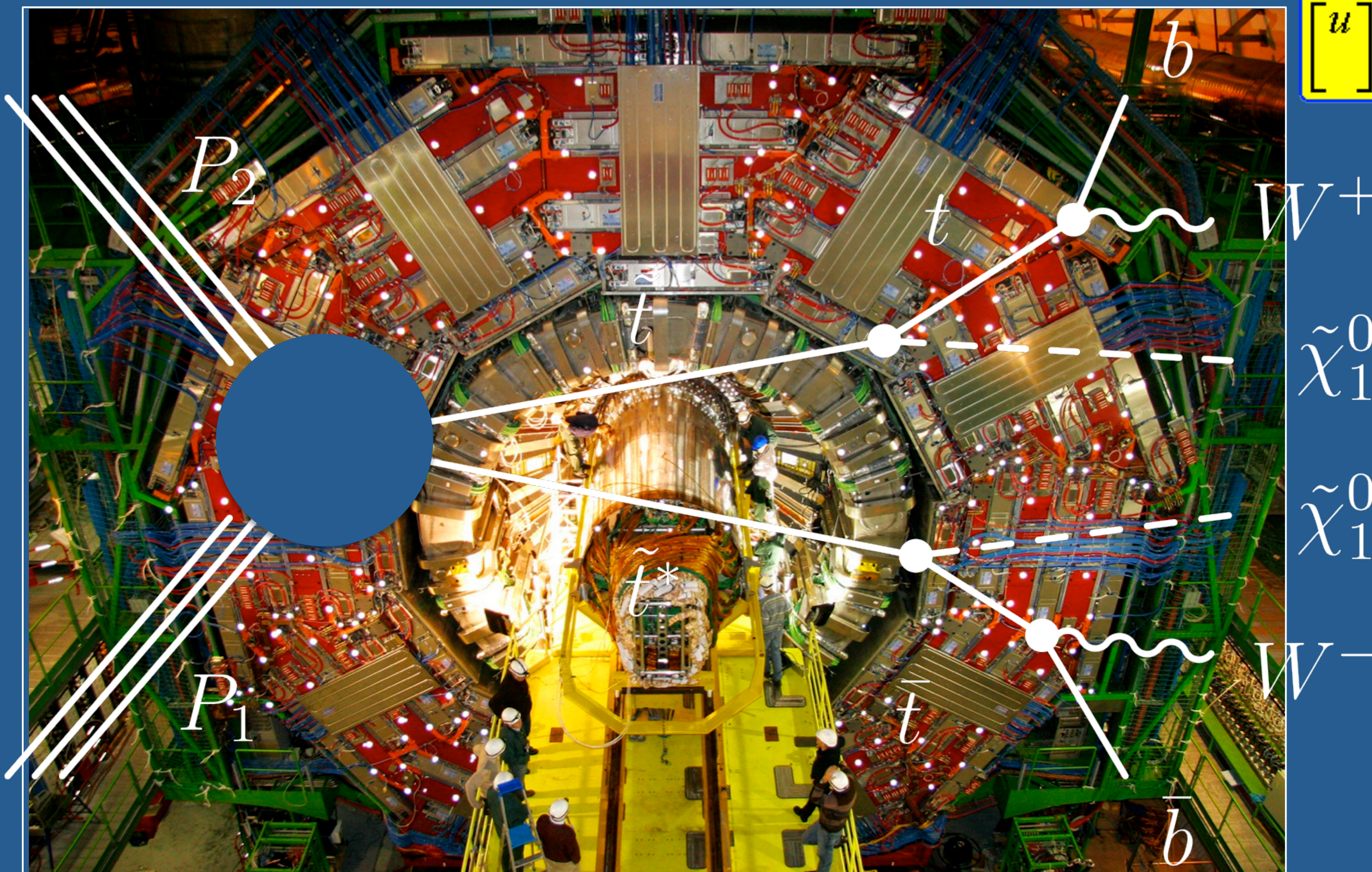
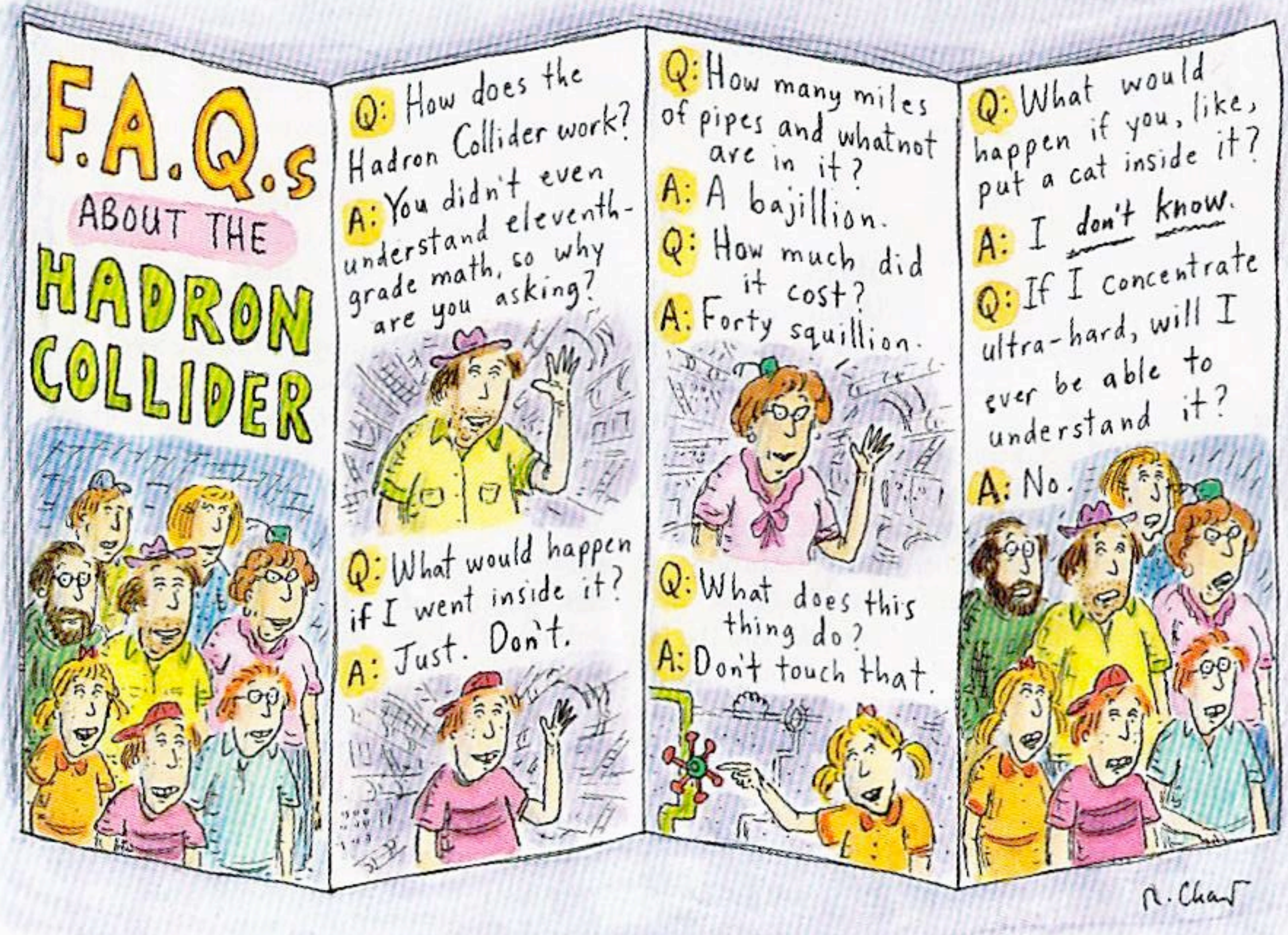
# Searching for Supersymmetry at the LHC

*Jeffrey D. Richman (UC Santa Barbara)*




Colloquium, Department of Physics, University of New Mexico,
Albuquerque, November 7, 2014


F.A.Q.s
ABOUT THE
HADRON COLLIDER
Q: How does the Hadron Collider work?
A: You didn't even understand eleventh-grade math, so why are you asking?
Q: What would happen if I went inside it?
A: Just. Don't.
Q: How many miles of pipes and whatnot are in it?
A: A bajillion.
Q: How much did it cost?
A: Forty squillion.
Q: What does this thing do?
A: Don't touch that.
Q: What would happen if you, like, put a cat inside it?
A: I don't know.
Q: If I concentrate ultra-hard, will I ever be able to understand it?
A: No.
R. Chast

# Outline

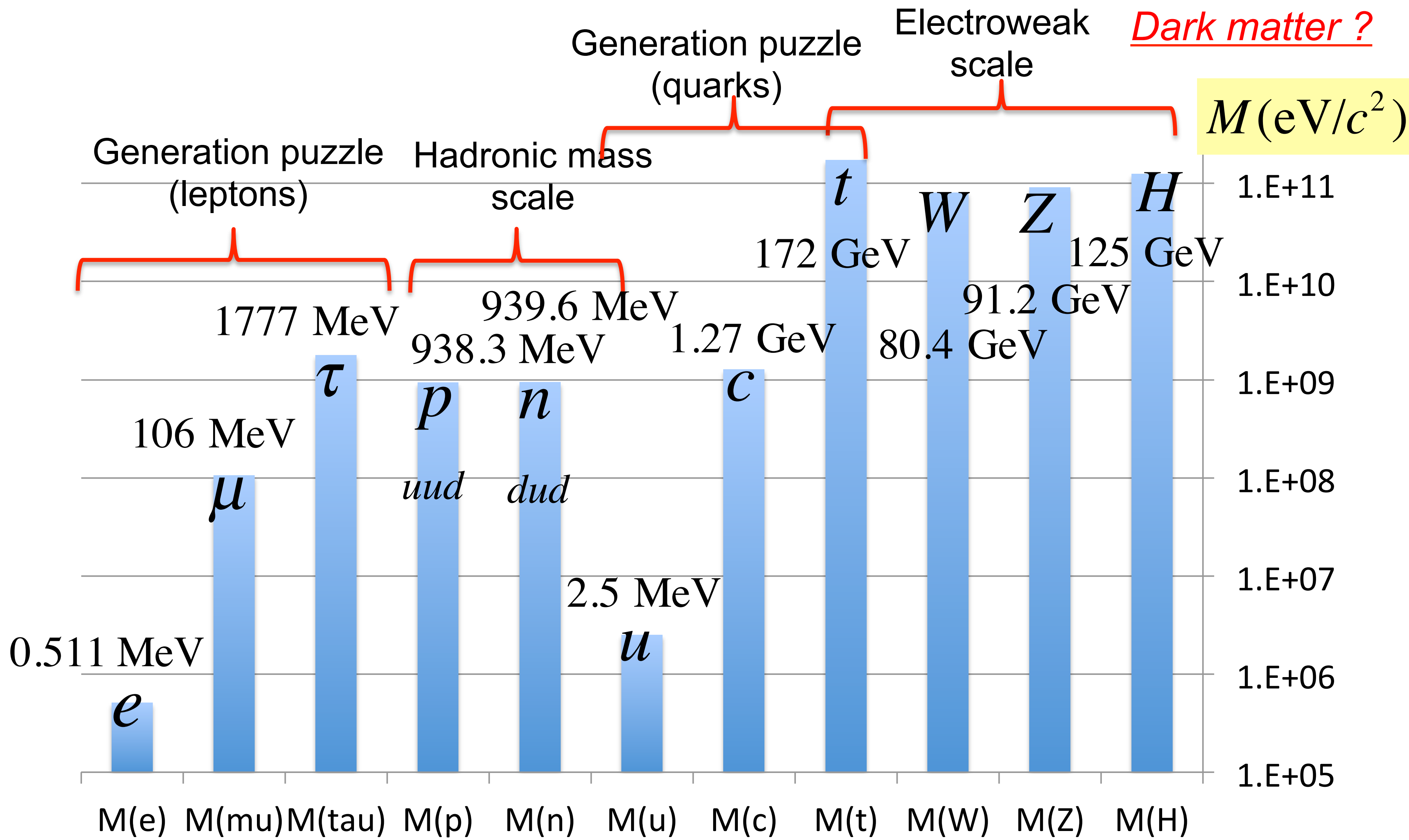
- Overview: mass scales
- What is supersymmetry?
- The Higgs, SUSY, and "naturalness"
- The LHC and CMS
- Searching for dark matter, scalar quarks, gluinos,...
- Prospects for Run 2 and beyond
- Conclusions

Drawing courtesy Sergio Cittolin

**CMS PUBLIC SUSY RESULTS**
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

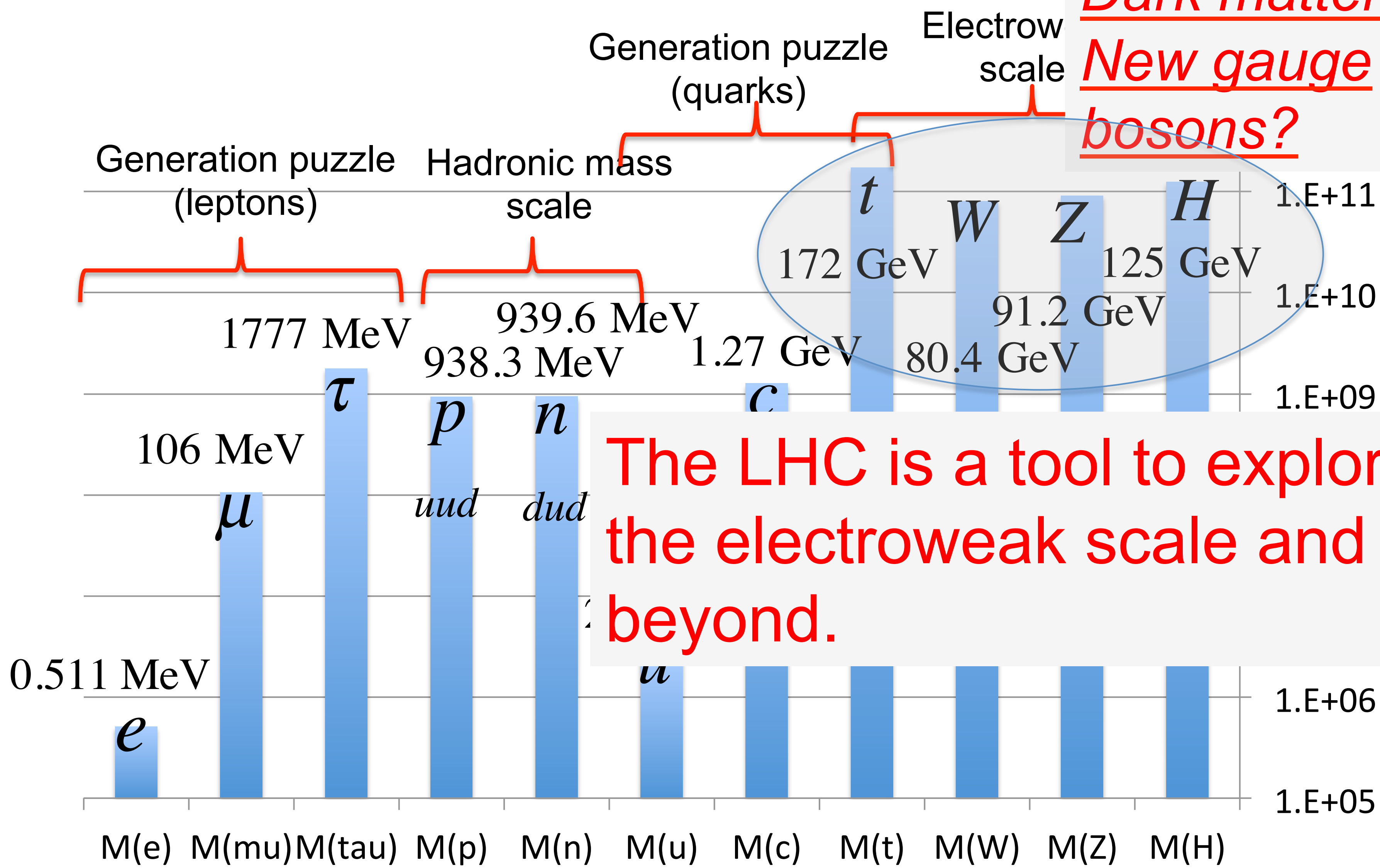
**Most results use 19.5 $fb^{-1}$ ($\sqrt{s}$ =8 TeV).**

# Key mass scales in particle physics




Si band gap: $\simeq 1.1$ eV $\quad m(\nu) \sim 0.1$ eV? $\quad m(\tilde{g}) \sim 2$ TeV? $M_{Planck} \approx 10^{18}$ GeV

# Key mass scales in particle ph




*SUSY?,*
*Dark matter ?*
*New gauge bosons?*

The LHC is a tool to explore the electroweak scale and beyond.

Si band gap: $\simeq 1.1$ eV $\quad m(\nu) \sim 0.1$ eV? $\quad m(\tilde{g}) \sim 2$ TeV? $\quad M_{Planck} \approx 10^{18}$ GeV

# Symmetries in particle physics

- Theories of particle physics are built around a set (group) of assumed symmetry transformations that leave the action invariant.

$$S = \int \mathcal{L}\, d^4x \underbrace{\rightarrow}_{} S' = S$$

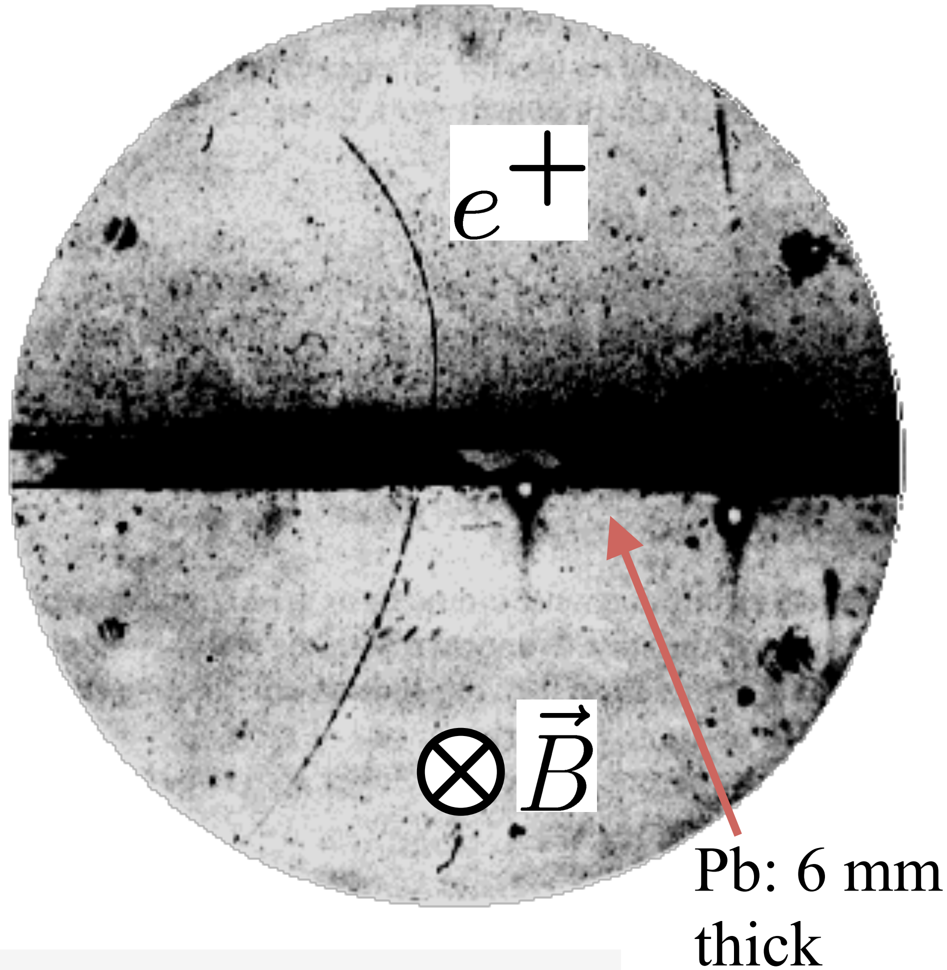
symmetry (same laws of physics, whether using unprimed or primed degrees of freedom)!

under specified *group* of transformations acting on fields or coordinates

| Symmetry | Symmetry operation | Consequences |
|---|---|---|
| Spacetime symmetries | Poincaré group: act on spacetime coords | Laws of physics are invariant under Poincare xfs; cons. of ***P***, ***J***, etc. |
| Continuous global symmetries | e.g., U(1) phase xf's | Conservation of charge (additively conserved quantum numbers) |
| Gauge (local) symmetries | $SU(3)_c \times SU(2)_L \times U(1)_Y$ is gauge group of SM | Specify the form of interactions; predict specific gauge fields |
| Discrete symmetries | C, P, T, CP, CPT | Matter-antimatter relations, parity, time-reversal, etc. |

# Matter, antimatter, and CPT

- Dirac relativistic wave equation (1928): extra, “negative-energy” solutions.
- Positron interpretation confirmed by C.D. Anderson (cosmic ray experiment) at Caltech.




$$a \to \bar{a}: \quad q_a = -q_{\bar{a}} \quad m_a = m_{\bar{a}} \quad \tau_a = \tau_{\bar{a}} \quad (CPT)$$

P.A.M. Dirac, Proc. Roy. Soc. (London), **A117**, 610 (1928); ibid., **A118**, 351 (1928).
C.D. Anderson, Phys. Rev. **43**, 491 (1933).

## Author lists were shorter back in 1933...

MARCH 15, 1933 PHYSICAL REVIEW VOLUME 43

# The Positive Electron

CARL D. ANDERSON, *California Institute of Technology, Pasadena, California*

(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

*Editor*

ON August 2, 1932, during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber (magnetic field of 15,000 gauss) designed in the summer of 1930 by Professor R. A. Millikan and the writer, the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence in this case of a particle carrying a electrons happened to produce two tracks so placed as to give the impression of a single particle shooting through the lead plate. This assumption was dismissed on a probability basis, since a sharp track of this order of curvature under the experimental conditions prevailing occurred in the chamber only once in some 500 exposures, and since there was practically no

# Supersymmetry transformations

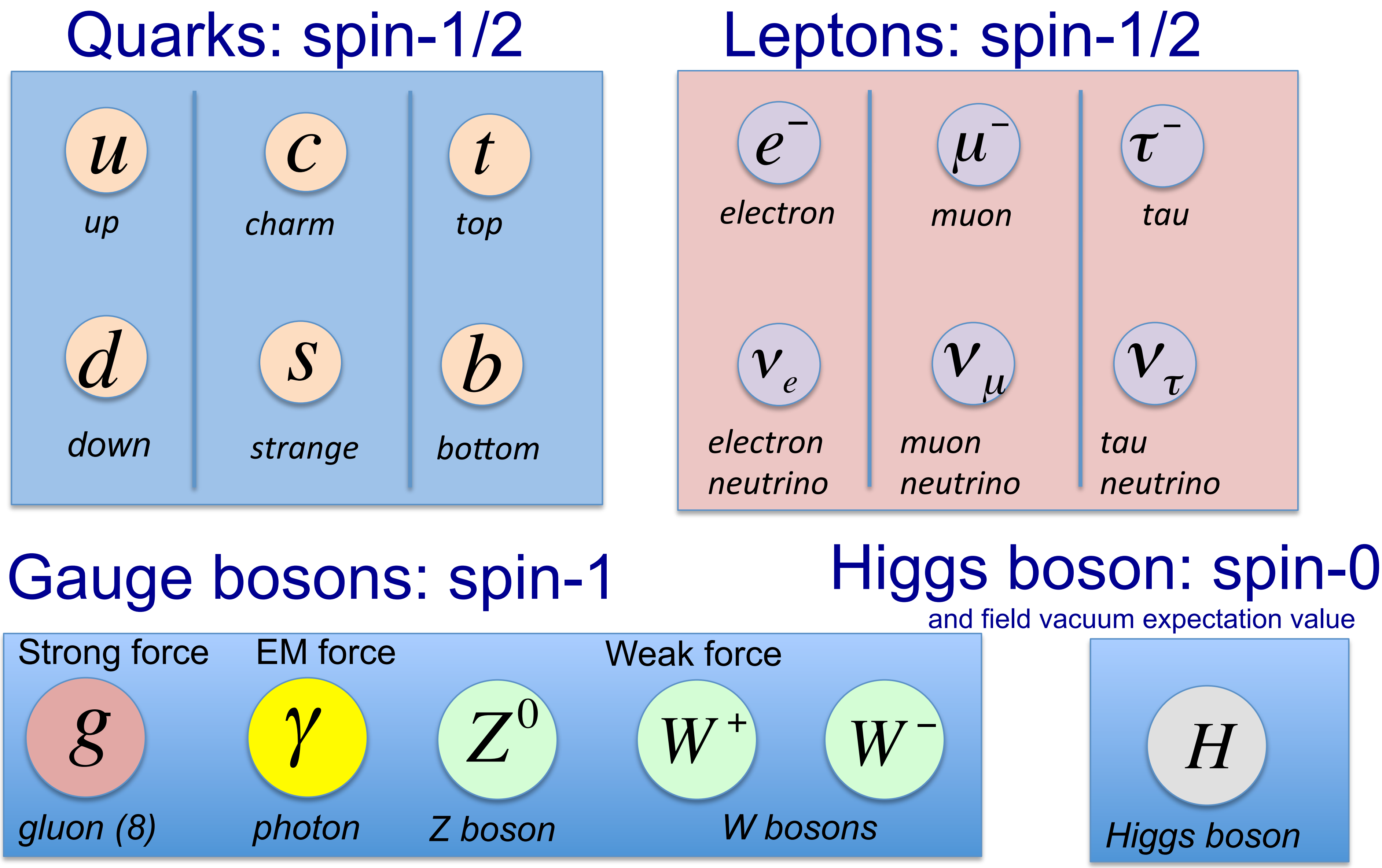
- SUSY xf's map *fermionic and bosonic* degrees of freedom onto each other, e.g., $e^-(s=1/2) \rightarrow \tilde{e}^-(s=0)$
- *Q* = generator of SUSY transformation

$$Q\underbrace{|s\rangle}_{\text{boson (J=0 or J=1)}} = \underbrace{|f\rangle}_{\text{fermion (J=1/2)}}$$

Q must be fermionic in character!

- The charges (interaction couplings) are <u>unchanged</u>.
- Doubles the numbers of degrees of freedom in the particle spectrum (but CPT did that too!)
- Unlike CPT, don't see SUSY partners with same masses as SM → *if SUSY exists, it must be broken*.

# Particle content of the SM



# Simple (naïve) SUSY spectrum

scalar quark → squarks: spin-0

| $\tilde{u}$ up squark | $\tilde{c}$ charm squark | $\tilde{t}$ top squark |
|---|---|---|
| $\tilde{d}$ down squark | $\tilde{s}$ strange squark | $\tilde{b}$ bottom squark |

scalar lepton → sleptons: spin-0

| $\tilde{e}^-$ selectron | $\tilde{\mu}^-$ smuon | $\tilde{\tau}^-$ stau |
|---|---|---|
| $\tilde{\nu}_e$ electron sneutrino | $\tilde{\nu}_\mu$ muon sneutrino | $\tilde{\nu}_\tau$ tau sneutrino |

Gauginos: spin-1/2 "-ino" → J=1/2 Higgsino: spin-1/2

| Strong force | EM force | | Weak force | |
|---|---|---|---|---|
| $\tilde{g}$ | $\tilde{\gamma}$ | $\tilde{Z}^0$ | $\tilde{W}^+$ | $\tilde{W}^-$ |
| gluino (8) | photino | Zino | Wino | |

| |
|---|
| $\tilde{H}$ |
| Higgsino |

# Scalar SUSY particles and chiral multiplets

- The SM is a chiral theory: the L and R chiral projections of the fermion fields have different EW interaction quantum numbers.
  - L projections are $SU(2)_L$ doublets
  - R projections are $SU(2)_L$ singlets

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad u_R, \quad d_R$$

- Each chiral projection of a SM fermion has SUSY scalar partner (preserving degrees of freedom).

$$e^- \nearrow e^-_L \leftrightarrow \tilde{e}^-_L \qquad\qquad t \nearrow t_L \leftrightarrow \tilde{t}_L$$

$$e^- \searrow e^-_R \leftrightarrow \tilde{e}^-_R \qquad\qquad t \searrow t_R \leftrightarrow \tilde{t}_R$$

partner of the R-handed $e^-$; has J=0, no helicity.

