Introduction to Particle Physics & Applications

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What I am going to do …

- **Explain why we need particle colliders**
- **Show examples of discoveries in particle physics before the Large Hadron Colliders**
- **Describe the searches and discovery of the Higgs boson**
- **Highlight unresolved mysteries and prospect**

Relativistic kinematics revision

I assume you are OK with simple relatistic kinematics, such as the relation

$$E^2 = p^2 c^2 + m^2 c^4$$

which I'll write (setting c=1) $E^2 = p^2 + m^2$ ("natural units" ħ=c=1)

trivially giving $m^2 = E^2 - p^2$

The rest mass of the particle, *m*, can be evaluated in any inertial frame and is always the same – it is a *Lorentz invariant*

This generalises to a system of particles, where we talk about the *invariant mass*

$$m_{inv}^2 = (\sum_i E)^2 - (\sum_i \vec{p})^2$$

For a system of two colliding particles, m_{inv} is normally written $\surd s$ (the centre-of-mass energy) - it too is (naturally) a Lorentz invariant quantity

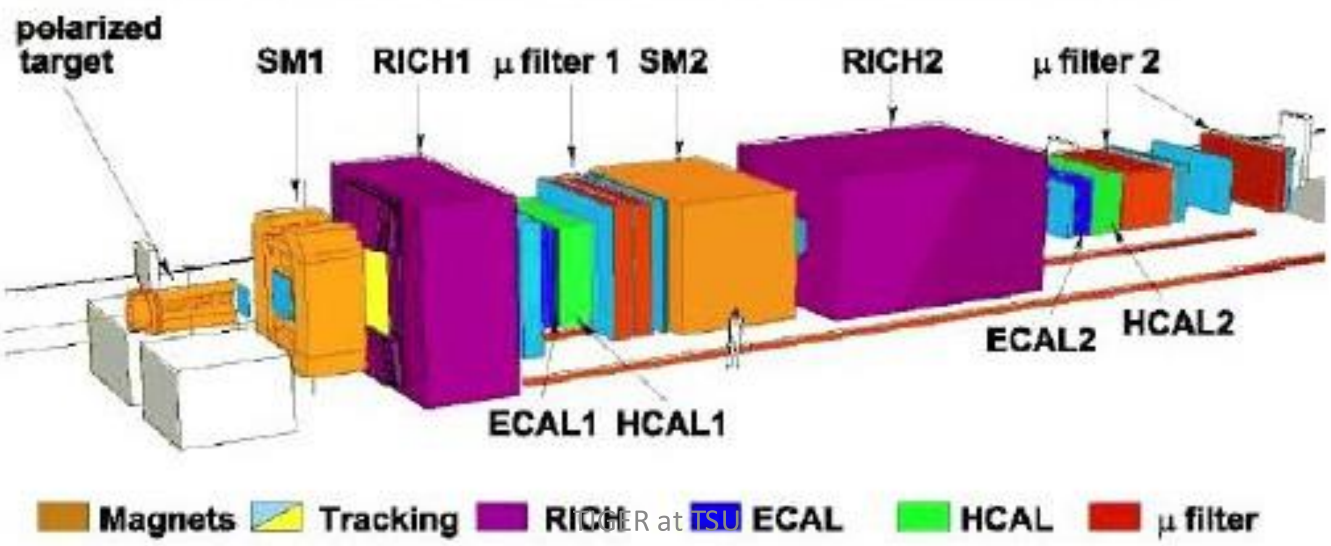
Why colliders?

High-energy *experiments* use accelerators in two ways: fixed targets or colliders

- Fixed target
  - Beam of energy E strikes a target particle with mass m

$$(E,\mathbf{p}) \longrightarrow \bullet \quad (m,\mathbf{0})$$

  - Provided $E \gg m$, centre-of-mass energy $\sqrt{s} \approx \sqrt{2Em}$
  - Because the beam can be stopped by the target, high luminosities are possible
  - Boosted collision system in the lab frame (can be good or bad)



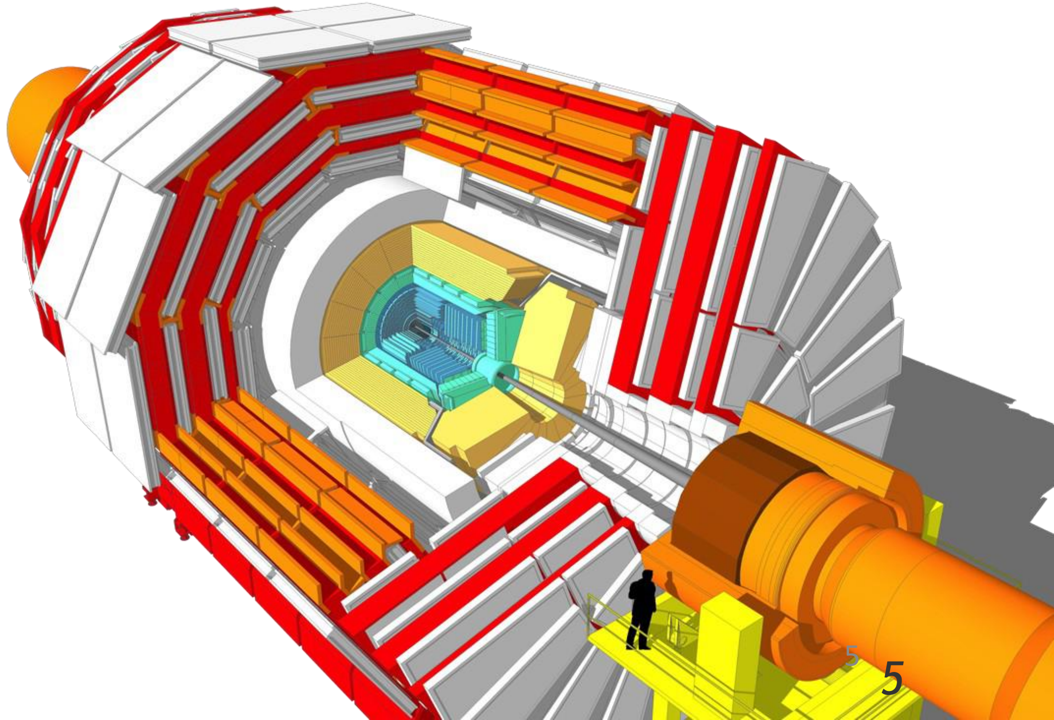
Why colliders?

High-energy *experiments* use accelerators in two ways: fixed targets or colliders

- Colliders
  - Two beams collide, usually particles having same m and equal and opposite momenta

$$(E,\mathbf{p}) \longrightarrow \longleftarrow (E,-\mathbf{p})$$

  - Provided $E \gg m$, centre-of-mass energy $\sqrt{s} \approx 2E$ – *grows with E rather than* $\sqrt{E}$
  - *Much* higher $\sqrt{s}$ for e.g. 100 GeV to TeV beams
  - Big challenge to have high luminosities → squeezed beams, many bunches … …
  - Must accelerate two beams - complexity



Why colliders?

At high beam energy

Fixed target

- $\sqrt{s} \approx \sqrt{(2Em)}$
- very high luminosities "easily" possible
- boosted collision system in the lab

Colliders

- $\sqrt{s} \approx 2E$
- high luminosities difficult
- must accelerate two beams – complexity
- may be in CM frame of final system (e^+e^-)

If you want to study very rare processes, fixed target often wins
e.g. neutrino experiments!
(but not always – B factories)

If you want to search for new physics at high masses/energies – better build a collider

Rates, luminosities and cross-sections

In a collider, the rate, dN_a/dt, of events produced for a given process *a* is:

$$dN_a/dt = \sigma_a L$$

where

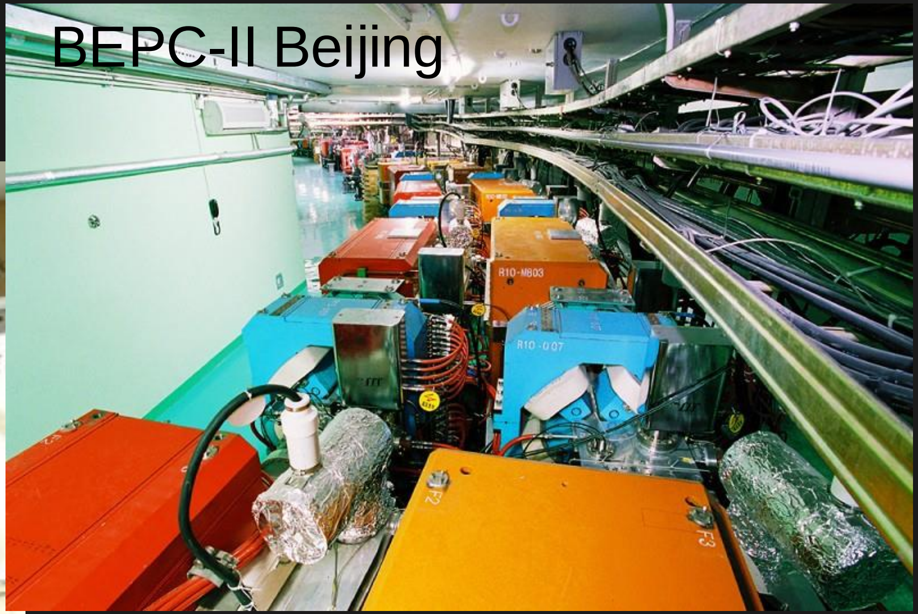
- σ_a is the *cross-section* for the process
  - units of area (1 barn = 10^{-28} m^2 = 10^{-28} cm^2)
  - typically mb, μb, nb, pb and fb are (all) met for different processes!
  - it depends on the physics process, eg. pp → W + anything and the centre-of-mass energy $\sqrt{s}$
- L is the instantaneous luminosity, usually called the luminosity
  - units of inverse-area per unit time (typically ~10^{34} cm^{-2} s^{-1} at LHC)
  - Process-independent, depends only on the beam characteristics

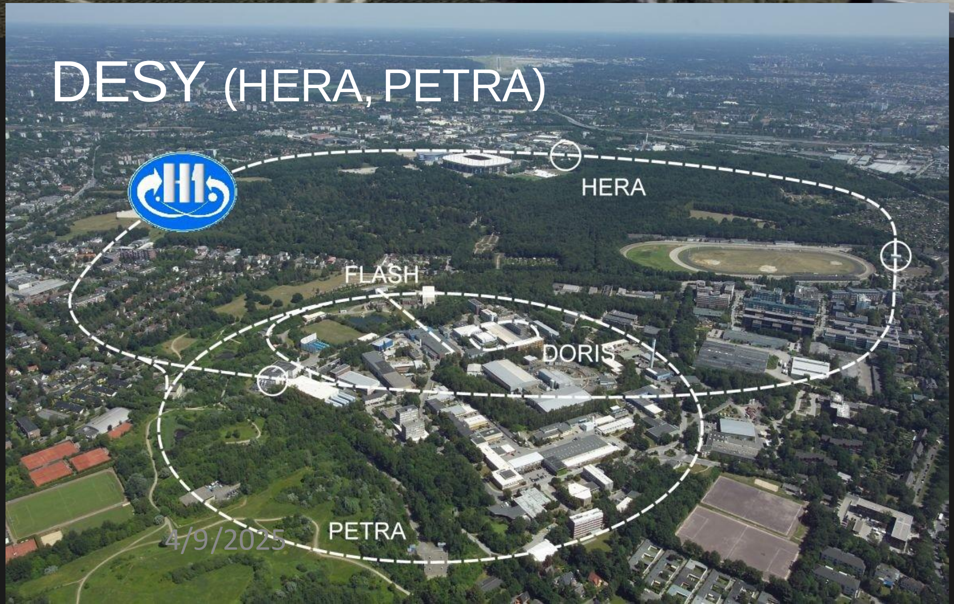
Integrated version:

$$N_a = \sigma \int L dt$$

where $\int L dt$ is the integrated luminosity, typically expressed in fb^{-1}

Particle colliders have a long history



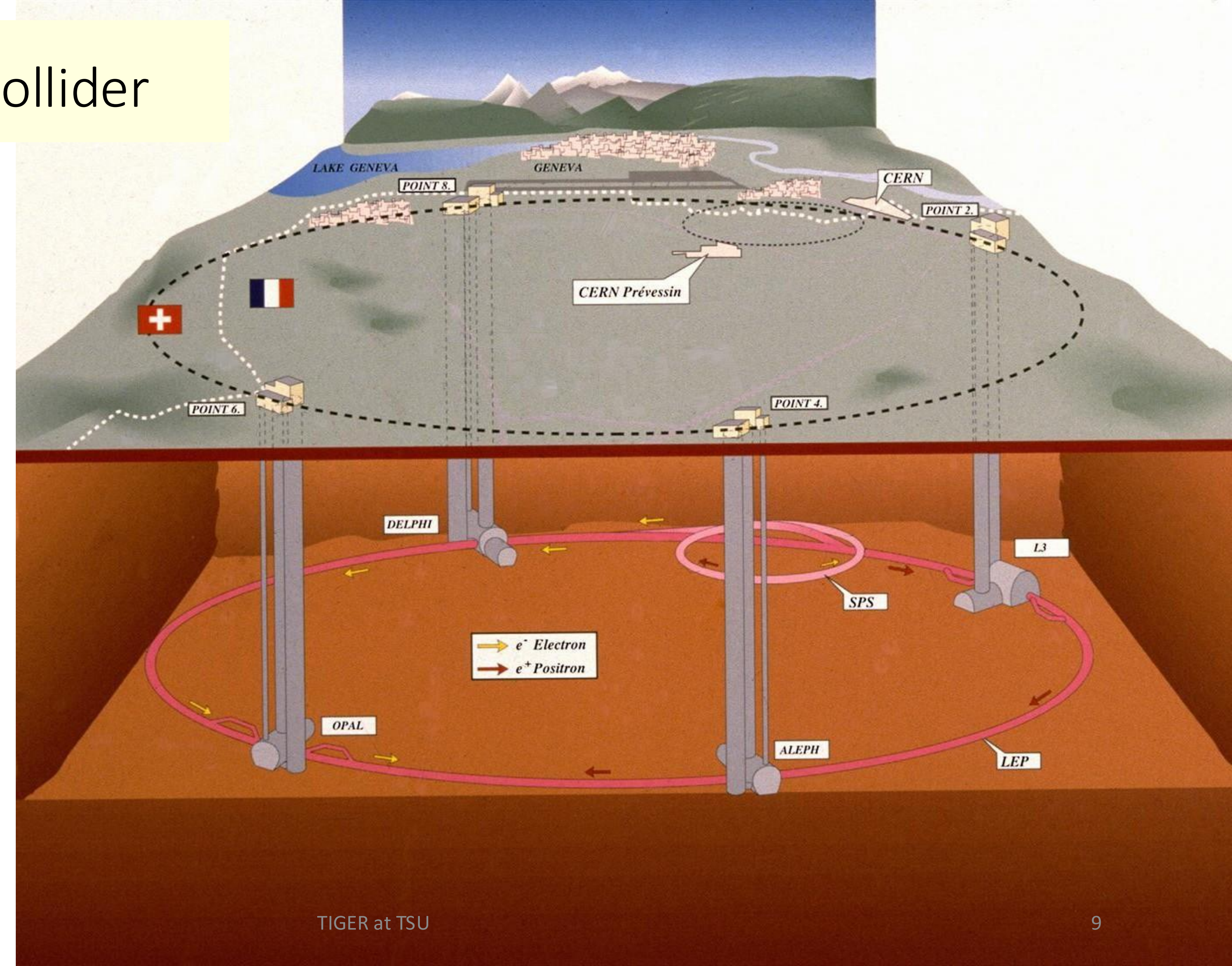


The LEP e^+e^- Collider

Large Electron-Positron Collider

Huge 27km circumference tunnel excavated in the 1980's

Four experiments, all aiming at all physics topics accessible ("general purpose detectors")



LEP data

Centre-of-mass energy √s=88-209 GeV

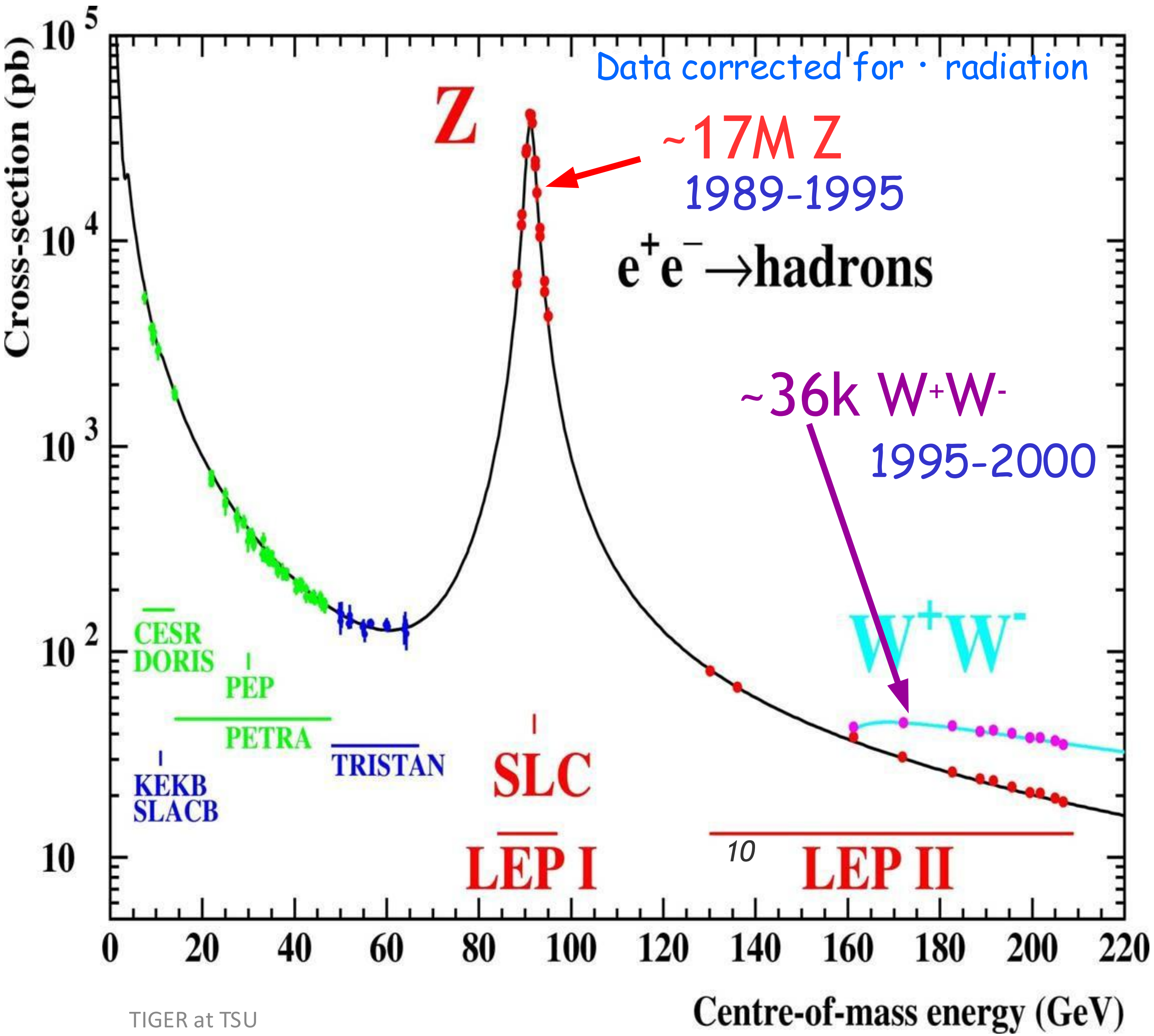
- LEP-1 at Z peak
- LEP-2 at high energy

