Progress & Puzzles at the TeV scale: Recent results from the CMS experiment at the Large Hadron Collider

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Colloquium, University of Pittsburgh
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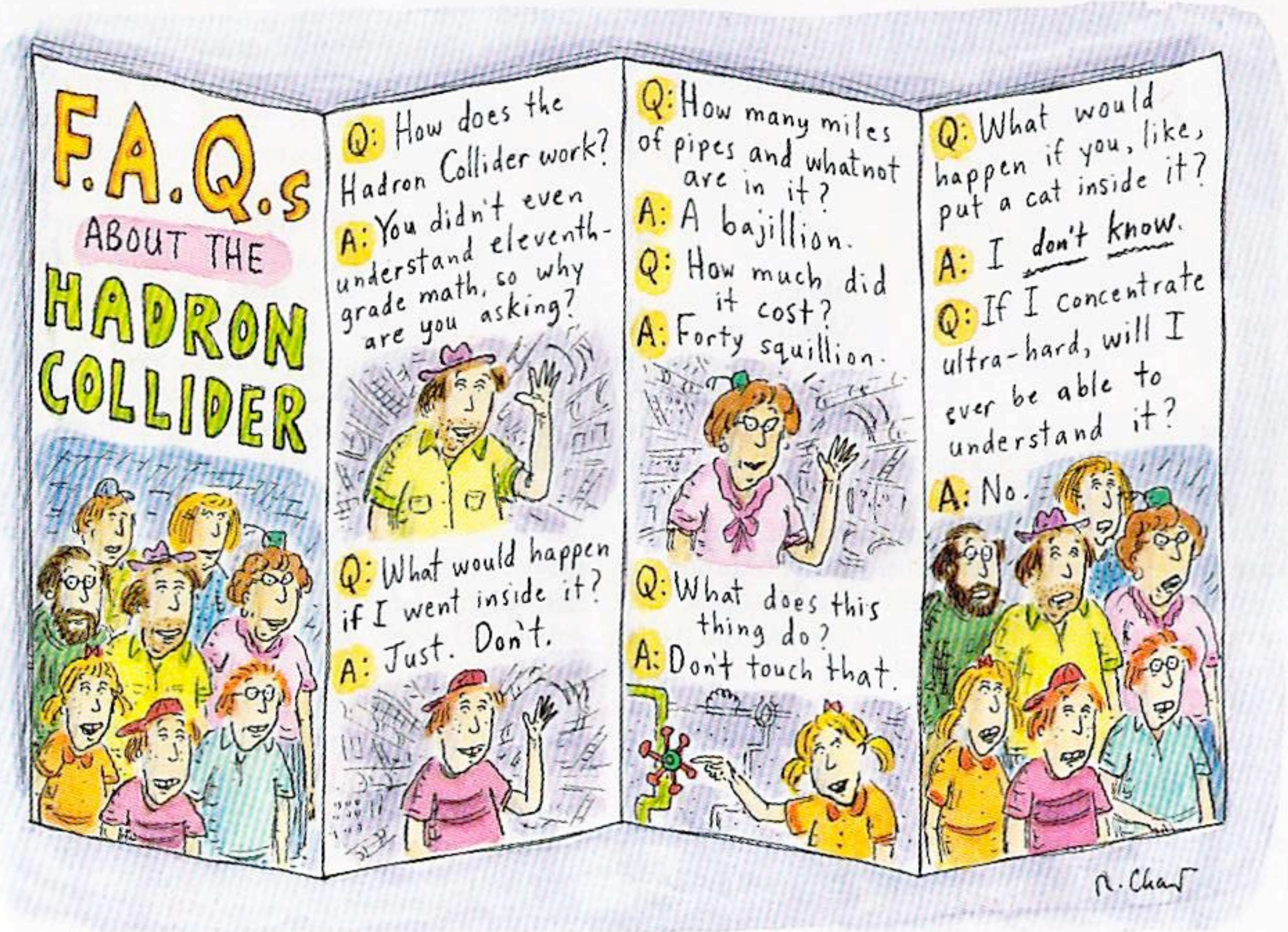
Outline

- The LHC and the CMS detector
- Basics of LHC physics
- Foundations: standard model physics
- Progress on the Higgs boson
- Puzzles and mysteries at the TeV scale
- Searches for supersymmetry and other new physics; implications
- Looking forward: the HL-LHC

Drawing courtesy Sergio Cittolin, CMS

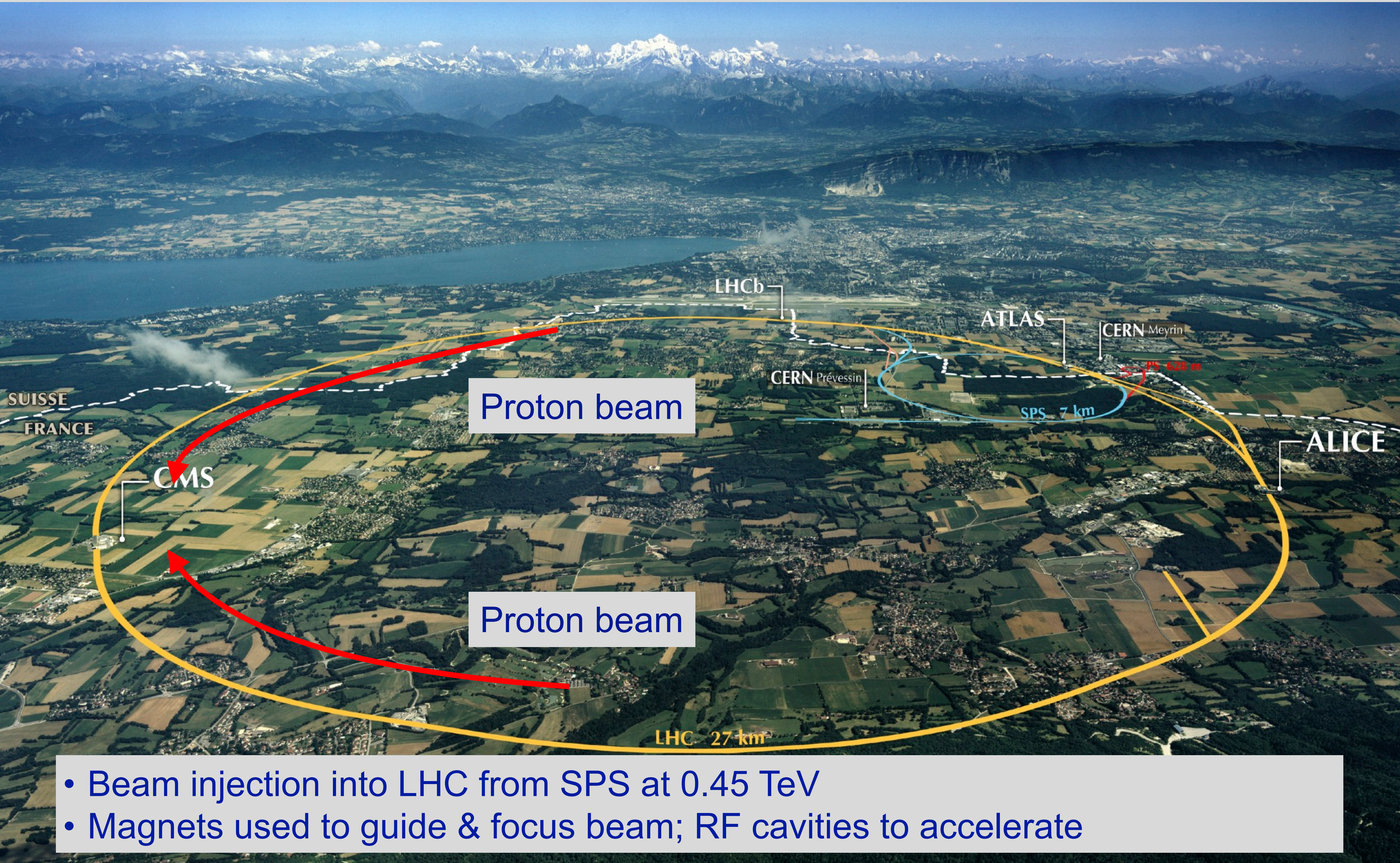
Note: extremely close collaboration with theoretical physics/particle phenomenology community has been essential for this physics program!

The LHC in popular culture



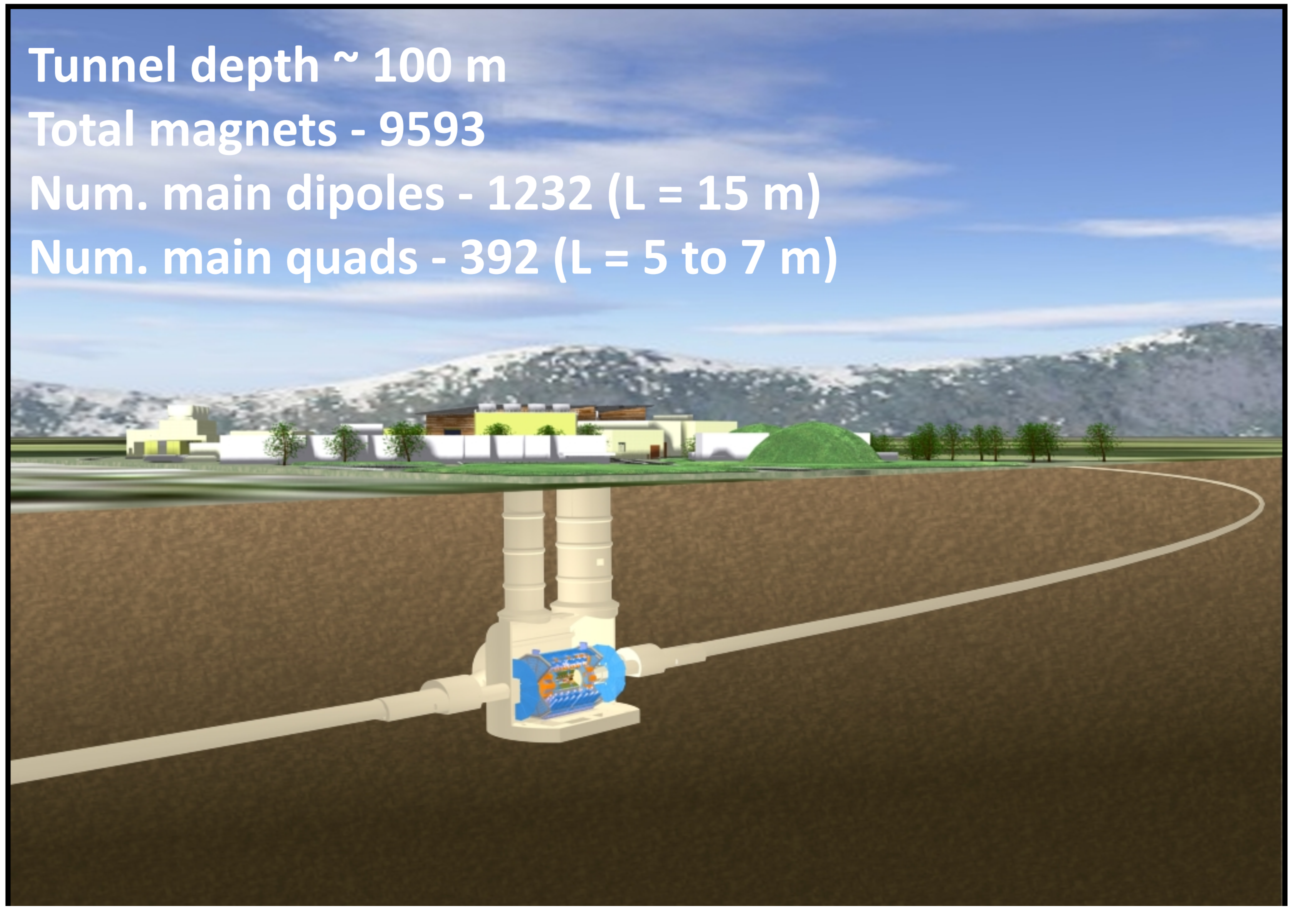
Large Hadron Collider

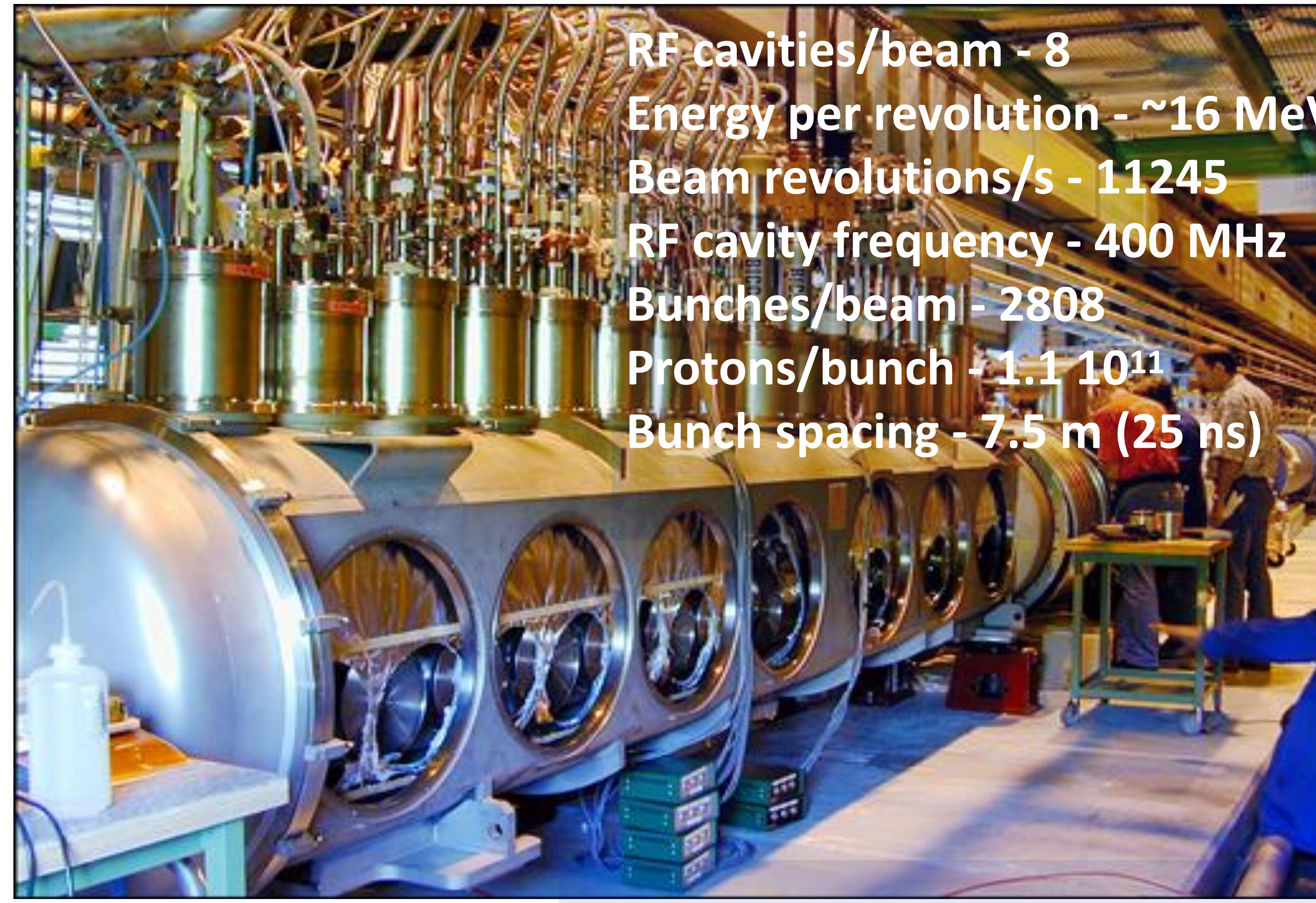
pp collisions: $E_{CM} = 2E_{beam}$ = 7, 8 TeV (Run 1), 13 TeV (Run 2)

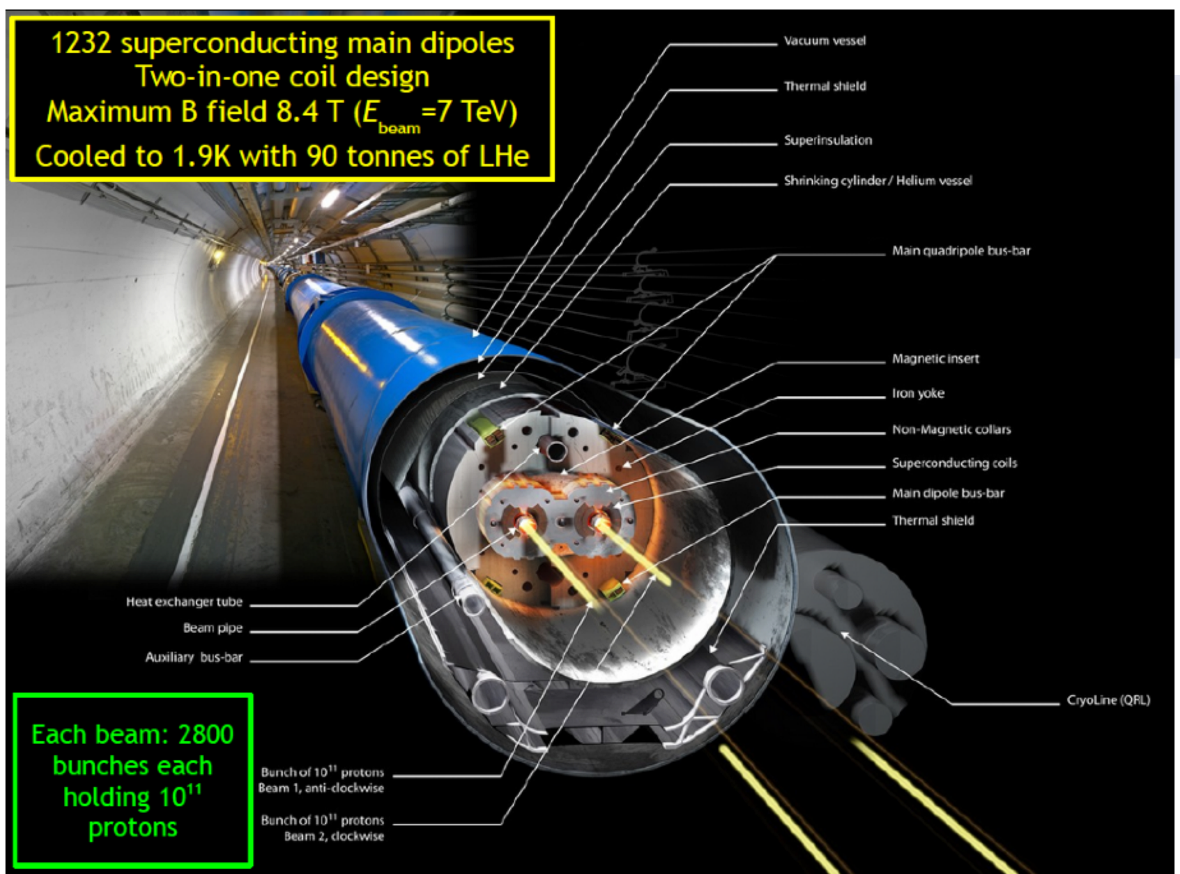


- Beam injection into LHC from SPS at 0.45 TeV
- Magnets used to guide & focus beam; RF cavities to accelerate

Inside the LHC Ring



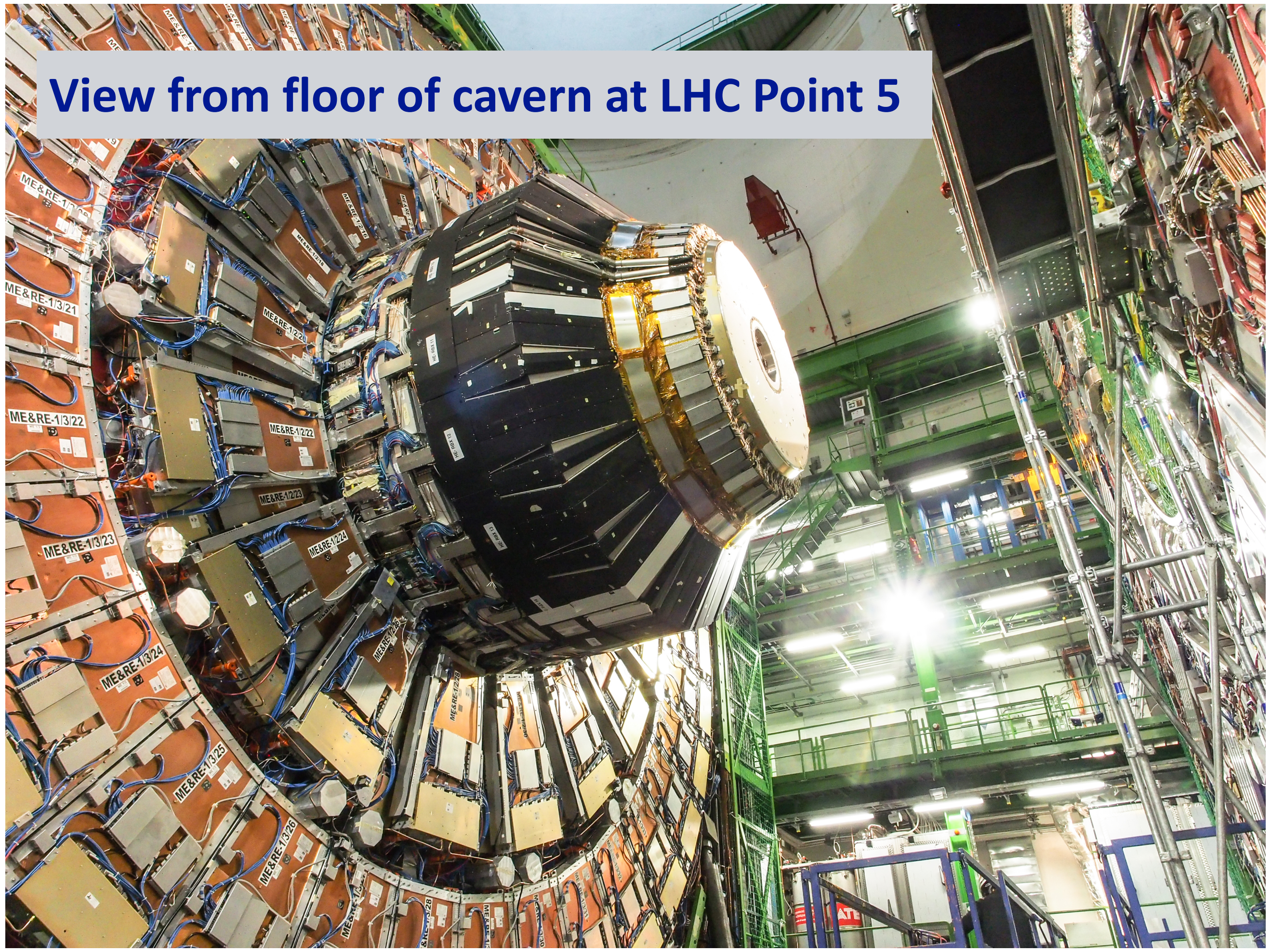


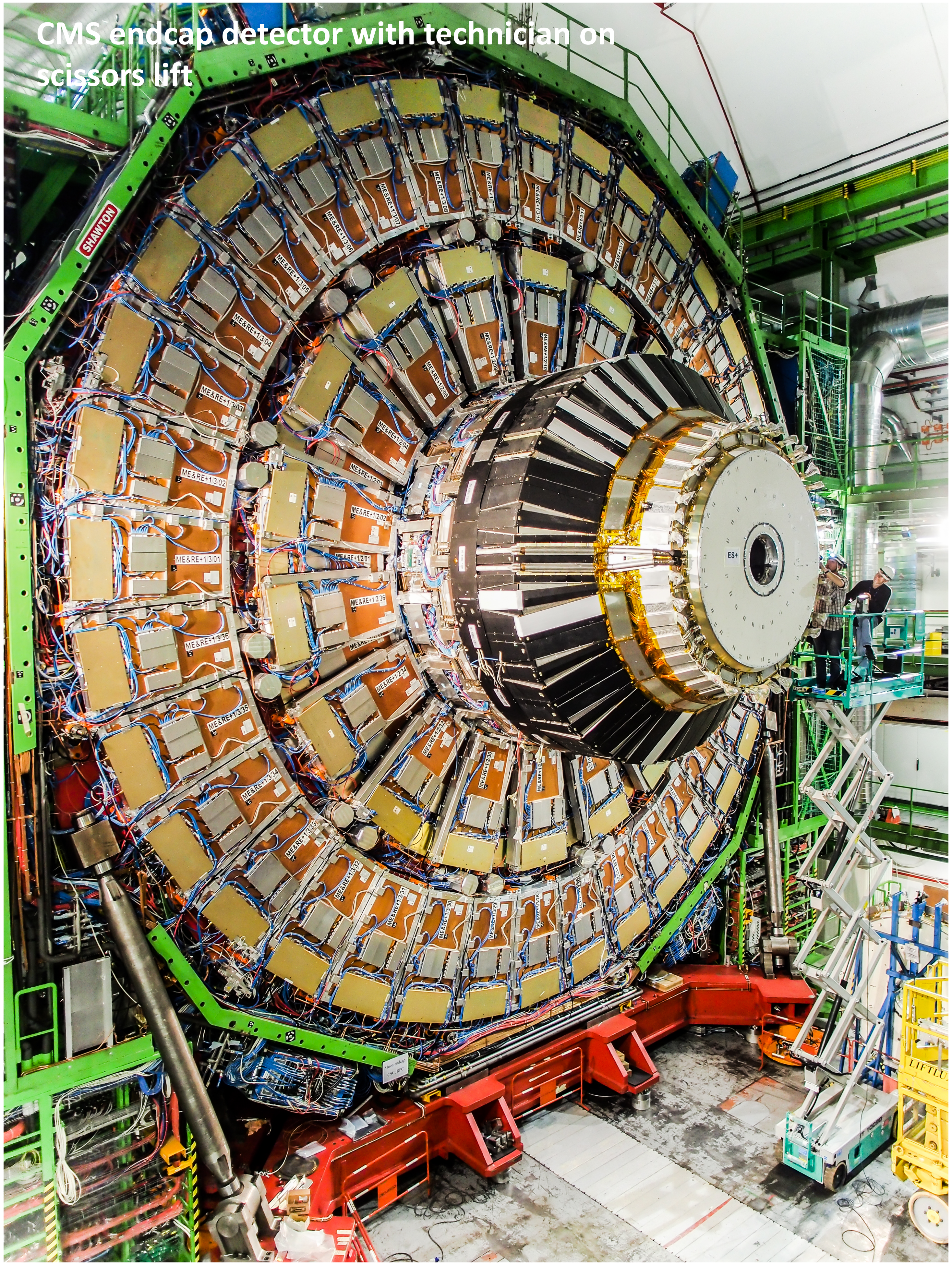


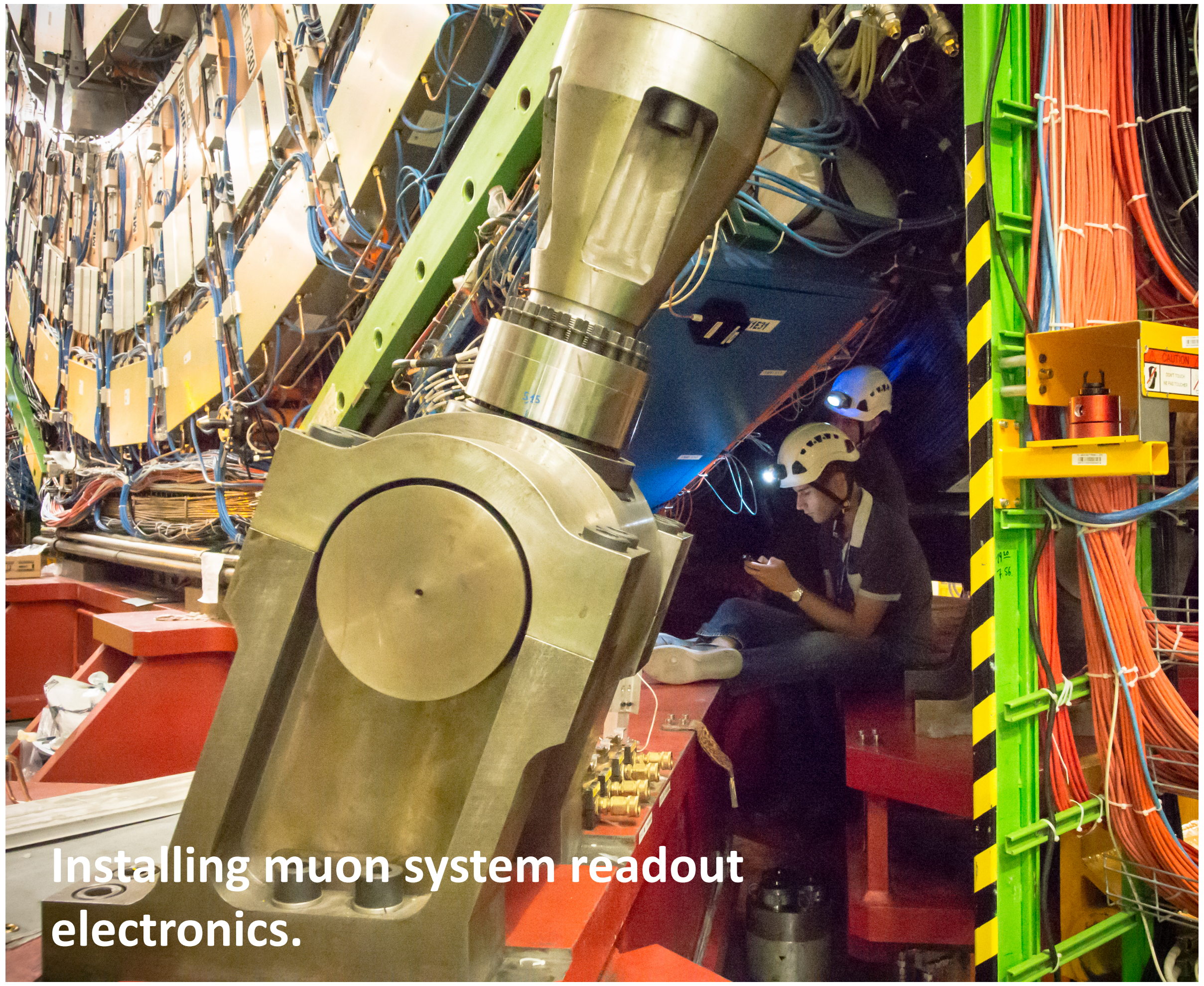

Surface buildings at LHC Point 5 (CMS) near Cessy, France

Security system at LHC Point 5 (CMS)


Access tunnel to LHC cavern for CMS experiment


View from floor of cavern at LHC Point 5

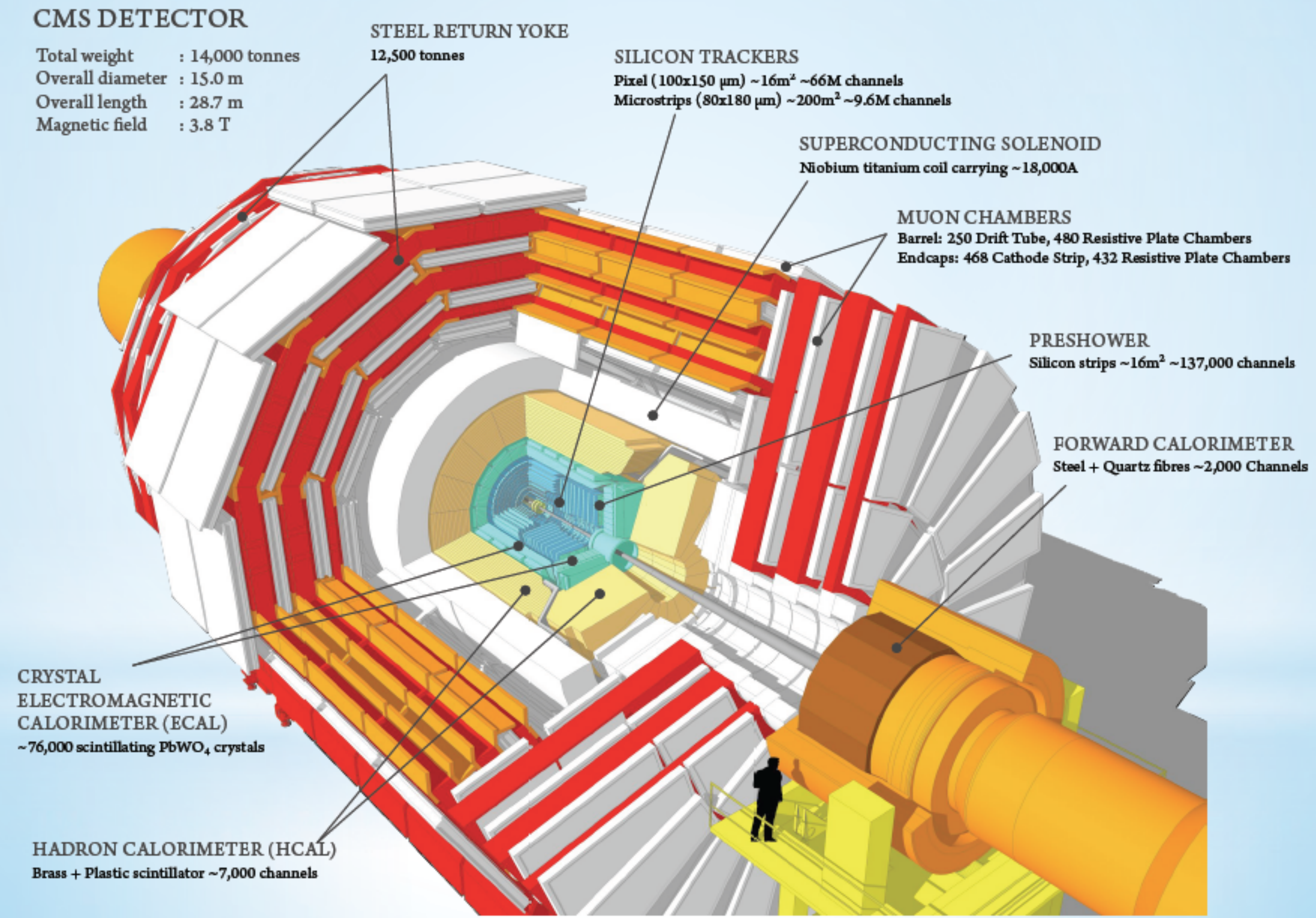

CMS endcap detector with technician on scissors lift


Installing muon system readout electronics.

