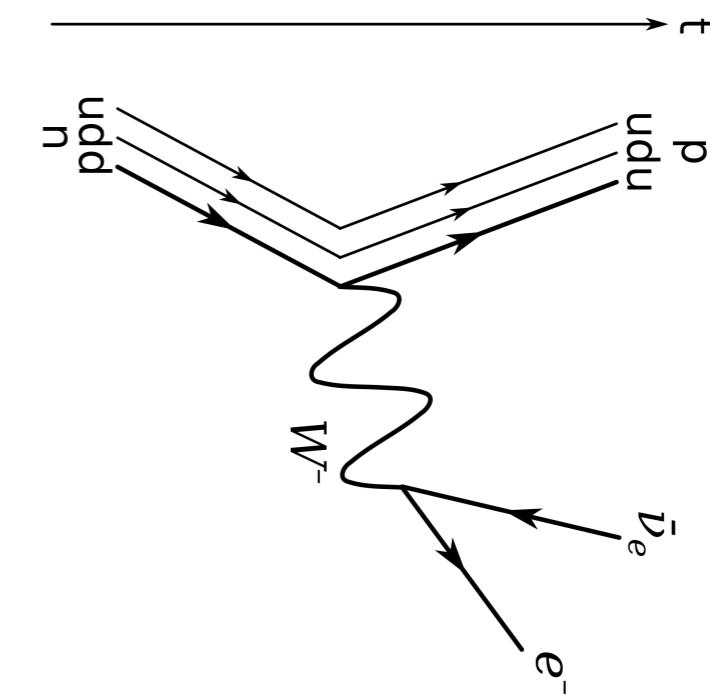
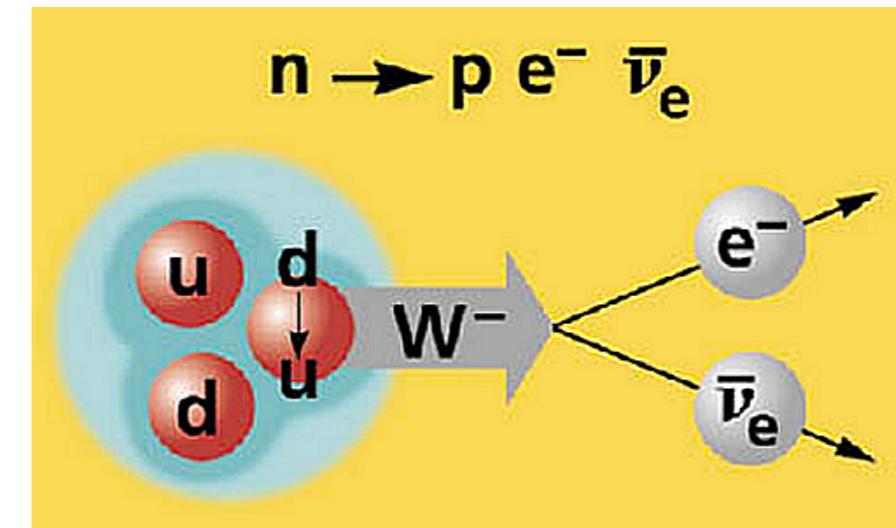
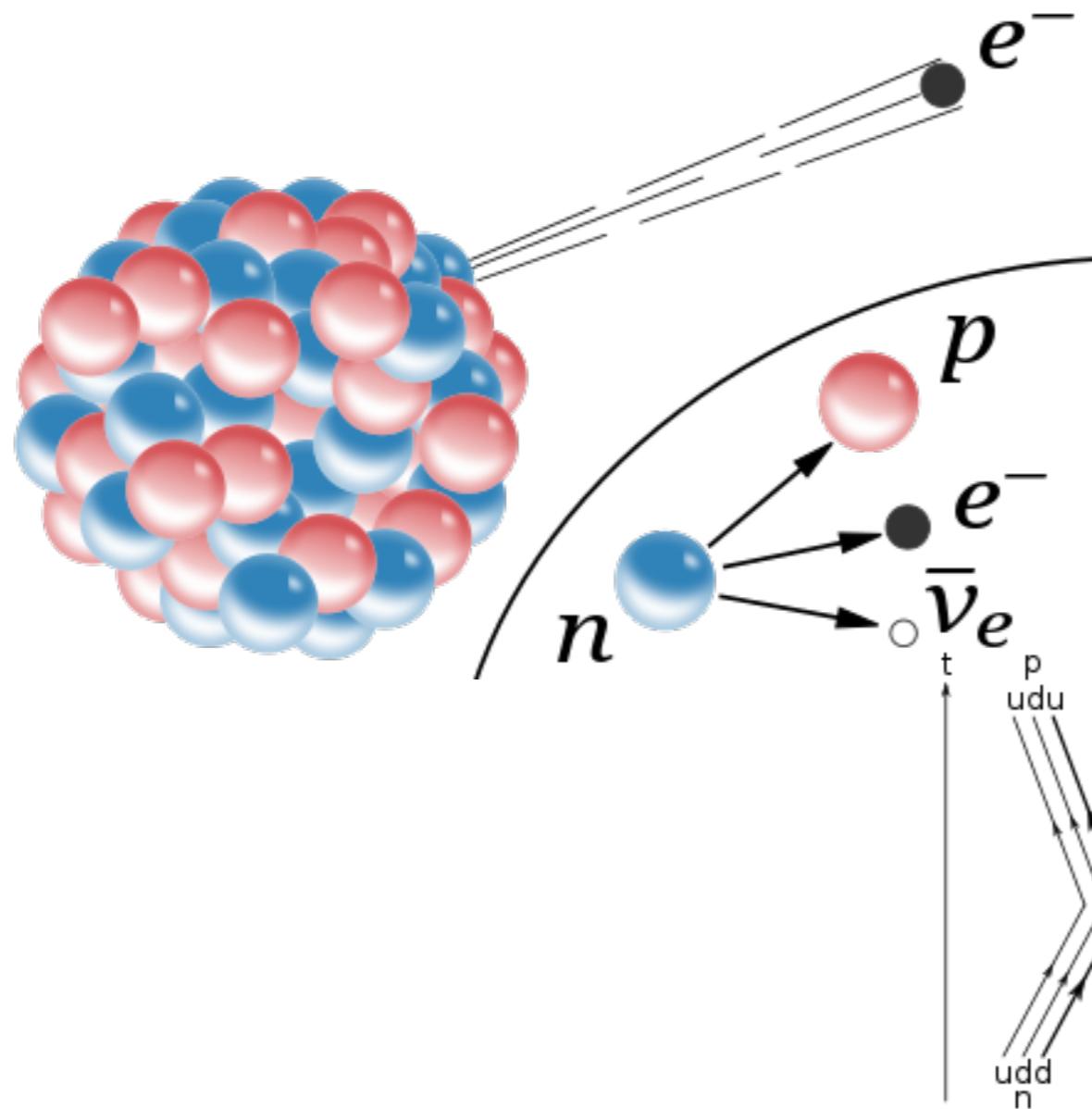


Weak Interactions



- The Weak interaction is described by W and Z bosons

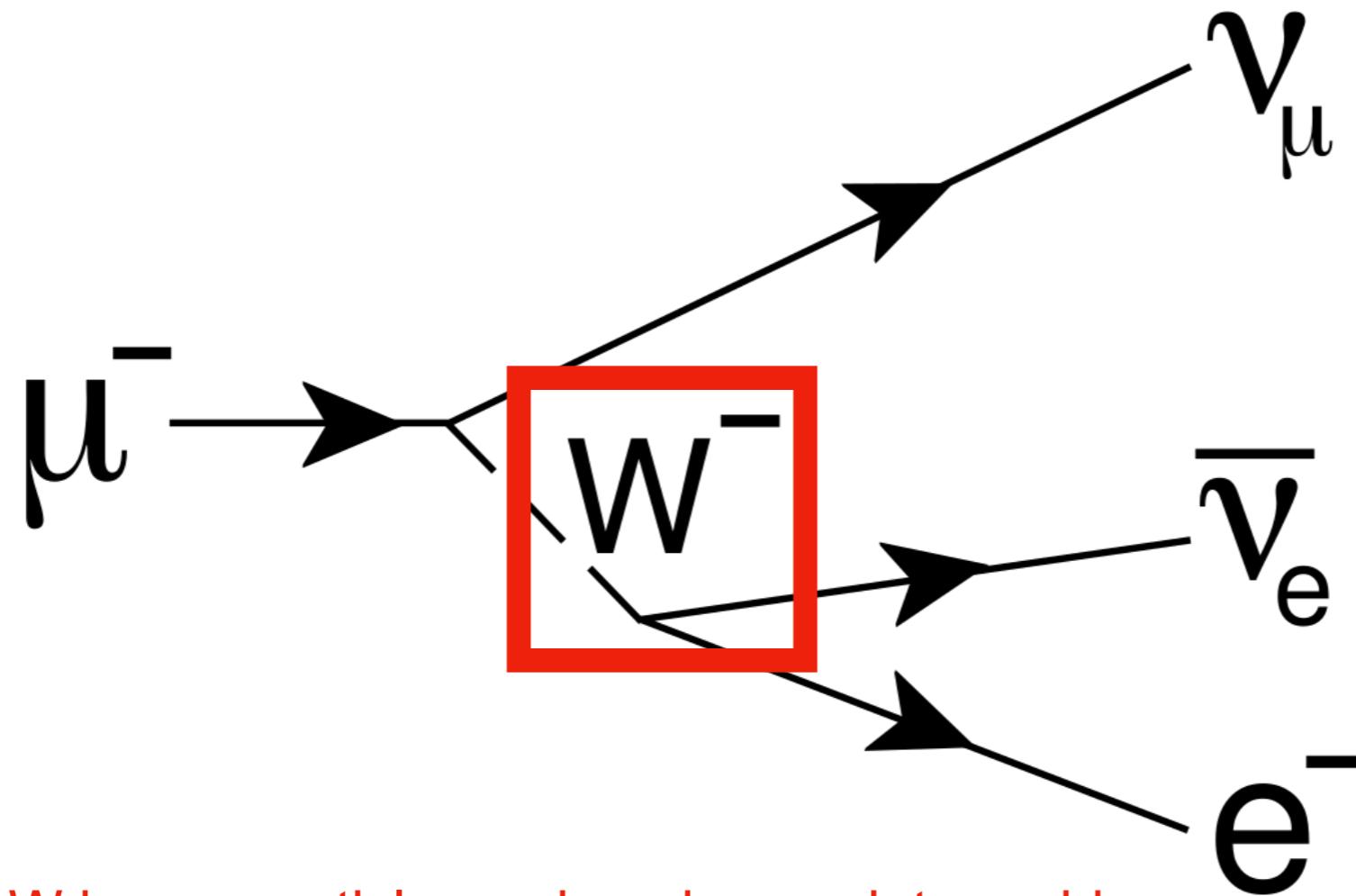
Weak Interactions



- The Weak interaction is described by W and Z bosons

What really is this?

- Weak interaction is actually a very strong interaction
 - Its just mediated by a heavy particle



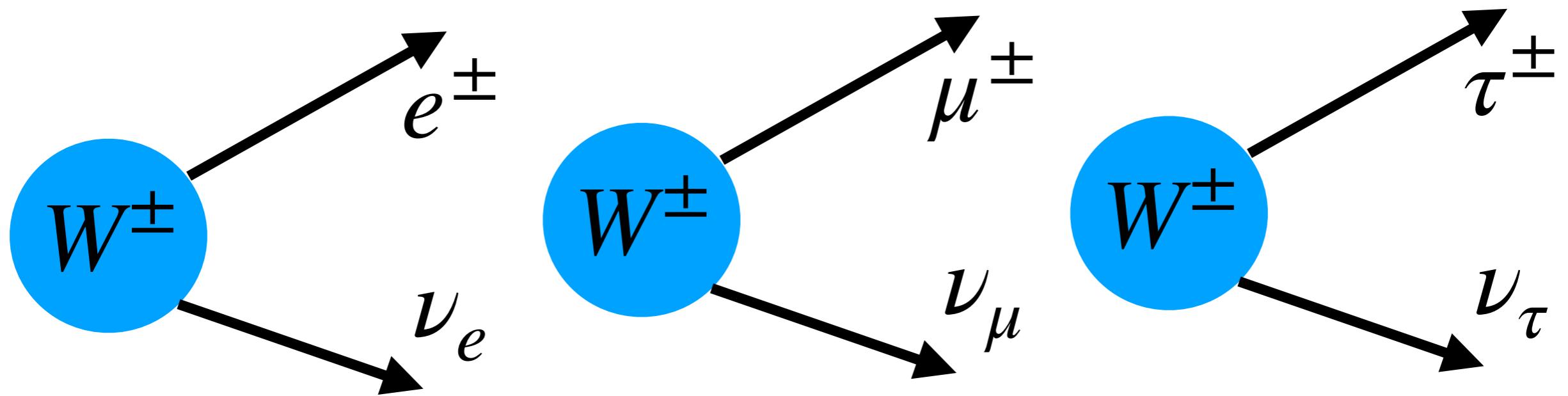
Heavy W boson particle produced as an intermediary

All the Fundamental² Particles

Standard Model of Elementary Particles

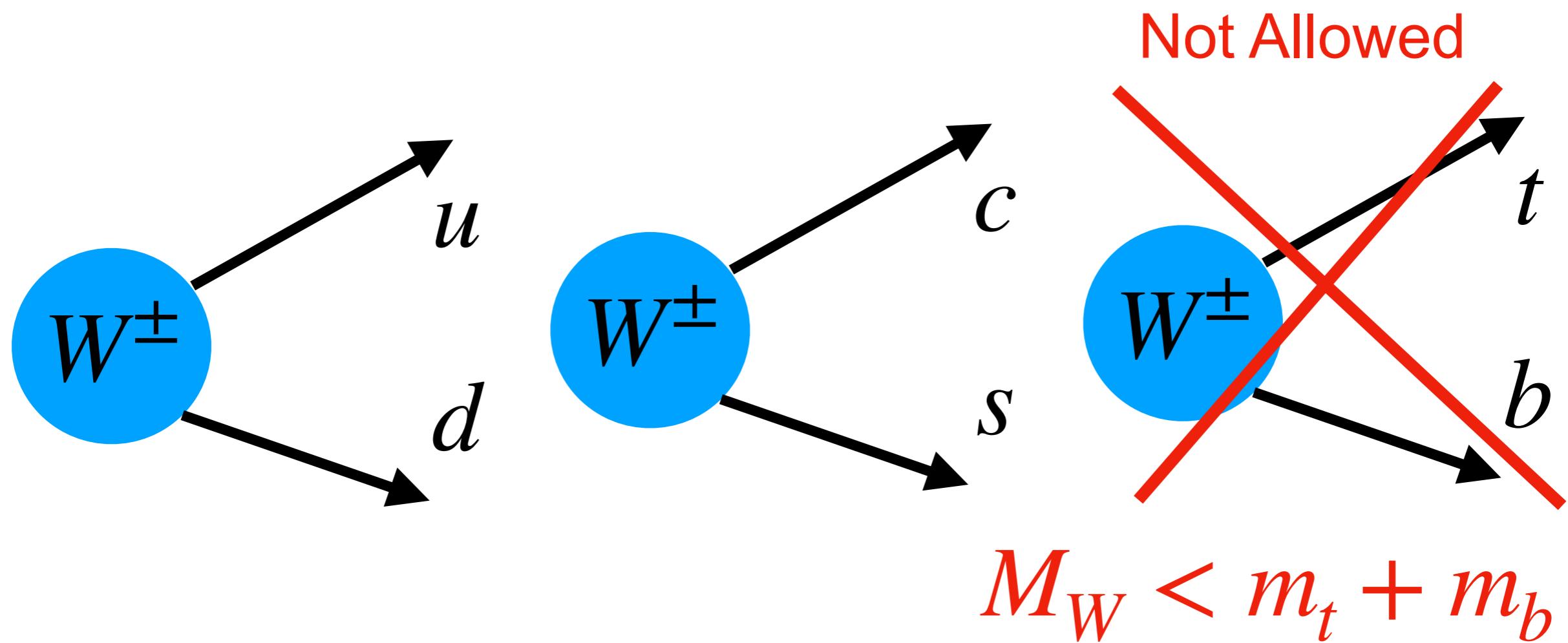
three generations of matter (fermions)					interactions / force carriers (bosons)	
QUARKS	I	II	III			
	mass $\approx 2.2 \text{ MeV}/c^2$	mass $\approx 1.28 \text{ GeV}/c^2$	mass $\approx 173.1 \text{ GeV}/c^2$	charge $2/3$	charge $2/3$	charge $2/3$
u up	$2/3$	$2/3$	$2/3$	0	0	0
d down	$-1/3$	$-1/3$	$-1/3$	1	1	1
LEPTONS	e electron	$0.511 \text{ MeV}/c^2$	$105.66 \text{ MeV}/c^2$	-1	-1	-1
	ν_e electron neutrino	$<1.0 \text{ eV}/c^2$	$<0.17 \text{ MeV}/c^2$	$1/2$	$1/2$	$1/2$
	μ muon	$105.66 \text{ MeV}/c^2$	$1.7768 \text{ GeV}/c^2$	0	0	0
	ν_μ muon neutrino	$<0.17 \text{ MeV}/c^2$	$<18.2 \text{ MeV}/c^2$	$1/2$	$1/2$	$1/2$
GAUGE BOSONS VECTOR BOSONS			Z boson	$91.19 \text{ GeV}/c^2$	0	1
SCALAR BOSONS			W boson	$80.39 \text{ GeV}/c^2$	± 1	1
			Higgs	$124.97 \text{ GeV}/c^2$	0	0

