Physics at Large Hadron Collider

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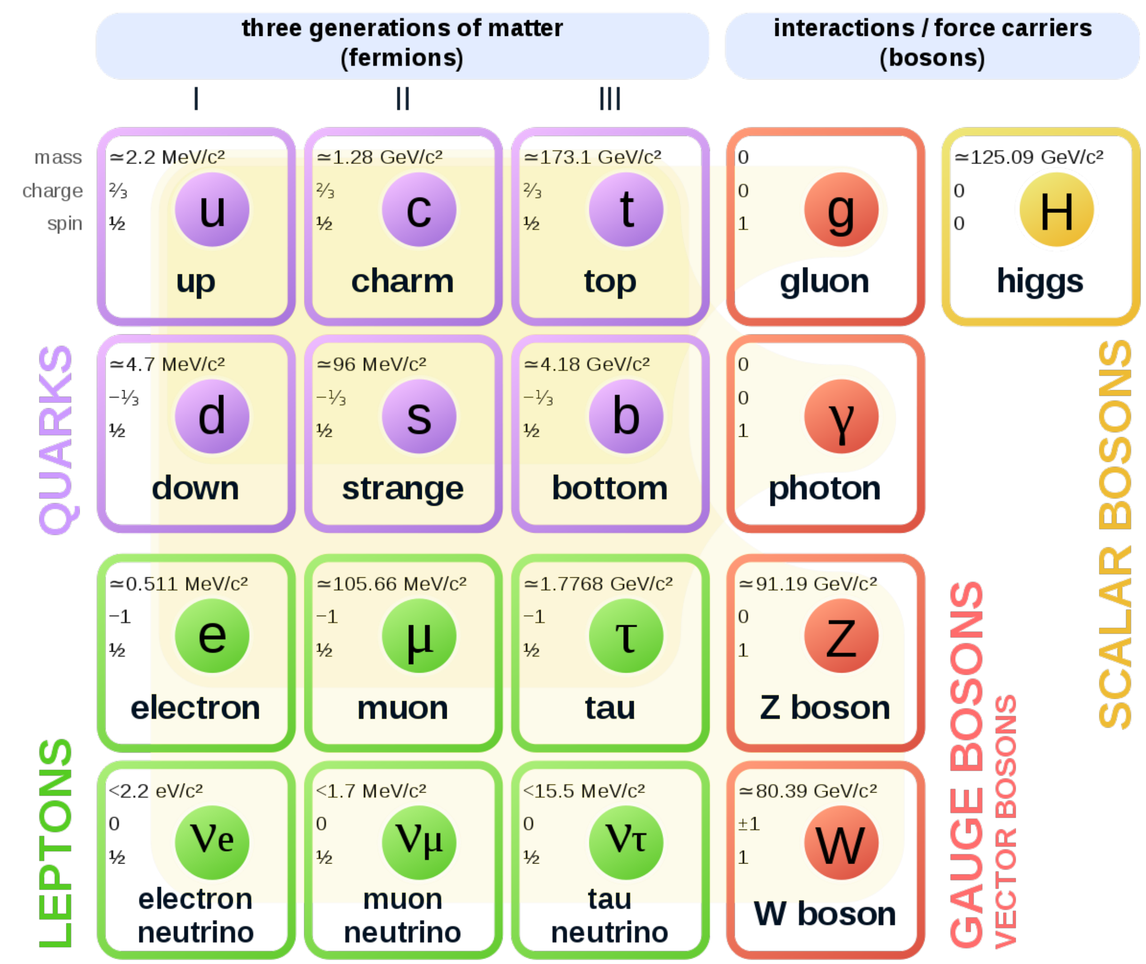
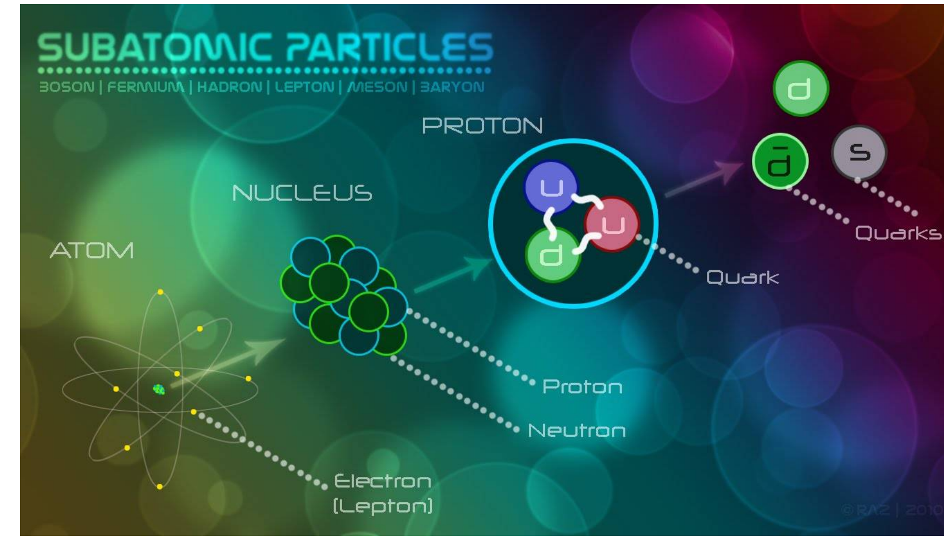
Standard Model

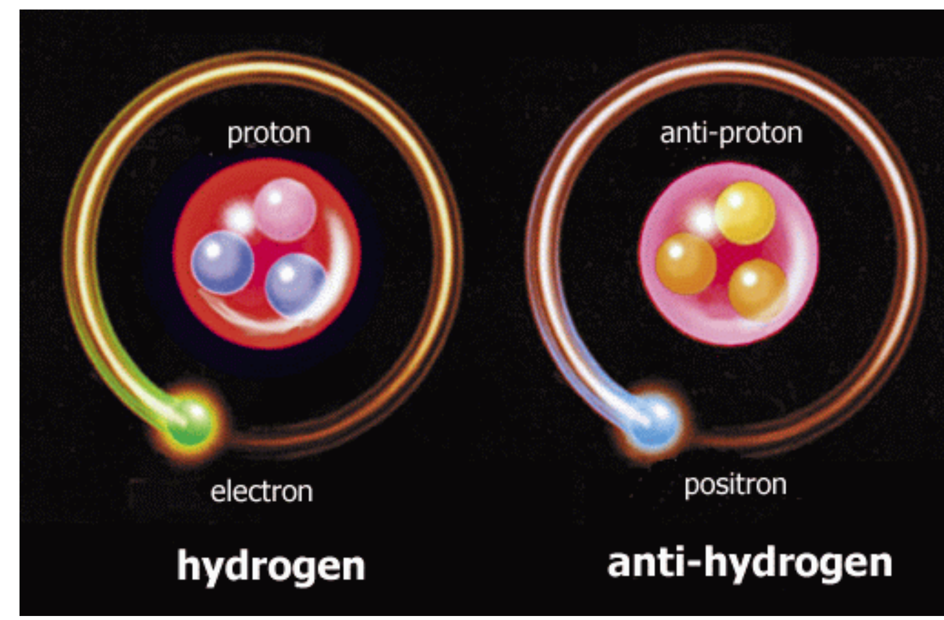
- ▻ Extremely predictive theory since its inception
- ▻ Last missing piece discovered just 10 years ago
  – Compare to gravitational waves and general relativity
- ▻ Has successfully resisted 50 years of falsification
- ▻ *We already know it is incomplete*
  – e.g. neutrinos are massive
- ▻ It cannot address some basic curiosities and questions about our Universe

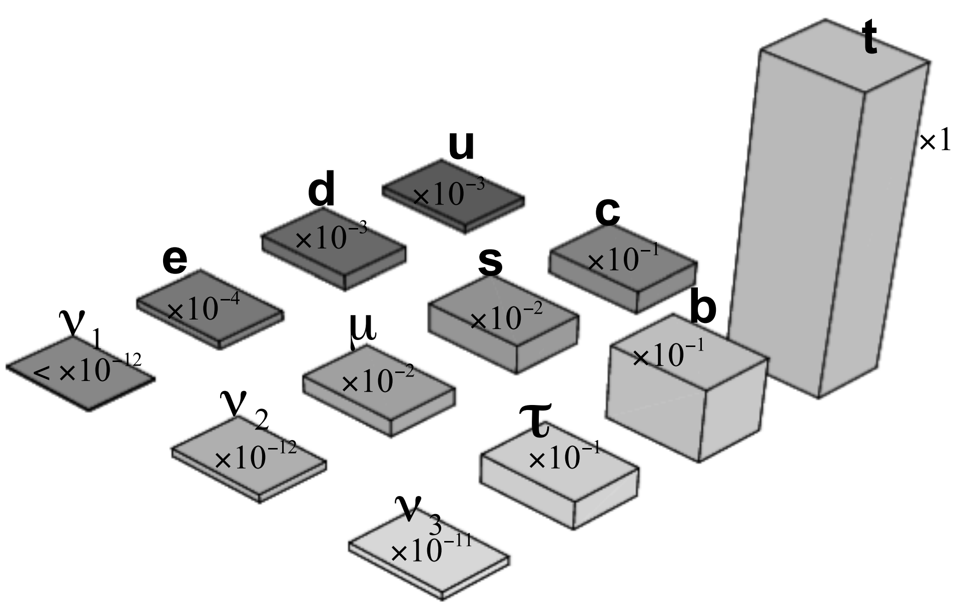


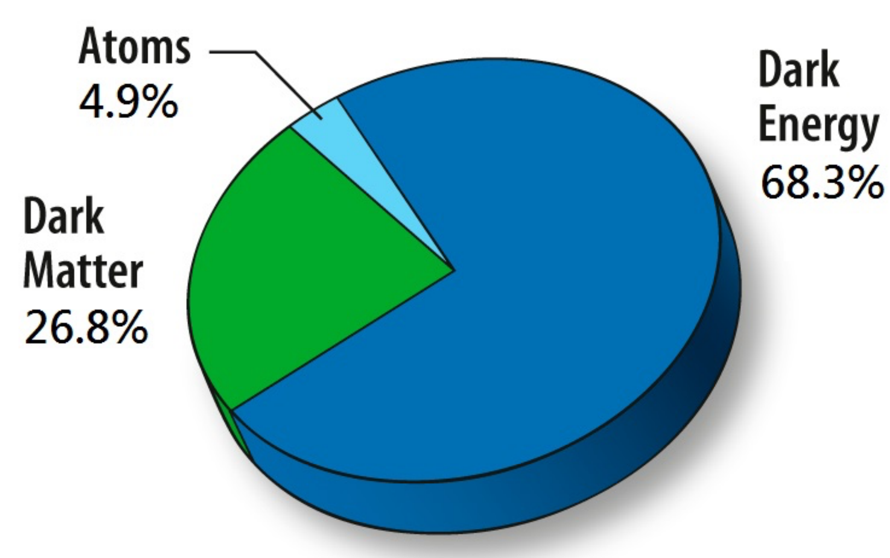
A few questions and curiosities

- What is the origin of mass?
- Have we found ***the*** Higgs boson?
- What is the origin of mass hierarchy?
- Where is all the anti-matter in our Universe?
- What is Dark Matter?

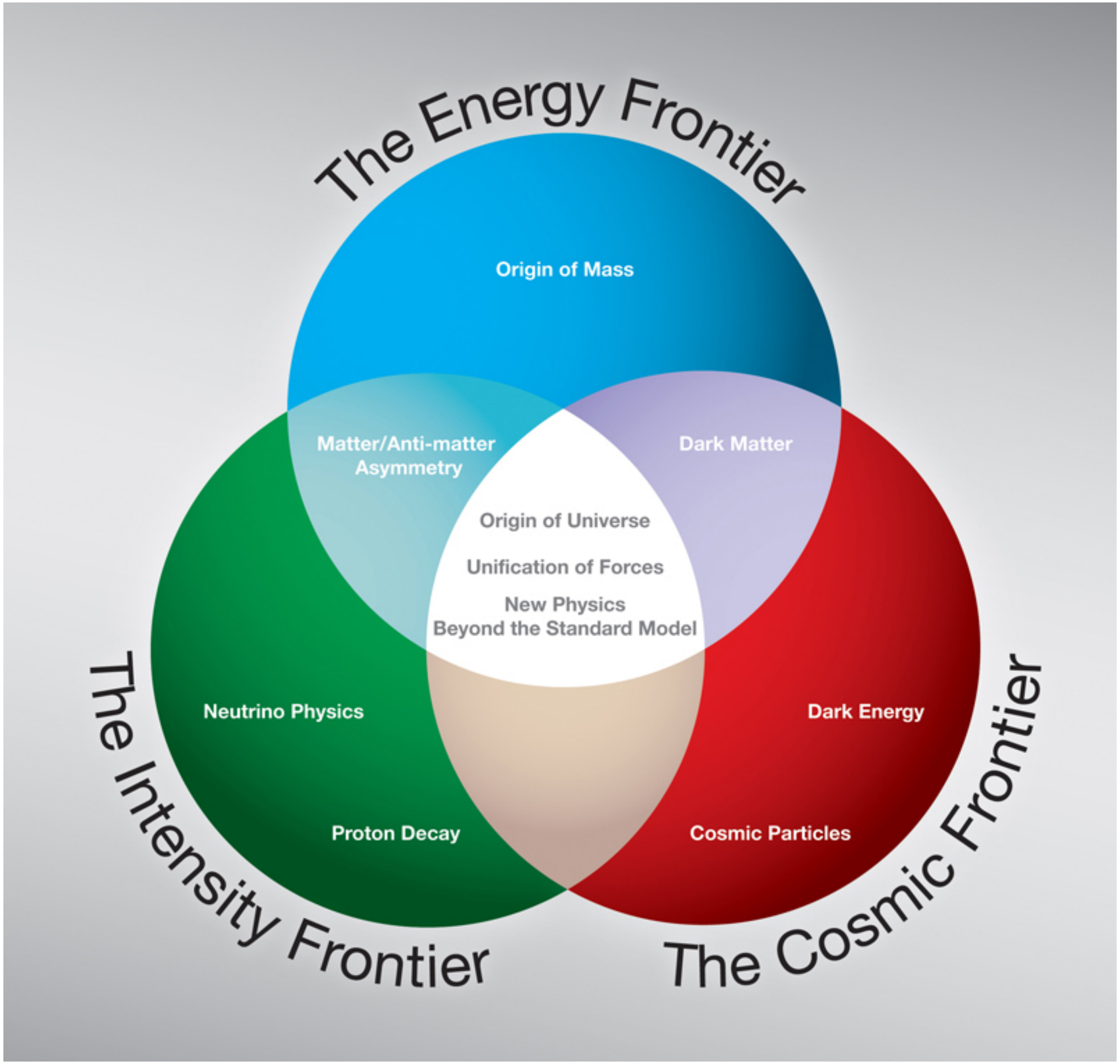








Multi-prong Approach



Evolution of Particle Colliders

Temperature

Energy

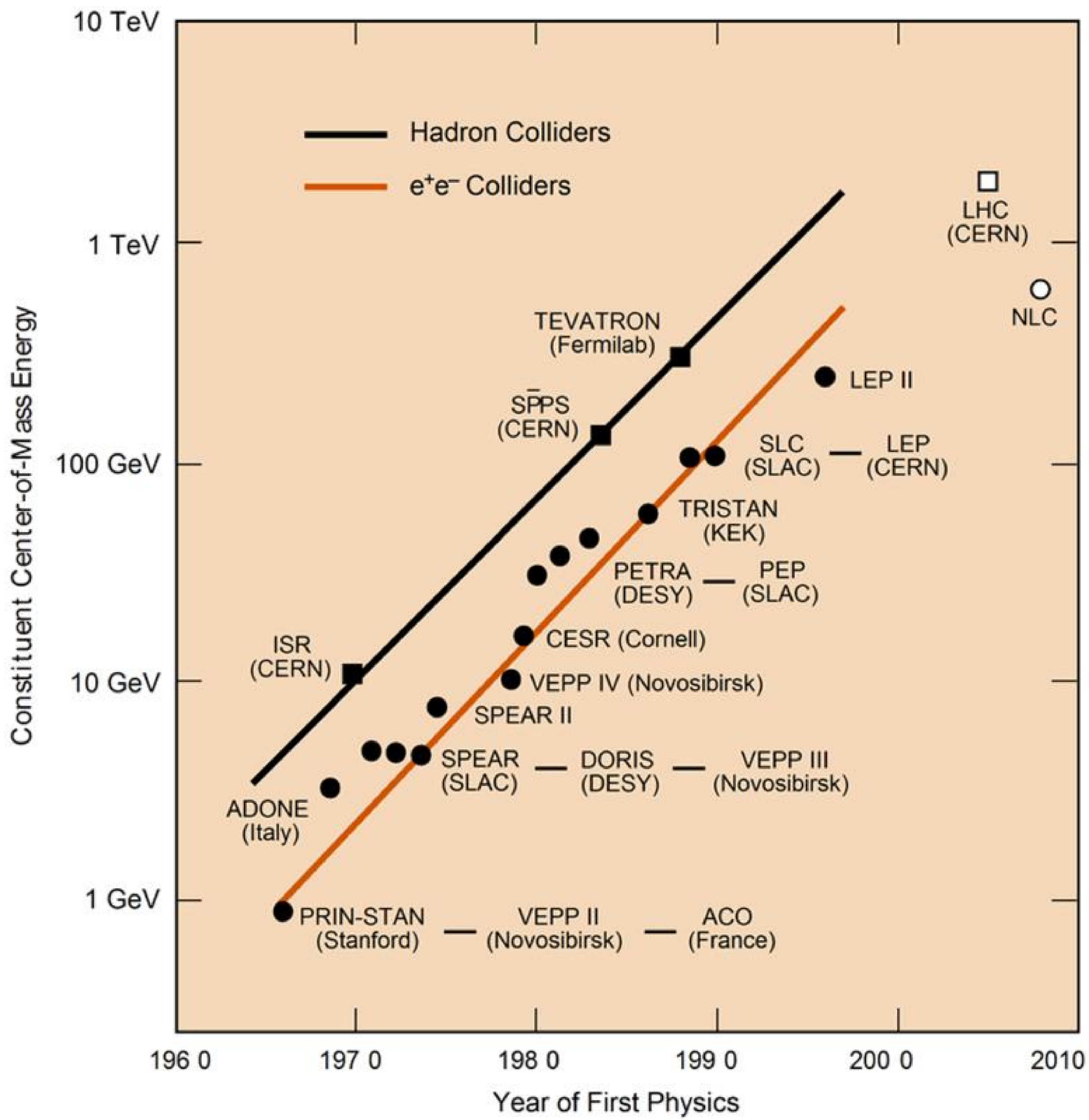
10^{14} K

10^{13} K

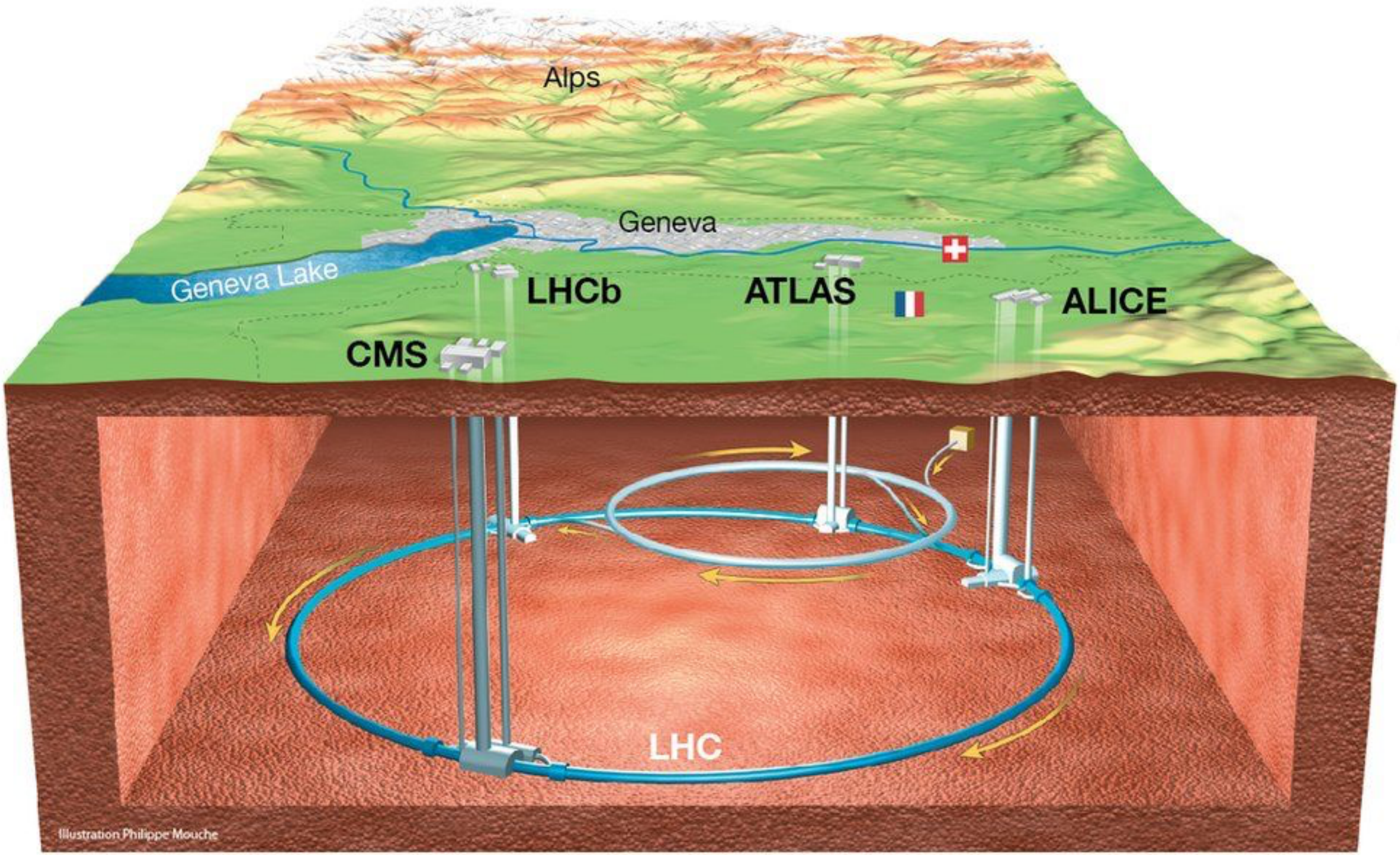
10^{12} K

10^{11} K

10^{10} K

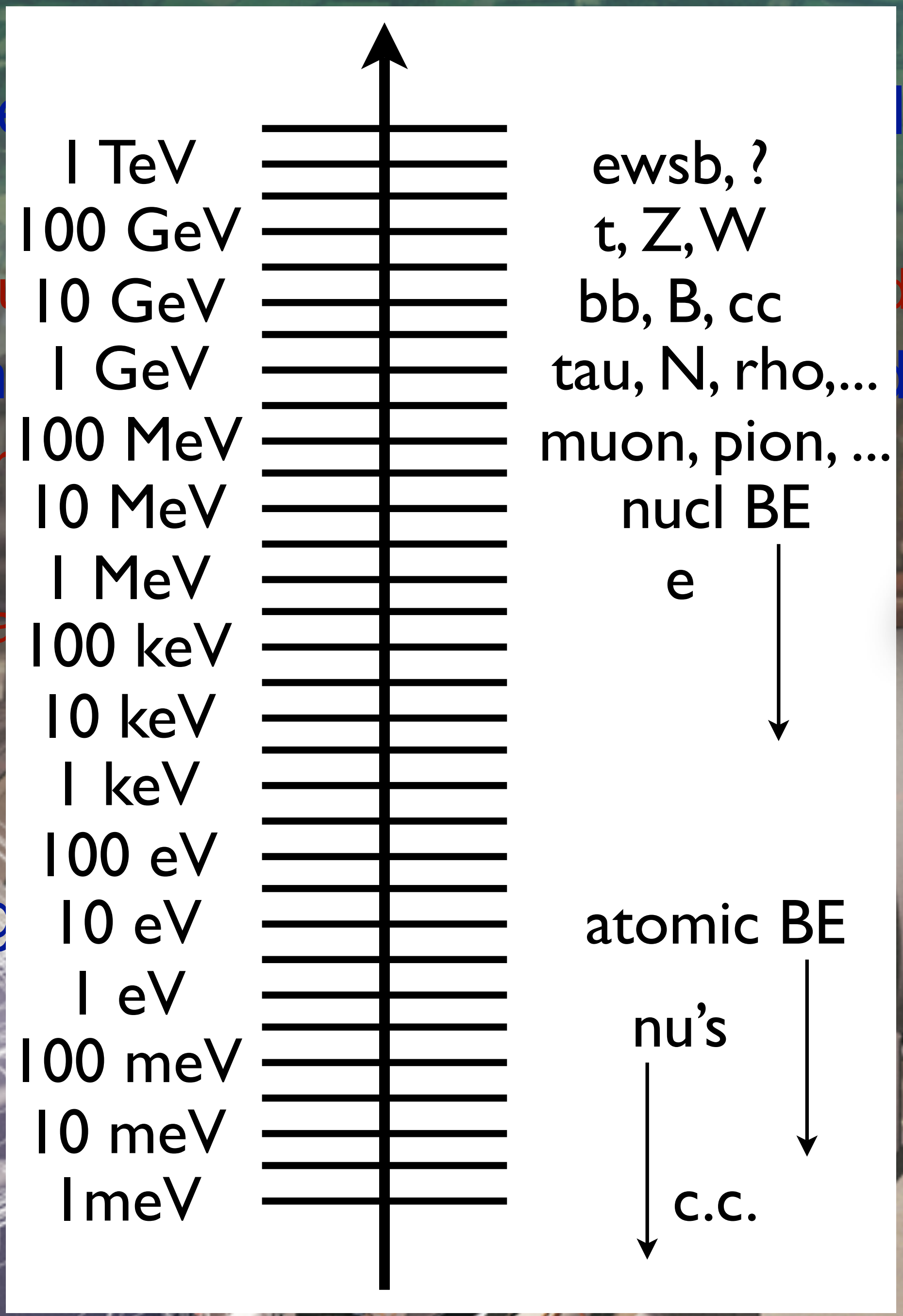


Large Hadron Collider at CERN

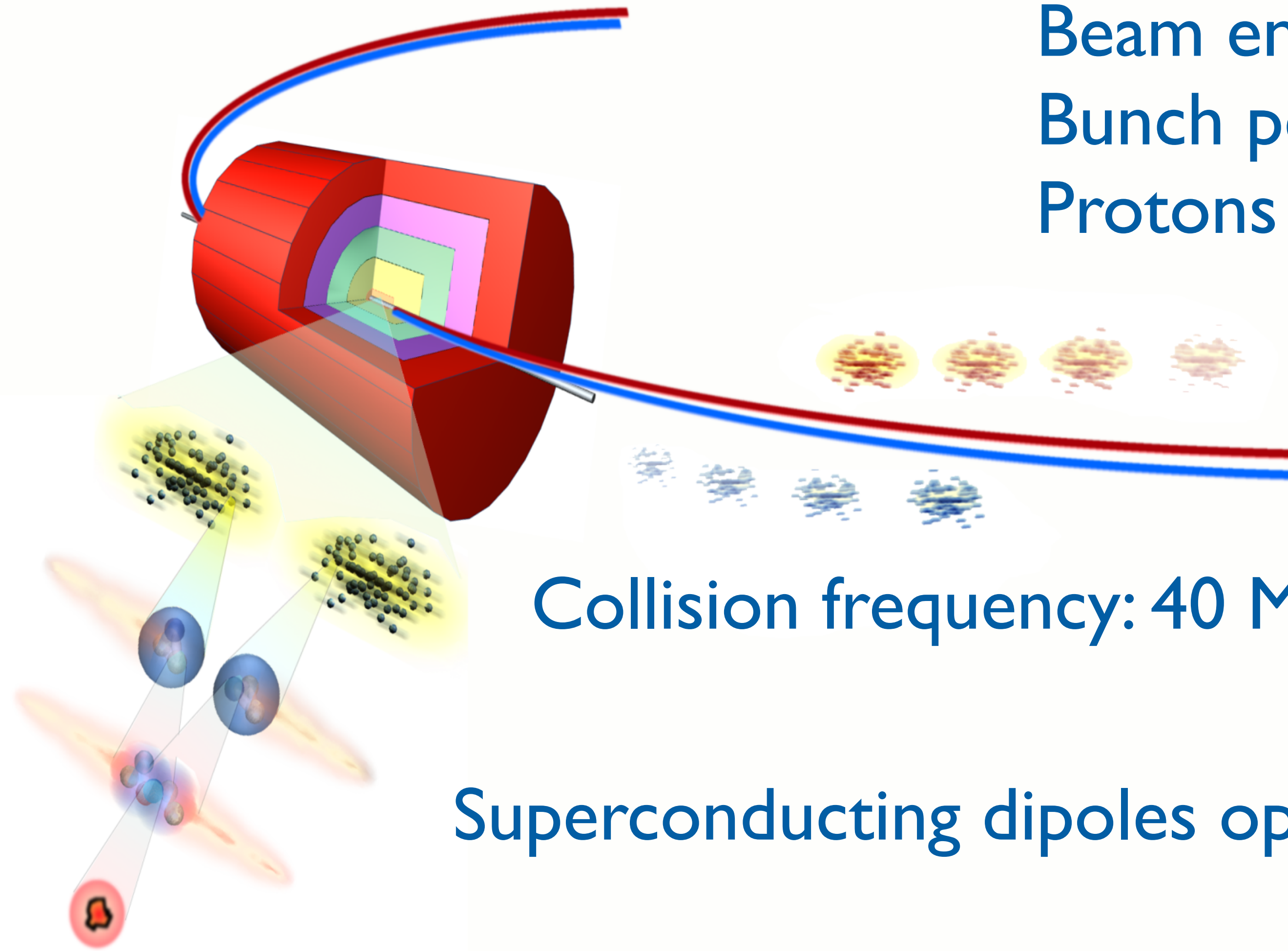


Large Hadron Collider

- Provide ultimate test of our understanding of the universe
- A new machine at the frontier of energy
  - Unexplored territory, not just precision test
- Primary objectives
  - Find Higgs boson pr
  - If found, measure its
    - decay rates, spin, q
  - Search for new phen
    - New bosons and fe
    - Compositeness
    - Dark matter candida
- Many questions arise
  - Why so large?
  - Why such high energ
  - How to discriminate



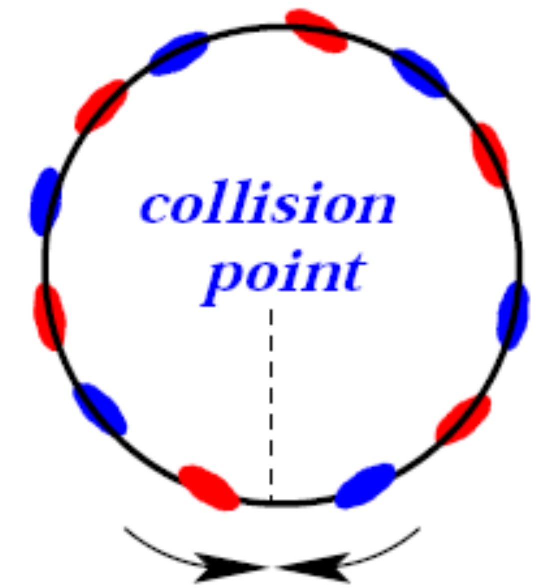
Facts About LHC



Beam energy: 7 TeV

Bunch per beam: 2835

Protons per beam: 10^{11}



Collision frequency: 40 MHz

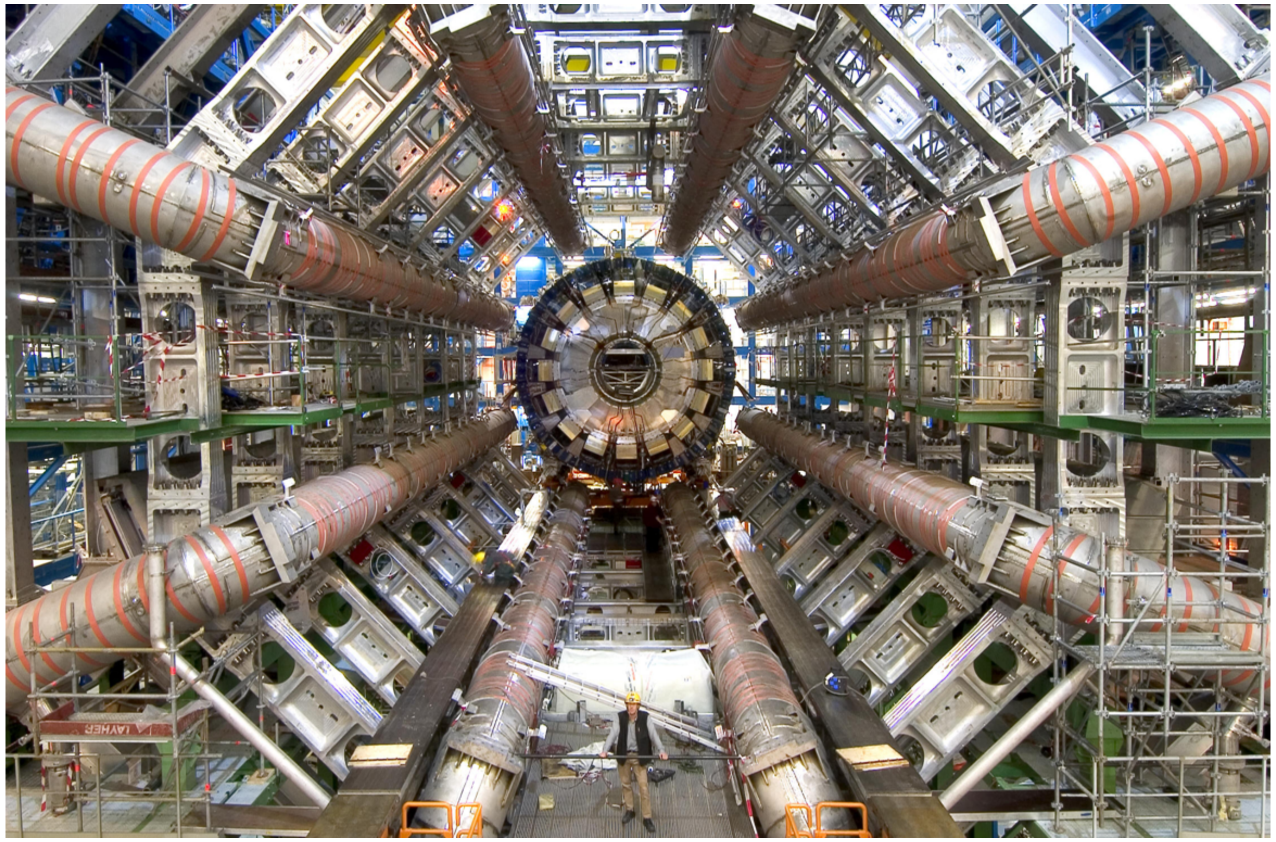
Superconducting dipoles operated at 1.9 K

