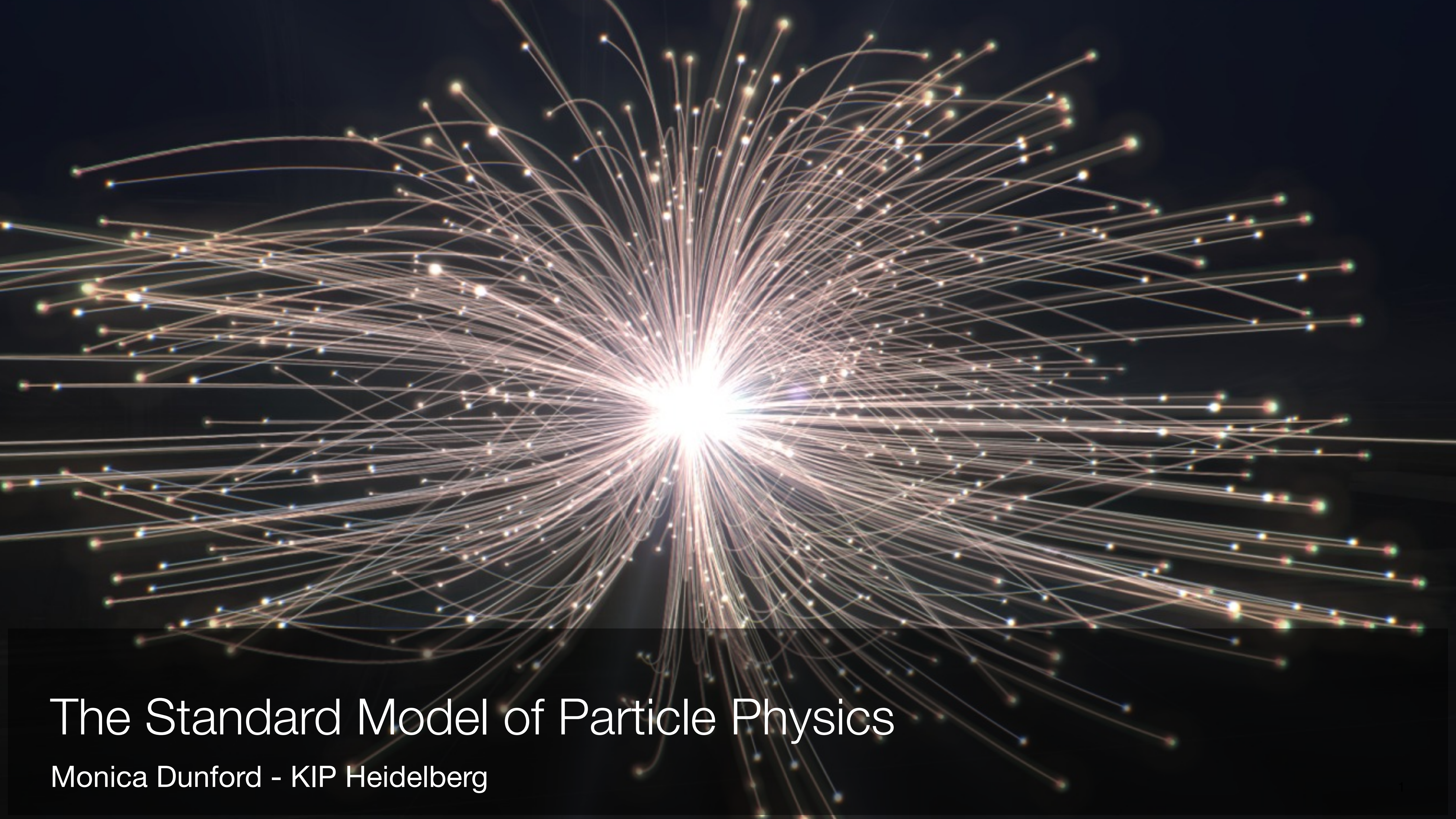




The Standard Model of Particle Physics

Monica Dunford - KIP Heidelberg



From Lonely Planet Guidebook:

“Hotter than hell itself in the summer. Fresno is a town that is best to just drive past. However, if you must stop, here are a few suggestions...”





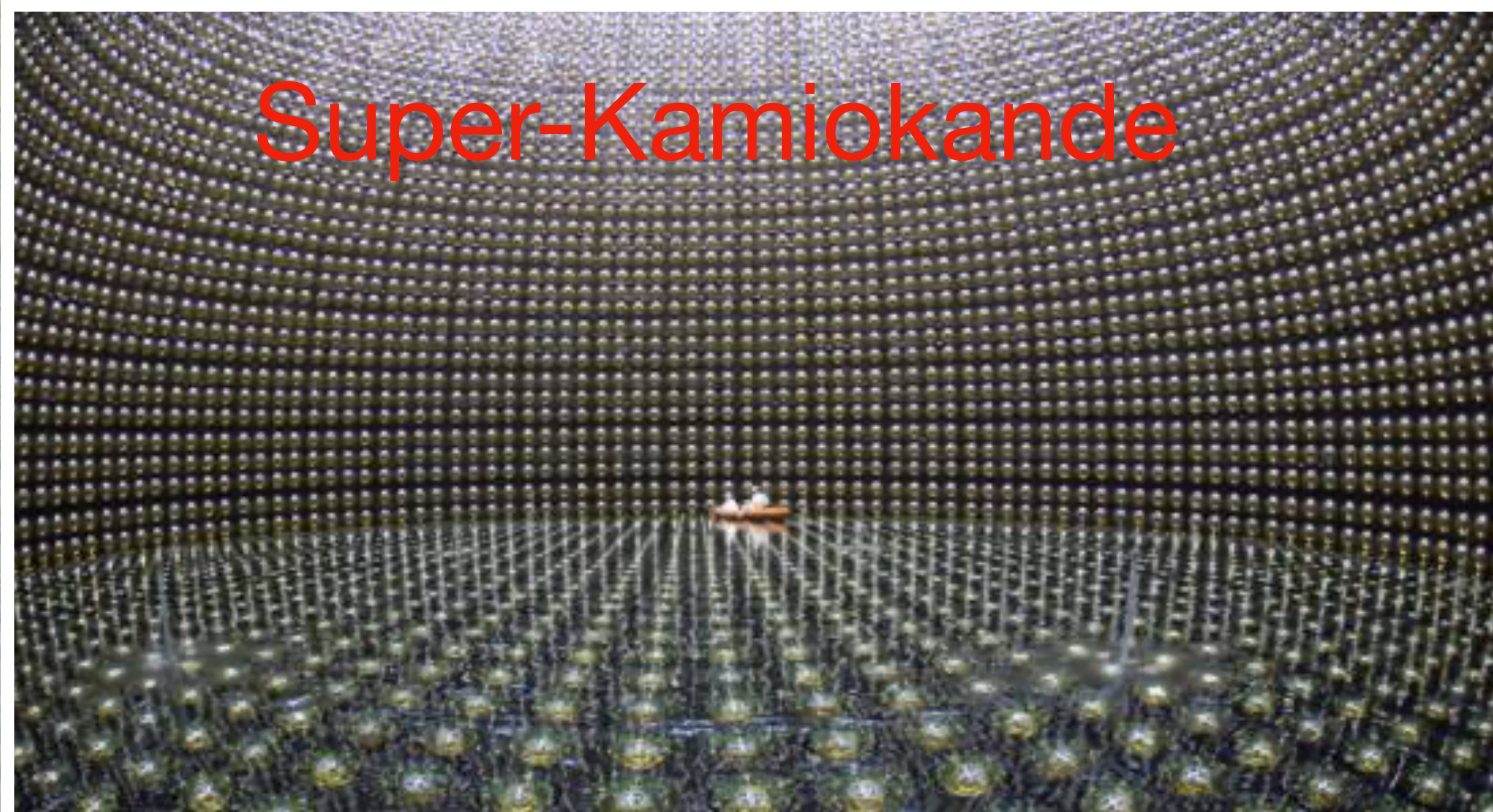
Milagro



Irvine Michigan
Brookhaven experiment



Super-Kamiokande

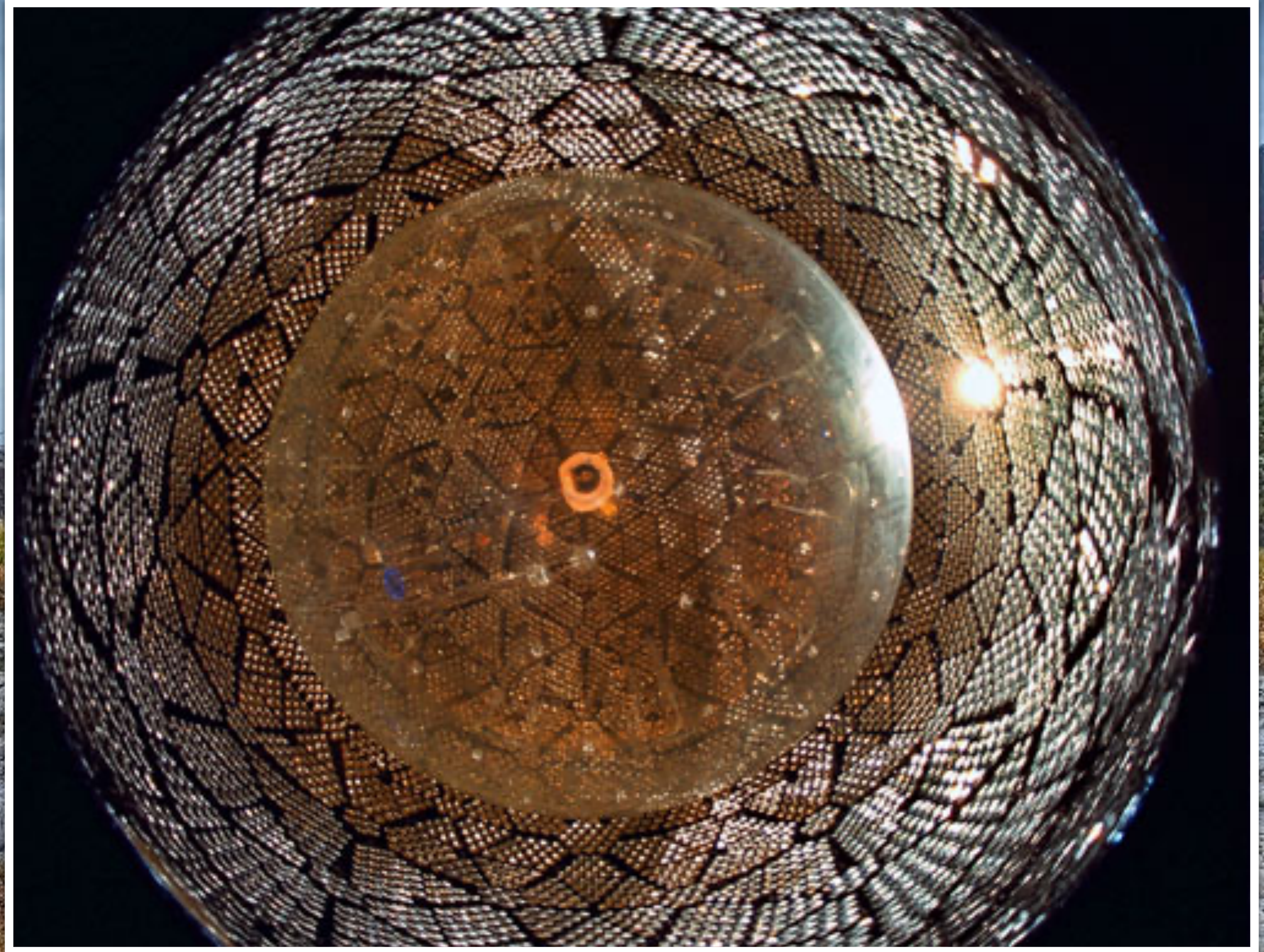


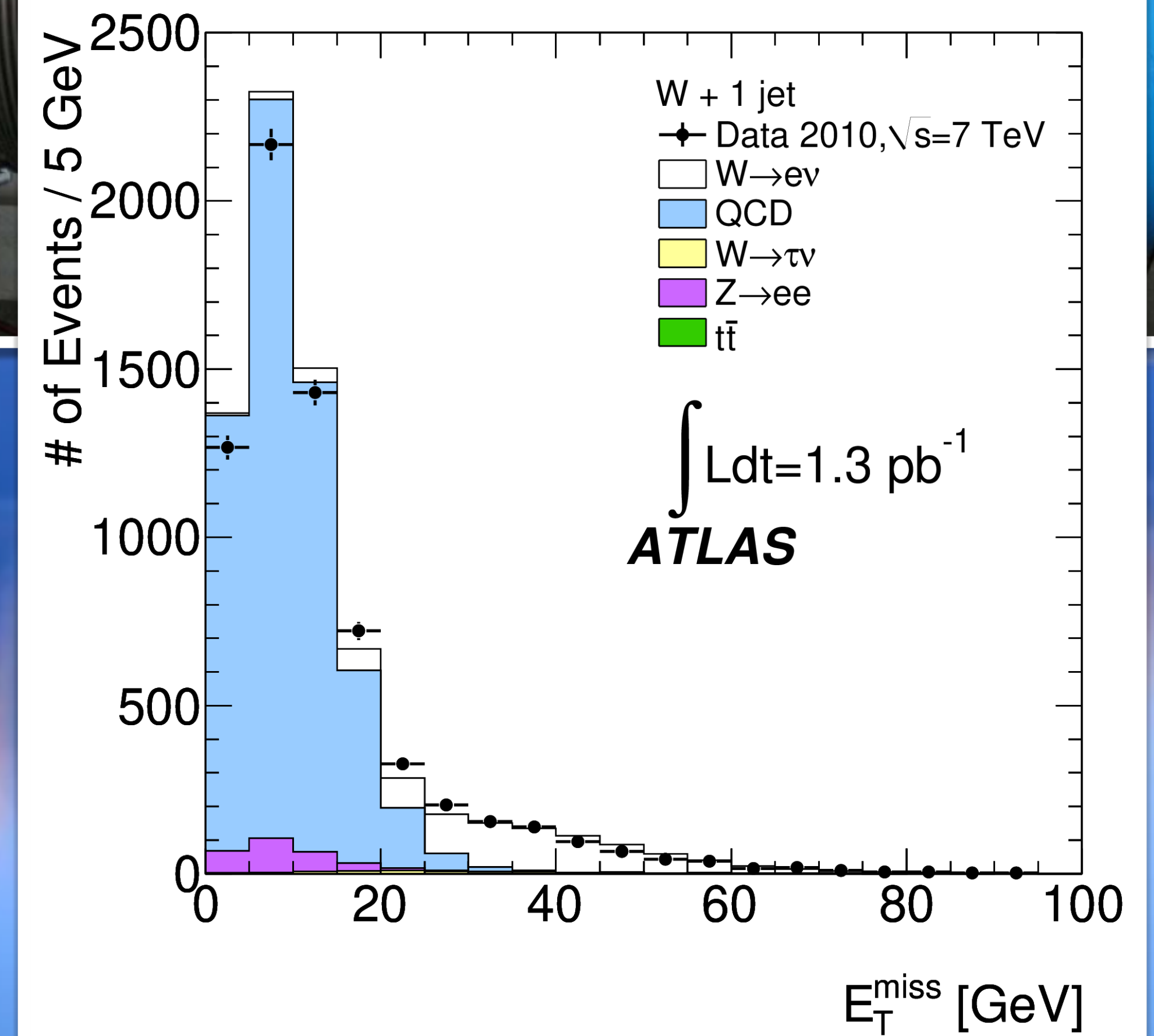
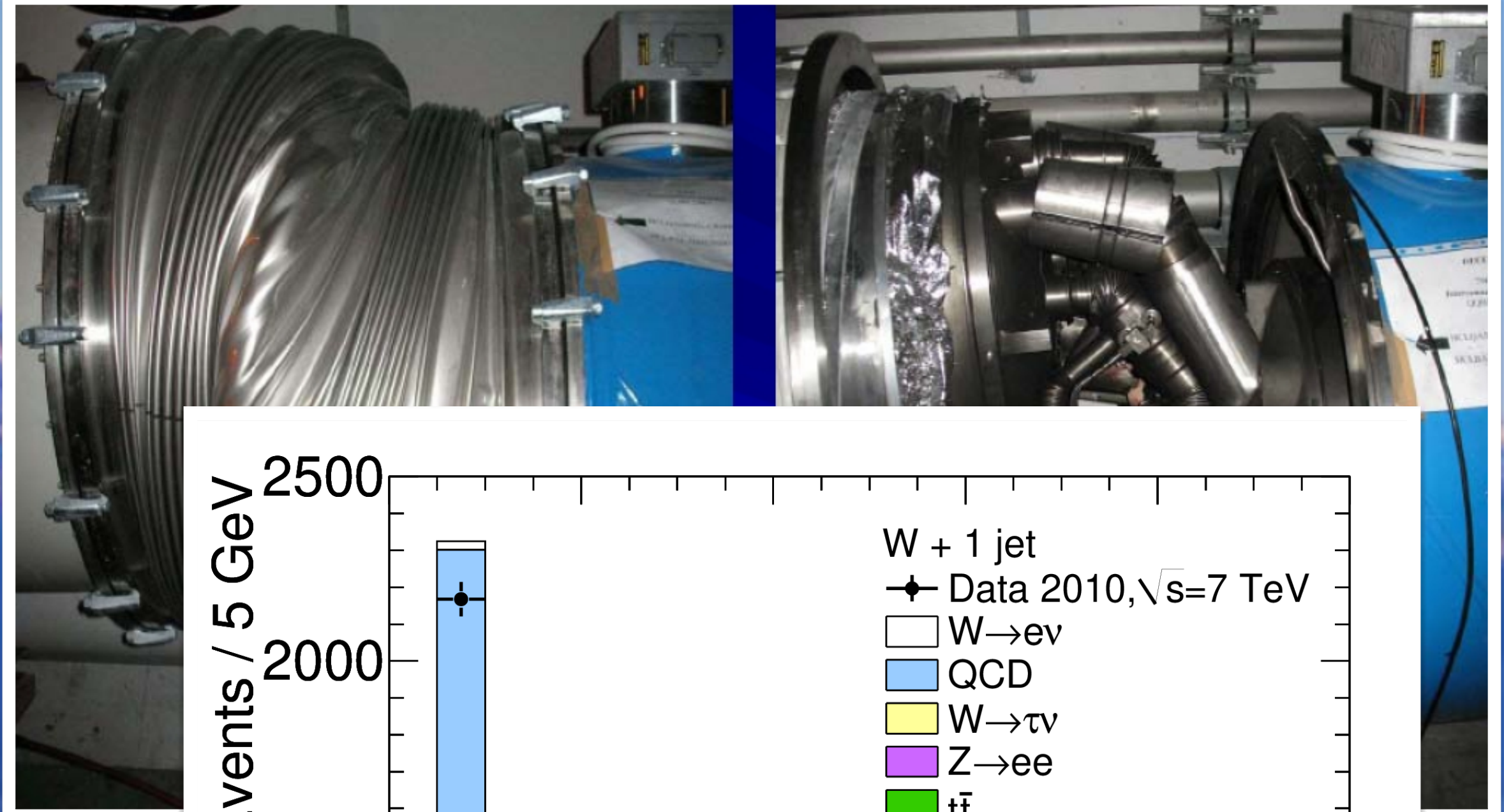
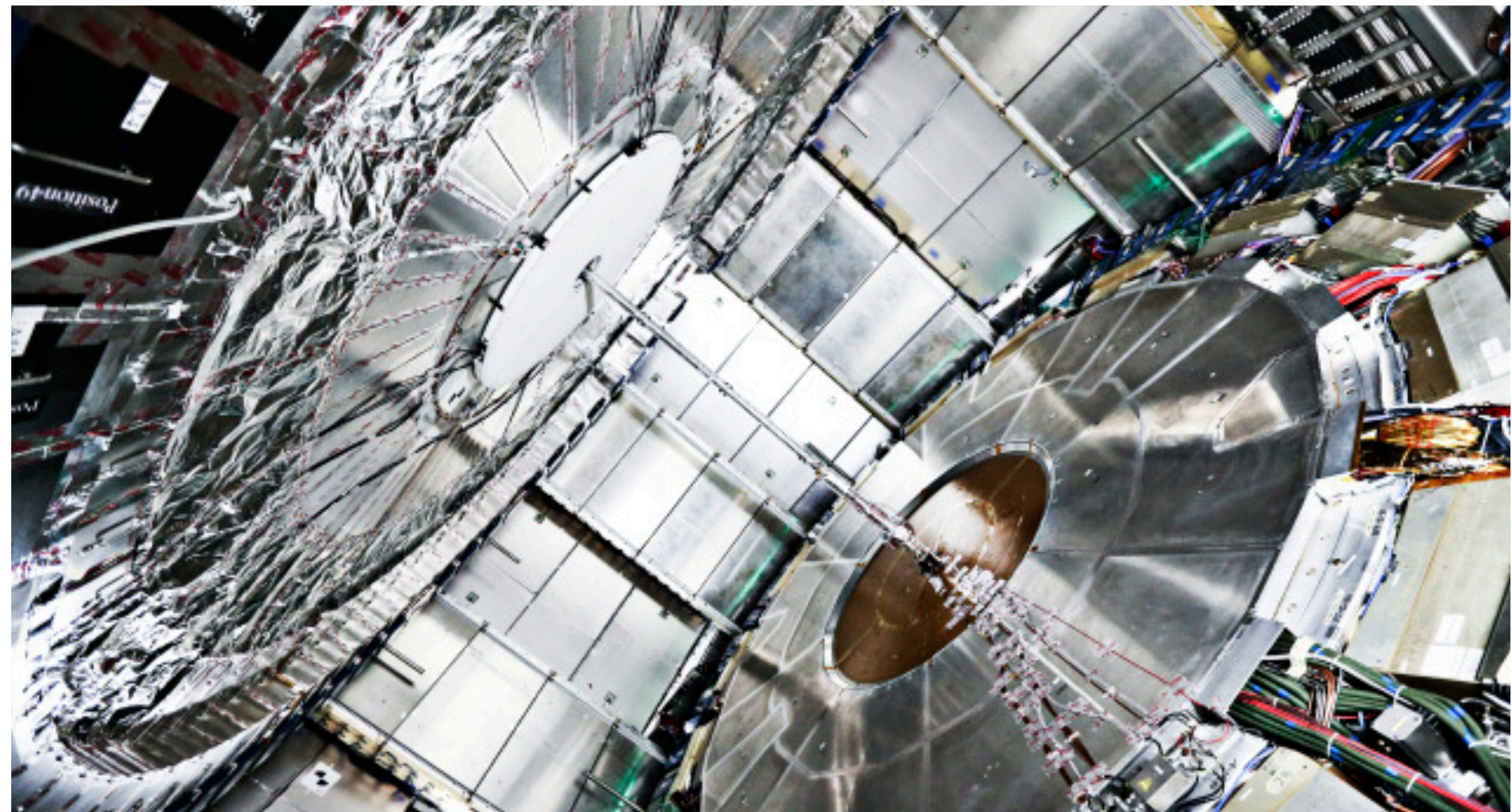
D-Zero



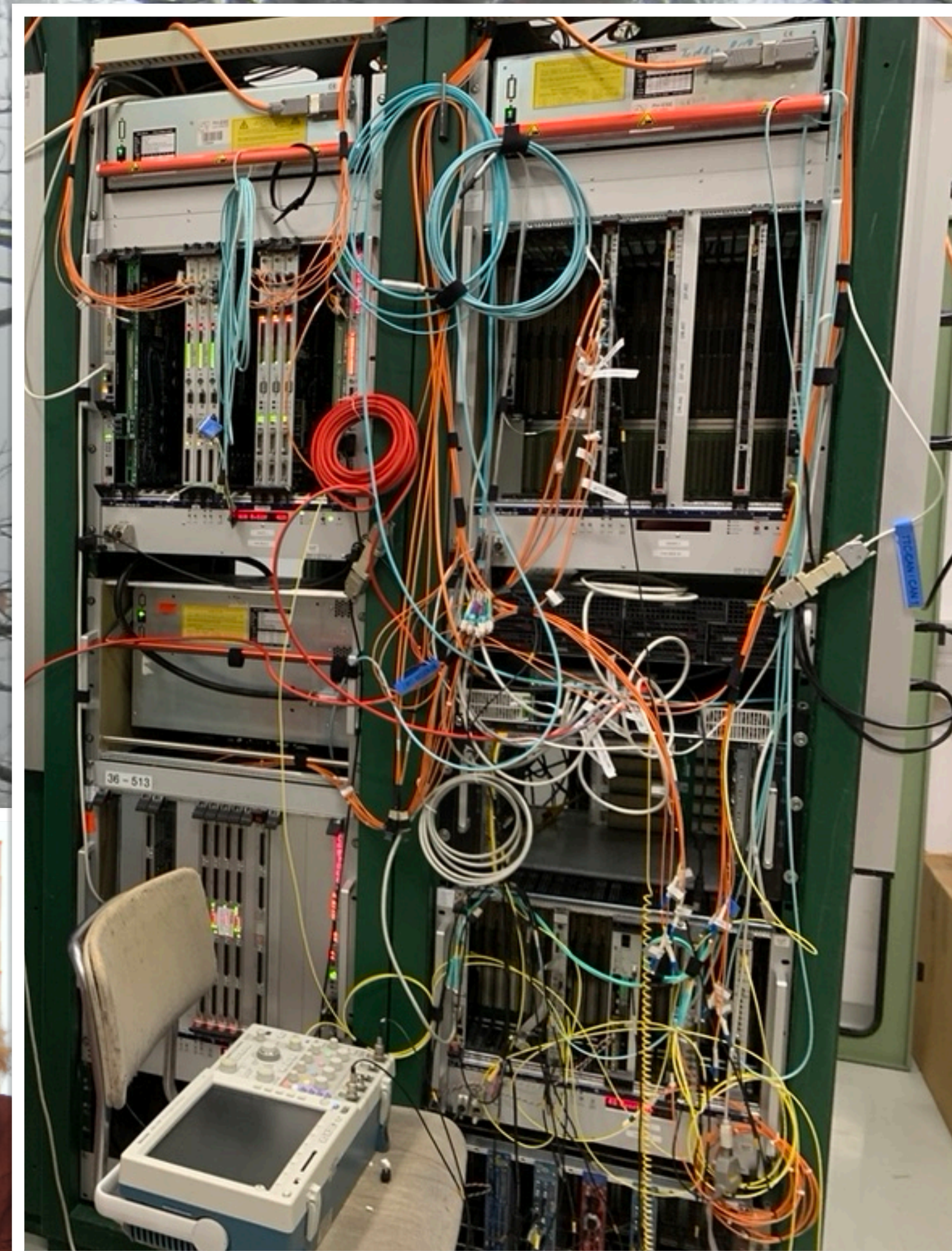


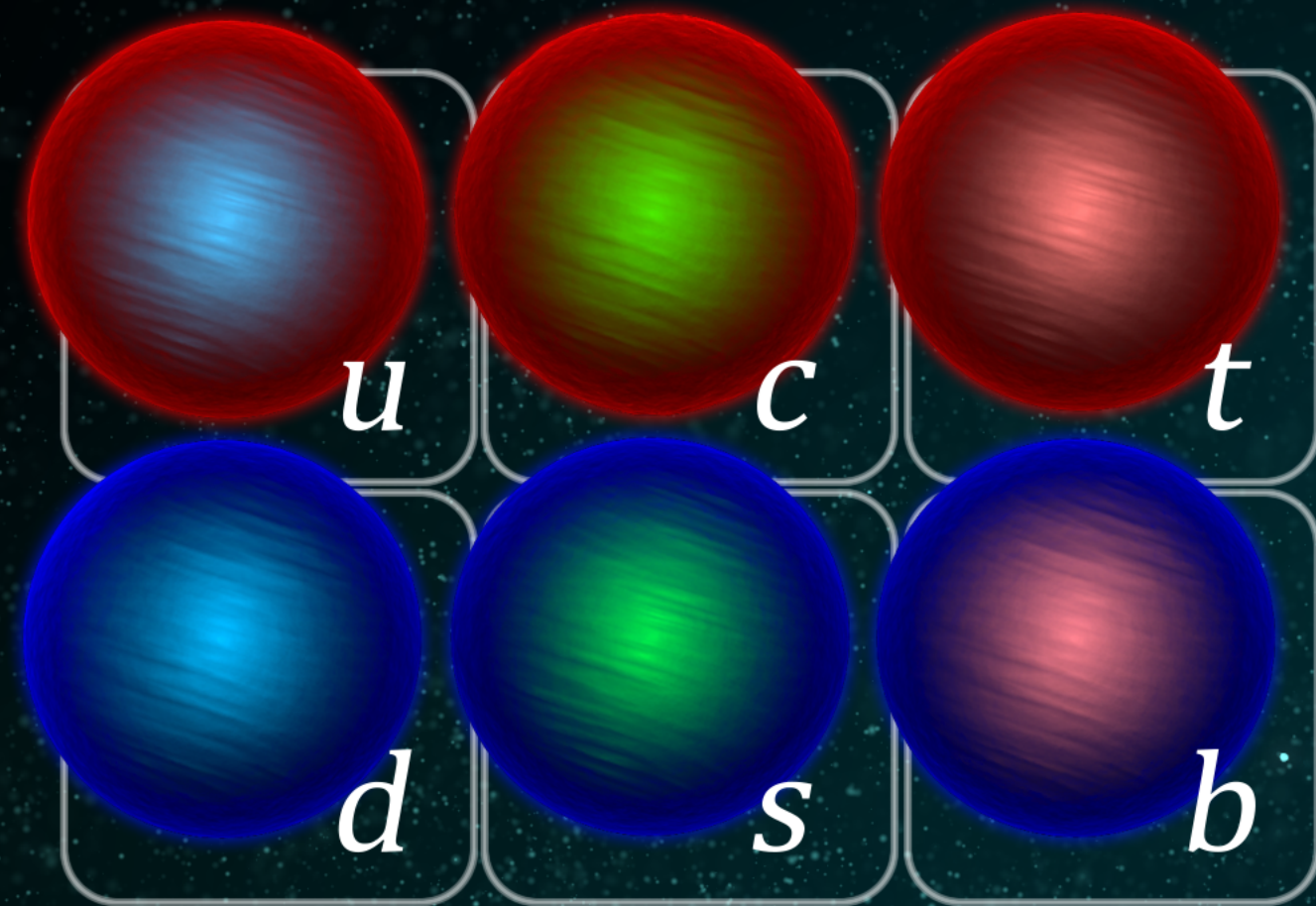
Sudbury Neutrino Observatory



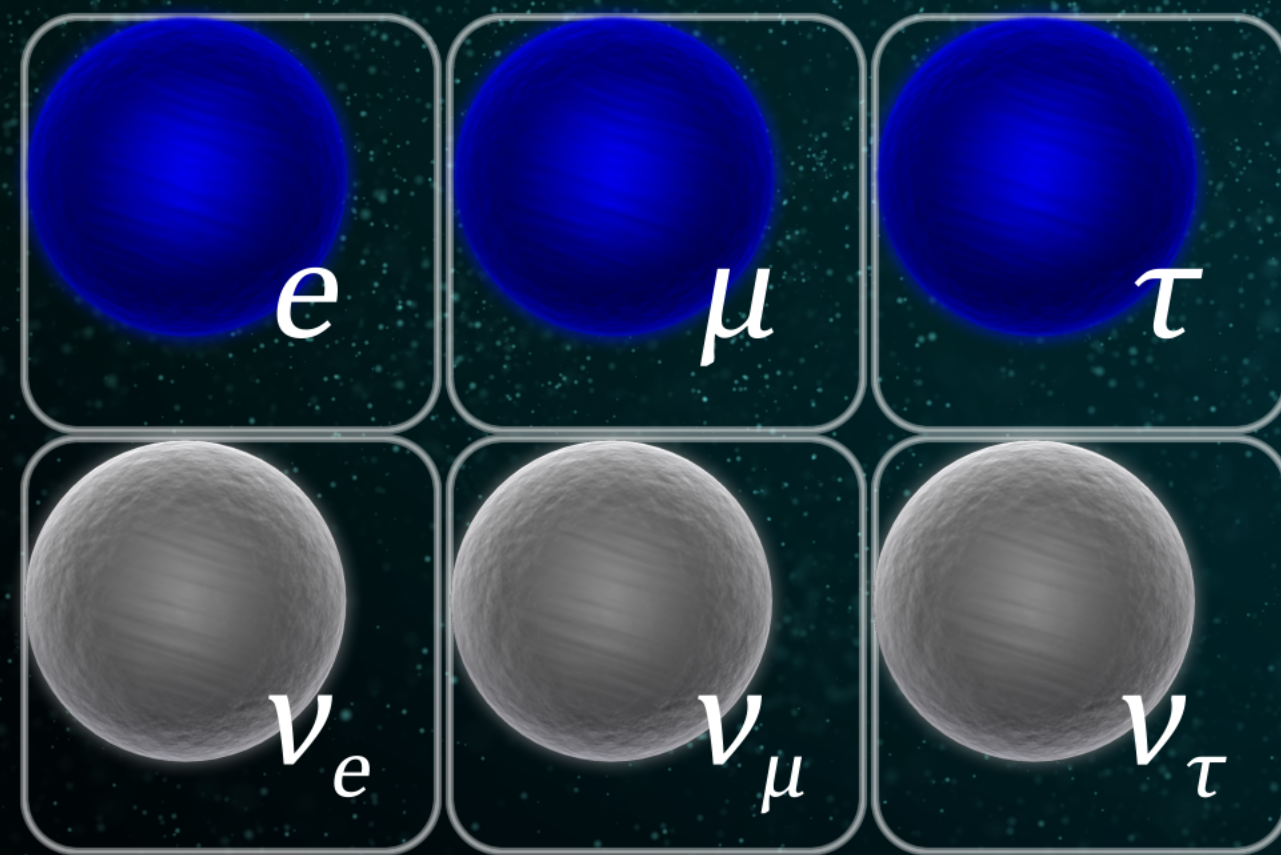




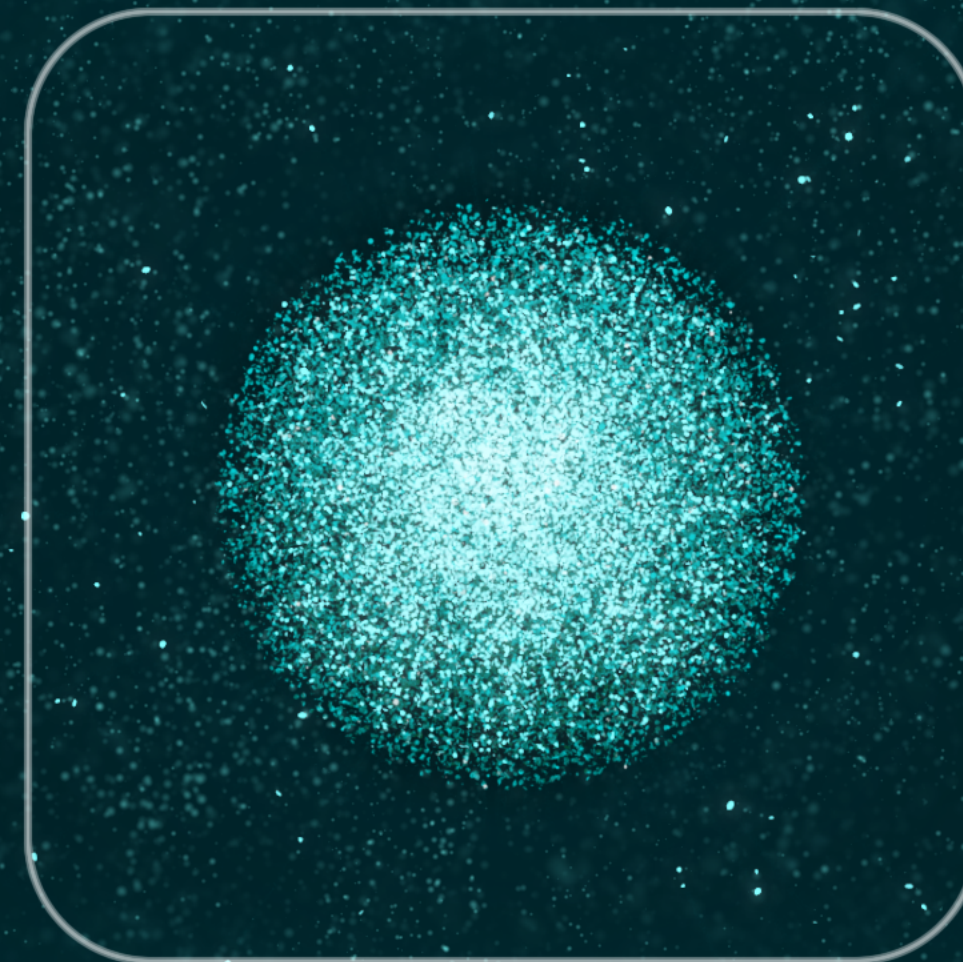




Quarks



Leptons

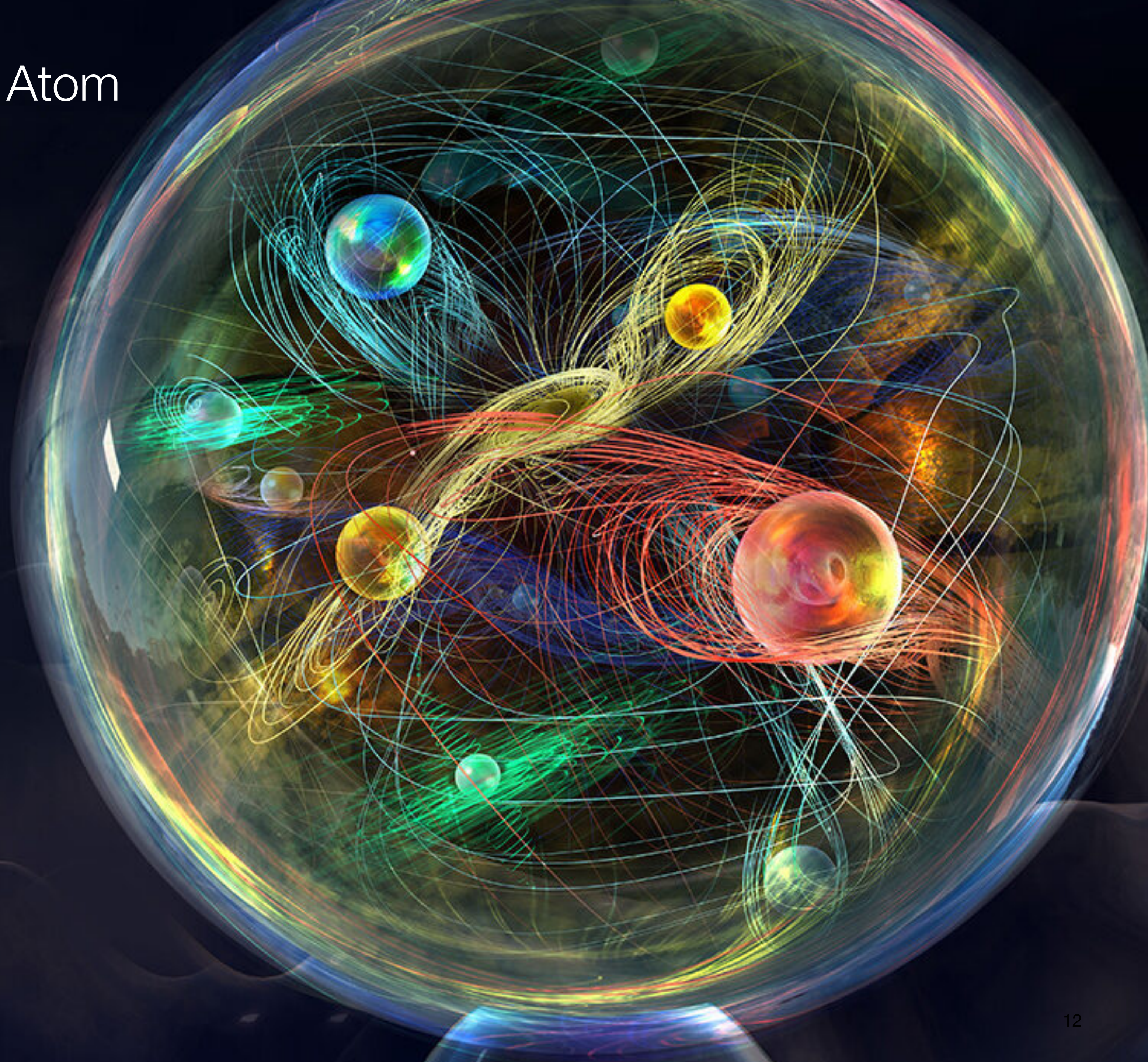
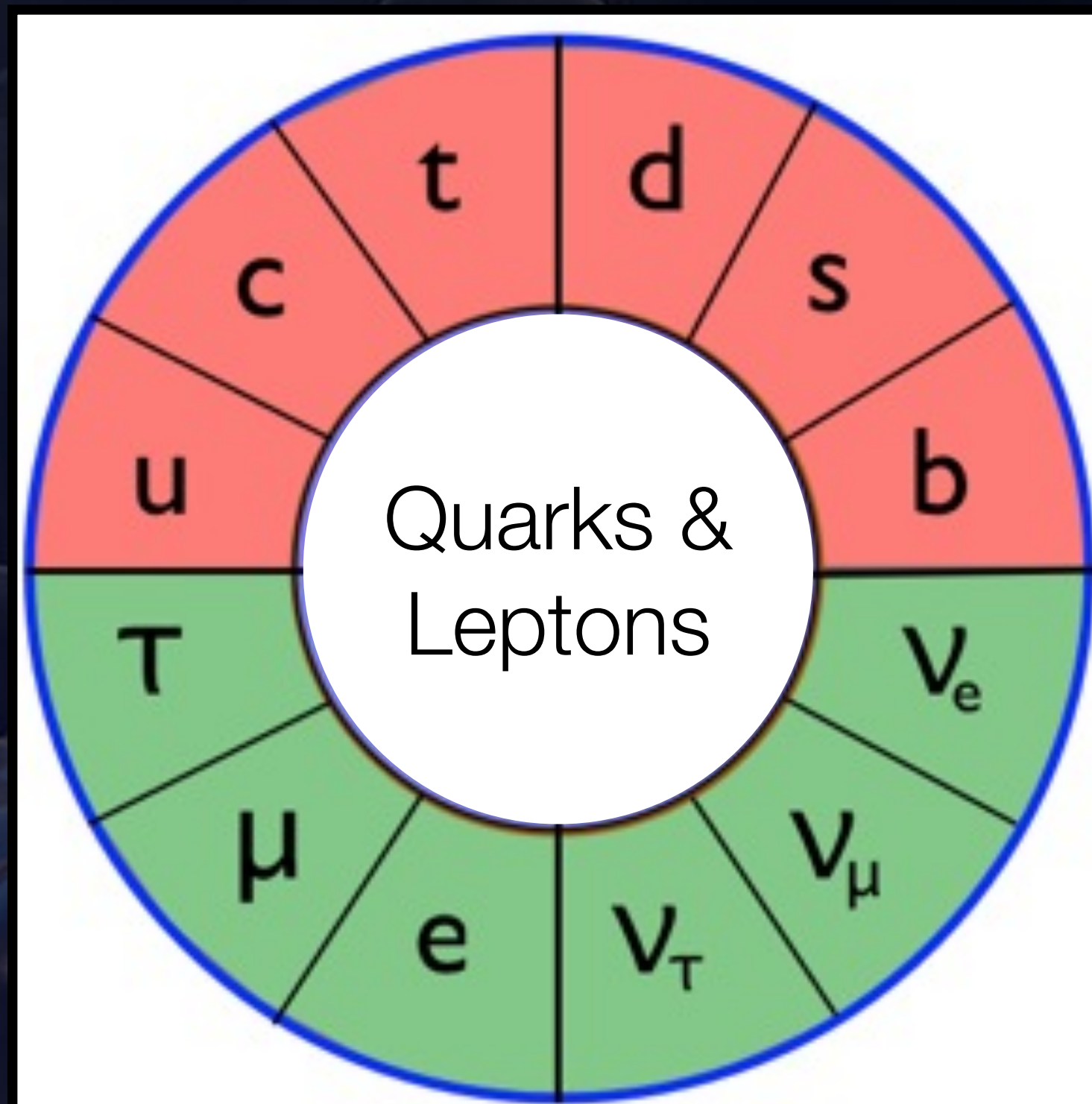


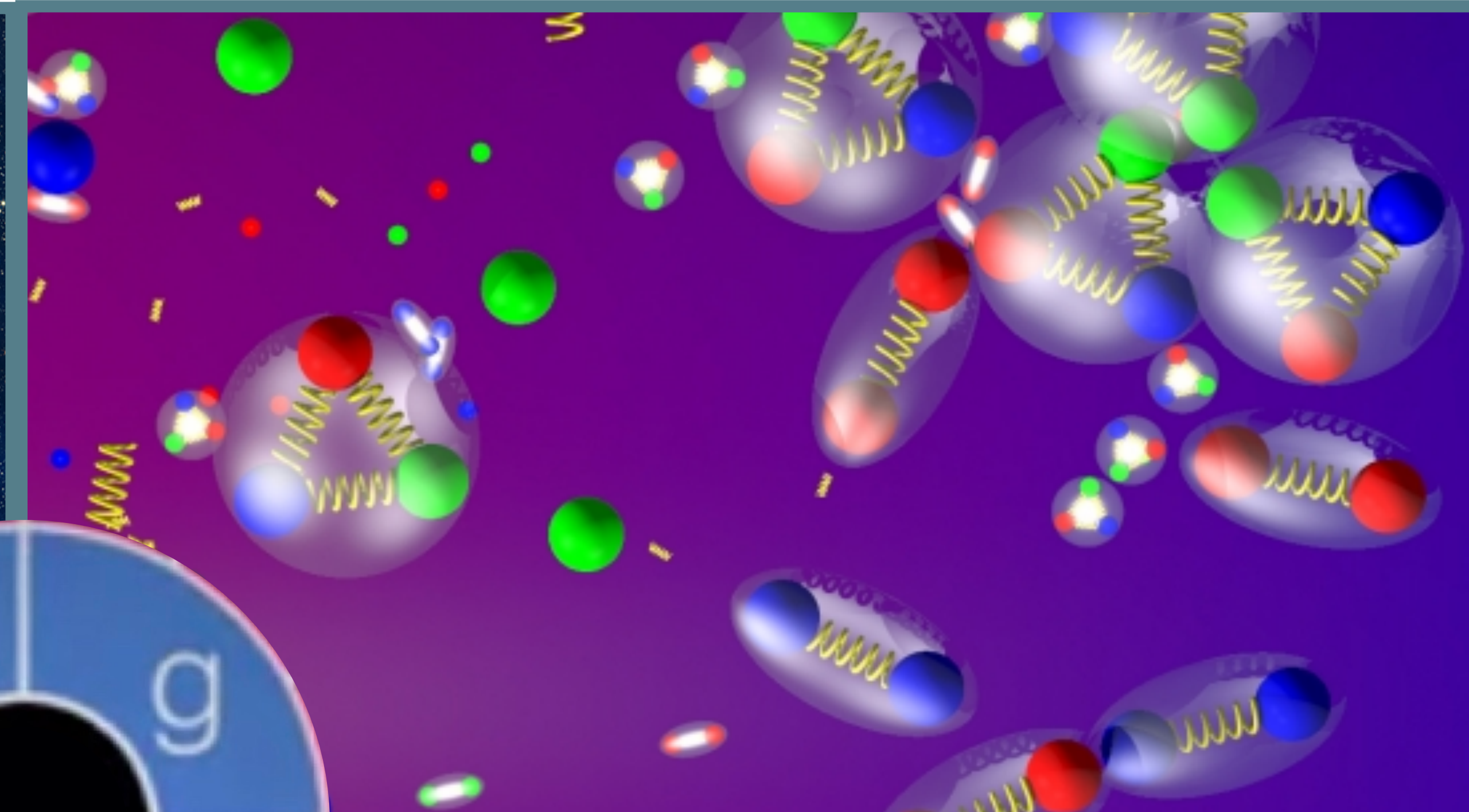
Higgs boson



Forces

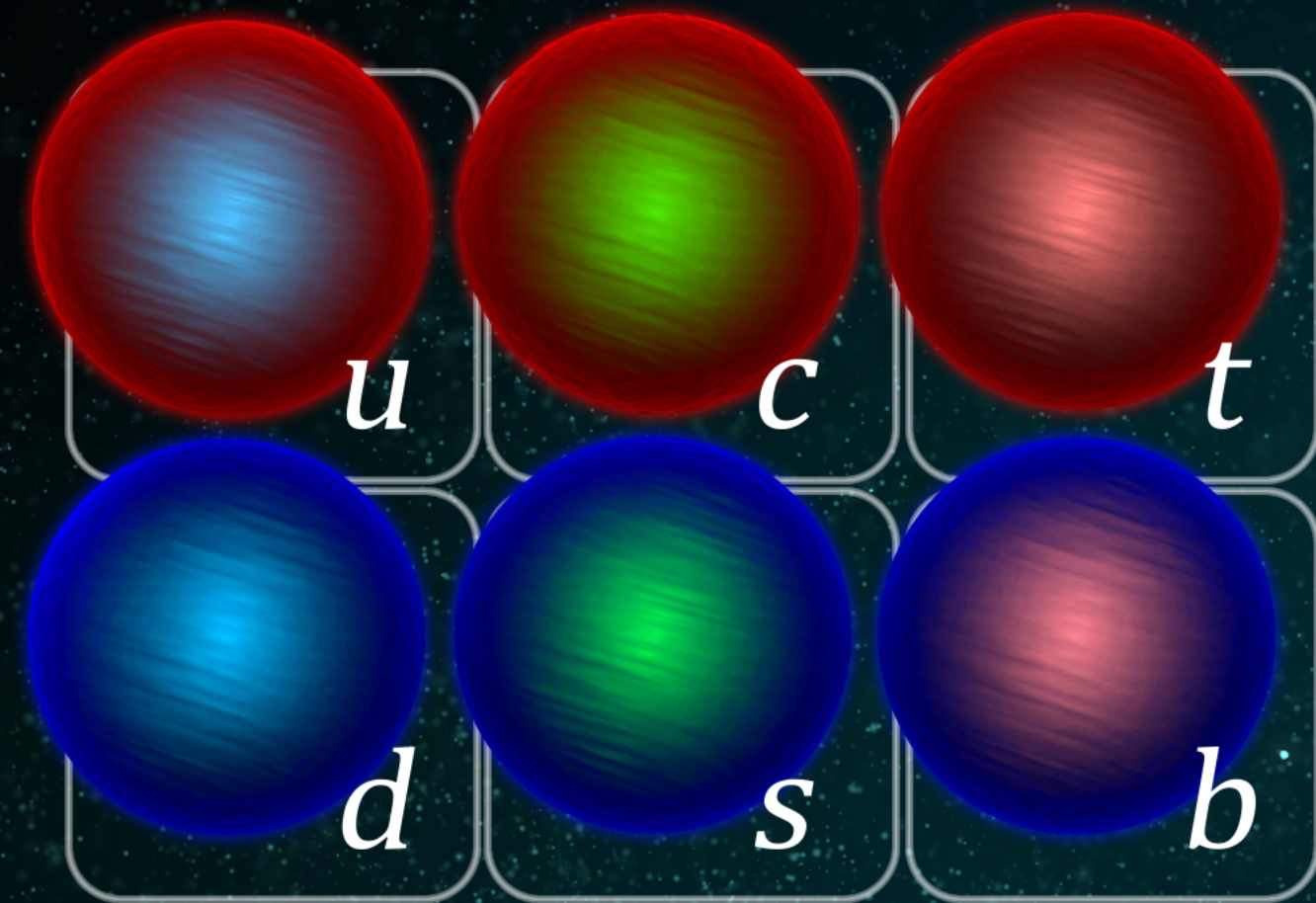
Hydrogen Atom



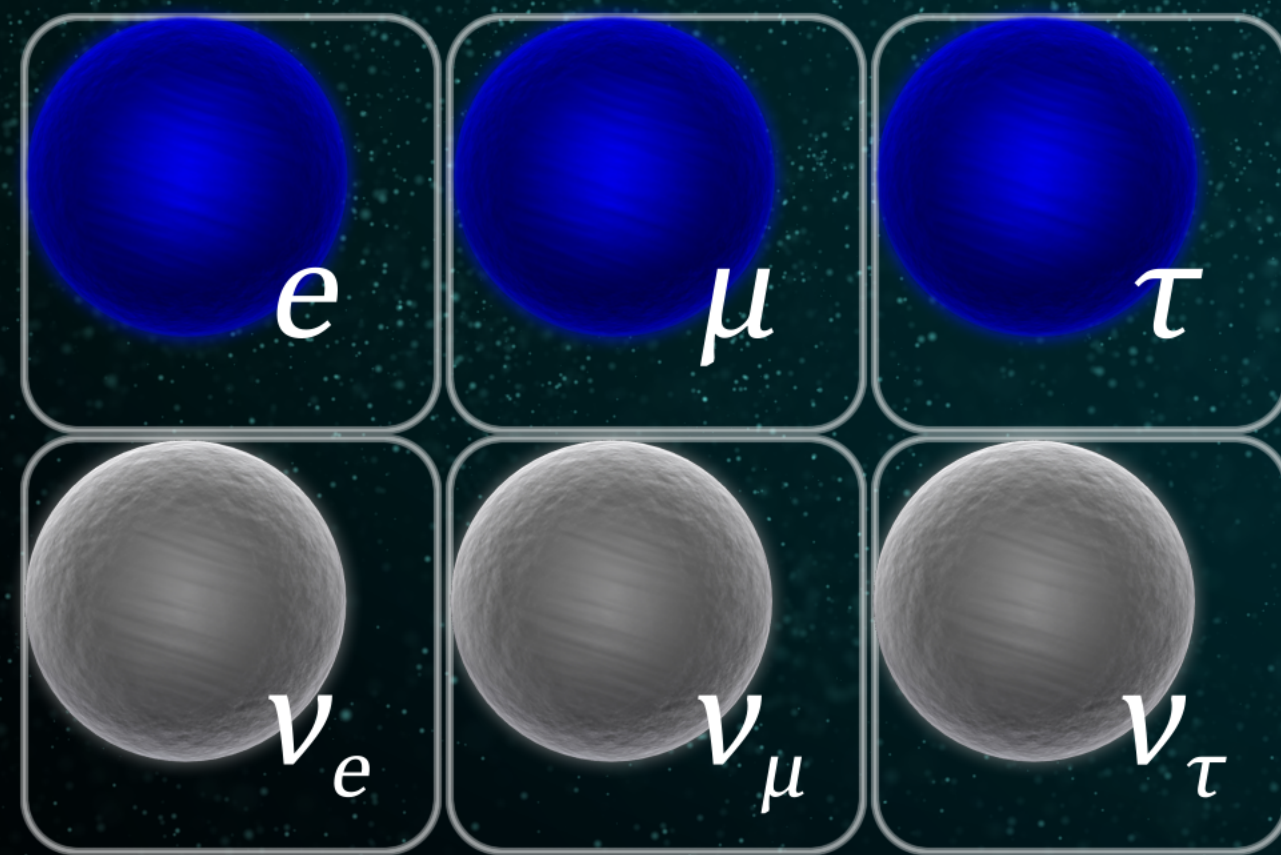




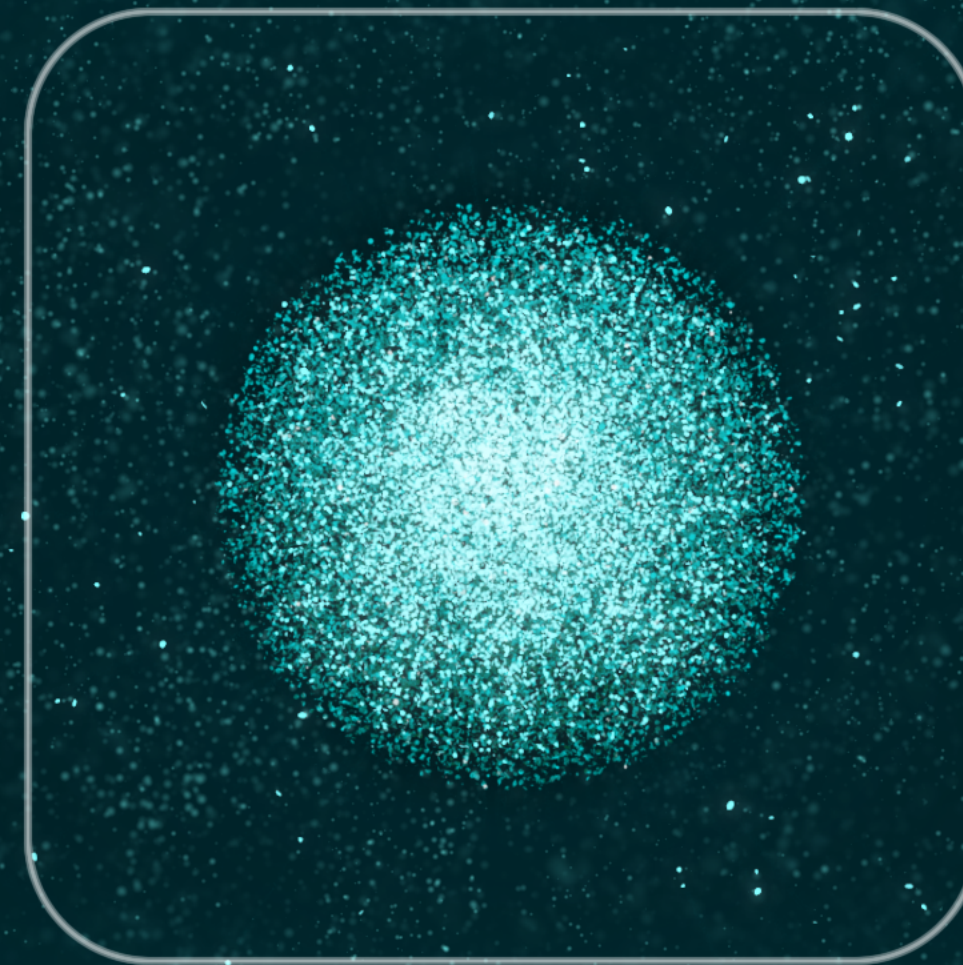
Particle physics isn't about particles



Quarks



Leptons

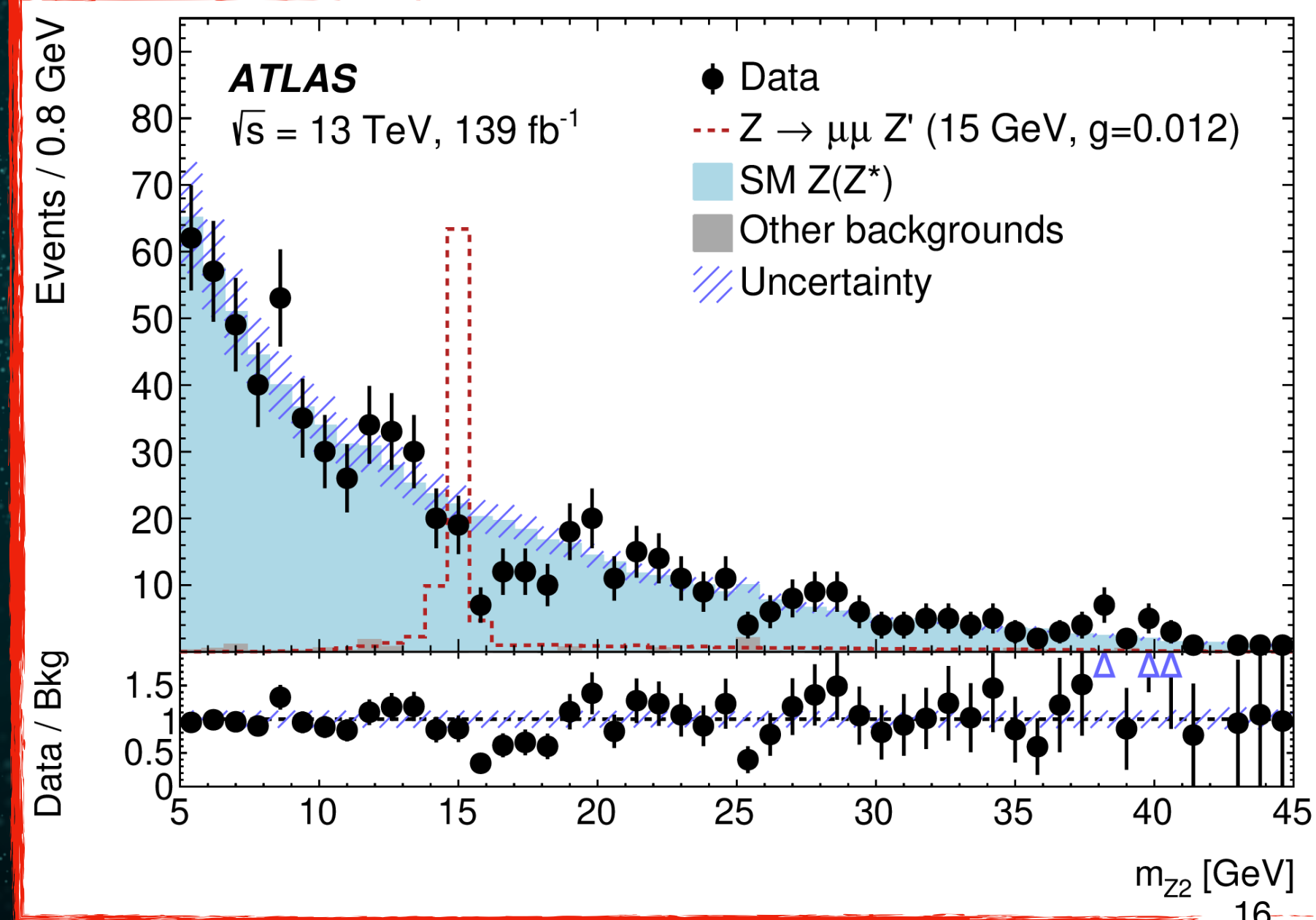
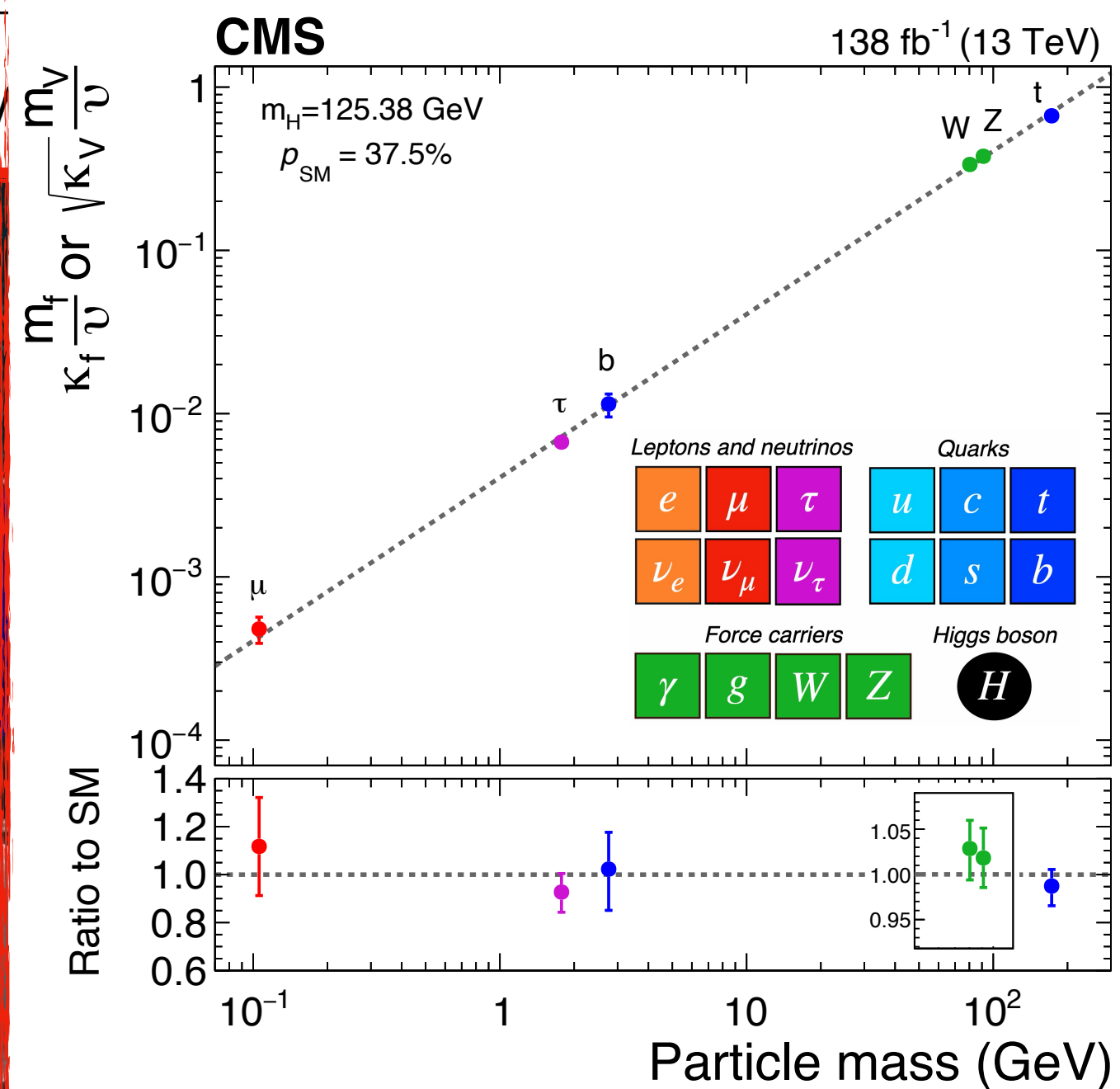
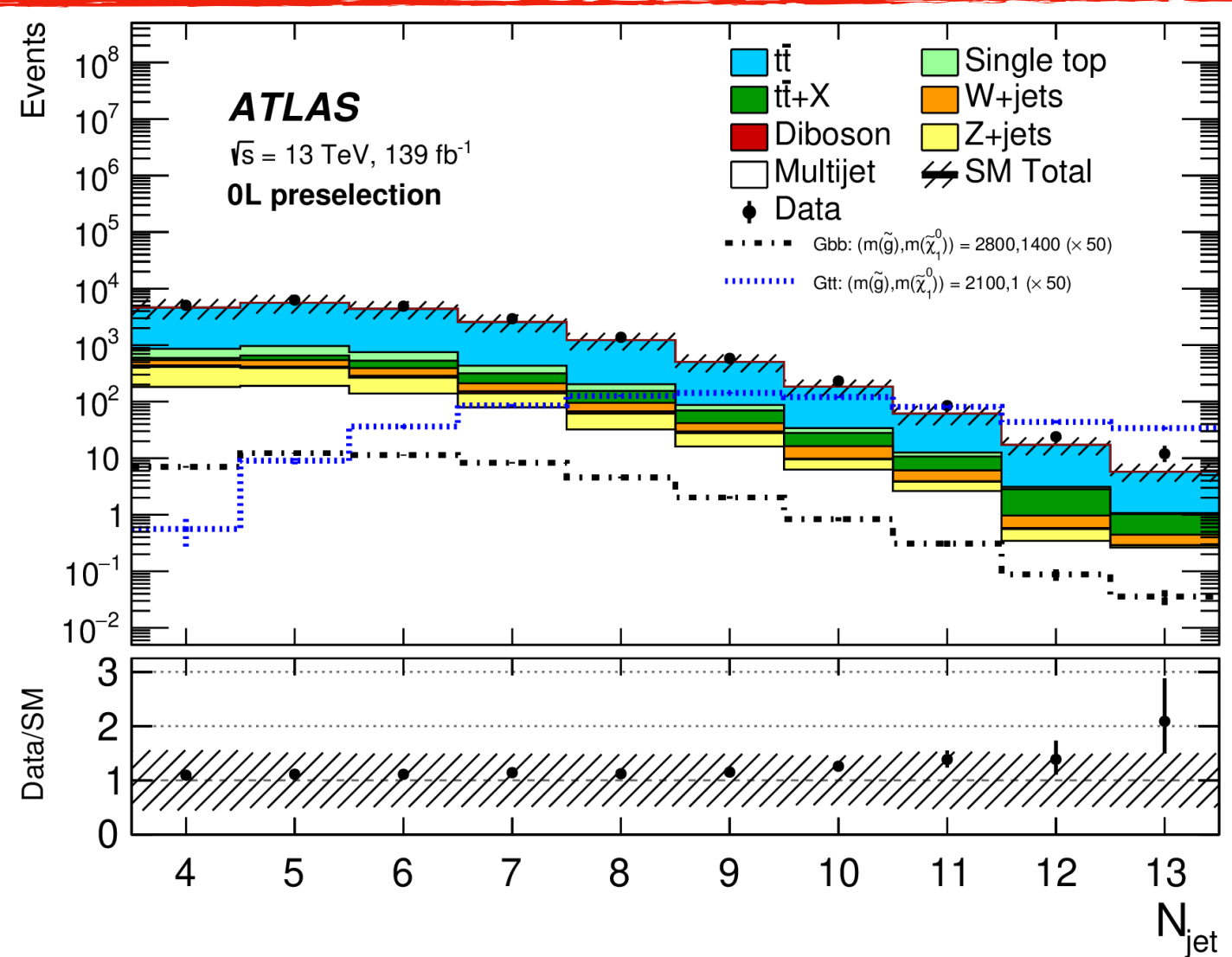
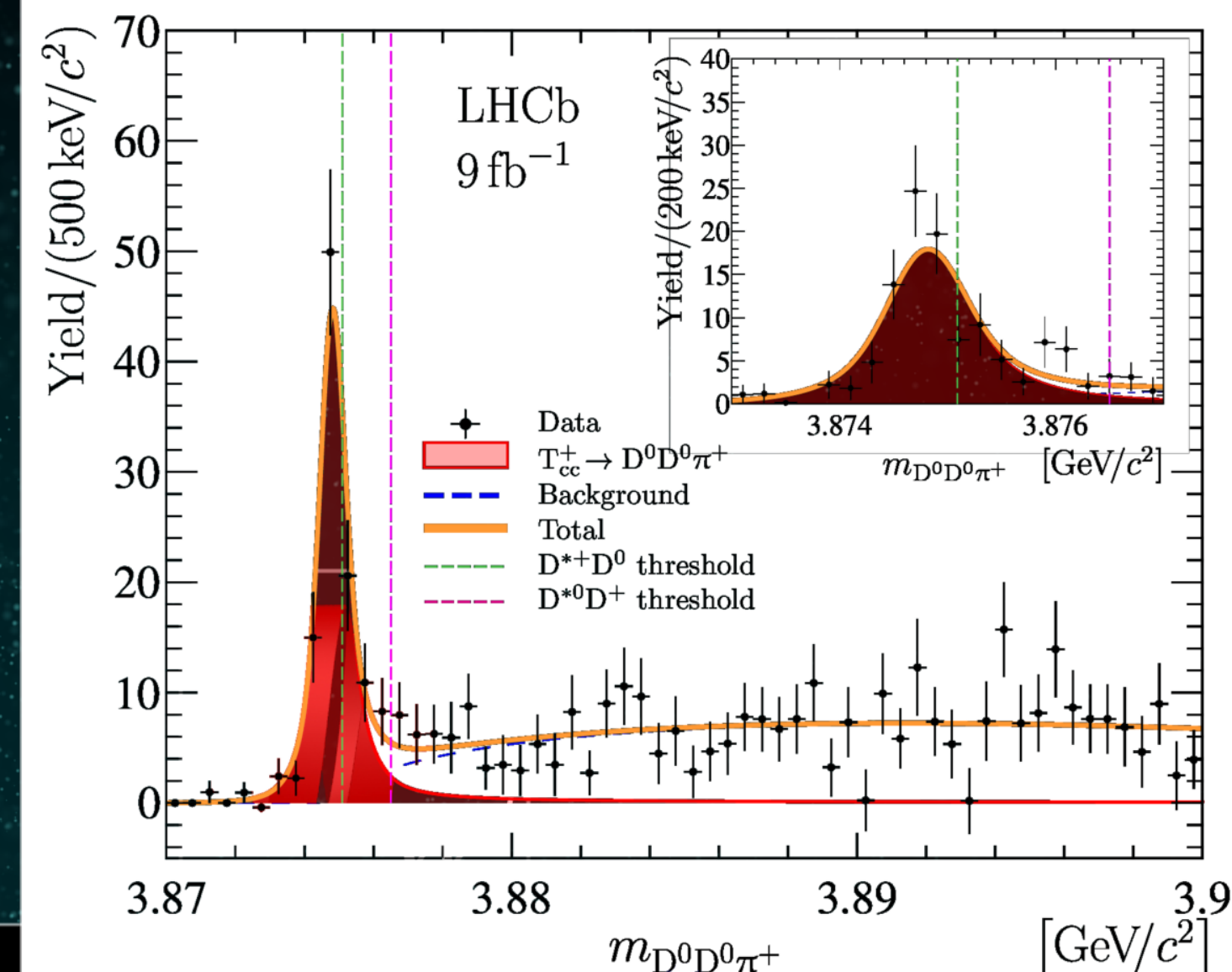
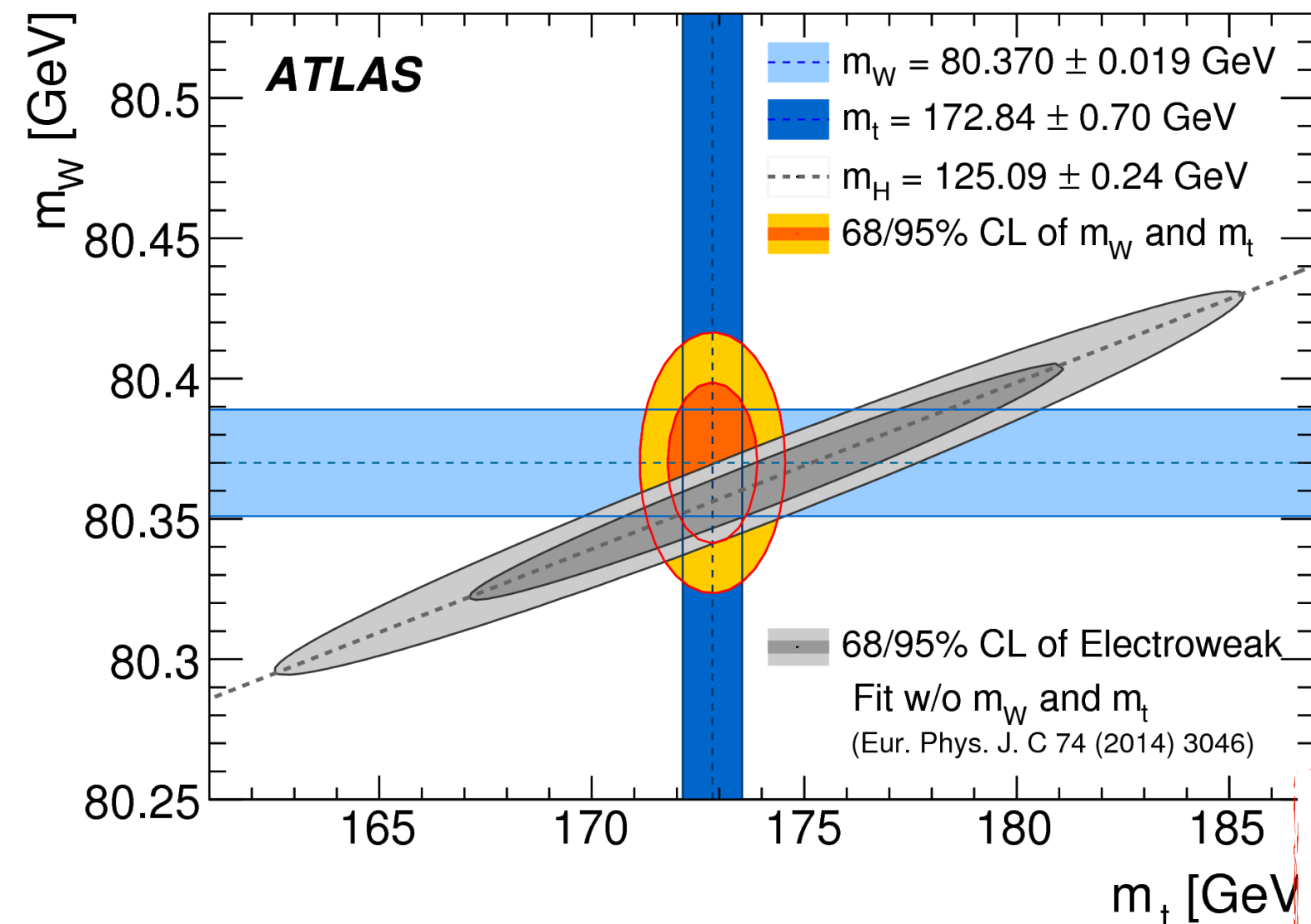


Higgs boson



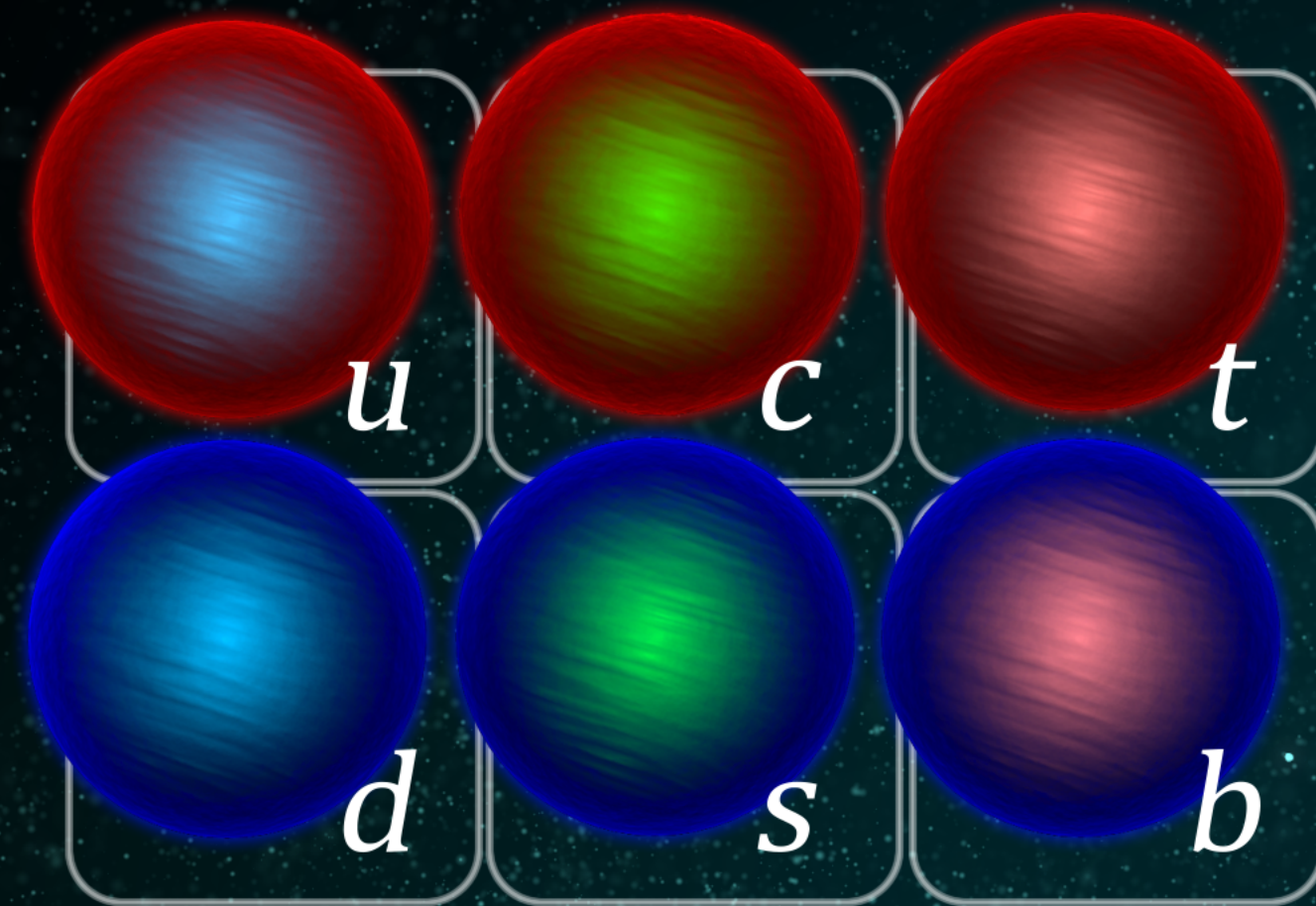
Forces

Use particles for their properties...



As keys to unlock fundamental principles

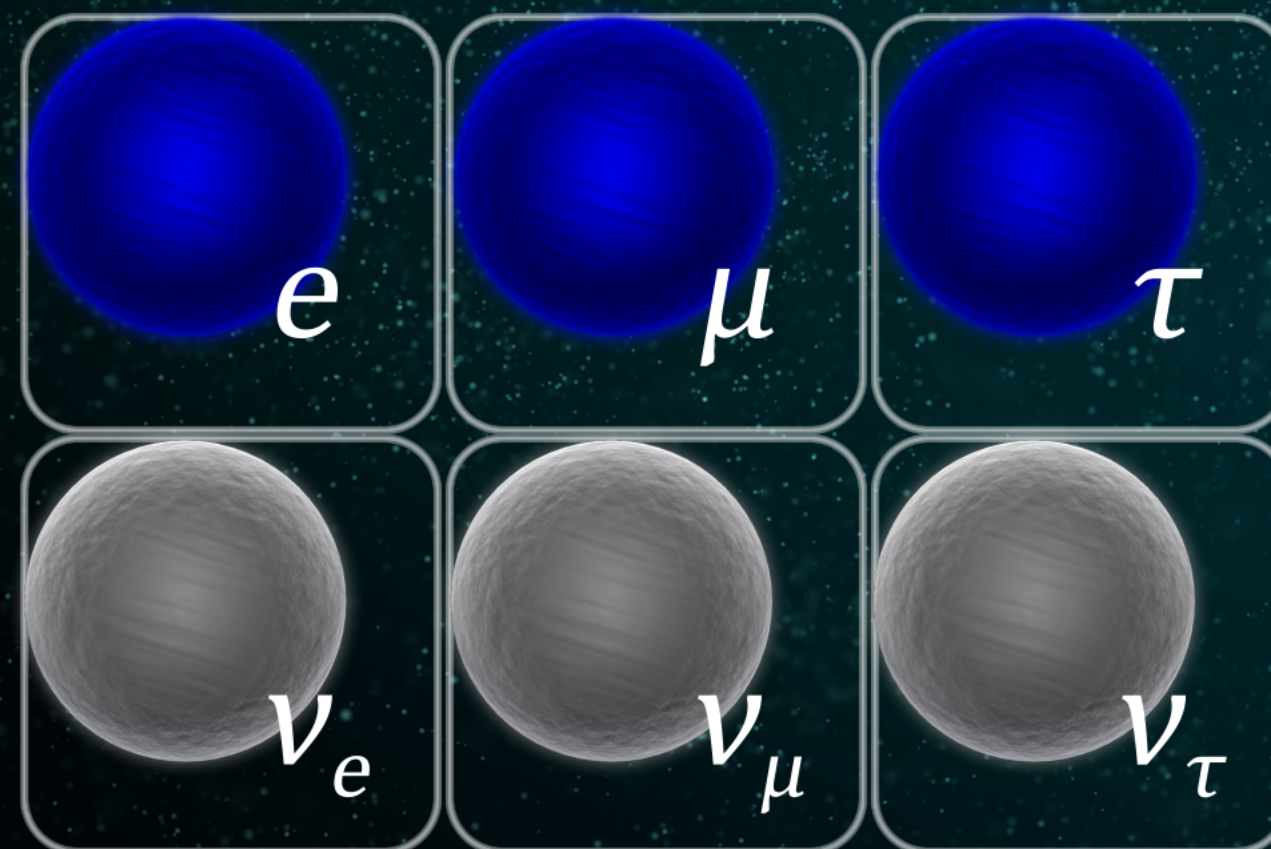
Mass hierarchy



Quarks

CP Violation

Additional particles?

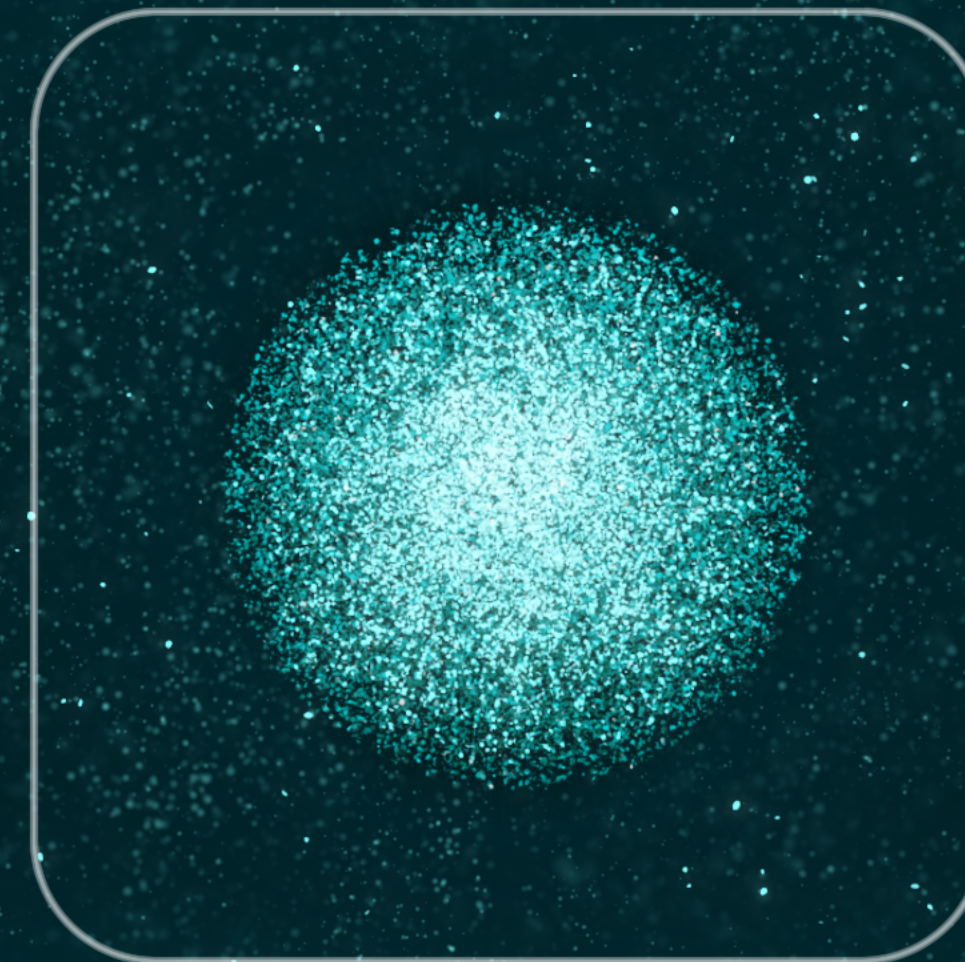


Leptons

Majorana vs. Dirac

Why is neutrino mixing so large?

Composite Higgs?



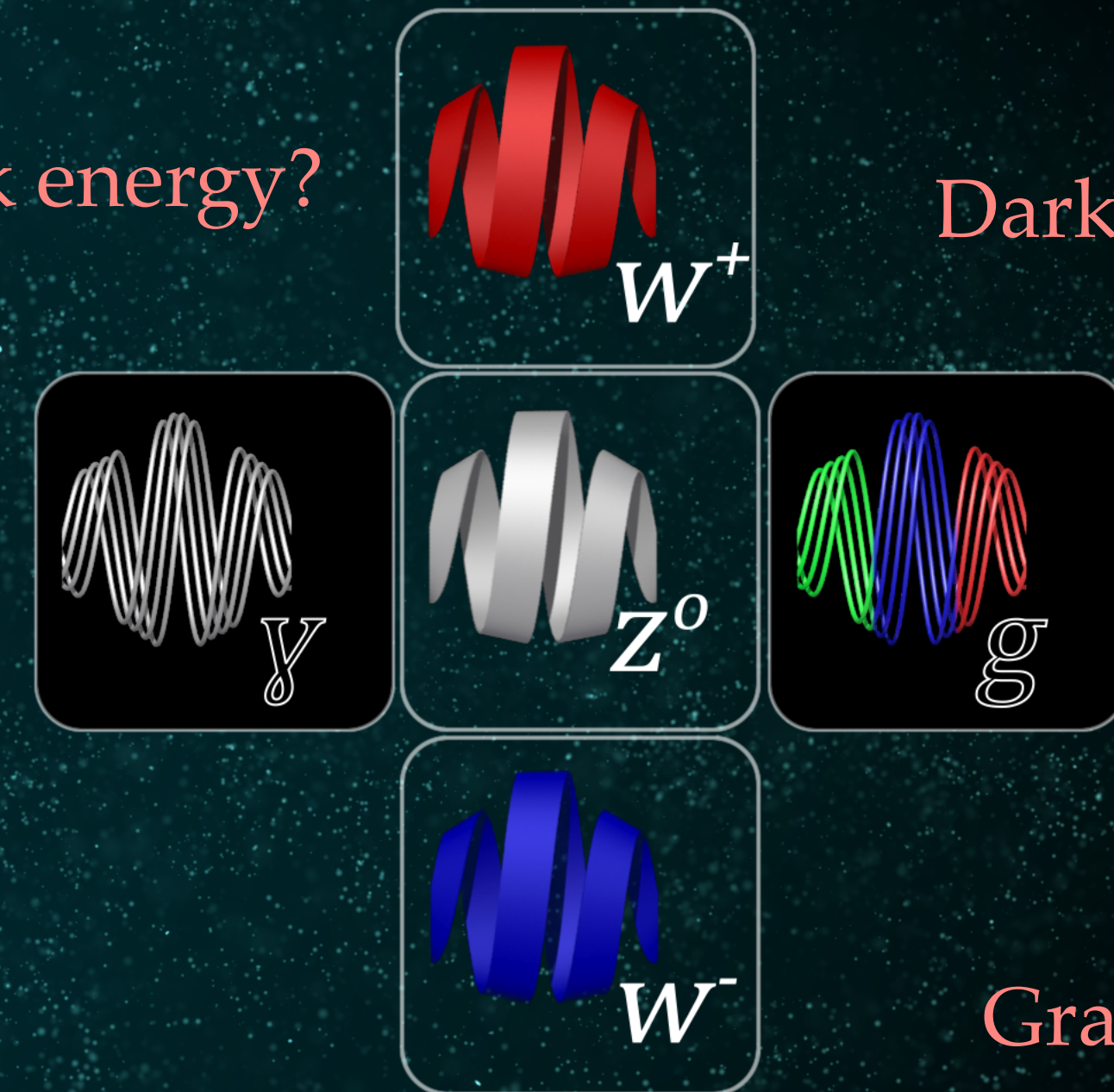
Higgs boson

Who breaks electroweak symmetry?

