The Road Ahead

SLAC Summer Institute
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Age-old

- Questioning the fundamental nature of our universe is probably as old as the human race
  - In every age it has been a key driver of human curiosity
  - Rephrased with each new insight to
    - Focus on some set of observable phenomena and
    - Ponder what these observations mean, what underlies them
    - e.g. the motions of the planets were observed and modeled over many centuries

In the process, we established,

"The Scientific Method"*

which was no small feat…

**Recommended reading: S. Weinberg, `To Explain the World'*

Modern giants

- It is said that we are standing on the shoulders of giants! Does this mean it's getting easier?
  - No! In just about every respect it's getting harder…
- And what we mean by giants has, of necessity, changed dramatically. It now encompasses
  - Global collaborations of experimental physicists with systems of unprecedented scale, and capability.
  - Theoretical physicists everywhere in continuous contact

Aside: HEP is often cited for its high cost. It is not so much more costly. Funds are pooled from across the globe to produce shared large facilities that ***stand out****. We may be first in this game, but this is a trend that other areas will increasingly face over time.*

Where are we now (expt.)?

- Particle Physics
  - Many discoveries (W, Z, top, Higgs…) and precision measurements consistent with Standard Model (SM)
- Astrophysics and Cosmology
  - Abundant evidence for physics beyond the SM
    - Non-baryonic dark matter
    - Neutrino oscillations ($m_\nu \neq 0$ but very nearly …)
    - Cosmic matter-antimatter asymmetry
    - Cosmic density fluctuations consistent with inflation
    - Accelerating expansion of the universe / Dark Energy

These are our observations

They phrase our questions

Current questions*

- What is dark Matter?
  - What couplings to SM particles, what quantum nos., mass(es)?
- What are neutrinos?
  - What is the mass hierarchy? Do they violate CP?
  - What is the mechanism by which neutrino mass is generated? Are they Dirac, Majorana, or …?? How does this fit into the bigger picture?
- What is the Higgs?
  - What's the nature of electroweak symmetry breaking? Is there more to it than the Brout-Englert-Higgs (BEH) mechanism?
  - What is the Higgs potential? What are the Higgs couplings? (is it alone? Is it composite?) What symmetry protects the Higgs at this low mass?
  - What can we learn about its connection to the top? Are there top partners ?
- What else can we find Beyond the Standard Model (BSM)?
  - SUSY? Extra Dimensions? Hidden Valleys?... So many possibilities!
  - What can we learn from precision measurements, rare processes? How precise, how rare?

**A representative list, with slight personal bias in the ordering*

And…*

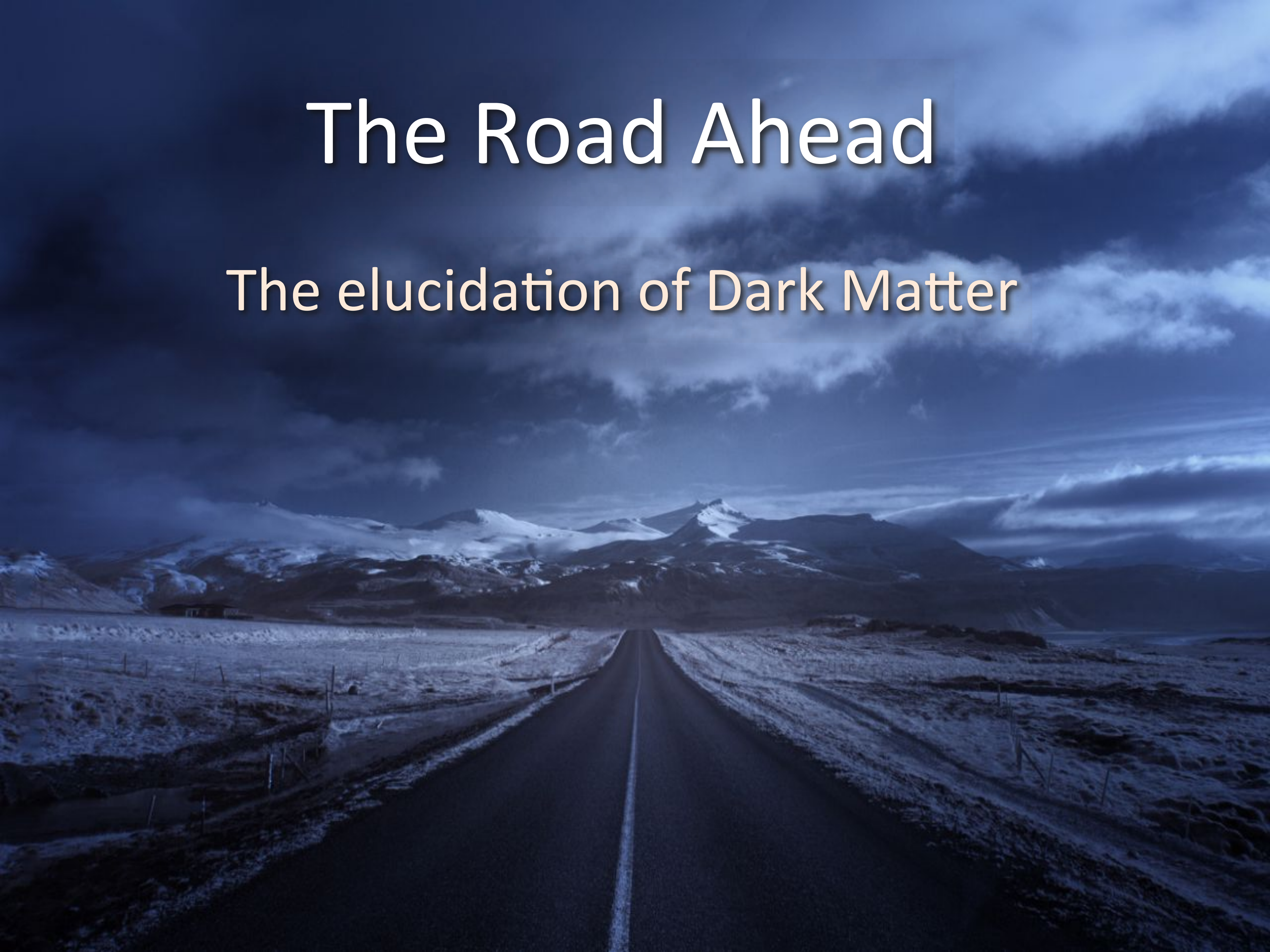
- What is the landscape of the unseen universe?
  - I.e. what are the implications of the first observations of gravity waves from black hole mergers and what else will this new window open our eyes to?

- What is behind cosmic inflation
  - What is dark energy? Is it a field or simply a parameter in the larger theory – simply a cosmological constant (CC)?
    - What do we do with the CC problem?

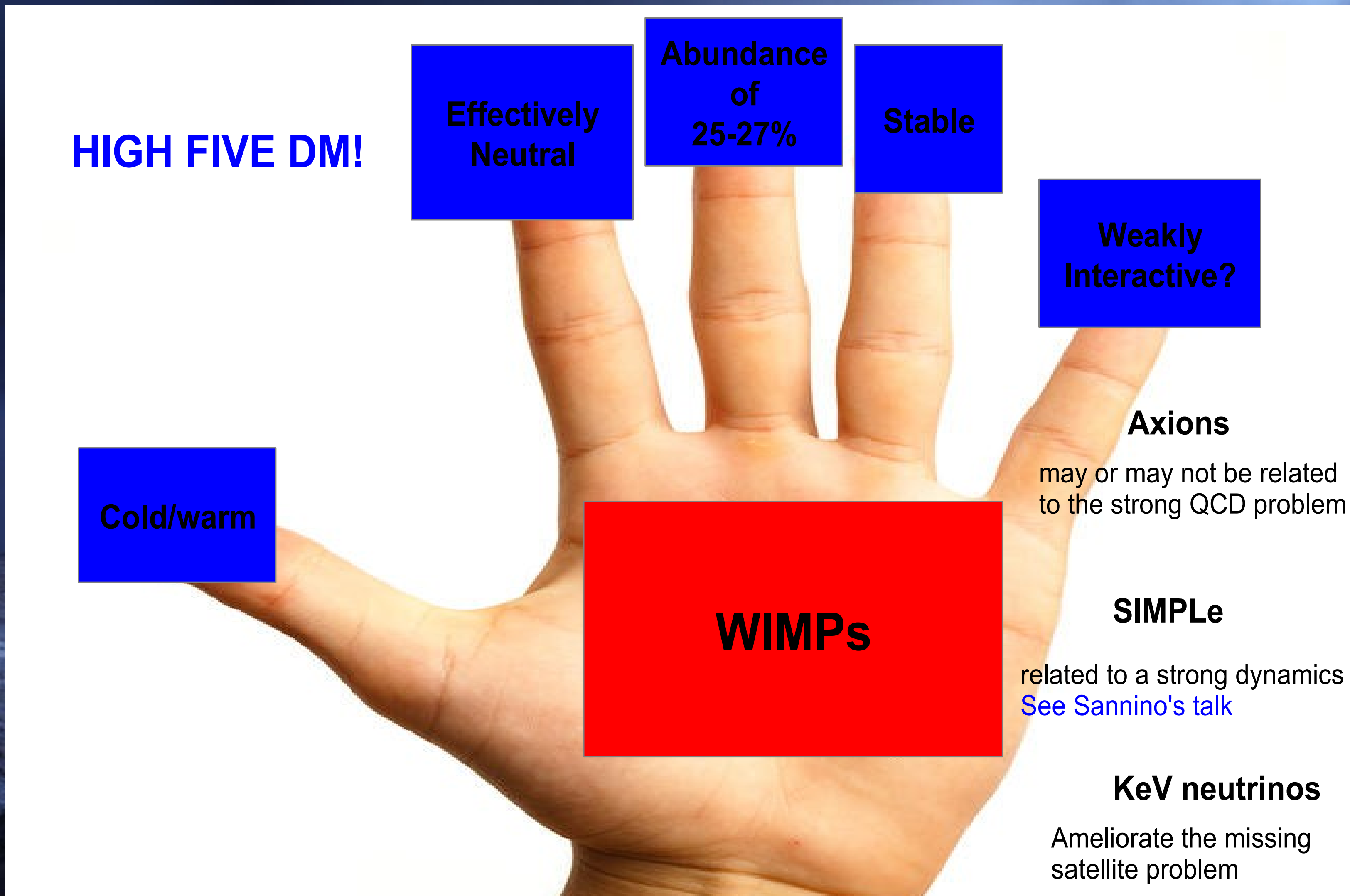
**Extremely exciting but not covered in this talk*

The Road Ahead

The elucidation of Dark Matter



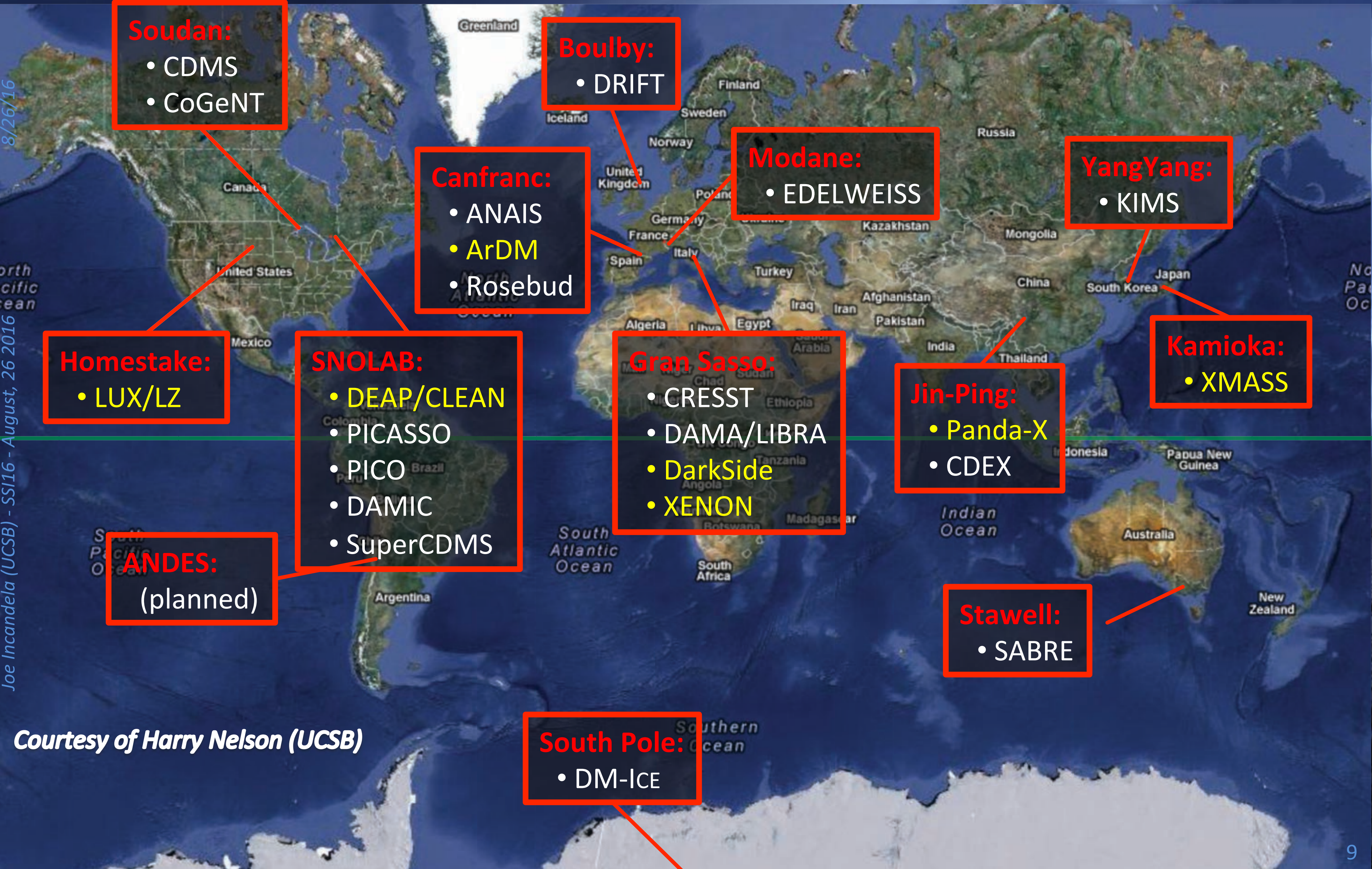
What do we (think we) know about DM?



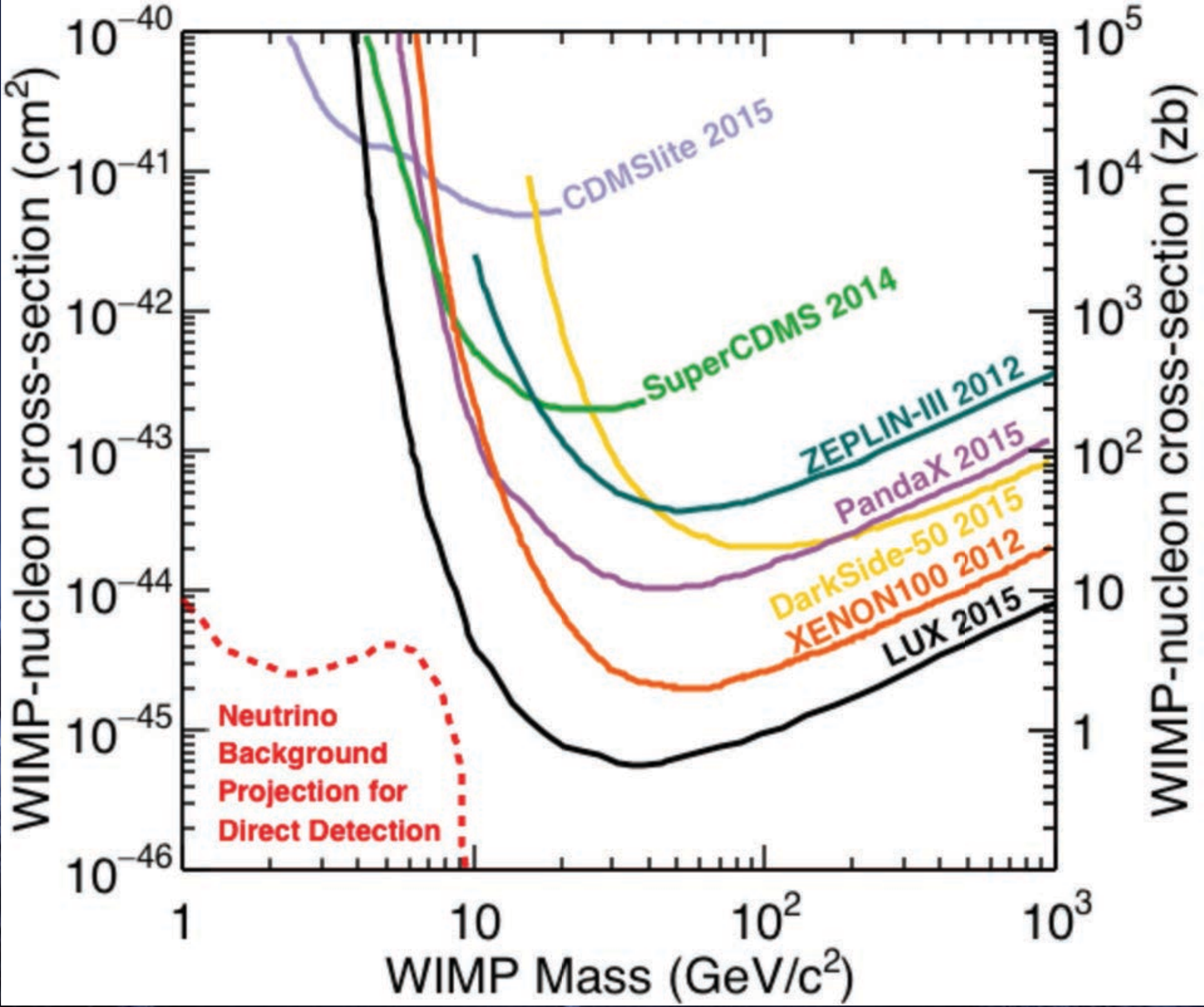
Courtesy of Farinaldo Queiroz (MPIK) Moriond 2016

Global Direct Dark Matter (DDM) Search Program

(Noble Liquid Detectors in Yellow)



Searching High and Low

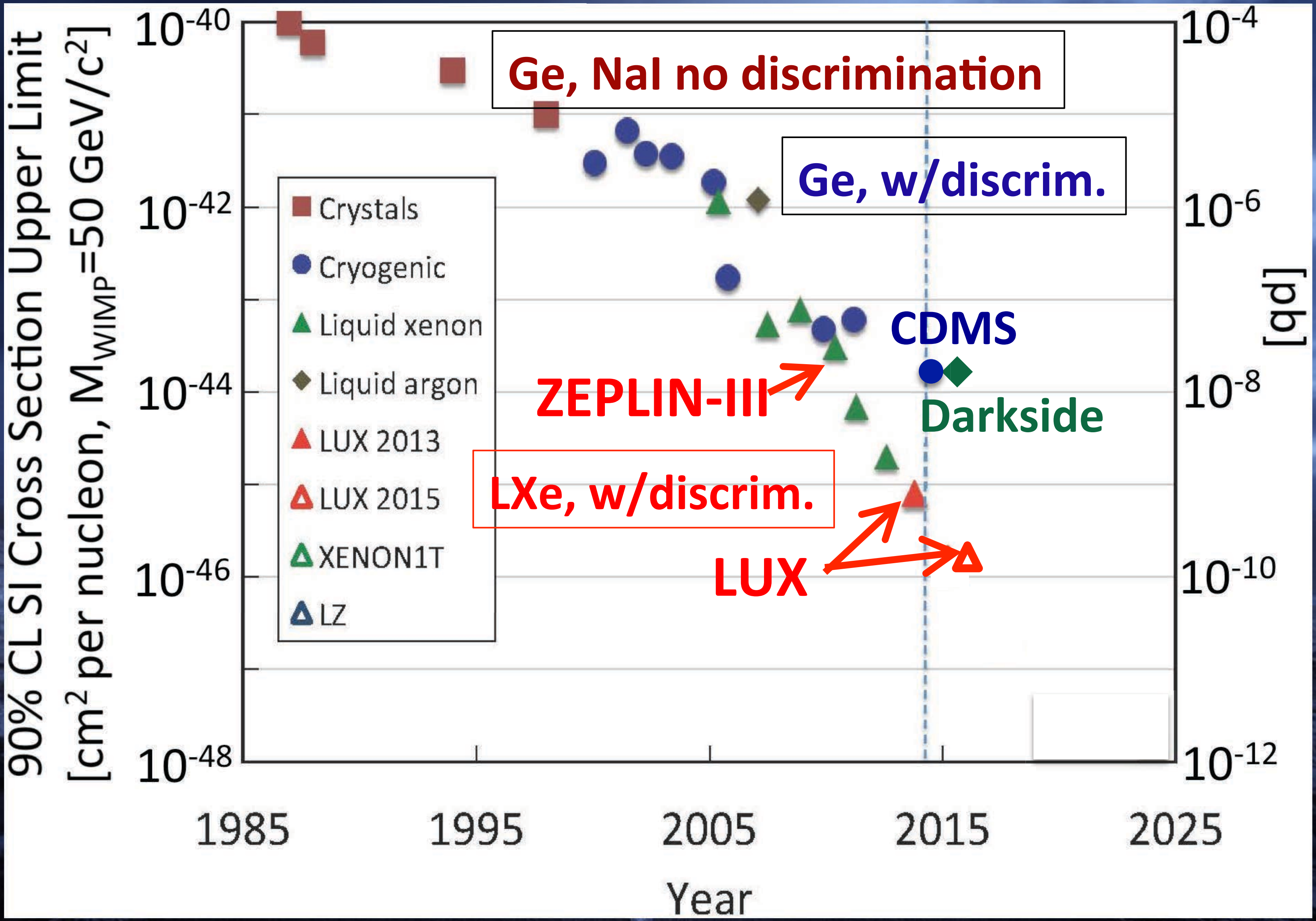


Low Mass Region – SuperCDMS

High Mass Region – Xenon/Argon

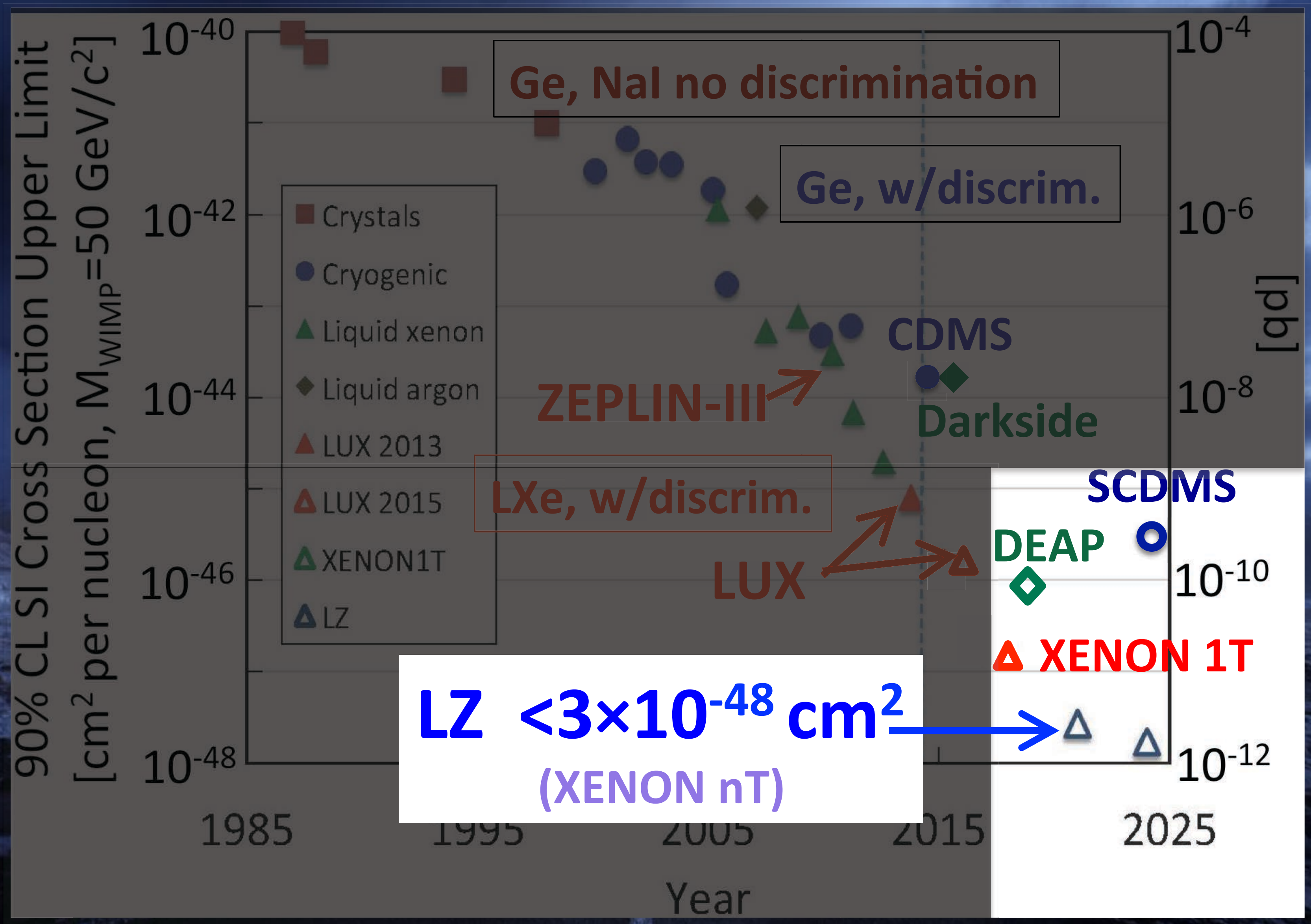
Adapted from slide by Harry Nelson (UCSB)

Direct Dark Matter (DDM) Searches



Adapted from slide by Harry Nelson (UCSB)

DDM searches - near future



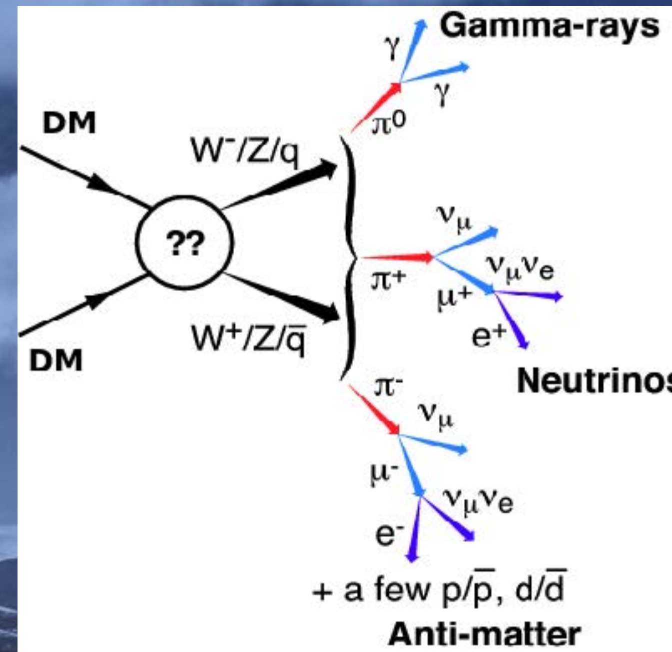
Adapted from slide by Harry Nelson (UCSB)

Indirect DM (IDM) Searches

- ~30 GeV Excess*
  - First Observation: Possible Evidence for Dark Matter Annihilation In The Inner Milky Way
    - Goodenough, Hooper, arXiv:0910.2998
  - Fermi-LAT Observations of High-Energy Gamma-Ray Emission Toward the Galactic Center

    "After subtracting the interstellar emission and point-source contributions from the data a residual is found that is a sub-dominant fraction of the total flux".