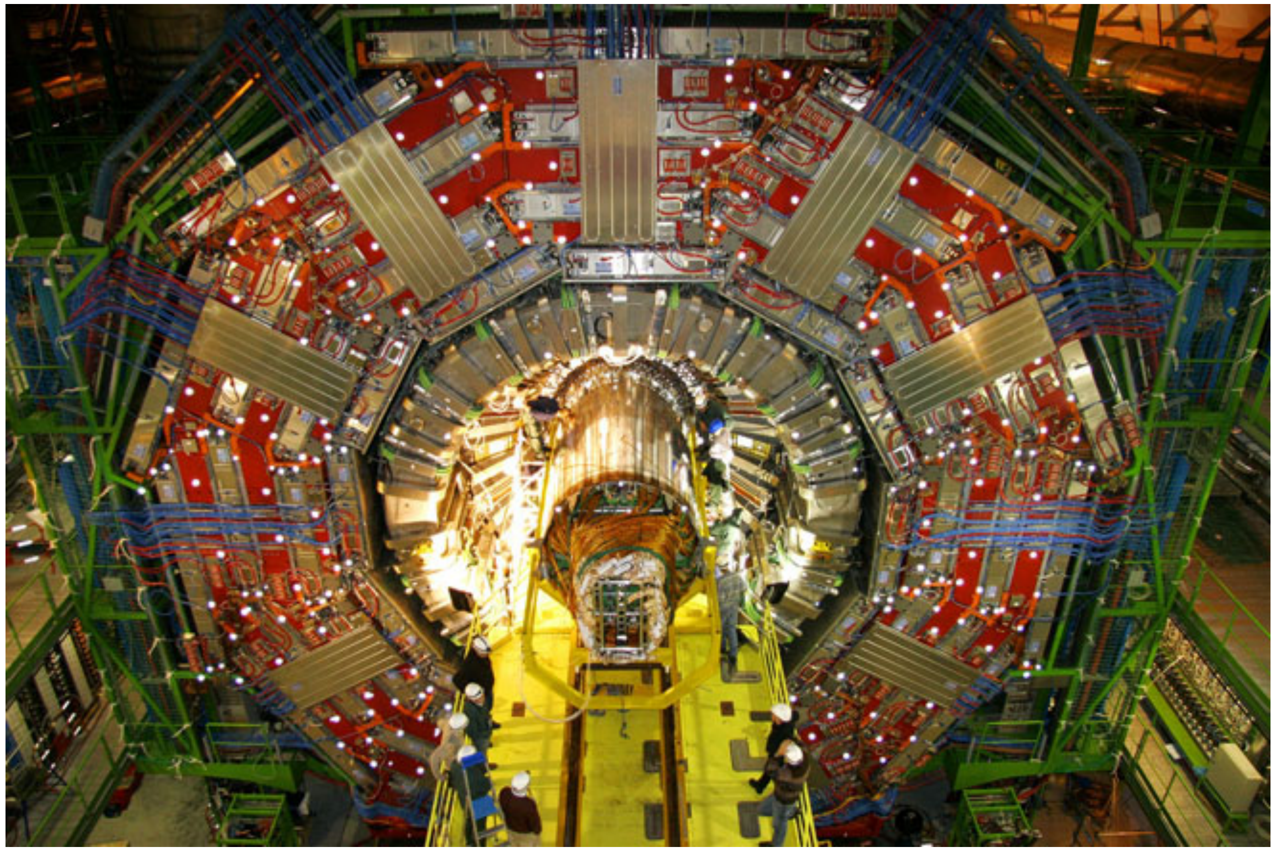
- Energy stored in LHC magnets when operating at 14 TeV: 10.4 GJ
  - Enough to melt 12 tons of Copper!
  - The kinetic energy of an A380 at 700 km/hour
- Kinetic energy of 1 proton bunch: 129 kJ
- Kinetic energy of beam: 362 MJ

Four Experiments at LHC

Gigantic Digital Camera

- Very heavy digital camera
  - 40 million pictures per second
  - Almost 100 million pixels
  - 3D pictures
- >100'000 of CPUs used to quickly filter data
  - 10'000 pictures selected each second
- Only 1000 pictures stored on disk
  - pictures selected within 100 ms
- 22 million GigaByte of data each year (>1 million DVD)
  - Data hosted and analysed at computing centers worldwide





Falsification of Standard Model

- Multiple and redundant measurements of well known quantities
  - different methods
  - different contexts
  - different technologies

The Known Knowns

- Measurement of very small and precise predictions
  - variety of such observables across the spectrum
  - typically referred to as indirect search for New Physics
  - At LHC now merging with standard Physics thanks to amount of data

The Known Unknowns

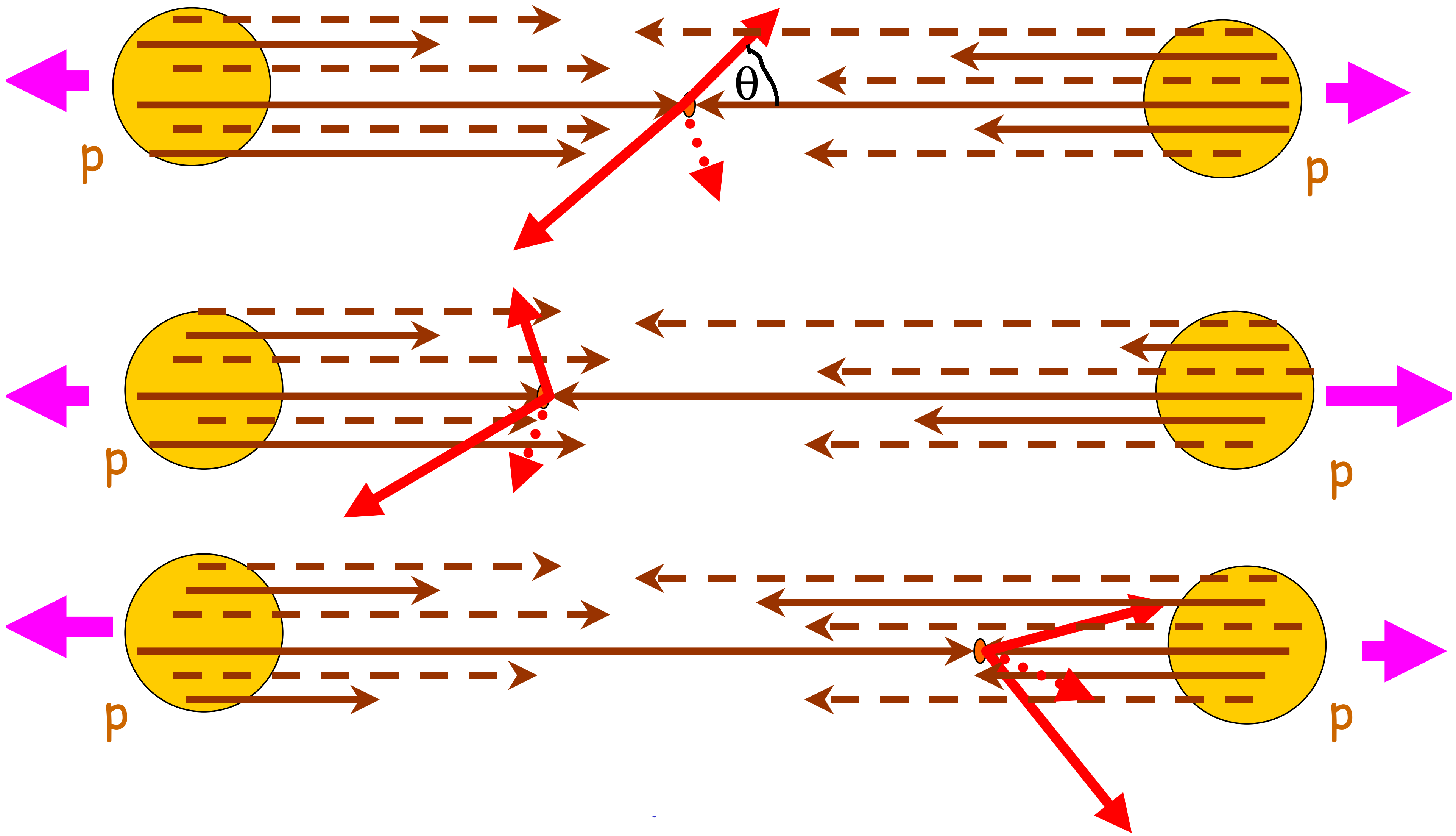
- Search for the exotic
  - chasing more or less crazy ideas by theory friends
    - often motivated by some big question
  - Taking advantage of capabilities of detectors for unconventional signatures

The Unknown Unknowns

- New computational tools for more efficient data mining and increasing sensitivity
- New technologies to improve detection techniques and try new avenues

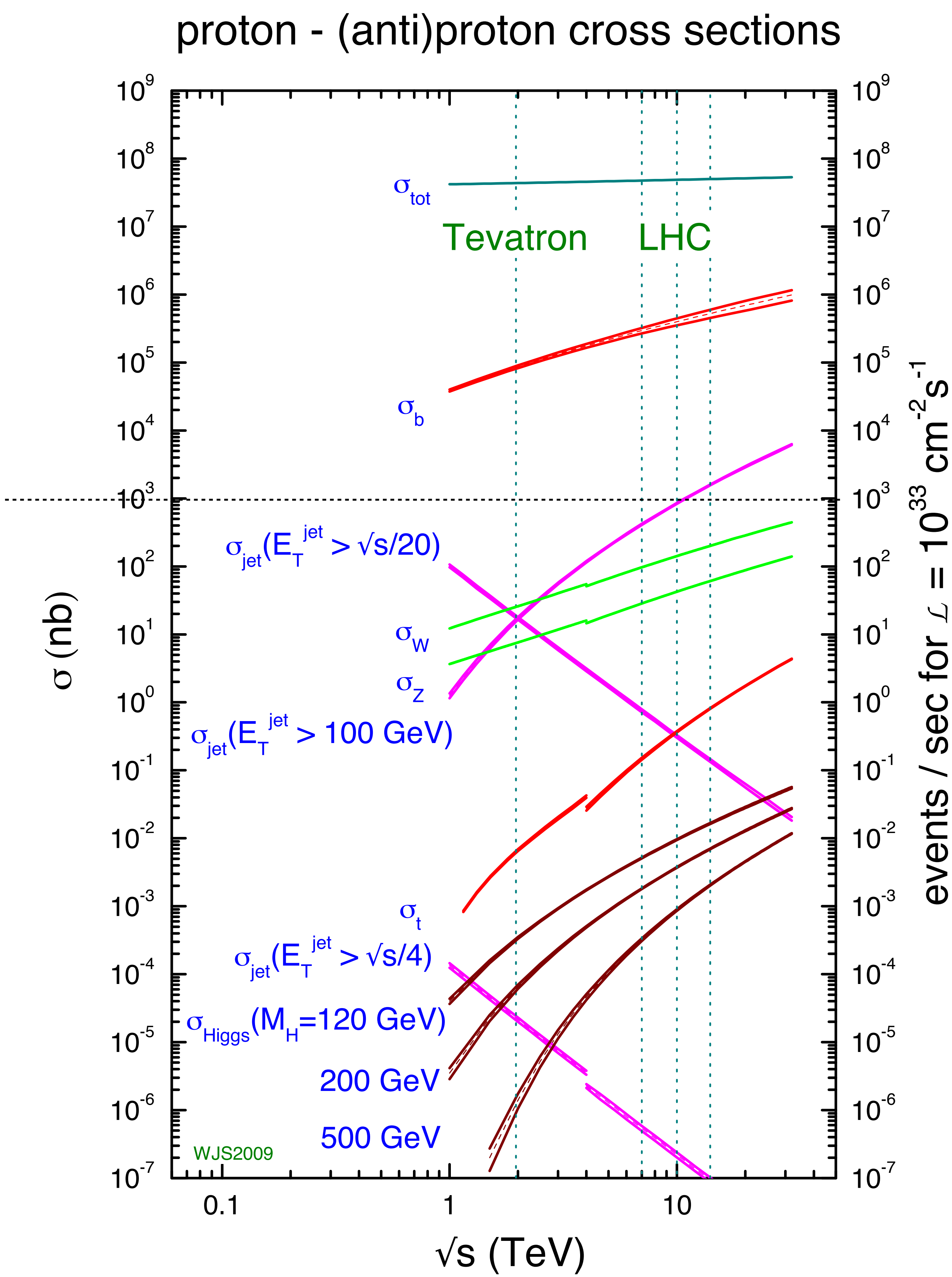
Boost of Center of Mass

$$p_1 = x_1 \cdot E_{beam} \qquad p_2 = x_2 \cdot E_{beam}$$

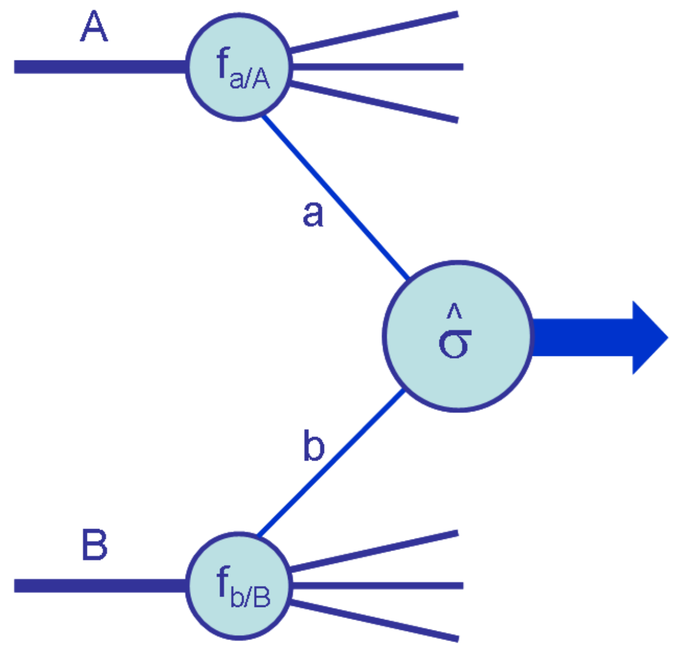


- ▻ No a-priori knowledge of the boost: x_i different and unknown
- ▻ Cannot determine boost unless ALL particles in final states reconstructed
  - – Not feasible
- ▻ Lorentz-invariant quantities: transverse momentum, invariant mass, cross section

Physics Production at LHC



Proton-proton Cross Section



$$\sigma_{AB} = \sum_{a,b=q,g} \left[\hat{\sigma}_{ab}^{\mathrm{LO}} + \alpha_S(Q^2)\hat{\sigma}_{ab}^{\mathrm{NLO}} + \ldots\right] \otimes f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2)$$

$$\sigma_X = \boxed{\sum_{a,b}} \int_0^1 dx_a dx_b \boxed{f(x_a, flav_a, Q^2) f(x_b, flav_b, Q^2)} \cdot \boxed{\sigma_{ab\to X}(x_a, x_b, Q^2)}.$$

Sum over initial partonic states a,b

Parton Density Function

hard scattering cross-section

Parton Density Functions

$f_i(x,Q^2)$ $\begin{cases} i = u_v,\ d_v,\ g \text{ and sea} \\ x = p_{parton} / E_{beam} \ \ \textbf{parton momentum fraction} \\ Q^2 = \textbf{momentum transfer} \end{cases}$

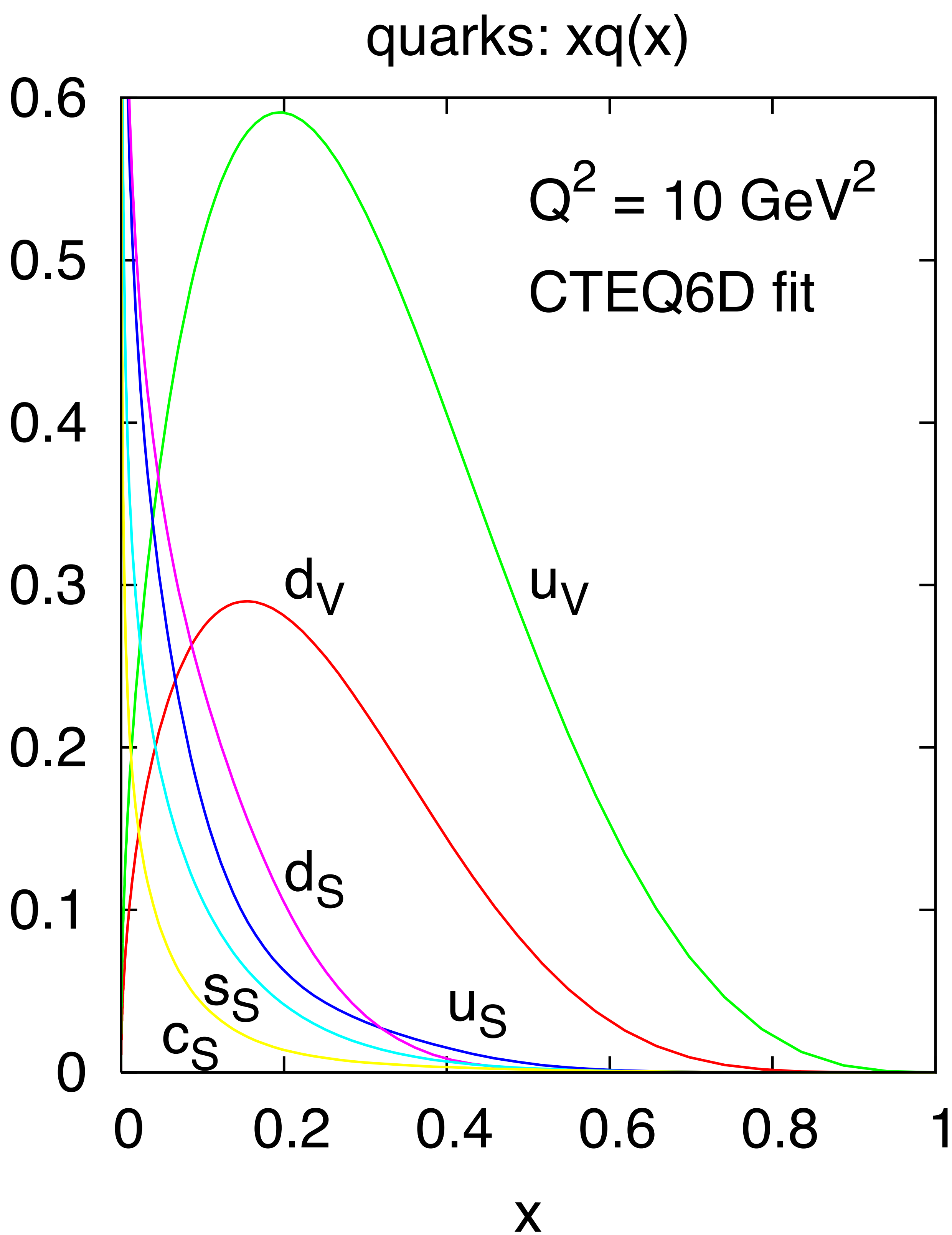
How are PDF's determined?

QCD predicts the scale dependence of $f_i(x,Q^2)$ through DGLAP evolution equations BUT does not accurately predict the x-dependence which has non perturbative origin

1. the x-dependence is parameterised at a fixed scale Q_0^2:
   - **valence quarks: $f \sim x^{\lambda}\ (1\text{-}x)^{\eta}\ P(x)$**
   - **sea/gluon: $f \sim x^{-\lambda}\ (1\text{-}x)^{\eta}\ P(x)$**

   different parameterisations and no.of free parameters used
2. $f_i(x,Q^2)$ is evolved from Q_0^2 to any other Q^2 by numerically solving the DGLAP equations to various orders (LO,NLO, NNLO)
3. the free parameters are determined by fit to data from experimental observables **(data from HERA experiments H1, ZEUS ,fixed target DIS experiments ,CDF, D0)**

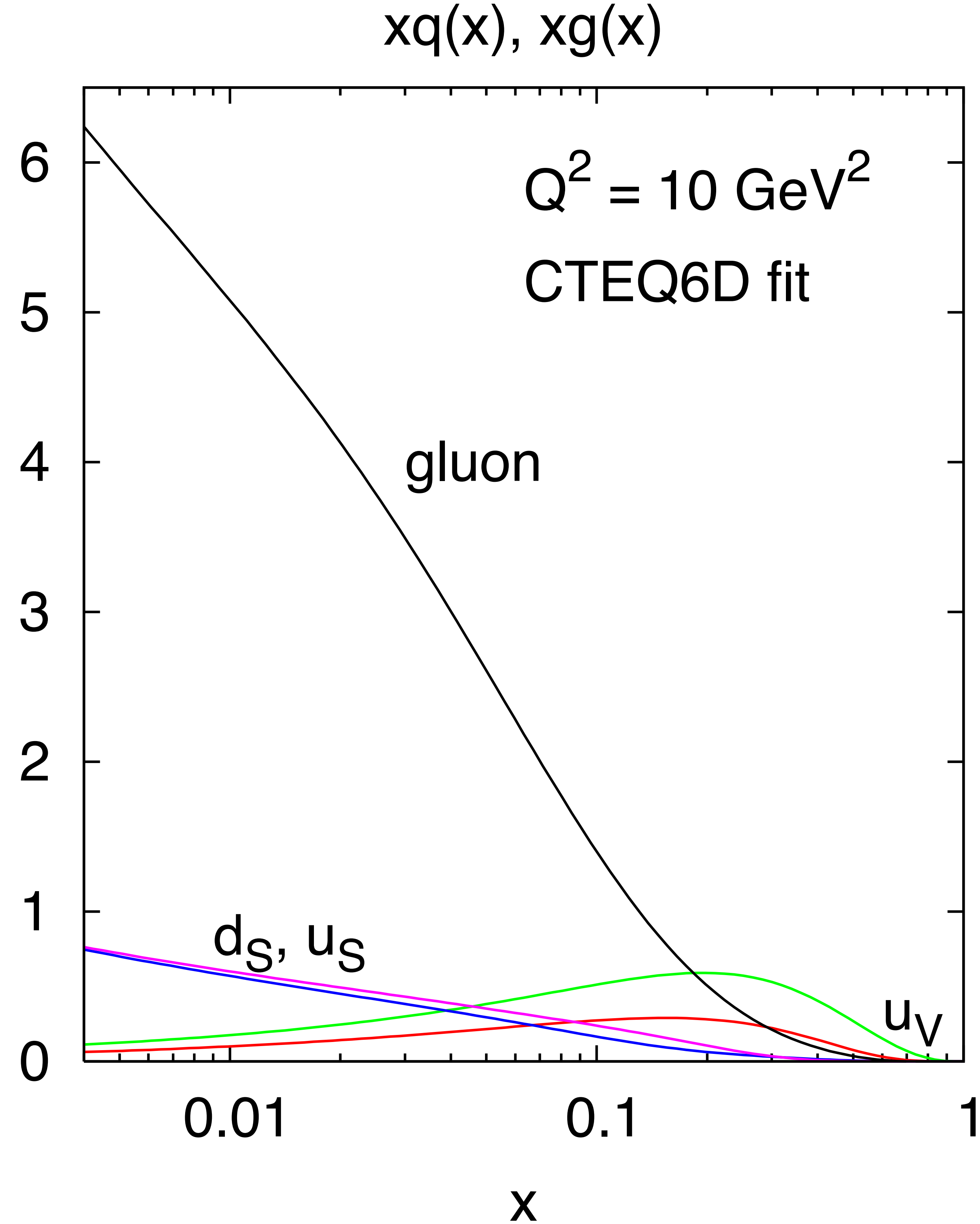
Form of Pdfs



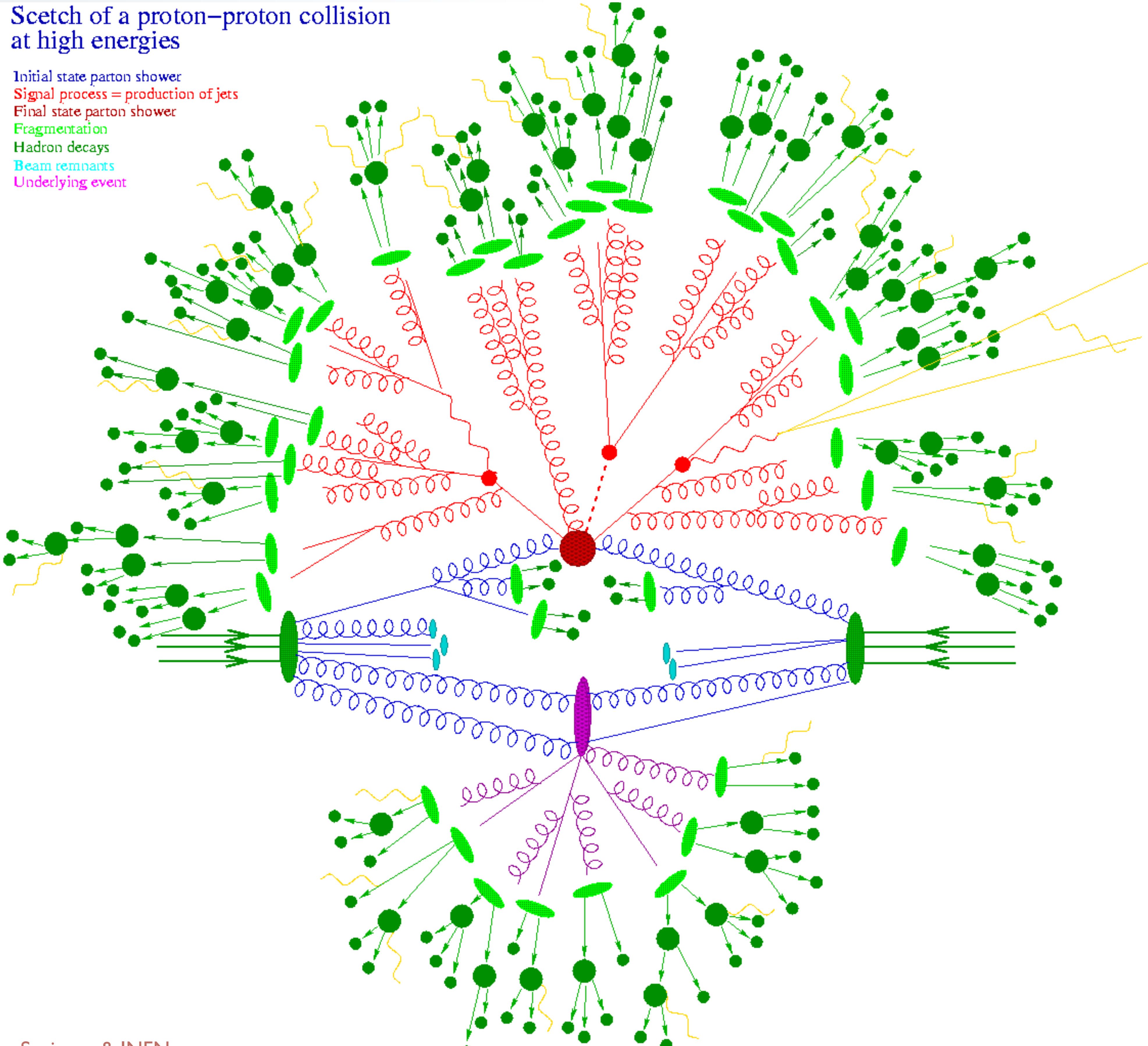
- valence quarks ($u_V = u - \bar{u}$) are *hard*
  $x \to 1 : xq_V(x) \sim (1-x)^3$
  quark counting rules
  $x \to 0 : xq_V(x) \sim x^{0.5}$
  Regge theory
- sea quarks ($u_S = 2\bar{u}, \ldots$) fairly *soft* (low-momentum)
  $x \to 1 : xq_S(x) \sim (1-x)^7$
  $x \to 0 : xq_S(x) \sim x^{-0.2}$

Gluon Density Function

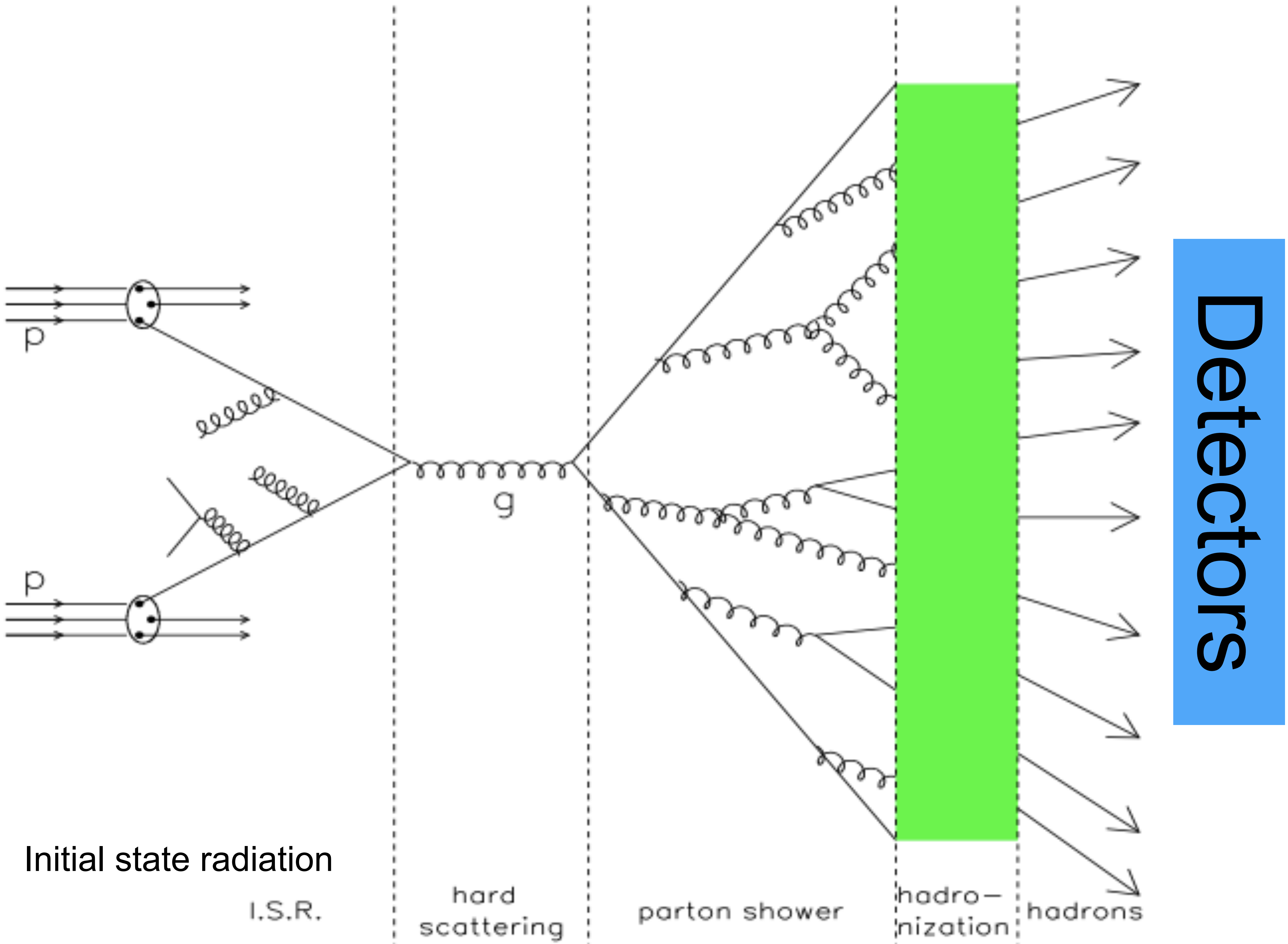
- ▻ Gluons dominate by far at low x
- ▻ LHC dominated mainly by gluon-gluon fusion (hard scattering of 2 gluons) at low x
- ▻ Different experimental signatures for qq, q-anti-q and qg hard scattering
  - – also very different cross sections



