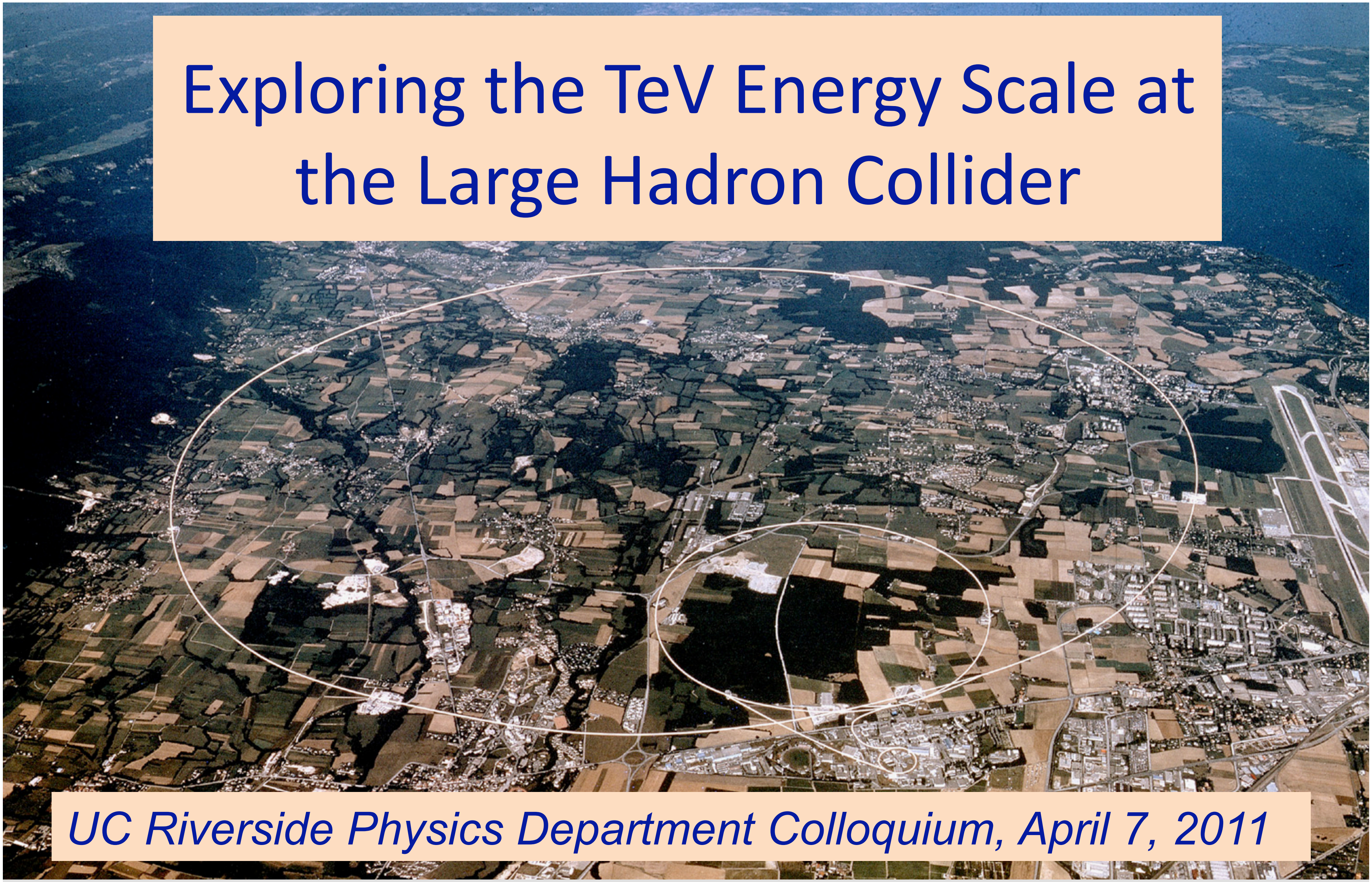
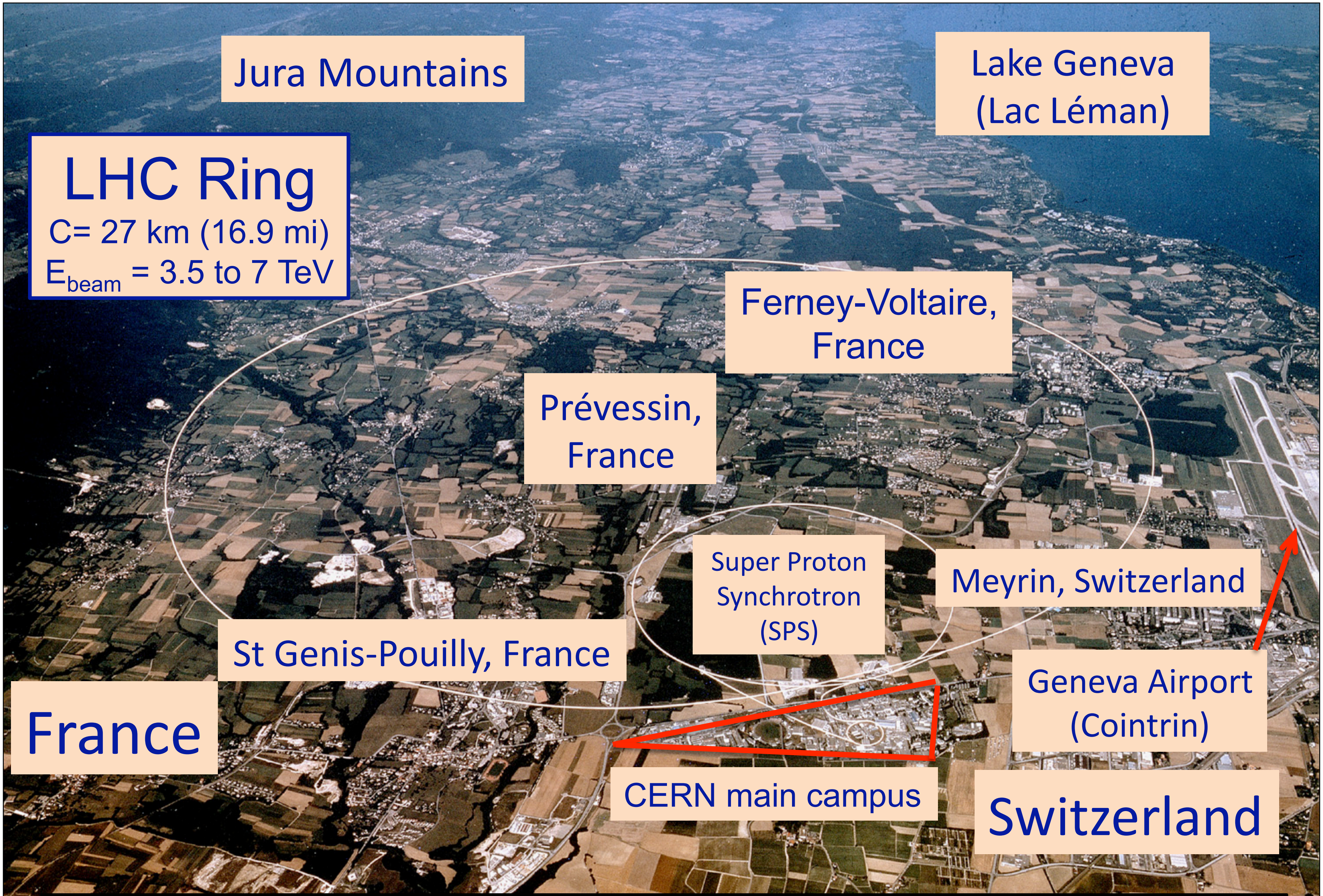
Exploring the TeV Energy Scale at the Large Hadron Collider



UC Riverside Physics Department Colloquium, April 7, 2011

Jeffrey D. Richman
Department of Physics
University of California, Santa Barbara



CERN: European Organization for Nuclear Research

Over Lac Léman (Lake Geneva)
View towards the east (Switzerland)

Over the Rhône River
View towards the west (France)

A few questions about the science...

- Why is the TeV (10^{12} eV) energy scale interesting?
- What is supersymmetry? What is the Higgs boson?
- What does this have to do with cosmology, astrophysics, and dark matter?
- How does the accelerator work? Why are we colliding protons rather than other types of particles?
- What happens when protons collide?
- How do the detectors work? What do they measure?
- How do the results look so far? What would a discovery look like?

Questions about life at the LHC...

- How are the collaborations organized? Is there a lot of politics?
- How did we build the experiments?
- What is it like to be a graduate student? Is it fun?
- What is the connection between the LHC and the early development of the World Wide Web?
- Why am I in my pajamas for meetings every week? How do I hide this from my colleagues?
- What is going to happen in the next couple of years?
- How is the food at CERN? How late is the cafeteria open?

Experimentalists vs. Theorists

- Theorists ask…
  - How will we know if the New Physics is SUSY?
  - How will we determine mass scale…and the full spectrum?
  - How will we determine the underlying Lagrangian?
- What experimenters think about…
  - Is there a leak? Will the trigger really work?
  - How much calorimeter noise is there?
  - How big is the QCD background?
  - <u>How can we be sure that an excess of events is not just due to tails of distributions from SM processes?</u>

Particles of the Standard Model

the stuff we mostly know about…

QUARKS (J=1/2)

u up	c charm	t top	$q = +\frac{2}{3}\lvert e\rvert$
d down	s strange	b bottom	$q = -\frac{1}{3}\lvert e\rvert$

LEPTONS (J=1/2)

e^- electron	μ^- muon	τ^- tau
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

GAUGE BOSONS (J=1)

Strong Int.	EM Int.	Weak Interactions		
g	γ	Z^0	W^+	W^-
gluon (8)	photon	Z boson	W bosons	

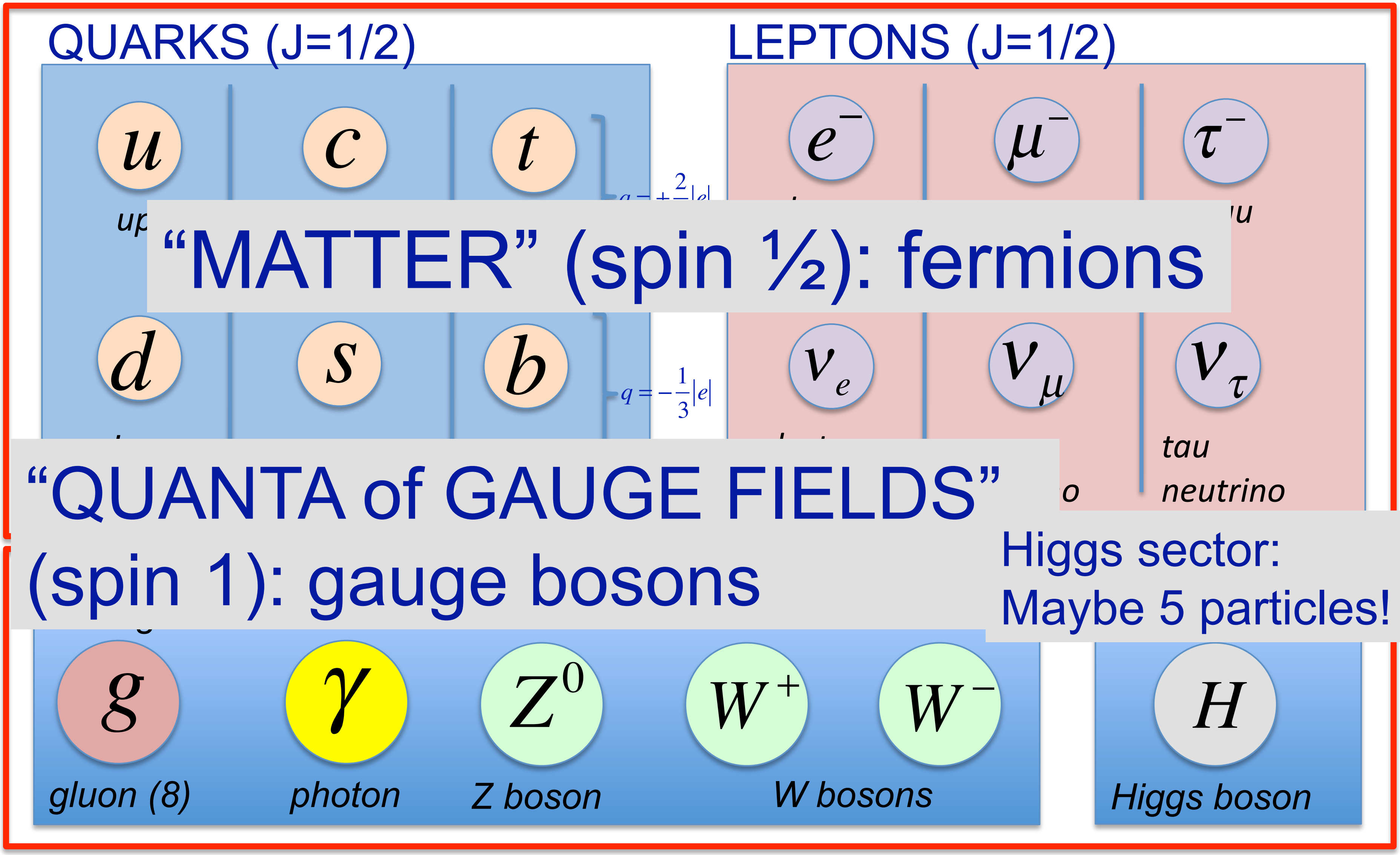
Higgs boson (J=0)

and vacuum expectation value

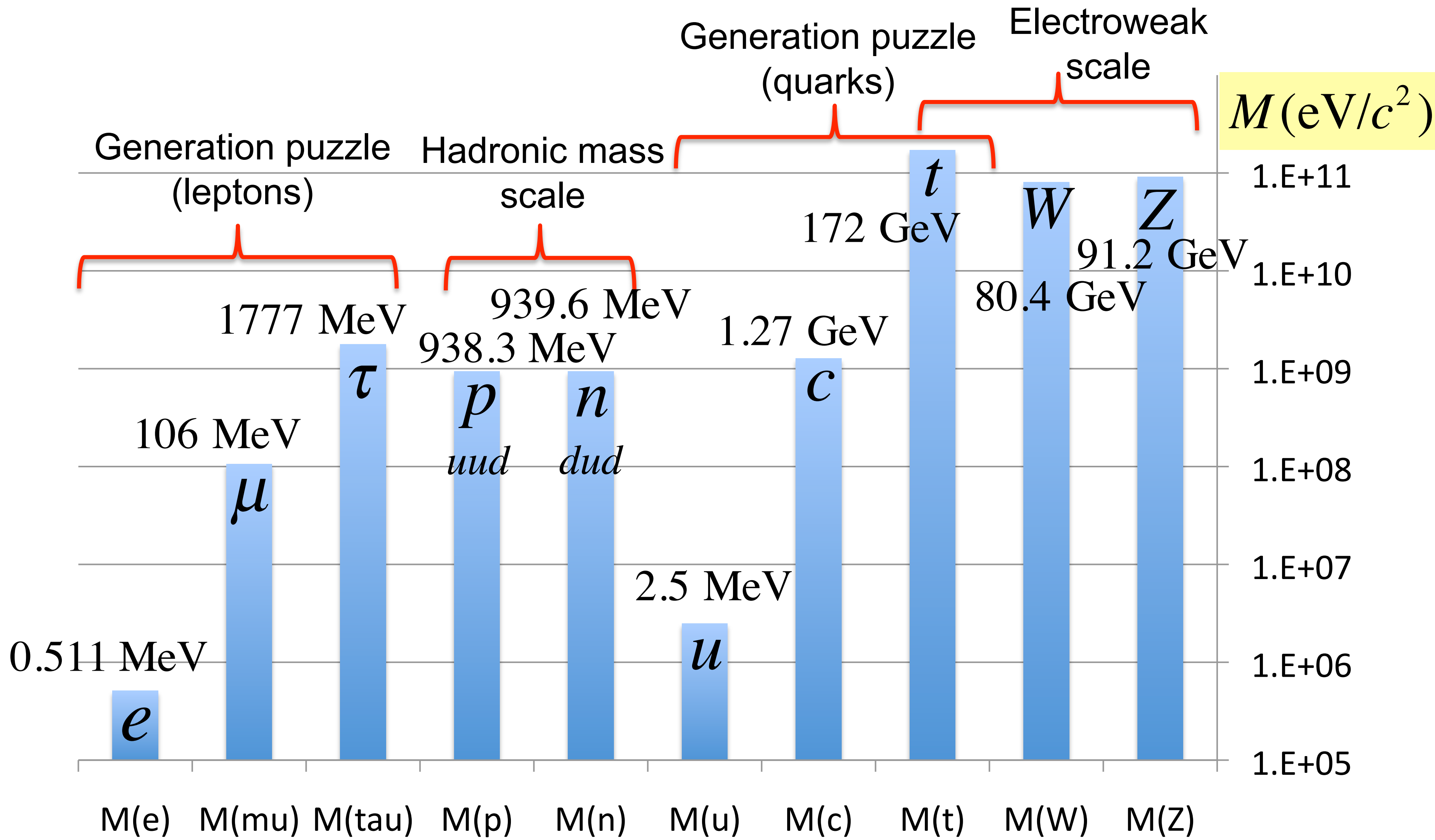
H

Higgs boson

Particles of the Standard Model



Mass scales in particle physics



$m(\nu) \sim 1$ eV? Si band gap: $\simeq 1.1$ eV $m(\tilde{g}) \sim 1$ TeV? $M_P \sim 10^{19}$ GeV

The hypothesis of *supersymmetry*

scalar QUARKS "squarks" (J=0)

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

$q = +\frac{2}{3}|e|$ (up, charm, top)

$q = -\frac{1}{3}|e|$ (down, strange, bottom)

scalar LEPTONS "sleptons" (J=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

GAUGE BOSON PARTNERS (J=1/2)

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

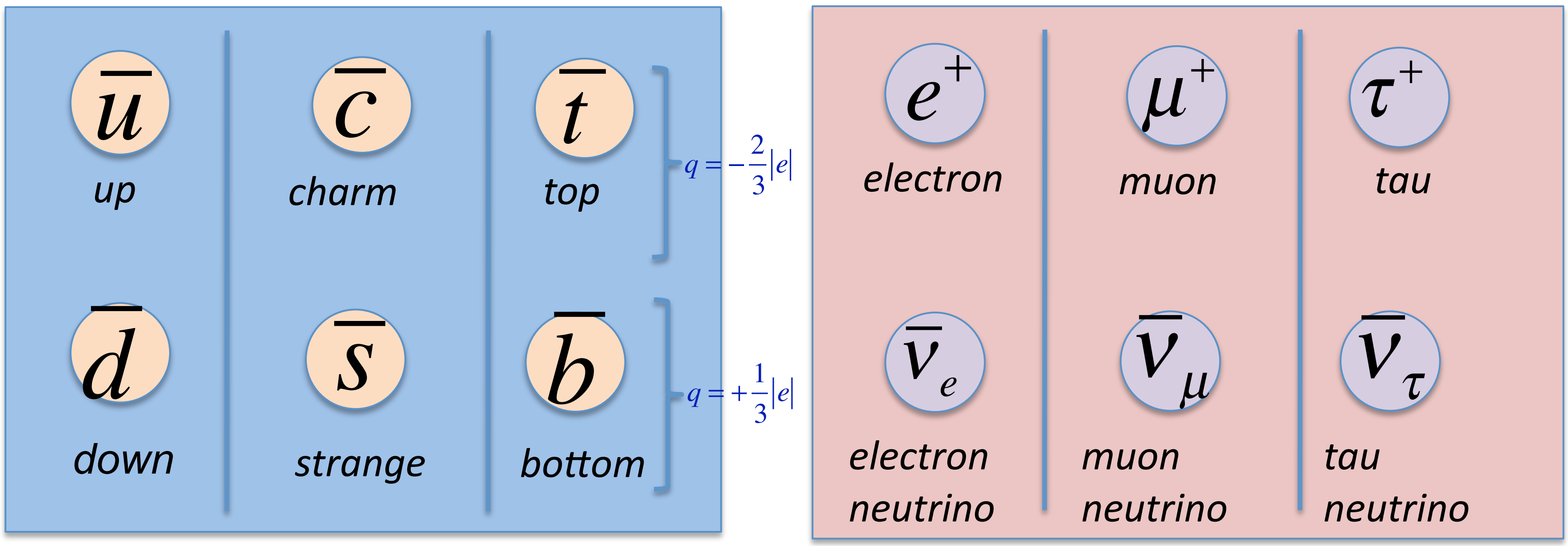
Higgsinos (J=1/2)

$\tilde{H}^0, \tilde{H}^\pm, \tilde{h}^0, \tilde{A}^0$

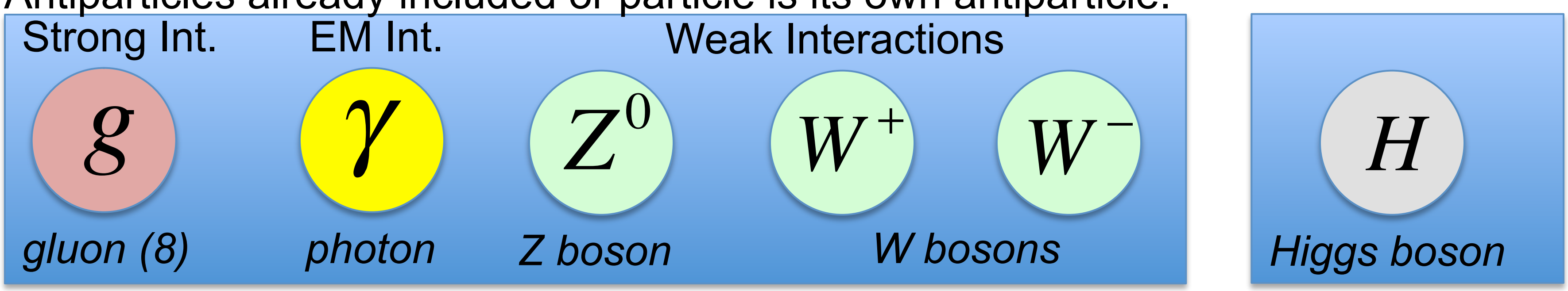
Higgs partners

Matter and anti-matter

For every type of particle, there is a corresponding type of antiparticle. These have all been observed. However, the particle vs. antiparticle content of the universe is extremely asymmetric!

