High Energy Physics aside the Large Hadron Collider

What are we, and where do we come from? - Searching for flavour in beauty

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38C3, Hamburg, 29.12.2024

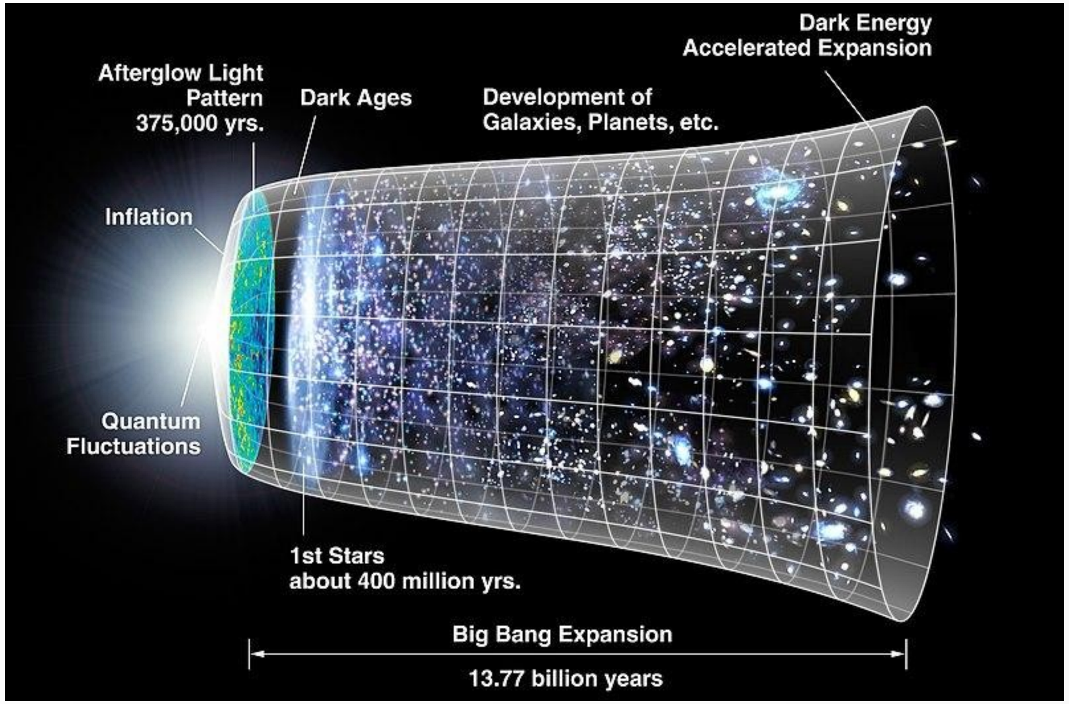
Disclaimer

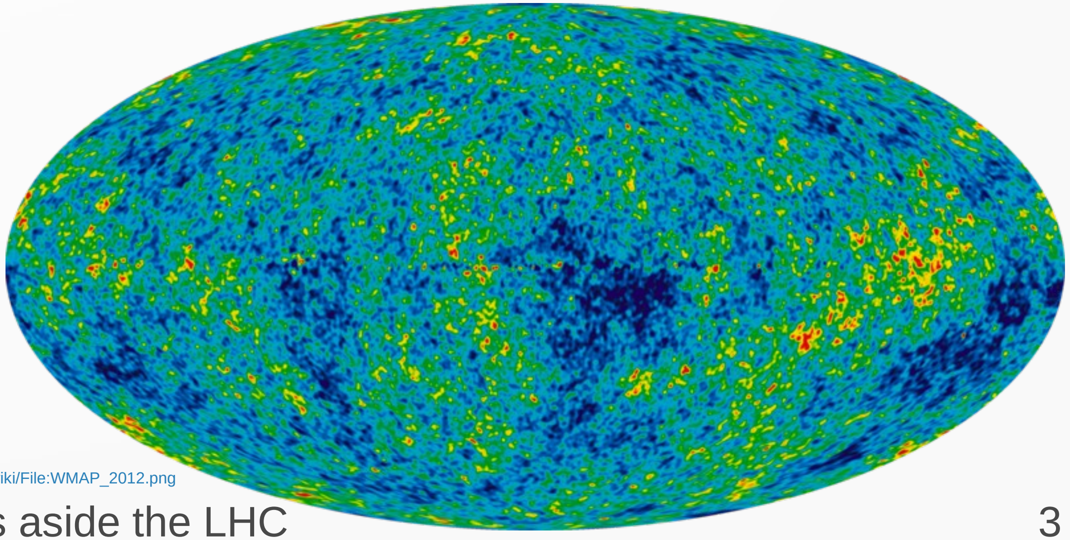
- Though I’m part of the Belle II collaboration and thus will use Belle II as an example, this is not an official Belle II talk. All facts and opinions stated are my own and don’t necessarily reflect the positions of Belle II.
- Many things will be (over)simplified.

Where do we come from?

- Evolution of the universe after the big bang for 13.77 Gyears
- From our point everything looks the same
  - Cosmic microwave background radiation of 2.7 K
  - There should have been equal amounts of matter and antimatter at the big bang
  - Imbalance: ~1:5,000,000,000

https://en.wikipedia.org/wiki/File:CMB_Timeline300_no_WMAP.jpg





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    This is us!

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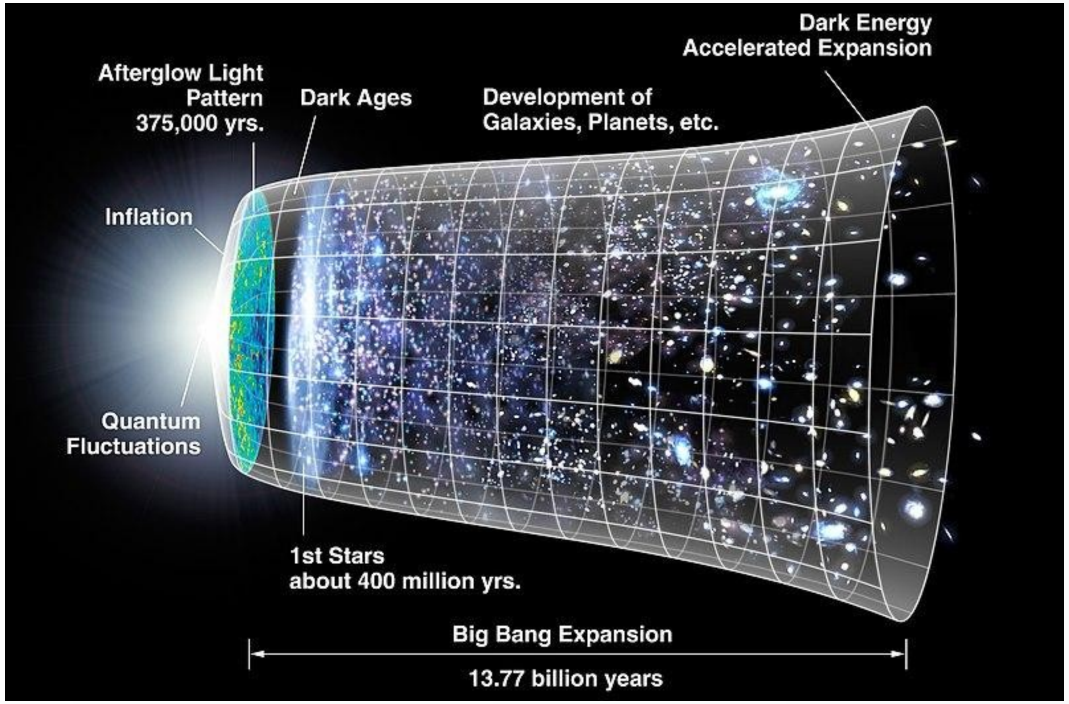

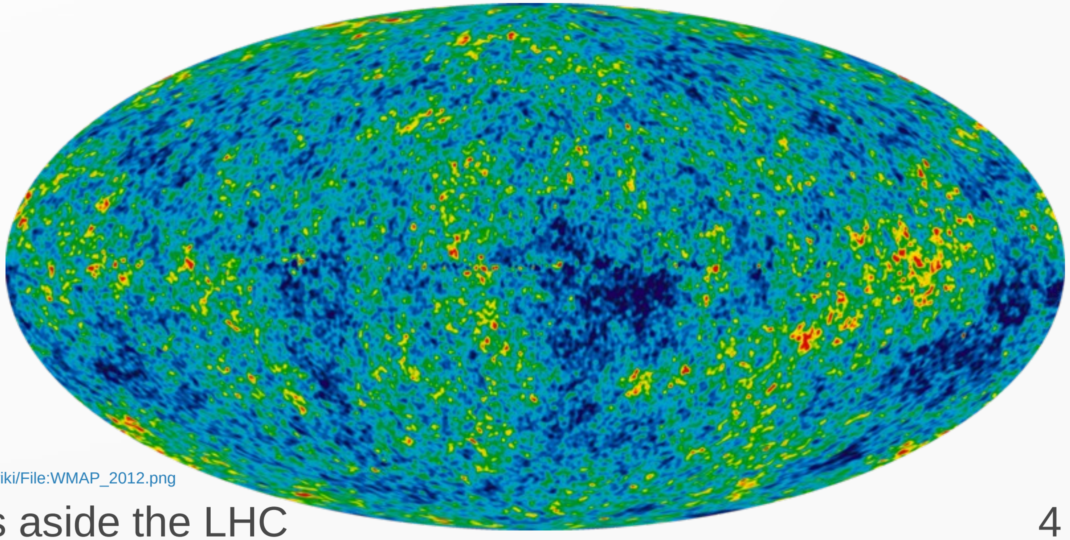

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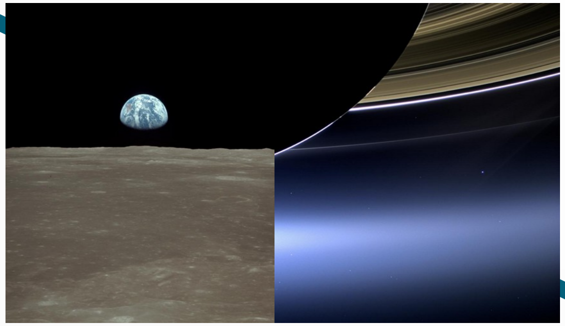
What is High energy physics about?