# SUSY spectrum in gauge/higgs sector (MSSM)

| Particle | *J* | Degrees of freedom |
|---|---|---|
| $W^+$ | 1 | 3 |
| $W^-$ | 1 | 3 |
| $Z$ | 1 | 3 |
| $\gamma$ | 1 | 2 |
| $H$ | 0 | 1 |
| $h$ | 0 | 1 |
| $H^+$ | 0 | 1 |
| $H^-$ | 0 | 1 |
| $A$ | 0 | 1 |
| Total | | 16 |

| Particle | *J* | Degrees of freedom |
|---|---|---|
| $\tilde{W}^+$ | 1/2 | 2 |
| $\tilde{W}^-$ | 1/2 | 2 |
| $\tilde{Z}$ $\vert$ $\tilde{W}^0$ | 1/2 | 2 |
| $\tilde{\gamma}$ $\vert$ $\tilde{B}$ | 1/2 | 2 |
| $\tilde{H}$ | 1/2 | 2 |
| $\tilde{h}$ | 1/2 | 2 |
| $\tilde{H}^+$ | 1/2 | 2 |
| $\tilde{H}^-$ | 1/2 | 2 |
| Total | | 16 |

Mixing

| Particle | J | Degrees of freedom |
|---|---|---|
| $\tilde{\chi}_1^+$ | 1/2 | 2 |
| $\tilde{\chi}_1^-$ | 1/2 | 2 |
| $\tilde{\chi}_2^+$ | 1/2 | 2 |
| $\tilde{\chi}_2^-$ | 1/2 | 2 |
| $\tilde{\chi}_1^0$ | 1/2 | 2 |
| $\tilde{\chi}_2^0$ | 1/2 | 2 |
| $\tilde{\chi}_3^0$ | 1/2 | 2 |
| $\tilde{\chi}_4^0$ | 1/2 | 2 |
| Total | | 16 |

If lightest neutralino is LSP, then can be dark matter candidate.

Gauginos = SUSY partners of SM gauge bosons
Higgsinos = SUSY partners of higgs bosons
Neutralinos = mix of neutral gauginos and higgsinos
Charginos = mix of charged gauginos and higgsinos
EWKinos = term that denotes neutralinos or charginos

The gluino ($\tilde{g}$) is special: because of color, it cannot mix with any other particles.

# MSSM parameter count

| Sector of MSSM | Number of parameters |
|---|---|
| Standard Model parameters | 18 |
| 1 Higgs parameter, analogous to Higgs mass in SM | 1 |
| Gaugino/higgsino sector | 5 |
| Gaugino/higgsino sector – CP violating phases | 3 |
| Squark and slepton masses | 21 |
| Mixing angles to define squark and slepton mass eigenstates | 36 |
| CP violating phases | 40 |
| Total | 124 |

In cMSSM, SUSY is described by just 4 continuous real params + 1 sign.

# The New York Times, January 5, 1993

January 5, 1993

## 315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE

Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $6ʒ million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.

In trying to ferret out ever deeper layers of nature's secrets, scientists are being forced to accept a markedly slower pace of discovery in many fields of research, and the consequent rising cost of experiments has prompted public and political criticism.

...ouch.

# Why are we still looking for SUSY?

## Hierarchy problem

~$10^{18}$ GeV

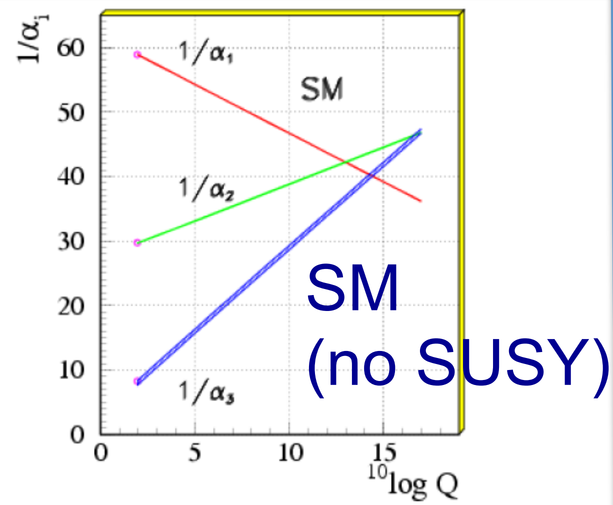
Planck scale
(quantum gravity )

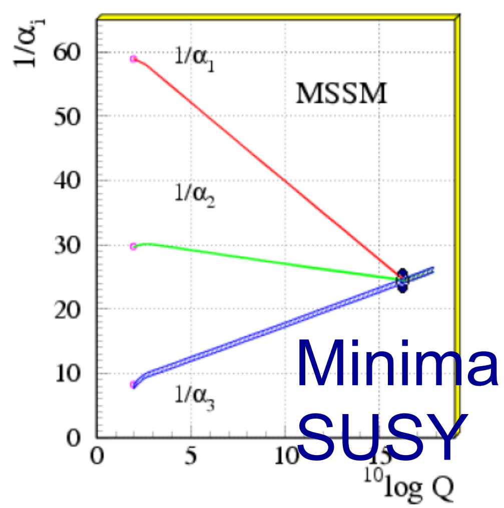
Separation of scales
is stabilized by SUSY.

~$10^{2}$ GeV

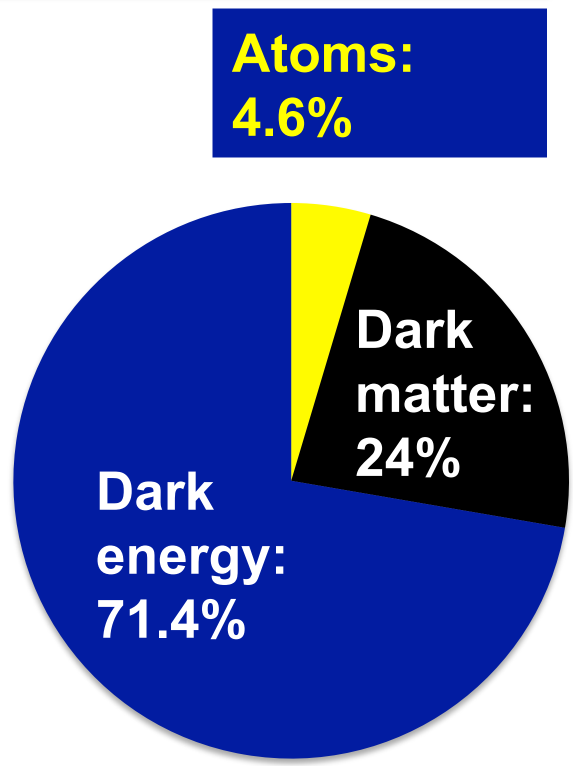
Electroweak scale
(unstable in SM)

## Unification of couplings



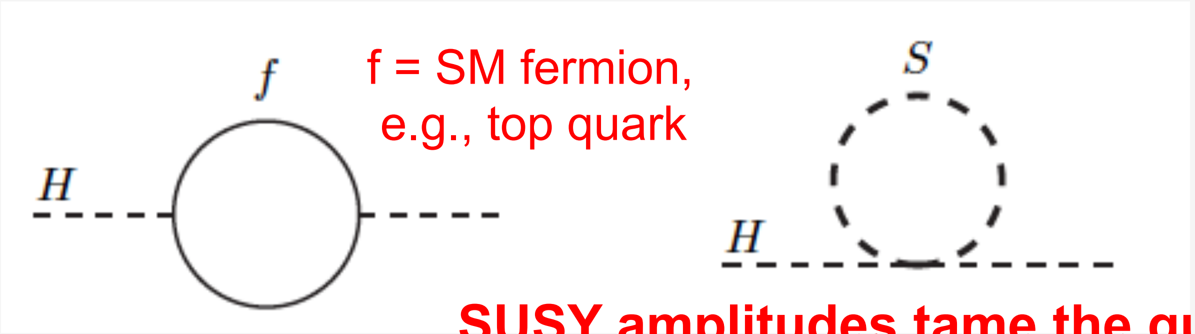

## Dark matter




SUSY provides dark matter candidate particle (Lightest Supersymmetric Particle); in MSSM this is neutralino.

# The Higgs and the Gauge Hierarchy Problem

- Evidence is very strong that the new particle discovered at m ≈ 125 GeV is a/the Higgs boson, with the quantum numbers $J^{PC} = 0^{++}$ (scalar).
- Assuming that it is an *elementary scalar* particle, the Higgs mass is subject to enormous shifts due to short distance quantum corrections.
- These corrections pull the Higgs mass up to a high physical scale, e.g., the Planck scale!




f = SM fermion, e.g., top quark

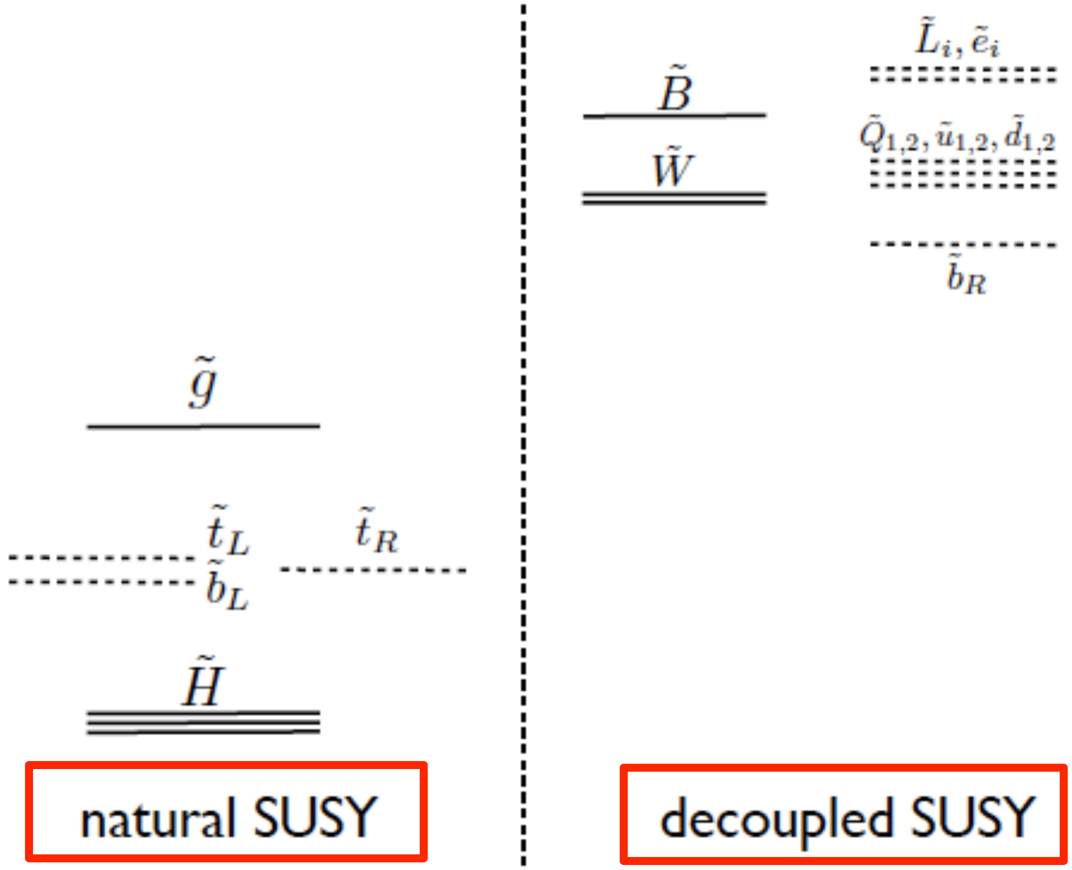
S = SUSY scalar partner, e.g., top squark

**SUSY amplitudes tame the quantum corrections!**

# “Natural SUSY endures”: the current fashion

Only part of the SUSY spectrum an be constrained by naturalness considerations.

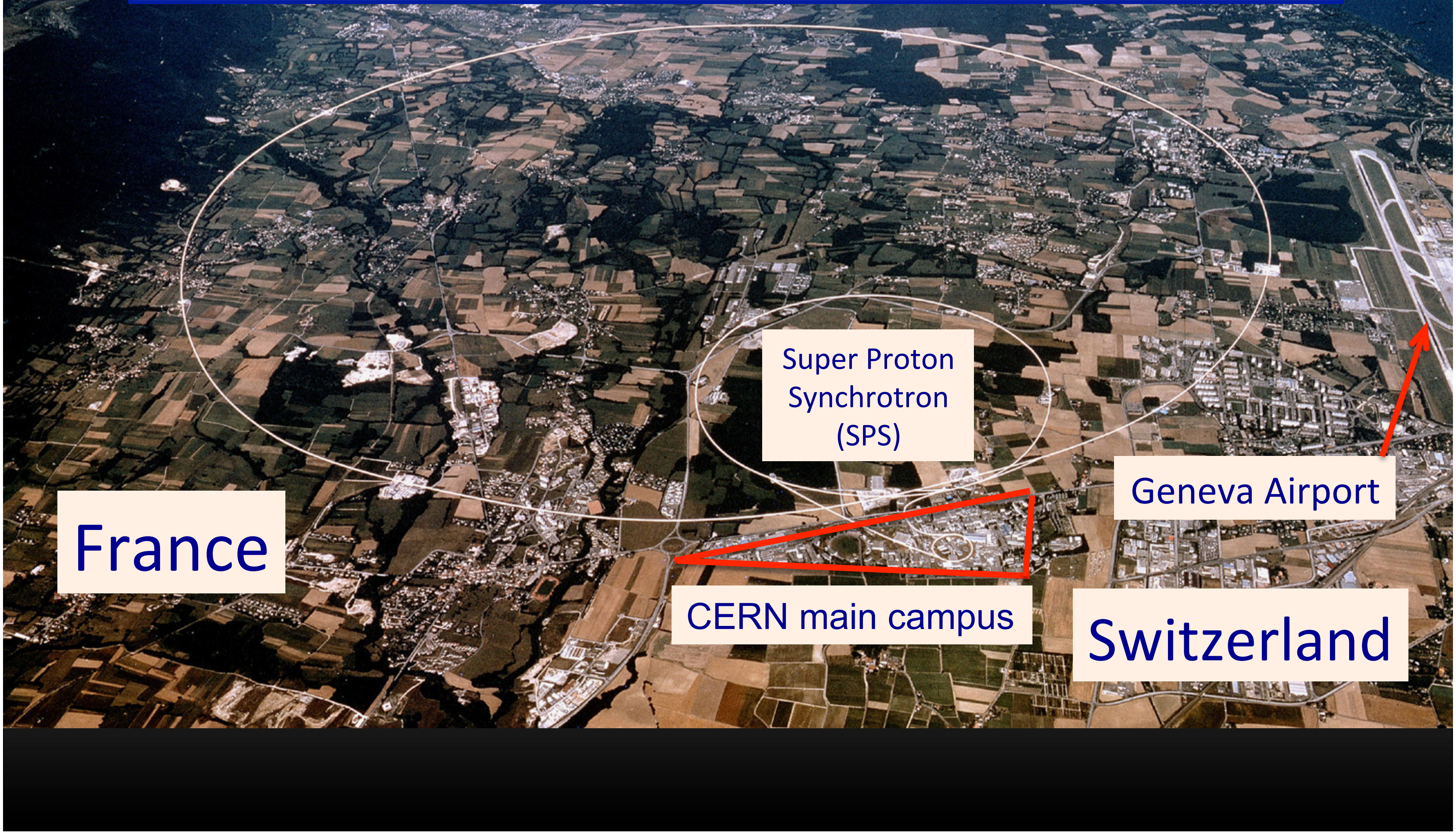
M. Papucci, J.T. Ruderman, and A. Weiler http://arxiv.org/abs/1110.6926



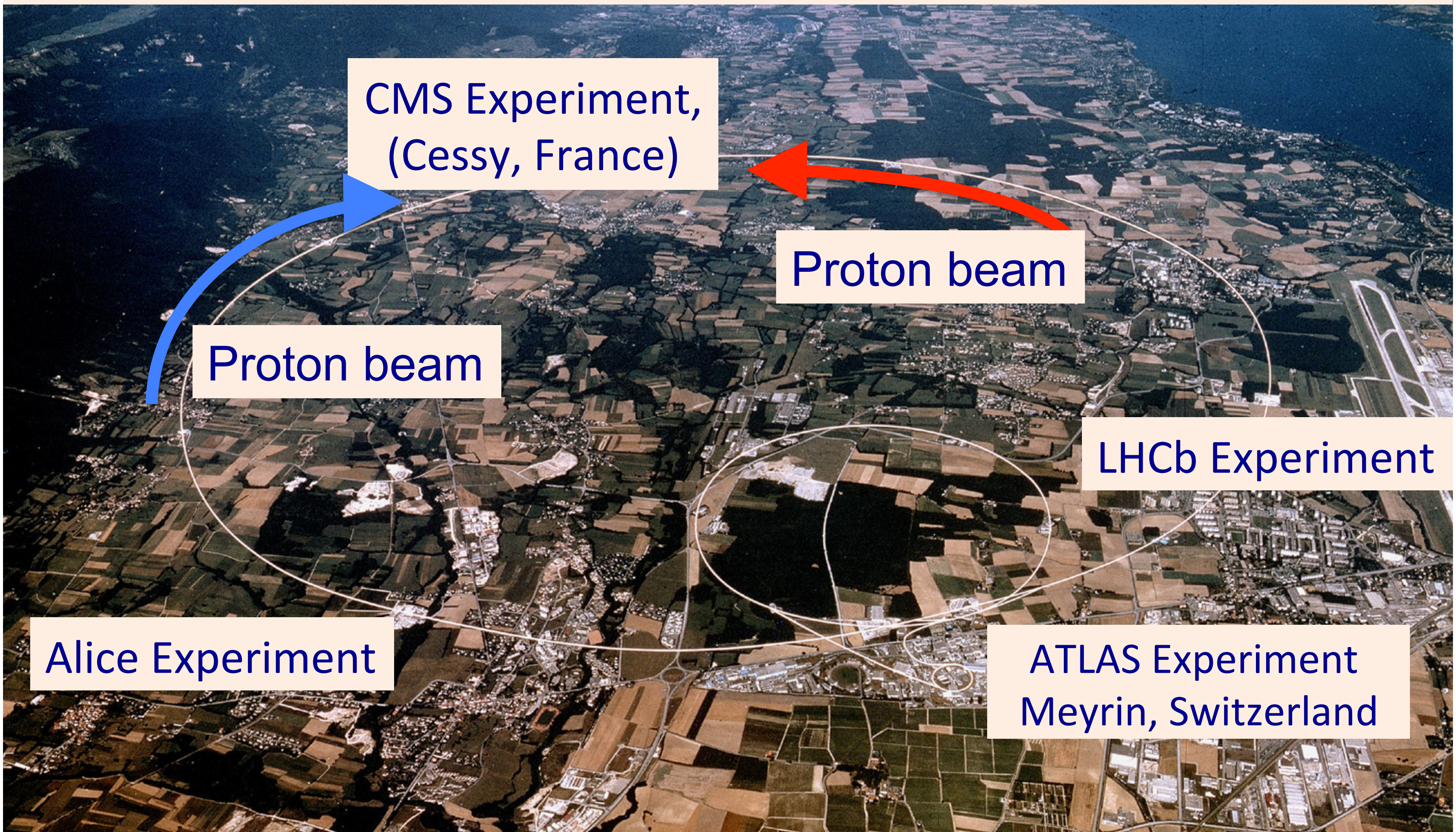
# Large Hadron Collider

C= 27 km (16.9 mi)

$E_{CM}$ = 2E(beam) = 8 TeV (Run 1), 13 TeV (Run 2)

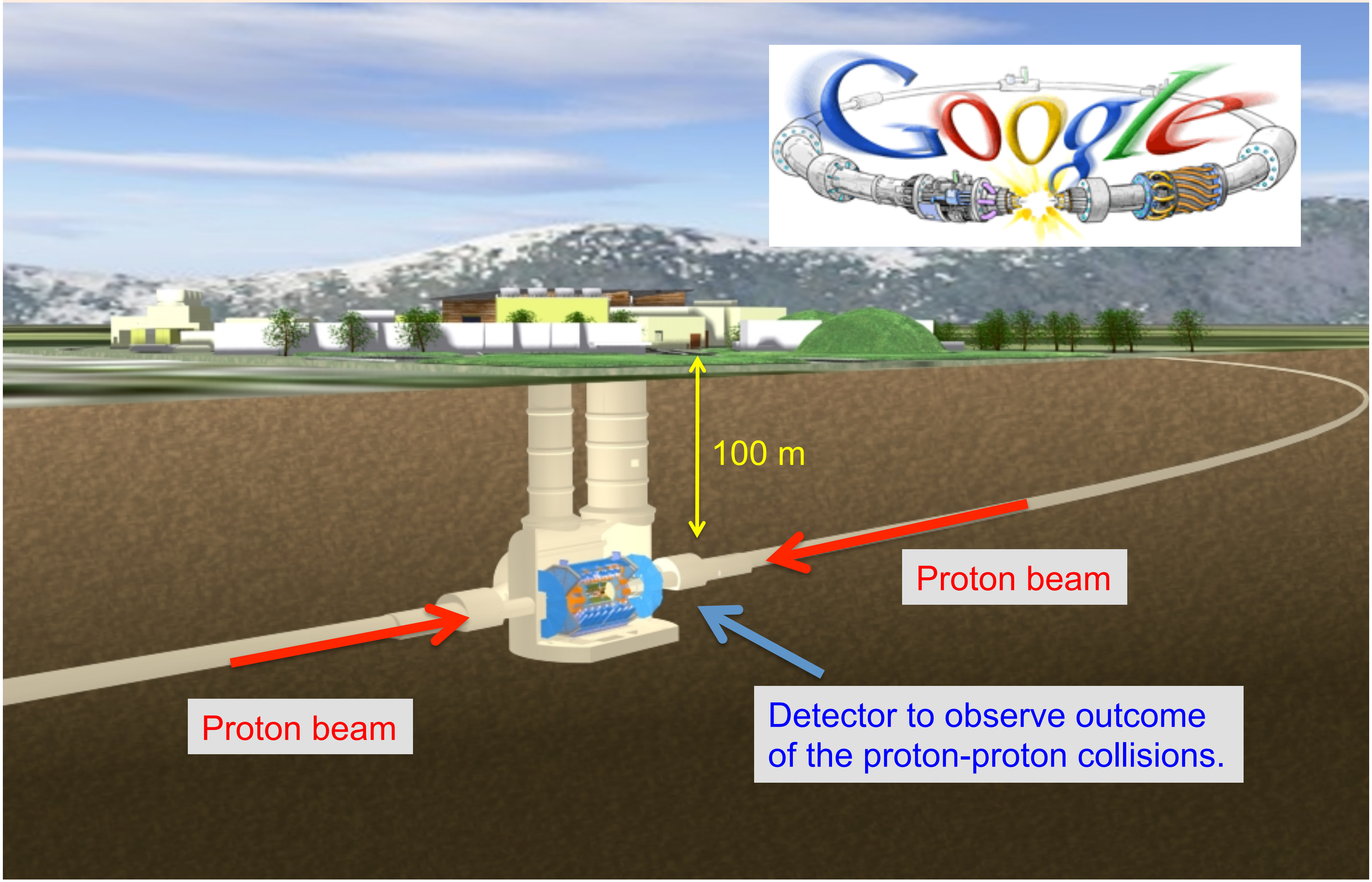


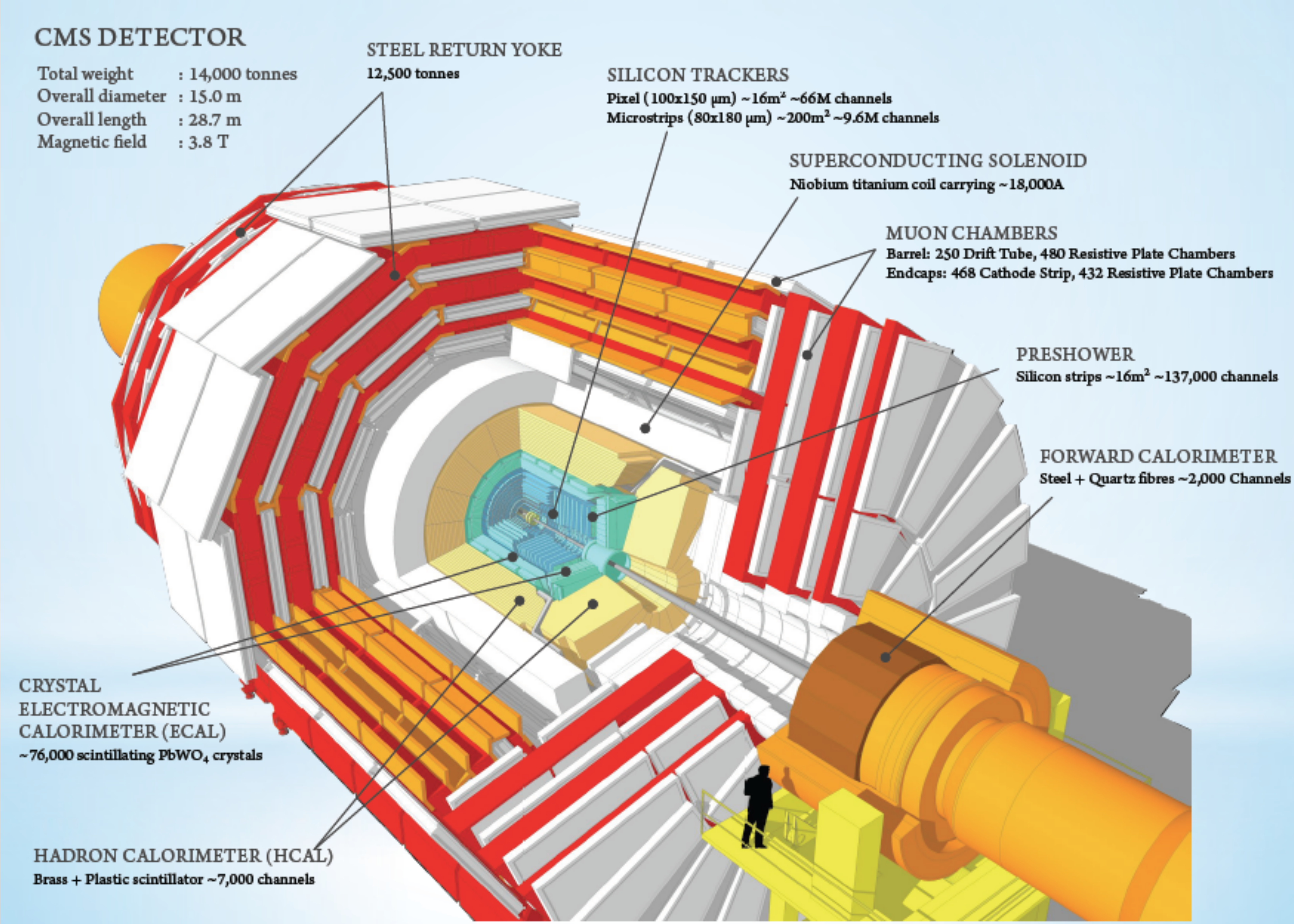
# LHC ring: 2 separate magnetic “highways”



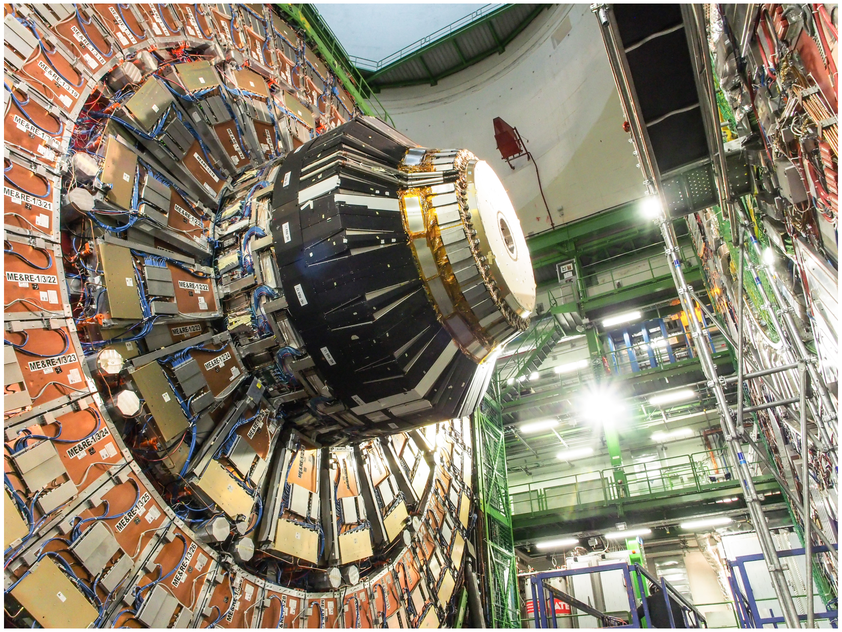

- 9300 magnets, including 1232 15-meter dipoles.
- Radio-frequency EM cavity devices to accelerate beams (8/beam; 40 MHz)

