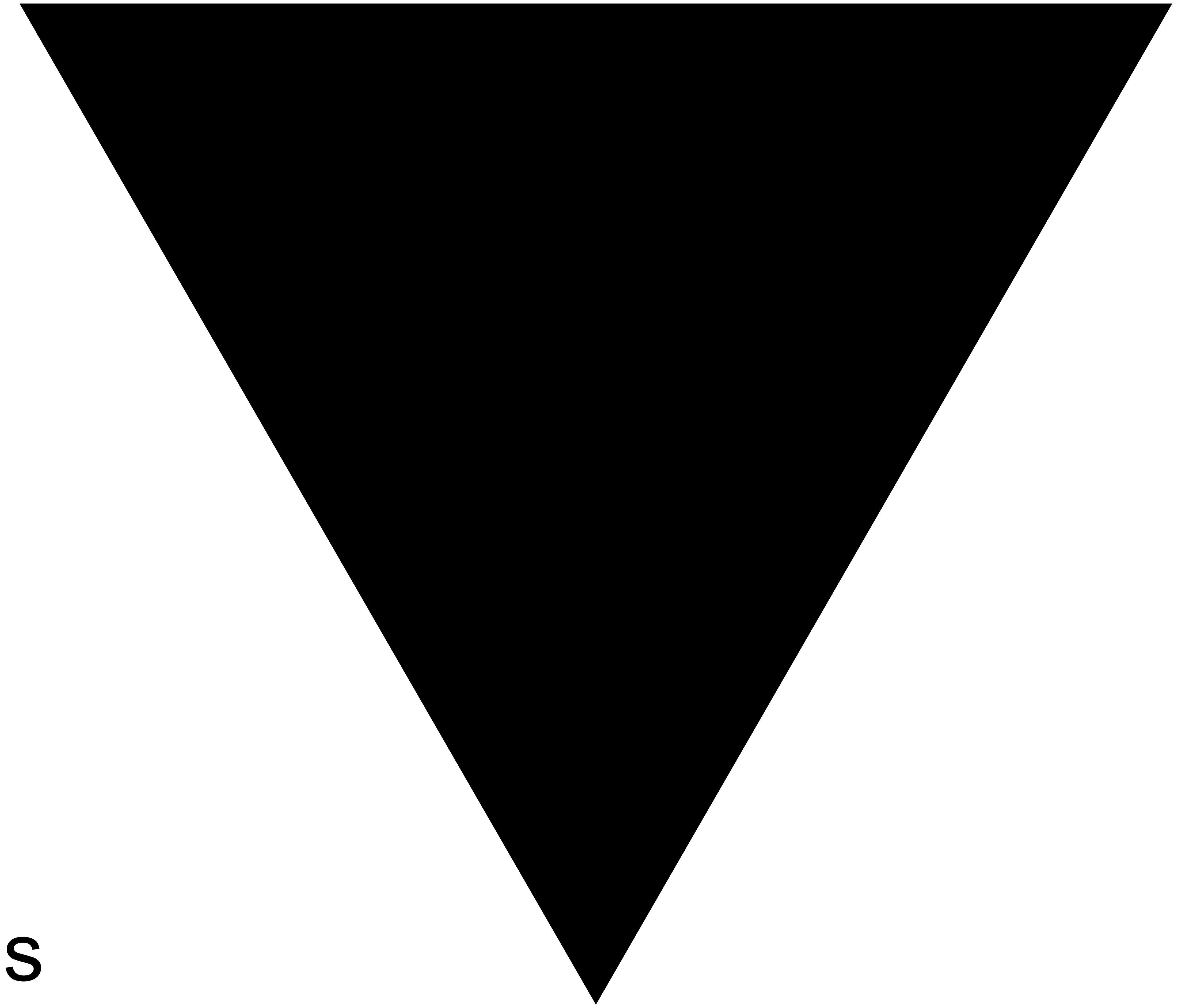
FUTURE ACCELERATORS: A MUON COLLIDER?

Prof. dr. Tristan du Pree
Nikhef Topical Lectures
20 – 22 March 2024

MY PROFESSIONAL LIGHTCONE

2050

Retirement



Start physics studies

2000

MY PROFESSIONAL LIGHTCONE

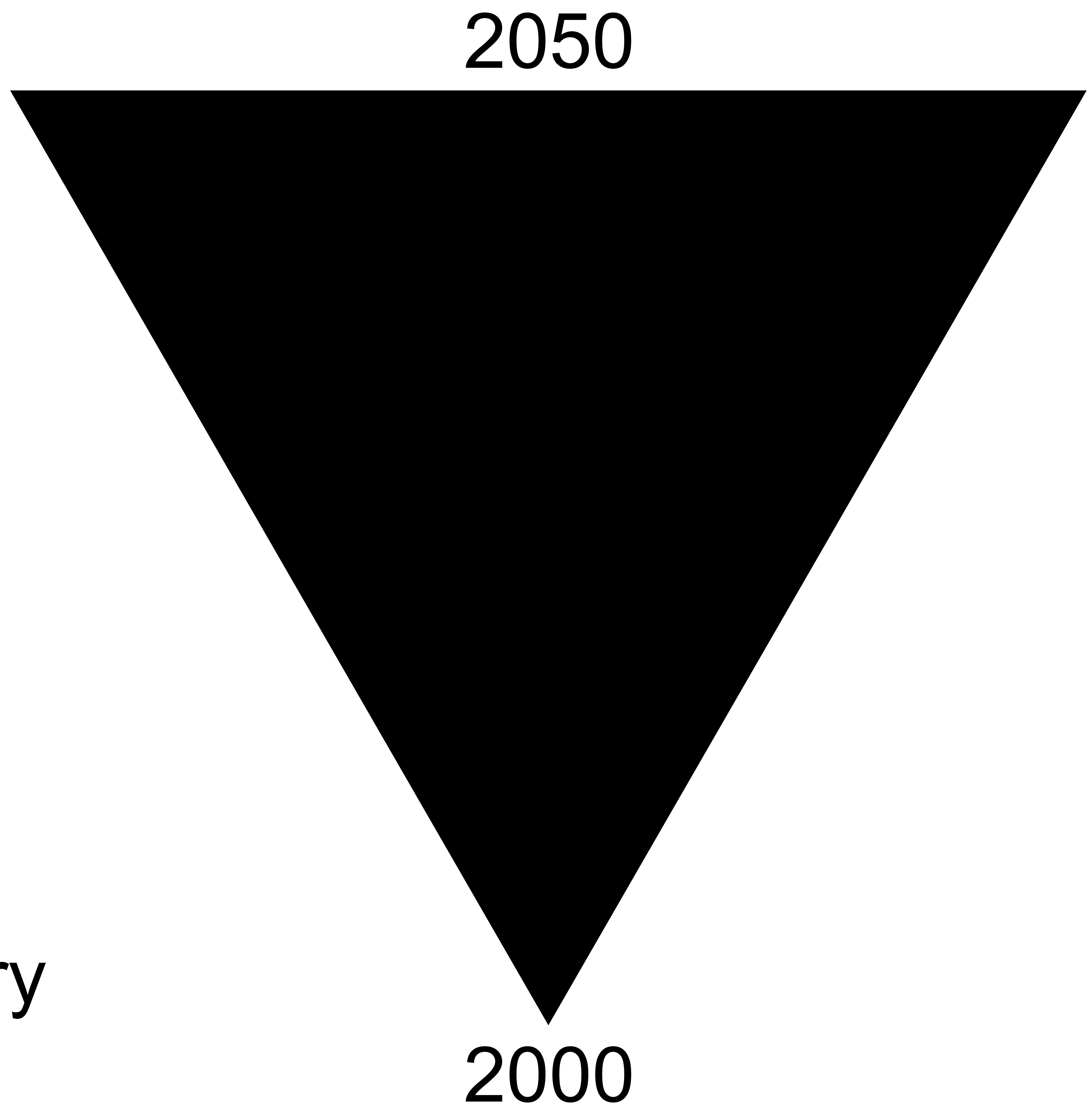
Retirement

2017++ ATLAS

2010-17 PD CMS

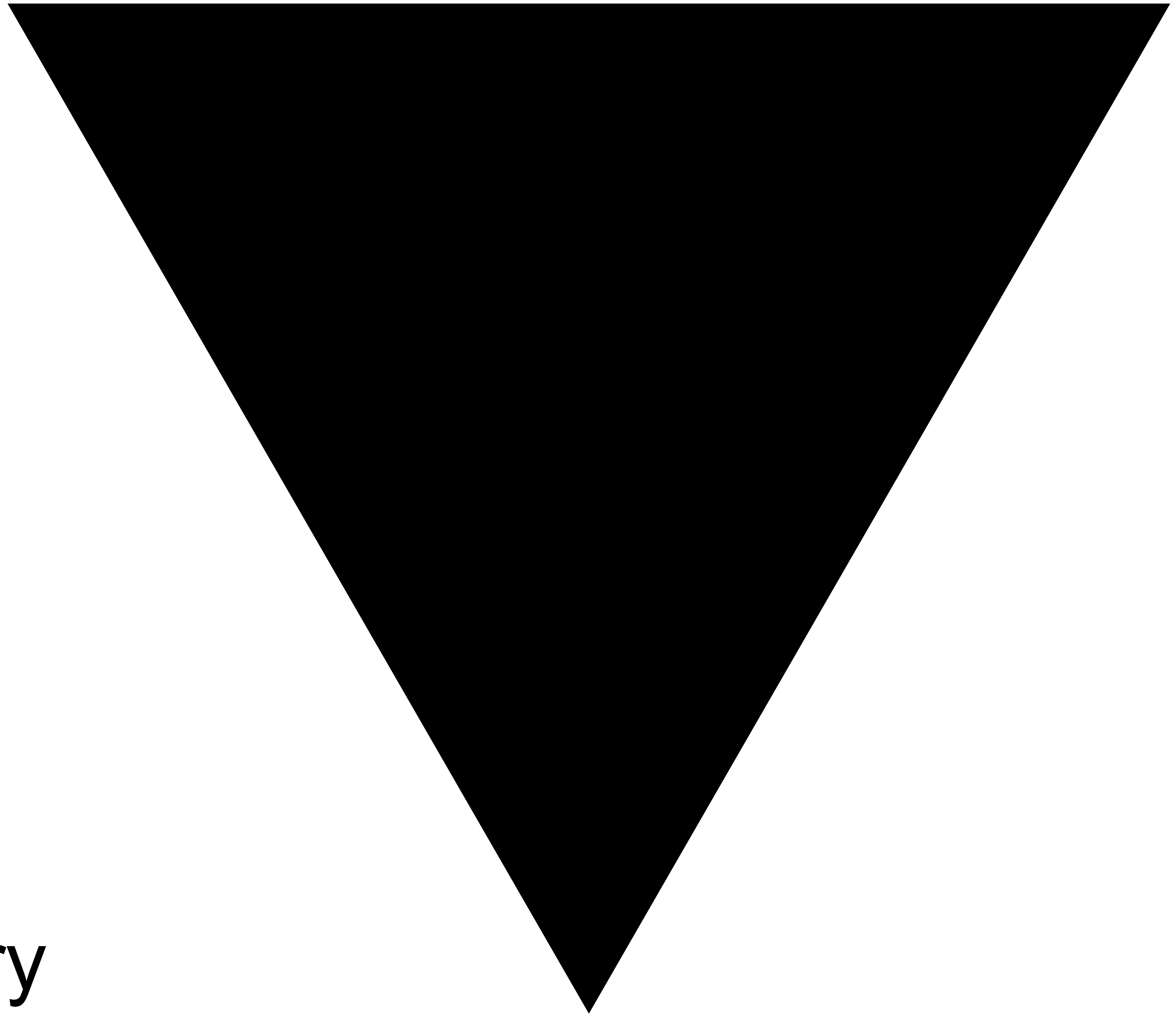
2006-10 PhD LHCb

2000-05 MSc Theory



MY PROFESSIONAL LIGHTCONE

2050



2000

Retirement

2017++ ATLAS

2010-17 PD CMS

2006-10 PhD LHCb

2000-05 MSc Theory

New collider?

2022 C^3

2020 MuCol

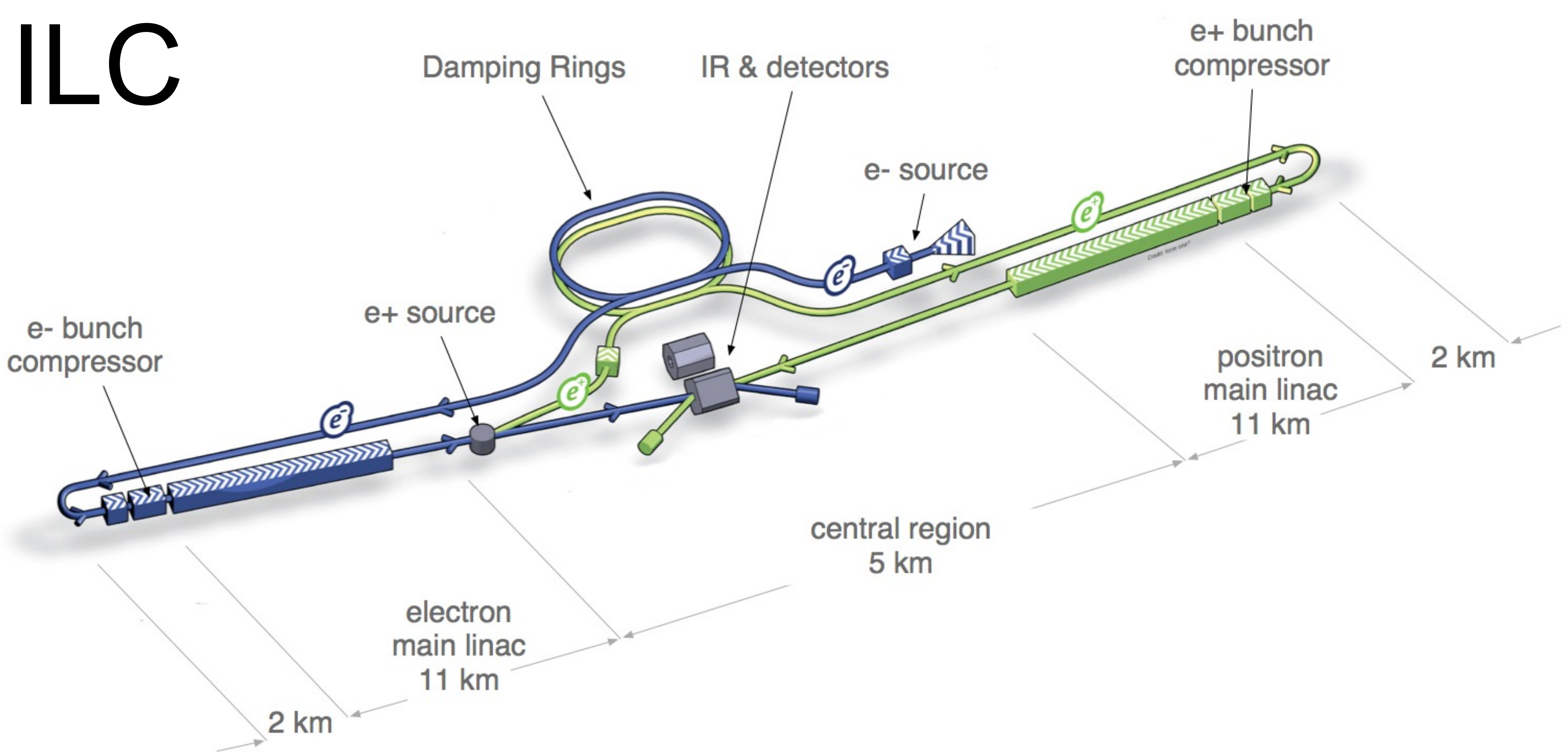
2017 FCC report

2013 ILC cand.site

2008 Start of the LHC

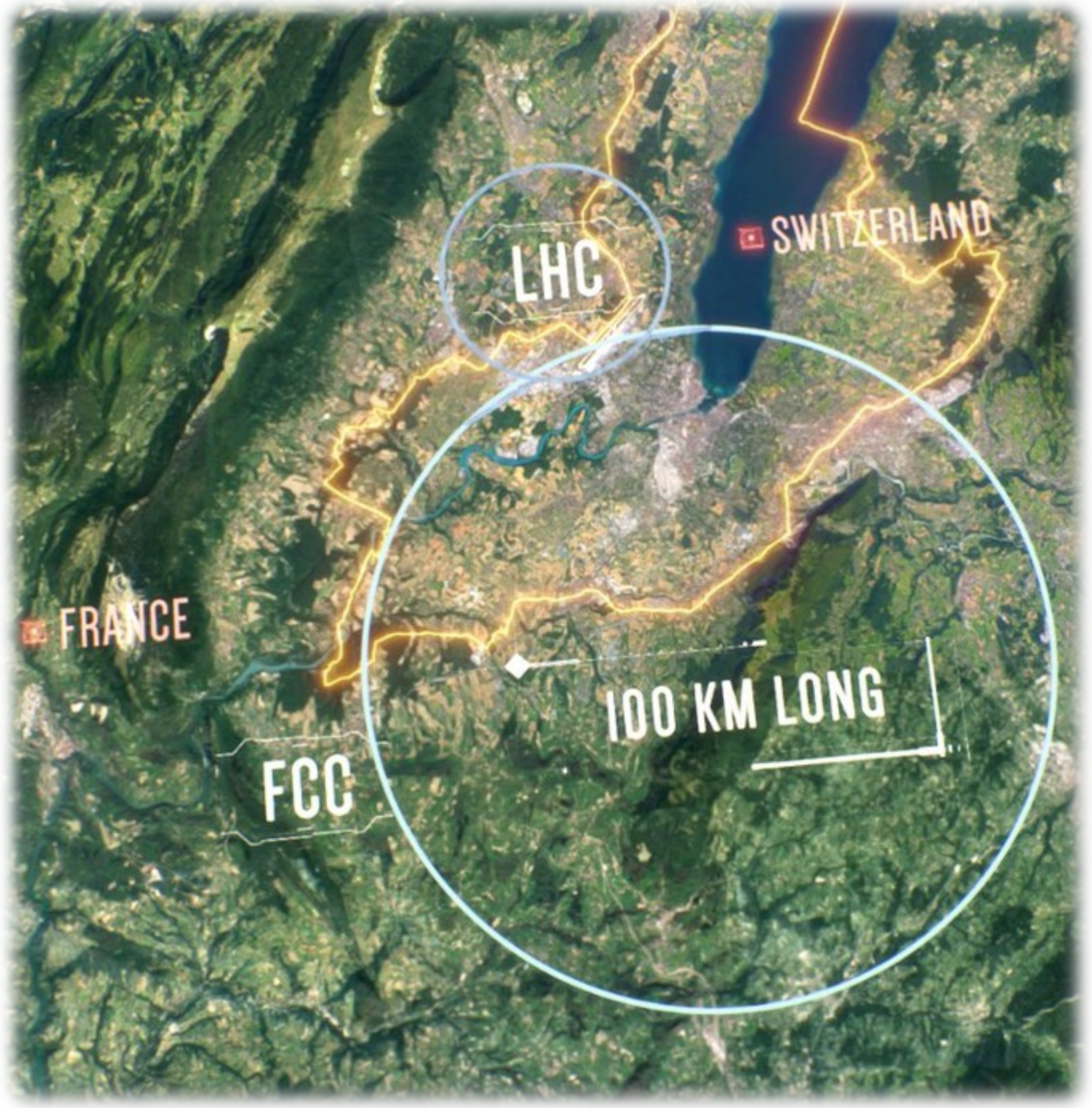
MY ACTIVITIES

ILC



2013: Site visit

FCC



2017: Yellow report co-author
2021-23: FCC national contact

C^3

2022+: Accelerator alignment R&D

Muon Collider

2020+: Enthusiastic co-author

MY PLAN FOR THE NEXT 1.5 HOURS

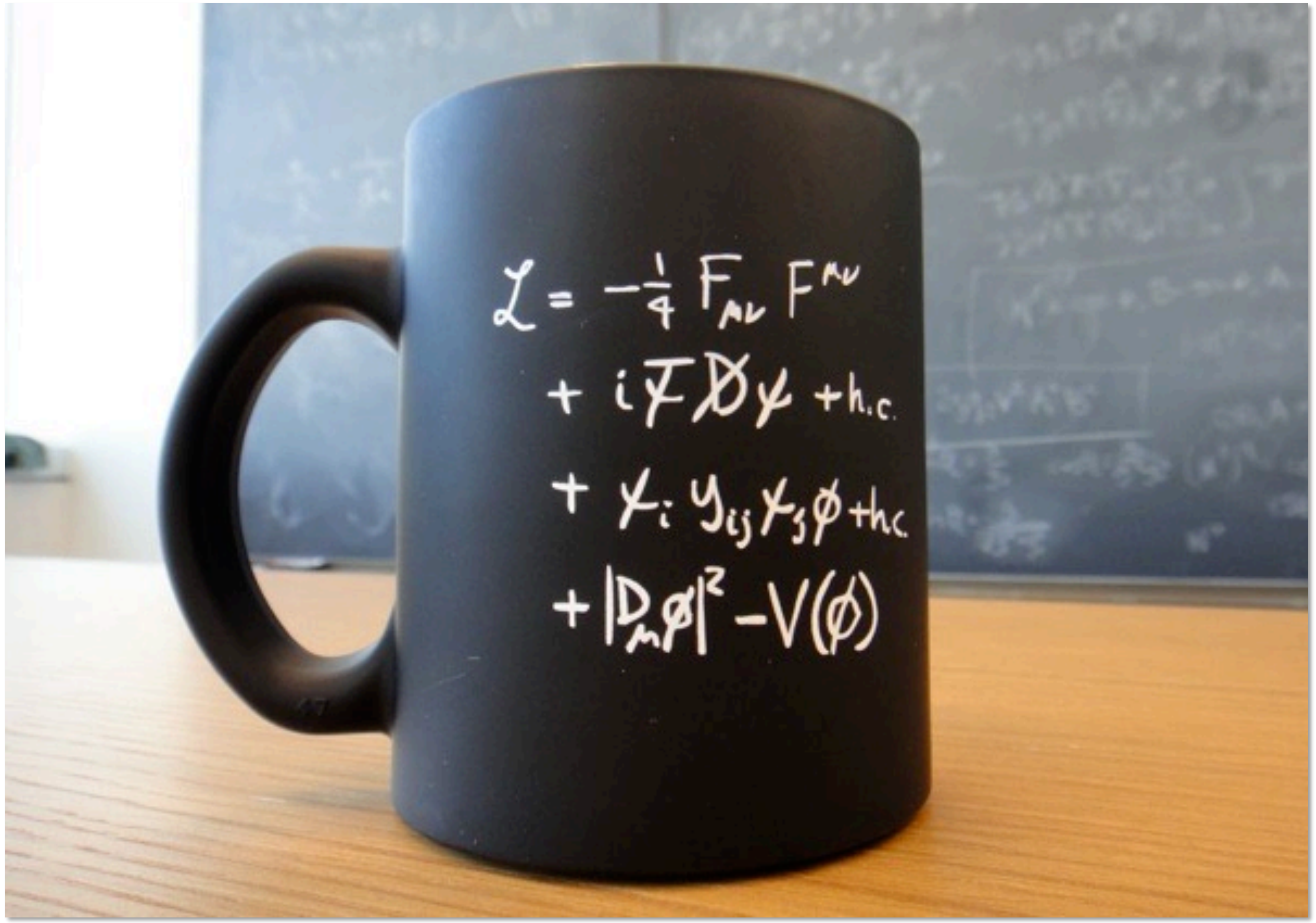
Give you motivation for future accelerators

- Inspire you to be enthusiastic
  - For any next particle collider
- Give you some information
  - So you know the options
- Explain a bit about muon colliders
  - And the pros/cons of other proposals

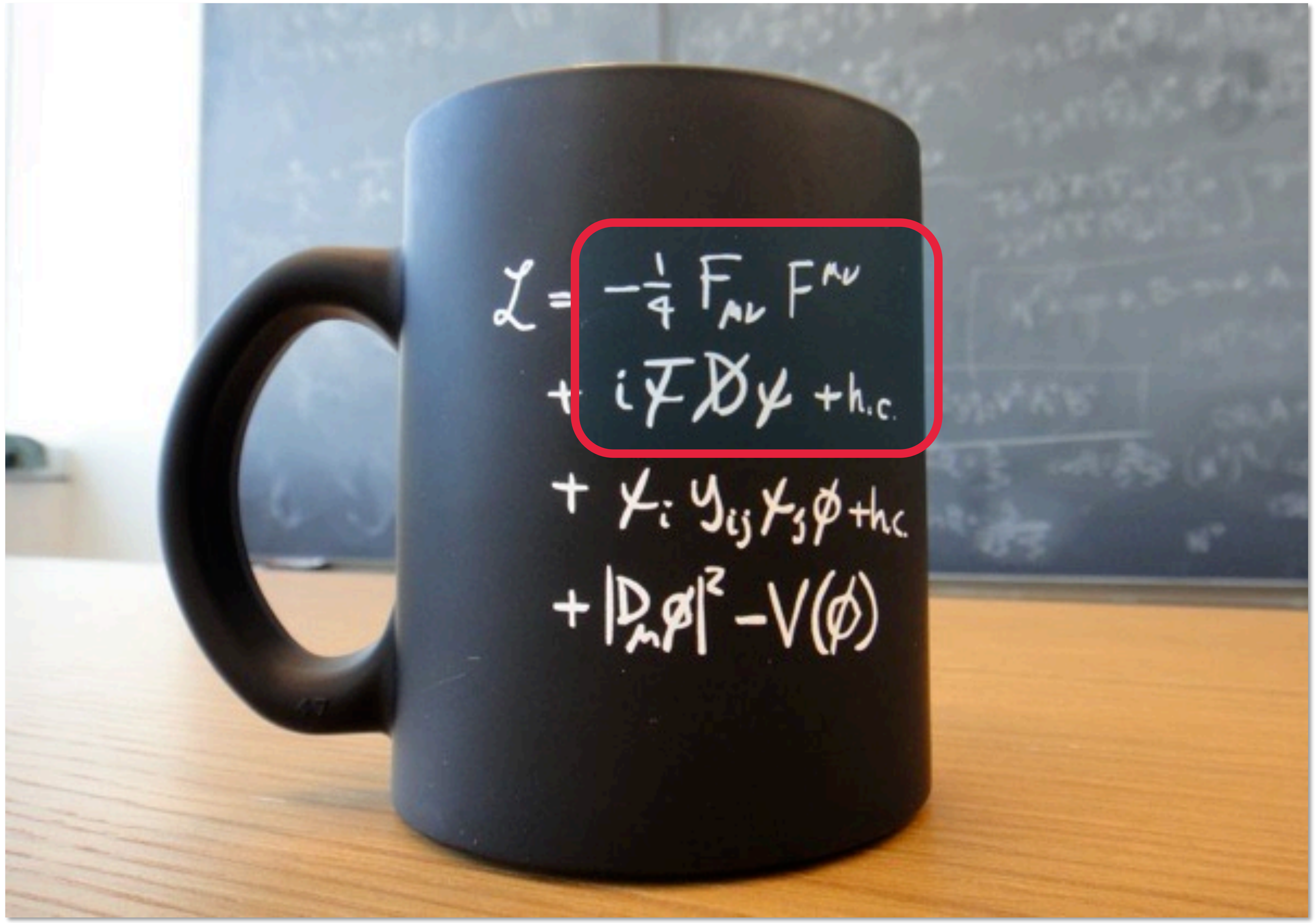
But first: Some physics at the LHC!

THE STANDARD MODEL

Lagrangian

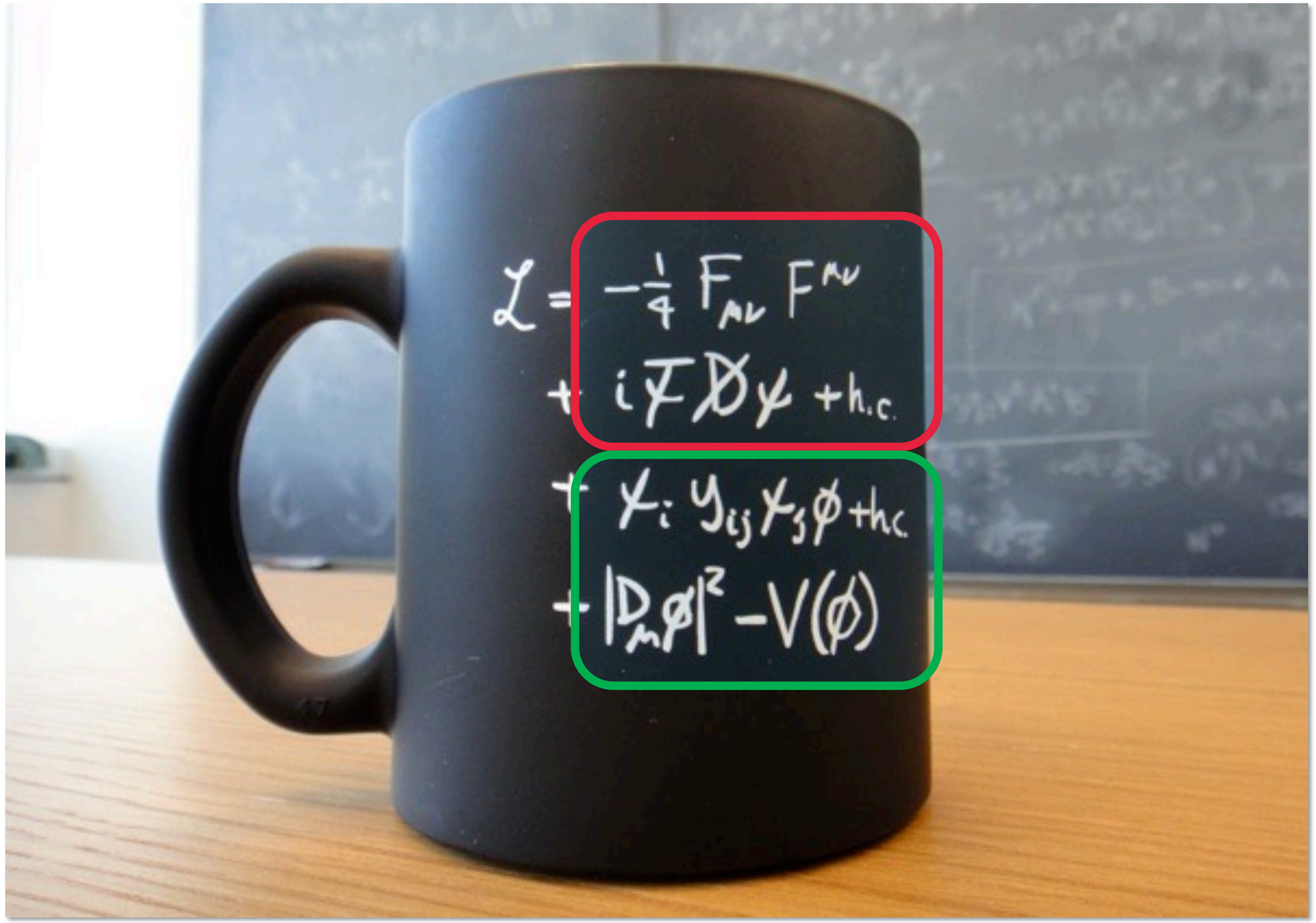


THE STANDARD MODEL



19th & 20th century

THE STANDARD MODEL

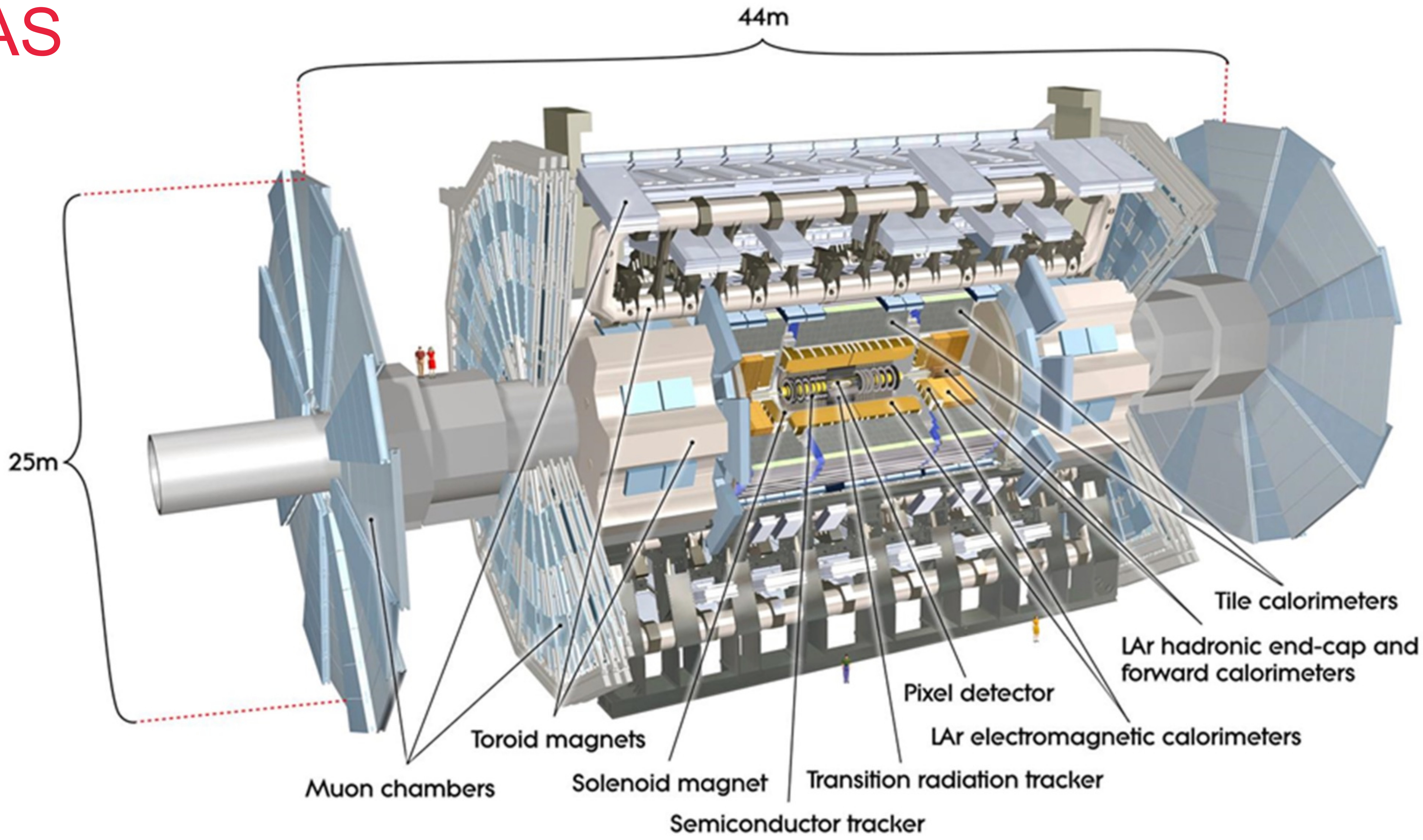


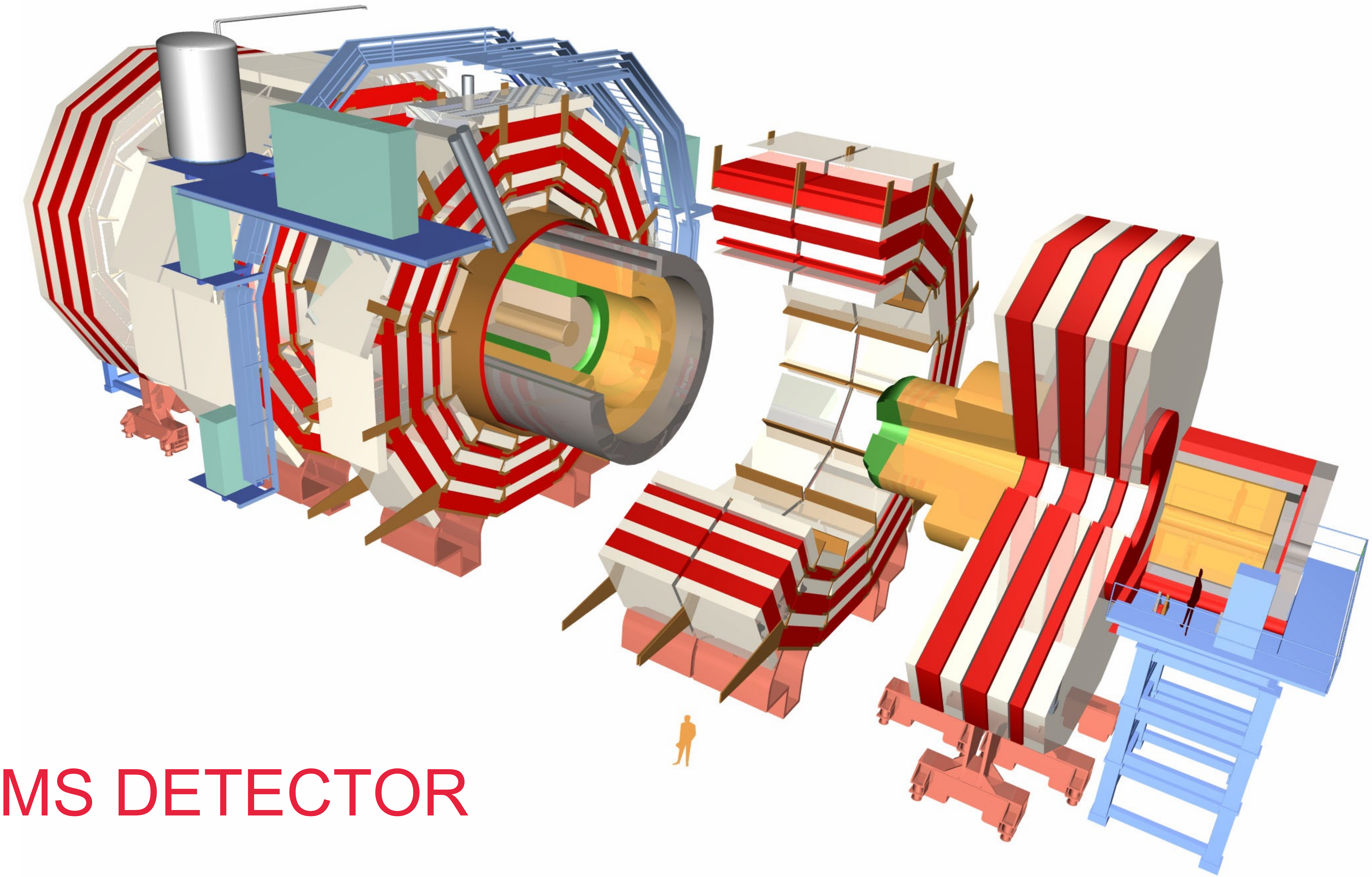
19th & 20th century

Since 2012!

OUR CURRENT COLLIDER

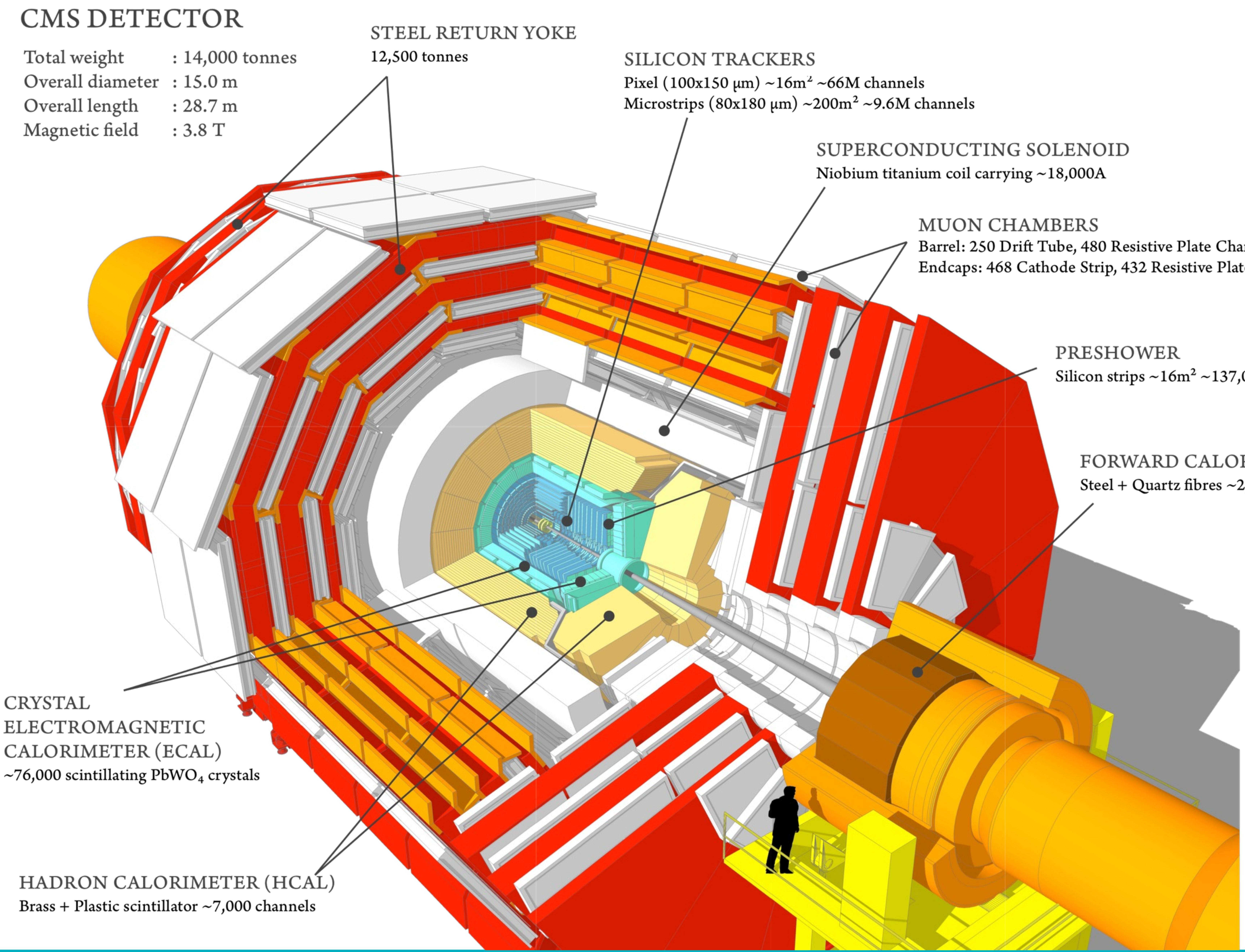
ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Transition radiation tracker
Muon chambers
Solenoid magnet
Semiconductor tracker

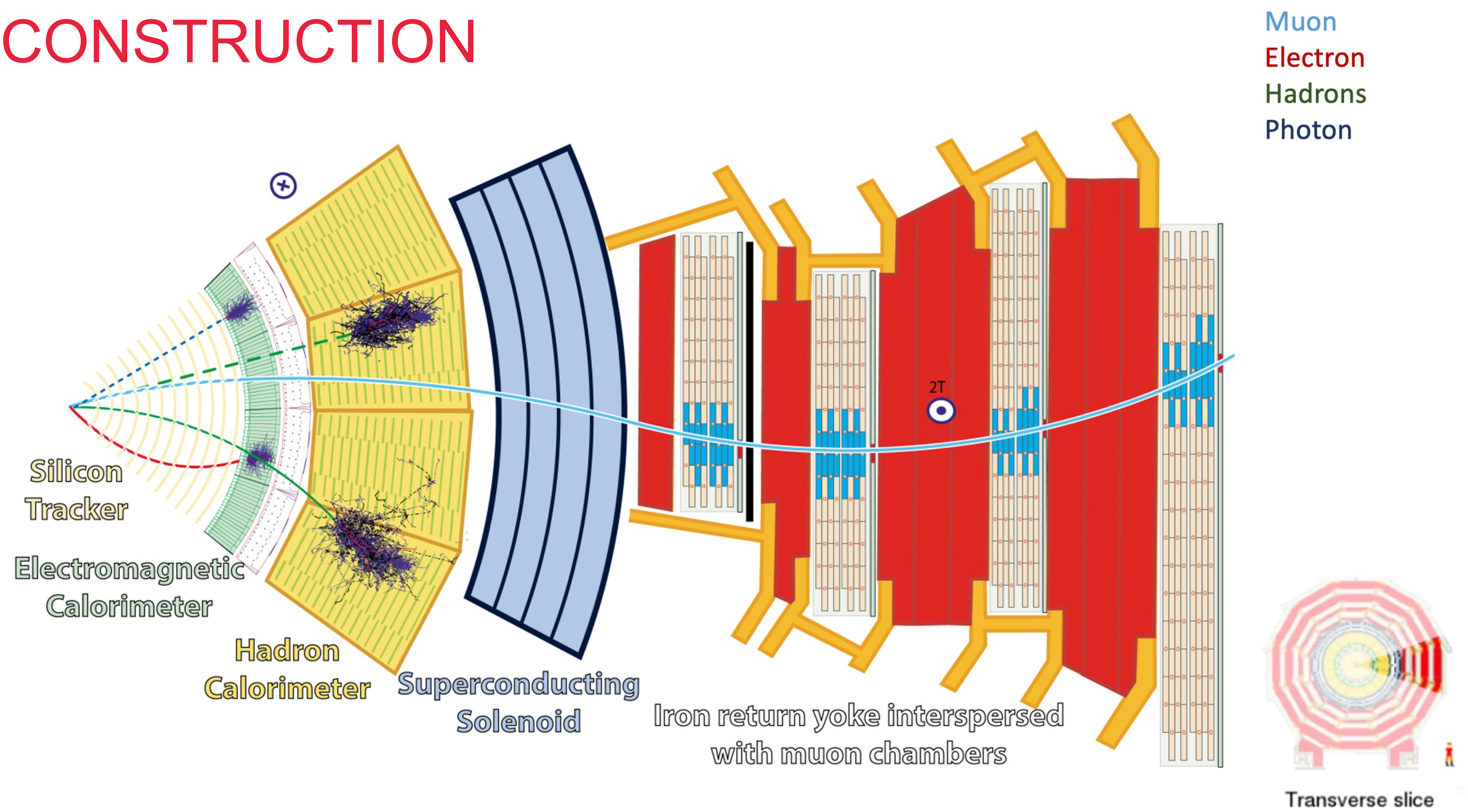


CMS DETECTOR

CMS

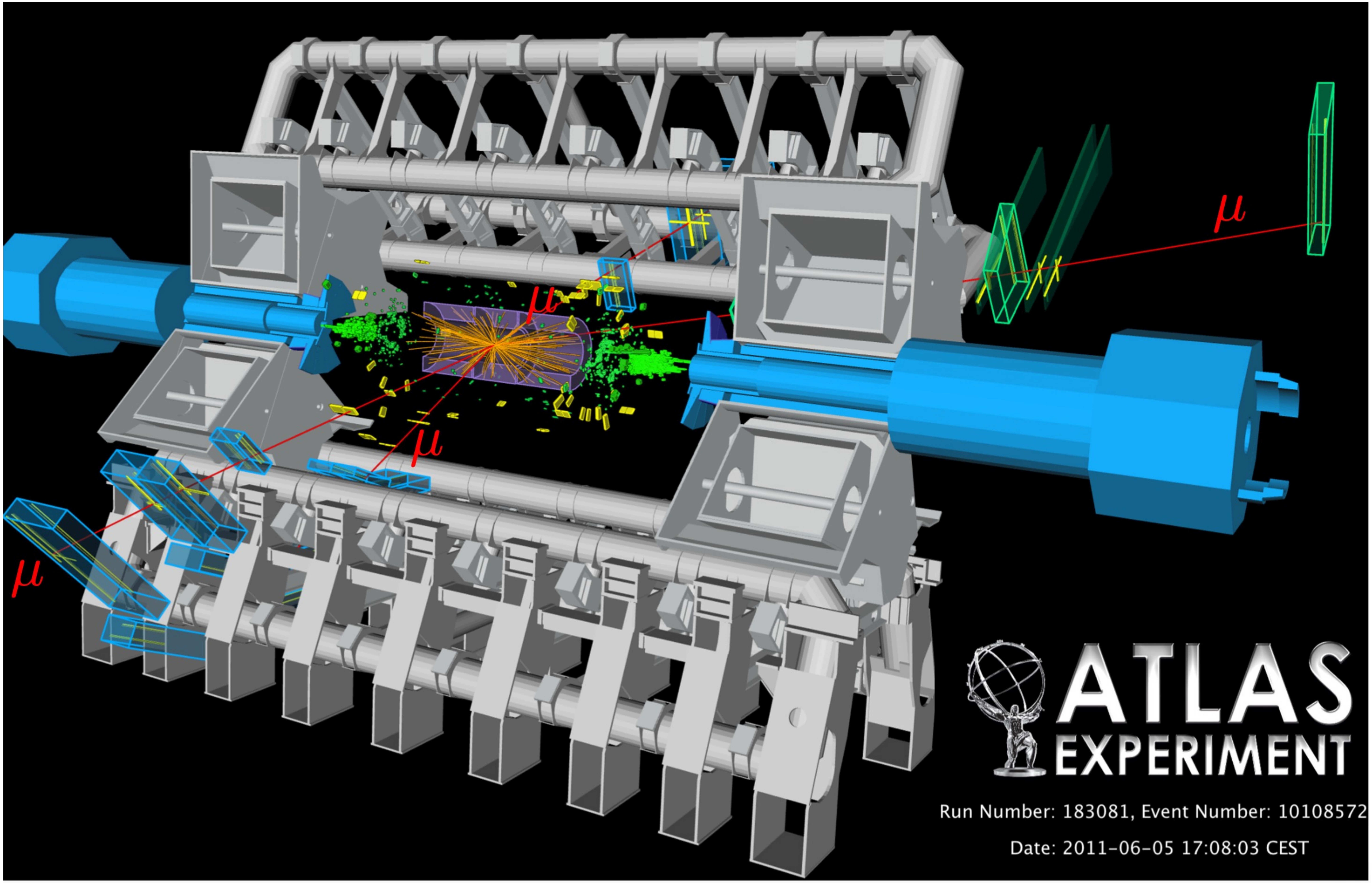

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

RECONSTRUCTION




CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354
H→Z(ee)Z(μμ)
electron
electron
muon
muon

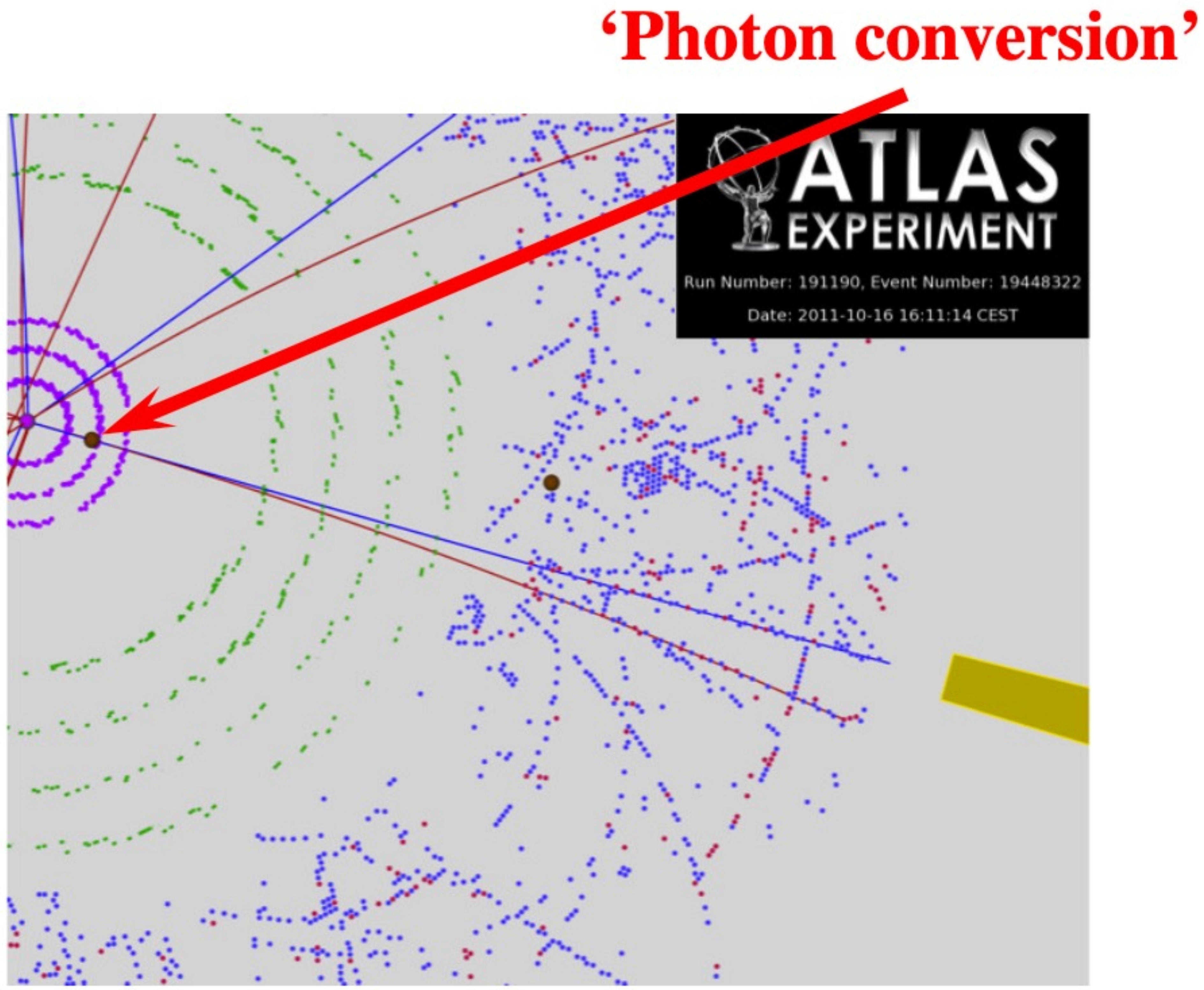
H→ZZ

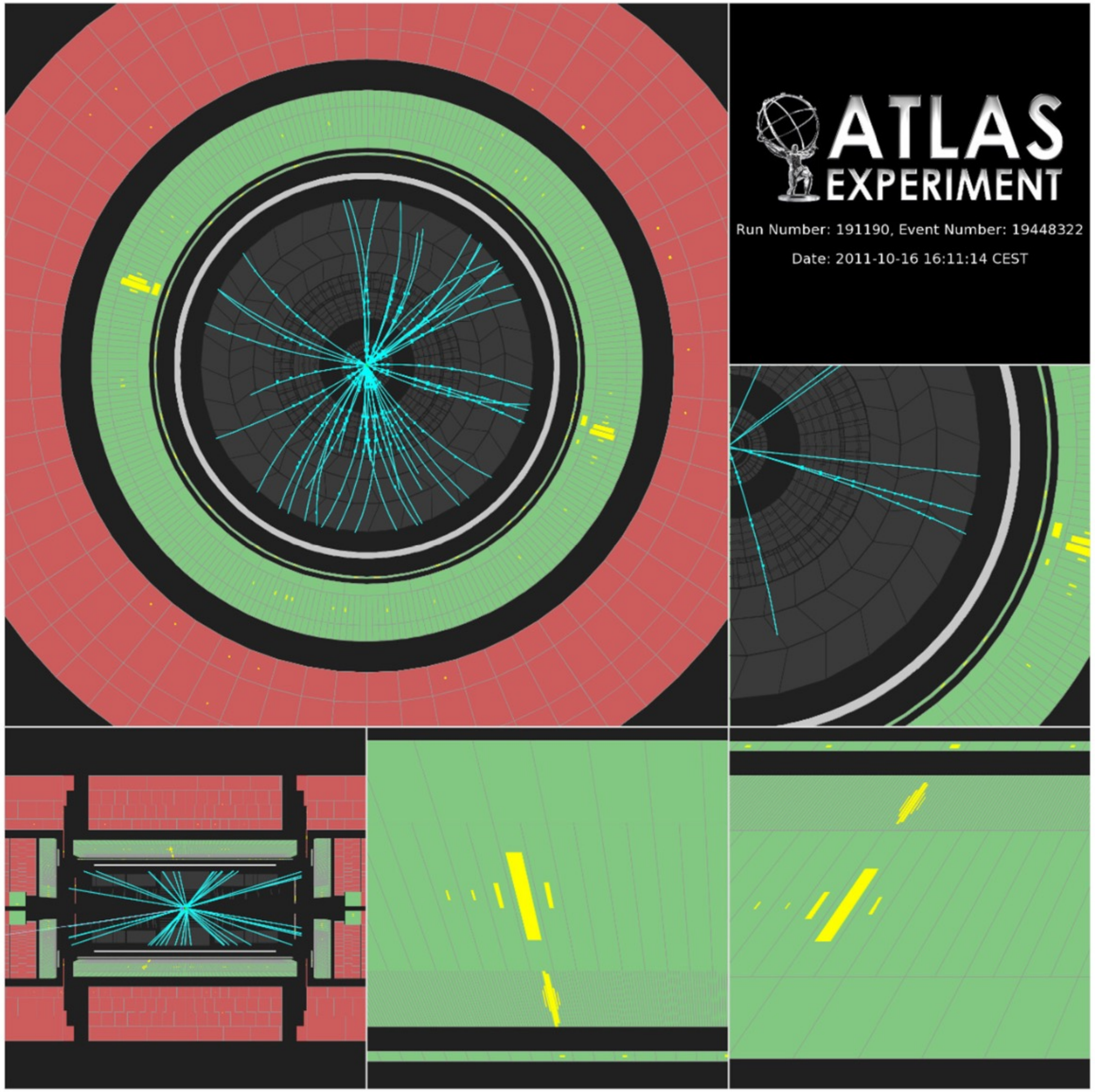

μ
μ
μ
μ
ATLAS
EXPERIMENT
Run Number: 183081, Event Number: 10108572
Date: 2011-06-05 17:08:03 CEST