From huge to tiny

https://esawebb.org/images/weic2327c/

Very large scales
- O(ly)
- Galaxies, galaxy clusters

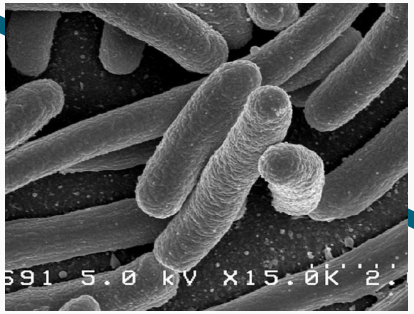
https://www.esa.int/ESA_Multimedia/Images/2019/02/Earth_seen_from_NASA_s_Apollo_11_and_ESA_s_Cassini



Large scales
- O(Tm) – O(Gm)
- Solar systems, stars, …

Our daily life
- O(Mm) – O(mm)

https://de.wikipedia.org/wiki/Automobil#/media/Datei:Ford_T_Jon_Sullivan.jpg

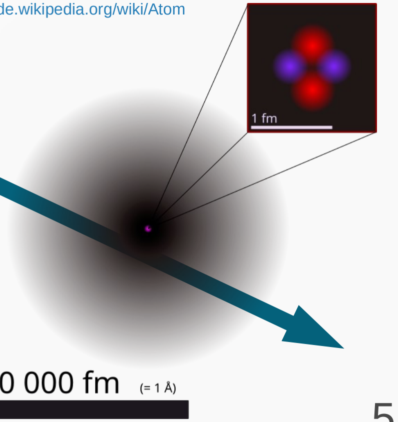


Micro and nano scale
- O(µm) – O(nm)
- Bacteria, viruses, …

https://de.wikipedia.org/wiki/Escherichia_coli#/media/Datei:E._coli_Bacteria_(7316101966).jpg

Atomic scale
- ≪ O(nm)
- Atoms, molecules

https://de.wikipedia.org/wiki/Atom



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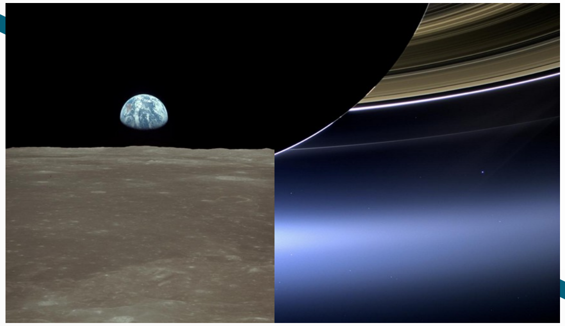

Sub-atomic scales

- nuclear and particle physics
- High energy physics (HEP) is about understanding what happens at < 10^{-15} m

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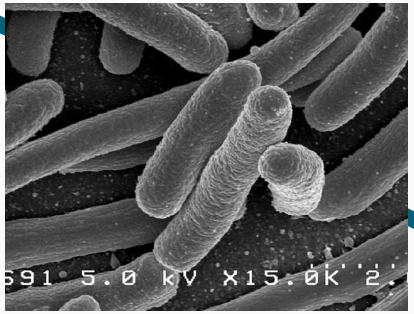

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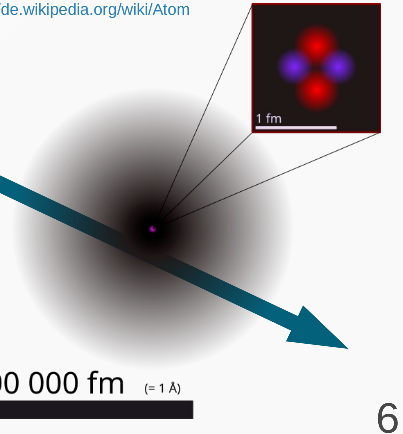
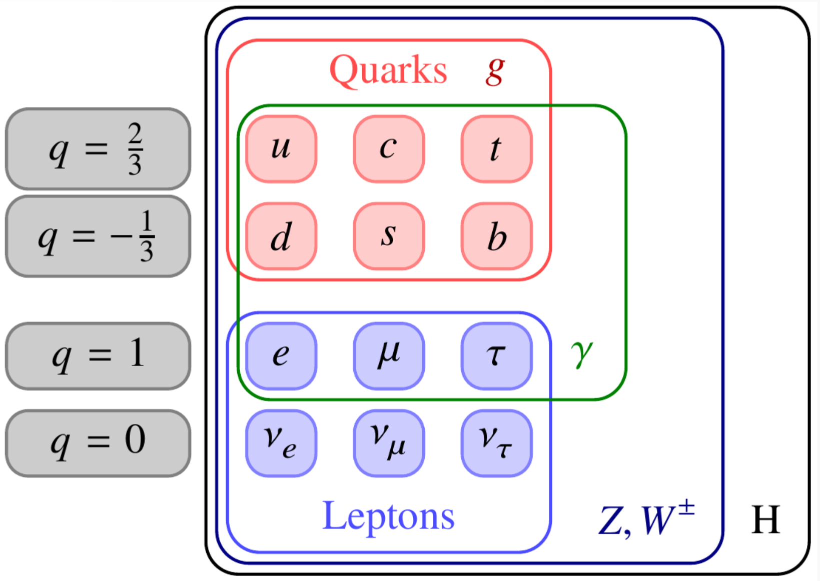


Standard model of HEP

- Standard Model (SM) is a very successful theory of the nanoscopic world
  - Particles and anti-particles, bound states
- Has some shortcomings:
  - Neutrinos are not massless
  - Only describes 5% of the universe, does not contain dark matter (15%) nor dark energy (70%)
  - Does not contain enough matter-antimatter asymmetry to explain us
- Where did all the antimatter go?



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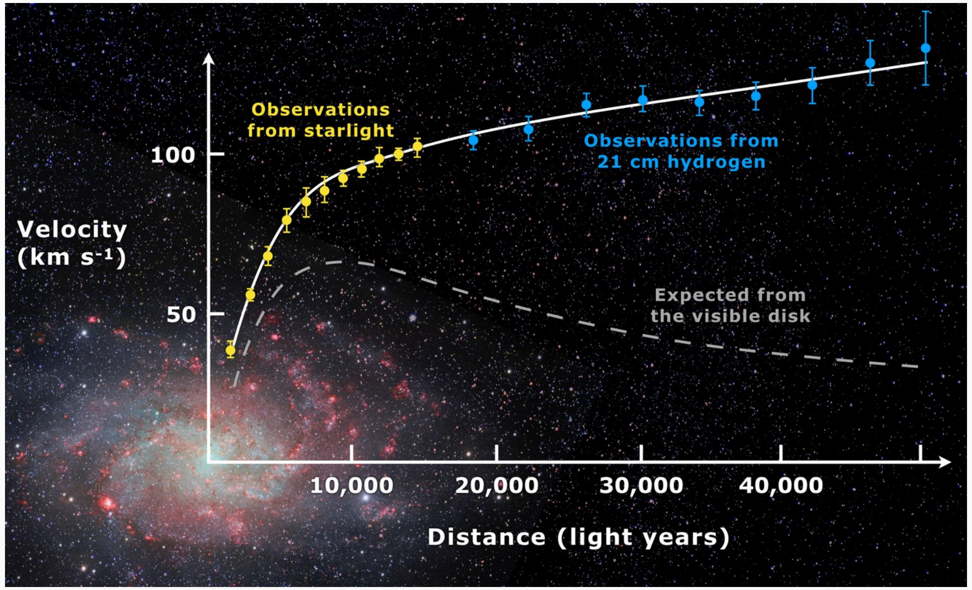

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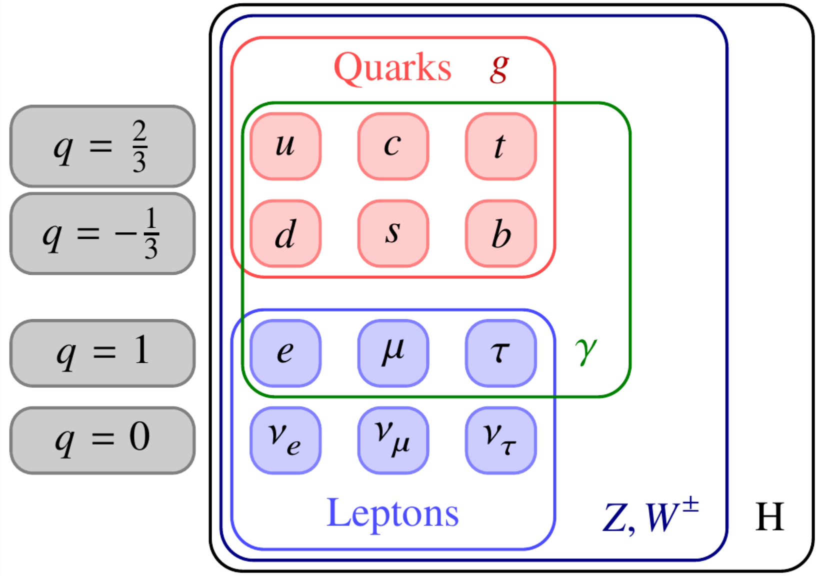

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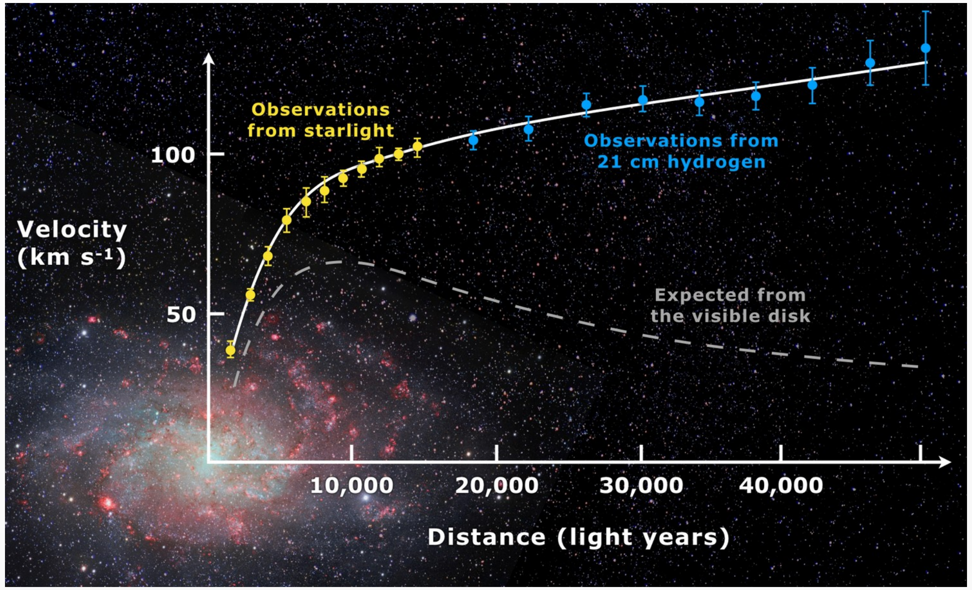

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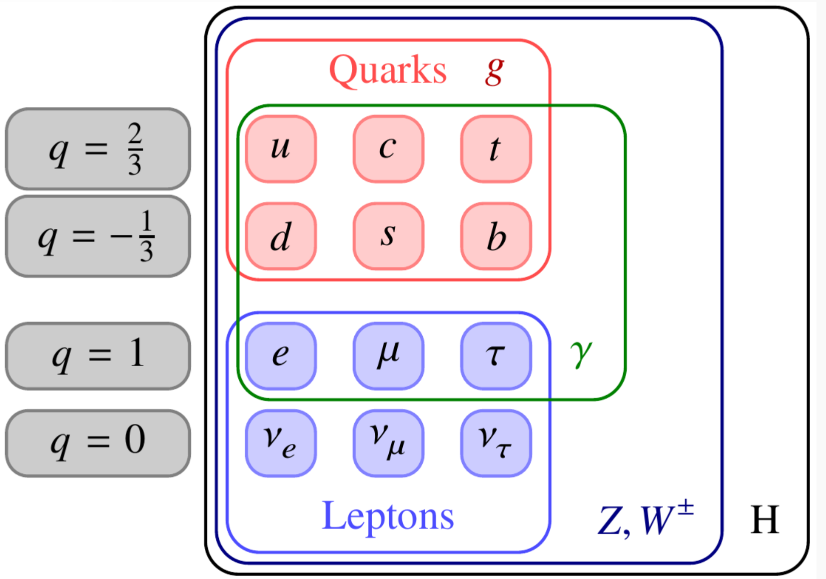