Why is θ_{13} so small?

Dark energy?

Dark matter?



Forces

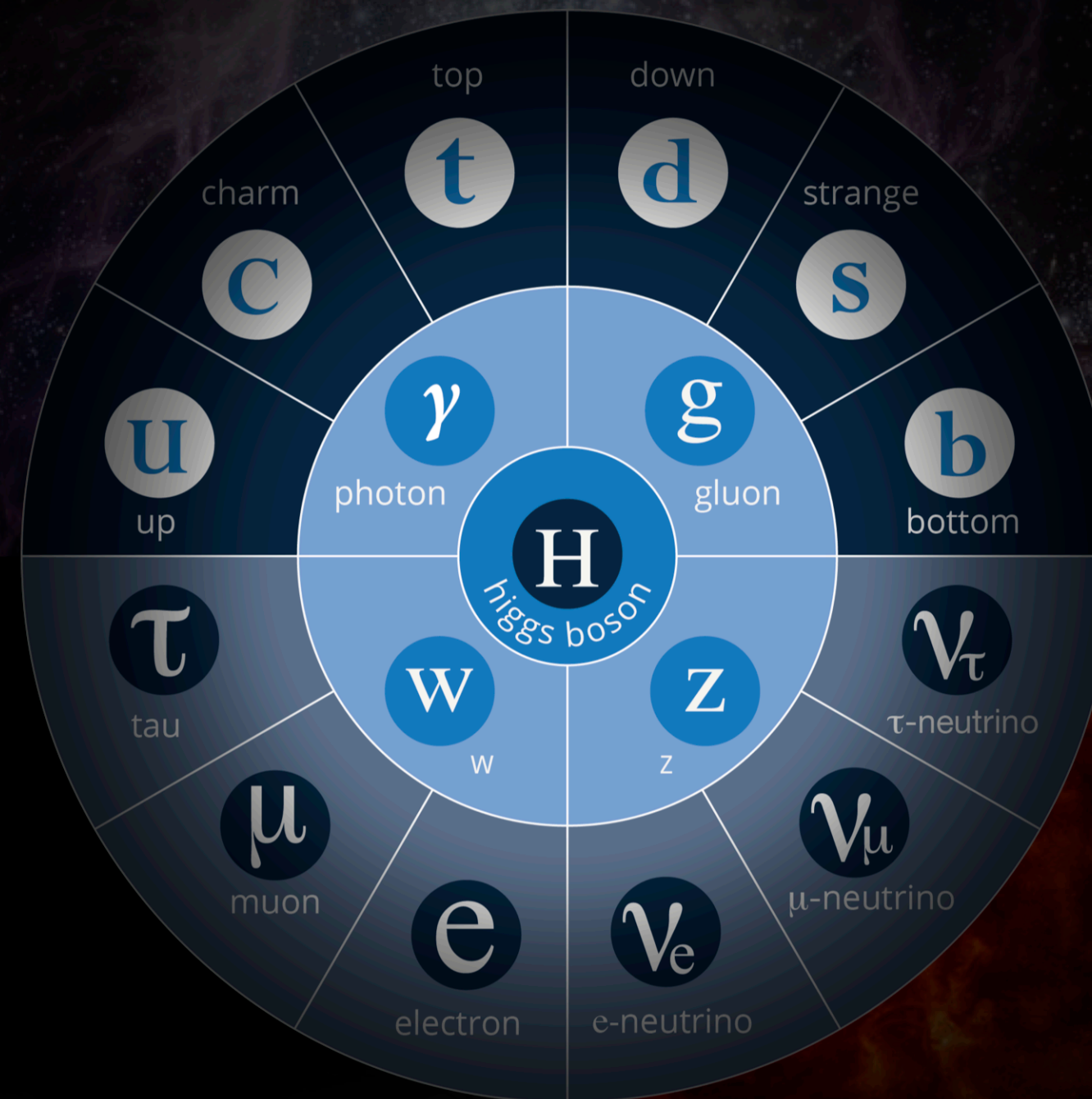
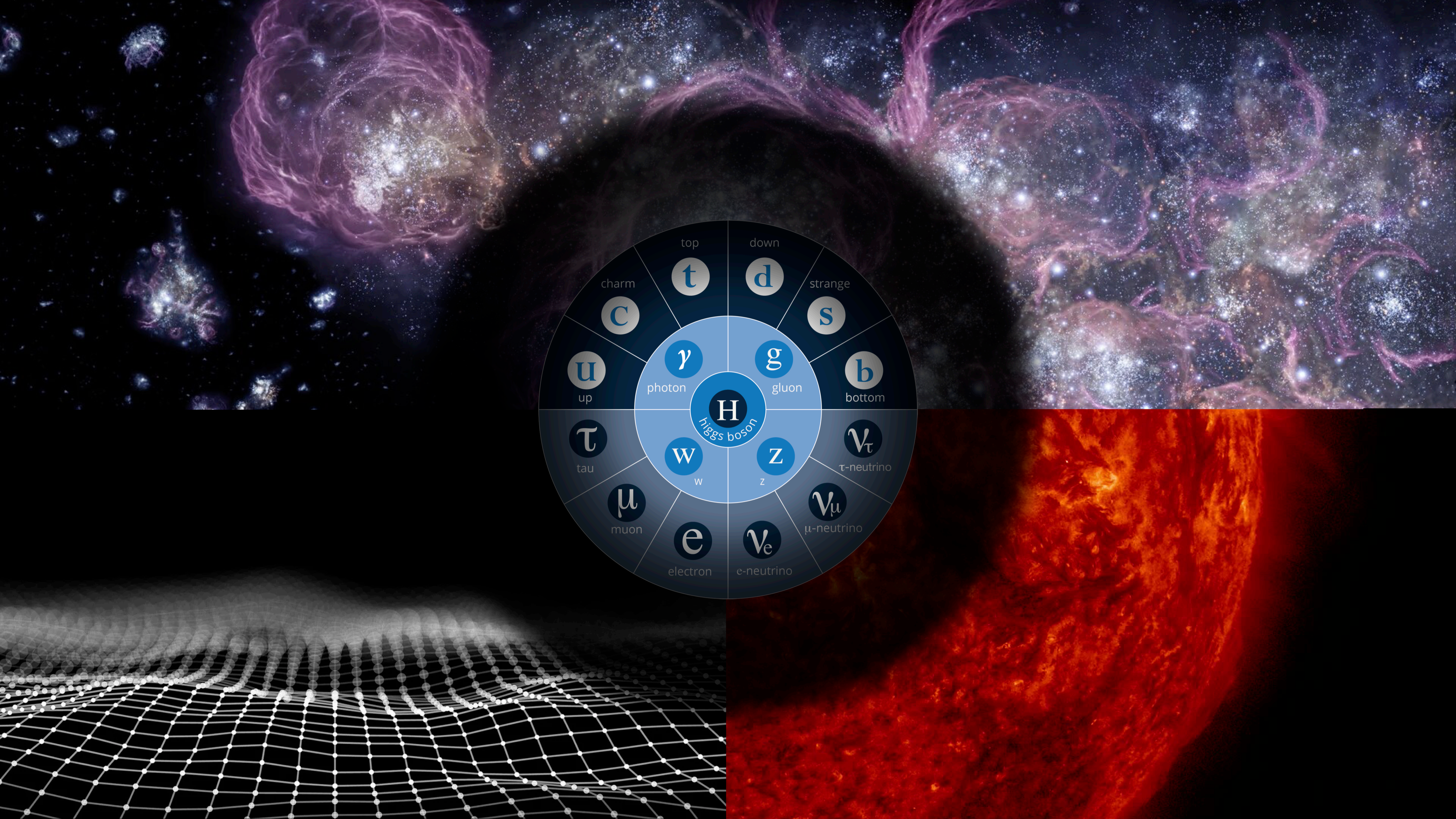
Gravity?

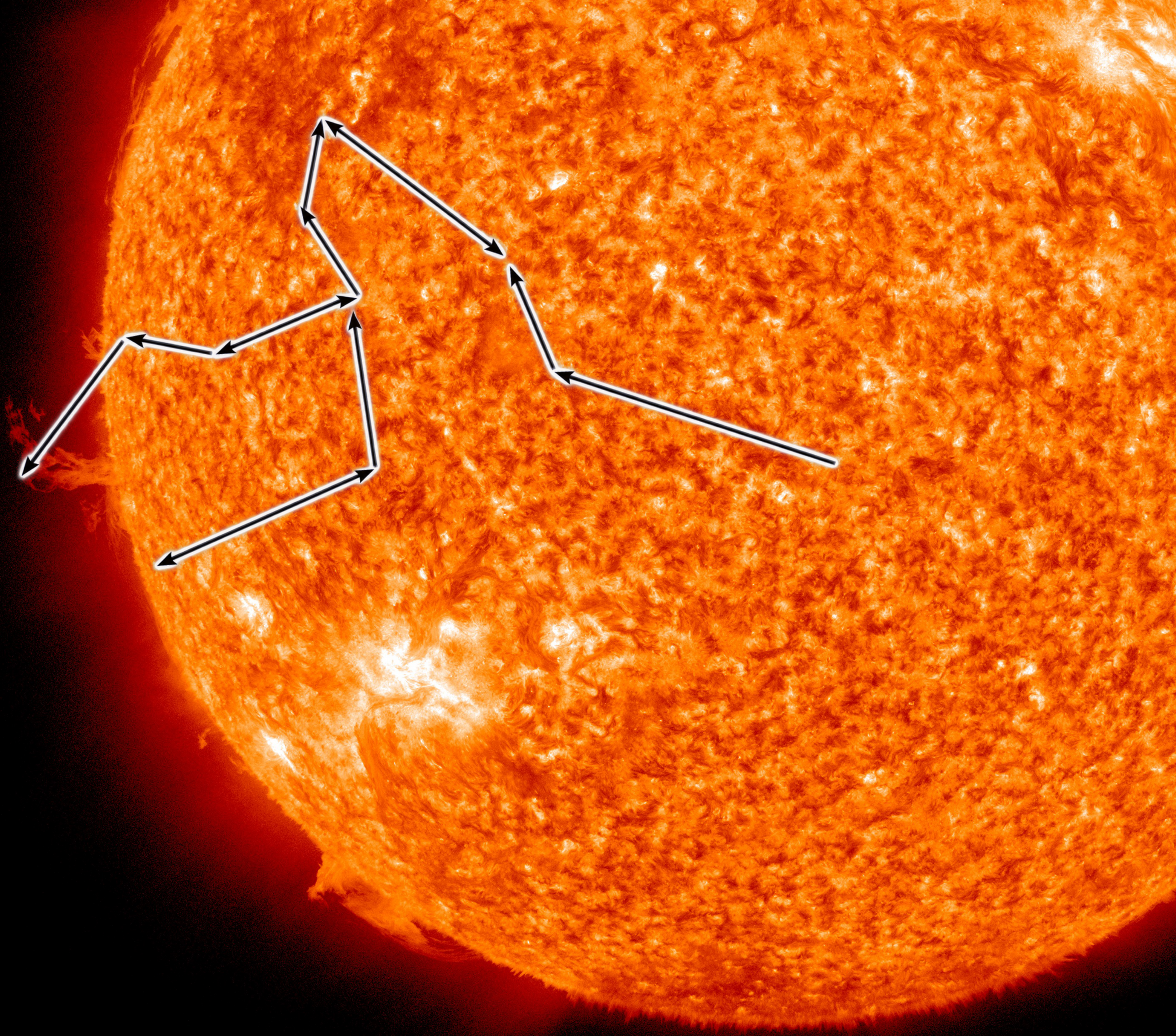
Theories beyond the Standard Model?

Unified forces?



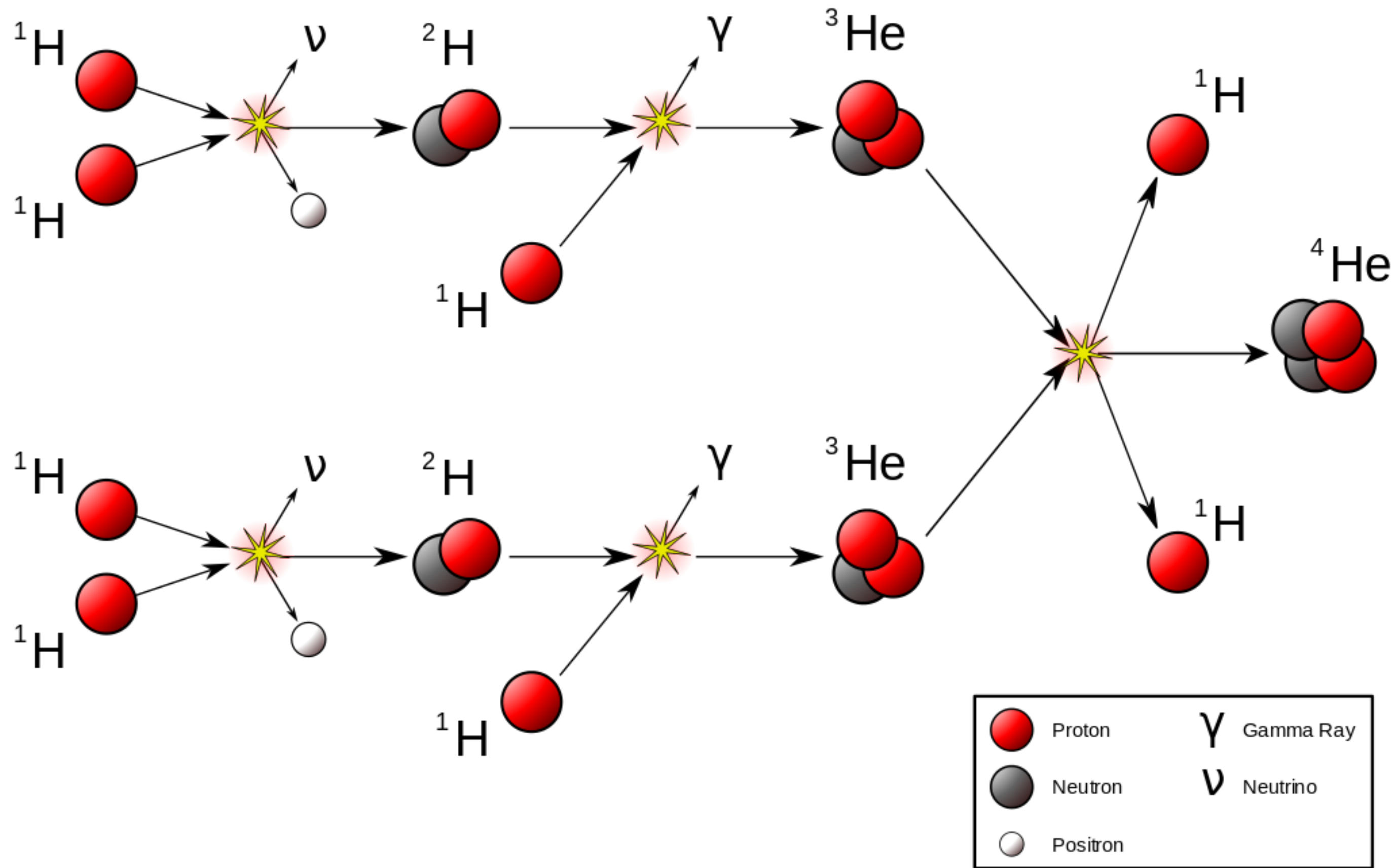
ACCELERATING SCIENCE

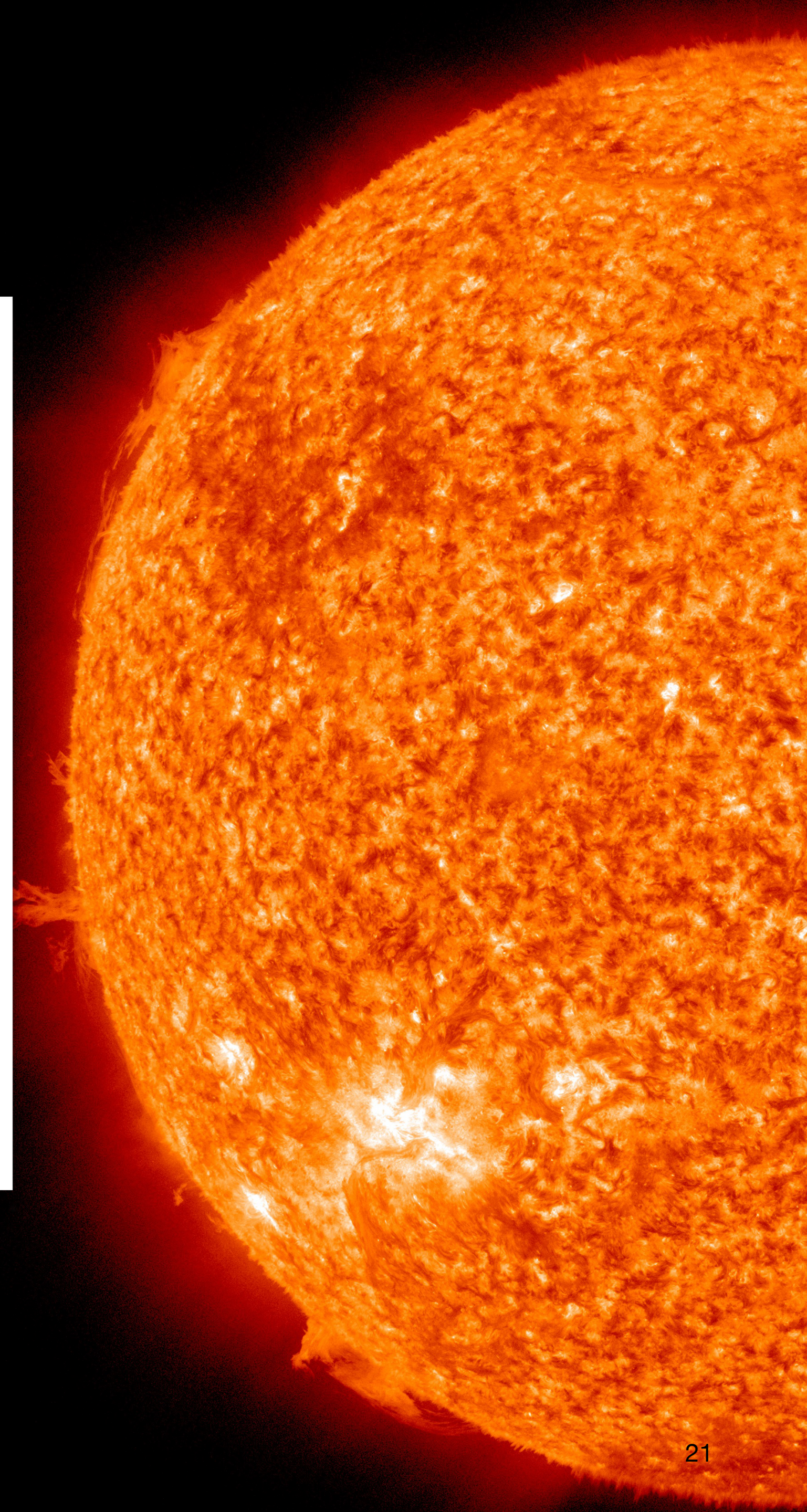
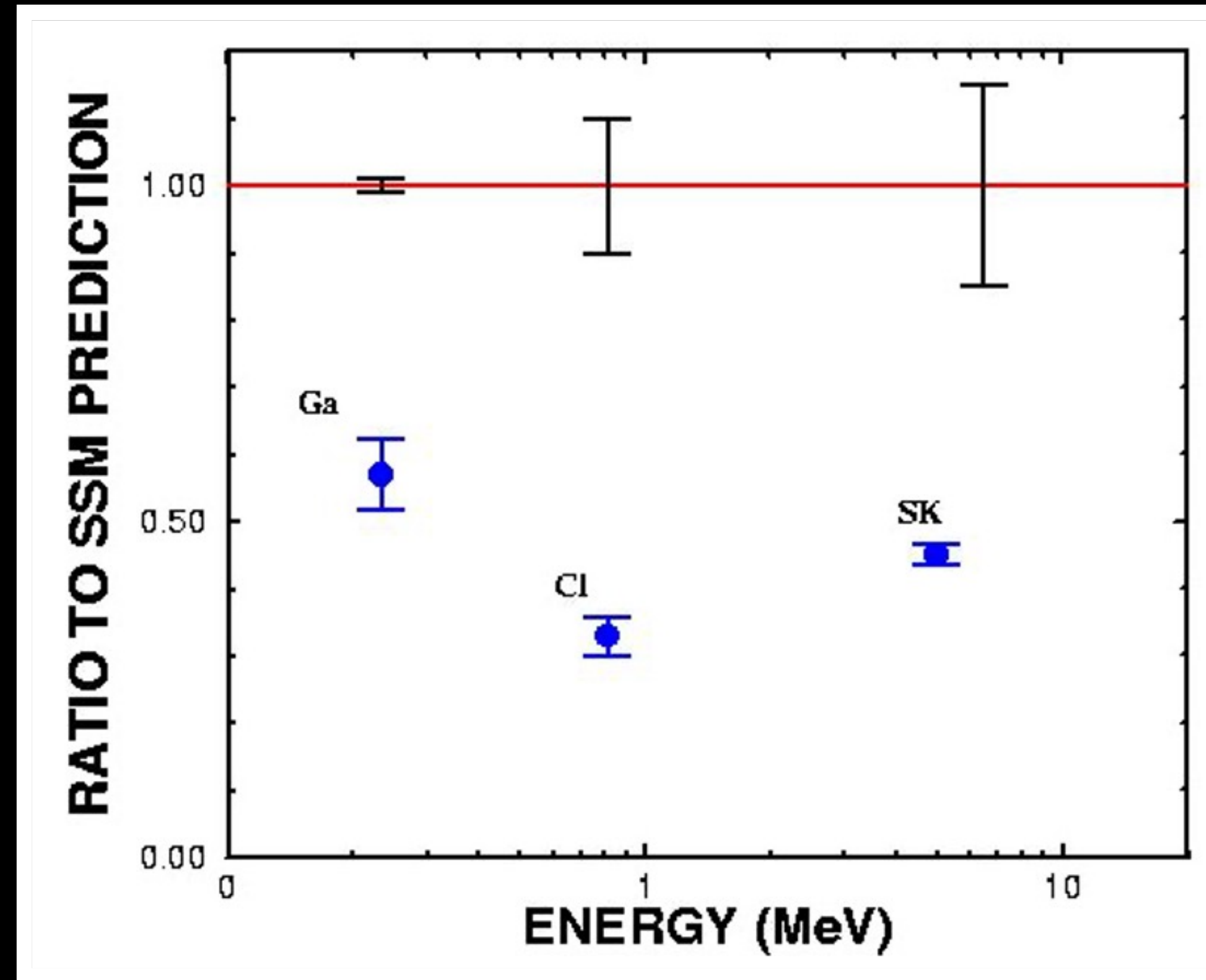
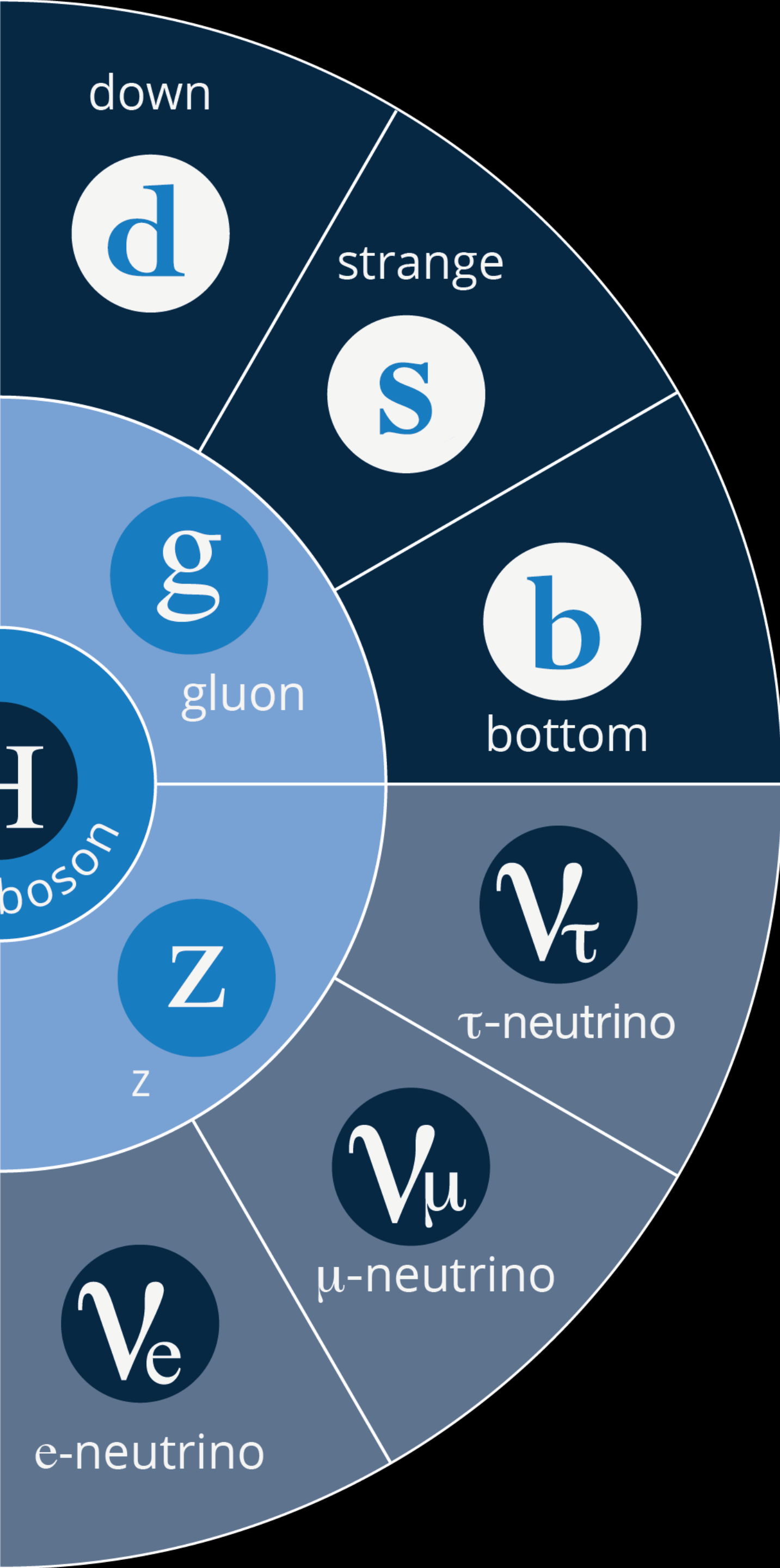


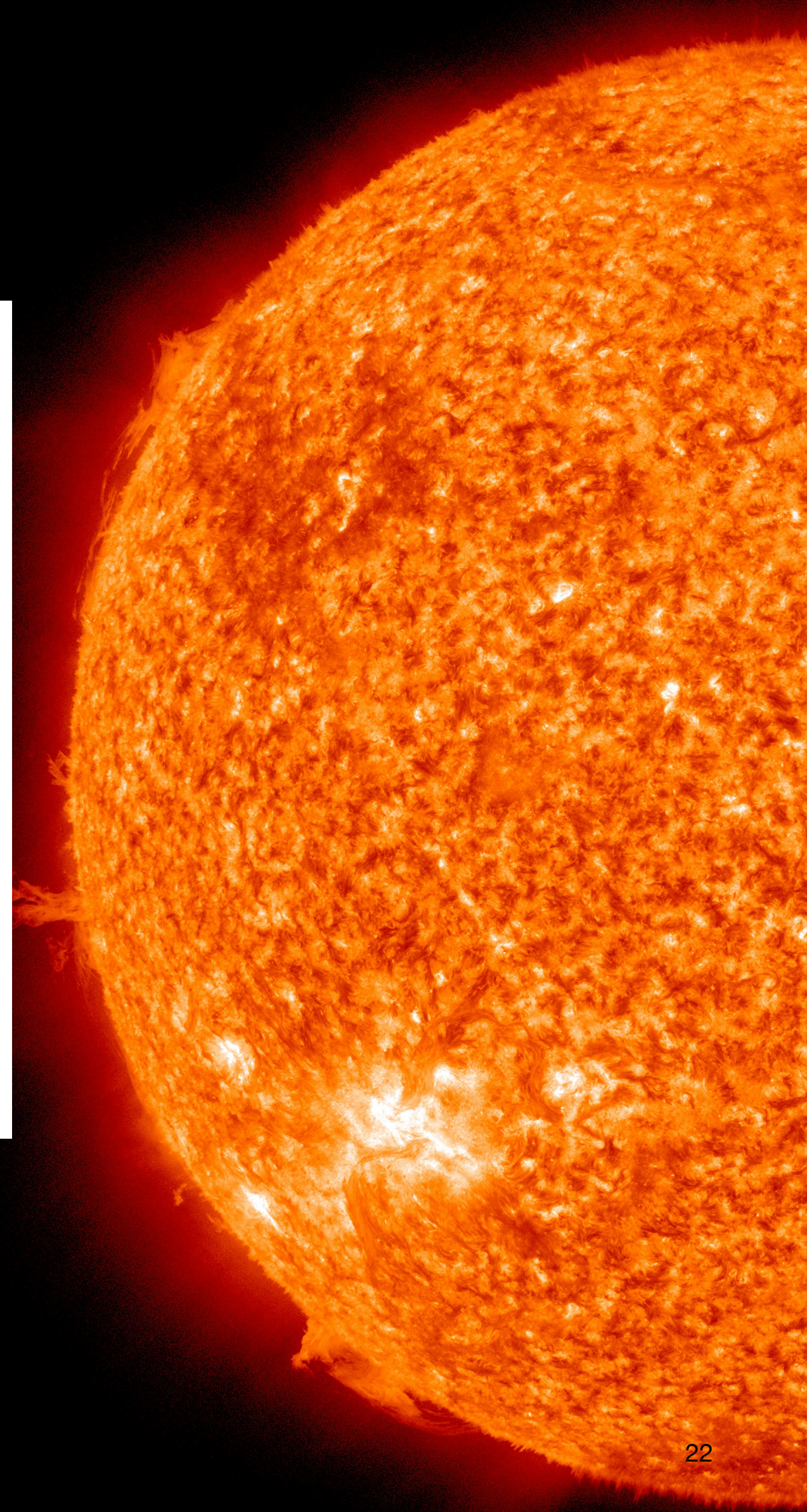
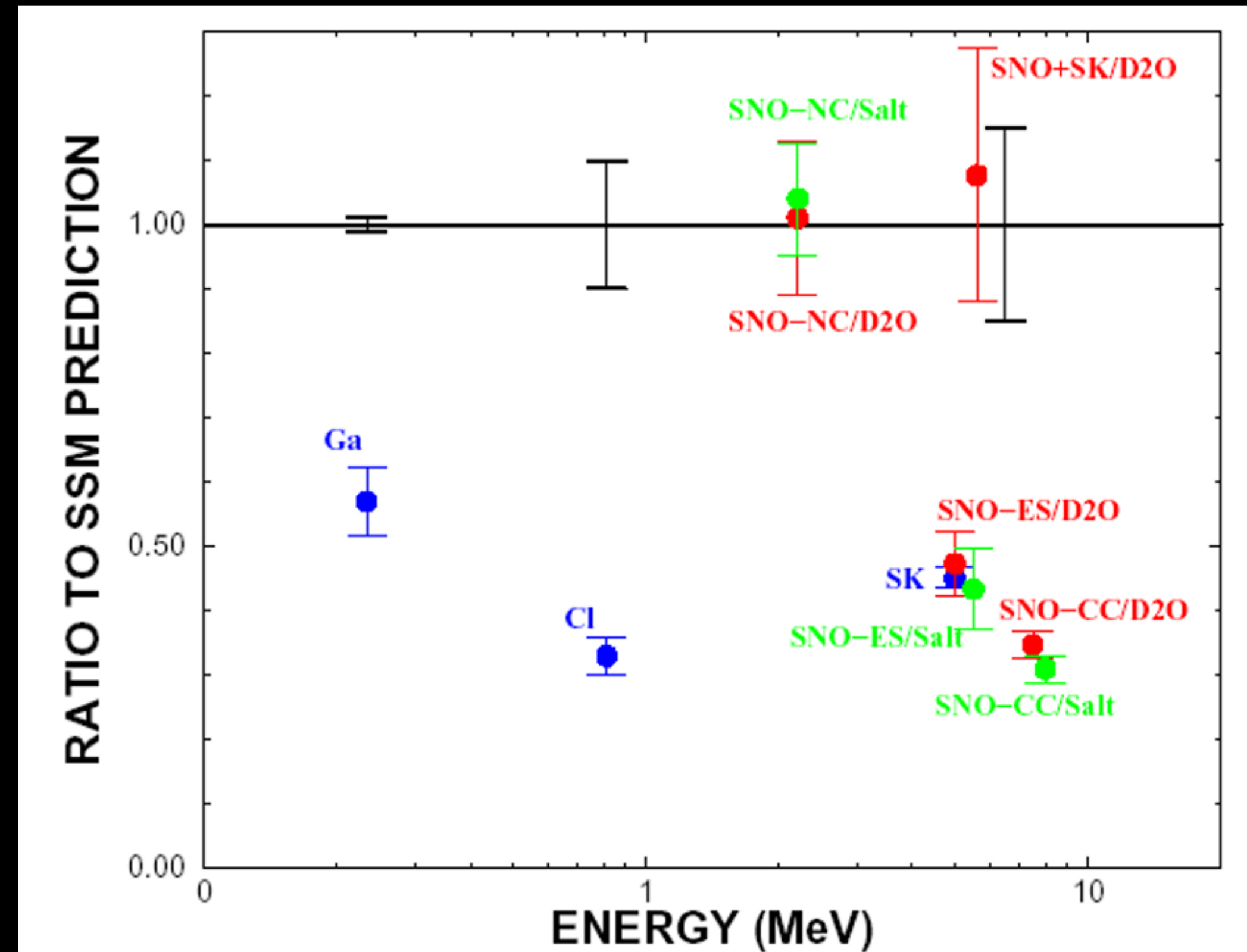
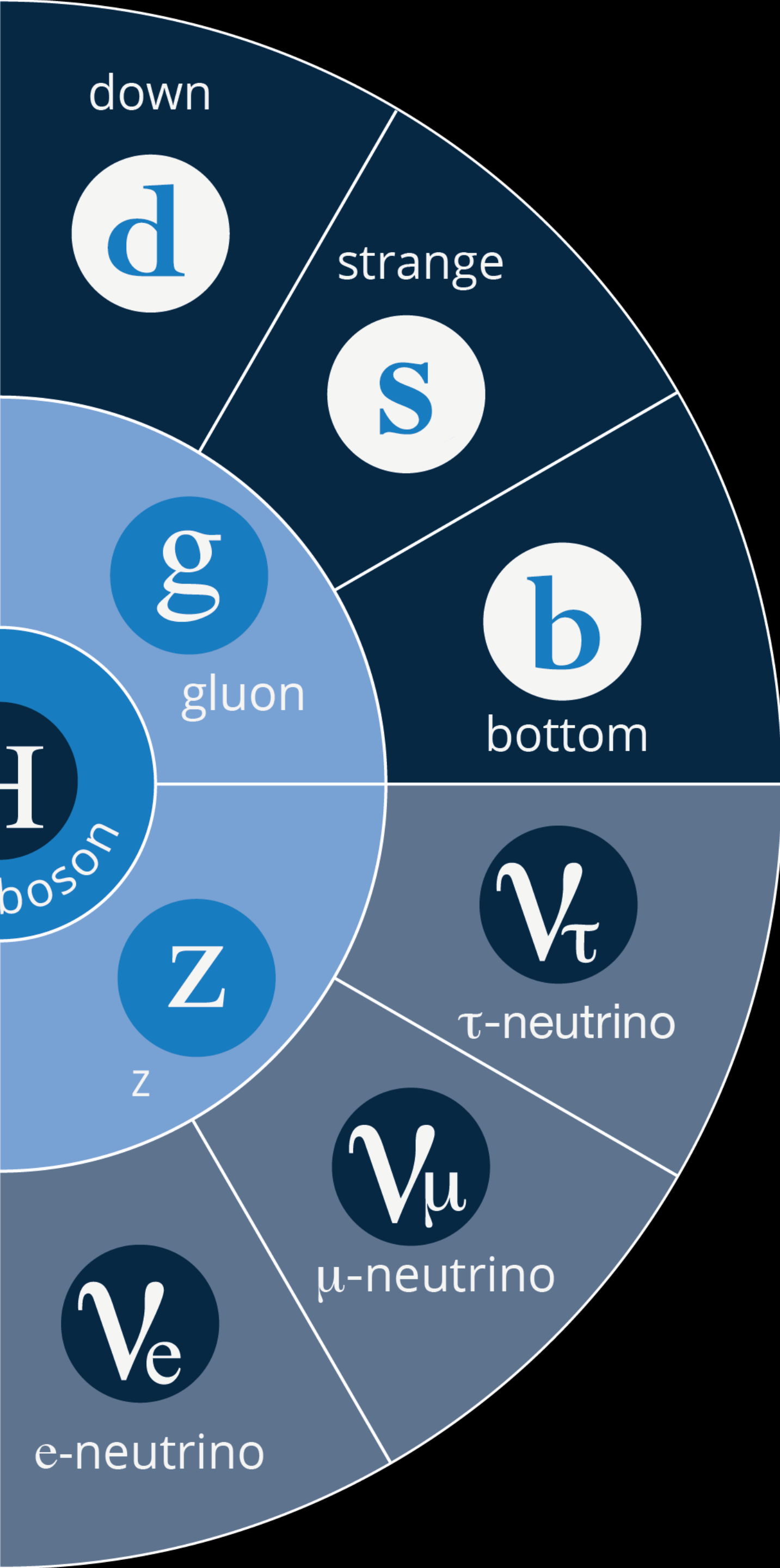


Light needs ~200,000
years to reach the sun's
surface

Use neutrinos!

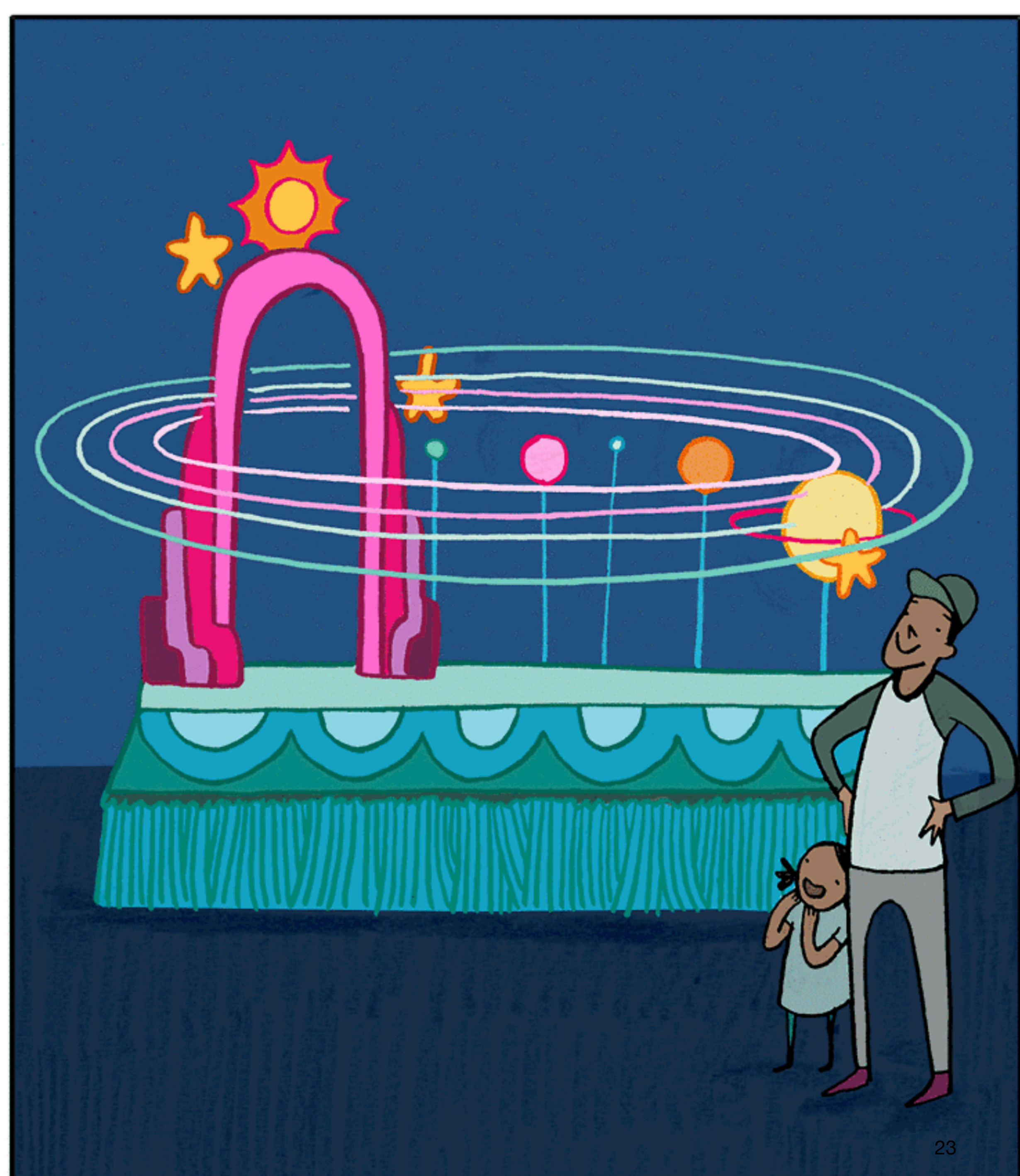








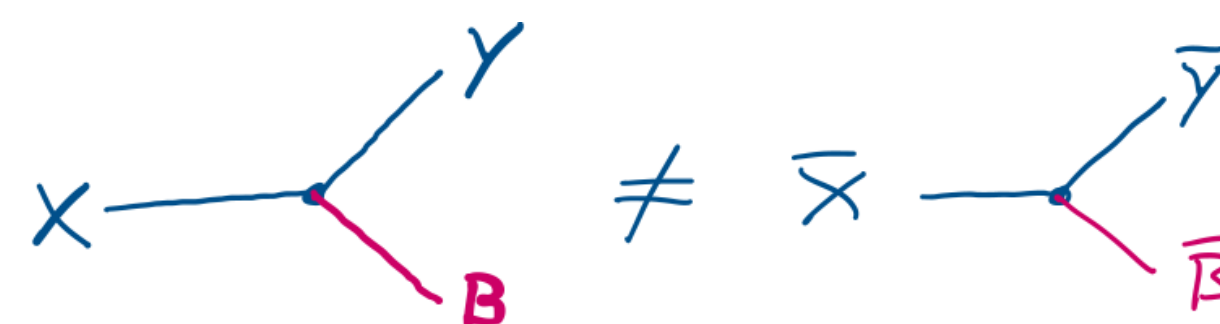
From Symmetry Magazine: Artwork by Sandbox Studio, Chicago with Corinne Mucha



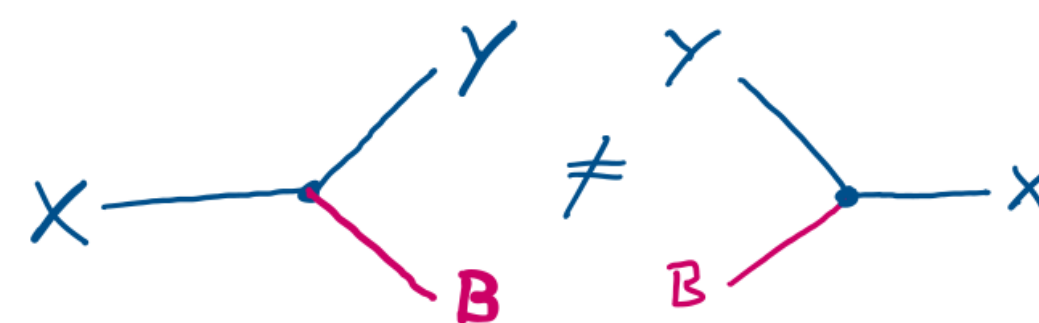
Sakharov Conditions



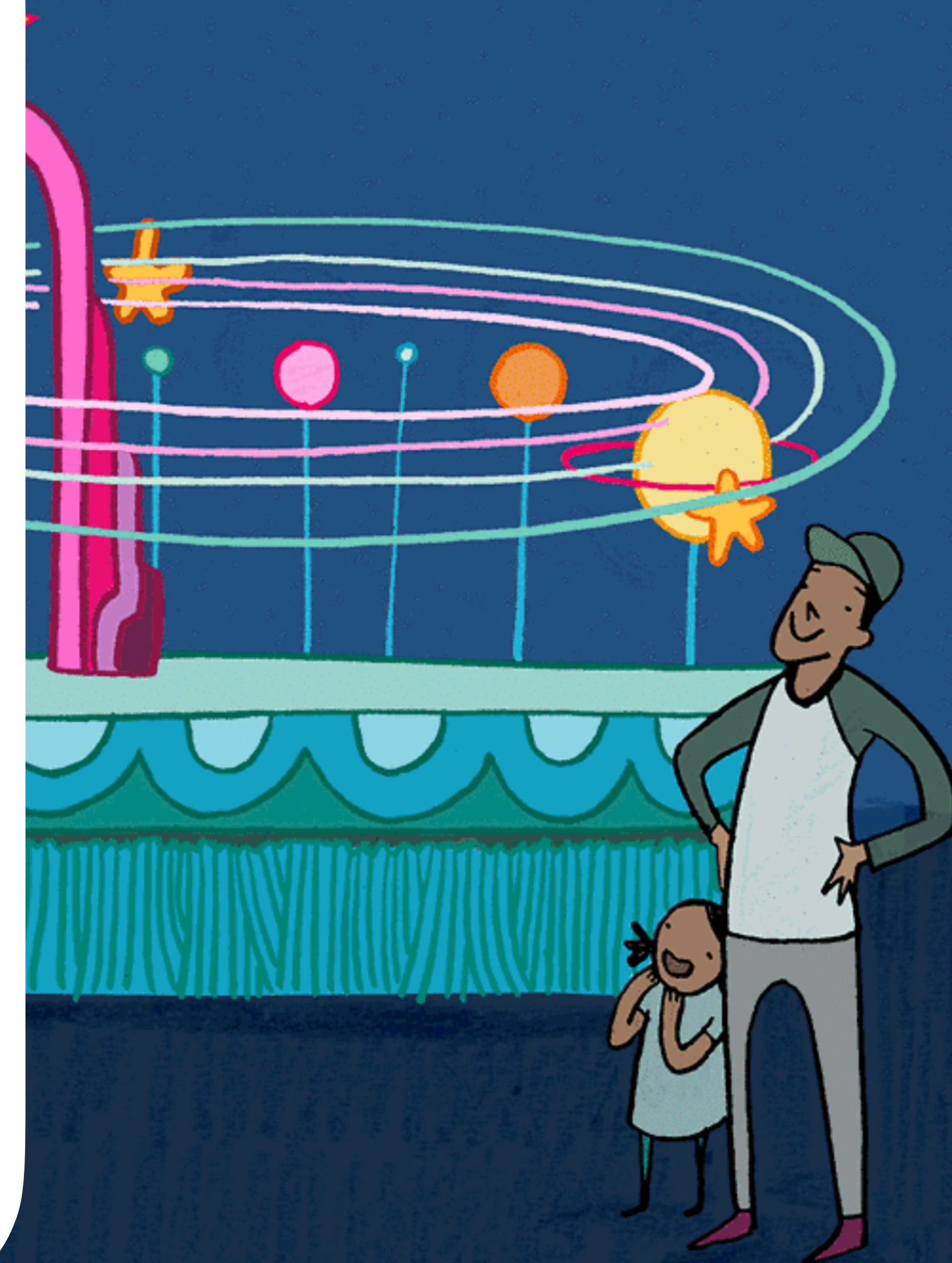
Baryon number violation



C and CP violation



Out of equilibrium



Sakharov Conditions

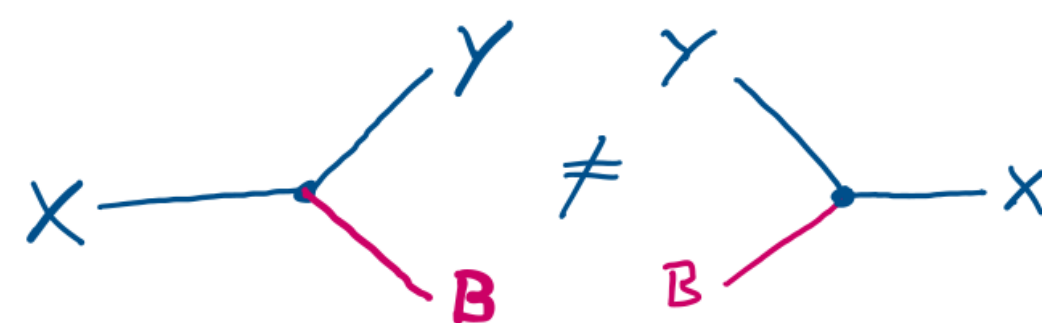


Baryon number violation

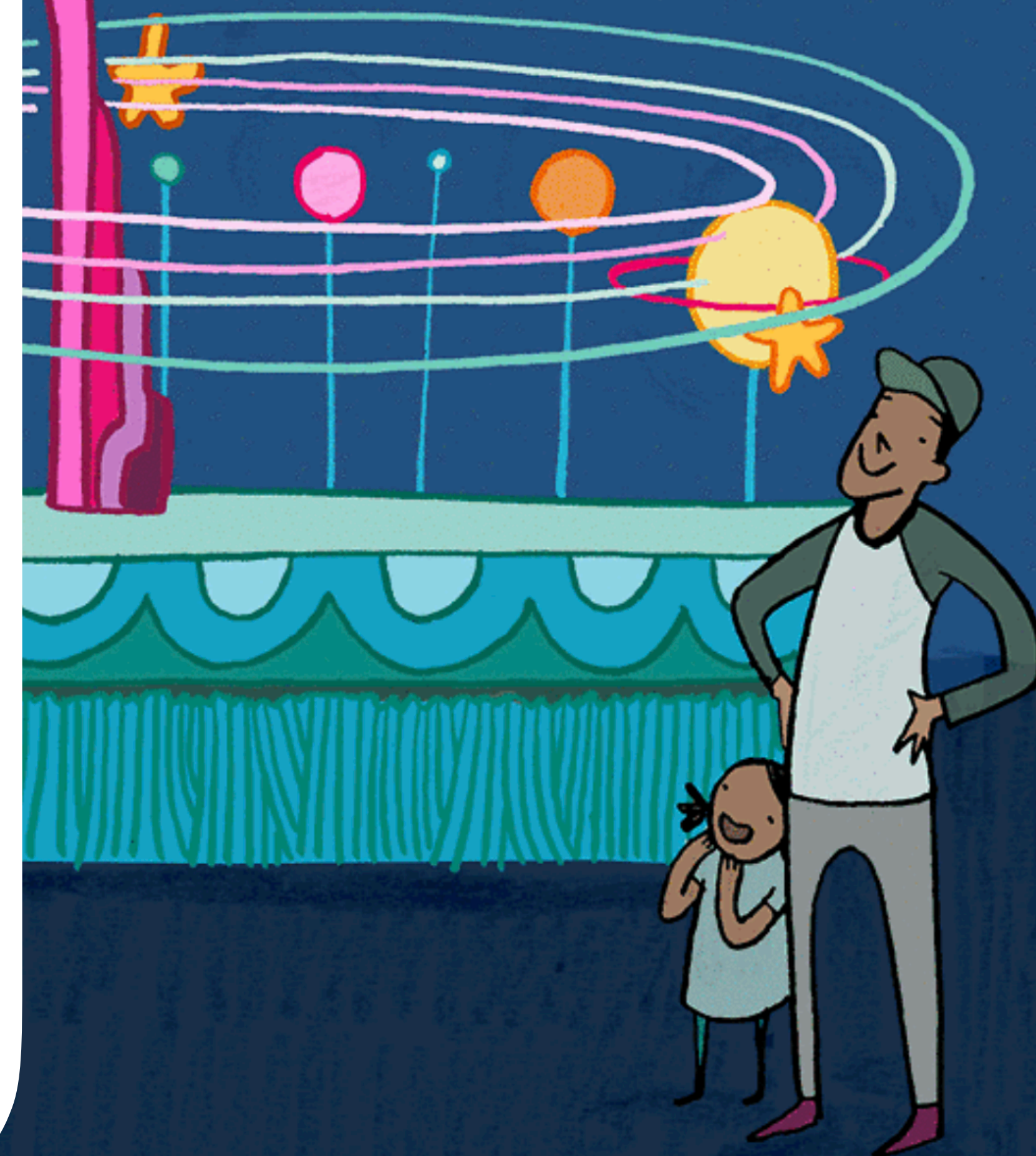
Allowed at high temperatures



C and CP violation



Out of equilibrium



Anti-matter



10,000,000,000

Matter



10,000,000,001

Anti-matter



10,000,000,000

Matter



10,000,000,001

10,000,000,000,000,000,001

Sakharov Conditions



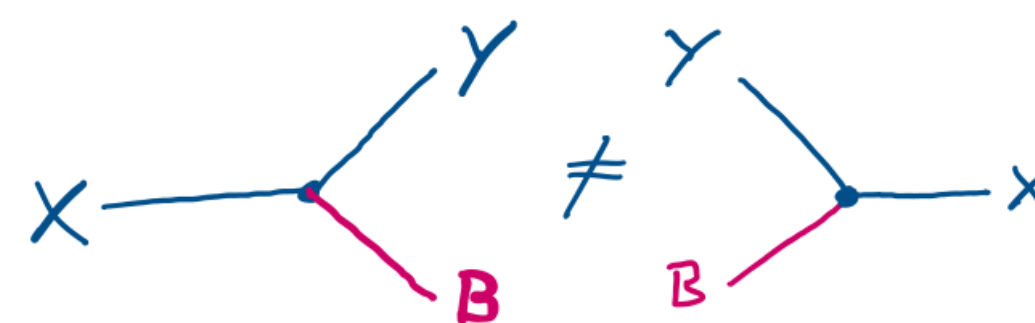
Baryon number violation

Allowed at high temperatures

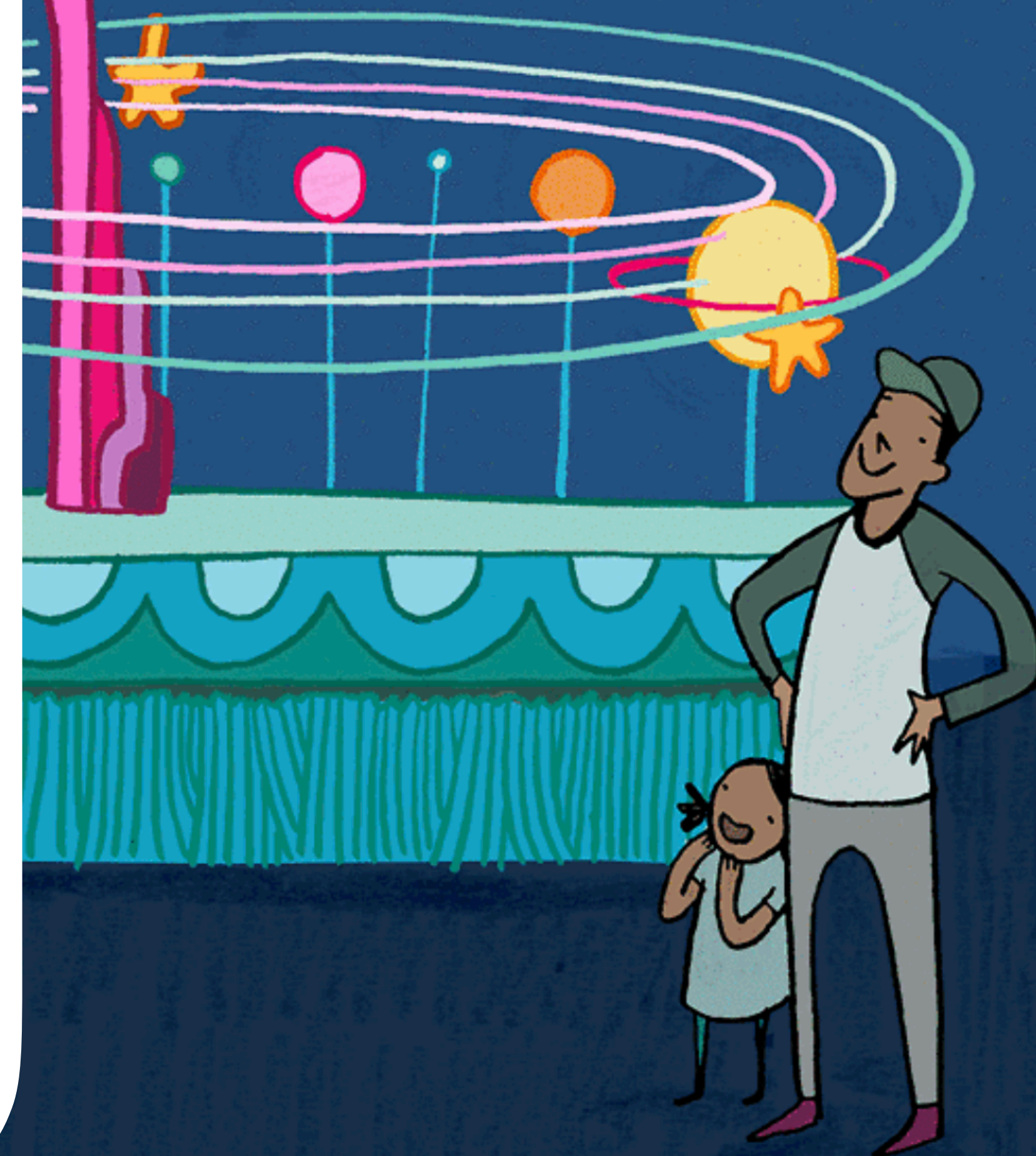


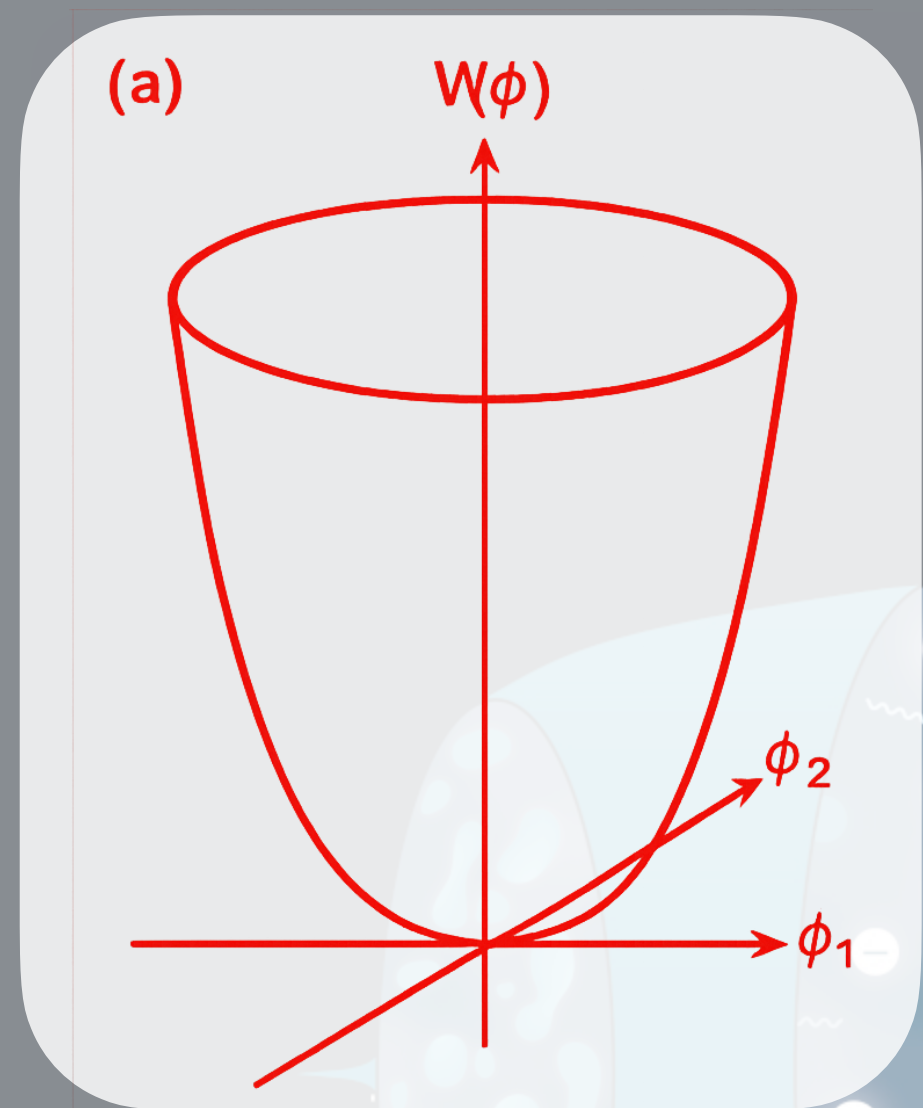
C and CP violation

Off by 8-10 orders of magnitude

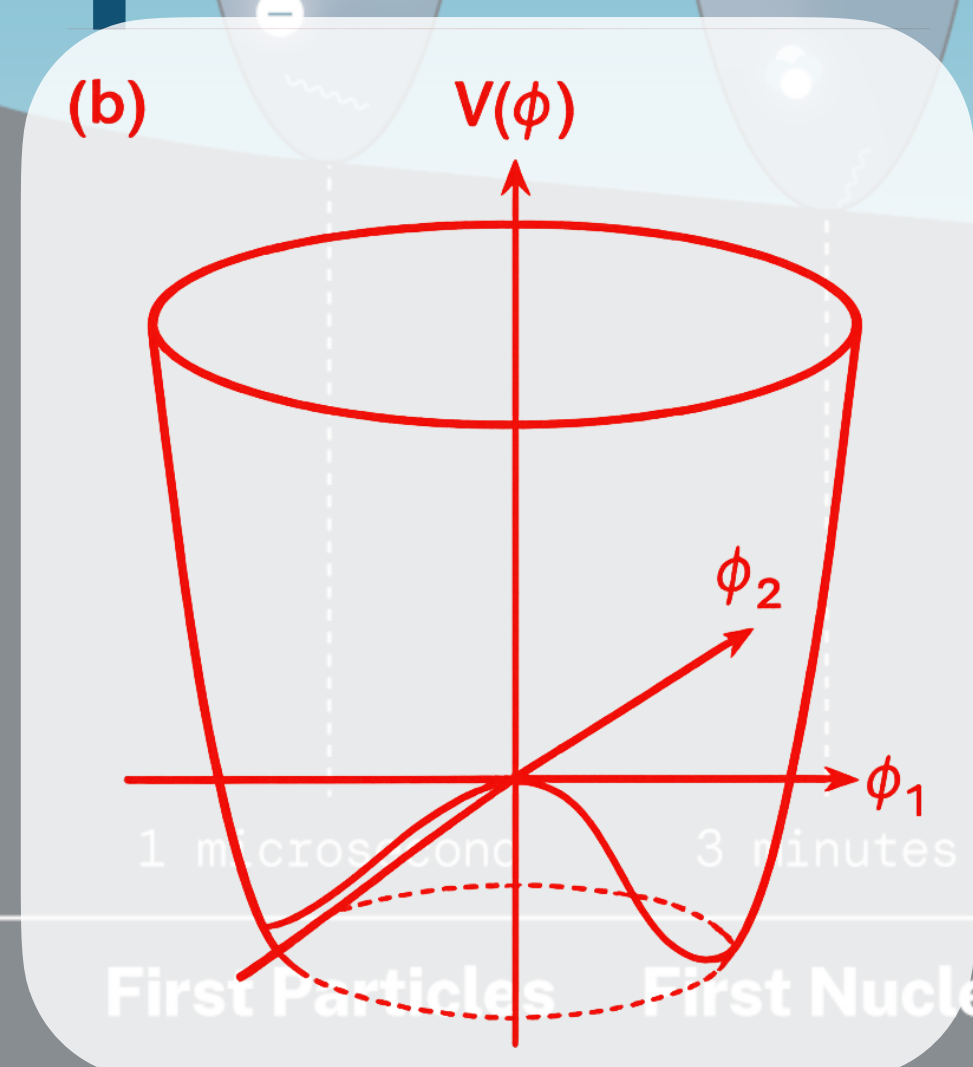


Out of equilibrium





Electroweak symmetry is restored
Higgs vacuum expectation value is zero
W, Z and fermions are effectively massless



The Higgs potential develops a minimum away from zero
The Higgs field chooses one of many equivalent vacuum states (spontaneous symmetry breaking)
W, Z and fermions are massive

10^{-32} seconds

1 microsecond

3 minutes

380,000 years

200 million years

400 million years

10 billion years

13.8 billion years

Inflation

Initial expansion

First Particles

Neutrons, protons, and electrons form

First Nuclei

Helium and hydrogen form

First Light

The first atoms form

First Stars

Gas and dust condense into stars

Galaxies & Dark Matter

Galaxies form in dark matter cradles

Dark Energy

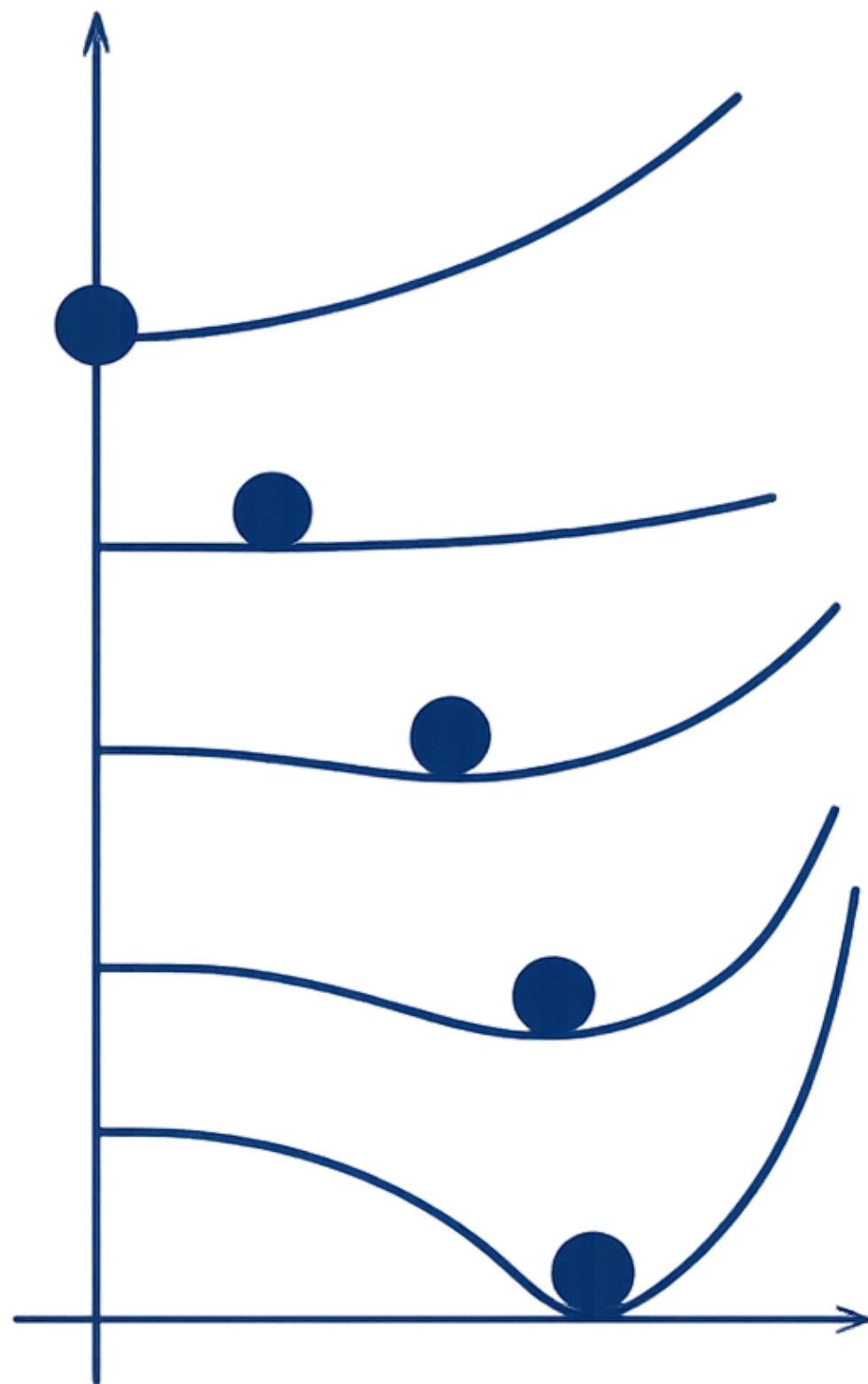
Expansion accelerates

Today

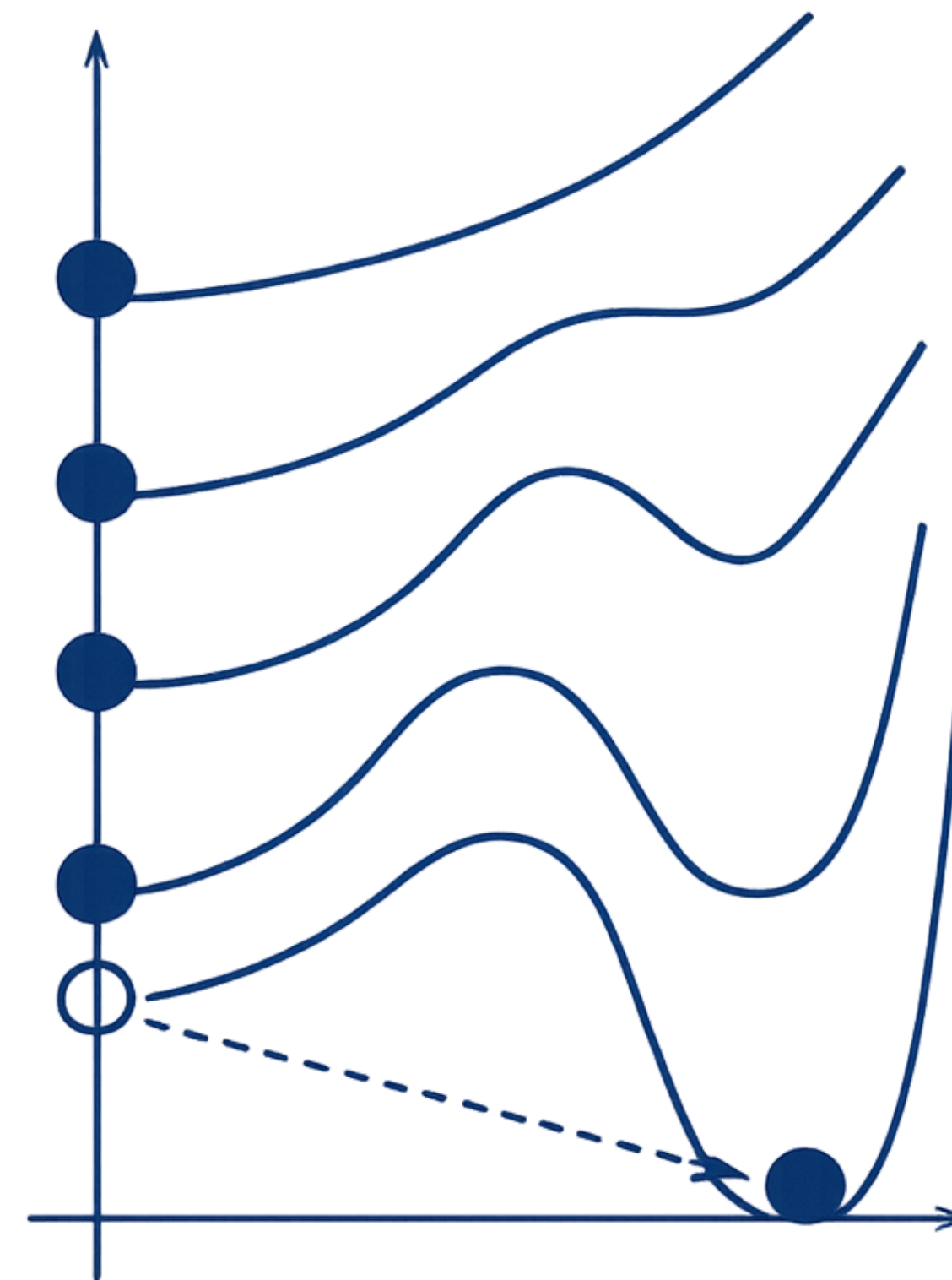
Humans observe the universe

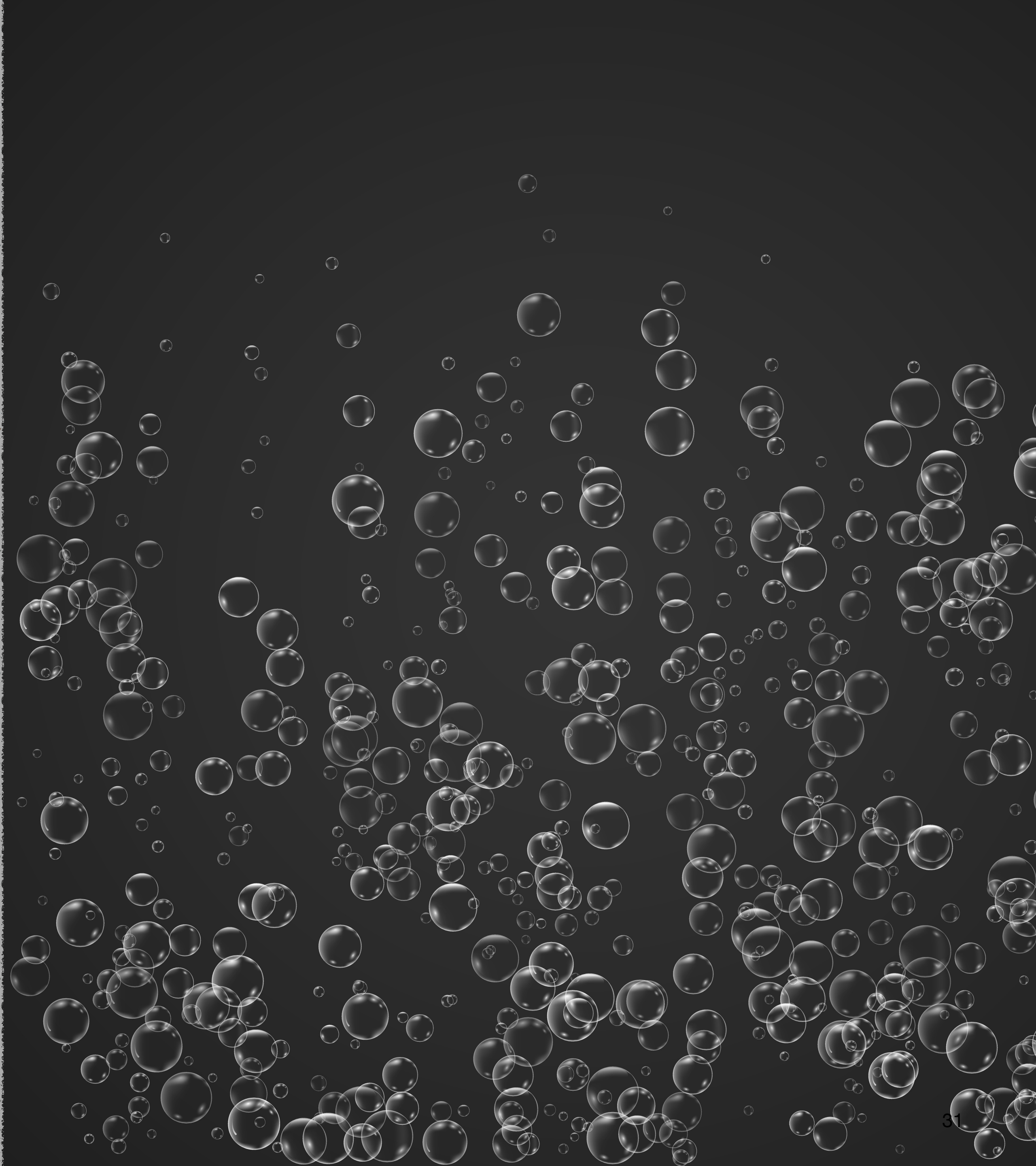
Two ways to break the symmetry

Crossover transition

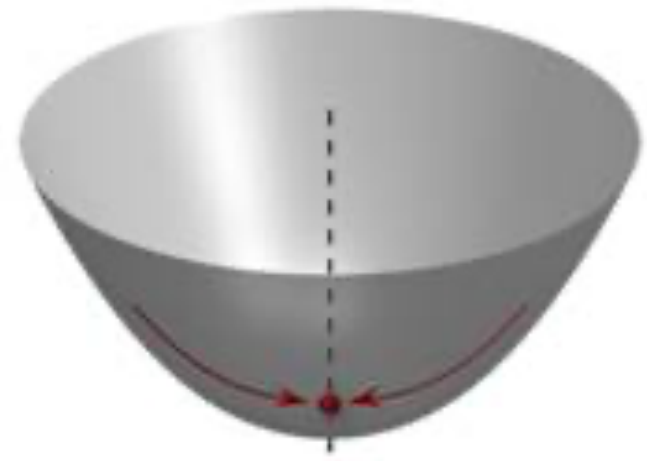


First order



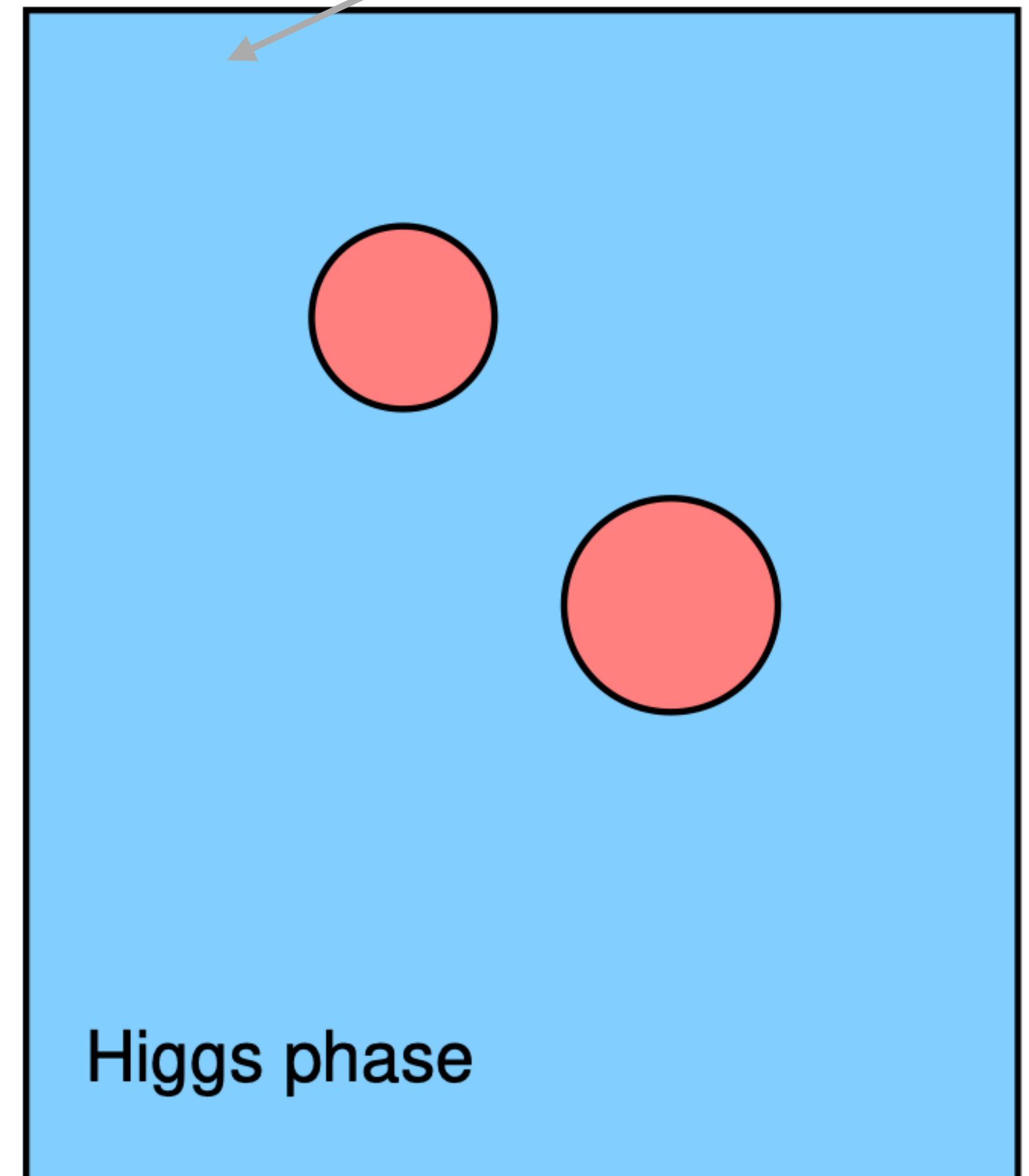
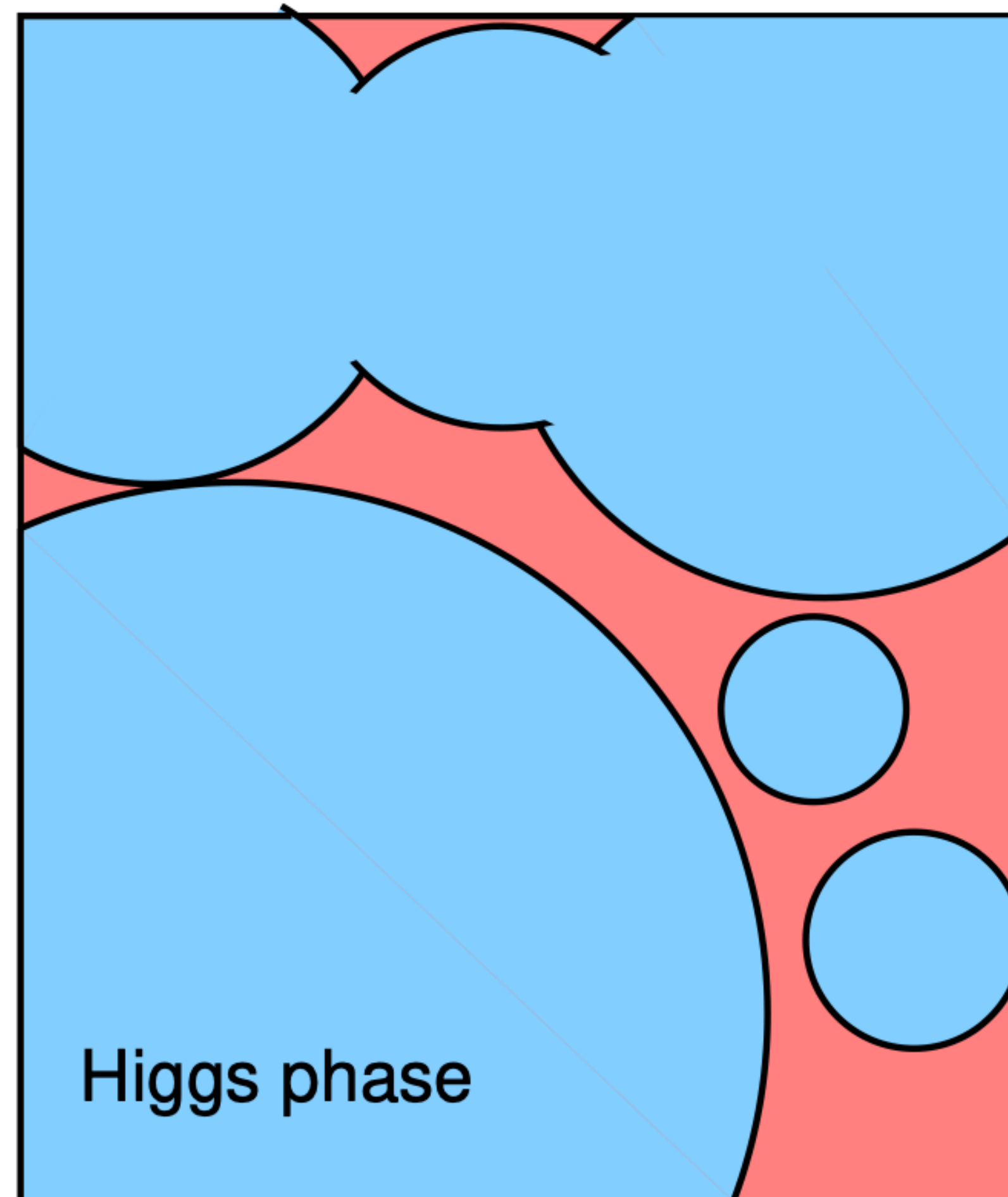
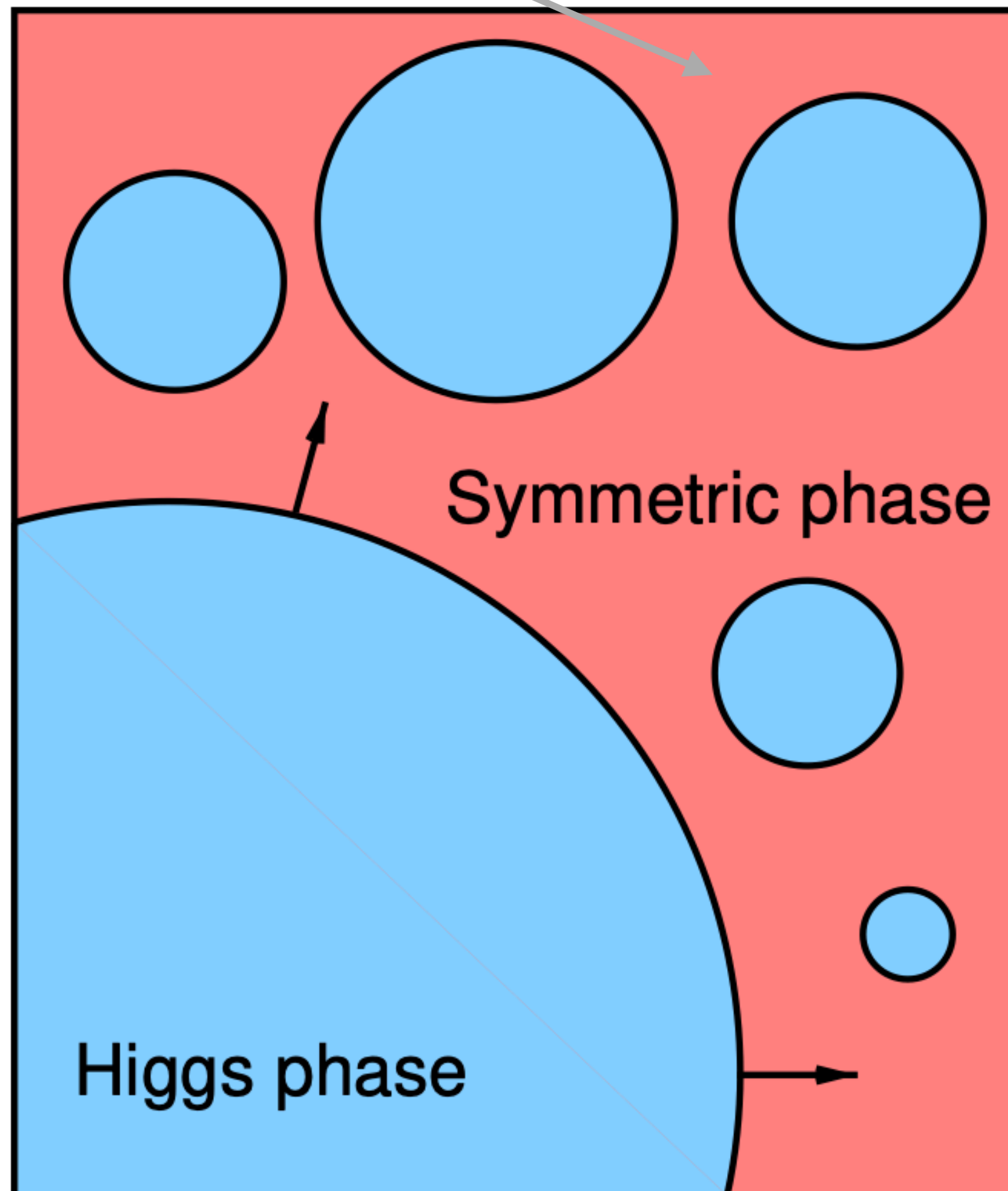
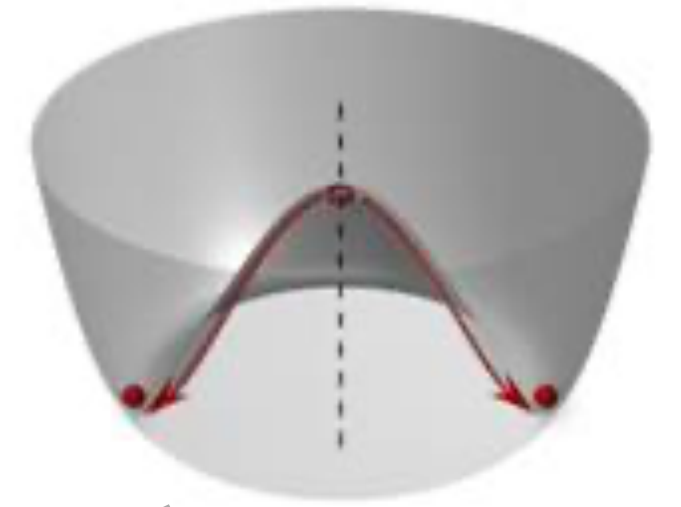