Pictorial Representation of p-p Collision

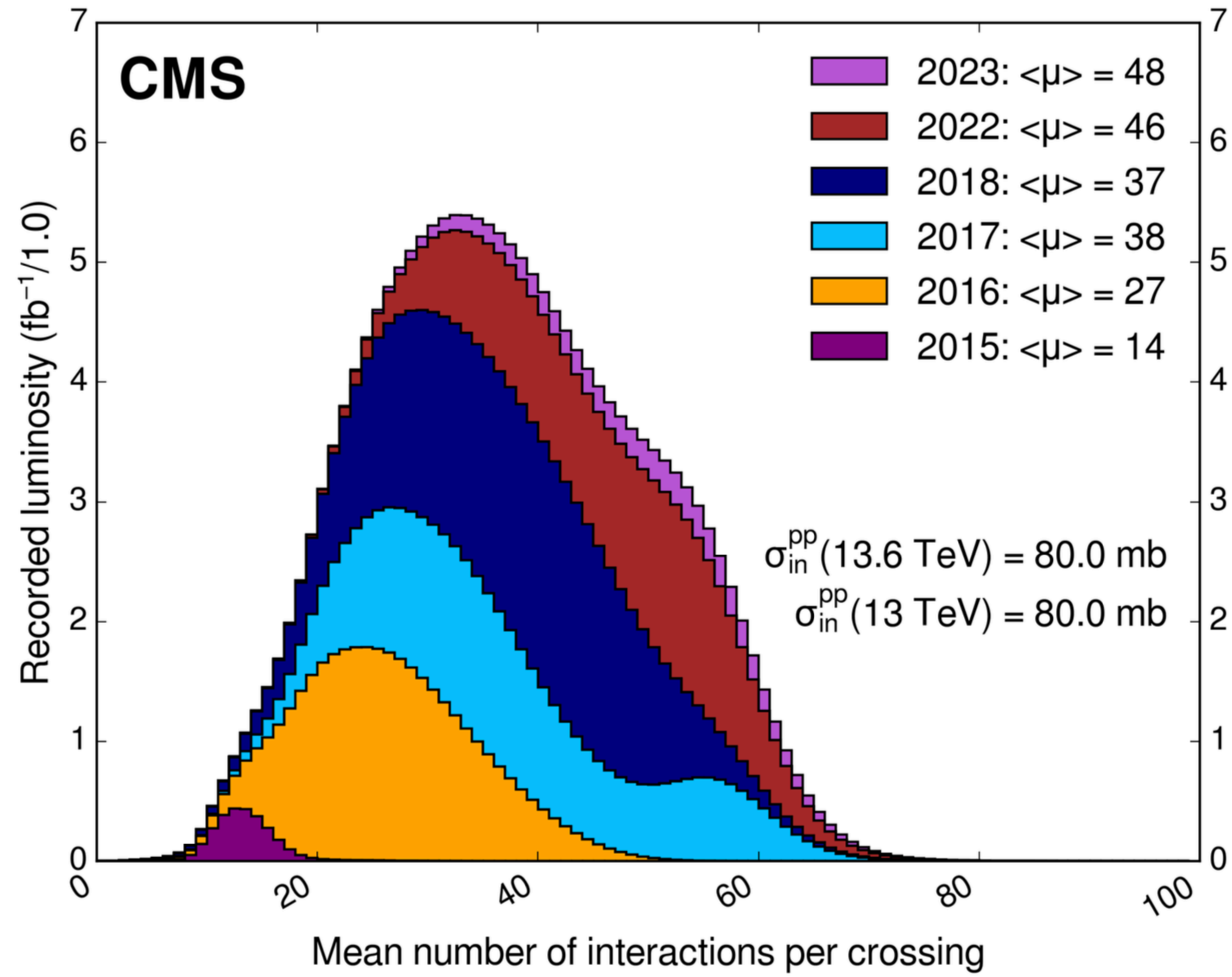


Hadron Hadron Collisions



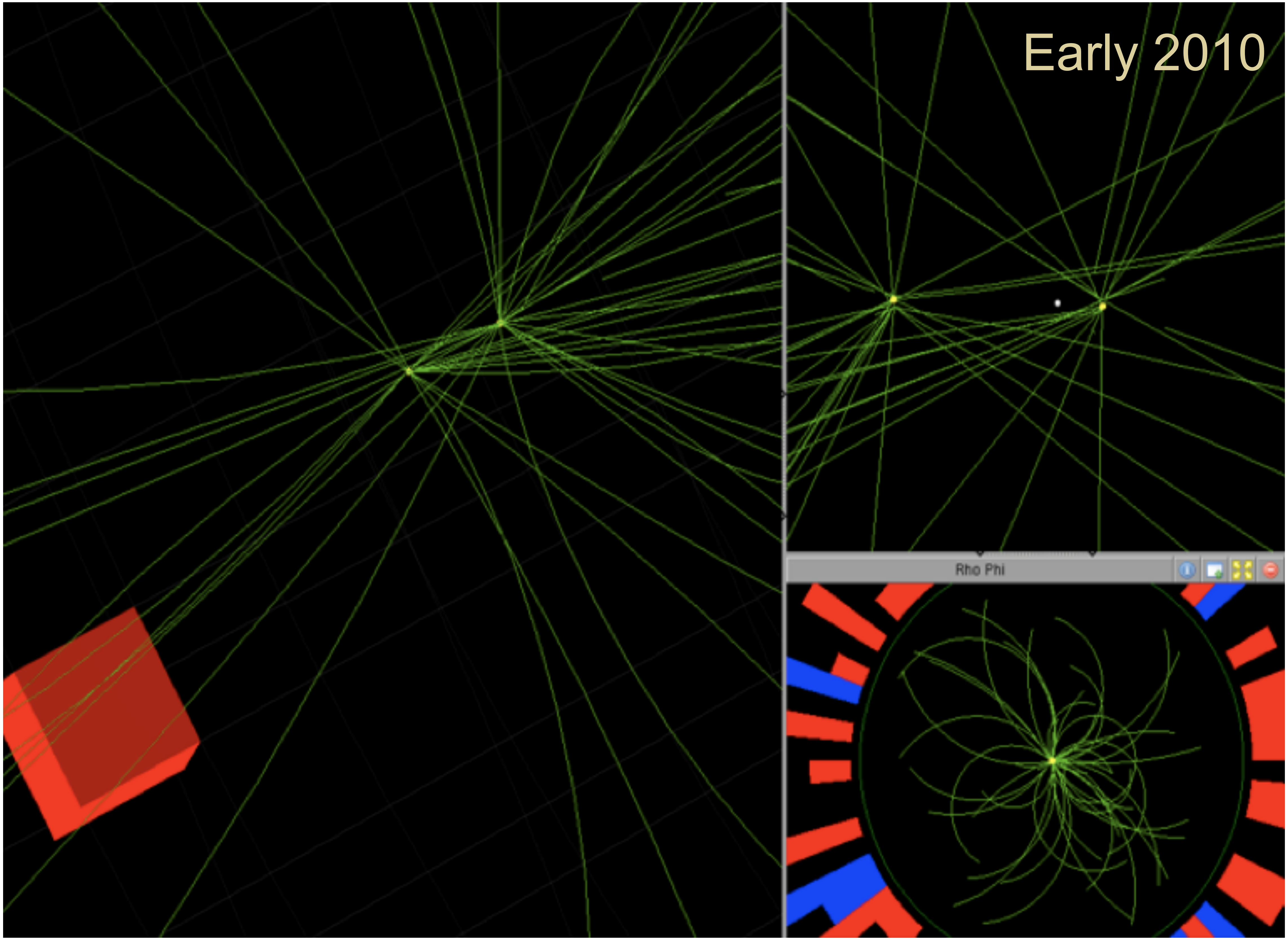
Pile-Up

- ▻ High probability of more than 1 proton-pair interaction with
  - ○ smaller beam section
  - ○ higher number of protons per bunch
- ▻ Typically one interesting hard-scattering of interest
  - – the "event" causing the trigger

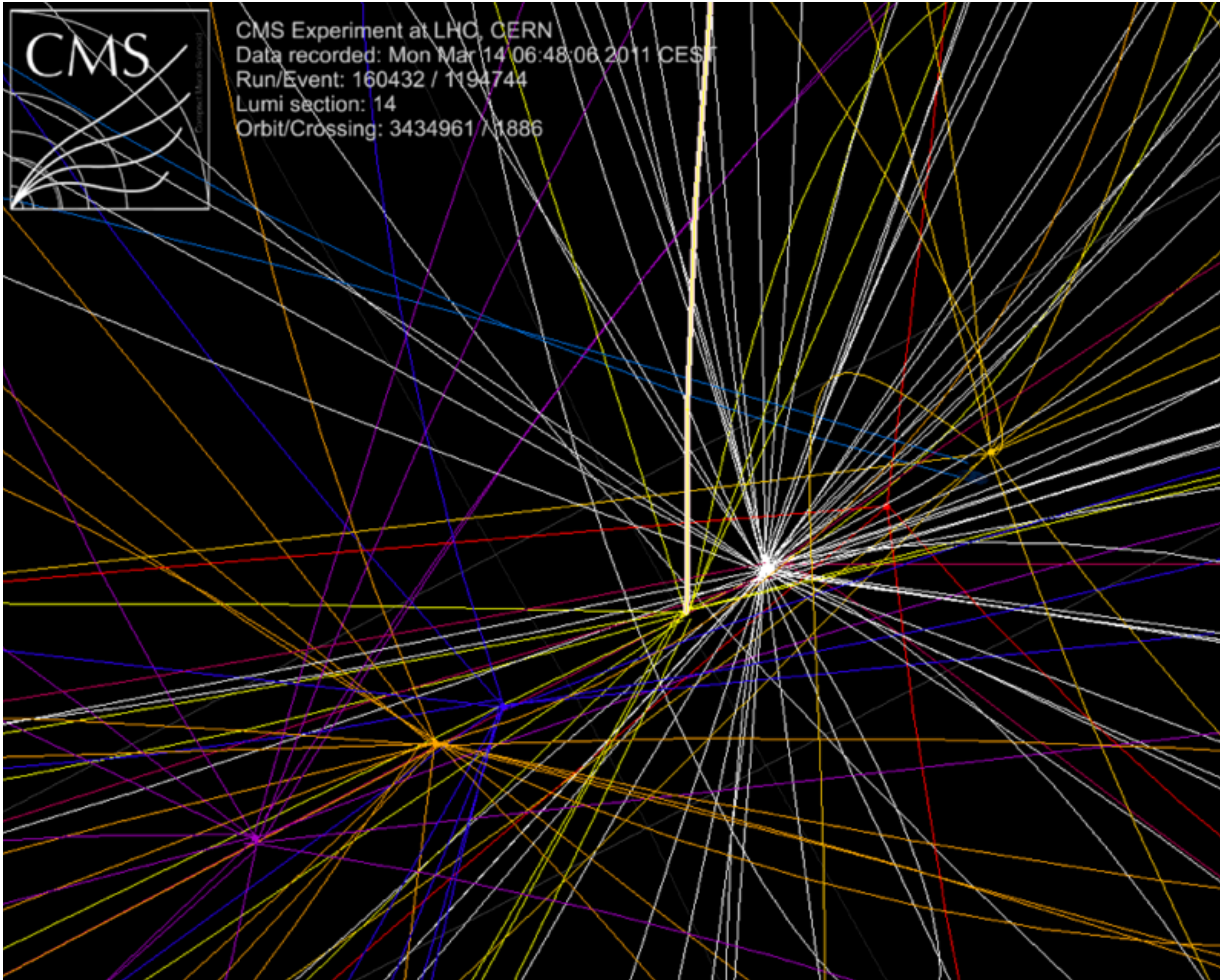


- ▻ Additional collisions in same bunch crossing increase average energy density in detectors
  - – higher occupancy
  - – distortion or mis-measurement of energy in calorimeters
  - – Potential inefficiency in track reconstruction in very busy events
- ▻ Much larger event processing time
  - – Increasing computing power to keep up with data

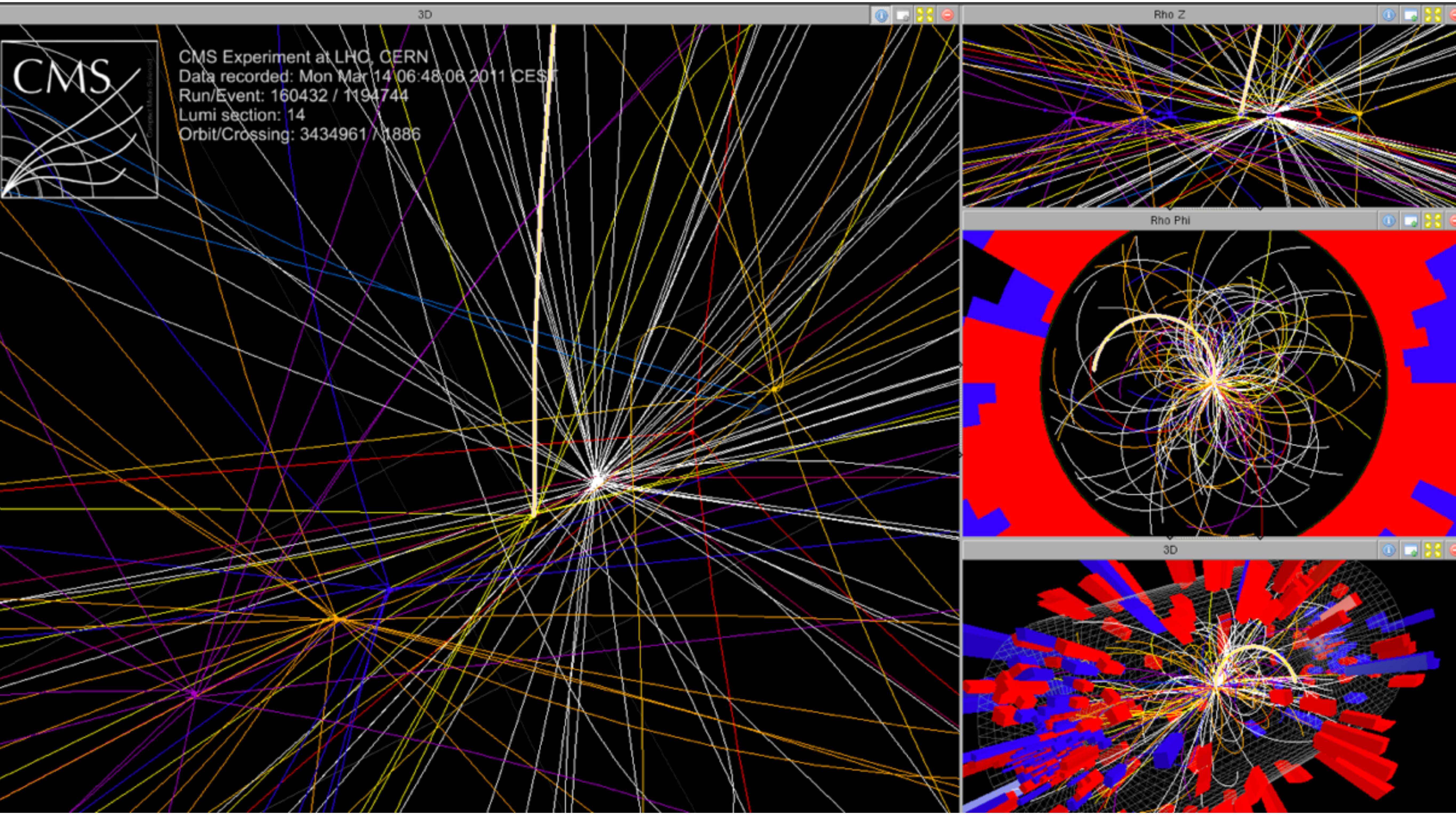
Pile-Up at Low Luminosity



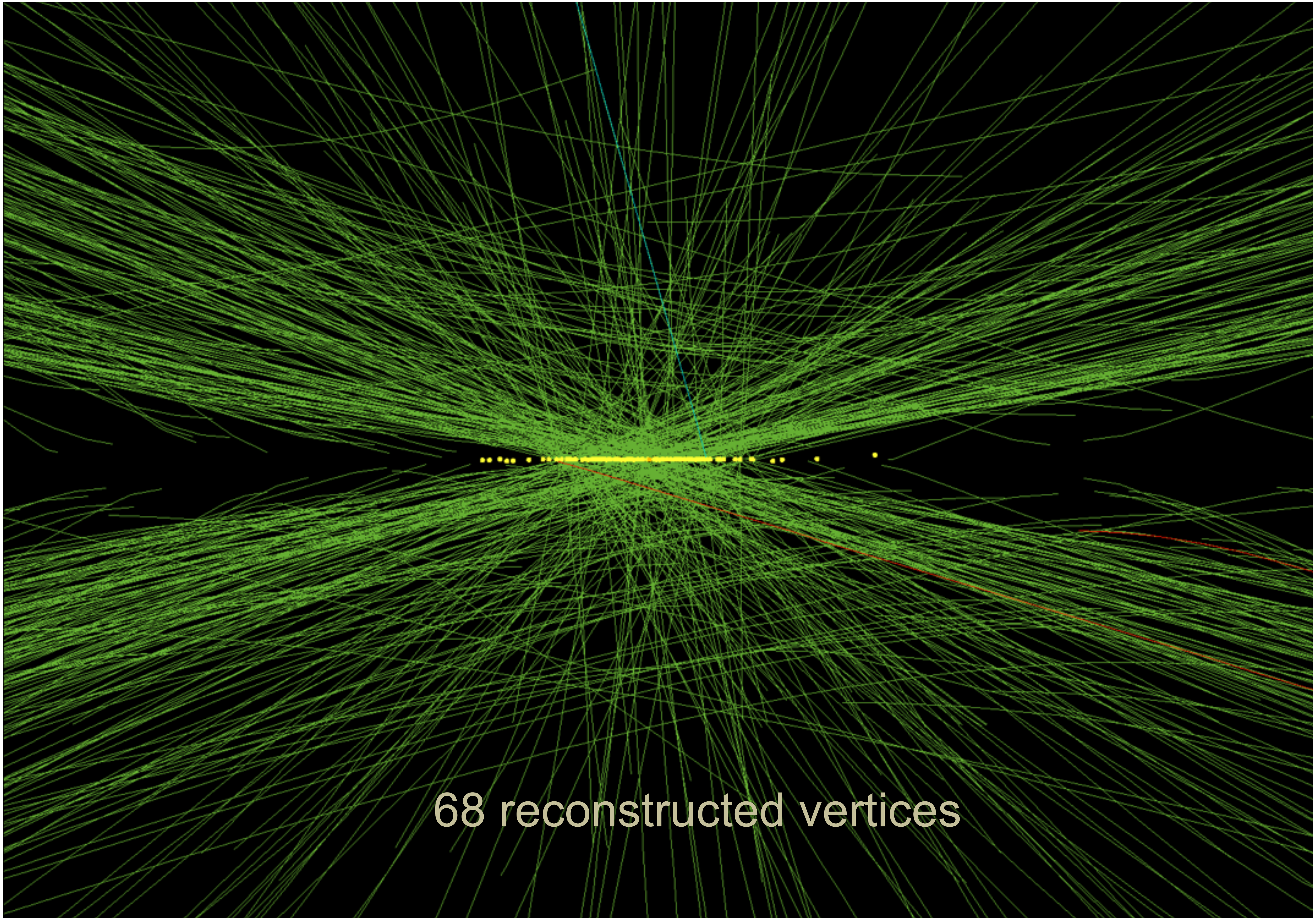
Pile-Up Early 2011

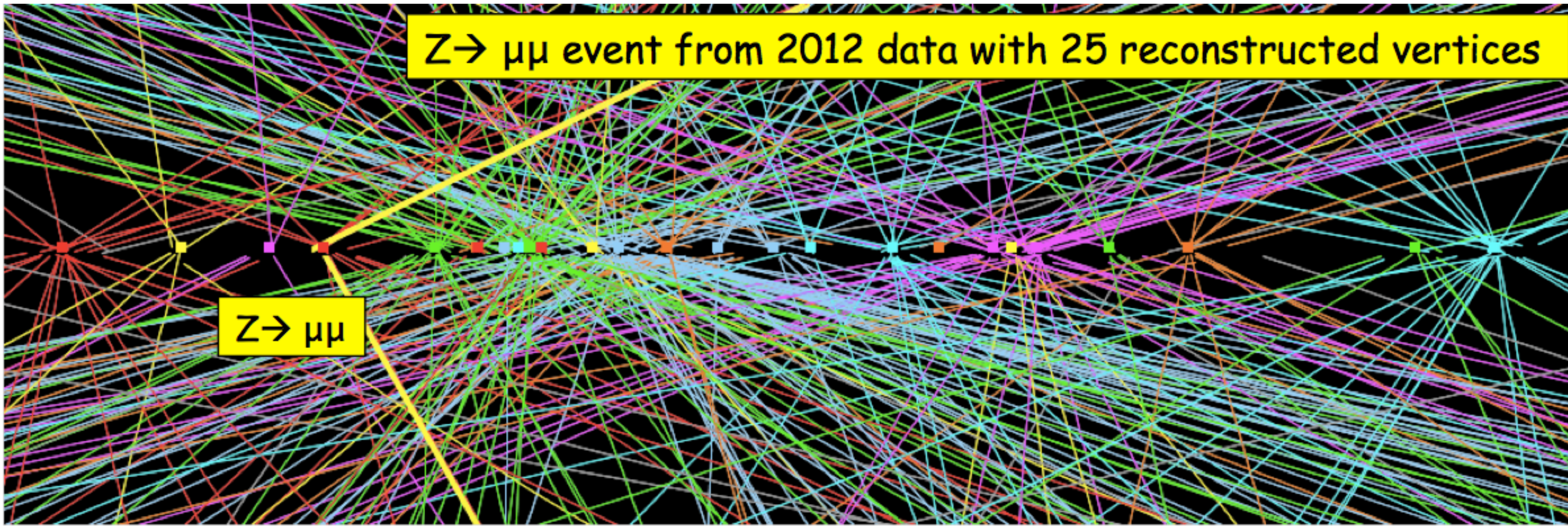


Pile-Up Early 2011

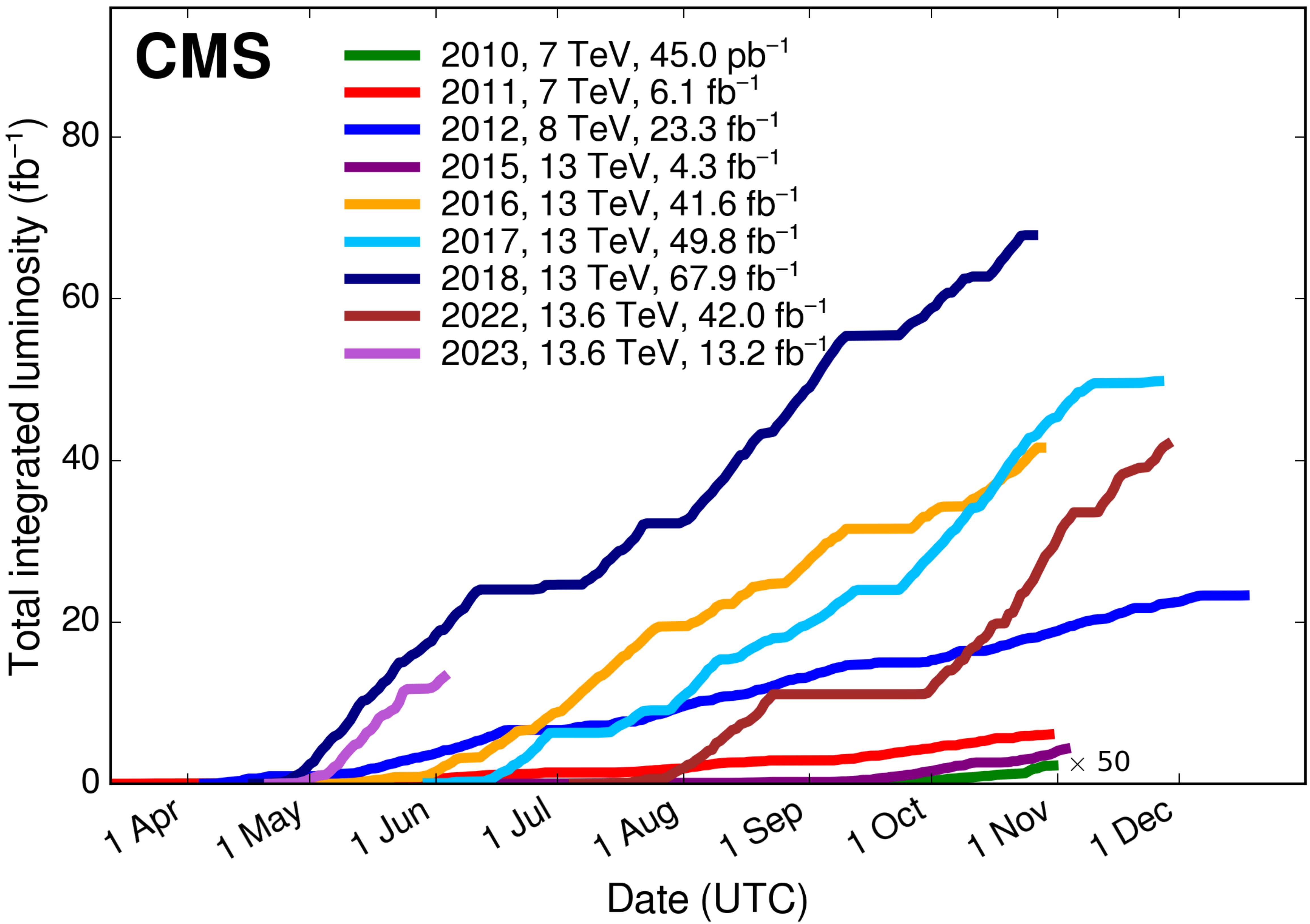


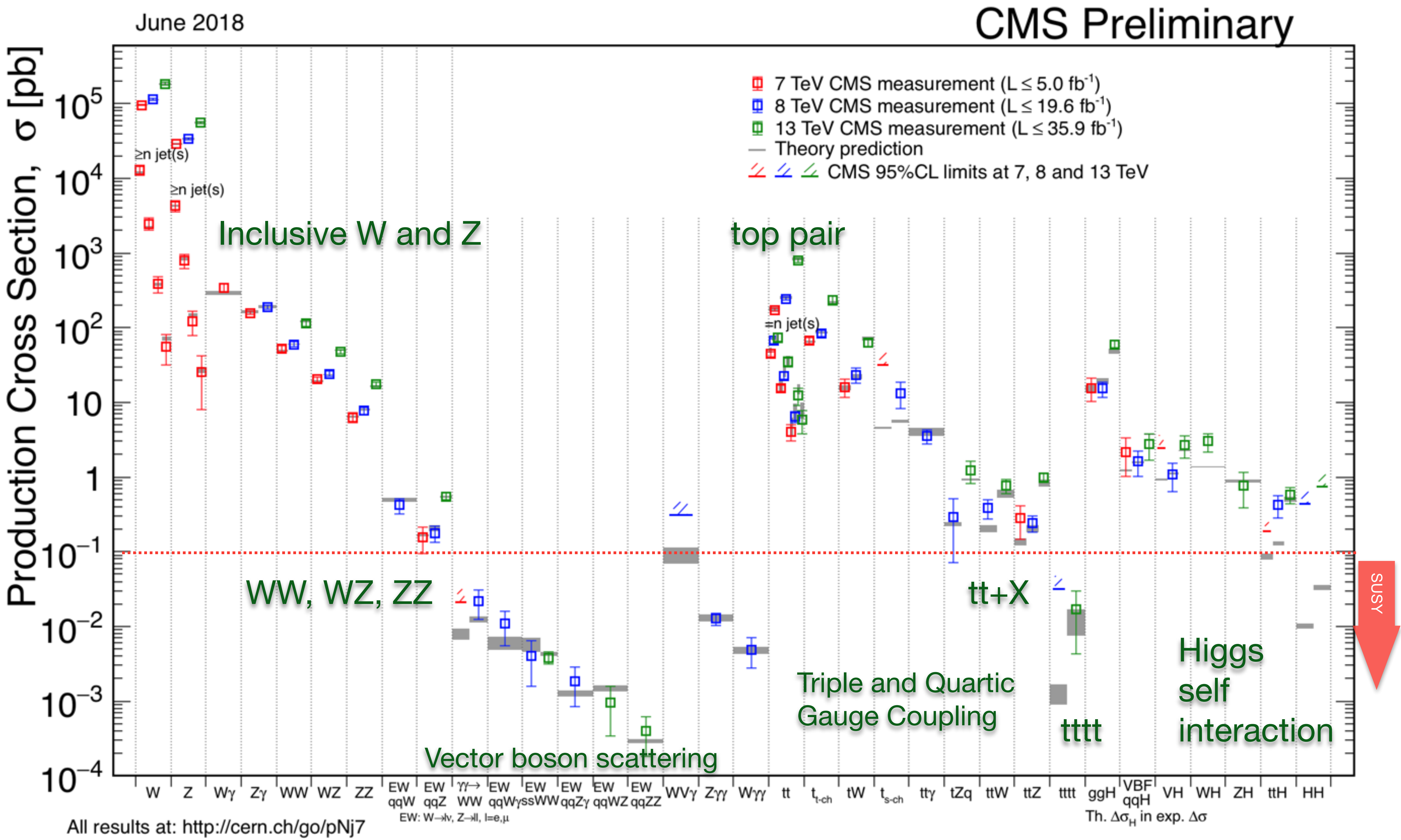
High Pile-Up Event in 2012




Z→ μμ event from 2012 data with 25 reconstructed vertices
Z→ μμ

Integrated luminosity





Standard Model

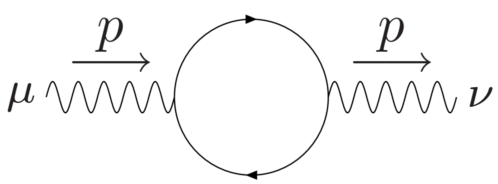
New Physics through Precision

Why the Higgs boson?

- ▻ Gauge invariance of Electroweak theory requires all fermions and W and Z to be massless
- ▻ Discovery of W and Z in 1983 proved them to be pretty heavy
- ▻ Need a mechanism to dynamically generate mass for all particles and conserve the gauge invariance
- ▻ Higgs mechanism and goldstone bosons address this problem
- ▻ Experimental evidence needed to validate theory
  - Predict Higgs production processes and decay rates
- ▻ Direct search
  - produce Higgs and look for decay products: invariant mass and characteristic kinematics
- ▻ Indirect search
  - Calculate contribution of Higgs in corrections to well known SM processes
  - Combined analysis of all precisely measured Z-pole observables and check validity with different Higgs mass assumptions

Generating Mass for W and Z

- Propagator for massless vector bosons at tree level

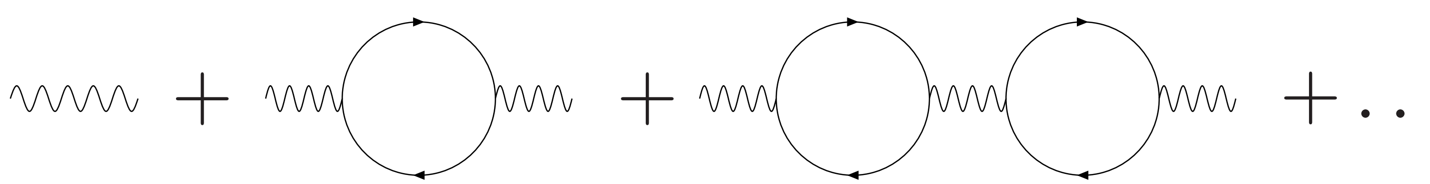


$$i\,\Pi_{\mu\nu}(p) \equiv i(p_\mu p_\nu - p^2 g_{\mu\nu})\Pi(p^2)$$

Gauge invariance

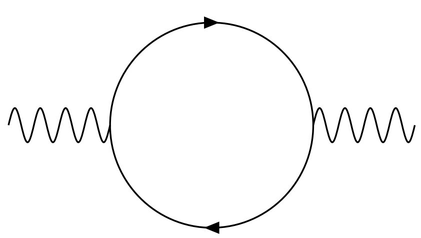
$$p^\mu \Pi_{\mu\nu}(p) = p^\nu \Pi_{\mu\nu}(p) = 0$$

- Renormalized propagator at higher order



$$= \frac{-i(g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2})}{p^2[1+\Pi(p^2)]}$$

- For a massless scalar particle in the loop



$$\Pi(p^2) \underset{p^2\to 0}{\simeq} \frac{-g^2 v^2}{p^2} \longrightarrow p^2[1+\Pi(p^2)] = p^2 - g^2 v^2$$

- For p=0 we have our vector boson with m = gv !

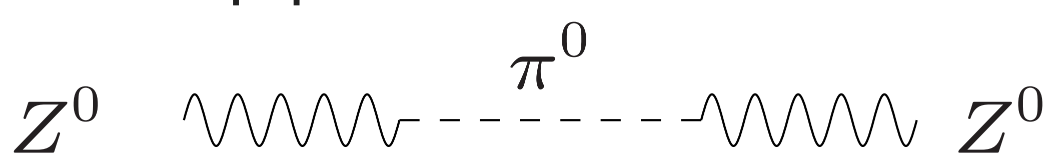
- Do we have already any such scalar?