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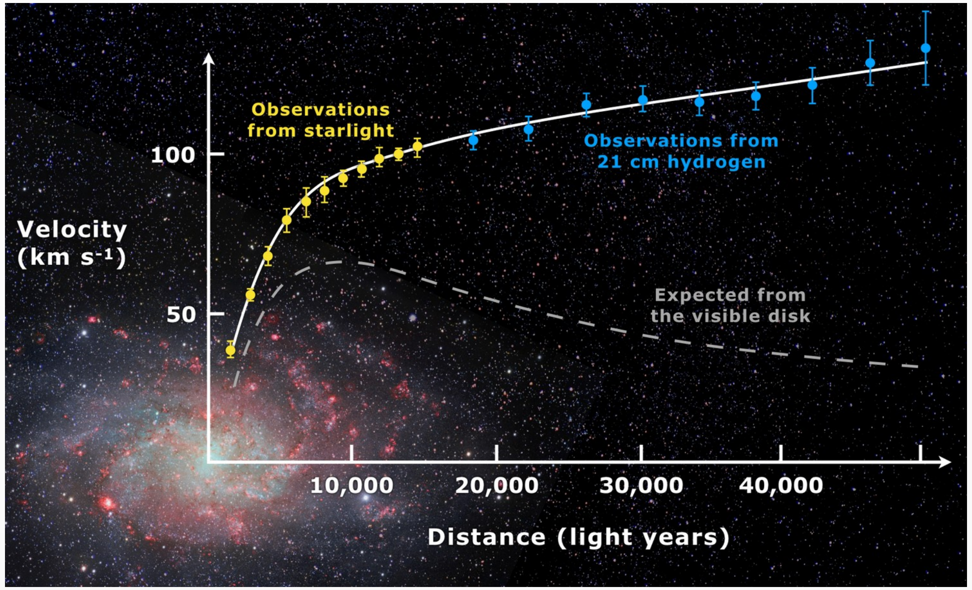
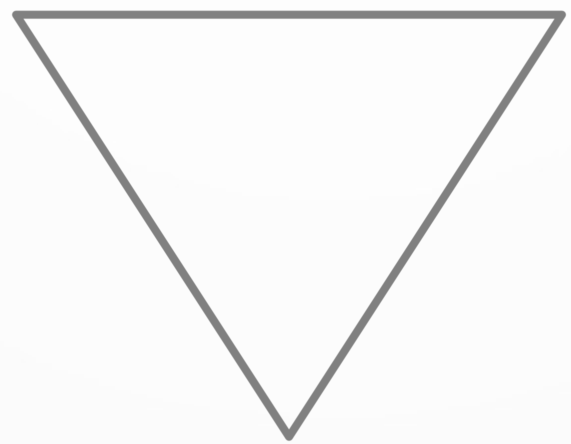


Flavours of HEP

Energy Frontier

- Highest achievable energies, energy O(TeV)
- **Direct** discoveries of new particles
- Examples: experiments at LHC: ATLAS, CMS, LHCb, Alice



Flavours of HEP

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Flavours of HEP

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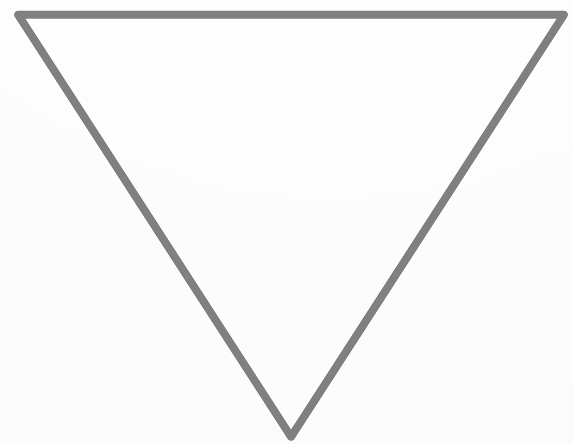
Astrophysics Frontier

- Particles from astrophysical sources
  - Neutrinos, photons, charged particles, …
- Examples: IceCube, SuperKamiokande, PierreAuger, ANTARES, KM3NeT...



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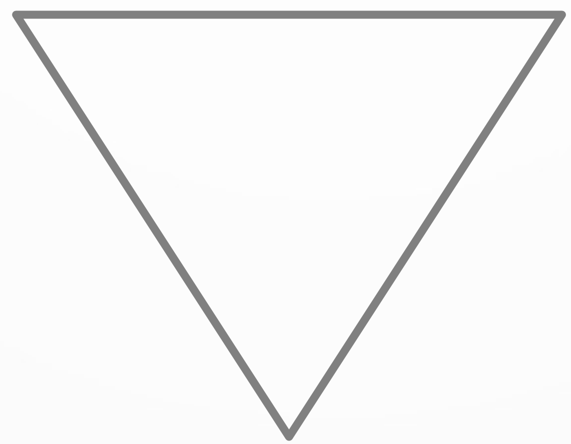


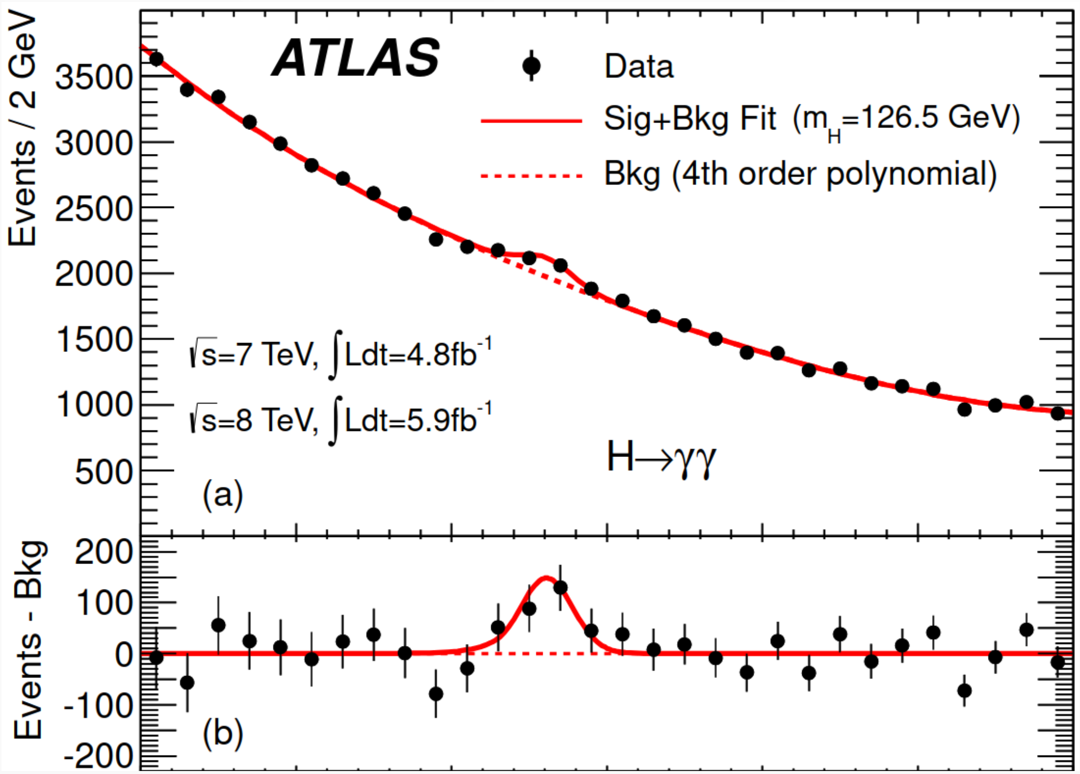
Precision / Intensity Frontier

- Dedicated experiments at lower energies with well understood intial conditions, energies usually O(GeV)
- **Indirect** discoveries of new particles
- Examples: BaBar (past), Belle (past), BES III, Belle II, but also LHC experiments; g-2

Direct vs indirect discoveries (simplified)

Direct

- Finding a new particle by measuring its mass



https://arxiv.org/pdf/1207.7214

Indirect

- Finding (tiny) deviations from standard model predictions
  - Often in rare processes

But both can be hint to new physics beyond the standard model

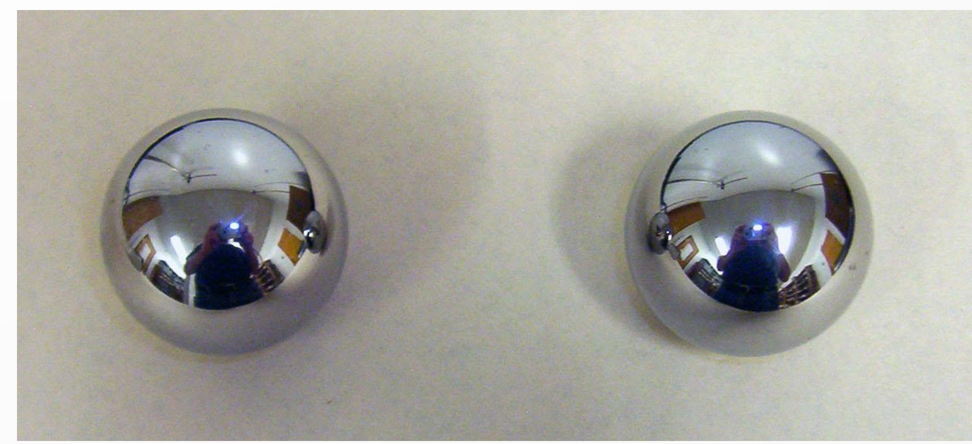
Precision physics

- New physics effects must be **tiny**, or only start playing a role at **much higher energies**
- Collect large data sets to measure small deviations from standard model predictions via indirect effects
  - Be very strict on which data you keep for an analysis to remove background (true for all experiments)

Precision physics

- Colliding cars (protons) vs small colliding steel balls (electons)
  - Debris flys in all directions vs simple mathematical prediction for two elastic scattering of two steel balls

https://uk.sports.yahoo.com/news/why-do-f1-cars-break-up-so-dramatically-in-a-133726844.html?guccounter=1



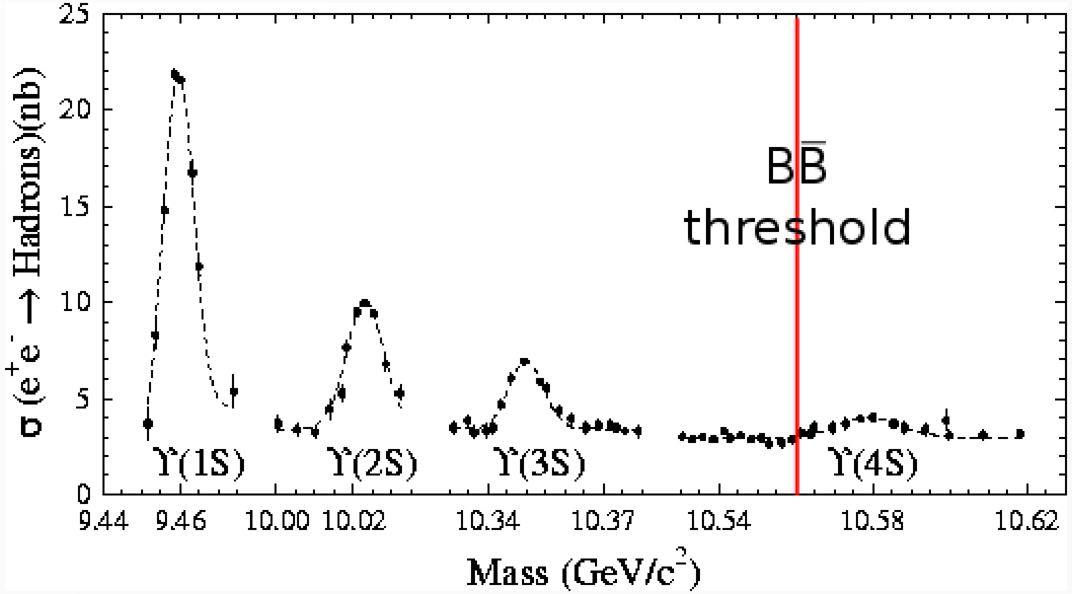
$$\vec{v}_a = \frac{l_{ao} m_a + l_{bo} m_b + (l_{bo} - l_{ao})\, m_b\, e}{m_a + m_b}\, \vec{u}^{\,e}_{ao} + l_{ap}\, \vec{u}^{\,e}_{ap}$$

$$\vec{v}_b = \frac{l_{ao} m_a + l_{bo} m_b + (l_{ao} - l_{bo})\, m_a\, e}{m_a + m_b}\, \vec{u}^{\,e}_{ao} + l_{bp}\, \vec{u}^{\,e}_{bp}$$

https://berndneumann.eu/en/2024_3dcollision.php

Precision physics – How?