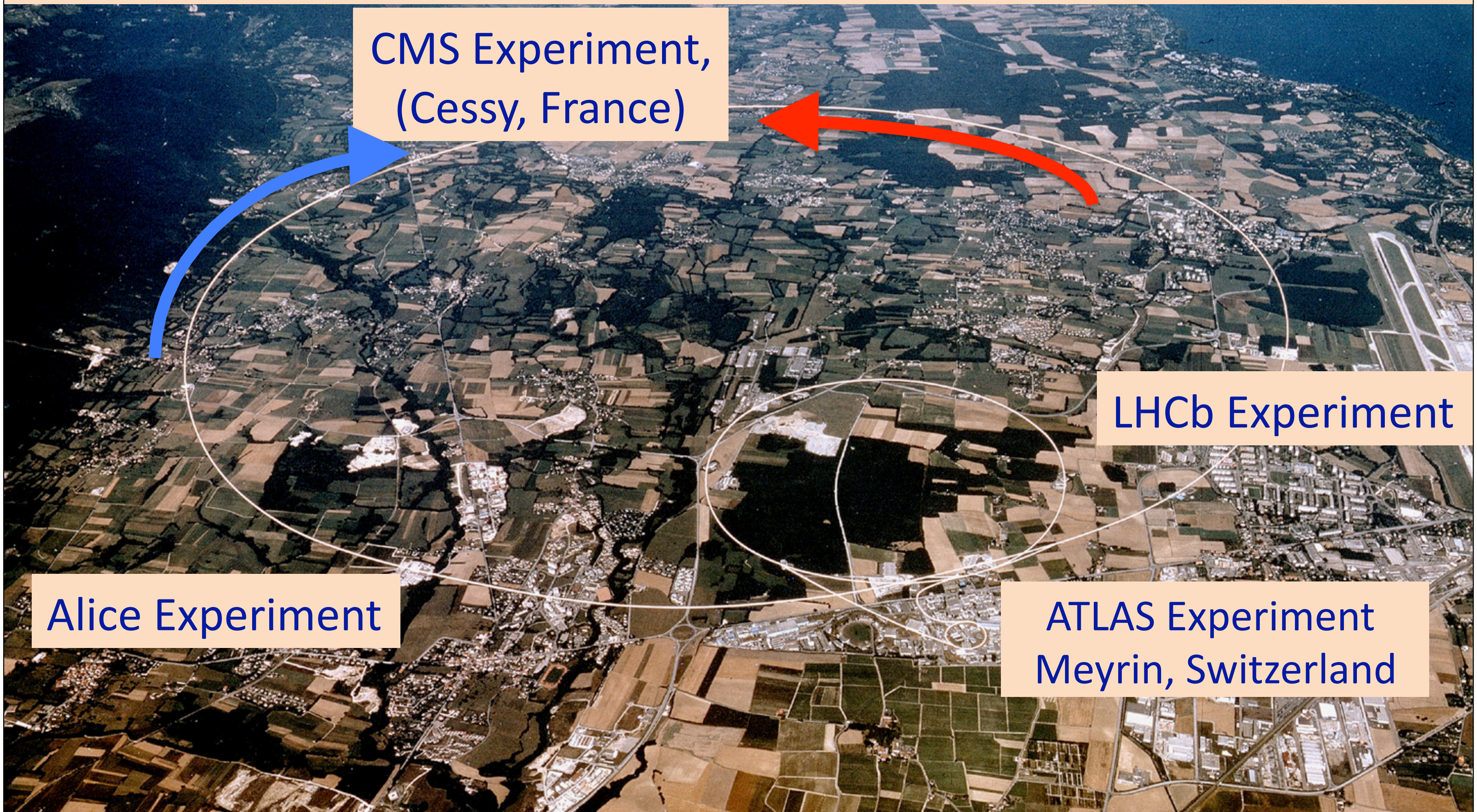


Antiparticles already included or particle is its own antiparticle.



LHC ring:

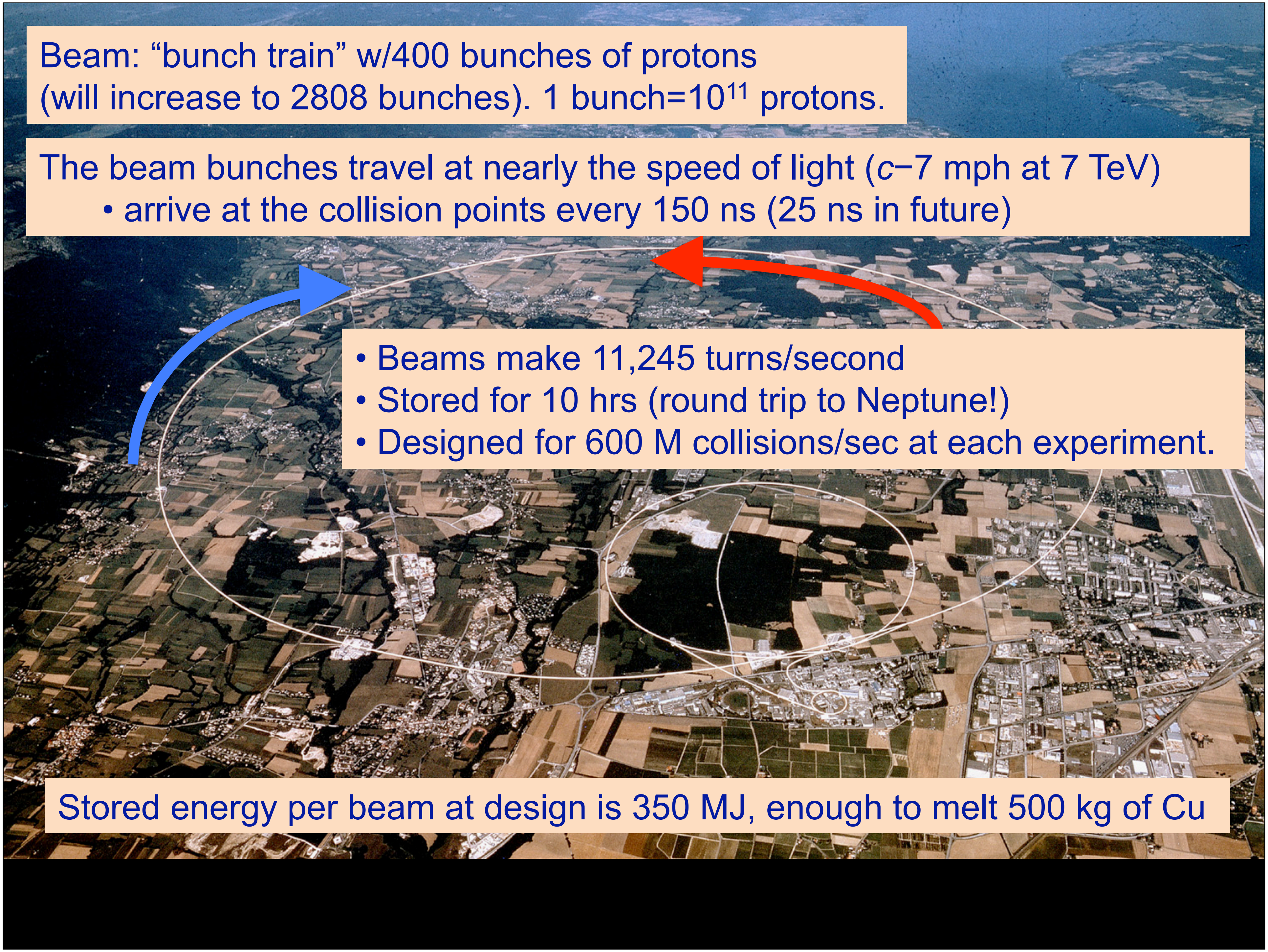
- 2 separate magnetic “highways”; 9593 magnets, incl. 1232 15-meter dipoles.
- Radio-frequency EM cavity devices to accelerate beams (8/beam; 40 MHz)



Beam: “bunch train” w/400 bunches of protons (will increase to 2808 bunches). 1 bunch=10^{11} protons.

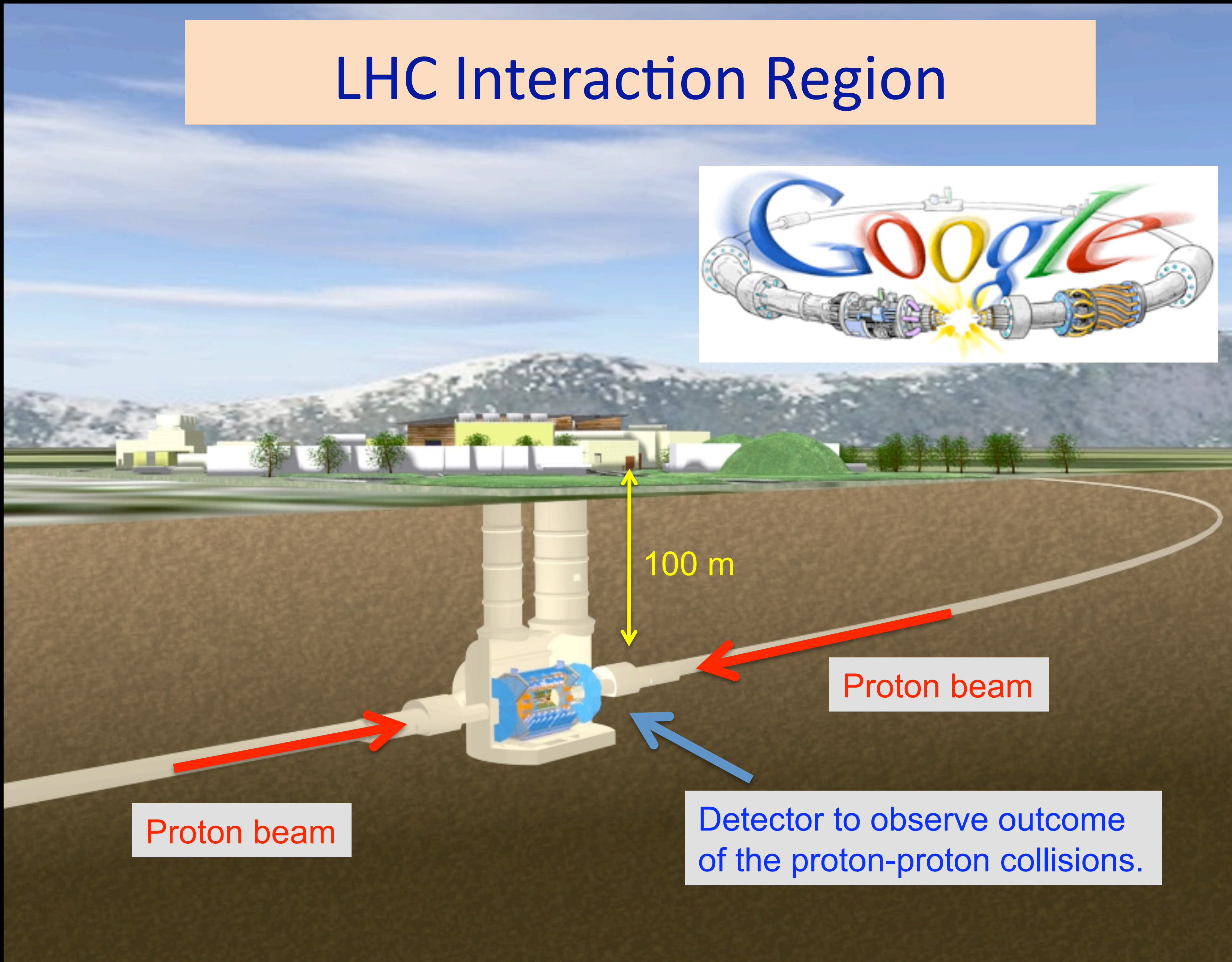
The beam bunches travel at nearly the speed of light (c−7 mph at 7 TeV)

- arrive at the collision points every 150 ns (25 ns in future)



- Beams make 11,245 turns/second
- Stored for 10 hrs (round trip to Neptune!)
- Designed for 600 M collisions/sec at each experiment.

Stored energy per beam at design is 350 MJ, enough to melt 500 kg of Cu


LHC Interaction Region
100 m
Proton beam
Proton beam
Detector to observe outcome of the proton-proton collisions.

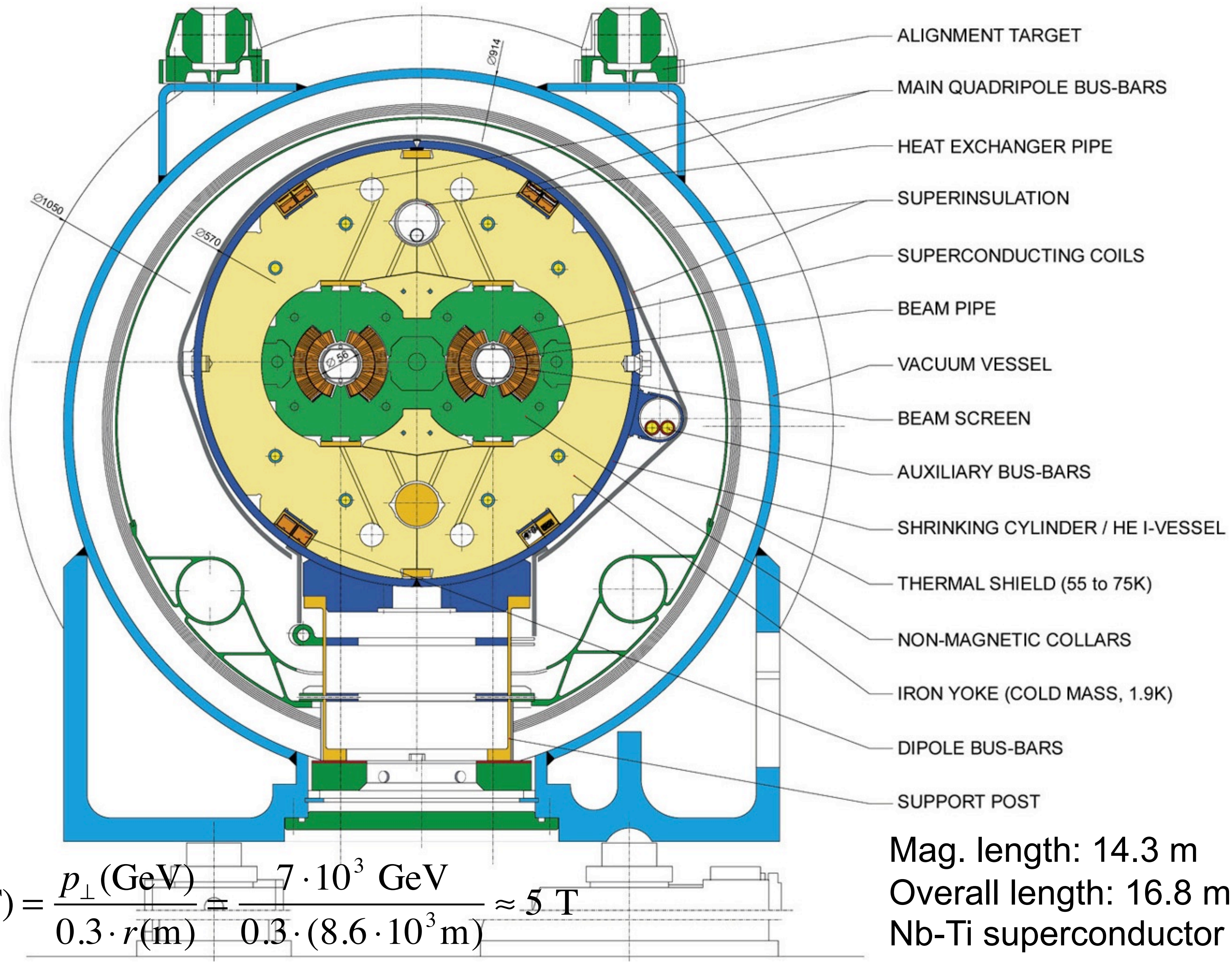
Inside the LHC Tunnel

Inside the LHC Tunnel

Total magnets	9593
Num. main dipoles	1232 (L=15 m)
Num. main quads	392 (L= 5 to 7 m)
RF cavs/beam	8
Bunches/beam	2808
Protons/bunch	$1.1\ 10^{11}$
Collisions/sec	$600\ 10^{6}$
Bunch spacing (min.)	7 m (25 ns)
Dipole field	8.33 T
Dipole op. temp.	1.9 K
Dipole current	11,850 A
Design luminosity	$10^{34}\ cm^{-2}s^{-1}$

LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DI/MM - HE107 - 30 04 1999



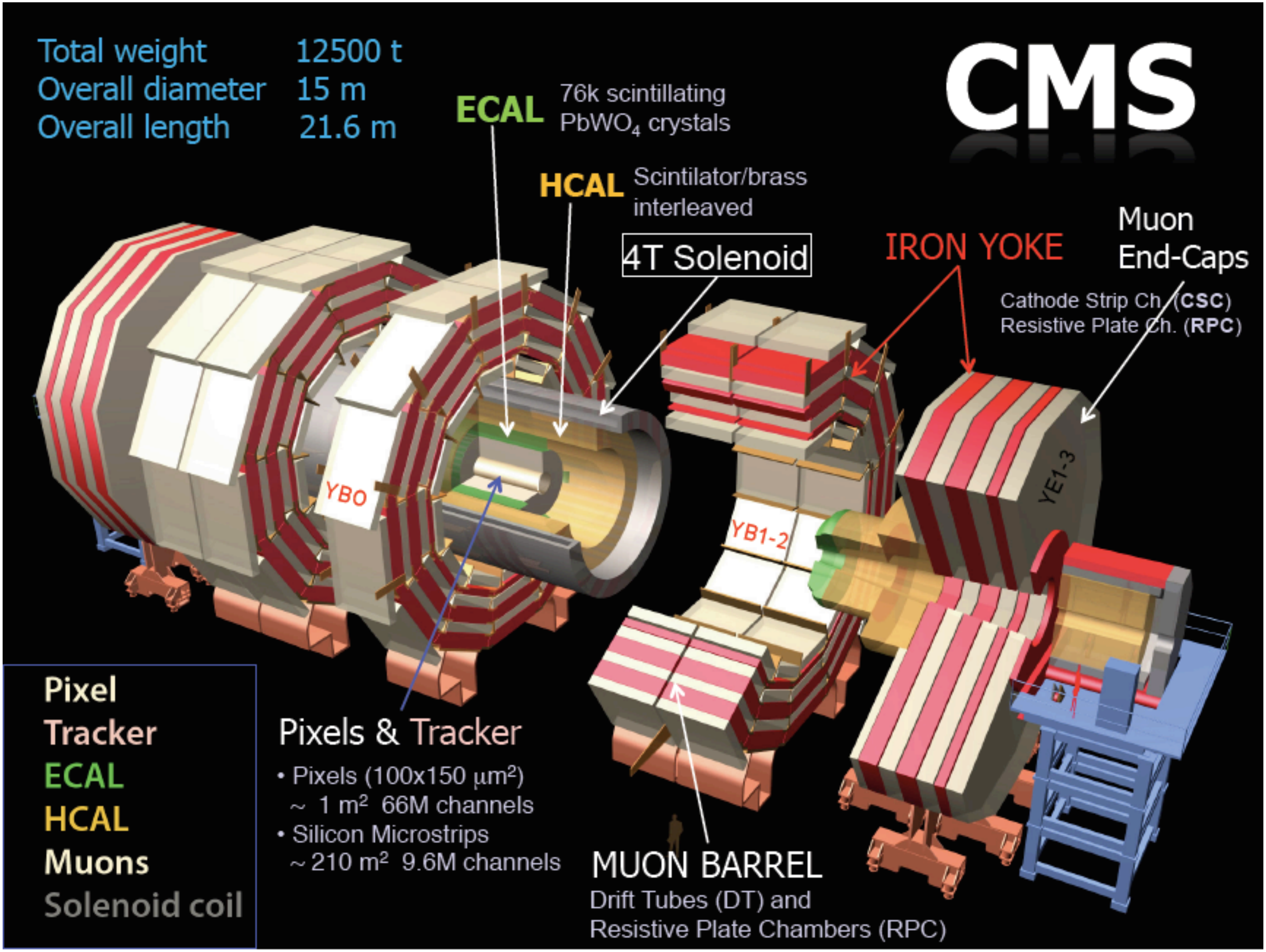
$$B(\mathrm{T}) = \frac{p_{\perp}(\mathrm{GeV})}{0.3 \cdot r(\mathrm{m})} = \frac{7 \cdot 10^{3}\ \mathrm{GeV}}{0.3 \cdot (8.6 \cdot 10^{3}\,\mathrm{m})} \approx 5\ \mathrm{T}$$

Mag. length: 14.3 m
Overall length: 16.8 m
Nb-Ti superconductor

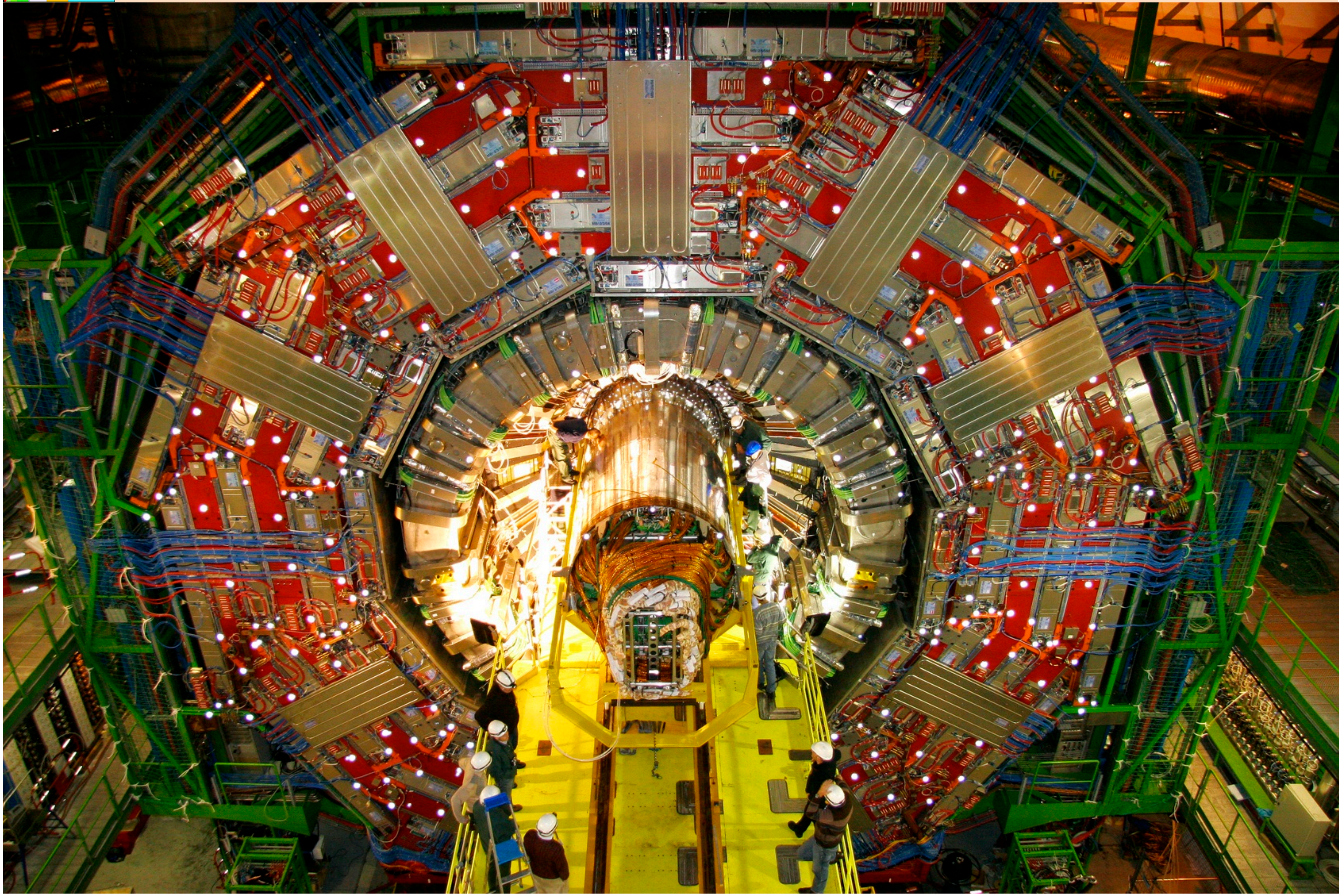
LHC Control Room: Hollywood Version

Angels and Demons, © Sony pictures.
(BTW, they also make computer displays).

