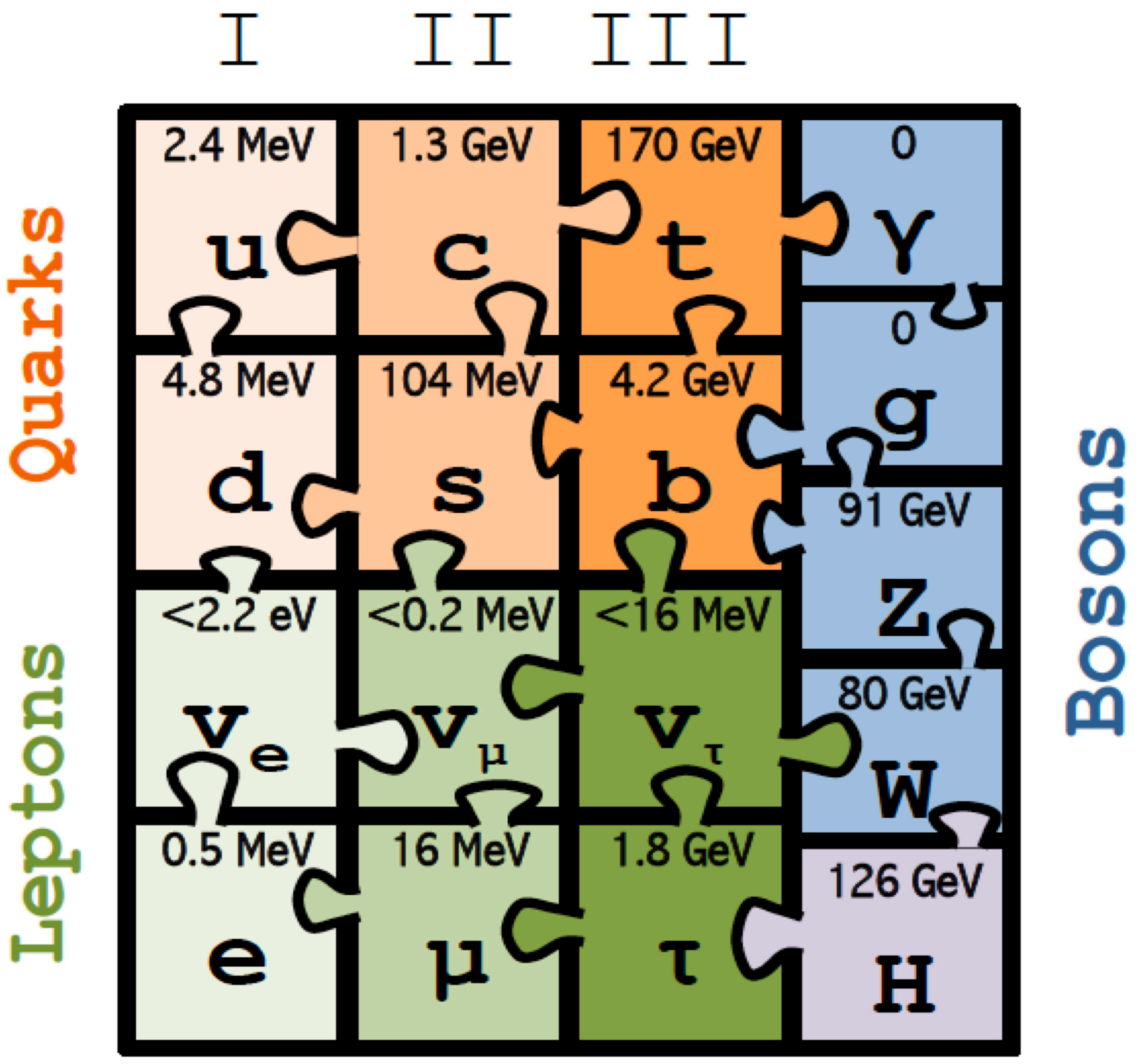
(a bit belated) Introduction to The Standard Model

Mykola Khandoga (LPNHE)

JRJC 2021, La Rochelle 17-23 October 2021



A bit of history. Roaring 40s

- A lot is invested in nuclear physics
- Great advancements in nuclear physics
- QED is born - the first QFT
- A real boom in physics
- Serious consequences

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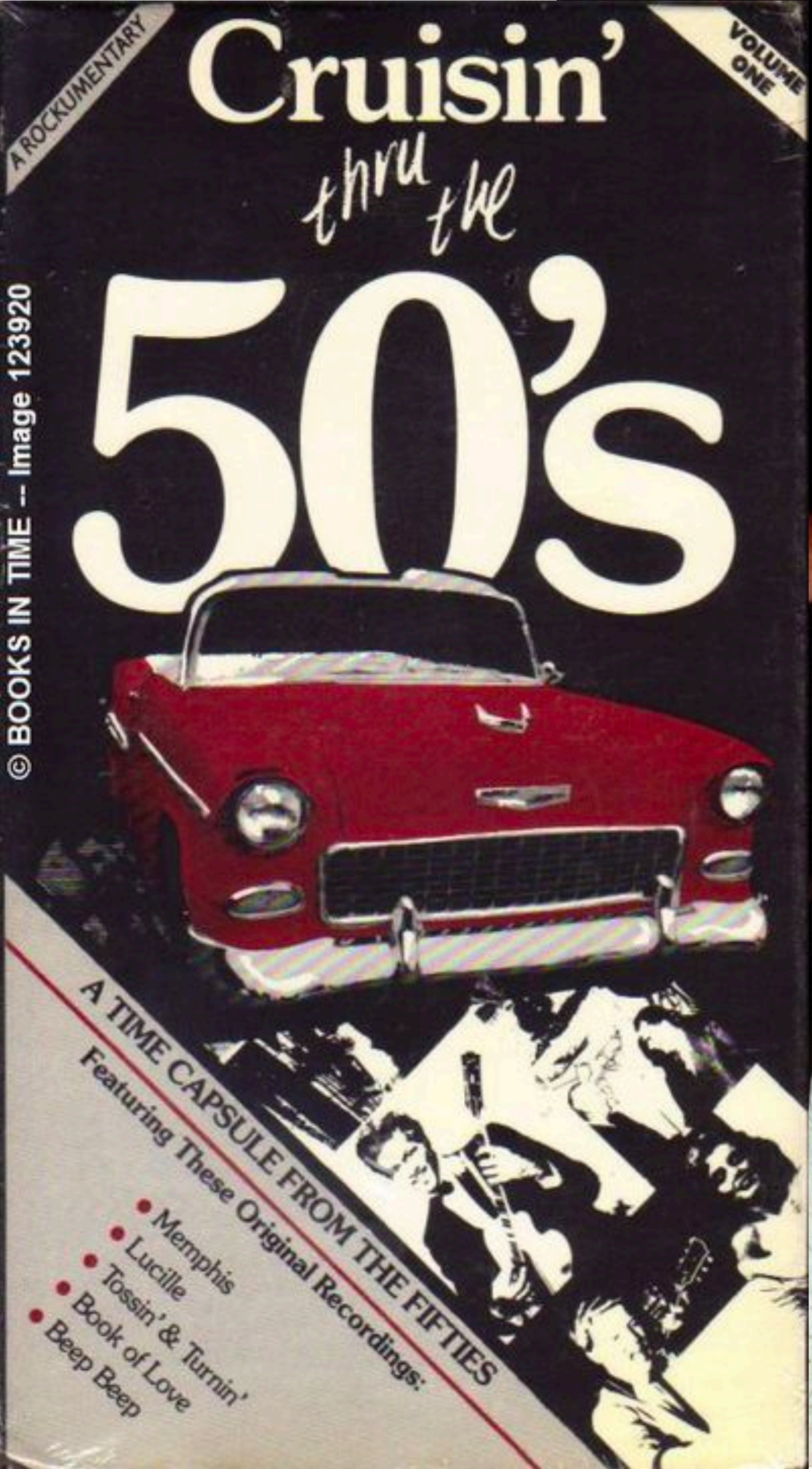

Furious 50s

Accelerators!
PS at CERN

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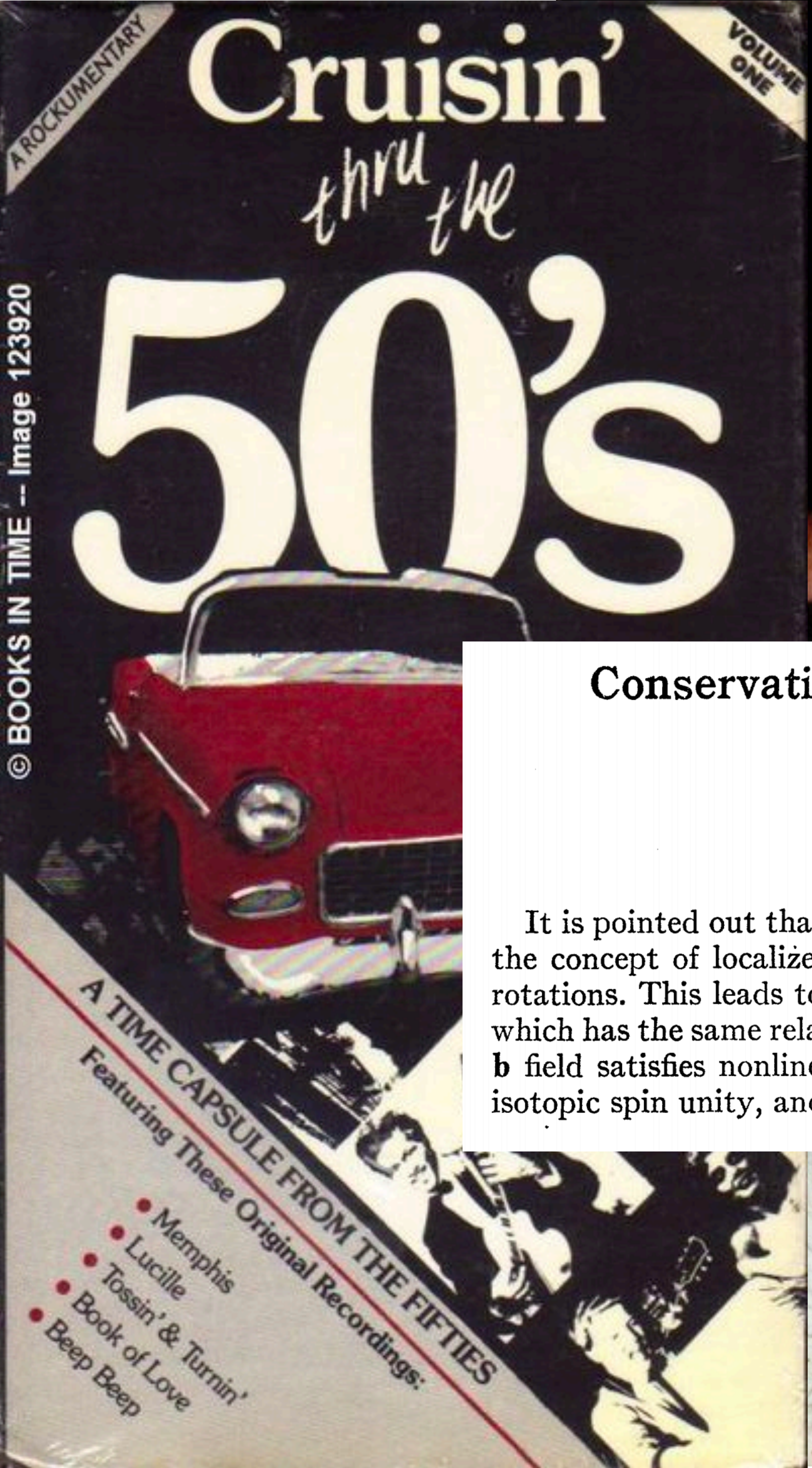
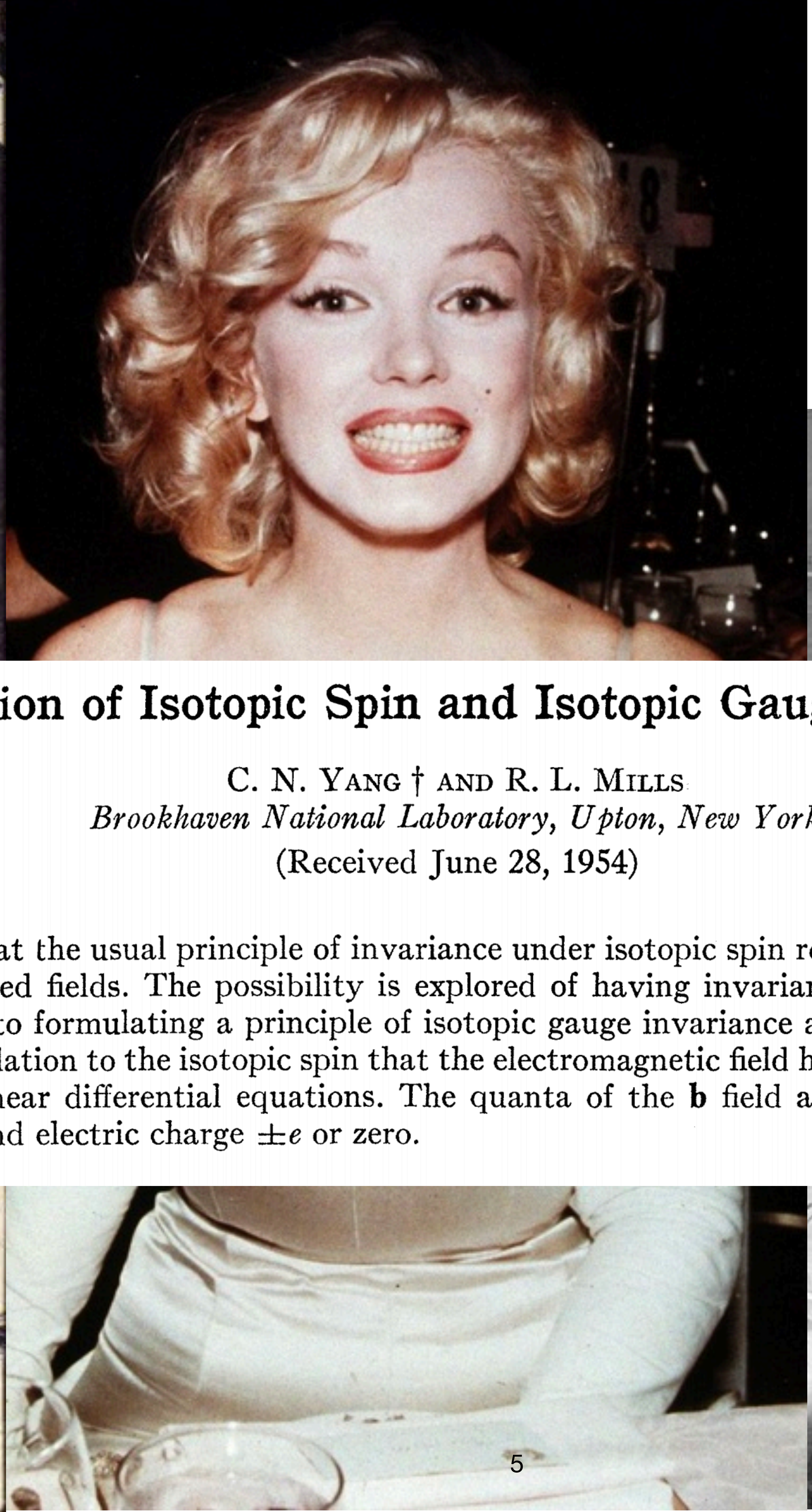
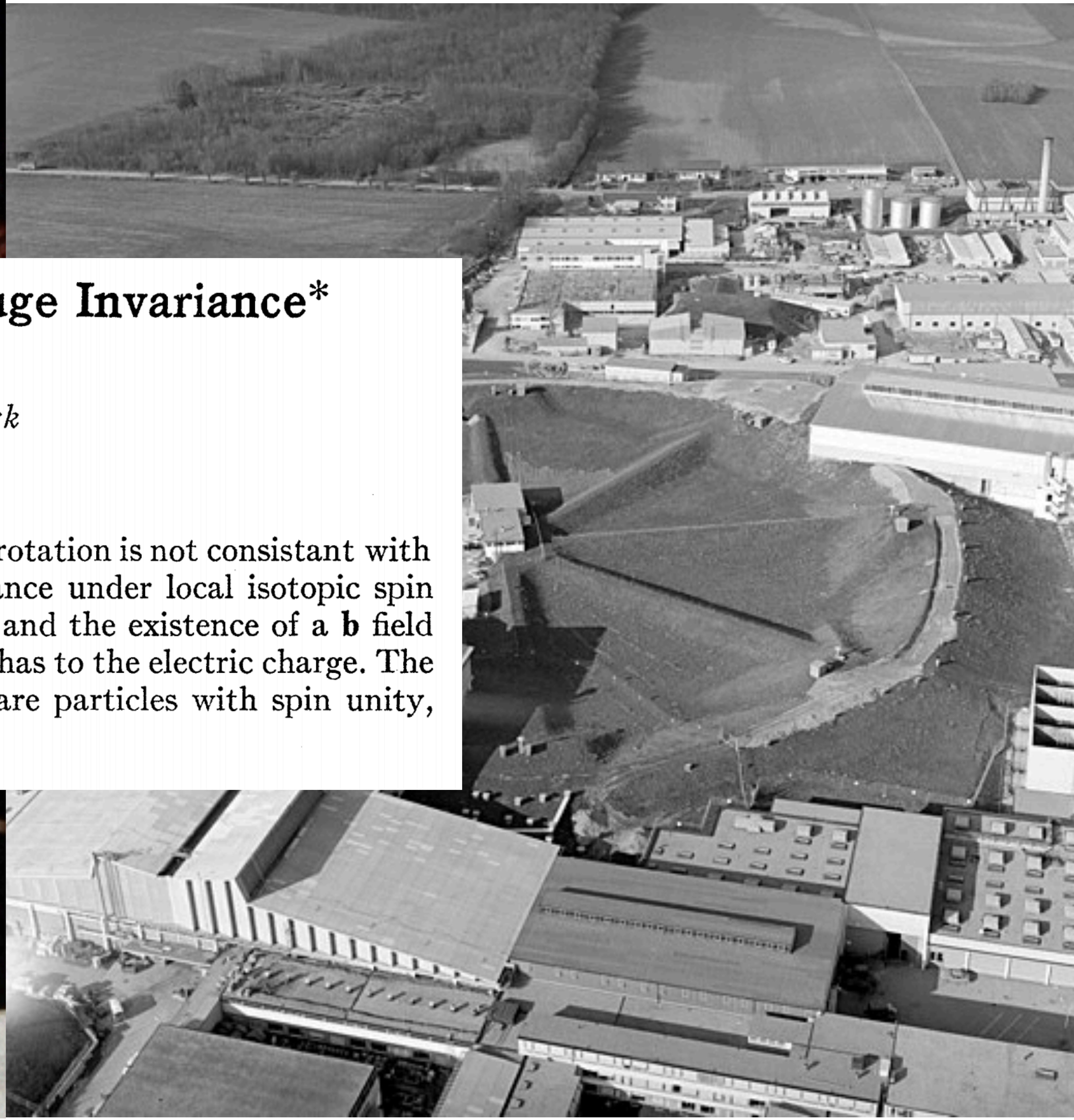






Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. Yang † and R. L. Mills
Brookhaven National Laboratory, Upton, New York

(Received June 28, 1954)

It is pointed out that the usual principle of invariance under isotopic spin rotation is not consistant with the concept of localized fields. The possibility is explored of having invariance under local isotopic spin rotations. This leads to formulating a principle of isotopic gauge invariance and the existence of a **b** field which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge. The **b** field satisfies nonlinear differential equations. The quanta of the **b** field are particles with spin unity, isotopic spin unity, and electric charge $\pm e$ or zero.

Screaming 60s

Lots of experimental data - lack of theoretical explanation

- QED is there - but the same approach does not work with the other fundamental forces

- Weak interaction breaks CP symmetry - what are the force carriers?

- Accelerators keep delivering -> particle zoo keeps growing. What are the fundamental constituents?

- What's the nature of the strong force?

Some of the Particles in the "Particle Zoo"

p^+ n^0 Σ^- Σ^0 Σ^+ Σ^{++} Δ^- Δ^0 Δ^+ Δ^{++}

Λ^0 e^+ e^- π^+ π^0 π^-

Ω^- Ω^0 Ω^+ τ^+ τ^-

Ξ^- Ξ^0 Ξ^+ Ξ^{++} ρ^+ ρ^0 ρ^-

μ^+ μ^- ω γ

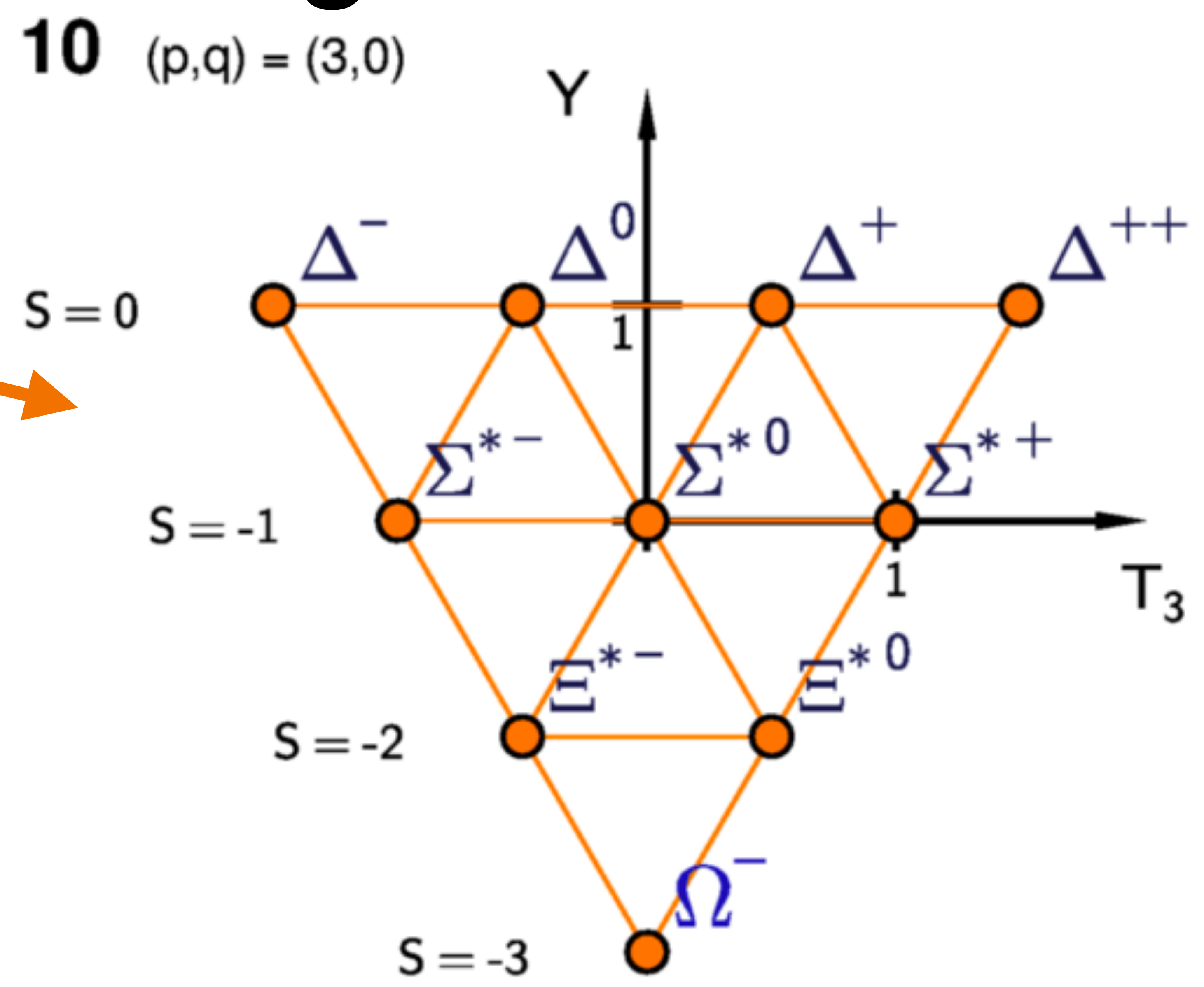
η η' ϕ

ν_e ν_μ ν_τ K^+ K^0 K^-

Screaming 60s

The theorists take over - it starts to come together for the strong force

- The particle zoo is tamed by the eightfold way and quarks (but what breaks quark mass symmetry?)
- Yang-Mills gauge fields idea from 1954 is reapplied to strong fields
- Quarks have an colour quantum number and interact through SU(3)-symmetric gauge field
- Massless force carriers assume asymptotic freedom and confinement
- There is no general mathematical solution to the Yang-Mills fields problem up until now



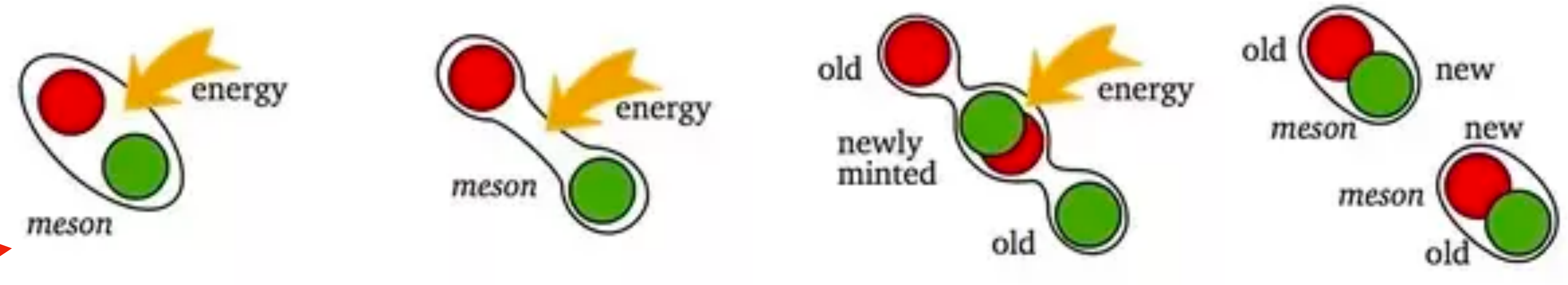


Figure –1.5: Inseparability of quarks and antiquarks in spite of investing ever more energy

An nice way to earn \$$10^6$ for the theorists from CMI

Screaming 60s

The theorists take over - it starts to come together for the weak force

- Short-range nature of weak interaction assumes massive charged bosons
- SU(2)xU(1) unification proposed
- Massive neutral boson was required by this unification
- Massive -> gauge symmetry broken
- What breaks the symmetry here?

