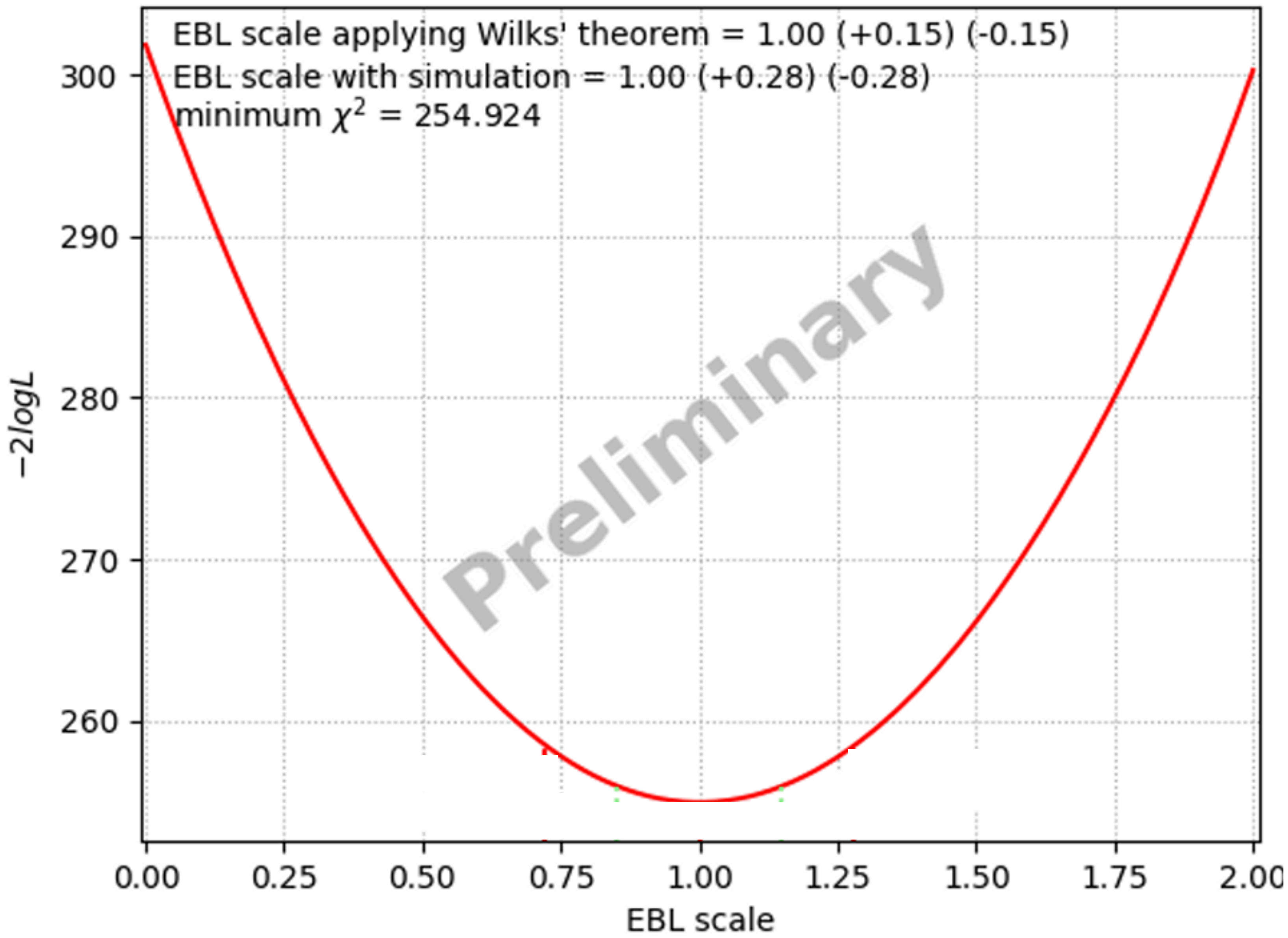
Lecture 8
Understanding Jets

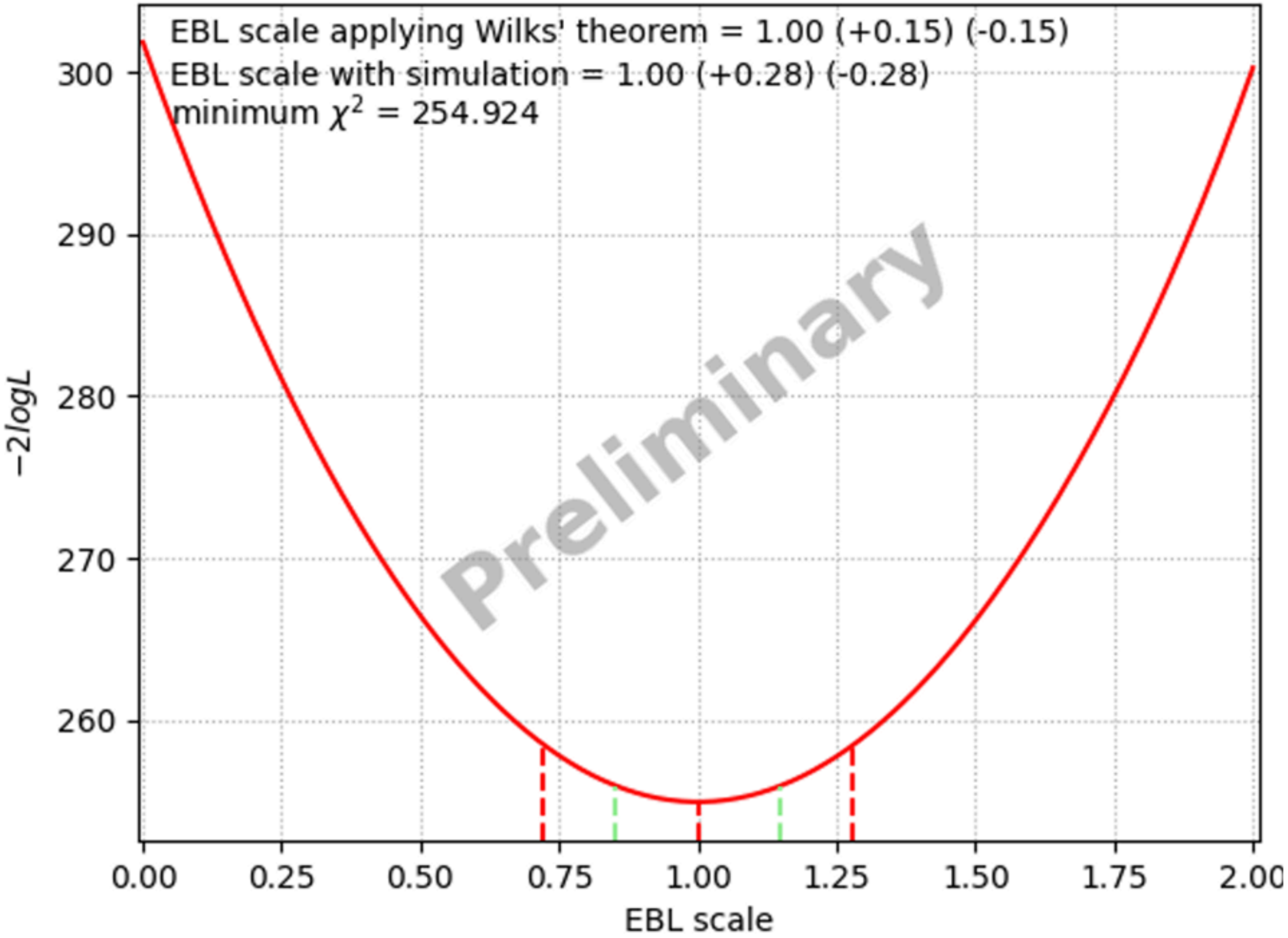
Recap

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



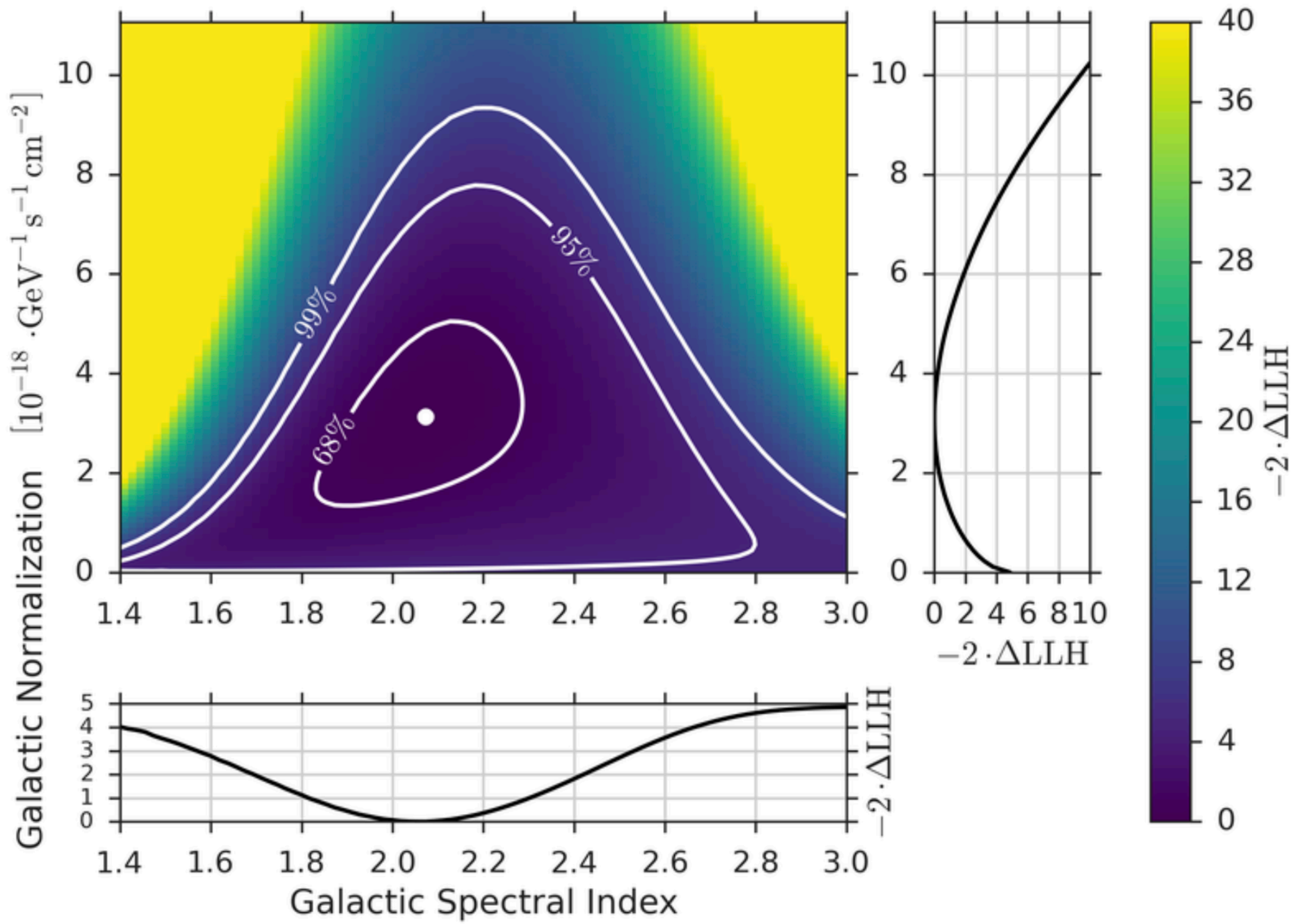
Recap

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



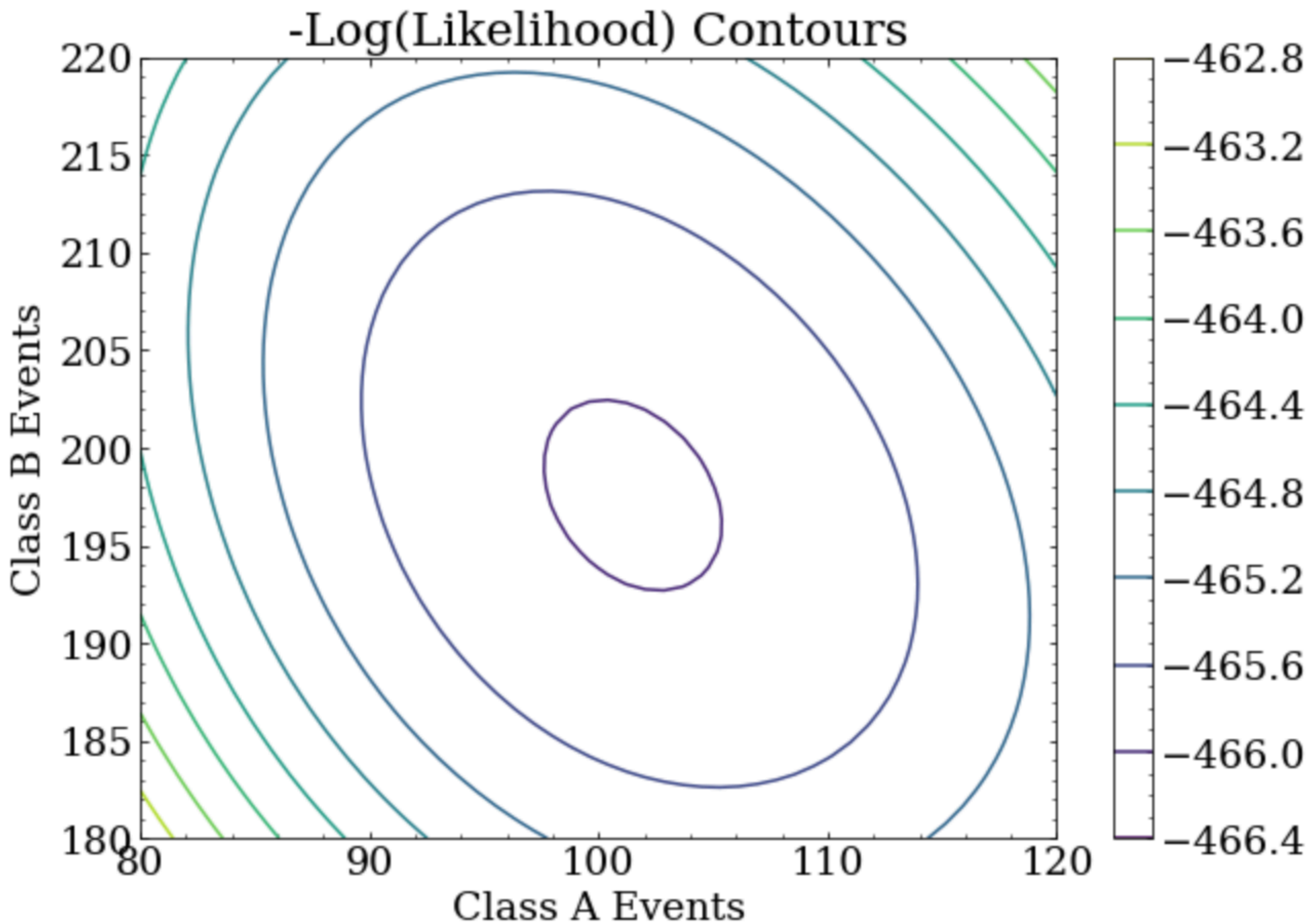
Random Talk

1D and 2D

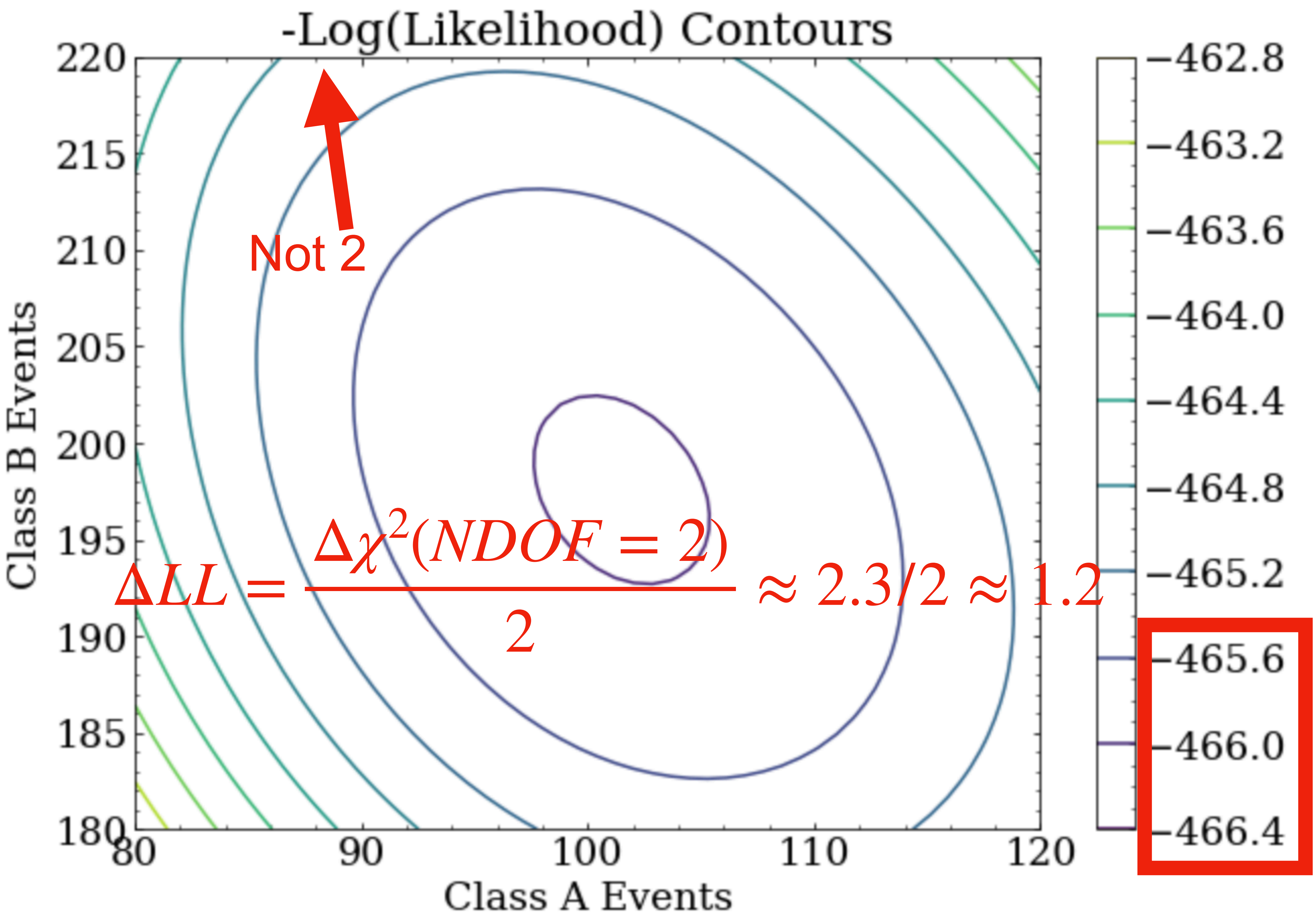


99%
95%
68%
Galactic Normalization $[10^{-18} \cdot \mathrm{GeV}^{-1} \mathrm{s}^{-1} \mathrm{cm}^{-2}]$
Galactic Spectral Index
$-2 \cdot \Delta\mathrm{LLH}$
0
2
4
6
8
10
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
12
16
20
24
28
32
36
40

Which line for a 2D

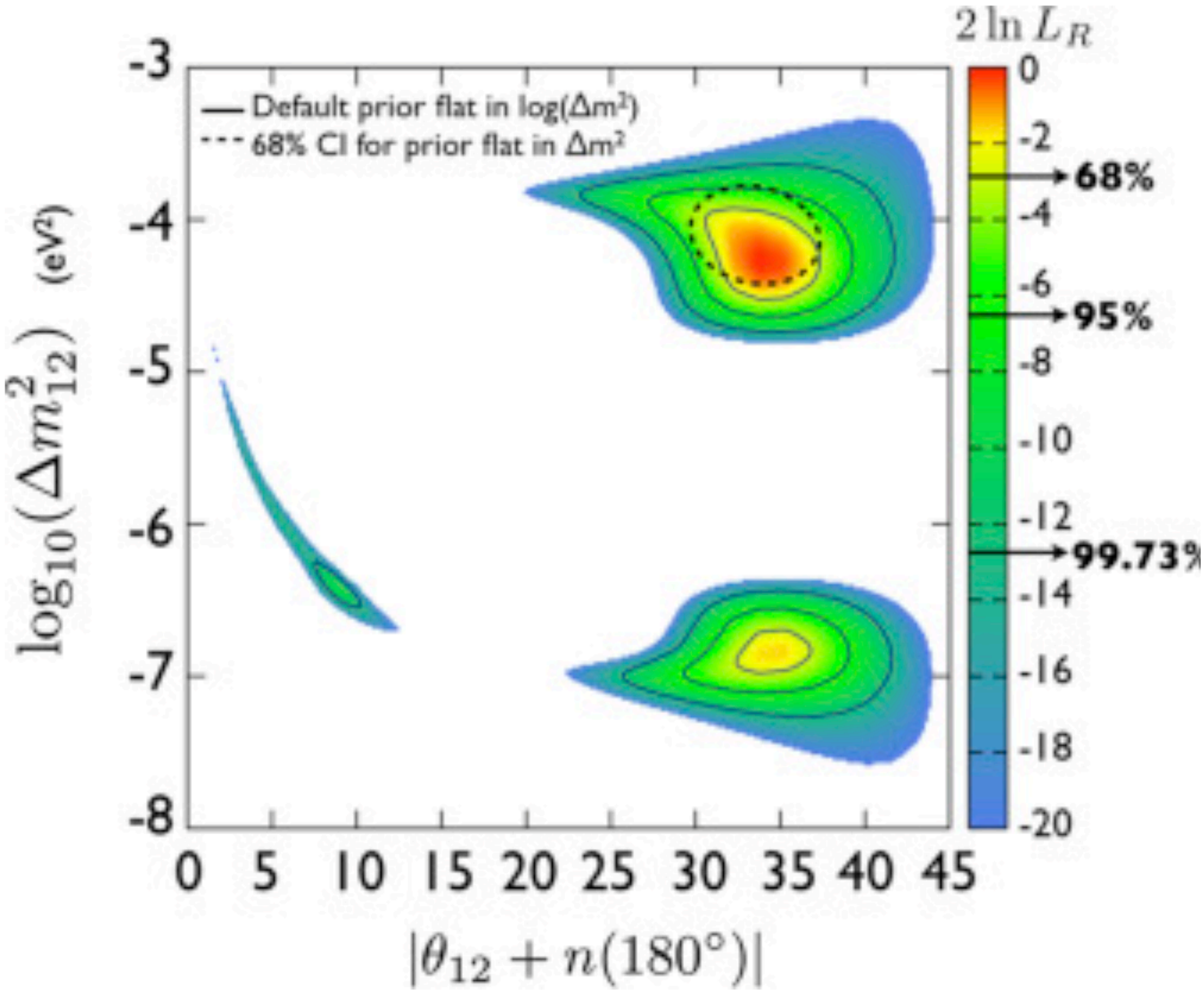


Which line for a 2D



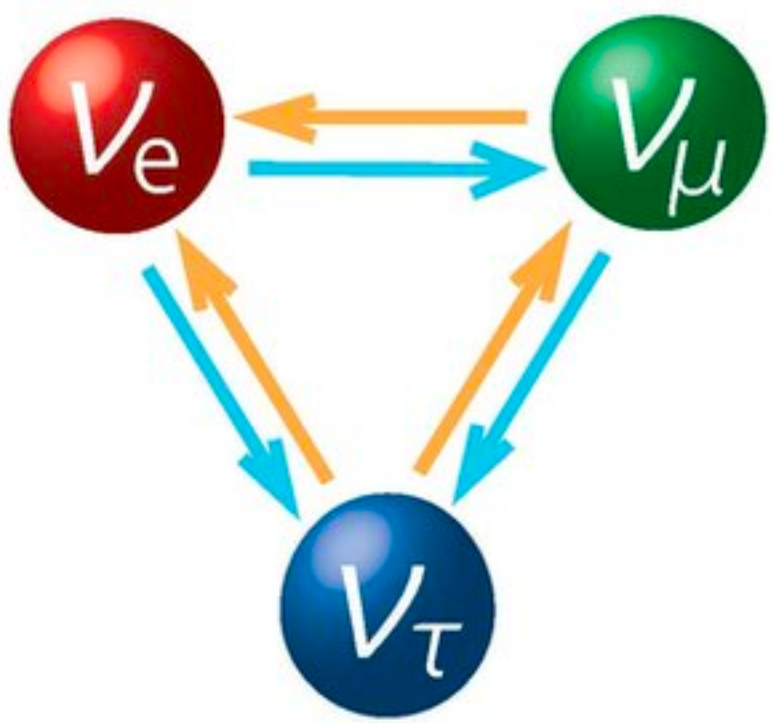
$$\Delta LL = \frac{\Delta\chi^2(NDOF = 2)}{2} \approx 2.3/2 \approx 1.2$$

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



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
  - 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?