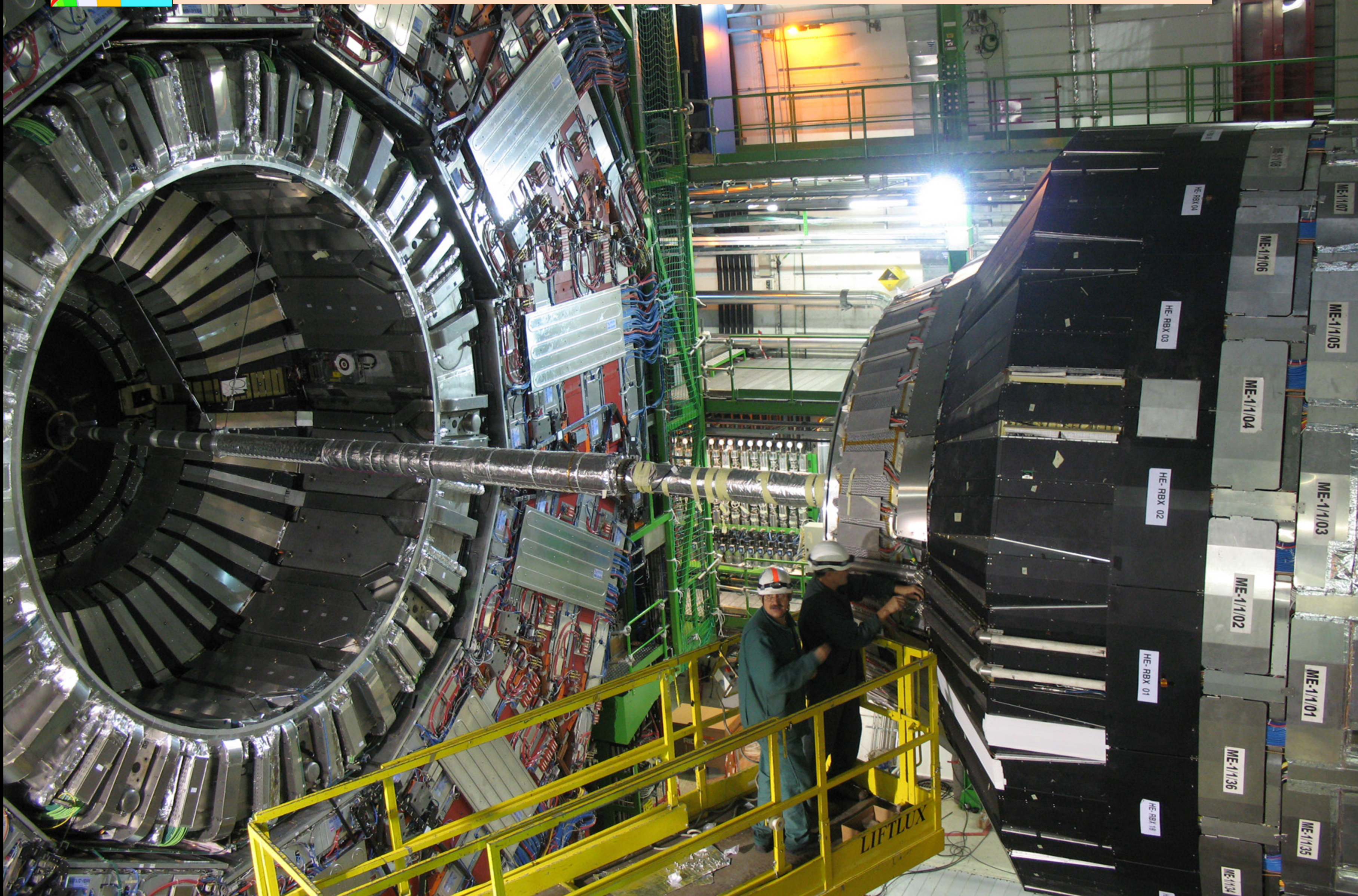
LHC Control Room: the real thing


Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m
CMS
ECAL
76k scintillating PbWO4 crystals
HCAL
Scintilator/brass interleaved
4T Solenoid
IRON YOKE
Muon End-Caps
Cathode Strip Ch. (CSC)
Resistive Plate Ch. (RPC)
YB0
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm²) ~ 1 m² 66M channels
• Silicon Microstrips ~ 210 m² 9.6M channels
MUON BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)

CMS Silicon Tracker Installation: Dec 2007

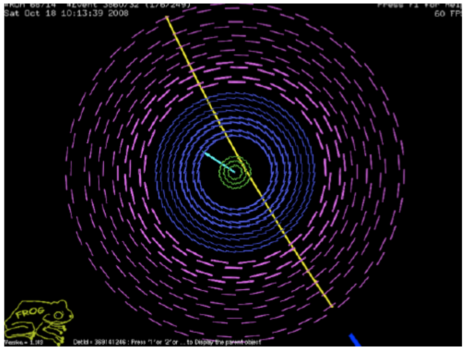


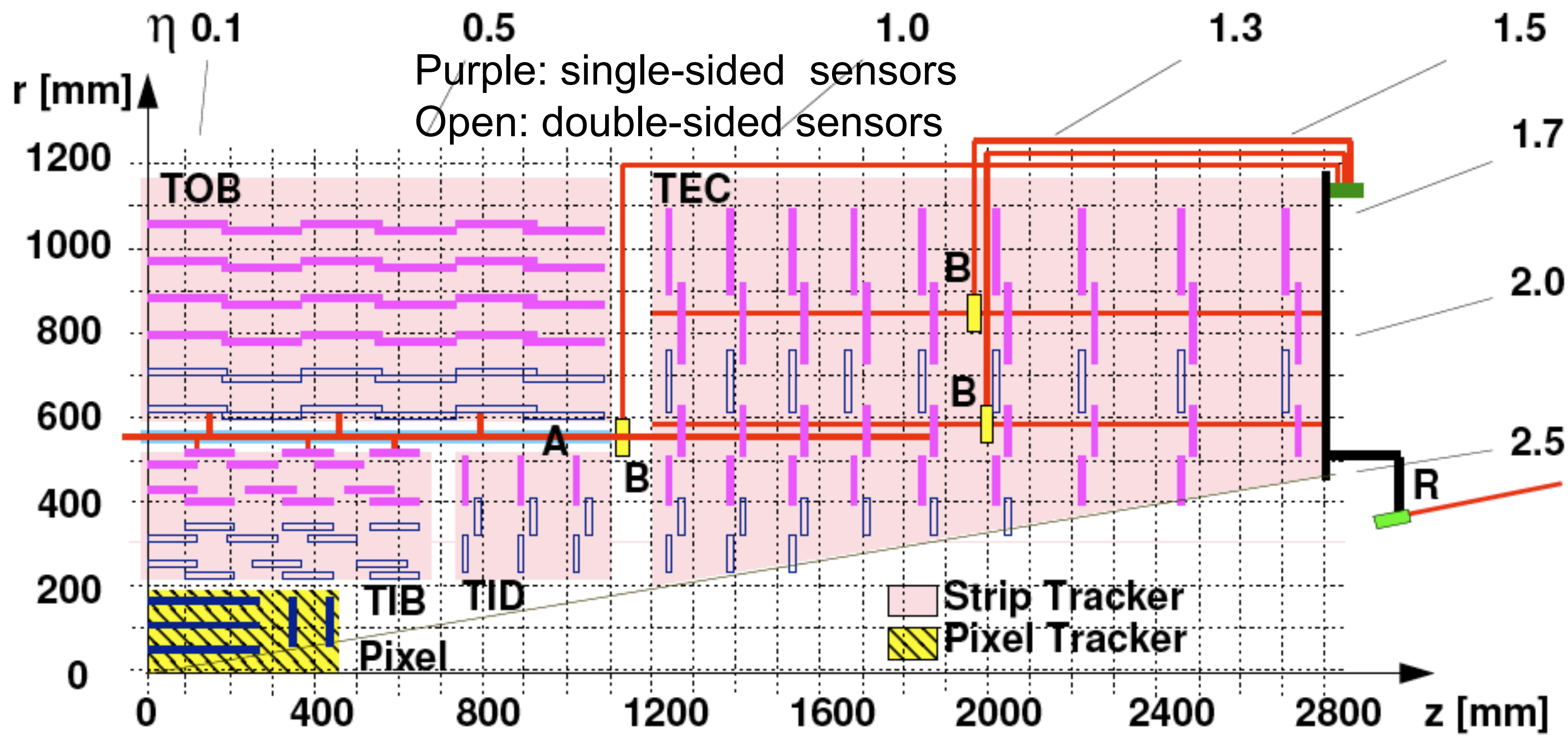
CMS Detector with Accelerator Beam Pipe



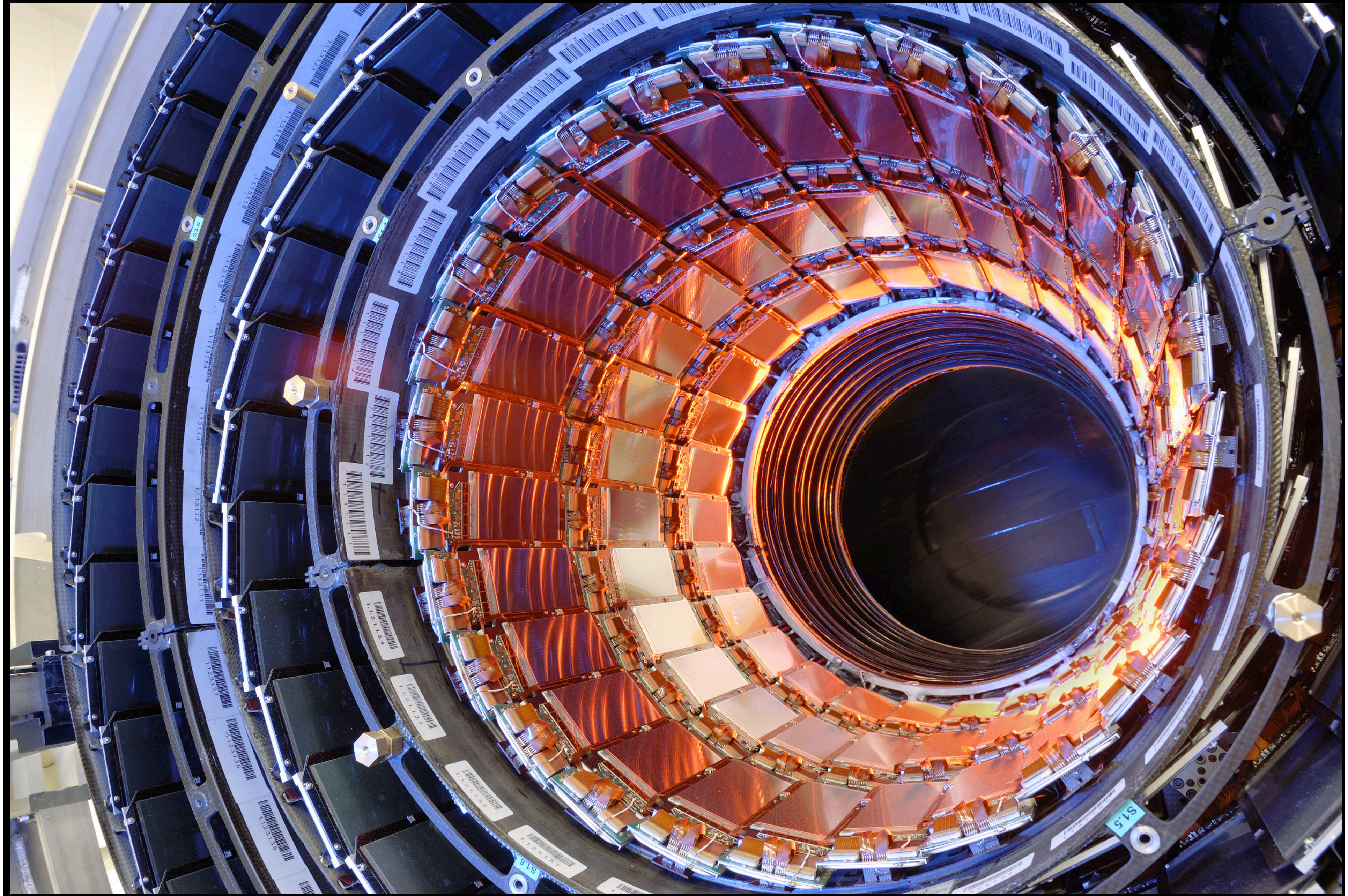
CMS Tracker: Silicon Strips

- Largest silicon tracker ever built: ~200 m^2
- Inner+outer barrel: 4+6 layers; 10-14 points
- 9.3 M strips, pitch 80-180 μm; 97.2% working
- Sensor thickness: 320 μm; 500 μm





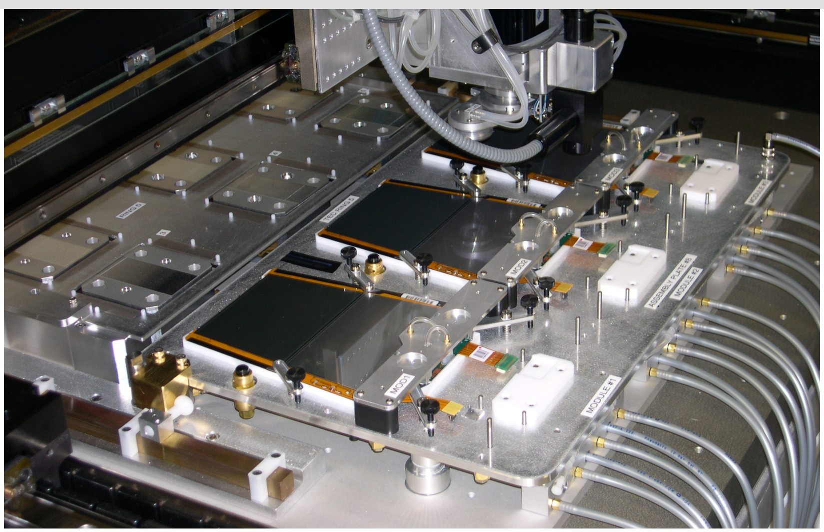
CMS Silicon-Strip Particle Tracking Detector



Working on the CMS Silicon Strip Tracker

UCSB silicon-strip module assembly team

Module construction on gantry



Module installation at CERN

Collisions at 7 TeV

http://cdsweb.cern.ch/journal/CERNBulletin/2010/14/News%20Articles/1246424?ln=fr

http://press.web.cern.ch/press/PressReleases/Releases2010/PR07.10E.html

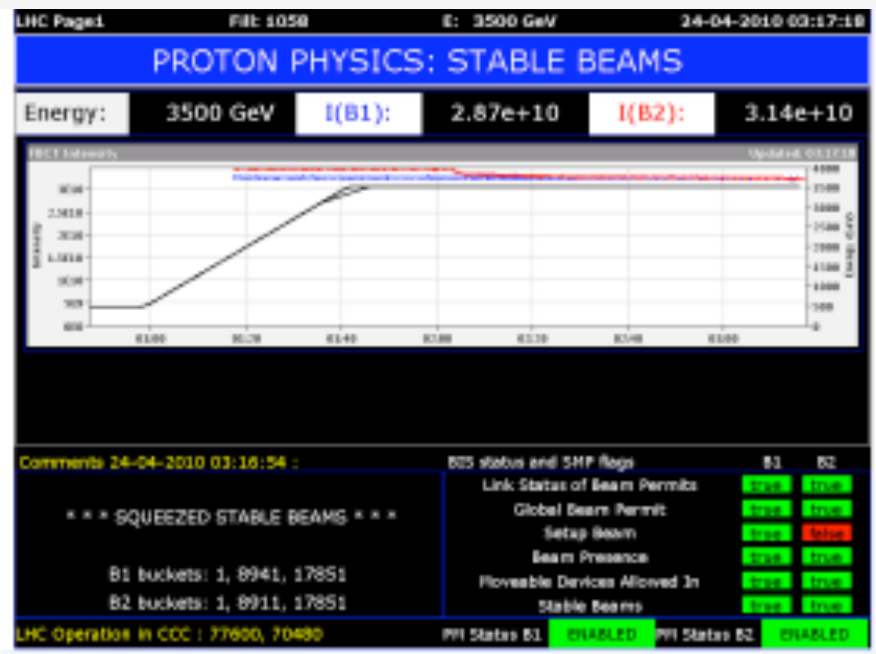
Nous avons réussi !

Presque 20 années de travail acharné accompli par des centaines de personnes ont permis au Grand collisionneur de hadrons (LHC) de passer du rêve à la réalité. Le LHC a livré aujourd'hui

March 30, 2010: 1st 7 TeV Collisions

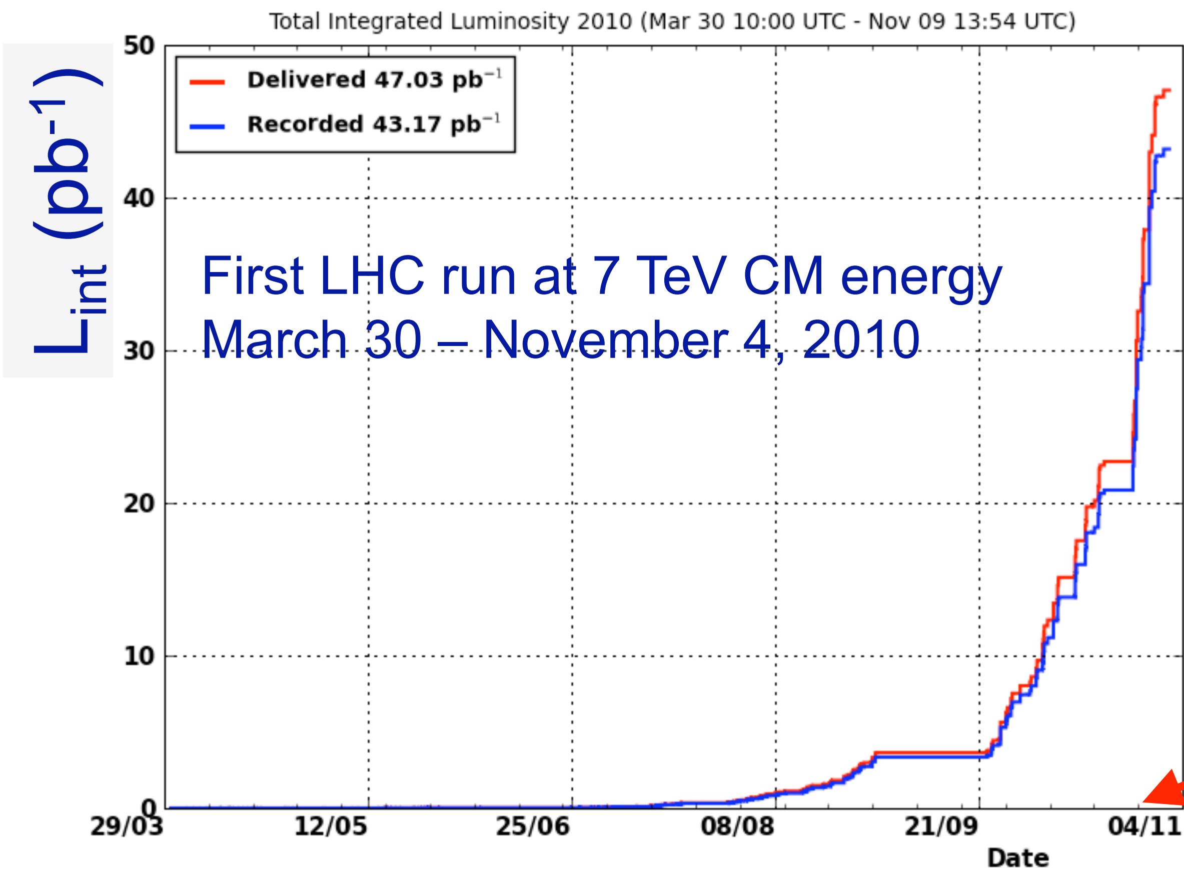
Il y a quelques instants à la CCC

May 1-2, 2010, squeezed, stable beams (30 hrs), $L>1.1\times 10^{28}$ $cm^{-2}s^{-1}$



http://cdsweb.cern.ch/journal/CERNBulletin/2010/18/News%20Articles/1262593?ln=en

CMS *Integrated Luminosity* vs. Time



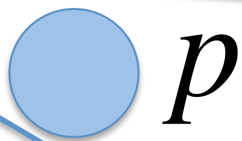
pb^{-1} = events/pb

4 November 2010

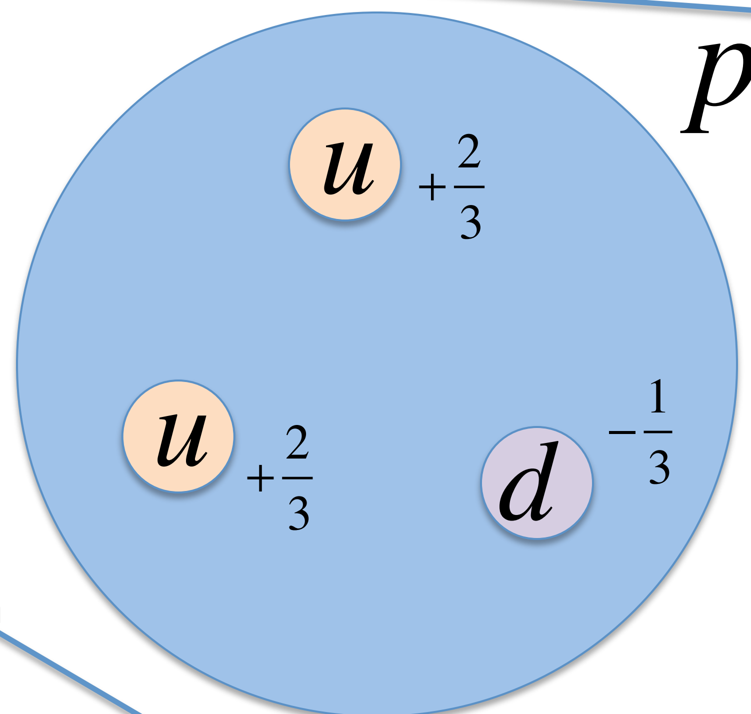
Example: in some SUSY model, the cross section is 40 pb; we would then have

$$N_{events} = 43.17 \text{ pb}^{-1} \cdot 40 \text{ pb} = \text{ 1727 events produced}$$

A first look inside of the proton



Quarks!