Screaming 60s

The theorists take over - it starts to come together

- Short-range nature of weak interaction assumes massive charged bosons
- SU(2)xU(1) unification proposed
- Massive neutral boson was required by this unification
- Massive -> symmetry broken
- What breaks the symmetry here? Same answer as for the quarks.

The Higgs mechanism (by Brout-Englert-Higgs-Hagen-Guralnik-Kibble)

The Standard Model is born:

SU(3)xSU(2)xU(1)

The marriage of strong and electroweak gauge fields.

Looks cool. Is it true though?

Experiment is to tell.

The Standard Model

Experiments catch up

- 1973 - neutral current interaction (Gargamelle)
- UA1 and UA2 discover W and Z in 1983
- And finally...

A Higgs boson was discovered in 2012

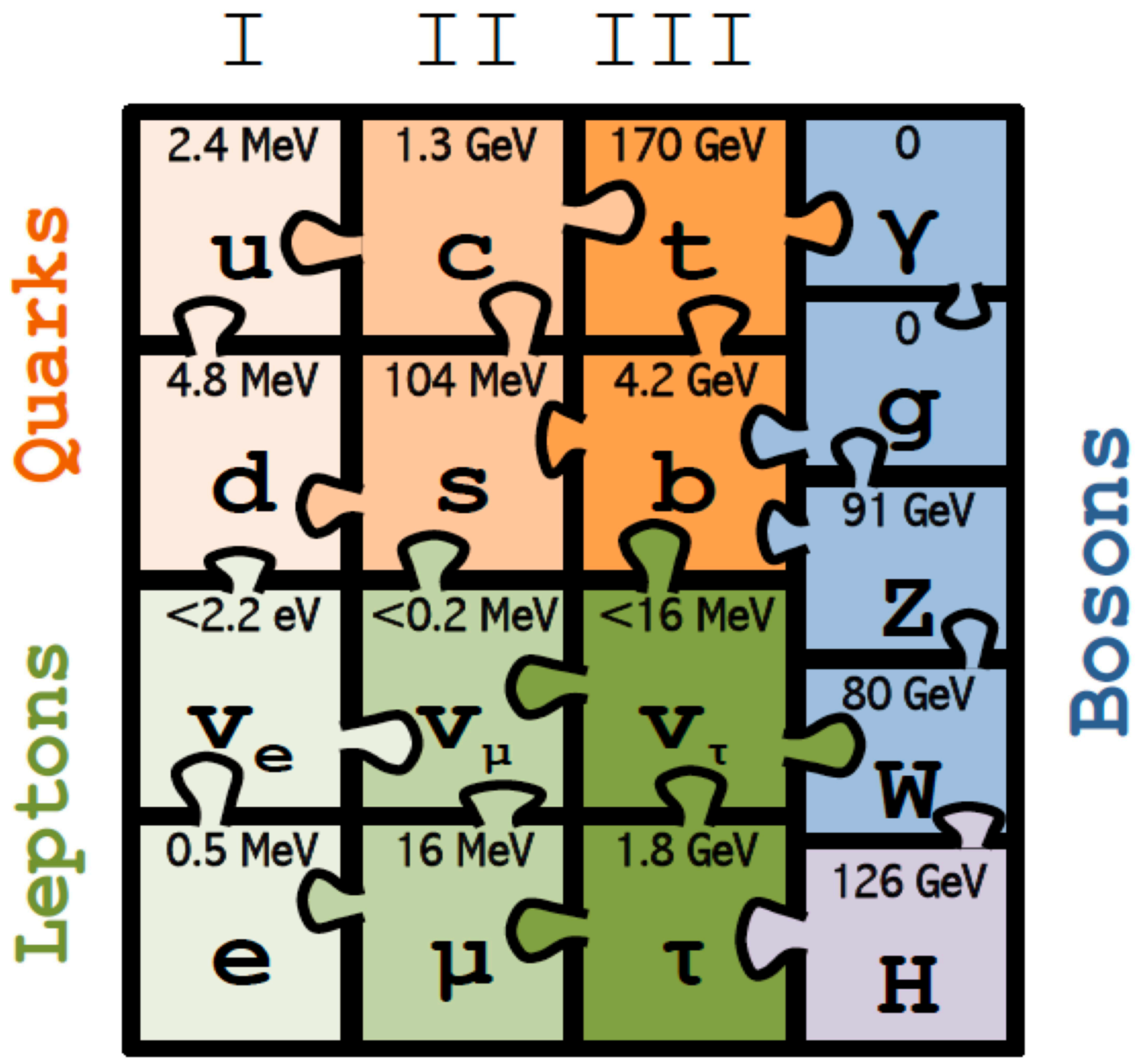
What is happening now?

We have discovered all of the SM particles, are we done?

More is less. Just because you know the QCD Lagrangian doesnt mean you know all of its physics.

—Andrew Larkoski

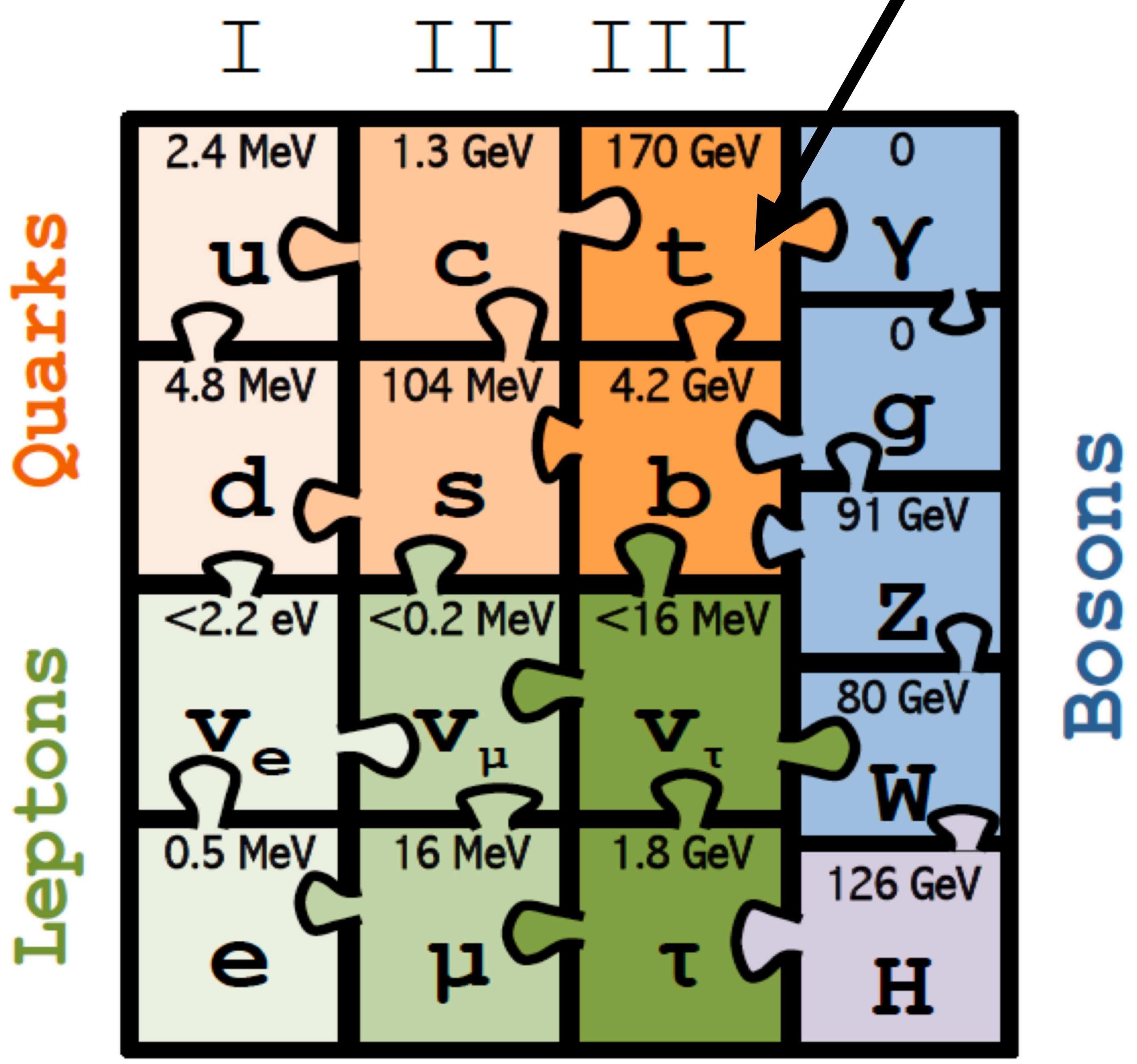
- Observation of production modes and decay channels predicted by the Standard Model
- Precision measurements of the SM input parameters
- Precision tests of the SM predictions
- A lot of physics is still to observe and to understand



The Standard Model

Investigated from every side

Top physics:
$t \rightarrow Wb$ no hadronization
heaviest known particle



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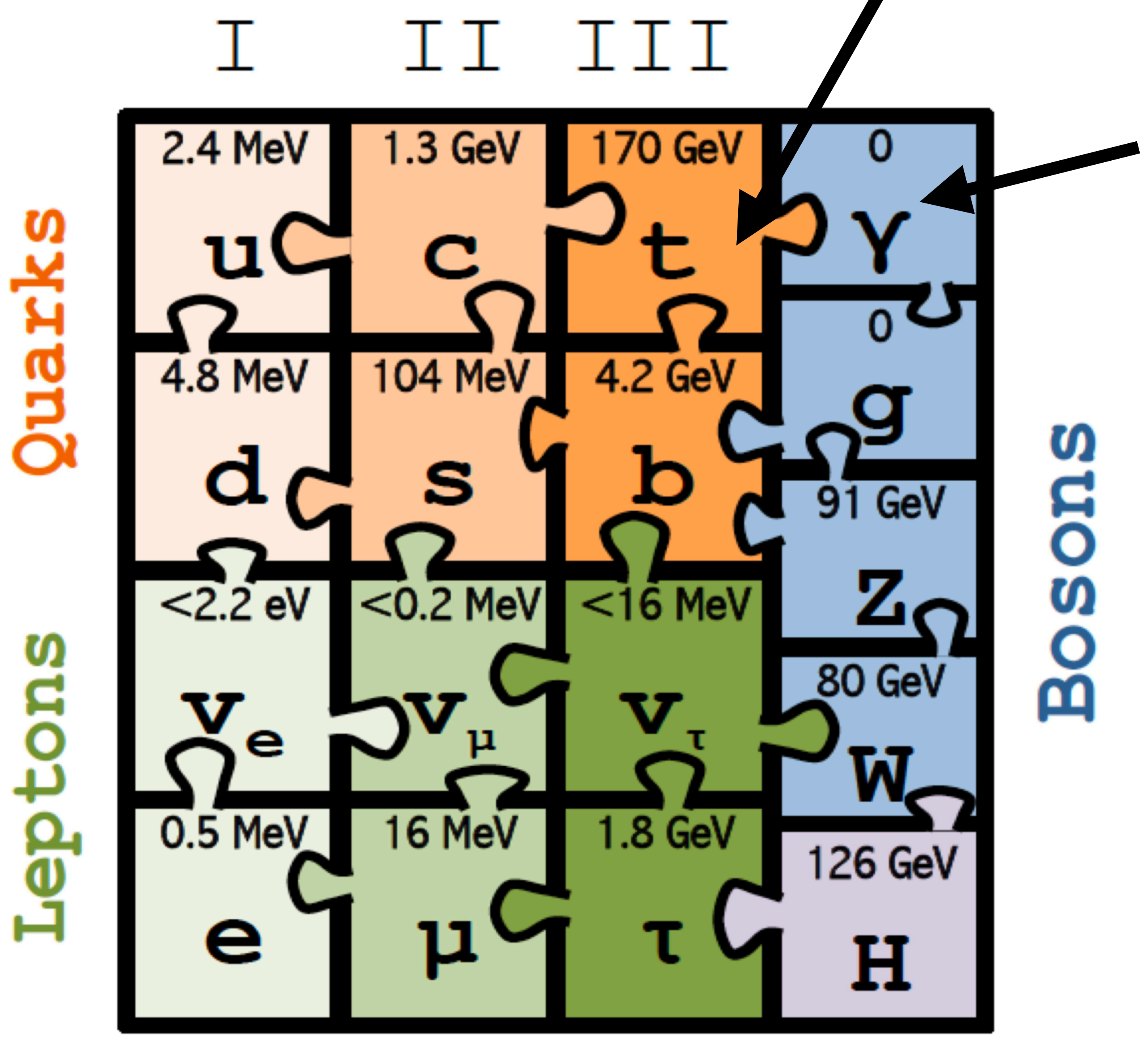

Electrodynamics:
light-by-light scattering

Electroweak physics:
$W/Z/\gamma$ interactions
precise tool to probe SM
(really complicated in the hadron-dominated LHC environment)

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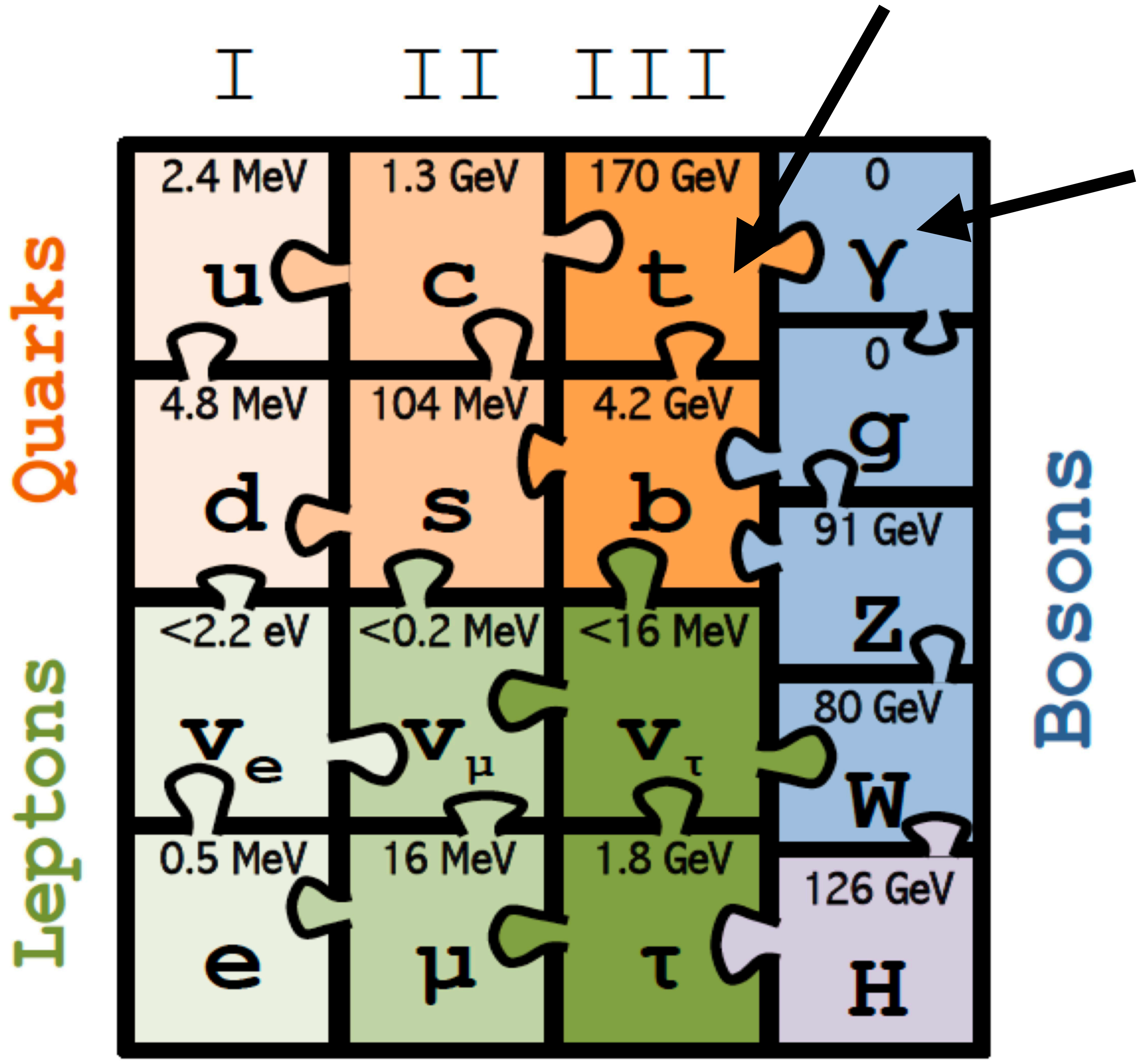

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The next talk by Luka Selem -> measurement of WZ polarization

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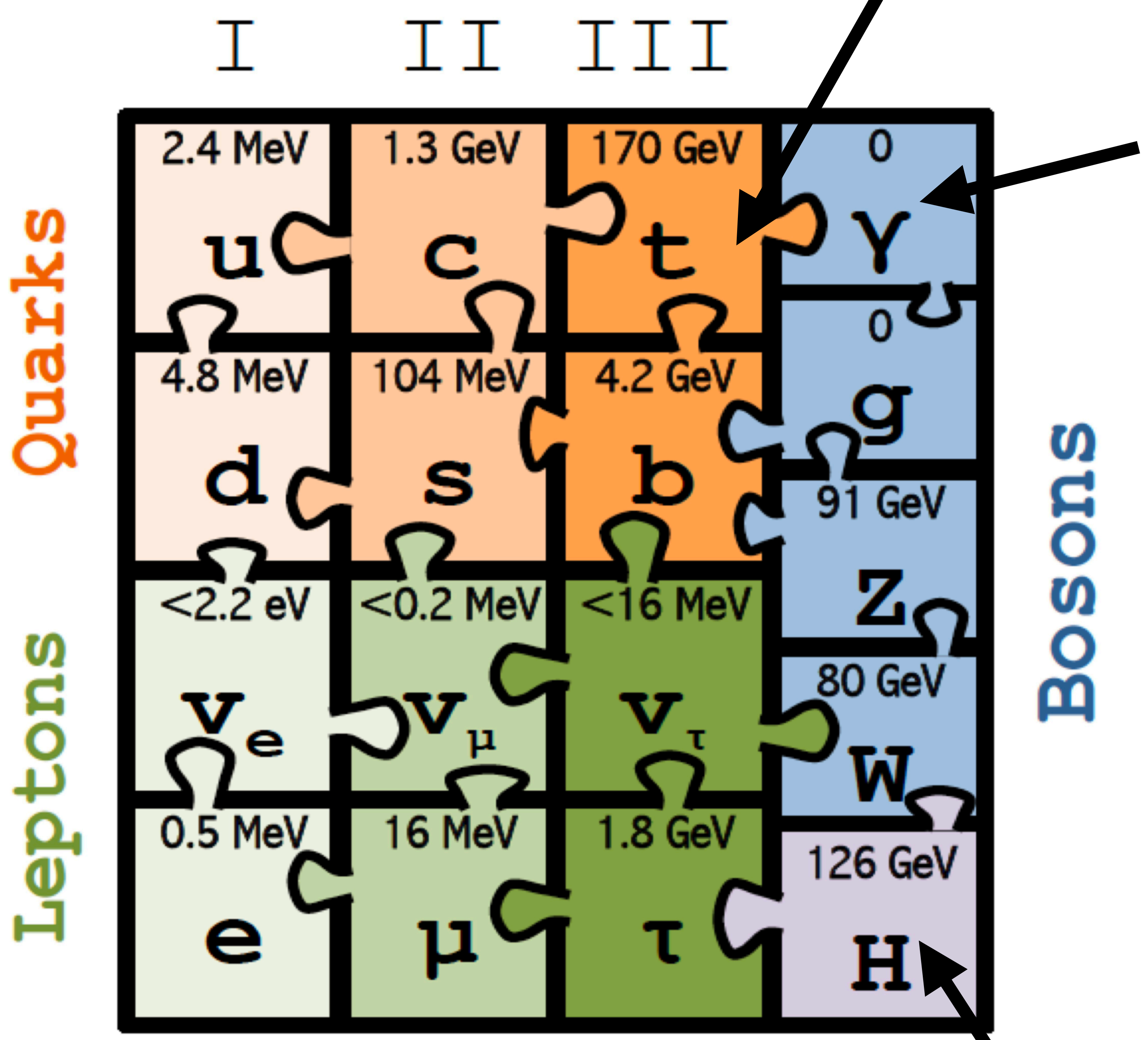

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Higgs physics:
¿The particle we see in the detector = particle predicted by the SM?

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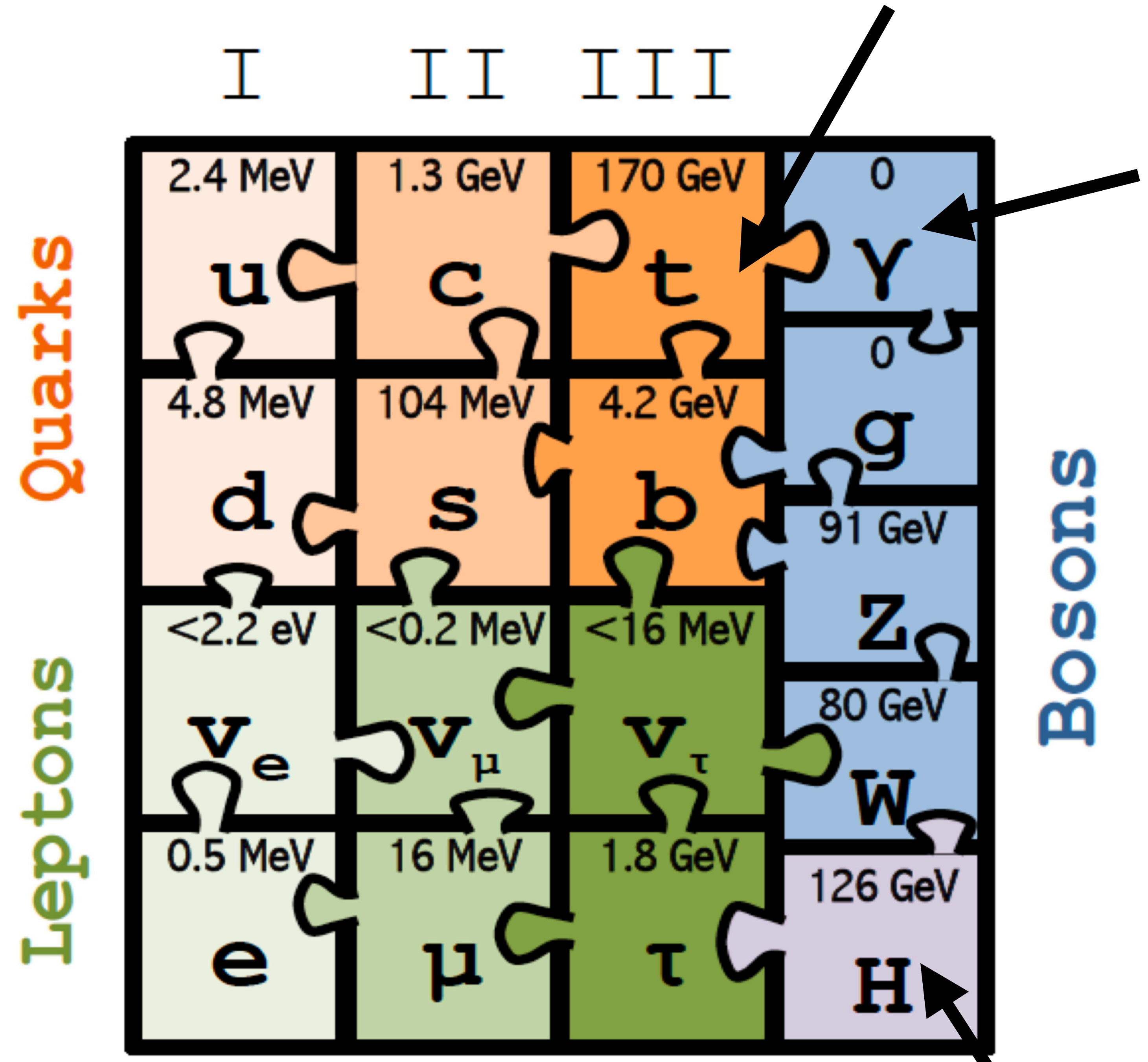

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Arnaud Maury has tried to parametrise an off-shell H->4l X-section using ML

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Talk by Mario Sessini -> is Higgs boson indeed so hopelessly scalar as the SM predicts?