Neutrinos oscillate into other neutrinos

Nobel Prize

The Nobel Prize in Physics 2015

Takaaki Kajita
Arthur B. McDonald

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The Nobel Prize in Physics 2015

© Nobel Media AB. Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

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Arthur B. McDonald

Prize share: 1/2

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

Neutrino Mixing

Particle Eigenstates

$$\boxed{|\nu_\alpha>} = \boxed{\sum_{i=1}^{3} U^*_{\alpha i}|\nu_i>}$$

Mass Eigenstates

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

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

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

Neutrino Mixing

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

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

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

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

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

Neutrino Mixing

Master Formula

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

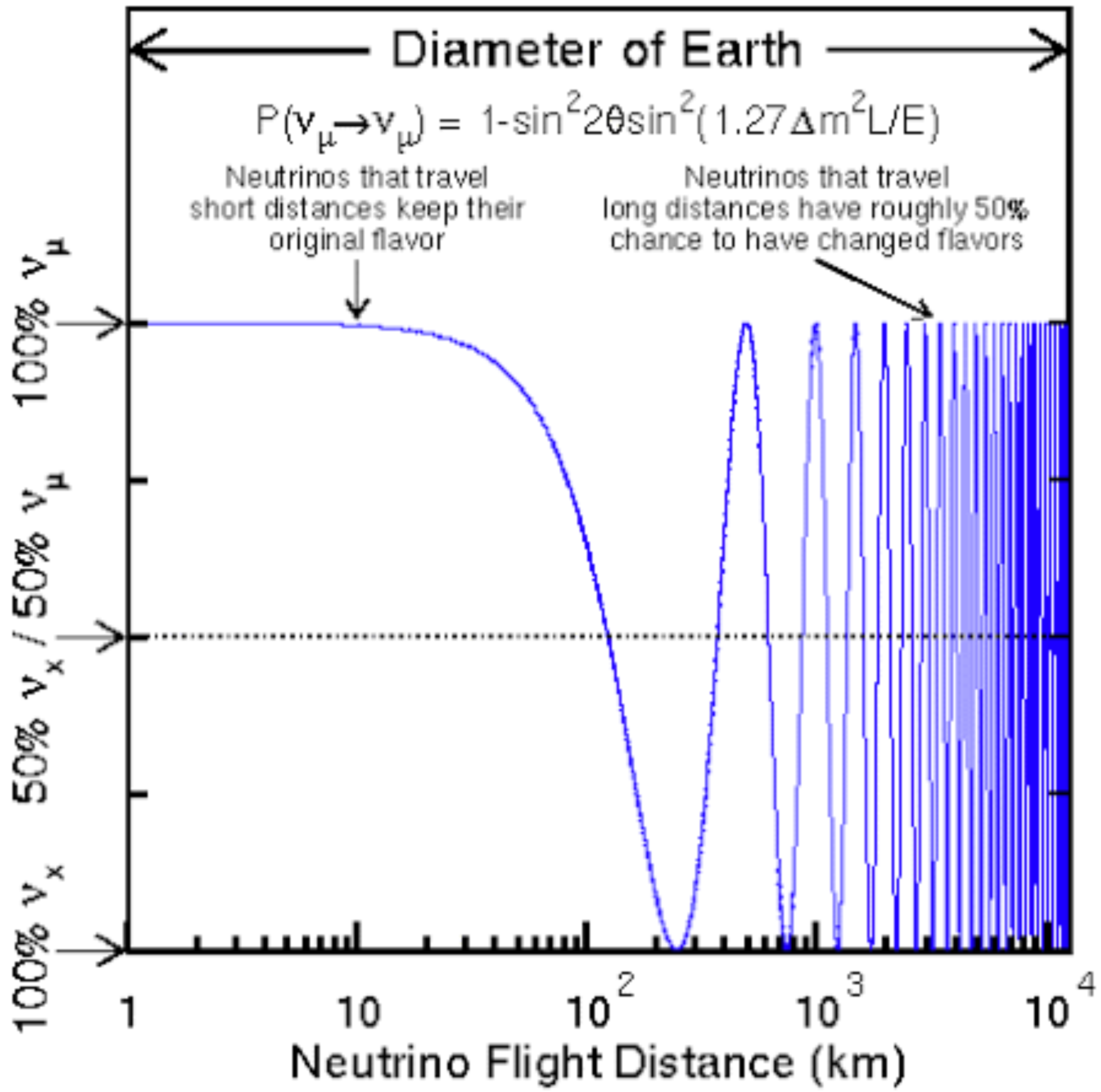
$$\simeq 1 - \sin^2 2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{atm.}}{E}L\right),$$

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

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

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

Observing Oscillations



Neutrinos oscillate distance

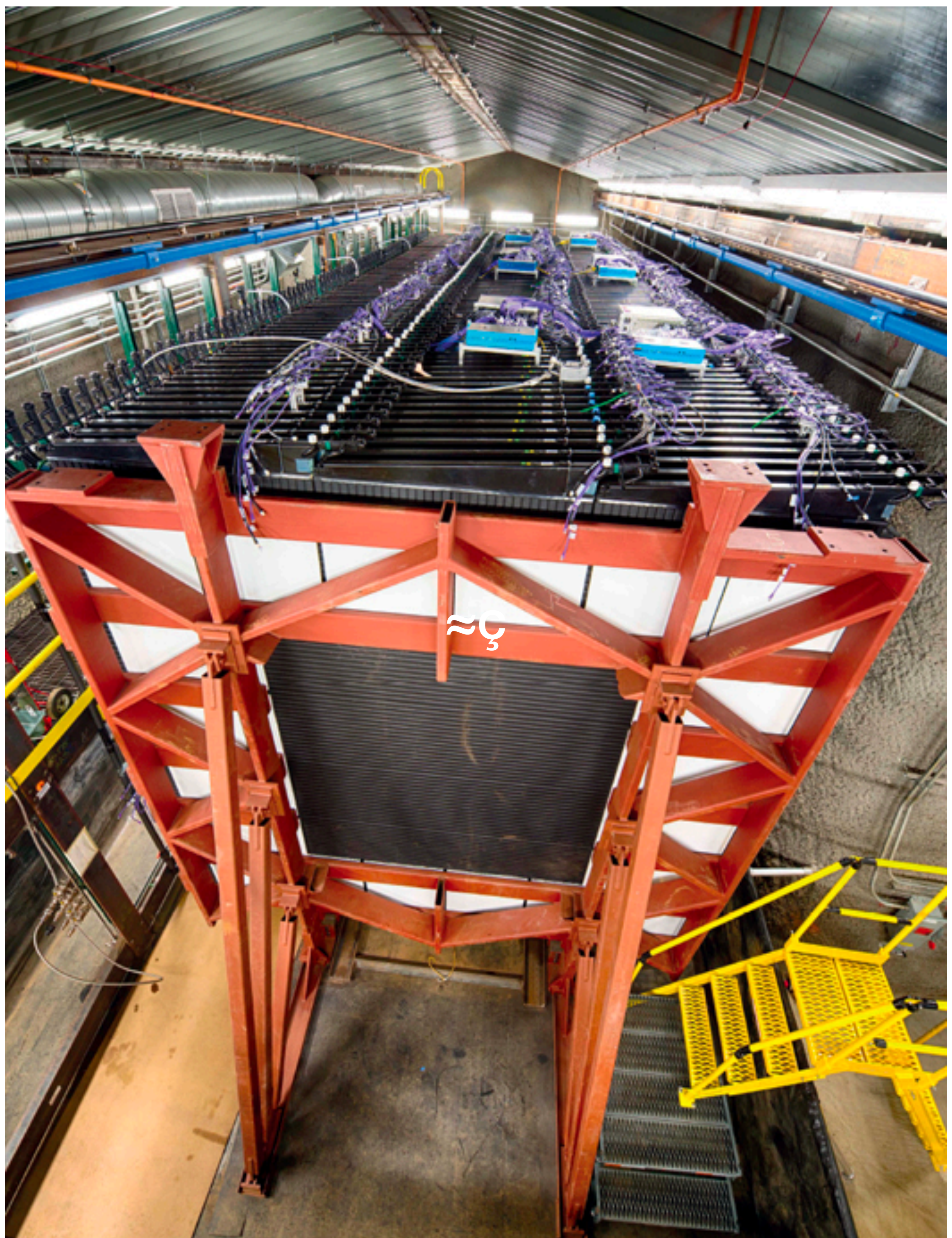
Muon neutrino beam

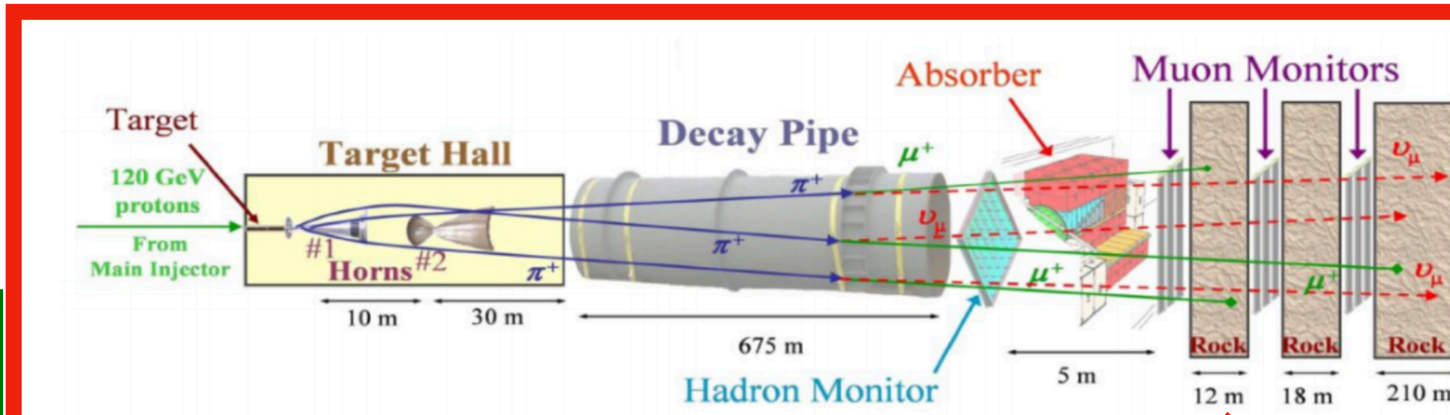
A long Distance

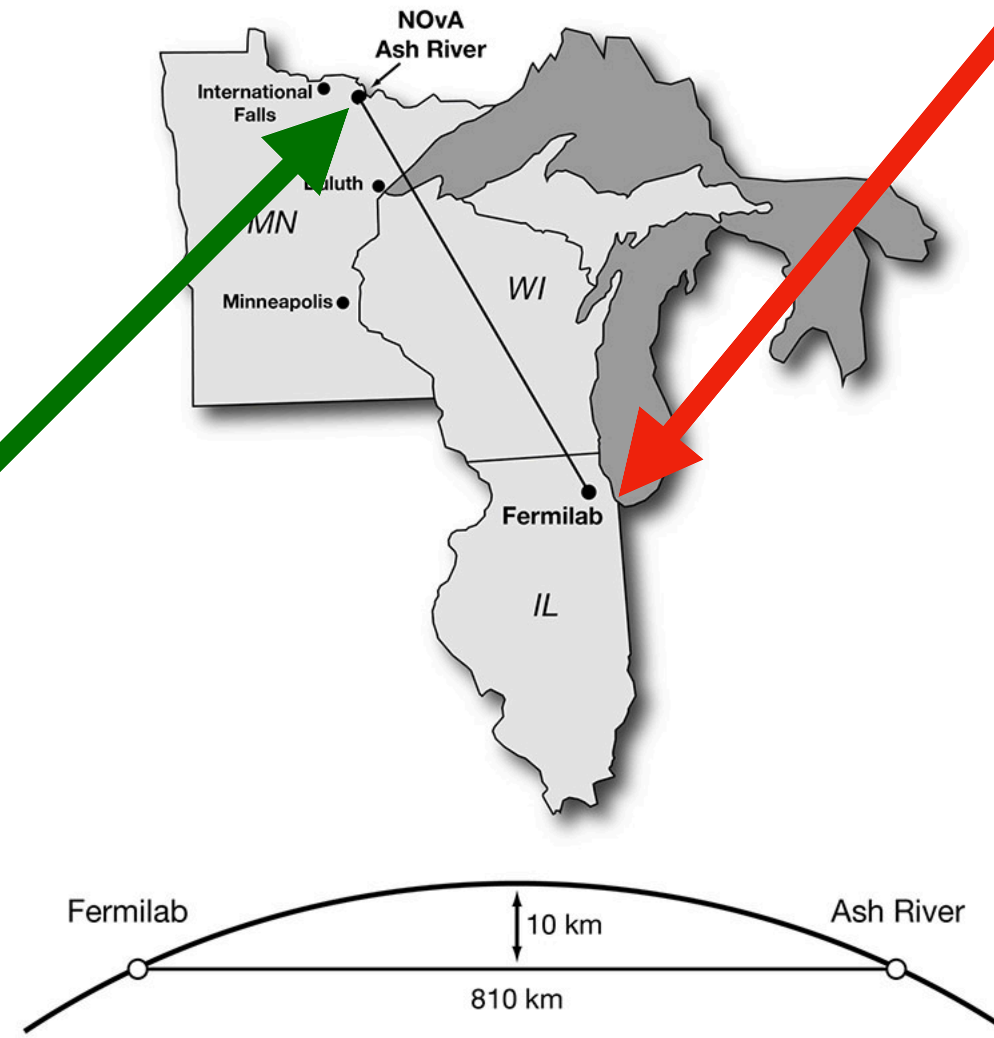
Muon+Electron+Tau Neutrinos

NOvA Detector

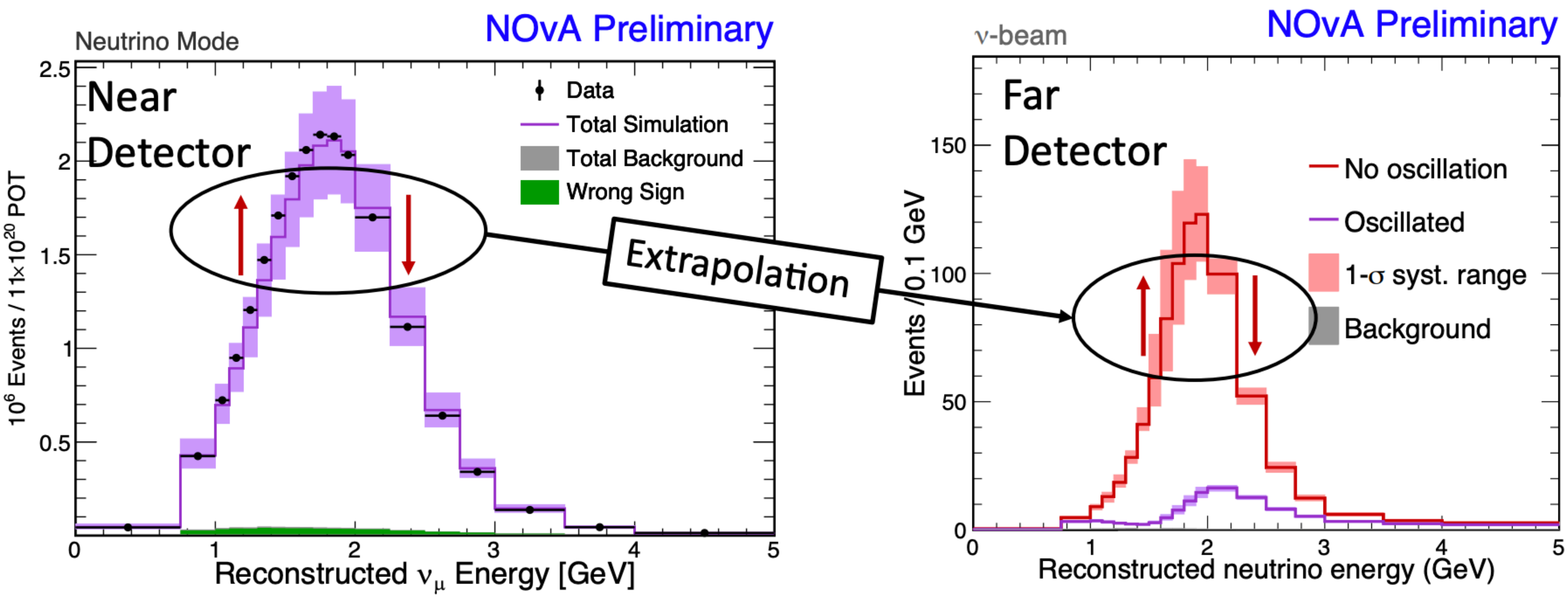
Neutrino Beam
From Fermilab (Near Chicago)
To Minnesota (Near Canada)







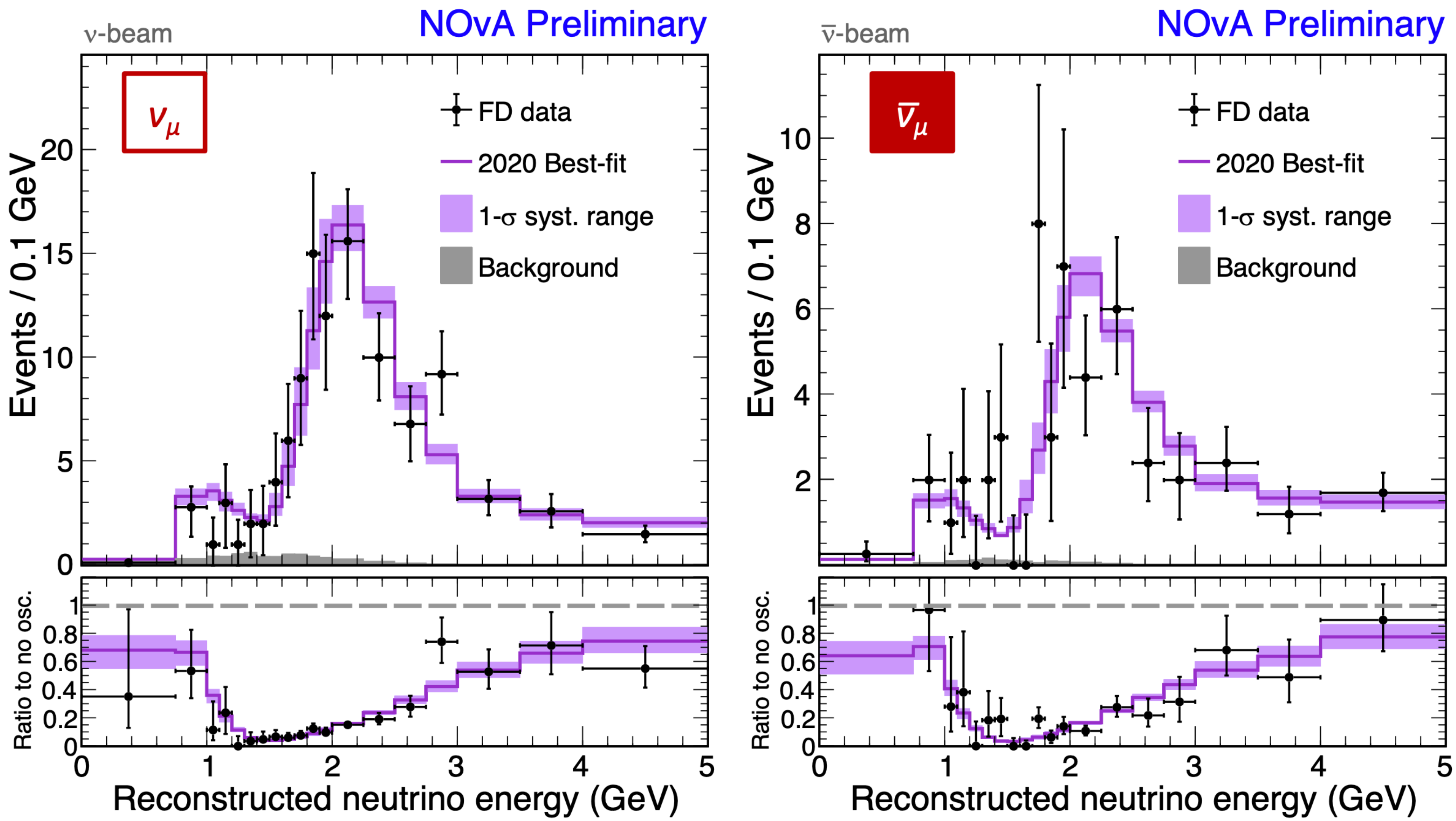
NOvA Data



- 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

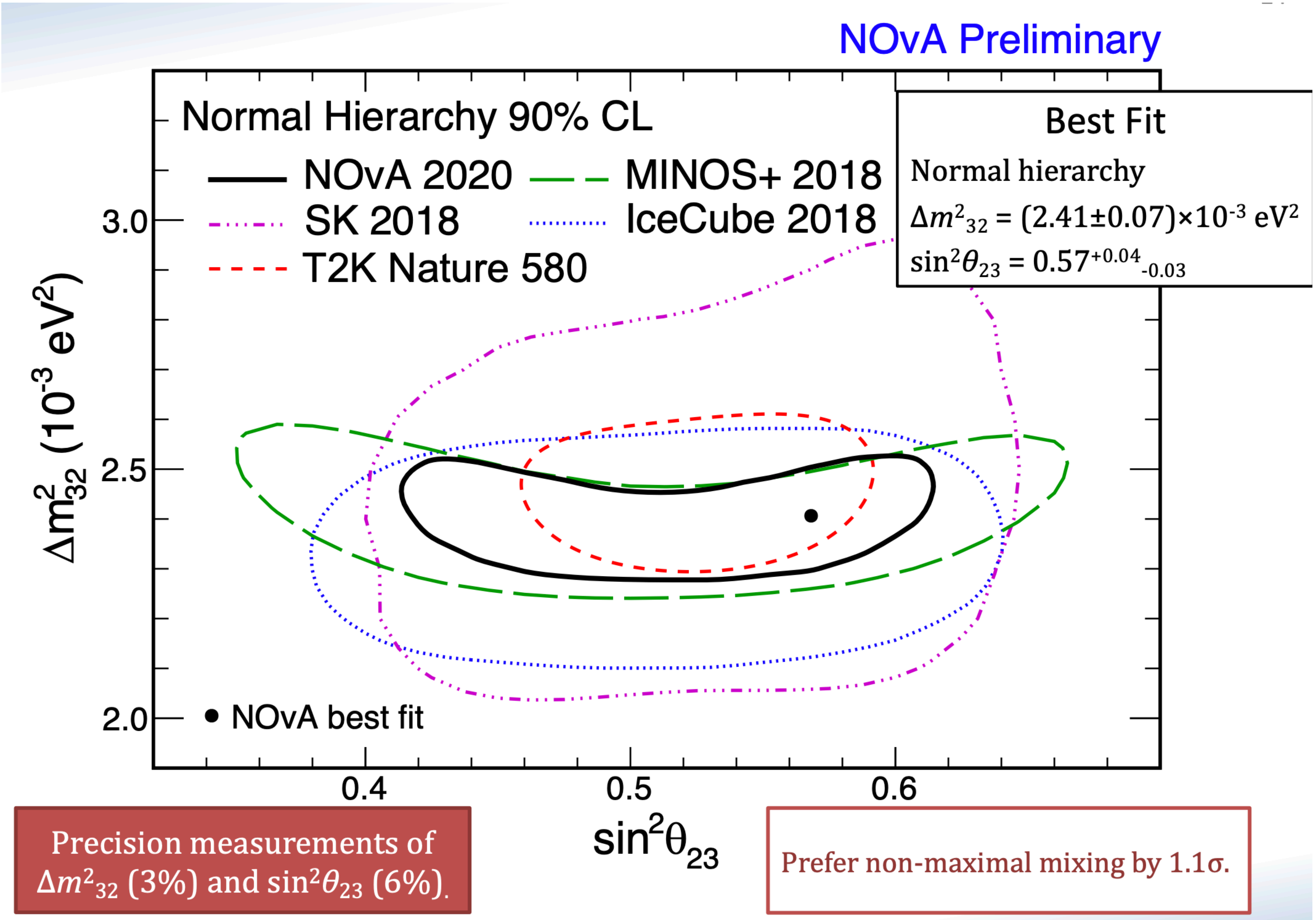
https://indico.fnal.gov/event/43209/contributions/187840/attachments/130740/159597/NOvA-

NOvA Data



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

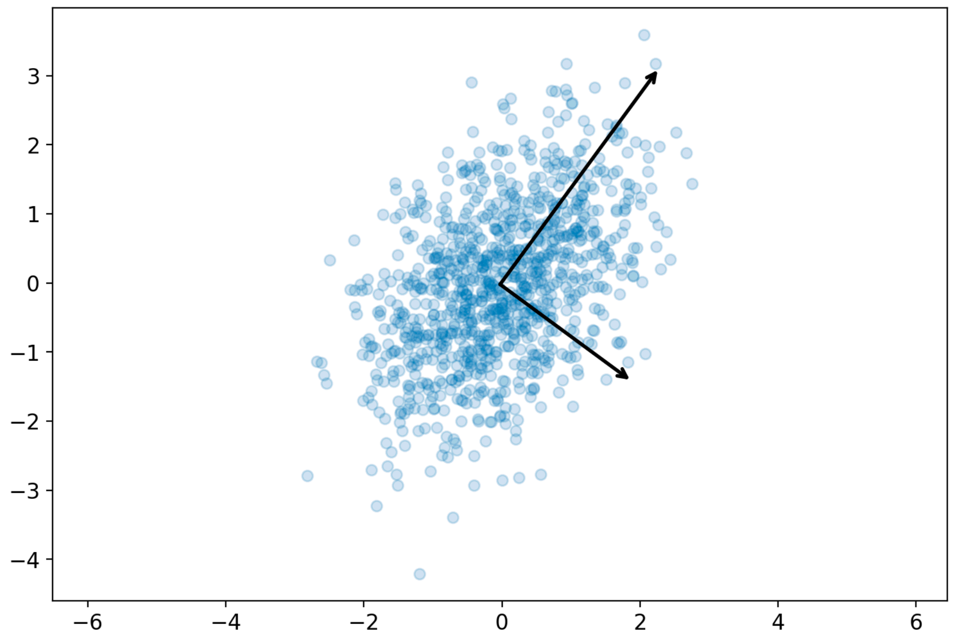
NOvA Result



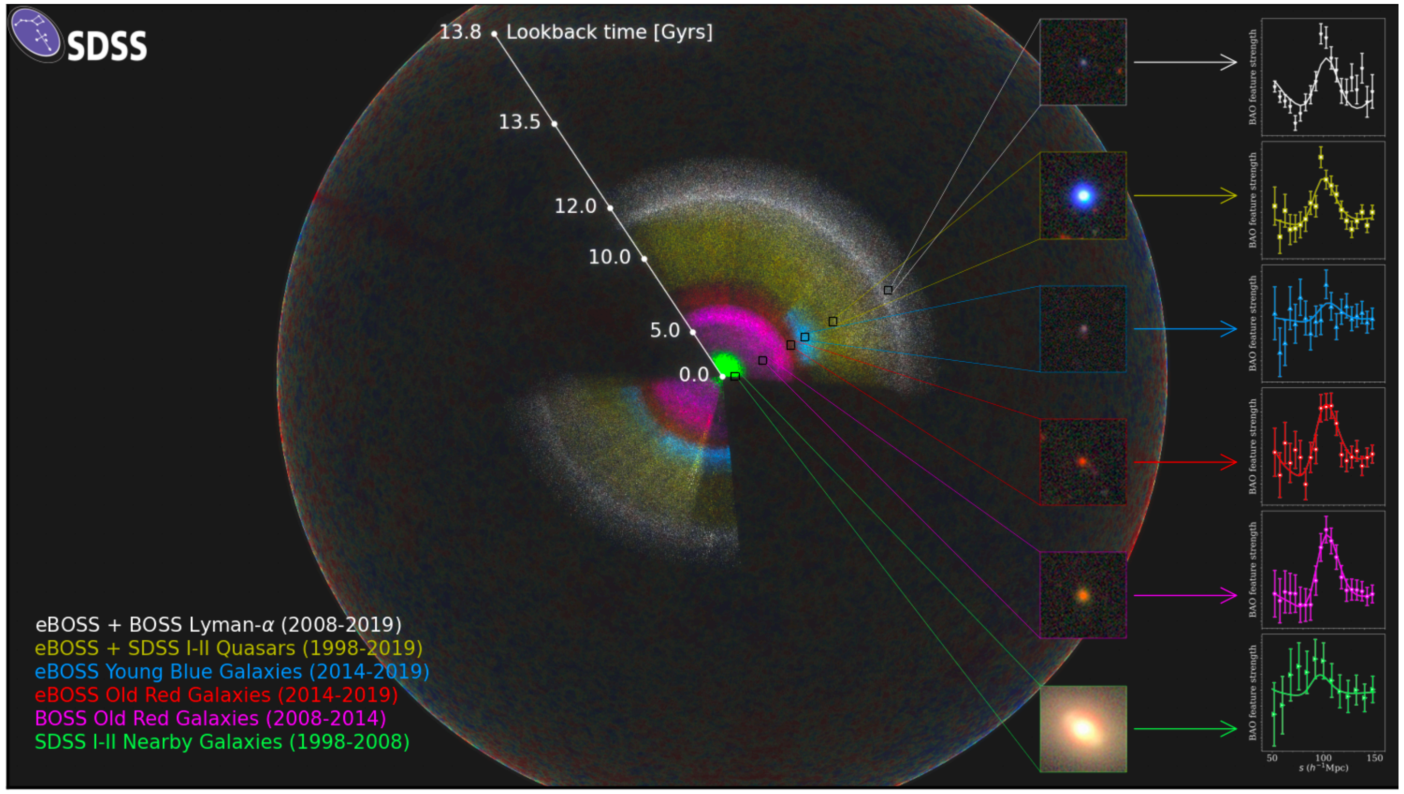
- From those plots: Lets look at those results