$$r_{proton} \approx 10^{-13}\ \text{cm}\ = 1\ \text{fm}$$

$$A_{geom} \approx \pi r_{proton}^2 \approx 30 \cdot 10^{-27}\ \text{cm}^2 = 30\ \text{mb}$$

sets the scale for the total cross section

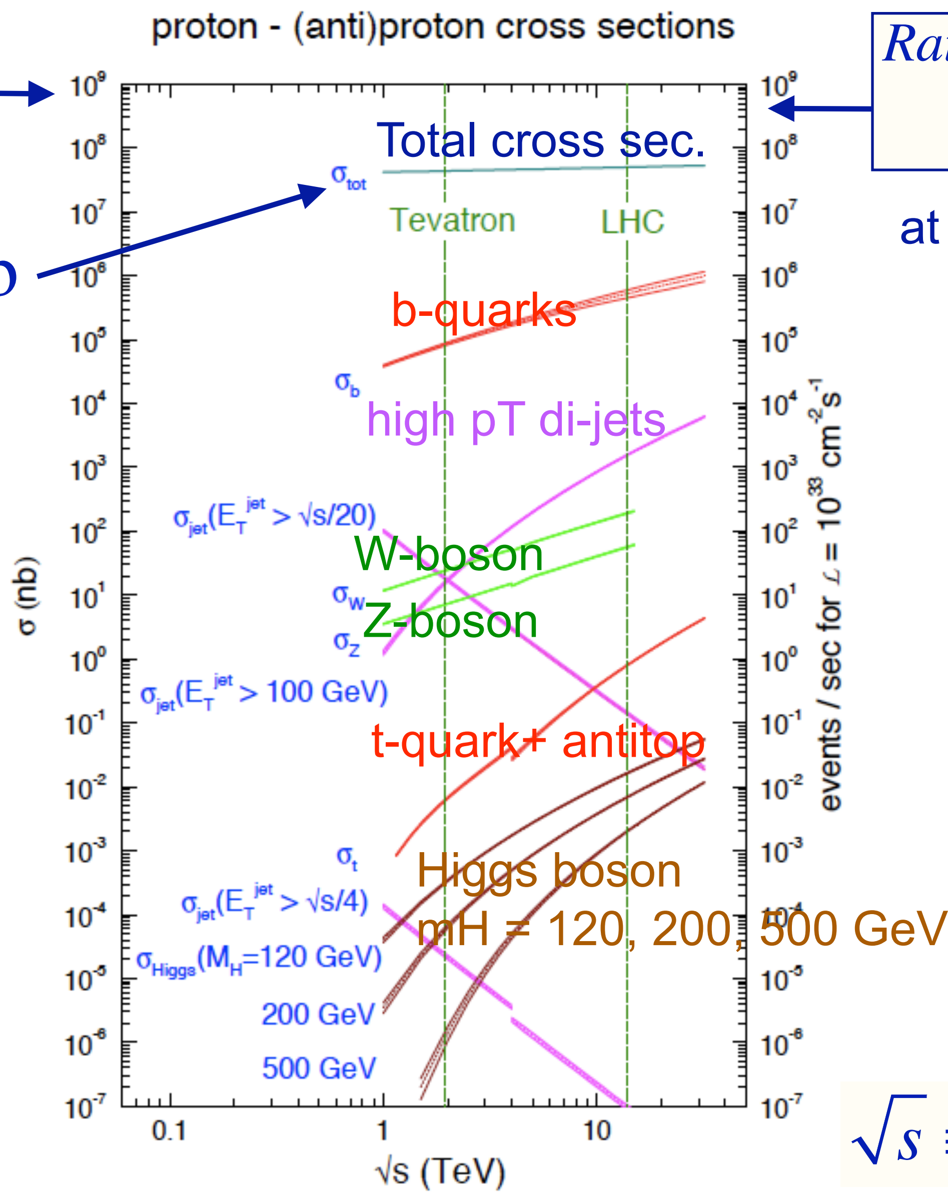
Rest energy (mass) of proton: 0.9 GeV
Energy of proton in LHC beam: 3,500 GeV
<u>Constituent particles of proton share this energy.</u>

$$p = udu$$
$$n = dud$$

Cross section vs. cm Energy in p + p

$\sigma(pp)$

$\sigma_{TOT} \sim 50$ mb



$$Rate(process\ i) = L_{accel} \cdot \sigma(process\ i)$$

at $L_{accel} = 10^{33}$ cm^{-2} s^{-1}

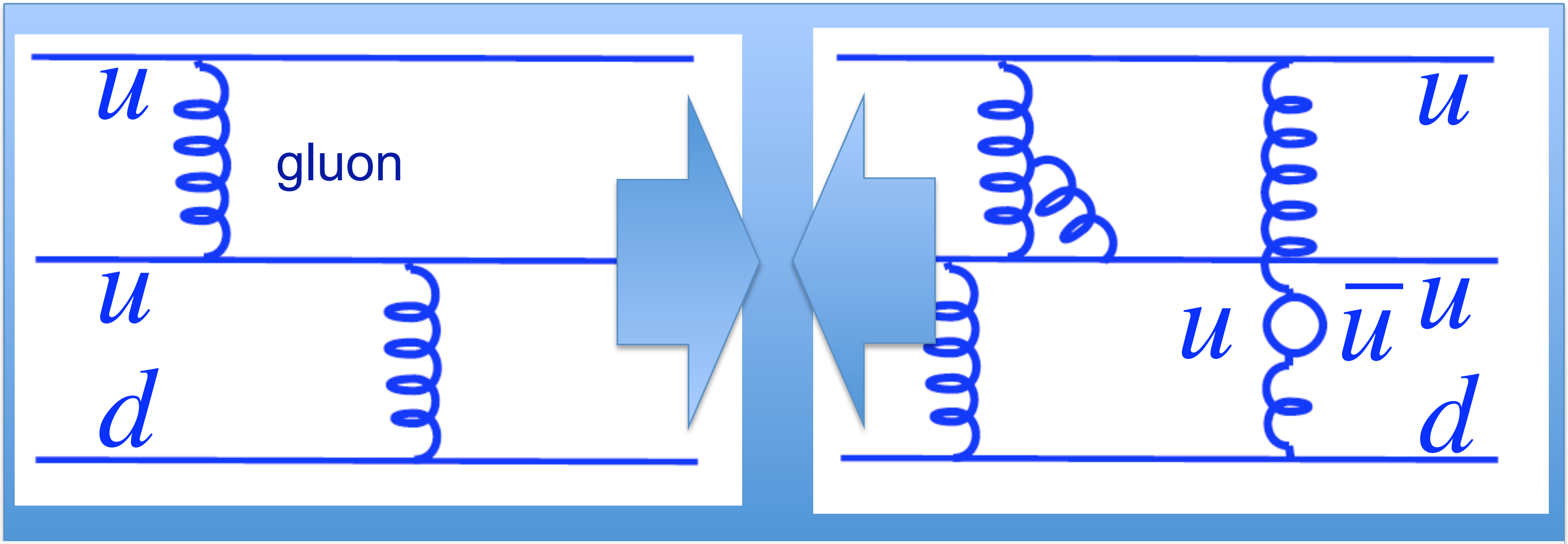
In 2010, achieved
$L_{accel} = 2 \cdot 10^{32}$ cm^{-2} s^{-1}

In 2011, may reach
$L_{accel} = 5 \cdot 10^{33}$ cm^{-2} s^{-1}

$\sqrt{s} \equiv CM$ energy

Quarks interact inside a proton

Life is complicated inside a proton...so the collisions can be too!



- QCD = quantum chromodynamics: “strong” interactions of quarks & gluons (“color” charge).
- Gluons are the quanta that mediate the strong force, just as photons are the quanta of the EM force.

  (Nobel Prize 2004: Gross, Politzer, Wilczek)

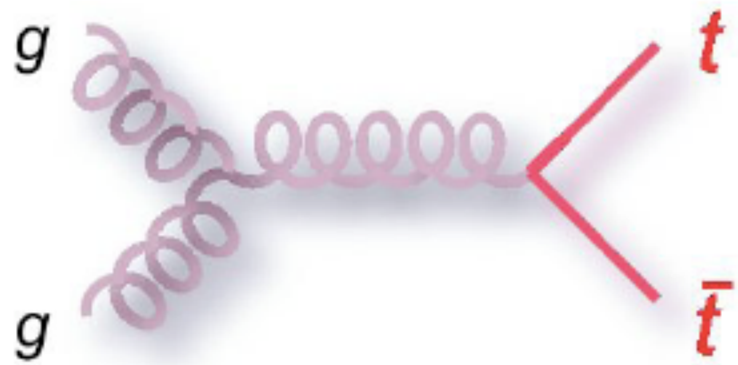
Hadron = particle made up of quarks & gluons ➔ “Hadron collider”

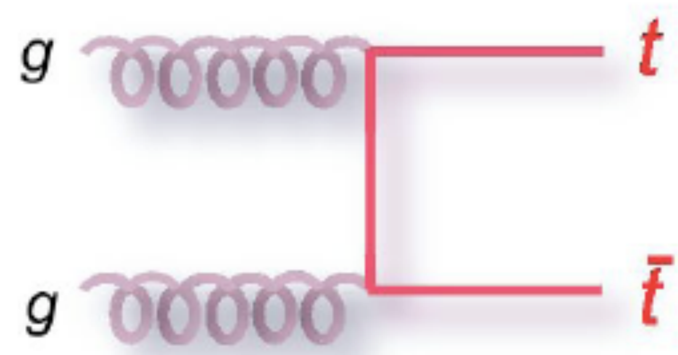
Feynman's Van: Particle Interactions

Example: production of top quarks

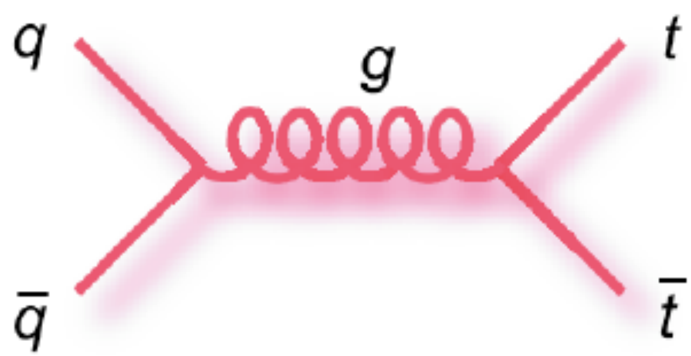
Strong interaction process, but suppressed by m(t)≈175 GeV.

Gluon-gluon fusion: ~85%





Quark-antiquark annihilation: ~15%

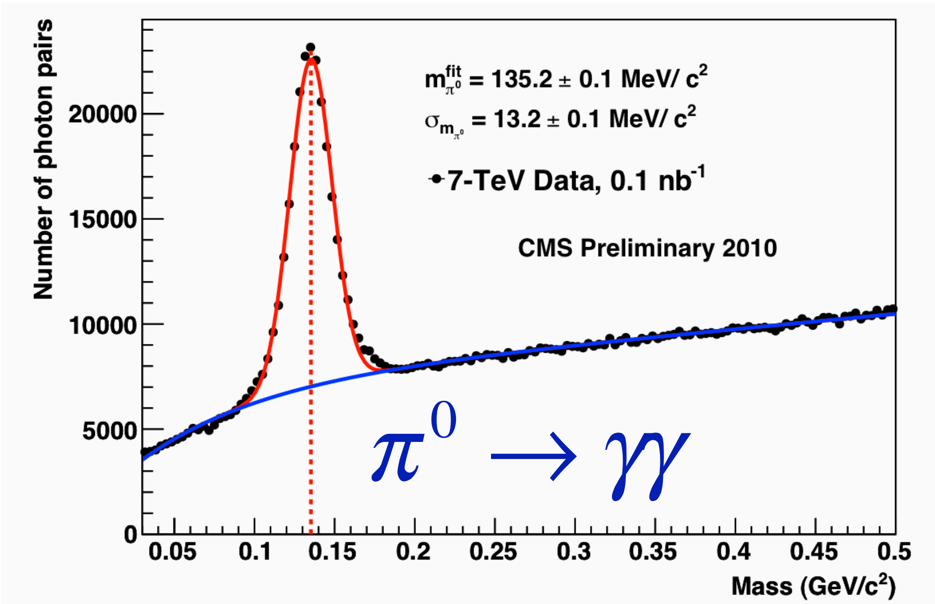


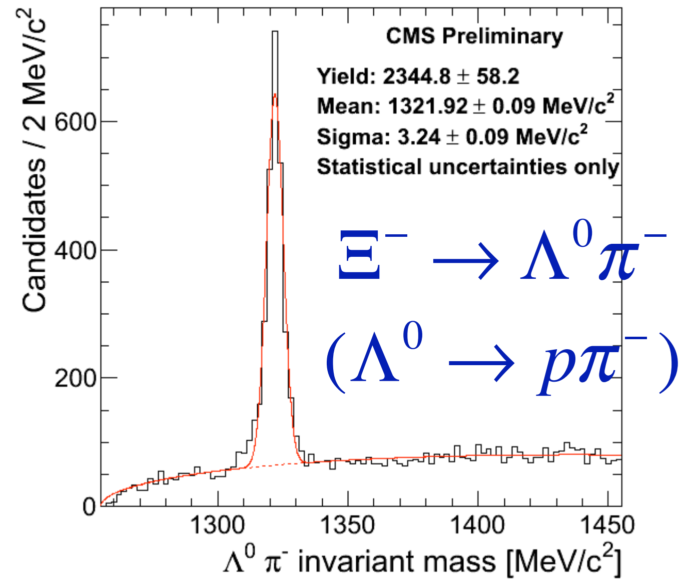
Unlike photons, which do not carry electric charge, gluons carry color charge and can couple directly to each other.

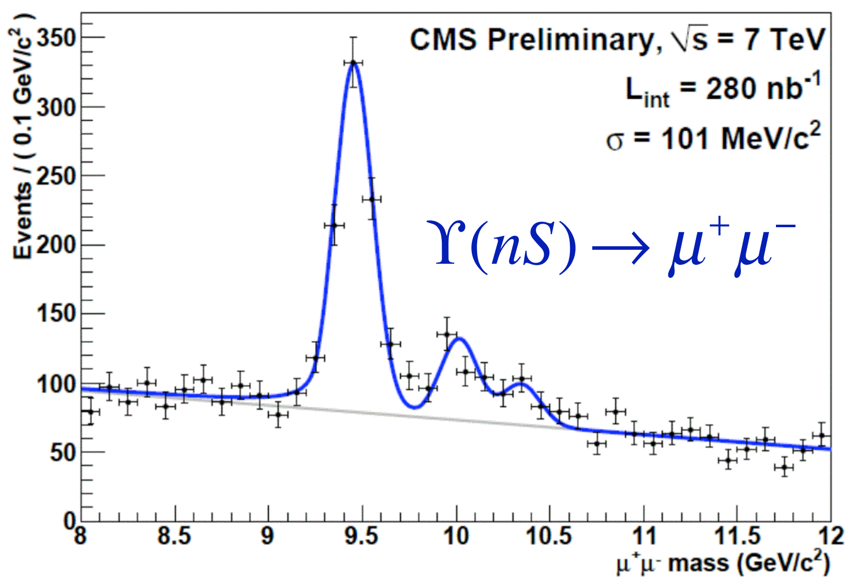
Strategies for detecting particles

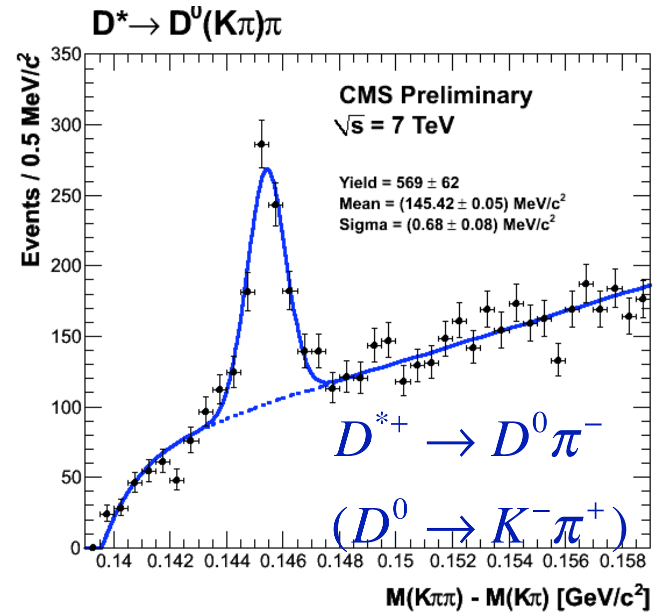
1. Neutrinos: weak interactions only – are escape artists, but their escape can be detected with momentum conservation → "Missing momentum".
2. Charged leptons: EM and weak interactions only; are your friends (e, mu); but tau decays in flight, so is tricky.
3. Photons: EM interaction in $PbWO_4$ crystals.
4. Quarks and gluons: strong, EM, & weak interactions form collimated sprays of particles called "jets" as the energy in the color field pair produces qq pairs.
5. Z, W bosons, and many other particles decay rapidly, within the beam pipe. Infer parent particle mass from 4-momenta of daughters: $m_{parent}^2 = (p_1 + p_2)^2$

A few well known mesons (qq̄) and baryons (qqq)

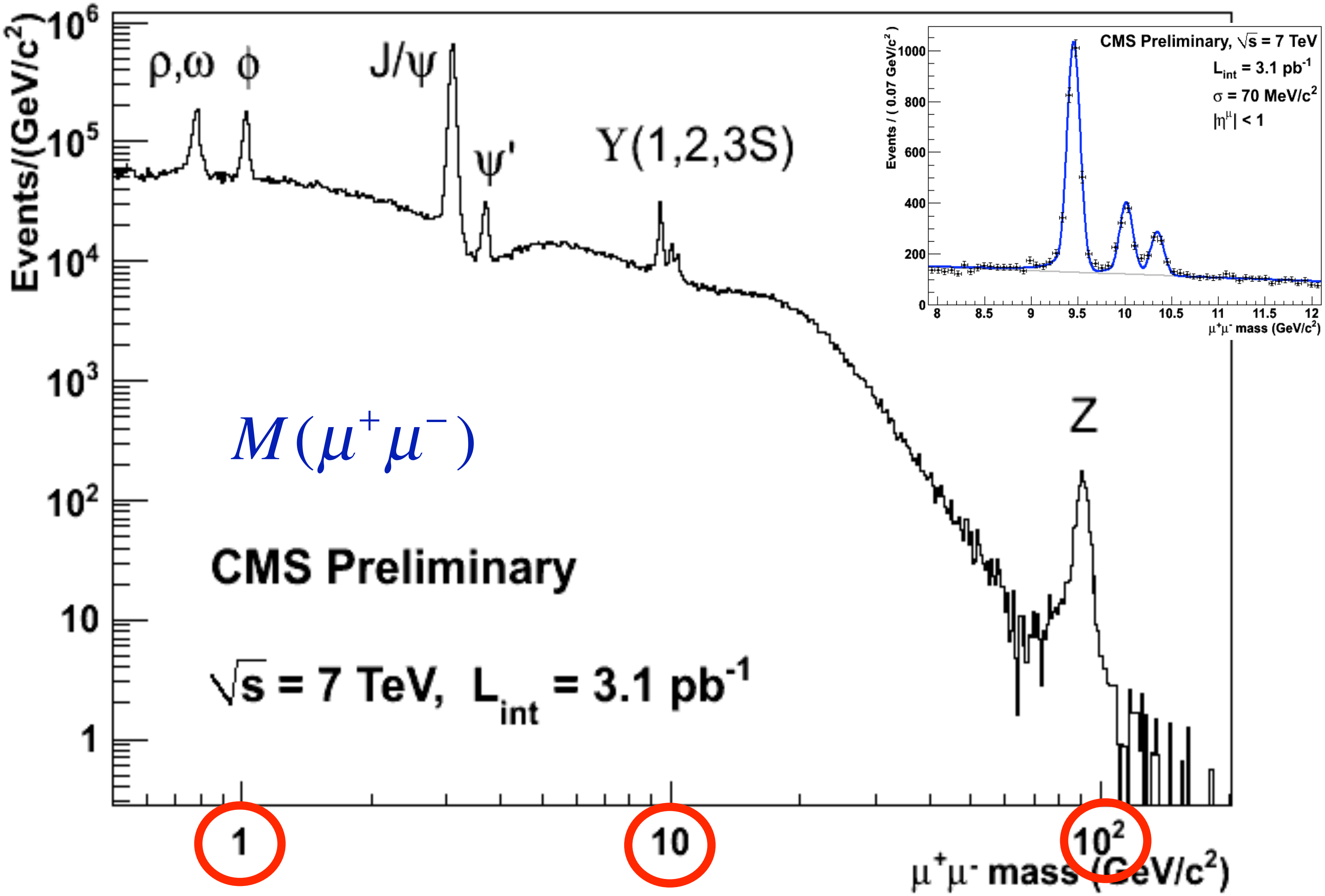






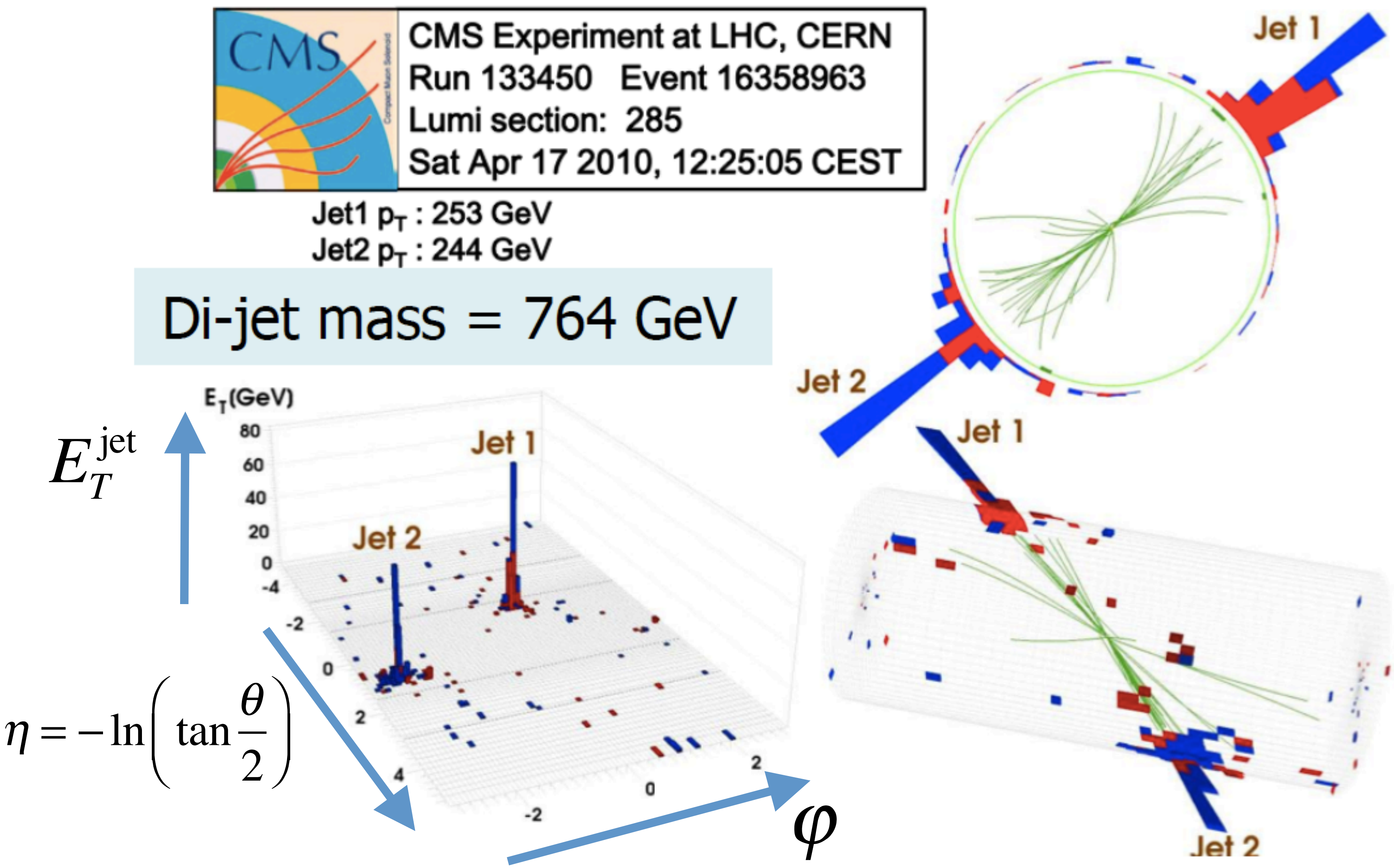


Particles decaying to $\mu^+\mu^-$ in CMS



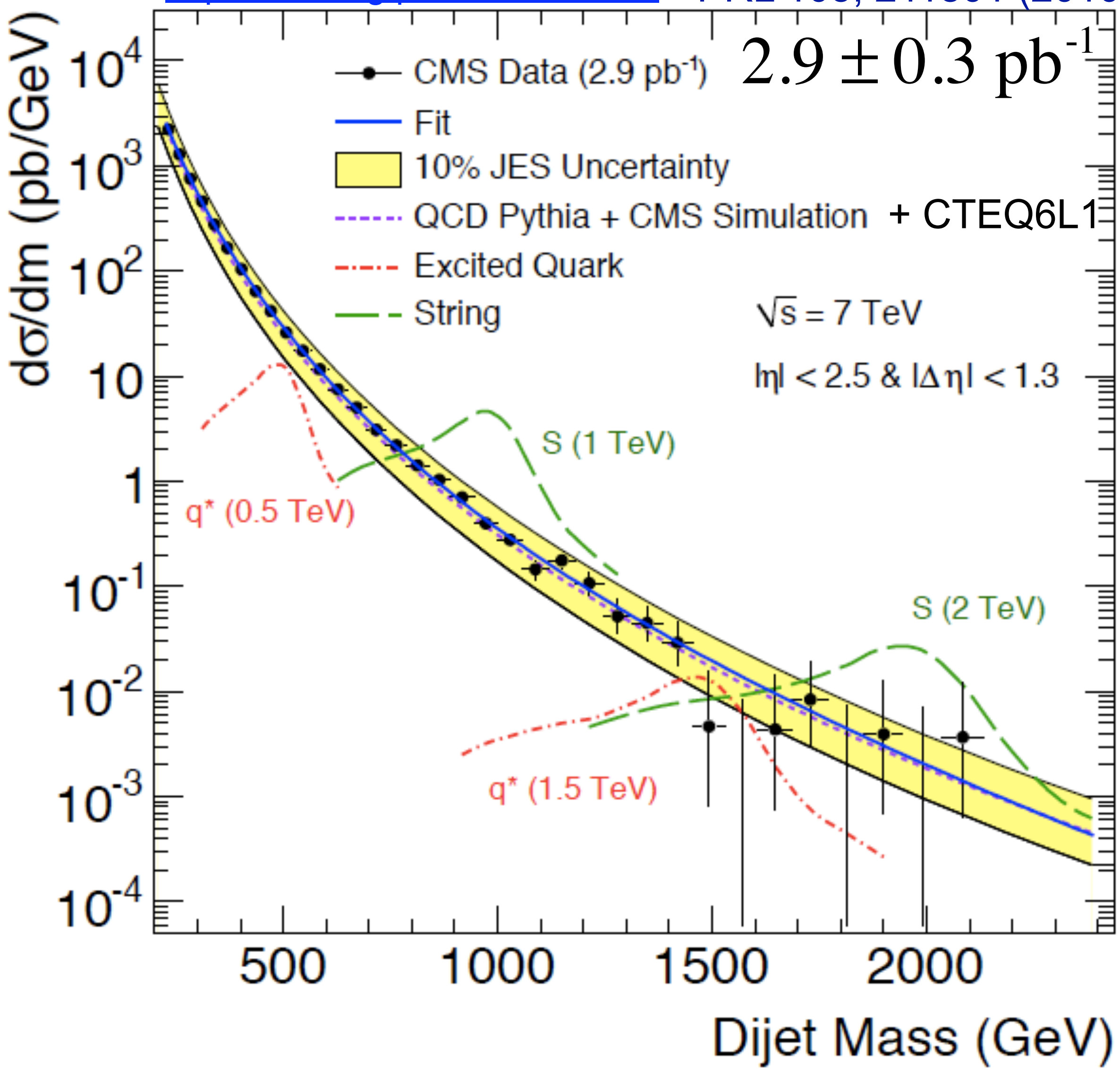
Di-jet Event at 7 TeV

Jet: collimated spray of particles from high momentum quark or gluon.