Generating W and Z Mass with π^0

- W and Z couple to charge and neutral currents

$$\mathcal{L}_{\text{int}} = g_Z j^Z_\mu Z^\mu + g_W (j^W_\mu W^{+\mu} + \text{h.c.})$$

- Charged and neutral pions have very small mass (compared to other hadrons) and are massless in the limit of massless quarks!
- Pions in the loop provided needed mass term $\Pi(p^2) = -g_Z^2 f_\pi^2 / p^2$

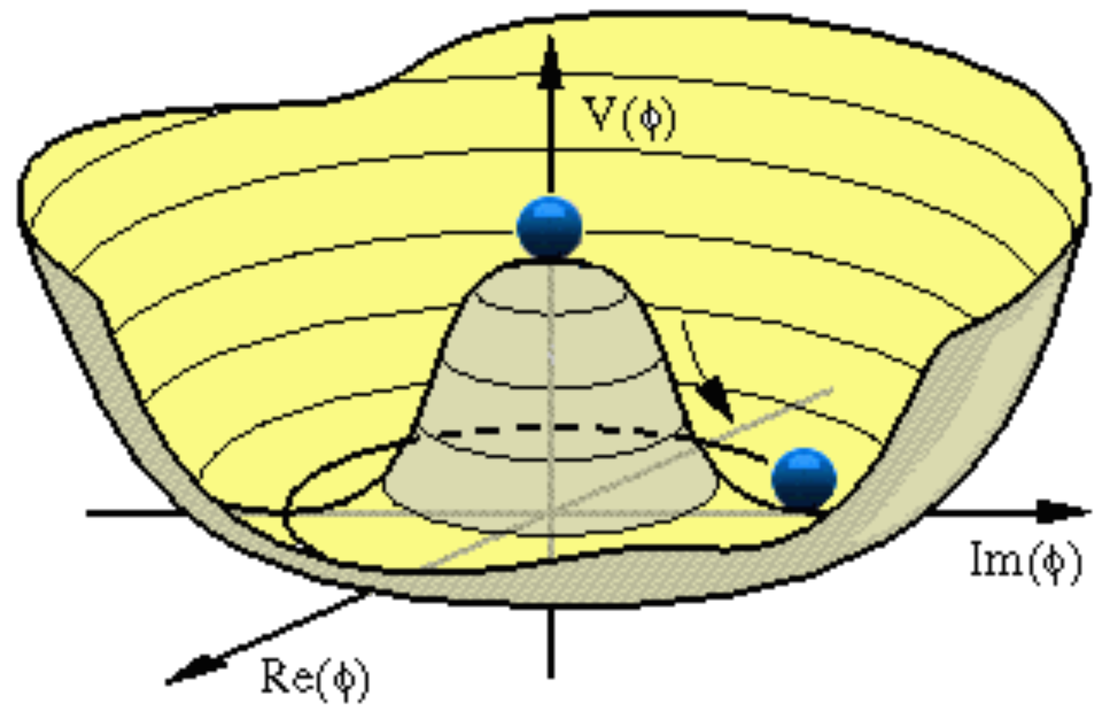


- Prediction for W and Z mass $m_W = g_W f_\pi \quad m_Z = g_Z f_\pi$
- Pion decay constant measured from decay rate to be $f_\pi = 93$ MeV
- W and Z mass related in SM through $\dfrac{m_W}{m_Z} = \dfrac{g_W}{g_Z} \equiv \cos\theta_W \simeq 0.88$
  – Good agreement with measurement
- We know $g_Z \simeq 0.37$ which corresponds to m_Z = 35 MeV!
  – Off by 3 orders of magnitude!
- Need a new scalar for dynamic mass generation

Spontaneous Symmetry Breaking

- New complex SU(2) doublet with four degrees of freedom (massless scalar particles)
- Self-interaction potential

$$V(\Phi) = \frac{\lambda}{4}(\Phi^\dagger\Phi - \tfrac{1}{2}v^2)^2$$



- Non-zero vacuum expectation value (VEV) generates one massive scalar
  - remaining 3 scalar absorbed by W, Z, and photon

$$\langle\Phi^0\rangle = v/\sqrt{2}$$

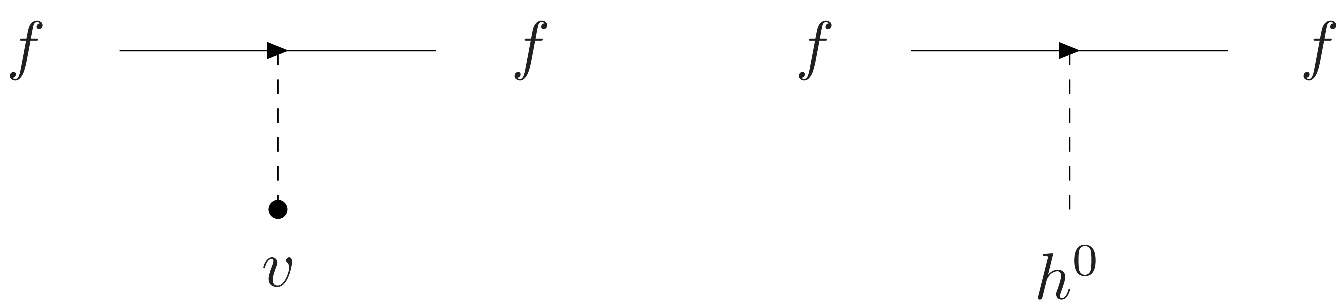
- We want this scalar to couple to generate correct mass $m_Z = g_Z v \simeq 91$ GeV
- Therefore the VEV must be $v = 246$ GeV
- New massive scalar particle commonly known as Higgs Boson $m_h = \frac{1}{2}\lambda v^2$
  - Interactions, decay rates known precisely
  - But its **mass not fixed and must be measured**

Fermion Mass thanks to Higgs

- In addition to Z and W, also fermions acquire mass in SM thanks to Yukawa coupling to Higgs boson

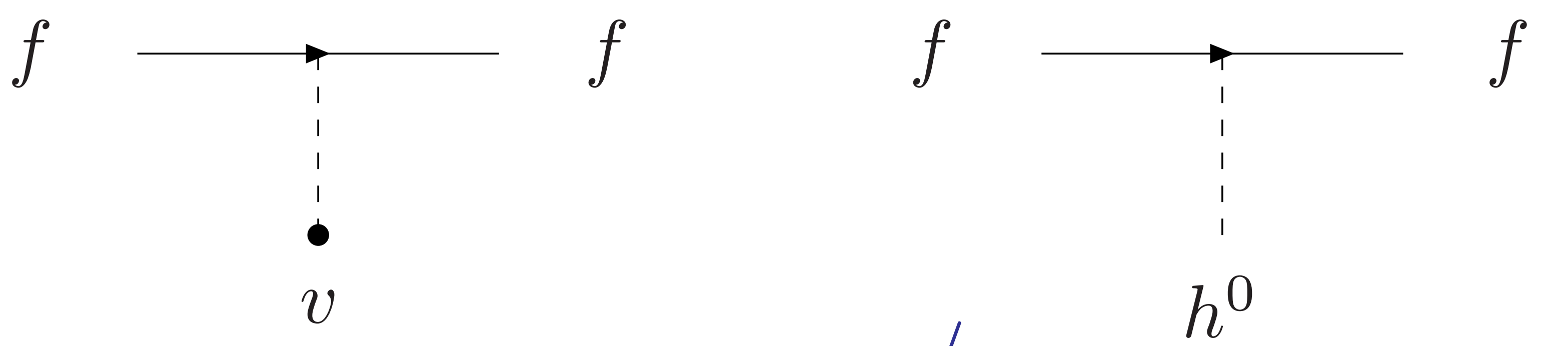
$$\mathcal{L}_{\text{Yukawa}} = -h_u(\bar{u}_R u_L \Phi^0 - \bar{u}_R d_L \Phi^+) - h_d(\bar{d}_R d_L \Phi^{0\,*} + \bar{d}_R u_L \Phi^-) + \text{h.c.}$$

fermions	SU(2)	U(1)$_Y$
$(\nu\,,\,e^-)_L$	2	-1
e^-_R	1	-2
$(u\,,\,d)_L$	2	$1/3$
u_R	1	$4/3$
d_R	1	$-2/3$

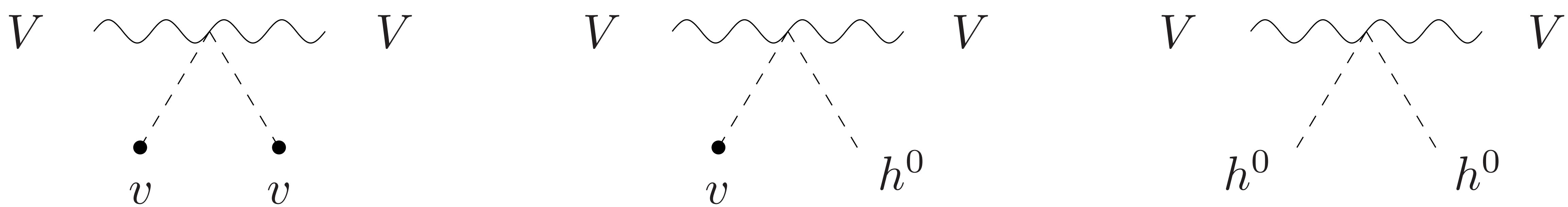


- Coupling proportional to fermion mass $g_{hf\bar{f}} = m_f/v$
  - Will determine Higgs decay branching fractions

Higgs Couplings



$$g_{hf\bar{f}} = m_f/v$$

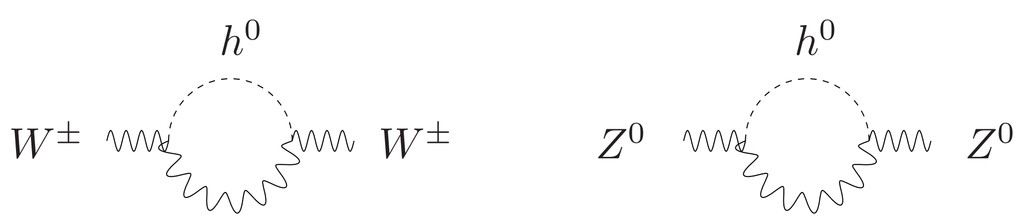


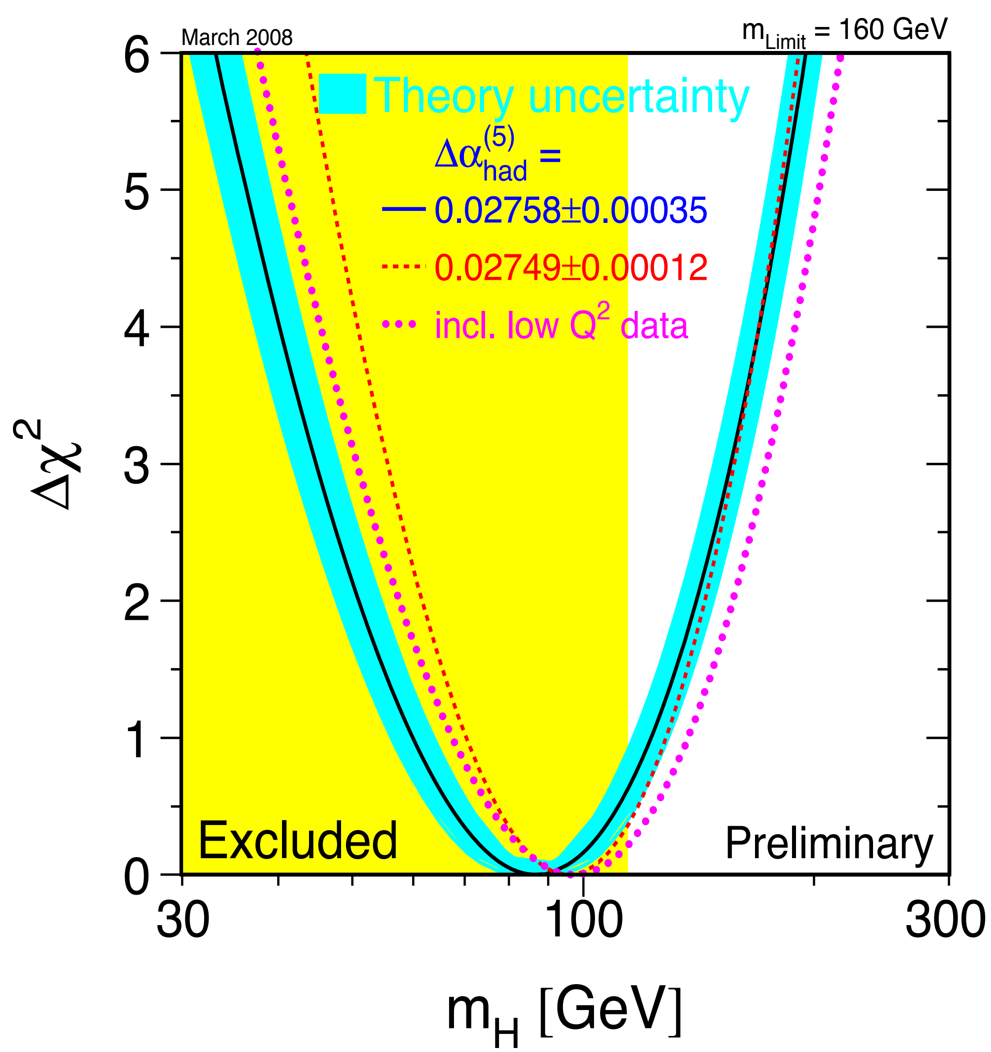
$$g_{hVV} = 2m_V^2/v \qquad g_{hhVV} = 2m_V^2/v^2$$

- ▻ Higgs coupling enhanced for heavier particles
- ▻ Vector bosons always preferred to fermions
  - – But must be kinematically allowed
- ▻ Fixing mass of Higgs fixes decay rates for all final states

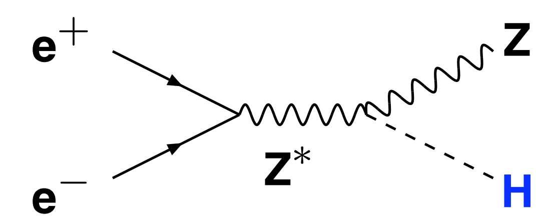
Experimental Constraints on Higgs Mass

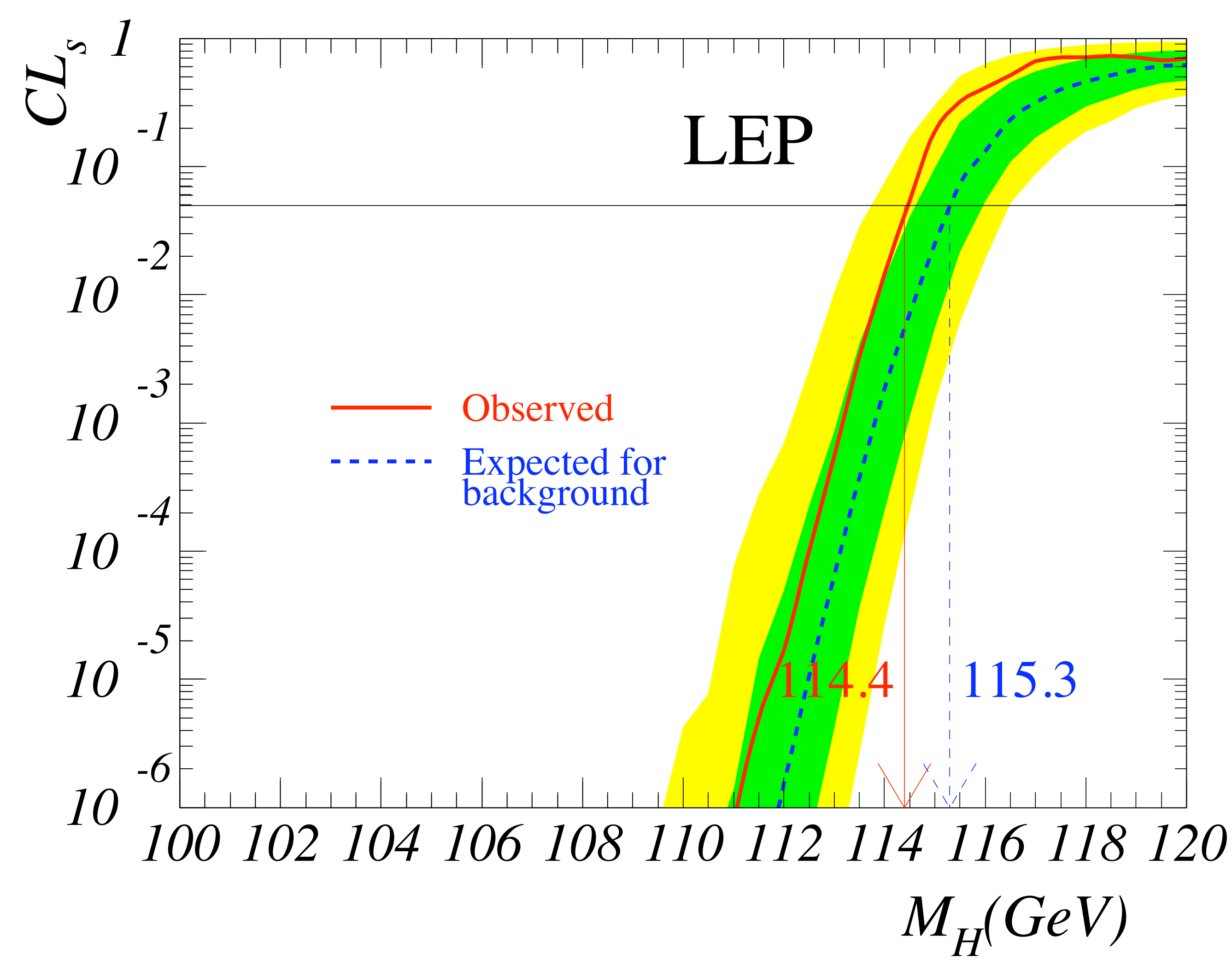
- Indirect search through precision measurement of SM sensitive to radiative corrections to Higgs in loops