# LHC Interaction Region

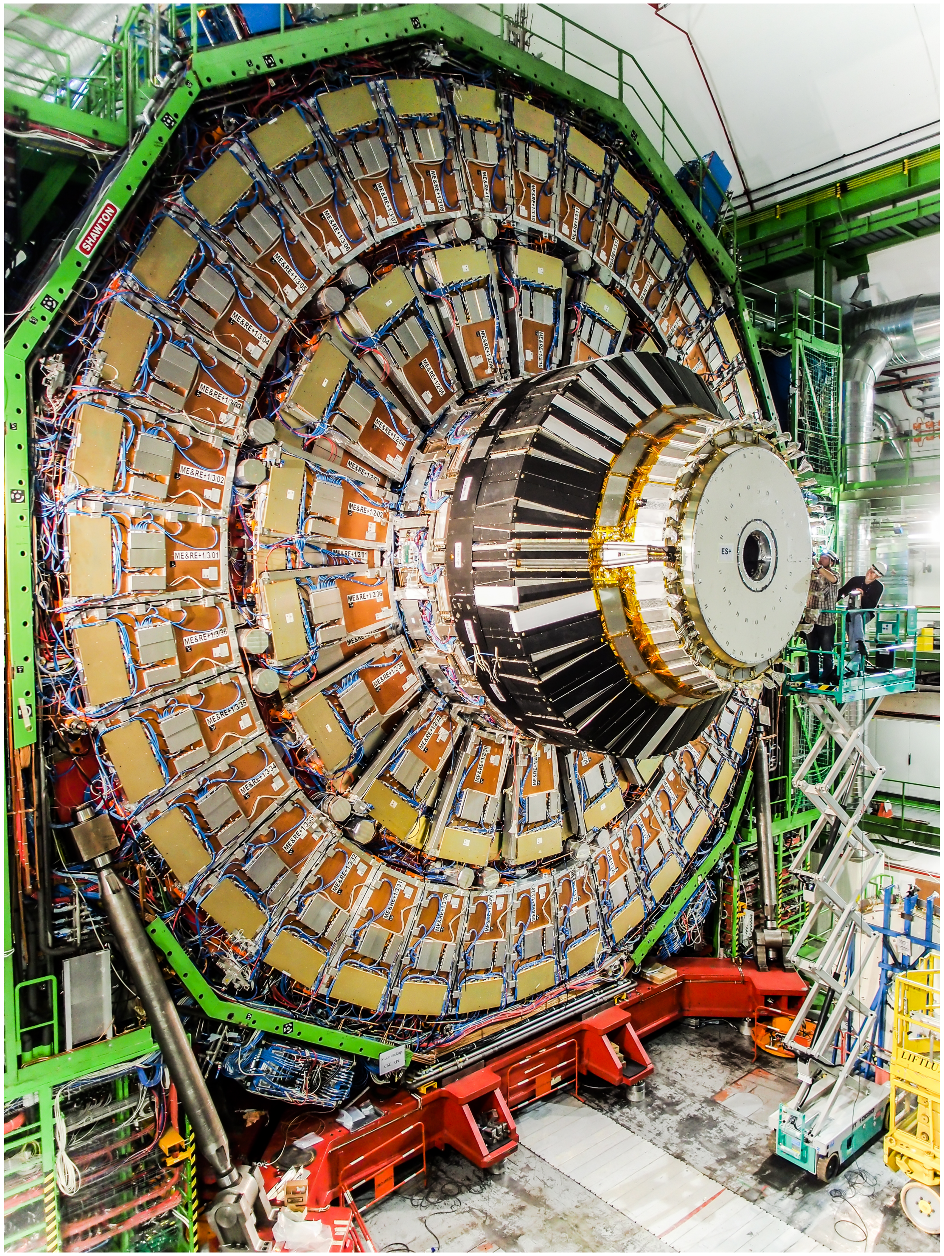


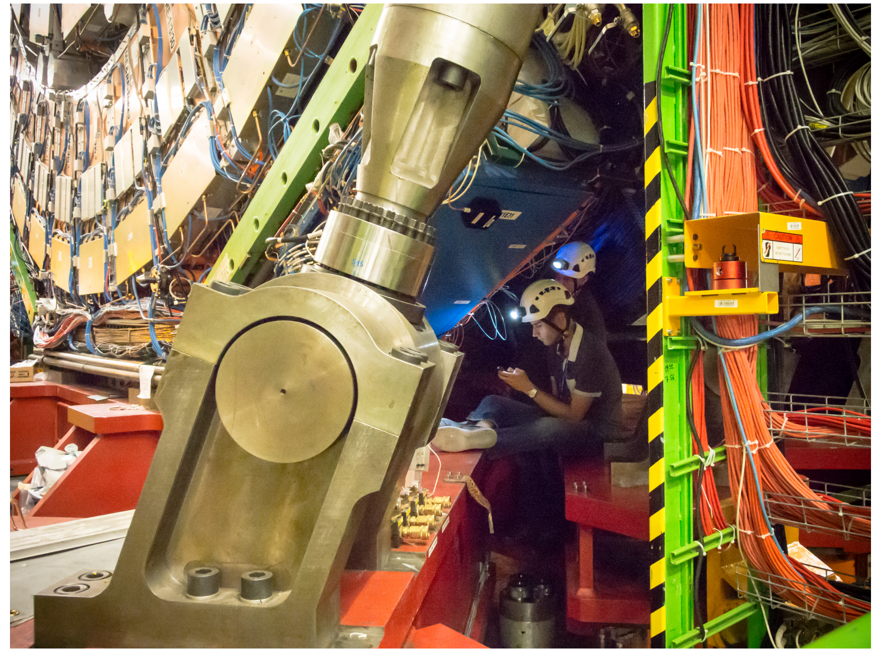

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

# Working on the CMS detector

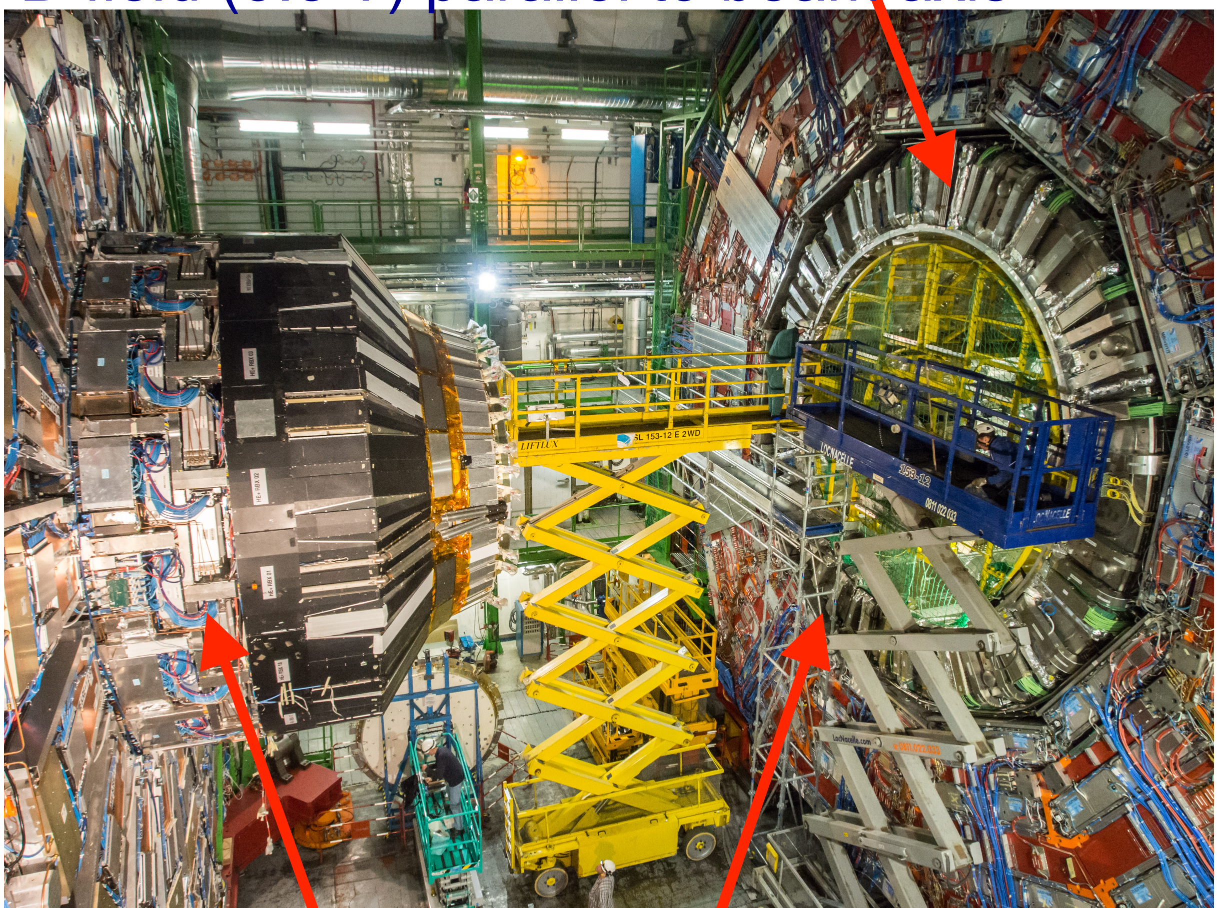
# Installing CMS muon readout electronics



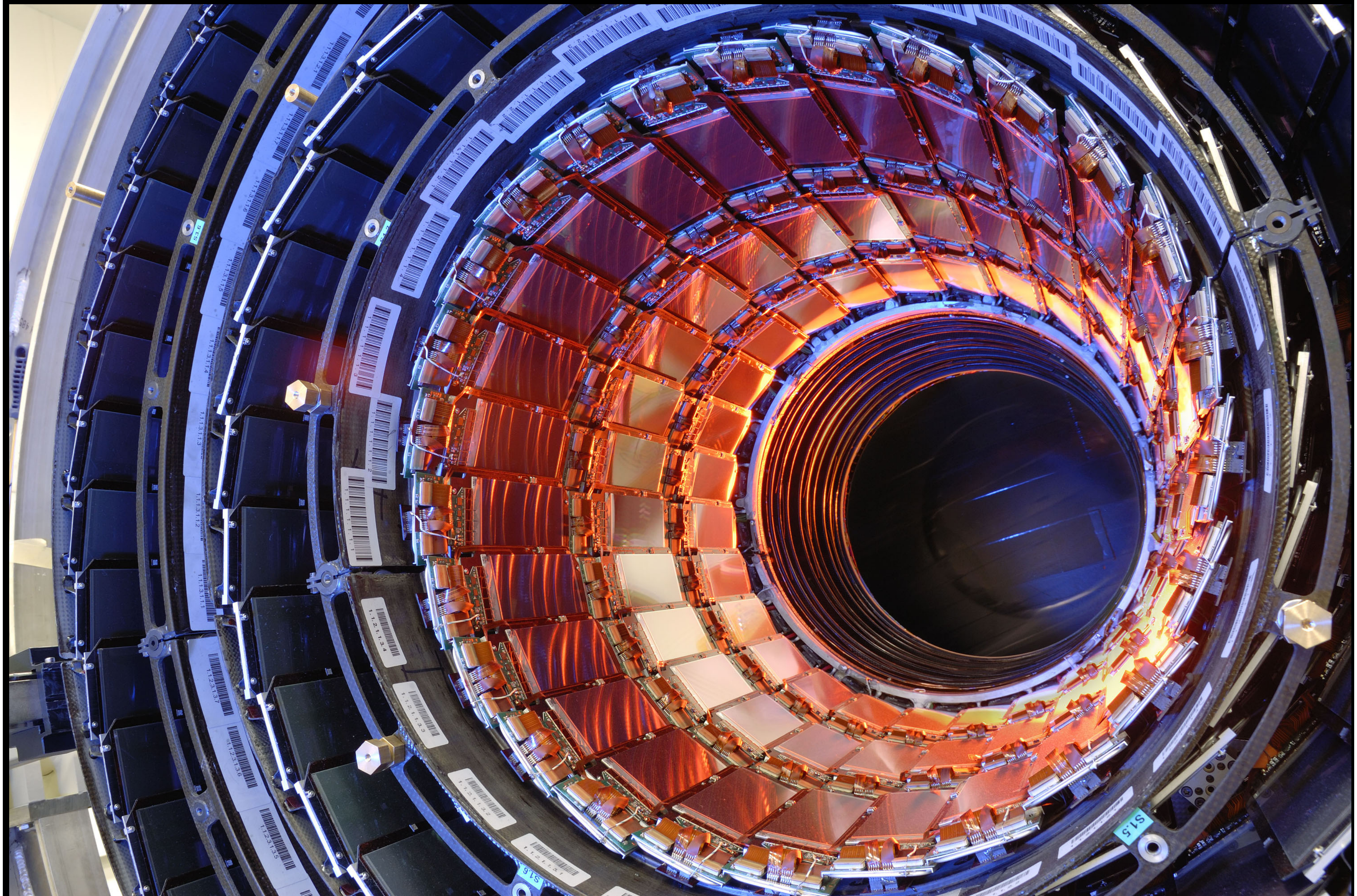
# Installing muon readout electronics

Superconducting solenoid (6m diameter):
B-field (3.8 T) parallel to beam axis




Endcap detectors    Central barrel detectors

# CMS Silicon-Strip Tracker Inner Barrel Detector

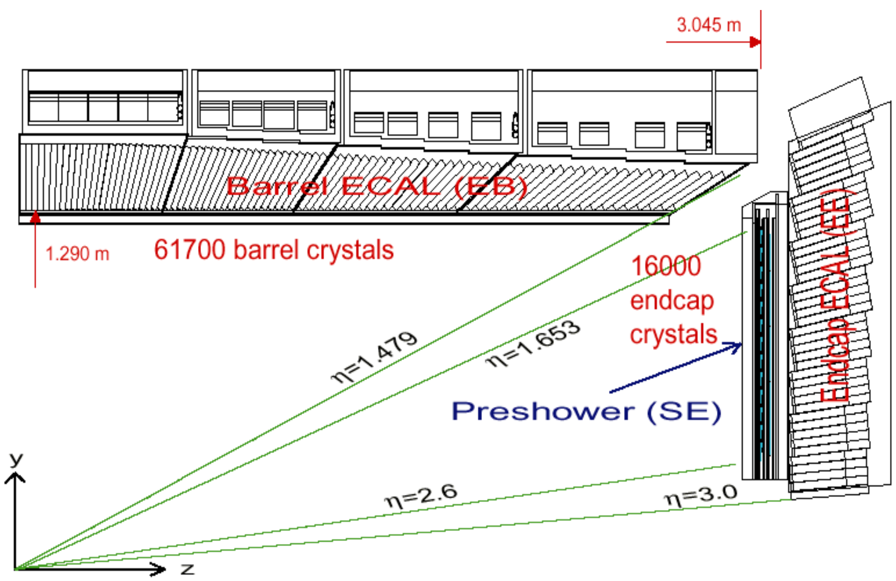


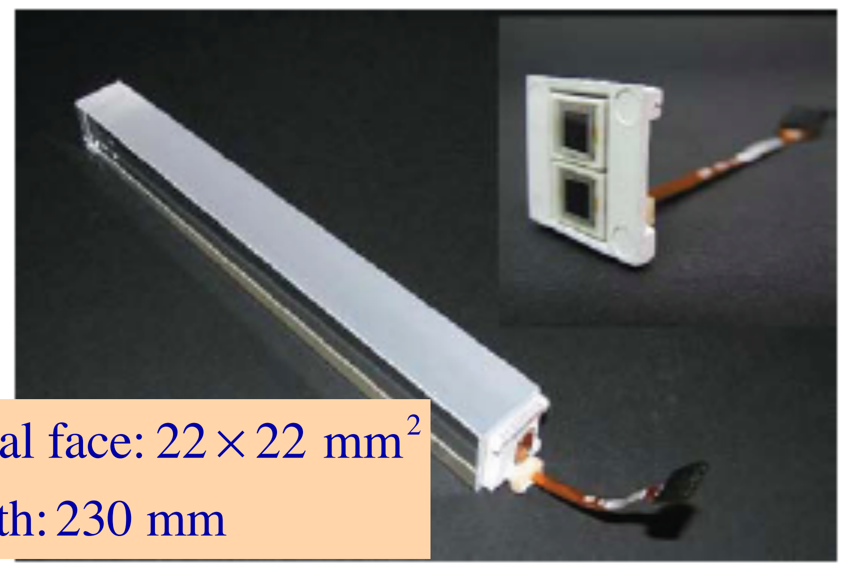
# CMS Electromagnetic Calorimeter (ECAL)

- Barrel/Endcap: 61,200 / 2×7,324 $PbWO_4$ crystals
- Rad-hard, very fast (80% of light in 25 ns)
- 25.8 and 24.7 $X_0$; about 1 $\lambda_0$ ($X_0$ = 0.89 cm)
- Barrel inner radius: 129 cm (operates in B field!)
- Low light yield (30 γ/MeV); use avalanche photodiodes
- Coverage: |η|<1.479 (barrel), 1.479<|η|<3.0 (endcap)