Search for X → gg, gq, $q\bar{q}$ in di-jet mass distribution

http://arxiv.org/pdf/1010.0203v1 PRL 105, 211801 (2010)



Use two highest pT jets in each event.

Compute di-jet invariant mass:

$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

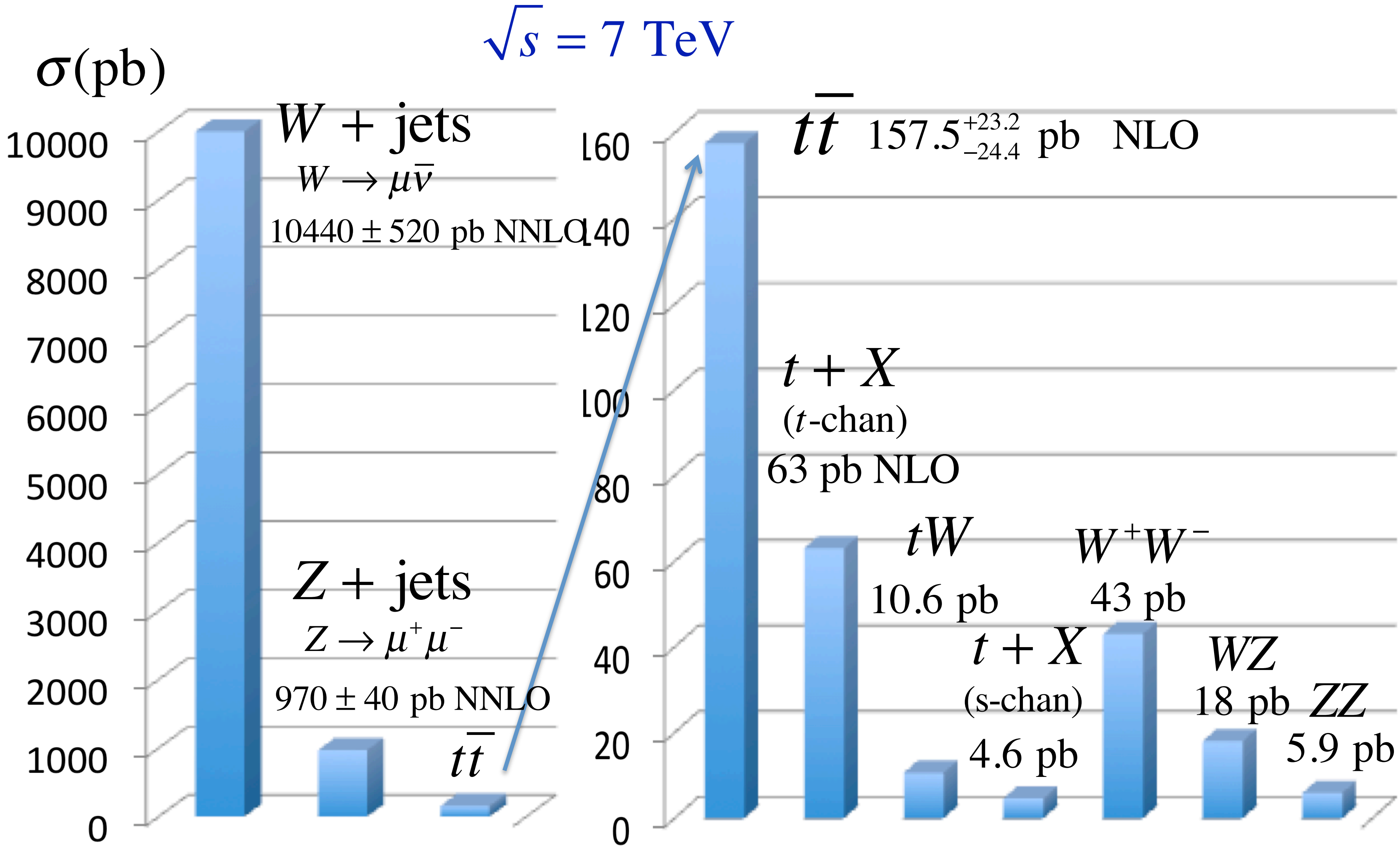
Mass distribution is well described by QCD di-jet production.

With current data, no evidence for particles decaying to dijets.

0.5<M(q*)<1.58 TeV excluded

Single-jet trigger, 50 GeV threshold; 99.5% efficient for M(jj)>220 GeV.

Cross Sections for Key SM Processes



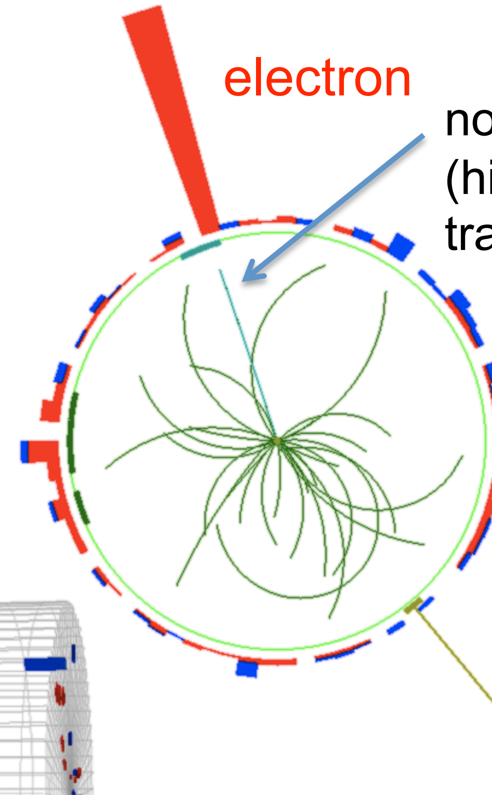
W boson decaying to electron + neutrino

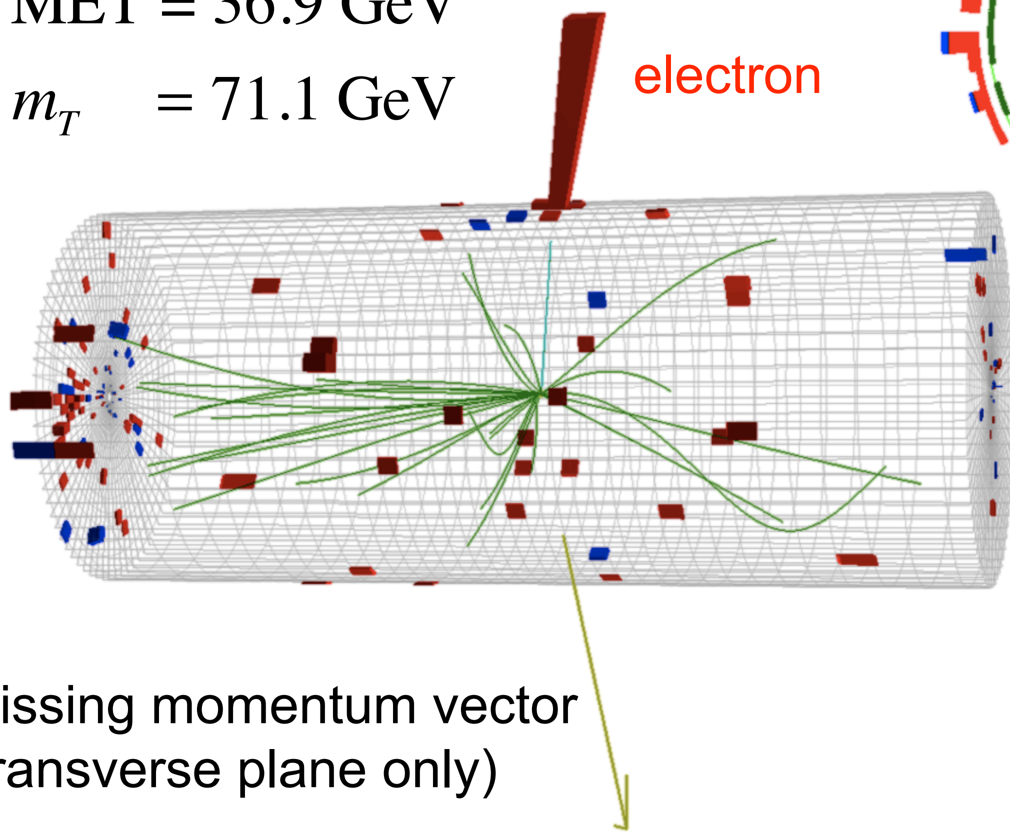
CMS Experiment at LHC, CERN
Run 133874, Event 21466935
Lumi section: 301
Sat Apr 24 2010, 05:19:21 CEST

$$p_T(e) = 35.6 \text{ GeV}$$

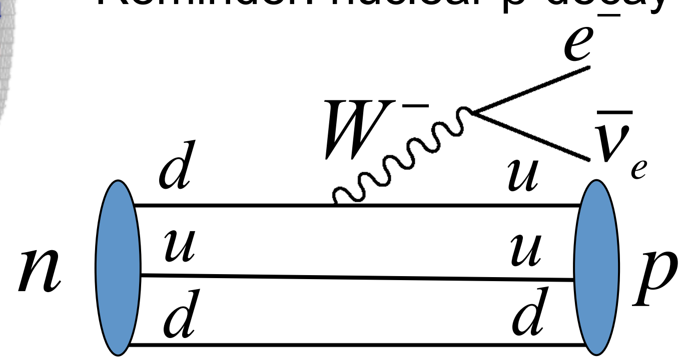
$$\text{MET} = 36.9 \text{ GeV}$$

$$m_T = 71.1 \text{ GeV}$$





Reminder: nuclear β-decay

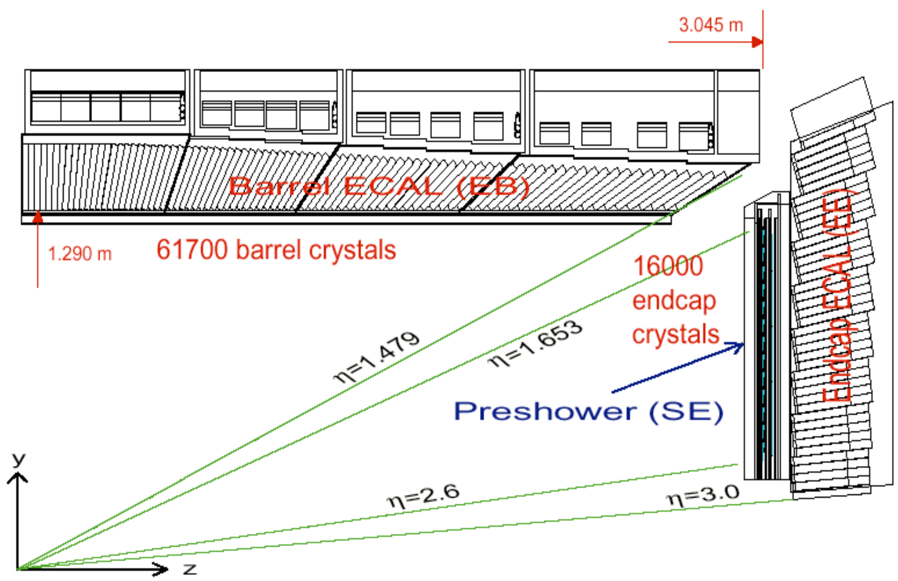


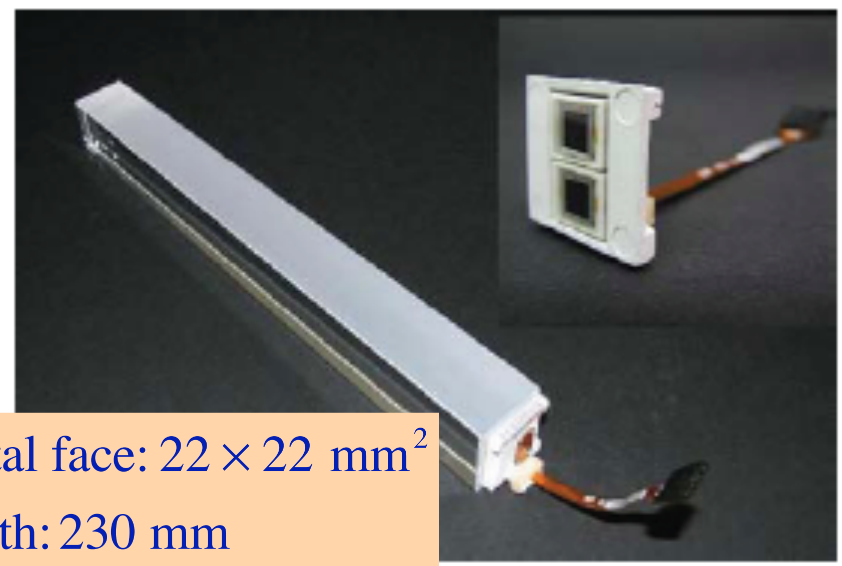
CMS Electromagnetic Calorimeter (ECAL)

- 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 λ_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)

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

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

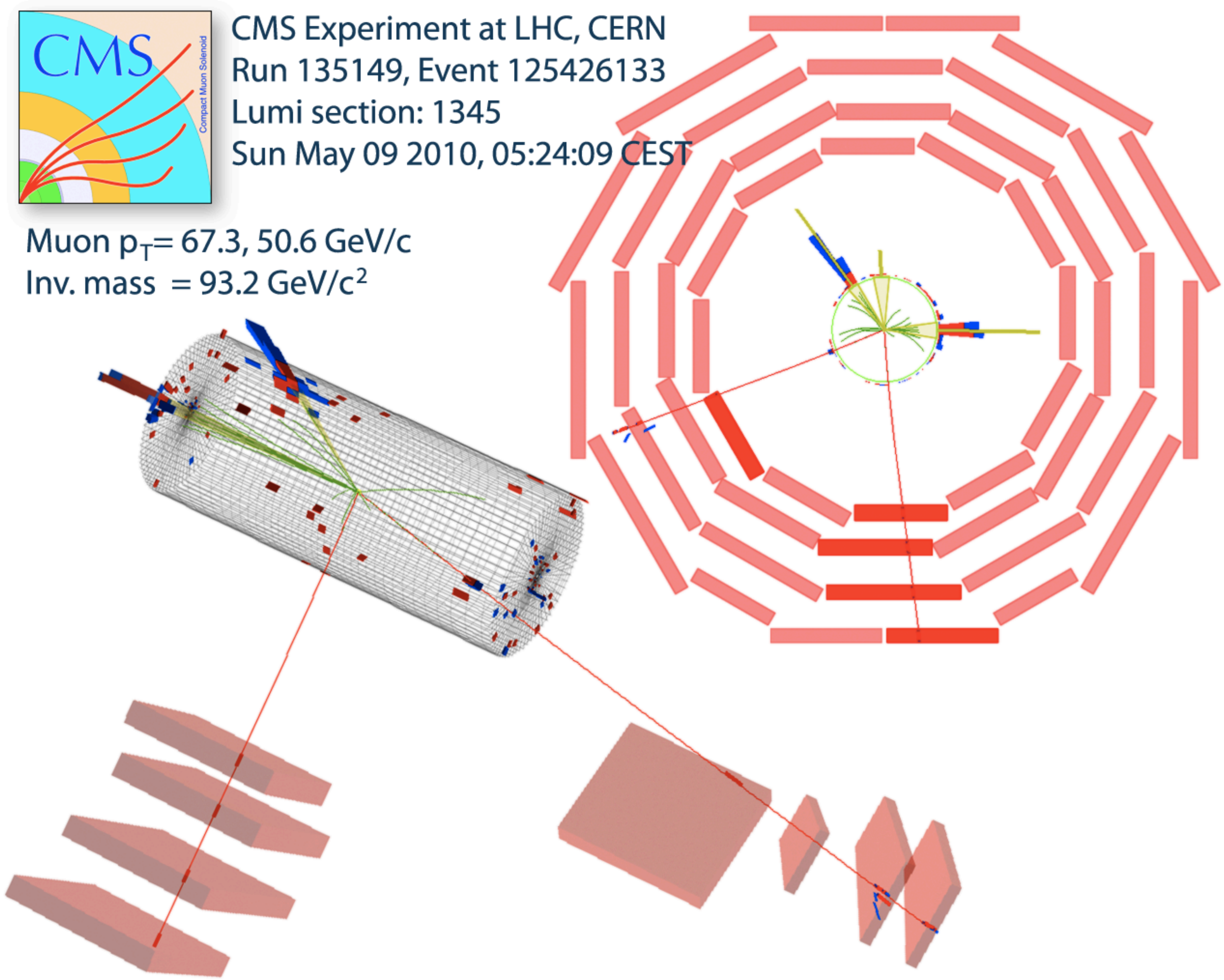




Crystal face: $22 \times 22 \text{ mm}^2$

Length: 230 mm

Z boson decaying to $\mu^+\mu^-$ in CMS



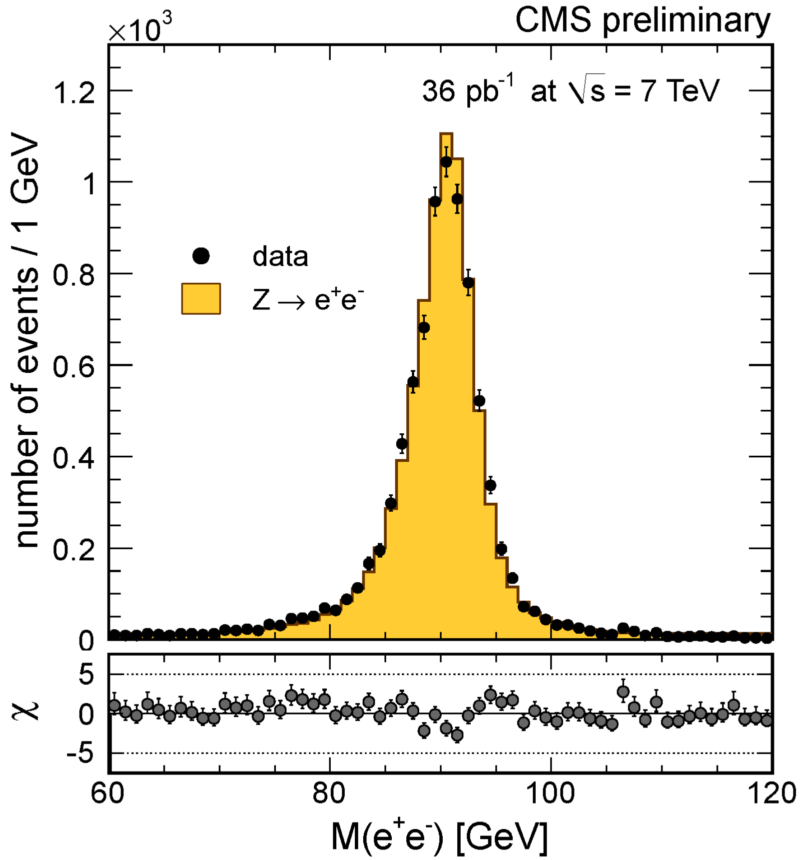
Measurement of Z boson cross section in CMS

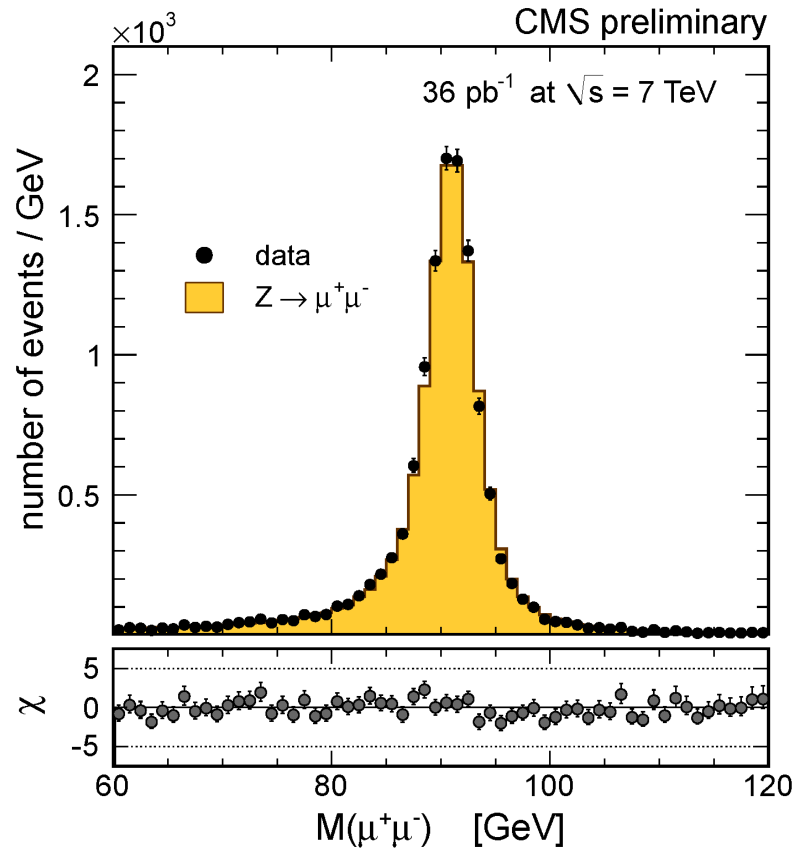
$pp \to Z\ (+\ \text{jets})$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

$Z \to e^+e^-$ $E_T(e) > 20\ \text{GeV}$

$Z \to \mu^+\mu^-$ $p_T(\mu) > 20\ \text{GeV}/c$





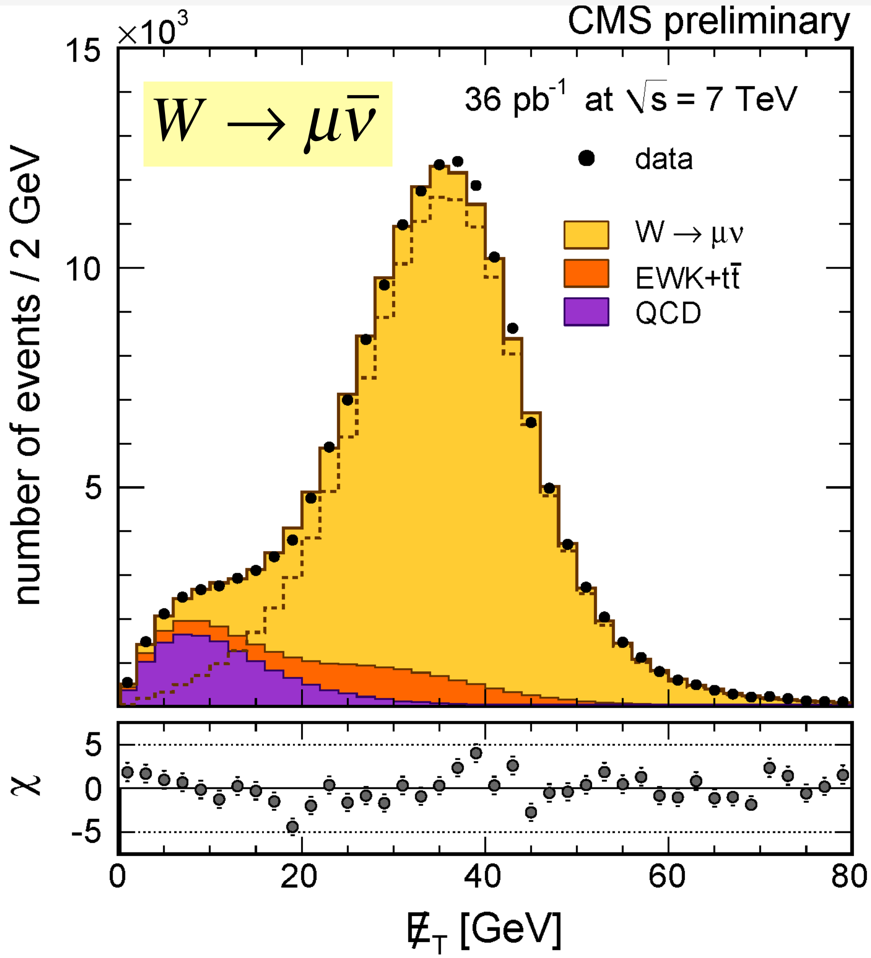
$N_{\text{tot}}(e^+e^-) = 8442;\quad N_{\text{back}}(e^+e^-) = 36 \pm 12$