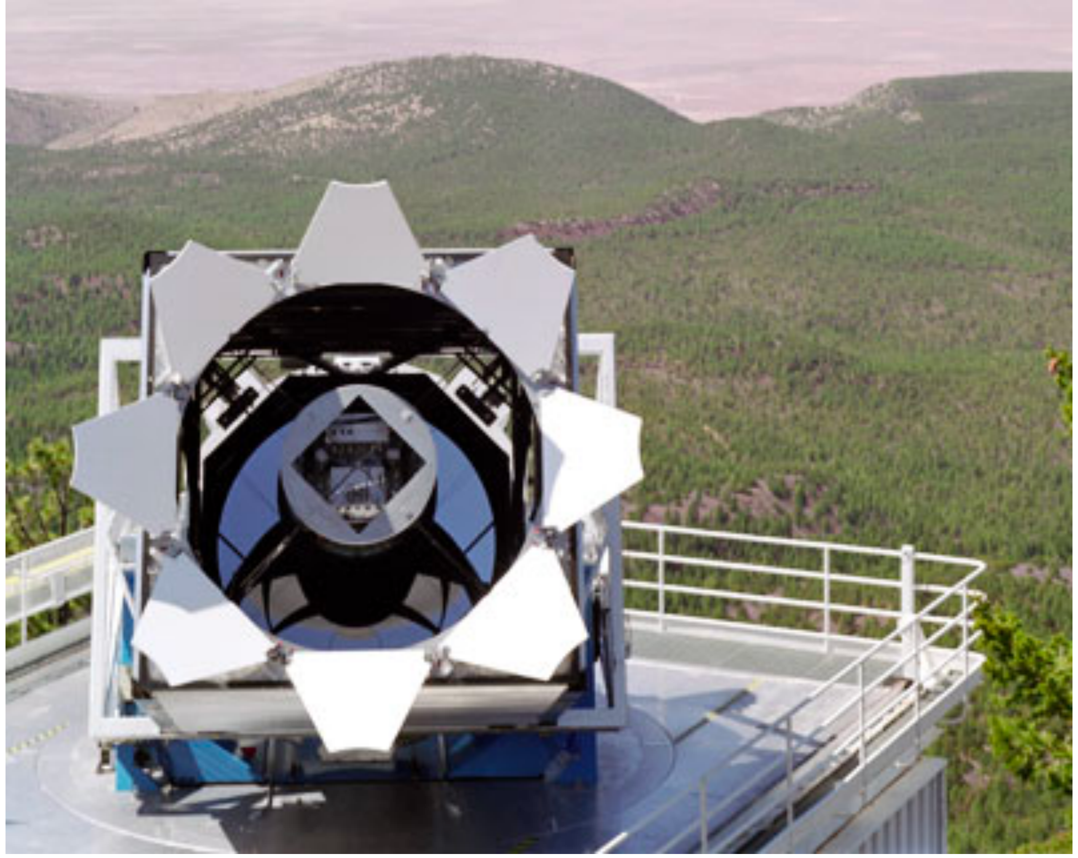
Principal Component Analysis

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



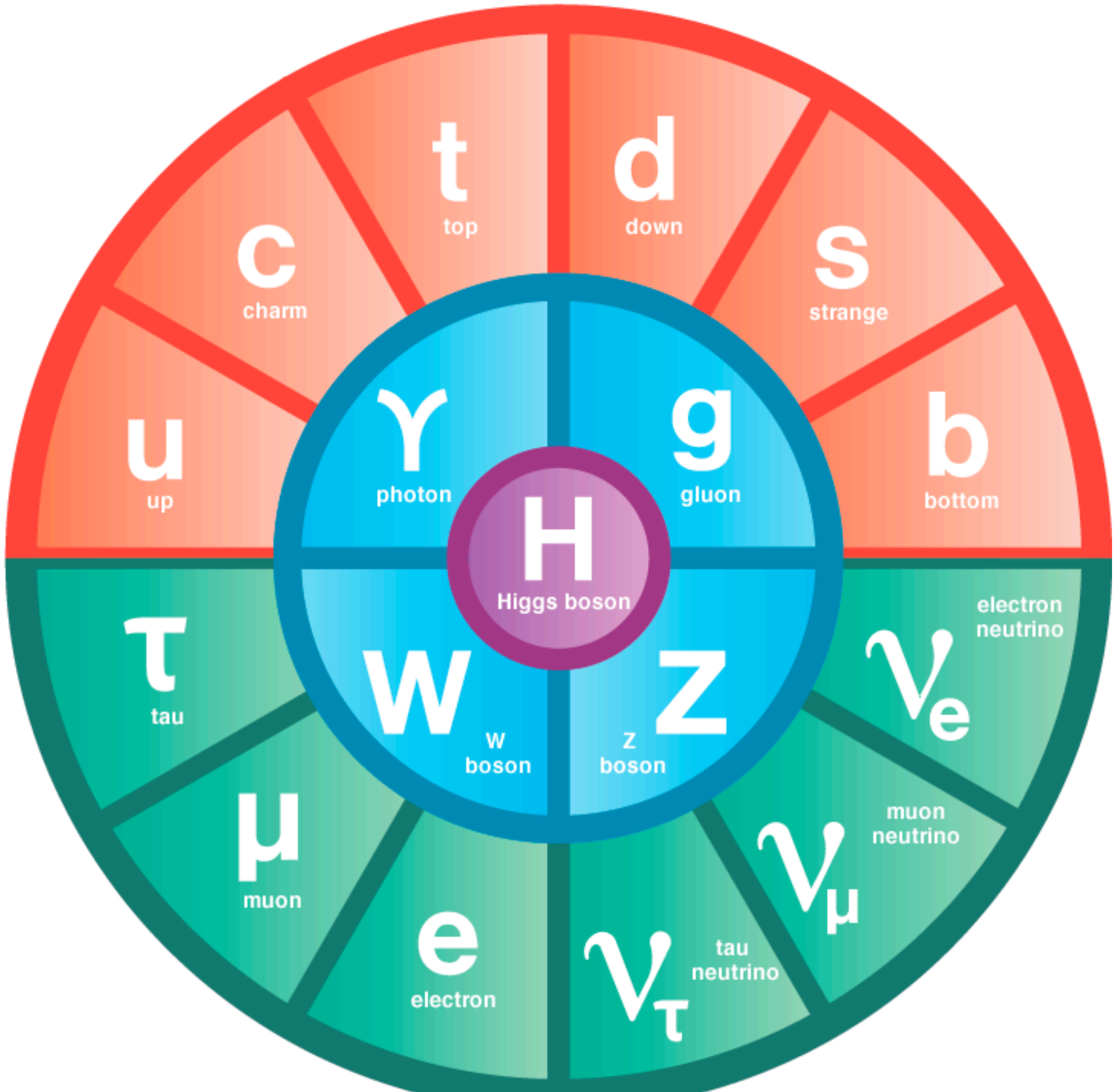
SDSS


SDSS
13.8 Lookback time [Gyrs]
13.5
12.0
10.0
5.0
0.0
eBOSS + BOSS Lyman-α (2008-2019)
eBOSS + SDSS I-II Quasars (1998-2019)
eBOSS Young Blue Galaxies (2014-2019)
eBOSS Old Red Galaxies (2014-2019)
BOSS Old Red Galaxies (2008-2014)
SDSS I-II Nearby Galaxies (1998-2008)
BAO feature strength
50
100
150



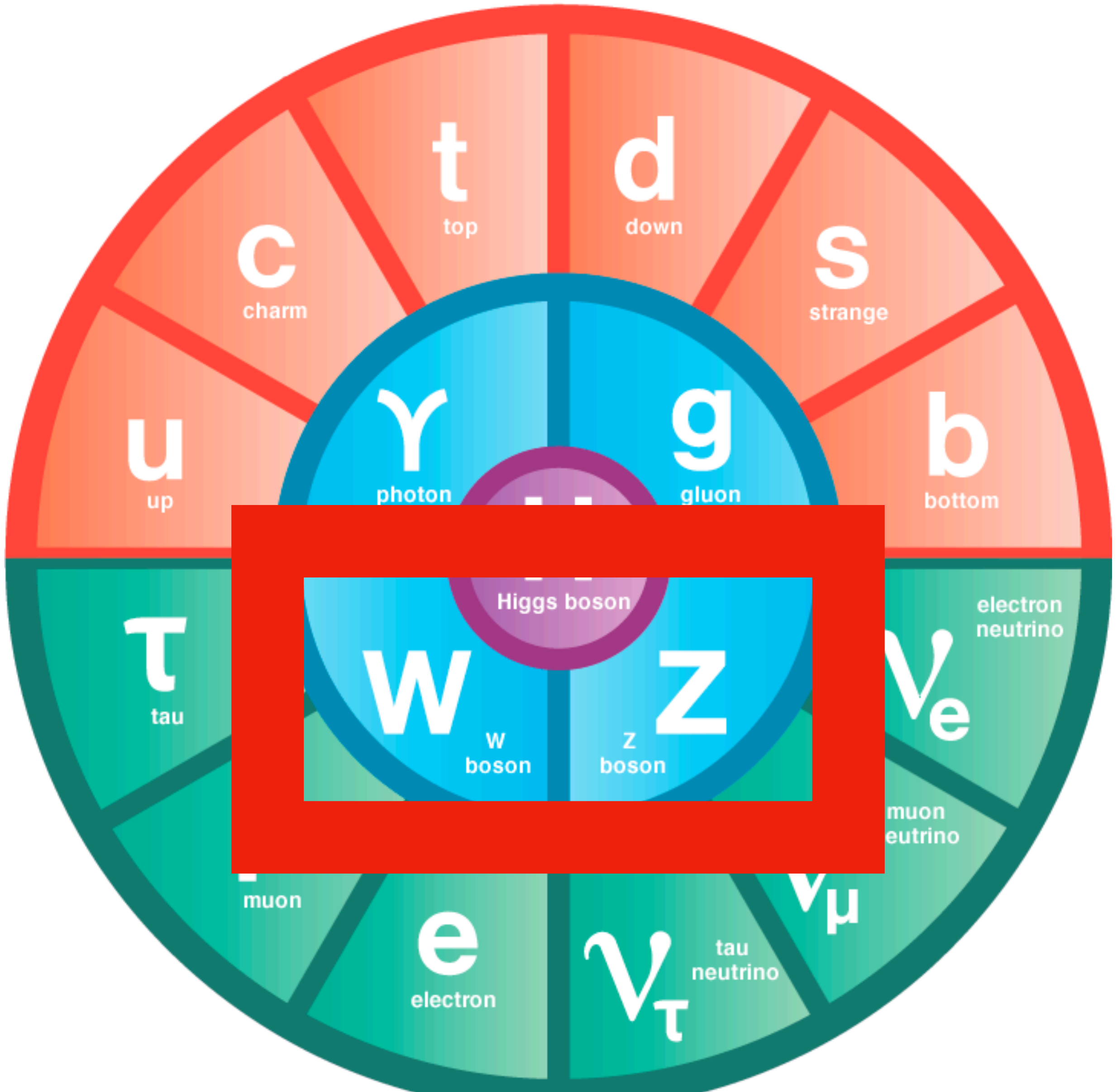
Laboratory

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



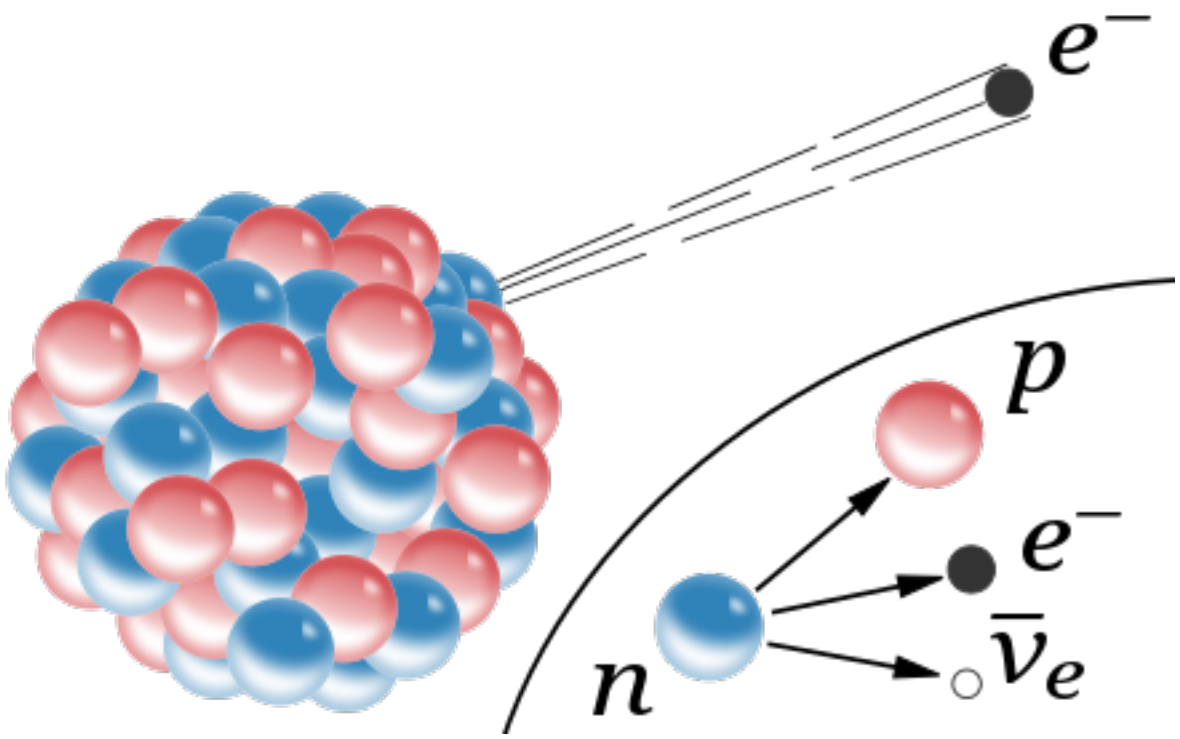
Laboratory

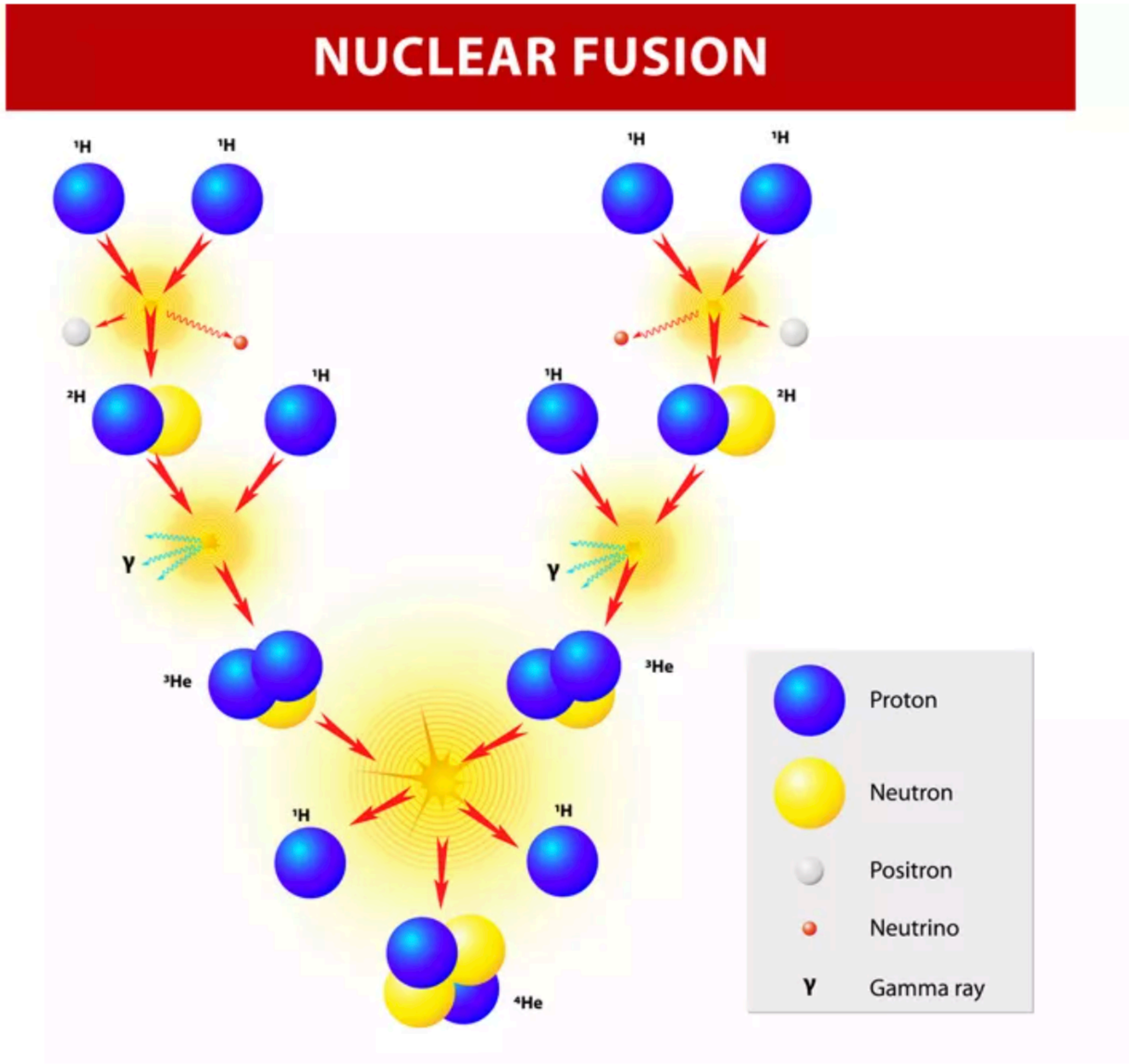
- The challenge of this lab is to fin the W and Z boson
  - These are the particles that cover the Weak Boson Interaction



Fundamental Forces

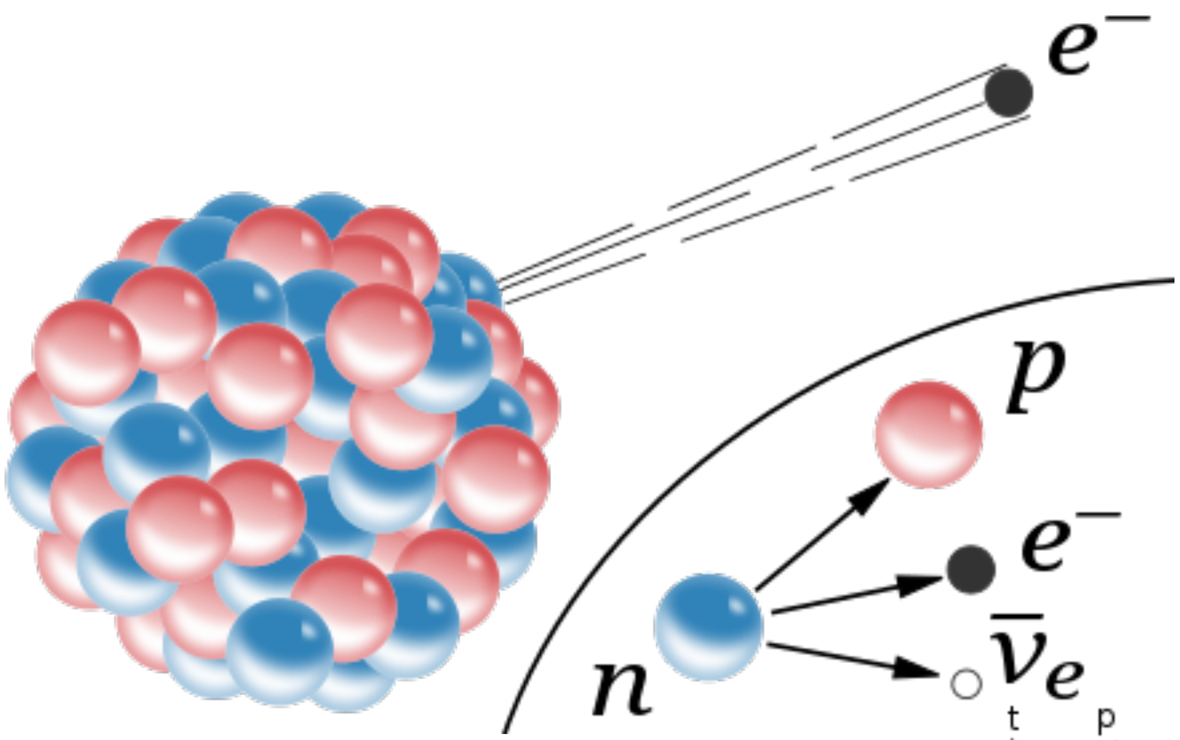
Weak Interactions

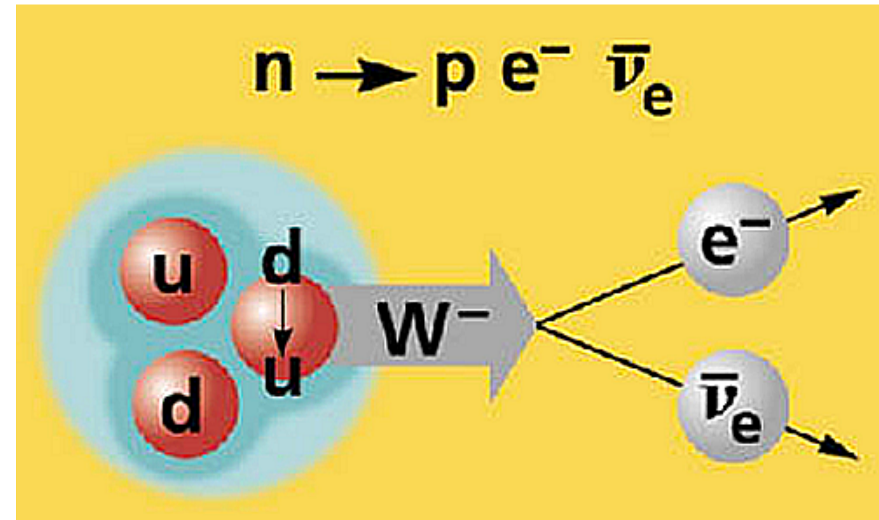


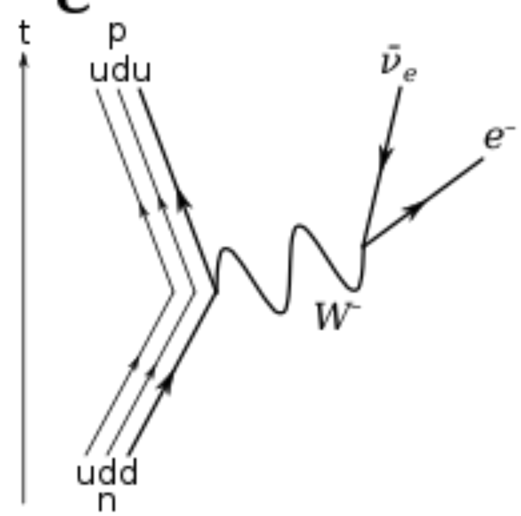


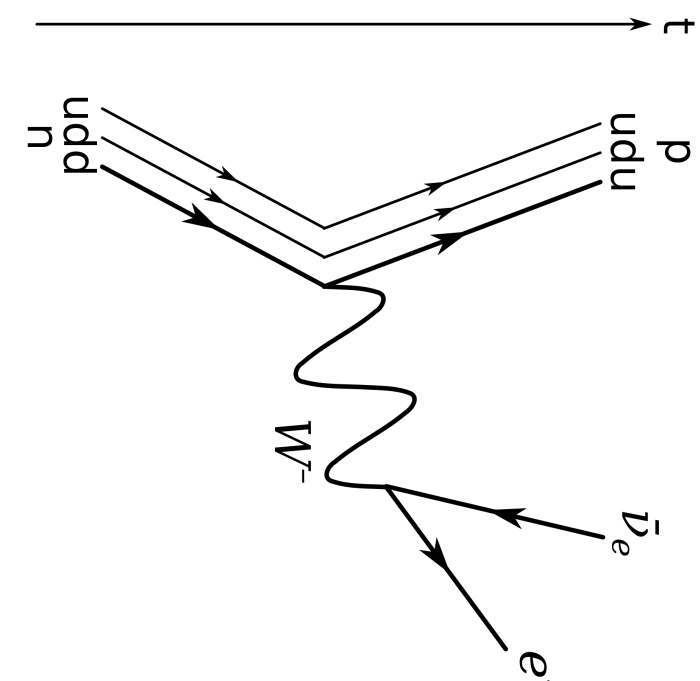
- The Weak interaction is described by W and Z bosons