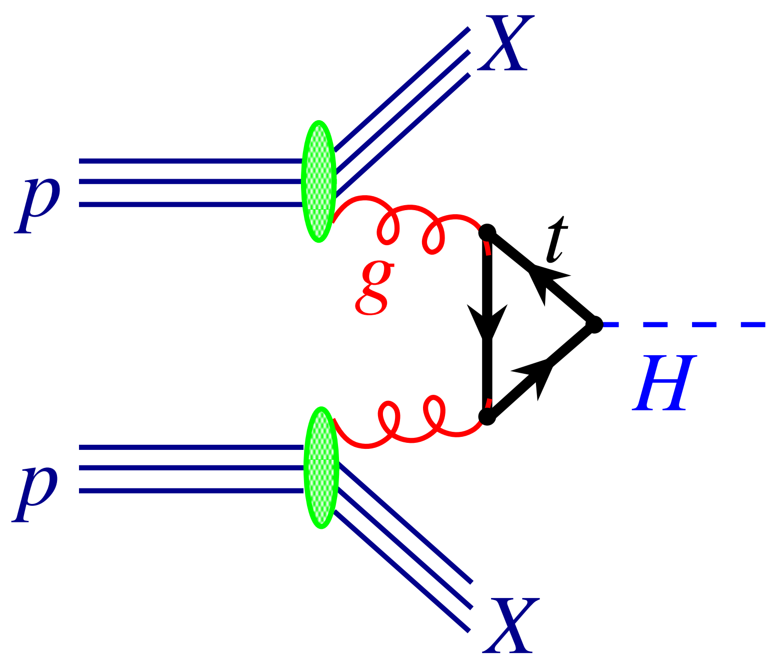


- Direct search at LEP in Higgs-strahlung production channel

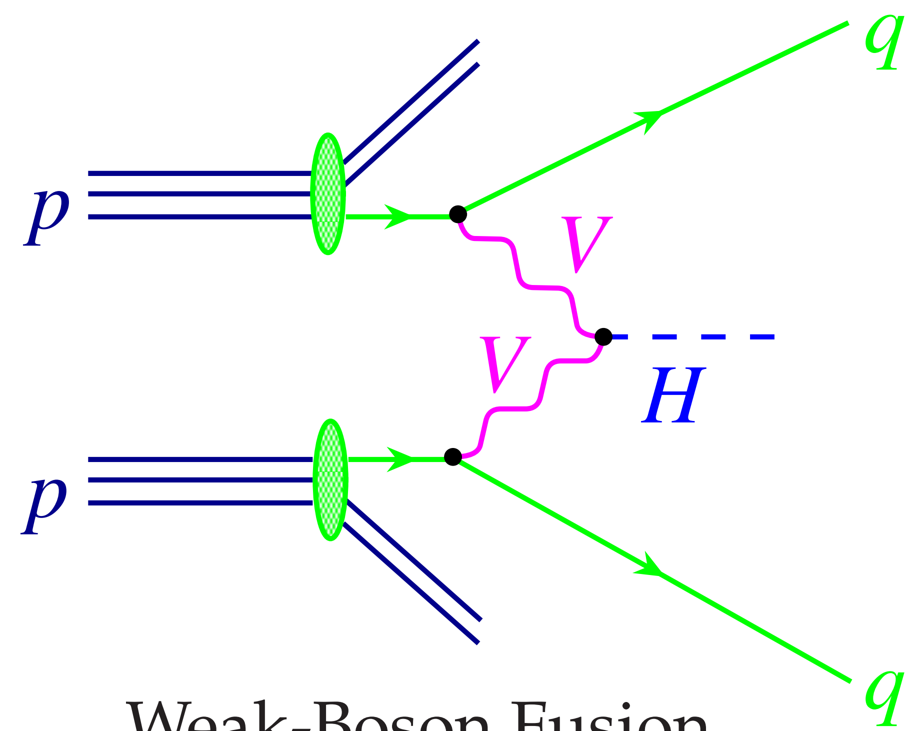




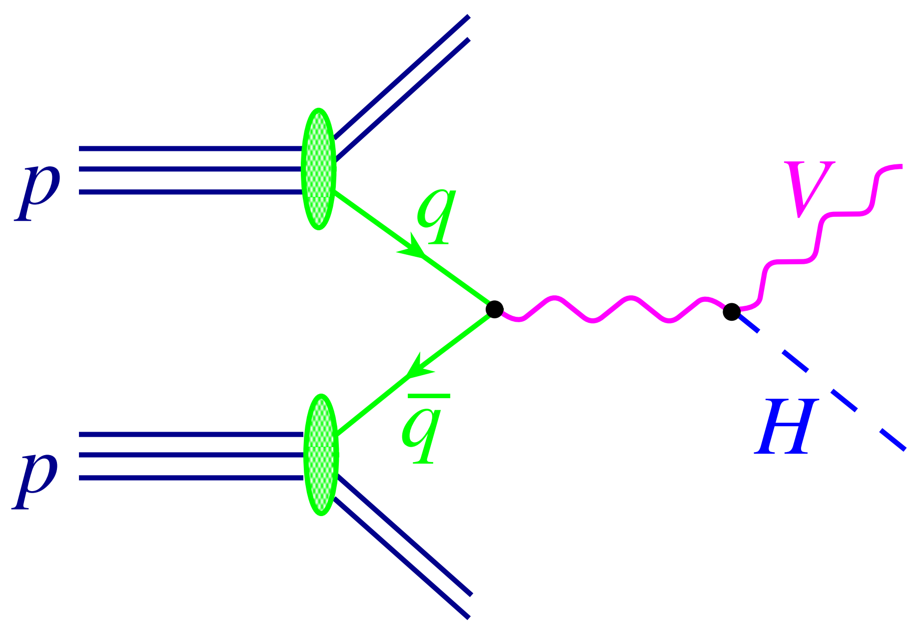
Higgs Production at Hadron Colliders



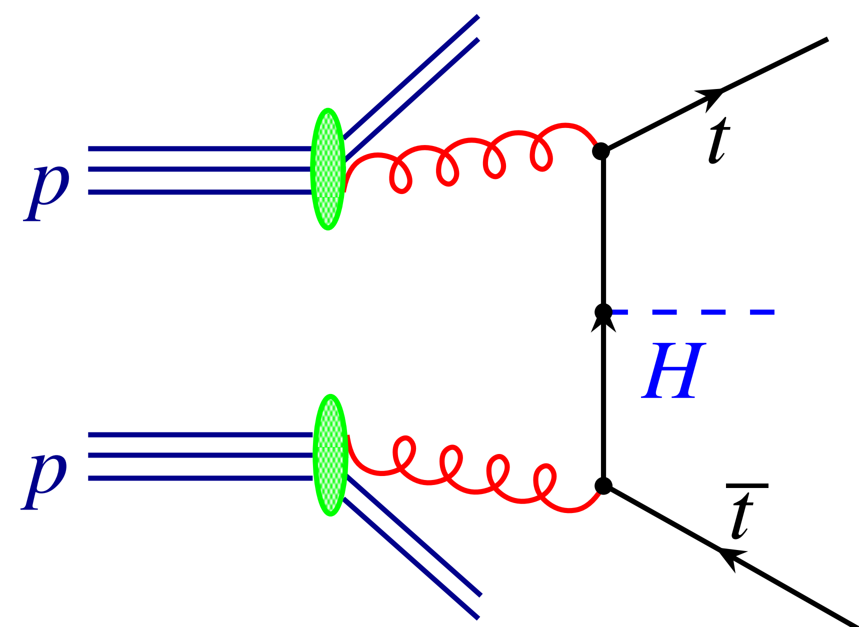
Gluon fusion



Weak-Boson Fusion

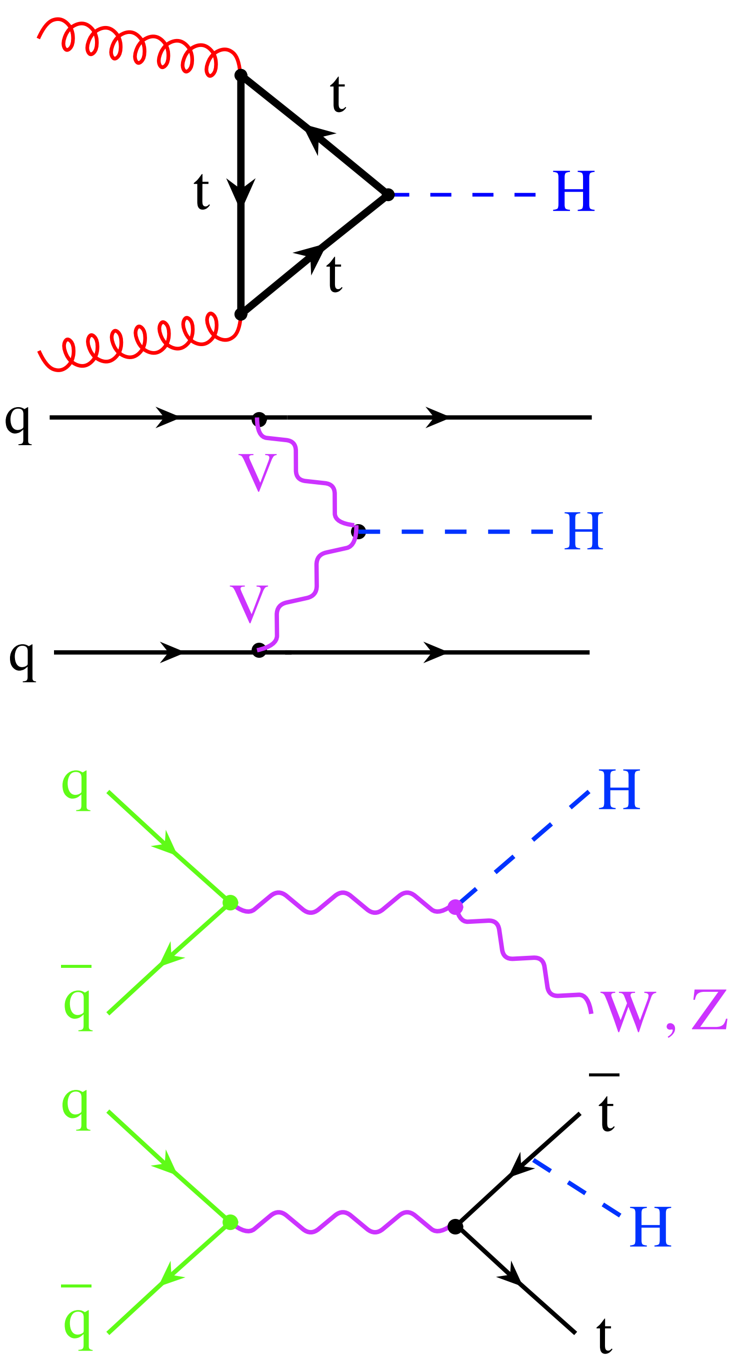


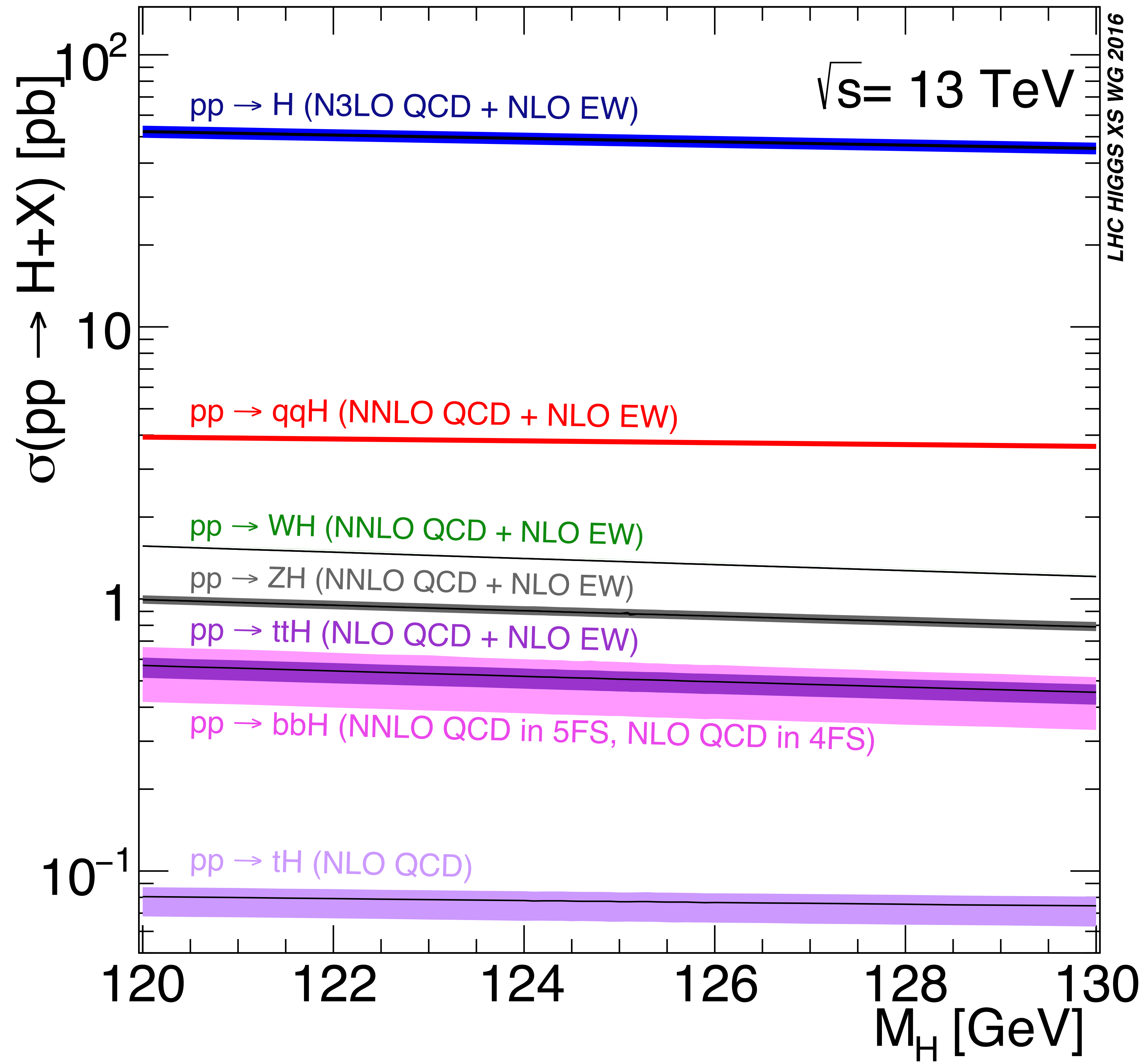
Higgs Strahlung



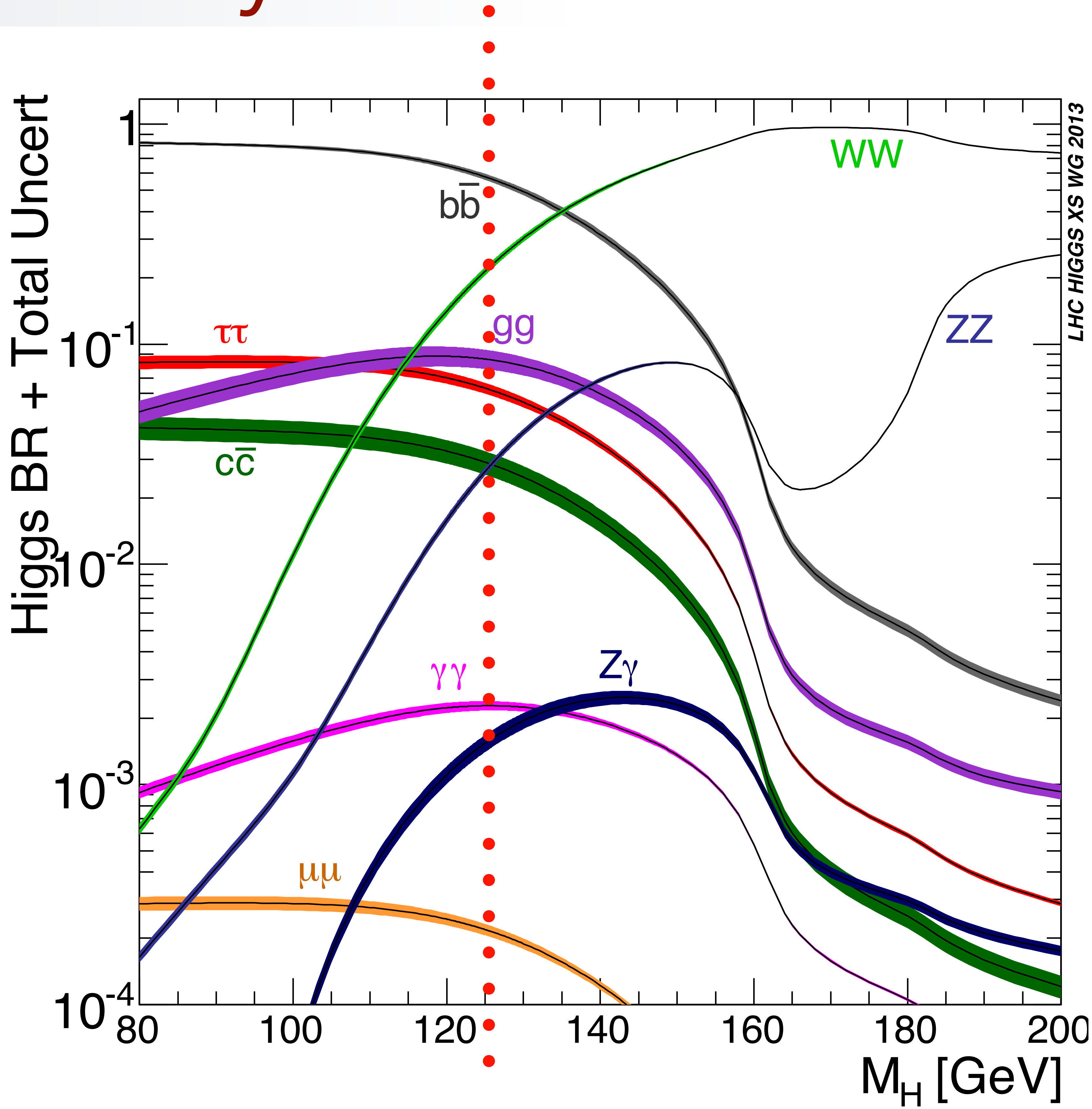
$t\bar{t}H$

Higgs Production Cross Section



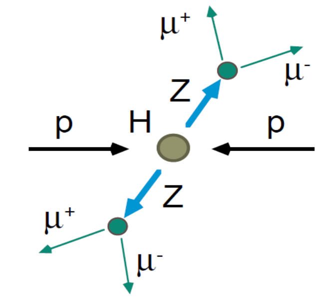


Higgs Decay

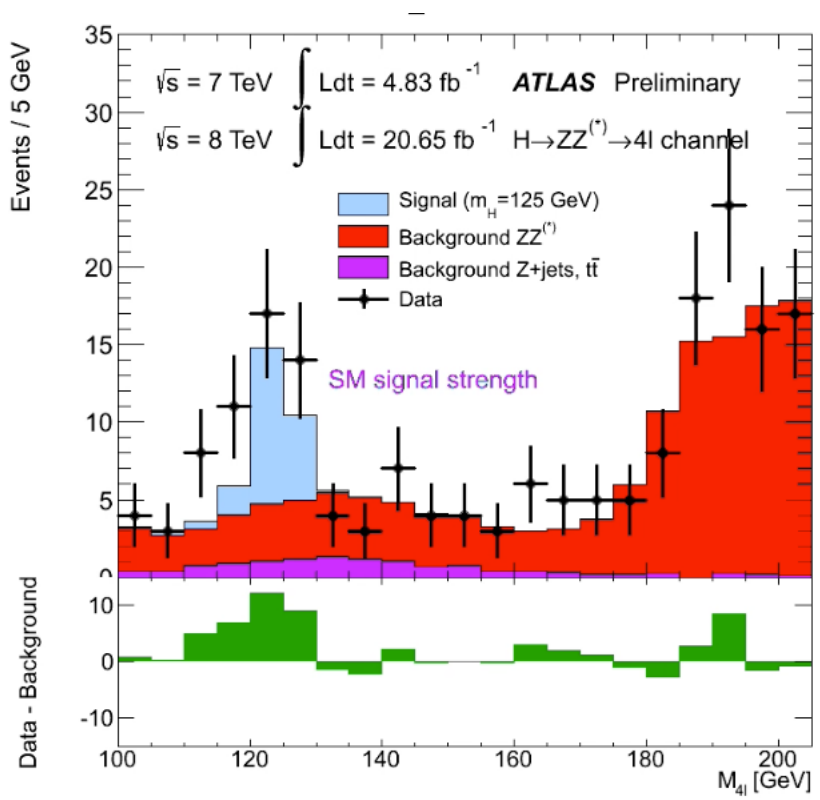


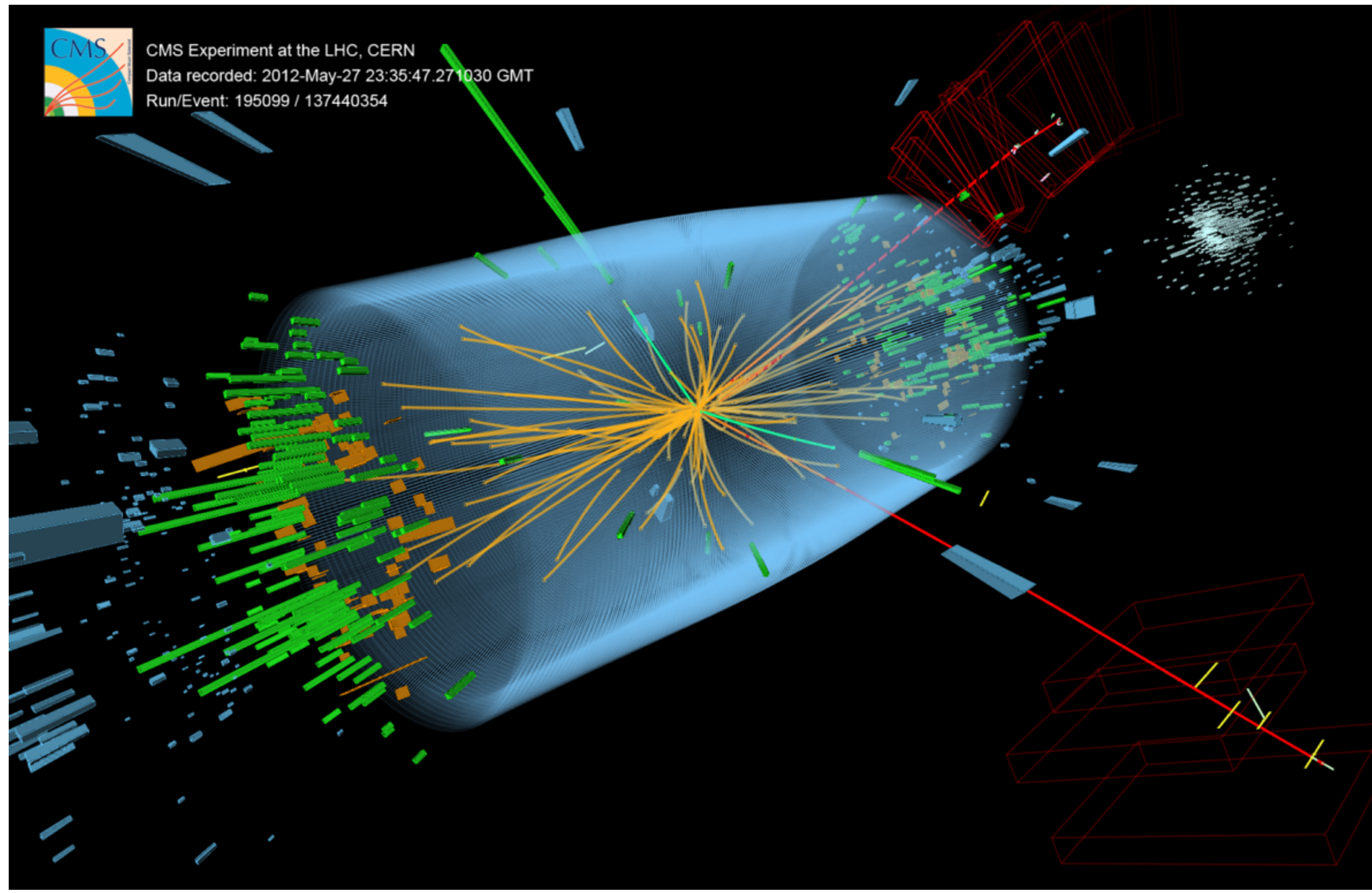
Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]
LHC HIGGS XS WG 2013
WW
$b\bar{b}$
ZZ
gg
$\tau\tau$
$c\bar{c}$
$Z\gamma$
$\gamma\gamma$
$\mu\mu$

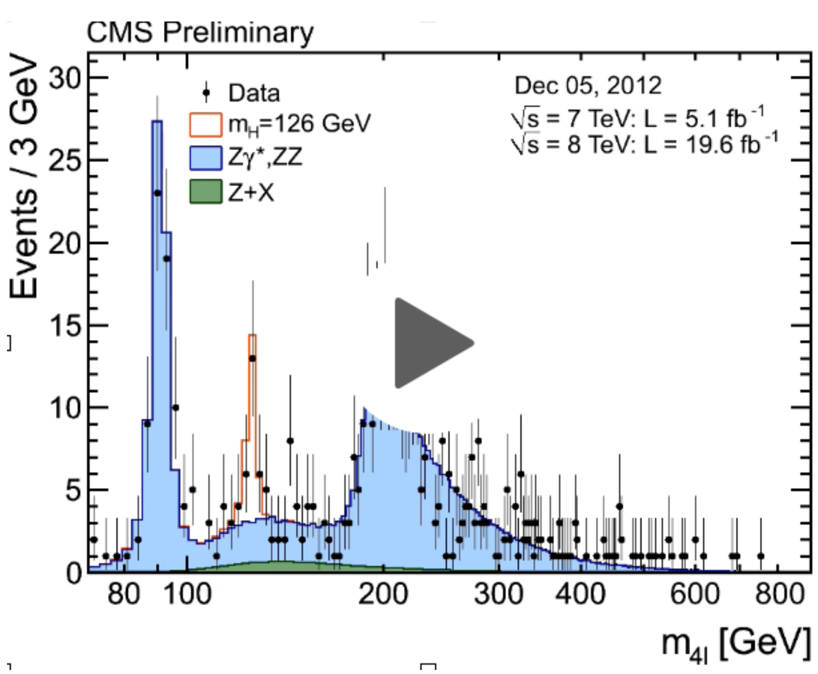
Higgs decay to ZZ (leptons)



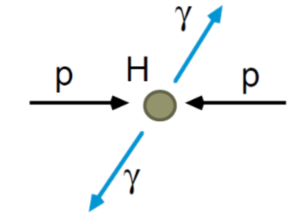
$$mass = \sqrt{\bar{p}_1^2 + \bar{p}_2^2 + \bar{p}_3^2 + \bar{p}_4^2}$$



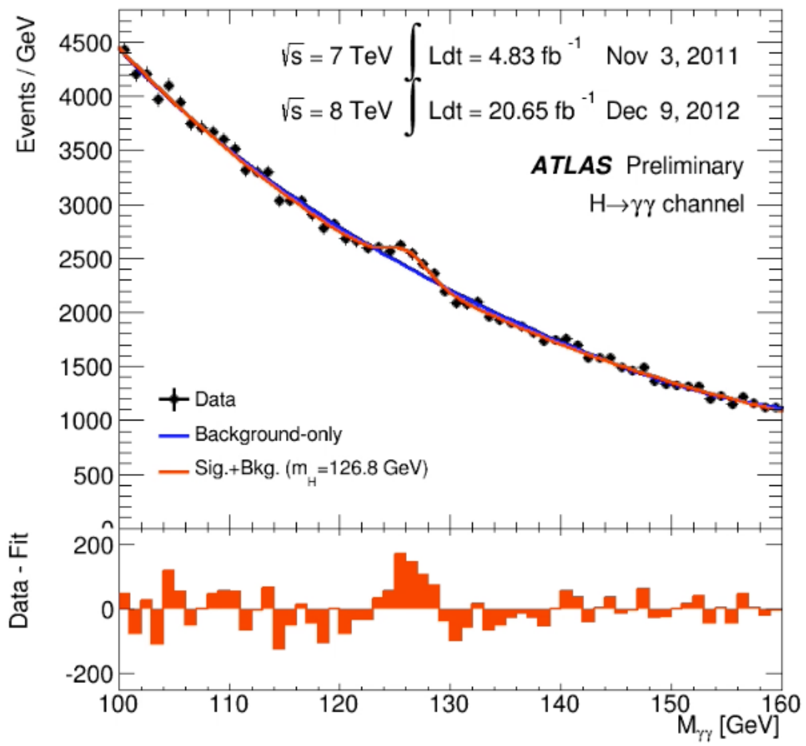


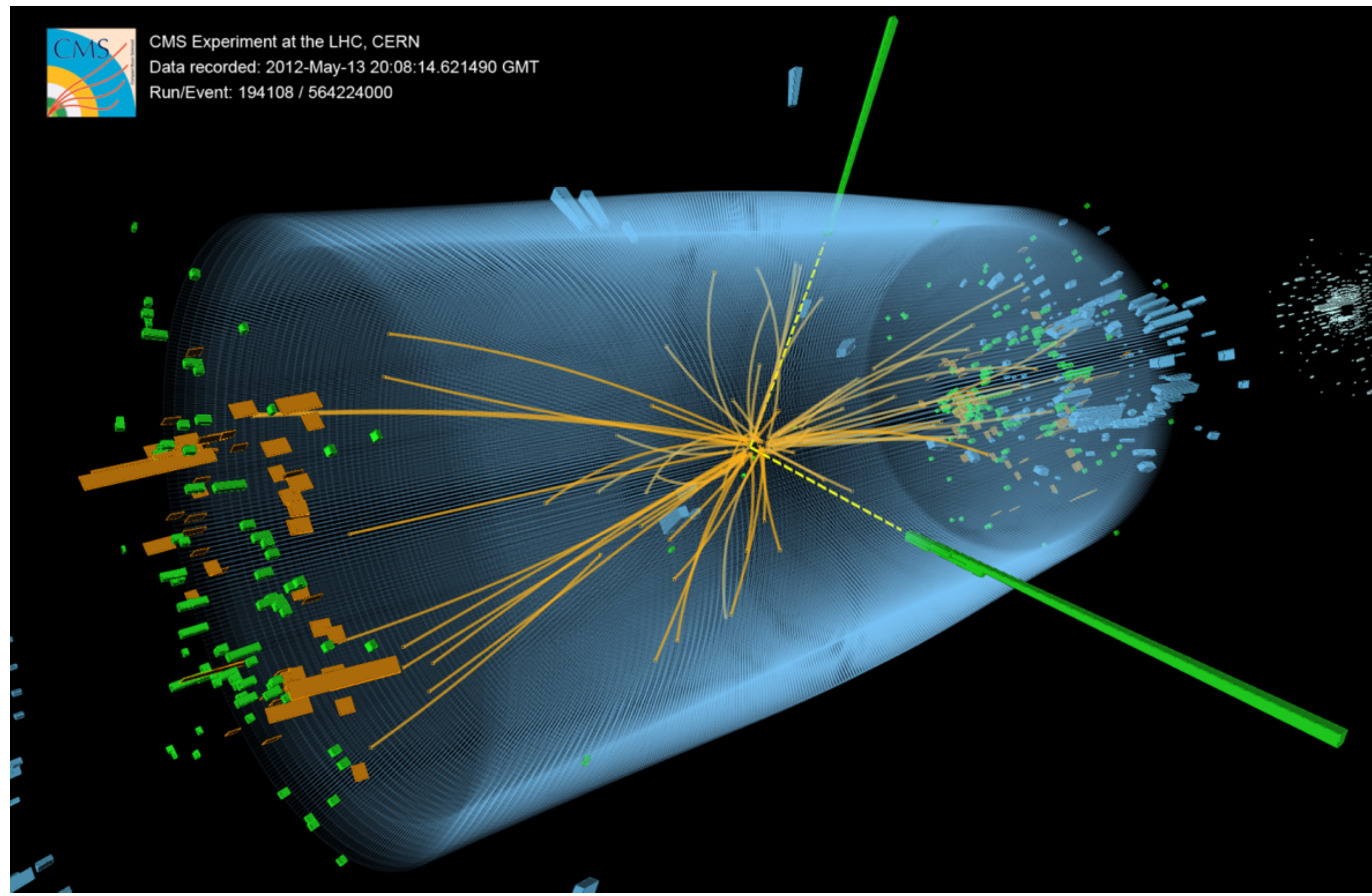


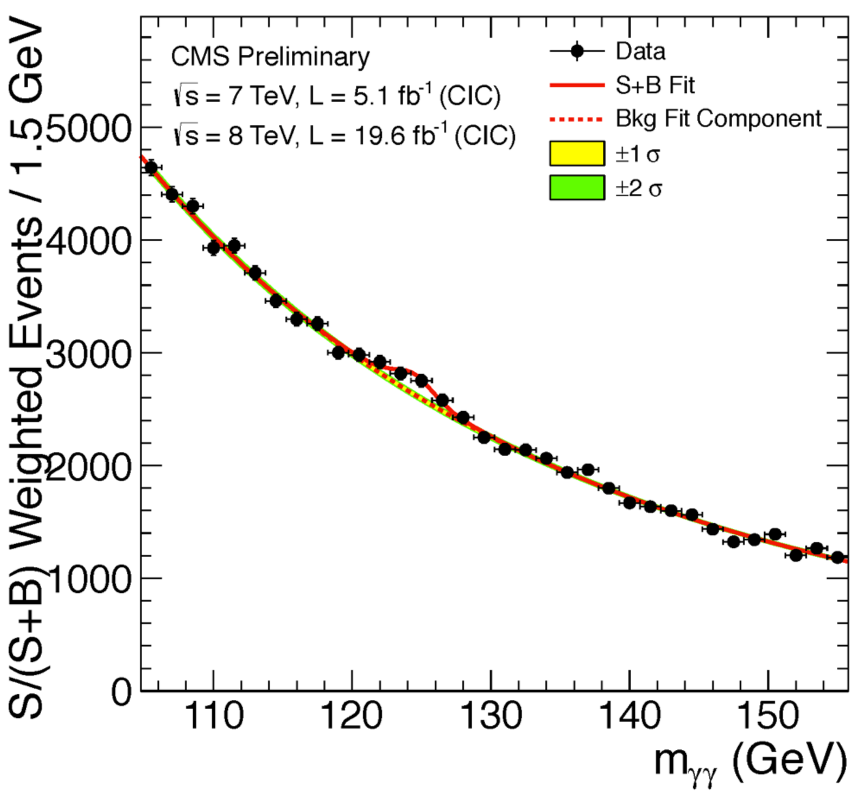
Higgs decay to Photons



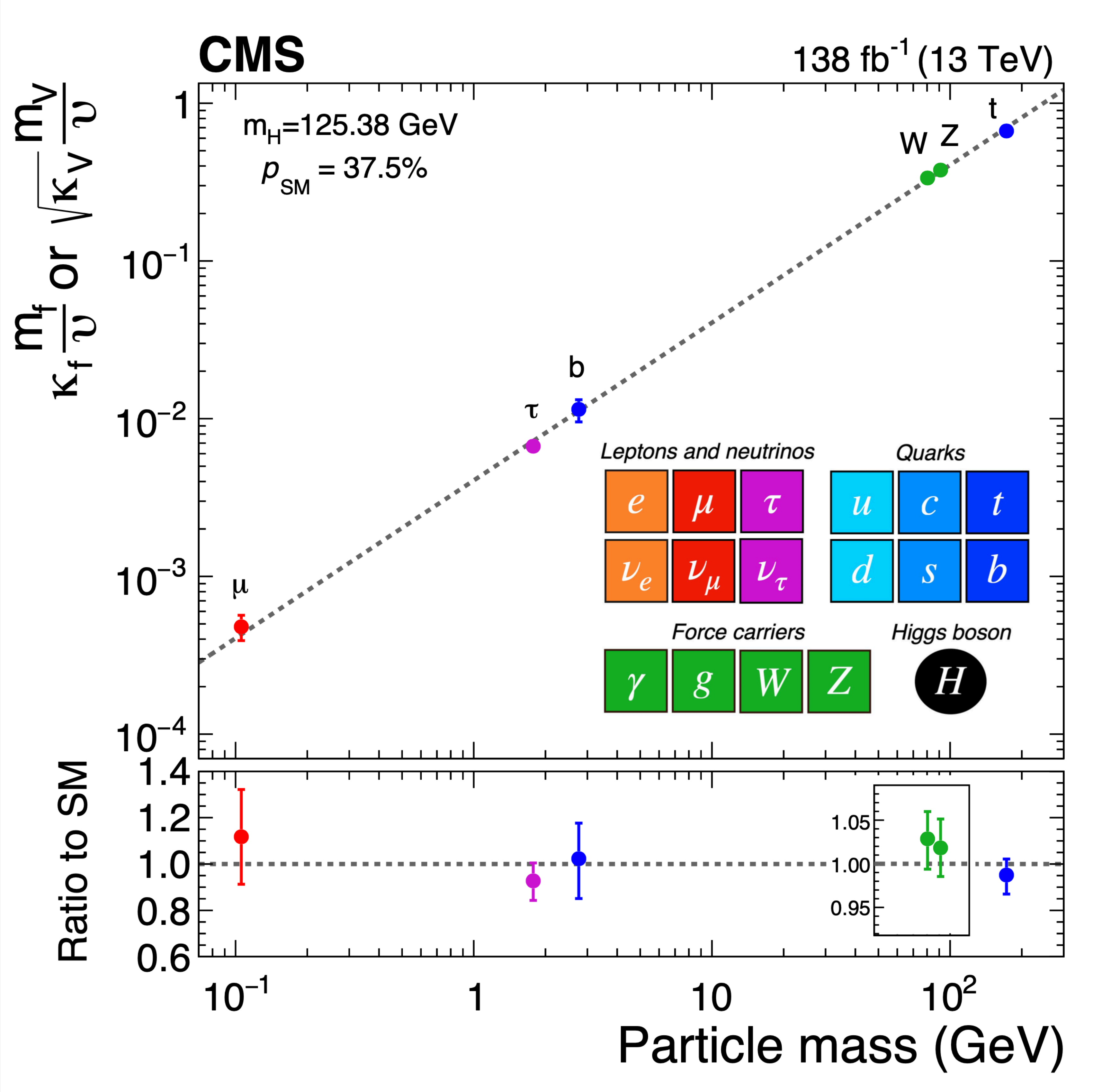
$$mass = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{12})}$$







Higgs couplings today



Energy Frontier after Higgs Discovery

- Intense scrutiny of Higgs and Yukawa sector

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi$$

Precision Electroweak and QCD

$$+|D_\mu\phi|^2 - V(H)$$

Higgs properties
Higgs self interaction

$$+Y_{ij}\psi_i\psi_j\phi + \text{h.}c.$$

Higgs coupling to bosons and fermions
CKM matrix and CP Violation

- While keeping a wide open eye on new phenomena

$$+\mathcal{L}_{\mathrm{New}}$$

New light and heavy particles
Lepton flavour universality violation
Leptoquarks
SUSY
Long-lived particles
Dark matter

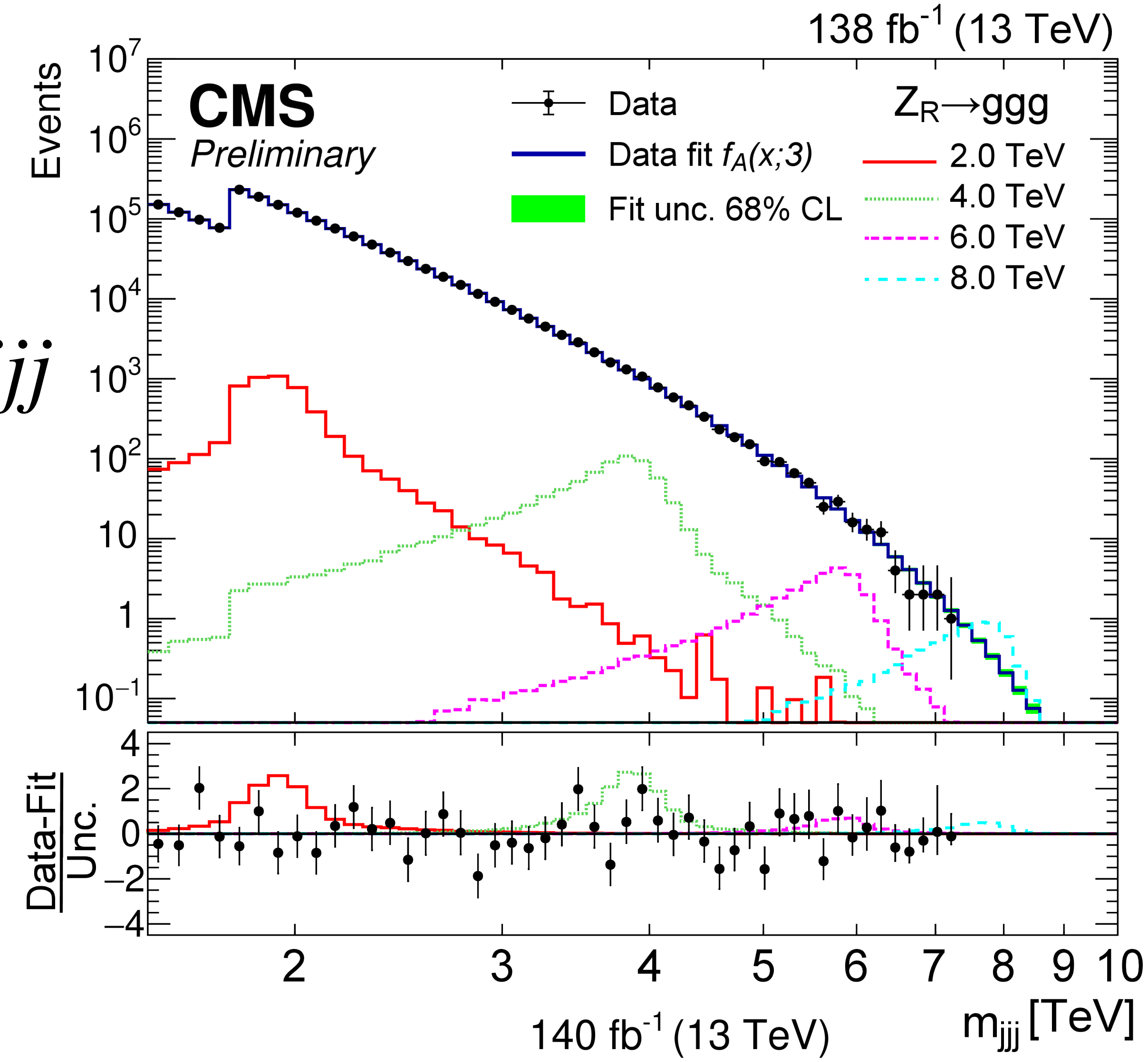
Search for new resonances

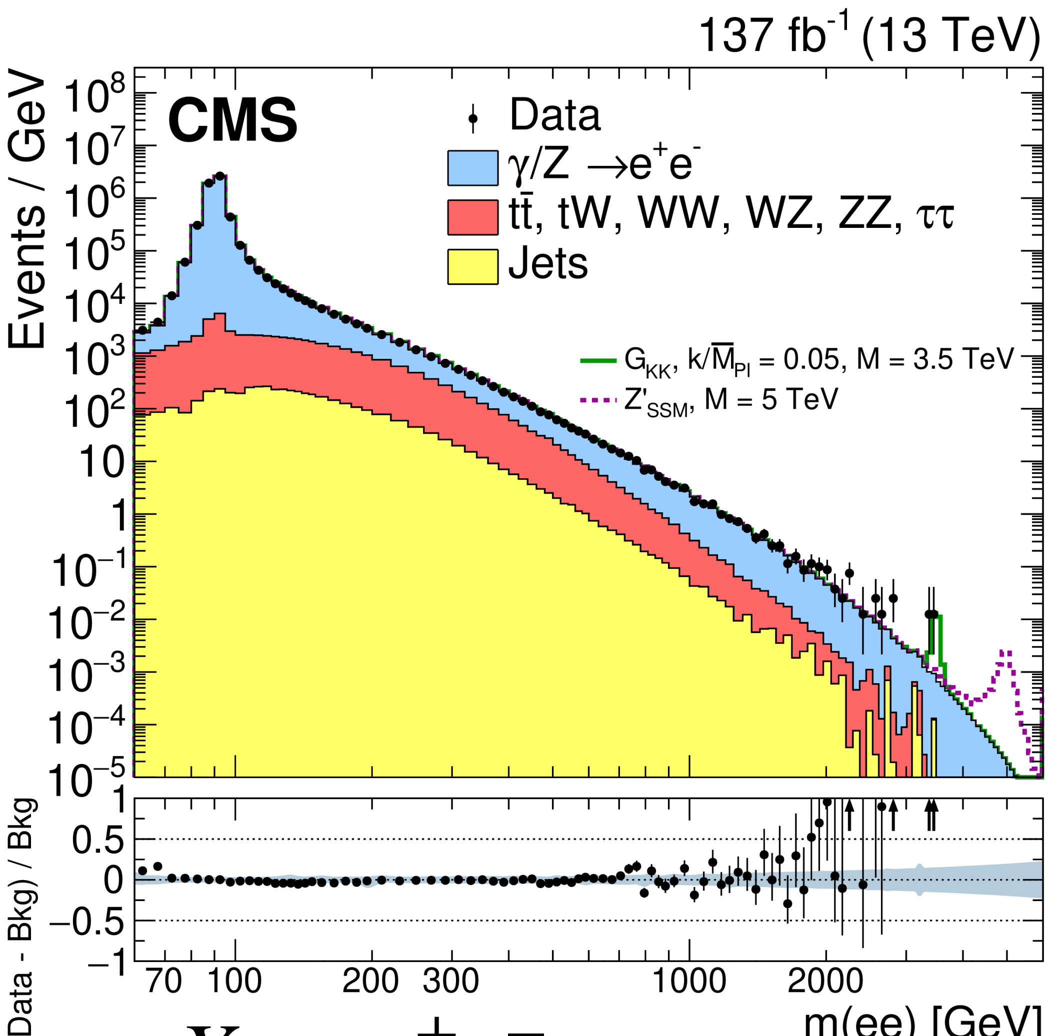
Detector Understanding (time)

- Two-body resonances from day one: leptons, photons, jets
  - detector effects not critical
  - sensitive to bumps right away
- Increase complexity and multiplicity of final state
  - better understanding and calibration of detector
- Final states with X + MET
- Really exotic signatures such as long-lived particles
  - control of detector conditions over longer period
  - ultimate calibration and alignment
  - optimisation of dedicated algorithms