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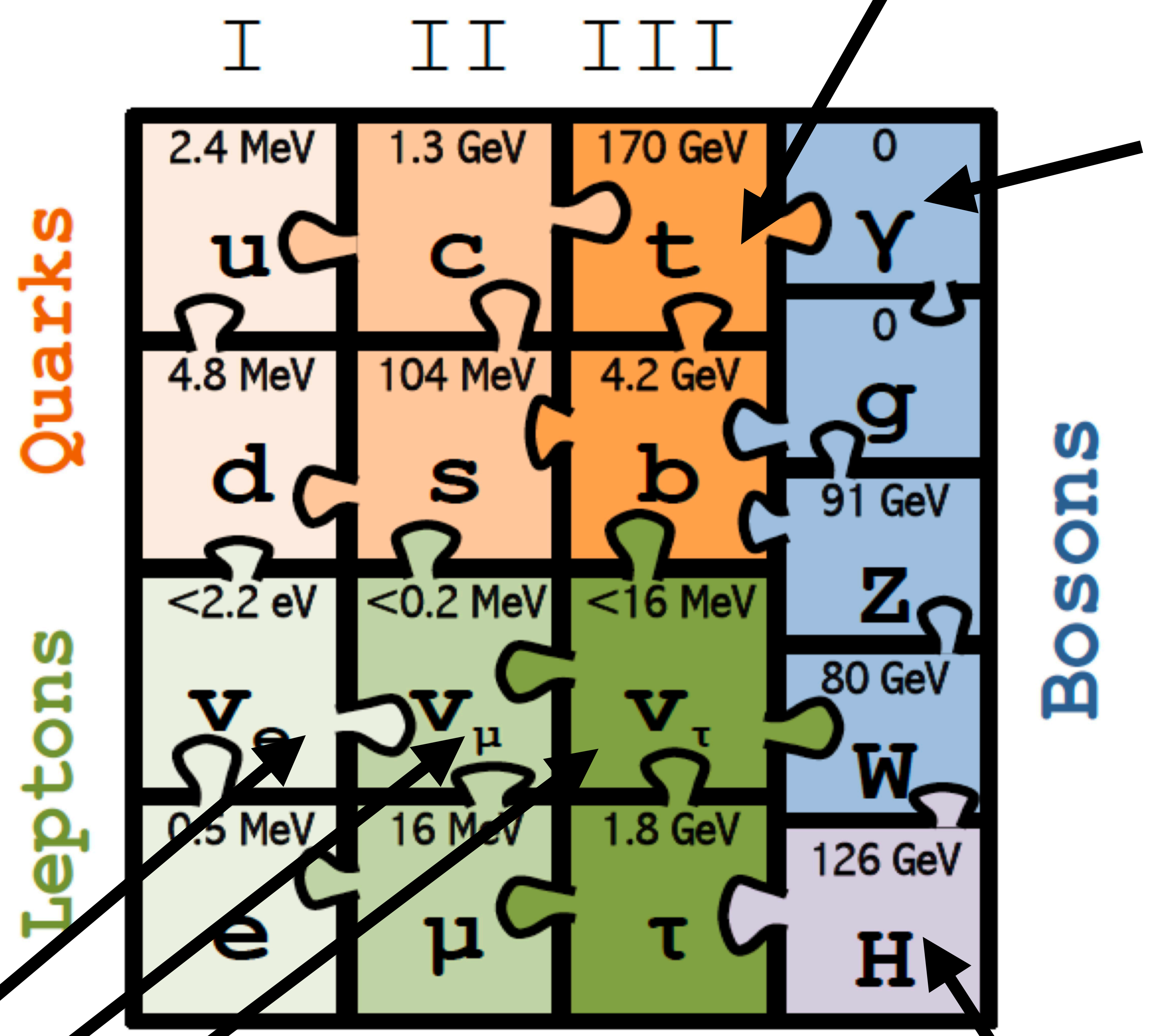

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Neutrino physics:
- Interacts only weakly
- very small mass

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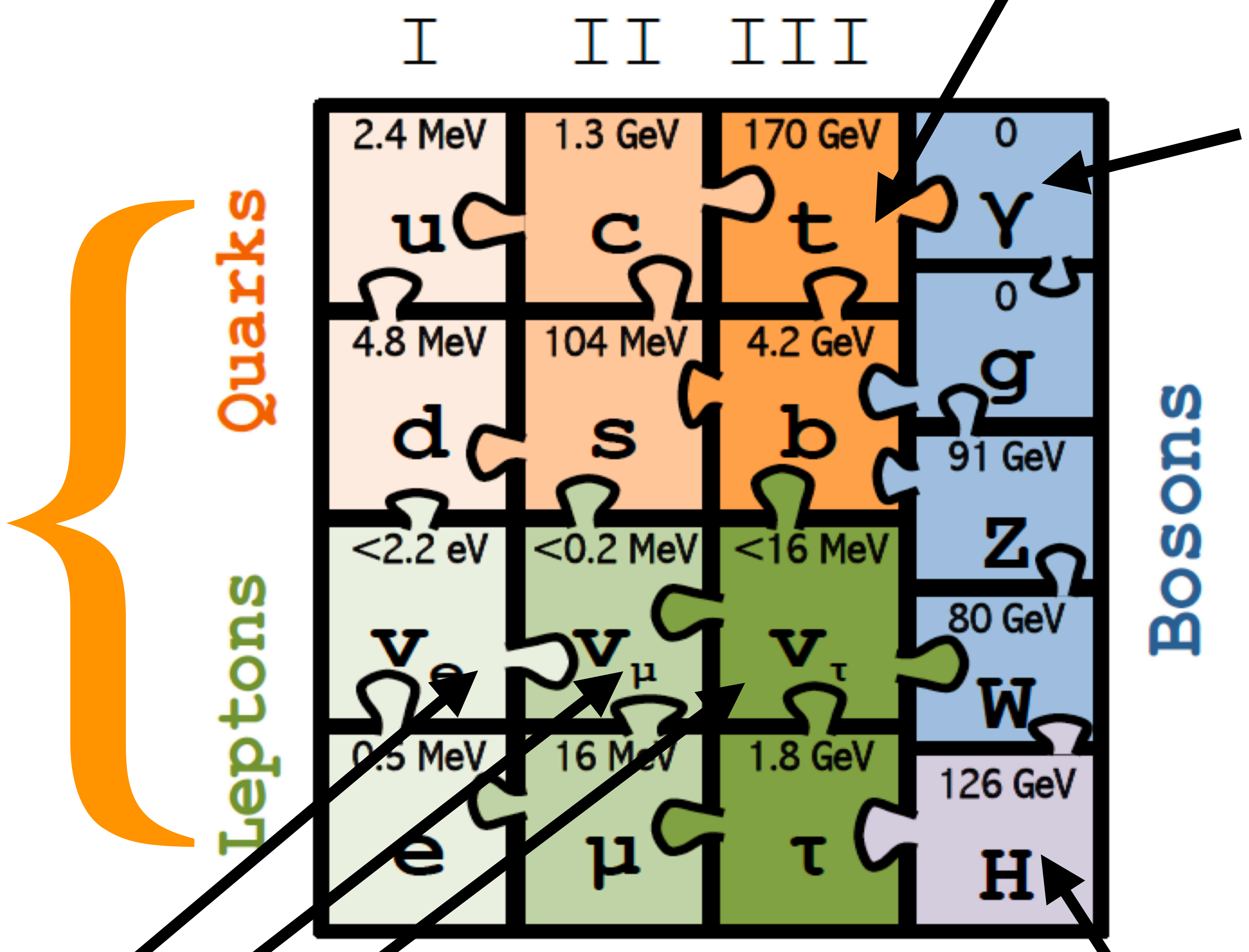
Flavour physics:

- mixings and couplings
- symmetry violation
- matter-antimatter asymmetry



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Halime Sazak will tell us about the measurement of the CKM angle

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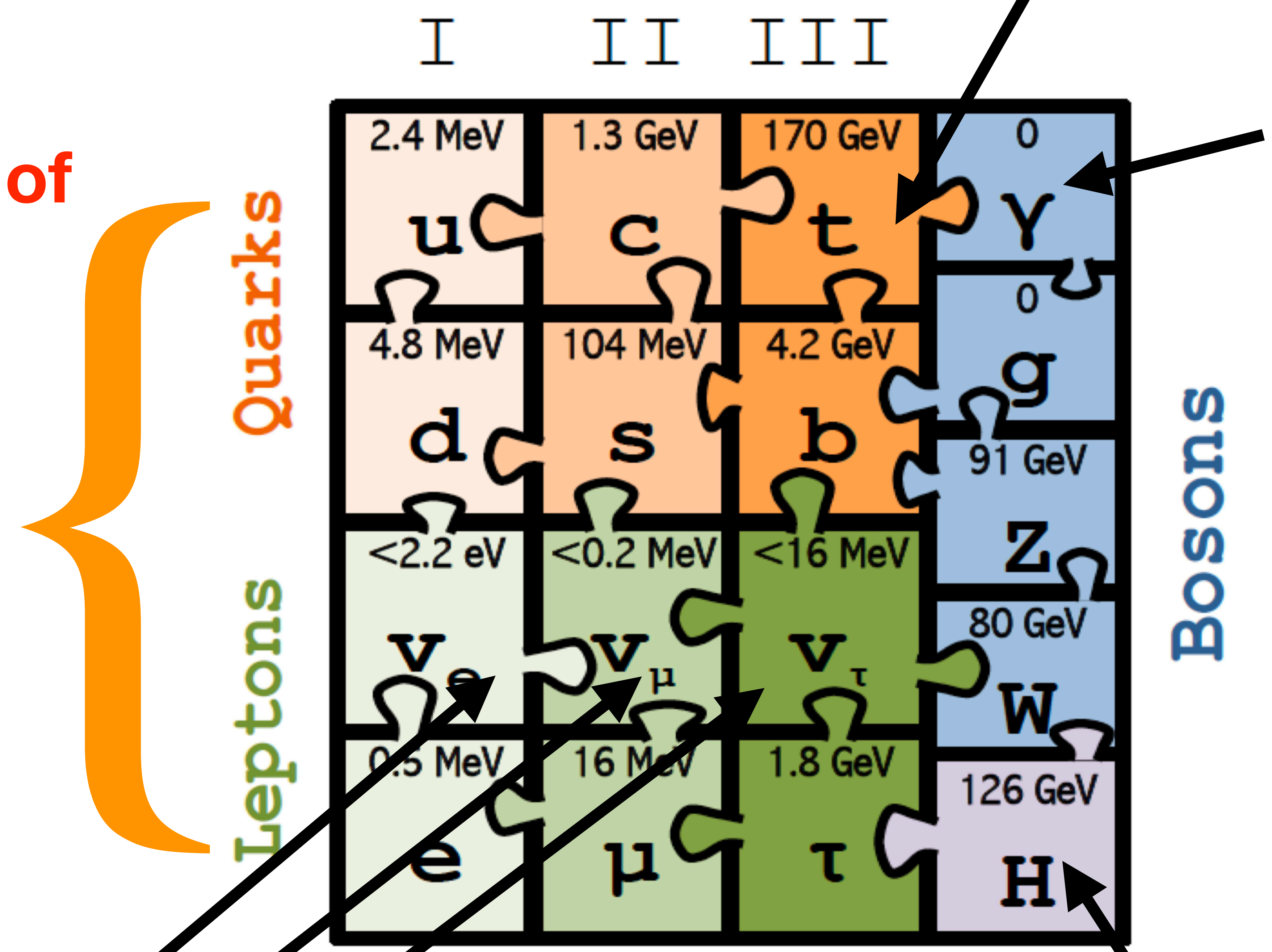

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The Standard Model

Investigated from every side

QCD physics:
- Strong interaction
- quarks + gluons
- bridging theoretical QCD objects (partons) and experiment (jets)

- Hadron physics

Flavour physics:
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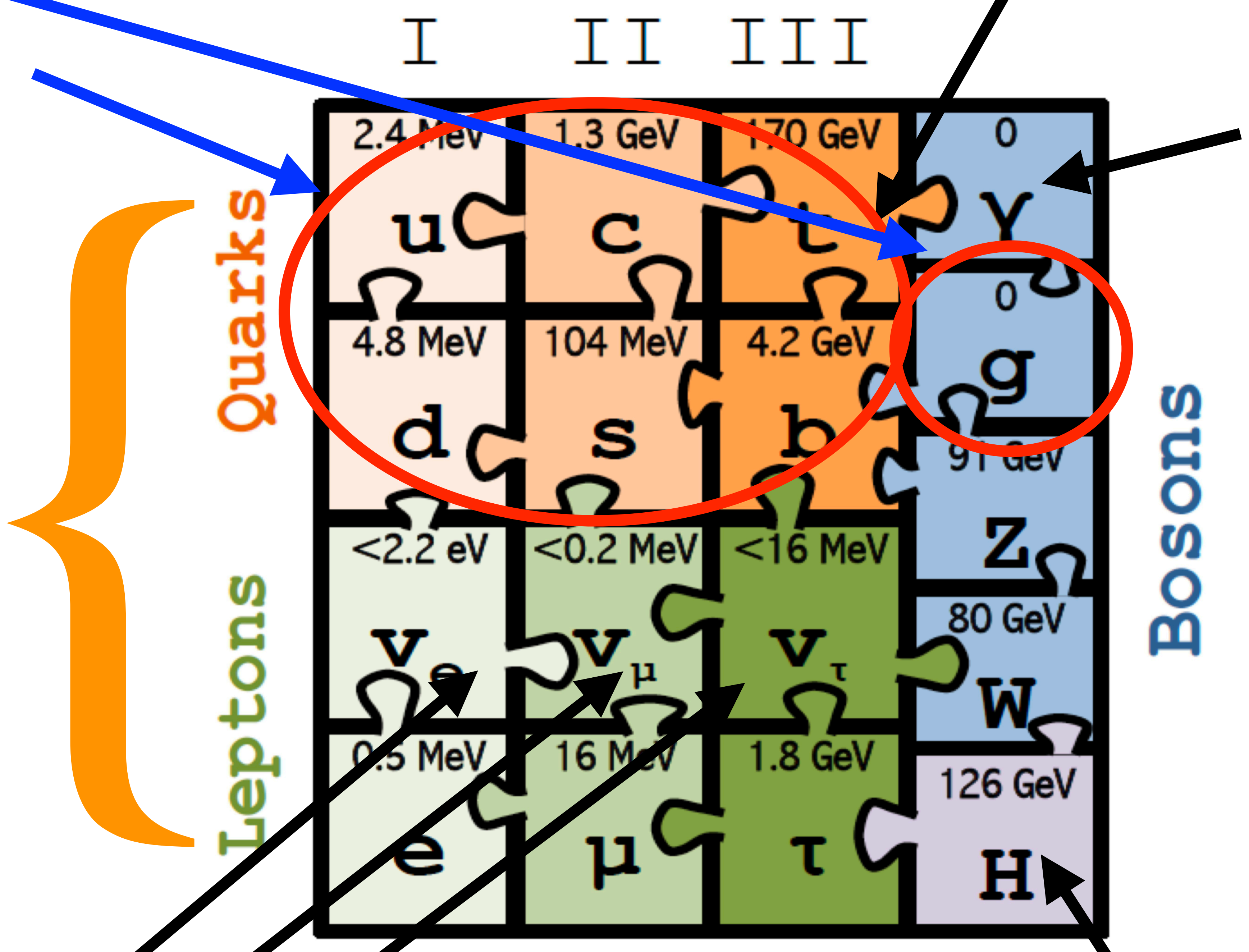

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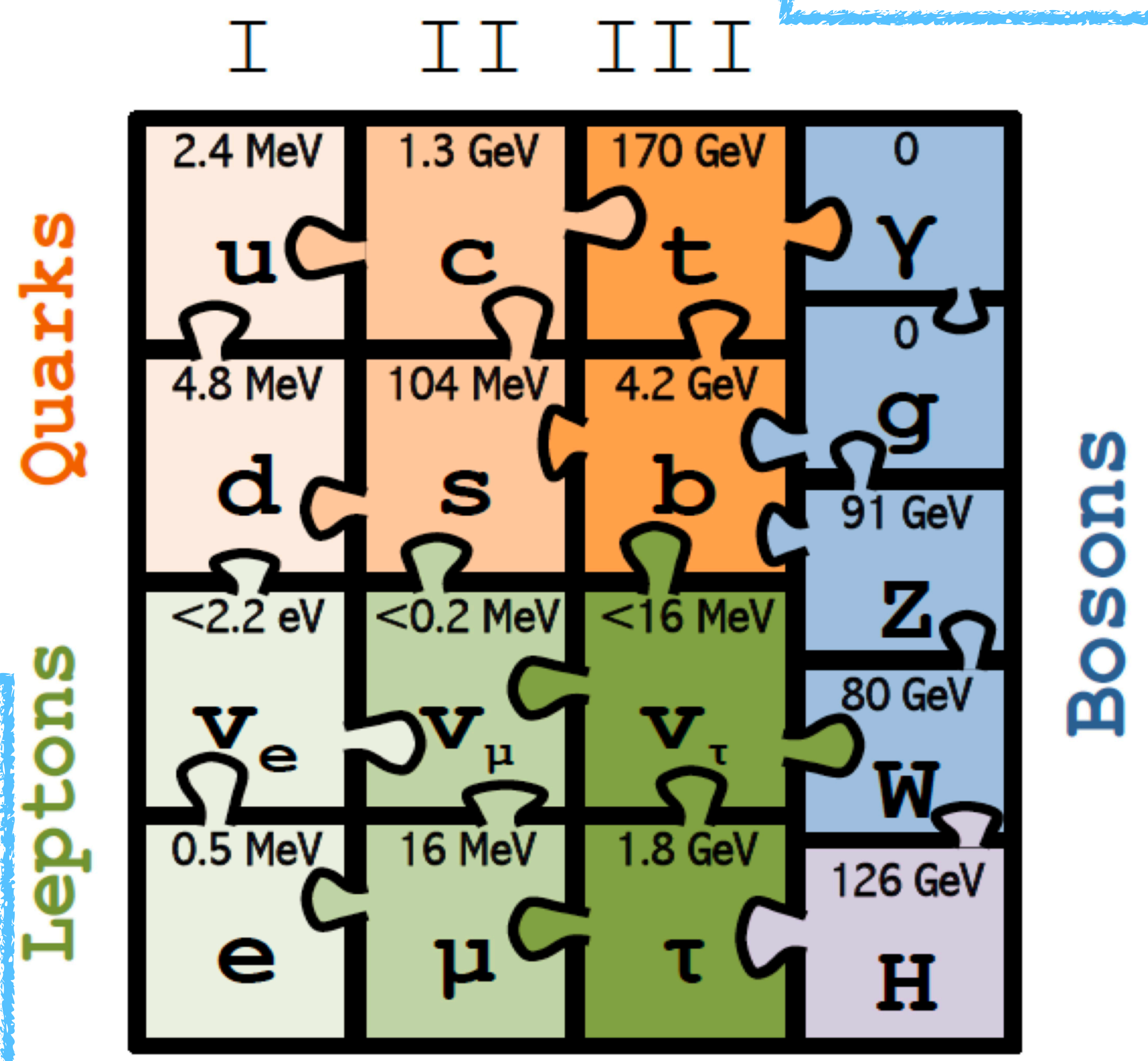
What do we want to measure?

Couplings
rare processes (multiboson, VBS, four tops, Higgs)
differential x-sections, W/Z VBF

Symmetry conservations
e.g. lepton universality

α_s
jet production, top production cross-sections, splitting scales, jet substructure, QGP manifestations



m_t
Direct and indirect measurement

?

m_W
Measurement of p_T^W and m_W
Comparison with SM electroweak fits (interplay top and Higgs)

$\sin^2\theta_W$
Drell-Yang angular coefficients A_{FB}

The Standard Model

What do we want to measure?

Océane Perrin will enlighten us about Higgs self-coupling measurement

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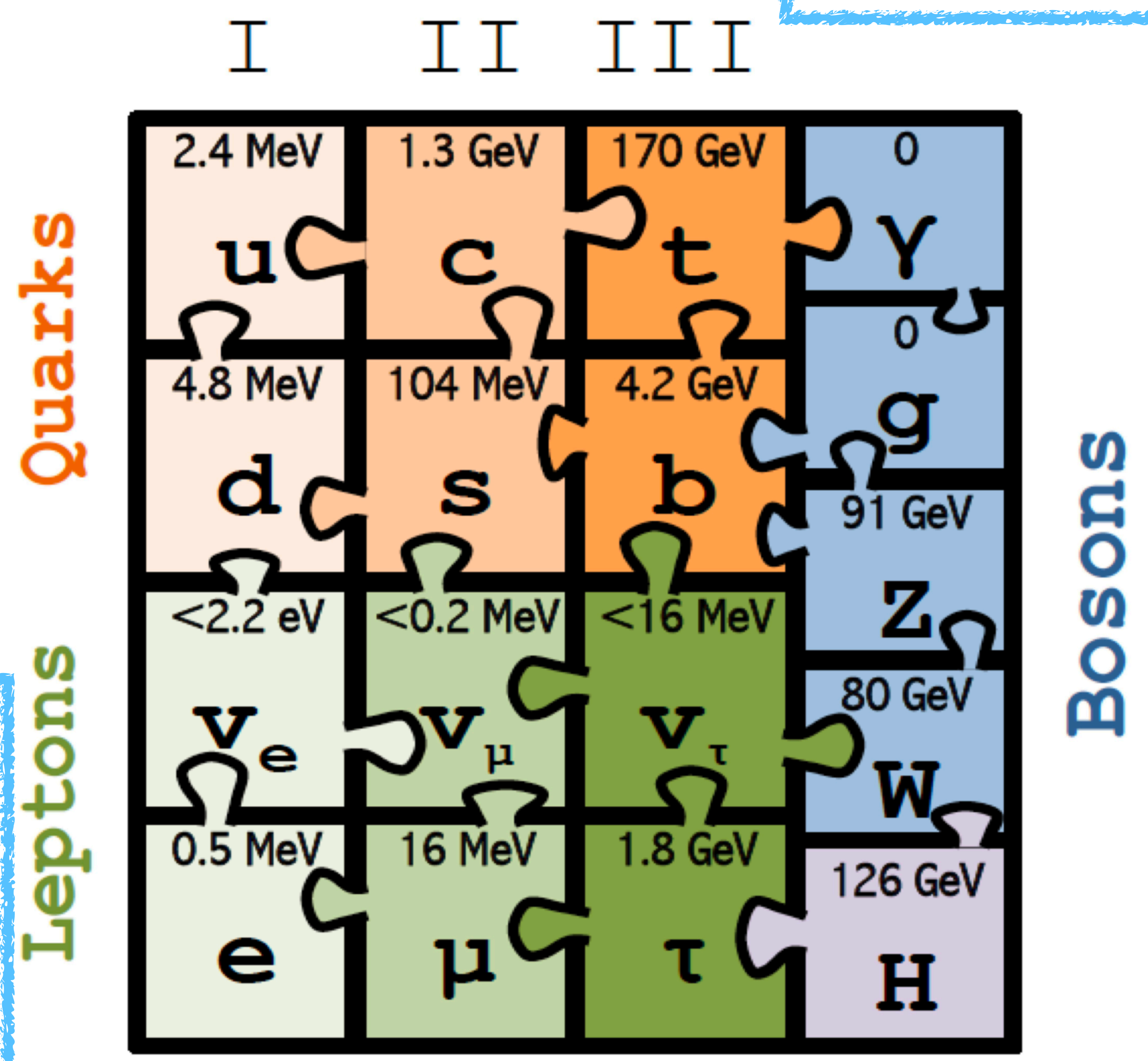

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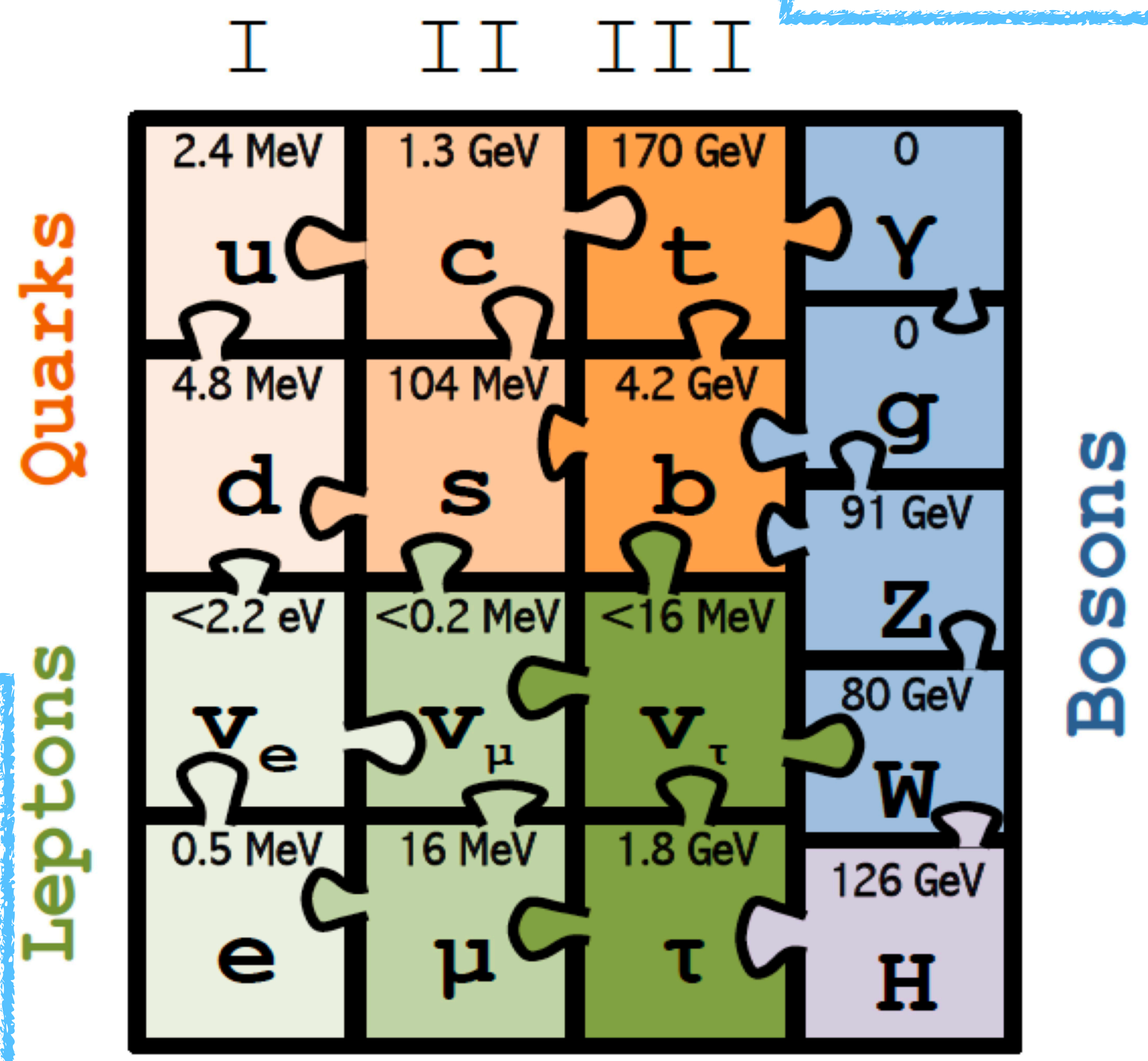