$$\frac{\sigma_E}{E} \approx 0.8\% - 0.4\%$$

$$(E \approx 25 - 200 \text{ GeV})$$



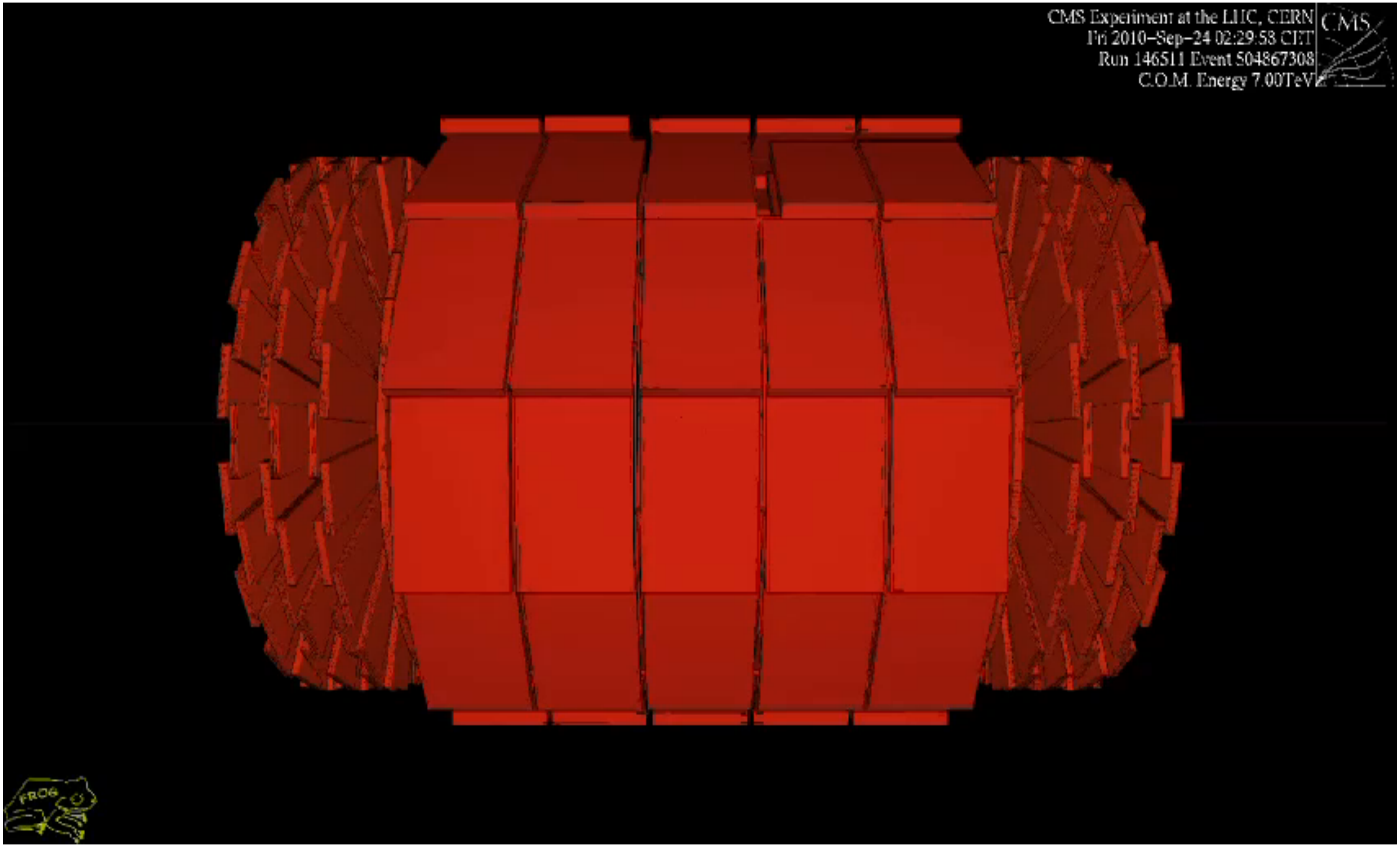



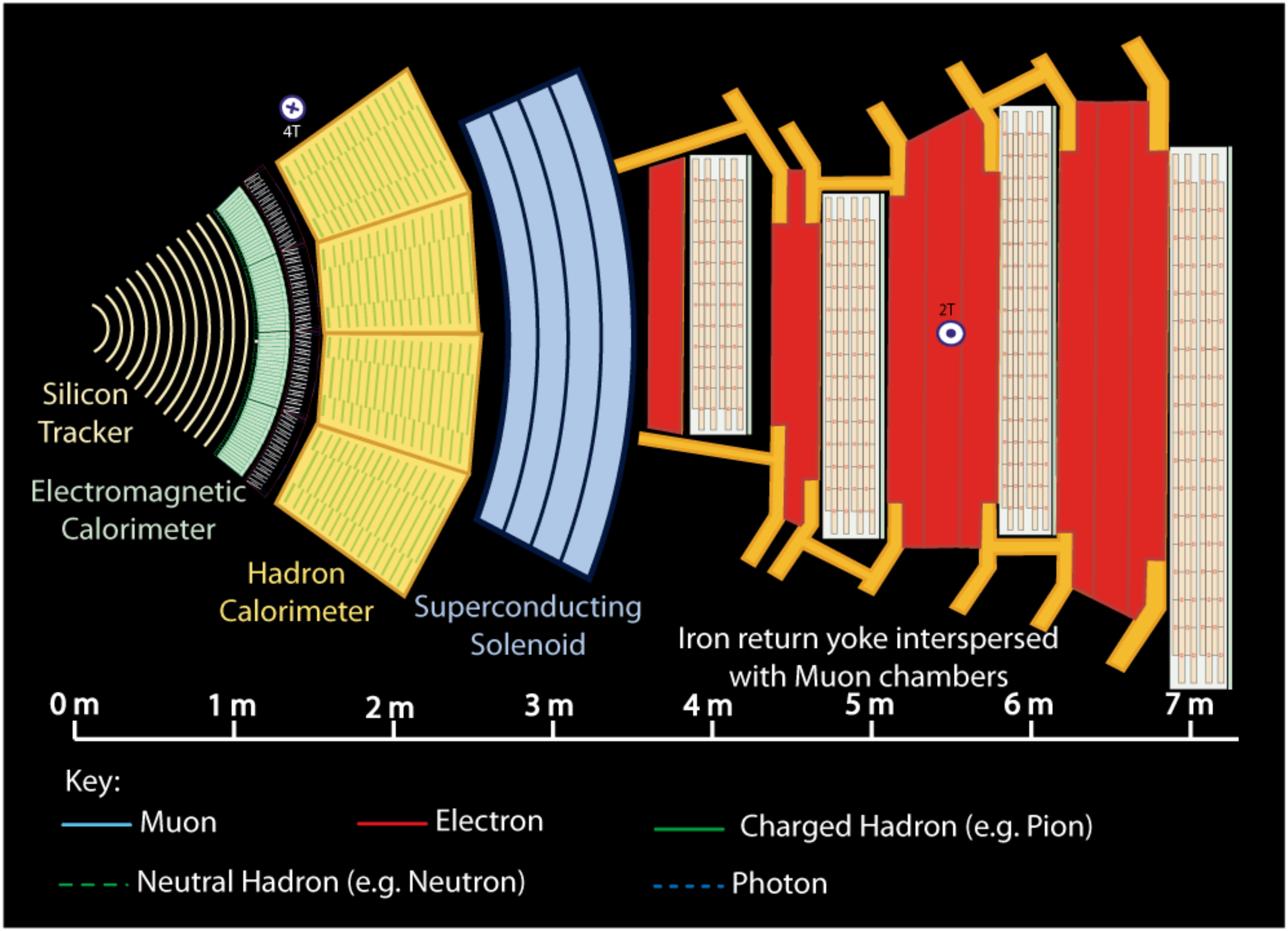
Crystal face: $22 \times 22$ mm$^2$

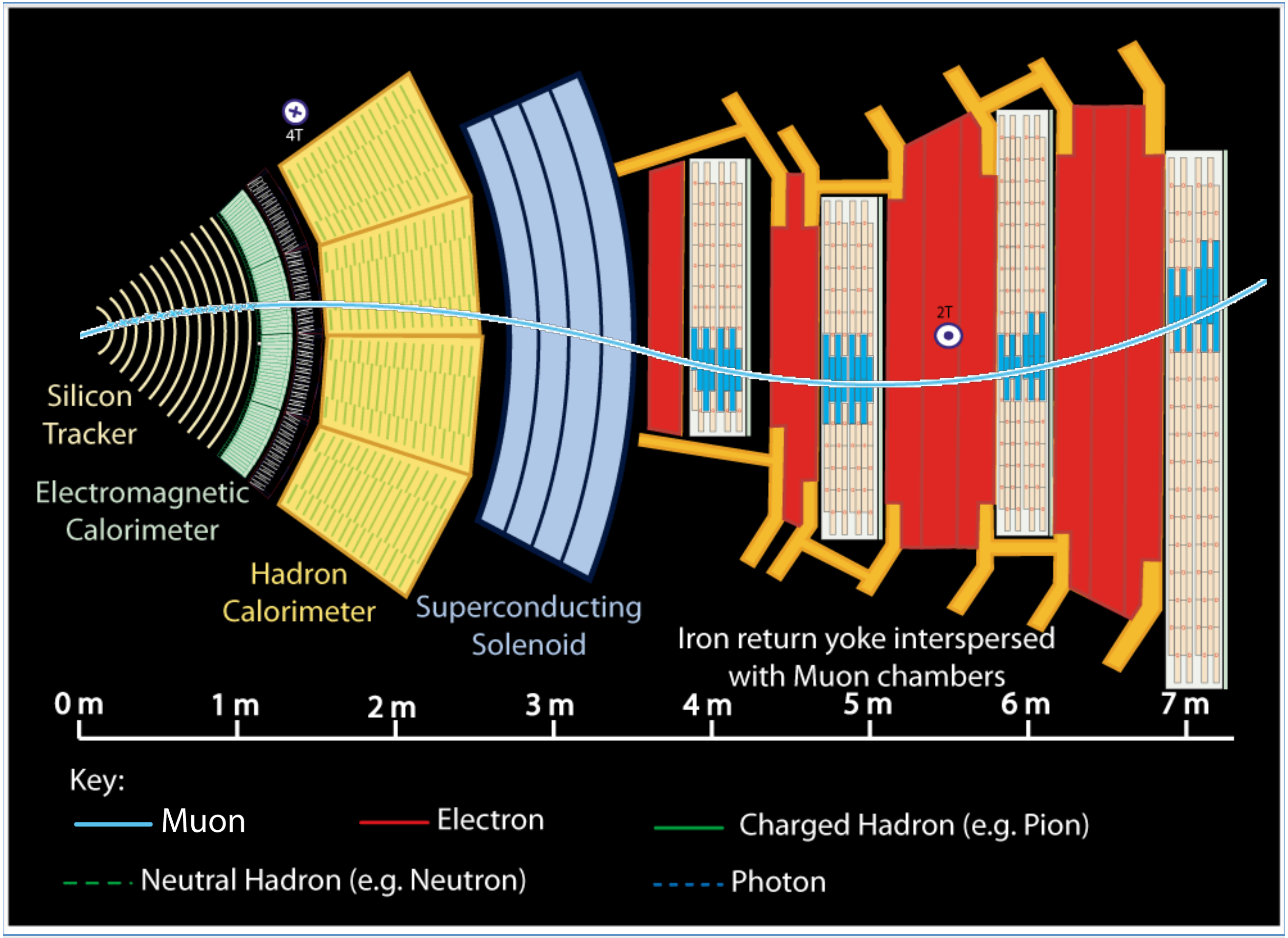
Length: 230 mm

# Beam Pipe at LHC Point 5

# Proton-proton collision in CMS: animation




4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



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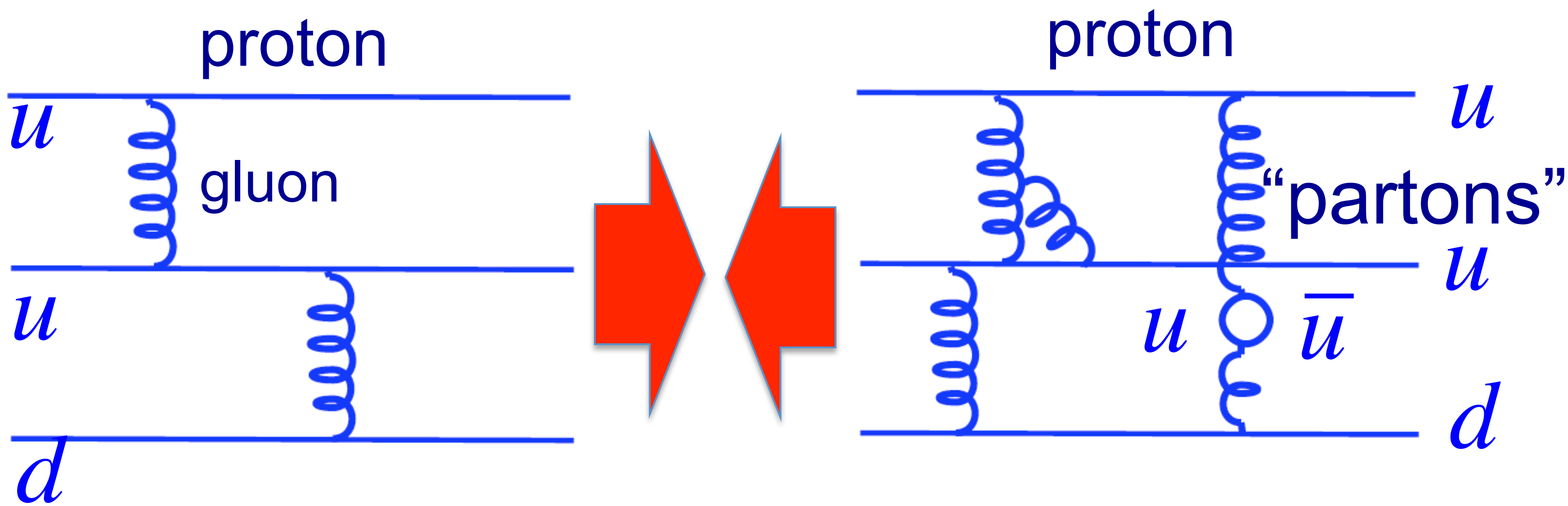
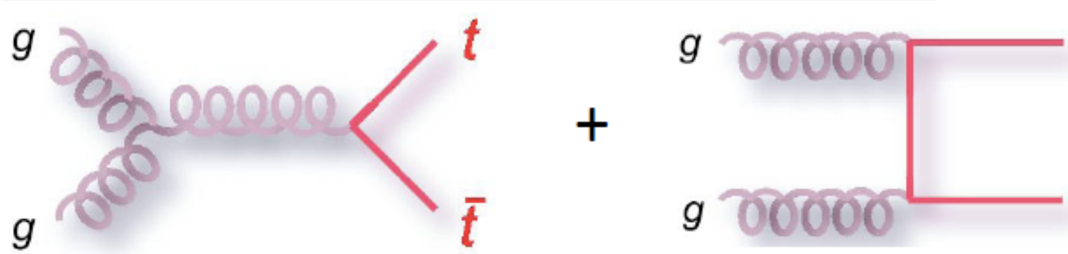
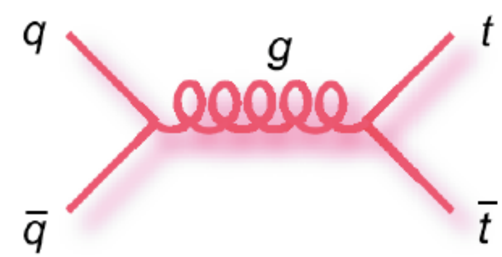
# Proton-proton collisions




Top-quark pair production via gluon-gluon fusion.

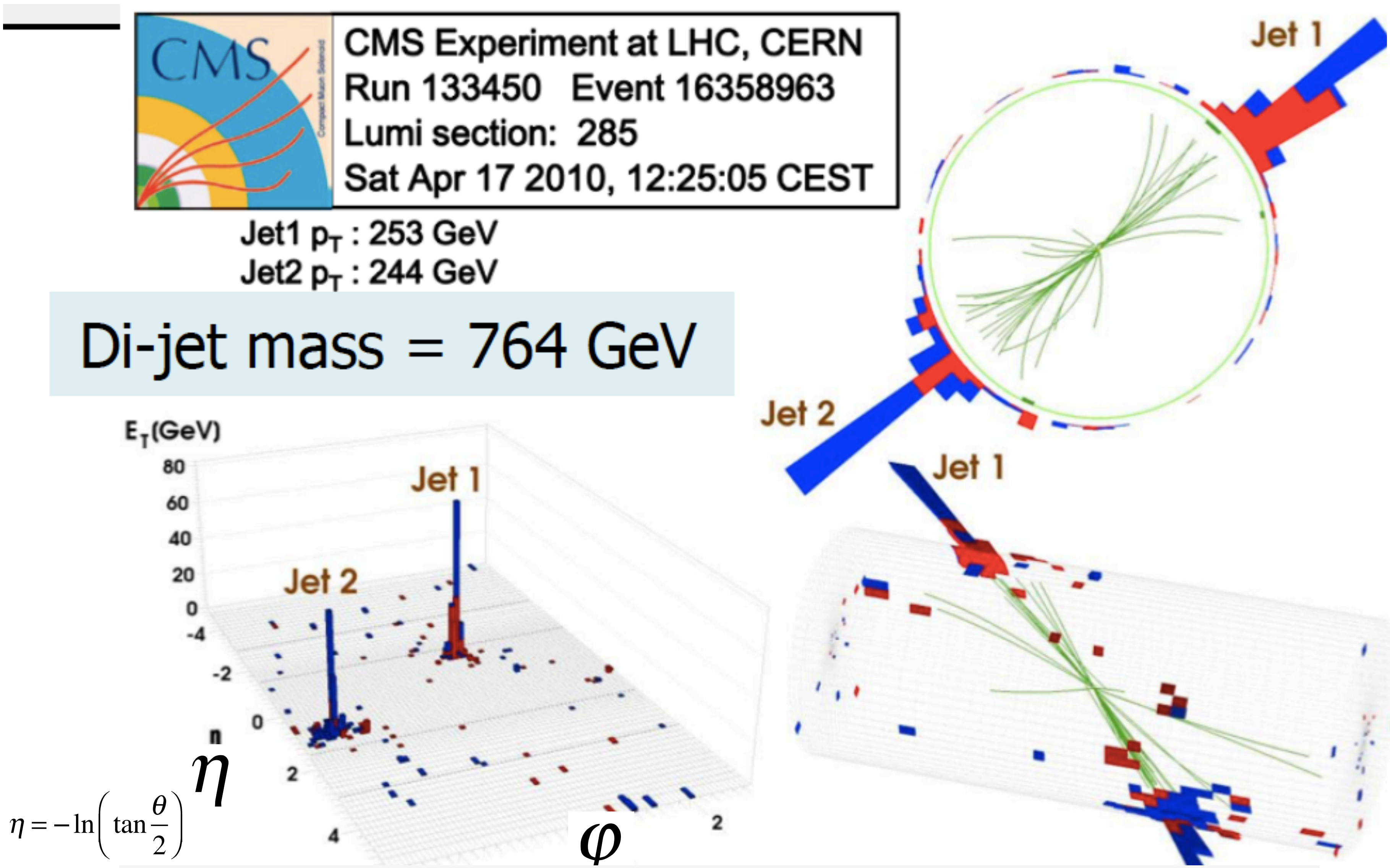
Top-quark pair production via quark-antiquark annihilation.



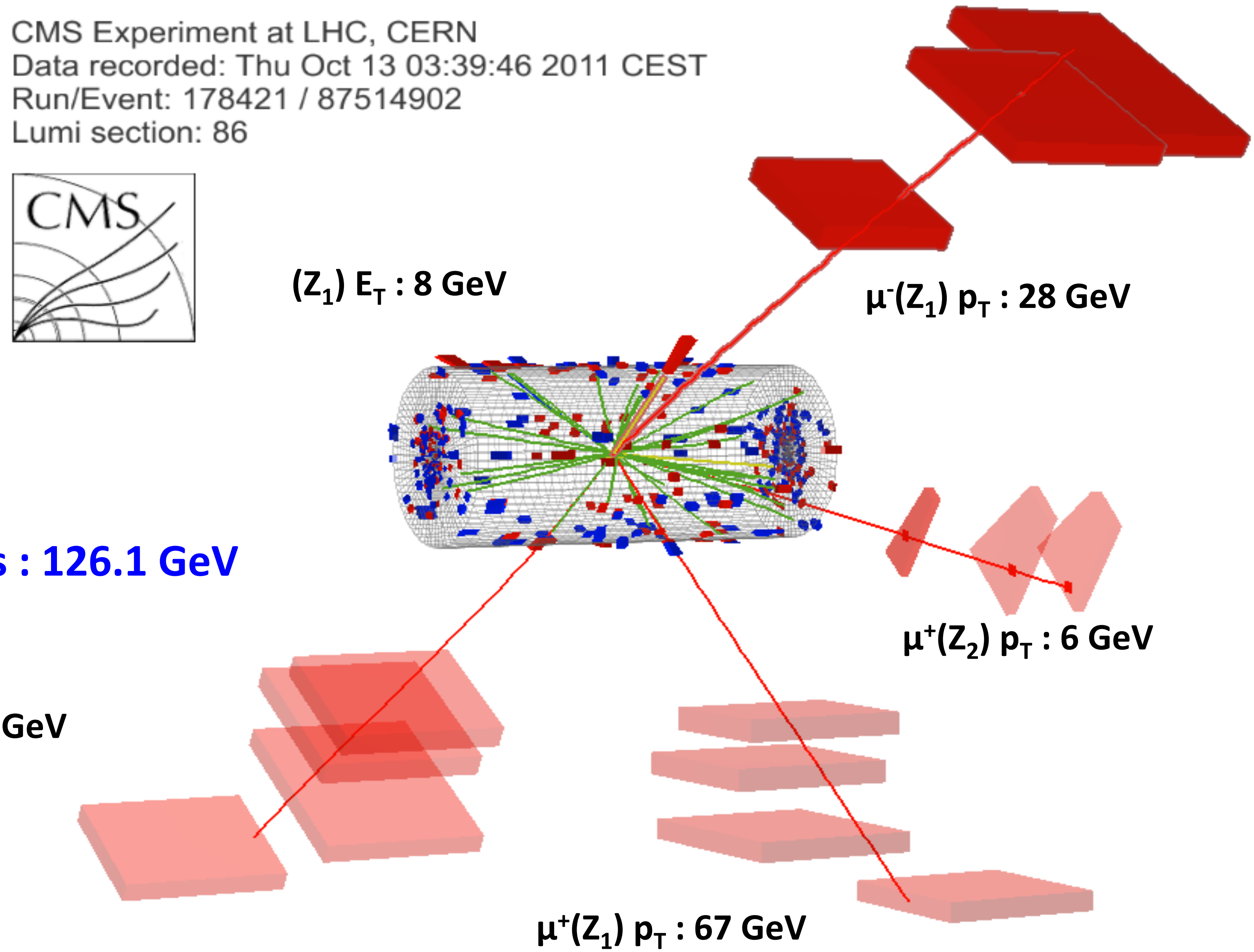

Broad range of CM energies for parton-parton collision.
A priori, we don't know the Lorentz boost to this rest frame!

# Huge QCD cross section: pp → jets




**Jet pT resolution: 15% for pT=10 GeV, 8% for pT =100 GeV, 4% for pT= 1 TeV**

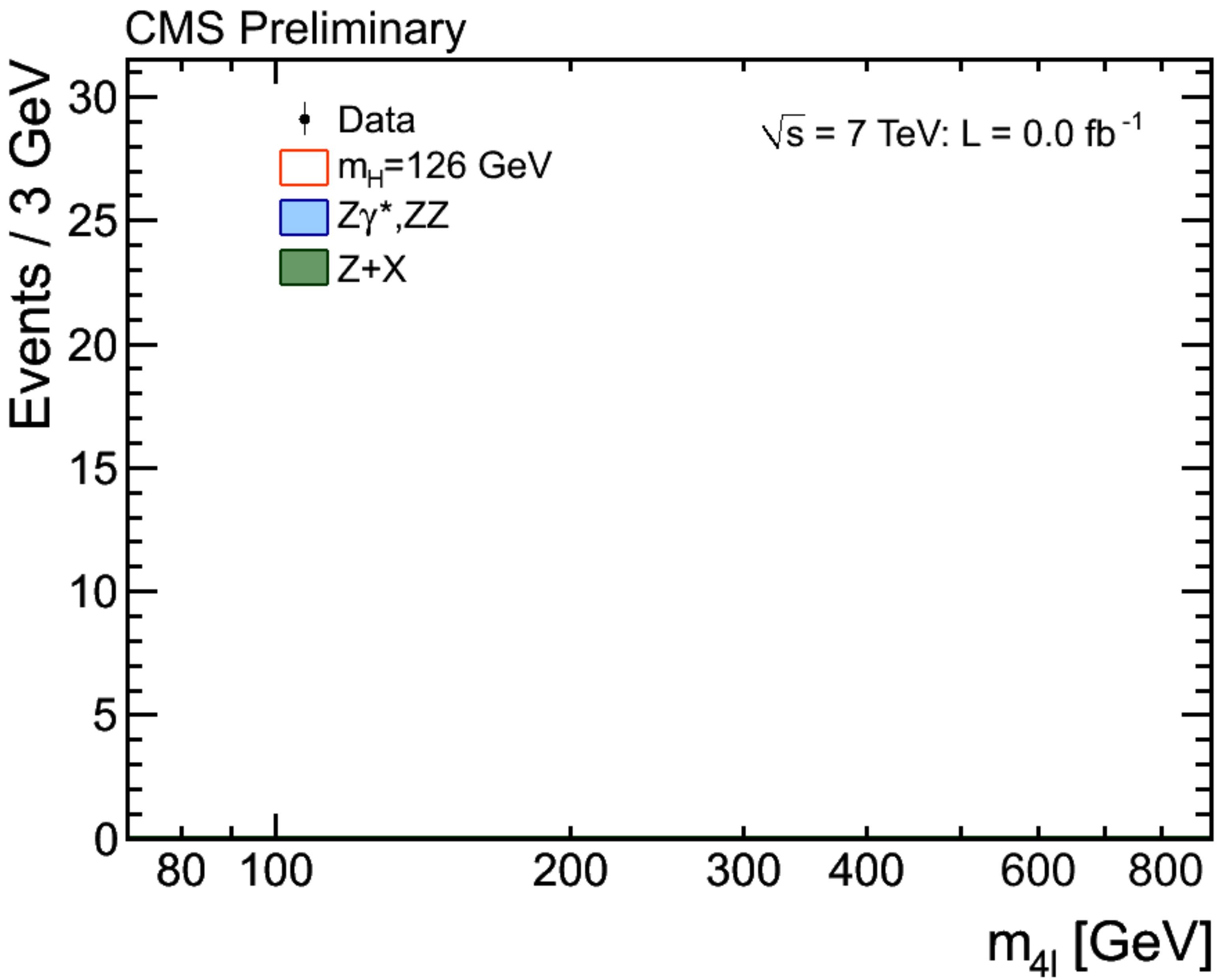
# H→ ZZ*, Z→$\mu^+\mu^-$ , Z*→$\mu^+\mu^-$




**7 TeV DATA**

**4μ+γ Mass : 126.1 GeV**

# Higgs boson → two Z bosons → 4 leptons



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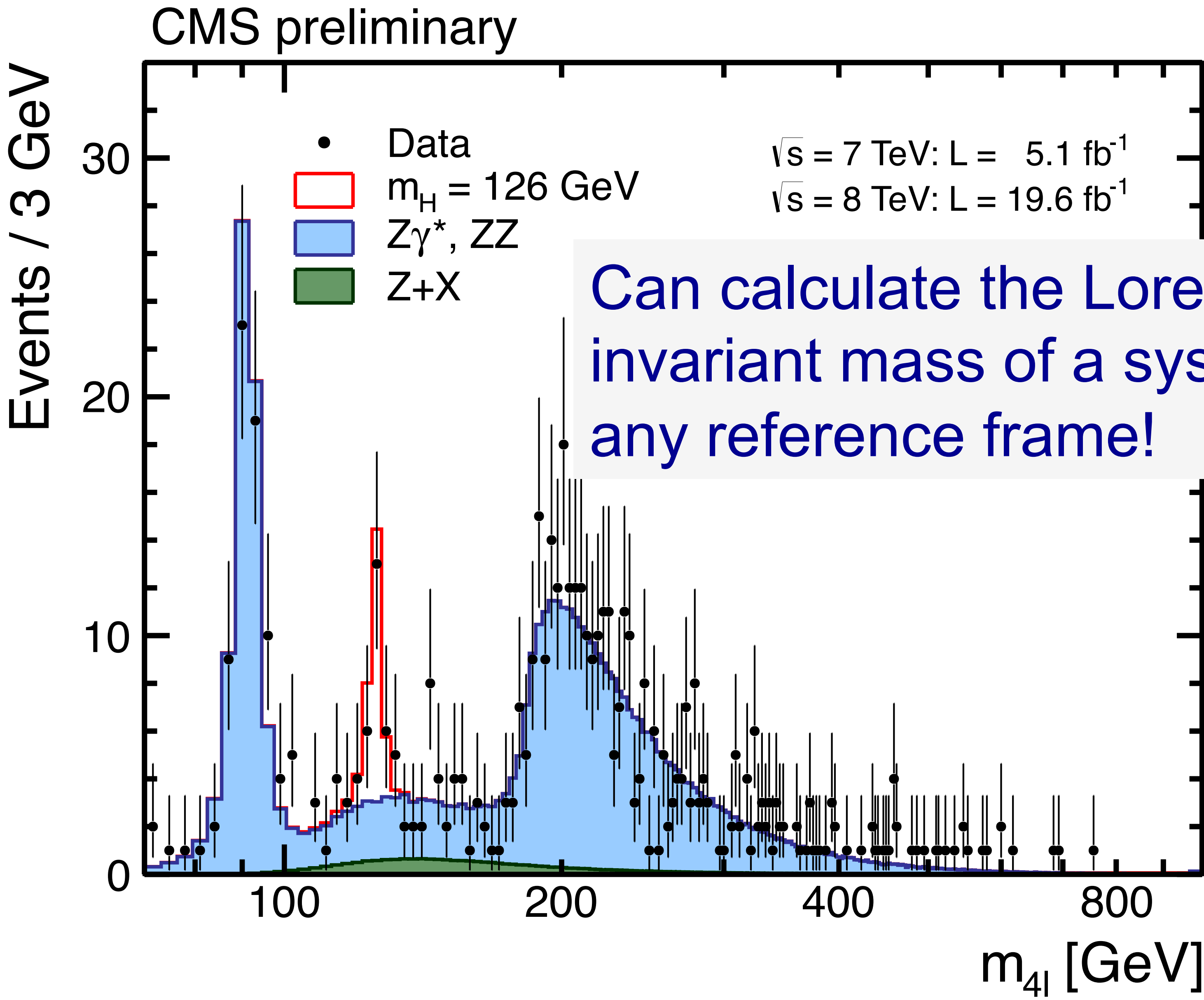
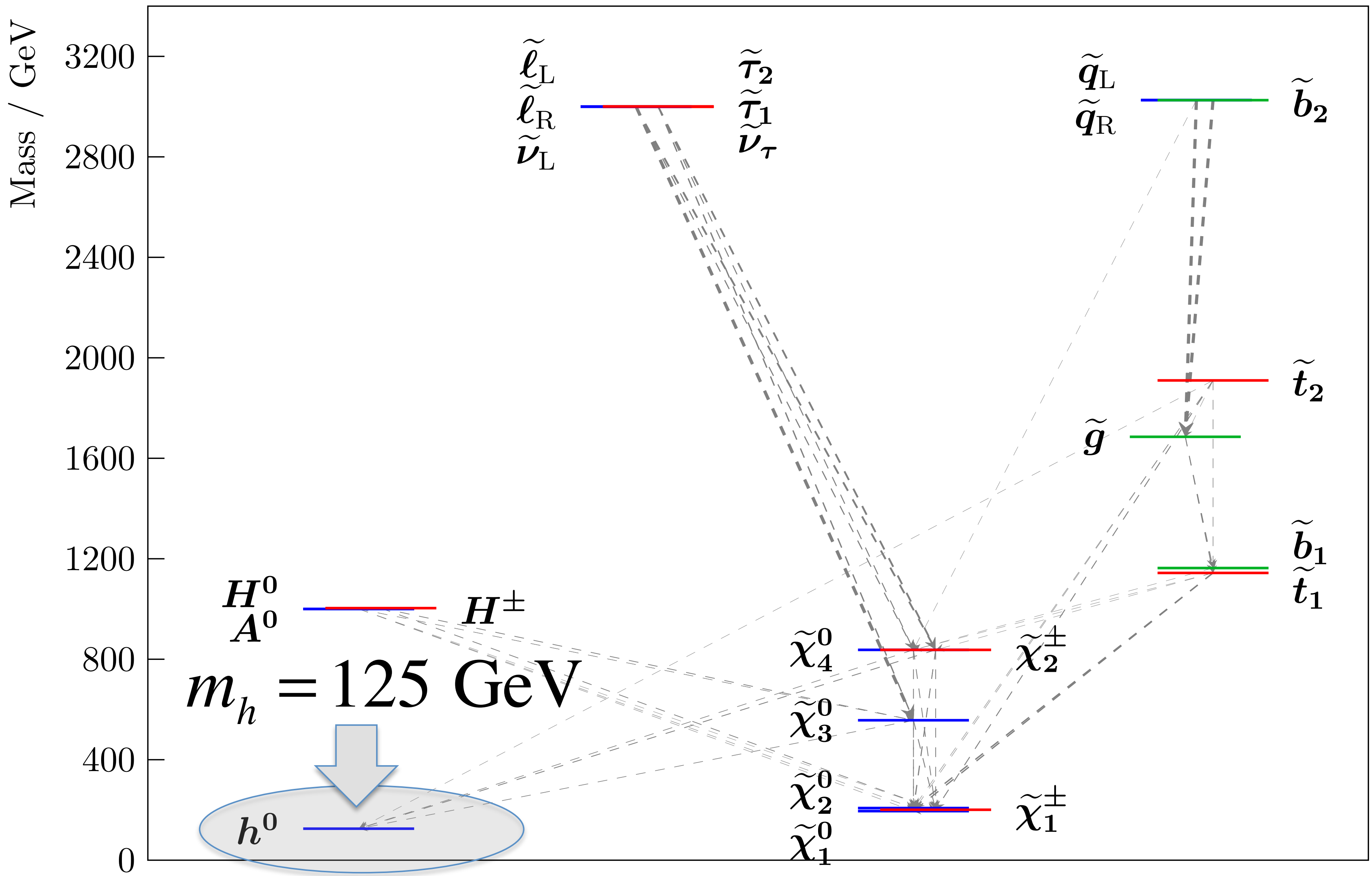



Can calculate the Lorentz-invariant mass of a system in any reference frame!

# An example of a "natural" SUSY model ("NM3")



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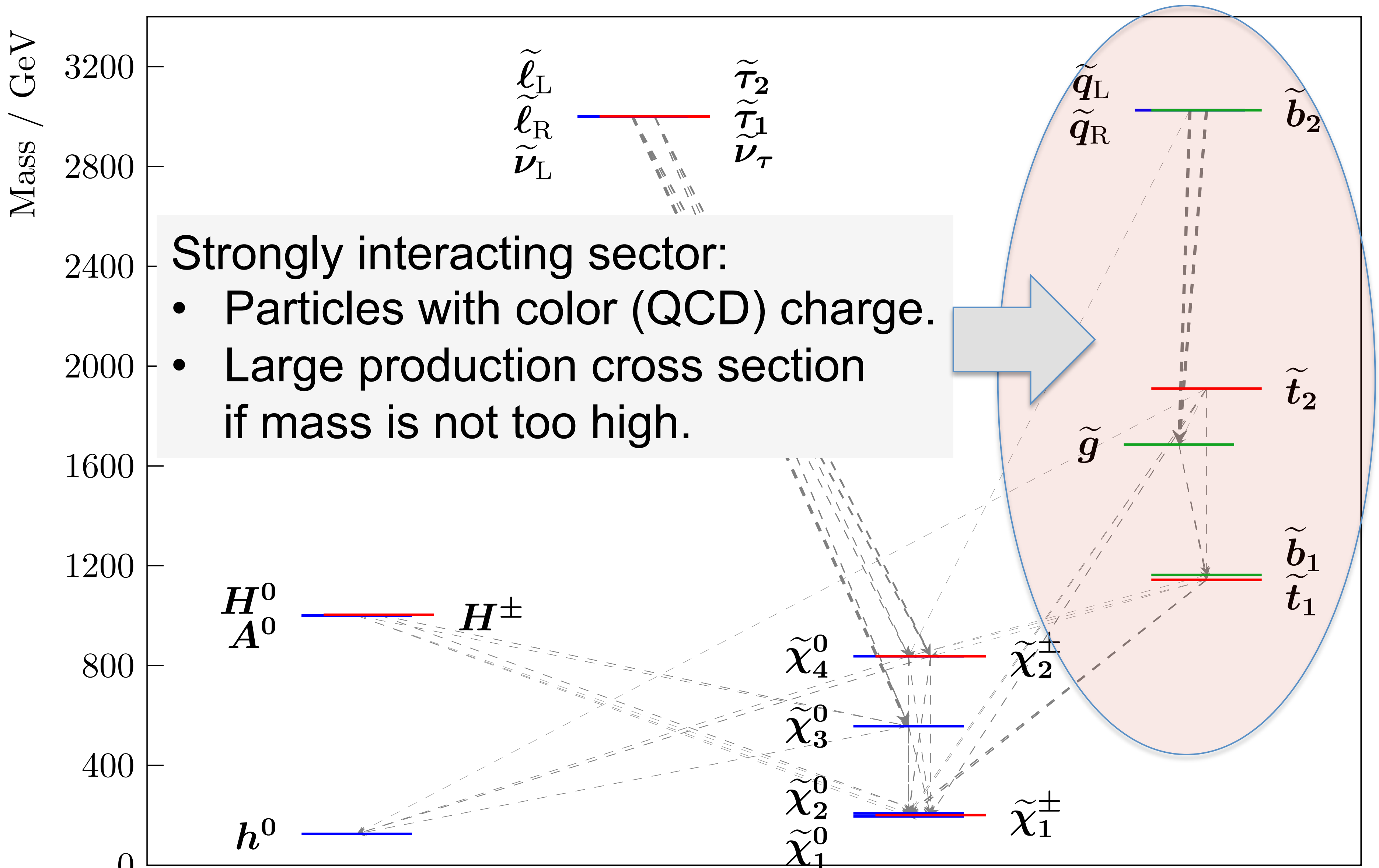
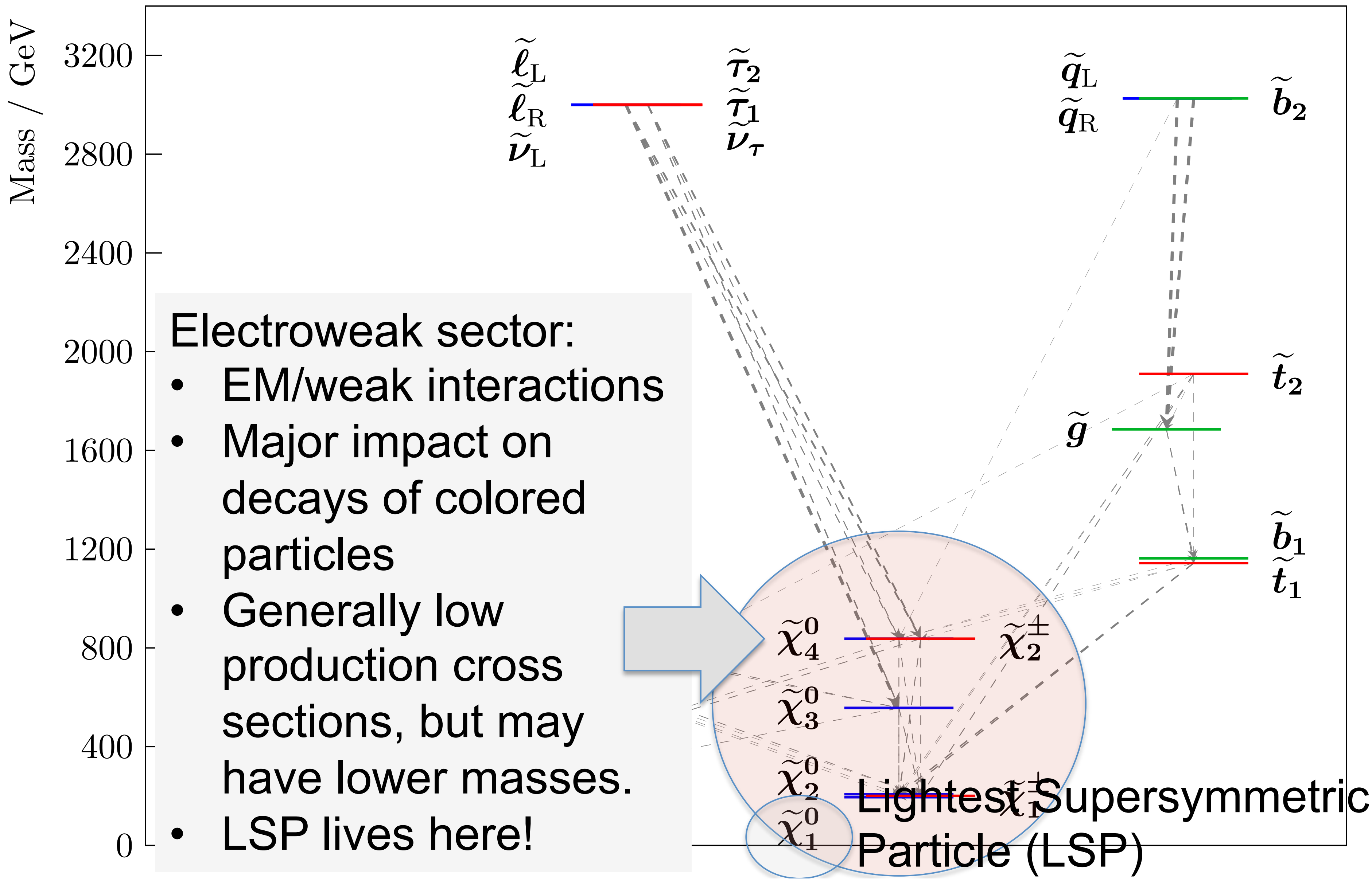