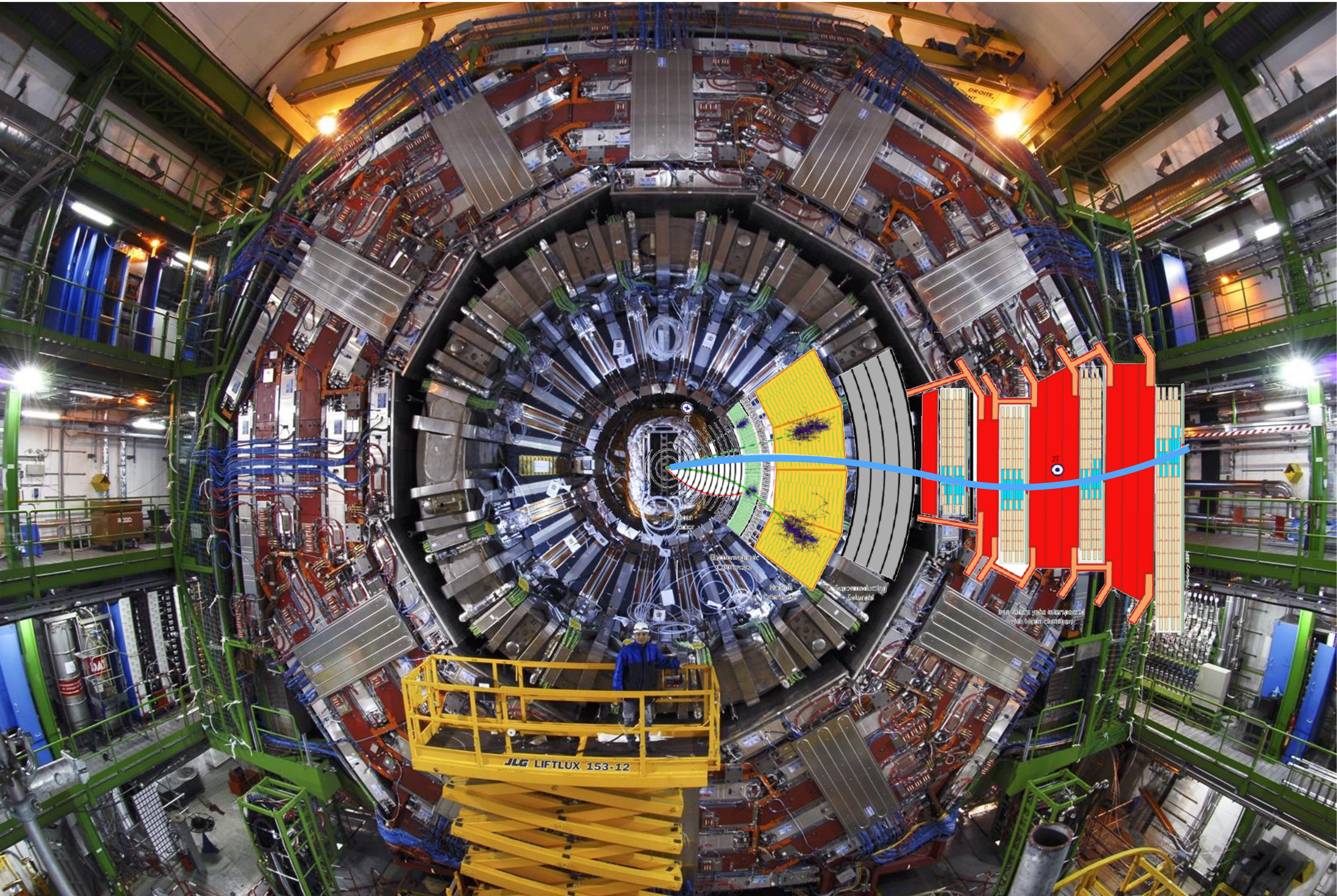

Installing muon system readout electronics.

End view of CMS detector barrel region, viewed from top of endcap detector

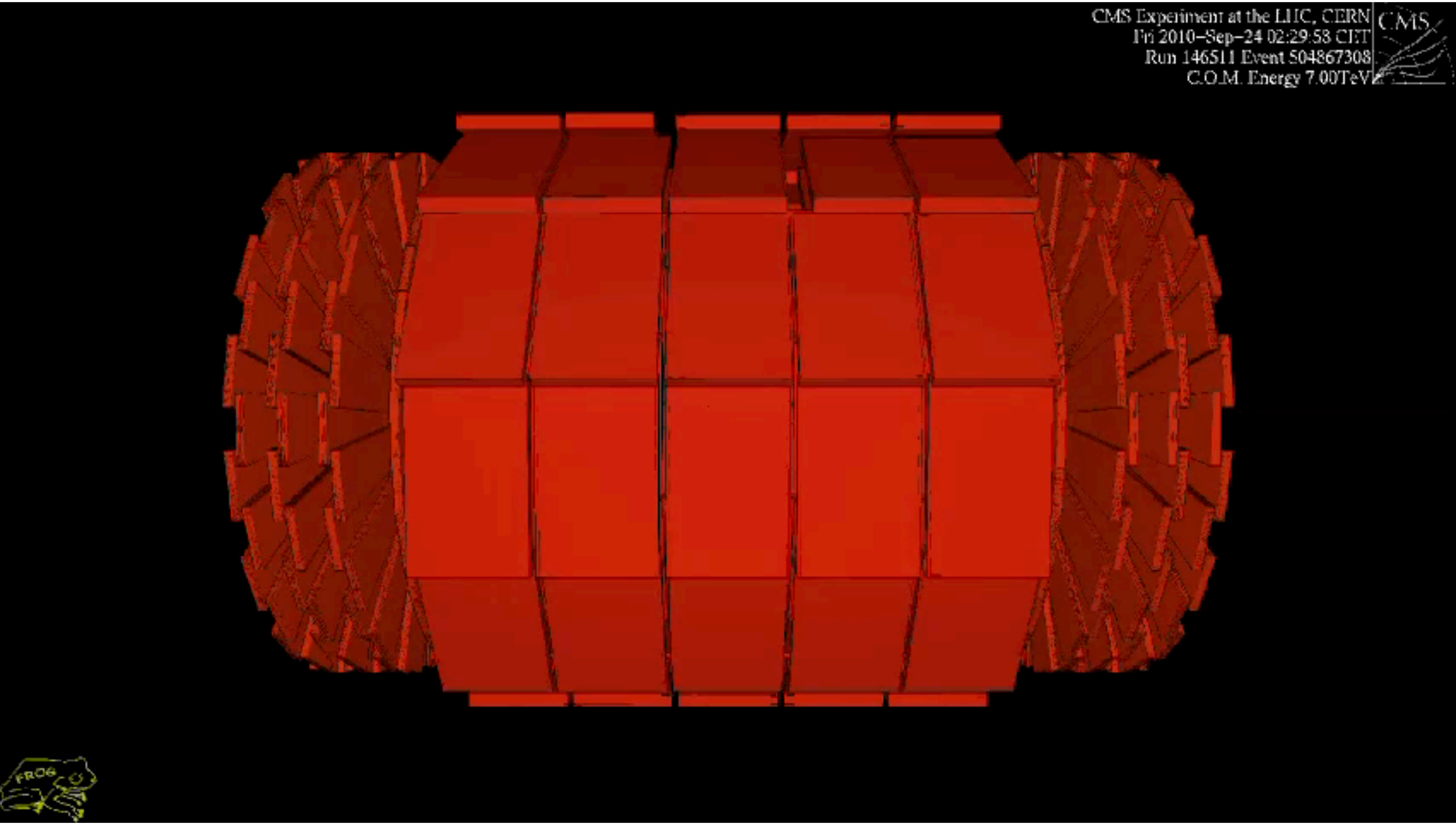
Try to cover as much of 4π solid angle as possible…



CMS detector - Barrel Section



Animated event display



Reconstruction of decays of short lived particles.

$$p^\mu = p_1^\mu + p_2^\mu + \ldots \qquad m = \sqrt{(p_1^\mu + p_2^\mu + \ldots)^2}$$

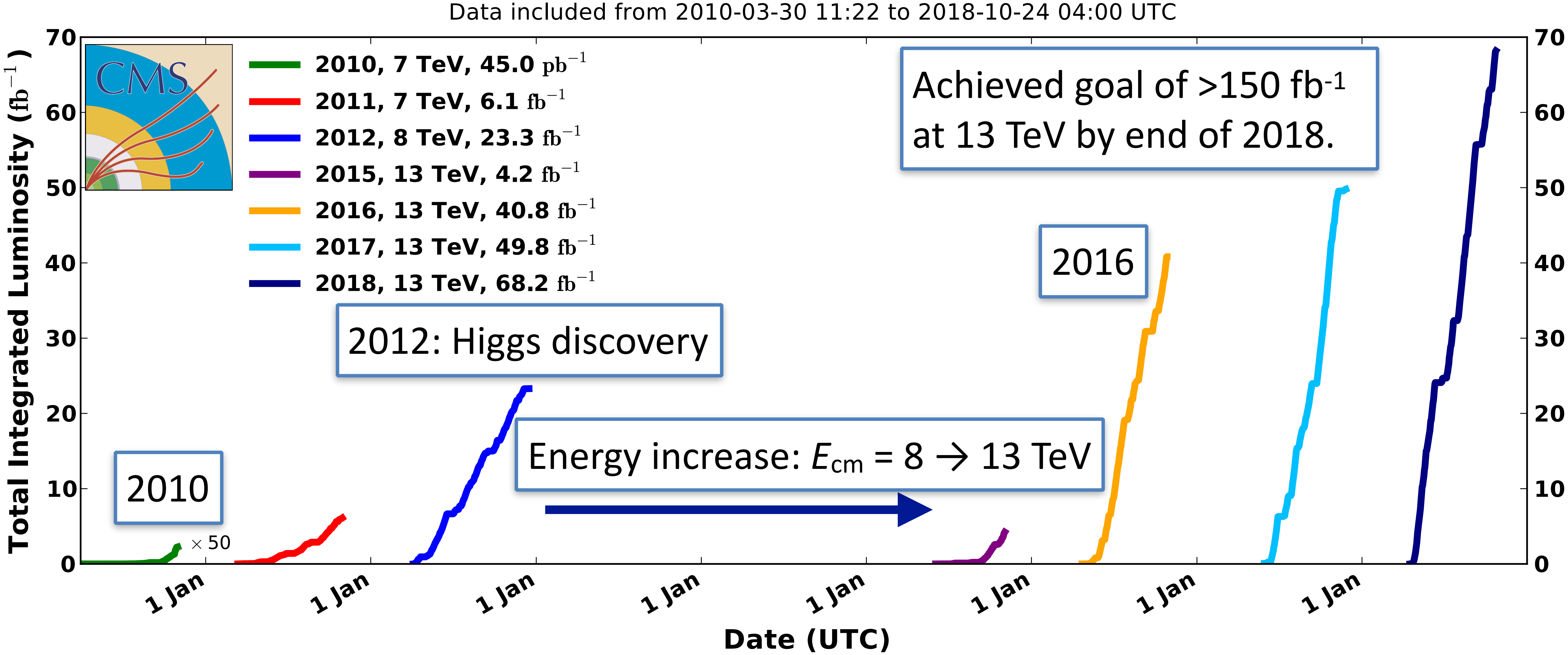
LHC & CMS Data Taking History: Luminosity

- LHC operations have been remarkably stable, with steadily improving performance. CMS data collection effic. ~94% (2018).

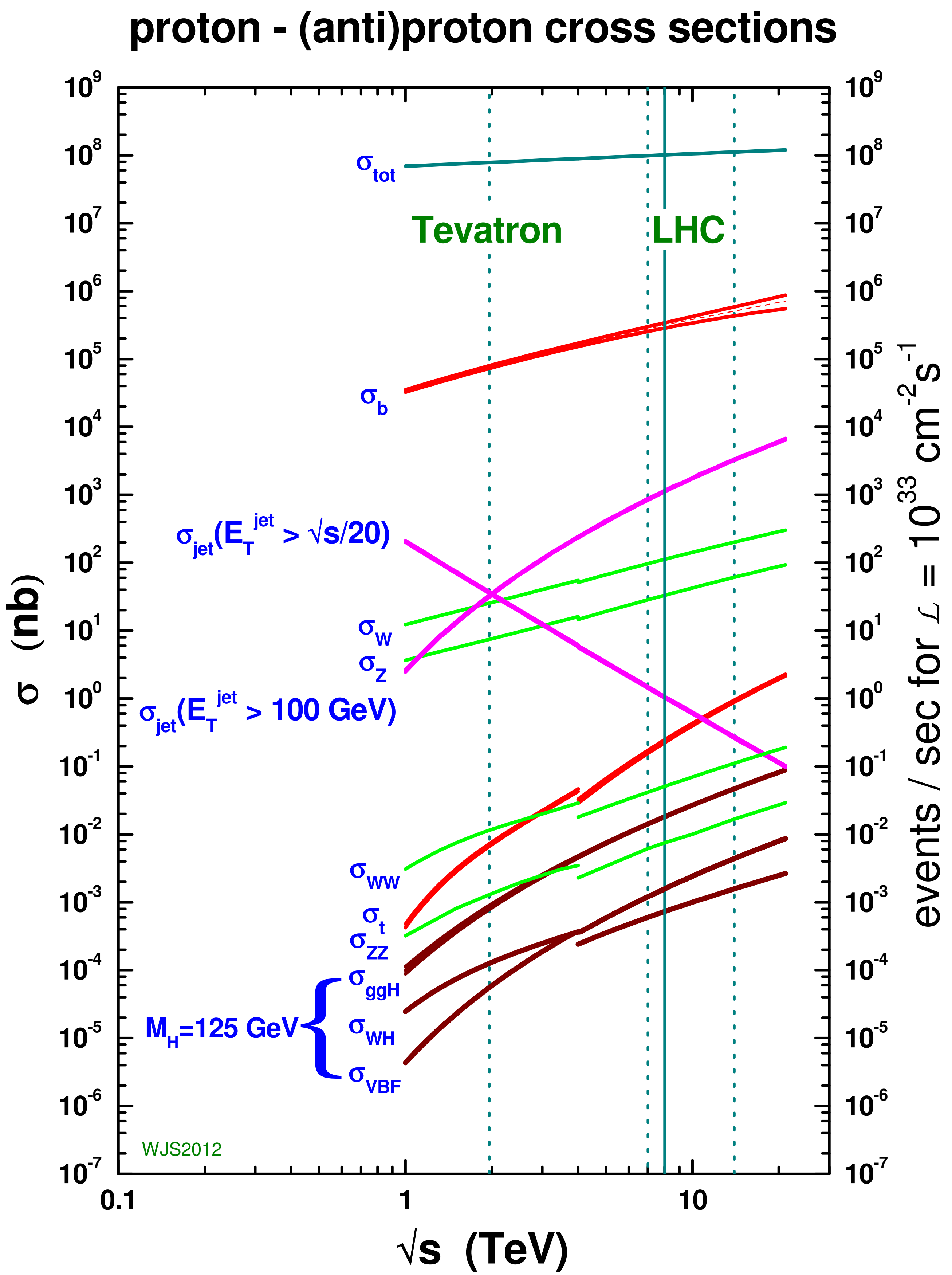
$$L = \frac{N_1 N_2 \cdot f}{4\pi\sigma_x\sigma_y} \qquad R_{i=process} = L \cdot \sigma_i \qquad N_i^{events} = \int L\,dt \cdot \sigma_i$$

Count Accelerator Theory/ Measure

$$L_{\text{peak}} \approx 2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$$



Basics of LHC physics: cross sections



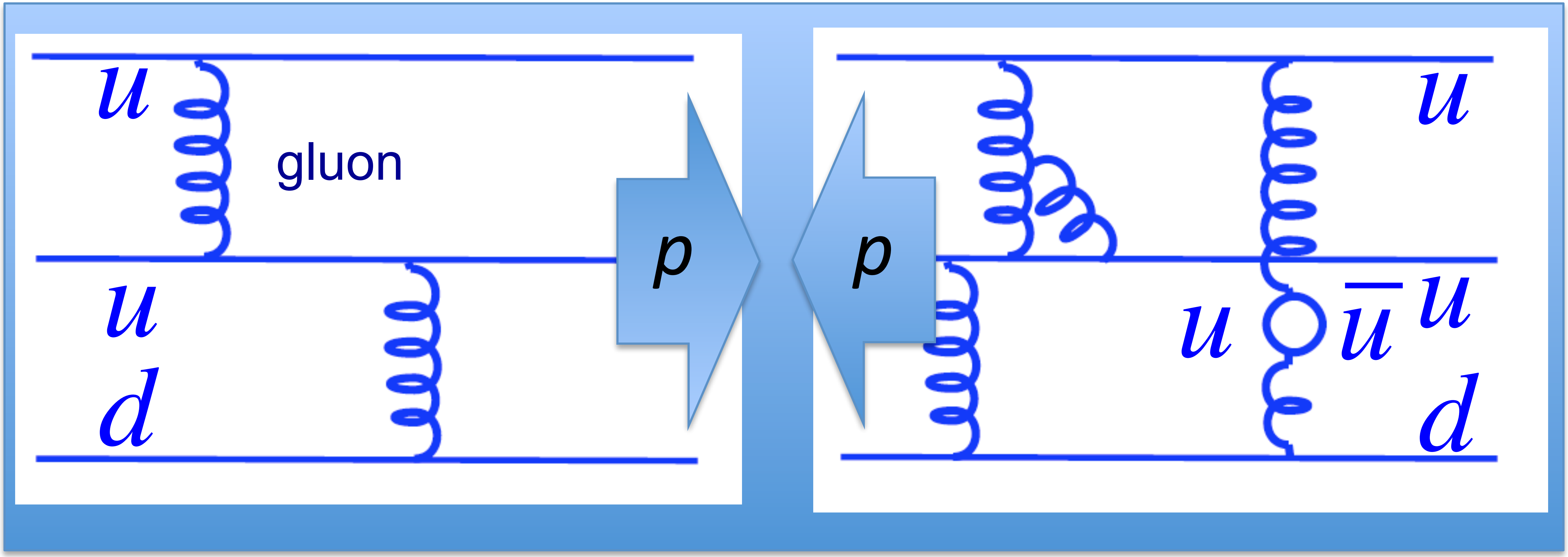
http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html\

- Basic pp cross section is very roughly geometrical.

$$\sigma_{pp} \sim \pi r^2_{proton} \sim \pi \cdot (1\ \mathrm{fm})^2$$
$$\sim \pi (10^{-26}\ \mathrm{cm}^2) \sim 30\ \mathrm{mb}$$

- But cross sections for key processes are much smaller and vary over many (~15) orders of magnitude.
- Depending on how you count, there are ~hundreds of processes to measure and study.
- Currently, ~800 CMS papers.

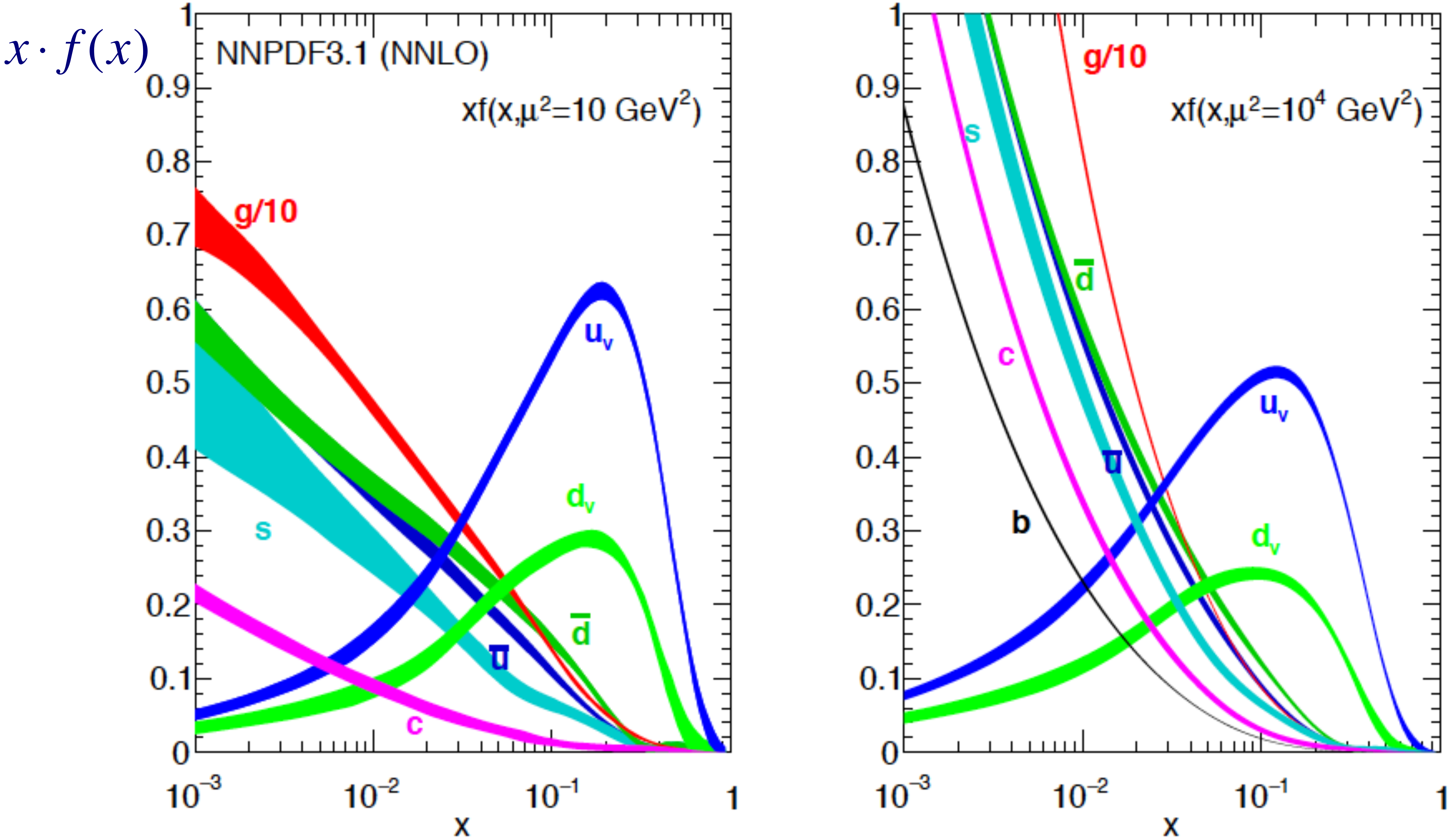
Basics of LHC physics: partons in the proton



- Protons are composite objects!
- The nominal *uud* quark content of a proton is just a rough approximation. The full "parton" content includes other types of quarks as well as gluons. Much of the LHC physics program results from gluon-gluon collisions.
- CM frame of parton-parton collision is boosted w.r.t. lab frame.

Basics of LHC physics: partons in the proton

- Fraction of proton momentum carried by a parton: *x*



- Parton distribution functions from the NNPDF collaboration.

https://arxiv.org/abs/1706.00428

Particle content of the Standard Model

Quarks: spin-1/2

u *up*	c *charm*	t *top*
d *down*	s *strange*	b *bottom*

Leptons: spin-1/2

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

Gauge bosons: spin-1

Strong force	Weak force			EM force
g	W^+	W^-	Z^0	γ
gluon (8)	*W bosons*		*Z boson*	*photon*

Higgs boson: spin-0

& field vacuum expectation value

H

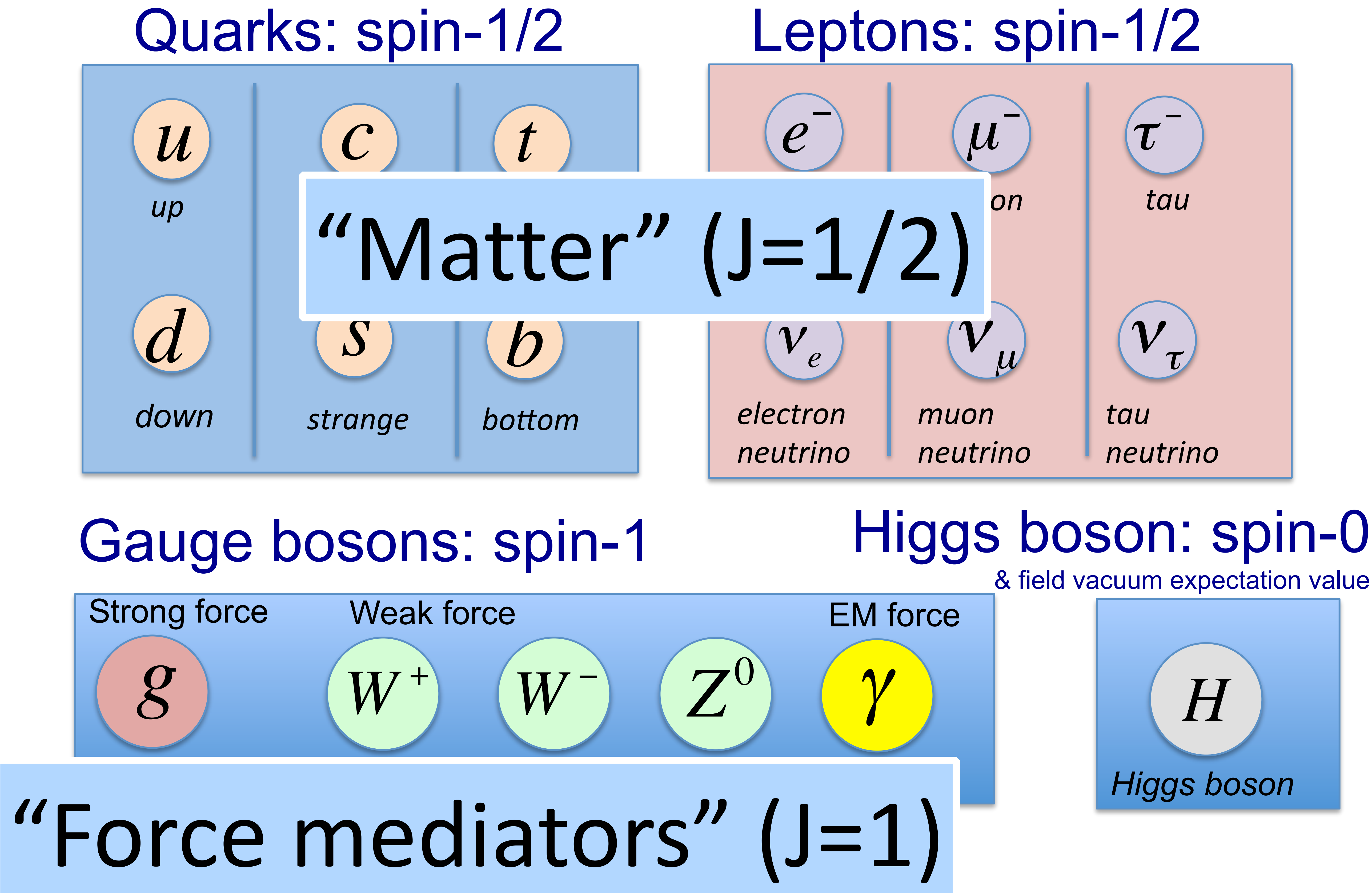
Higgs boson

$\boxed{SU(3)_C}$ $\quad g_s$

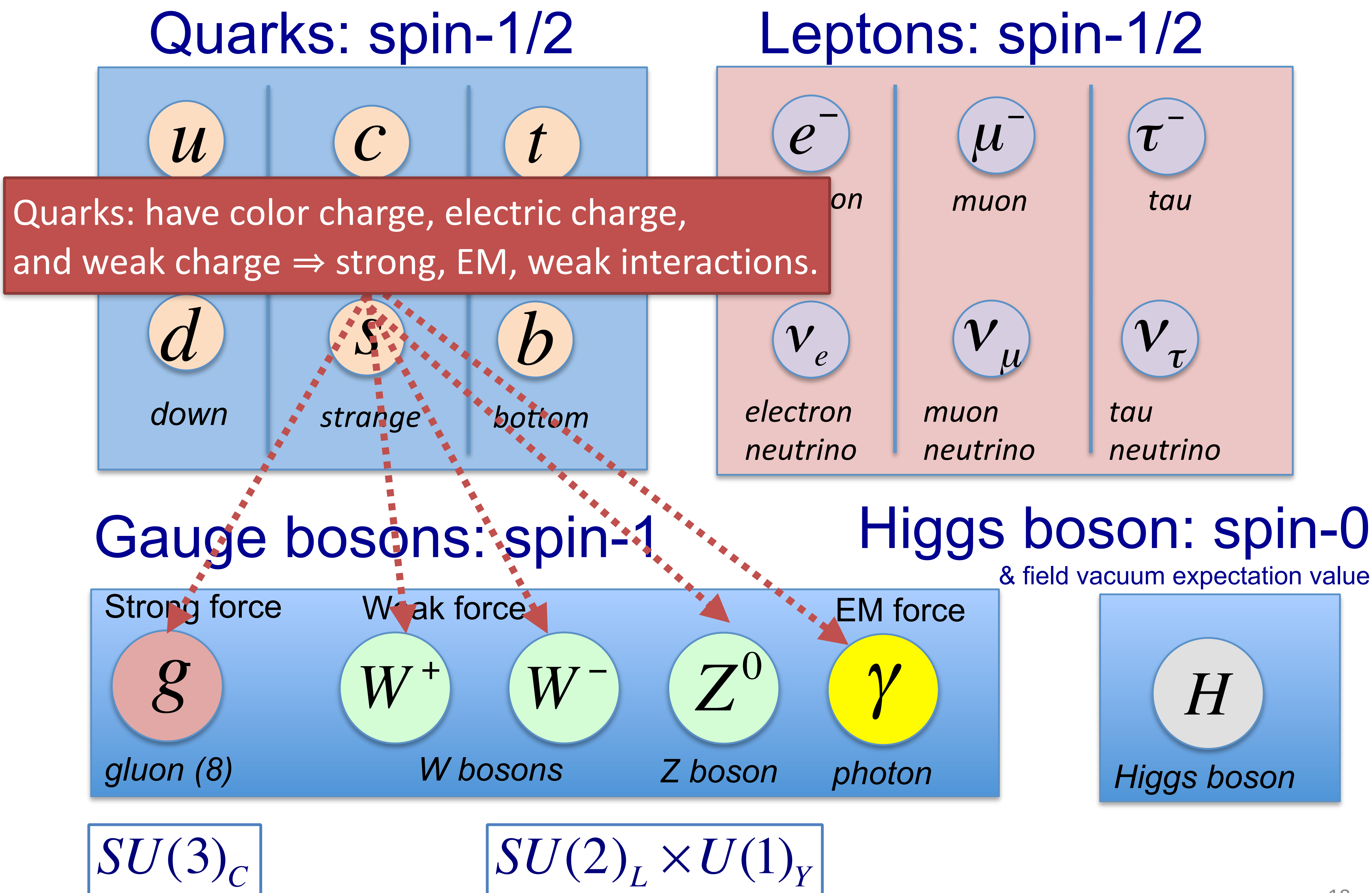
$\boxed{SU(2)_L \times U(1)_Y}$ $\quad g \quad g'$