- Collide electons and positrons
  - Very well known initial state
- Get new particles ($E = mc^2$)
  - Use E to roughly define the particles of interest
- Current examples:
  - BES III in China:
    "Charm and τ factory"
    E = ~3-5 GeV
  - Belle II in Japan: "Beauty factory"
    E = 10.58 GeV



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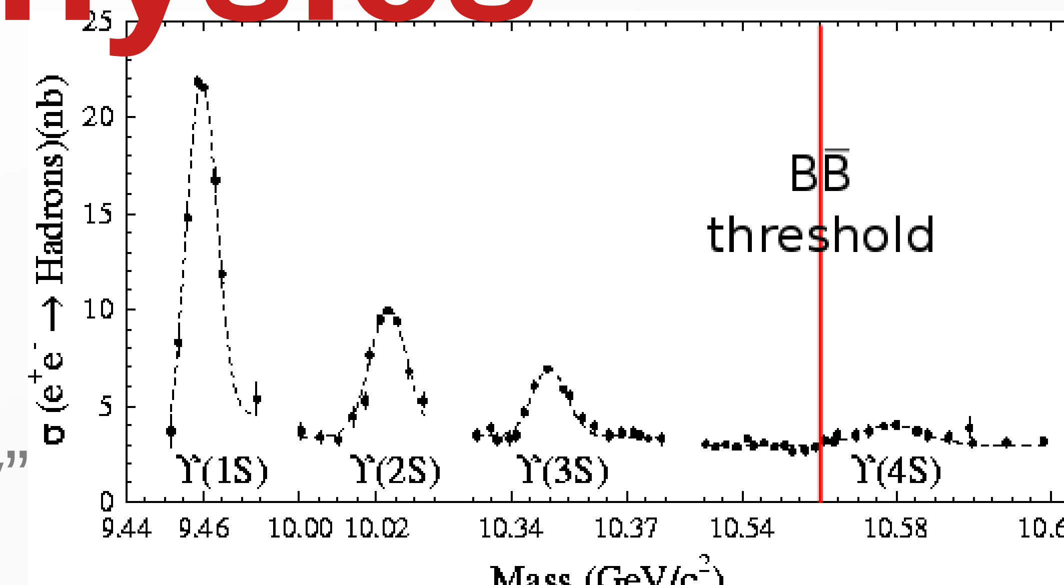
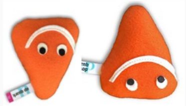


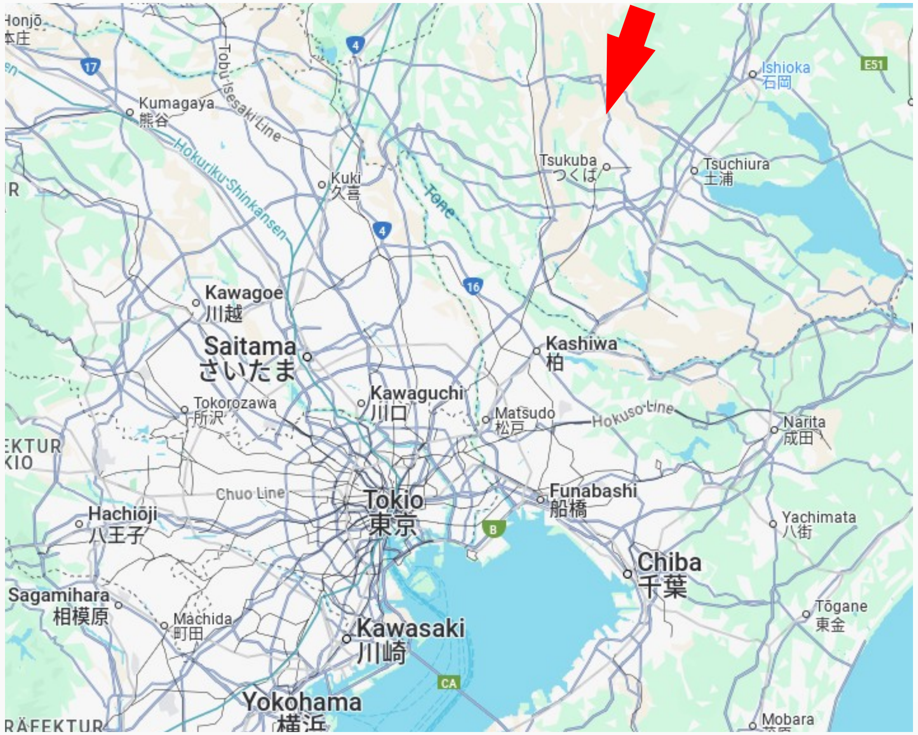
What are the particles? (oversimplified)

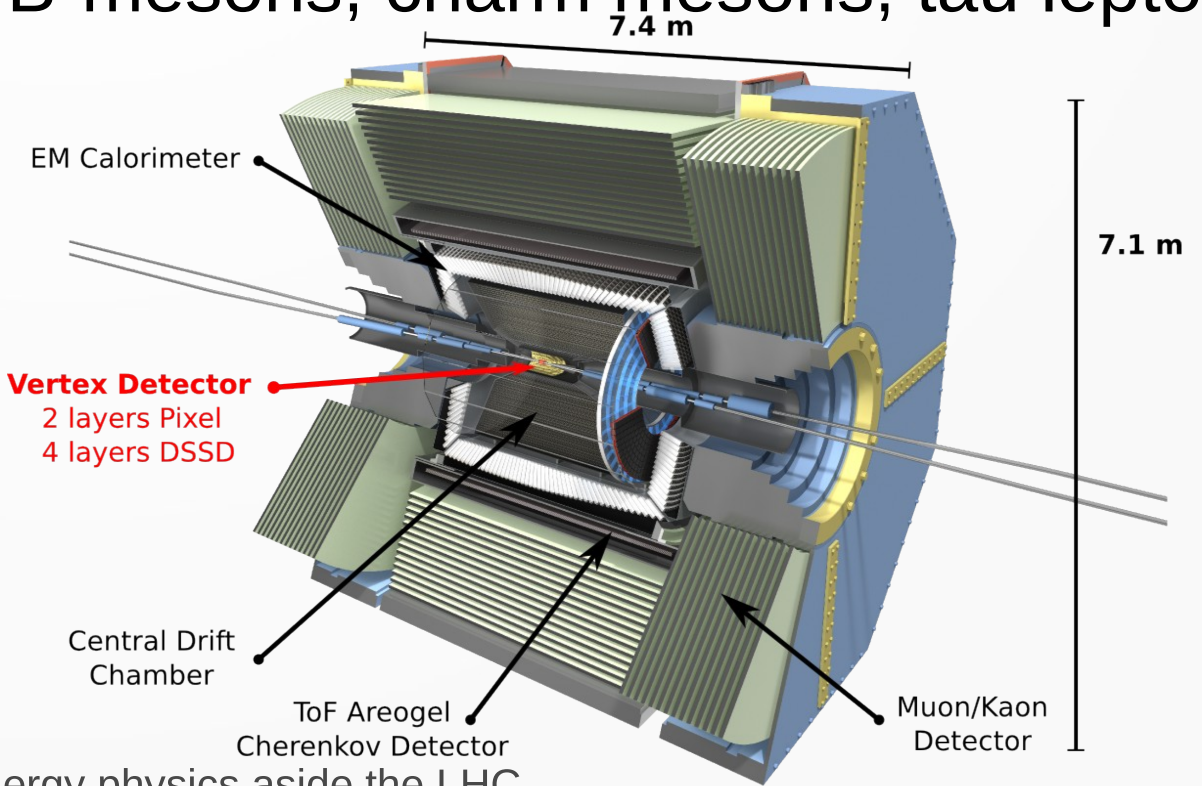
- Distinguish mesons and hadrons List of particles
- Decays happen from heavy to light
- Mesons: from heavy to light – roughly
  - Quarkonium: $b\bar{b}$ or $c\bar{c}$  
  - B-mesons: b + a lighter antiquark  
  - D-mesons: c + a lighter antiquark  
  - K-meson: s + a lighter antiquark  
  - Lighter mesons: combinations of u and d quarks 
- Hadrons:
  - Proton and neutron
  - There are many other….

https://www.particlezoo.net/collections/quarks

Belle II

- Located at the SuperKEKB accelerator at the KEK laboratory in Tsukuba, Japan, >1000
- B-factory:
  - Produces and investigates B-mesons, charm mesons, tau leptons





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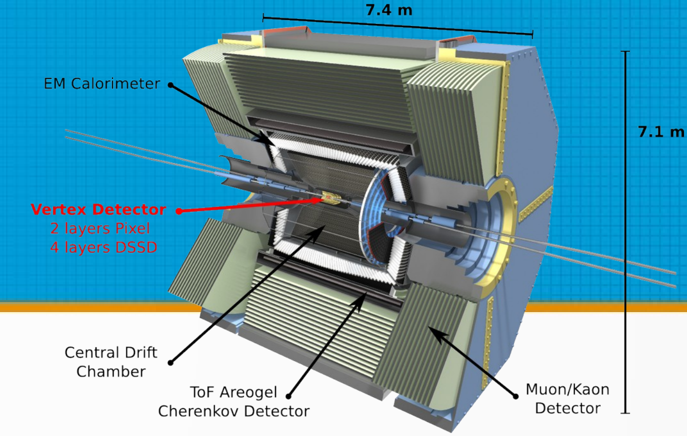
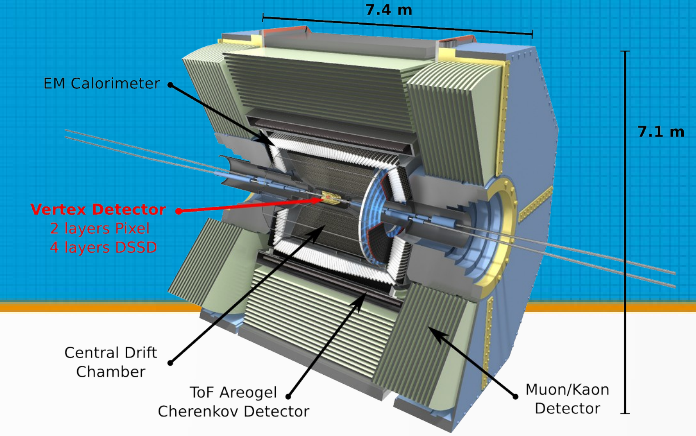


What does a particle detector consist of?

- Interaction point / region

Belle II



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  - Usually silicon pixel detector
  - pixel size O(10-100 µm)

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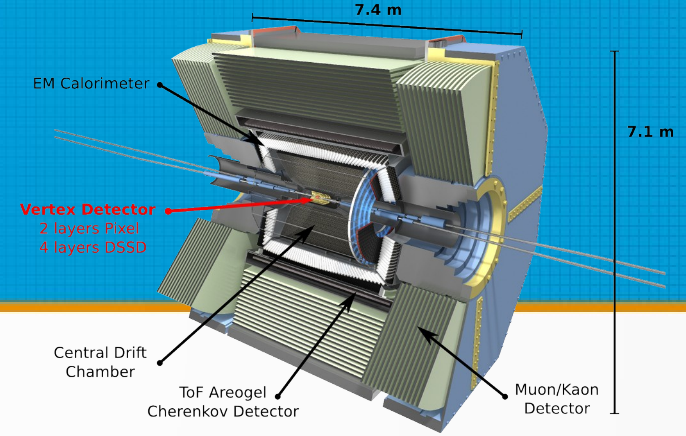

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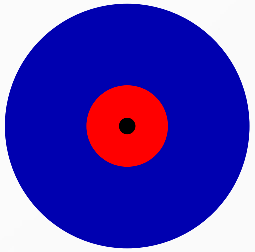

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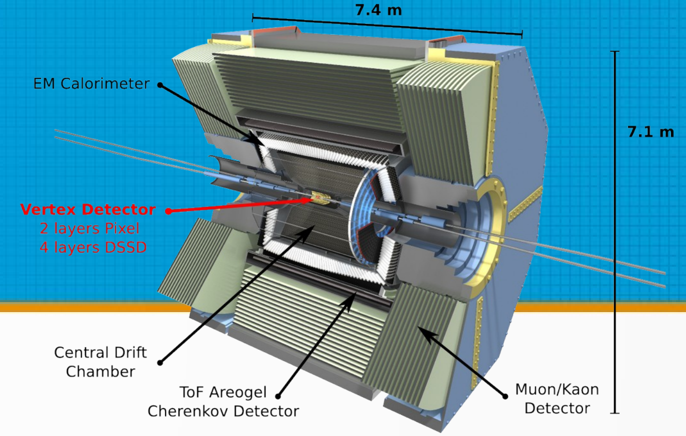