Unbroken Symmetry

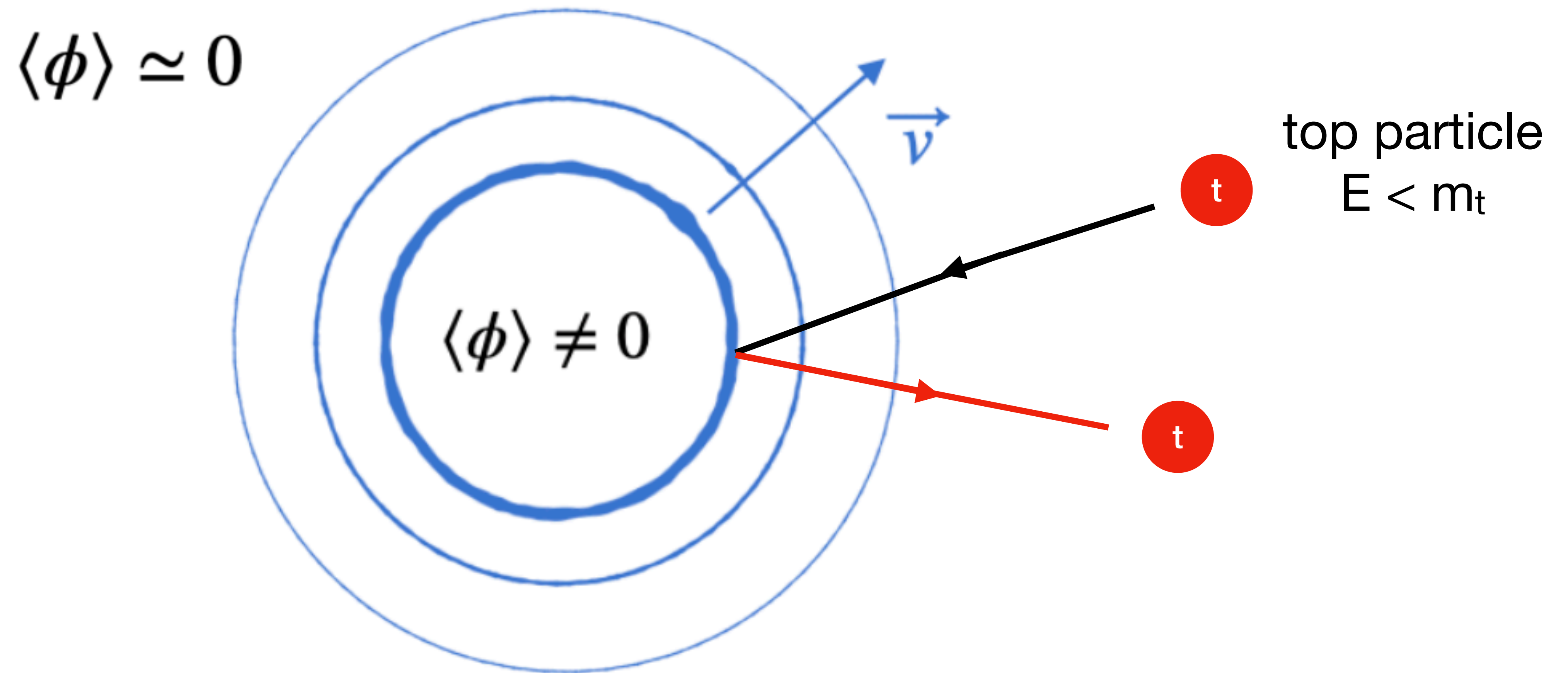


The boiling universe

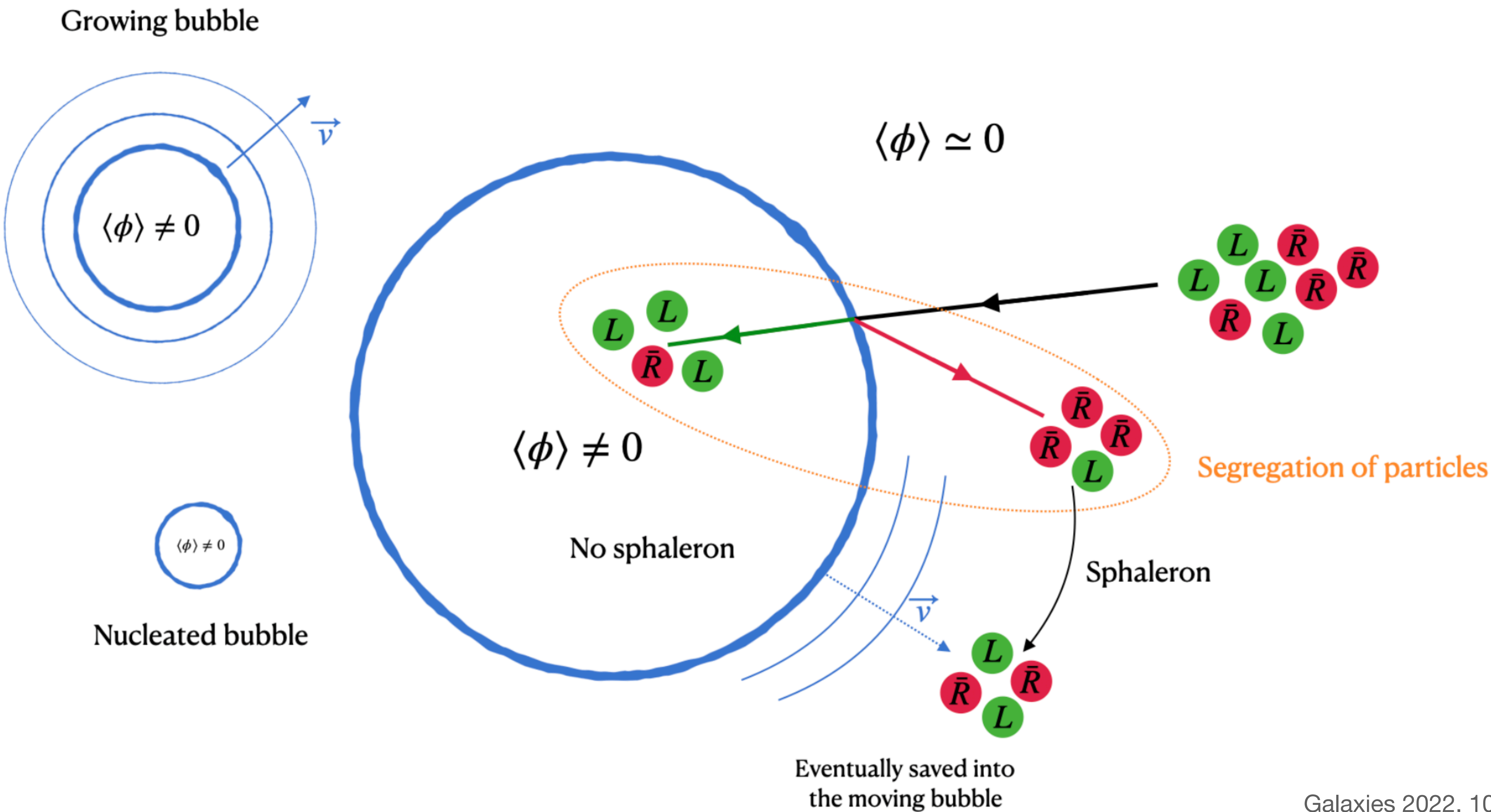
Broken Symmetry

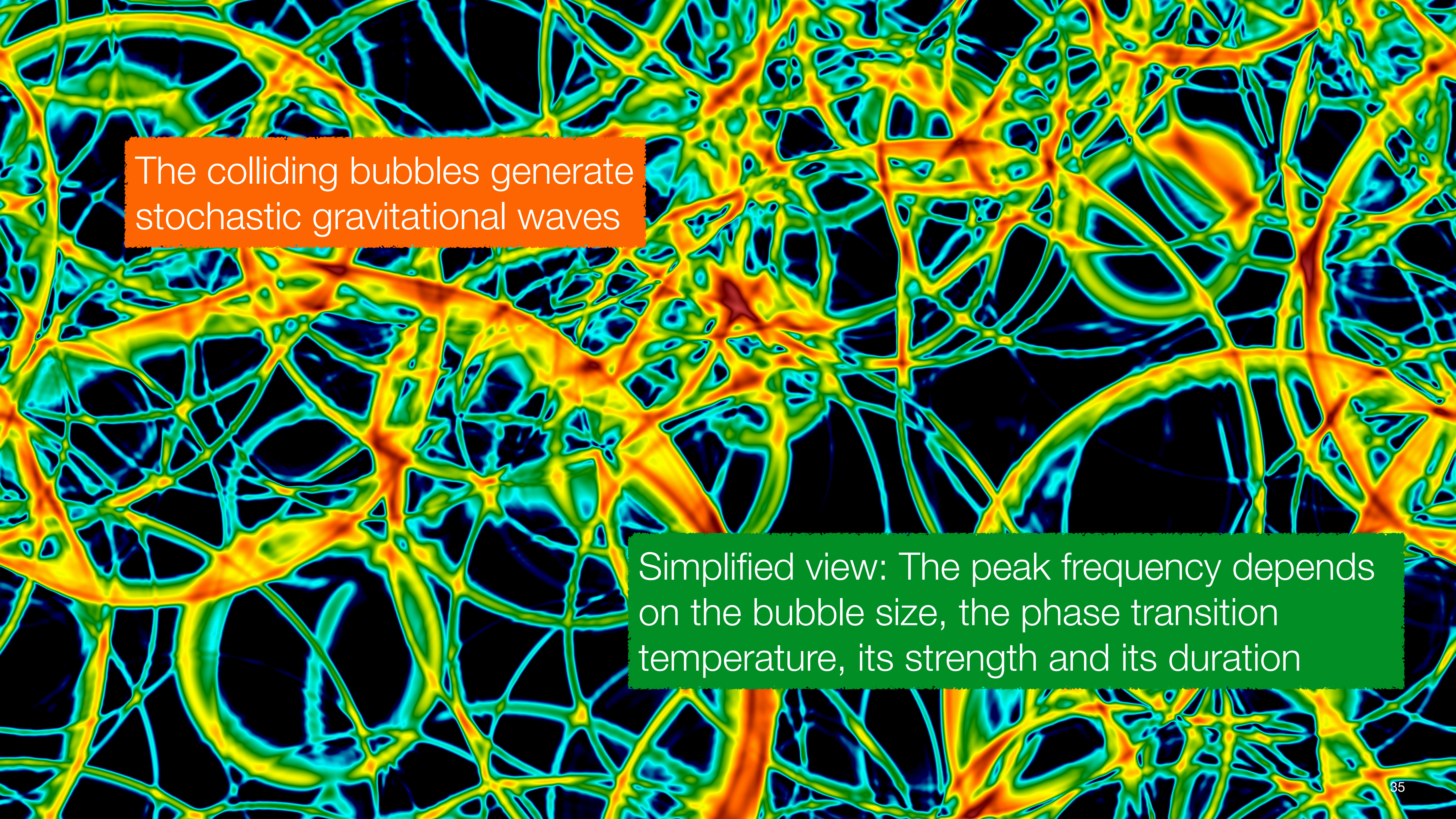


Generating matter/anti-matter differences



Generating matter/anti-matter differences

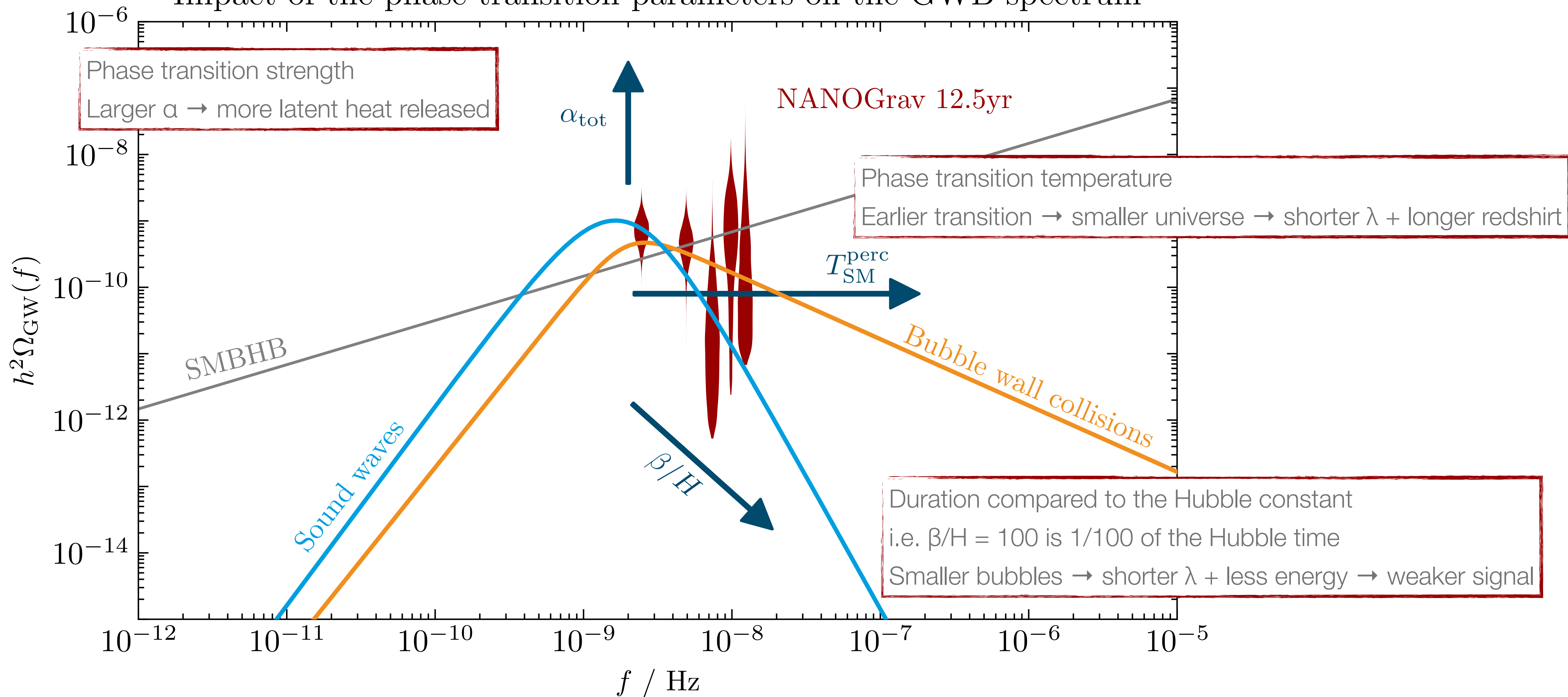


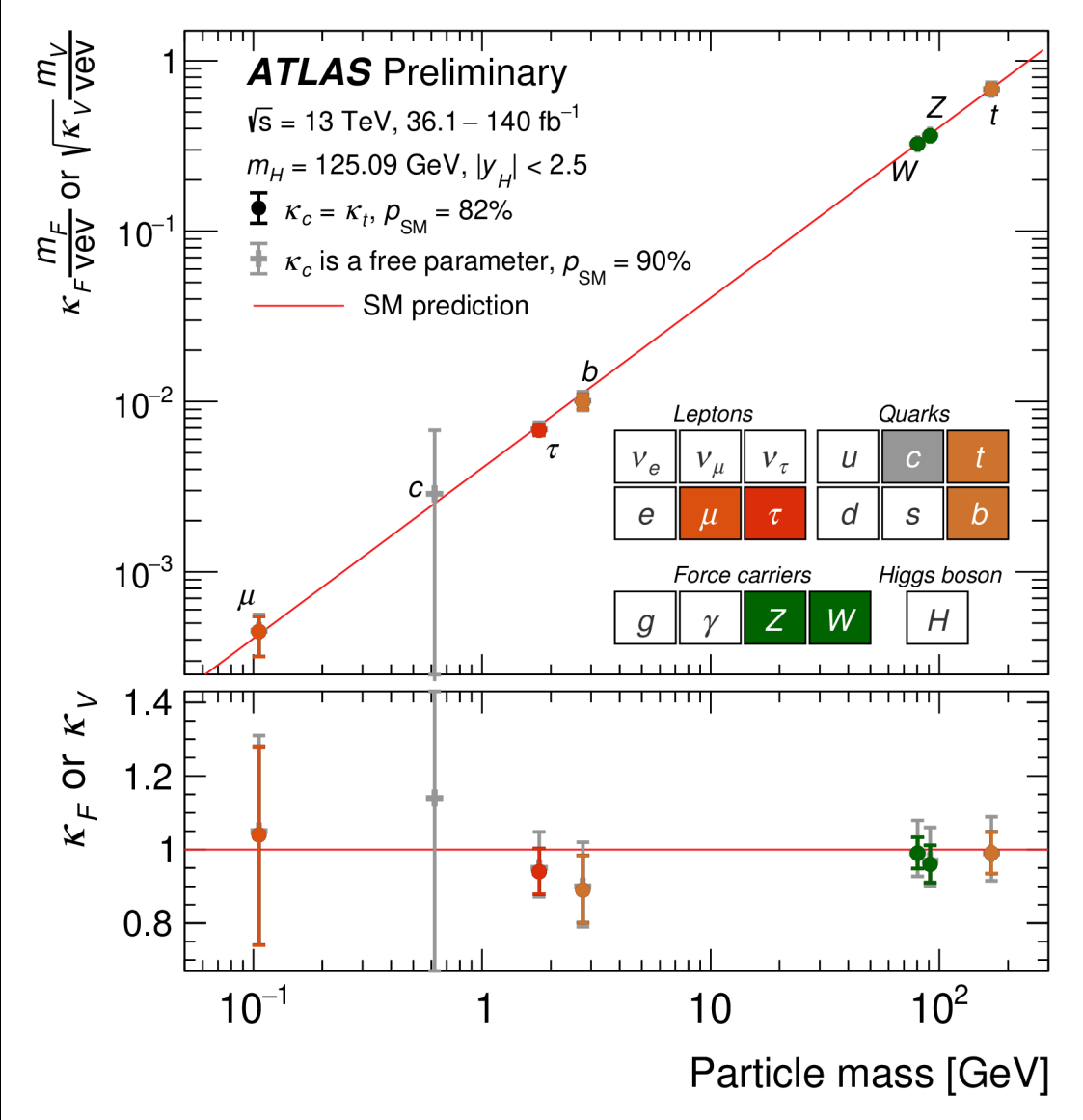


The colliding bubbles generate stochastic gravitational waves

Simplified view: The peak frequency depends on the bubble size, the phase transition temperature, its strength and its duration

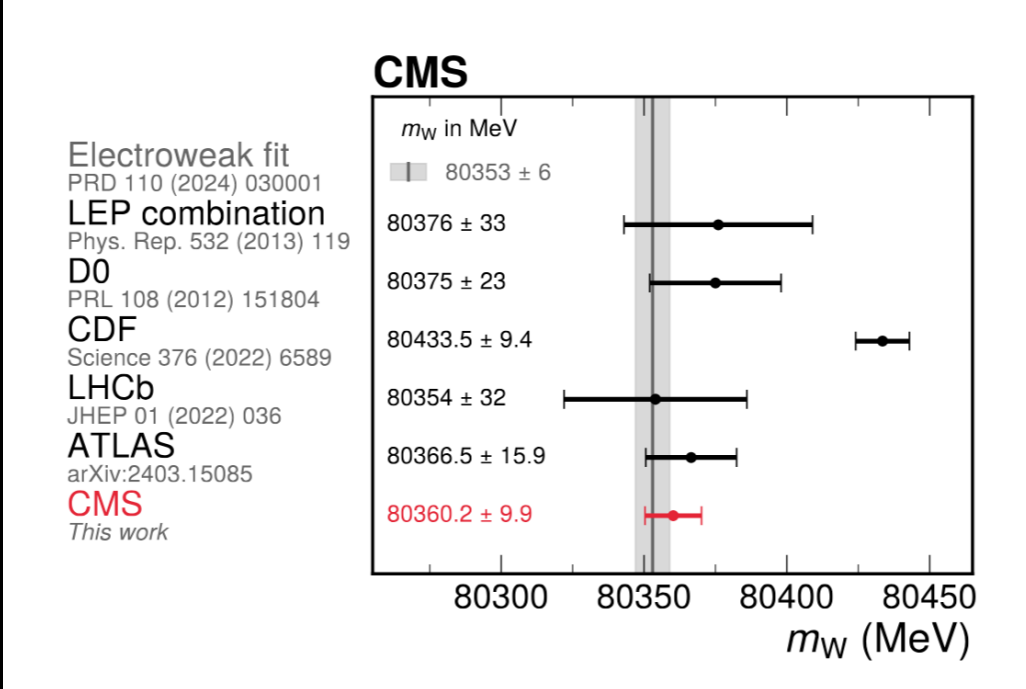
Impact of the phase transition parameters on the GWB spectrum



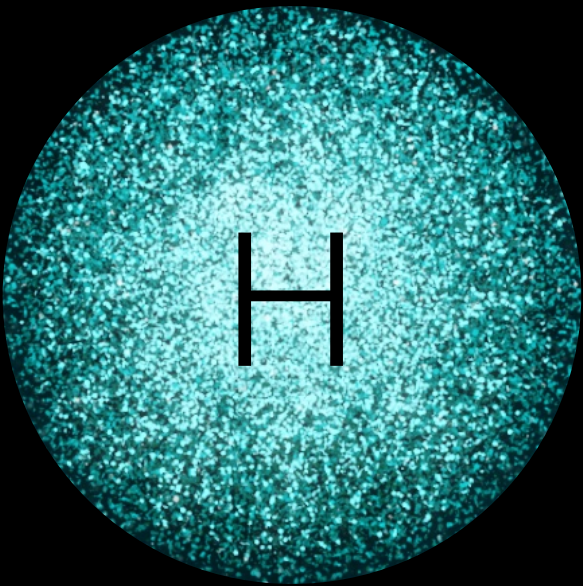


Couplings
scale with
particle mass

Custodial
symmetry of
W/Z masses

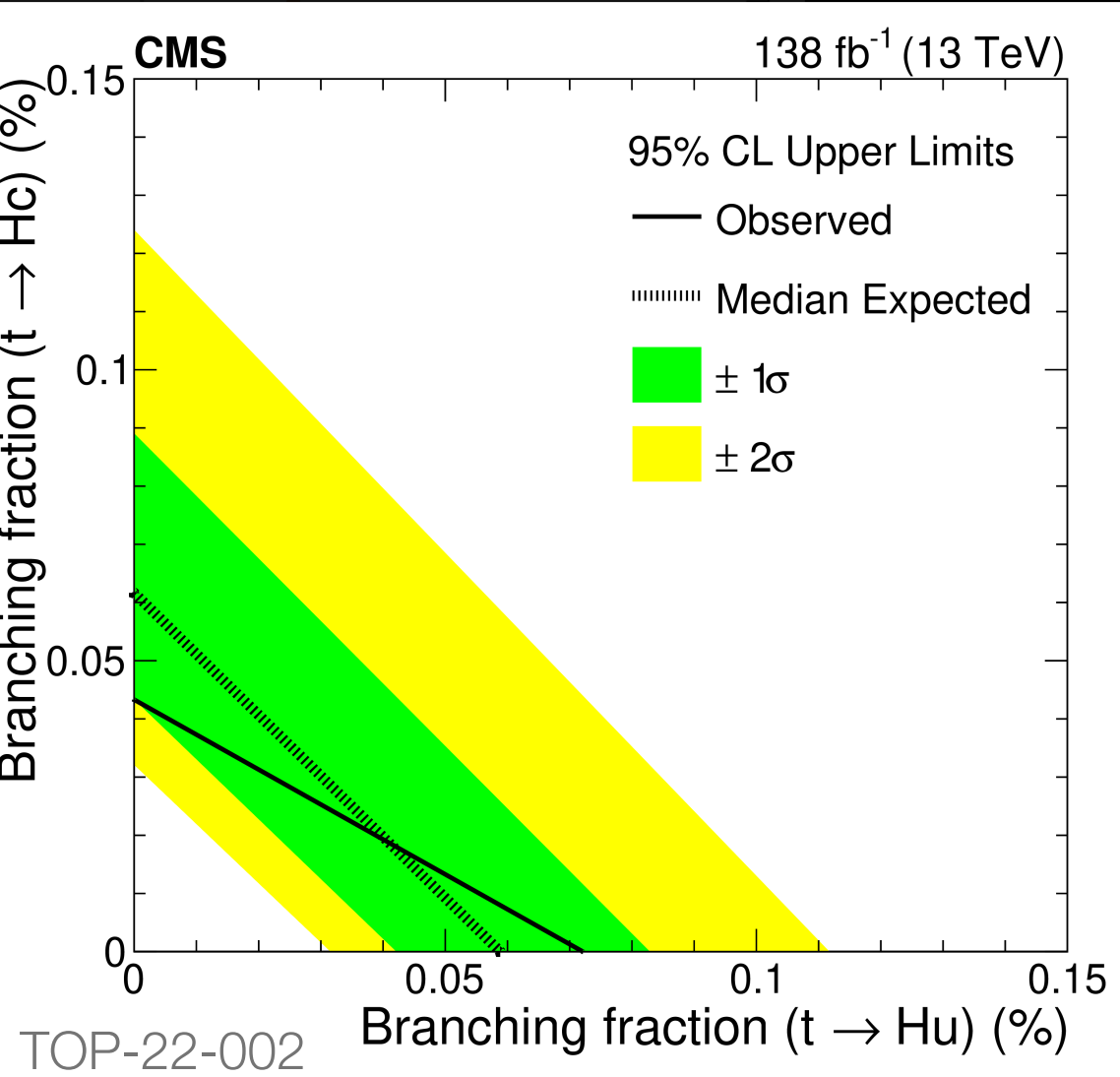
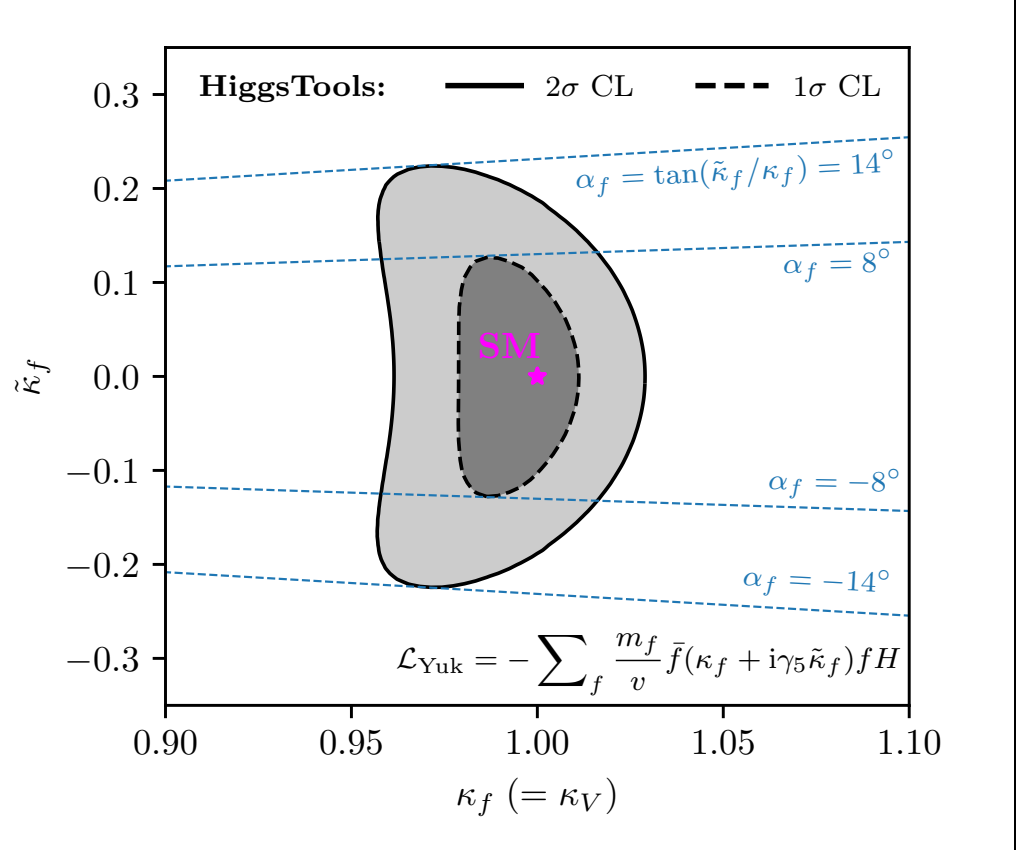


This Standard Model



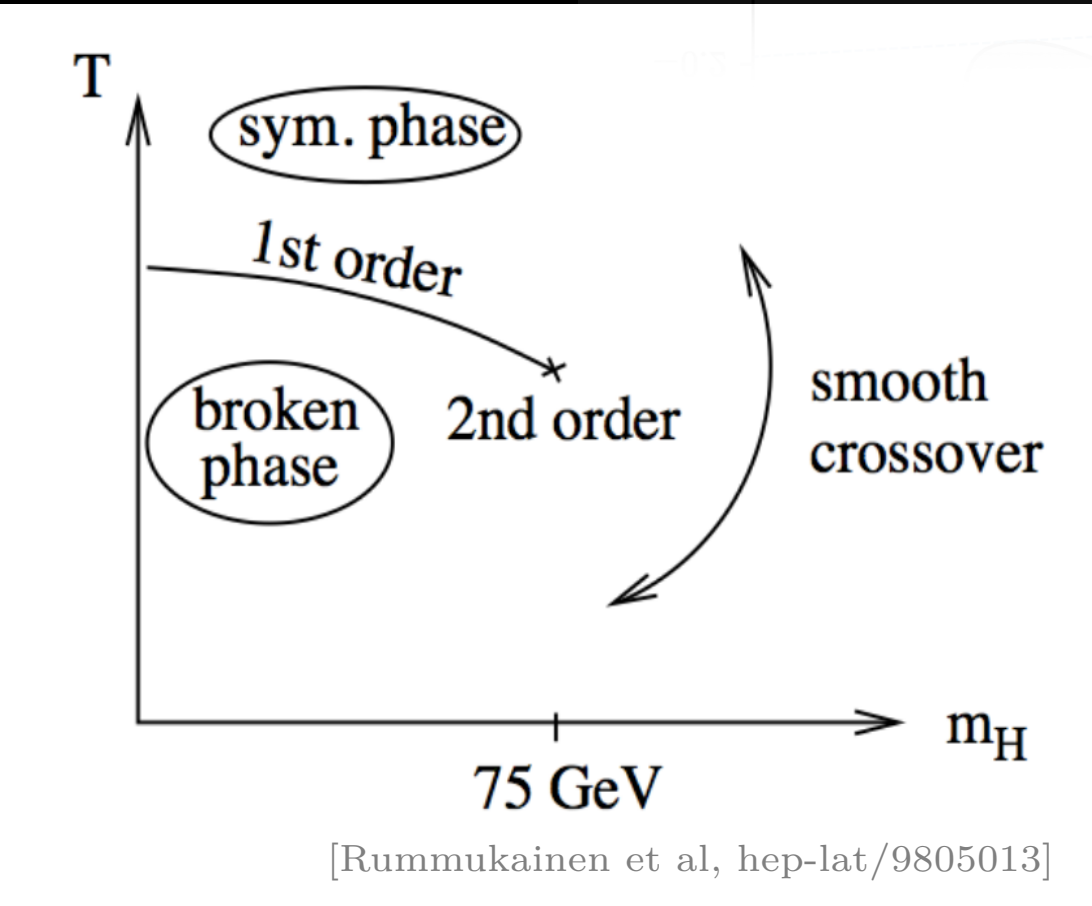
predicts...

No CP violation in
the Higgs potential

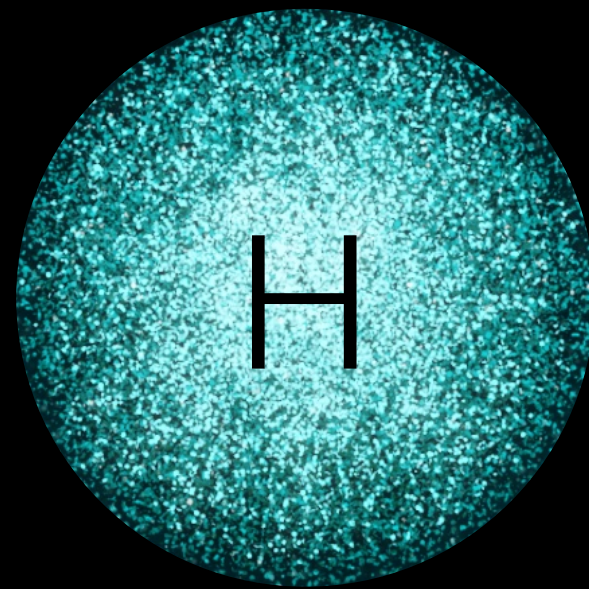


No (tree-level) flavour
changing couplings

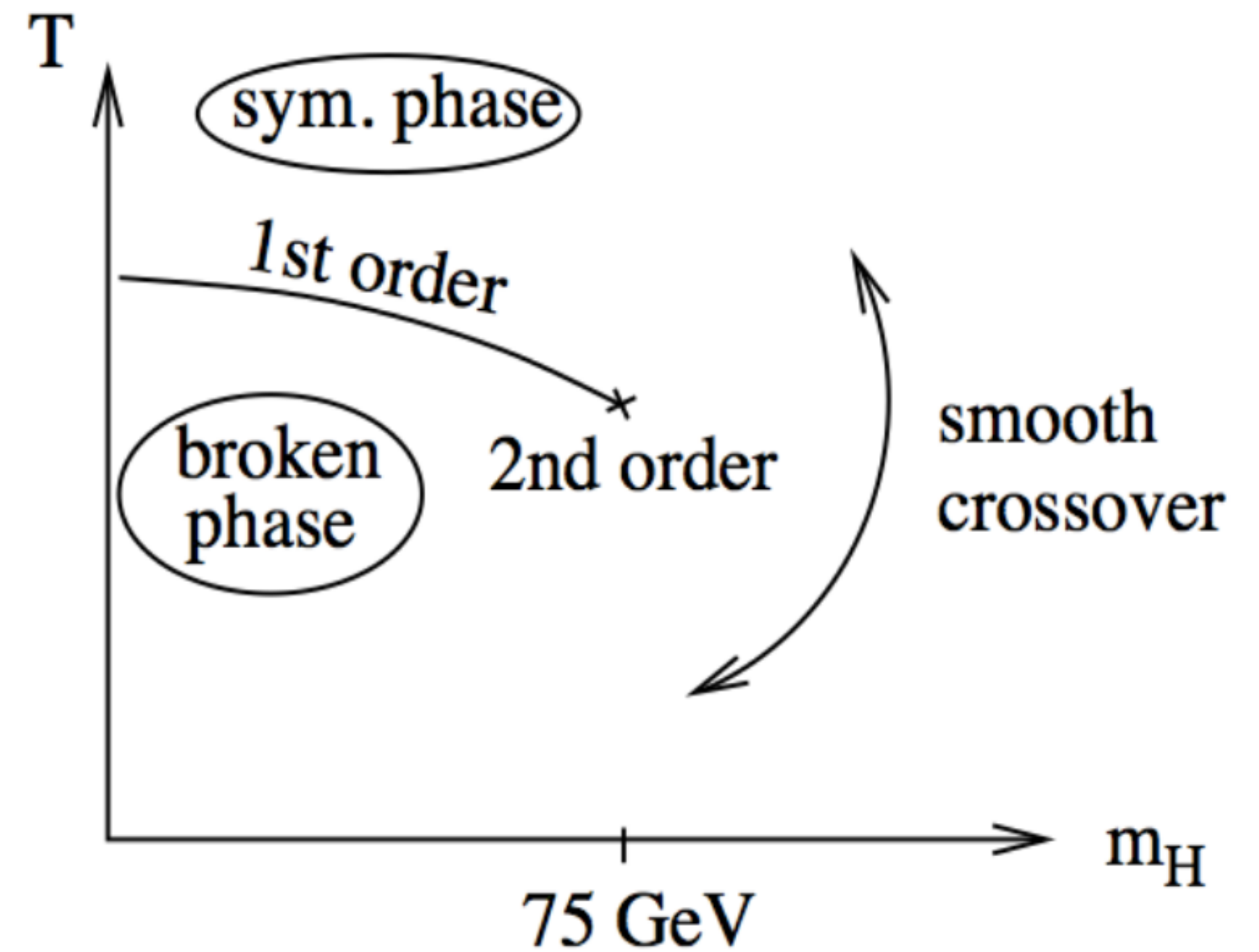
The type of electroweak
phase transition in the
early universe



A 125 GeV



prediction



[Rummukainen et al, hep-lat/9805013]

[Rummukainen et al, hep-lat/9805013]

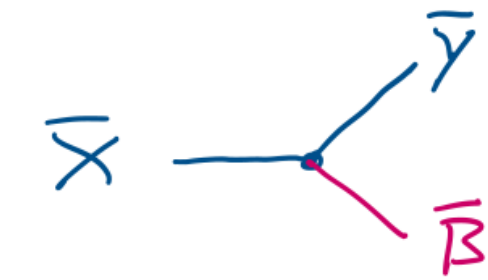
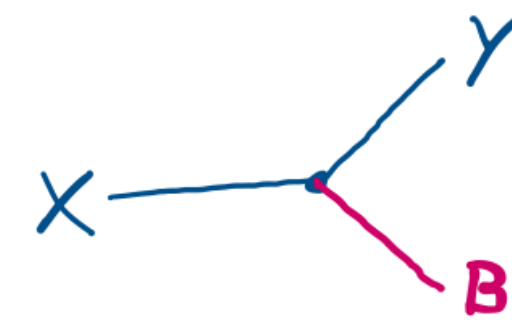
125 GeV

There is no strong electroweak phase transition in the early universe



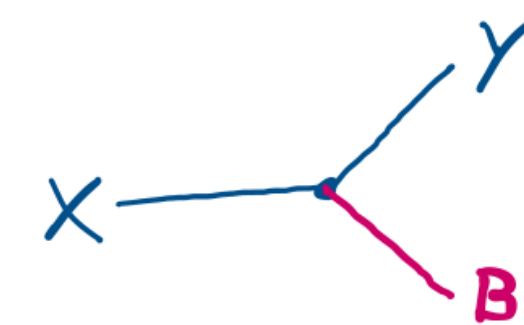
The SM's prediction of our universe

Sakharov Conditions

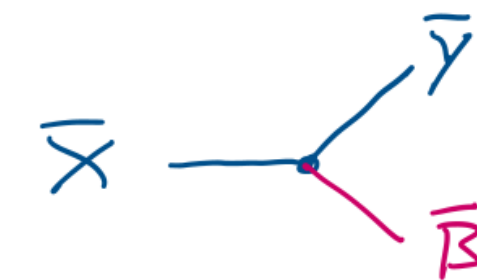


Baryon number violation

Allowed at high temperatures

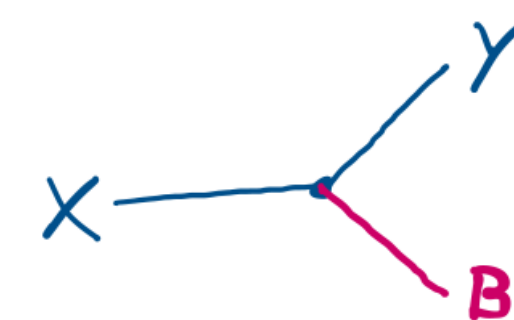


$\neq$

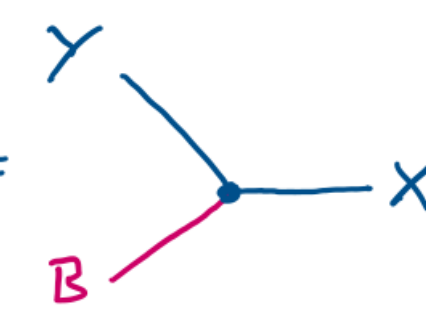


C and CP violation

Off by 8-10 orders of magnitude



$\neq$

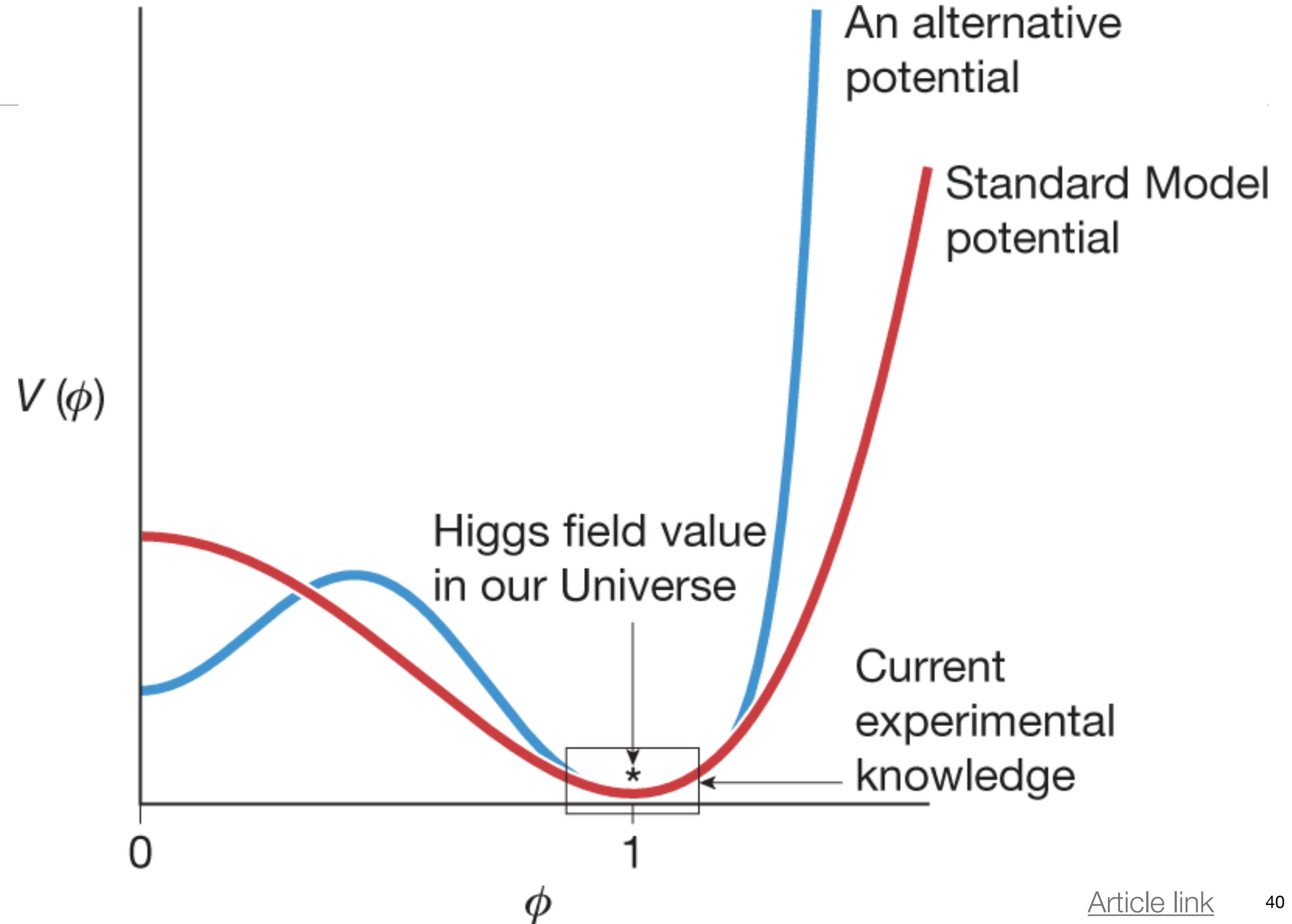


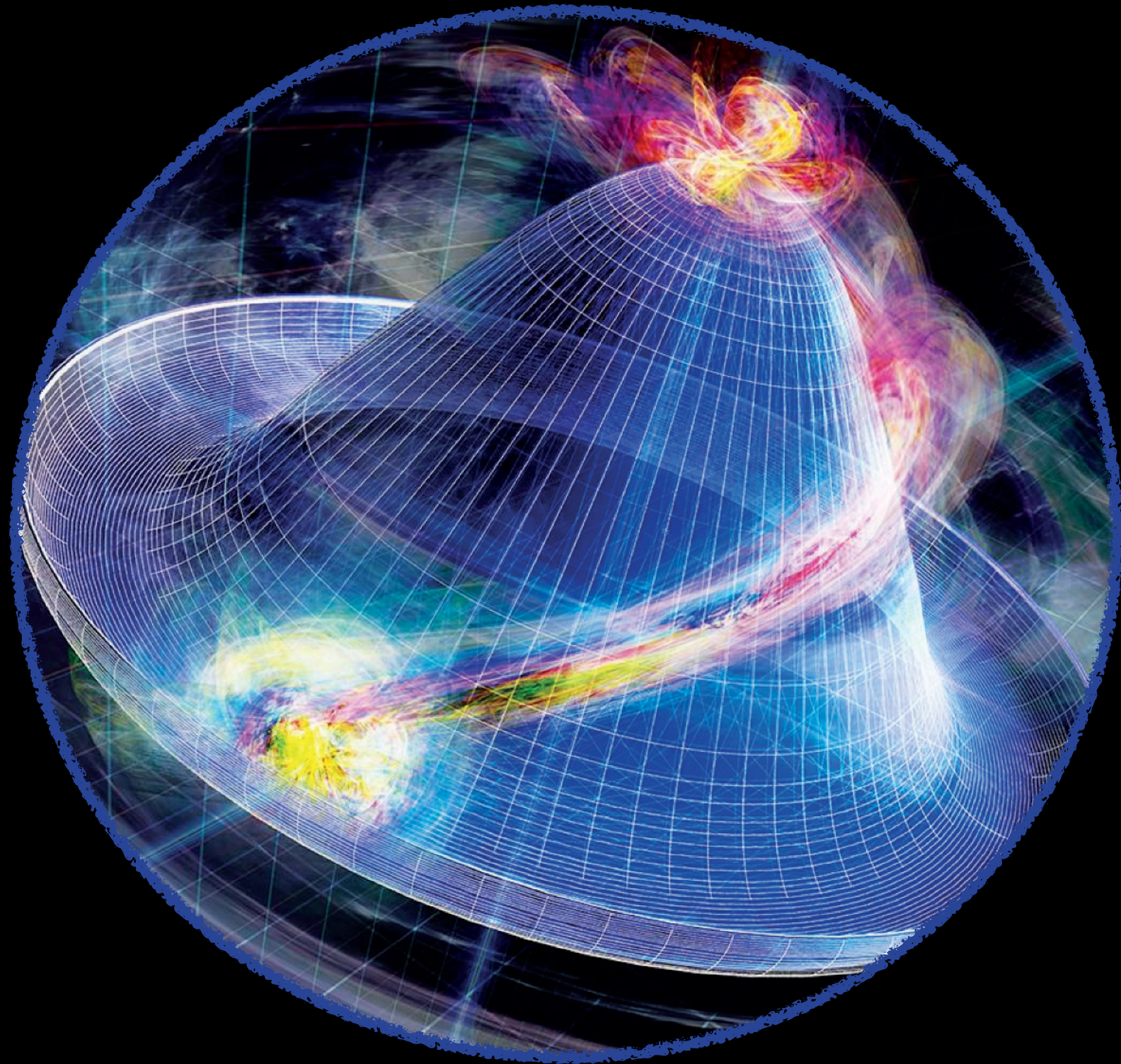
Out of equilibrium

No strong phase transition

However...

Our current state of knowledge is limited



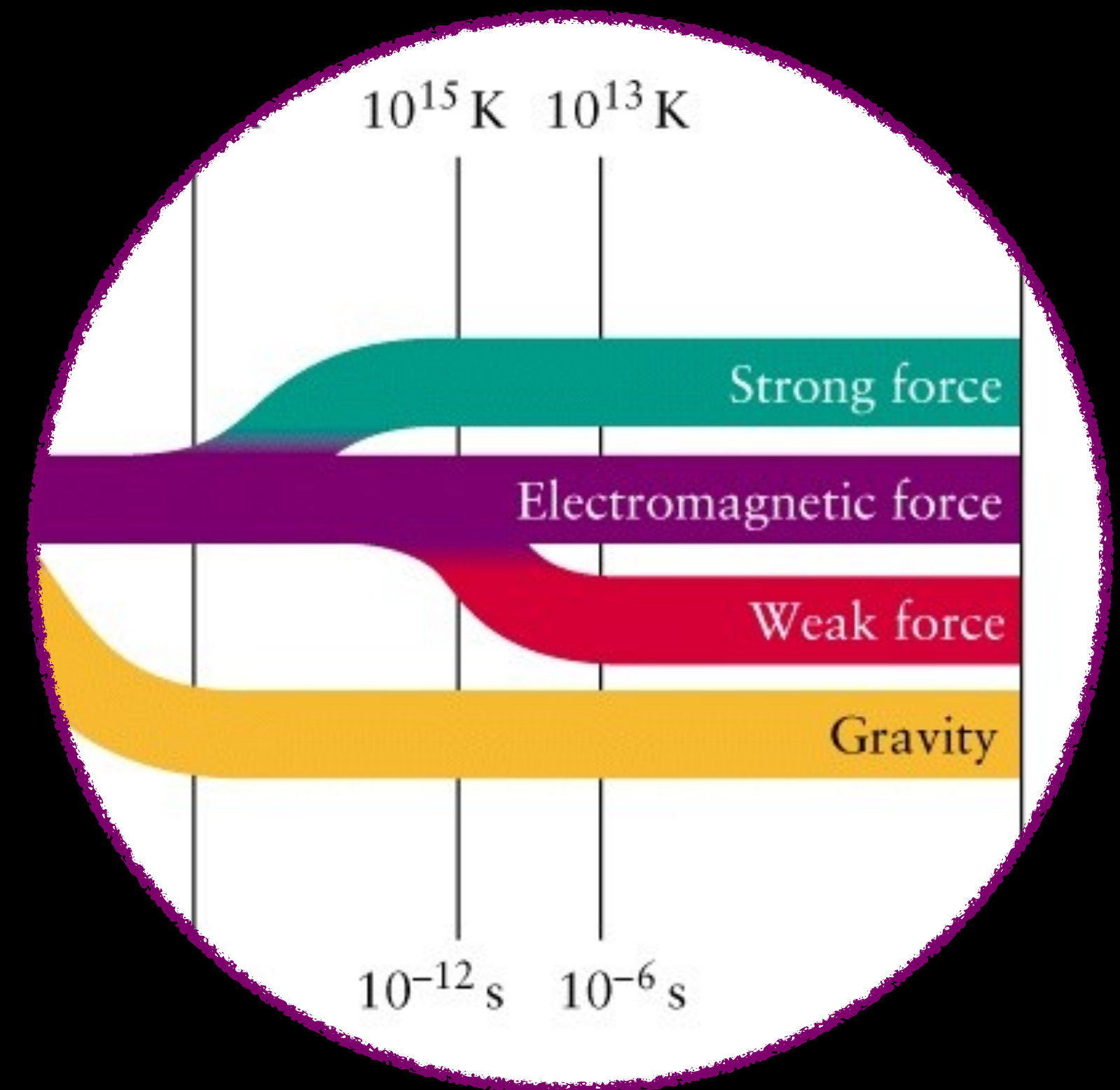


Symmetries

- How symmetry predicts interactions
- Physics example: same-sign WW scattering
- Experimental theme: Jet identification

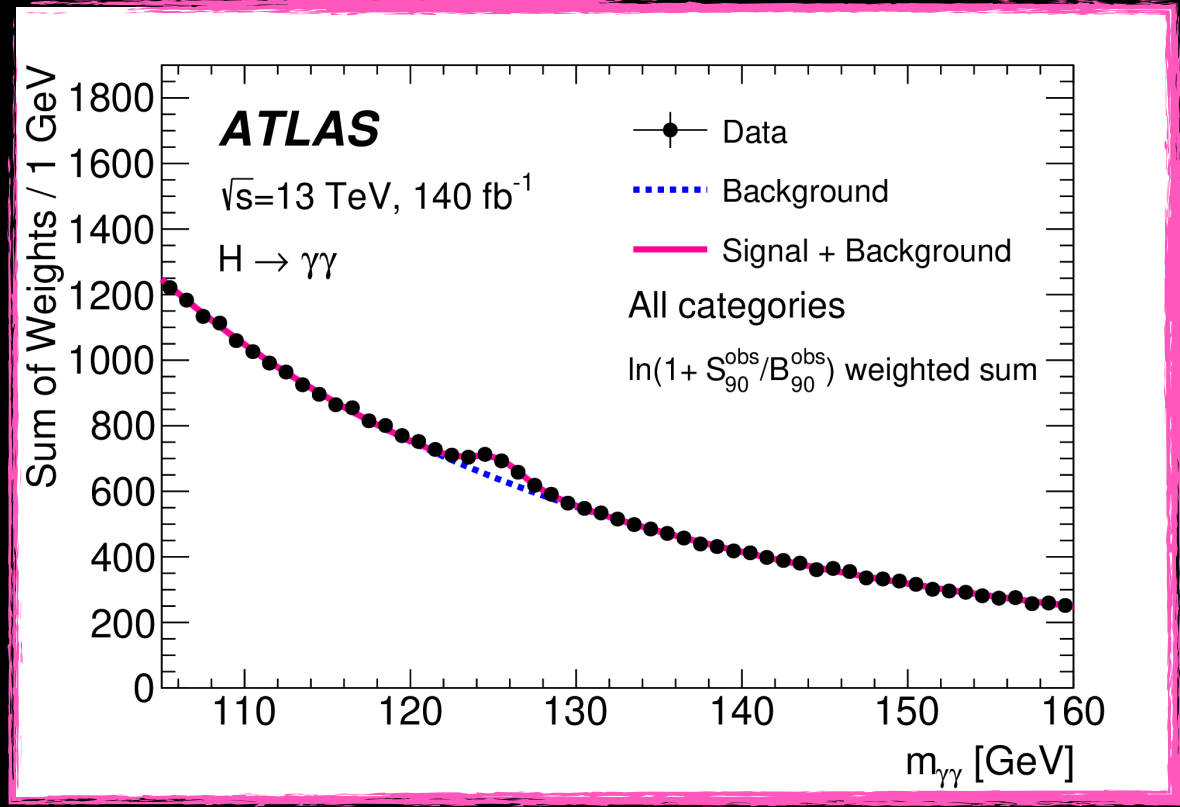
Scales

- How physics changes with energy (temperature)
- Physics examples: W mass + strong force coupling
- Experimental theme: How to design a measurement

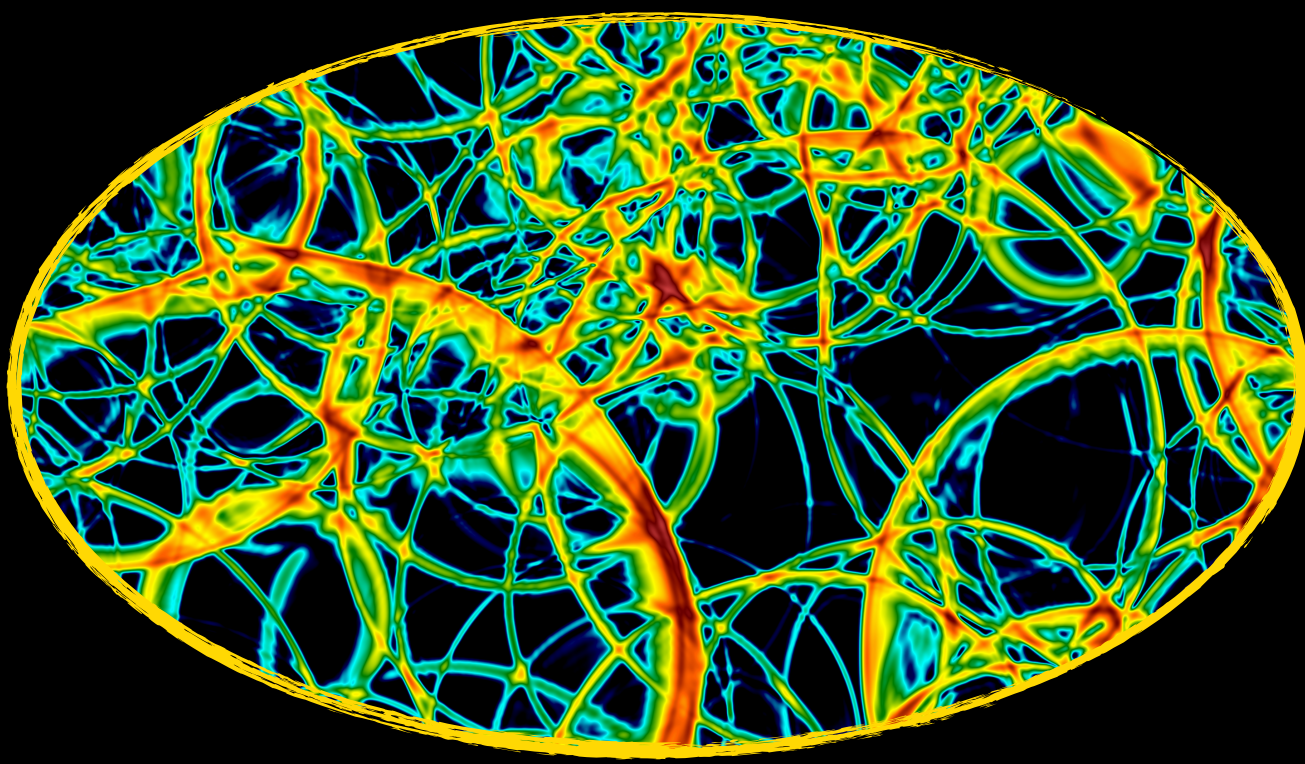


The ingredients to electroweak symmetry breaking

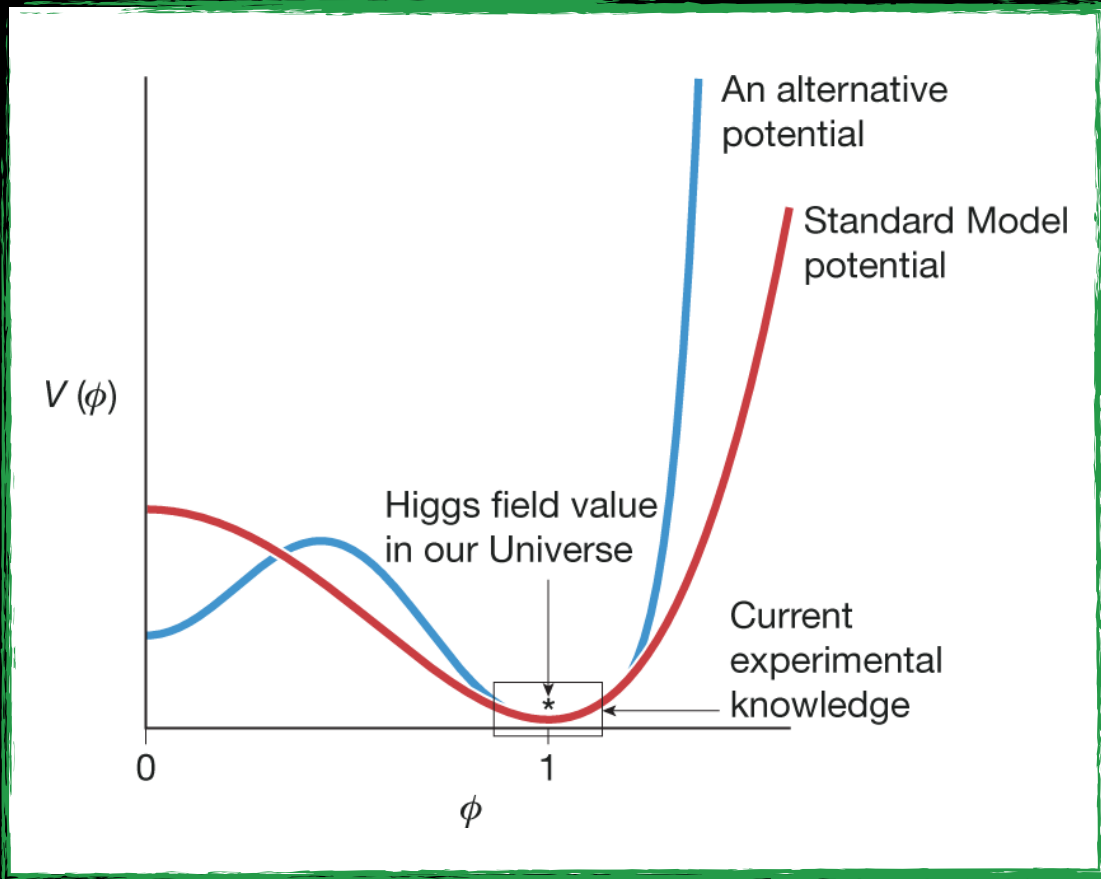
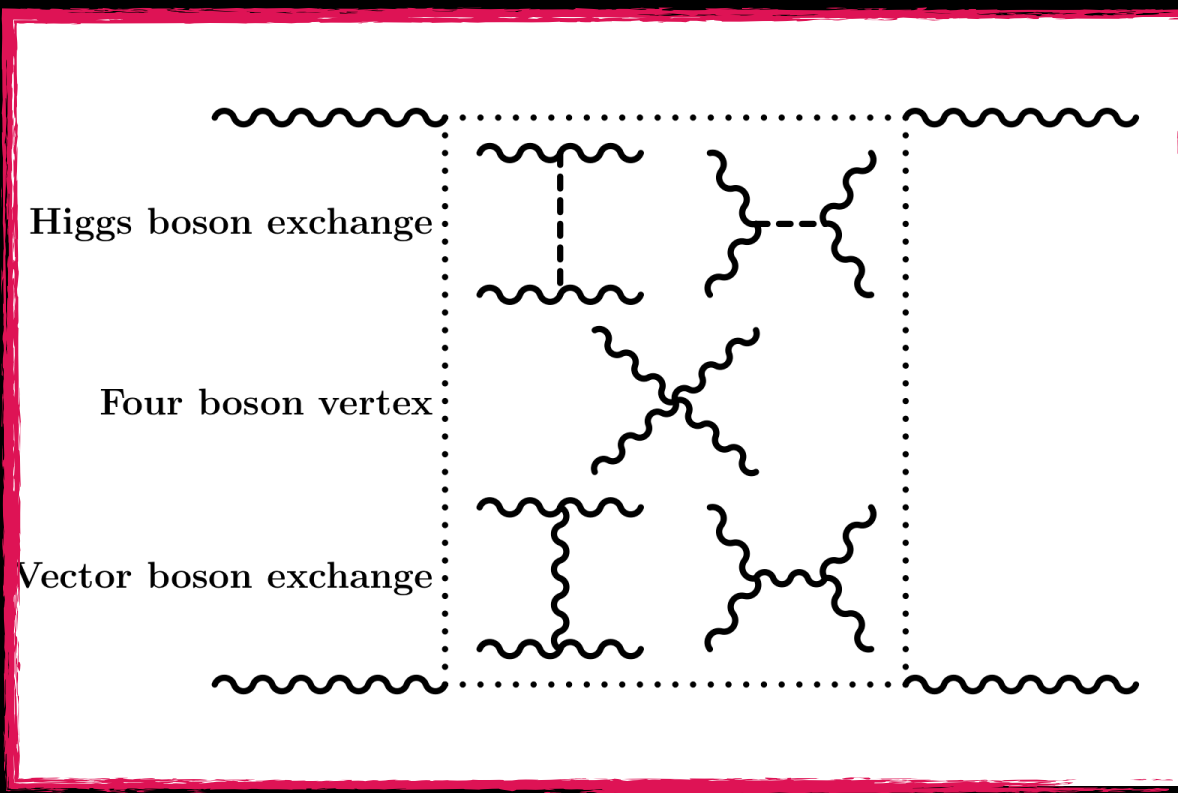
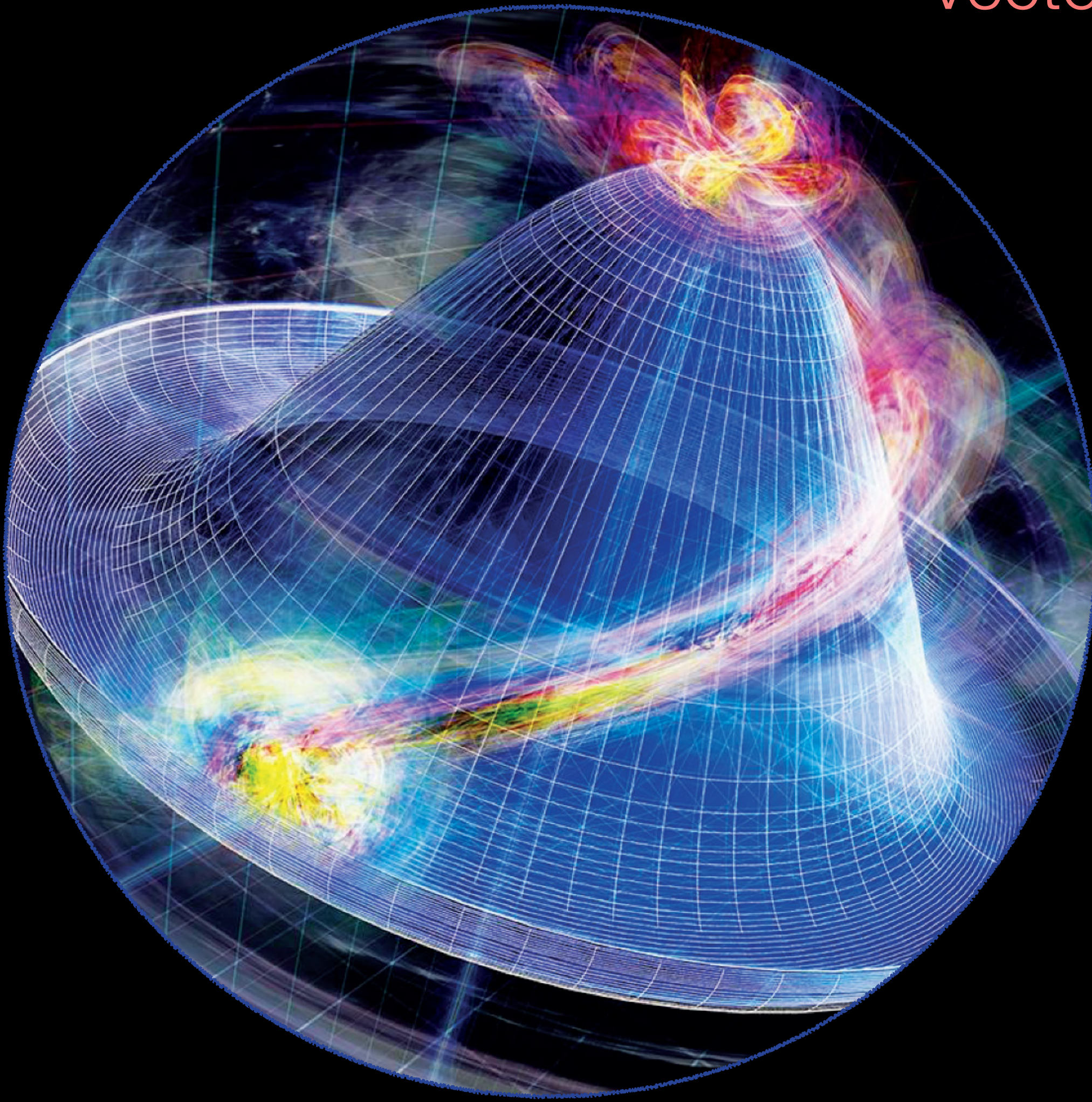
Vector boson polarisation



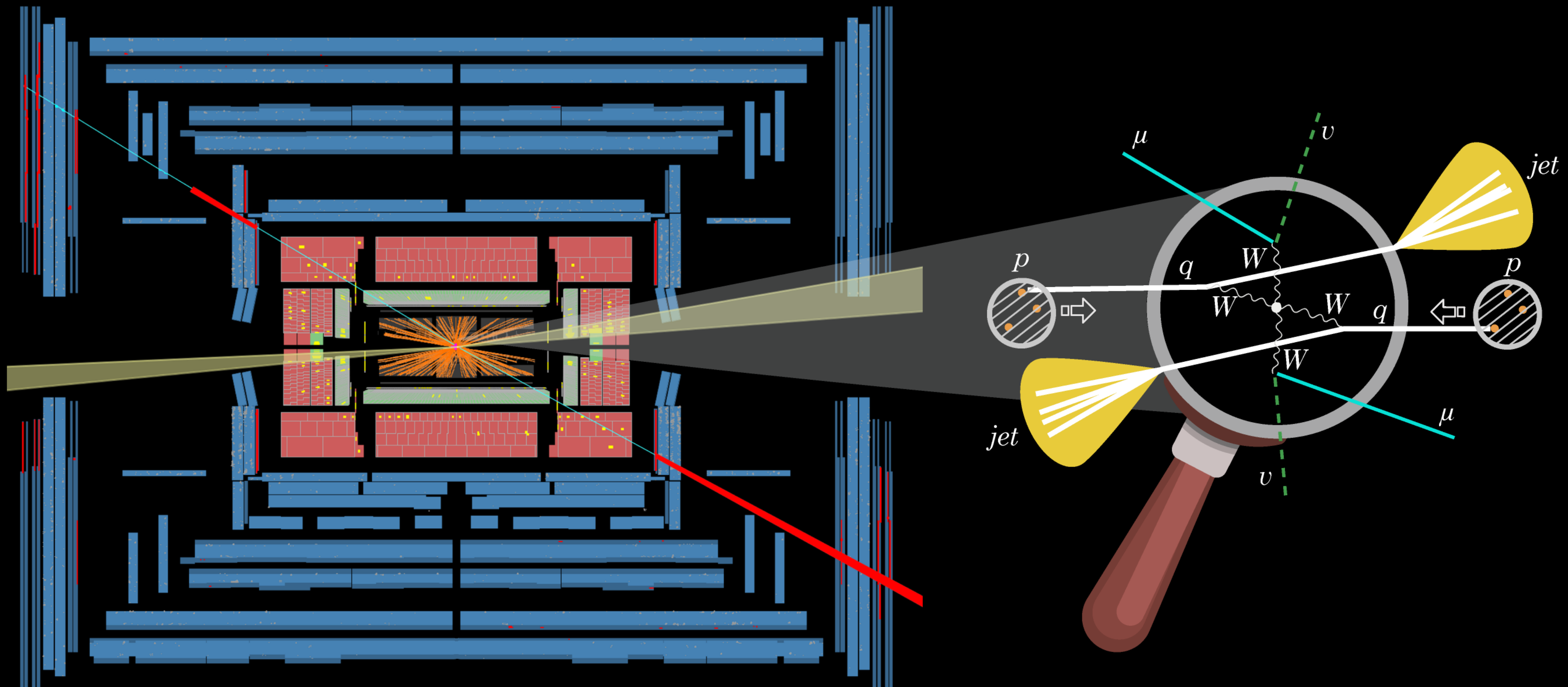
Precision Higgs



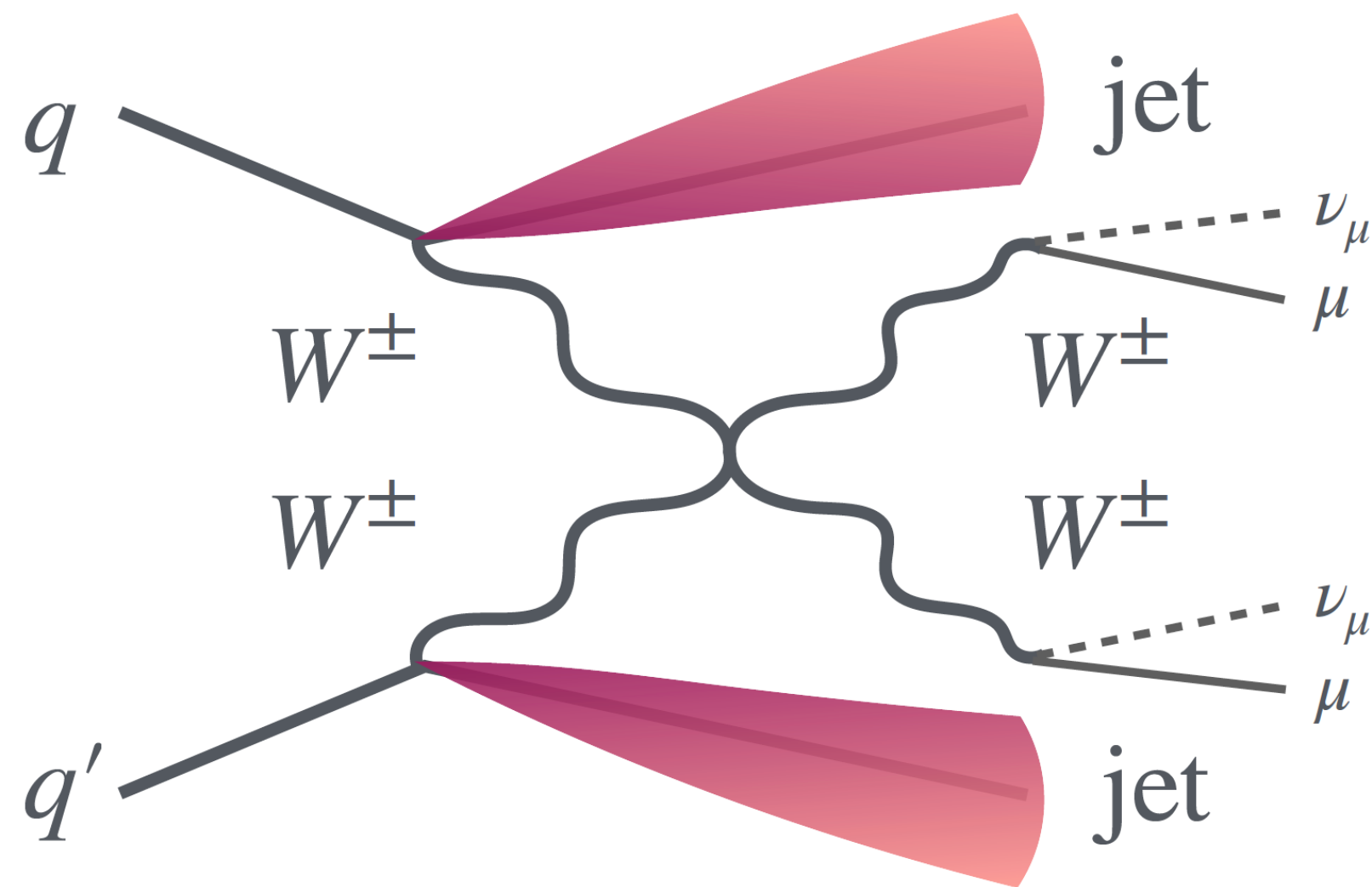
Additional Higgs?



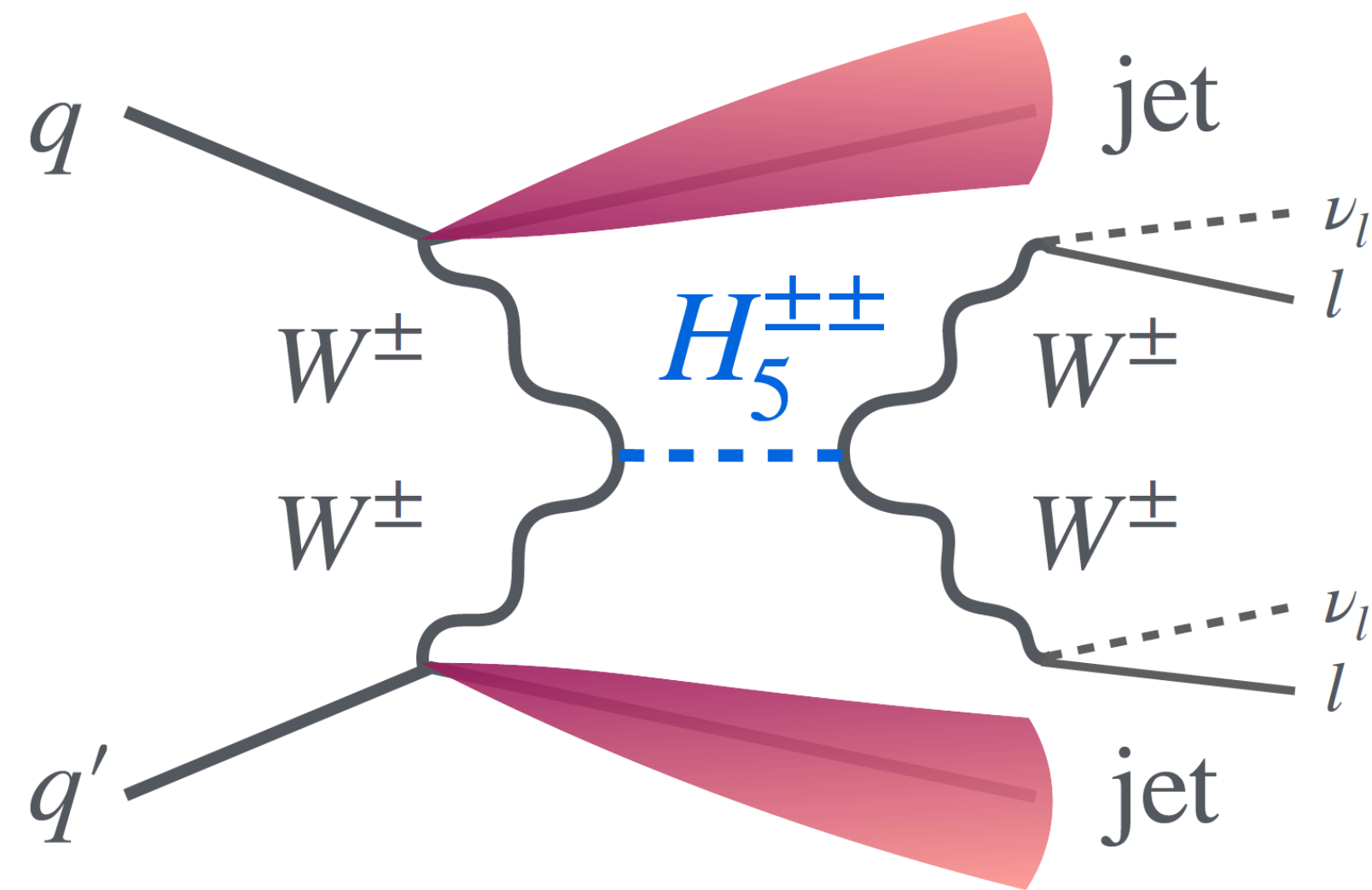
Higgs self-coupling



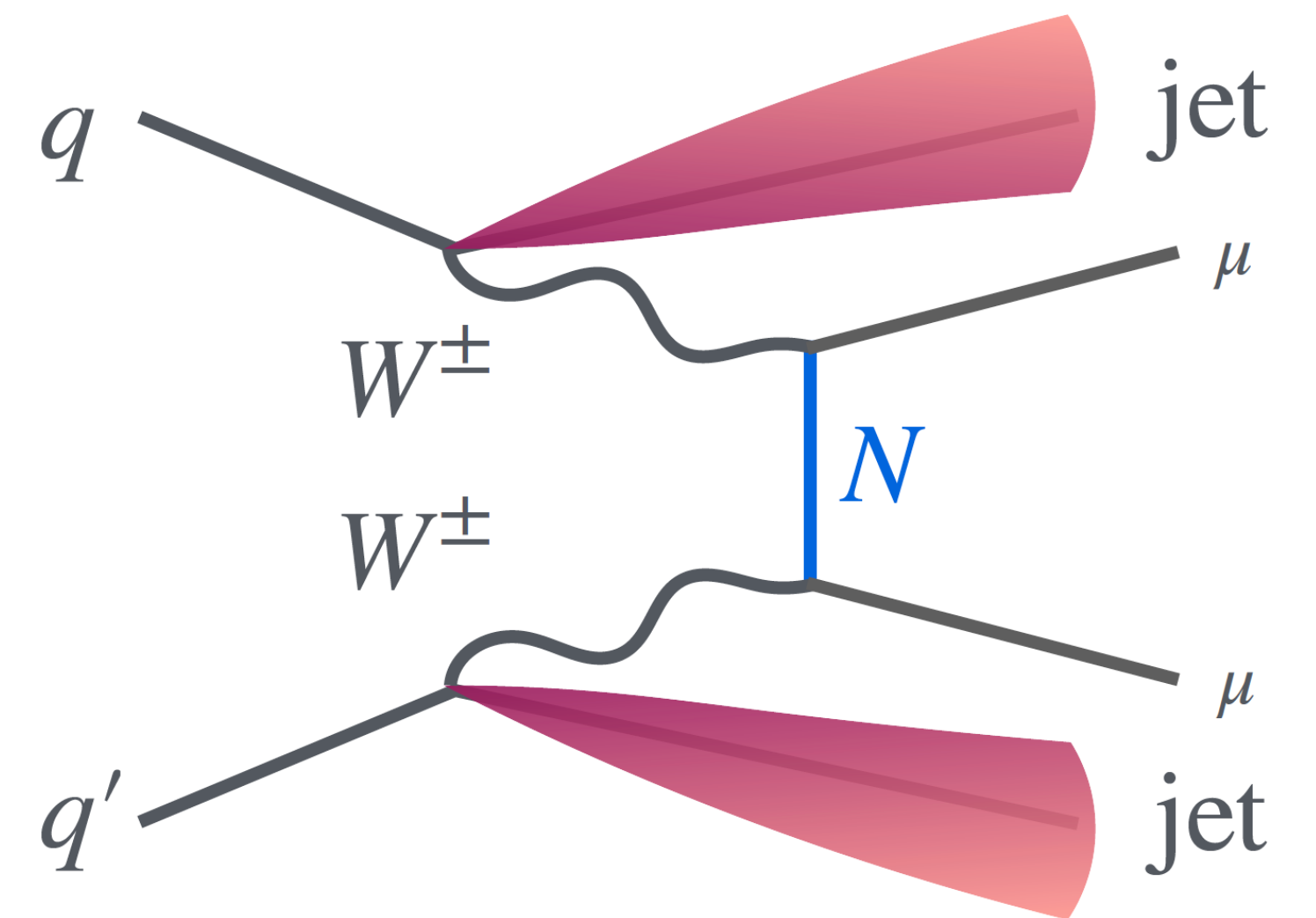
There maybe more happening in the middle than I think



What the SM predicts

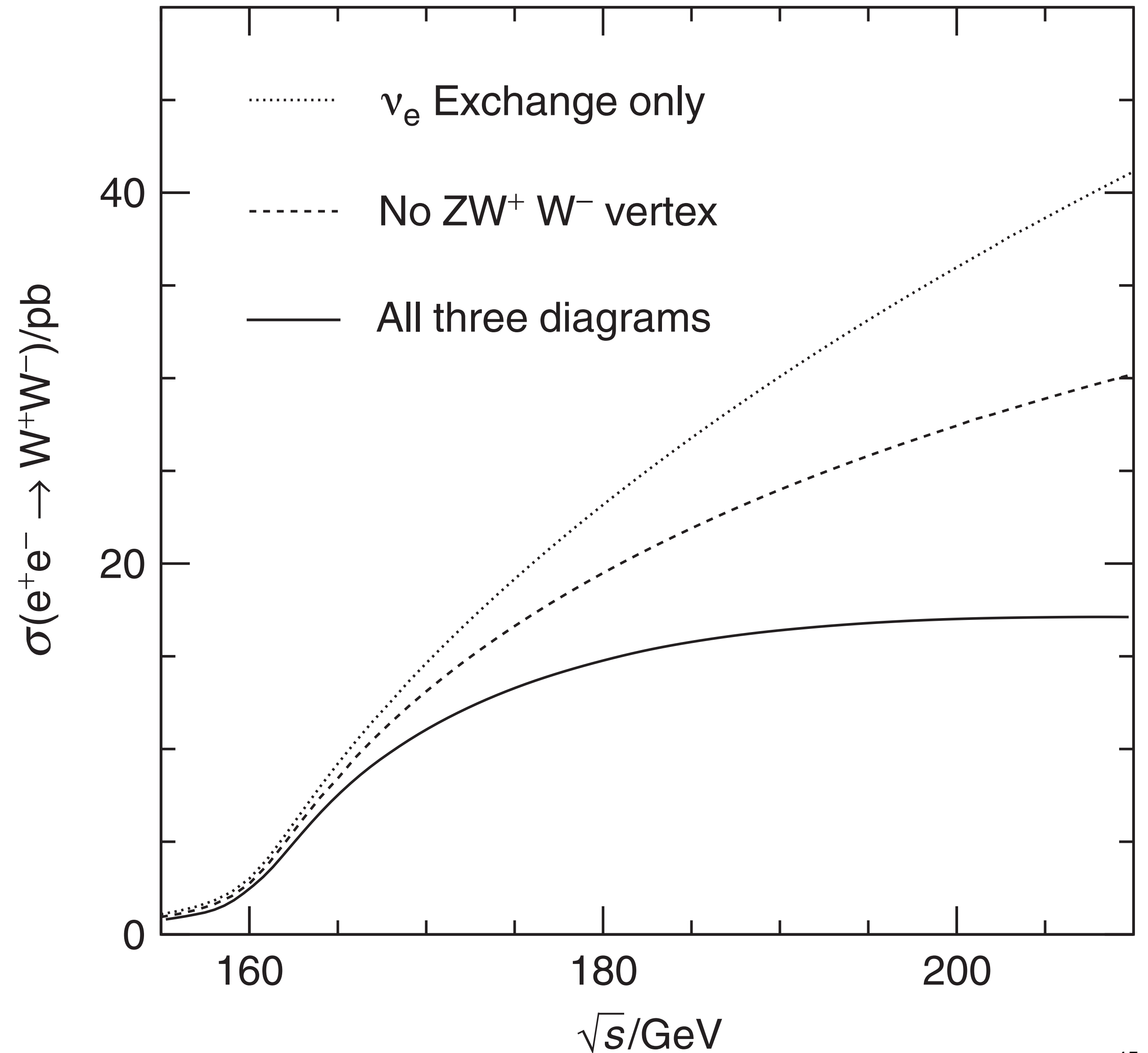
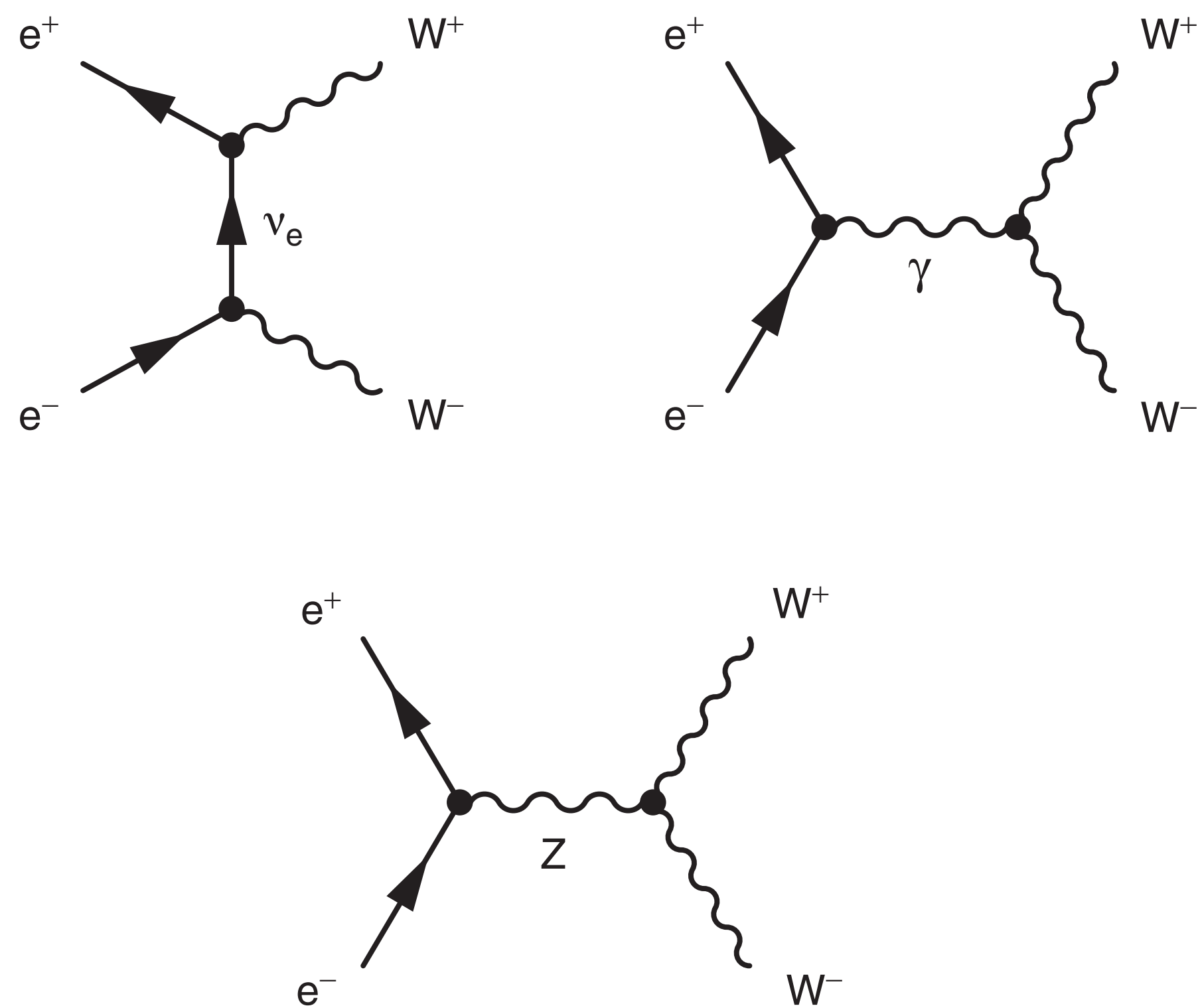


Additional Higgs?

