A brief overview of the physics we do at the LHC

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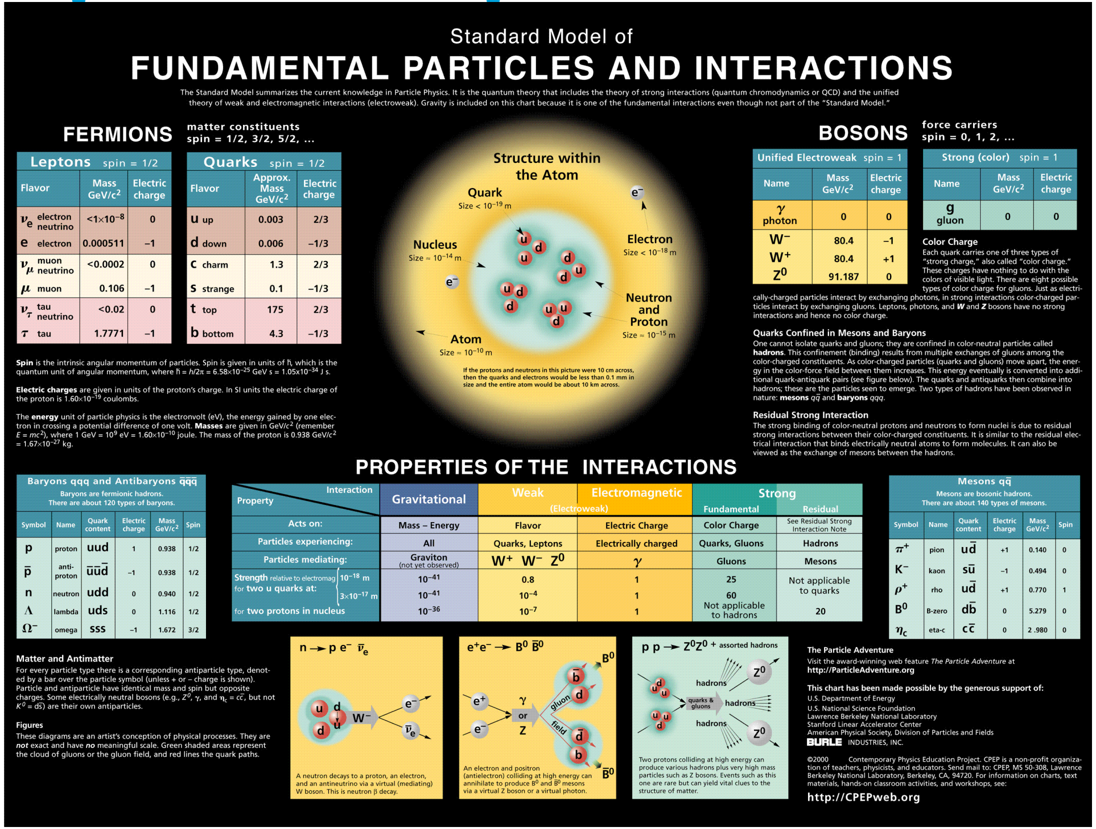
Microscopic description of the world



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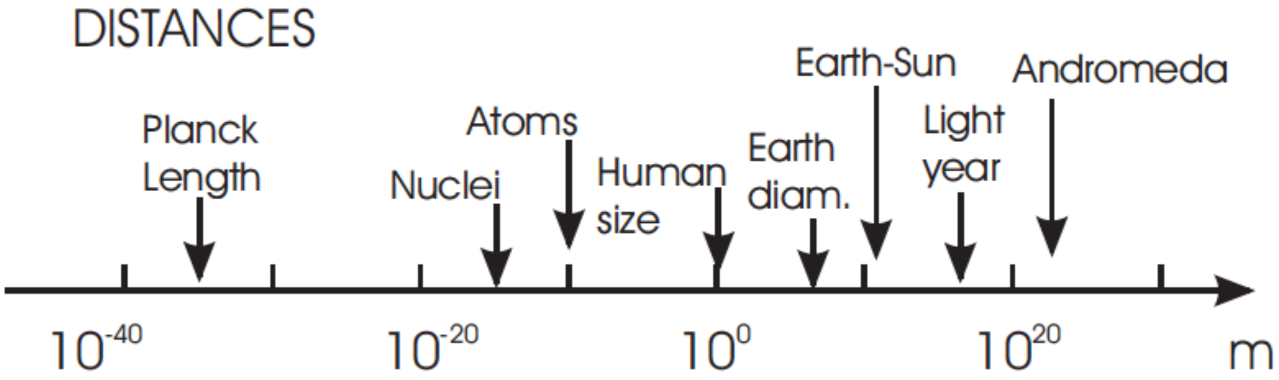
Test theory that describes the world at small distance scales…

~10fm = 10^{-14}m ~12742 Km ~2.5x10^{6} light years

10^{-35}m 1.7m ~149.6x10^{6} Km



~20-250pm = 20-250x10^{-12}m ~9.46x10^{12} Km

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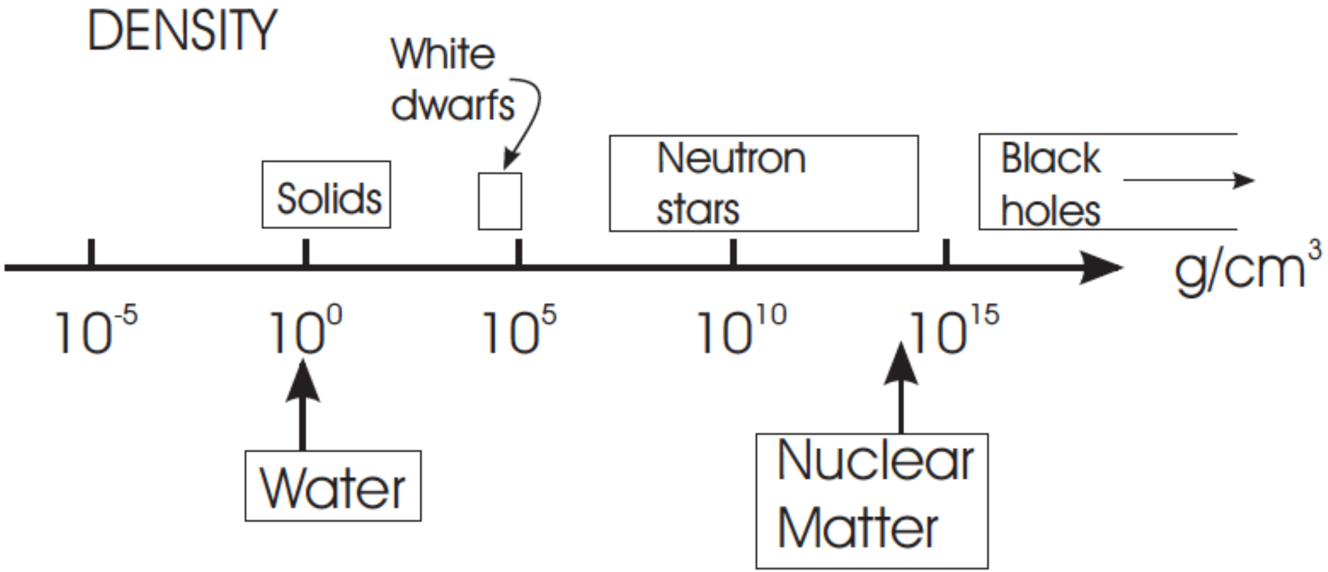
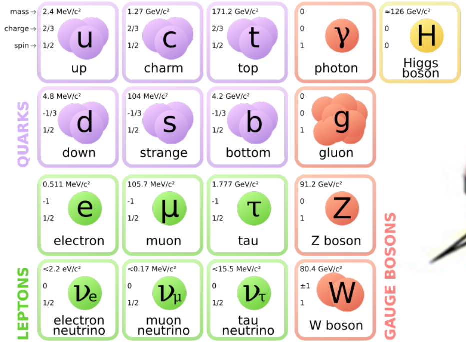
And large density scales…

~10^9 Kg/m^3 ~10^{17} Kg/m^3



~10^{19} Kg/m^3

The Standard Model of particle physics



SM Lagrangian density
(Source: symmetry magazine)*

$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu$$

2

$$- \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^-$$

3

$$- \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)]$$

4

$$+ \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j)$$

5

$$+ \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

*Fun fact

Written by Thomas Gutierrez professor of Physics at CalPoly (California Polytechnic State University)

He derived it from Diagrammatica, a theoretical physics reference written by Nobel Laureate Martinus Veltman

In Gutierrez's dissemination of the transcript, **he noted a sign error he made somewhere in the equation**

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…built on (broken) symmetries

- A system is normally described by its Lagrangian
  - The Lagrangian can be found from first principles or can be deduced through the conservation laws of the system
  - Noether's theorem connects symmetries with conservation laws
    - "Every symmetry in nature yields a conservation law and inversely every conservation law reveals an underlying symmetry"
      - Momentum conservation: invariance under a translation in space
      - Angular momentum conservation: invariance under rotation in space

Emmy Noether
(1882 - 1935)

...built on (broken) symmetries

	Conserved quantities	Gauge transformation	Symmetry group	Field
QED	(Hyper)charge: Q	$\Psi \rightarrow \Psi^{'} = e^{ig\Lambda}\Psi$	U(1)	A_μ (1 photon) 
Weak	Weak isospin $\Psi = \begin{pmatrix} e \\ \nu_e \end{pmatrix}$ $\Psi = \begin{pmatrix} u \\ d \end{pmatrix}$	$\Psi \rightarrow \Psi^{'} = e^{\frac{ig\tau^j\Lambda^j}{2}}\Psi$	SU(2)	A_μ (3 bosons, $W^{\pm}$, Z^0) 
QCD	Colour $\Psi = \begin{pmatrix} \Psi_R \\ \Psi_B \\ \Psi_G \end{pmatrix}$	$\Psi \rightarrow \Psi^{'} = e^{\frac{ig\lambda^\alpha\Lambda^\alpha}{2}}\Psi$	SU(3)	A_μ (8 gluons, g) 

The theoretical pillars of the Standard Model

Quantum ElectroDynamics (QED)

The Nobel Prize in Physics 1965
Sin-Itiro Tomonaga, Julian Schwinger, Richard P. Feynman

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The Nobel Prize in Physics 1965

Sin-Itiro Tomonaga
Prize share: 1/3

Julian Schwinger
Prize share: 1/3

Richard P. Feynman
Prize share: 1/3

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman *"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"*.

Electroweak Unification (GSW)

The Nobel Prize in Physics 1979
Sheldon Glashow, Abdus Salam, Steven Weinberg

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The Nobel Prize in Physics 1979

Sheldon Lee Glashow
Prize share: 1/3

Abdus Salam
Prize share: 1/3

Steven Weinberg
Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

Quantum ChromoDynamics (QCD)

The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

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The Nobel Prize in Physics 2004

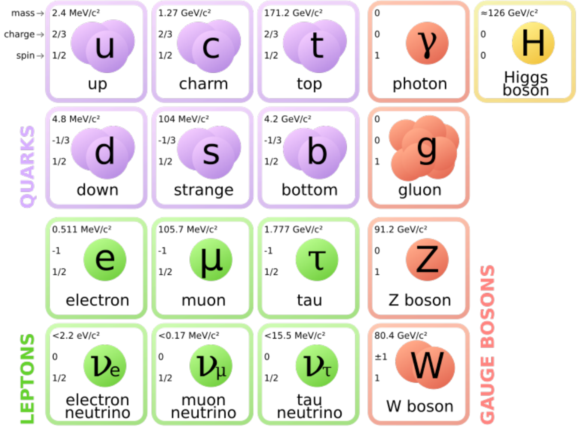
David J. Gross
Prize share: 1/3

H. David Politzer
Prize share: 1/3

Frank Wilczek
Prize share: 1/3

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.