LEP-1: high precision measurements of Z

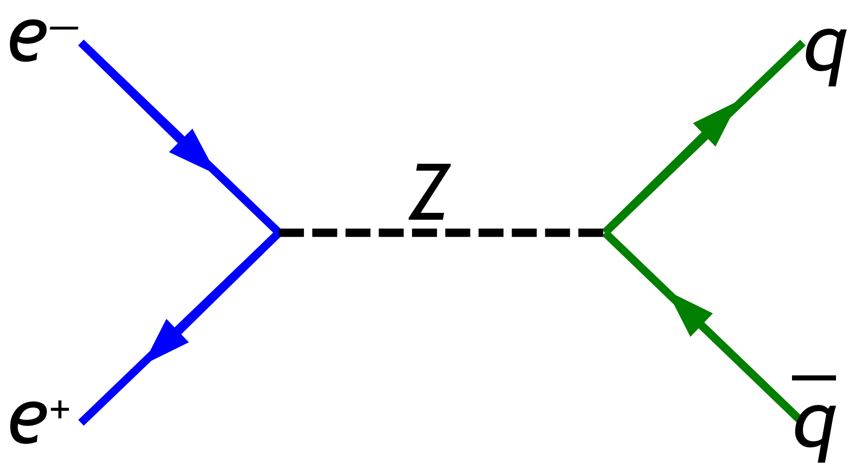
- Z mass, width, couplings to fermions
- Number of light neutrino species …

LEP-2: WW and ZZ production

- W mass and couplings
- Searches …



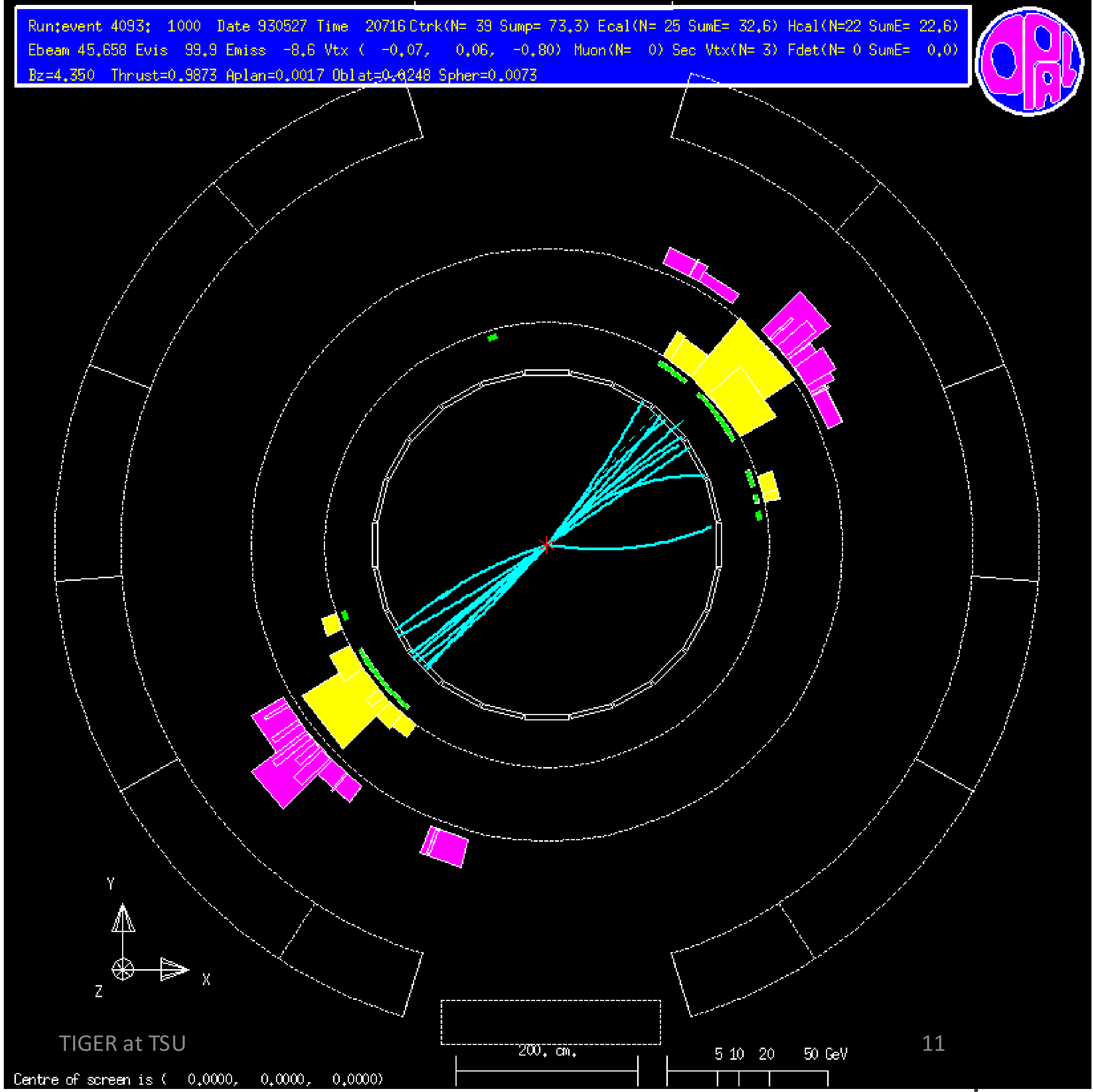
$e^+e^- \longrightarrow$ hadrons at LEP
"2-jet" event



$e^+e^- \longrightarrow q\bar{q}$

Quarks hadronise to form two back-to-back jets

Rest of event is very clean in e^+e^- collisions – no “underlying event” as seen in hadron collisions



Tevatron

Tevatron at Fermilab, USA

Ran from 1986 – 2011

Proton-antiproton collisions at $\sqrt{s}$=1.8 to 1.96 TeV

Two experiments CDF and D0

Numerous physics measurements and observations (e.g. first observation of B-B time dependent oscillations)

The Tevatron's most famous achievement was to complete the family of quark flavours...

Discovery of the top quark

Co-discovered by CDF+D0 in 1995

Decay chain:

tt → WbWb

W→ℓν, W→qq'

At least one *b*-jet identified by looking for a displaced *b*-hadron decay

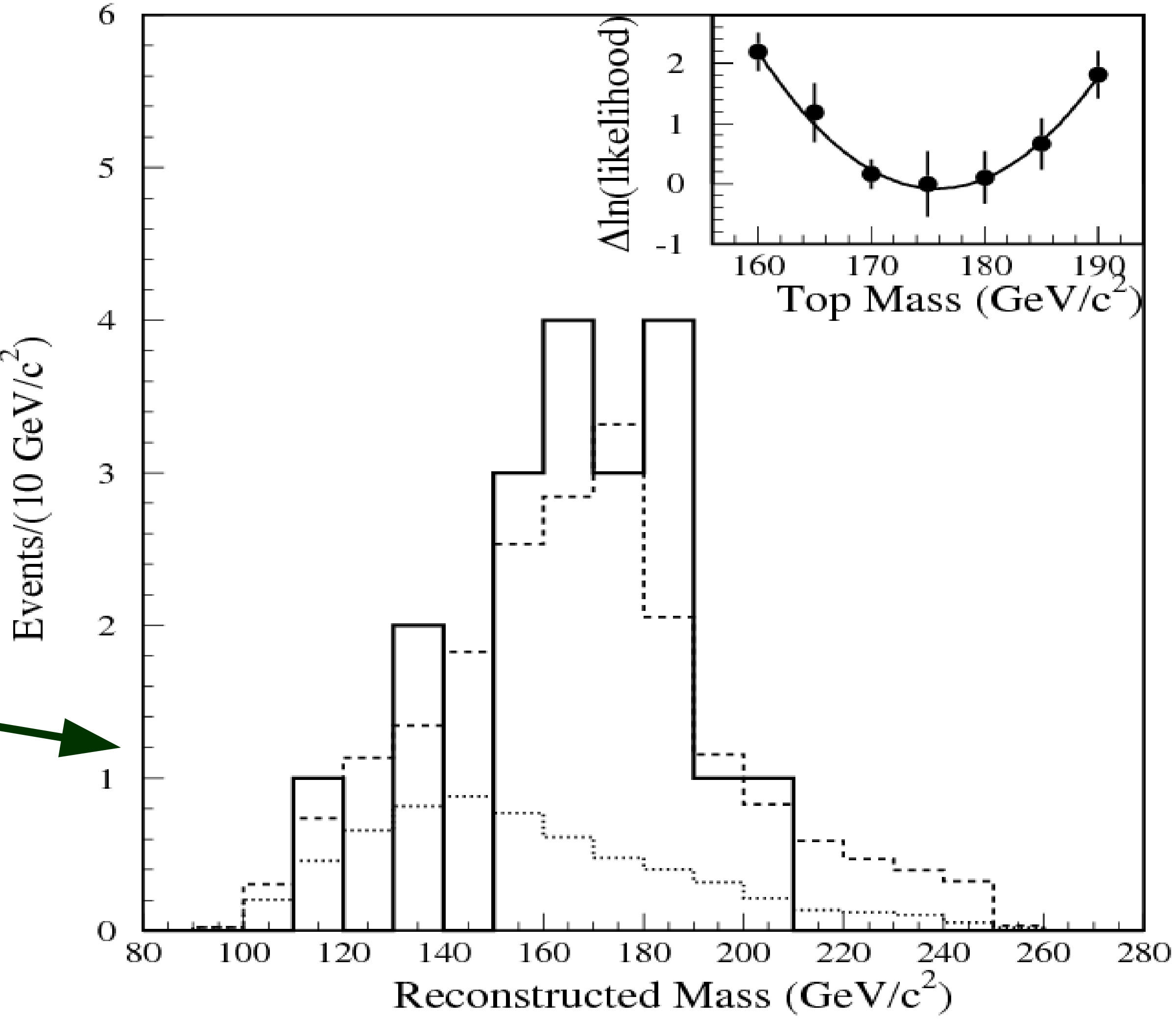
Reconstruct m(*tt*) from decay products (jets, leptons, missing-p_T)

FERMILAB-PUB-95/022-E
CDF/PUB/TOP/PUBLIC/3040

Observation of Top Quark Production in $\bar{p}p$ Collisions with the CDF Detector at Fermilab

Abstract

We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be 176 ± 8(stat.) $\pm$ 10(sys.) GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.



Mass of top quark ~ 175 GeV!!!

"Who ordered that?"

Preliminary Summary

- The CERN-SppS, CERN-LEP and Fermilab-Tevatron colliders in the 1980's and 1990's established and measured many processes, masses and interactions

- The electroweak bosons W, Z of the Standard Model were discovered by UA1/UA2, and measured with very high precision at LEP(+SLD)
  - Couplings of the Z to fermions very precisely probed
  - Interactions between gauge bosons started to be probed, but weakly

- Highly convincing that gauge theories are at the root of fundamental physics
  - Nobel prize to 't Hooft and Veltman in 1999

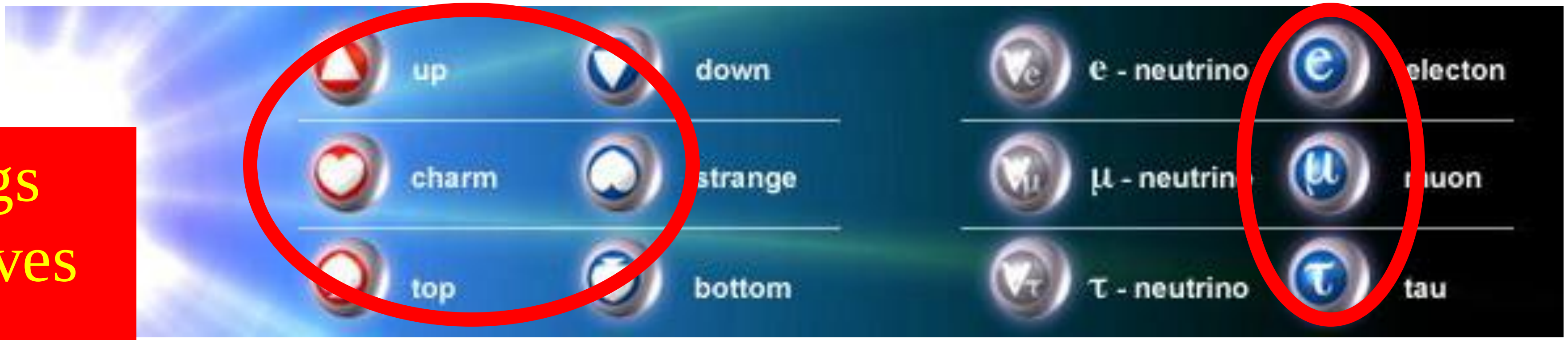
- The top quark was discovered at the Tevatron, and found to be shockingly heavy!

- However, many questions left, requiring the LHC
  - What breaks the electroweak symmetry (making the W,Z massive and the photon light)
  - What gives mass to fermions?
  - Is there new physics at the TeV energy scale?
  - Dark matter?
  - …

The 'Standard Model'

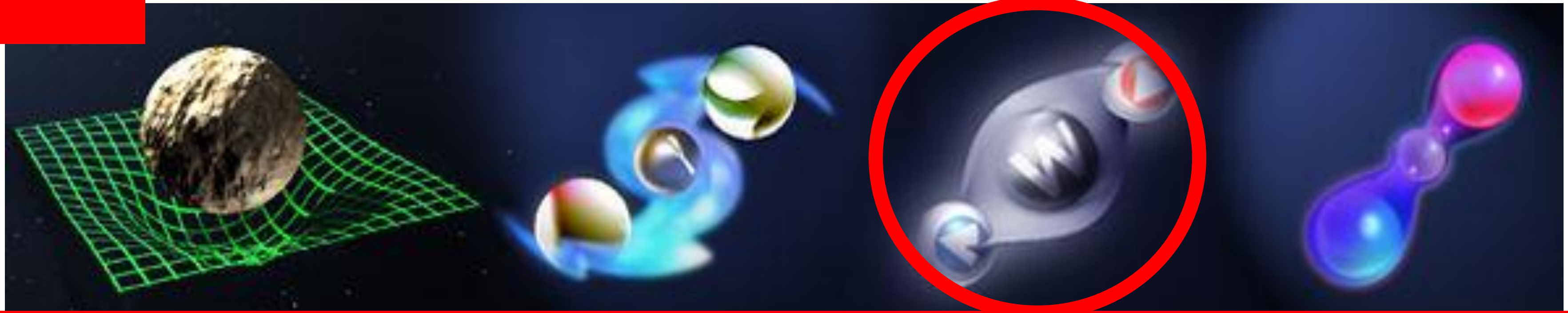
= Cosmic DNA

The matter particles



The Higgs boson gives mass to fundamental particles

The fundamental interactions



Gravitation | electromagnetism | weak nuclear force | strong nuclear force

Without Higgs …

… there would be no atoms

- massless electrons would escape at the speed of light

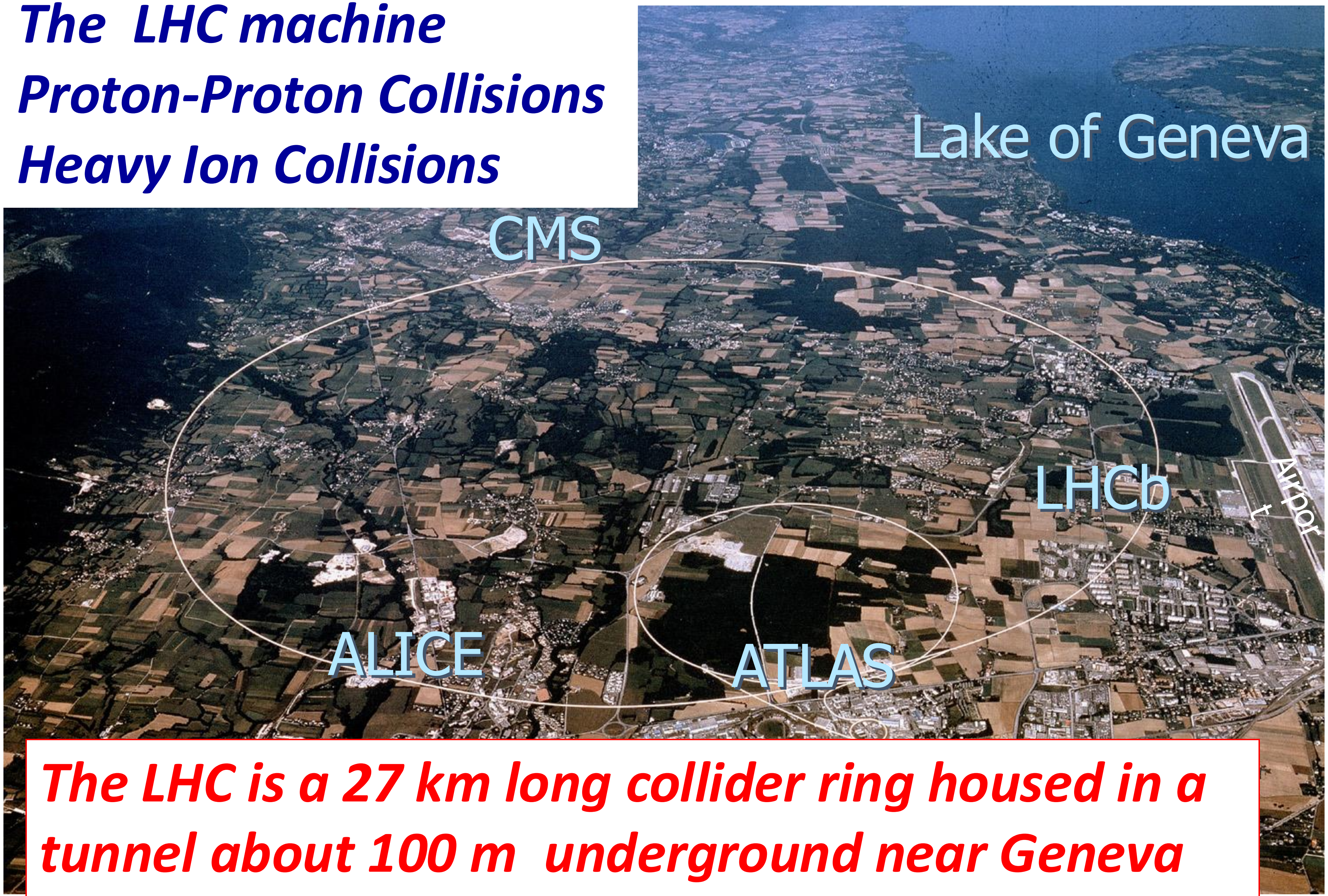
… there would be no heavy nuclei

… weak interactions would not be weak

- Life would be impossible: everything would be radioactive

Its existence is a big deal!