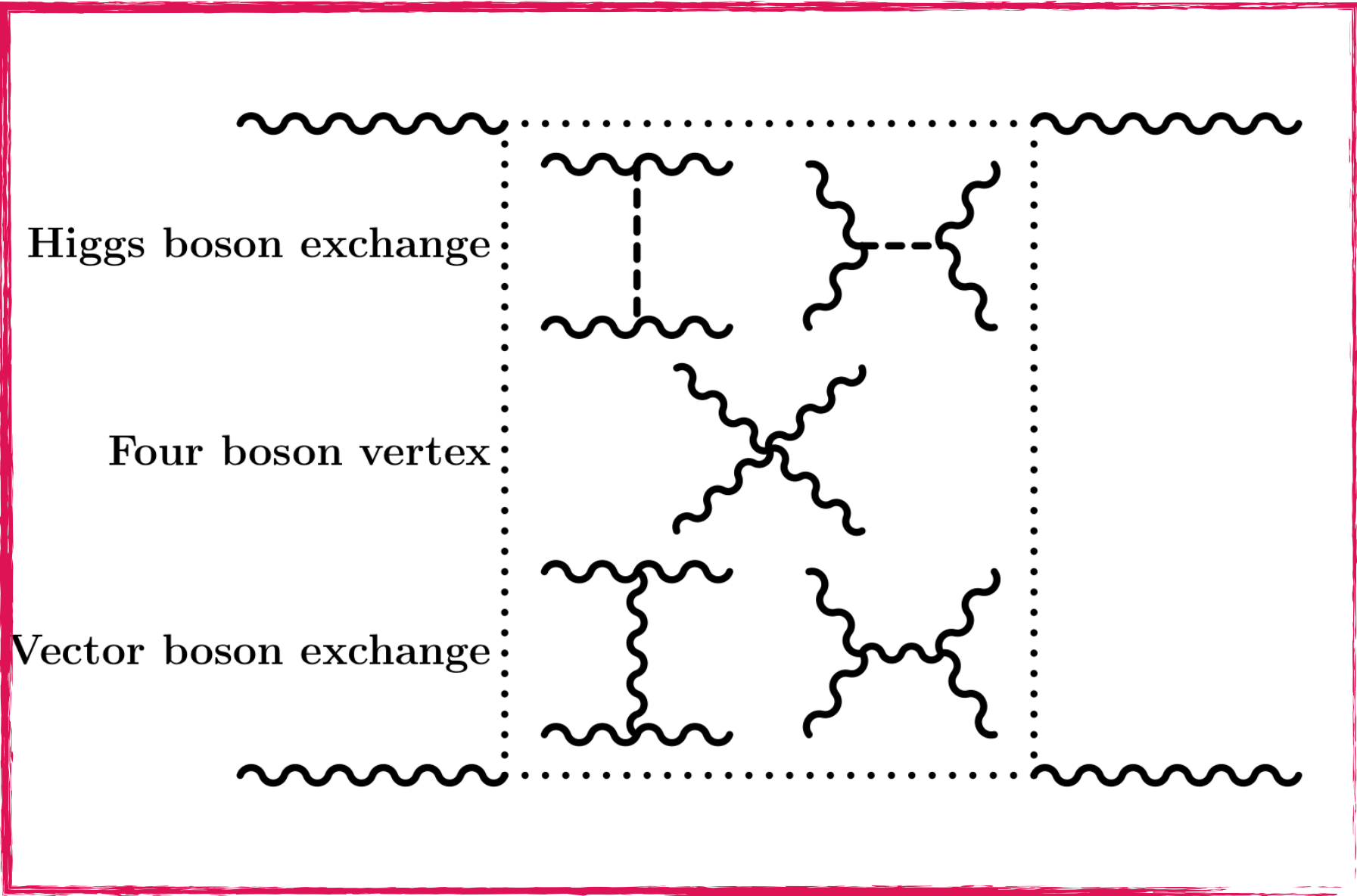


Majorana Neutrinos?

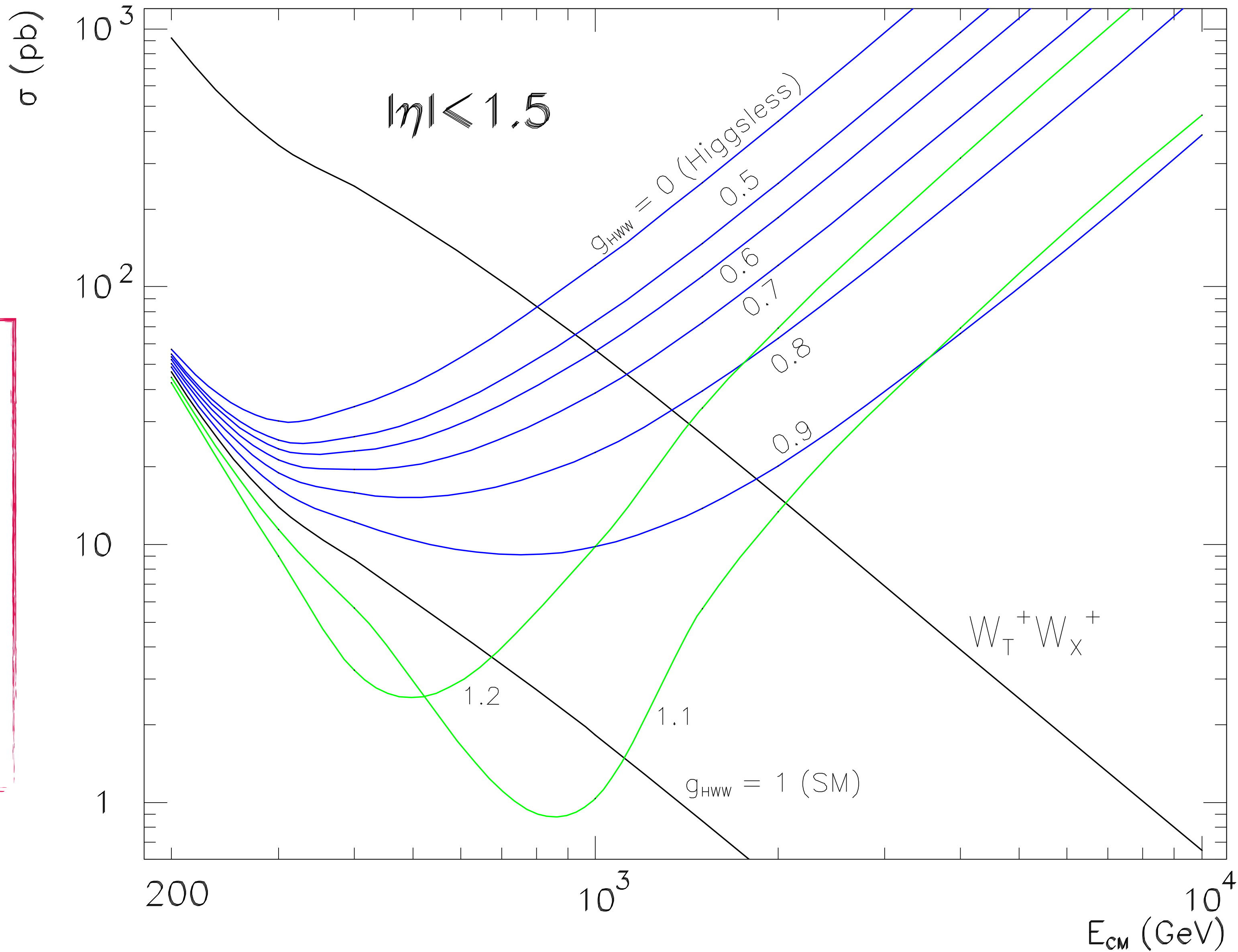
Nature doesn't violate unitarity - so neither should your theory



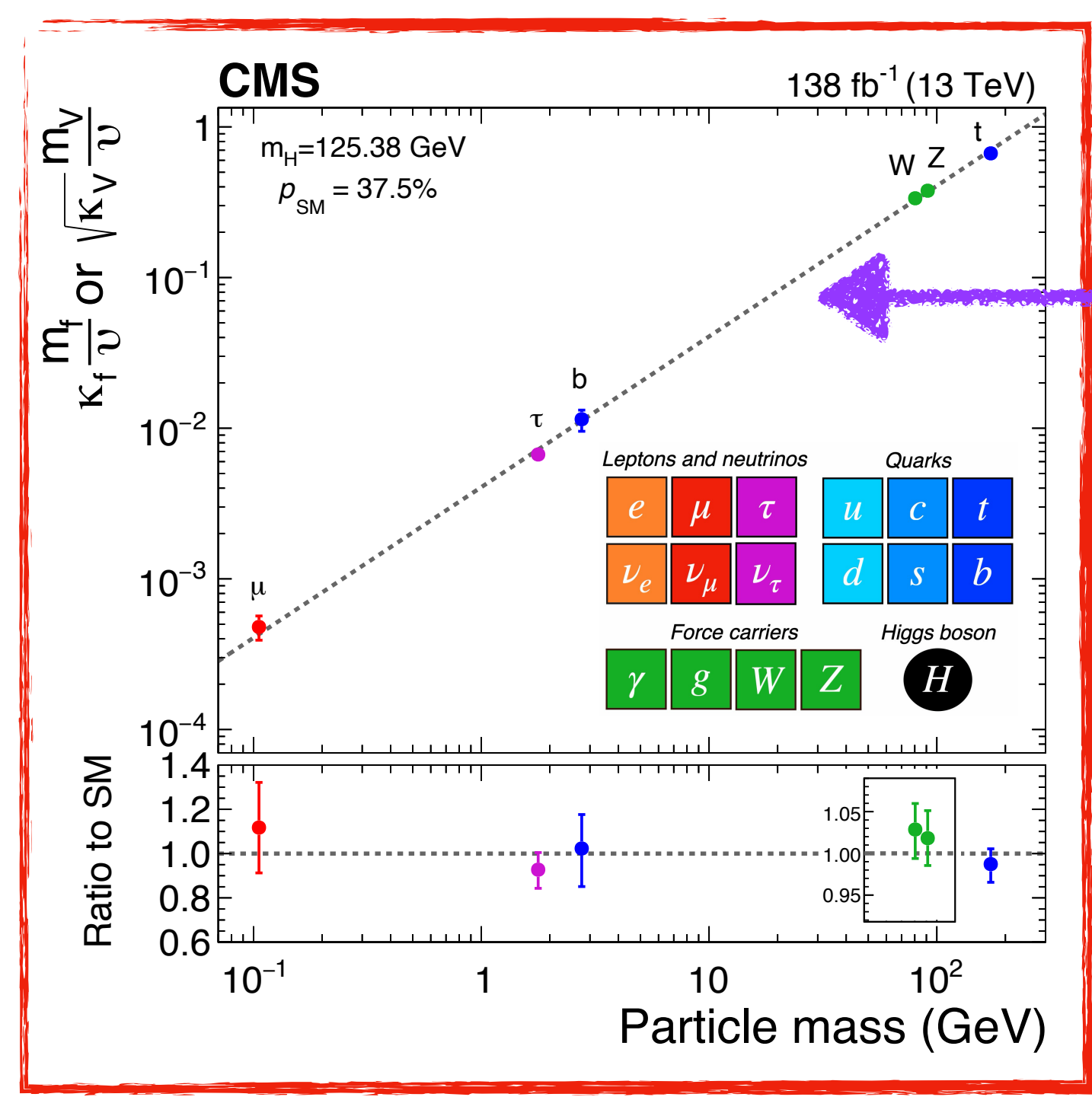
WW scattering



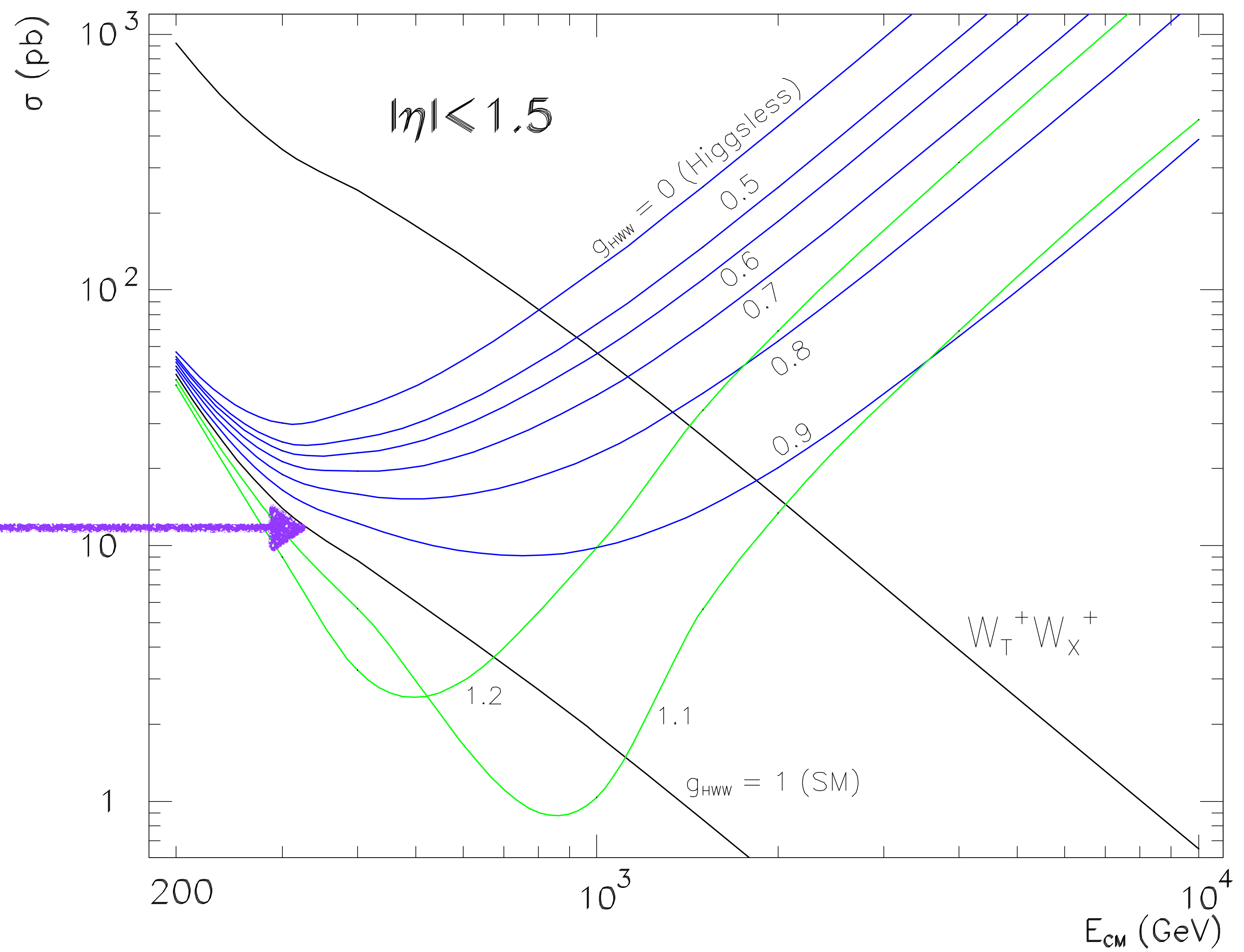
$W_L^+W_L^+ \rightarrow W_L^+W_L^+$ with modified Higgs couplings



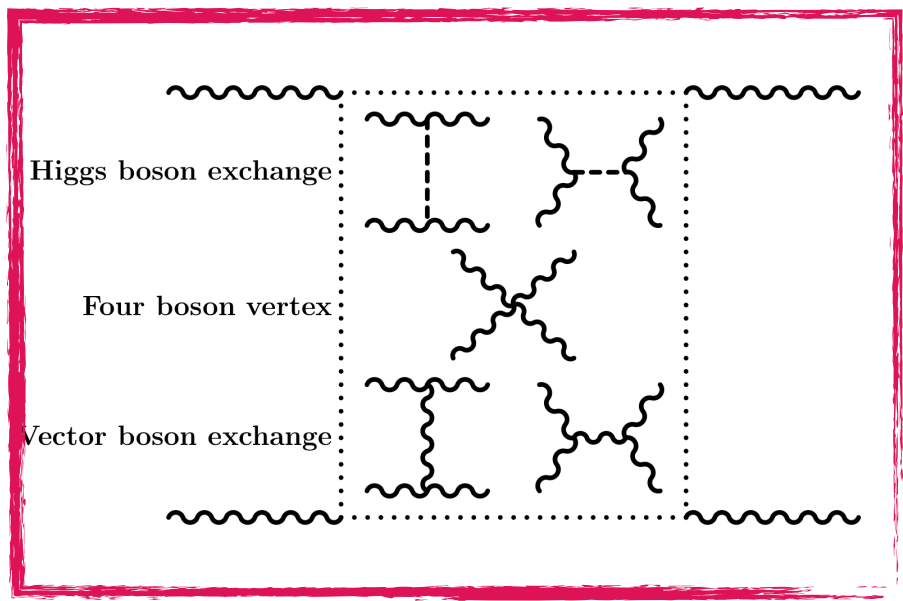
SM Prediction: the Higgs (i.e. its couplings) exactly make the scattering finite



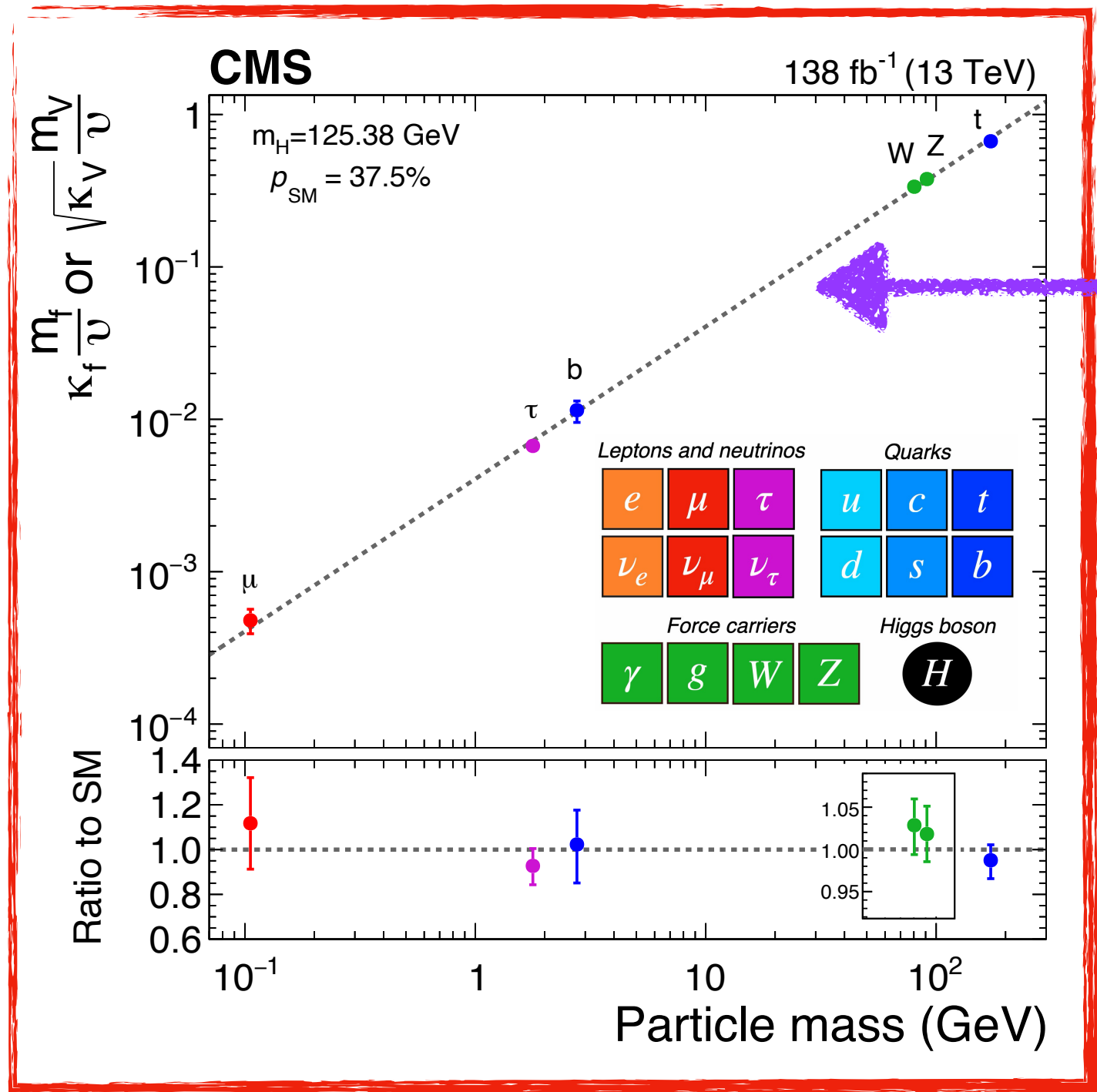
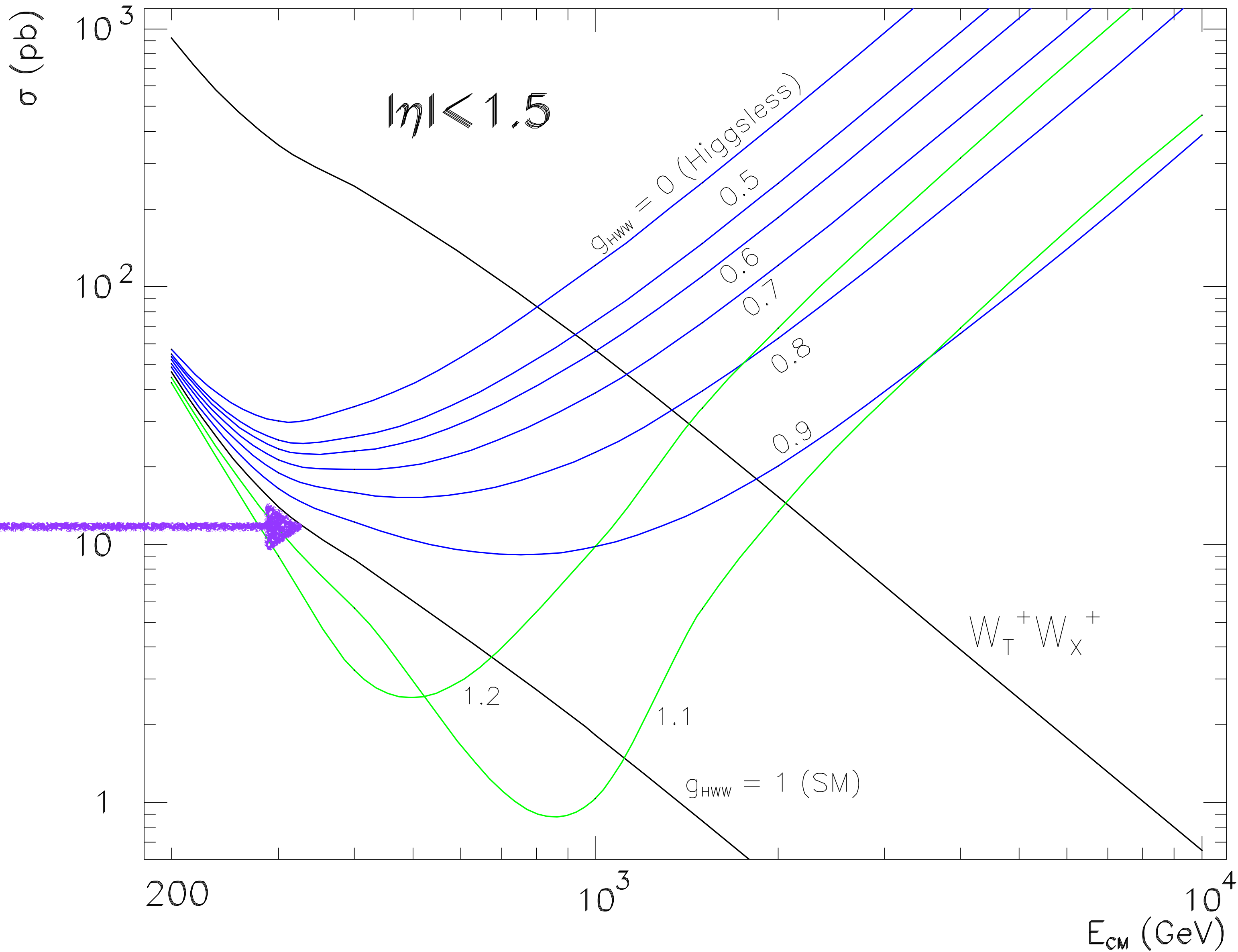
$W_L^+ W_L^+ \rightarrow W_L^+ W_L^+$ with modified Higgs couplings



If someone else is running around here, this breaks



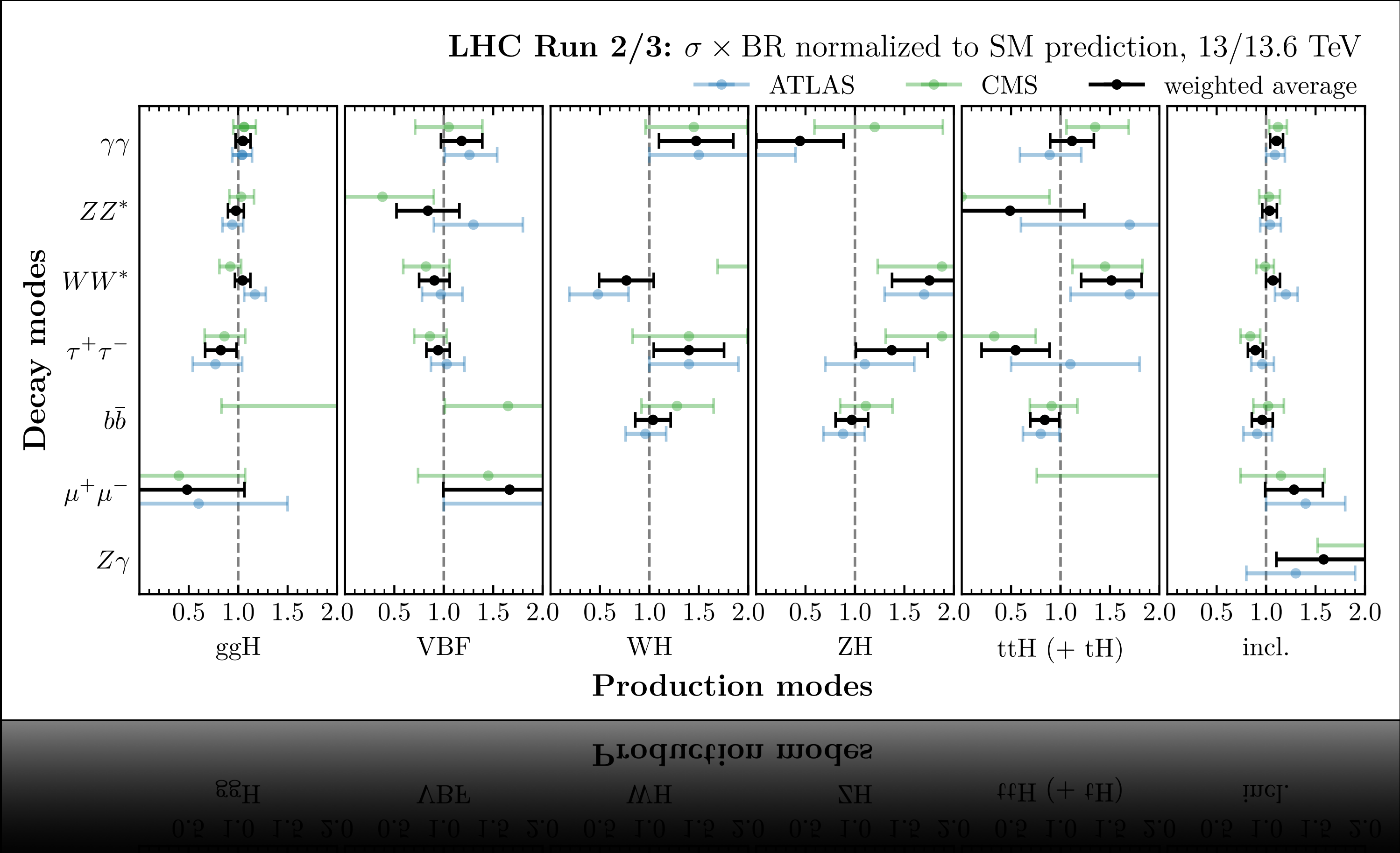
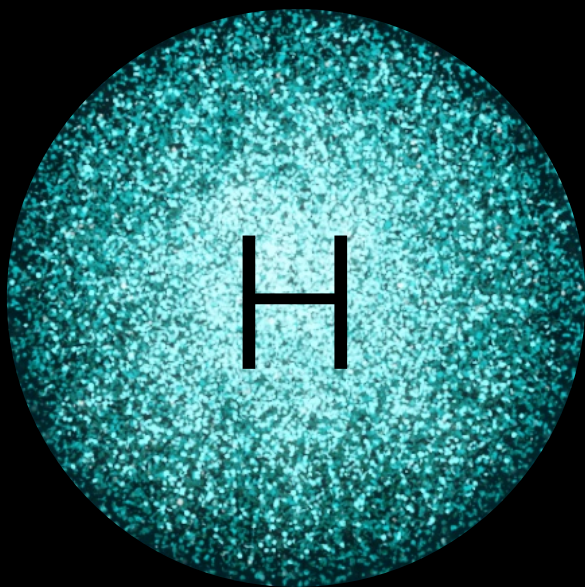
$W_L^+W_L^+ \rightarrow W_L^+W_L^+$ with modified Higgs couplings



How much wiggle room is there?

Work of Thomas Biekötter

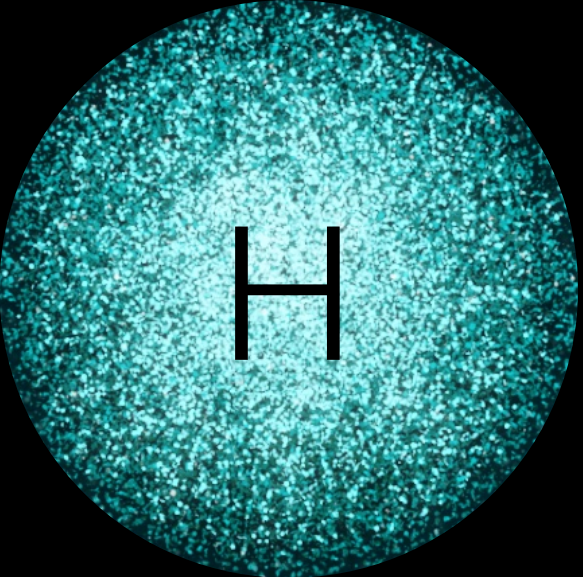
The simplest solution

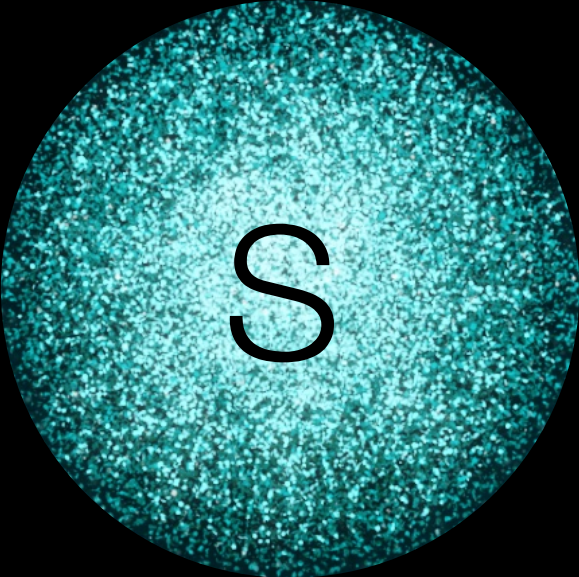


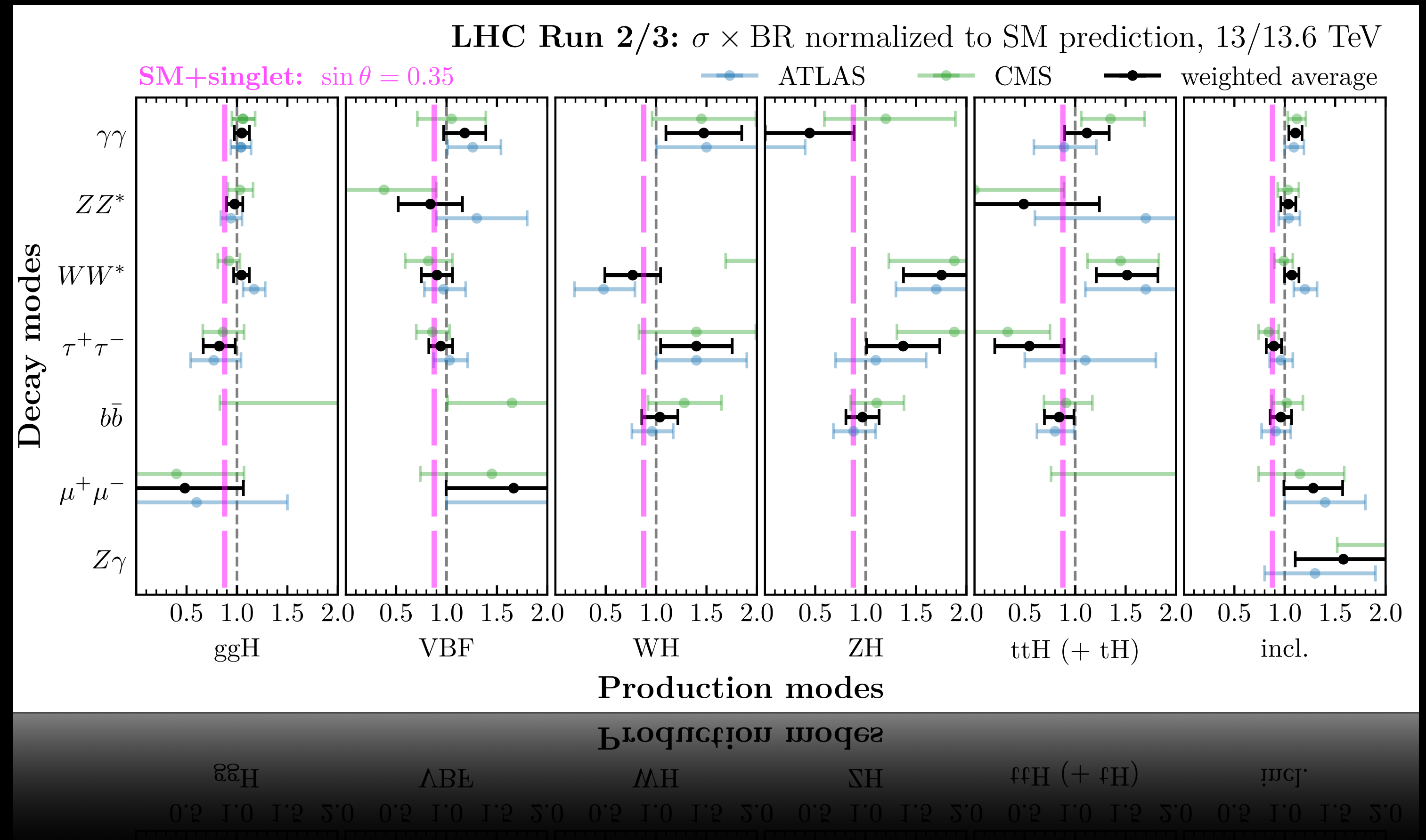
Data: [CMS-PAS-HIG-21-018] [ATLAS-CONF-2025-006], [CMS, 2509.22535] [ATLAS, 2207.00092] [ATLAS and CMS, 2309.03501]

The simplest solution

Work of Thomas Biekötter

 H
+ 2nd scalar
singlet

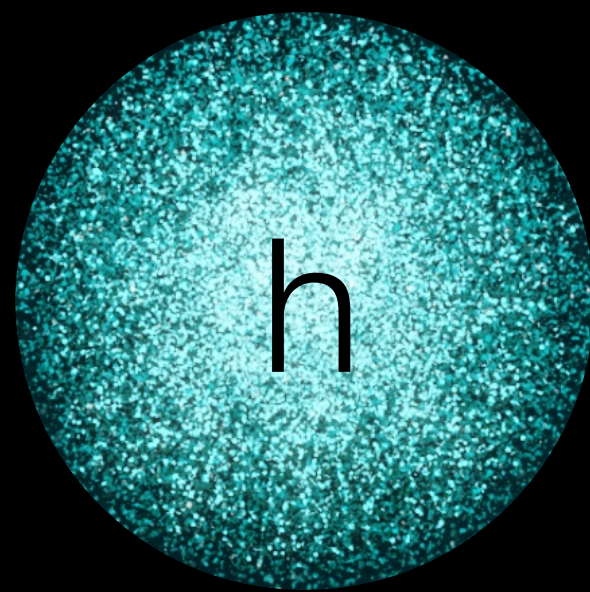
 S



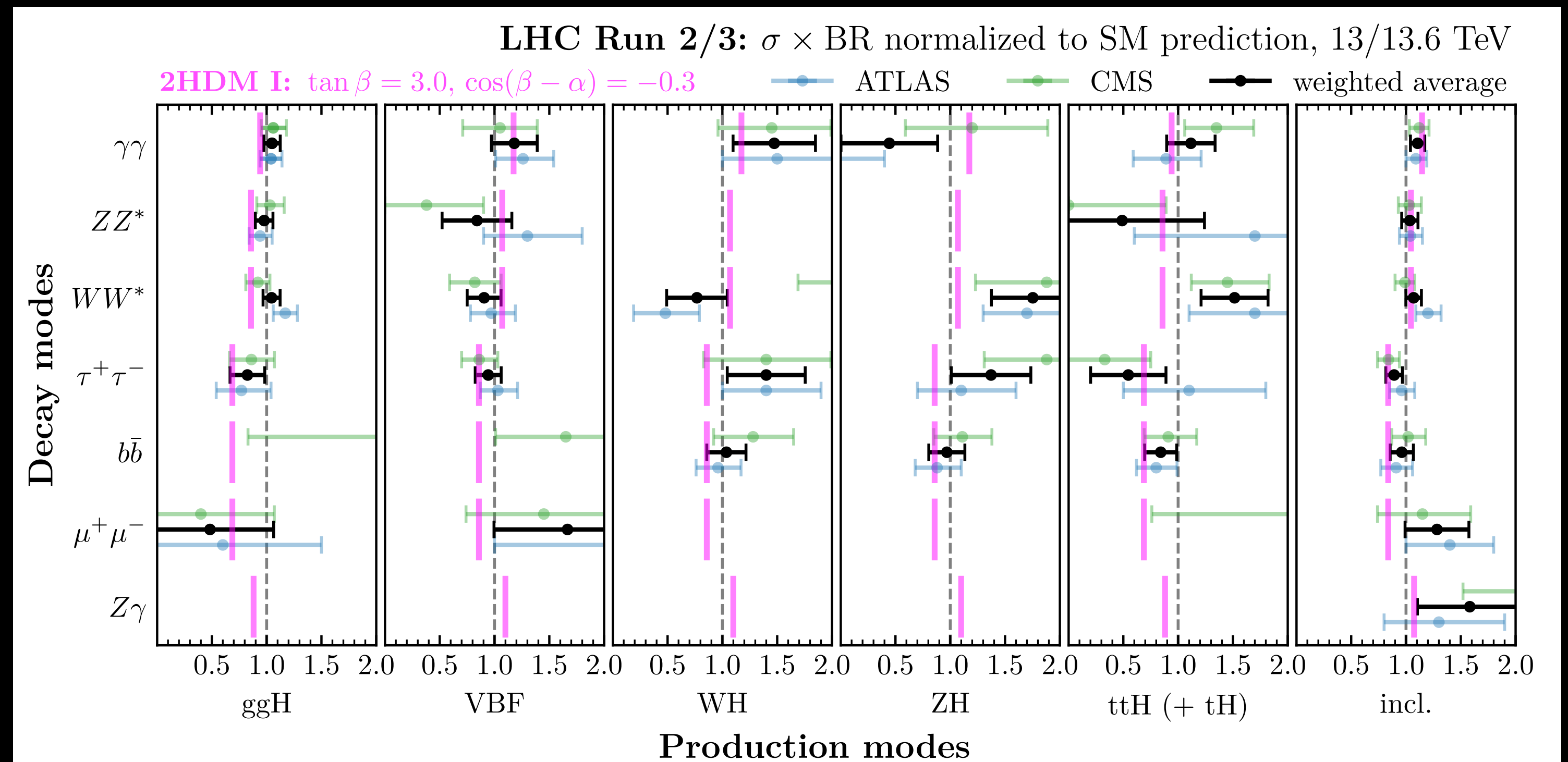
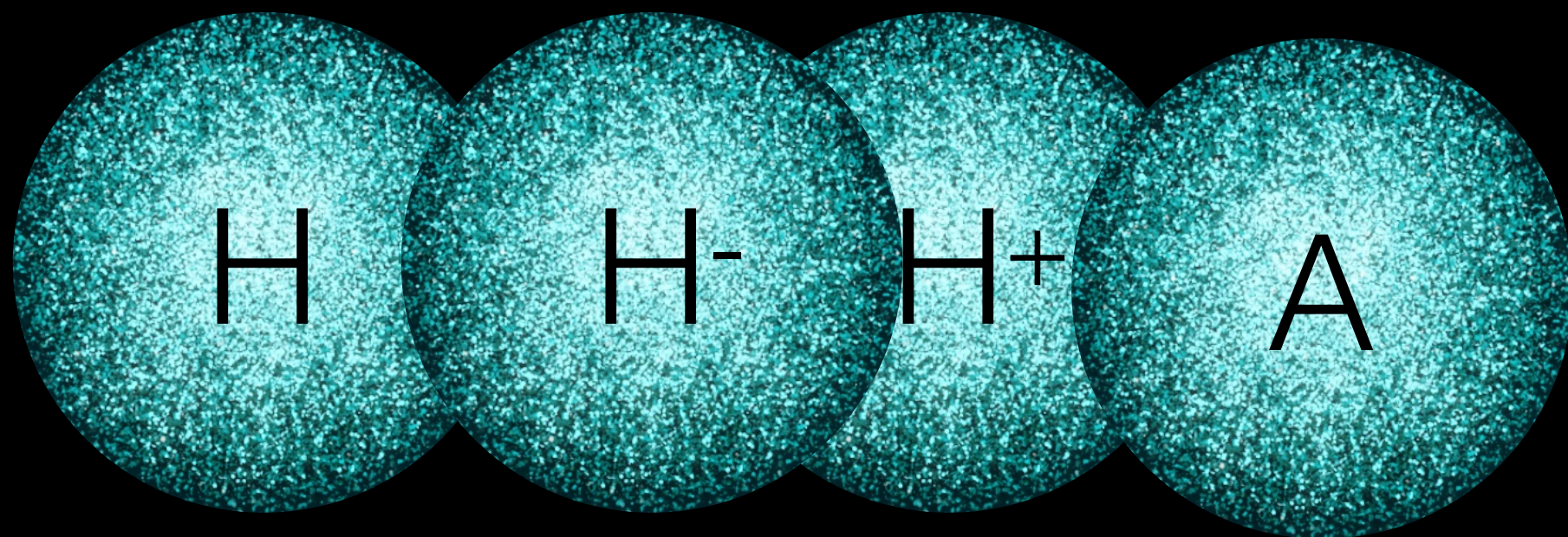
Data: [CMS-PAS-HIG-21-018] [ATLAS-CONF-2025-006], [CMS, 2509.22535] [ATLAS, 2207.00092] [ATLAS and CMS, 2309.03501]

The simplest solution

Work of Thomas Biekötter



+ 2nd scalar doublet

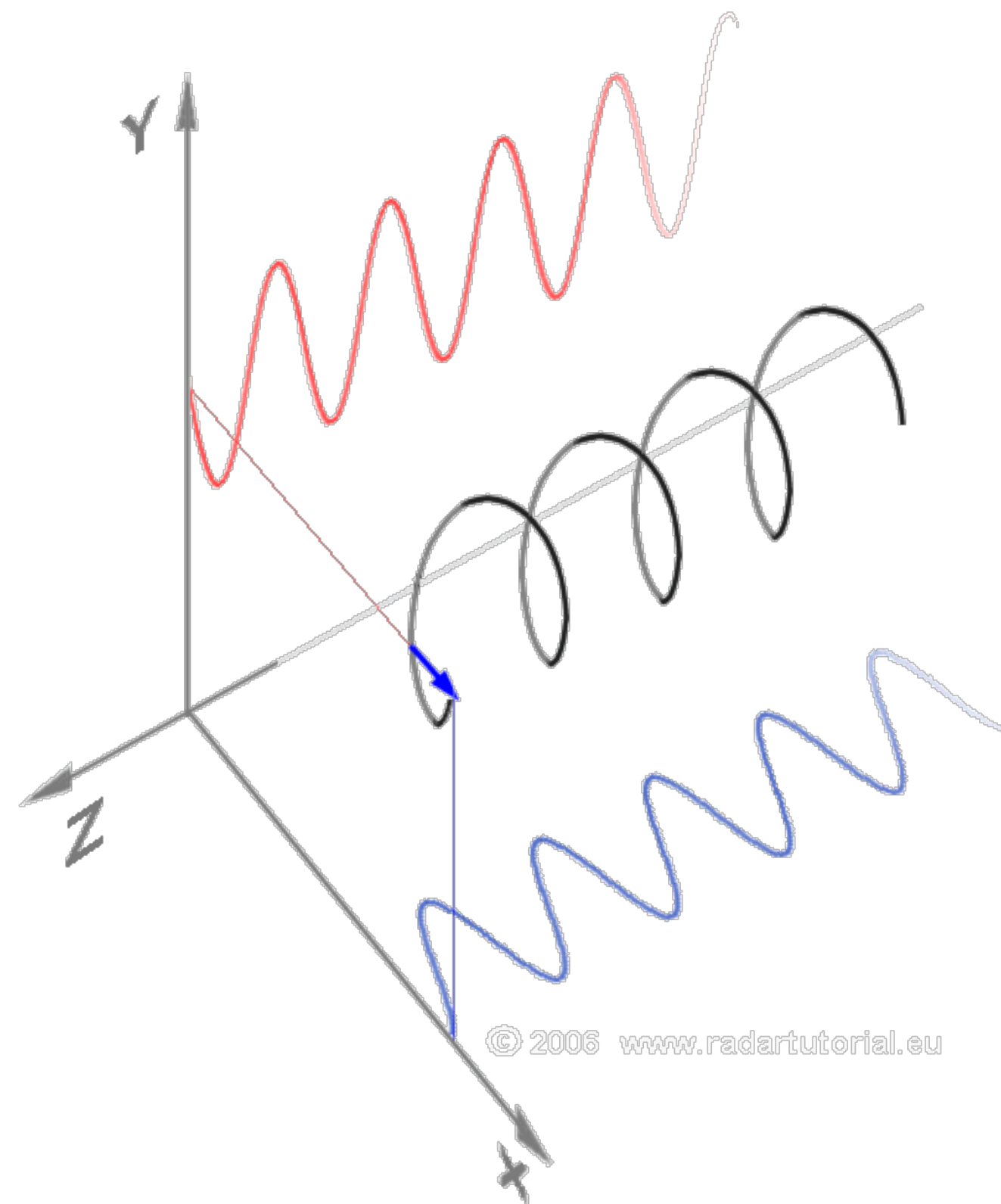


Production modes					
ggH	VBF	WH	ZH	ttH (+ tH)	incl.
0.2 1.0 1.2 5.0	0.2 1.0 1.2 5.0	0.2 1.0 1.2 5.0	0.2 1.0 1.2 5.0	0.2 1.0 1.2 5.0	0.2 1.0 1.2 5.0

Data: [CMS-PAS-HIG-21-018] [ATLAS-CONF-2025-006], [CMS, 2509.22535] [ATLAS, 2207.00092] [ATLAS and CMS, 2309.03501]

Polarisation for massive states

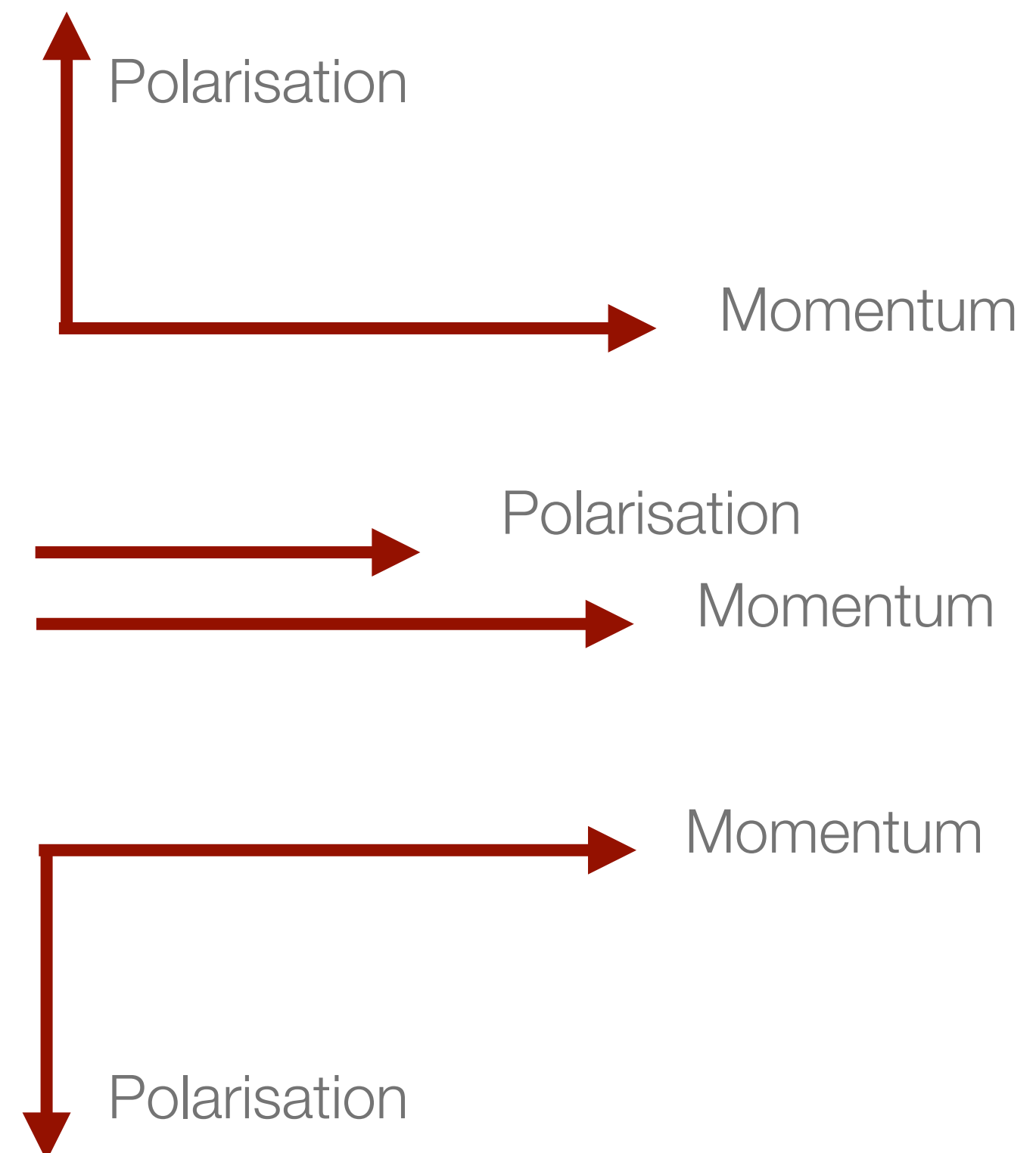
For photons, there are two perpendicular polarisation states



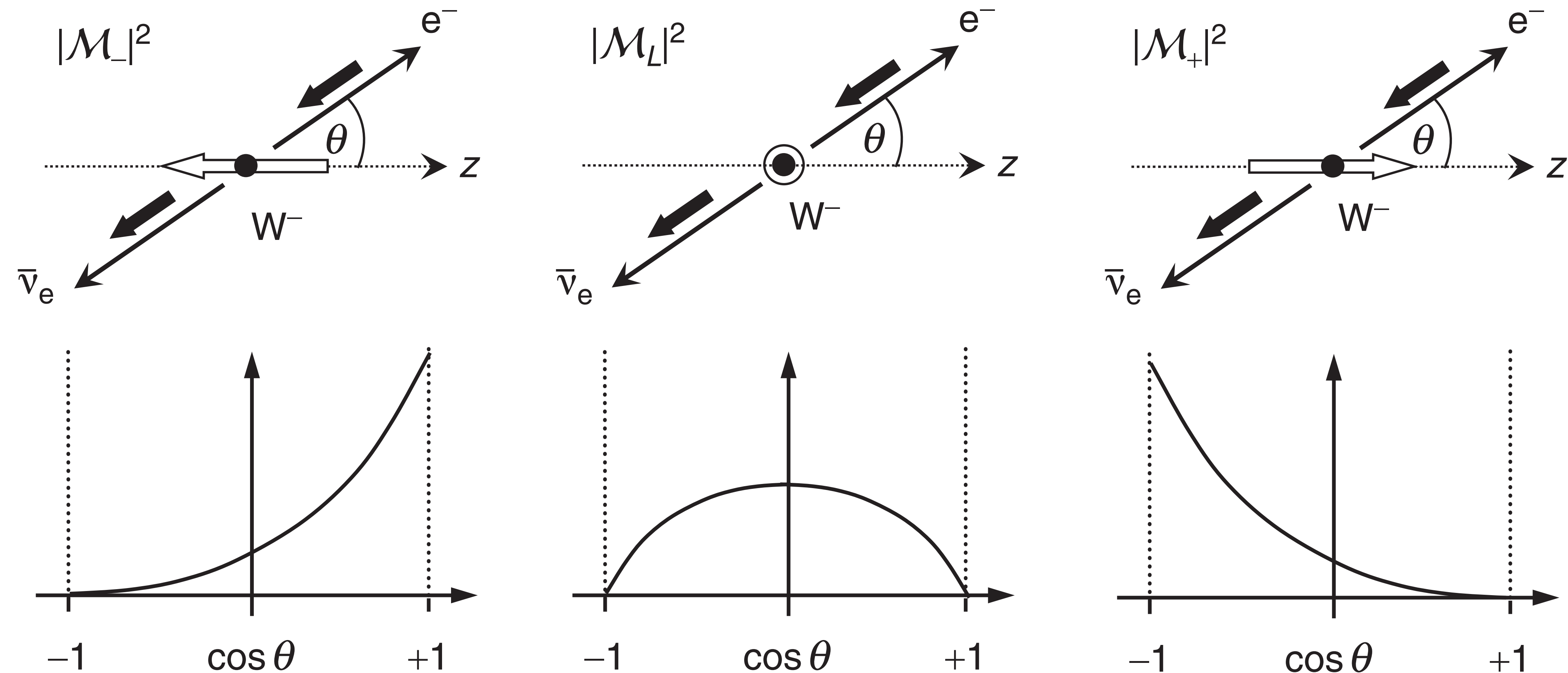
Massive particles have a rest frame!

There are three spin projections: $m_s = -1, 0, +1$

Leading to three polarization states

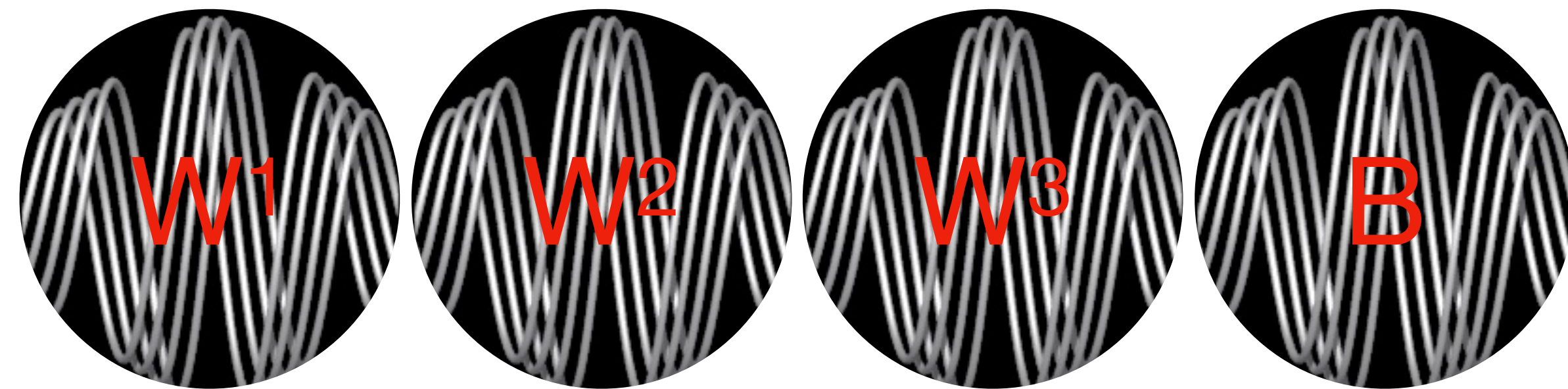


Measuring polarisation



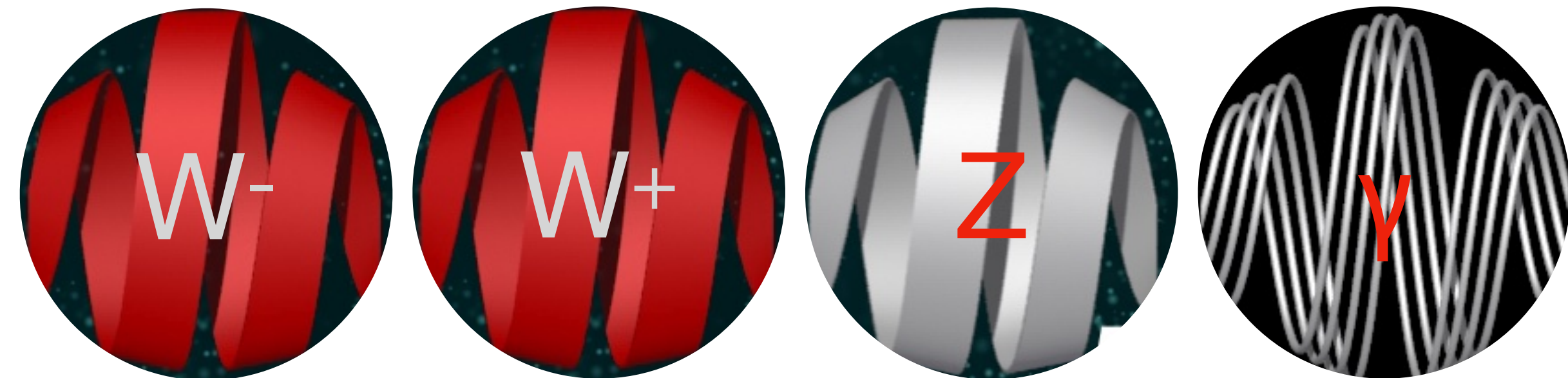
A brief aside... Counting degrees of freedom

Before EW symmetry breaking



Gauge sector: 4 massless boson x 2 Helicity states = 8 d.o.f.

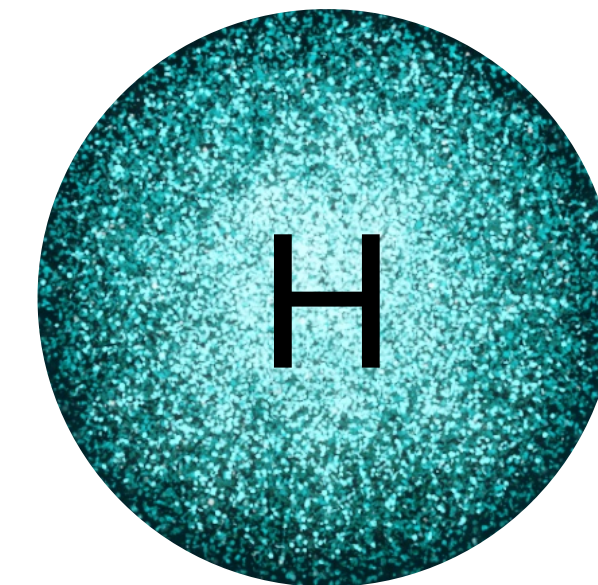
After EW symmetry breaking



Gauge sector: 3 massive bosons x 3 polarisations +
1 massless boson x 2 polarisations = 11 d.o.f.

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

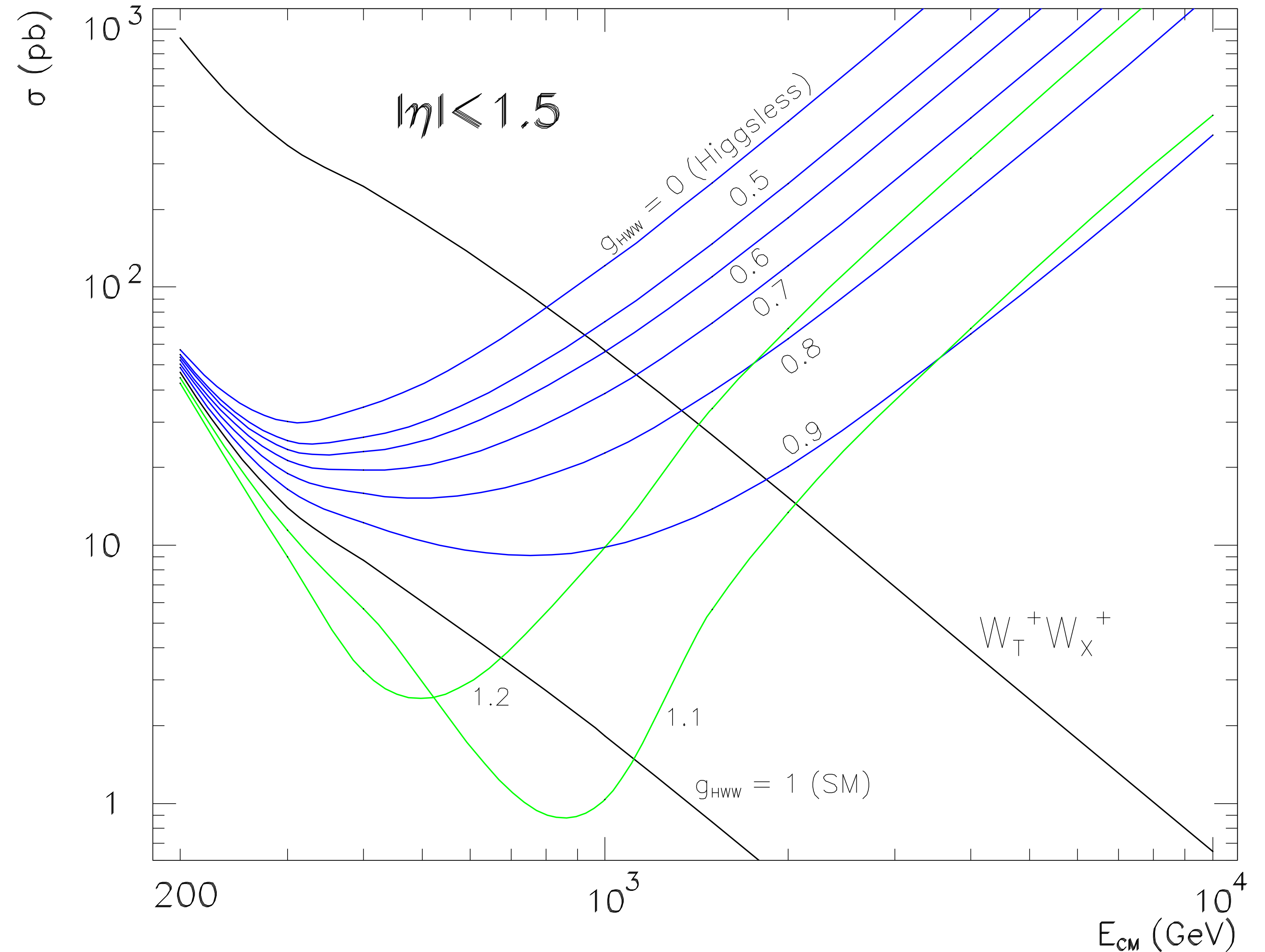
Higgs sector: 4 real scalars = 4 d.o.f



Higgs sector: 1 real scalars: 1 d.o.f

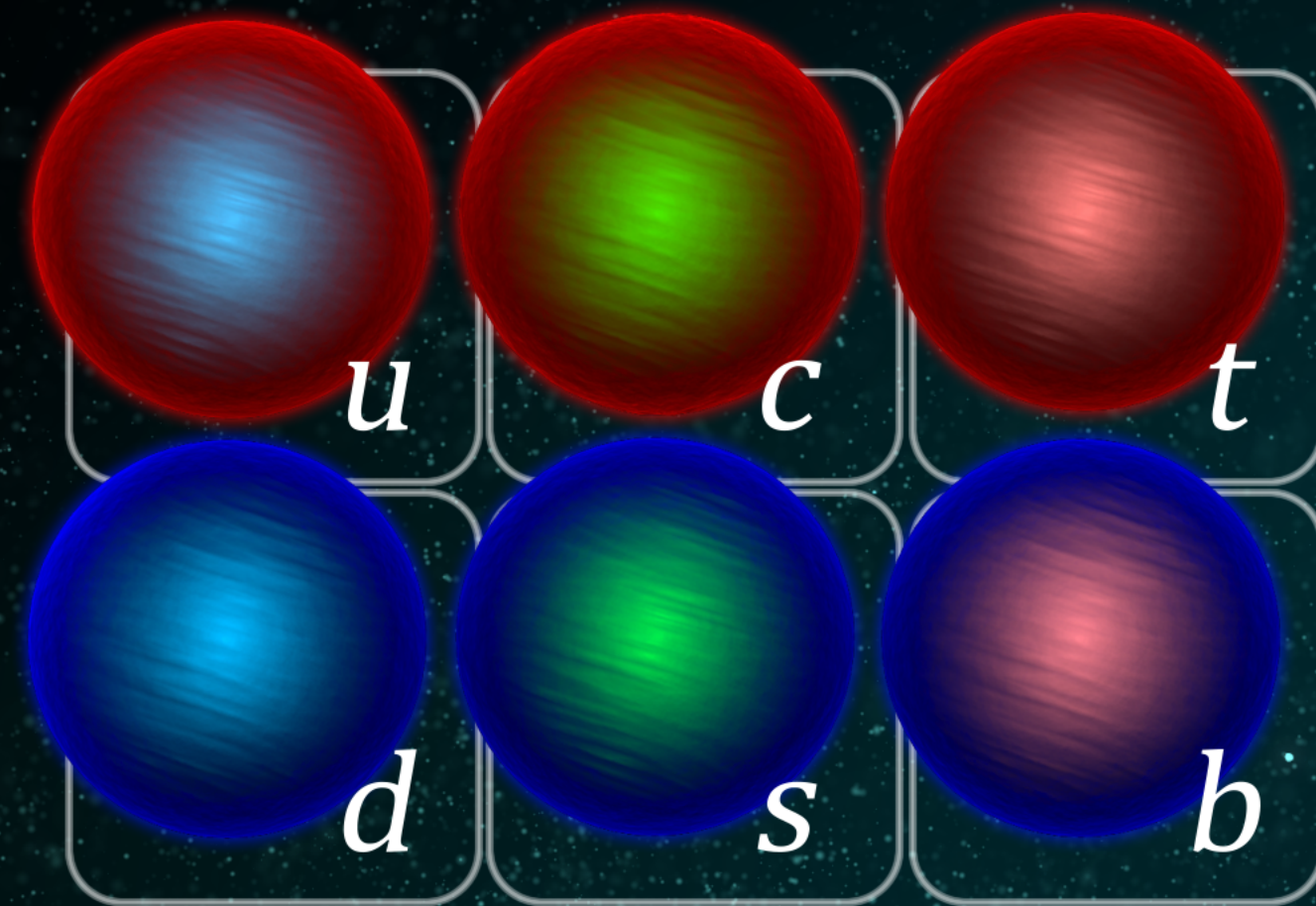
$W_L^+ W_L^+ \rightarrow W_L^+ W_L^+$ with modified Higgs couplings

The longitudinal polarisation carries all the sensitivity

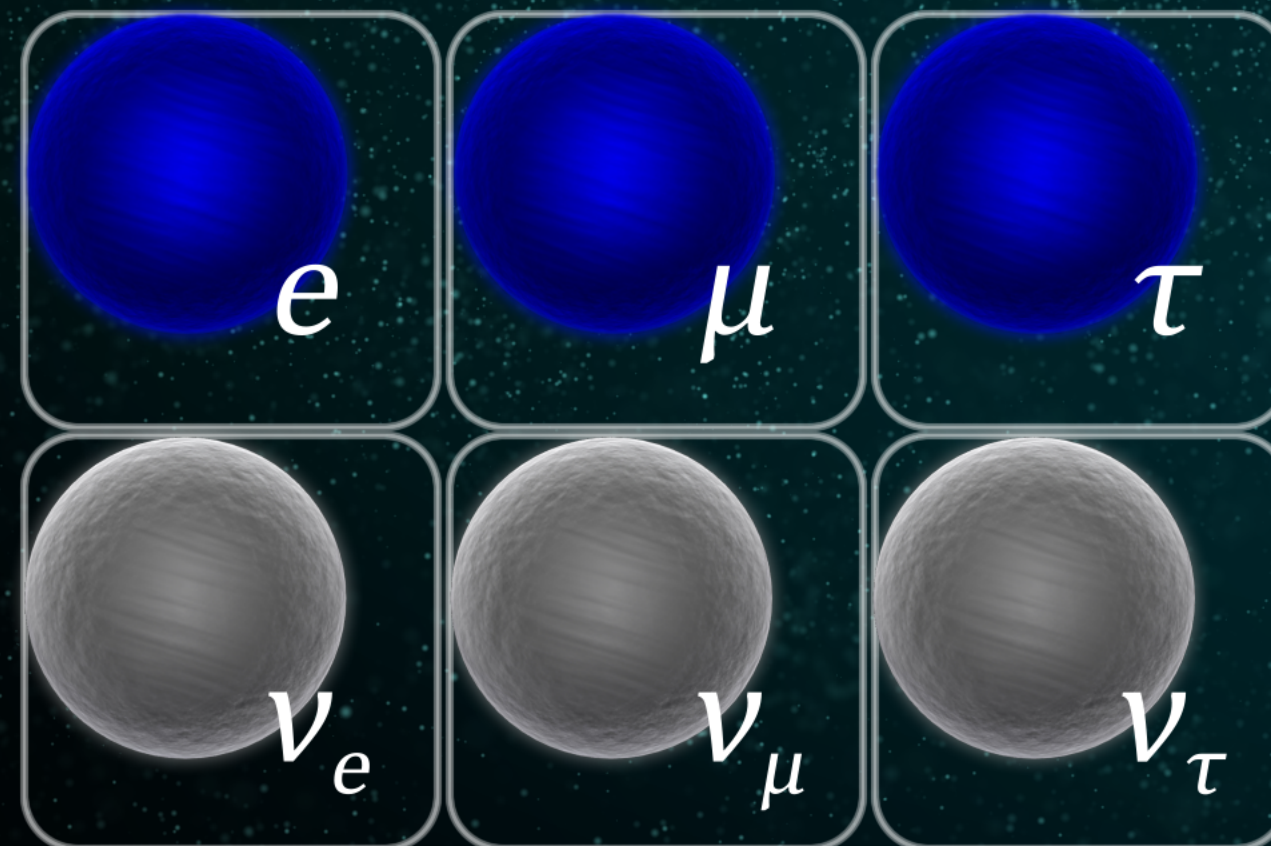


Let's measure it!

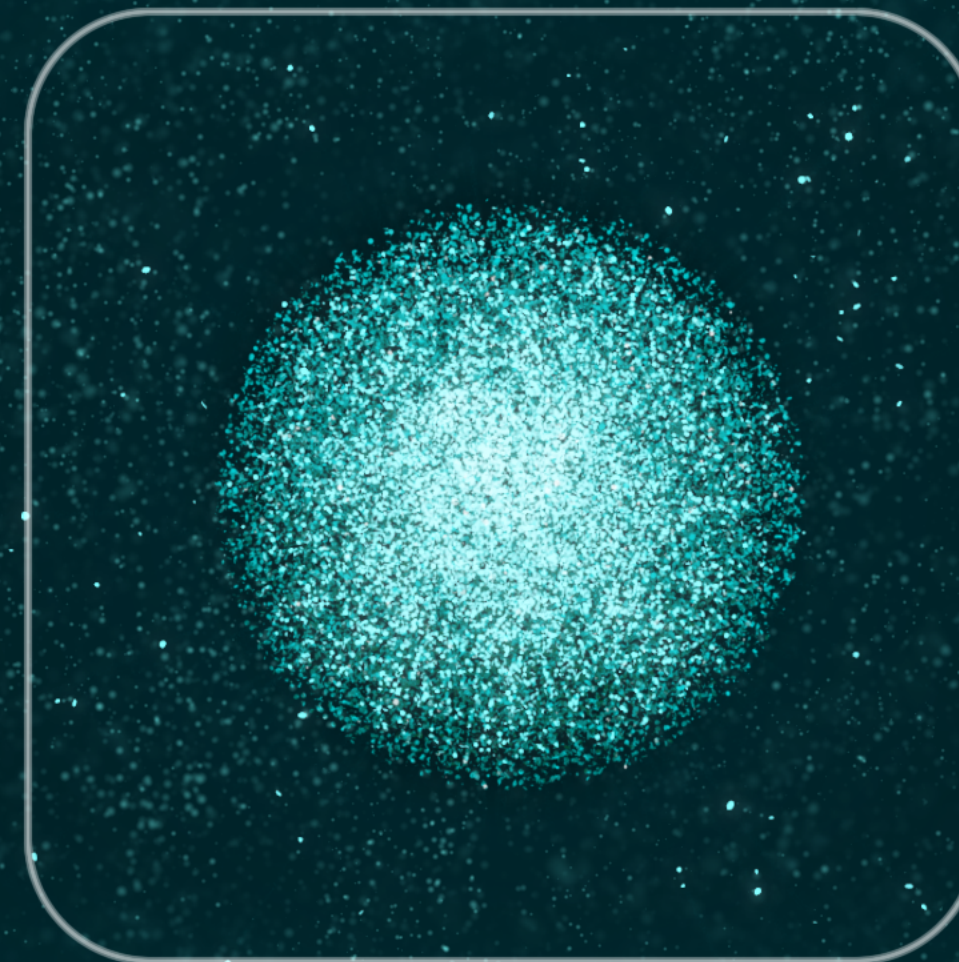
Theory's view of the SM



Quarks



Leptons

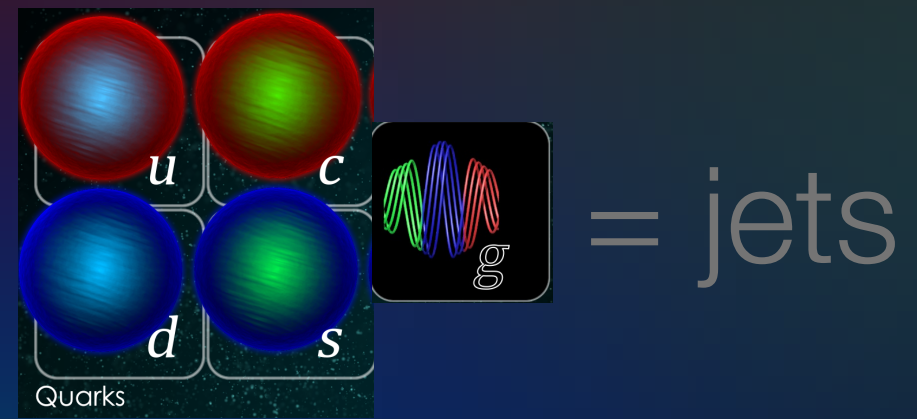


Higgs boson



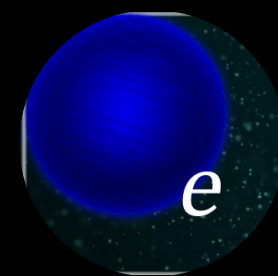
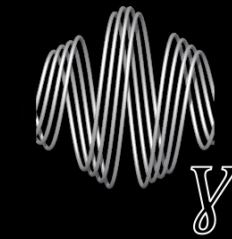
Forces

Detector's view of the SM



Directly

Indirectly

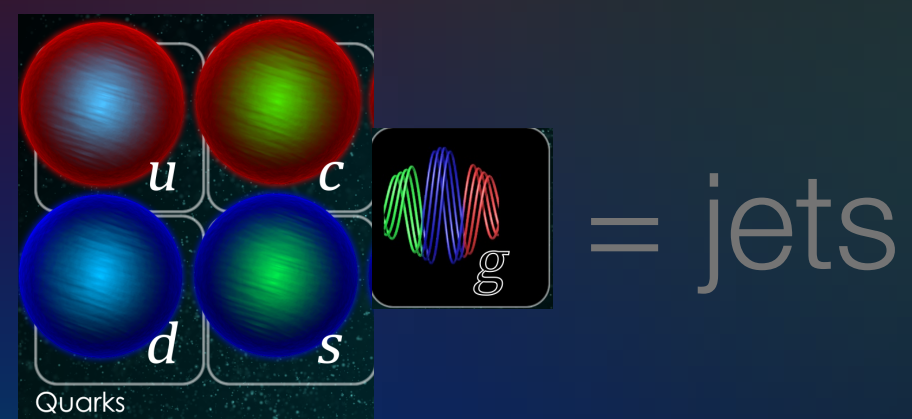


τ

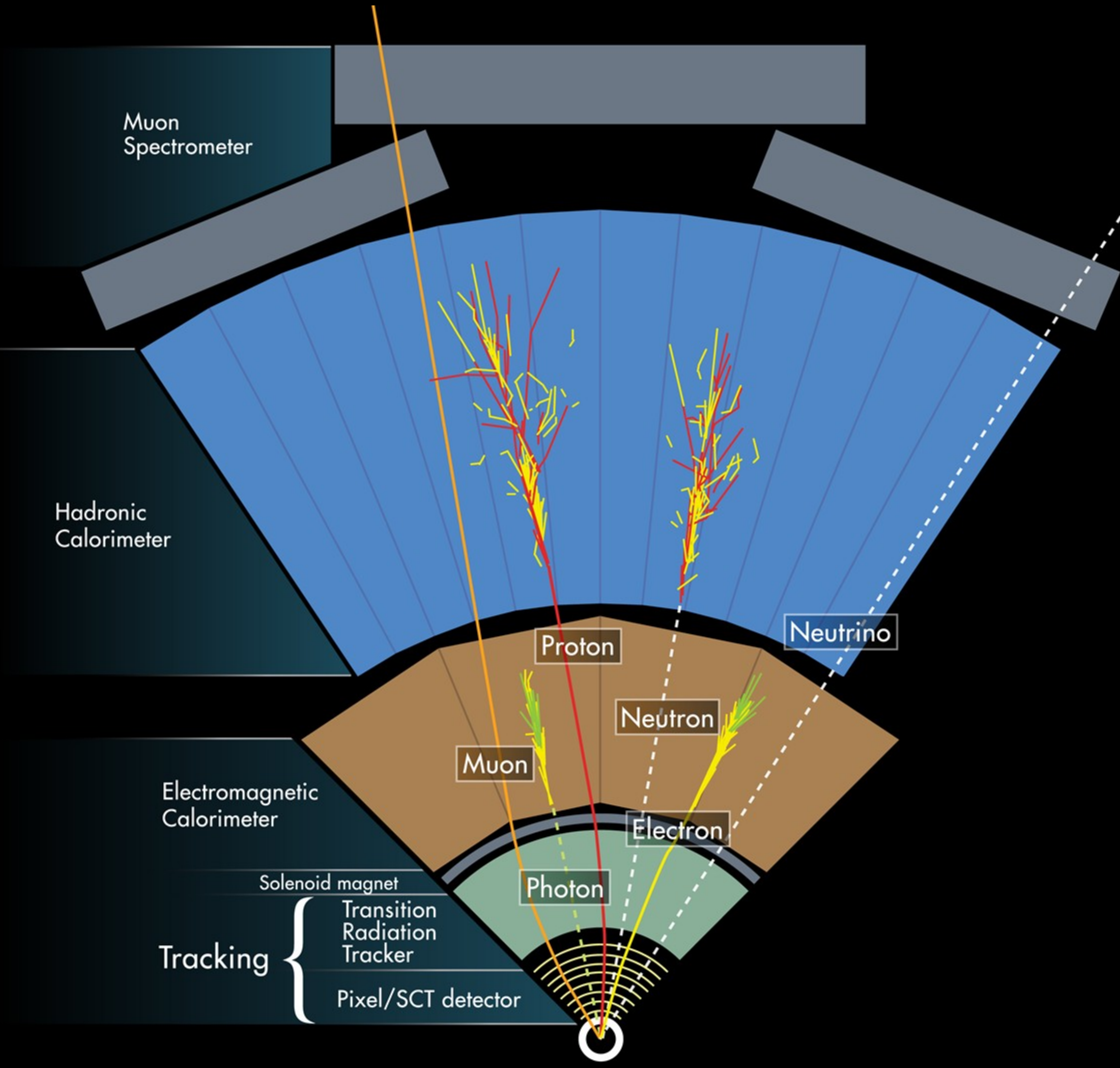
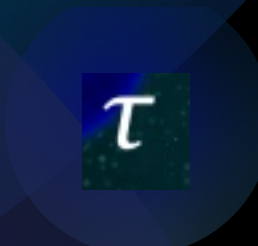
b-quarks

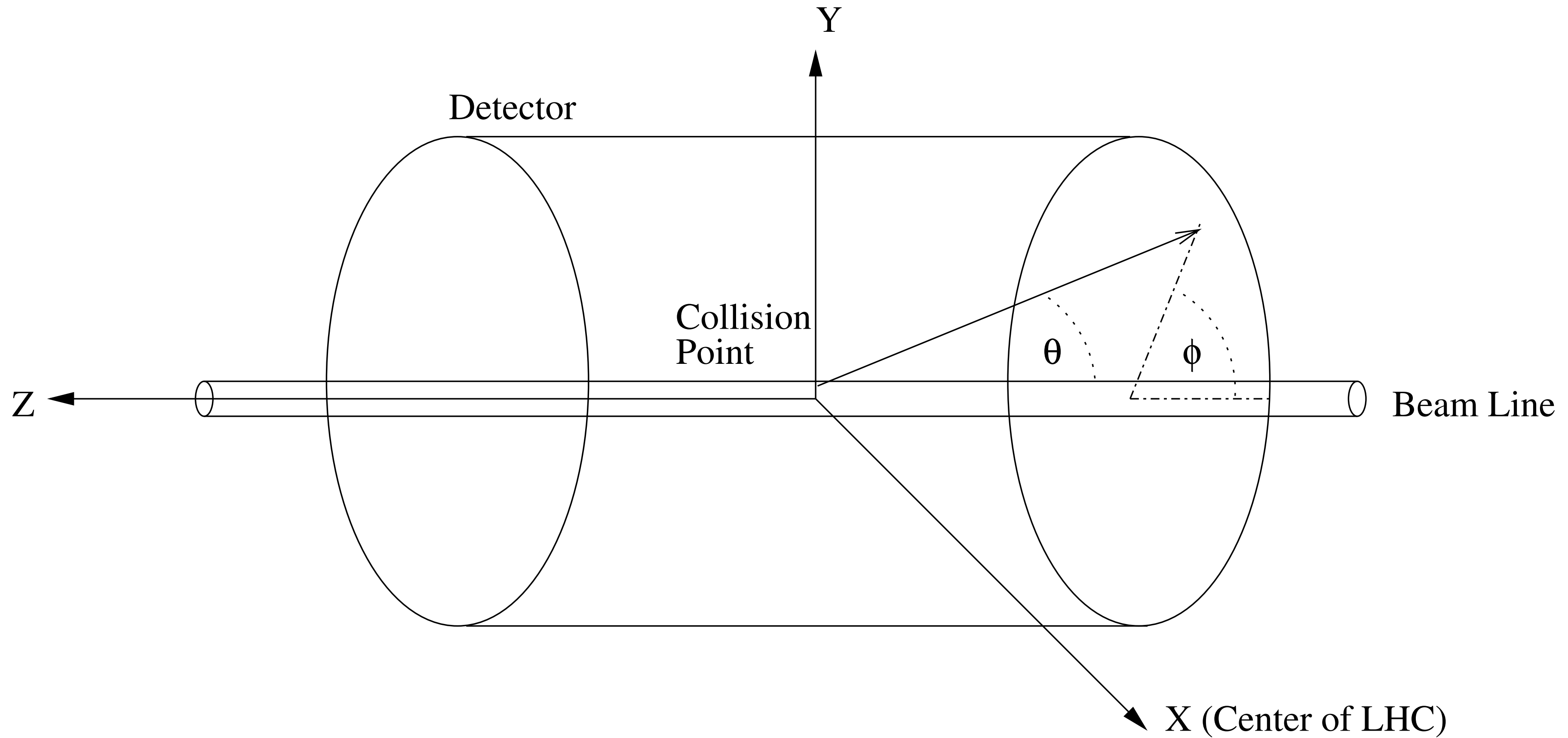


Detector's view of the SM



b-quarks





Pseudo rapidity

$$\eta = -\ln \left(\tan \frac{\theta}{2} \right)$$

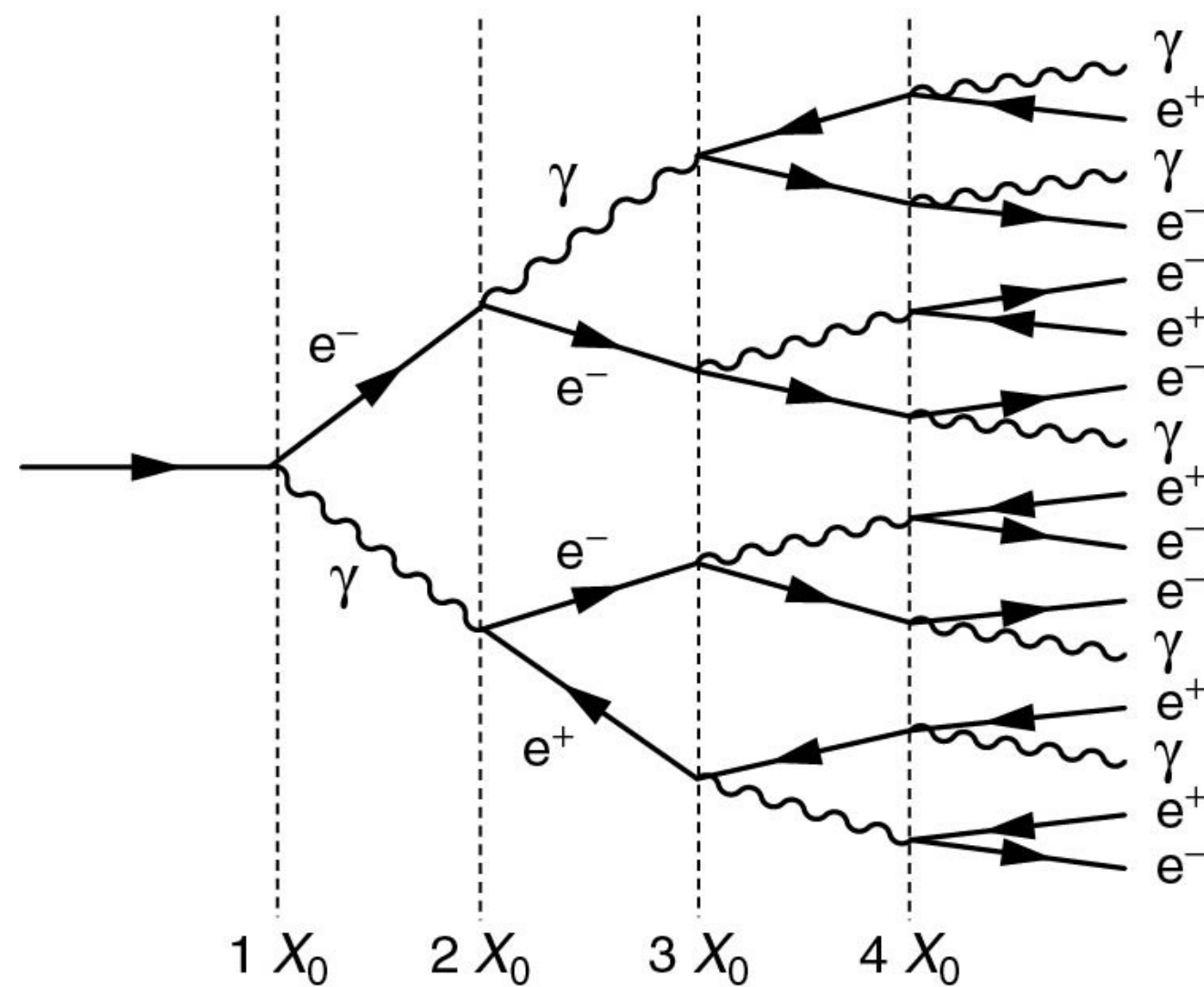
E, P in transverse plane

$$p_T = P \sin \theta$$

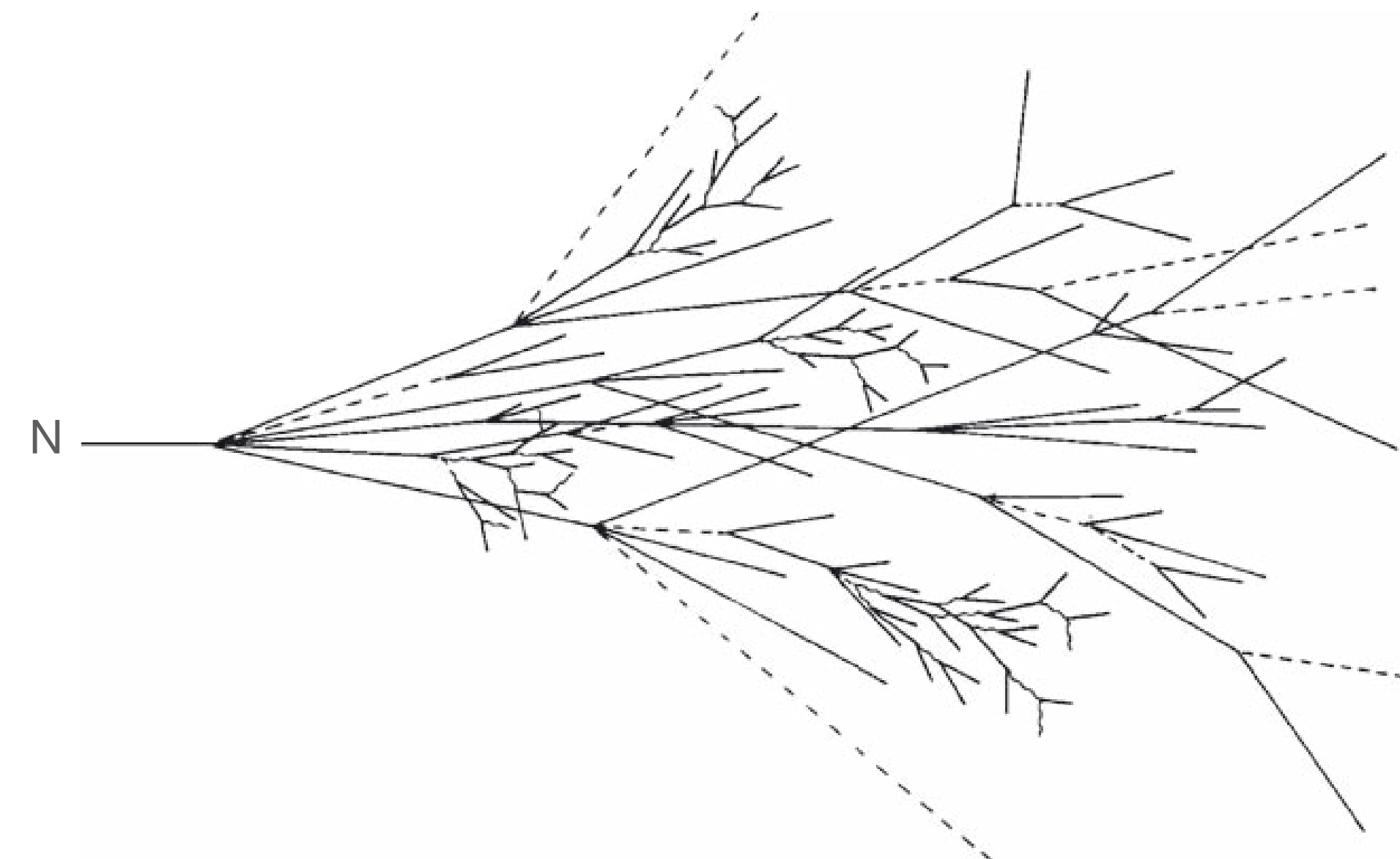
$$E_T = E \sin \theta$$

So... Experimentally not all particles are equal

- Muons, electrons, photons are most precise, hadrons less so
- Comes down to how particles lose energy in material