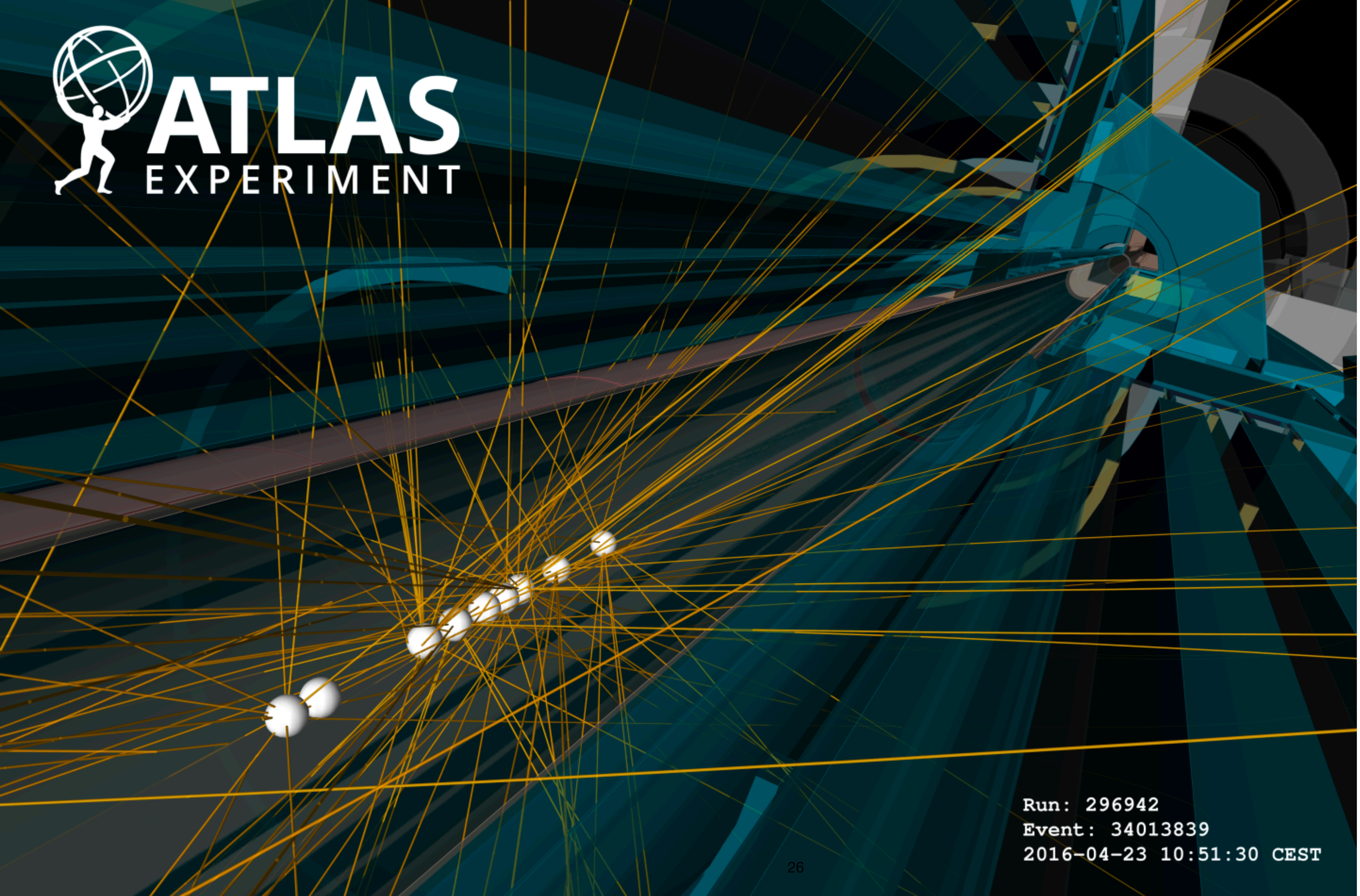
New physics
The SM was (and still is) a great theoretical success
Shall we finally break it?

m_W
Measurement of p_T^W and m_W
Comparison with SM electroweak fits (interplay top and Higgs)

$\sin^2\theta_W$
Drell-Yang angular coefficients A_{FB}

The LHC

- 27 km circumference particle collider at CERN
- Operates at 13 TeV center-of-mass energy (Run 2)
- Delivers unprecedented luminosity: Tevatron collected 1 fb^{-1} in 2001-2005, LHC made 146 fb^{-1} in 2015-2018



bunches of protons cross every 25 ns

here you see 9 collisions per bunch crossing

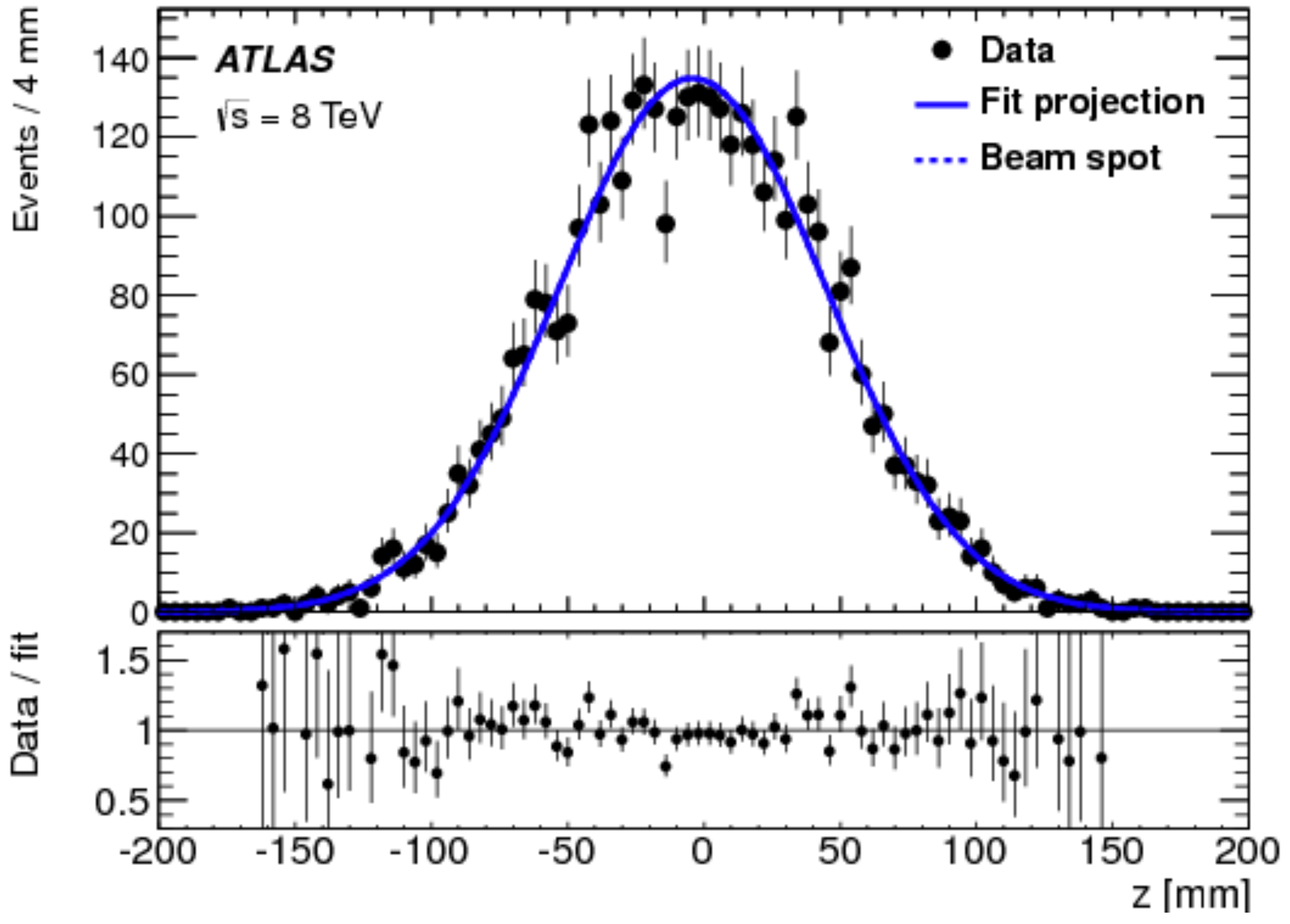
~ 100 collisions per bunch crossing

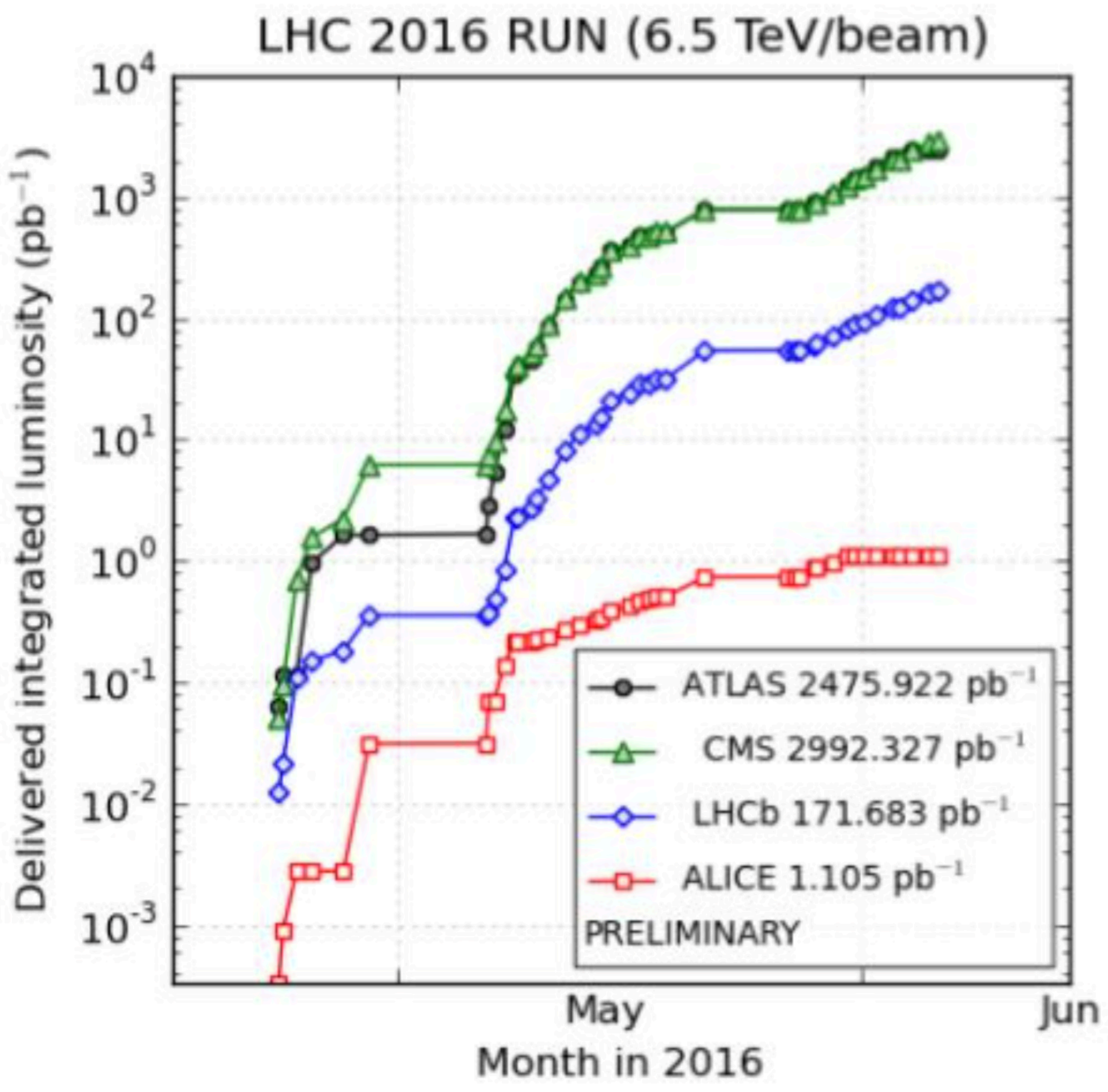
Luminosity collected by the detectors

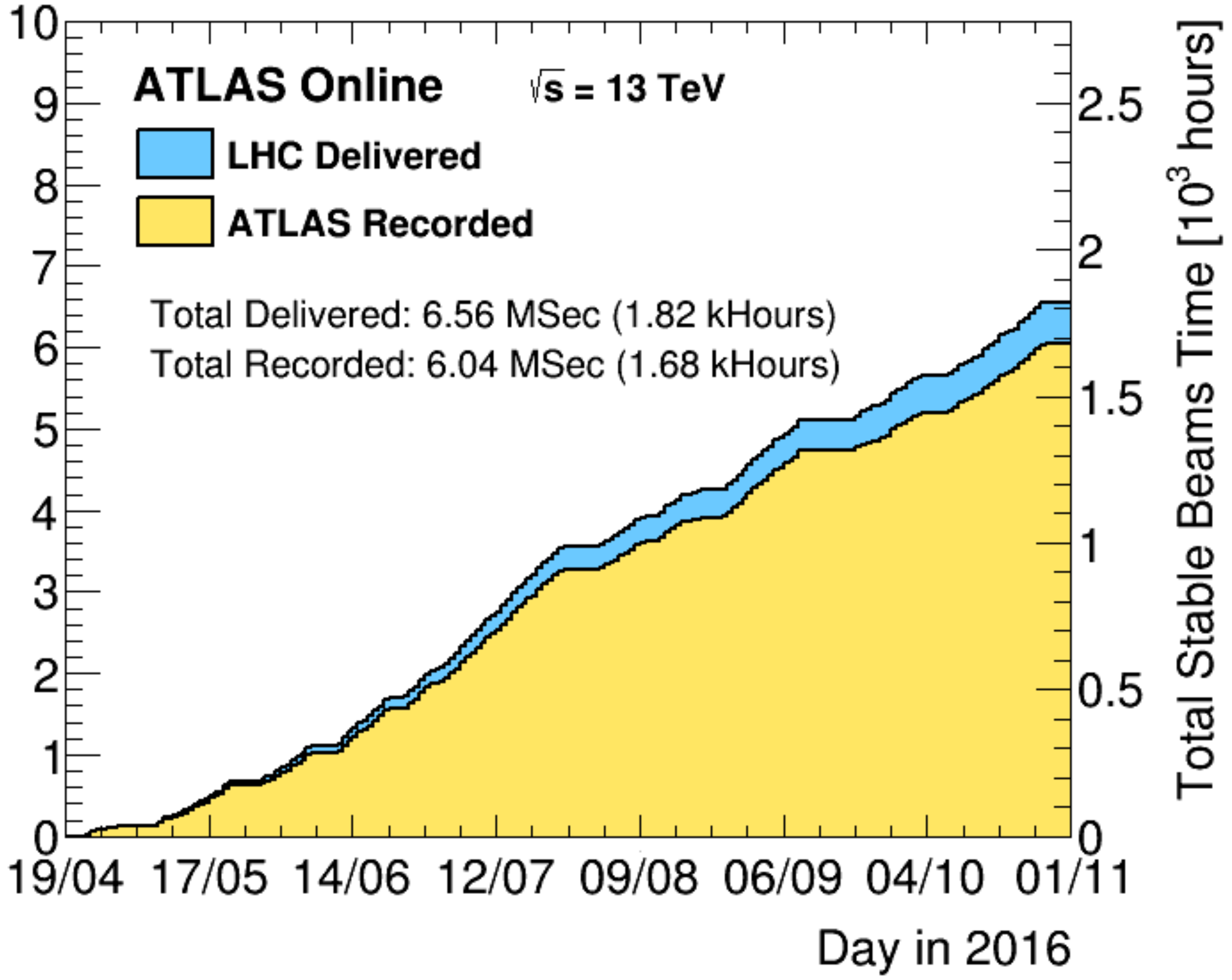
$$N_{events} = \sigma(E_{CoM}) \times L$$

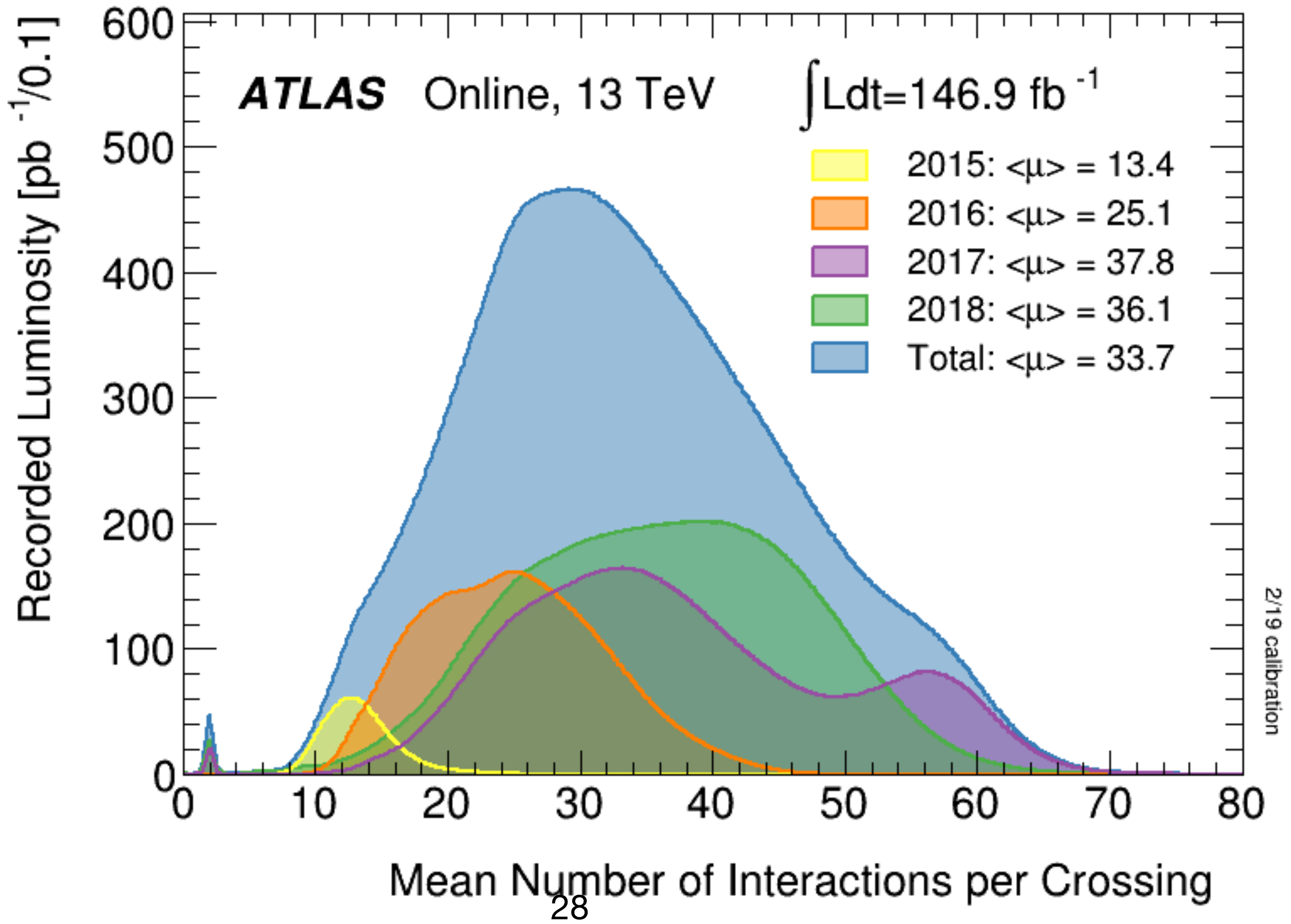
- 1 fb^{-1} at 13 TeV gives ~ 100k $W^+ \to e^+\nu$
- Higher luminosity -> more events -> rare processes
- High pile-up -> aggressive radiation + systematics

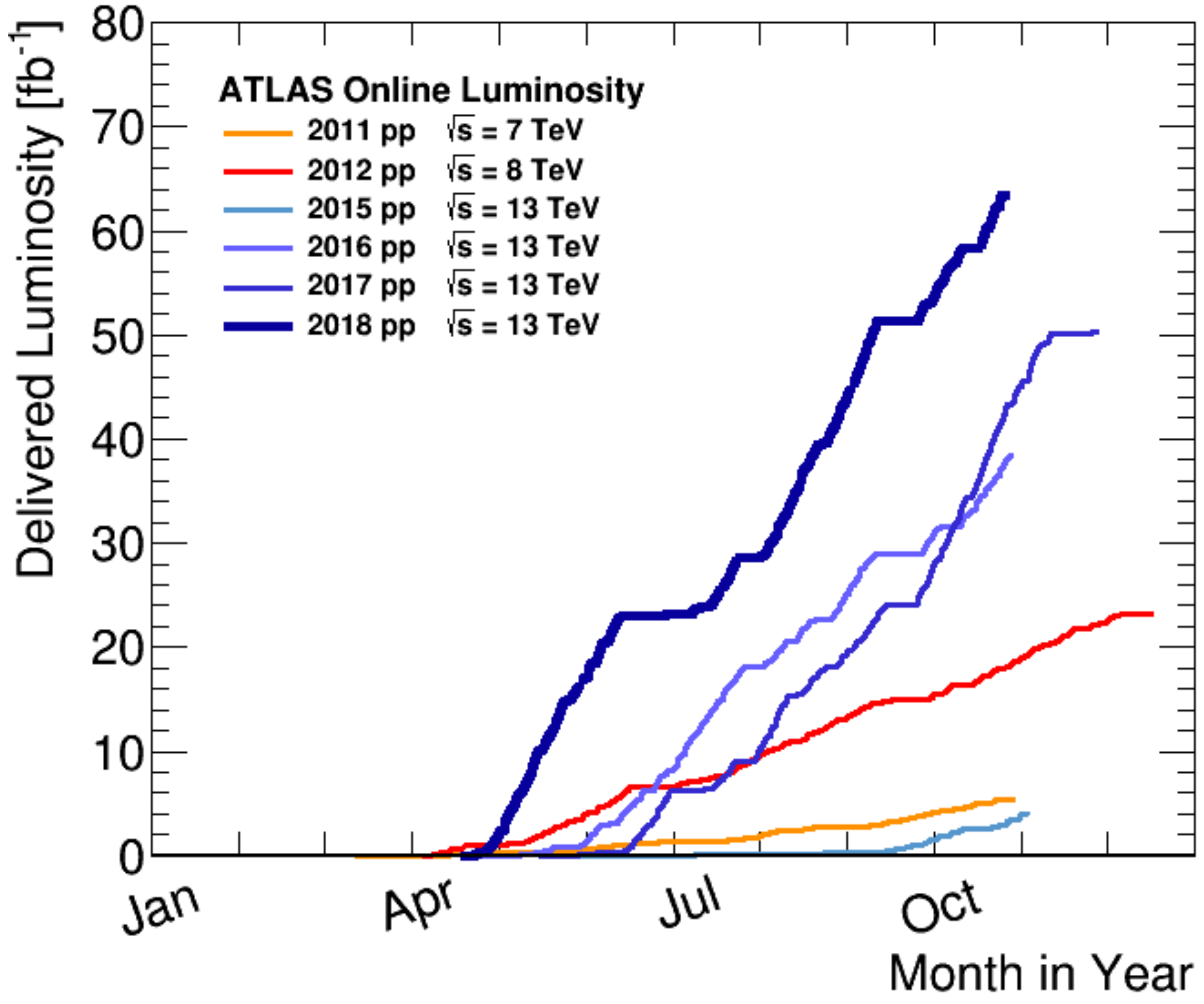
bad for the detector   bad for precision measurements