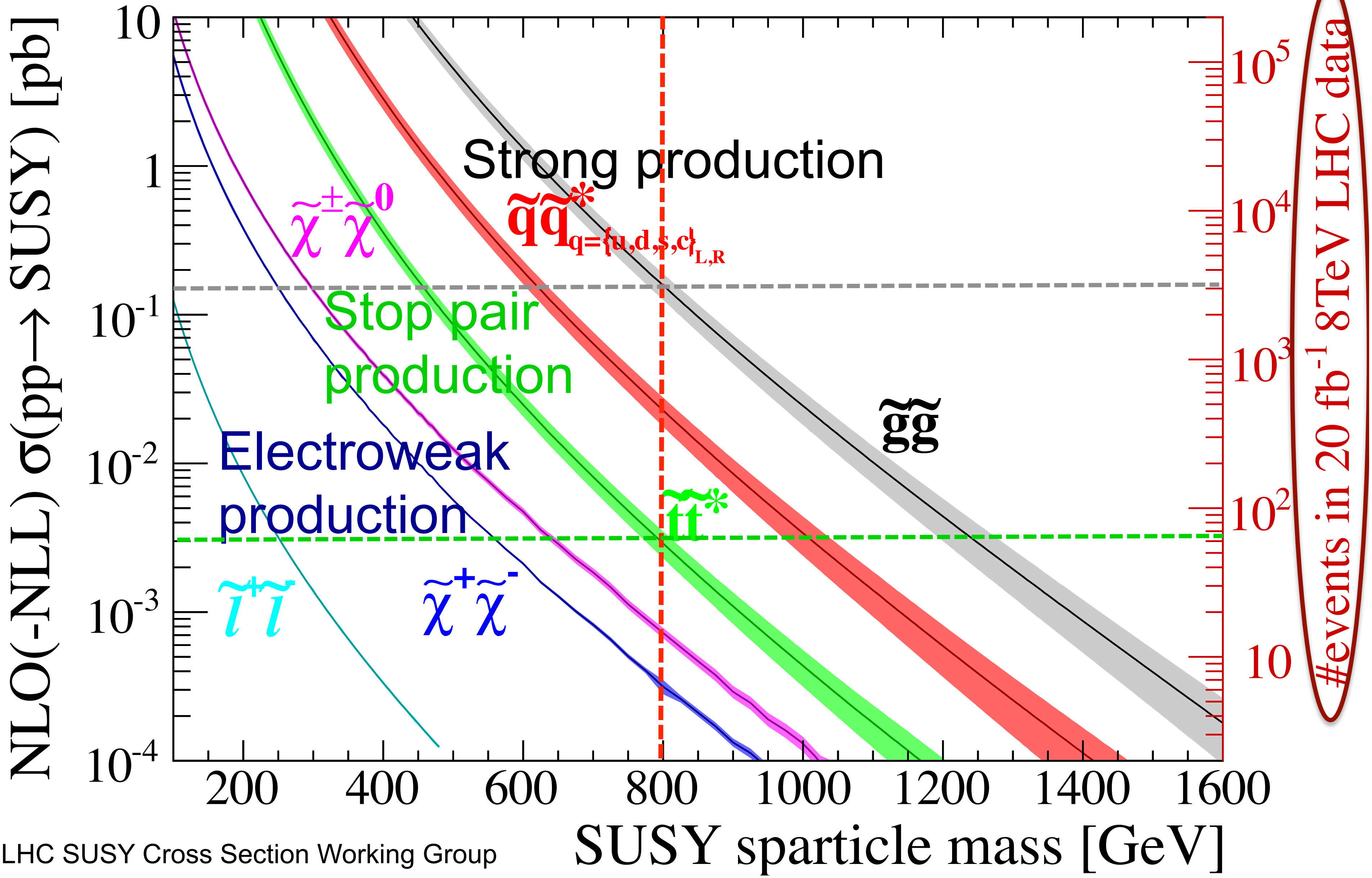
# An example of a “natural” SUSY model (“NM3”)




Electroweak sector:

- EM/weak interactions
- Major impact on decays of colored particles
- Generally low production cross sections, but may have lower masses.
- LSP lives here!

# Big themes: production and decays

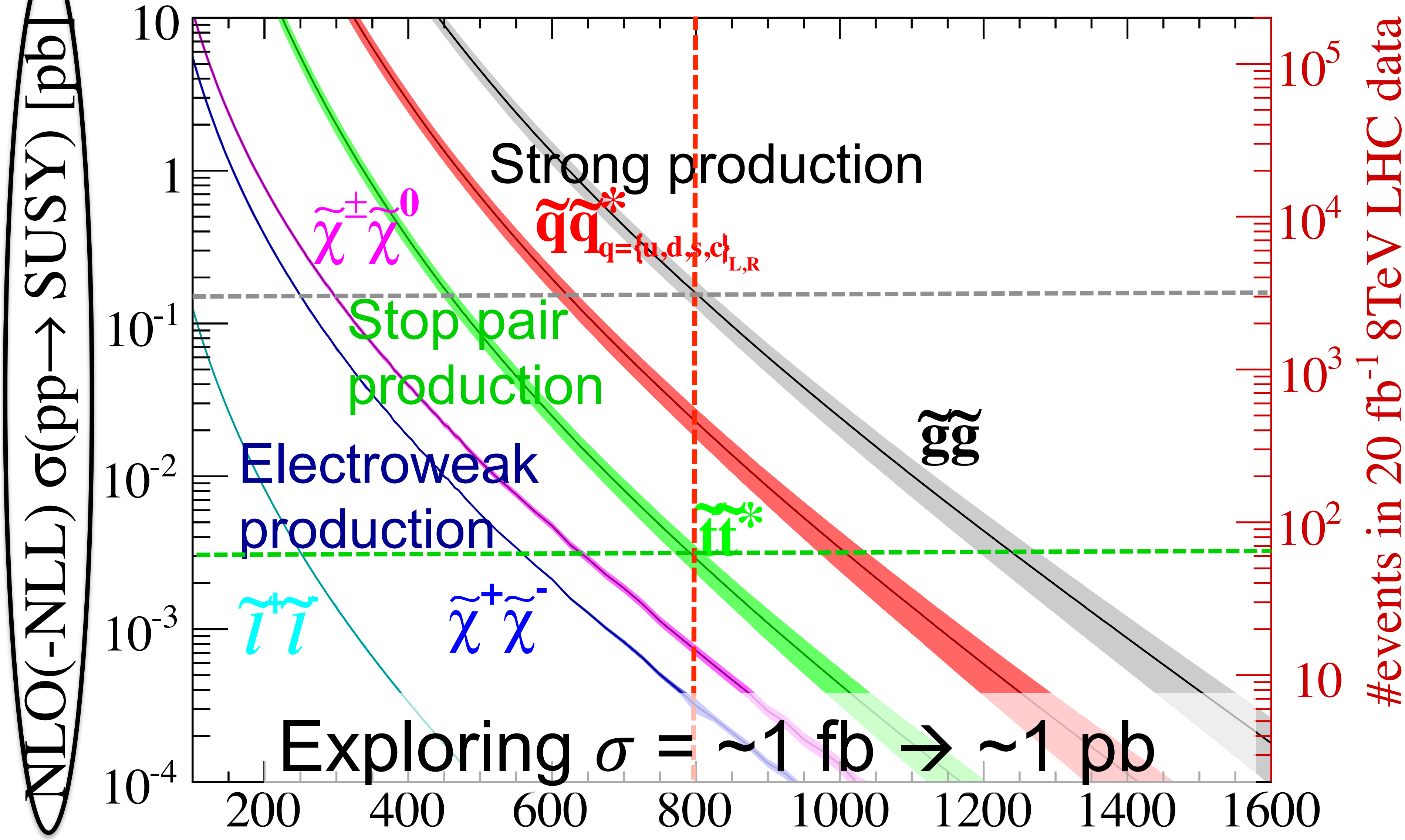



LHC SUSY Cross Section Working Group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections

arXiv:1206.2892

# Big themes: production and decays

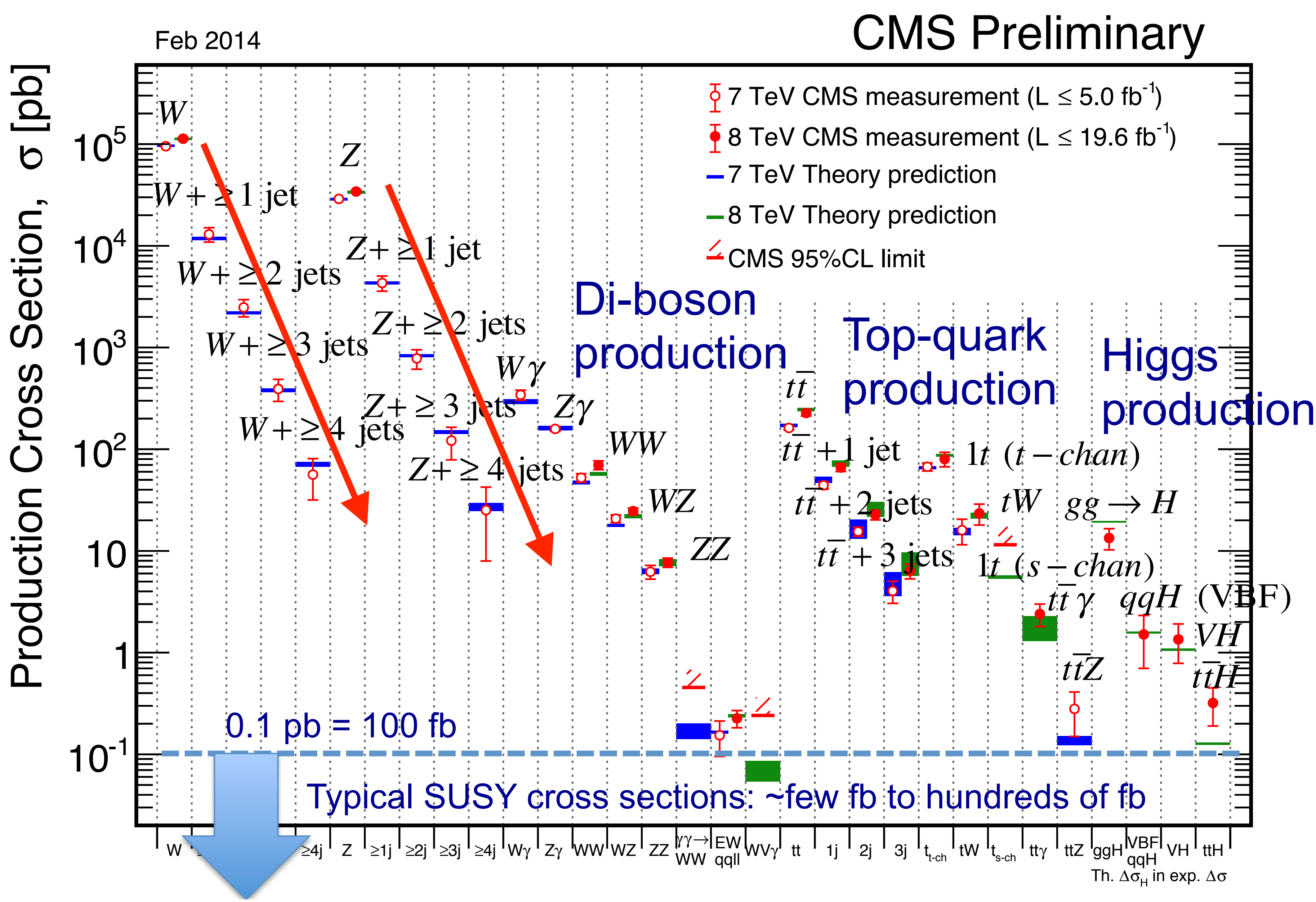



LHC SUSY Cross Section Working Group

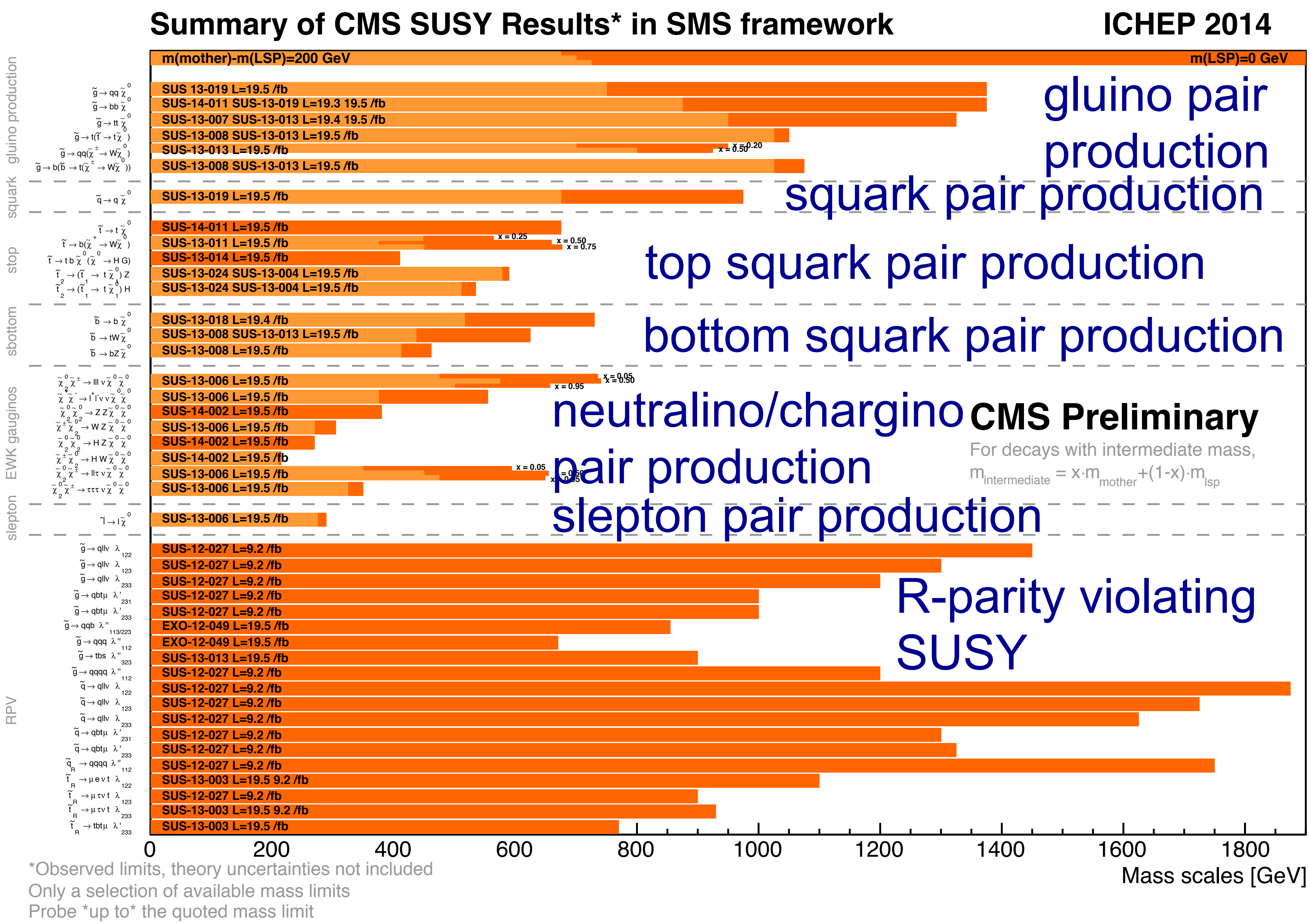
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections

arXiv:1206.2892

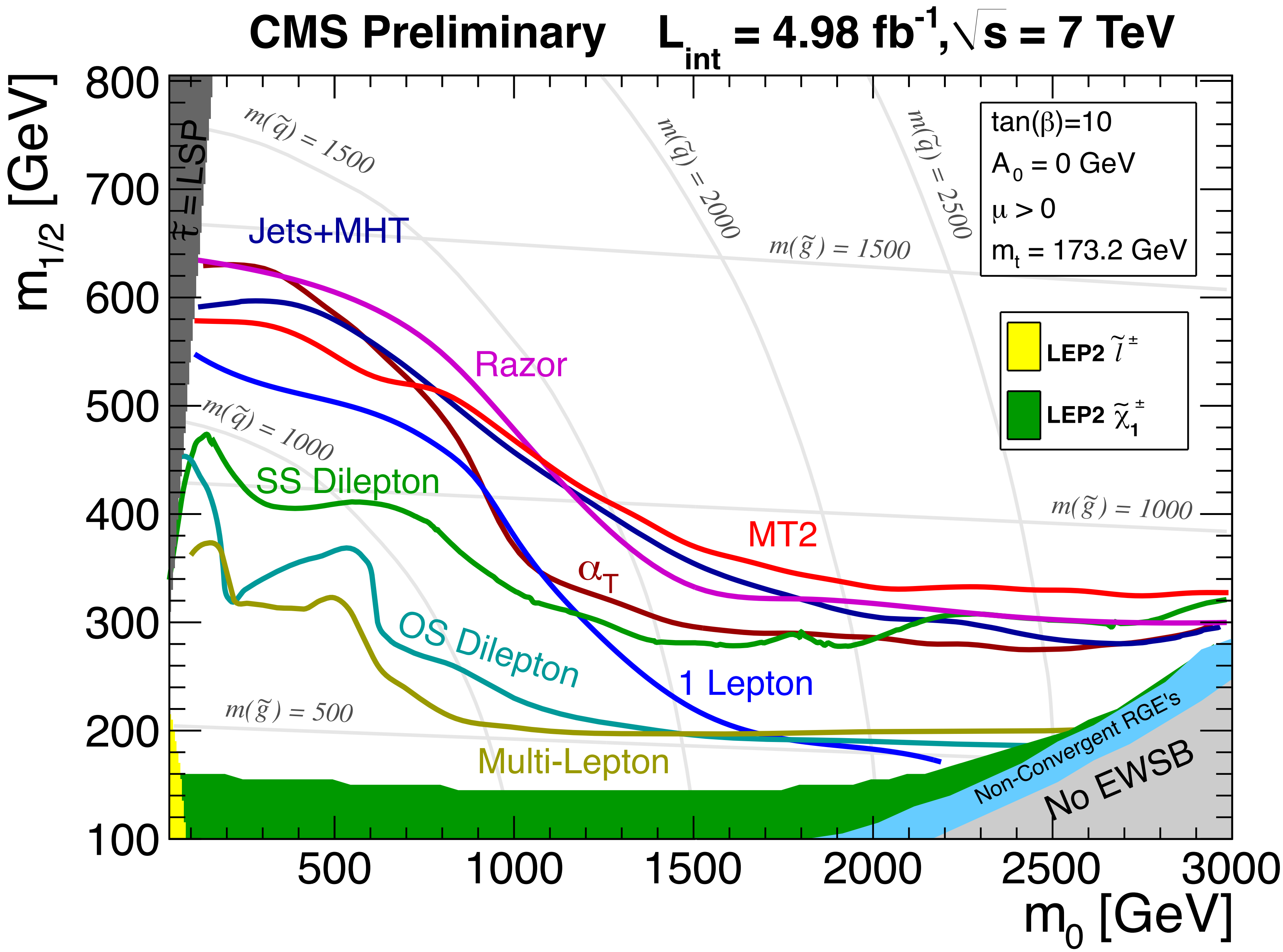
# Measurements of SM processes in CMS



# CMS SUSY Results (ICHEP 2014)



# Formulating SUSY – a short history

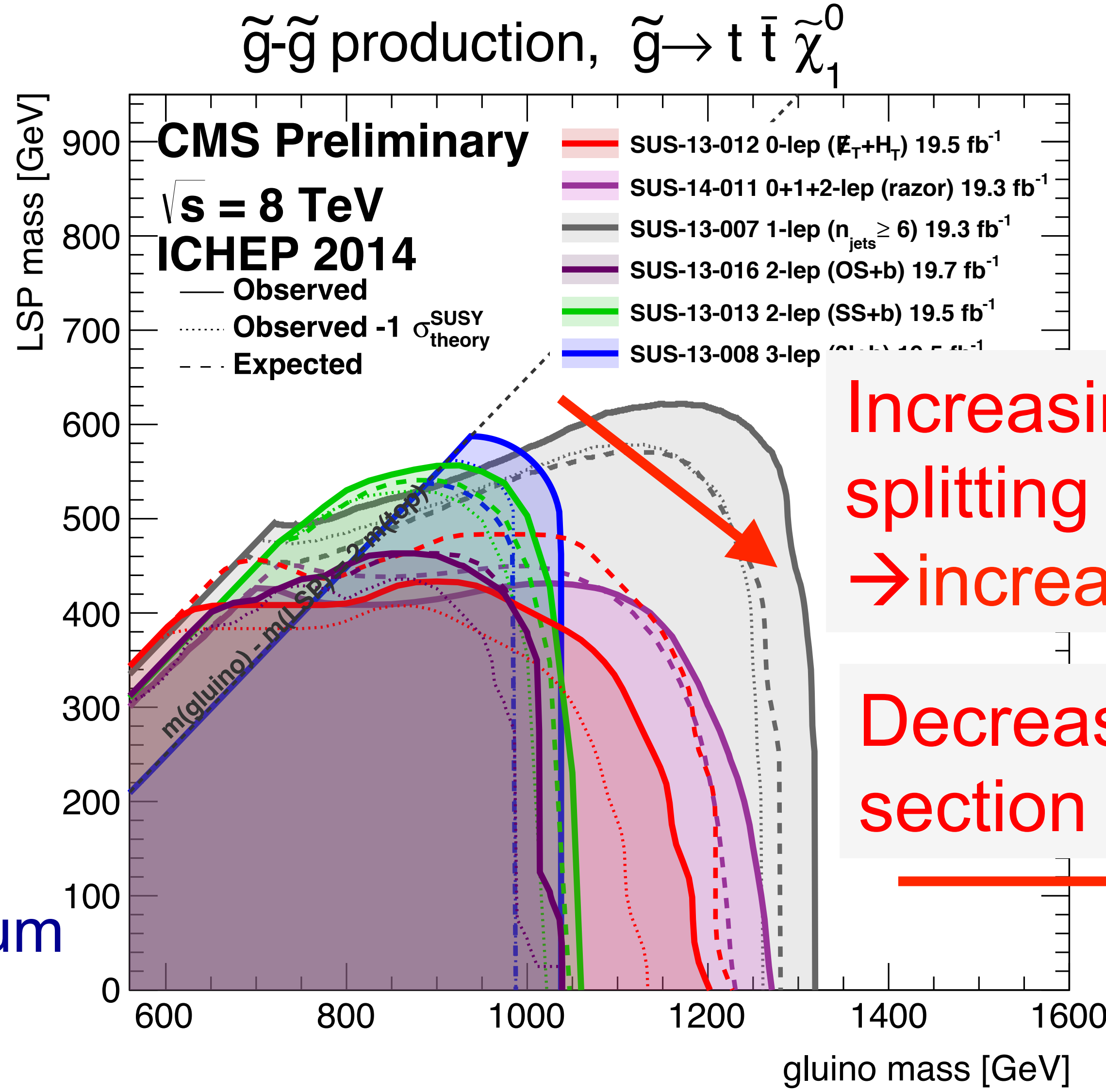


# Results for gluino pair production with $\tilde{g} \rightarrow t\bar{t}\,\tilde{\chi}_1^0$

$M(\tilde{\chi}_1^0)$

Mass of LSP

Maximum gluino mass limit at minimum LSP mass.

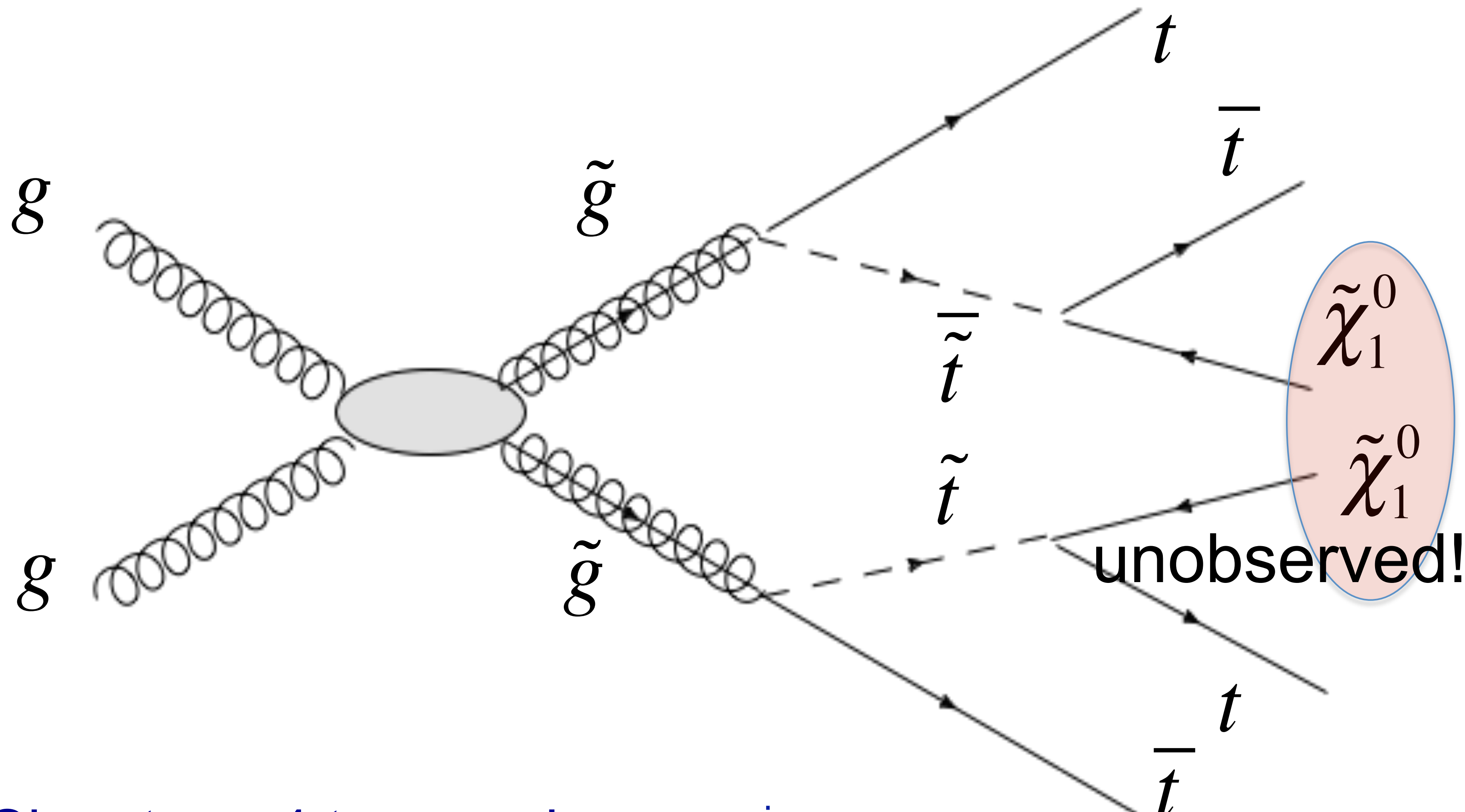



Increasing mass splitting
→increasing MET

Decreasing cross section

Mass of pair-produced particle $M(\tilde{g})$

# Gluino pair production and decay to stop




Signature: 4 top quarks + $p_T^{miss}$

LSPs are unobserved: cannot reconstruct mass peaks!

