Introduction into Particle Physics for Data Scientists

Course Structure

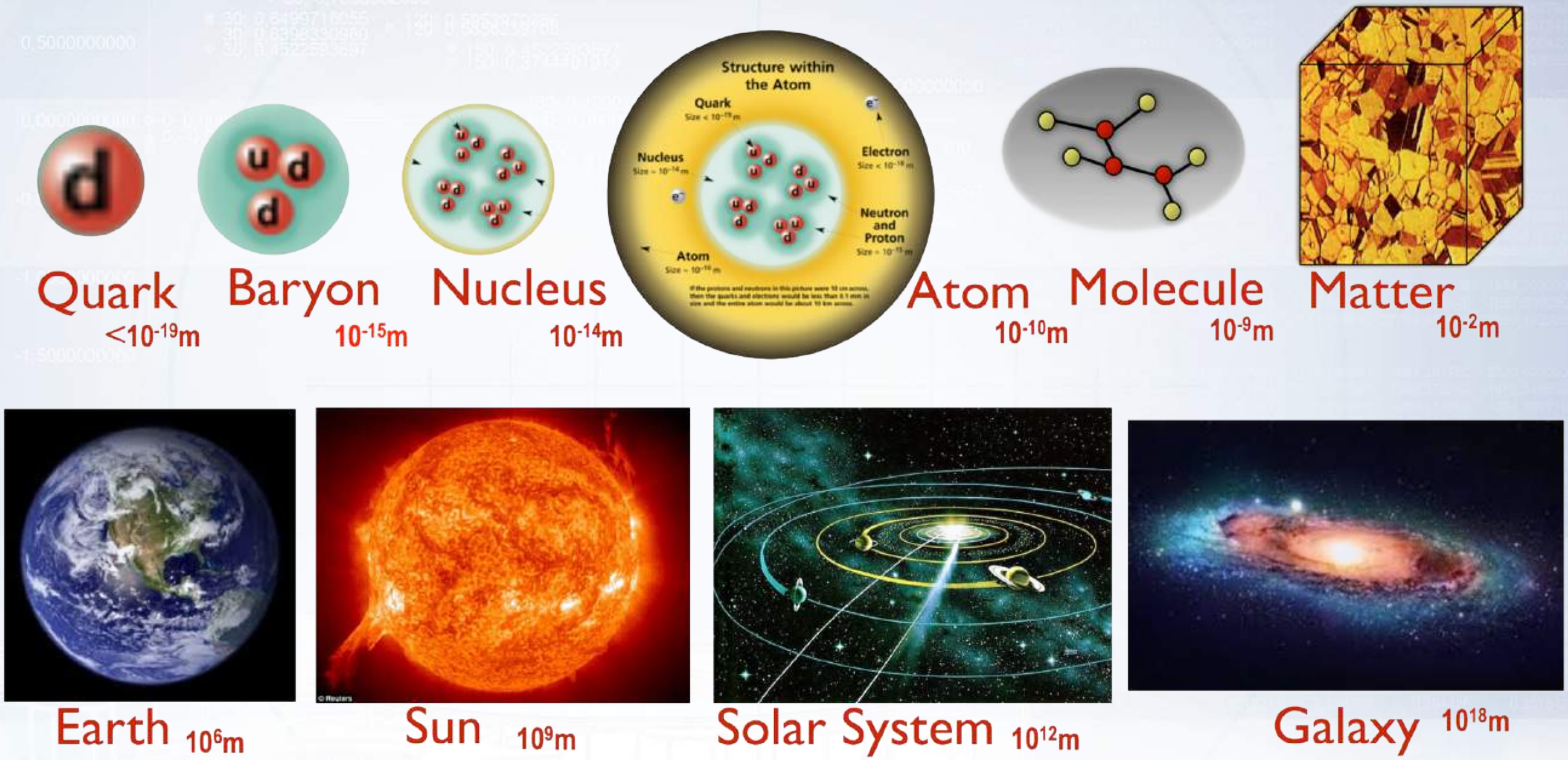
- Introduction. Particle Physics meets Machine Learning (ML). Examples of applications;
- Particle detector structure. Particle identification;
- ML and New Physics search;
- Dark matter search at SHiP experiment;
- Experiment design pptimization.

Why Particle Physics?

- The most fundamental understanding of the Universe;
- Global challenge to the Humanity;
- A lot of puzzles unsolved;
- Requires advanced Machine Learning;
- Source of technologies for everyday life.

Disclaimer: Particle Physics subject is much more complex than described here. We do not guarantee completeness, accuracy or applicability of the information therein to your Particle Physics adventure. The sole reason for the simplifications is to allow for a more prominent Universe picture to emerge that will help you to get engaged in the beautiful journey of the Universe exploration!

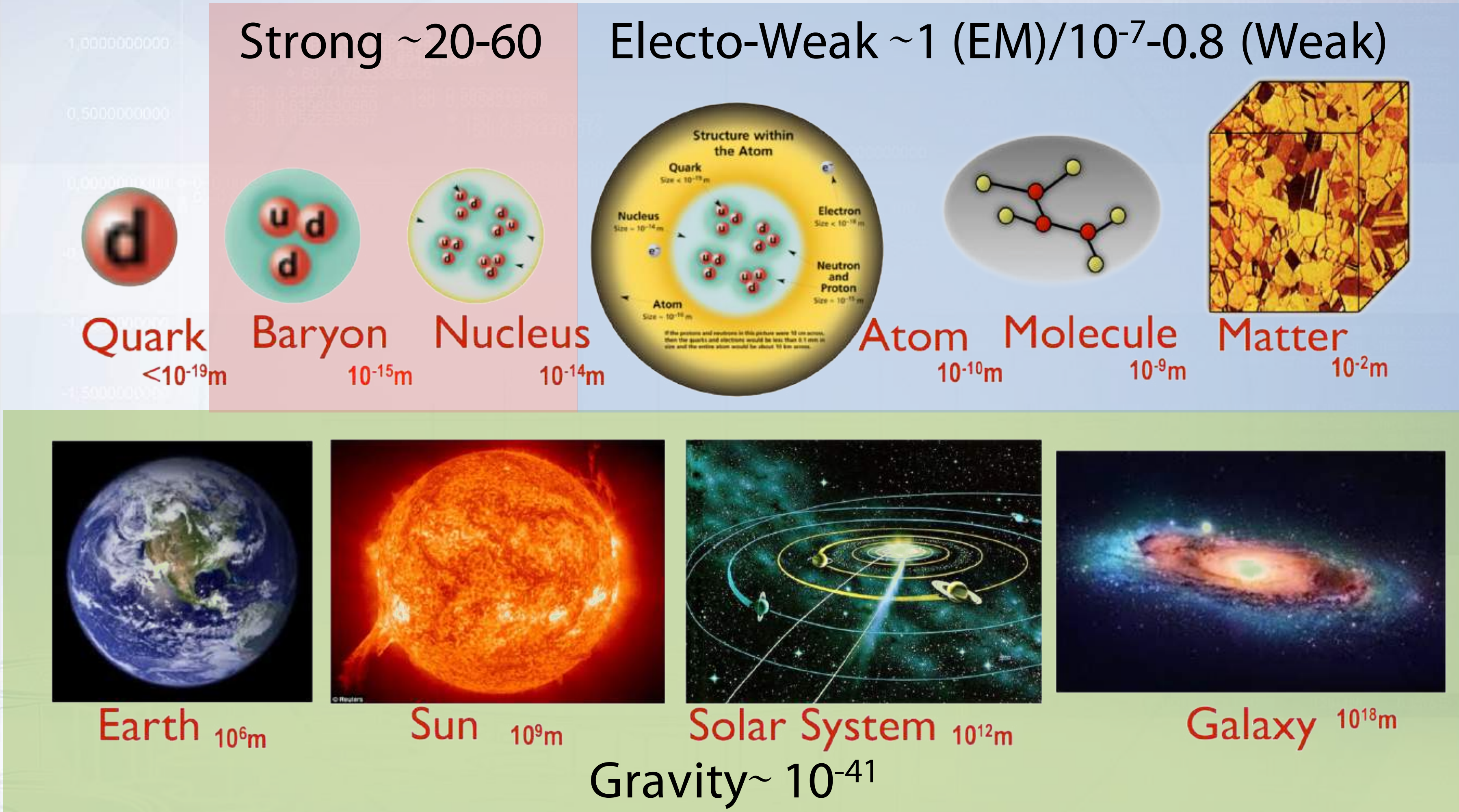
Scales of our Universe



Visible Universe Today is around 10^{27} m

http://bit.ly/2tfxP8I

Scales of our Universe



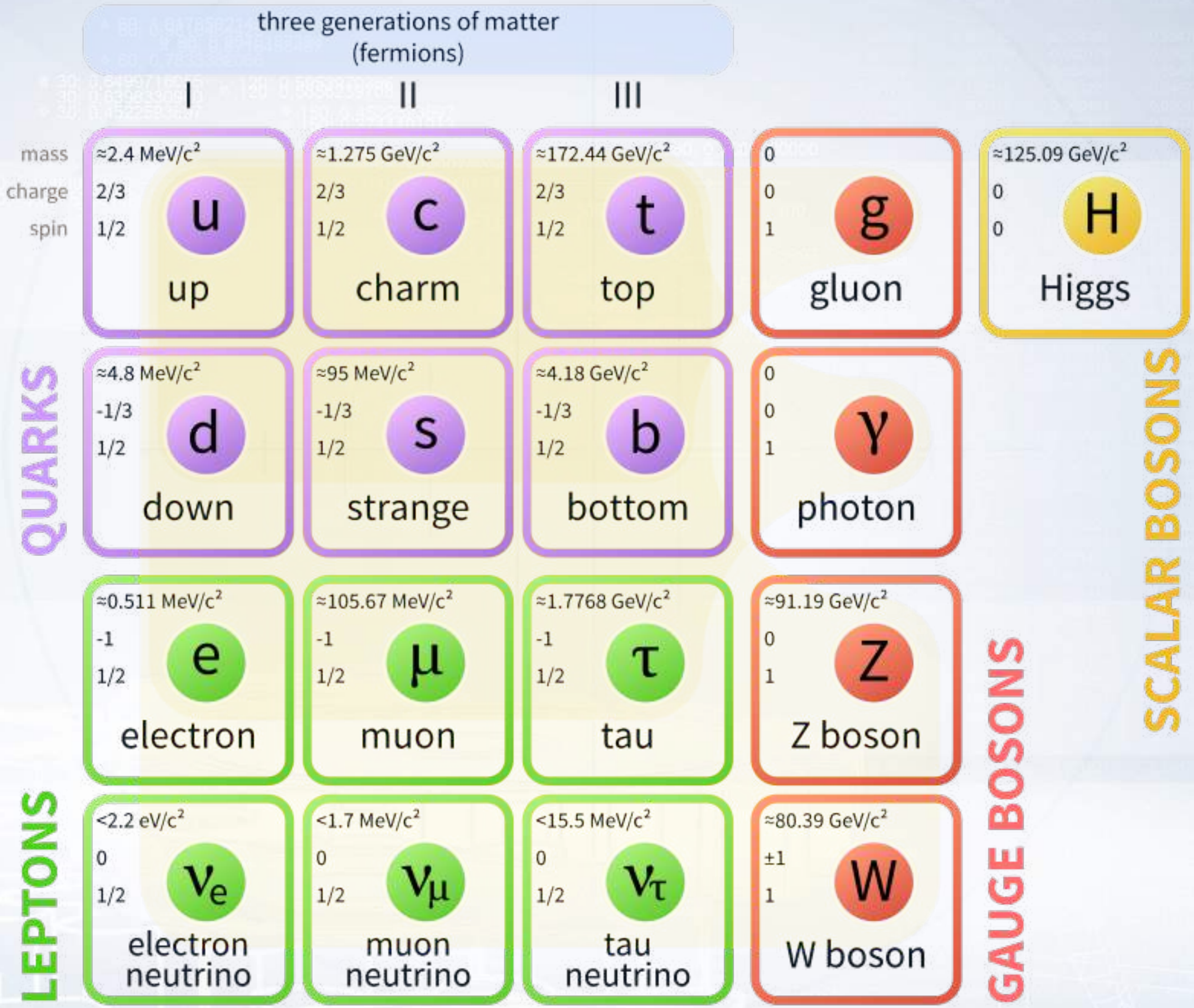
Each "structure" is due to some fundamental force.
The stronger the force the smaller the structure.