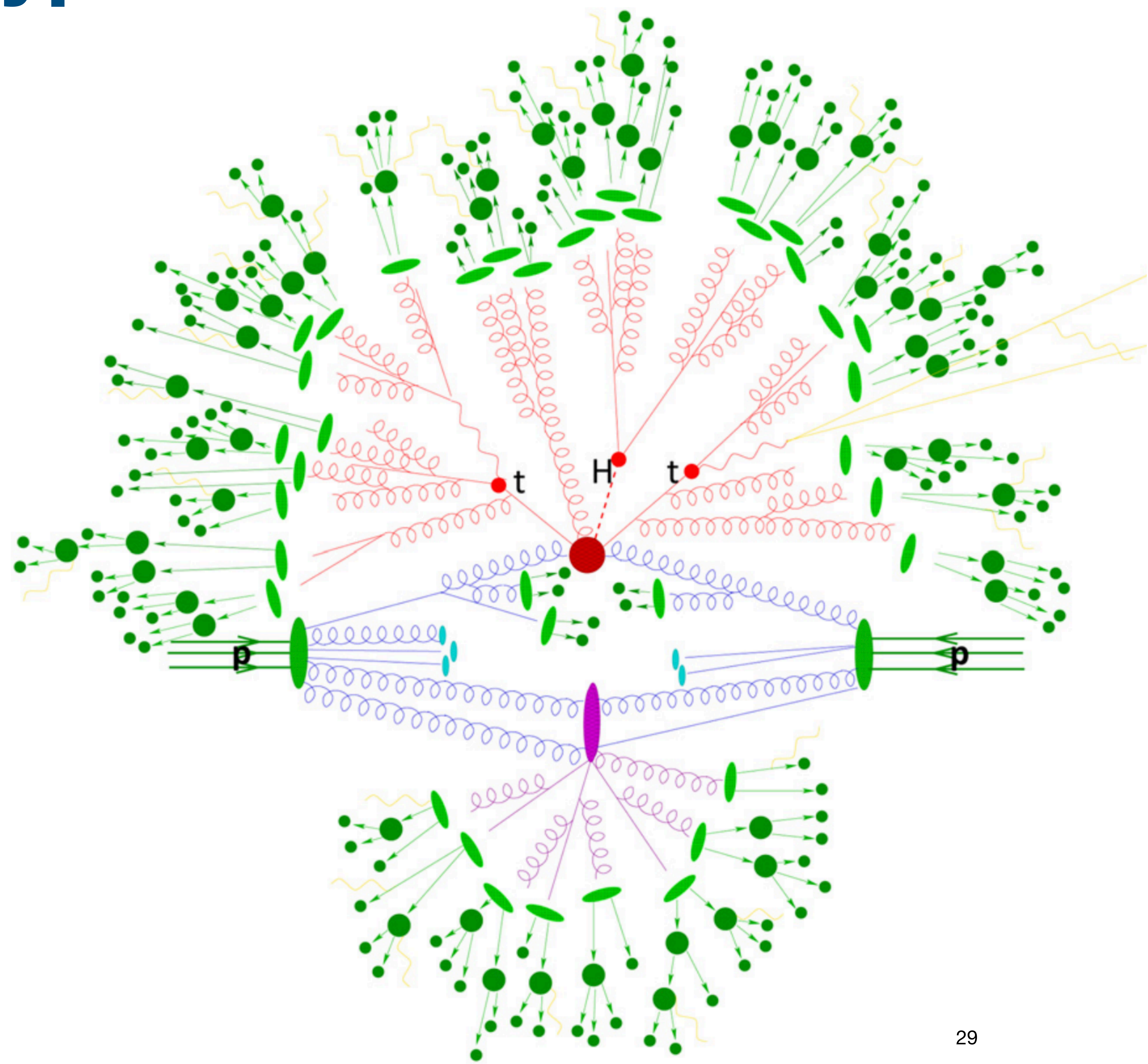








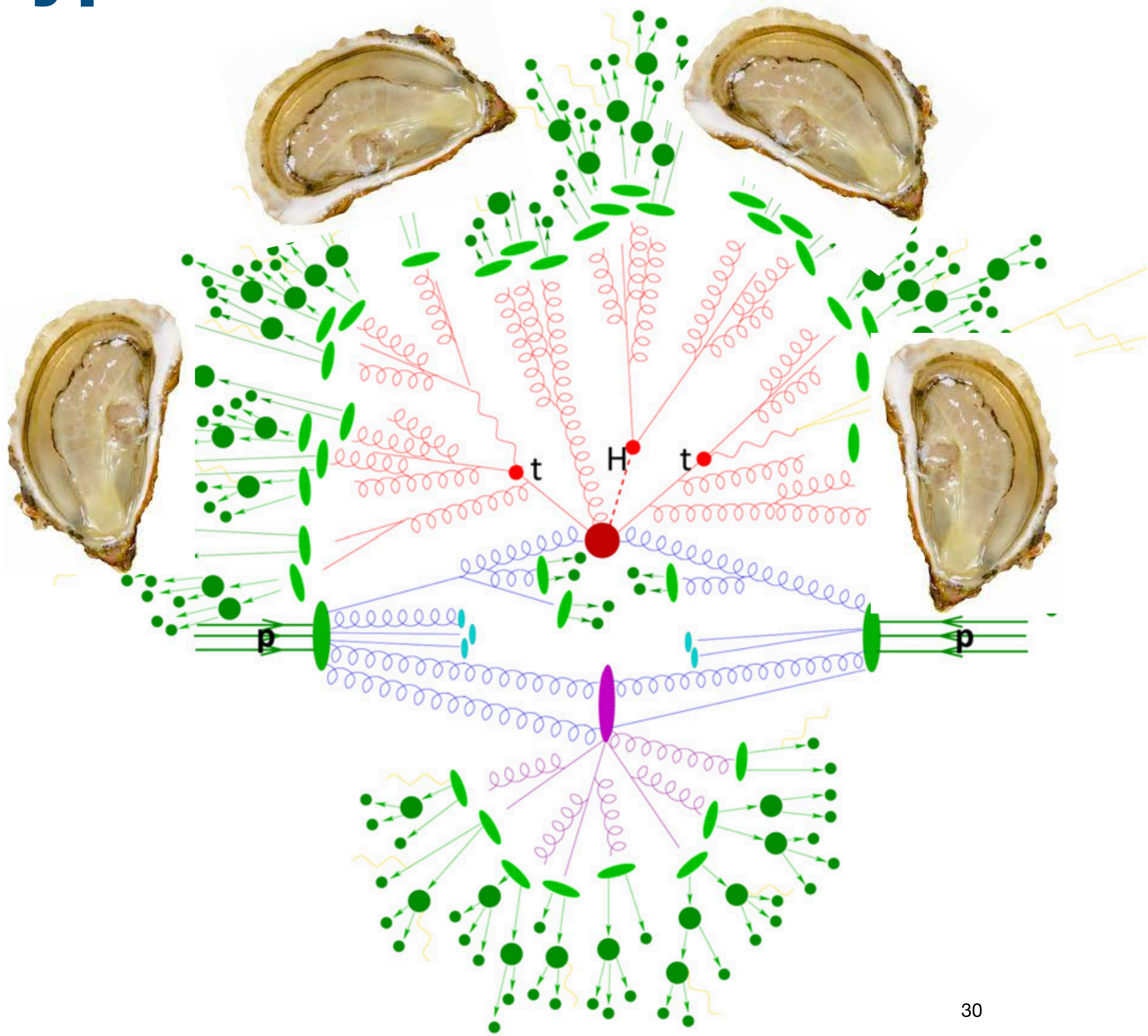
Typical collision is like



The realm of QCD

- A couple of partons have a hard scattering
- Other partons can interact via soft scattering
- Radiation
- Hadronization
- Fragmentation
- Multiple interactions

Typical collision is like



The realm of QCD

- A couple of partons has a hard scattering
- Other partons can interact via soft scattering
- Radiation
- Hadronization
- Fragmentation
- Multiple interactions
- Oyster final states are quite common (scraping them them out of the detector is the true reason for Run 3 delay)

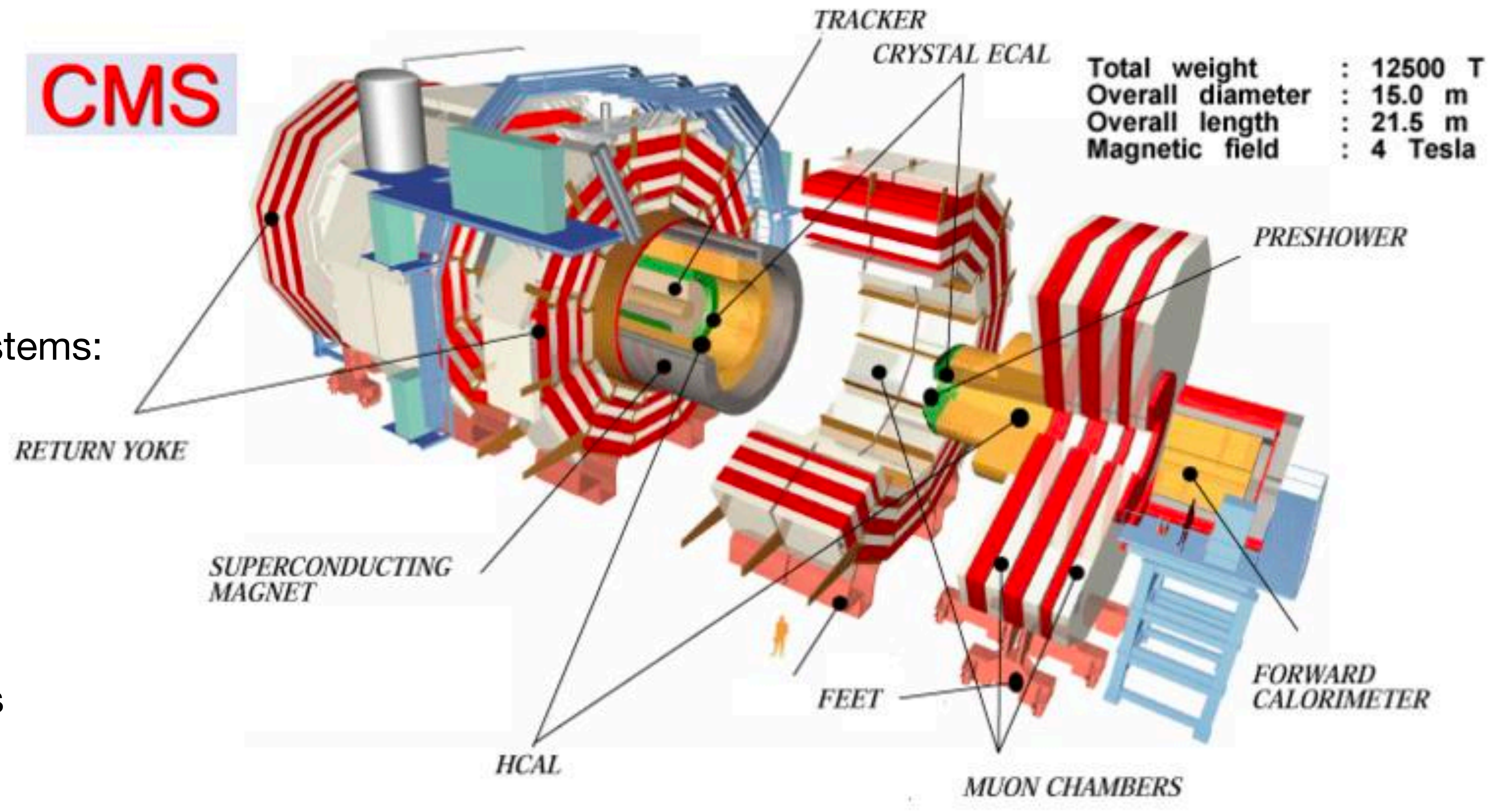
The CMS detector

Multi-purpose

Onion-like

Has 4 main subsystems:

- Inner detector
- ECal
- HCal
- Muon chambers



The ATLAS detector

Multi-purpose

Onion-like

Has 4 main subsystems:

- Inner detector
- EM Calorimeter
- Hadronic Calorimeter
- Muon detectors

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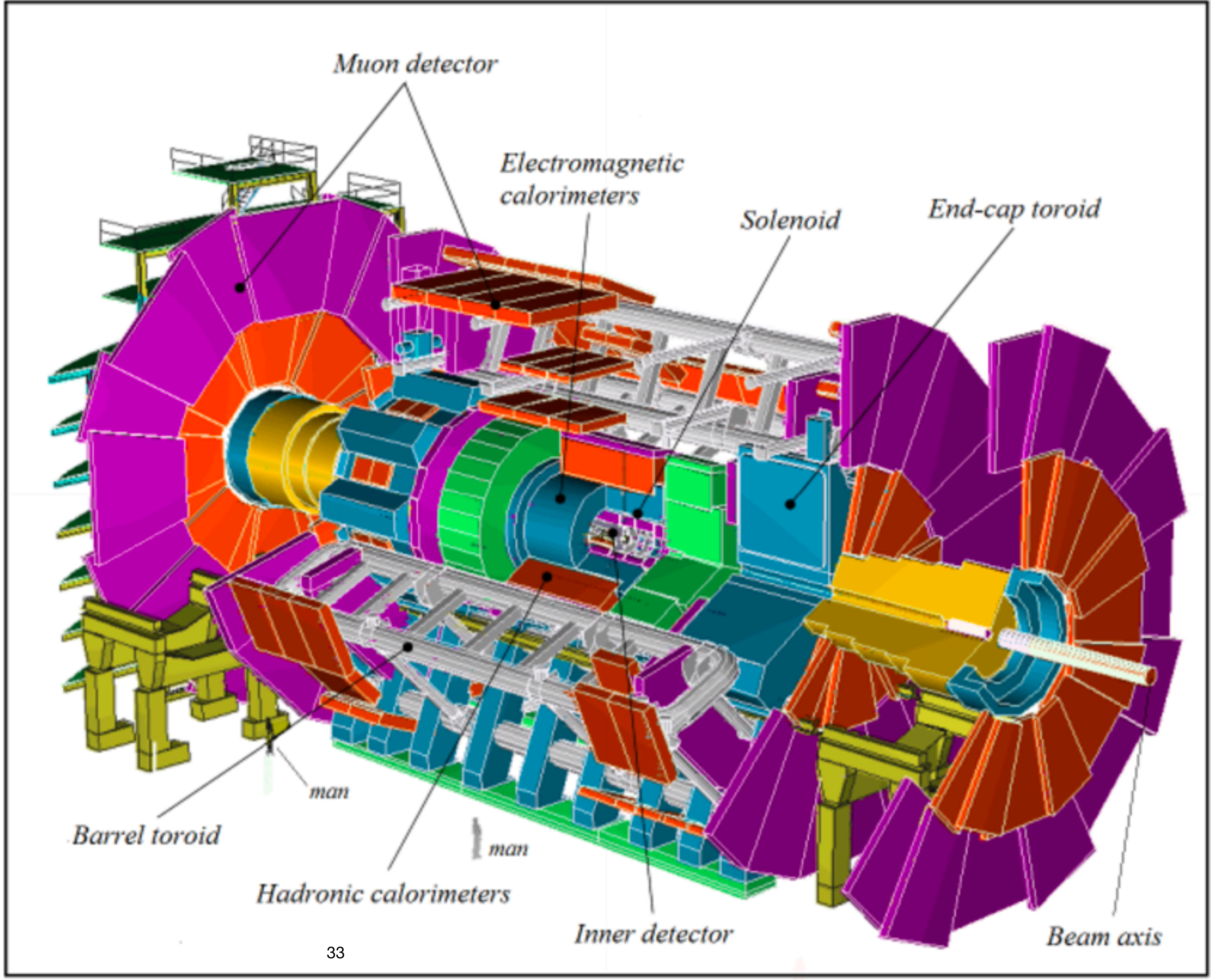

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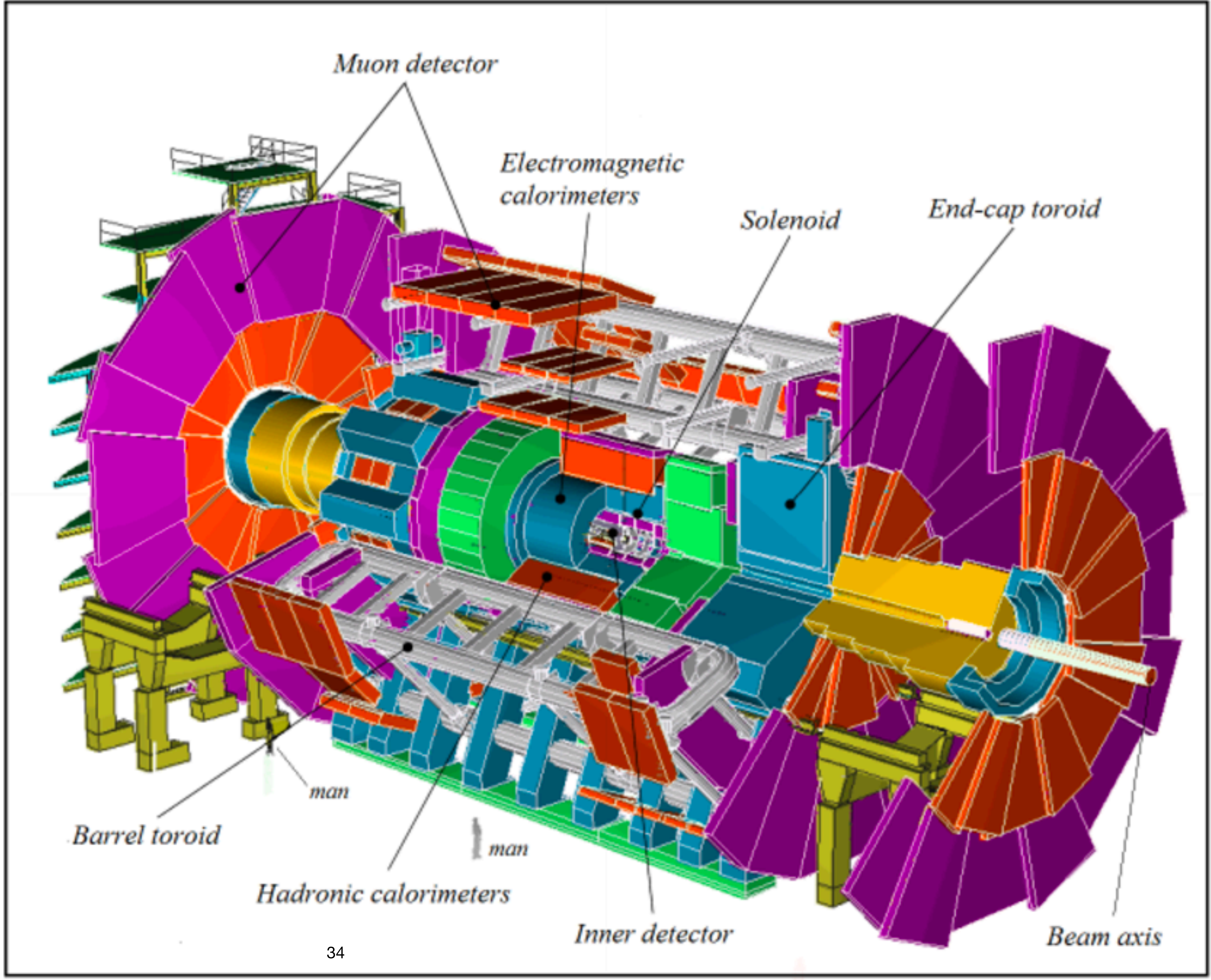
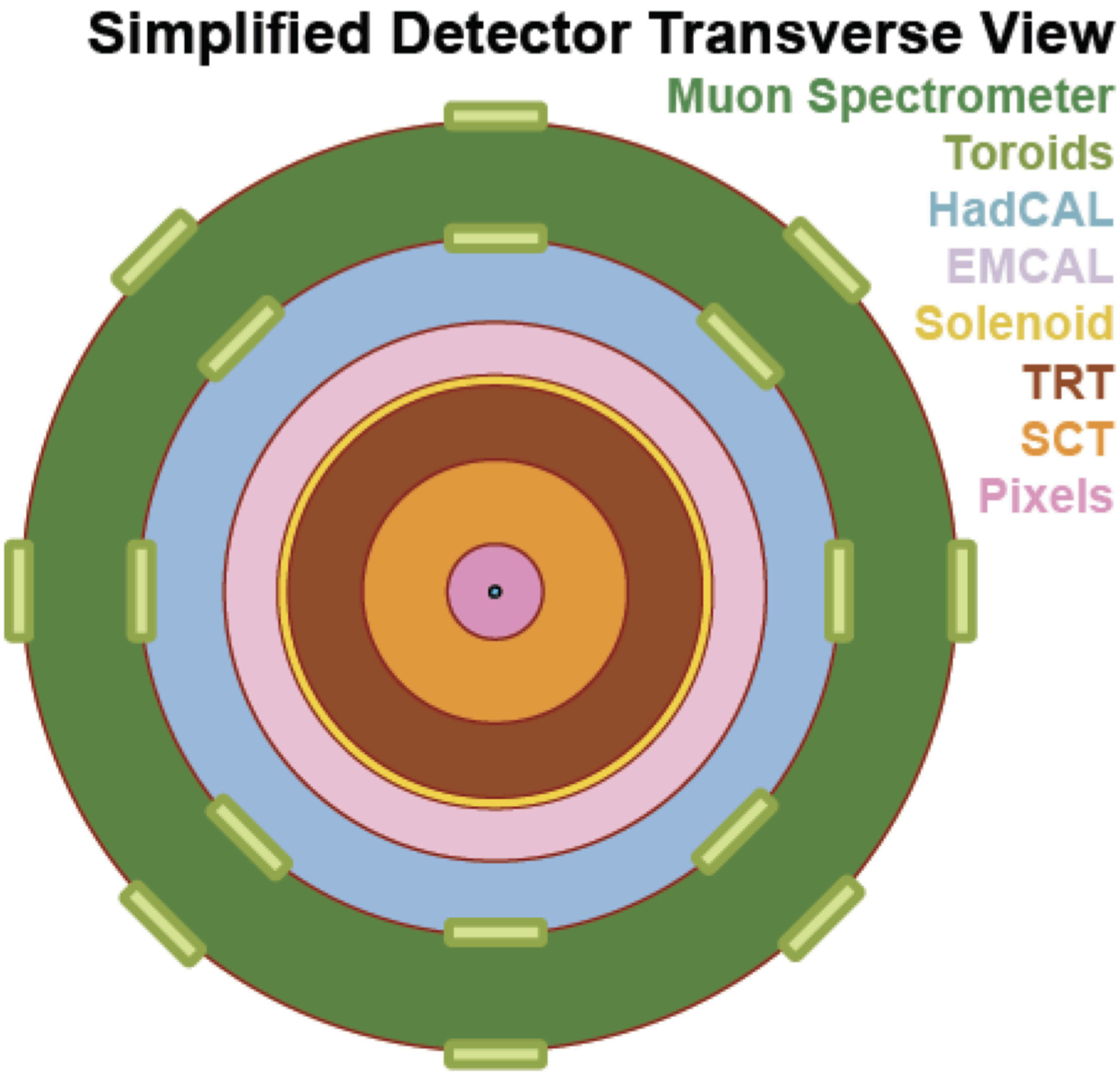
Arnaud Maury is to share his developments in tracking algorithms improvement



What do we see?

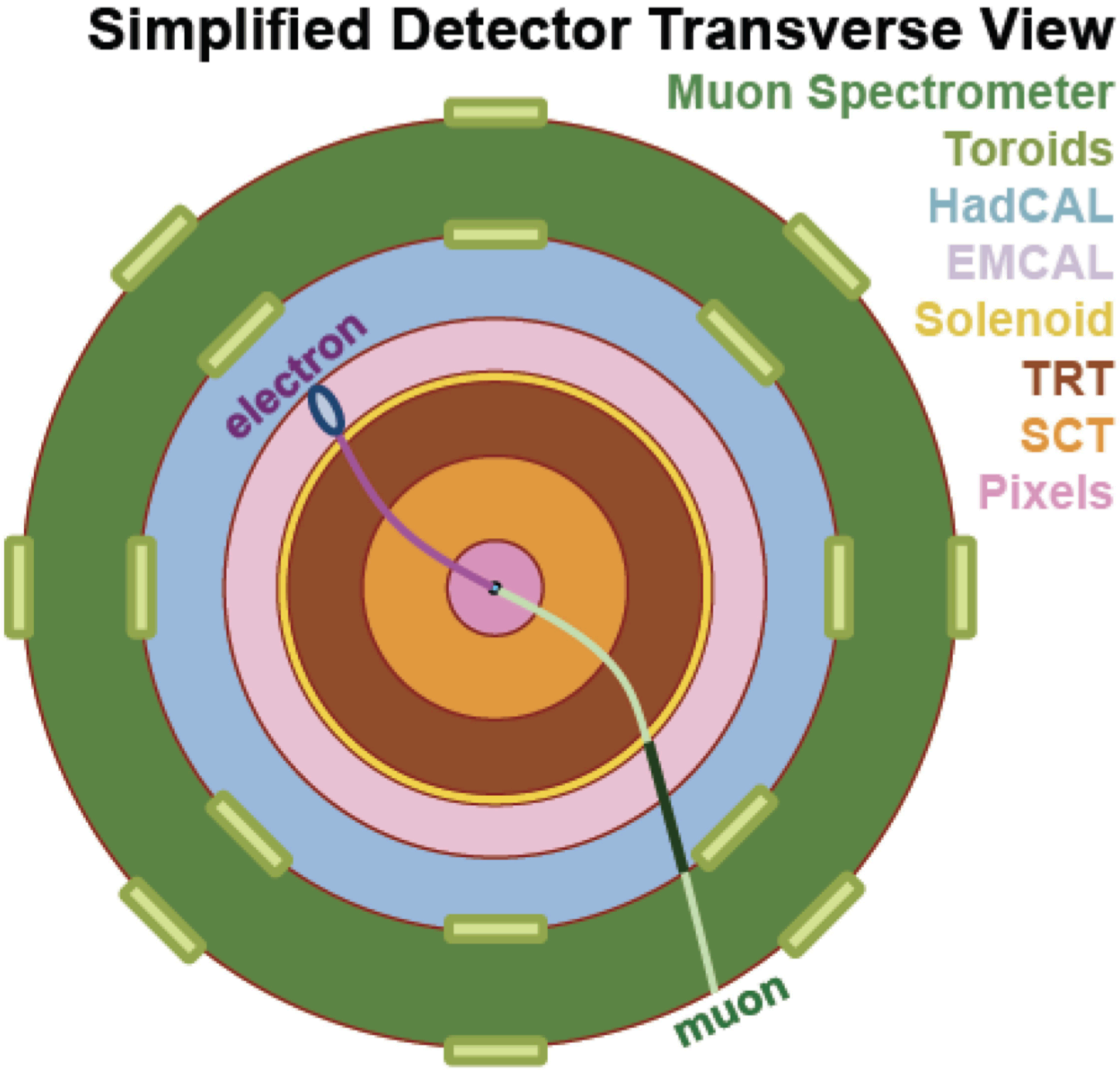
- The particle has to live long enough to reach the detector
- Most of the particles of interest (W/Z/H, quarks, gluons) we reconstruct from their decay products and emissions (leptons, photons, hadrons)



Lepton detection

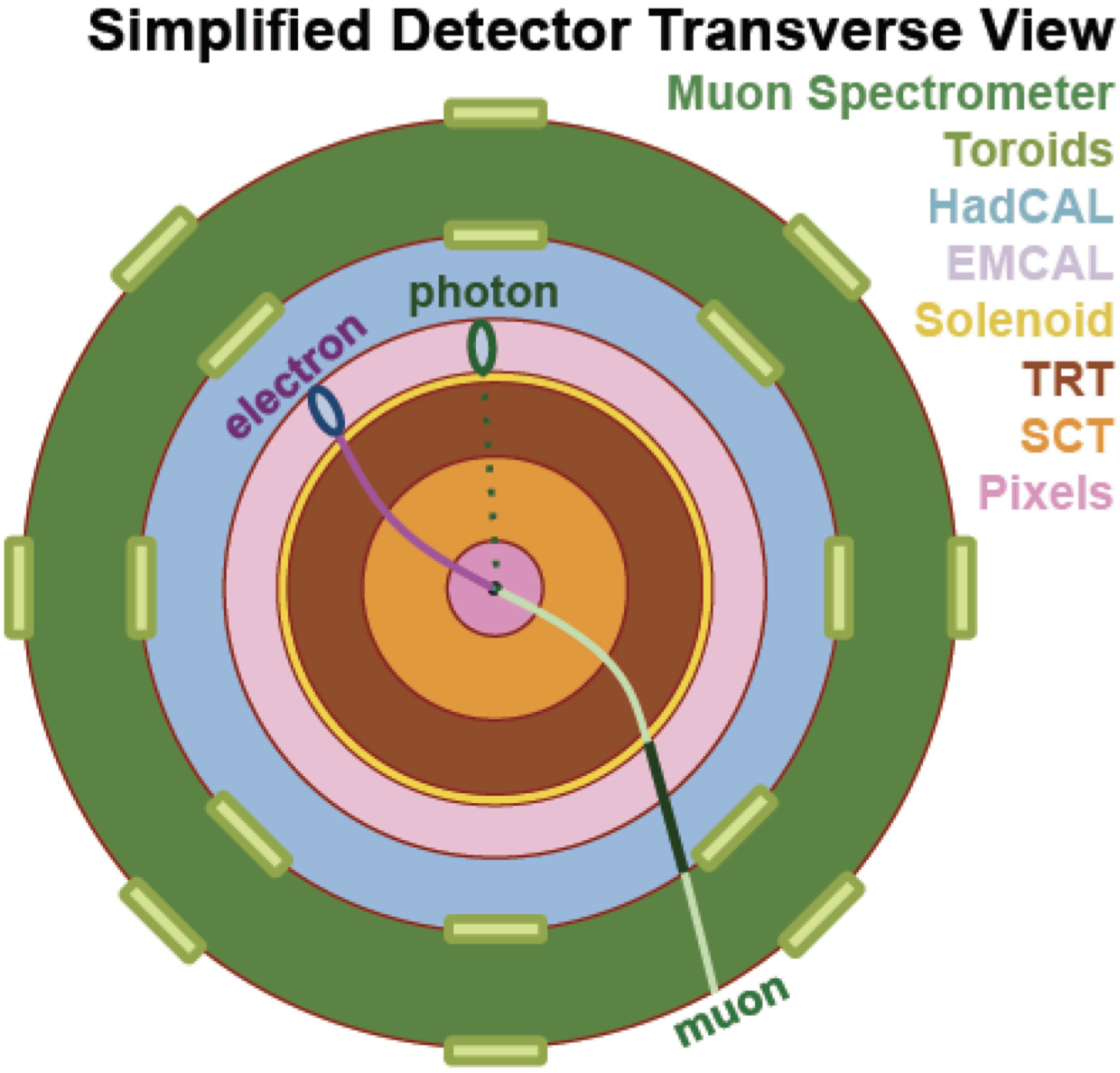
- Electrons create an electromagnetic shower and mostly die in the EM calorimeter. Reconstructed from the tracker and EMCal

- Muons normally penetrate the detector. Reconstructed from the tracker and muon spectrometer.