    - Fermi-LAT, arXiv:1511.02938

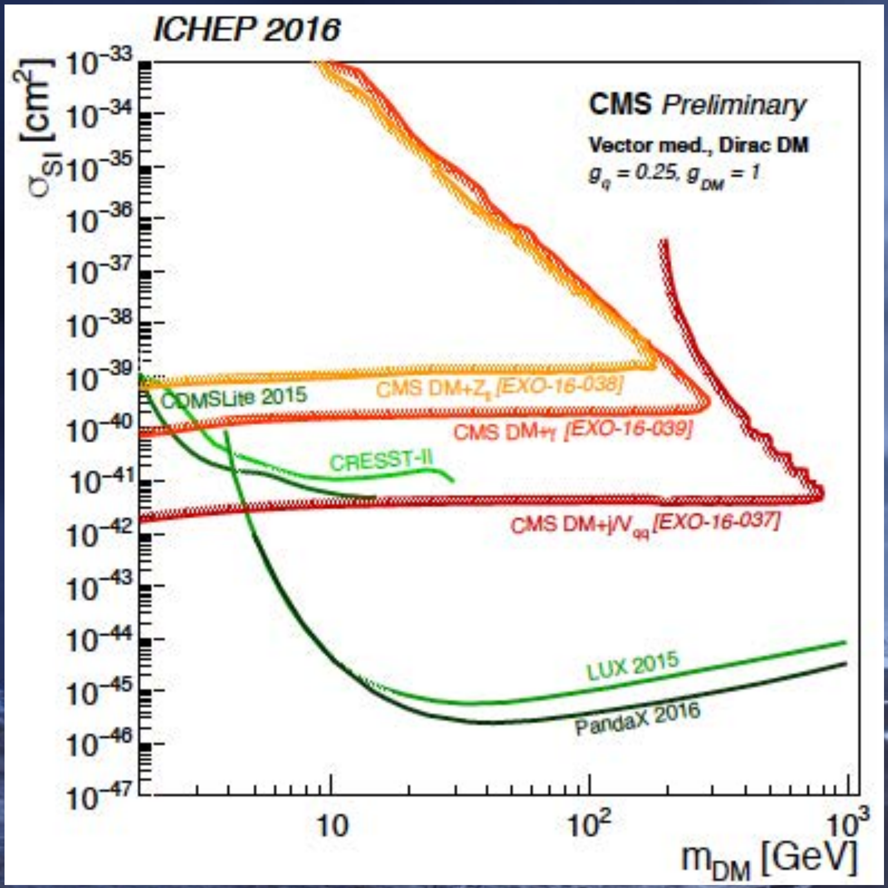


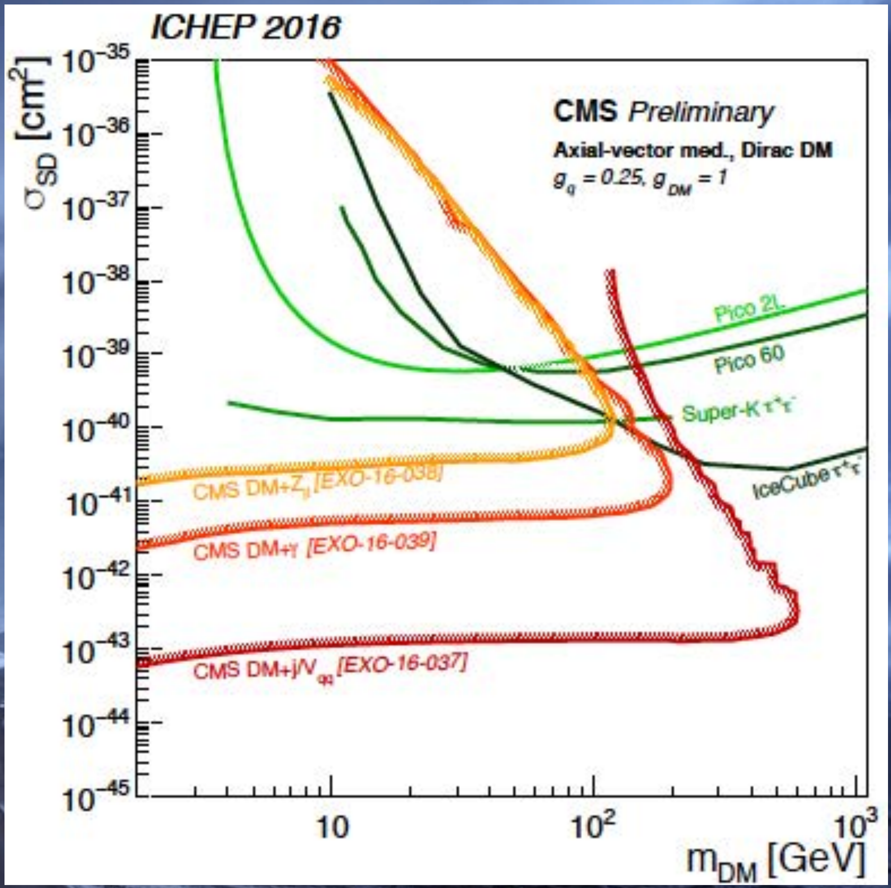
- Dwarf Galaxy Data
  - So far does not corroborate it, but may not exclude it either..
  - Eventually will resolve the question…

There's a "~3.5 keV" excess also (perhaps even more controversial)

From slide by Farinaldo Queiroz (MPIK)

DM Searches @ LHC





Spin Independent:
LHC Loses, except at low mass

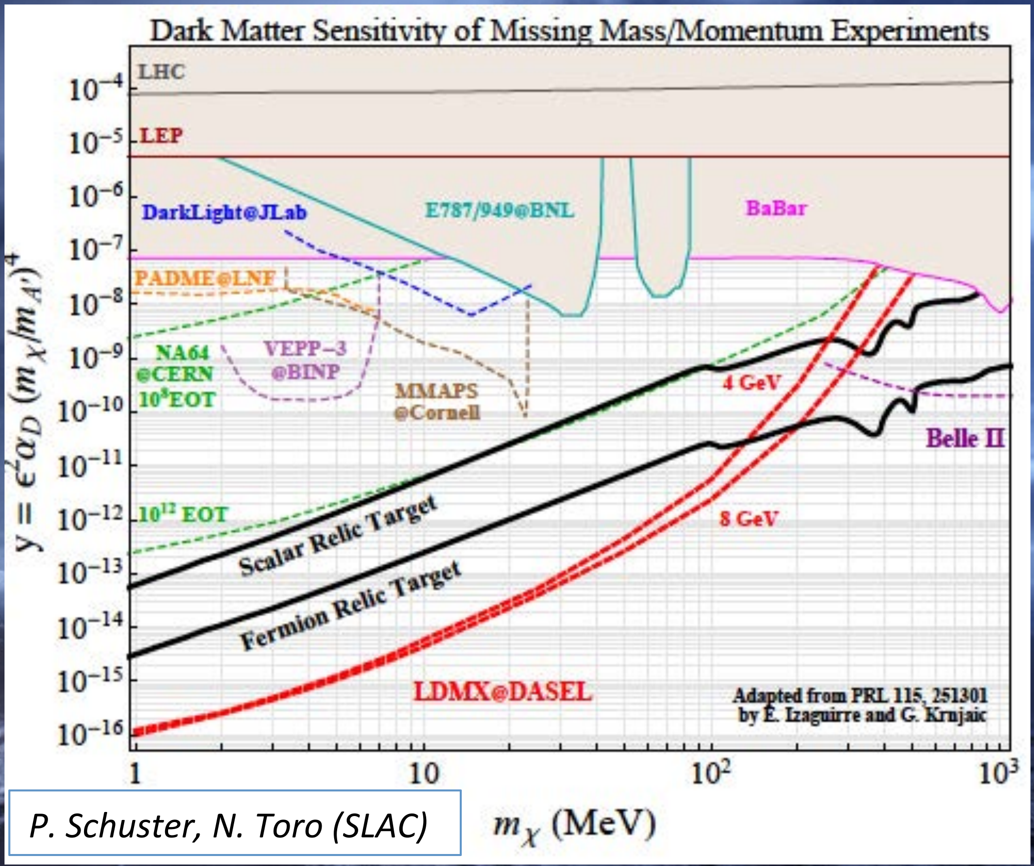
CMS observed exclusion 90% CL

- CMS DM+j/V$_{qq}$ *[EXO-16-037]*
- CMS DM+γ *[EXO-16-039]*
- CMS DM+Z$_{ll}$ *[EXO-16-038]*

Spin dependent:
LHC wins, except at high mass

Filling the cracks: Future DM Searches

- Extend what we have
  - **IDM:** powerful telescopes
  - **DDM:** until run hard into the neutrino wall?
  - **Colliders:** attack new high mass phase space and fill holes where possible
- And then do more…
  - **Beam dumps:** probe e to light q mass range…
    - Isn't this the first place you'd want to look?
  - ***Potential programs***
    - **SPS to search for Hidden Particles (SHiP) @ CERN**
    - **DArk Sector Expt's at LCLS-II (DASEL) @ SLAC**



P. Schuster, N. Toro (SLAC)

Yield-Limited DM sensitivity of E_T^{miss} expt. vs. current and proposed limits … y= dimensionless interaction strength… black lines = minimum interaction strengths consistent with scalar and fermion thermal relic Dark Matter

We’ll interact with DM soon…

Then we’ll want to know everything about it…

- We’ll need information from as many experiments, of as many types as possible.
- Ideally, we’ll be able to produce it in the lab …
  - I.e. with accelerators *to* understand it fully, *eventually*
  - May need a dedicated machine – e+e- collider

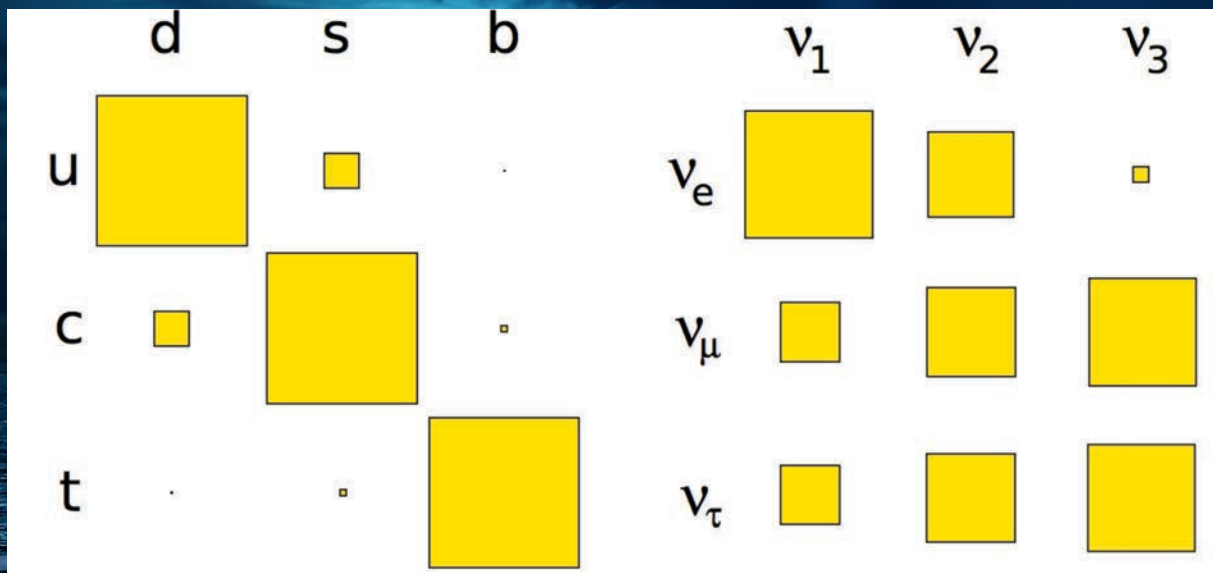
The Road Ahead

Neutrinos

Thanks to Alex Himmel (FNAL) for ν slides

What have we learned?

- Neutrinos oscillate, and so have mass…
  - *Last year's Nobel and Breakthrough prize*
- They mix more than quarks



Cabbibo-Kobayashi-Maskawa

Pontecorvo–Maki–Nakagawa–Sakata

Questions for Neutrinos

- What is the mass Hierarchy?
    - *Needed to develop a model of neutrino mass.*
    - *Also has consequences for neutrinoless double beta decay and cosmological measurements.*
- Do they violate *CP* ?
    - Could be a major step in our understanding of the matter-antimatter asymmetry
    - Some recent results are hinting…
- What are their masses?
- Are they Dirac or Majorana?
- Are there light sterile neutrinos?

Lots to do and learn

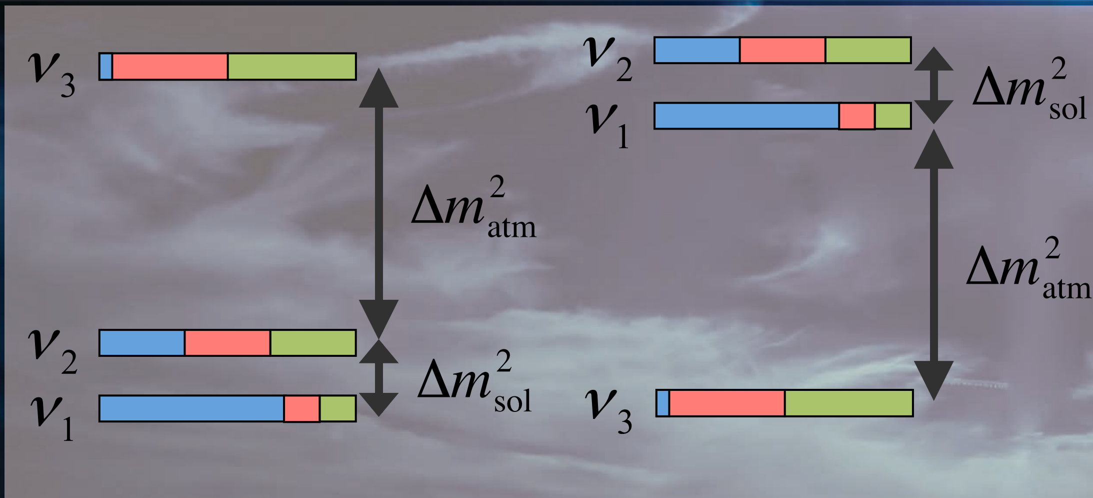
- What is the neutrino mass hierarchy?
  - Interesting for developing a model of neutrino mass.
  - Also has consequences for neutrinoless double beta decay and cosmological measurements.
- Are neutrinos *CP*-violating?
- Are there light sterile neutrinos?
- What are the absolute neutrino masses?
- Are neutrinos Dirac or Majorana?

Oscillation Experiments

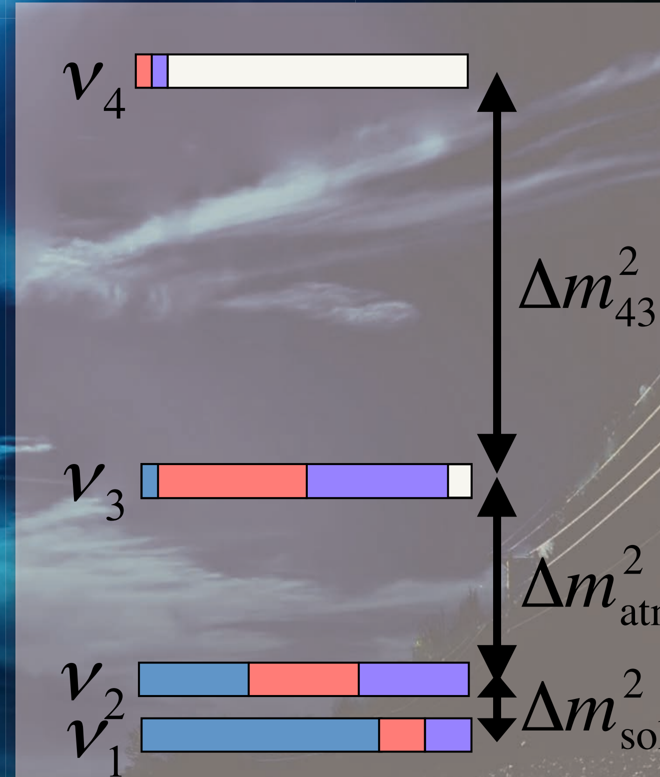
Direct mass measurements

Neutrinoless ββ decay

Neutrino Mass Hierarchy



Normal vs. Inverted Hierarchy



Sterile neutrino?

Reactor Oscillation experiments

- Current
- Daya Bay, RENO, Double Chooz
- First confirmed non-zero θ_{13}
  - Required for CP violation
- Measure anti-ν_e disappearance.
  - Measures θ_{13}
  - Competitive measurements of atmospheric (larger) Δm^2

- Future
- JUNO and RENO-50
  - Anti-ν_e disappearance, but at a longer baseline.
  - Precise measurements (<1%) of θ_{12}, and both Δm^2 values
  - Resolve the mass hierarchy
    - by precise measurement of the interference between "solar" and "atmospheric" oscillations

Long-baseline Oscillation experiments

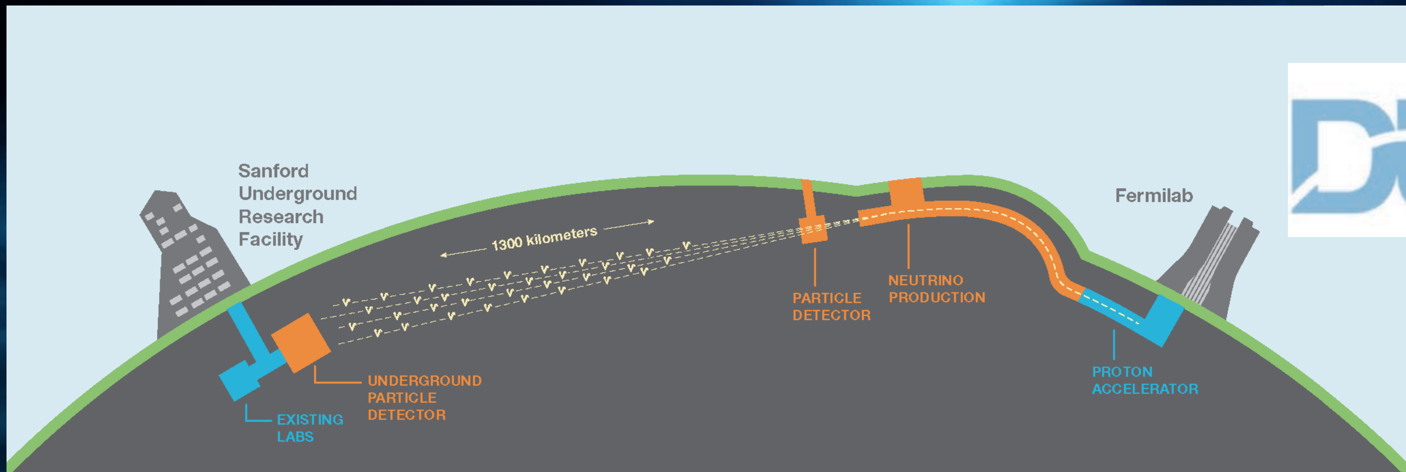
Current

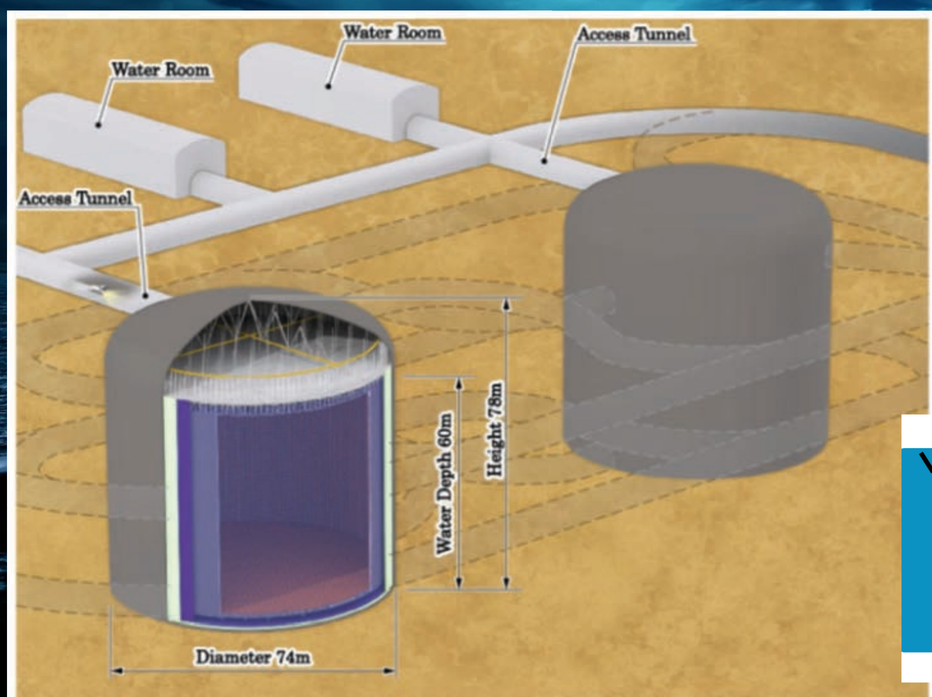
- NOvA & T2K
- Demonstrated appearance of a new flavor through oscillation.
- Measuring ν_μ disappearance, and $\nu_\mu \rightarrow \nu_e$ appearance.
  - Measurements of ϑ_{13}, ϑ_{23}, Δm^2
  - May resolve the mass hierarchy via matter effects in oscillations
    - Sensitivity depends on true oscillation parameter values.
  - Sensitive to δ_{CP} but not enough to exclude δ_{CP}=0 at 5σ.

• Future

- DUNE & Hyper-K
- Measuring ν_μ disappearance, and $\nu_\mu \rightarrow \nu_e$ appearance
  - Mass hierarchy w/confidence
  - *CP* violation at 5σ if it's there.
  - Precision atmospheric mixing parameters

DUNE & Hyper-K


Sanford Underground Research Facility
1300 kilometers
Fermilab
EXISTING LABS
UNDERGROUND PARTICLE DETECTOR
PARTICLE DETECTOR
NEUTRINO PRODUCTION
PROTON ACCELERATOR


Water Room
Water Room
Access Tunnel
Access Tunnel
Water Depth 60m
Height 78m
Diameter 74m

And more …

Neutrinoless ββ Decay

- SNO+, KamLAND-Zen, EXO, Majorana, GERDA, NEMO, CUORE…
  - Results now or in the very near future
- Double beta decay is proportional to the absolute neutrino mass and requires Majorana neutrinos
  - $\Delta m^2_{\beta\beta}$ also depends on oscillation parameters and mass hierarchy.
- Variety of detection techniques using different decaying isotopes.
- Current scale: 100's of kgs.
  - Many designed as upgradable to ton-scale
  - At ton-scale, should observe the decay *if* the hierarchy is inverted.

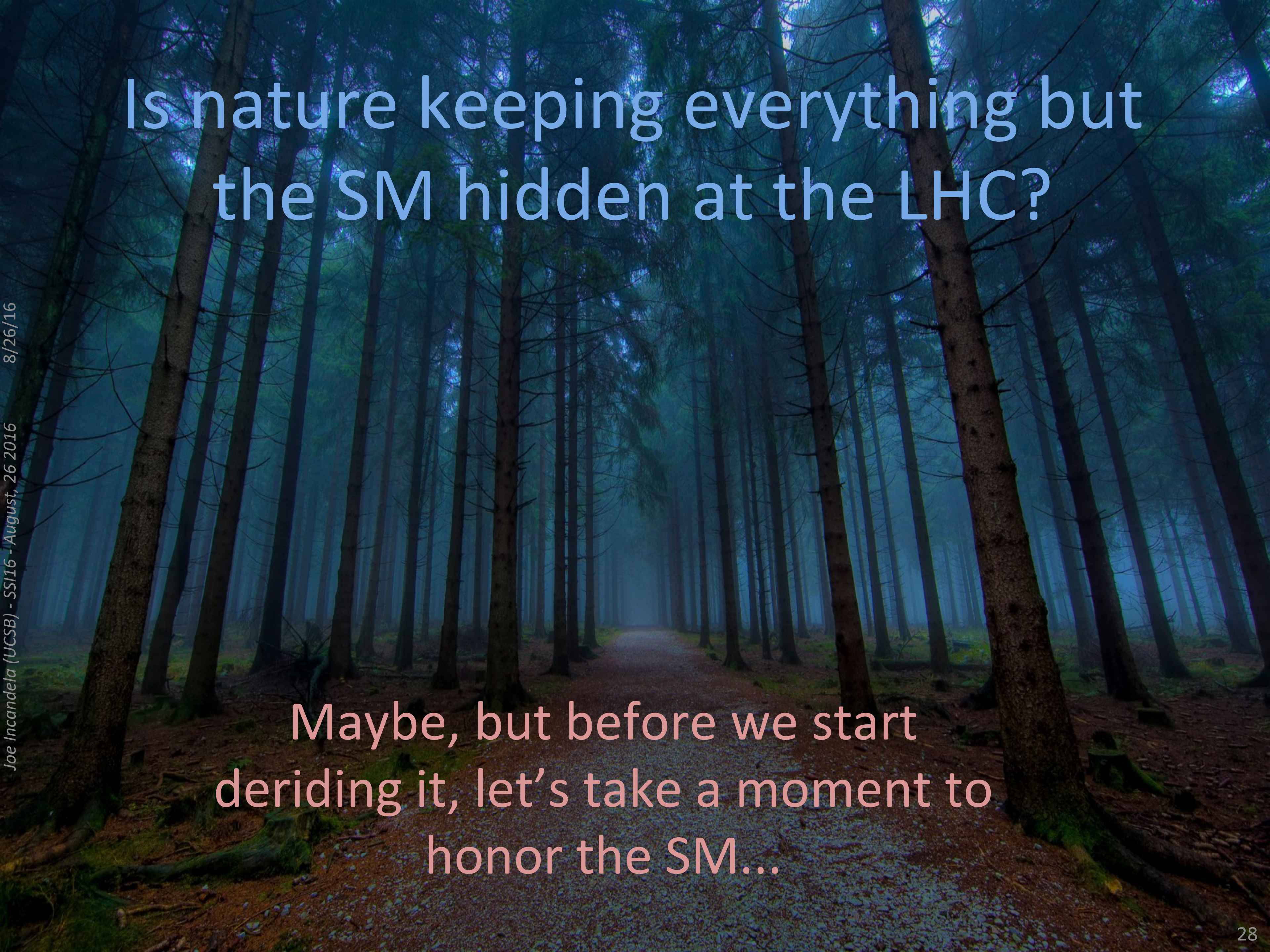
Direct mass measurements

- Tritium beta decay endpoint
  - Requires an extremely precise measurement of electron energy.
  - Current: Katrin
    - With a very large spectrometer
    - First results expected in ~2018
  - Future: Project 8
    - Measure electron cyclotron frequencies,
      - since we can make frequency measurements very precisely.
- Electron capture on Holmium
  - Future: NuMECS, Holmes, ECHo
    - Precise calorimetry is critical, as well as how Holmium is integrated into the detector.

The Road Ahead

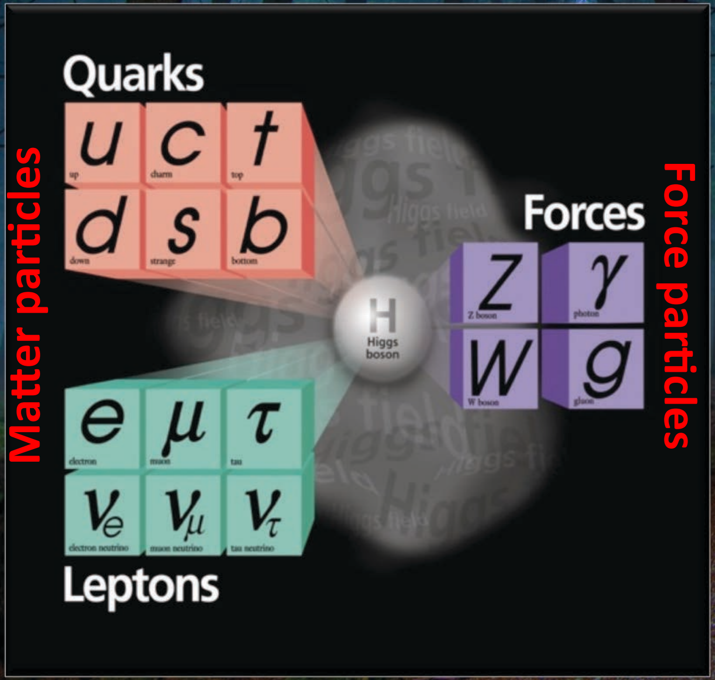
SM and Higgs

Is nature keeping everything but the SM hidden at the LHC?


Is nature keeping everything but the SM hidden at the LHC?
Maybe, but before we start deriding it, let's take a moment to honor the SM...