http://bit.ly/2tfxP8I

Standard Model (SM) of Elementary Particles

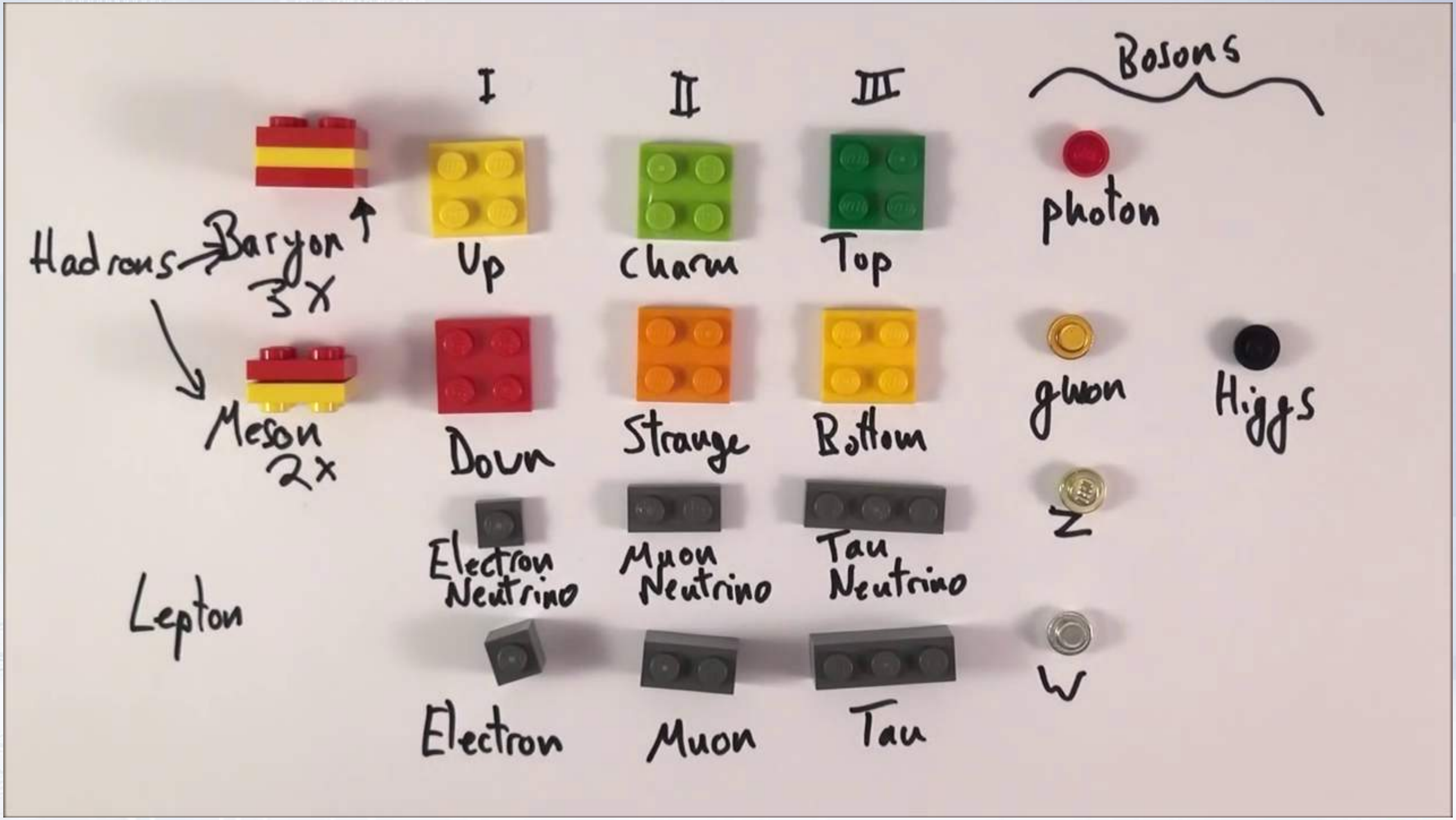
http://bit.ly/2JanWvJ

Standard Model (SM) of Elementary Particles



https://simple.wikipedia.org/wiki/Standard_Model

Standard Model (SM) of Elementary Particles



https://www.youtube.com/watch?v=edgsmtUH954

Standard Model (SM) Shortcomings

- Gravity not included! Why gravity is so much weaker than everything else?
- Why masses of particles differ so massively?
- SM misses great deal of the Universe: No Dark Matter candidate. Can't explain Dark Energy.
- SM requires 19 unrelated and arbitrary parameters (e.g. lepton (electron, muon) masses)...Why these values?
- Also the asymmetry between matter and anti-matter is too negligible according to the SM to explain why we exist!

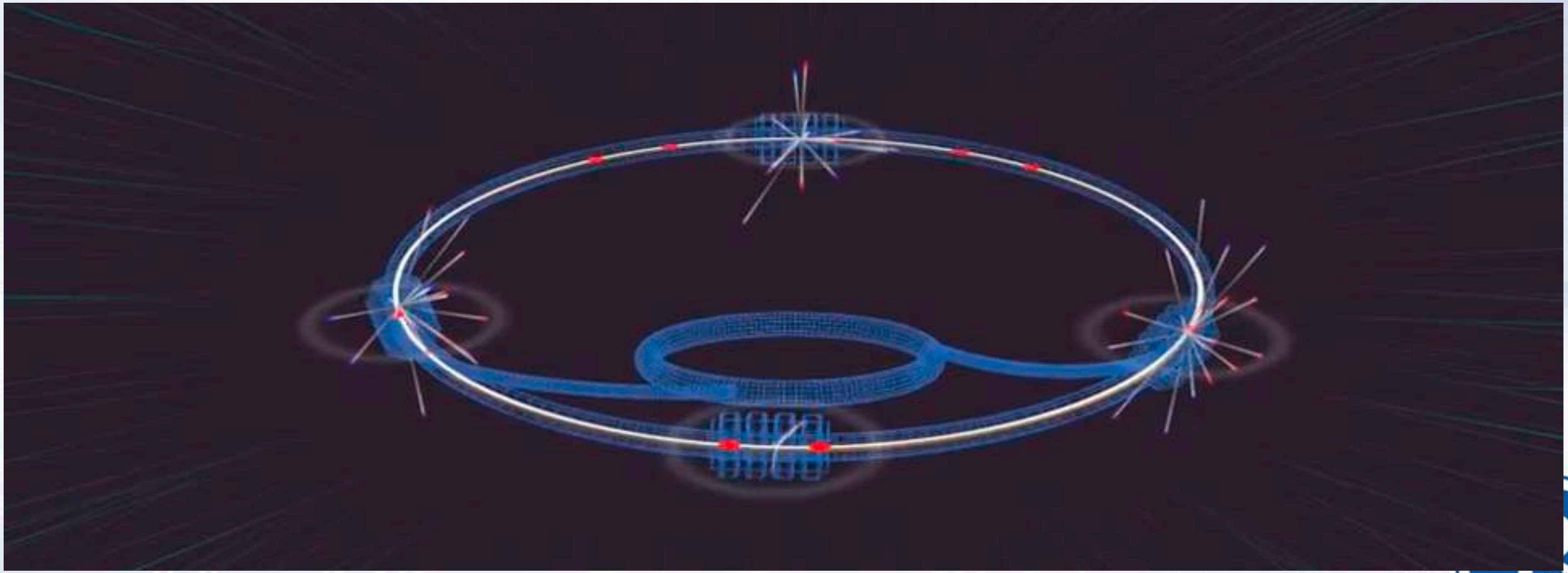
Experimental Particle Physics

CERN

- The world largest international laboratory
- More than 20 experiments – international collaborations
- Birthplace of the WWW
- Large Hadron Collider – arena for the Universe models contest

ABC of LHC

- 27 km-long tunnel, 50-175 meters deep
- Proton speed: 0,99999999 c
- Total collision Energy: up to 14 TeV
- 4 “big” detectors: ALICE, ATLAS, CMS, LHCb
- 40 mln bunch collisions per second
- Tens of petabytes of data per year