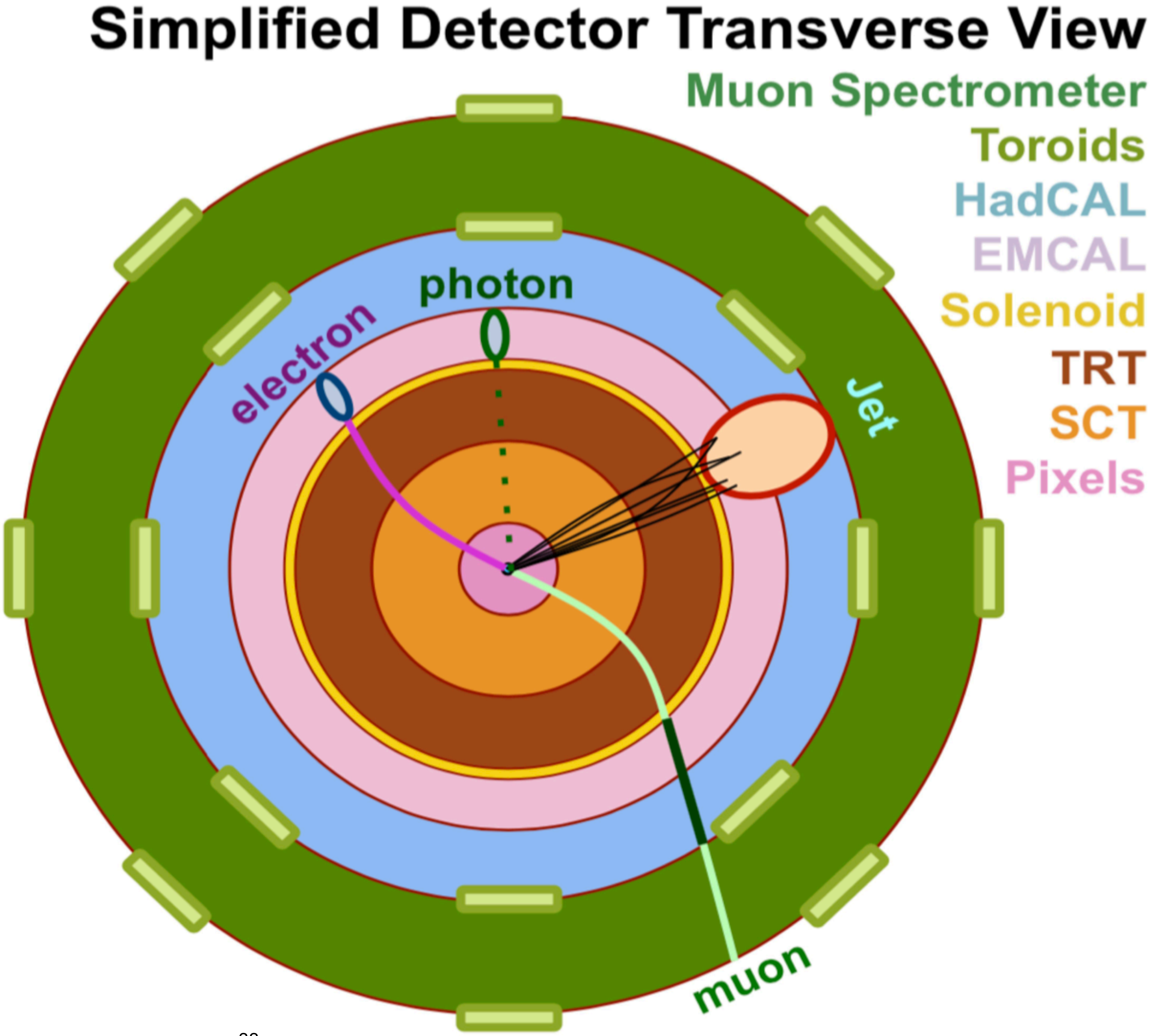
Photons detection

- Photons create an electromagnetic shower and end their short (but glorious) life in the EM calorimeter right next to the electrons. Photons are not seen in the tracker.



Hadron detection

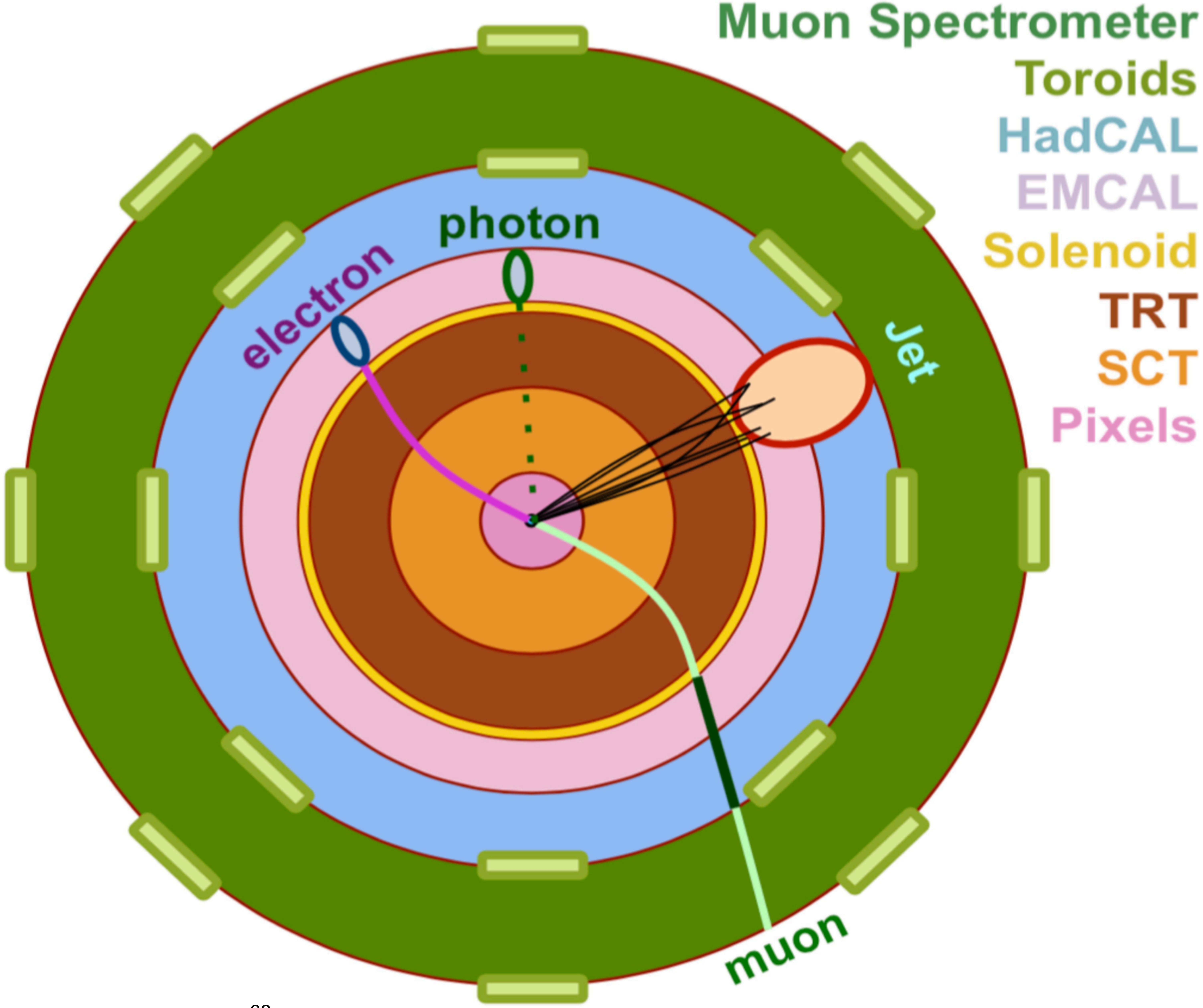
- Charged hadrons are seen in the tracker
- All hadrons are seen in the EMCal + HadCal



Jets

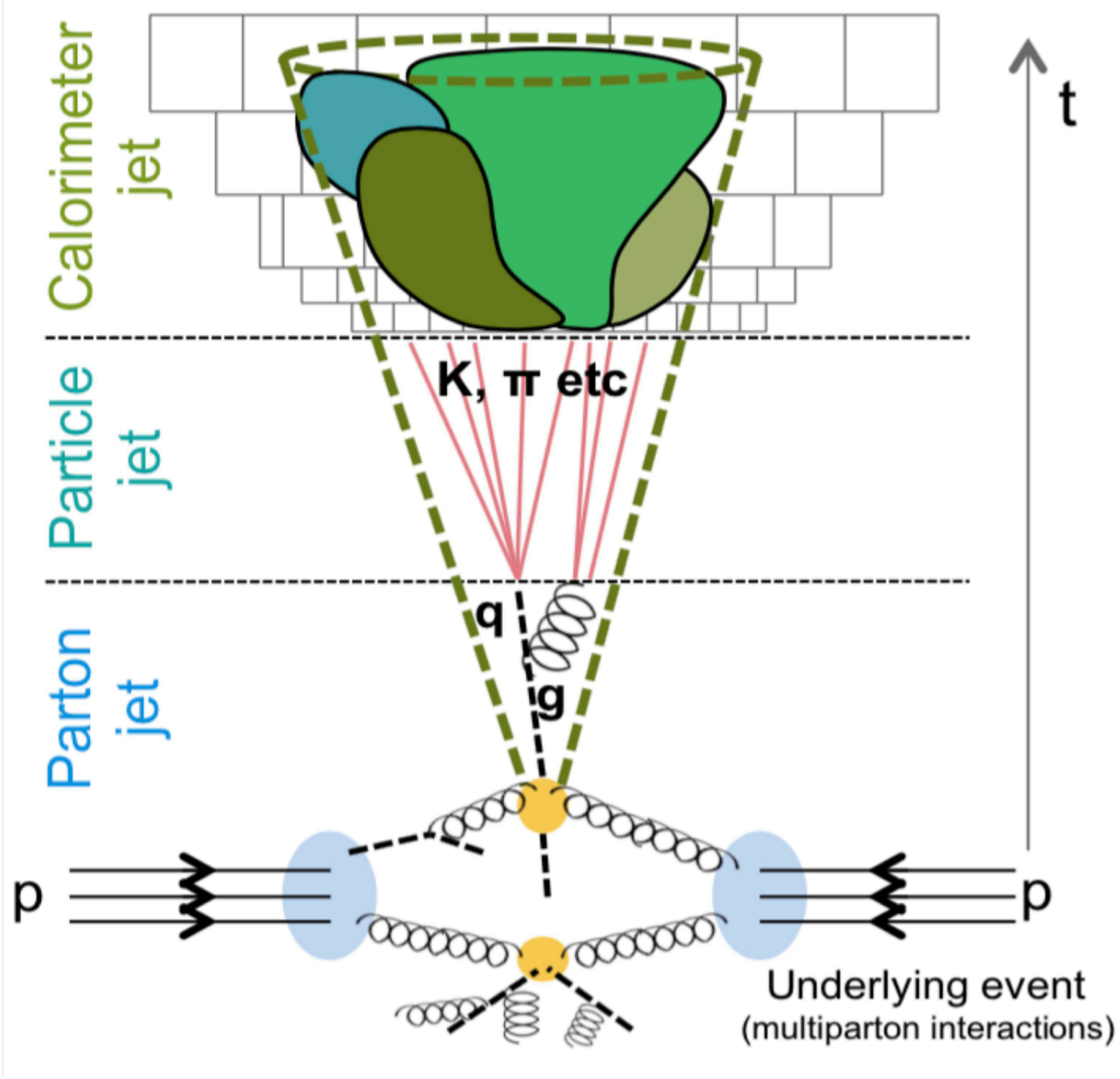
- A complex object that we have to deal with in experiment
- The confinement does not allow us to see coloured objects.
- In a desperate attempt to cover their naked colour, hot coloured objects create an avalanche of particles that eventually hadronizes.