The Standard Model

- Over the last ~100 years: The discovery of many sub-atomic particles and advances in theoretical physics has led to **The Standard Model of Particle Physics**
- A "Periodic Table" of fundamental particles



Described by one simple equation!

$$\mathcal{L}_{SM} =$$

$$-\frac{1}{2}\partial_\nu g^a_\mu\partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu$$

$$-\partial_\nu W^+_\mu\partial_\nu W^-_\mu - M^2W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H - \frac{1}{2}m_h^2H^2 - \partial_\mu\phi^+\partial_\mu\phi^-$$

$$-M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h\left[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h$$

$$-igc_w\left[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)\right]$$

$$-igs_w\left[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)\right]$$

$$\frac{1}{2}g^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2\left(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu\right) + g^2s_w^2\left(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu\right)$$

$$g^2s_wc_w\left[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu\right] - g\alpha\left[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right]$$

$$-\frac{1}{8}g^2\alpha_h\left[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H$$

$$-\frac{1}{2}ig\left[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right] + \frac{1}{2}g\left[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right]$$

$$+\frac{1}{2}g\frac{1}{c_w}Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^-$$

$$-\phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2W^+_\mu W^-_\mu\left[H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2$$

$$2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+)$$

$$\frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1s_w^2A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda$$

$$\bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)]$$

$$\frac{ig}{4c_w}Z^0_\mu\left[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)\right]$$

$$\frac{ig}{2\sqrt{2}}W^+_\mu\left[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right] + \frac{ig}{2\sqrt{2}}W^-_\mu\left[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_jC^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right]$$

$$\frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}\left[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)\right] - \frac{g}{2}\frac{m_e^\lambda}{M}\left[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)\right]$$

$$\frac{ig}{2M\sqrt{2}}\phi^+\left[-m_d^\kappa(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right] + \frac{ig}{2M\sqrt{2}}\phi^-\left[m_d^\lambda(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right]$$

$$\frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^-$$

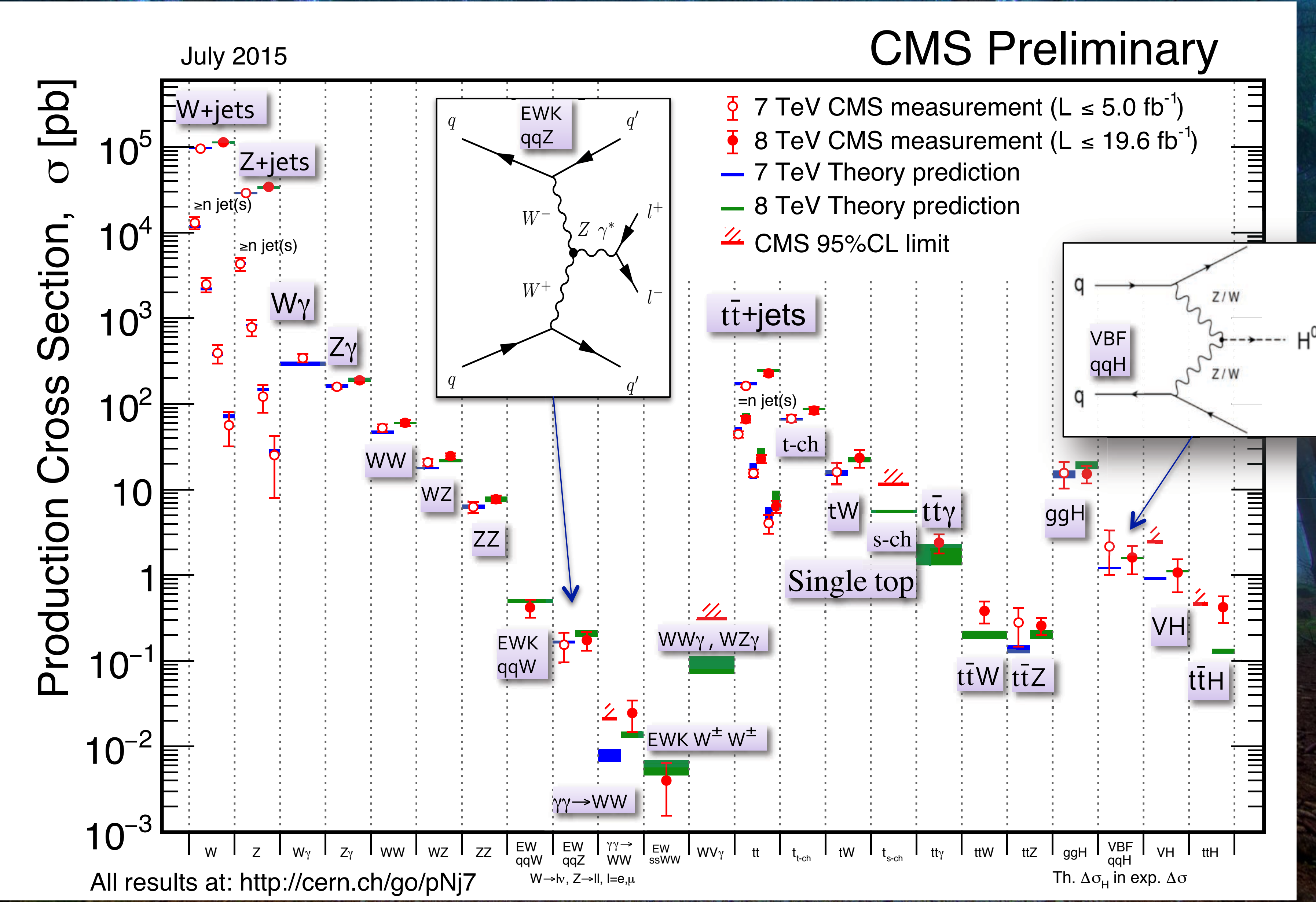
$$+\bar{X}^0\left(\partial^2 - \frac{M^2}{c_w^2}\right)X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+)$$

$$+igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H$$

$$+\frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-]$$

$$+\frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

Amazing breadth of results

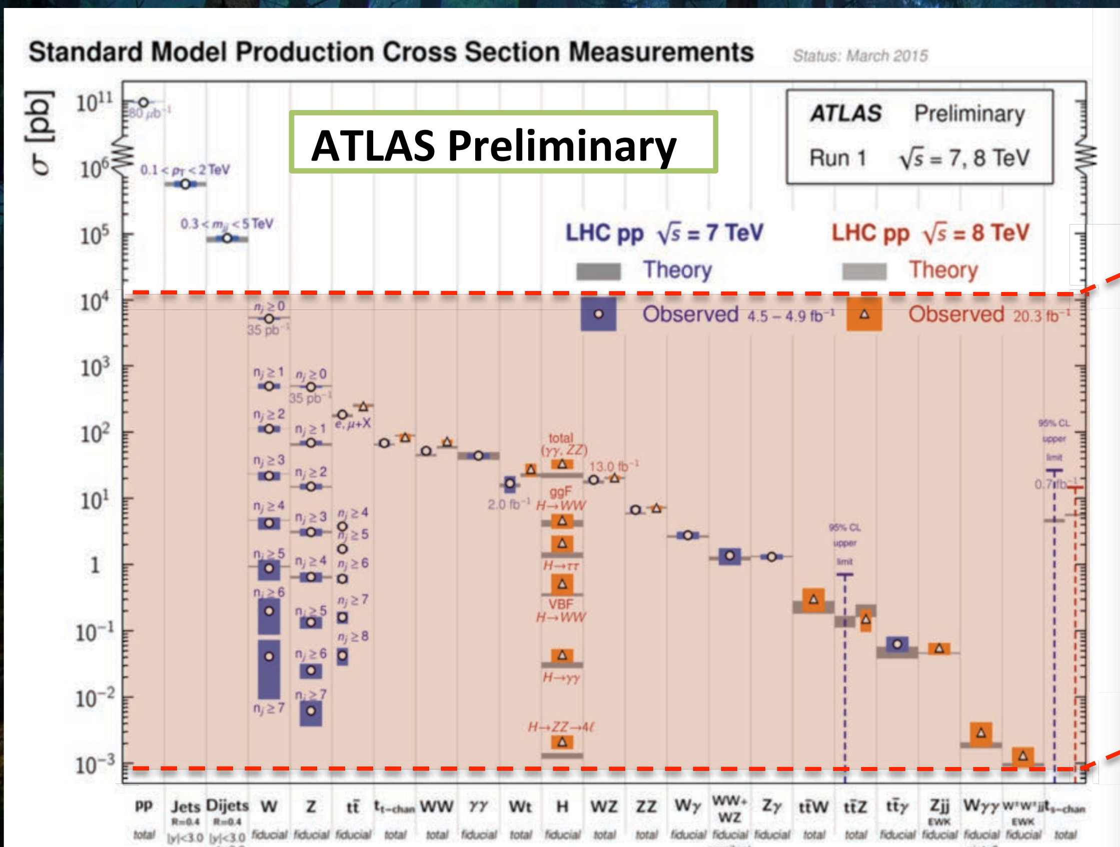


The `Next-to' revolution:

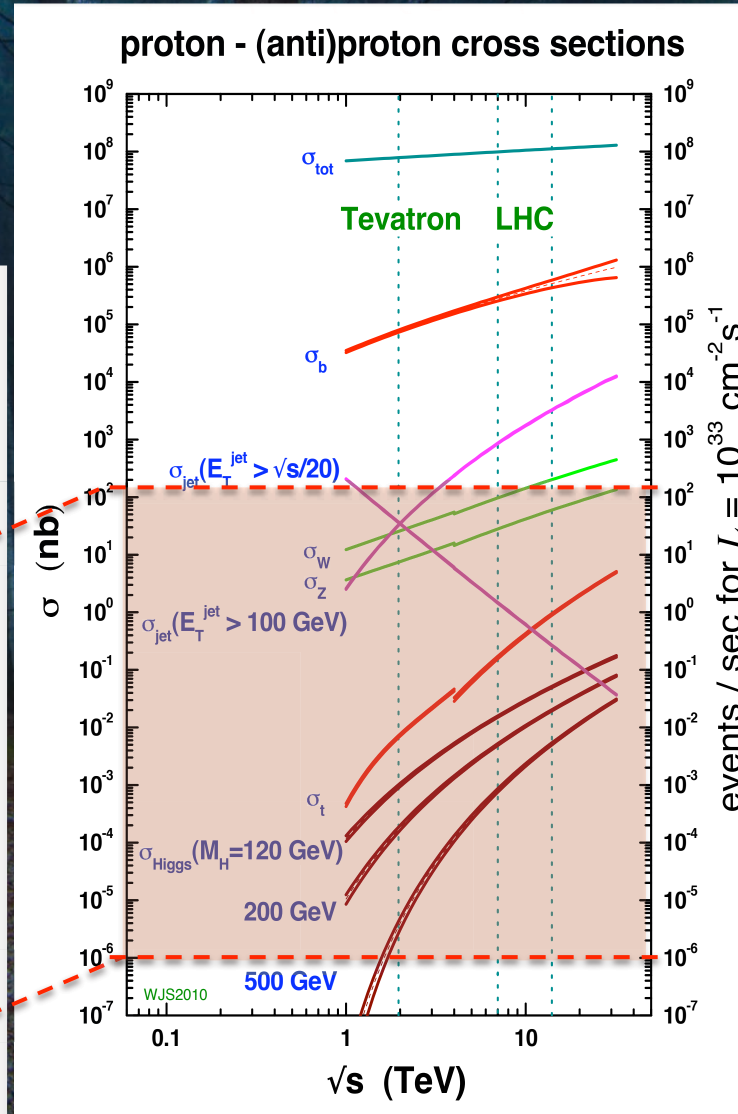
- SM Production, including Higgs
  - NLO, NNLO and recently N3LO
  - Parton Distributions at NNLO
- Thank you, theory community!

Precision over >8 orders

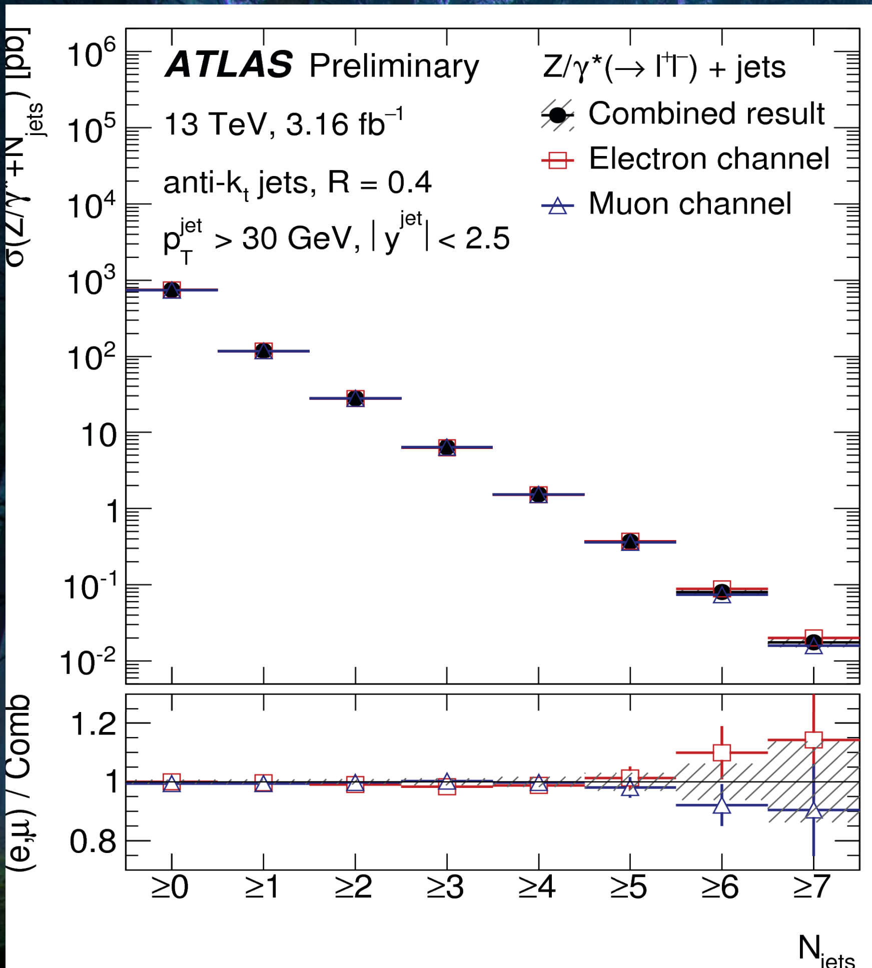
At a depth of 6 orders …

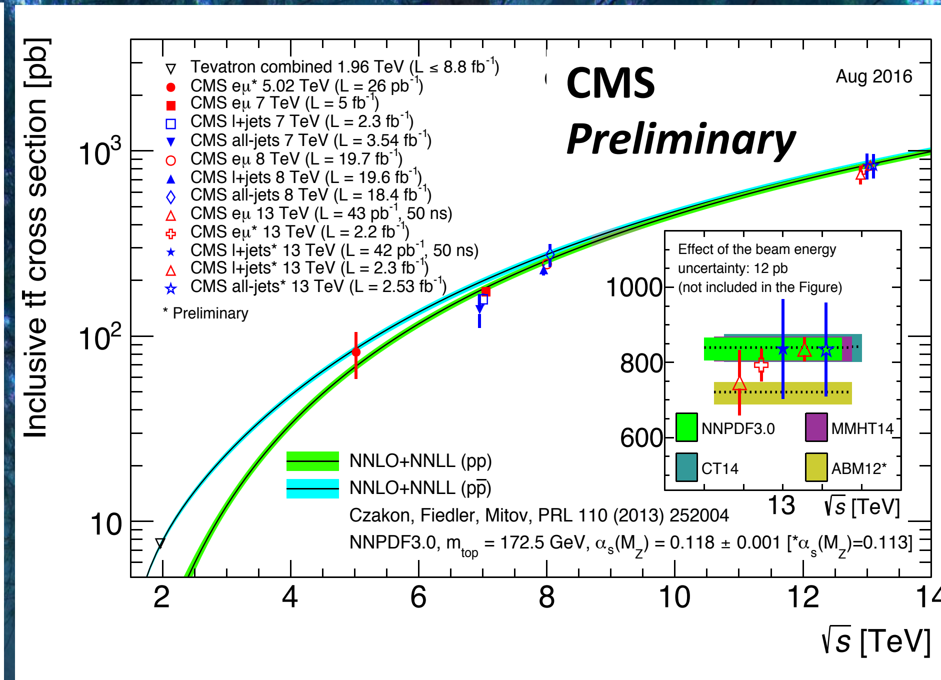


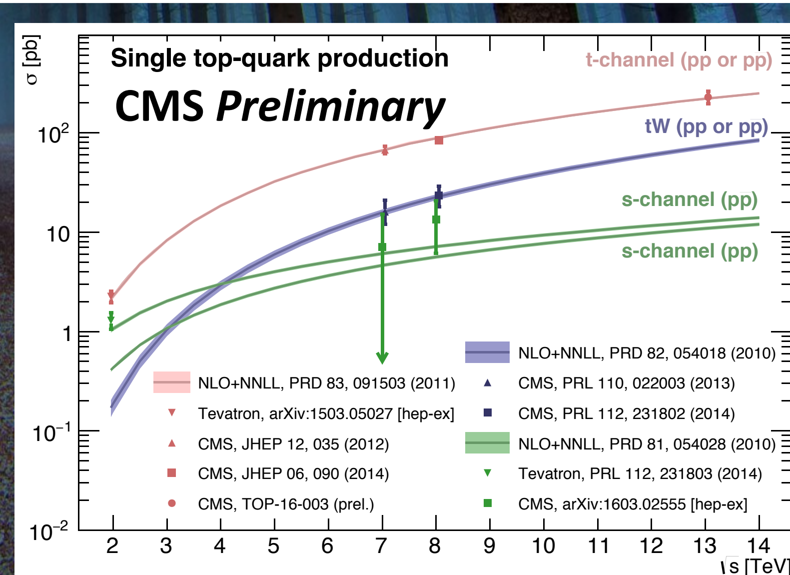
Adapted from a slide from Marumi Kado



√s=13 TeV, impressive speed to new results







The experiments are tackling relatively difficult measurements very early in Run 2

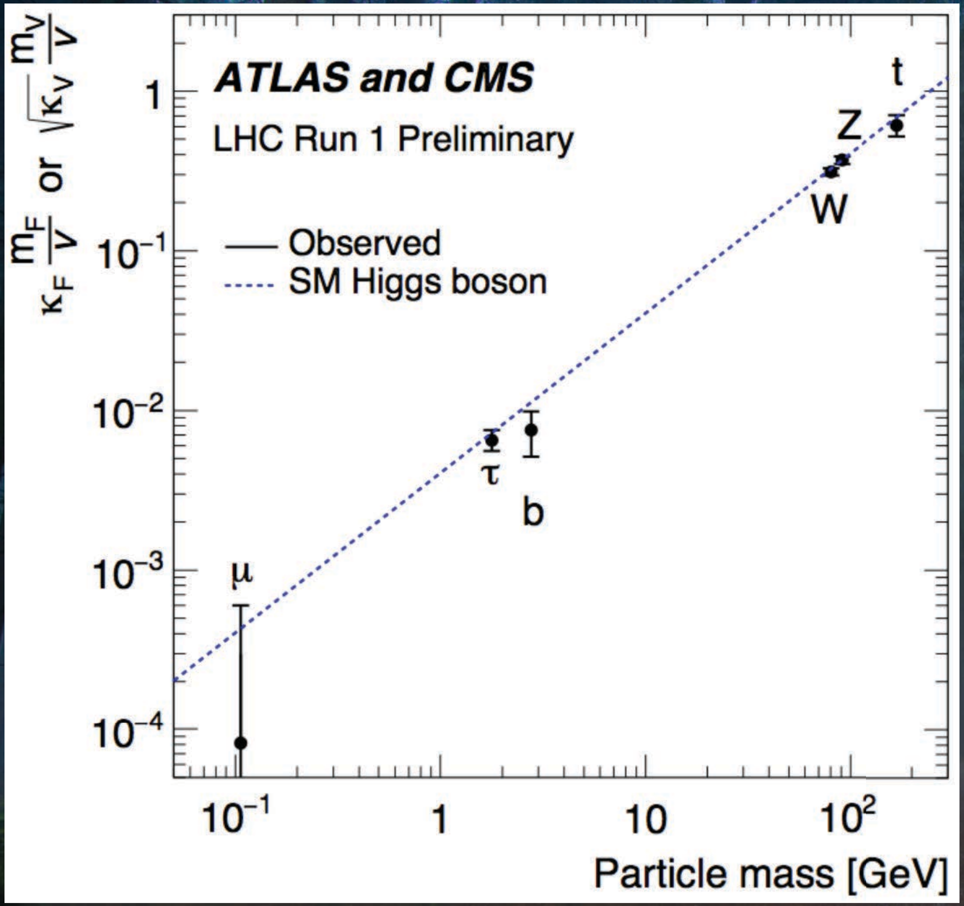
- Experienced and well understood detectors

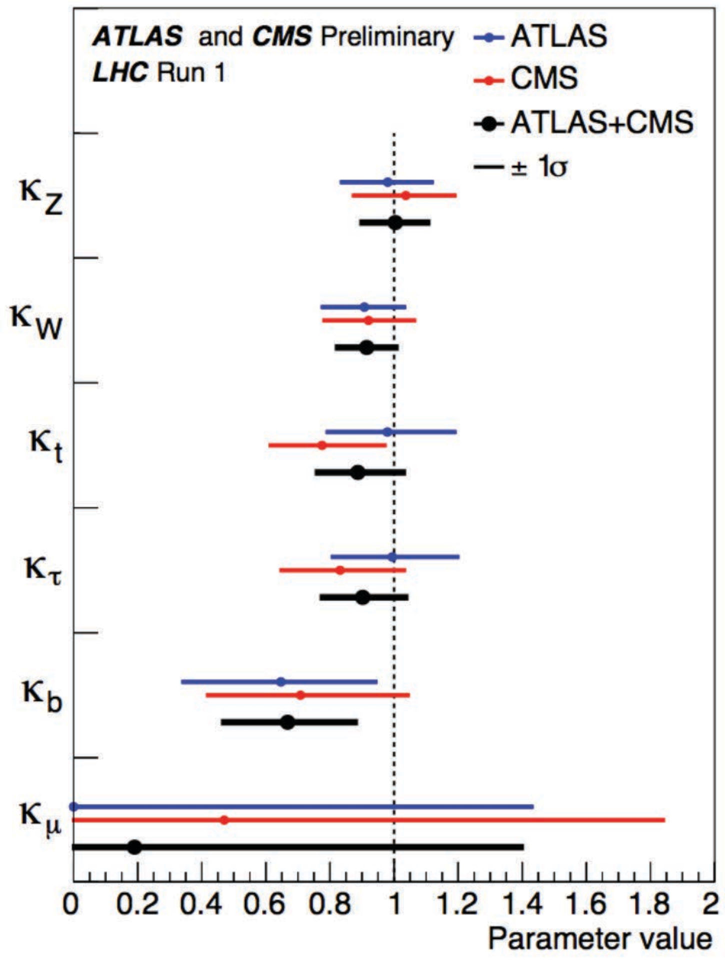
Et tu Brout Englert Higgs?

The `holy grail of physics’

Is it empty, or is there something inside?

H125 Couplings: ATLAS+CMS Run 1 Combo





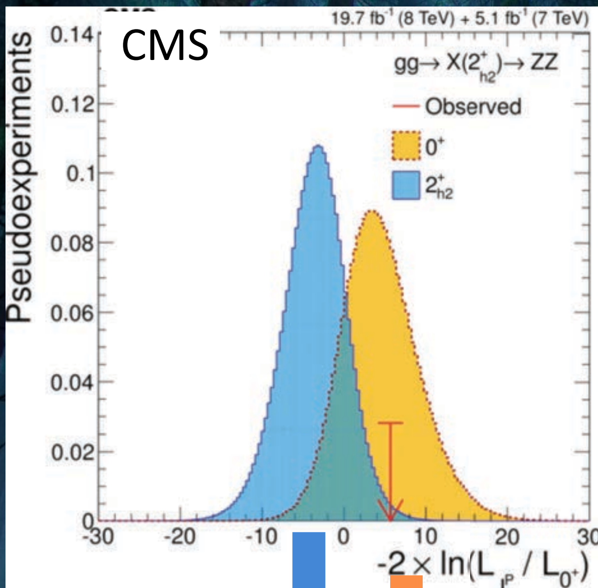
All compatible with SM Higgs expectations

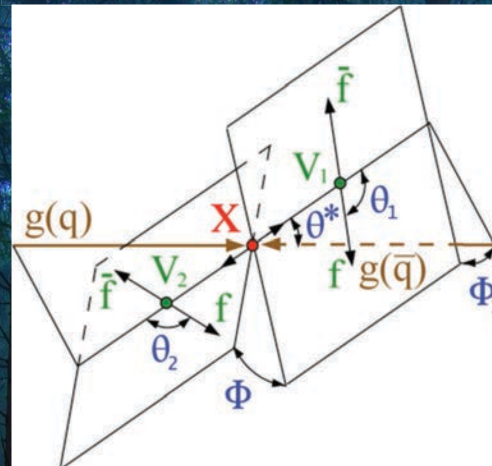
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

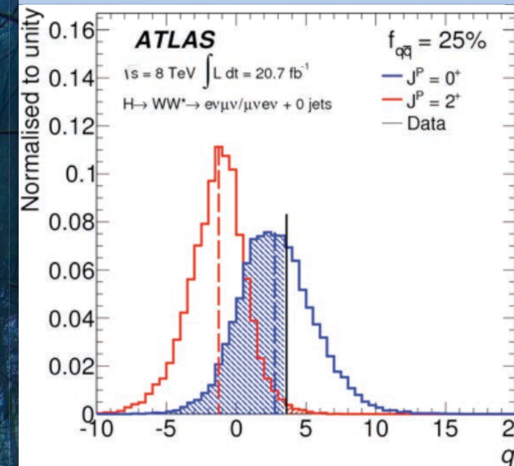
Spin-Parity

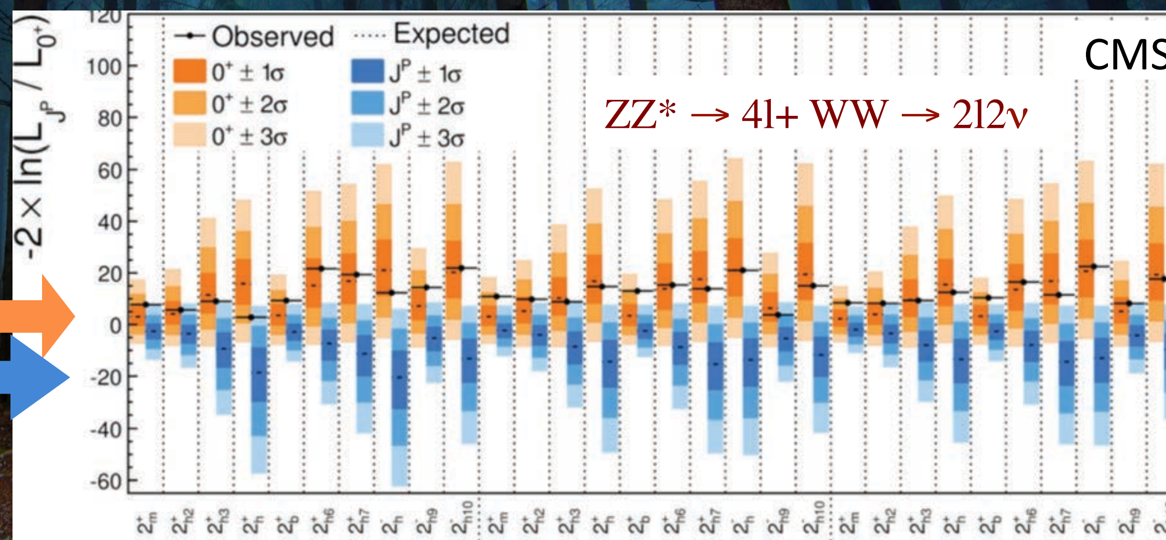
- H→ZZ* →4l:
  M_{Z1},M_{Z2}, 5 angles

- H → WW* →lνlν
  - $\Delta\phi_{ll}$, M_{ll} ..