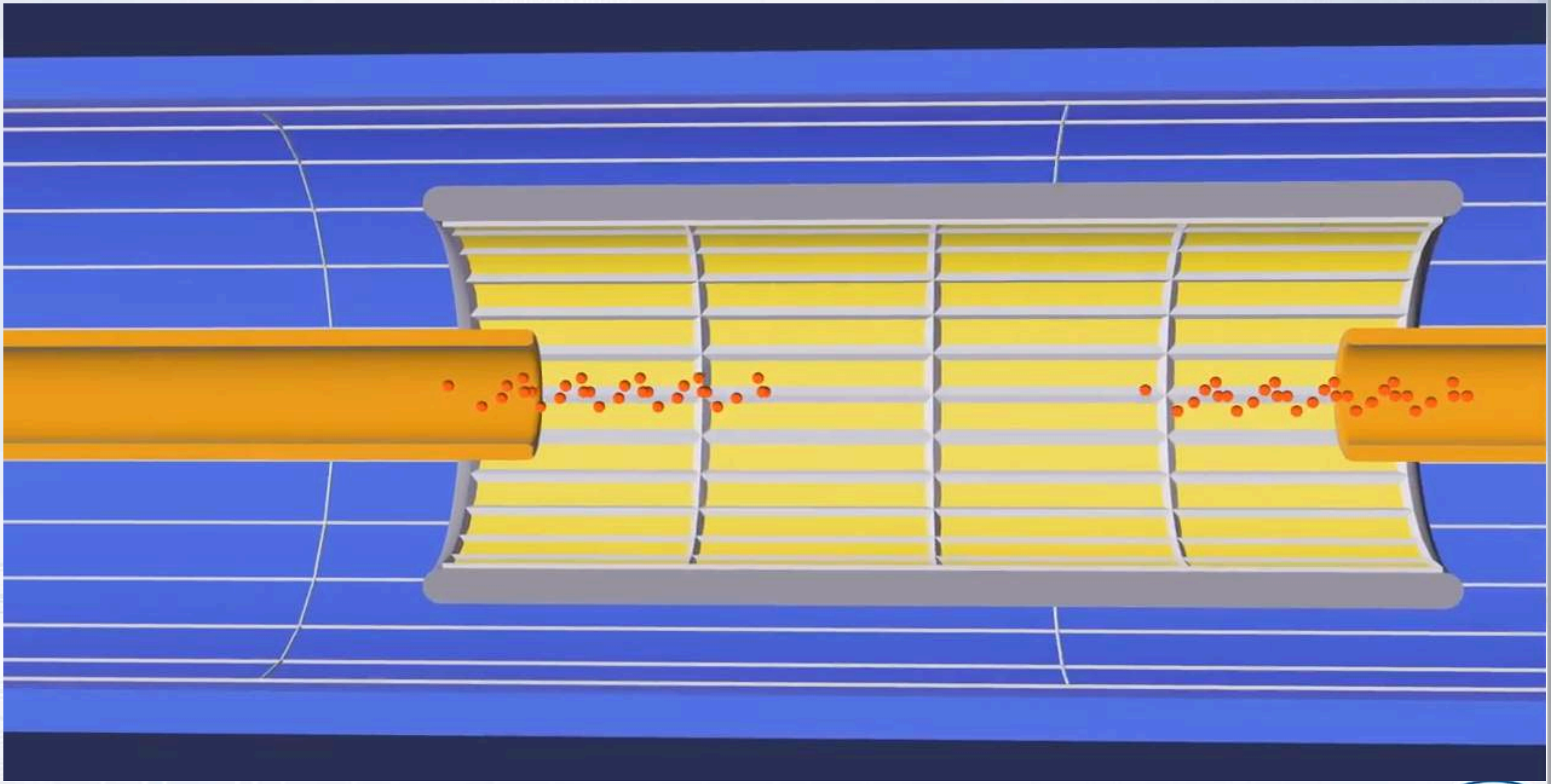


PostScience/https://postnauka.ru/animate/83458

Main stages

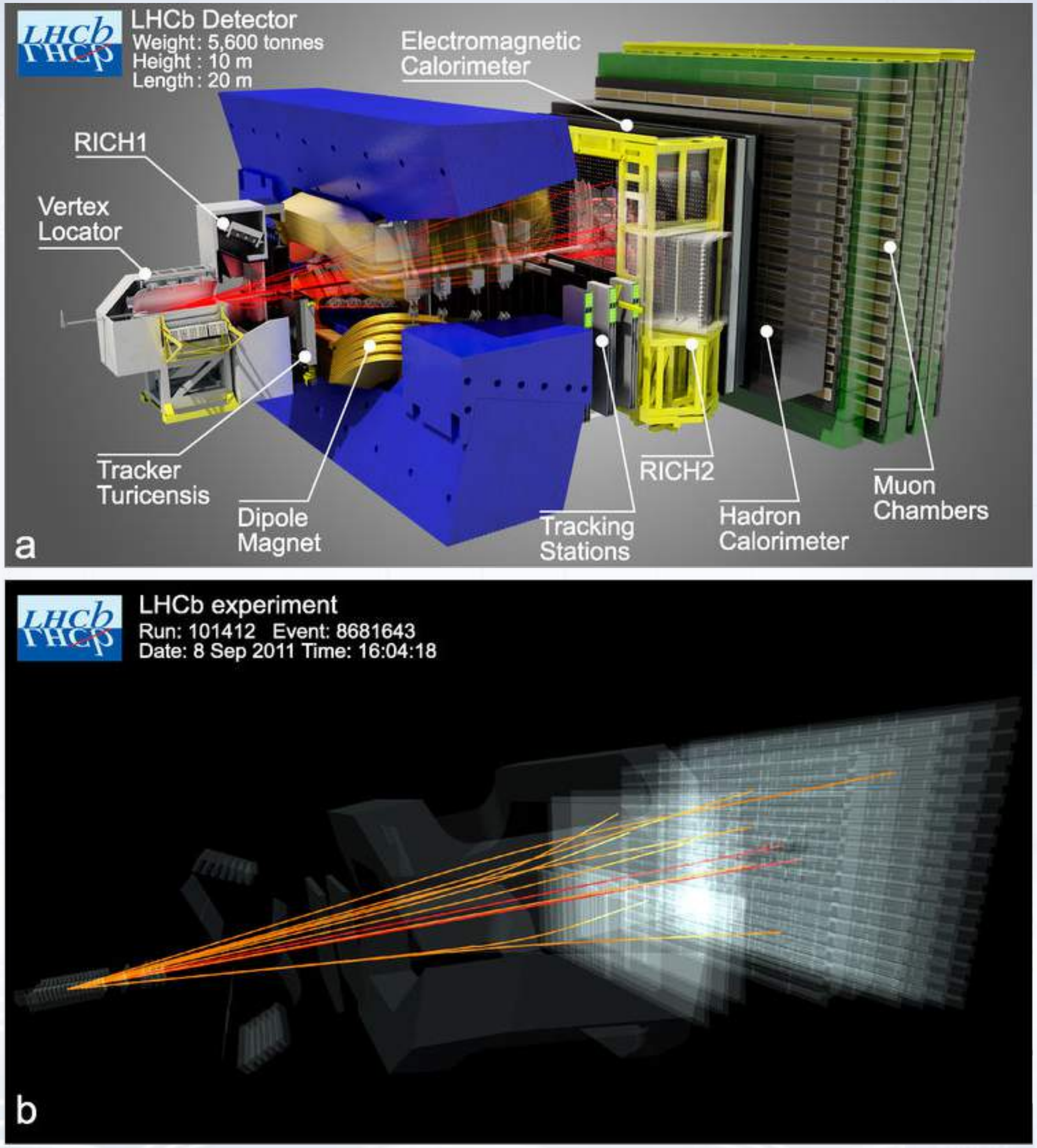
- Create protons out of Hydrogen, accelerate to 0,99999999 c
- Smash bunches of protons (‘*events*’)
- Convert raw detector information into ‘*hits*’ (pixels)
- Reconstruct particle trajectories – ‘*tracks*’, ‘*jets*’, ‘*showers*’
- Identify types of particles
- Reconstruct decay structure
- Filter meaningful events
- Analyse statistical properties

Smashing Protons



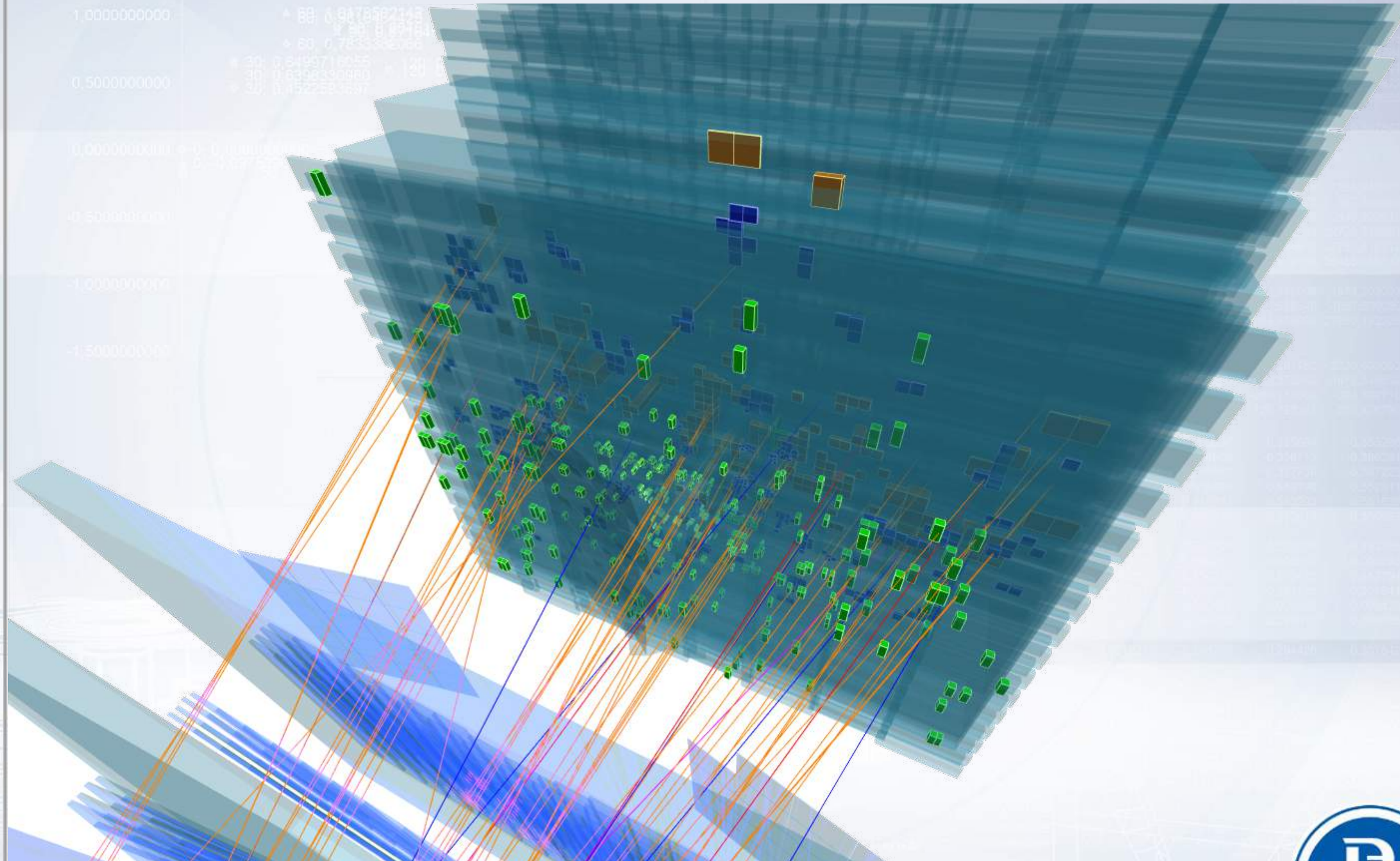
PostScience/https://postnauka.ru/animate/83458