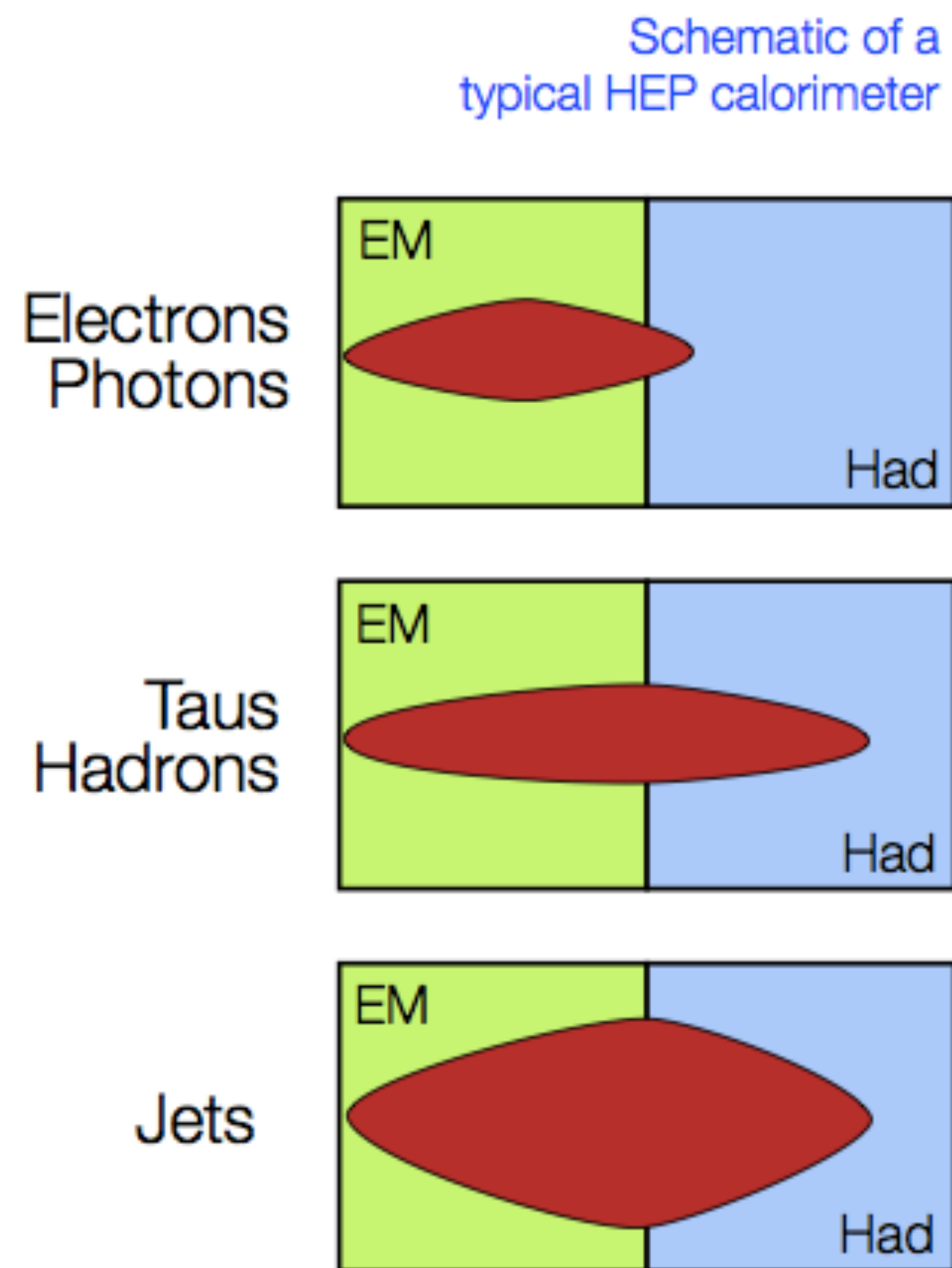


EM shower - many interactions, fluctuations are small (i.e. EM showers look similar)



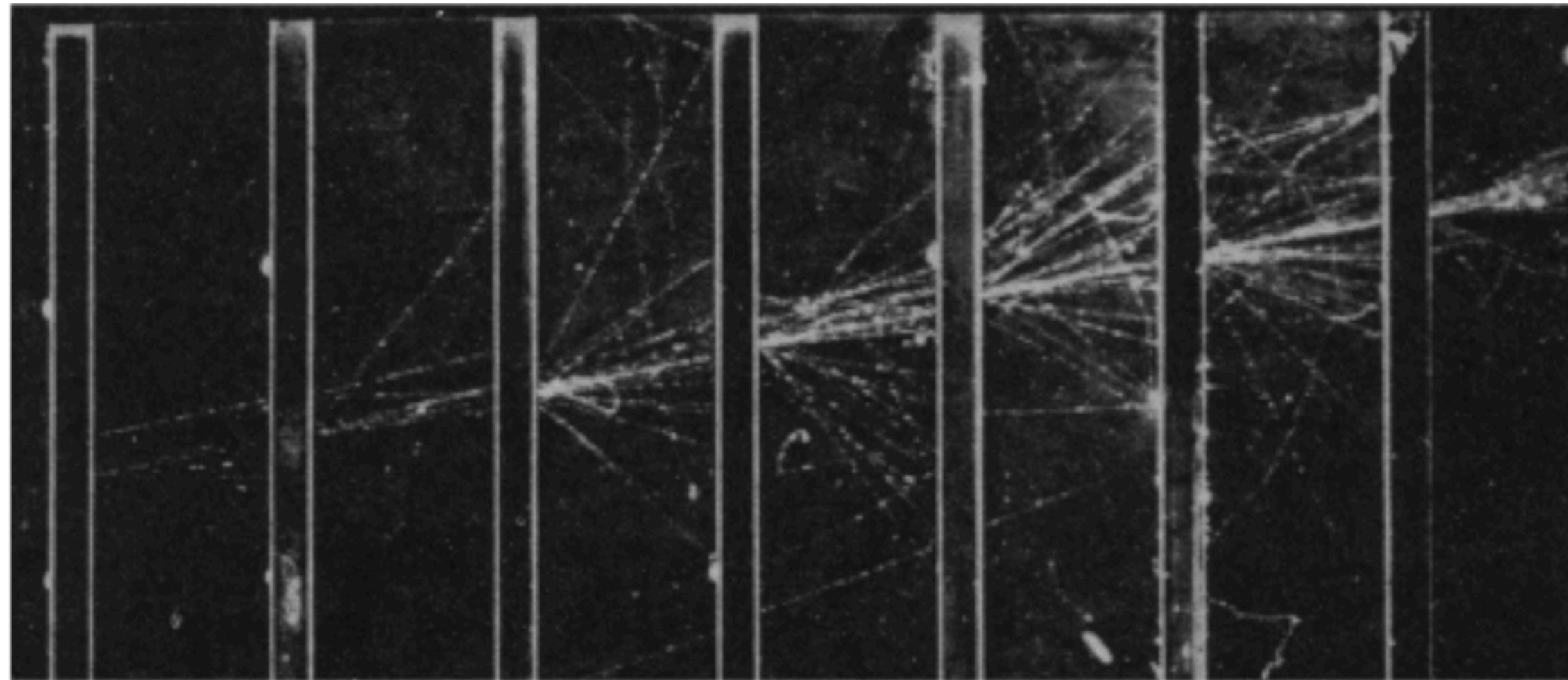
Hadronic shower - energy loss via strong interaction and ionisation. Final state varies, large shower-to-shower variations

What that means in my detector



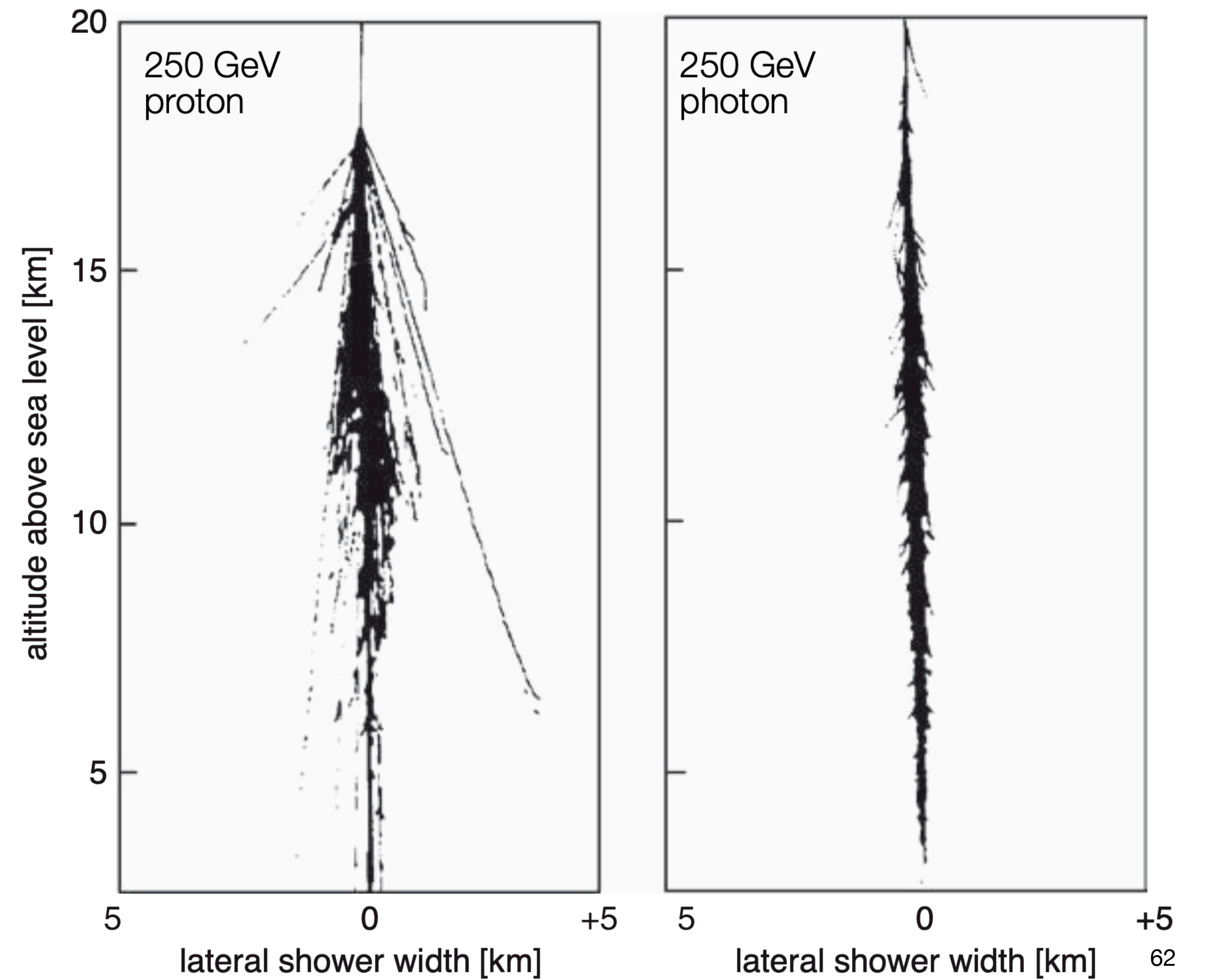
- Electrons lose energy quickly, showers are short and compact
- Hadrons penetrate material deeper ... “the foil is essentially empty”
→ HCAL bigger than ECAL
- Depth segmentation helps to distinguish electrons versus jets

Some examples



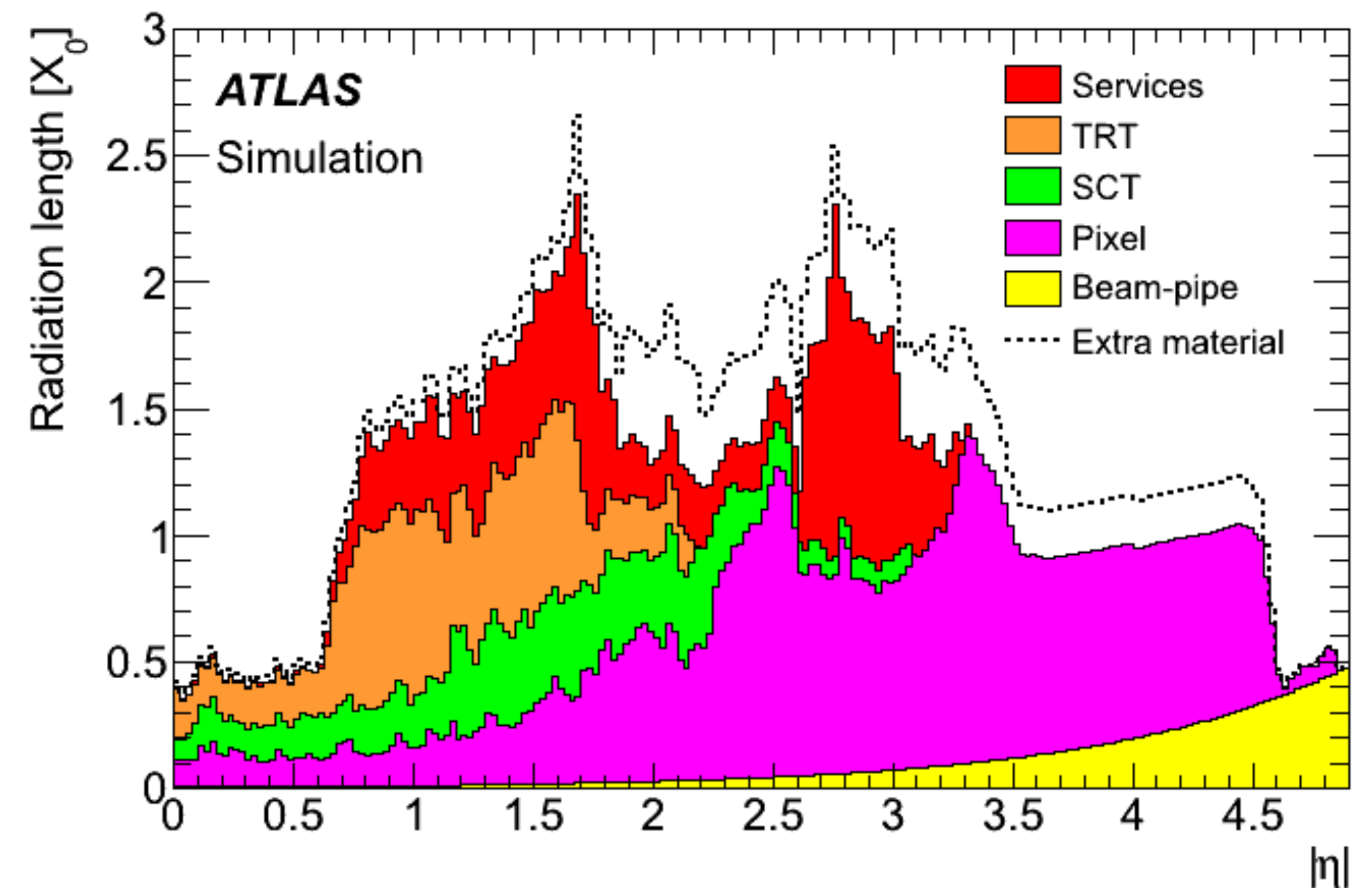
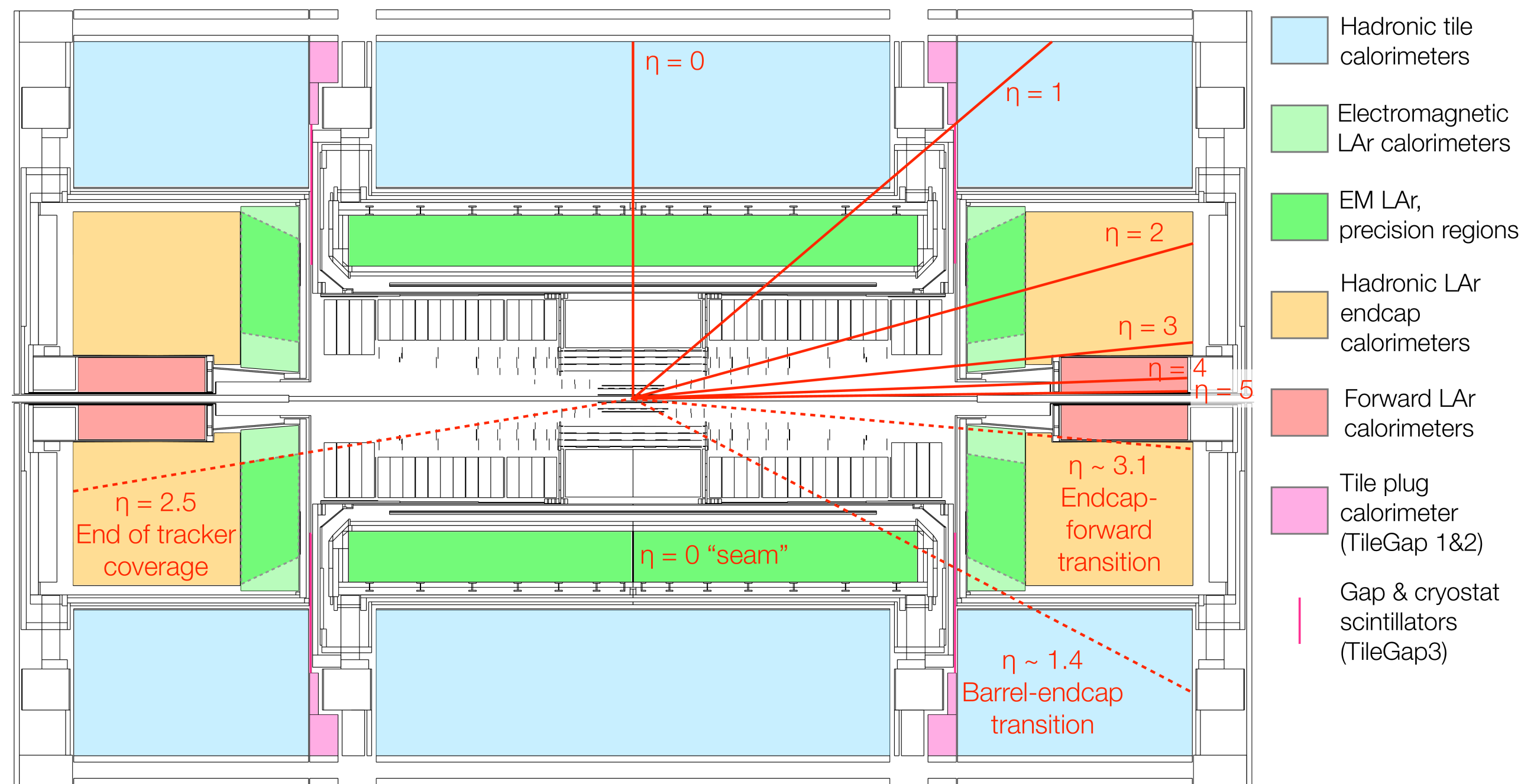
EM shower in a sampling calorimeter

Air shower simulation



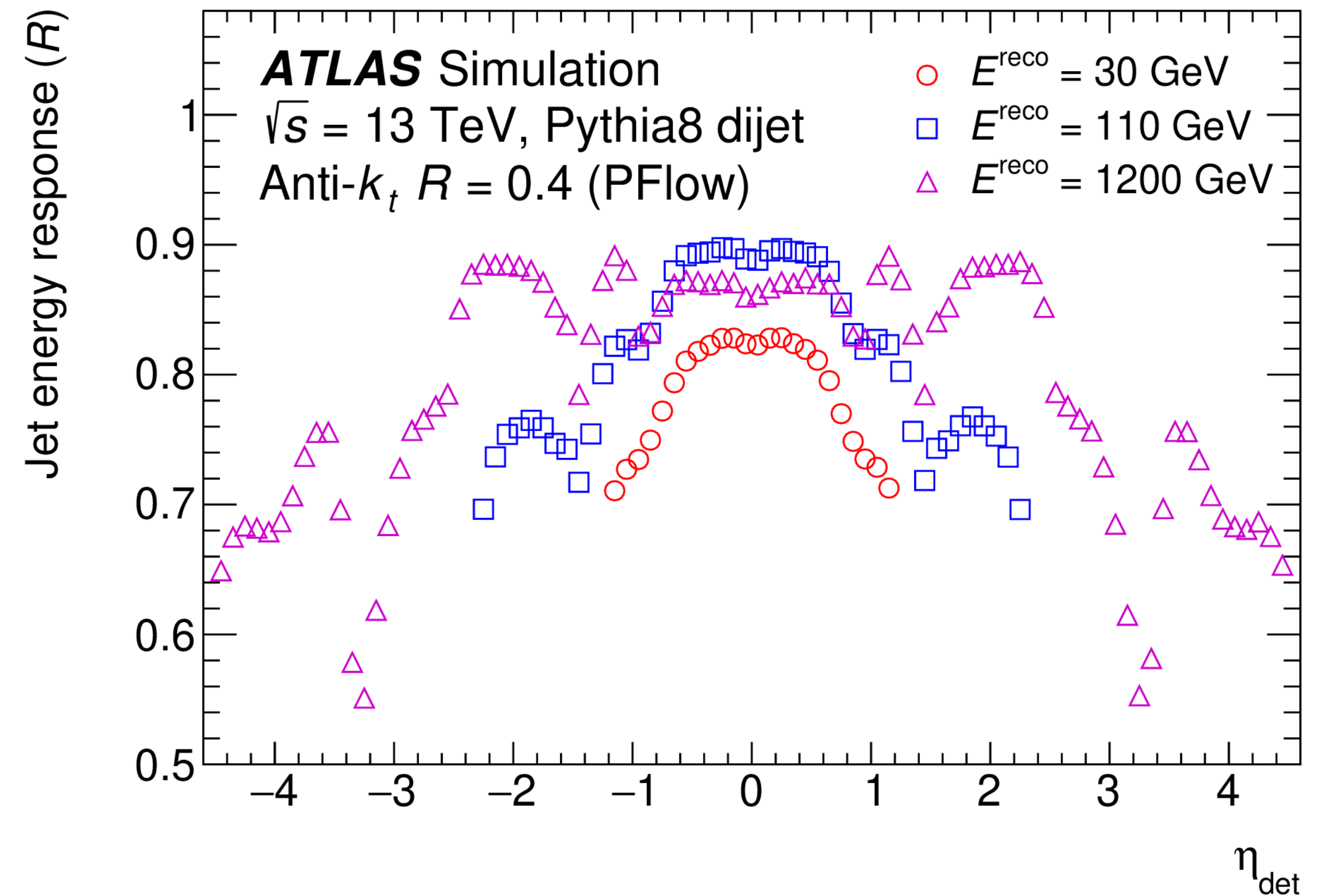
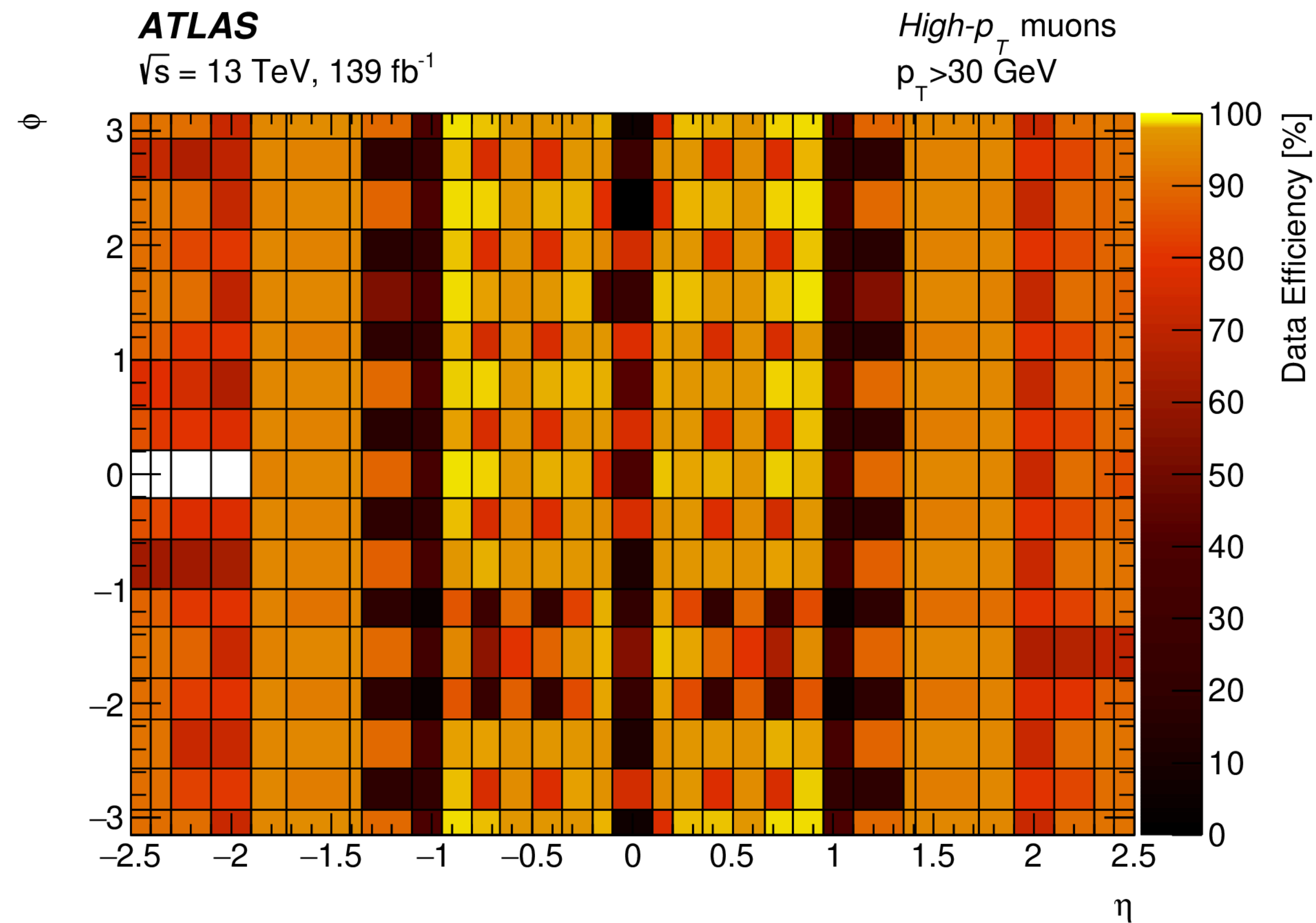
The detector also gets in the way of itself

- Must account and correct for many effects - like pile-up, different detector technologies, material budget



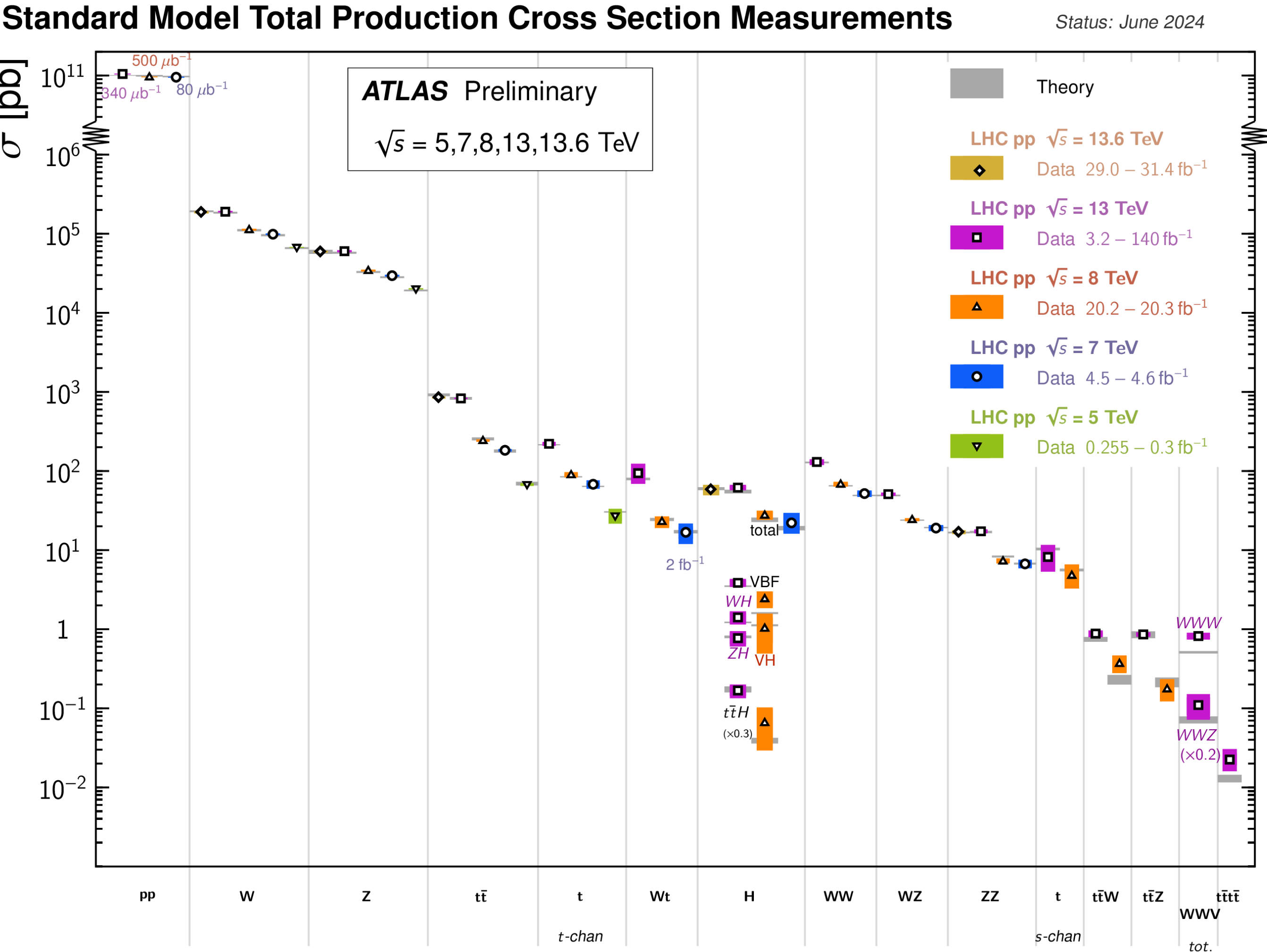
The detector also gets in the way of itself

- Often have strong η dependence, some corrections can be large

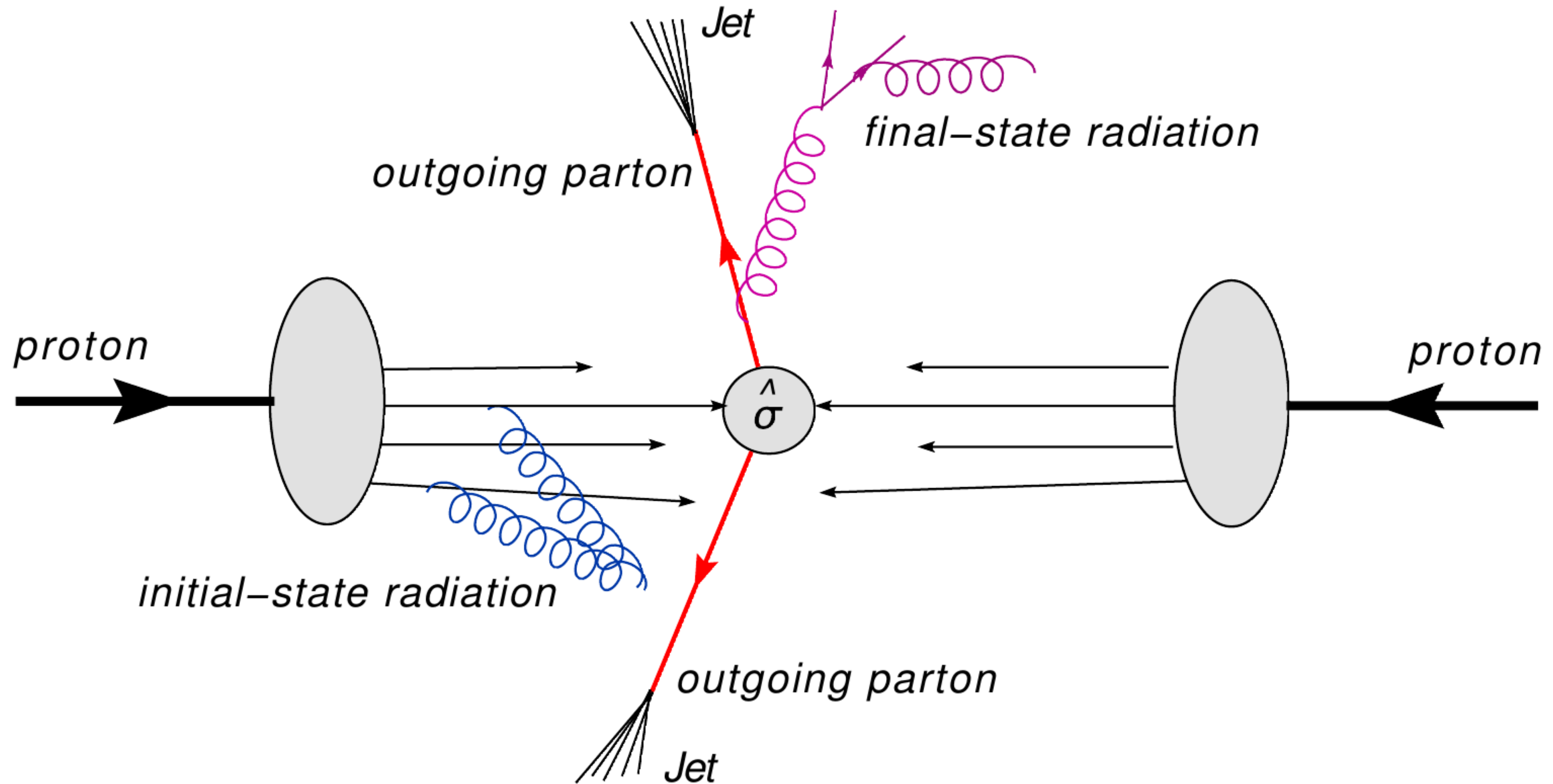


So... Theoretically not all particles are equal

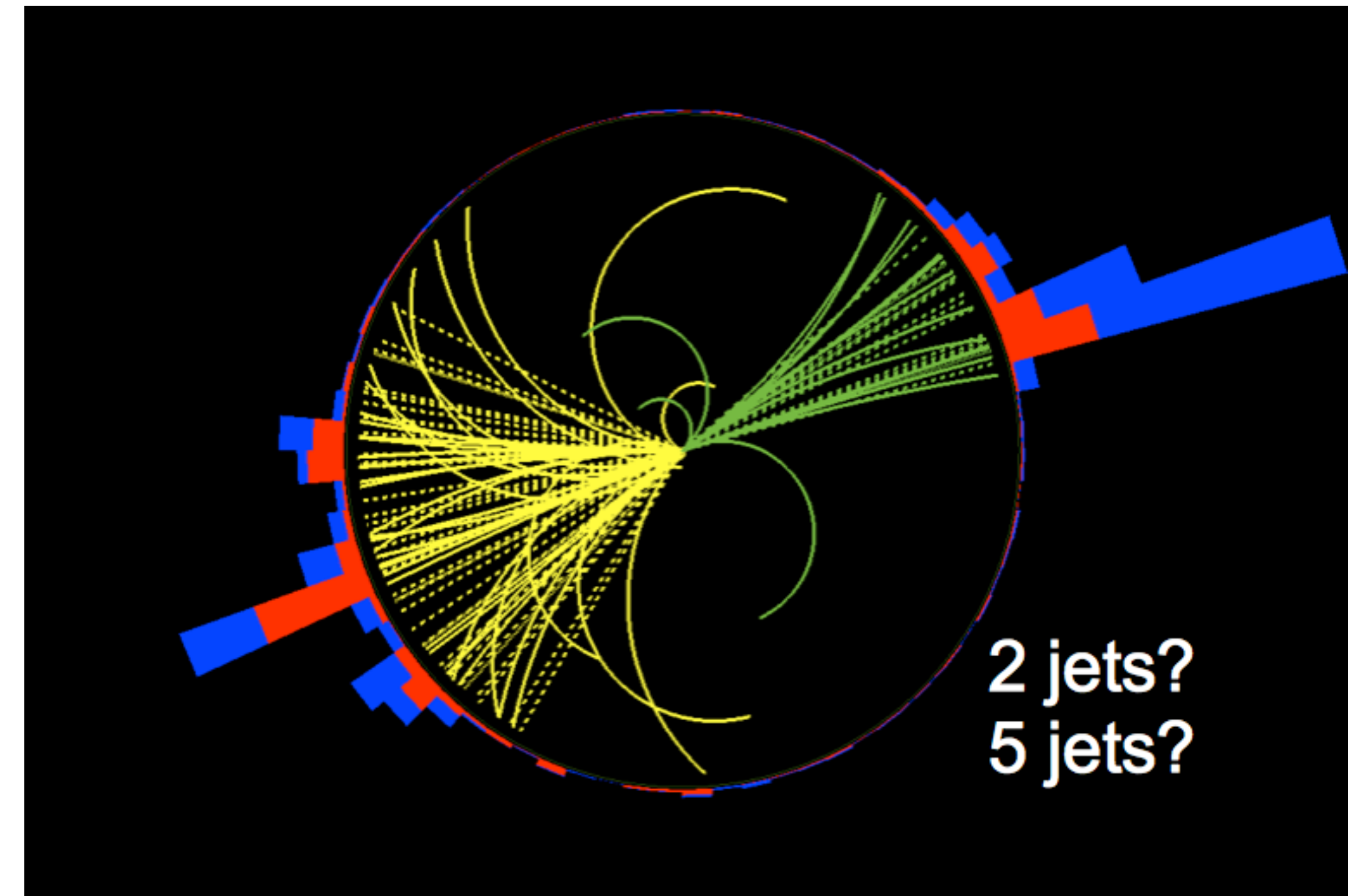
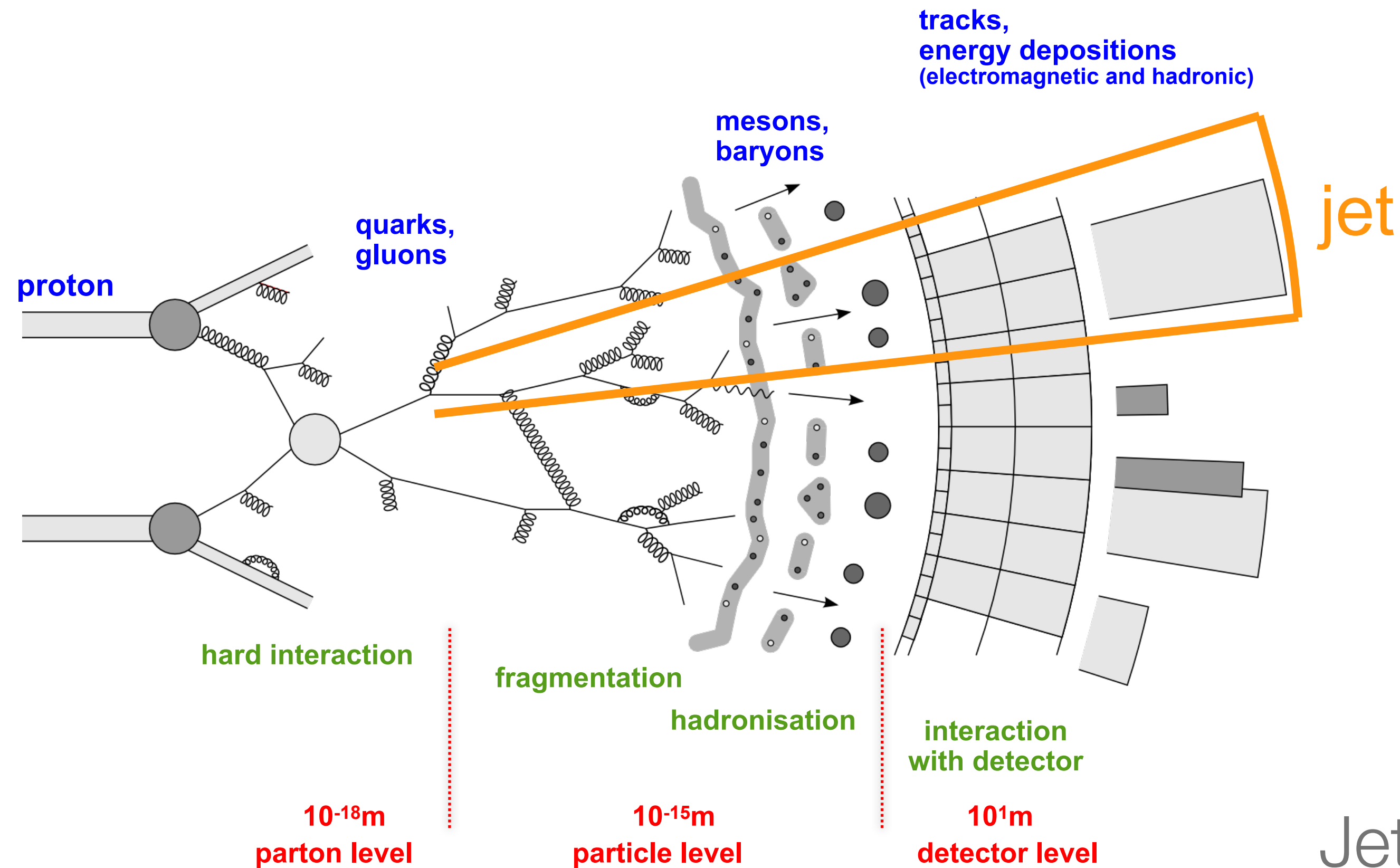
- QCD dominates (i.e. we produce a lot of jets)
- For the W/Z decays to hadrons dominate
- For Higgs, decays to b-quarks and taus dominate



So... Protons are great, but also a mess

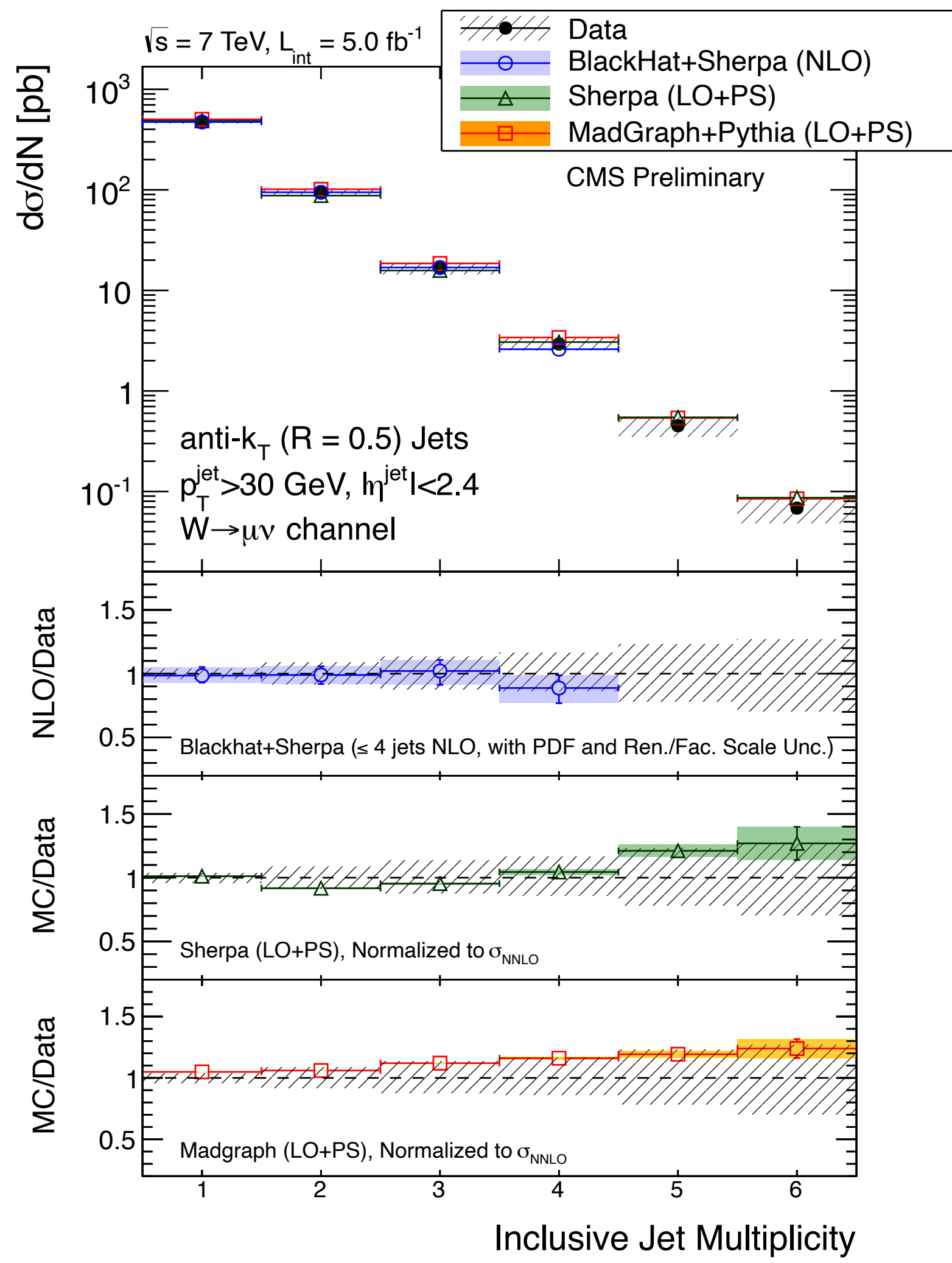


To make calculations tractable, we break this up

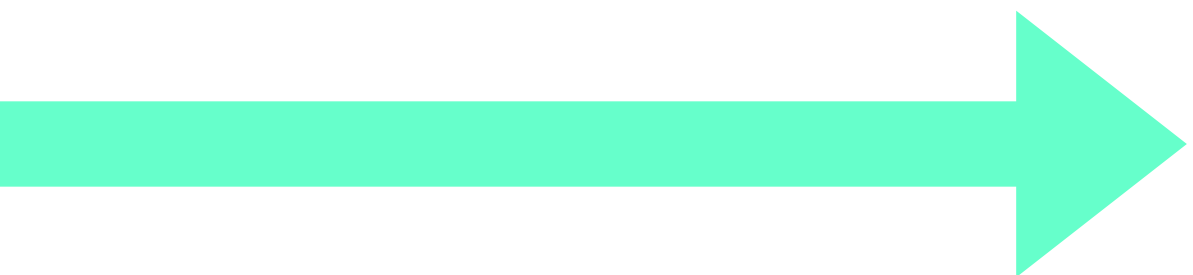


Jet reconstruction is ambiguous
In the end a 'jet' is what you define it to be

ATLAS and CMS jet results can not be compared directly



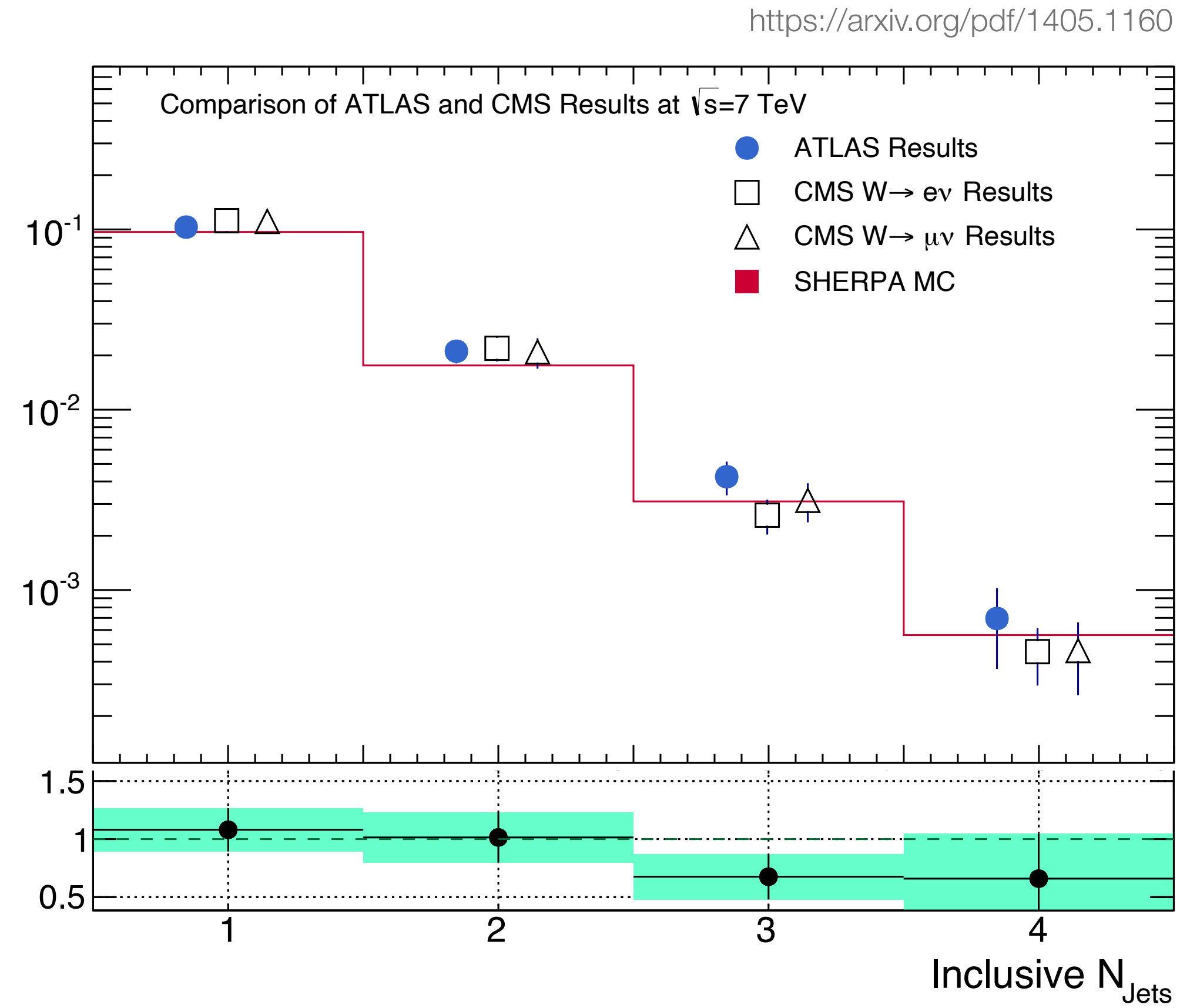
Putting ATLAS and CMS jet results on the same plot



requires corrections up to 25%

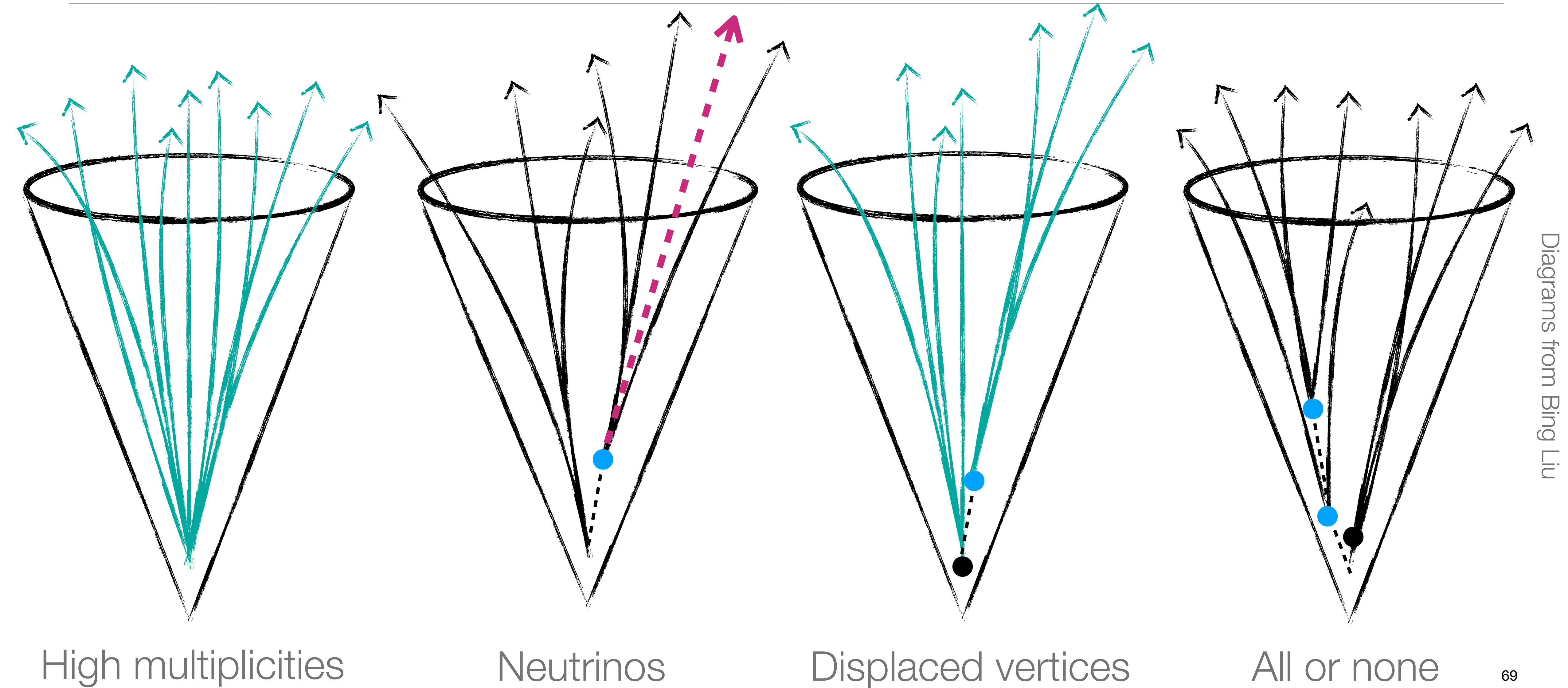
$$1/\sigma_{\text{fid}} \times \sigma(\geq N_{\text{jets}})$$

Ratio

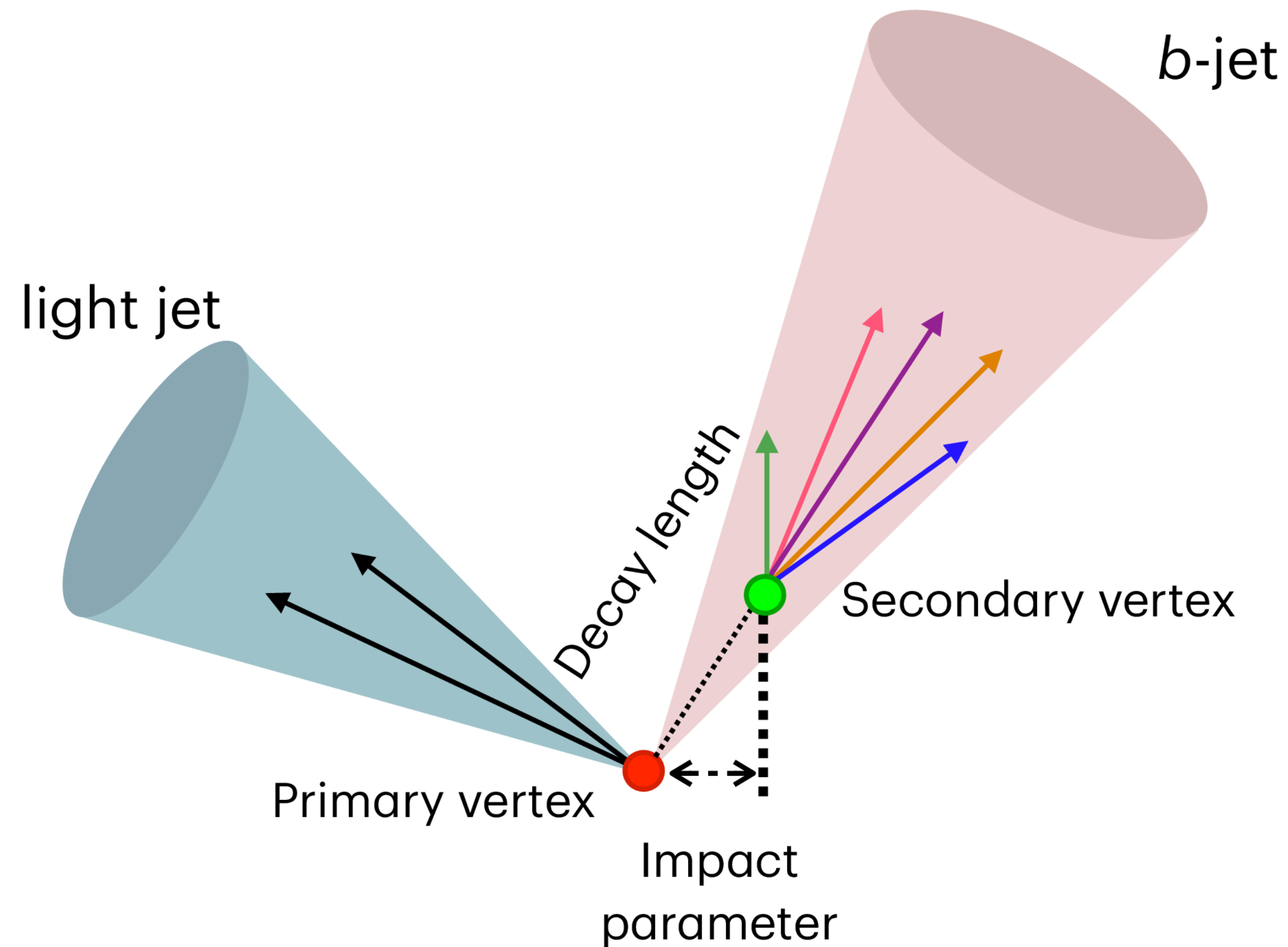


<https://arxiv.org/pdf/1405.1160>

Every jet looks different - but are there general properties?

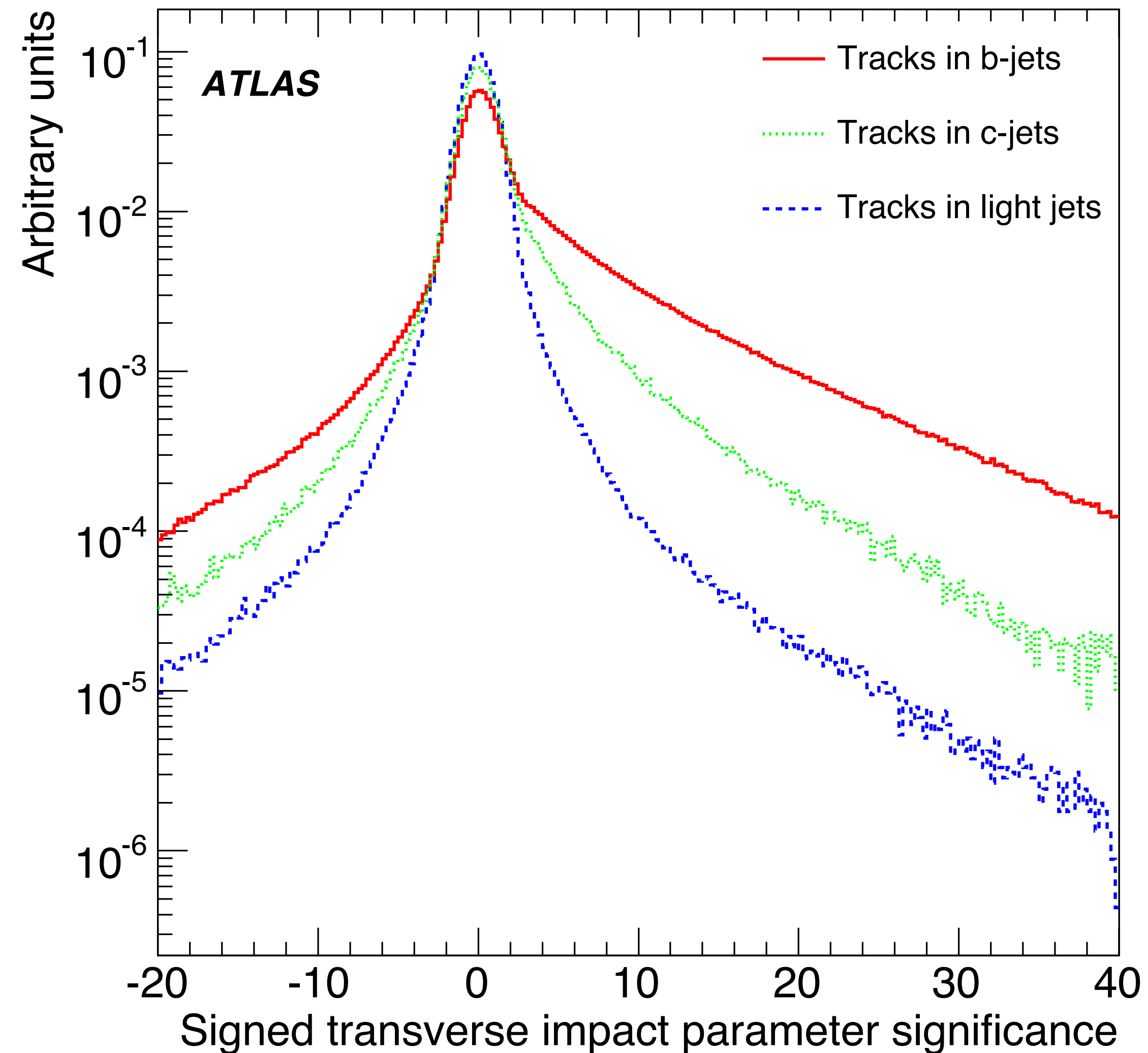


Two examples: b-quarks



The lifetime of the b-quark is long enough that its decay vertex is displaced from the interaction vertex

Two examples: b-quarks

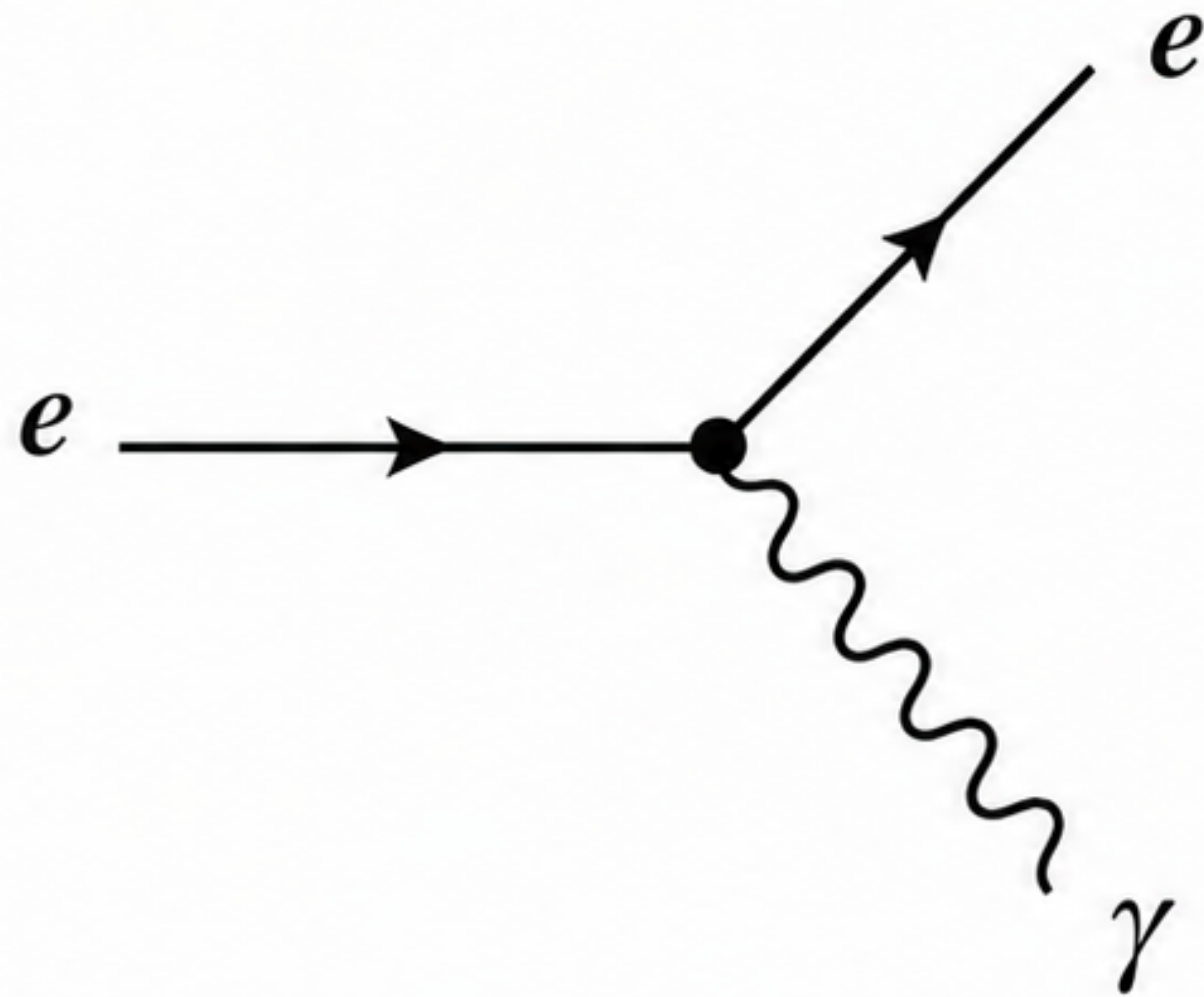


Exploit this to distinguish b- and c-quarks

Two examples: Quarks vs Gluons

QED

$$e \rightarrow e + \gamma$$

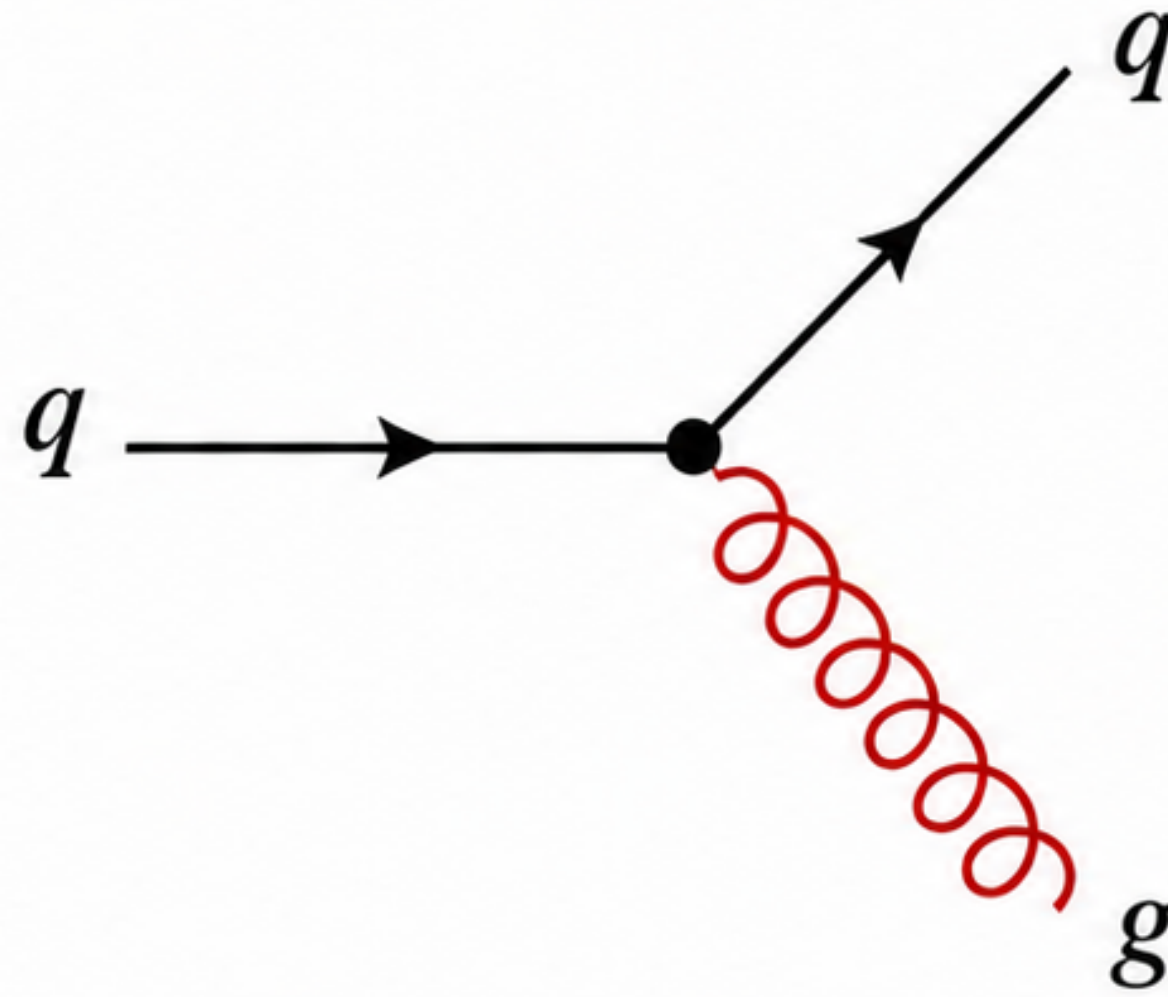


(no $\gamma\gamma\gamma$ vertex)

$$\begin{aligned} \text{Coupling} &\propto eQ\sqrt{\alpha} \\ &\propto Q^2\alpha \end{aligned}$$

QCD

$$q \rightarrow q + g$$

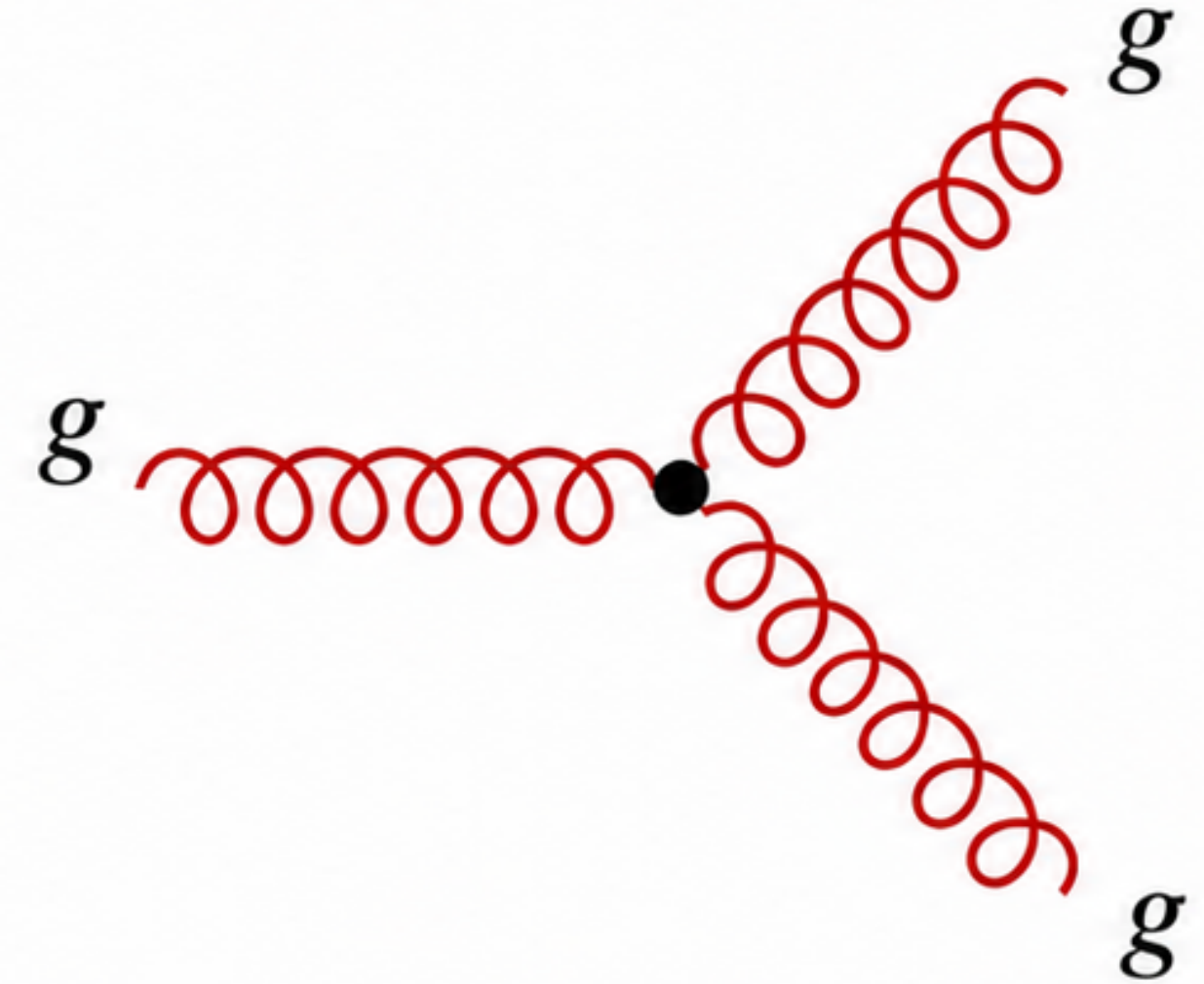


$$(C_F = \frac{4}{3})$$

$$\text{Coupling} \propto \alpha_s C_F$$

QCD

$$g \rightarrow g + g$$

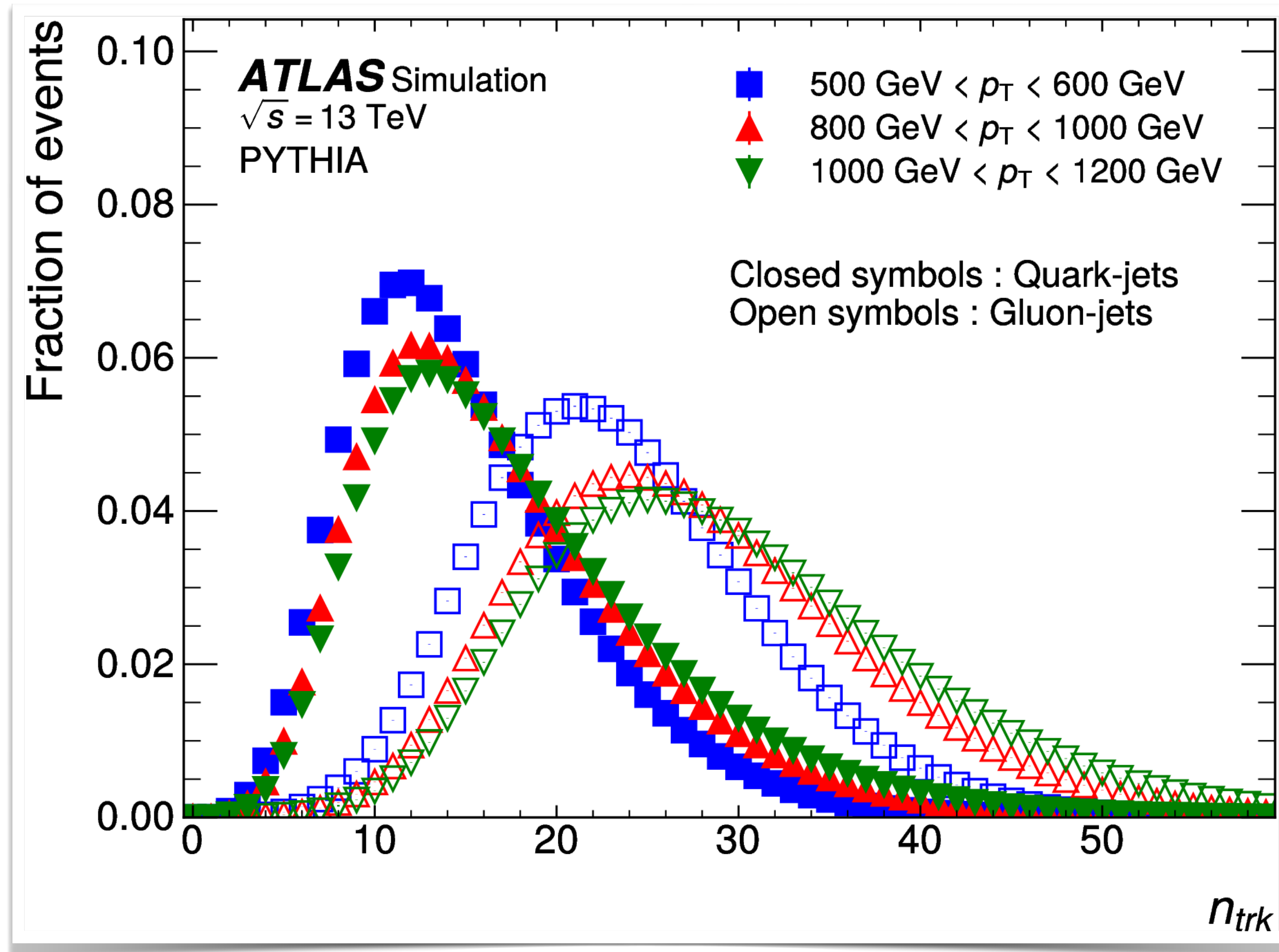


$$(C_A = 3)$$

$$\text{Coupling} \propto \alpha_s C_A$$

Gluons radiate more often!

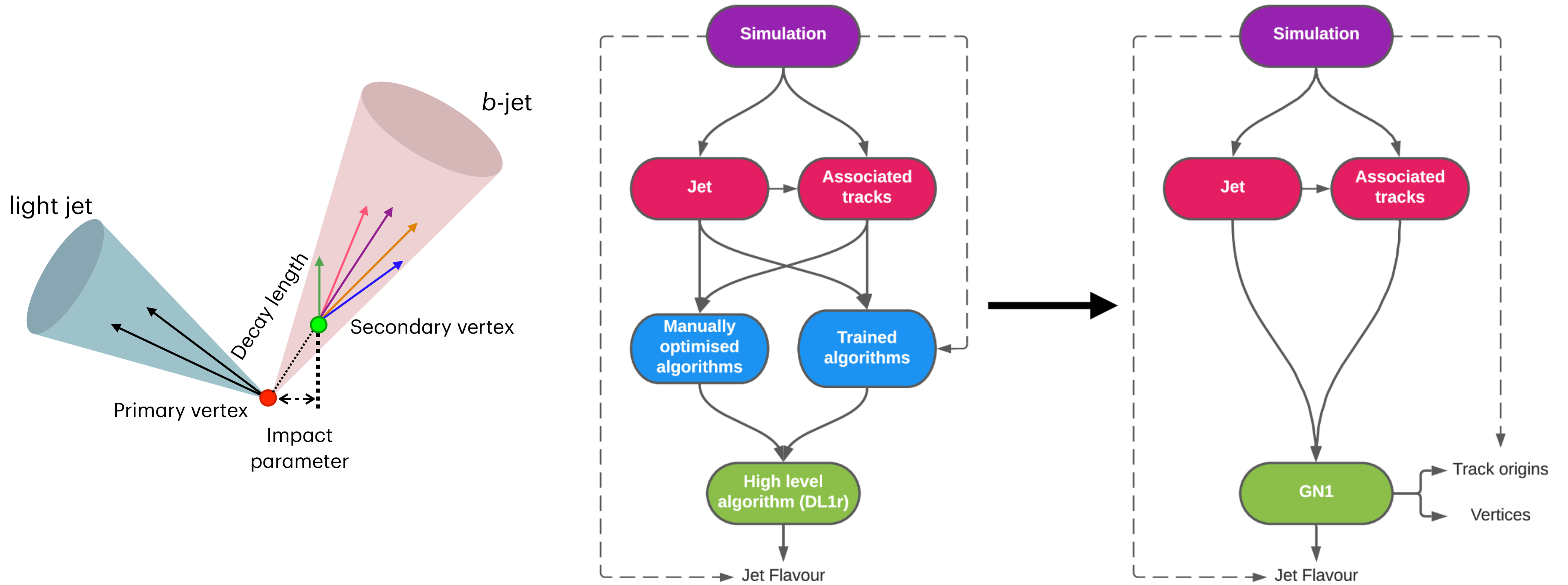
Two examples: Quarks vs Gluons



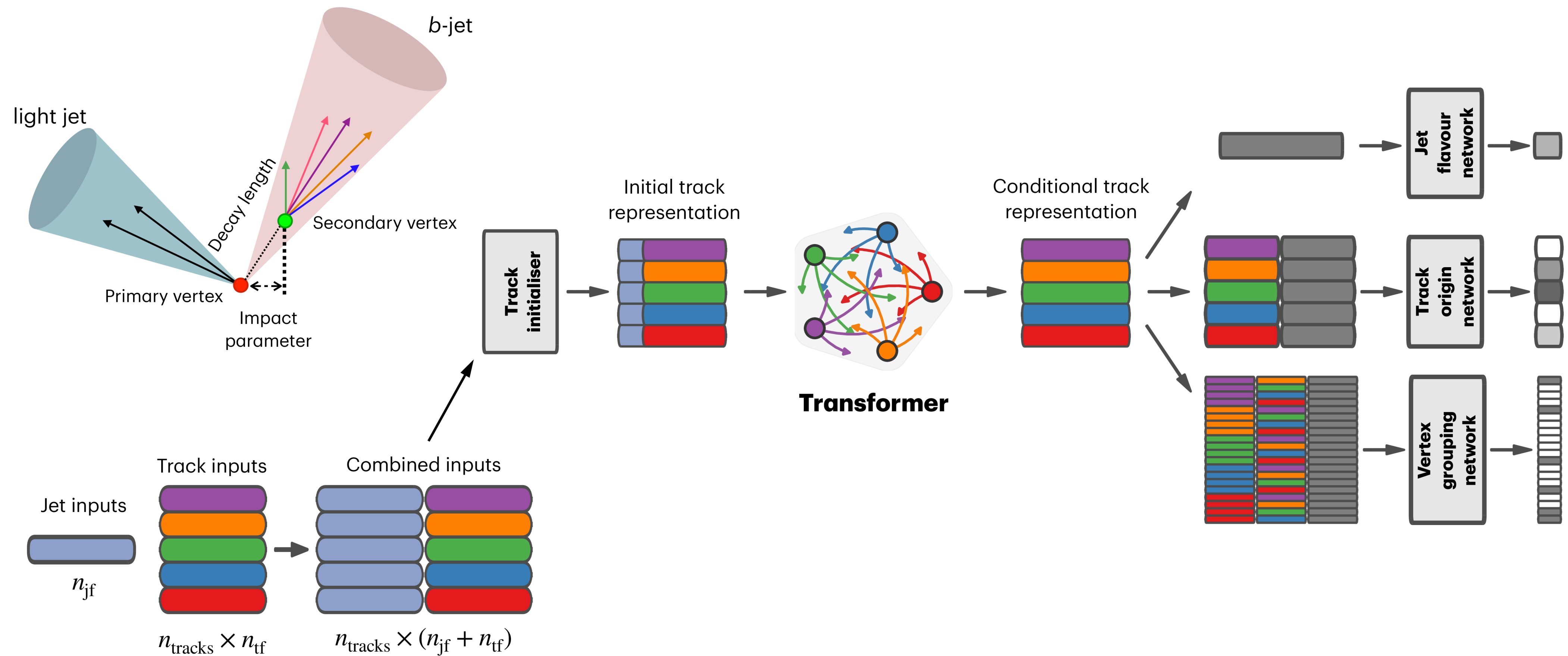
Gluons radiate more often!