The missing piece…



The Higgs mechanism

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
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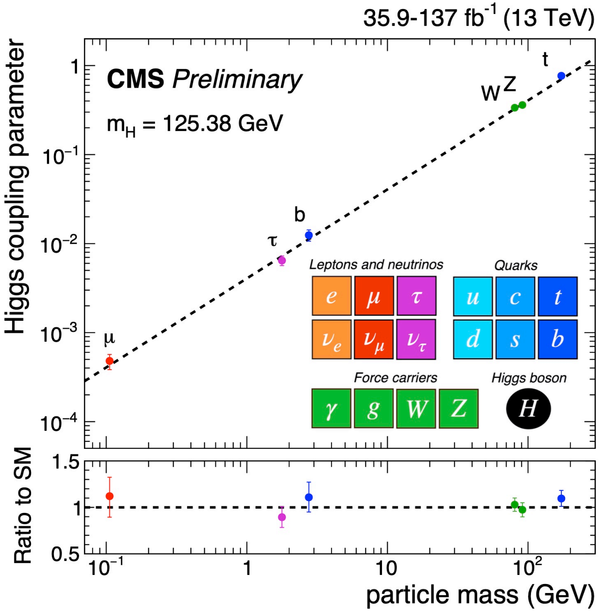
Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Gives mass to particles…



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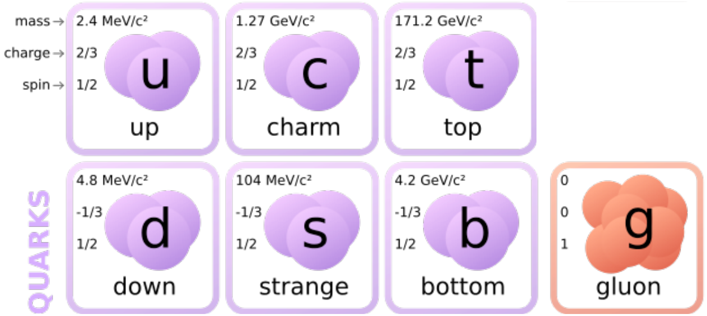
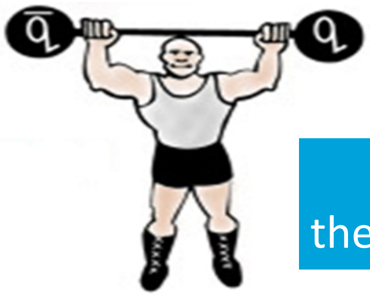
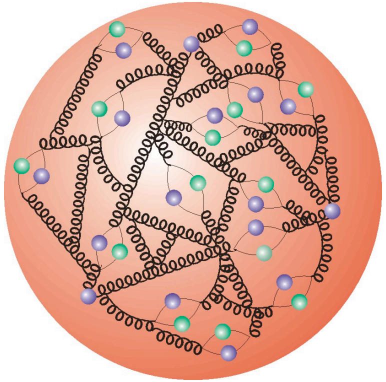
Valid statement for elementary particles!

Quarks and gluons can not be found free in nature!!!

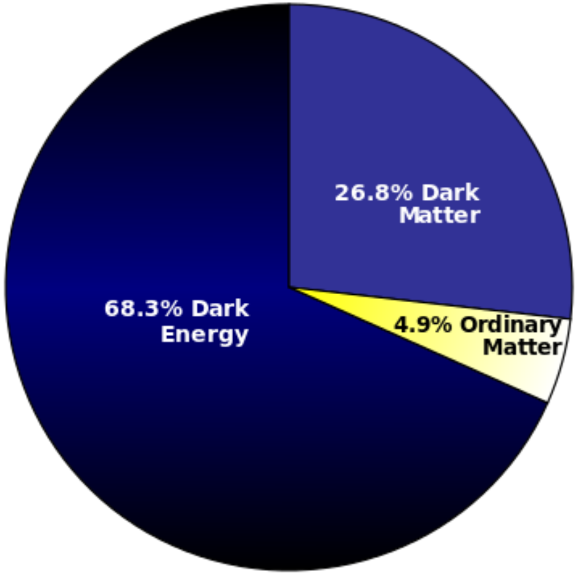




Spoiler alert:
the proton is by far more complicated



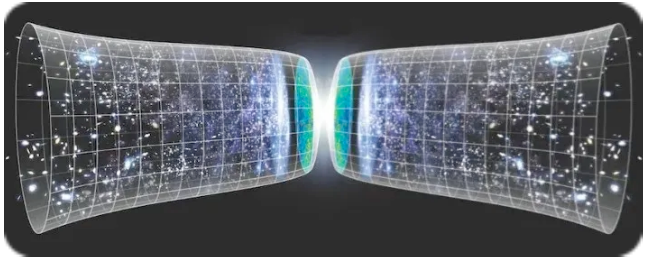
The SM is successful but not a complete theory…



The SM is successful but not a complete theory…

Some of the questions the Standard Model can not answer

- Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?



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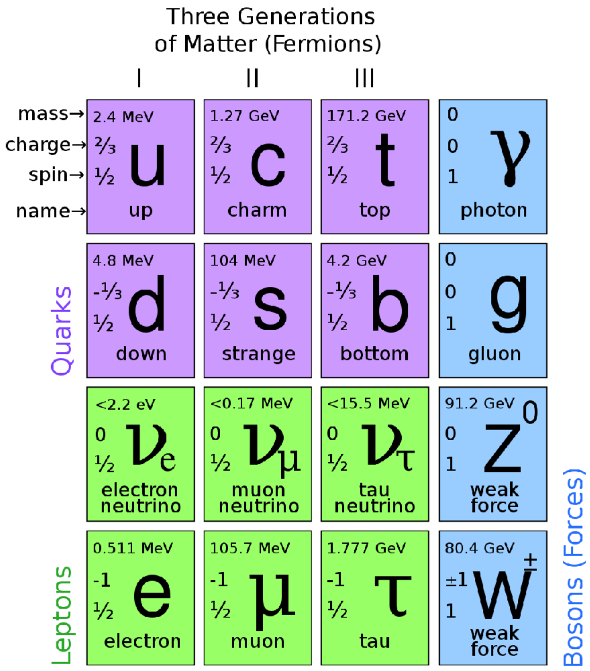

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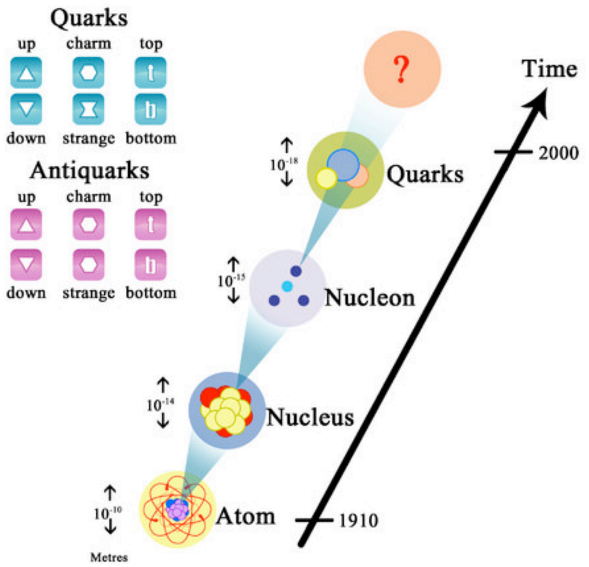

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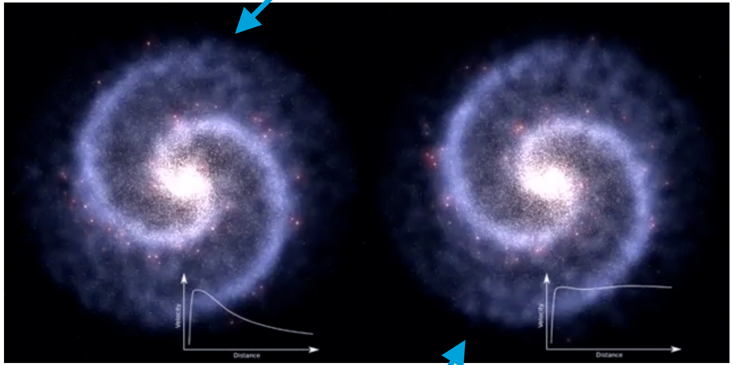
- What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

How fast stars should be rotating around the center of spiral galaxies

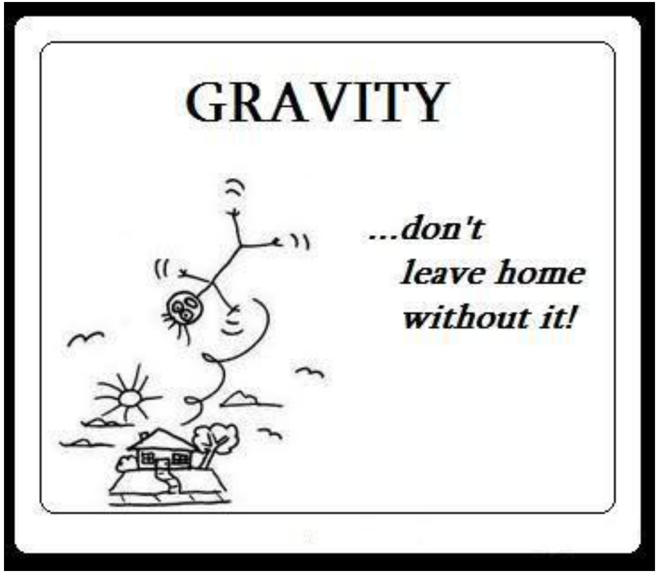


How fast stars are actually rotating around the center of spiral galaxies

The SM is successful but not a complete theory…

Some of the questions the Standard Model can not answer

- Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?
- Why are there exactly three generations of quarks and leptons?
- Are quarks and leptons actually fundamental, or made up of even more fundamental particles?
- What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?
- How does gravity fit into all of this?



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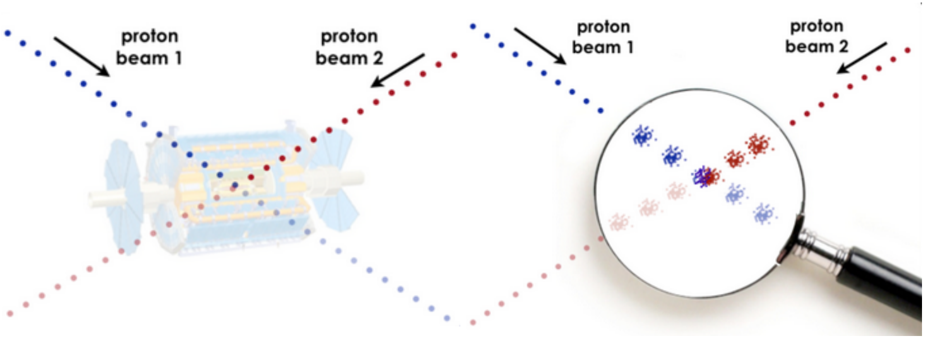
Studies of SM and beyond in the lab

Delivers pp collisions for ~11 months per year and PbPb (or pPb) for one month

Some of the challenges

- Protons accelerated to 6.8TeV per beam ($1eV \sim 1.602 \times 10^{-19}$ J)
- Center of mass energy of 13.6TeV

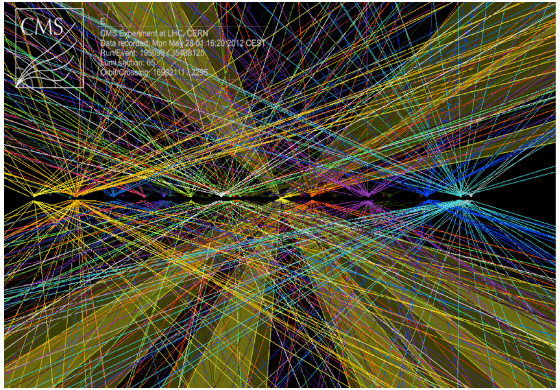
$$\sqrt{s} = \sqrt{(E_1 + E_2)^2 - (\vec{P}_1 + \vec{P}_2)^2} = \sqrt{P_\mu P^\mu}$$



- Proton bunches separated by 25ns (40MHz)
- Each bunch contains 10^{11} protons
- Luminosity determines the rate of events
  - Typical transverse beam sizes of $\sigma_x \sim 16$ μm

$$\mathcal{L} = \frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

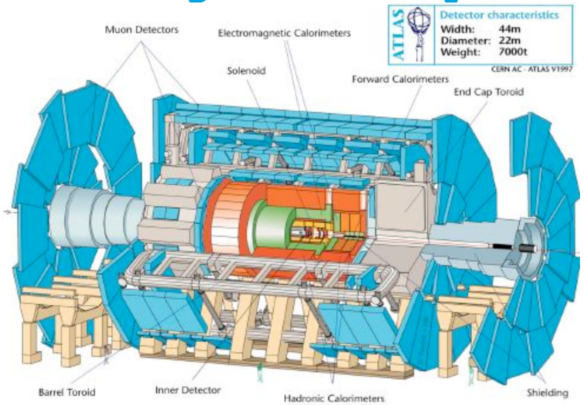
- Typical inelastic pp cross-section @LHC energies $\sigma_{pp} \sim 80\text{-}100\text{mb} \sim 10^{-25}\text{cm}^2$