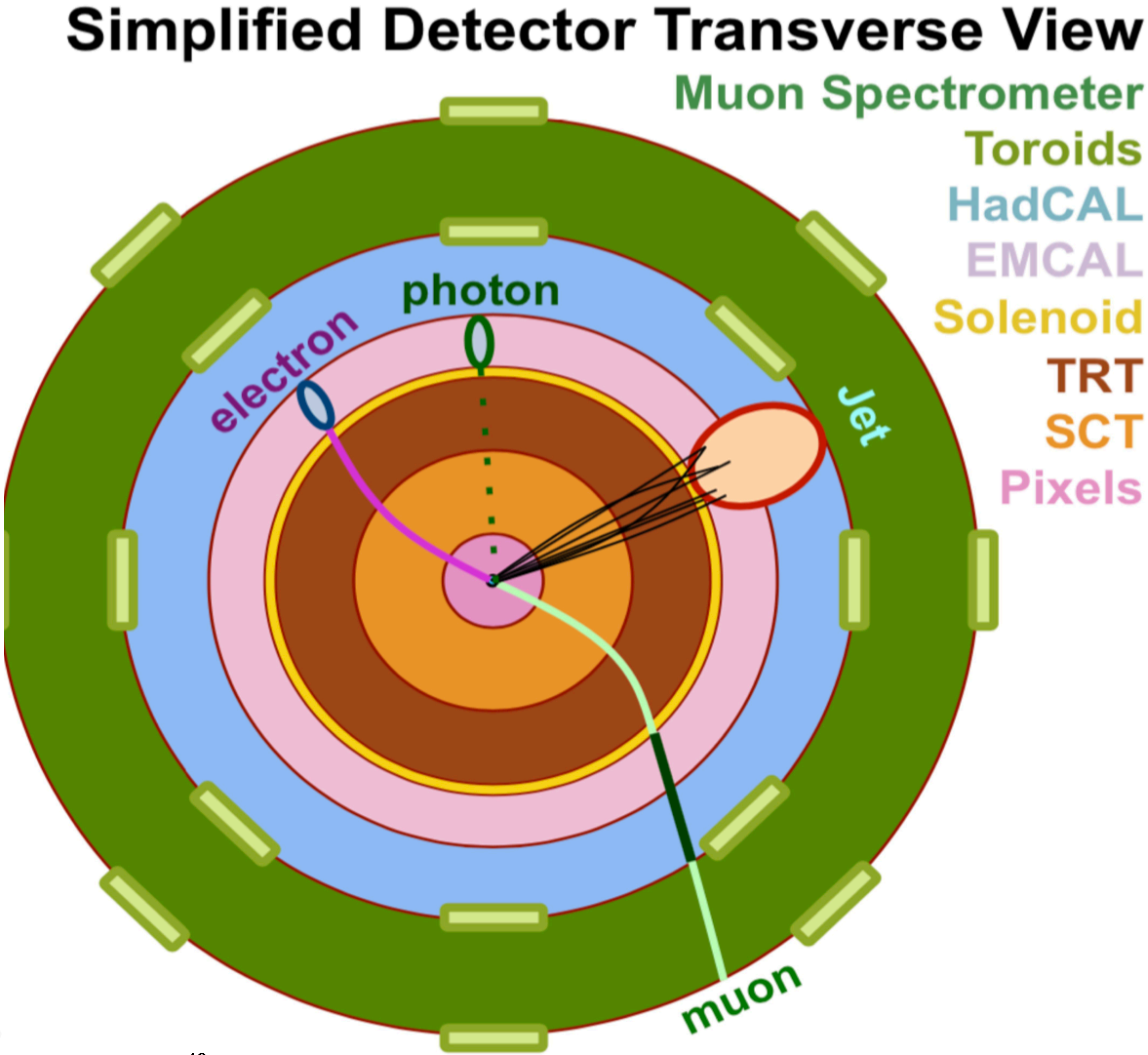
Simplified Detector Transverse View



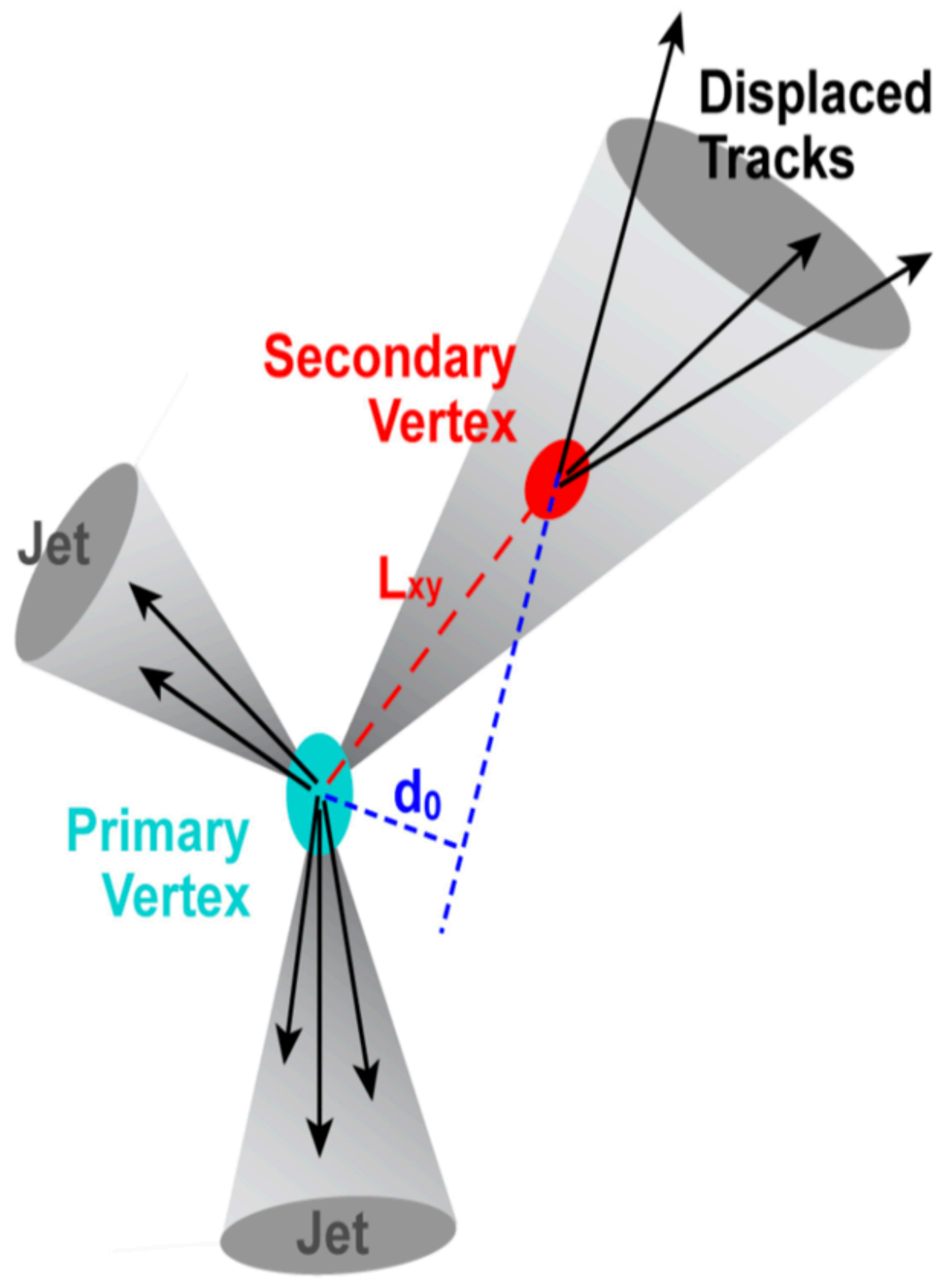
Jets

- In the detector we see a collimated shower of hadrons, leptons and photons



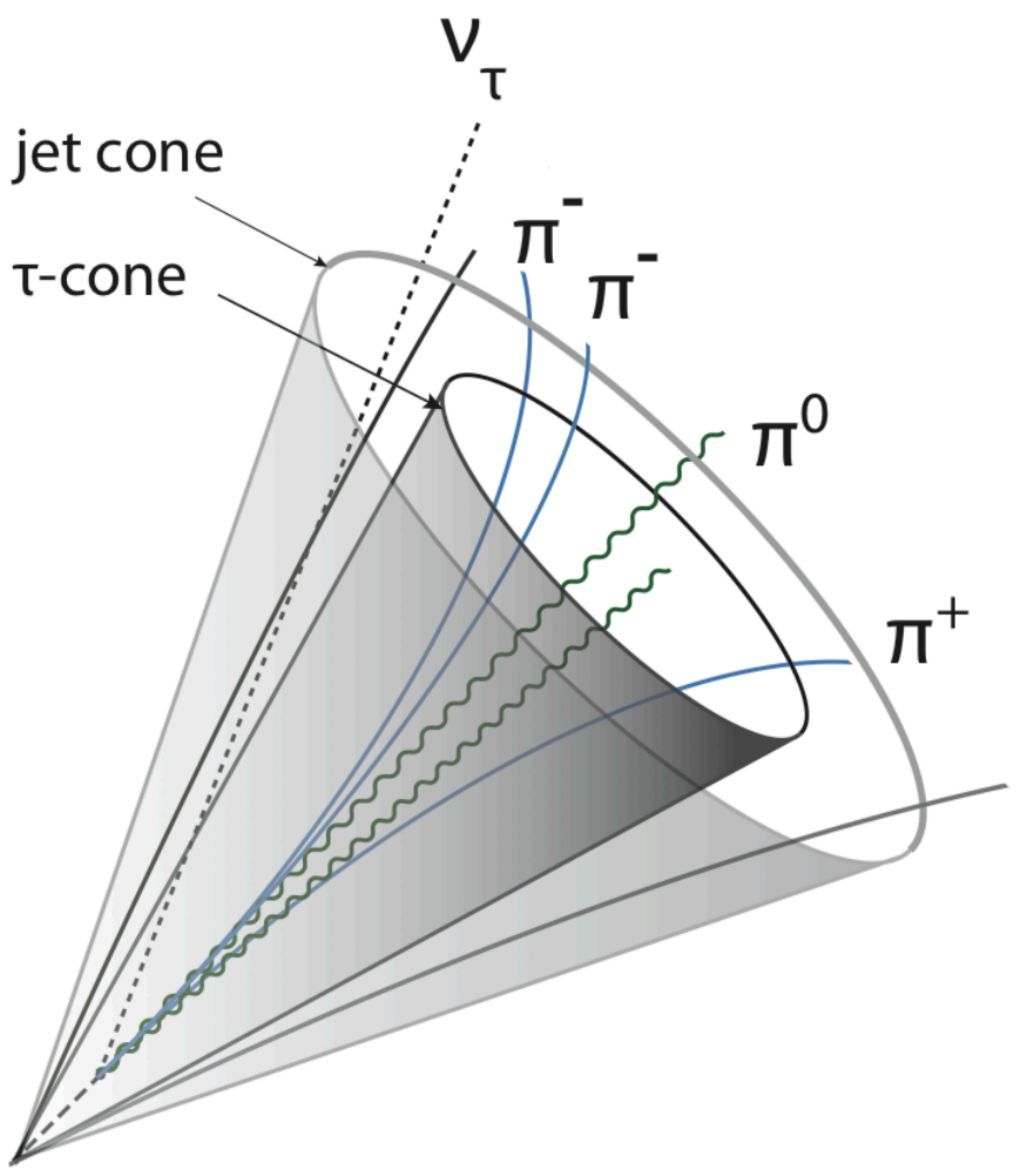


b-quarks



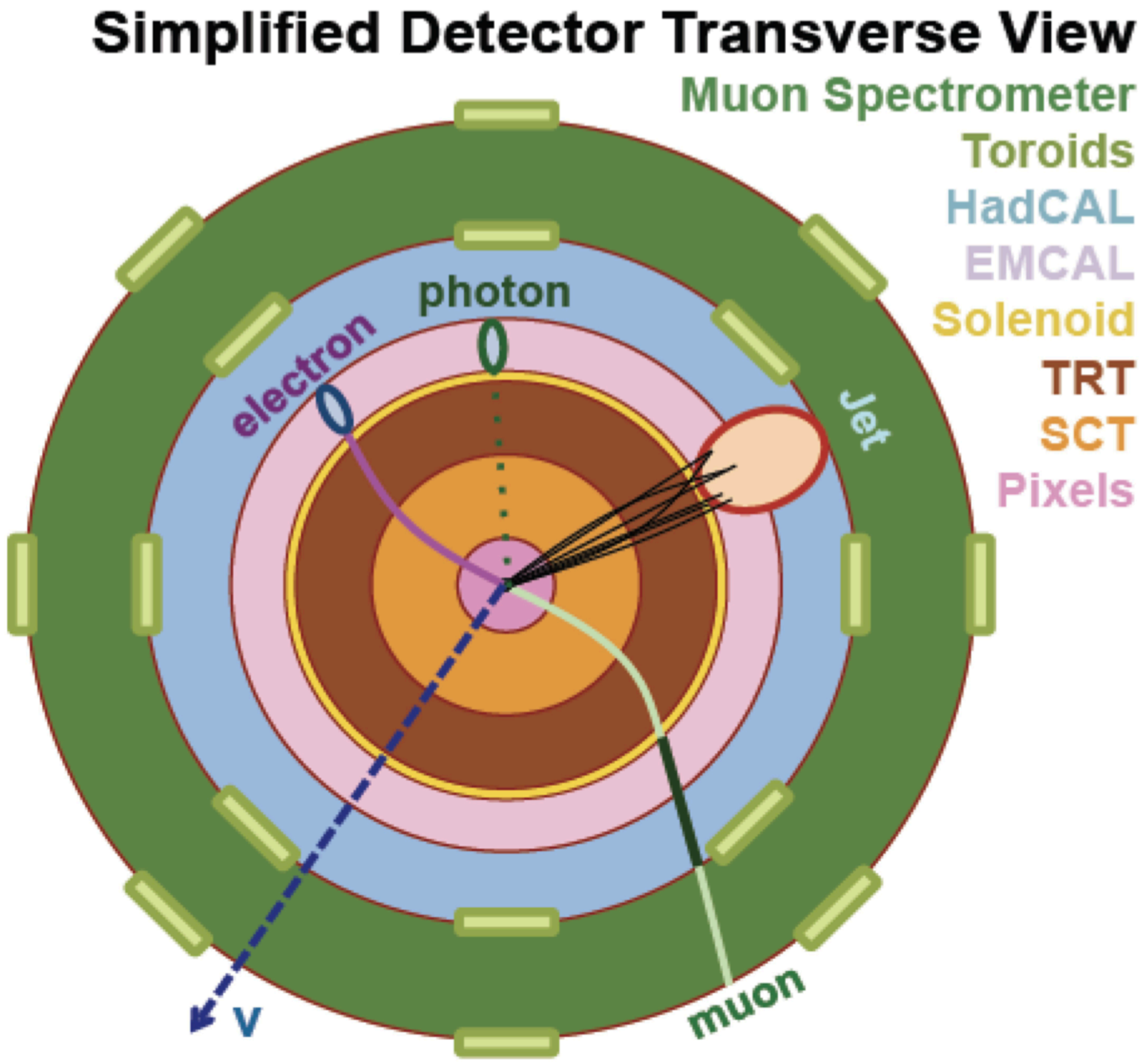
- weak decay of the b-quark is suppressed, so it travels a bit ->displaced vertex
- extremely important for top and Higgs

tau leptons



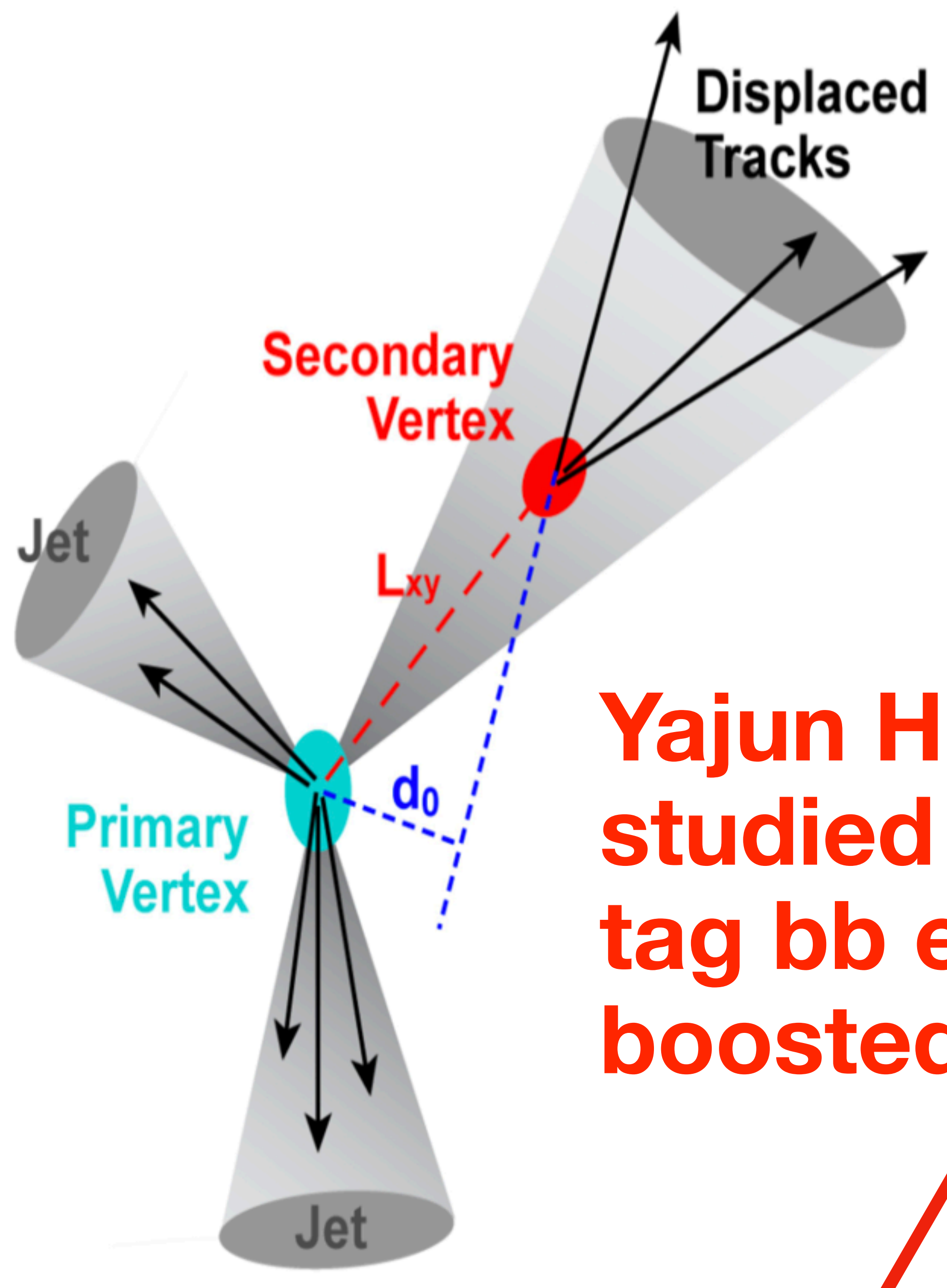
- much heavier than electrons and muons
- decays into a jet, but a smaller one

neutrinos



- neutrinos are invisible
- measured indirectly by computing the missing ET from momentum conservation ($\Sigma p_T = 0$)

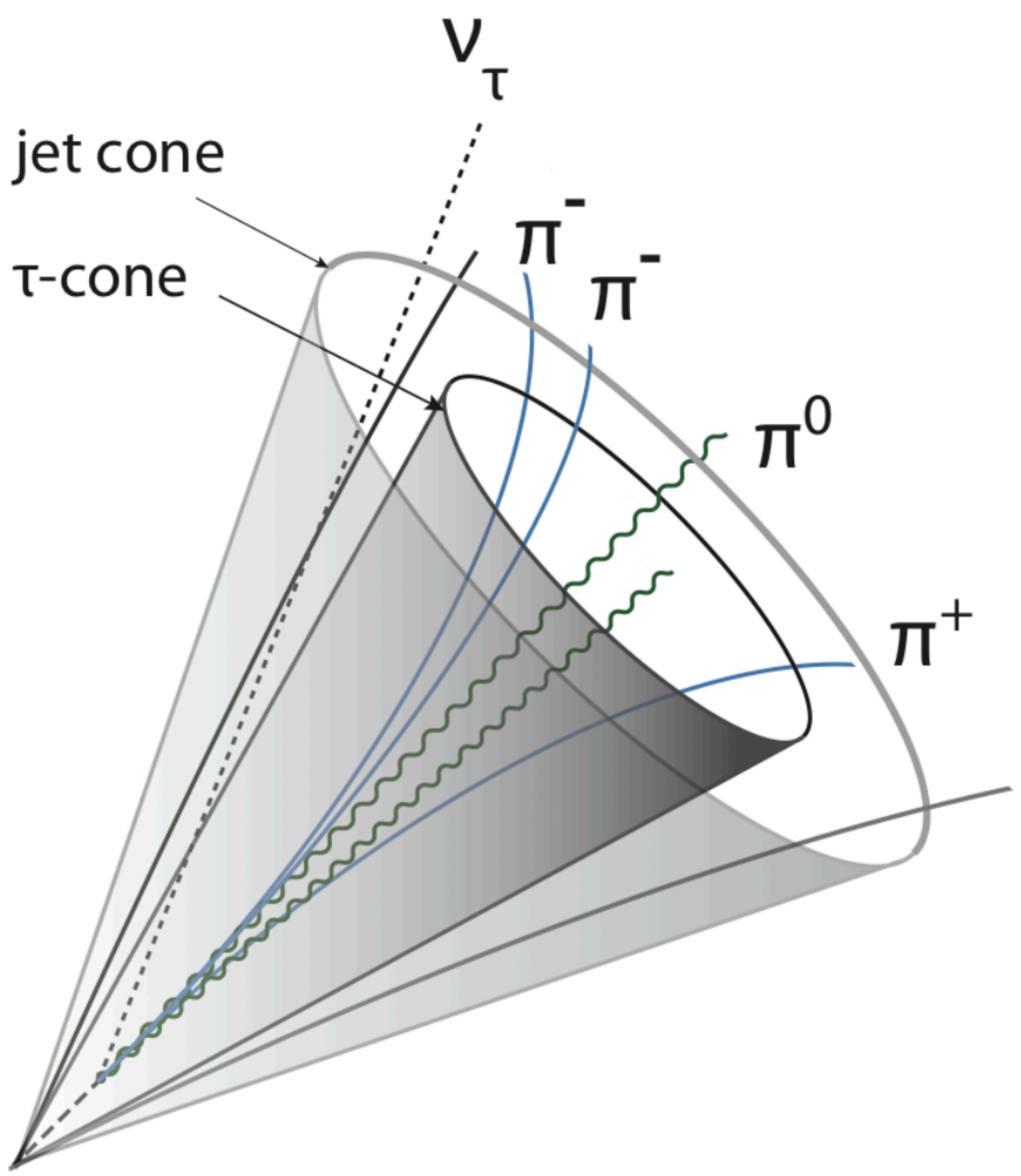
b-quarks



Yajun He has studied the ways to tag bb events in boosted regime

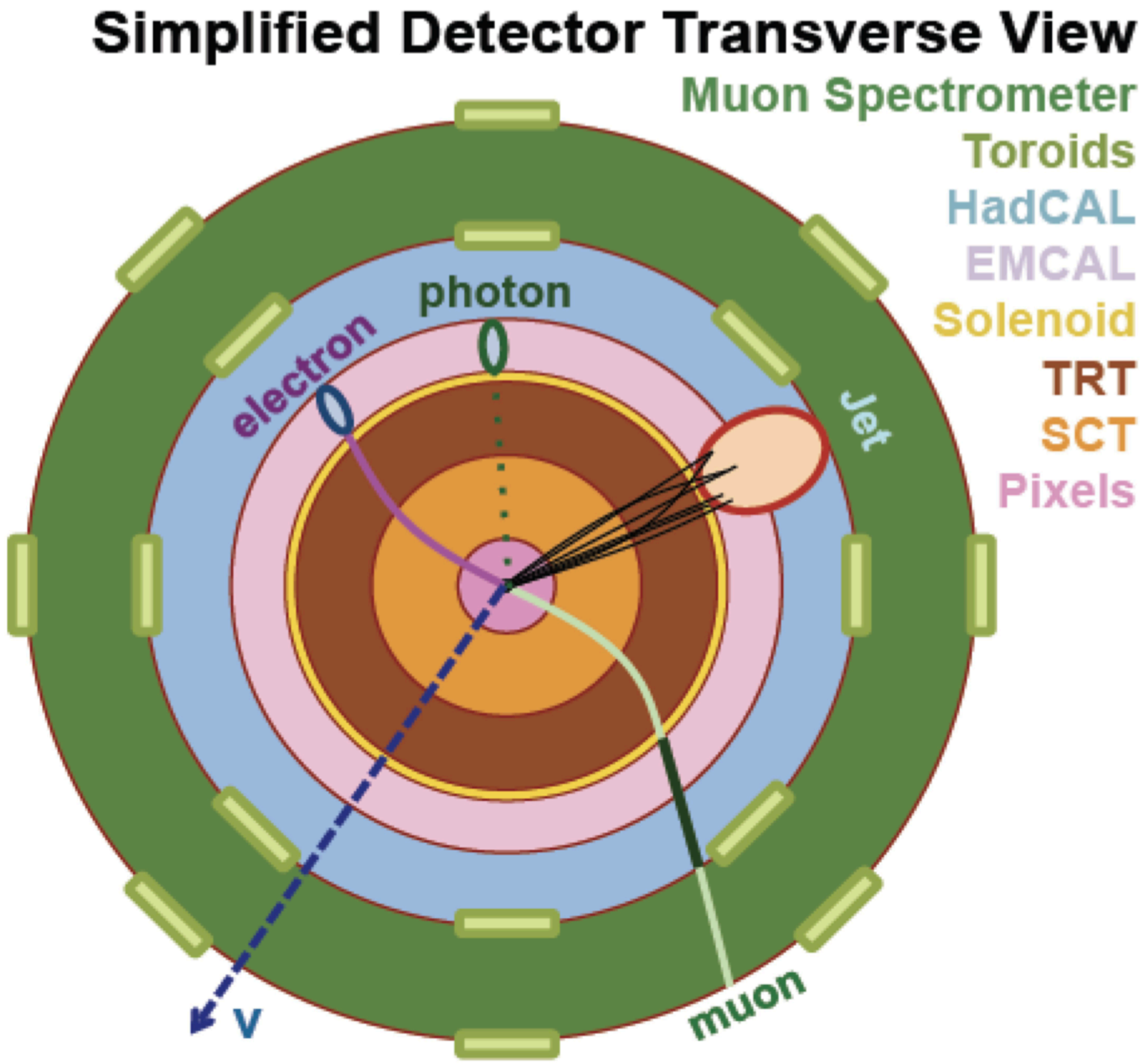
- weak decay of the b-quark is suppressed, so it travels a bit ->displaced vertex
- extremely important for top and Higgs

tau leptons



- much heavier than electrons and muons
- decays into a jet, but a smaller one

neutrinos



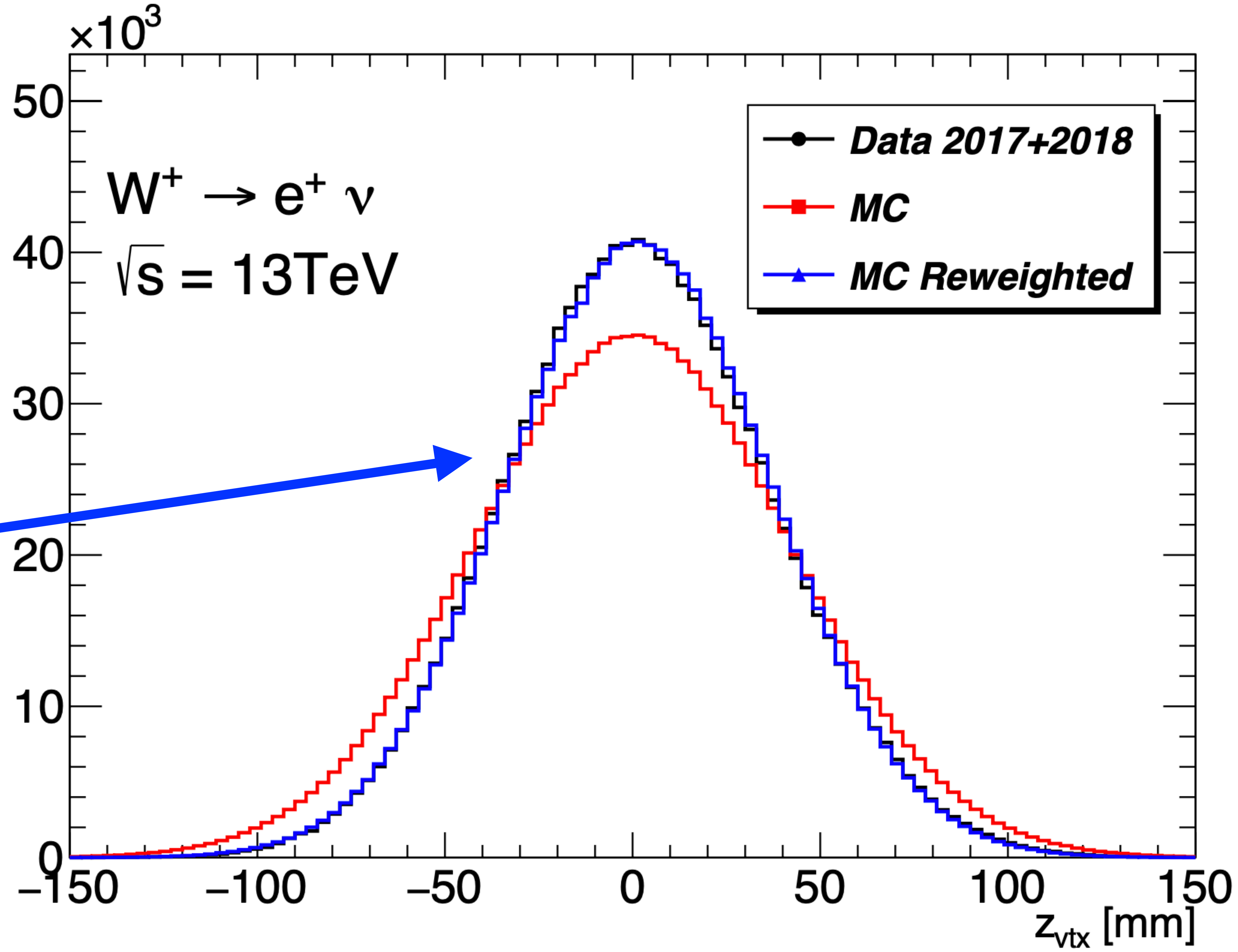
- neutrinos are invisible
- measured indirectly by computing the missing ET from momentum conservation ($\Sigma p_T = 0$)

Monte-Carlo calibration

Everyday routine of the LHC analysers

- Modern MC generators encode the best of our theoretical knowledge, calculated to incredible precision
- The detector and its interaction with generated particles is modelled very well
- Residual inconsistencies remain
- Corrected via data-driven corrections

Typical (and simple) situation:
the Z vertex position distribution is not modelled properly.
We derive corrections from the data and set the distribution right.



Monte-Carlo calibration

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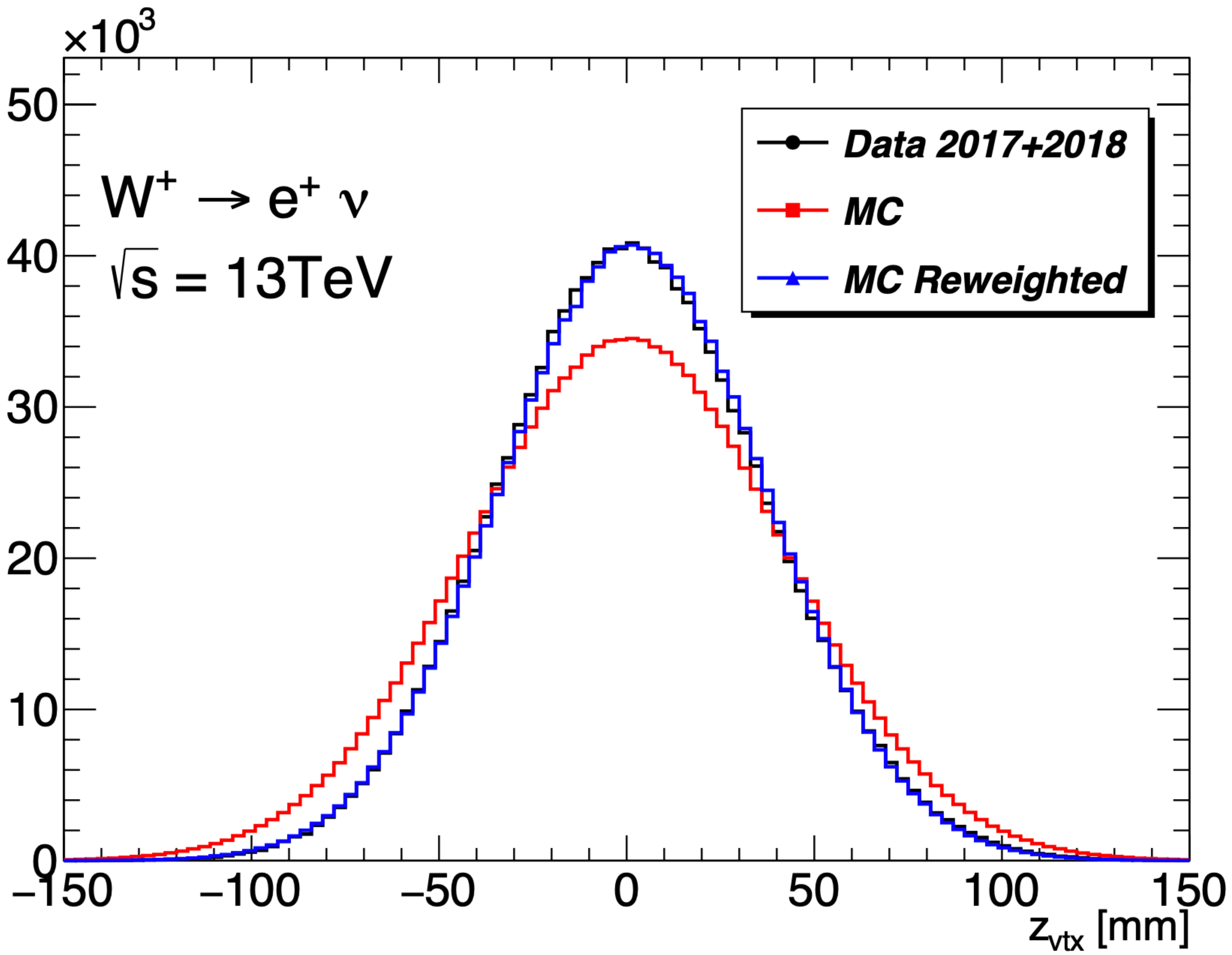
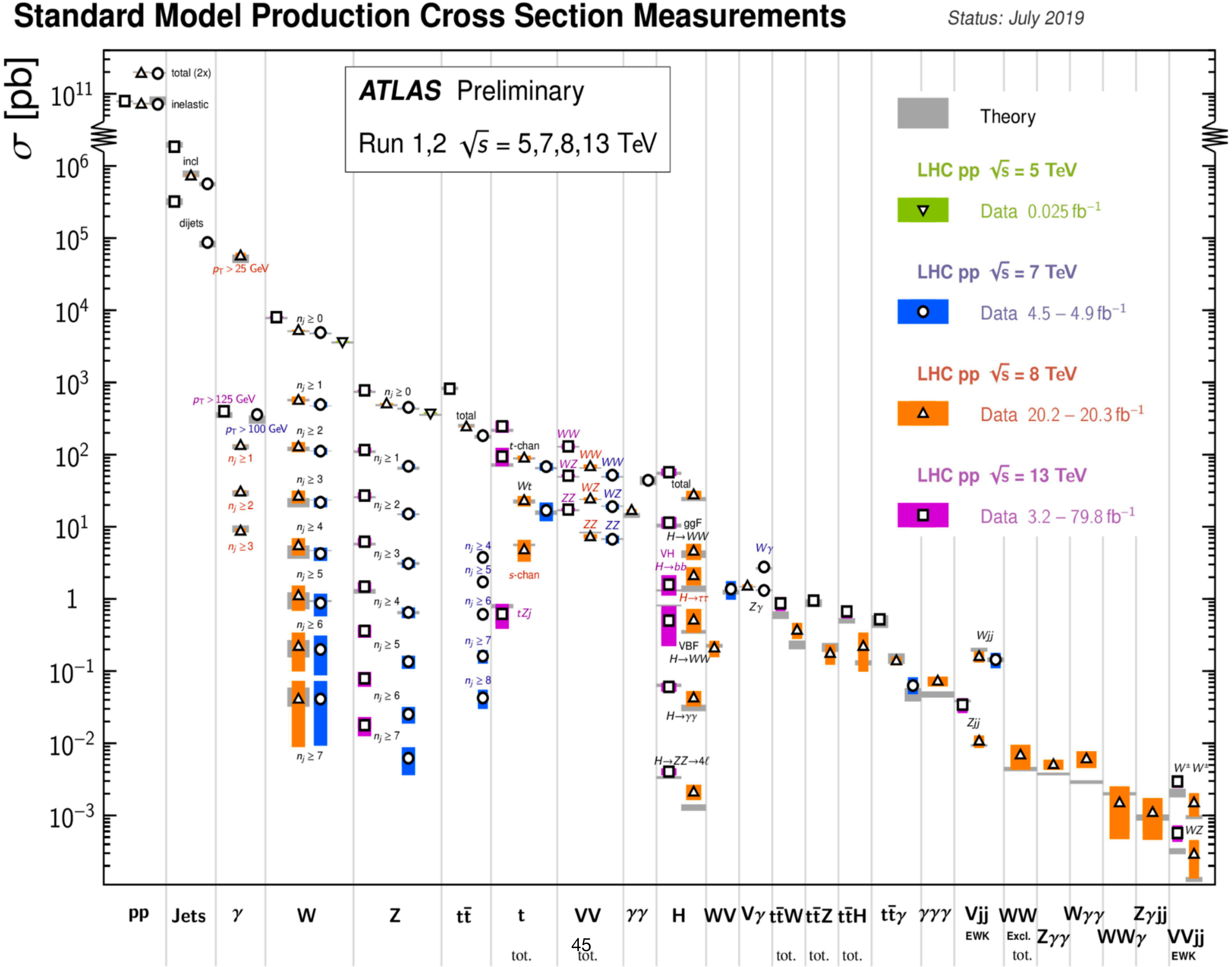
Juan Salvador TAFOYA VARGAS knows how to correct electron energies in the EMCal