Leads to wider jets with more tracks or calorimeter deposits

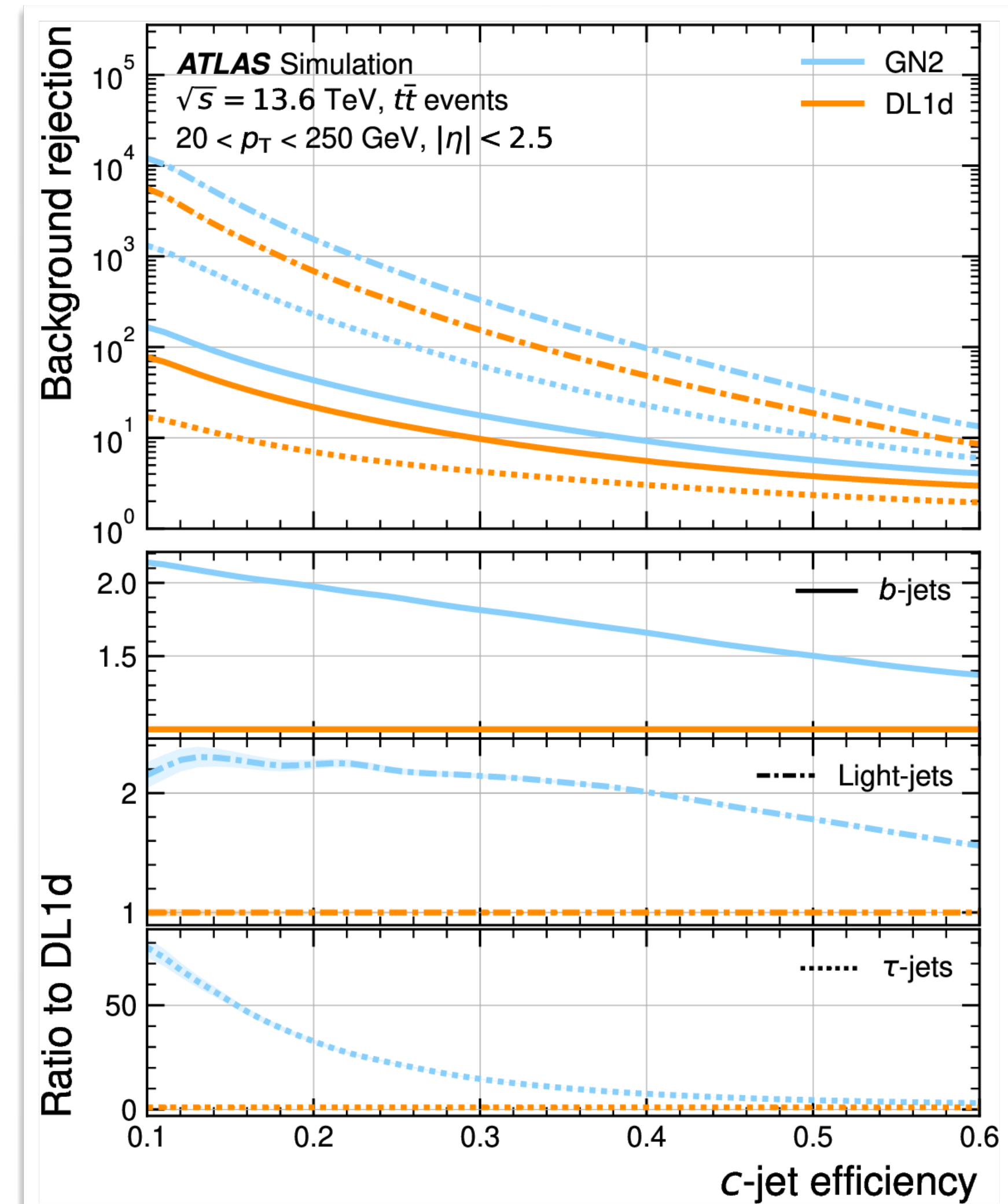
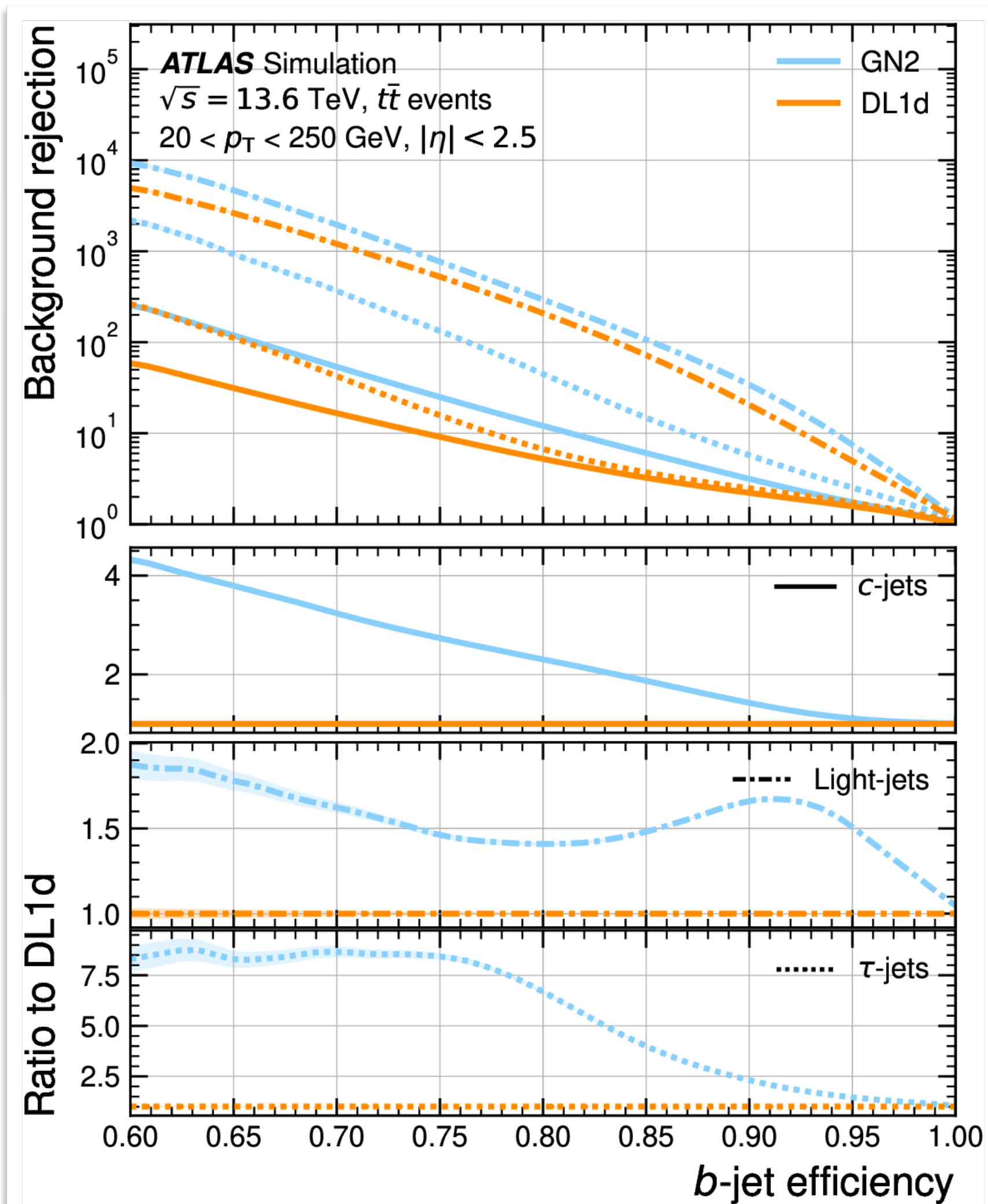
New approaches in flavour tagging

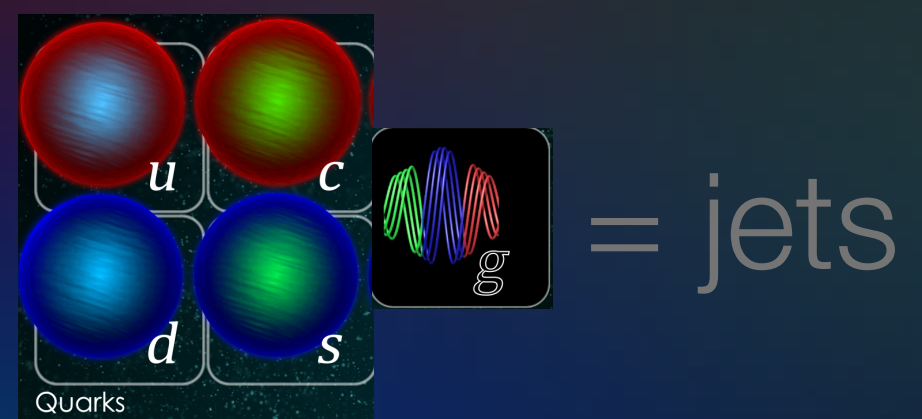


A flavour tagging example



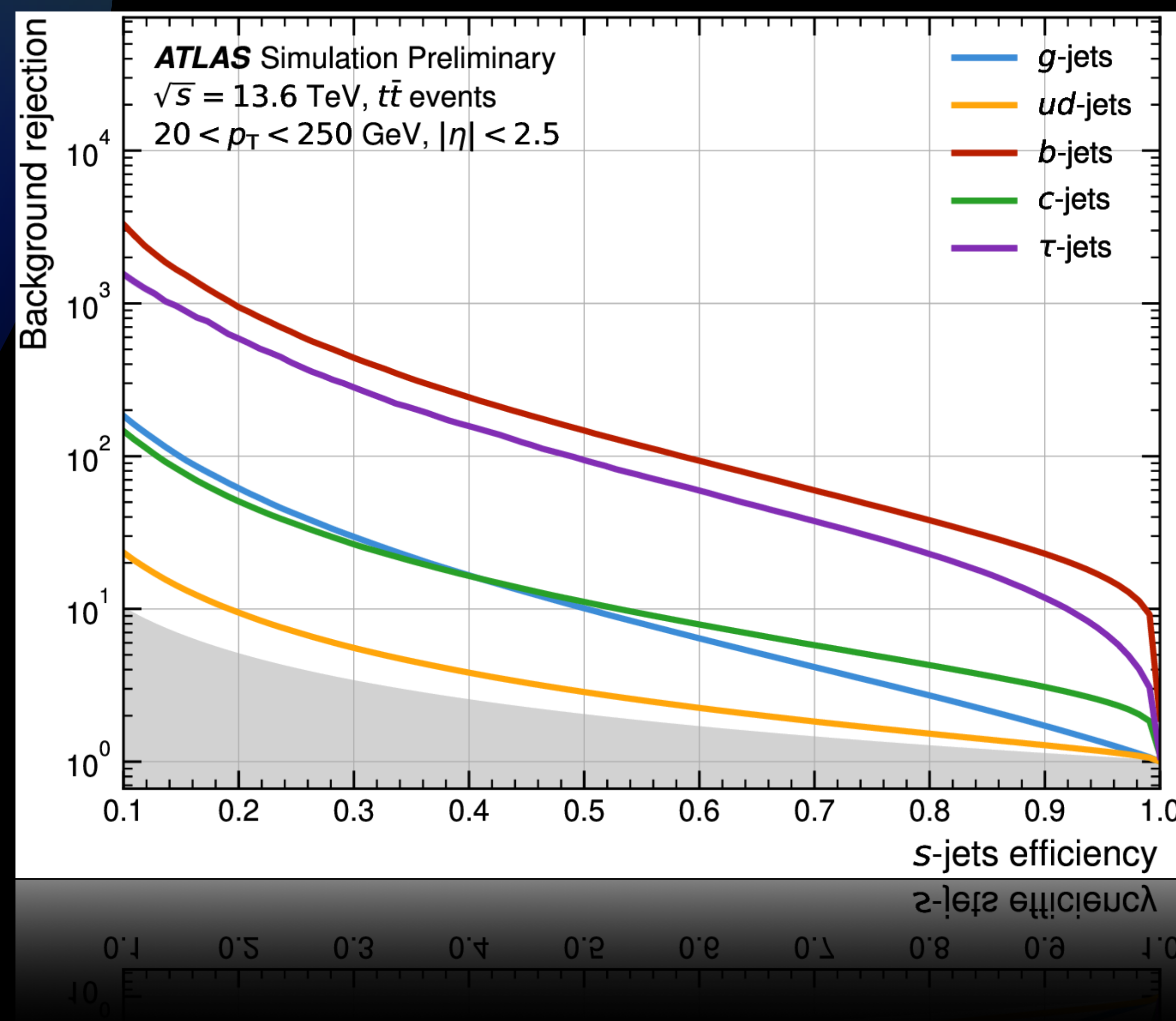
A flavour tagging example



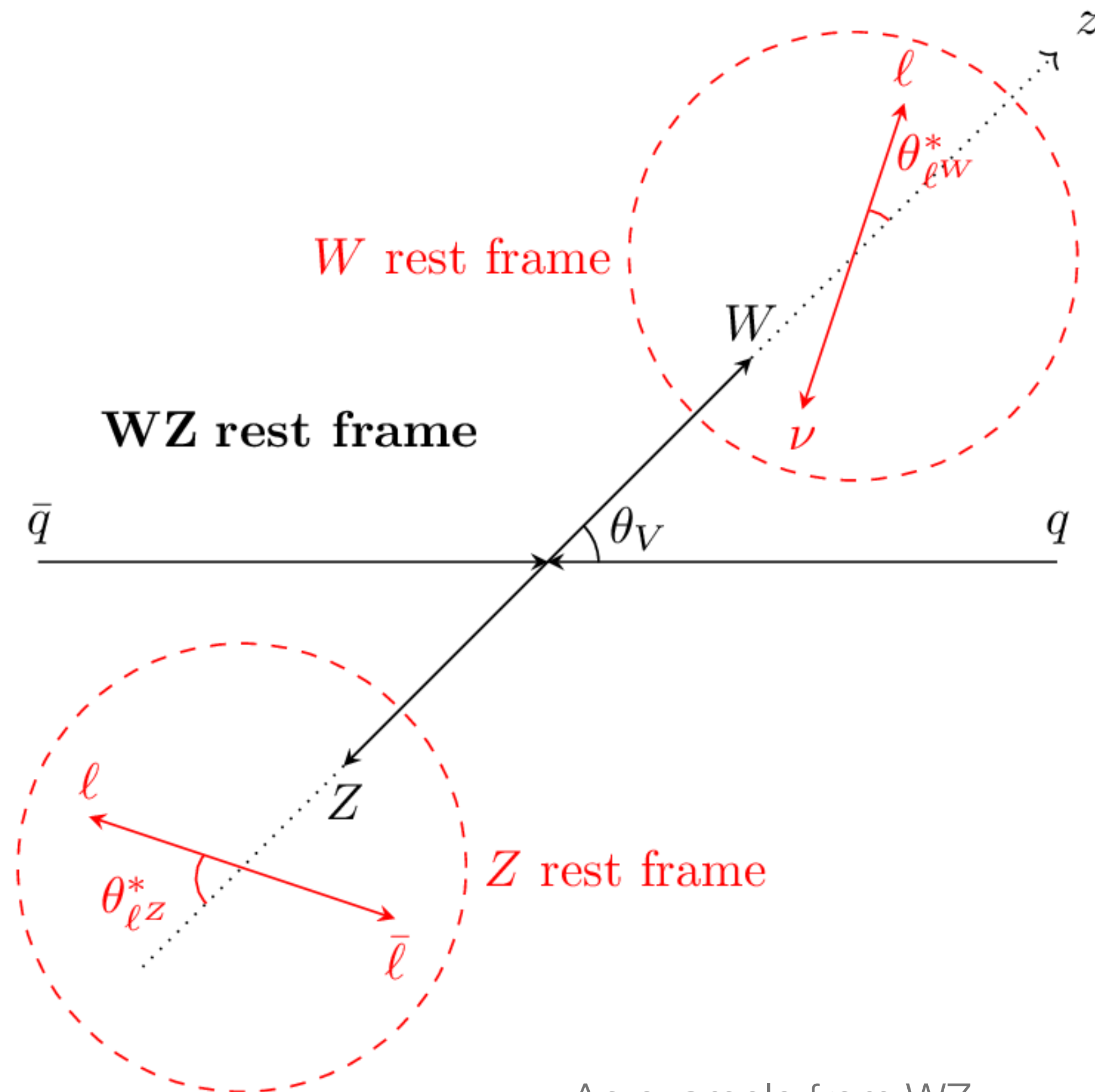


τ

b-quarks



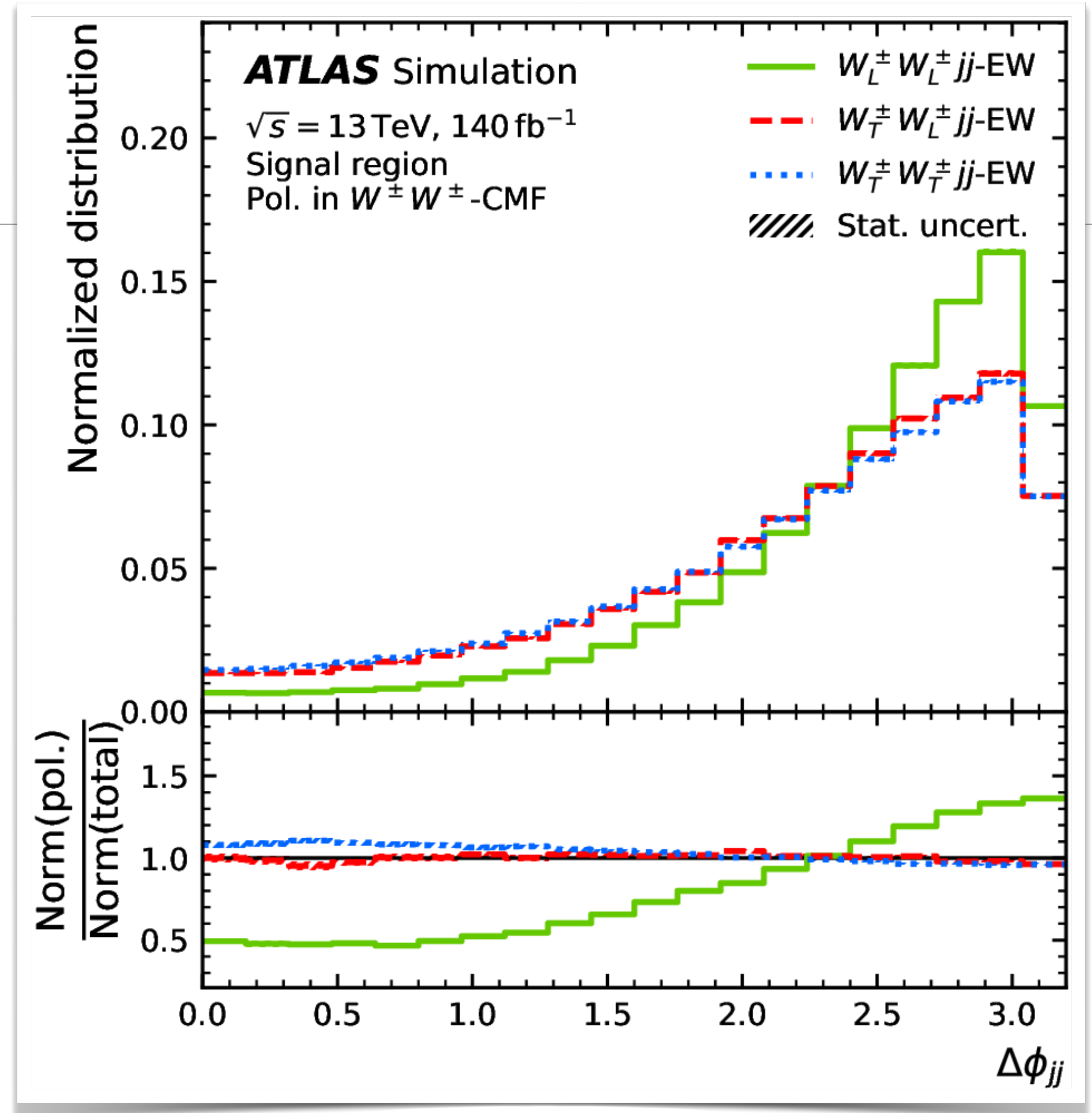
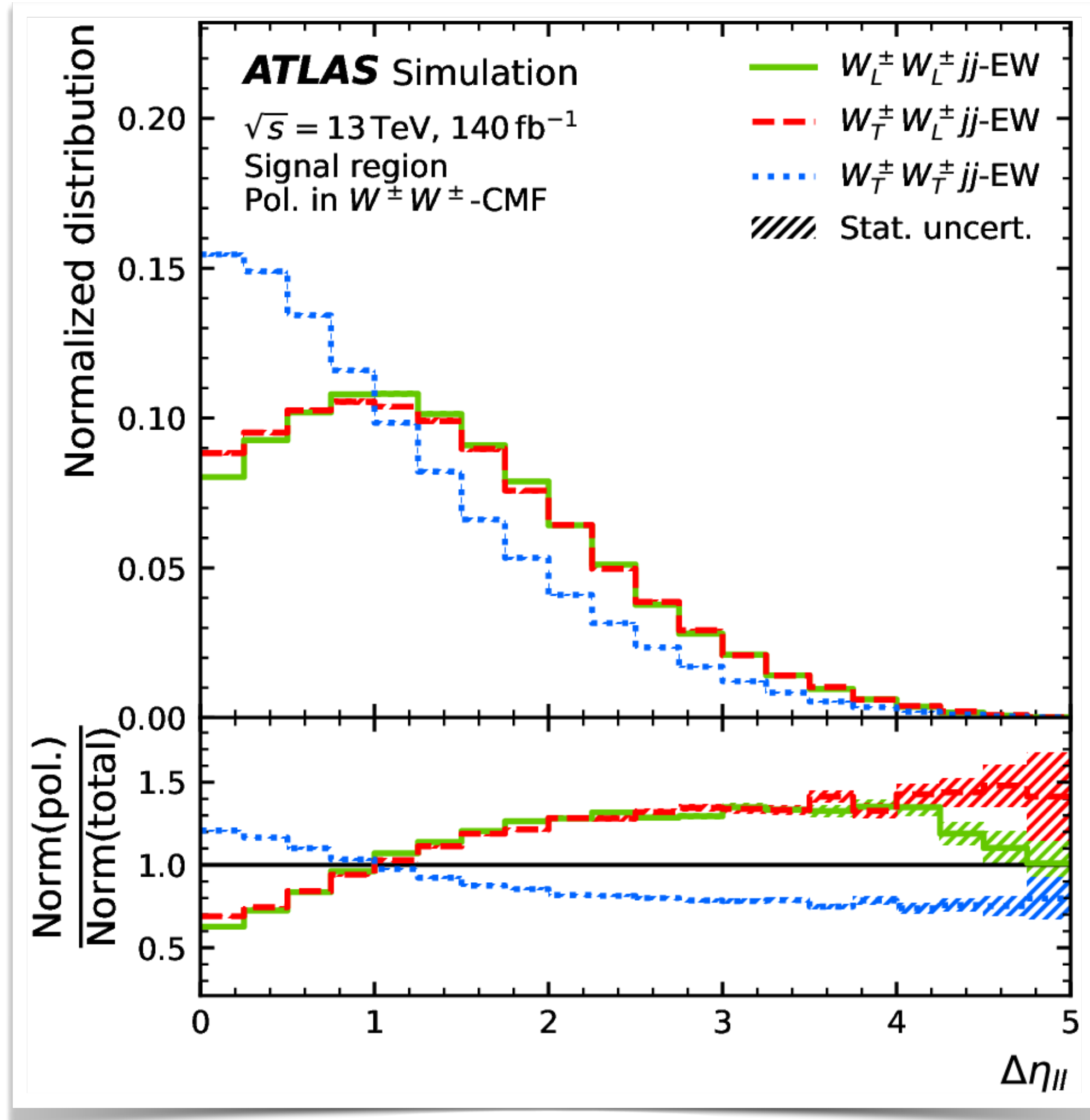
Jet ID for q/g is still work-in-process - what are my handles?



Polarisation is frame dependent

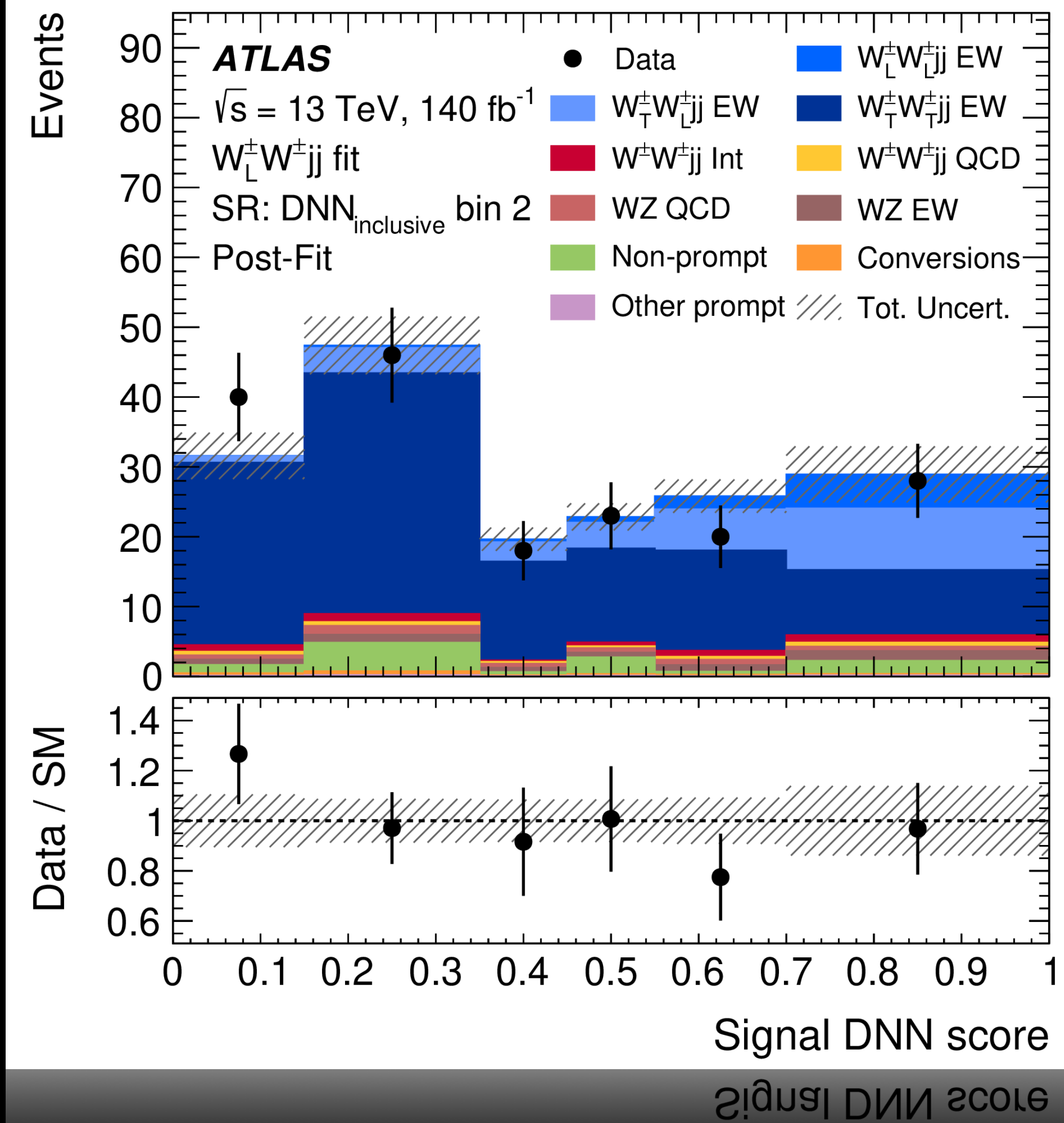
An example from WZ

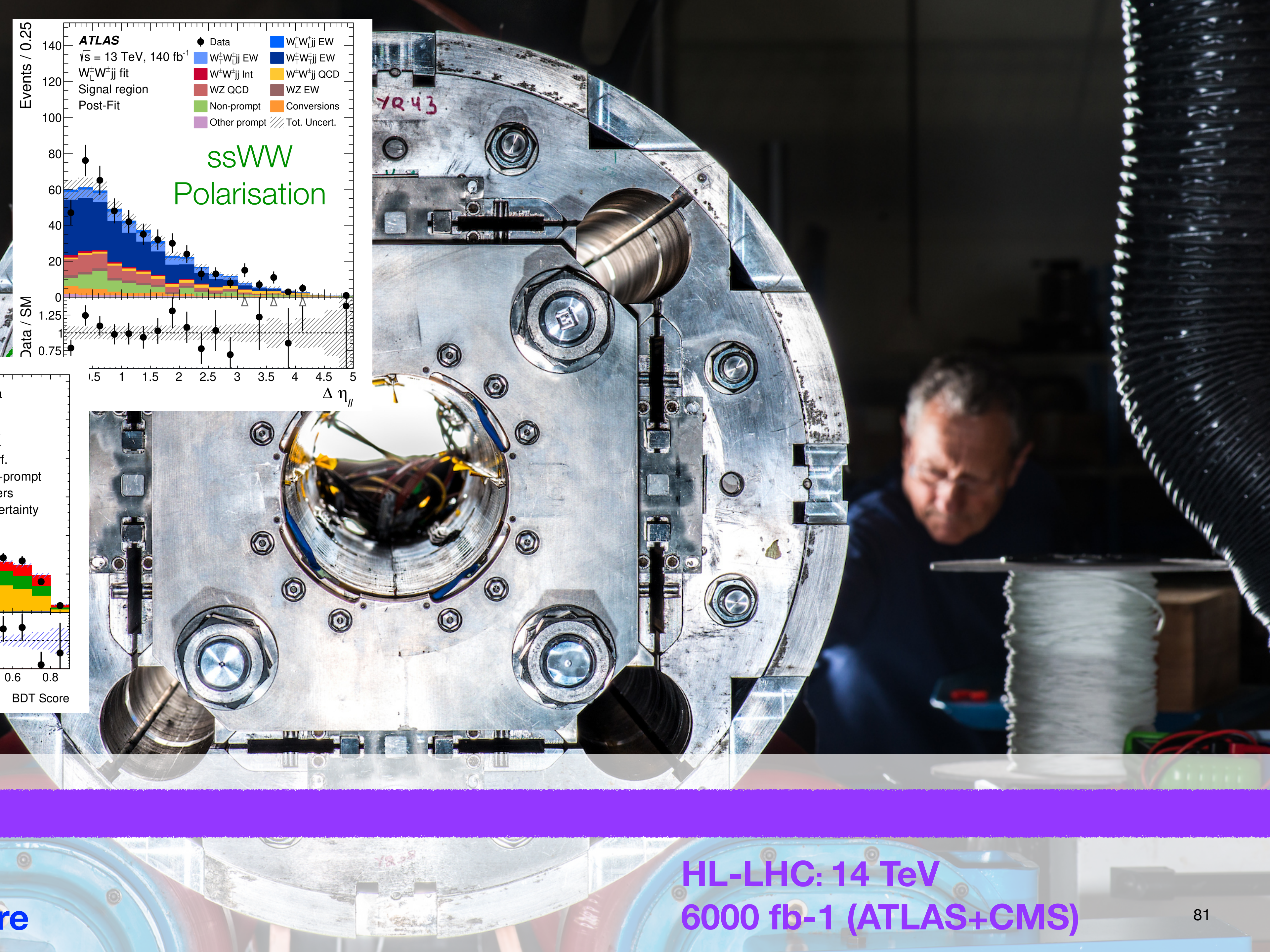
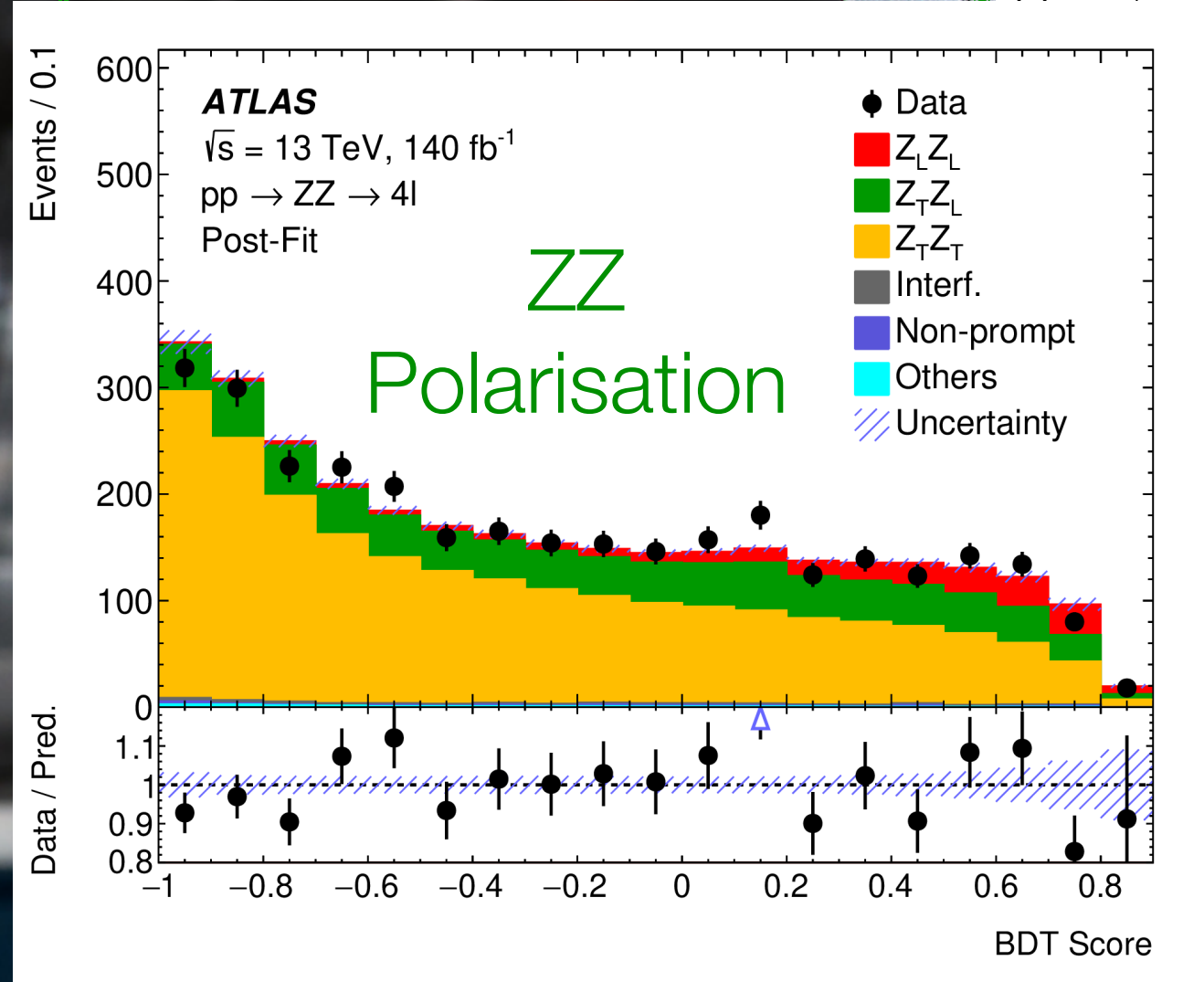
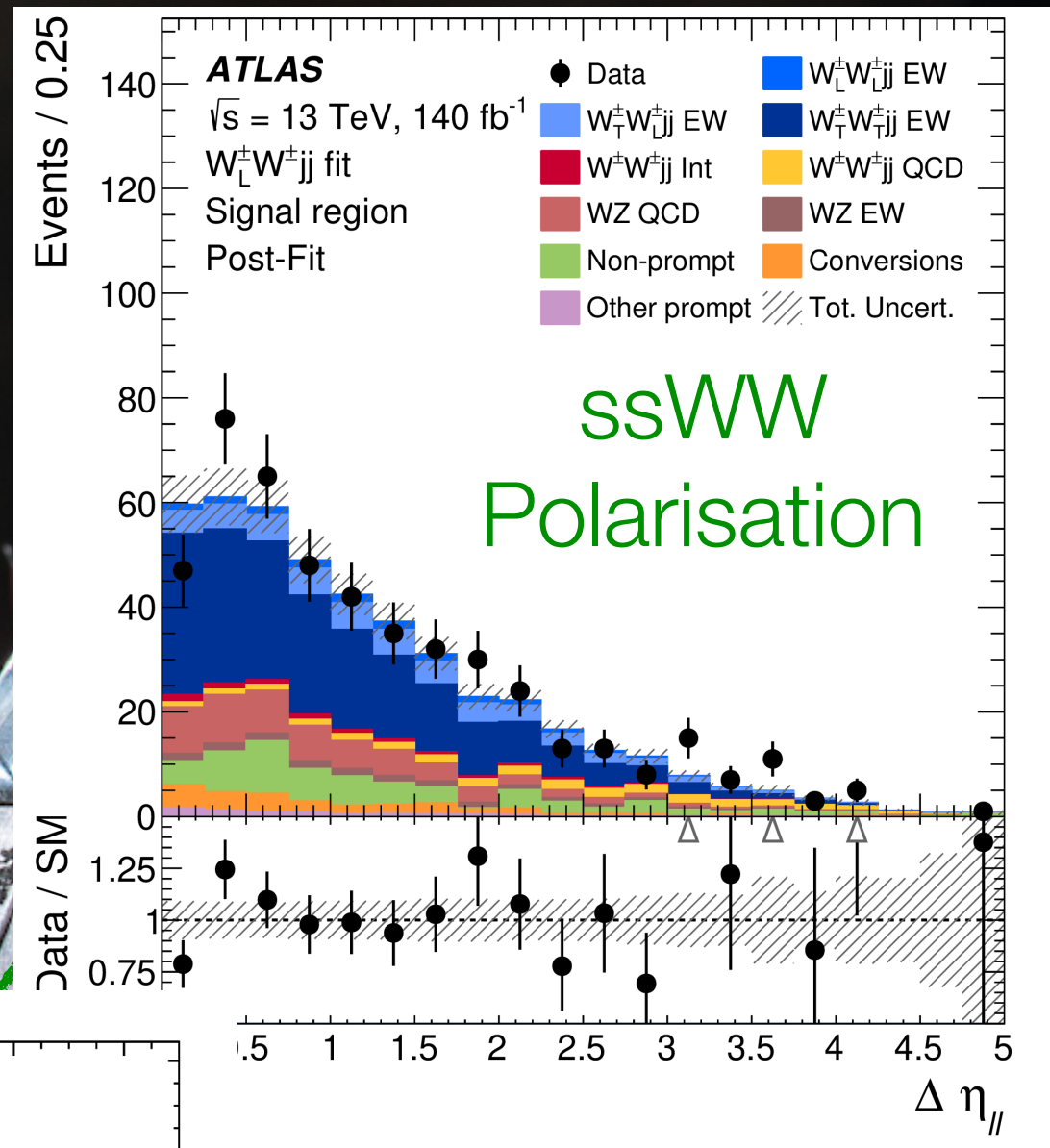
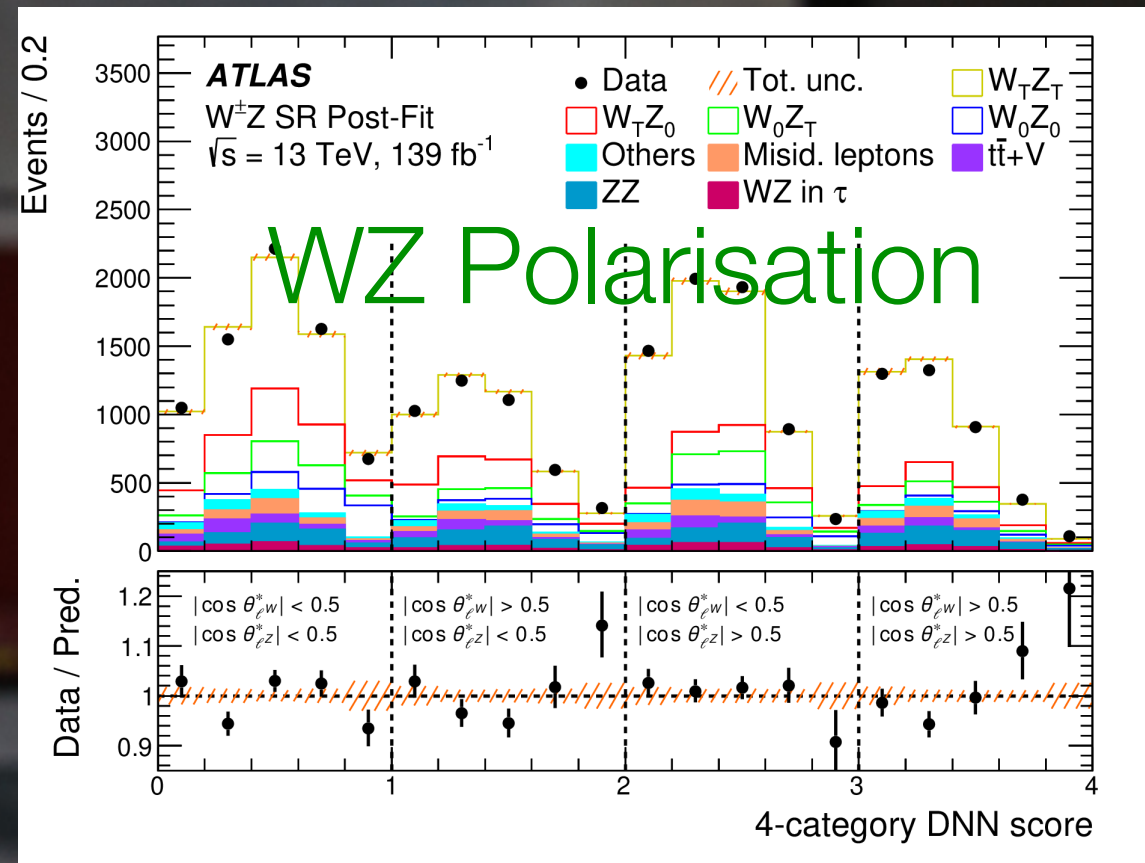
Back to the polarisation



Same-sign WW Polarisation

- 3.3 standard deviations significance of at least one longitudinally polarised W boson

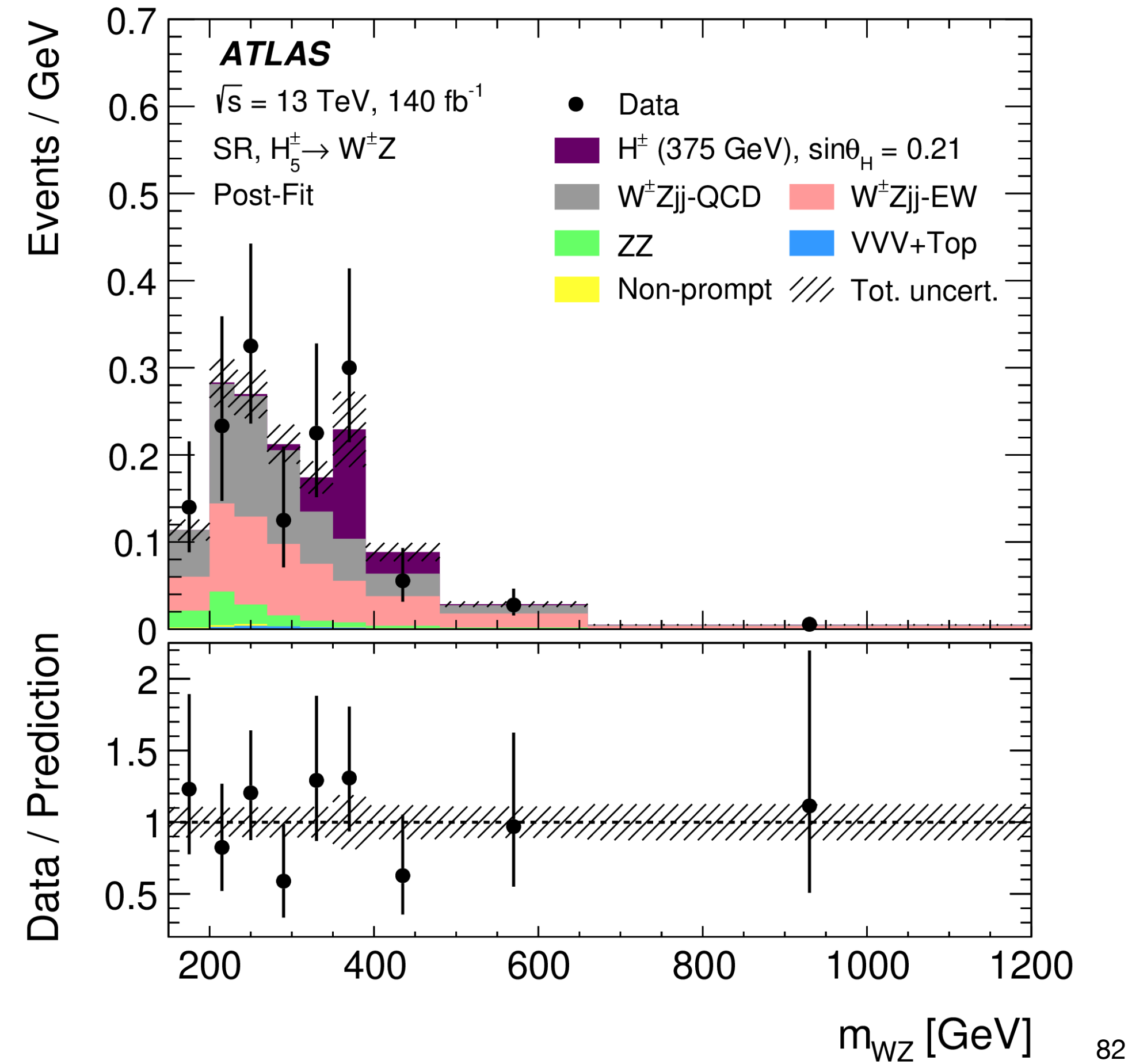
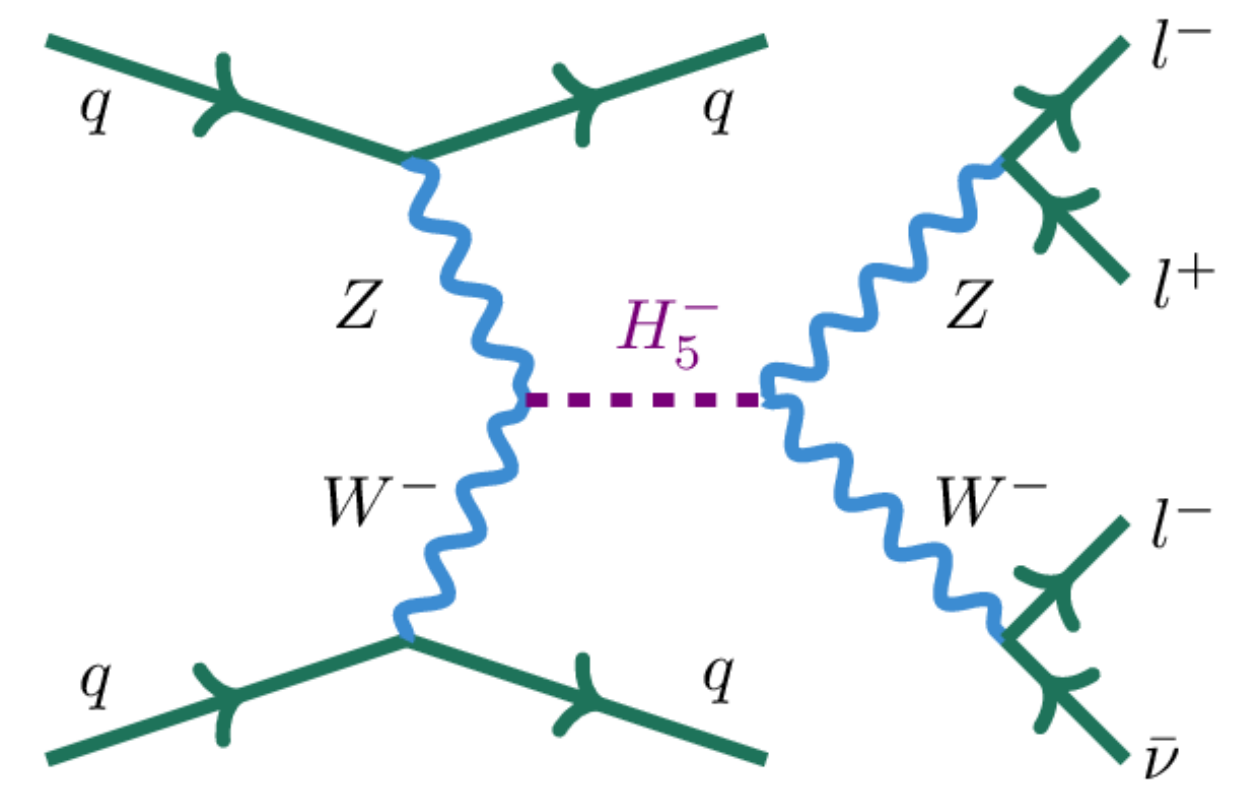
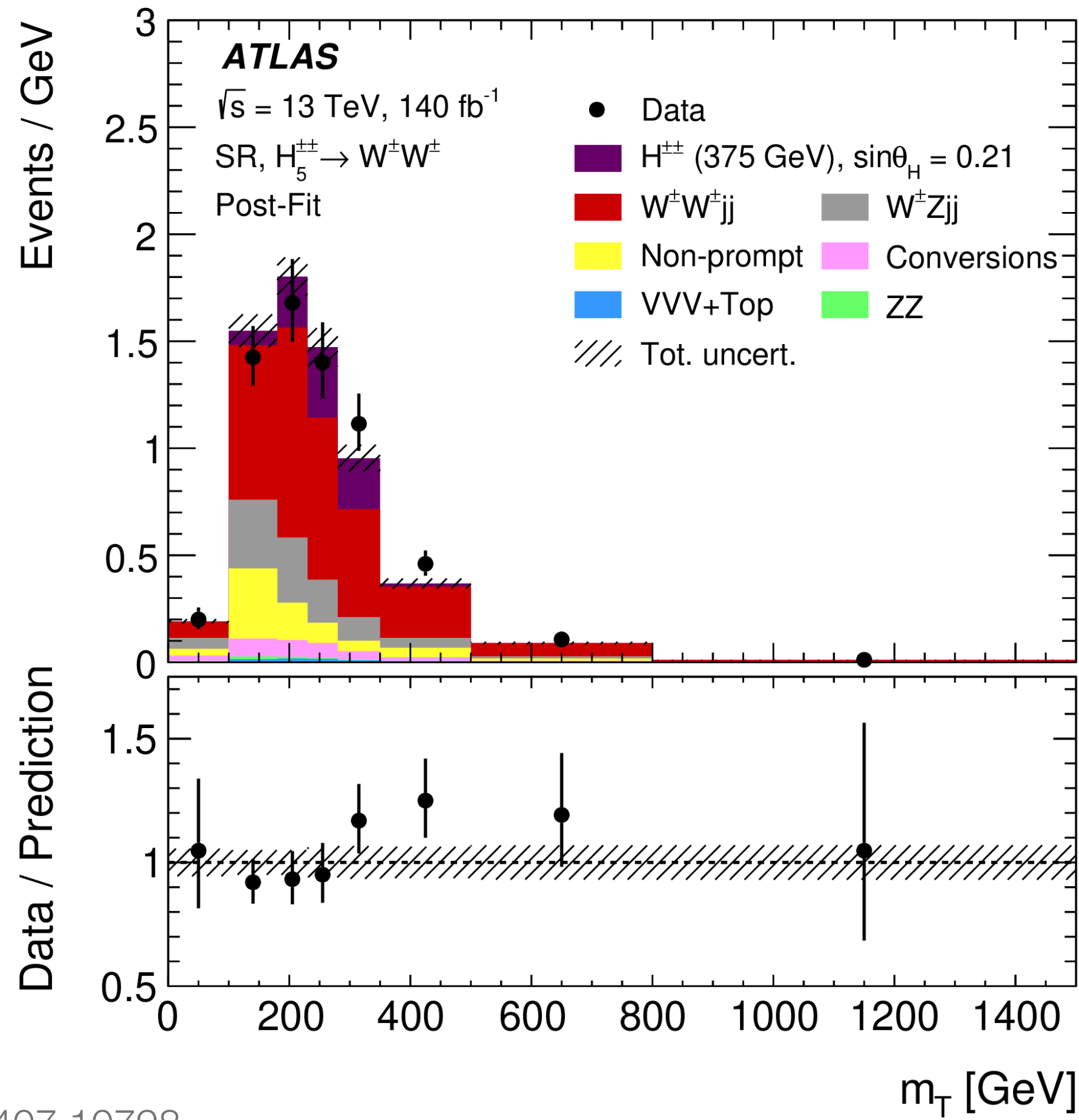
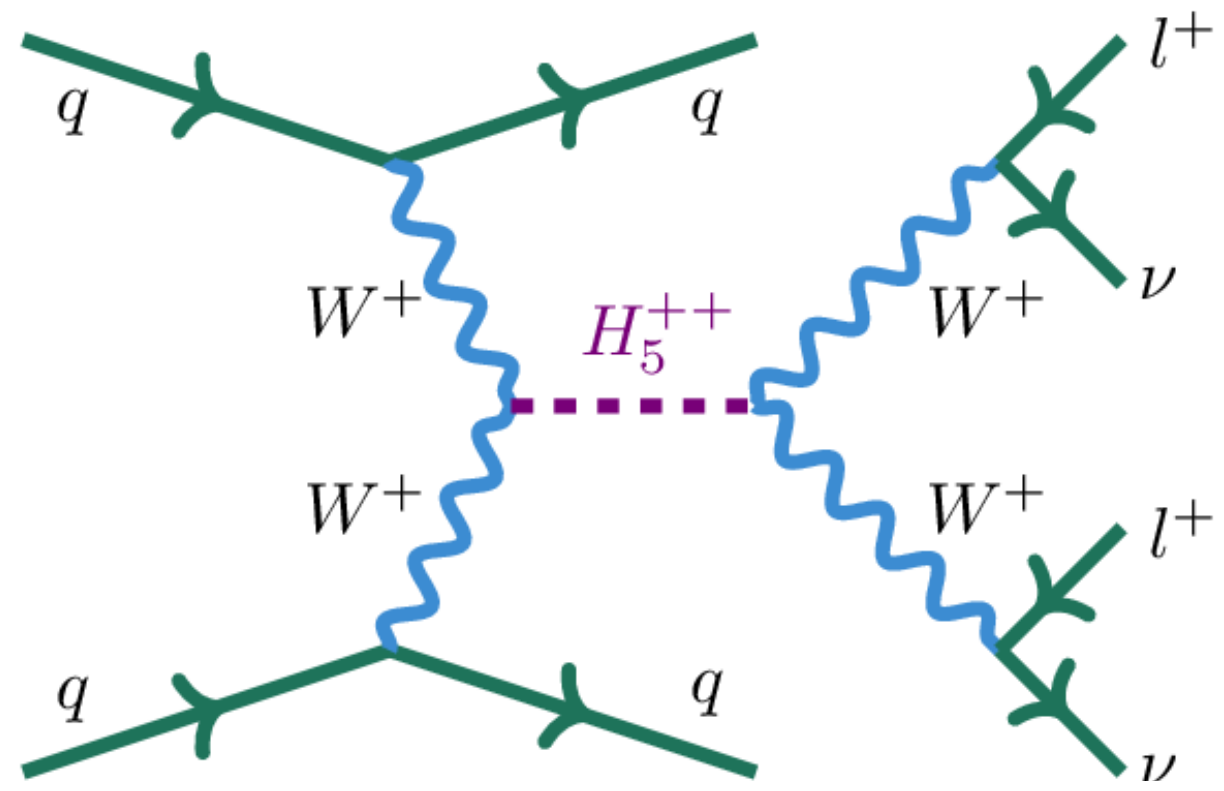


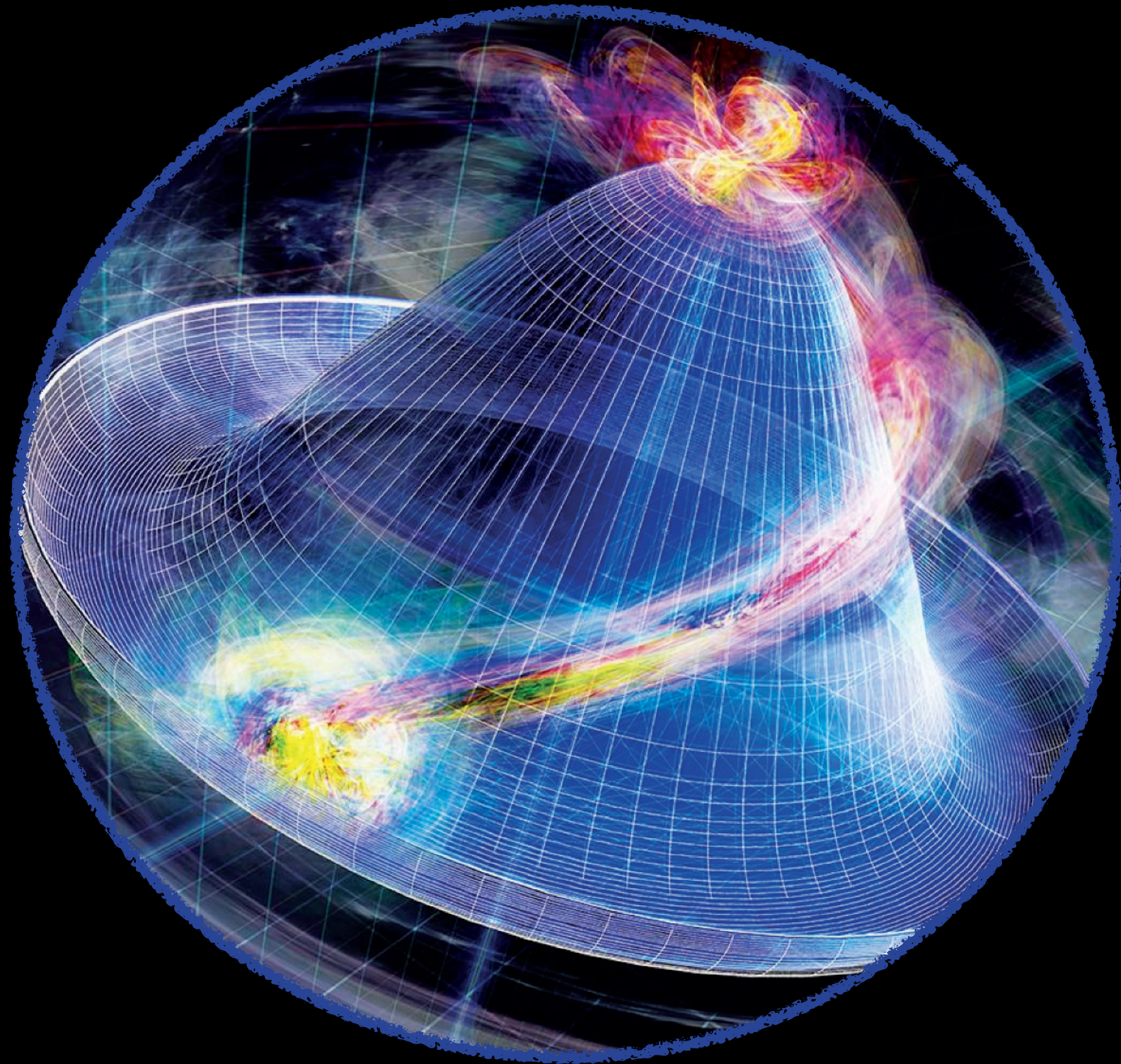


Run 2
Run 1

Run 3:
We are here

HL-LHC: 14 TeV
6000 fb^{-1} (ATLAS+CMS)



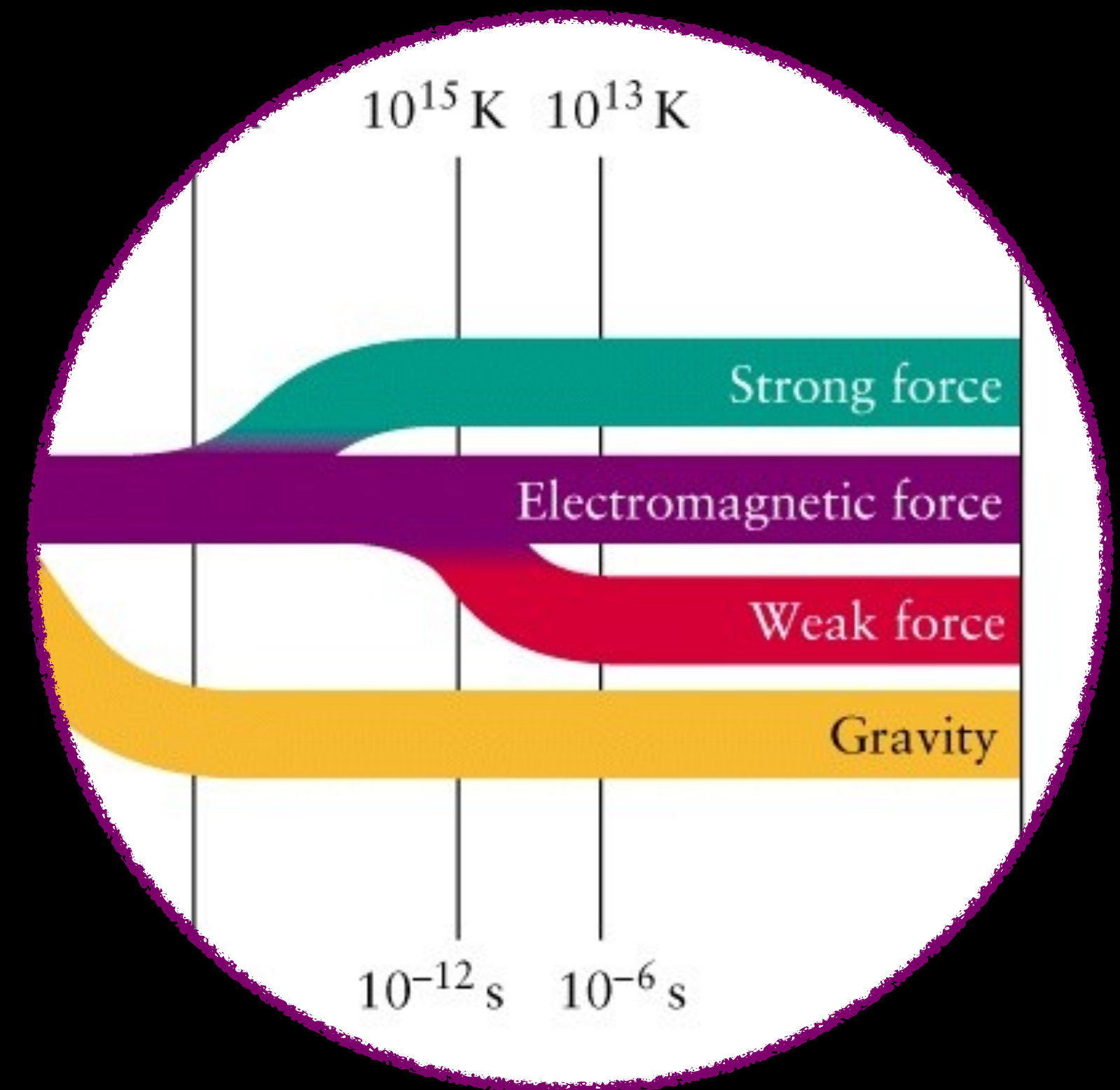


Symmetries

- How symmetry predicts interactions
- Physics example: same-sign WW scattering
- Experimental theme: Jet identification

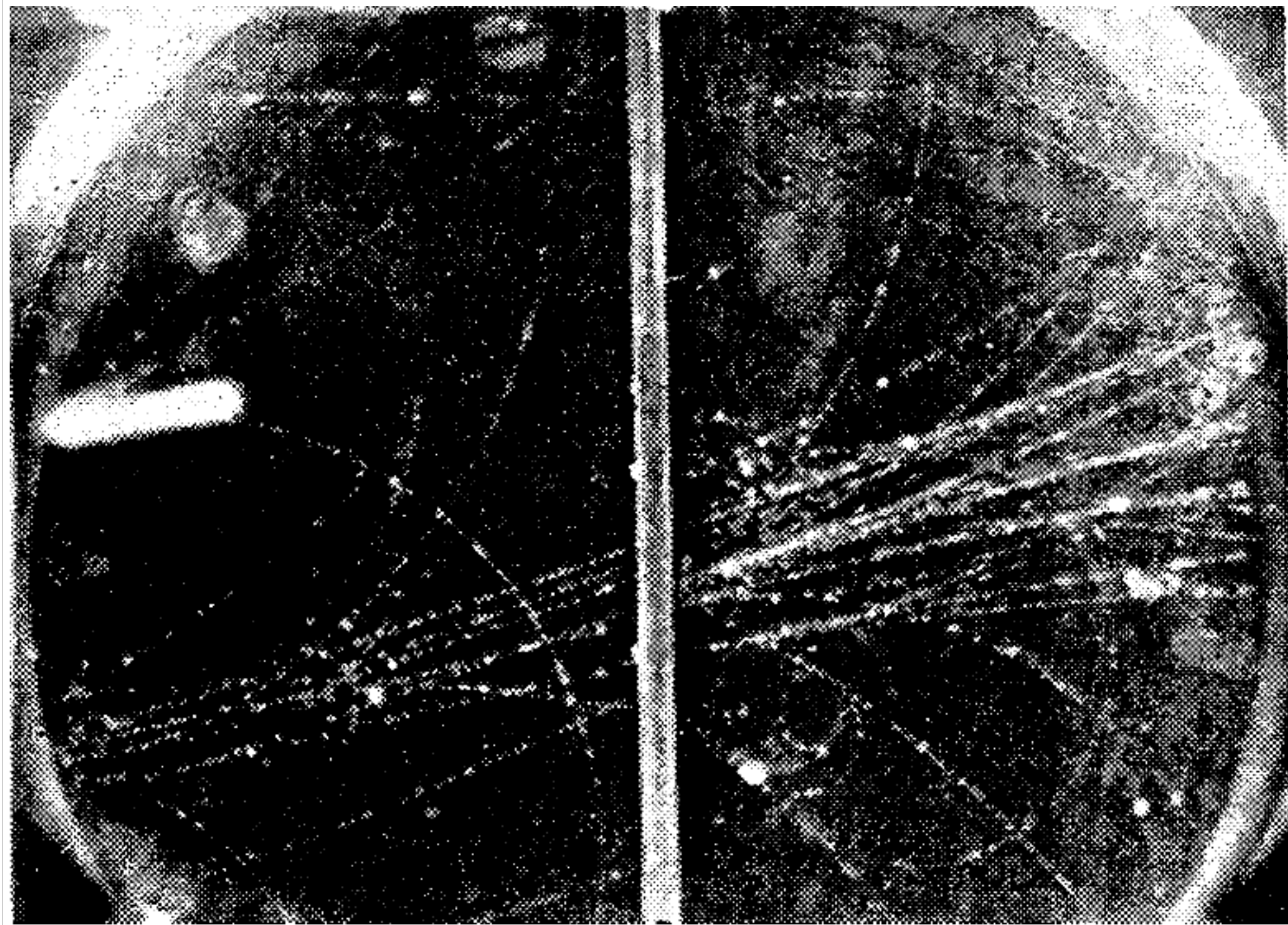
Scales

- How physics changes with energy (temperature)
- Physics examples: W mass + strong force coupling
- Experimental theme: How to design a measurement

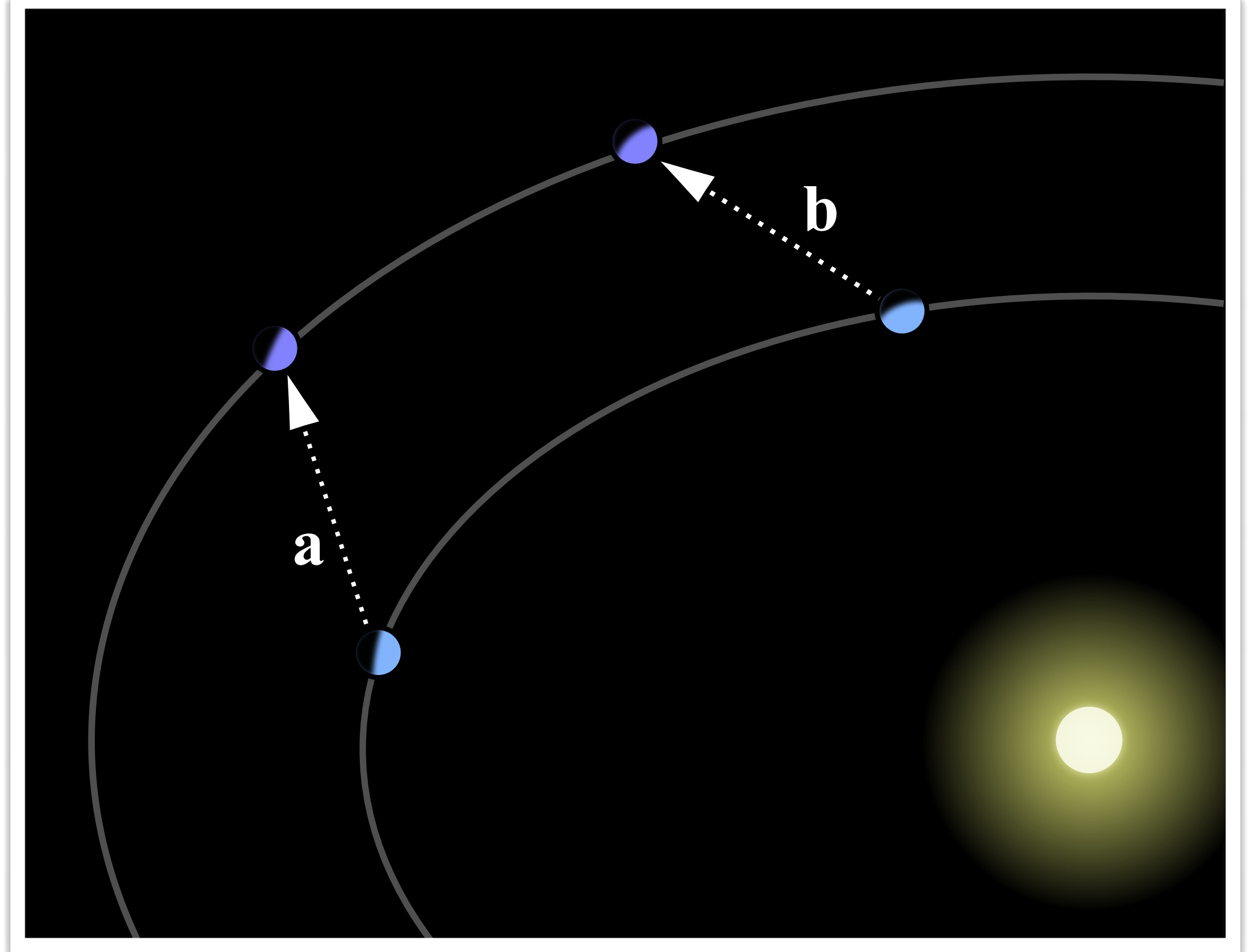


How does physics change with energy - Two paths

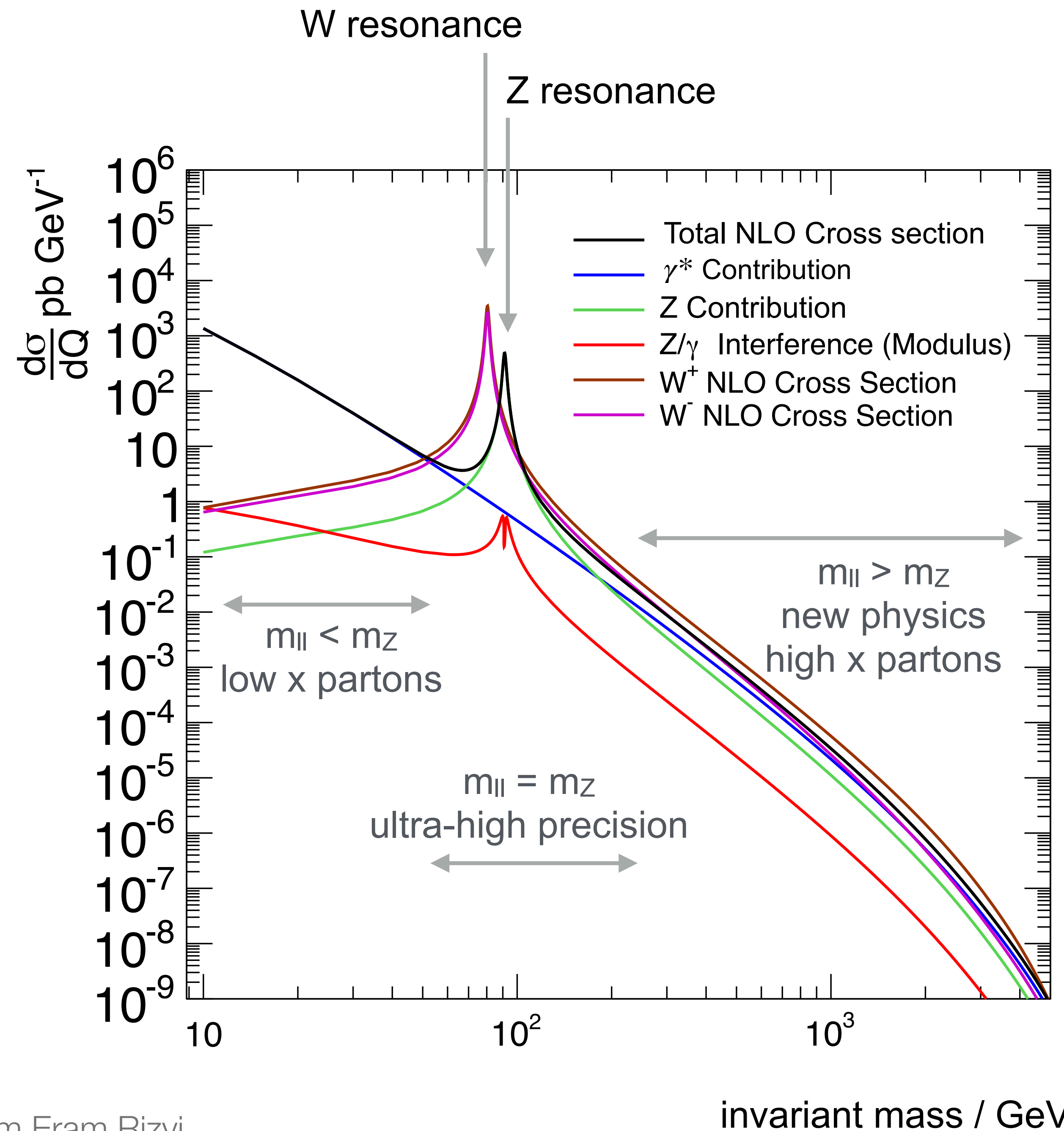
Energy - i.e. the muon discovery



Precision - i.e. Neptune's discovery



Many of the universe most exciting things involve high energy/density/temperature 84

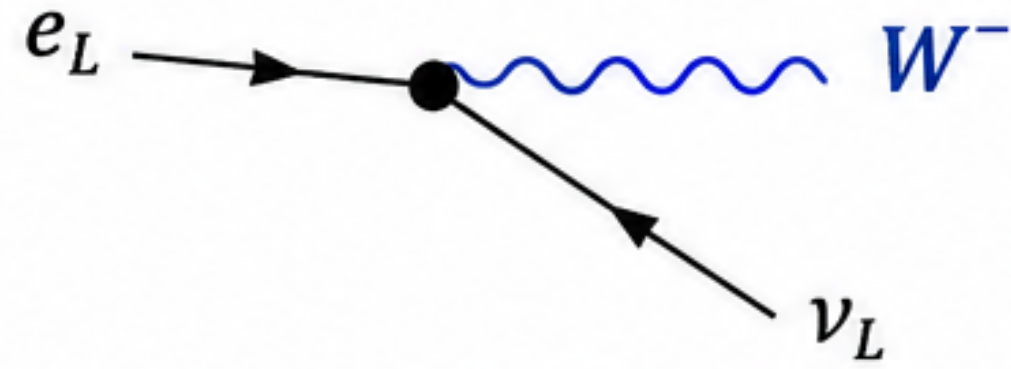


The W and Z bosons:
very similar and yet so different

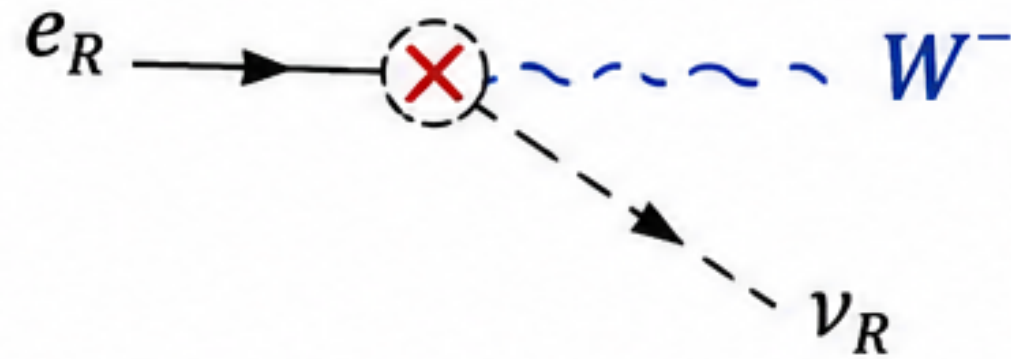
Feynman Diagrams

$W^\pm$

Left-handed
(allowed)
✓



Right-handed
(forbidden)
✗



$W^\pm$: Couples only to **left-handed** fermions.

Couplings (relative strength)

Left-handed
($e_L \rightarrow \nu_L + W$)



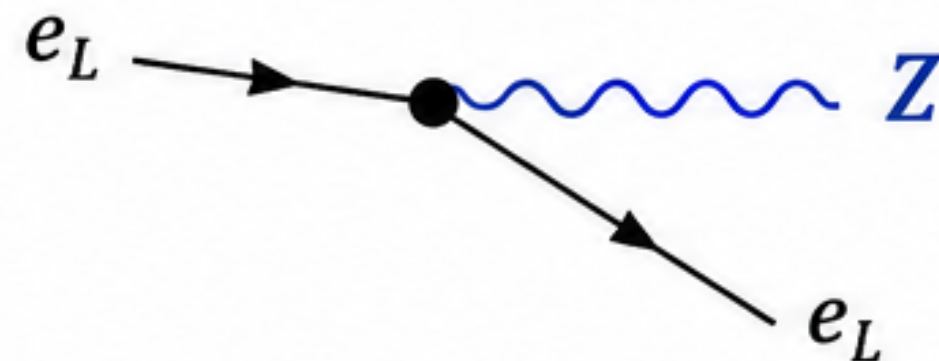
Right-handed
($e_R \rightarrow \nu_R + W$)



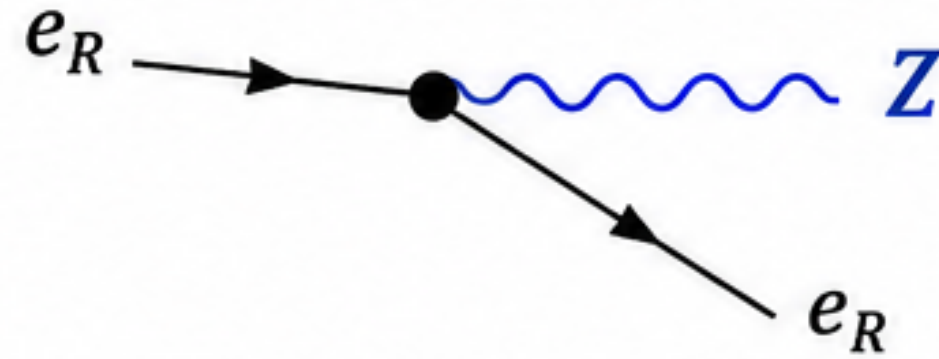
relative coupling strength

Z

Left-handed
(allowed)
✓



Right-handed
(allowed)
✓



Z : Couples to **both** chiralities,
with different strengths.

Left-handed
($e_L \rightarrow e_L + Z$)



Right-handed
($e_R \rightarrow e_R + Z$)