ZZ* → 4l+ WW → 2l2ν

- H→ γγ
  - Spin 1 excluded (Landau Yang Thm)

Spin 2 Excluded > 99.9% CL

Big news week March 2013

Big news week March 2013

Big news week March 2013


SIMON FRASER UNIVERSITY
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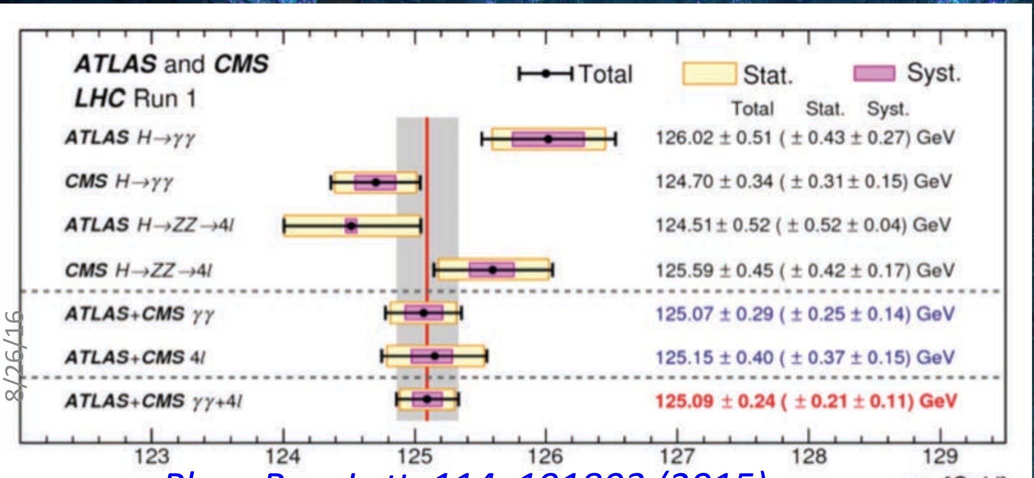
ISSUES AND EXPERTS

Higgs boson and new pope confirmed

March 14, 2013

Combined CMS+ATLAS Higgs Mass



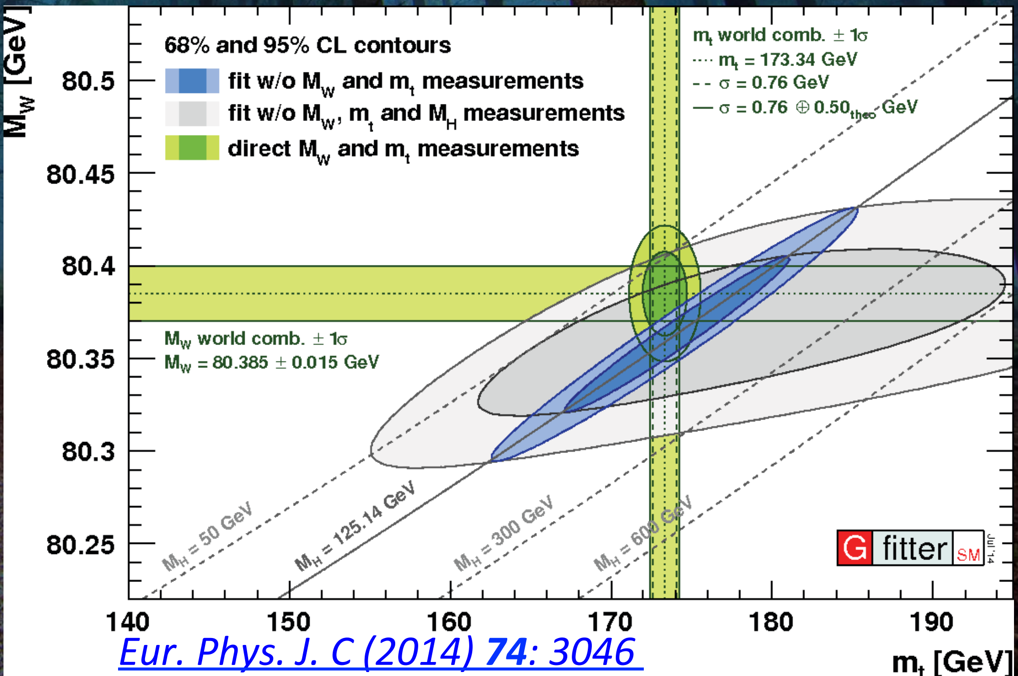
Phys. Rev. Lett. 114, 191803 (2015)

±0.2% uncertainty

125.09±0.24 (±.21 ±0.11) GeV

Global Electroweak fit is over-constrained with M_H known

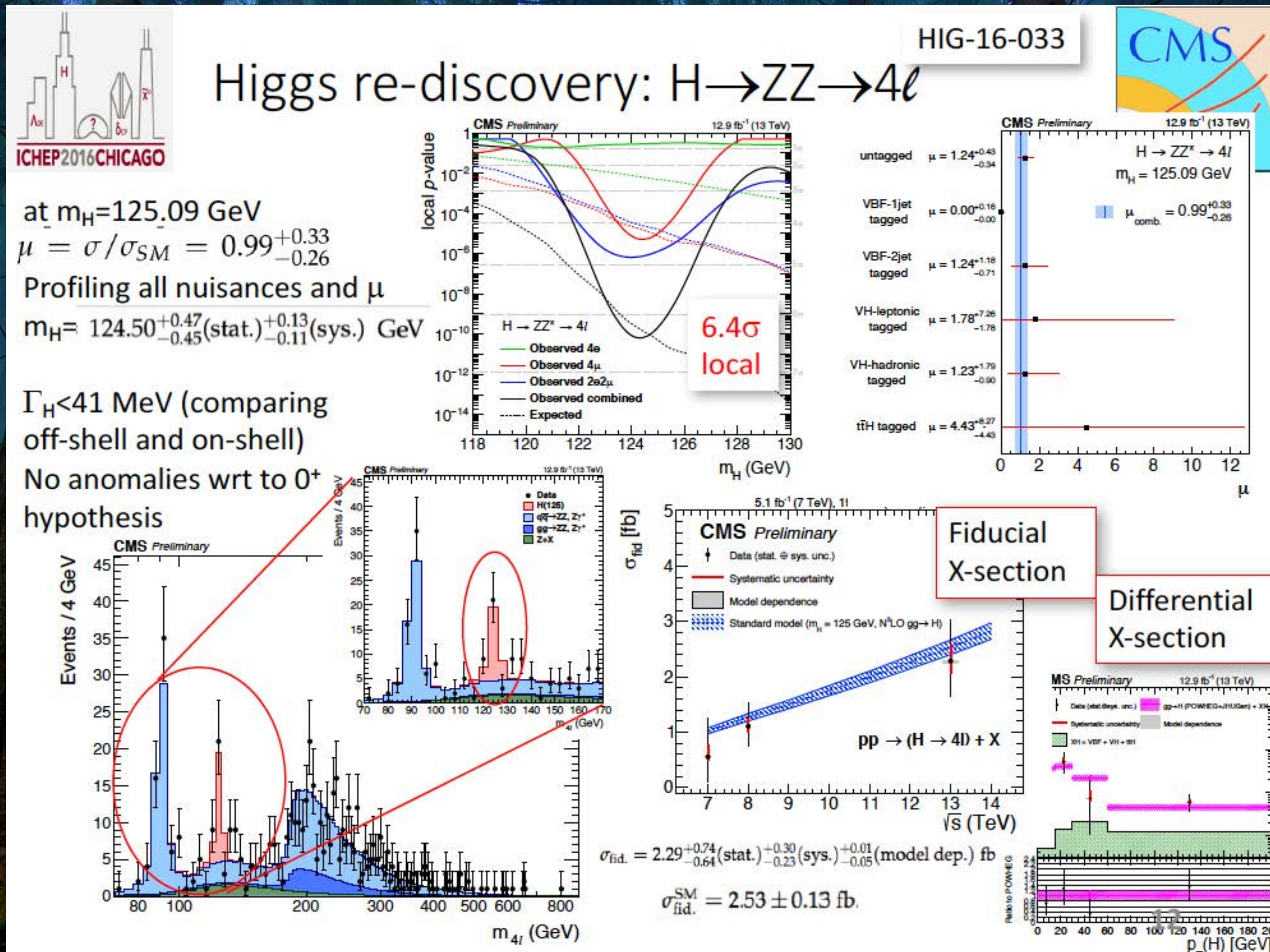
⇒ Check for self-consistency.



Eur. Phys. J. C (2014) **74**: 3046

The global electroweak fit (NNLO)

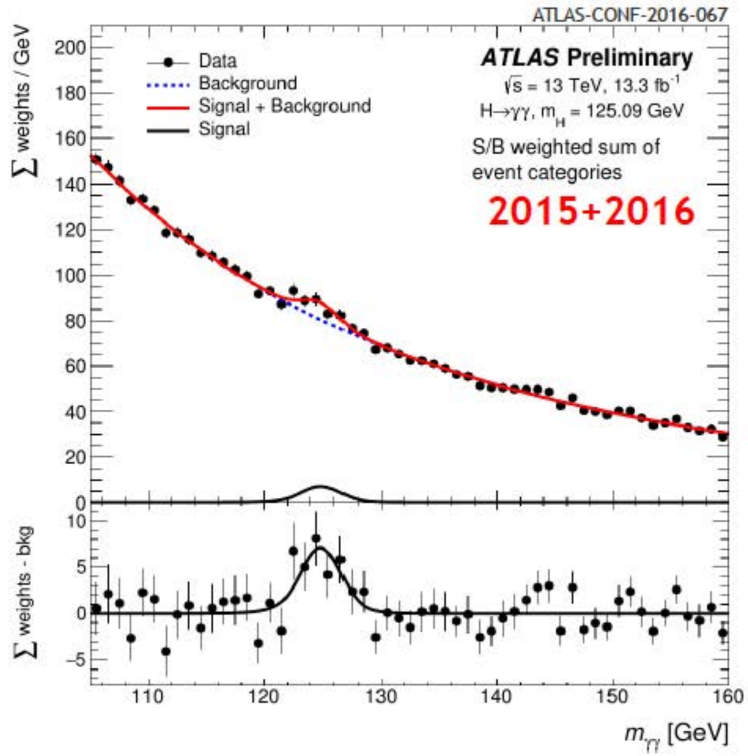
BTW: It's still there… $H \rightarrow ZZ^* \rightarrow 4\ell$ at $\sqrt{s}$=13 TeV



*Tiziano Camporesi – ICHEP 2016

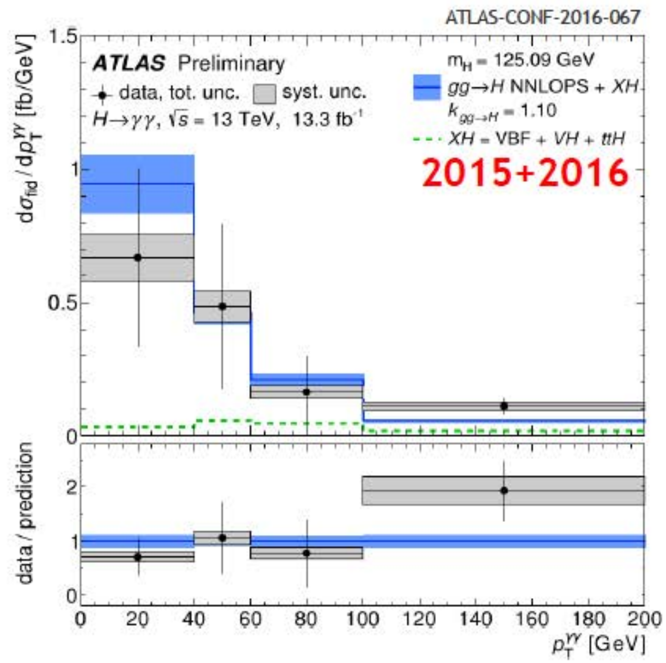
And H→γγ at √s=13 TeV

H→γγ



Event categories enhance sensitivity and help separate production modes

- Clear signal, rate consistent with SM H expectation
- Fiducial and differential cross-section measurements



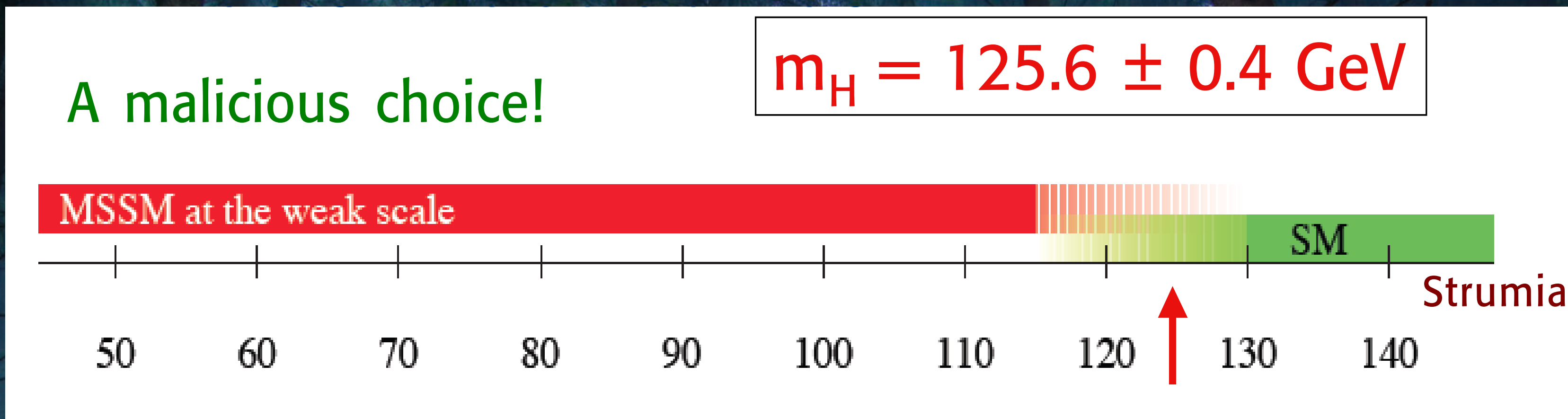
$$\sigma_{\text{fid}} = 47.0 \pm 13.9\,(\text{stat.}) \pm 5.4\,(\text{syst.})\ \text{fb}$$

SM prediction $62.8\,^{+3.4}_{-4.4}$ fb

D Charlton / Birmingham - 8 August 2016, ICHEP Chicago 16

*Dave Charlton – ICHEP 2016

As expected?*



Nobel Symposium,
May 12-17,2013 Uppsala

*G. Altarelli: https://indico.cern.ch/conferenceDisplay.py?confId=239571

Getting to know the Higgs…

The precise measurements of Higgs couplings are crucial in order to determine to what extent it is SM

Contino

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 \ldots$$

$$- \left(m_W^2 W_\mu W_\mu + \frac{1}{2}m_Z^2 Z_\mu Z_\mu\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right)$$

$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}} \bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + c_{2\psi}\frac{h^2}{v^2} + \ldots\right) + \ldots$$

a ~ hVV
c ~ hff

It would really be astonishing if no deviation from the SM is seen!

*G. Altarelli: https://indico.cern.ch/conferenceDisplay.py?confId=239571

Naturalness out the window?

The Higgs:
so simple yet so unnatural

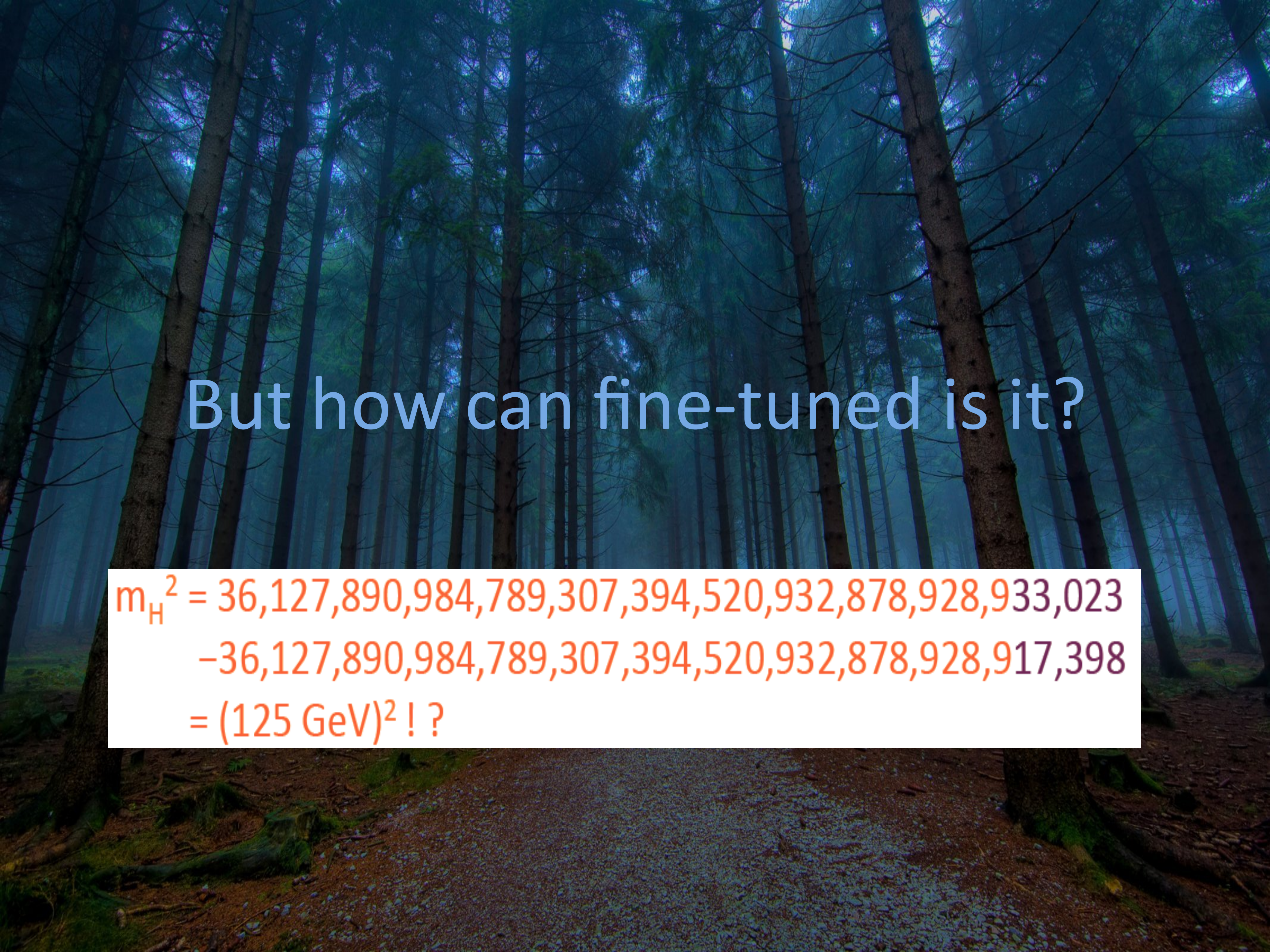
Guido Altarelli

The crisis of the naturalness principle

Has been and is the main motivation for new physics at the weak scale

But at present our confidence on naturalness as a guiding principle is being more and more challenged

**G. Altarelli: https://indico.cern.ch/conferenceDisplay.py?confId=239571*



But how can fine-tuned is it?

$$m_H^2 = 36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}933{,}023$$

$$-36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}917{,}398$$

$$= (125\ \text{GeV})^2\ !\ ?$$


Multiverse?

Future LHC Higgs Measurements

Observable number of Higgs events per LHC experiment through High Lumi (HL) period

	2013	**~2018**	**~2024**	**~2037**
$H \to ZZ^* \to 4\ell$	20	120	450	4,000
$H \to \gamma\gamma$	350	4,000	15,000	130,000
$H \to \tau\tau$ (VBF)	50	700	2,600	20,000

H125@HL-LHC

- Run 1 precision 20-50% on μ (10-25% on couplings)
- Need ~3% to probe TeV particles in loops

Deviation of Higgs couplings from SM due to particles with M~1 TeV

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

HL-LHC 3000 fb^{-1} Higgs physics:

- Most couplings with 2 - 8% ⇒ x3 improvement from 300 fb^{-1} LHC results
- Access to important rare decays

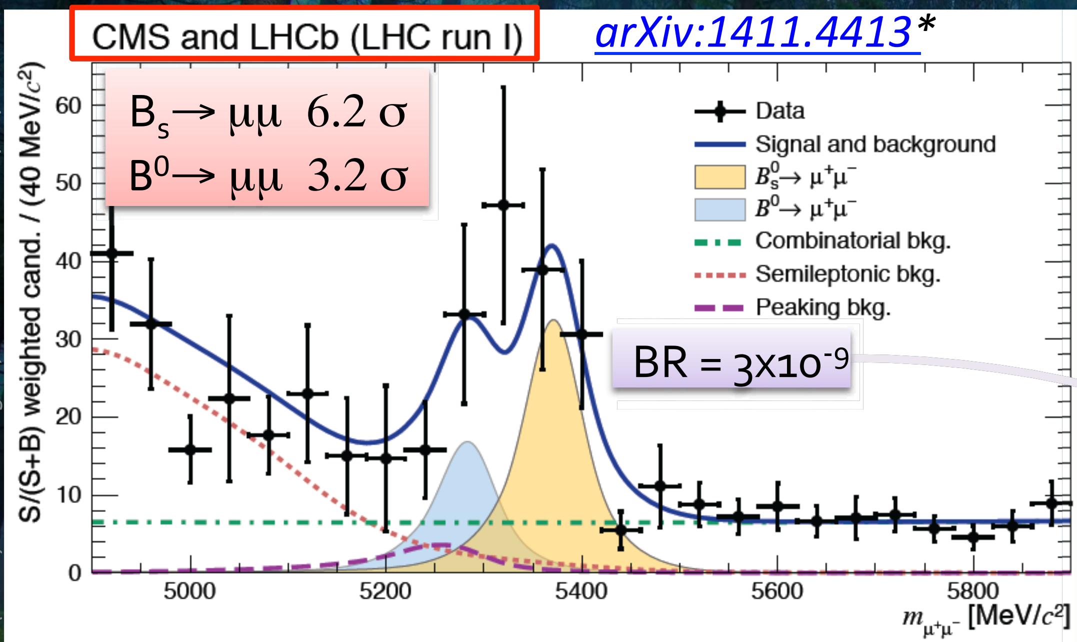
CMS projections for coupling precision (*arXiv:1307.7135*)

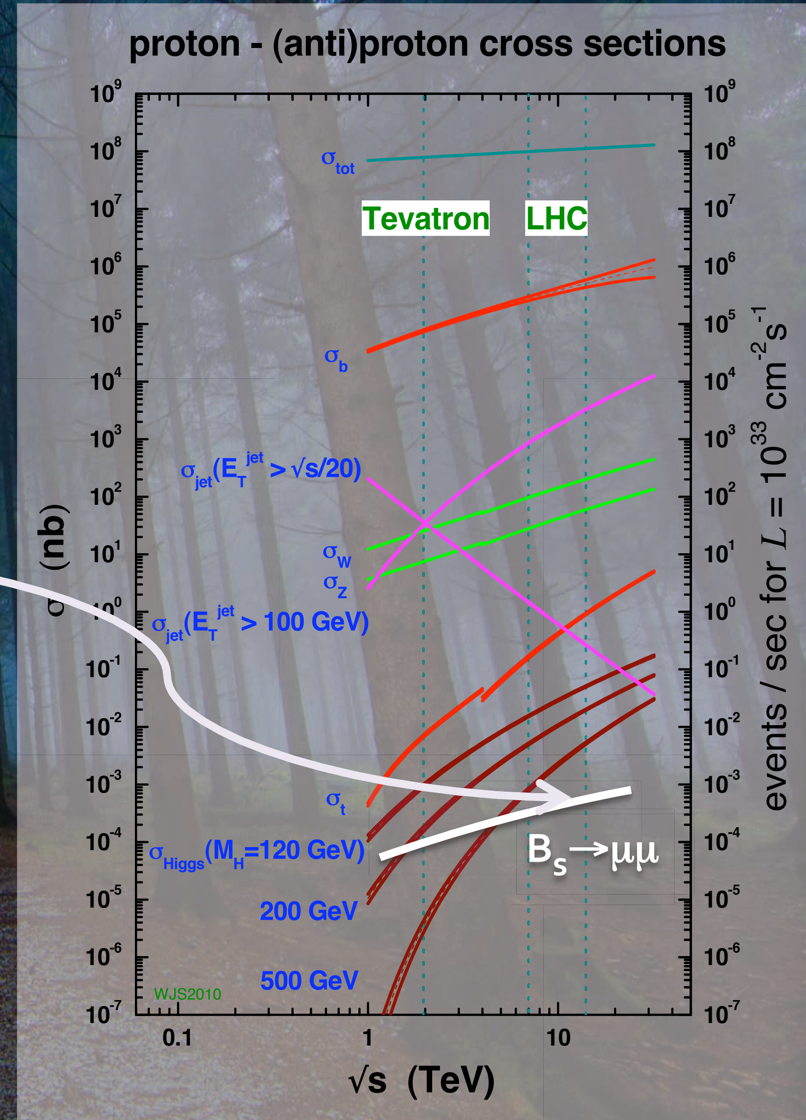
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

Higgs Snowmass report (arXiv:1310.8361)

After 30 years of searching B → μμ

B → μμ



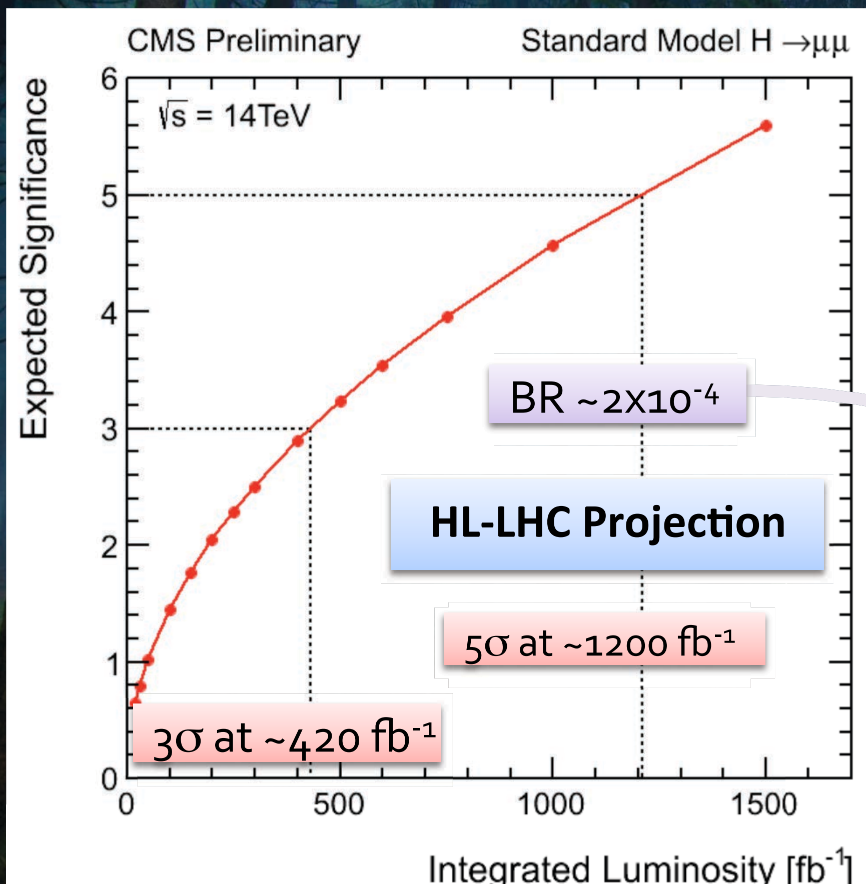


*Published in Nature

**Significance calc. using Wilks' theorem: Ratio of Branching Fractions compatible with SM at 2.3 σ

And even more rare…

$H \rightarrow \mu\mu$

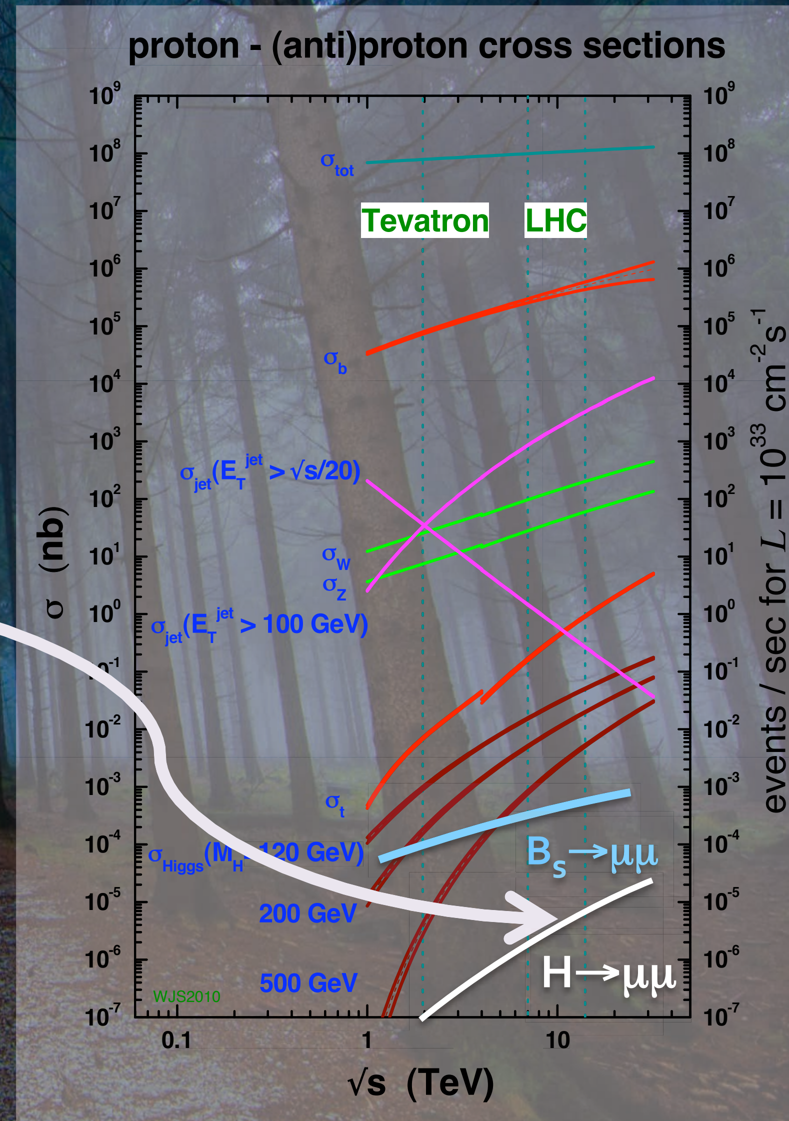


BR ~2x10^{-4}

HL-LHC Projection

5σ at ~1200 fb^{-1}

3σ at ~420 fb^{-1}



Top and Higgs

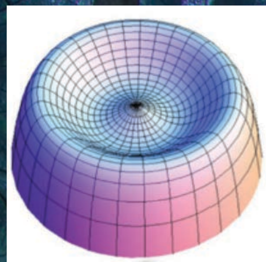
…all models of new physics ... must contain… partners of the top quark. In the most important models, including supersymmetry and models with new space-time dimensions, it is the coupling of the Higgs fields to the top quark and its partners that causes the Higgs field to develop a symmetry-breaking value in all of space.