Detector: Sub-atomic Digital Camera

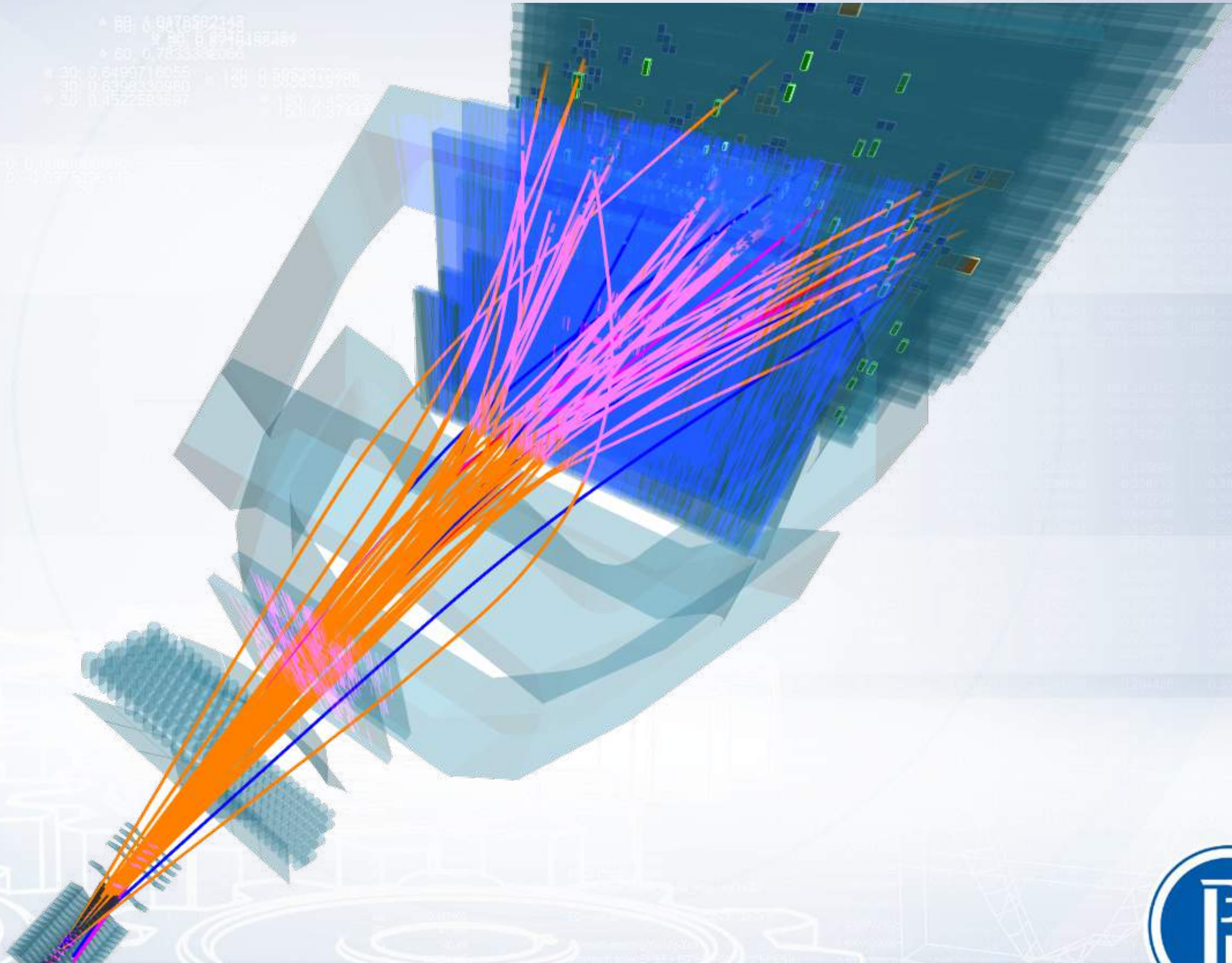


http://go.nature.com/2prxxGY

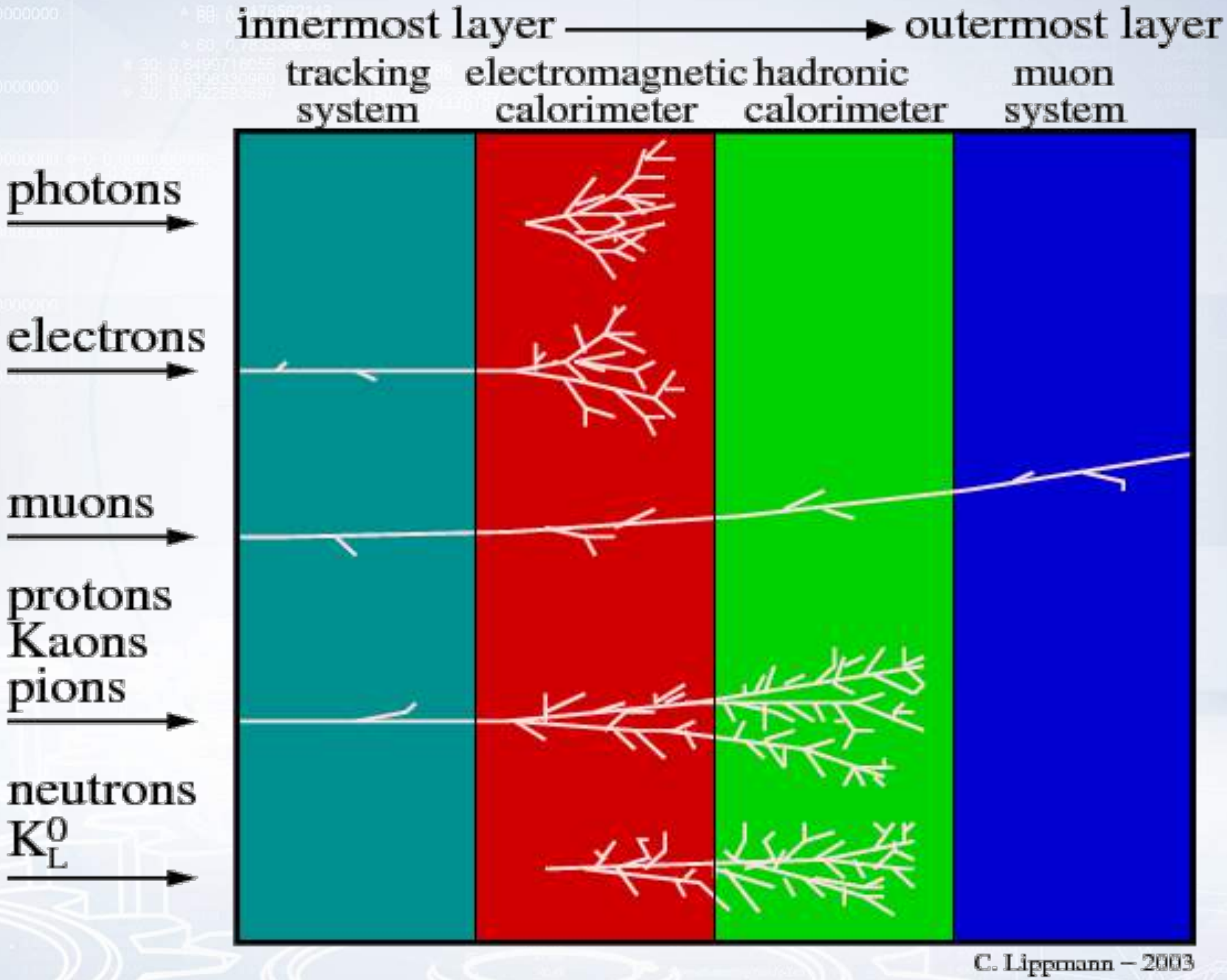
Pixels



Tracks

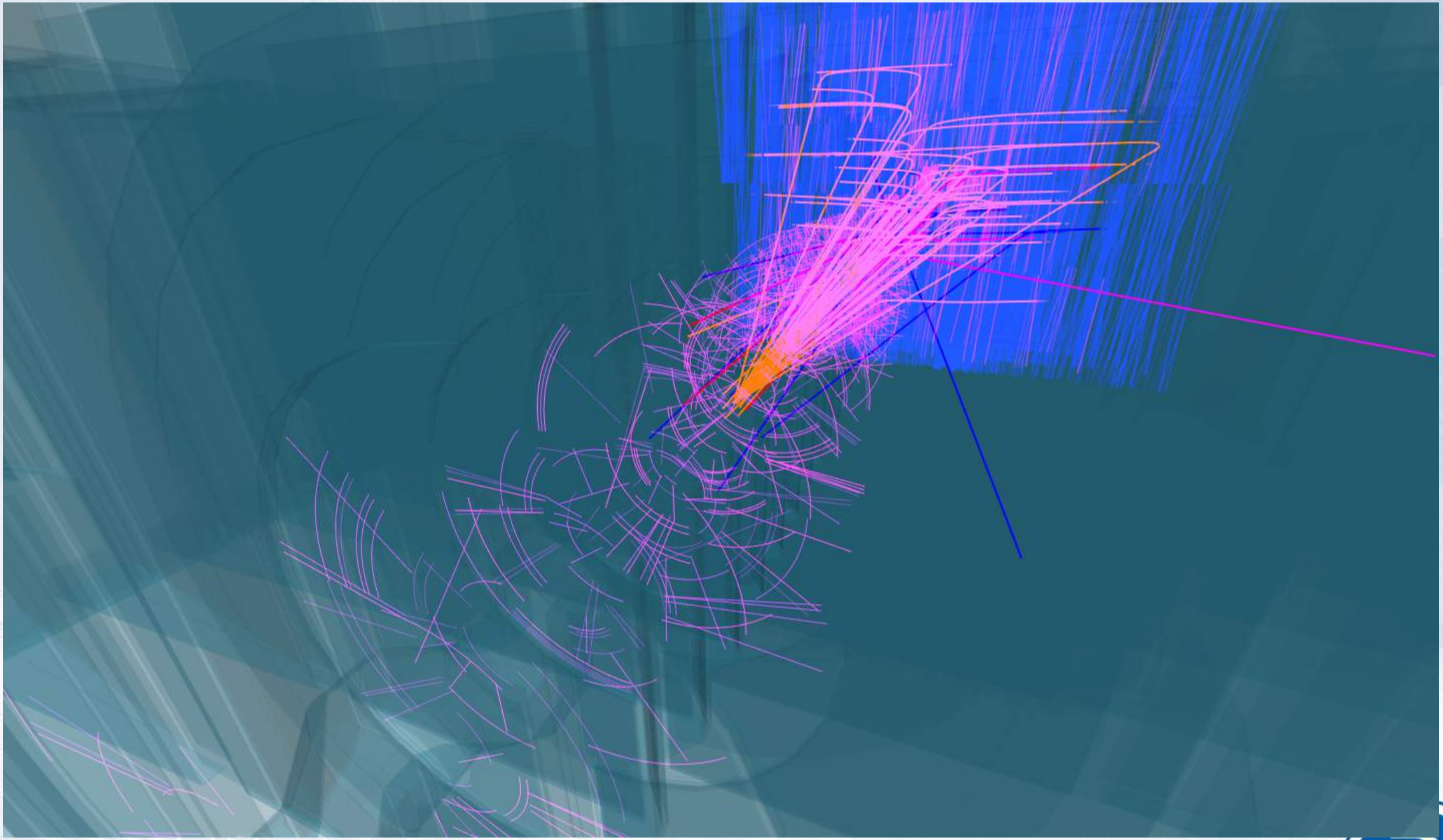


Particle Identification

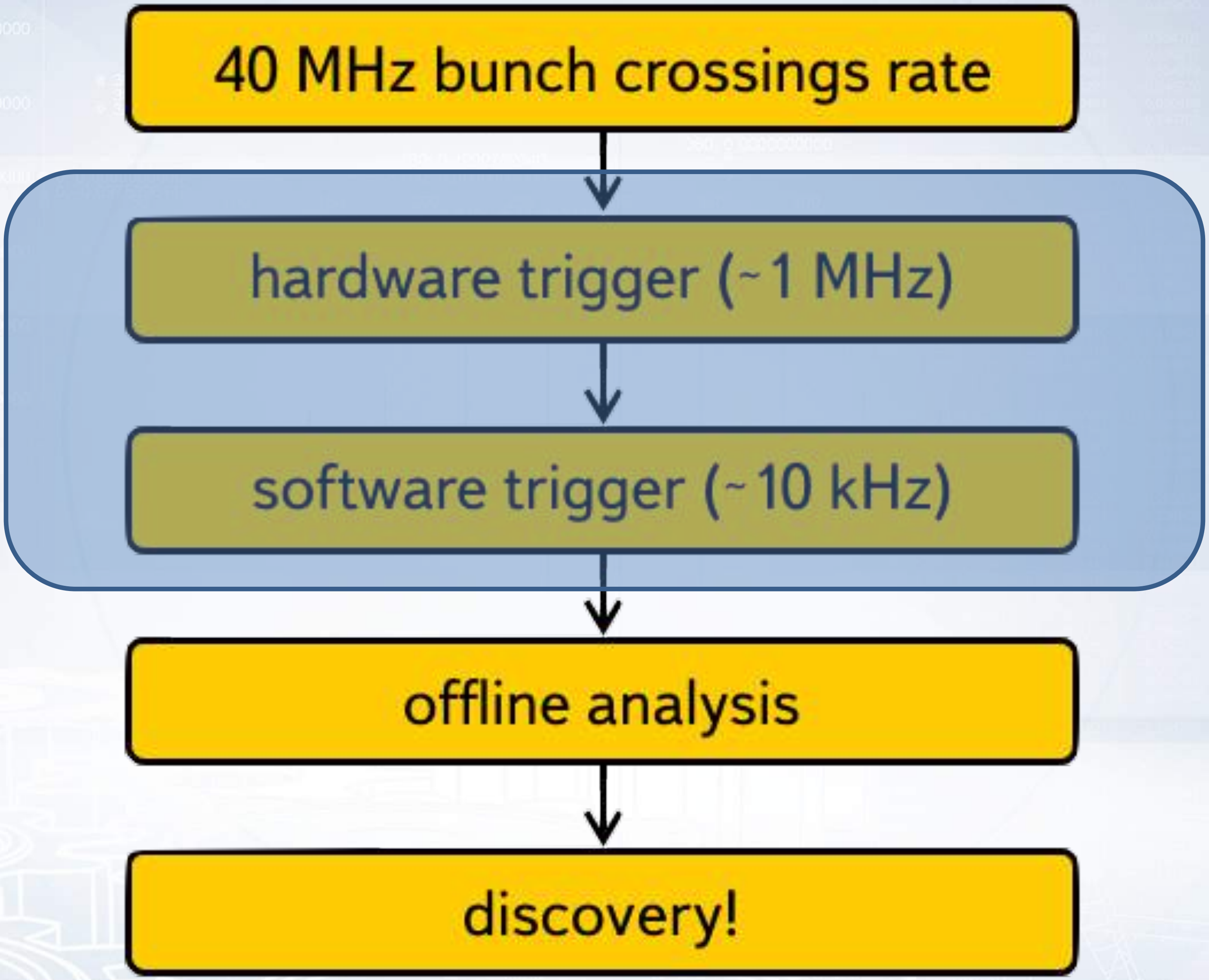


Lippmann / https://inspirehep.net/record/884672/plots

Decay Recostruction



Triggers


40 MHz bunch crossings rate
hardware trigger (~1 MHz)
software trigger (~10 kHz)
offline analysis
discovery!

How CERN Works

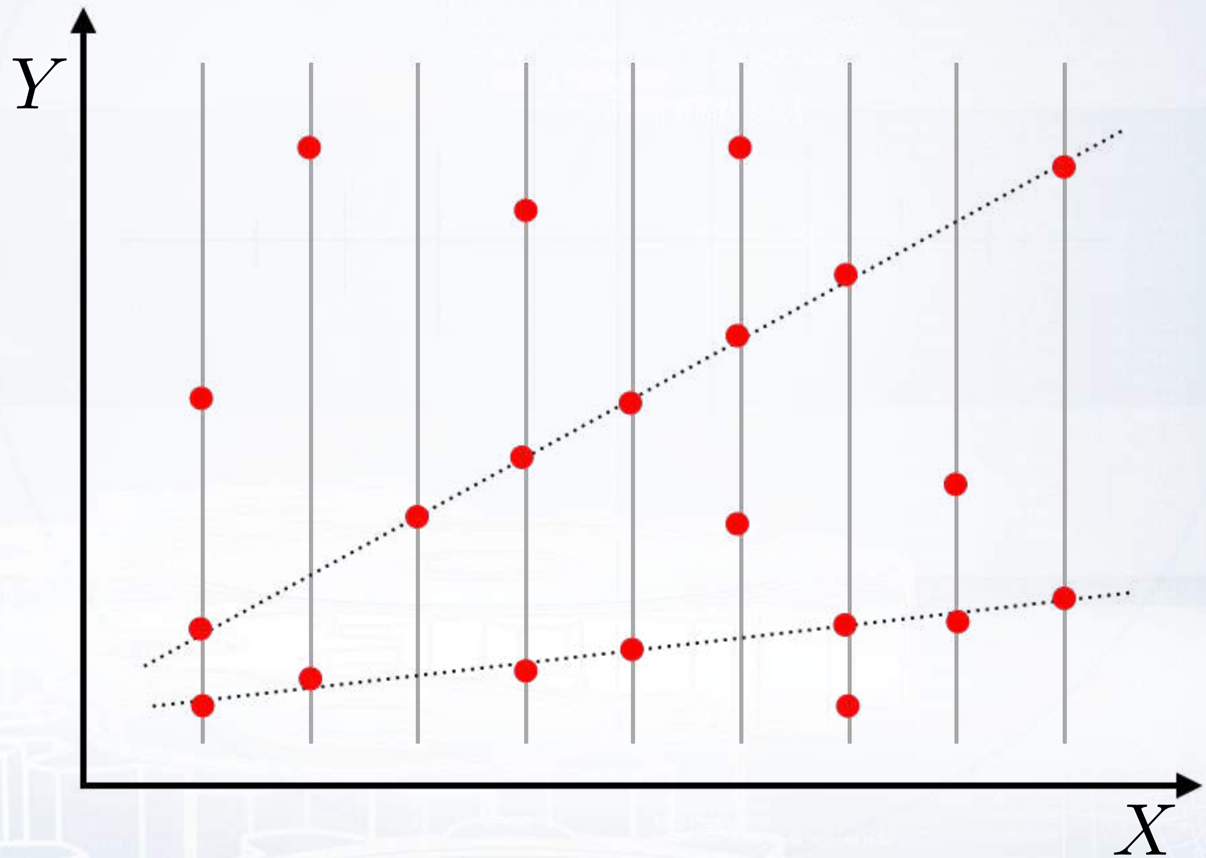
https://videos.cern.ch/record/2020780

Machine Learning Challenges

- **Precise and fast particle tracking:**
  - **single tracks, shower,** jets.
- **Particle identification;**
- Fast and accurate online data processing and filtering;
- Anomaly detection:
  - data quality monitoring;