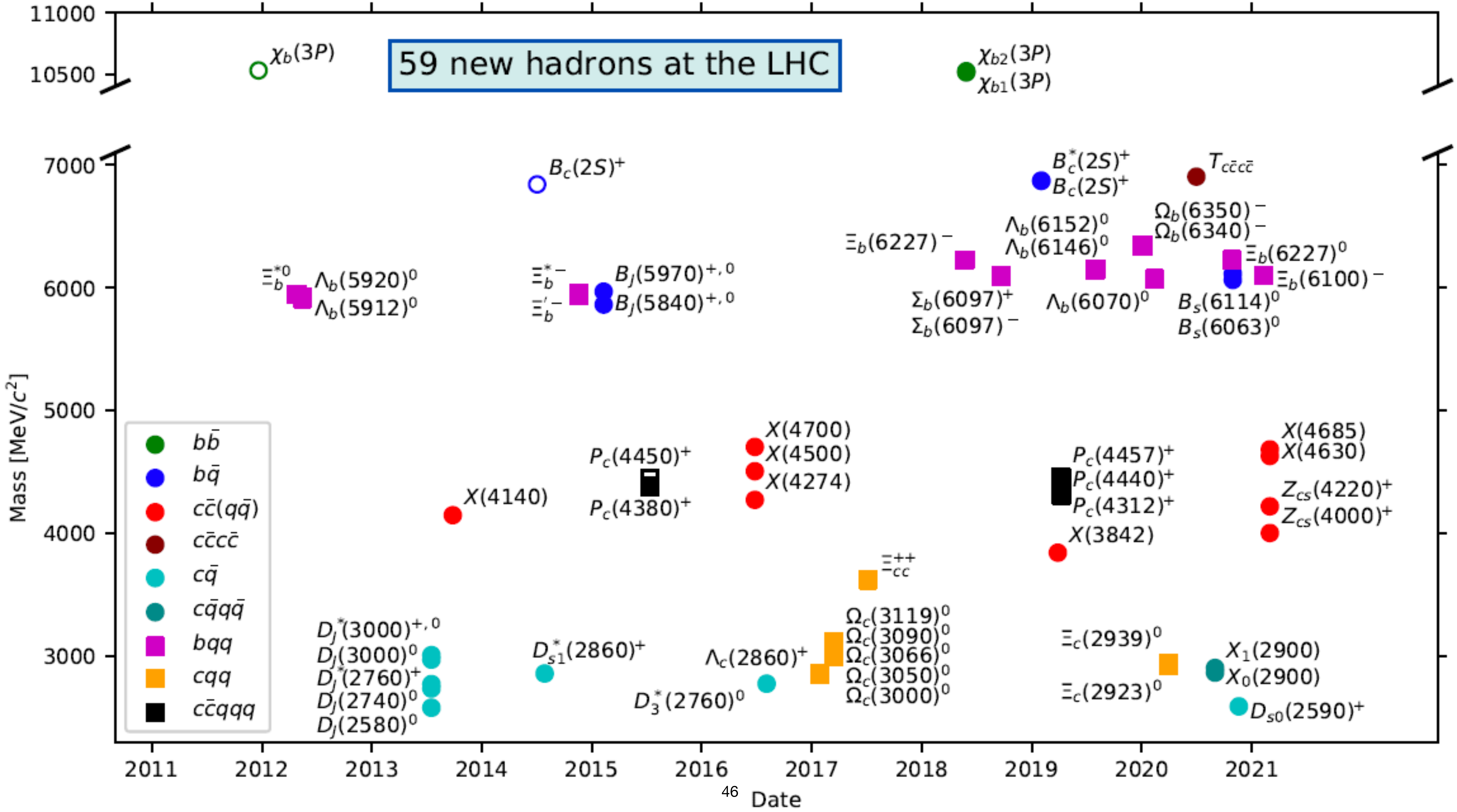
Romain BOUQUET was able to derive b-jet energy scale corrections



So far the SM reigns supreme in the LHC domain



Particle zoo is growing, well domesticated now



Conclusions

- The ball is now on the experimental side (personal opinion)
- Probe the limits of the SM and look beyond - it's up to us
- The upcoming ATLAS/CMS upgrades will push the limits of what can be observed for the SM processes

Most evident sources of improvements

- Even better PDF fits and tunes
- New analysis algorithms (including ML)
- Improved precision of the theoretical predictions/MC

Conclusions

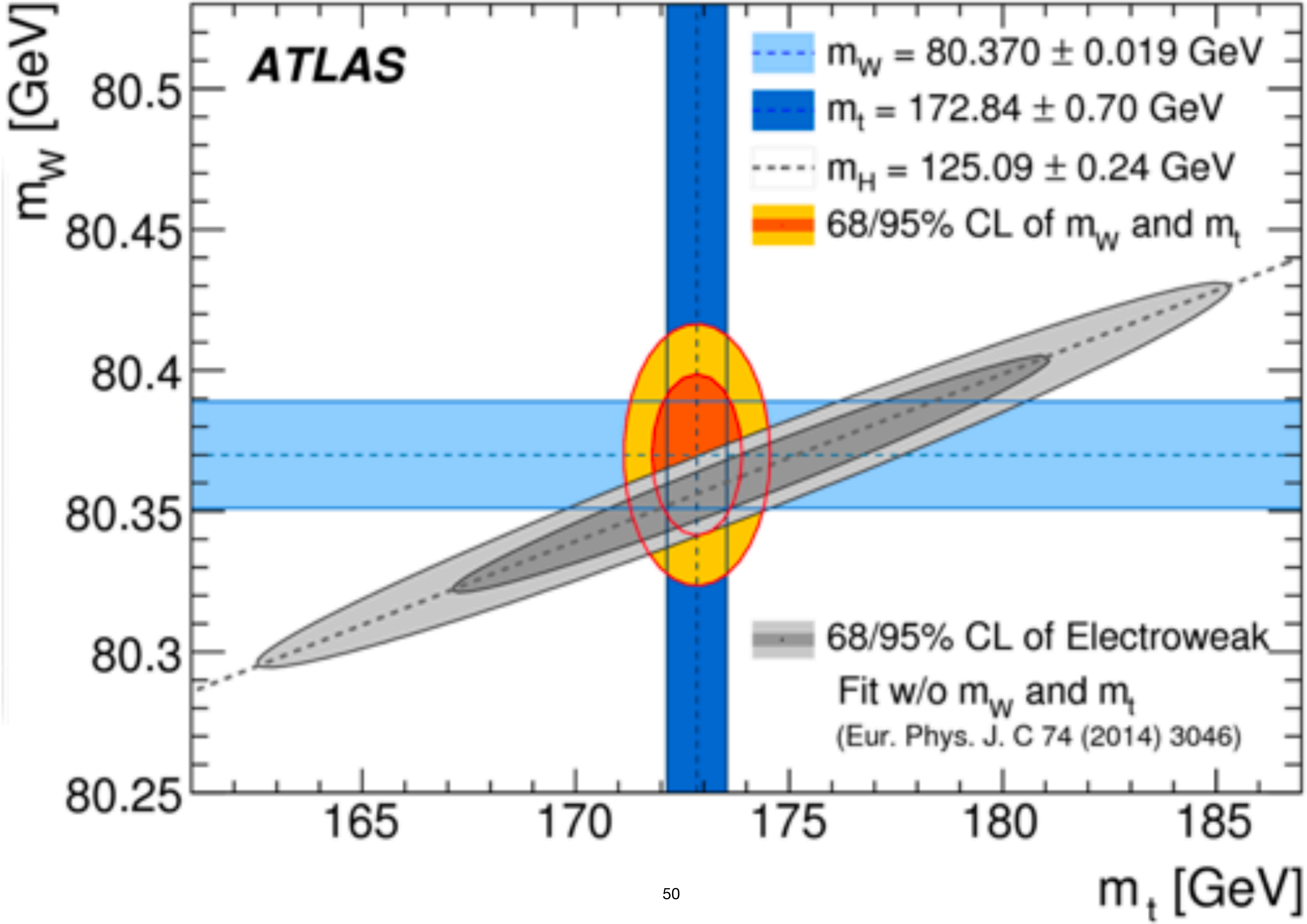
- The ball is now on the experimental side (personal opinion)
- Probe the limits of the SM and look beyond - it's up to us
- The upcoming ATLAS/CMS upgrades will push the limits of what can be observed for the SM processes

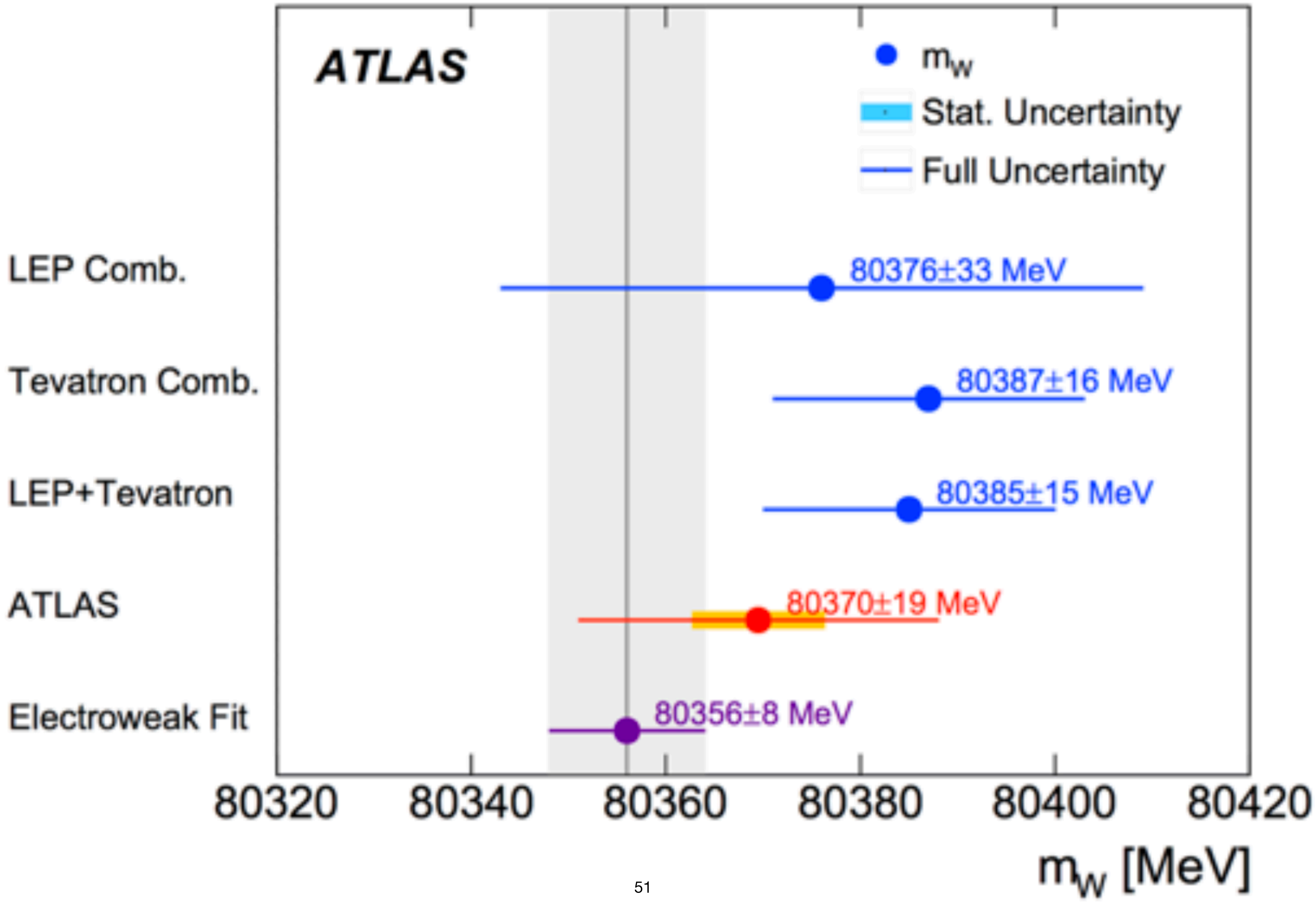
Merci!

Thank you!

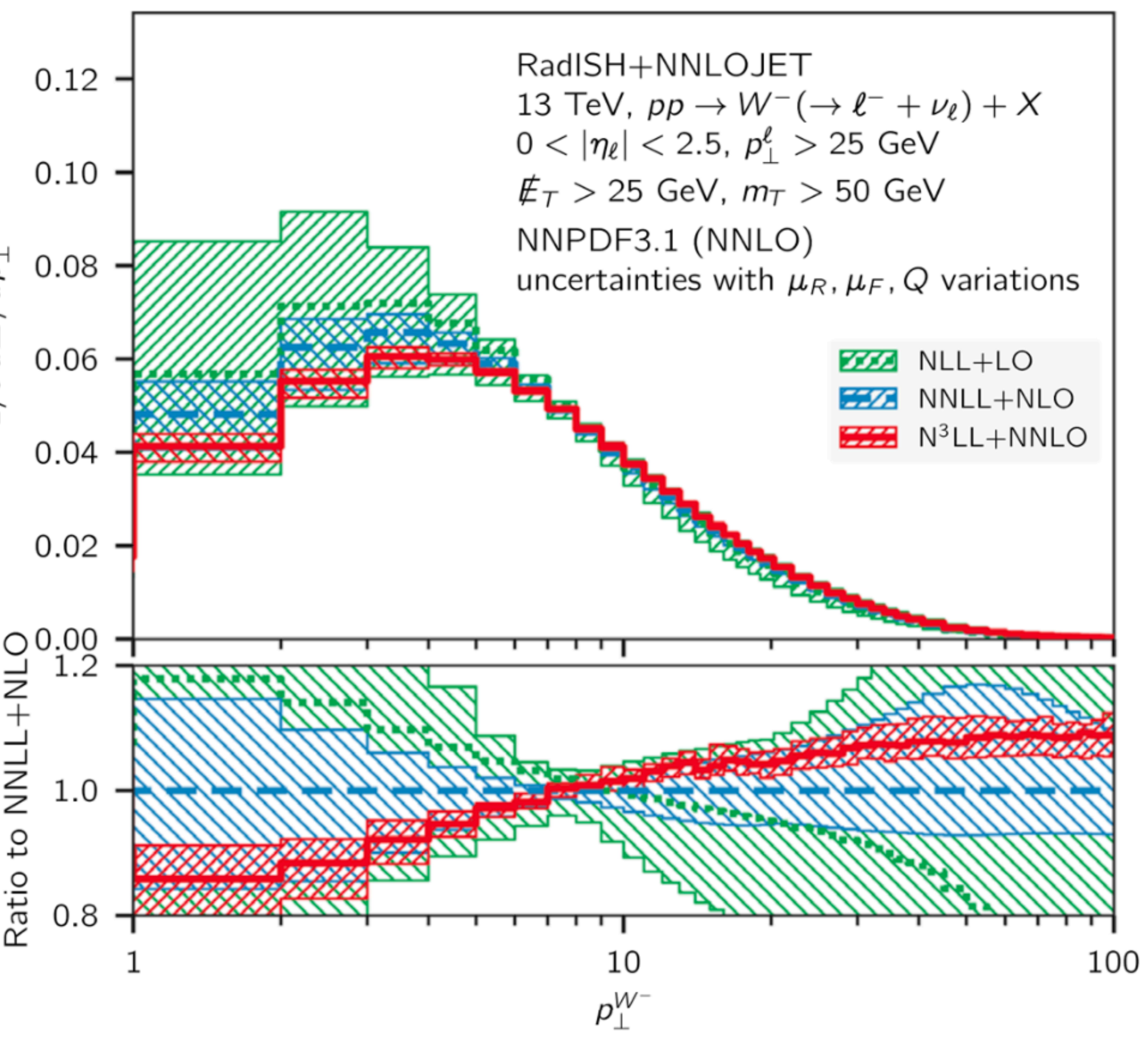
Дякую!

Backup

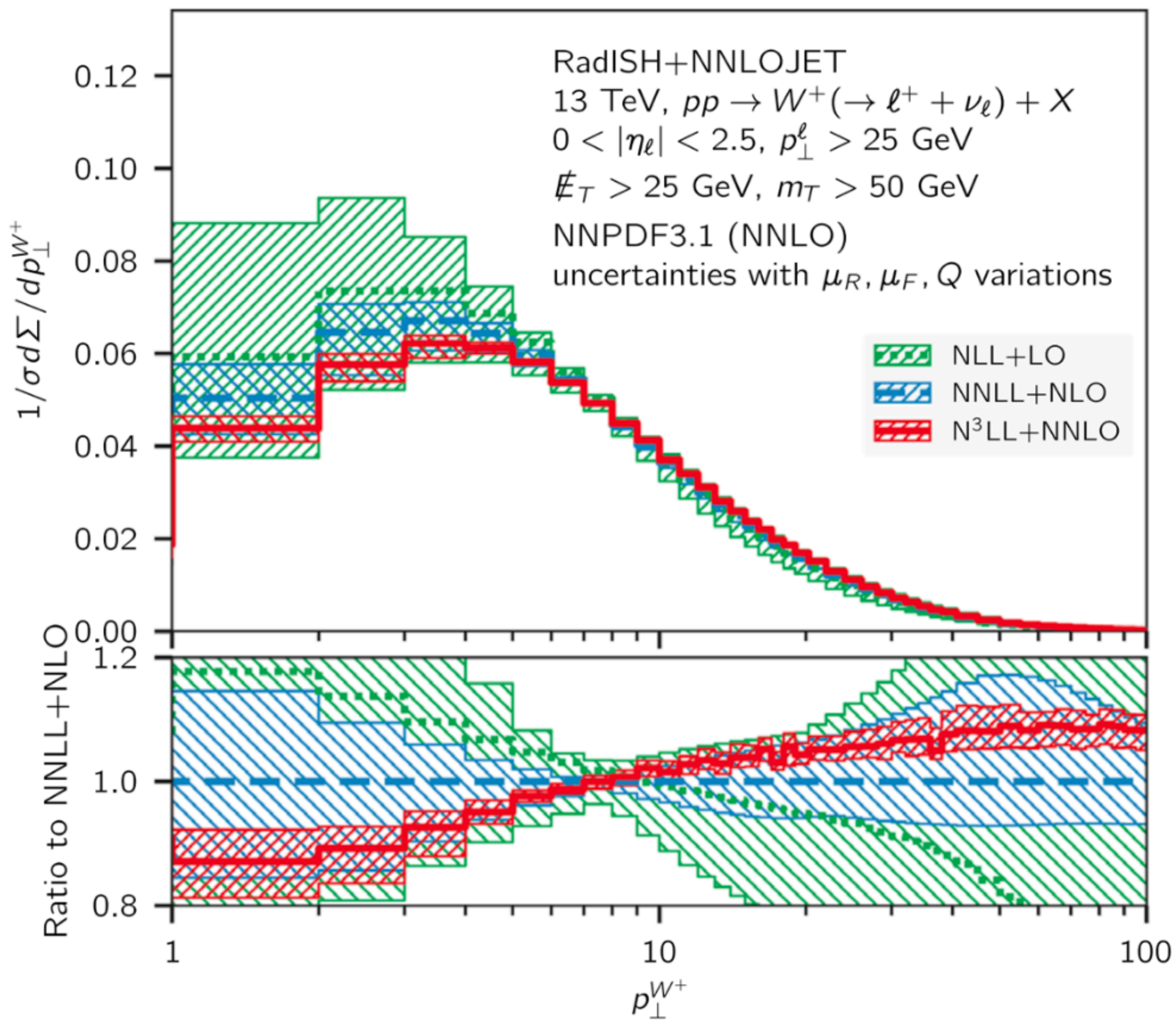

ATLAS
m_W [GeV]
m_t [GeV]
80.25
80.3
80.35
80.4
80.45
80.5
165
170
175
180
185
m_W = 80.370 ± 0.019 GeV
m_t = 172.84 ± 0.70 GeV
m_H = 125.09 ± 0.24 GeV
68/95% CL of m_W and m_t
68/95% CL of Electroweak
Fit w/o m_W and m_t
(Eur. Phys. J. C 74 (2014) 3046)



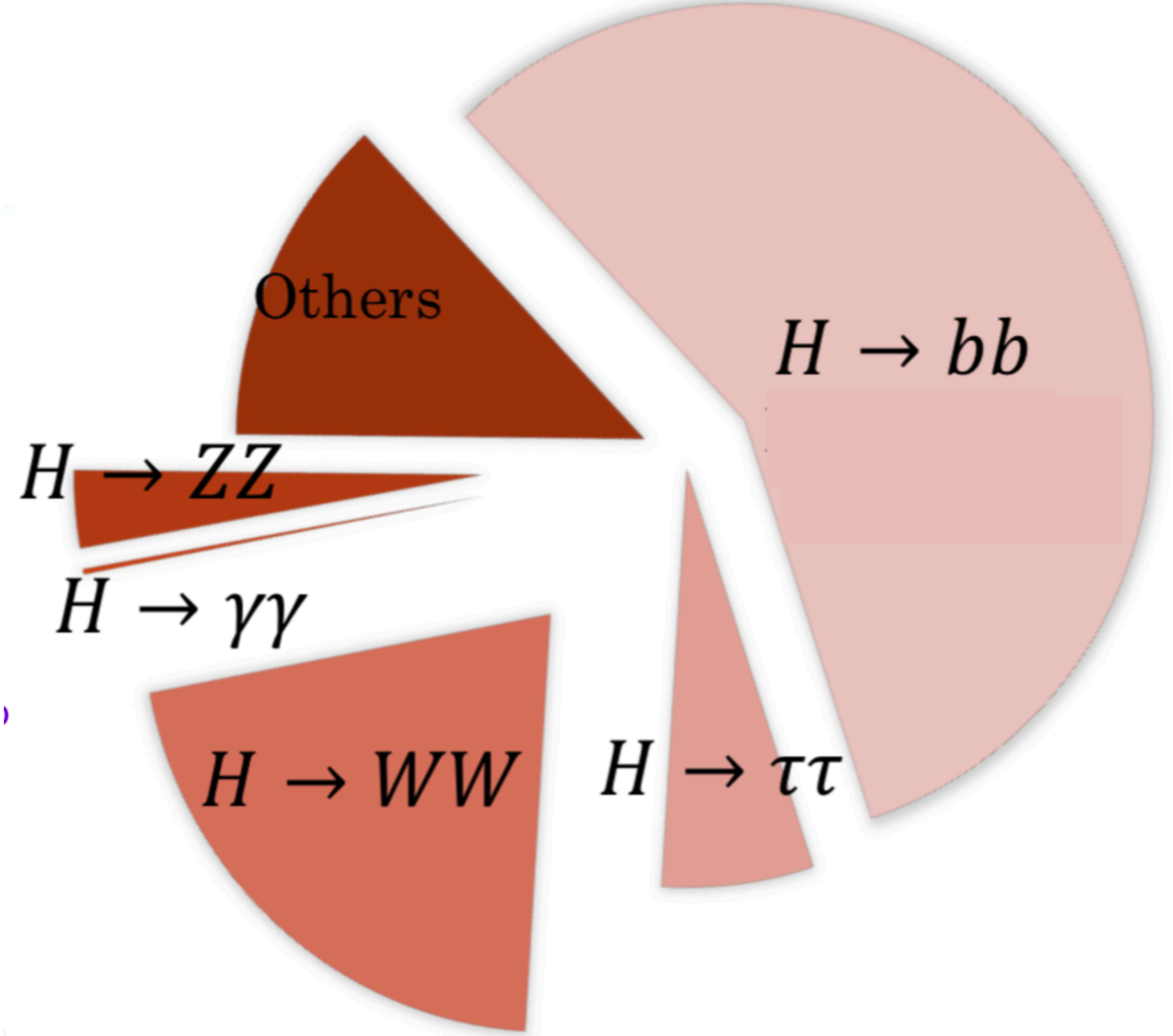
ATLAS
m_W
Stat. Uncertainty
Full Uncertainty
LEP Comb.
80376±33 MeV
Tevatron Comb.
80387±16 MeV
LEP+Tevatron
80385±15 MeV
ATLAS
80370±19 MeV
Electroweak Fit
80356±8 MeV
80320
80340
80360
80380
80400
80420
m_W [MeV]



(a) W^- transverse momentum spectrum [75].



(b) W^+ transverse momentum spectrum [75].



Others
$H \to bb$
$H \to ZZ$
$H \to \gamma\gamma$
$H \to WW$
$H \to \tau\tau$