Physics Case for the ILC

arXiv:1506.05992v2

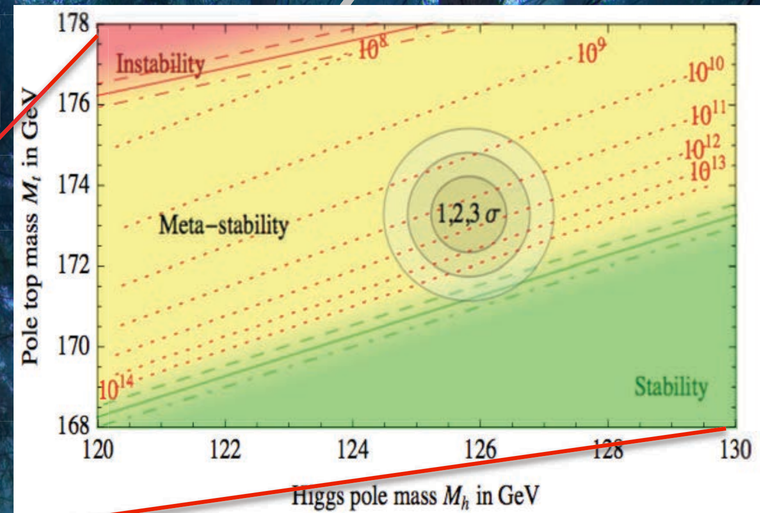
LHC should see $t\bar{t}H$ within a few Halloween's …

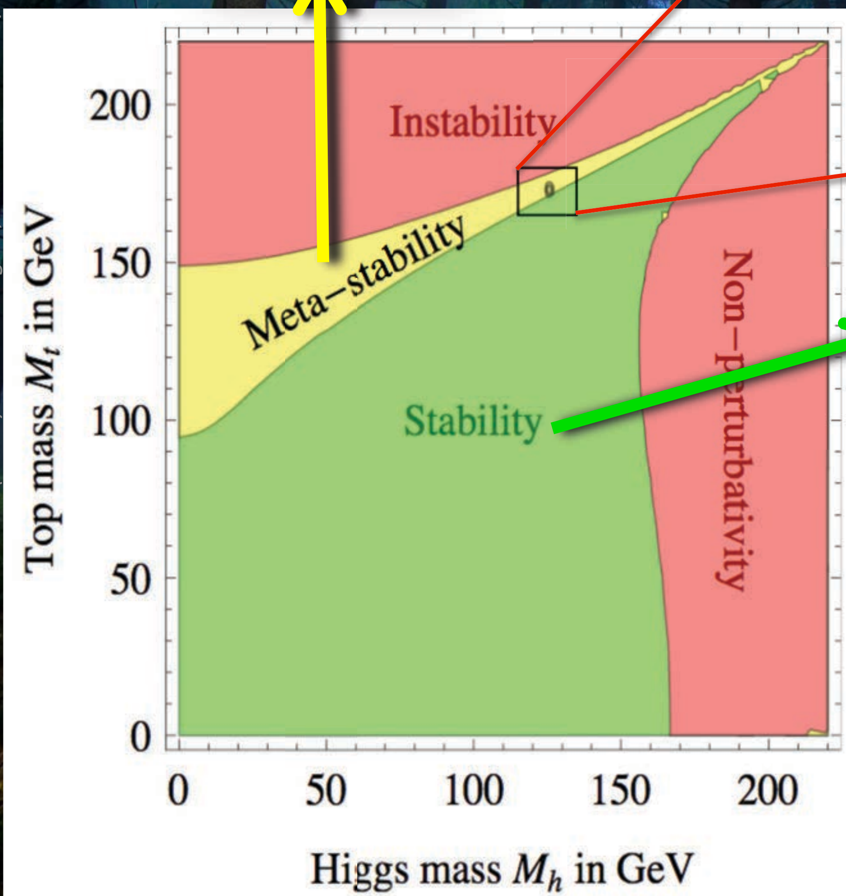
Near-criticality

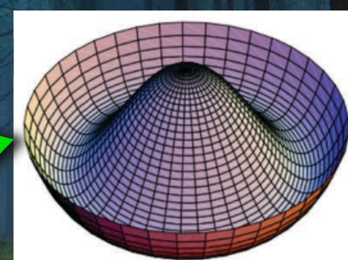


m_{top} ~ 173 GeV

m_H ~ 126 GeV







Slide adapted from A. Strumia, Moriond EWK 2013

Near-criticality

m_{top} ~ 173 GeV

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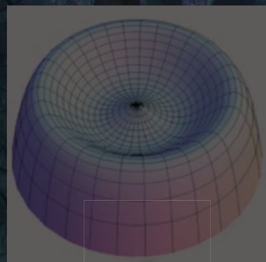
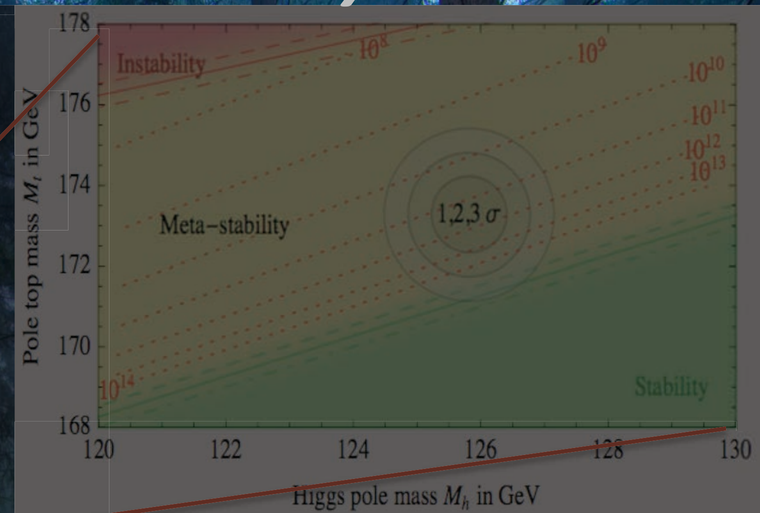
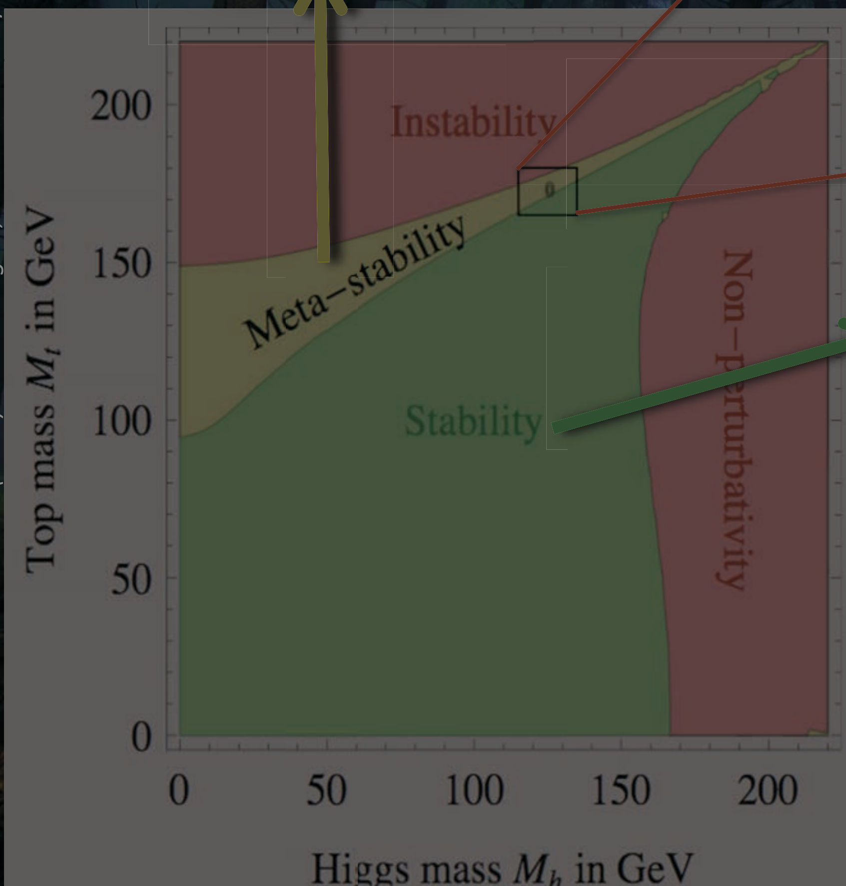
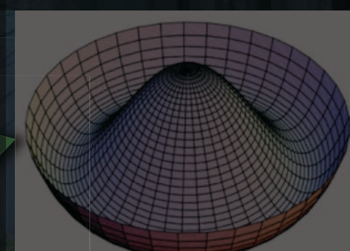
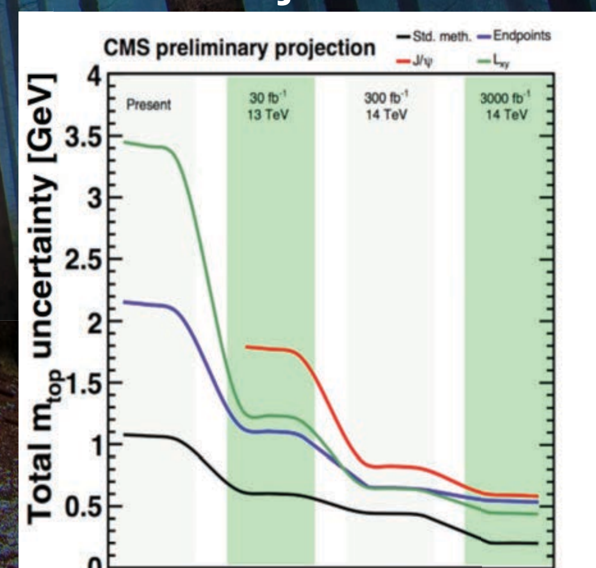








HL-LHC Projection



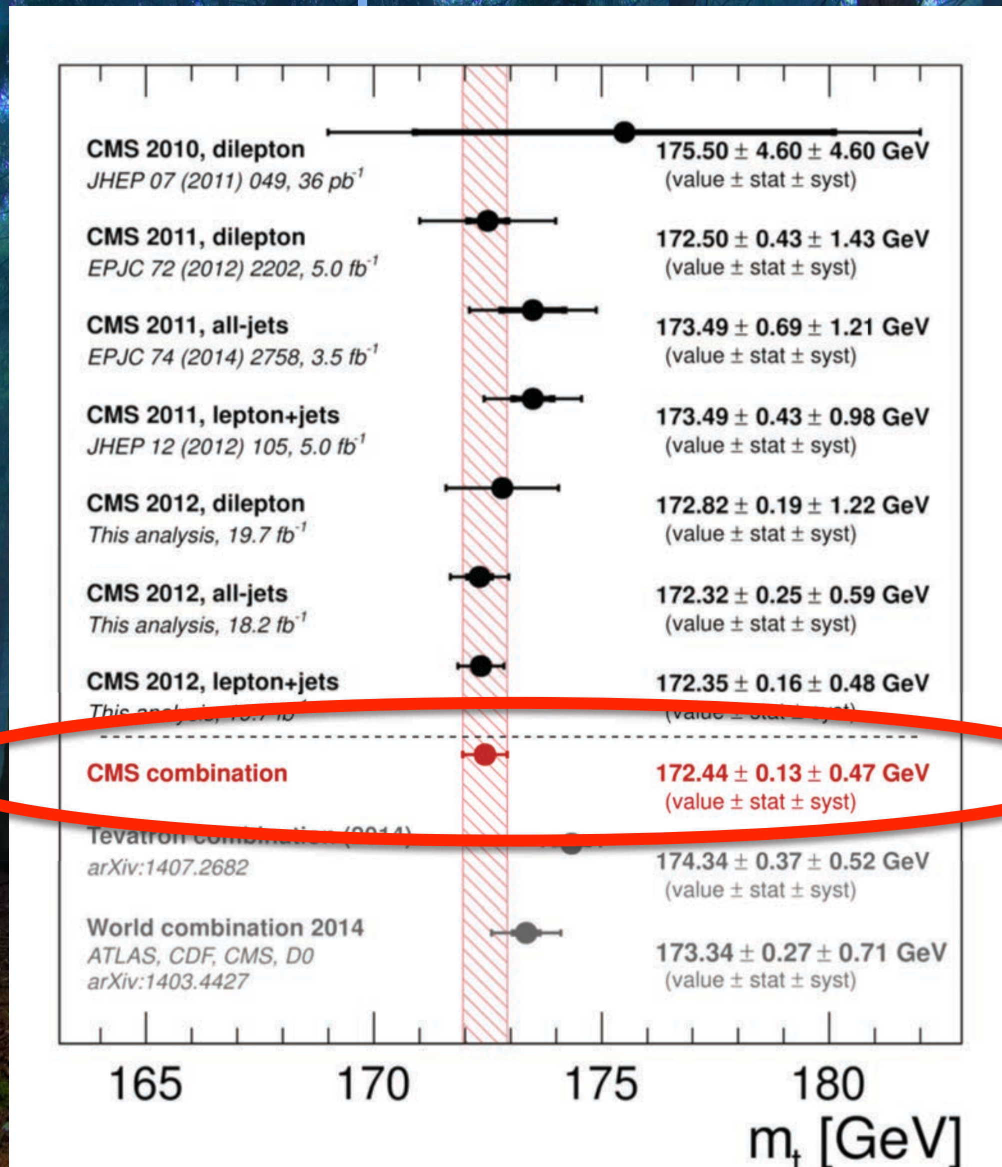
CMS-PAS-FTR-13-017

$3\ ab^{-1}$	Per expt.
Δm_t	~ 200 MeV
Δm_H	~ 50 MeV
Δm_W	< 10 MeV ?
$\Delta \Gamma_H$	< 10 MeV?

Slide adapted from A. Strumia, Moriond EWK 2013

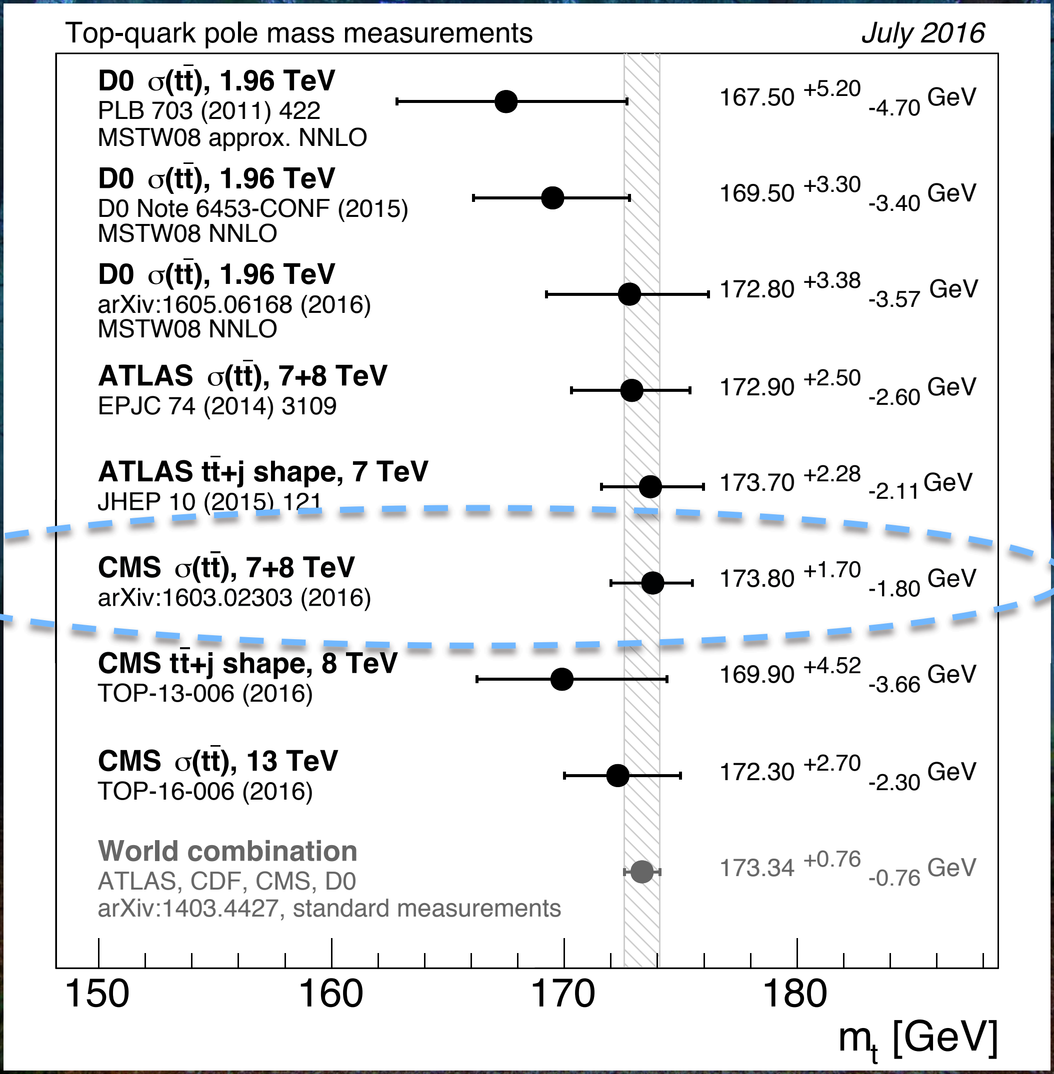
Top Mass

Extremely precise!



If only we knew what it is that we're measuring !

Top mass from $t\bar{t}$ cross-section



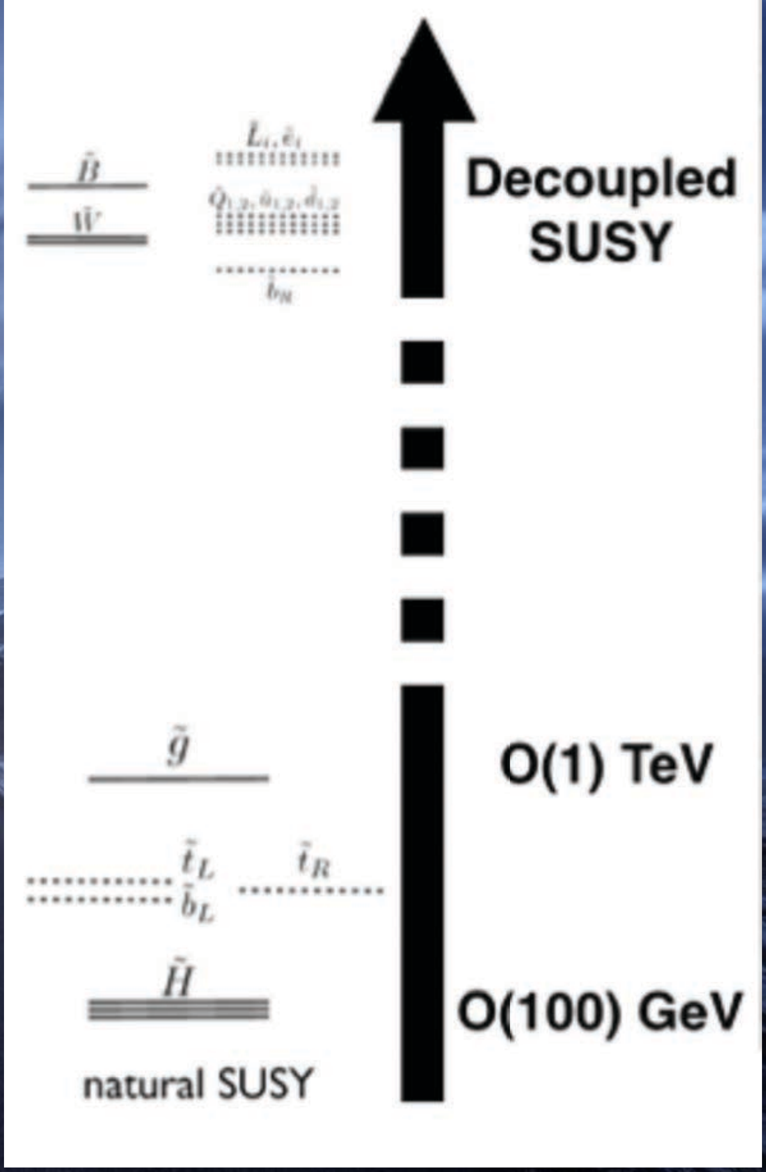
173.8 $^{+1.7}_{-1.8}$ GeV

Need much greater precision, ultimately

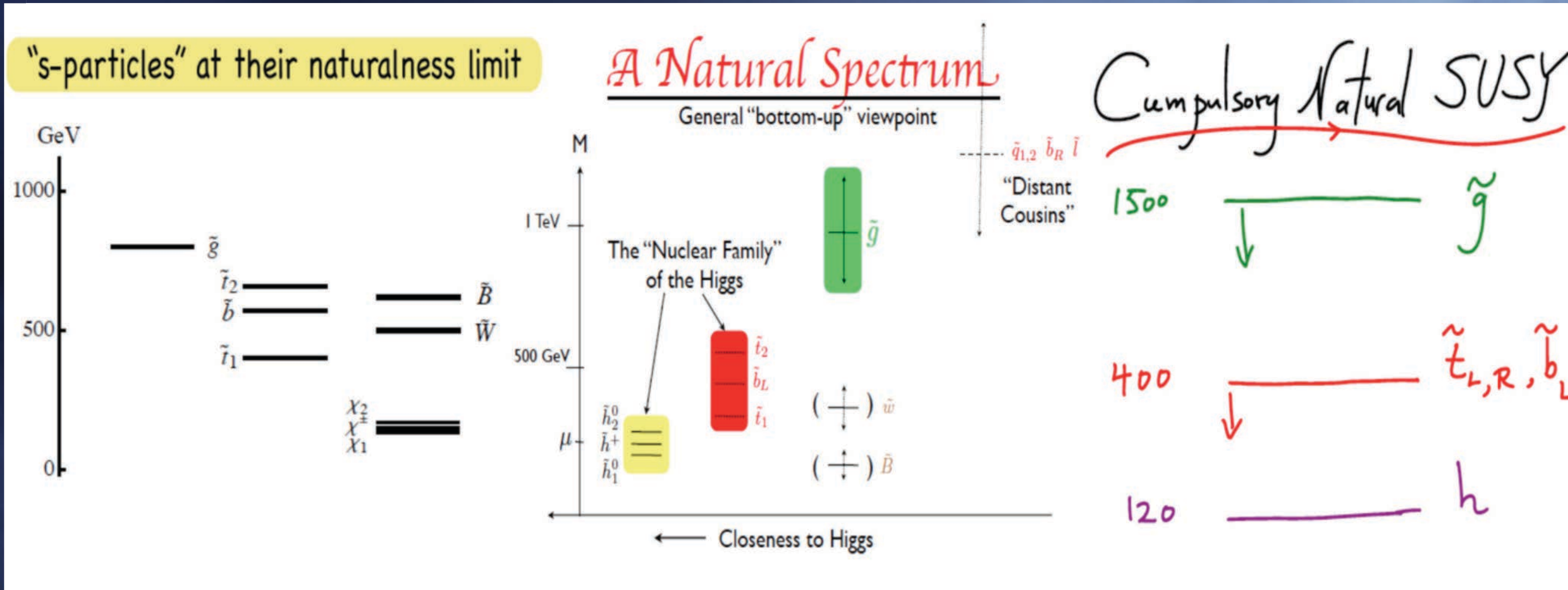
Beyond the SM

Focus is now (mostly) on natural SUSY

- 7 TeV limits indicated that much of the spectrum is decoupled
  - 1st and 2nd generation s-quarks, now swept to high mass scales
    - Also necessary in order to avoid things known not to be there
      - i.e. flavor changing neutral currents (FCNC) & electric dipole moments (EDM)
- To address the hierarchy problem, part of the spectrum must remain light
  - Which s-particles remain light and how light they remain varies with the details of the SUSY Model and its parameters



Partners to 3rd generation and Weak bosons



- SM particles that couple most strongly to the Higgs are key
  - Residual differences - e.g. between the mass of the top and those of s-tops – produce residual fine-tuning
    - Fine-tuning is reduced from a part in 10^{34} to a part in $\sim 10^{1} – 10^{3}$ provided the stop masses are not too large … and depending on model and parameters

See for instance: P. Lodone arXiv:1203.6227v2

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

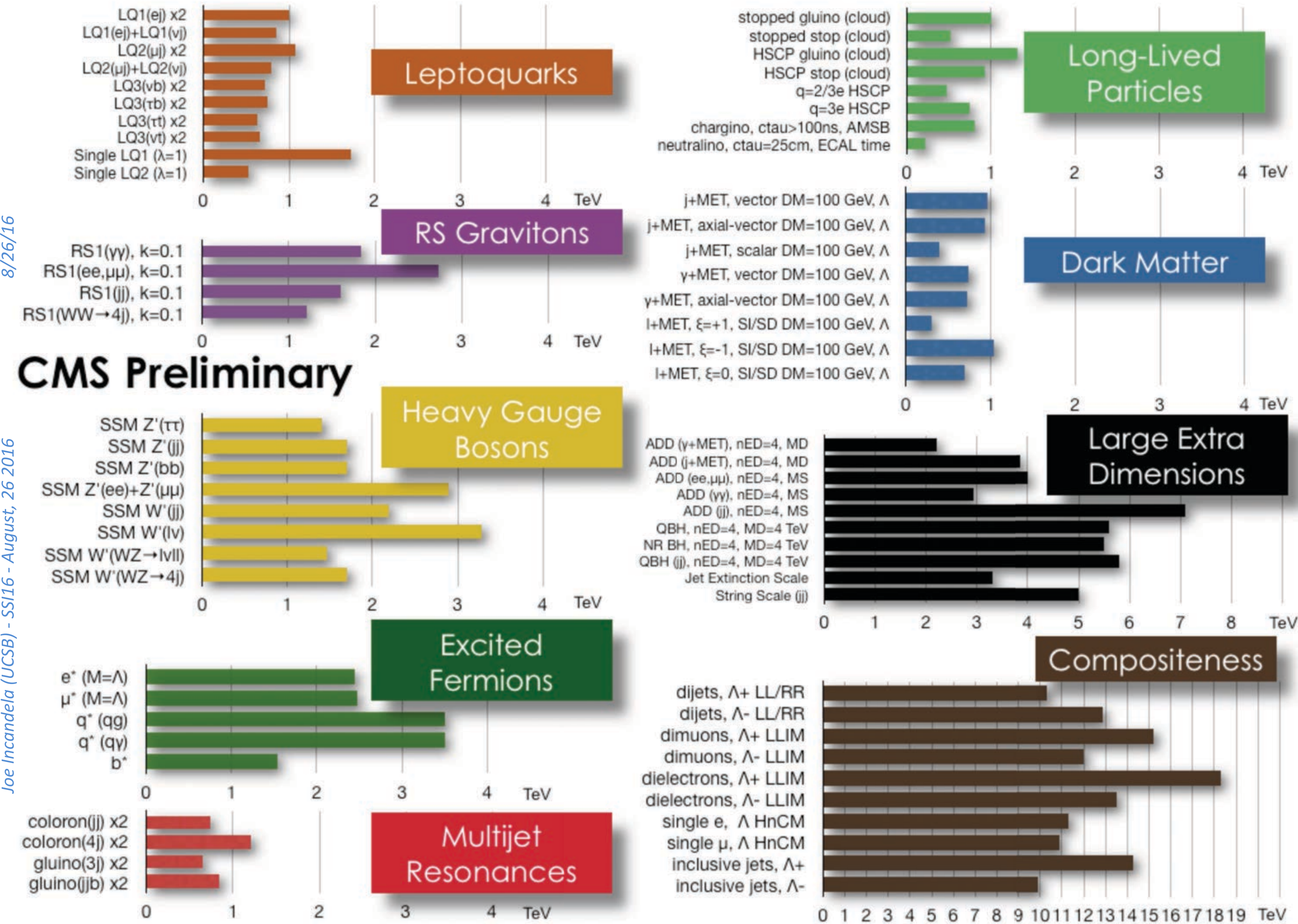
$\sqrt{s}$ = 7, 8 TeV

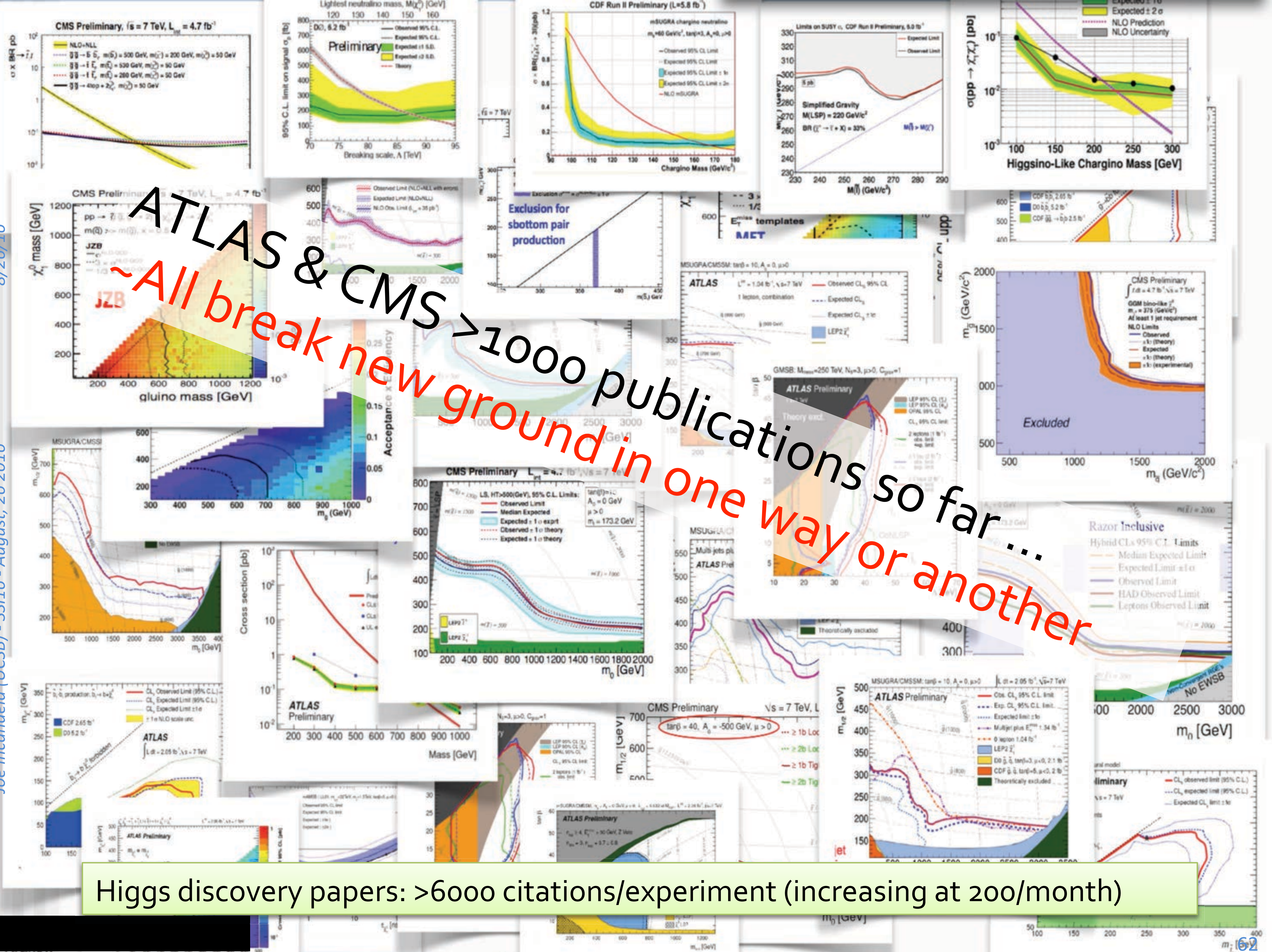
$\sqrt{s}$ = 7 TeV | $\sqrt{s}$ = 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$	1.8 TeV	$m(\tilde{q})$=$m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(1^{st}$ gen. $\tilde{q})$=$m(2^{nd}$ gen. $\tilde{q})$	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$	100-440 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<10 GeV	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$	780 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1503.03290
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0-1 e,μ	2-6 jets	Yes	20	$\tilde{g}$	1.26 TeV	$m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	1507.05525
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$	1.32 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$	1.25 TeV	$m(\tilde{\chi}_1^0)$<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	850 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	$m(\tilde{G})$>1.8×10^{-4} eV, $m(\tilde{g})$=$m(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$	275-440 GeV	$m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$	110-167 GeV; 230-460 GeV	$m(\tilde{\chi}_1^{\pm})$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$	90-191 GeV; 210-700 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	700 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	420 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	250 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$	124-361 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$	482 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$	1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})$+$\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	435 GeV	2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$	1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$	1.35 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	870 GeV	$m(\tilde{\chi}_1^0)$=600 GeV	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$	100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$	0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	490 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

10^{-1} — 1 — **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.


Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
0 1 2 3 4 TeV
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
0 1 2 3 4 TeV
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
0 1 2 3 4 TeV
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
0 1 2 3 4 TeV
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4 TeV
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
chargino, ctau>100ns, AMSB
neutralino, ctau=25cm, ECAL time
0 1 2 3 4 TeV
Dark Matter
j+MET, vector DM=100 GeV, Λ
j+MET, axial-vector DM=100 GeV, Λ
j+MET, scalar DM=100 GeV, Λ
γ+MET, vector DM=100 GeV, Λ
γ+MET, axial-vector DM=100 GeV, Λ
l+MET, ξ=+1, SI/SD DM=100 GeV, Λ
l+MET, ξ=-1, SI/SD DM=100 GeV, Λ
l+MET, ξ=0, SI/SD DM=100 GeV, Λ
0 1 2 3 4 TeV
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
ADD (jj), nED=4, MS
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
QBH (jj), nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
0 1 2 3 4 5 6 7 8 TeV
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 TeV
CMS Exotica Physics Group Summary – Moriond, 2015



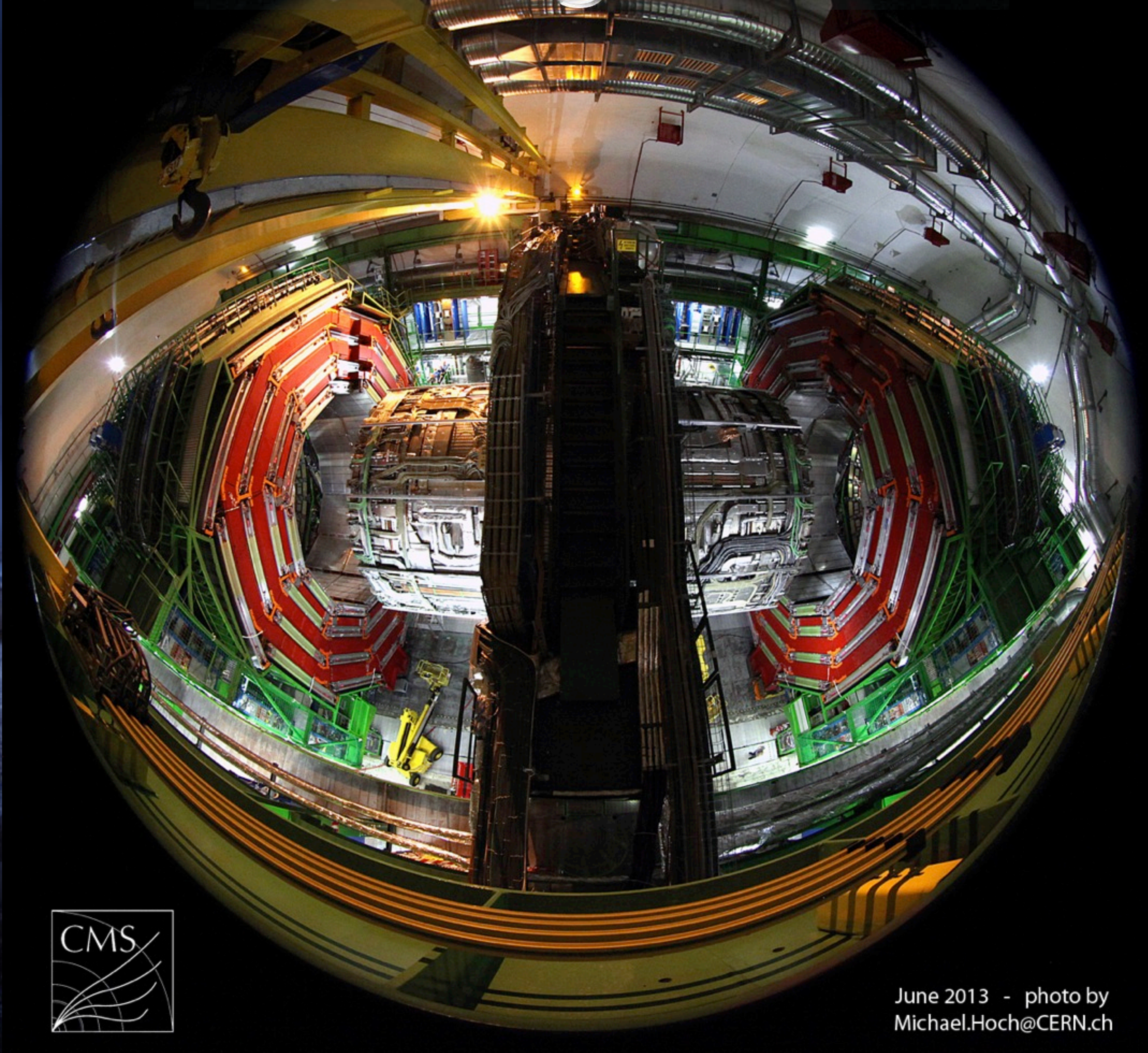
ATLAS & CMS >1000 publications so far …

~All break new ground in one way or another

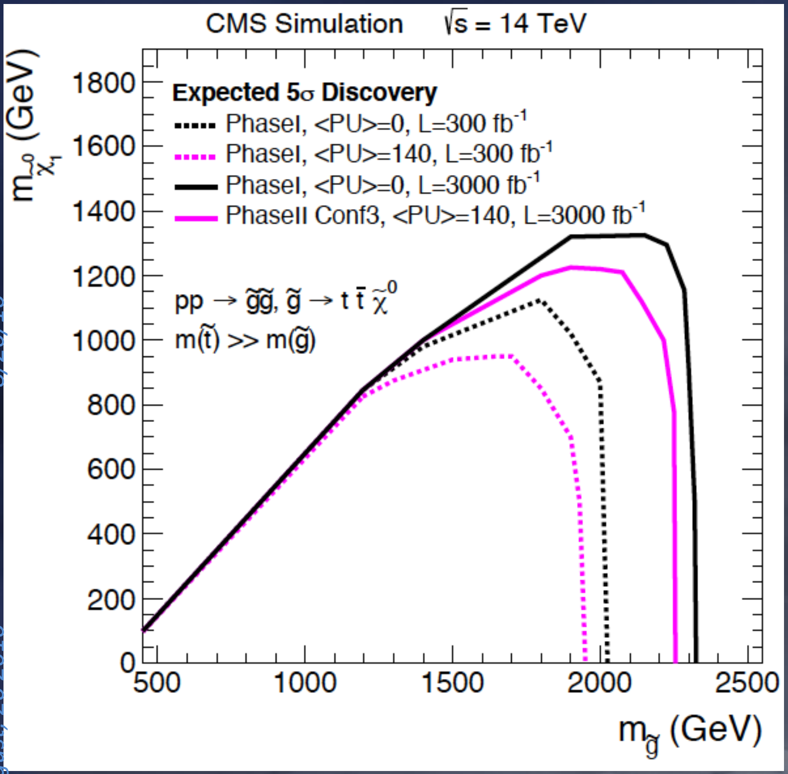
Higgs discovery papers: >6000 citations/experiment (increasing at 200/month)

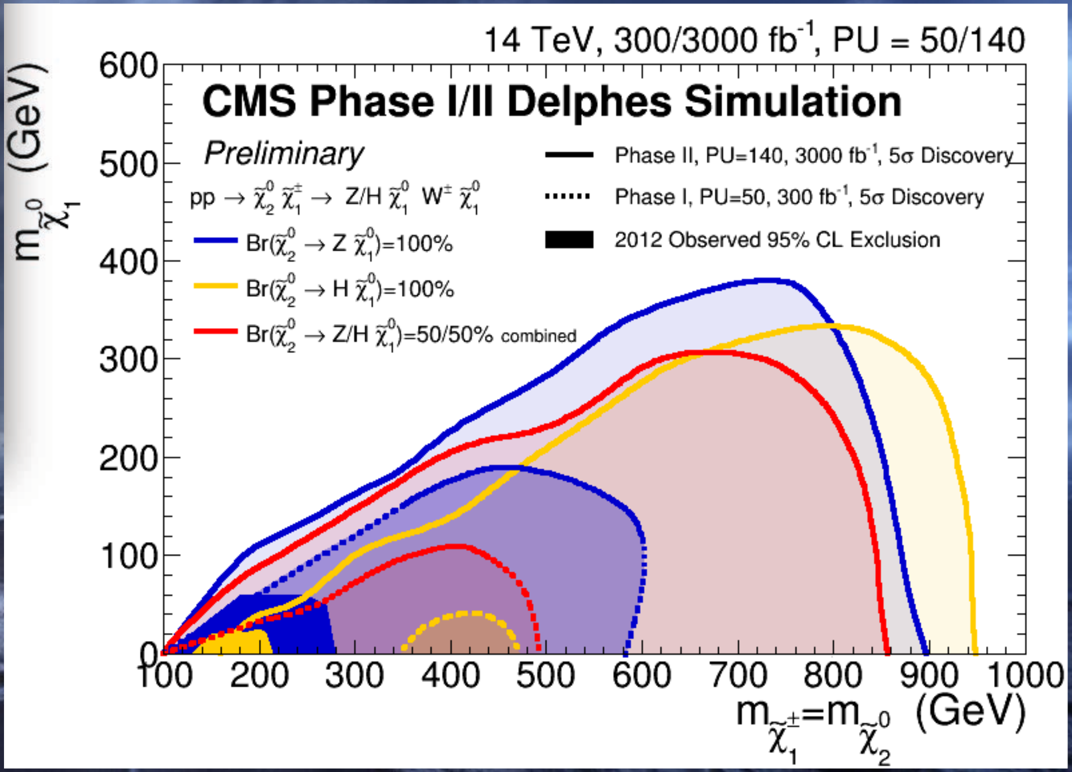
[redacted]

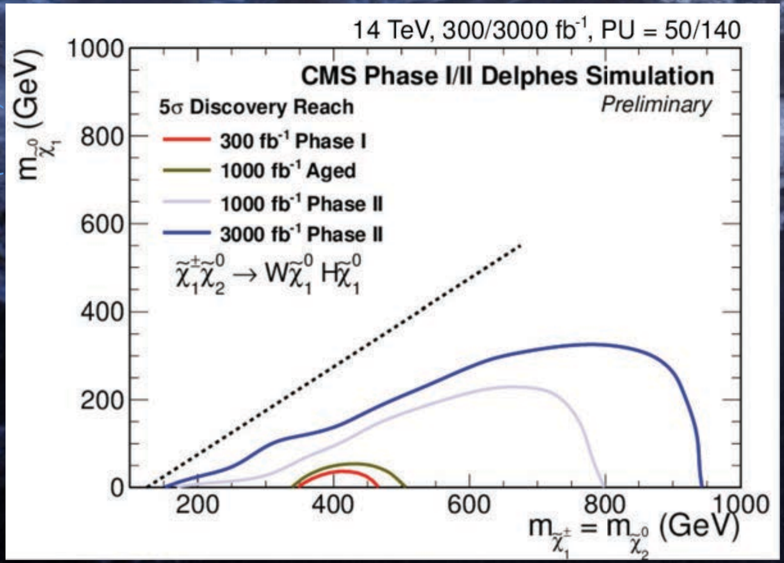
Looking ahead



SUSY at the HL-LHC

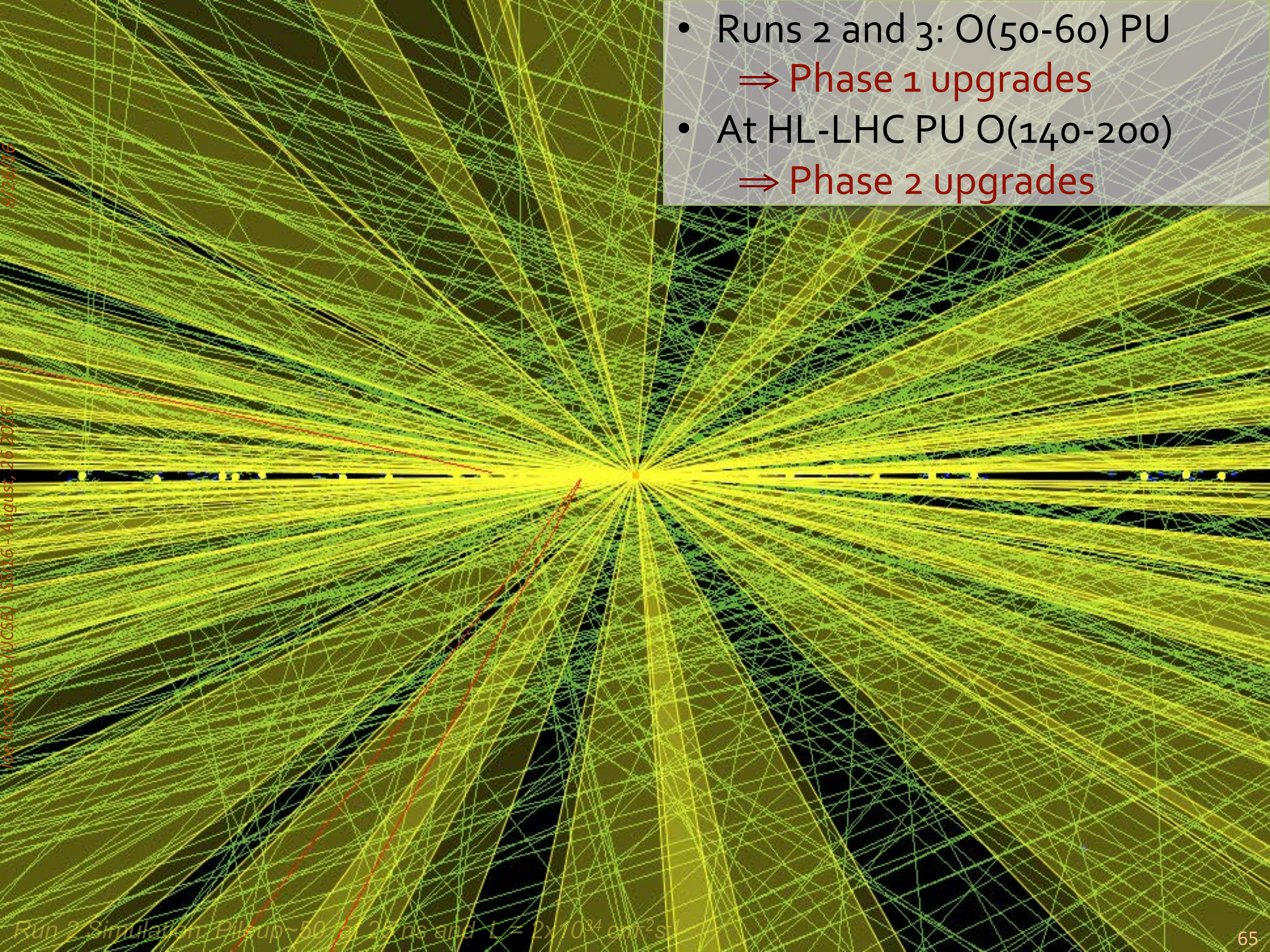






Mass reach into very interesting territory

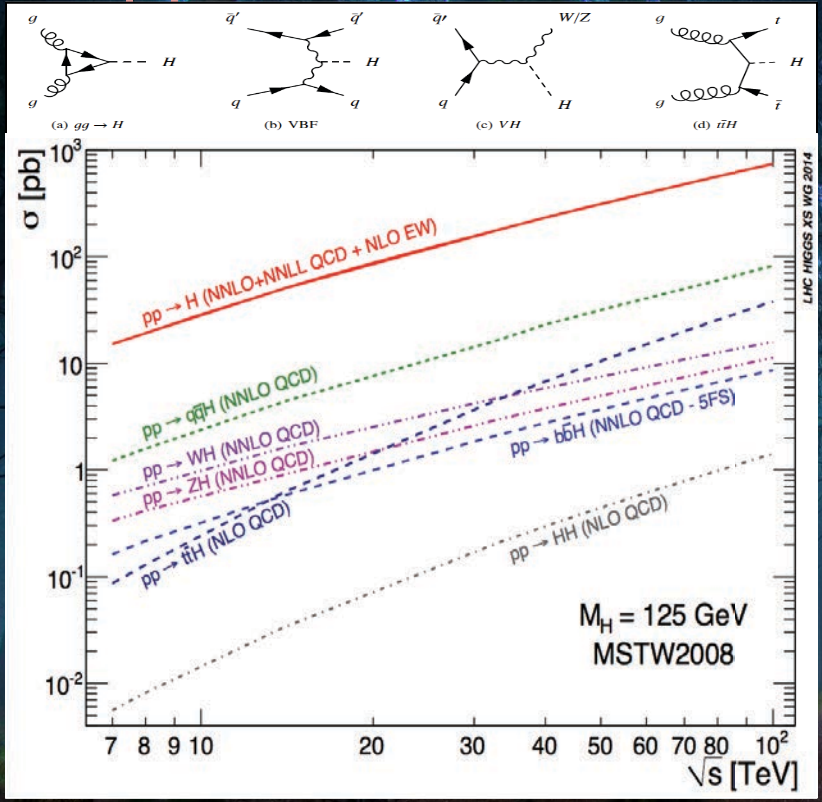
- Runs 2 and 3: O(50-60) PU
  - ⇒ Phase 1 upgrades
- At HL-LHC PU O(140-200)
  - ⇒ Phase 2 upgrades



Run 2 Simulation: Pileup~50 at 25 ns and L = $2x10^{34}$ $cm^{-2}s^{-1}$

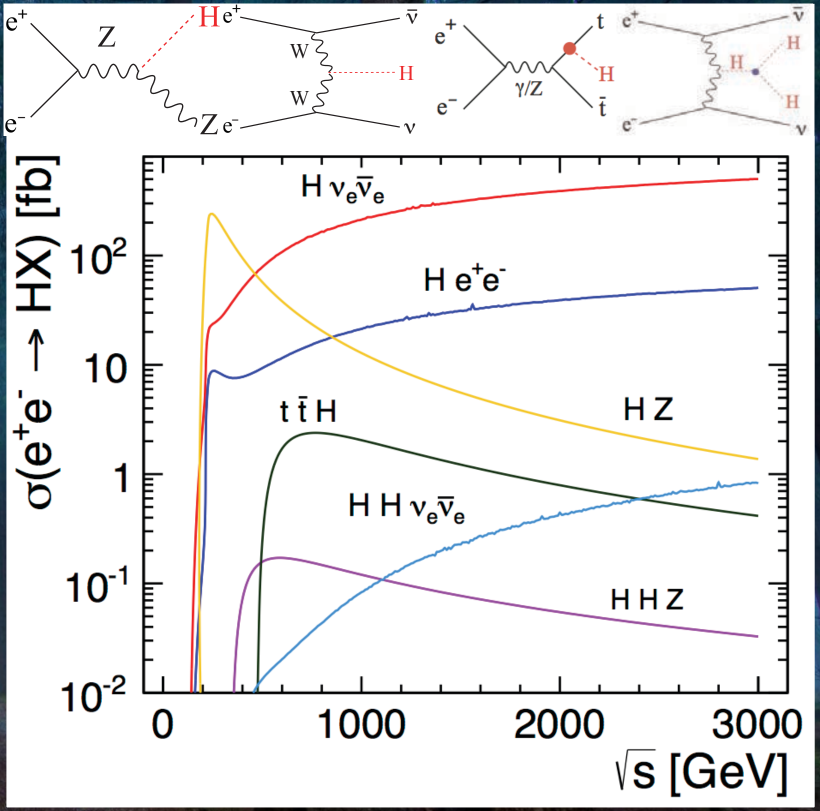
Further Ahead: Big machines & Higgs

pp colliders



- High energy, huge cross-sections
  - Rare decays, heavy states (ttH, HH)
- QCD (big) backgrounds
  - not all channels accessible
- Model-dependent Couplings
  - Γ_H and σ (H) from SM

e+e- colliders

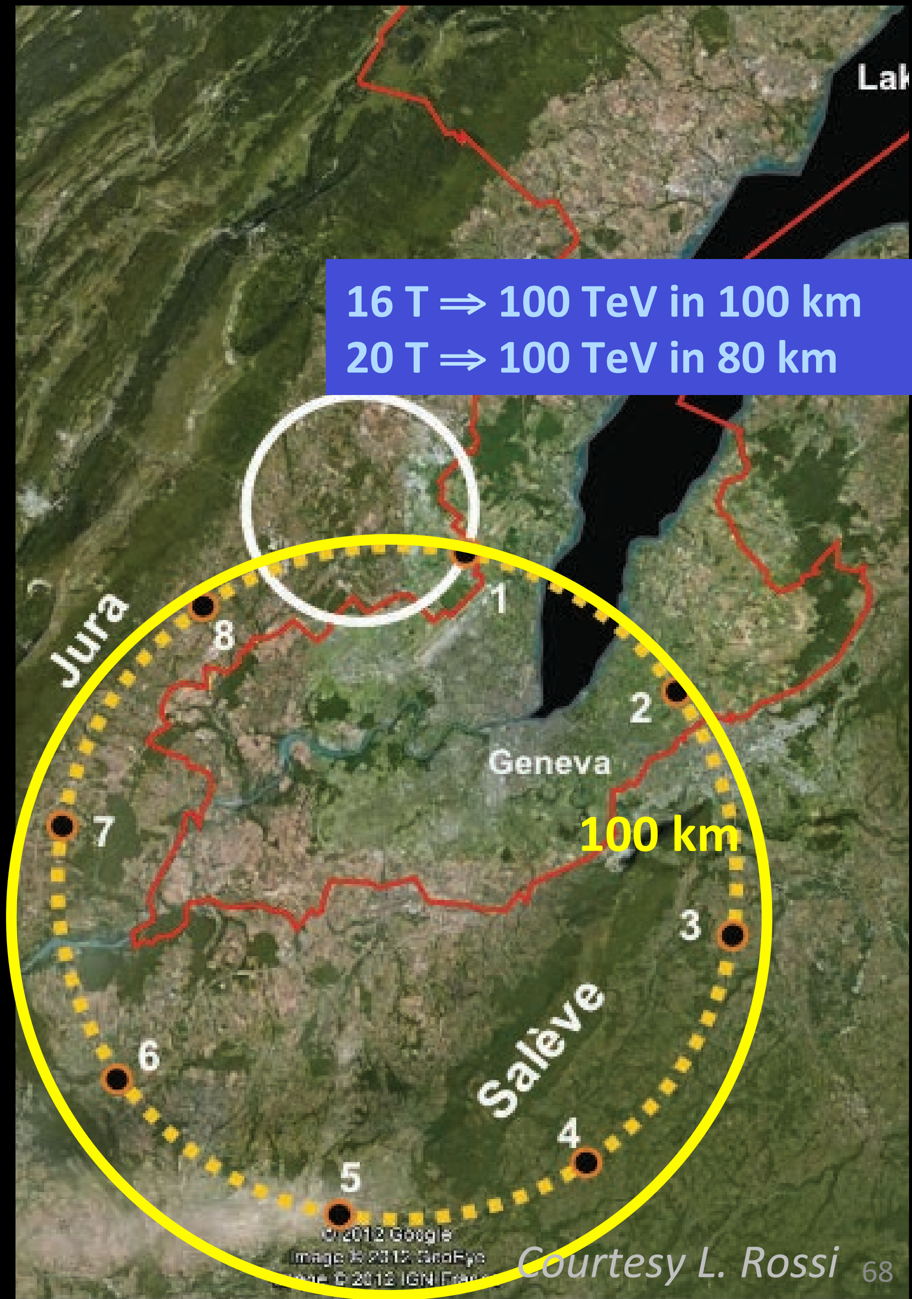


- EW (small)Backgrounds
  - All decay modes accessible ⇒ Γ_H
  - ttH and HH for √s ≥ 500 GeV
- Model-independent couplings

Future Circular Colliders

CERN FCC

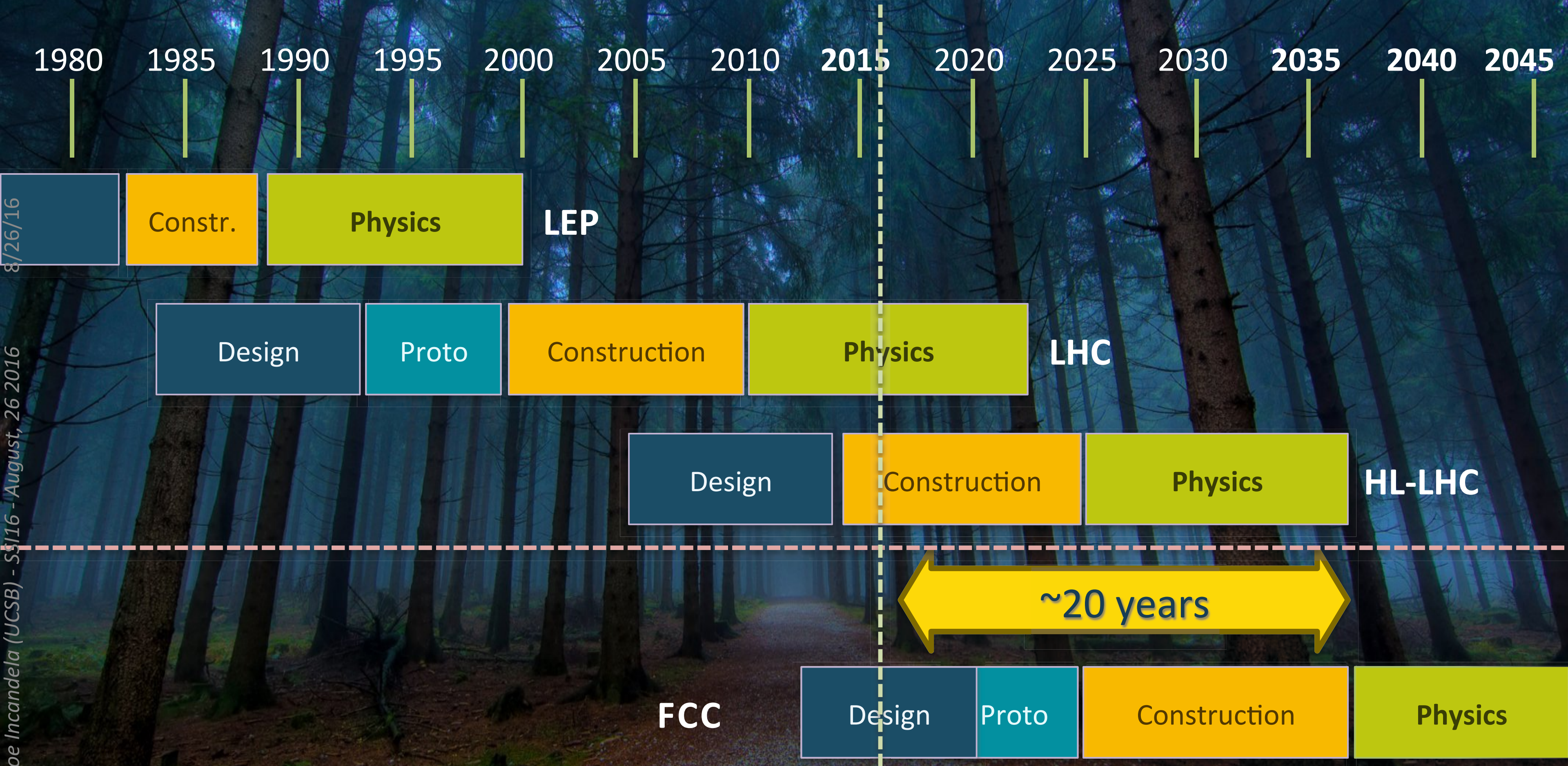
- Int'l FCC collab. (CERN as host lab) to study:
  - pp-collider (FCC-hh
    - EW symmetry breaking
      - And unification
      - Higgs potential
    - Very high mass states
      - Corner SUSY and naturalness t
  - e+e- collider (FCC-ee)
    - An intermediate step for high precision studies of Higgs, W/Z, top
  - p-e (FCC-he) option



Courtesy L. Rossi

Adapted from slide by Michael Benedikt

CERN Circular Colliders & FCC



- Must advance fast now to be ready for the period 2035 – 2040
- Goal of phase 1: CDR by end 2018 for next update of European Strategy

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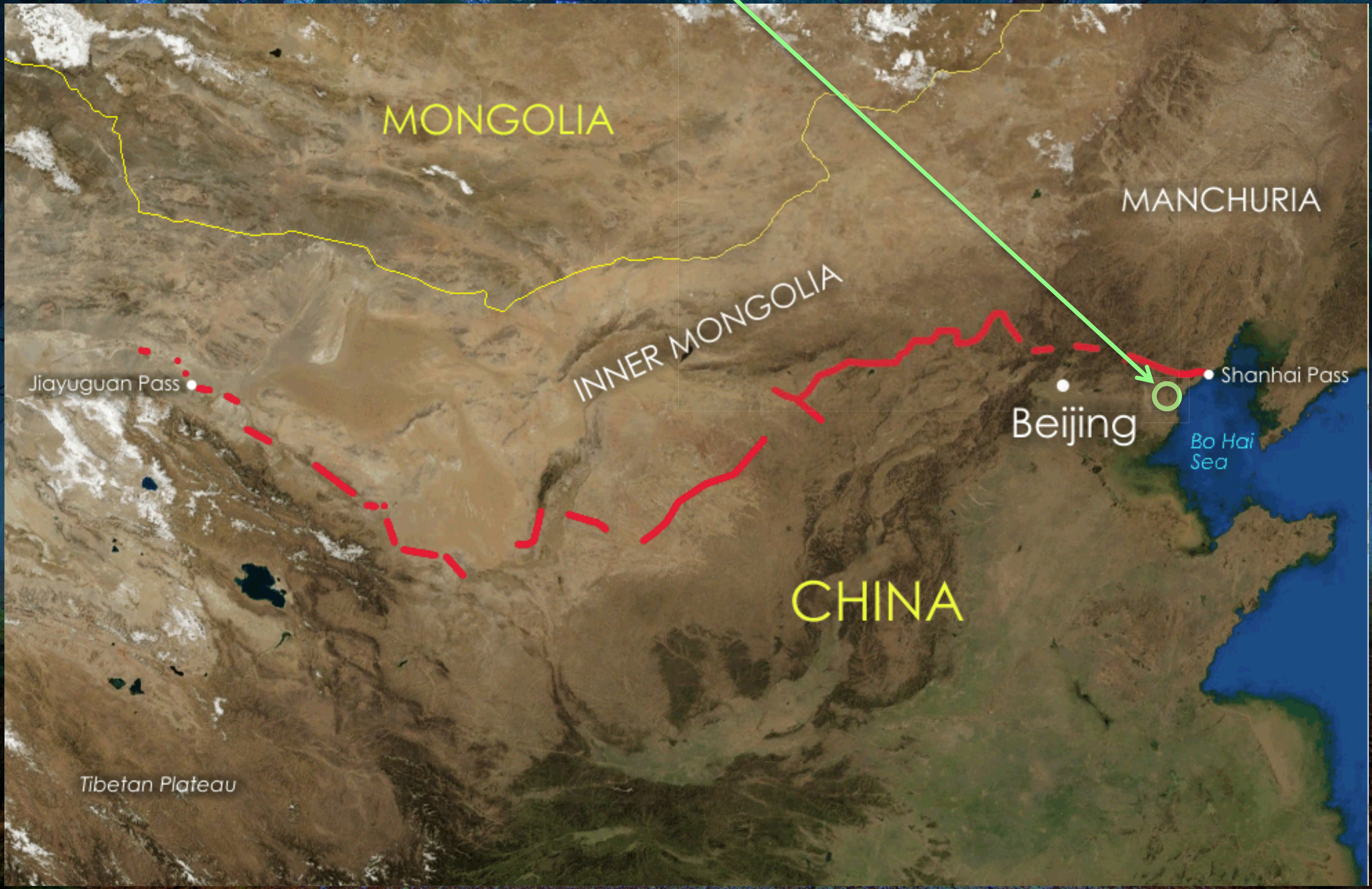
The Great Ring of China ?