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H→γγ
photon
photon

DIPHOTON

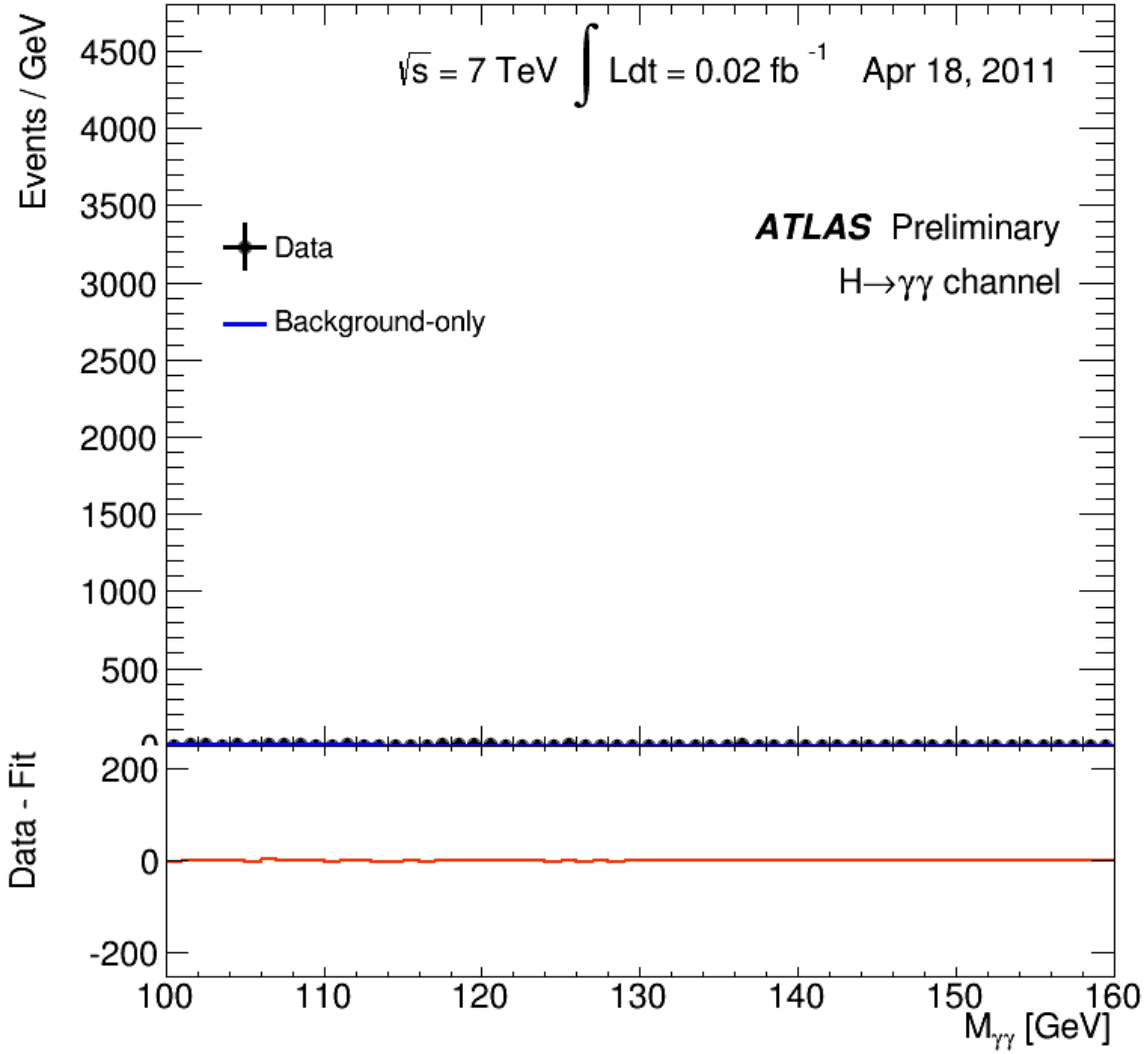
$H \rightarrow \gamma\gamma$ with $\gamma \rightarrow e^+e^-$



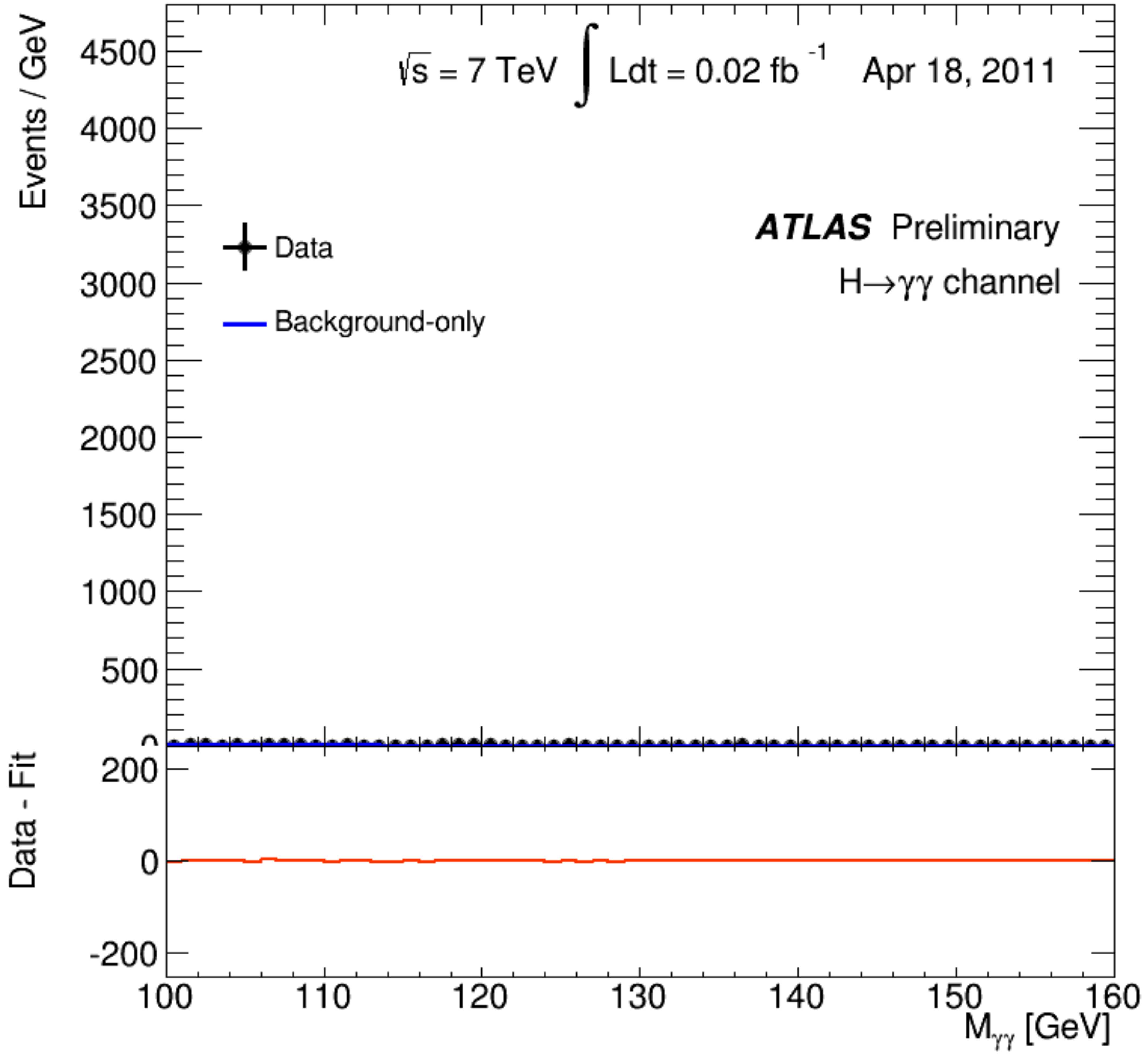


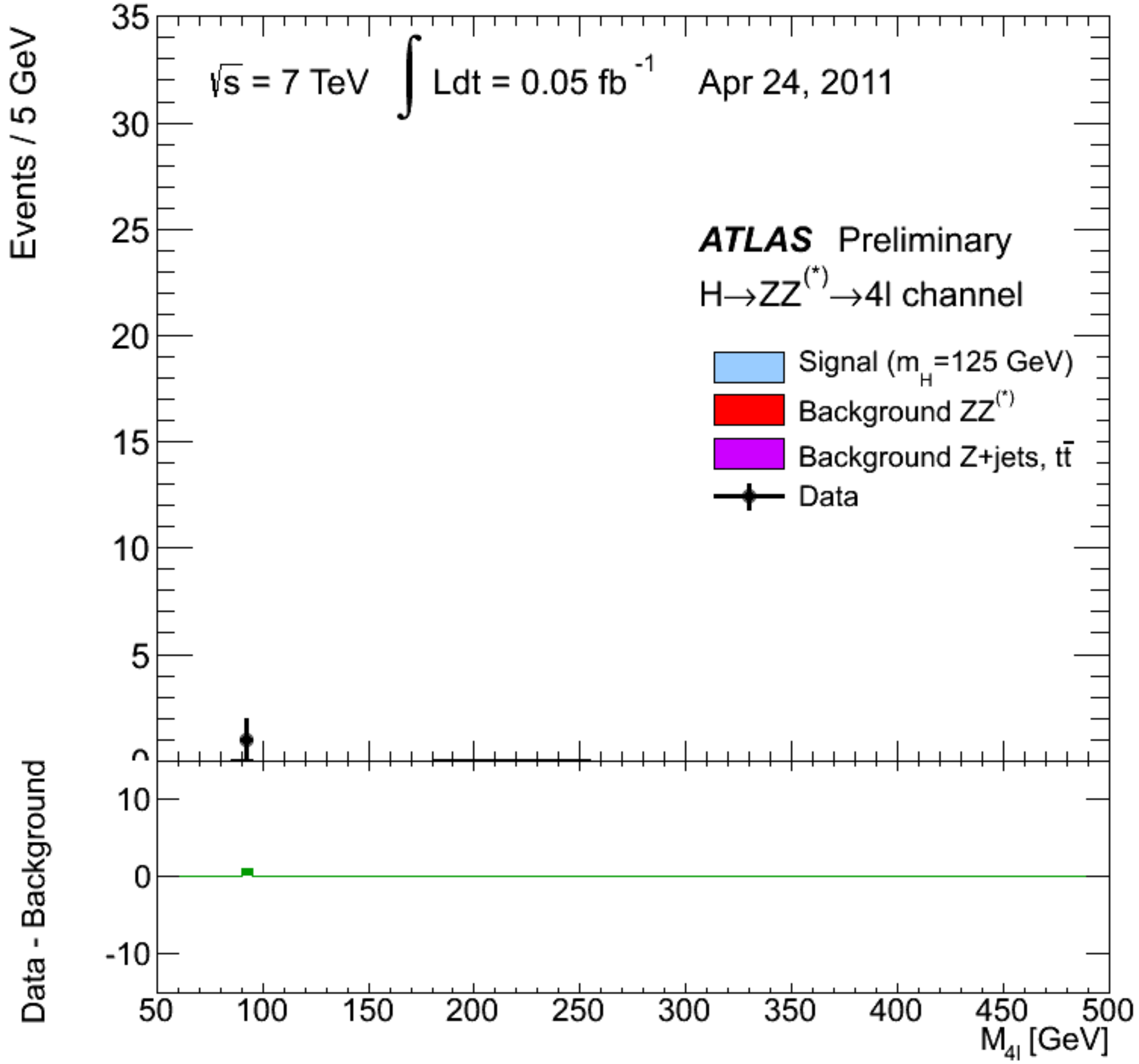
4 July 2012

A BUMP IN THE DATA



BUMPS IN THE DATA

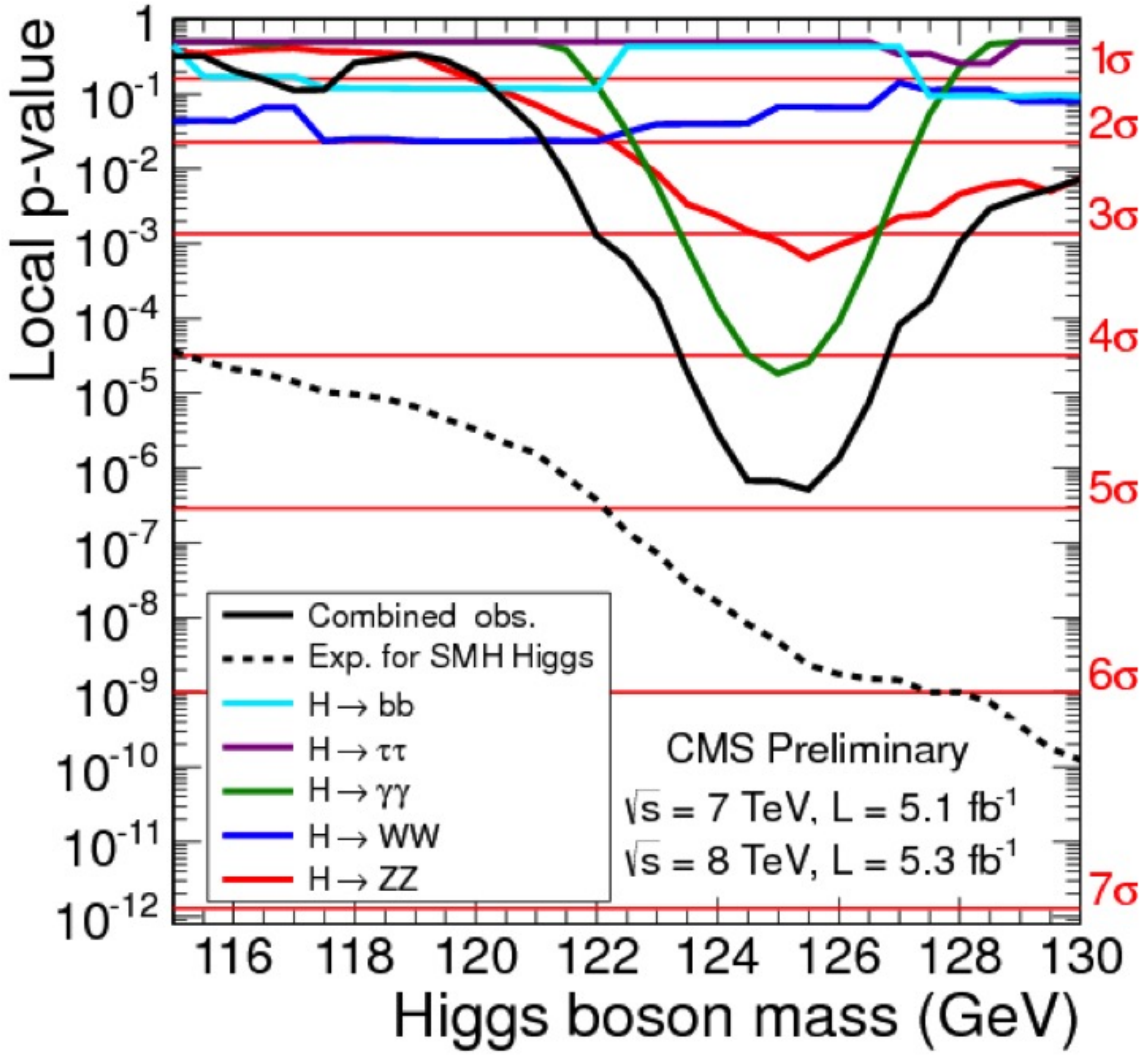


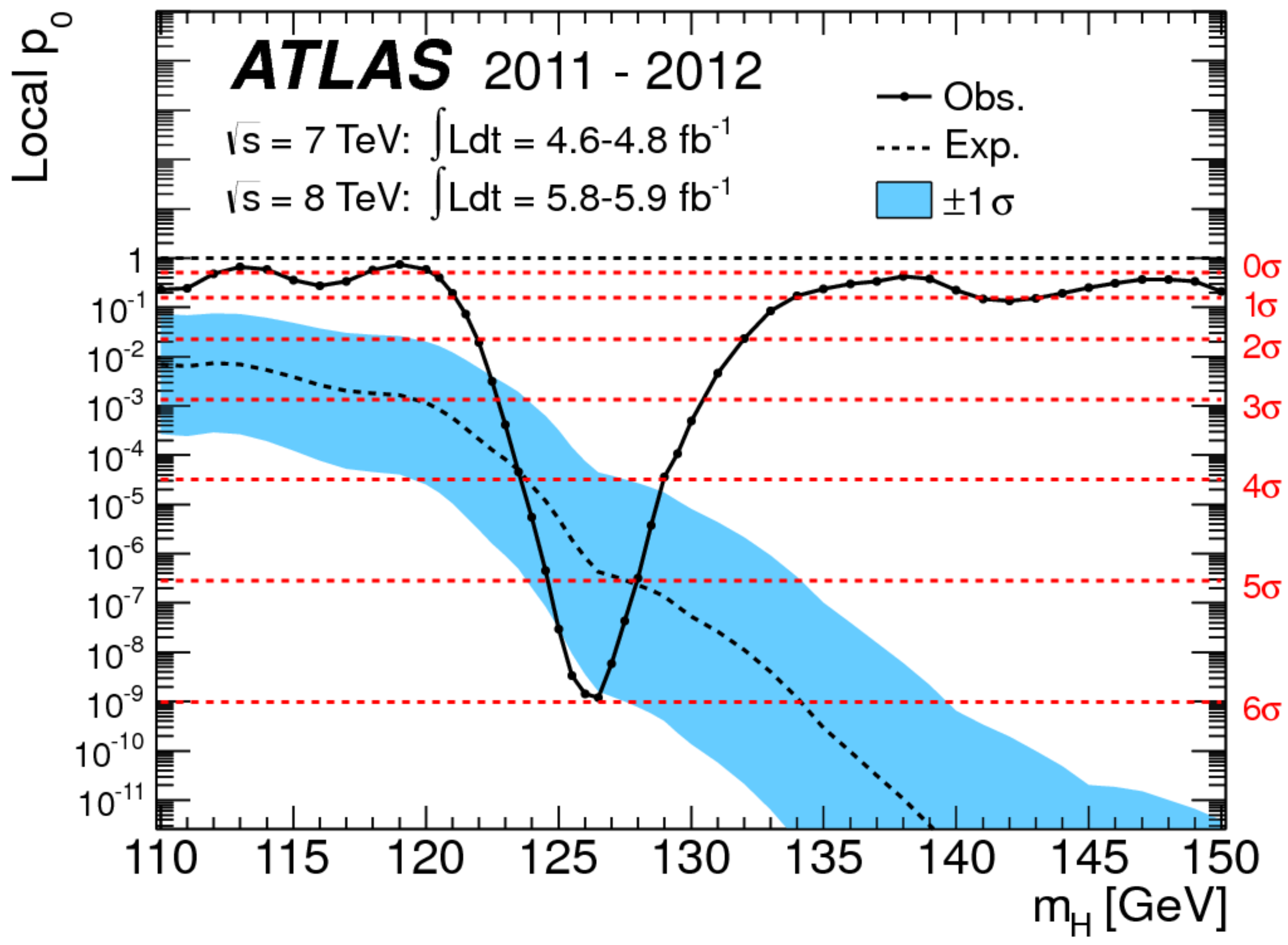


DISCOVERY

P-values

- ATLAS
- CMS





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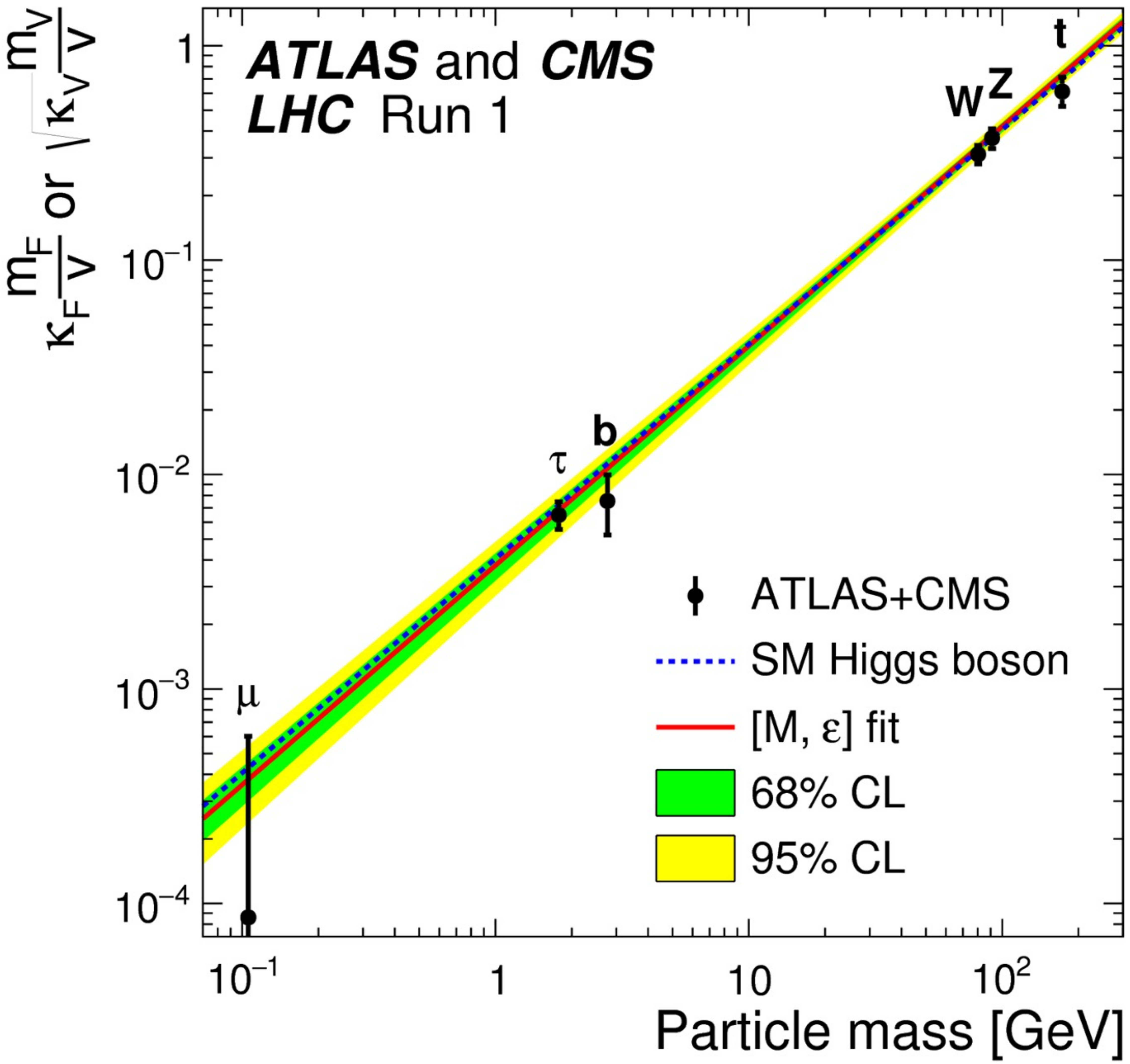
DISCOVERY!

P-values

- ATLAS
- CMS

DISCOVERY!

MASS VS COUPLING



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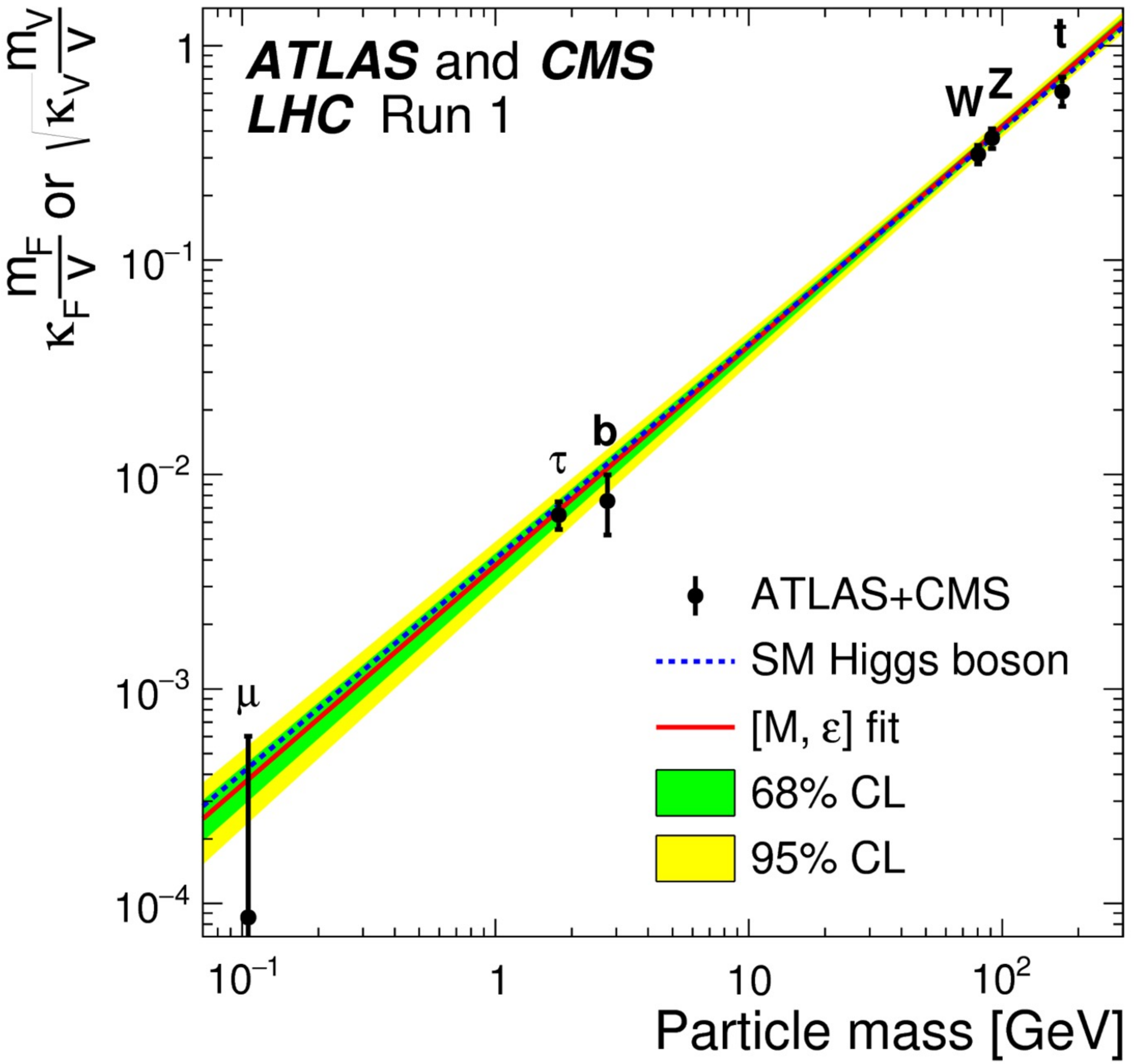
MASS VS COUPLING

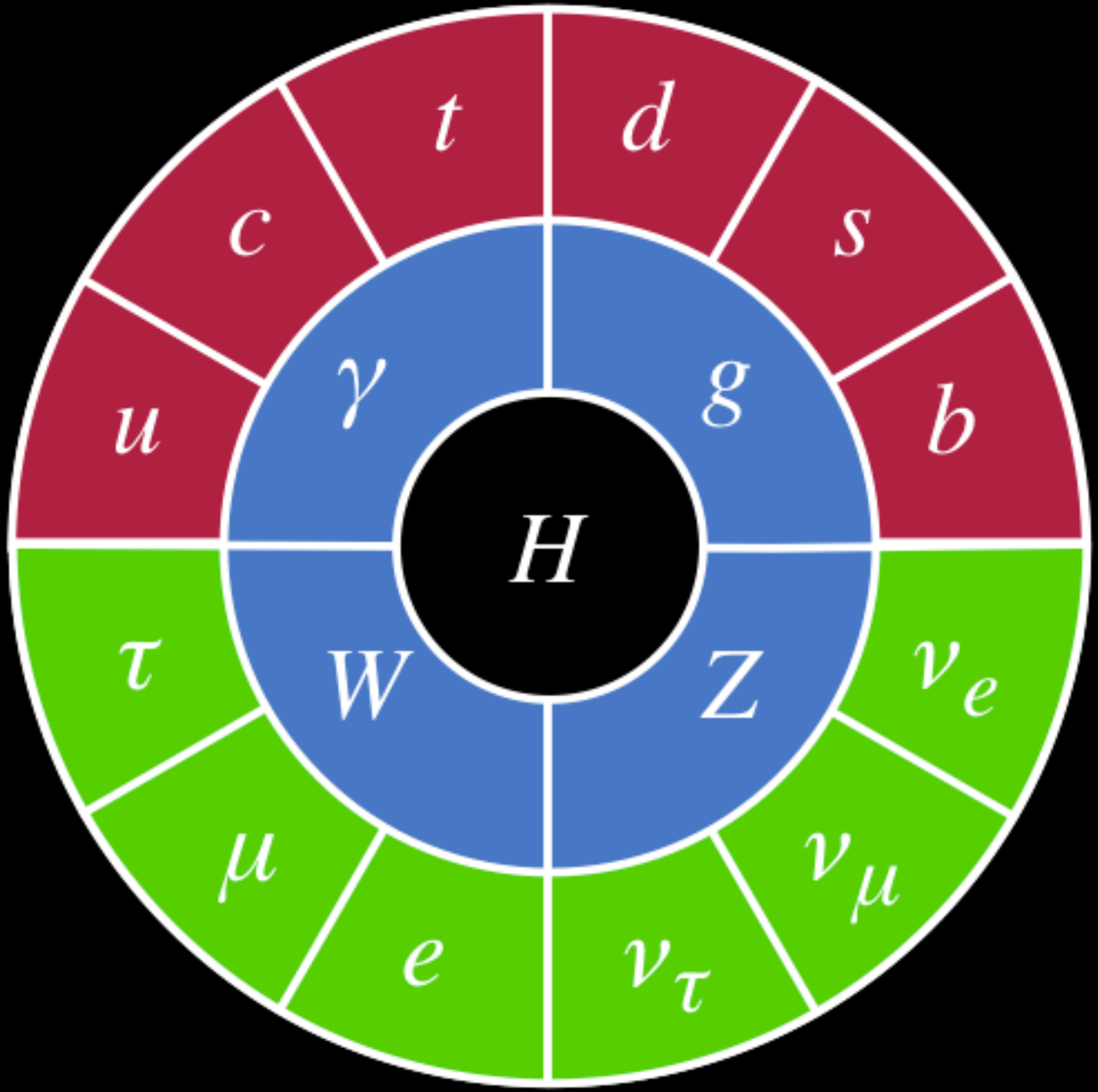
$$g_{H^0 f\bar{f}} = \frac{m_f}{v}$$

$$g_{H^0 VV} = \frac{2M_V^2}{v}$$



NOBEL PRIZE 2014

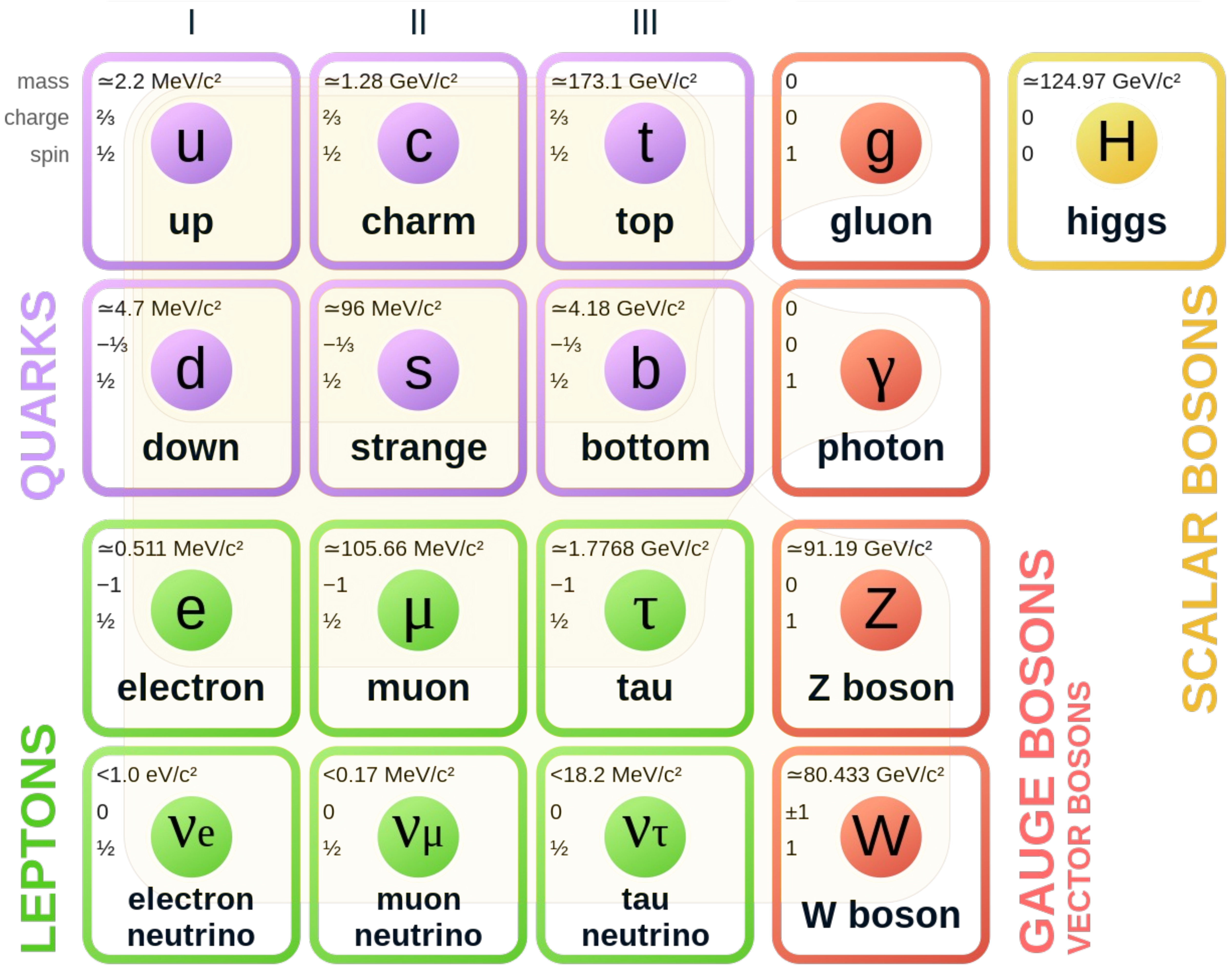
'…through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider.'


H
γ
g
W
Z
u
c
t
d
s
b
τ
μ
e
ν_τ
ν_μ
ν_e

INTERACTIONS

Higgs evidence

- Diboson
  - H→VV
  - H→WW
  - H→γγ



INTERACTIONS

Higgs evidence

- Diboson
  - H→VV
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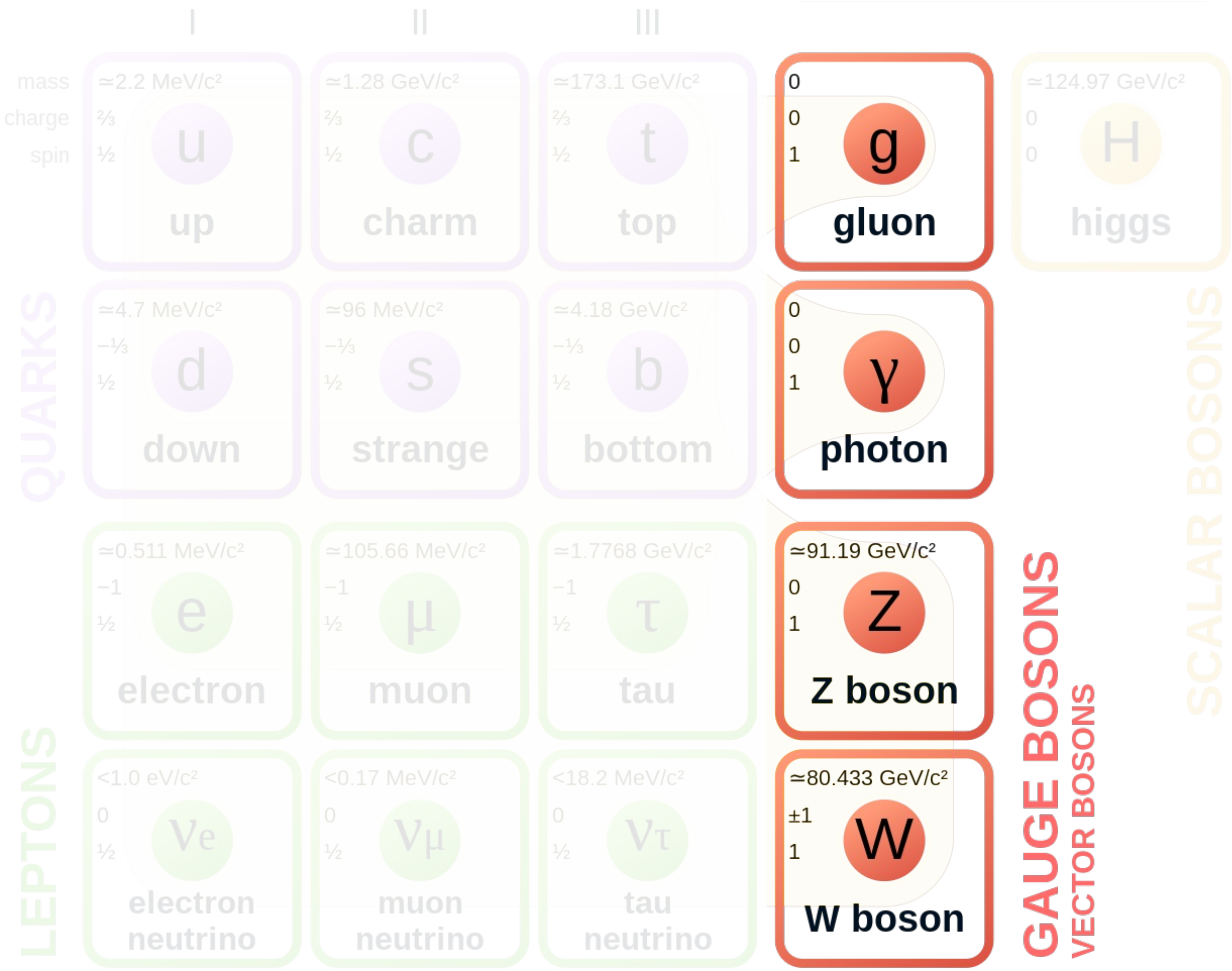
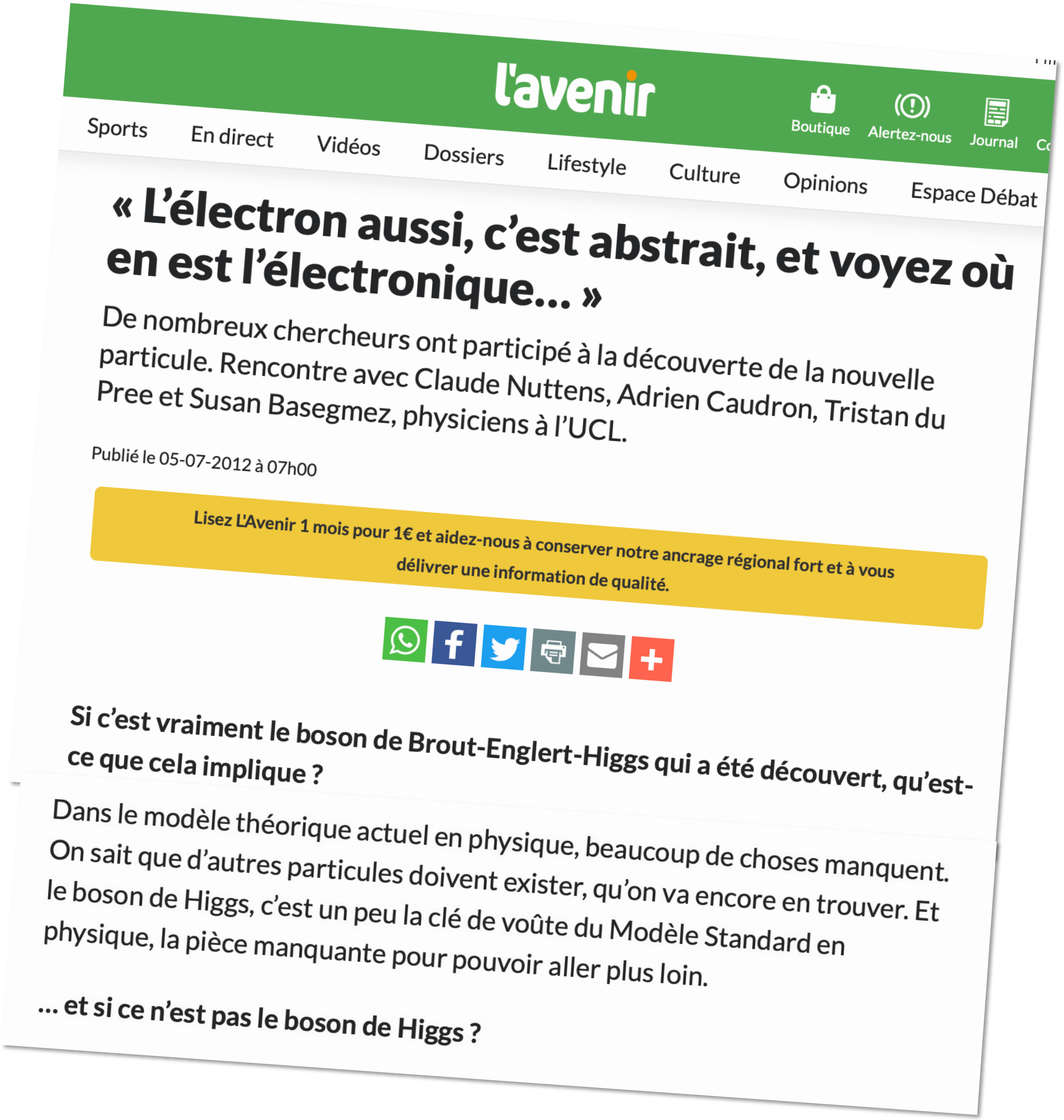


Coupling to fermions?

HIGGS TO FERMIONS?

2012: TdP in Brussels

- The city of F.Englert



l'avenir

Boutique Alertez-nous Journal

Sports En direct Vidéos Dossiers Lifestyle Culture Opinions Espace Débat

« L'électron aussi, c'est abstrait, et voyez où en est l'électronique… »

De nombreux chercheurs ont participé à la découverte de la nouvelle particule. Rencontre avec Claude Nuttens, Adrien Caudron, Tristan du Pree et Susan Basegmez, physiciens à l'UCL.

Publié le 05-07-2012 à 07h00

Lisez L'Avenir 1 mois pour 1€ et aidez-nous à conserver notre ancrage régional fort et à vous délivrer une information de qualité.

Si c'est vraiment le boson de Brout-Englert-Higgs qui a été découvert, qu'est-ce que cela implique ?

Dans le modèle théorique actuel en physique, beaucoup de choses manquent. On sait que d'autres particules doivent exister, qu'on va encore en trouver. Et le boson de Higgs, c'est un peu la clé de voûte du Modèle Standard en physique, la pièce manquante pour pouvoir aller plus loin.

… et si ce n'est pas le boson de Higgs ?

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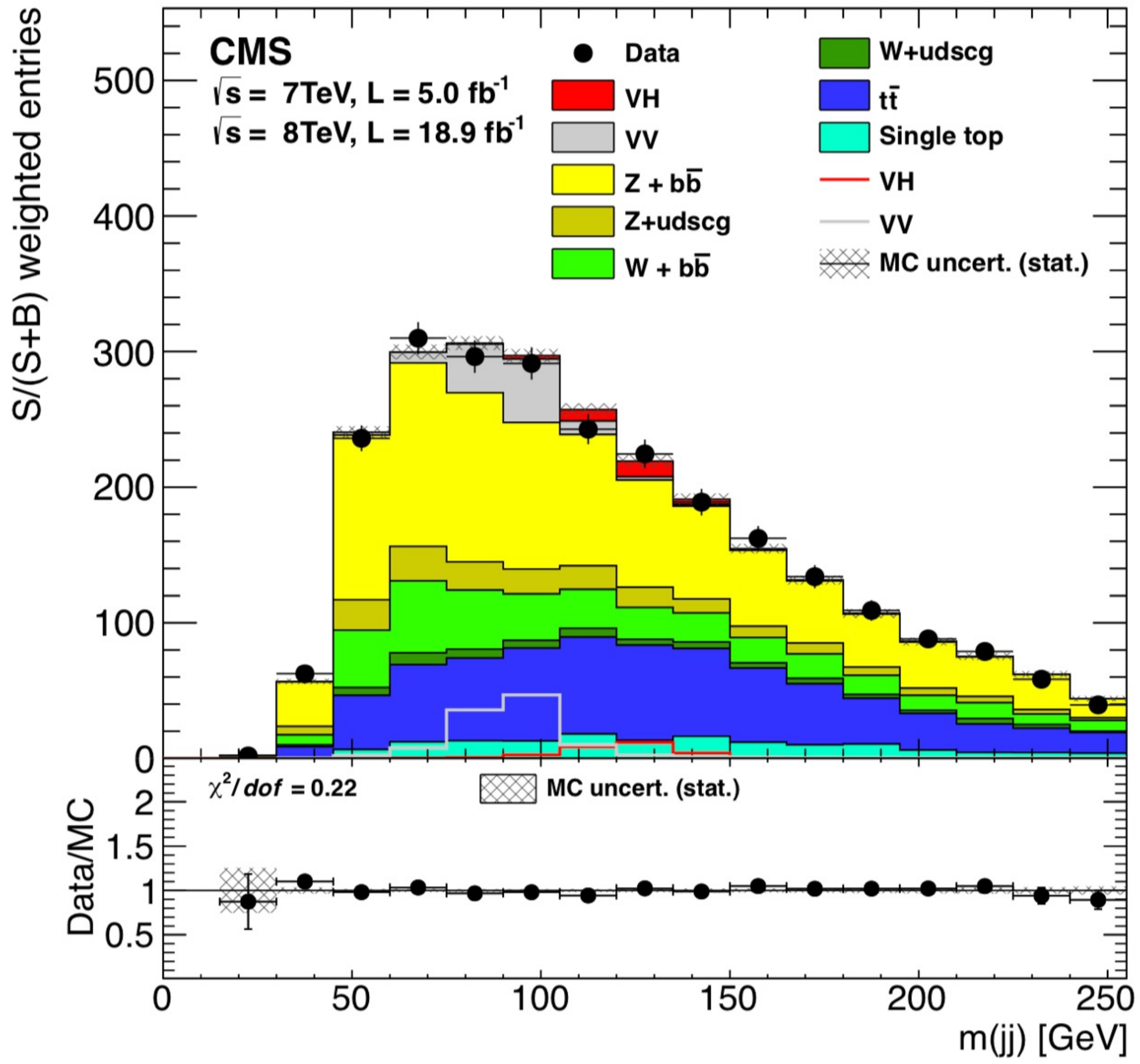
H→BB

Main decay channel

- 57%

But very challenging

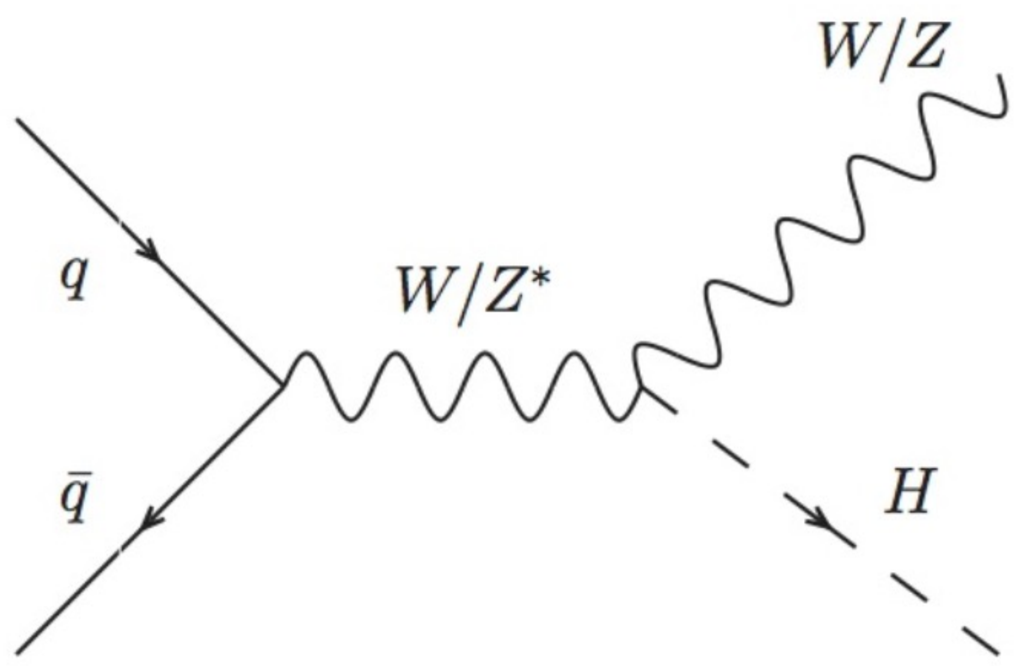
- VH production
  - Large background
  - Broad resolution

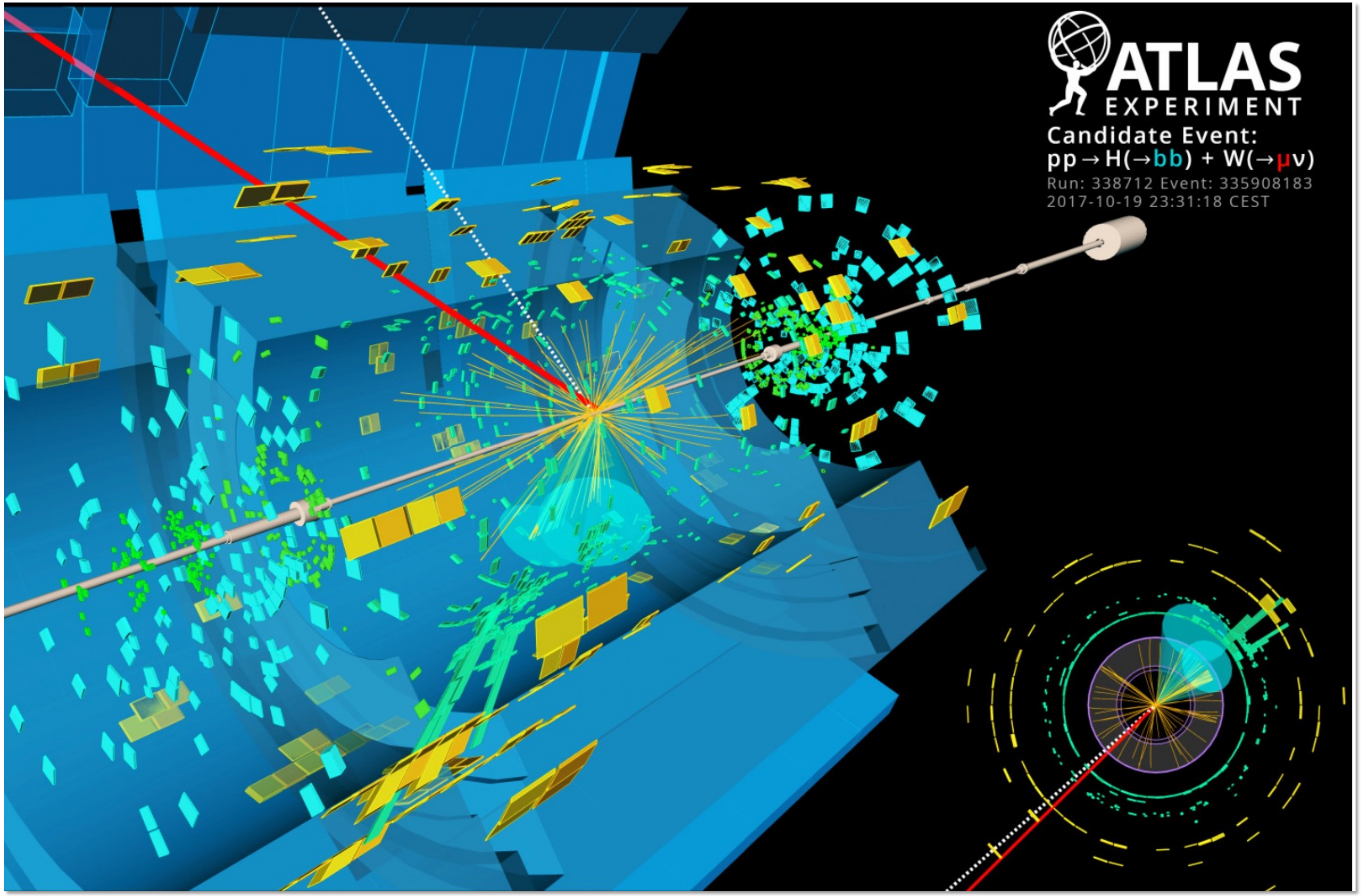


FERMIONS

LHC Run-2

- W(μν)H(bb)





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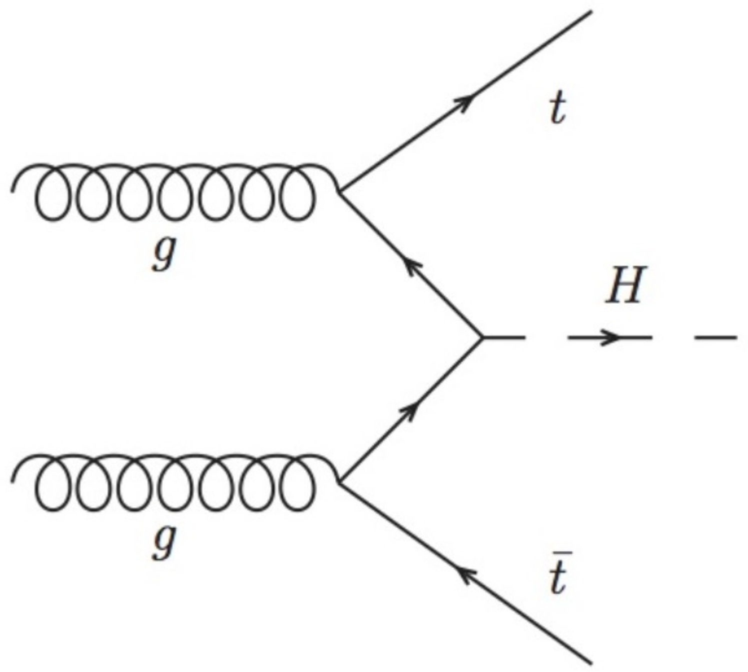
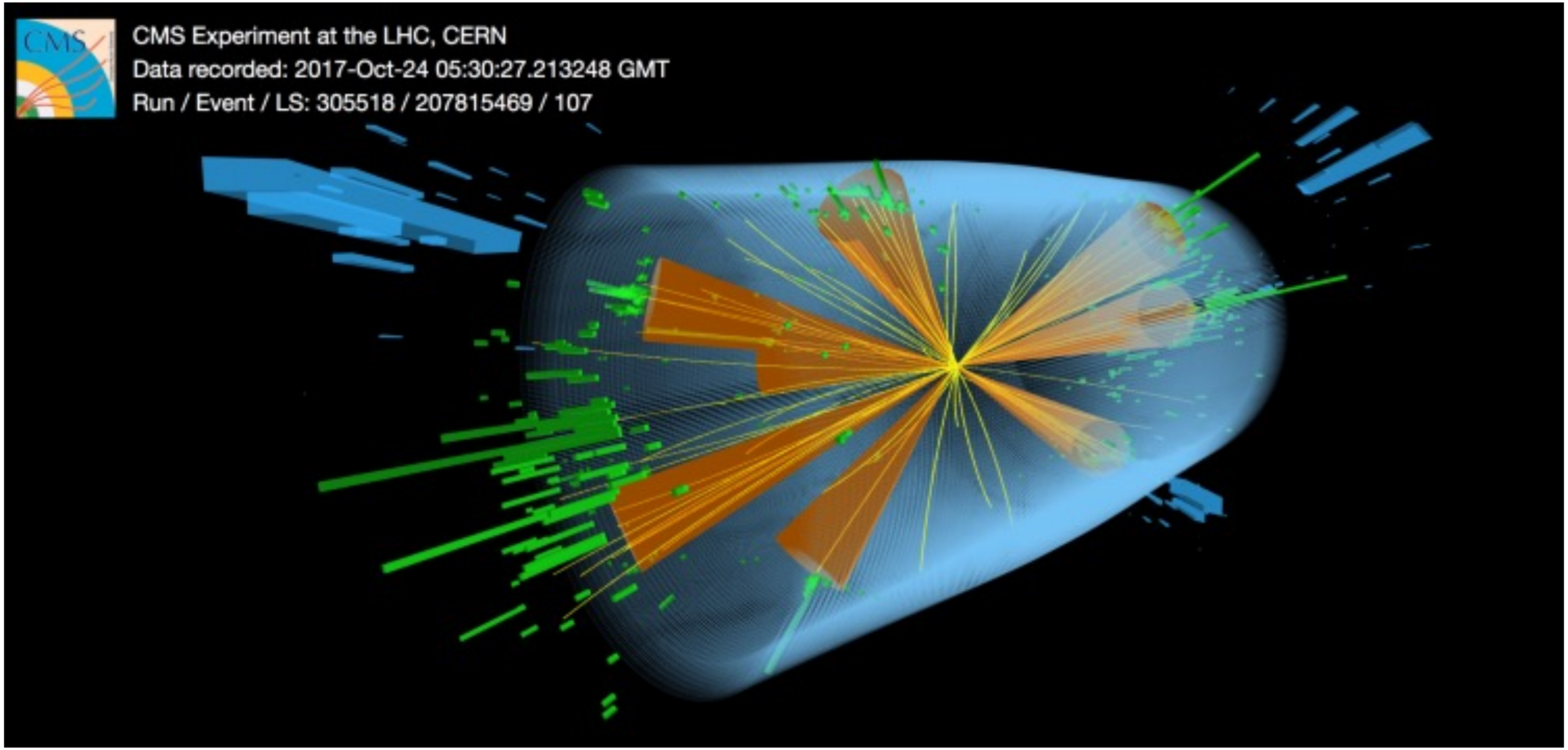
FERMIONS

LHC Run-2

- ttH





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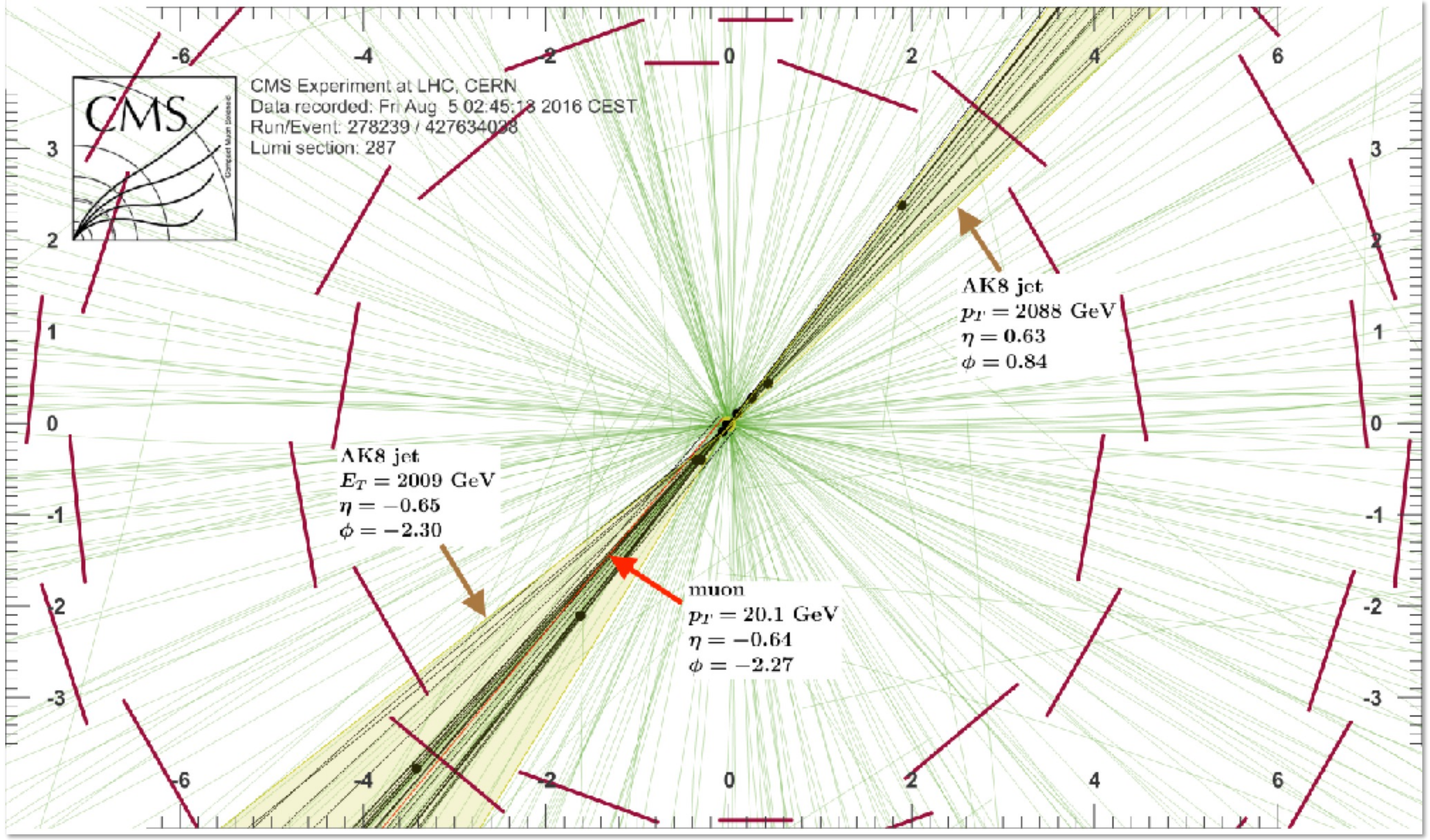
PILEUP

B-tagging important for physics

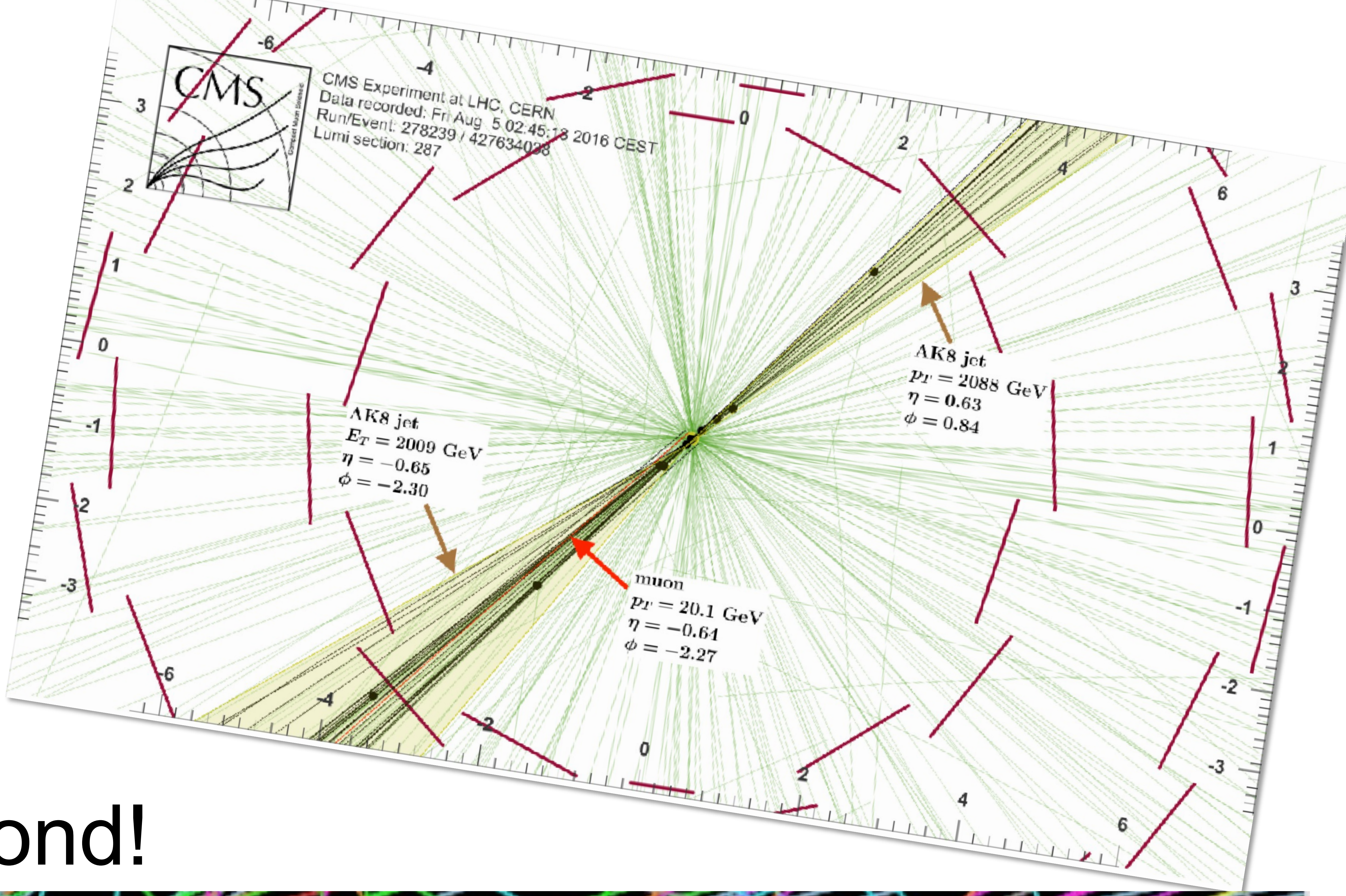
- Displaced vertices
- Challenging environment



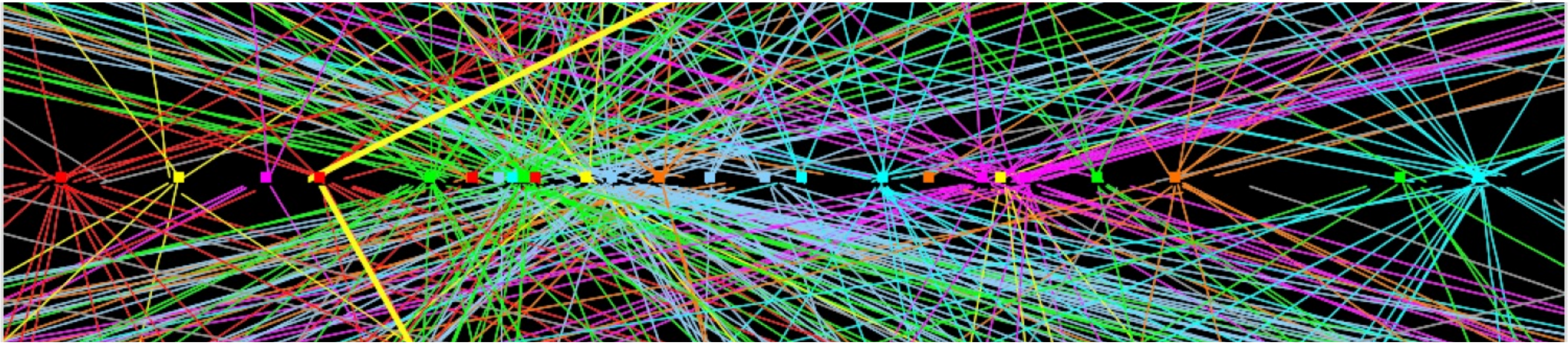
PILEUP

B-tagging important for physics

- Challenging environment
  - Pileup up to ~100!