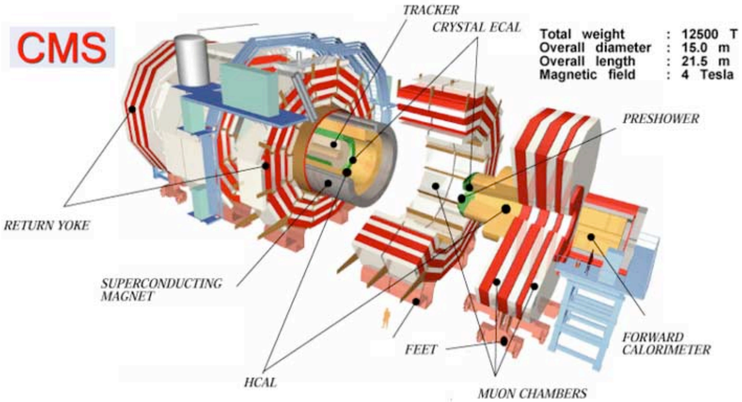


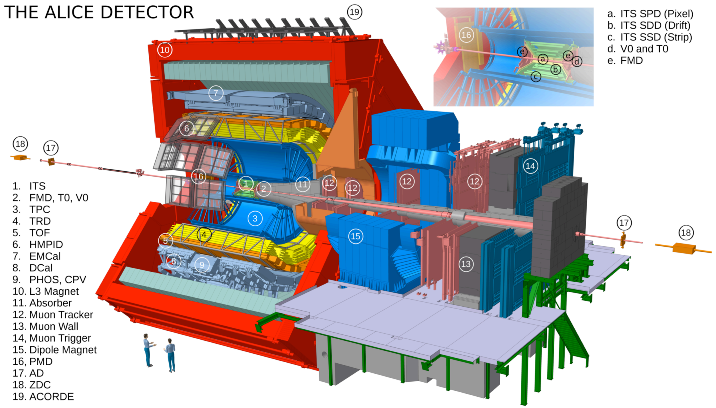
Find the mean number of pp collisions per bunch crossing

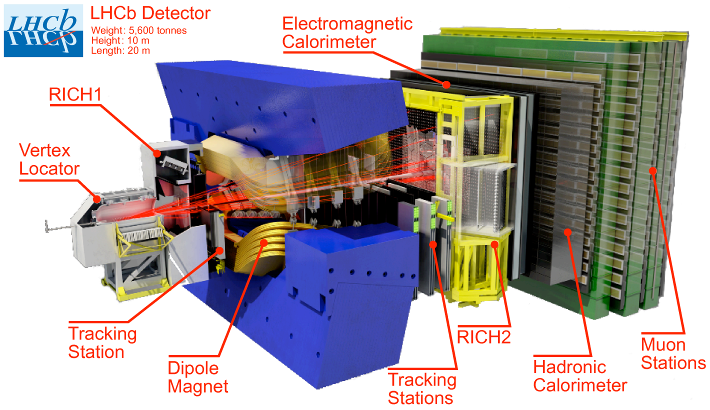
$$\mu = \mathcal{L} \times \sigma_{pp}$$

The 4 major experiments









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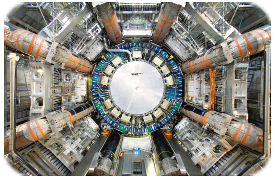
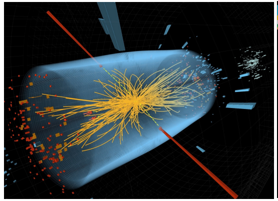
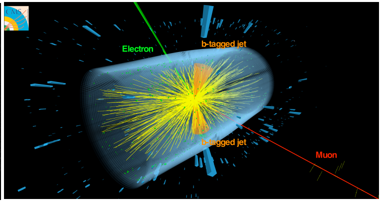
The 4 major experiments

ATLAS/CMS

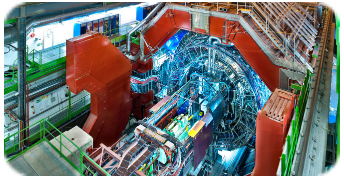


Test of the Standard model, Higgs, searches for physics beyond the standard model

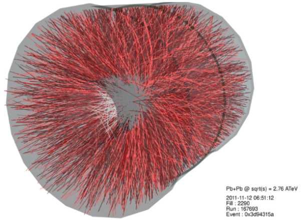




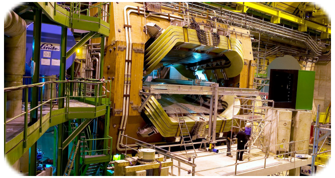
ALICE



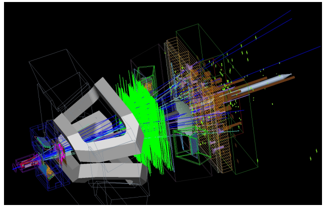
Test of Quantum ChromoDynamics at extreme temperatures and densities, quark gluon plasma and strong phase transition



LHCb

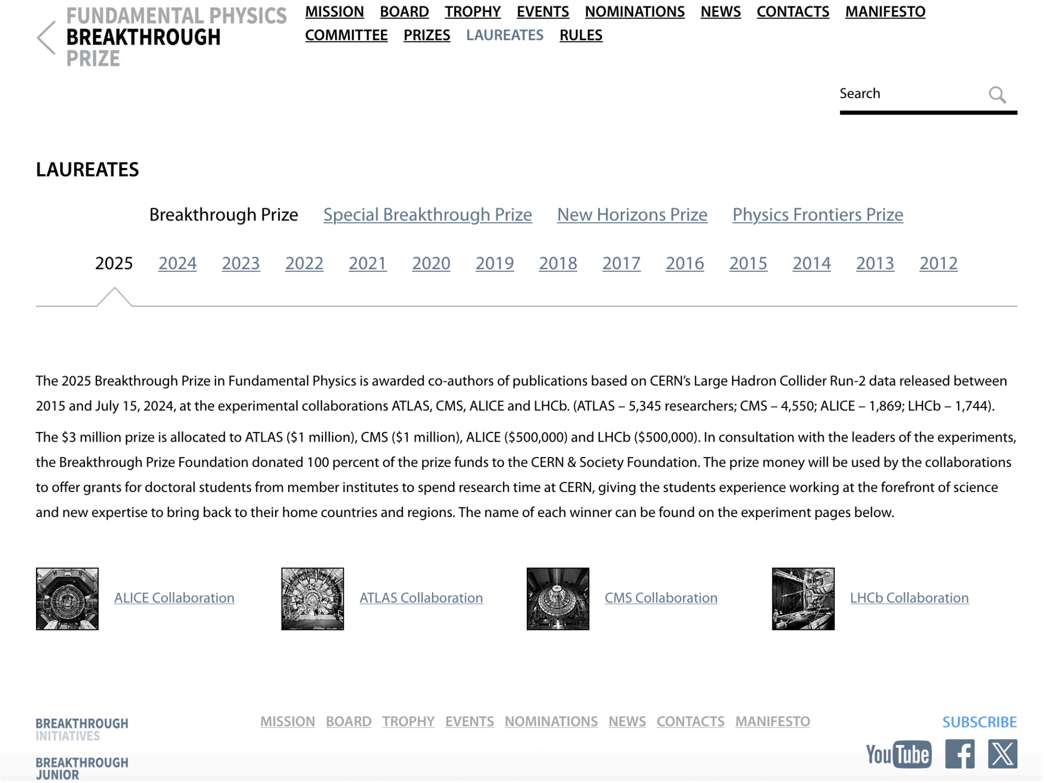


Test of the Standard model, matter-antimatter asymmetry, searches for physics beyond the standard model



What have we learned from the LHC?

- LHC, experiments, software & computing, and physics analysis all perform beyond design.
- Many new analyses ideas emerged that were not thought of during the design phase
- One major discovery and many more surprises!



FUNDAMENTAL PHYSICS BREAKTHROUGH PRIZE

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LAUREATES

Breakthrough Prize | Special Breakthrough Prize | New Horizons Prize | Physics Frontiers Prize

2025 2024 2023 2022 2021 2020 2019 2018 2017 2016 2015 2014 2013 2012

The 2025 Breakthrough Prize in Fundamental Physics is awarded co-authors of publications based on CERN's Large Hadron Collider Run-2 data released between 2015 and July 15, 2024, at the experimental collaborations ATLAS, CMS, ALICE and LHCb. (ATLAS – 5,345 researchers; CMS – 4,550; ALICE – 1,869; LHCb – 1,744).

The $3 million prize is allocated to ATLAS ($1 million), CMS ($1 million), ALICE ($500,000) and LHCb ($500,000). In consultation with the leaders of the experiments, the Breakthrough Prize Foundation donated 100 percent of the prize funds to the CERN & Society Foundation. The prize money will be used by the collaborations to offer grants for doctoral students from member institutes to spend research time at CERN, giving the students experience working at the forefront of science and new expertise to bring back to their home countries and regions. The name of each winner can be found on the experiment pages below.

ALICE Collaboration | ATLAS Collaboration | CMS Collaboration | LHCb Collaboration

BREAKTHROUGH INITIATIVES

BREAKTHROUGH JUNIOR

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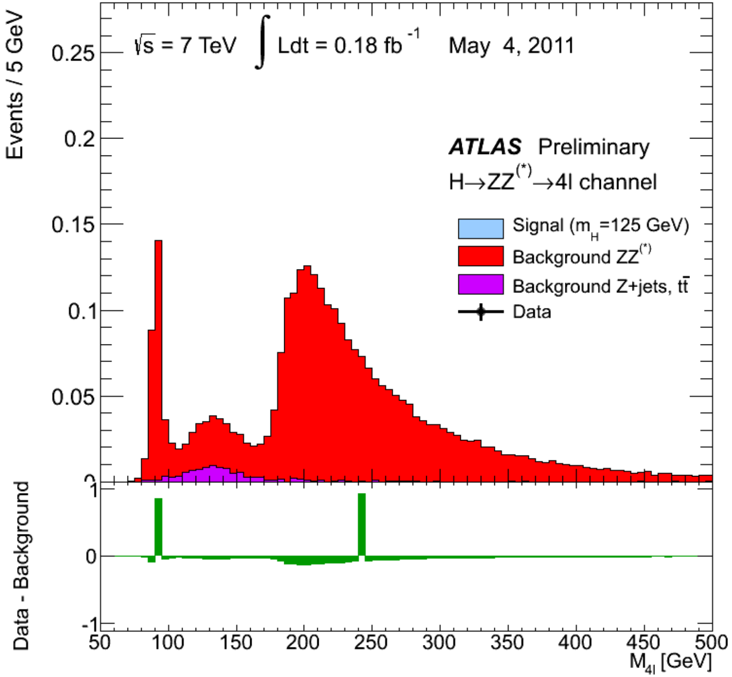
Test of the SM and studies for BSM

Maastricht University

Panos.Christakoglou@maastrichtuniversity.nl

The major discovery

July 2012 @ CERN



The Higgs mechanism

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

What have we learned from the LHC?