$$e = \frac{gg'}{\sqrt{g^2 + (g')^2}} = g \sin\theta_W$$

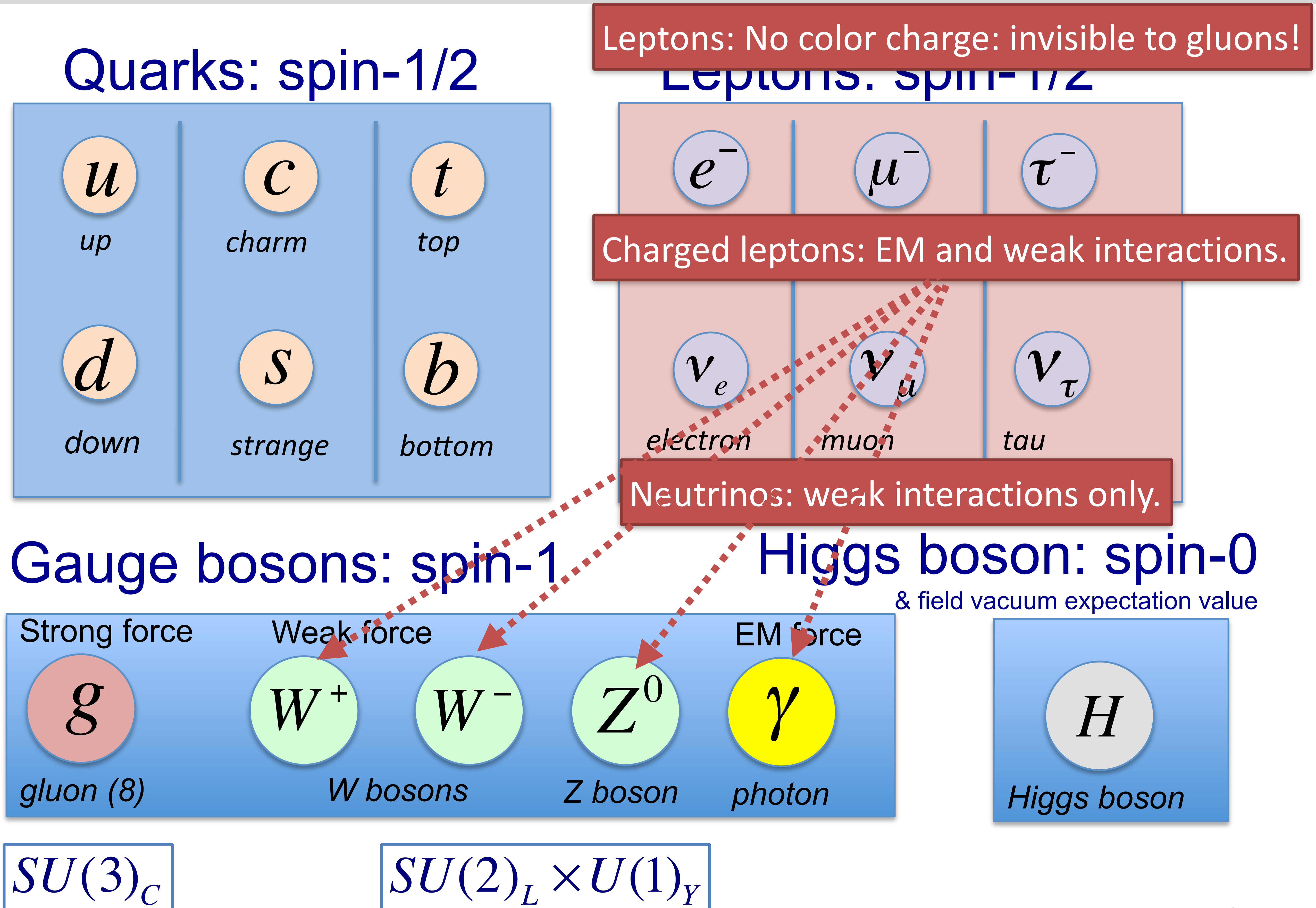
Particle content of the Standard Model



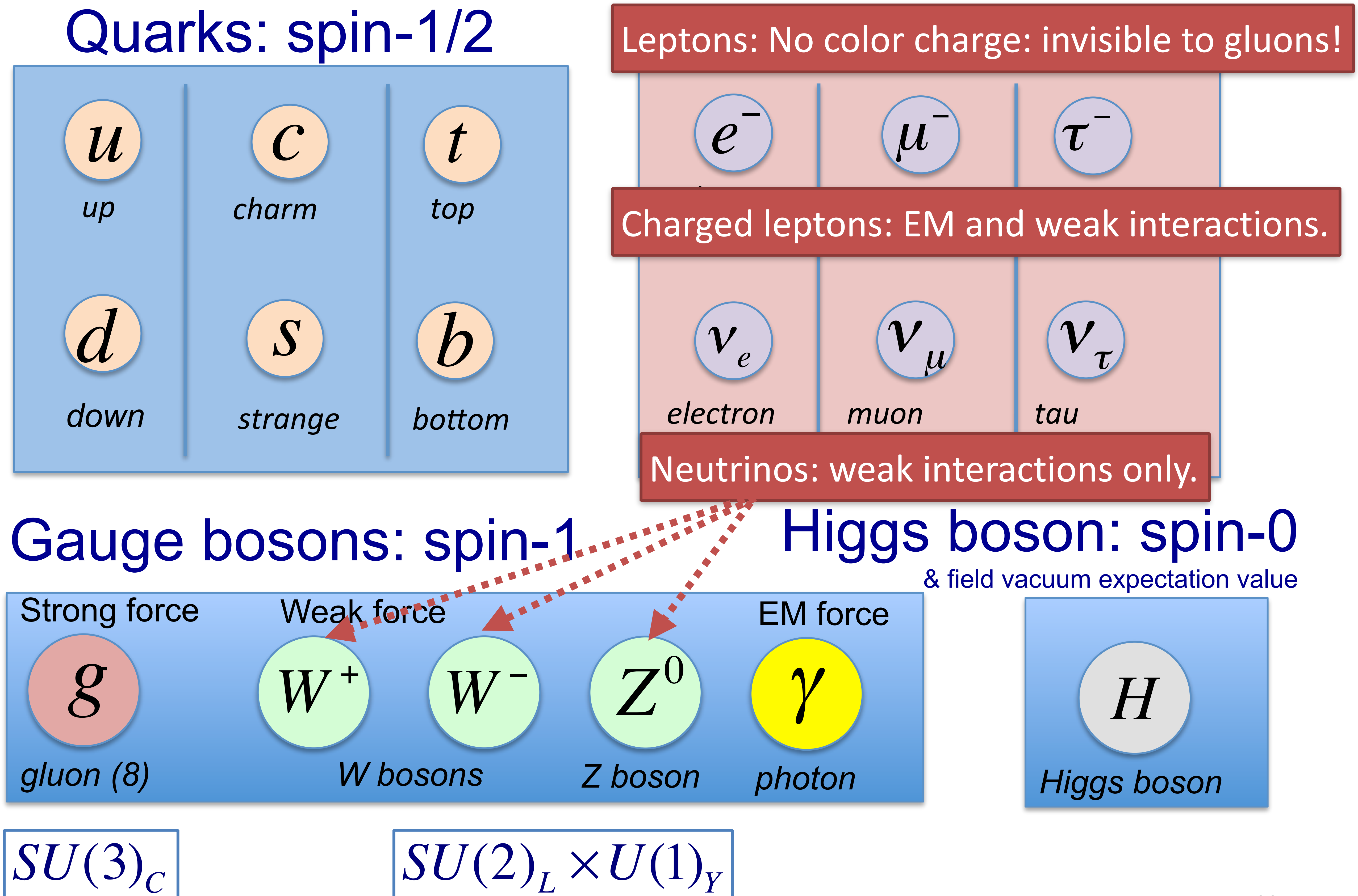
Particle content of the Standard Model



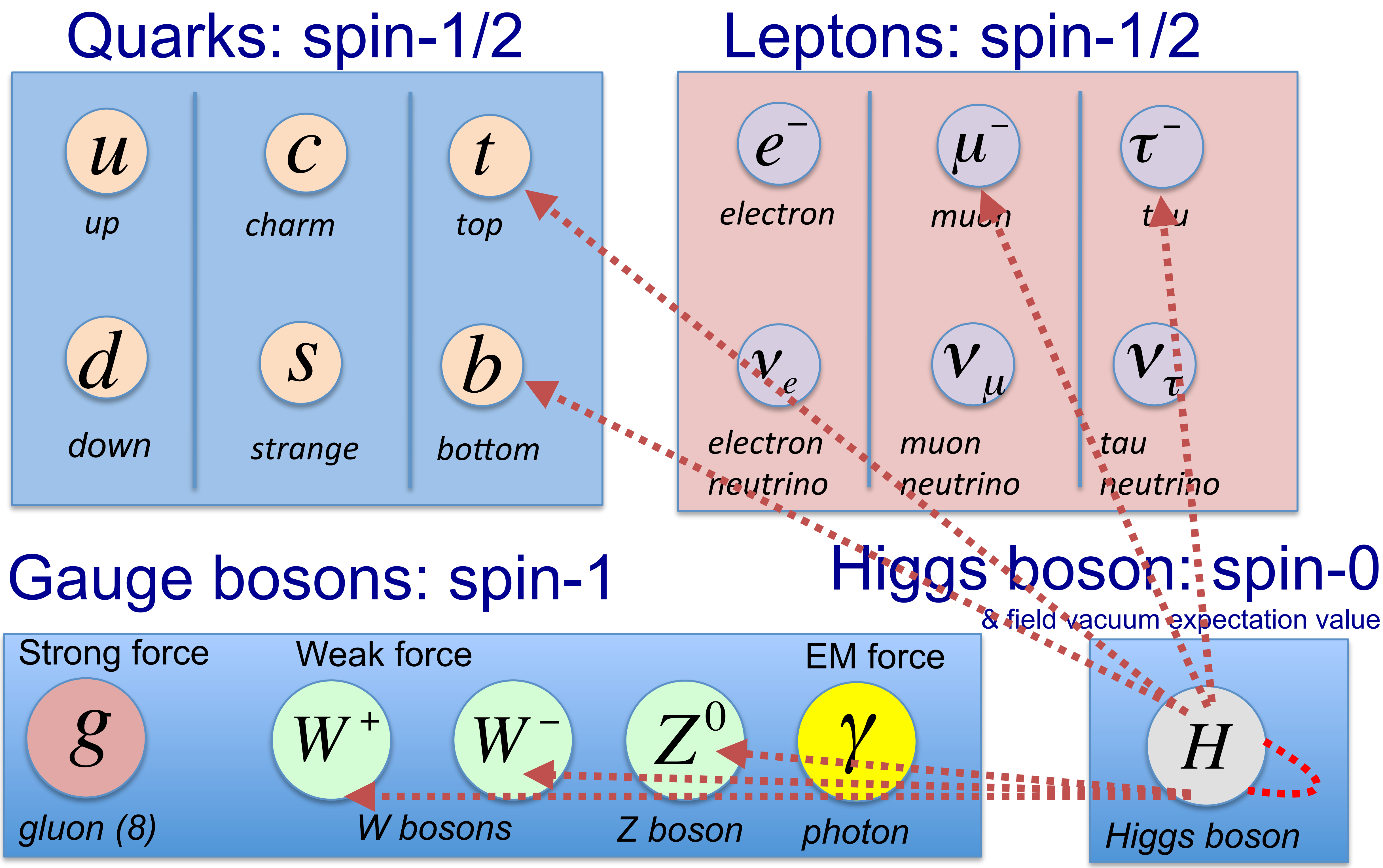
Particle content of the Standard Model



Particle content of the Standard Model

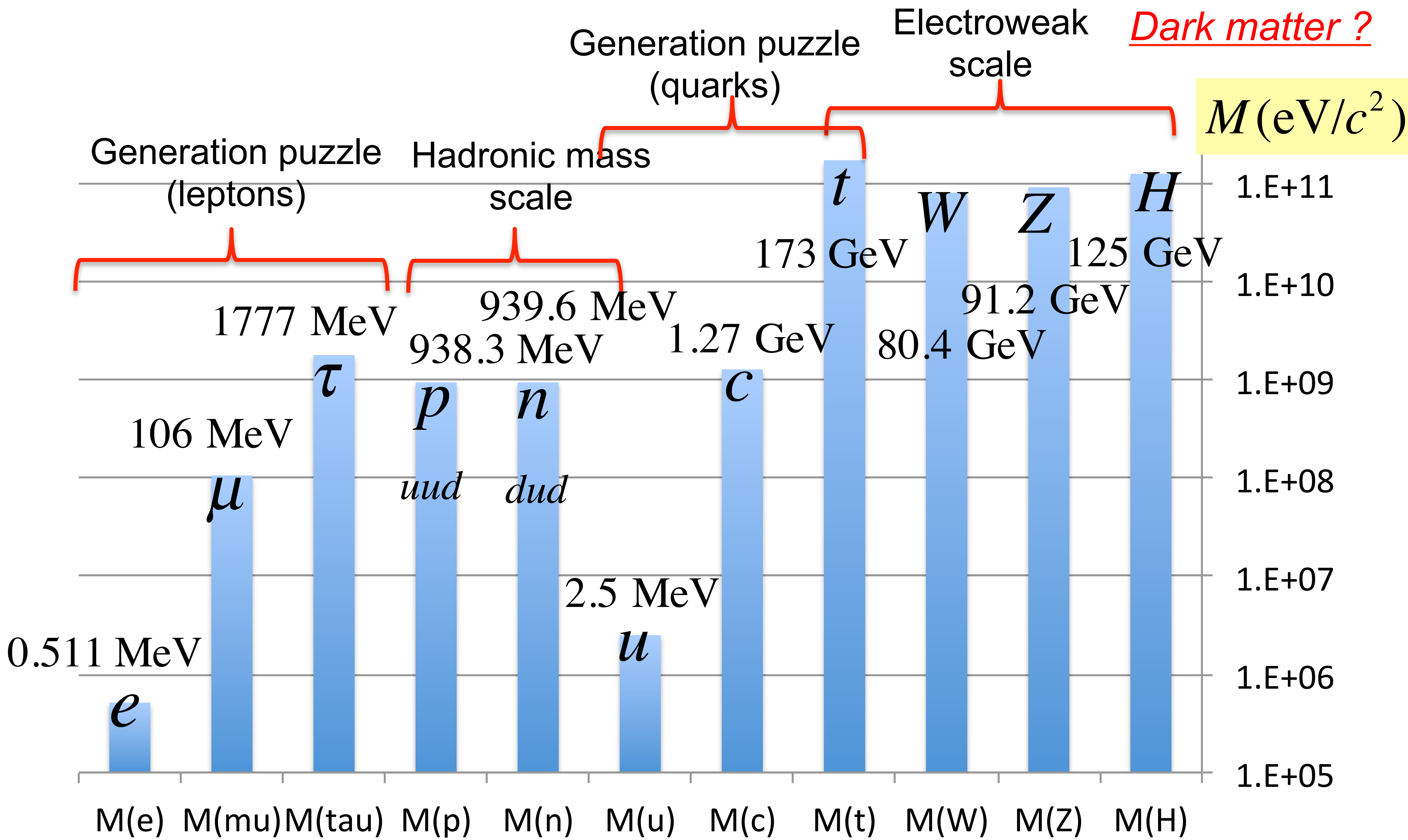


Particle content of the Standard Model



Higgs physics program: want to fully test all experimentally accessible processes to test SM predictions.

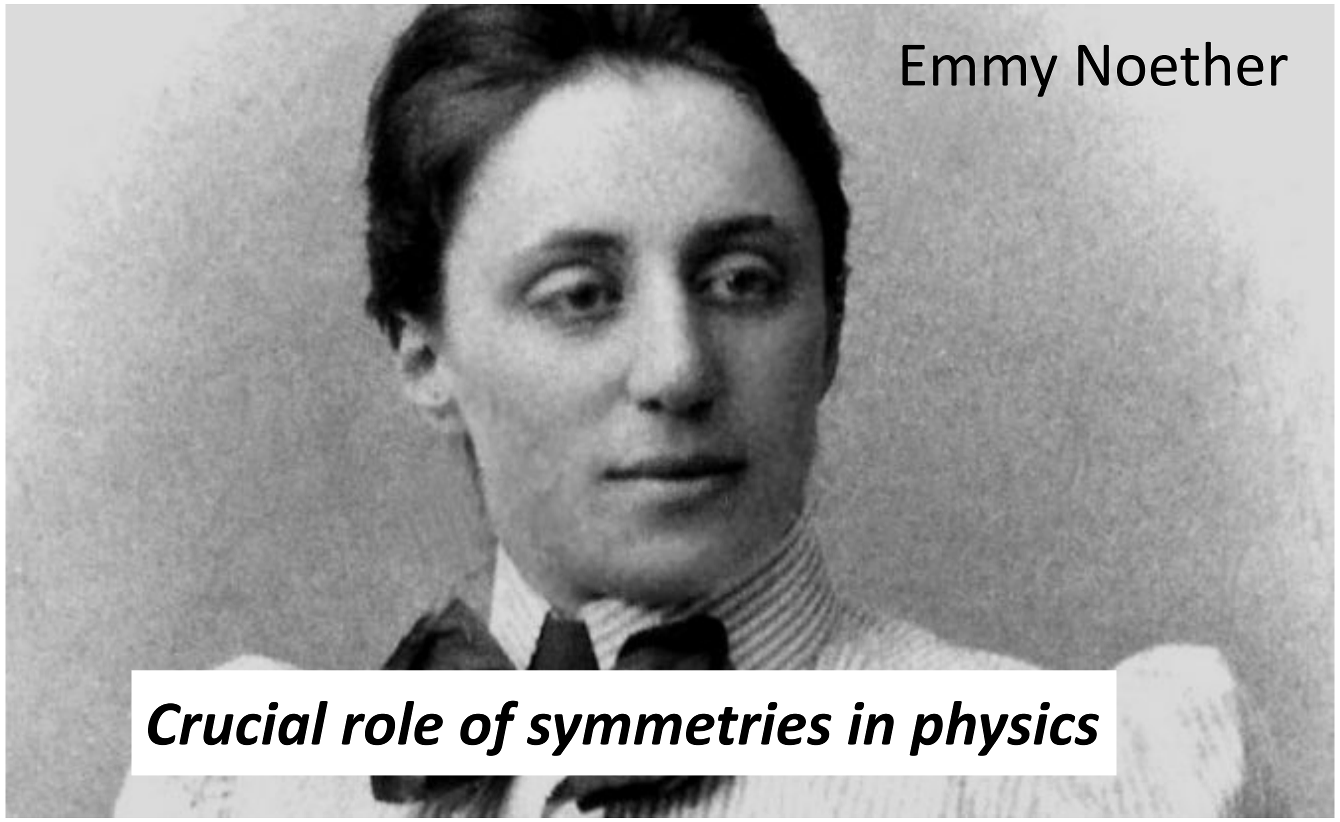
Mass scales in particle physics



Neutrino masses! m(ν) ≲ 0.1 eV (?) - another key mass scale!

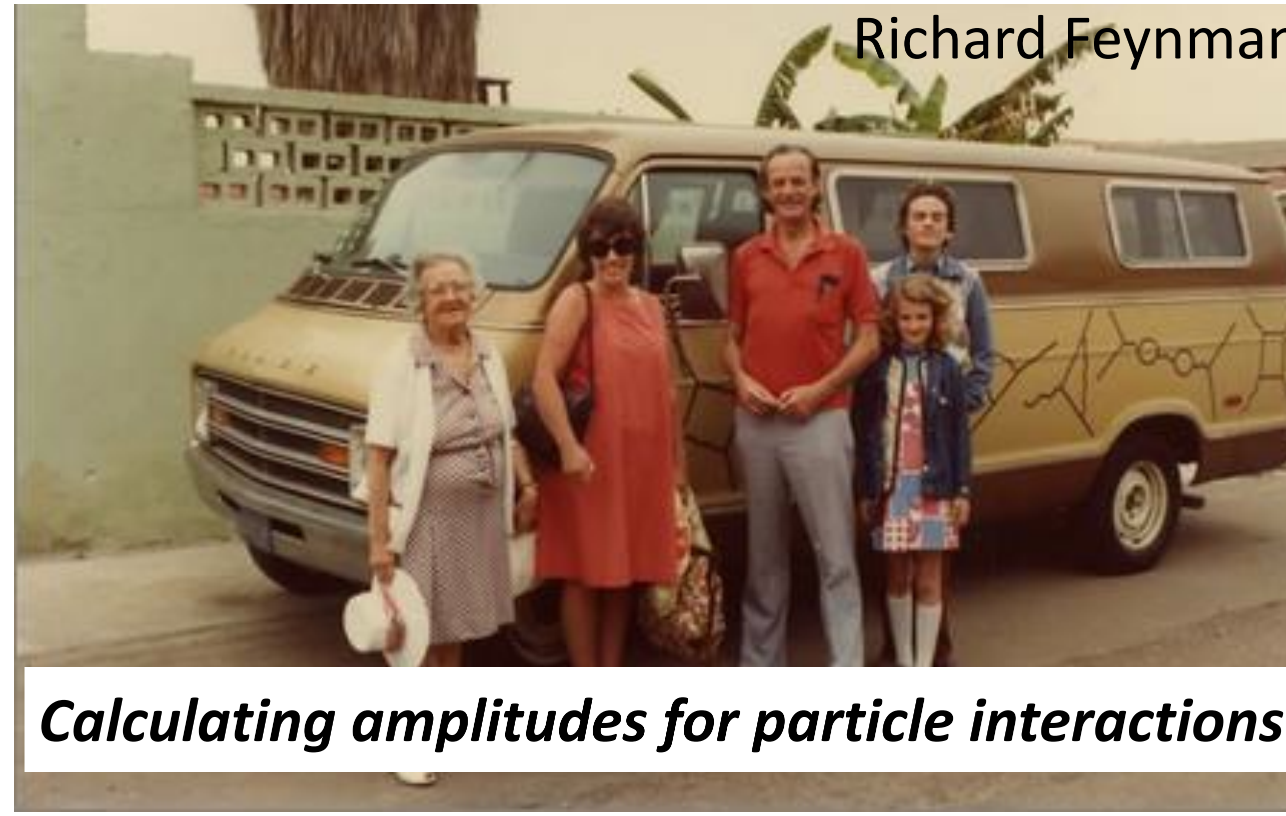
$M_{\mathrm{Planck}} \approx 10^{18}$ GeV

Some key people and ideas



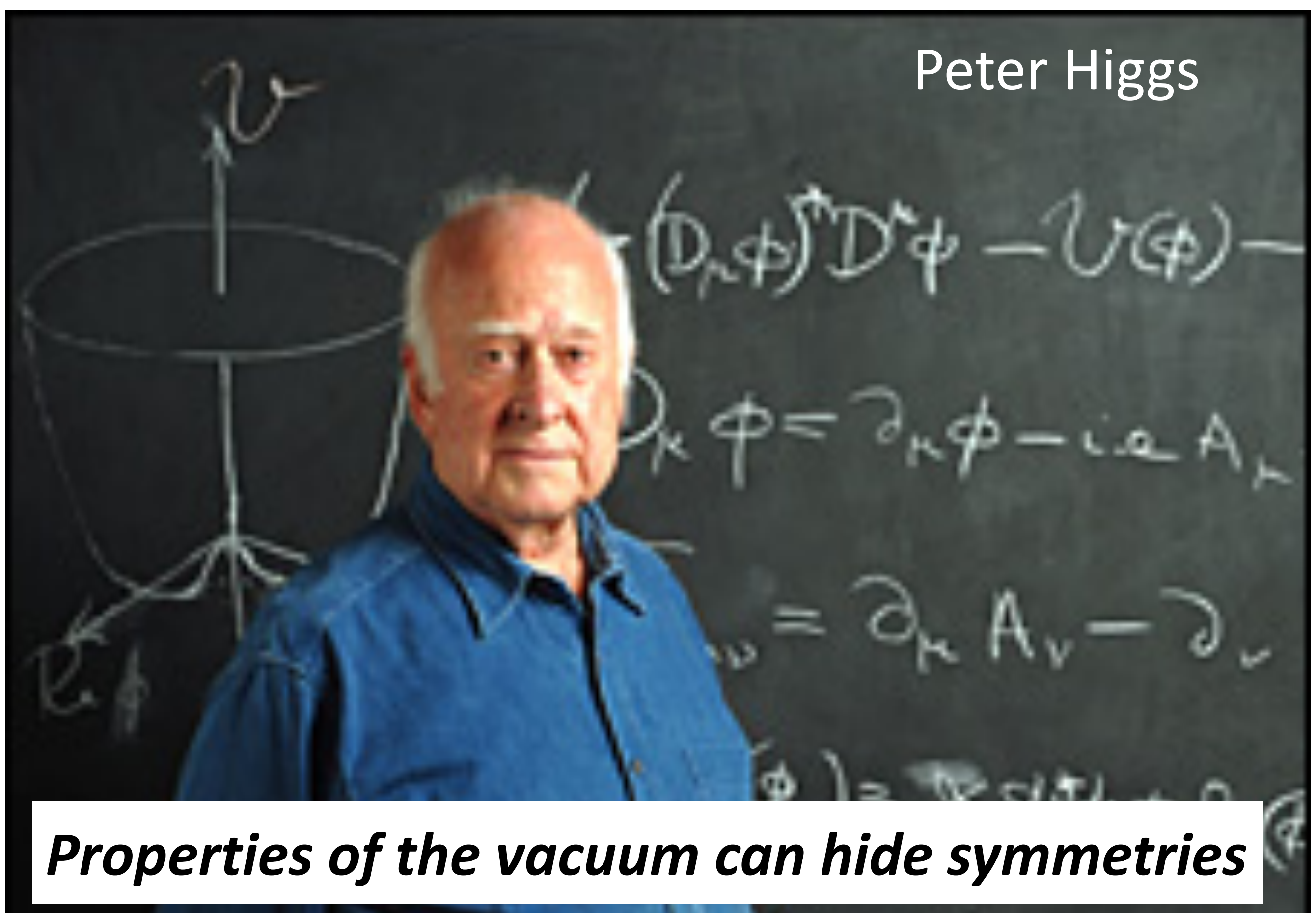
Emmy Noether

Crucial role of symmetries in physics



Richard Feynman

Calculating amplitudes for particle interactions



Peter Higgs

Properties of the vacuum can hide symmetries

Vera Rubin

The dominant component of matter in the universe has not been identified

A dialog about the weak interactions

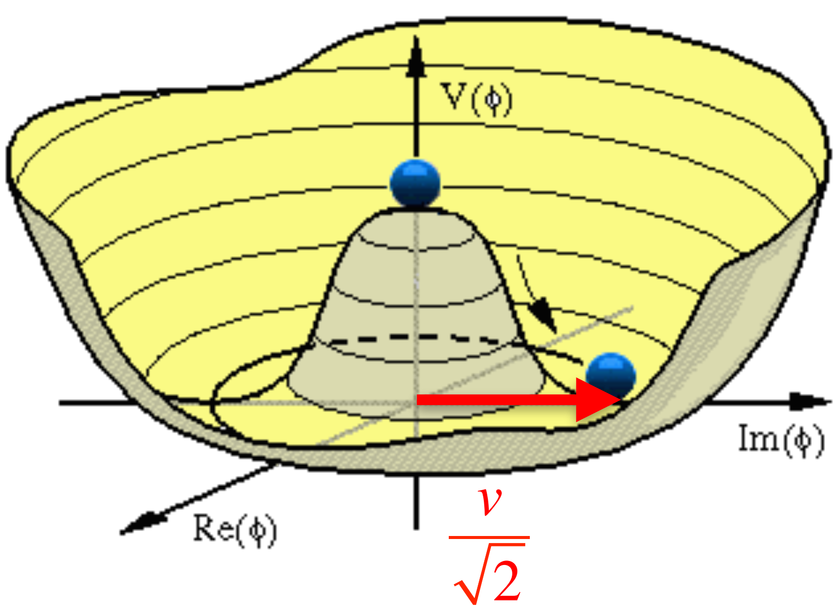
- Student: “Why are the weak interactions *weak*?”
- Professor: “They aren’t *actually* weak, at least compared with electromagnetic interactions. In fact, they are unified into a single electroweak theory.”
- Student: “Well, then, why are these interactions that aren’t really weak called weak interactions?”
- Professor: “The weak coupling is similar to the EM coupling, but weak processes at low energies are suppressed by the large mass of the mediating particle, either a W or a Z boson.”
- Student: “I get it: electromagnetic processes don’t have this suppression because the photon, the quantum of the field mediating the interaction, is massless.”
- Professor: “Precisely.”

…the next day

- Student: "I think there is a problem with your story about the weak interactions and the heavy W and Z bosons."
- Professor: "What is that?"
- Student: "The weak interactions are described by a gauge theory, and the gauge bosons are not allowed to have mass, because this would destroy the gauge symmetry. Mass terms are not permitted in the Lagrangian."
- Professor: "Go away!"
- Professor Higgs (entering): "Wait, your student is right! Interactions with a special spin-0 field can give masses to gauge bosons, making it appear that the gauge symmetry is broken, even though it actually isn't! If my theory is correct, there should be a new J=0 particle with remarkable properties!"

The role of the Higgs field in the SM

- The SM is a gauge theory built on the symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$. The SM is highly predictive.
- But, explicit mass terms in the Lagrangian violate this symmetry. ***How are particle masses compatible with the gauge symmetry?***
- Higgs mechanism: spontaneous symmetry breaking (SSB) hides the underlying symmetry and explains how particles *acquire* masses.