W boson Properties



- W boson interacts with many different particles

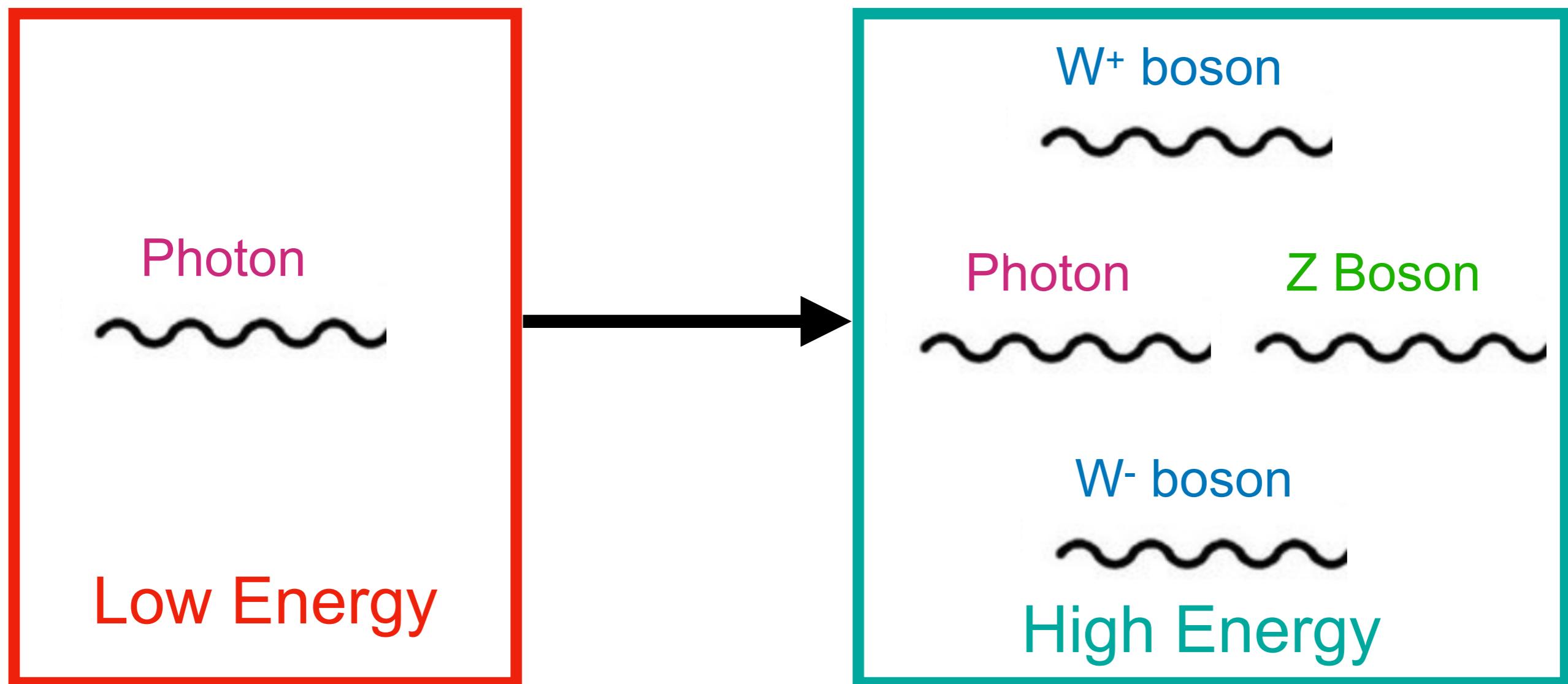
W boson Properties



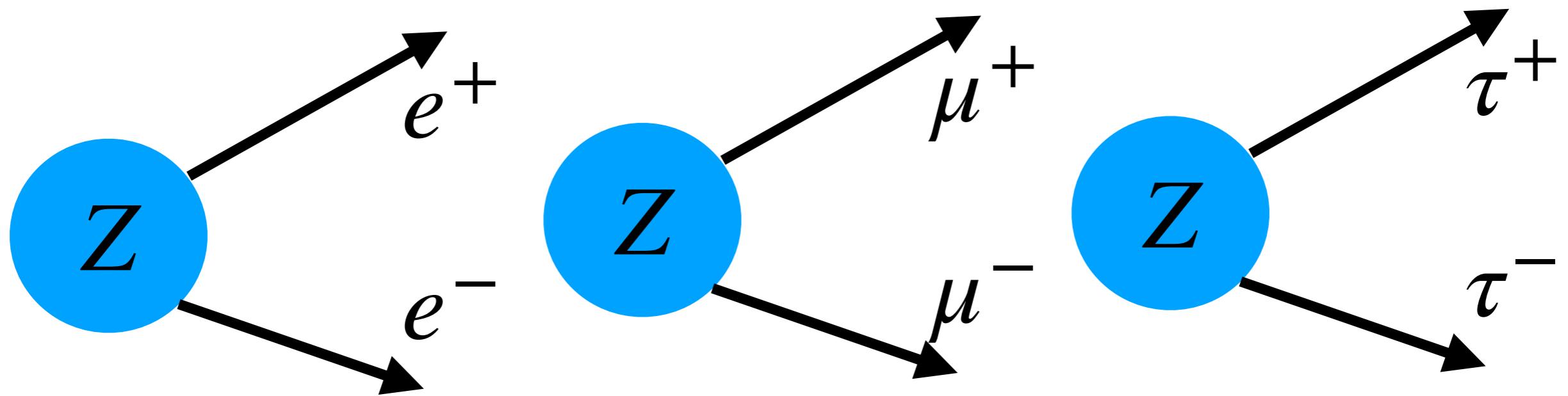
- W boson interacts with many different particles
 - These don't happen frequently b/c W boson is heavy

Electroweak Bosons

- Weak force is combined with EM forces to be electroweak
 - Practically, from low to high energy new forces turn on



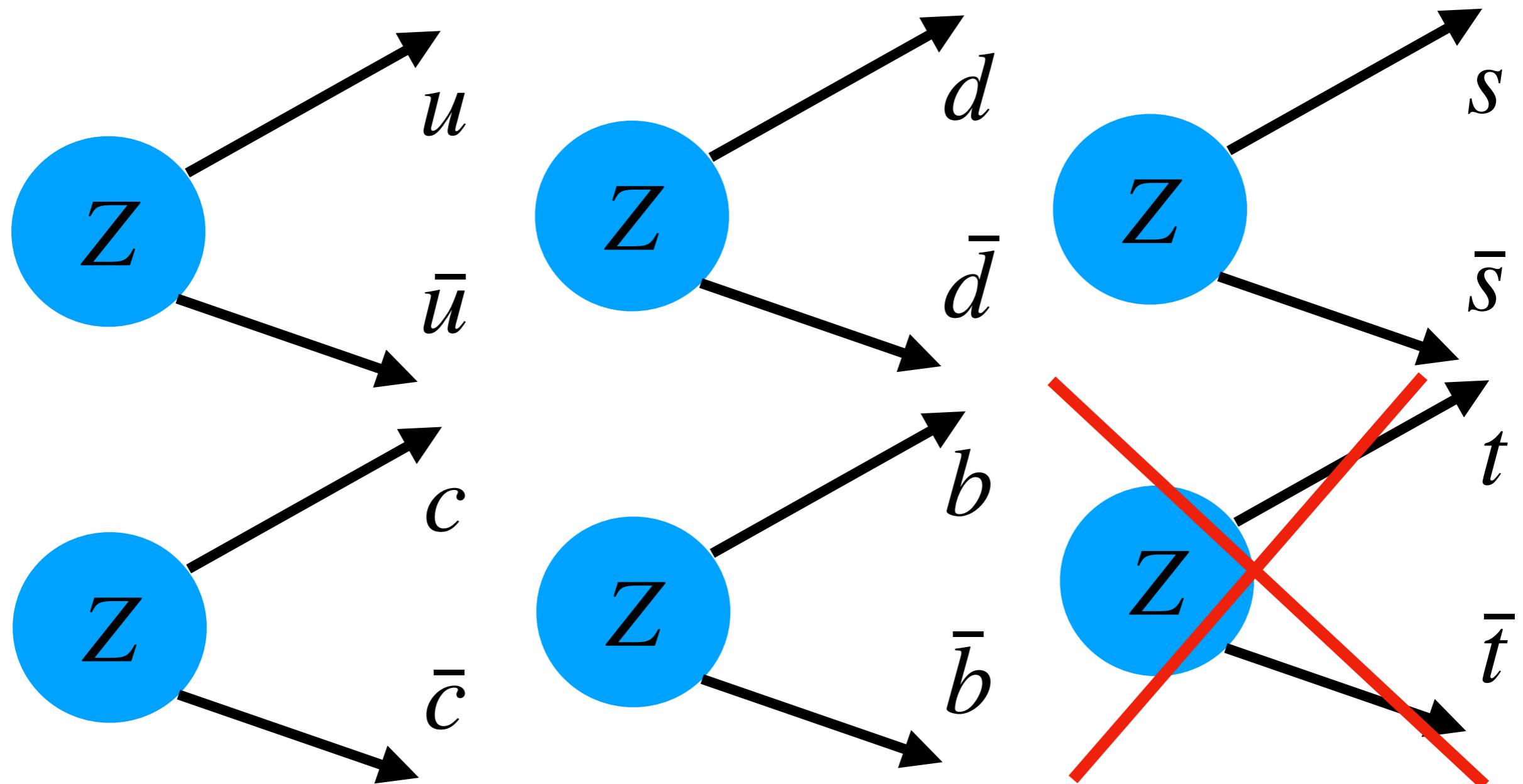
Z boson Properties



- Z boson is like a heavy photon (no charge, but heavy)
- Can decay to leptons

Z boson Properties

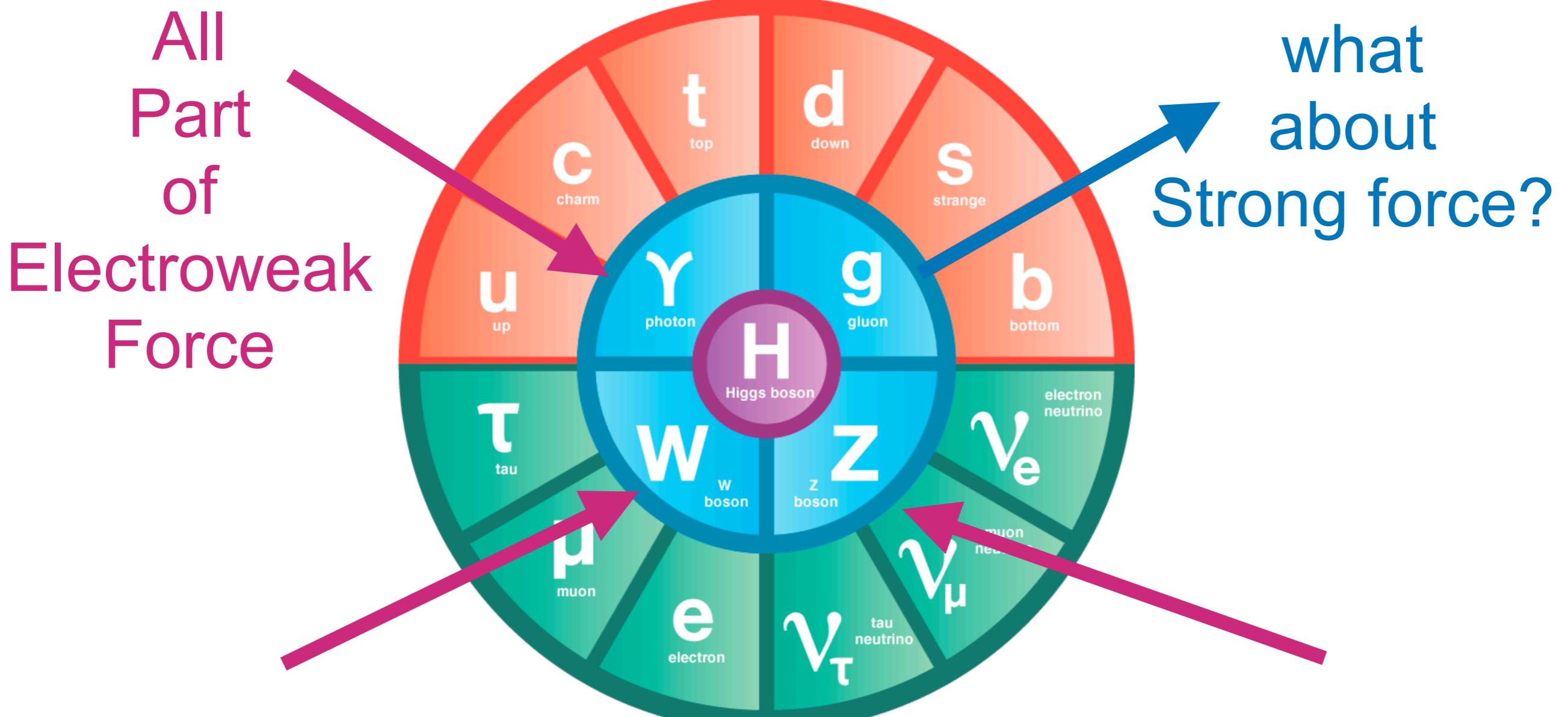
Decays to all quarks, except top



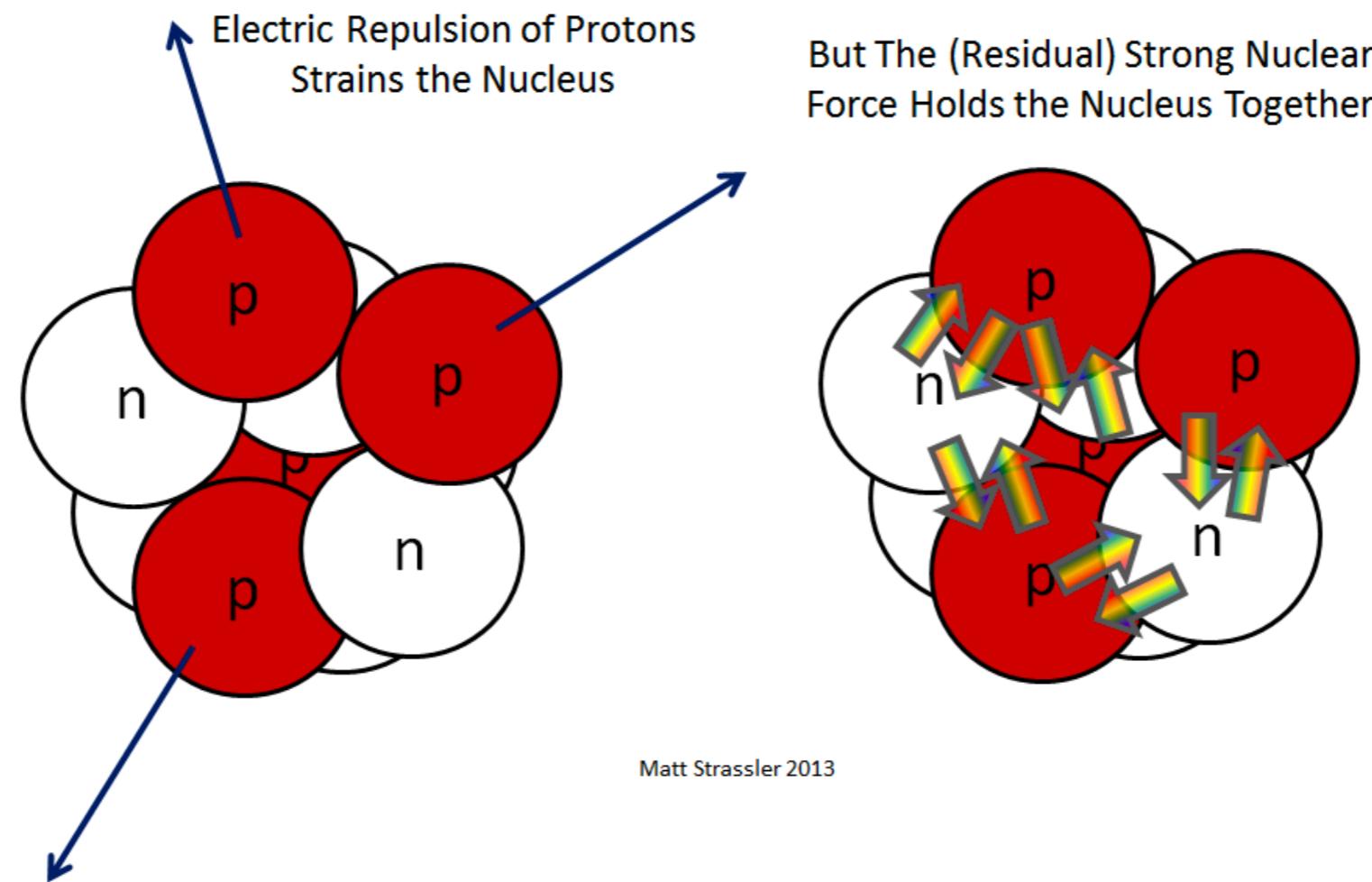
- Z boson is like a heavy photon (no charge, but heavy)

The Forces

- The challenge of this lab is to fin the W and Z boson
 - These are the particles that cover the Weak Boson Interaction