A needle in 40 million haystacks per second!



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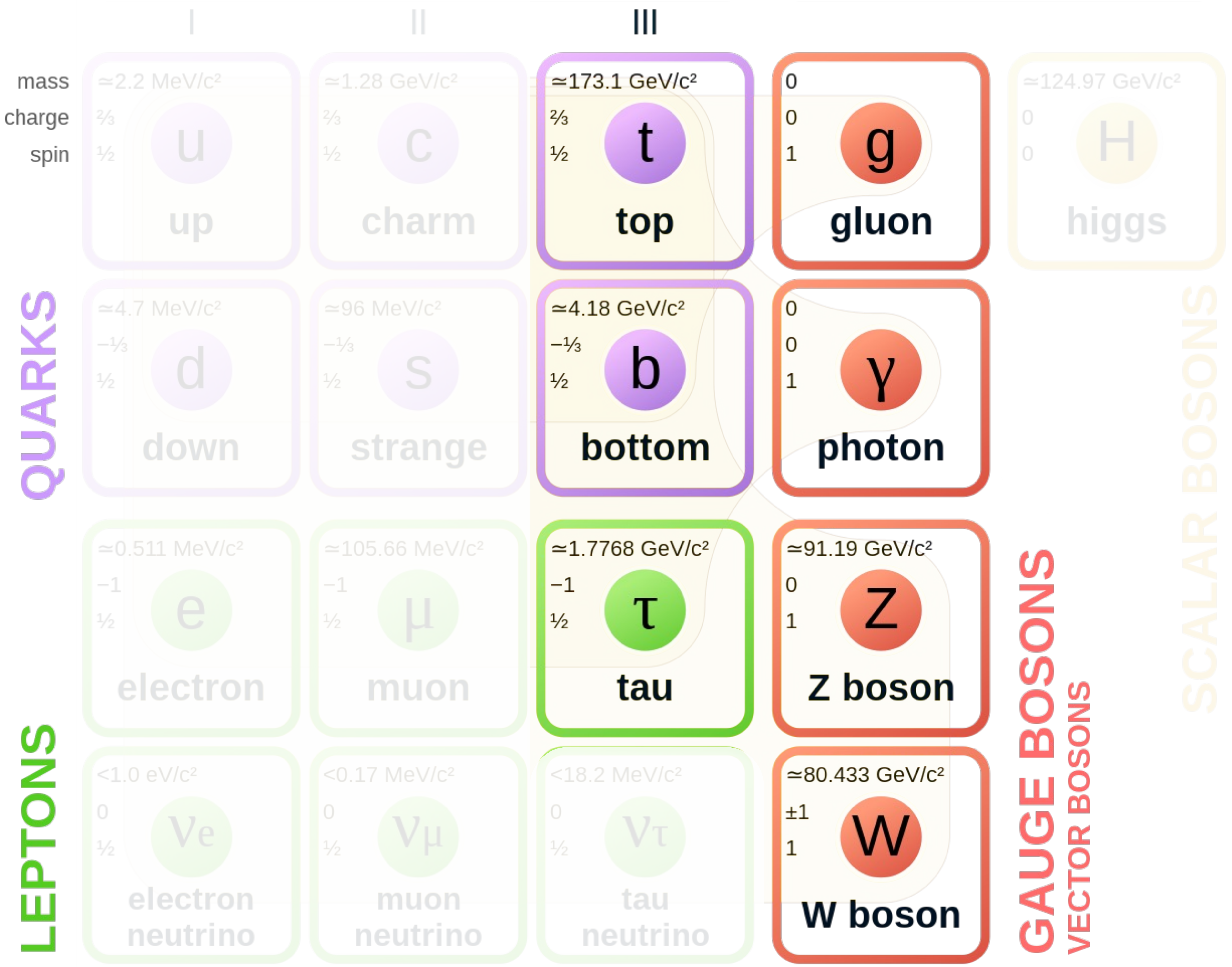
✅ HIGGS: DONE

Decays observed at LHC

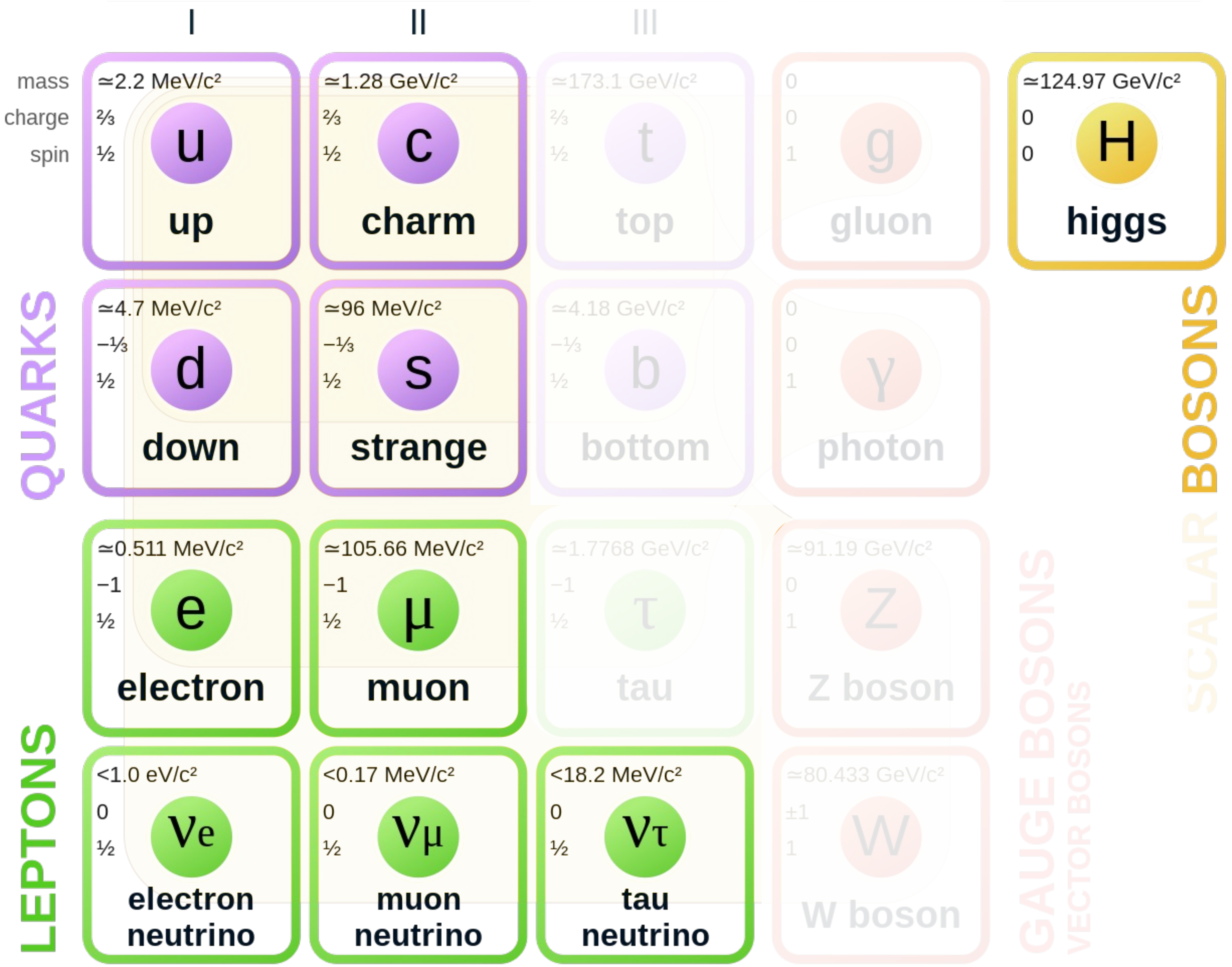
- Diboson
  - H→VV
  - H→WW
  - H→γγ
- Fermions
  - 3rd gen



HIGGS: TO DO

Higgs interactions

- 2nd gen?
- 1st gen?
- Self-interaction?
- Invisible particles?
  - Neutrinos?
  - Dark Matter?



HIGGS QUESTIONS

Why 3 generations?

Mass patterns?

Neutrino masses?

Dark Matter?

Dark Energy?

Inflation?

Anti-matter?

Baryogenesis?

?

ESPPU STATEMENT

High-priority future initiatives

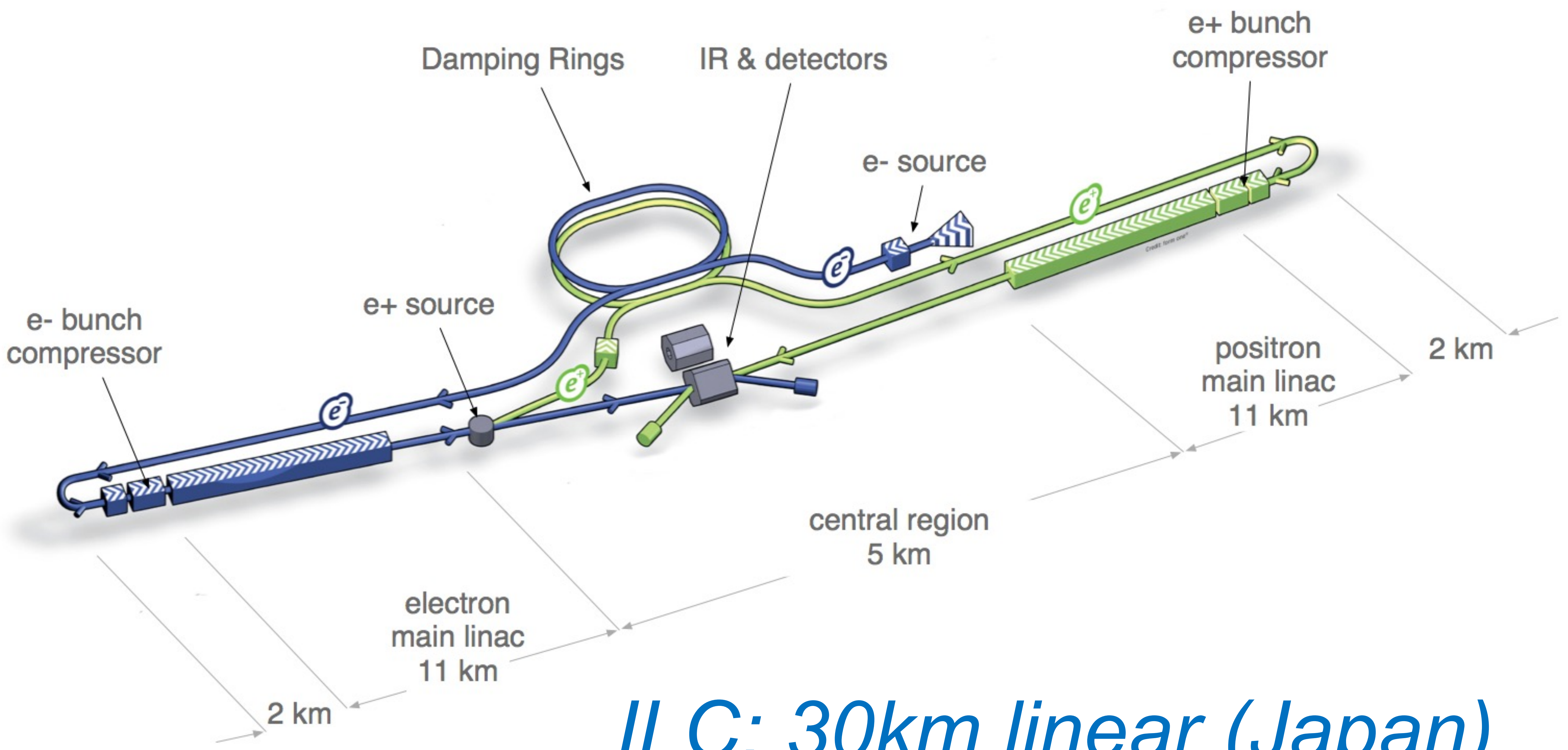
A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

FCC-ee: THE NEXT COLLIDER?

PHOTO: J. WENNINGER

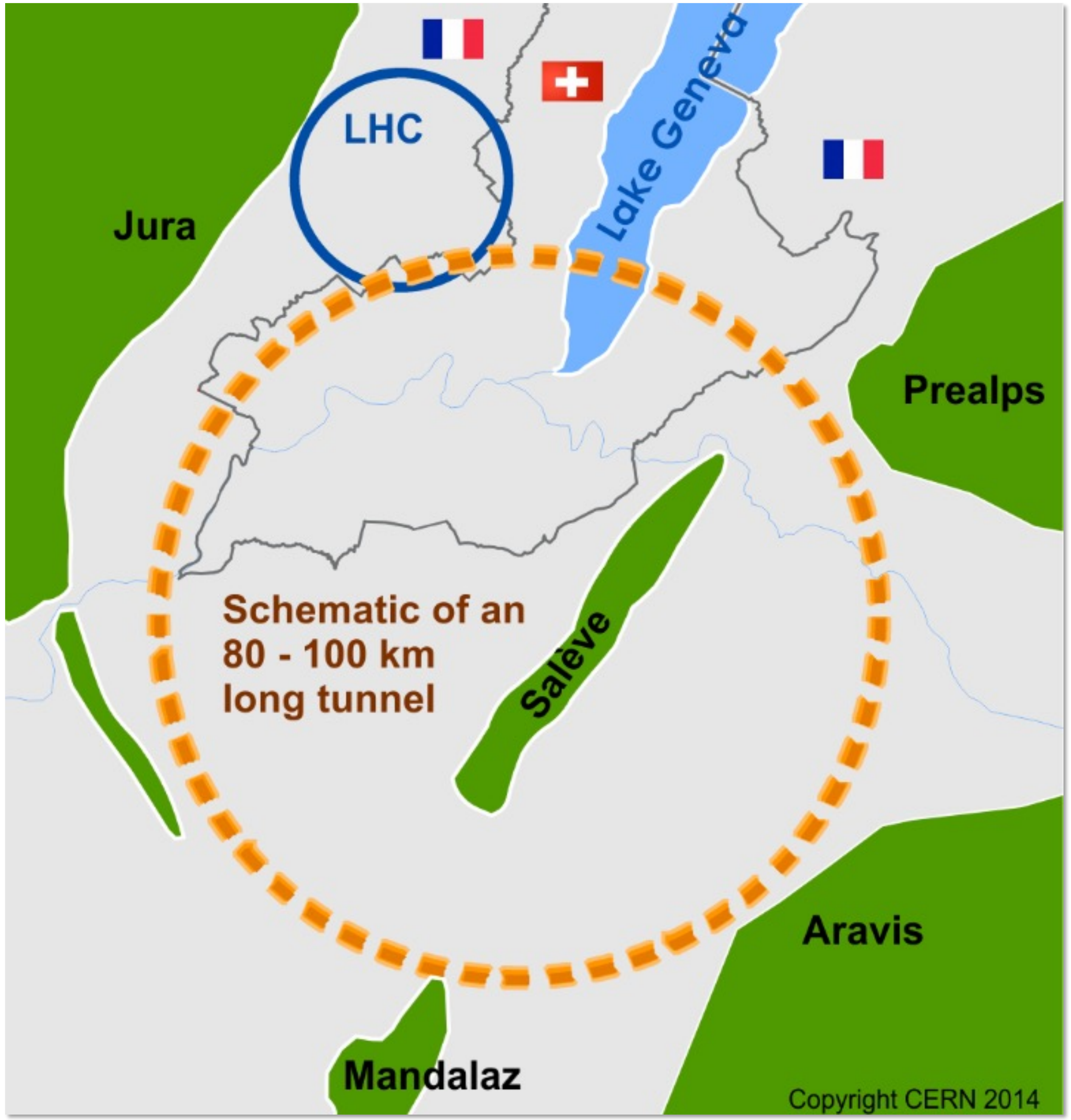
E+E-

Two main proposals



ILC: 30km linear (Japan)

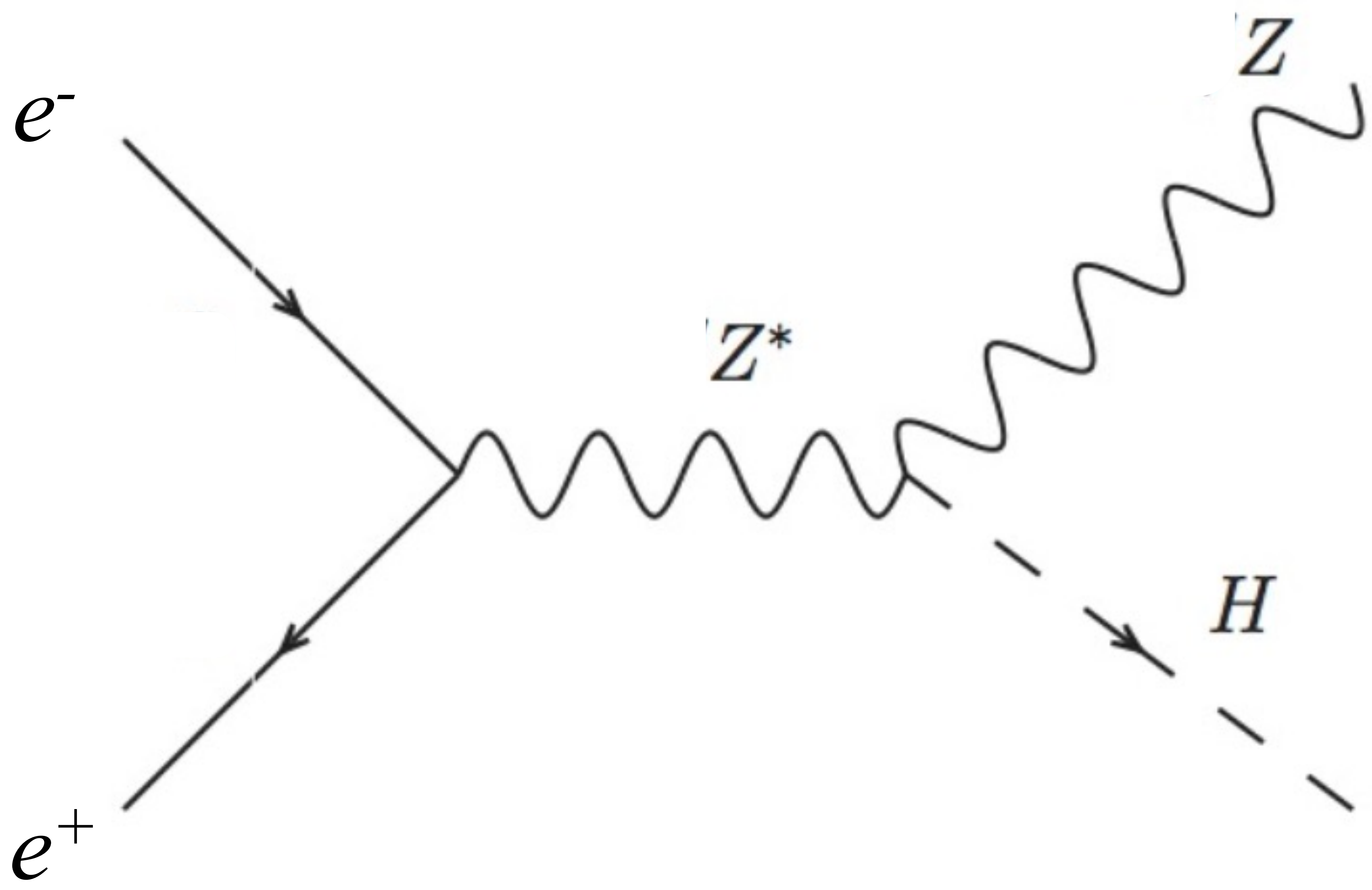
FCC-ee: 90km circular (CERN)



HIGGS PRODUCTION

Higgs production at e^+e^-

- ~240 GeV sufficient
  - ZH associated

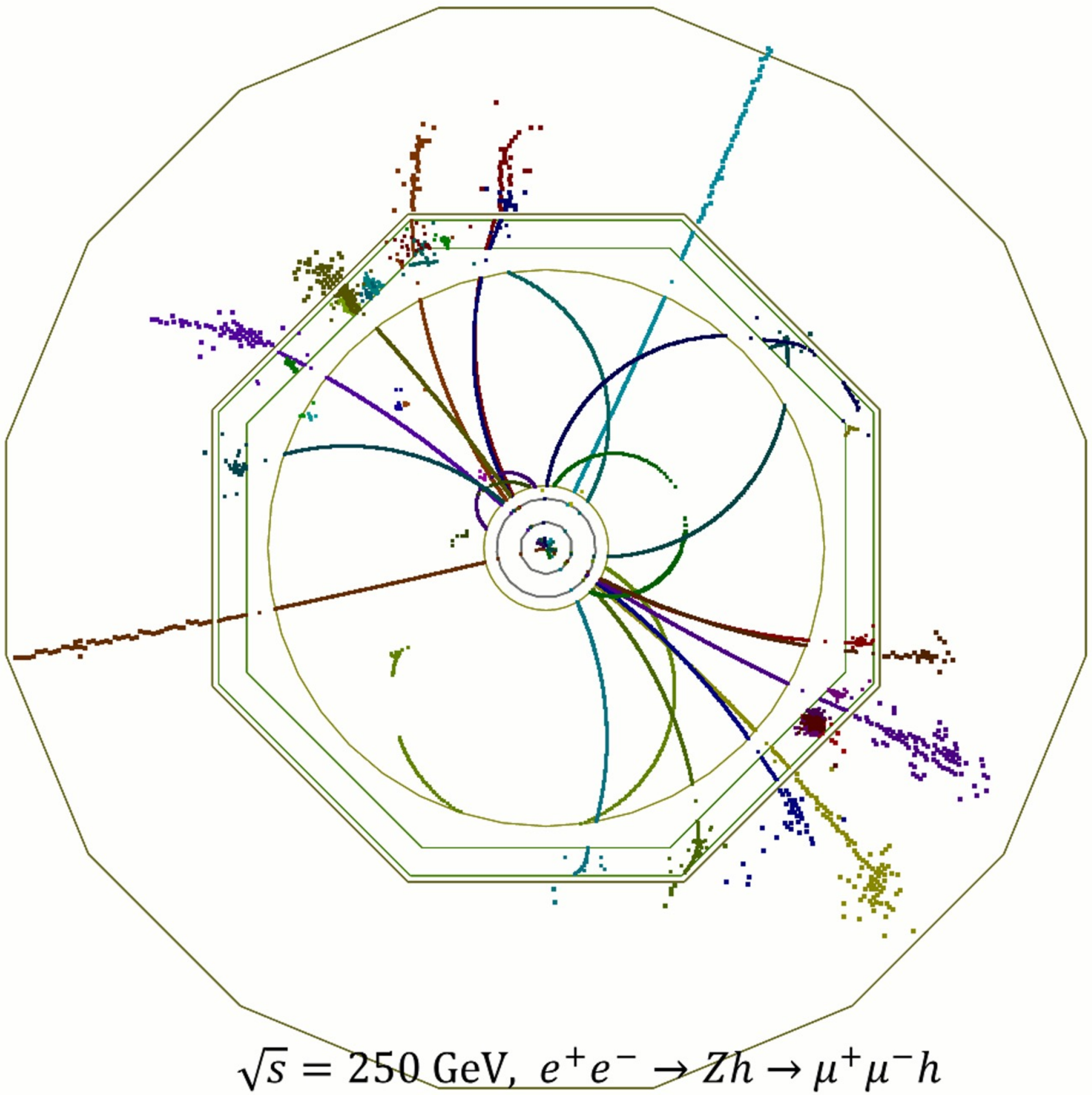


H→CC AT E+E-

Clean ILC event

Precision Higgs studies

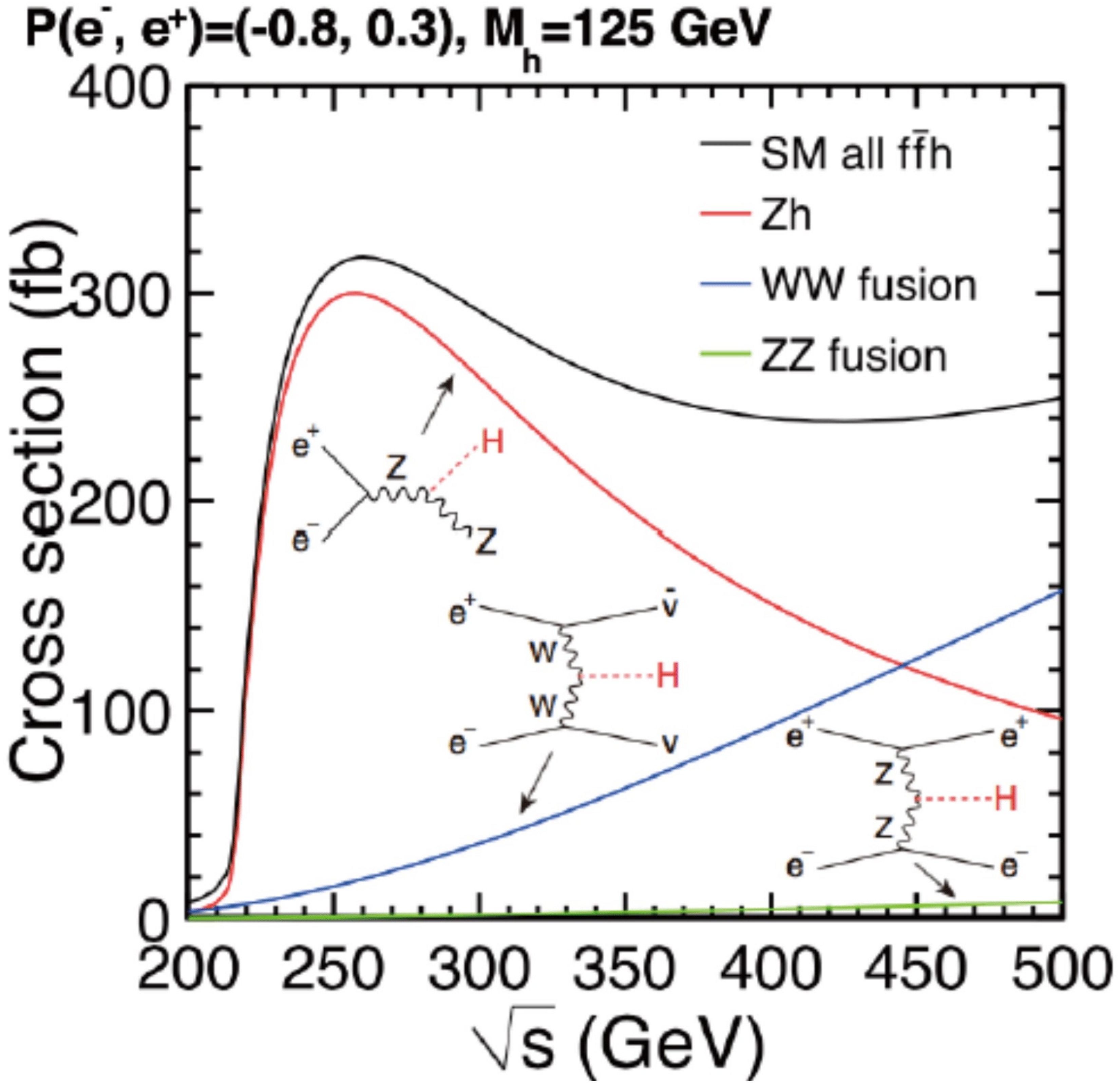
- e^+e^-: clean events
  - Little backgrounds
  - Accurate reconstruction

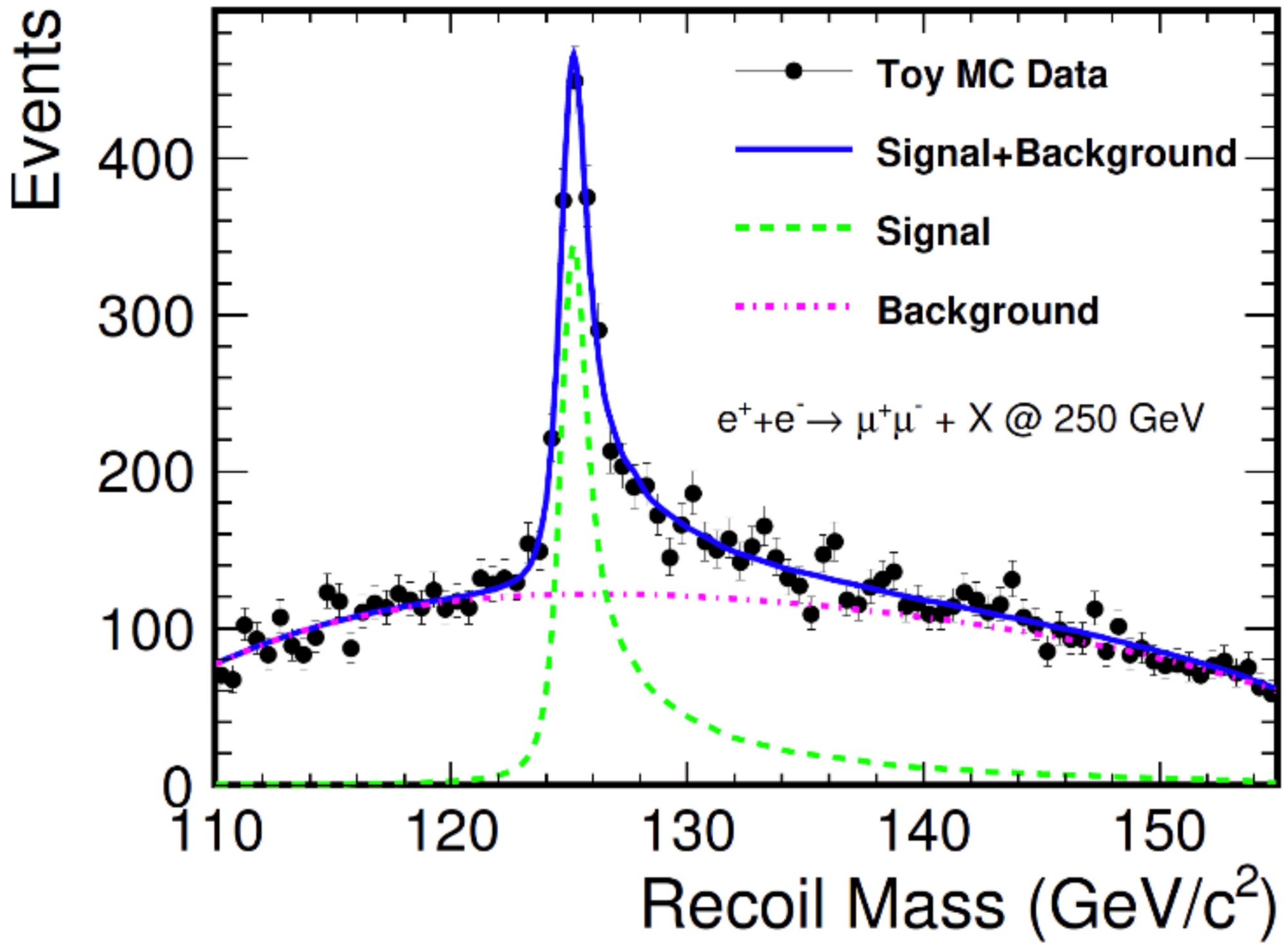


$\sqrt{s} = 250$ GeV, $e^+e^- \to Zh \to \mu^+\mu^- h$

ANALYSIS

ILC example

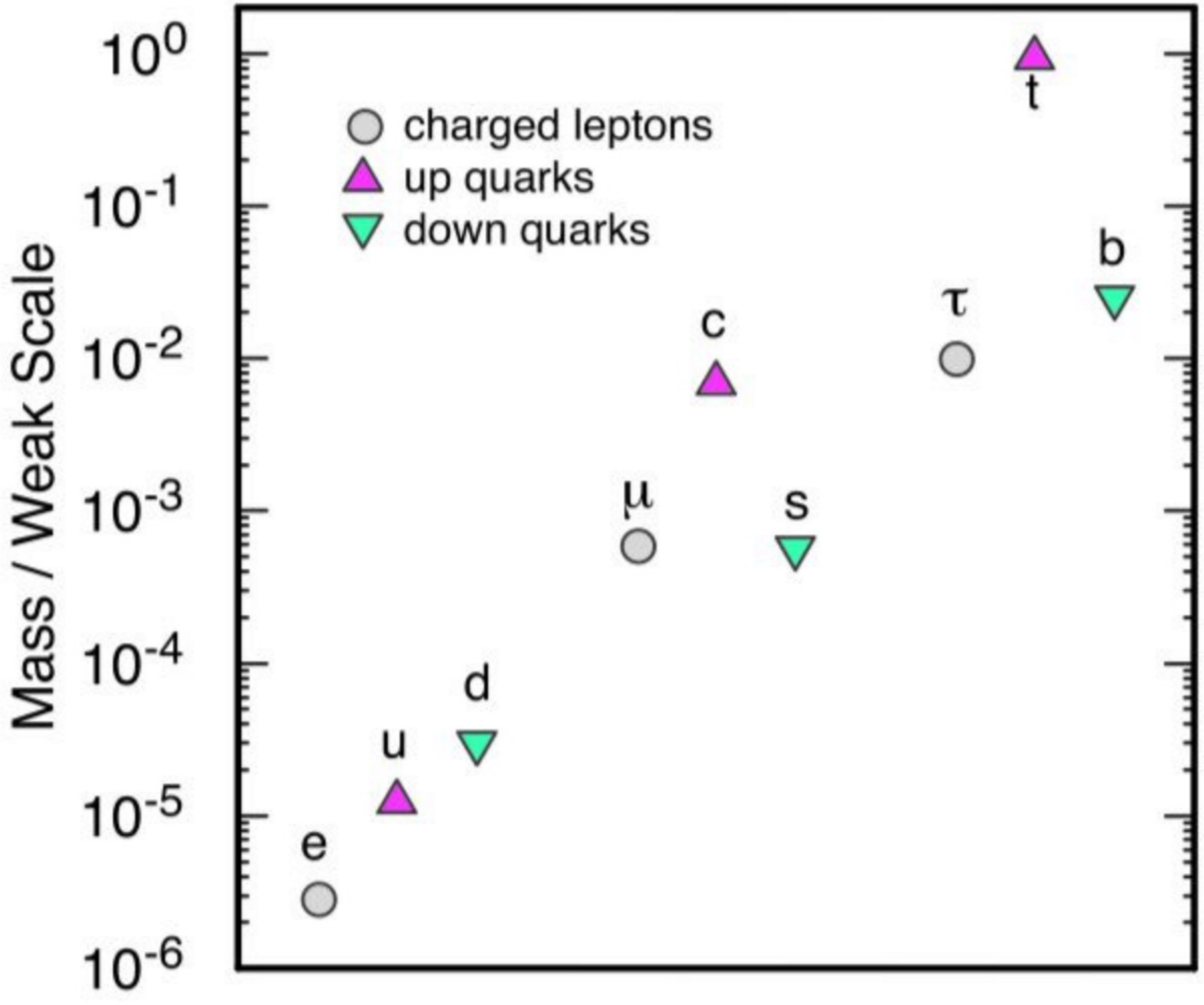




FERMION MASSES

Masses of charged fermions

- Deeper reason?
  - We don't know (yet)



Tristandard Model? ;)

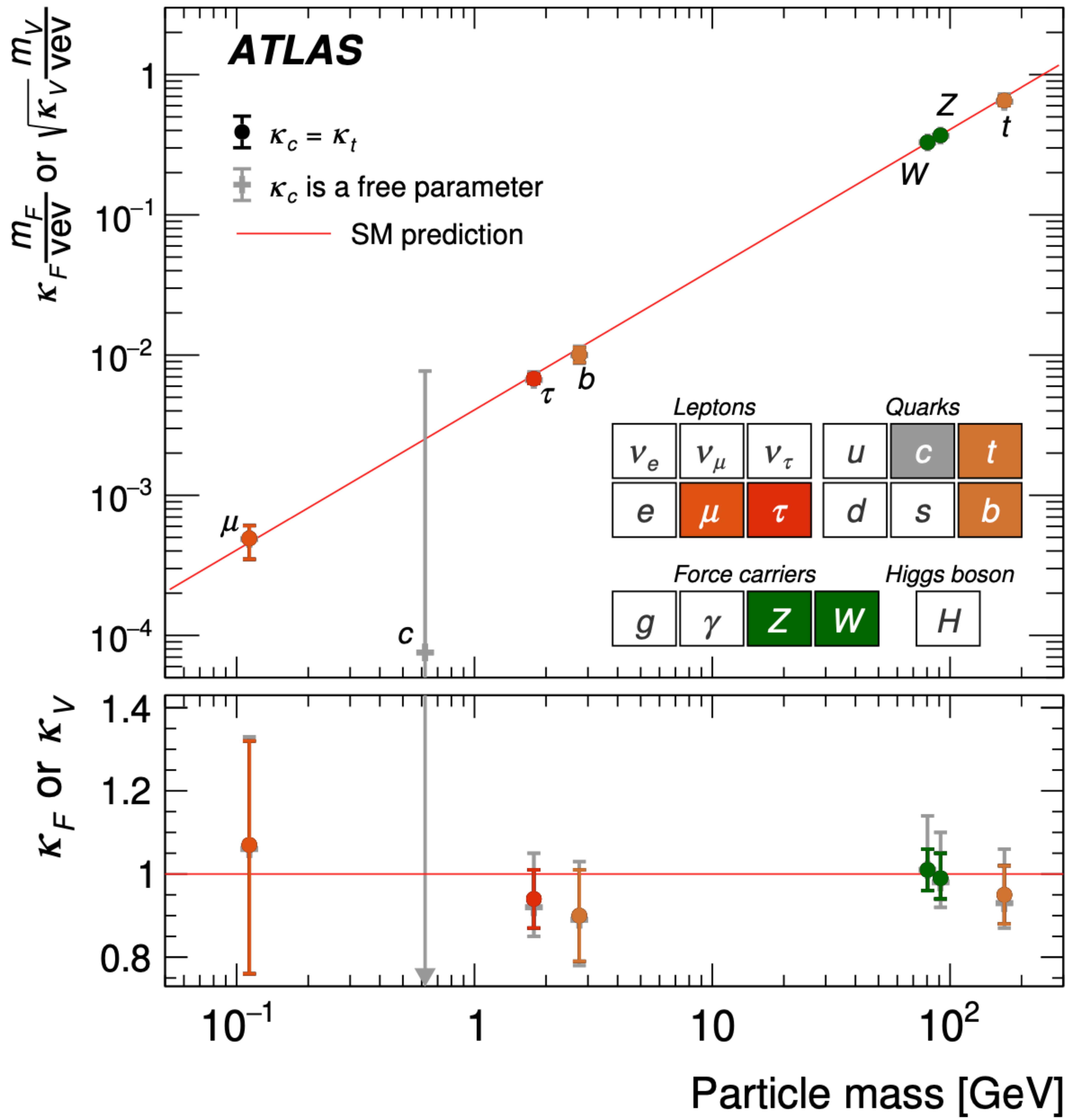
HIGGS

Second generation: H→cc

- First glimpse at HL-LHC?
  - e^+e^- collider would be ideal

M.Stamenkovic
PhD UvA 2022

Nature, 4 July 2022



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DARK MATTER

Related to Higgs?

HIGGS INVISIBLE

Invisible particles

- Dark Matter
- Neutrinos

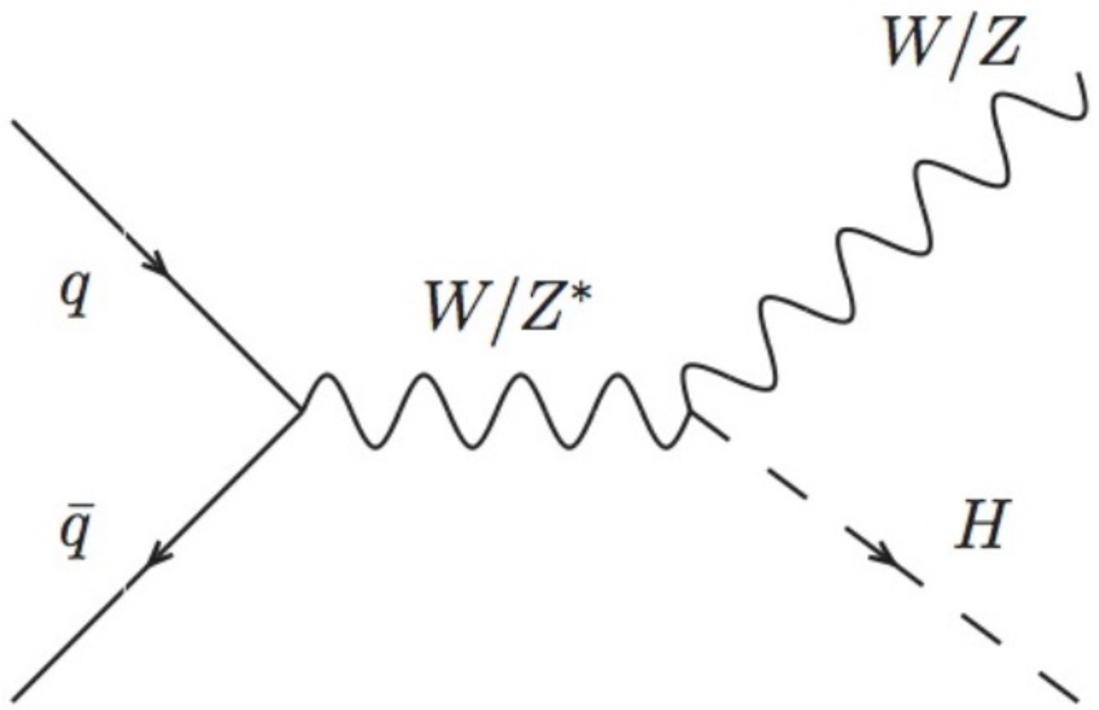
How do they get mass?

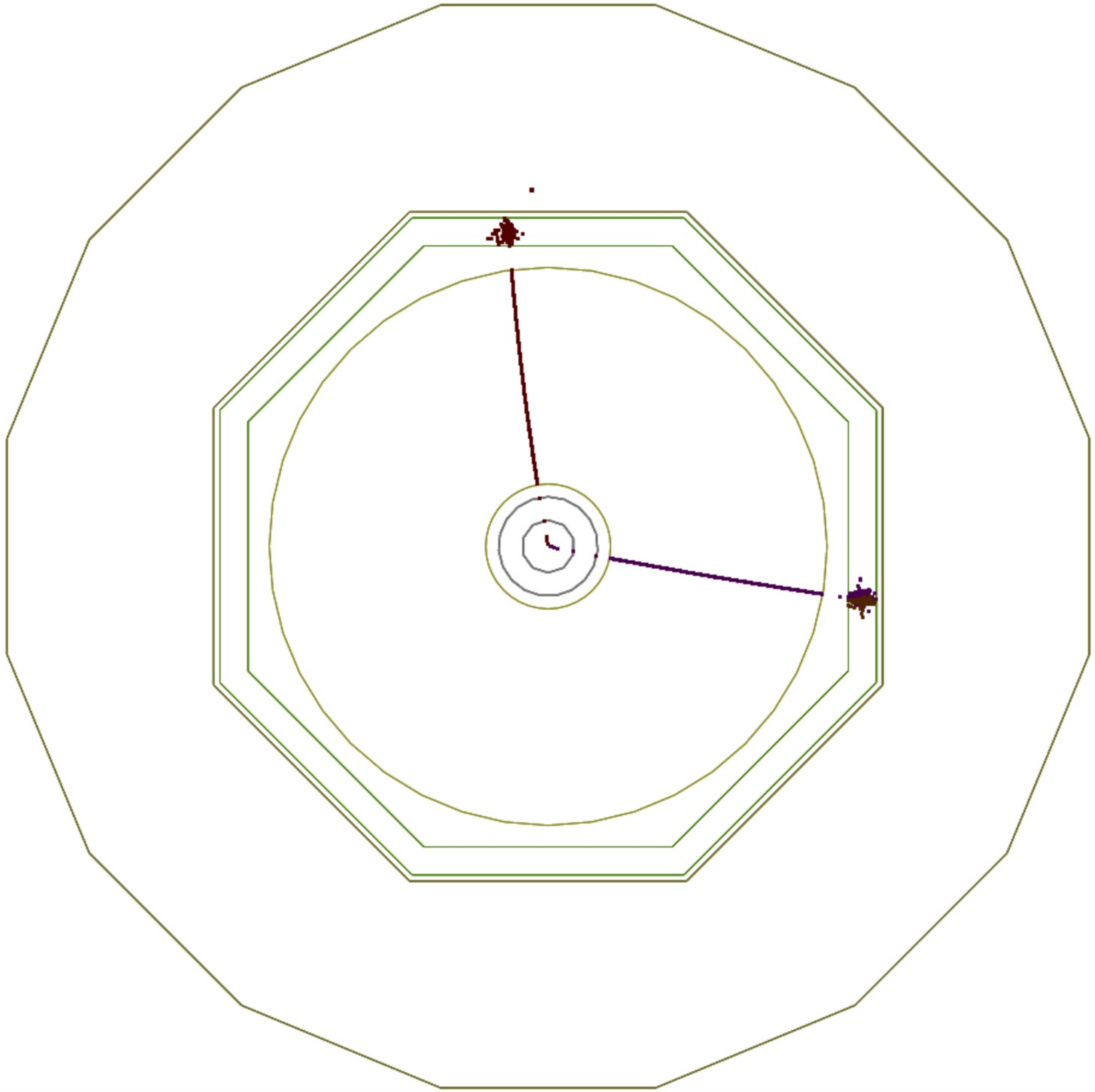
- Higgs interaction?

HIGGS INVISIBLE

Use ZH recoil

- Z(ll)H(inv)
  - ILC event



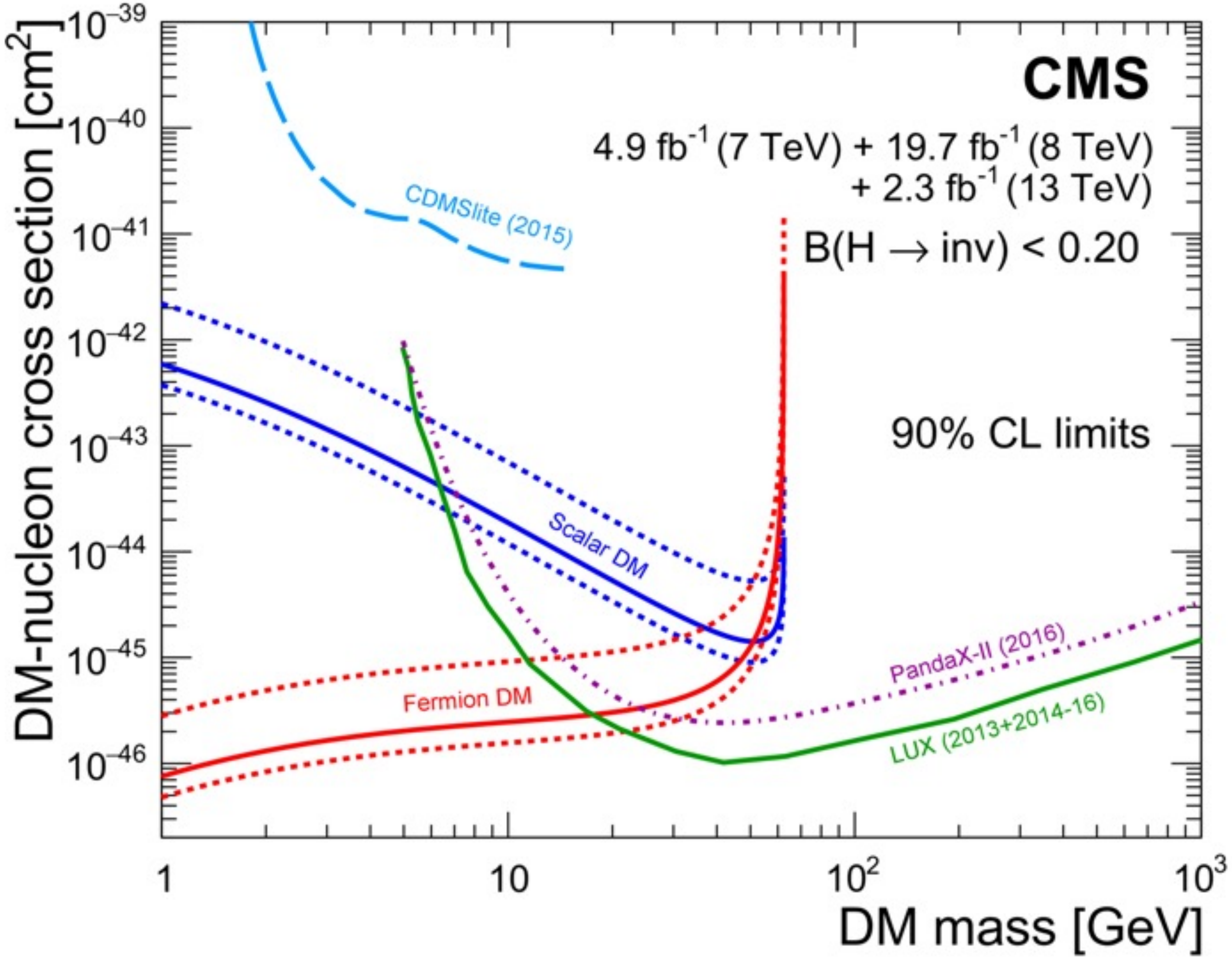


HIGGS INVISIBLE

Dark Matter

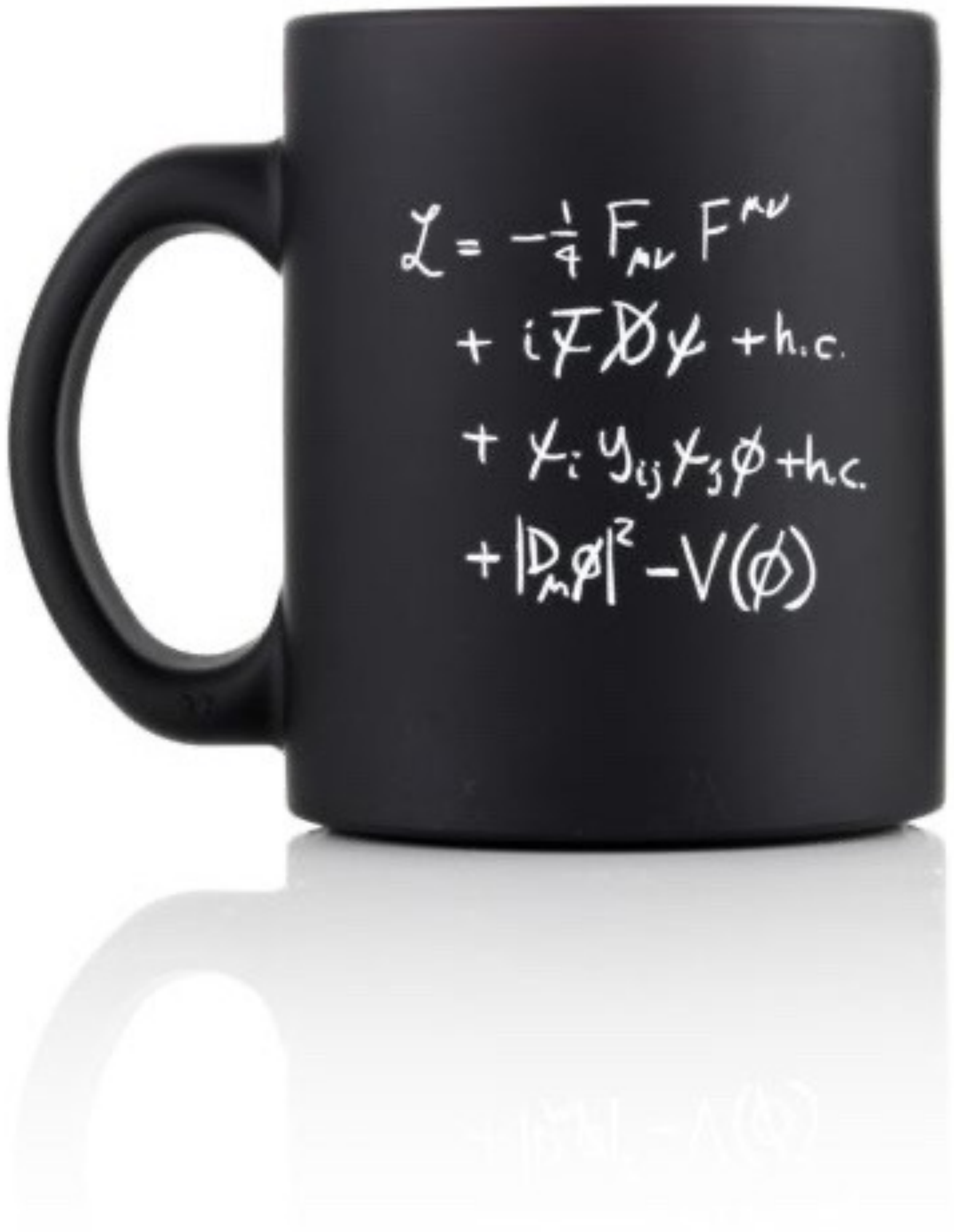
- Higgs interaction?
  - Complementarity

Will make a large jump at an e+e- collider



UNIFICATION?