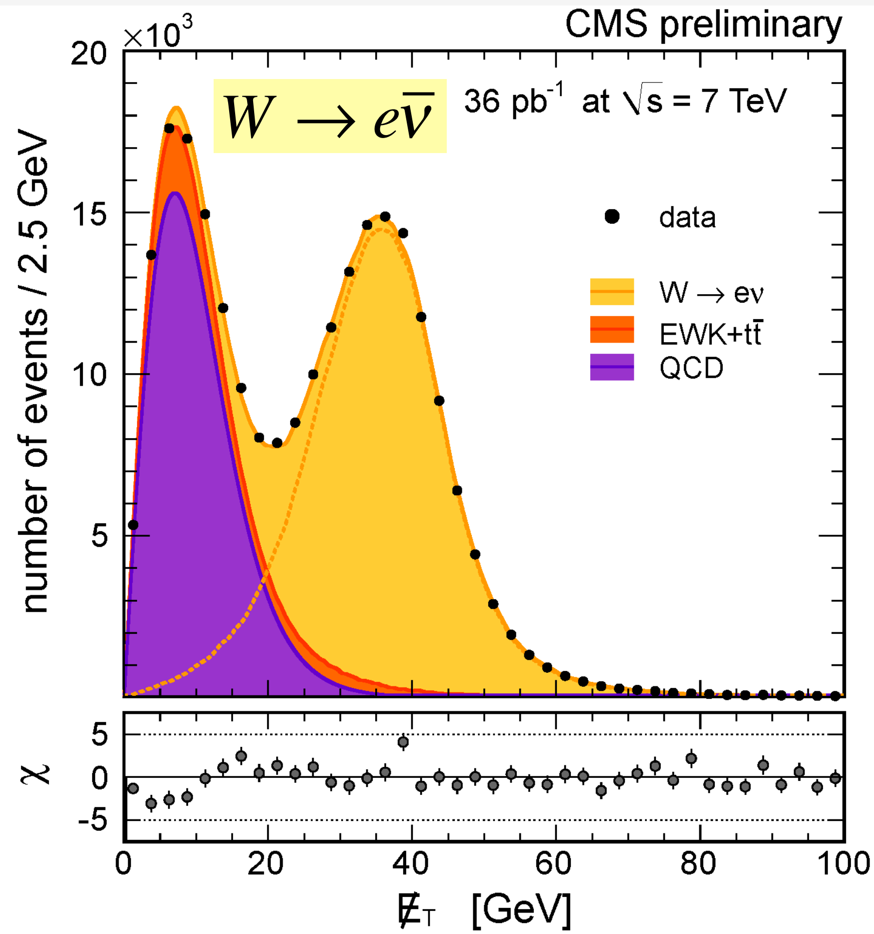
3 pb^{-1}: arXiv 10.1007 JHEP 01, 080 (2011)

Backgrounds are extremely small – not visible on linear scale!

Measurement of the W boson cross section in CMS

Missing momentum vector (transverse to beam)➔ measurement of neutrino





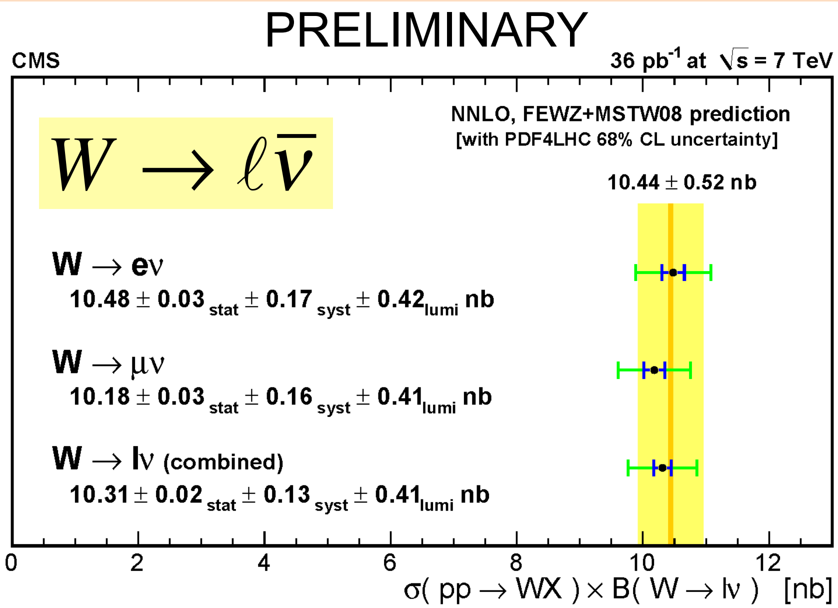
$$N_{tot}(W^+ \to \mu^+ \nu_\mu) = 84{,}292 \pm 292$$

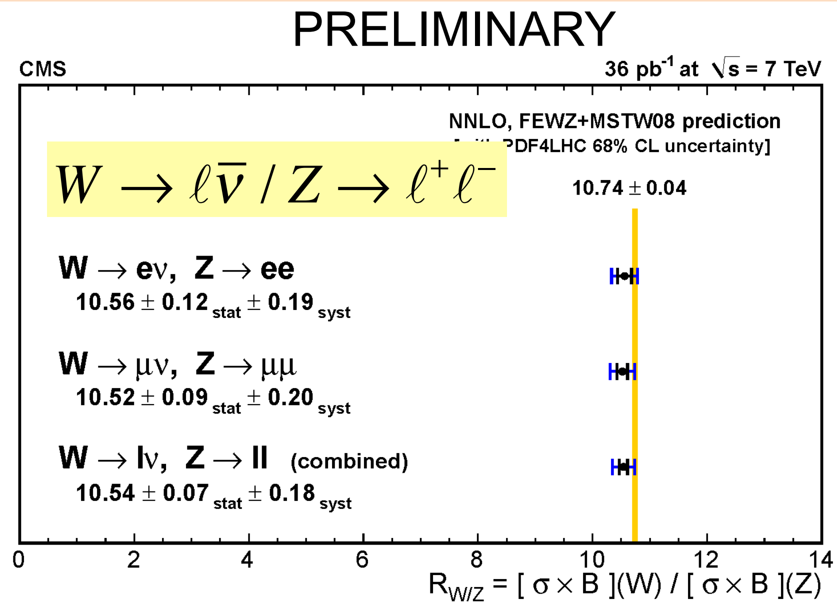
$$N_{tot}(W^- \to \mu^- \bar{\nu}_\mu) = 56{,}818 \pm 240$$

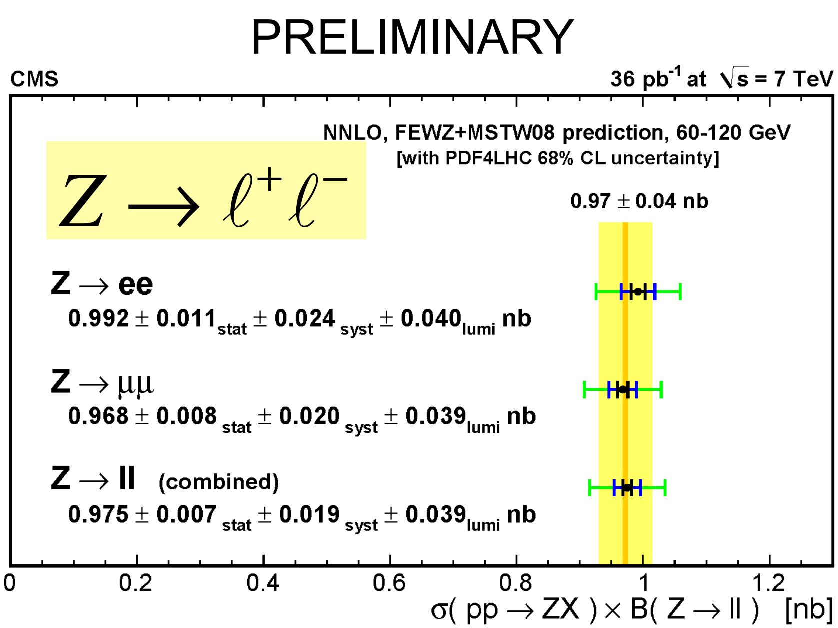
$$N_{tot}(W^+ \to e^+ \nu_e) = 81{,}568 \pm 297$$

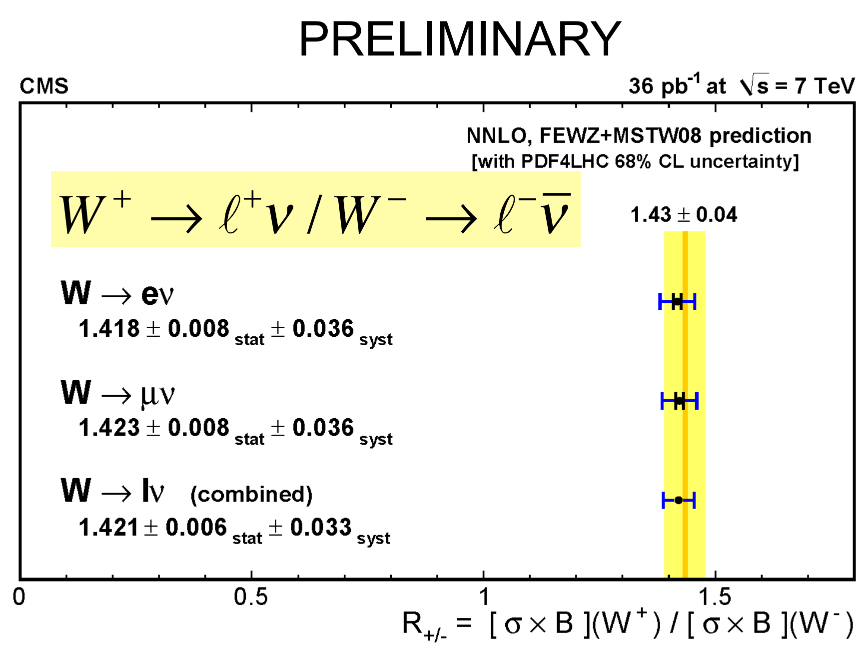
$$N_{tot}(W^- \to e^- \bar{\nu}_e) = 54{,}760 \pm 246$$

Measurement of W, Z boson cross sections in CMS

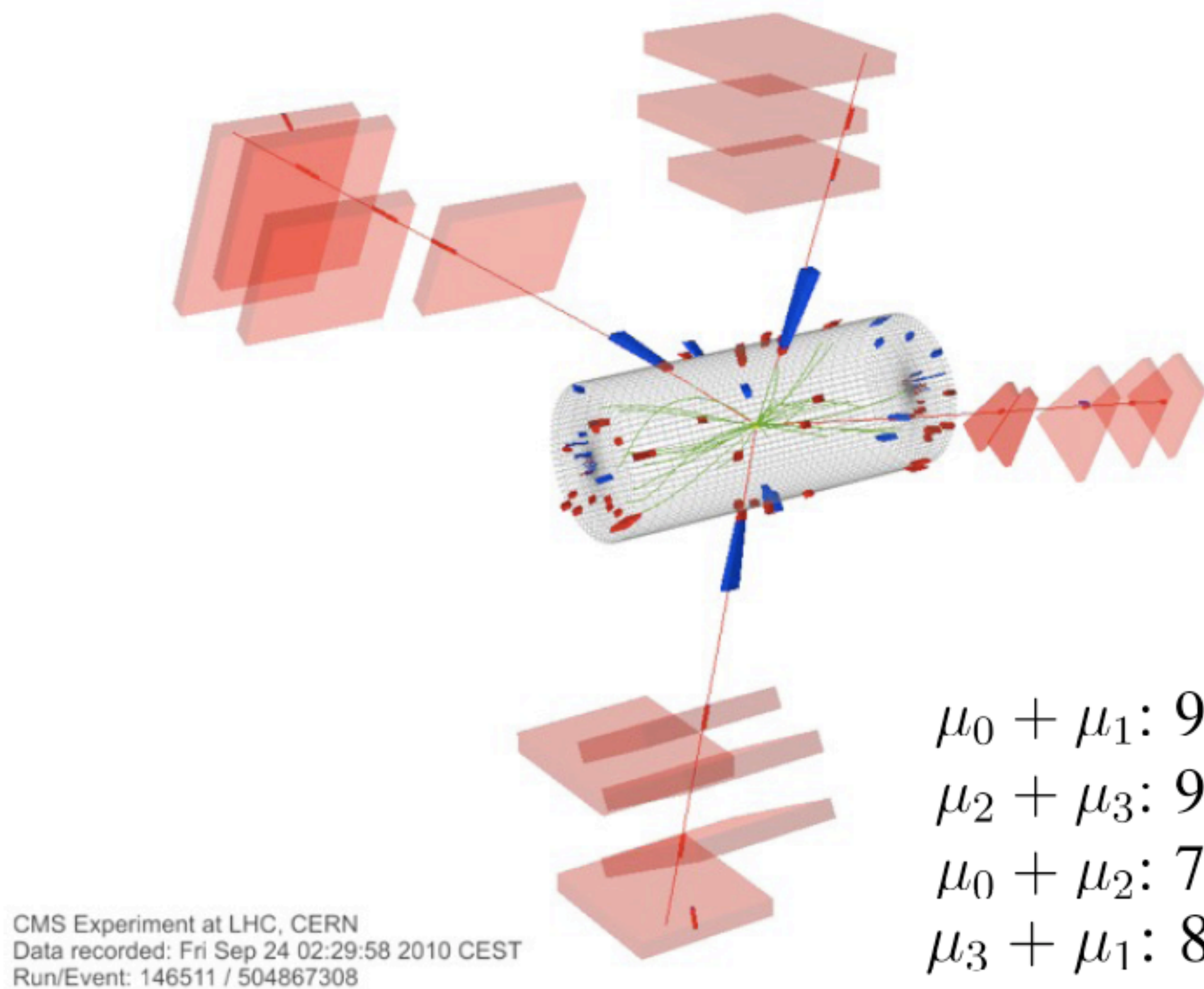








$pp \rightarrow Z\ (\rightarrow \mu^+\mu^-) + Z\ (\rightarrow \mu^+\mu^-)$



$\mu_0 + \mu_1$: 92.15 GeV

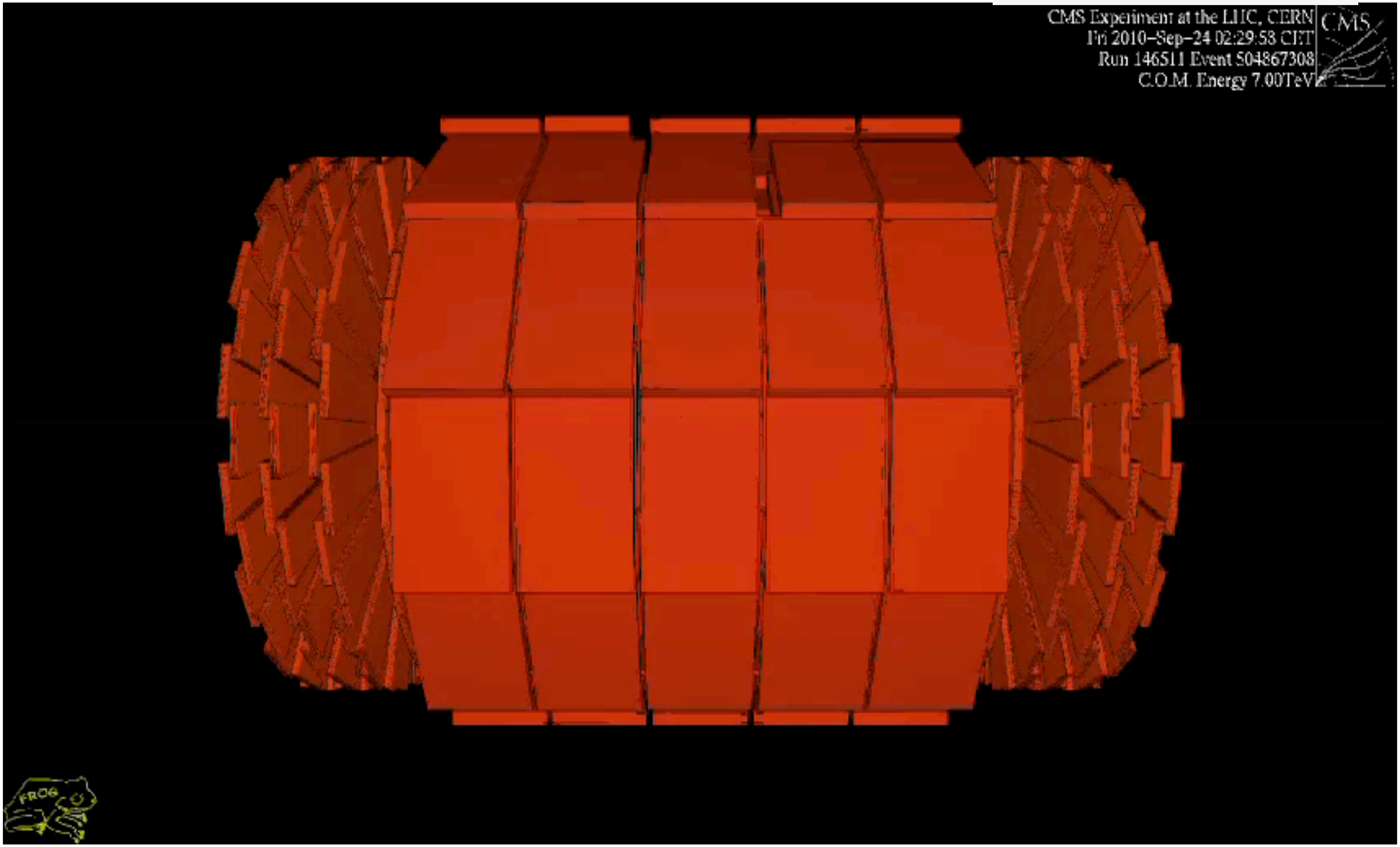
$\mu_2 + \mu_3$: 92.24 GeV

$\mu_0 + \mu_2$: 70.12 GeV

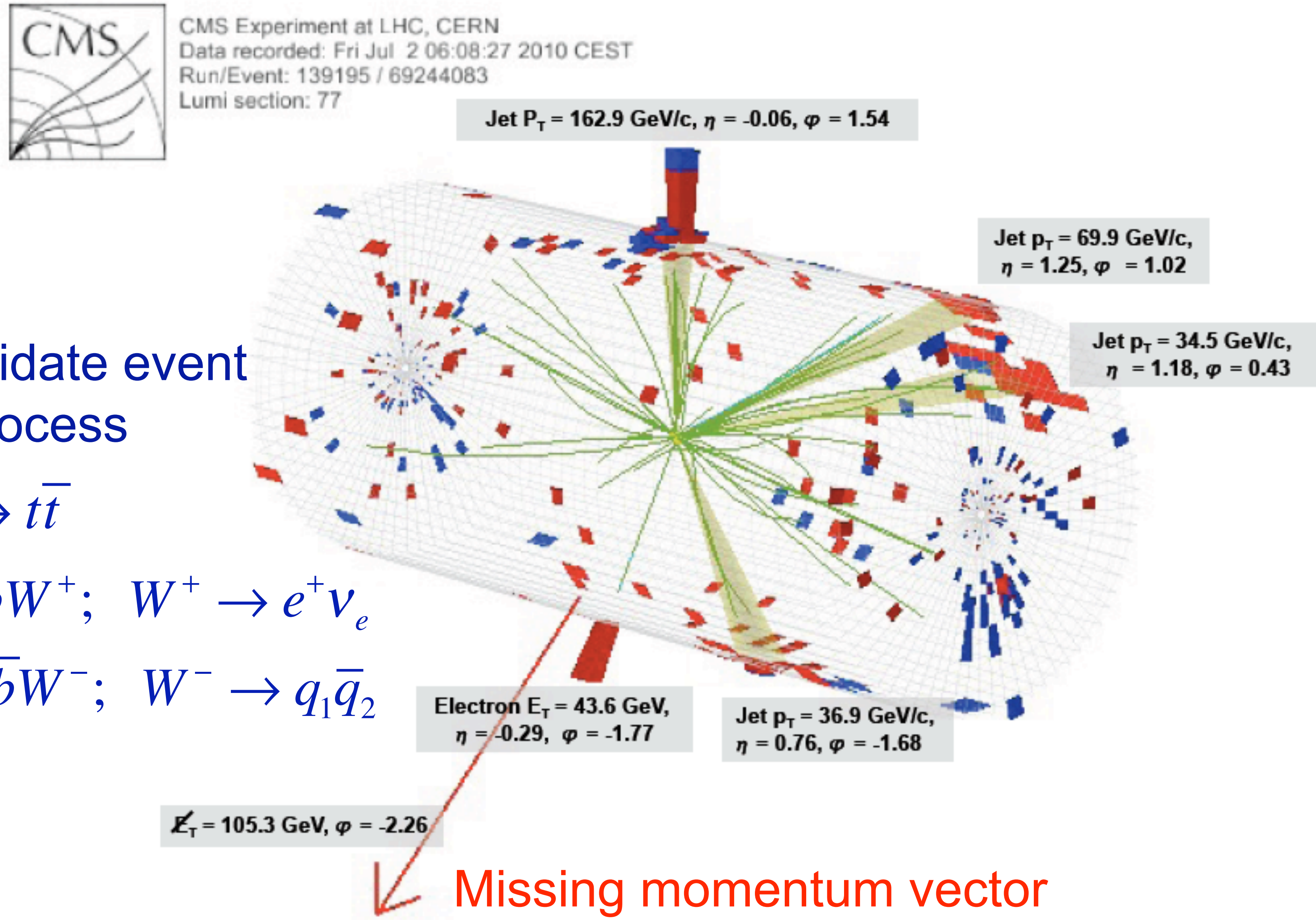
$\mu_3 + \mu_1$: 83.1 GeV

$pp \rightarrow Z\,(\rightarrow \mu^+\mu^-) + Z\,(\rightarrow \mu^+\mu^-)$

(animation of real event)