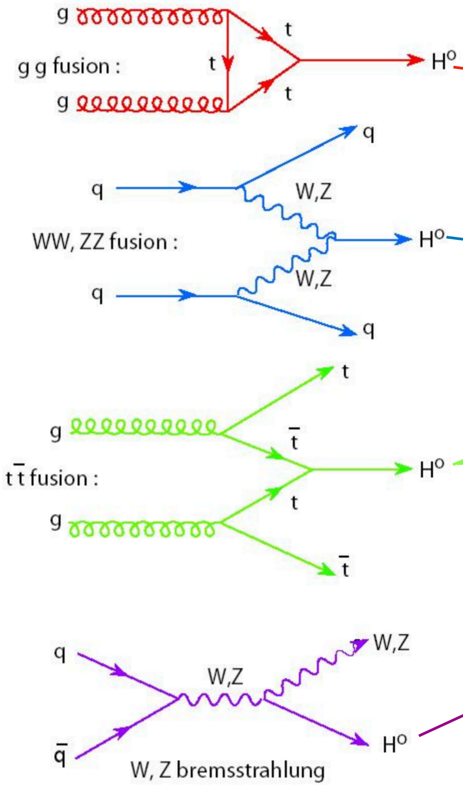
Higgs production channels

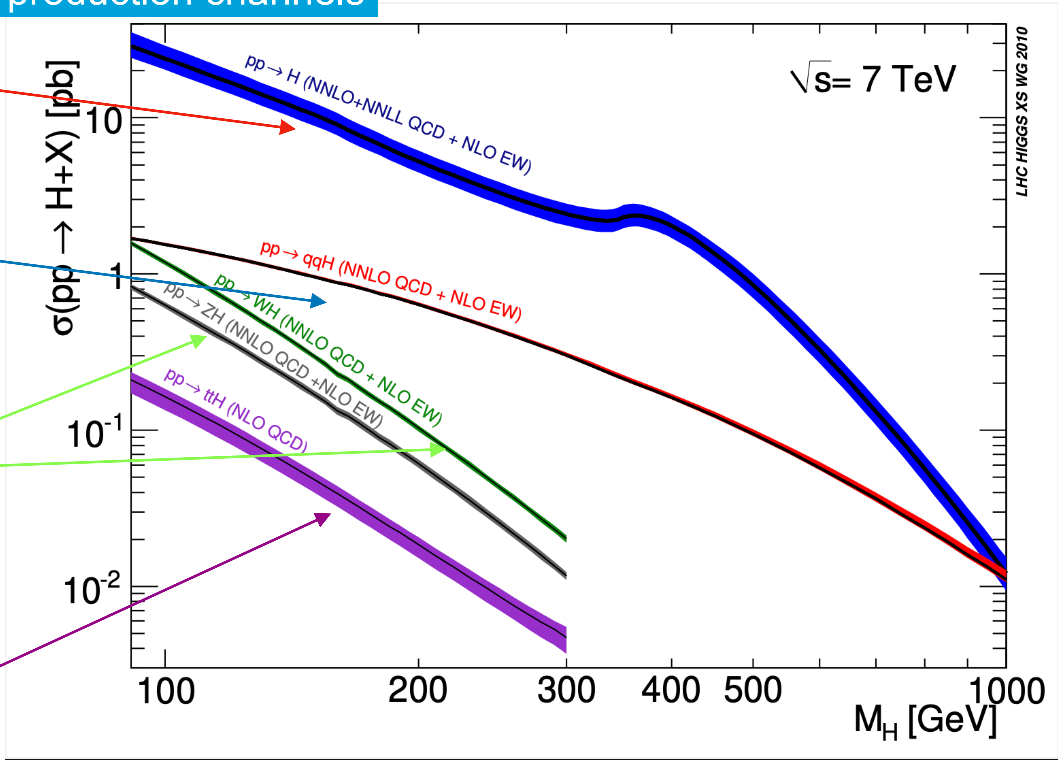
Gluon fusion

Vector boson fusion

tt associated production

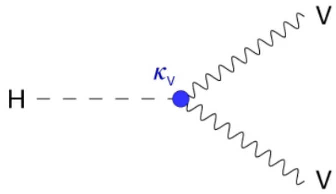
Vector boson radiation



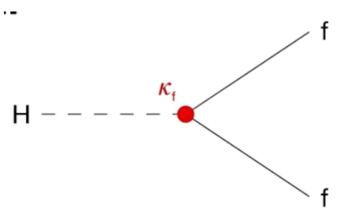


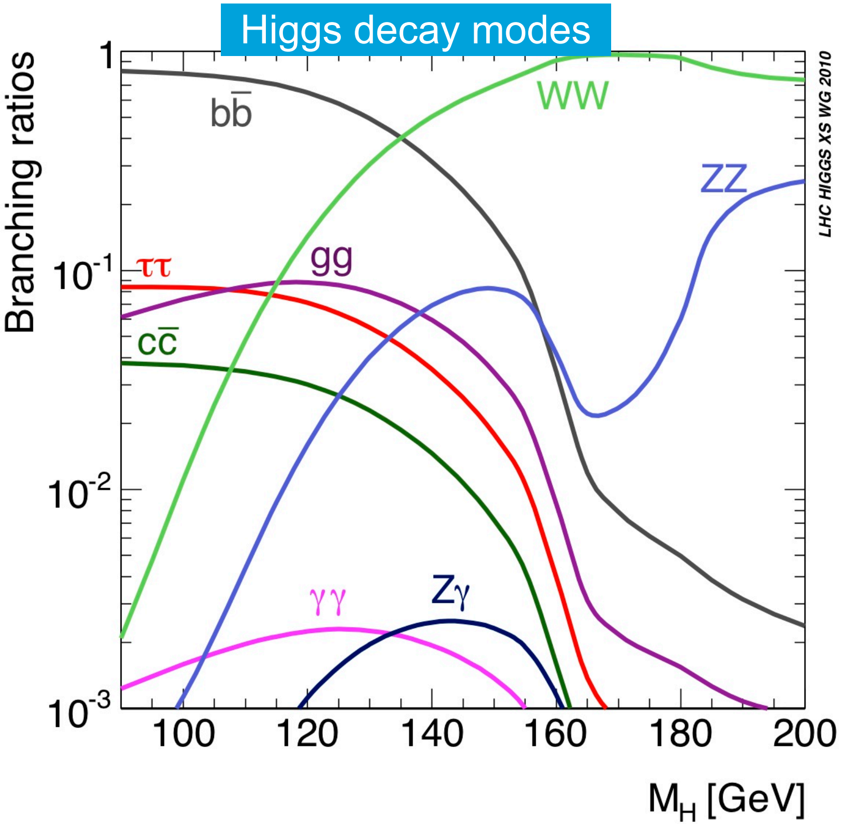
What have we learned from the LHC?

Vector bosons

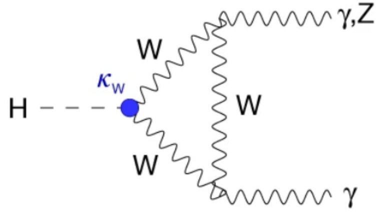


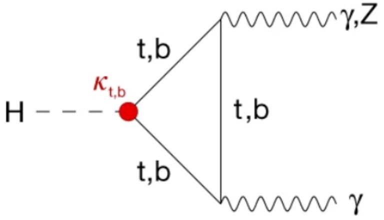
Fermion-antifermion pair





Photon pair

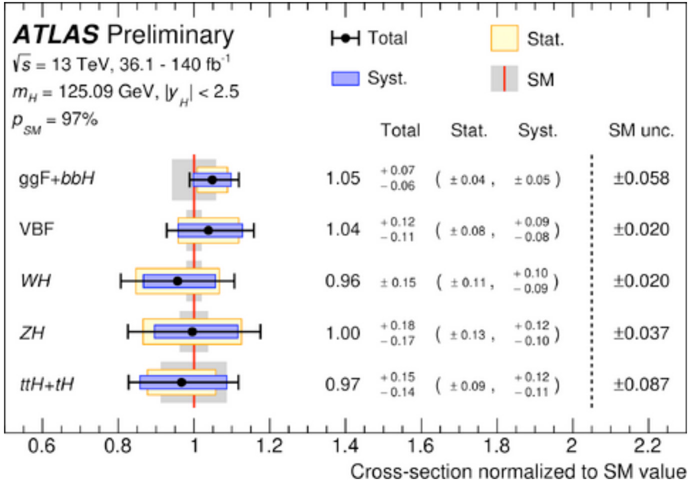


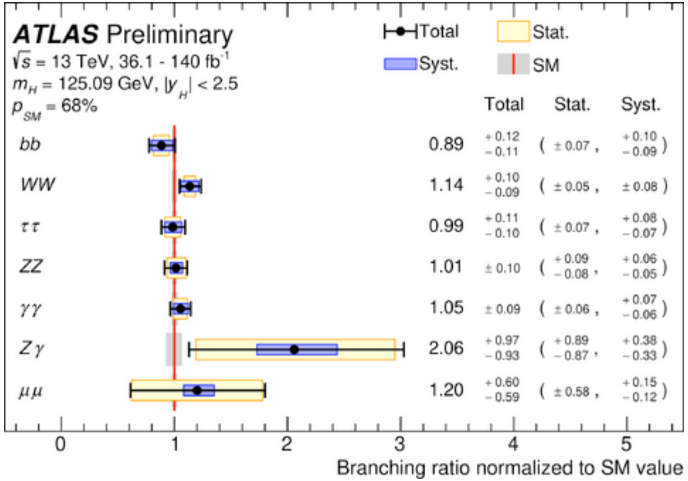


Photon-Z pair

The SM strikes back: Higgs production/decay

ATLAS-CONF-2025-006



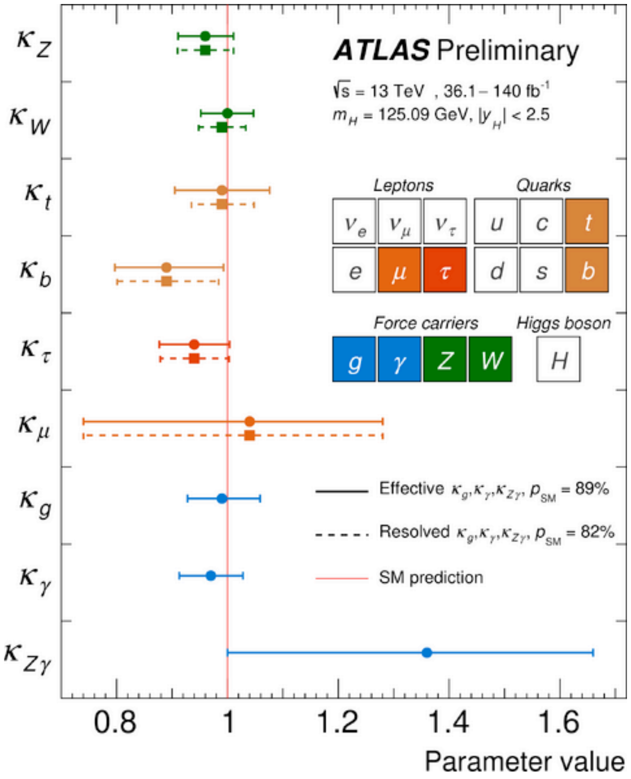


Observed cross-sections for the main Higgs boson production modes, relative to their SM predictions.

Observed branching ratio values in the H→bb, H→WW*, H→ττ, H→ZZ*, H→γγ, H→Zγ and H→μμ decay modes, relative to their SM predictions.

Panos.Christakoglou@maastrichtuniversity.nl

The SM strikes back: Higgs coupling

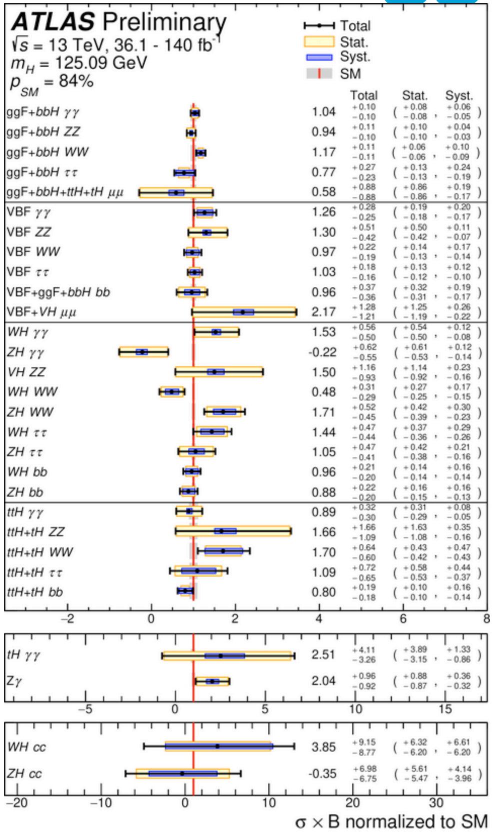


Observed values for Higgs boson coupling modifiers relative to the SM expectation shown as a vertical red line.

ATLAS-CONF-2025-006

The SM strikes back: Higgs coupling

Observed (left) and expected (right) values of the measurements of products of production cross-sections and branching ratios, relative to their SM predictions.



ATLAS-CONF-2025-006

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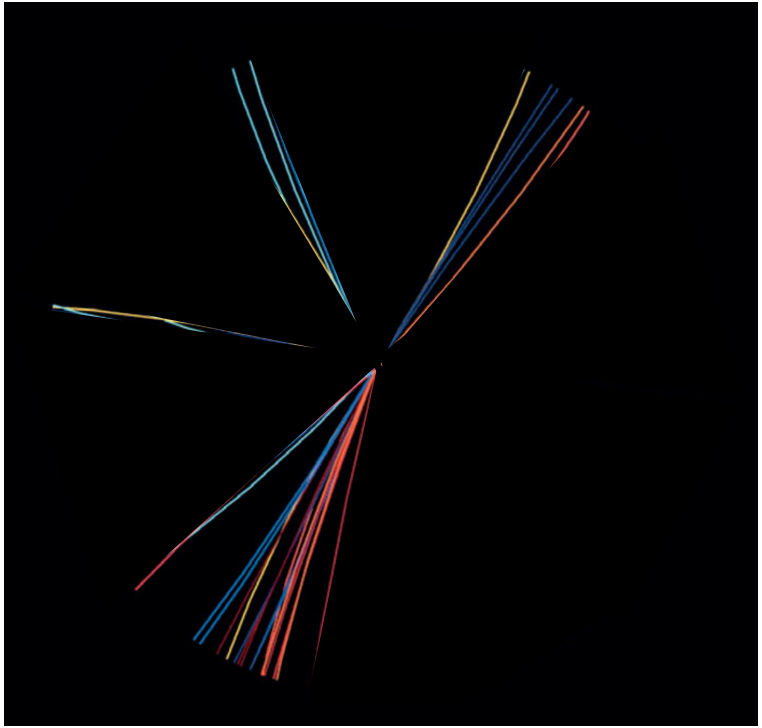
Studying primordial matter in the lab