From SM mug to GUT cup?



?

Dark Matter
Dark Energy
3 generations
GUT

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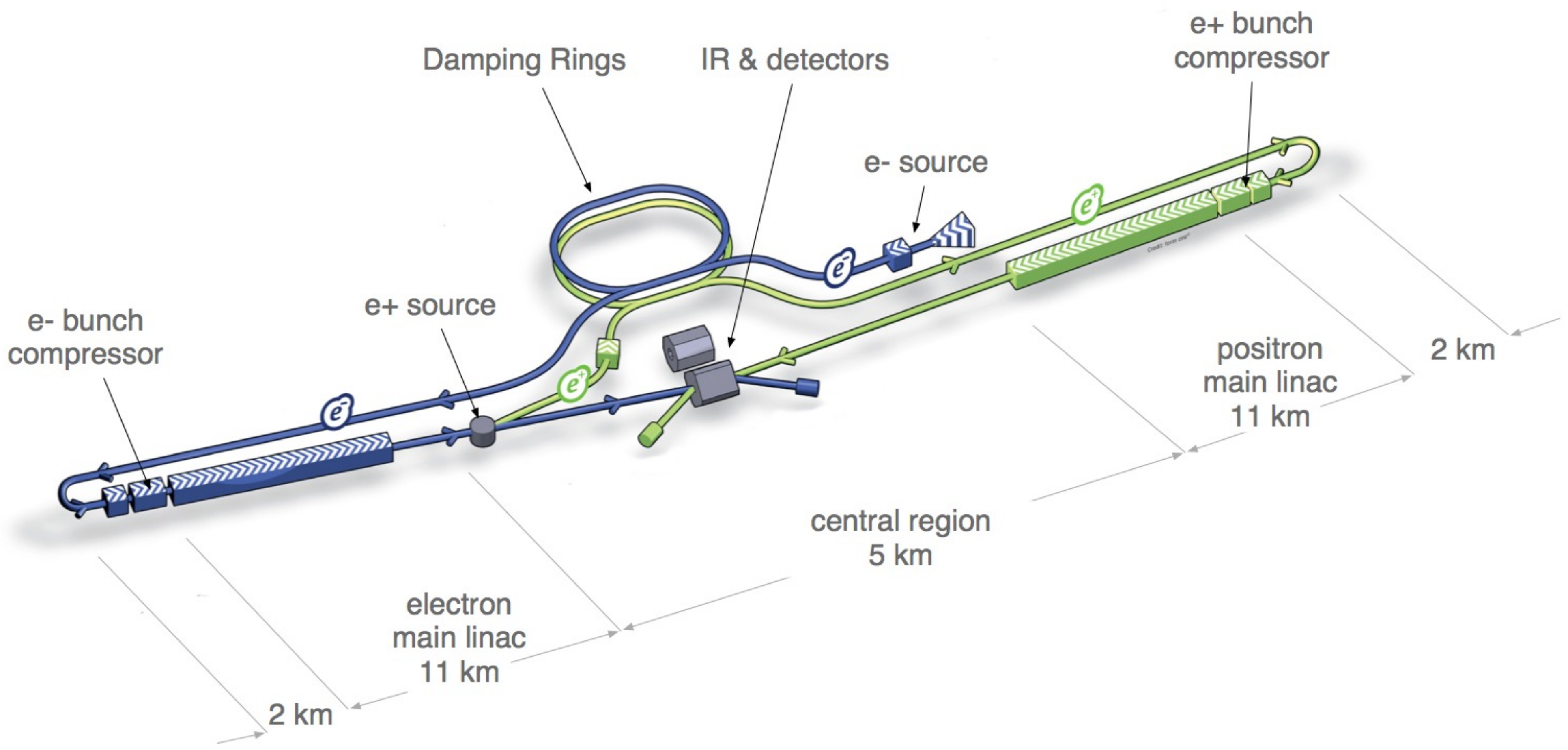
E+E- OPTIONS

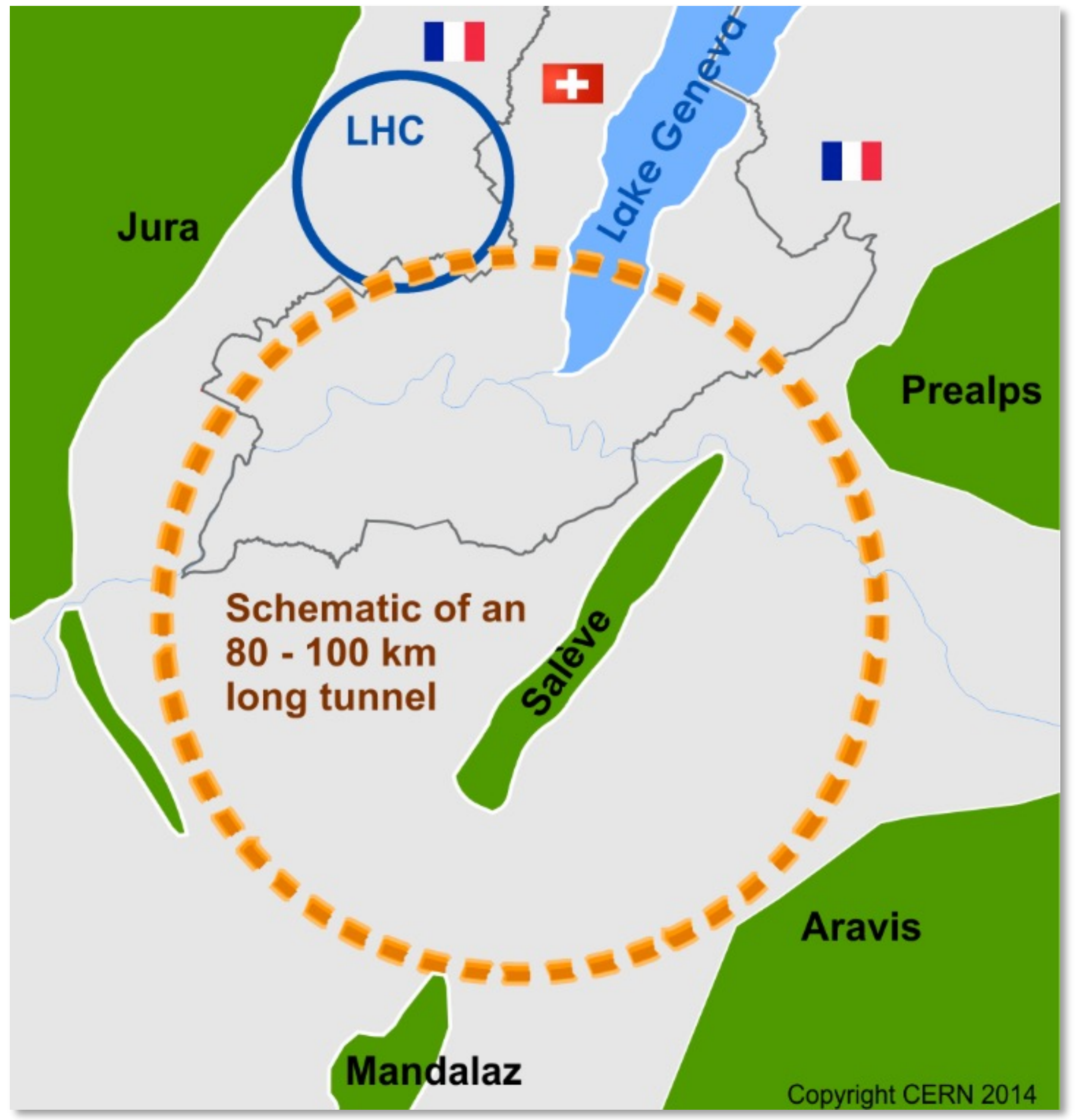
Linear

- Technology ready
- Extend for higher energy
- Lower luminosity

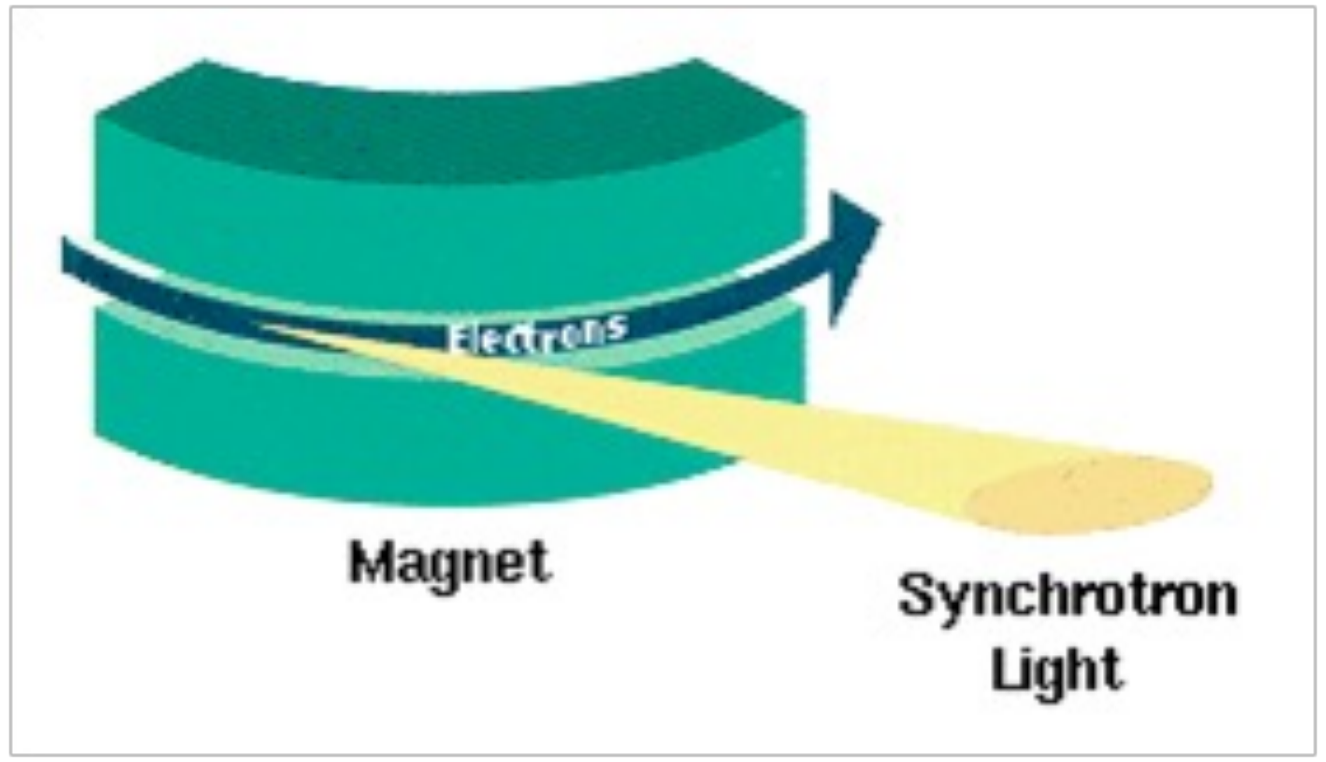


Circular

- Larger luminosity
- Can reuse for pp
- Maximal energy



SYNCHROTON RADIATION



Charged particles in circular orbit: energy loss

- Acceleration in magnetic field: photon emission
  - "Synchrotron radiation"

Emitted power:

$$\Delta P = \frac{2q^2a^2}{3c^3} \longrightarrow \Delta P = \frac{2q^2\gamma^4 v^4}{3c^3\rho^2}$$

- Acceleration: a^2
  - γ^4 and $1/\rho^2$

Energy loss per orbit:

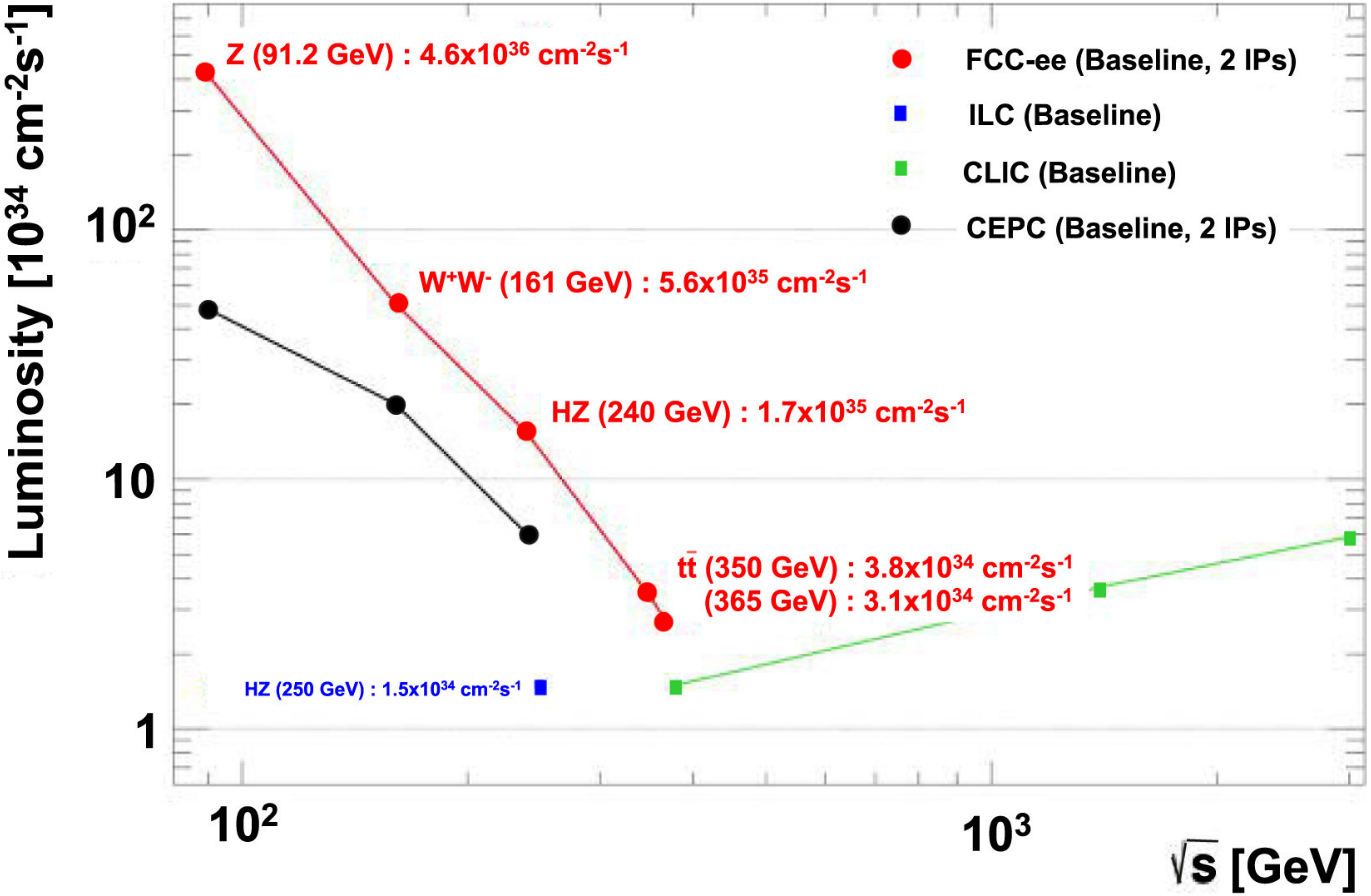
$$\Delta E = \frac{4\pi q^2 E^4}{3\rho\ m_q^4 c^4}$$

- So $1/m_q^4$

LUMINOSITY

e^+e^- projects

- ZH
- Z, WW, tt

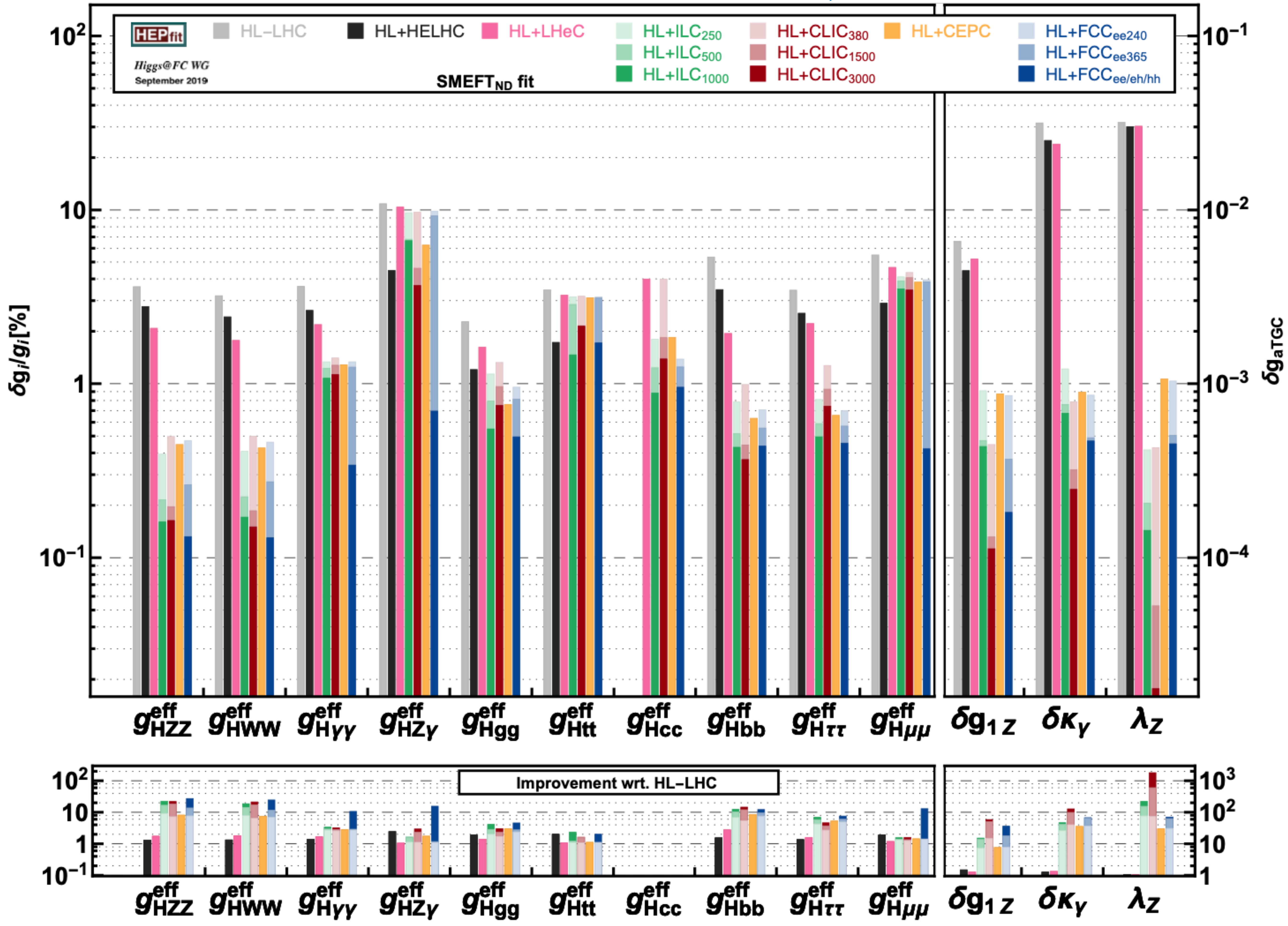


HIGGS FACTORY SENSITIVITY

All e^+e^- proposals perform similar

- A big step in Higgs physics
  - Factor ~10 wrt HL-LHC
  - Particulary K_W, K_Z, K_b, K_c

W.Verkerke et al, arXiv:1905.03764



Main limitations:

- Direct BSM search
- Higgs self-coupling

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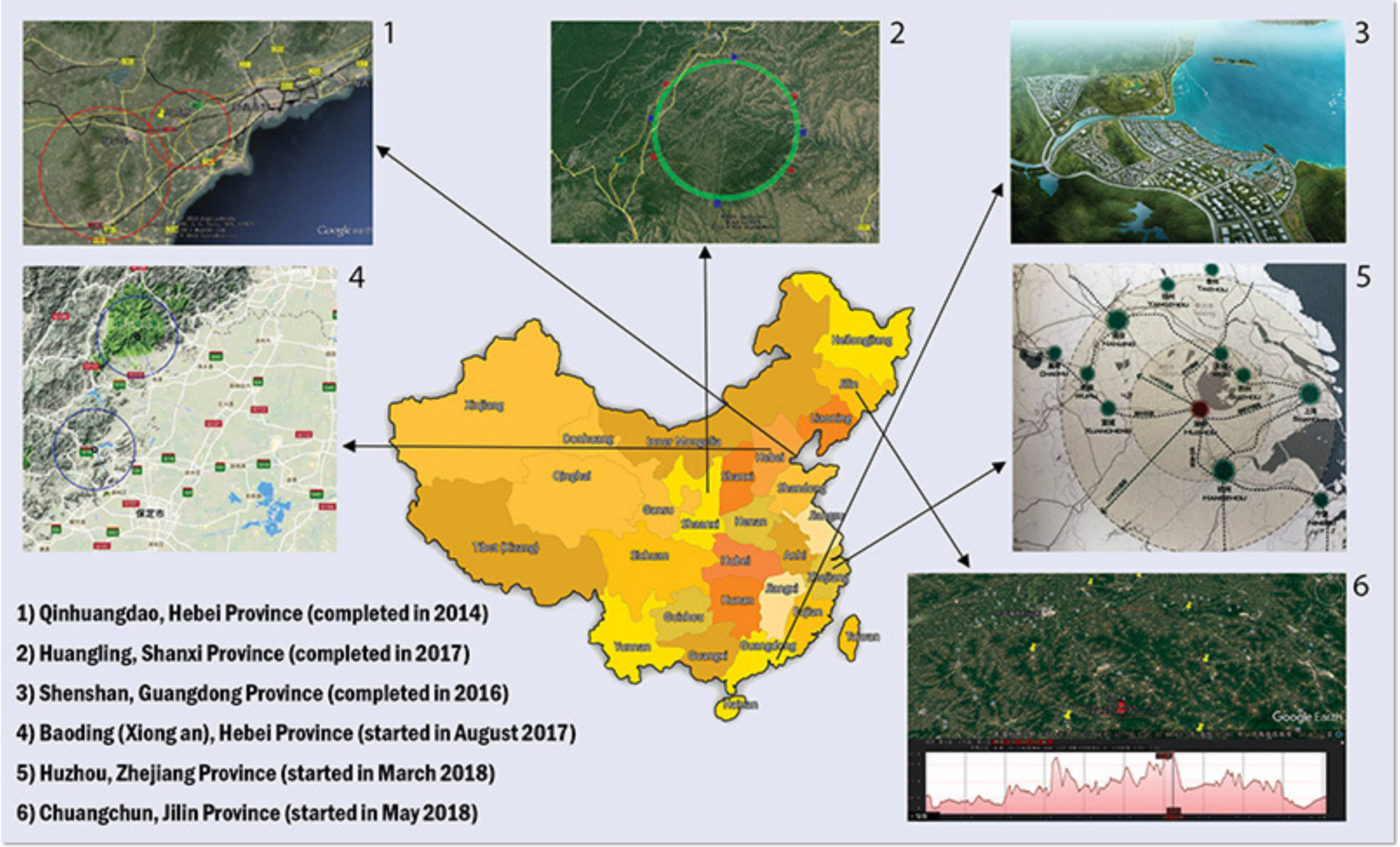
CHINA

CepC plans

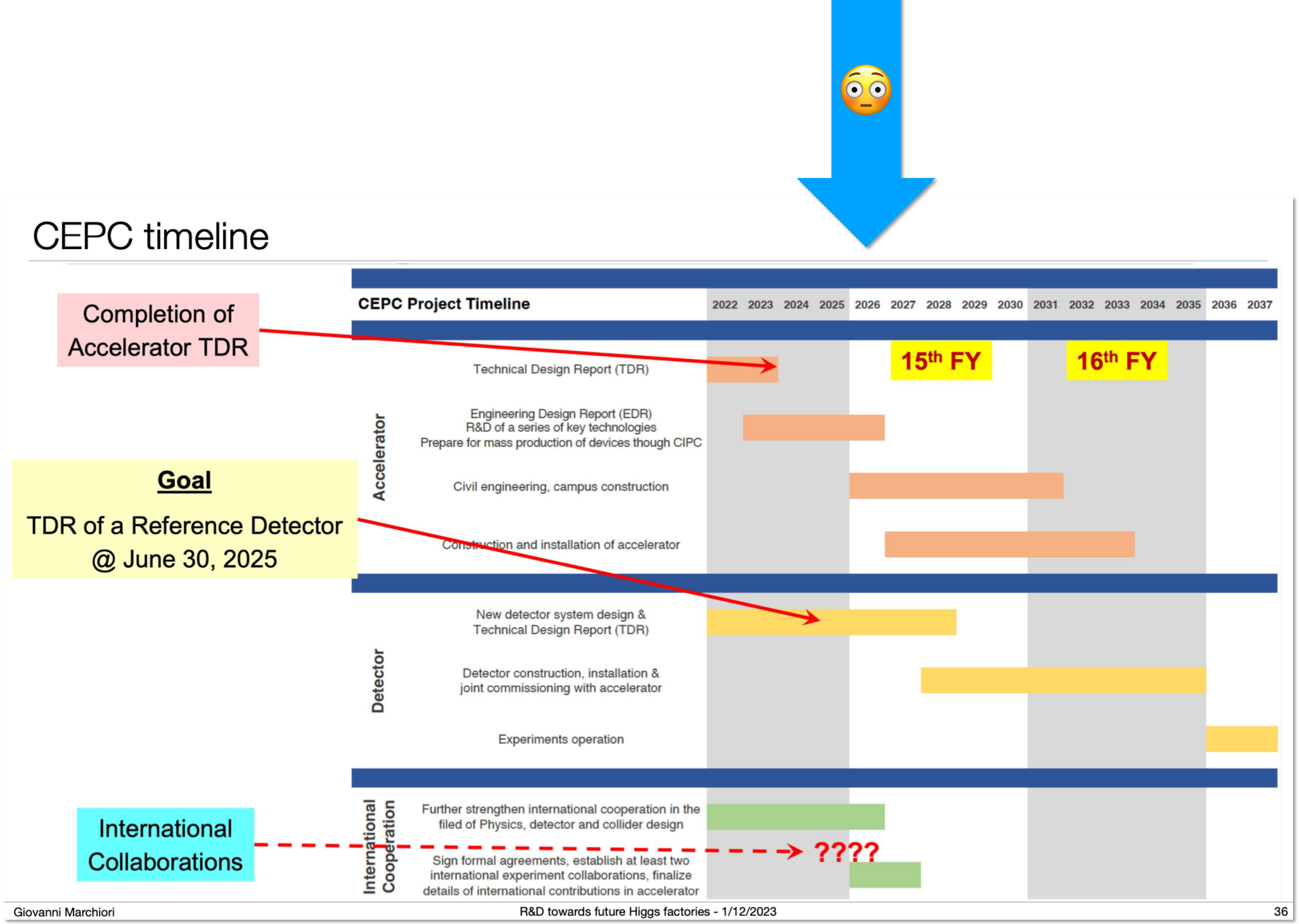
- Similar to FCC
  - Site studies advanced



CHINA

CepC timeline

- Civil engineering start in 2026!?
  - This would be gamechanger



E+E- CONS

Main limitations of e^+e^-:

- Direct BSM search
- Higgs self-coupling
  - Relatively low lumi at ZHH production

To probe self-coupling

- Need accelerator with higher energy

Self-coupling sensitivities:

- HL-LHC ~50%
- ILC/FCC-ee ~50% (loops)

Higher energy

- CLIC ~15%
- FCC-hh and MuCol: few %

➔ So we need to go to higher energy

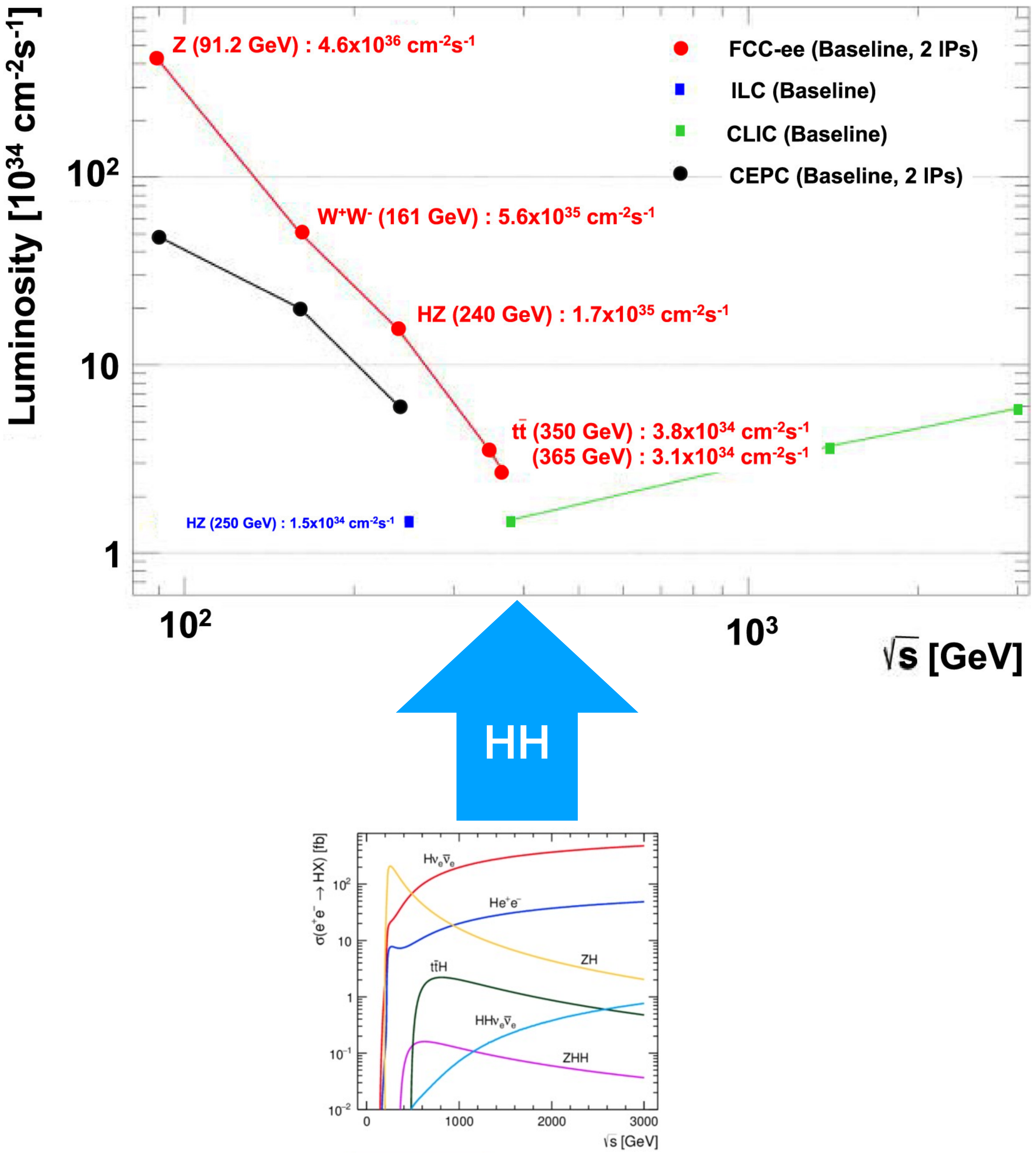
E+E- CONS

Main limitations of e^+e^-:

- Direct BSM search
- Higgs self-coupling
  - Relatively low lumi at ZHH production

To probe self-coupling

- Need accelerator with higher energy



➔ So we need to go to higher energy

FCC-hh: The Next Hadron Collider?

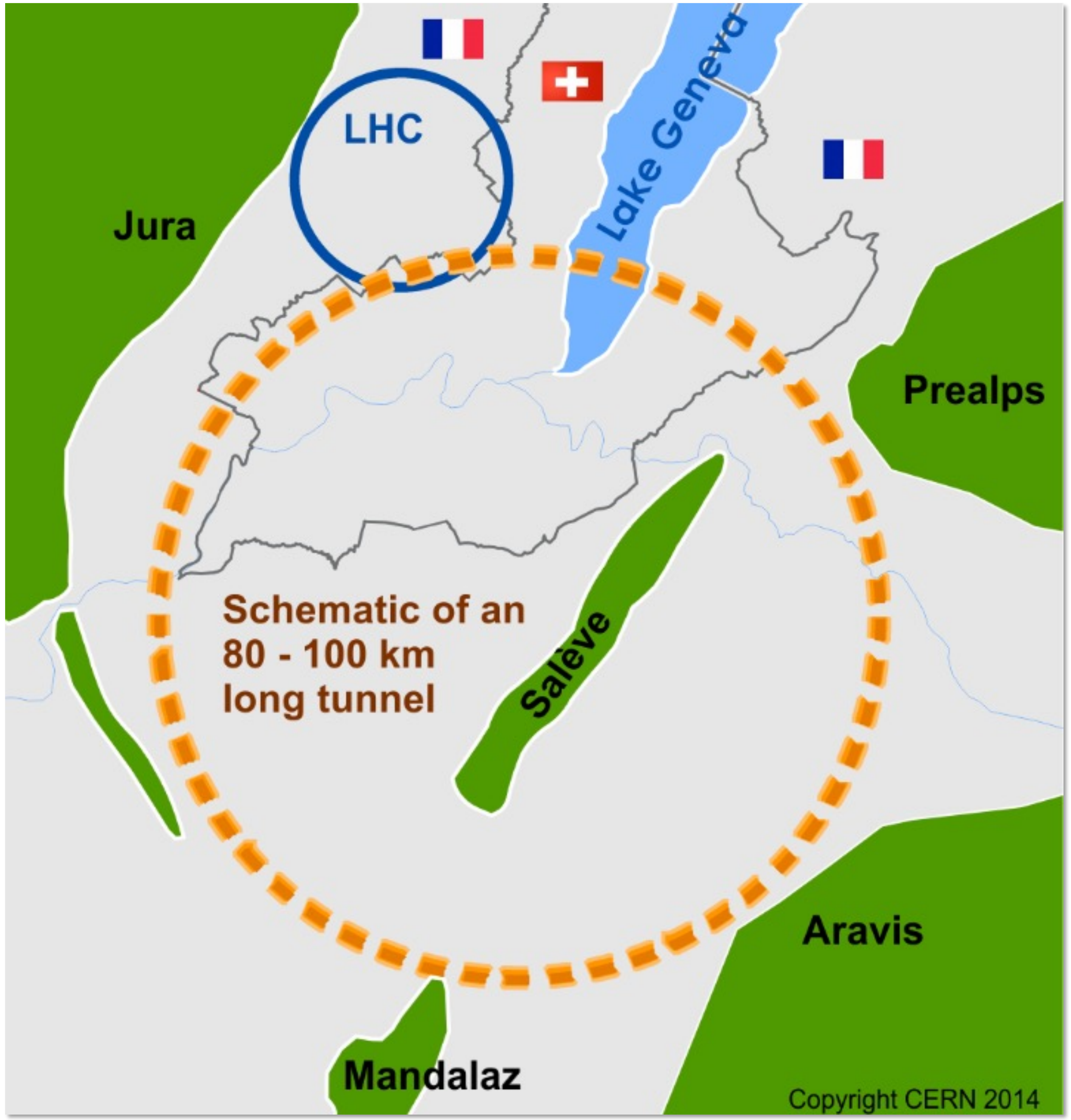
PHOTO: J. WENNINGER

HADRON COLLIDERS

The LHC is great

- “The LHC is an everything machine”
  - – A.Hoecker
- FCC is a large LHC:
  - Bigger ring
  - Stronger magnet

Not limited by synchroton radiation



CYCLOTRON

1931: The cyclotron

- Lawrence at Berkeley
  - First version: 11cm

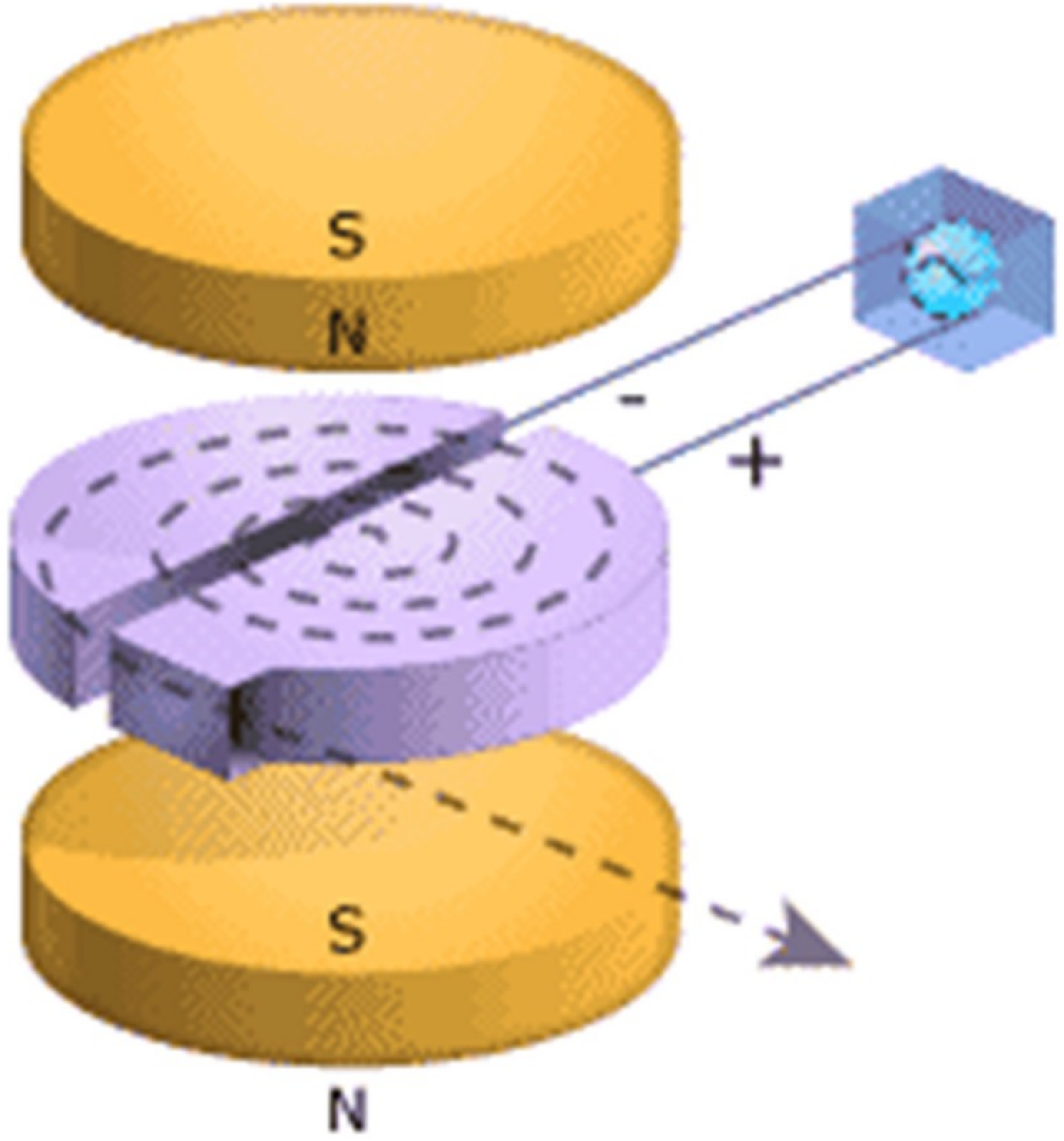
CYCLOTRON

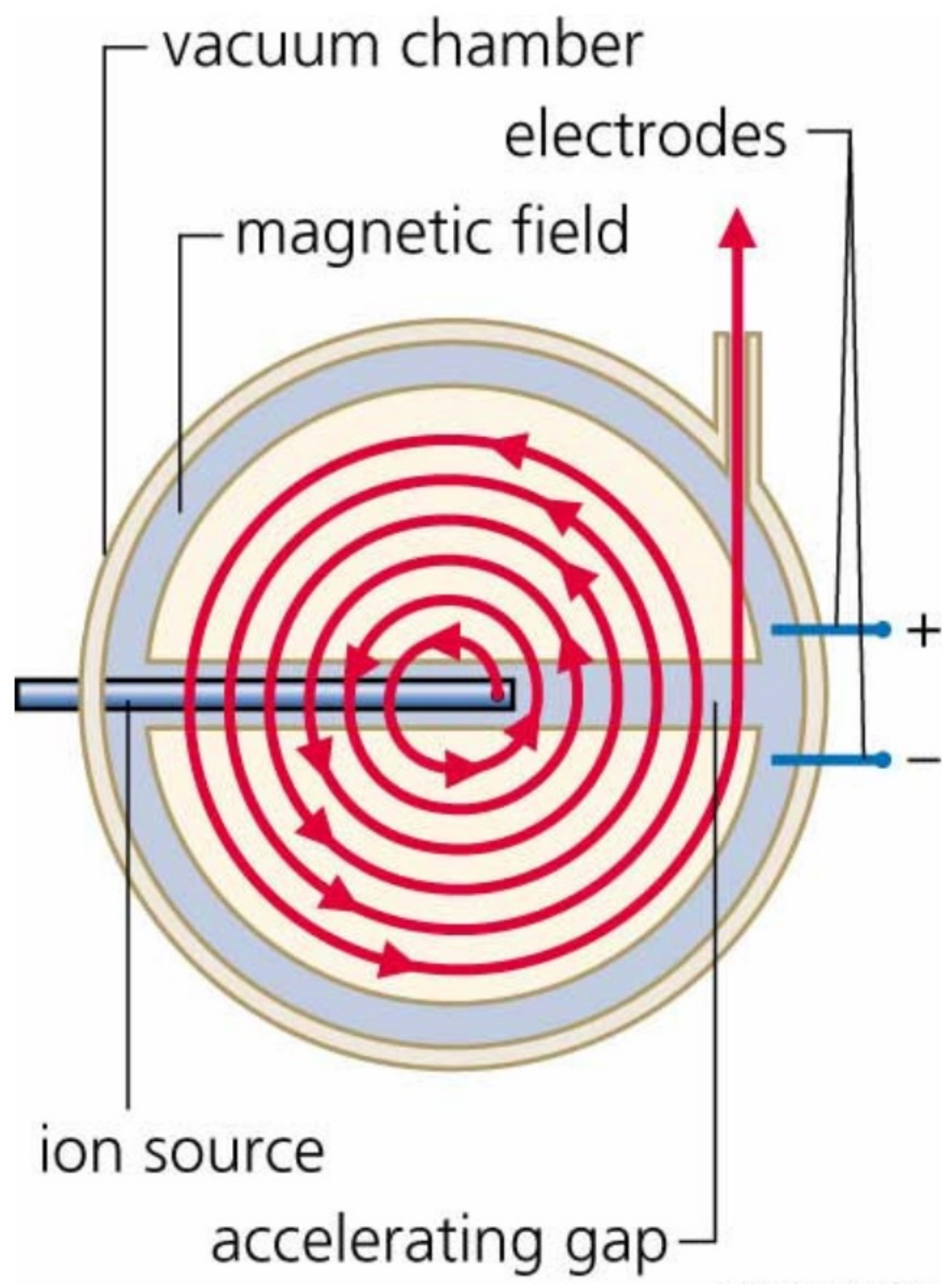
1931: The cyclotron

- Lawrence at Berkeley

Lorentz Force:

$$\frac{d\vec{p}}{dt} = \vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$





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CYCLOTRON

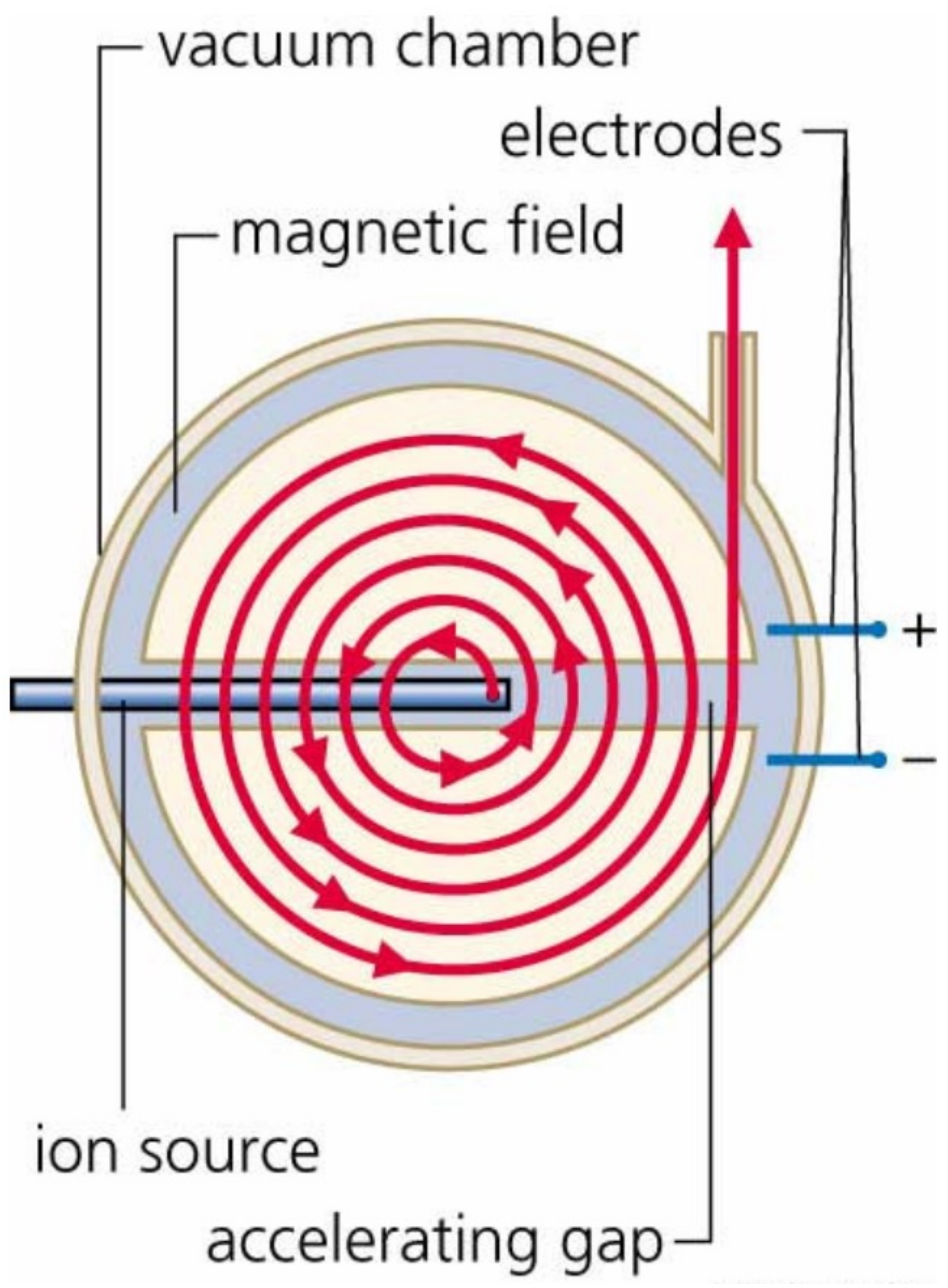
How does the momentum depend on B, q, R?

1931: The cyclotron

- Lawrence at Berkeley

$F_{Centripetal} = F_{Lorentz}$

- $mv^2/R = q \times v \times B$



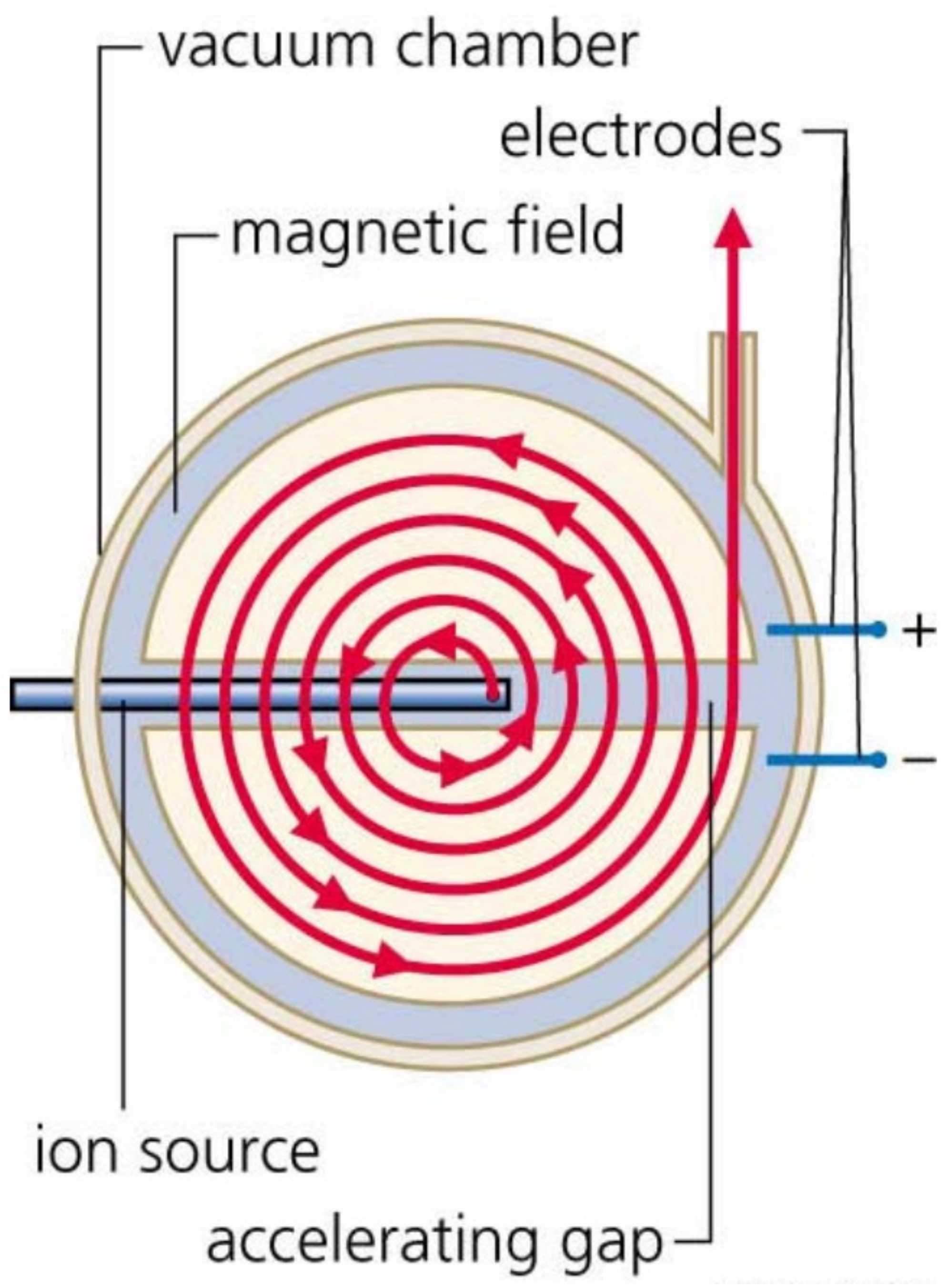
CYCLOTRON

1931: The cyclotron

- Lawrence at Berkeley

$F_{Centripetal} = F_{Lorentz}$

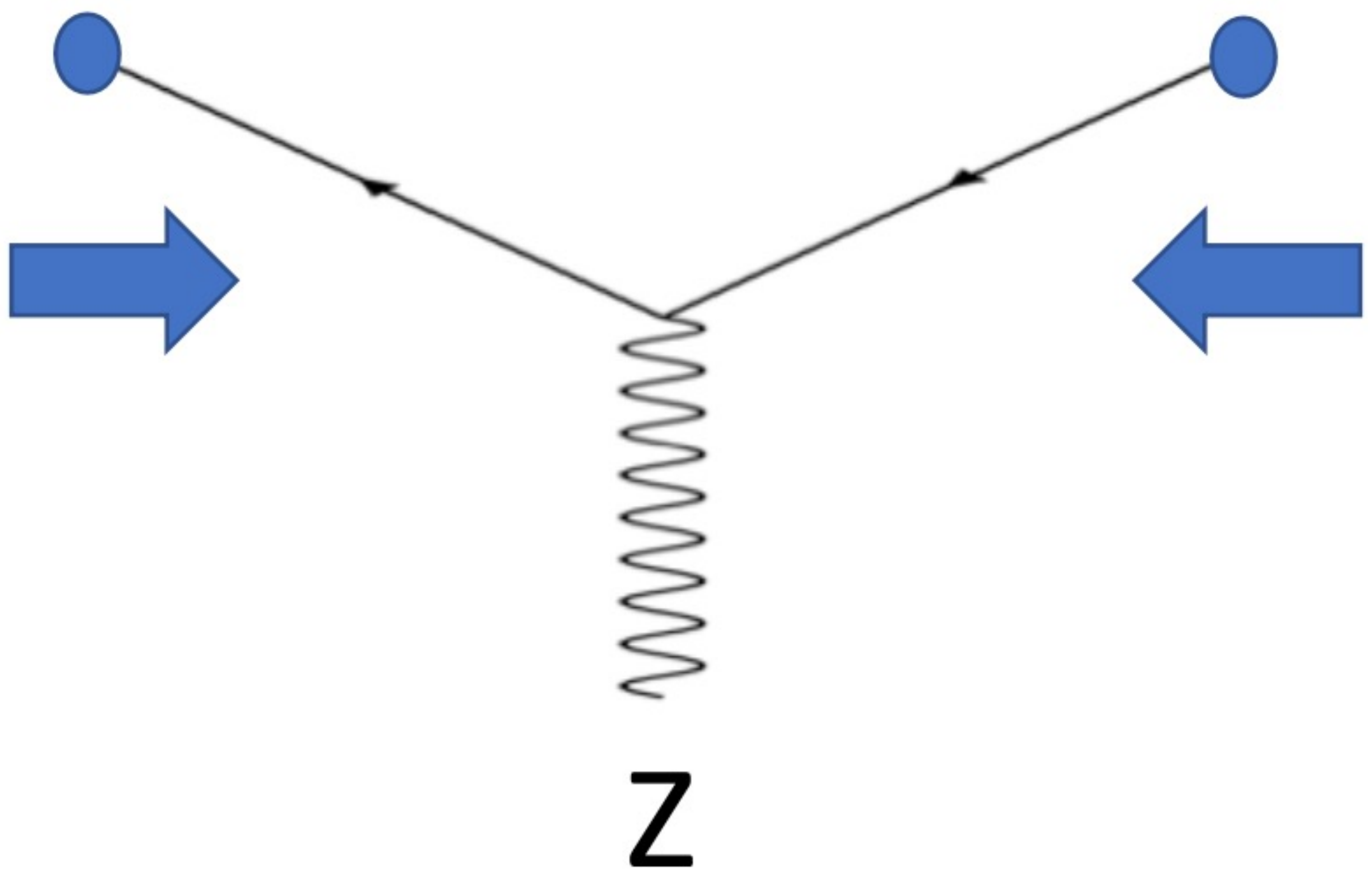
- $mv^2/R = q \times v \times B$
  - Momentum:
    $p = q \times B \times R$