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



Candidate event for process

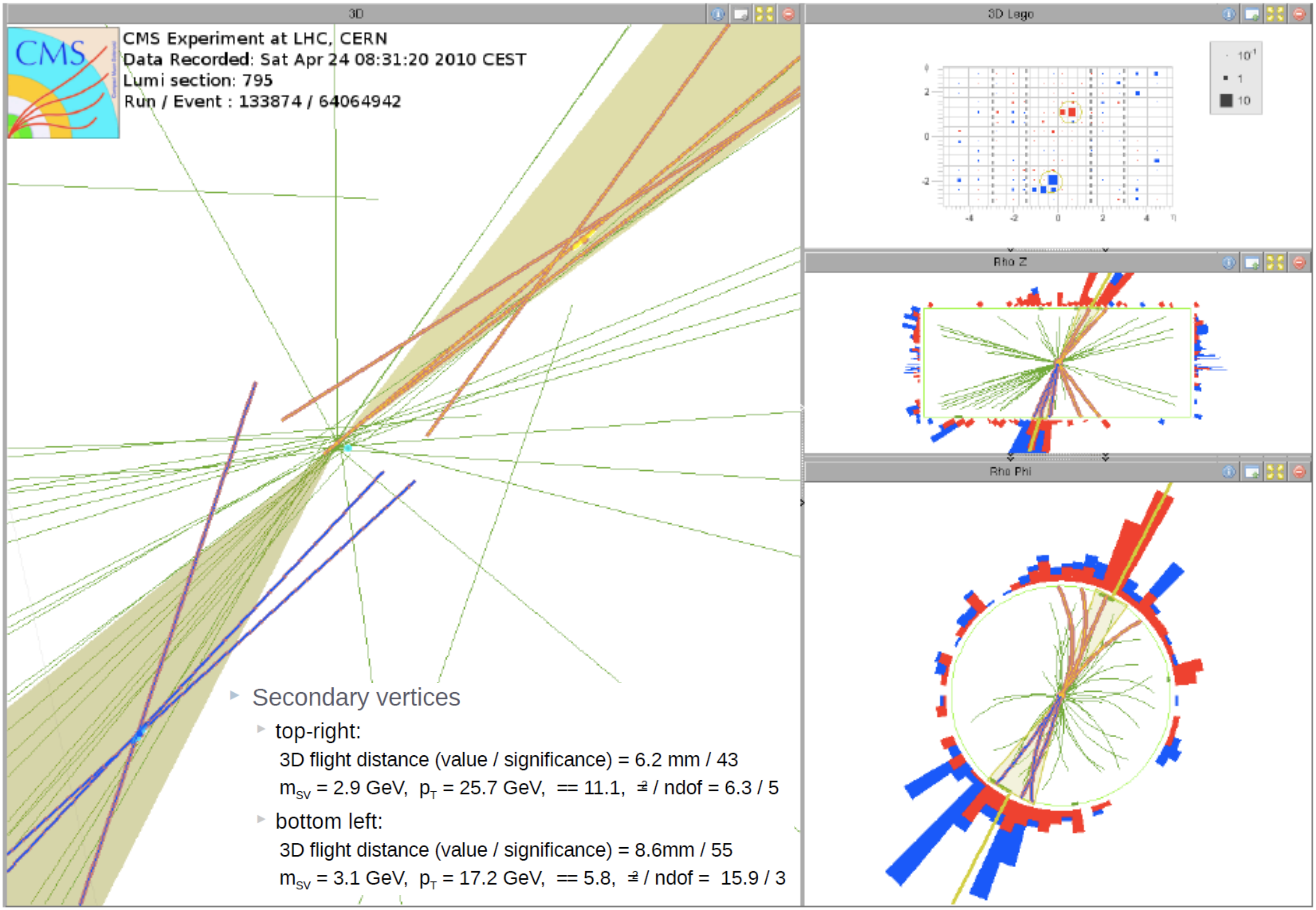
$$pp \rightarrow t\bar{t}$$

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

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

Missing momentum vector from neutrino

b-quark identification using displaced decay vertices

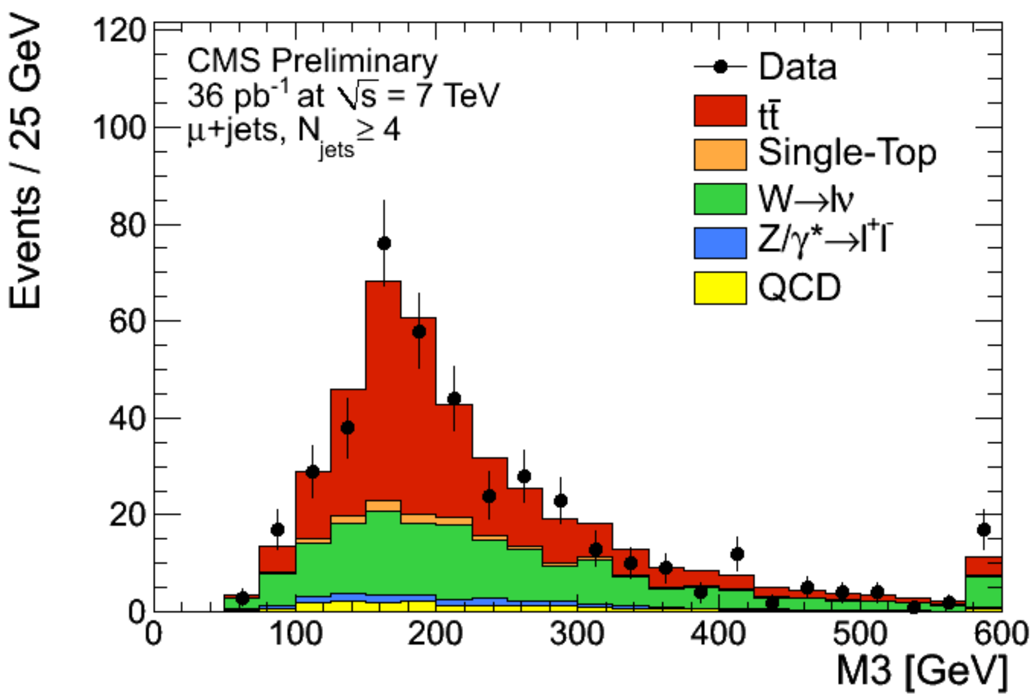


- Secondary vertices
  - top-right:
    3D flight distance (value / significance) = 6.2 mm / 43
    m_{SV} = 2.9 GeV, p_T = 25.7 GeV, == 11.1, ² / ndof = 6.3 / 5
  - bottom left:
    3D flight distance (value / significance) = 8.6mm / 55
    m_{SV} = 3.1 GeV, p_T = 17.2 GeV, == 5.8, ² / ndof = 15.9 /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

Signals for $t\bar{t}$ production

Single-lepton channel

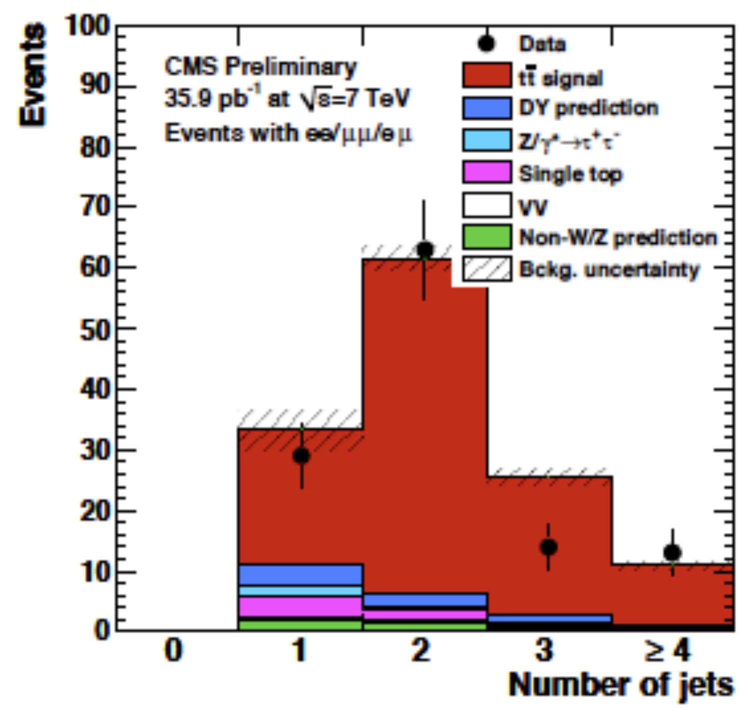
$$t \to bW^+;\;\; W^+ \to \mu^+\nu_\mu$$
$$\bar{t} \to \bar{b}W^-;\;\; W^- \to q_1\bar{q}_2$$



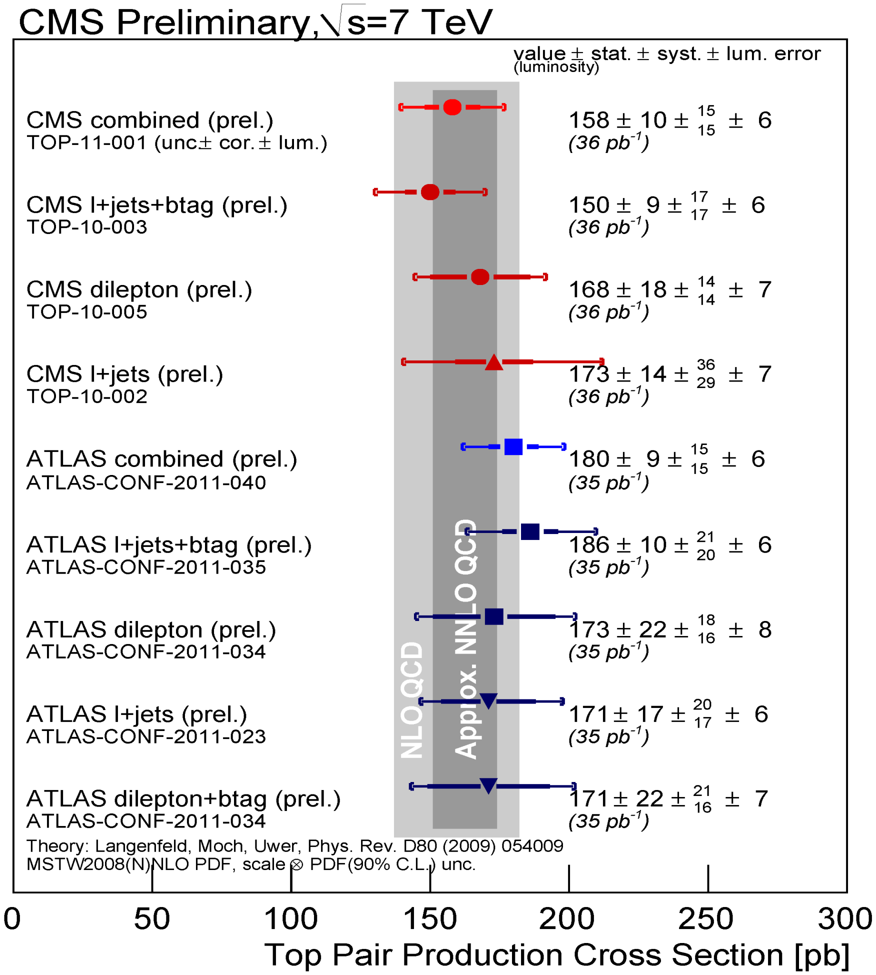
Di-lepton channel

$$t \to bW^+;\;\; W^+ \to \ell^+\nu_\ell$$
$$\bar{t} \to \bar{b}W^-;\;\; W^- \to \ell^-\bar{\nu}_\ell$$

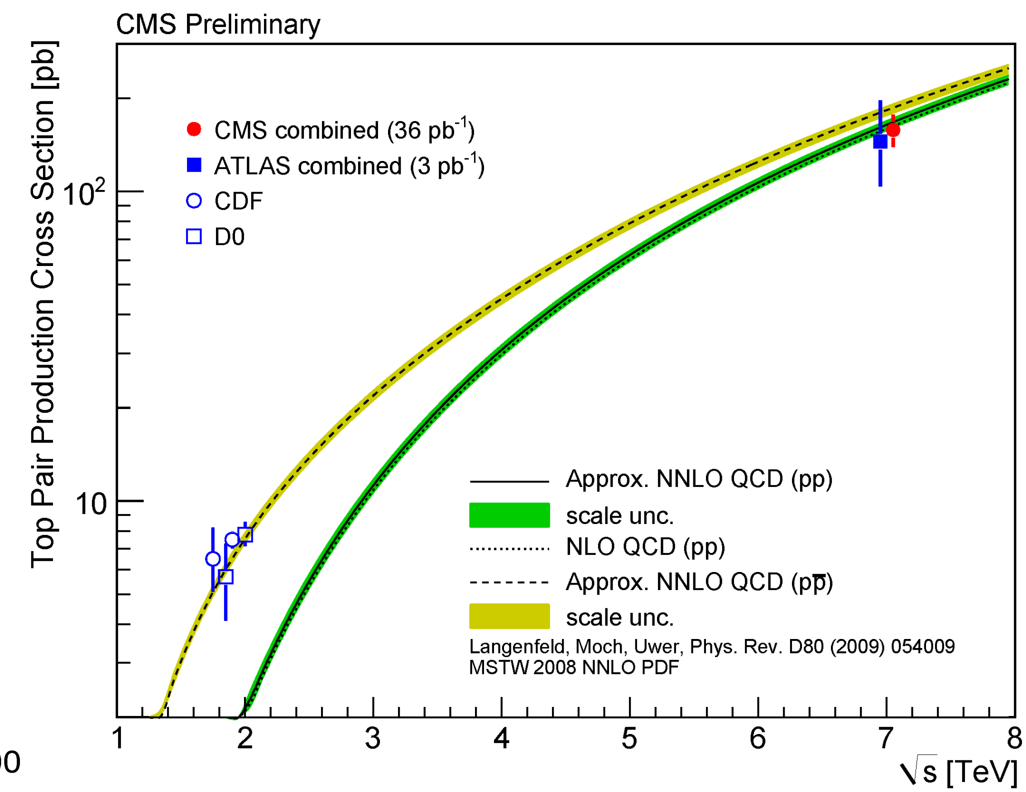
at least 1 b-tagged jet required



Summary of $t\bar{t}$ cross section results

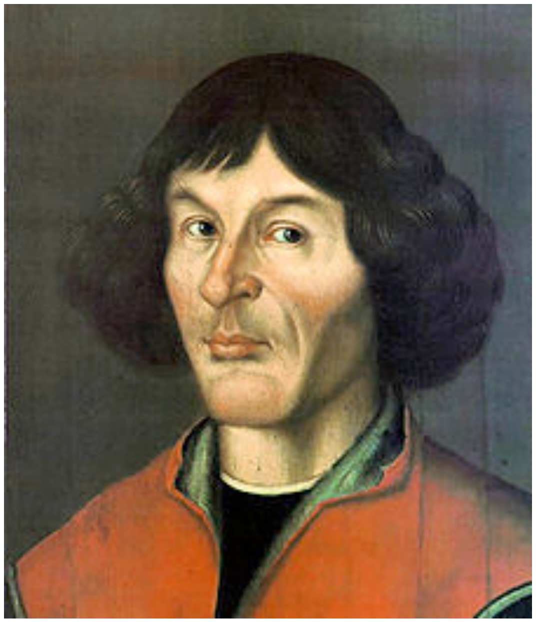


LHC (pp) vs. Tevatron ($p\bar{p}$)



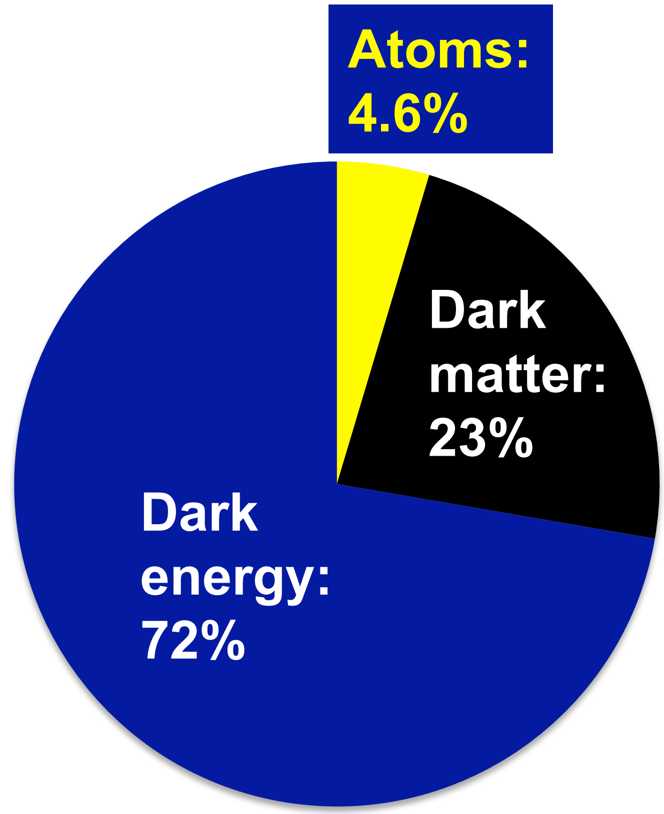
$t\bar{t}$ cross section results are in good agreement with Standard Model prediction.

The dark matter revolution



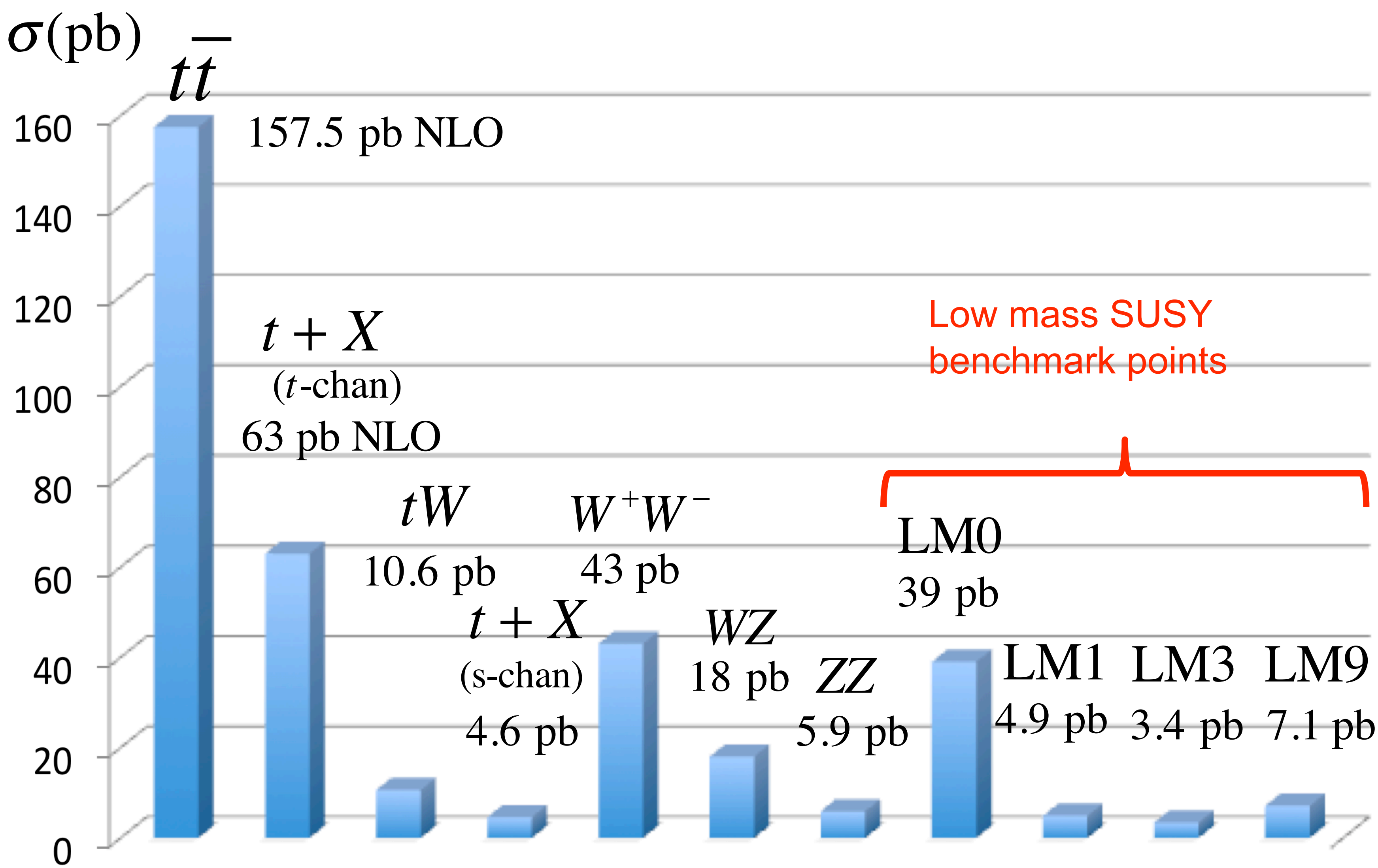
Nicolaus Copernicus (1473-1543): heliocentric model

Vera Rubin (1928-): dark matter in galaxies

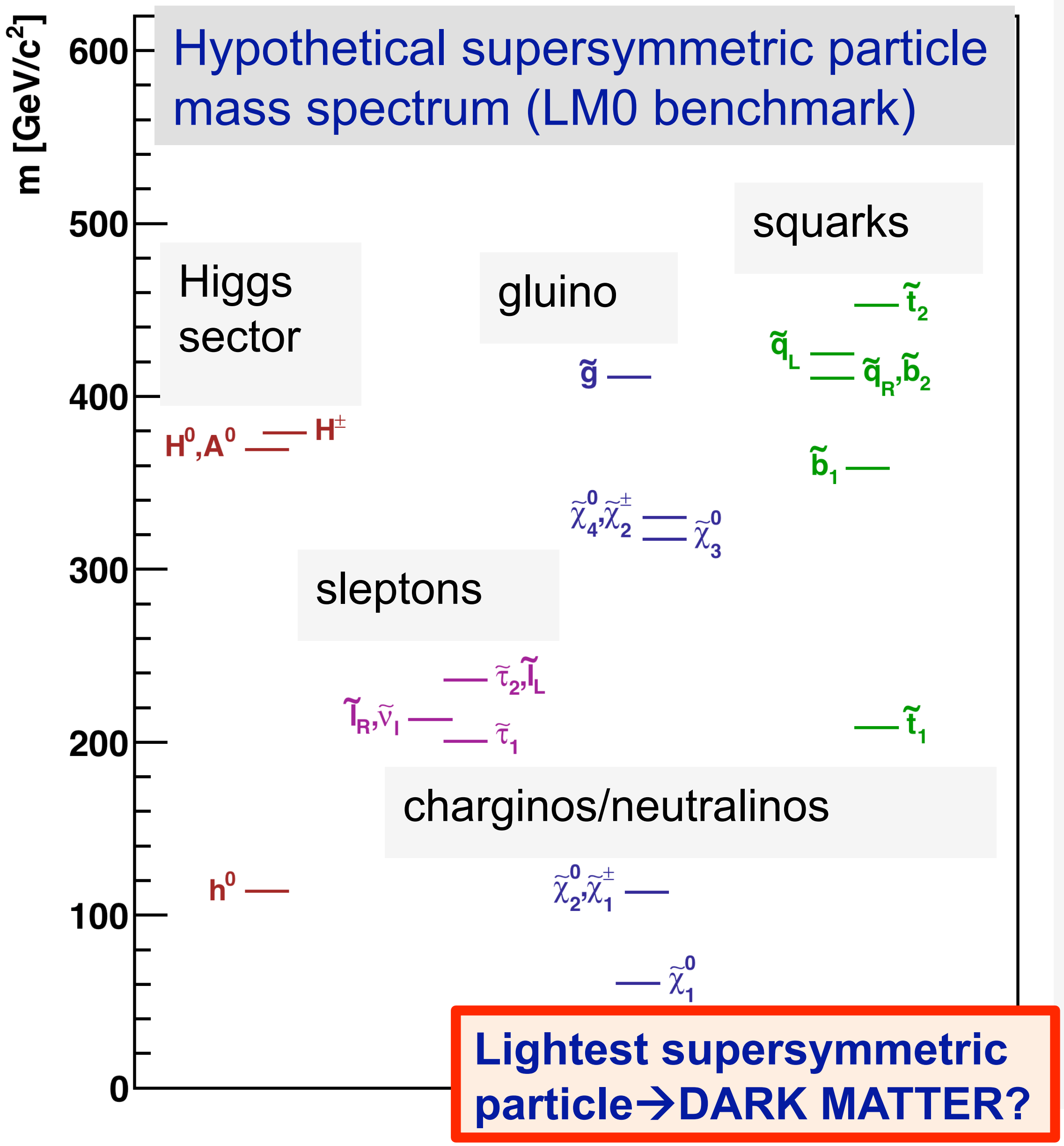


We aren't at the center of the solar system (or anything else), and we aren't made up of the dominant form of matter...