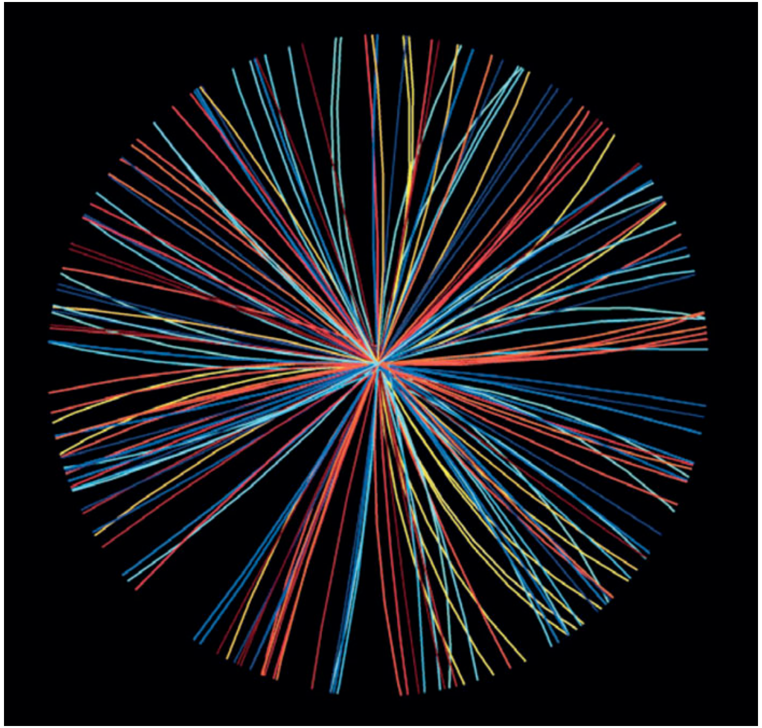
Maastricht University

Panos.Christakoglou@maastrichtuniversity.nl

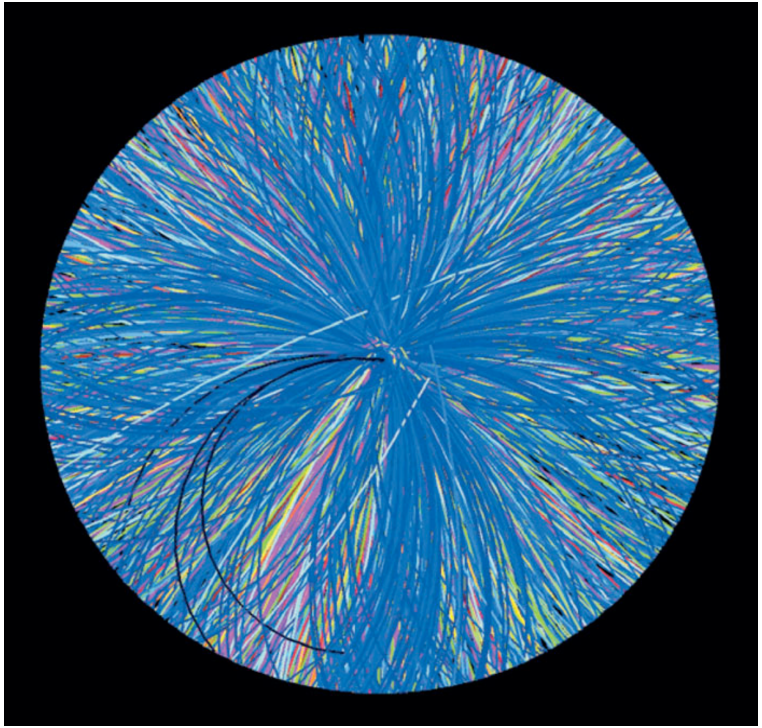
The LHC as a proton-proton collider



The LHC as a proton-ion collider



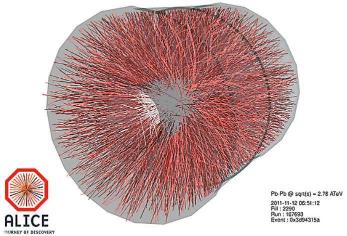
The LHC as a heavy-ion collider

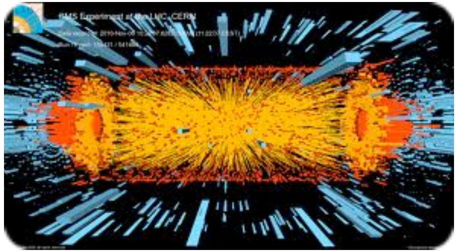


Studying QCD matter at extreme conditions

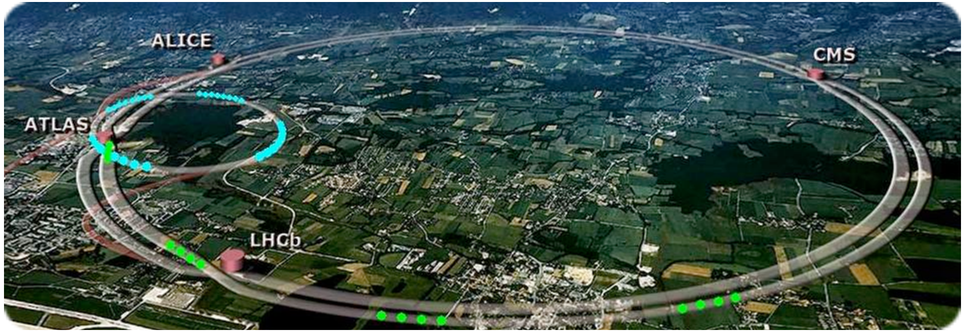
Series of experiments at:

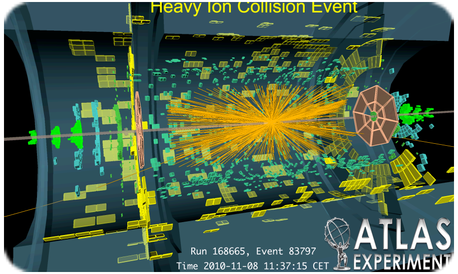
- Bevalac (HI between 1980-1993)
- AGS (Si/Au beams ~1986-1994)
- SPS (S/Pb beams ~1987-Today)
- RHIC (Au beams, 2000-Today)
- LHC (Pb beams, 2010-Today)

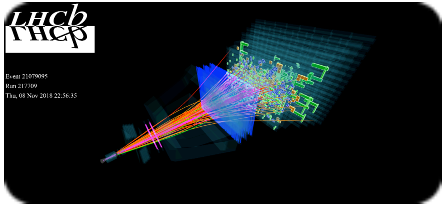




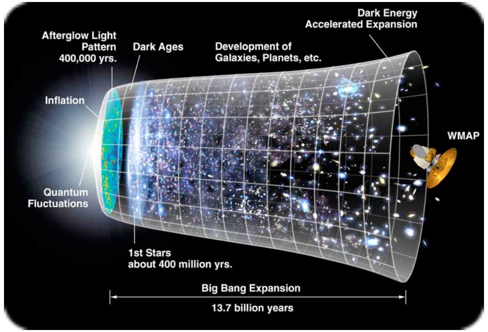
CERN-LHC

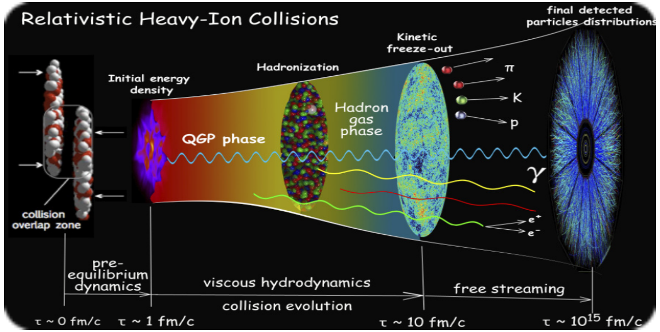






The Quark Gluon Plasma





- A state of matter where the quarks and gluons should eventually be the relevant degrees of freedom
- Existed few μs after the Big-Bang (the universe crossed this phase after expanding and cooling down): Studying the strong phase transition ➞ study primordial matter
- QCD: Phase transition beyond a critical temperature (~170 MeV) and energy density (~0.5 GeV/fm^3) ➞ accessible in the laboratory ➞ heavy-ion collisions

$T_{(QGP\text{-}transition)}$~170MeV ➞ 10^{12} degrees

↓

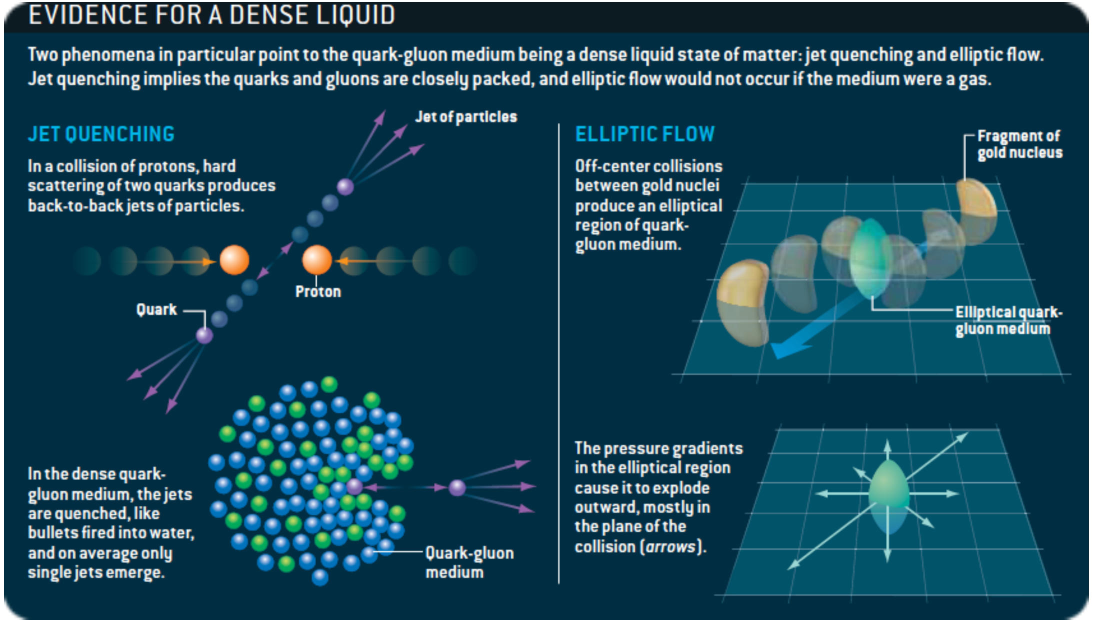
$T_{(Sun's\ core)}$~10^7 degrees

↓

$T_{(QGP\text{-}transition)}$ 10^5x$T_{(Sun's\ core)}$

In what state was the early universe?

M. Roirdan and W. Zajc, Scientific American 34A May (2006)



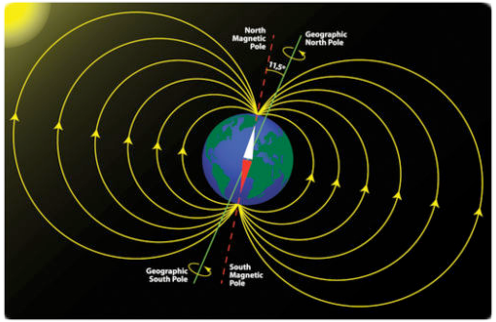
- Early universe filled with QGP
  - from a couple of μs after its creation

The early universe was in a liquid state!!!