# Missing energy: the Wolfgang Pauli letter...

Open letter to the group of radioactive people at the
Gauverein meeting in Tübingen.

Copy

Physics Institute of
the ETH Zürich

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now called neutrinos!

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment $\mu$. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then $\mu$ is probably not allowed to be larger than $e \cdot (10^{-13}\text{cm})$.

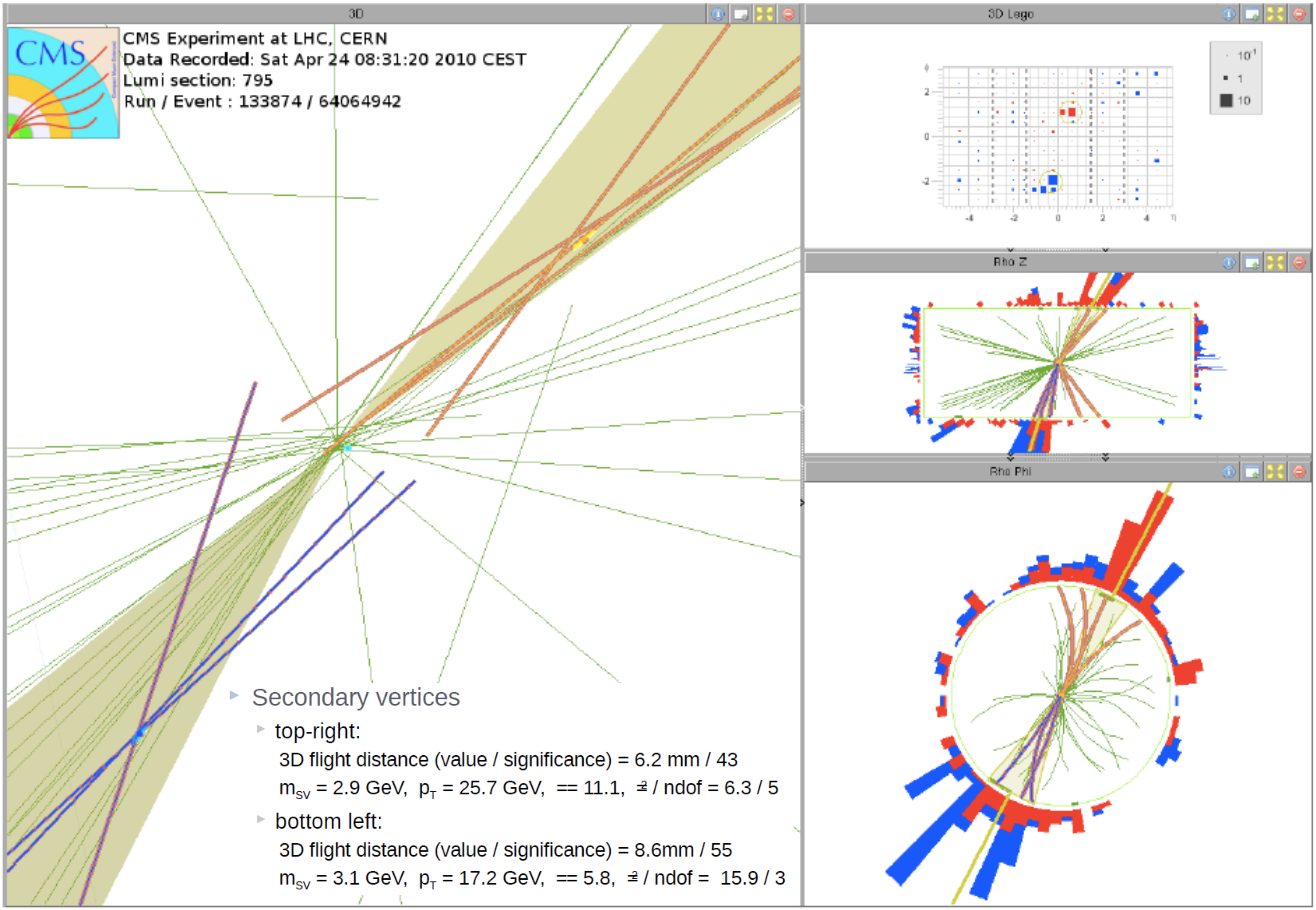
But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

signed W. Pauli

[Translation: Kurt Riesselmann]

# b-quark identification using displaced decay vertices

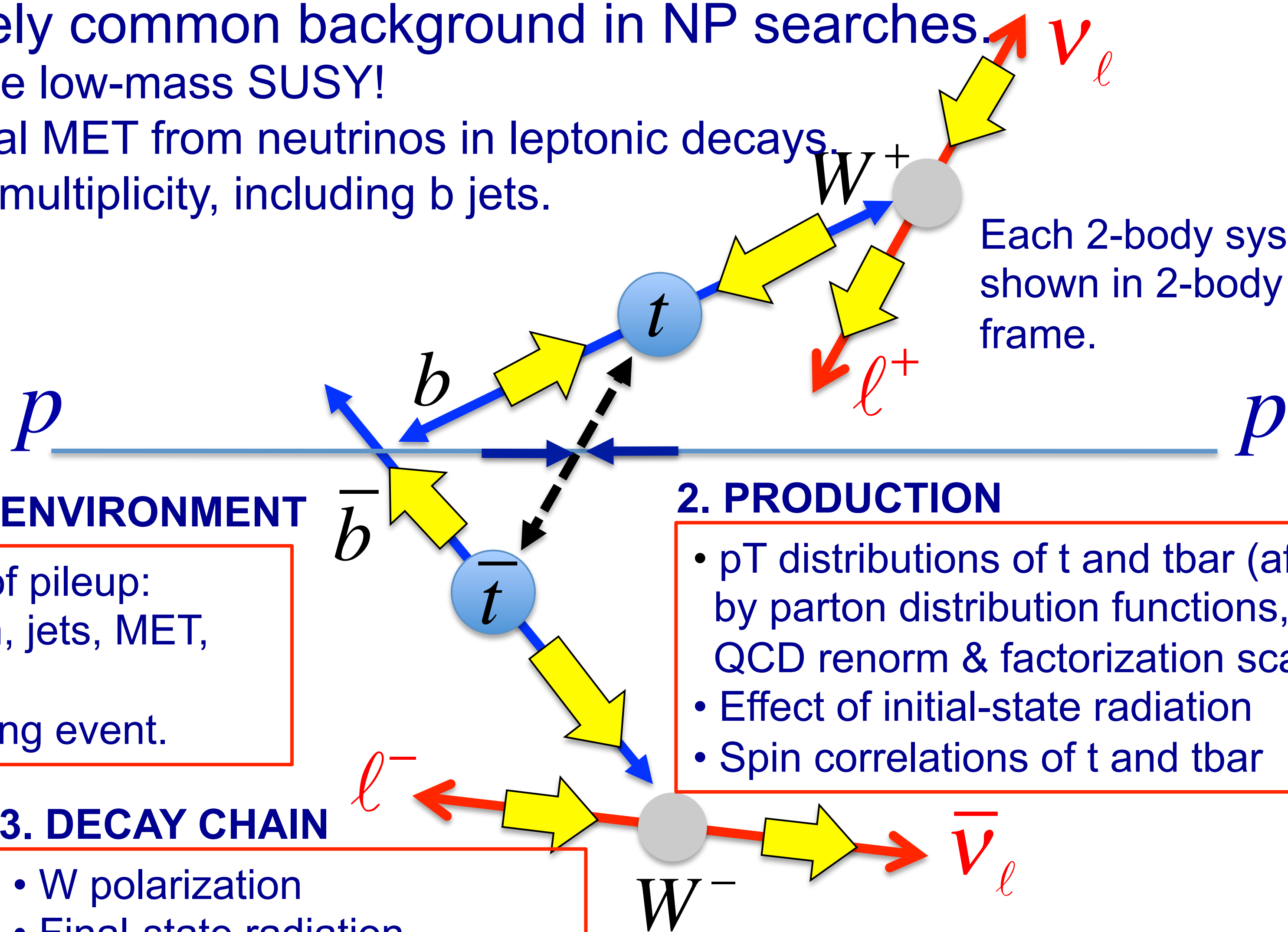



- Secondary vertices
  - top-right:
    3D flight distance (value / significance) = 6.2 mm / 43
    $m_{SV}$ = 2.9 GeV, $p_T$ = 25.7 GeV, == 11.1, $\chi^2$ / ndof = 6.3 / 5
  - bottom left:
    3D flight distance (value / significance) = 8.6mm / 55
    $m_{SV}$ = 3.1 GeV, $p_T$ = 17.2 GeV, == 5.8, $\chi^2$ / ndof = 15.9 / 3

# Anatomy of a background: ttbar

Extremely common background in NP searches.

- looks like low-mass SUSY!
- large real MET from neutrinos in leptonic decays.
- high jet multiplicity, including b jets.




Each 2-body system shown in 2-body rest frame.

**1. EVENT ENVIRONMENT**

- Effects of pileup: isolation, jets, MET, vertices
- Underlying event.

**2. PRODUCTION**

- pT distributions of t and tbar (affected by parton distribution functions, QCD renorm & factorization scales)
- Effect of initial-state radiation
- Spin correlations of t and tbar

**3. DECAY CHAIN**

- W polarization
- Final-state radiation
- Decay branching fractions

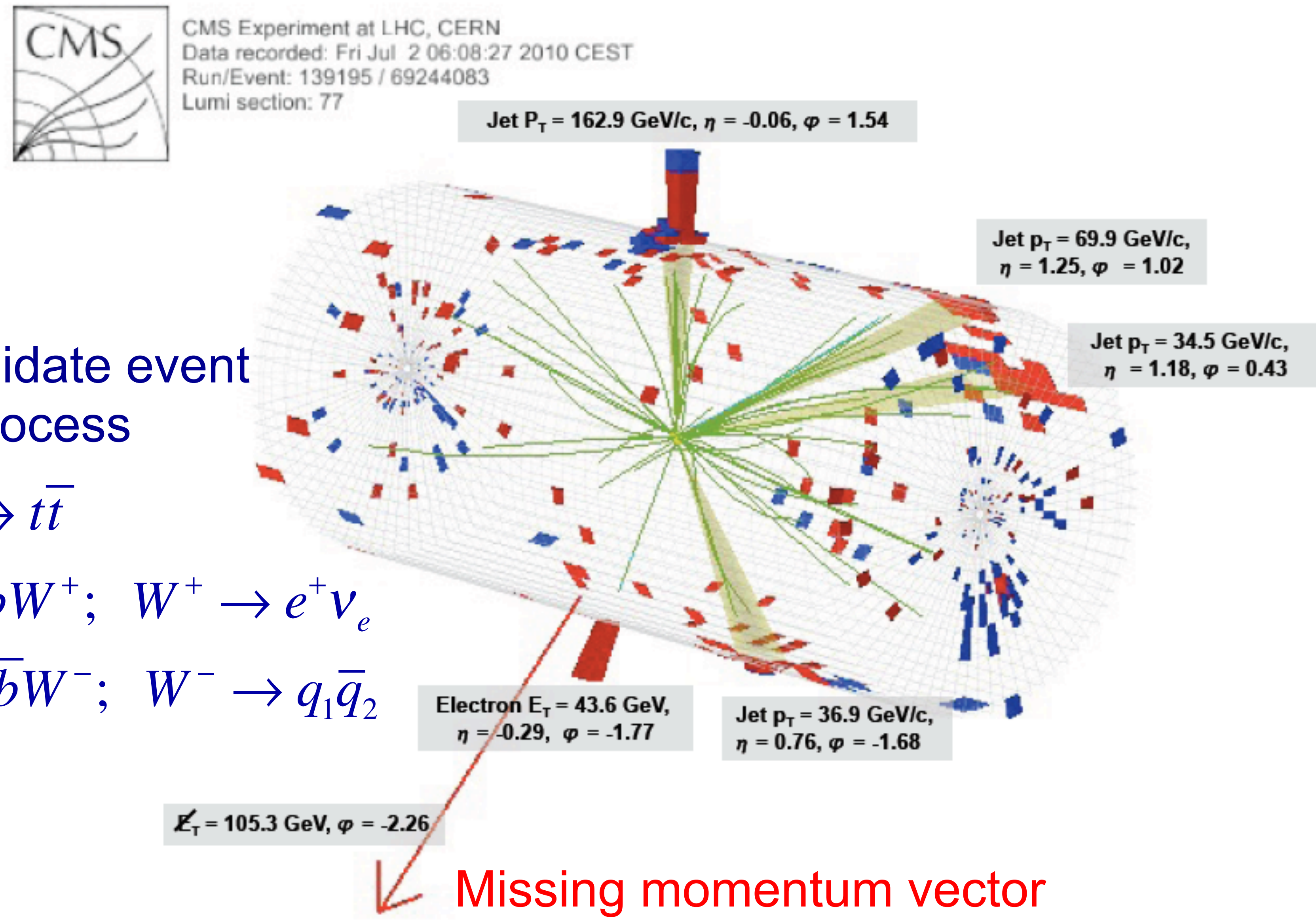
# Most "SUSY-like" process in SM: $pp \rightarrow t\bar{t}$

Candidate event for process

$$pp \rightarrow t\bar{t}$$

$$t \rightarrow bW^+; \;\; W^+ \rightarrow e^+\nu_e$$

$$\bar{t} \rightarrow \bar{b}W^-; \;\; W^- \rightarrow q_1\bar{q}_2$$




Missing momentum vector from neutrino

# Generic hadronic SUSY search using MHT

SUS-13-012 https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13012

- Signature: Jets + MHT; events with leptons are vetoed
  - Jets: ≥3 jets with $p_T$ > 50 GeV, no b-tagging.
  - Veto event if MHT vector is ≈aligned with any of 3 leading jets.
- Bin data in
  - HT
  - missing HT (MHT)
  - Jet multiplicity (3—5, 6—7, ≥8 jets)

$$H_T = \sum_{j=jets} \left|\vec{p}_T^{\,j}\right|$$

$$\not{H}_T = \left|\vec{\not{H}}_T\right| = \left|-\sum_{j=jets} \vec{p}_T^{\,j}\right|$$

- Background estimation: largely data driven.

- ttbar with W→$l\,\nu$
- W → $l\,\nu$ + jets
- ttbar with W→$\tau$ (→h) $\nu$
- W → $\tau$ (→h) $\nu$ + jets

Control sample: Single-lepton + jets + MHT

- Z→$\nu\nu$ + jets

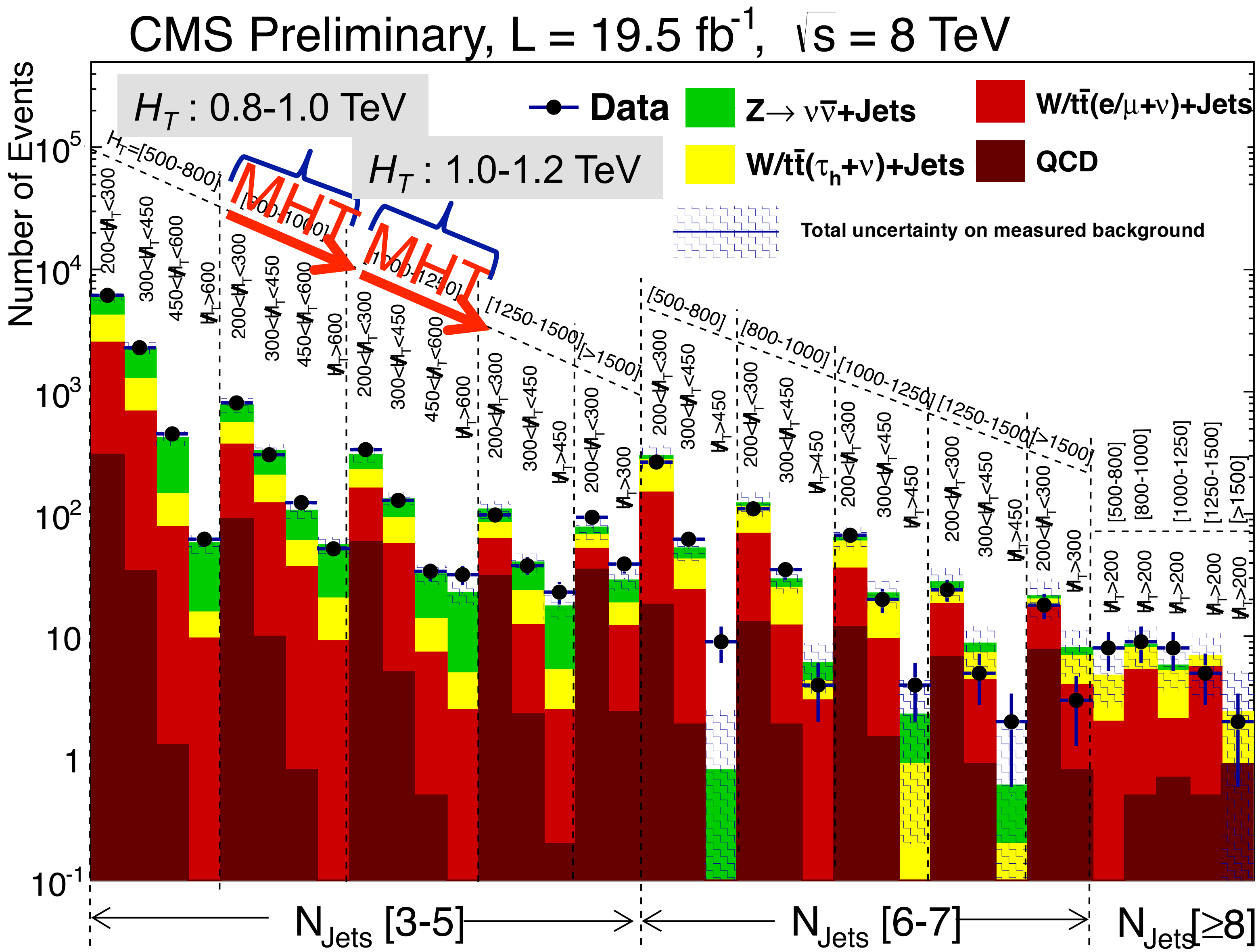
Control samples:
$\gamma$ + jets,
Z($\mu\mu$)+jets

- QCD multijet events
MHT ~ aligned with high pT jet.

Control sample:
Multijets with re-balance and smear procedure

# Distribution in bins of N(jets), $H_T$, and $\not{H}_T$

CMS SUS-13-012



# Statistical interlude

See CMS PAS SUS-13-012, Table 1, p. 10
Njets: 6-7
HT: 500-800 GeV
MHT>450 GeV

- Consider the bin with
  - N(observed) = 9 events
  - N(background) = 0.8 ± 1.7 events
- First, let's ignore the uncertainty on the background. What is the probability for a Poisson with μ=0.8 to fluctuate to at least 9 events?
  - Prob( $n \geq 9$ | $\mu = 0.8$ ) = $1.8 \times 10^{-7}$

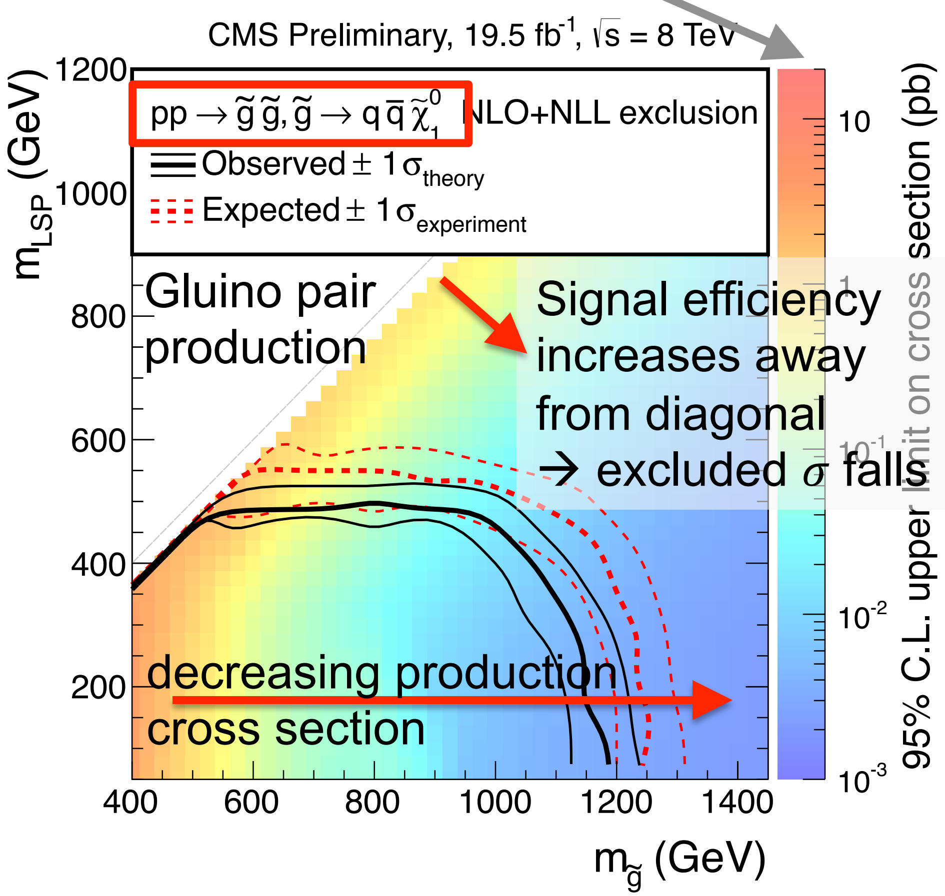
  Have we discovered new physics?
- NO! The uncertainty is crucial!
  - Prob( $n \geq 9$ | $\mu = 0.8 \pm 1.7$) ≈ 0.15
- This example highlights the importance of quantifying the uncertainties on the SM backgrounds.

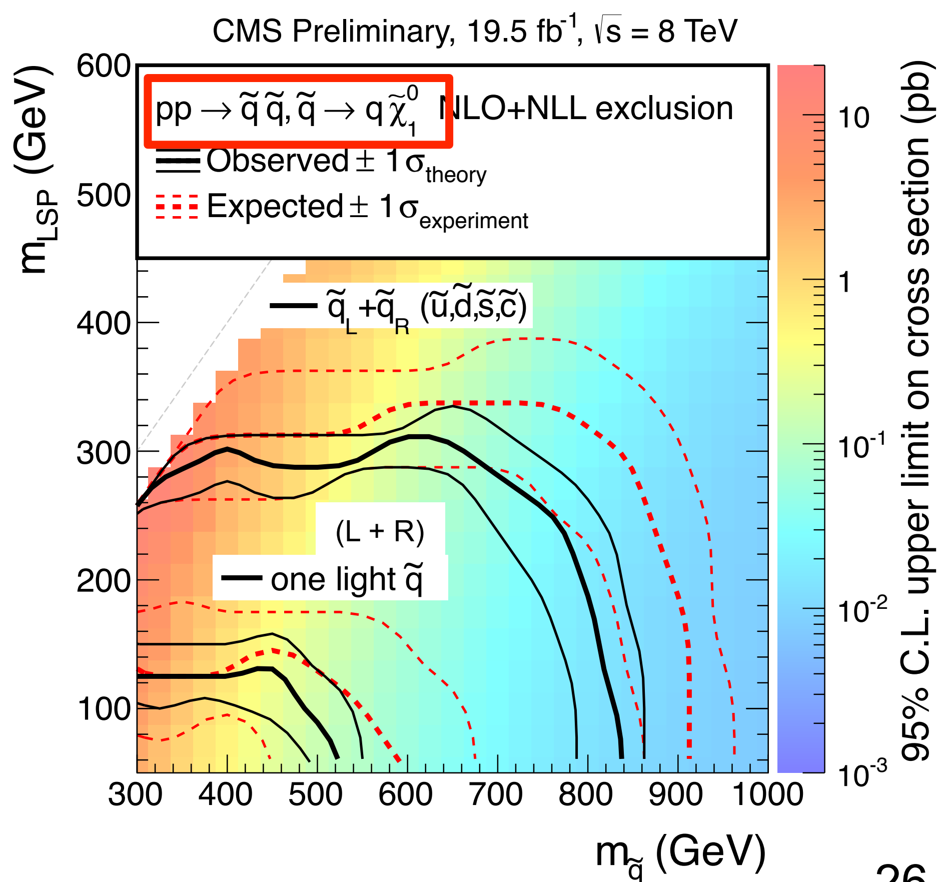
# Search for generic jets and MET: results

- Simplified model exclusion plots

CMS SUS-13-012

1. Compute excluded cross section for each model in param space
2. Compare to reference cross section to see if model excluded
   - Assume 100% branching fraction for stated process!