Weak Interactions





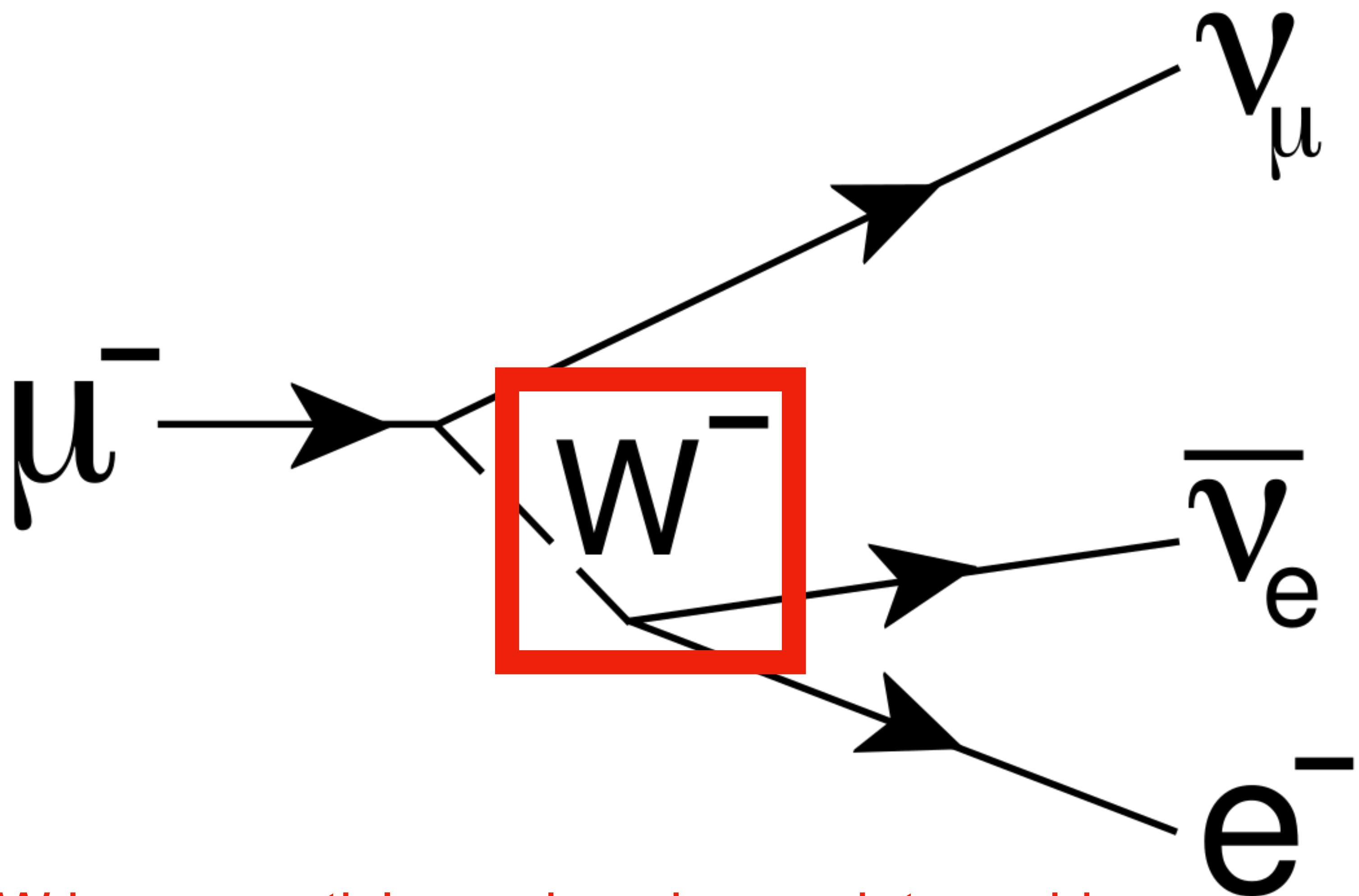




- The Weak interaction is described by W and Z bosons

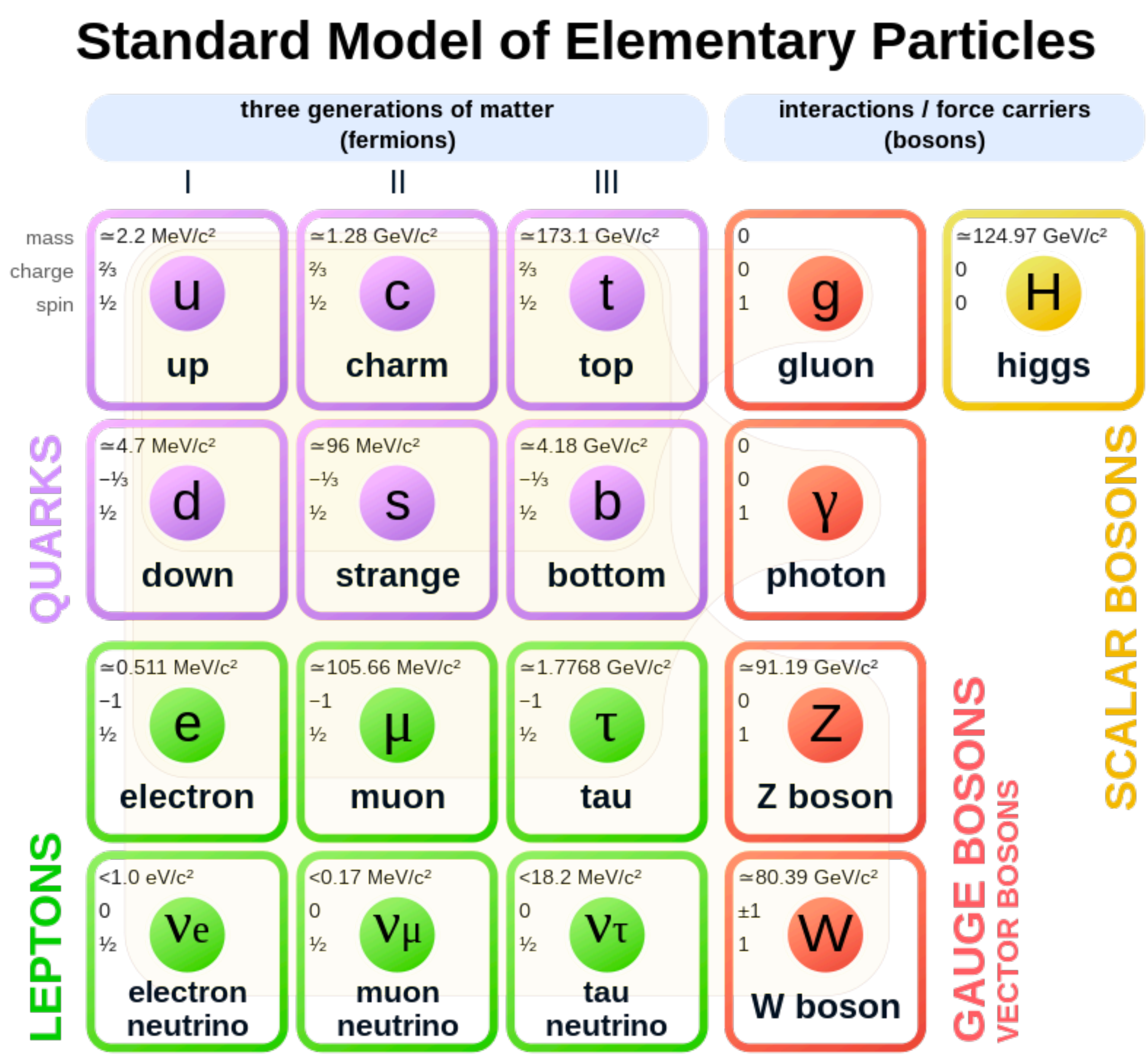
What really is this?

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

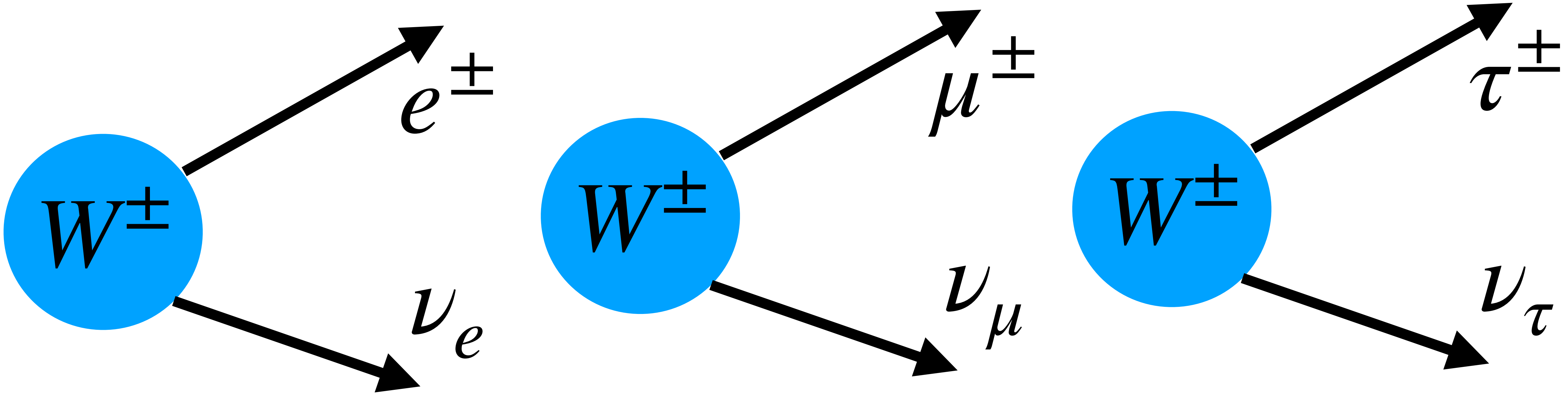


Heavy W boson particle produced as an intermeidary

All the Fundamental Particles

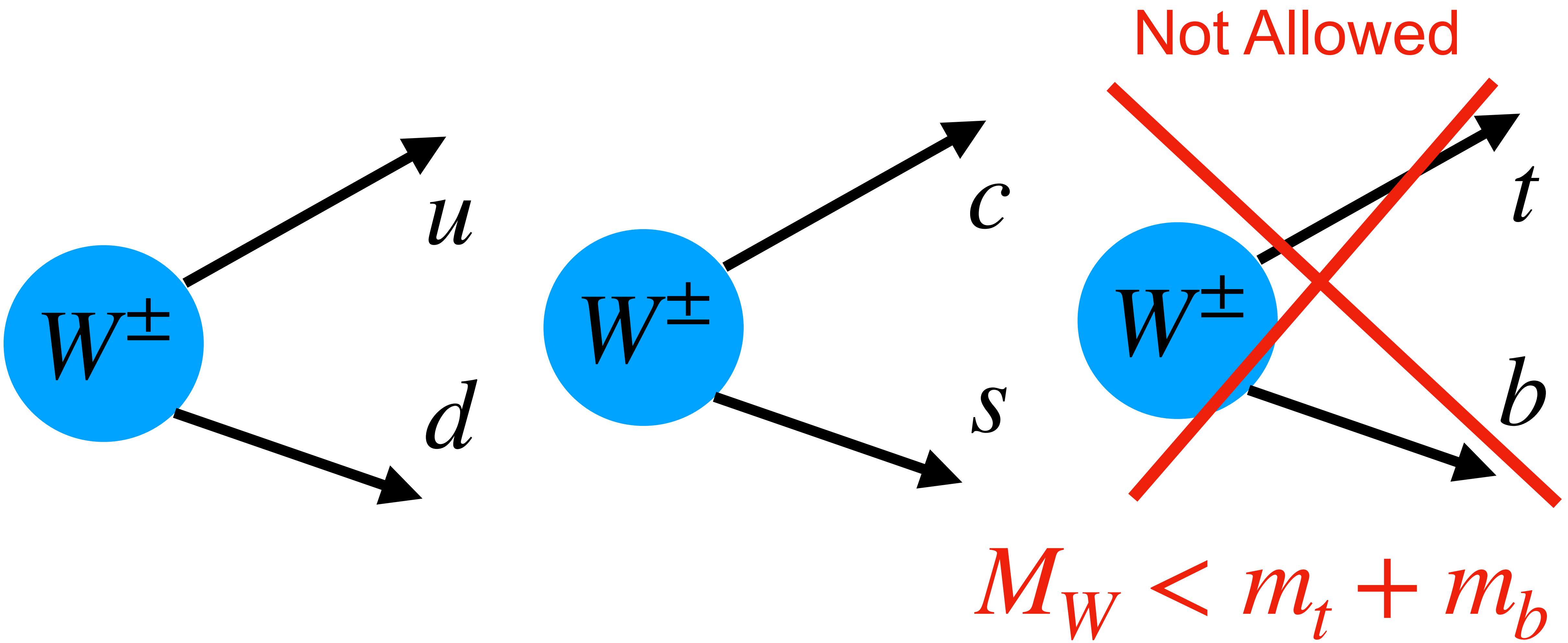


W boson Properties



- W boson interacts with many different particles

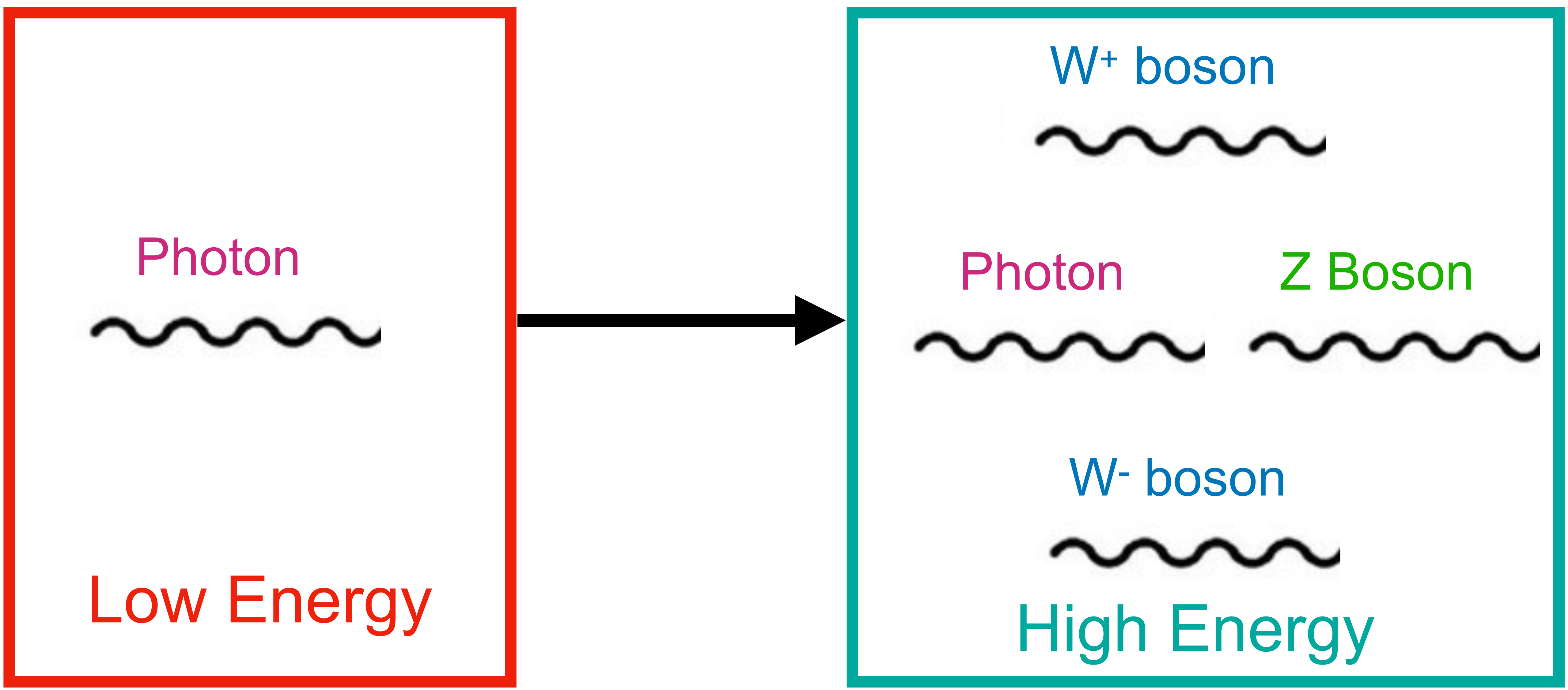
W boson Properties



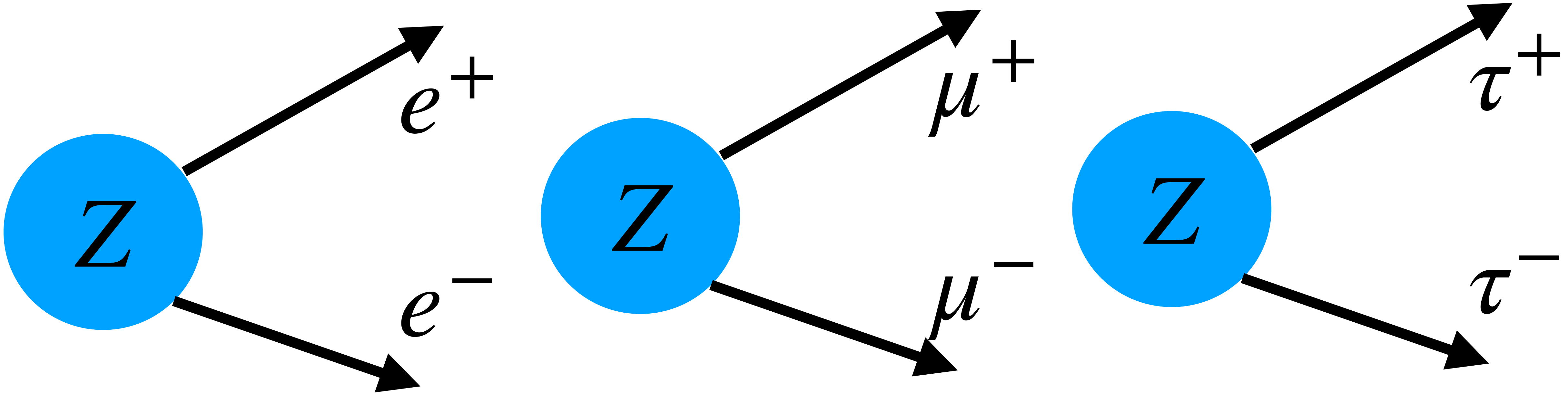
- W boson interacts with many different particles
  - These don't happen frequently b/c W boson is heavy

Electroweak Bosons

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



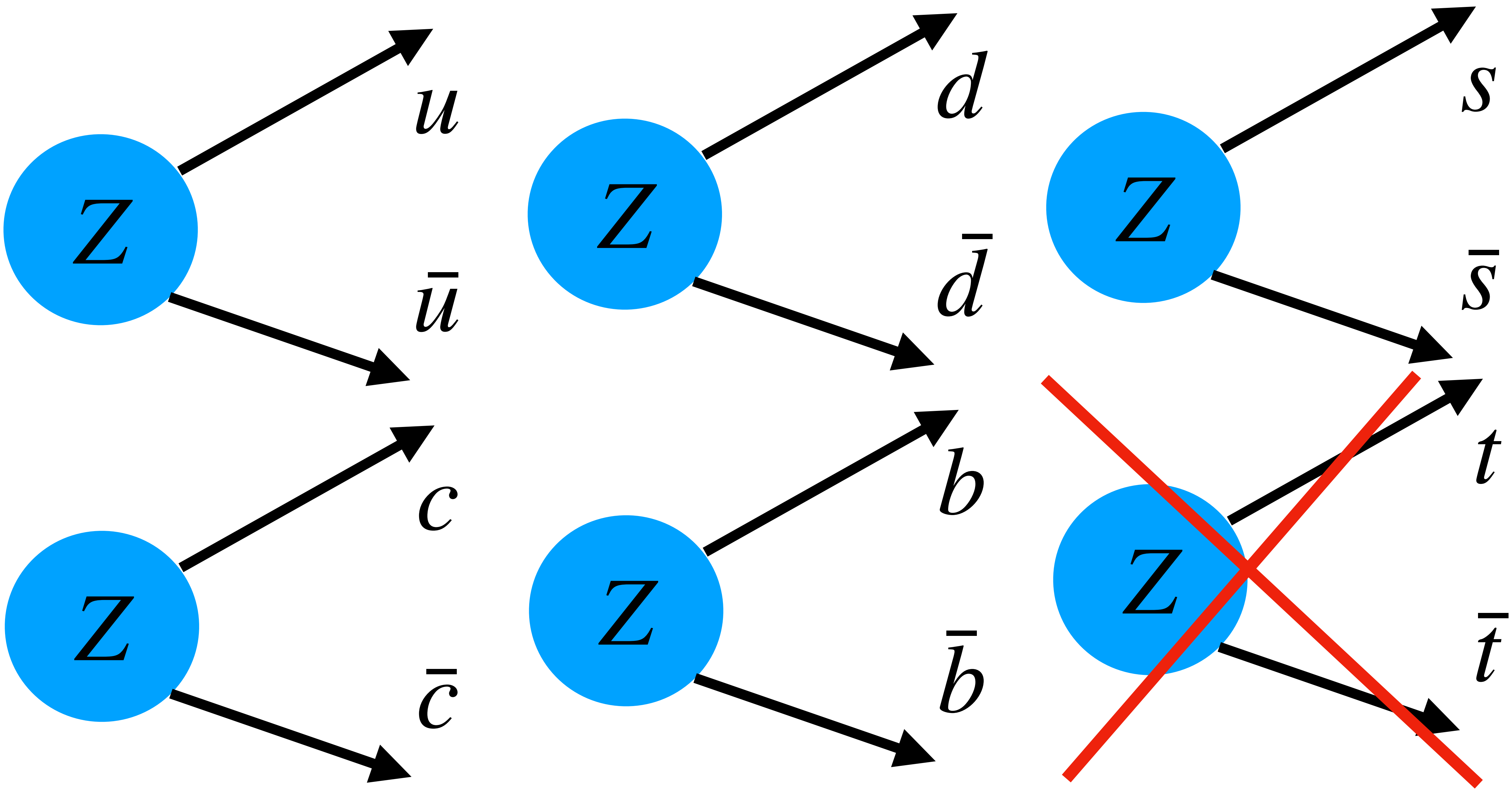
Z boson Properties



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

Z boson Properties

Decays to all quarks, except top

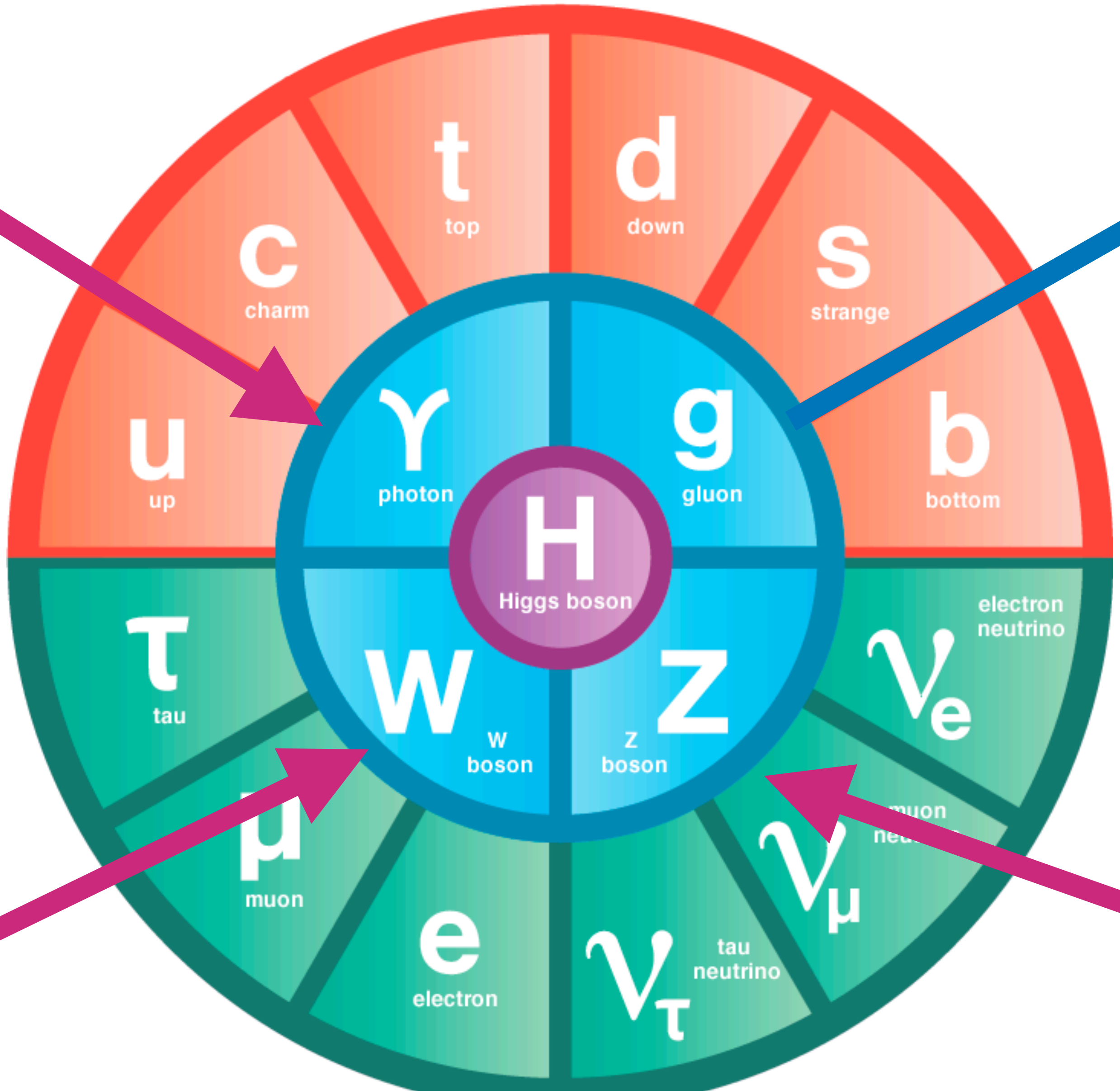


- Z boson is like a heavy photon (no charge, but heavy)

The Forces

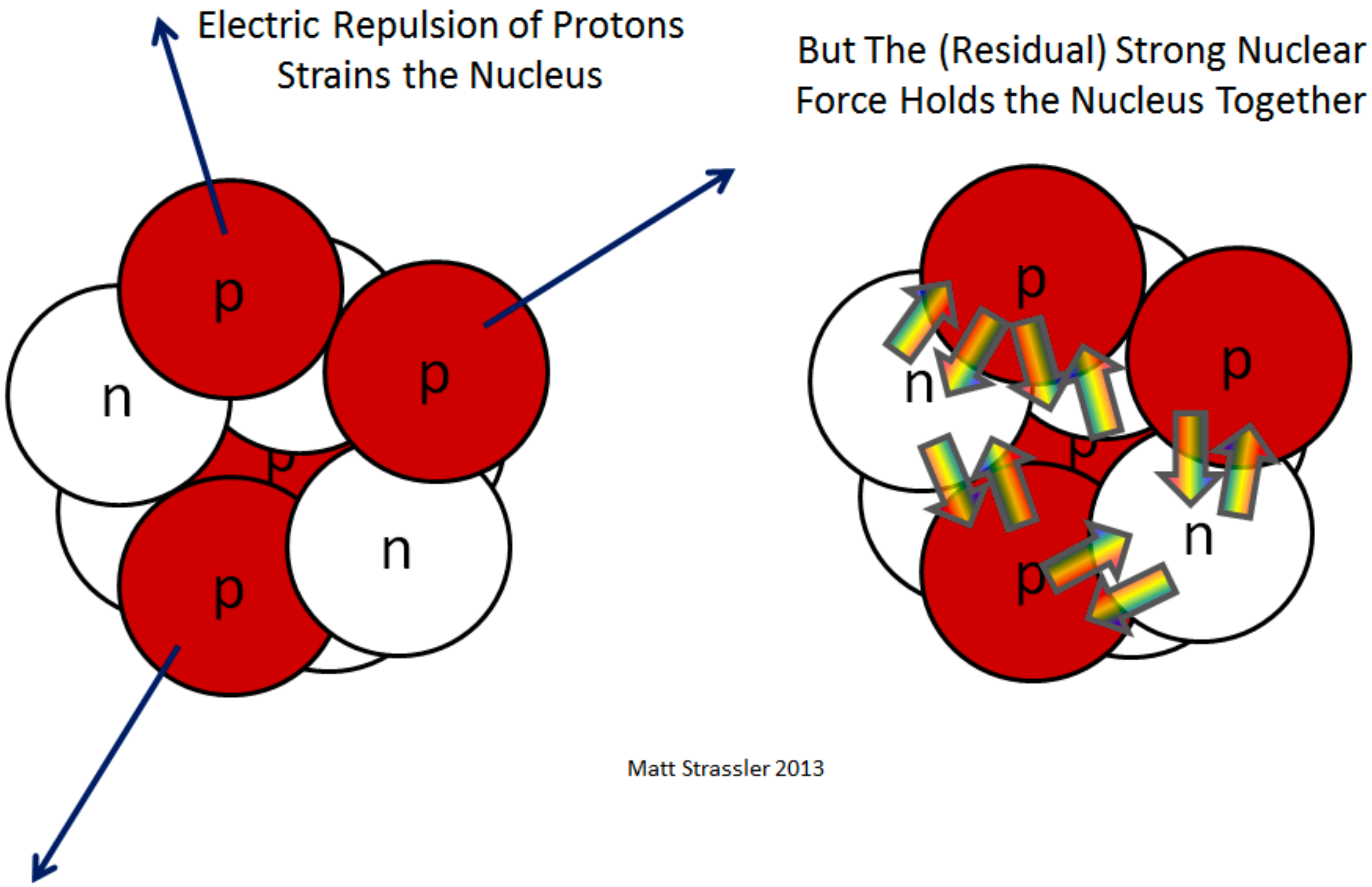
- The challenge of this lab is to fin the W and Z boson
  - These are the particles that cover the Weak Boson Interaction

All Part of Electroweak Force



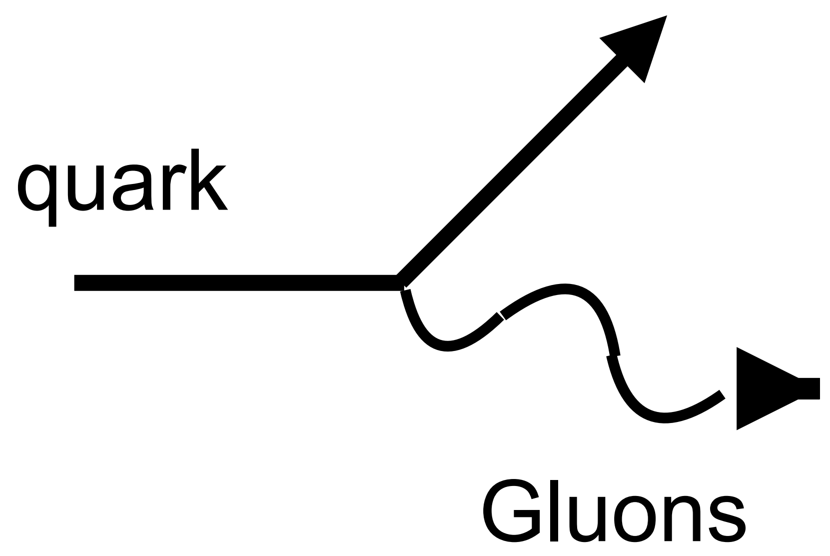
what about Strong force?