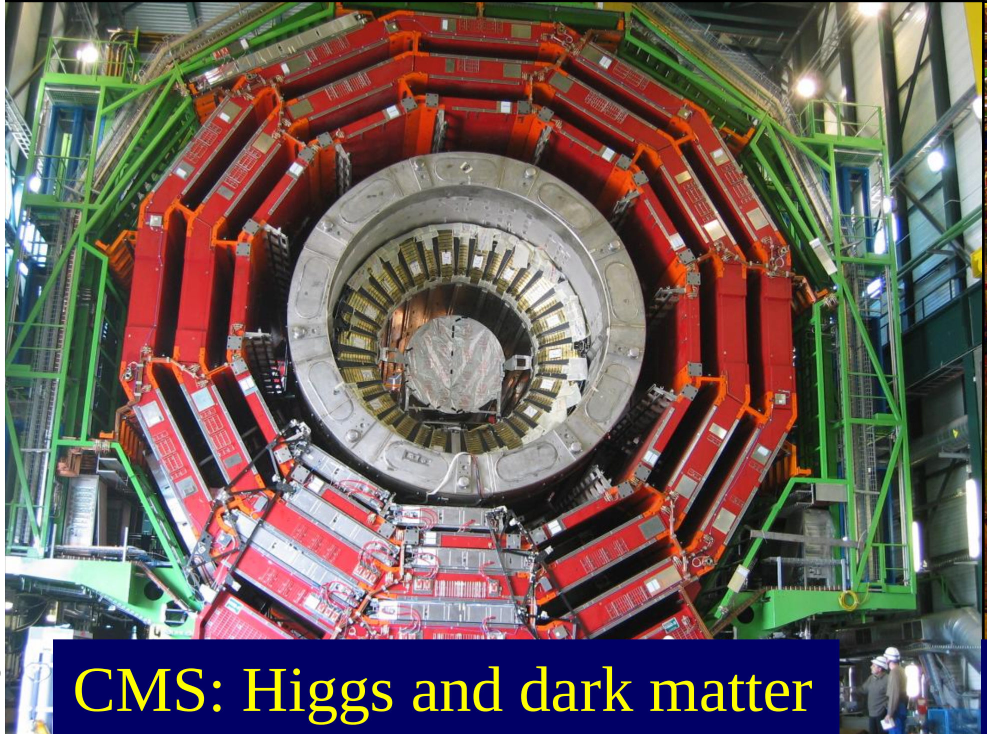
The LHC machine
Proton-Proton Collisions
Heavy Ion Collisions



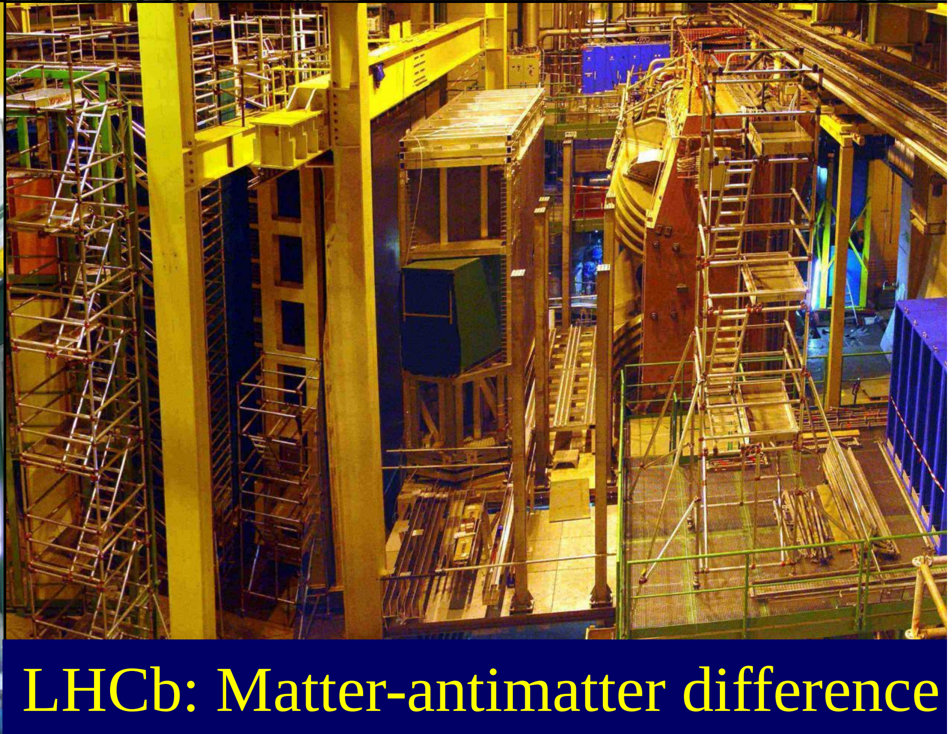
The LHC is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

ALICE: Primordial cosmic plasma

ATLAS: Higgs and dark matter

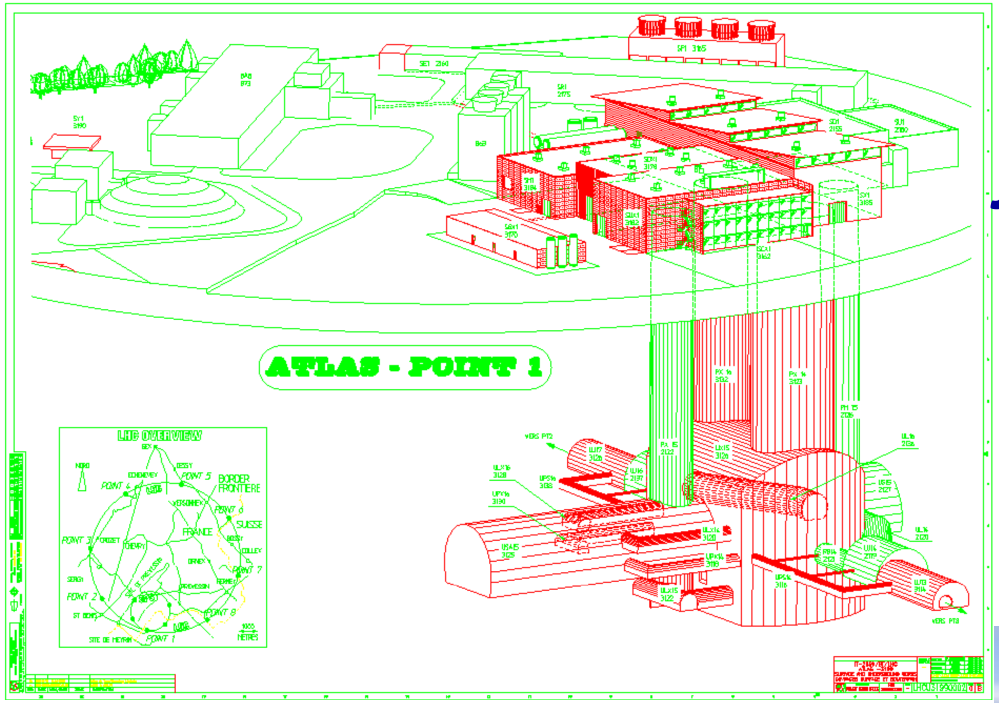


CMS: Higgs and dark matter

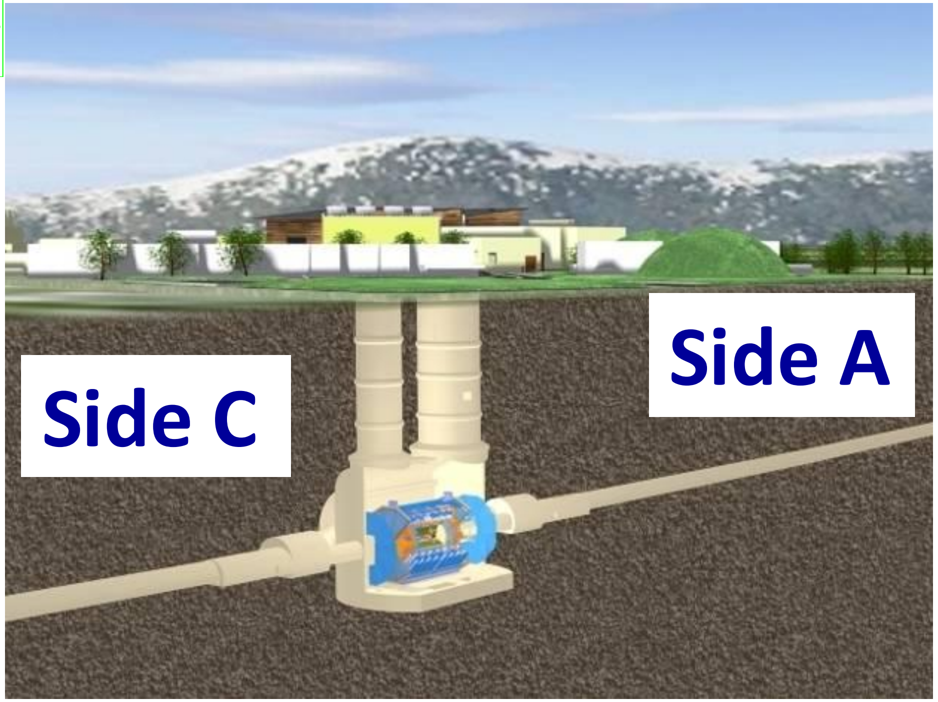


LHCb: Matter-antimatter difference

The Underground Cavern for the ATLAS Detector



Length = 55 m
Width = 32 m
Height = 35 m

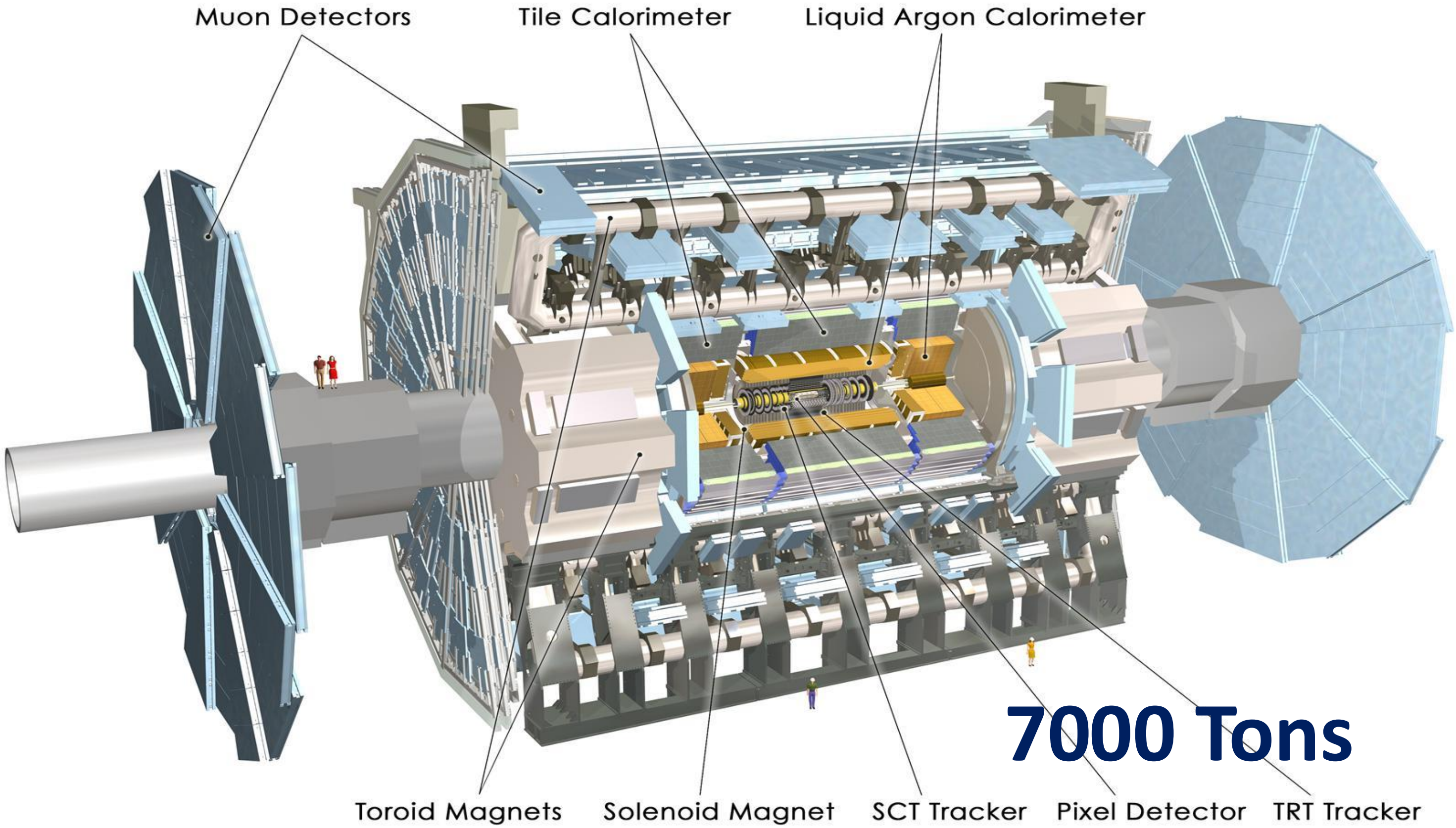


ATLAS Detector at the LHC

~3000 Physicists
550M Suisse Franks

45 m

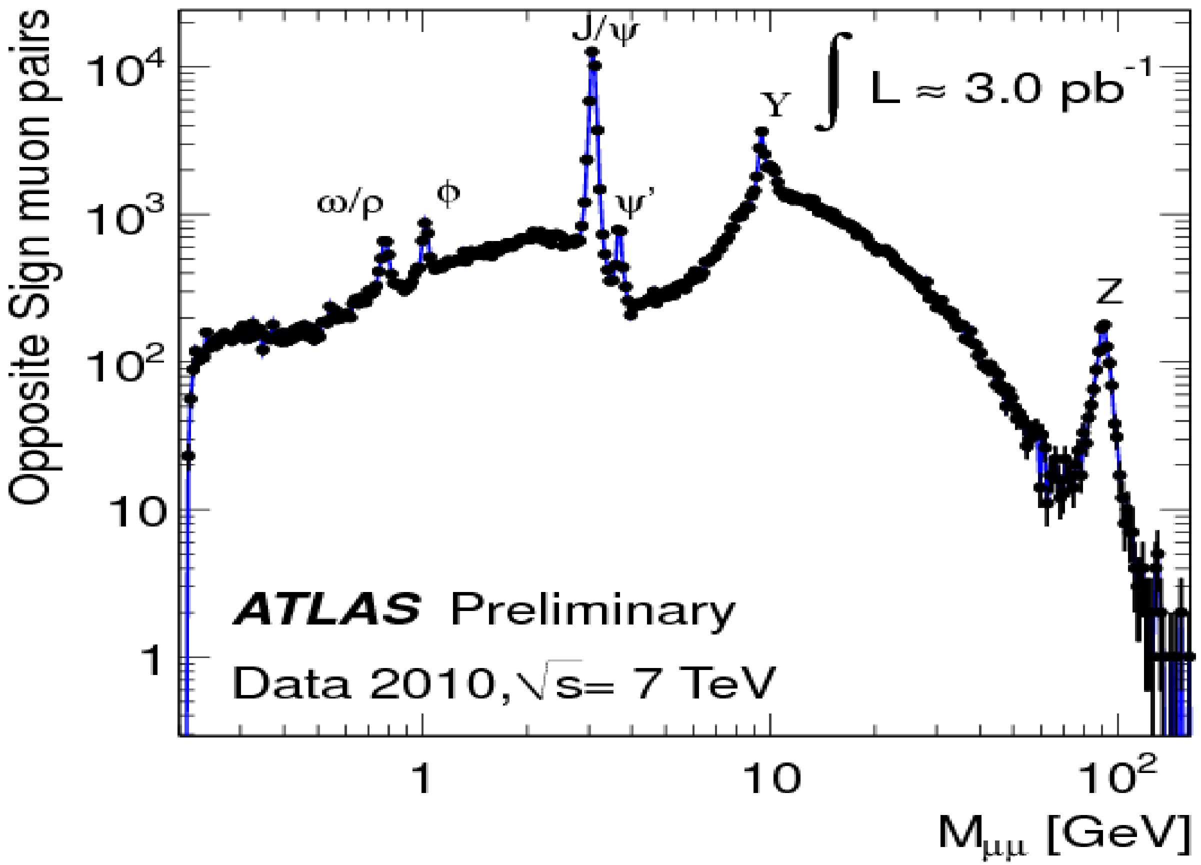
24 m



7000 Tons

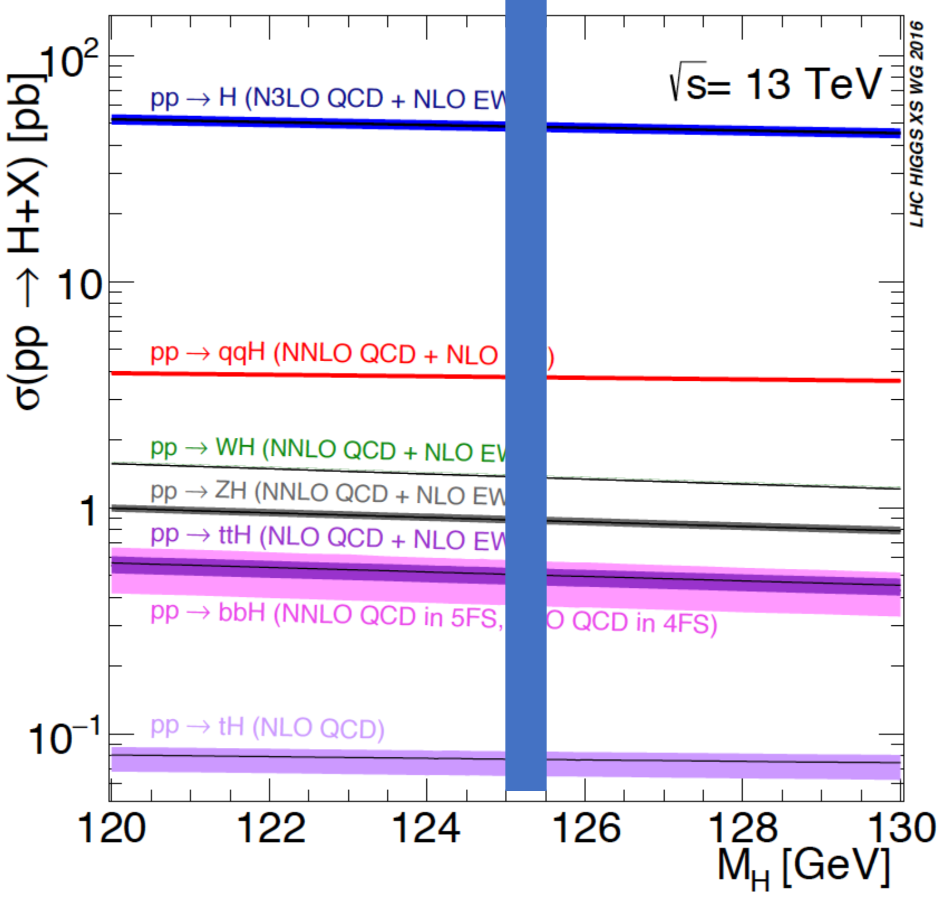
Confirming previous measurements or discoveries