  - infrastructure monitoring.
- **Detector design optimization (bayesian optimization, surrogate modelling).**

Tracking Example

- For a given set of hits recognize particle tracks of certain shapes: straight lines, circles, etc.



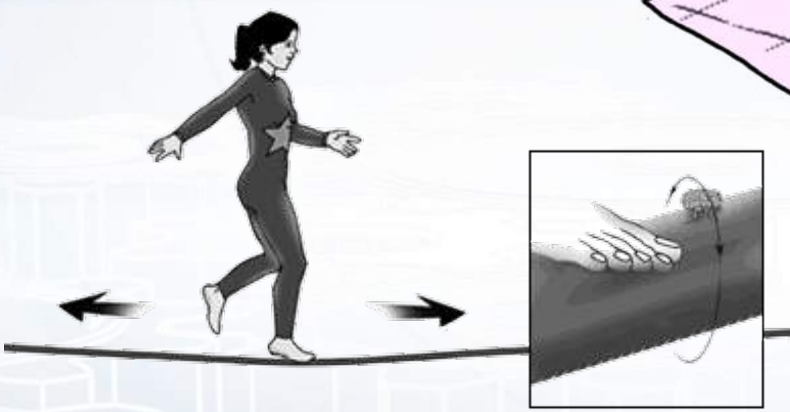
- Estimate the tracks parameters

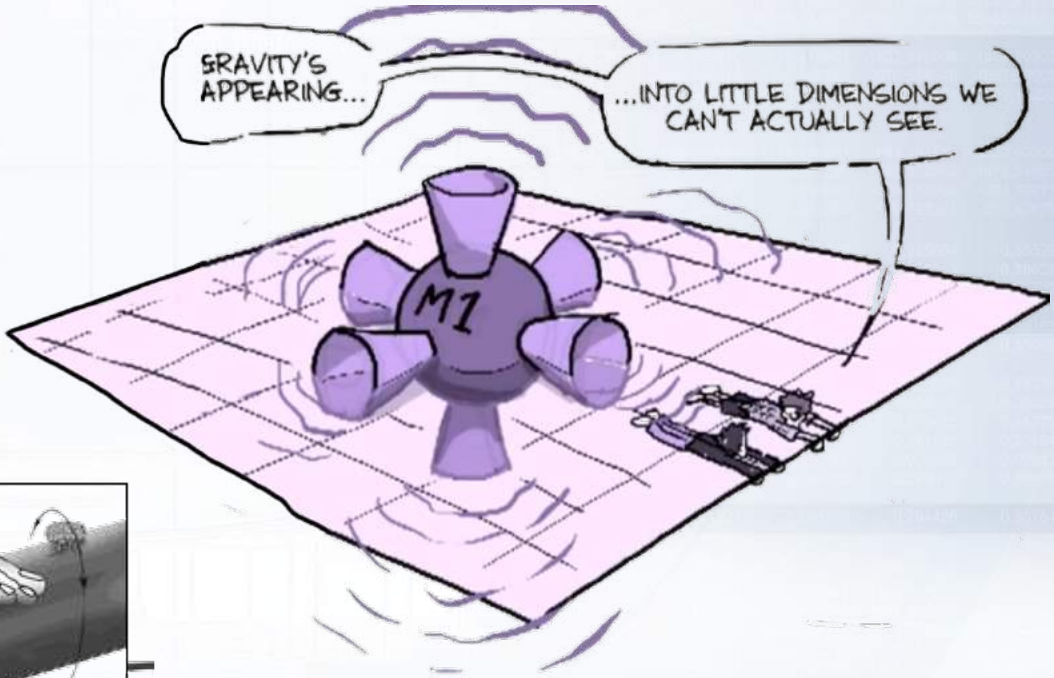
Testing Hypotheses Experimentally

Extra Dimensions

Why is gravity so much weaker than the other forces?

- Large Extra Dimension (LED models)
- Graviton
- Micro black-holes



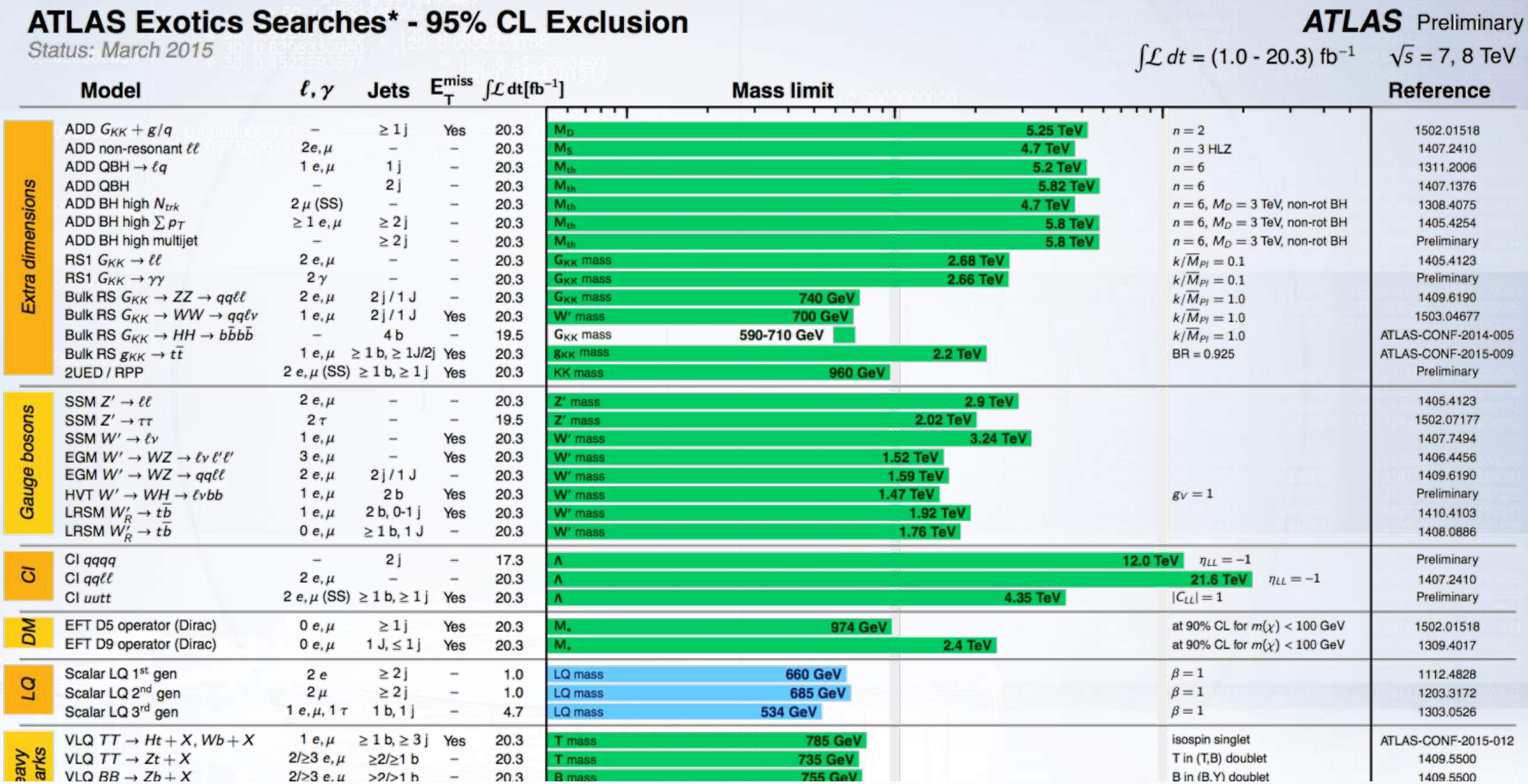


https://www.youtube.com/watch?v=BMvT2sriq34

- <blah blah про атлета>
- Each decay happens with own probability (*branching ratio*), but
- different theories may give different predictions for it, thus
- measuring actual value is a good key for theory discrimination.