Strong Force



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

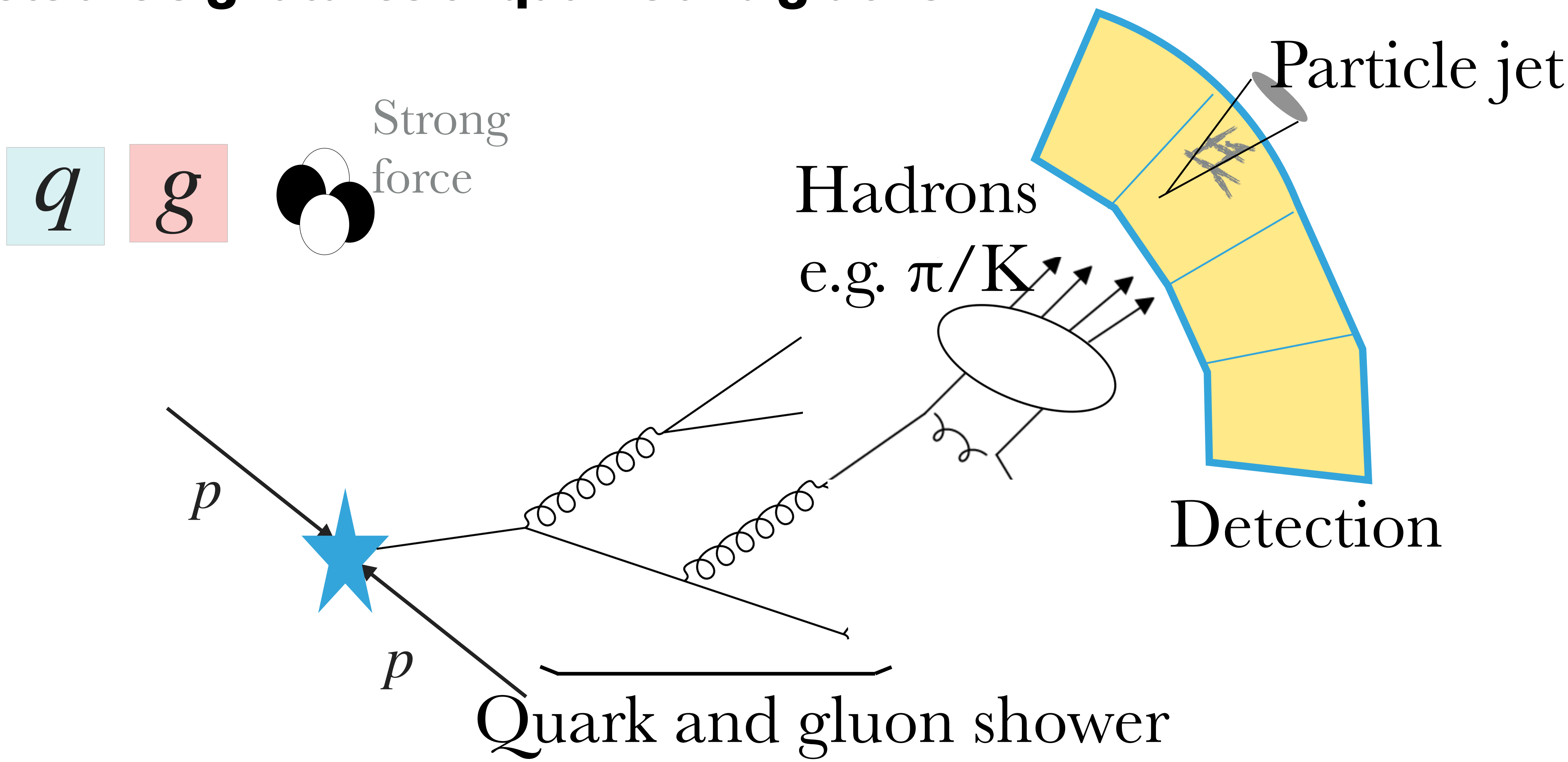
Strong Force Production



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

What you know now:

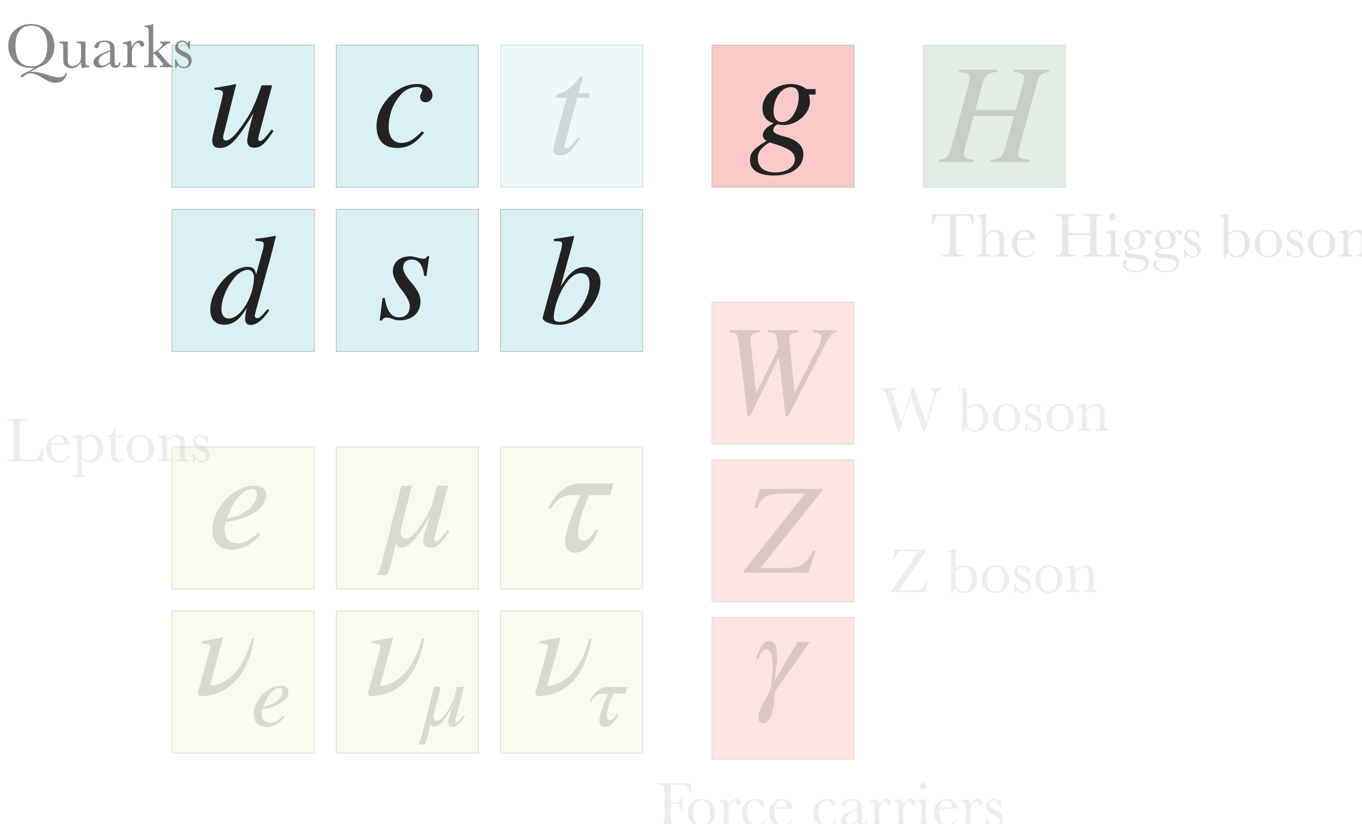
Jets are signatures of quarks and gluons

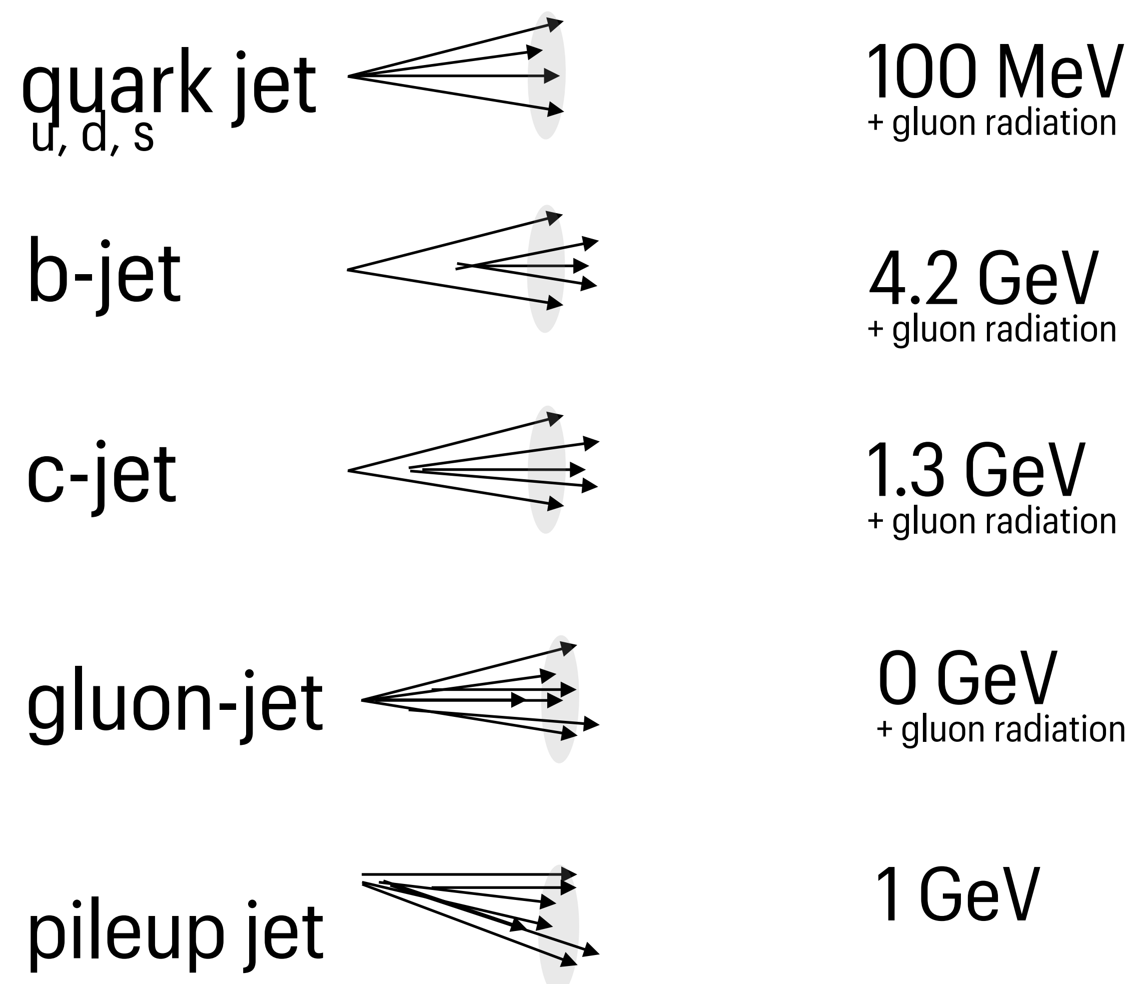


From J. Thaler

What you know now:

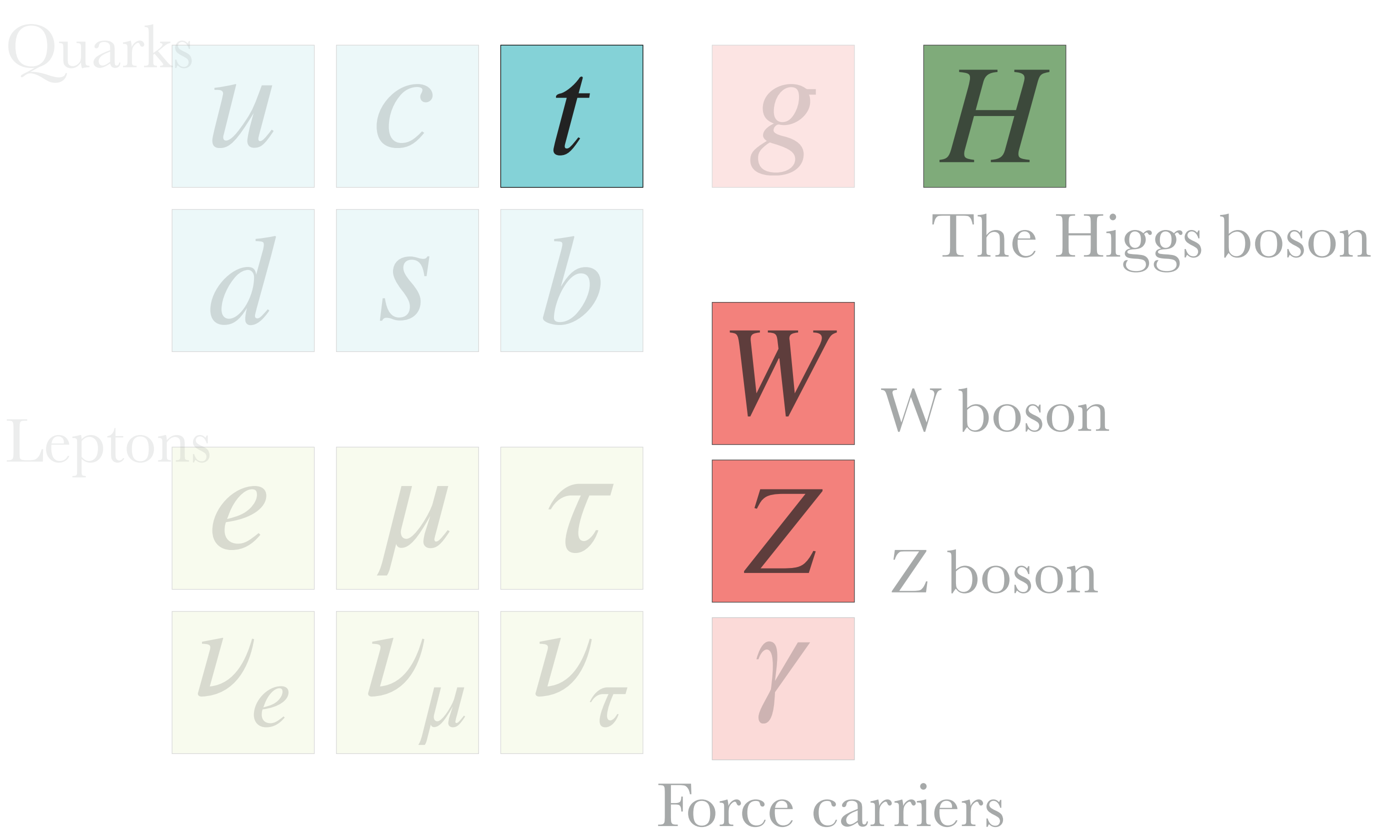
Jets of the Standard Model

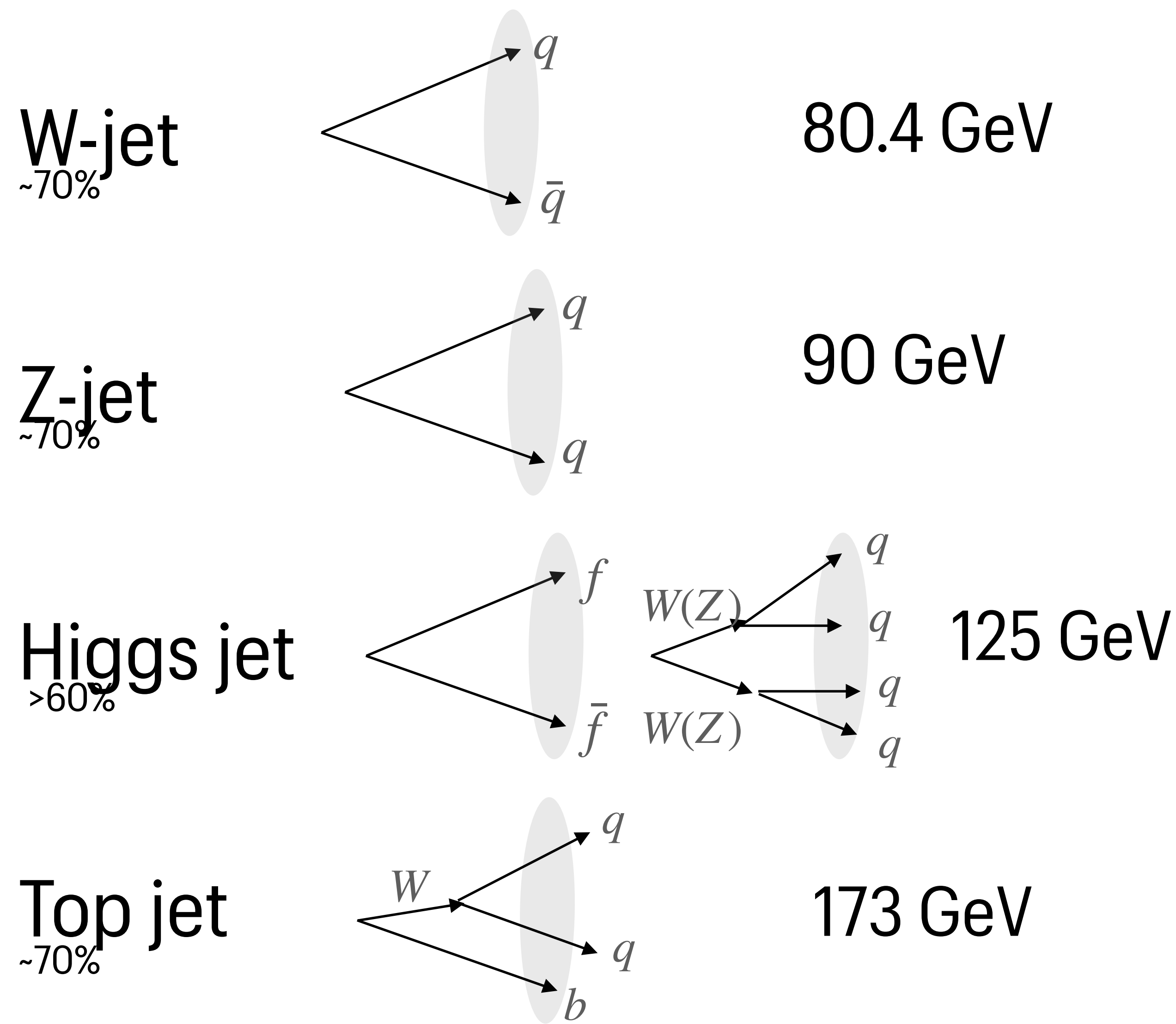




What you know now:

Jets of the Standard Model

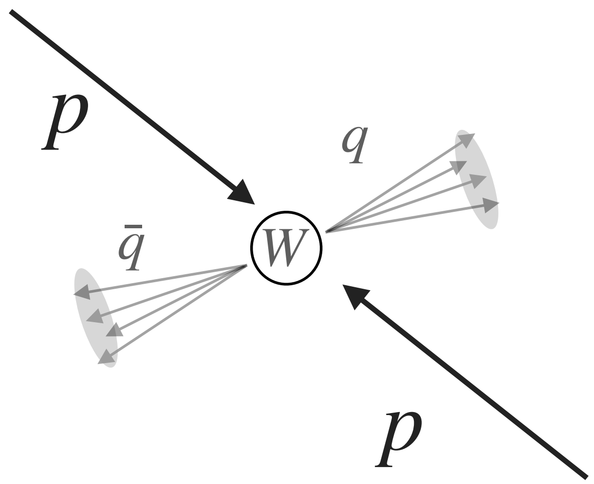




High boost

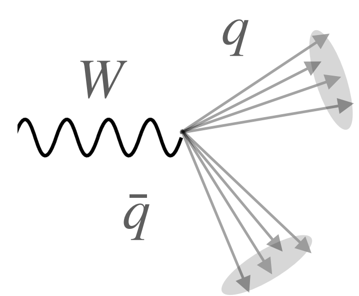
Let’s consider a W-decay

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



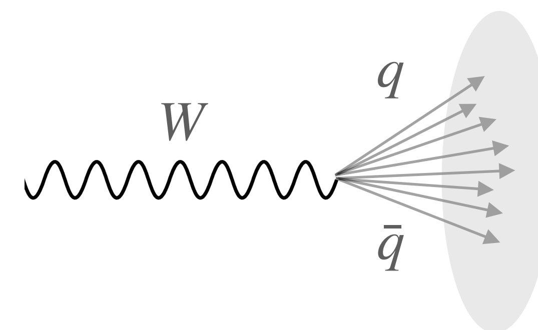
At ~rest

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



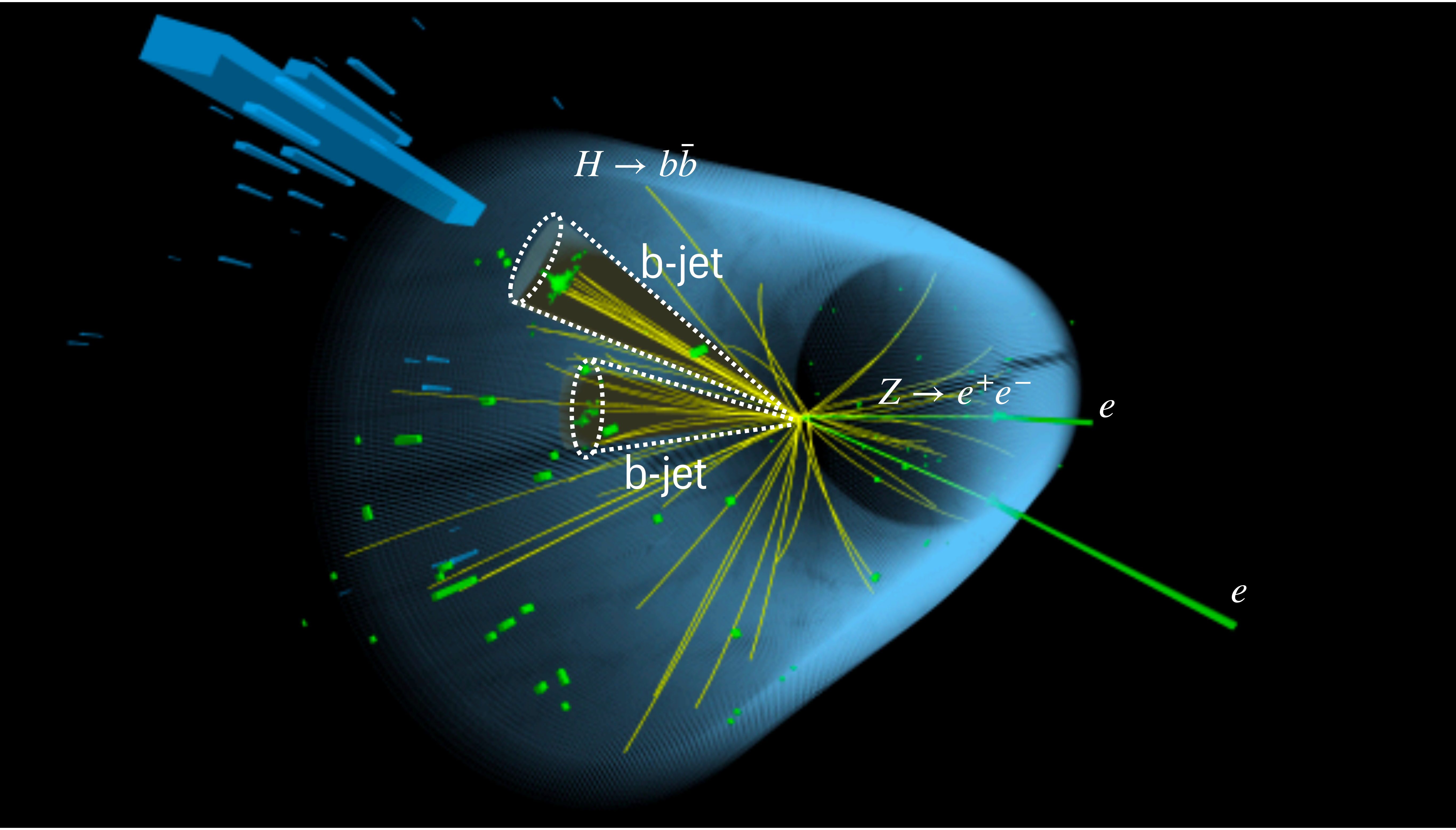
low W-momentum
(p_T~100 GeV)