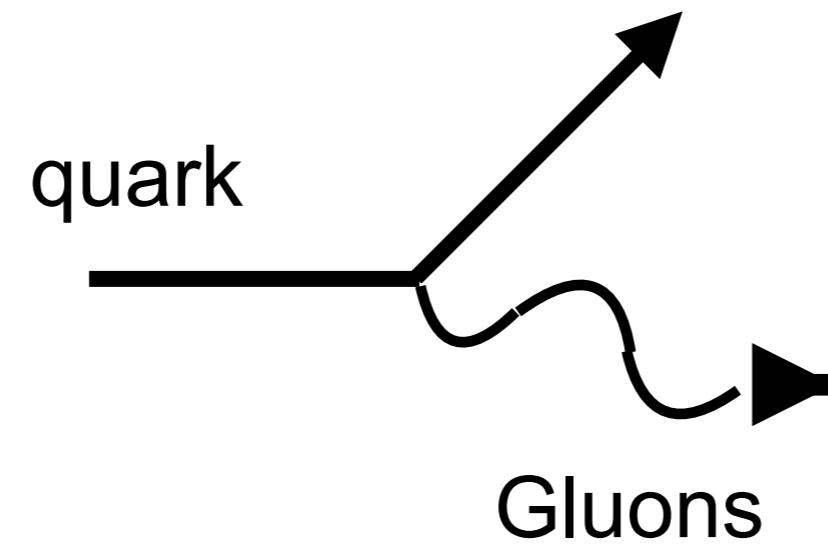


Strong Force



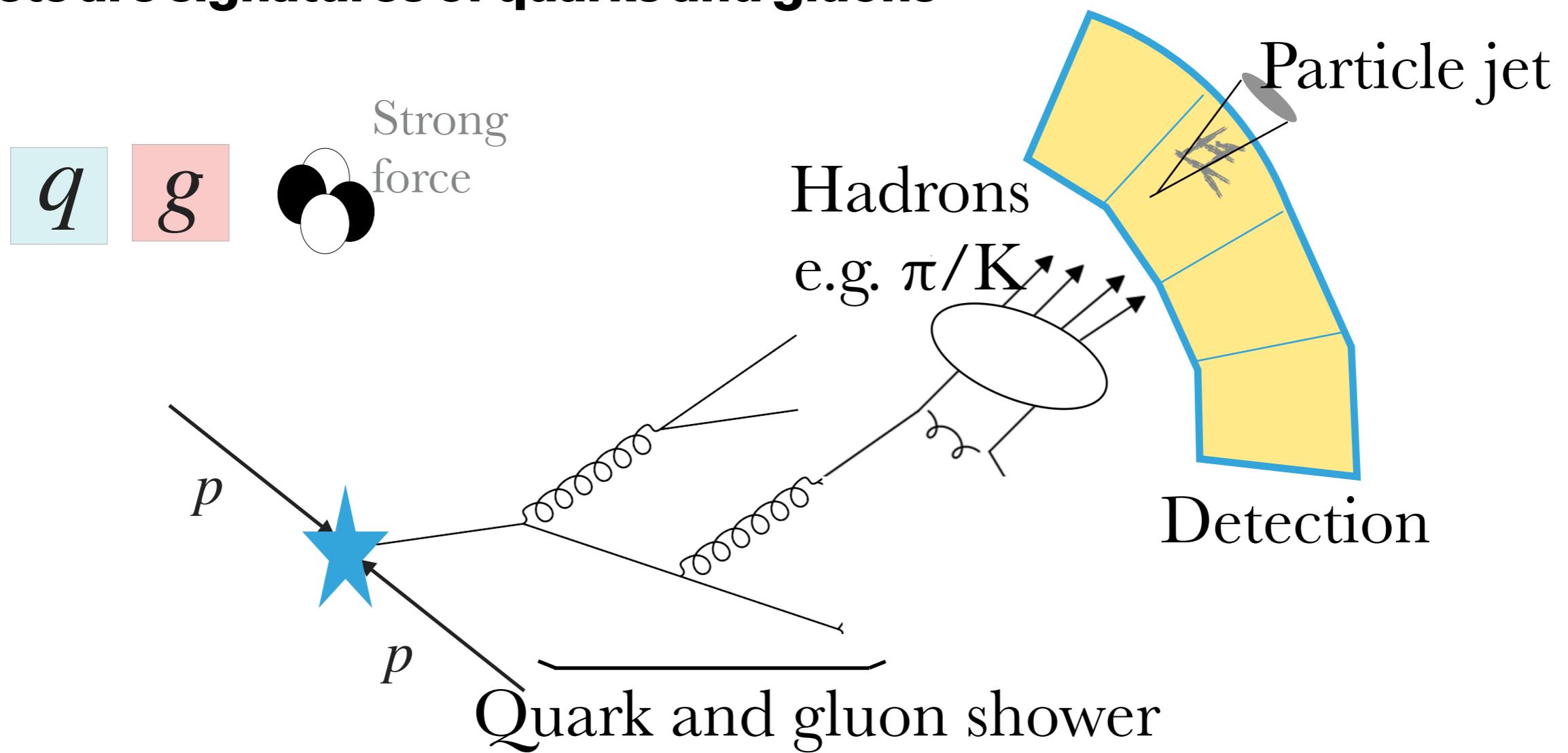
- Strong force is what bins quarks together
 - This is how we get protons

Strong Force Production

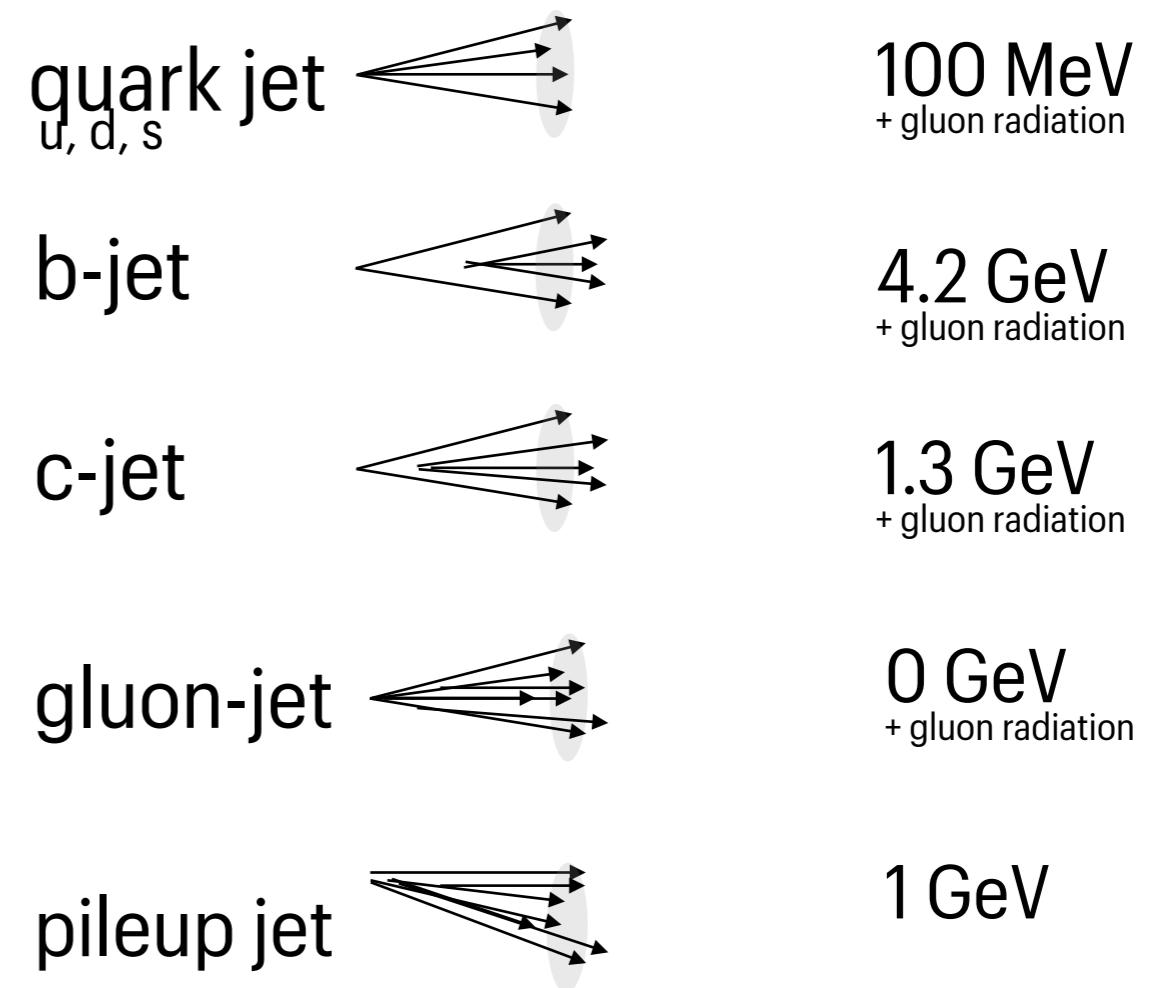
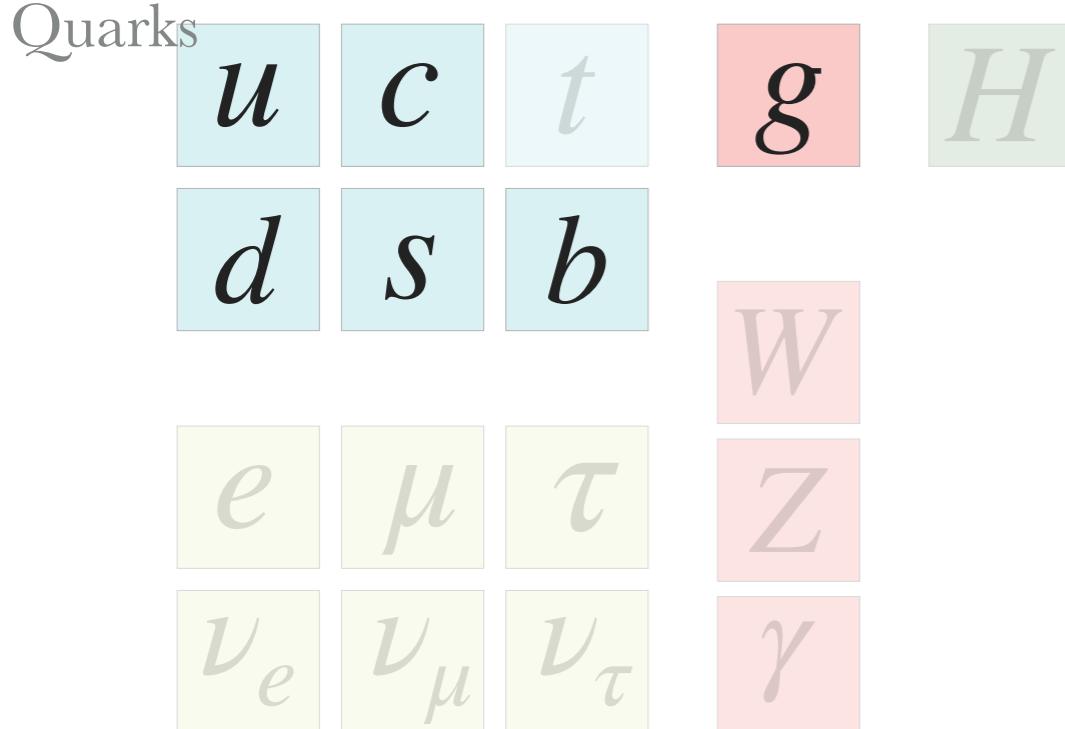


- Strong force
 - At high energy quarks can get produced which radiate gluons

What you know now: Jets are signatures of quarks and gluons

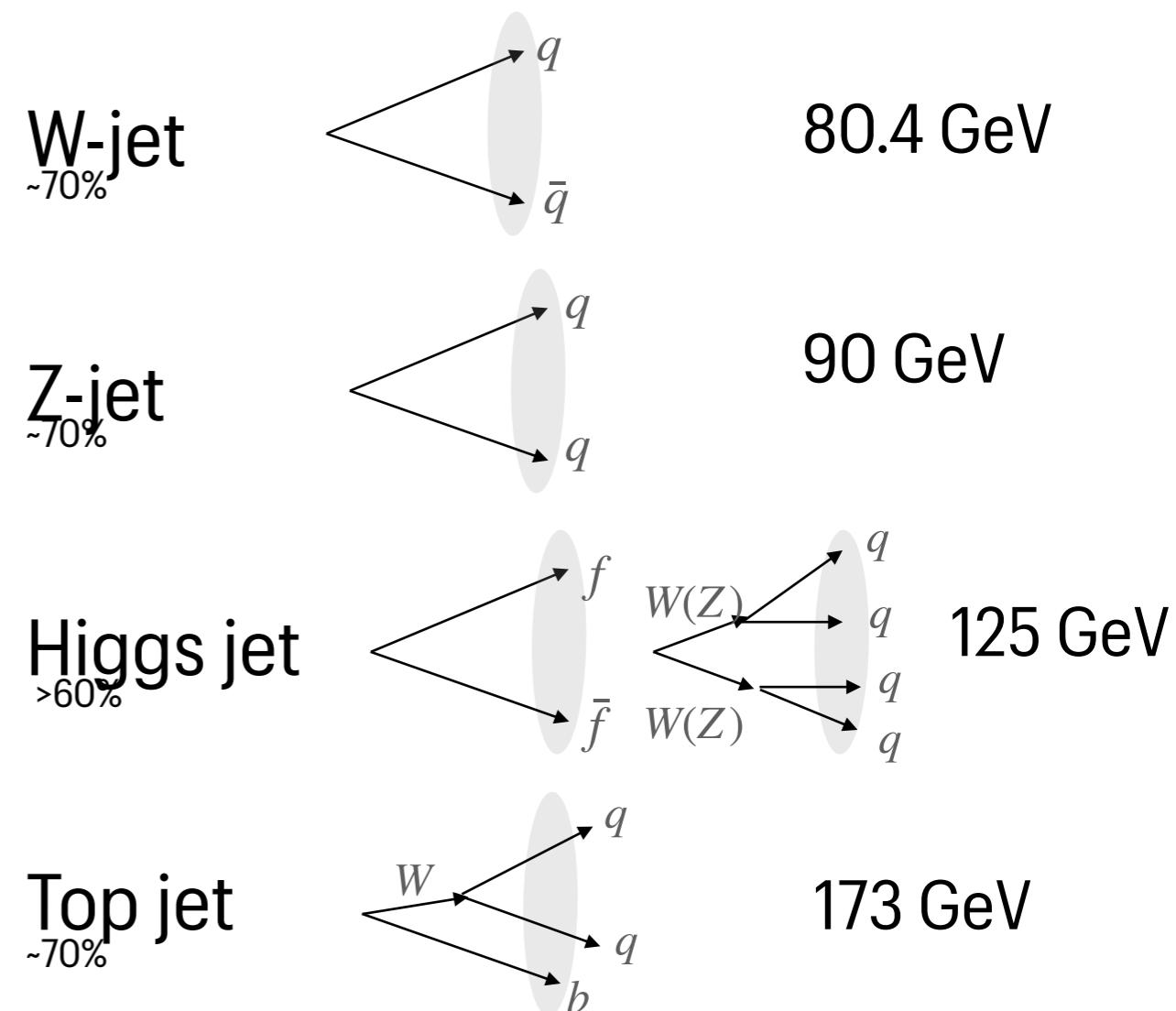
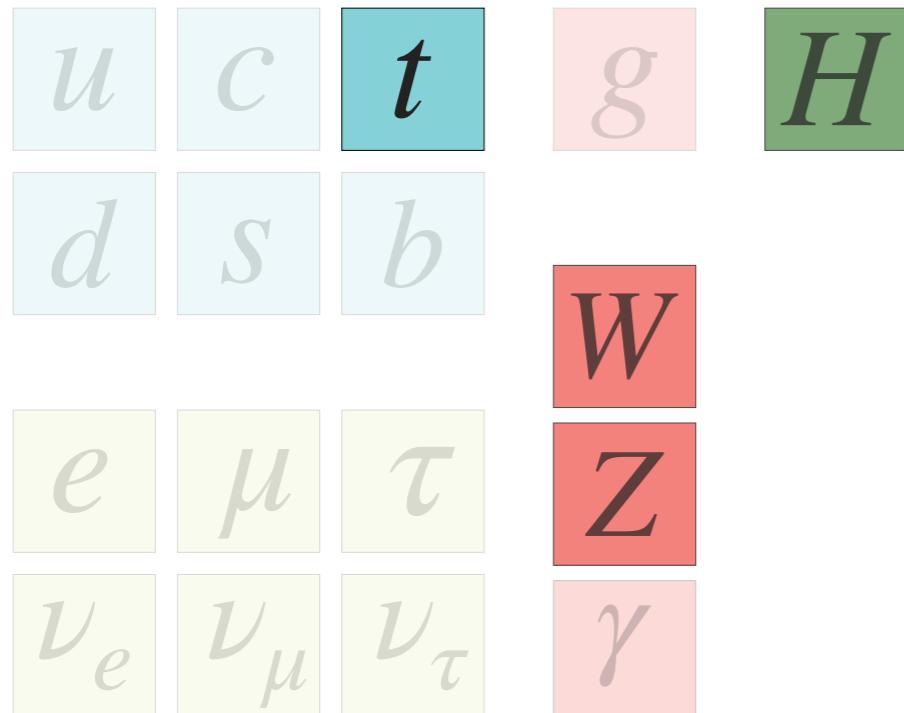


What you know now: Jets of the Standard Model



What you know now:

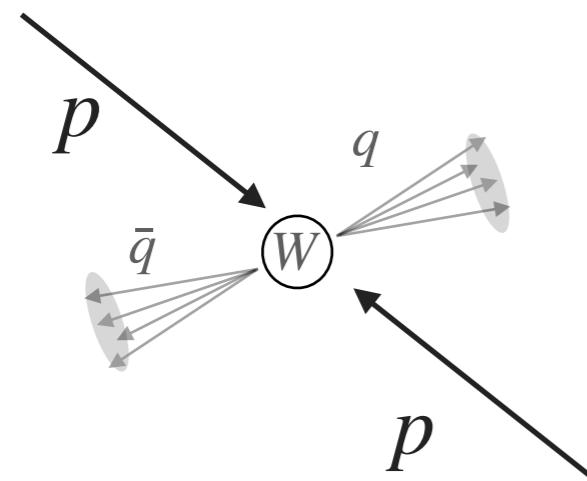
Jets of the Standard Model



High boost

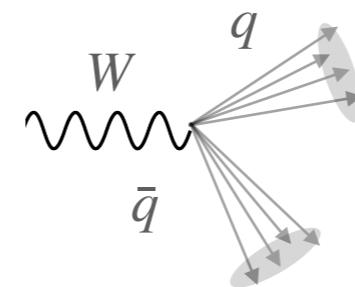
Let's consider a W-decay

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



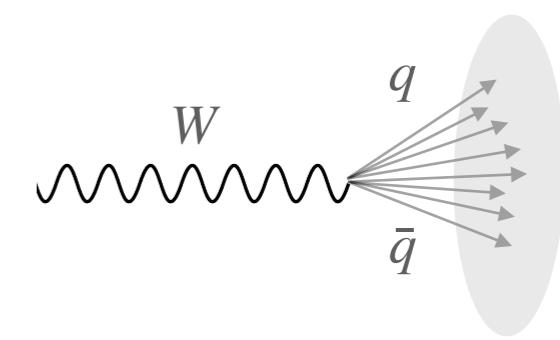
At ~rest

$$\Delta R(q\bar{q}) \approx \pi$$



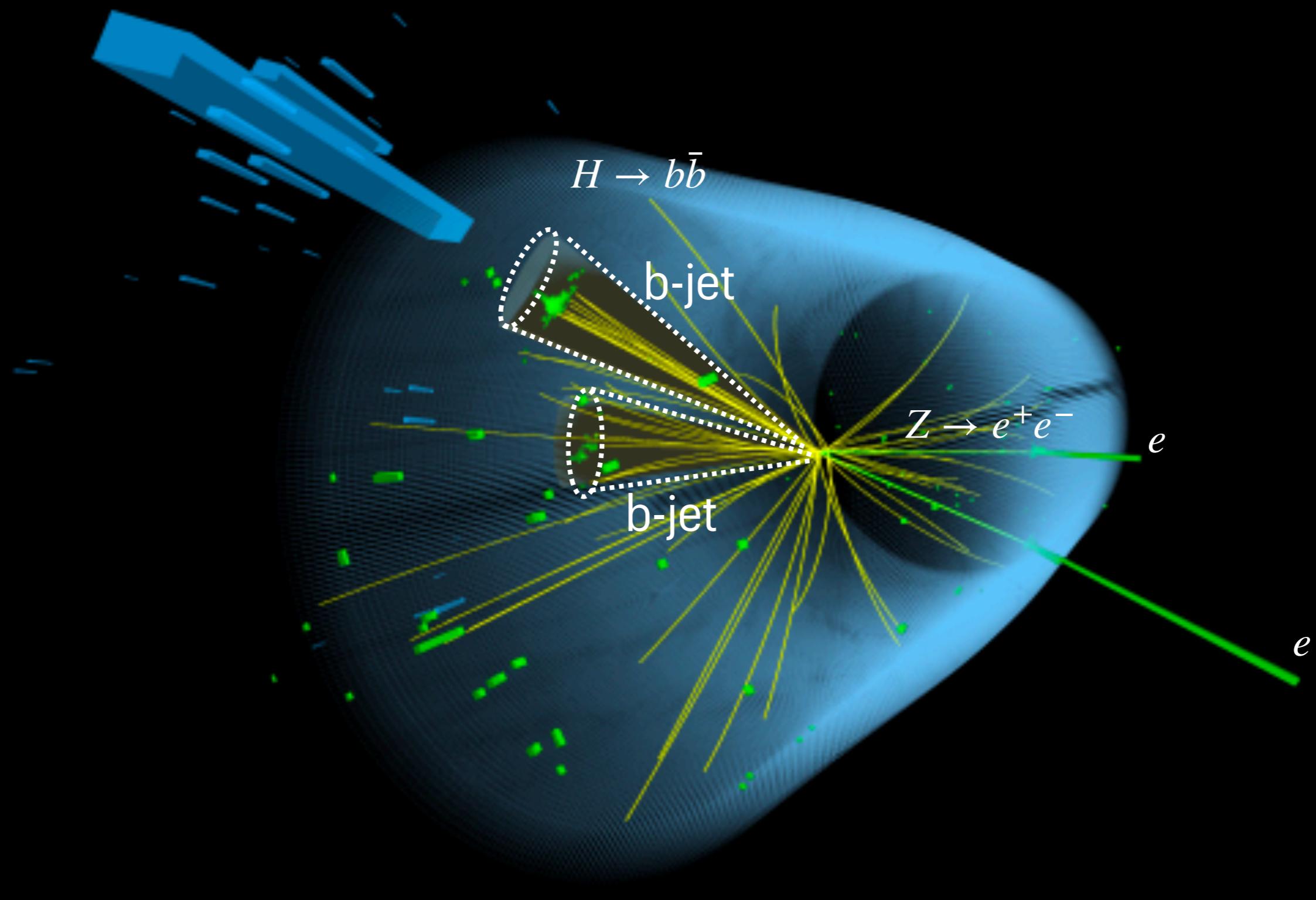
low W-momentum
($p_T \sim 100$ GeV)

$$\Delta R(q\bar{q}) \approx \pi/2$$



high **boost**
($p_T > 200$ GeV)

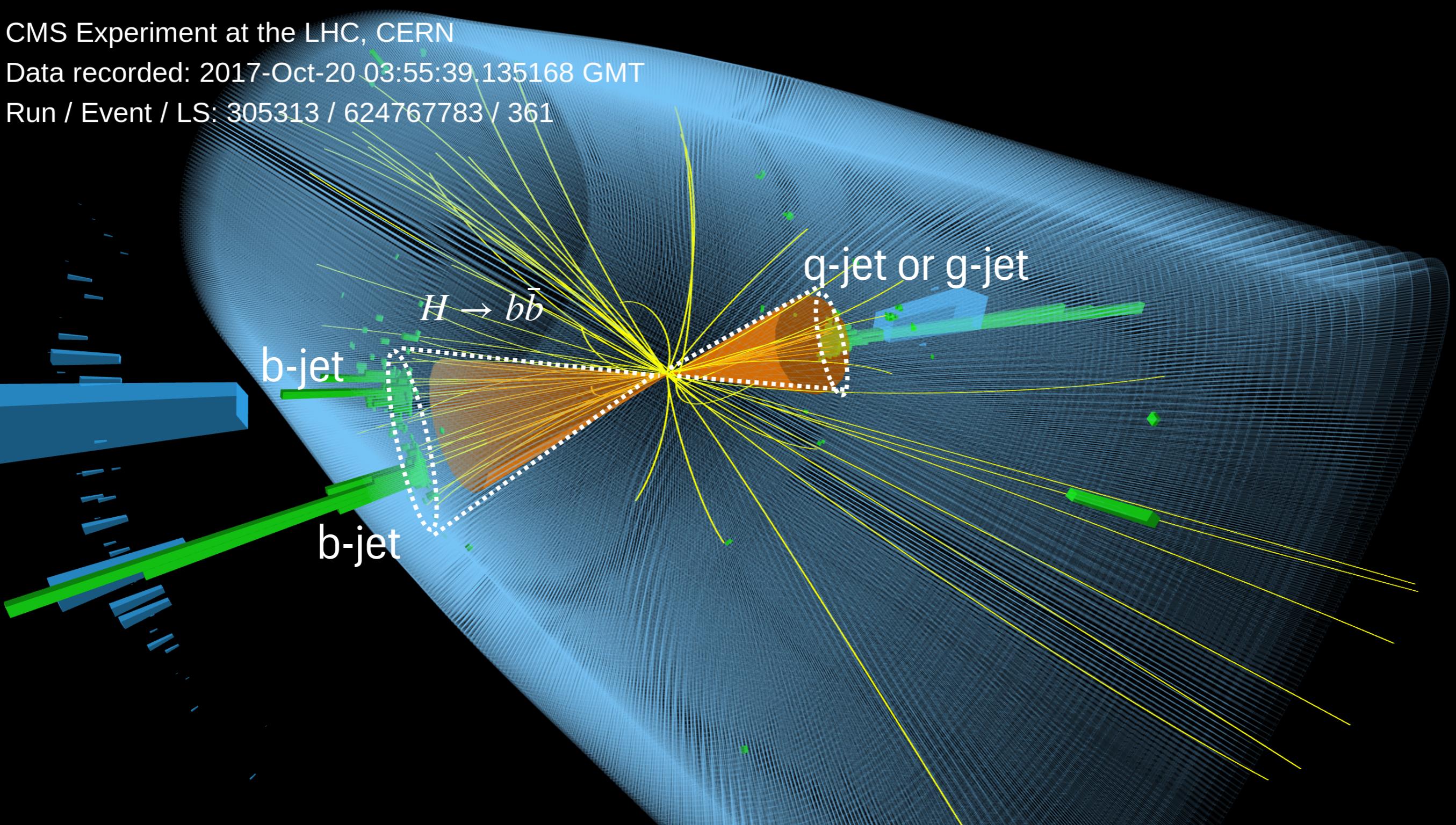
$$\Delta R(q\bar{q}) < 0.8$$



CMS Experiment at the LHC, CERN

Data recorded: 2017-Oct-20 03:55:39.135168 GMT

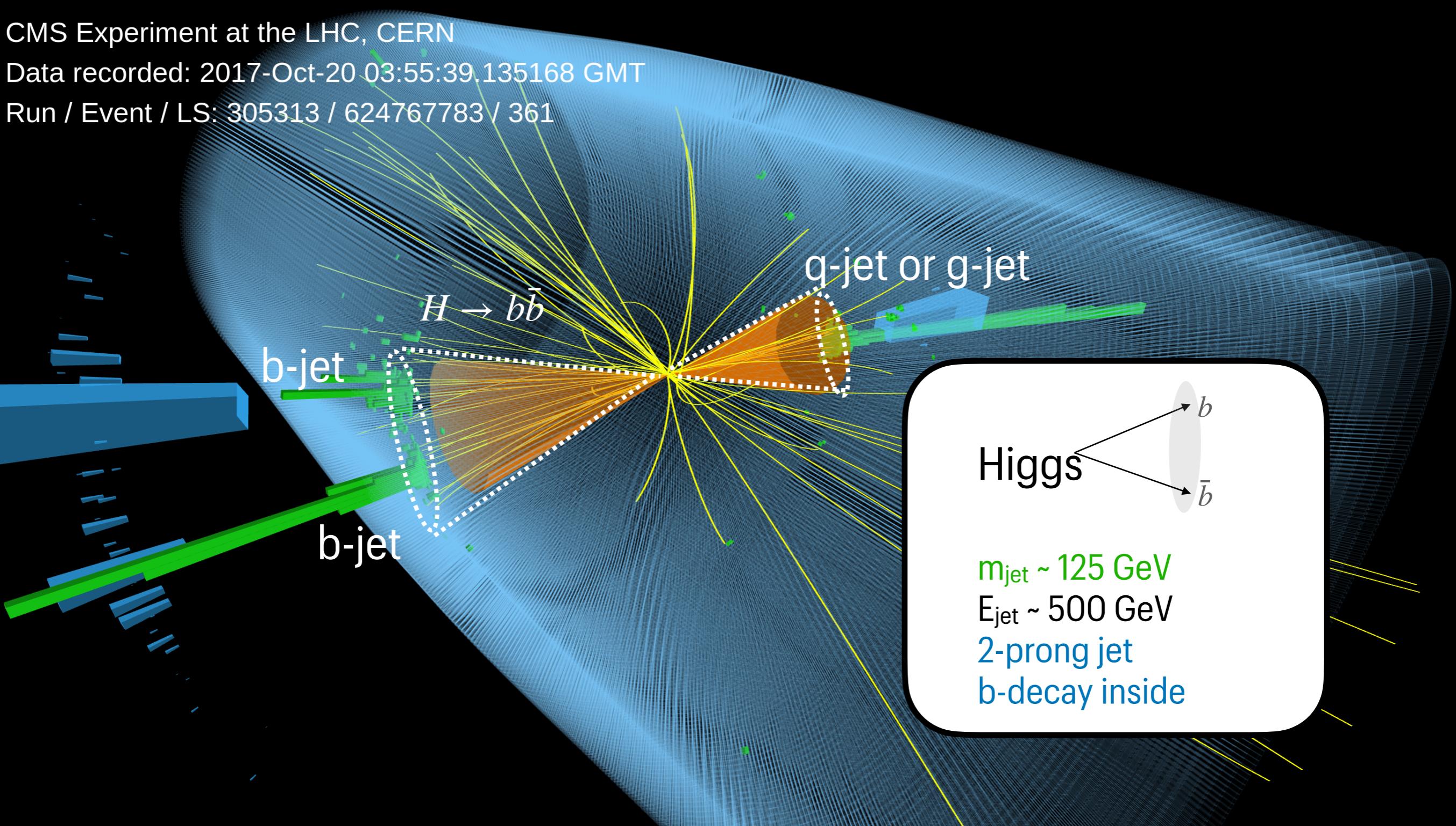
Run / Event / LS: 305313 / 624767783 / 361



CMS Experiment at the LHC, CERN

Data recorded: 2017-Oct-20 03:55:39.135168 GMT

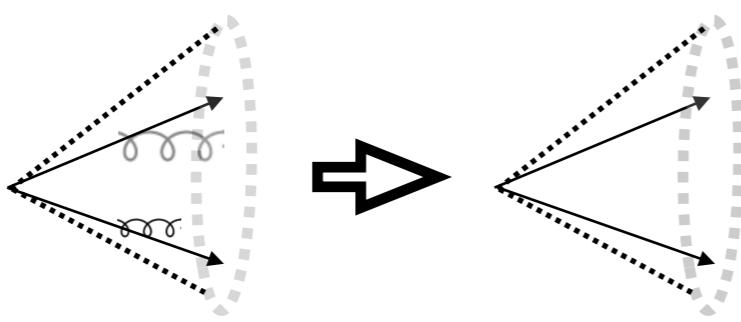
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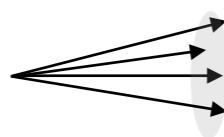
Jet substructure

Resolving emissions within the jet

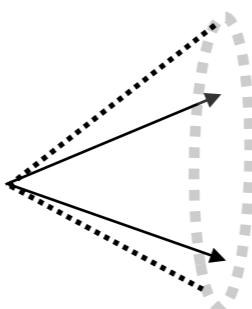
Jet grooming



Jet tagging



VS.



Higgs



$m_{jet} \sim 125 \text{ GeV}$

$E_{jet} \sim 500 \text{ GeV}$

2-prong jet

b-decay inside

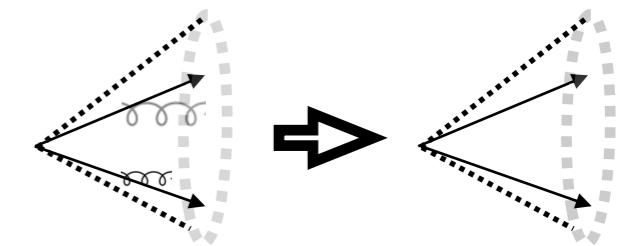
Jet grooming



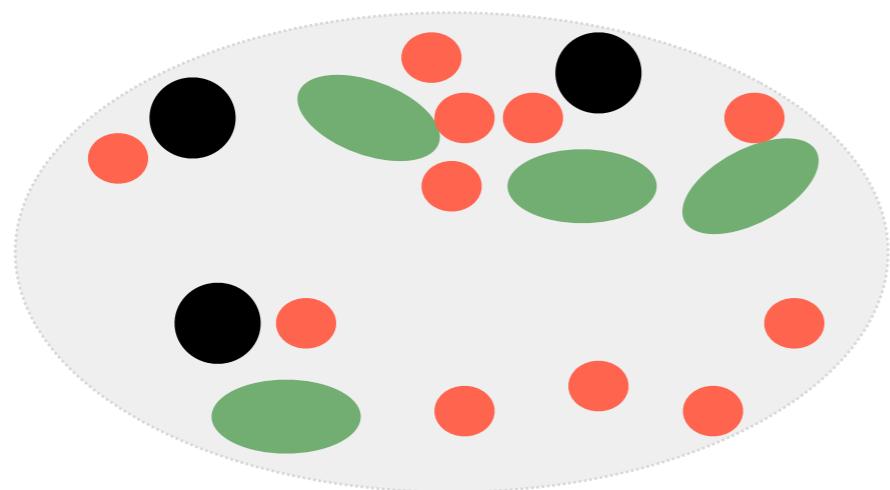
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Removing a jet's soft and wide-angle radiation

