Manfred Jeitler

LHC results and future collider projects

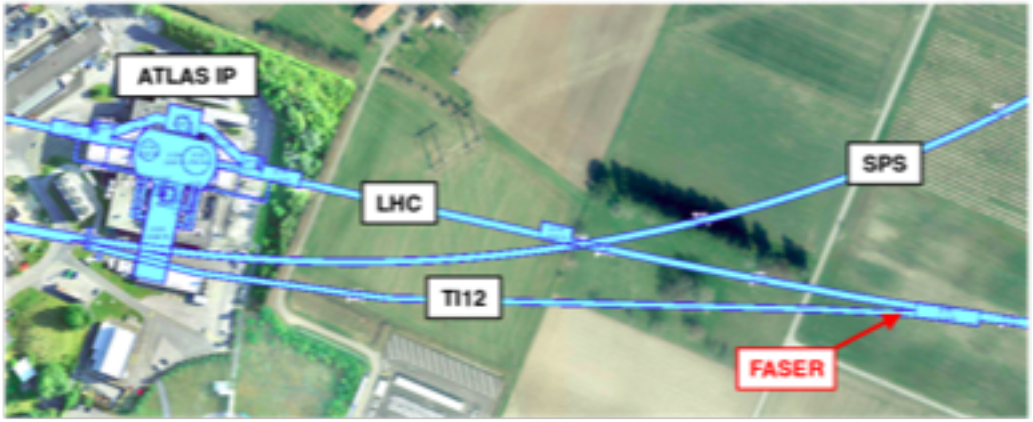
Lecture 3: Beyond the Standard Model and future colliders

contact

- feel free to contact me by email:
  - manfred.jeitler@cern.ch
- slides are also at
  - https://jeitler.web.cern.ch/jeitler/LECTURES/Baikal_2021/
  - (also Powerpoint sources with animations)
- I am looking forward to seeing you at CERN!

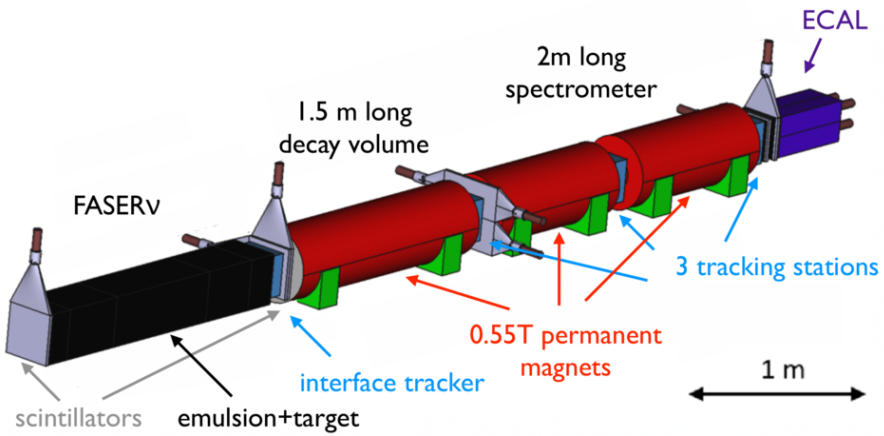
Igor's comment: FASER (and FASERν)

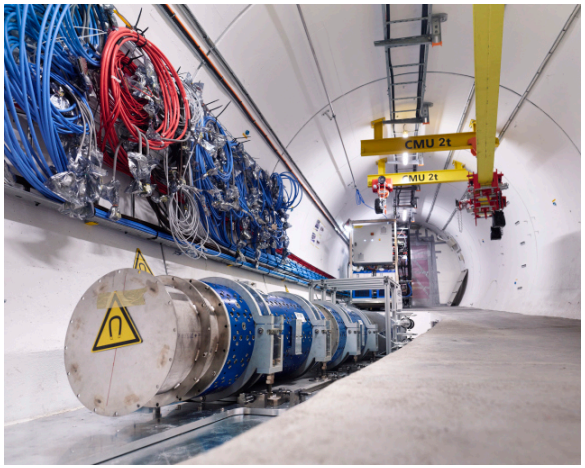
- yes, there are plans to study neutrinos at LHC
- but not those from decays in rare events
- only those from abundant particles collinear to beams
- study not only neutrinos but also other very weakly interacting particles (BSM particles such as axions, dark photons, ...)

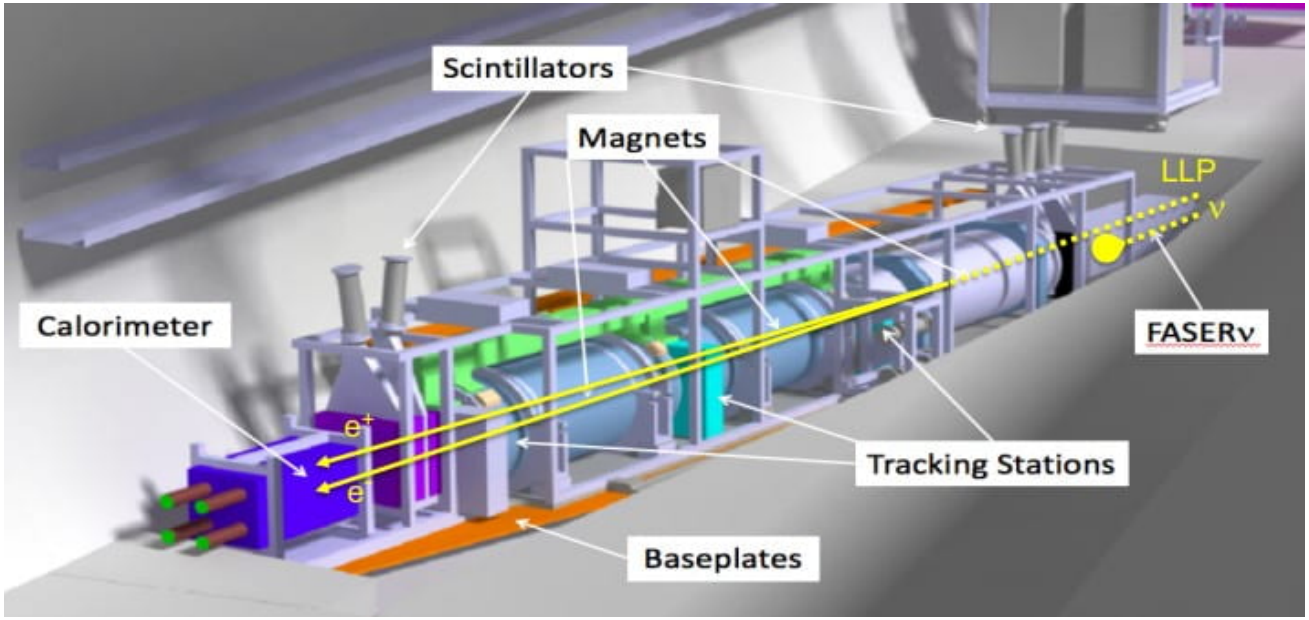


"parasitic" production

FASER and FASERν





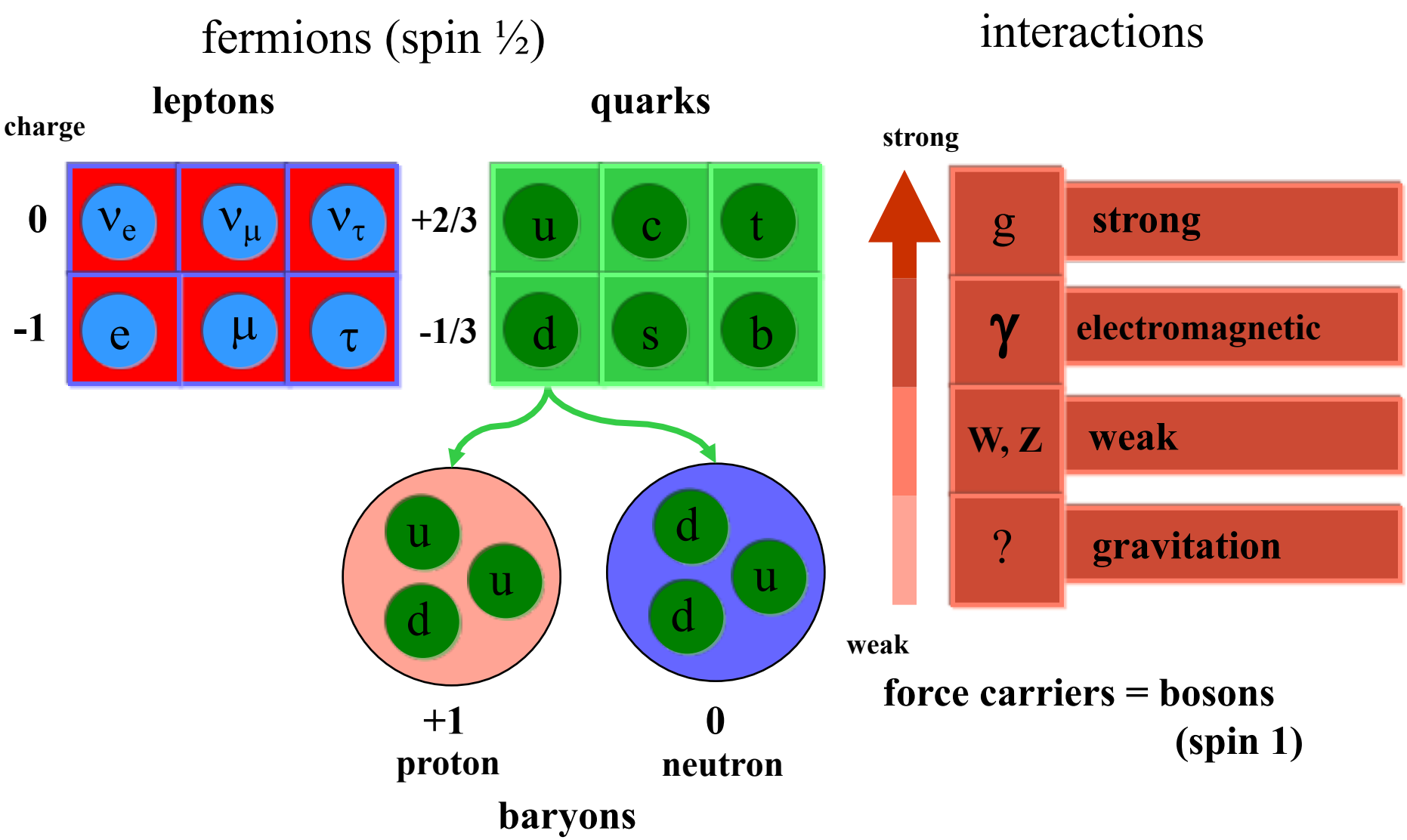


BSM:

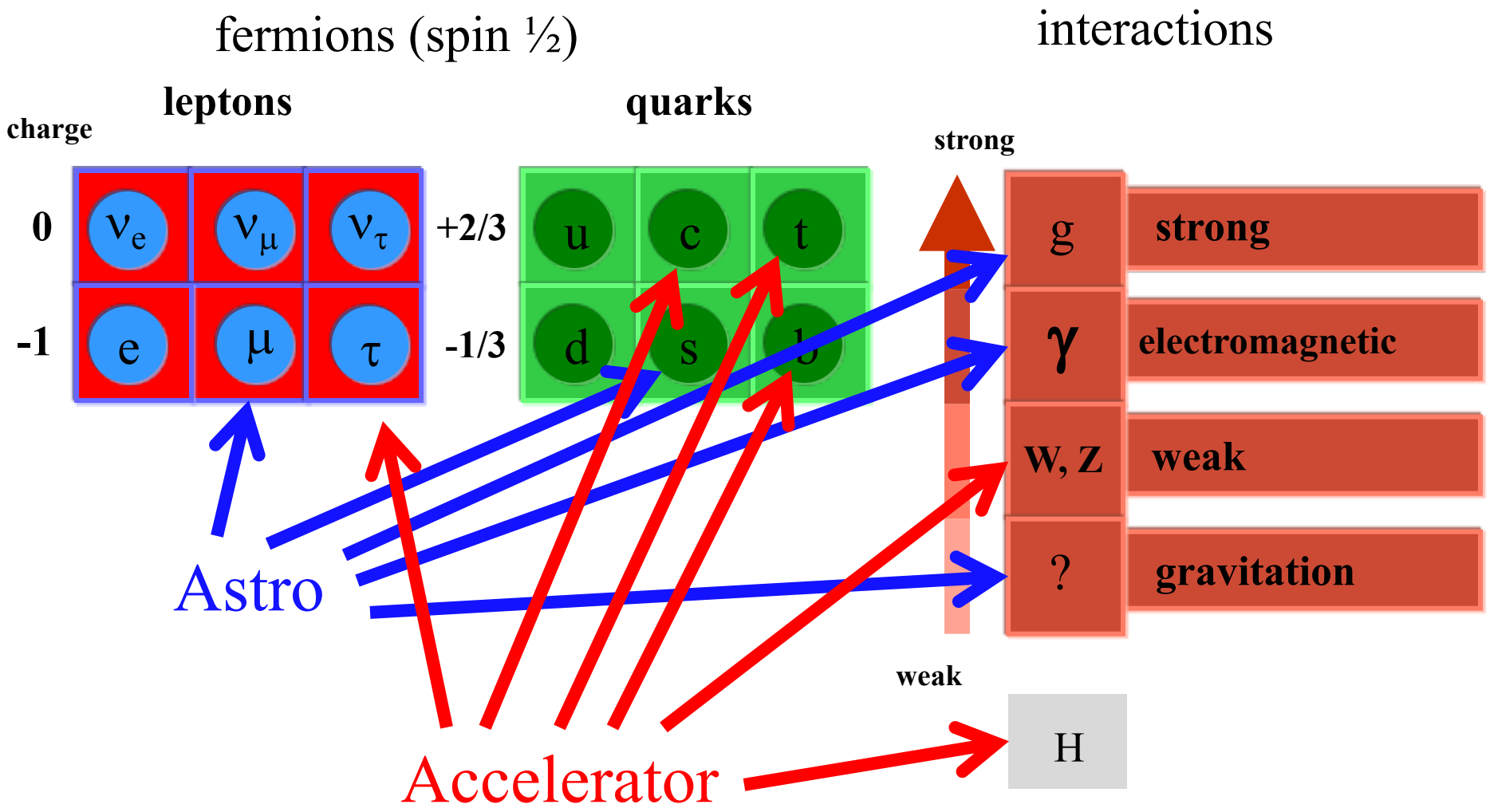
PHYSICS BEYOND THE STANDARD MODEL

The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10⁻⁵ seconds
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ second
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
(Li)
(He)
(D)
H
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium
what is here?