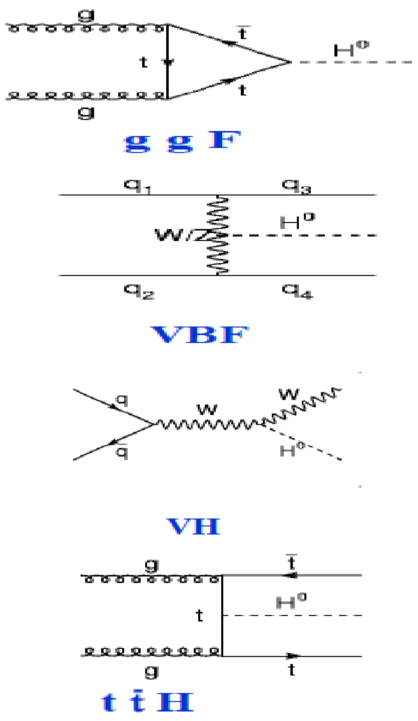
- Before we do new searches, we have to show that we measure accurately what is already known

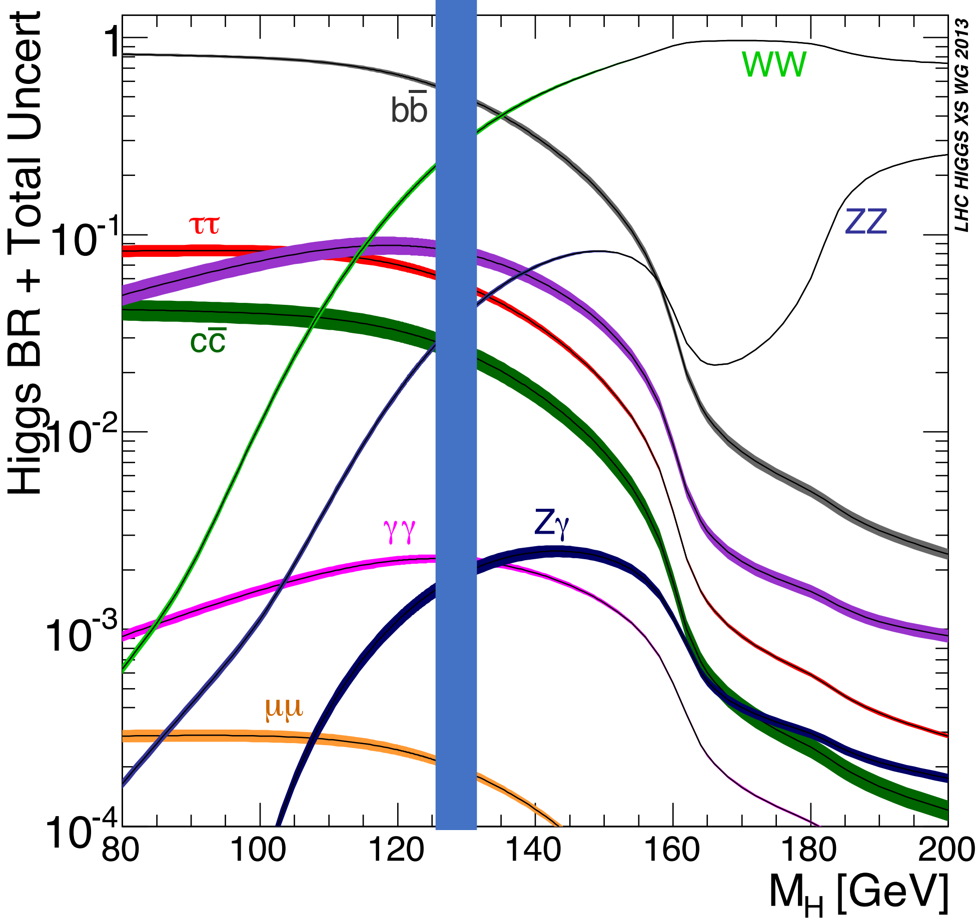


Higgs boson production and decays

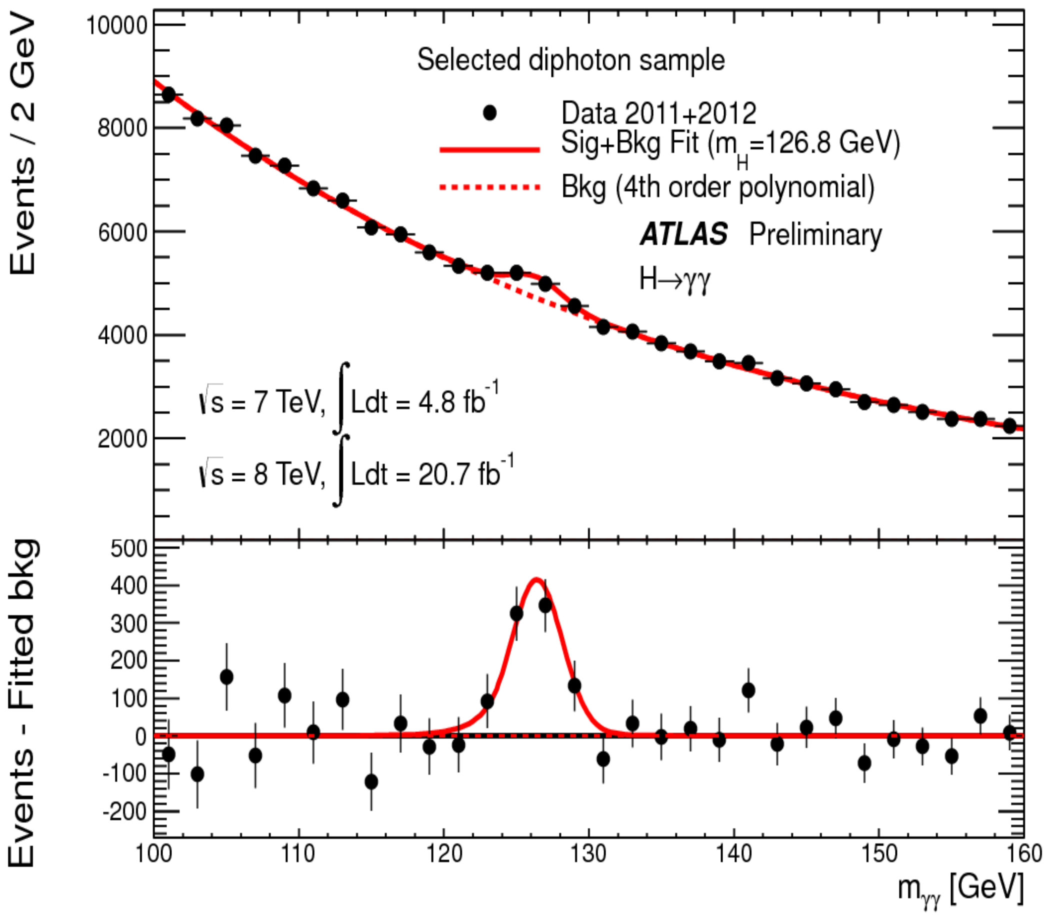
The ATLAS and CMS Experiments at the LHC have discovered, independently, a Higgs boson with mass around 125 GeV using these productions and decay modes