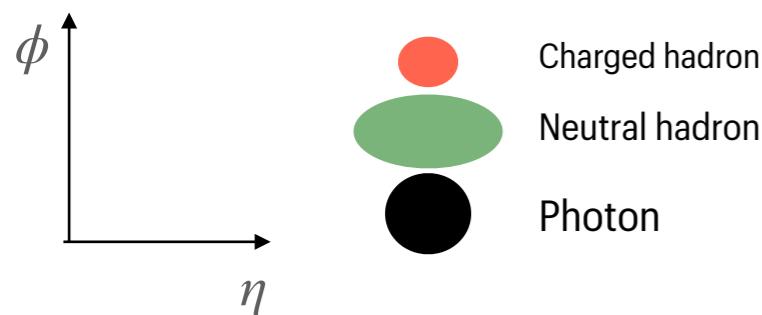
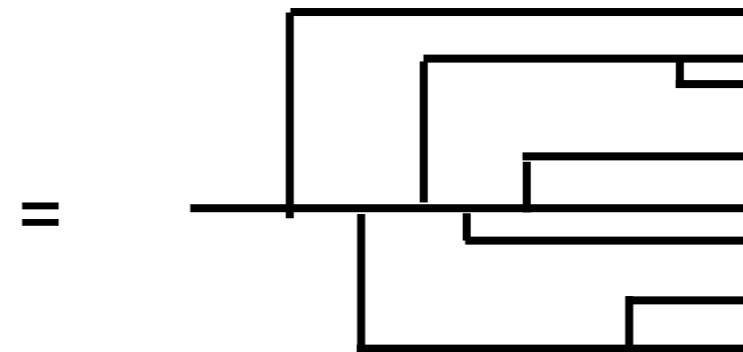
Grooming declustering



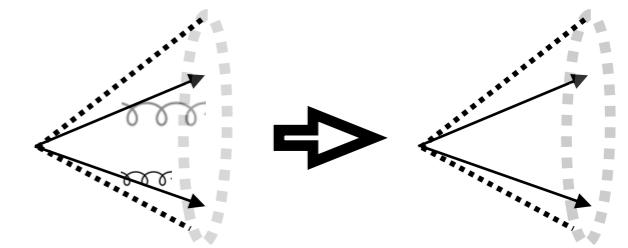
Original jet



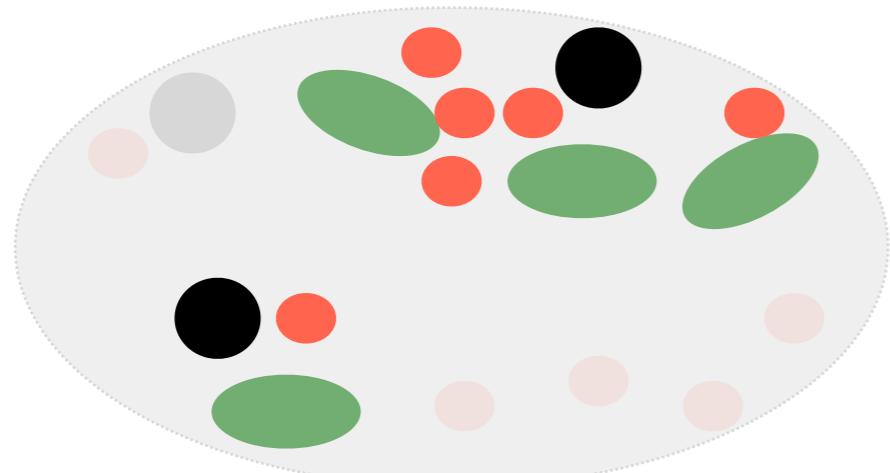
In a clustering tree



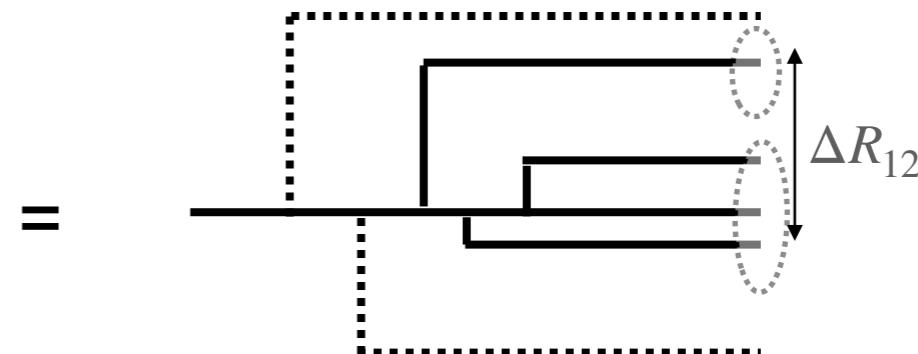
Grooming declustering



Groomed jet

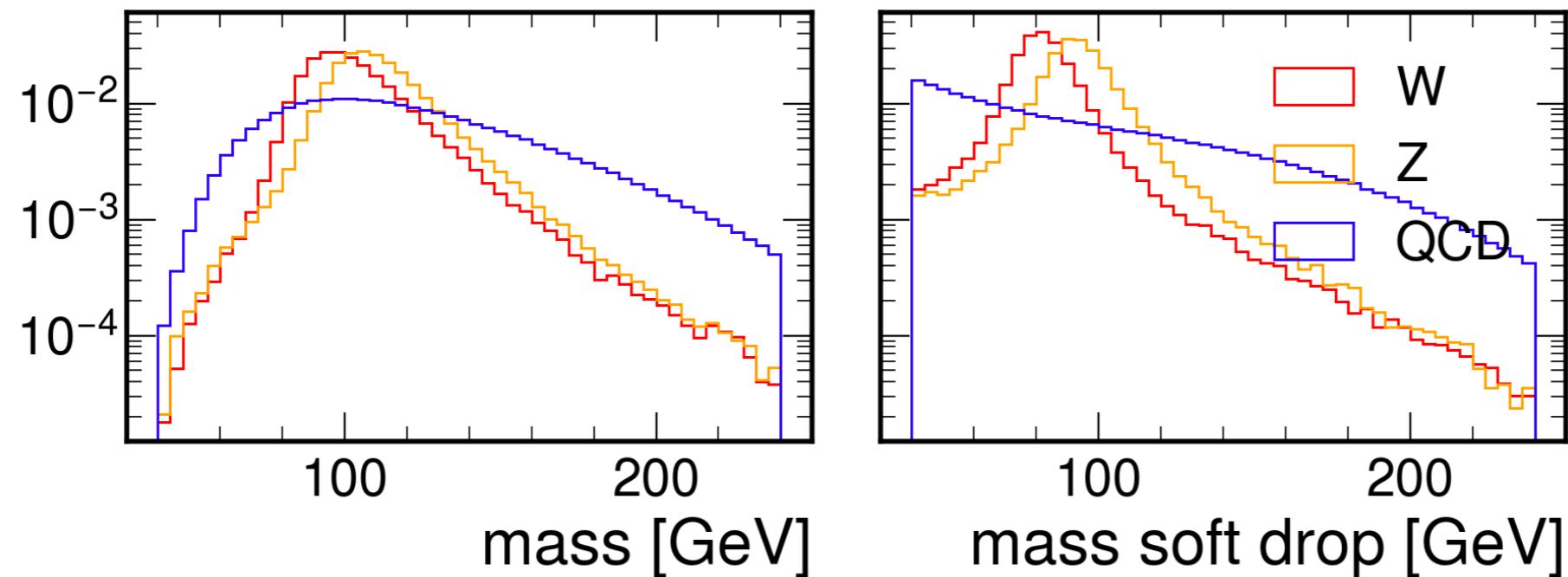
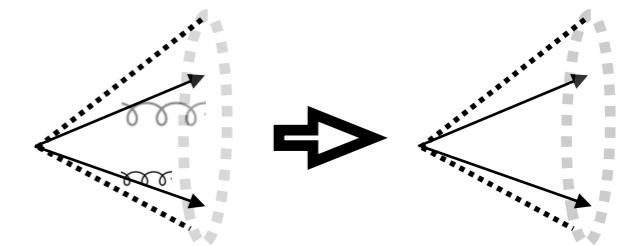


Groomed clustering tree



- Grooming algorithms iteratively decluster a jet
- The soft-drop algorithm removes lowest p_T sub-jets failing pairwise condition $z > z_{cut} \left(\frac{\Delta R_{12}}{R} \right)^\beta$ with $z = \frac{\min(p_T^1, p_T^2)}{p_T^1 + p_T^2}$

Calculating groomed mass



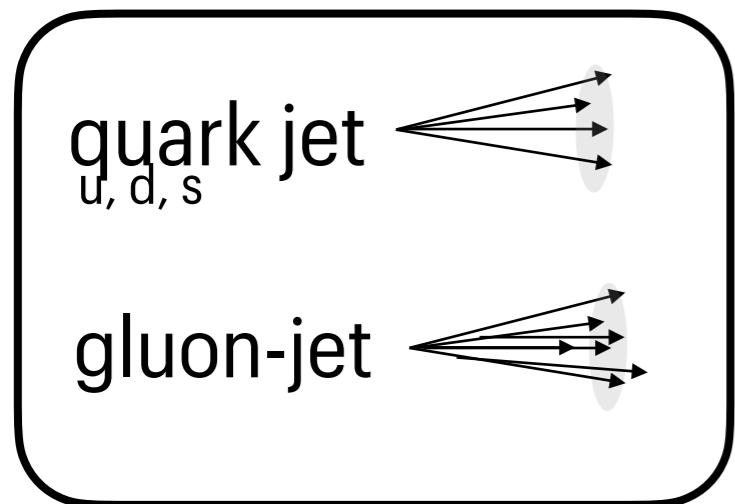
- Improves the mass *resolution* of a jet (removes away excess radiation)
- Brings the mass of background jets (QCD) to low mass

Jet tagging

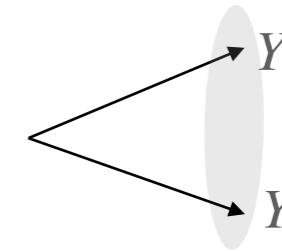


Characterizing a jet's internal decay

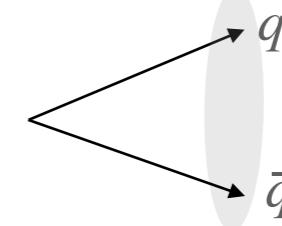
Signatures:



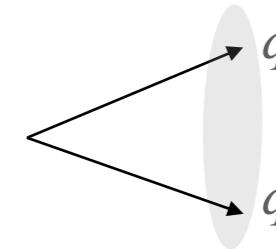
X-jet



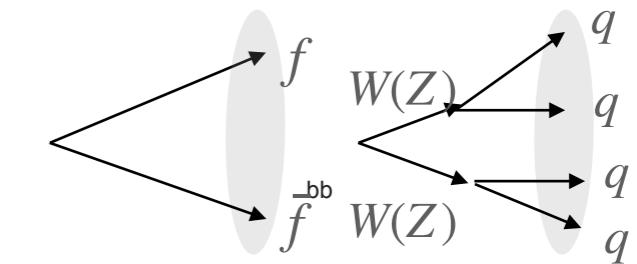
W-jet



Z-jet



Higgs jet

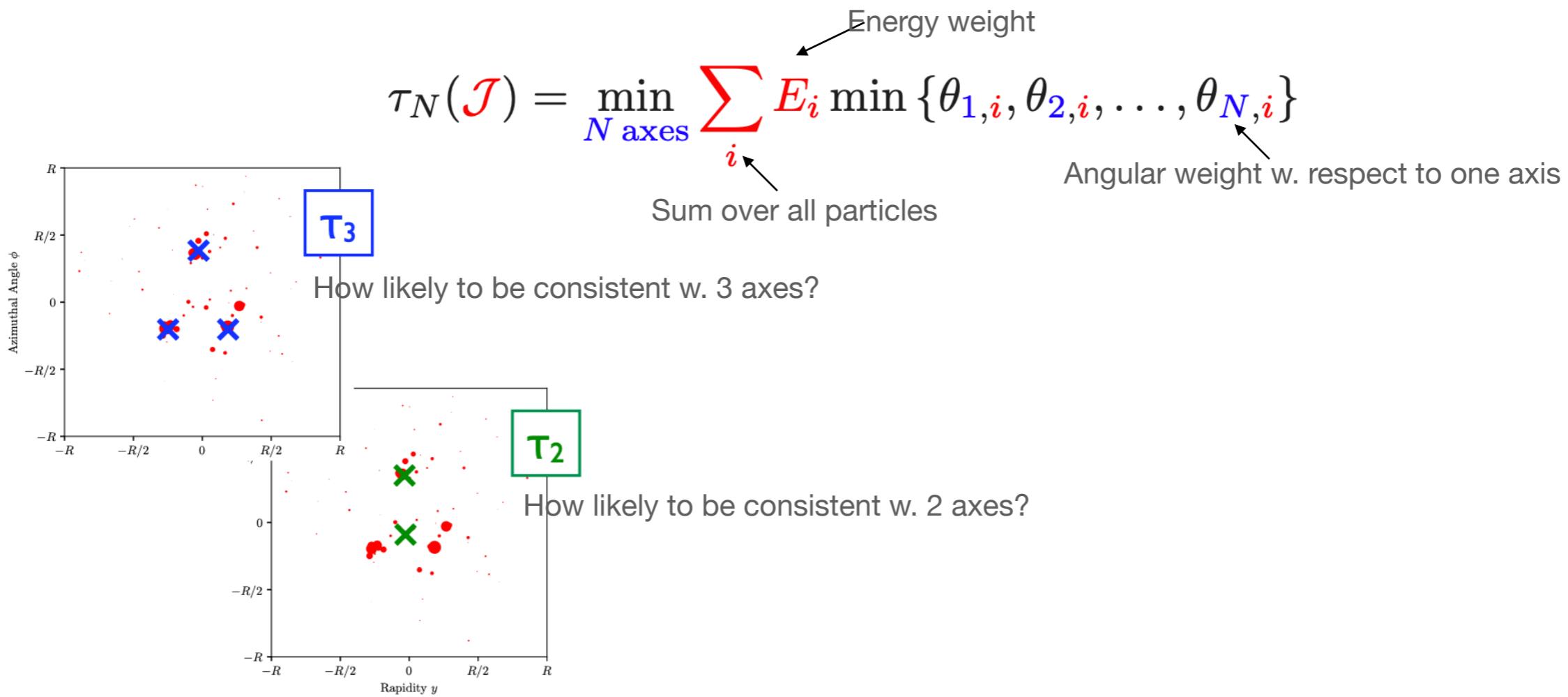


Top jet



N-subjetiness

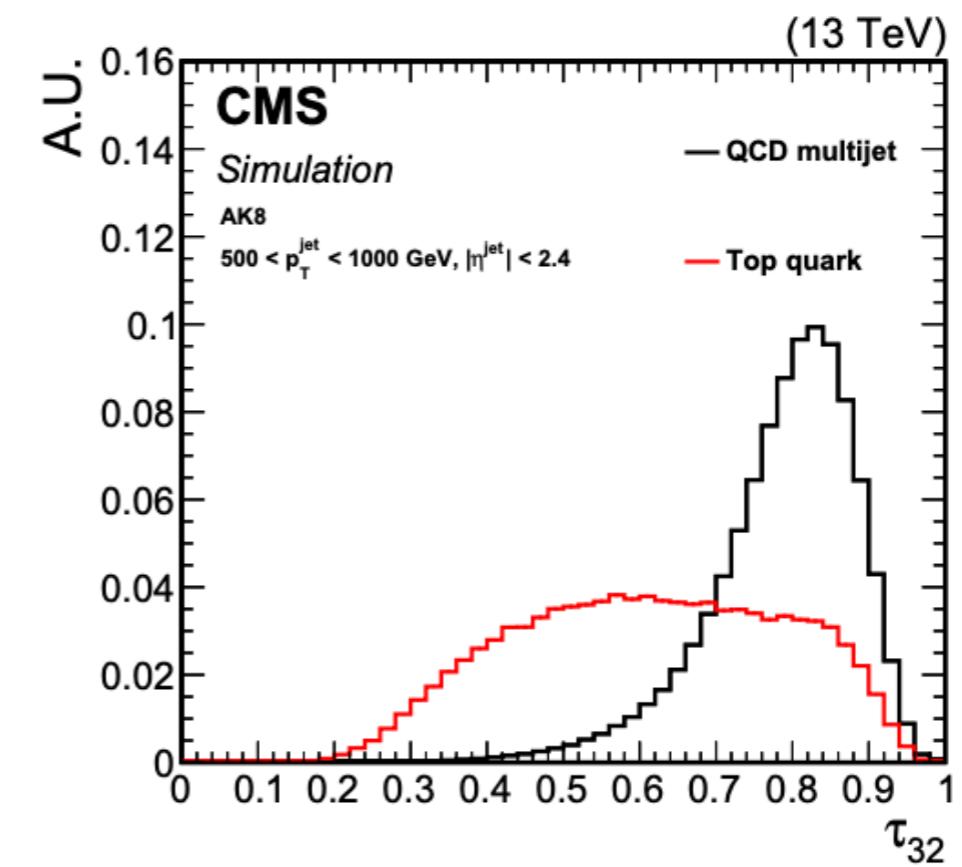
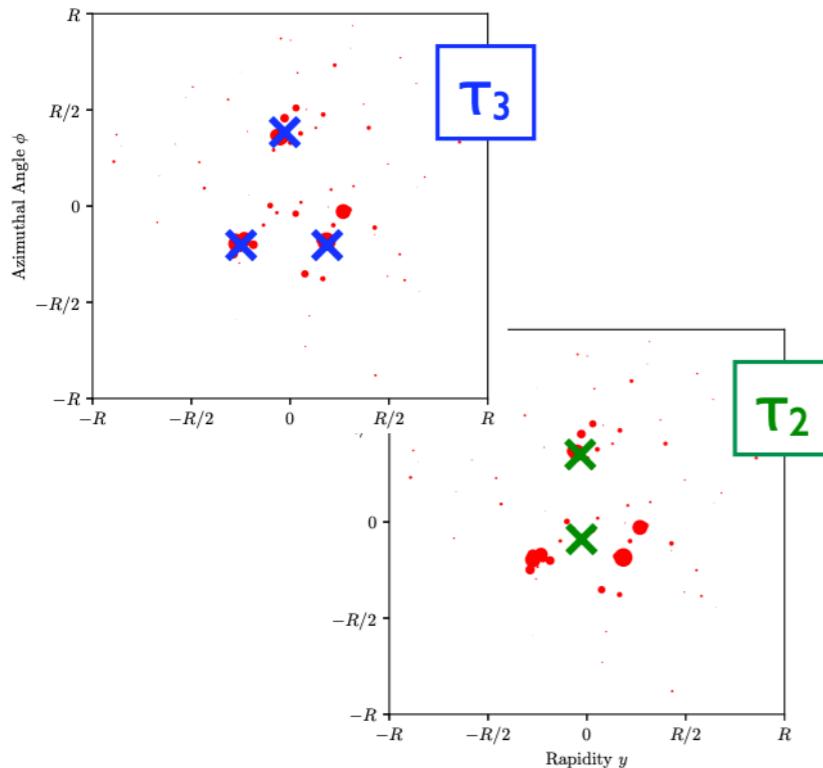
Counting the number of “prongs” for almost a decade