relative coupling strength

→ fermion

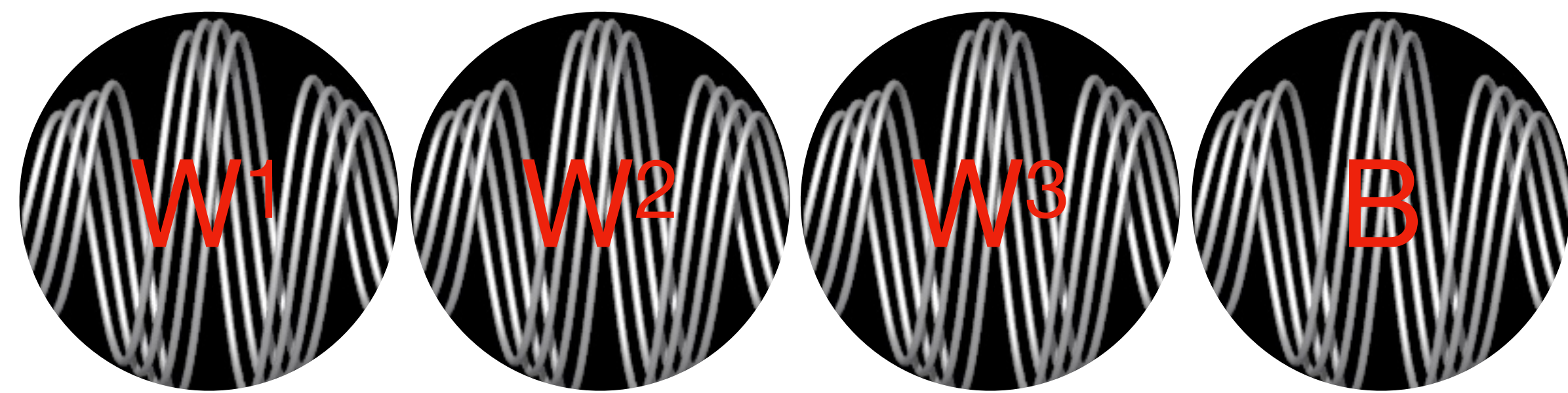
~~~~~  $W^\pm, Z$  bosons

● allowed vertex

⊗ no tree-level coupling



# Before and after EW symmetry breaking



The Z is a hybrid particle of the neutral weak boson W3, (left-handed only couplings) and the hypercharge boson B (both)

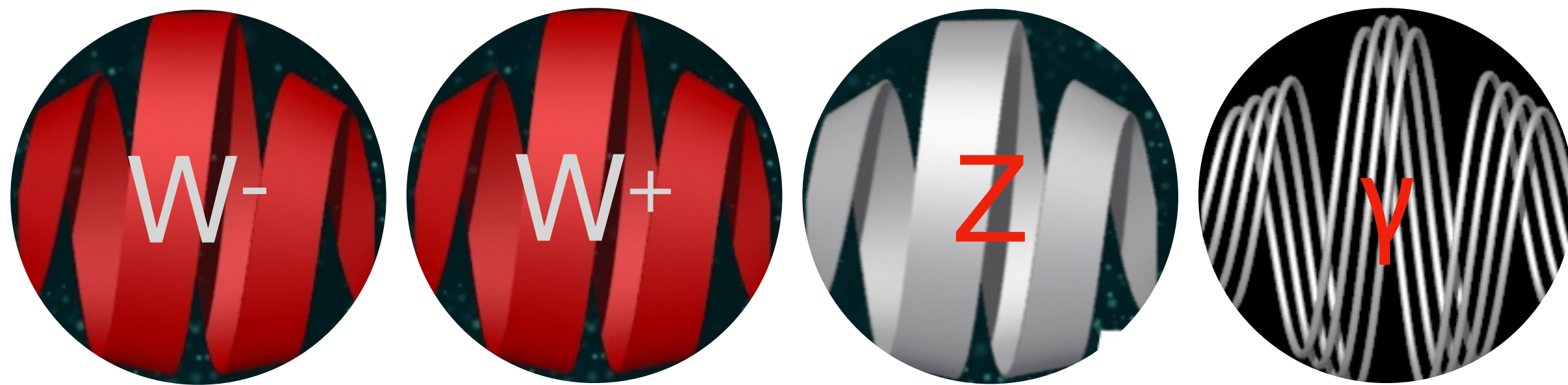
For the photon, the W3 and B components combine to produce a purely EM coupling



$$A_\mu = \cos \theta_W B_\mu + \sin \theta_W W_\mu^3,$$
$$Z_\mu = -\sin \theta_W B_\mu + \cos \theta_W W_\mu^3.$$



# The masses of the W and Z



$$A_\mu = \cos \theta_W B_\mu + \sin \theta_W W_\mu^3,$$
$$Z_\mu = -\sin \theta_W B_\mu + \cos \theta_W W_\mu^3.$$

$$m_W = \frac{1}{2} g_W v$$

$$m_A = 0 \quad \text{and} \quad m_Z = \frac{1}{2} v \sqrt{g_W^2 + g'^2}$$

$$\frac{g'}{g_W} = \tan \theta_W$$

The weak mixing angle describes how the EW gauge fields mix to form the physical Z boson and photon and relates the W, Z boson masses to each other



# Custodial symmetry

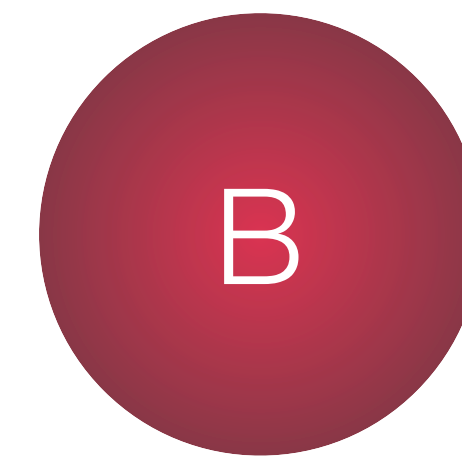
---

The W boson mass tests the symmetry that protects the structure of the EW theory

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W}$$

$\rho$  is not equal to one when something distinguishes the W from the Z.

i.e Every correction to  $\rho$  must come from a source that breaks custodial symmetry

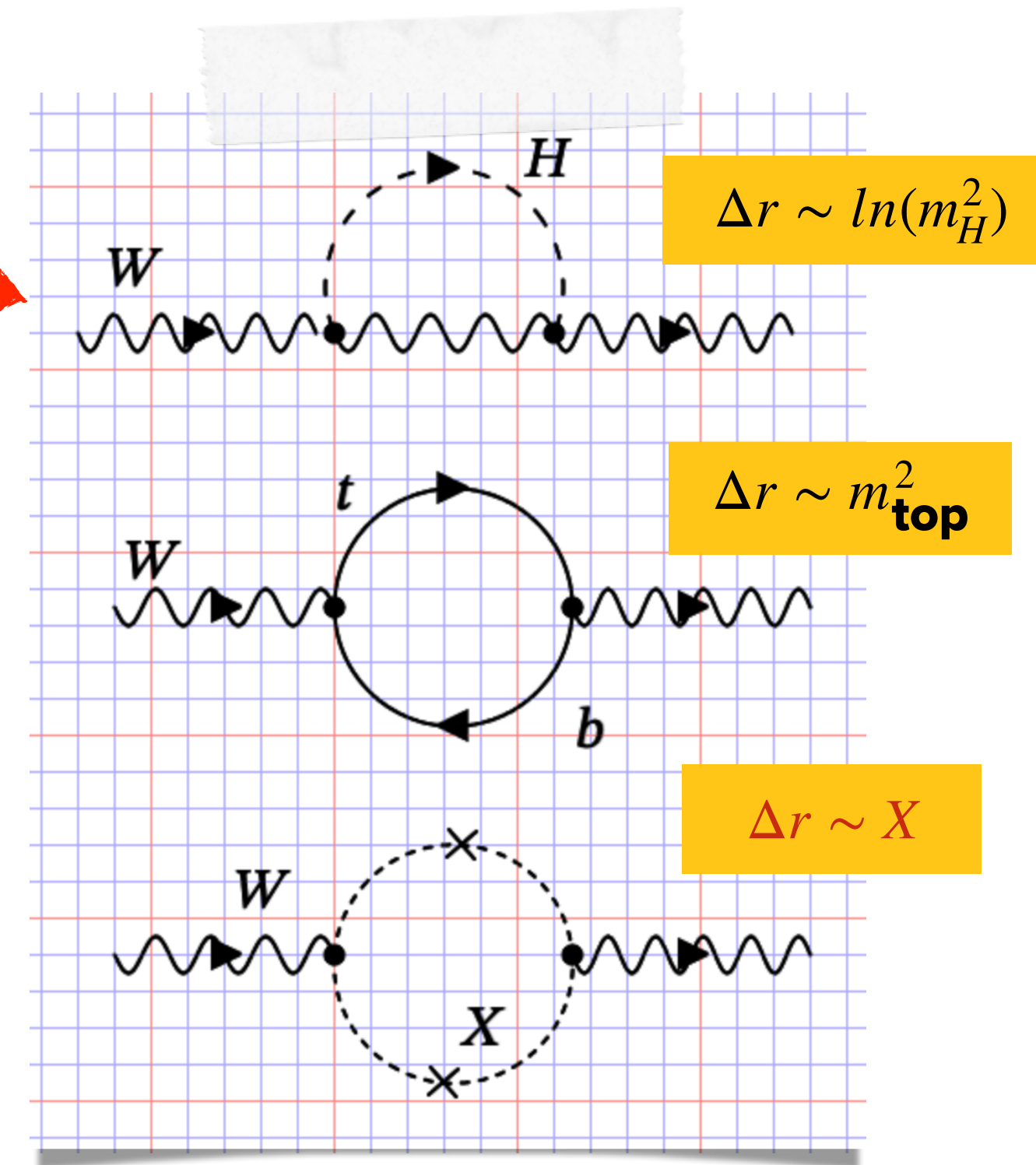
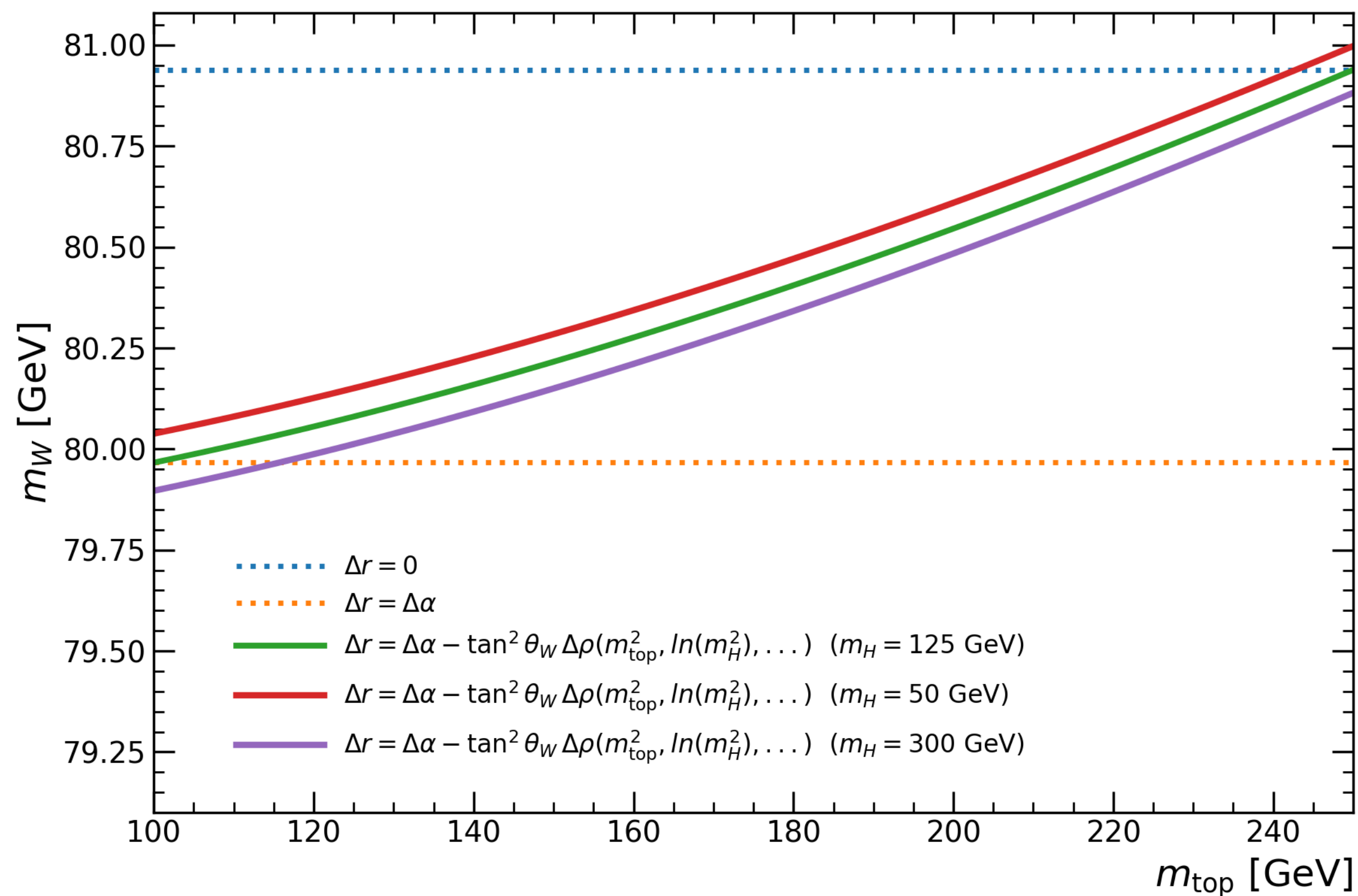


Top



# A very interconnected model

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F (1 - m_W^2/m_Z^2) (1 - \Delta r)}$$



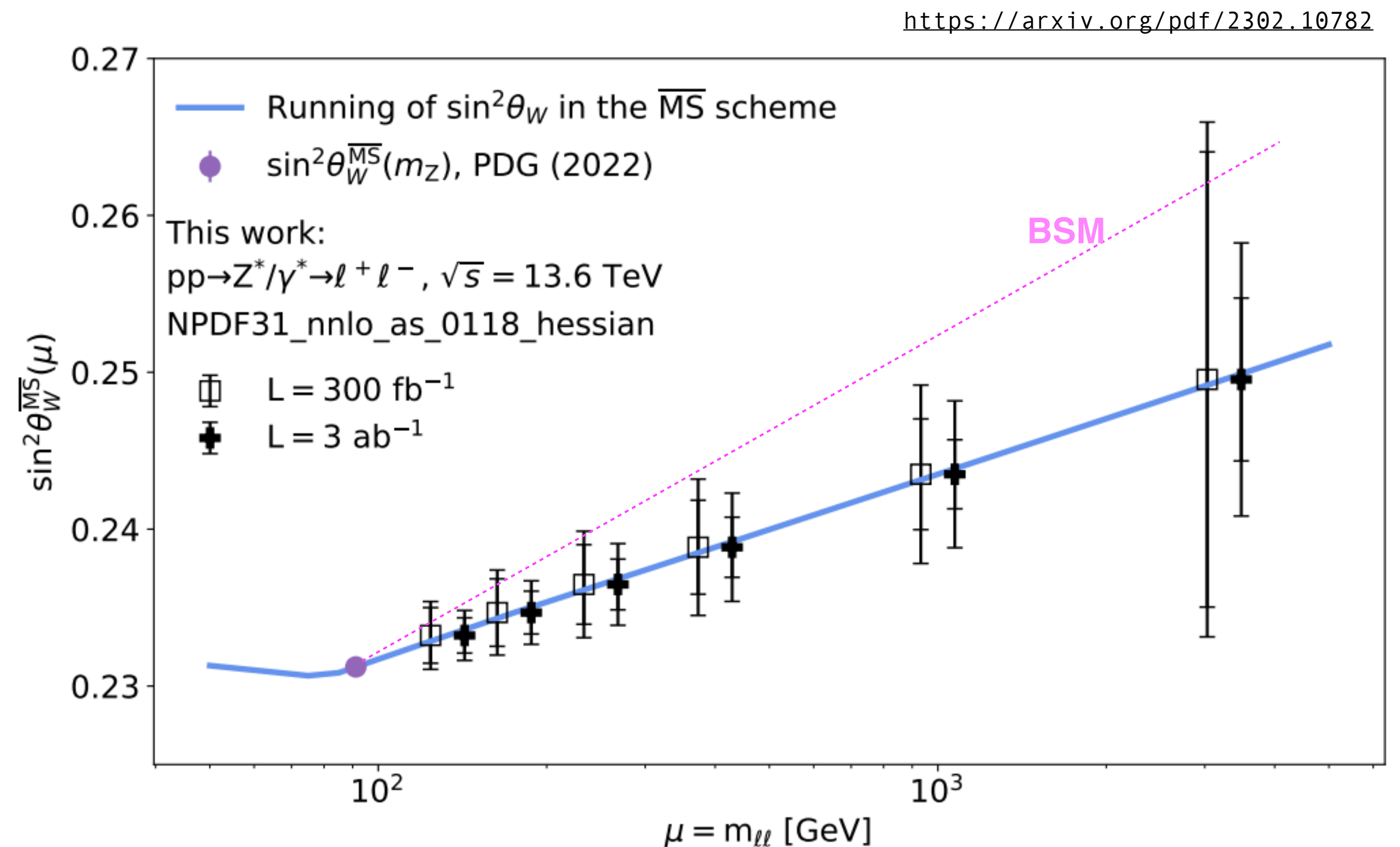
The W mass was historically used to predict the top-quark mass before it was discovered.



# Testing how the mixing ‘runs’ with energy

The EW mixing angle value is expected to show an energy dependence which can be predicted(\*)

- ▶ This scale dependence arises from quantum corrections that modify the coupling
- ▶ Precise measurements of this running can reveal deviations from the Standard Model.

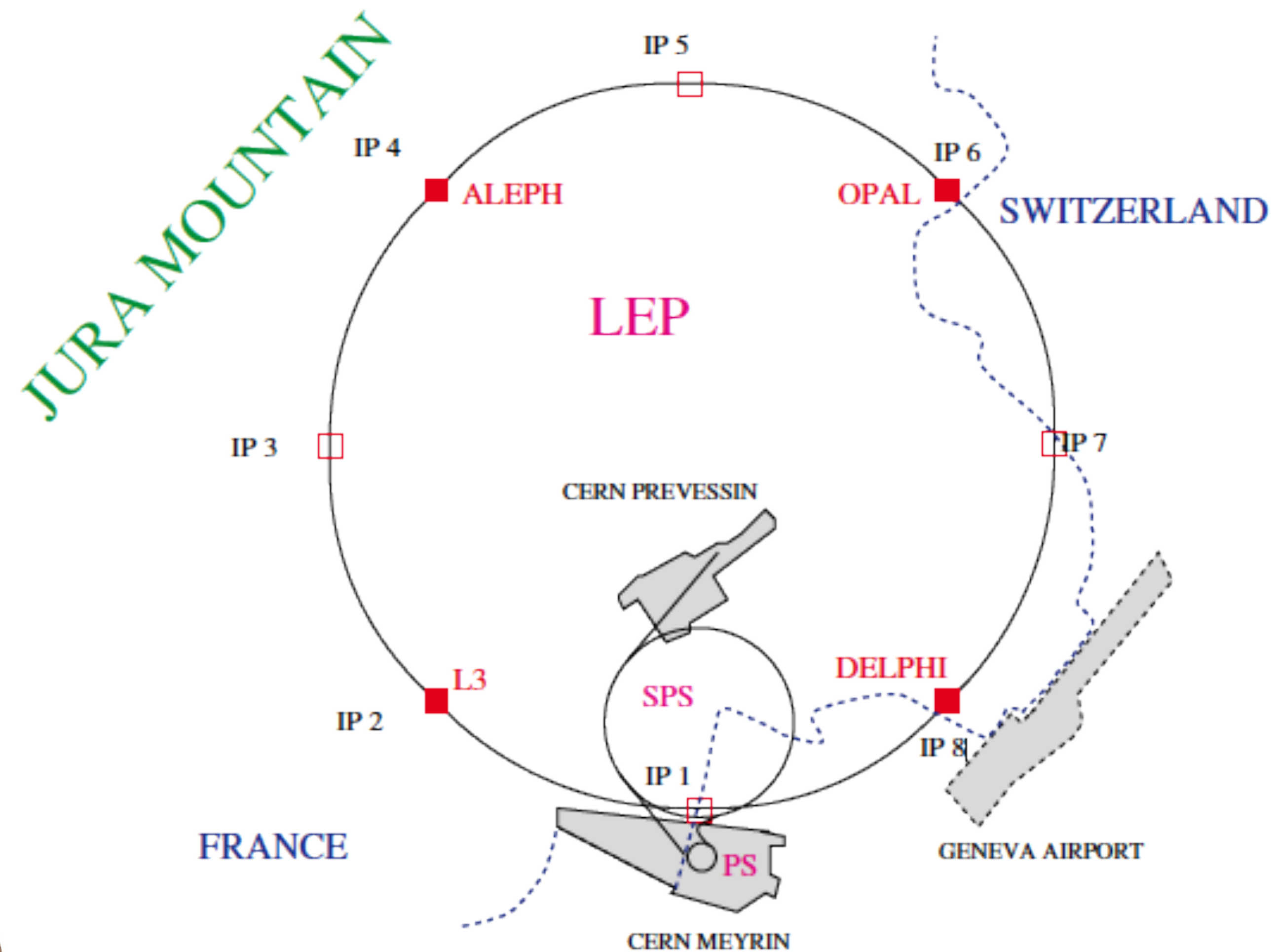




Let's measure it!

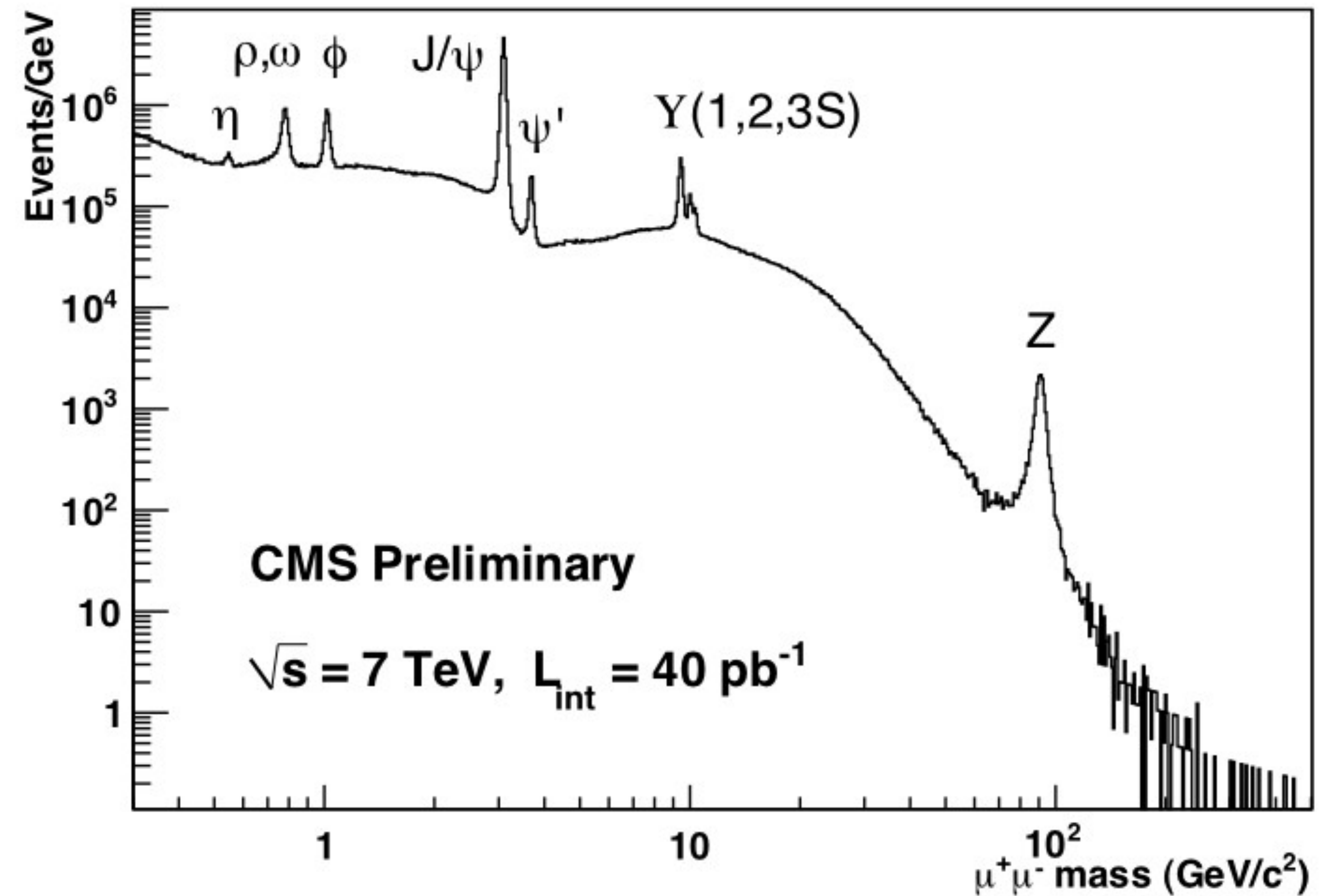
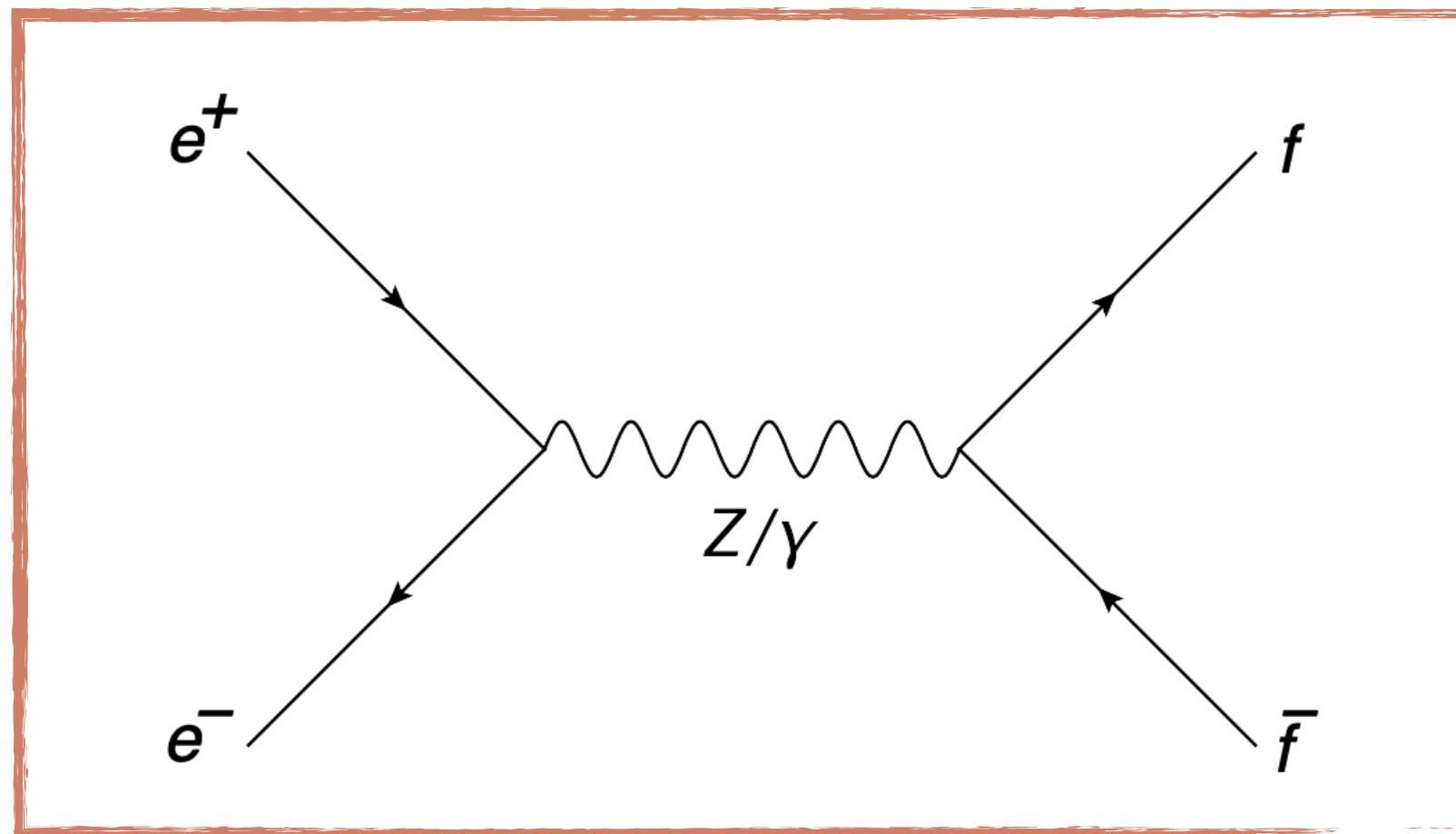






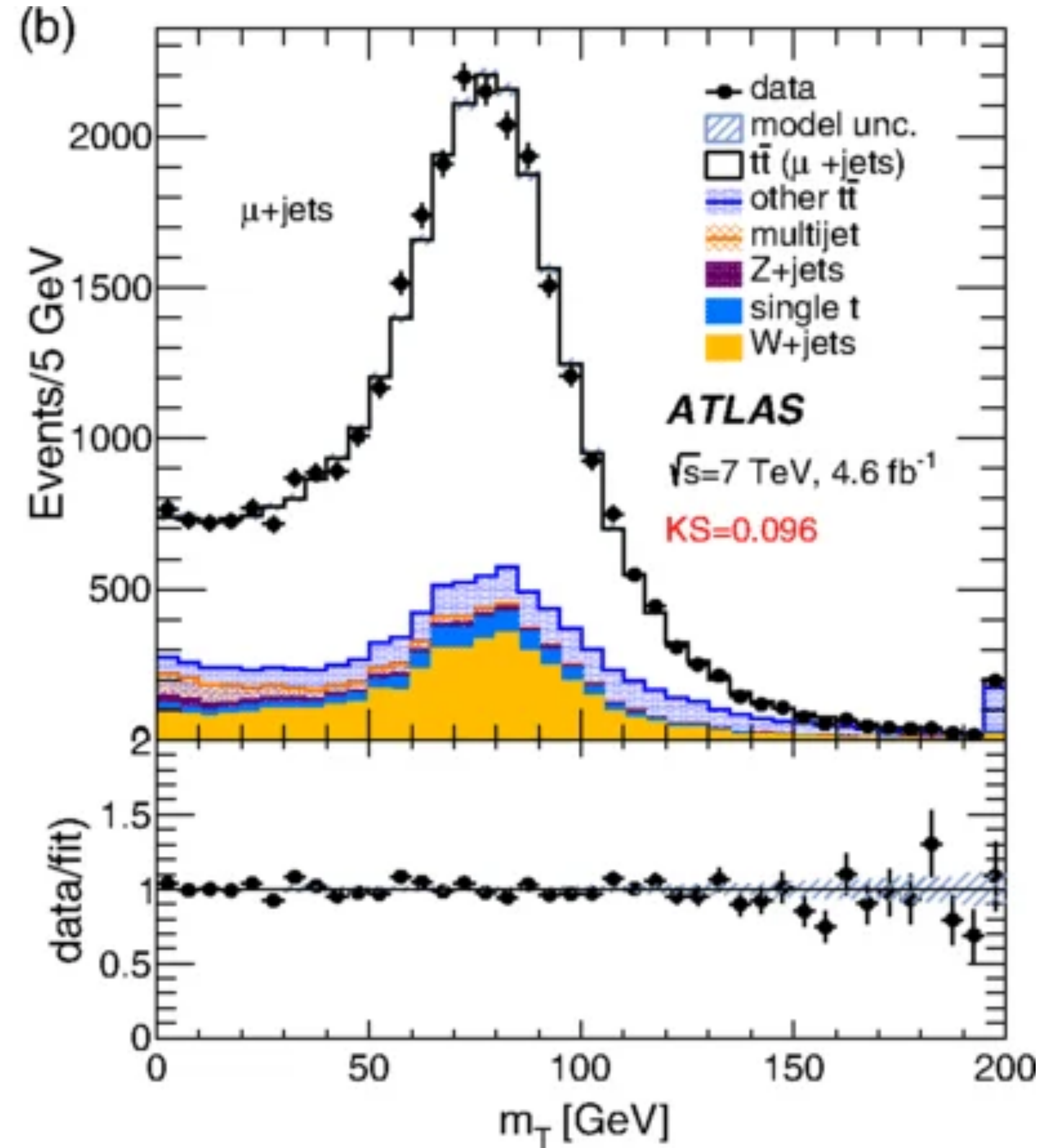
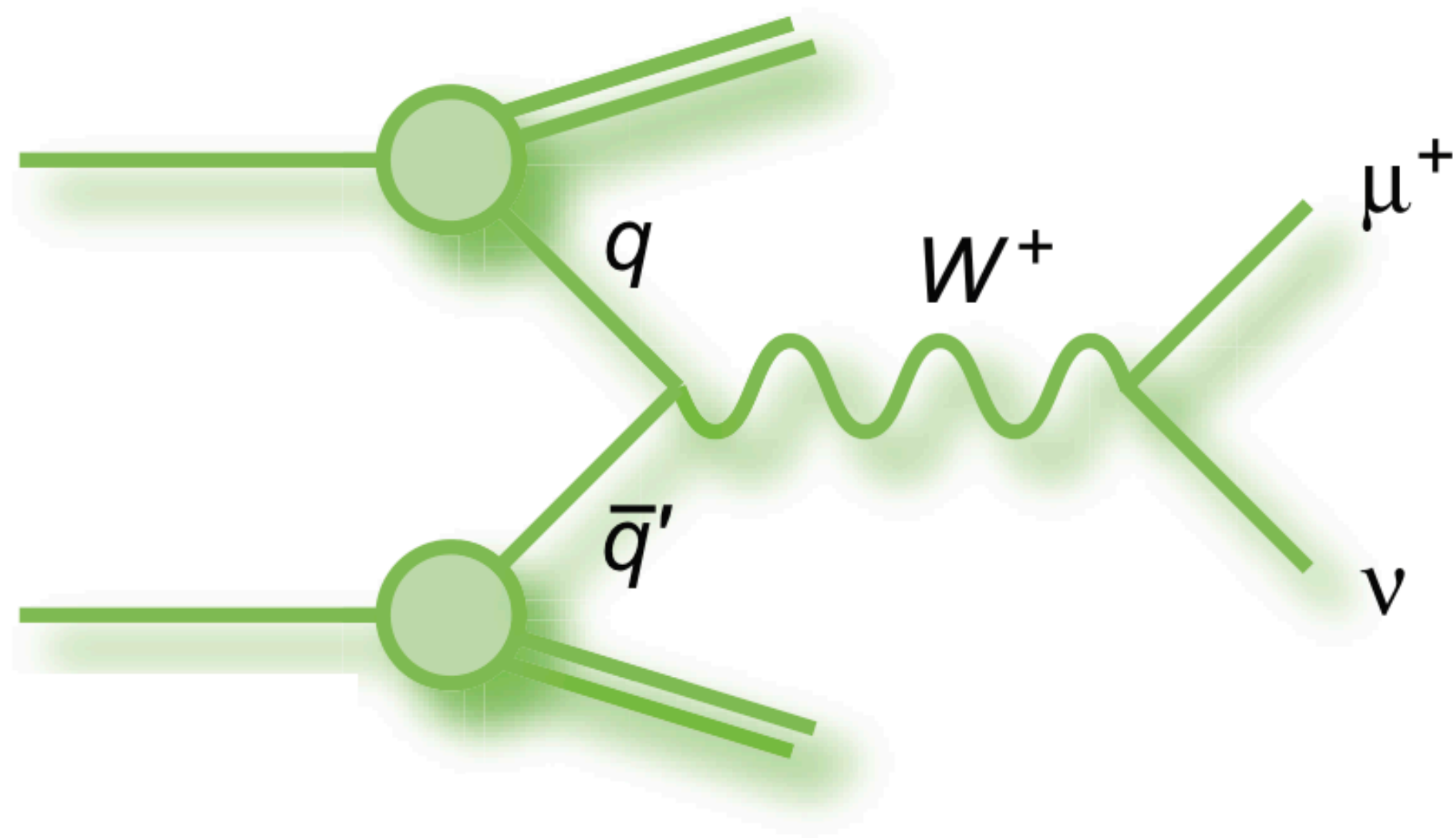


# The Z mass - Life is good





Compare to the W distribution

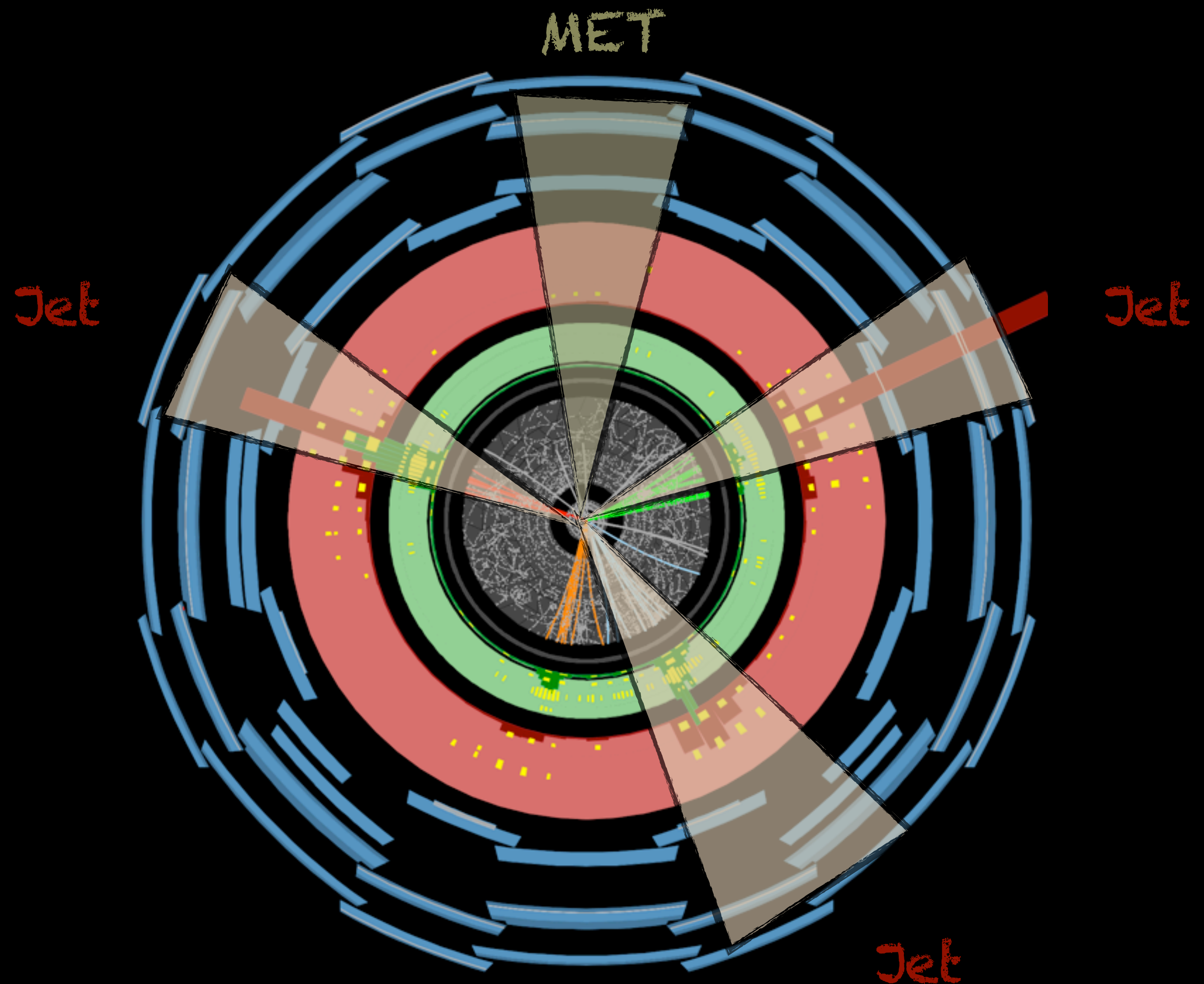




Neutrino are not detected

See only its 'shadow' in the transverse plane, via missing transverse energy

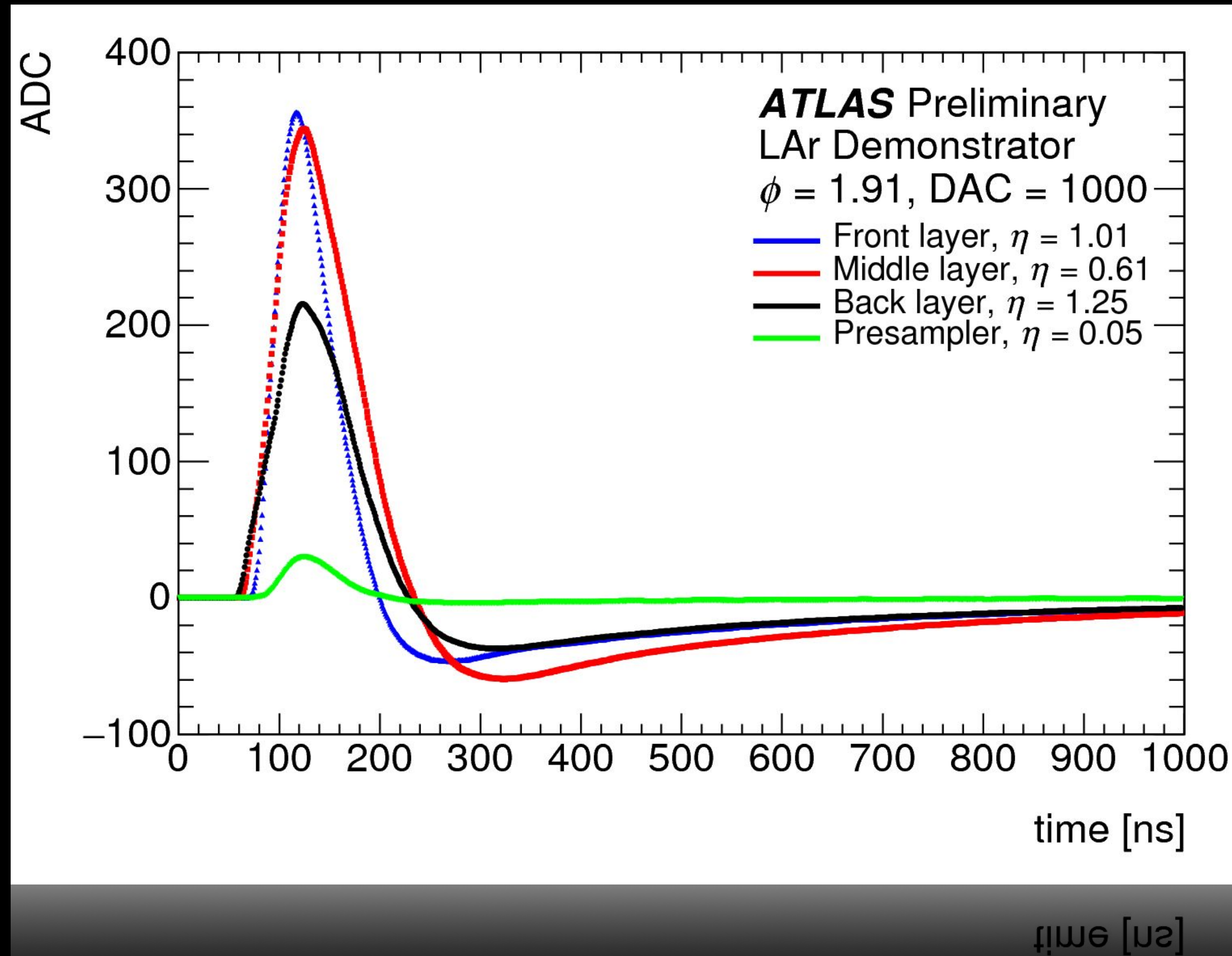
Since it relies on everything else being well measured, it is the weakest link



$$\text{Energy}_{xy} \text{ Missing} = \text{Energy}_{xy} \text{ before} - \text{Energy}_{xy} \text{ measured}$$



# Defining a measurement



What I detect



What I want to measure



# Expressing this mathematically

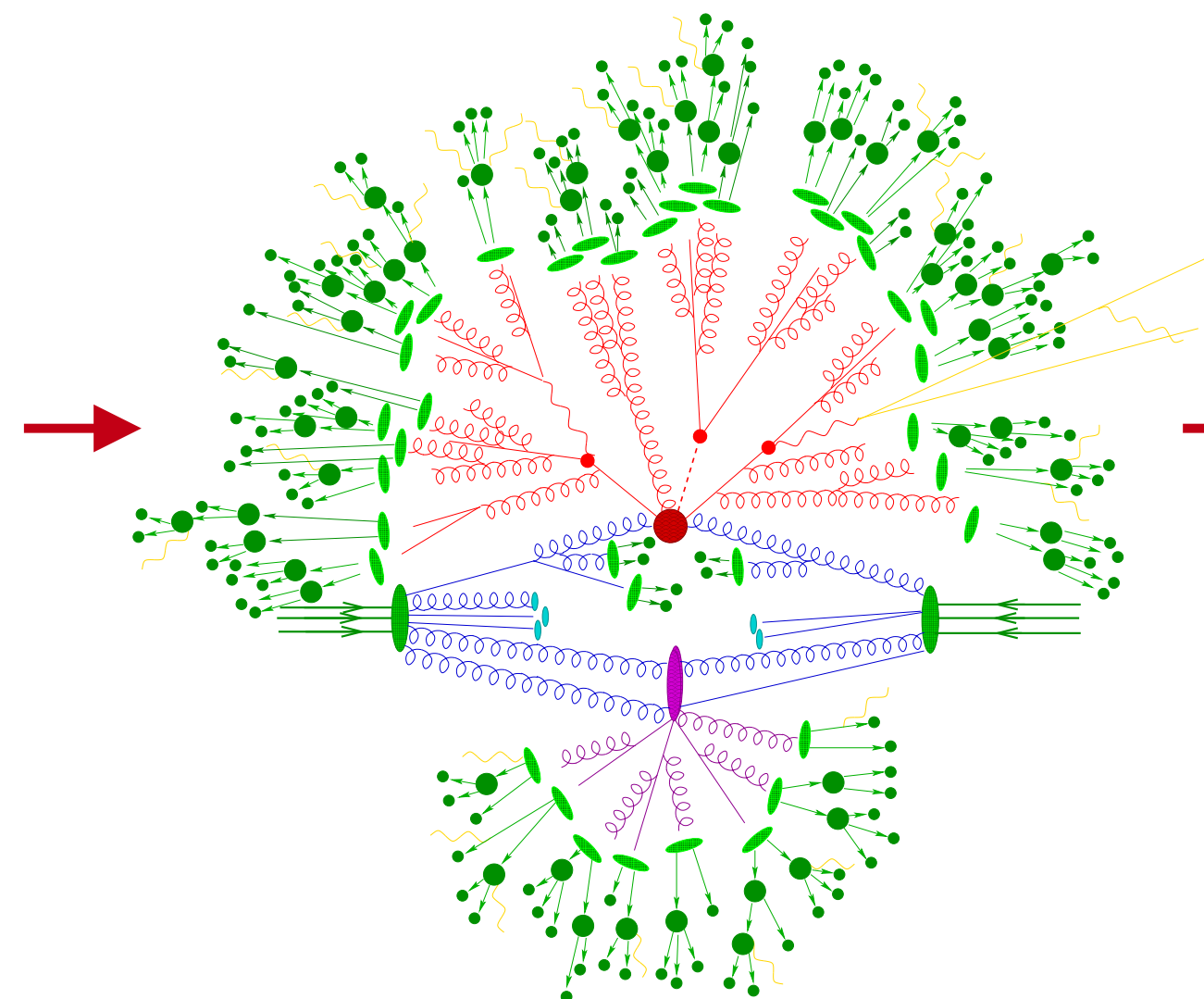
$$p(x | \theta) = \int dz_D dz_S dz_P p(x | z_D) p(z_D | z_S) p(z_S | z_P) p(z_P | \theta)$$

parton level  $z_P$



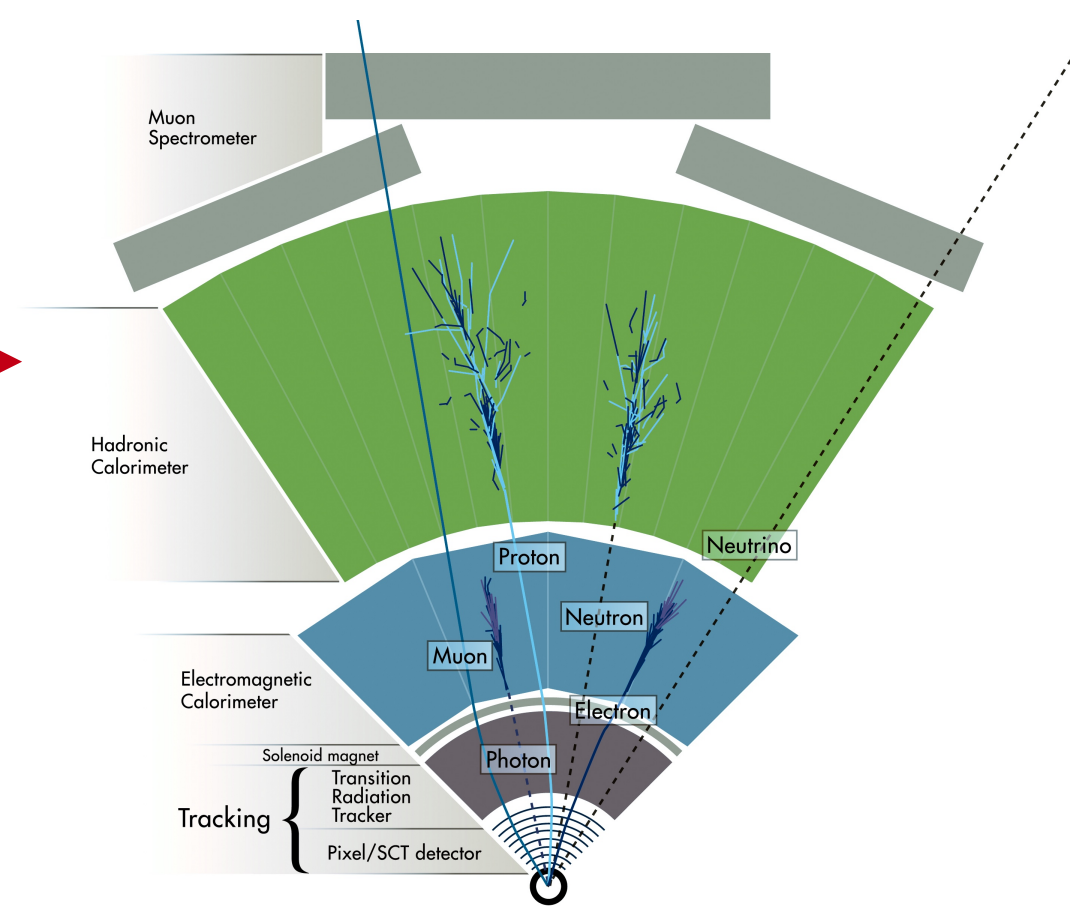
The dependence on parameters  $\theta$  is here.

parton shower  $z_S$

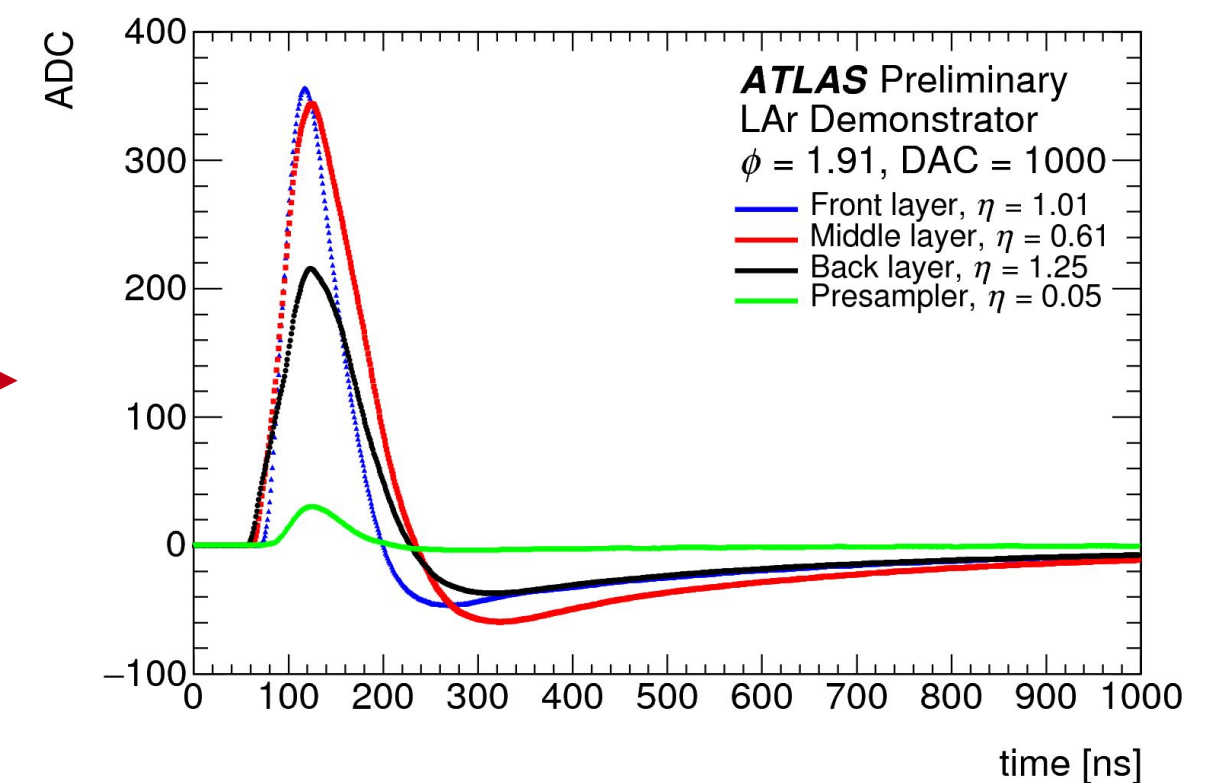


JHEP 0902 (2009) 007

detector interaction  $z_D$



observables  $x$





# My ingredients to determining W mass

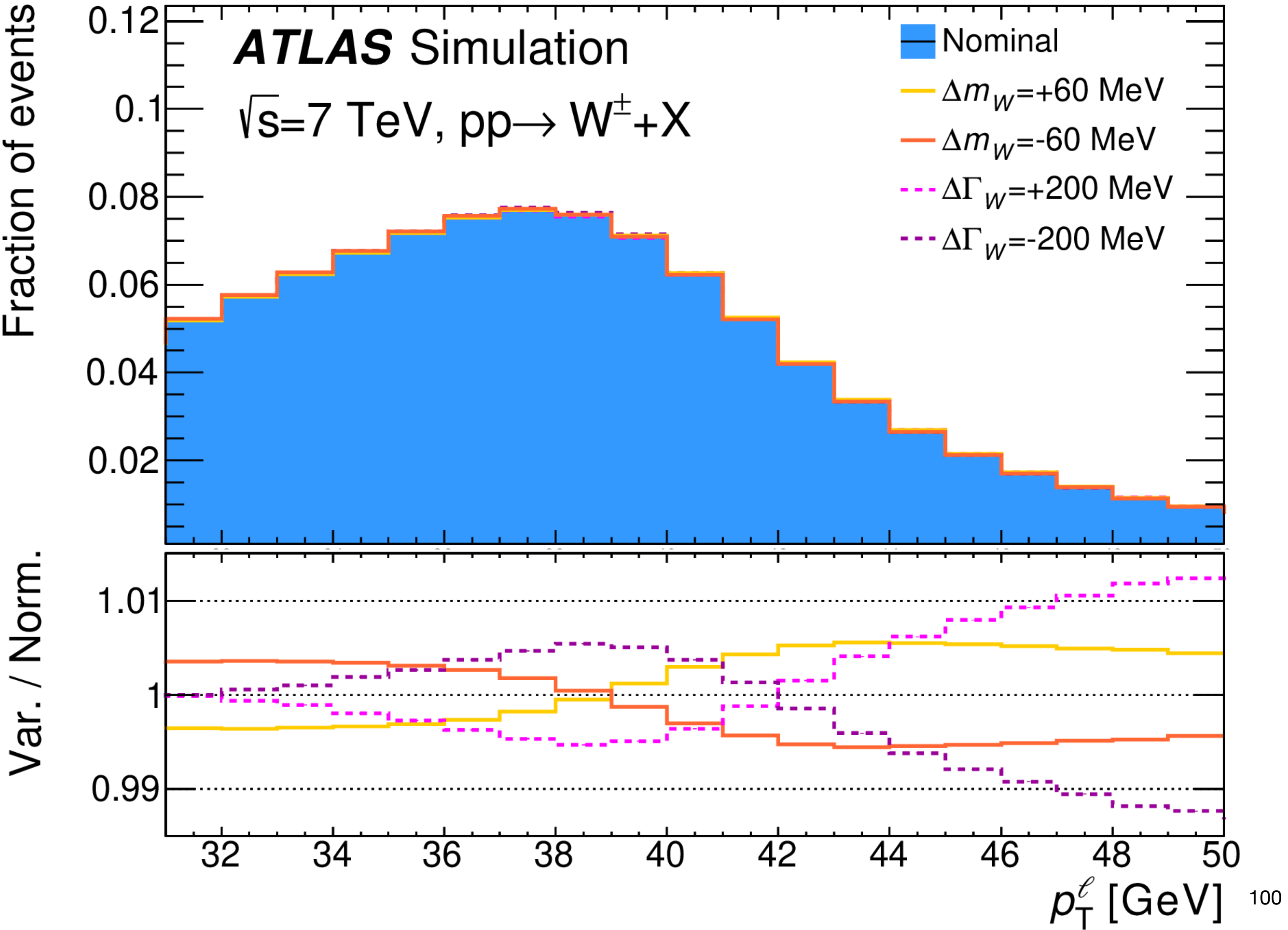
---

1. Need an detector observable that is sensitive the value of the mass?
2. Need a theoretical prediction of that observable and its mass dependence
3. Need verify that my detector itself doesn't mimic that signature

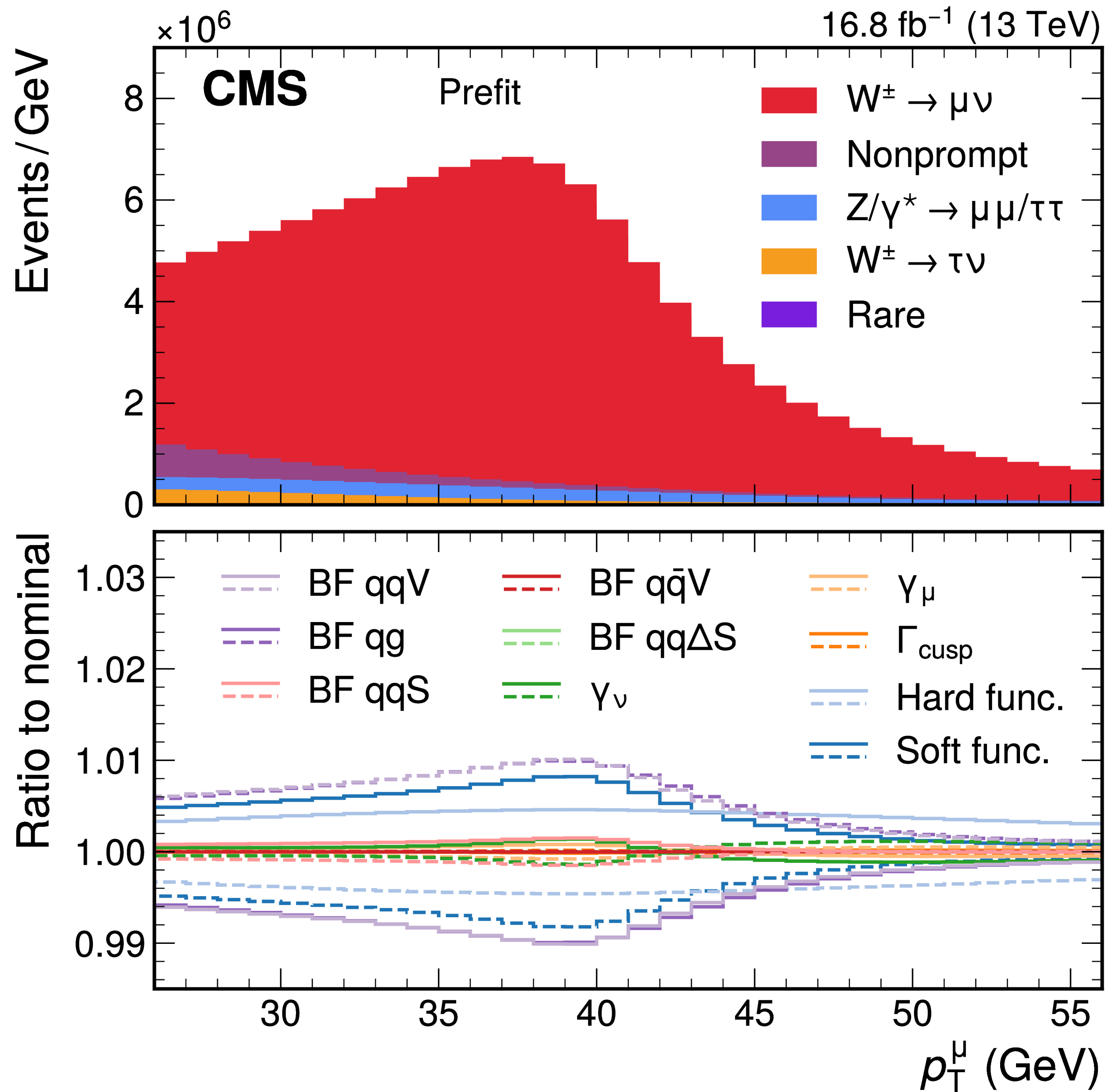


# The imprint of the W mass

Measurement goal is  
a precision of 10 MeV







Theory modeling

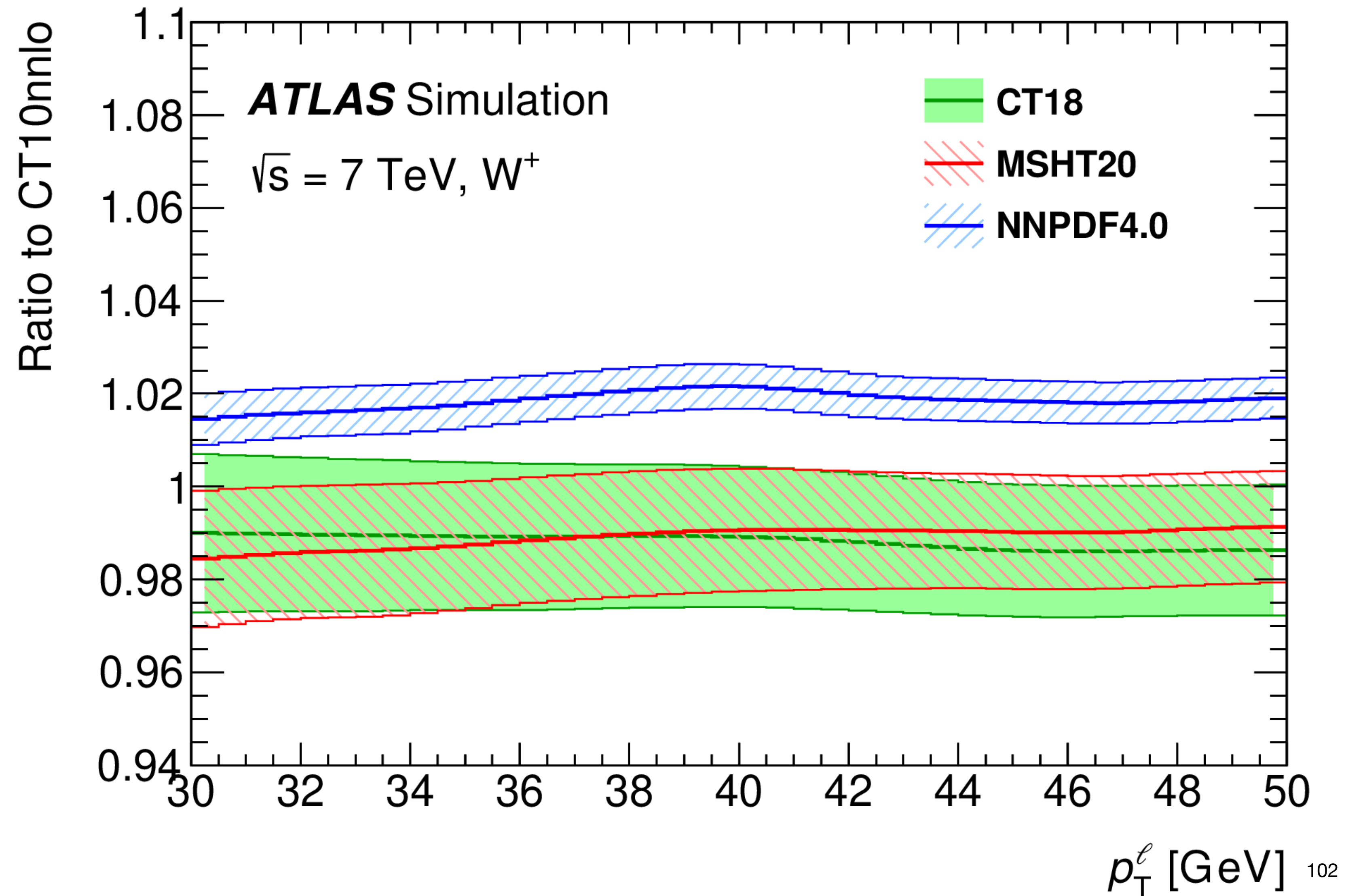
Need to utilize the differences in the shape to constrain the uncertainties



# The proton is complicated...

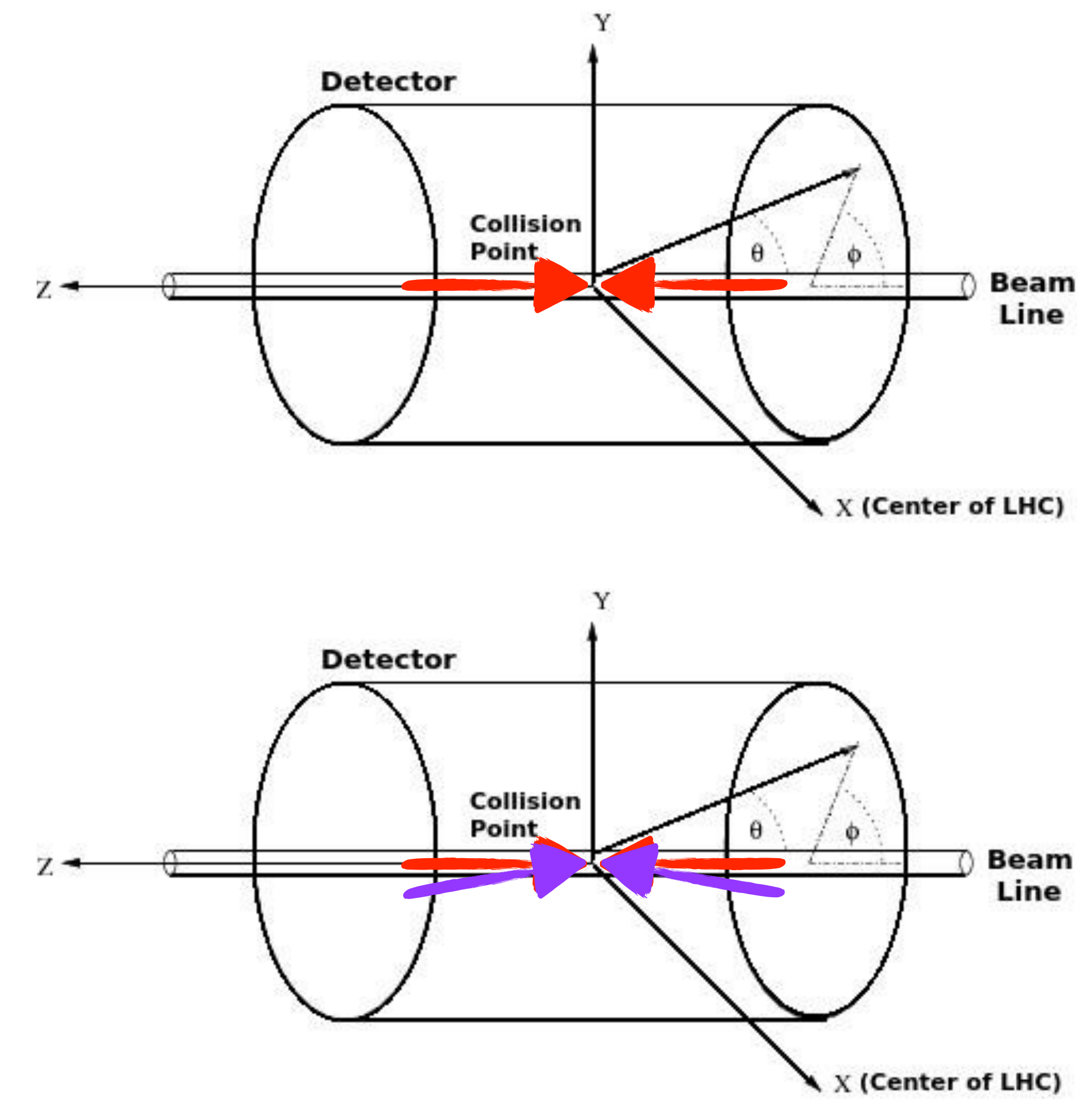
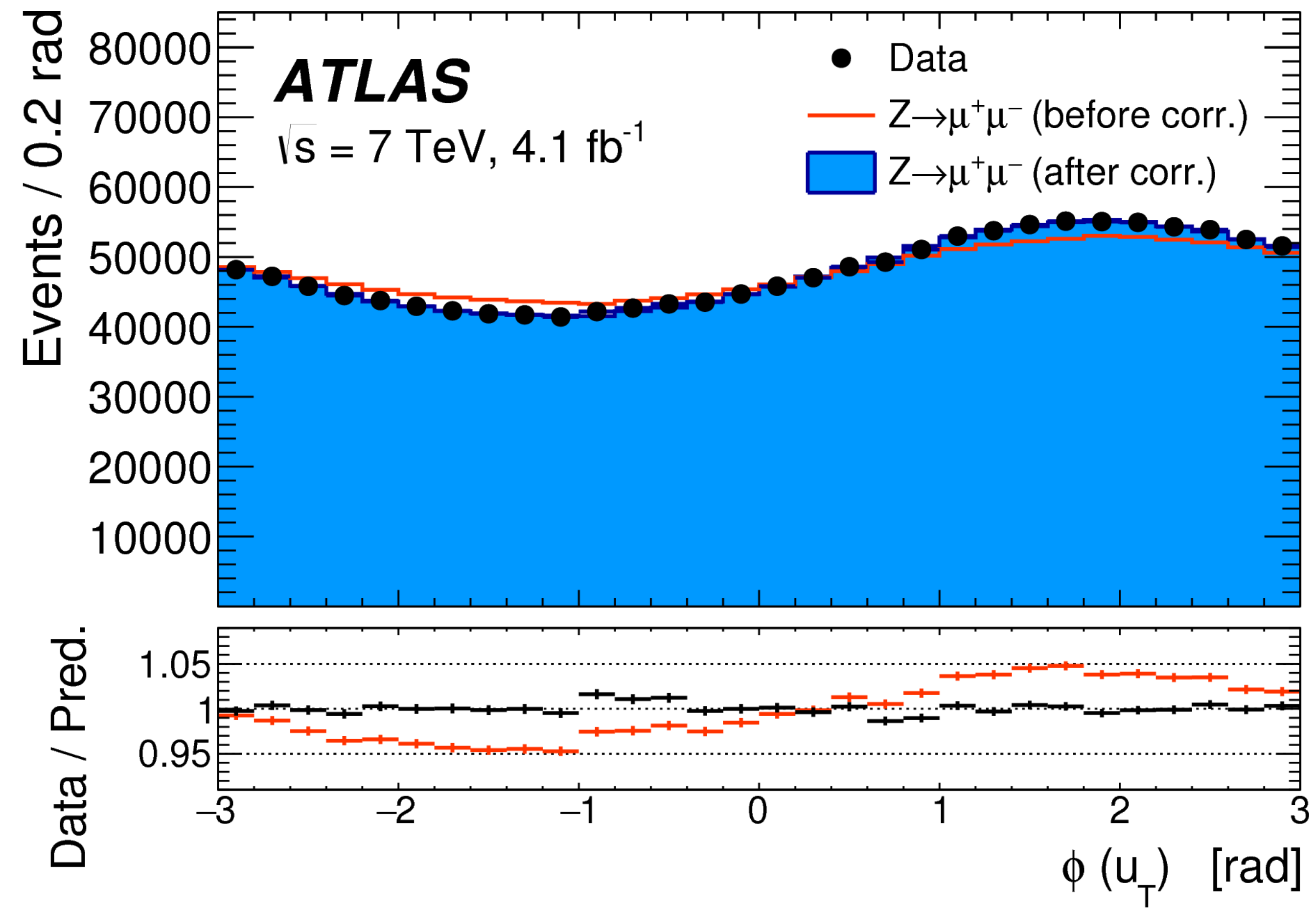
Allowing PDFs to be constrained in a fit is controversial.

The PDF is already obtained via a fit to various (including LHC) data

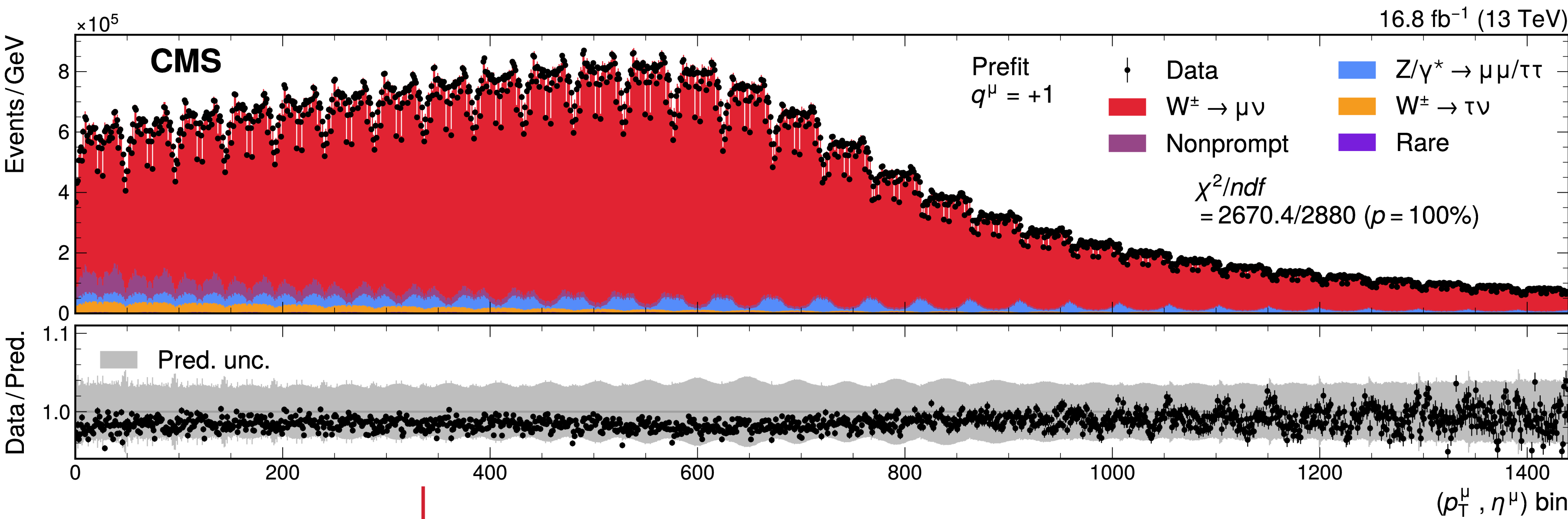




# Can my detector mimic the signal?

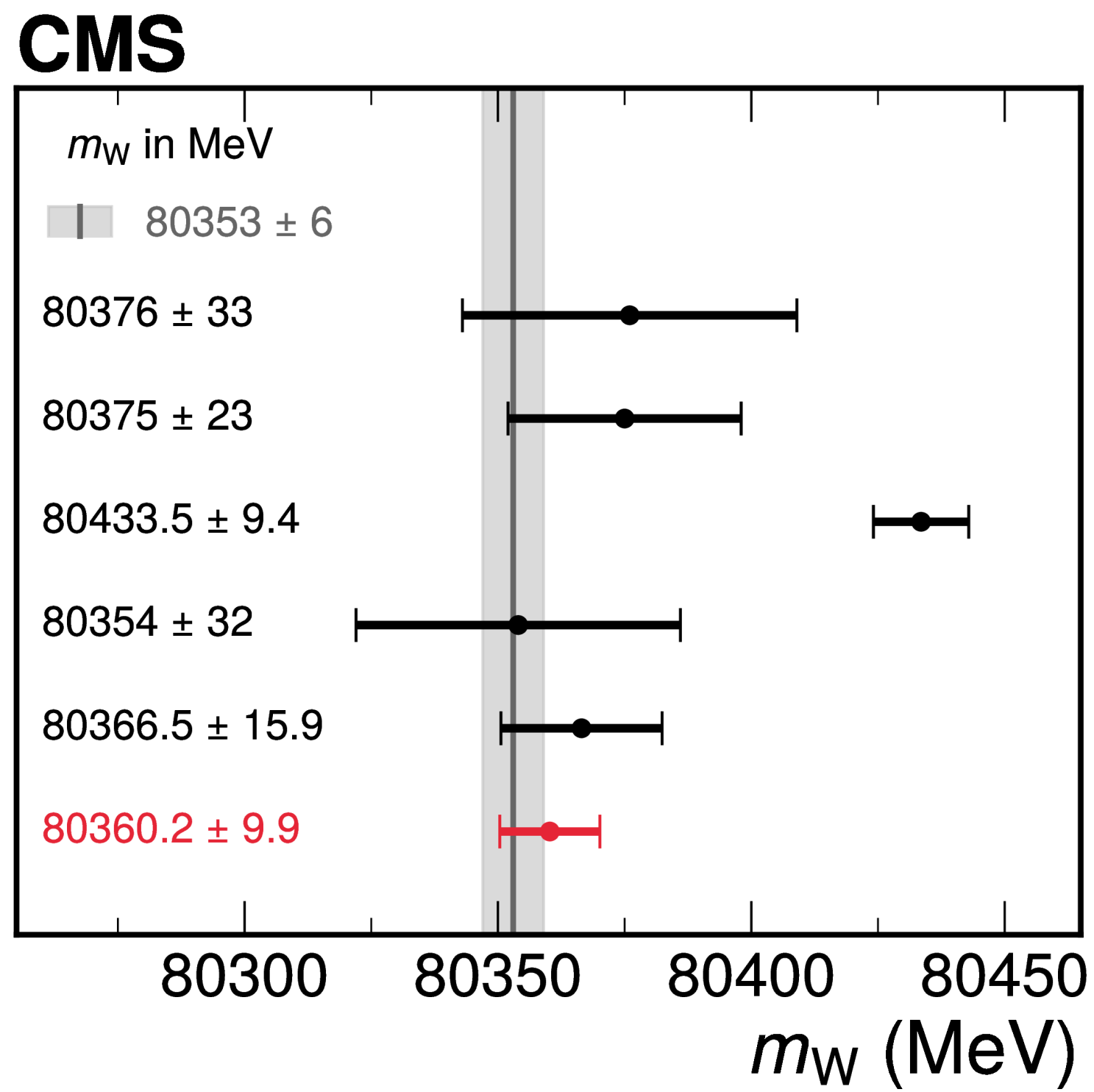






Throw it all into one massive fit and to get back one number

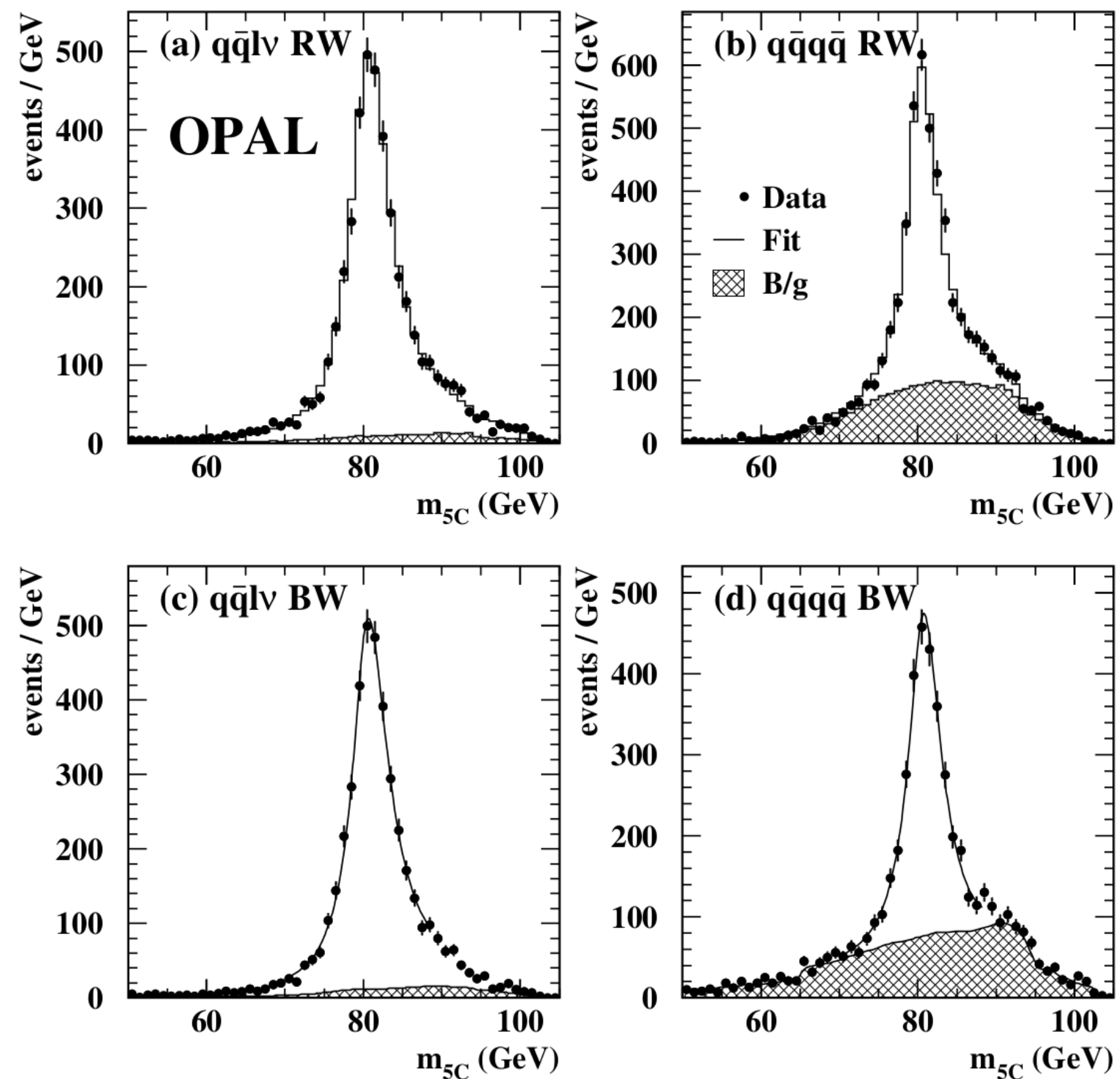
Electroweak fit  
 PRD 110 (2024) 030001  
**LEP combination**  
 Phys. Rep. 532 (2013) 119  
**D0**  
 PRL 108 (2012) 151804  
**CDF**  
 Science 376 (2022) 6589  
**LHCb**  
 JHEP 01 (2022) 036  
**ATLAS**  
 EPJC 84 (2024) 1309  
**CMS**  
*This work*



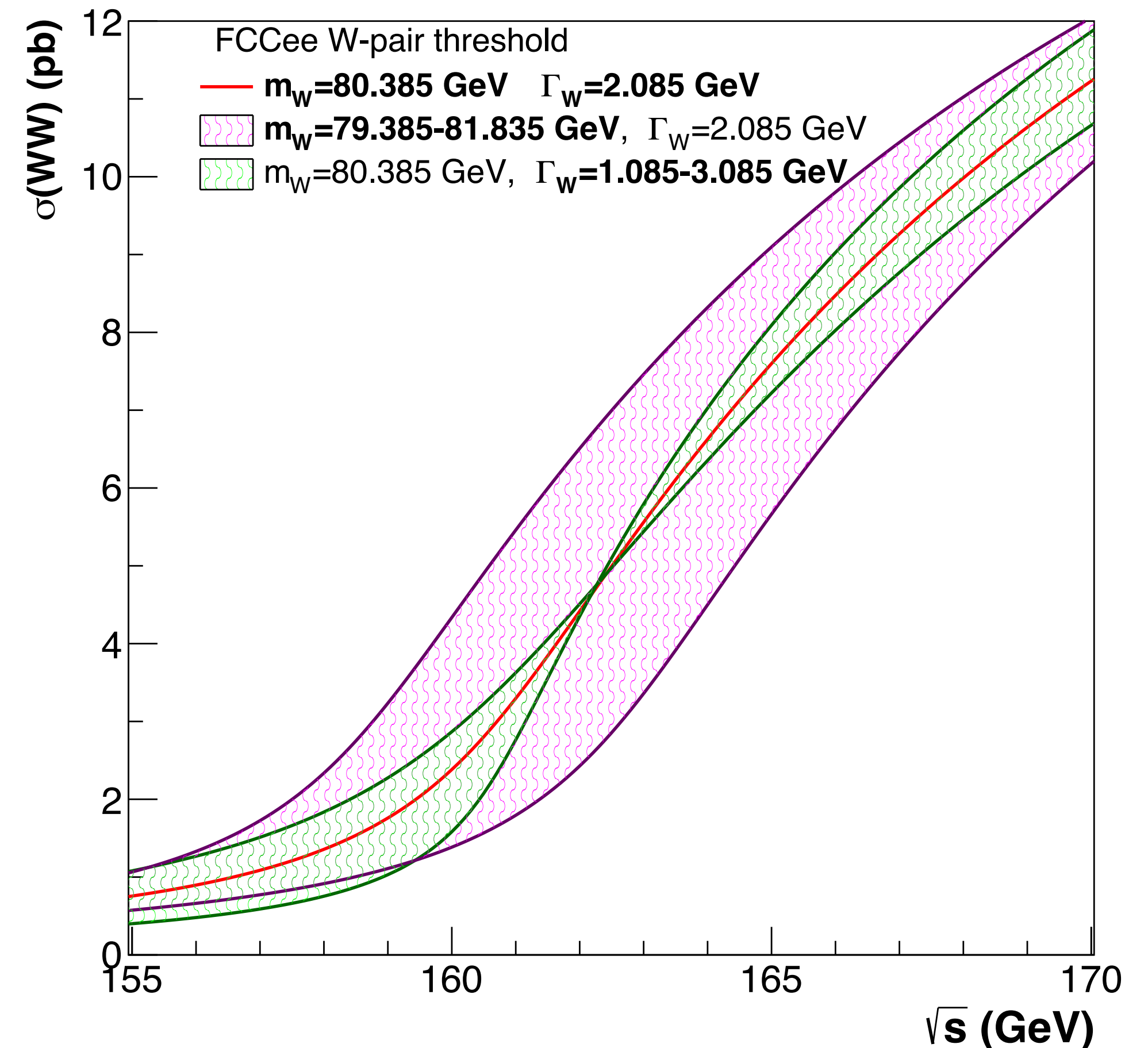


# The W mass at a future collider

LEP results mainly based  
on kinematic constraints

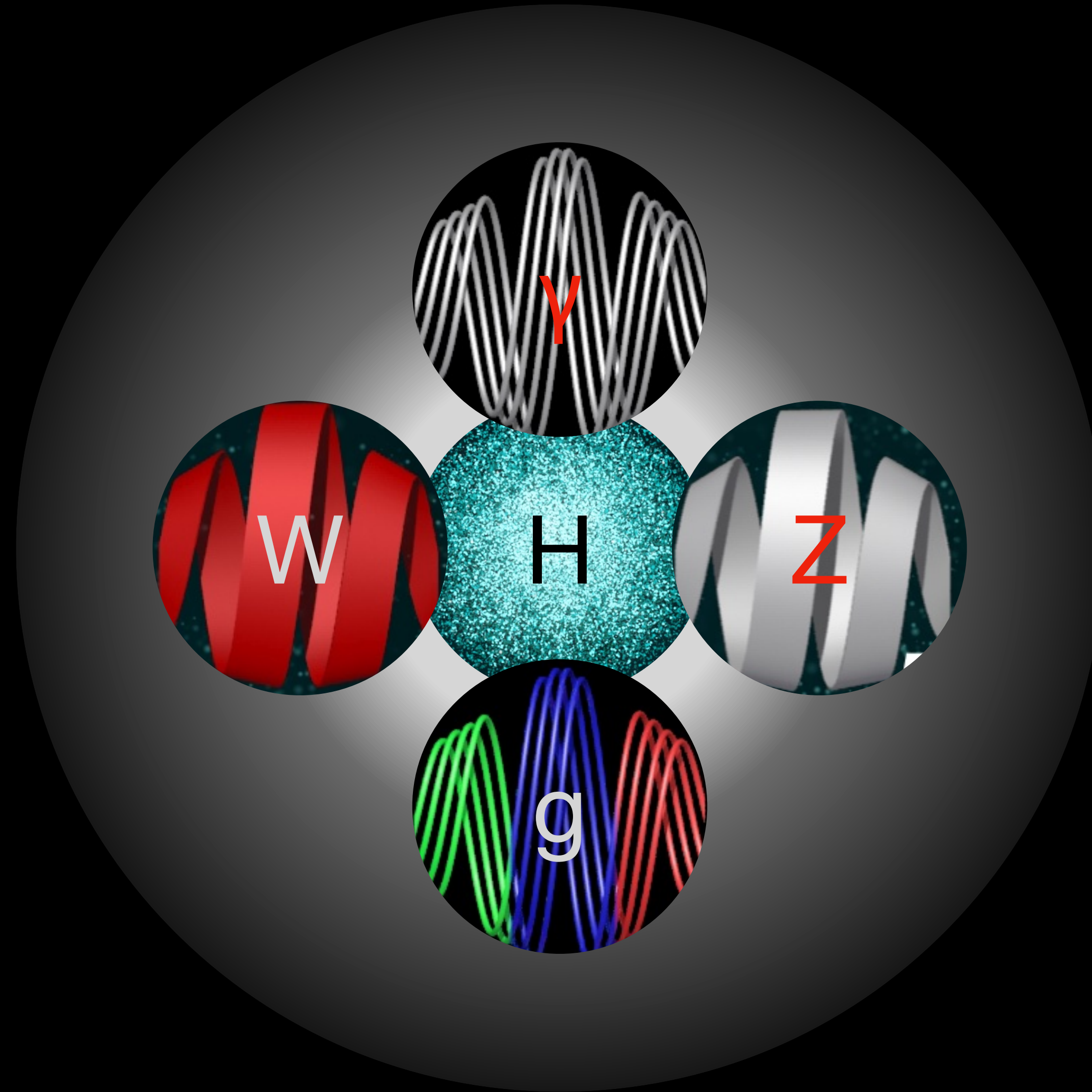


FCCee projects  $\sim 0.5$  MeV  
precision via a cross section scan



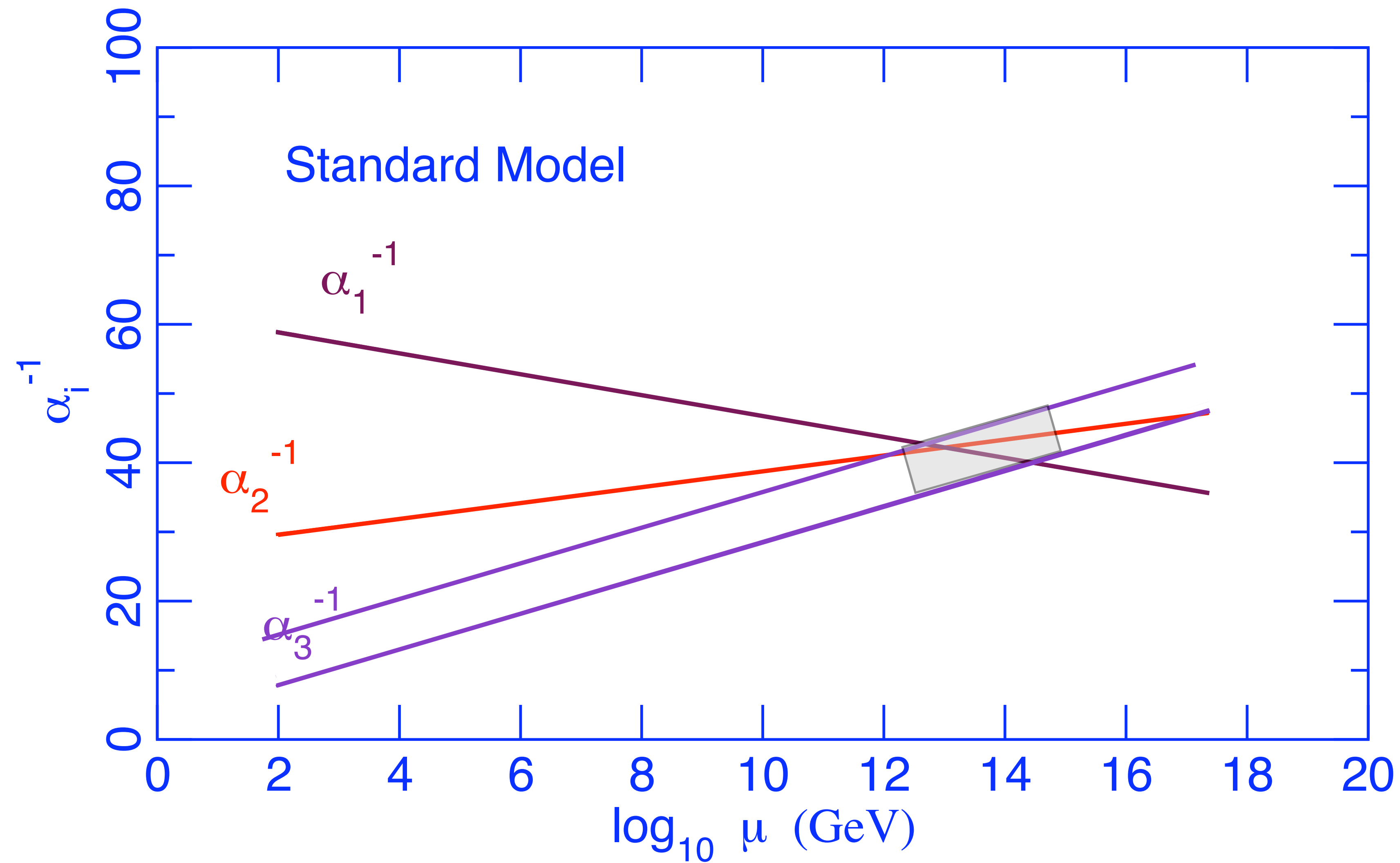


How physics changes with energy