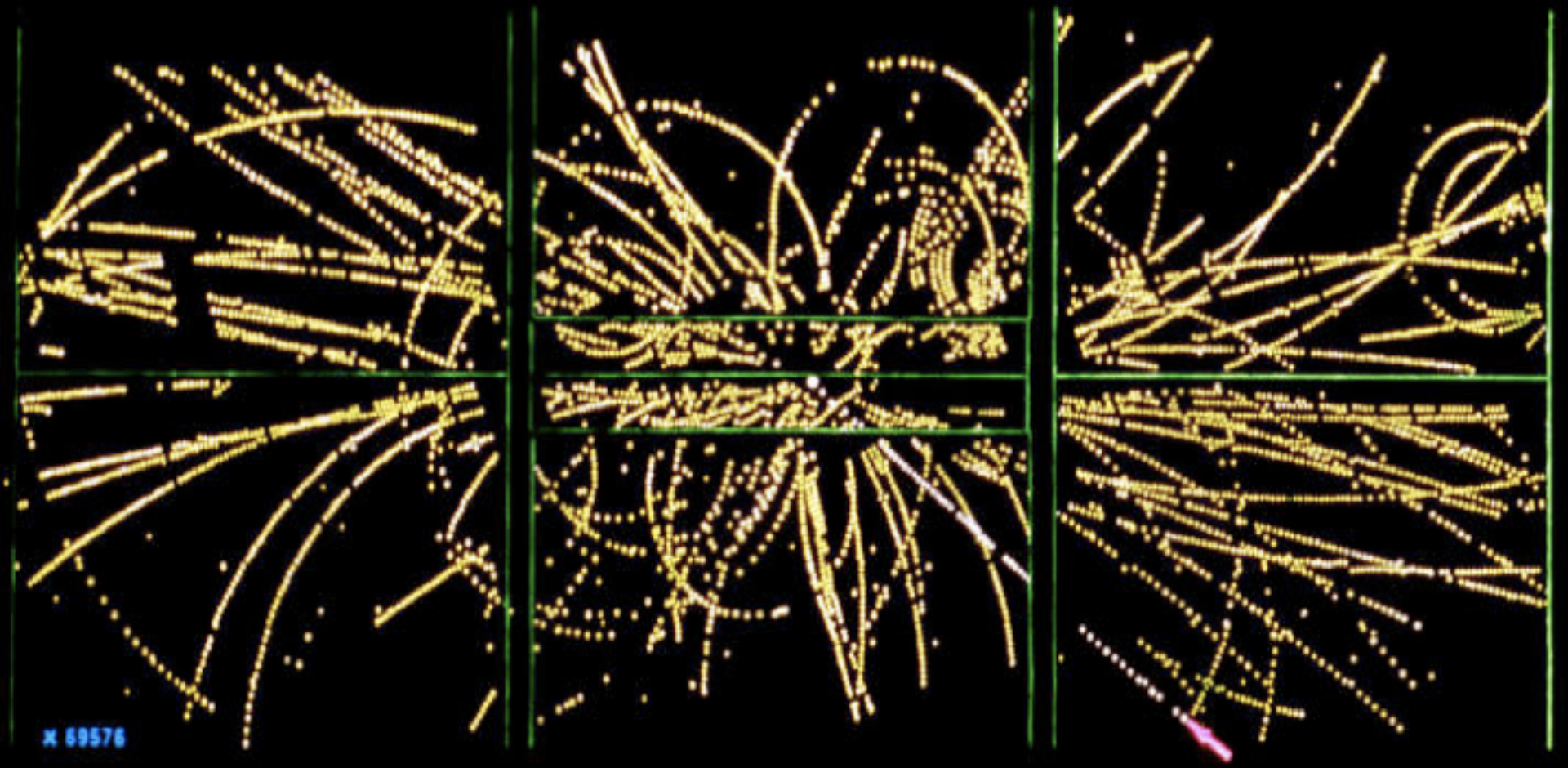
the Standard Model



the Standard Model

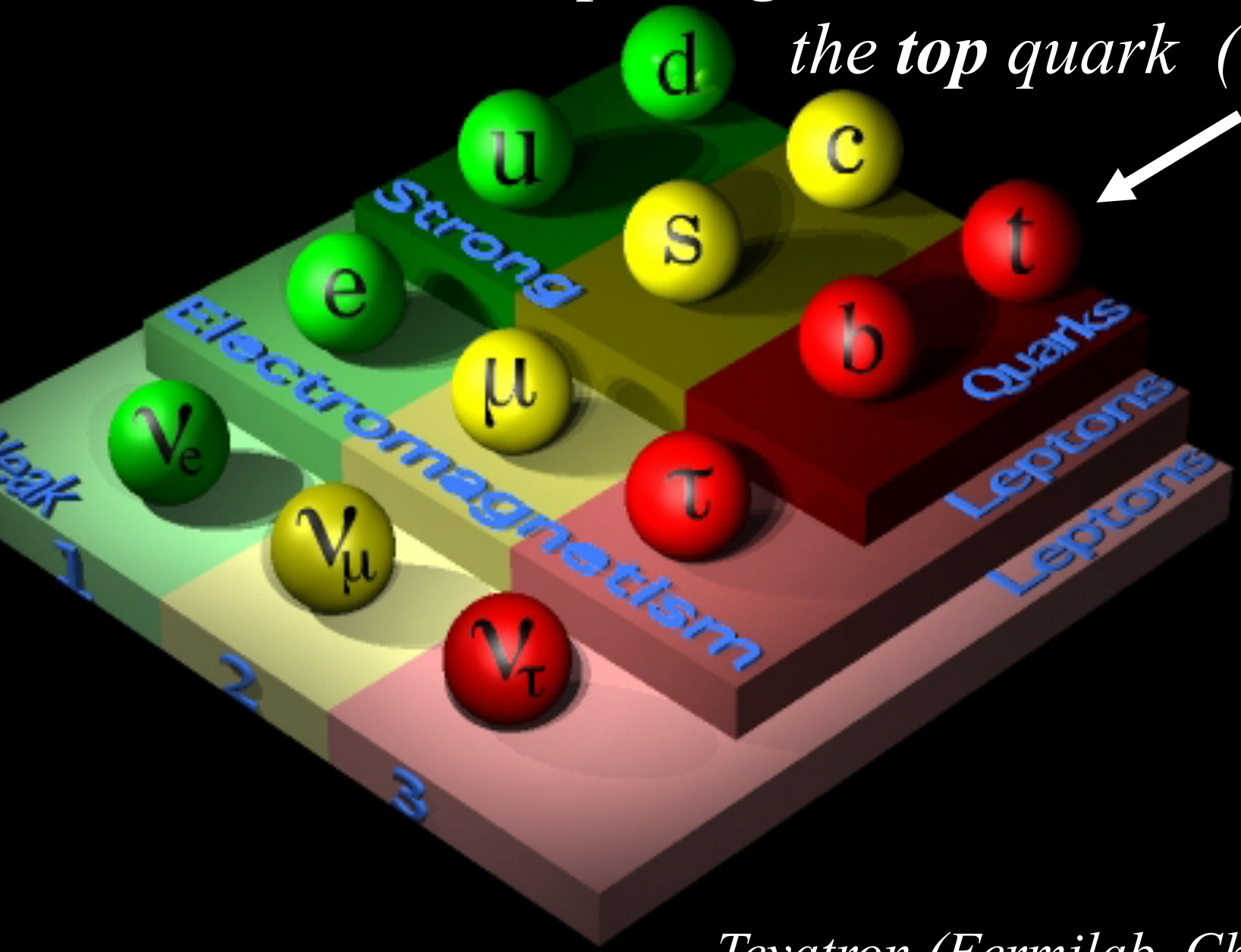


completing the Standard Model: the $W^{\pm}$ and Z^0 bosons (1983)



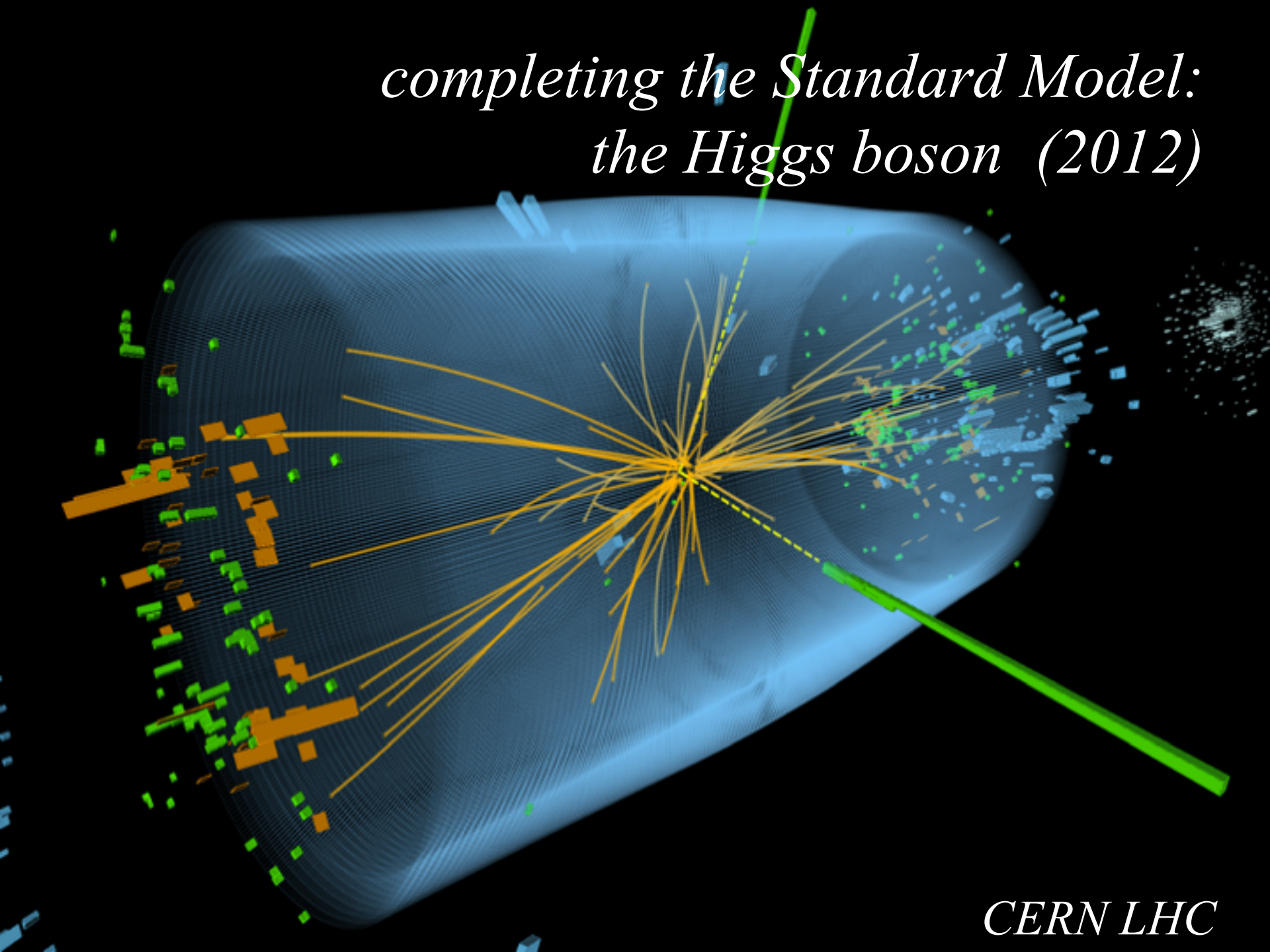
CERN SPS

completing the Standard Model:
*the **top** quark (1995)*



Tevatron (Fermilab, Chicago)

completing the Standard Model:
the Higgs boson (2012)