BTR topic

The strongest magnetic field in nature…

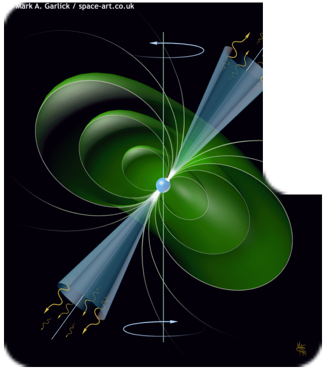
Earth's magnetic field: ~0.5 G

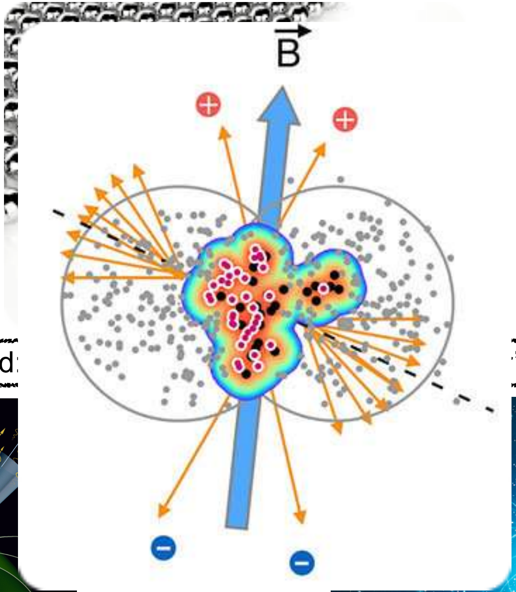


Common magnet: ~50 G

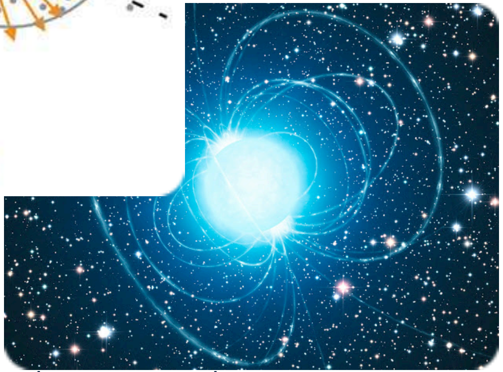
The strongest man-made field: ~10^6 G

Pulsar's magnetic field





's field: 10^{12} - 10^{15} G



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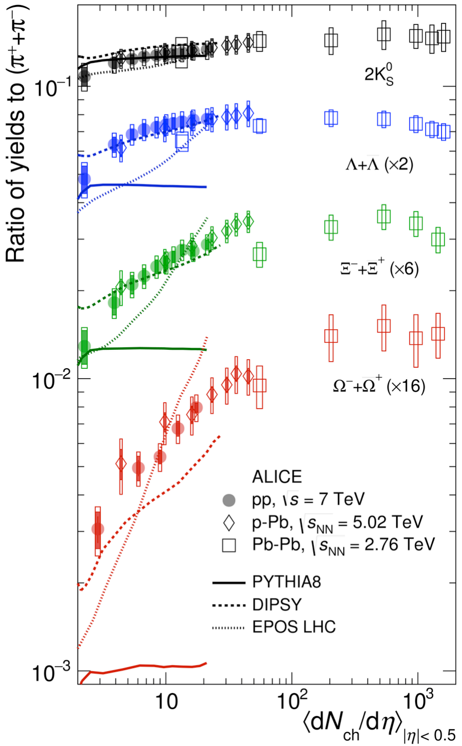
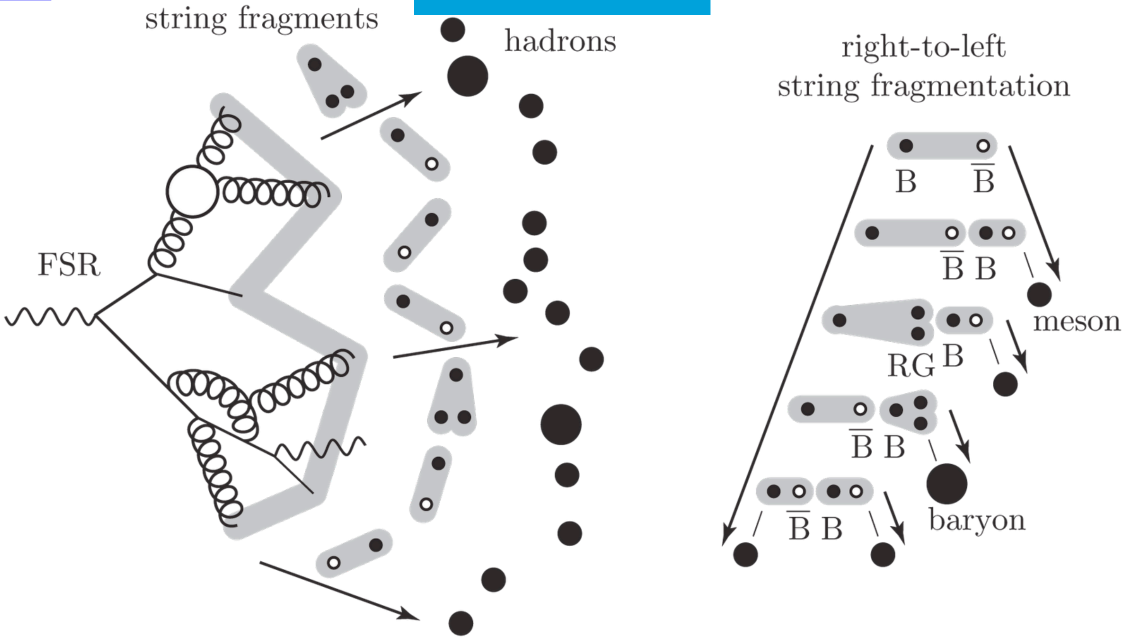
How does nature produce particles?

Nature Physics 13 (2017) 535-539



Hadronisation



Particle production mechanism is still a mystery

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How do we detect these particles?

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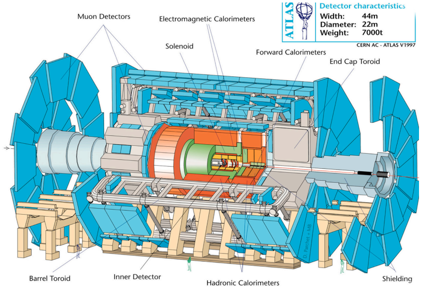
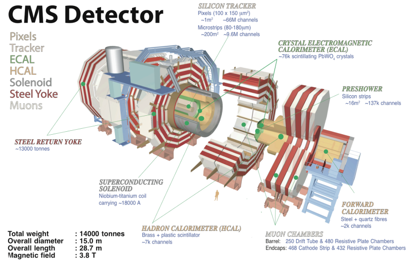
How do we get such plots?

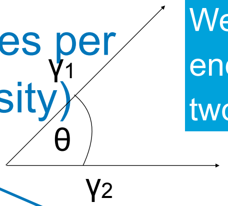


$$m_{inv} = \sqrt{P_\mu P^\mu} = \sqrt{(E_{\gamma,1} + E_{\gamma,2})^2 - (\vec{P}_{\gamma,1} + \vec{P}_{\gamma,2})^2}$$

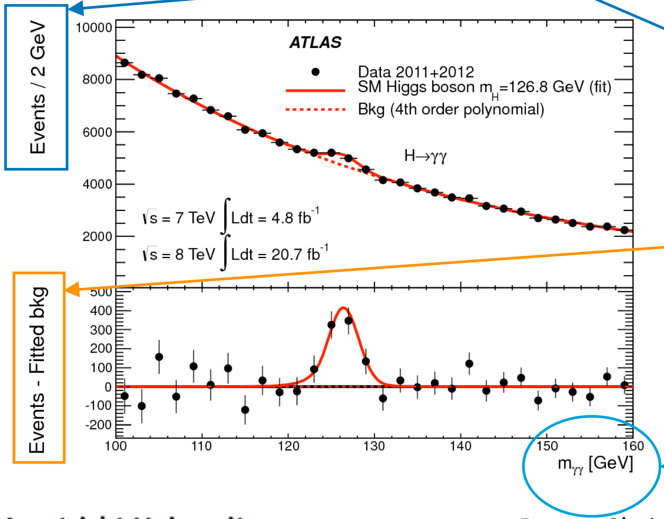
$$m_{inv} = \sqrt{2E_{\gamma,1}E_{\gamma,2}(1 - \cos\theta)}$$



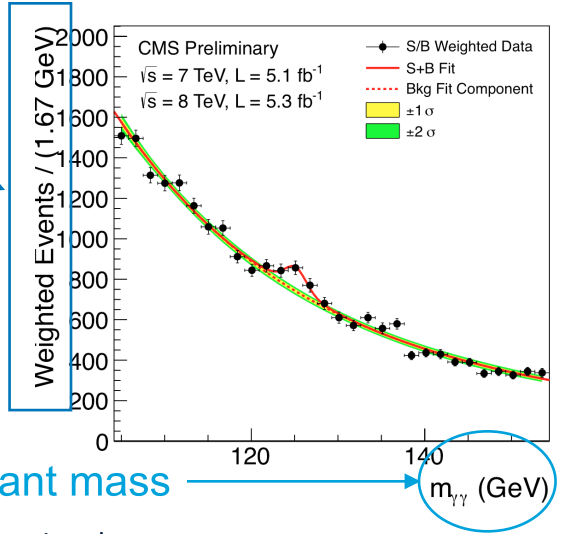
Number of entries per bin width (~density)



We need to measure the energy and the angle of the two photons



Data points - fit



Invariant mass

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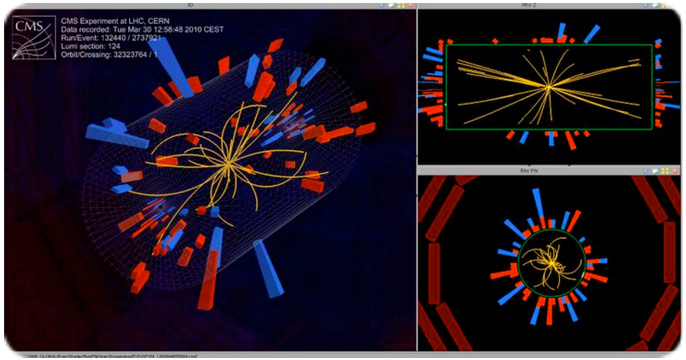
Interaction of particles with matter

- The goal of (modern) particle physics experiments is to reconstruct and identify all particles produced in a collision
- Usage of various techniques reflected in the experimental setup
- Profit from knowledge of how particles interact with matter
  - Interaction of charged particles with matter
  - Electromagnetic interactions of electrons and photons
  - Strong interactions of charged and neutral hadrons



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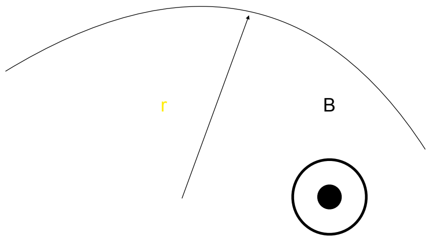
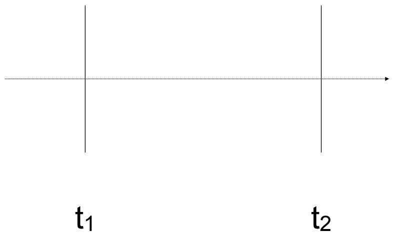
Detection vs identification

- Detection: did a particle cross a given area?
- Identification: what kind of particle crossed a given area?
  - Requires measurement of the mass and the charge of a particle
- In most cases detectors are placed inside a magnetic field
  - Measure the momentum of a particle through its curvature
  - Measure velocity through the time-of-flight technique



$$r = \frac{P}{ZeB} \propto \frac{P}{Z} = \frac{m\gamma\beta c}{Z}$$



$$\Delta t = \frac{l}{\beta}$$

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Basic setup

- To measure the momentum of particles, a suitable magnetic field is applied inside this barrel region

- **Electrons** are identified as charged-particle tracks that leave hits in the **tracking detectors** and subsequently initiate an electromagnetic shower in the **electromagnetic calorimeter**

Basic setup

- **Neutral particles** are either reconstructed in the **tracking detectors** (e.g. decays) or their energy is measured in **calorimeters**
  - **Photons** are identified in the electromagnetic calorimeter as sources of isolated showers
  - **Neutral hadrons** will interact with the material in the hadronic calorimeter and initiate an isolated hadronic shower

Basic setup

- **Charged hadrons** will be reconstructed from their hits in the **tracking detectors**, followed by the combination of a **small energy deposition** via ionisation energy loss in the **electromagnetic calorimeter** and a **large energy deposition** in the **hadronic calorimeter**

- **Muon tracks** are detected by **special detectors** outside the calorimeters are sensitive to their passage, in combination with hits in the **tracking detectors** and very **small energy deposition** in both the **electromagnetic and the hadronic calorimeters**

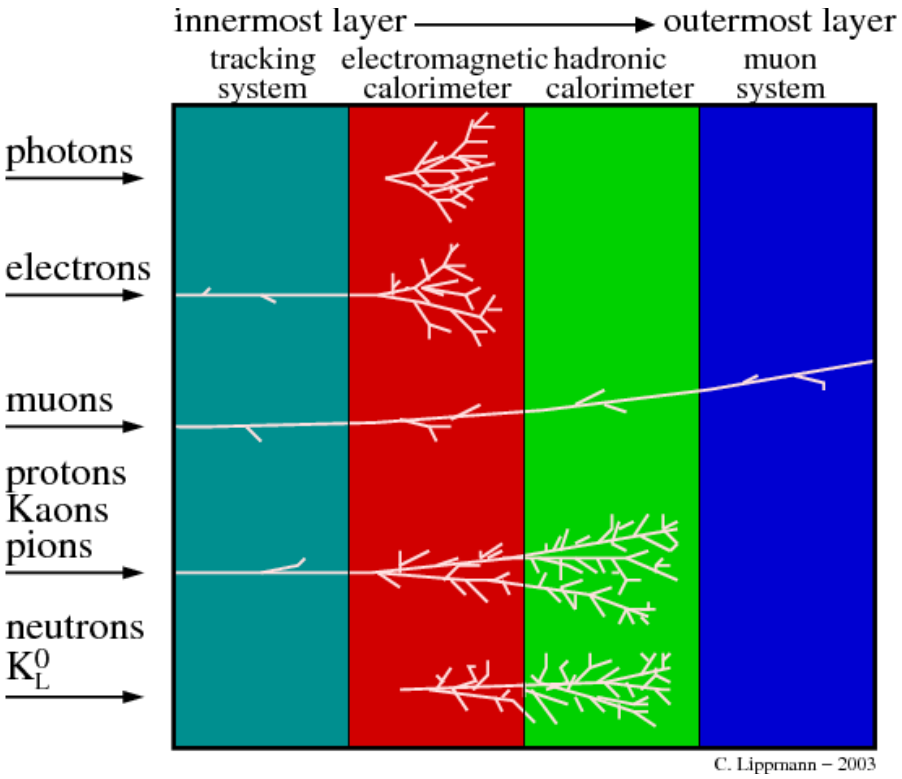
Basic setup

- One of the last pieces of the puzzle is the detection of **neutrinos**
  - Neutrinos barely interact with matter
  - However they are carriers of important information and thus need to be accounted for
  - Their presence in modern particle physics experiments, whose purpose is not solely the detection of neutrinos, is through the presence of missing momentum, defined as