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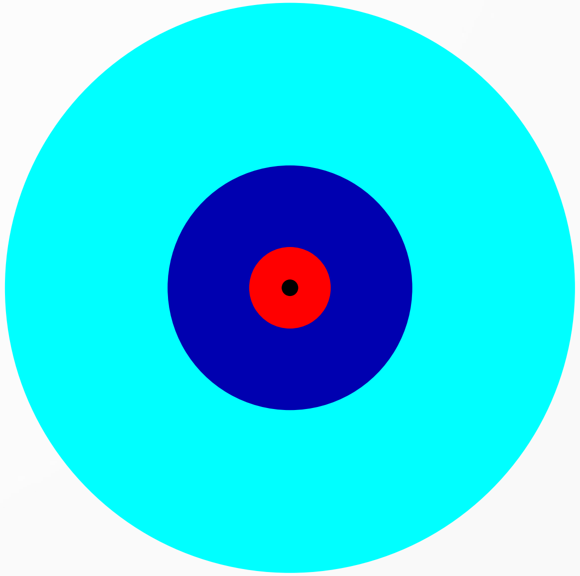

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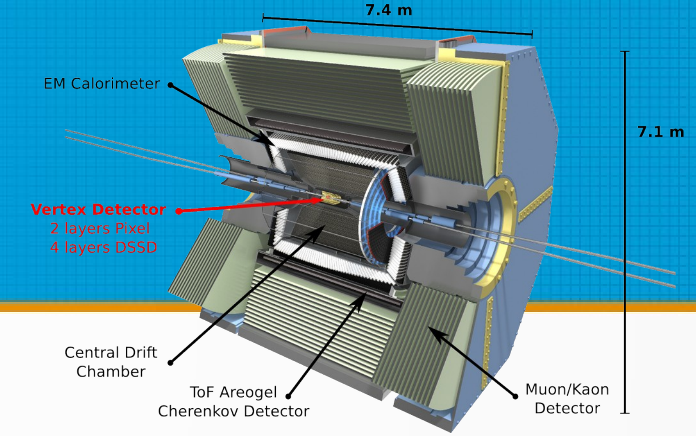

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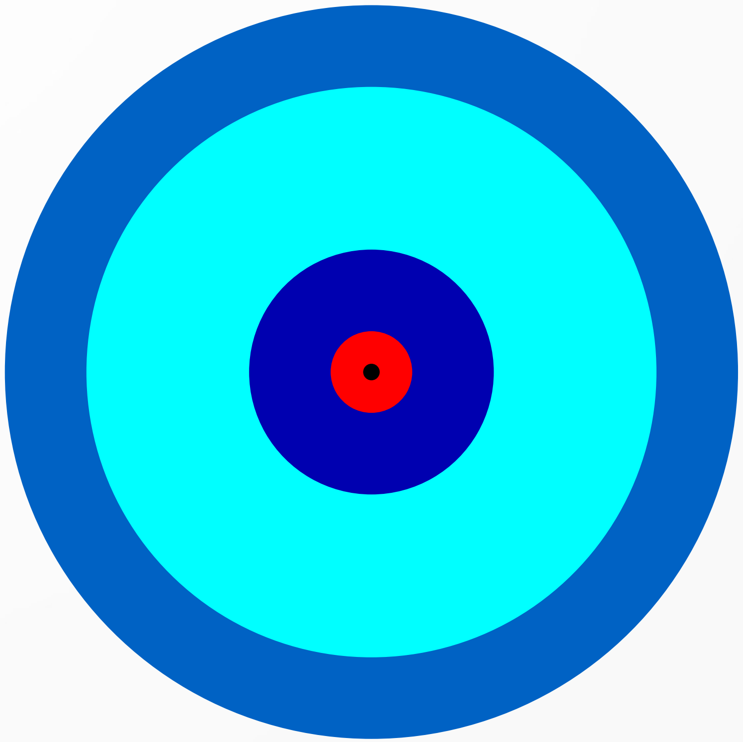

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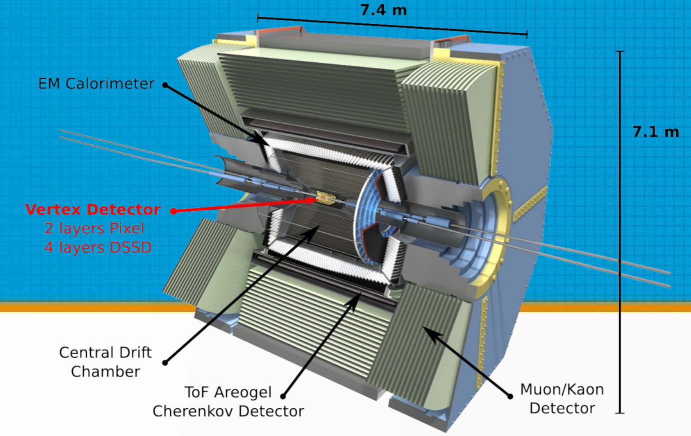

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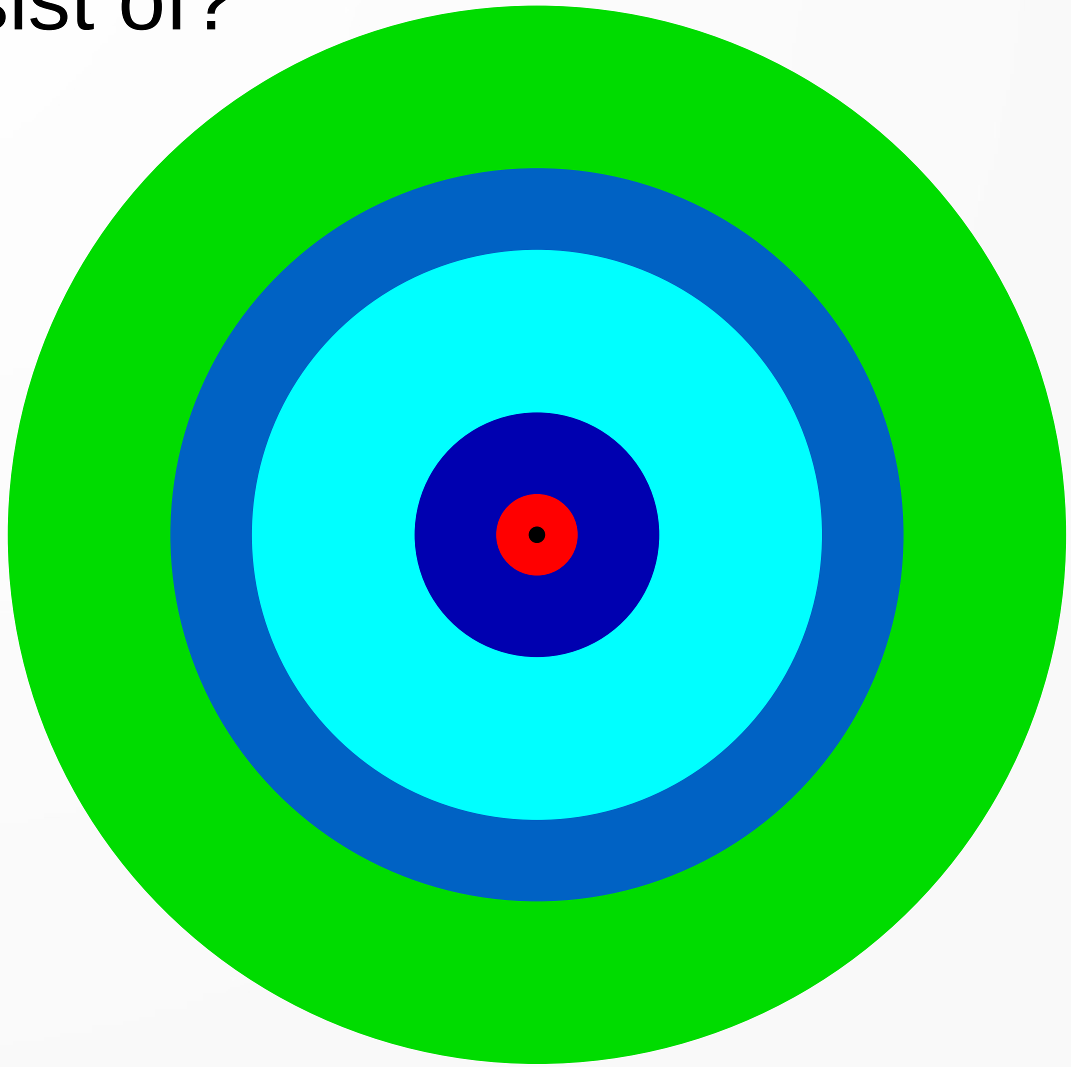
  - Dedicated system to identify KL0 and µ



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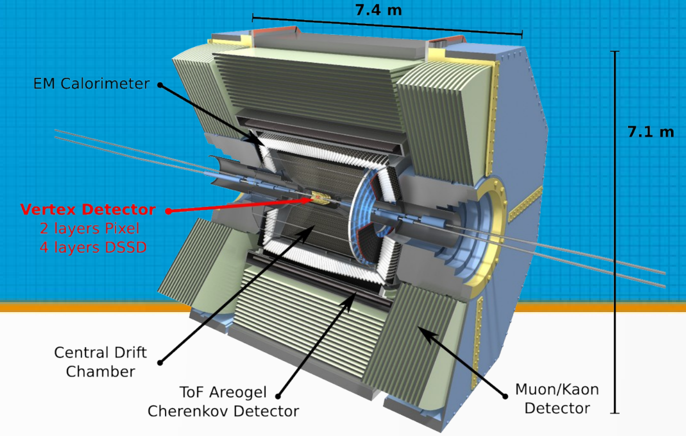