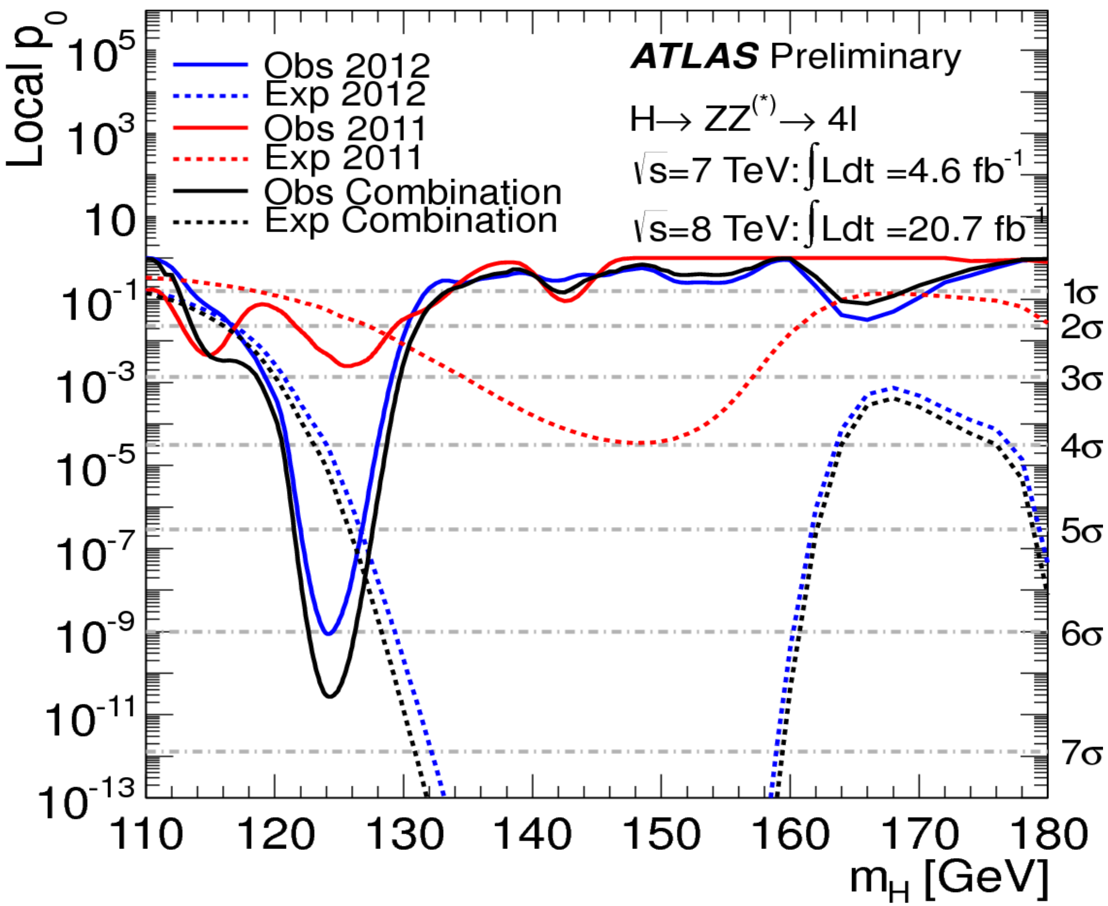




The Higgs Boson Discovery

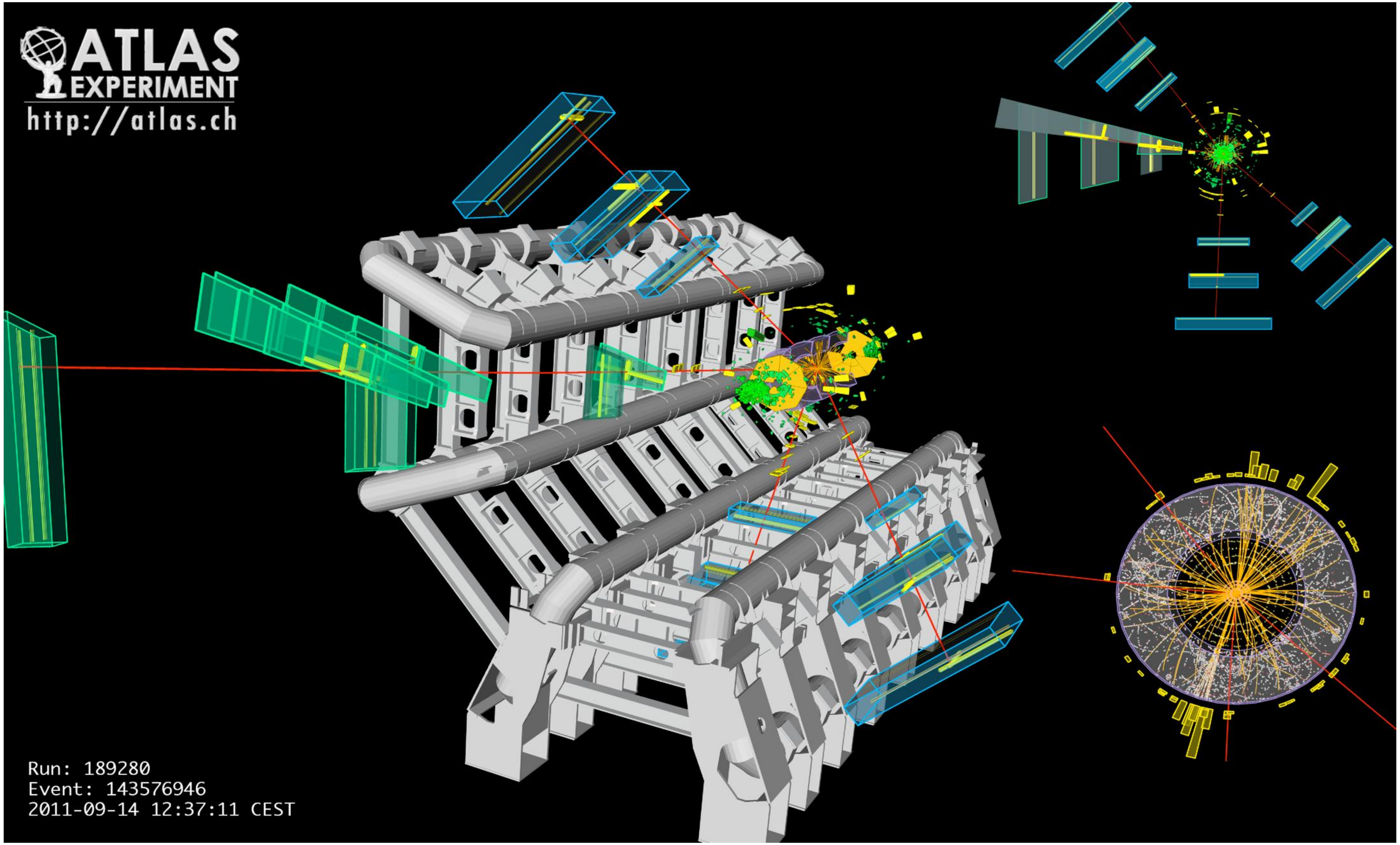


Single channel discovery: 7.4σ

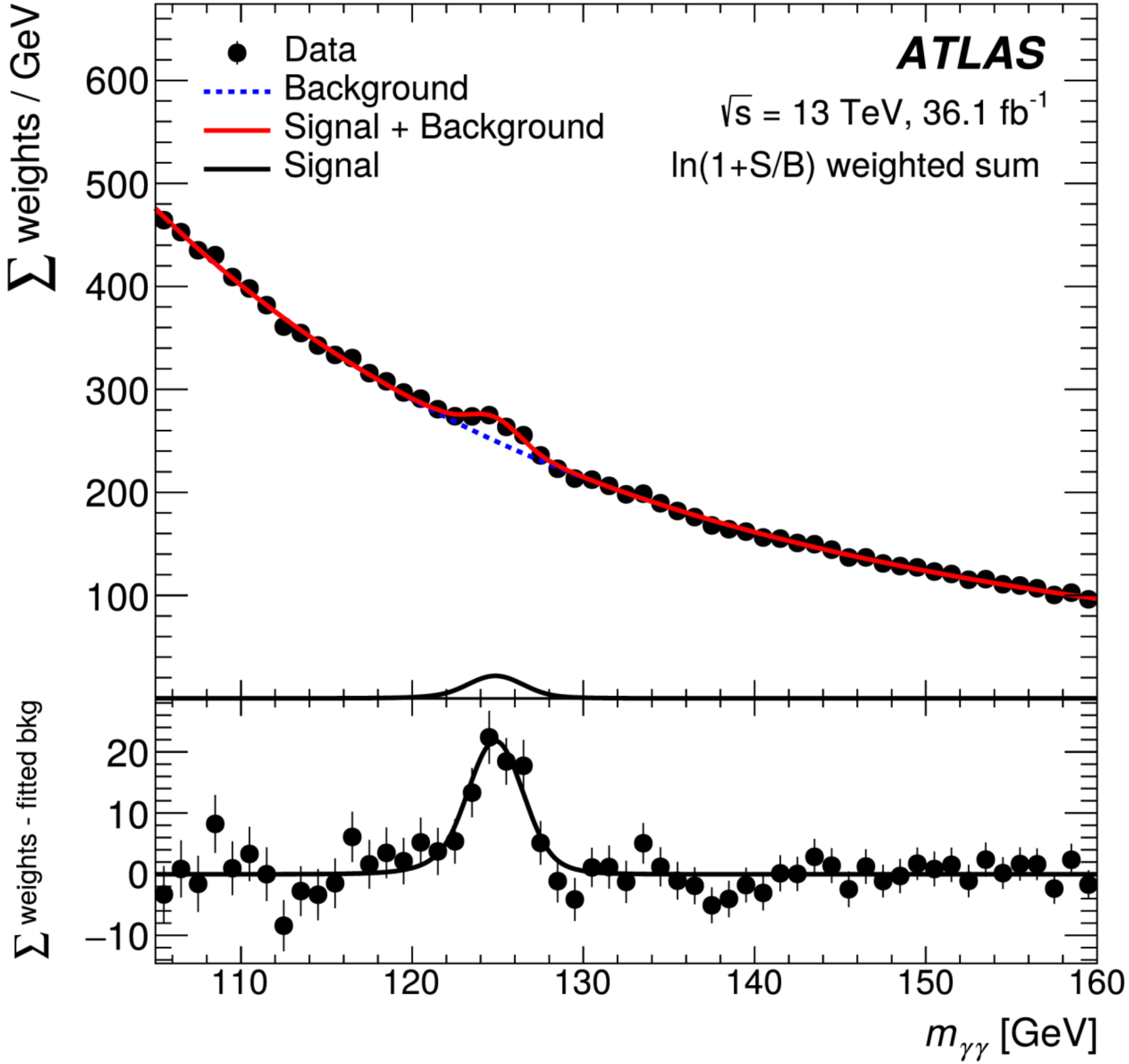


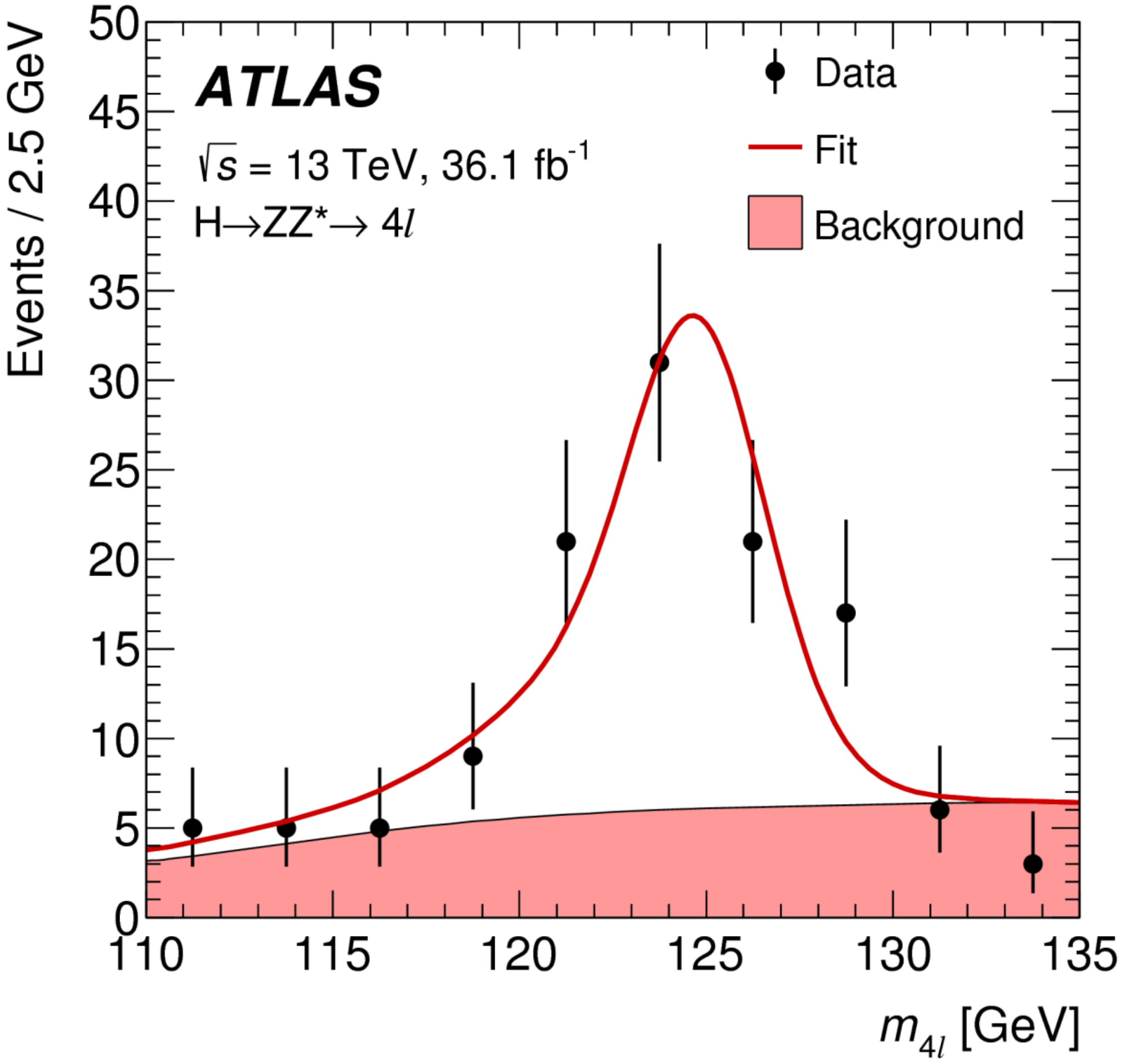
Single channel discovery: 6.6σ

Higgs → 4 muons Candidate



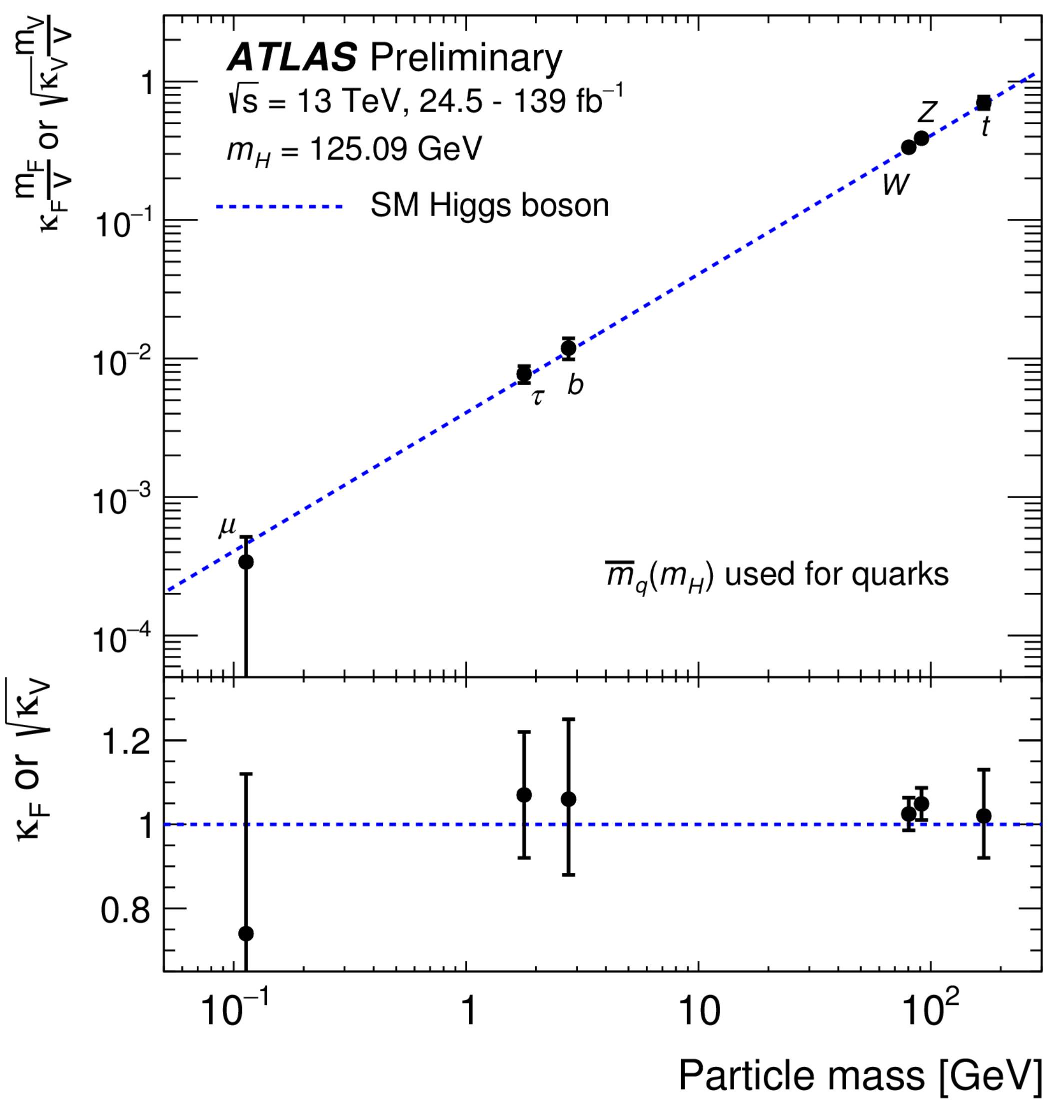
Higgs →γγ, ZZ





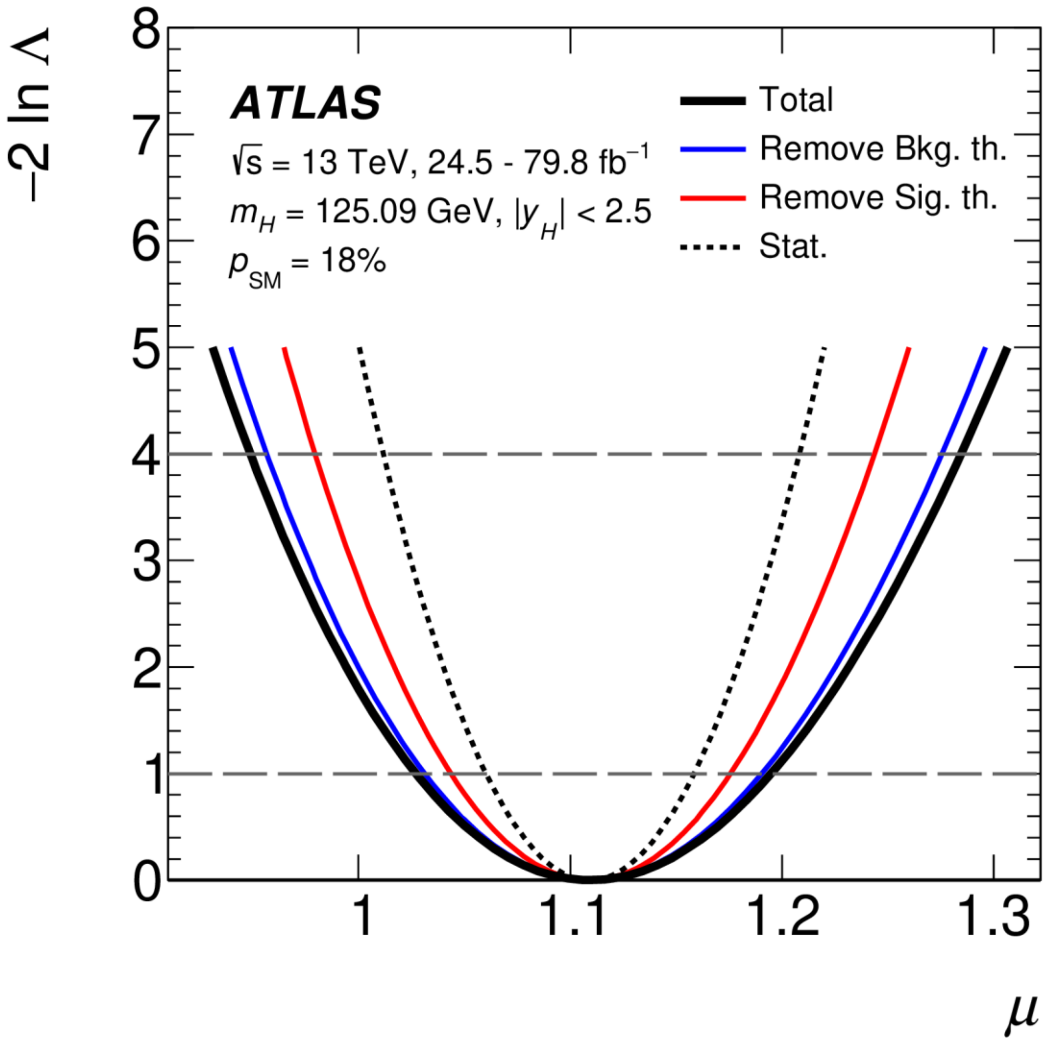
Discovery confirmed in later measurements