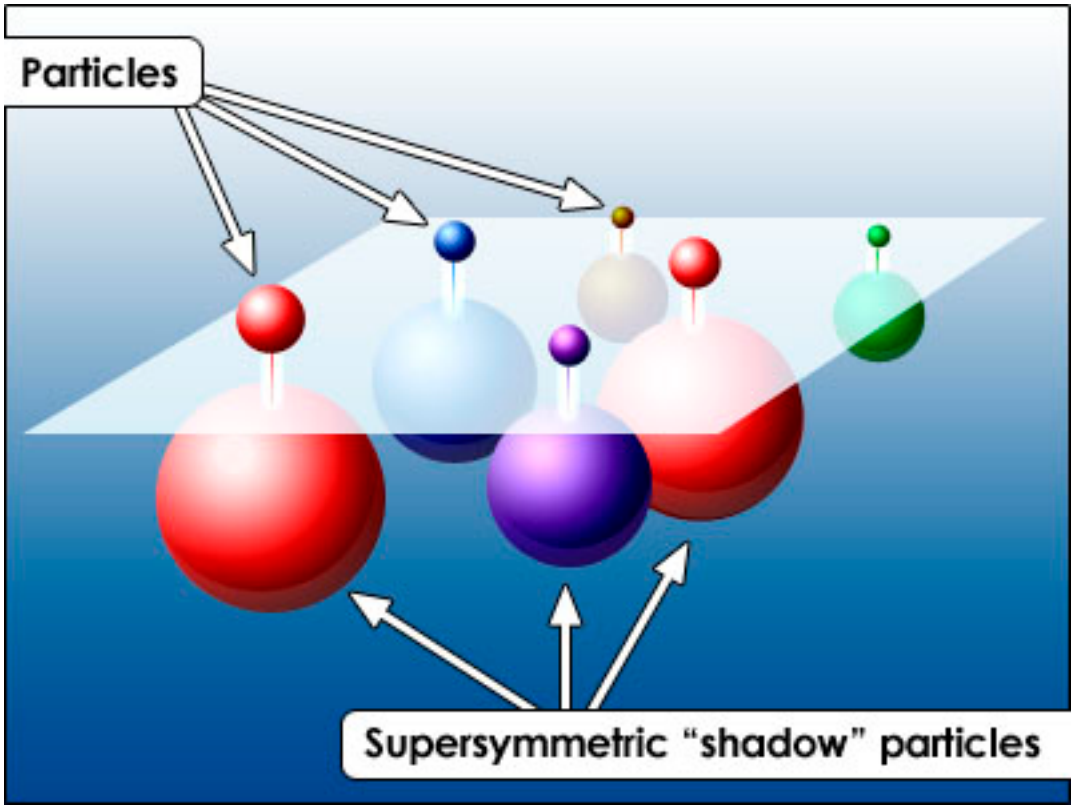


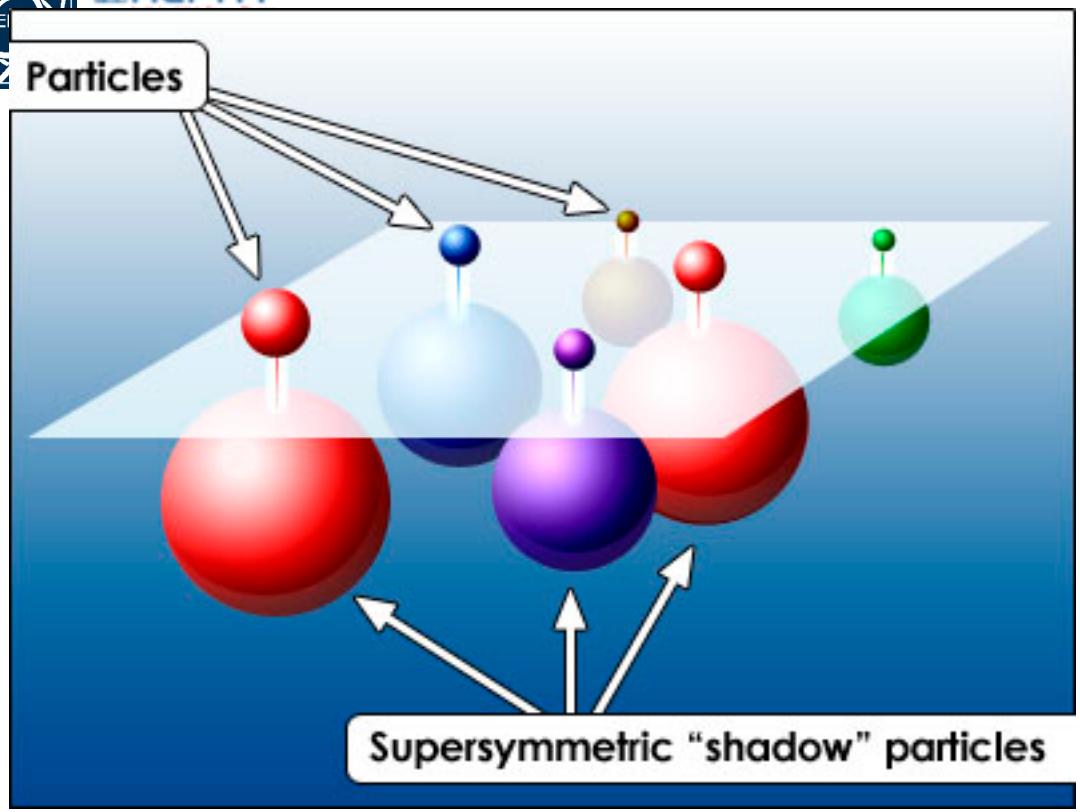
CERN LHC

deficiencies of the SM

- does not incorporate gravity
- no mechanism for EWSB
  - Electroweak Symmetry Breaking
  - Scalar potential put in by hand: $V(H) = -m_H^2 |H|^2 + \frac{\lambda}{2}|H|^4$
- gauge couplings unification – GUT – does not work!
  - cannot accommodate $\mathrm{SU}(3) \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ in $\mathrm{SU}(5)$ or $\mathrm{SO}(10)$ because coupling strengths do not match at any energy
- radiative corrections to the Higgs mass reveals the so-called 'naturalness' or 'hierarchy' Problem
- no candidate for a dark matter particle
- Each of these problems has a supersymmetric solution.
  - Does not mean that nature features any/all!

Supersymmetry

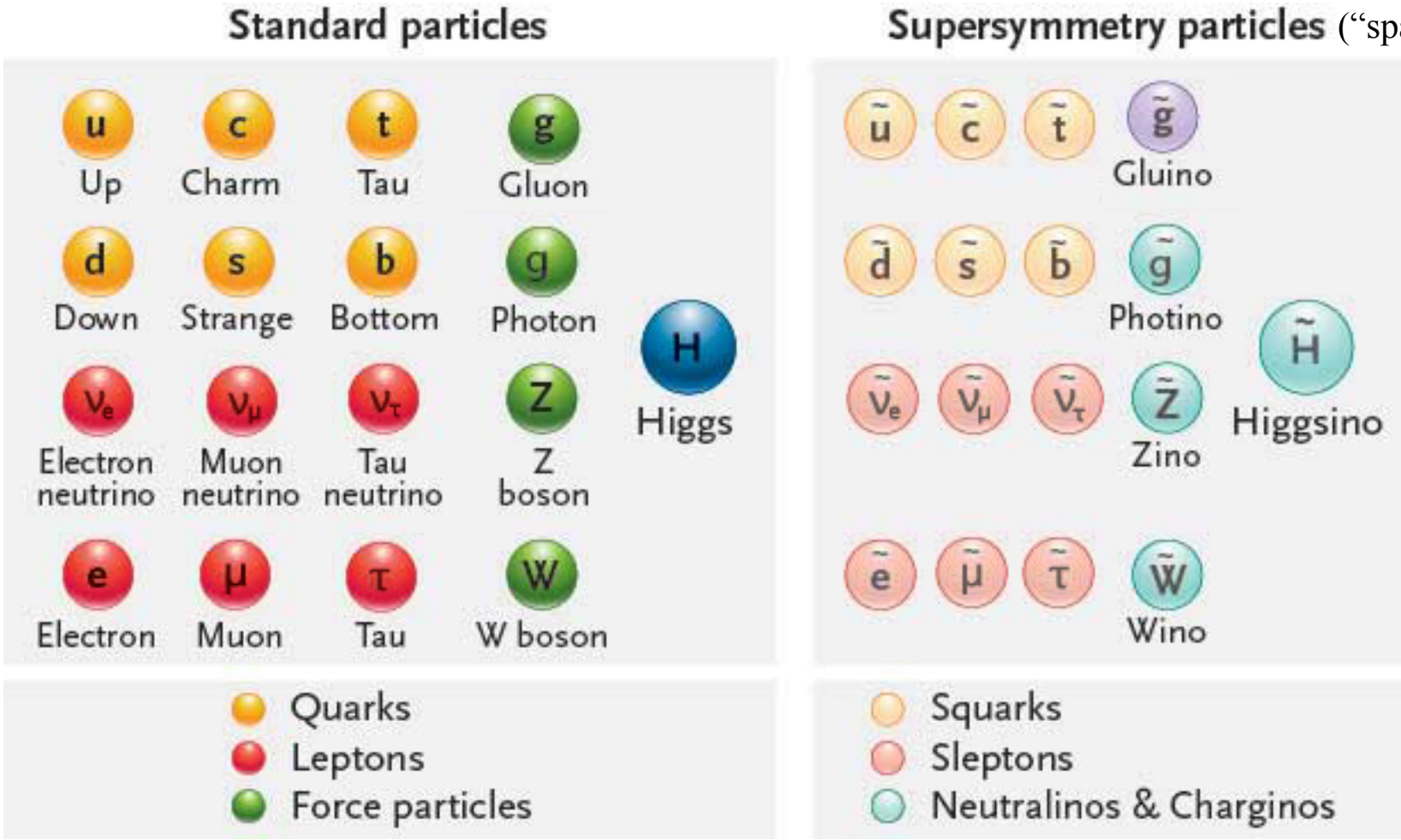




Supersymmetry

- Every fundamental matter particle and every force carrier should have a massive "shadow" particle.
- This relationship between matter particles and force carriers is called **supersymmetry**.
- For example, for every type of quark there may be a type of particle called a "squark".

Supersymmetry ("SUSY")

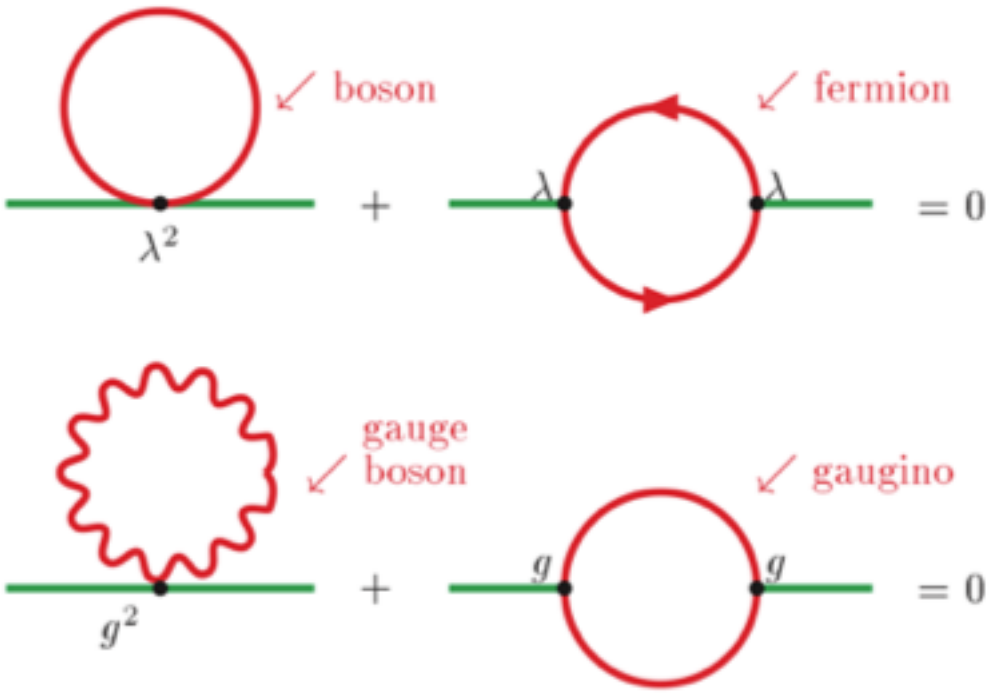


Sheldon Glashow: "Half of the particles have already been discovered!"

(sorry about the "neutrino" – historical naming!)

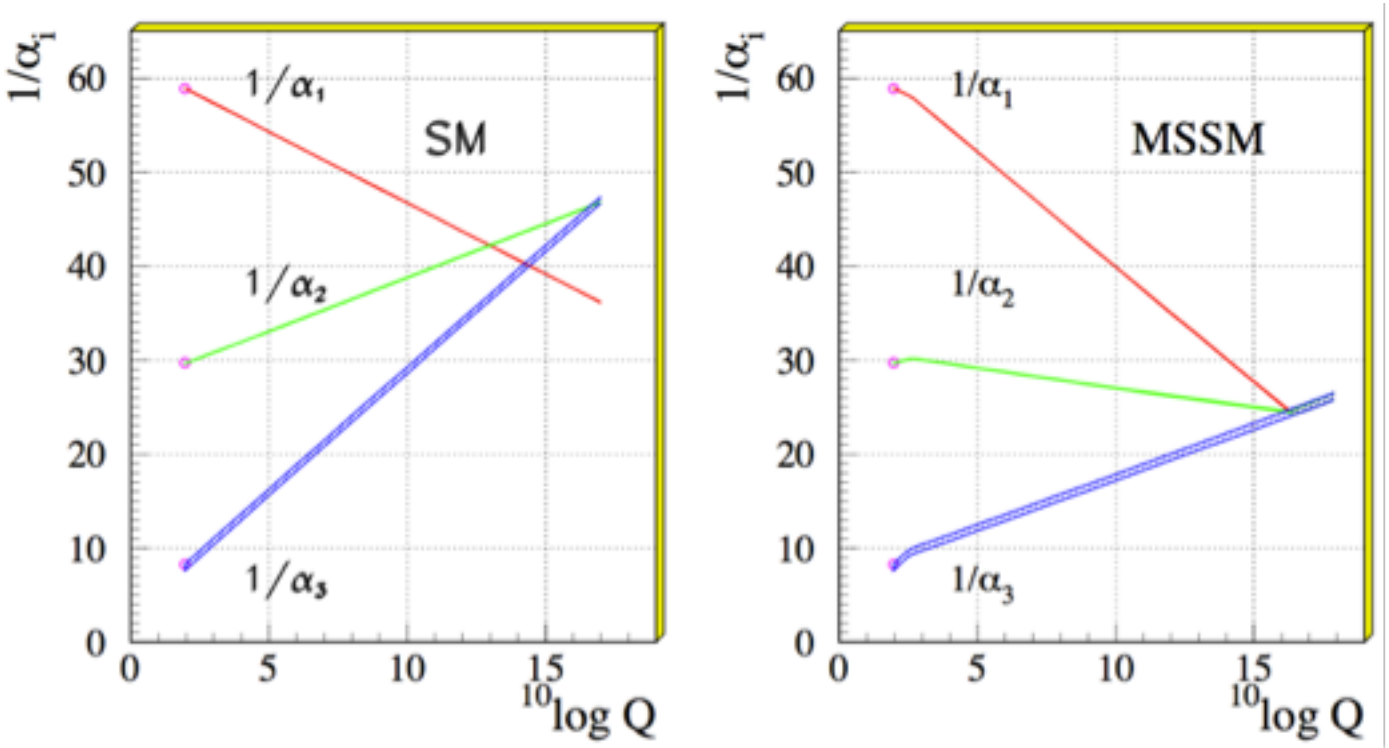
stop ($\tilde{s}$) physics

Cancellation of quadratic terms (divergences)