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

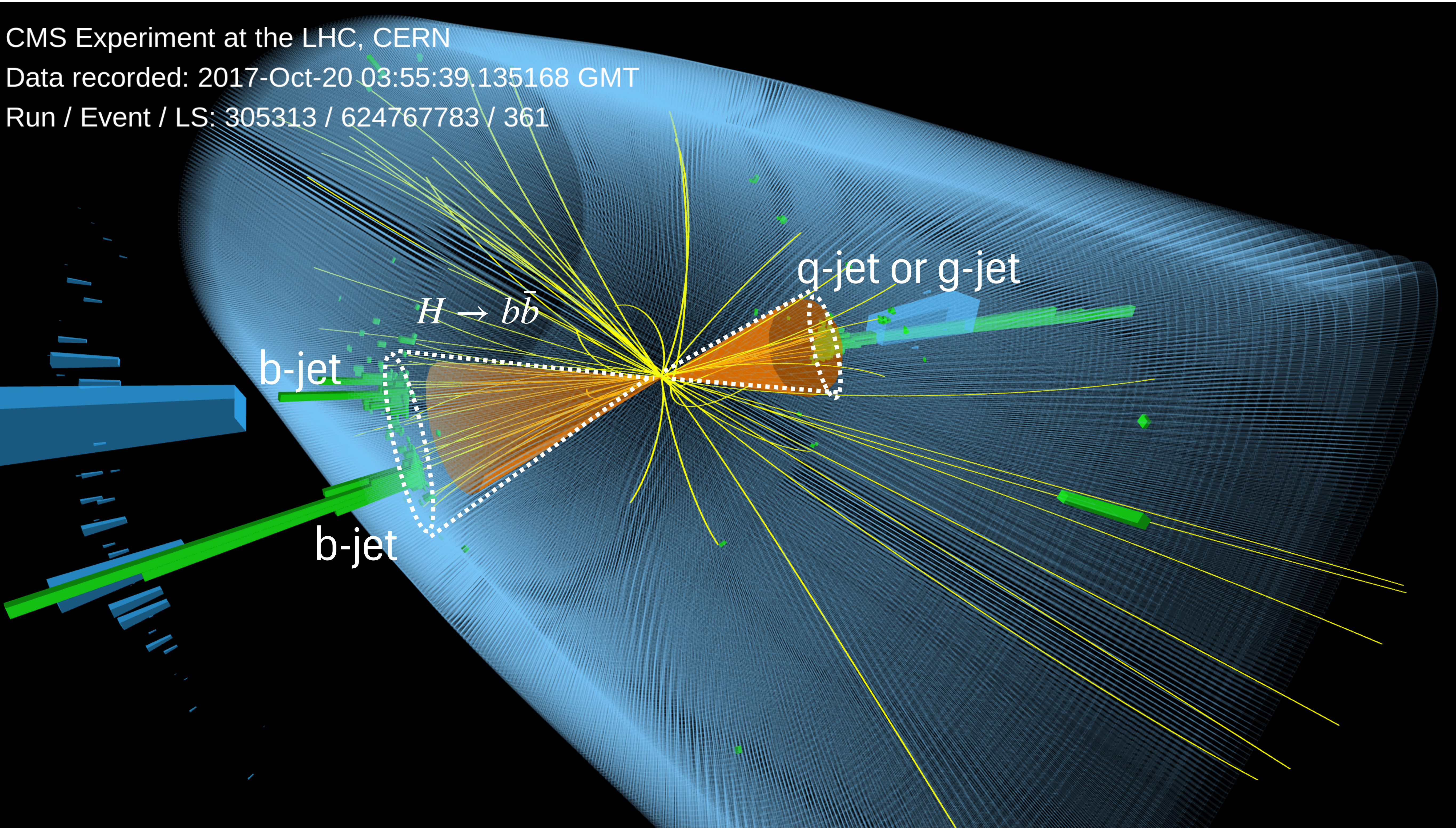


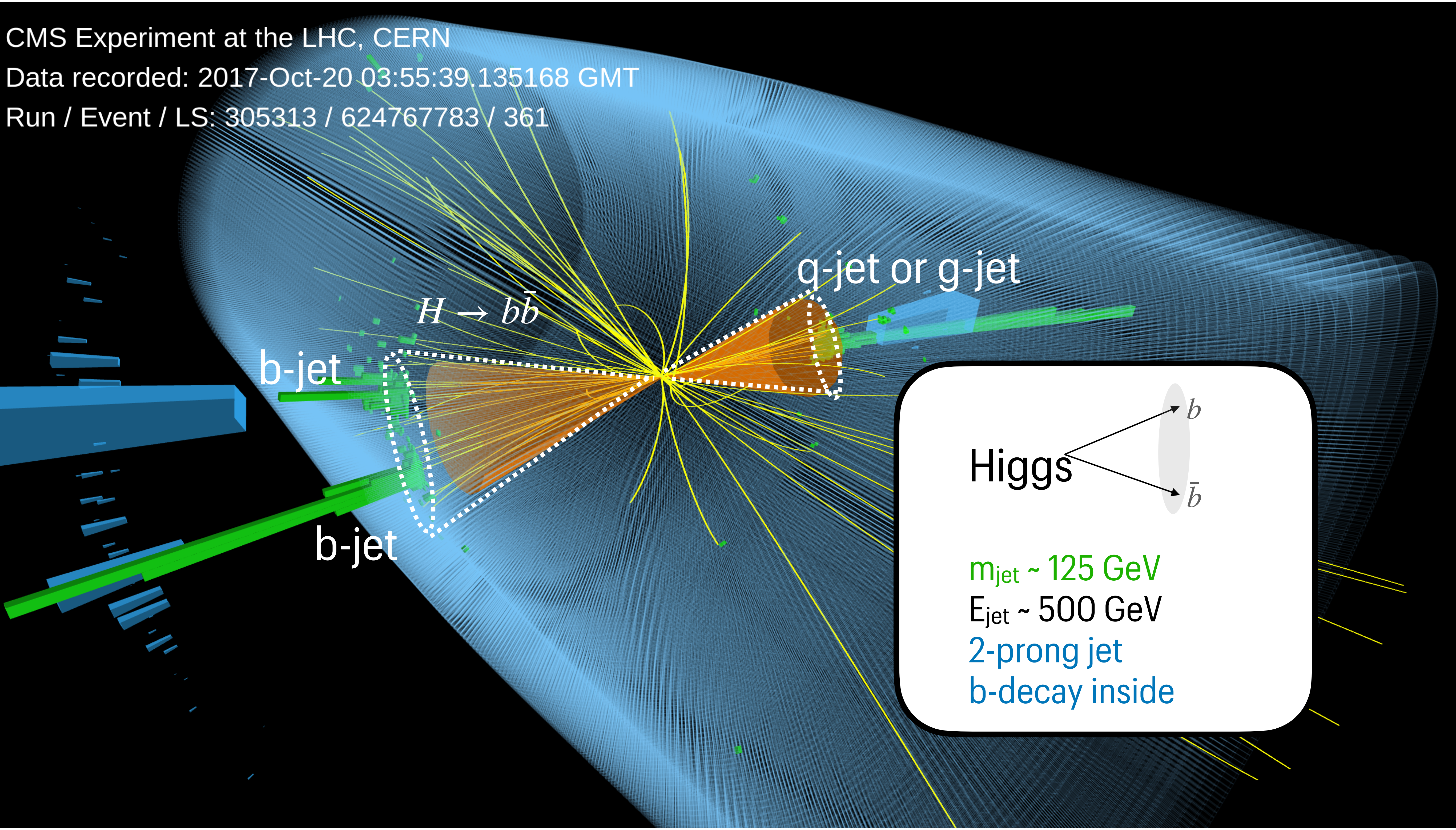
high boost
(p_T>200 GeV)

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



$H \to b\bar{b}$
b-jet
b-jet
$Z \to e^+e^-$
e
e


CMS Experiment at the LHC, CERN
Data recorded: 2017-Oct-20 03:55:39.135168 GMT
Run / Event / LS: 305313 / 624767783 / 361
q-jet or g-jet
$H \to b\bar{b}$
b-jet
b-jet

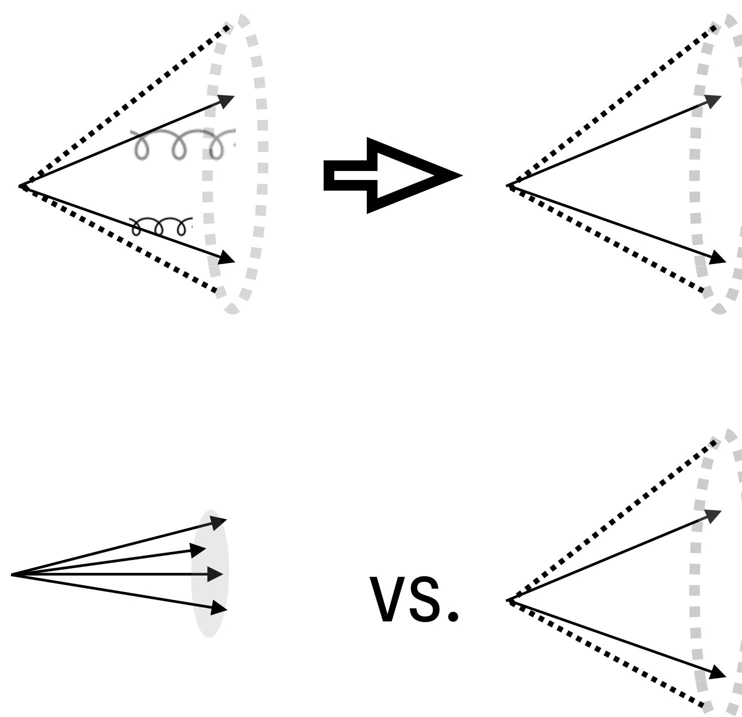

CMS Experiment at the LHC, CERN
Data recorded: 2017-Oct-20 03:55:39.135168 GMT
Run / Event / LS: 305313 / 624767783 / 361
q-jet or g-jet
$H \rightarrow b\bar{b}$
b-jet
b-jet
Higgs
b
$\bar{b}$
m_{jet} ~ 125 GeV
E_{jet} ~ 500 GeV
2-prong jet
b-decay inside

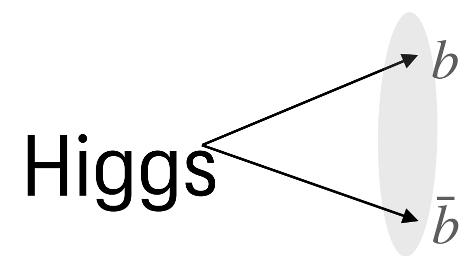
Jet substructure

Resolving emissions within the jet

Jet grooming

Jet tagging



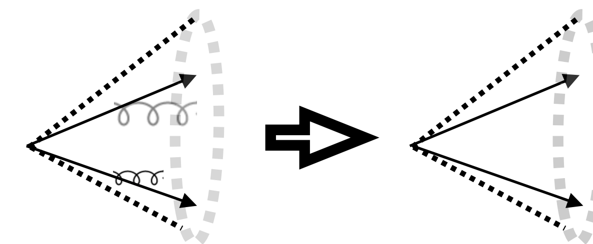


m_{jet} ~ 125 GeV
E_{jet} ~ 500 GeV
2-prong jet
b-decay inside

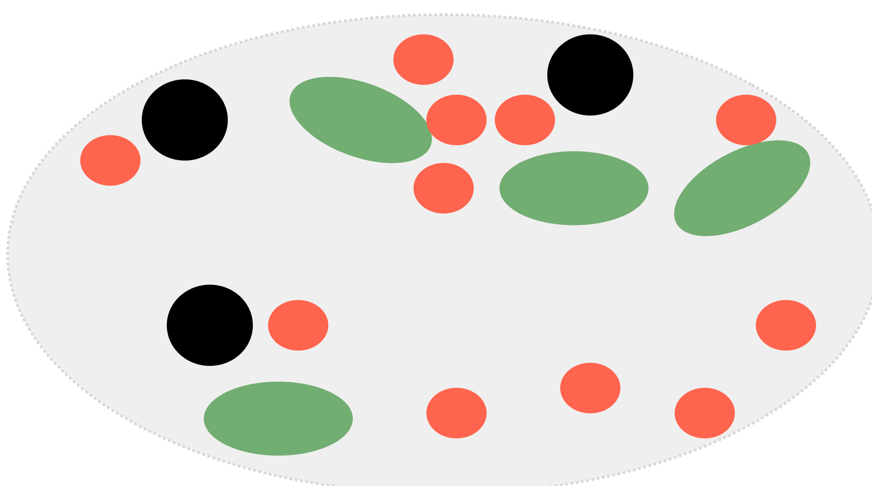
Jet grooming

Removing a jet's soft and wide-angle radiation

Grooming declustering



Original jet



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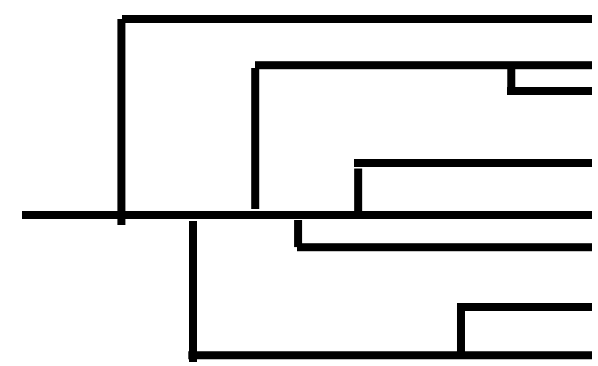
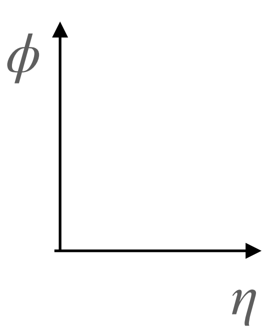
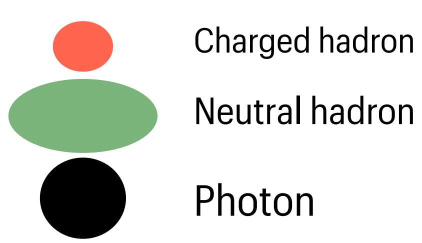
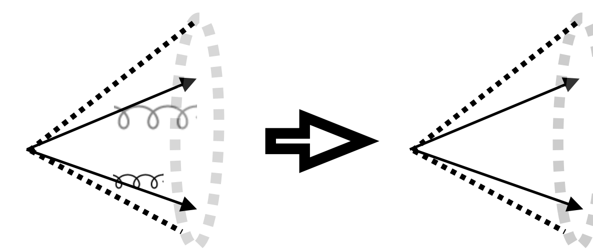
In a clustering tree





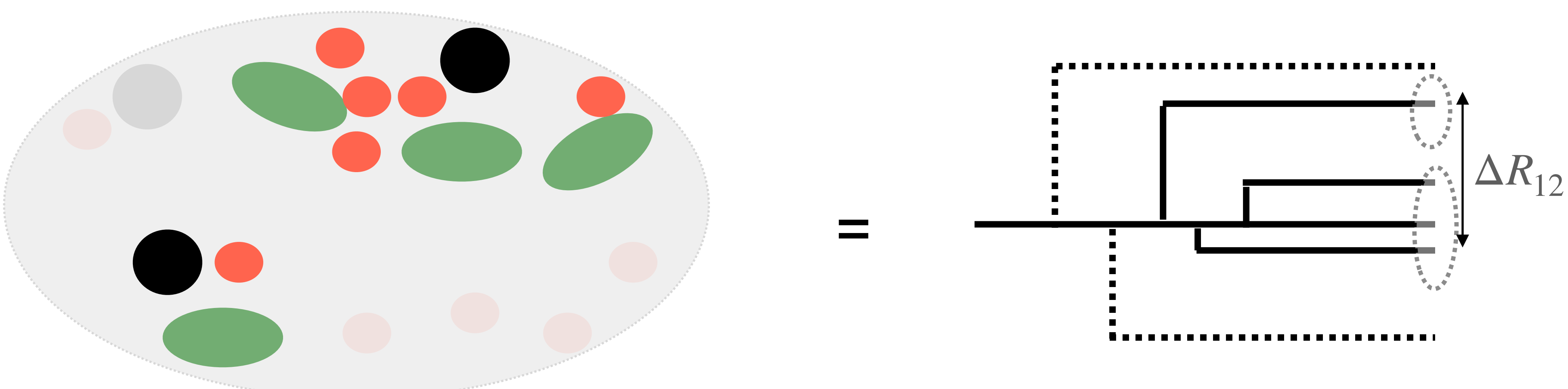


Grooming declustering



Groomed jet

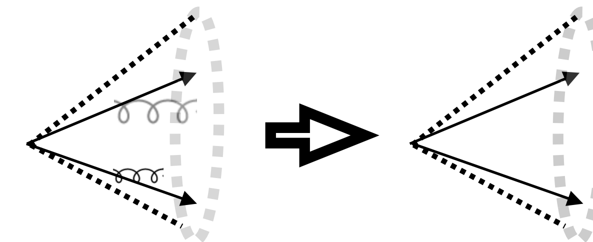
Groomed clustering tree

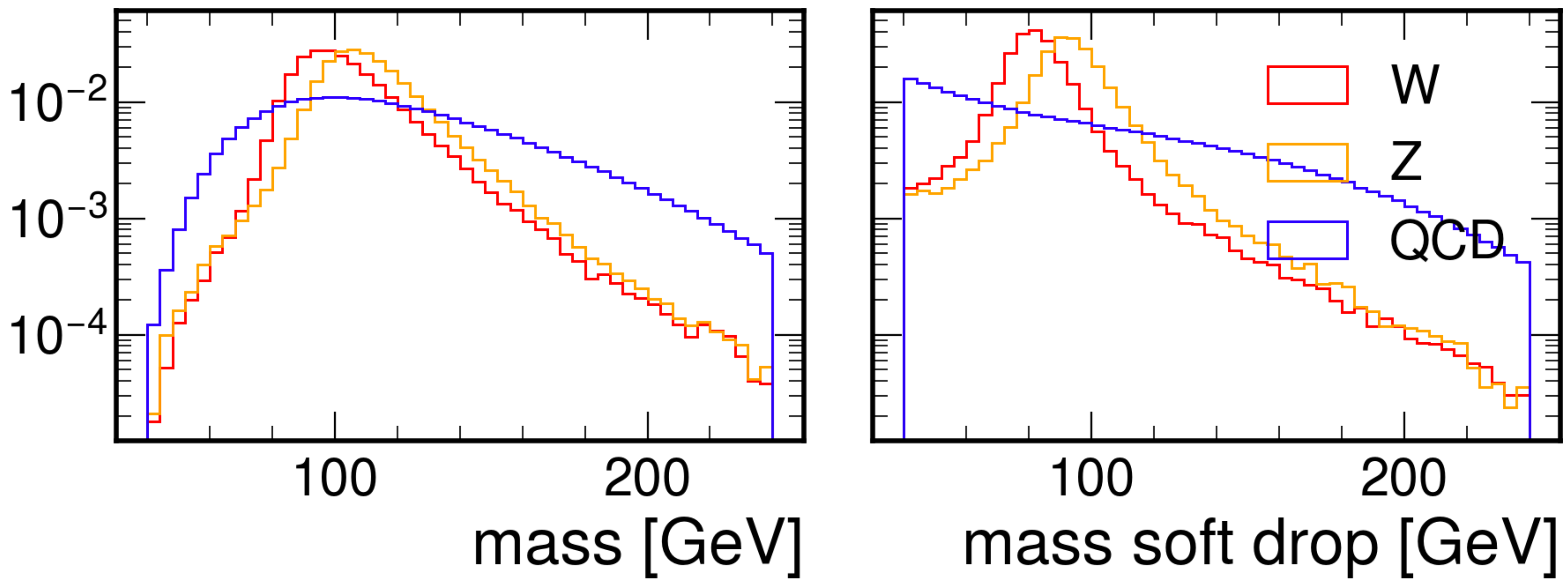


- Grooming algorithms iteratively decluster a jet
- The soft-drop algorithm removes lowest p_T sub-jets failing pairwise condition

$$z > z_{cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta} \quad \text{with} \quad z = \frac{\min(p_T^1, p_T^2)}{p_T^1 + p_T^2}$$

Calculating groomed mass



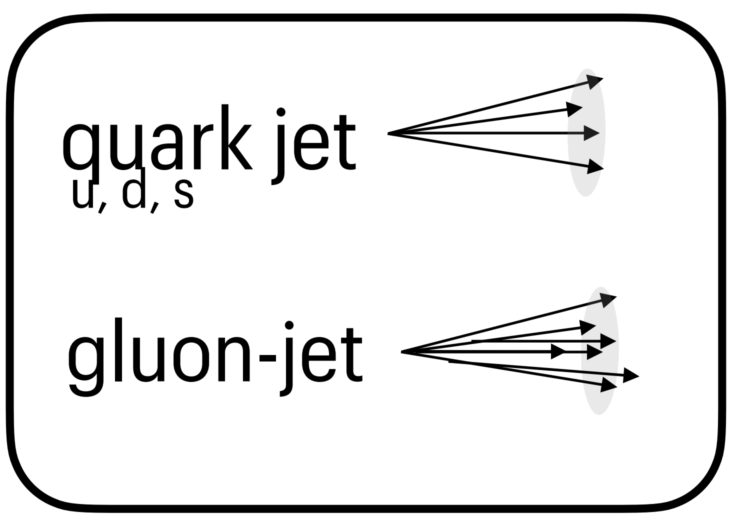


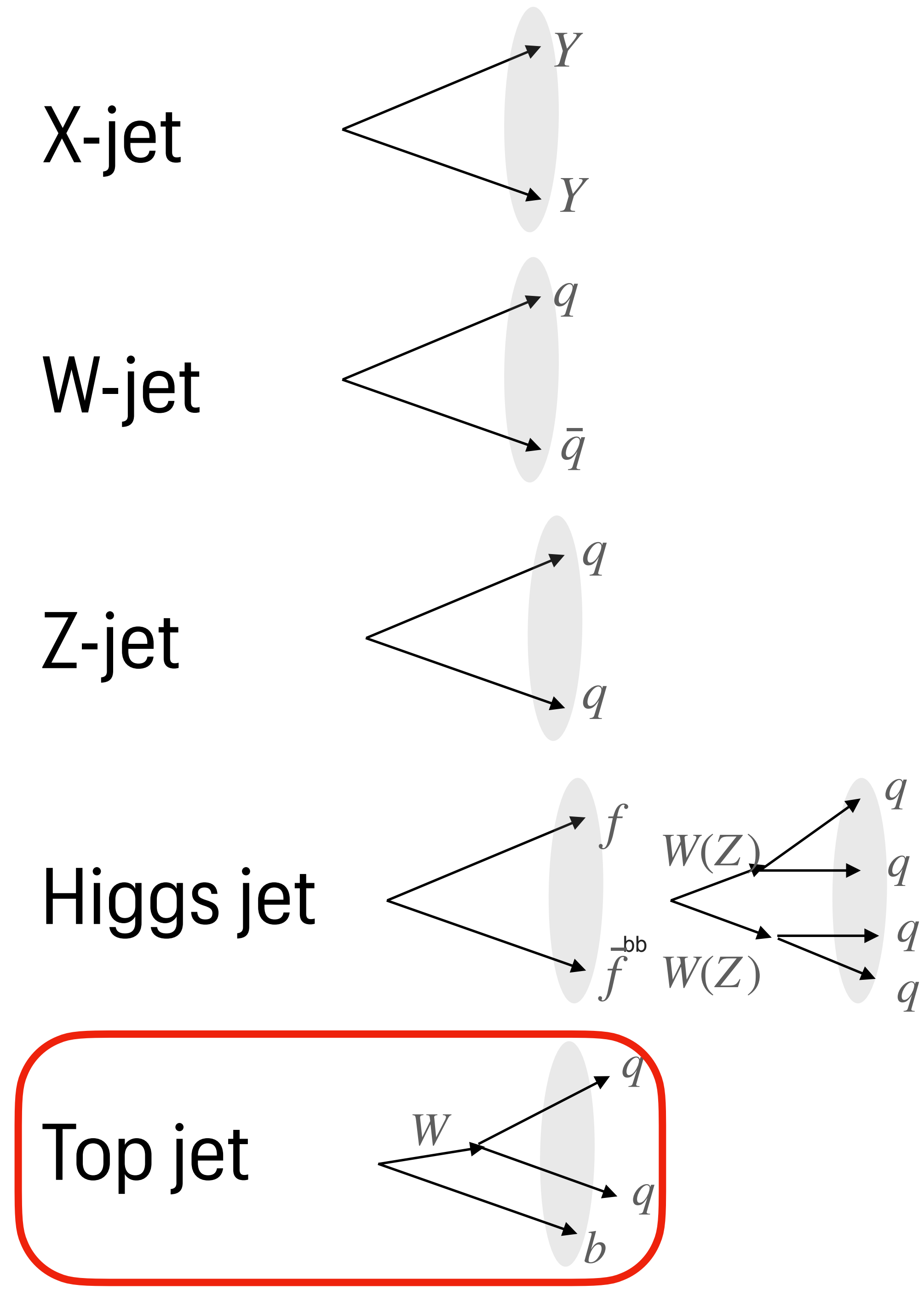
- Improves the mass *resolution* of a jet (removes away excess radiation)
- Brings the mass of background jets (QCD) to low mass

Jet tagging

Characterizing a jet’s internal decay

Signatures:


quark jet
u, d, s
gluon-jet


X-jet
Y
Y
W-jet
q
q̄
Z-jet
q
q
Higgs jet
f
f̄
bb
W(Z)
W(Z)
q
q
q
q
Top jet
W
q
q
b

N-subjetiness

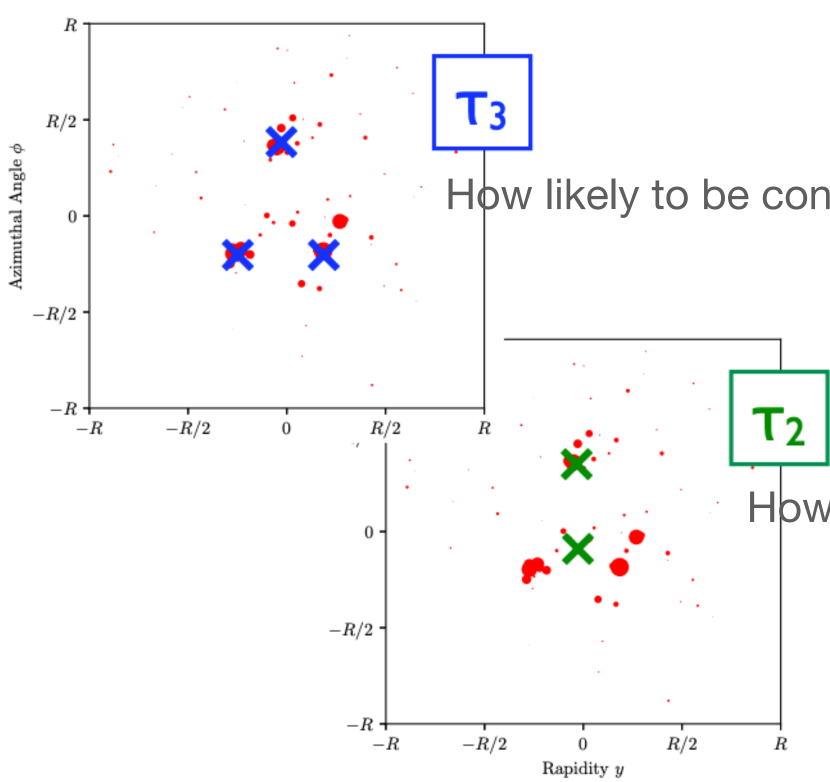
Counting the number of "prongs" for almost a decade

Energy weight

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

Sum over all particles

Angular weight w. respect to one axis



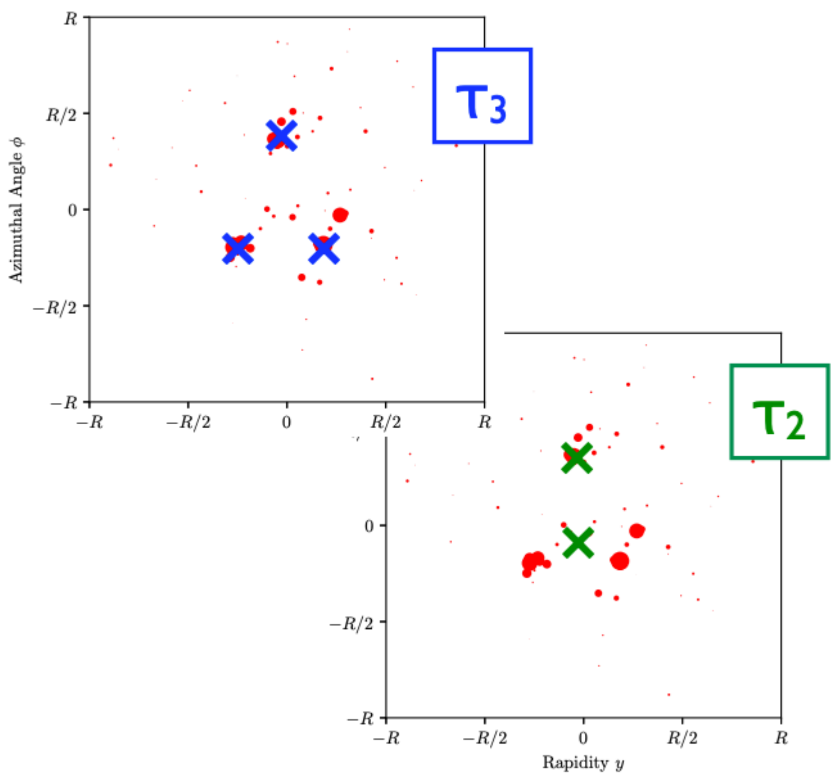
How likely to be consistent w. 3 axes?