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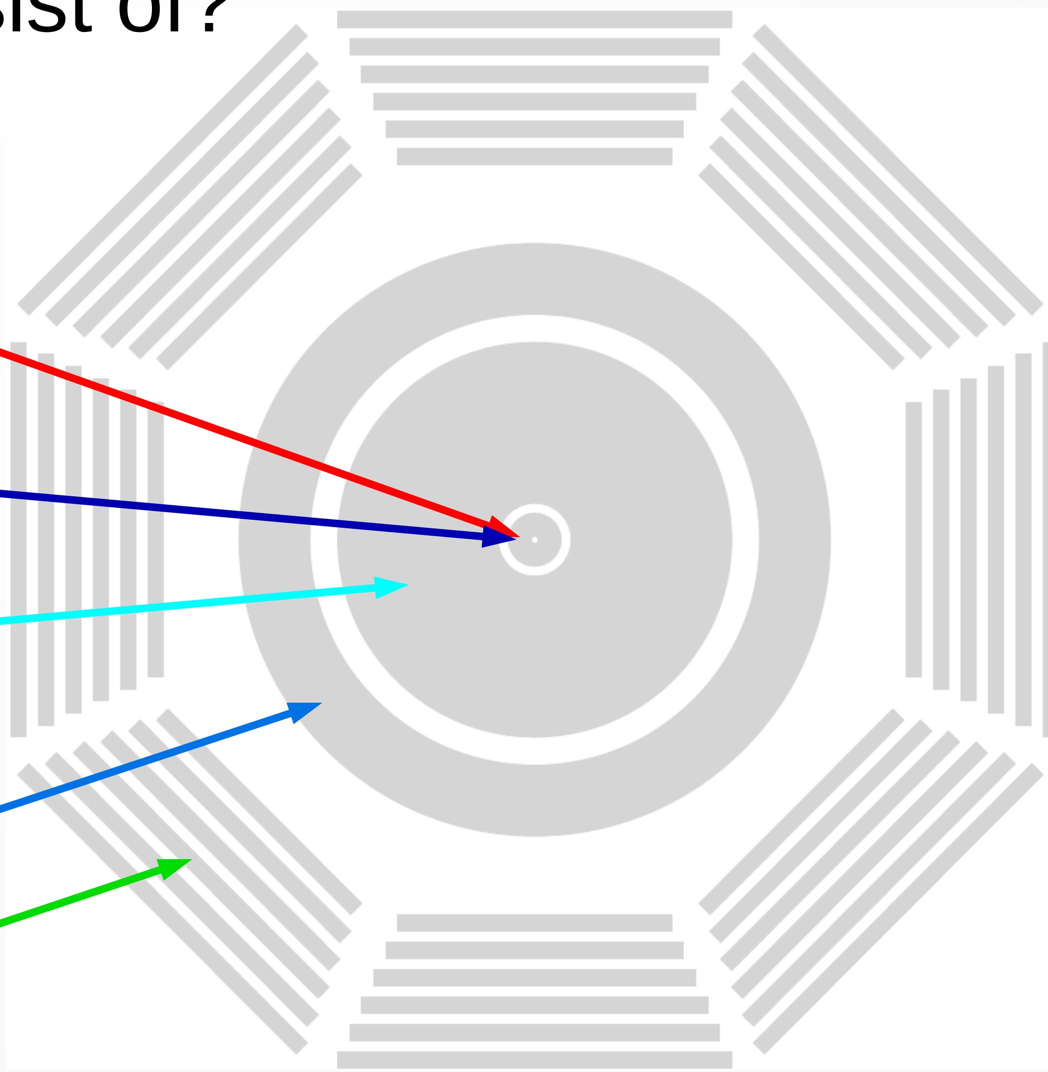

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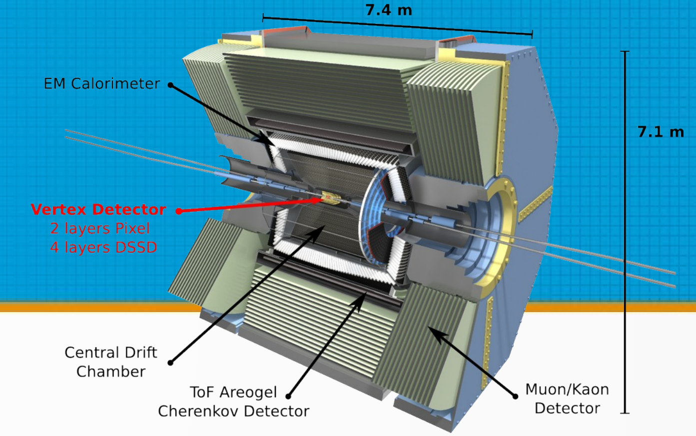

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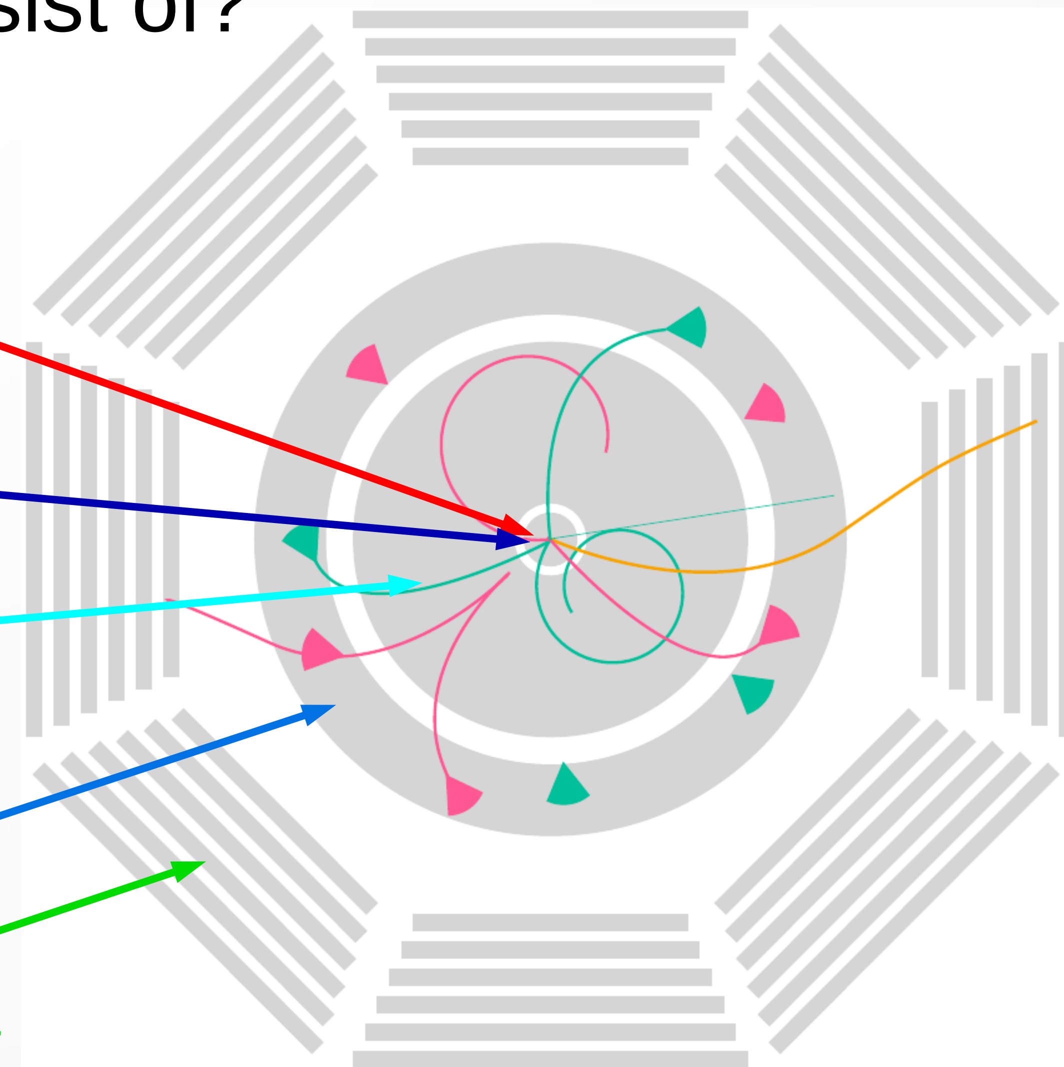
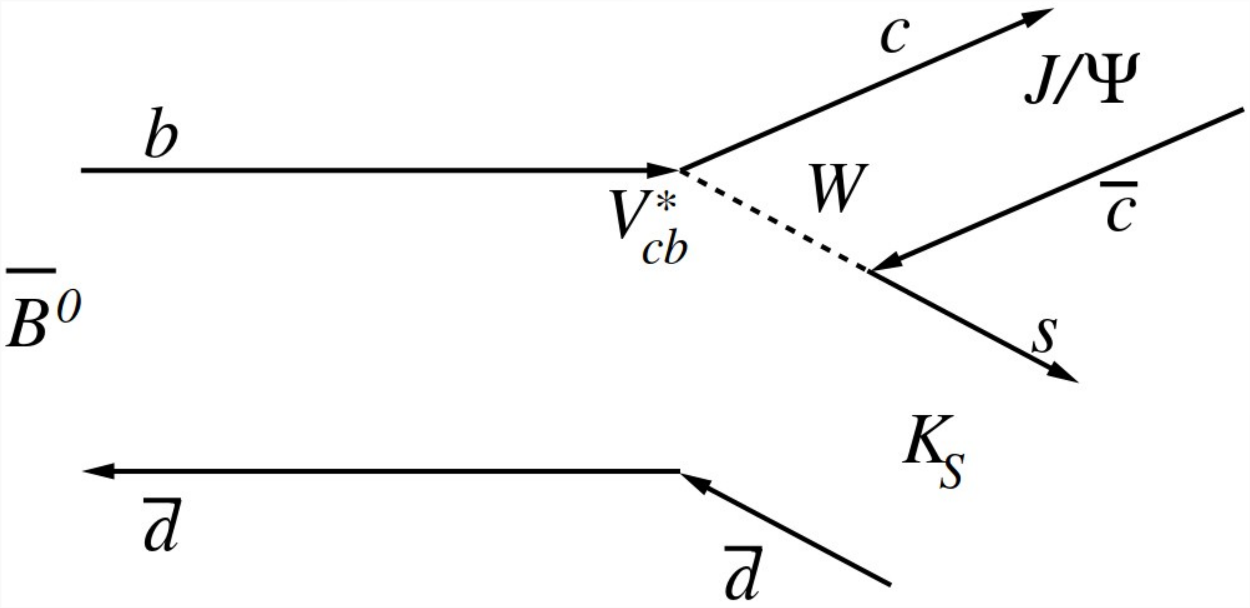


Flavour physics at Belle II

- B-mesons decay to lighter particles
  - Most straight forward process “tree decays”

Tree decay



https://arxiv.org/pdf/1406.6311

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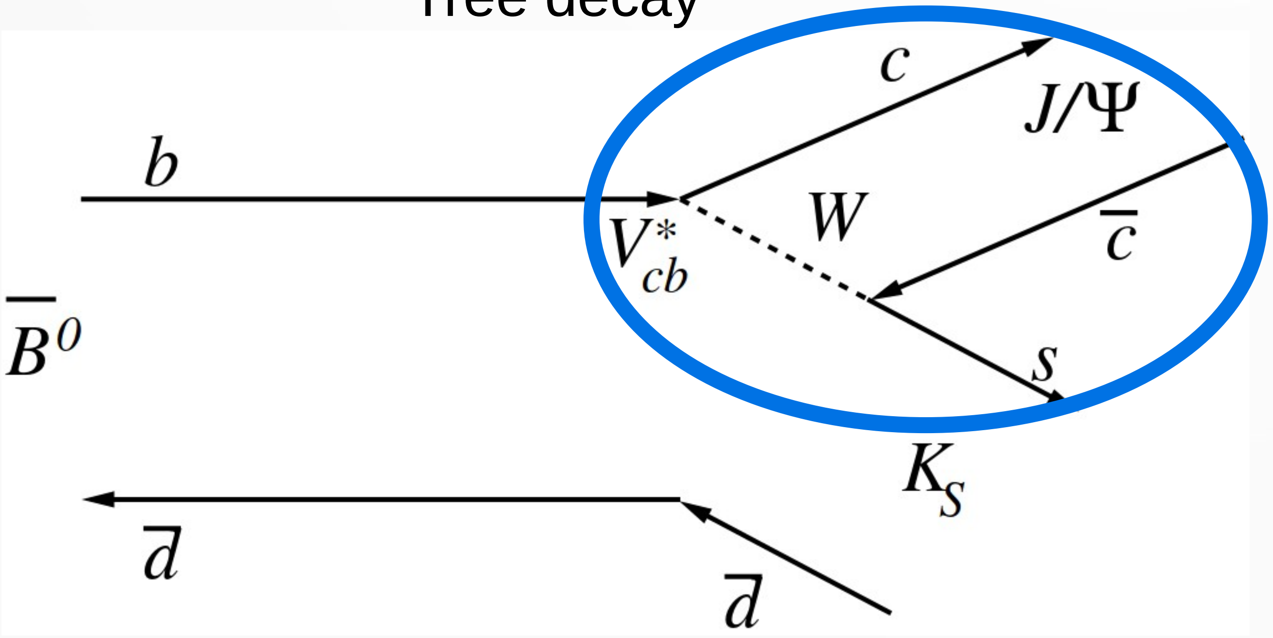