- to avoid quadratic divergences in Higgs mass, otherwise "**fine-tuning**" would be needed
  - "naturalness"
- sadly, none of the bosons and fermions in the Standard Model can serve as SUSY partners for each other
  - → job for experimentalists

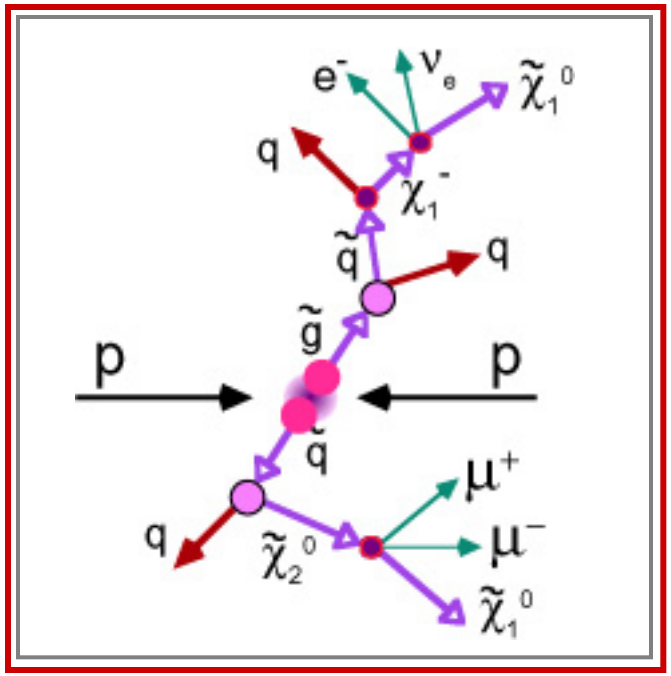
Running Coupling constants: Grand Unification (GUT)

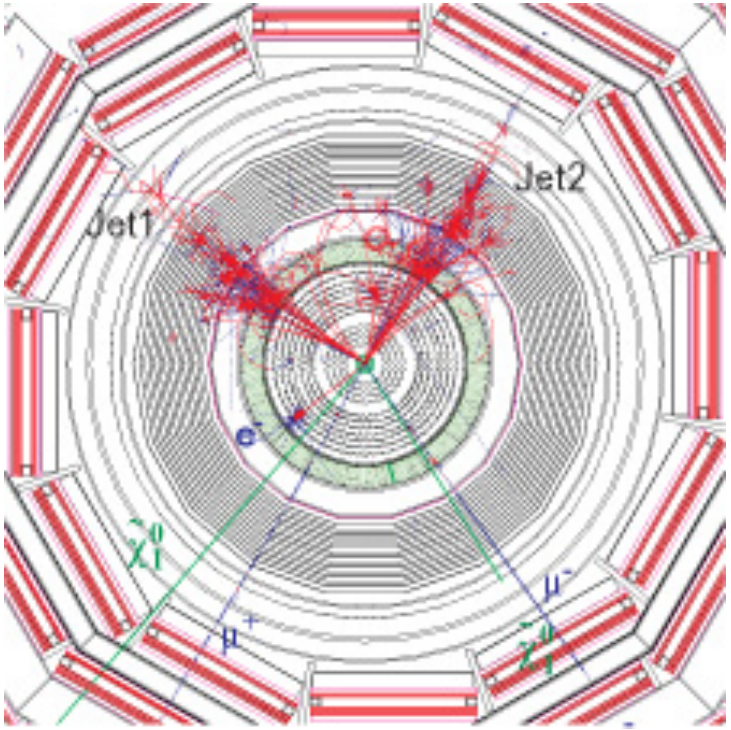


- **U(1)** (hypercharge) **$SU(2)_{left}$** **SU(3)** (color)
- coupling constants get almost equal at high energies
- but not quite, in Standard Model (left)
- perfect match in Supersymmetry (right)

squarks, gluinos

supersymmetric particles might have (had) spectacular signatures due to cascade decays

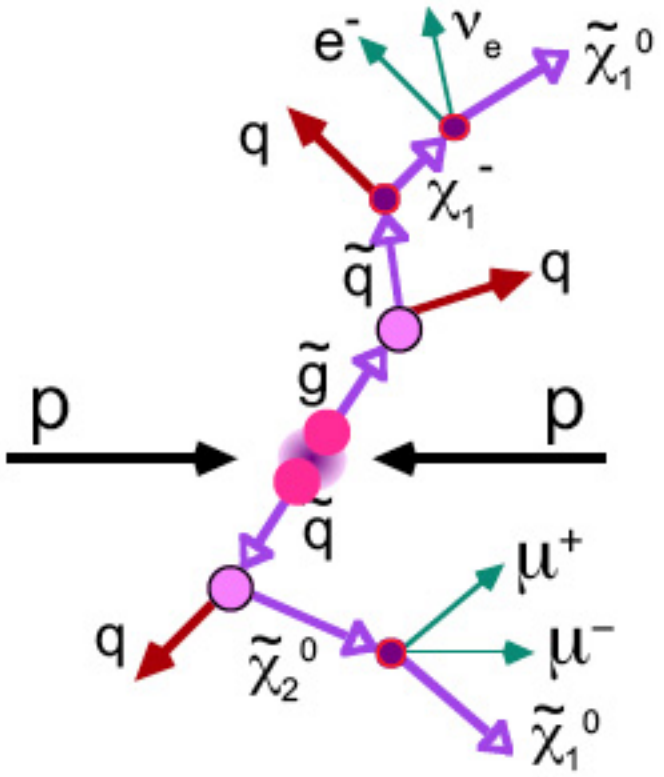


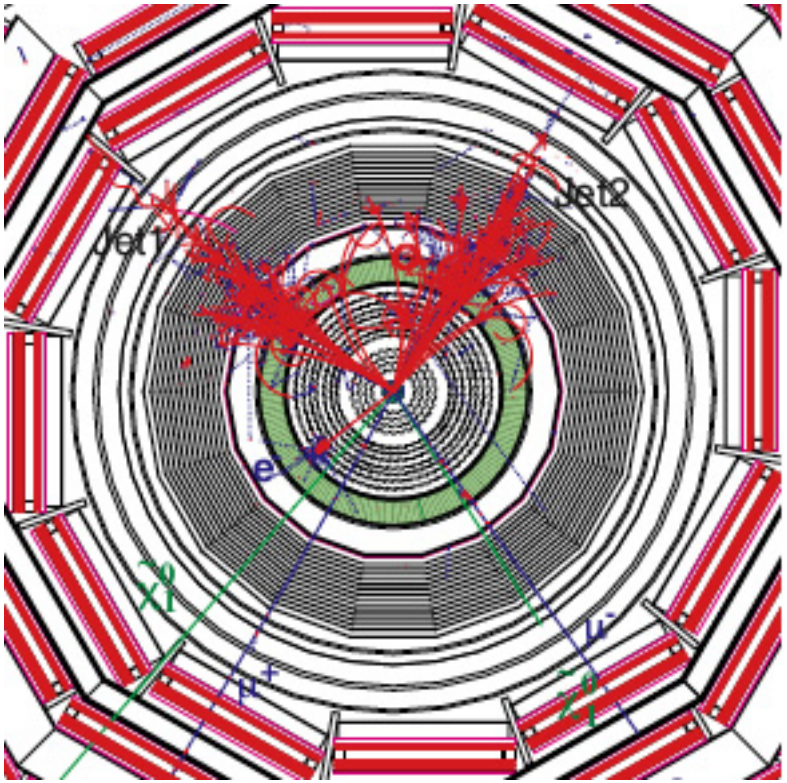


pp -> $\tilde{q}\tilde{q}$

possible L1-Trigger:
several leptons: "e/γ" or μ (any combination)
several jets
missing transverse momentum