Complex Higgs doublet field

$$\varphi(x) \equiv \begin{pmatrix} \varphi_1(x) + i\varphi_2(x) \\ \varphi_3(x) + i\varphi_4(x) \end{pmatrix}$$

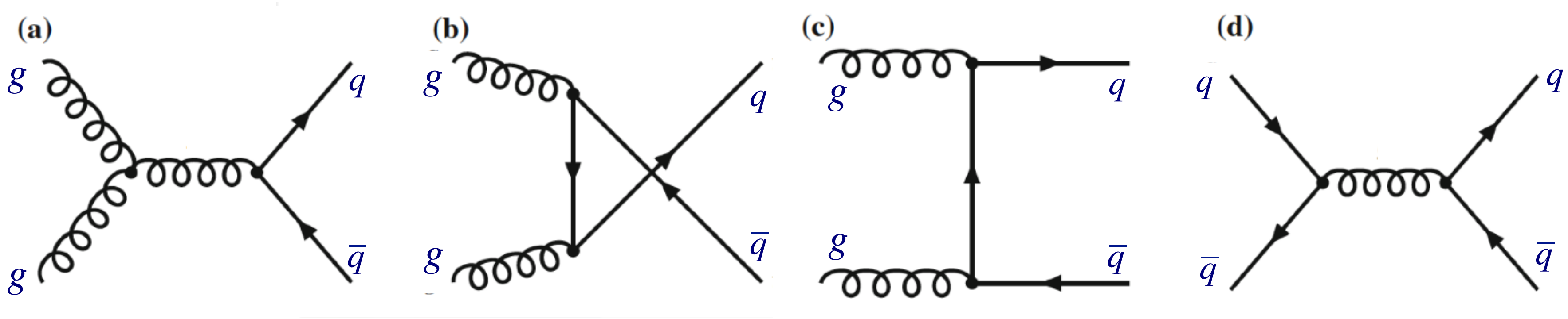
$$\varphi(x) \to \frac{1}{\sqrt{2}} \begin{pmatrix} \sigma_1(x) + i\sigma_2(x) \\ v + \eta_1(x) + i\eta_2(x) \end{pmatrix}$$

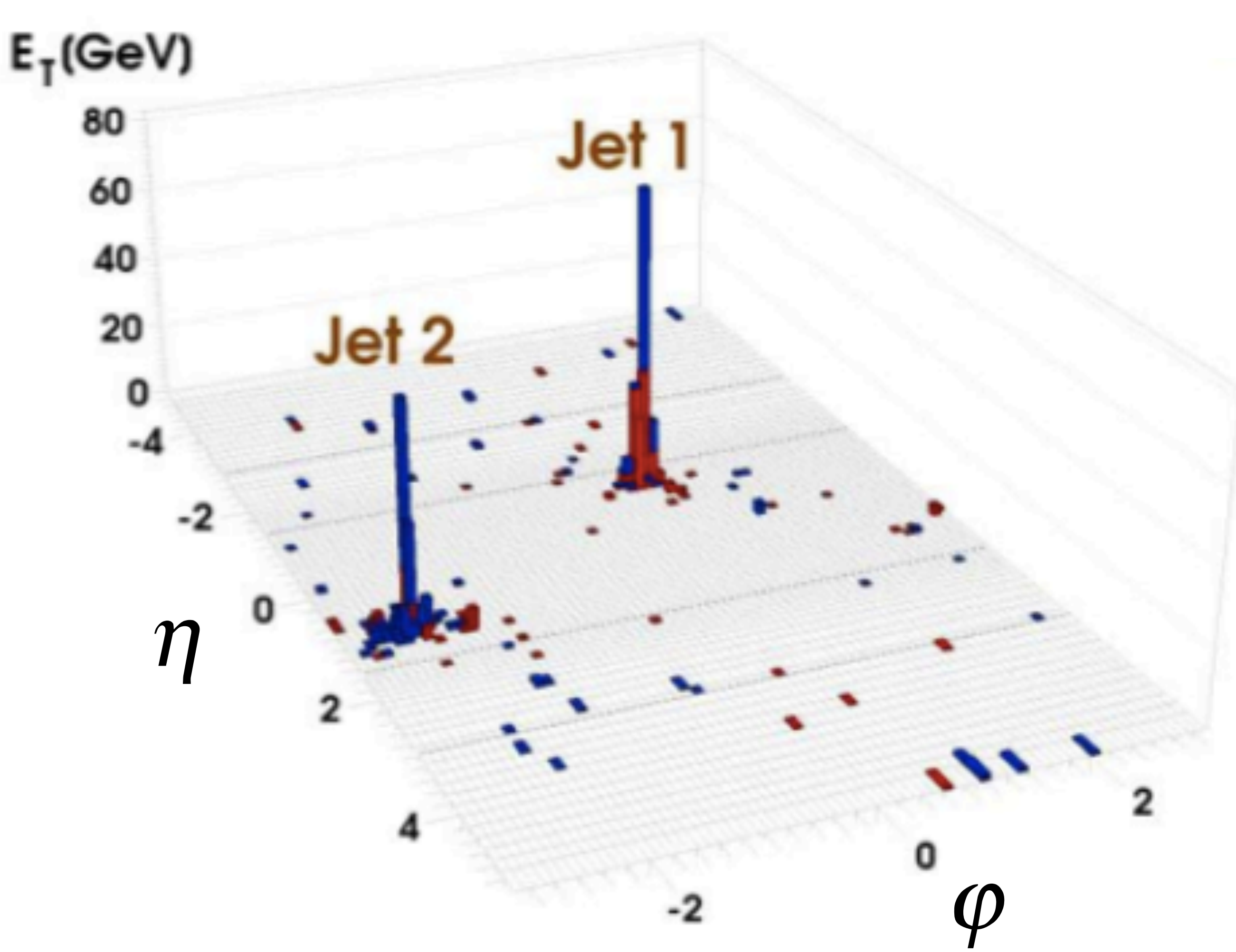
Higgs field vacuum expectation value

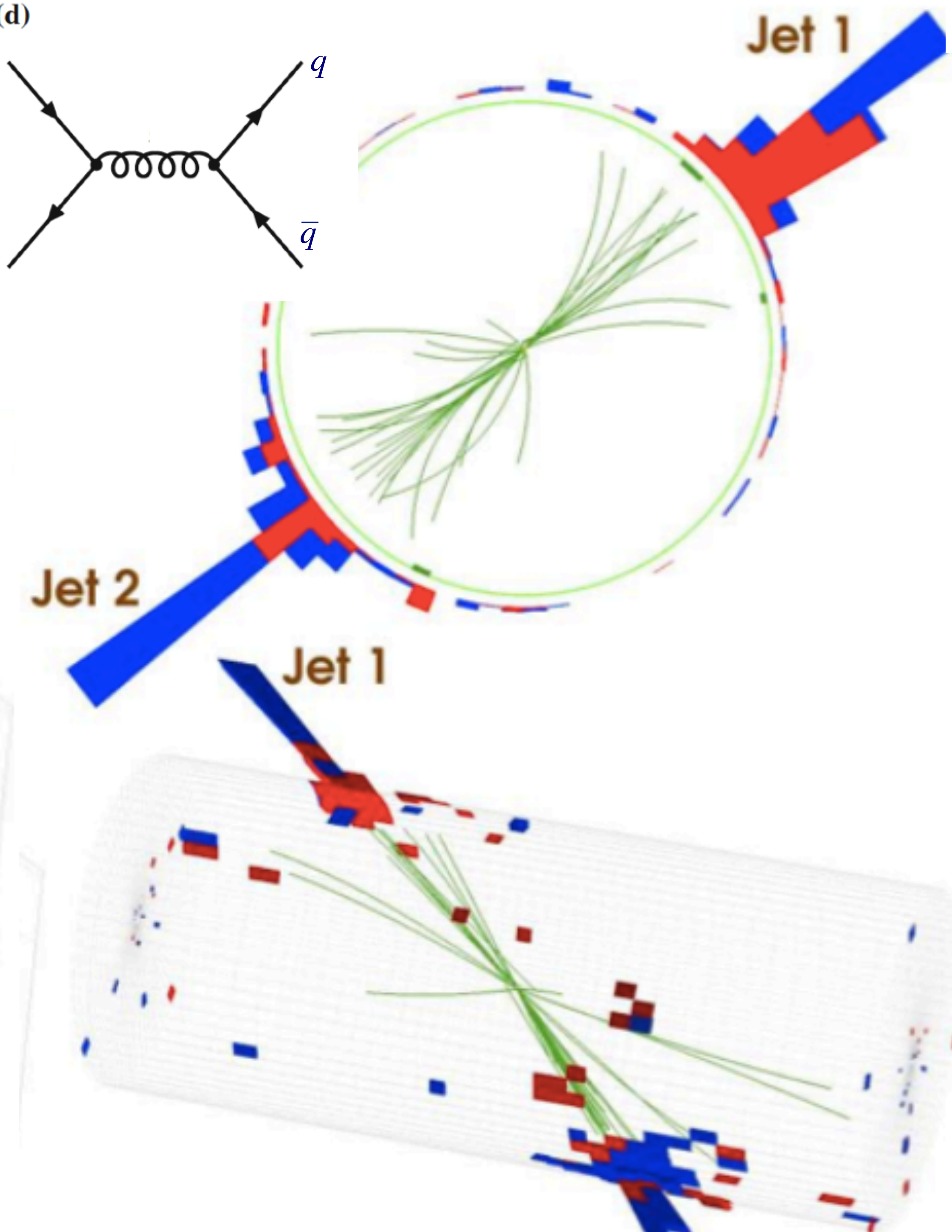
$$\begin{aligned}\mathcal{L} = &-\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ &+ i\bar{\psi}\not{D}\psi \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. \\ &+ |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

SM processes at the LHC: dijet production

Strong interaction process ⇒ very large cross section.







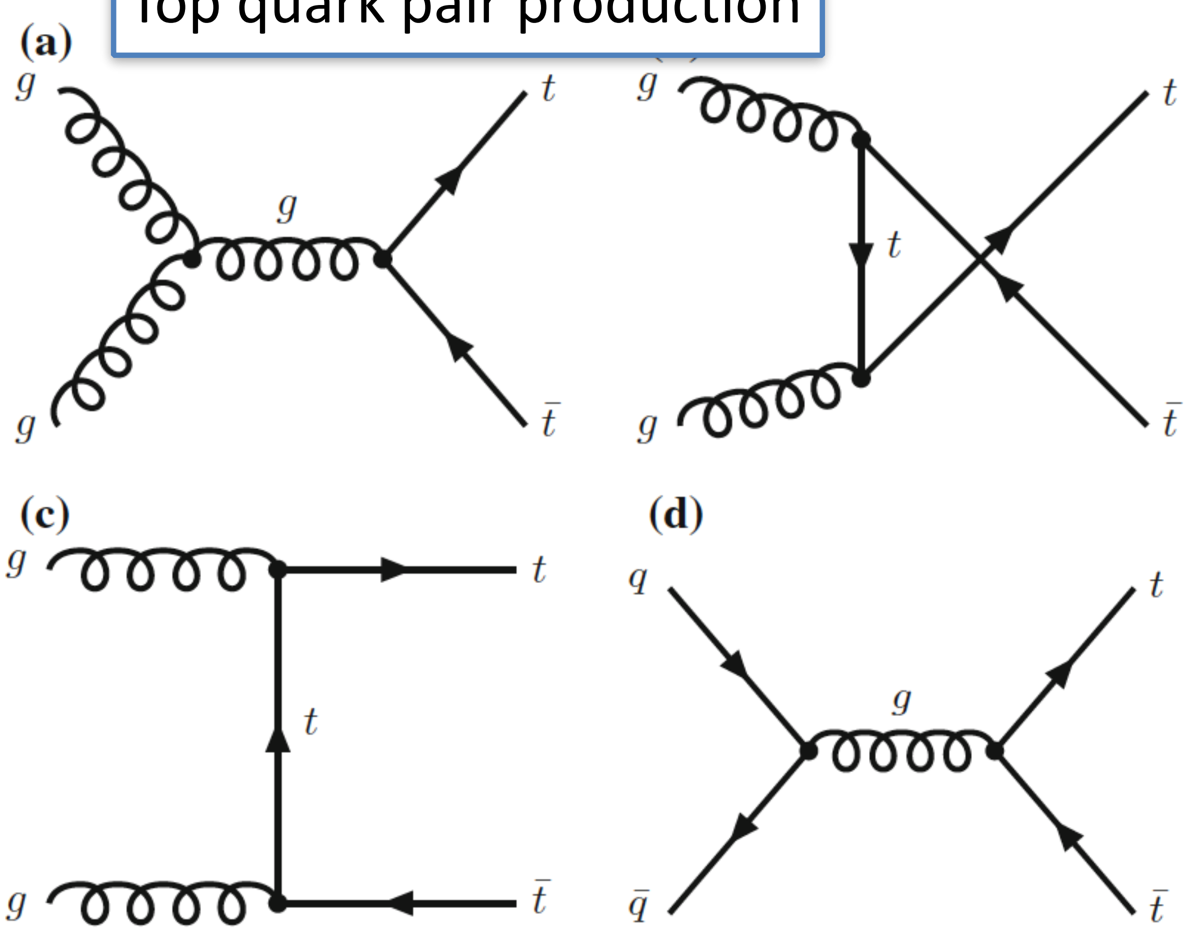
Jet pT resolution: 15% for pT=10 GeV, 8% for pT =100 GeV, 4% for pT= 1 TeV

SM processes at the LHC - top quark production

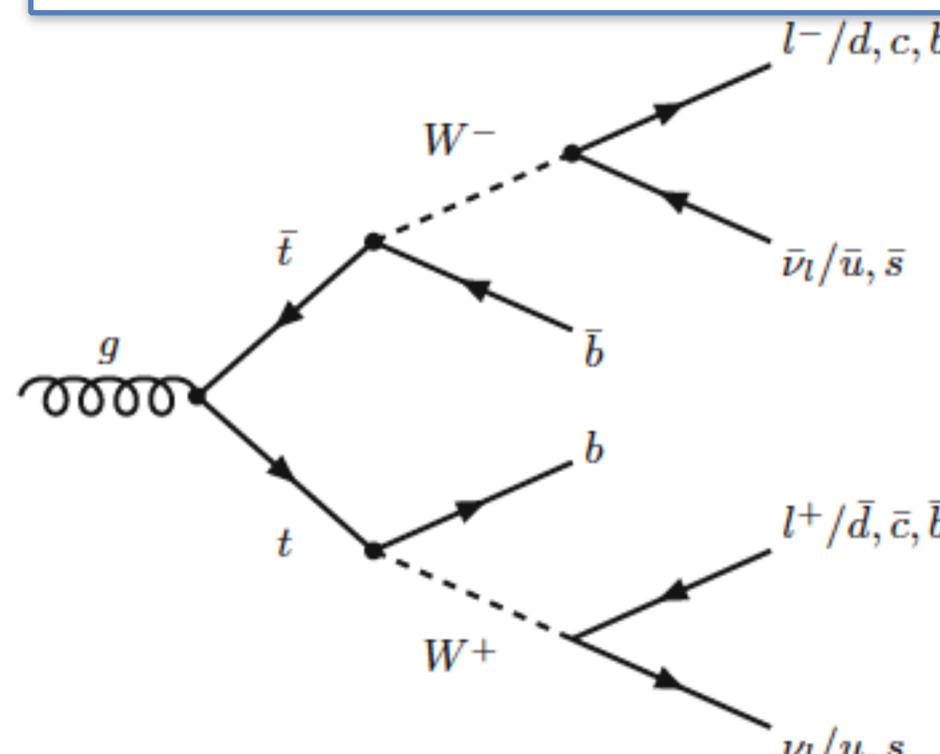
- Top quark is the heaviest particle (173 GeV) in the SM.
- Top quark production is key background in new physics searches.
- Plays key role in Higgs boson production.
- Searches for new physics often involve top quarks.

$$Z' \to t\bar{t} \qquad\qquad \tilde{t} \to t\tilde{\chi}_1^0$$

Top quark pair production



Top quark decay: essentially only 1 mode!

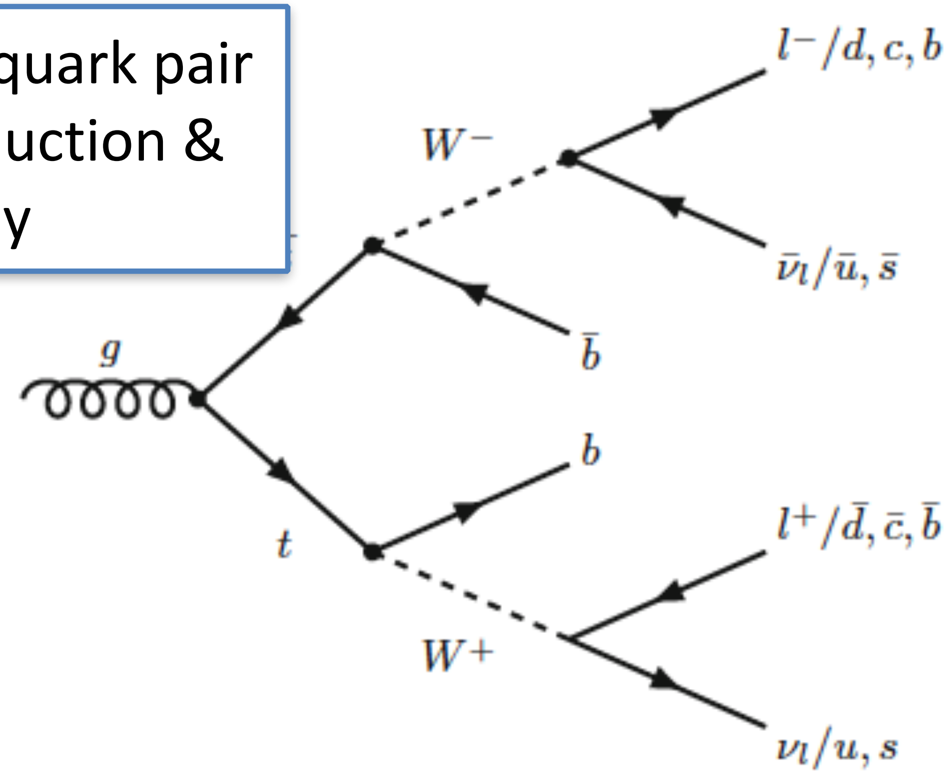


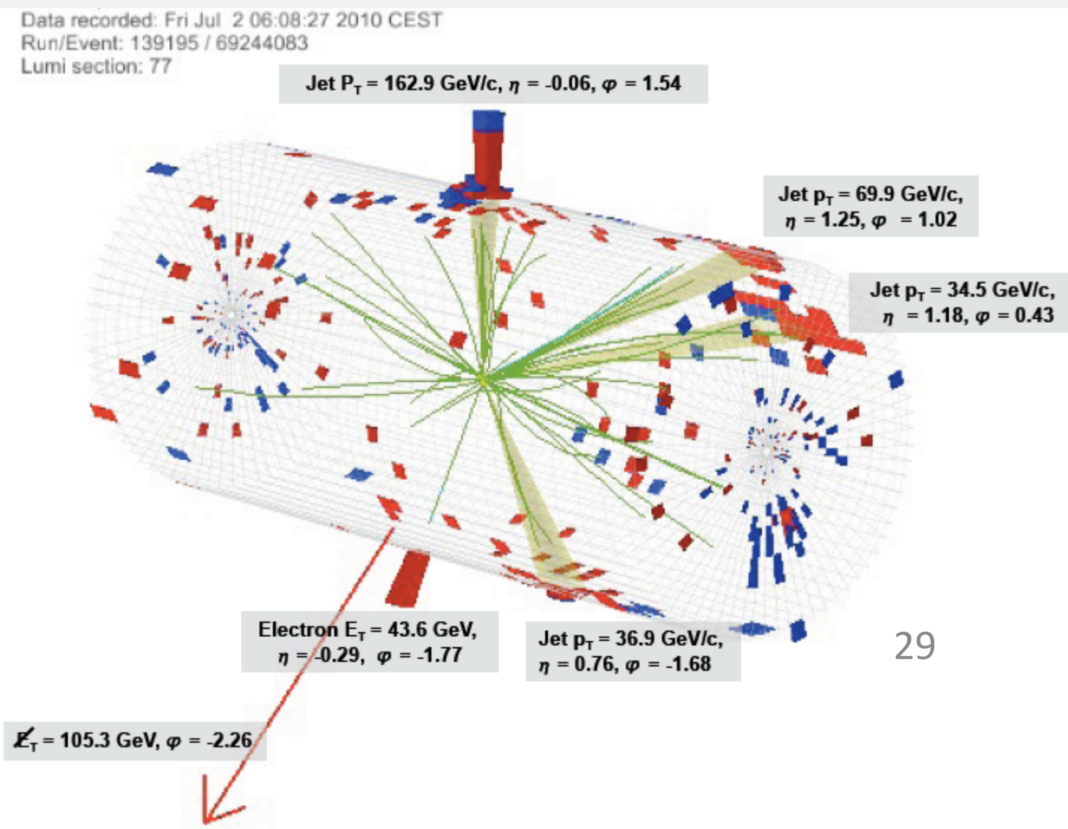
Top quarks decay before they hadronize!

SM processes at the LHC - list of main ingredients

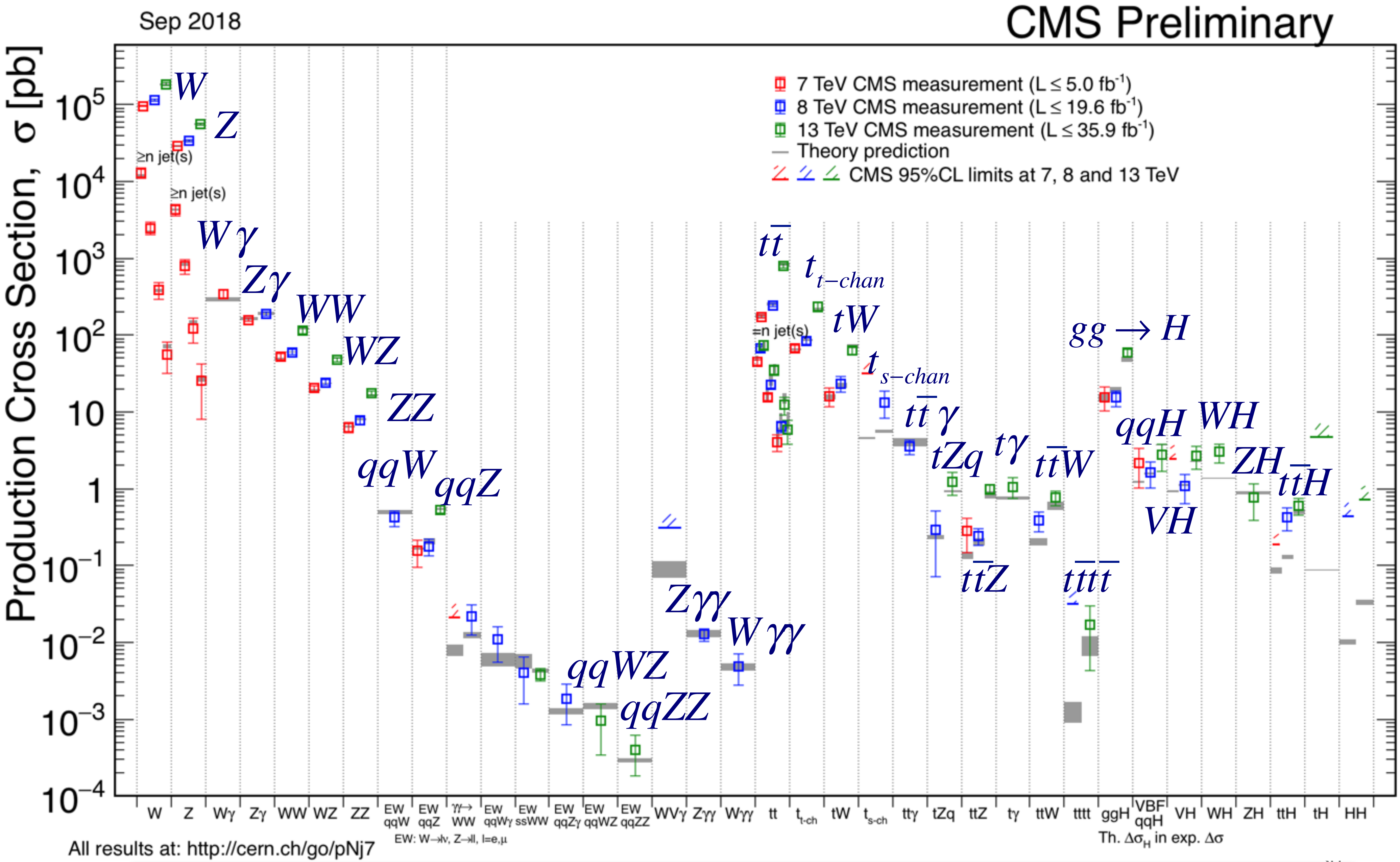
- **Gluons and quarks** (except top) - QCD “jets,” collimated streams of hadrons following the momentum direction of the gluon/quark. **b-quark jets** (“b jets”) have displaced vertices due to long lifetime of b quark. Also: jets from initial-state radiation.
- **Muons, electrons and photons** - highly distinctive
- **Taus** - difficult because they decay with a short lifetime.
- **Neutrinos** give “missing” momentum; measure ⊥ to beam-axis.

Top quark pair production & decay





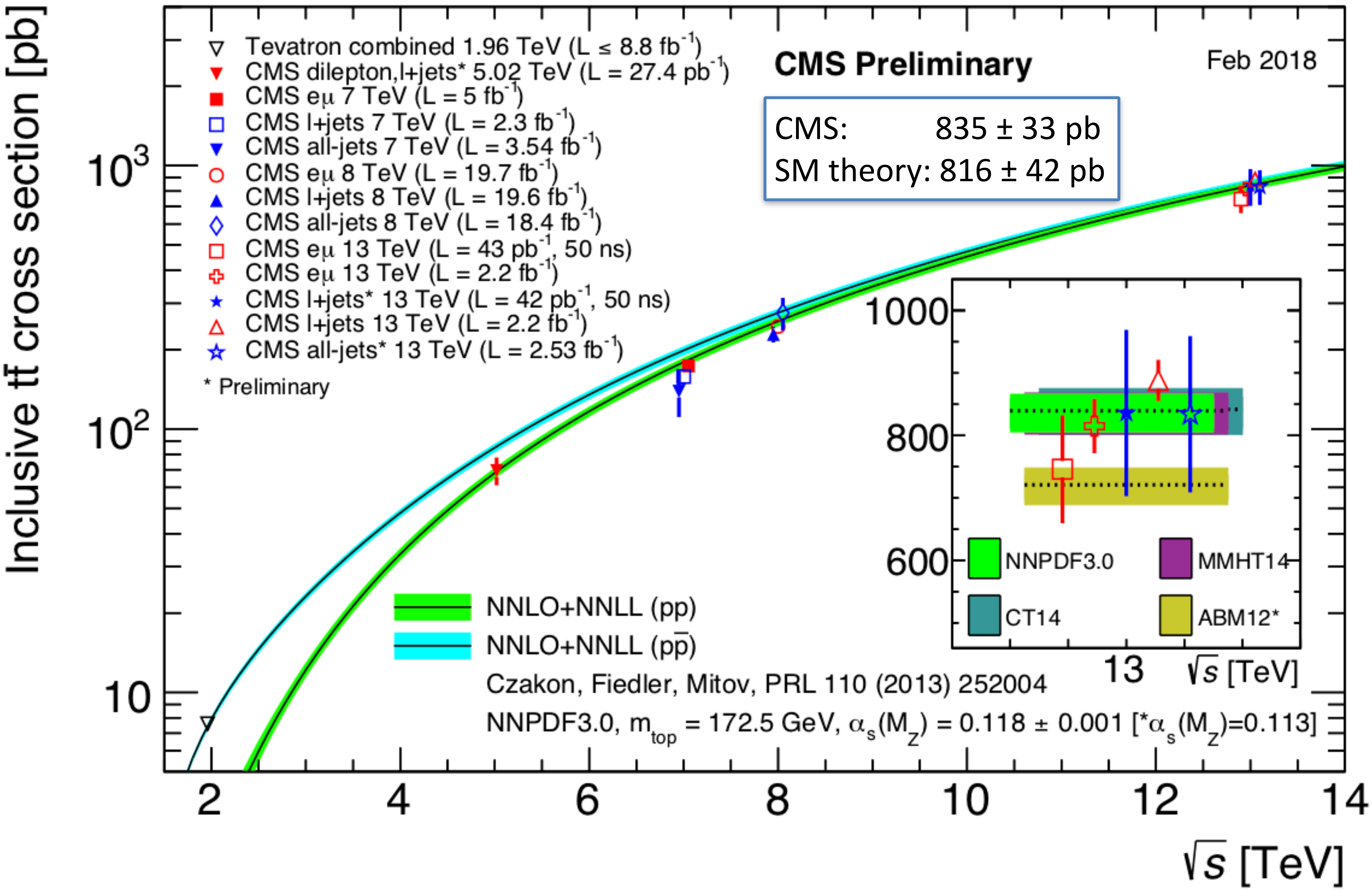
Cross section measurements for SM processes



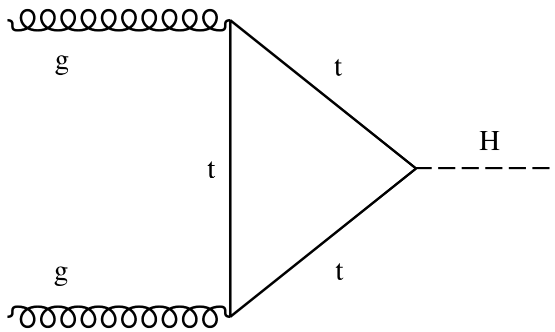
Provides broad check of our understanding of SM backgrounds for new physics searches.