N-subjetiness

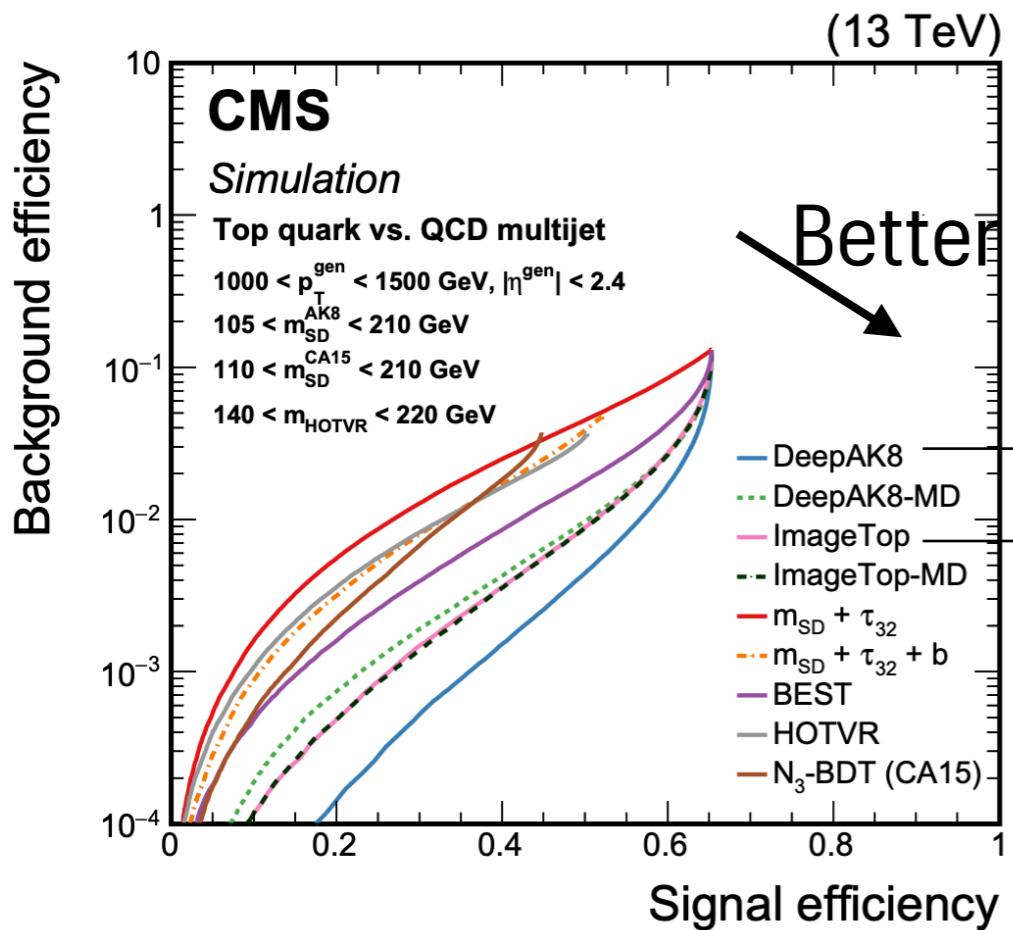
Counting the number of “prongs” for almost a decade

$$\tau_N(\mathcal{J}) = \min_{N \text{ axes}} \sum_i E_i \min \{\theta_{1,i}, \theta_{2,i}, \dots, \theta_{N,i}\}$$

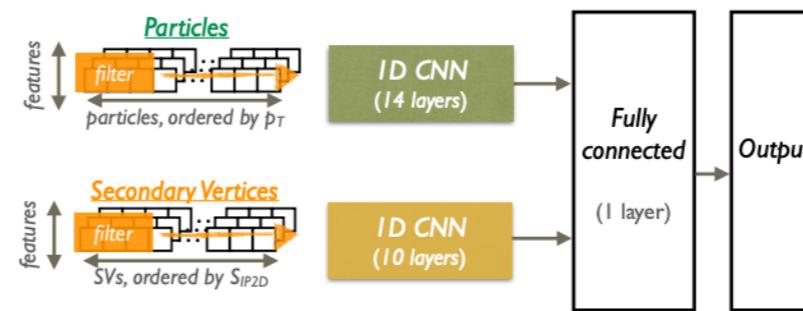


Deep Learning taggers

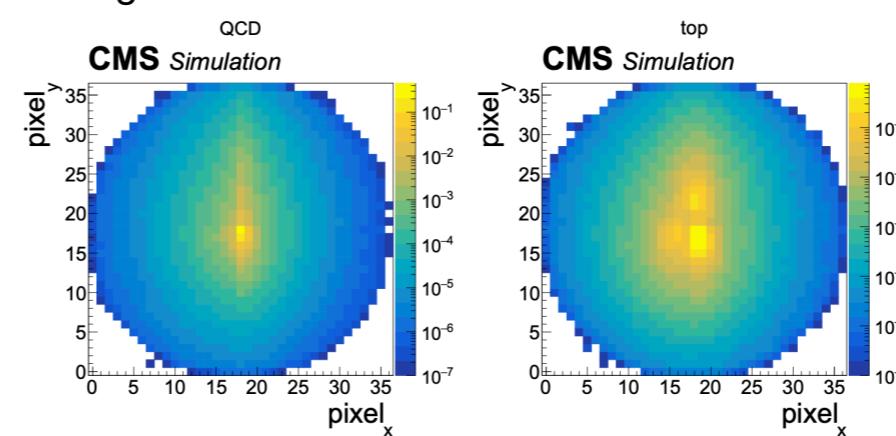
The rise of machine learning: two examples in CMS



Particles can be sent to NN
Ignores multi-particle correlation



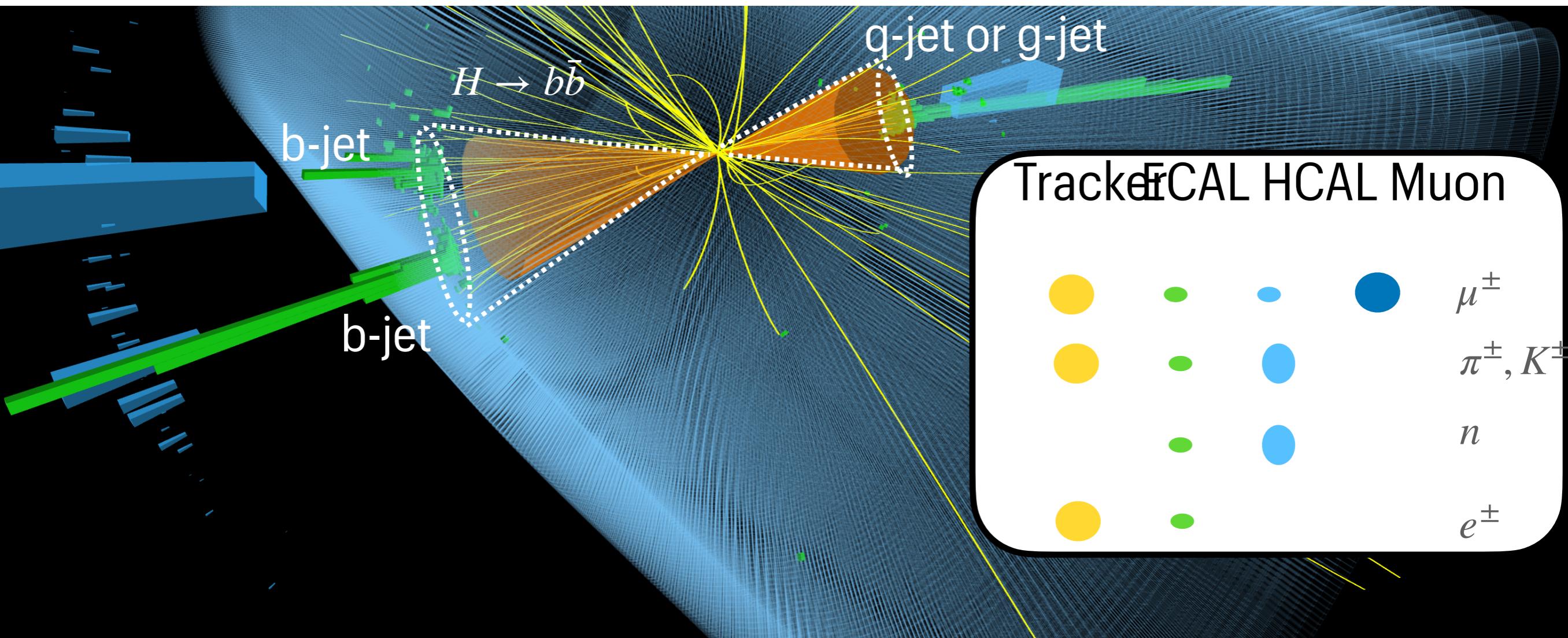
Represent jets as images
Images are not Lorentz invariant



How to better represent a jet in ML?

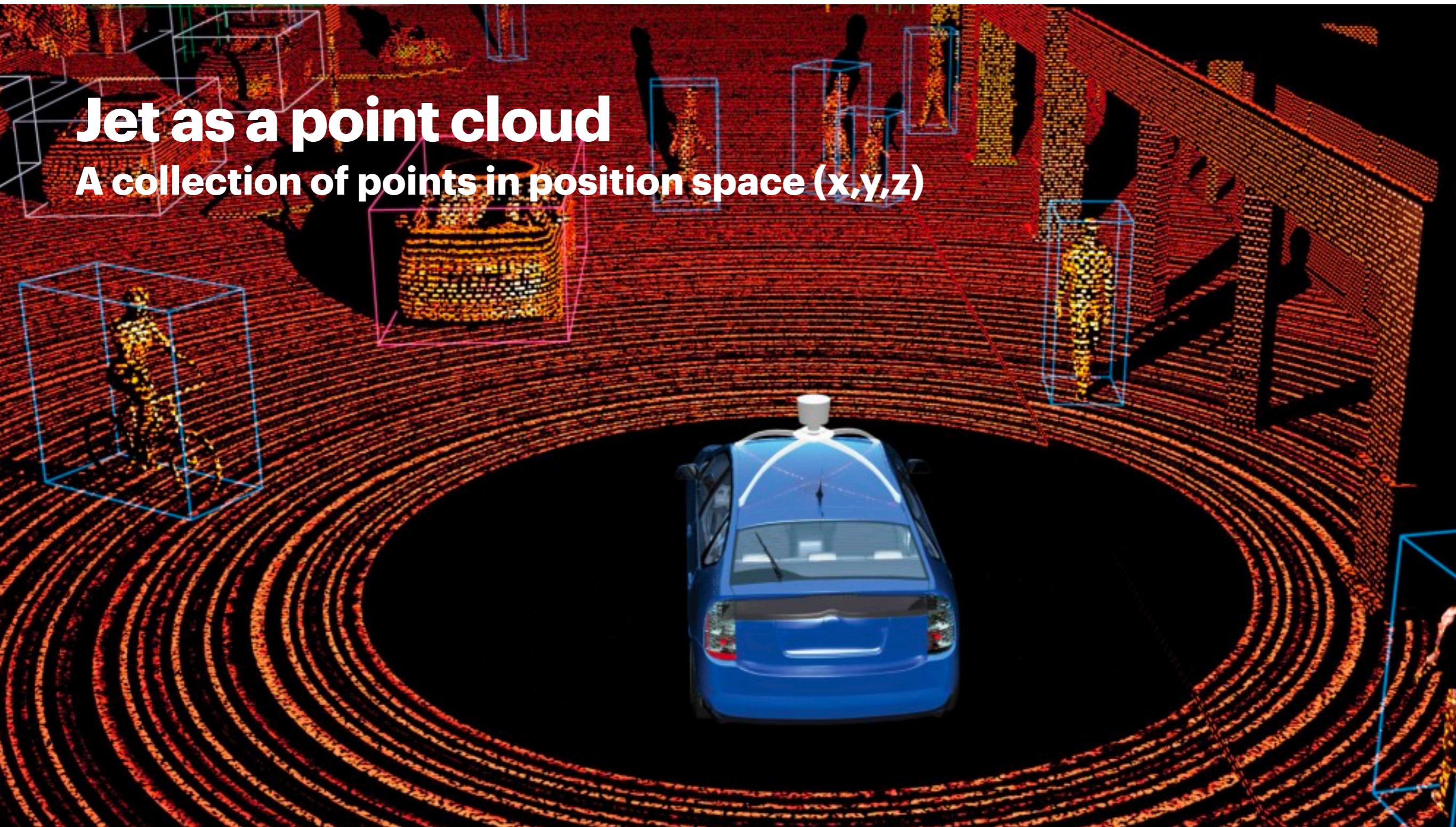
A collision event

A collection of particles in momentum space



Jet as a point cloud

A collection of points in position space (x,y,z)

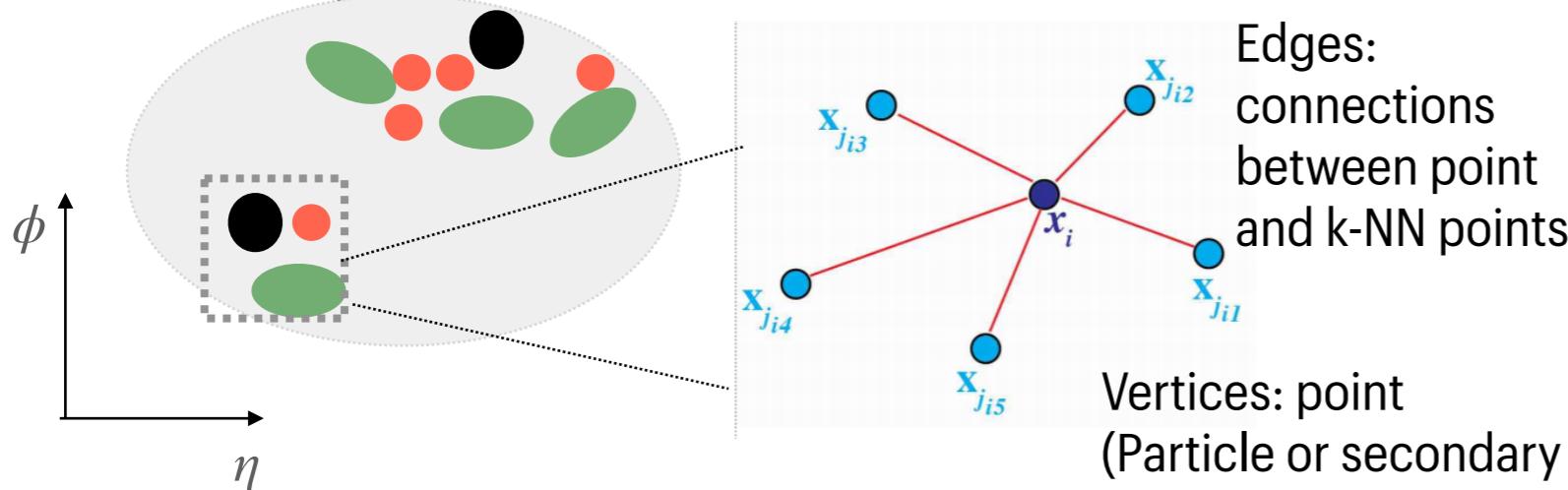


Particle-Net

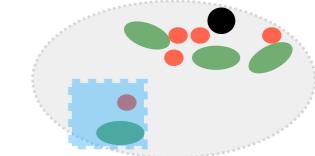
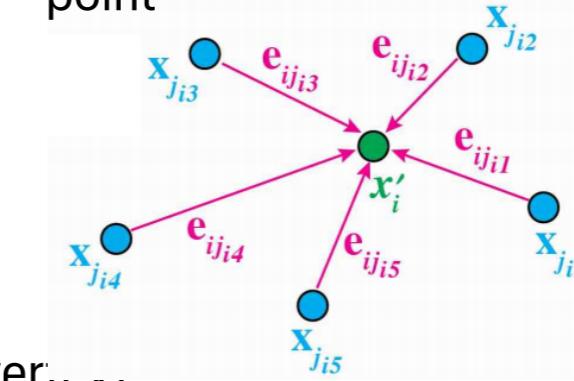
A graph neural network using particle-clouds

- For a jet: we have 2D information of particles, but also energy/momenta, charge/particle ID, track quality/impact parameter, etc.