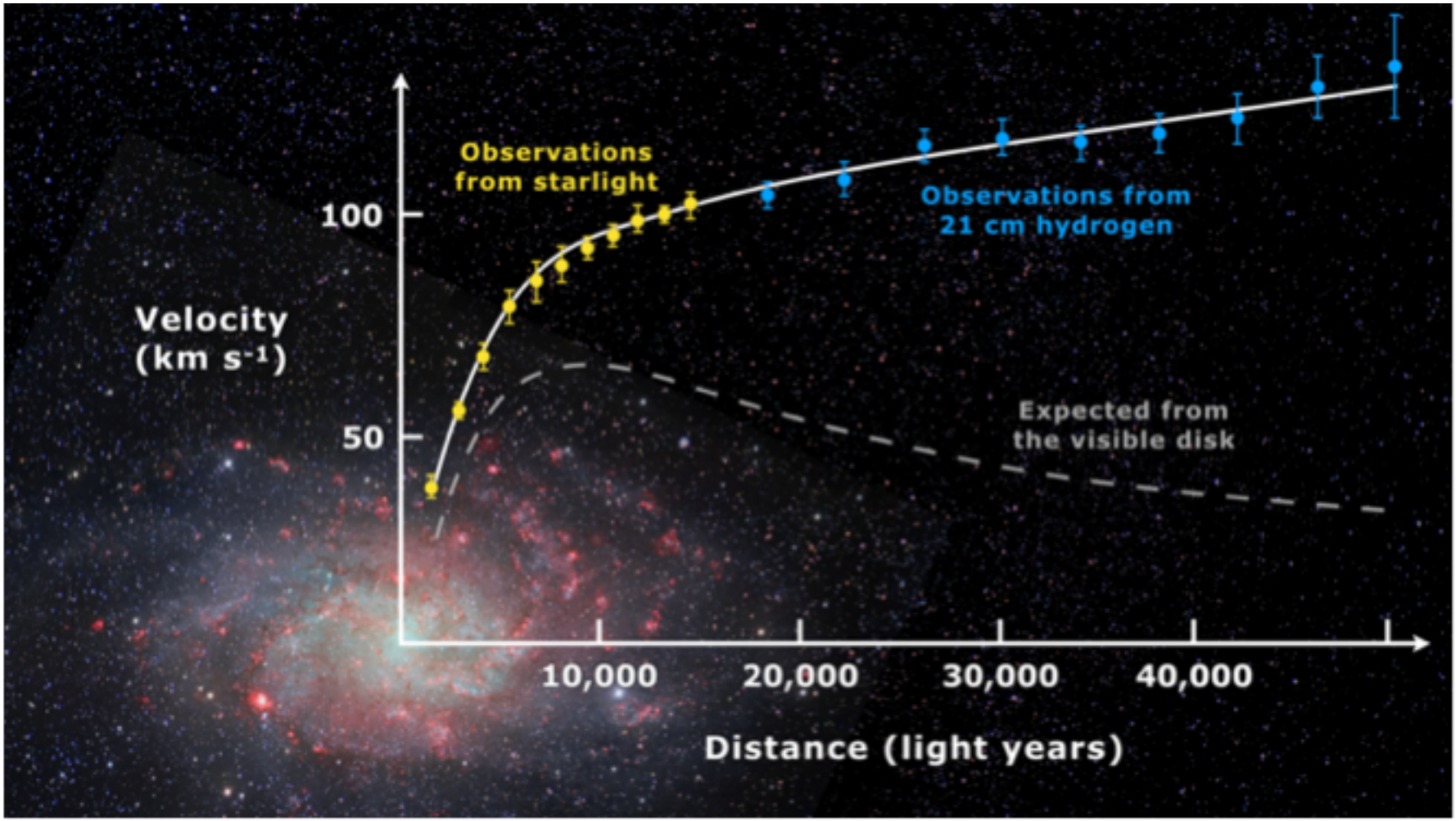
How to see SUSY decays



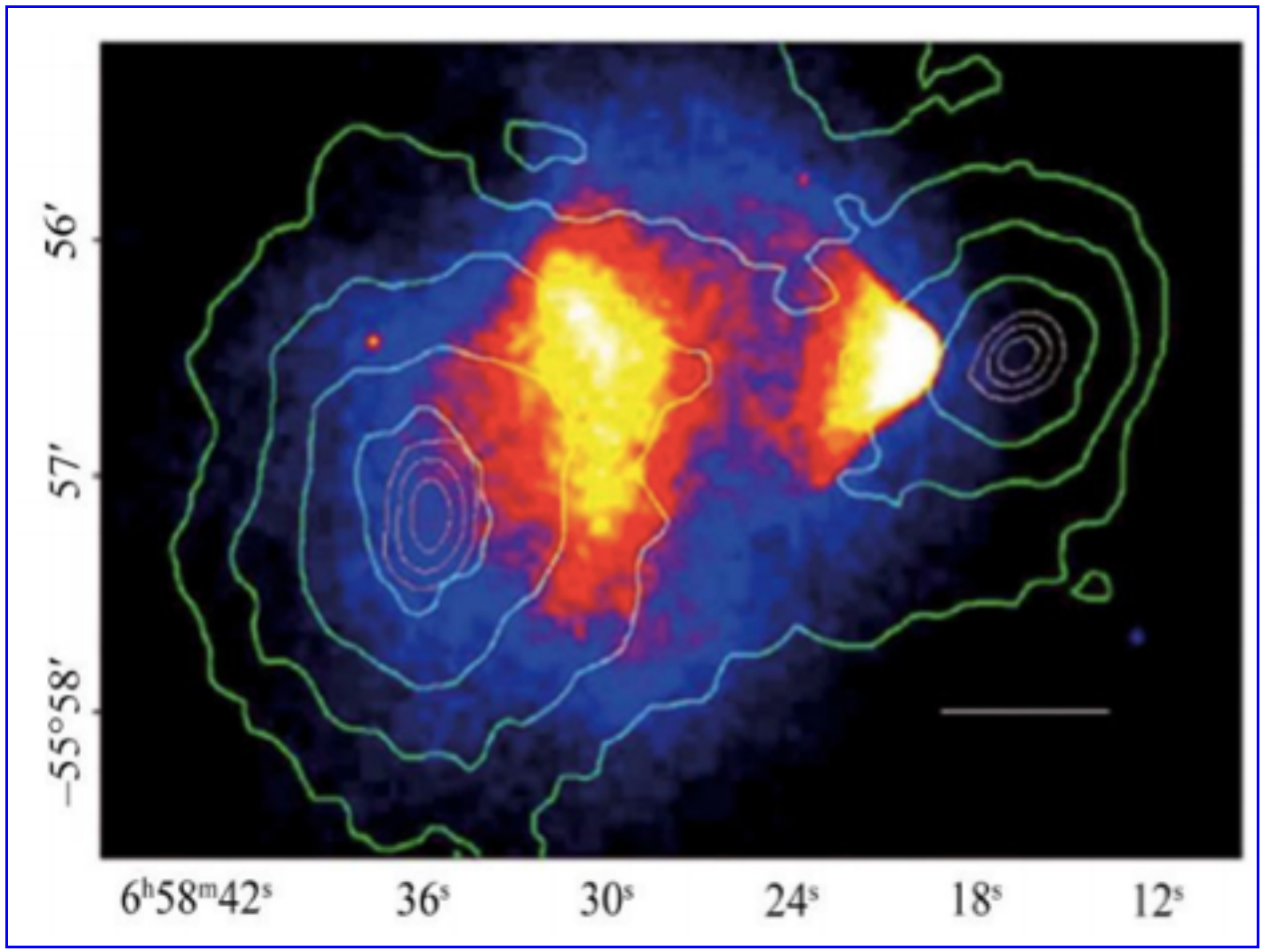


- Supersymmetric ("SUSY") particles could show very clear signatures due to cascade decays
- but none have been found so far!

Dark Matter: galaxy rotation curves



bullet cluster: evidence for Dark Matter



- Colliding galaxy cluster system 1E0657-558 with contours of gravitational mass density (lines) and visible matter density (colors)

dark matter: MACHOS vs WIMPS

massive astrophysical cosmic halo objects?
weakly interacting massive particles?

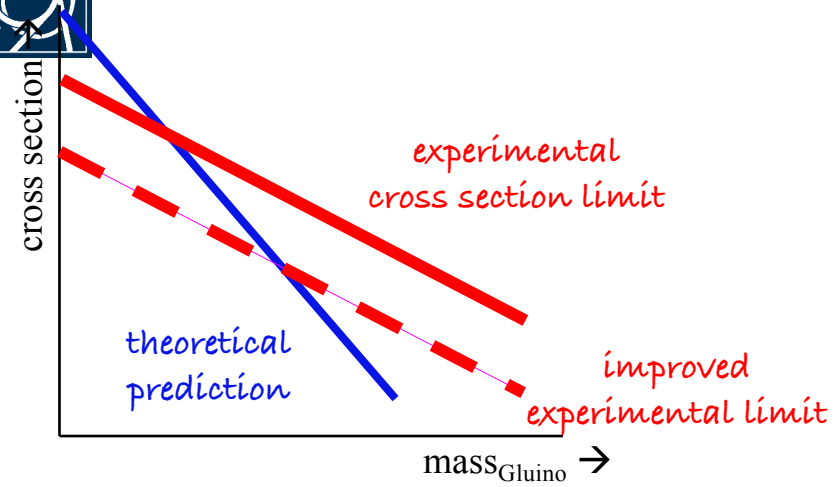
questions of cosmology to particle physics:
Why is there more matter than anti-matter in the universe?
What is the universe made of? What is **dark matter**?
What is **dark energy**?

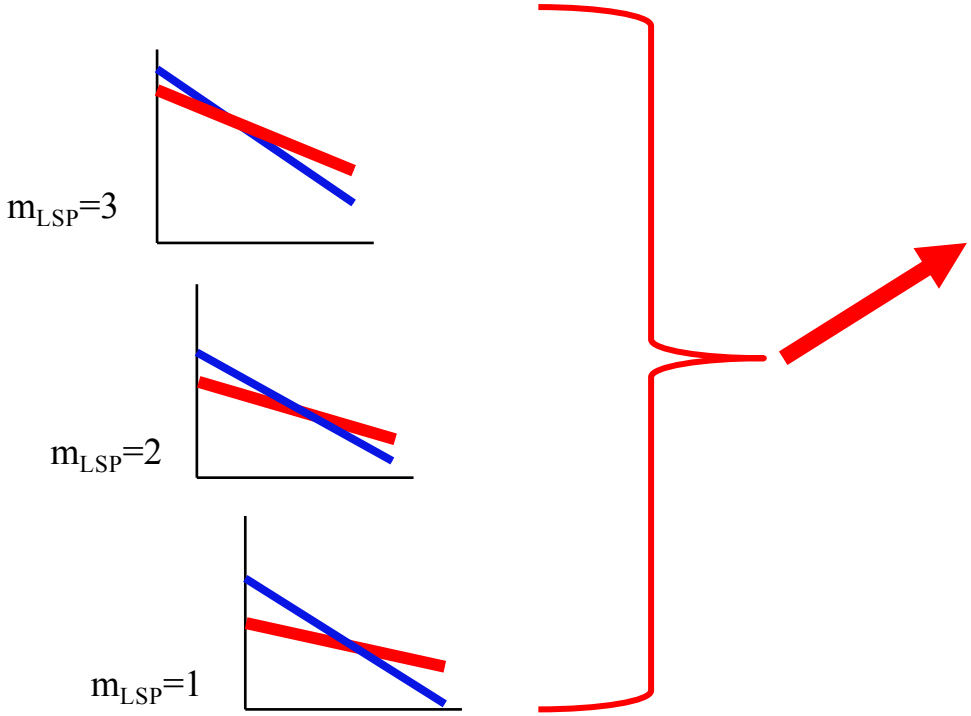
➔answers to these questions concerning the largest scales might come from the physics of the smallest scales - elementary particle physics

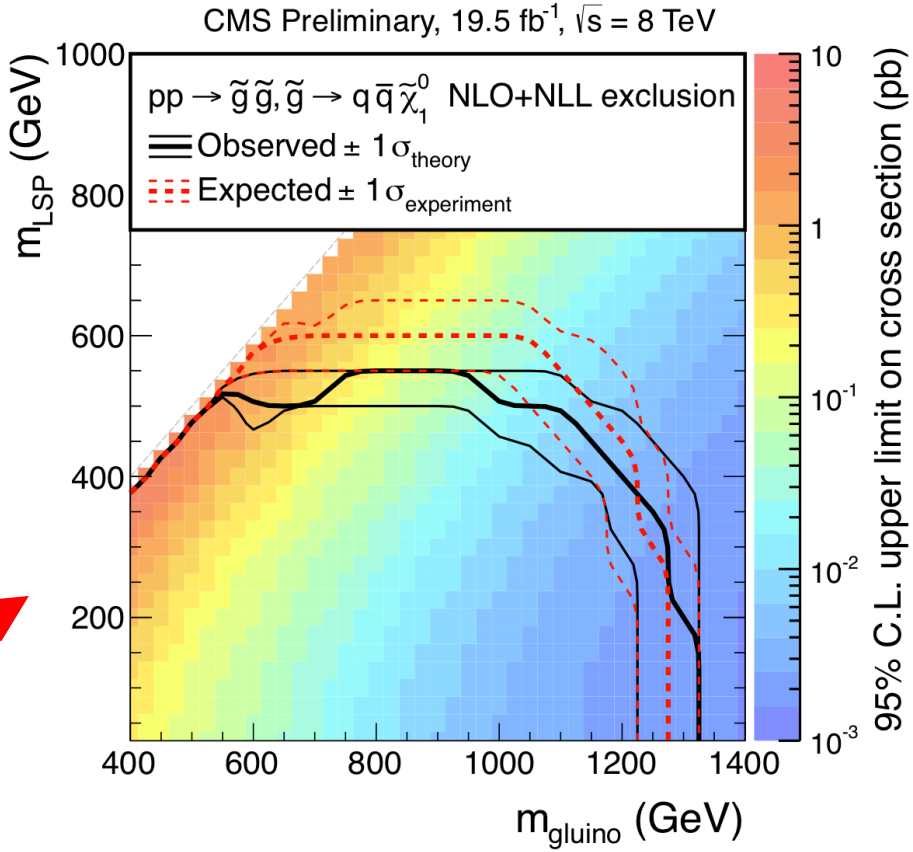
WIMP "miracle"

- one (popular) theory: supersymmetric particles have to decay into other supersymmetric particles
  - if "R-parity" is conserved
- then the lightest supersymmetric particle ("LSP") must be stable
  - and obviously very hard to detect
- this *could* be the dark-matter particle
  - particle with mass of "weak scale" (~100 GeV) would have the right co-annihilation probability to yield the observed dark-matter density → "WIMP miracle"
  - but miracles do not always happen ...

if we don's see anything: exclusion plots







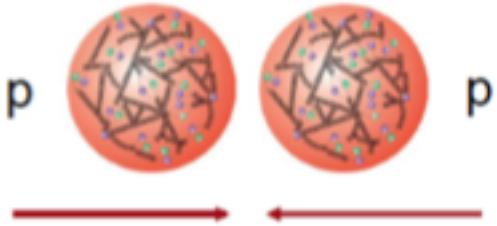
- shading: experimental limit
- lines: intersection with theory predictions

FUTURE ACCELERATORS

aims of accelerators

- intensity frontier
  - high-precision experiments
- energy frontier
  - find new particles
  - learn about basics of interactions
    - » "unification" at higher energies: electroweak interactions, grand unification
  - cosmology: what the universe looked like soon after the Big Bang

- discovery through precision
- study known particles



- discovery through broadband and highest energies

HL-LHC
"High-Luminosity LHC"

- being built, will go online after 2026
- same energy as LHC
  - or maybe slightly higher (14 TeV) – depends on magnets
- higher luminosity
  - instantaneous luminosity: from 10^{34} cm^{-2} s^{-1} to 5×10^{34} cm^{-2} s^{-1}
  - integrated luminosity: 3000 fb^{-1}
    - » remember: 1 barn = 10^{-24} cm^2 → 1 fb = 10^{-39} cm^2
- upgrade of detectors
- upgrade of data acquisition

- *this is where you can do your Ph.D. thesis!*

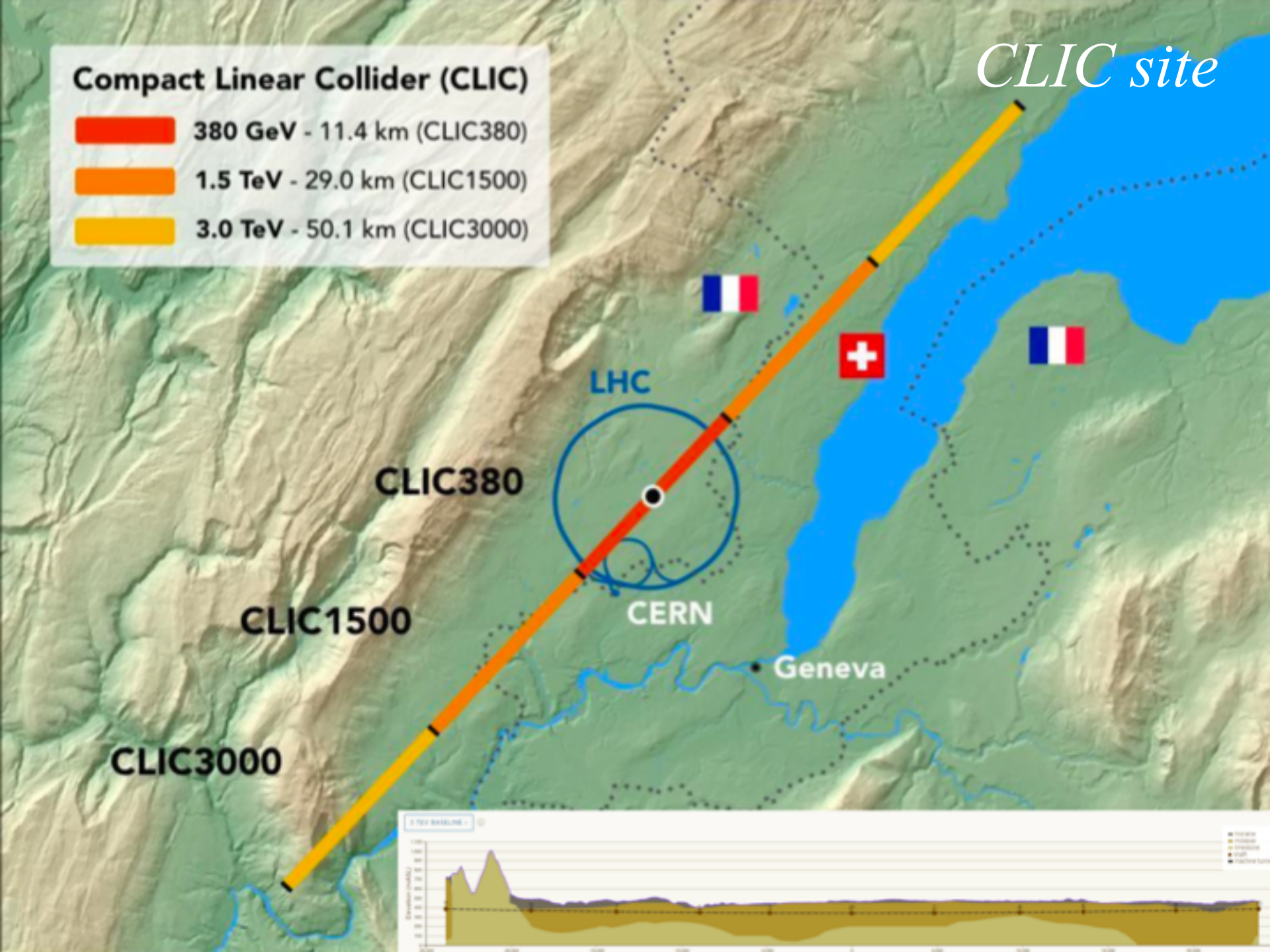
Future colliders under discussion

- electrons:
  - ILC
    - » International Linear Collider
  - CLIC
    - » CERN Linear Collider
  - FCC-ee
    - » Future Circular Collider, CERN
  - CEPC
    - » Circular Electron-Positron Collider, China
- protons:
  - FCC-hh
  - SPPC
    - » Super Proton-Proton Collider, China
  - HE-LHC
- muons