Top quark pair production

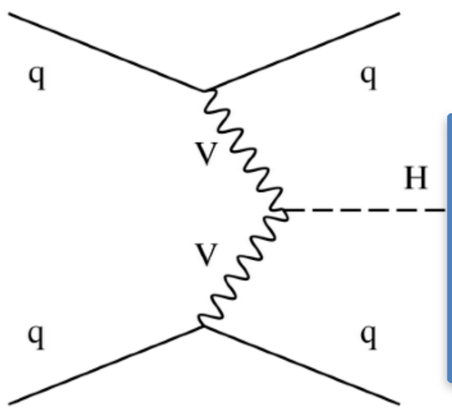
Production rate ~ 10 Hz



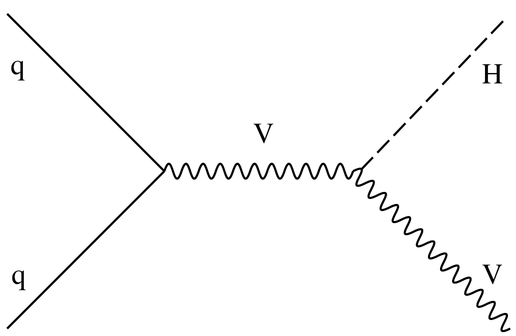
Higgs boson production processes



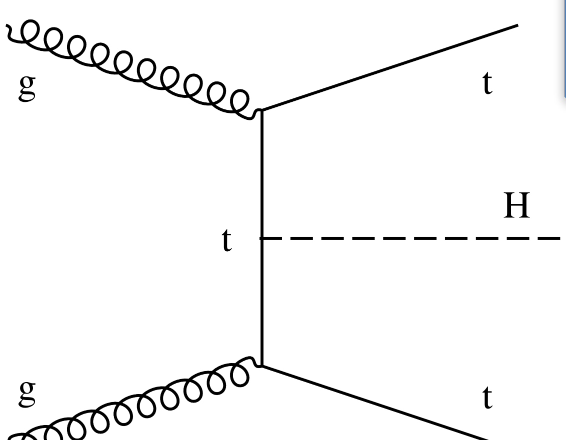
Gluon-gluon fusion
“ggF”: 48.5 pb (88%)
N3LO QCD, NLO EW



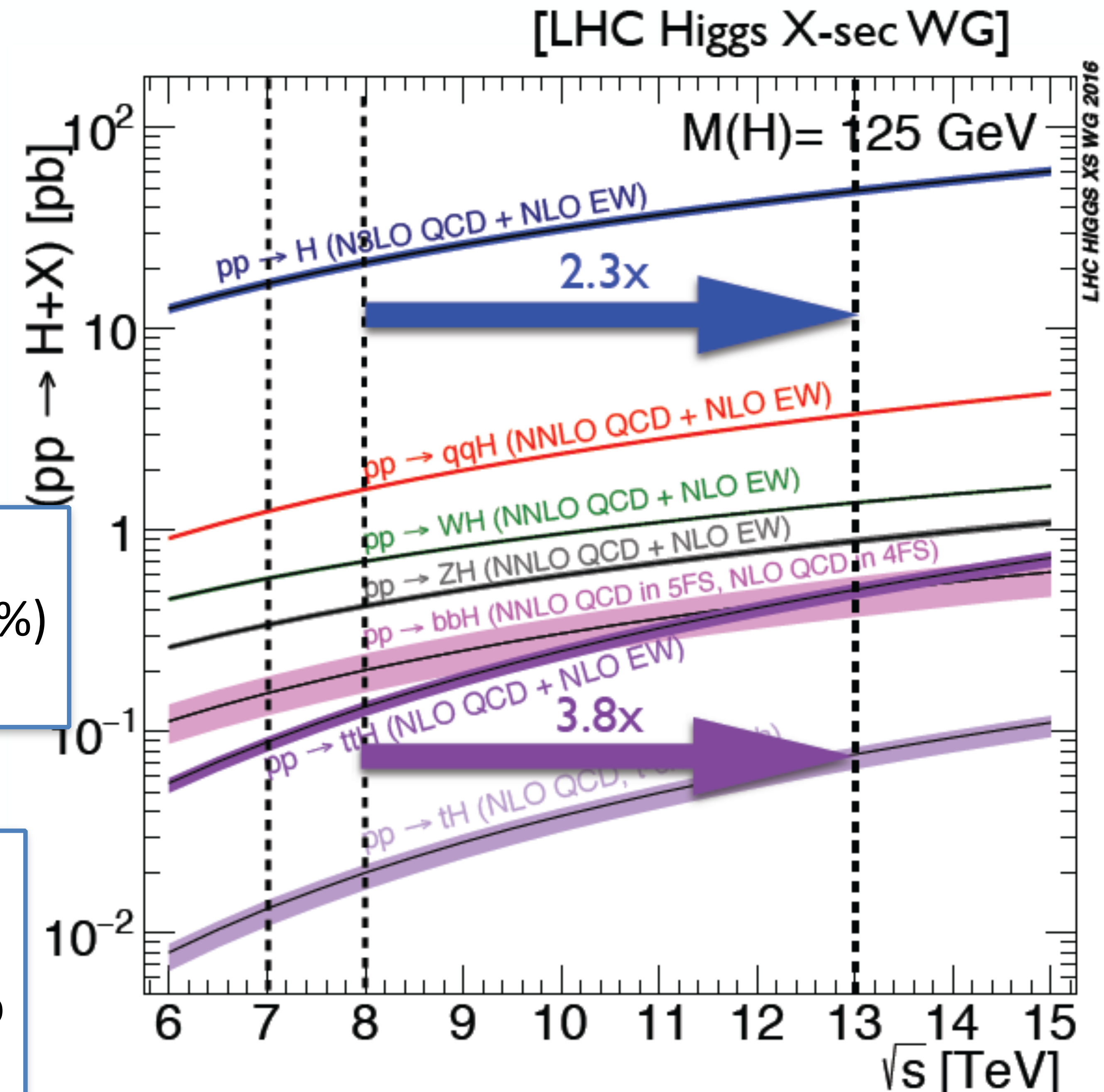
Vector-boson fusion
“VBF” or “qqH”: 3.78 pb (7%)
NNLO QCD, NLO EW



(W, Z) + H associated production
0.88 (ZH) + 1.37 (WH) pb (4%)
NNLO QCD, NLO EW



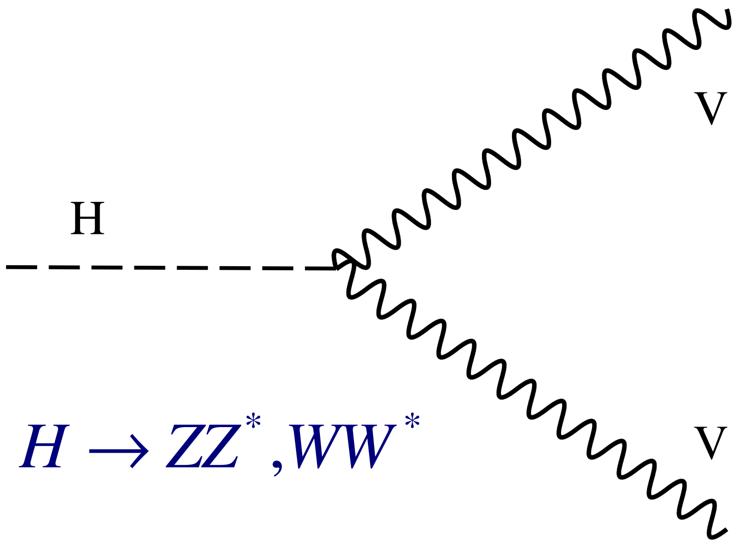
ttH associated production
0.51 fb (1%)
NLO QCD, NLO EW



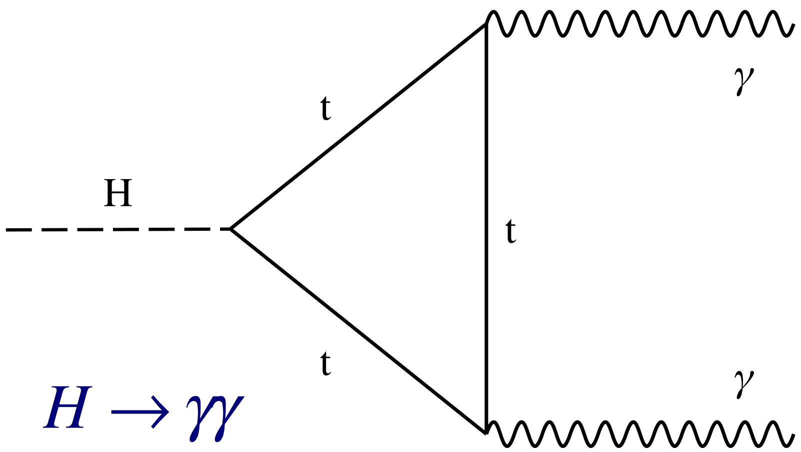
All of these production processes have now been observed, adding to confidence in our picture of the Higgs boson and providing more ways to study it.

https://arxiv.org/abs/1610.07922v2

Higgs boson decay modes (SM)

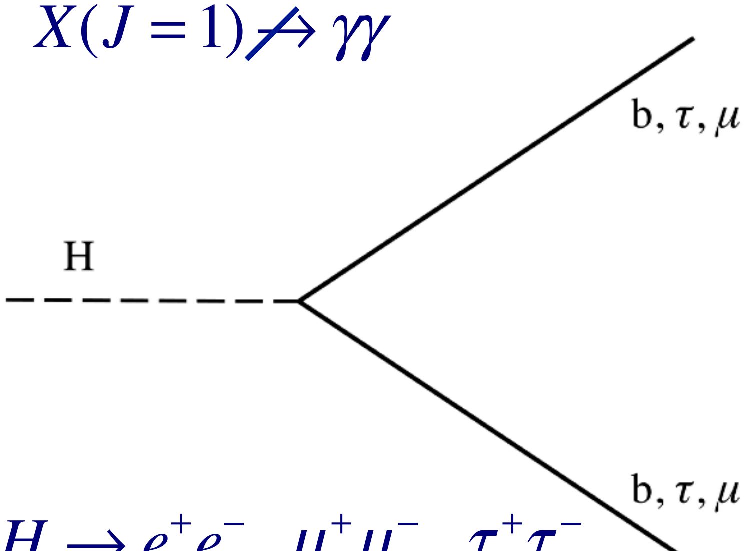


$H \to ZZ^*, WW^*$



$H \to \gamma\gamma$

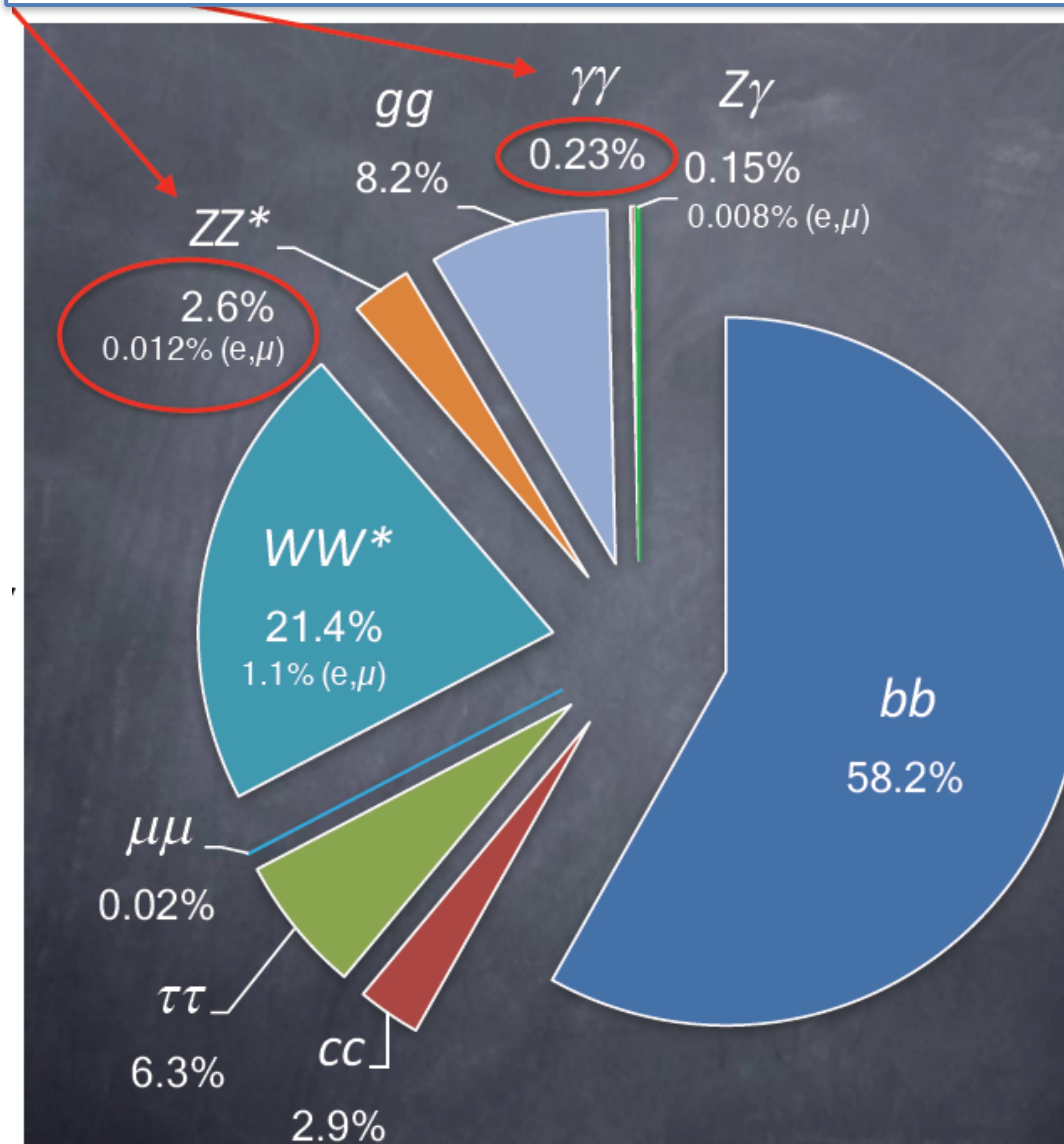
$X(J=1) \not\to \gamma\gamma$



$H \to e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^-$

$H \to u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ b\bar{b}$

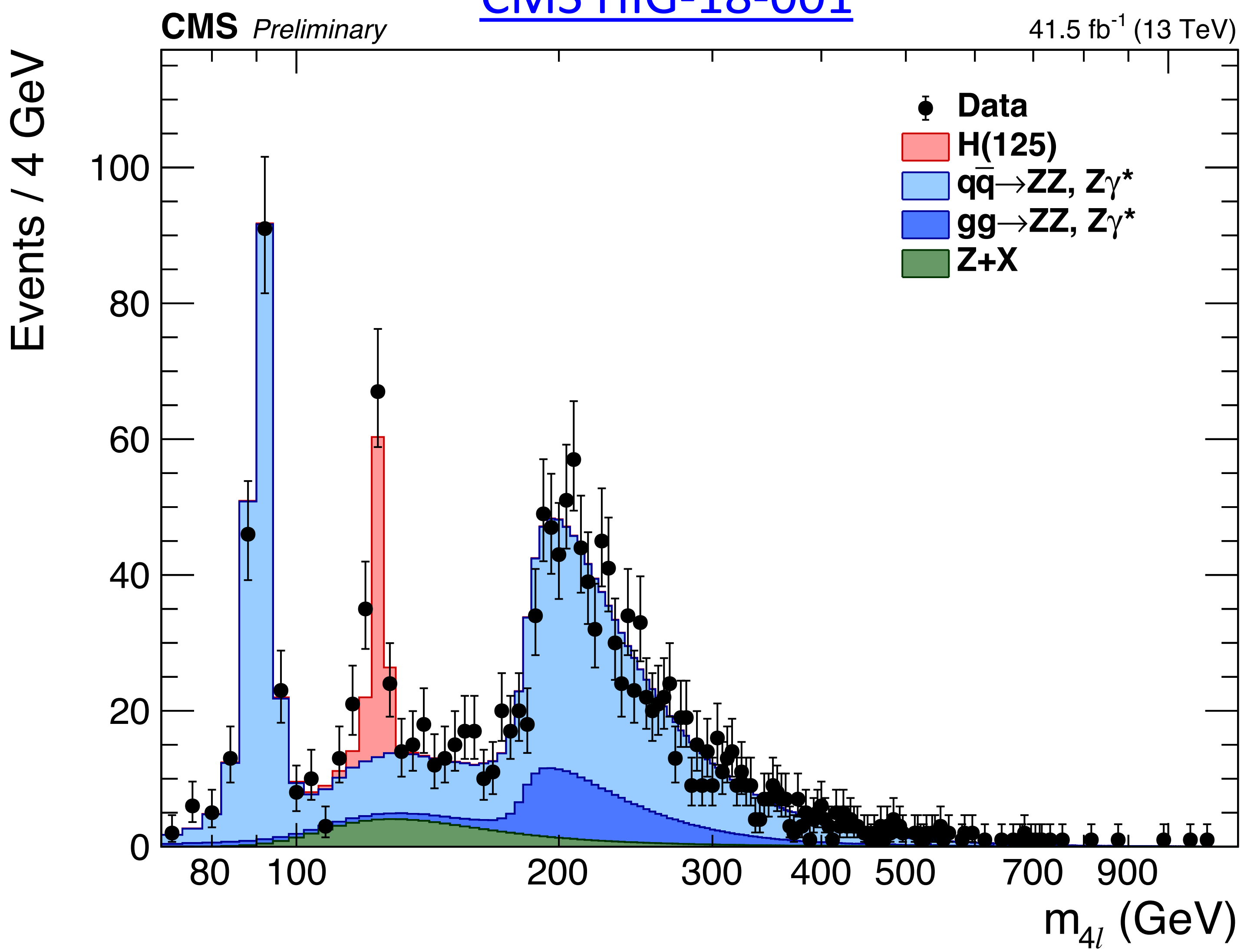
Most accessible experimental modes with high mass resolution.

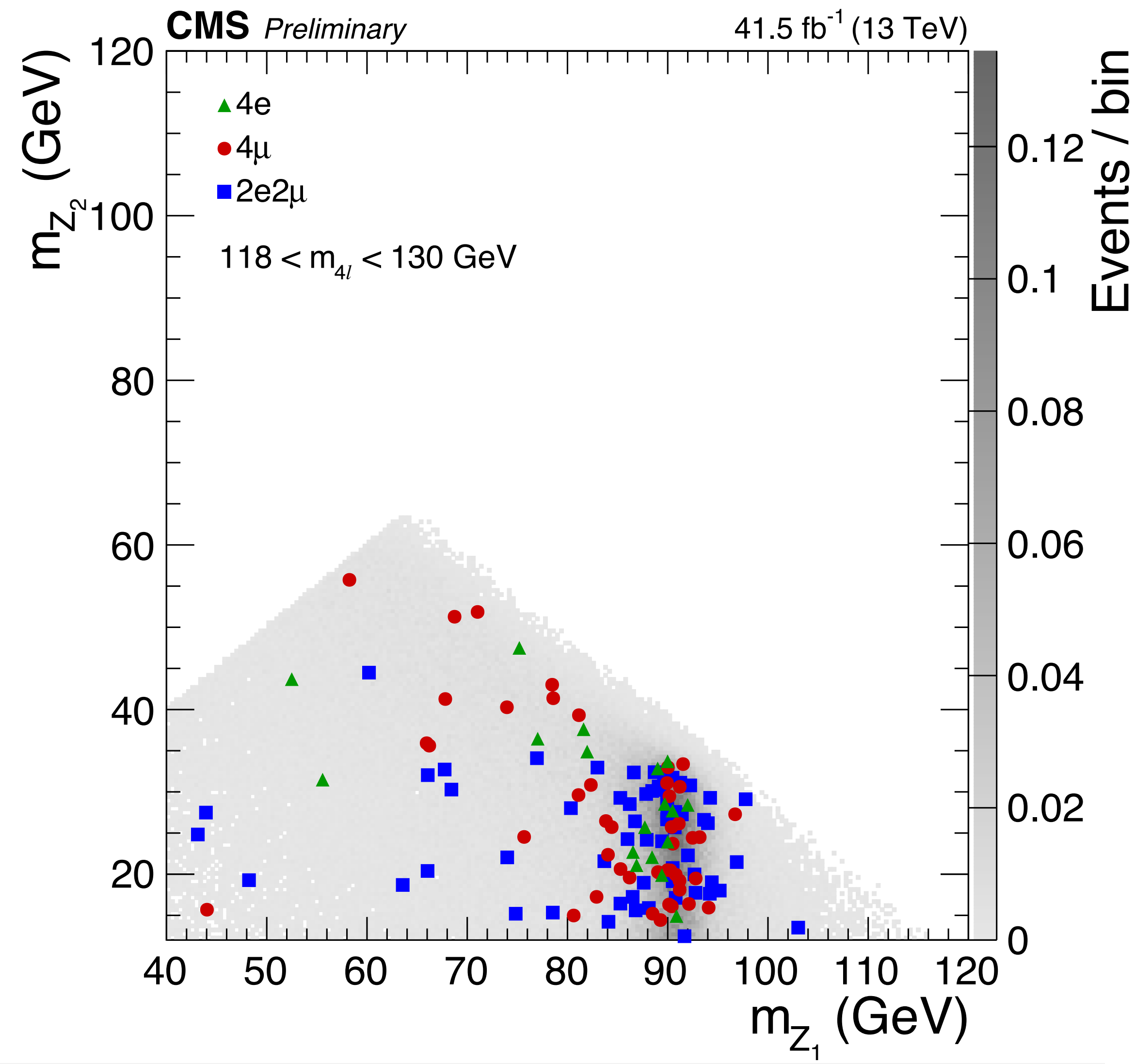


G. Piacquadio, ICHEP 2018

H→ ZZ*→ 4 leptons ($e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, $\mu^+\mu^-\mu^+\mu^-$)

CMS HIG-18-001

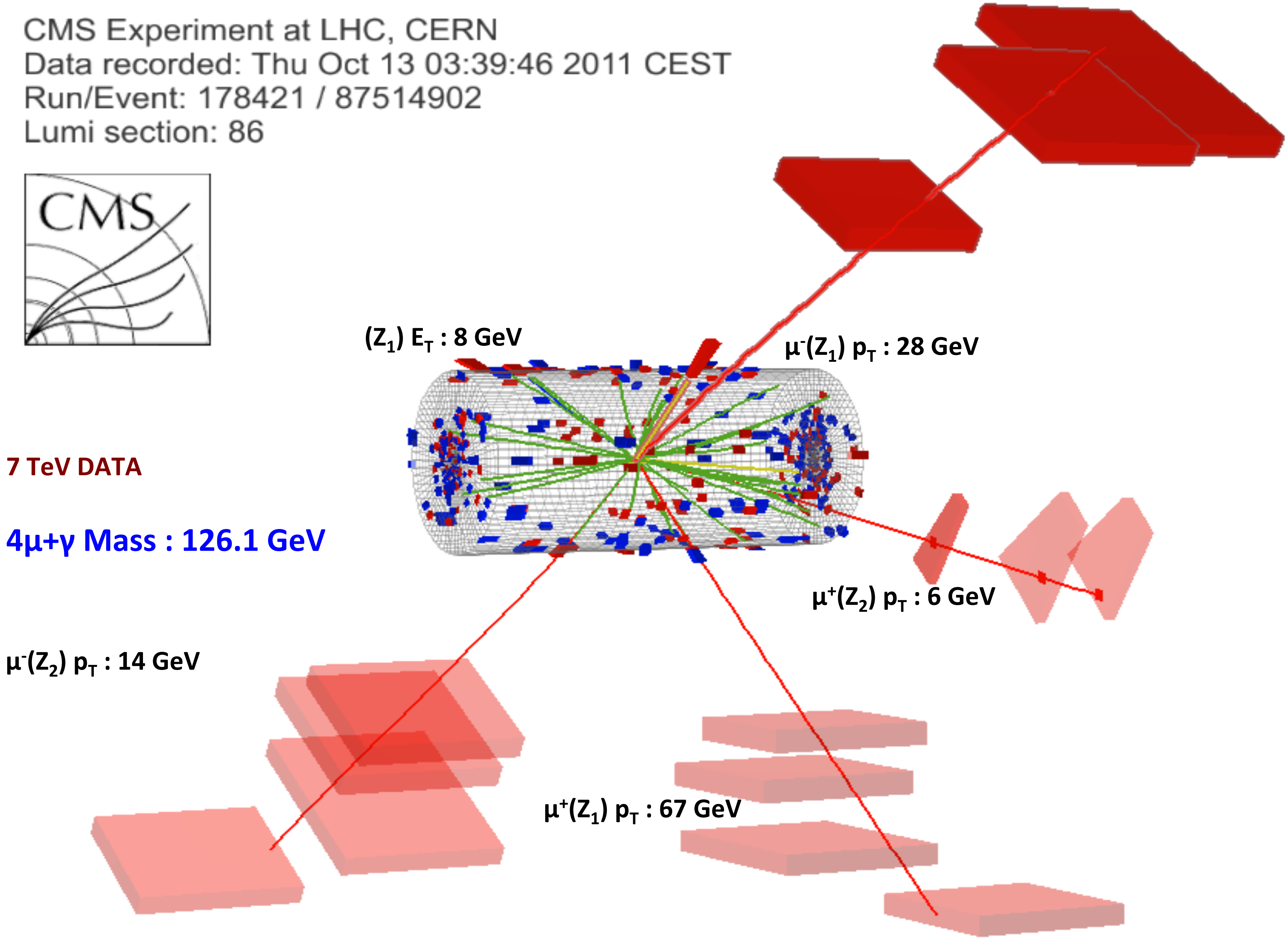




- Cross section, all channels: $\sigma/\sigma_{SM} = 1.10\,^{+0.19}_{-0.17}$
- Fitted Higgs mass: m(H) = 125.26 ± 0.20 (stat) ± 0.08 (sys) GeV (CMS HIG-16-041); use per event (from per-lepton) resolutions.
- Lepton momentum scale uncertainty 0.05%-0.3%

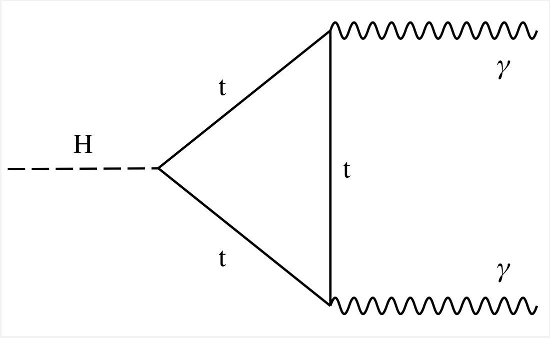
H→ ZZ*→ $\mu^{+}\mu^{-}\mu^{+}\mu^{-}$ candidate event

CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 03:39:46 2011 CEST
Run/Event: 178421 / 87514902
Lumi section: 86

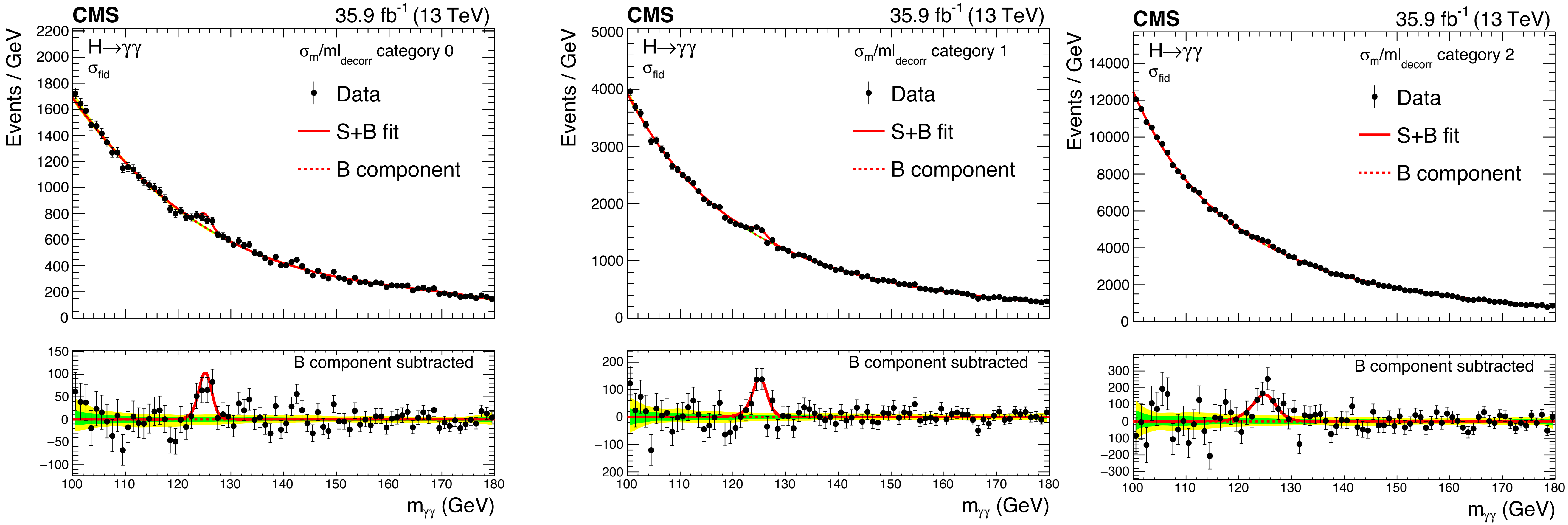


$H \to \gamma\gamma$

- Surprising decay mode, because the "H couples to mass"

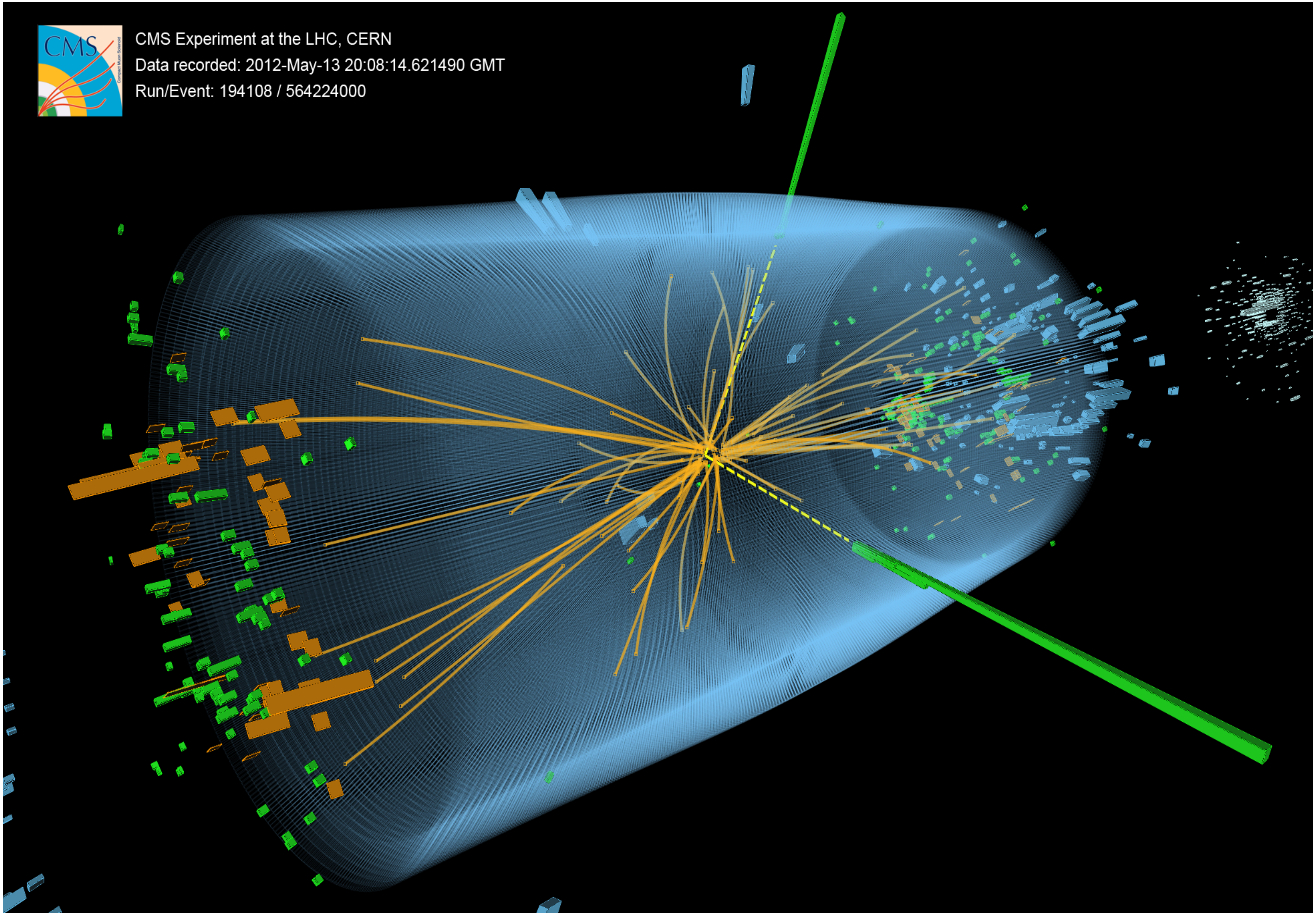


- Discovery mode even with large background and small branching fraction. Excellent photon energy resolution.



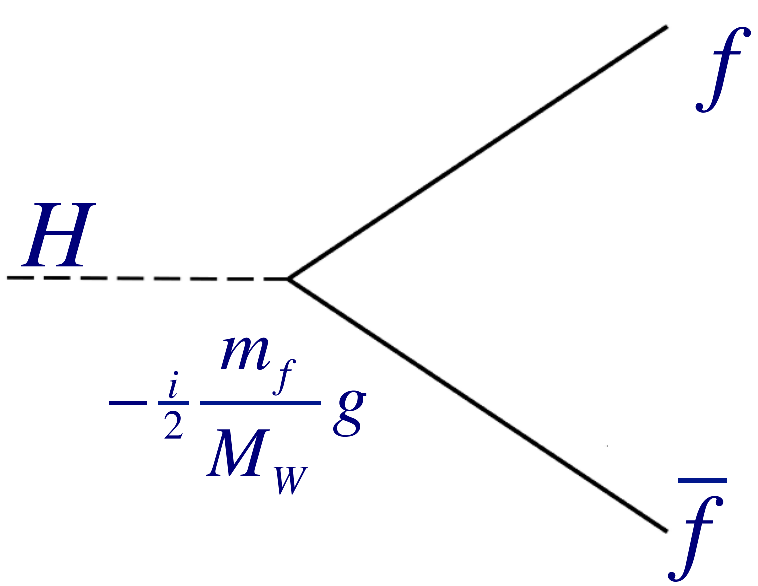
http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-17-025/index.html

H→$\gamma\gamma$ candidate event

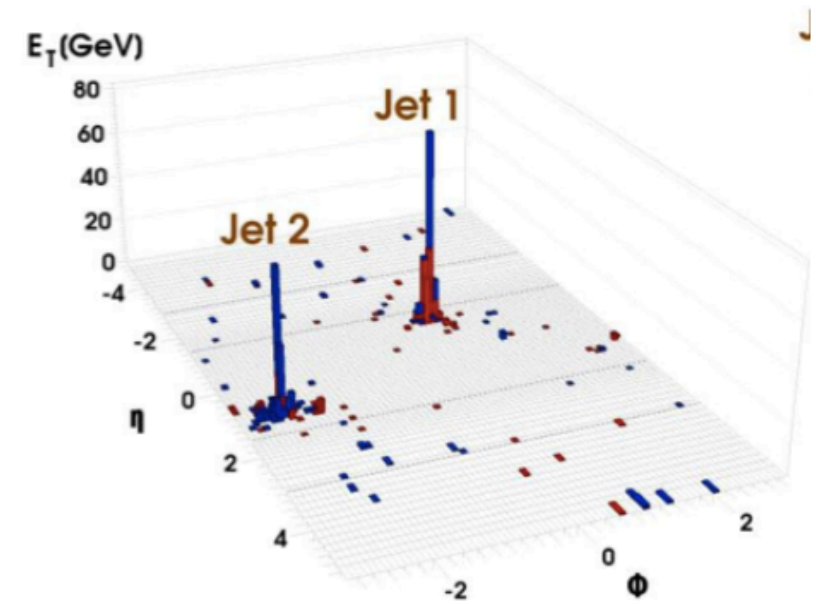


Higgs decays to fermions: H→f$\bar{f}$

- Major progress in observing H→f$\bar{f}$ decays, including some very recent results included here.
- Now have set of measurements for decays to 3rd generation quarks and leptons: H→$\tau^+\tau^-$, ZH with H→b$\bar{b}$, t$\bar{t}$H
- A long term goal is to measure H→$\mu^+\mu^-$, providing confirmation of the couplings to second-generation fermions.
- Backgrounds are an enormous challenge. Data analysis needs to be very clever!