Jet as a particle cloud Each cloud is a graph Perform convolution Get ID
Unordered representation



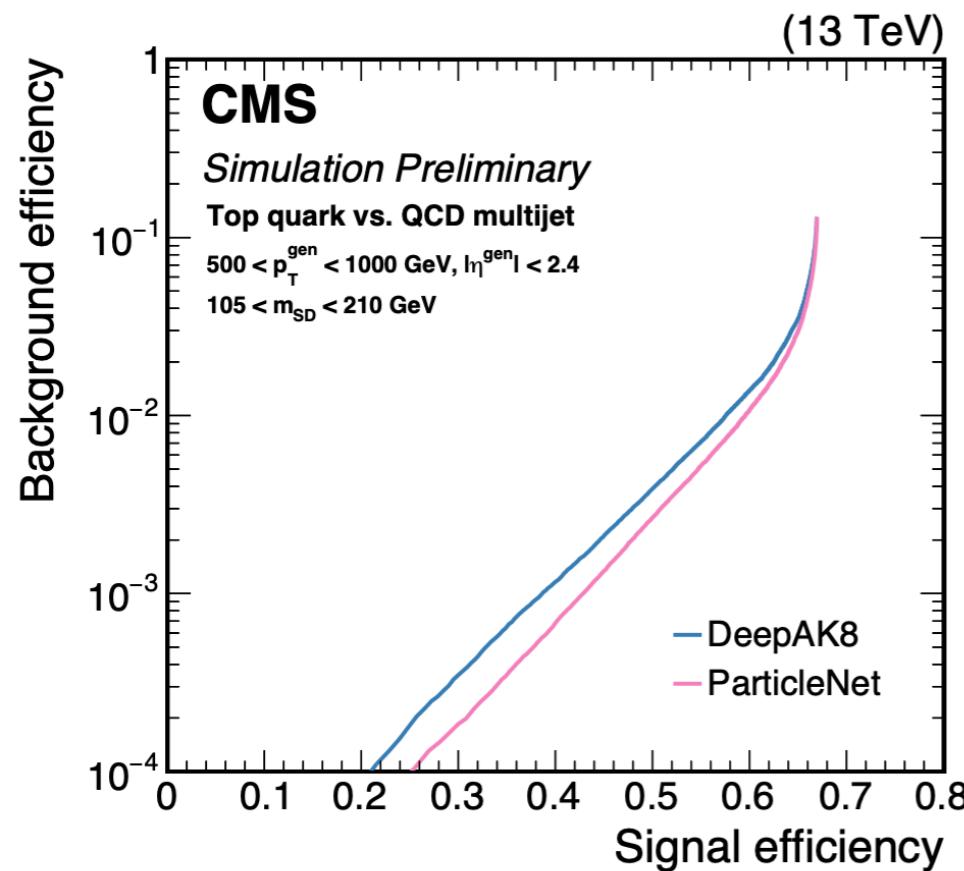
EdgeConv outputs a set of learned features for each point



Binary classification from all learned features

Particle-Net

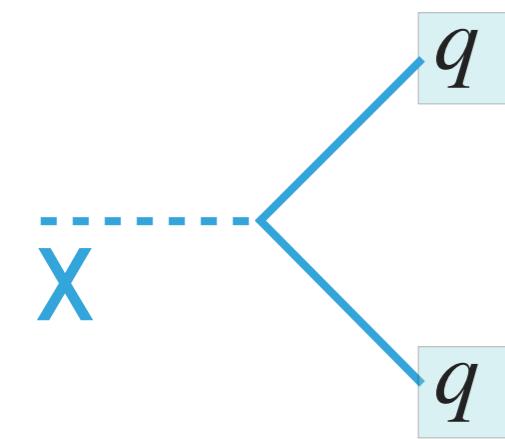
A graph neural network using particle-clouds



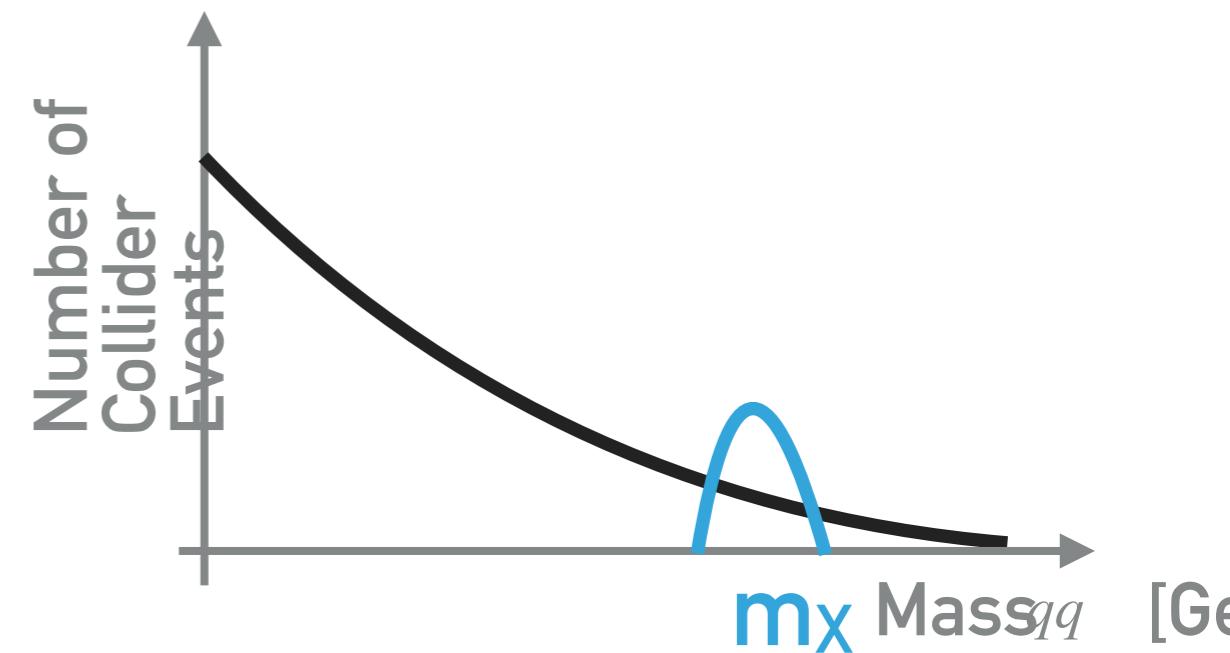
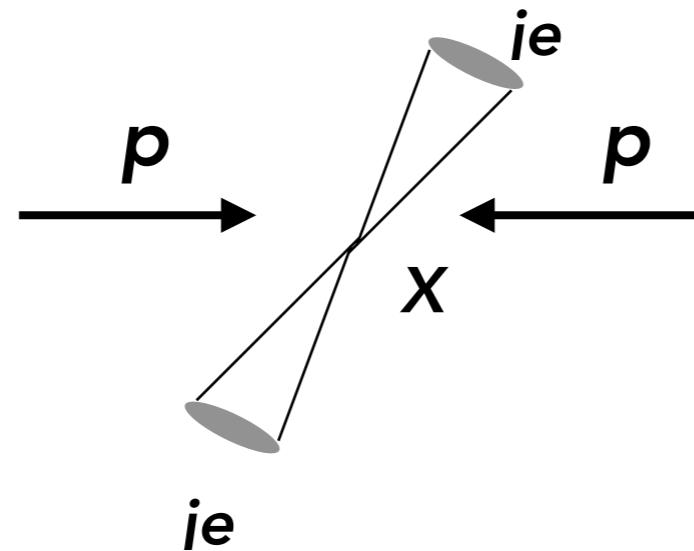
- A step in the right direction: Networks and correlations can be included (the most powerful discrimination in CMS)
- Still a long way to go:
 - More on DL by Dylan

Low mass (qq) resonances

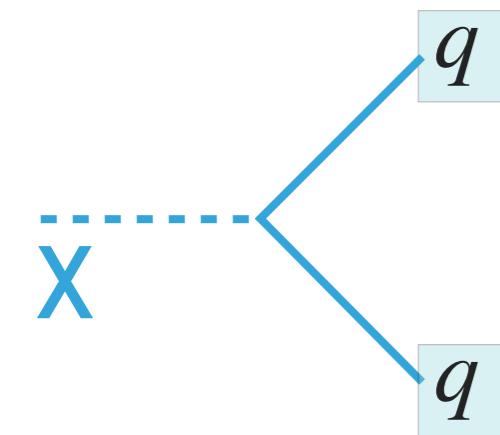
Looking for a resonance At the LHC



$p_T < 200 \text{ GeV}$
 $m_X > 500 \text{ GeV}$

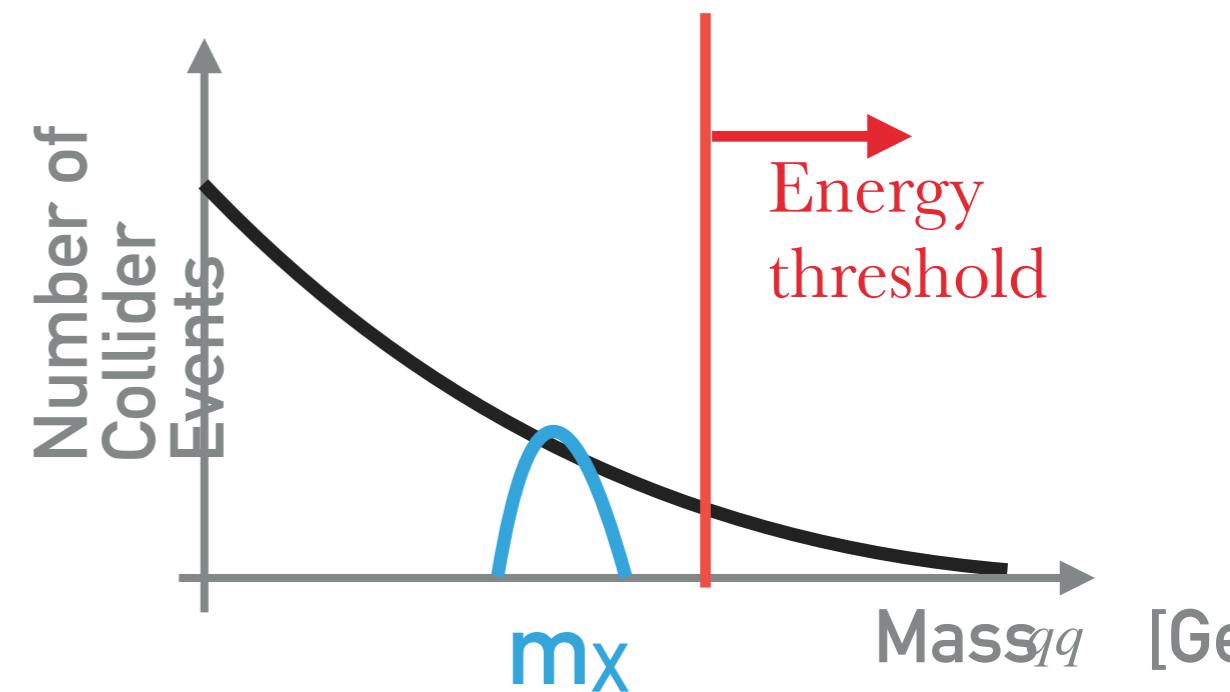
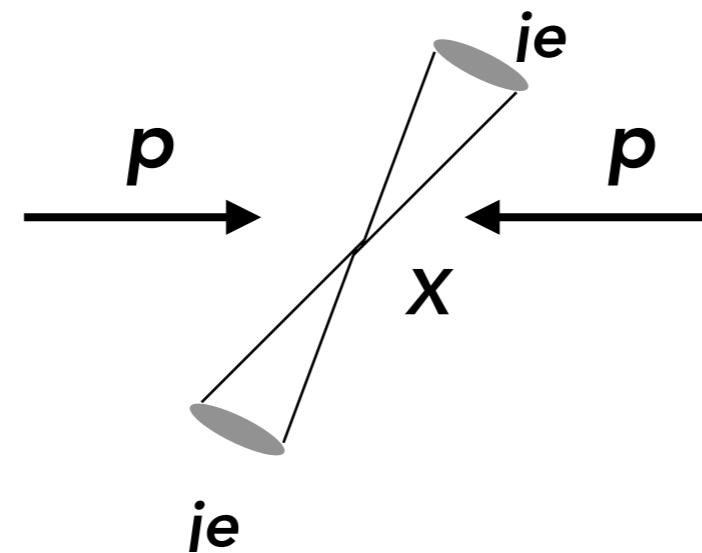


If $m_X < 500 \text{ GeV}$, event does not get saved
LHC has tight energy thresholds (mass thresholds)



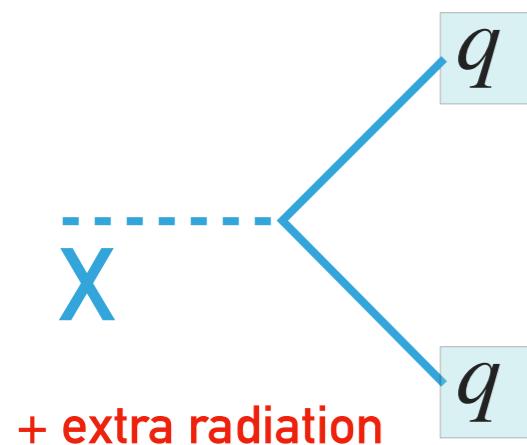
$p_T < 200 \text{ GeV}$

$m_X < 500 \text{ GeV}$



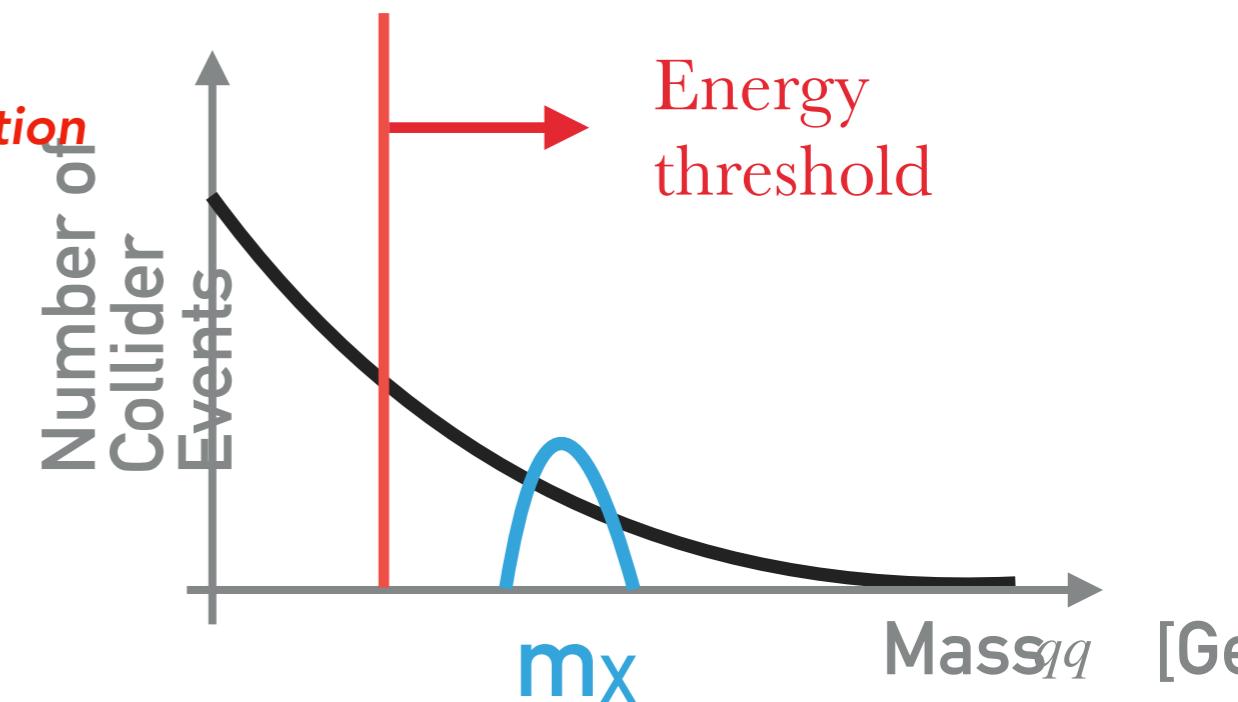
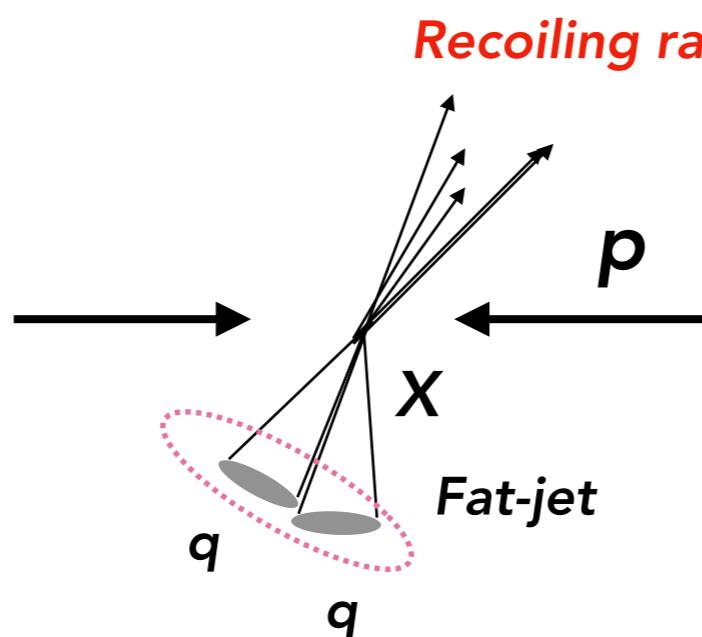
How to save these events

Boost them!