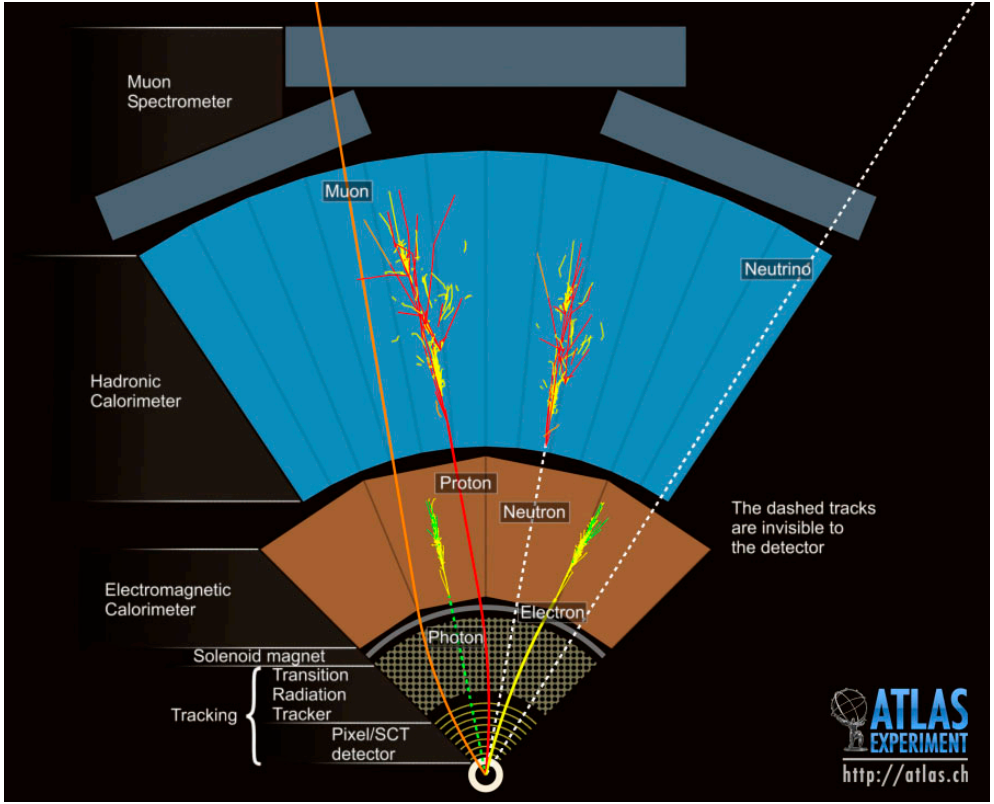
$$\vec{P}_{\text{missing}} = -\sum_{i=1}^{N} \vec{P}_i$$

    - where the sum extends over all measured momenta of all observed particles in all directions of an event
    - If all particles produced in the collision are detected, this sum should be zero provided that the collisions take place in the centre-of-mass frame
    - Any significant deviation from zero indicates the presence of energetic neutrinos in the event

Basic considerations



An example…



Muon
Spectrometer
Muon
Neutrino
Hadronic
Calorimeter
Proton
Neutron
The dashed tracks
are invisible to
the detector
Electromagnetic
Calorimeter
Electron
Photon
Solenoid magnet
Transition
Radiation
Tracker
Tracking
Pixel/SCT
detector
ATLAS
EXPERIMENT
http://atlas.ch

And a bit of computing…

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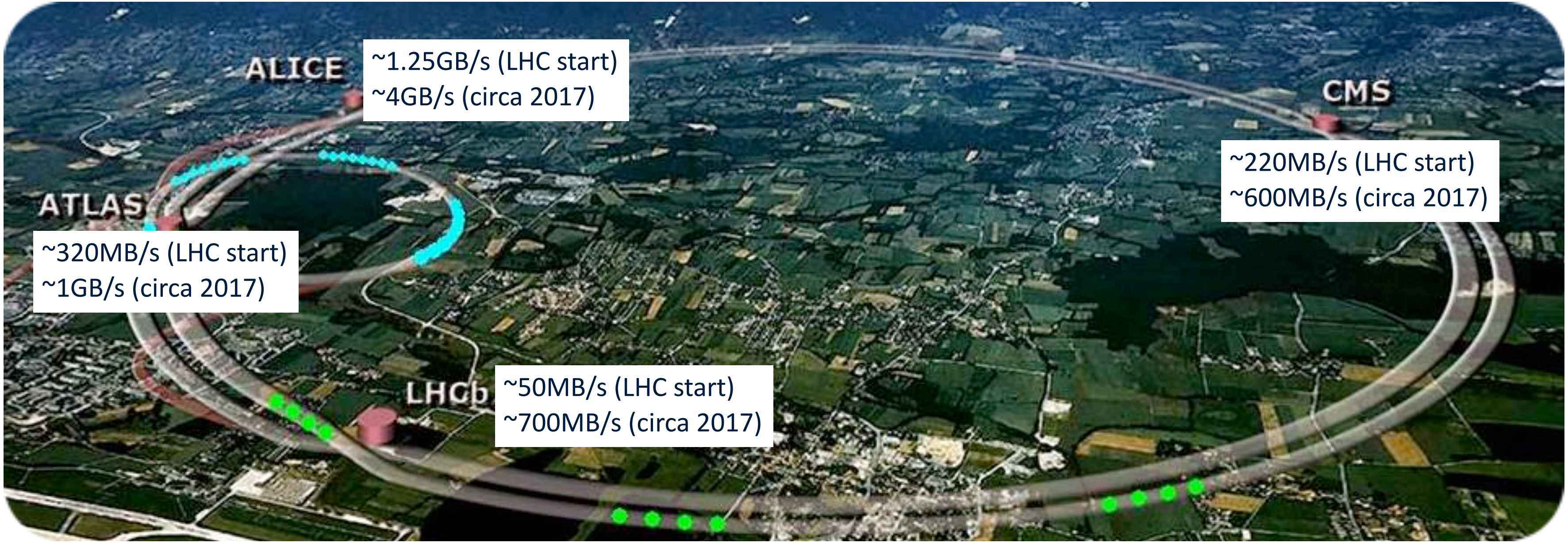
The LHC: DAQ/reconstruction/storage

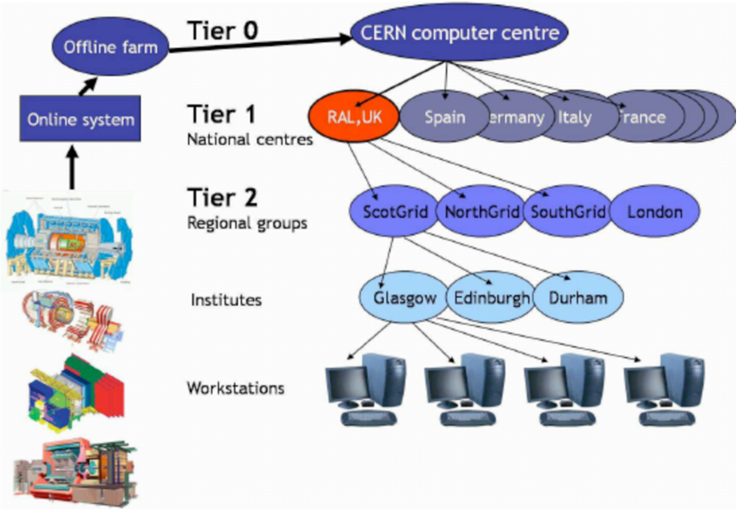
Delivers pp collisions for ~11 months per year and PbPb (or pPb) for one month

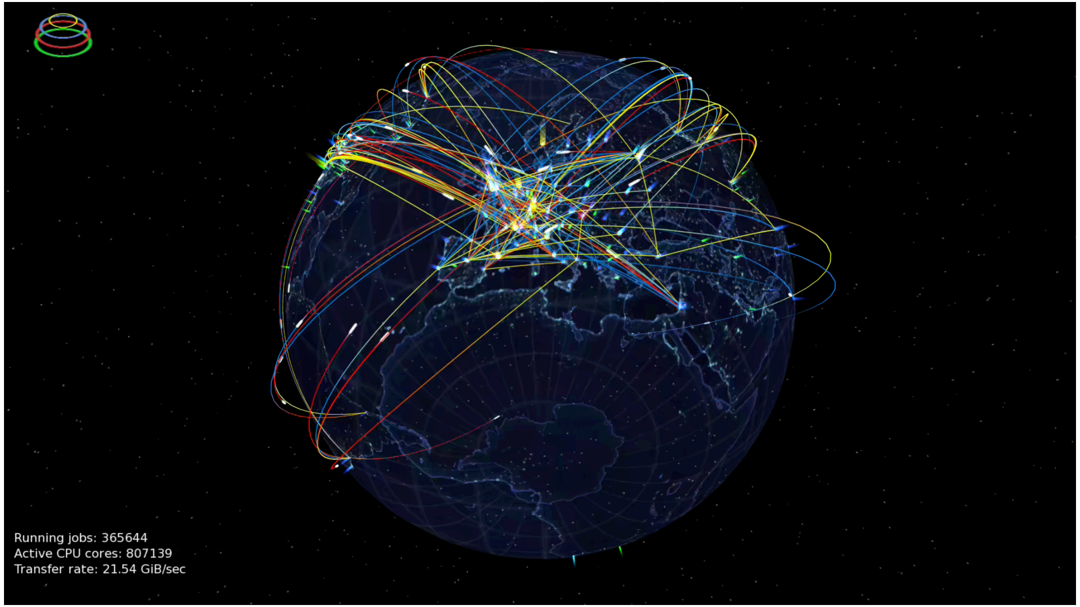


1 PB/s of data generated by the detectors, up to 60 PB/year of stored data: raw and reconstructed collisions data, calibration runs, MC data

The worldwide LHC computing GRID (WLCG)

An international collaboration to distribute and analyse LHC data



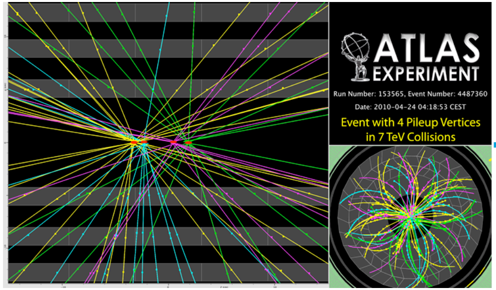


Integrates computer centers worldwide with heterogeneous architectures that provide computing and storage resources into a single infrastructure accessible by all LHC physicists

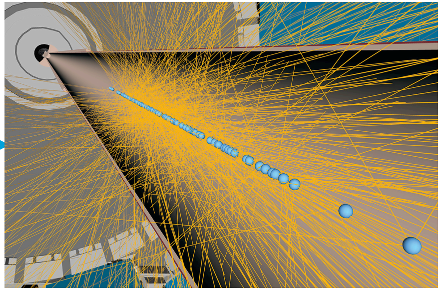
Some of the challenges at the LHC

- Extreme event rates of 40MHz
- Extreme pile-up in pp collisions:
  - Up to 200 overlapping proton-proton interactions per bunch crossing at HL-LHC
  - ~**10,000 detector hits** per event in tracking systems
  - Makes it extremely hard to tell which hit belongs to which particle/interaction
- Extreme track densities in heavy ion collisions
- Low momentum tracking is essential → unique focus of ALICE

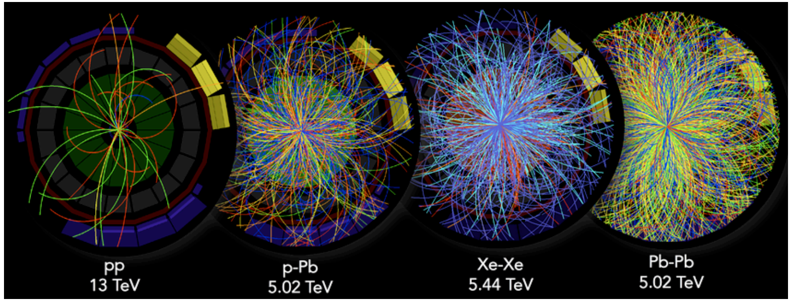
Run 1@LHC



HL-LHC



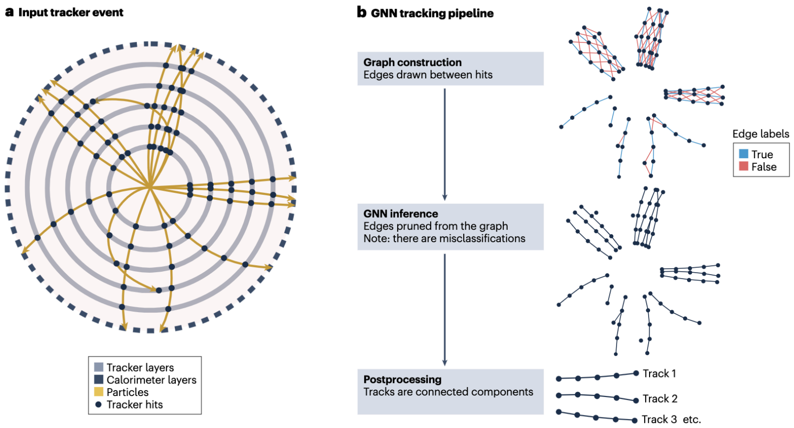
Heavy-ions@LHC



New paradigm

- AI/ML Models (GNNs, CNNs, Transformers)
  - Capable of learning **global event structure**,
  - Robust, in principle, to missing hits, pile-up, and non-ideal detector conditions
- Usage of GPUs or/and **FPGAs**:
  - excellent for **parallelizable** workloads like clustering, track seeding, real-time pattern recognition (e.g., trigger applications).
- Quantum computing
  - Collaboration with DACS or/and GWFP

G. DeZoort et al., Nature Rev. Phys. (2023)



Questions?