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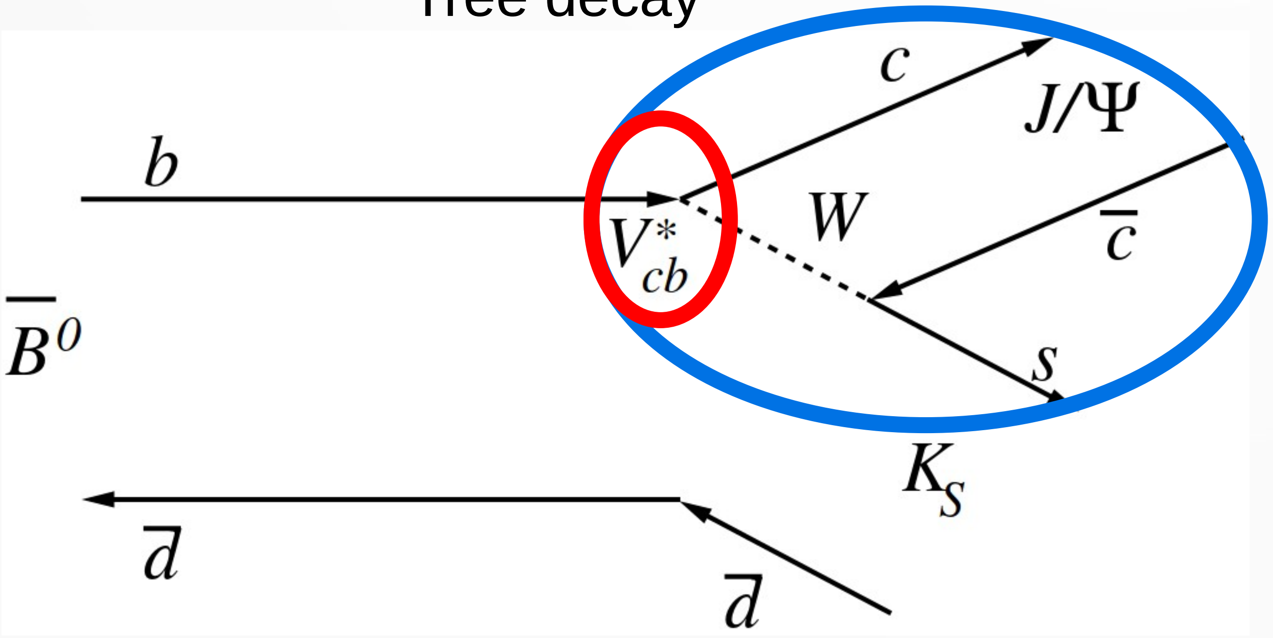

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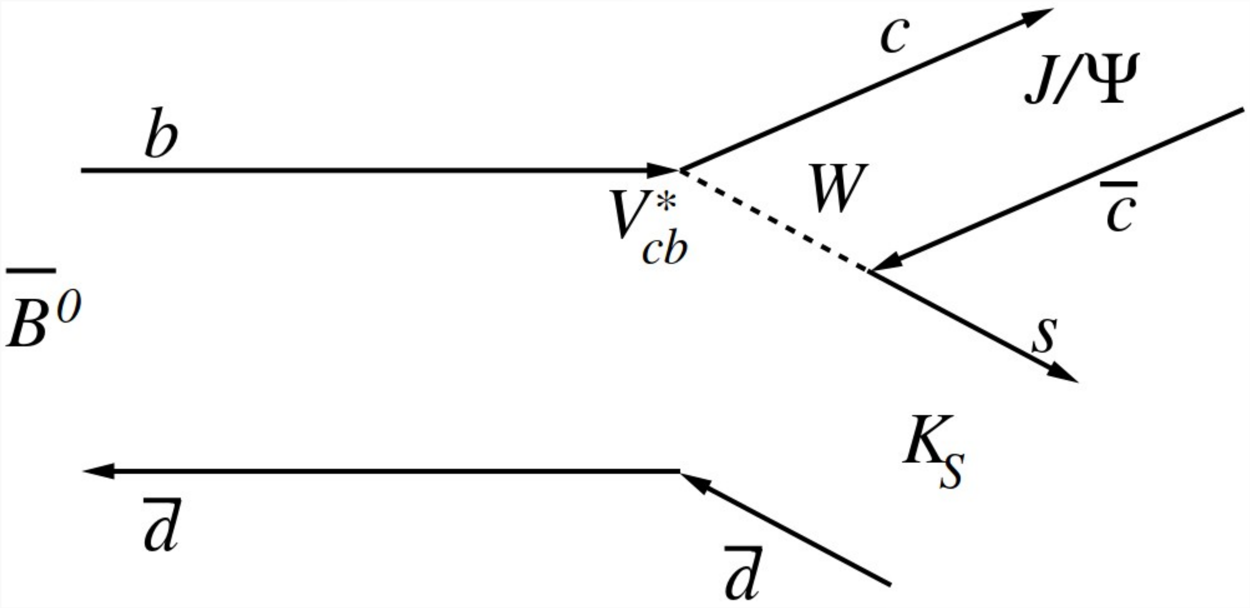
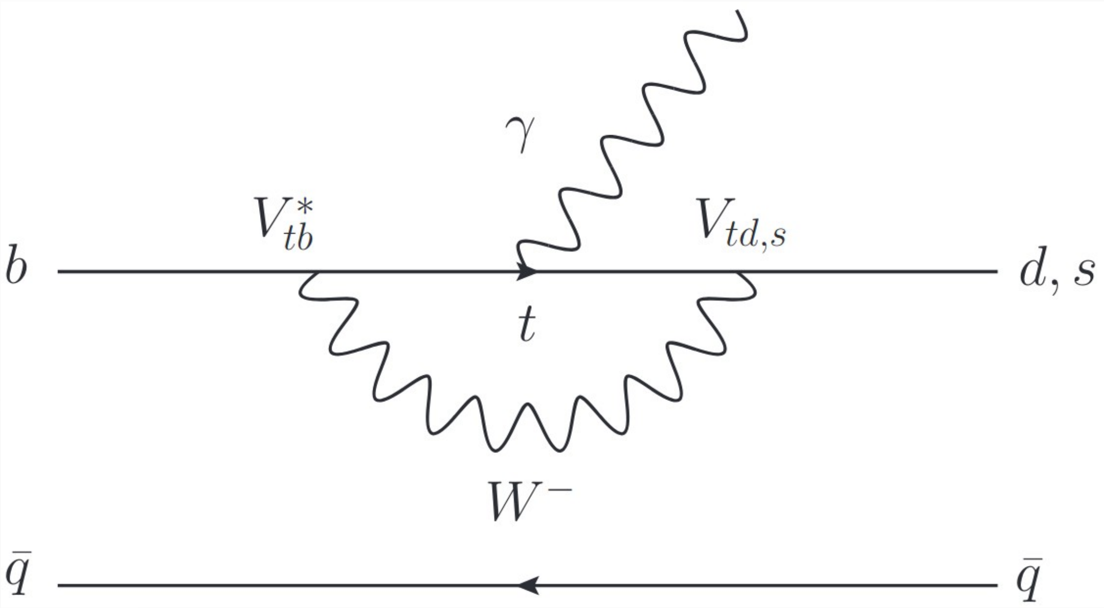
  - Most straight forward process “tree decays”
  - New physics can hide in “loop decays”

Tree decay



https://arxiv.org/pdf/1406.6311

Loop decay

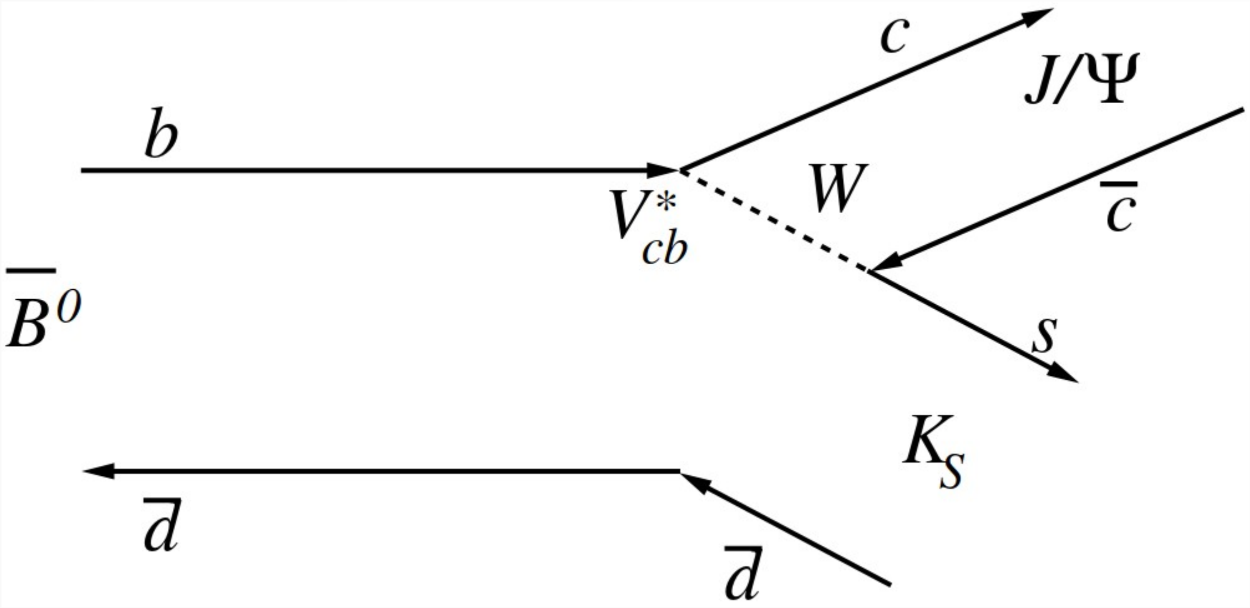


https://arxiv.org/pdf/1406.6311

Flavour physics at Belle II

- B-mesons decay to lighter particles
  - Most straight forward process “tree decays”
  - New physics can hide in “loop decays”

Tree decay



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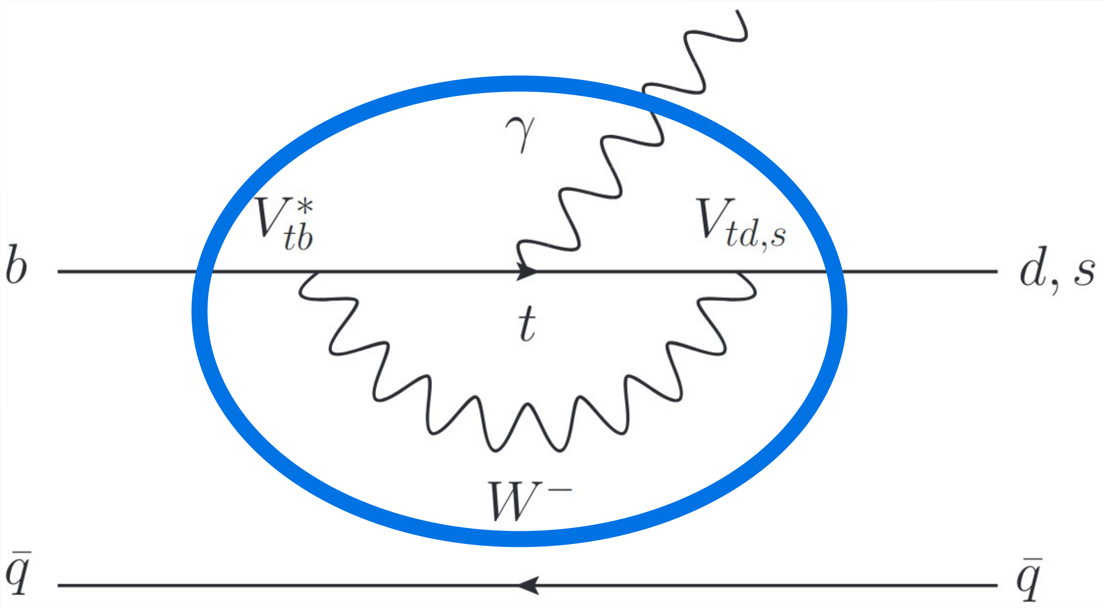
Loop decay