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CMS PAS SUS-13-012

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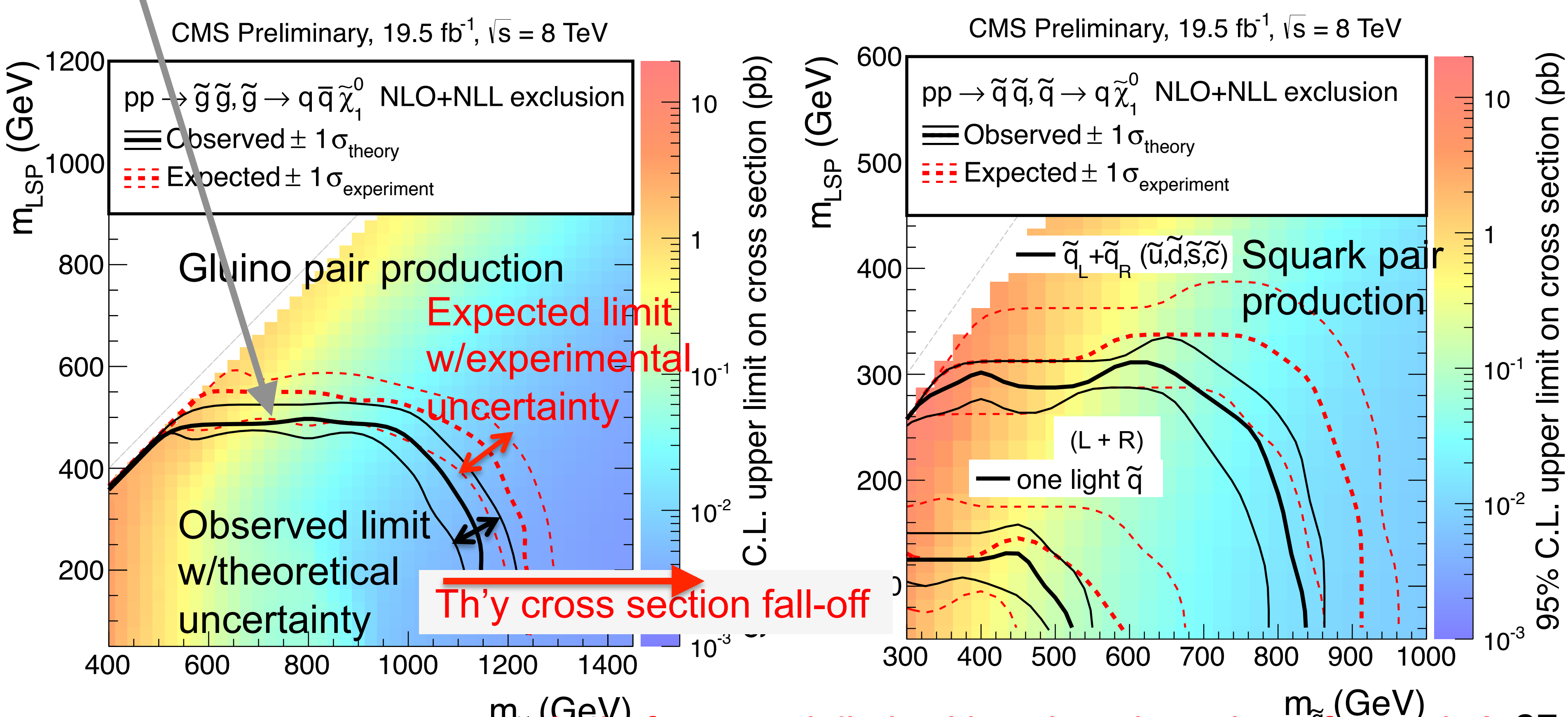
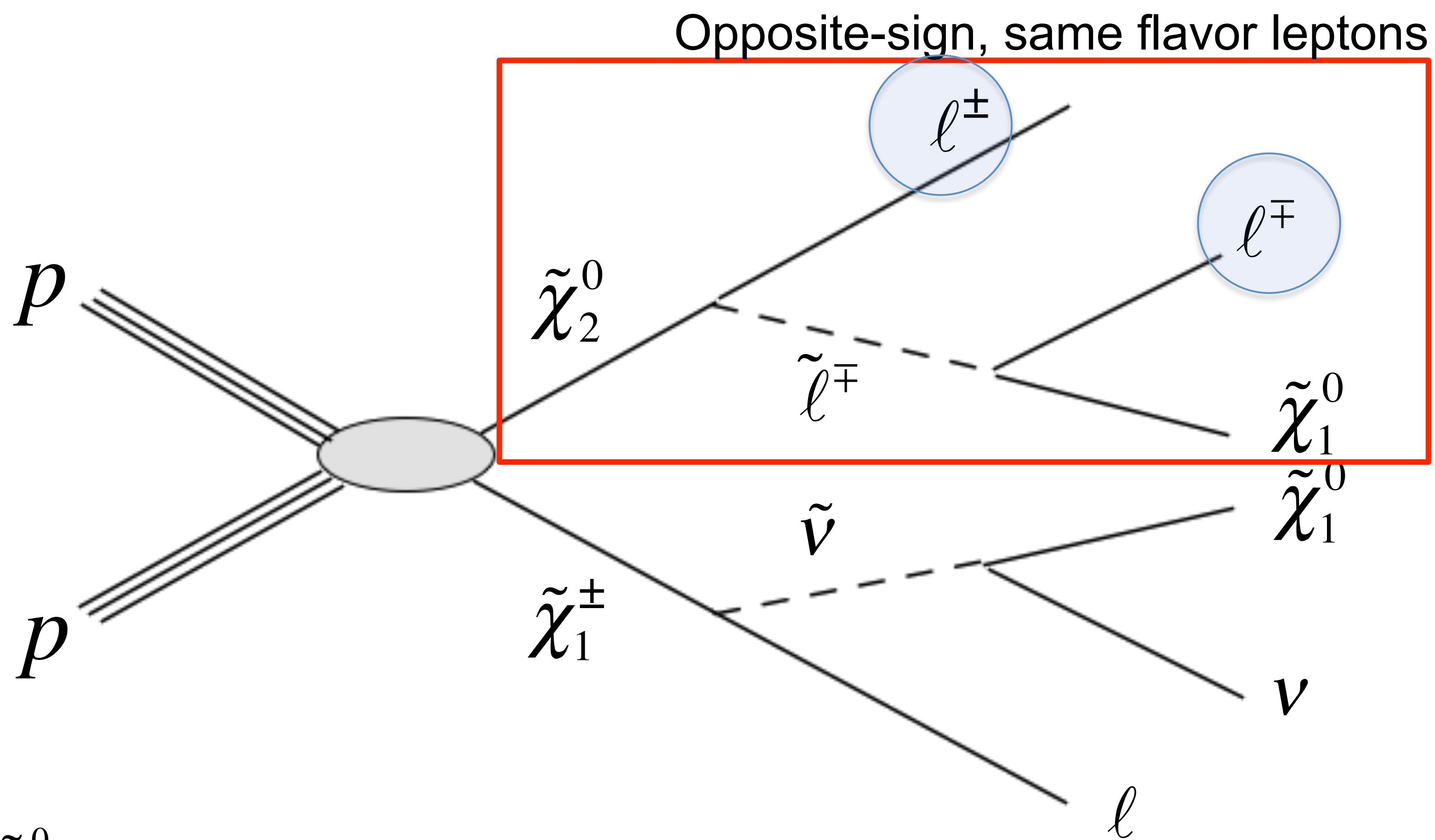



As before, weak limit with reduced number of squarks!

# The famous neutralino dilepton cascade

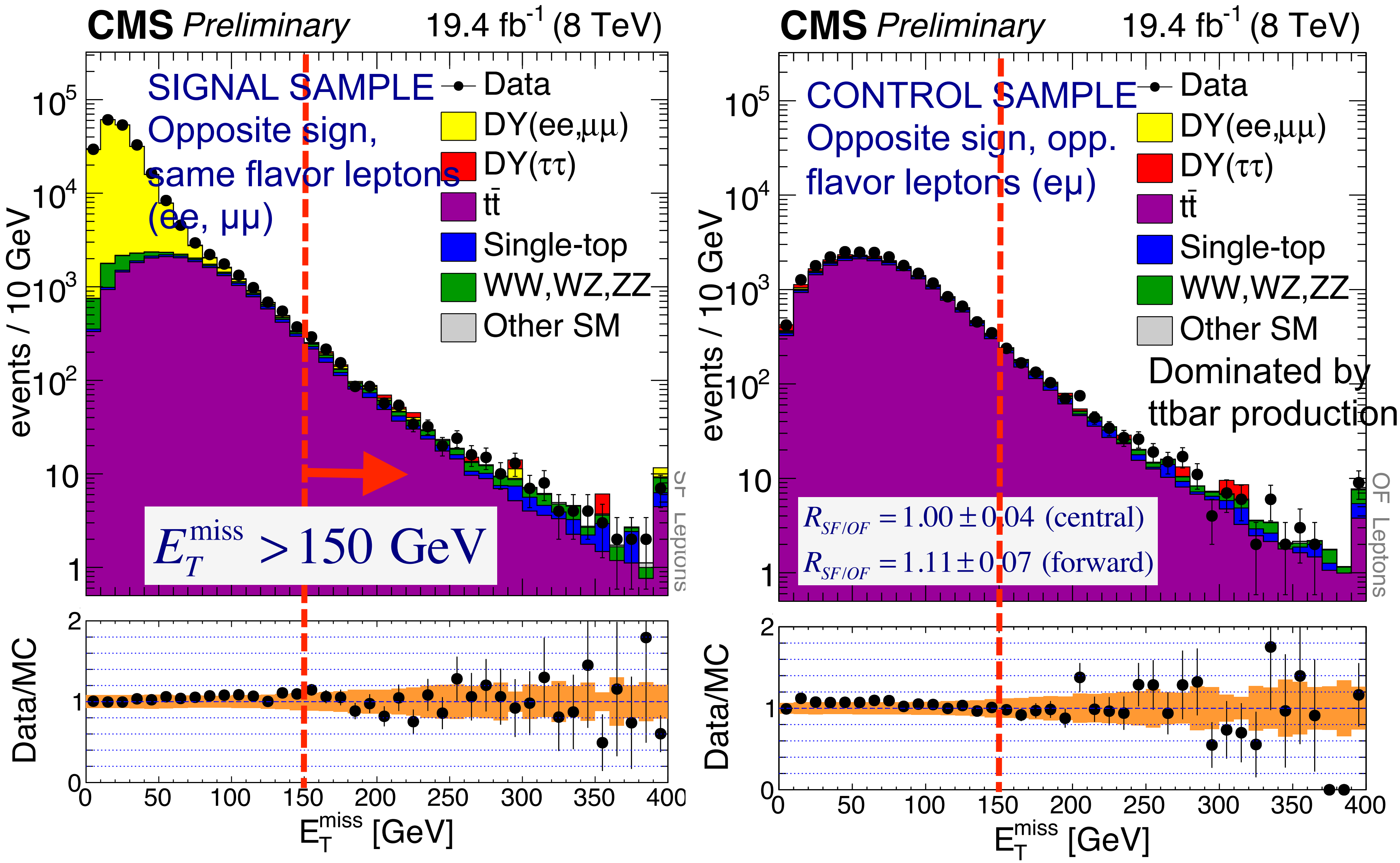



The $\tilde{\chi}_2^0$ can be produced in any process, not just direct EW production.

$$m_{\ell^+\ell^-}(\max) = \sqrt{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)} / m_{\tilde{\ell}}$$

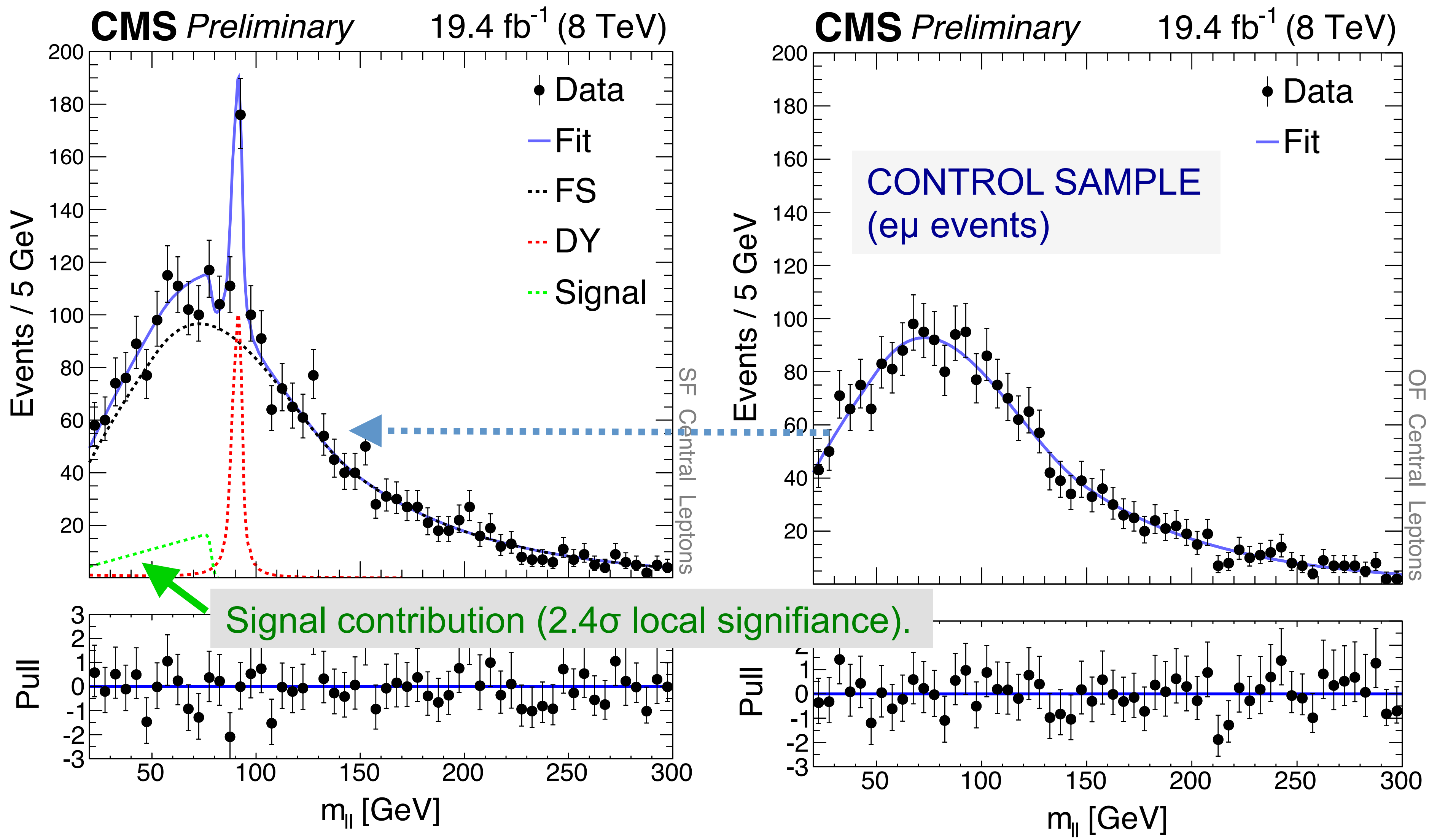
# Search for SUSY in opposite sign dileptons

$m_{\ell^+\ell^-} > 20$ GeV, $N(\text{jets}) \geq 2$ $(p_T > 40$ GeV$)$

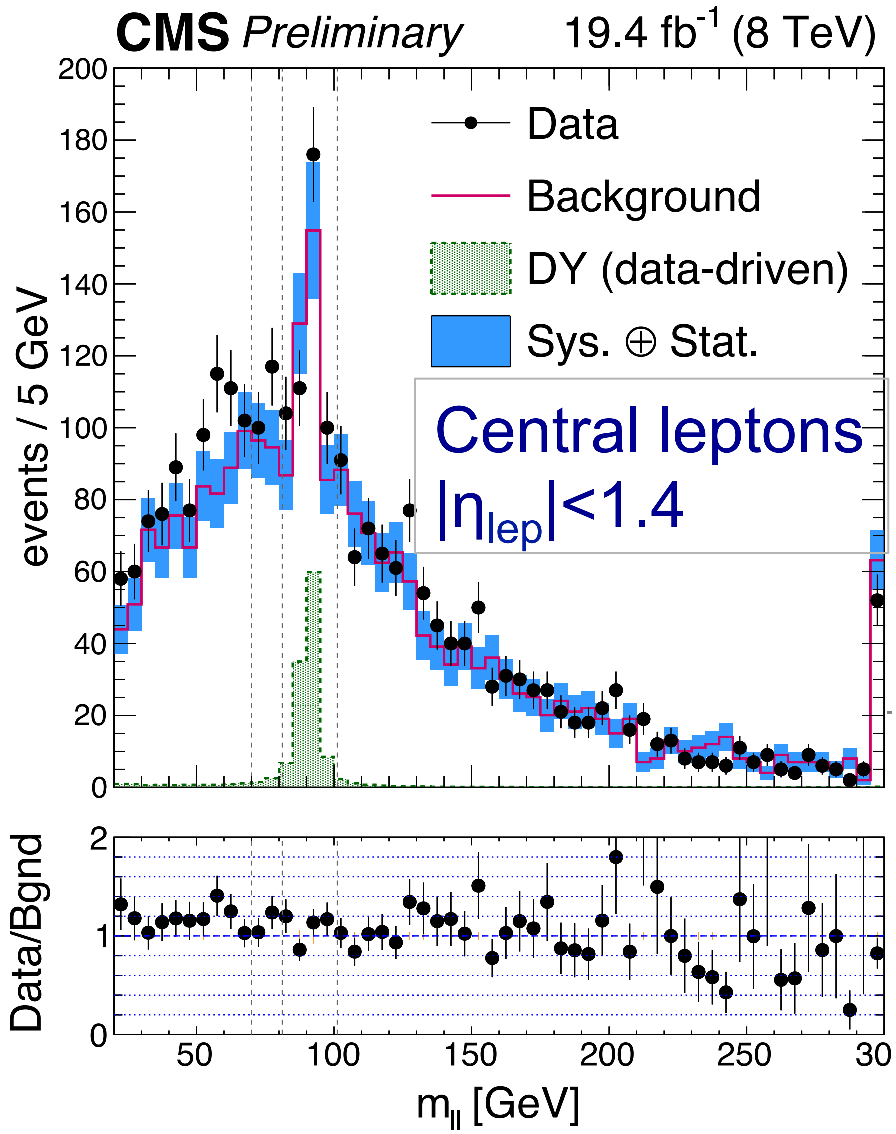


# Search for SUSY in opposite sign dileptons

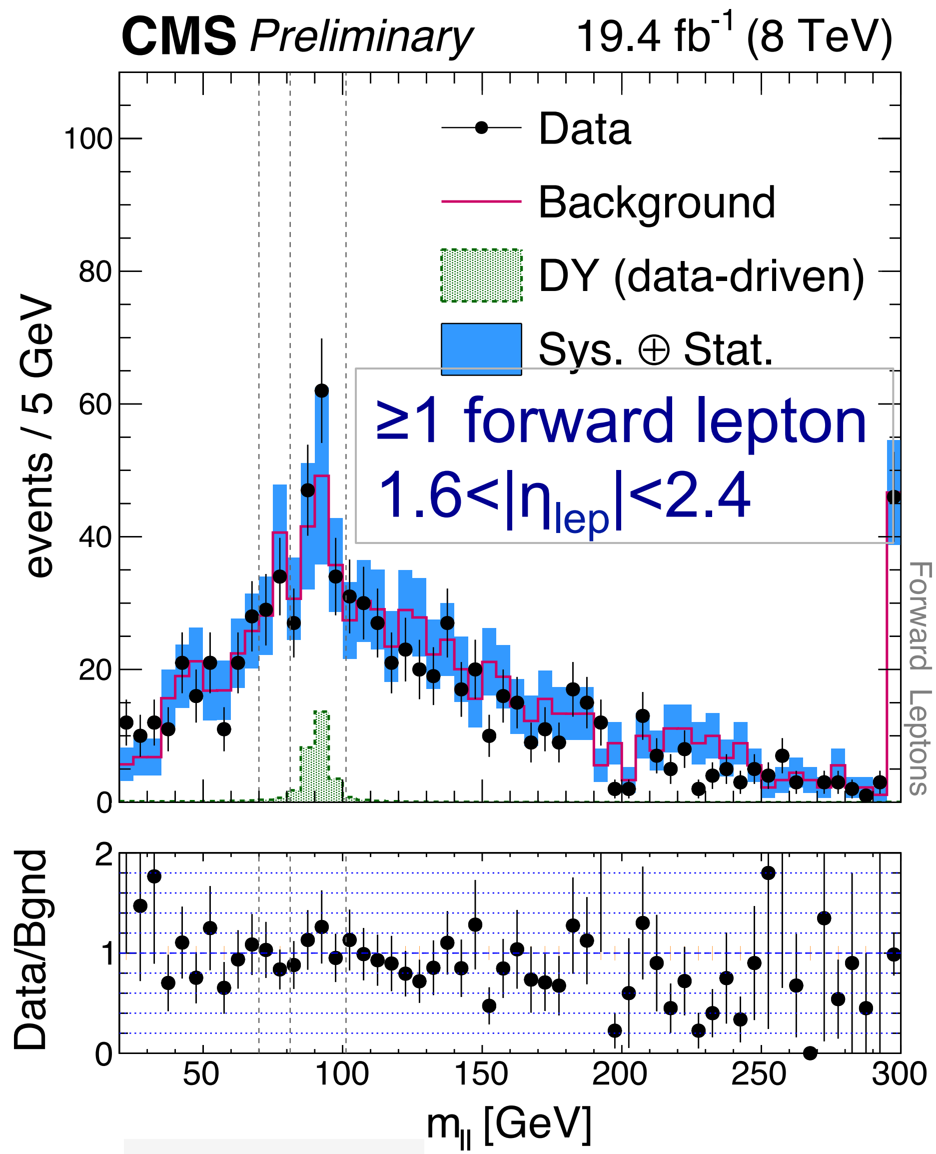
Fit opposite sign dilepton mass distribution to shapes from (1) Flavor Symmetric (FS) background, Drell Yan, and signal.



# Search for SUSY in opposite-sign dileptons

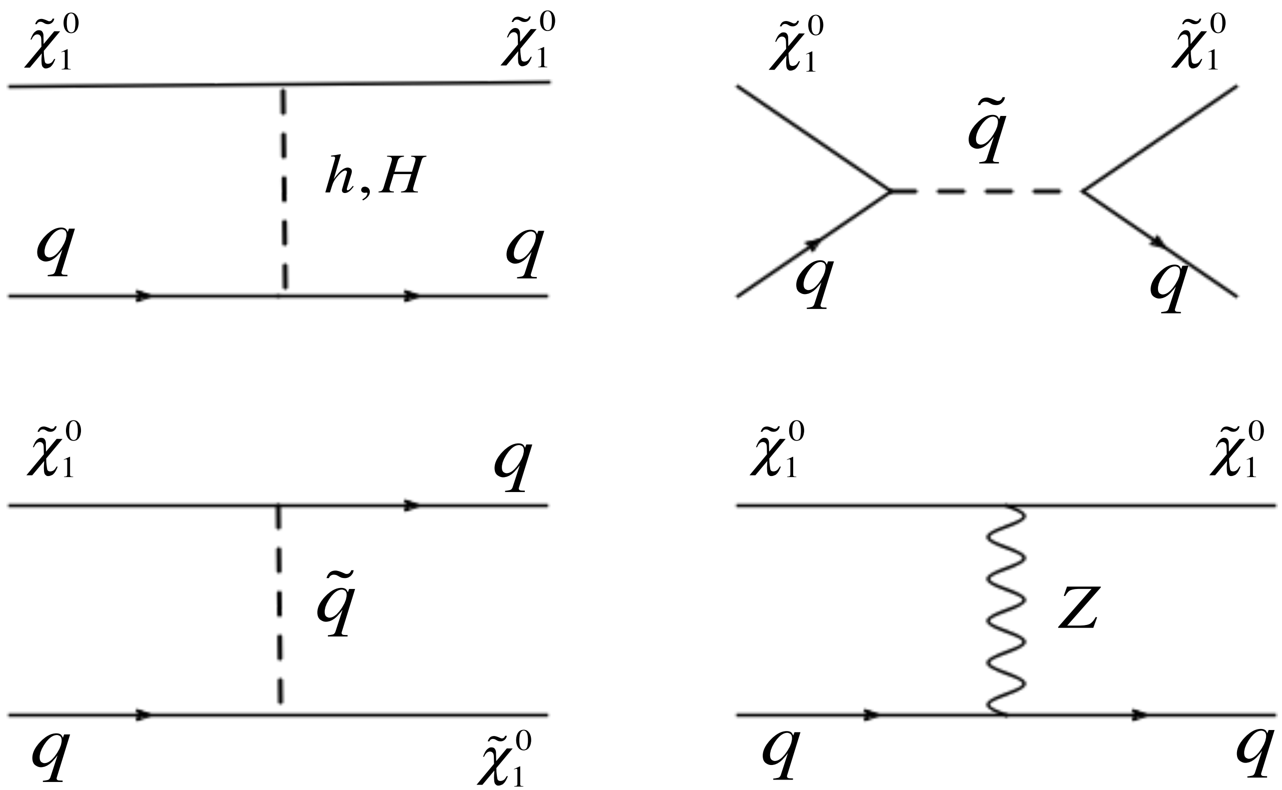



2.6σ excess (not significant)

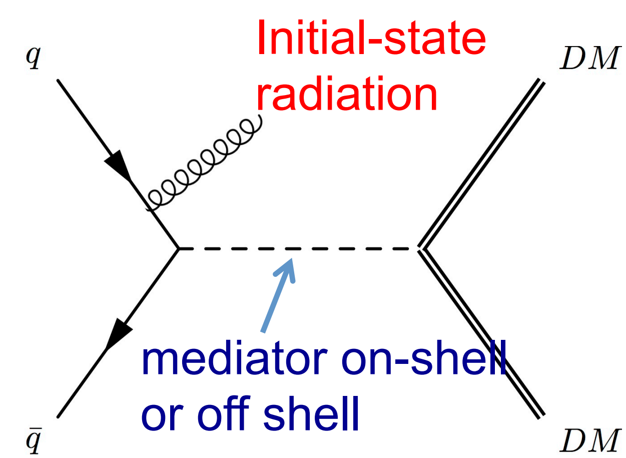



0.3σ excess

# Interactions of neutralinos with matter

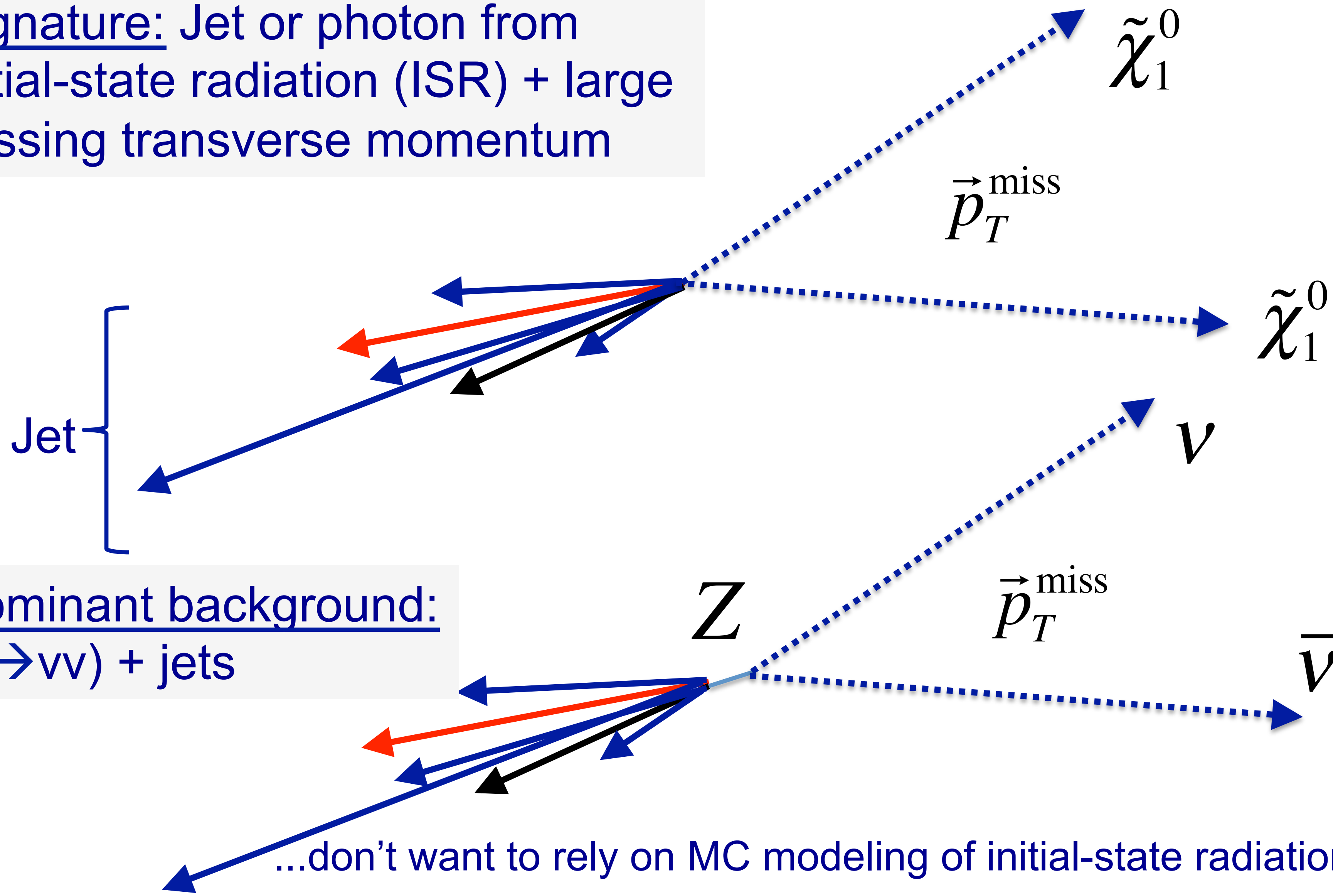



- Above: direct dark matter detection processes: doesn't have to be SUSY!
- Use crossing to get $q + \overline{q} \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0$
- How to see $q + \overline{q} \rightarrow$ invisible?