Cross Sections for SM vs. Low-mass SUSY benchmark points



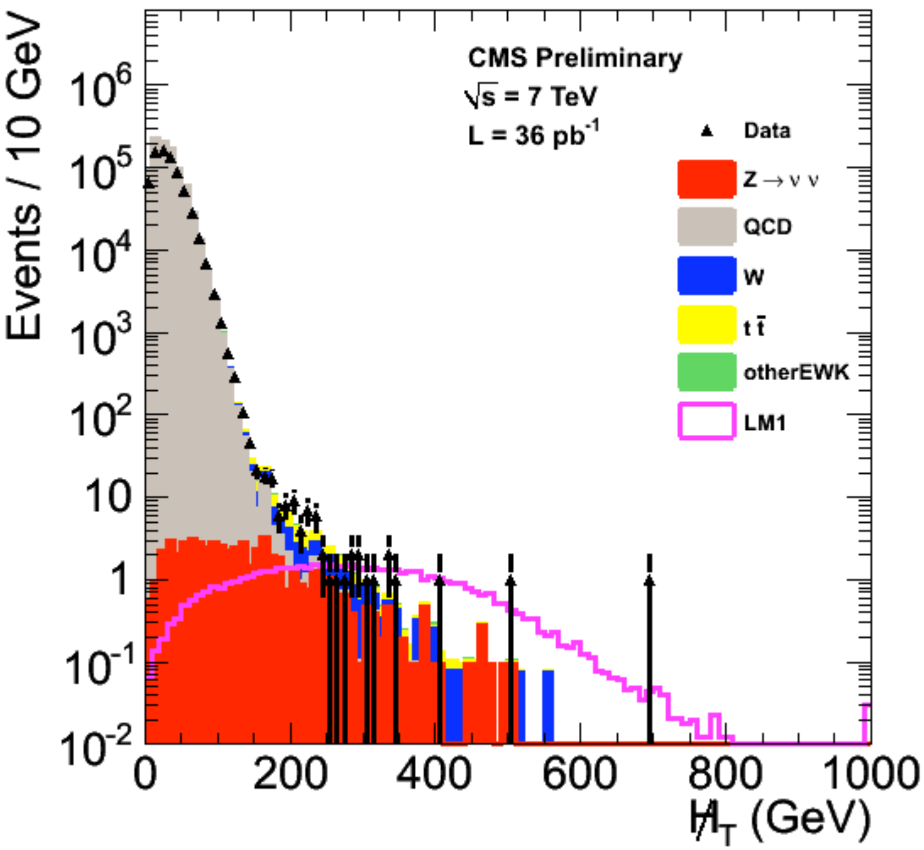
A new spectroscopy?



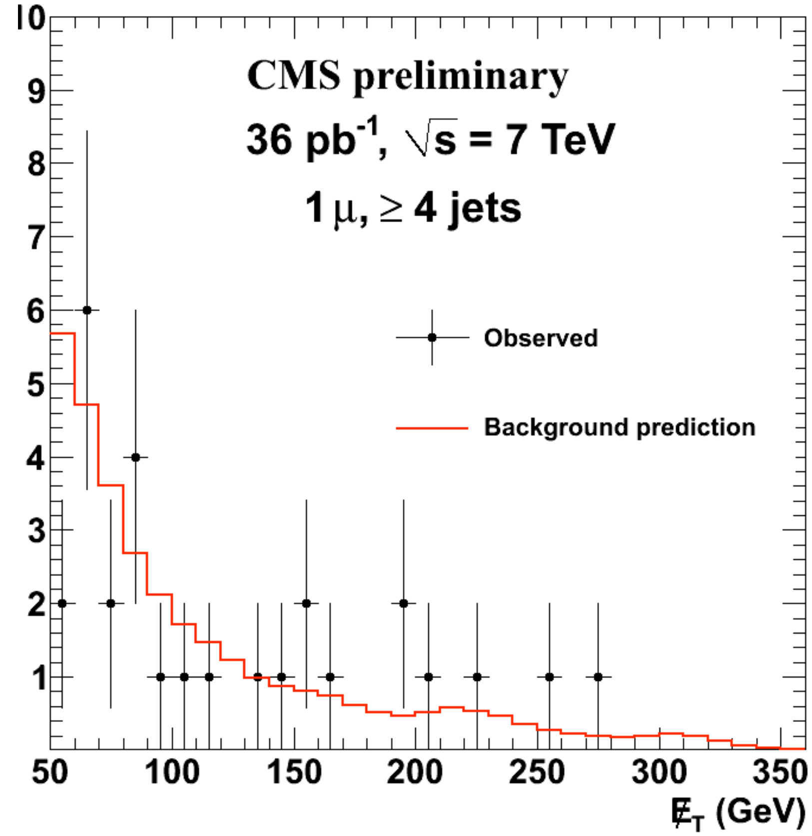
- Key element of SUSY searches: large (>200 GeV) missing momentum due to production of two LSPs.
- Broad range of signatures, with leptons, photons, b-quarks,...+ missing transerse momentum ("MET").

Early SUSY Searches

Jets + missing transverse momentum search

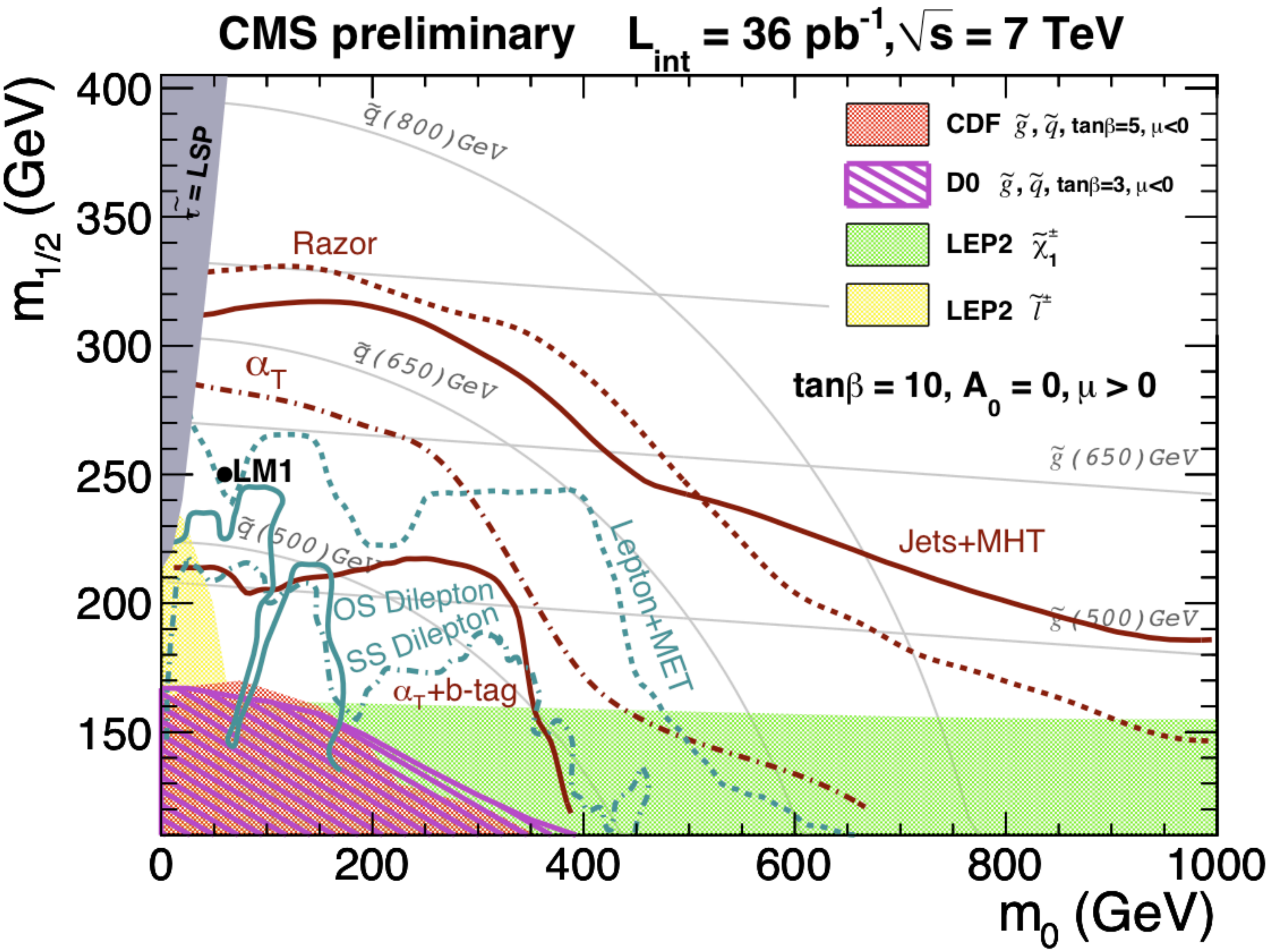


Jets + 1 lepton + missing transverse momentum search



No significant excess event yields observed so far, but amount of data is very modest. Sensitivity will improve dramatically in 2011-2012.

CMS mSUGRA exclusion curves



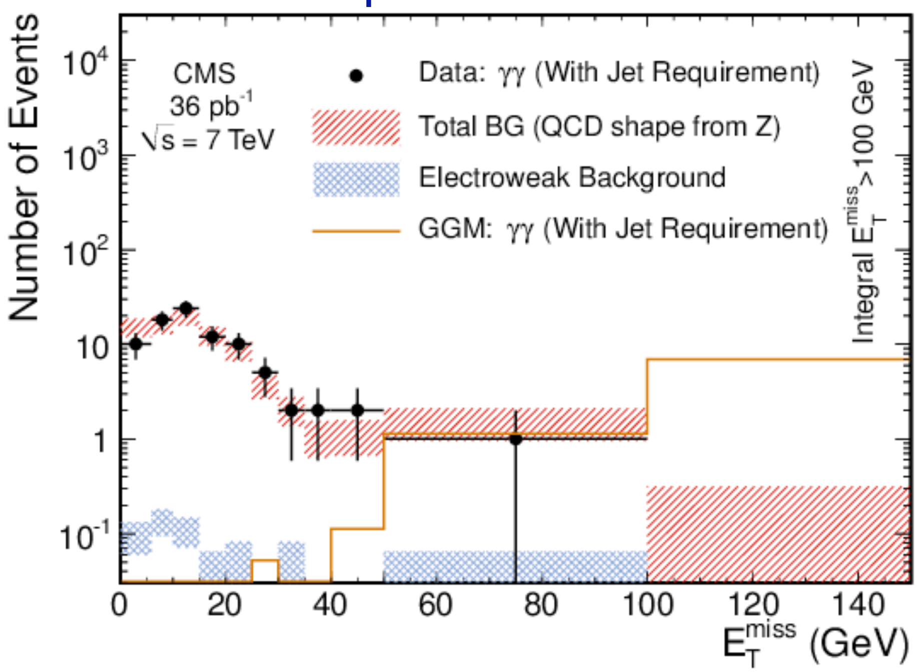
CMS SUSY sensitivity is now well beyond that of the Tevatron.

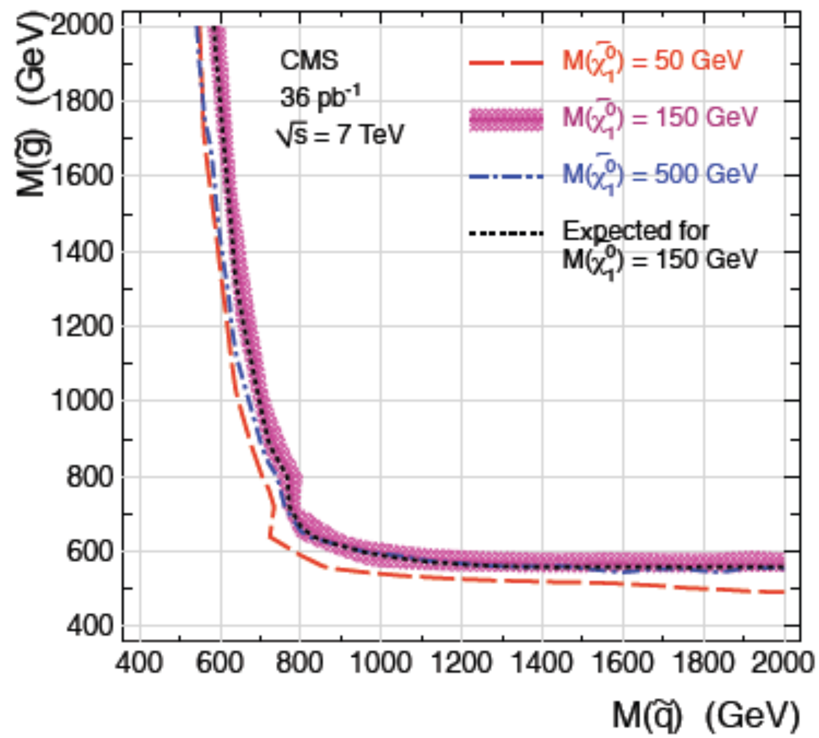
Search for General Gauge Mediated SUSY

LSP is gravitino: $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$

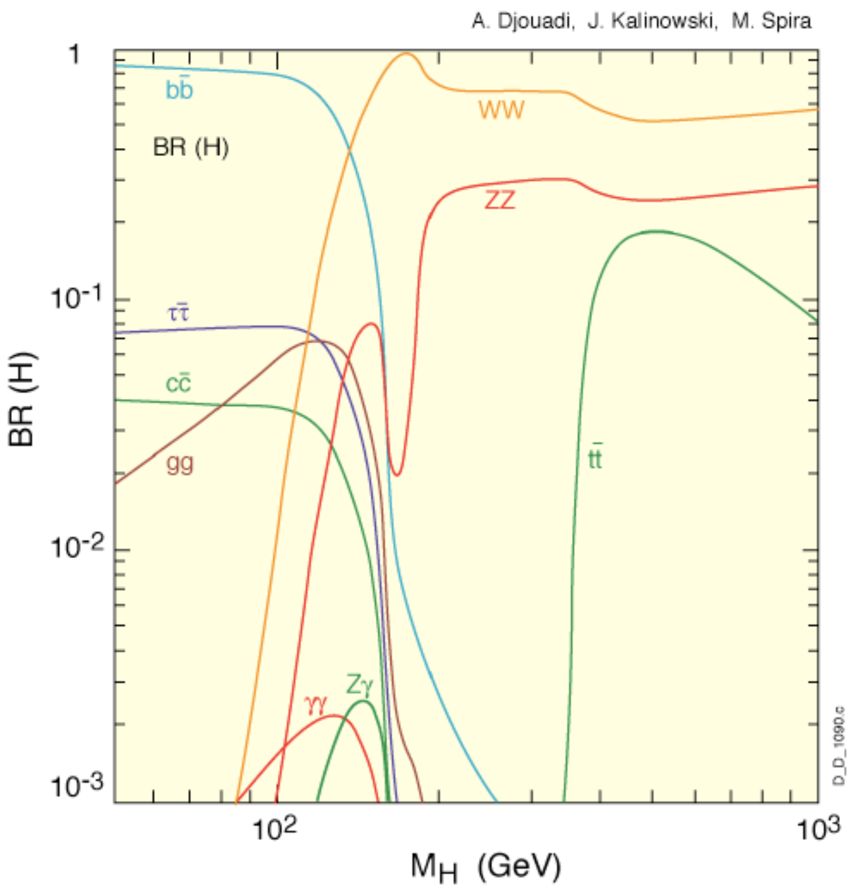
Signature: 2 photons, jets, missing transverse momentum

2 photon channel





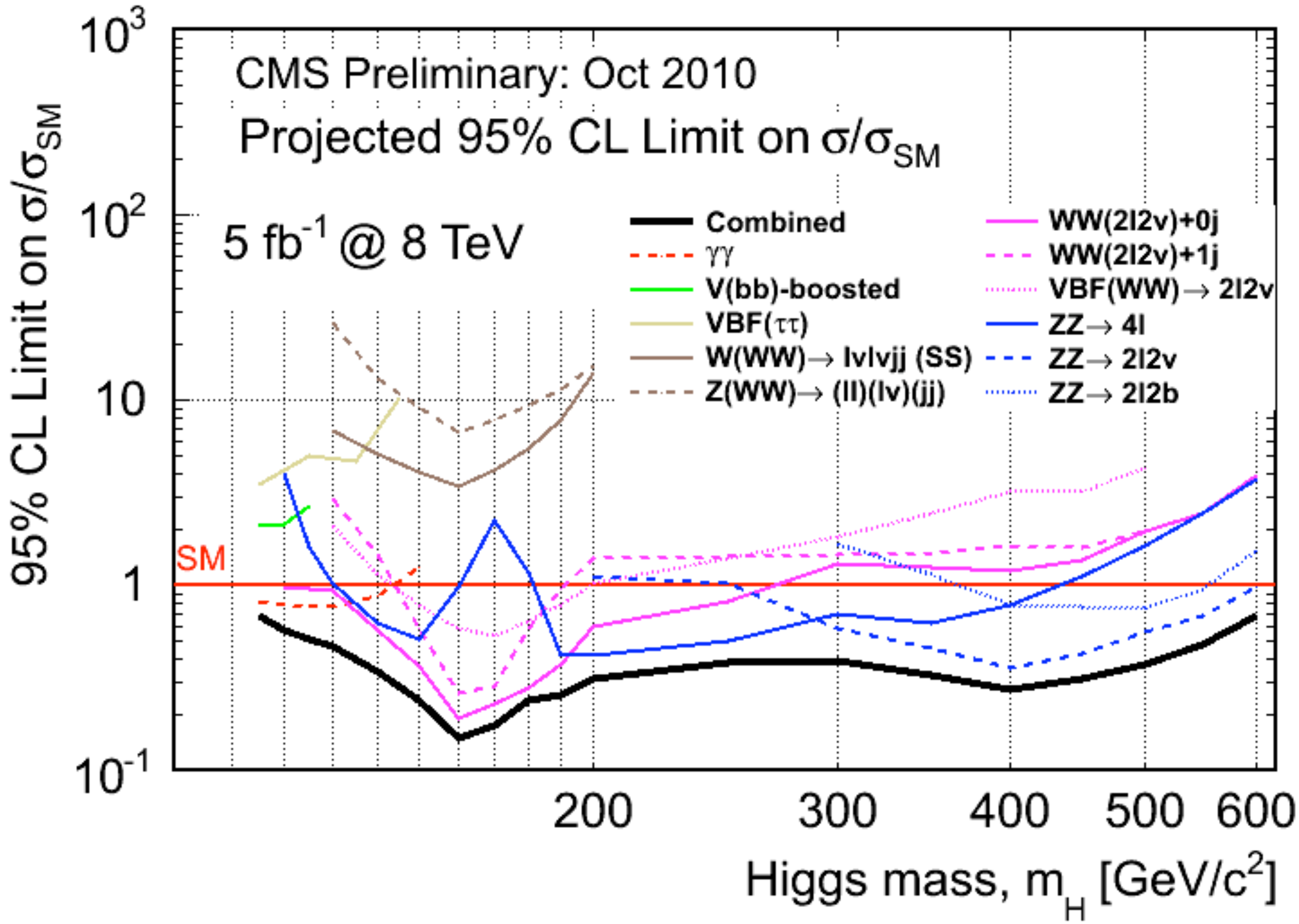
Background dominated by QCD; determined using contro l samples in the data. Good sensitivity to strong production scenarios.



Channels included	Higgs mass range used in analyses (GeV)
$H \rightarrow \gamma\gamma$	115-150
VBF $H \rightarrow \tau\tau$	115-145
VH, H→bb (highly boosted)	115-125
VH, H→WW→lvjj	130-200
H→WW→2l2v + 0/1 jets	120-600
VBF H→WW→2l2v	130-500
H→ZZ→4l	120-600
H→ZZ→2l2v	200-600
H→ZZ→2l2b	300-600

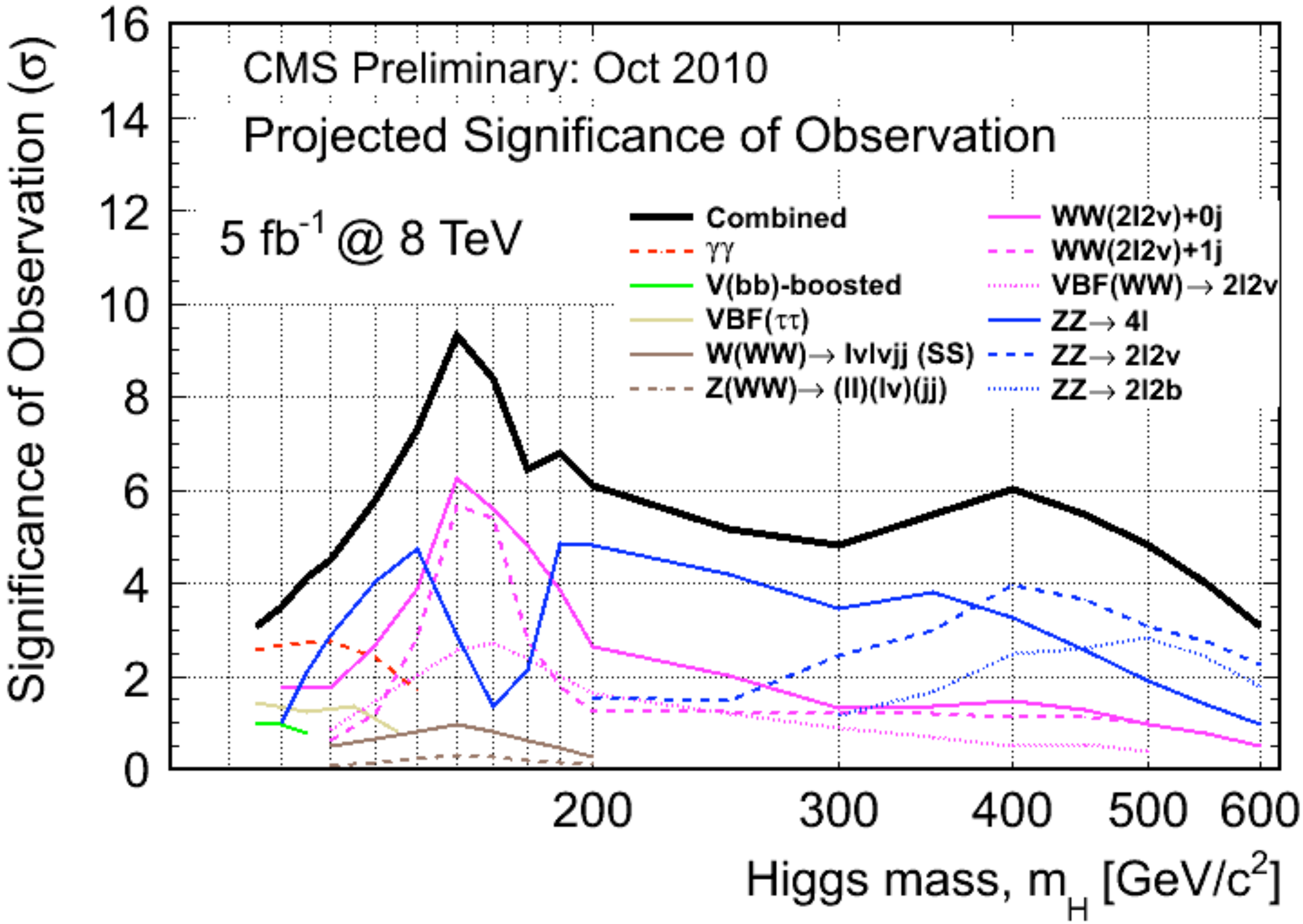
Higgs branching fractions as a function of m(H).

CMS Higgs Sensitivity (I)



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

CMS Higgs Sensitivity (II)



Conclusions/Prospects

- The LHC is working and has achieved its luminosity goal for this run (10^{32} $cm^{-2}s^{-1}$). Next year the luminosity will be much higher.
- We have observed and measured key Standard Model benchmark processes: W, Z, $t\bar{t}$, + many others.
- With the current data sample, we will surpass the Tevatron in sensitivity for many new physics scenarios, including SUSY.
- Proton running resumes starting in Feb; high expectations for accumulating well over 1 fb^{-1} in 2011. This is the start of a 15-20 year physics program.

A bit of history...

Information Management: A Proposal

Tim Berners-Lee, CERN
March 1989, May 1990

This proposal concerns the management of general information about accelerators and experiments at CERN. It discusses the problems of loss of information about complex evolving systems and derives a solution based on a distributed hypertext system.

Many of the discussions of the future at CERN and the LHC era end with the question - ªYes, but how will we ever keep track of such a large project?º This proposal provides an answer to such questions. Firstly, it discusses the problem of information access at CERN. Then, it introduces the idea of linked information systems, and compares them with less flexible ways of finding information.

(Sir) Tim Berners-Lee and early development of the World Wide Web

- Berners-Lee proposed the WWW in March 1989 while working at CERN.