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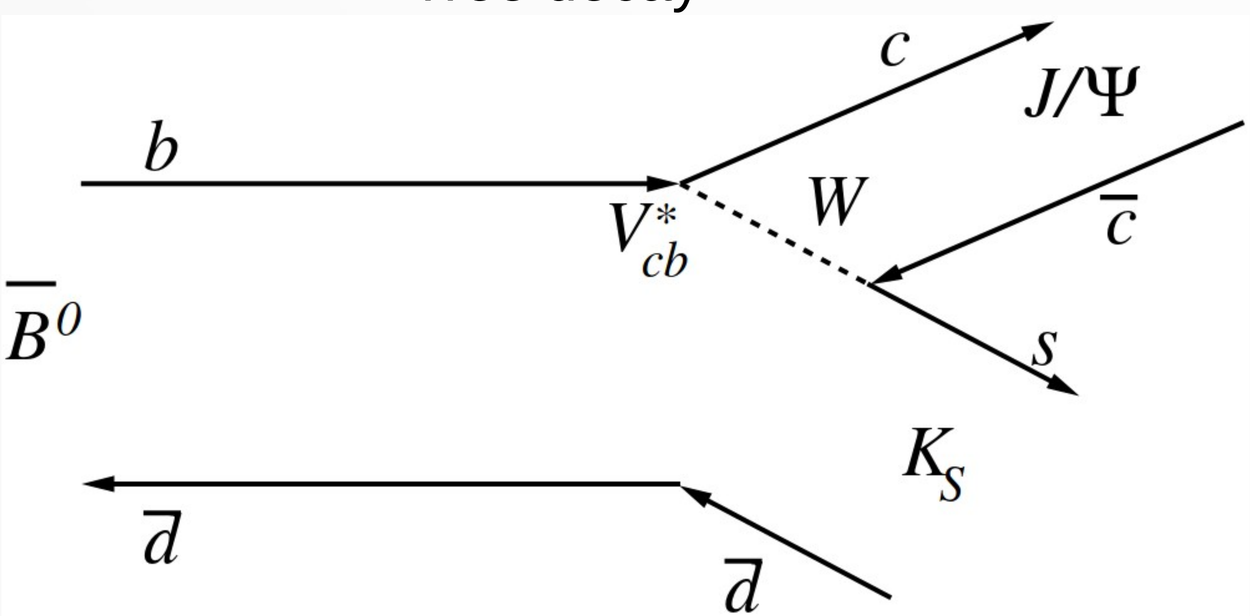
Flavour physics at Belle II

- B-mesons decay to lighter particles
  - Most straight forward process “tree decays”
  - New physics can hide in “loop decays”, e.g. charged Higgs boson

Tree decay



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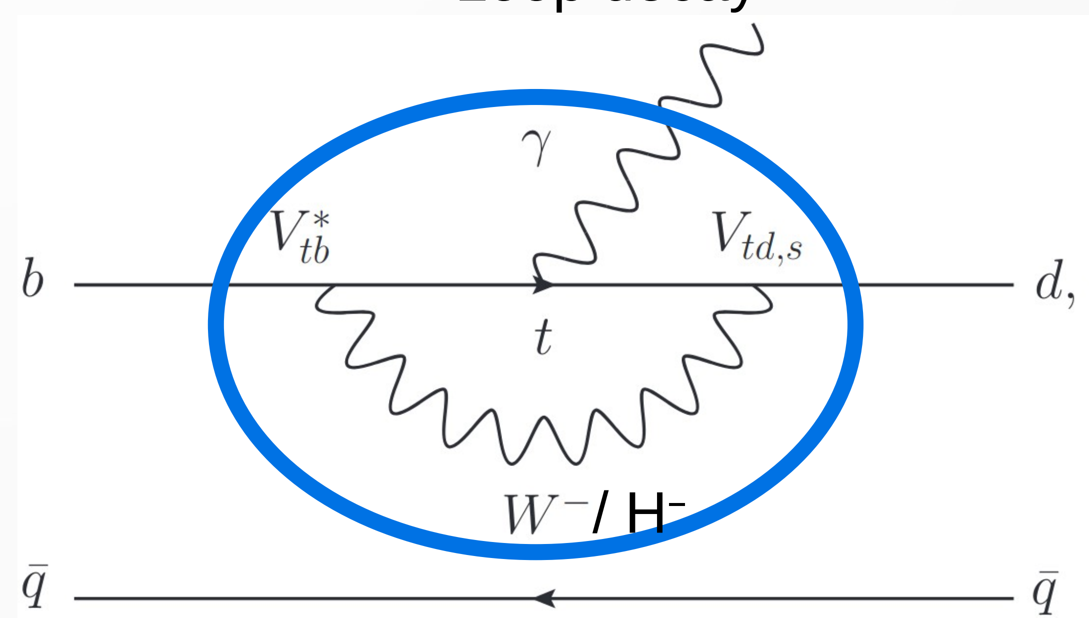
Loop decay



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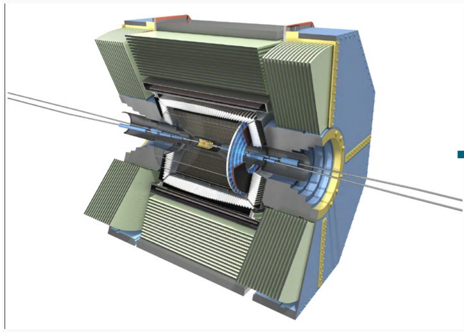
Taking data at high frequencies



Collision every ~4 ns (~250 MHz) → First level trigger (L1) (FPGAs) → Event pre-selection Output ~30 kHz → High level trigger (HLT) (CPU farm) → Final event selection Output O(kHz) O(GB/s) → Storage disk & tape

- Custom made hardware
  - Detecor and readout
- Custom software (C, C++, Python, …)
- Massive employment of FPGAs
- Some LHC numbers for perspective
  - Collisions every 25 ns (40 MHz)
  - First pre-selection on detector level
  - L1 output (FPGA, GPU): O(100 kHz)
  - L2 output (CPU); O(1 kHz)
  - L3 (HLT, CPU) output: O(100 Hz), O(10 GB/s)

Reconstruction and analysis software

- All self-developed over > 10 years
- C++, Python, Fortran
- Compilation only on x86_64 Linux
- Increasing usage of machine learning at all stages
- Heavily relies on external software
  - Usually open source under different licences
  - ROOT developed at CERN
  - Generators for physics processes (most of the Fortran code)
  - Geant4 for detector simulation
  - Many python packages for various purposes

Reconstruction and analysis software

- All self-developed over > 10 years (sometimes > 20-30 years)
- C++, Python, Fortran, Java, Julia, Cuda, …
- Compilation only on x86_64 Linux (might not be true for all)
- Increasing usage of machine learning at all stages
- Heavily relies on external software
  - Usually open source under different licences
  - ROOT developed at CERN
  - Generators for physics processes (most of the Fortran code)
  - Geant4 for detector simulation
  - Many python packages for various purposes

The bigger picture

- All experiments want to get more precise – in all aspects
  - Higher event rates, more granular detectors
    –> Ever higher data rates of O(100 GB/s)
  - Massive impact on trigger systems and software

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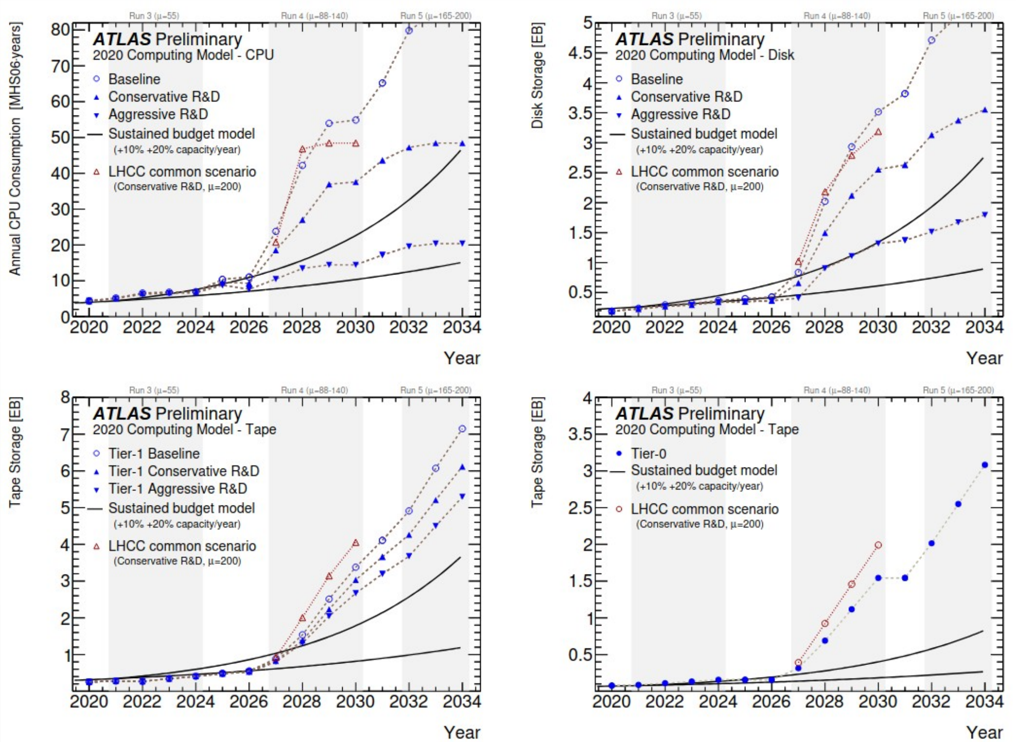
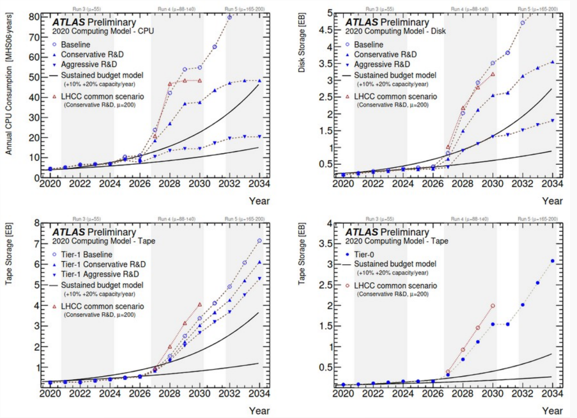


https://cds.cern.ch/record/2729668/files/LHCC-G-178.pdf

The bigger picture

- All experiments want to get more precise – in all aspects
  - Higher event rates, more granular detectors
    –> Ever higher data rates of O(100 GB/s)
  - Massive impact on trigger systems and software
  - Need more simulated data as well
    - Full analysis first done on simulated data before looking into data (“blinded analysis”)
    - Usually need more simulated data than actual data, sometimes 10x
      –> comes on top the computation cost for just reconstruction



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–> Need huge computational infrastructures and very performant and efficient software (CPU **and** memory)

The bigger picture

- Meet the Wordwide LHC Computing Grid (WLCG)
  - Distributed computing system all over the world
  - Dedicated high bandwidth connections between sides
  - 1.4 M cores, 1.5 EB of storage (disk and tape)
  - Used by all big experiments
  - Only possible due to the www – also envisioned at CERN
- Heavy usage of Machine Learining
  - State of the art already in data analysis
  - Growing interest in detector simulation using neural networks
    - Simulation of e.g. calorimeters is very costly
    - Can speed up simulations by orders of magnitude with similar accuracy

WLCG
Worldwide LHC Computing Grid

Summary

- High Energy Physics is more than CERN and the LHC
  - Flavour physics is exciting and can lead to interesting insights
- A lot of research on our very own origin is performed in labs and experiments all around the world
  - Only possible with large collaborations
- We are investigating the core “illegal instructions” of the universe and the standard model
  - Missing antimatter
  - Dark matter and dark energy
- Requires cutting edge technology and software
  - HEP without machine learning would be nearly impossible

Thanks for having me!