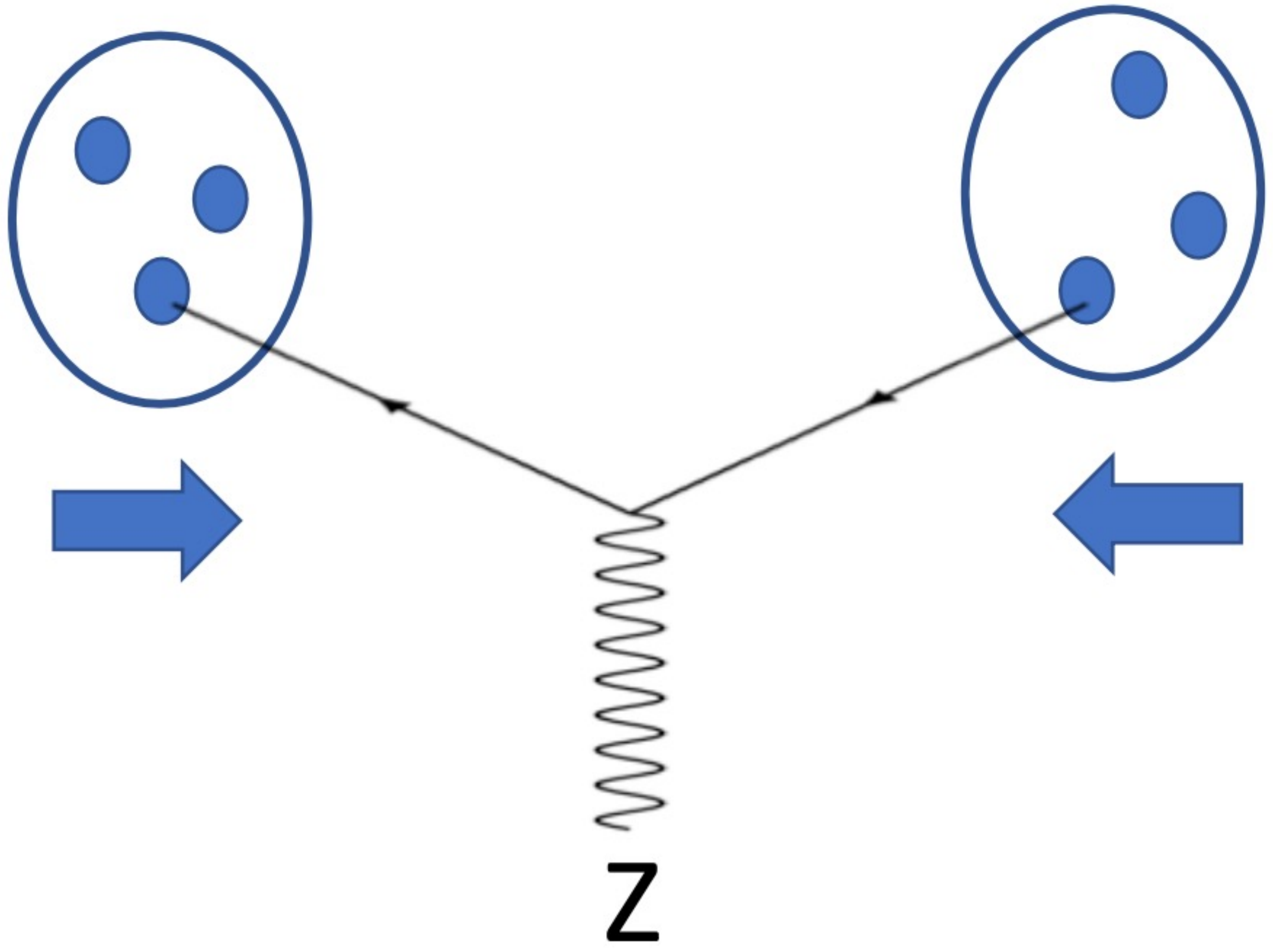
EE VS PP

ee

- synchrotron radiation



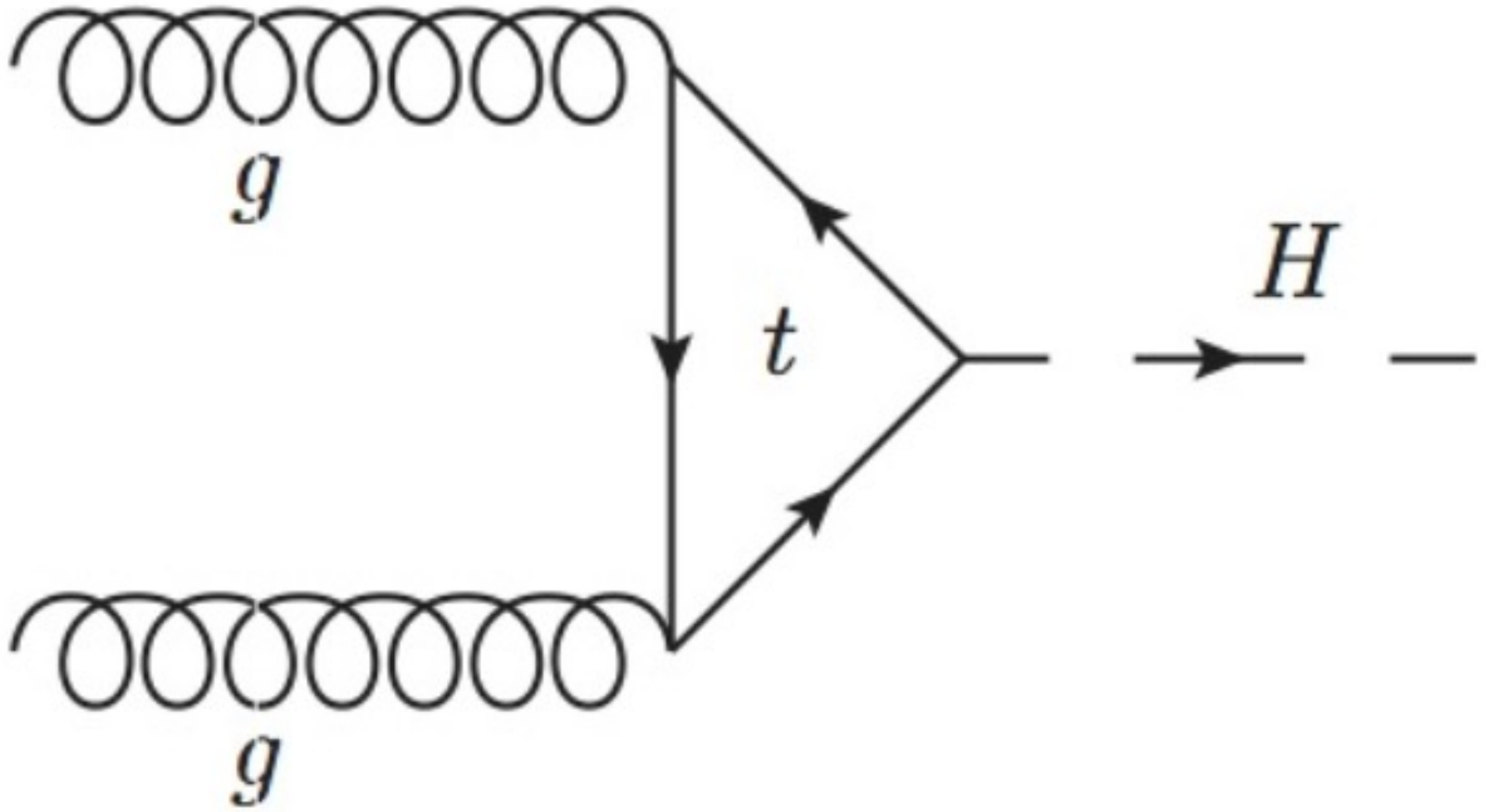
- pp
  - proton energy fraction



LHC

Higgs at the LHC

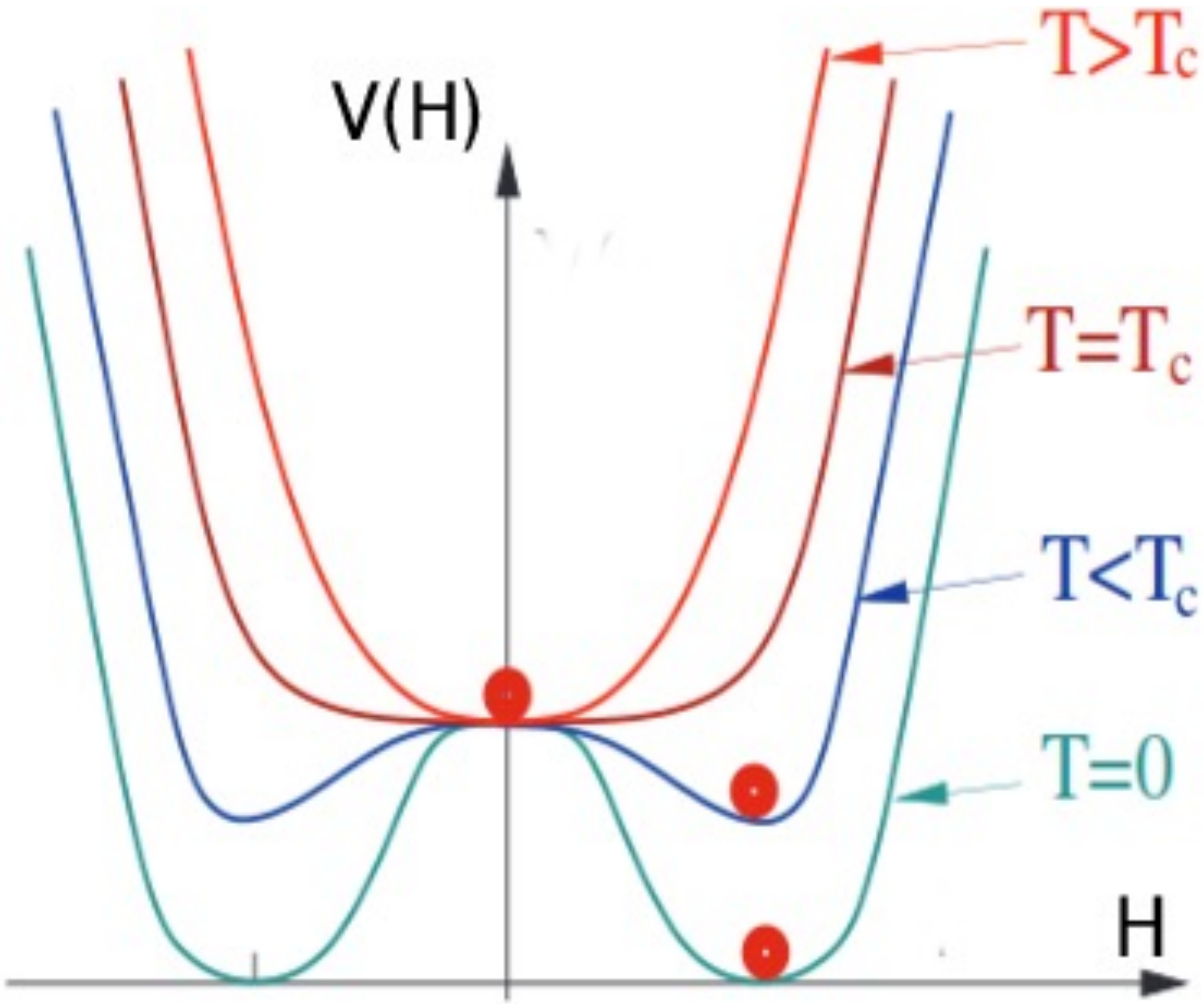
- pp @14 TeV
  - Gluon fusion



ANTI-MATTER

Phase transition

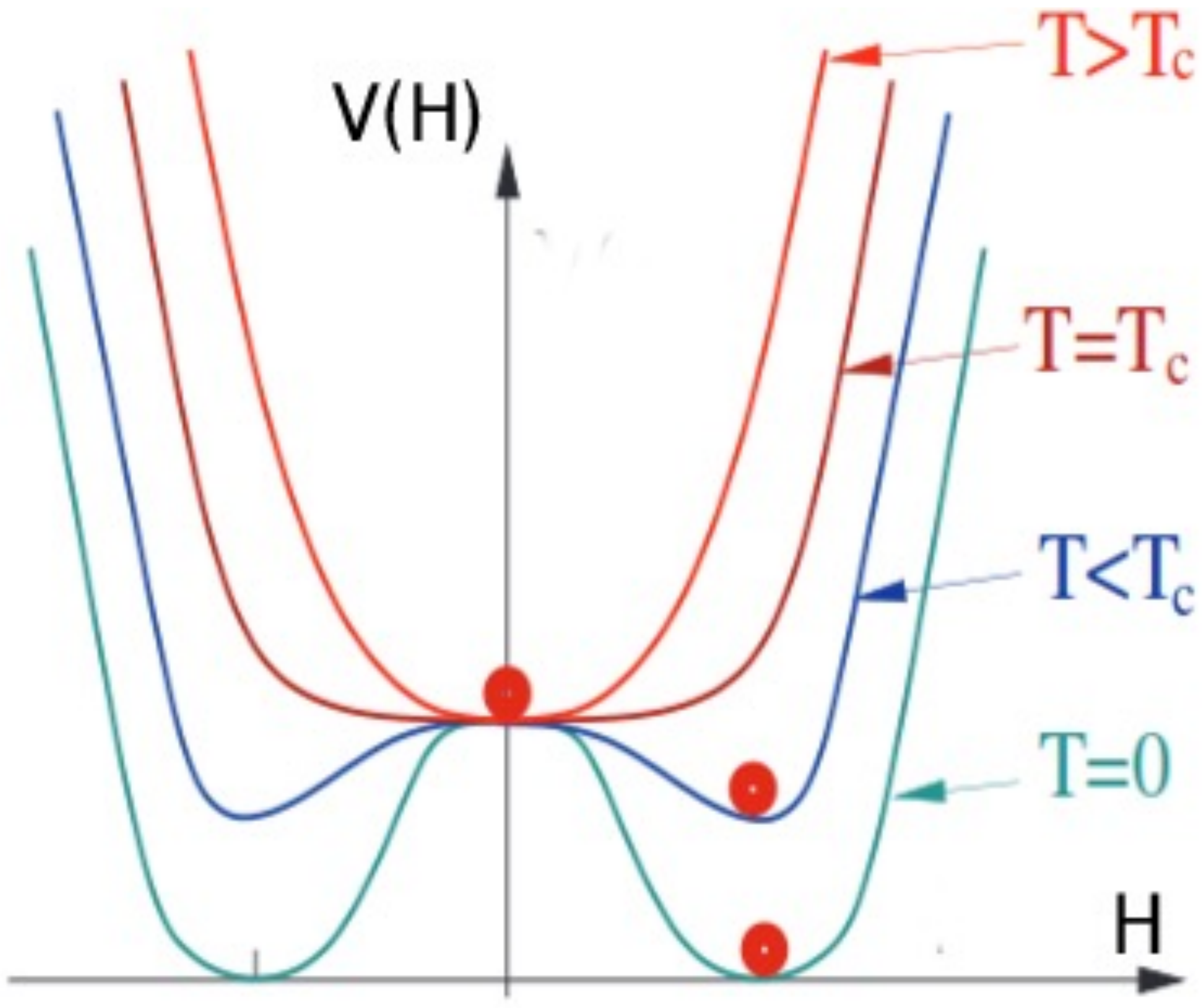
- Standard Model
  - Smooth 2nd order

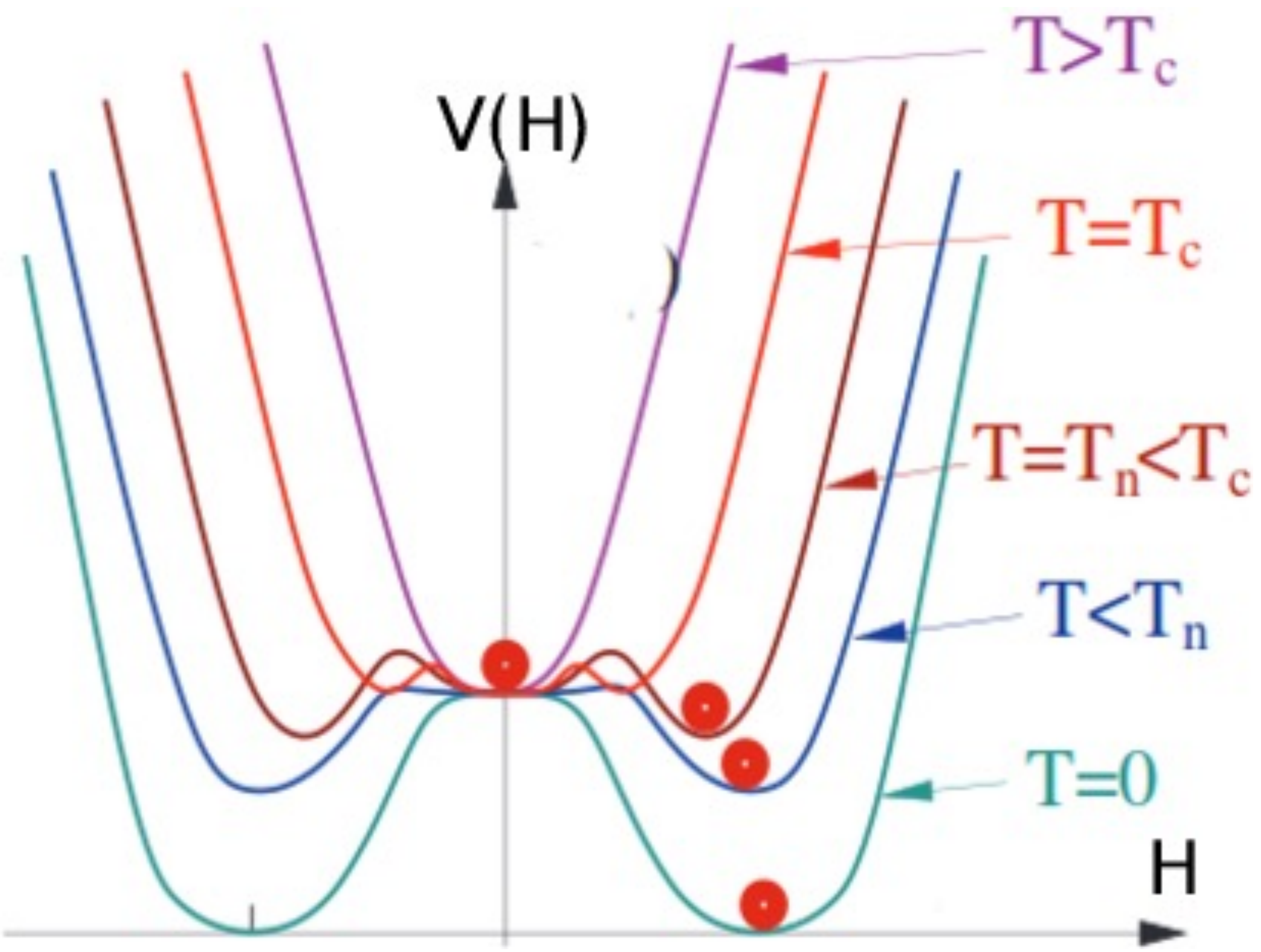


ANTI-MATTER

Phase transition

- 2nd order
  - Smooth
- 1st order
  - Abrupt



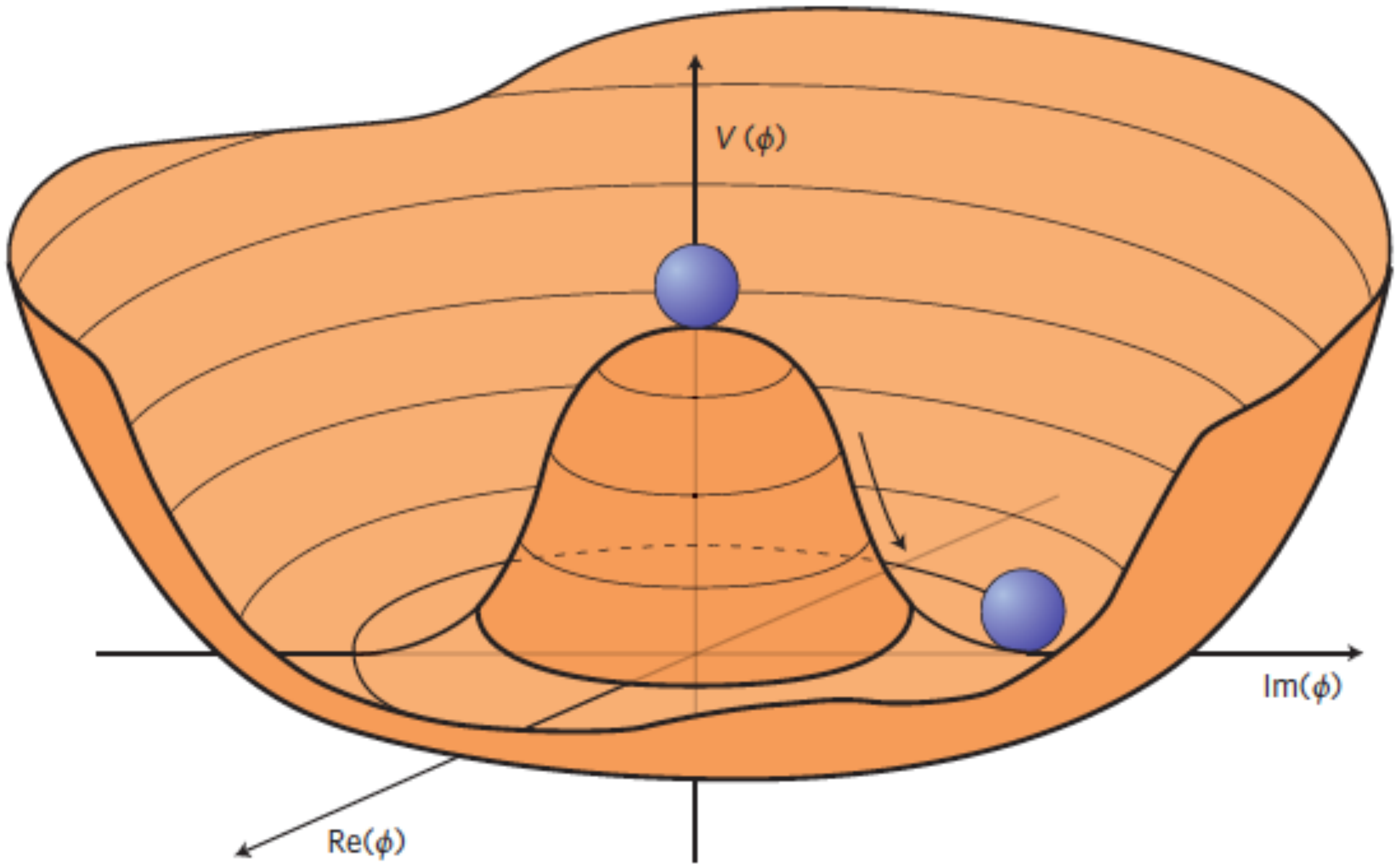


We need new physics beyond the standard model

HIGGS POTENTIAL

Quadratic and quartic terms

- $V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$
  - Self-interaction!



HIGGS POTENTIAL

Quadratic and quartic terms

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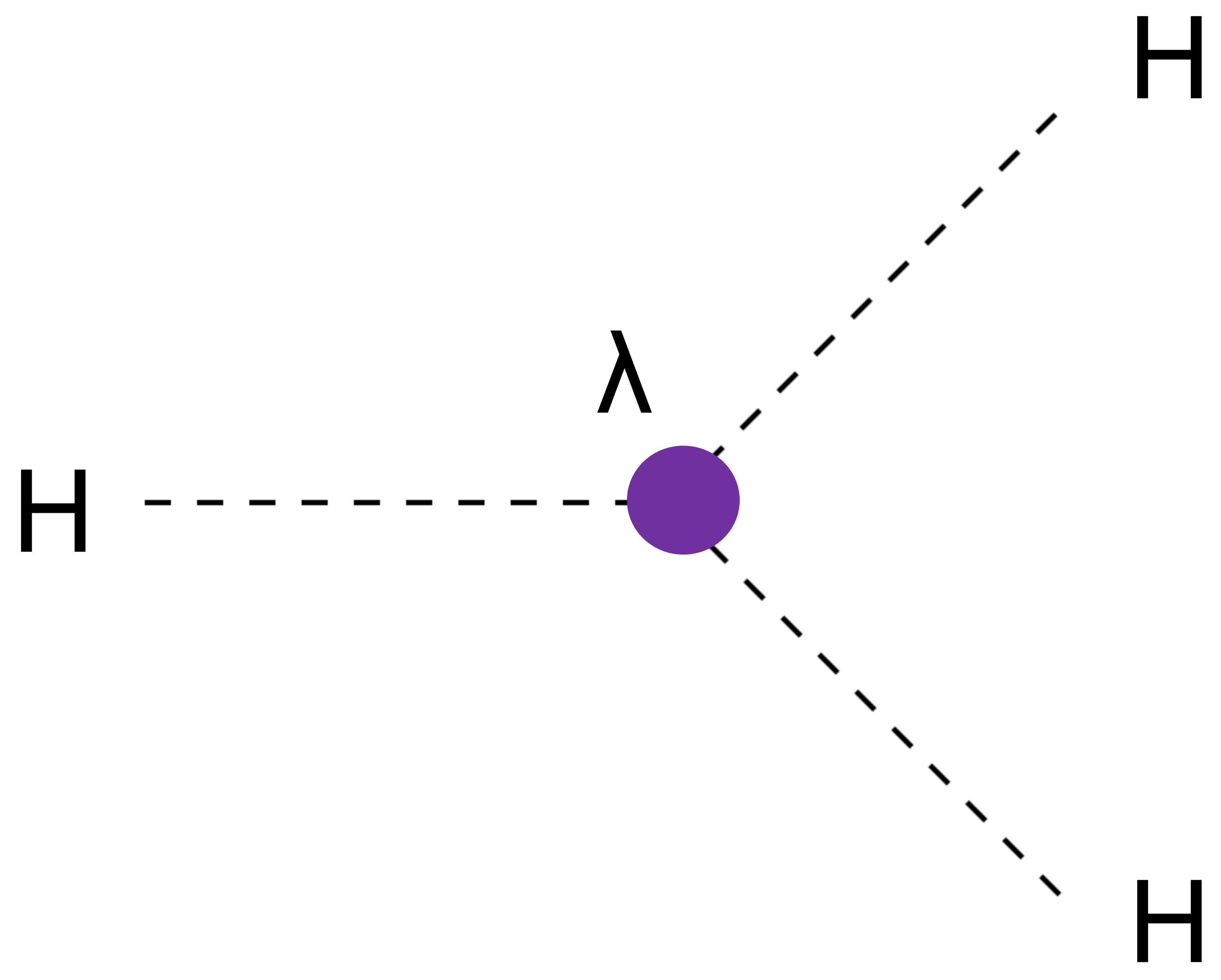
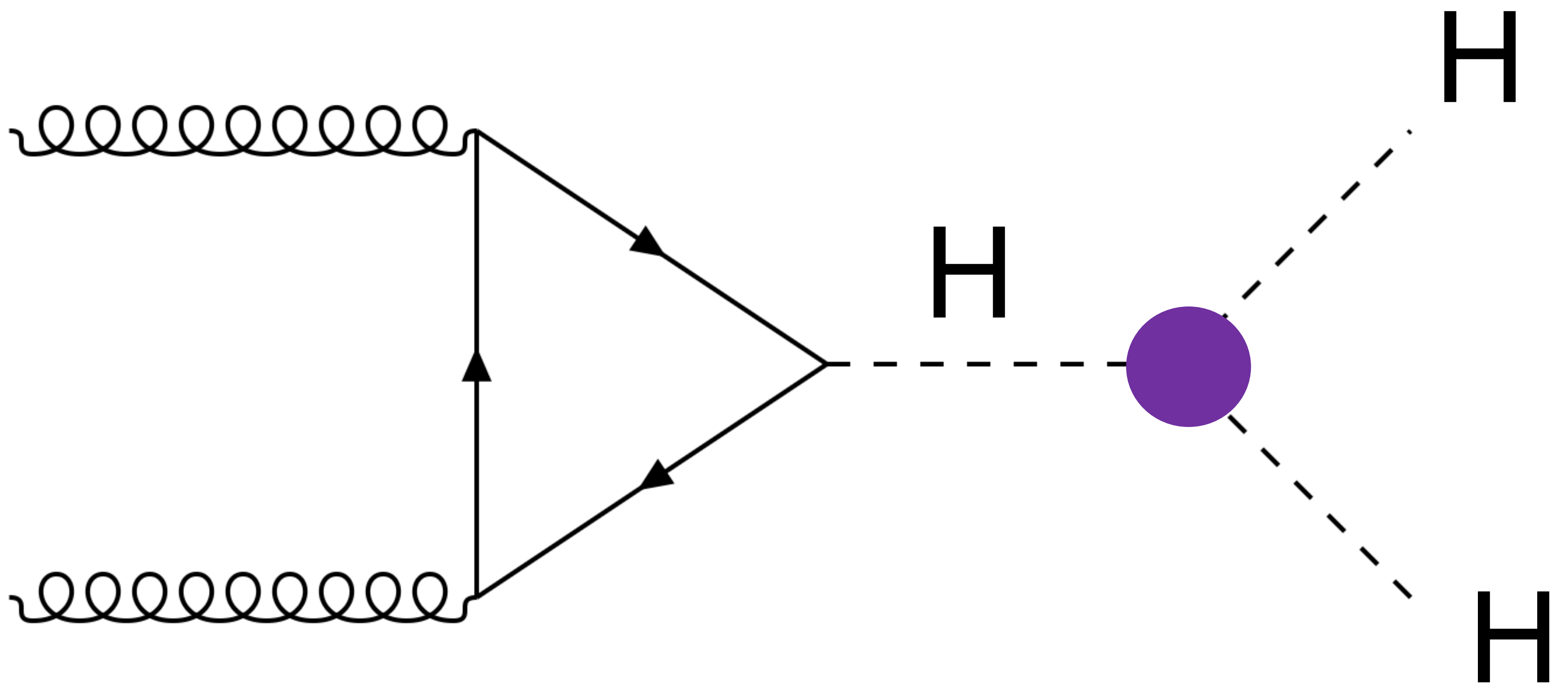


How would you measure this?

DI-HIGGS

Search for HH production!

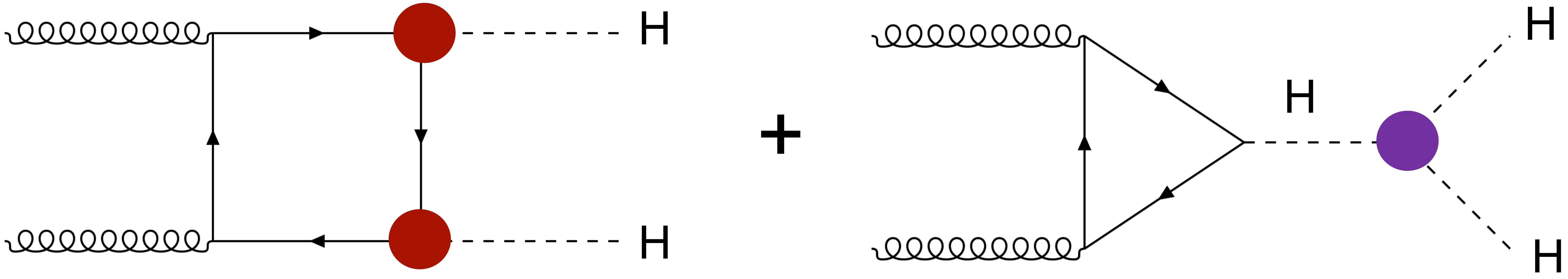
- Nikhef PhD studies



DI-HIGGS

HH production

- Challenge: interference!



HH @ FCC-HH

The search for Double-Higgs is the main subject of HL-LHC

- Learn about Higgs potential
  - HL-LHC: sensitivity to K_{λ}~50%
  - FCC-hh: sensitivity to K_{λ}~5%

We need to go to the energy frontier

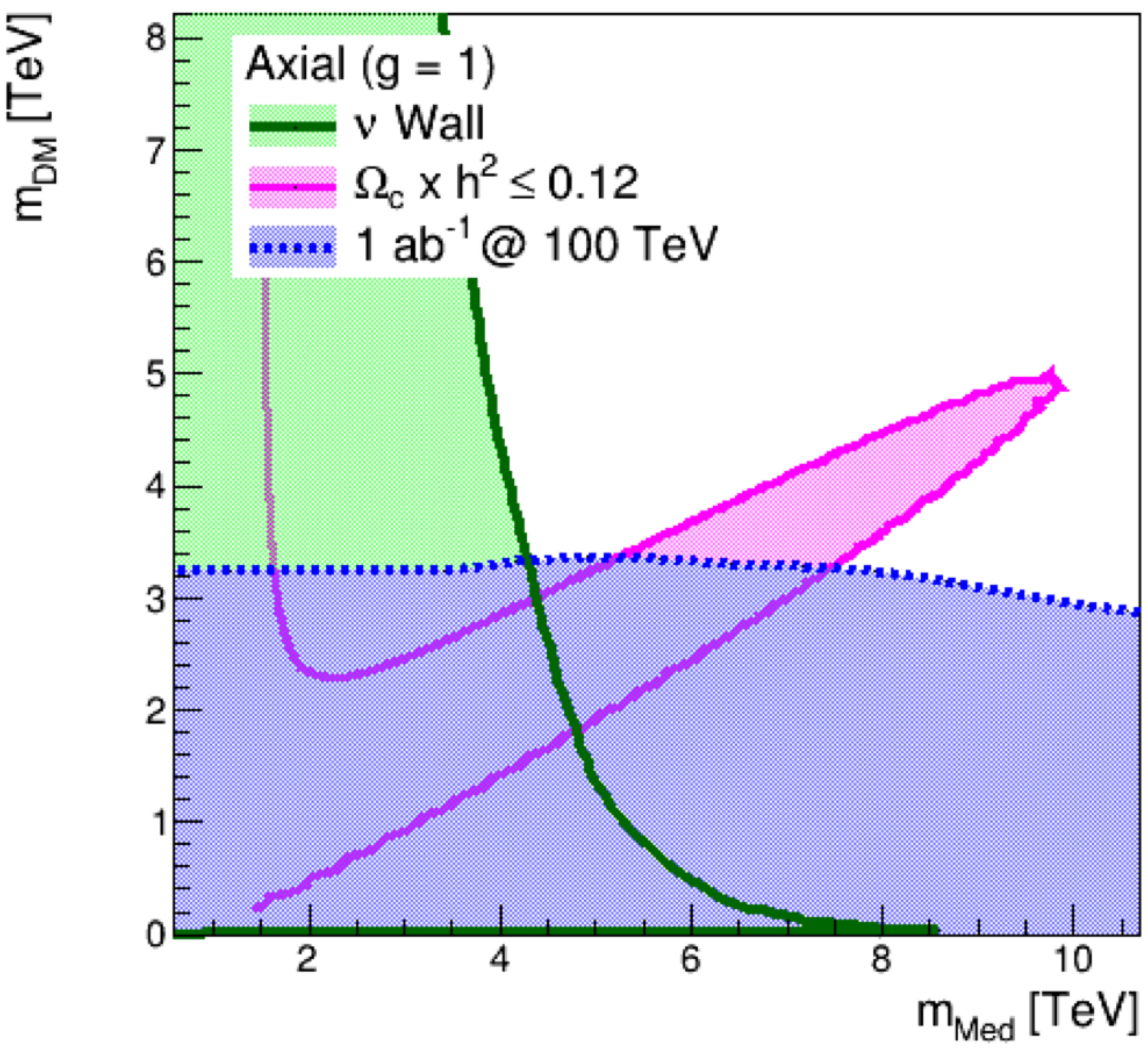
- For example, FCC-hh

BSM @ FCC-HH

Direct searches (e.g. Dark Matter)

- FCC-hh scales LHC BSM limits
  - Basically by a factor 100/14~7

T.du Pree et al, arXiv: 1603.08525

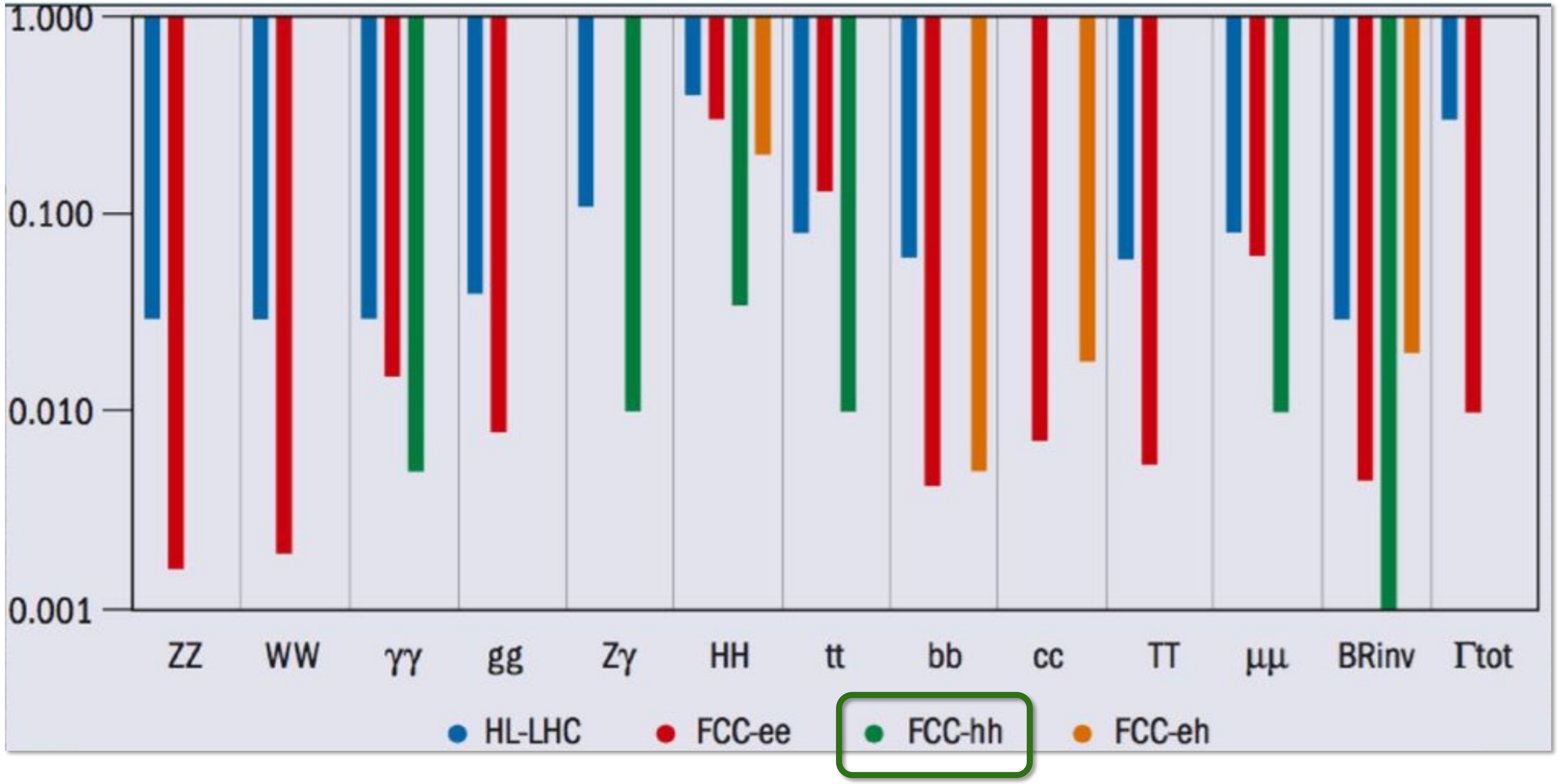


From LHC to FCC-hh

FCC-HH SUMMARY

FCC-hh prospects

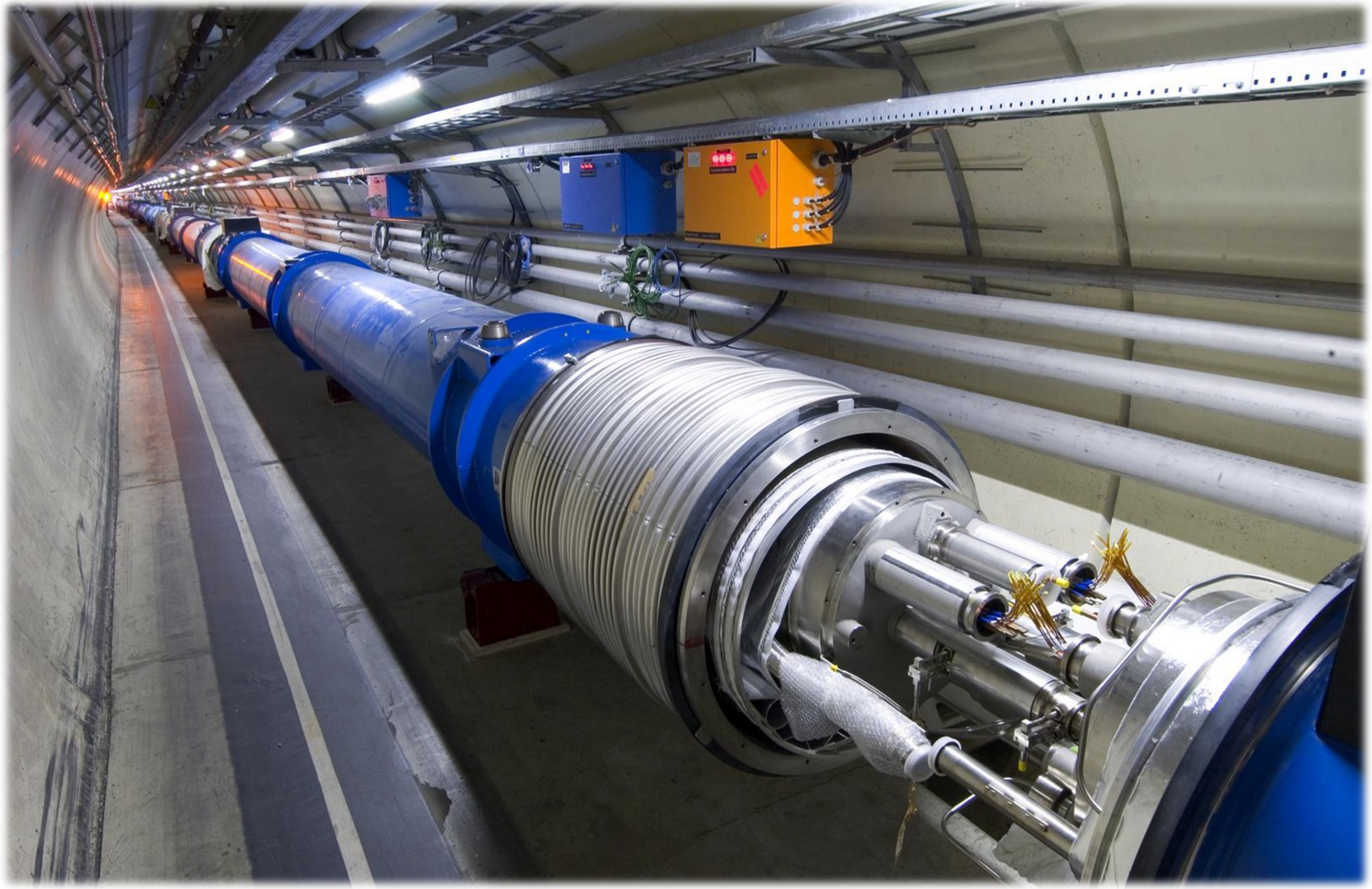
- Also a Higgs factory
  - ttH, H→μμ, H→inv
- BSM new scale
  - 100/14
- H self-coupling
  - Di-Higgs



MAGNETS

LHC → FCC-hh

- NbTi: 8T
- Nb_3Sn: 16T?



Main challenge:

- $$$

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LET'S FINALLY TALK ABOUT A MUON COLLIDER

MUON COLLIDER

What we want:

- Precision

  AND
- Energy

THE MUON SHOT

Enthusiasm on various continents

- Recent strategy updates
  - ESPPU and P5

European Strategy of Particle Physics Update – June 19, 2020:

High-priority future initiatives [..]

In addition to the high field magnets the **accelerator R&D roadmap** could contain:

[..] an **international design study** for a **muon collider**, as it represents **a unique opportunity** to achieve a *multi-TeV energy domain beyond the reach of e^+e^- colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider.

The biggest challenge remains to produce an intense beam of cooled muons, ……

Exploring the Quantum Universe

2.3 The Path to a 10 TeV pCM

Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where decisions will be taken collectively from the outset by the partners. This differs from current and past international projects in particle physics, where individual laboratories started projects that were later joined by other laboratories. The proposed program aligns with **the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

…

In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

…

Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

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COLLIDER OPTIONS

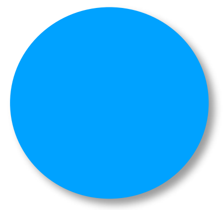
e^+e^-

✅ Precision physics

❌ Energy limited

COLLIDER OPTIONS

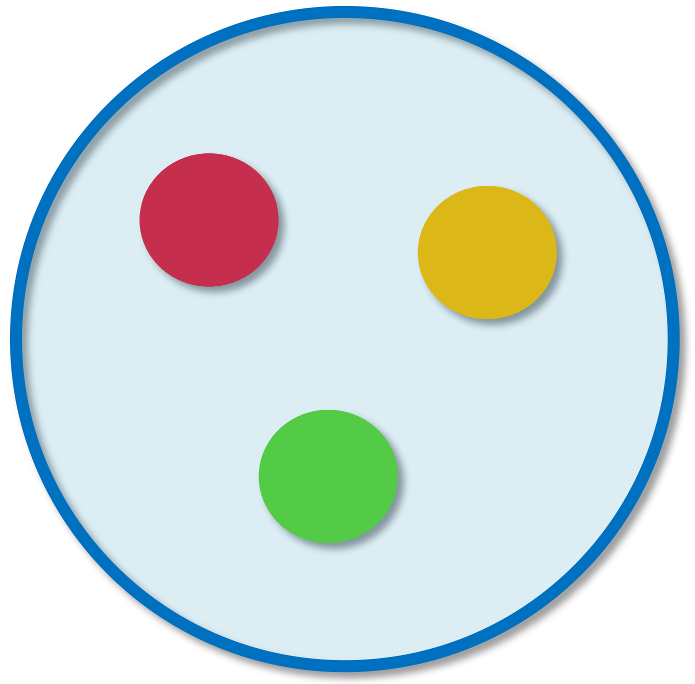
e^+e^-



✅ Precision physics

❌ Energy limited

pp

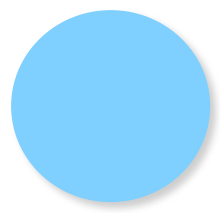


✅ Higher energy

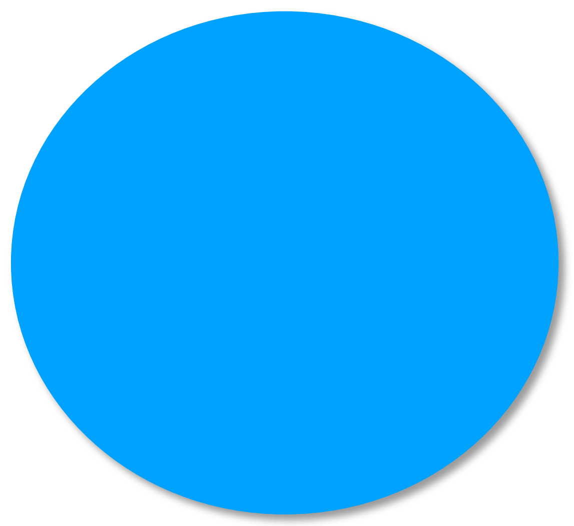
❌ Messy & suboptimal

THE BEST OF BOTH WORLDS!

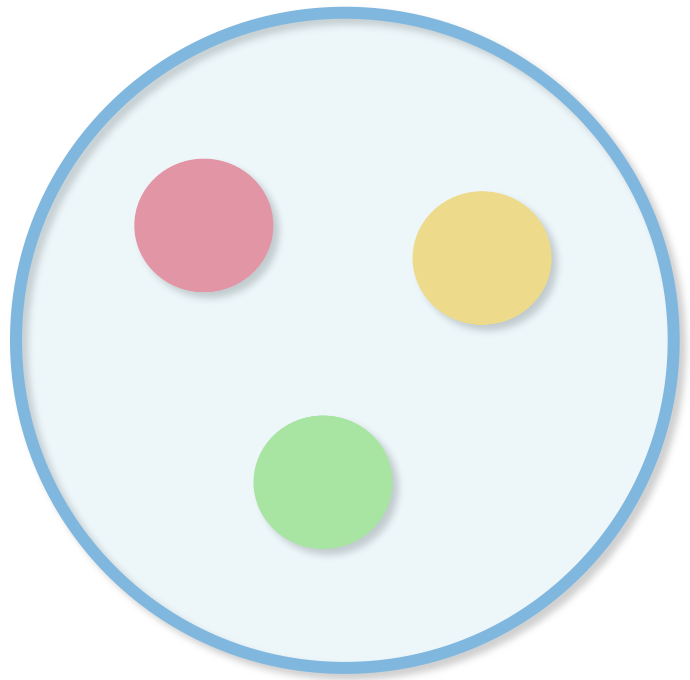
$\mu^+\mu^-$



m_e = 0.5 MeV



m_μ = 106 MeV

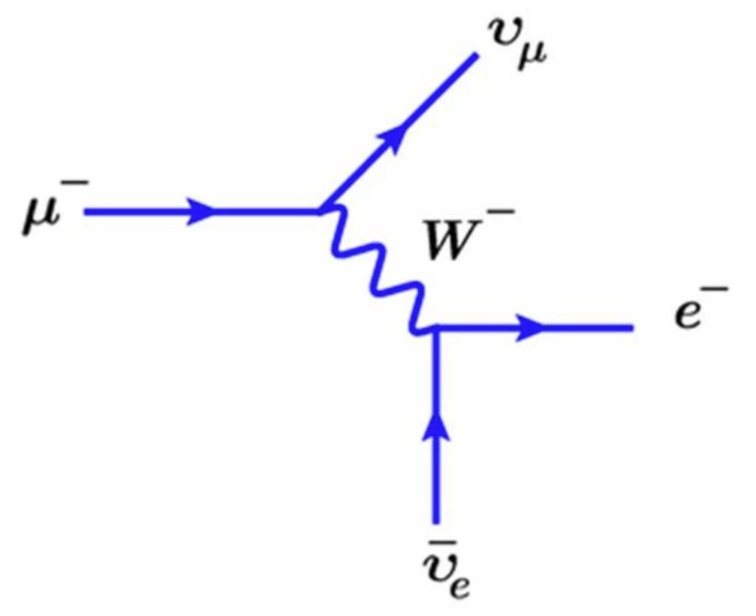


m_p = 938 MeV

✅ Precision physics

✅ And high energy

MAIN CHALLENGE



So, what's the catch?

- Finite lifetime
  - τ_μ = 2μs

Let's count to 2μs! ;-)

MAIN CHALLENGE

So, what's the catch?

- Finite lifetime
  - τ_μ = 2μs

But how long does a 5TeV muon live?

MAIN CHALLENGE

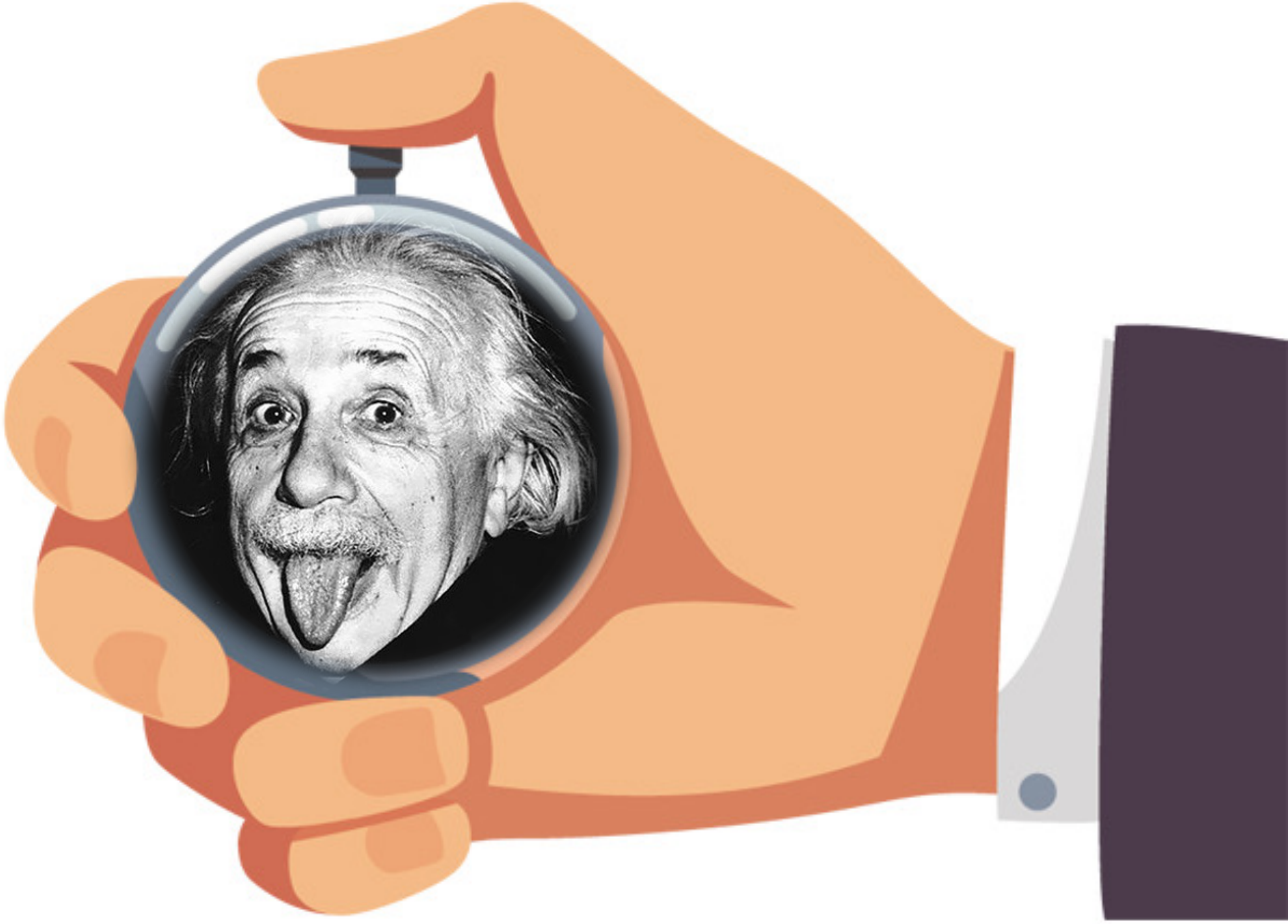
The main challenge:

- Finite lifetime
  - $\tau_\mu = 2\mu s$

Example: 5 TeV muon

- $\gamma = 50{,}000$
  - $\gamma\tau_\mu \sim 0.1s$

How many times does a muon go around the LHC ring?



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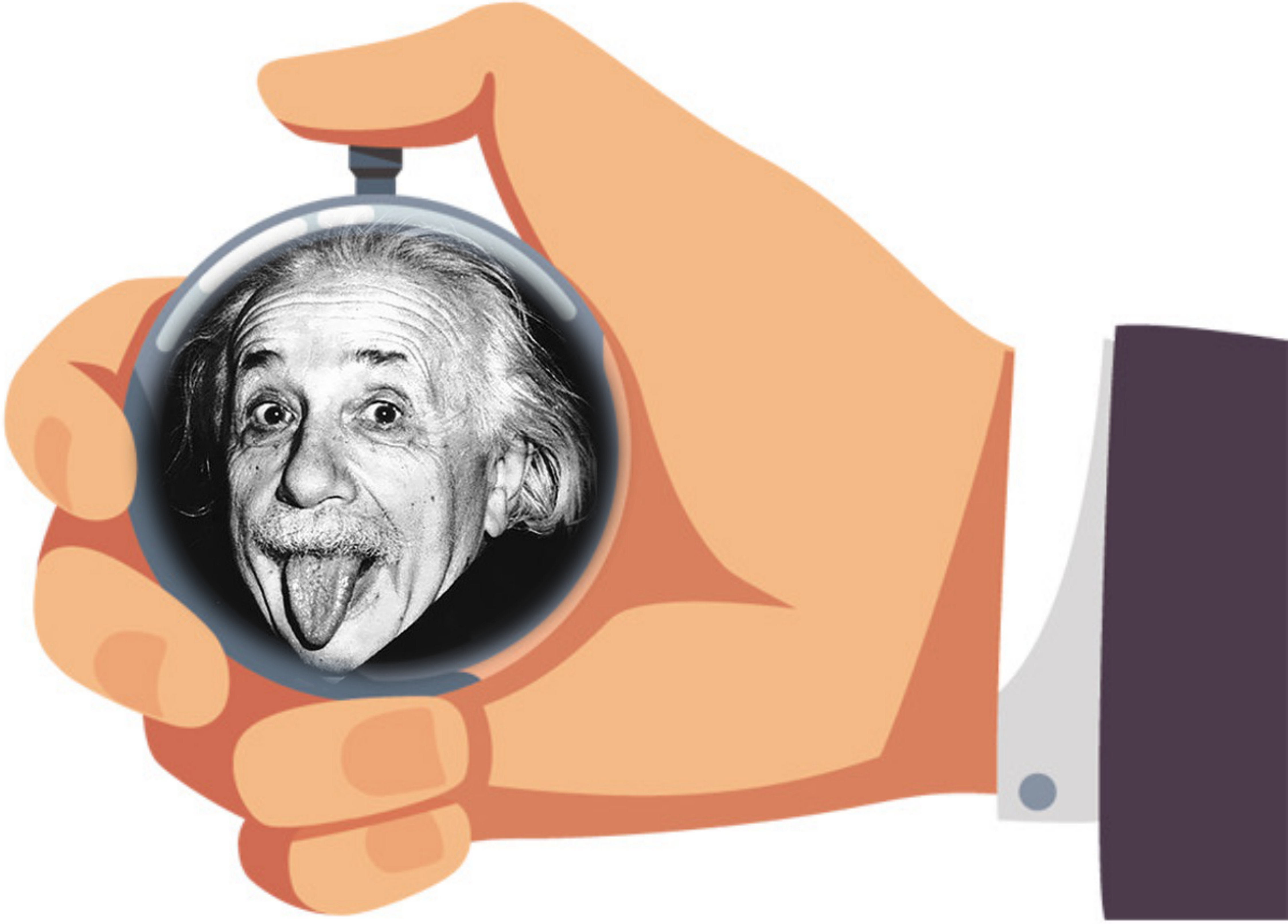
MAIN CHALLENGE

The main challenge:

- Finite lifetime
  - $\tau_\mu = 2\mu s$

Example: 5 TeV muon

- $\gamma = 50{,}000$
  - $\gamma\tau_\mu \sim 0.1s$
- $\gamma c\tau_\mu = 3x10^7 m$
  - 1000 x LHC!