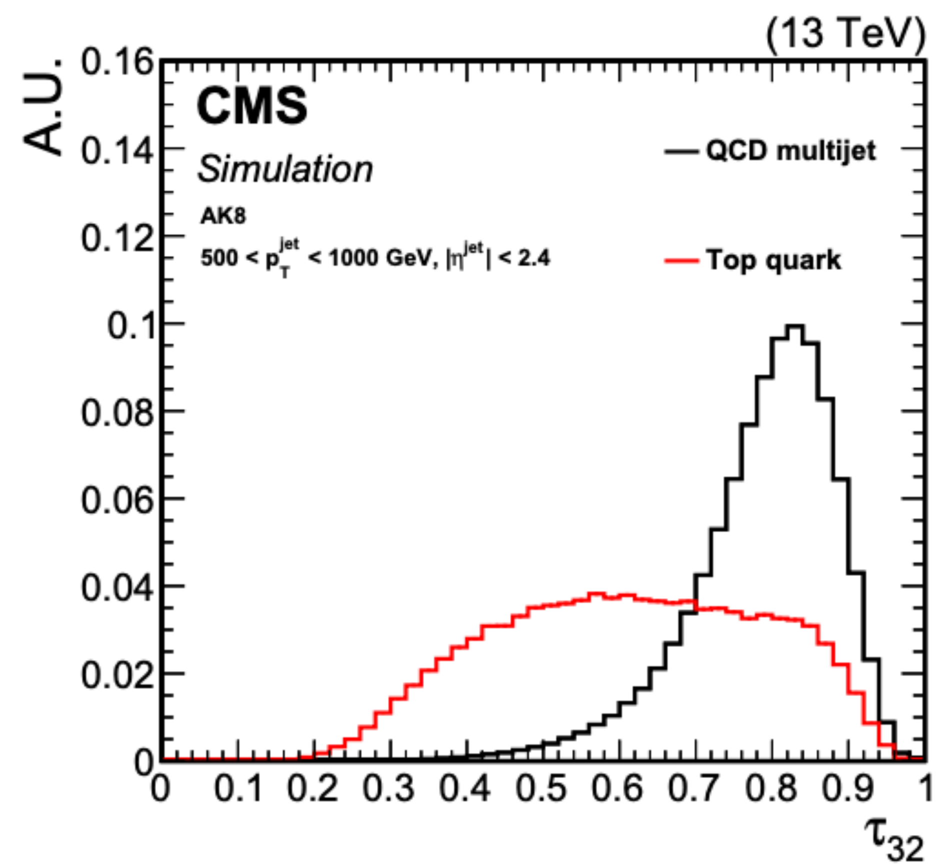
How likely to be consistent w. 2 axes?

N-subjetiness

Counting the number of "prongs" for almost a decade

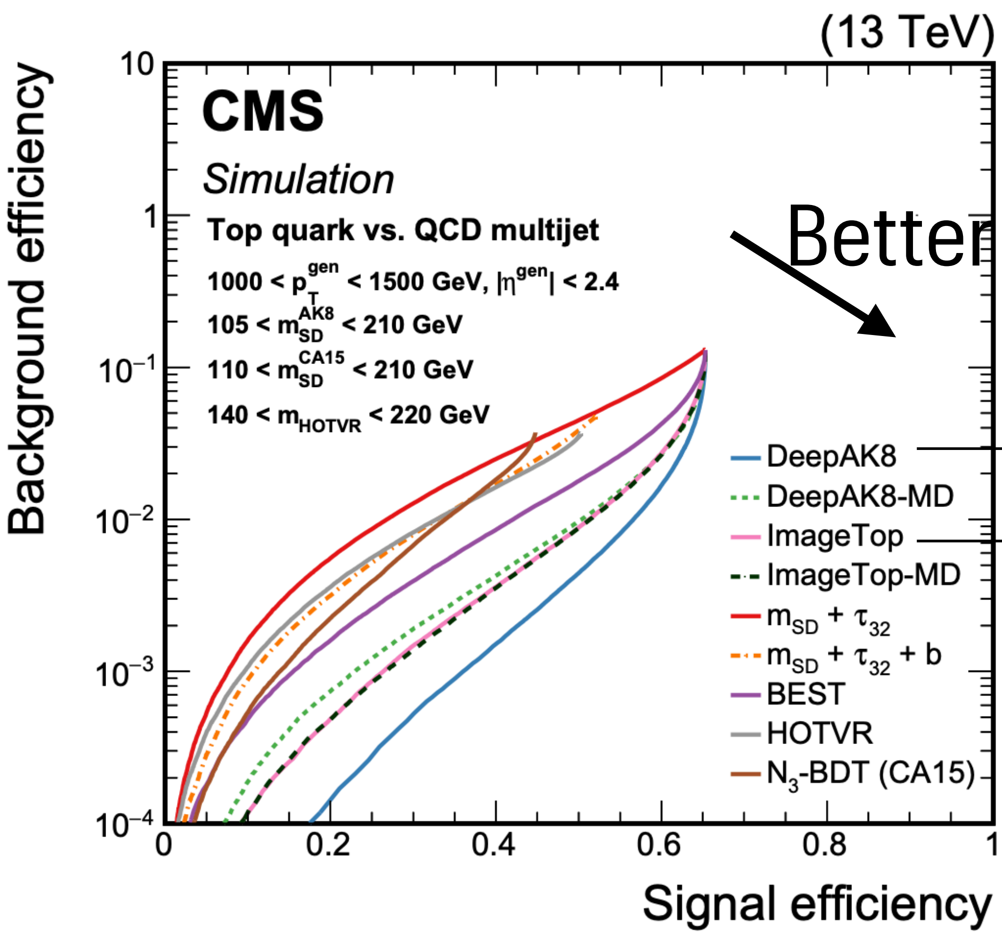
$$\tau_N(\mathcal{J}) = \min_{N \text{ axes}} \sum_i E_i \min\{\theta_{1,i}, \theta_{2,i}, \ldots, \theta_{N,i}\}$$





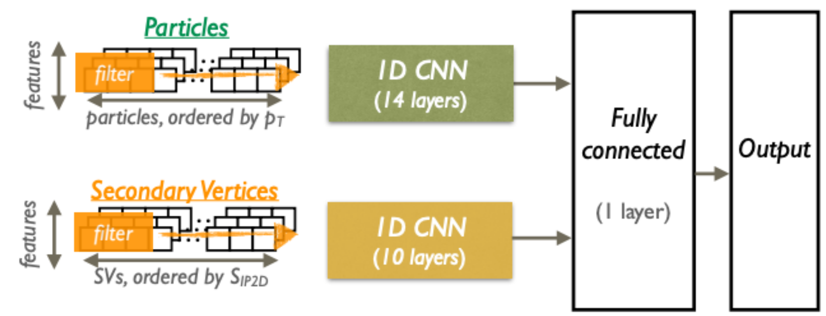
Deep Learning taggers

The rise of machine learning: two examples in CMS



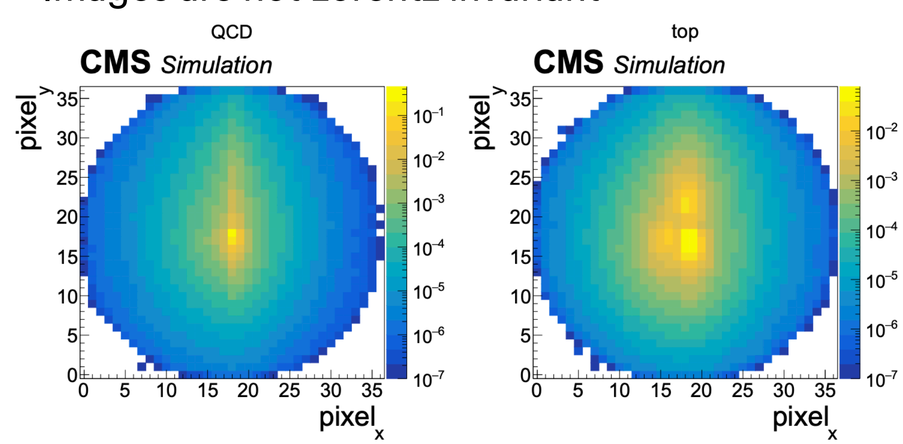
Particles can be sent to NN

Ignores multi-particle correlation



Represent jets as images

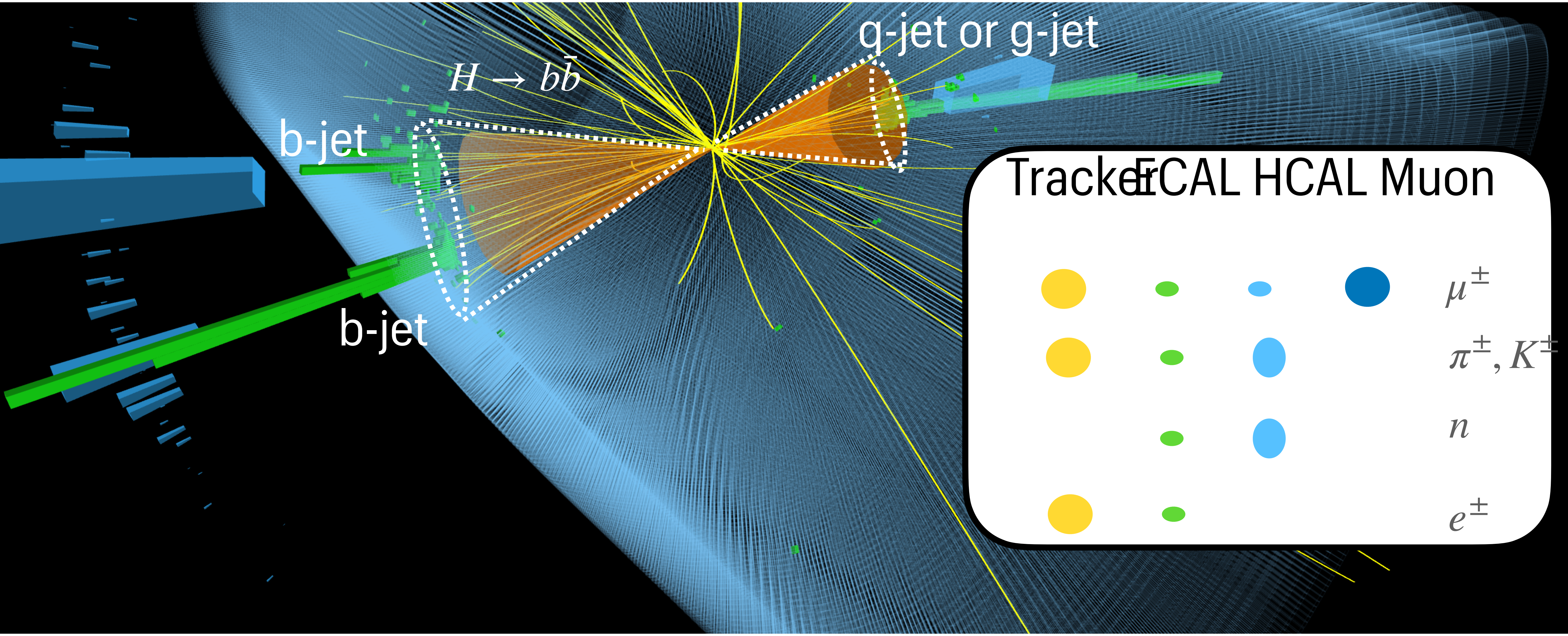
Images are not Lorentz invariant



How to better represent a jet in ML?

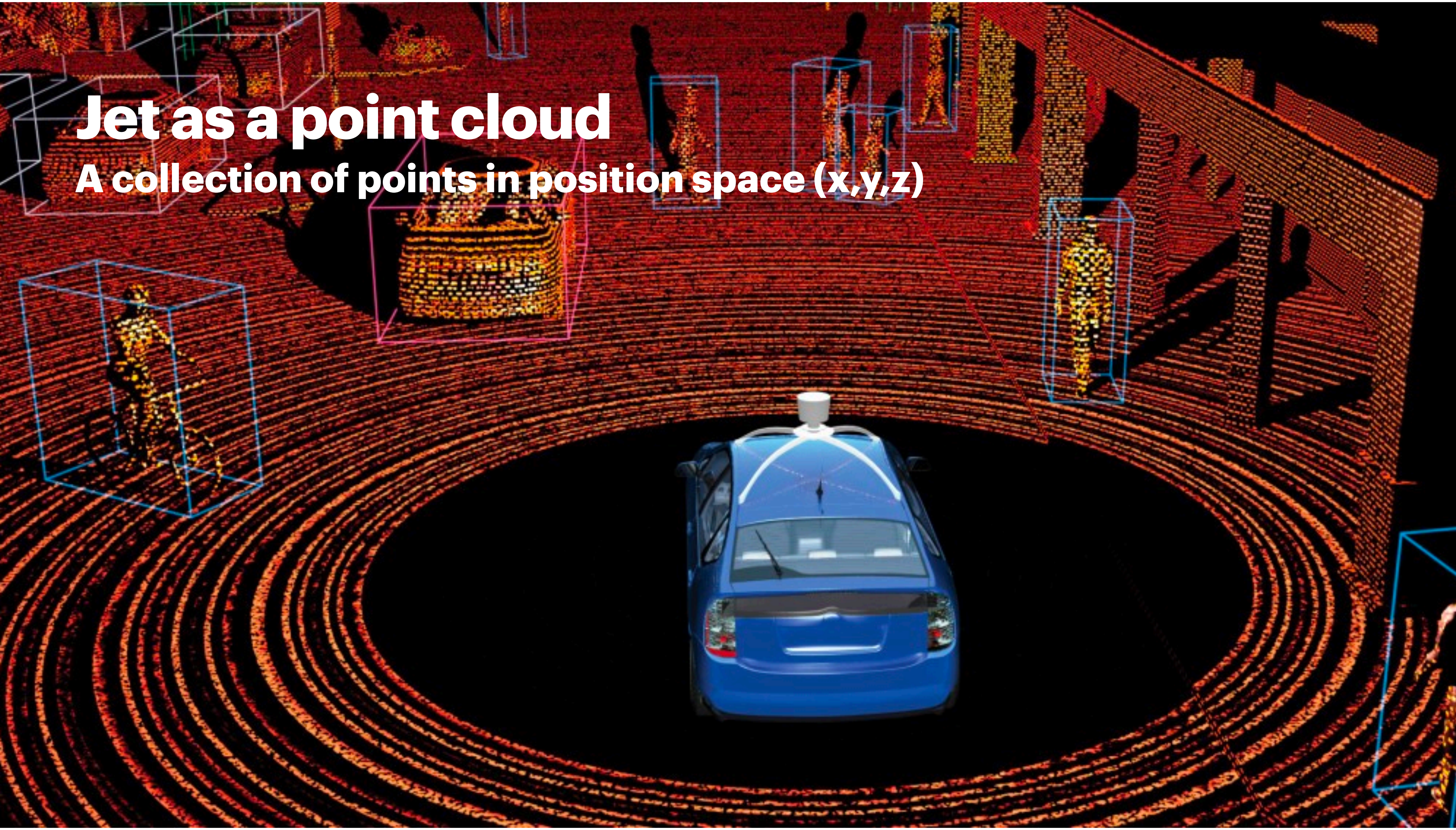
A collision event

A collection of particles in momentum space



Jet as a point cloud

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



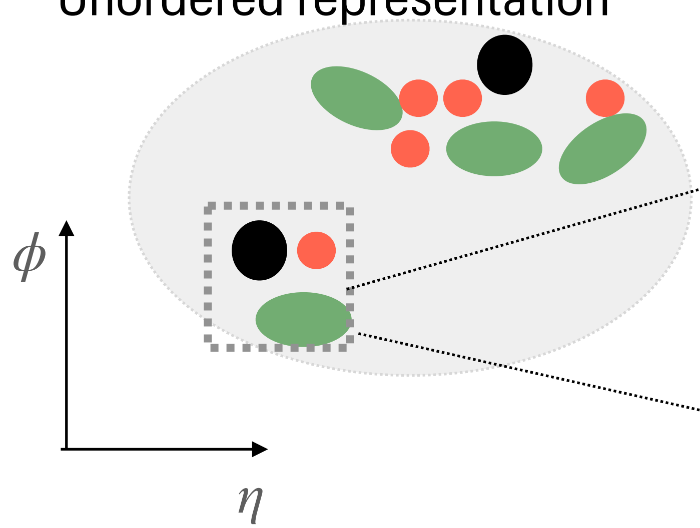
Particle-Net

A graph neural network using particle-clouds

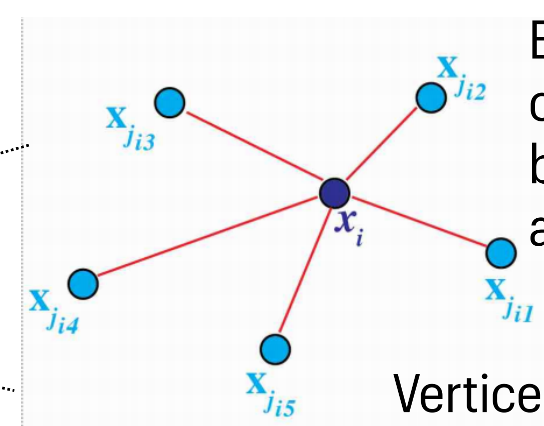
- For a jet: we have 2D information of particles, but also energy/momenta, charge/particle ID, track quality/impact parameter, etc.

Jet as a particle cloud

Unordered representation



Each cloud is a graph

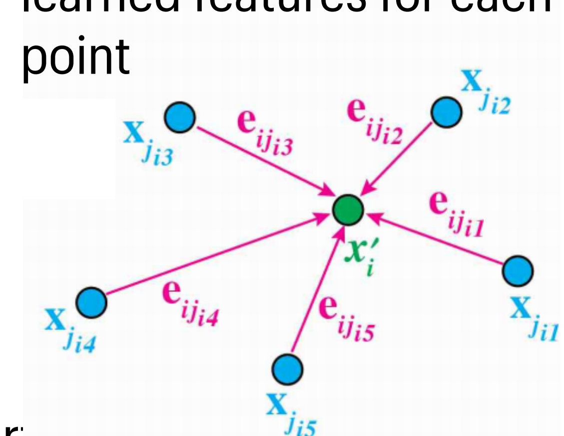


Edges: connections between point and k-NN points

Vertices: point (Particle or secondary vertex)

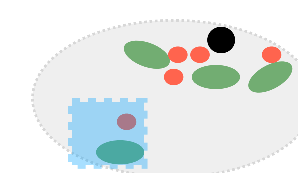
Perform convolution

EdgeConv outputs a set of learned features for each point



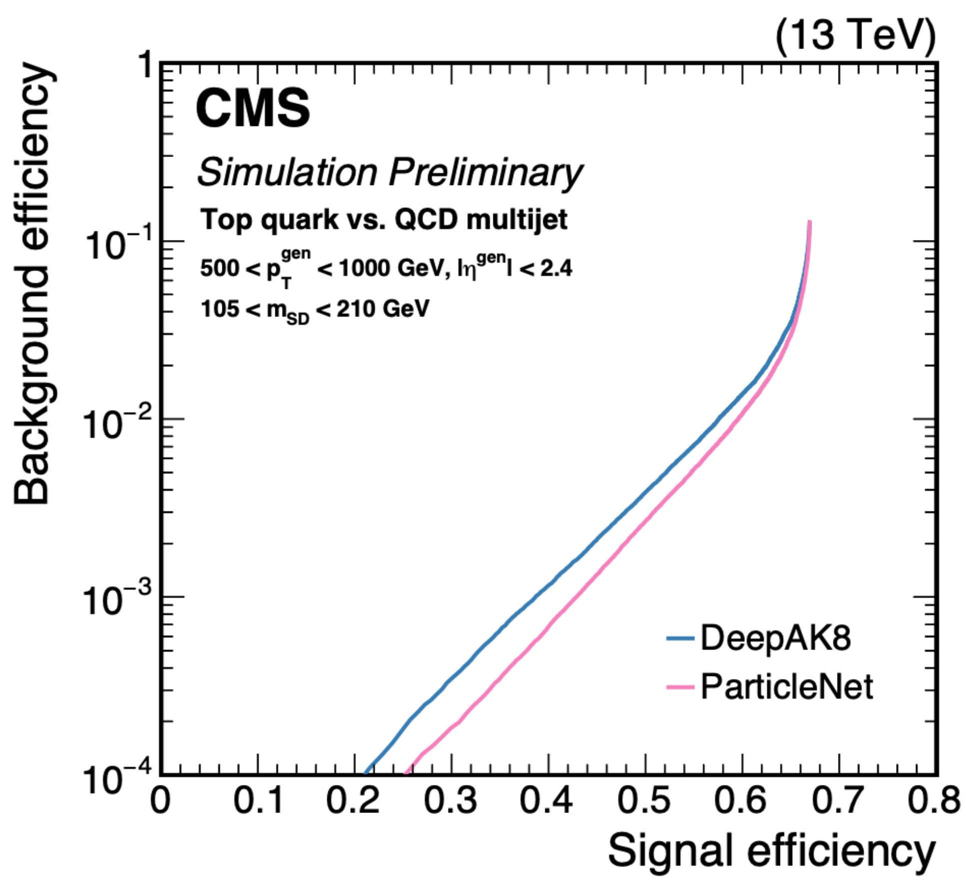
Get ID

Binary classification from all learned features



Particle-Net

A graph neural network using particle-clouds

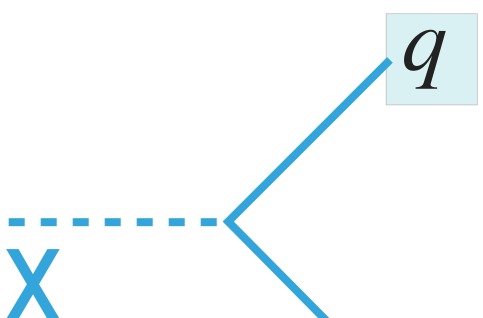


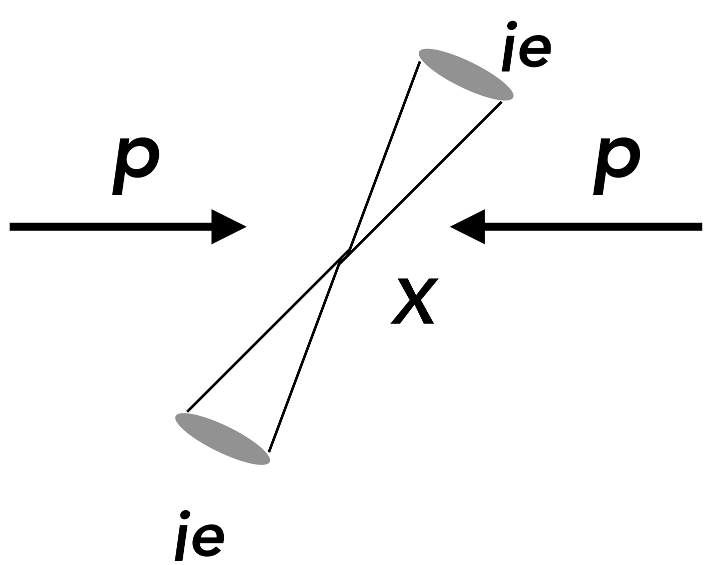
- A step in the right direction: Networks and correlations can be included (the most powerful discrimination in CMS)
- Still a long way to go:
  - More on DL by Dylan