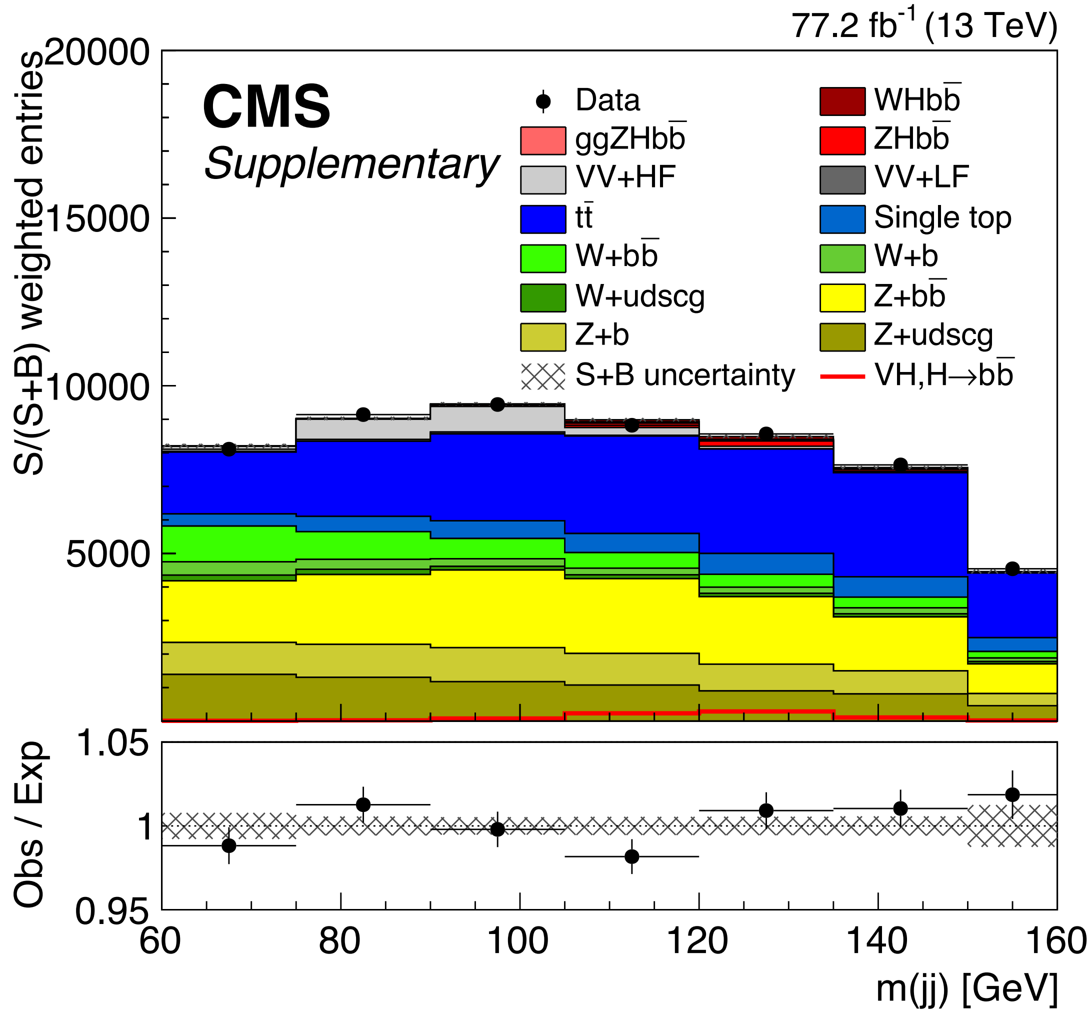
QCD dijet events are an enormous background

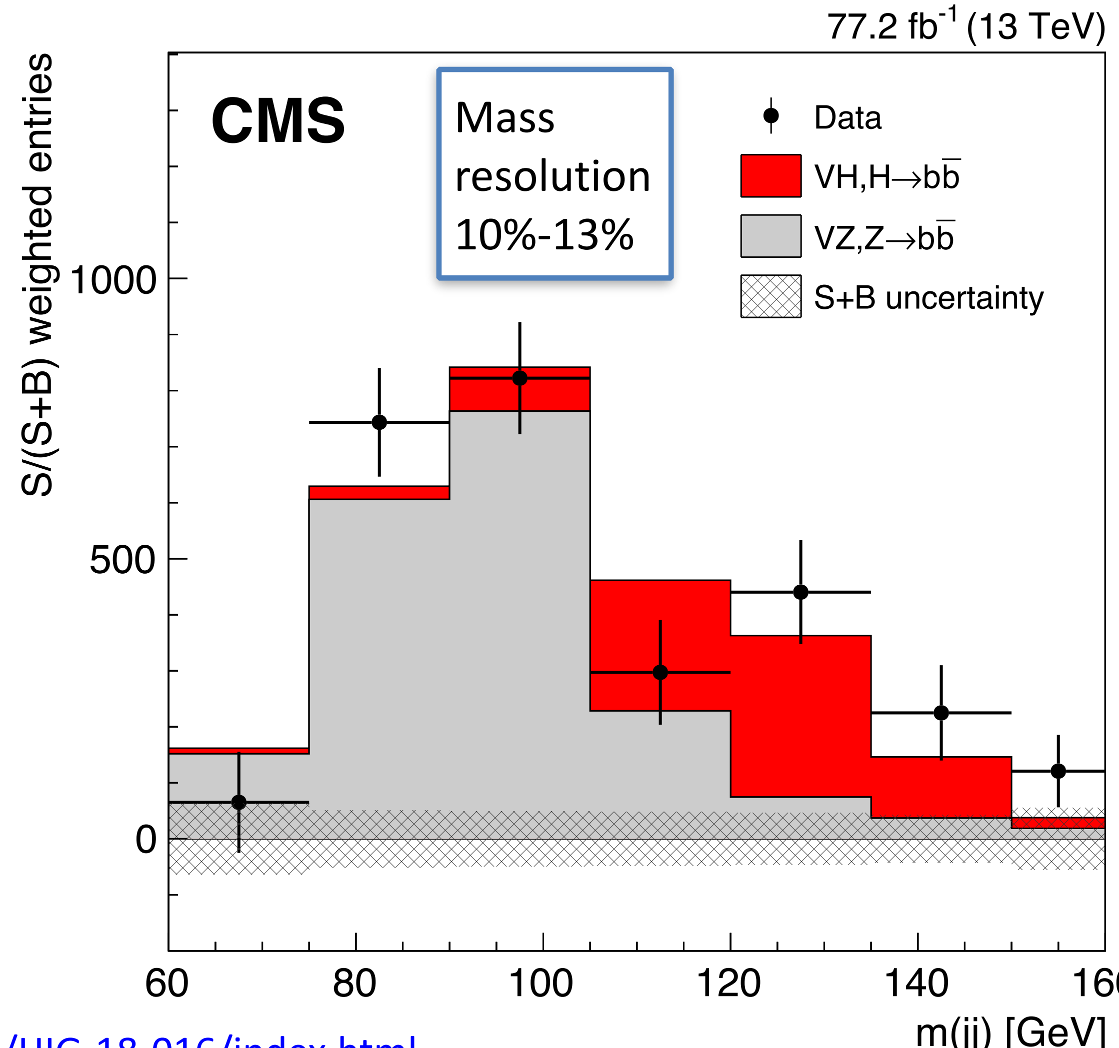


http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-16-043/index.html

Beating the QCD background: VH associated production

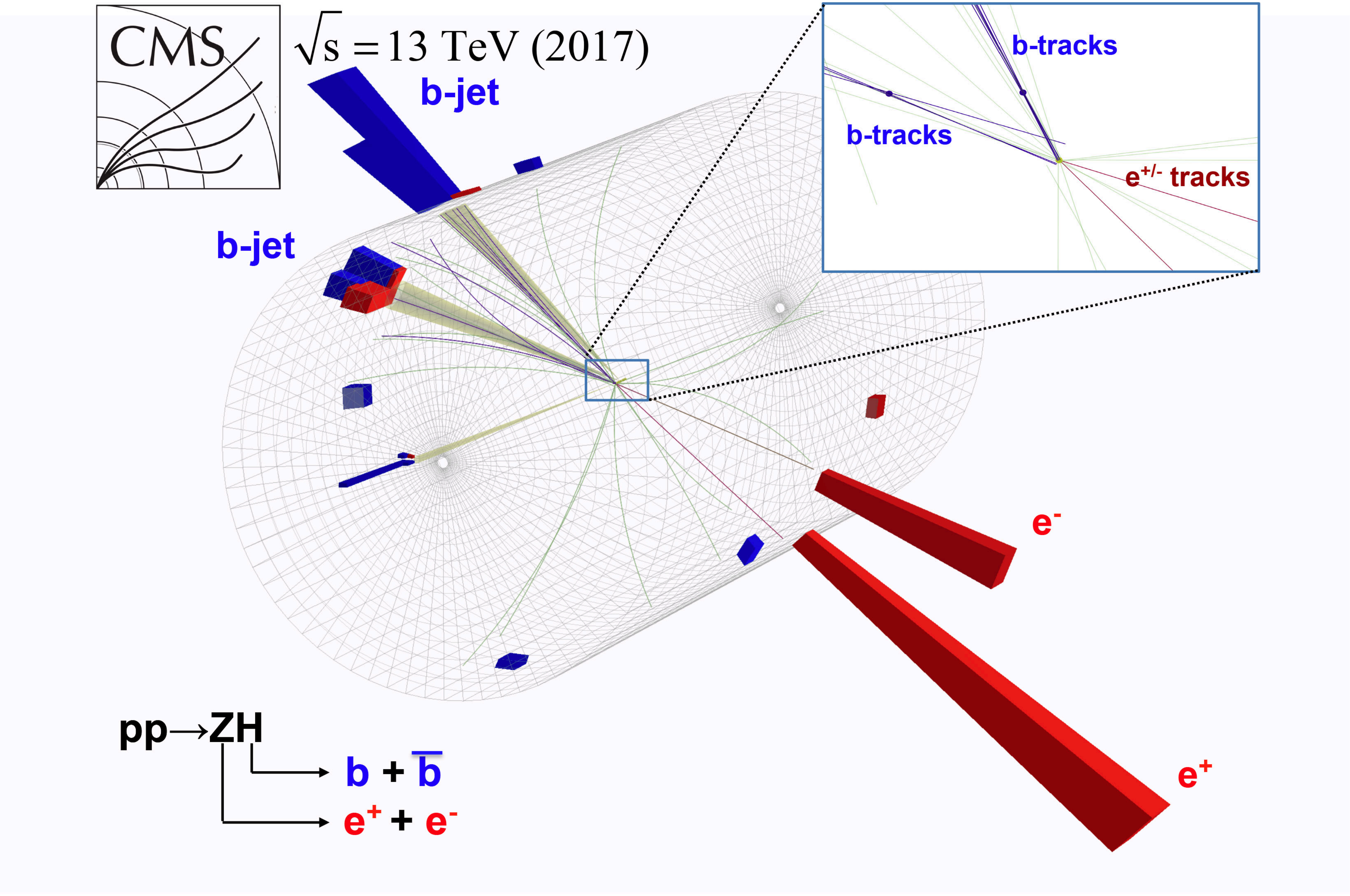
- Some Higgs bosons are produced in association with a vector boson (V = W or Z), providing a powerful tool for suppressing QCD background. Price is the lower production cross section.
- Search for processes with Z→ e^+e^-, $\mu^+\mu^-$, $\nu\bar{\nu}$ and W→ $e\nu$, $\mu\nu$.
- Significance: 5.6σ (expected 5.5σ), Signal strength 1.04 ± 0.20





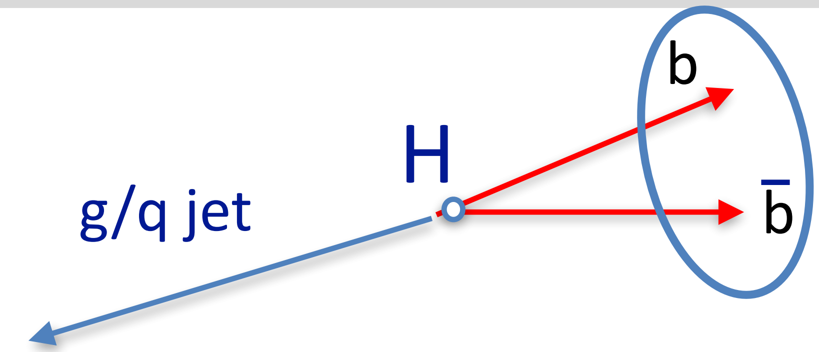
http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-18-016/index.html

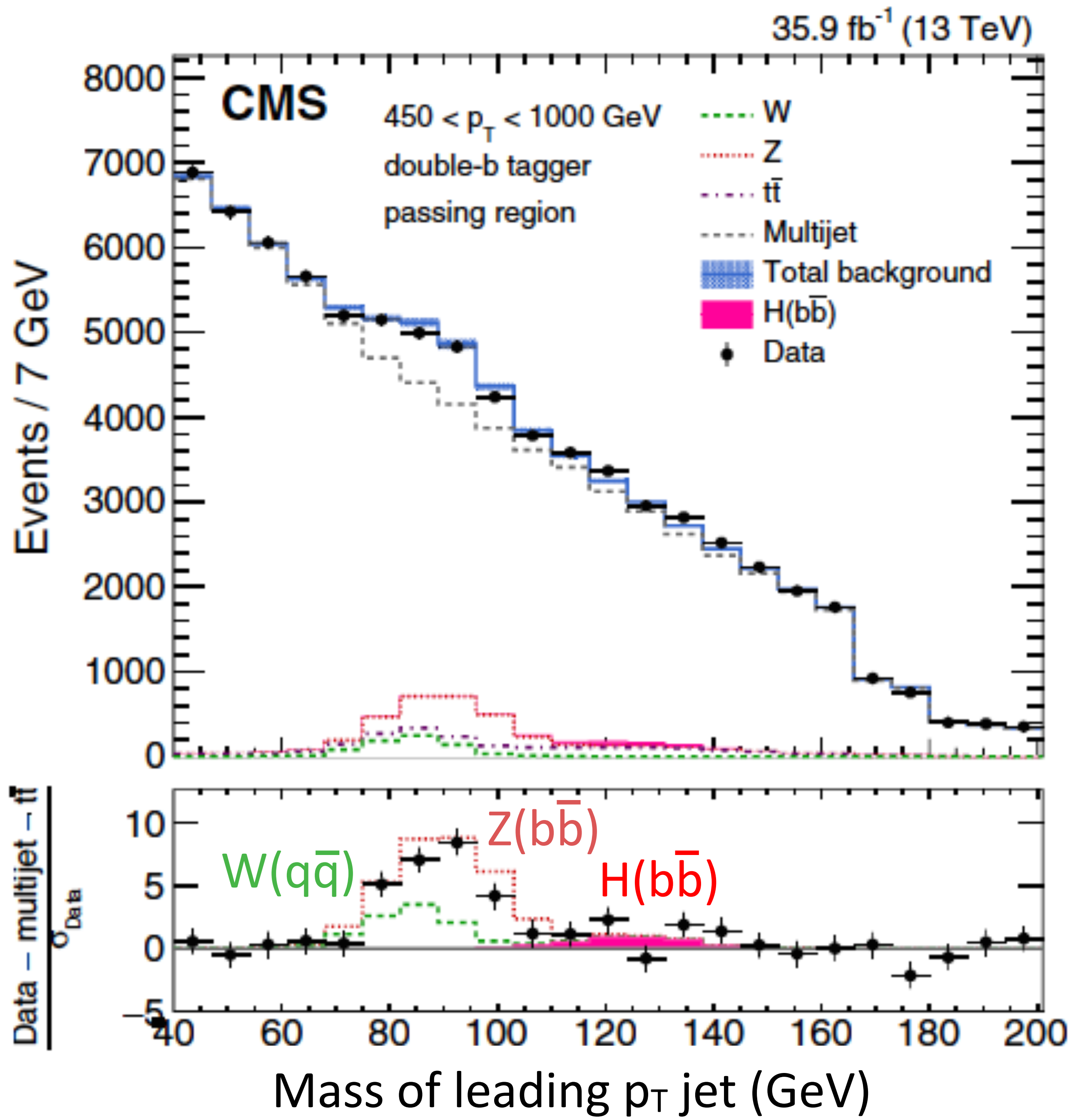
Event display for pp→ ZH, H→b$\bar{b}$



Beating the QCD background: Doing the “impossible”?

- Measurement of $H \rightarrow b\bar{b}$ in the gluon-gluon fusion channel long regarded as impossible.
- Enormous QCD dijet background (10^7 larger).
- New method uses Higgs production with high pT extra jet from ISR; gives highly boosted Higgs. Merged b jets!
- Z(bb) - merged jets: 5.1σ observed (expected 5.8σ).
- H(bb) - merged jets: 1.5σ (0.7σ) expected.



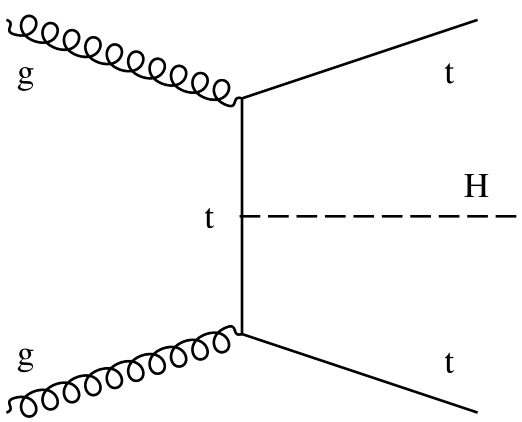


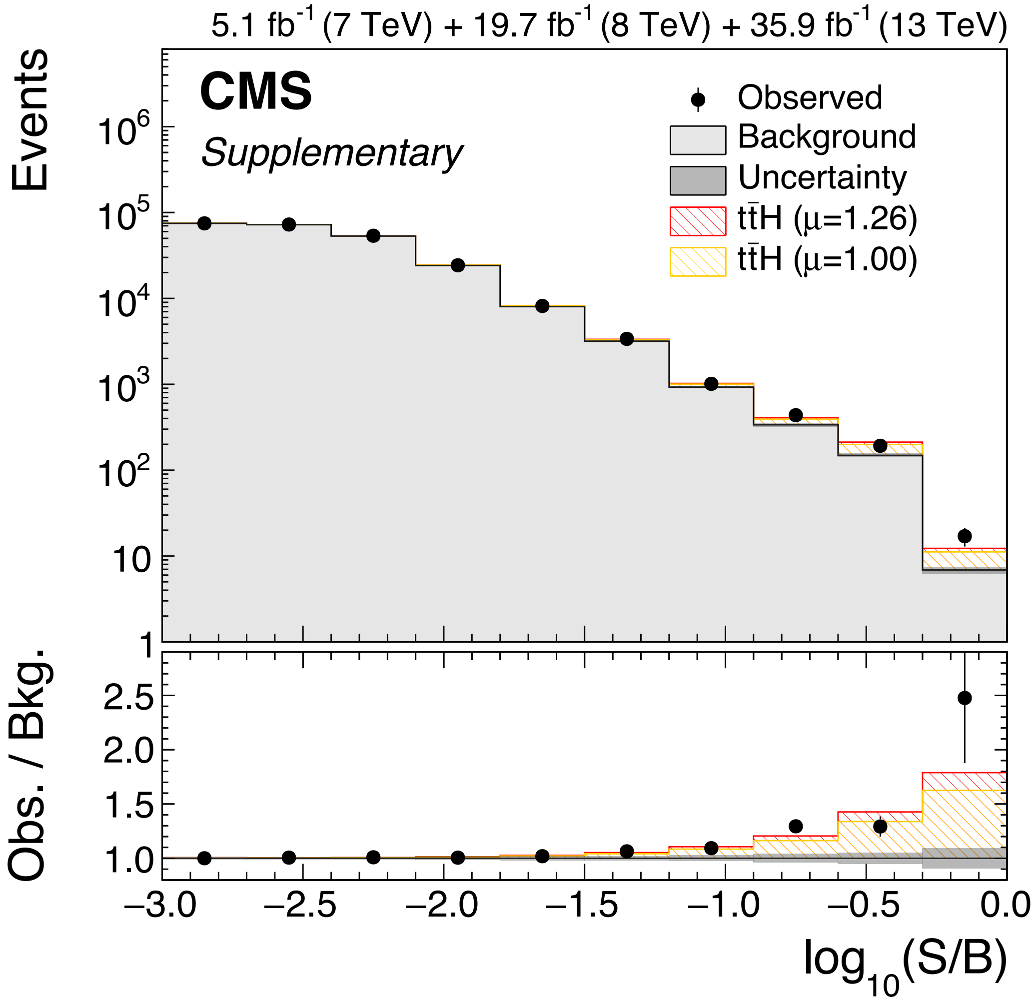
http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-17-010/index.html

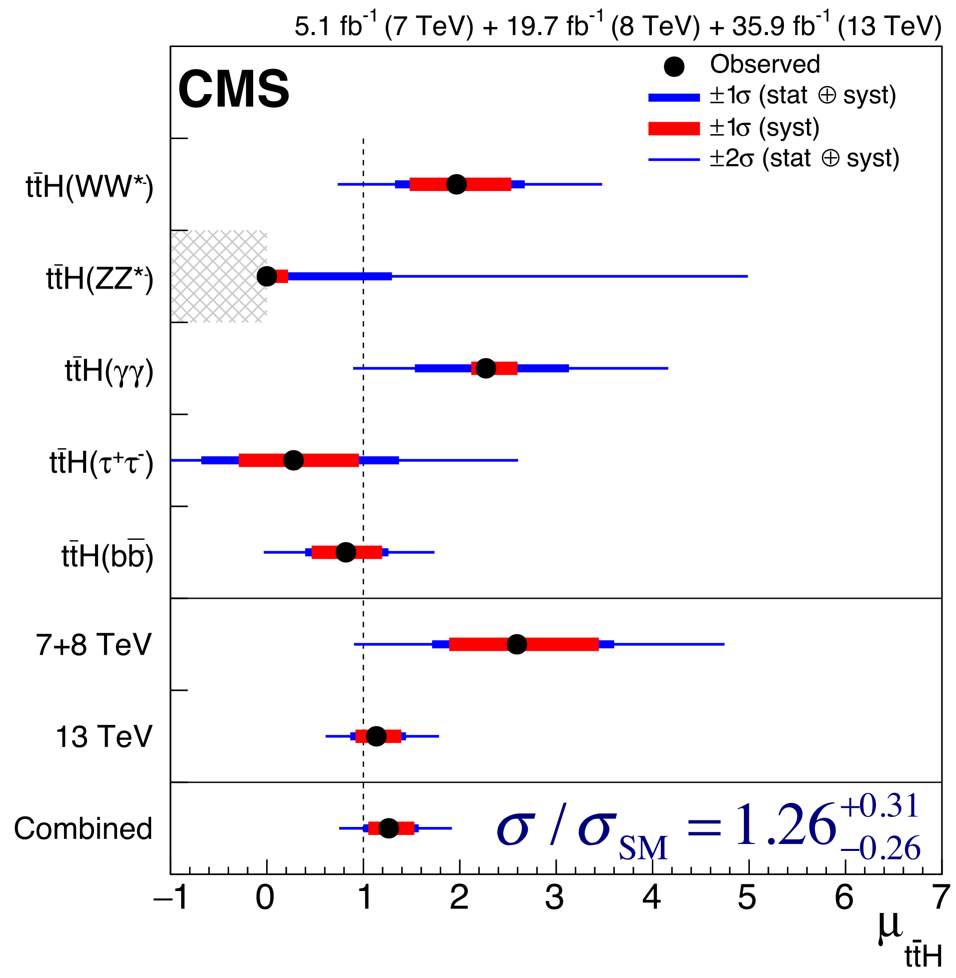
Higgs production in association with top quarks

- Probe the large Higgs-top quark coupling.
- Cross section is small $\sigma(t\bar{t}H) \approx 0.5$ pb
- Backgrounds: $\sigma(t\bar{t}) \approx 830$ pb, also $t\bar{t}bb$, $t\bar{t}Z$, and $t\bar{t}W$

http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-17-035/index.html



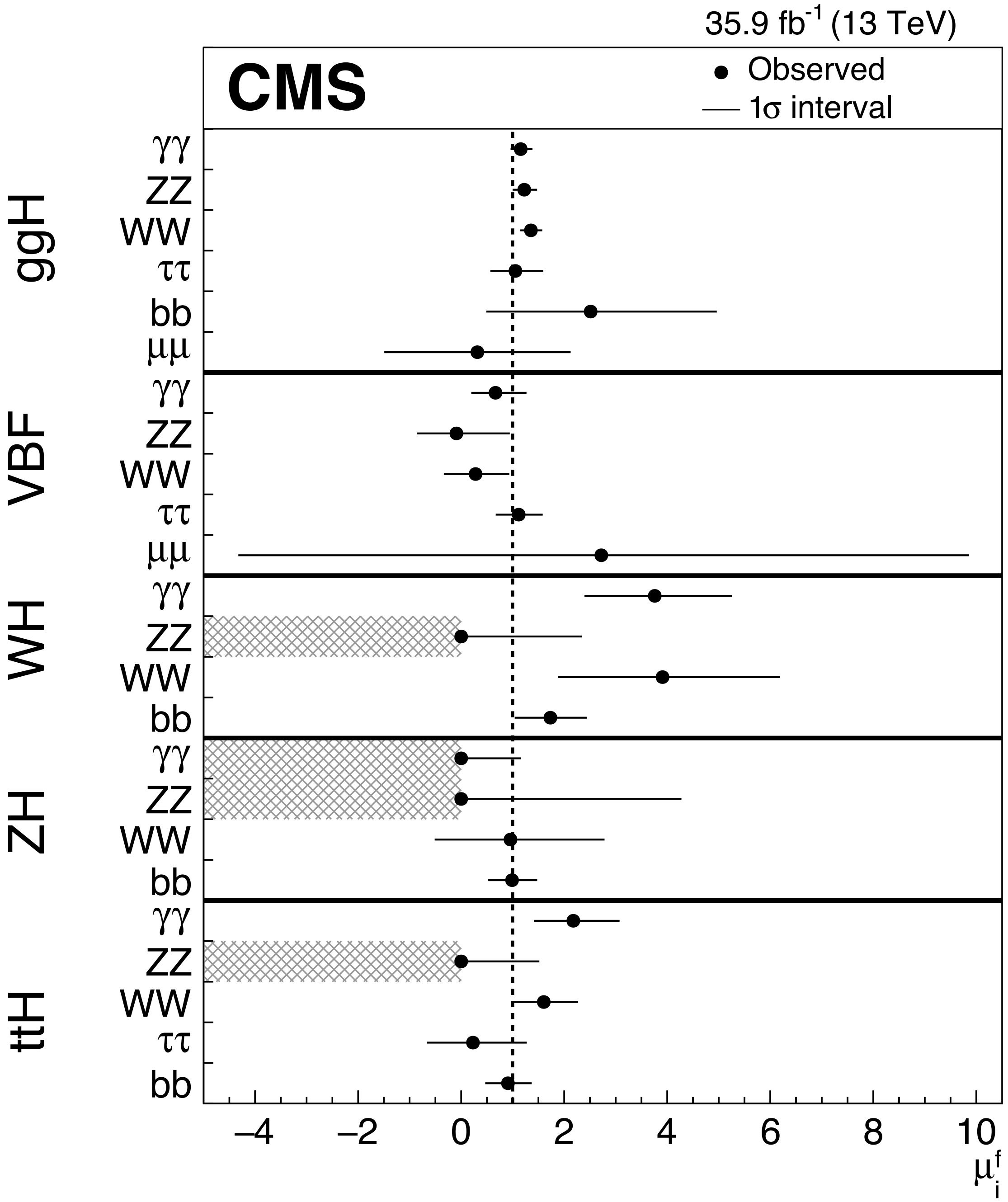




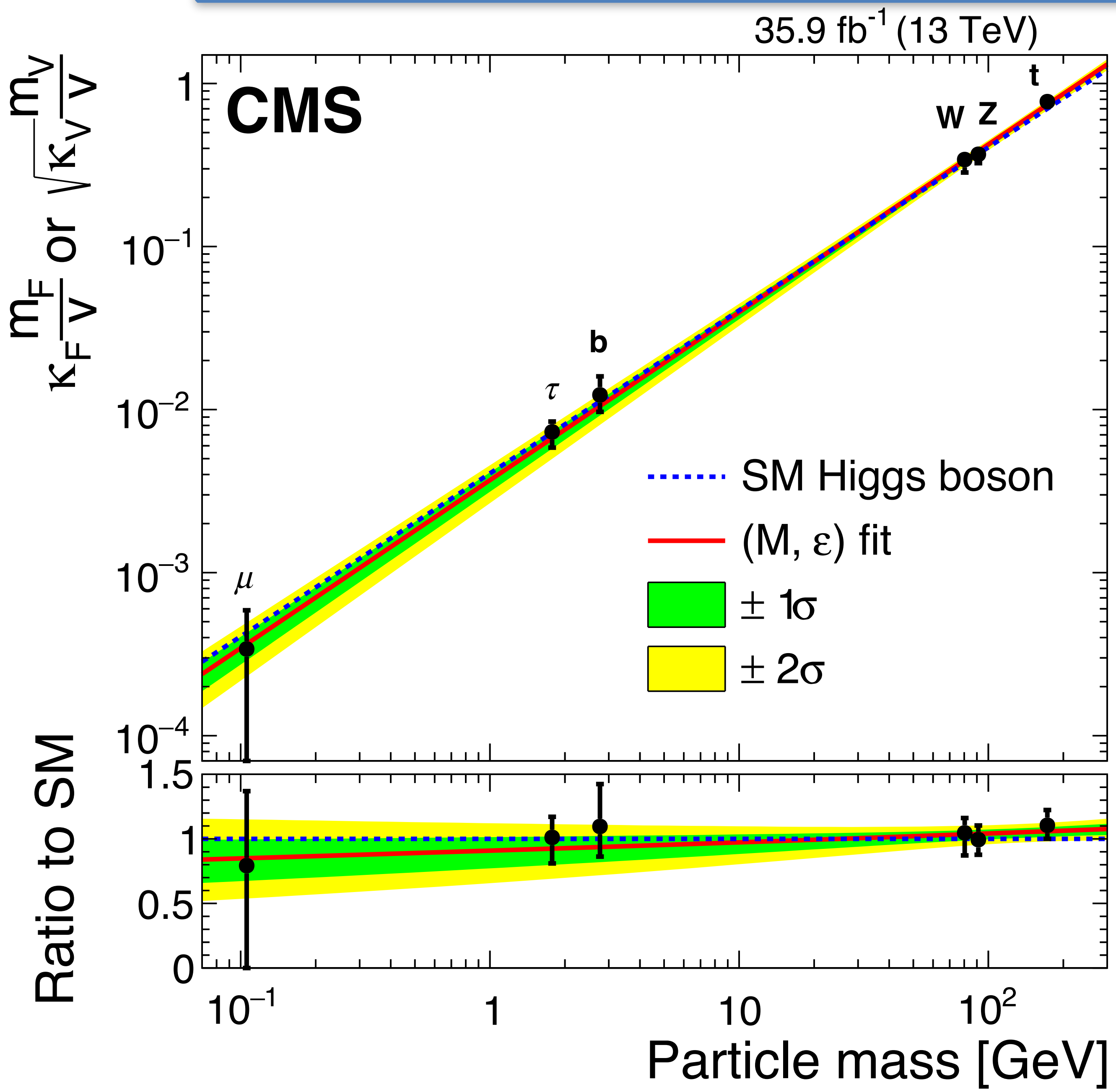
- Observed ttH production at 5.2σ significance (4.2σ expected).

Summary of Higgs couplings vs. mass

Ratio of measured σB values relative to SM predictions



Mass dependence of measured couplings compared to SM predictions.