Qinhuangdao (秦皇岛）



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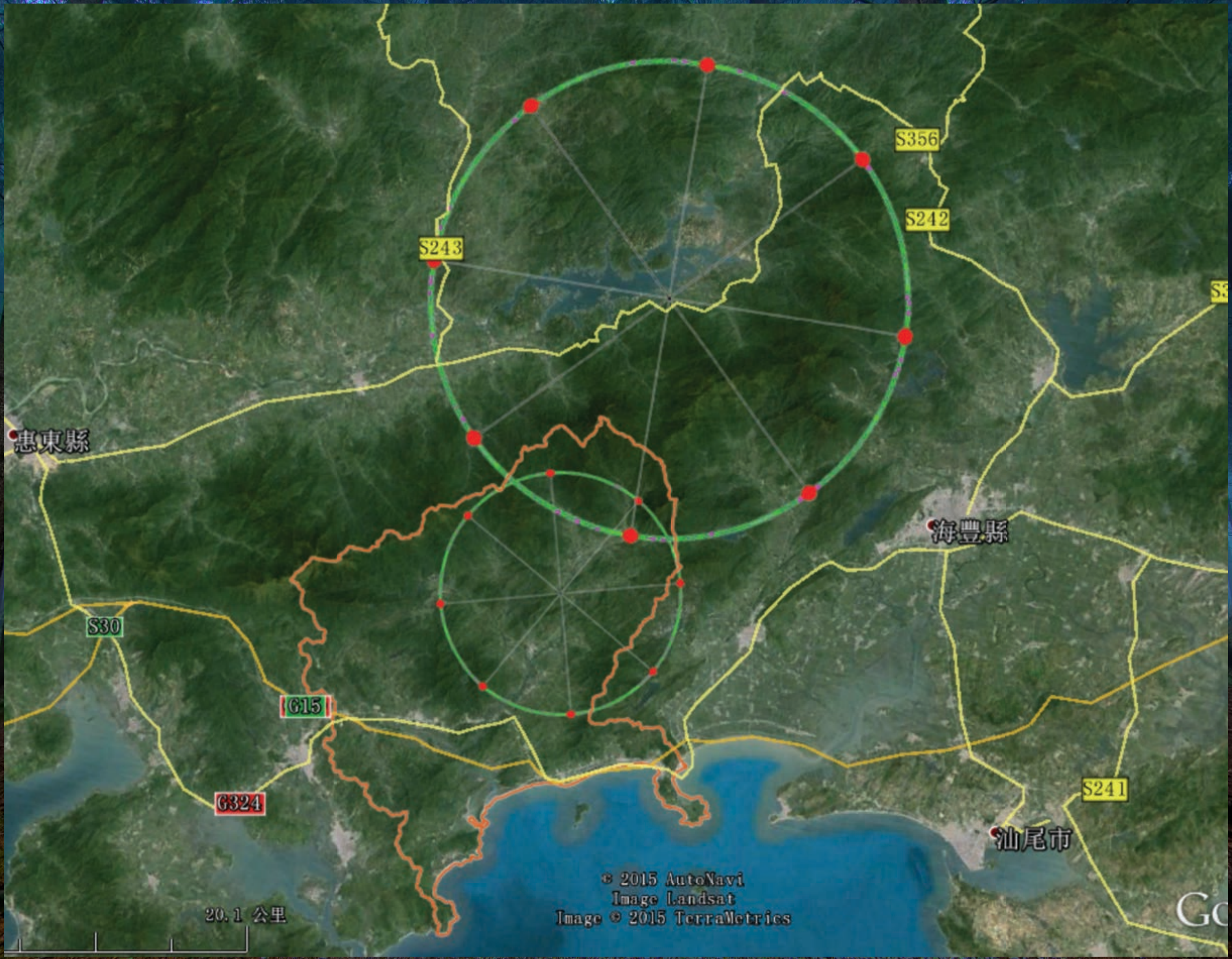
Qinhuangdao (秦皇岛）



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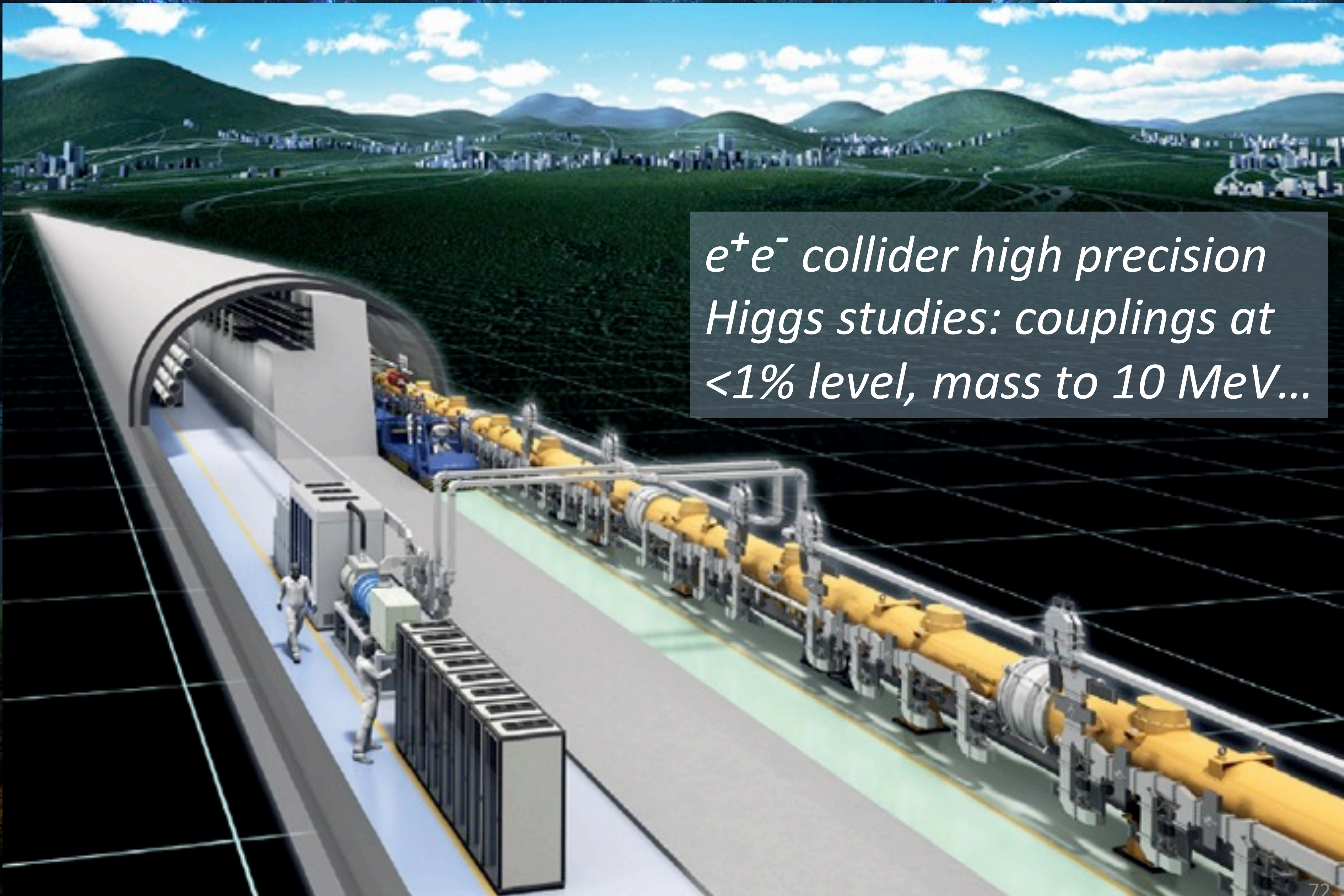
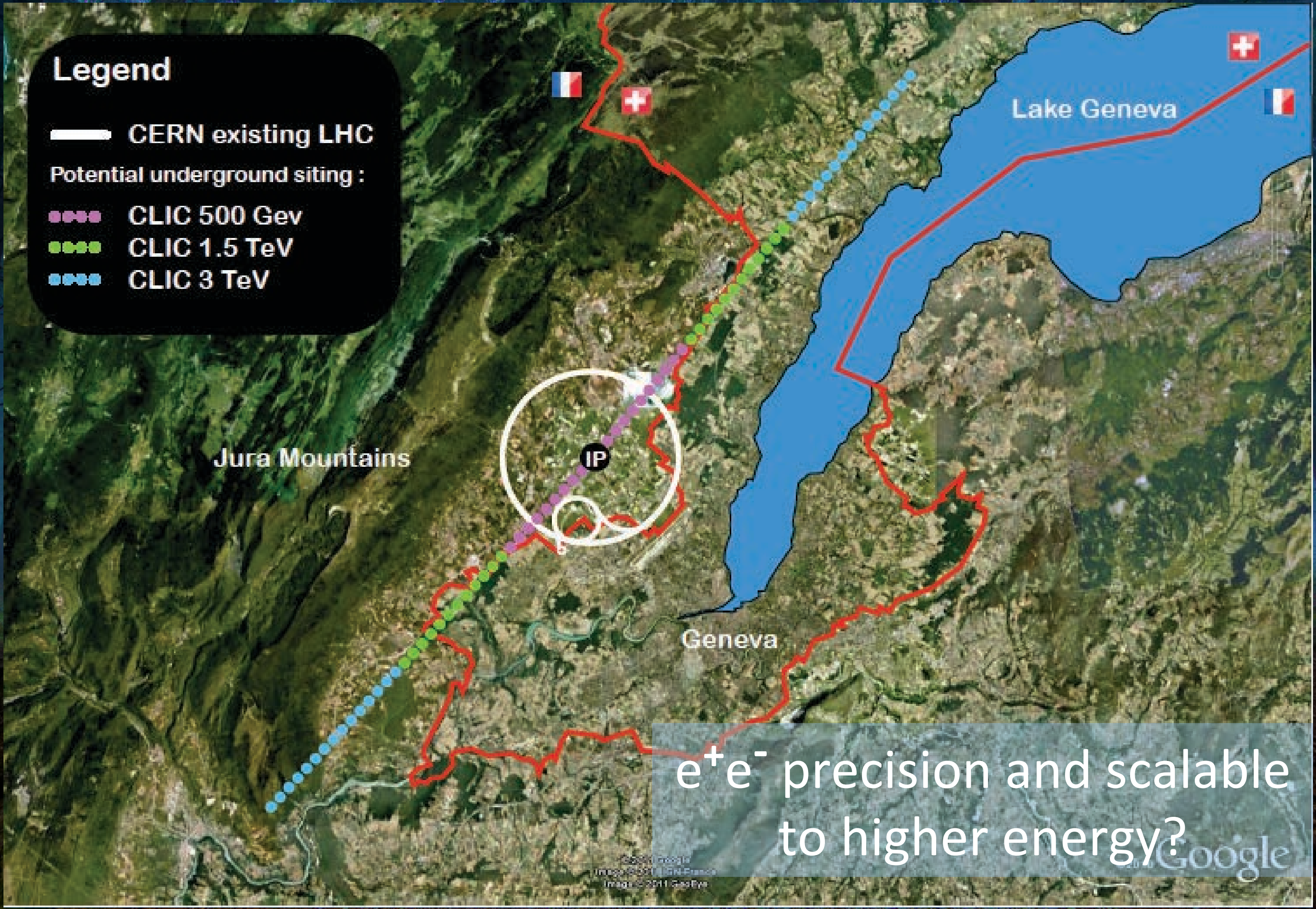
International Linear Collider (Japan)



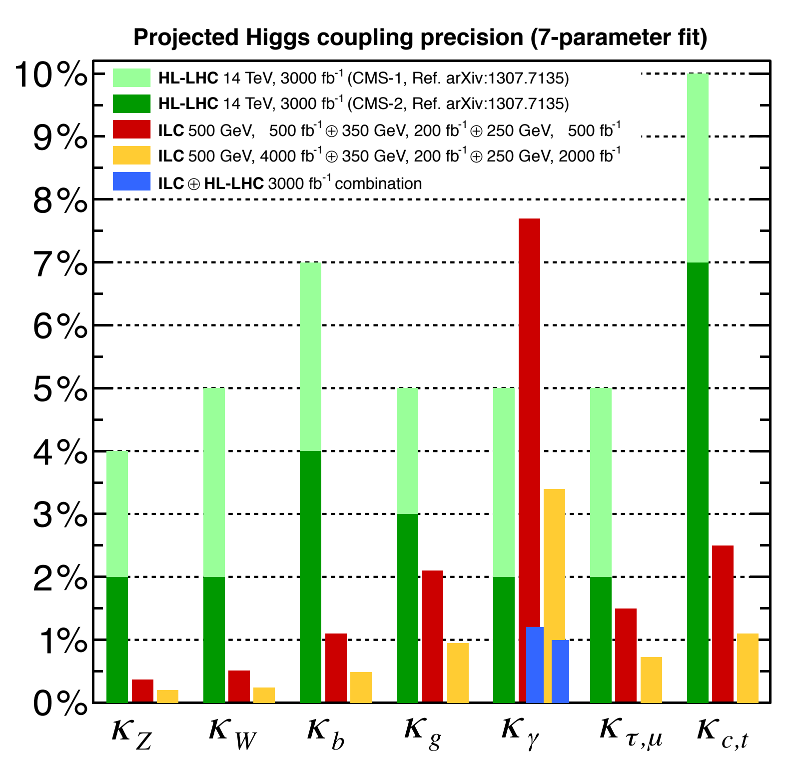
e^+e^- collider high precision Higgs studies: couplings at <1% level, mass to 10 MeV…

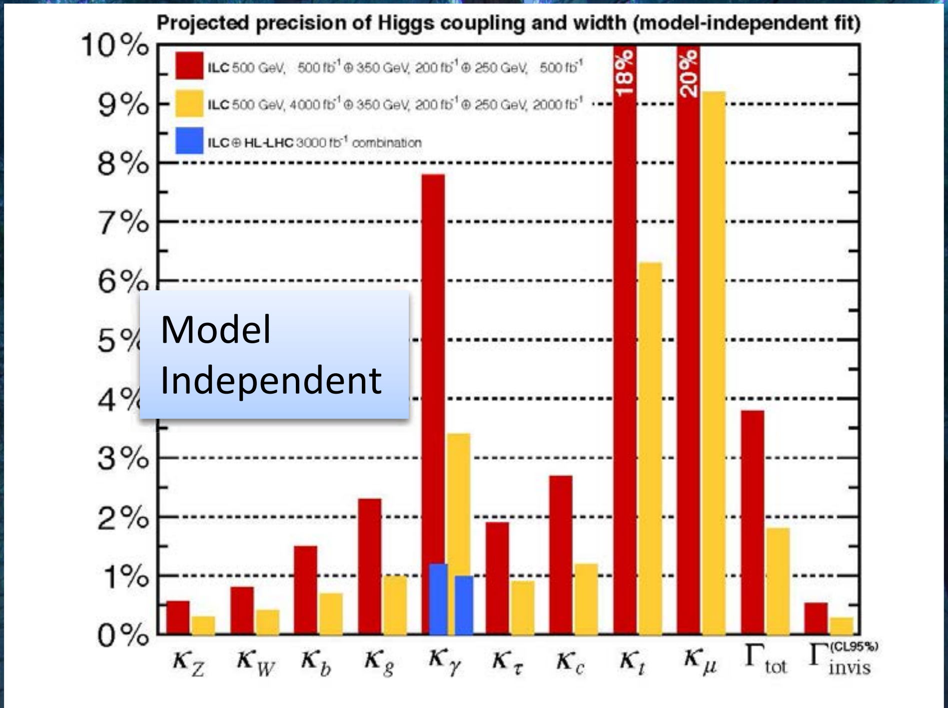
Linear e+e- collider at CERN (CLIC)



e^+e^- precision and scalable to higher energy?

e⁺e⁻ example : ILC*





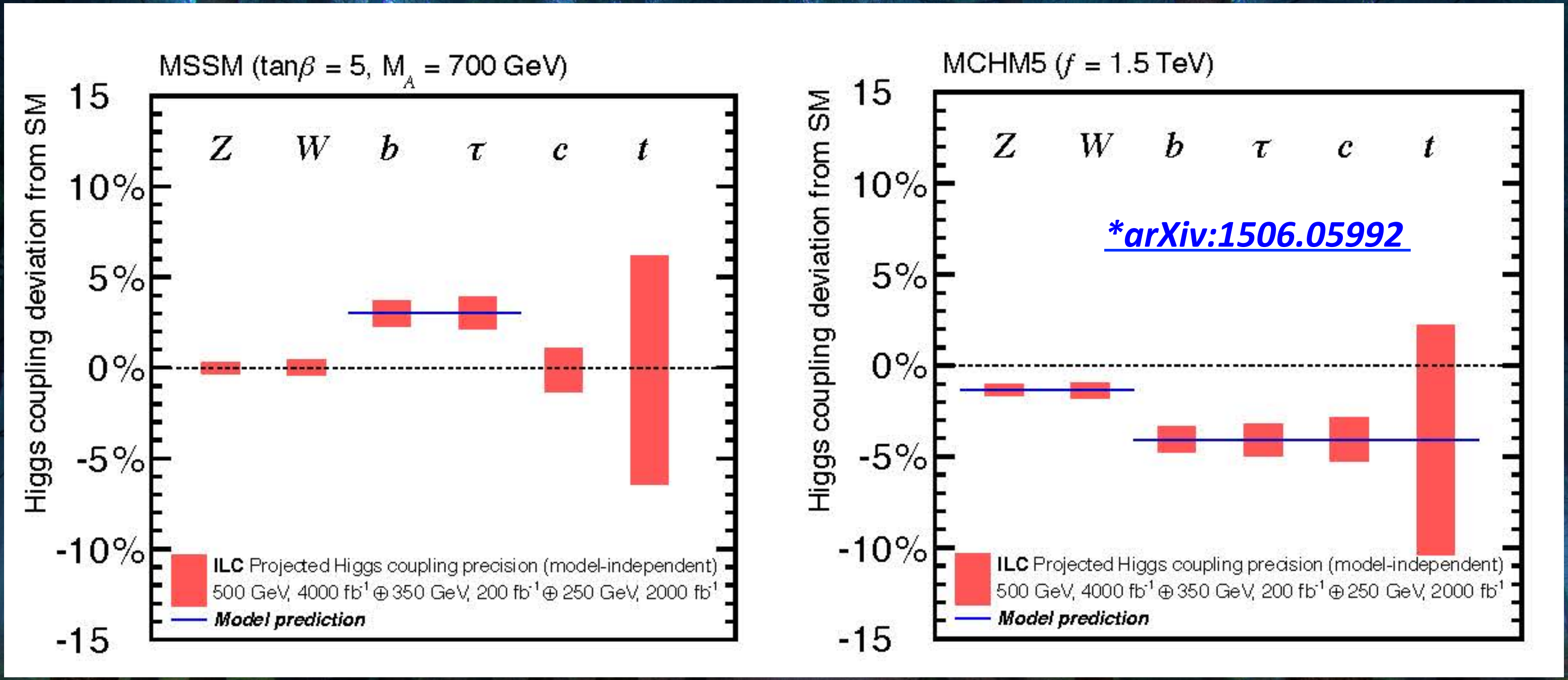
Higgs Couplings

With full dataset, precise model-independent determination of Higg's total width and stunning resolution of couplings including, tau, charm, bottom and top

Topic	Parameter	Initial Phase	Full Data Set	
Higgs	$g(hZZ)$	0.37	0.2	%
	$g(hWW)$	0.51	0.24	%
	$g(hb\bar{b})$	1.1	0.49	%
	$g(hgg)$	2.1	0.95	%
	$g(h\gamma\gamma)$	7.7	3.4	%
	$g(h\tau\tau), g(\mu\mu)$	1.5	0.73	%
	$g(hc\bar{c}), g(ht\bar{t})$	2.5	1.1	%
	Γ_{tot}	1.8	0.96	%

*arXiv:1506.05992

ILC example: Distinguishing SUSY from a Higgs Composite Model

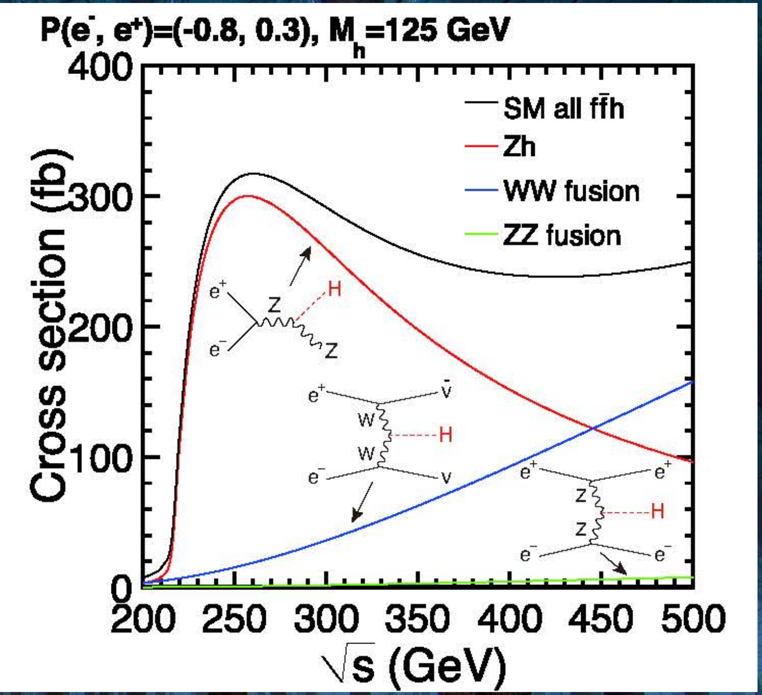


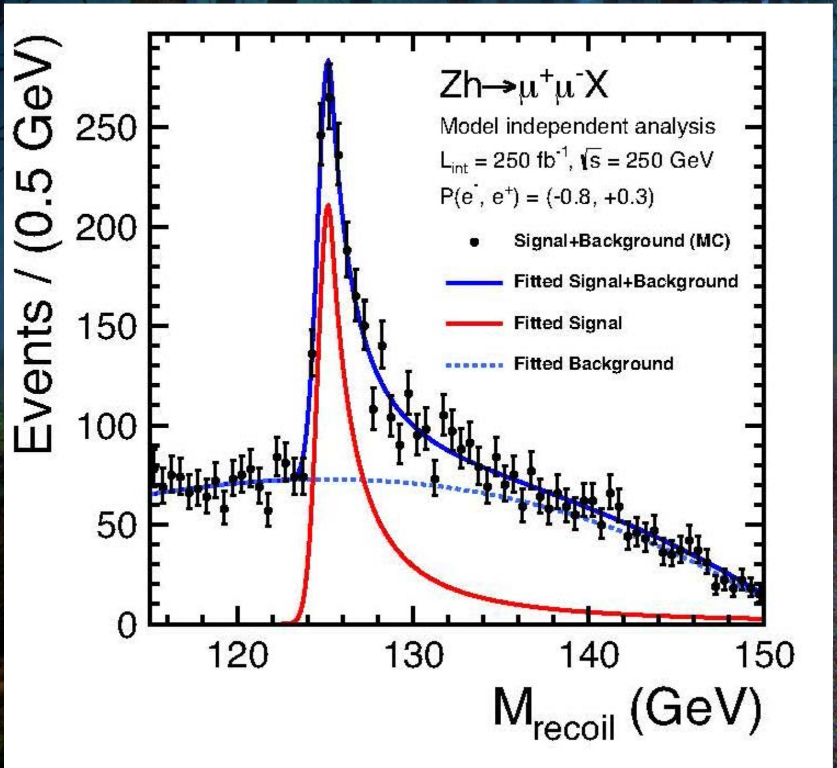
Potential to severely constrain the physics, really narrow down the models

Higgs mass

Higgs' production modes versus √s:

- *Higgstrahlung*
- *WW Fusion*
- *ZZ Fusion*





Higgs mass via recoil in Zh→ μμX events:

- σ_M < 30 MeV
- xsec uncertainty <1%

*arXiv:1506.05992

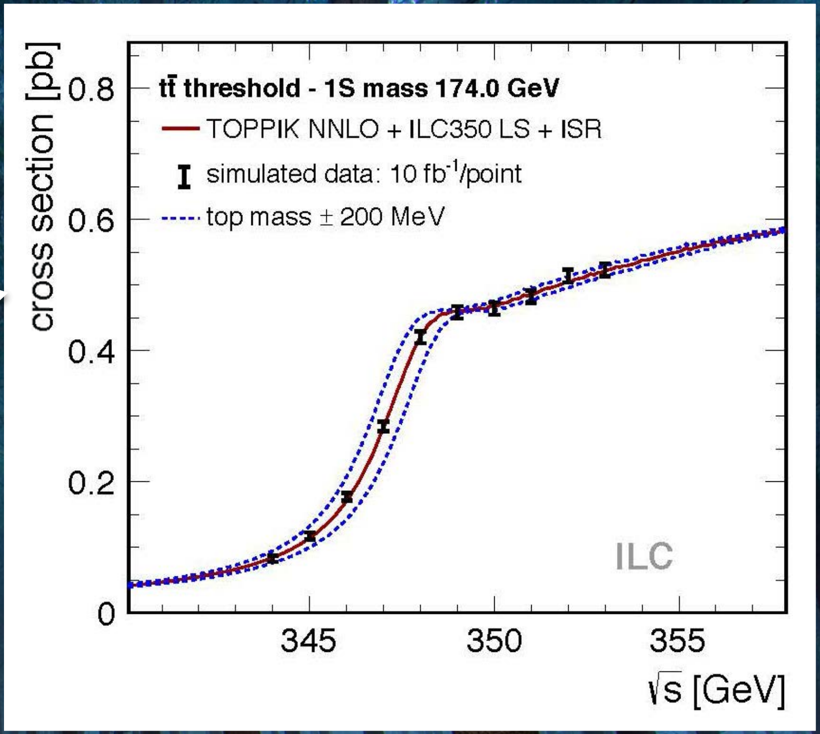
Joe Incandela (UCSB) - SSI16 - August, 26 2016

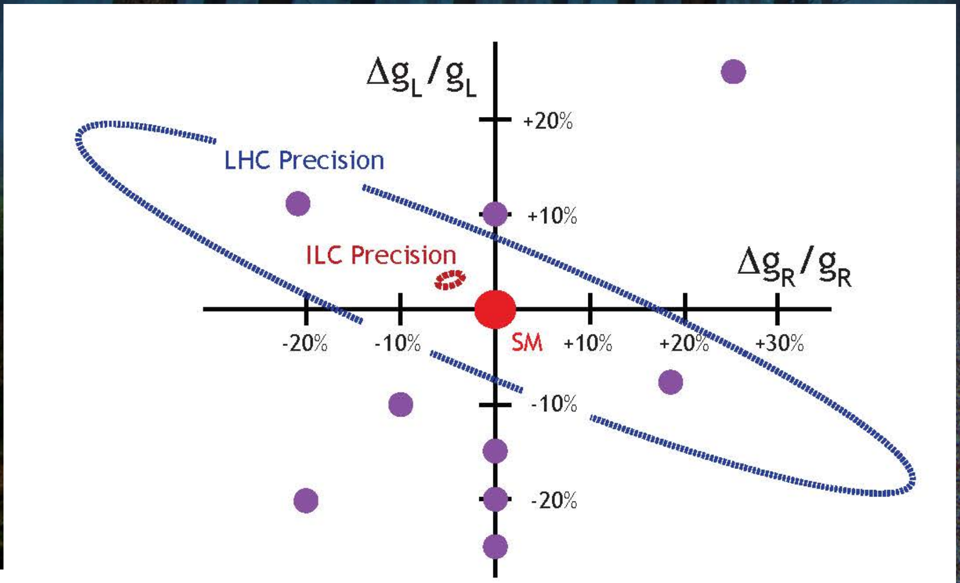
8/26/16

ILC Example: Higgs and Top

3-param fit to top threshold - stat. errors:

- Mass ± 17MeV
- Γ_t ± 26MeV
- λ_t ± 4%





Couplings of top to Z are very different in different BSM models. The polarization capabilities and resolution of e+e- machines provides powerful discrimination to eliminate many models and highlight viable ones

*arXiv:1506.05992

Big Machines: Higgs Reach

Machine	LHC	CEPC	ILC	CLIC	FCC-ee	FCC-pp
$\sqrt{s}$ [TeV]	14	0.24	0.25/0.5	0.38/1.4/3	0.24/0.35	100
$\int Ldt$ [ab^{-1}]	3/expt	5	6	4	13	40
Uncertainties on Higgs Couplings [%]						
κ_W	2-5	1.2	0.4	0.9	0.19	
κ_Z	2-4	0.26	0.3	0.8	0.15	
κ_g	3-5	1.5	1.0	1.2	0.8	
κ_γ	2-5	4.7	3.4	3.2	1.5	<1
κ_μ	~8	8.6	9.2	5.6	6.2	~2
κ_c	n/a	1.7	1.2	1.1	0.7	
κ_τ	2-5	1.4	0.9	1.5	0.5	
κ_b	4-7	1.3	0.7	0.9	0.4	
$\kappa_{Z\gamma}$	10-12	n/a	n/a	n/a	n/a	
Γ_H	n/a	2.8	1.8	3.4	1.0	
$B(H\rightarrow inv)$	<10	<0.28	<0.29	<1.0	<0.19	
κ_t	7-10	n/a	6.3	<4.0	13% tt scan	~1
κ_{HH}	???	35 (use κ_Z *Model Dep.*)	27	11	20 (use κ_Z *Model Dep.*)	5-10

from K_γ/K_Z, using K_Z from FCC-ee

rare decays: pp Competitive or better

from ttH/ttZ, using ttZ and H BR from FCC-ee

6.3 → 3% for 10% increase in √s!