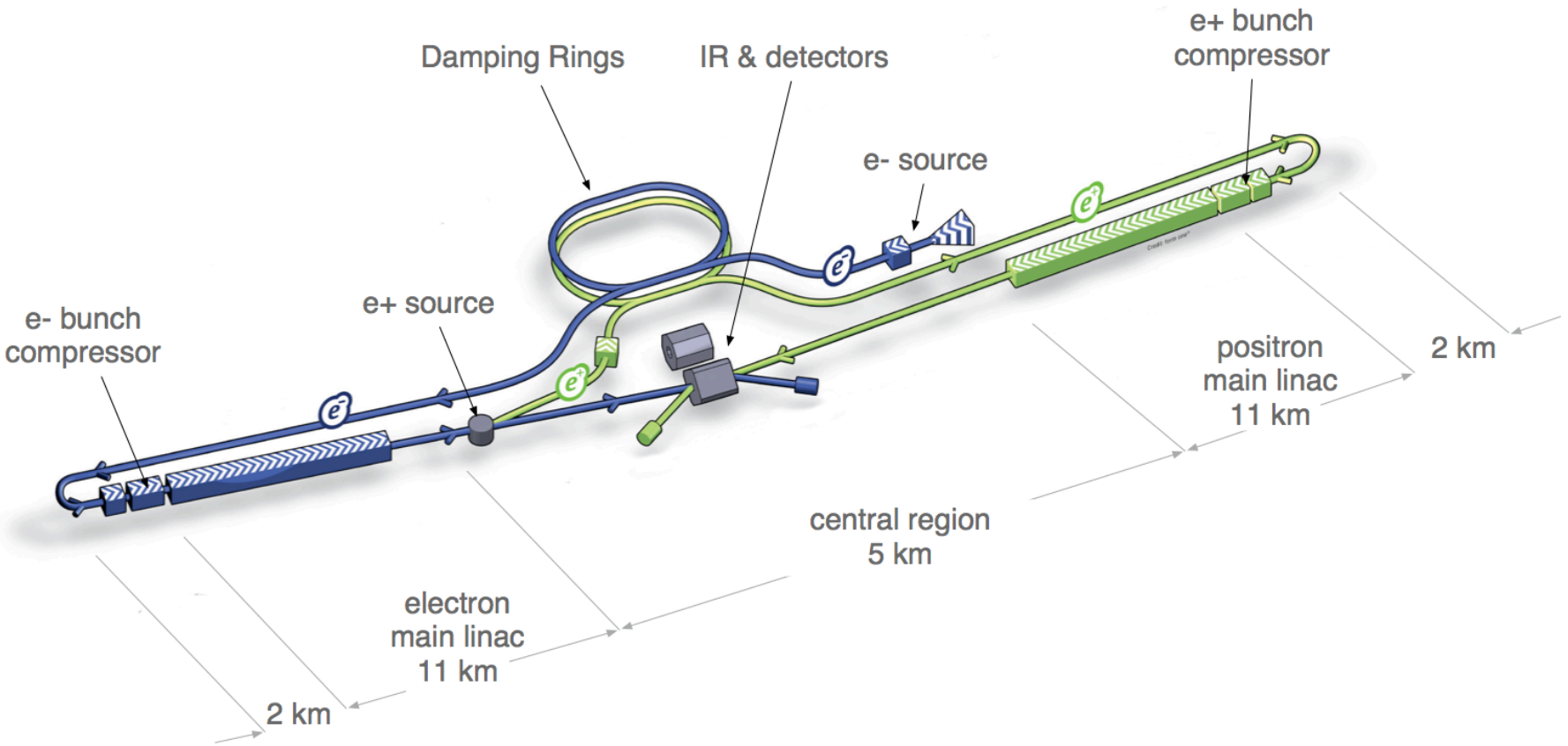
Linear Collider

- main arguments in favor:
  - clean signals
  - polarization of beams
  - energy extendable
    - » just add another few kilometers
- main arguments against:
  - lower luminosity
  - only one experiment / collaboration (?)
    - » although there are ideas of roll-in / roll-out

CLIC site

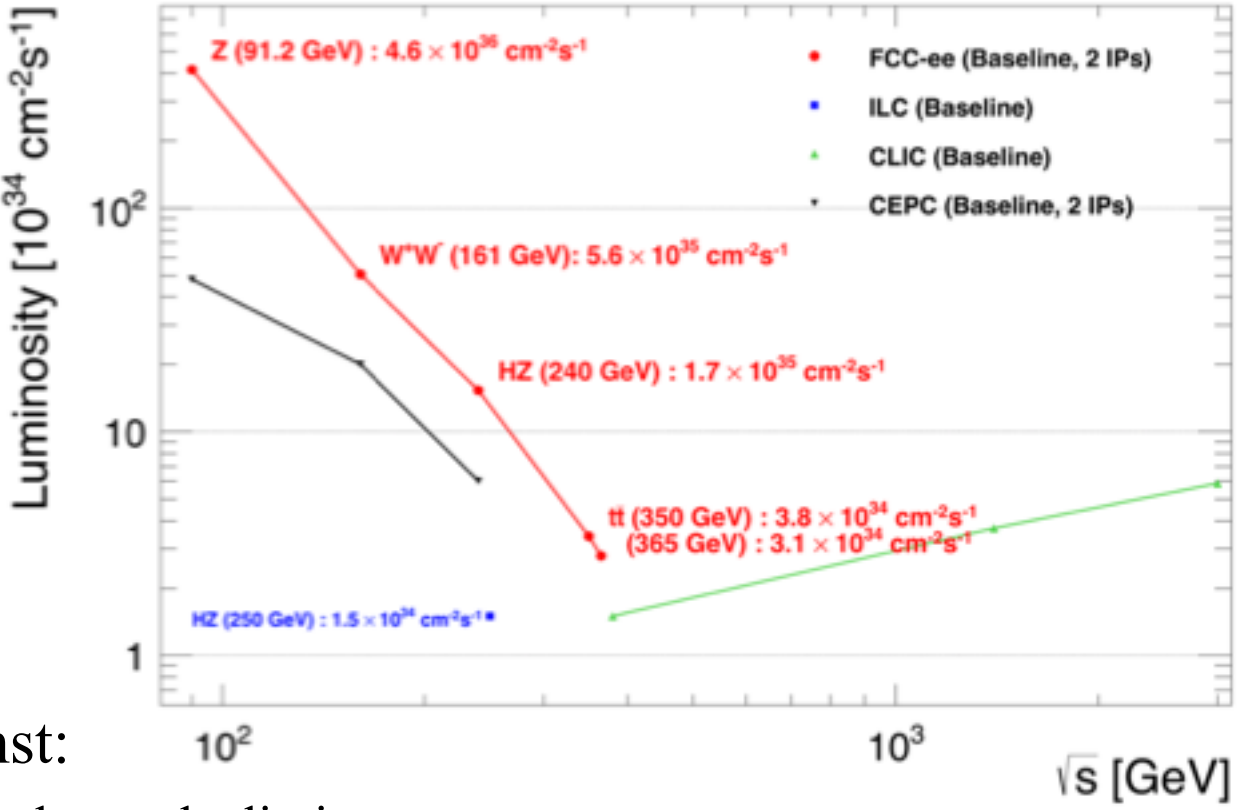

Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva

ILC (Japan)
"International Linear Collider"



Circular e^+e^- colliders (Higgs factories)

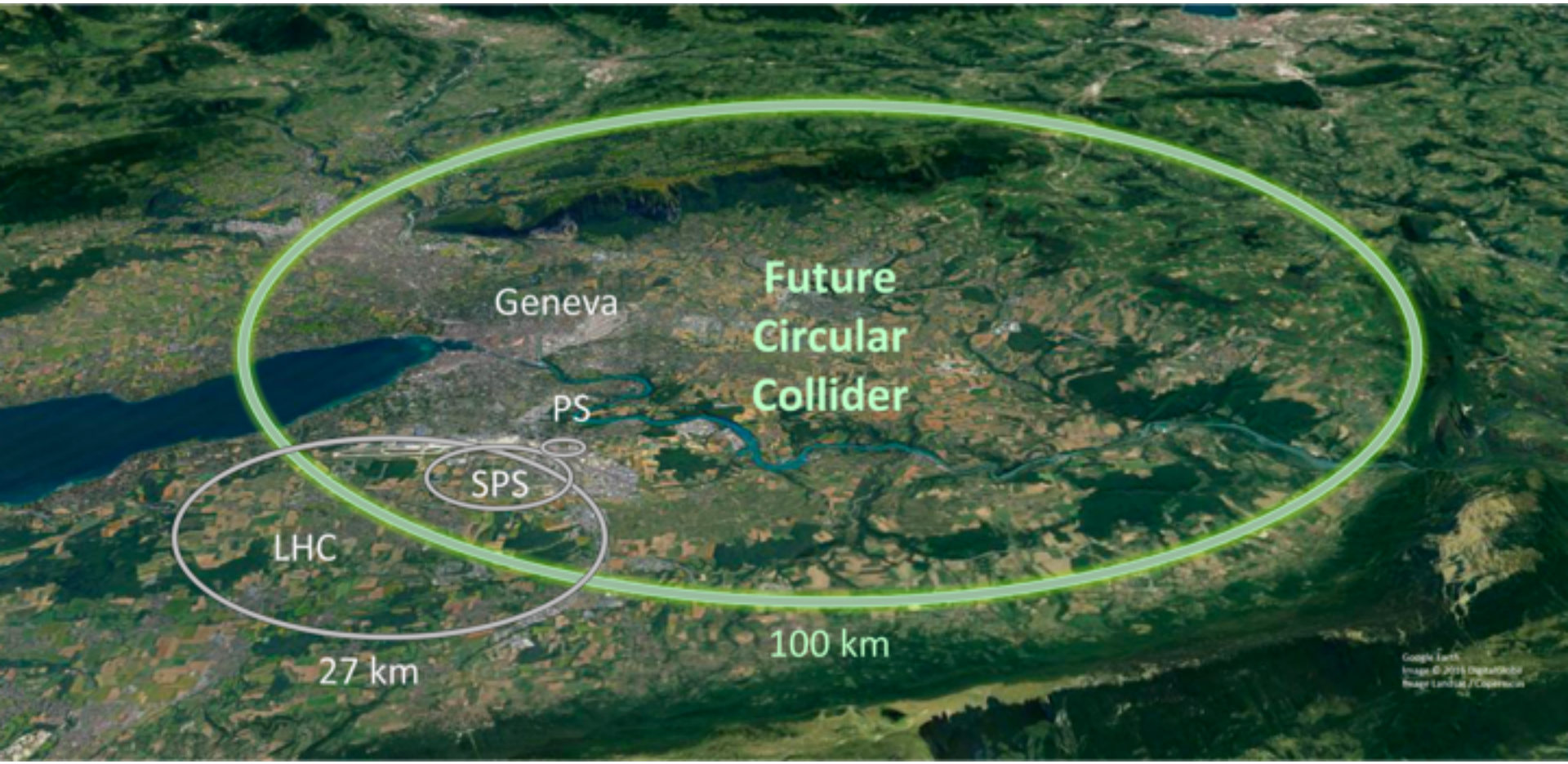
- main arguments in favor:
  - luminosity
    - » also at low energy
  - re-use tunnel and infrastructure for hadron collider



- main arguments against:
  - energy hard to upgrade beyond a limit
    - » but maybe this is not needed?
    - » physics argument: production of ZH, HH and tt
    - » but nothing beyond has been found that should be produced in "factory" mode
  - no polarization

FCC-ee

"Future Circular Collider"



- *this is where your children can do their Ph.D. thesis!*

FCC-hh

- synergy: use same tunnel and much of infrastructure twice
- proton-proton center-of-mass energy of 100 TeV
  - 30 ab^{-1}
- electron-proton collisions possible (FCC-eh)
  - center of mass energy 3.5 TeV
  - 2 ab^{-1}
- heavy ion collisions
- 100 km circumference
- 16-Tesla dipole magnets
  - Nb_3Sn (cannot use conventional NbTi)
- four interaction points