- Impressive pattern of agreement with SM, but precision is not yet high.

http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-17-031/index.html

Some puzzles and mysteries

Hierarchy problem

~10^{18} GeV

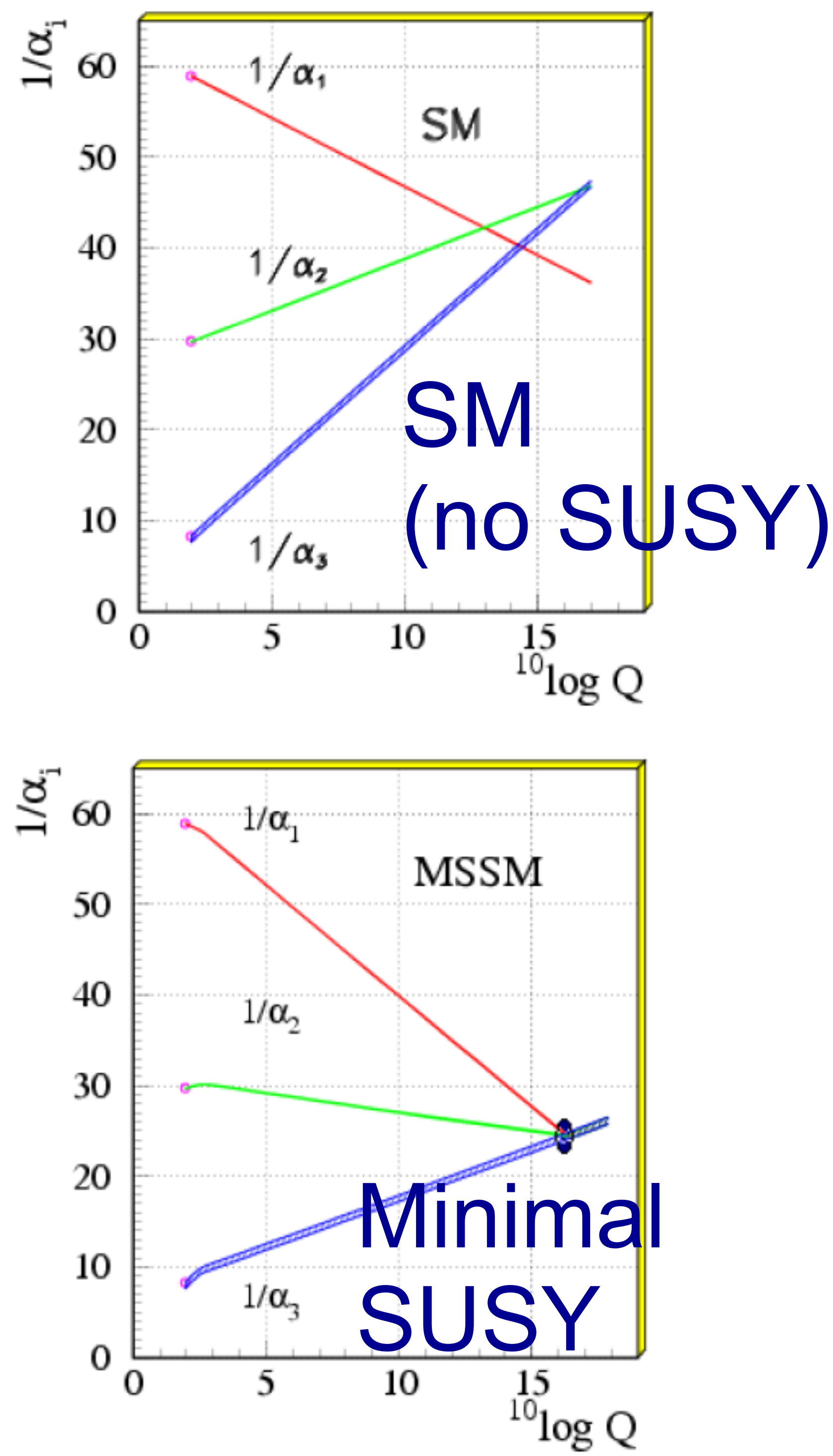
Planck scale (quantum gravity)

~10^{16}

~10^2 -10^3 GeV

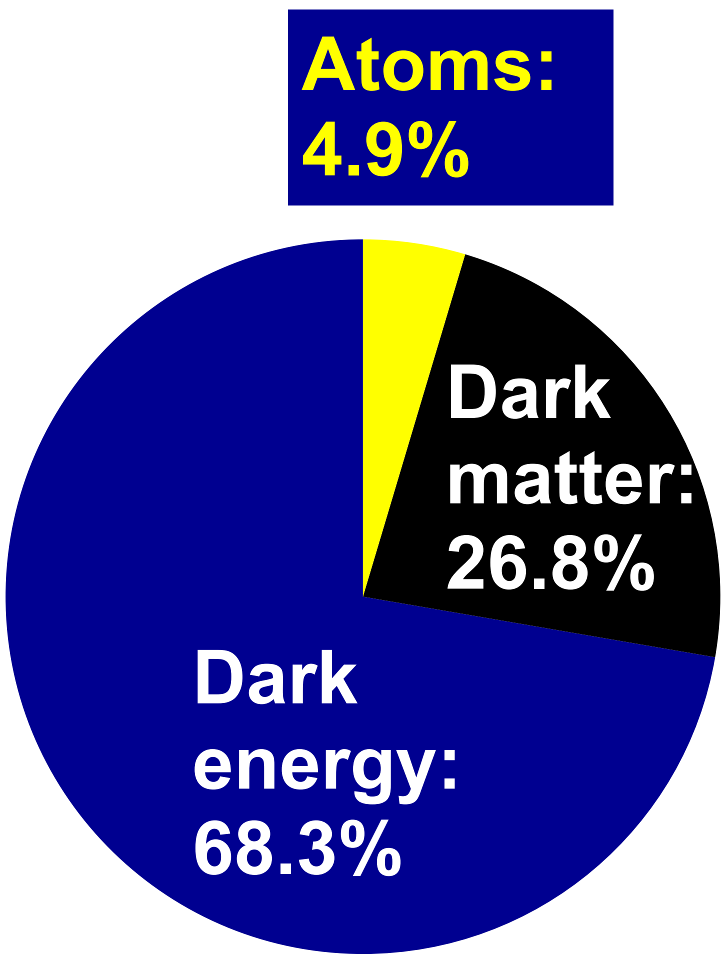
Electroweak scale (unstable in SM)

Unification of couplings



S. Raby, Particle Data Book.

Dark matter



Dark matter at TeV scale?

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

Supersymmetry basics

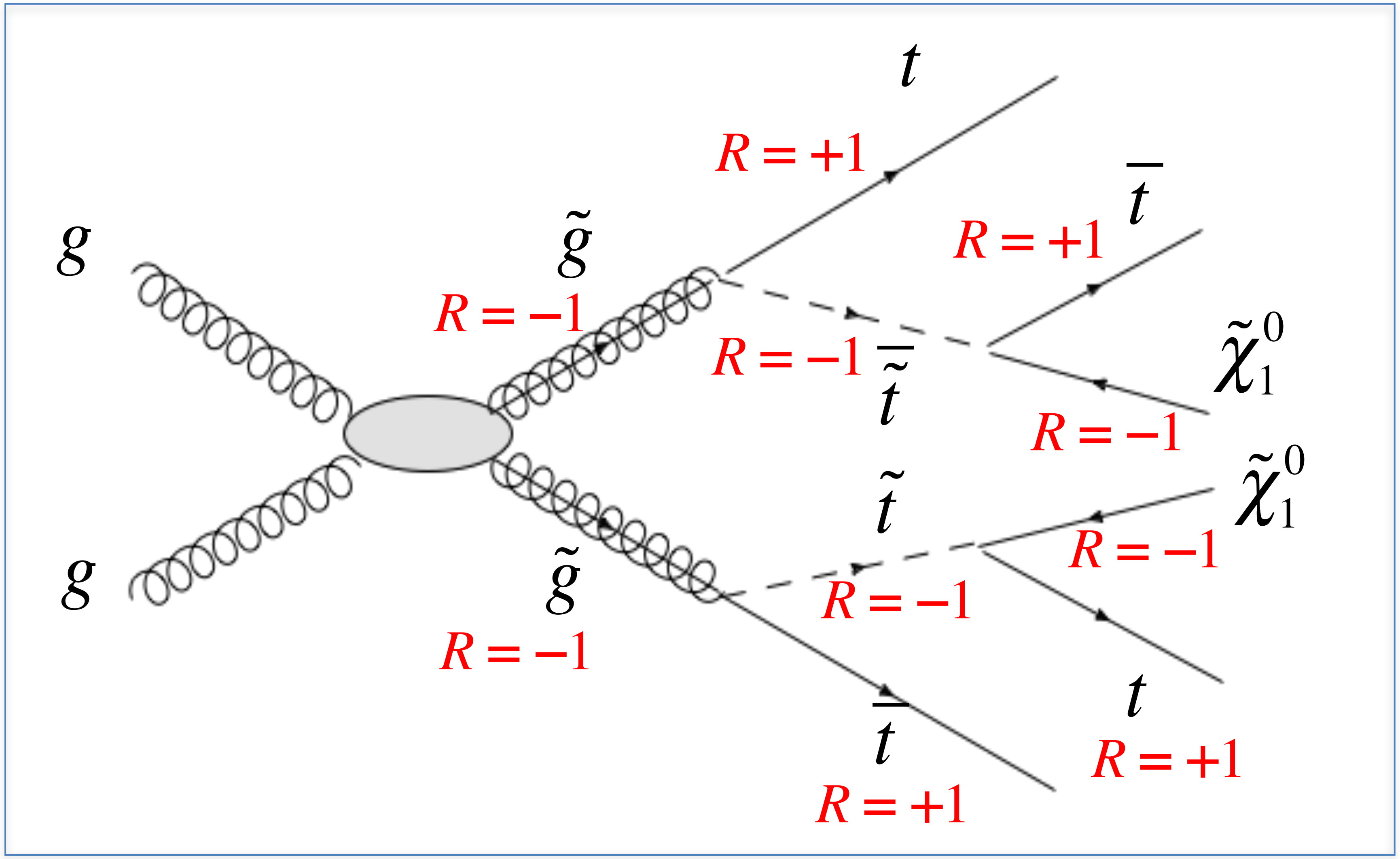
- The symmetry operation in SUSY is a mapping between fermionic and bosonic degrees of freedom.
  - "For every SM particle, there is a SUSY particle." (Well, sort of.)
  - Must be a broken symmetry: we don't observe SUSY partners with SM mass values. SUSY breaking → phenomenology
  - SUSY preserves the SM couplings (charges) of particles.
- R-parity: multiplicative quantum number that is conserved in many, but not all SUSY scenarios.

$$R = (-1)^{3(B-L)+2S}$$

	quark	lepton	gauge boson	Higgs boson	squark	slepton	gaugino/ Higgsino
3(B-L)+2S	3(1/3 - 0) +2(1/2) = 2	3(0 - 1) +2(1/2) = -2	3(0 – 0) +2 (1) = 2	3(0 – 0) +2(0) = 0	3(1/3 - 0) +2(0) = 1	3(0 – 1) +2(0) = -3	3(0 – 0) +2(1/2) = 1
R	1	1	1	1	-1	-1	-1

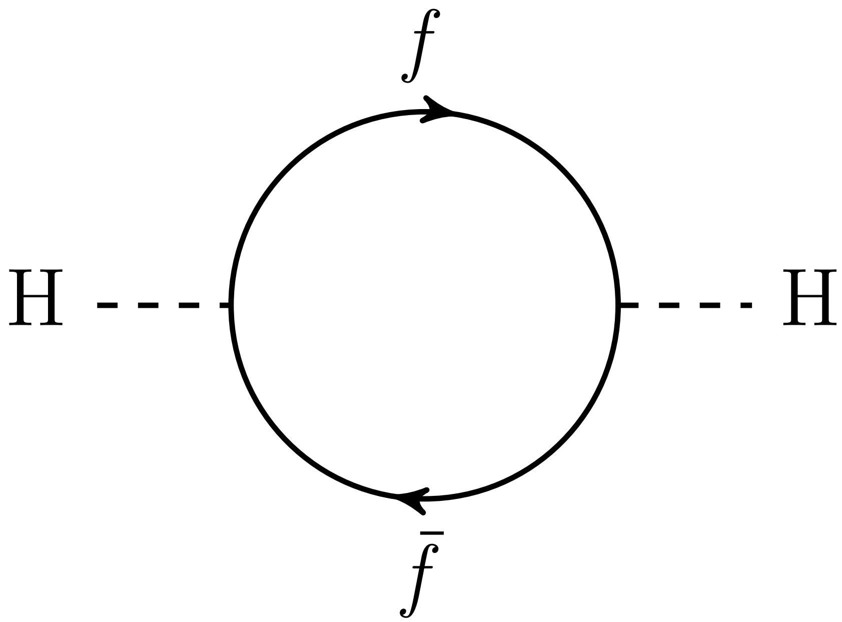
Supersymmetry basics

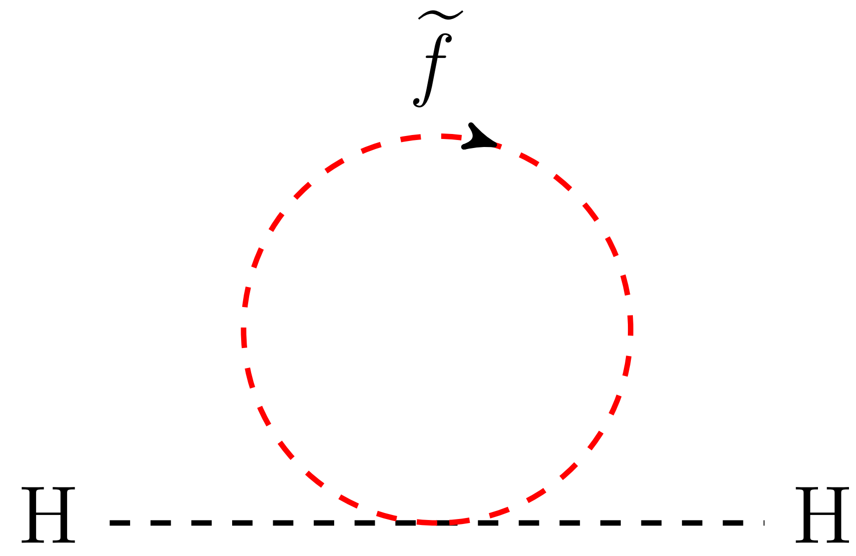
- "Curse of many parameters": MSSM has 124 (including SM).
- If R-parity is conserved, SUSY particles must be produced in pairs.
- The decay chain of each SUSY particle ends with the lightest SUSY partner (LSP), which is stable.
- If the LSP is only weakly interacting, it is a dark matter candidate.



SUSY can (in principle) address the hierarchy problem

C. Bust, A. Katz, S. Lawrence, and R. Sundrum, SUSY, the Third Generation and the LHC, https://arxiv.org/abs/1110.6670 and references on naturalness listed earlier.





$$\delta m_h^2 \approx -\frac{3\lambda_t^2}{8\pi^2}\Lambda^2 + \ldots$$

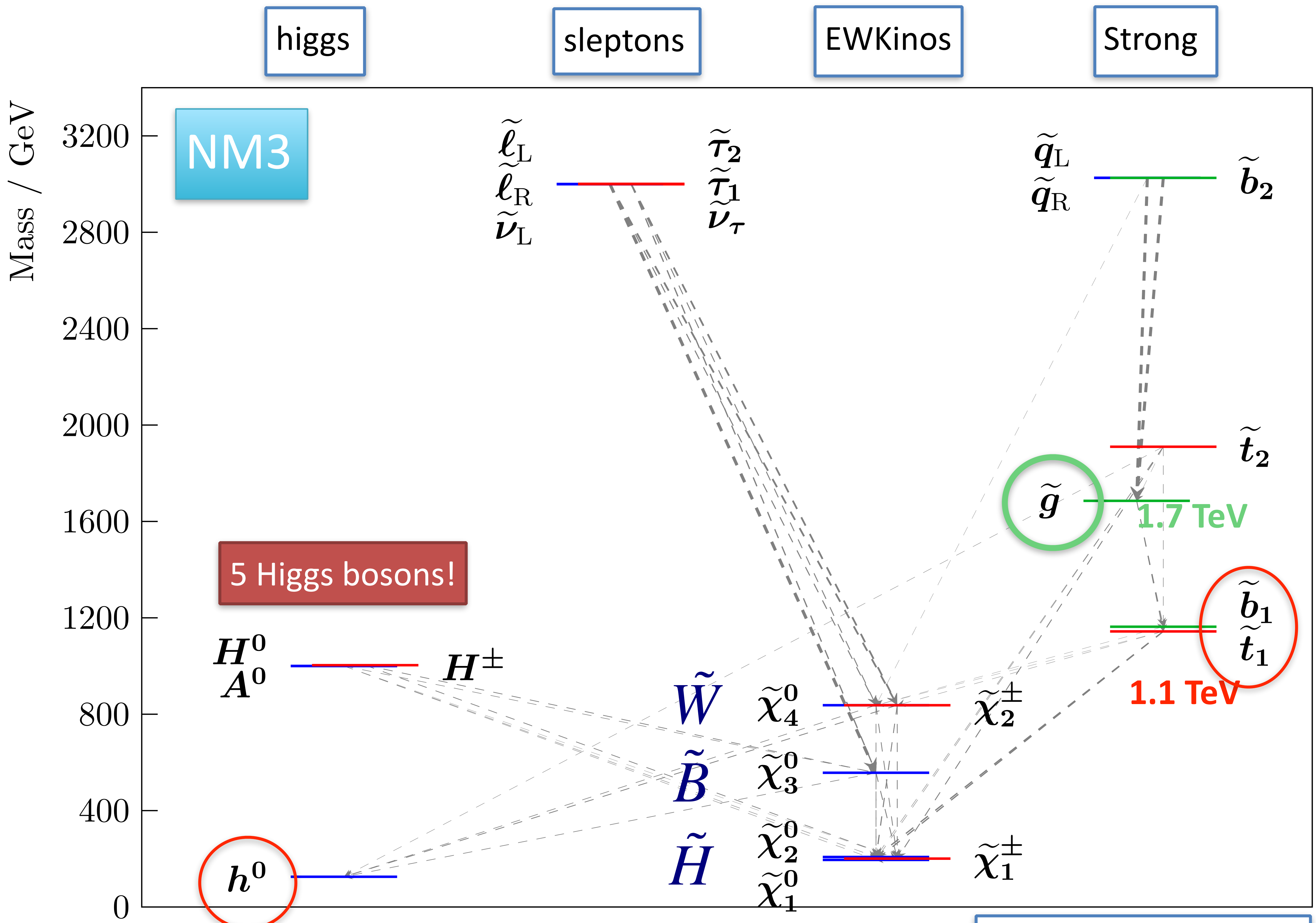
$$\delta m_h^2 \approx +\frac{3\lambda_t^2}{16\pi^2}\Lambda^2 + \ldots$$

but there are two of these…

$$m_{h_u}^2 = m_{h_u,0}^2 + \frac{3\lambda_t^2}{4\pi^2}(m_t^2 - m_{\tilde{t}}^2)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right) + \ldots$$

SUSY particles at the TeV scale can “solve” the fine tuning problem. But current limits on the top squark and gluino masses are putting this picture under stress.

Example: a particle spectrum in the MSSM



CMS PAS SUS-14-012

“Natural SUSY endures”: still the current fashion (?)

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

Stabilizing the EW scale in a “natural” way (without excessive fine tuning) involves only a subset of the SUSY spectrum. Which SUSY partners are constrained?

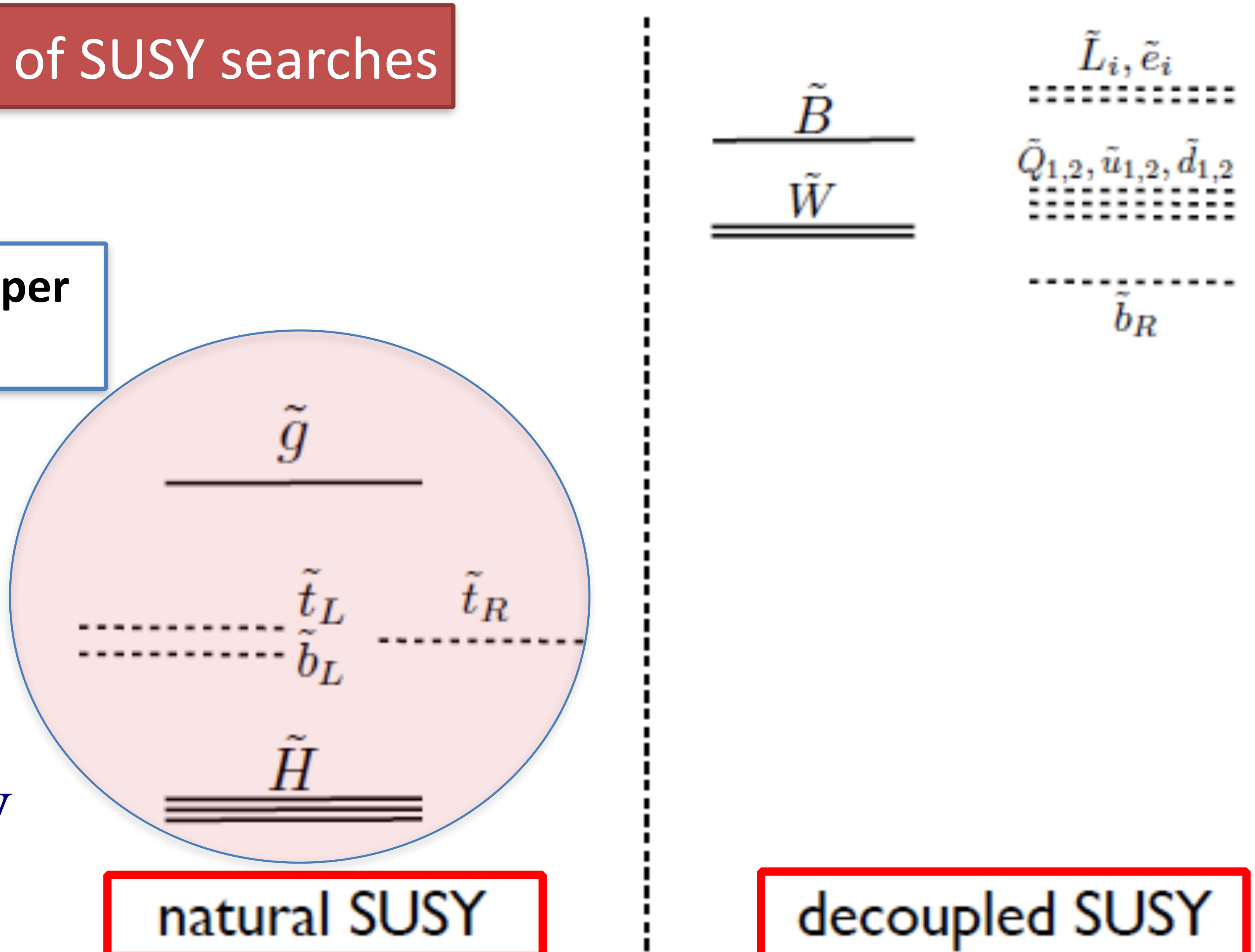
Focus of SUSY searches

Expected mass upper bound (rough):

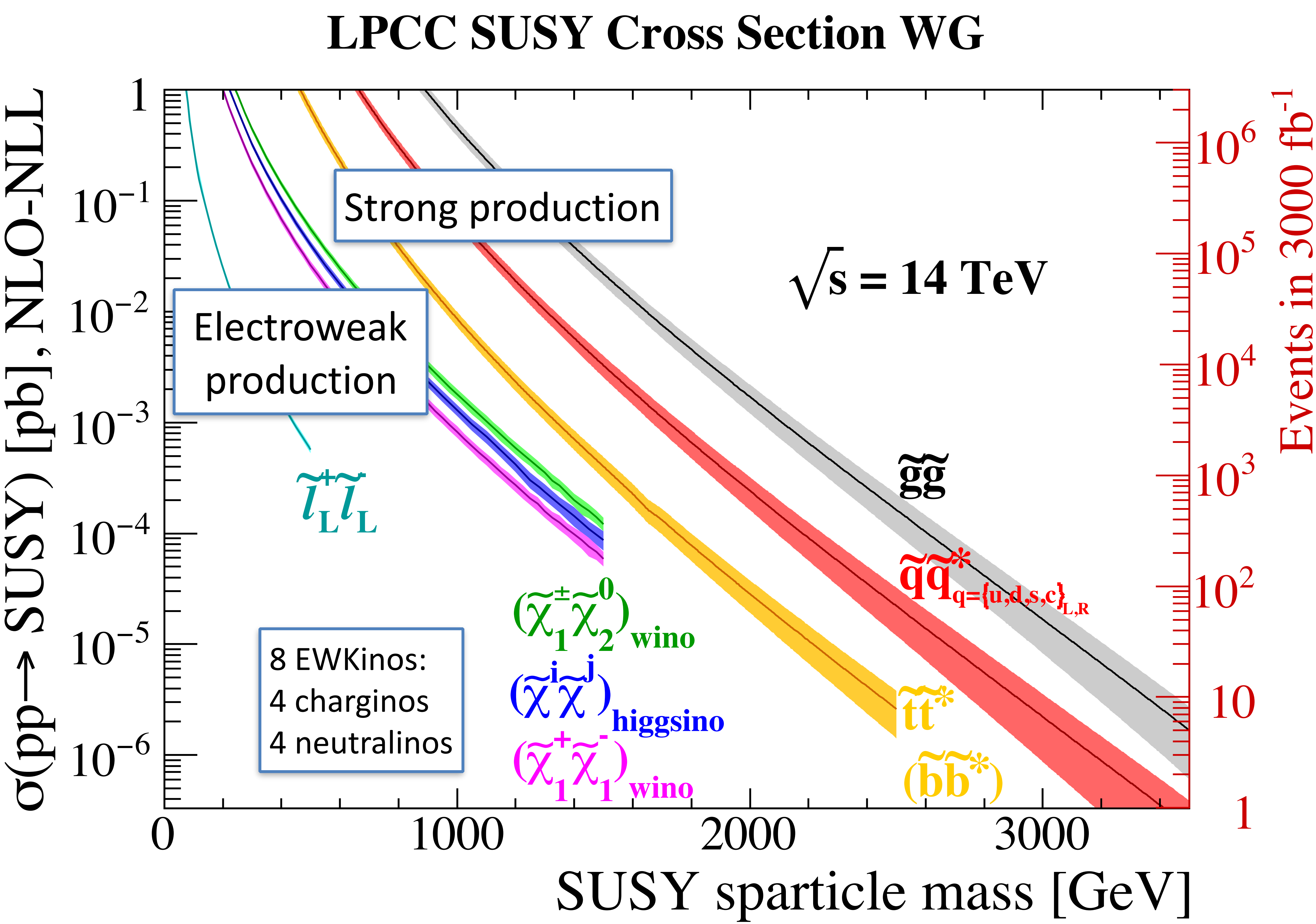
$$m_{\tilde{g}} \approx 2m_{\tilde{t}}$$

$$m_{\tilde{t}} \approx 400 \text{ GeV}$$

$$m_{\tilde{H}} \approx 200 \text{ GeV}$$



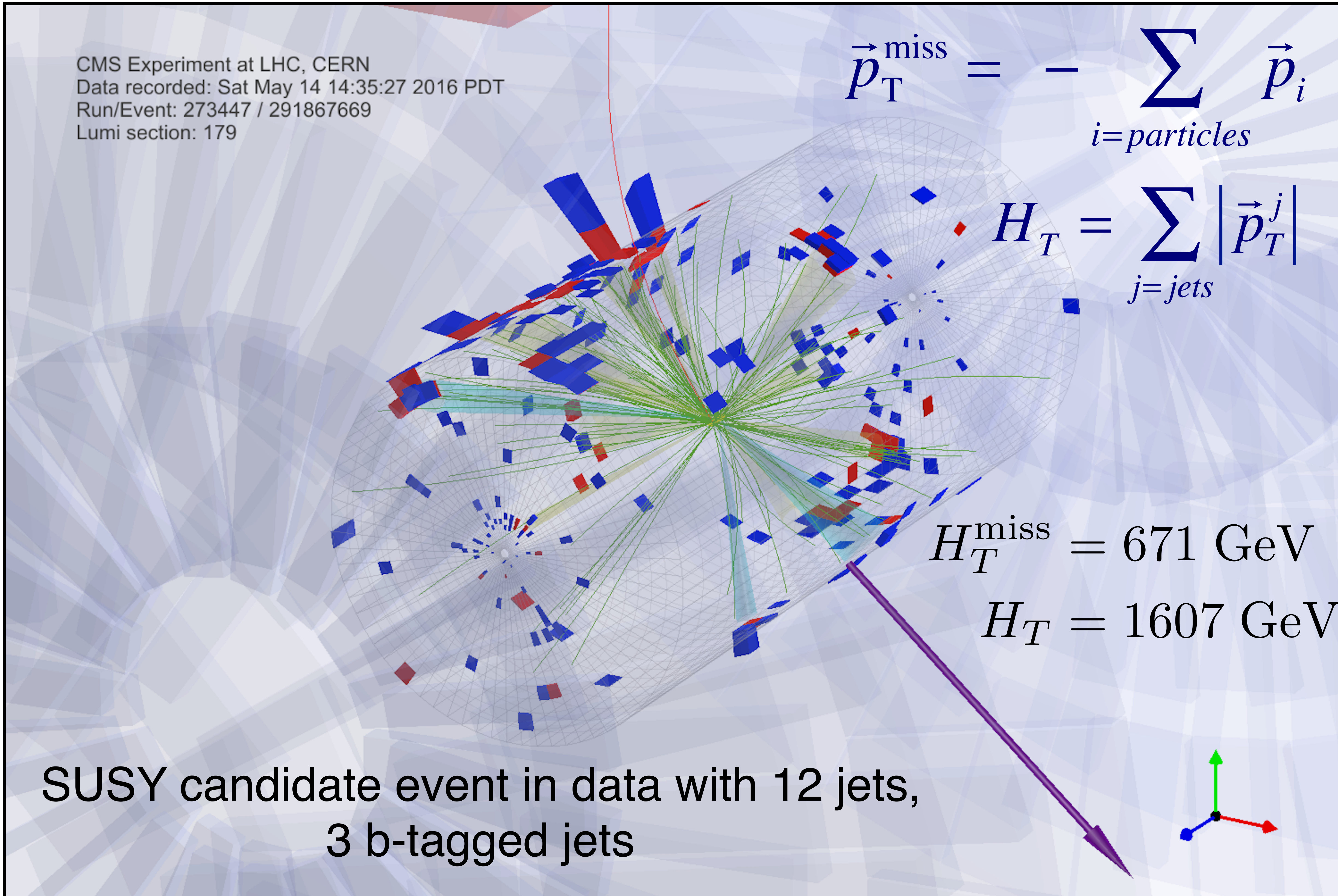
SUSY production cross sections



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

arXiv:1407.5066

Jets + p_T^{miss} search: candidate event



$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_{i=particles} \vec{p}_i$$

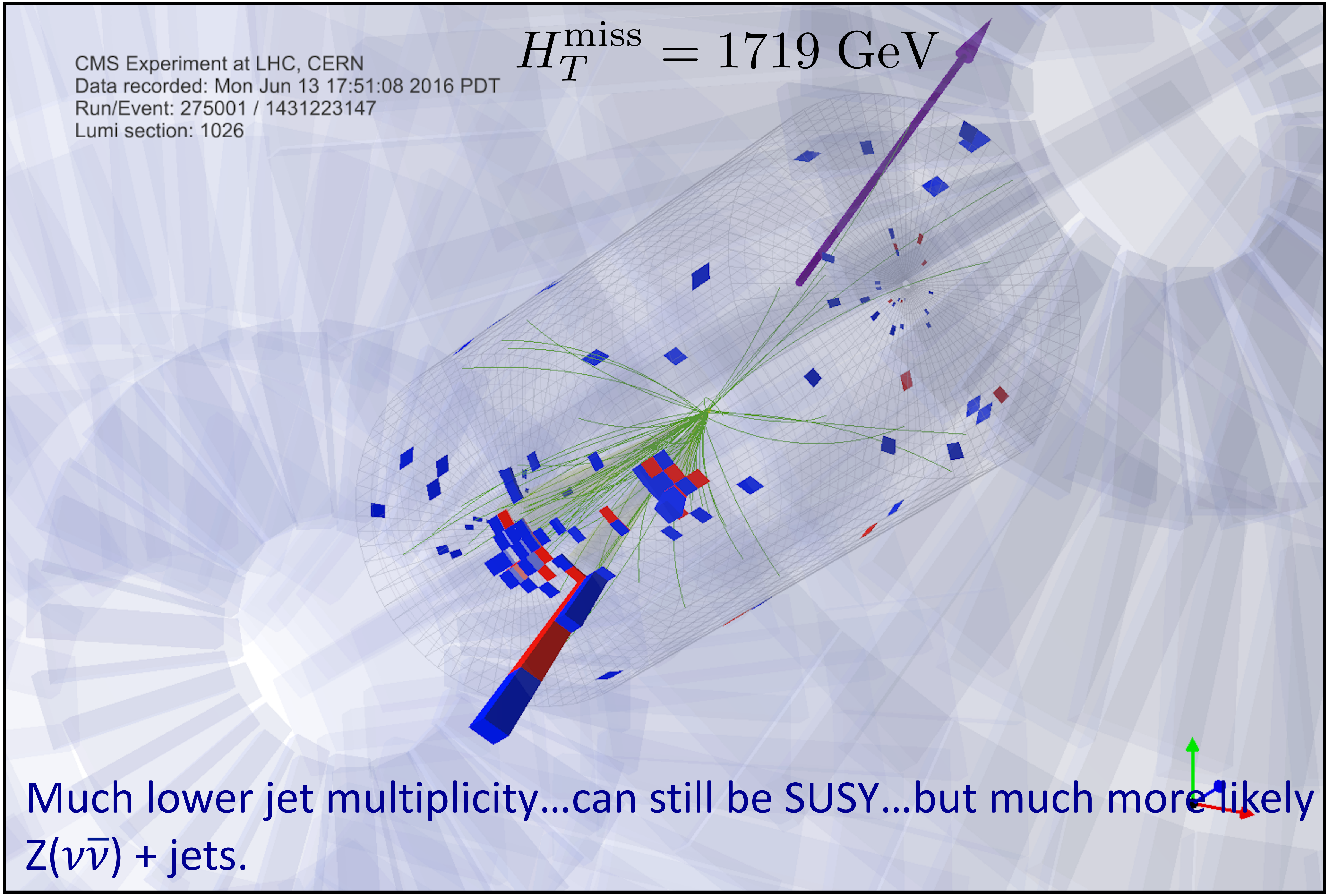
$$H_T = \sum_{j=jets} \left|\vec{p}_T^{\,j}\right|$$