Thank you for your attention

Theory of strong interactions

Quantum Chromo Dynamics (QCD) born in 1973

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field-theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Non-Abelian gauge theories have received much attention recently as a means of constructing unified and renormalizable theories of the weak and electromagnetic interactions.[1] In this note we report on an investigation of the ultraviolet (UV) asymptotic behavior of such theories. We have found that they possess the remarkable feature, perhaps unique among renormalizable theories, of asymptotically approaching free-field theory. Such asymptotically free theories will exhibit, for matrix elements of currents between on-mass-shell states, Bjorken scaling. We therefore suggest that one should look to a non-Abelian gauge theory of the strong interactions to provide the explanation for Bjorken scaling, which has so far eluded field-theoretic understanding.

The UV behavior of renormalizable field theories can be discussed using the renormalization-group equations,[2,3] which for a theory involving one field (say $g\varphi^4$) are

$$[m\partial/\partial m + \beta(g)\partial/\partial g - n\gamma(g)]\Gamma_{\text{asy}}^{(n)}(g; P_1, \ldots, P_n) = 0.$$

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

[14]Y. Nambu and G. Jona-Lasino, Phys. Rev. 122, 345 (1961); S. Coleman and E. Weinberg, Phys. Rev. D 7, 1888 (1973).
[15]K. Symanzik (to be published) has recently suggested that one consider a $\lambda\varphi^4$ theory with a negative λ to achieve UV stability at $\lambda = 0$. However, one can show, using the renormalization-group equations, that in such theory the ground-state energy is unbounded from below (S. Coleman, private communication).
[16]W. A. Bardeen, H. Fritzsch, and M. Gell-Mann, CERN Report No. CERN-TH-1538, 1972 (to be published).
[17]H. Georgi and S. L. Glashow, Phys. Rev. Lett. 28, 1494 (1972); S. Weinberg, Phys. Rev. D 5, 1962 (1972).
[18]For a review of this program, see S. L. Adler, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published).

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
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(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

The Nobel Prize in Physics 2004


David J. Gross


H. David Politzer


Frank Wilczek

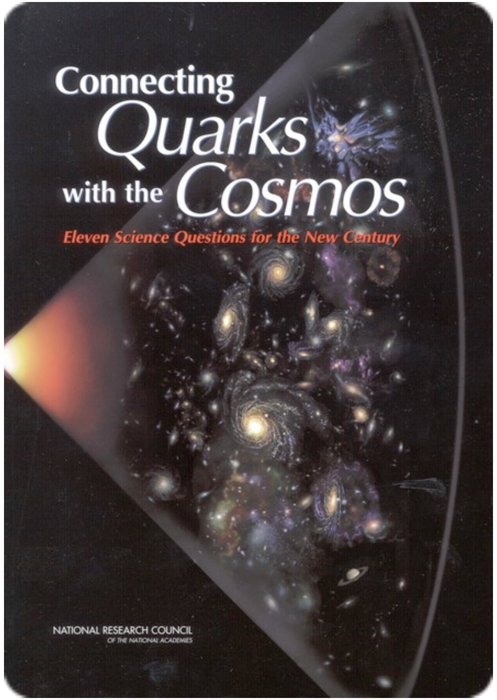
The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.

(SOME of the) scientific challenges (~2000)

How did the universe begin and evolve?

There is evidence that during its earliest moments the universe underwent a tremendous burst of expansion, known as inflation, so that the largest objects in the universe had their origins in subatomic quantum fuzz. The underlying physical cause of this inflation is a mystery.

In addition, the universe evolved passing through the EW and the strong phase transition, through a state of extreme conditions which are too of a complete mystery.



What are the new states of matter at exceedingly high density and temperature?

The theory of how protons and neutrons form the atomic nuclei of the chemical elements is well developed.

At higher densities, neutrons and protons may dissolve into an undifferentiated "soup of quarks and gluons", which can be probed in heavy-ion accelerators.

Densities beyond nuclear densities occur and can be probed in neutron stars, and still higher densities and temperatures existed in the early universe.

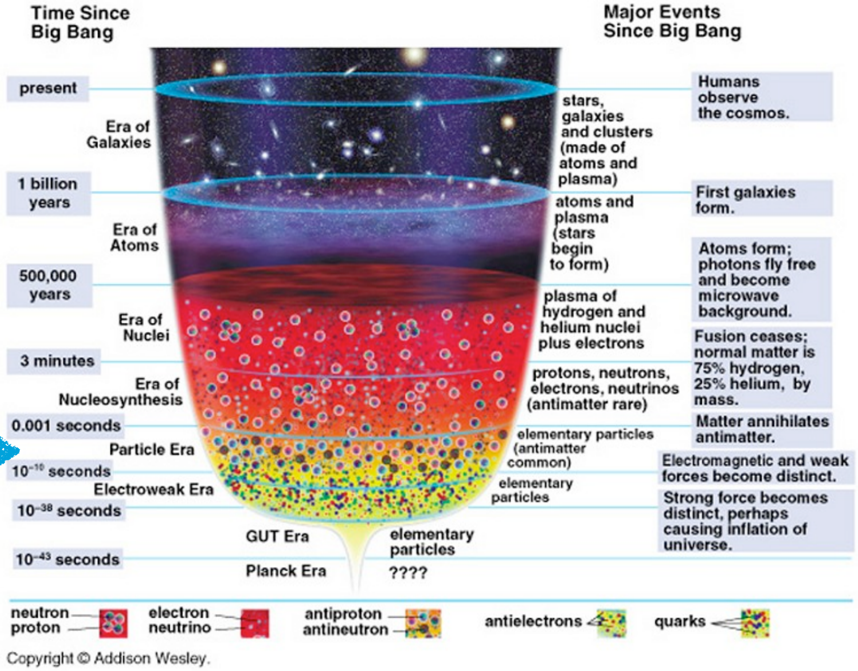
The early Universe

How did the universe begin and evolve?

There is evidence that during its earliest moments the universe underwent a tremendous burst of expansion, known as inflation, so that the largest objects in the universe had their origins in subatomic quantum fuzz. The underlying physical cause of this inflation is a mystery.

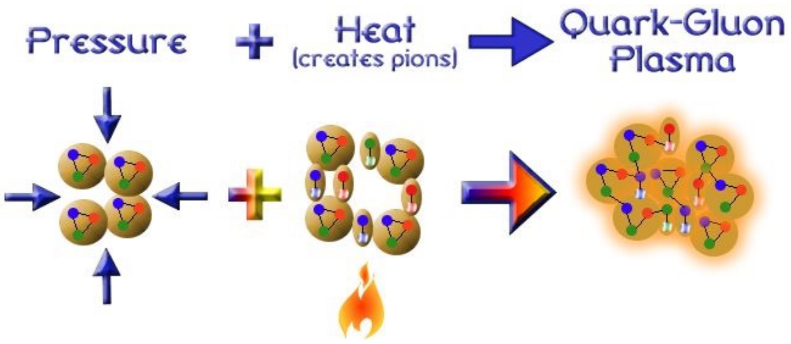
In addition, the universe evolved passing through the EW and the strong phase transition, through a state of extreme conditions which are too of a complete mystery.

Strong phase transition: Few μs after the start



Strong phase transition in the lab

- How can we recreate in the laboratory the necessary conditions for the phase transition to occur?
  - “Smash” large objects, accelerated at almost the speed of light to each other
    - Concentrate large amount of energy in a small volume
    - Create high pressure
    - Create high temperatures



Create similar conditions as the ones in the early universe:

Use heavy-ion collisions!!!

Panos.Christakoglou@maastrichtuniversity.nl

Studying QCD matter at extreme conditions

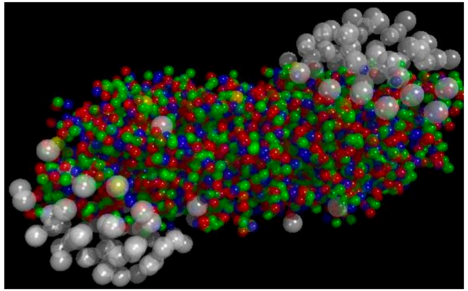
Series of experiments at:
- Bevalac (HI between 1980-1993)
- AGS (Si/Au beams ~1986-1994)
- SPS (S/Pb beams ~1987-Today)
- RHIC (Au beams, 2000-Today)
- LHC (Pb beams, 2010-Today)

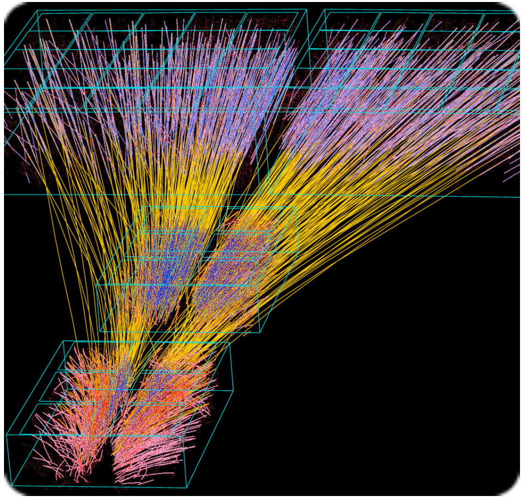
CERN-SPS

Fixed target experiments
(event display courtesy of NA49)

New State of Matter created at CERN

10 Feb 2000





Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

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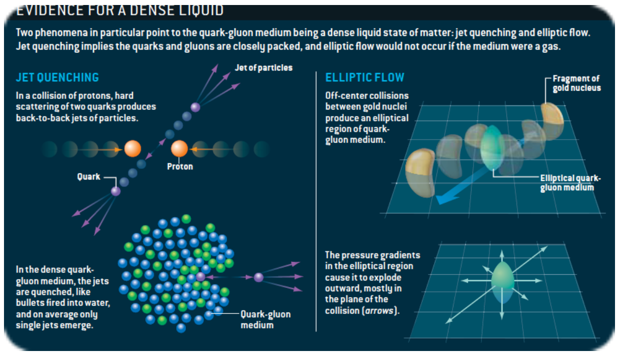
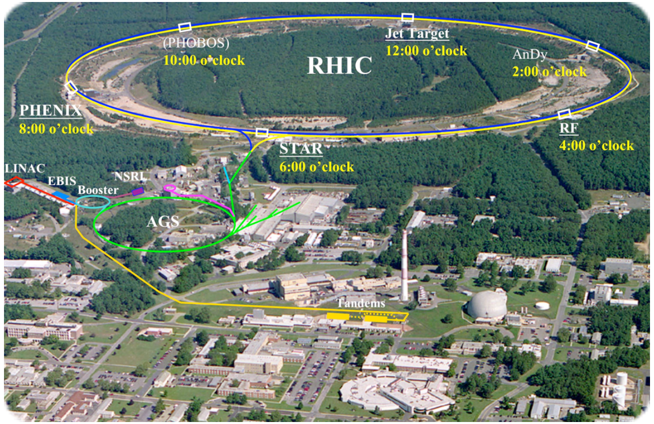
M. Roirdan and W. Zajc, Scientific American 34A May (2006)

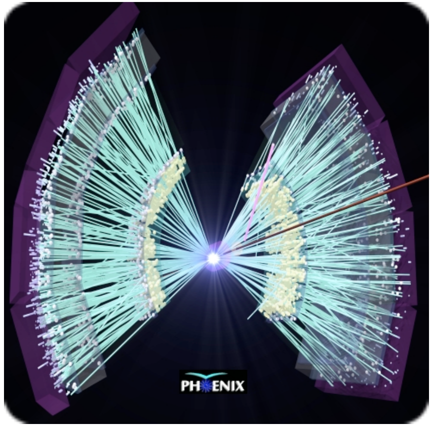


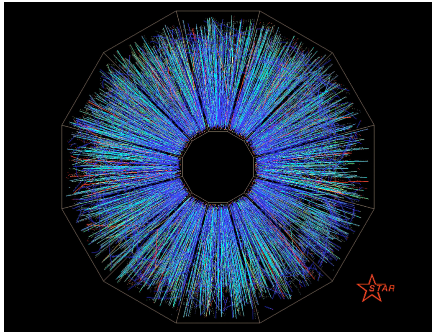
The birth of the perfect fluid paradigm

BNL-RHIC



Collider experiments (event displays courtesy of PHENIX and STAR)





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