Higgs coupling measurements

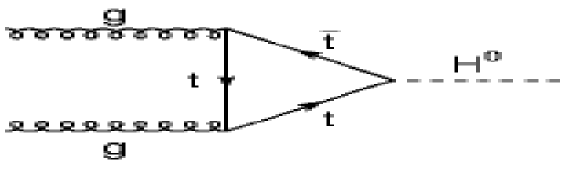


Signal Strength relative to SM

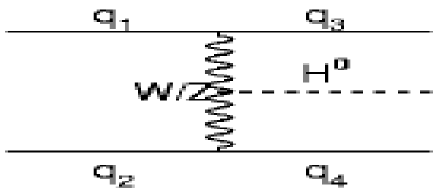
$\mu = 1.11 + 0.09 - 0.08$



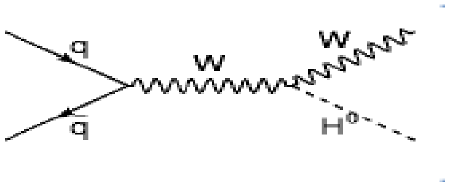
pp → H +X Cross section measurements



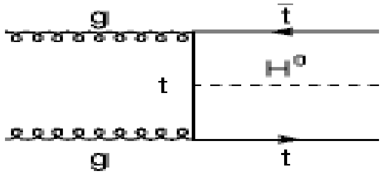
g g F



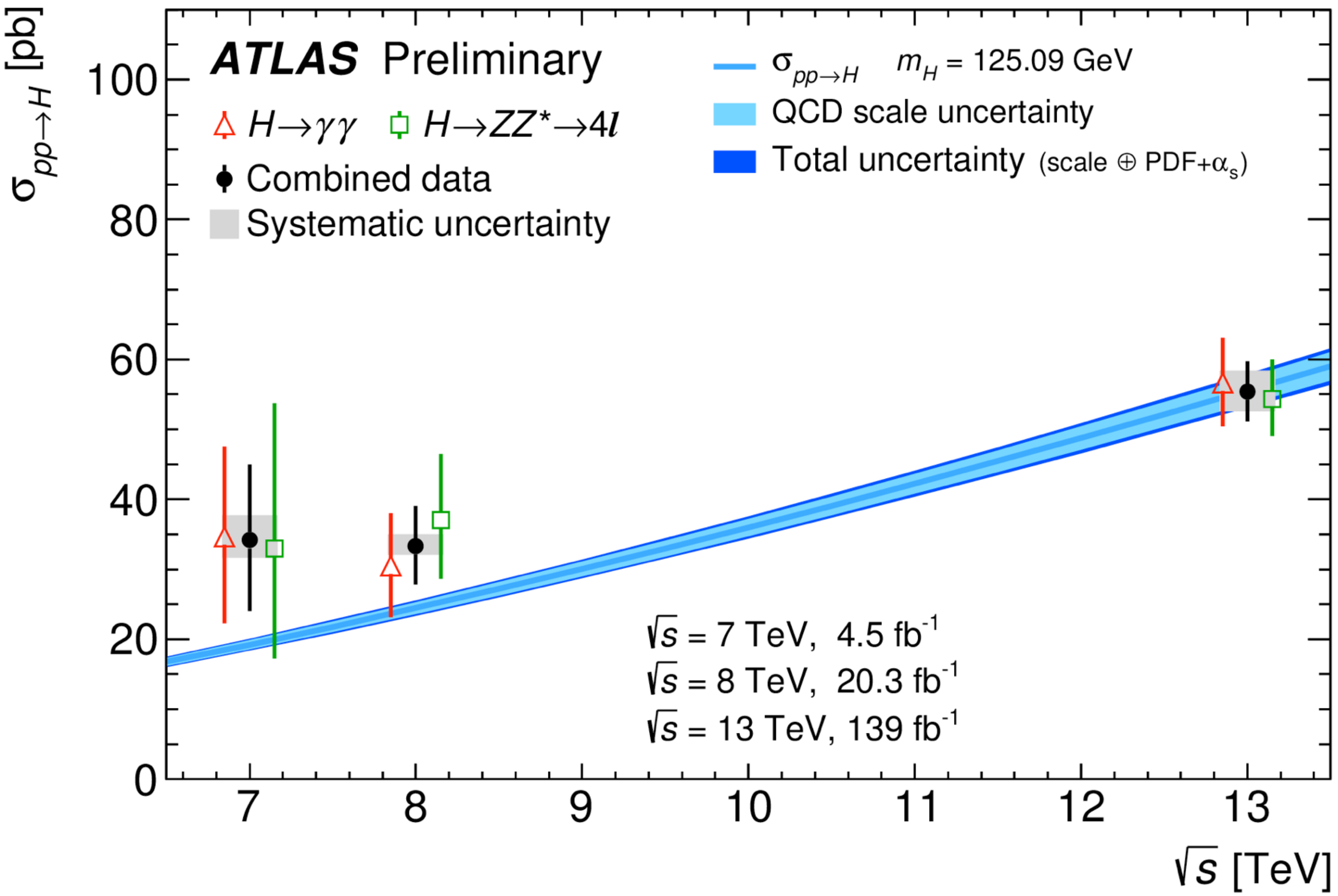
VBF



VH

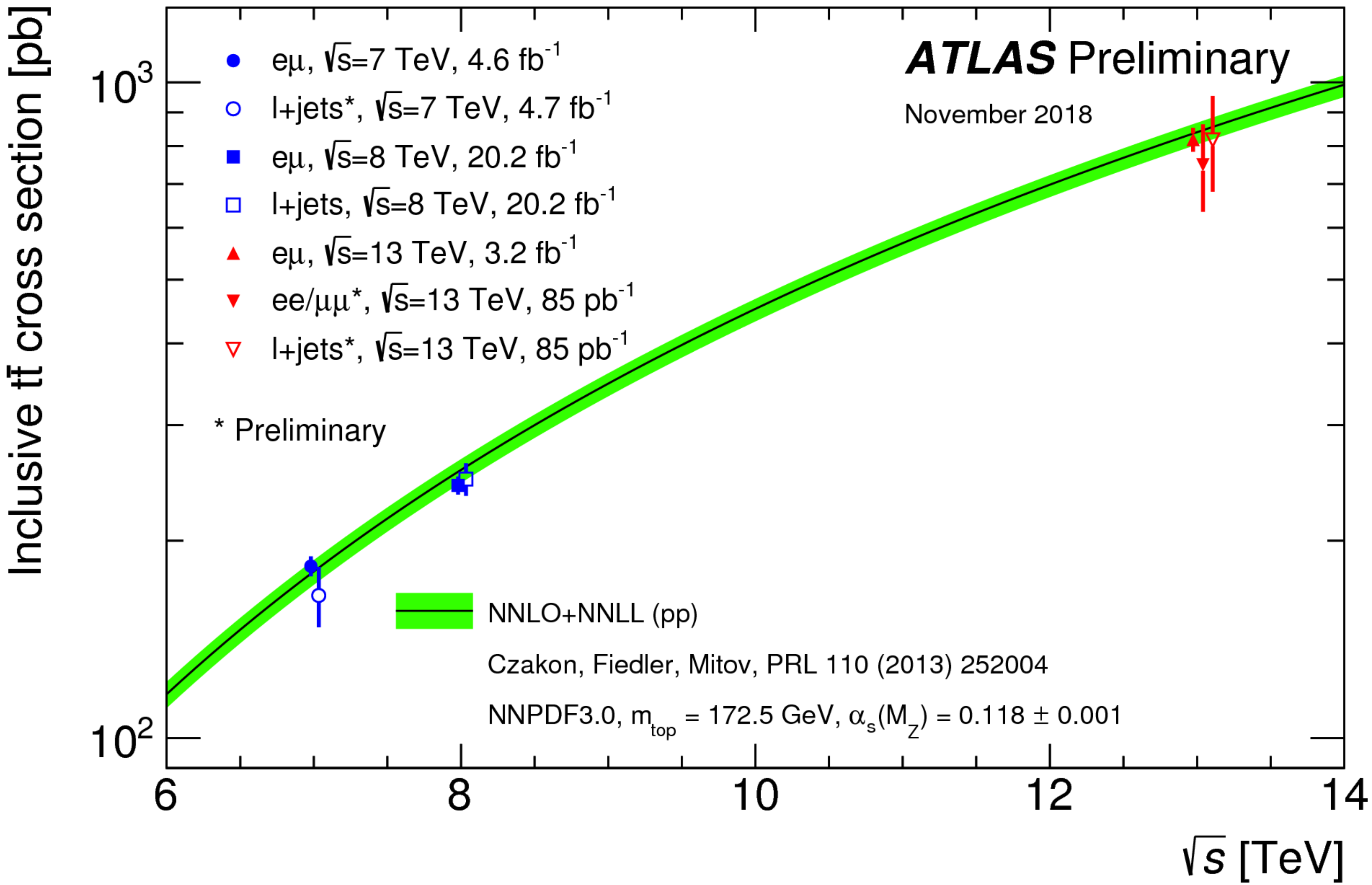


t t̄ H



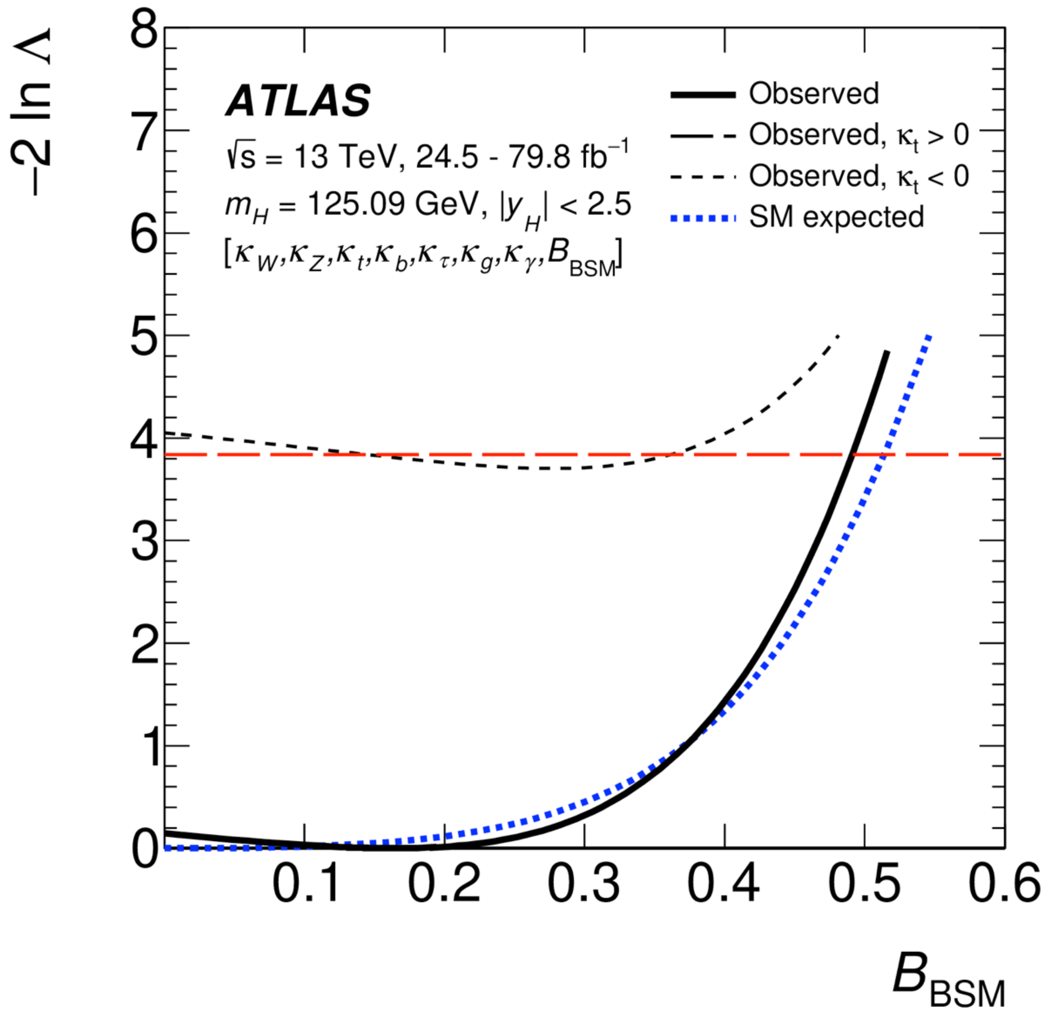
Top-quark sector

Summary of ATLAS measurements of the top-pair production cross-section as a function of the center-of-mass energy compared to the NNLO QCD calculation complemented with NNLL resummation (top++2.0).



H → BSM contribution to the Higgs width

BR [H→ BSM] < ~45%



Search for new physics

- **Higgs Discovery confirmed in later measurements**
- **Measurement of properties consistent with expectations from the SM**
- **But are there more than one Higgs boson?**
  - **Beyond-the-Standard-Model (BSM) Higgs searches**
- **We can use the Higgs boson as a portal to “new physics” :**
  - **Can we search for new physics in the decay of the Higgs boson?**
  - **Or in association with it?**
  - **Or in the small deviations in the properties with respect to the SM expectations?**

The Dark Matter Hypothesis

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a

  stronger gravitational field

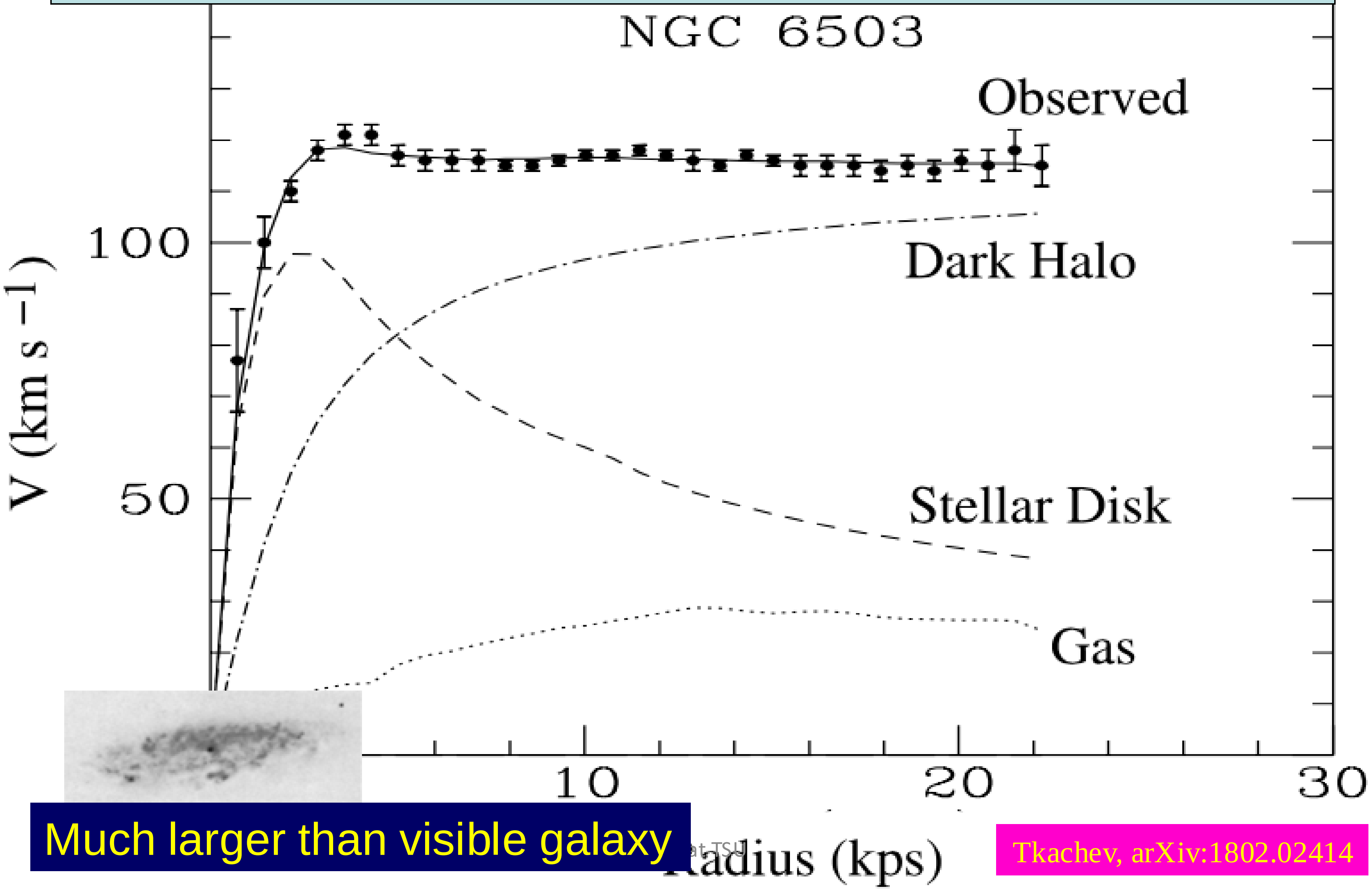
  than provided by the visible matter
- **Dark matter?**

The Rotation Curves of Galaxies

- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter
- **Further strong evidence for dark matter**