$$H_T^{\mathrm{miss}} = 671\ \mathrm{GeV}$$

$$H_T = 1607\ \mathrm{GeV}$$

SUSY candidate event in data with 12 jets, 3 b-tagged jets

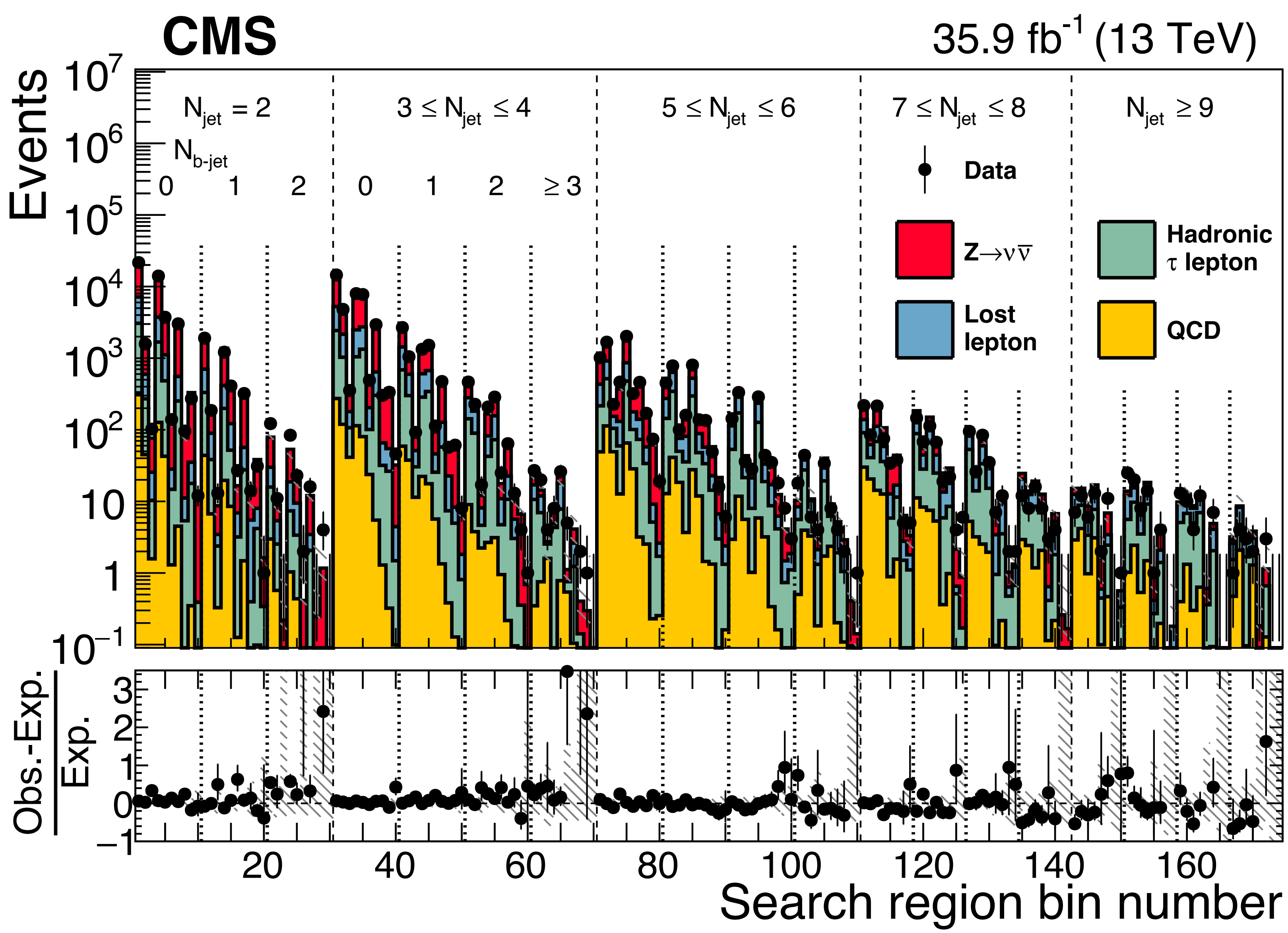
Jets + p_T^{miss} search: candidate event

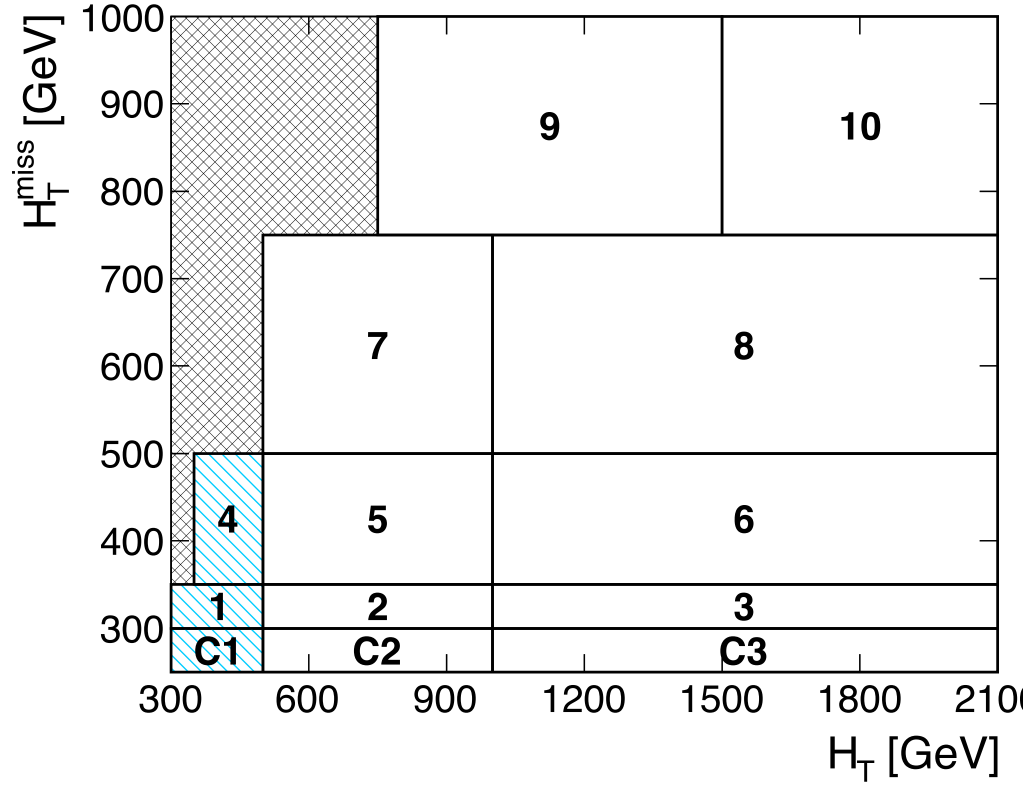


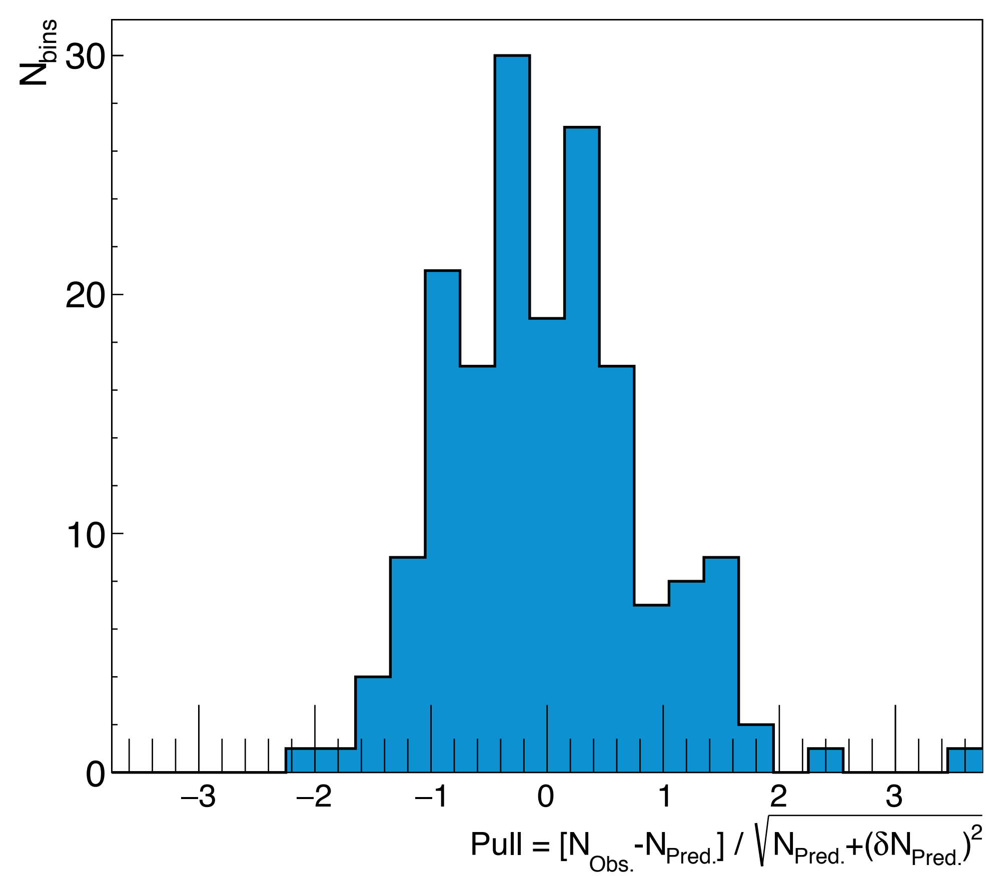
Much lower jet multiplicity…can still be SUSY…but much more likely $Z(\nu\bar{\nu})$ + jets.

Jets + p_T^{miss} search: observed yields in signal regions

Bin numbering: increasing: Njets, Nbjets, HT & HTmiss (order according to plot at right)

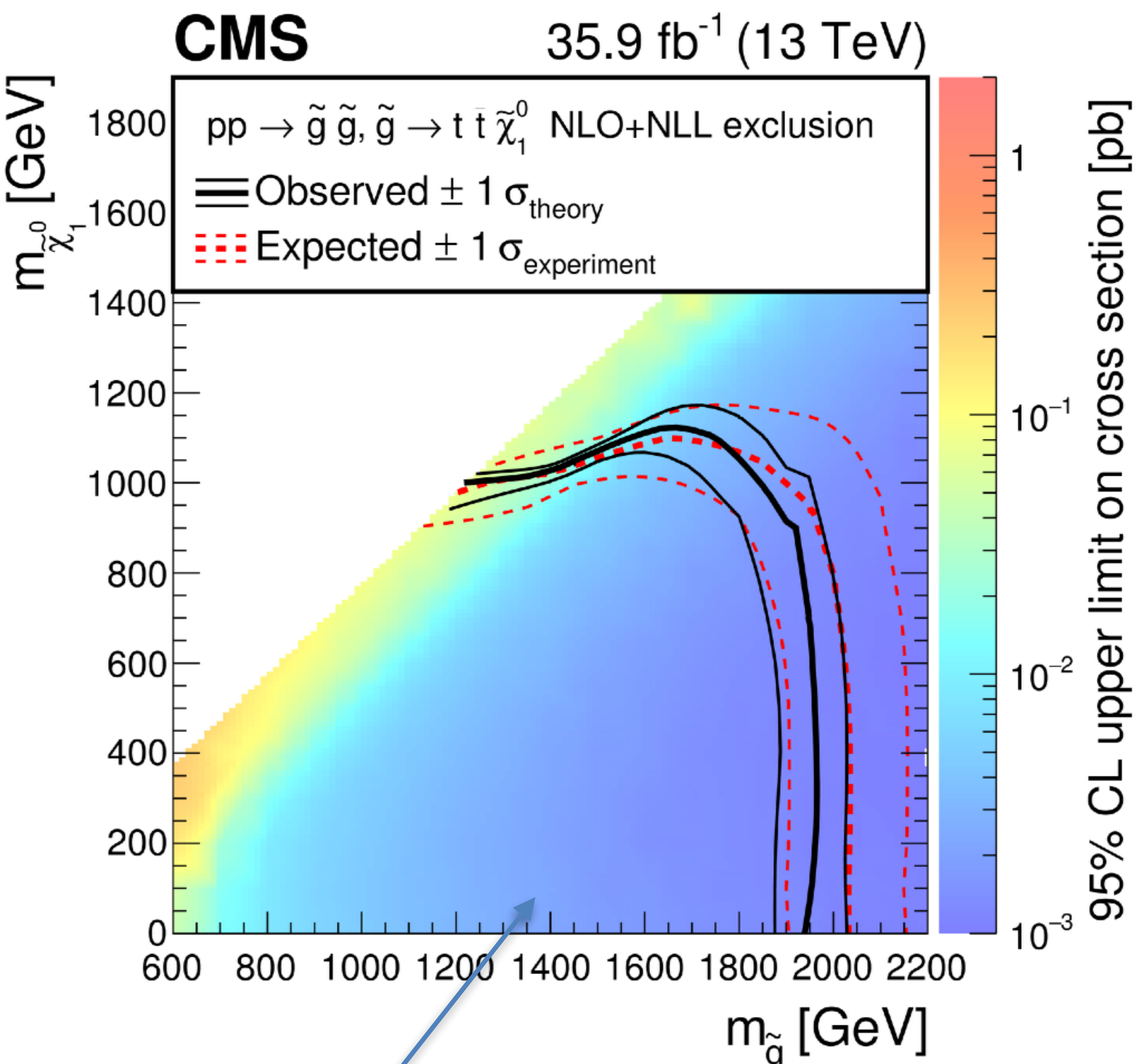


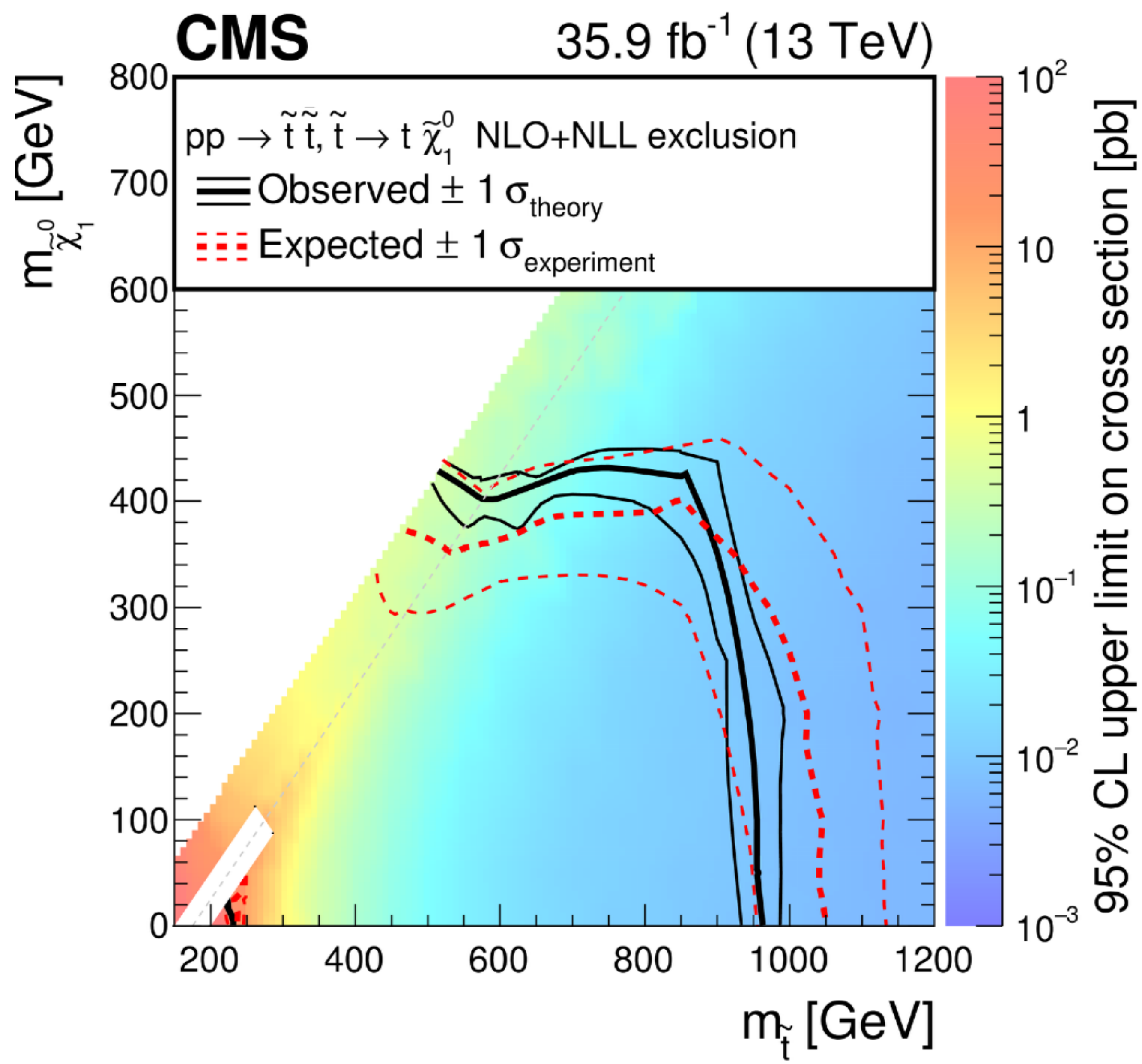




In each bin, each main background is predicted separately from control sample(s) in the data that is (are) dominated by that background.

Jets + p_T^{miss} search: example interpretations

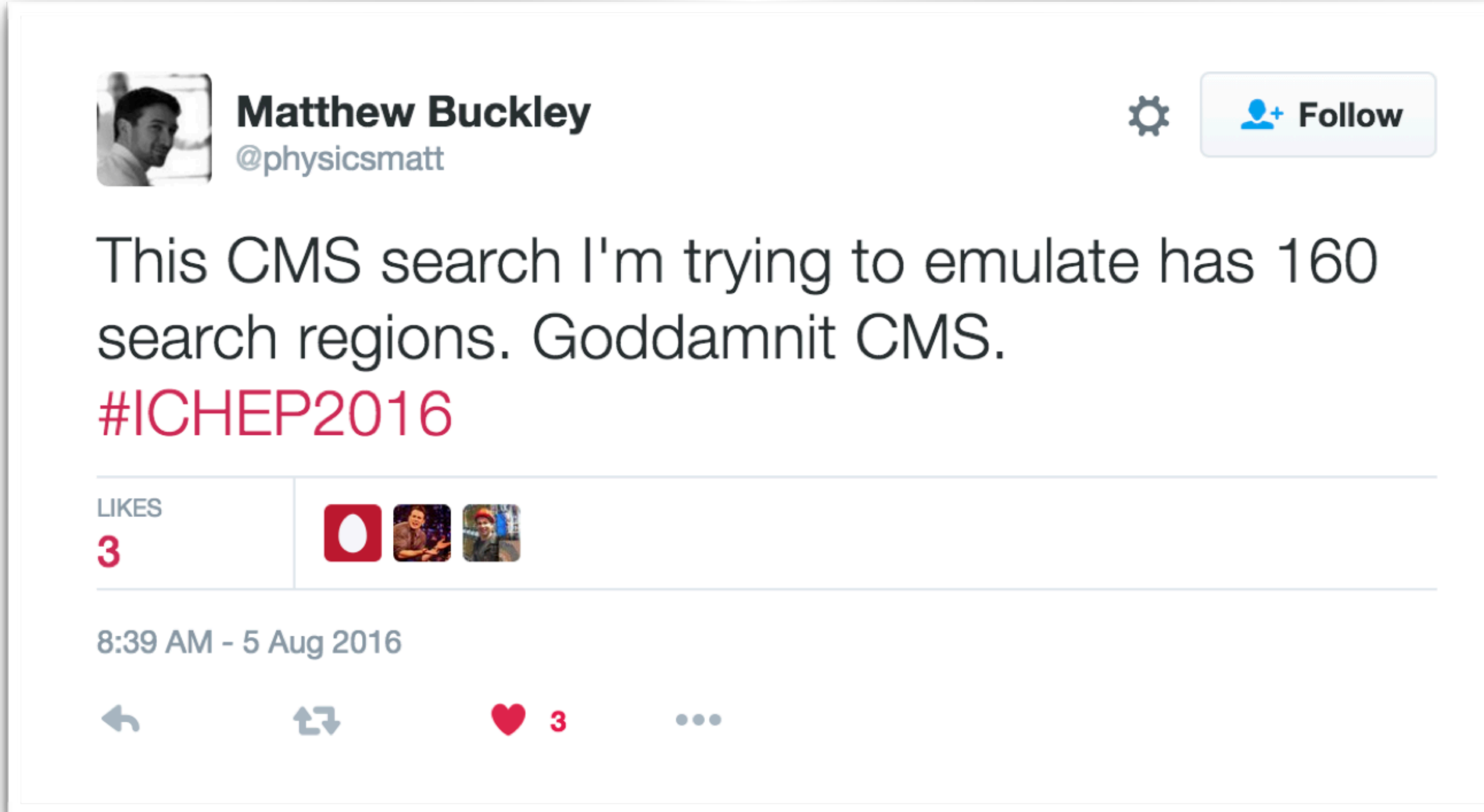




Color map shows the excluded cross section (95% CL)
Comparison of this cross section with a theoretical reference cross section for the signal gives the boundary of the excluded model points.

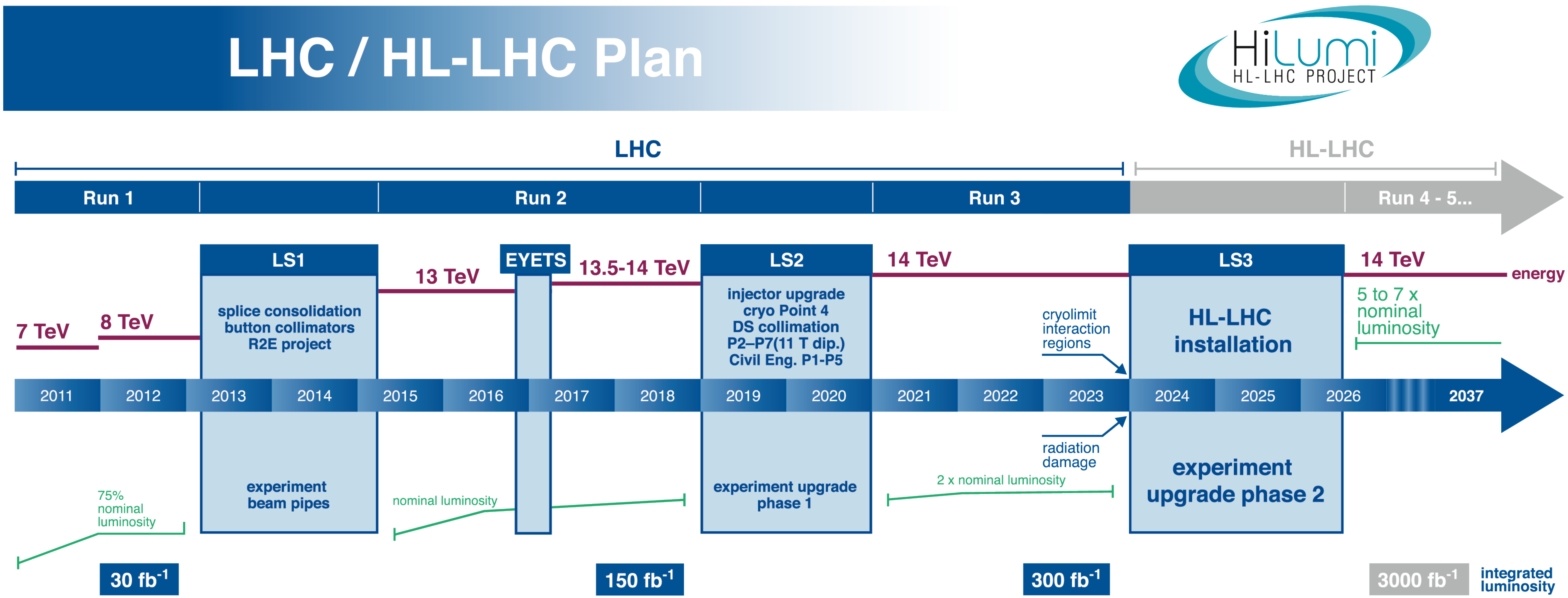
Many more interpretations available at
http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-16-033/index.html

Jets + p_T^{miss} search: commentary from a theorist



Our answer: you will find results for “aggregated search regions” (12 bins) in the paper!

Towards the High Luminosity LHC



- Accelerator upgrade is being accompanied by major upgrades to the detectors.
- CMS: new capabilities to handle increased data rate, multiple pp collisions per bunch crossing (pileup), radiation damage, and to improve trigger, tracking, calorimeters, and muon system.

Towards the High Luminosity LHC: CMS detector upgrade

L1-Trigger/HLT/DAQ

https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters

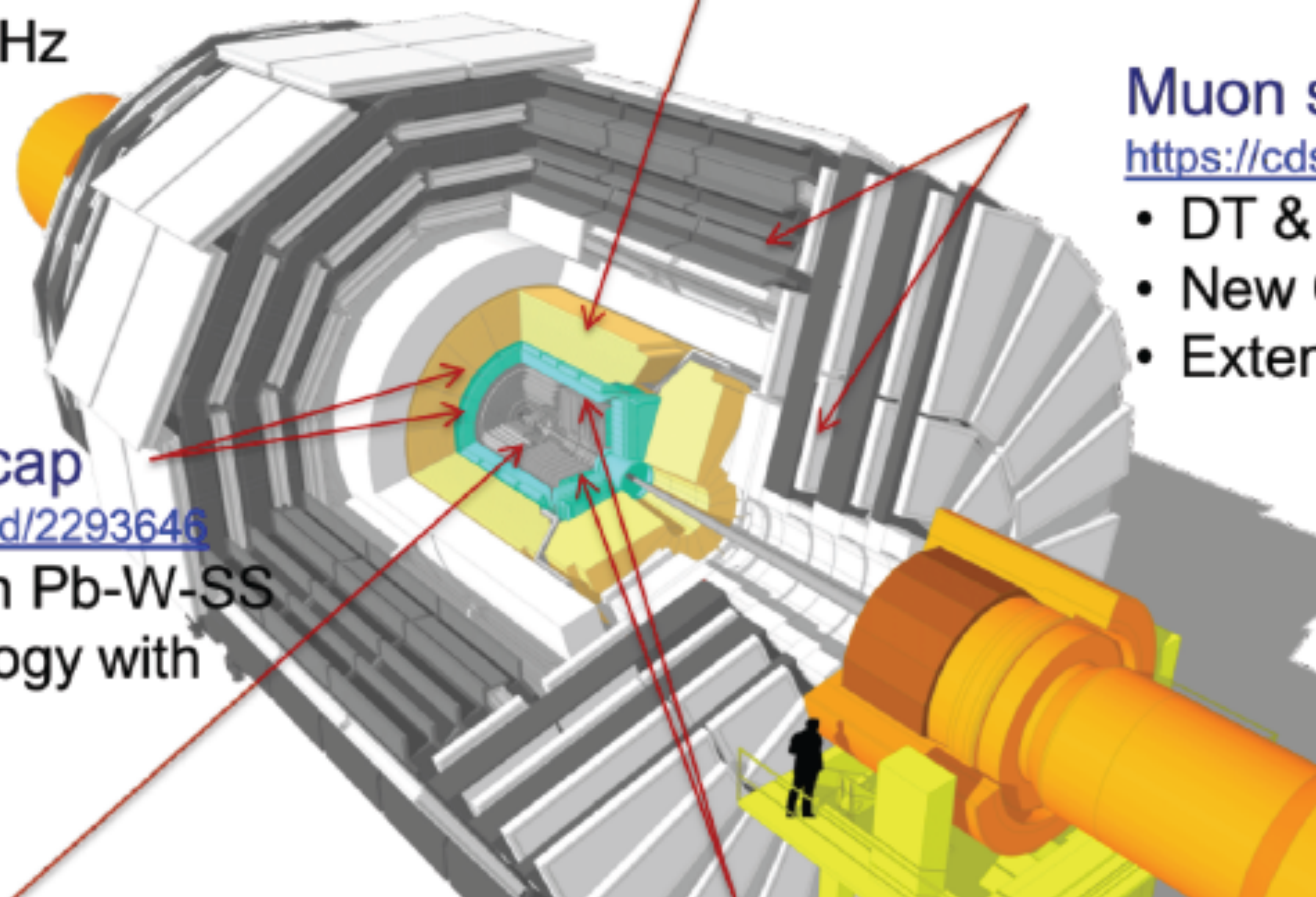
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3



Calorimeter Endcap

https://cds.cern.ch/record/2293646

- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure

https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8

MIP Timing Detector

https://cds.cern.ch/record/2296612

- ≃ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Conclusions/Perspective (I)

- Since the/a Higgs boson discovery in 2012 there has been major progress is studying its properties.
- This effort has expanded into a full physics program: 4 production processes and 7 decay modes are being studied, with detailed measurements of kinematic distributions underway.
- Will require very large data samples to fully explore critical Higgs decay modes. Increases in precision are extremely important for fully testing the Higgs sector of the SM.
- Holy grail is Higgs self-coupling (HHH vertex).
- So far, observe remarkable agreement with SM predictions involving both gauge boson and fermion couplings.

Conclusions/Perspective (II)

- But…we are puzzled.
- The SM is internally consistent (without further physics), but it appears to require an extraordinary degree of fine tuning of parameters to prevent quantum corrections from pulling the Higgs mass to the Planck scale. (Hierarchy problem.)
- This is a fundamental problem associated with the J=0 nature of the Higgs boson, assuming that it is an elementary (non-composite) particle. (We also don't have a candidate for dark matter, or answers to many other questions.)
- So far, no evidence has emerged for any proposed explanation, including supersymmetry.
- However, the frameworks for new physics offer an enormous range of phenomenological possibilities, and there are many scenarios that are currently difficult to probe. The jury is still out.

Conclusions and Perspective (III)

When you are on a voyage of discovery, you don't necessarily have a good idea of where you are.
We have only analyzed ~5% of the eventual LHC data sample! There may be more "continents" to be found!

Acknowledgments

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