New resonances

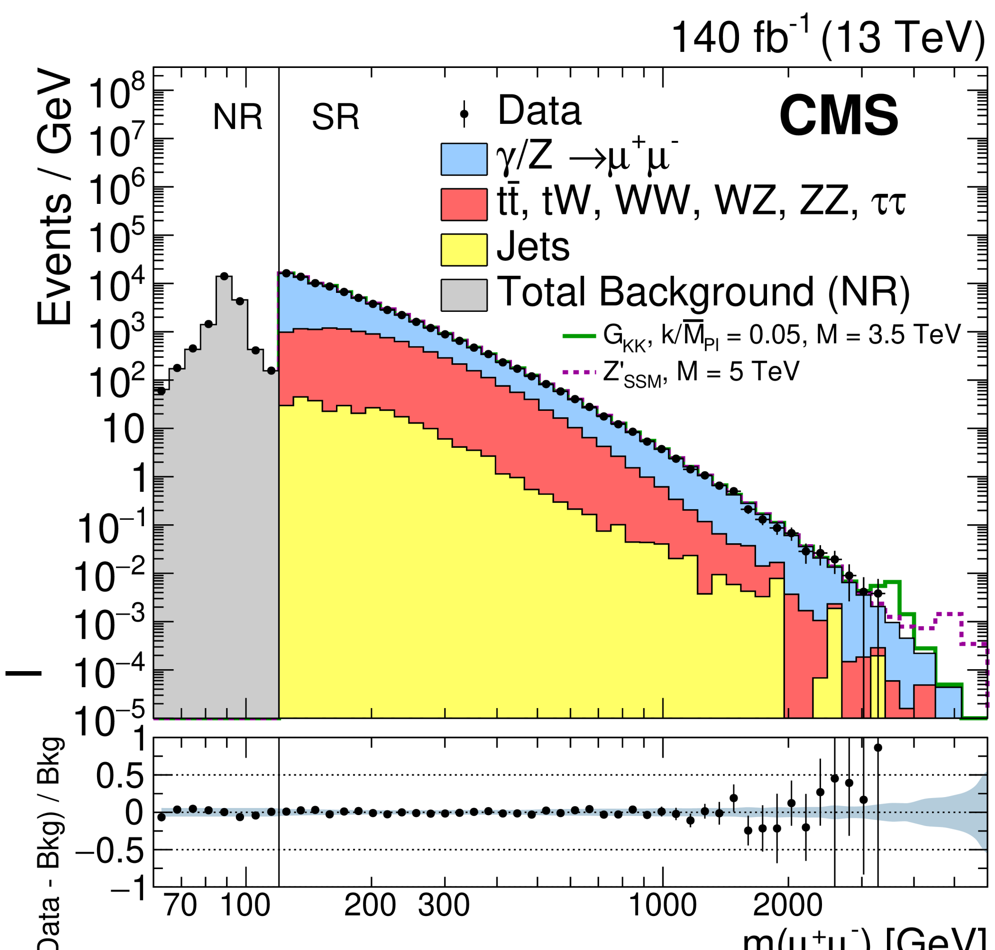
$X \to jjj$



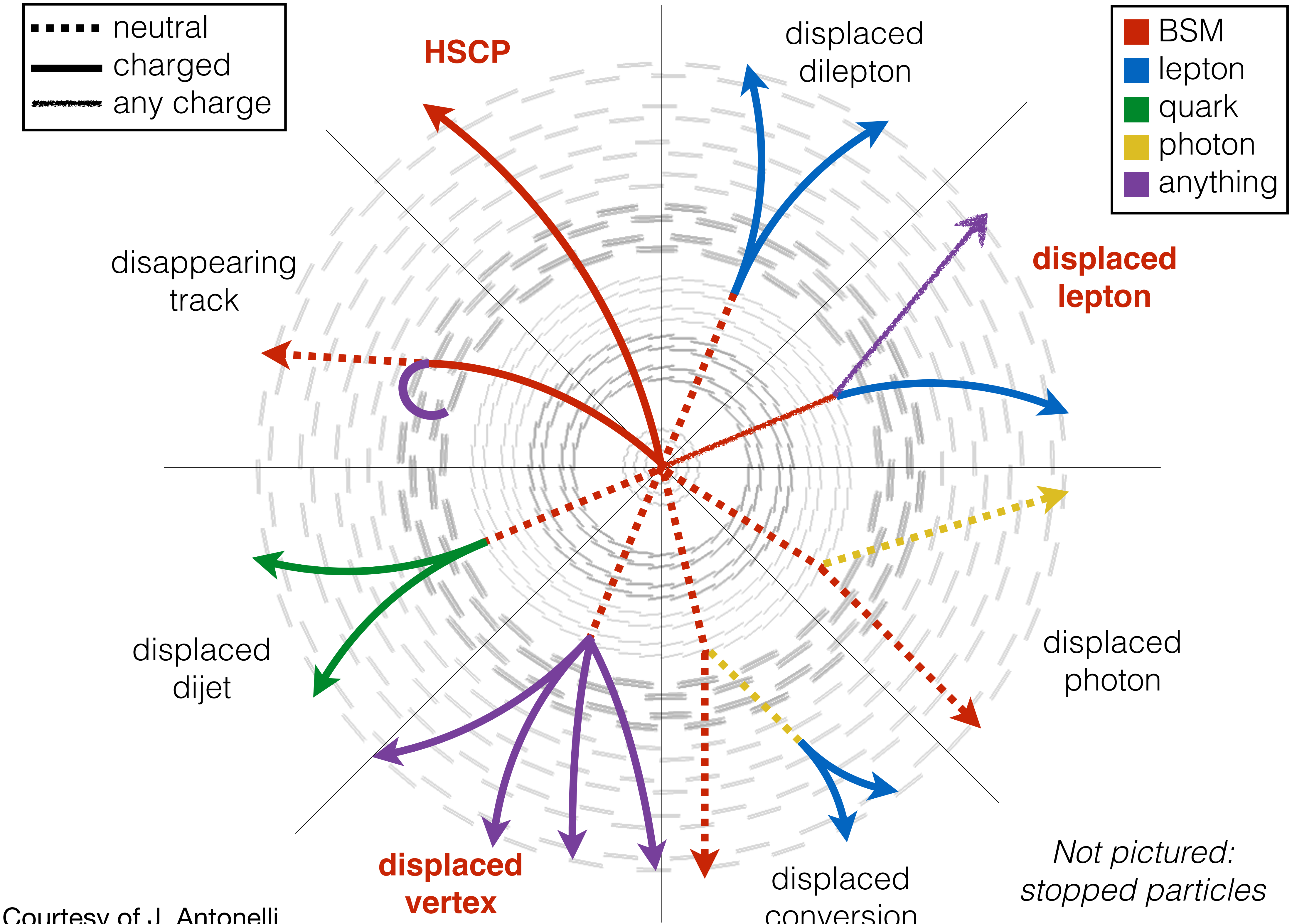


$X \to e^+e^-$

$X \to \mu^+\mu^-$



New Long-lived Particles?

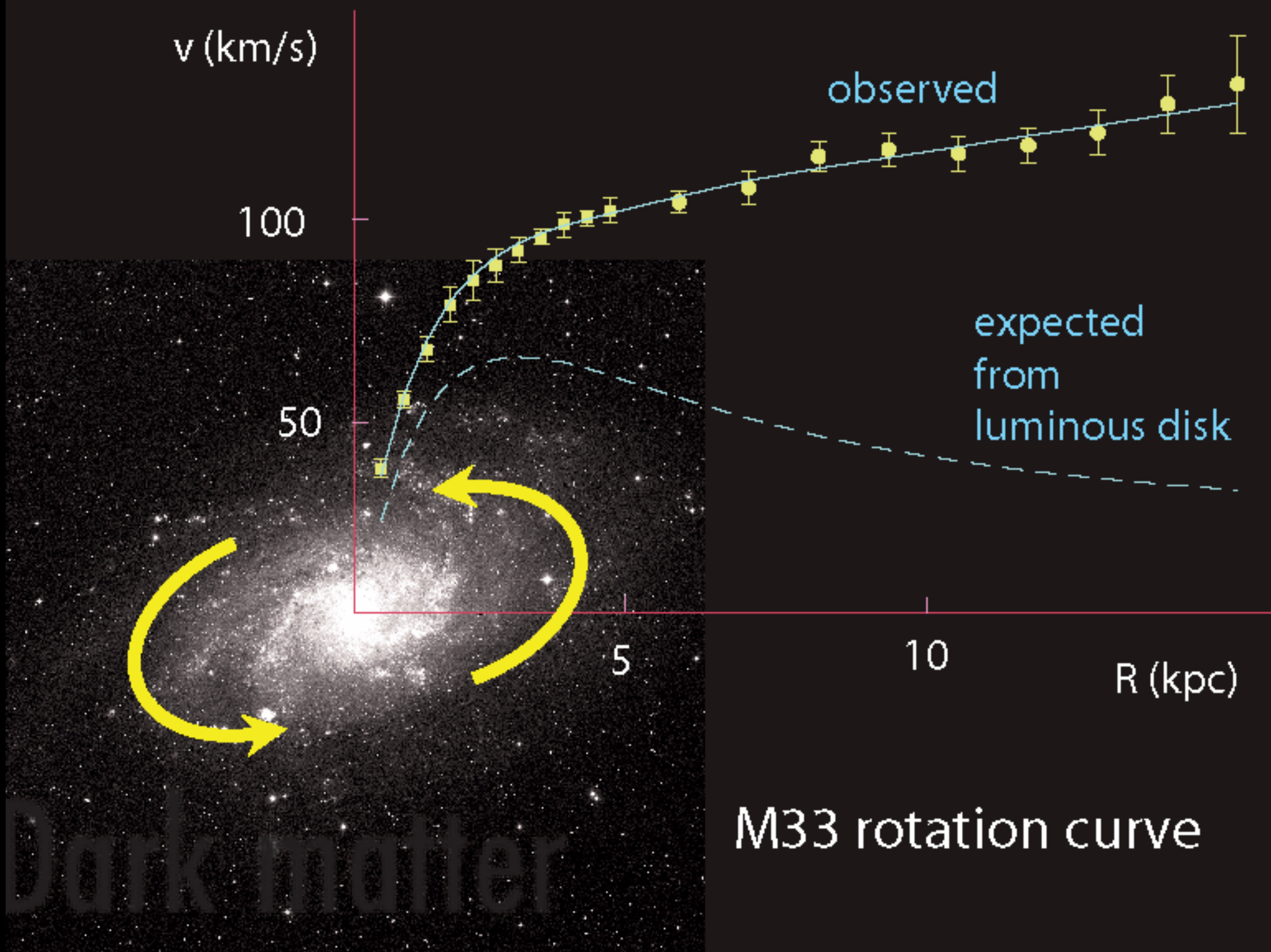


Courtesy of J. Antonelli


Dark Matter

Galaxy Rotation

In 1933, Fritz Zwicky calculated the mass of the Coma cluster using galaxies on the outer edge, and came up with a number 400 times larger than expected.



M33 rotation curve

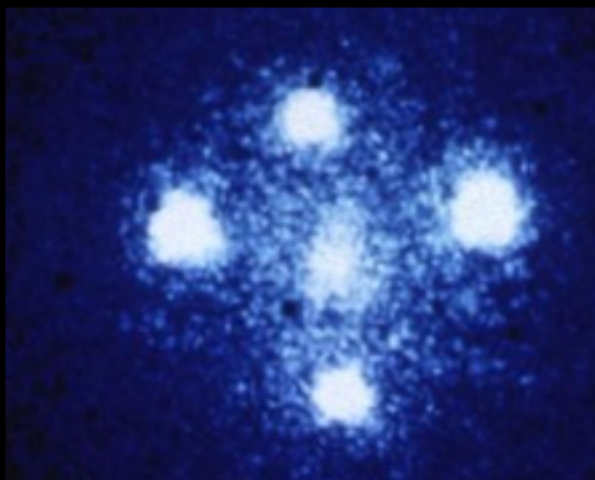
Vera Rubin

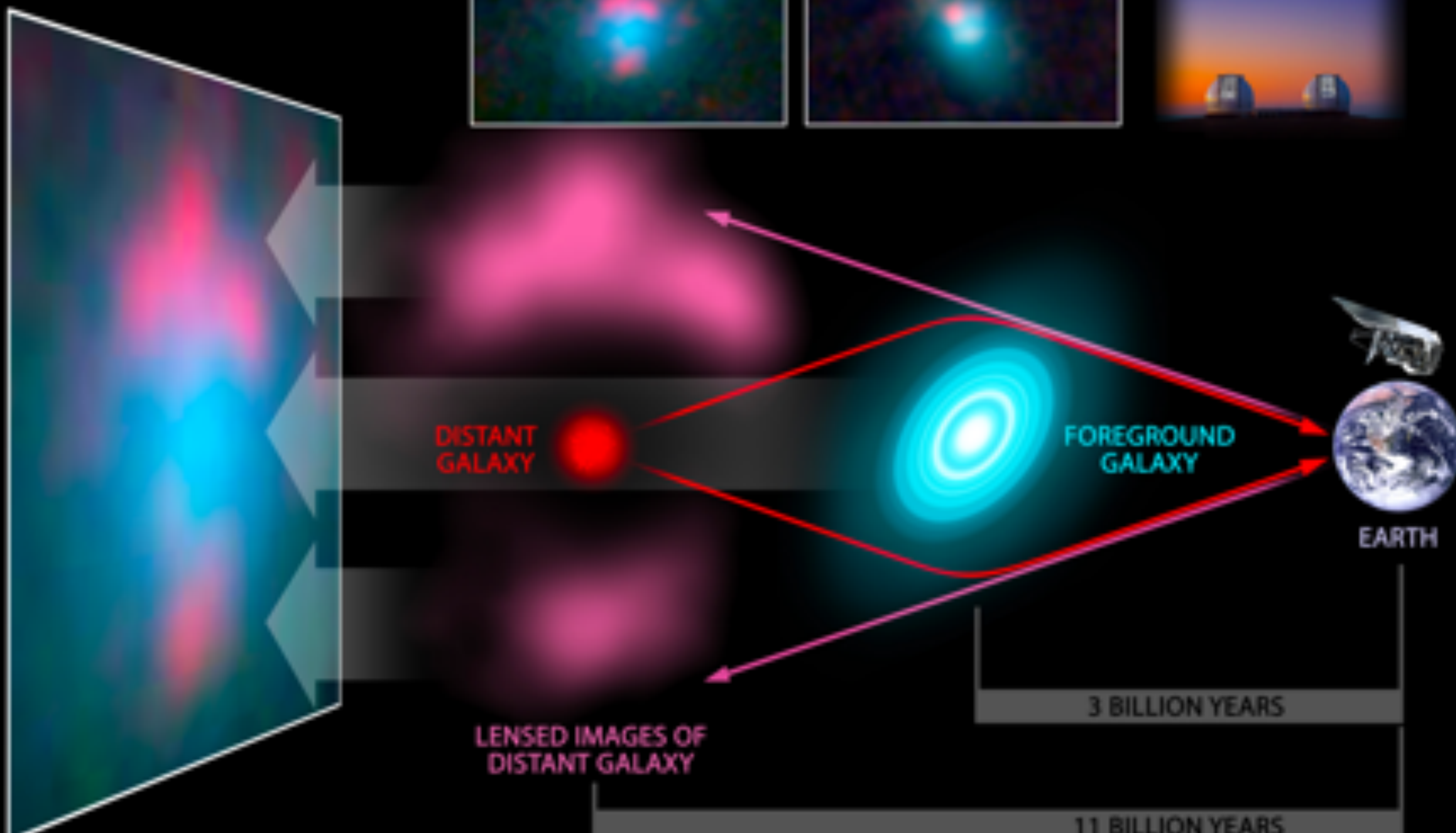
DARK MATTER HALO

BULLET CLUSTER

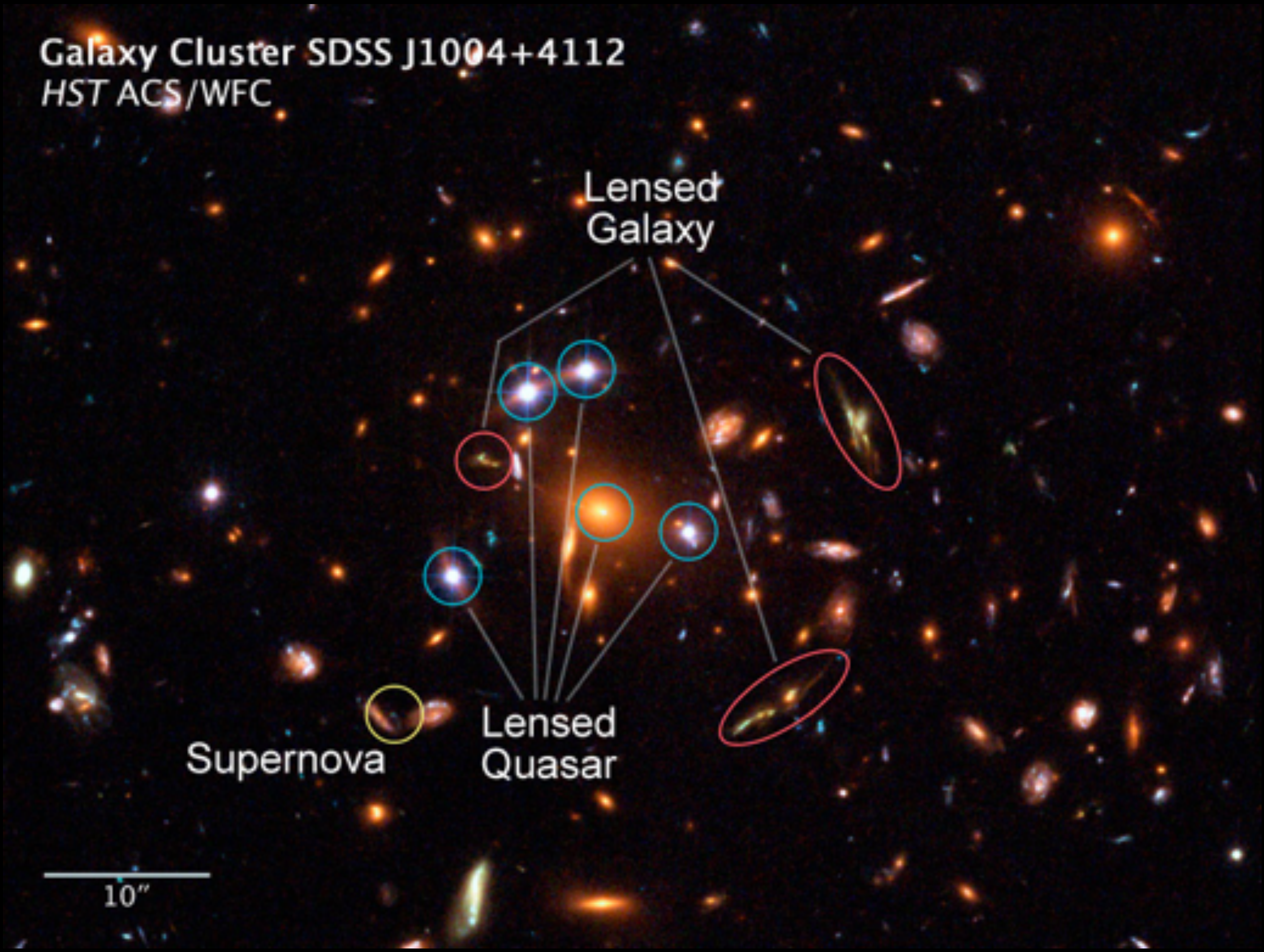
- Collision of galaxies in bullet cluster
  - lensing of background objects suggest at least 10x more Dark matter than visible mass

GRAVITATIONAL LENSING

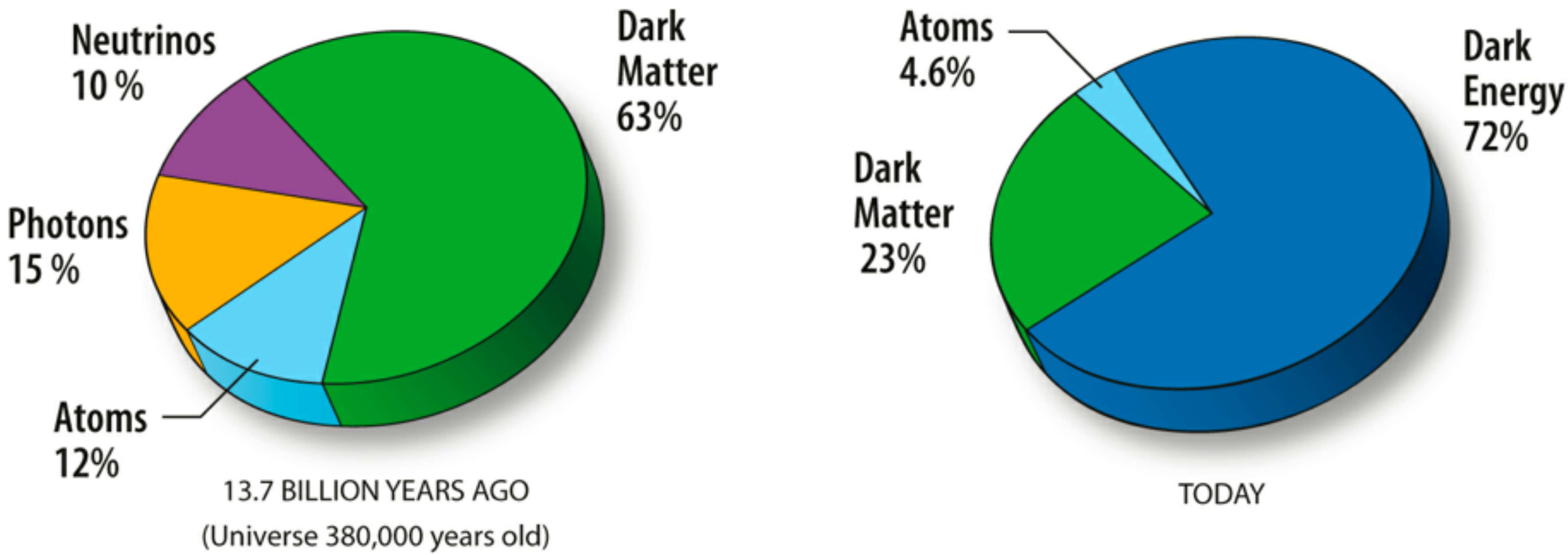




Gravitational Lensing



Universe Composition



- Strong astrophysical evidence for the existence of dark matter
  - Evidence from bullet cluster, gravitational lensing, rotation curves
  - Dark Matter six times more abundant than baryons
  - Contributes ~1/4 of the total energy budget!
- Particle description of Dark Matter being tested
  - can be tested also at LHC!

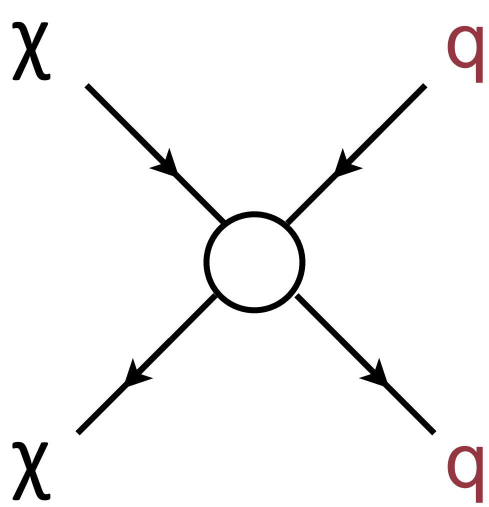
Candidate Dark Matter Particles

- Properties
  - long lived (old)
  - non-relativistic (slow)
  - no electric or color charge
  - very weak interaction with Standard Model particles
  - subject to gravity interaction

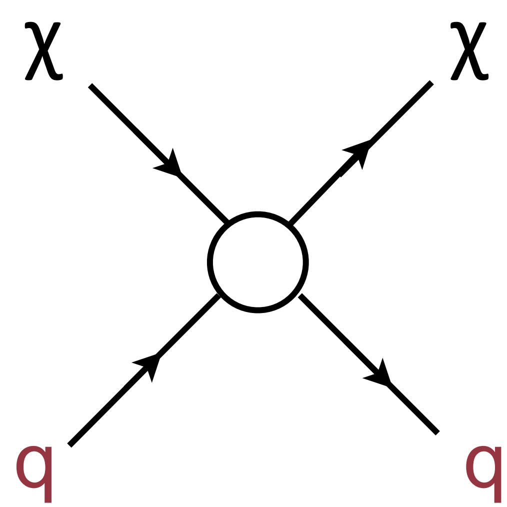
- Several potential candidates fulfilling these requirements for dark matter
  - Dark: weakly interacting with electromagnetic radiation
  - Hot & dark: ultra-relativistic velocities
    - neutrinos
  - Warm & dark: very high velocity
    - sterile neutrinos, gravitinos
  - Cold & dark: moving slowly
    - Lightest SUSY particle (neutralino, gravitino as LSP), Lightest Kaluza-Klein particles
  - Nonthermal relics:
    - Bose-Einstein condensate (BEC), axions, axion clusters, solitons, supermassive wimpzillas

Dark Matter Interaction

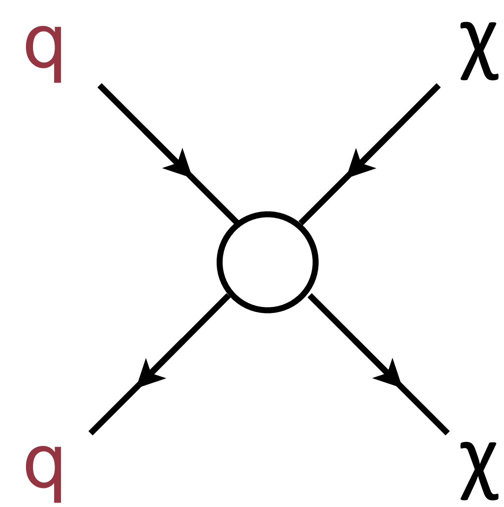
- Exact interaction of DM with ordinary matter determines relic abundance



Indirect Detection



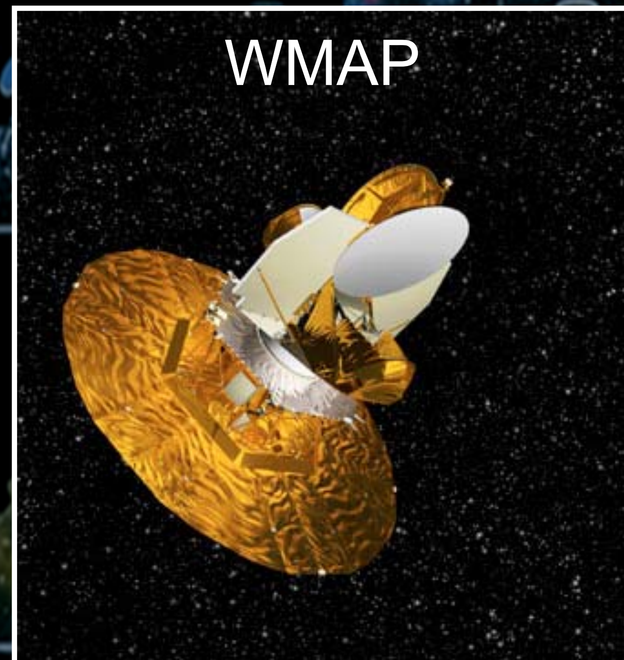
Direct Detection



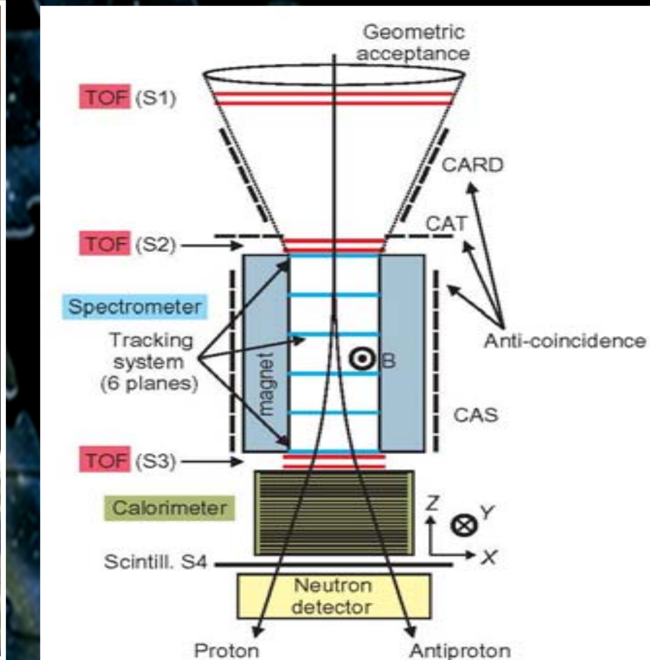
Production at Colliders

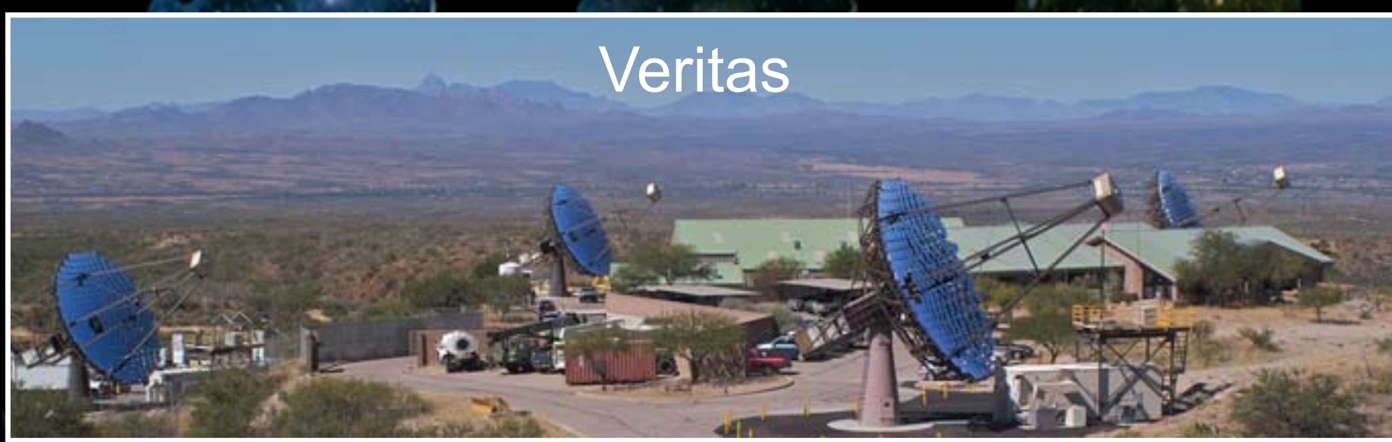
- Different experimental technique and detectors for each approach