ТЕХНИЧЕСКИЙ СЛАЙД

Theory Graveyard



ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2015

ATLAS Preliminary

$\int\mathcal{L}\,dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

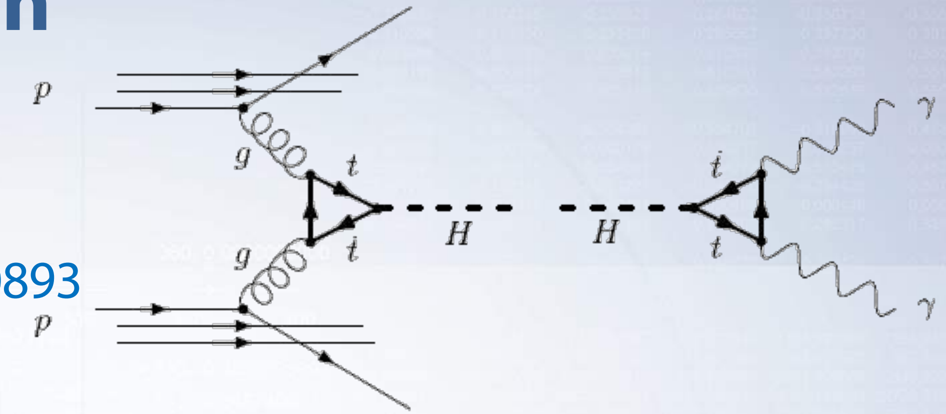
	Model	ℓ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	M_D 5.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	2e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH → ℓq	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	Preliminary
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	Preliminary
	Bulk RS $G_{KK} \to ZZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass 740 GeV	$k/\overline{M}_{Pl} = 1.0$	1409.6190
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	2 j / 1 J	Yes	20.3	W′ mass 700 GeV	$k/\overline{M}_{Pl} = 1.0$	1503.04677
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	ATLAS-CONF-2015-009
	2UED / RPP	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass 960 GeV		Preliminary
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	20.3	Z′ mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z′ mass 2.02 TeV		1502.07177
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	20.3	W′ mass 3.24 TeV		1407.7494
	EGM $W' \to WZ \to \ell\nu\,\ell'\ell'$	3 e, μ	–	Yes	20.3	W′ mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W′ mass 1.59 TeV		1409.6190
	HVT $W' \to WH \to \ell\nu bb$	1 e, μ	2 b	Yes	20.3	W′ mass 1.47 TeV	$g_V = 1$	Preliminary
	LRSM $W'_R \to t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	20.3	W′ mass 1.92 TeV		1410.4103
	LRSM $W'_R \to t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W′ mass 1.76 TeV		1408.0886
CI	CI qqqq	–	2 j	–	17.3	Λ 12.0 TeV	$\eta_{LL} = -1$	Preliminary
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	1407.2410
	CI uutt	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.35 TeV	$\lvert C_{LL}\rvert = 1$	Preliminary
DM	EFT D5 operator (Dirac)	0 e, μ	≥ 1 j	Yes	20.3	M* 974 GeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	M* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	1 e, μ, 1 τ	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	VLQ $TT \to Ht + X, Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	T mass 785 GeV	isospin singlet	ATLAS-CONF-2015-012
	VLQ $TT \to Zt + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	T mass 735 GeV	T in (T,B) doublet	1409.5500
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500

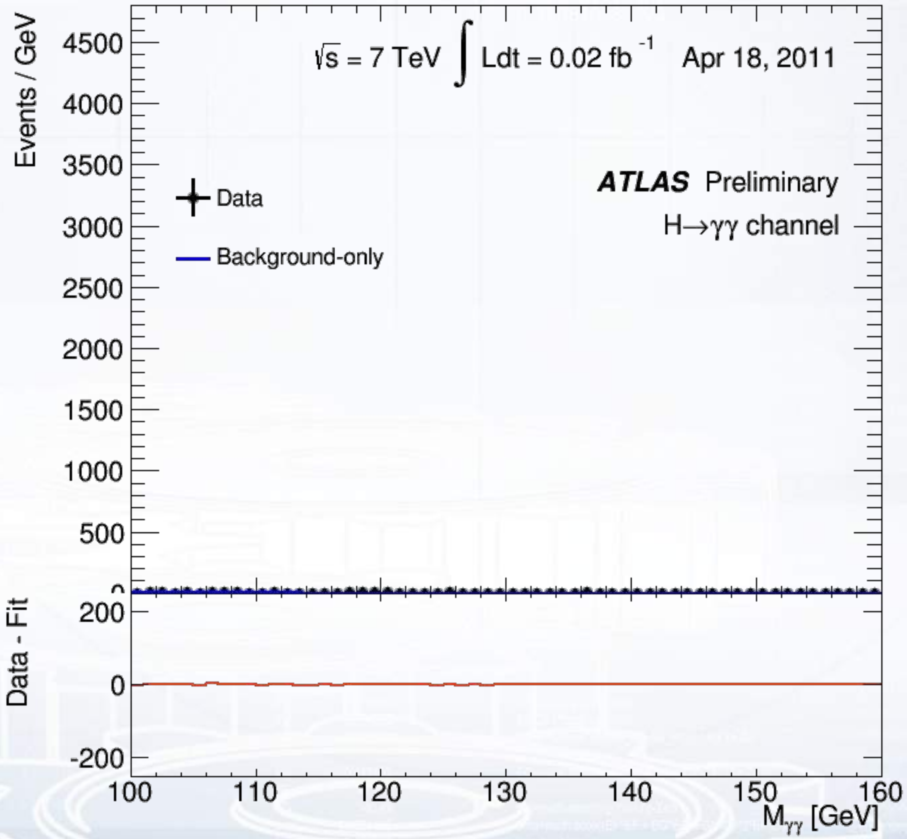
QFTHEP2015/ http://bit.ly/2FkadnH

Looking for Higgs Boson

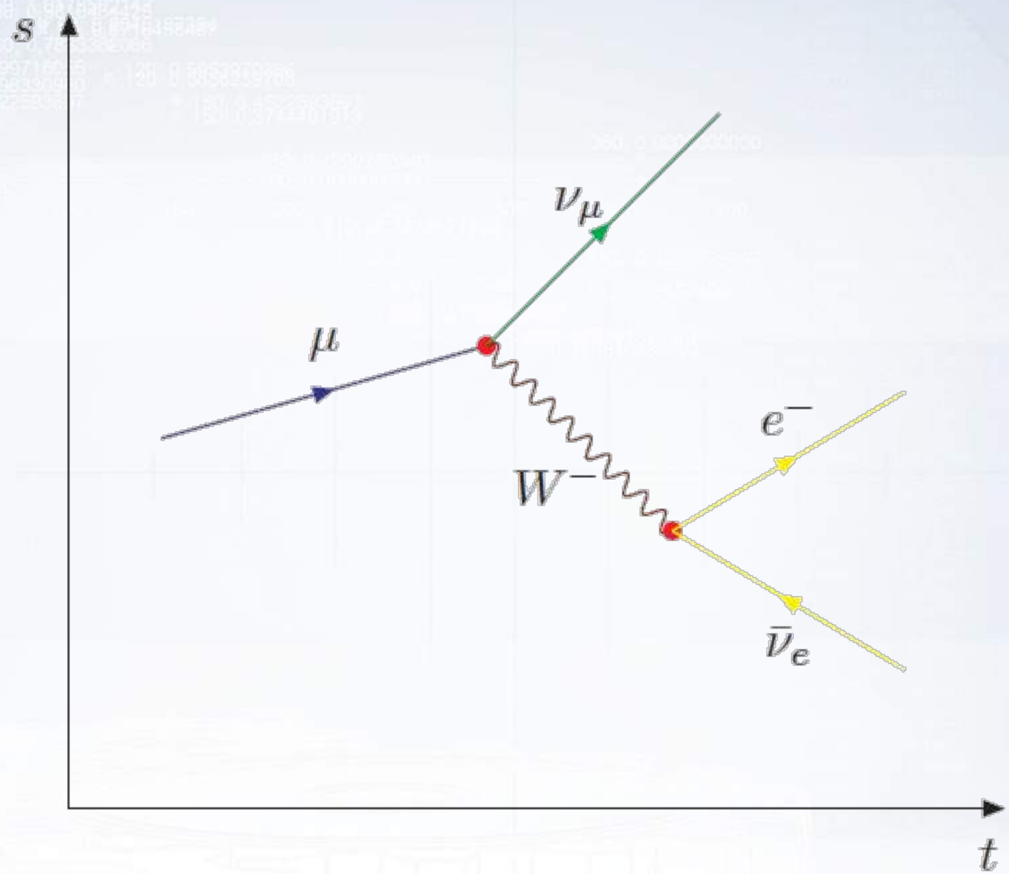
Looking for: $H \rightarrow \gamma\gamma$

https://cds.cern.ch/record/2230893





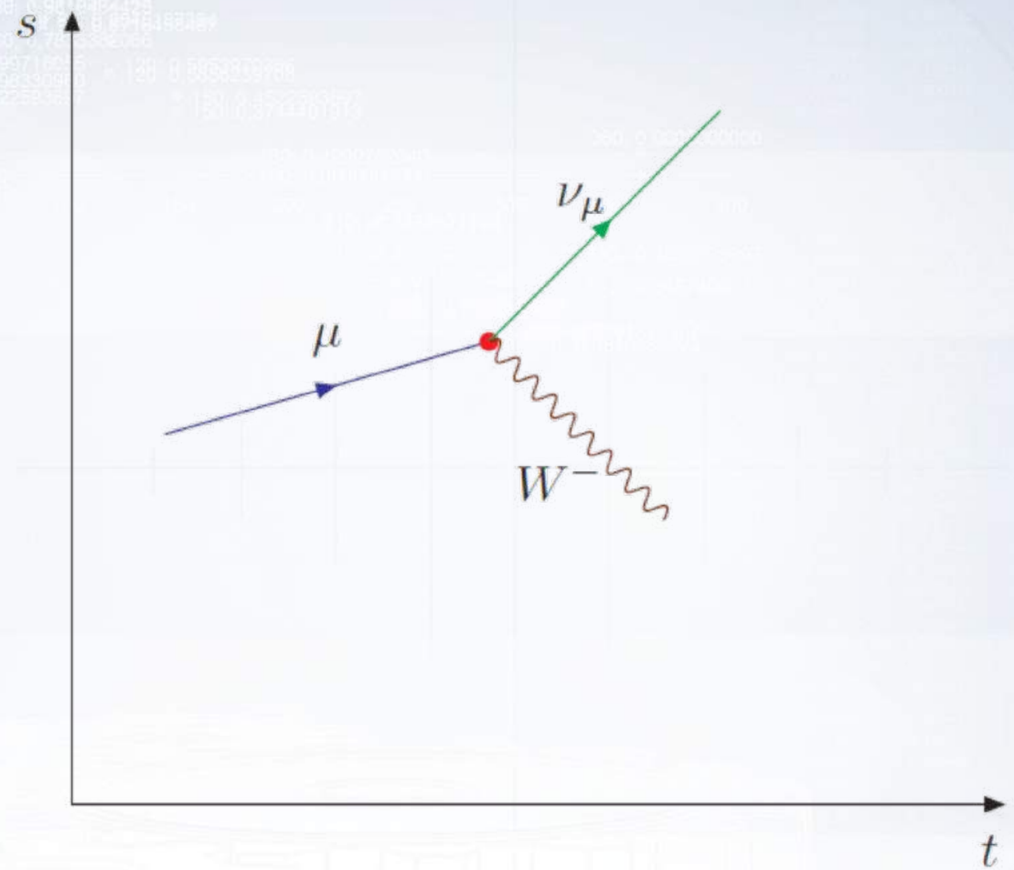
Feynman Diagrams Detour



Decay of a muon into a W^- particle and a muon neutrino

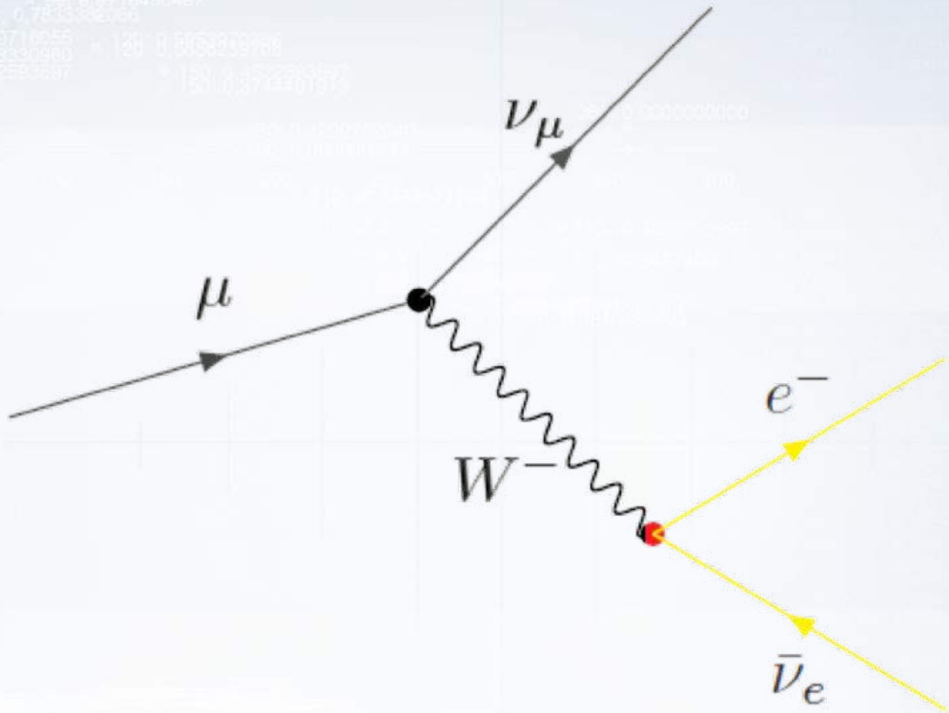
$$\mu \to \nu_\mu W^- \to e^- \bar{\nu}_e$$