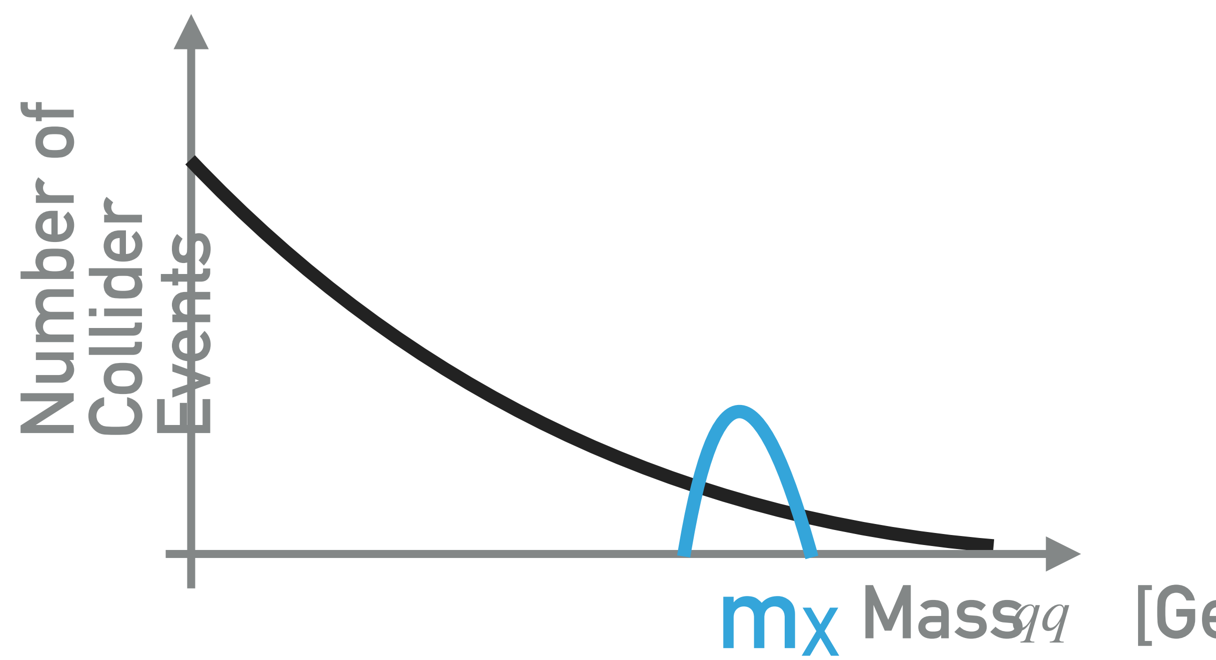
Low mass (qq) resonances

Looking for a resonance

At the LHC





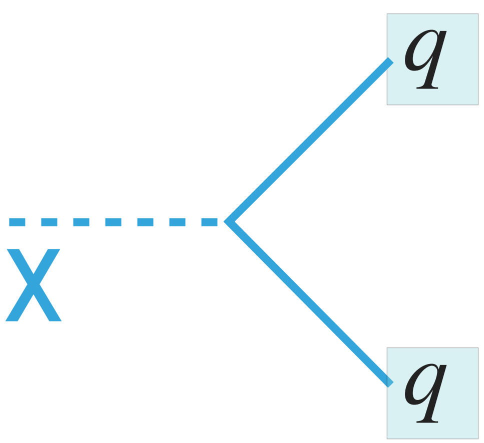


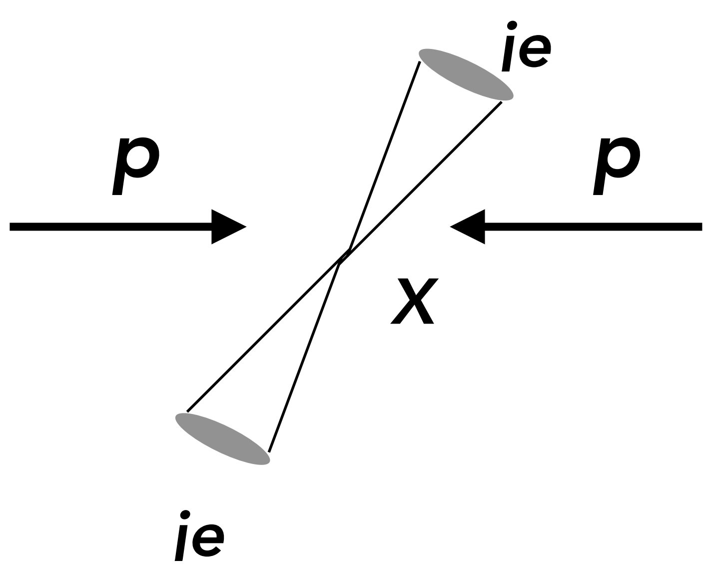
p_T < 200 GeV

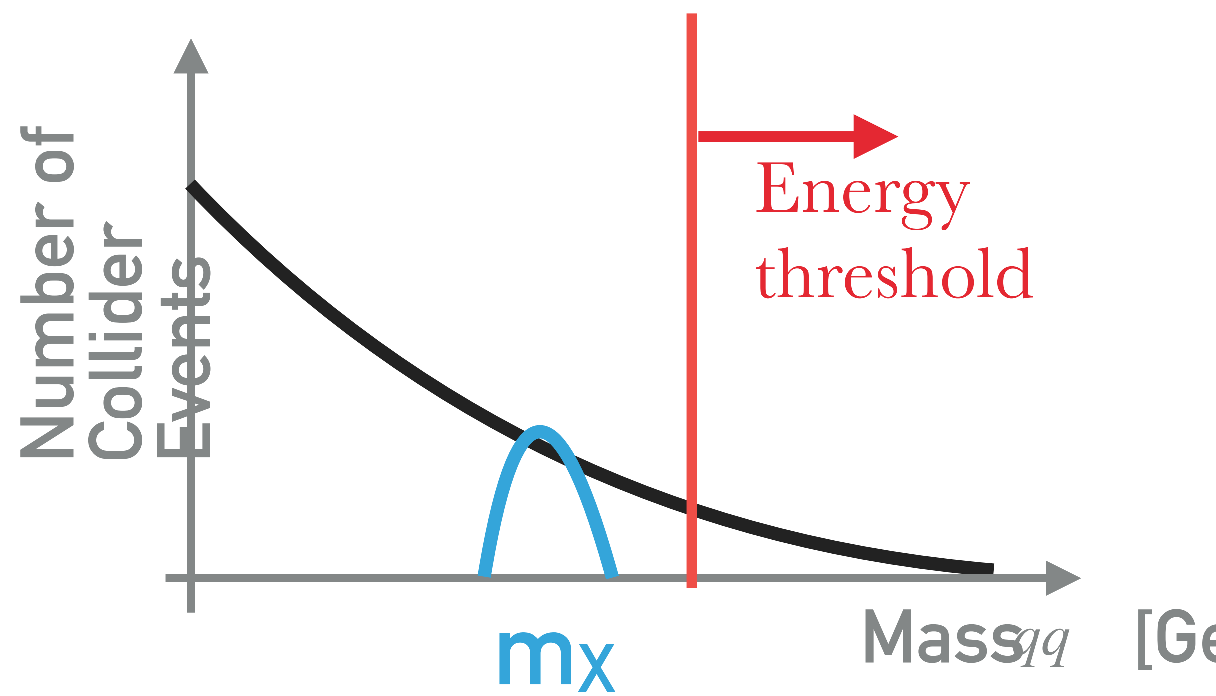
m_X > 500 GeV

If m_X < 500 GeV, event does not get saved

LHC has tight energy thresholds (mass thresholds)





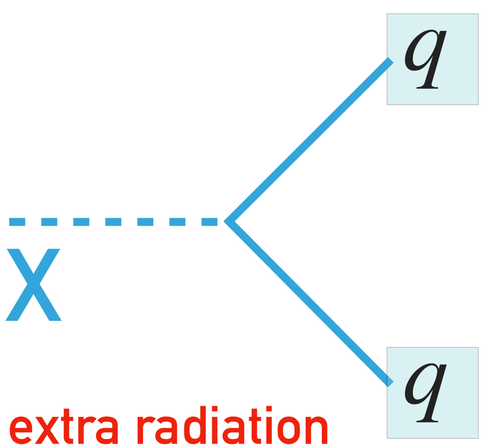


p_T < 200 GeV

m_X < 500 GeV

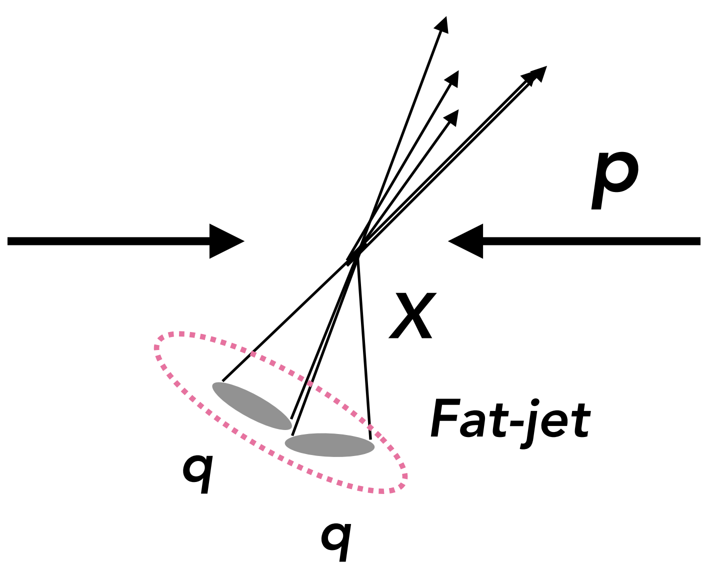
How to save these events

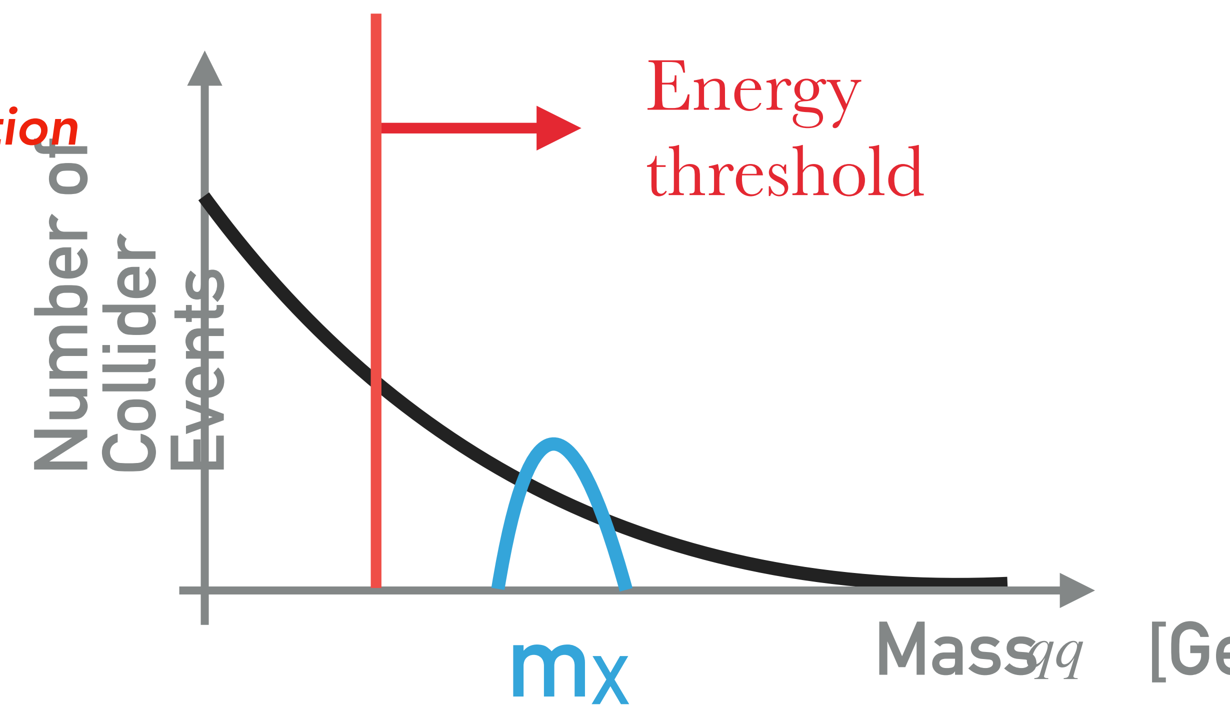
Boost them!



p_T > 450 GeV

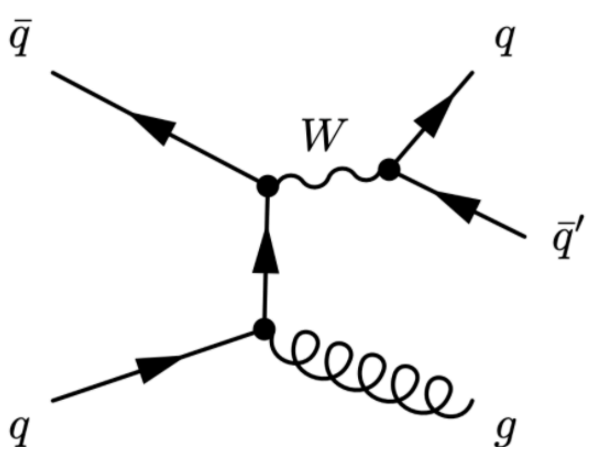
m_X < 500 GeV

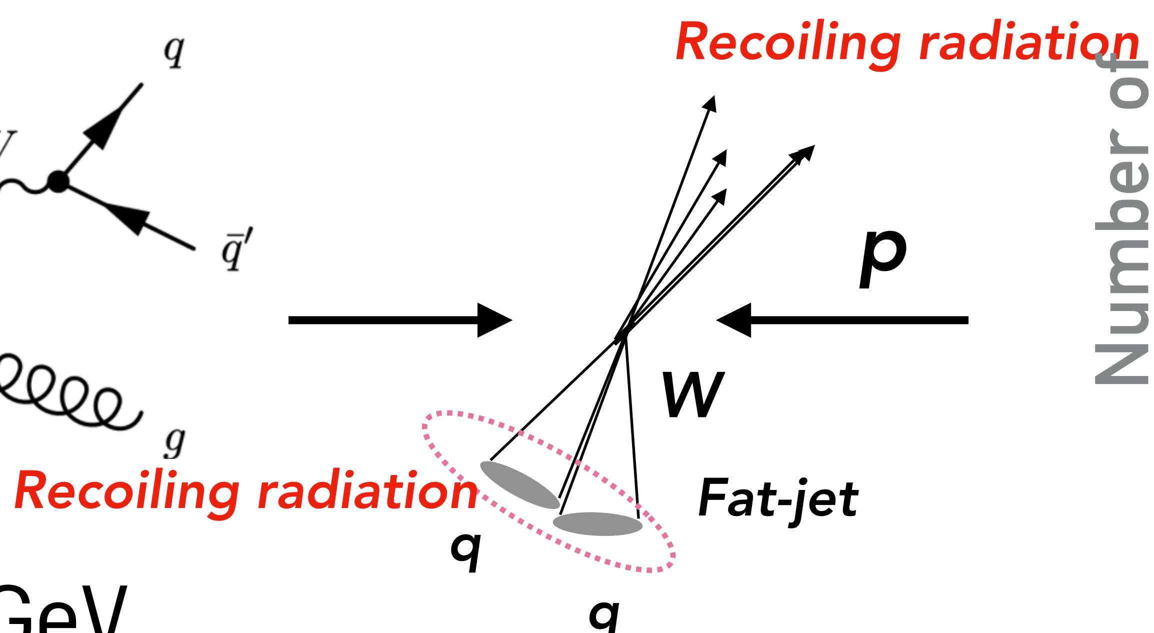


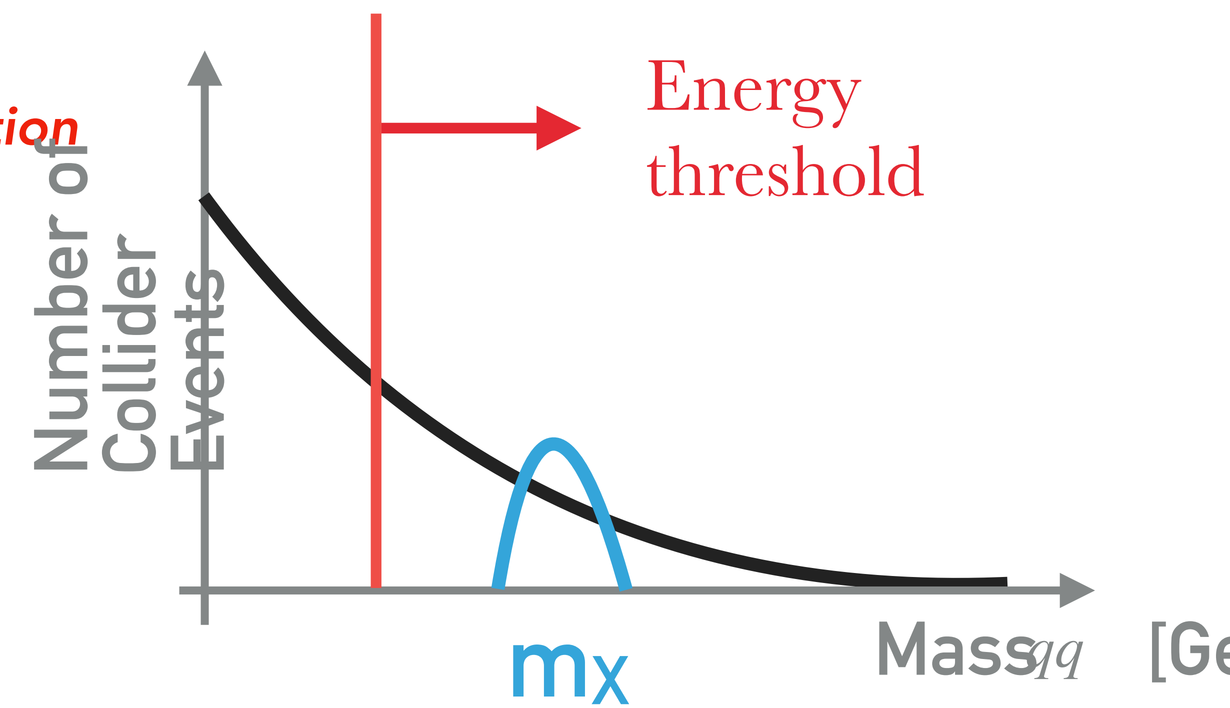


What the process looks like

And what you'll be looking for







p_T > 450 GeV

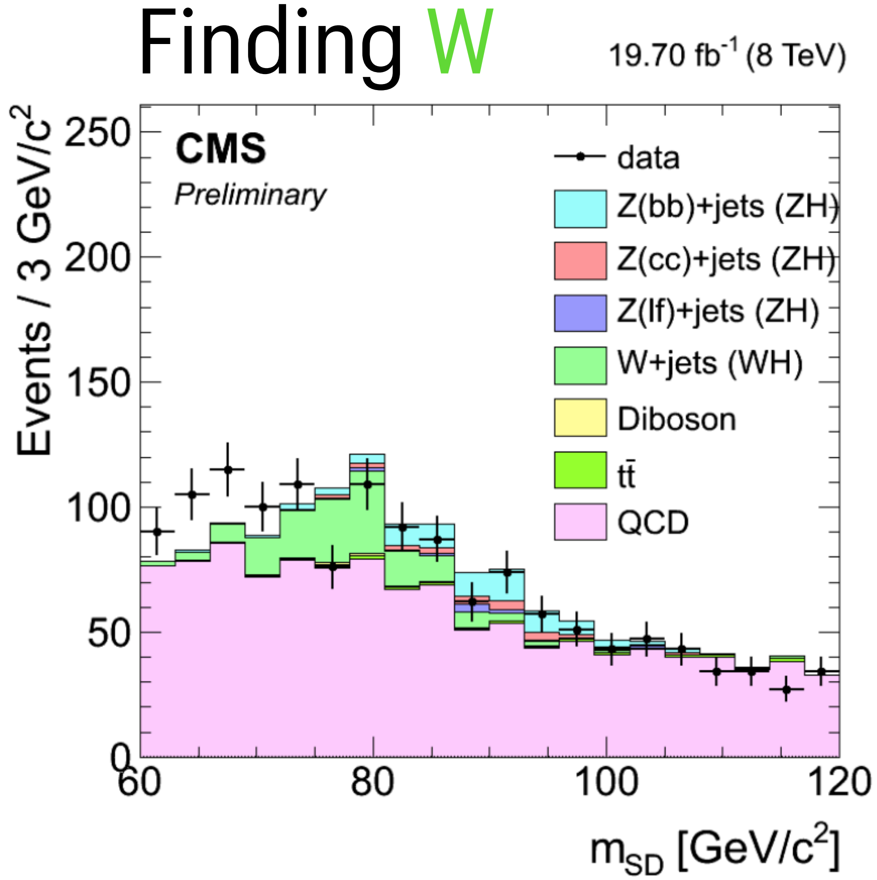
m_W ~ 80.4 GeV

Your goal: reproduce LHC results (or improve them)

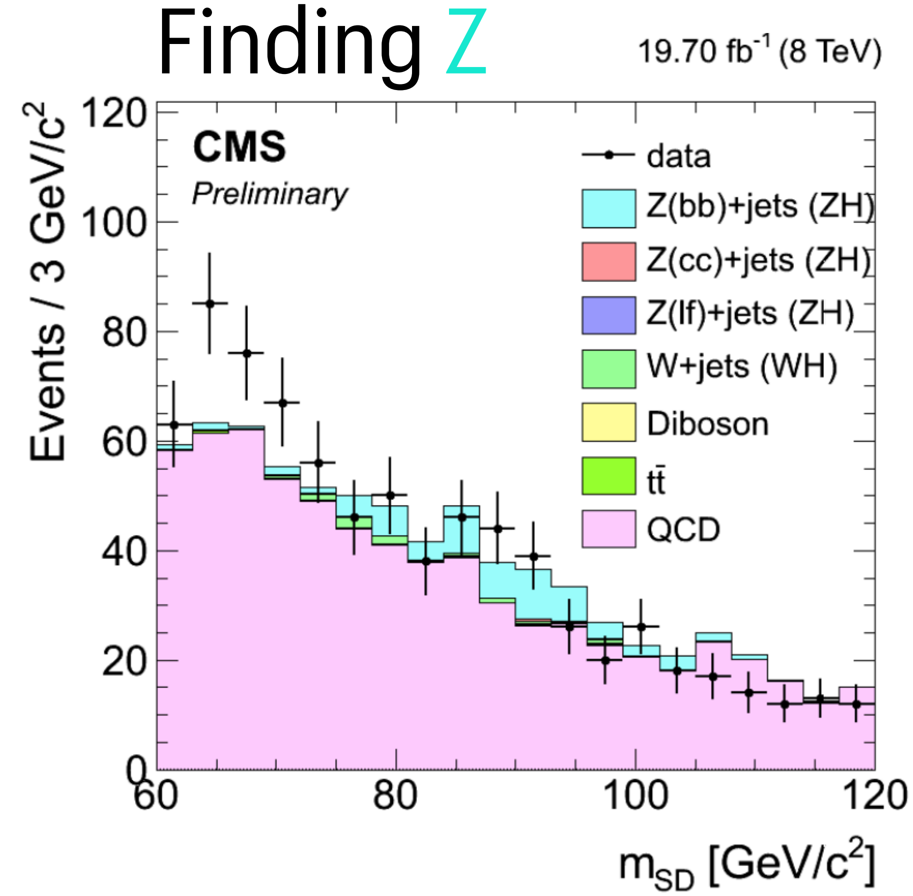
With 8 TeV data

@ 8 TeV (2015)

Finding W



Finding Z

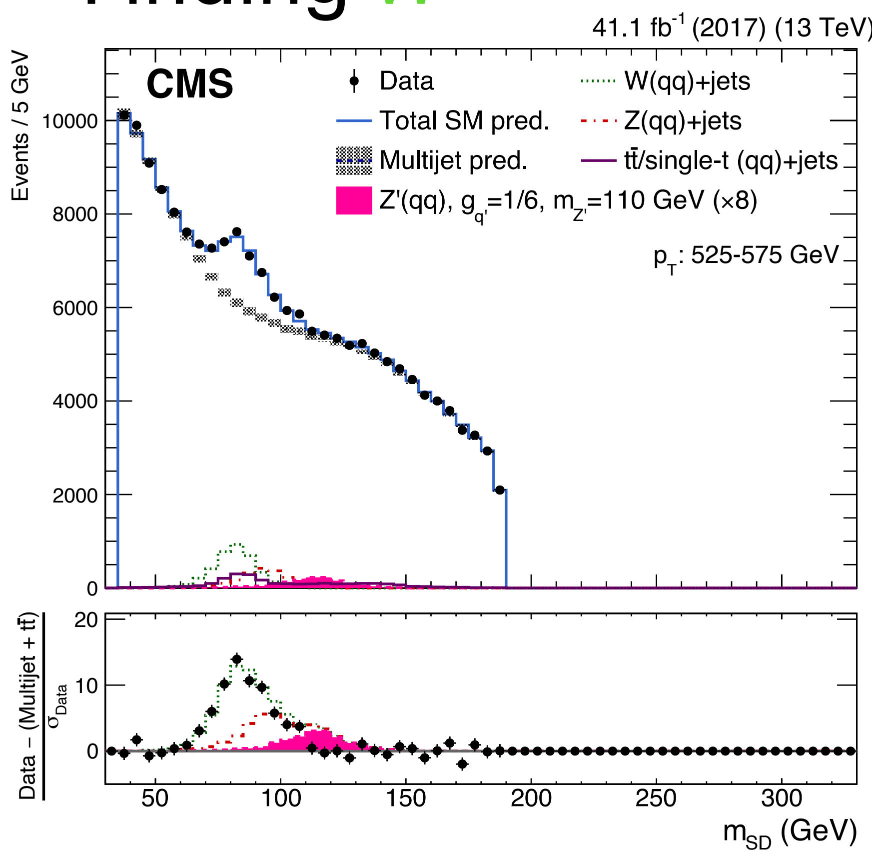


Your goal: reproduce LHC results (or improve them)

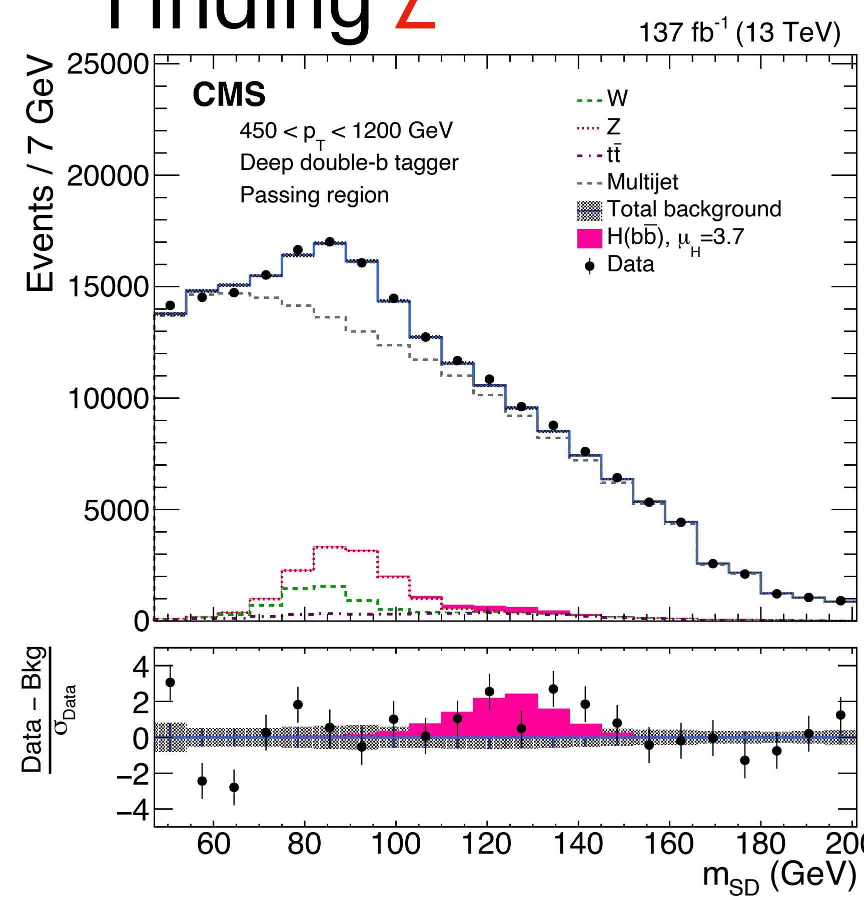
With 8 TeV data

@ 8 TeV (2015)

Finding W

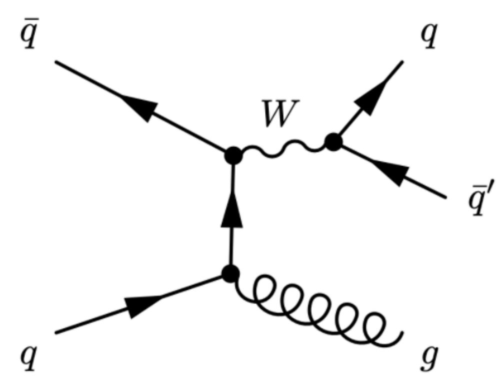


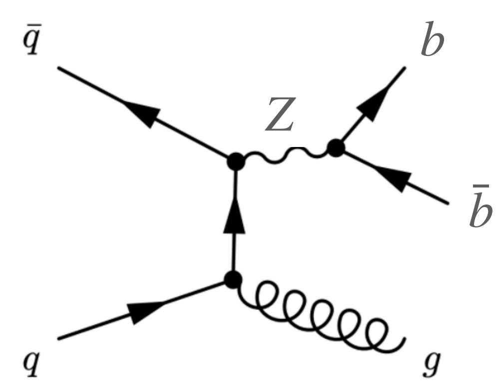
Finding Z



Project 2

Finding W(qq) and Z(qq) 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.