INDIRECT DETECTION



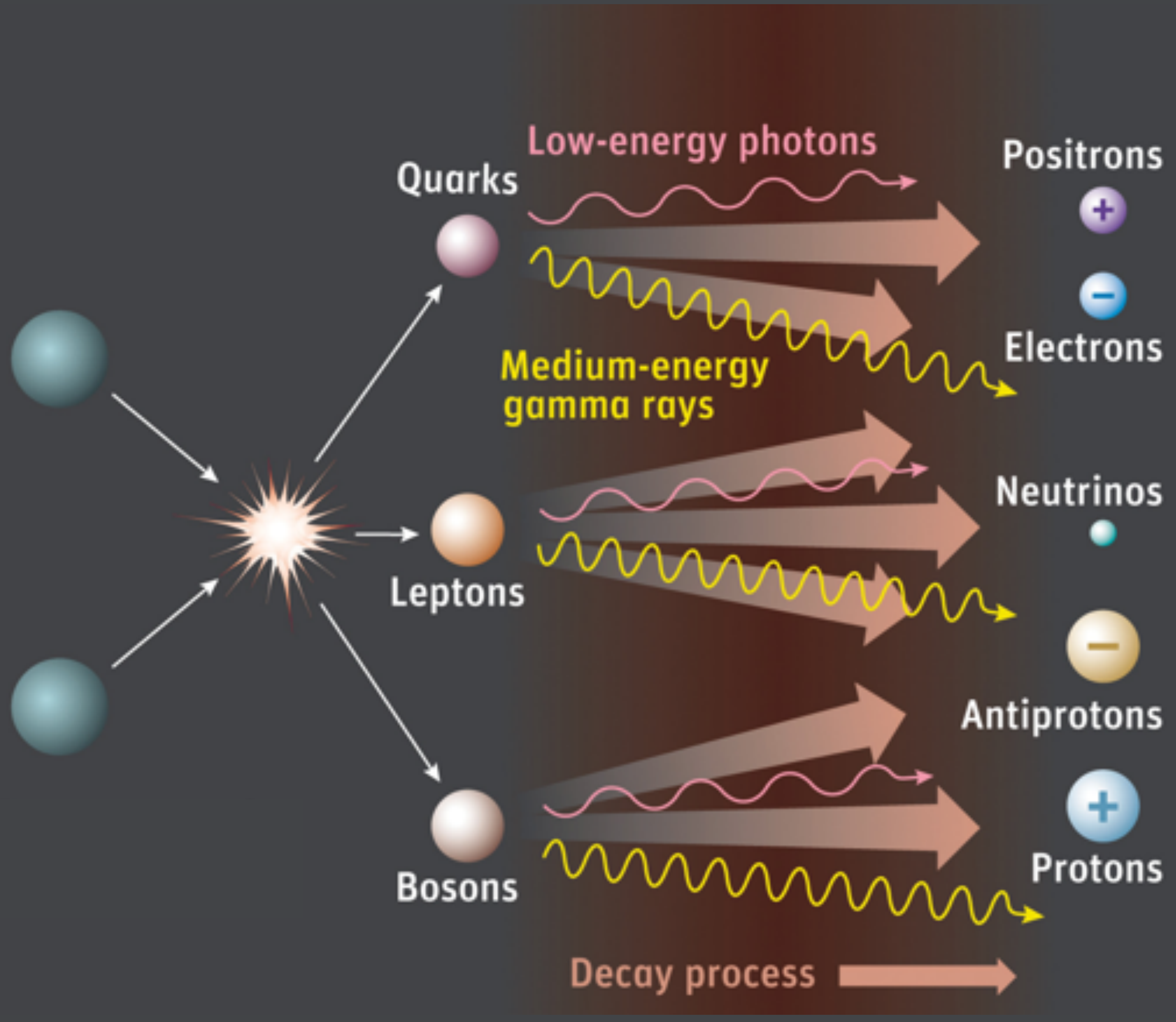
PAMELA



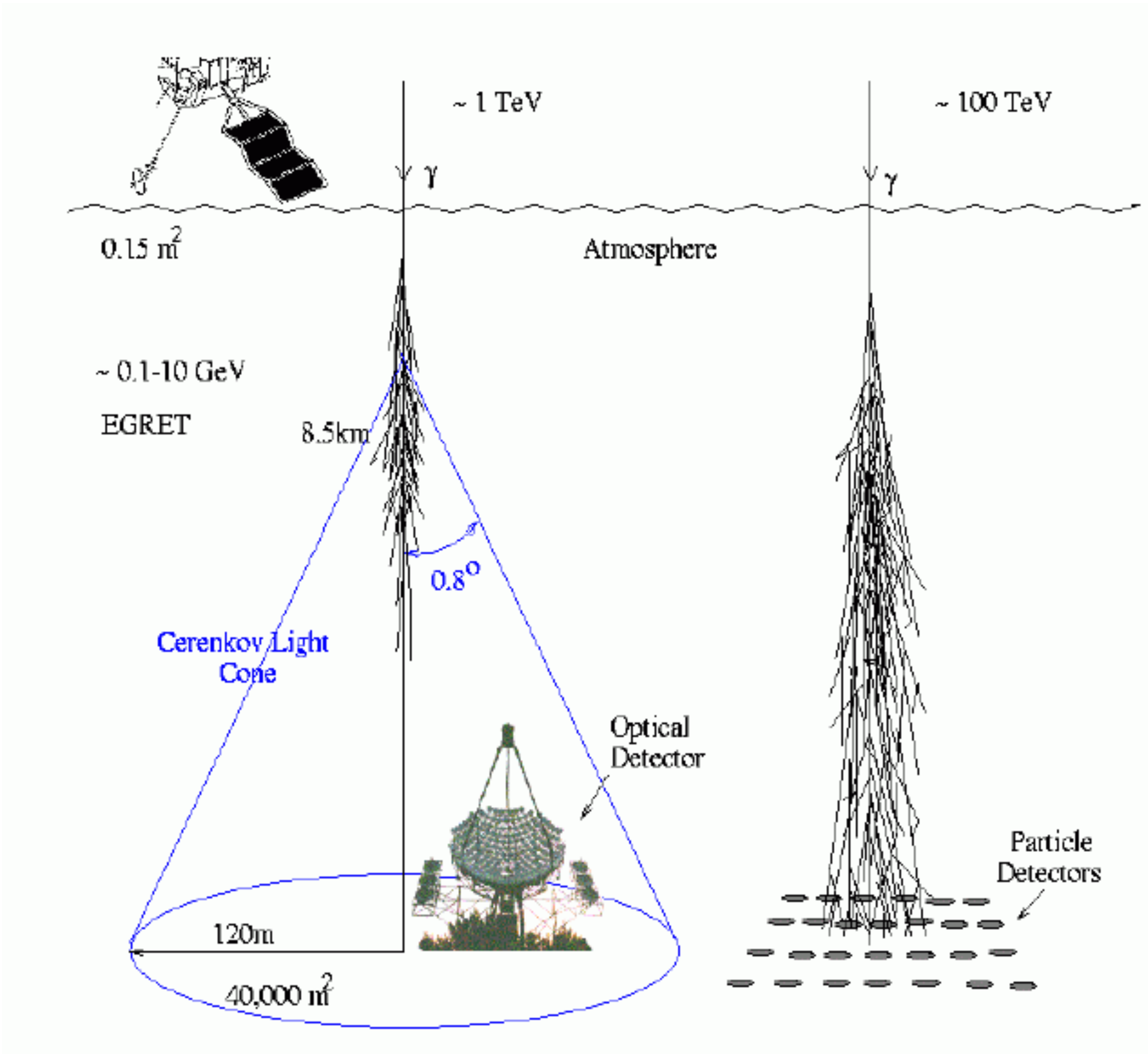


Indirect detection

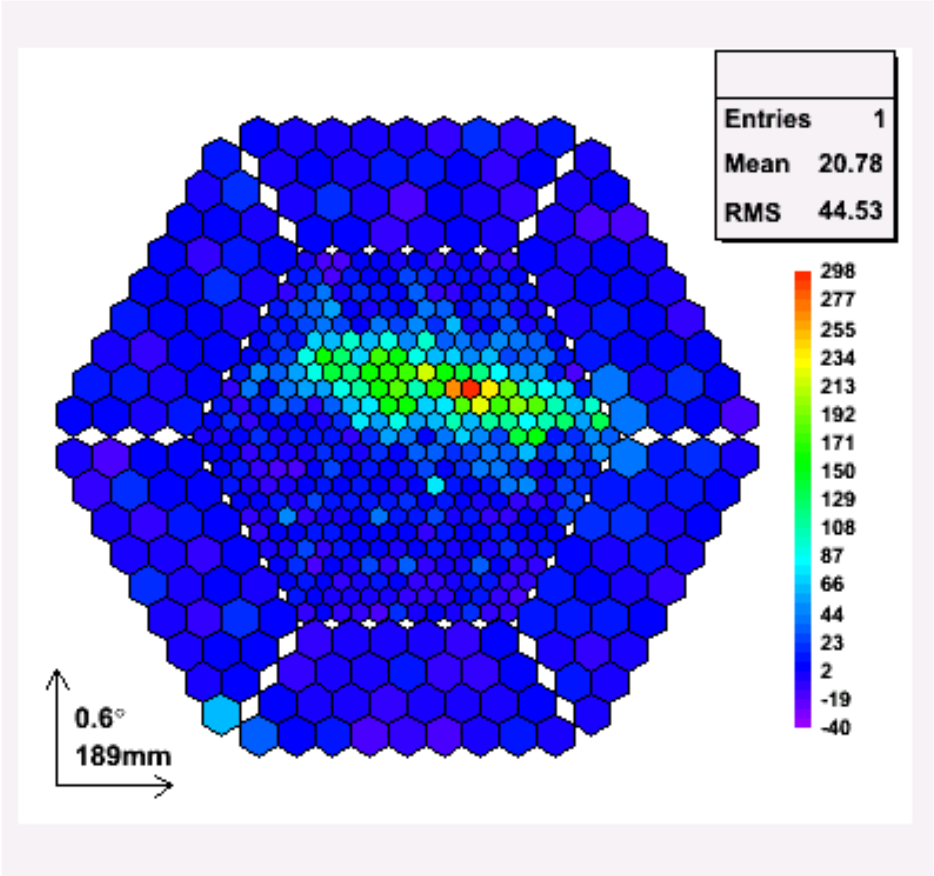
- Annihilation in high energy photons, particle-anti-particle pairs
- search for ultra-relativistic objects produced in galactic halo
  - observatory on earth or with satellites



Earth-Based Detection



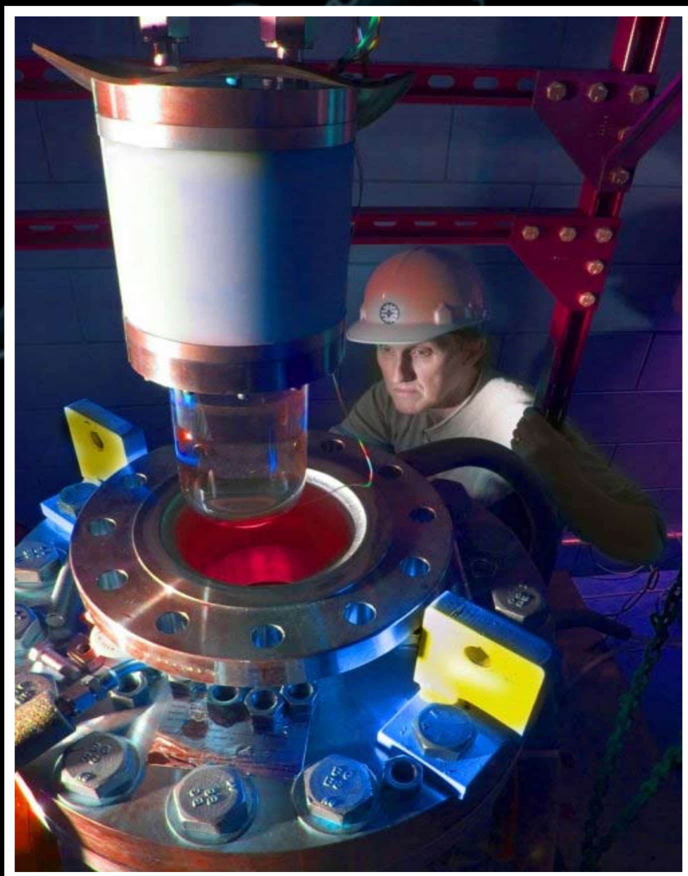
Cherenkov Shower



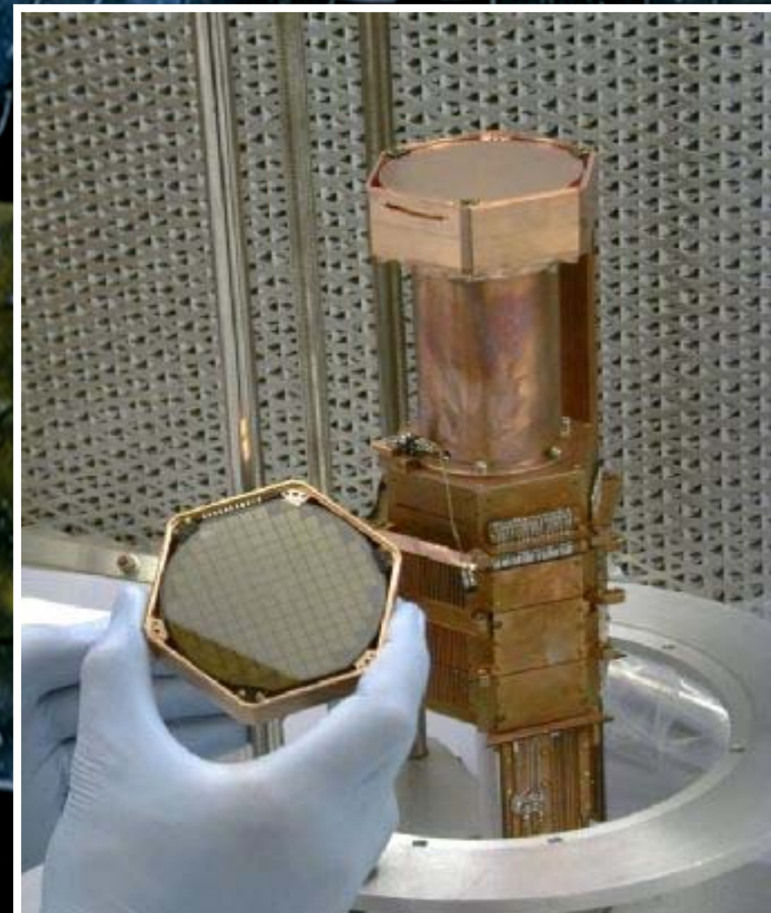
AMS @ ISS

Direct Detection

COUPP

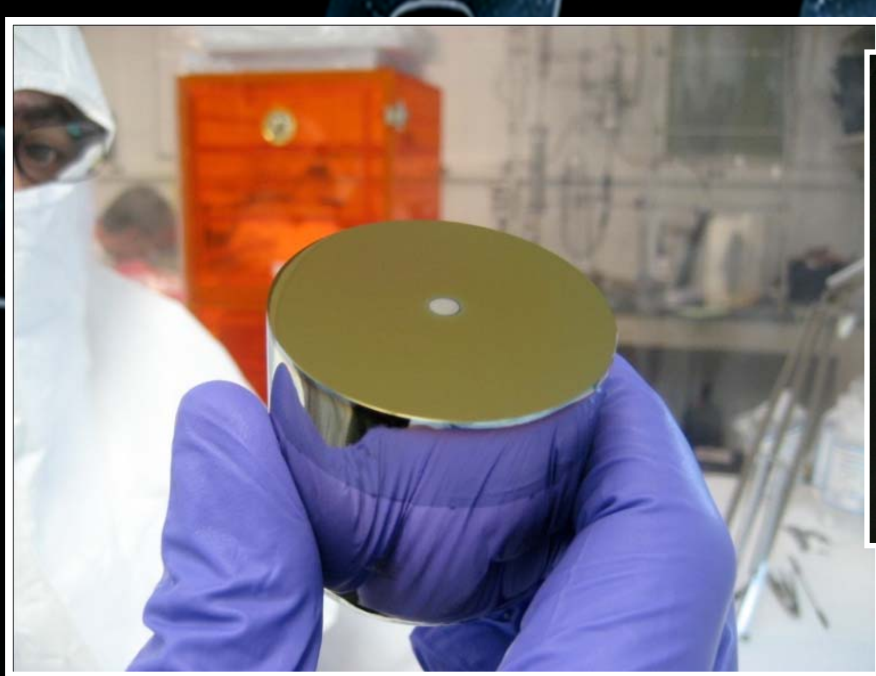


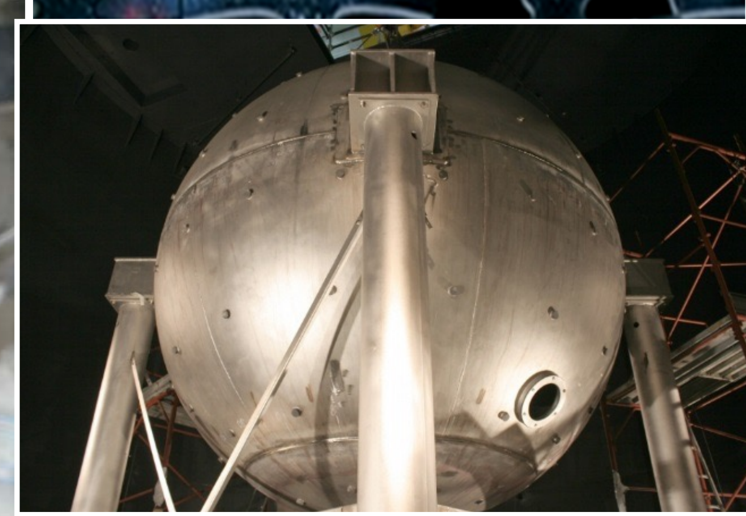
CDMS



CRESST

CoGeNT

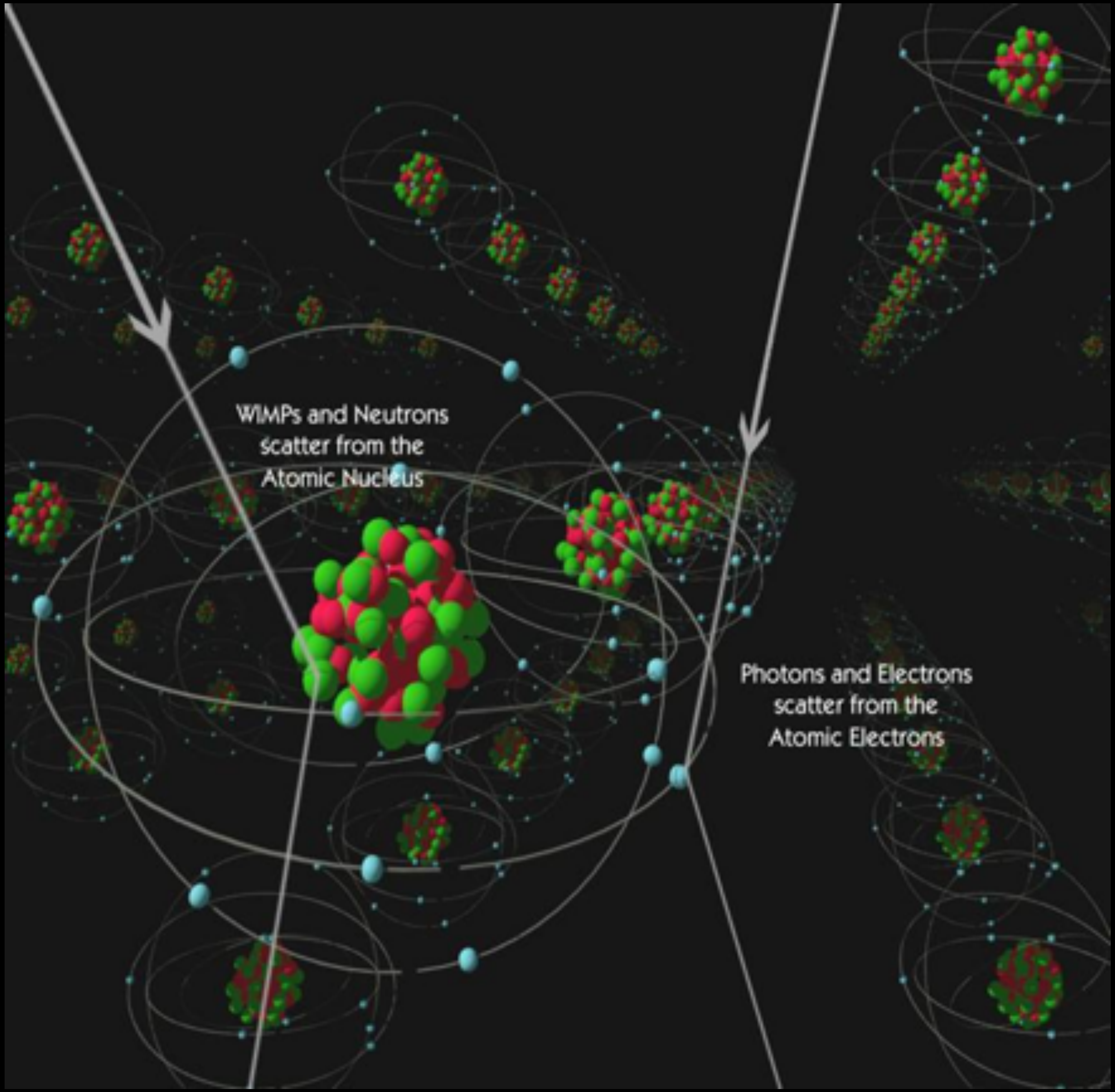




Darkside

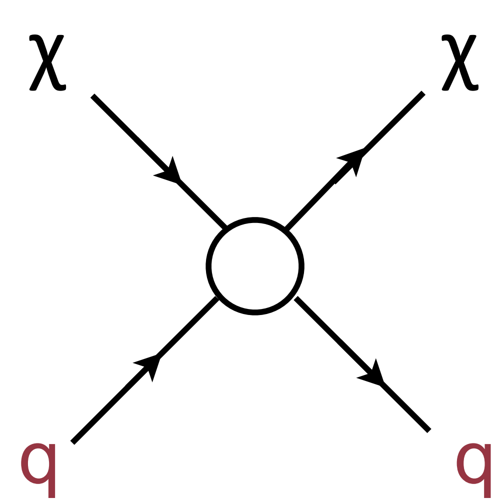
DAMA

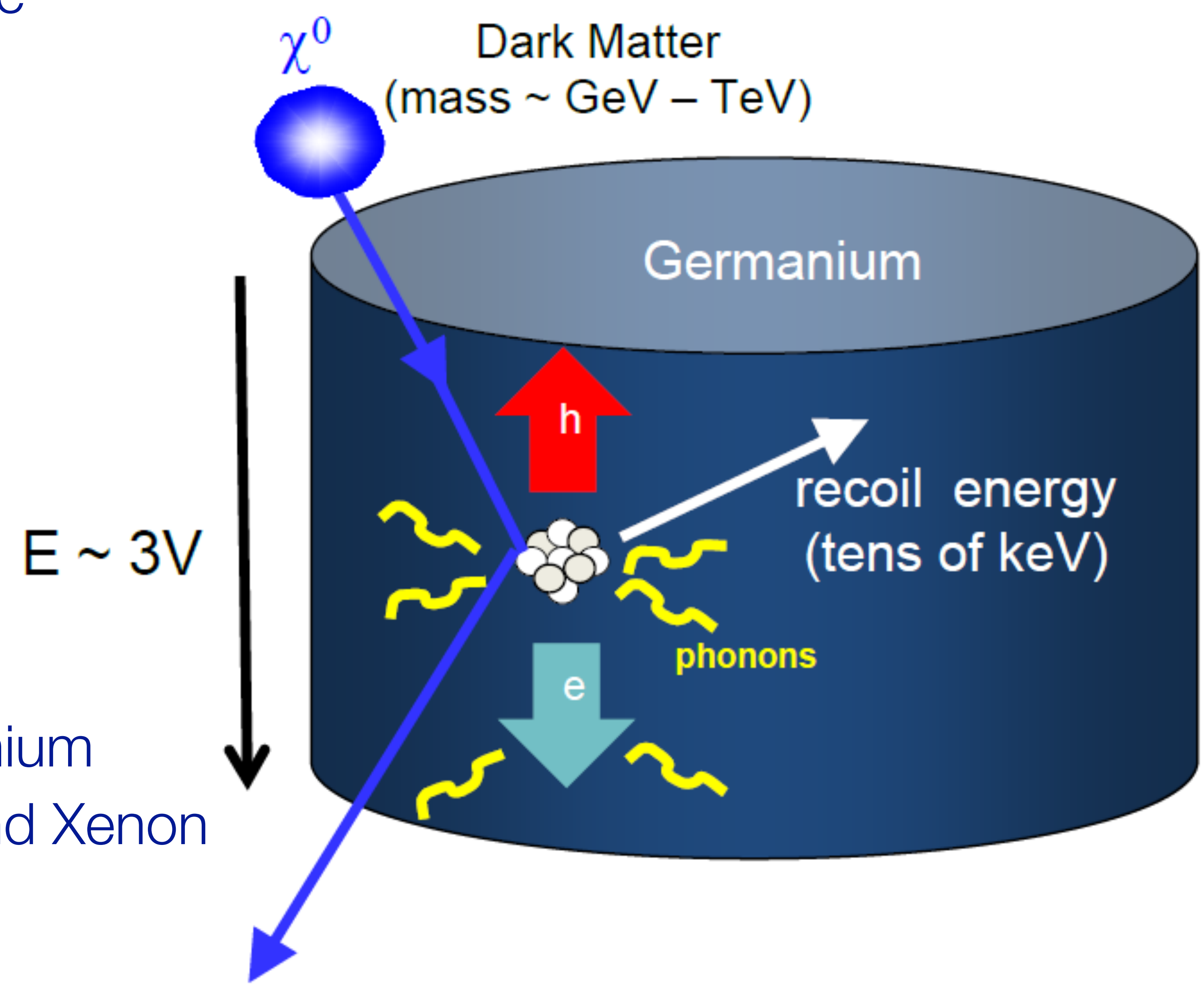
DIRECT DETECTION



Direct Detection

- Observe recoil of dark matter from nucleus
  - Extremely sensitive, extremely difficult... extremely successful!
  - Limited by threshold effects, energy scale, backgrounds
  - Low mass region not accessible



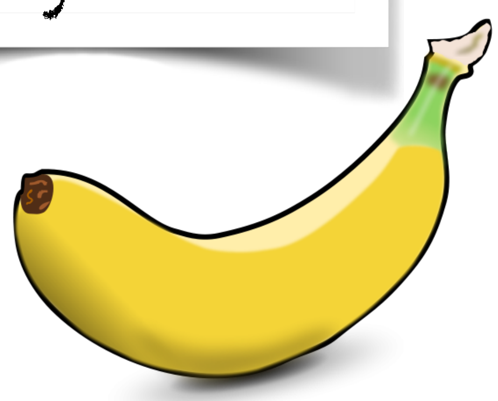


– Detection techniques
  - Heat, vibration: silicon, Germanium
  - Light: NaI, CsI, Liquid Argon and Xenon
  - Charge: Germanium, silicon, Gas and liquid Ar and Xe

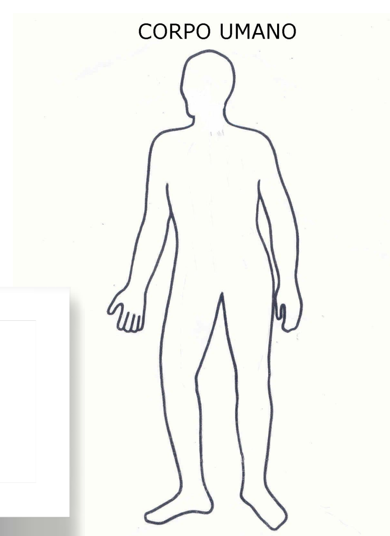
Natural Backgrounds

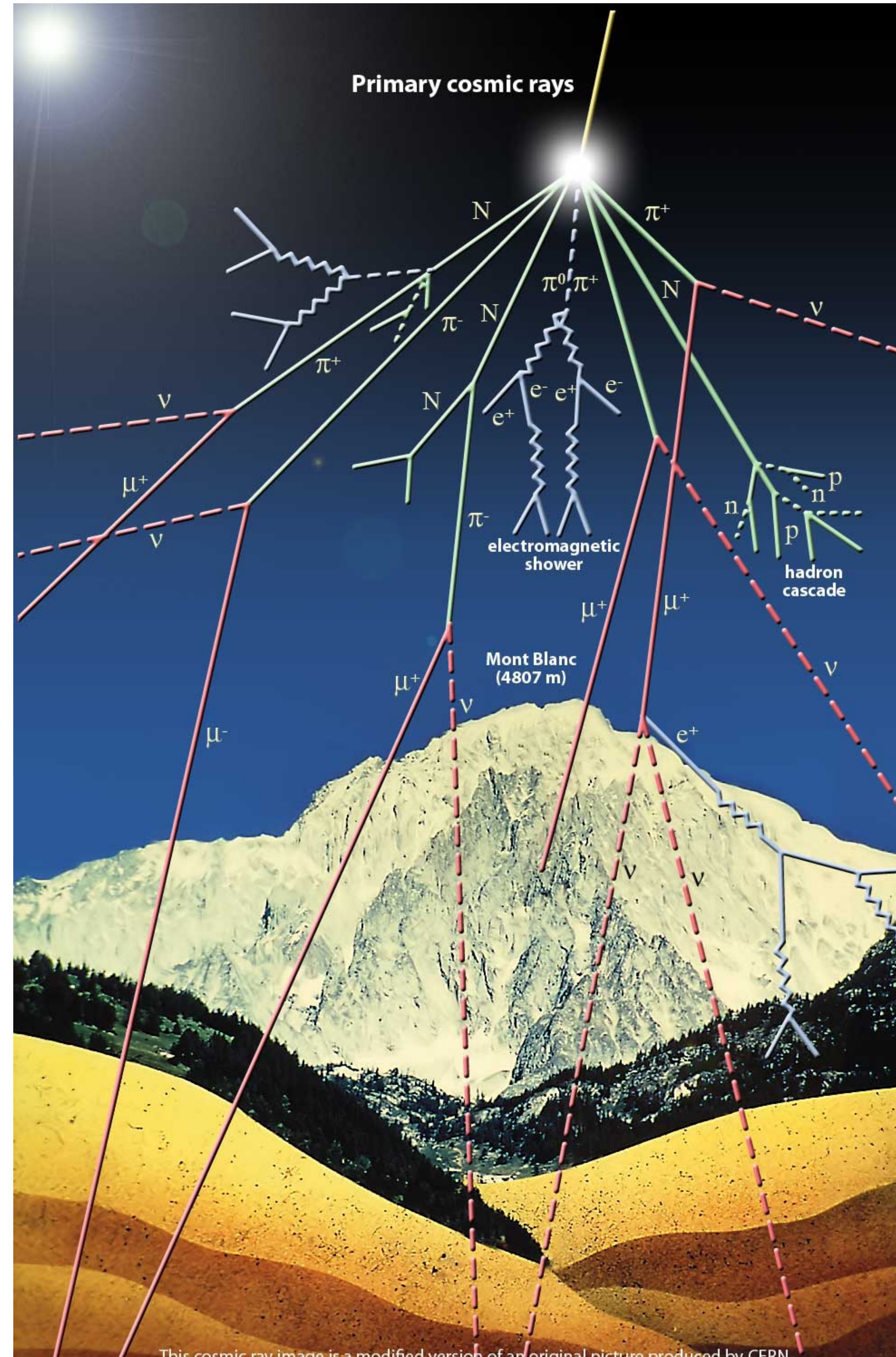
- Rare process subject to two major background
- Cosmic rays producing showers in the atmosphere
- Natural radioactivity!

15 decay/s

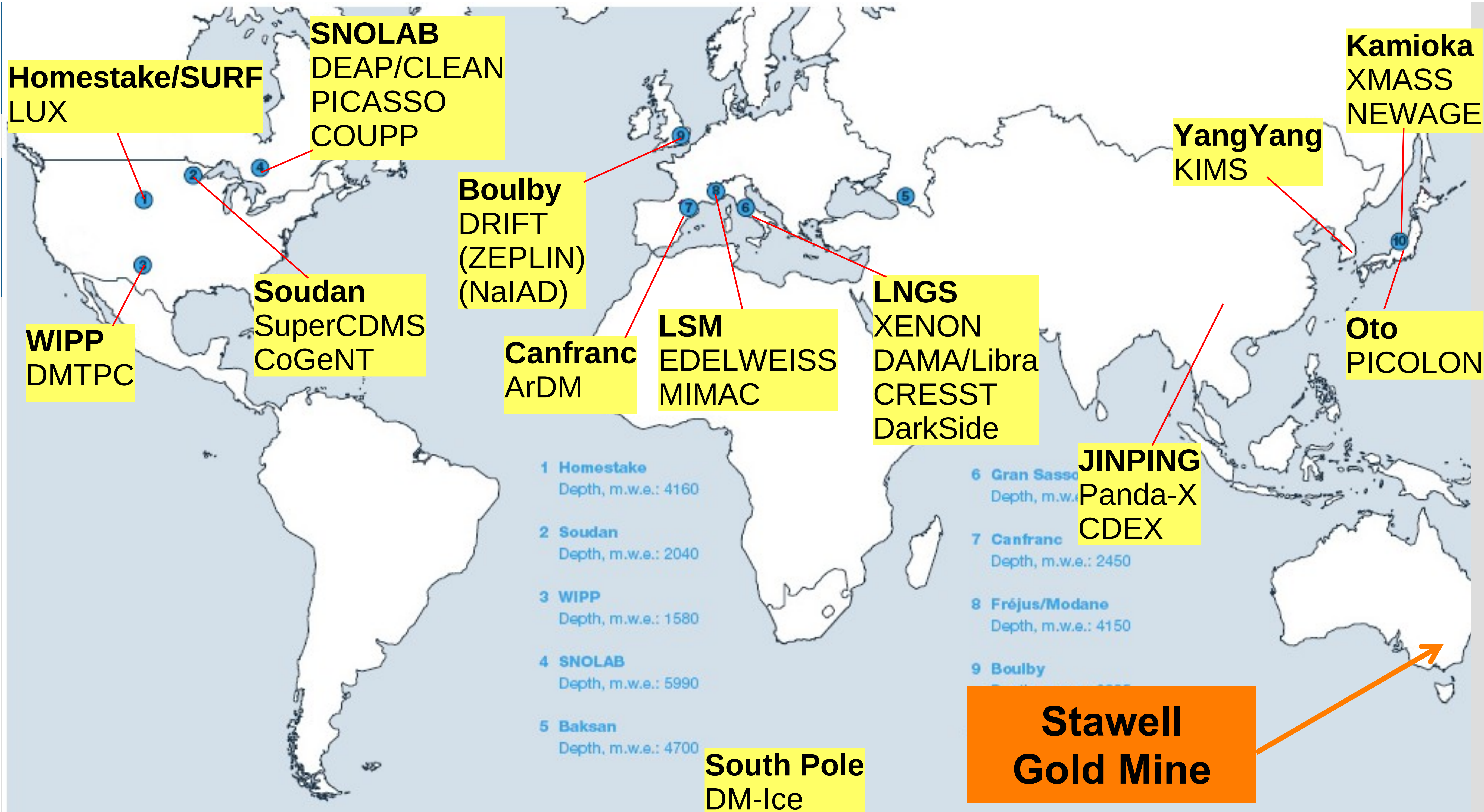


1 decay/s per gram





Underground Laboratories



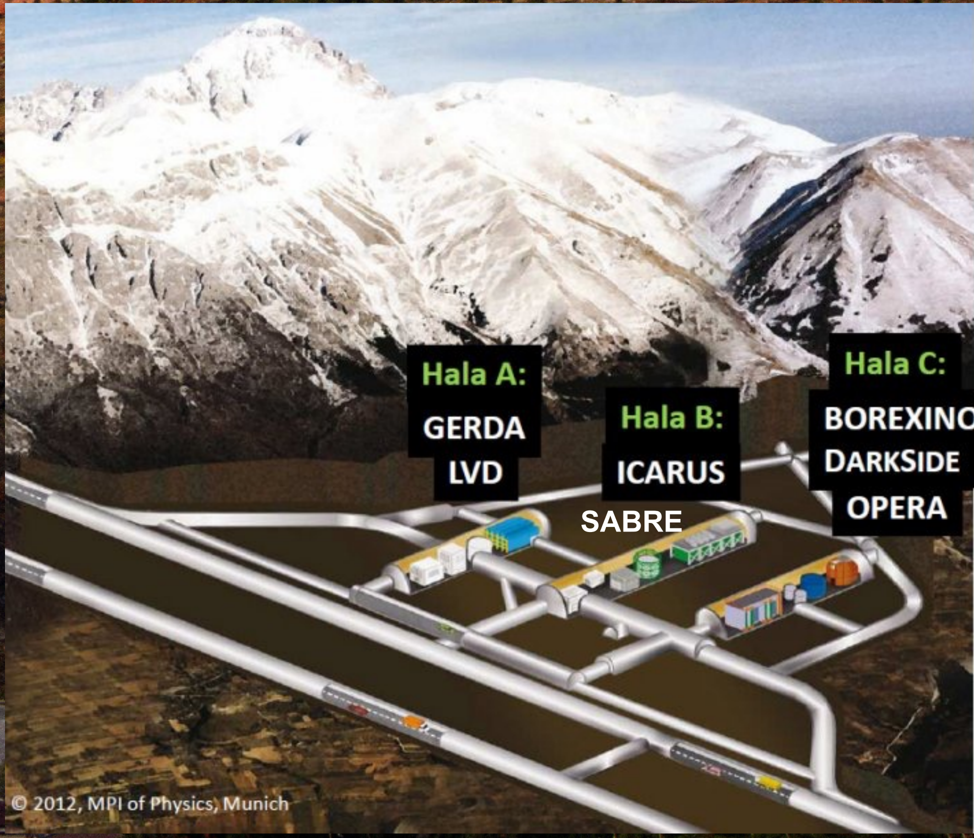
LABORATORI NAZIONALI DEL GRAN SASSO

1400 m di roccia sovrastante

Superficie: 17 800 m^2

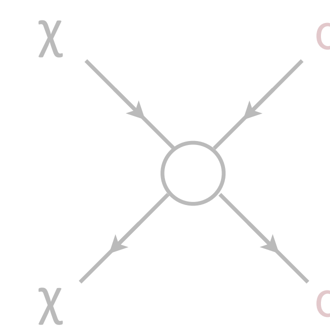
Volume: 180 000 m^3

Riduzione di un milione di volte del flusso di muoni

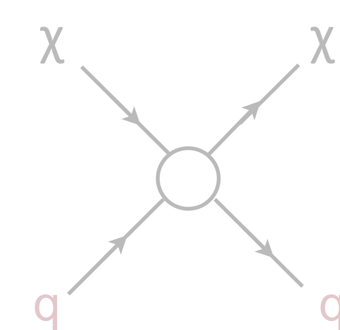


Dark Matter at LHC

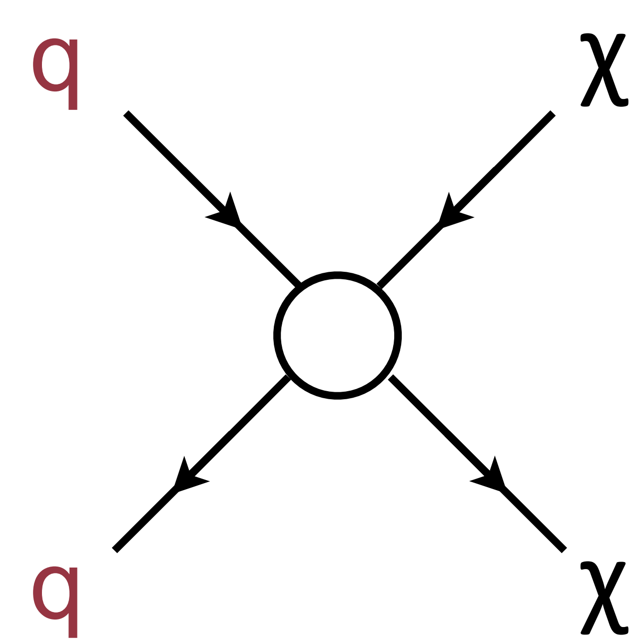
- Indirect detection
  - search for production of DM annihilation
  - high energy photons, particle-anti-particle pairs
  - search for ultra-relativistic objects produced in galactic halo
  - observatory on earth-bound or with satellites