Scanned at the American Institute of Physics

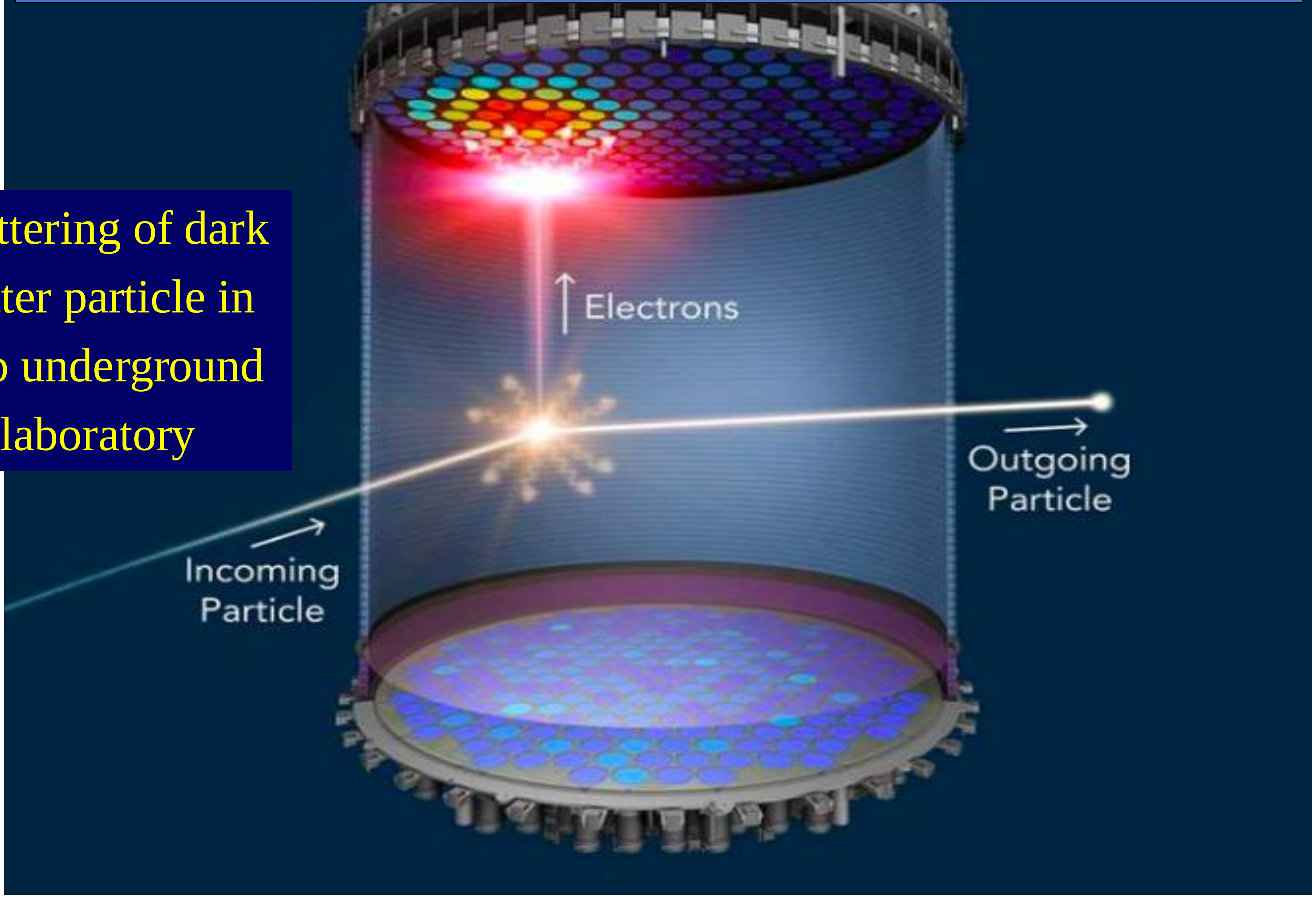
Sample Rotation Curve: NGC 6503



Much larger than visible galaxy

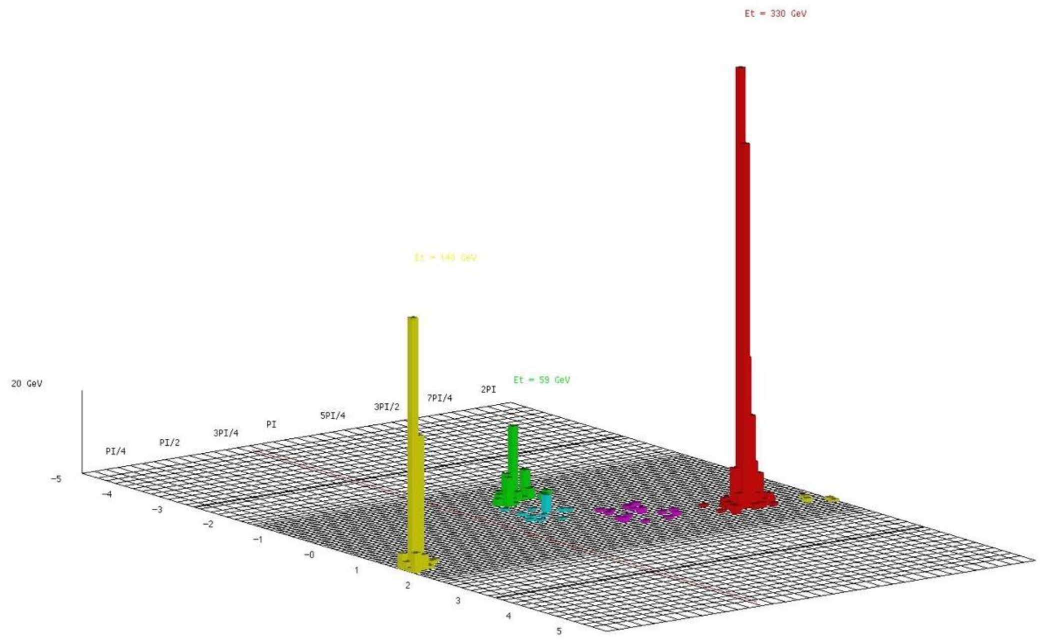
Tkachev, arXiv:1802.02414

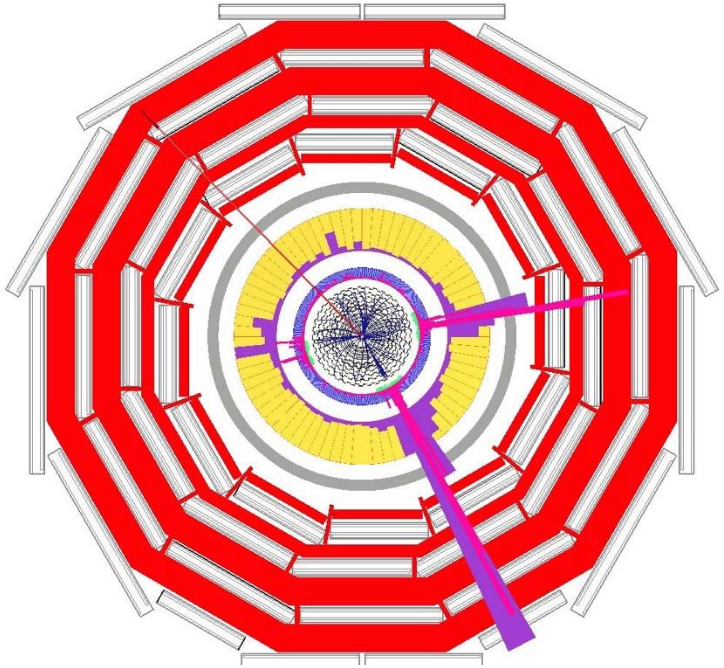
Direct Dark Matter Detection



Scattering of dark matter particle in deep underground laboratory

Classic Dark Matter Signature at LHC

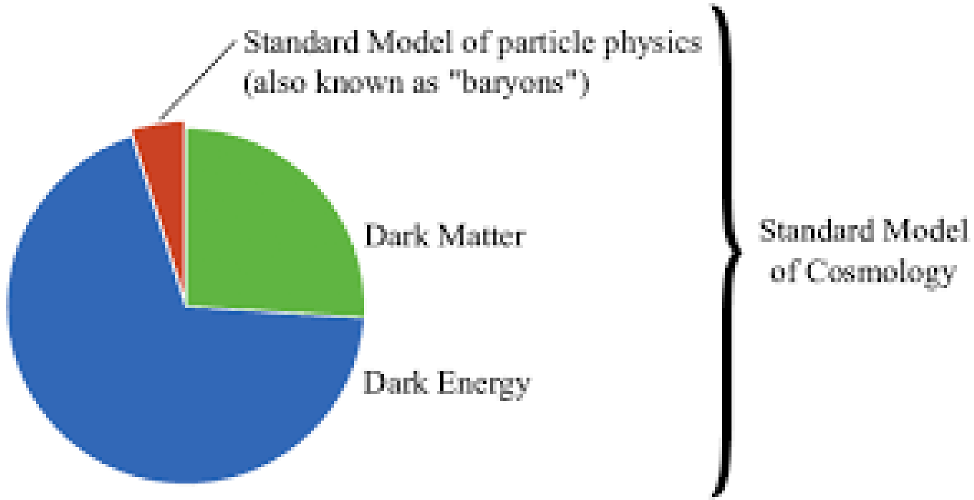


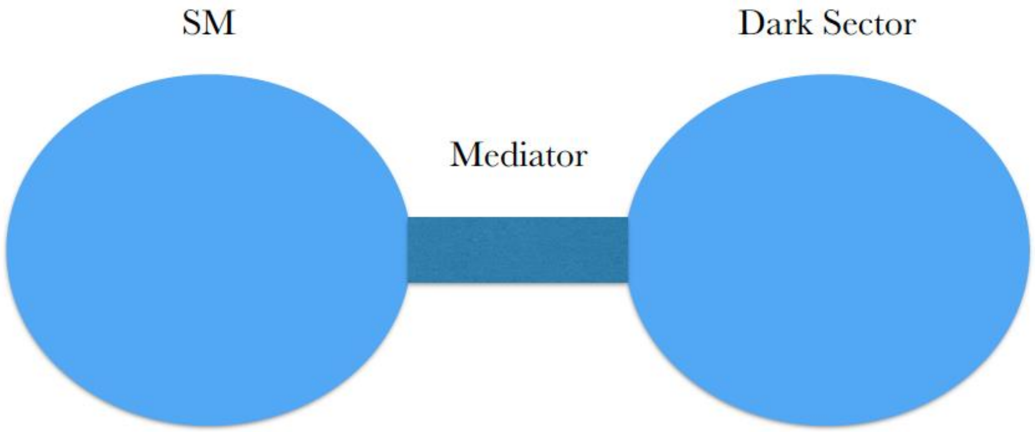


Missing transverse energy
carried away by dark matter particles

Dark Sector

- Dark Sector states as "New Physics" beyond the SM



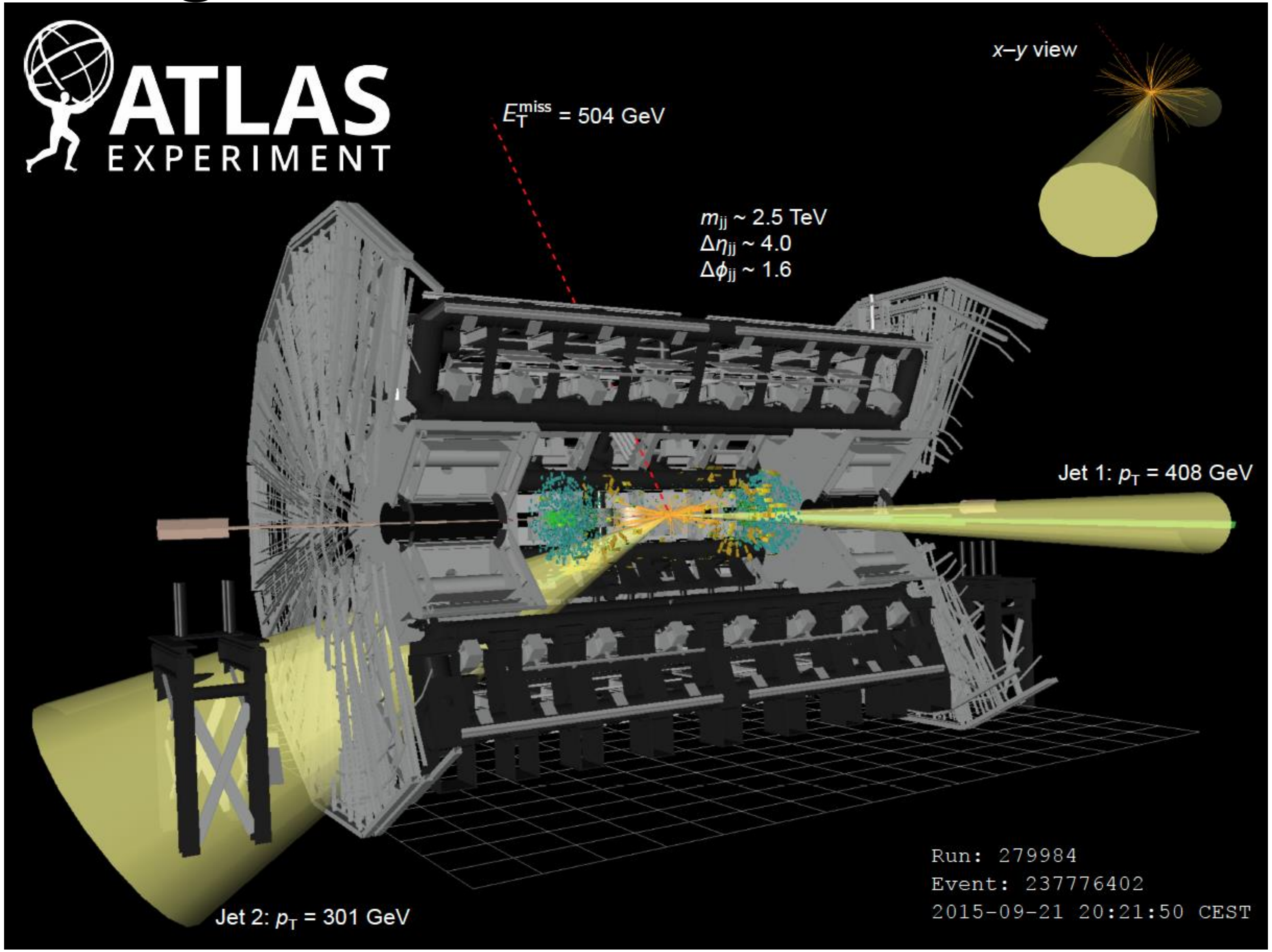


Need new force / interaction to connect SM to Dark Sector — portals. Weak couplings through kinetic mixing, Higgs or mass mixings

Dark Matter could just be one example of Dark Sector States

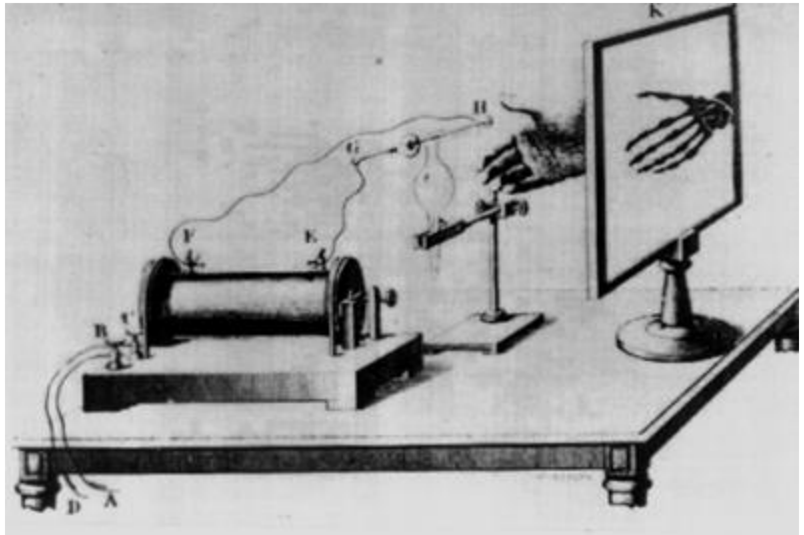
Some Classic Signatures at LHC

Missing transverse energy carried away by Dark Matter particles



VBF H → invisible

The beginnings of modern physics and of medical physics

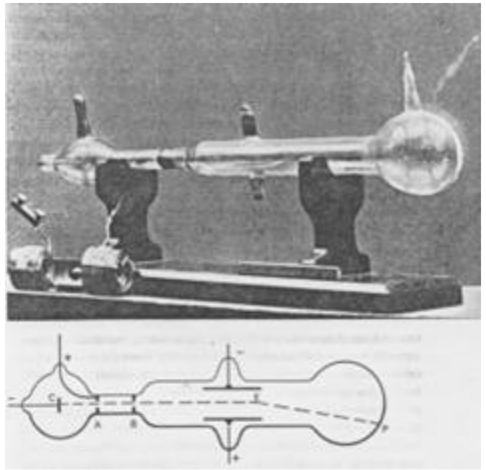


1895
discovery of X rays

Wilhelm Conrad
Röntgen

J.J. Thompson

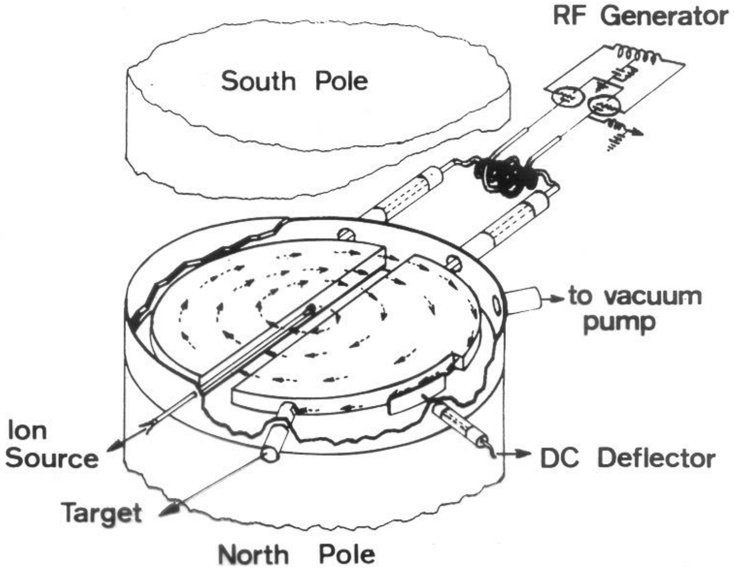
1897
"discovery" of the electron

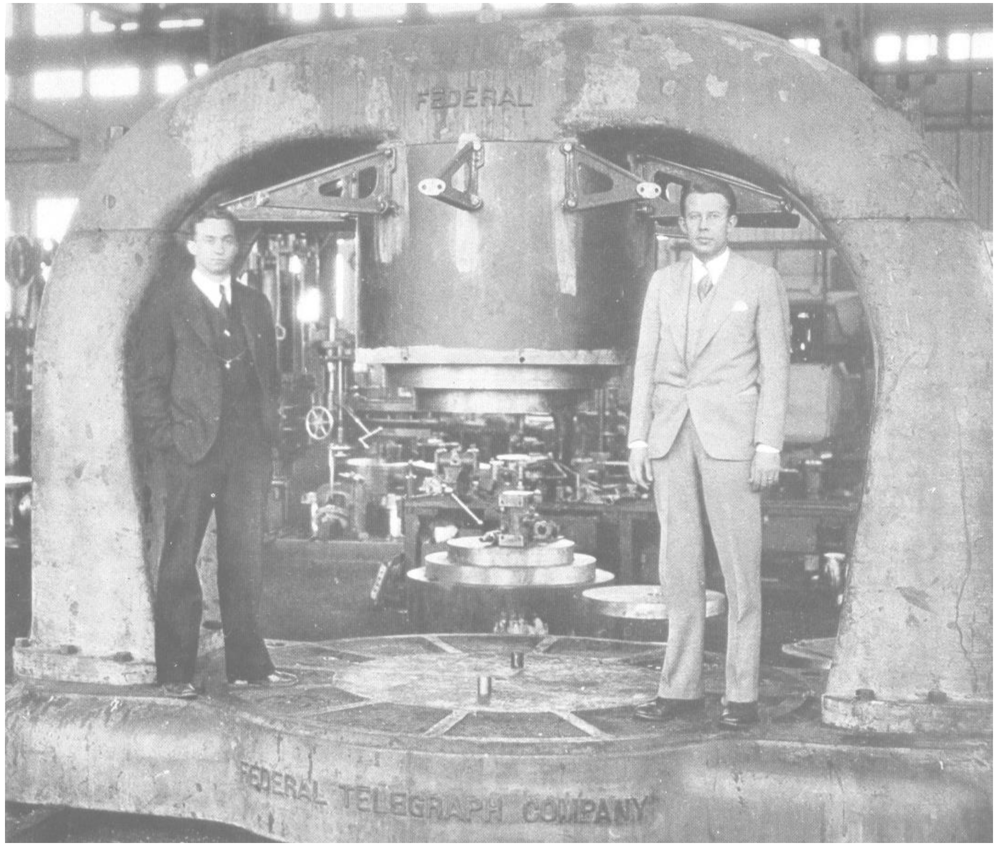


Courtesy Prof. Ugo Amaldi

Tools for (medical) physics: the cyclotron

1930
Ernest Lawrence invents the cyclotron





M. S. Livingston and E. Lawrence with the 25 inch cyclotron

Courtesy Prof. Ugo Amaldi

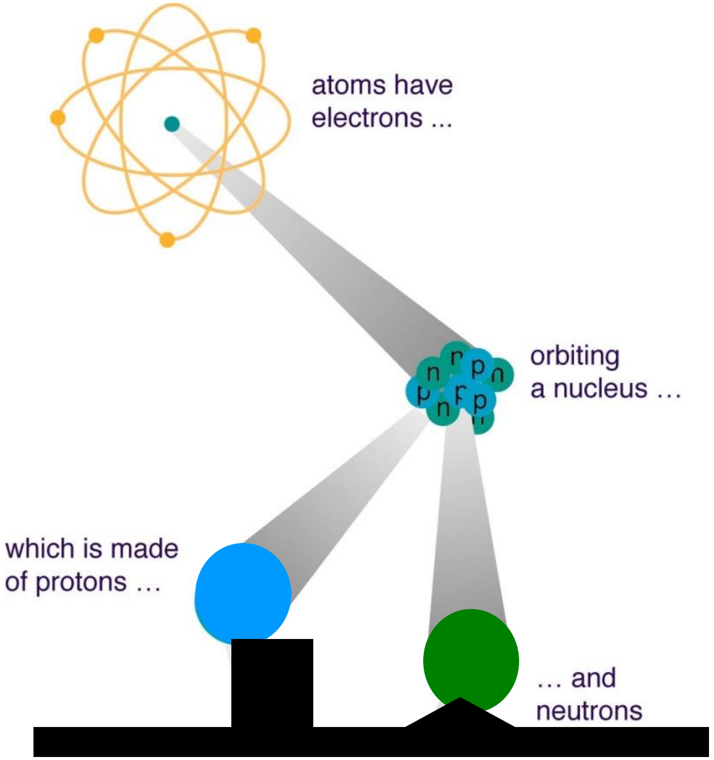
The beginnings of modern physics and of medical physics

James Chadwick
(1891 – 1974)

Courtesy Prof. Ugo Amaldi

1932

Discovery of the neutron



Cyclotron + neutrons = first attempt of radiation therapy with fast neutrons at LBL (R. Stone and J. Lawrence, 1938)

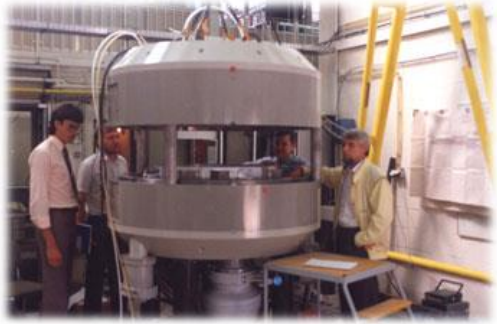
Particle accelerators for medical uses

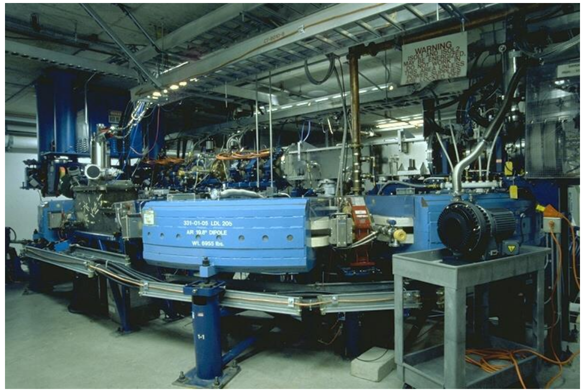
I. Production of radionuclides with (low-energy) cyclotrons
   i. Imaging (PET and SPECT)
   ii. Therapy

II. Electron linacs for conventional radiation therapy (including advanced modalities)

III. Medium-energy cyclotrons and synchrotrons for hadron therapy with protons (250 MeV) or light ion beams (400 MeV/u ^{12}C-ions)

IV. Compact proton accelerators for BNCT

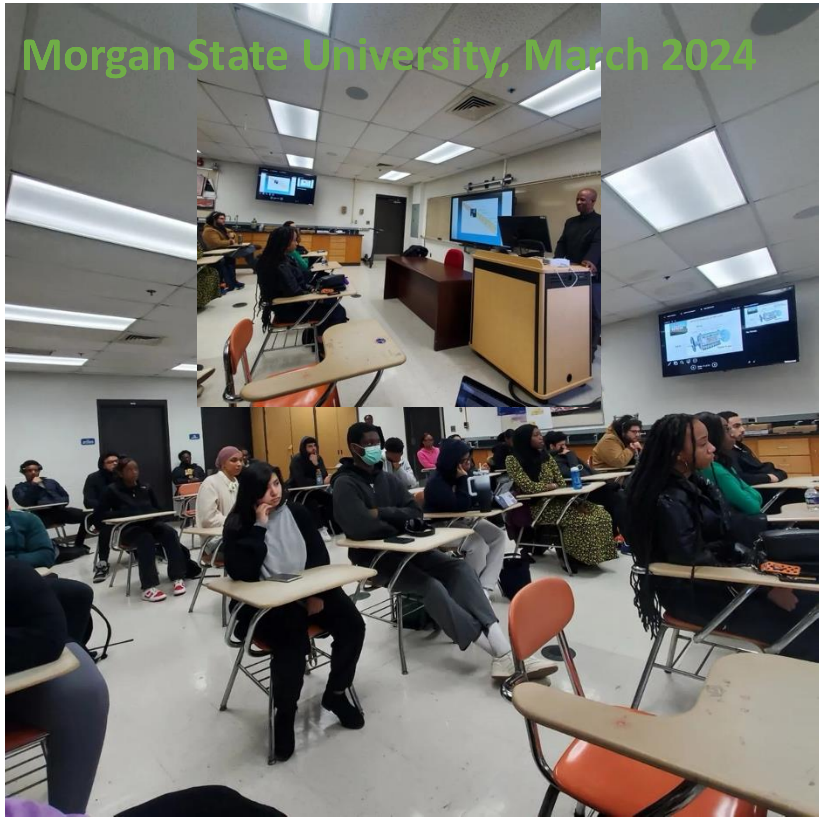




Broader Impact

1. **Community Outreach through QuarkNet**
   - ❖ Professional development programs for physics teachers and pupils
2. **US-ATLAS targeted outreach within USA**
   - ❖ Improved and sustained engagements with USA Institutes




Morgan State University, March 2024

3. **International Outreach to sustain competitive edge in science**
   - ❖ US-ATLAS Outreach: Africa, Asia, Latin America
   - ❖ The African School of Physics
   - ❖ The African Physics Strategy
   - ❖ Research visits
   - ❖ Mentorship / coaching

BNL, 2019, 2022-2024
ASP alumni visits for research

2019 (9)
2022-2023 (6+)
2023-2024 (6)
2019-2023: 22 alumni
From 10 countries

Areas of concentration:
Astrophysics & cosmology, nuclear physics, particle physics, light sources & materials characterization, nanoscience, nuclear instrumentation, radionuclide production & medical physics, particle accelerators, HEP computing.