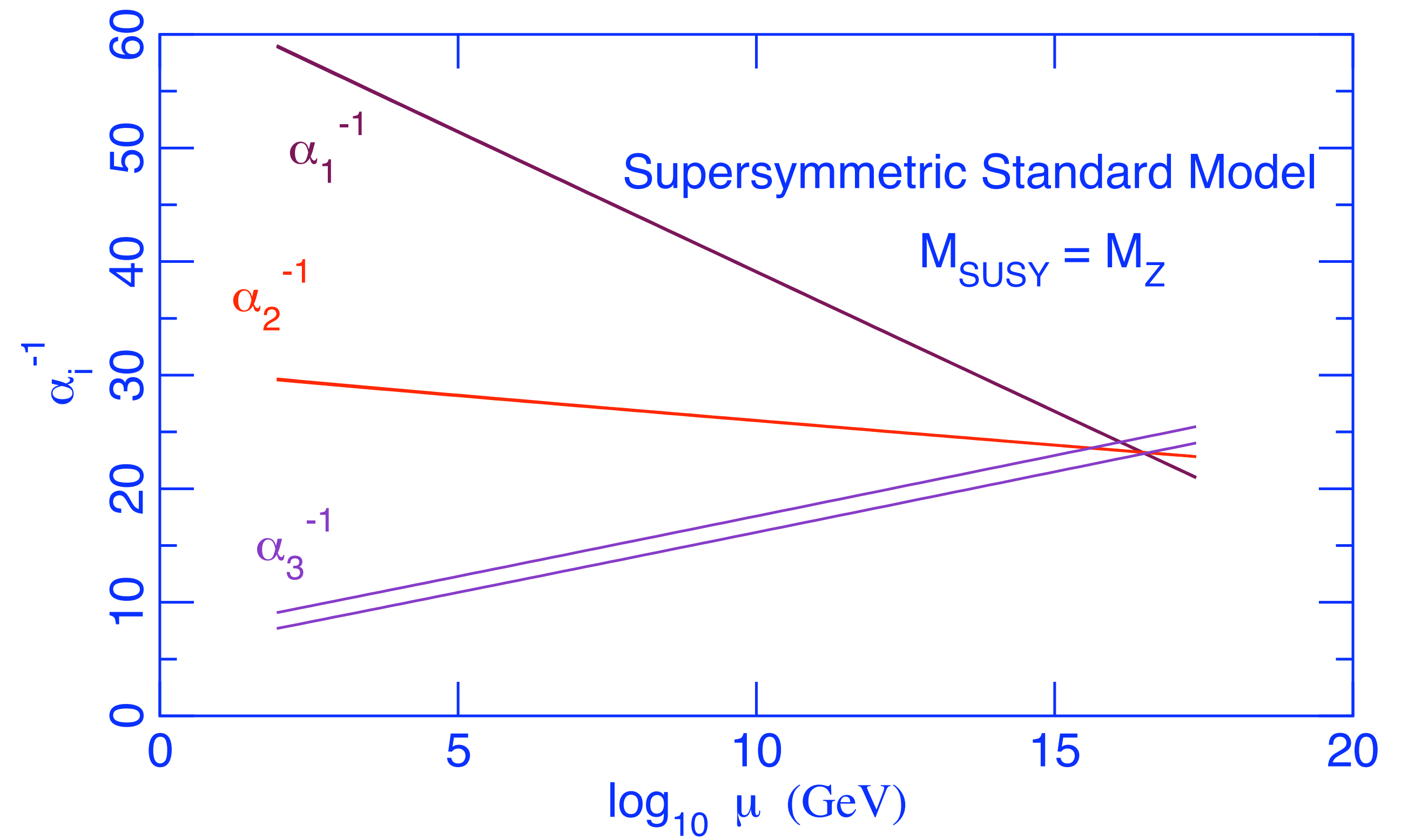
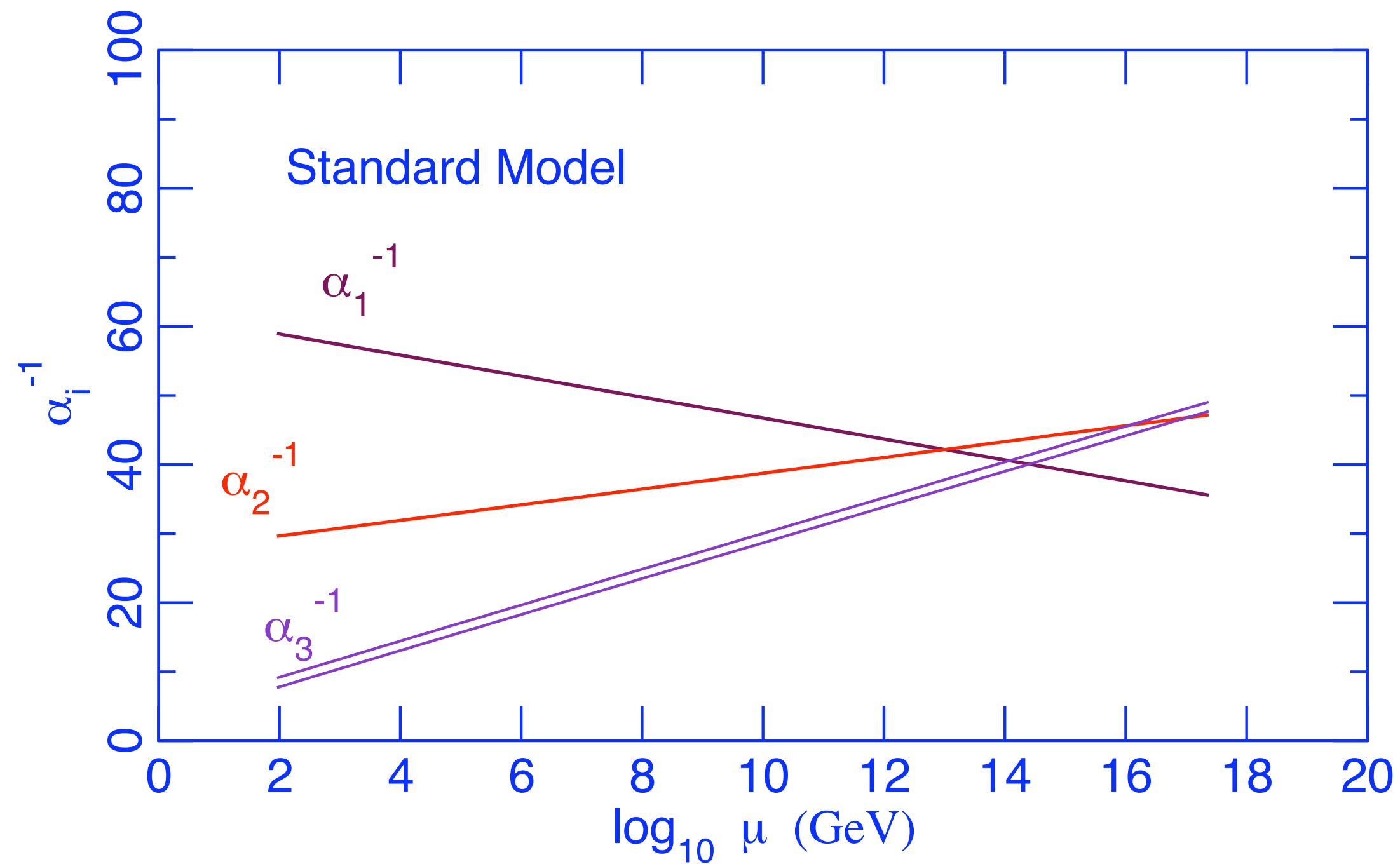
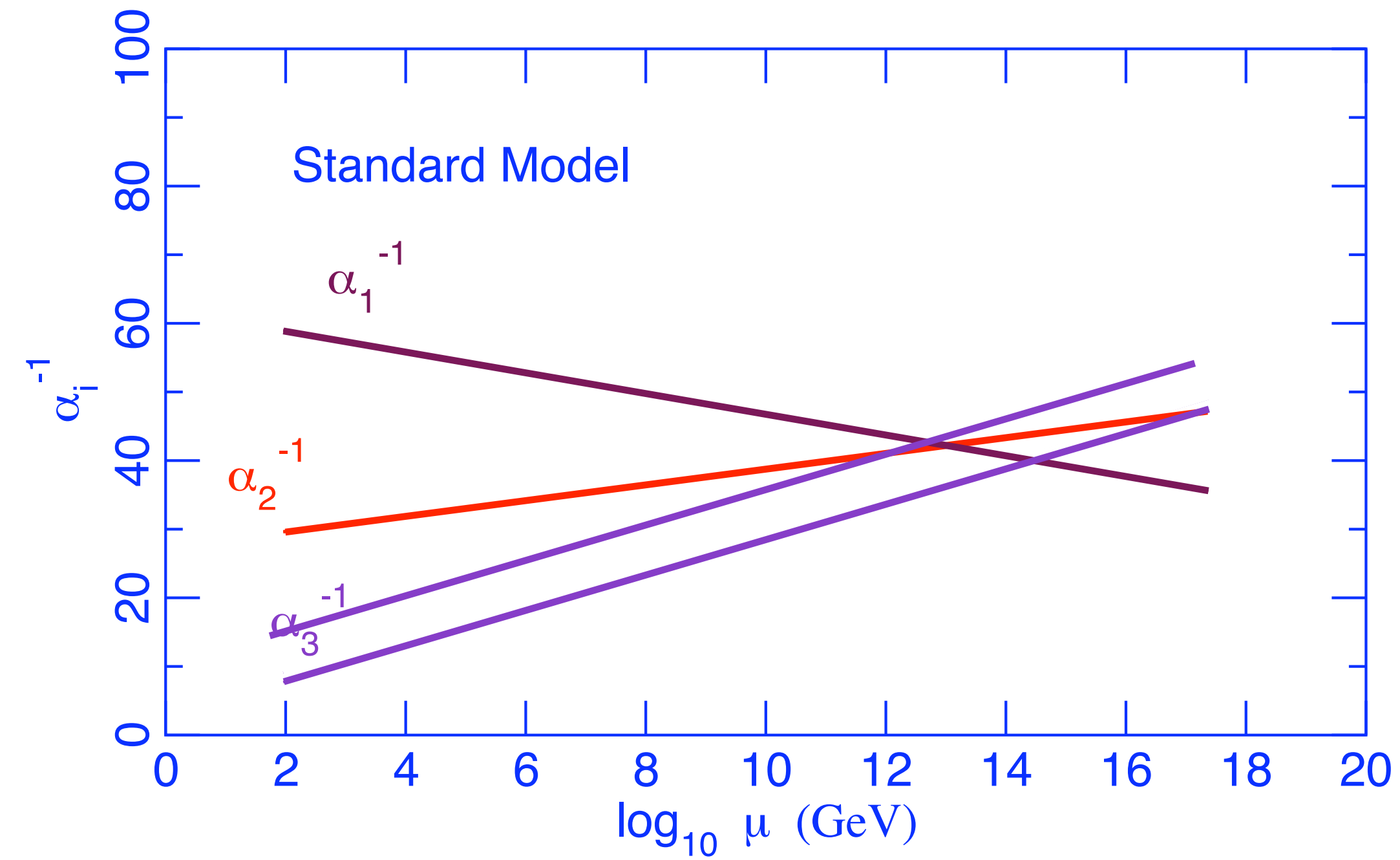


# A blast from the past

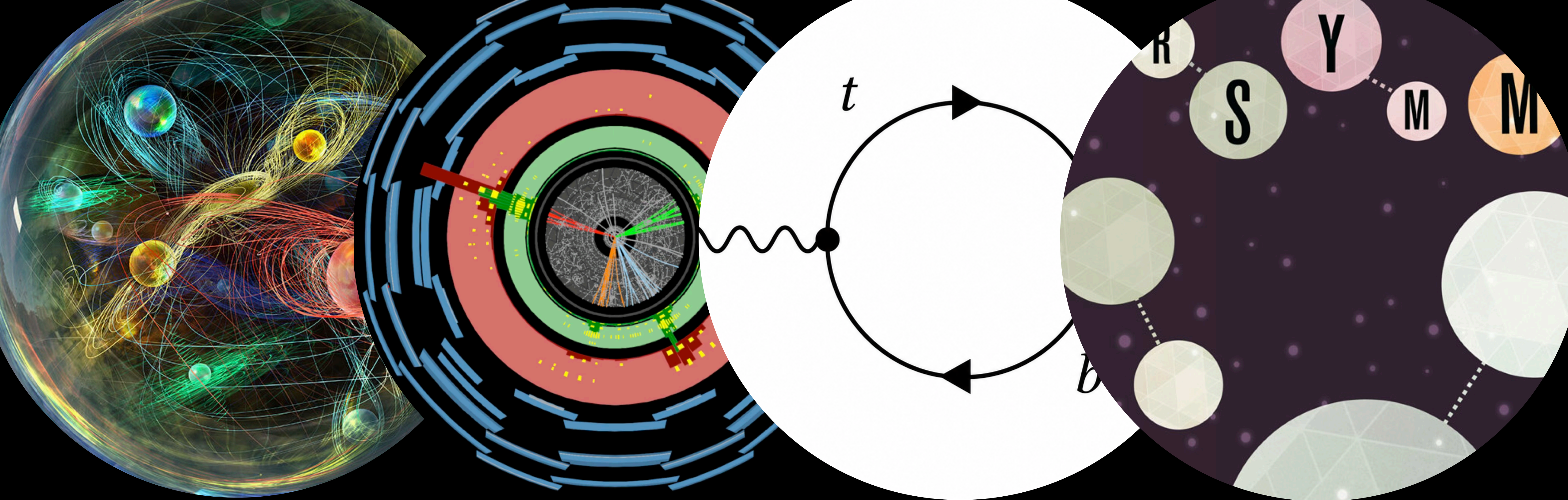




# A blast from the past





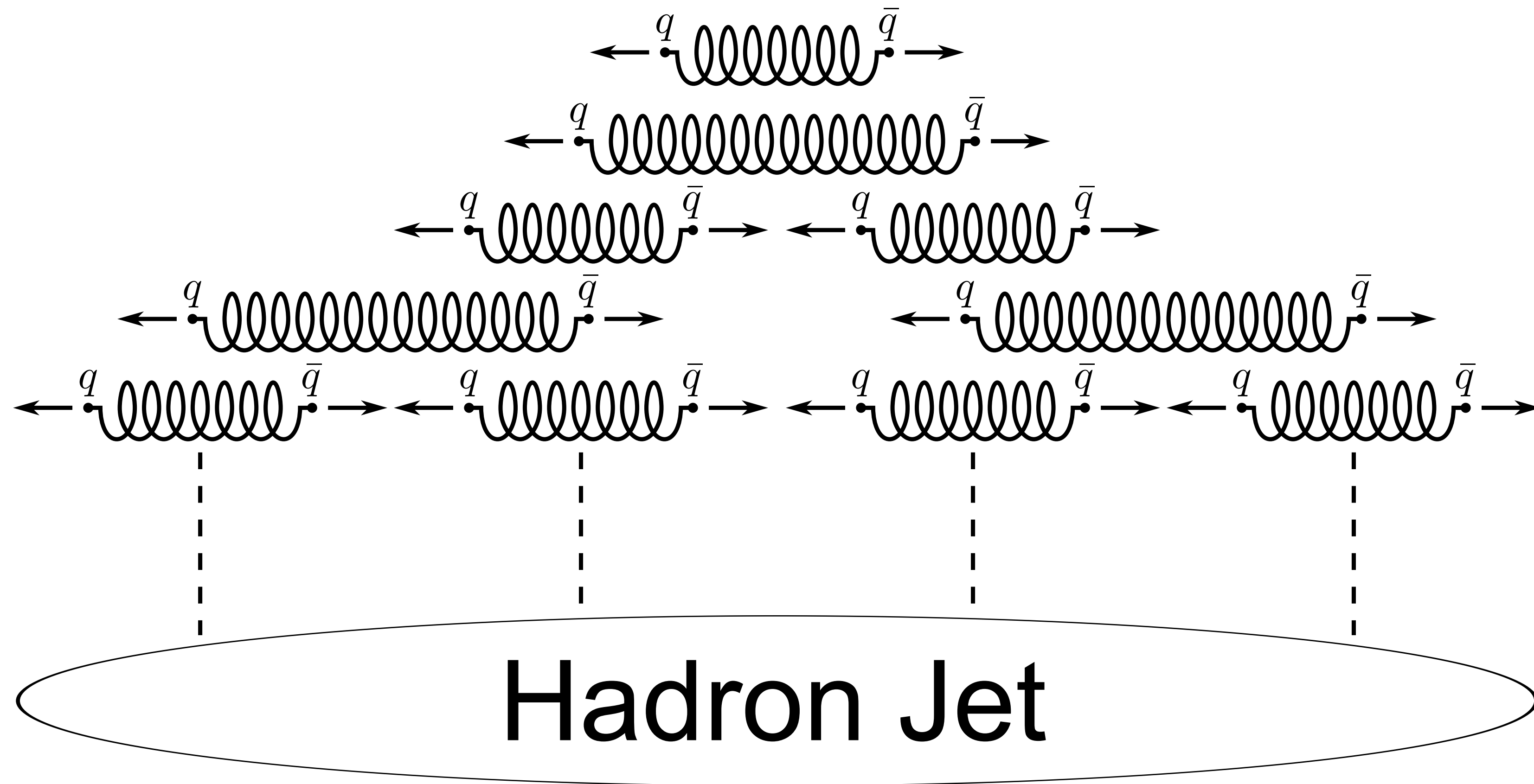


One parameter controls this scaling in QCD



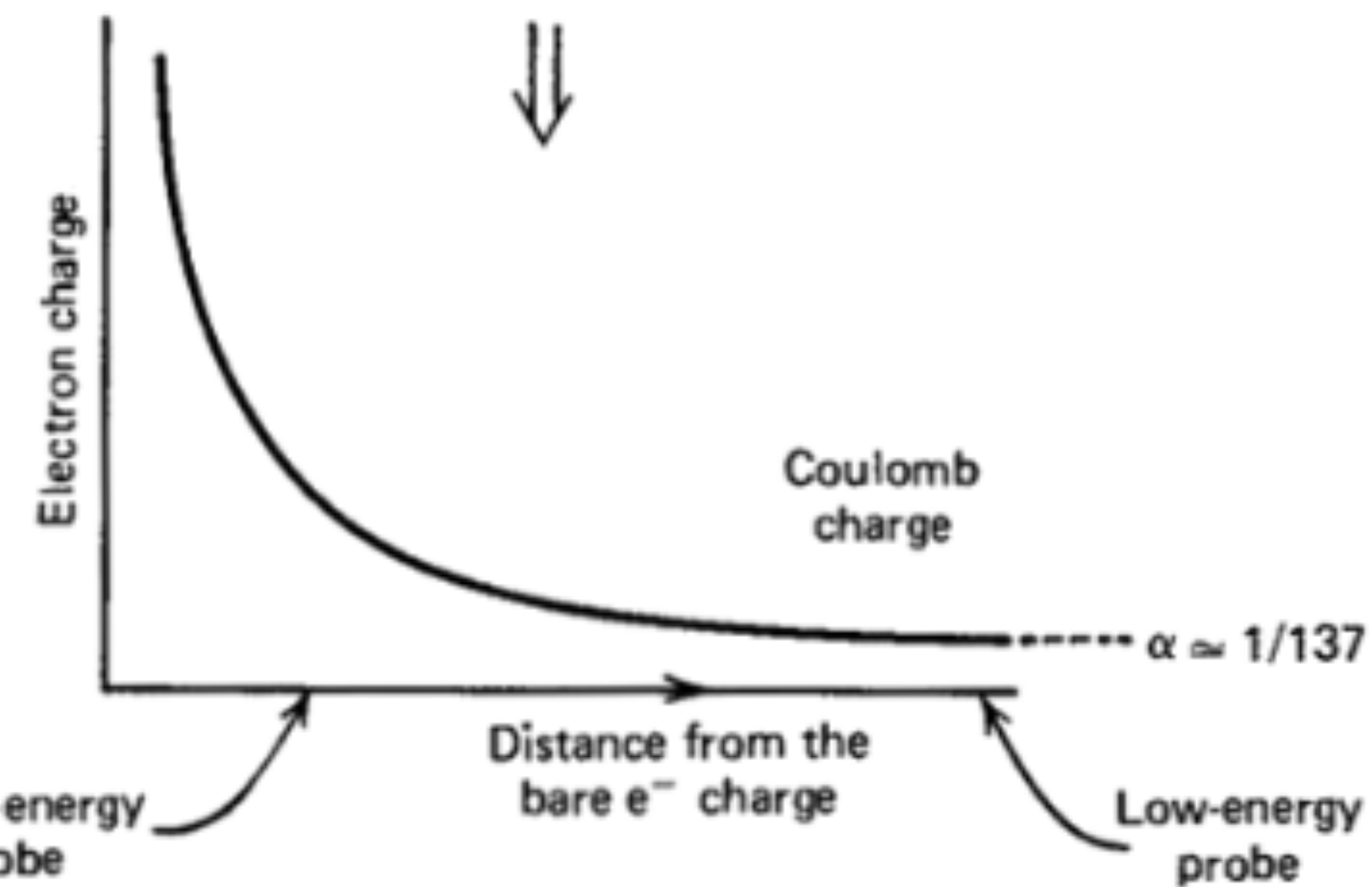
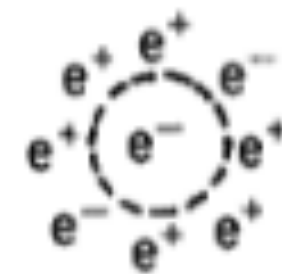
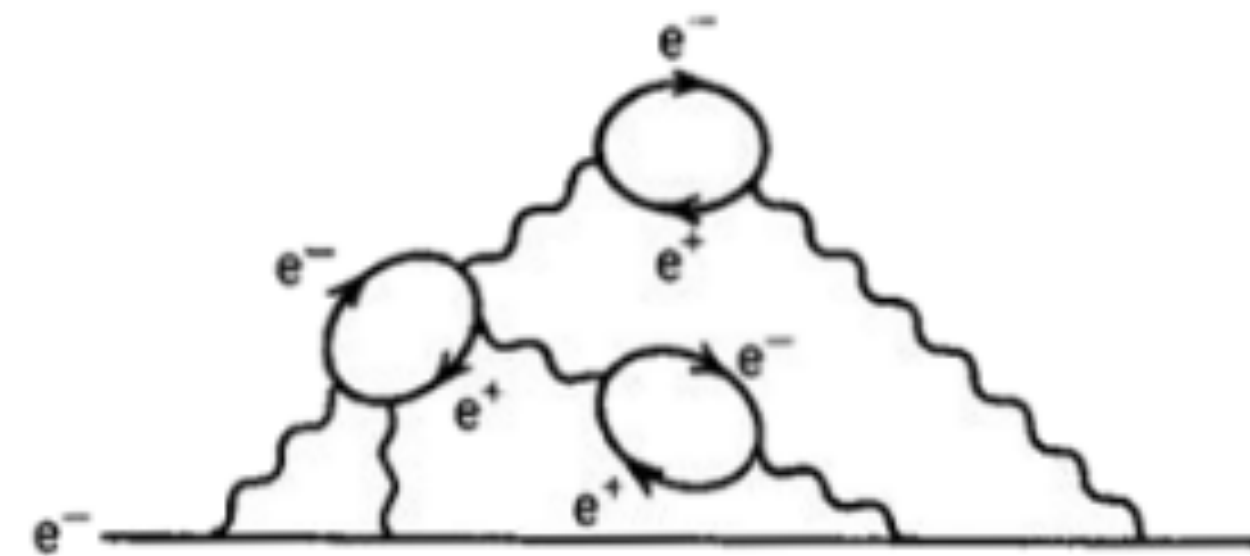
# Confinement

Strong force increases with increasing quark separation



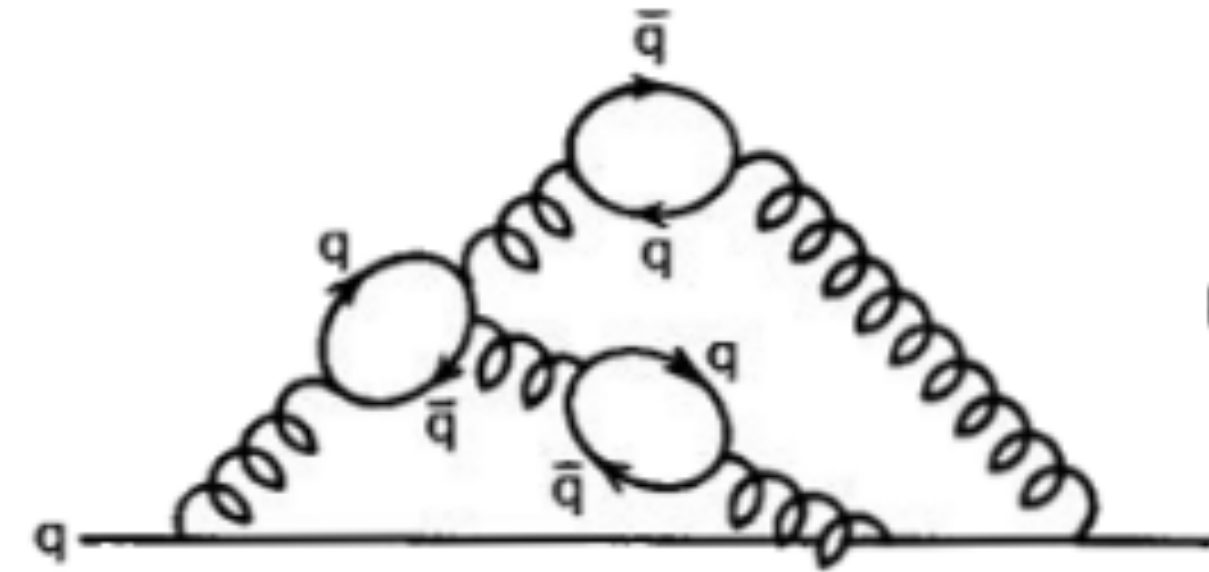


# Quantum electrodynamics (QED)

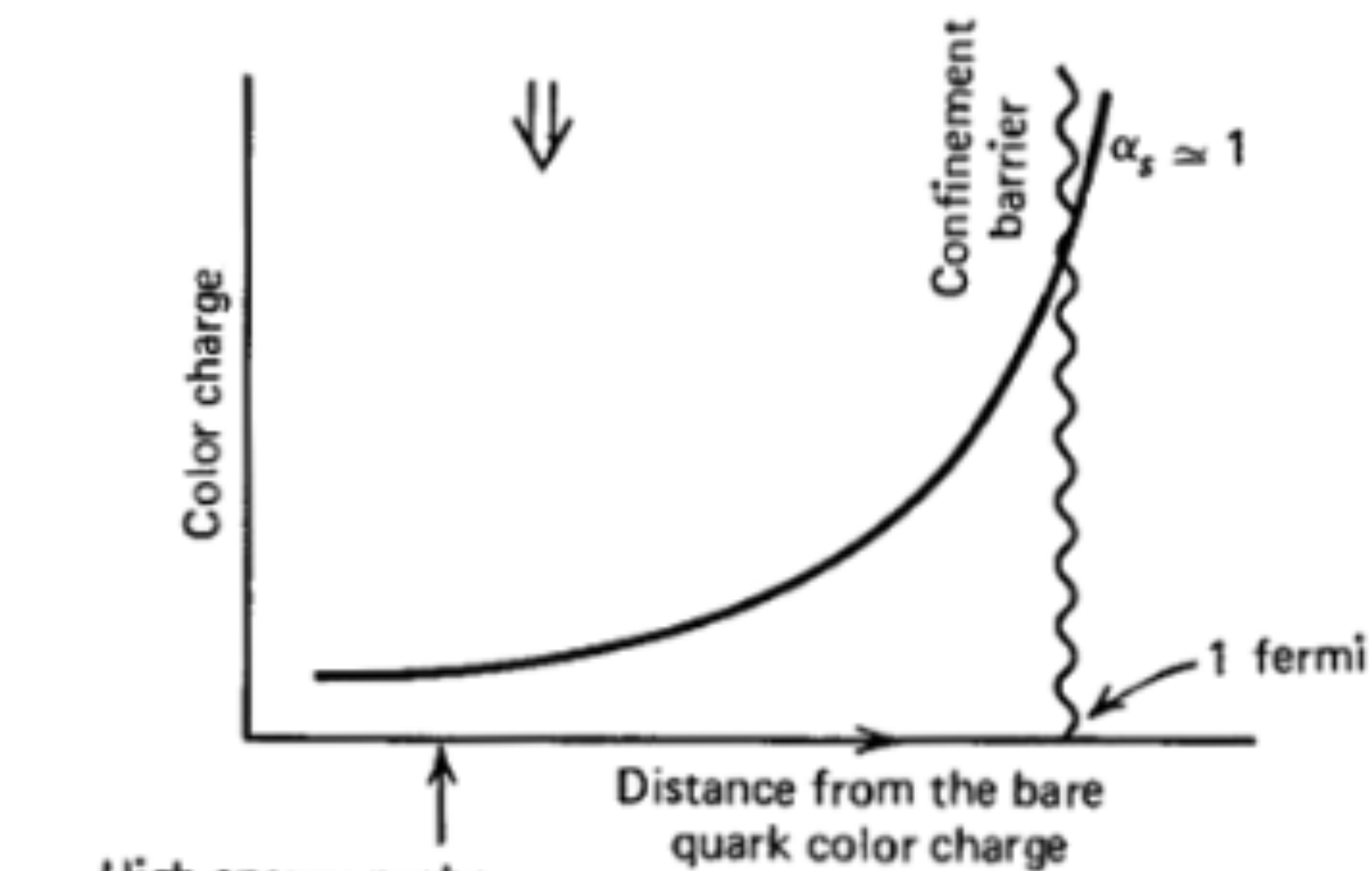
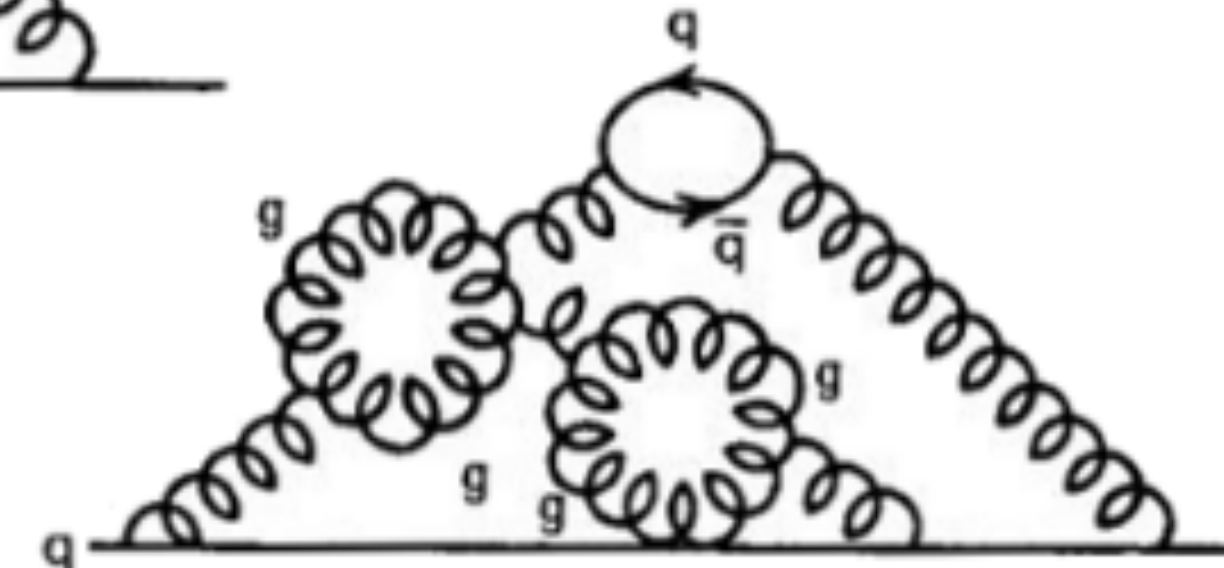


(a)

# Quantum chromodynamics (QCD)



but also



(b)

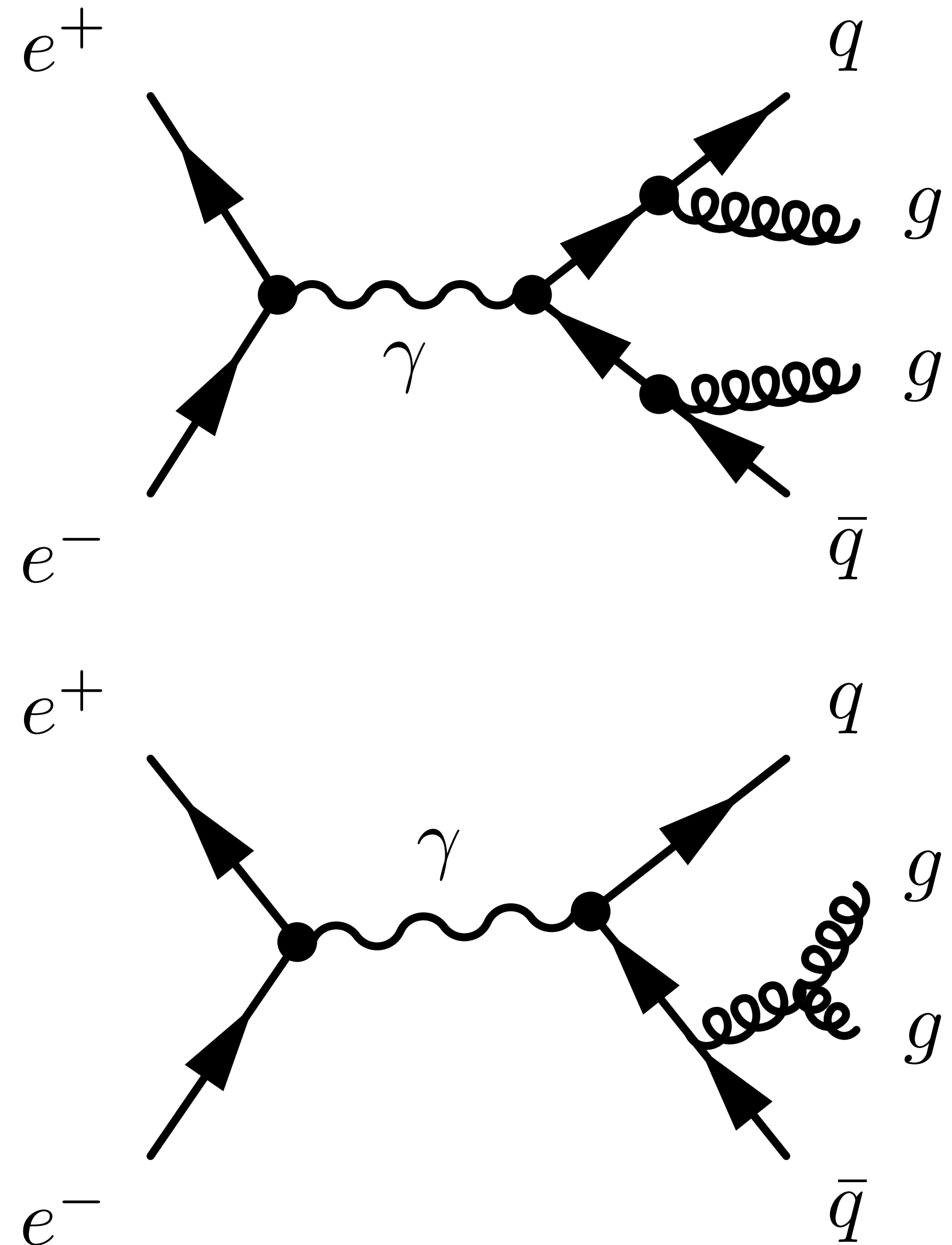
In QCD a color charge is preferably surrounded by the same color.



# Evidence of the gluon self-coupling

---

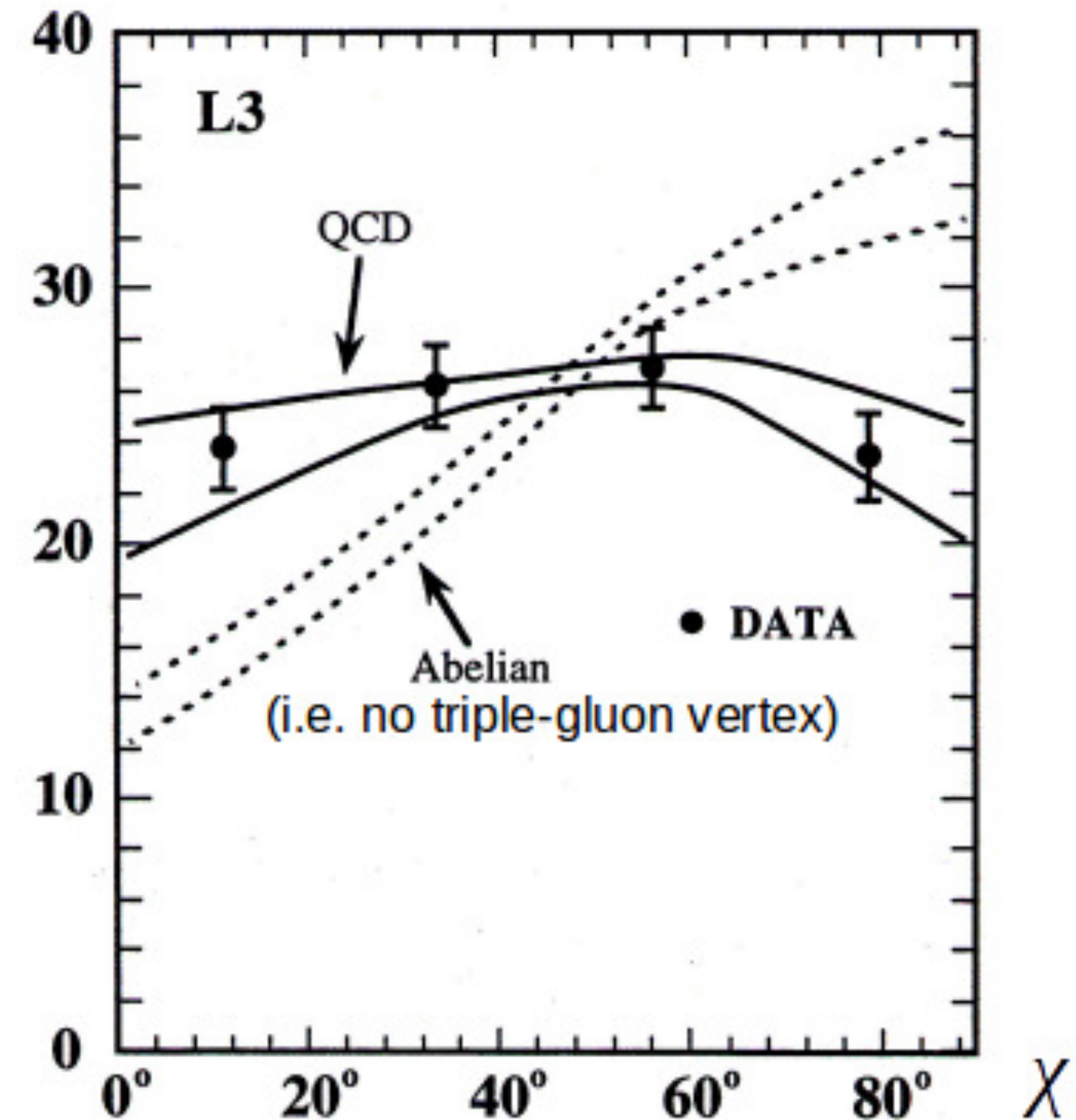
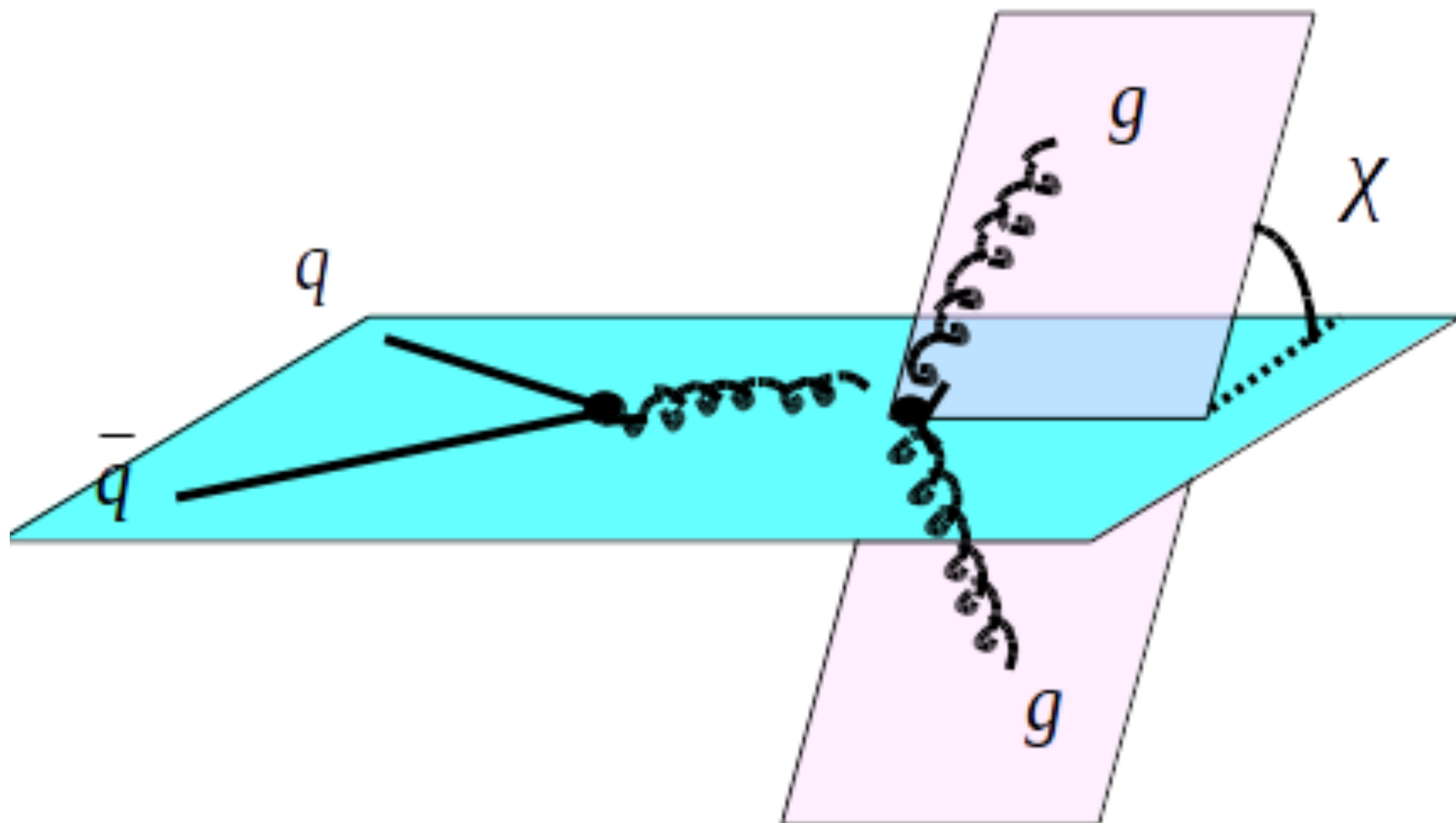
- A qqg vertex has two spin 1/2 quarks and one spin 1 gluon
- A three gluon vertex has three spin 1 gluons
- Leads to different angular distributions





# Evidence of the gluon self-coupling

Measure angle between the plane containing the “quark” jets and the plane containing the “gluon” jets

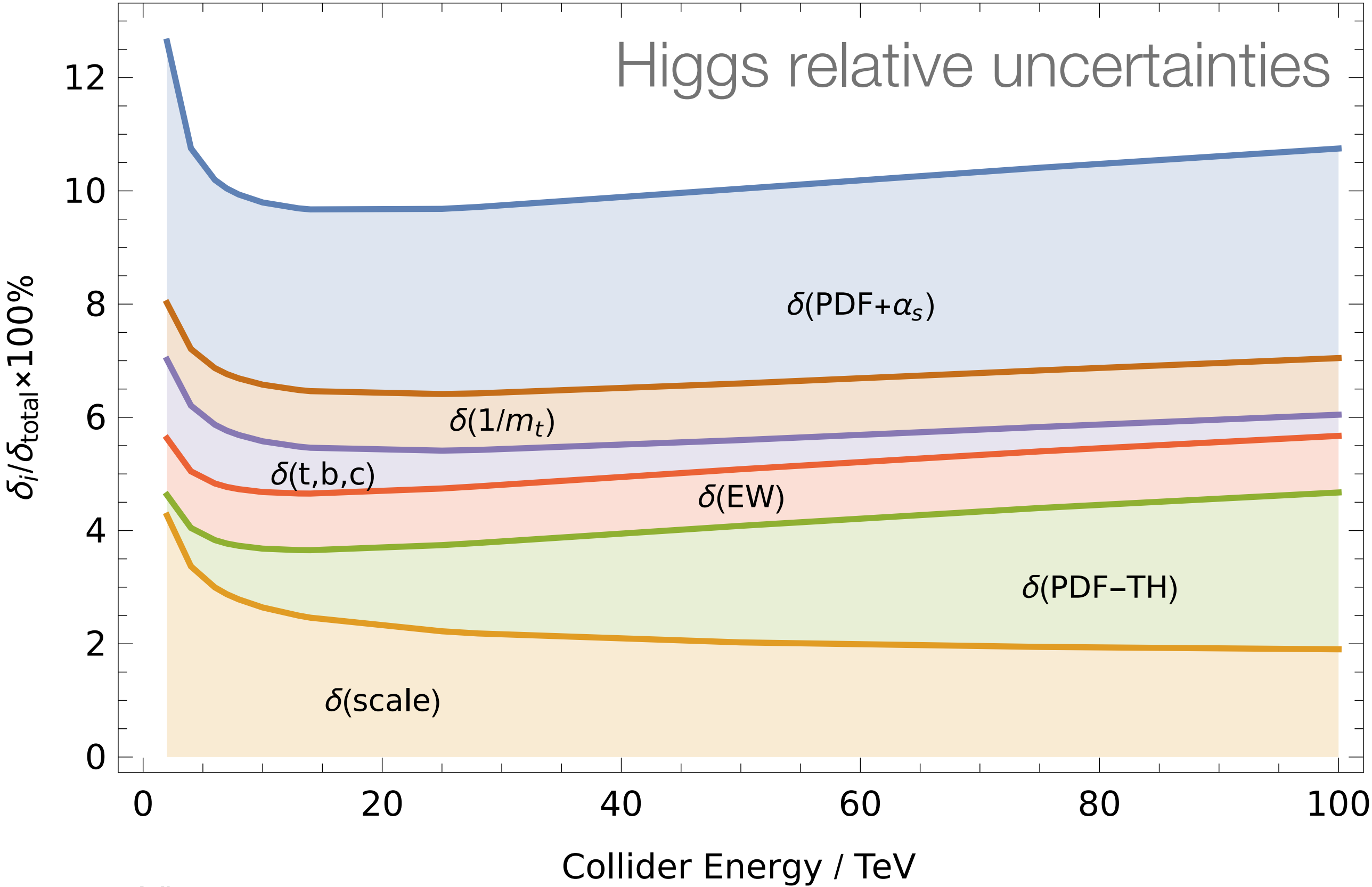




# The limitation to the strong coupling

Least precisely known and... leads to uncertainties everywhere

| Interaction     | Relative uncertainty                                 |
|-----------------|------------------------------------------------------|
| Electromagnetic | $\Delta\alpha/\alpha \approx 5.8 \times 10^{-11}$    |
| Weak            | $\Delta G_F/G_F \approx 5.1 \times 10^{-7}$          |
| Strong          | $\Delta\alpha_s/\alpha_s \approx 7.6 \times 10^{-3}$ |

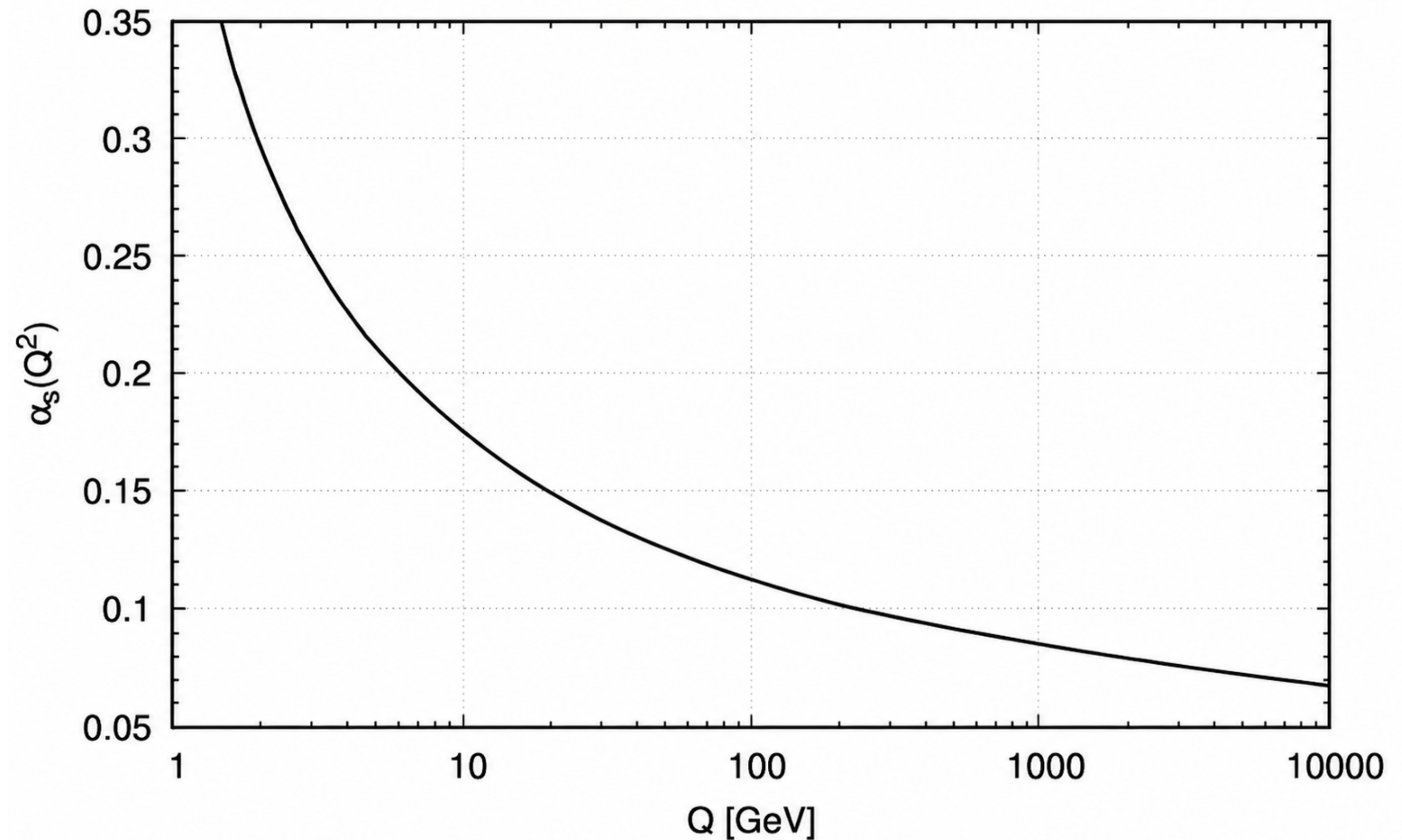




# The prediction

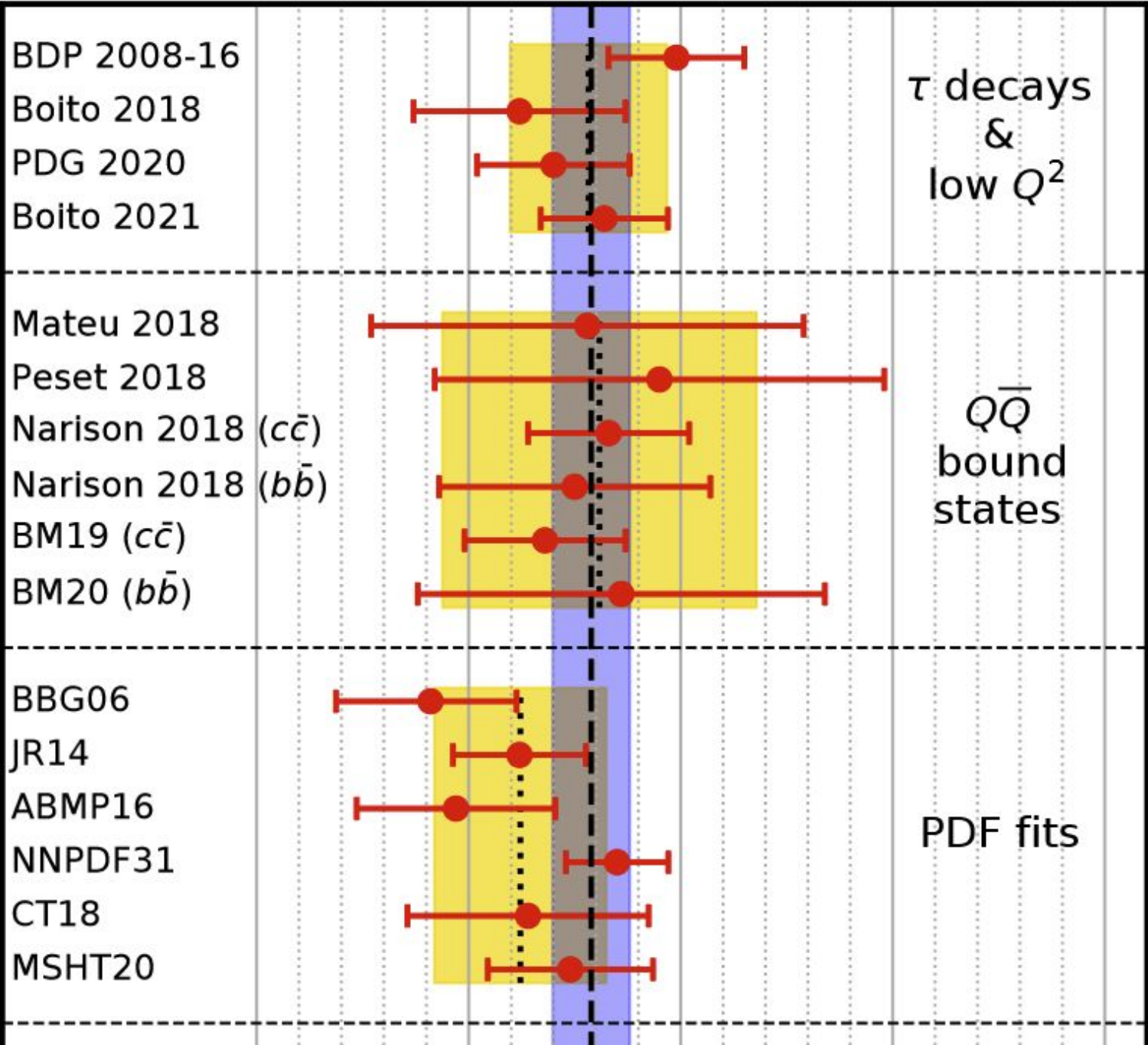
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This is 5 orders of magnitude -  
will need a range of  
experiments





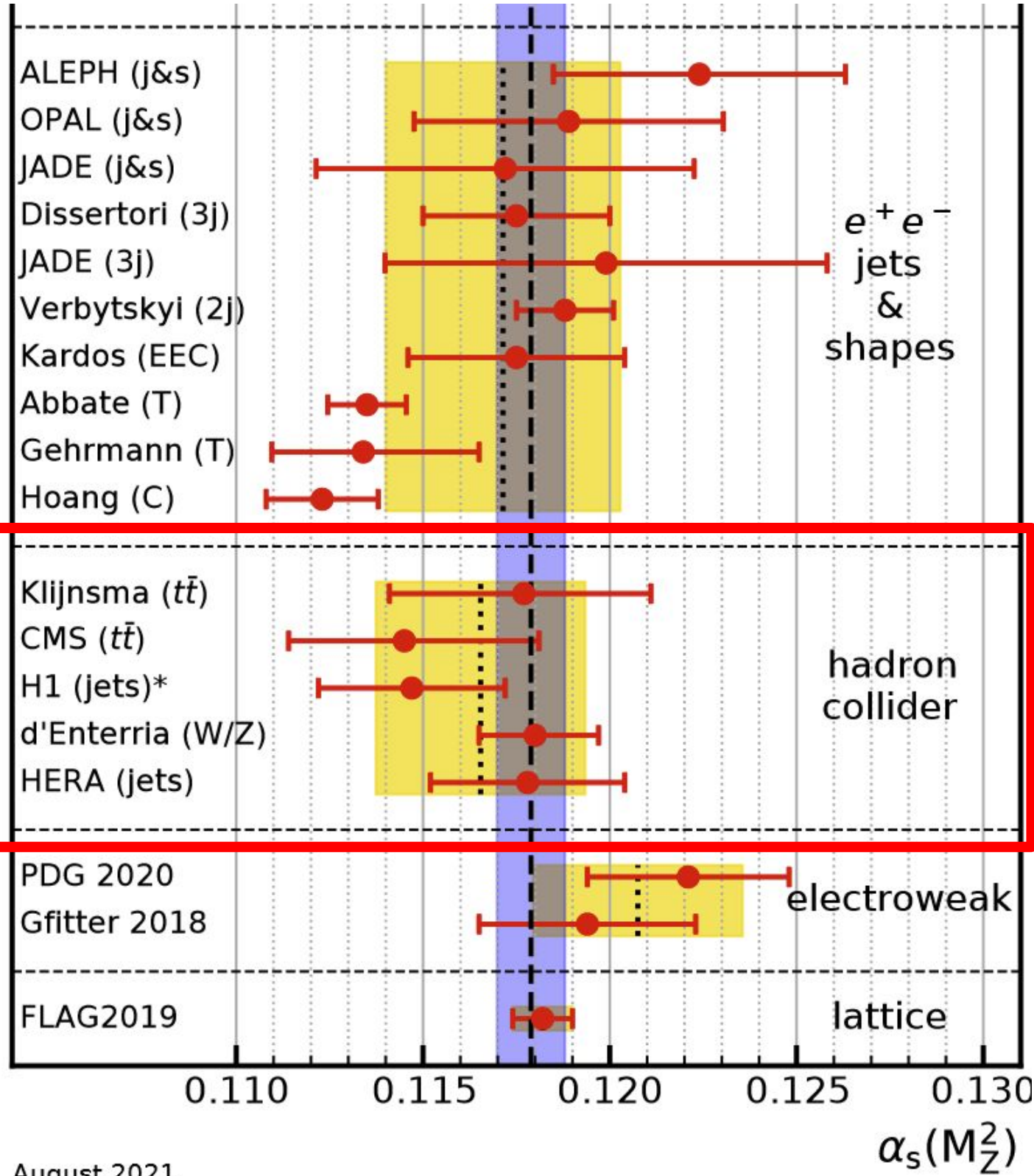
# Indeed! There are many ways to measure this



- Tau hadronic decays, spectral functions
  - precise at  $M \sim$  tau mass
  - N<sub>3</sub>LO predictions
- ←
- Heavy quarkonia decay predictions
  - NNLO
- 
- Electron-positron annihilation measured around MZ peak  
Re-analyzed LEP2 with NNLO
- ←
- Analyzing structure functions at NNLO
  - Combined with hadron collider data
- 
- Jet observable and tt-bar production  
Hadron colliders, precise at mid-to-high energy scales
- 
- LHC top quark and W mass measurements
- 
- Lattice QCD prediction

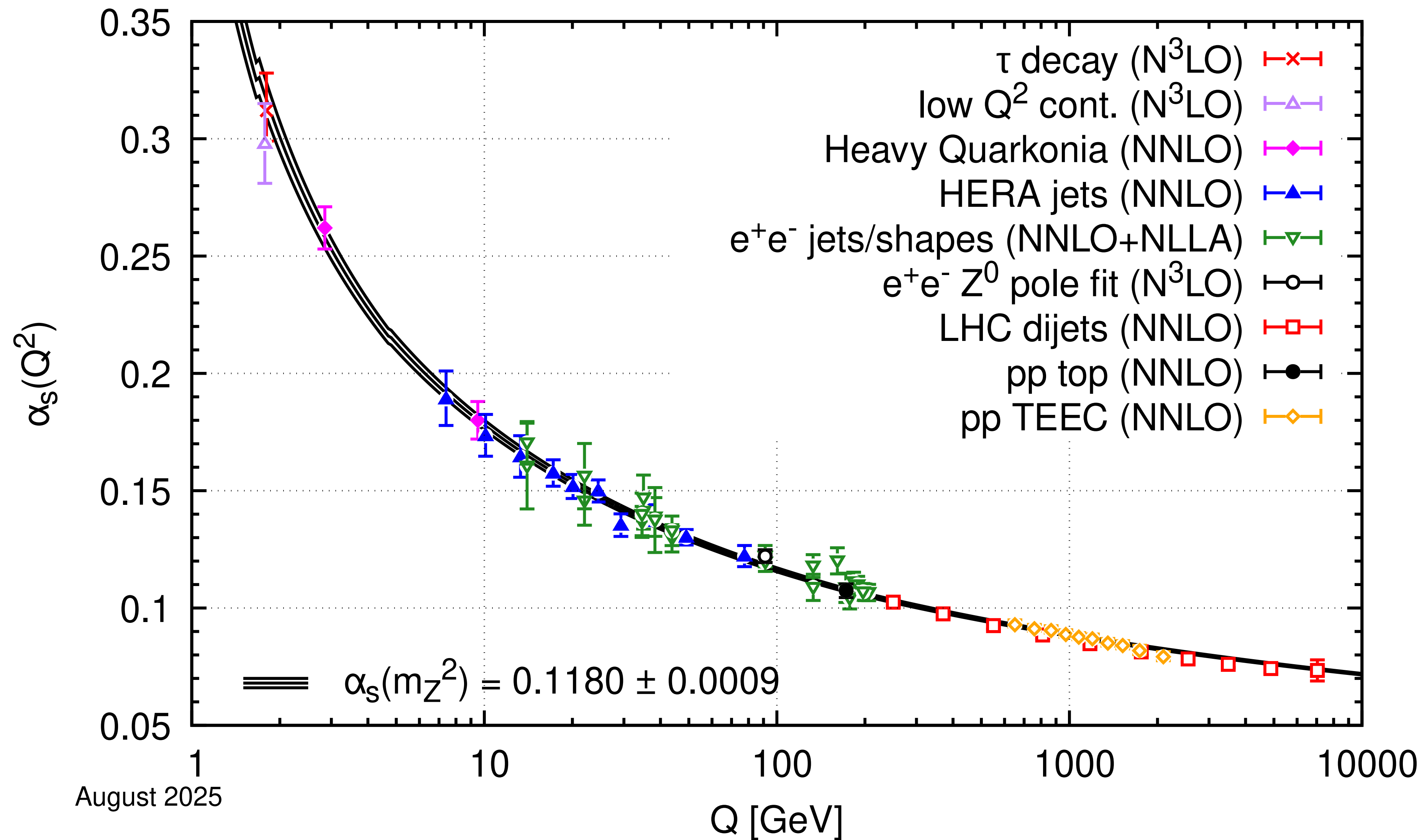
$$\alpha_s(M_Z^2) = 0.1179 \pm 0.0009.$$

(PDG world average)



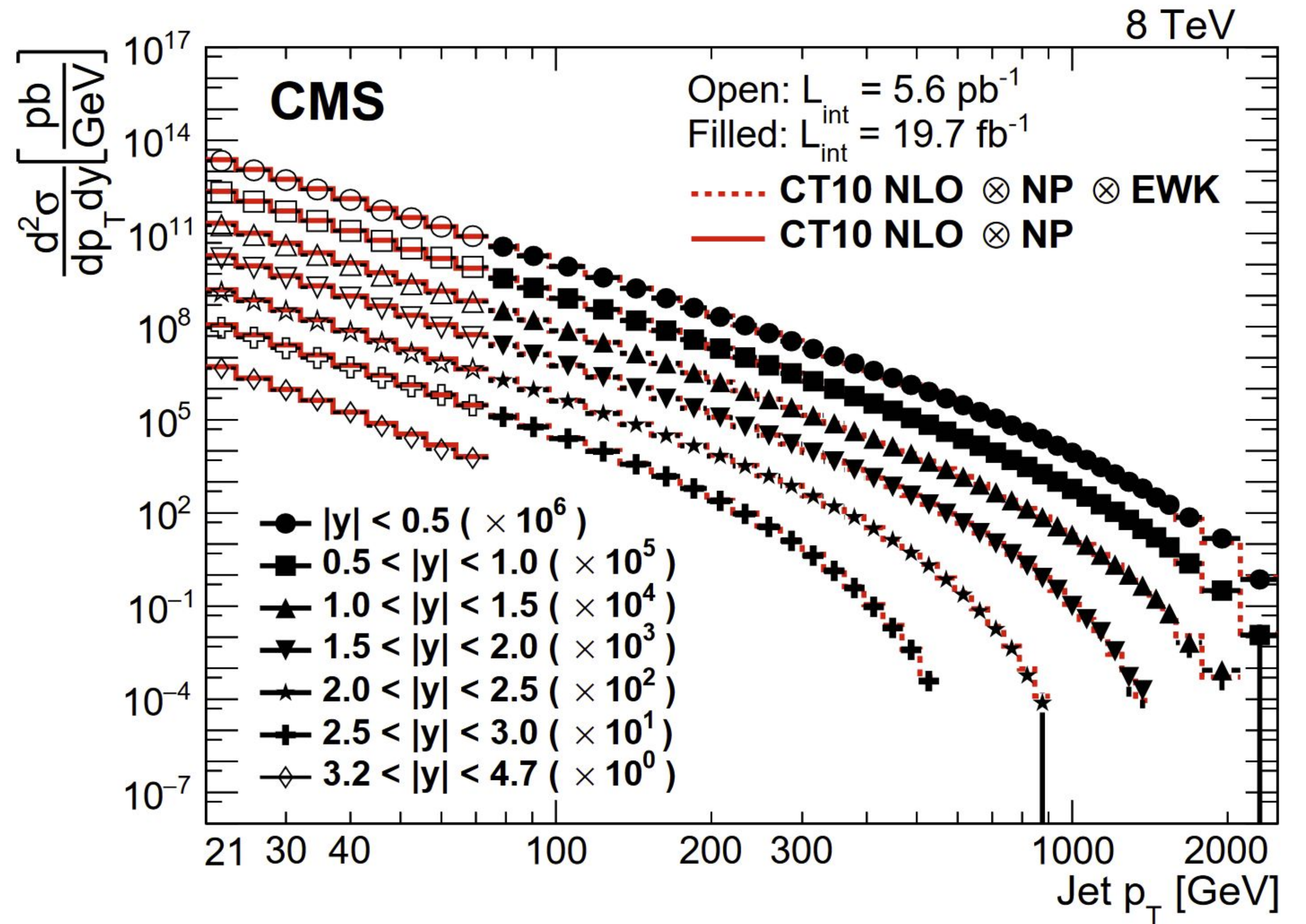
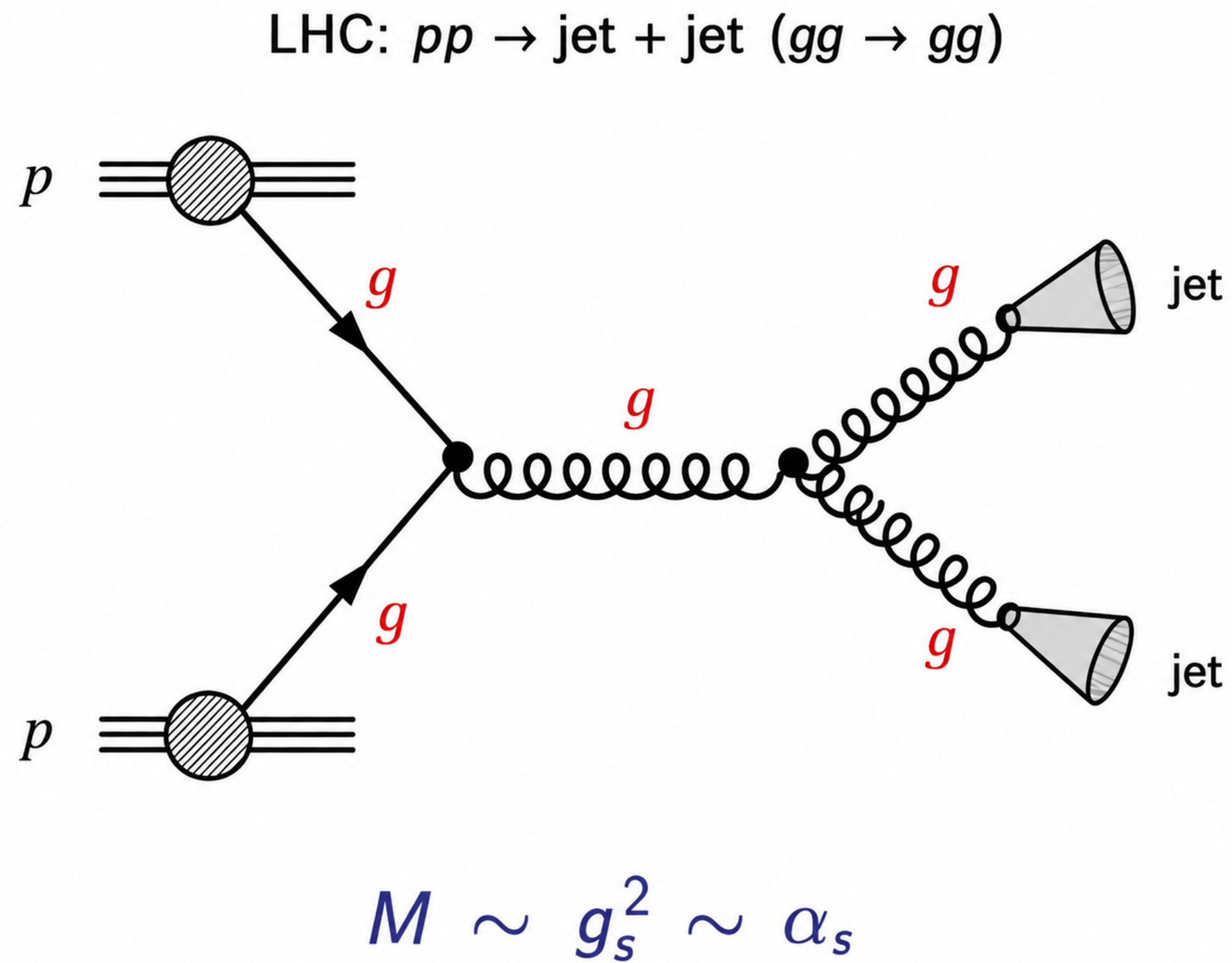


# The comparison to data



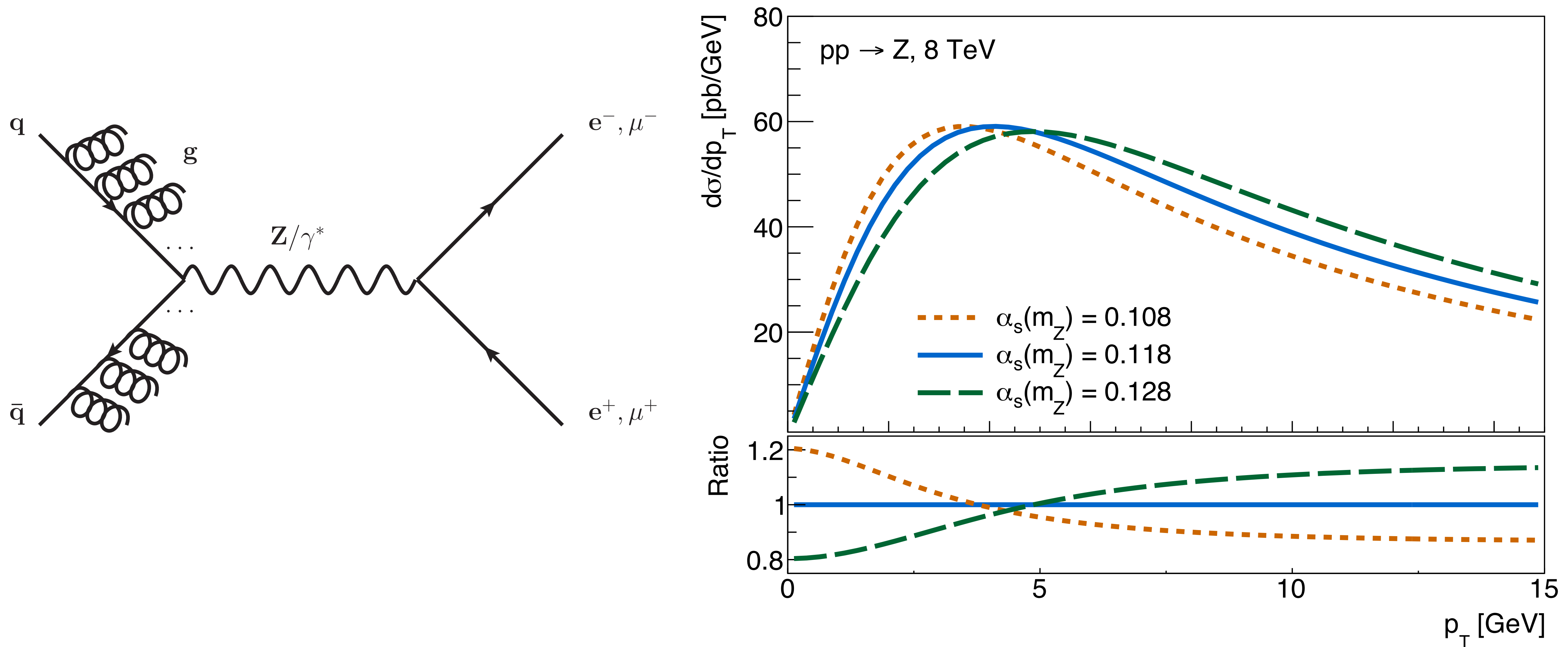


# Two examples: The textbook method - jet rates





# Two examples: Using the precision of the Z





In precision: many measurements make the difference

ATLAS ATEEC

CMS jets

W, Z inclusive

$t\bar{t}$  inclusive

$\tau$  decays

$Q\bar{Q}$  bound states

PDF fits

$e^+e^-$  jets and shapes

Electroweak fit

Lattice

World average

ATLAS Z  $p_T$  8 TeV

**ATLAS**  
Preliminary

- Hadron Colliders
- Category Averages PDG 2022
- Lattice Average FLAG 2021
- World Average PDG 2022
- ATLAS Z  $p_T$  8 TeV

$0.1185 \pm 0.0021$

$0.1170 \pm 0.0019$

$0.1188 \pm 0.0016$

$0.1177 \pm 0.0034$

$0.1178 \pm 0.0019$

$0.1181 \pm 0.0037$

$0.1162 \pm 0.0020$

$0.1171 \pm 0.0031$

$0.1208 \pm 0.0028$

$0.1184 \pm 0.0008$

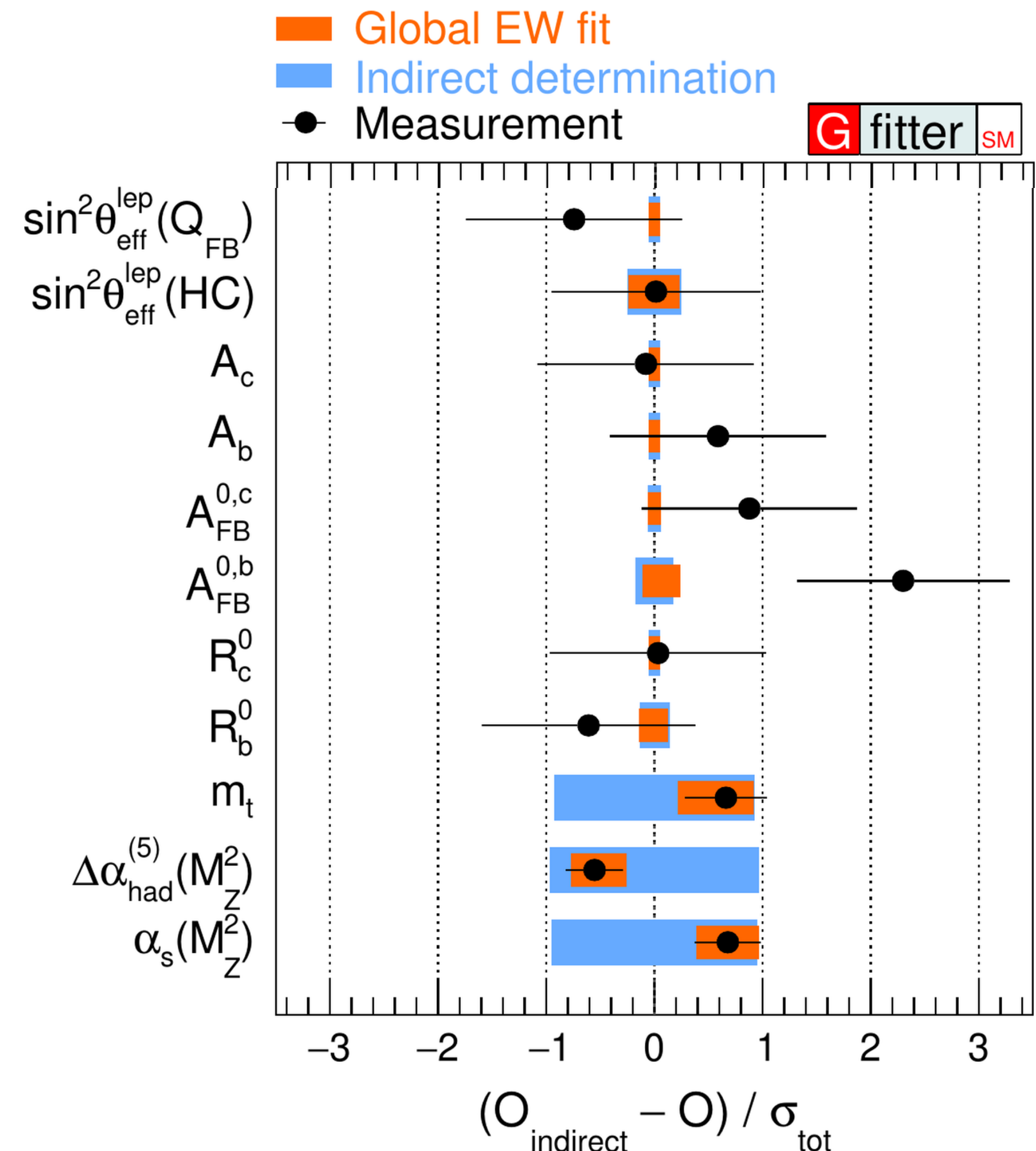
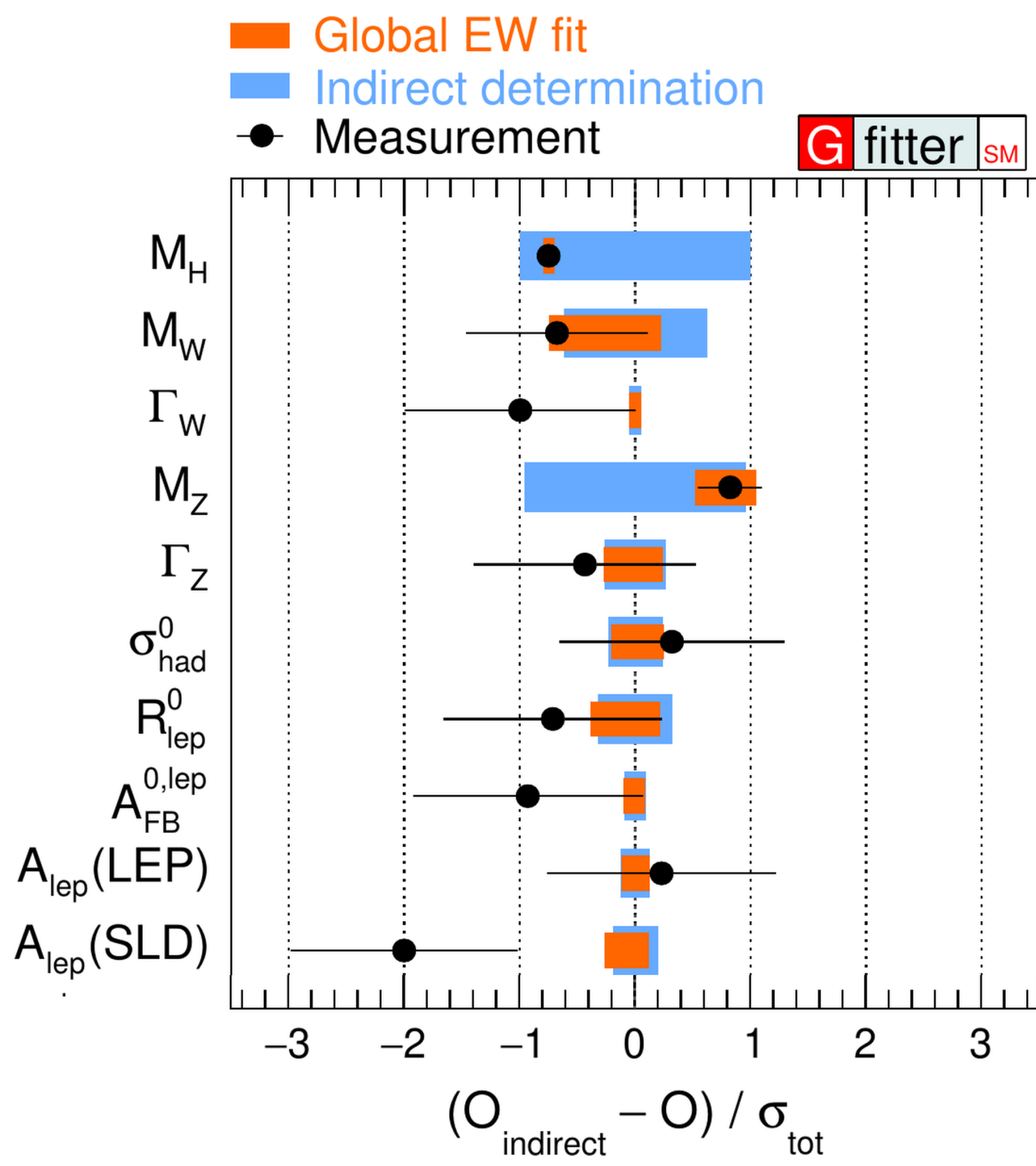
$0.1179 \pm 0.0009$

$0.1183 \pm 0.0009$

0.115 0.12 0.125 0.13  
 $\alpha_s(m_Z)$

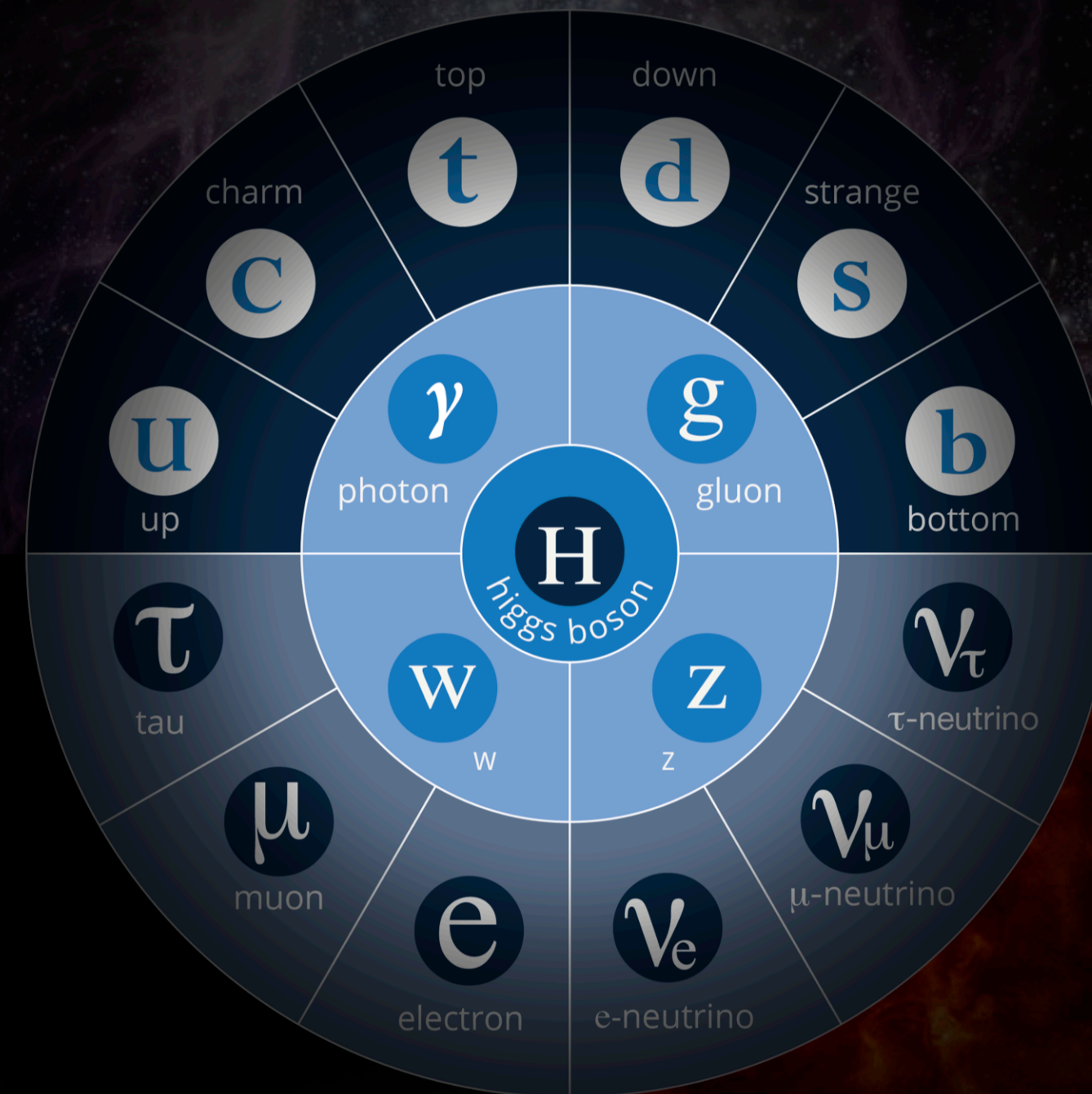


# Come on! Isn't the SM just one big fit anyway?



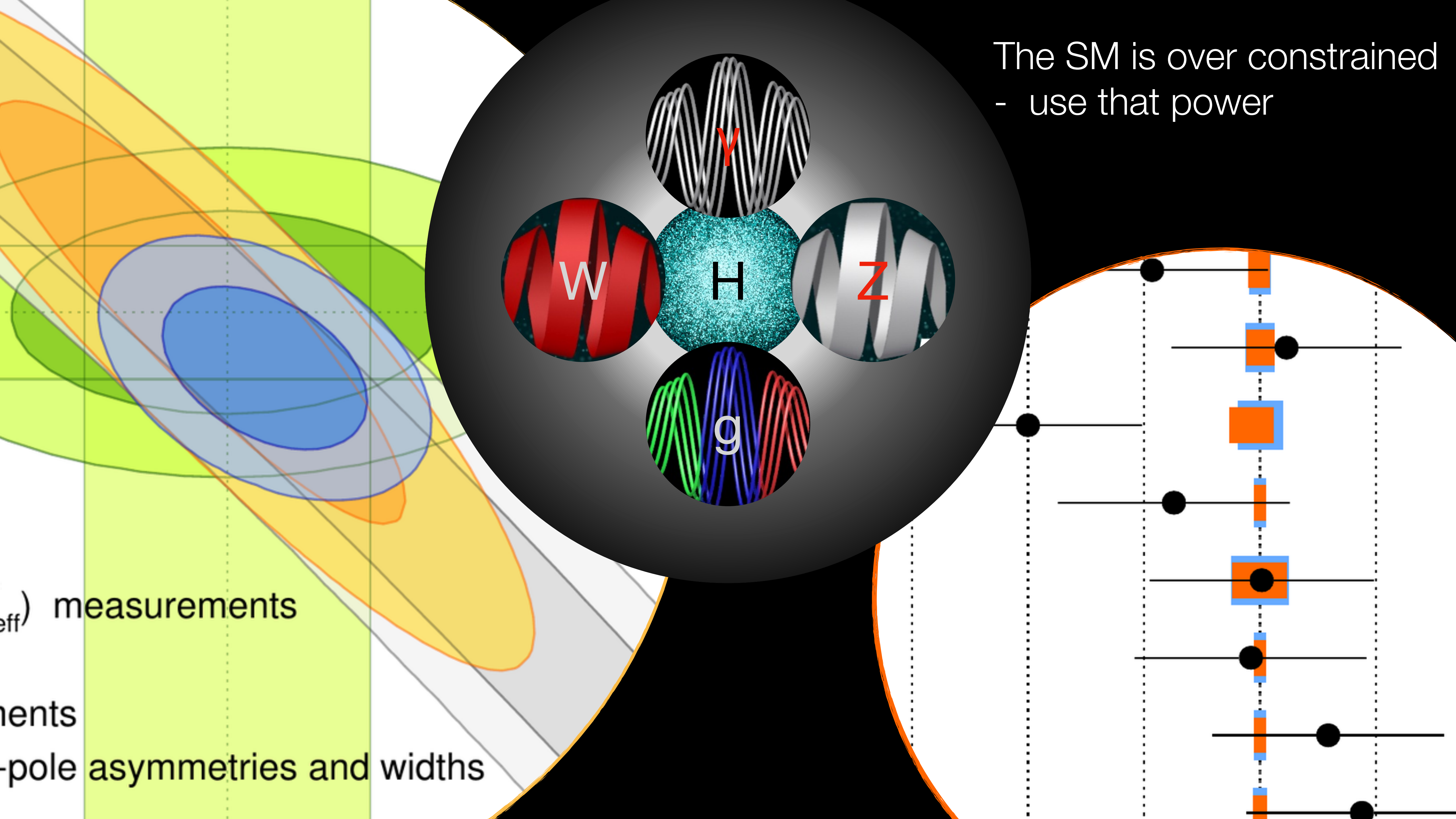


A Standard Model is never in isolation

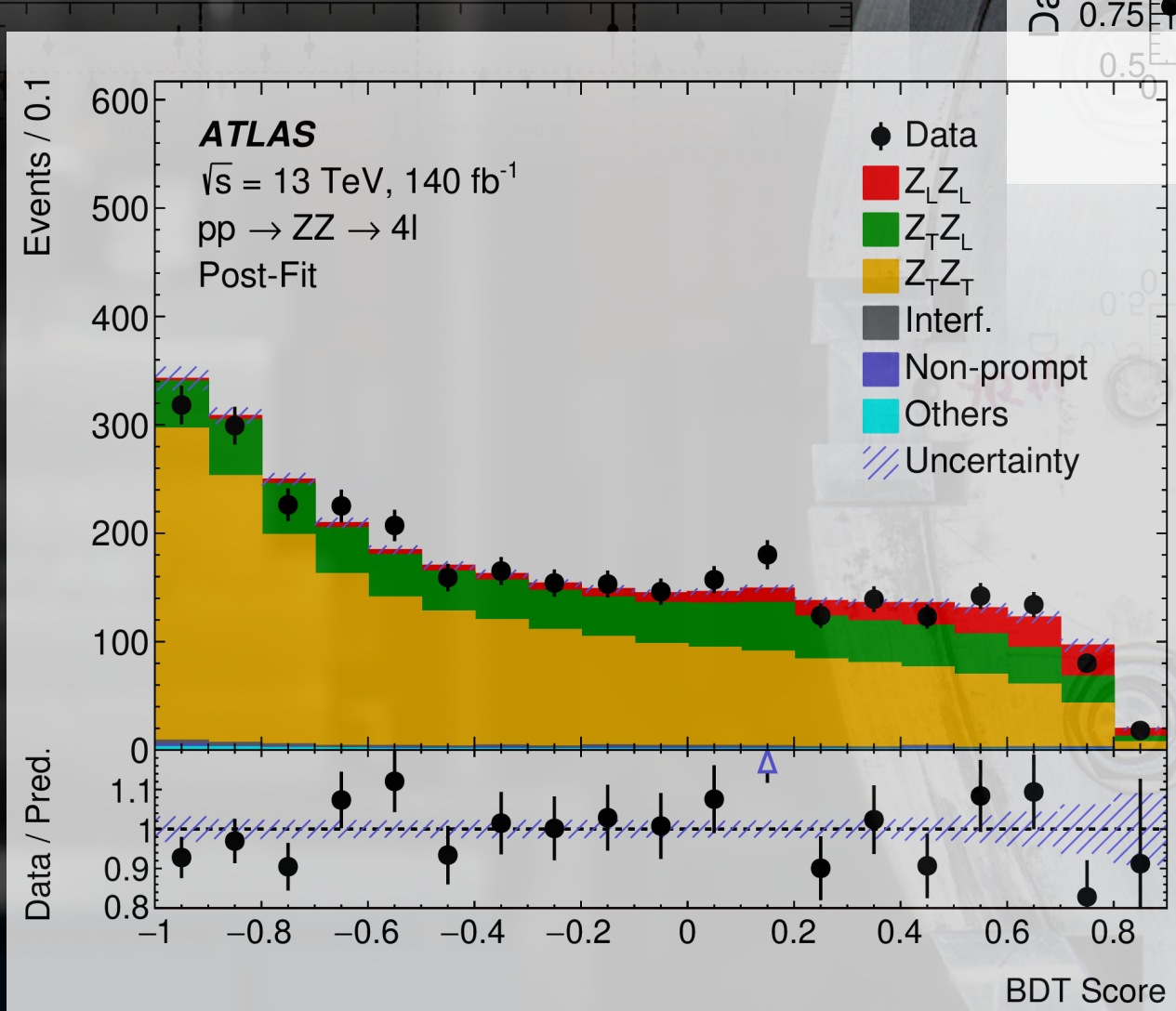
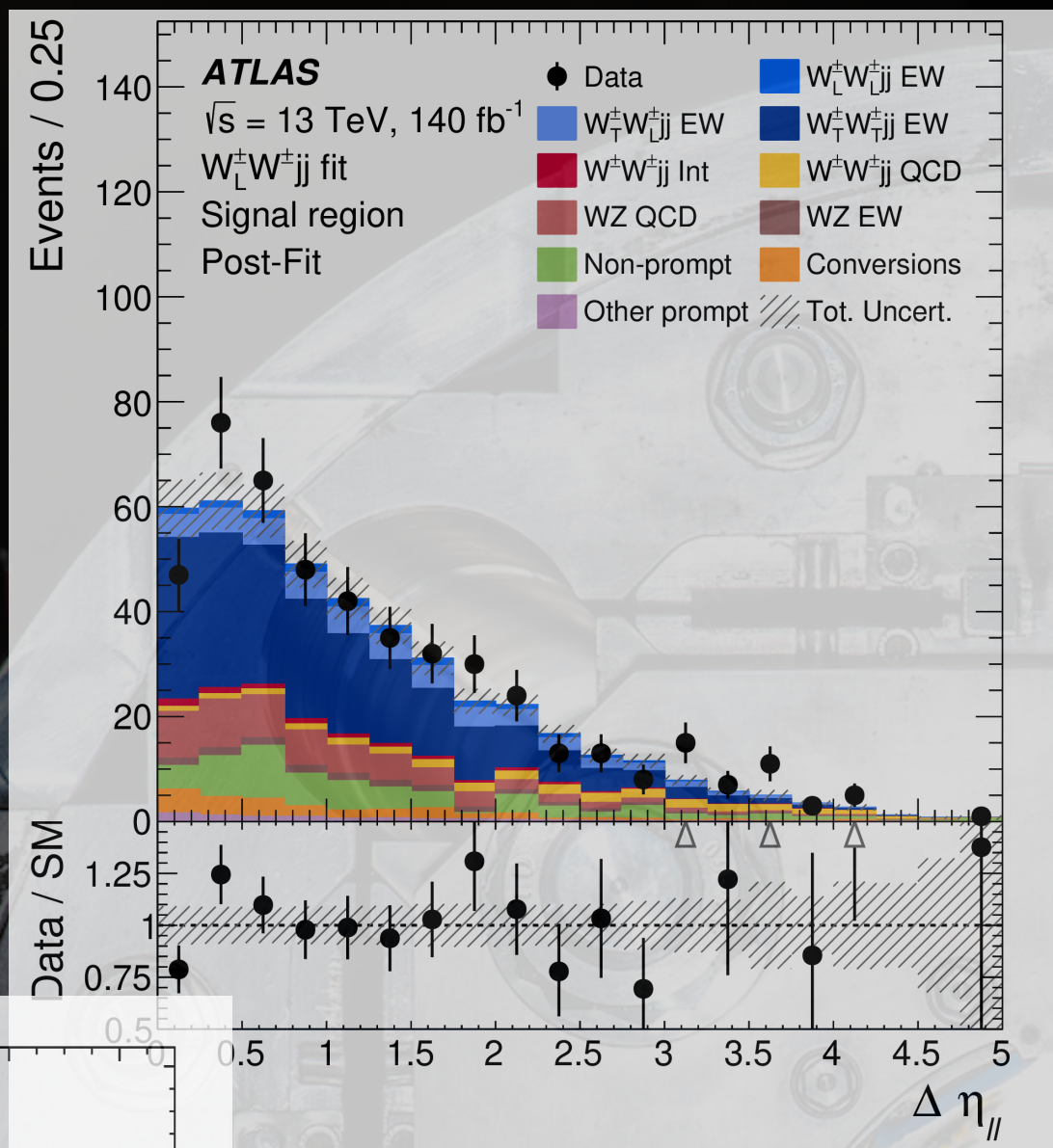
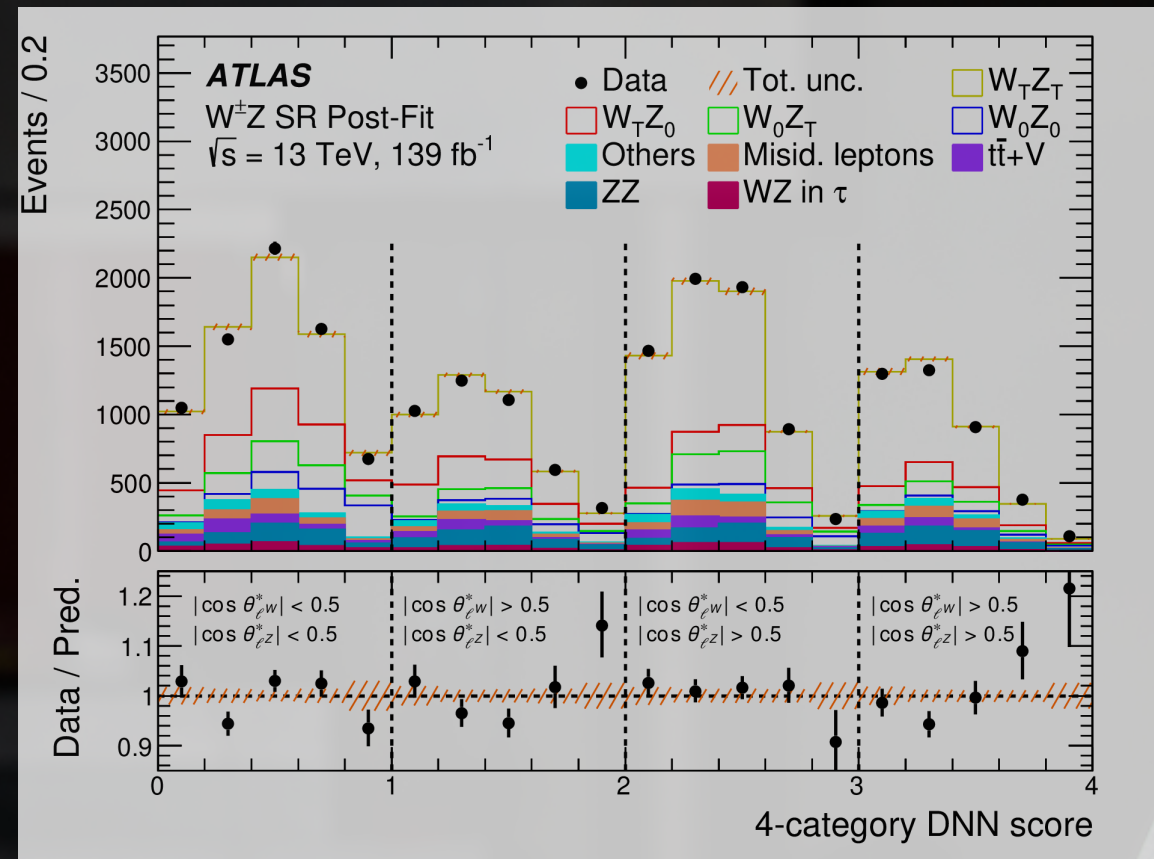




The SM is over constrained  
- use that power







I can make a long list of things that more senior people told me were not possible...

Sometimes it is beneficial to not be good listener

If you think you can do it, go for it



Back-up



# Photo Rights

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- All photos are from ATLAS or CERN unless noted here
- Sun light scattering: Astronomy: Roen Kelly
- Fusion: By Doctor C (Own work) [CC BY-SA 4.0, via Wikimedia Commons]
- Gluon Feynman diagram - By Joel Holdsworth (Joelholdsworth) - Non-Derived SVG of Radiate gluon.png, originally the work of SilverStar at Feynmann-diagram-gluon-radiation.svg, updated by joelholdsworth., Public Domain, <https://commons.wikimedia.org/w/index.php?curid=1764161>
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