Feynman Diagrams Detour



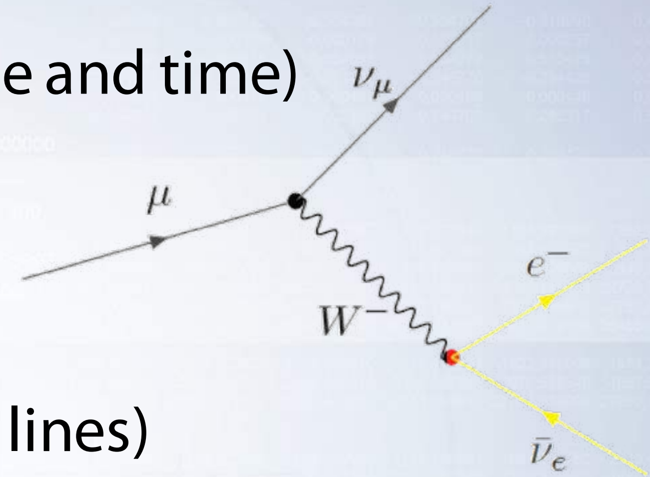
Interaction points are represented by vertices (red). It also mark places where charge, momentum and energy conservation must be valid

Feynman Diagrams Detour



The second vertex shows the creation of particles. Here, the W particle transofrms into an electron and an electron anti-neutrino.

Feynman Diagrams Detour

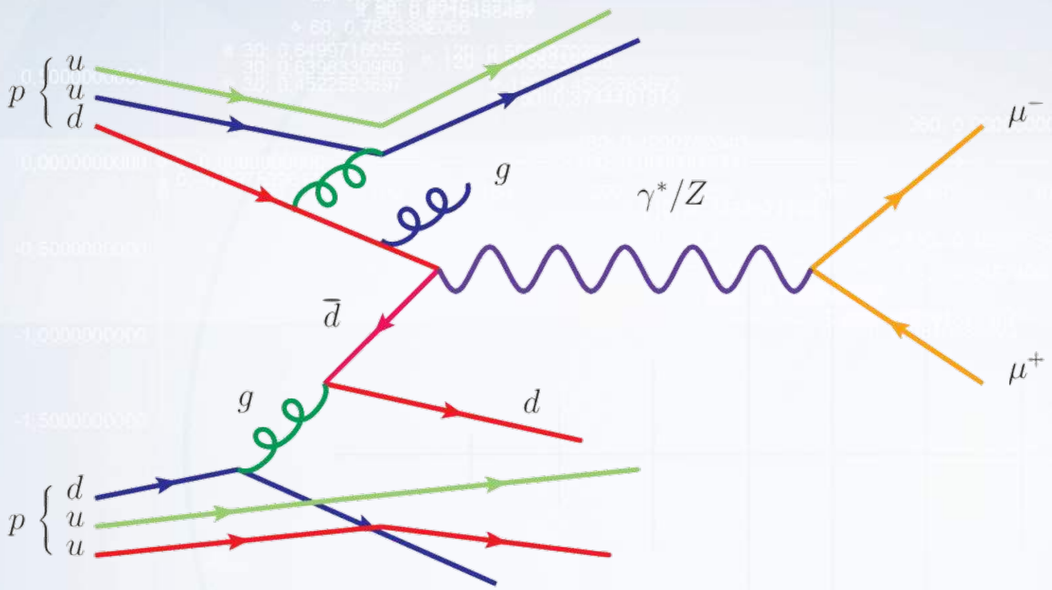


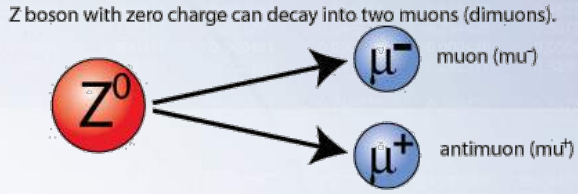
- Represent quantum process (space and time)
- Based on Quantim Field Theory
- Consist of
  - elementrary particles (straight lines)
  - Force representatives (bosons, wavy lines)
- Vertrex represent interaction point
  - Conservation of energy and momenta
- Allows for calculation of probability of the process

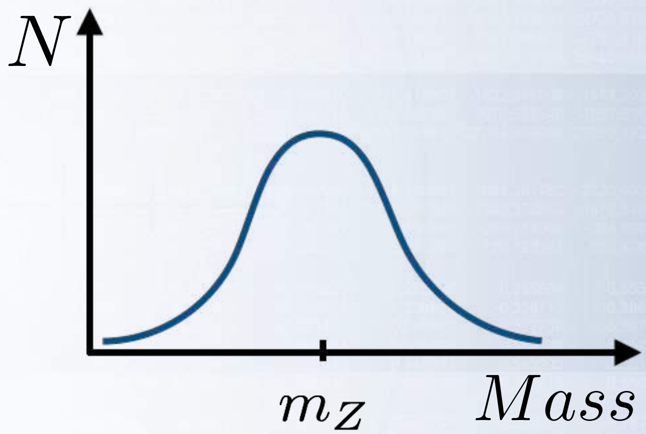
Z Boson

- Mediates weak interactions along with W-bosons
- Can decay into:
  - lepton, anti-lepton pair (10%)
  - Neutrino, anti-neutrino pair (20%)
  - Quark, anti-quark (70%)
  - http://pdglive.lbl.gov/Particle.action?init=0&node=S044
- Important part of SM jigsaw puzzle
- Discovered in 1983 at CERN

Process Probability Estimation







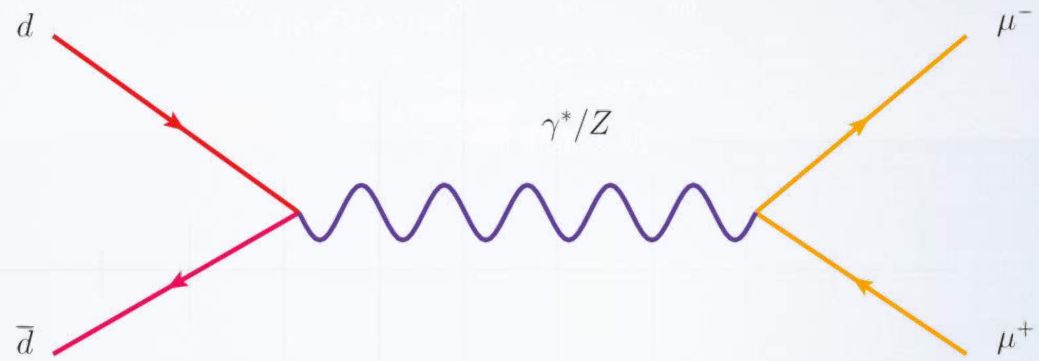
Process of particle (Z) decay is called *resonance* and its probability can be estimated from the diagram:

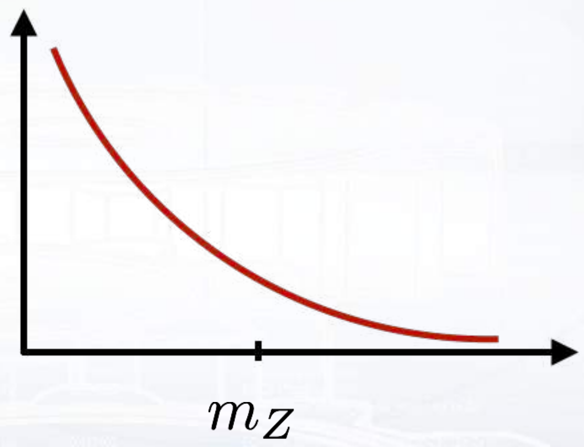
$$P \propto \frac{1}{((\mathbf{p}_Z)^2 - m_Z^2)^2 + \epsilon} = \frac{1}{((\mathbf{p}_{\mu^+} + \mathbf{p}_{\mu^-})^2 - m_Z^2)^2 + \epsilon}$$

http://www.quantumdiaries.org/author/richard-ruiz/

Background

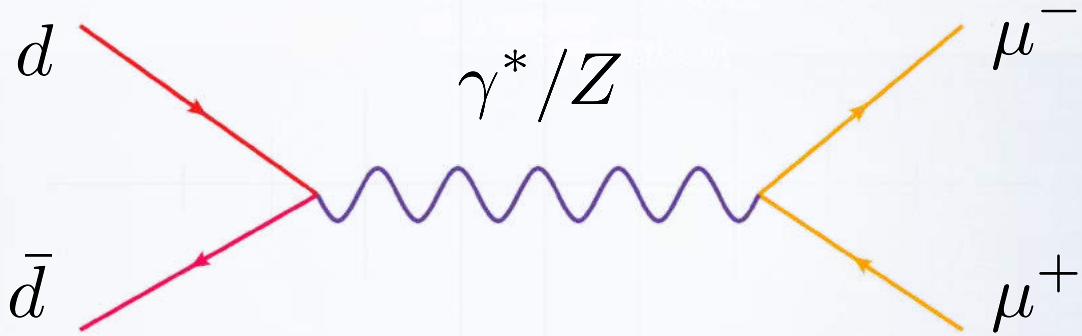
$$d + d \to \gamma \to \mu\mu$$ (Drell-Yan process)