- Direct detection
  - Observe recoil of dark matter from nucleus

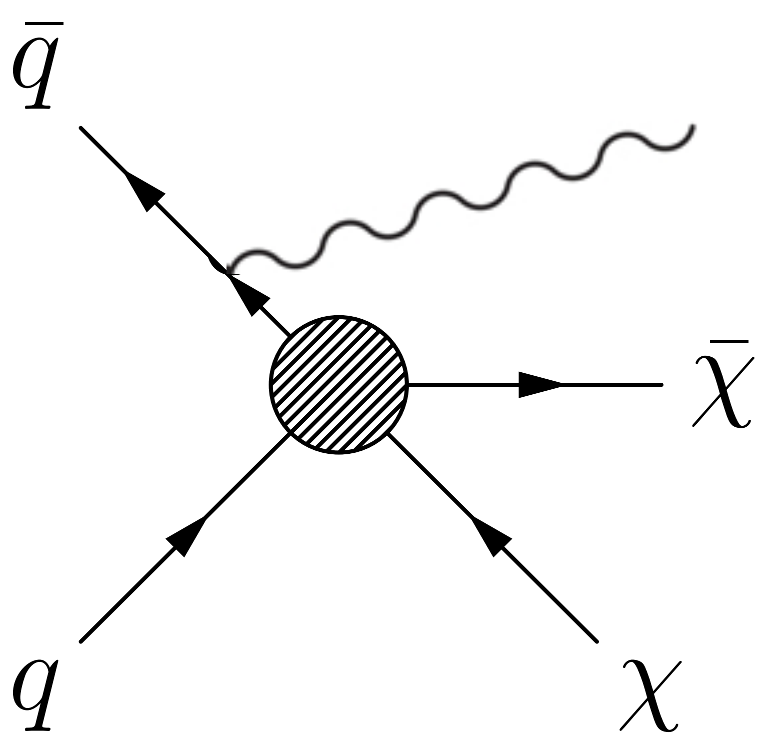


- **Pair production at LHC**
  - large missing energy in the detector
  - some handle needed to identify events of interest

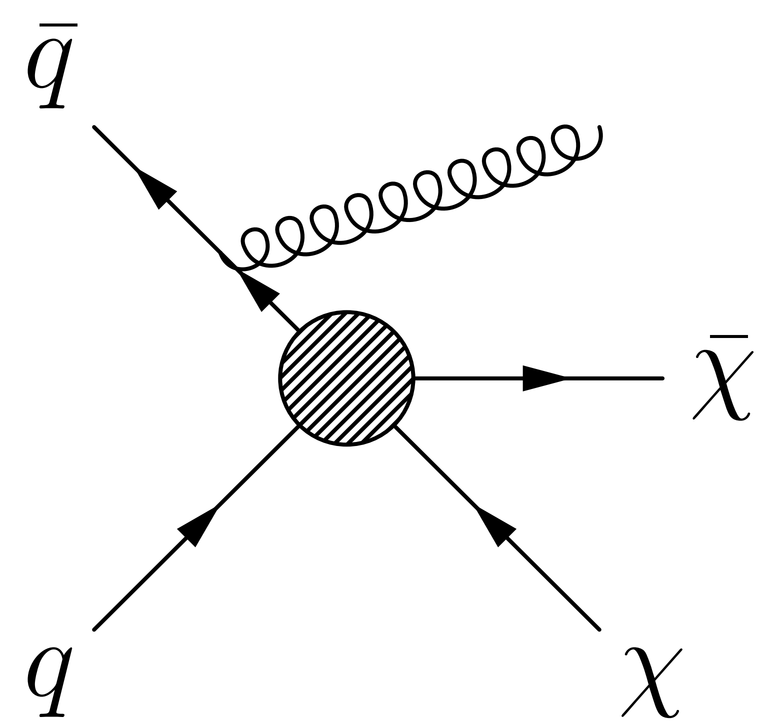


Dark Matter Production at LHC

- Photons and gluons can be radiated by initial partons
- Presence of high energy photon or jet(s) *in addition* to large missing transverse energy
- Gluon radiation at higher rate than photon
  - strong interaction vs. electromagnetic

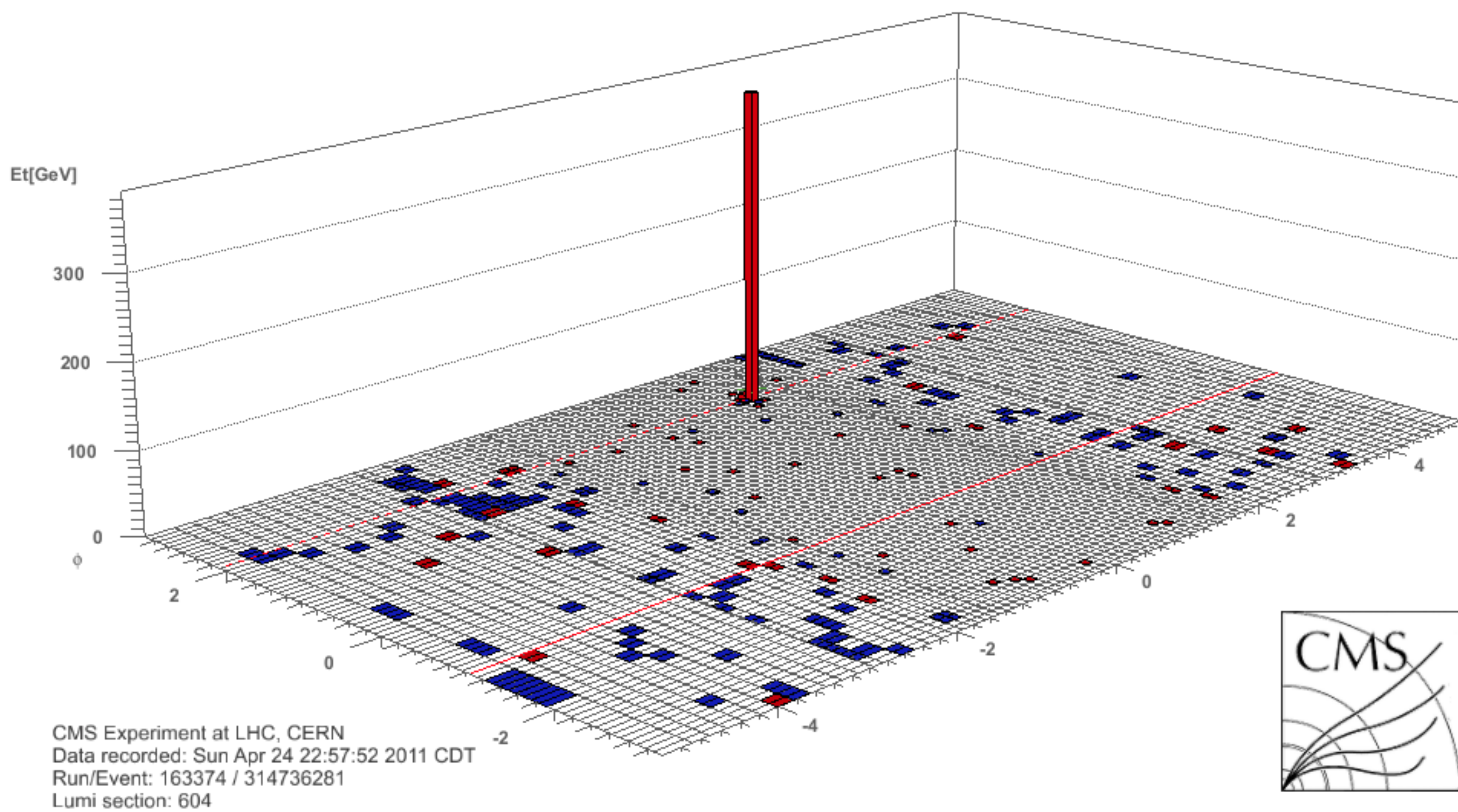


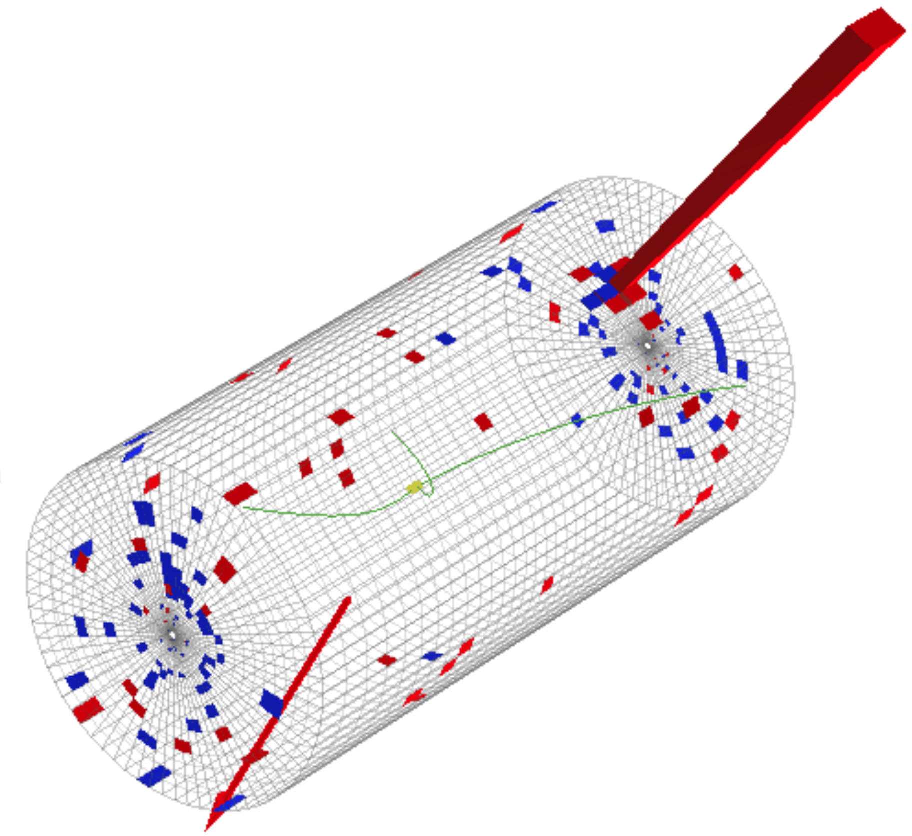
Monophoton + MET

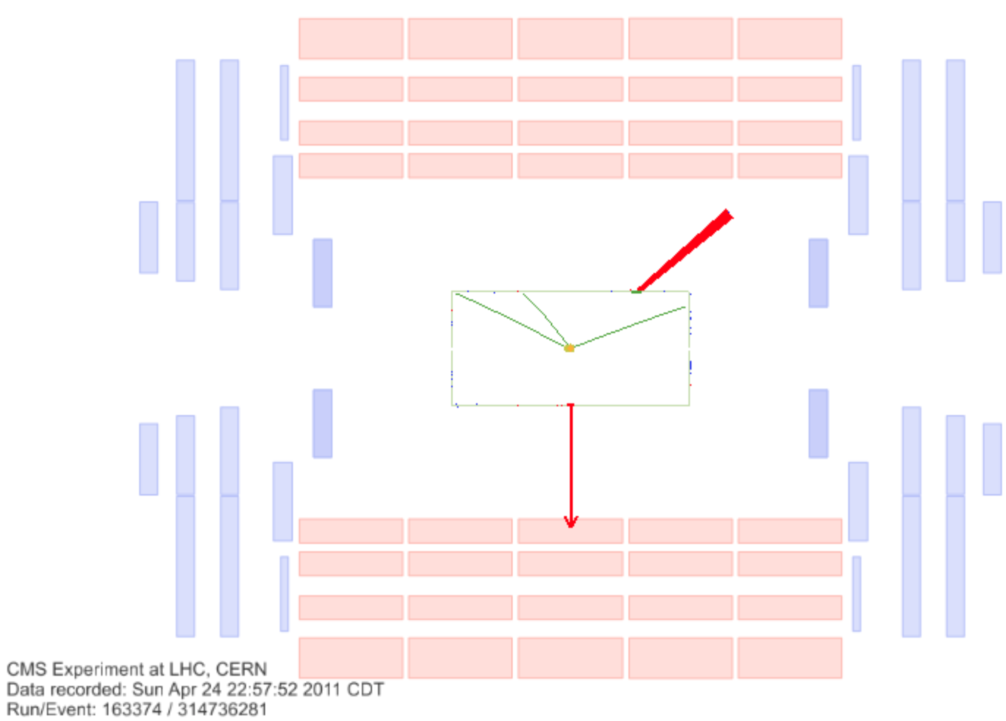


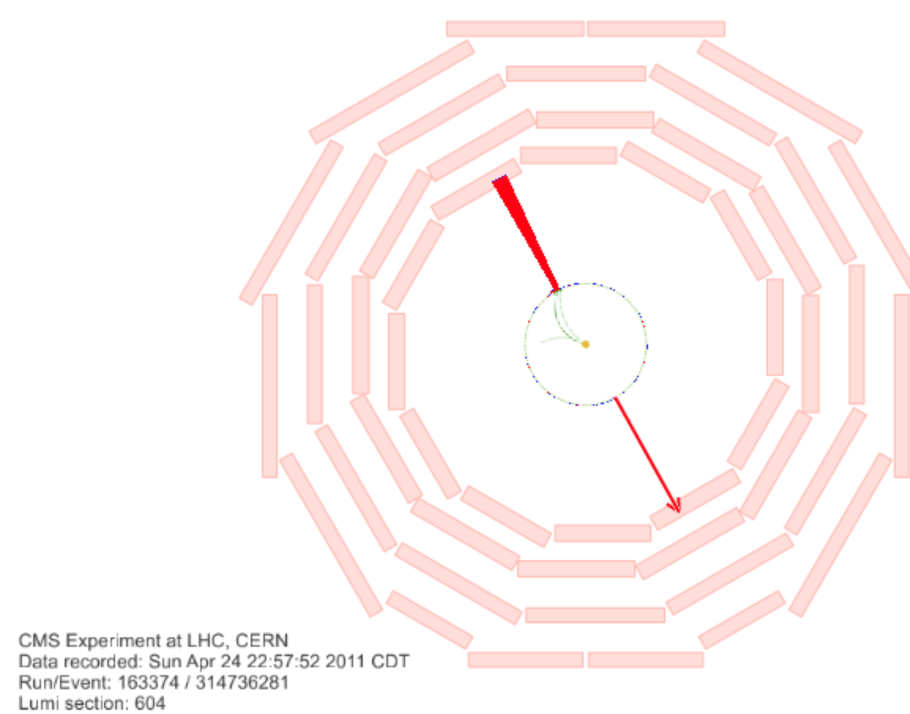
Monojet + MET

Monophoton Event

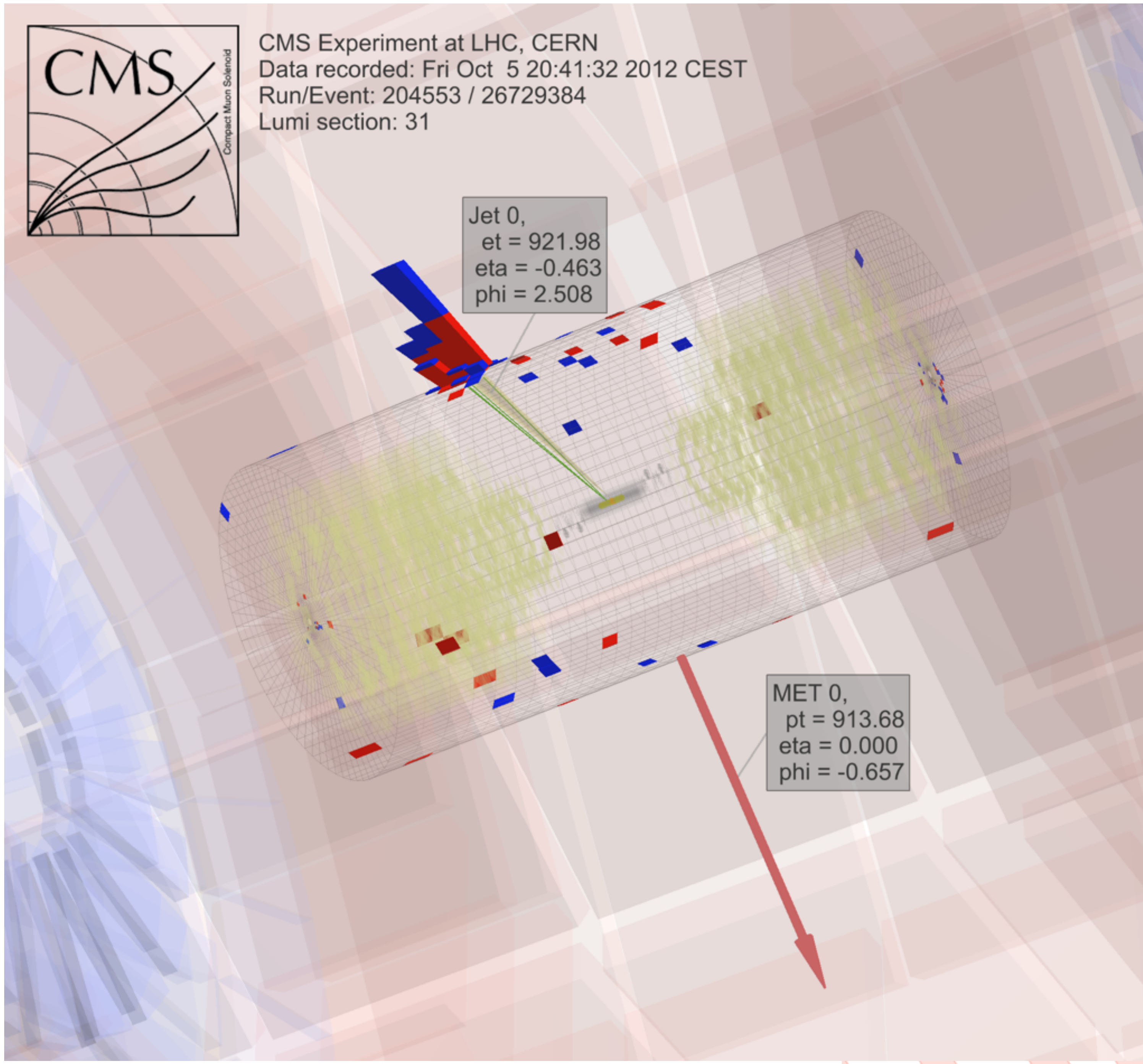


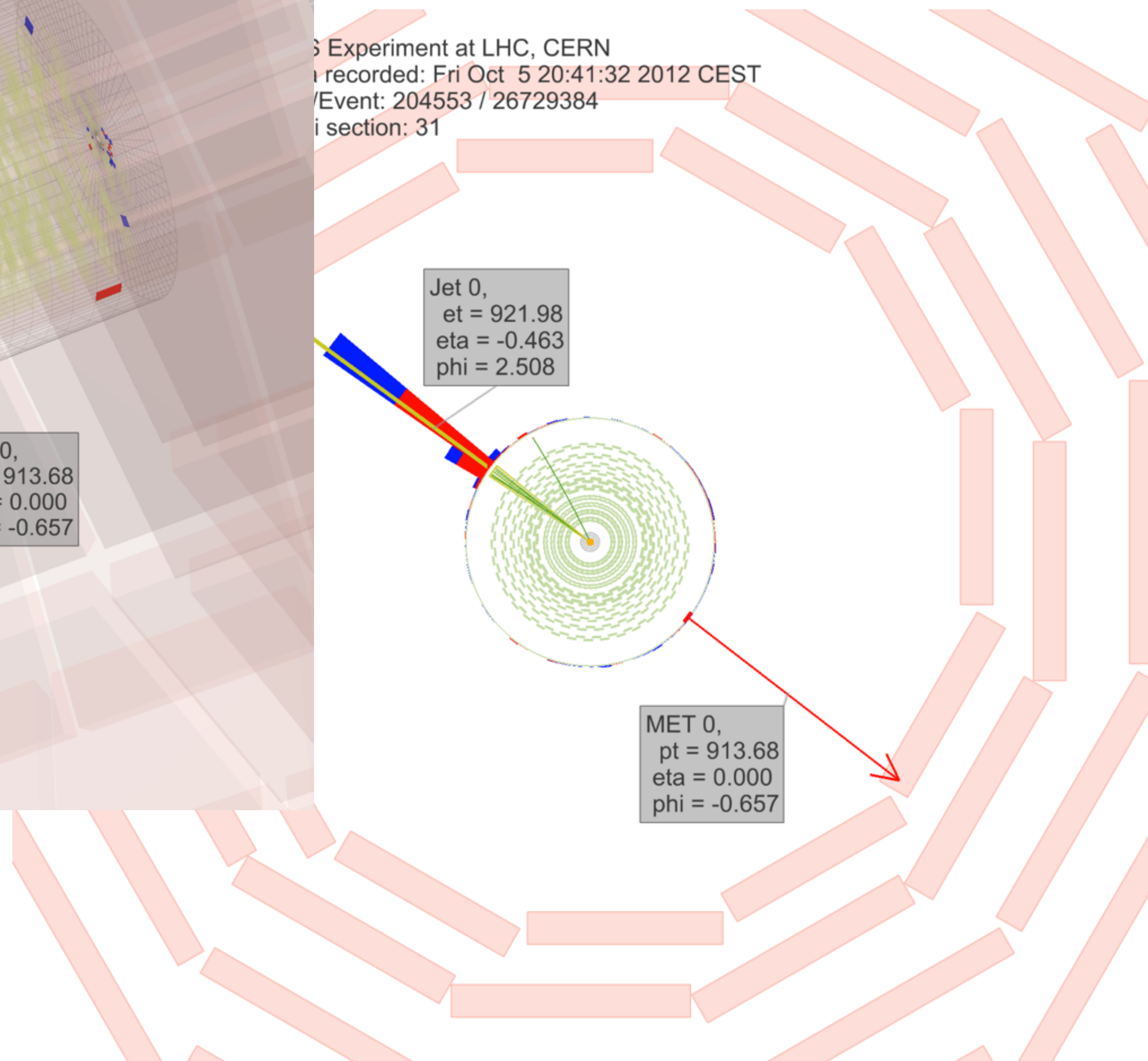




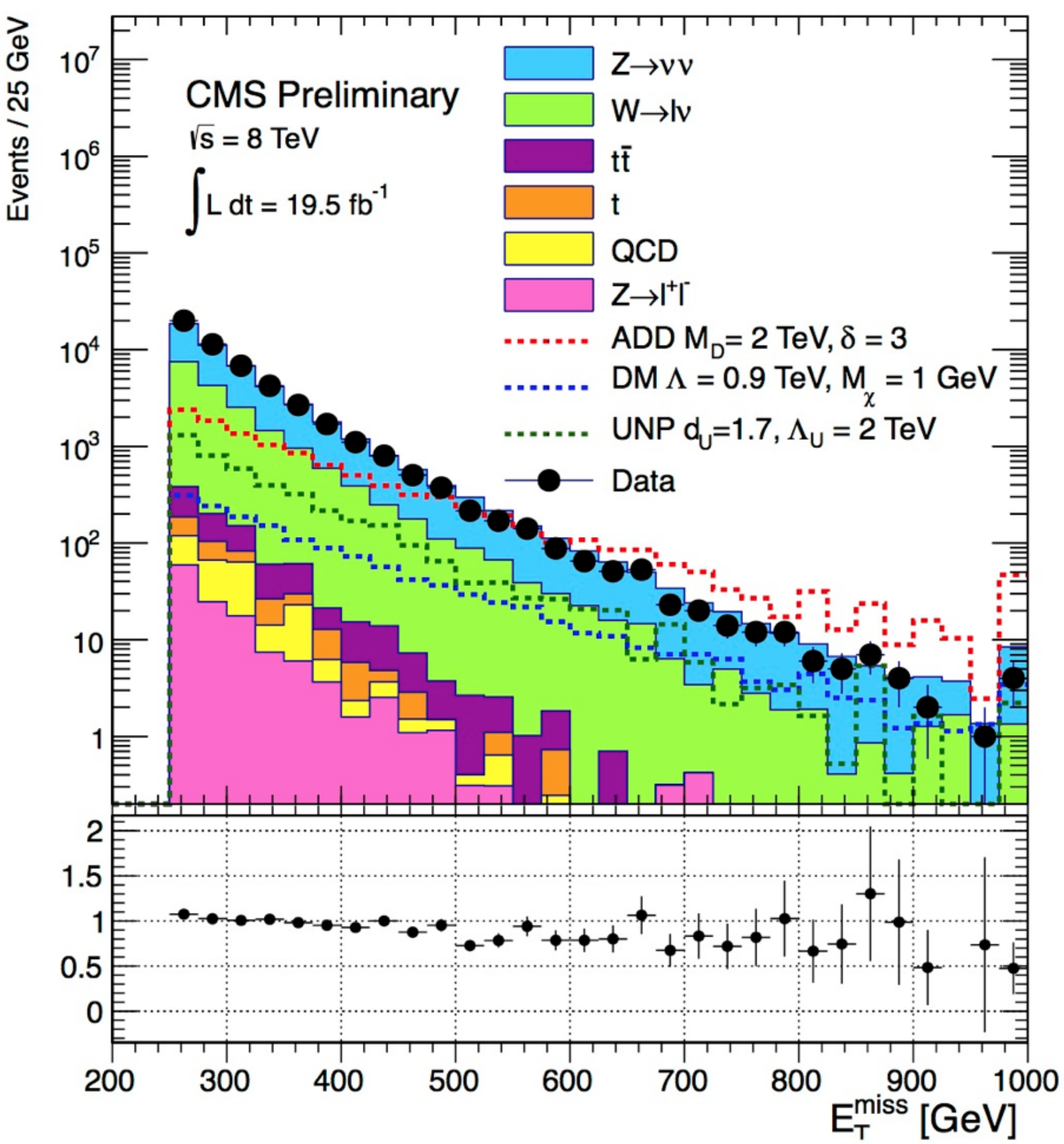


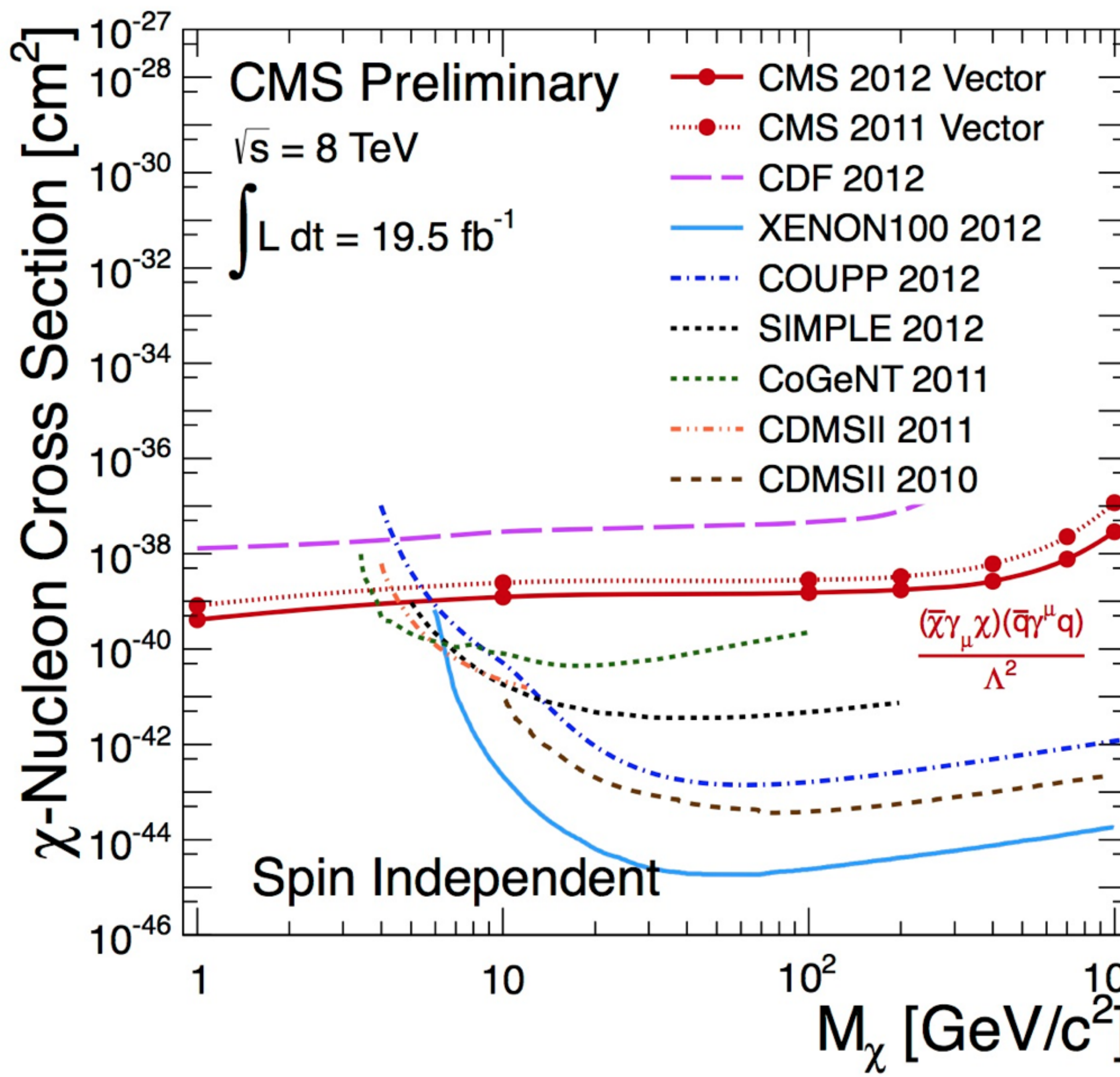
Monojet Event





Limits on Dark Matter Cross Section





Outlook

- LHC has established Yukawa interaction for third generation fermions
- Extensive program searching for new phenomena beyond the Standard Model
- Precision measurement of top and electroweak processes sensitive to deviation due to new physics
- *Exploration of new territory*
  for the first time without solid theoretical guidance