# Signature for dark matter at the LHC

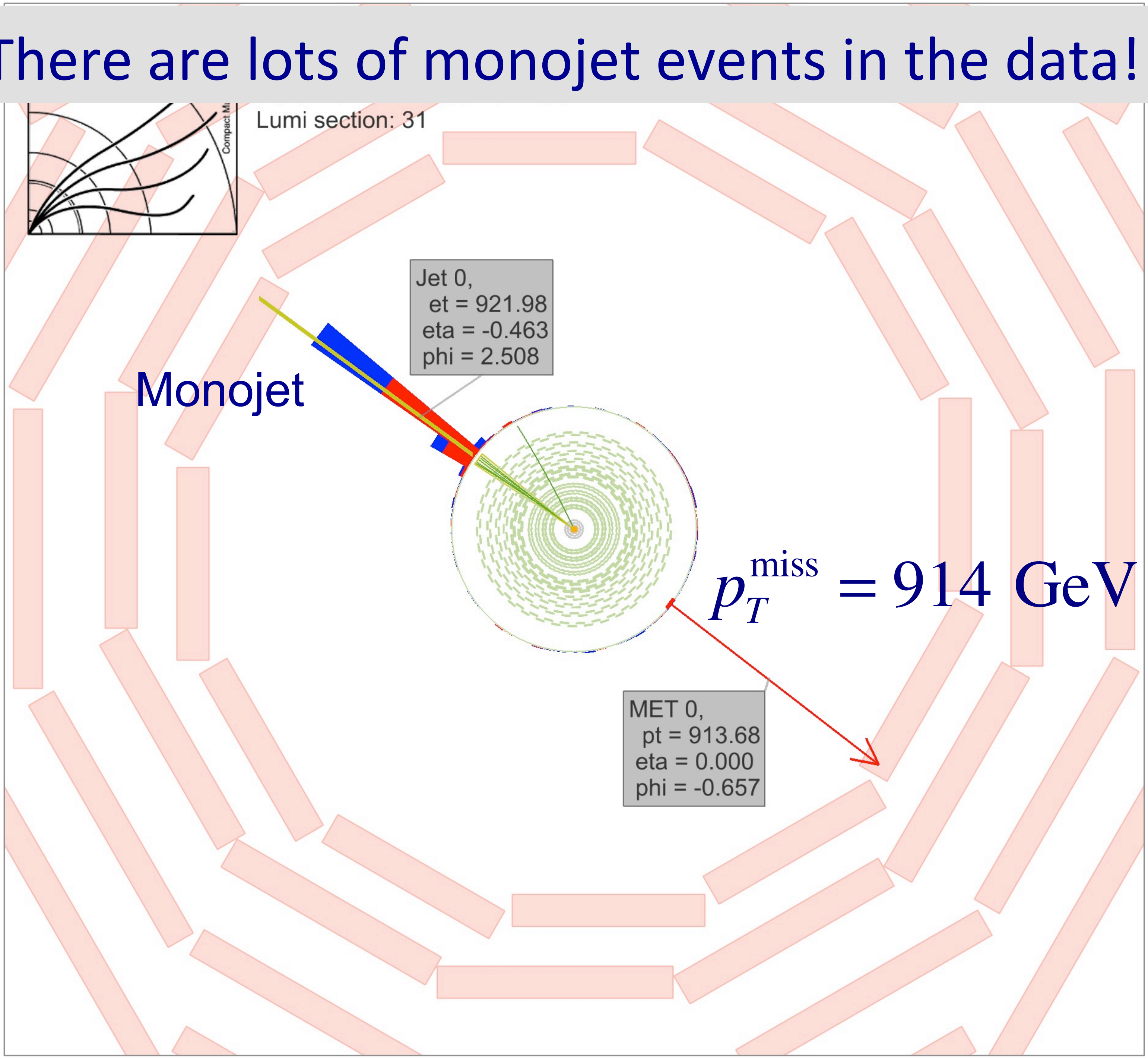
<u>Signature:</u> Jet or photon from initial-state radiation (ISR) + large missing transverse momentum




<u>Dominant background:</u> Z(→νν) + jets

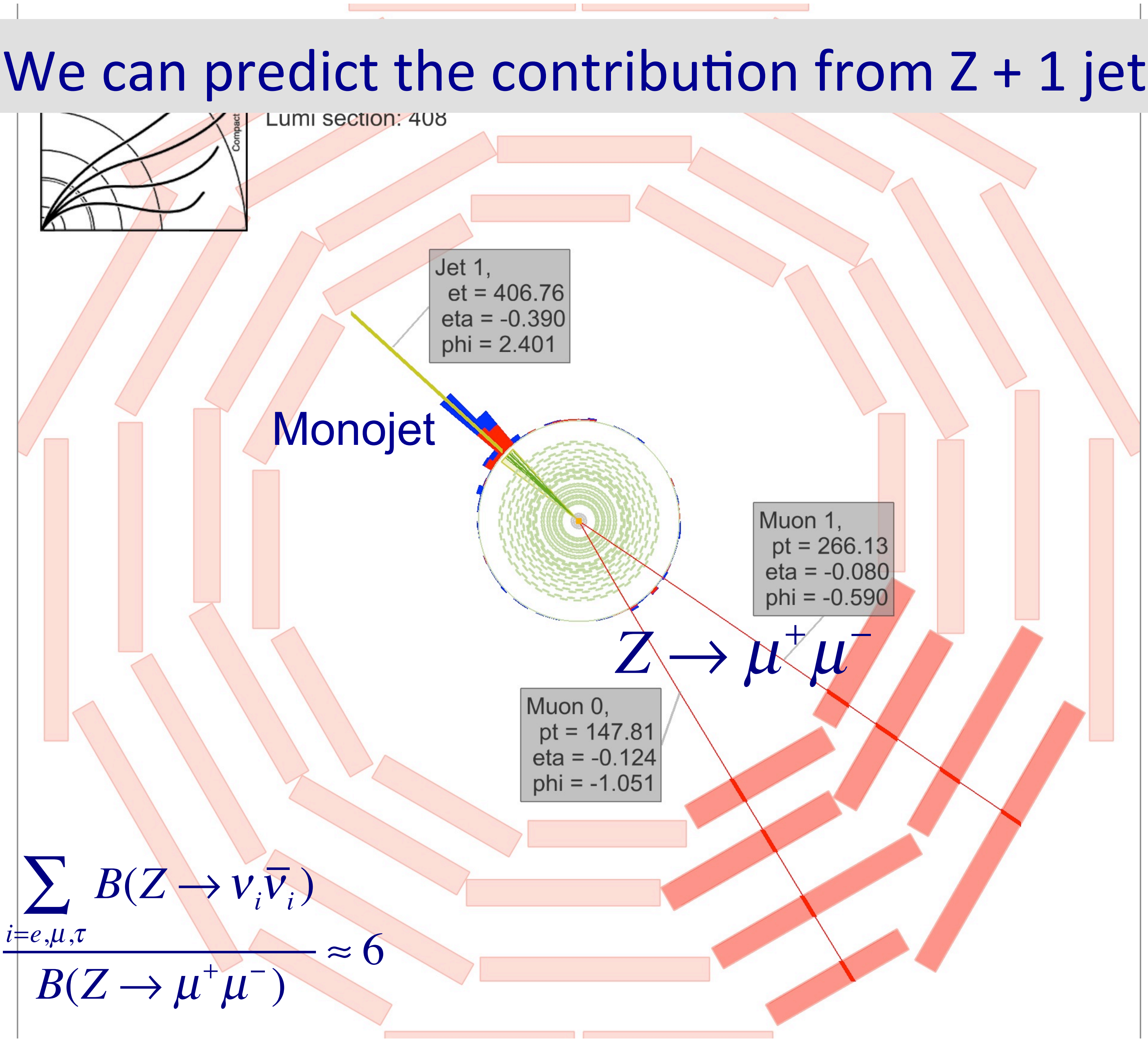
...don't want to rely on MC modeling of initial-state radiation

# There are lots of monojet events in the data!



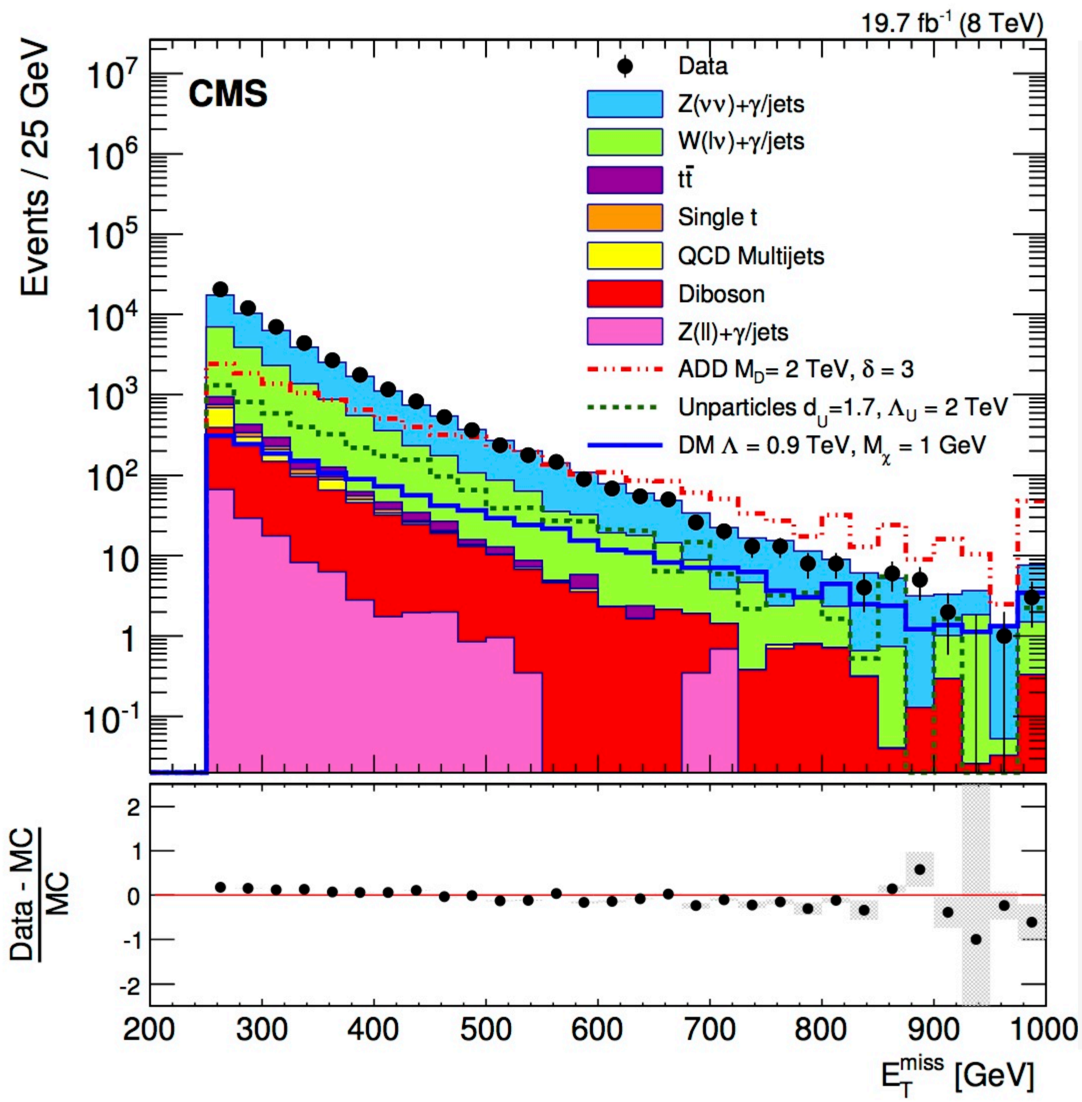

$$p_T^{\text{miss}} = 914 \text{ GeV}$$

# We can predict the contribution from Z + 1 jet



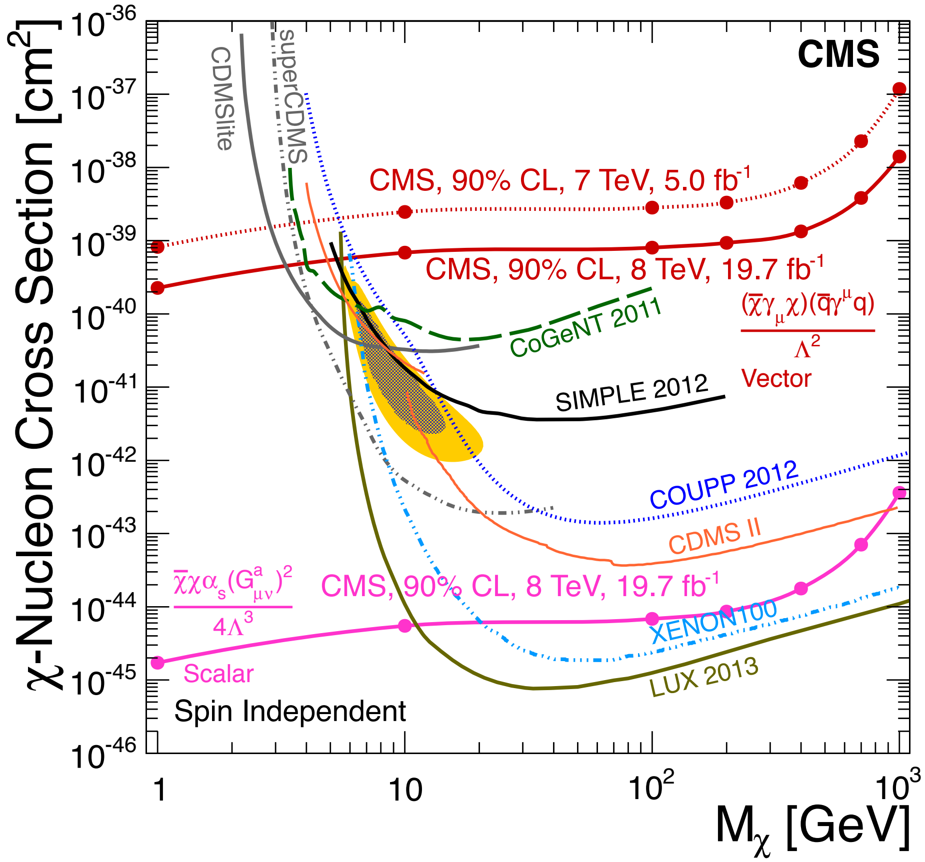

$$\frac{\sum_{i=e,\mu,\tau} B(Z \to \nu_i \bar{\nu}_i)}{B(Z \to \mu^+\mu^-)} \approx 6$$

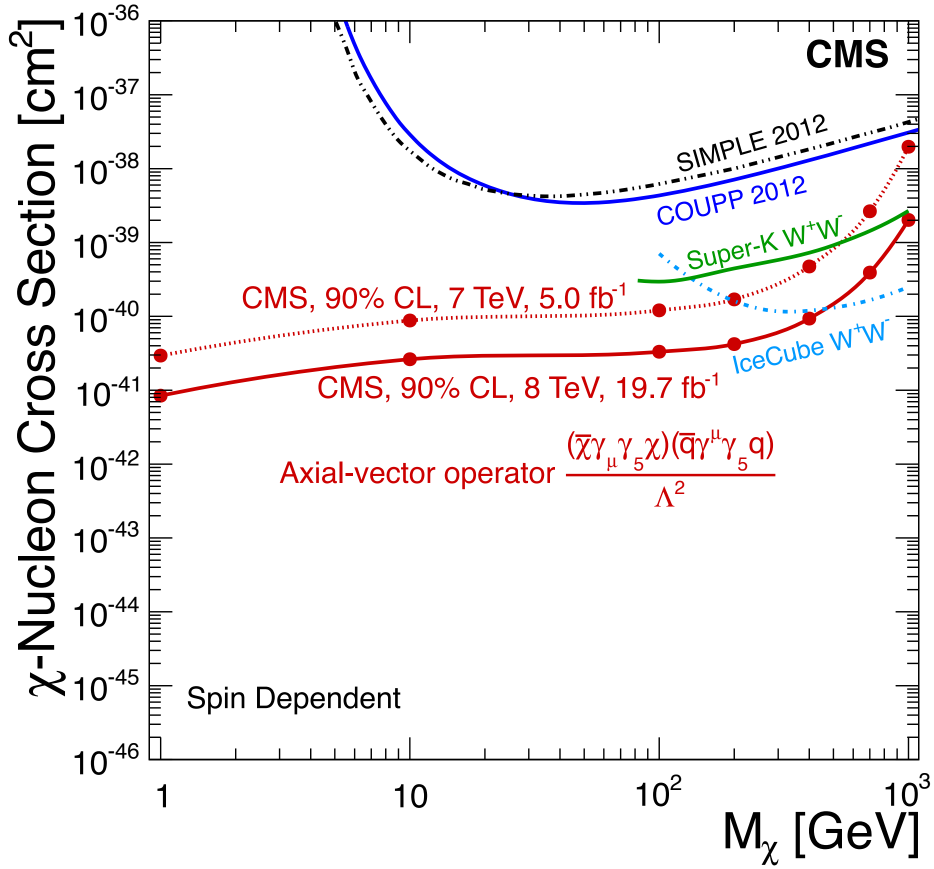
# Searching for dark matter: monojet search results



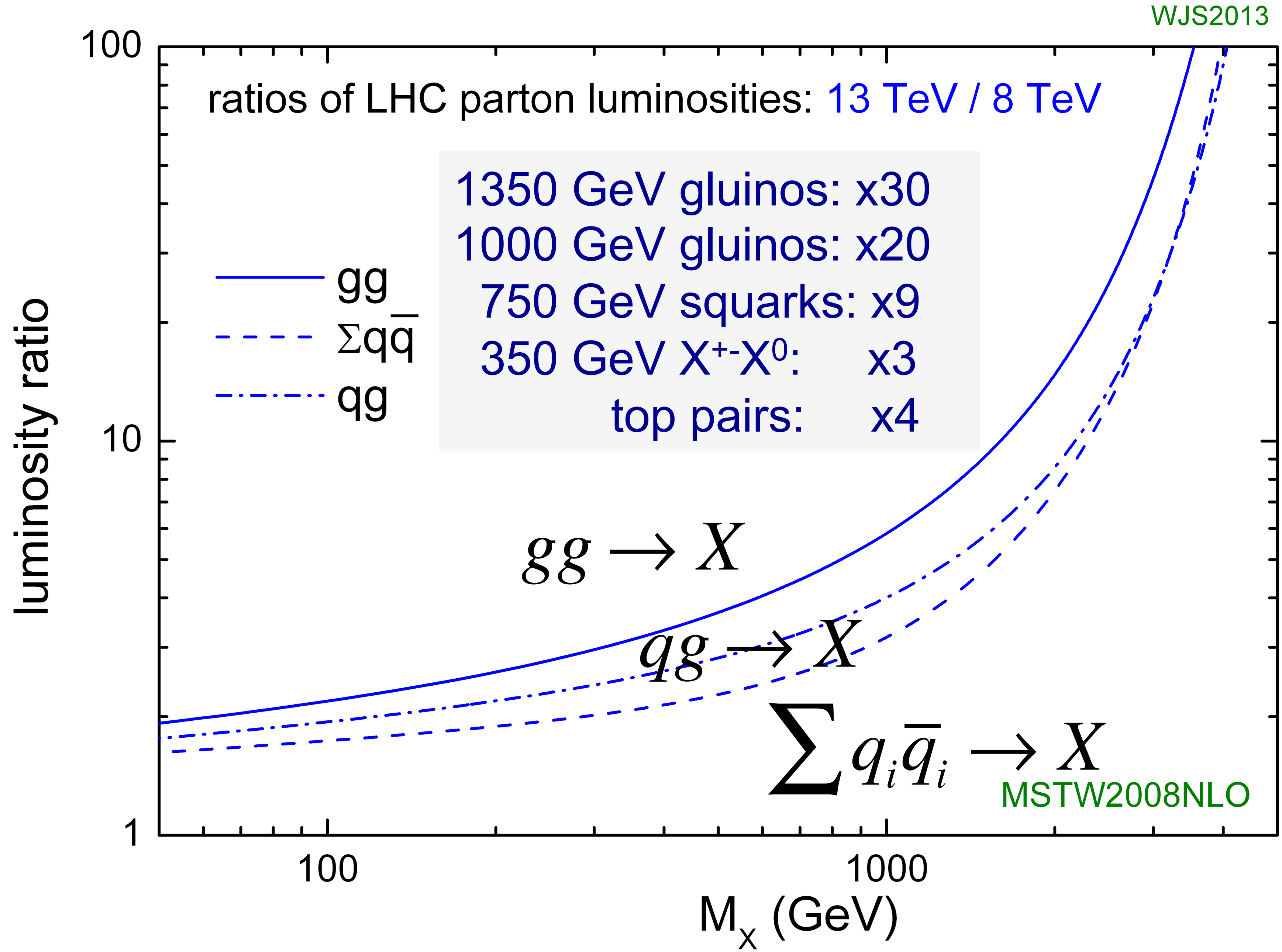

- MET > 250 GeV
- 1 central jet, pT>110 GeV.
- 2nd softer jet allowed, not back-to-back.
- Remarkable that QCD is so well controlled.
- Veto events with leptons
- Z→vv is dominant background; predict from Z→μμ control sample.

# Searching for dark matter: monojet search results



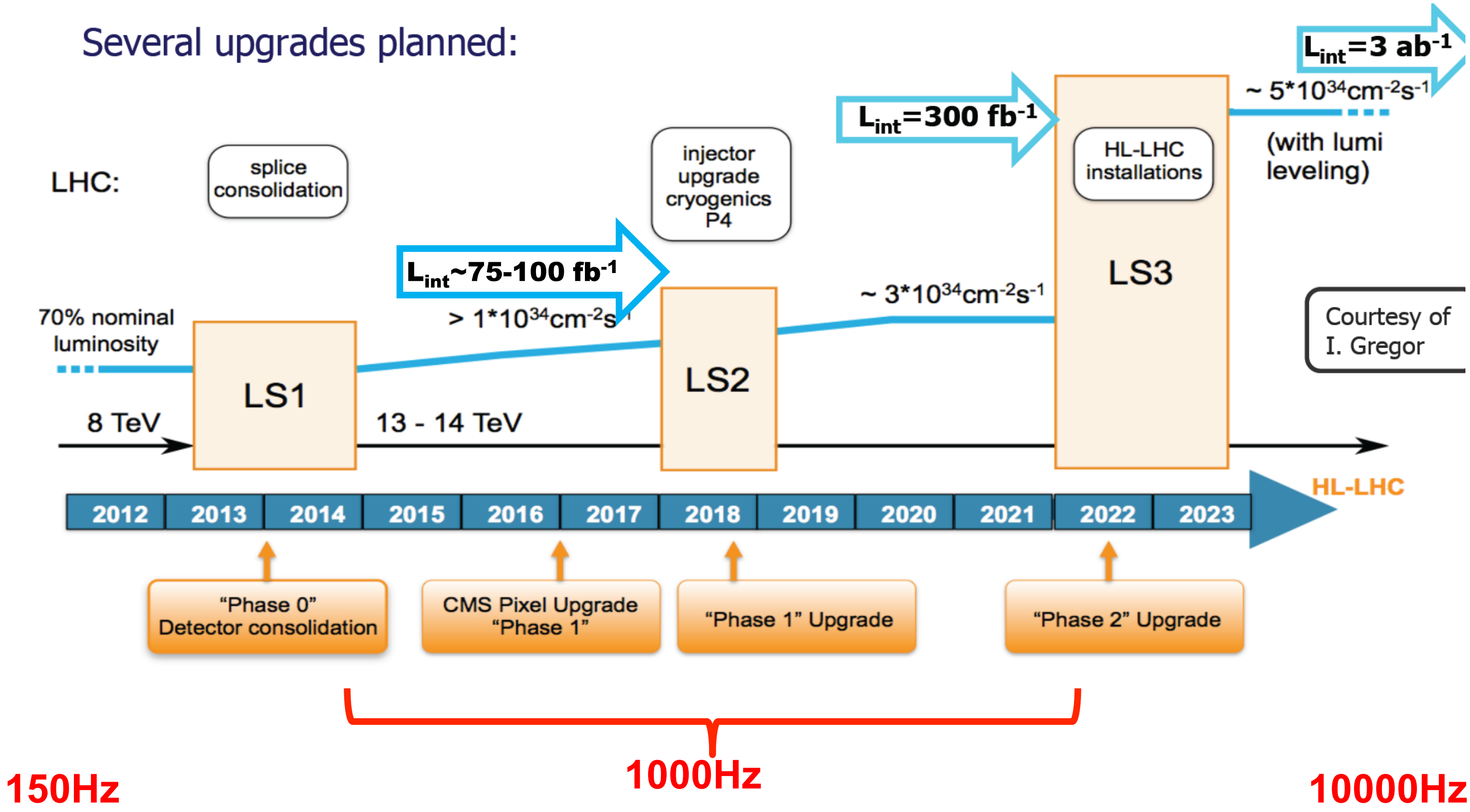



# Relative parton luminosities: 13 TeV vs. 8 TeV



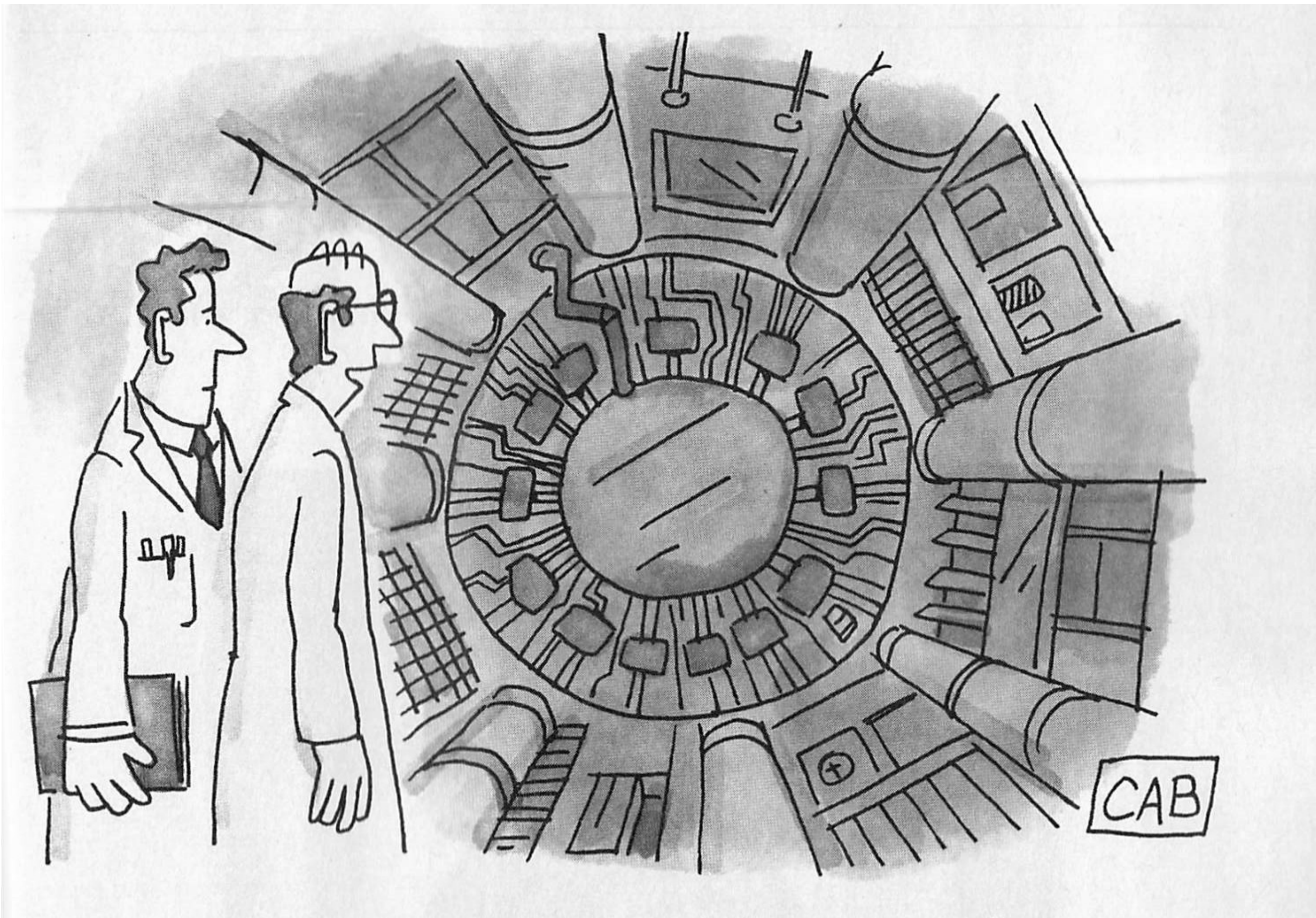
# LHC long-term plan

Several upgrades planned:




**Event Rate written to tape**

# ...is there a message here?




*"Once you have a collider, every problem starts to look like a particle."*

# Backups

# Search for neutralino/chargino production