FCC-hh physics reach

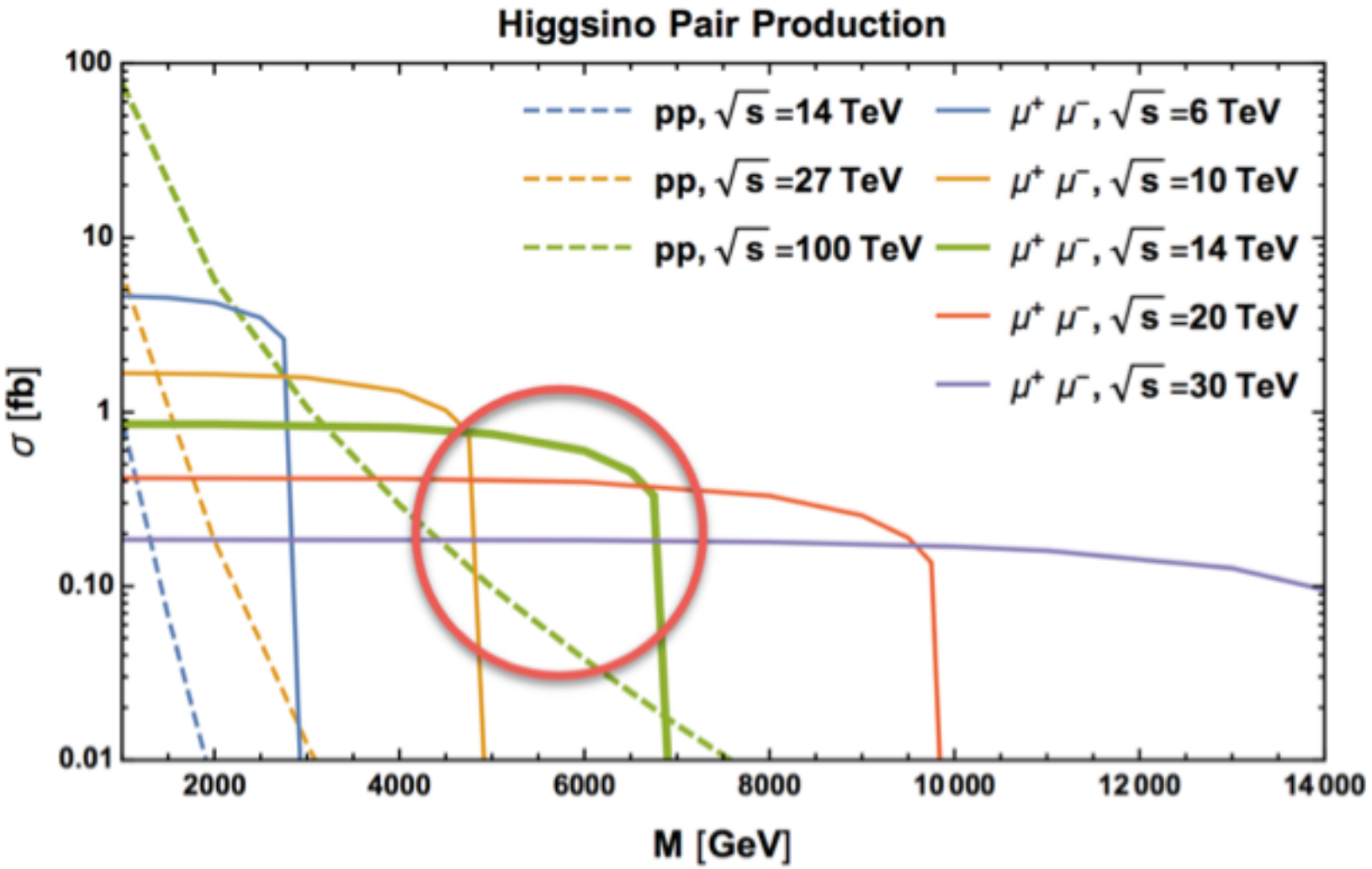
- Higgs self-coupling
- electroweak symmetry breaking phase transition
- conclusively detect, or exclude, WIMP candidates
  - mass of higgsino and wino-like WIMP candidates is theoretically constrained to be 1 and 3 TeV, respectively
- leptoquarks or Z' bosons
  - suggested by the current flavor anomalies in B decays
  - might be sufficiently large that can be directly seen only at 100-TeV hadron collider
- electron-hadron collisions
  - deep inelastic scattering is cleanest probe to resolve substructure and dynamics of hadronic matter

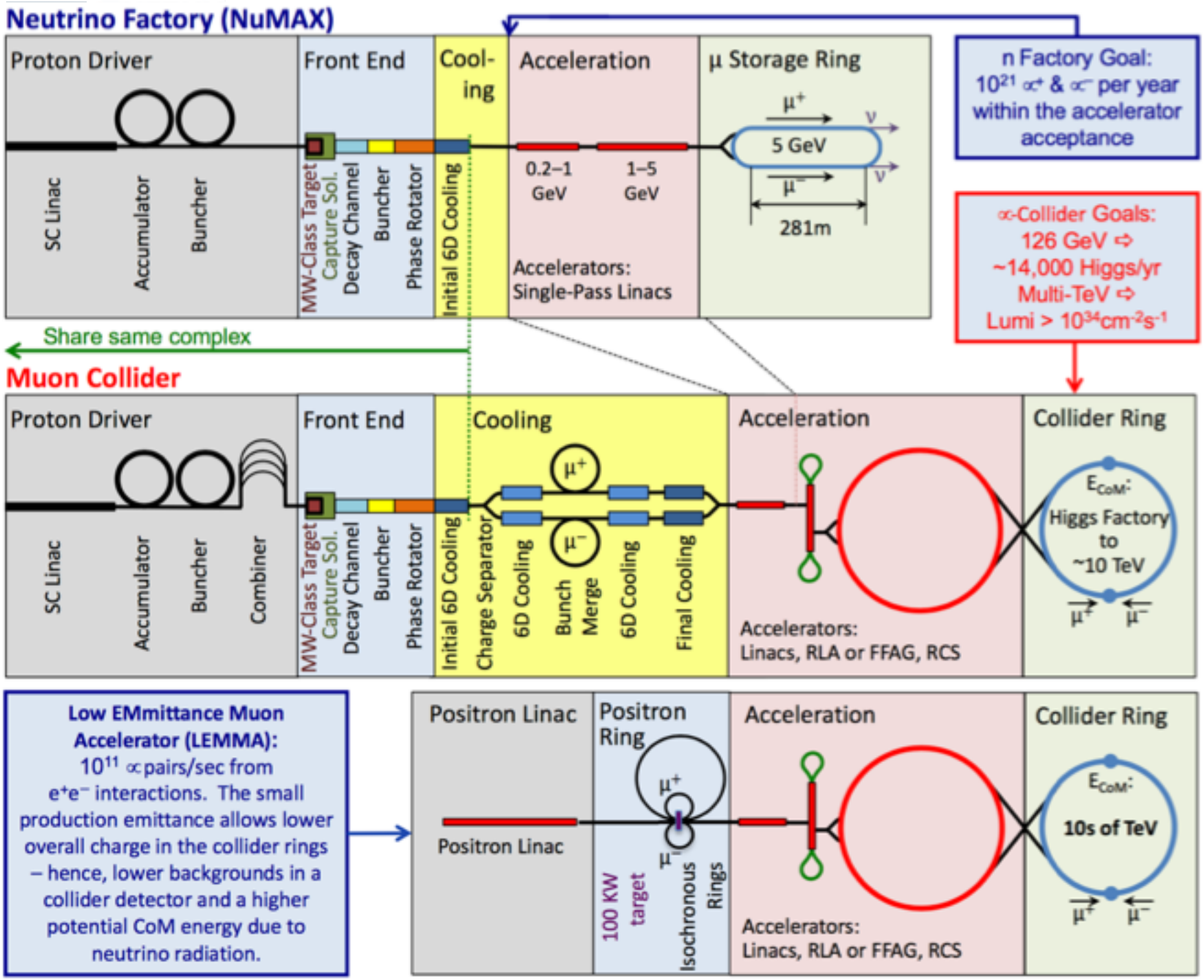
- *this is where your grand-children can do their Ph.D. thesis!*

Muon Collider

- The best choice!
  - heavy particles → synchrotron radiation not an issus
  - elementary particles → clear picture for analyzing data
- but hard because of finite muon lifetime
  - accelerate quickly
  - radiation issues (from neutrinos!)
  - high background from muon decay
- interesting energies:
  - 10 TeV >> LHC
  - 14 TeV ~ FCC-hh
  - 30 TeV = “amazing”
- must deliver sufficient luminosity
- long-term project!
- *this is where your great-grandchildren can do their Ph.D. thesis!*

Muon Collider




Neutrino Factory (NuMAX)
Proton Driver
SC Linac
Accumulator
Buncher
Front End
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Cool-ing
Initial 6D Cooling
Acceleration
0.2–1 GeV
1–5 GeV
Accelerators: Single-Pass Linacs
μ Storage Ring
μ+
ν
5 GeV
ν
μ−
281m
n Factory Goal: 10^21 ∝+ & ∝− per year within the accelerator acceptance
∝-Collider Goals: 126 GeV ⇨ ~14,000 Higgs/yr Multi-TeV ⇨ Lumi > 10^34cm^-2s^-1
Share same complex
Muon Collider
Proton Driver
SC Linac
Accumulator
Buncher
Combiner
Front End
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Cooling
Initial 6D Cooling
Charge Separator
6D Cooling
Bunch Merge
6D Cooling
Final Cooling
μ+
μ−
Acceleration
Accelerators: Linacs, RLA or FFAG, RCS
Collider Ring
E_CoM: Higgs Factory to ~10 TeV
Low EMmittance Muon Accelerator (LEMMA): 10^11 ∝ pairs/sec from e+e− interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.
Positron Linac
Positron Linac
Positron Ring
μ+
μ−
100 KW target
Isochronous Rings
Acceleration
Accelerators: Linacs, RLA or FFAG, RCS
Collider Ring
E_CoM: 10s of TeV

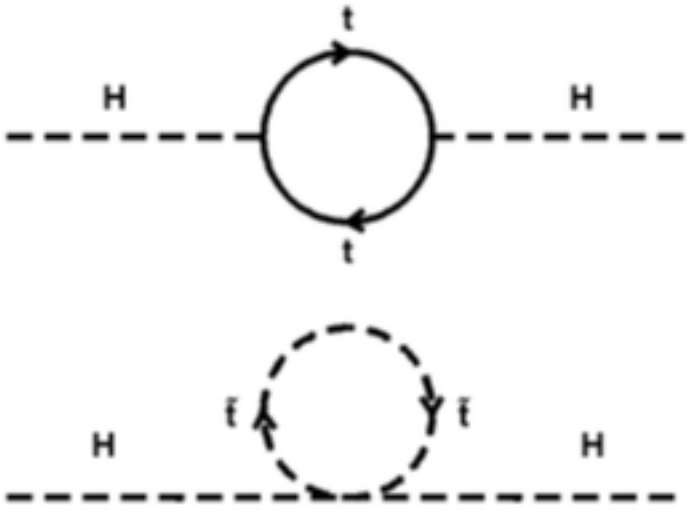
Important questions of today's particle physics:

- Why are particle masses so different?
  (And what determines their values?)
- Is there an overall (hidden) symmetry such as supersymmetry (SUSY) ⇨ "mirror world" of all known particles?.
- What is the nature of "dark matter" and "dark energy" in the universe?
- Why is there more matter than anti-matter?
  (CP-violation!)
- Why have neutrinos such small mass?
- Is there a Grand Unification which combines all interactions, including gravitation?
- Are there extra dimensions, D > 4 ? (⇨ string theory, …)

BACKUP

Supersymmetry ("SUSY")

- another 2 open problems in Standard Model:
- "**running coupling constants**" of electromagnetic, weak and strong interactions meet almost but not completely at the same point
- to avoid quadratic divergences in Higgs mass, "**fine-tuning**" is needed
- both problems can be solved by introducing a **symmetry between bosons and fermions**



Cancellation of the Higgs boson quadratic mass renormalization between fermionic top quark loop and scalar stop squark tadpole Feynman diagrams in a **supersymmetric** extension of the Standard Model

important questions of today's particle physics

(ongoing experiments)

- Why are particle masses so different?
  (And what determines their values?)

- Is there an overall (hidden) symmetry such as supersymmetry (SUSY) ⇨ "mirror world" of all known particles?.

- What is the nature of "dark matter" and "dark energy" in the universe?