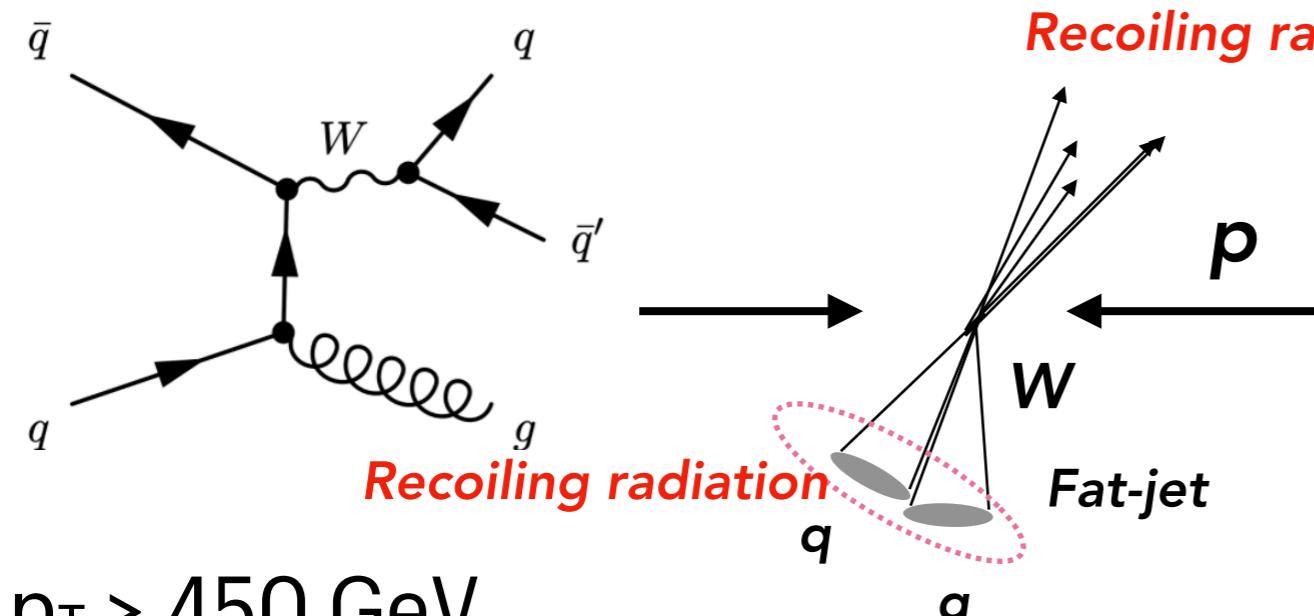
$p_T > 450 \text{ GeV}$

$m_X < 500 \text{ GeV}$



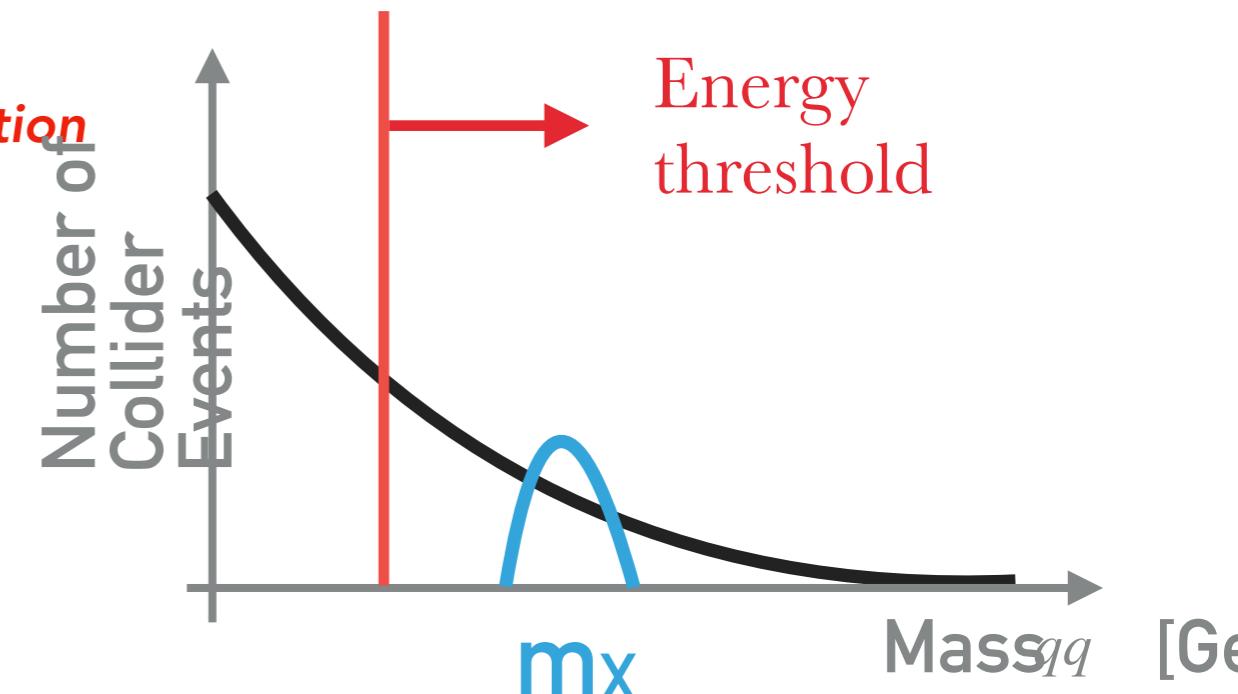
What the process looks like

And what you'll be looking for

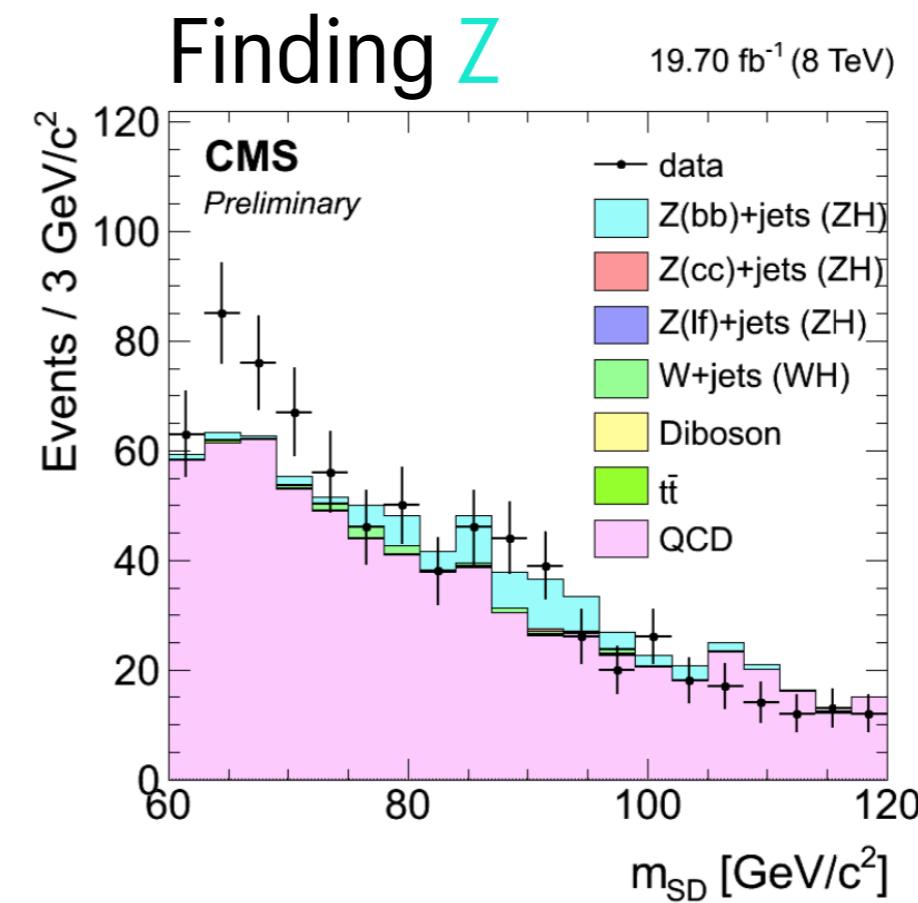
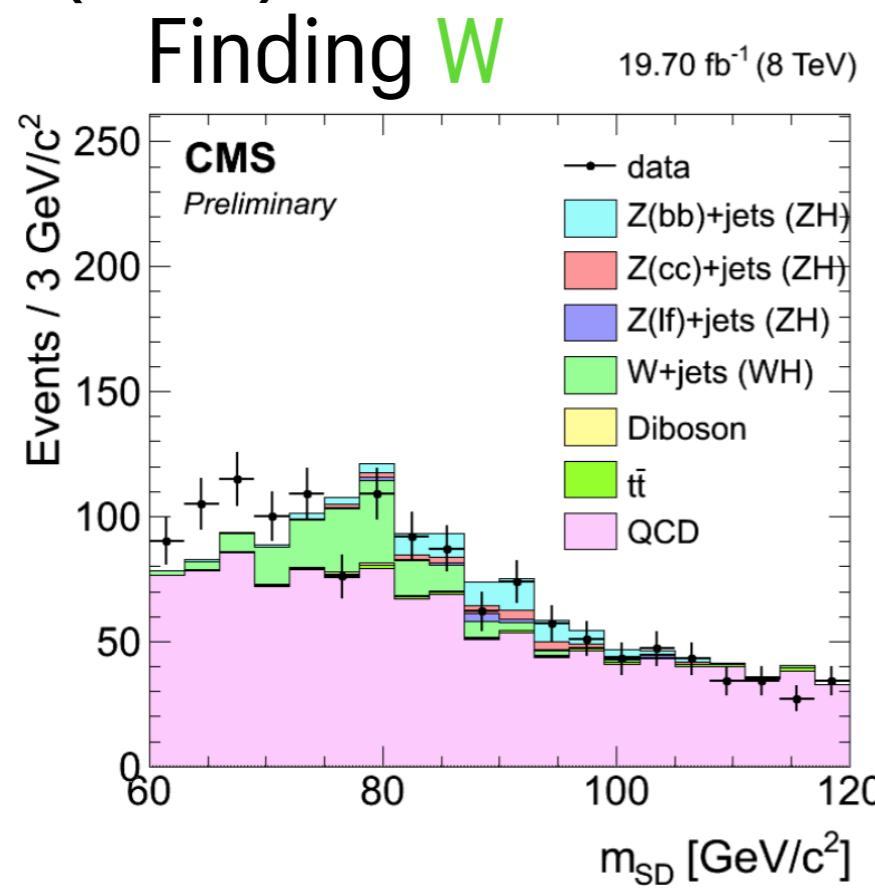


$p_T > 450 \text{ GeV}$

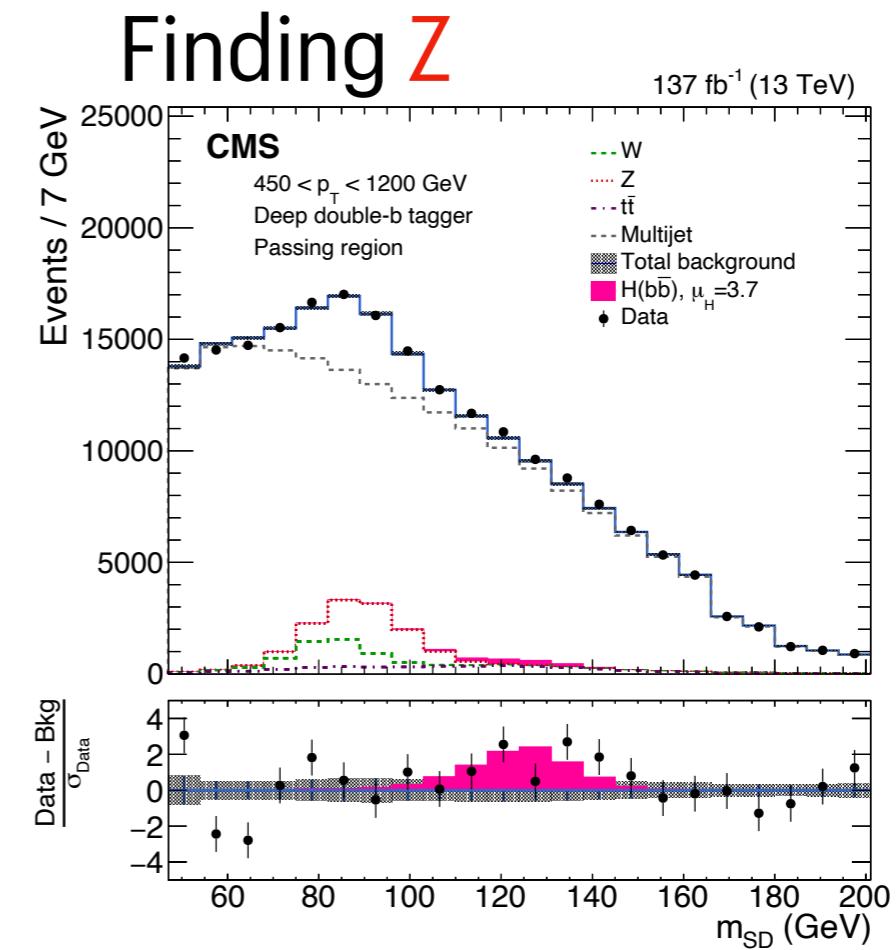
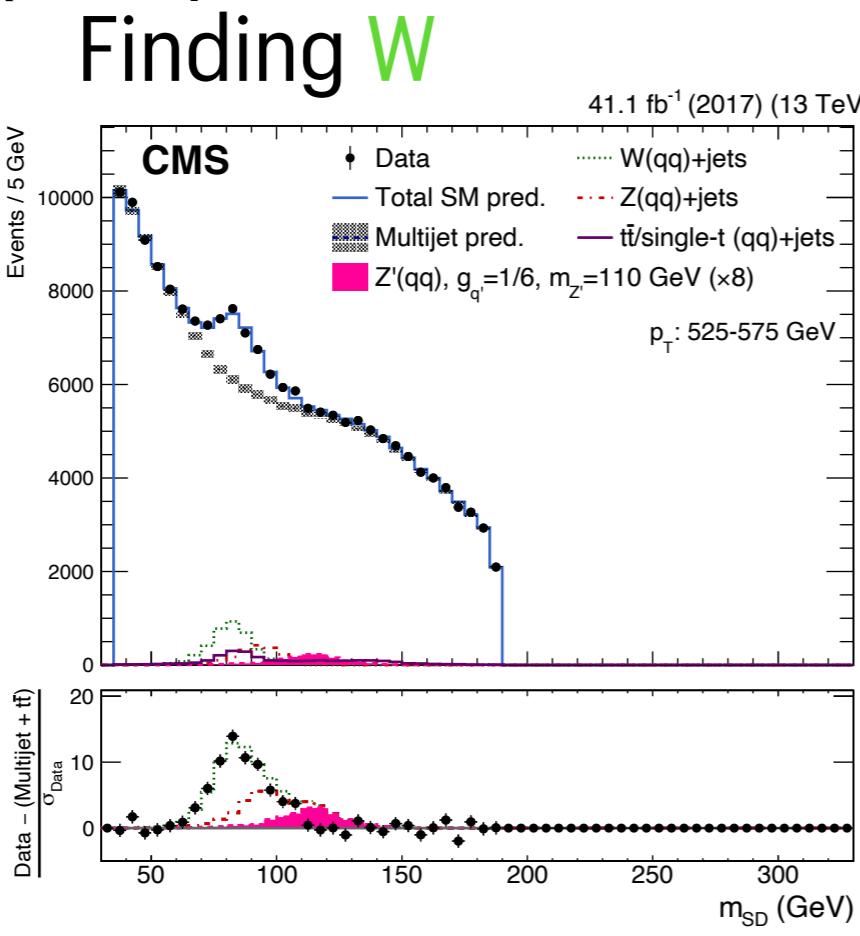
$m_W \sim 80.4 \text{ GeV}$



Your goal: reproduce LHC results (or improve them)
With 8 TeV data
@ 8 TeV (2015)

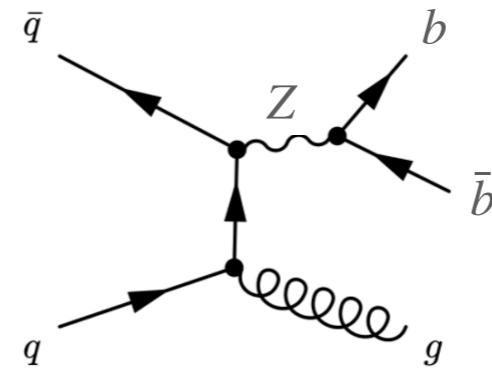
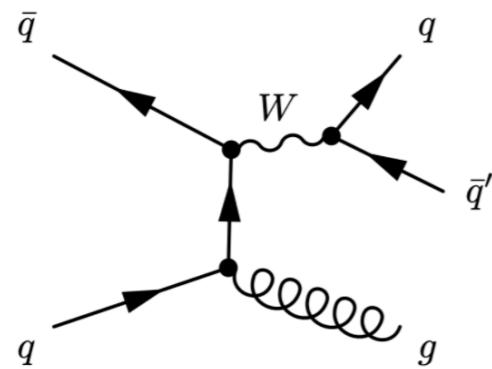


Your goal: reproduce LHC results (or improve them)
With 8 TeV data
@ 8 TeV (2015)



Project 2

Finding $W(q\bar{q})$ and $Z(q\bar{q})$ in 8 TeV LHC data



Introduction

In this lab we will investigate W bosons produced in the LHC's 8 TeV proton proton collisions. These samples were produced 4 years ago in a fun experiment that opened up the option of performing low mass resonance searches at the LHC. The studies done then have led to a wealth of results from both LHC experiments, ATLAS and CMS. To understand how this study works, we first need to introduce a few concepts.