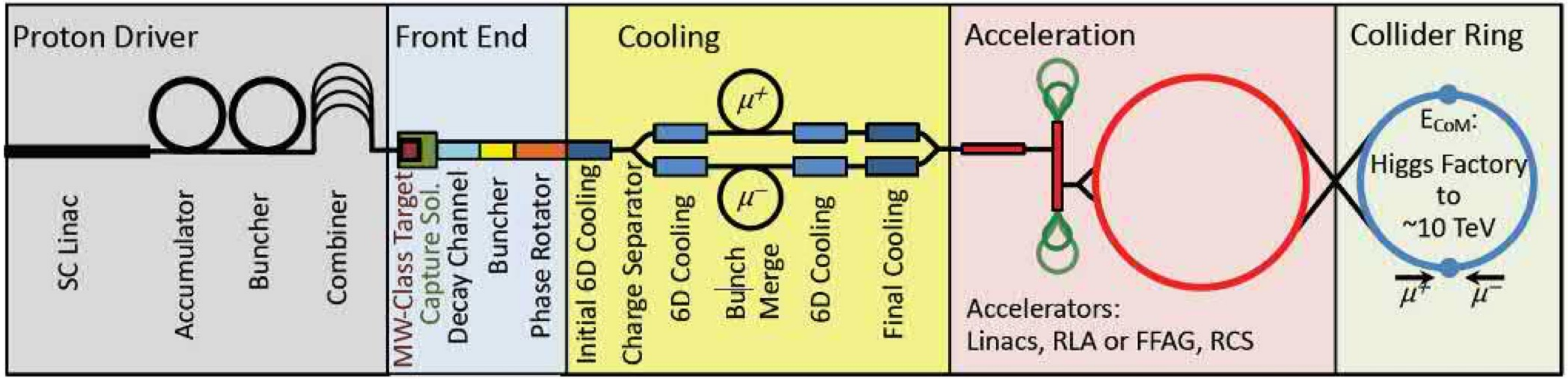


"Een echte muoncollider-fysicus kan niet zonder gamma"

MUON COLLIDER SCHEME

In 0.1s 😅

Approach: p → π → μ → cool → accelerate → collide



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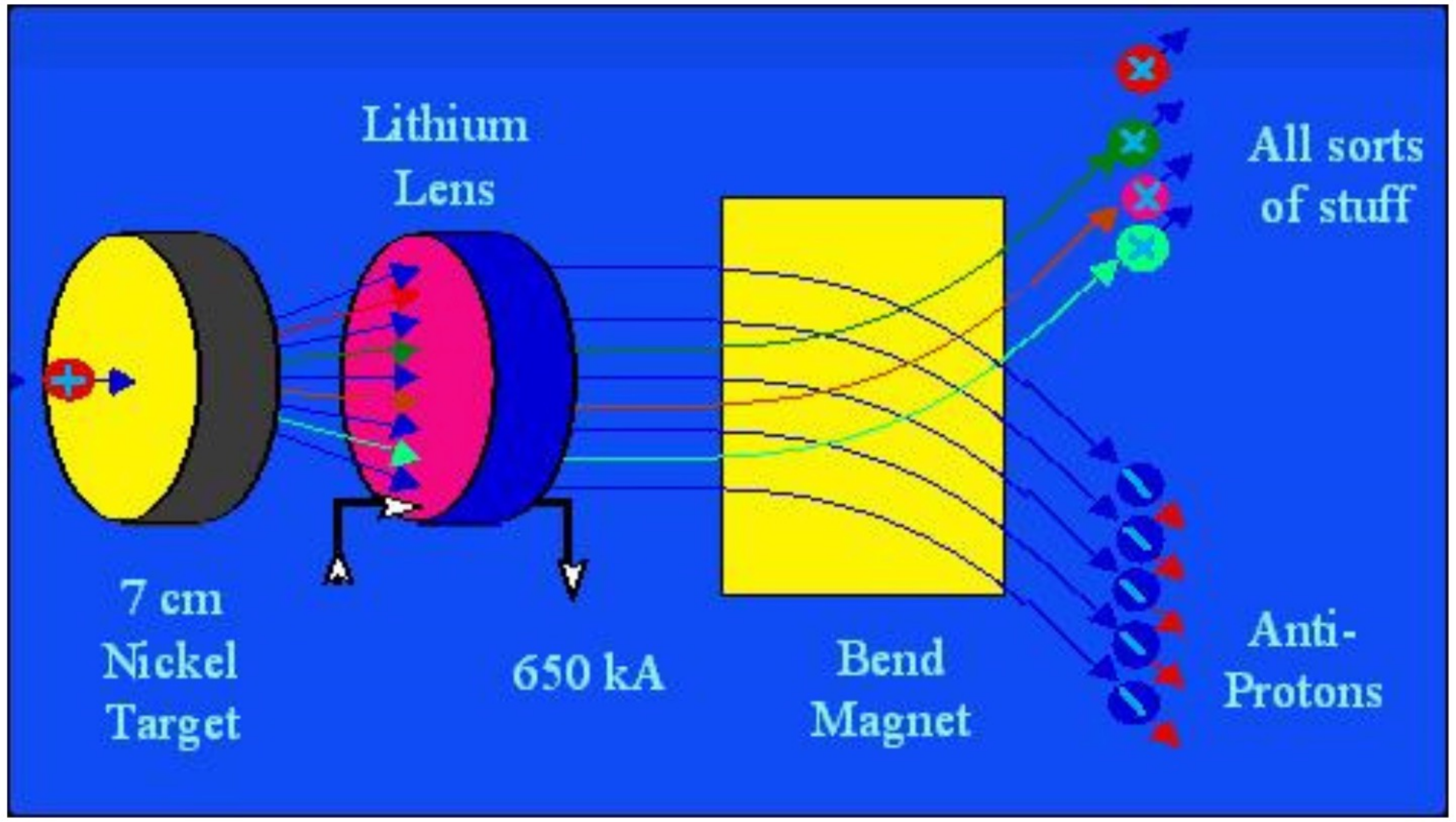
PARTICLE PRODUCTION

Example: anti-proton production

- Collide protons on target
- Select anti-protons (mass!)
  - Think of “carbon dating”



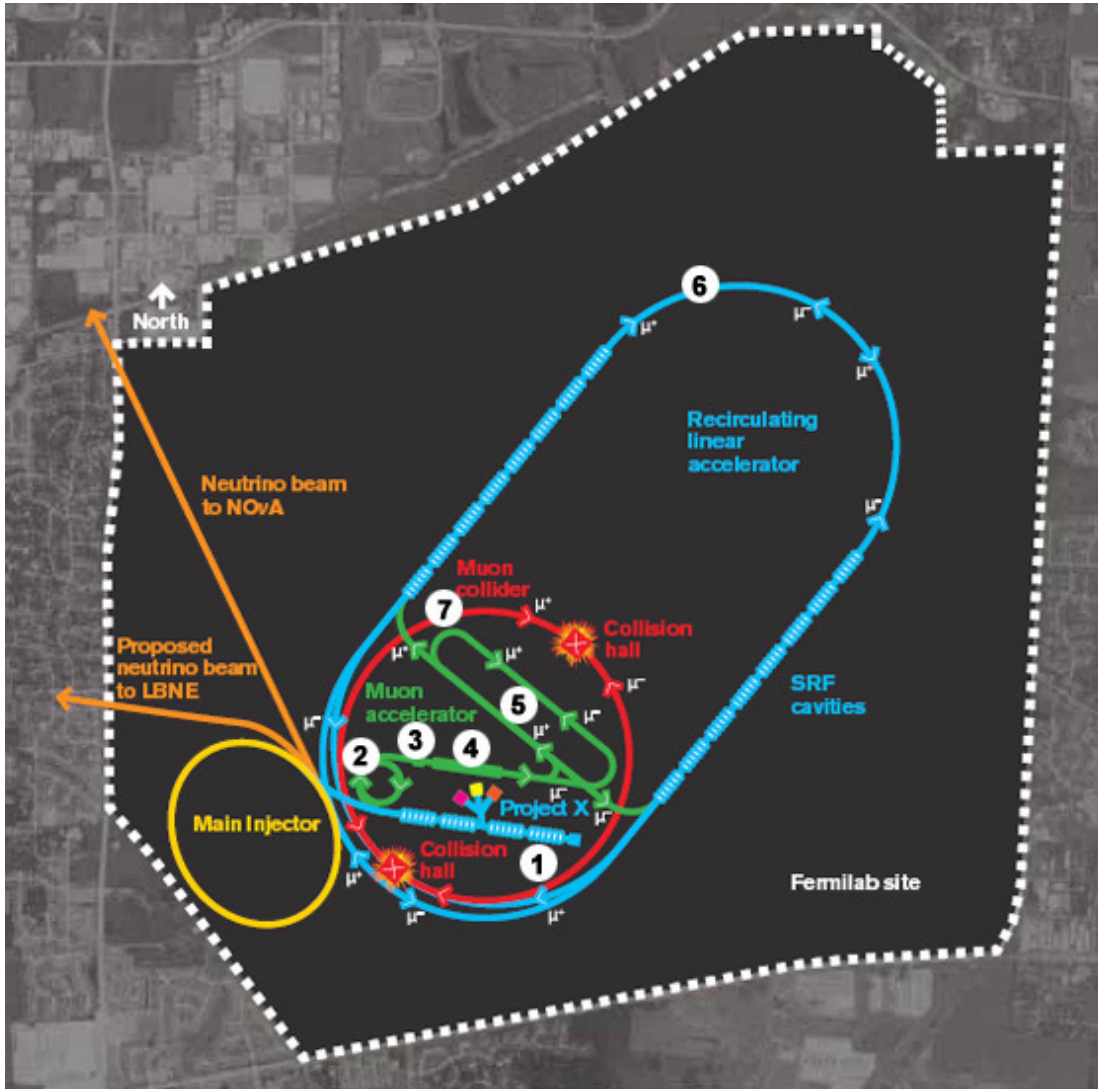
MUON COLLIDER LAYOUT

Separate accelerator + collider

- Strongest magnets in (relatively) small collider ring

Typically size of Fermilab or LHC

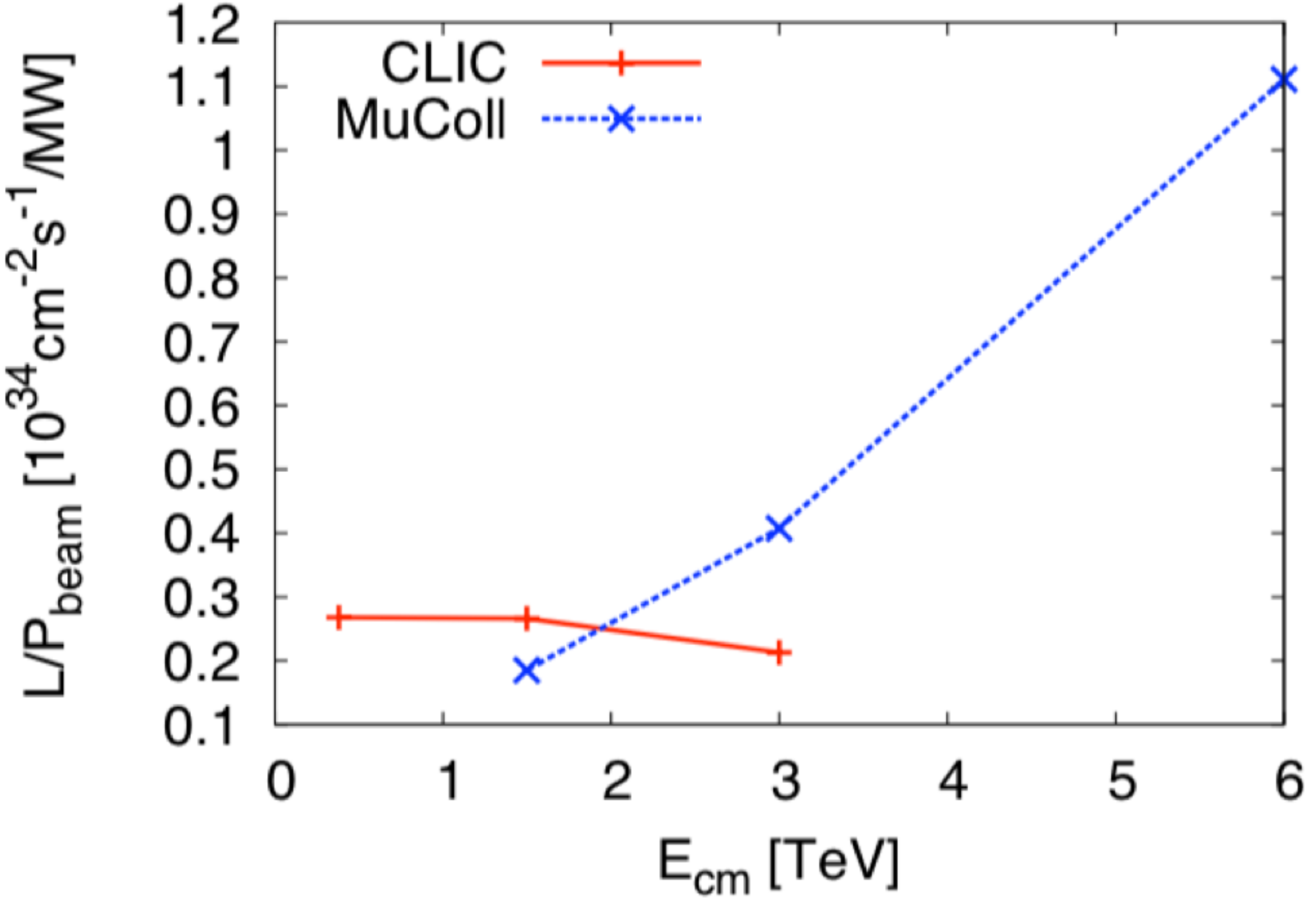
- 3-10 TeV



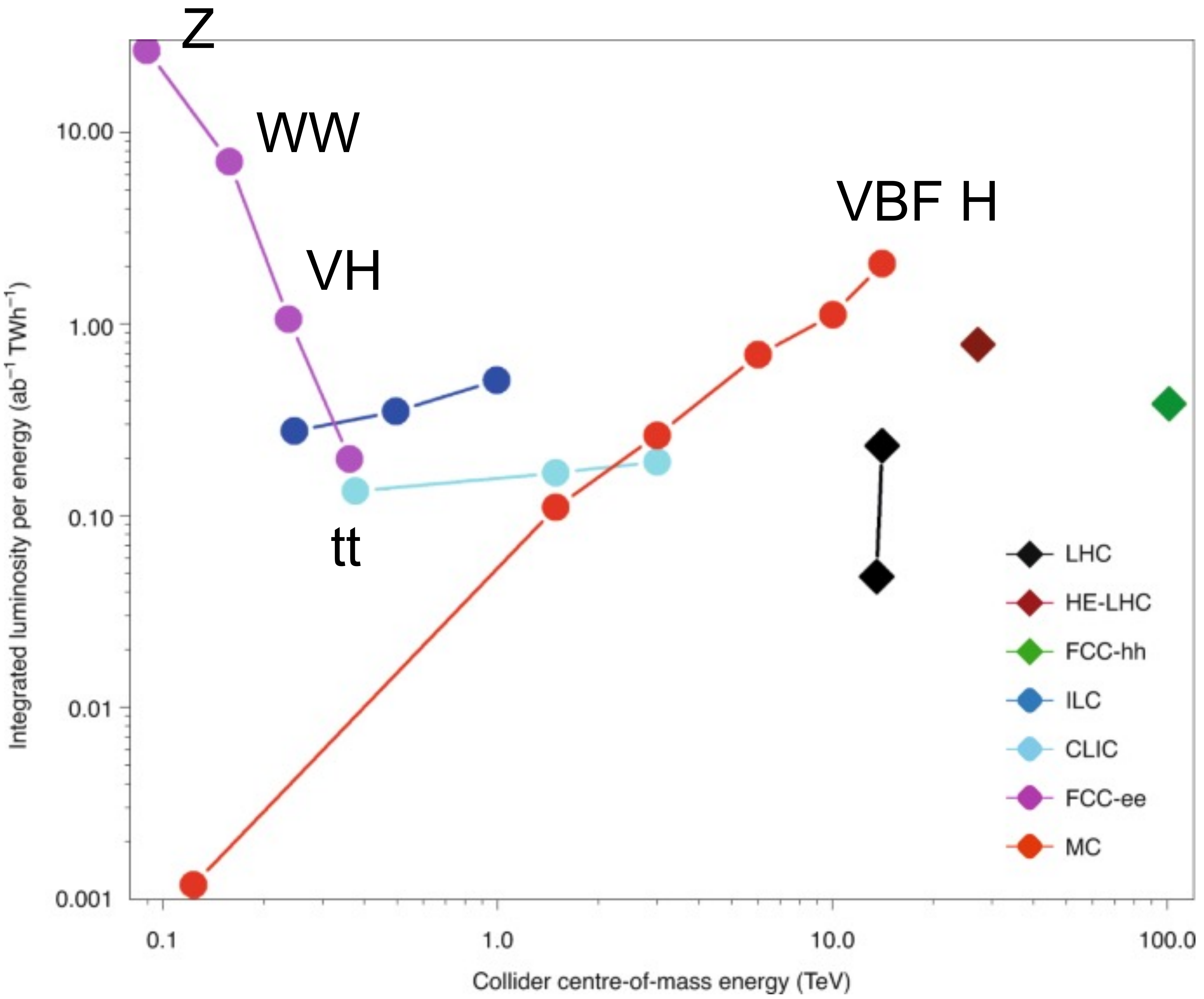
LUMINOSITY

Larger luminosity at large energy!

- Precision Higgs physics
- And probe new scale!



LUMI

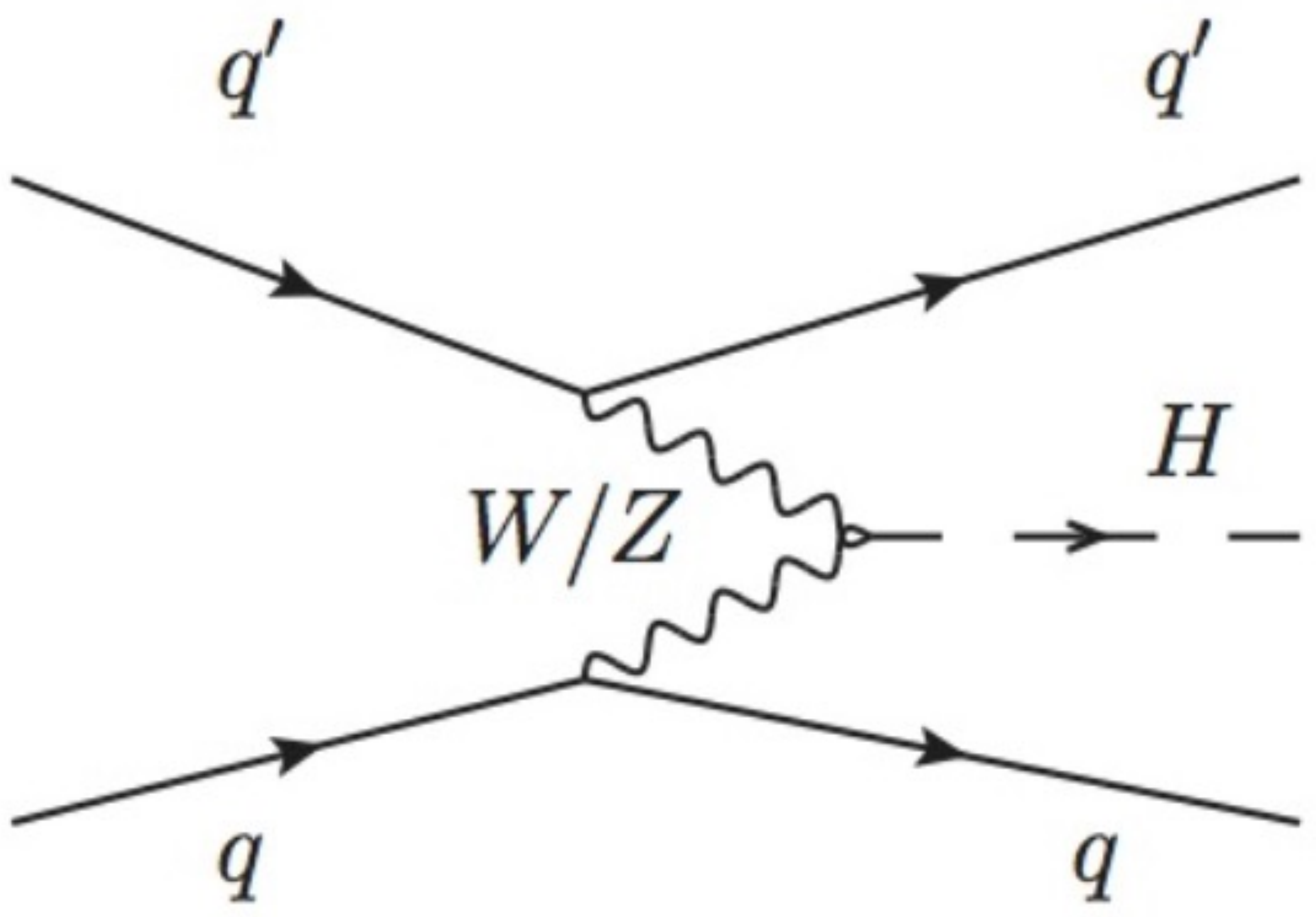


Z
WW
VH
tt
VBF H
10.00
1.00
0.10
0.01
0.001
Integrated luminosity per energy (ab^{-1} TWh^{-1})
0.1
1.0
10.0
100.0
Collider centre-of-mass energy (TeV)
LHC
HE-LHC
FCC-hh
ILC
CLIC
FCC-ee
MC

BOSON FUSION

Vector boson fusion @ LHC

- Forward jets
  at the LHC



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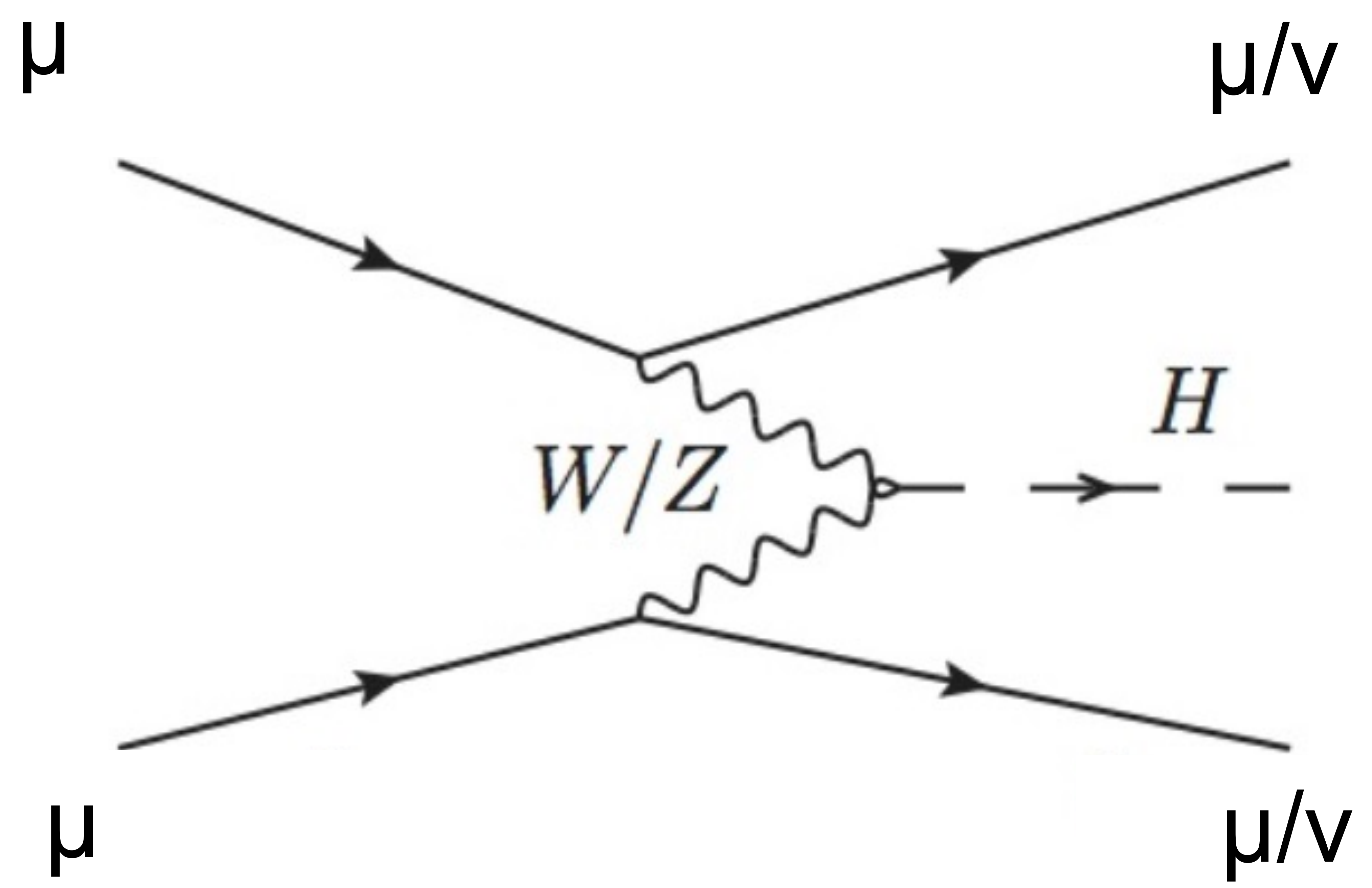
BOSON FUSION

Vector boson fusion @ MuC

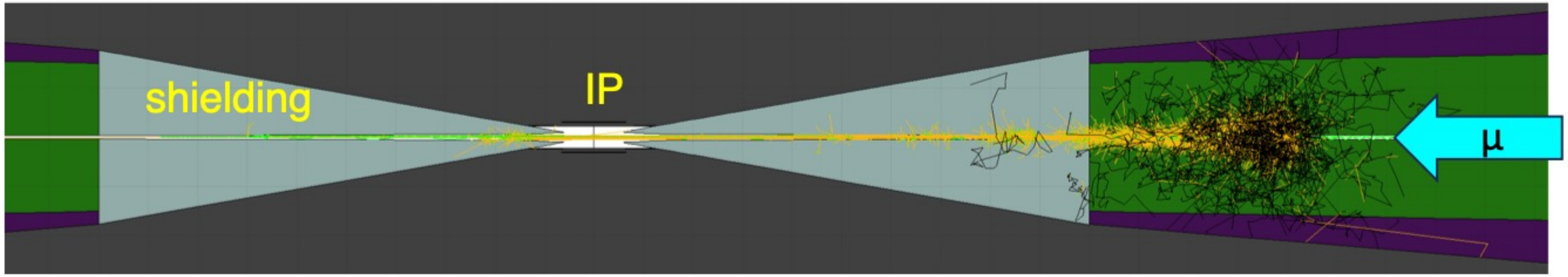
- Main production at high-energy muon collider
  - Higgs boson with forward muons or neutrinos



THE MAIN DETECTOR CHALLENGE

Beam Induced Background

- Muon decays
- Secondary products
  - In detector and in accelerator!



F. Collamati et al. 2021 JINST 16 P11009

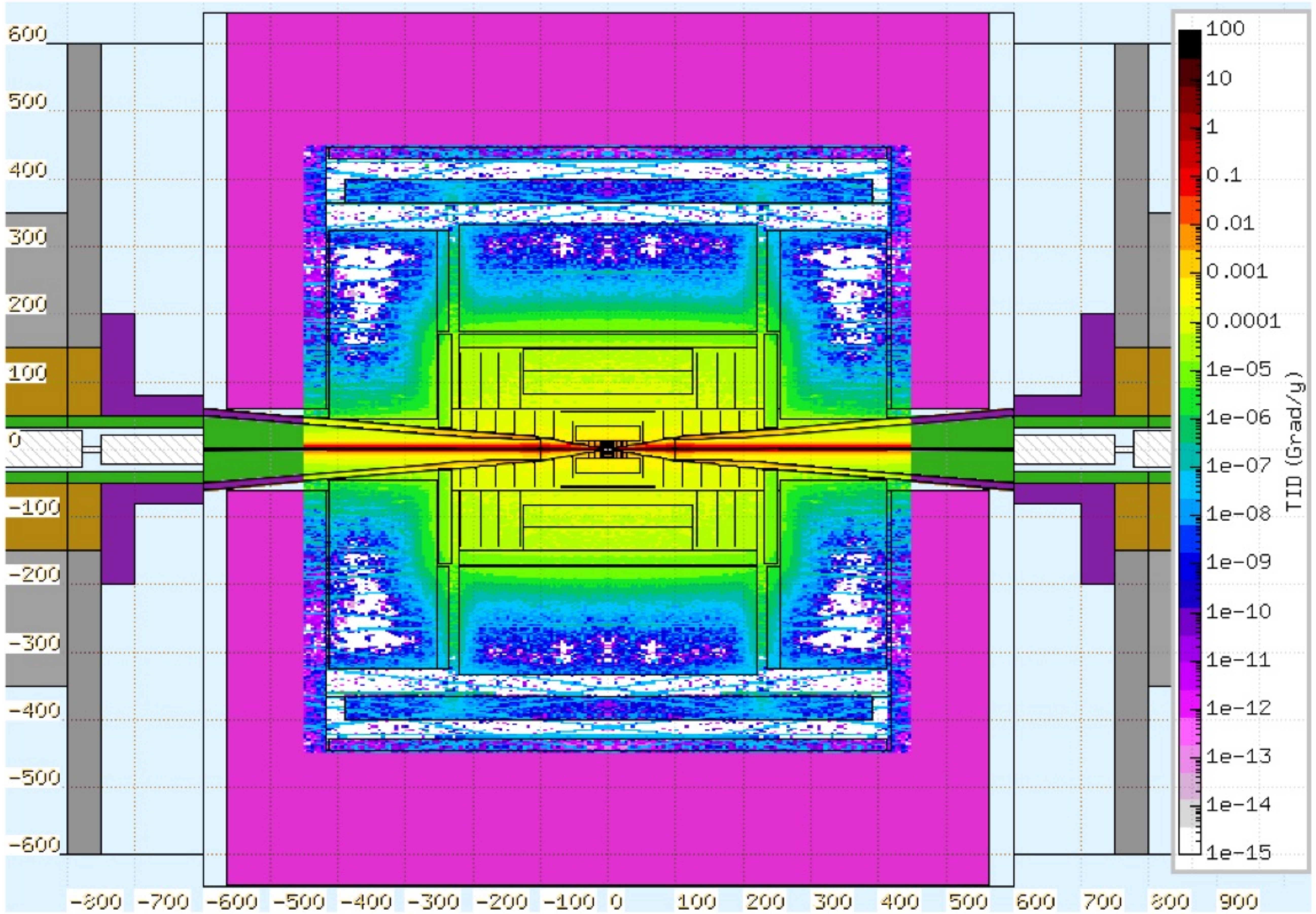
Single muon decay tracks

$N_{\mu}^{\pm} \sim 2x10^{12}$/bunch

DETECTOR DESIGN

5 TeV muon accelerator:

- 10^5 muon decays/m



Radiation requirements for detector similar to HL-LHC

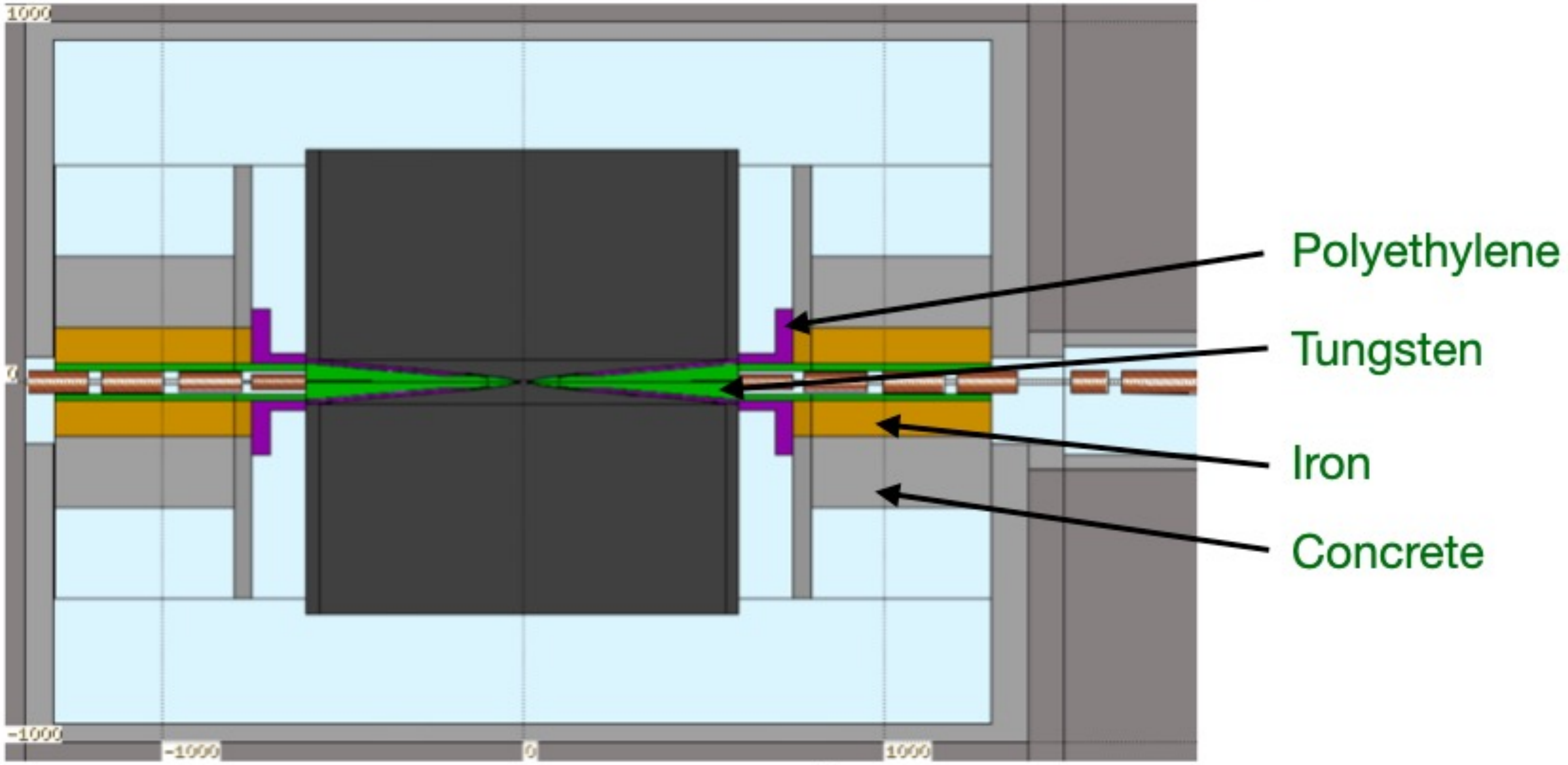
DETECTOR DESIGN

5 TeV muon accelerator:

- 10^5 muon decays/m

Mitigation:

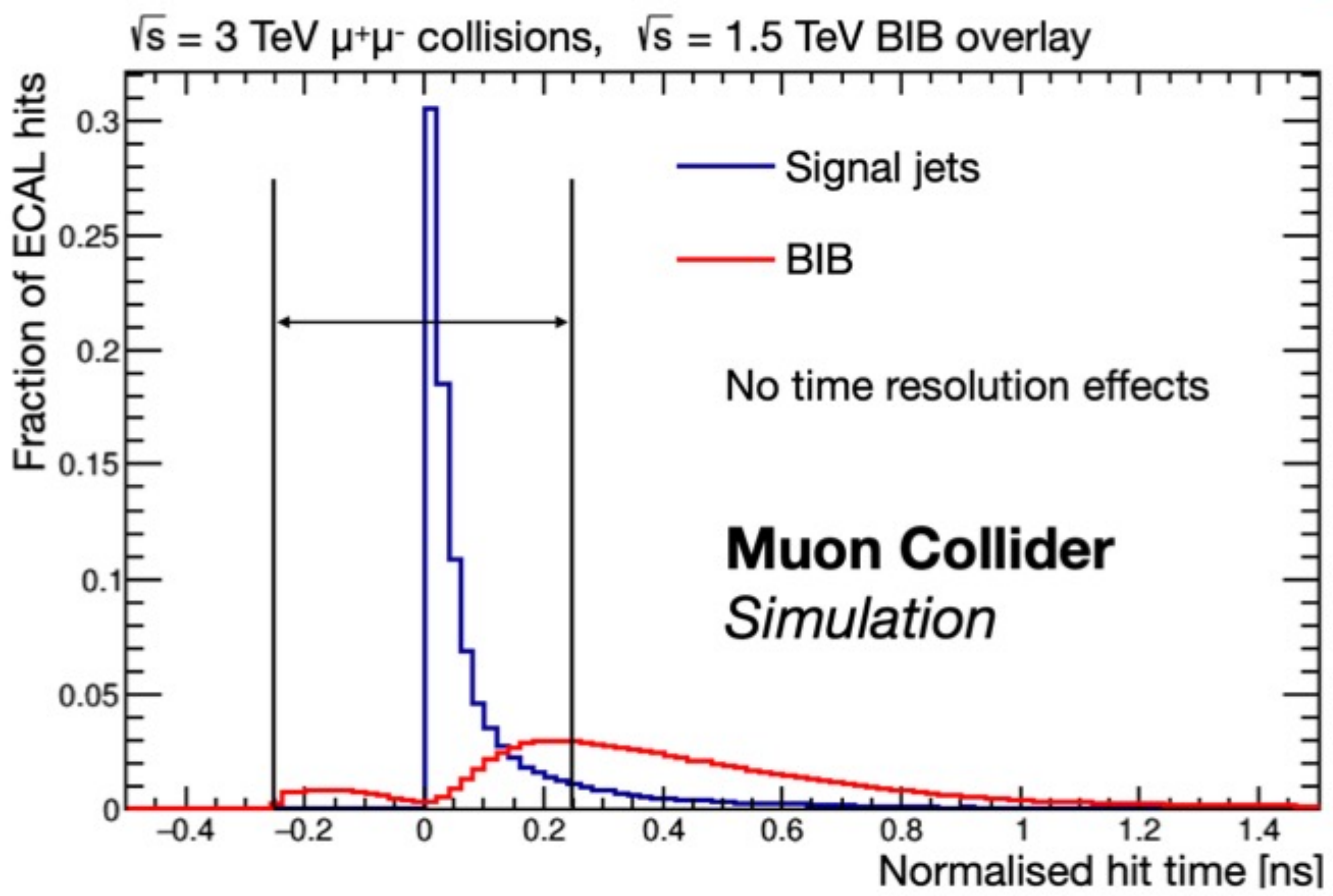
- Tungsten nozzle
  - Limits acceptance
  - Likely ~10 degrees

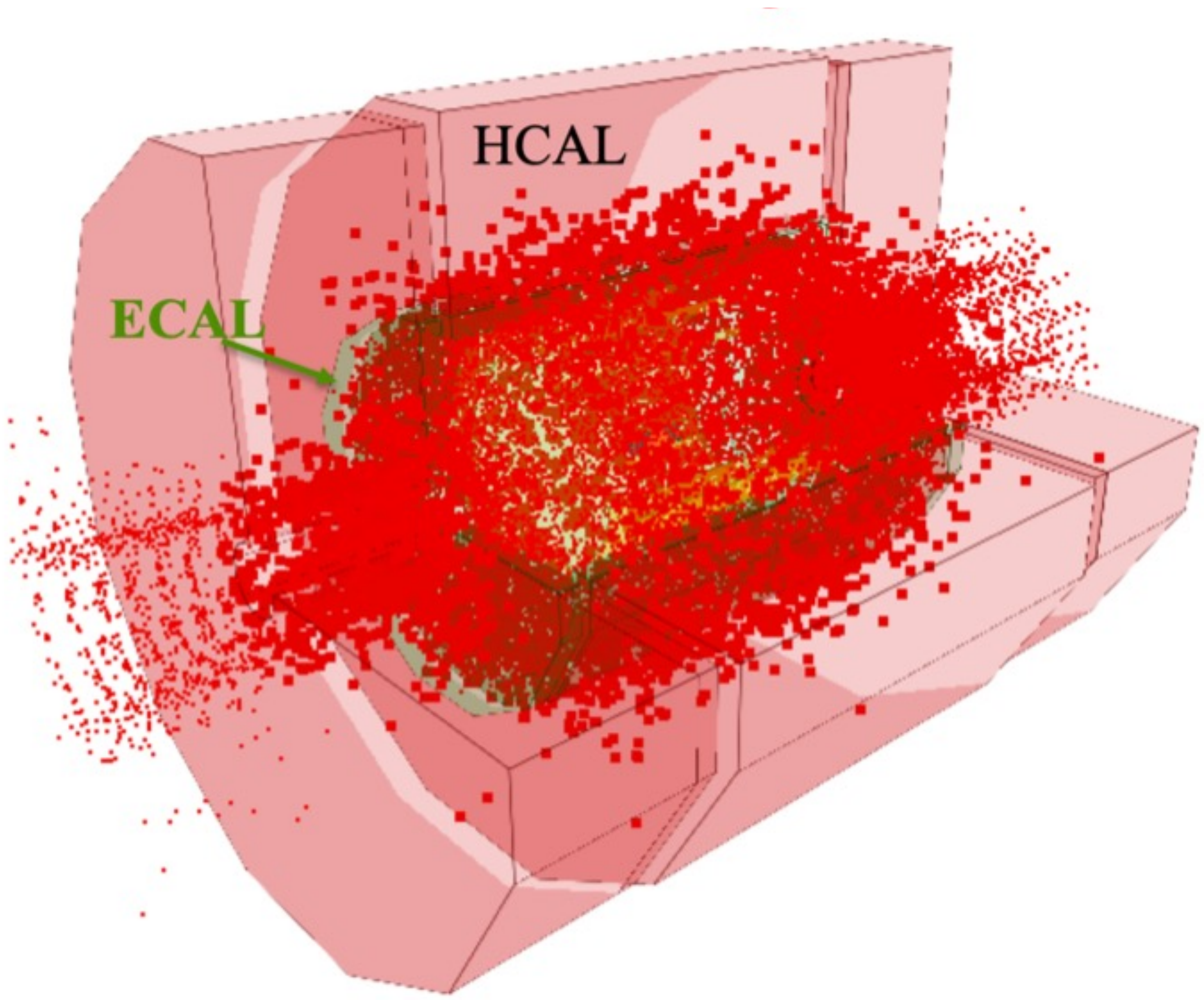


DETECTOR TECHNOLOGY

Main challenge: 'BIB'

- Beam Induced Background





Crucial solution: timing

- Trackers & Calorimeters

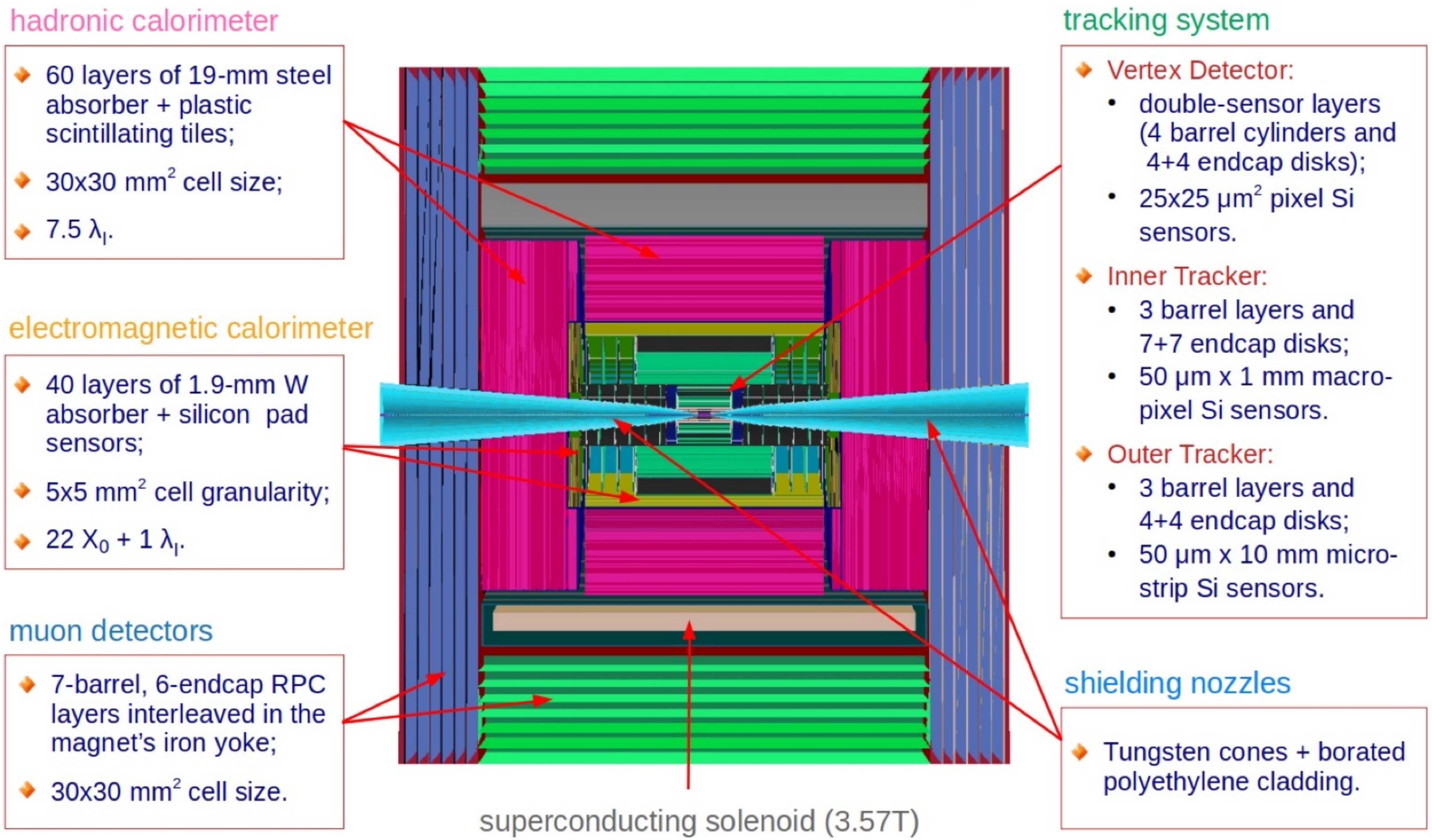
DETECTOR DESIGNS

3TeV detector concept

- Based on CLIC

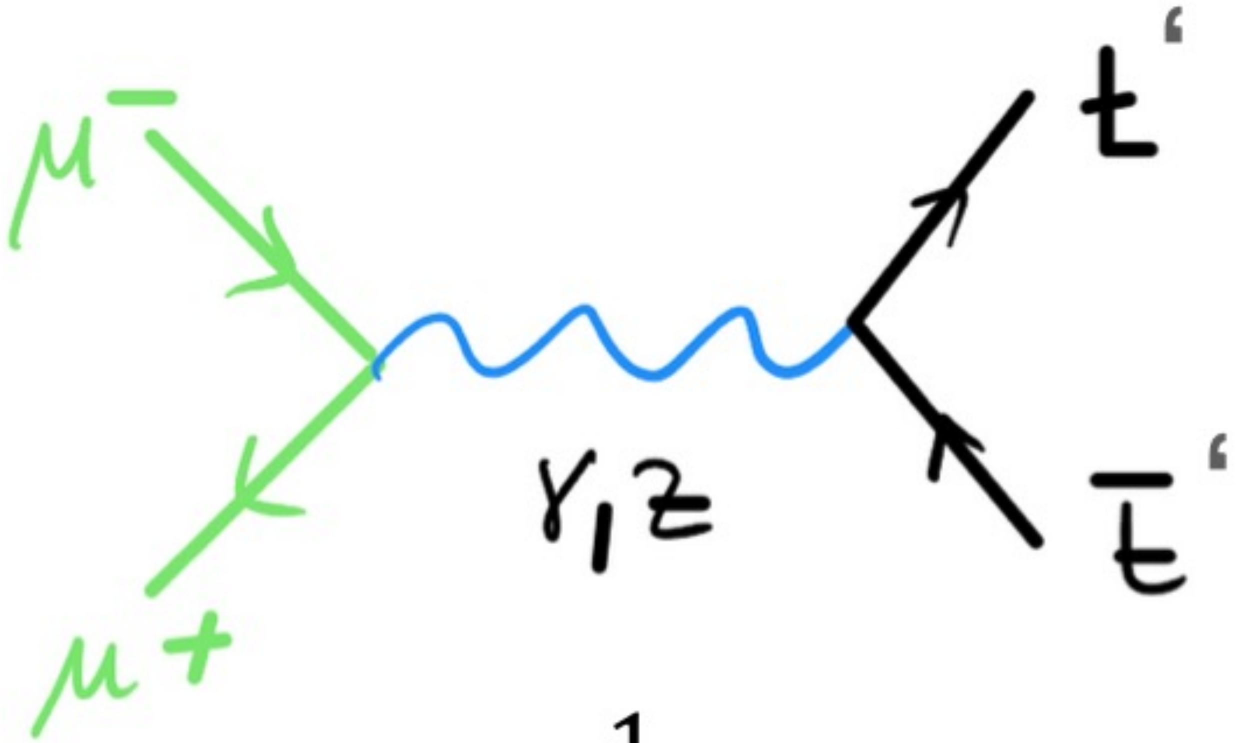
10 TeV design ongoing

- Magnet adjusted
- Deeper calorimetry



MUCOL PHYSICS

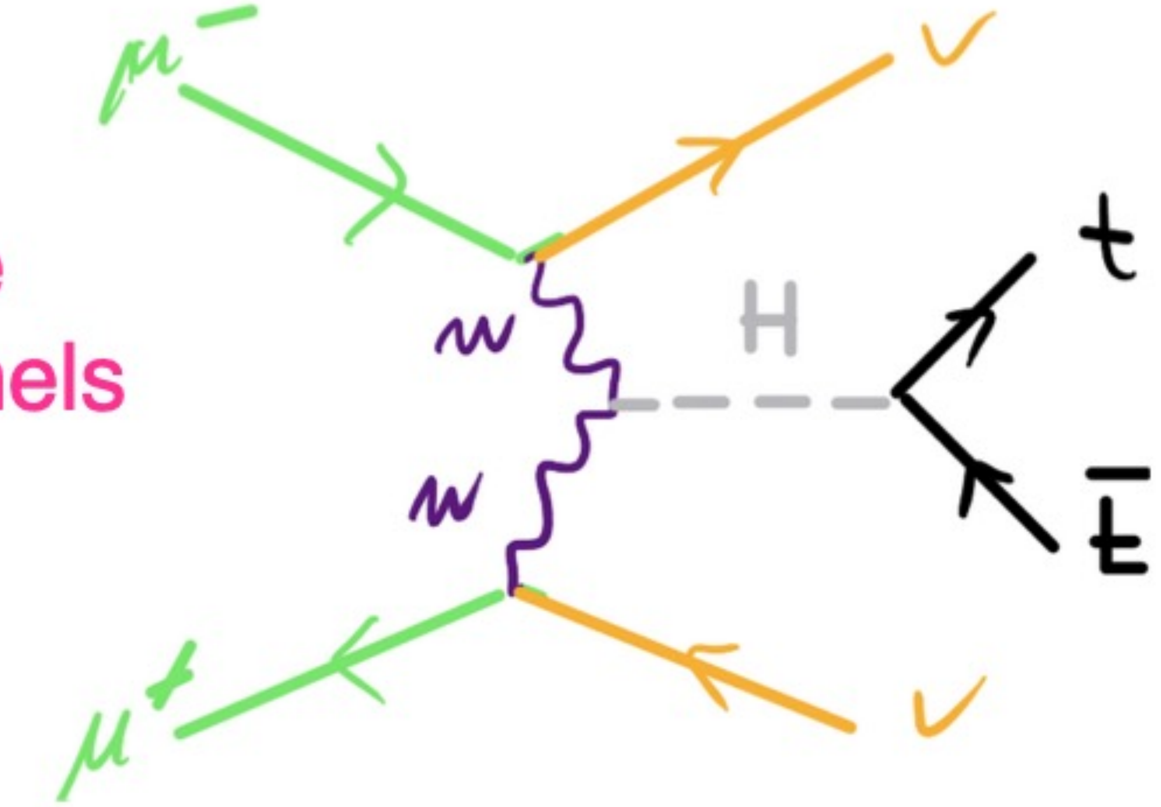
Multi-TeV collider: Higgs precision and Searches



$$\sigma \sim \frac{1}{s}$$

Energetic final states
(heavy particle or very boosted)

Different physics can be probed in the two channels

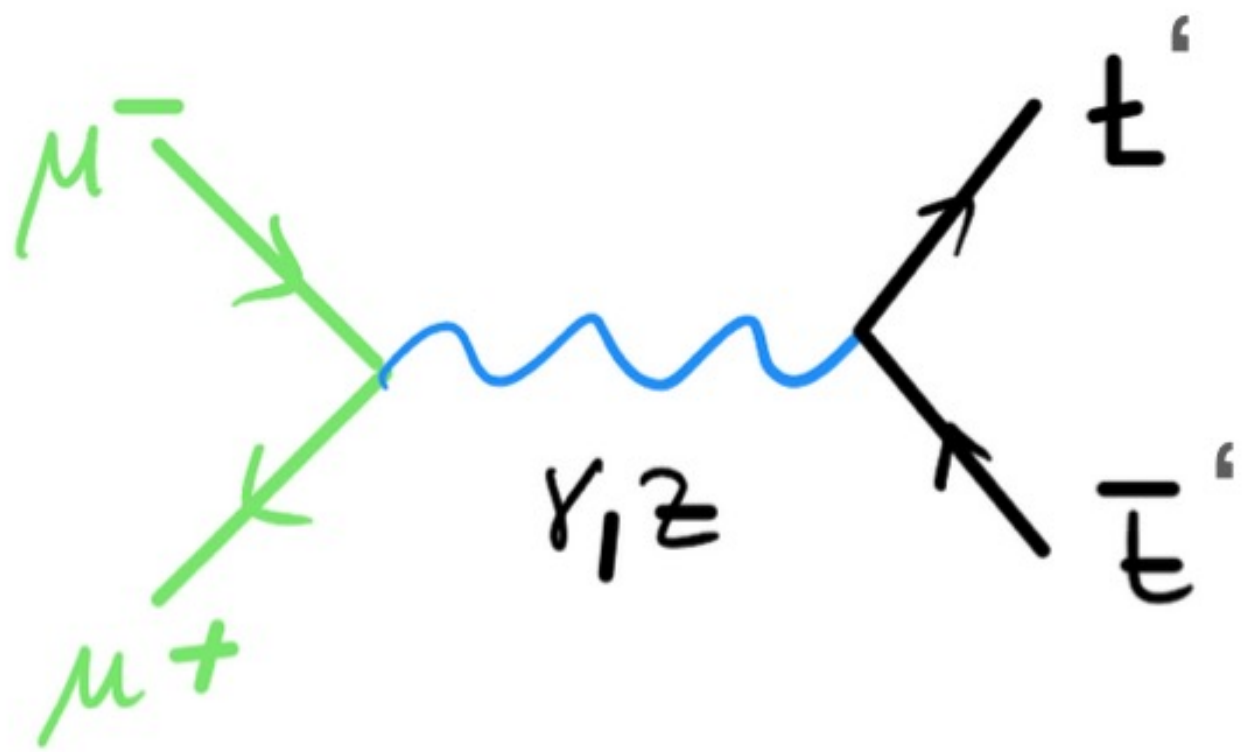


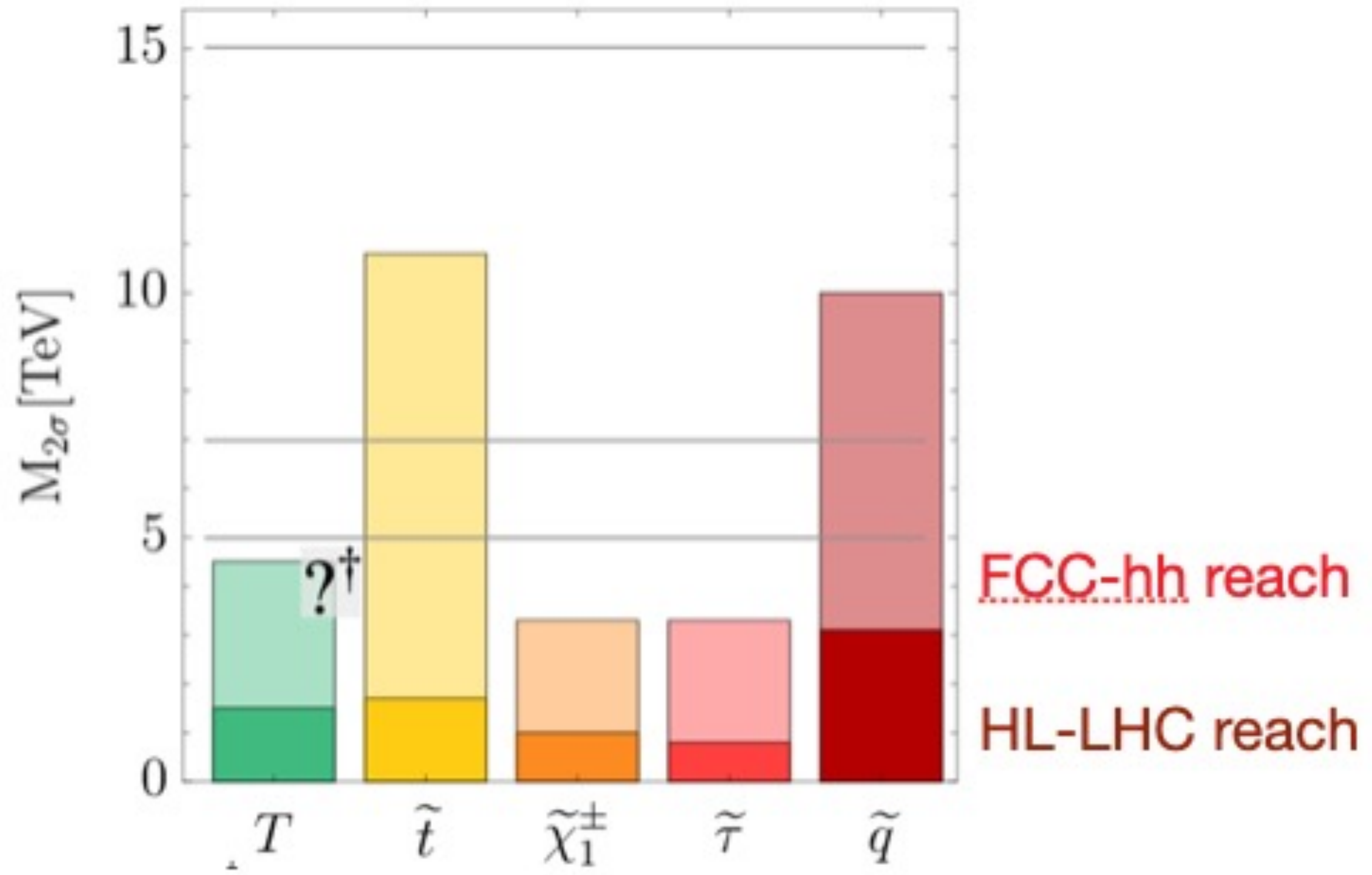
$$\sigma \sim \frac{1}{M^2} log^n \frac{s}{M}$$

Standard Model coupling measurements
Discovery light and weakly interacting particles

MUCOL PHYSICS

Multi-TeV collider: Higgs precision and Searches





BSM direct reach in similar ballpark as FCC-hh!