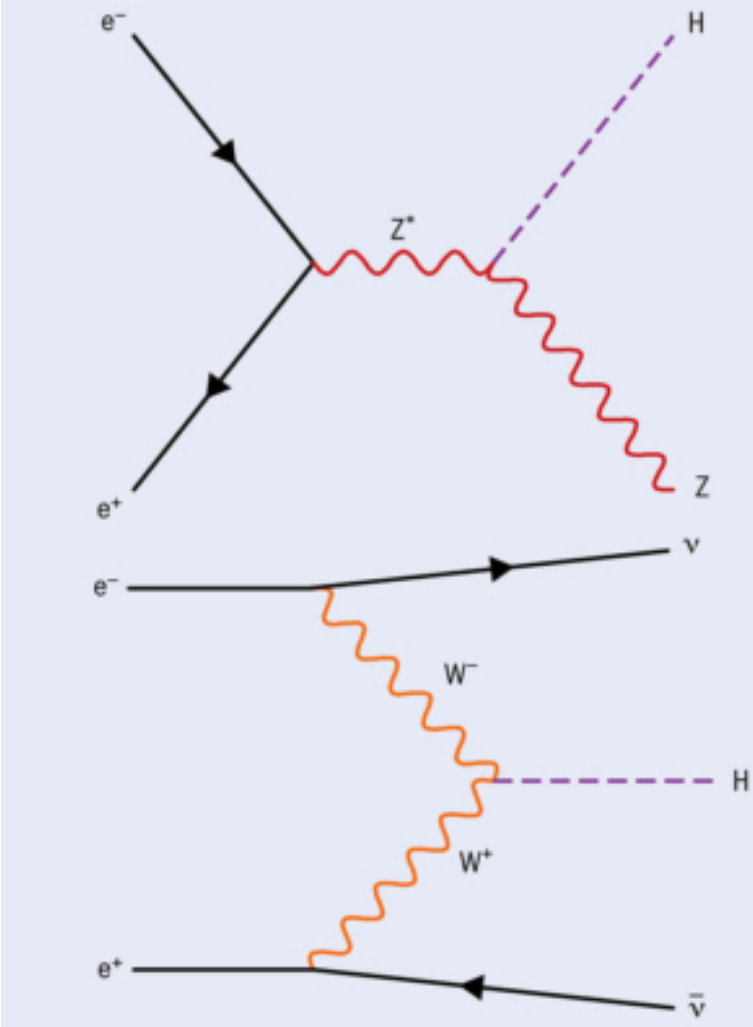
- Why is there more matter than anti-matter?

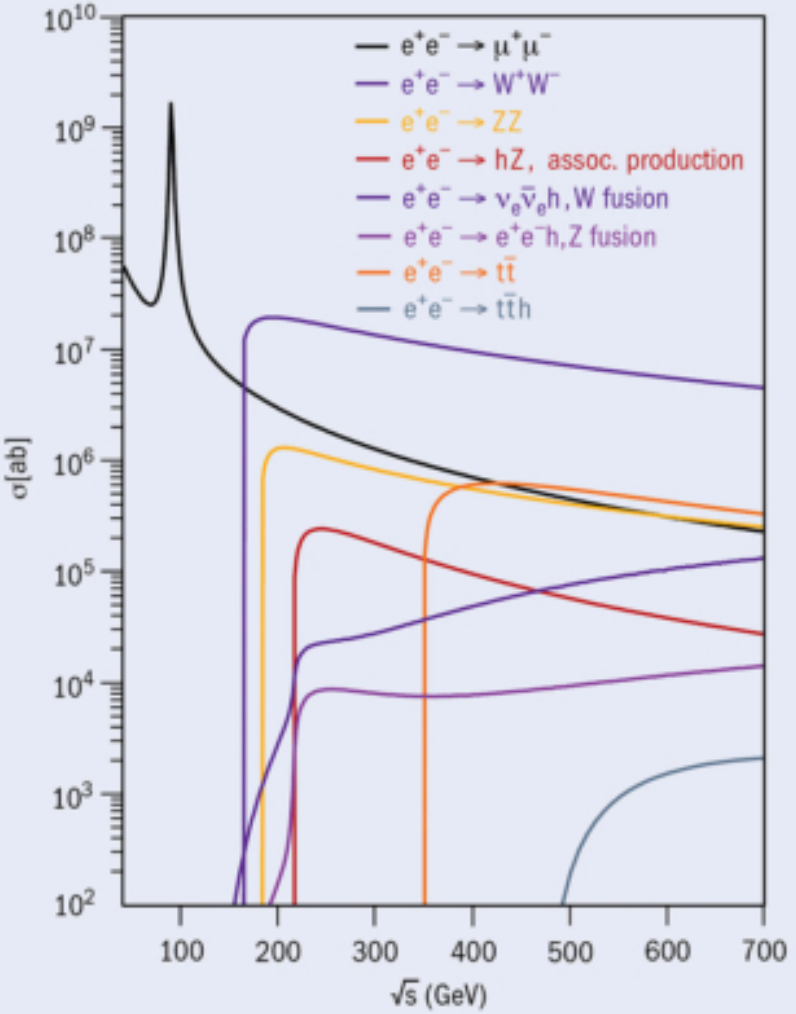
- Why have neutrinos such small mass?

- Is there a Grand Unification which combines all interactions, including gravitation?

- Are there extra dimensions, D > 4 ? (⇨ string theory, …)

Higgs production at e^+e^- collider





Linear Collider options

- ILC
  - TDR in 2013: 500 GeV, US $ 8 billion
  - re-baselined: 250 GeV, 40% cheaper
  - 129 MW power consumption
  - from: Marcel Stanitzki, CERN, 16 November 2018,
  - https://indico.cern.ch/event/759130/contributions/3148649/.../ecfa-plenary.pdf

- CLIC
  - 380 GeV (168 MW) 5.9 GCHF (7.3 for klystron option)
  - 1500 GeV (364 MW) +5.1 GCHF
  - 3000 GeV (589 MW) +7.3 GCHF
  - from: Philip Burrows, Lausanne, 8 April 2019
  - https://indico.cern.ch/event/789524/contributions/3340269/

- *CERN uses now: 1.2 TWh / year (= 137 MW averaged over year)*

Accelerator programs

Table 1: HEP accelerator programs with the currently existing efforts and possible future projects.

	Current Projects	Future Projects
Hadron Colliders	HL-LHC: 14 TeV/3 ab^{-1}	HE-LHC: 27 TeV/15 ab^{-1} FCC-hh: 100 TeV/30 ab^{-1} SPPC: 100 TeV/30 ab^{-1}
Lepton Colliders	SuperKEKB: 3.5 GeV e^+ on 7 GeV e^- /8 $\times 10^{35}/cm^2/s$ C-Tau at BINP: 2-5 GeV/1 $\times 10^{35}/cm^2/s$ ILC: 250 GeV/2 ab^{-1}, 80% & 30% pol.	ILC: 0.5 (1) TeV/4 (8) ab^{-1} CLIC: 0.38,1.5,3 TeV/0.5,1.5,3 ab^{-1} FCC-ee: 250 GeV/ 5 ab^{-1} CEPC: 240 GeV/ 5 ab^{-1} $\mu^+\mu^-$ colliders: 0.125, 3, 14 TeV e^+e^-1(3) TeV plasma colliders
Lepton-Hadron Colliders		LHeC: 60 GeV⊕7 TeV/1 ab^{-1} FCC-eh: 60 GeV⊕50 TeV/2 ab^{-1}
Intensity Frontier	J-PARC : 1.3 MW upgrade PIP-II: 1.2 MW/200 kton·MW·years for DUNE and >1.5 MW for precision program	PIP-III: 2.4 MW/ 700 kton·MW·years for DUNE Neutrino Factory: 10 GeV/5·$10^{20}\nu$/yr

From: APS (American Physical Society) Division of Particles and Fields Response to European Strategy Group Call for White Papers: Tools for Particle Physics

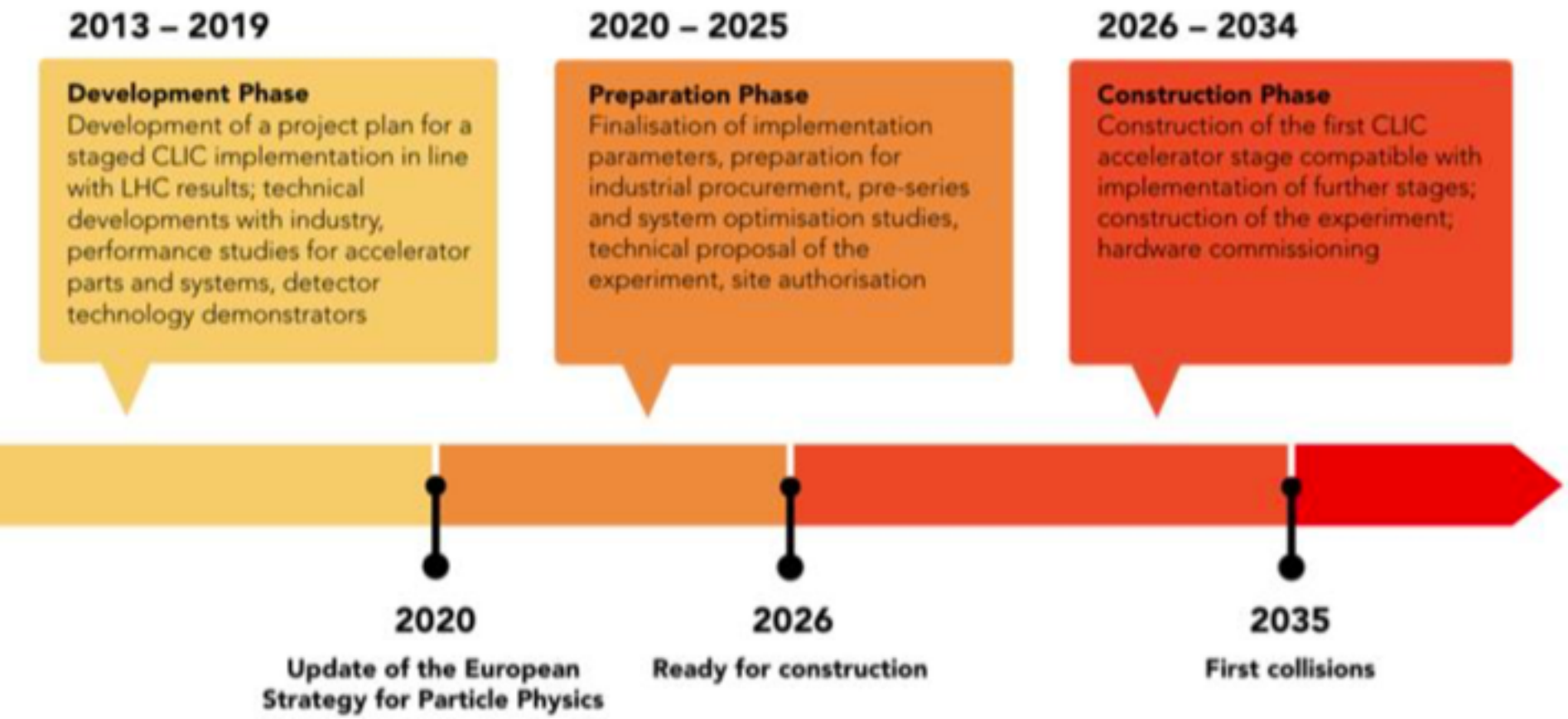
Circular e^+e^- colliders (Higgs factories)

- FCC-ee
  - *Future Circular Collider - ee (CERN)*
  - up to 365 GeV
  - 10.5 GCHF
    - » https://indico.cern.ch/event/765096/contributions/3298137/
  - *FCC-hh extension (100 TeV): 17 GCHF (24 GCHF without ee)*
- CEPC
  - *Circular Electron-Positron Collider (China)*
  - 240 GeV
    - » https://physicsworld.com/a/china-unveils-blueprint-for-huge-underground-higgs-factory/
  - US $ 4.3 ... 5 billion
    - » https://www.nature.com/articles/d41586-018-07492-w
    - » http://english.cas.cn/newsroom/news/201810/t20181023_199981.shtml
  - *SppC extension (100 TeV)*

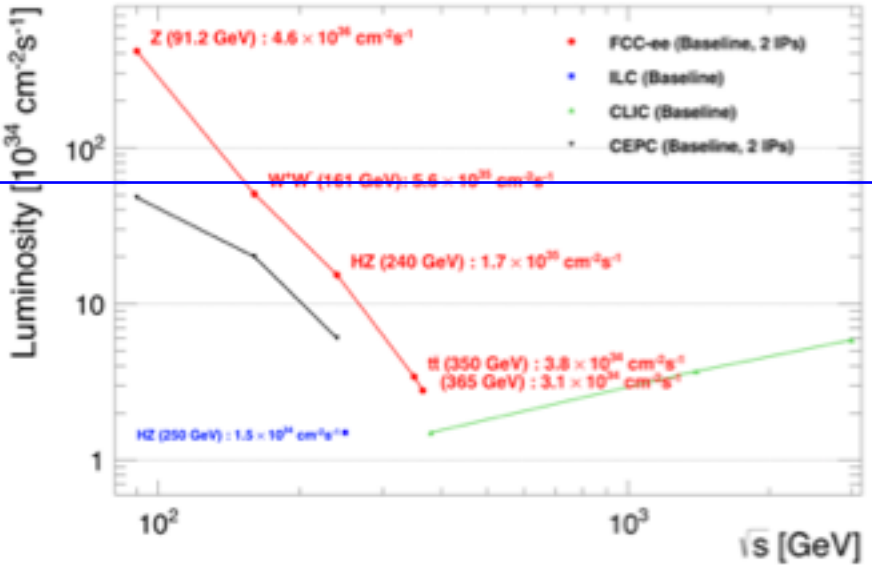
CLIC

- drive beam acceleration
  - klystron option for first stage (380 GeV)
- 380 GeV stage: 11.4 km tunnel
  - 3 TeV: 50 km
- accelerating gradient: 72 (100) MV/m

CLIC roadmap



FCC-ee



- staged implementation
  - figure shown before: Z, WW, ZH and $t\bar{t}$ operation points
  - learning curve
- two interaction points
- top-up injection scheme, implemented with a full-energy booster ring installed next to the collider
- precise measurement of the beam energy based on resonant depolarization
- 300 MW
  - slightly below in first stages, slightly above for top-top

HE-LHC

- idea: if you have not enough money for a 100-km tunnel ...
- ... just put stronger magnets (16 Tesla) into the LHC
- ... and run at 27 TeV

- not so easy: magnets might not fit into the present tunnel!

- price tag: 7.2 GCHF

Muon Collider R&D

- Muon Ionization Cooling Experiment (MICE)
  - Rutherford-Appleton Laboratory (RAL)
- Muon Accelerator Program (MAP)
  - USA
- Low Emittance Muon Accelerator (LEMMA)
  - Italy