Togo, September 2025

Conclusions

- **The Standard Model of particle physics is a very successful theory**
  - **Yet, there are things we do not understand, e.g. the nature of Dark Matter**
- **The discovered Higgs boson may be used as probe or portal to "new physics"**
  - **By searching for BSM particles in the decays of the Higgs boson,**

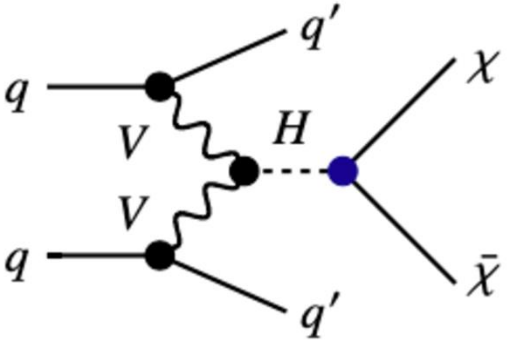
    e.g. H → invisible
- **So far, no signal of "new physics" detected**
- **There are many applications of nuclear & particle physics research as in nuclear medicine.**

Additional materials

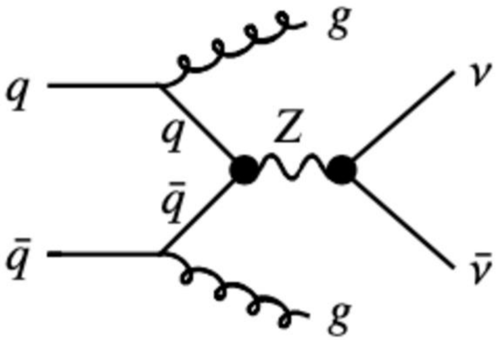
H → invisible

- **Some Dark Sector particle χ, neutral and stable over the range of the detector**
  - It is not a neutrino. A BSM-Particle
  - Its mass $m_\chi < m_H / 2$ such that $H \rightarrow \chi\chi$. The detector would be insensitive to such a decay, so we call it H → invisibles
- **If it is “invisible”, how do we detect it?**
  - Since the particle χ does not interact with the detector, it will escape, undetected, with some kinetic energy
  - By using conservation of 4-momentum, after accounting for all the other detected particles, we can infer how much energy/momentum is carried away, therefore missing
  - So, we can measure the missing transverse energy or the missing transverse momentum
  - **χ could be a candidate for Dark Matter particle**

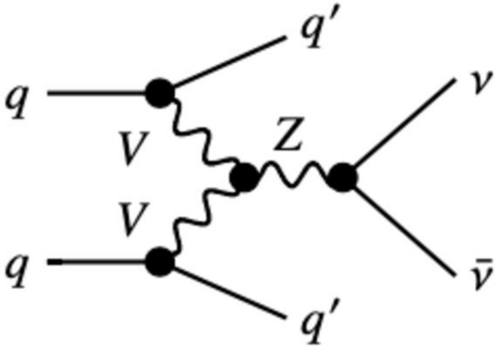
H → invisible



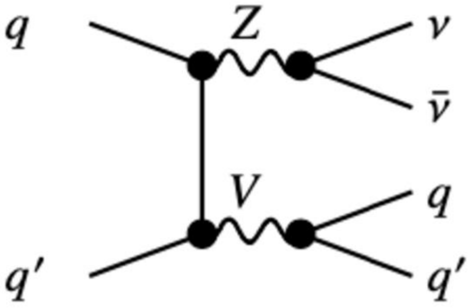
(a) Signal process



(b) Example diagram for the strong Z+jets background process



(c) Example diagram for the electroweak VBF Z+jets background process



(d) Example diagram for the electroweak diboson process

ASP Alumni at BNL 2023-2024

- 6 ASP alumni for the period of June 2023 - April 2024
  - From Kenya, Morocco, Senegal and Togo
  - 1 arrived on June 18, 2023
  - 4 arrived on July 31, 2023
  - 1 arrived on January 21, 2024

Dr. Sanae Samsam (Morocco), Accelerator Test Facility

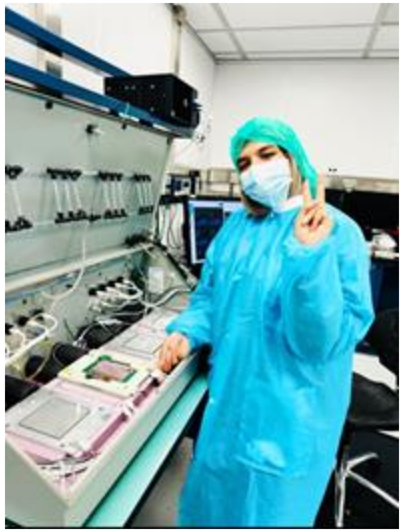
Gloria Maithya (Kenya), DUNE

Aissata Ly (Senegal), ITk

Instrumentation Division, CZT

Dr. Mounia Laassiri (Morocco)

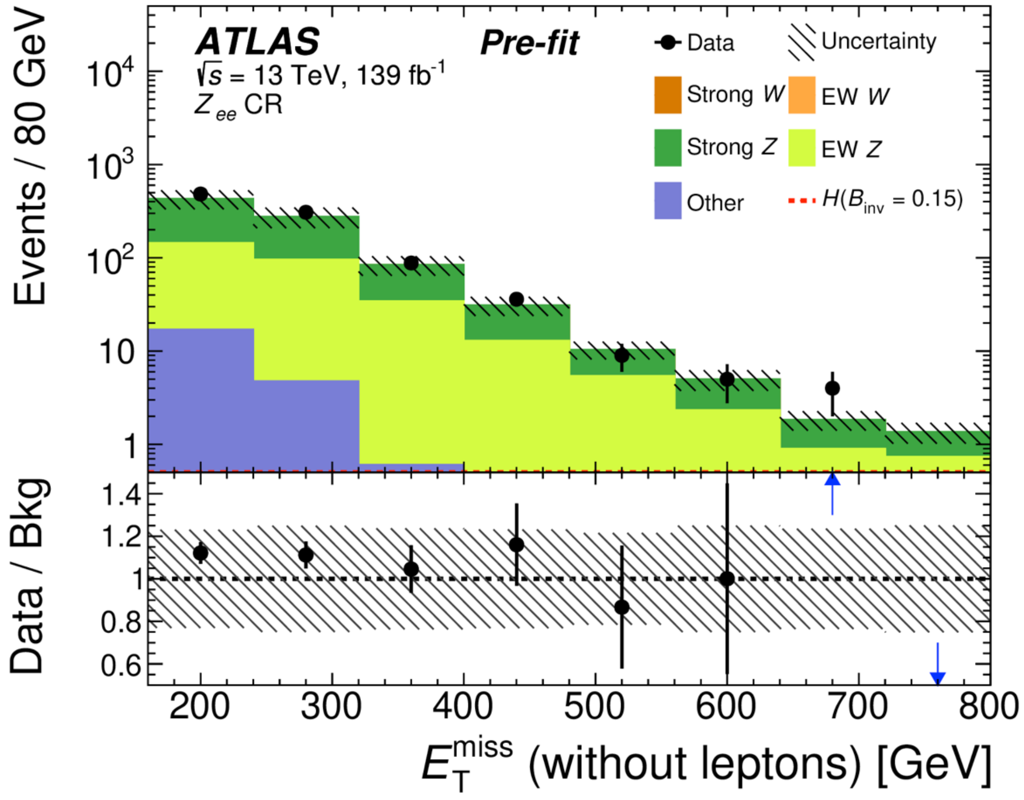
ATLAS ITk



Fatima Bendebba (Morocco),
ITk & di-Higgs

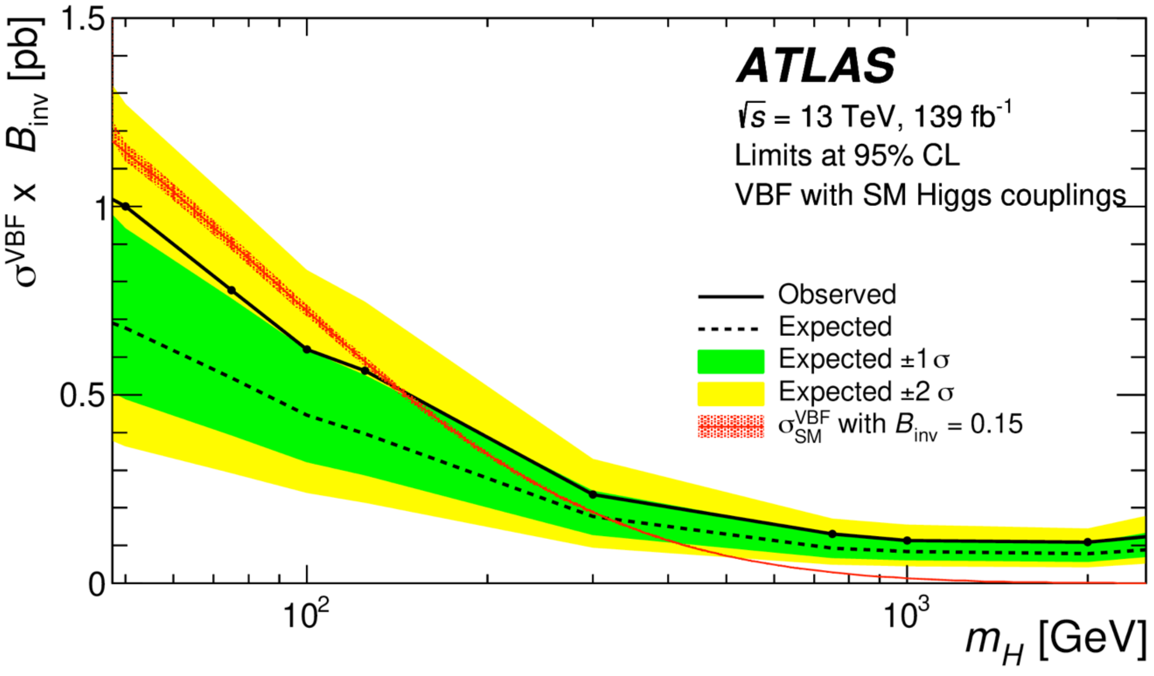
Augustin Sokpor (Togo), LGAD

H → invisible



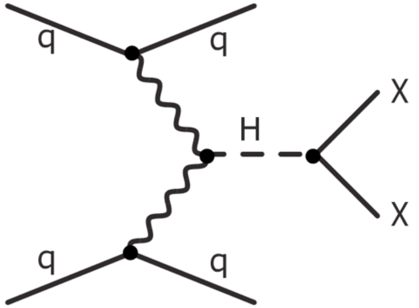
Branching Ratio Limit < 0.15 at 95% Confidence Level

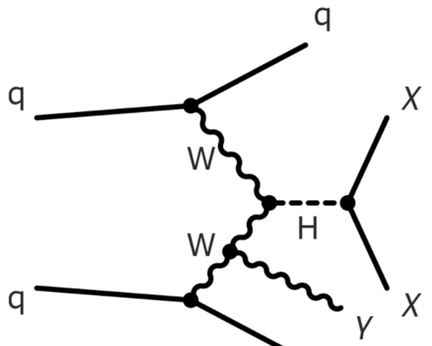
Upper bound on the Cross Section x BR of a generic scalar

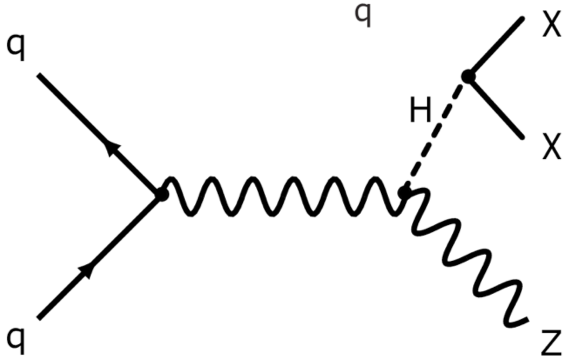


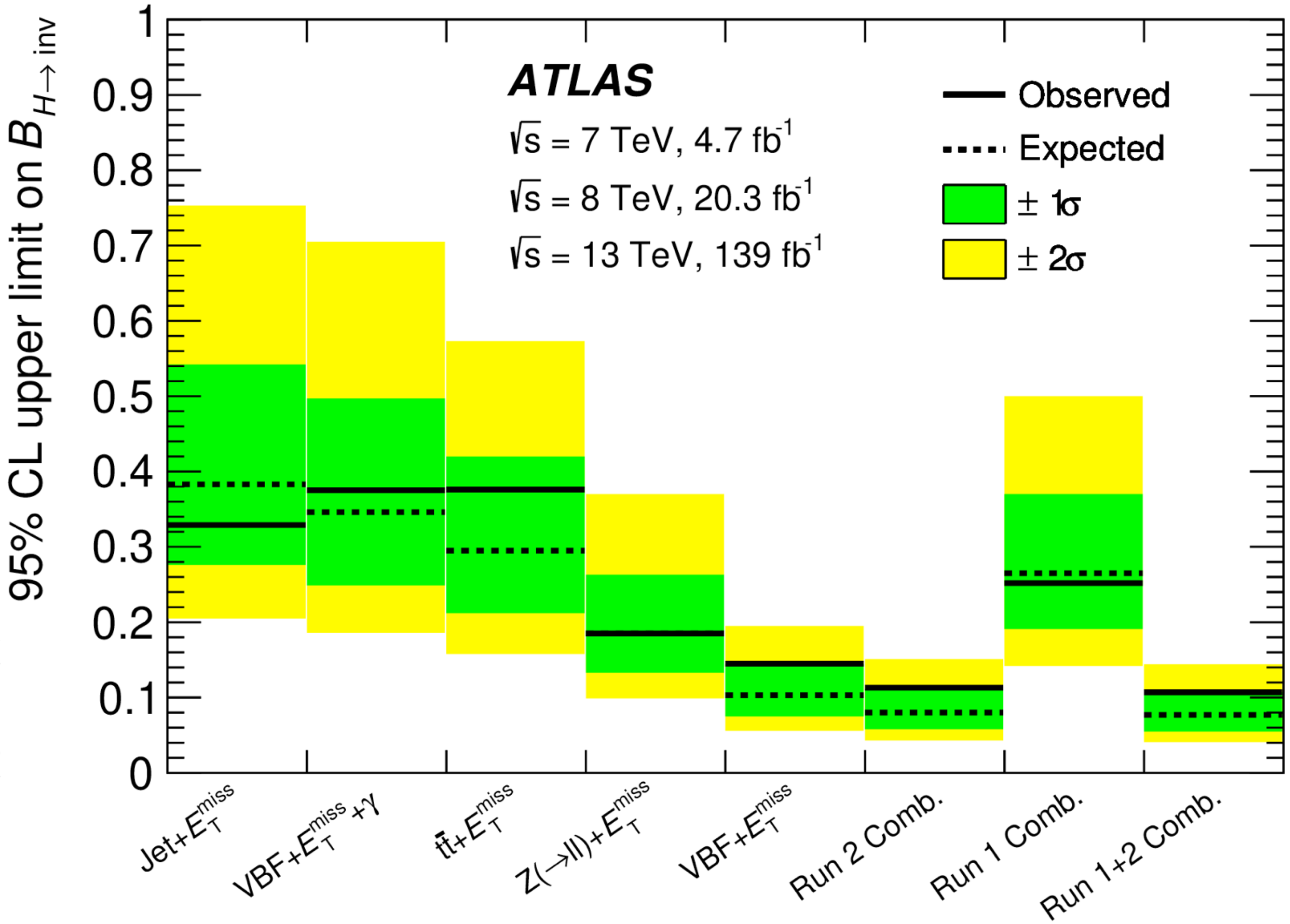
H → invisible combination

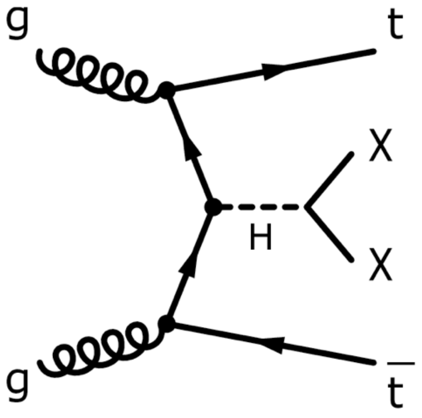
BR (H→ invisible) < 10% at 95% CL

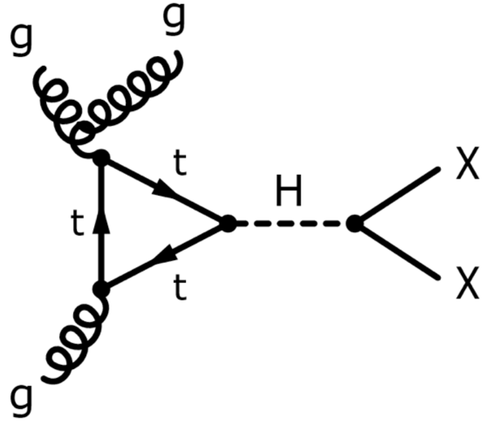












H → invisible — Dark Matter interpretation

Upper bound of the DM-Nucleon Scattering Cross Section