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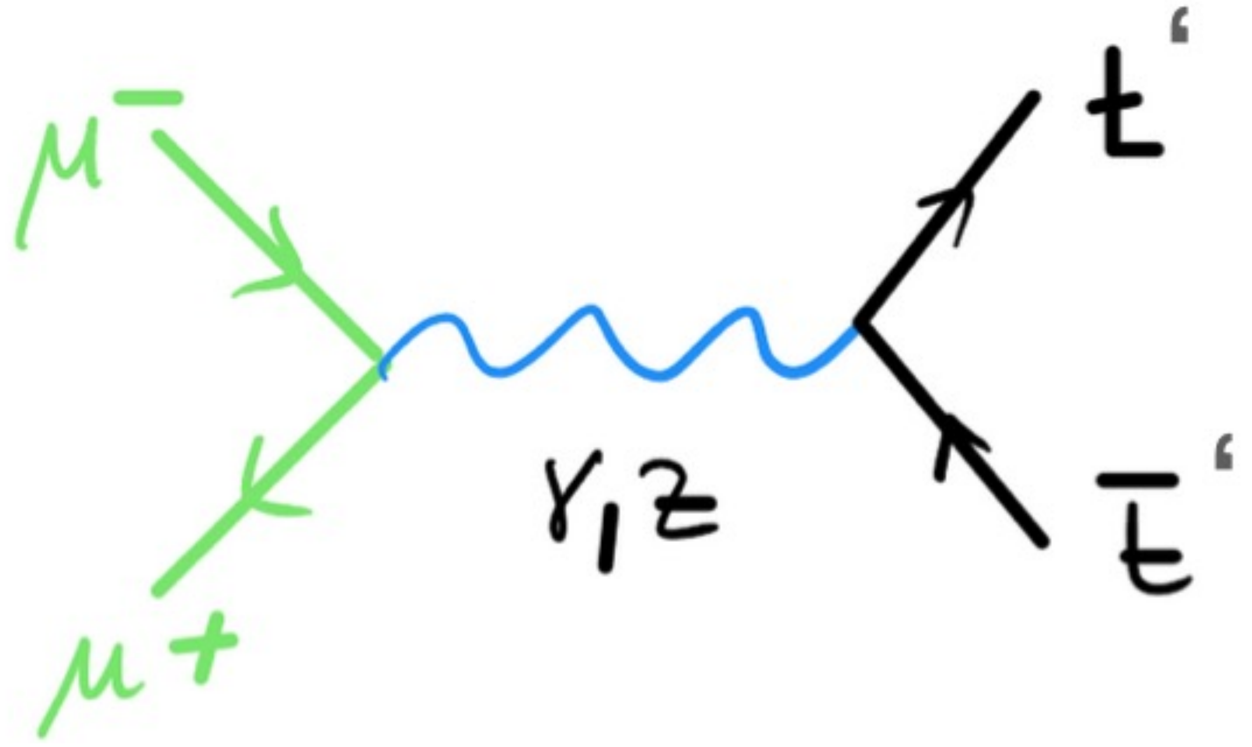
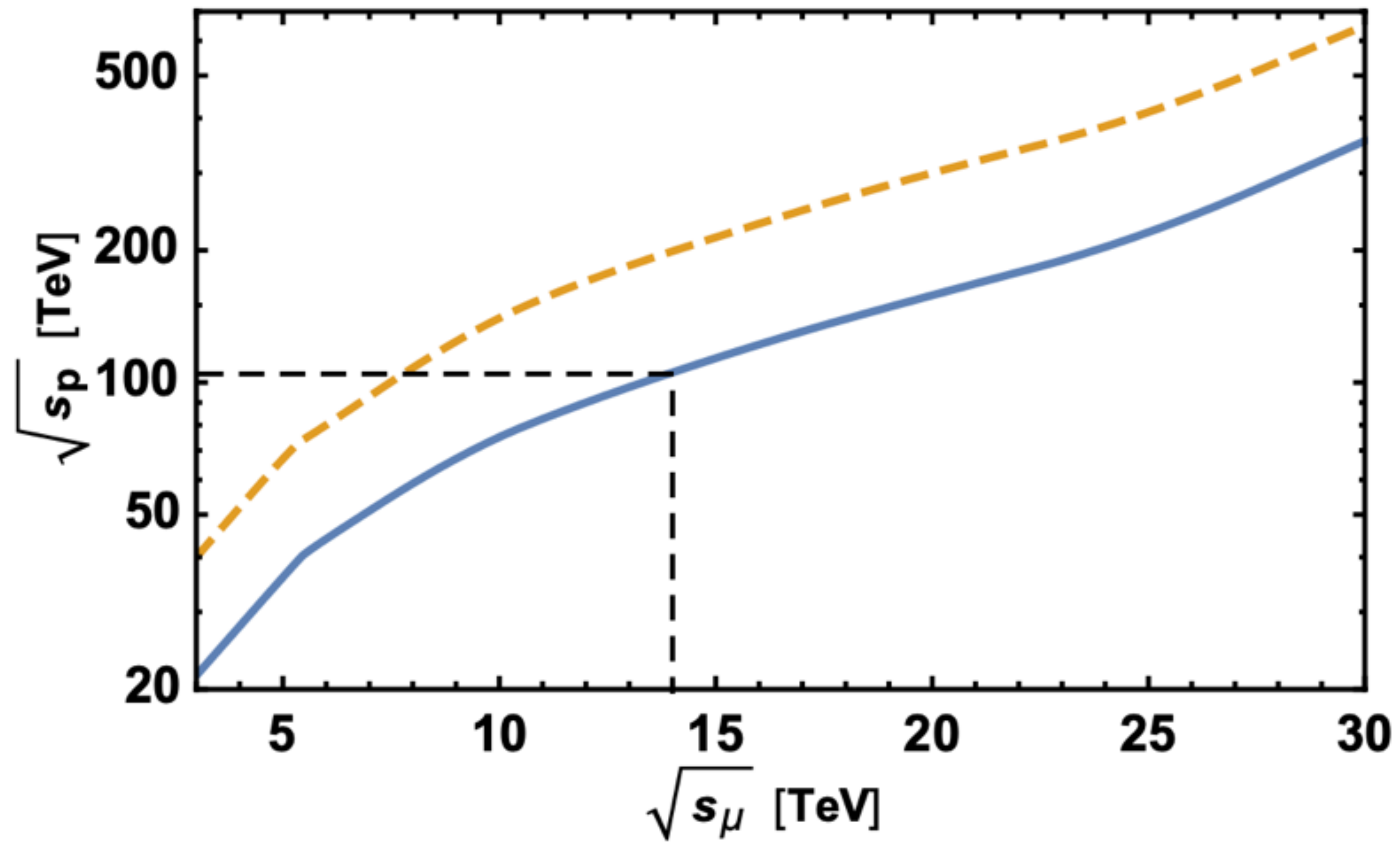
MUCOL PHYSICS

Multi-TeV collider: Higgs precision and Searches



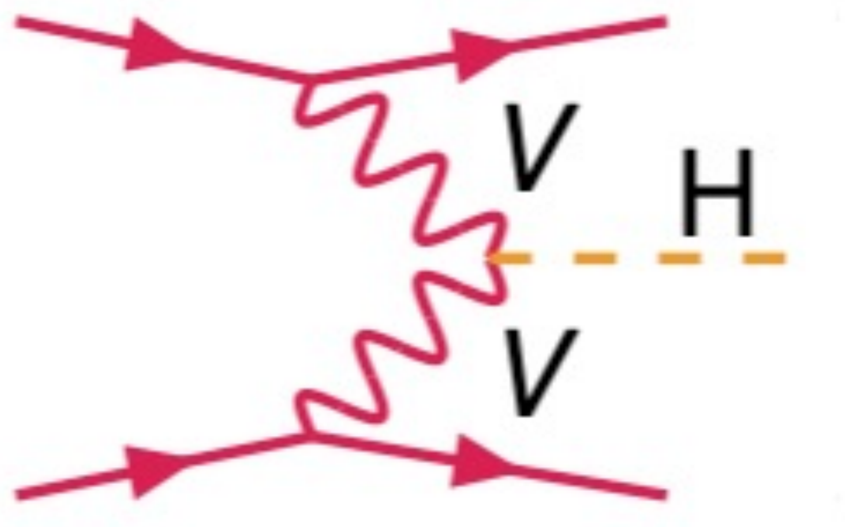


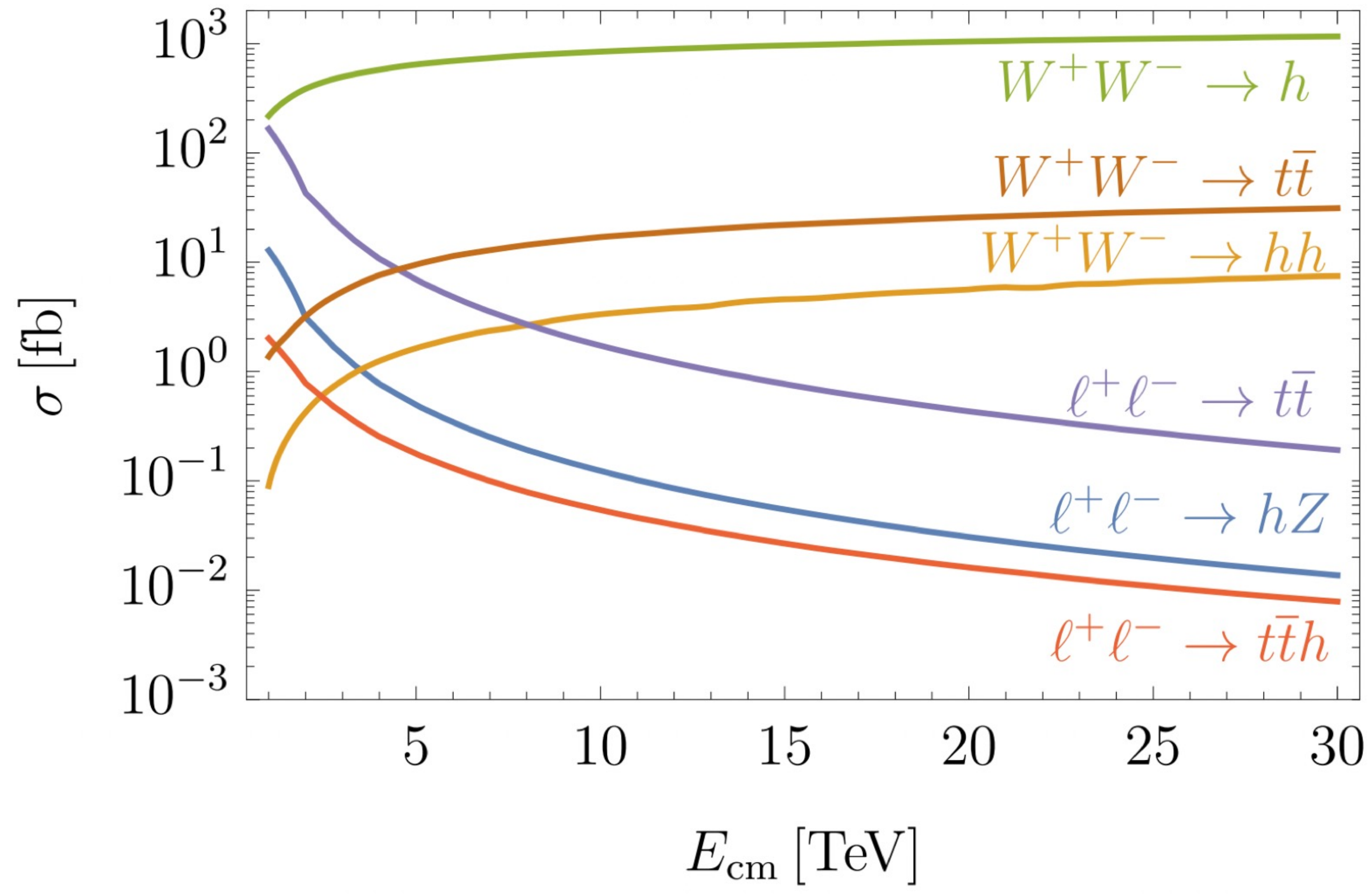
BSM direct reach in similar ballpark as FCC-hh!

MUCOL PHYSICS: HIGGS

VBF-H production increases with energy

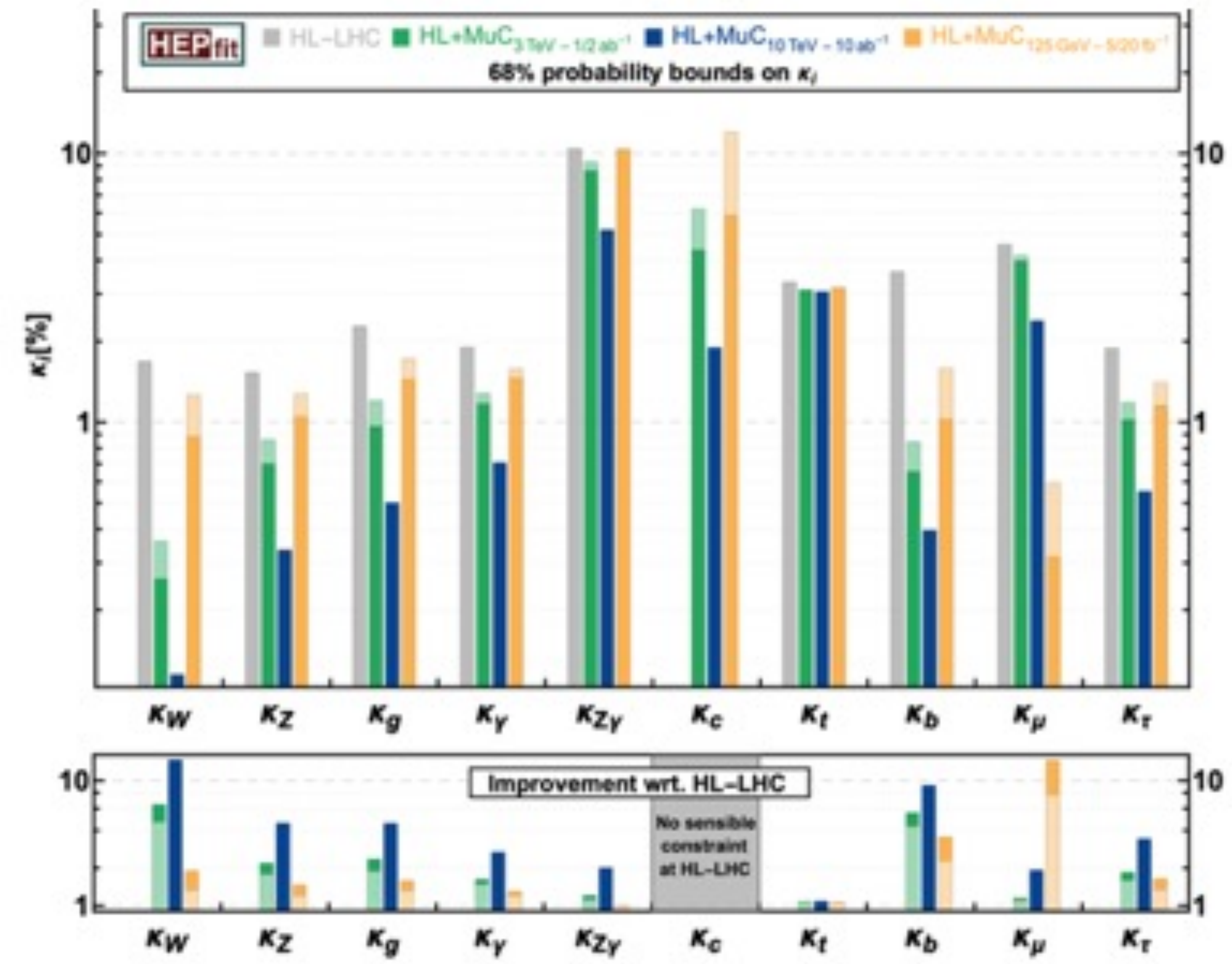
- 10/ab @ 10 TeV
  - 10,000,000 single-H





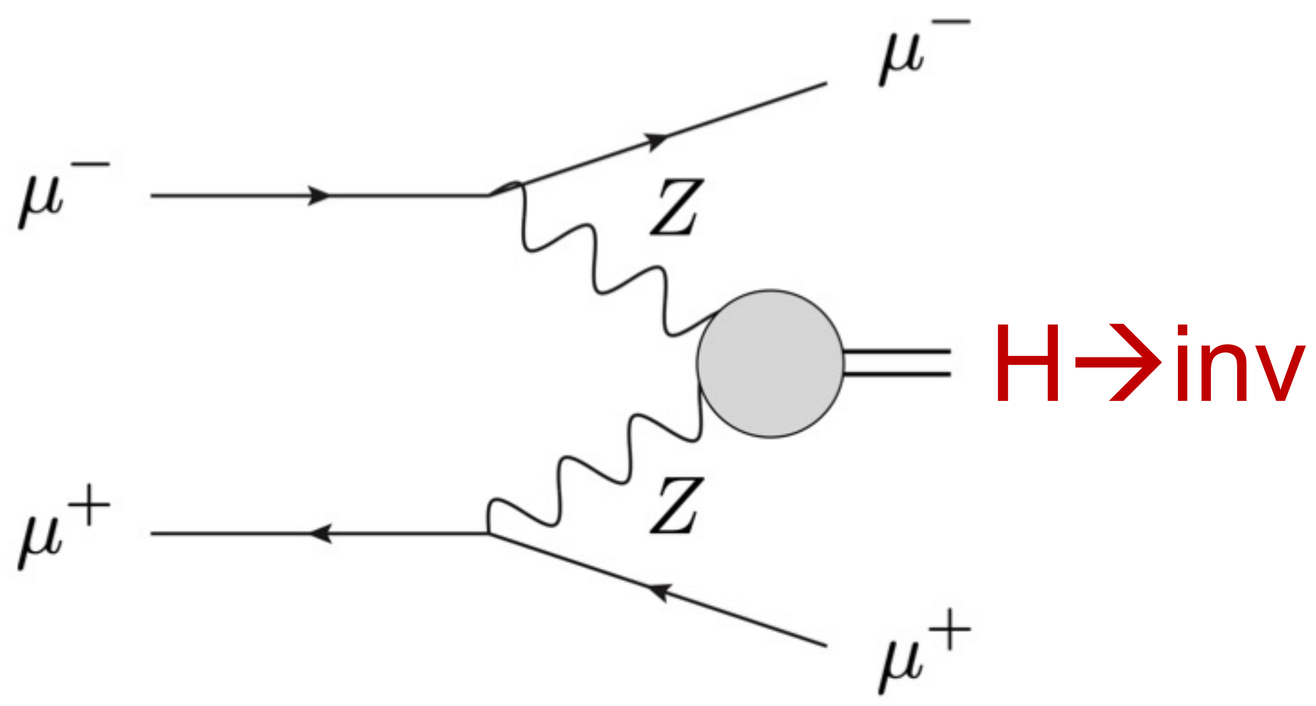
Sizable sensitivity improvement

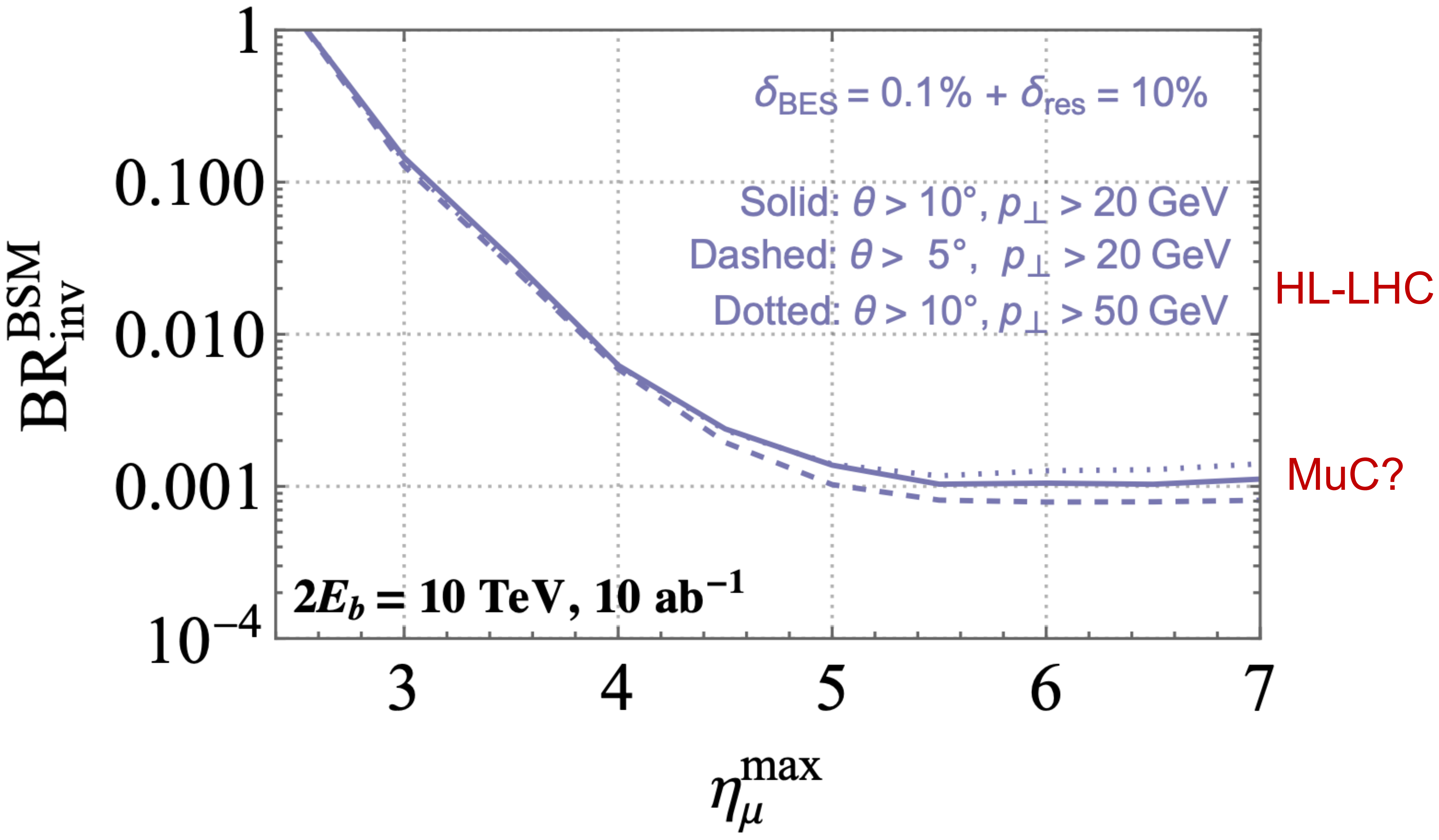
- K_W, K_Z, K_g, K_c, K_b, K_μ, K_τ,…
  - Comparable to (other) Higgs factories!



MUCOL PHYSICS: H→INV

H→ invisible: also use VBF





Forward muon tagging very important

- Challenging in BIB environment
  - Need maximal acceptance

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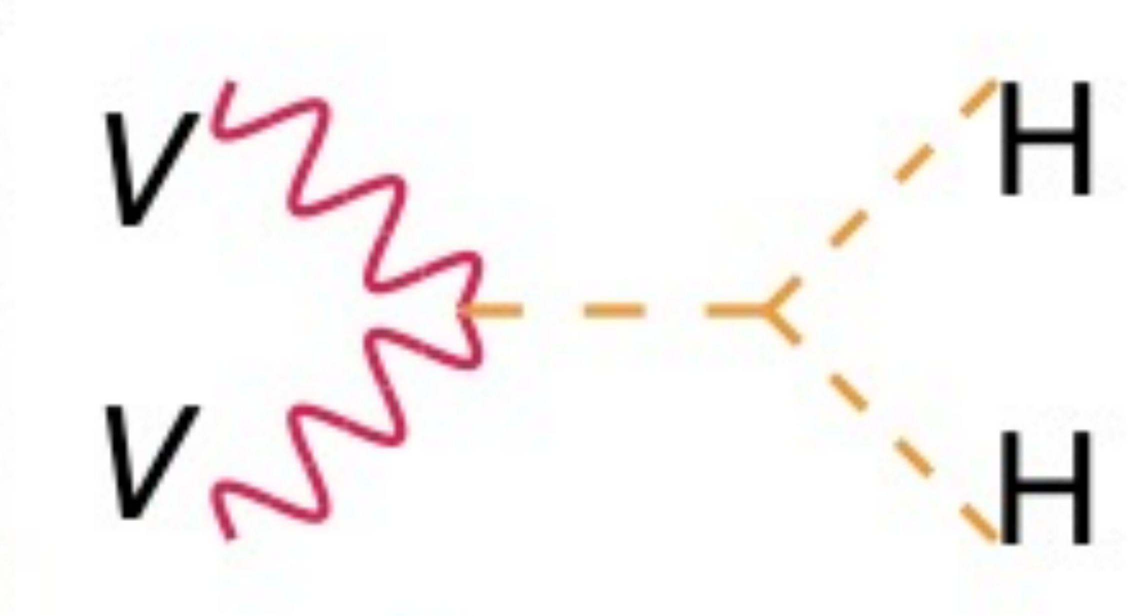
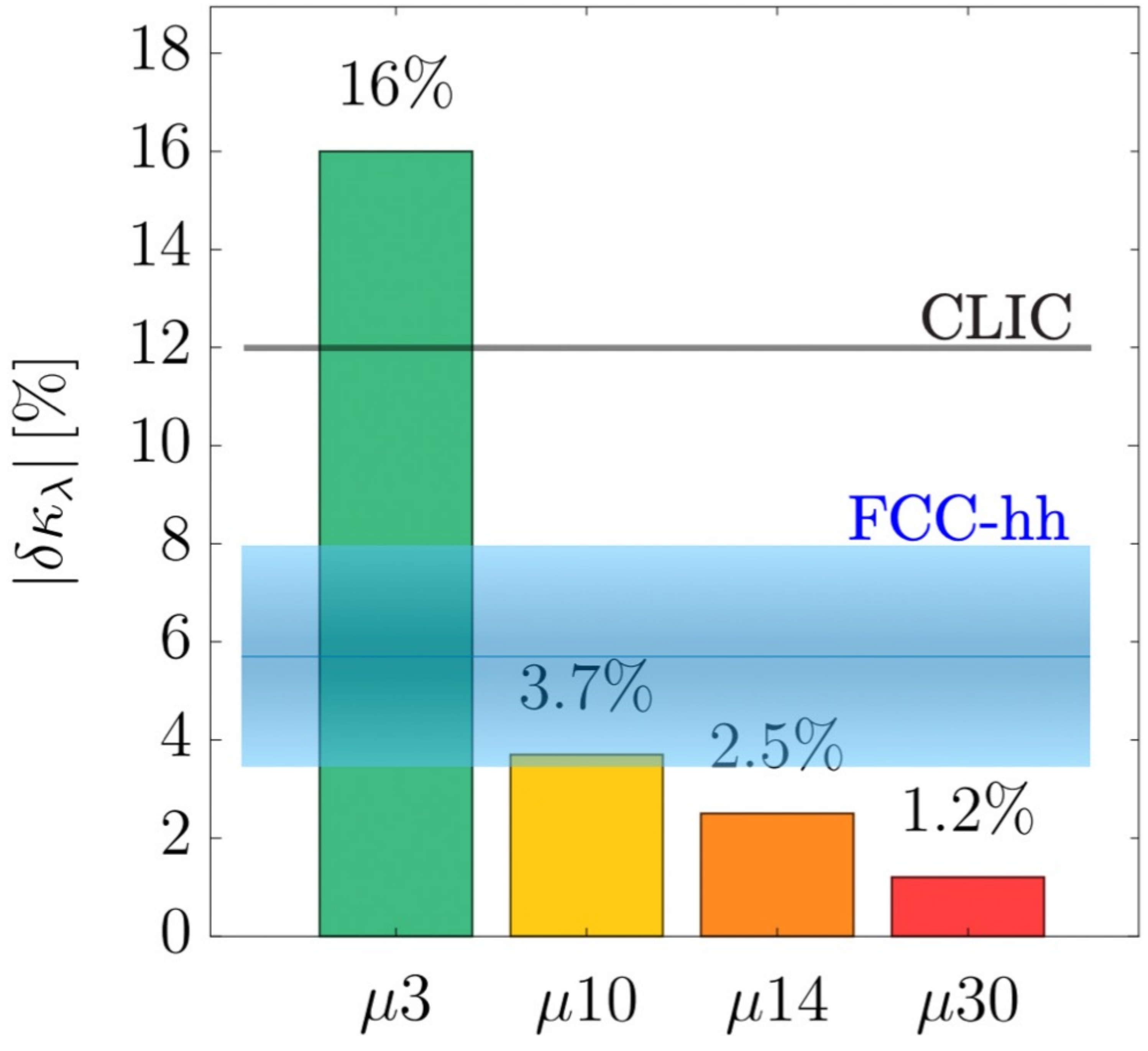
HH @ MUCOL

Self-coupling from HH

- 10/ab @ 10TeV
  - 30,000 VBF-HH

$$V = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v}(1+\delta\kappa_3) H^3 + \frac{m_H^2}{8v^2}(1+\delta\kappa_4) H^4$$





10TeV MuCol

- <5% uncertainty on the self-coupling
  - Similar to FCC-hh

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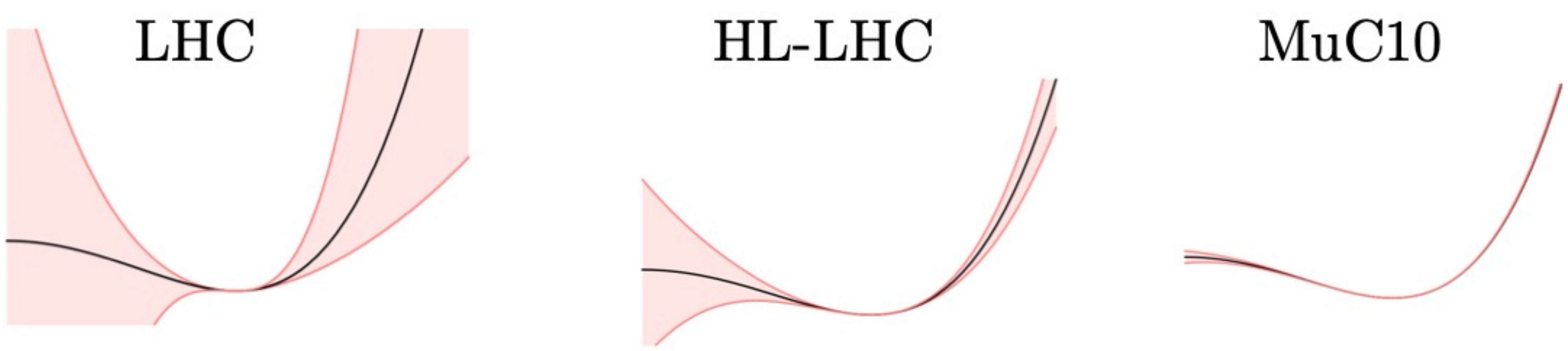


10TeV MuCol

- <5% uncertainty on the self-coupling
  - Constrain shape of Higgs potential

HH(H) @ MUCOL

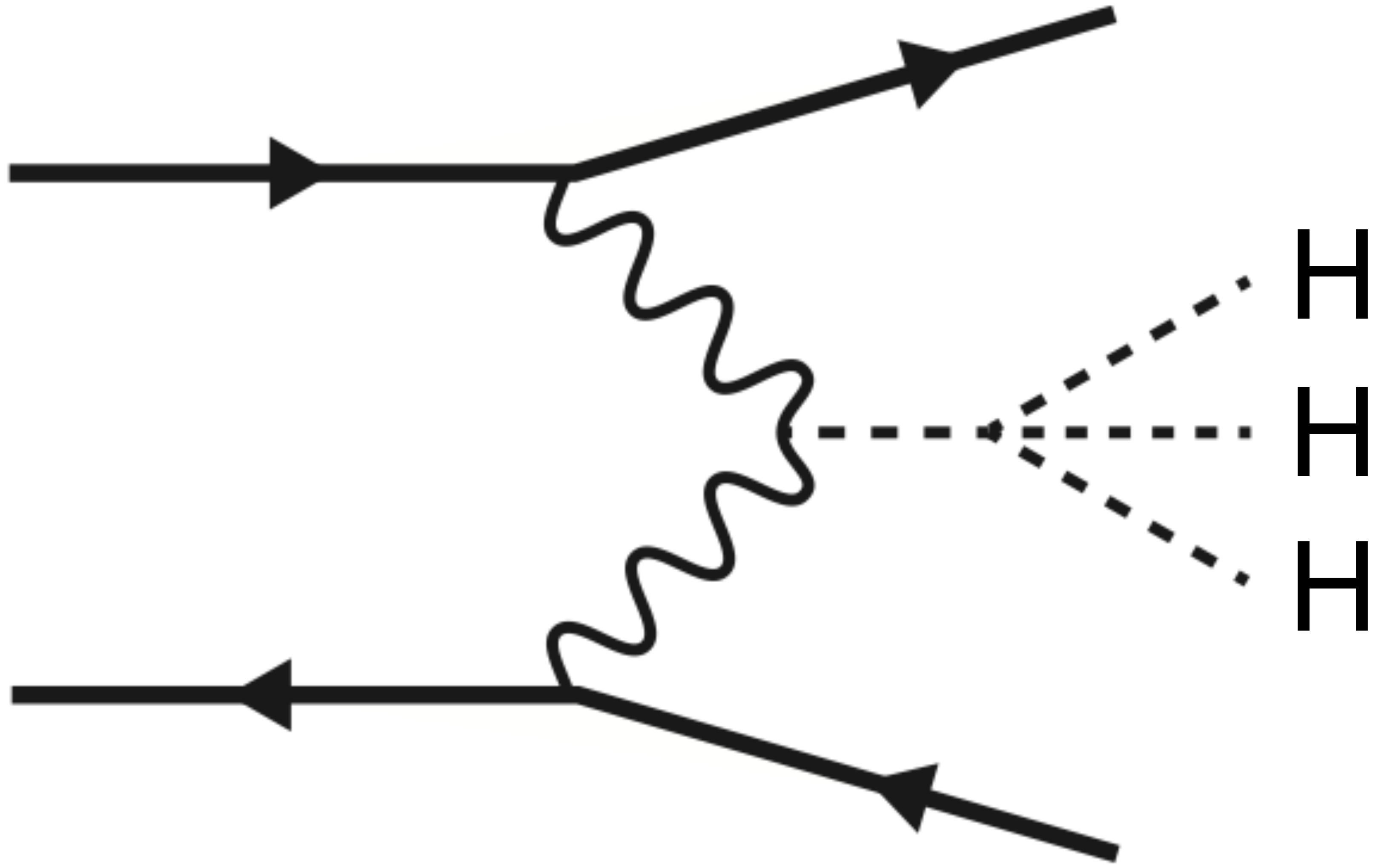
Self-coupling from HH(H)

- 10/ab @ 10TeV

$$V = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v}(1 + \delta\kappa_3) H^3 + \frac{m_H^2}{8v^2}(1 + \delta\kappa_4) H^4$$

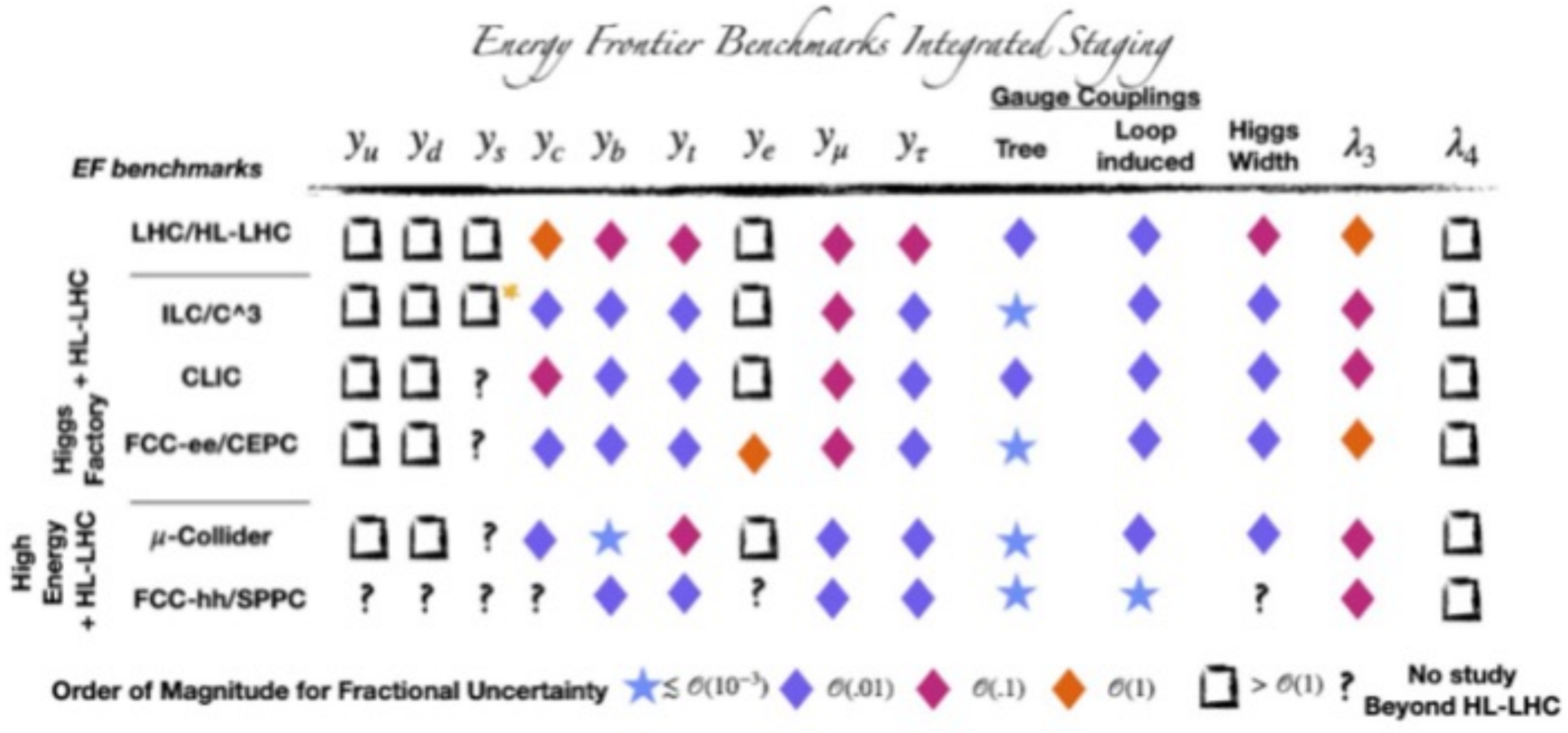
Constrain HH K_3 self-coupling

- Possibly even K_4
  - Unique HHH production



HIGGS PHYSICS SENSITIVITIES SUMMARY

Similar reach in Higgs physics for different future accelerators



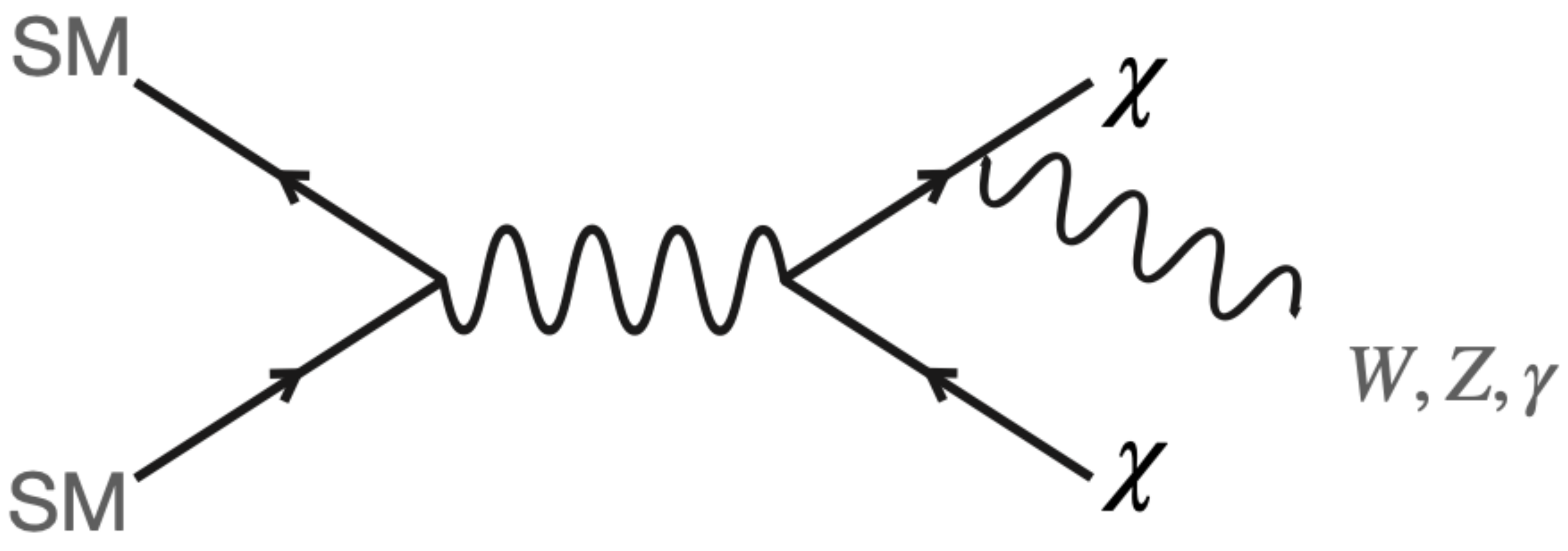
➔ The muon collider is a discovery machine and a precision machine!

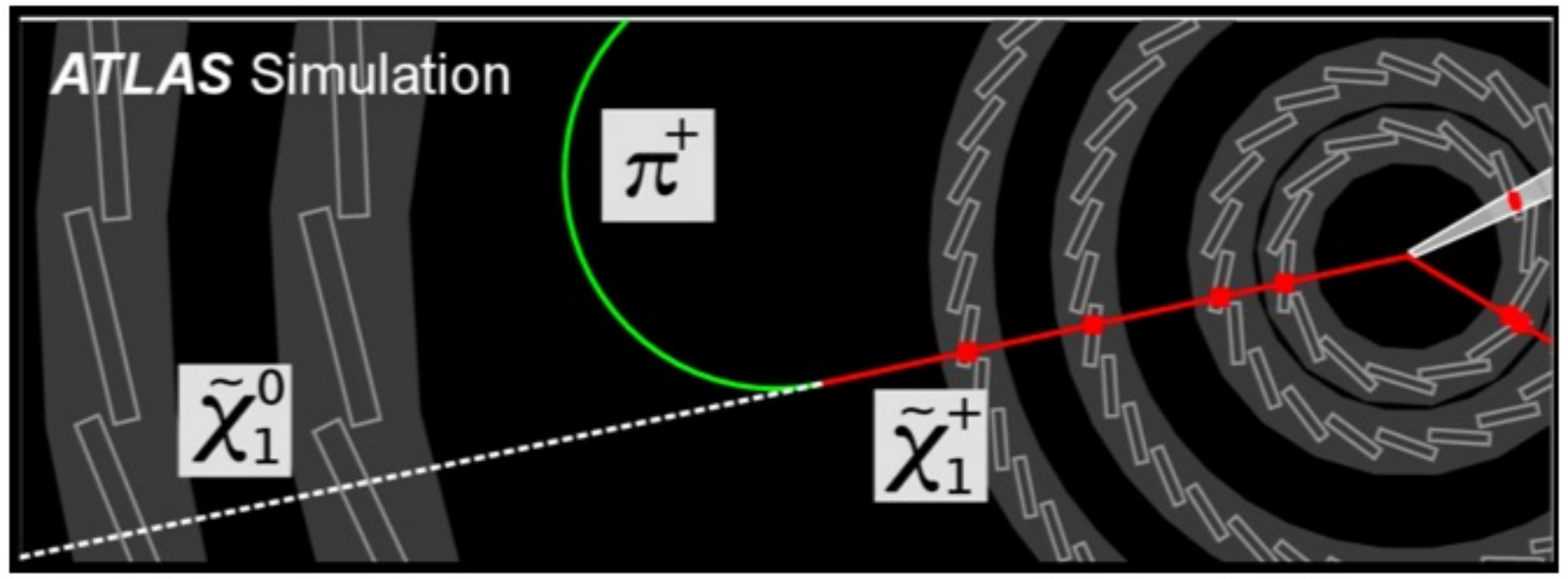
MUCOL SEARCHES

Long-lived particles?

Disappearing tracks?

χ stable or long lived $\qquad \chi^+ \to \pi^+ \chi^0$





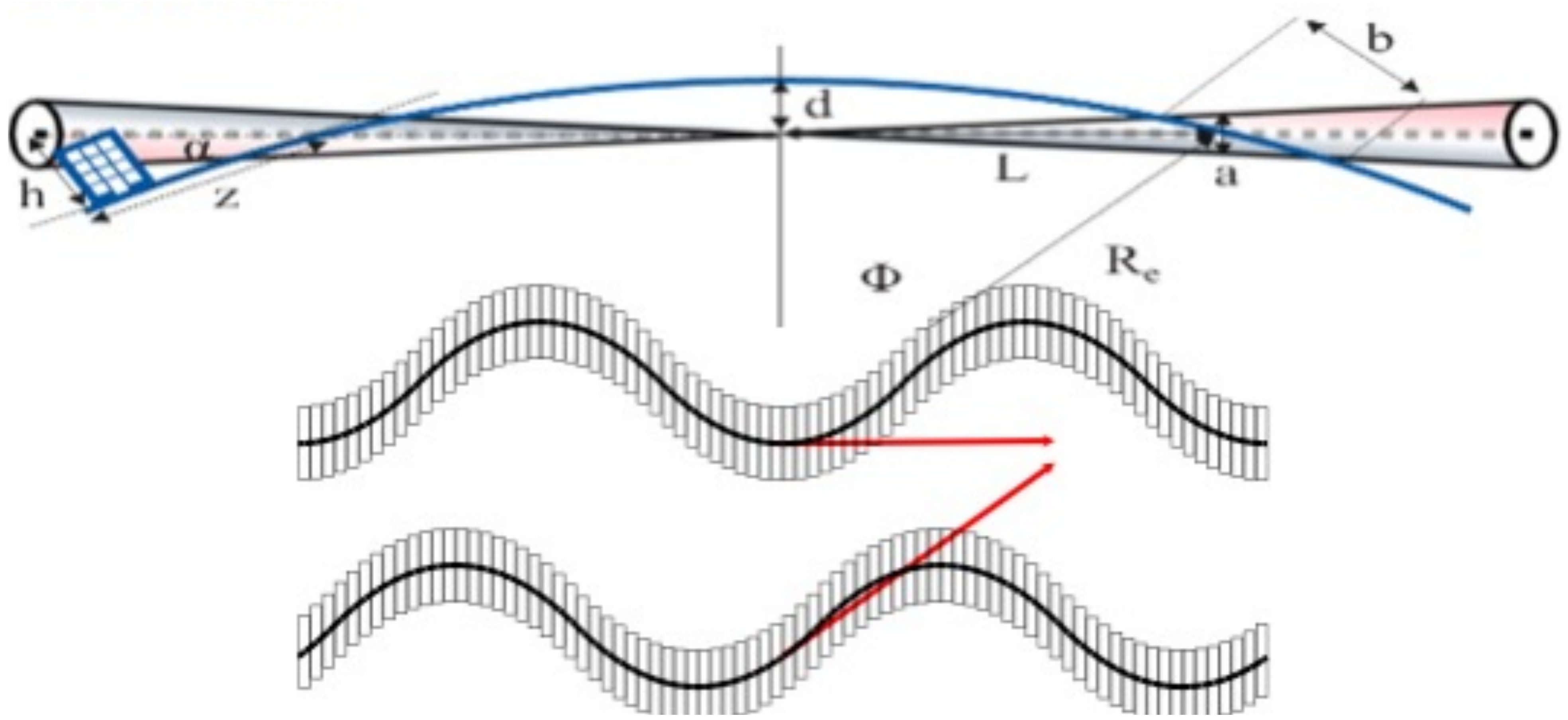
Beyond the baseline programme, challenging topologies

- Profit from timing information

NEUTRINOS

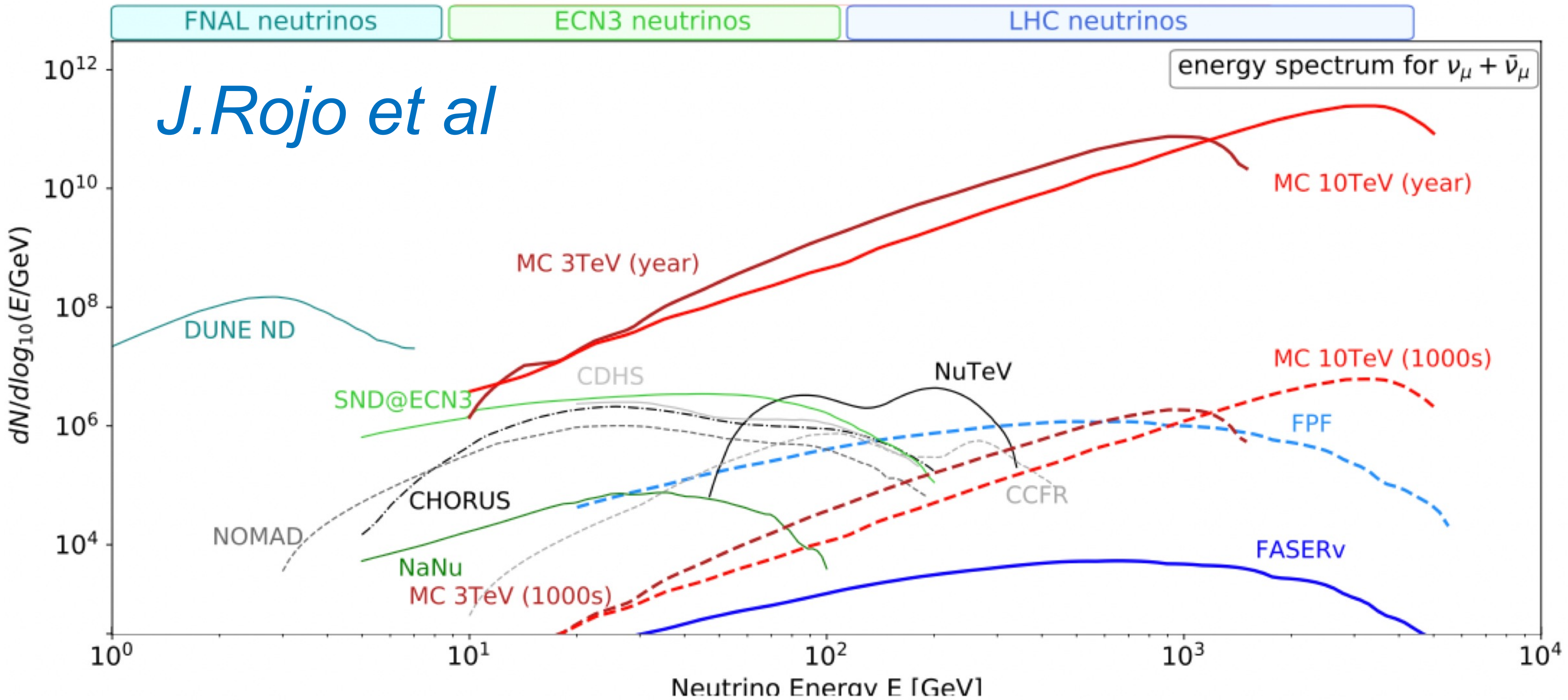
High-E neutrino radiation

- Known issue, mitigate:
  - By ‘wobbling’ the beam



Source for additional research!

- Neutrino physics
  - Use flat sections in ‘racectrack’
  - Short baseline



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MUCOL PHYSICS SUMMARY

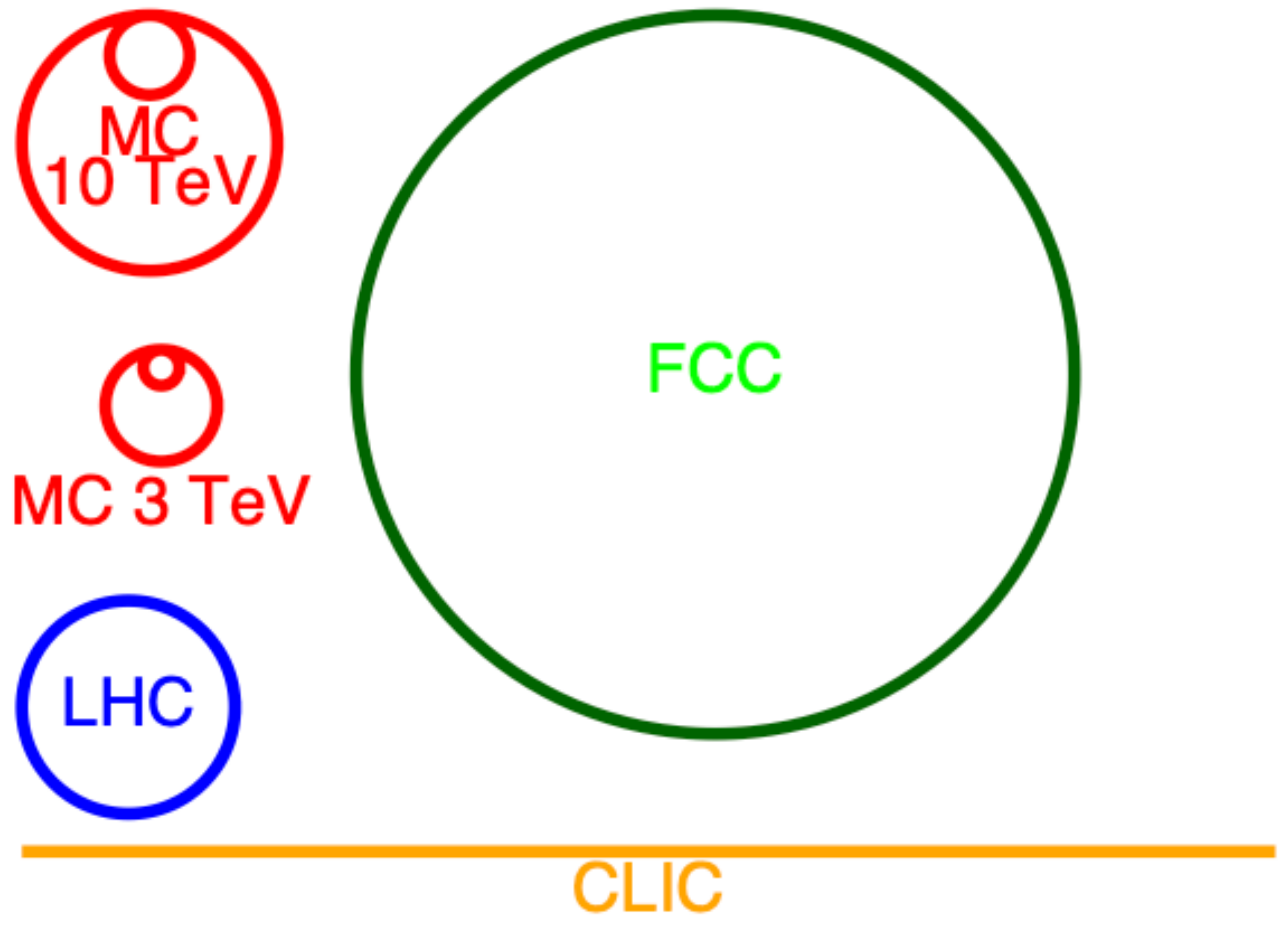
Main physics programme

- Higgs precision
- Higgs self-coupling
- New energy scale

Additional possibilities

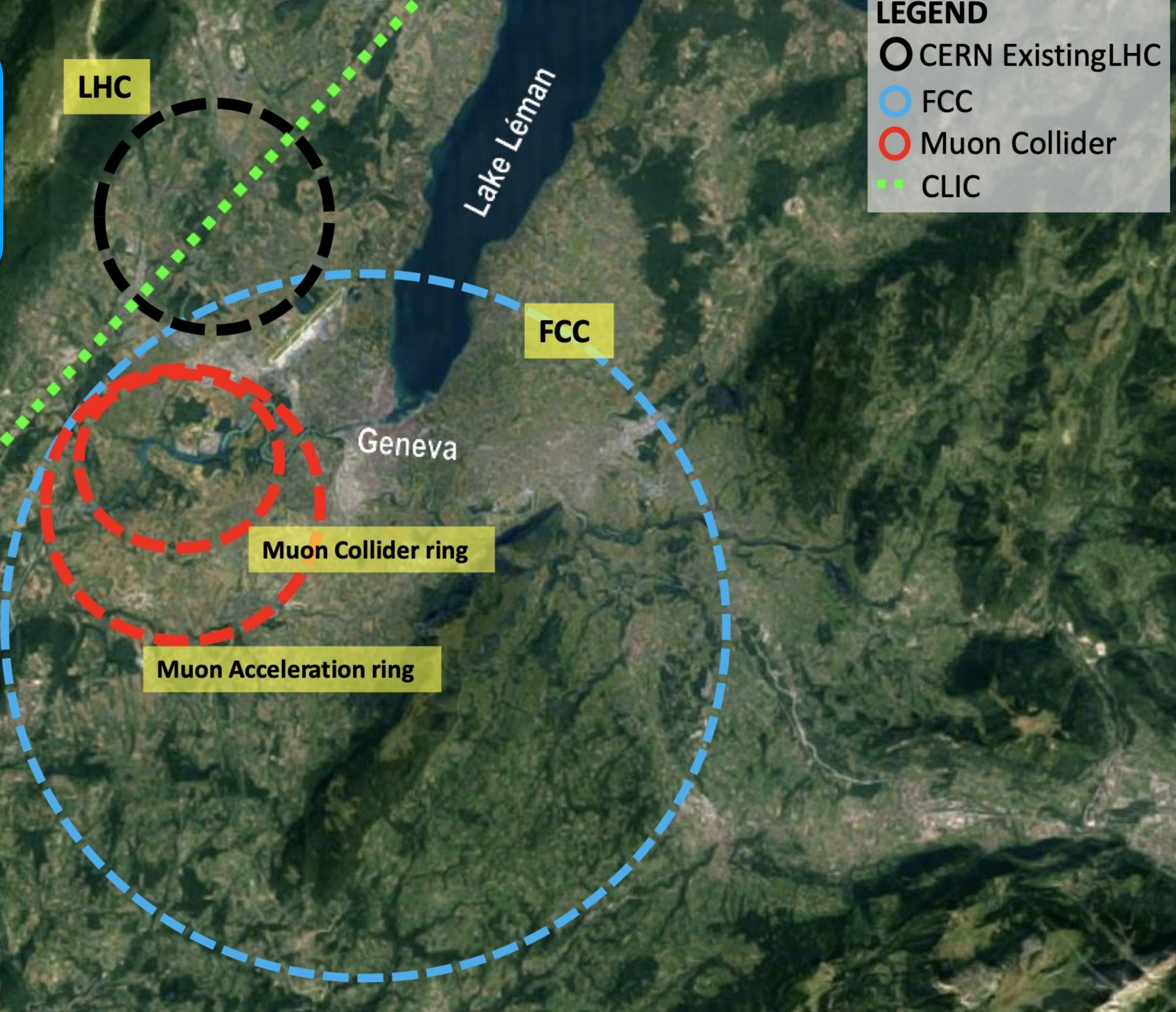
- Long-lived particles
- Neutrinos

And it’s compact!



CERN's future

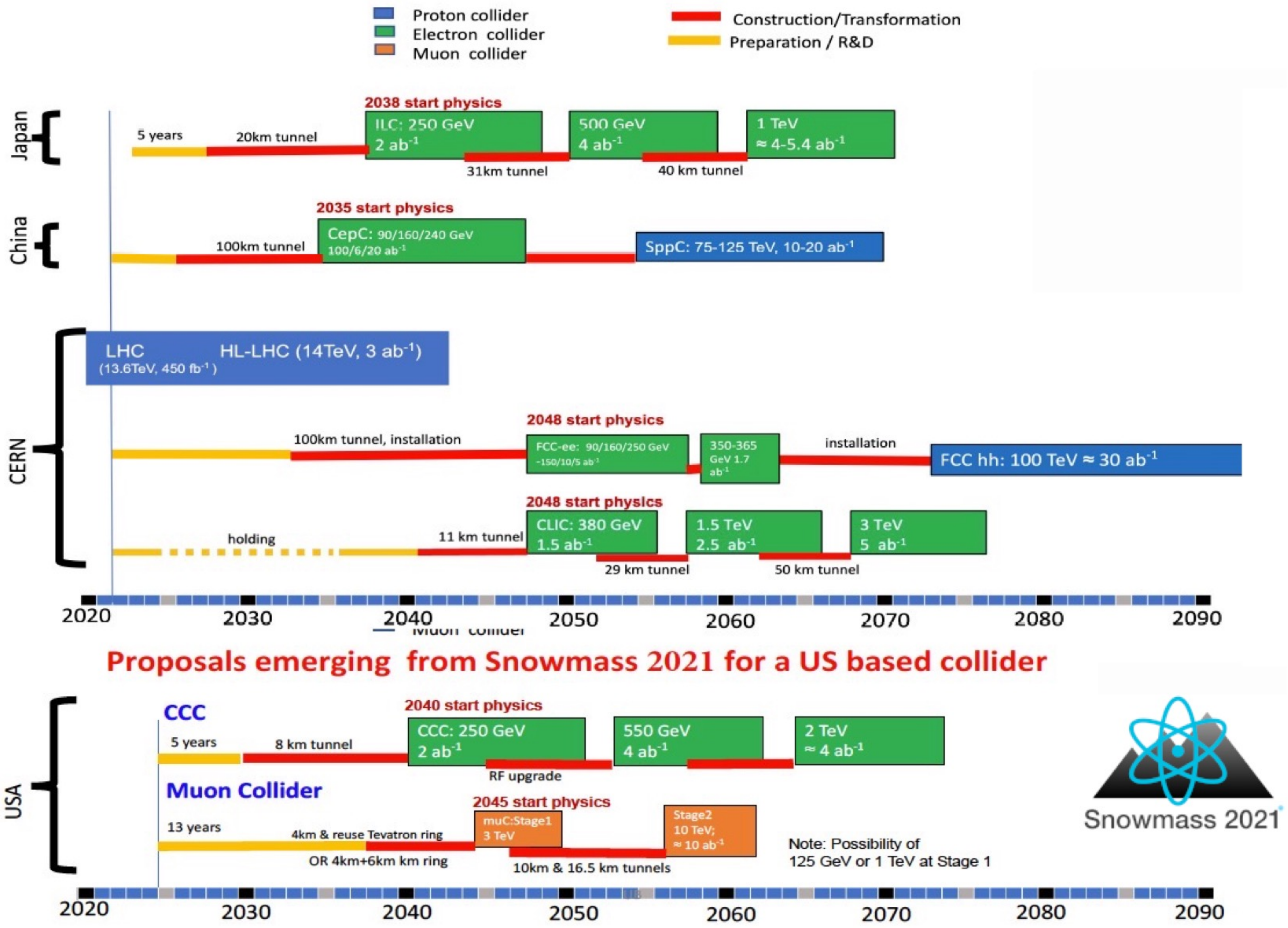
- HL-LHC
- + CLIC?
- + FCC?
- + MuCol?



TIMELINES

MuCol start in 2045?