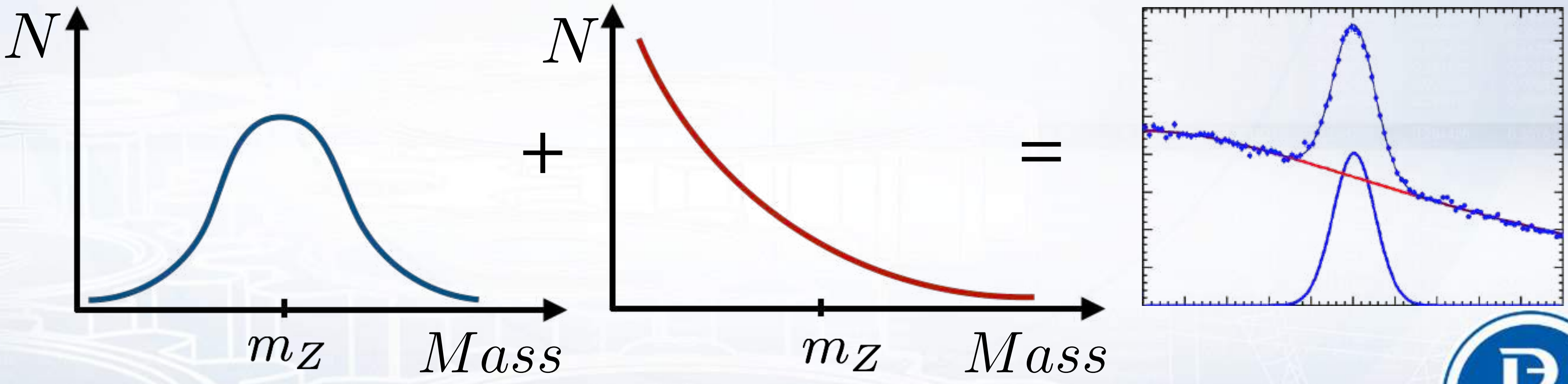




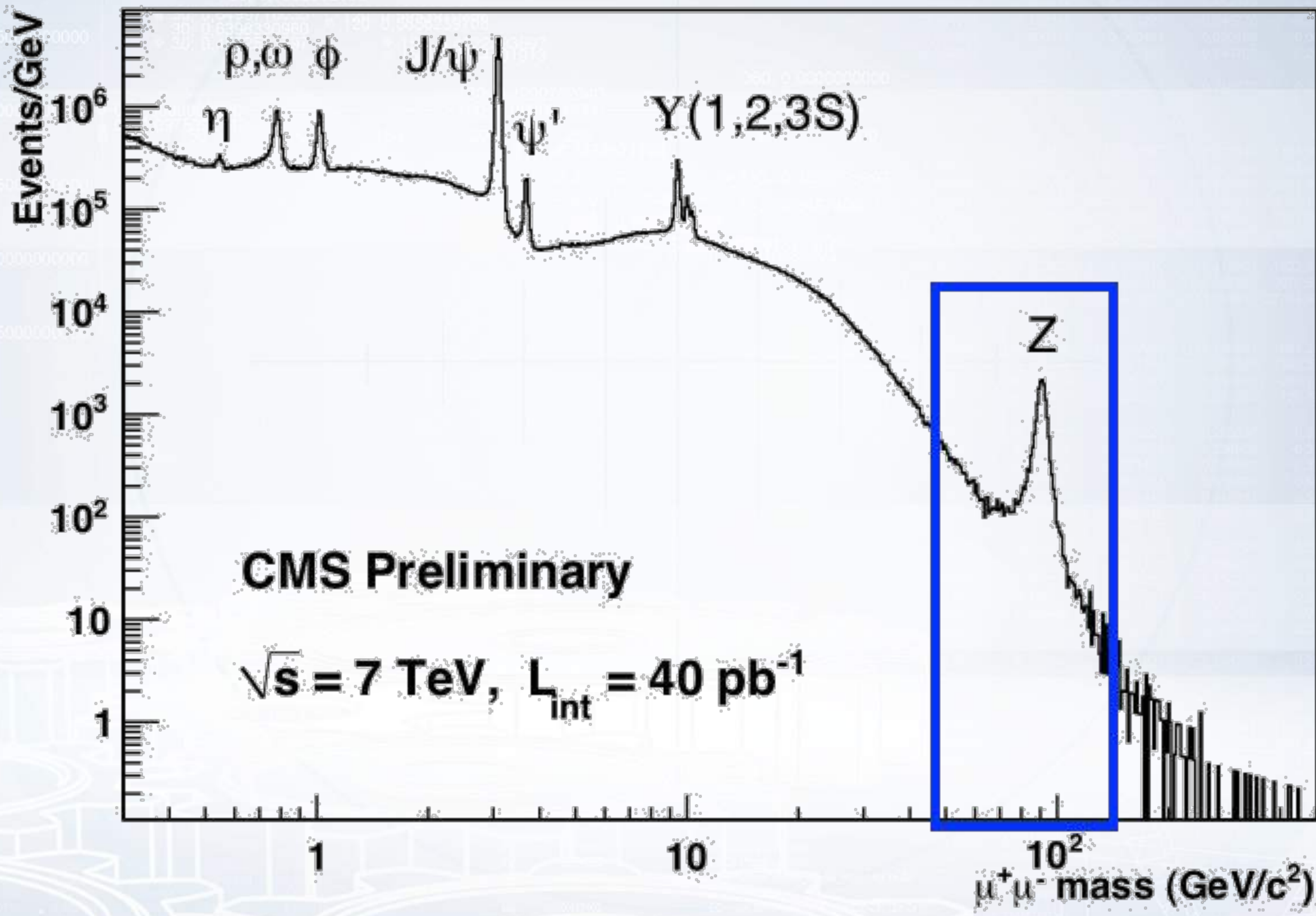
Signal and Background

- Signal: $d + d \rightarrow Z \rightarrow \mu\mu$
- Background: $d + d \rightarrow \gamma \rightarrow \mu\mu$ (Drell-Yan)





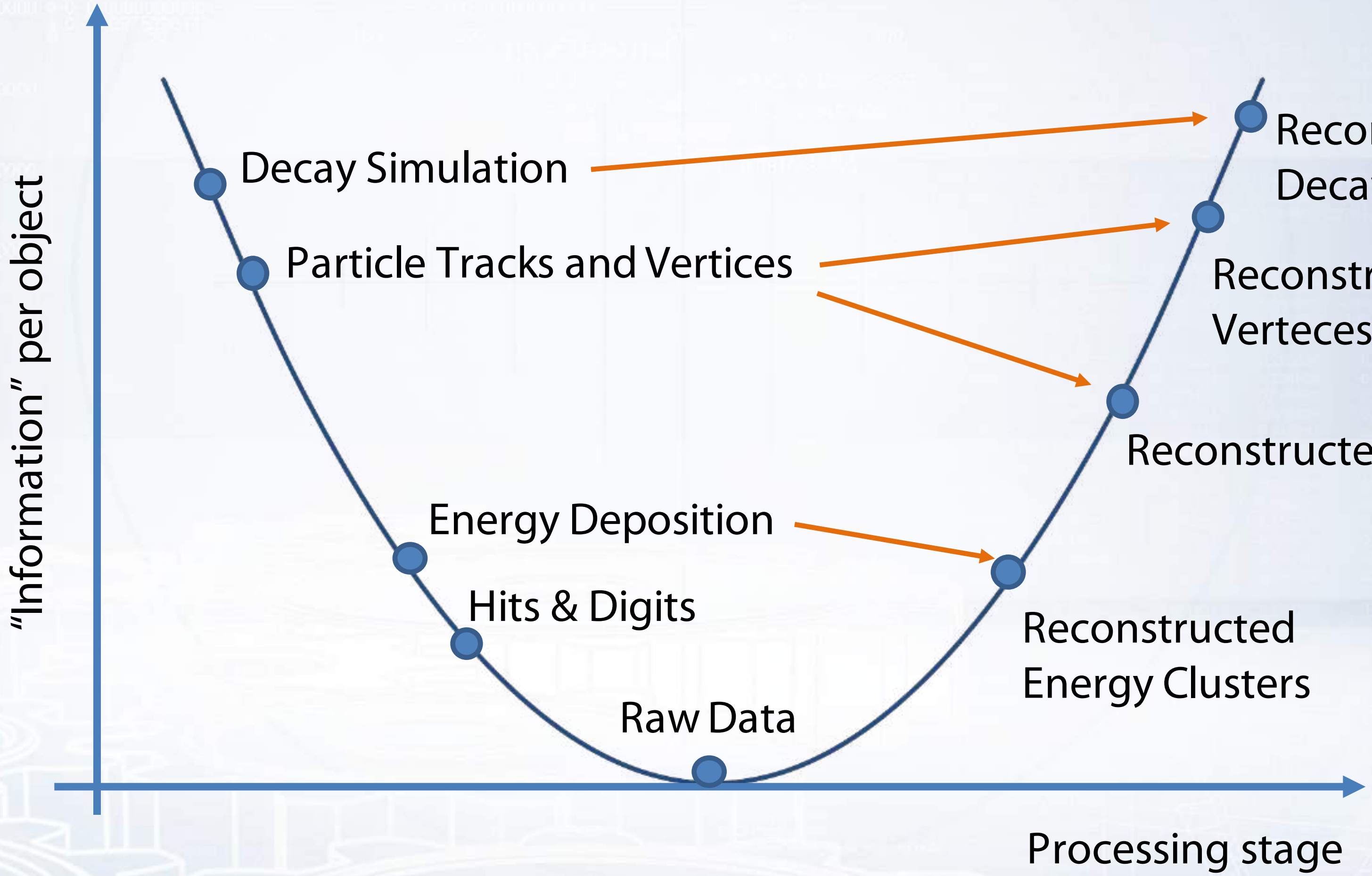
Dimuon Mass Spectrum



Particle Physics Simulation

Simulation in Physics Data Analysis

- Source of the precise information on particle decays
- Predecessor of data



Based on F. Carminati, K. Cranmer, V. Innocente

Simulation Packages

http://genie.hepforge.org/

http://home.thep.lu.se/Pythia/

Geant 4

https://geant4.web.cern.ch/geant4/

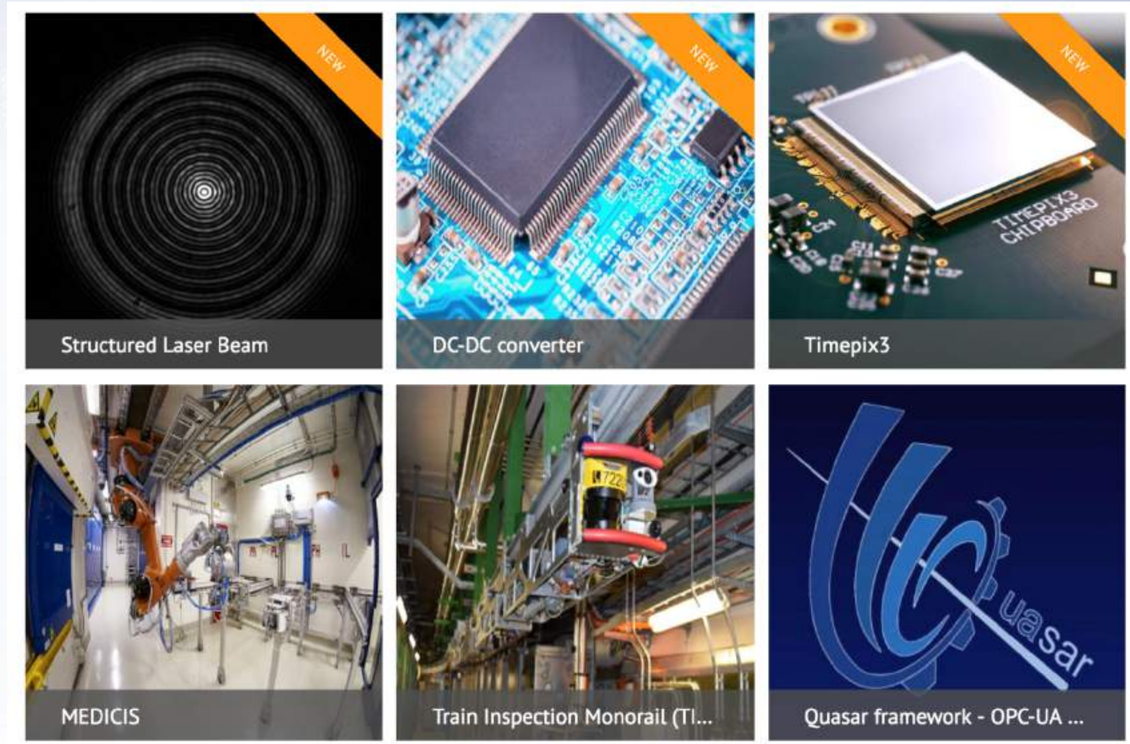
Much more at https://arxiv.org/pdf/1101.2599.pdf

Machine Learning Challenge Examples

- **Precise and fast particle tracking:**
  - **single tracks, shower,** jets.
- **Particle identification;**
- Fast and accurate online data processing and filtering;
- Anomaly detection:
  - data quality monitoring;
  - infrastructure monitoring.
- **Detector design optimization (bayesian optimization);**
- **Data Analysis (signal from background separation);**
- Simulation:
  - speed-up simulation using generative models;
  - simulator parameters optimization (tuning).

Science → Industry → Humanity

- WWW, Internet
- Muono-graphy
- Aerospace
- Cryogenics, ultra vacuum
- Medicine:
  - Ion radiotherapy
  - Hadron therapy
- Simulation toolkits (GEANT4, FLUKA)



https://kt.cern/technologies

Conclusion

- LHC is a huge sub-atomic microscope
- Search for the most basic components we are made of
- Solid theoretical foundation
  - still not complete (yet)
- Plenty of Machine Learning challenges
  - Data stream processing
  - Data analysis
  - Simulation
  - Experiment Design and optimization