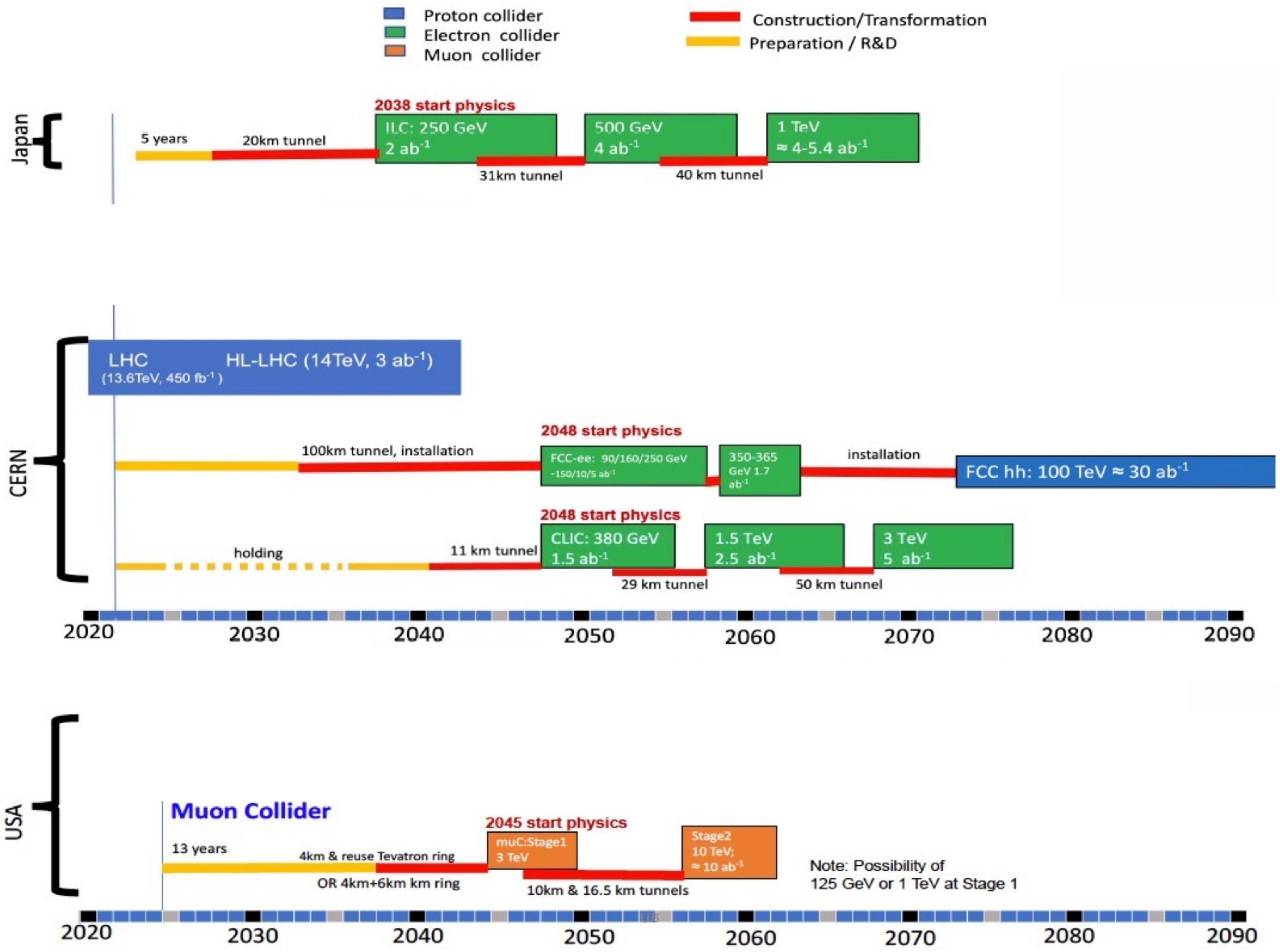
- Driven by technology



TIMELINES

MuCol start in 2045?

- Driven by technology
  - Timeline similar to other projects



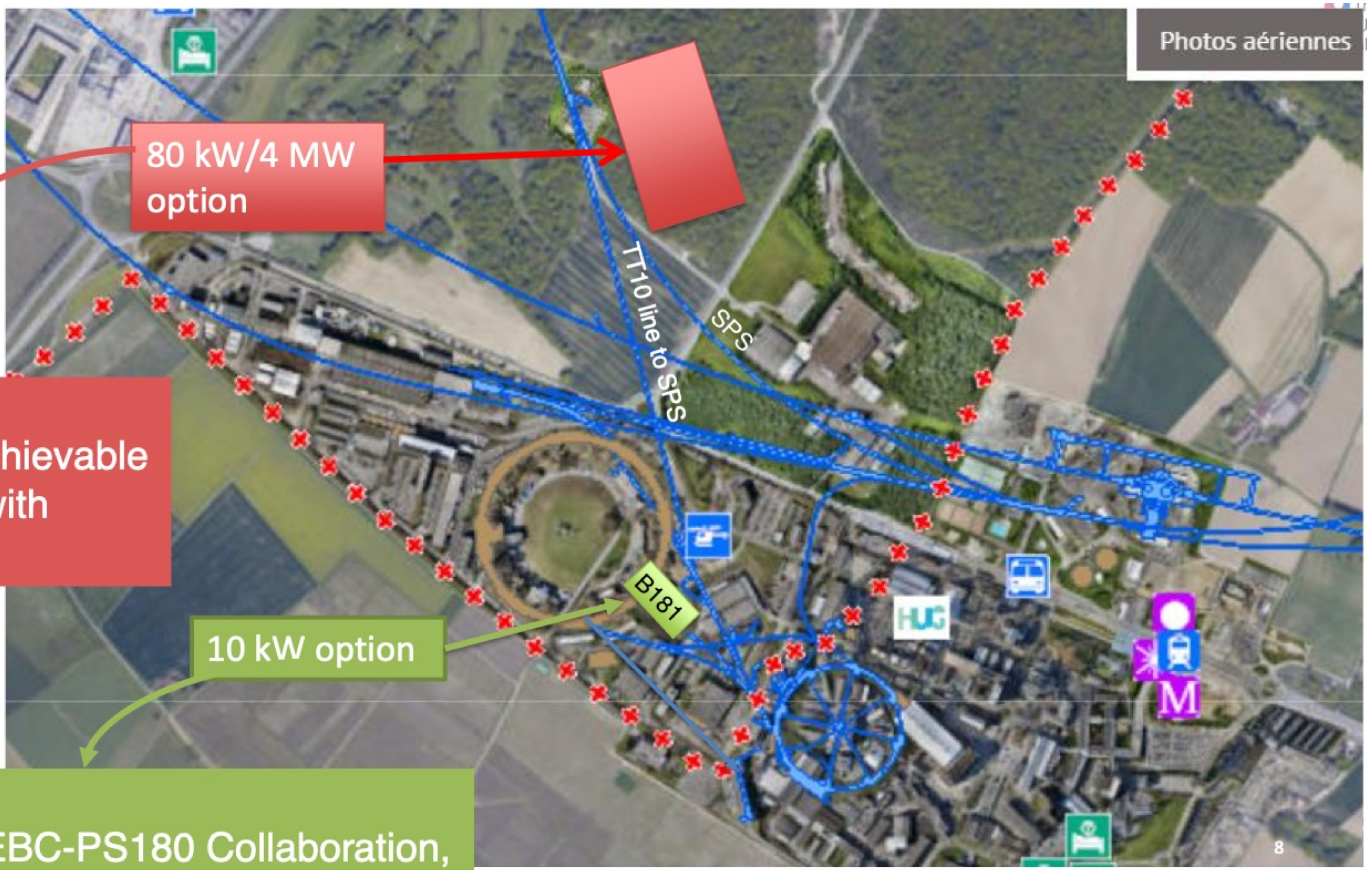
PLANS FOR A DEMONSTRATOR

D.Lucchesi, for the IMCC – 17 Oct 2023 at CERN

At CERN site?

Both use maximum intensity per pulse ~10^{13} ppp (or more) in pulses of few ns at 20+ GeV.
Different repetition rate:

- 1 pulse/few second
- 1÷2 pulse/per minute



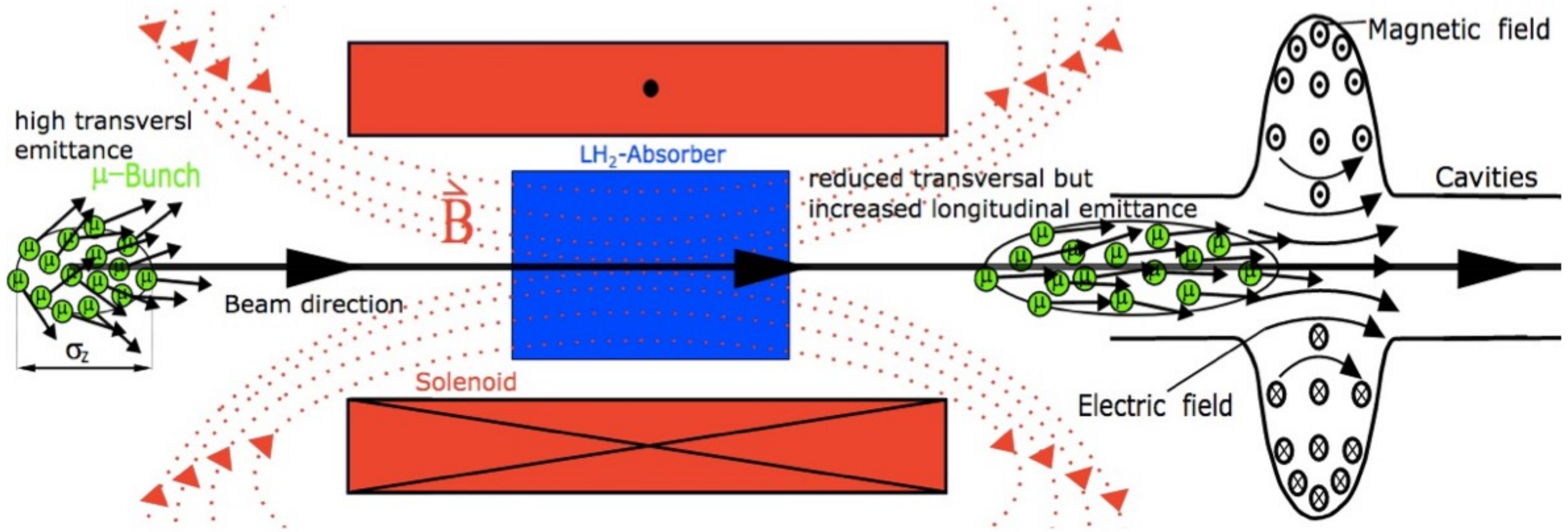
High power
O(80kW) on target easily achievable
No showstopper for 4 MW with beam at a depth of 40 m

Low power:
Reuse line of BEBC-PS180 Collaboration, decommissioned, extending it towards B181 (now magnet factory)

COOLING

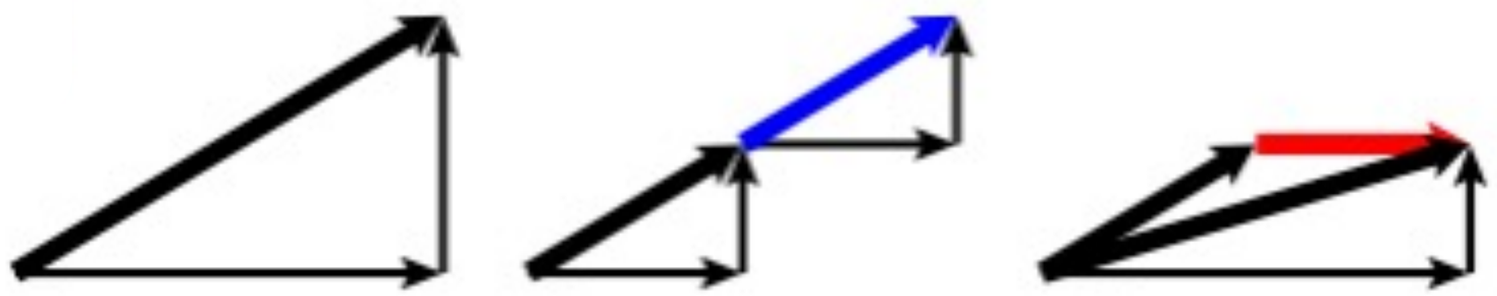
Main challenge

- ‘6D’ ionization cooling



Minimize energy loss:

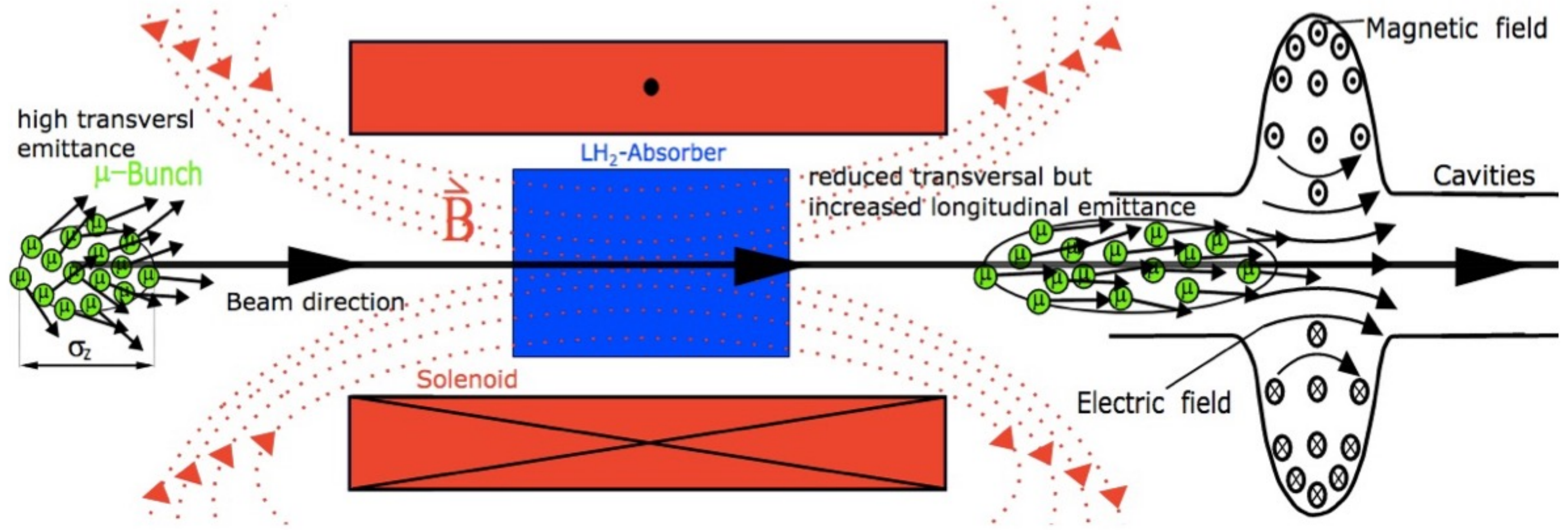
- Low-Z material → LH_2
  - In strong magnetic field



COOLING

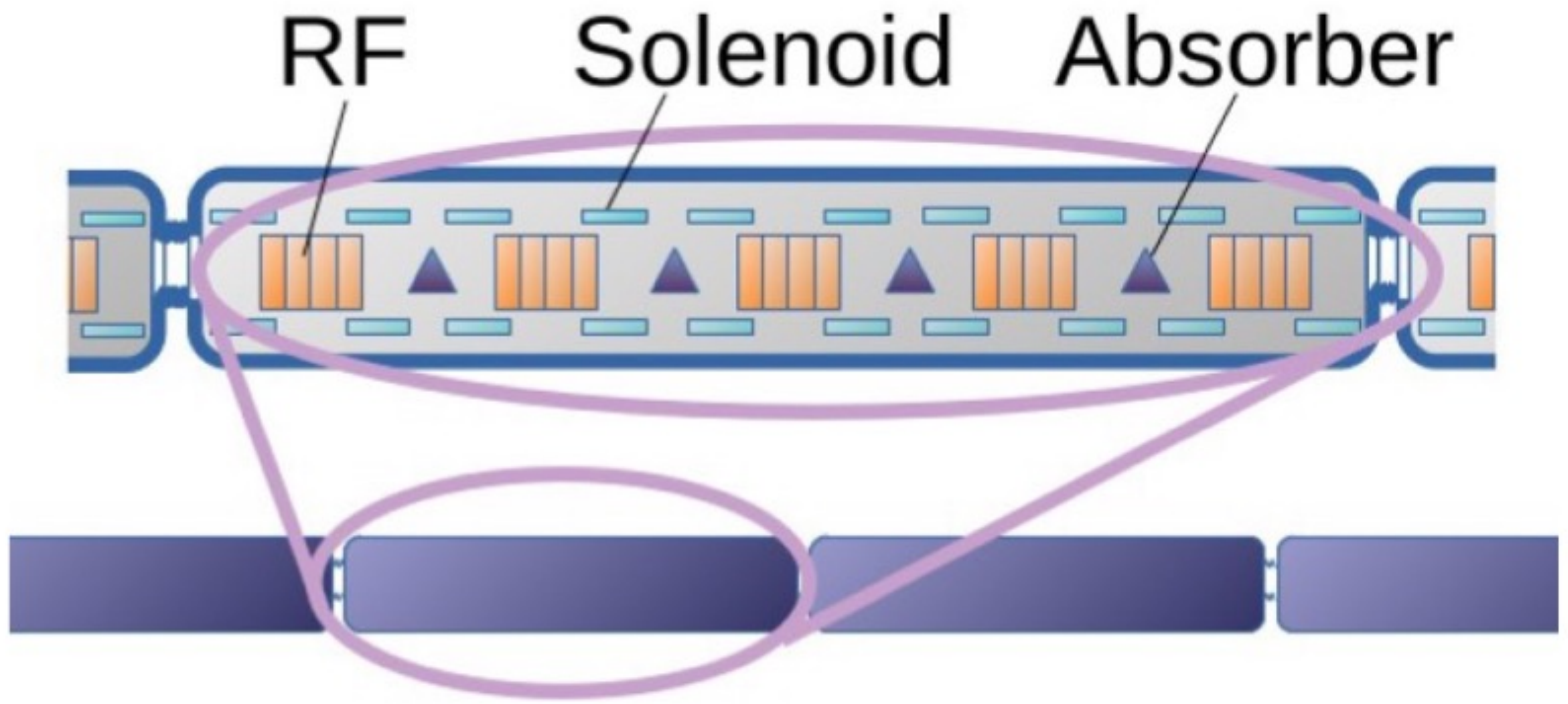
Main goal of demonstrator

- Prove cooling
  - Absorber + magnet + RF



Challenges

- Large bore solenoid
- High gradient RF
- Large intensity absorber
  - All together!



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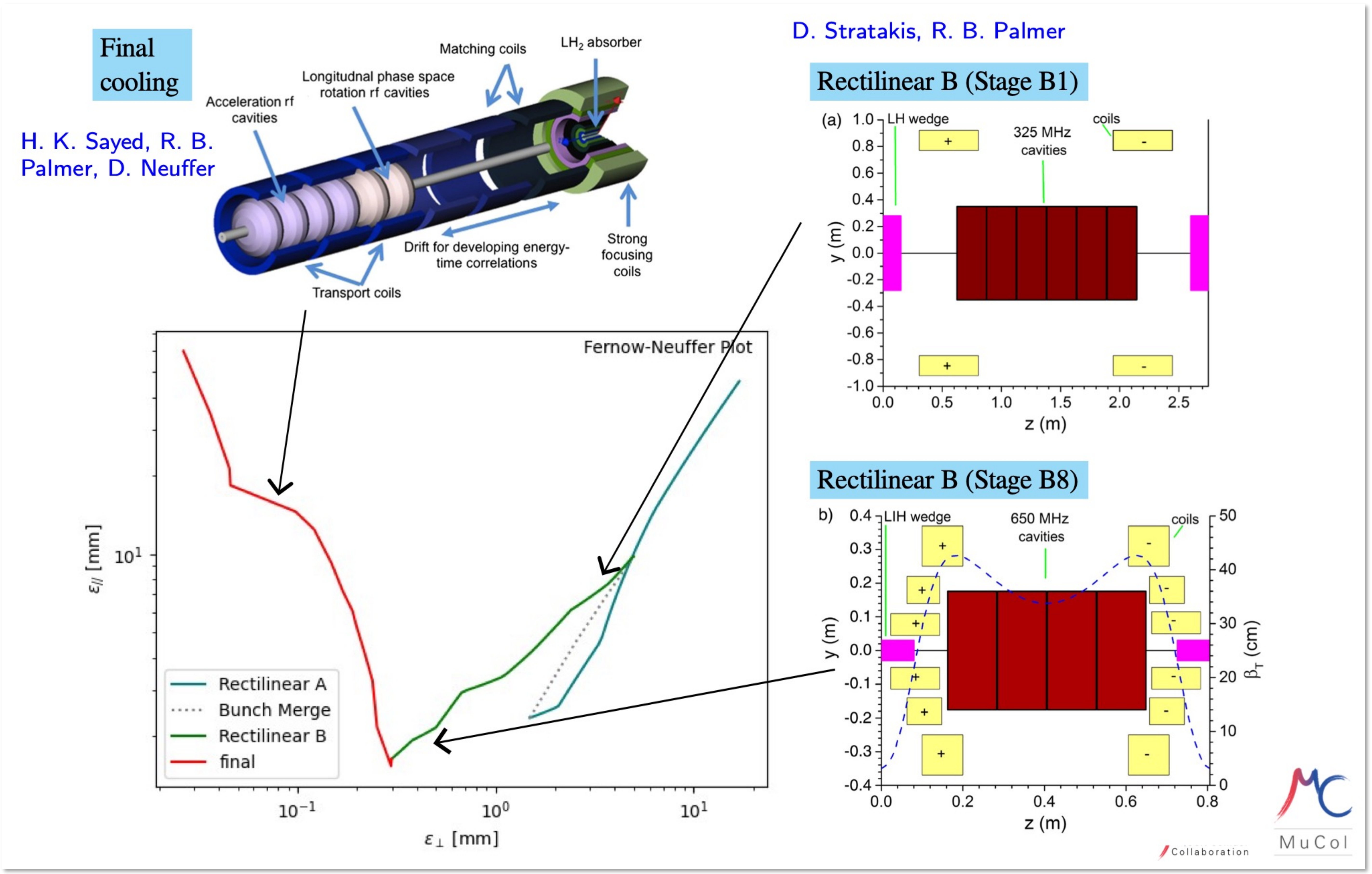
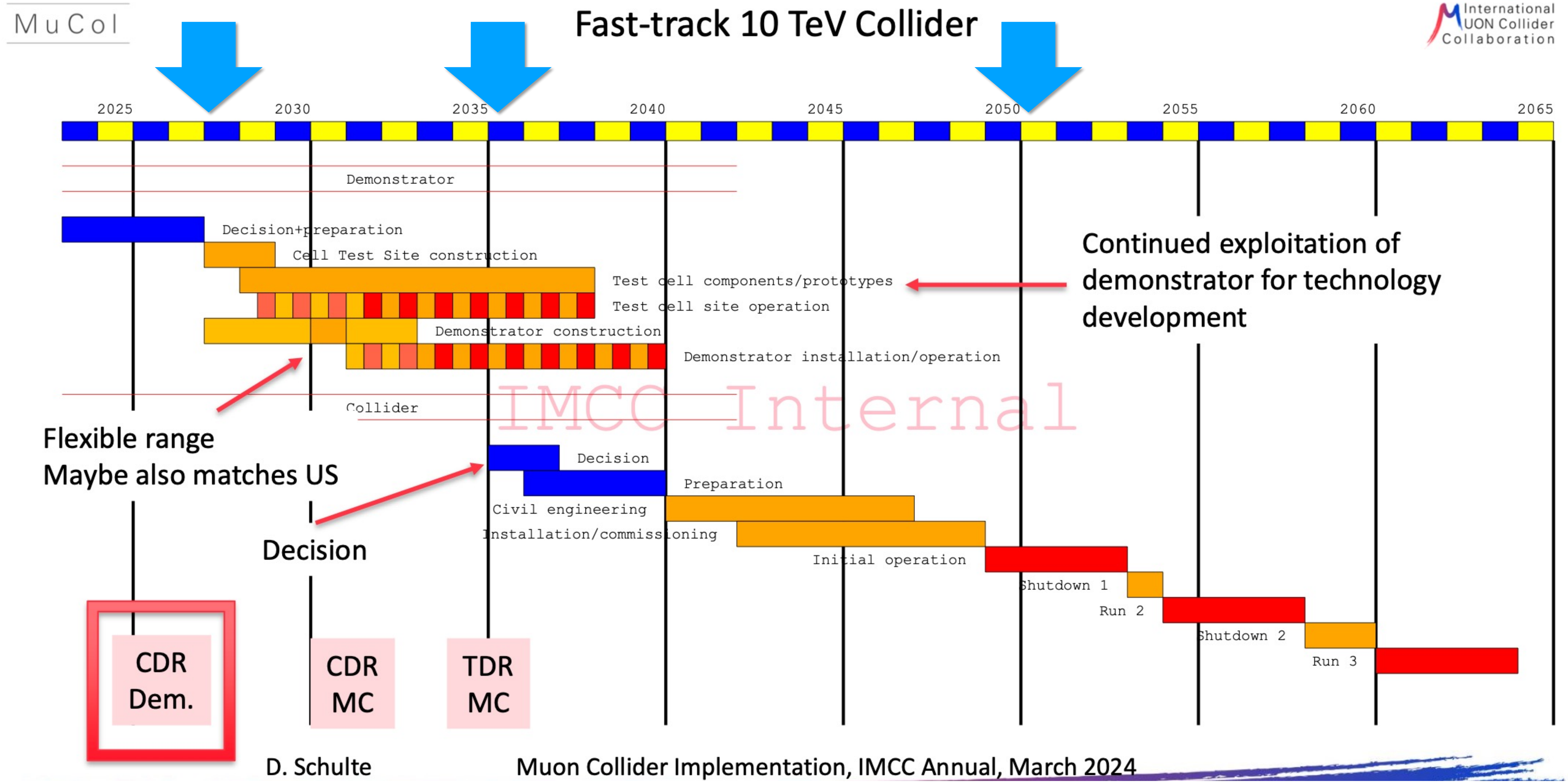


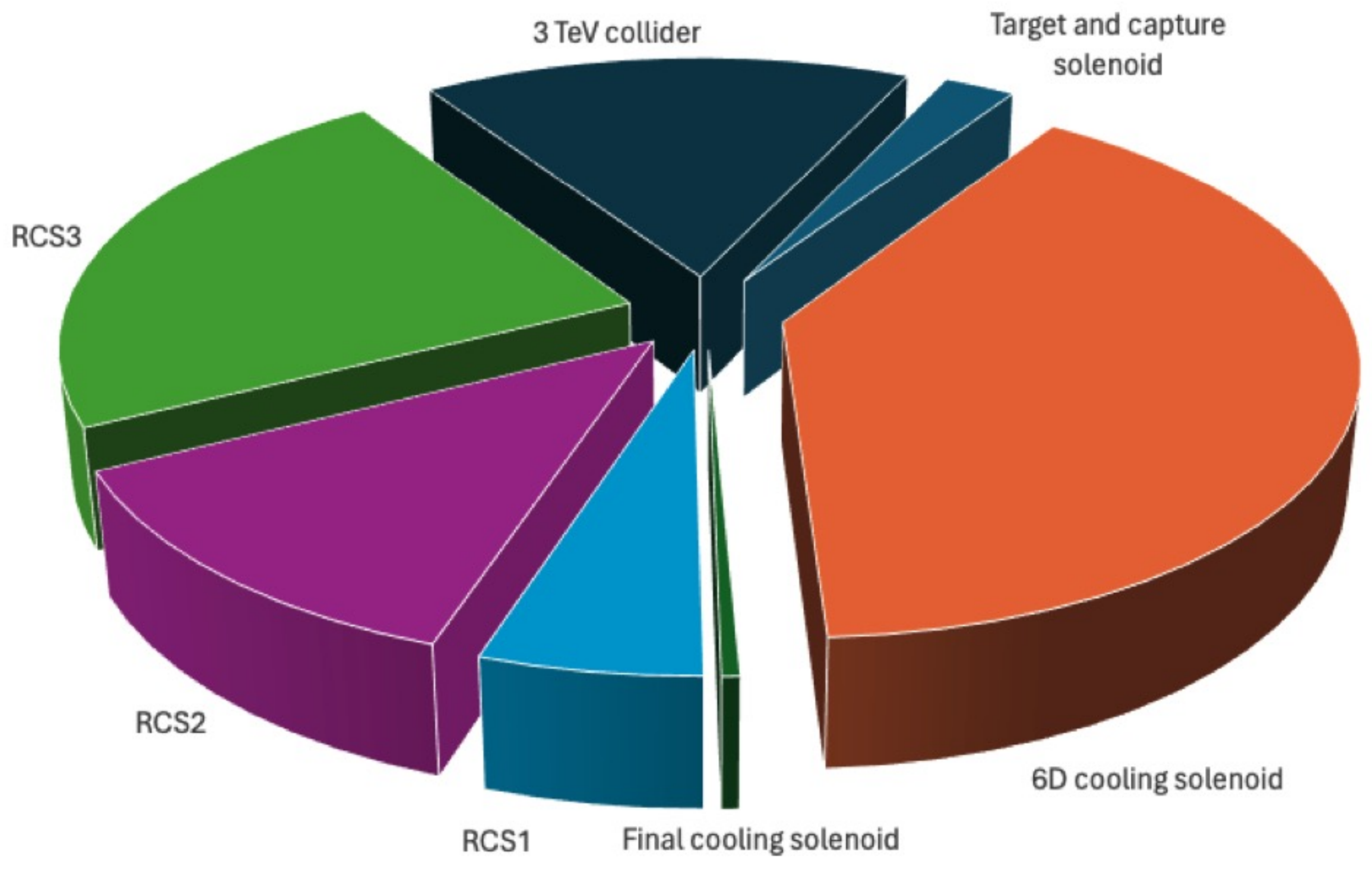
Example Timeline



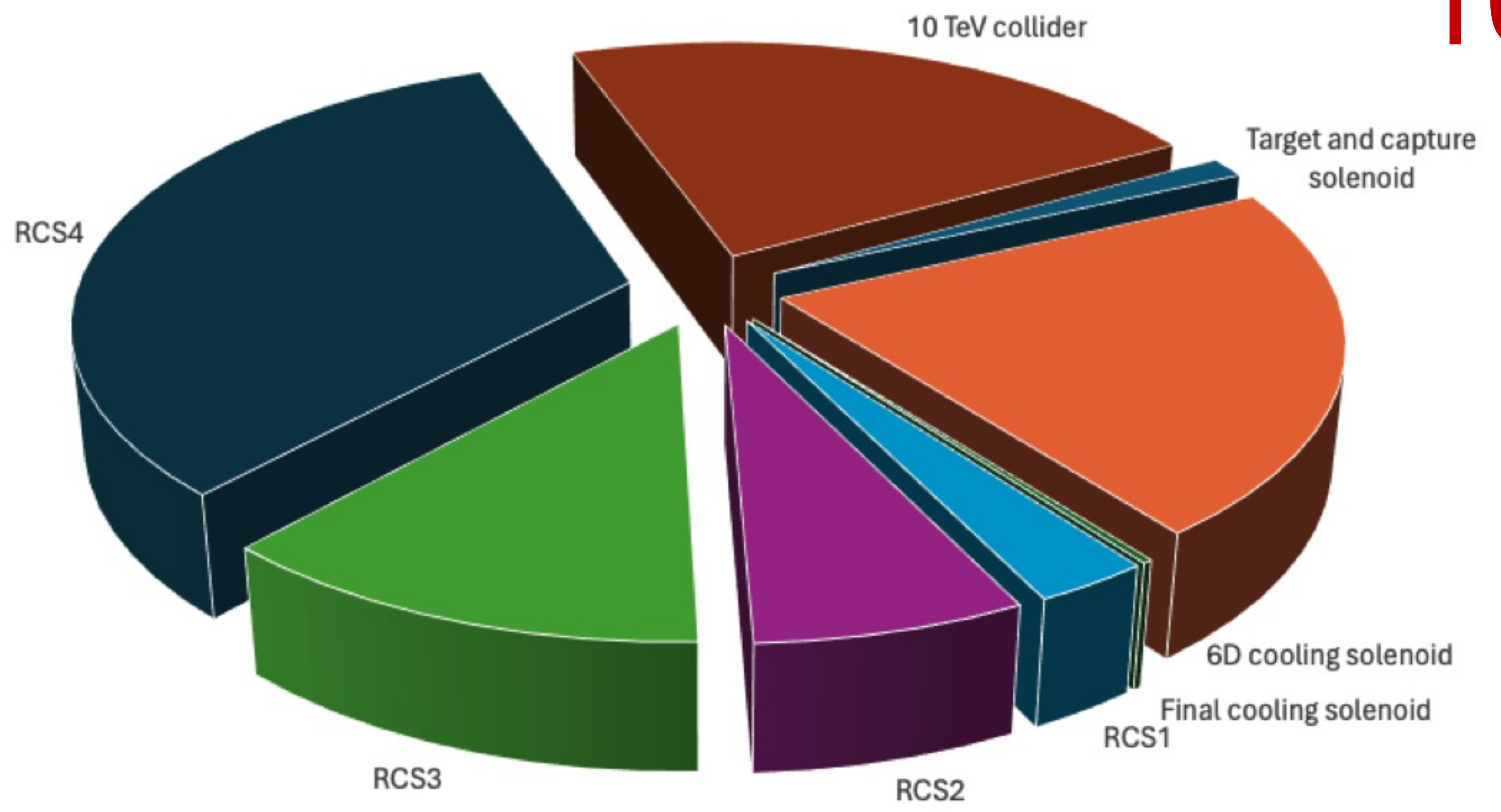
COSTS

Relative costs in MuCol project

3TeV



10TeV



Largest costs in 6D cooling and accelerator (RCS)

- Target, capture, final cooling only small fraction
  - Not dominated by (relatively) small collider

COSTS (1)

125-600 GeV

- Overall: 5-15B$
  - MuC on lower side of spectrum

Snowmass 21 - https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

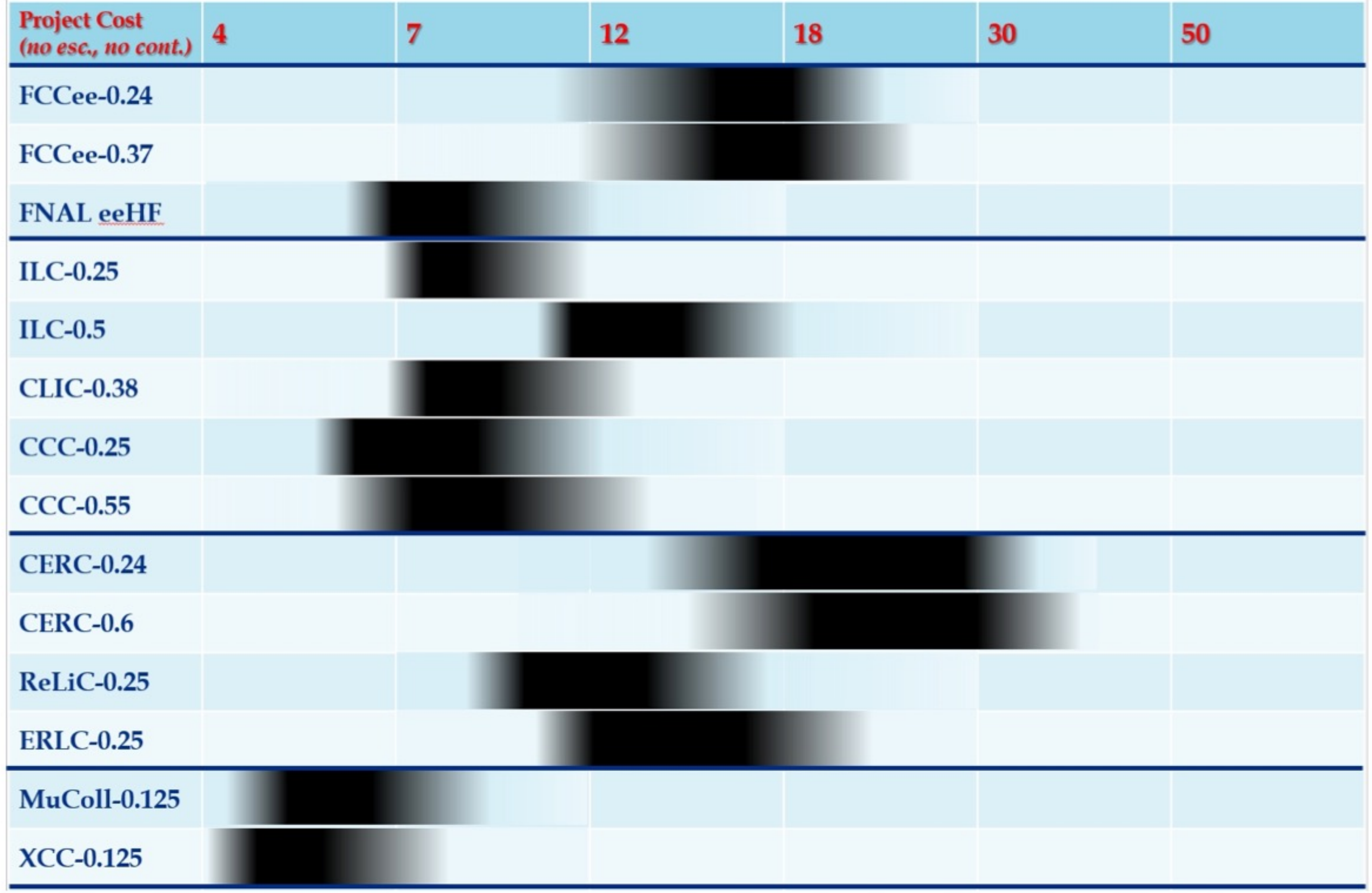


Figure 8. The ITF cost model for the EW/Higgs factory proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

COSTS (2)

1-10 TeV

- Overall: 10-30B$
  - MuC on lower side of spectrum

Snowmass 21 - https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

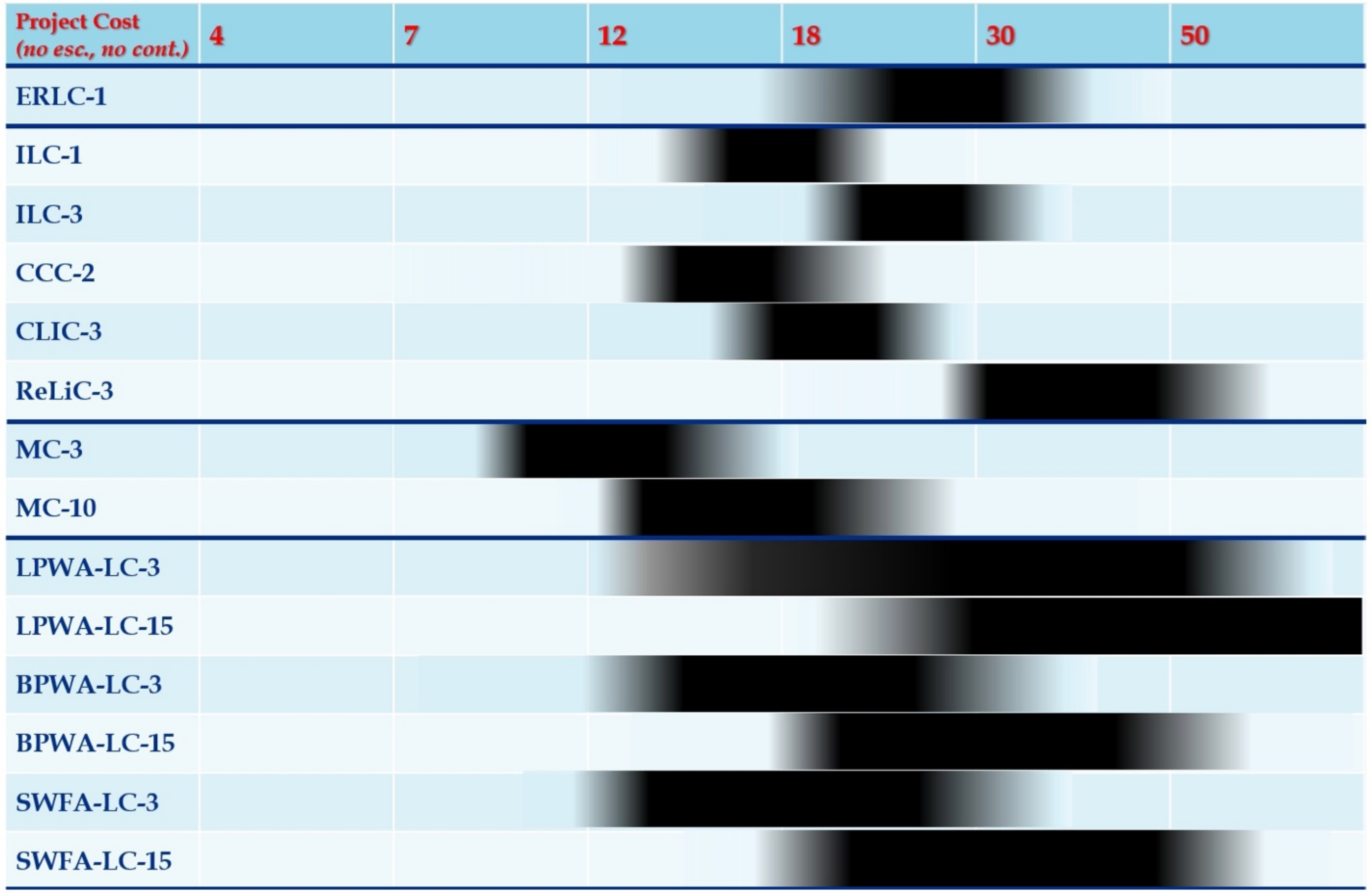


Figure 9. The ITF cost model for the multi-TeV lepton collider proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

COSTS (3)

Other projects

- FCC-hh >25B$

Snowmass 21 - https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

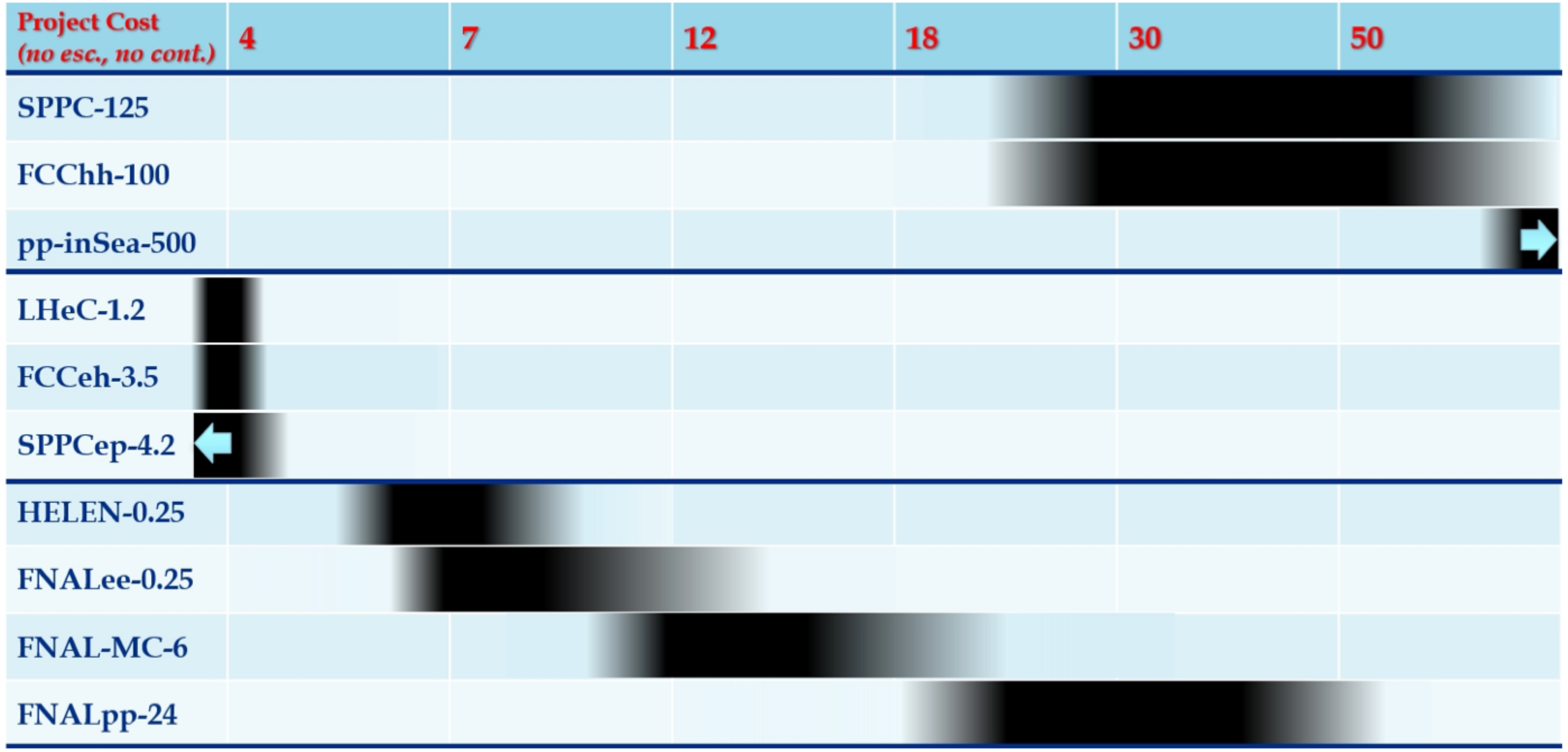
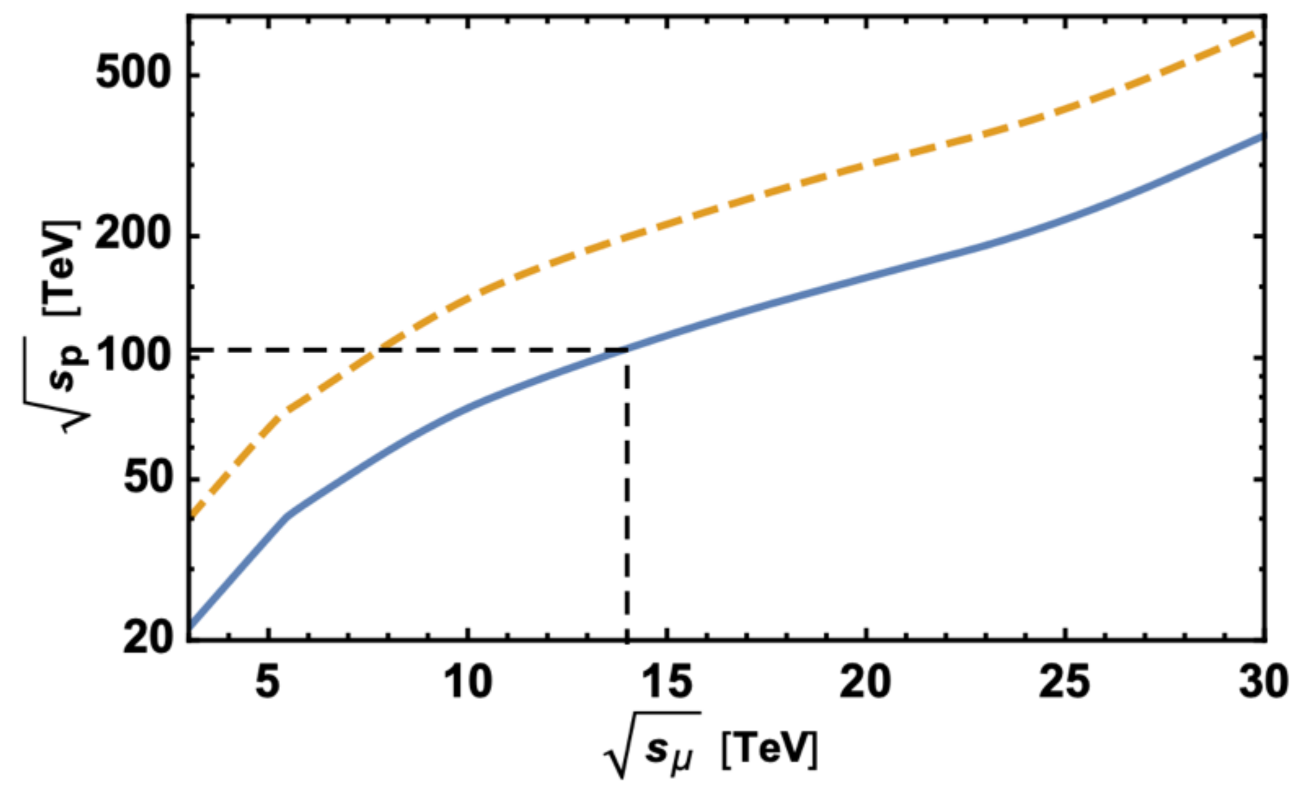


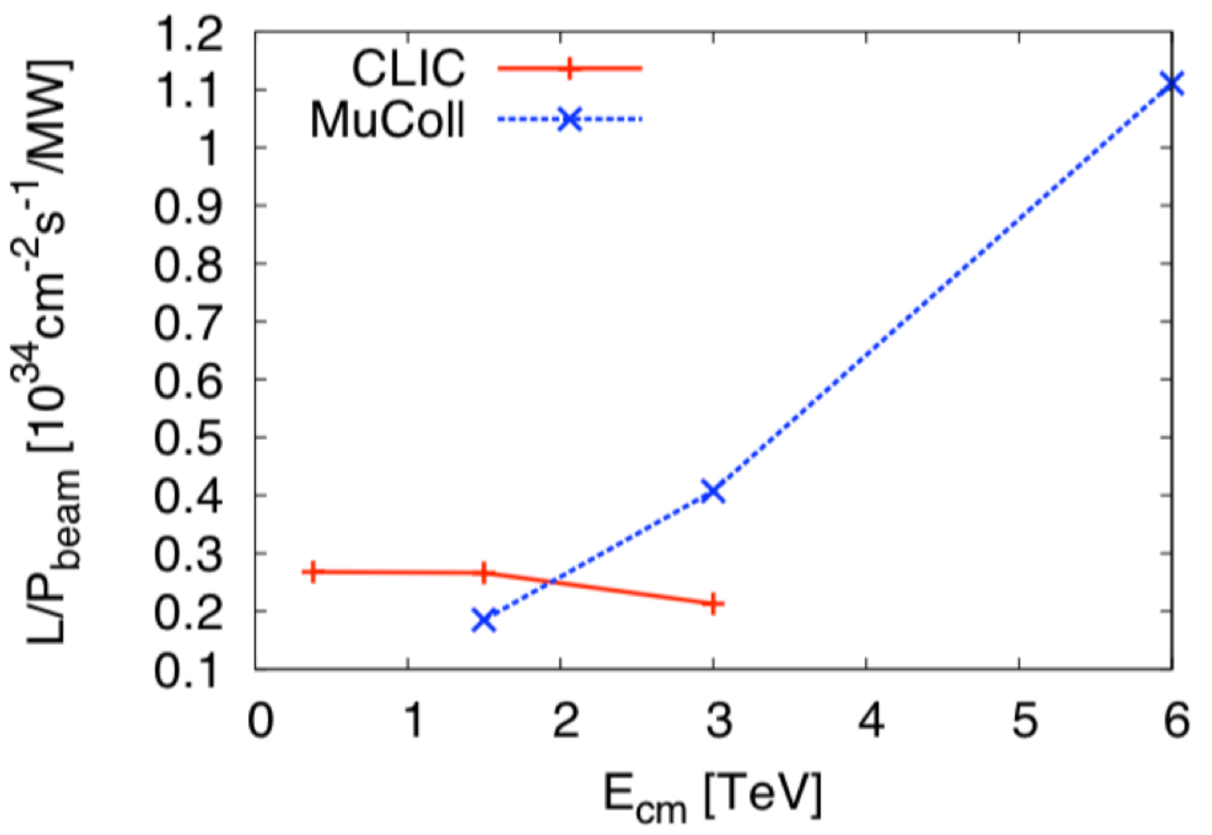
Figure 10. The ITF cost model for the energy frontier hadron collider, electron-proton colliders (incremental cost from hadron collider only) and for the proposed Fermilab site-filler colliders. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends are the cost estimate range for each machine. Right-arrow for the 500 TeV “Collider-in-the-Sea” indicates higher than 80 B$ cost. Left-arrow for the electron-proton “SPPC-CEPC” collider concept indicates smaller than 4 B$ cost.

MUON COLLIDER BENEFITS

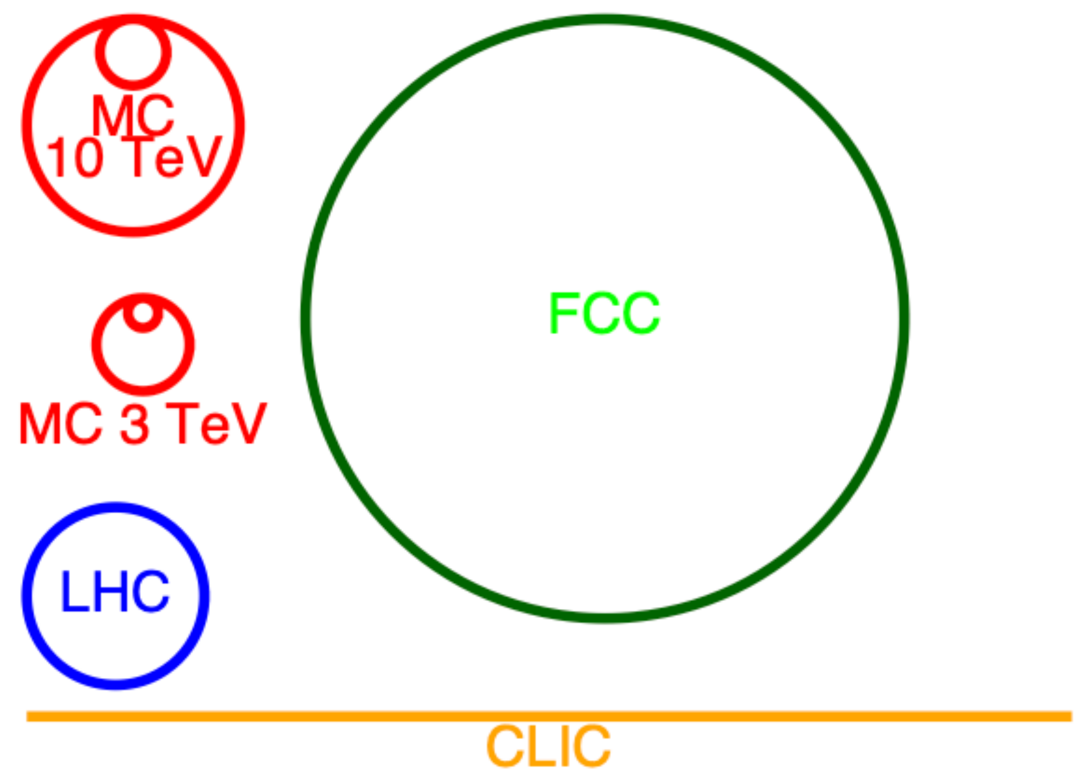
High energy
- Discovery machine
- Higgs self-coupling
  - Like FCC-hh



Precision physics
- Luminority frontier
- Higgs factory
  - Like FCC-ee



Compact & efficient
- √s=10 TeV: 10-30km
  - Like LHC



➢ And in the meantime we will do a lot of accelerator+detector R&D

MUON COLLIDER

Physics case of a muon collider is great

- But it might not even be the main criterium

Muon collider has many advantages

- Physics: Precision & Discovery
- Technology and Innovation
- Practicalities: Footprint & Cost
- Outreach: It’s New & Exciting!

The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A “muon shot” aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

Share full article

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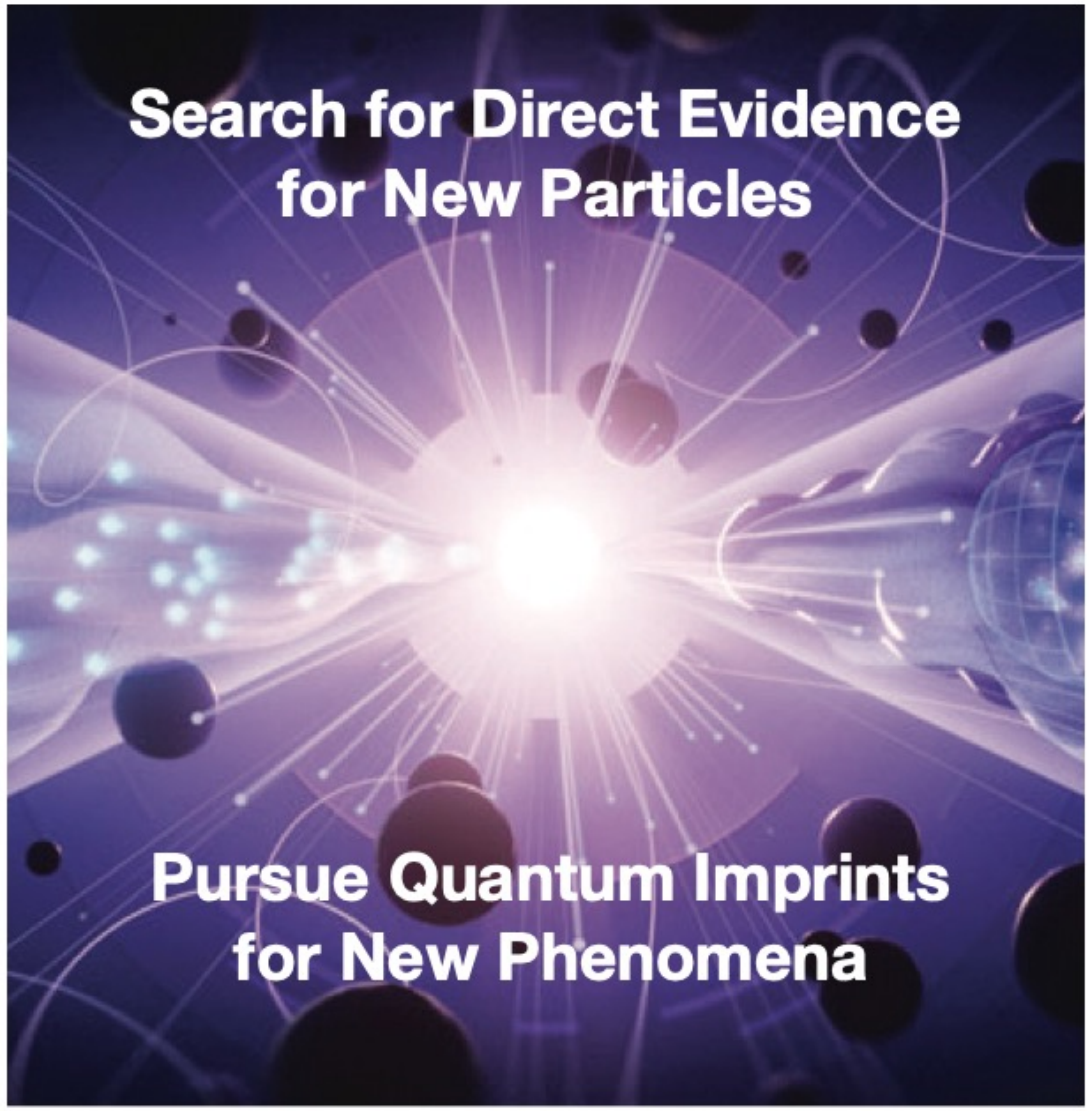
Now: Let’s study physics, detector, accelerator

CERN's future
- HL-LHC
- + CLIC?
- + FCC?
- + MuCol?

BACKUP

Explore the Quantum Universe



Decipher the Quantum Realm

Explore New Paradigms in Physics

Illuminate the Hidden Universe

ENJOY!

NPO2 met Diederik Jekel, 13 April 2022

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