HL-LHC: first direct observation of couplings to 2nd generation (H→ μμ)

Best precision FCC-ee ($\int Ldt$) but ttH and HH require linear e+e- and pp colliders (√s)

Theory uncertainties need to be improved to keep up with experiments!

Adapted from slide by F. Gianotti, Higgs Hunting 2015


The Road Ahead
Some thoughts…

Extend the neutrino and DM programs in the most promising directions…

This is obvious but it's good to be explicit…

Less obvious is how to decide what the next big colliders should be!

The Next Collider

e+e- collider

- Long overdue…
  - We cannot close the loop on new particles and their properties without e+e- data
  - Much to learn from $t\bar{t}$, H … even W and Z and of course any new particles
- Linear
  - Can get to higher energies (e.g. $t\bar{t}$ +Z/W, $t\bar{t}$H production)
  - Potentially higher polarization
- Circular
  - Potentially higher luminosities→ higher statistics
  - Side benefit: A tunnel for a hadron collider

pp collider

- 100 TeV (FCC-hh, SppC)
  - The right energy to fully understand EW symmetry breaking
    - Higgs potential
  - Reach (some kind of closure) with regard to SUSY and naturalness
- 28-33 TeV (HE-LHC)
  - Affordable step toward a higher energy machine
  - Substantially stronger program than HL-LHC without undermining the key elements of the 100 TeV colliders

HE-LHC

- **Double Higgs boson production @33 TeV is x6.1 that of 14 TeV: ~30% uncertainty on λ can be reduced to ~12%**
  - N.B. This is an ~8σ measurement vs. ~3σ evidence at the HL-LHC

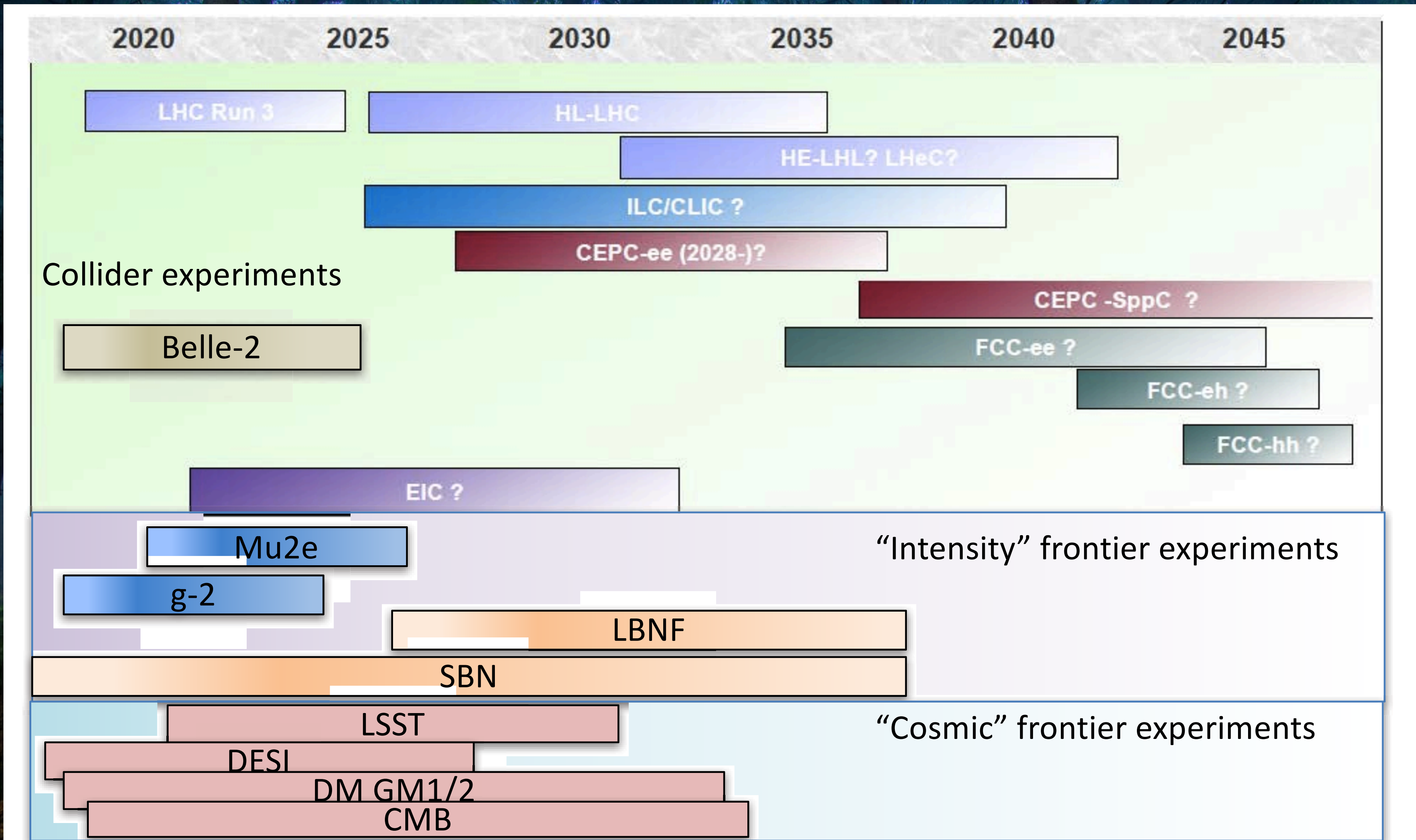
	N_{100}	N_{100}/N_8	N_{100}/N_{14}	N33	N33/N14	N100/N33
$gg \to H$	16×10^9	4×10^4	110	5.4×10^8	3.5	30
VBF	1.6×10^9	5×10^4	120	0.47×10^8	3.8	34
WH	3.2×10^8	2×10^4	65	1.4×10^7	2.9	22
ZH	2.2×10^8	3×10^4	85	0.9×10^7	3.3	24
$t\bar{t}H$	7.6×10^8	3×10^5	420	1.3×10^7	7.3	58

Assume 3 ab^{-1} @ 33 TeV [existing detectors, 10 years of running with the HL-LHC luminosity]

N.B. a factor of 7 in the N100/N33 is due to higher integrated luminosity

From G. Landsberg and J.I. - KITP Workshop – Next Machines- June 2016, UCSB

Timelines for Major Experiments



Vivian O'Dell ICHEP

Collider Scenarios

Carte Blanche

- Build them all!
- Linear
  - ILC or CLIC
- Circular

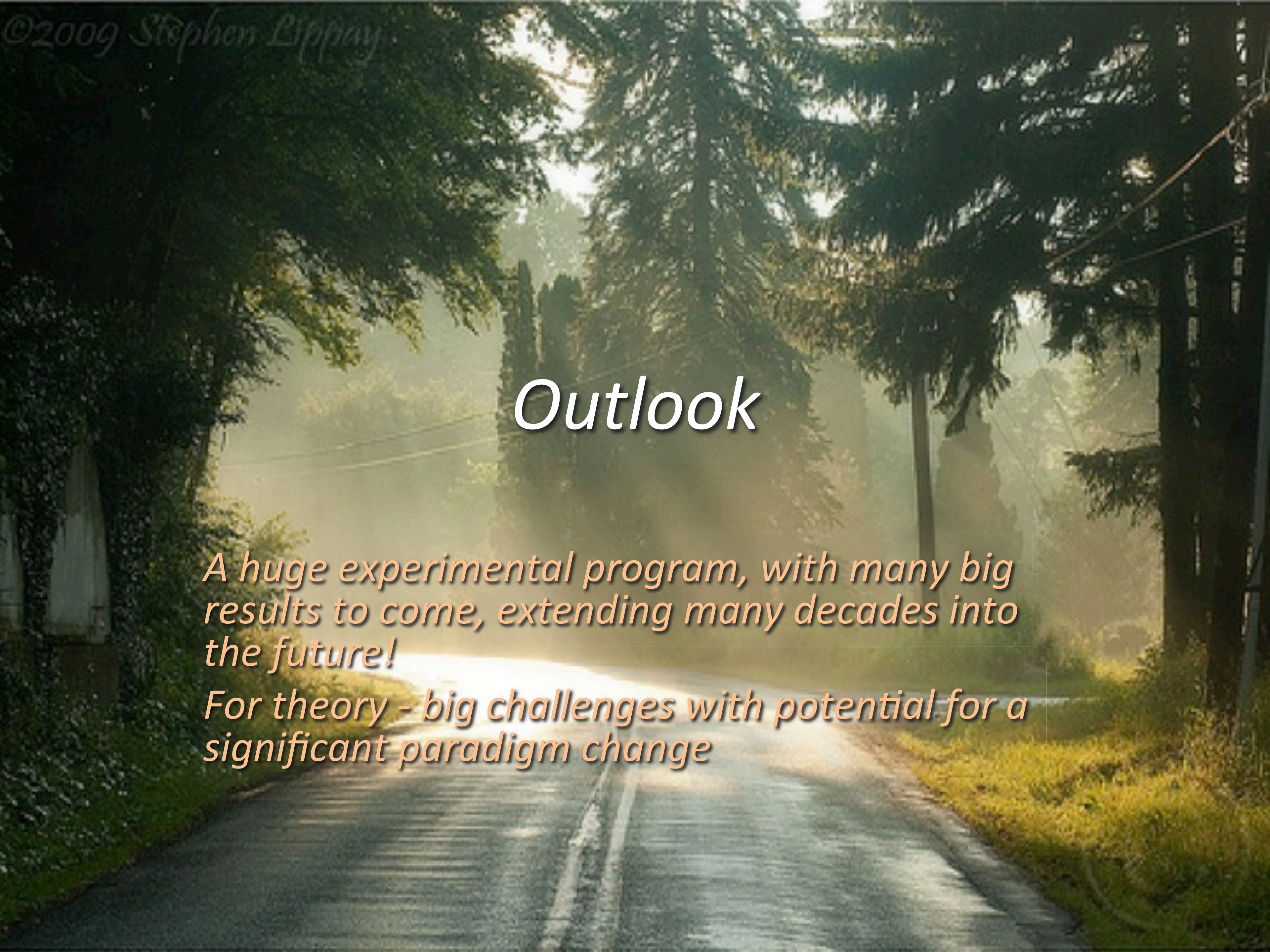
  CEPC→ SppC or FCC-ee → FCC-hh

Carte Jaune

- One e+e- collider
  - Choose one that can be funded and everyone get behind it!
- HE-LHC
  - A quasi-affordable upgrade
  - Keeps the hadron community energized, stimulates accelerator R&D
  - Develop and demonstrate new technologies
- Depending on what we learn
  - Make a pitch for the next machine when the time is right

Carte Rouge

- HE-LHC
  - That's all folks!



Outlook

A huge experimental program, with many big results to come, extending many decades into the future!

For theory - big challenges with potential for a significant paradigm change


The end

Additional Information…

Questions for HEP
(Slide from before LHC startup)

What is the origin of Electroweak Symmetry Breaking? **ATLAS, CMS**
→ Related to the Higgs boson

What is dark matter ? **ATLAS, CMS**

Why are there exactly 3 generations of fermions ?
Why is there so little antimatter in the Universe ?
(Nature's favoritism … which makes it possible for us to exist …) **LHCb** +ATLAS/CMS

What are the features of the primordial medium permeating the Universe ~10 μs after the Big Bang ? **ALICE** +ATLAS/CMS

Are there other forces?
Why is gravity so weak ?
Are there additional spatial dimensions ? **ATLAS, CMS**

Adapted from a slide from Fabiola Gianotti

Questions for HEP
(Slide from before LHC startup)

What is the origin of Electroweak Symmetry Breaking? **ATLAS, CMS**
→ Related to the Higgs boson

What is dark matter ? **ATLAS, CMS**

Note: New Physics beyond the Standard Model is needed in most cases. Experimental data and theoretical arguments indicate that this New Physics could manifest itself at the ~ TeV energy scale being explored by the LHC

Why are there exactly 3 generations of fermions ?
Why is there so little antimatter in the Universe ? **LHCb**
(Nature's favoritism ... which makes it possible for us to exist ...) ATLAS/CMS

LHC was built to address these and other fundamental questions

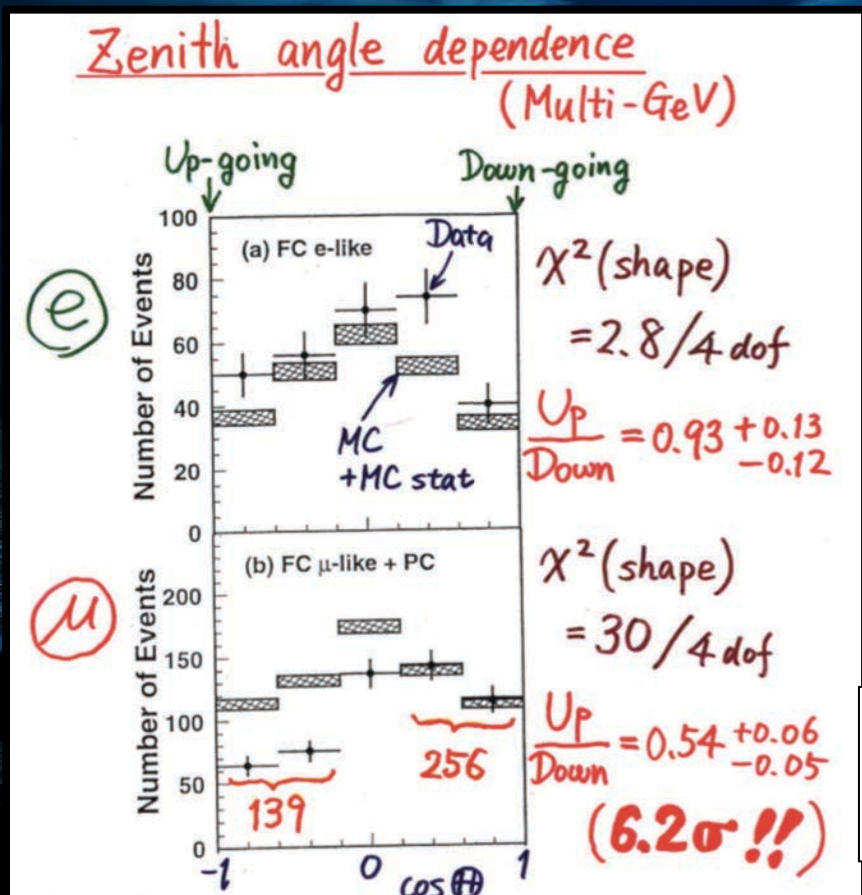
permeating the Universe 10 μs after the Big Bang ? **ALICE** +ATLAS/CMS

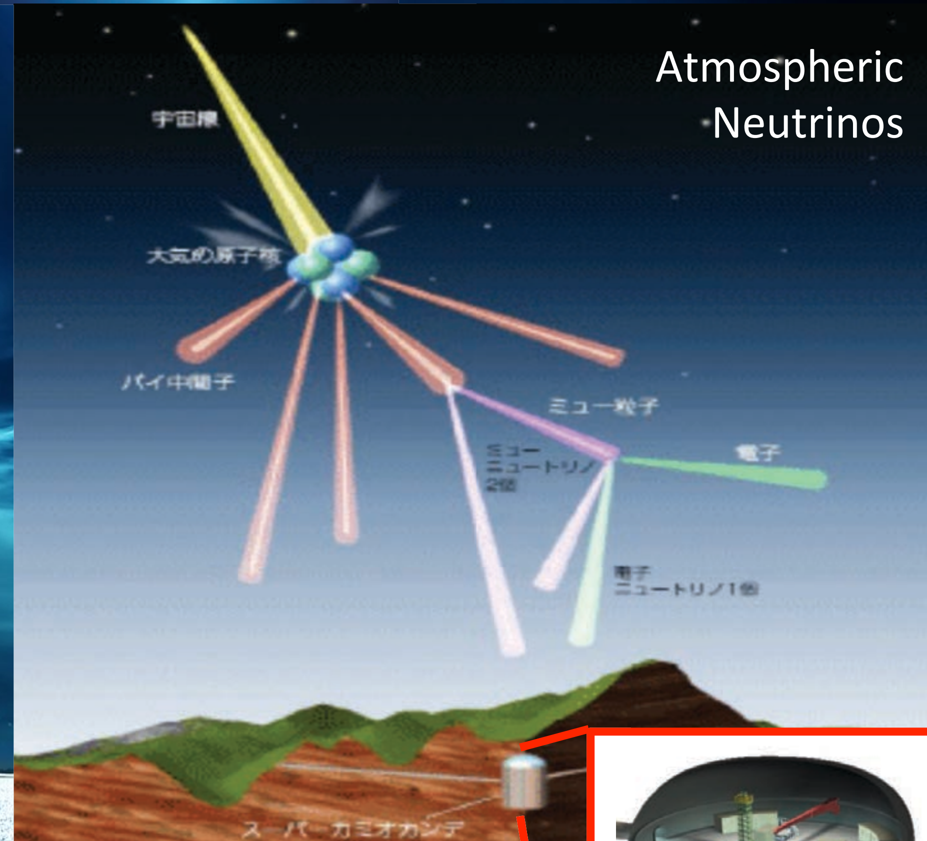
Are there other forces?
Why is gravity so weak ? **ATLAS, CMS**
Are there additional spatial dimensions ?

Adapted from a slide from Fabiola Gianotti

Super-K Figures

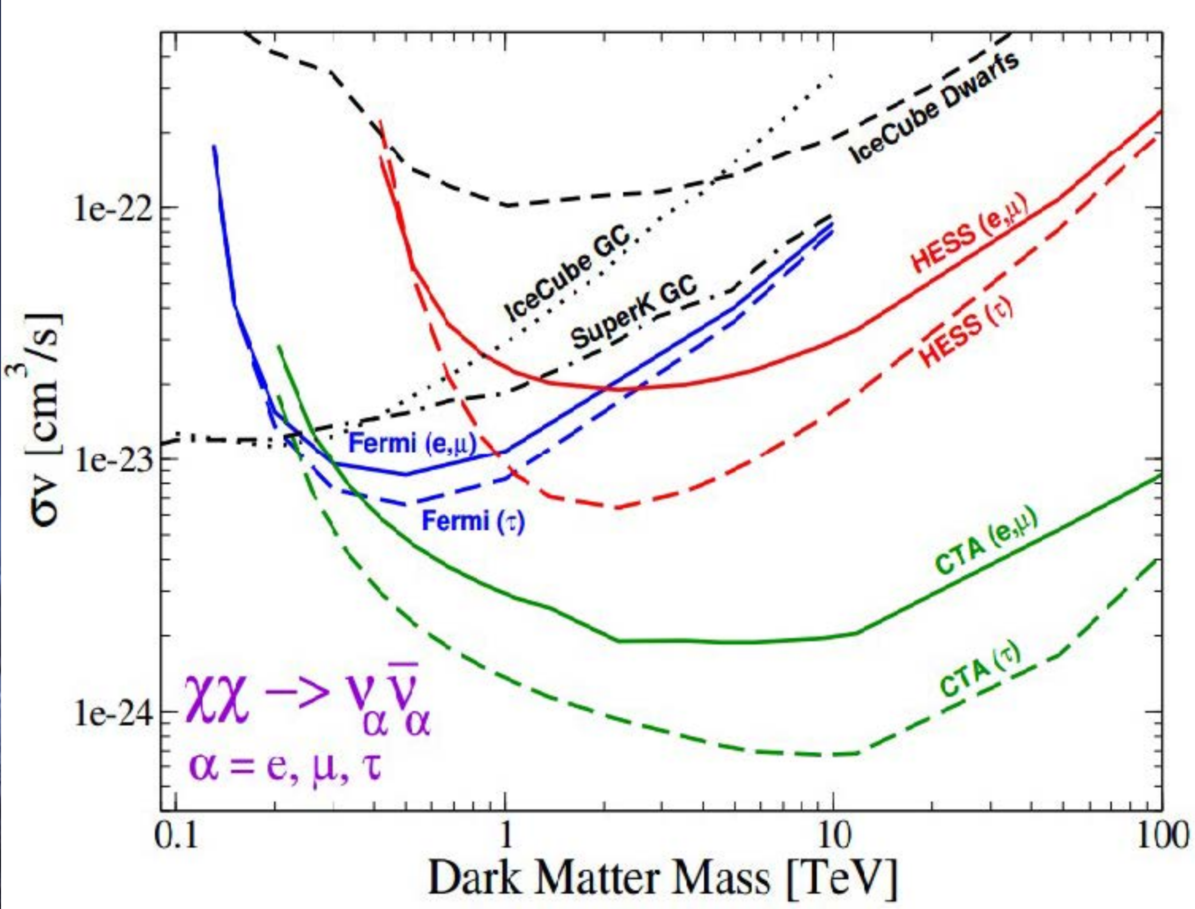
Discovered in 1998 by Super-Kamiokande





T. Kajita
Neutrino 1998

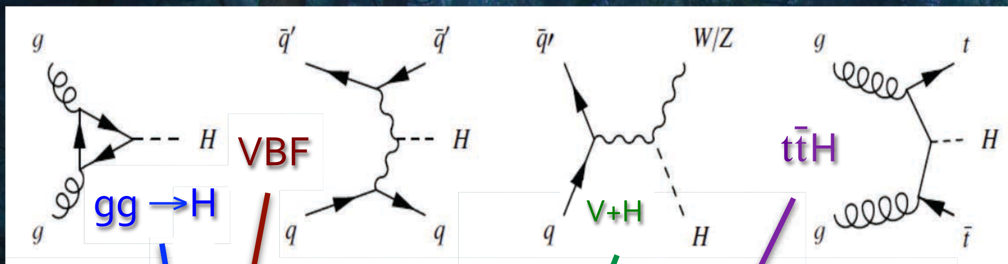
IDM γ telescopes

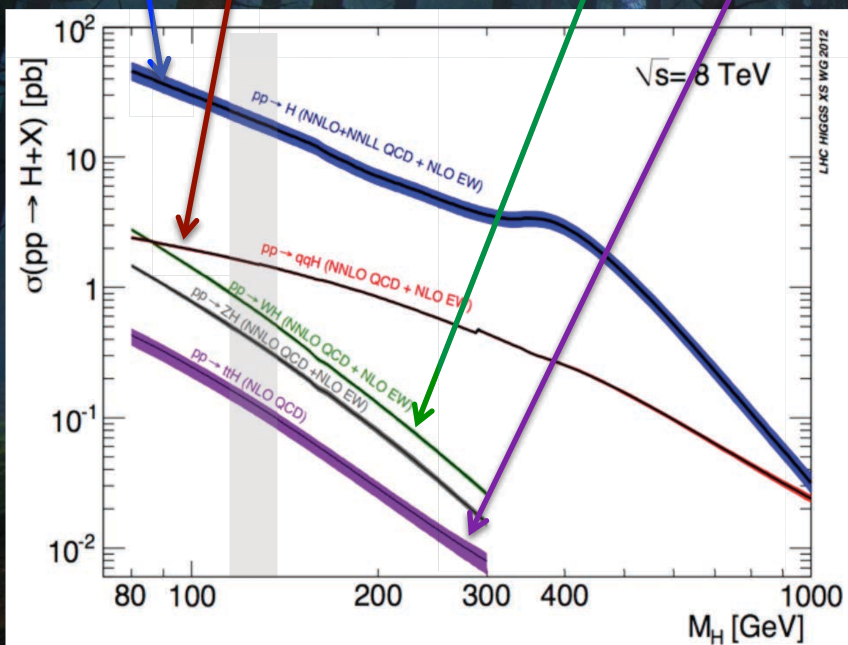


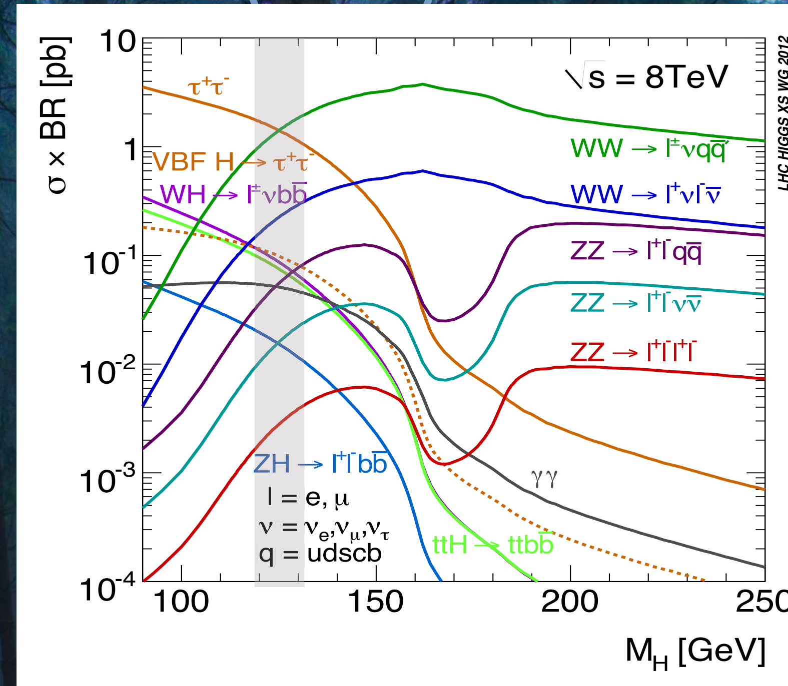
Comparable to, or more sensitive than, neutrino detectors to neutrino lines from dark matter annihilation

From slide by Farinaldo Queiroz (MPIK)

Production and decay modes (LHC) if SM







bb	WW	ττ	ZZ	γγ	Zγ	μμ
57%	22%	6.3%	2.7%	0.23%	0.15%	0.02%

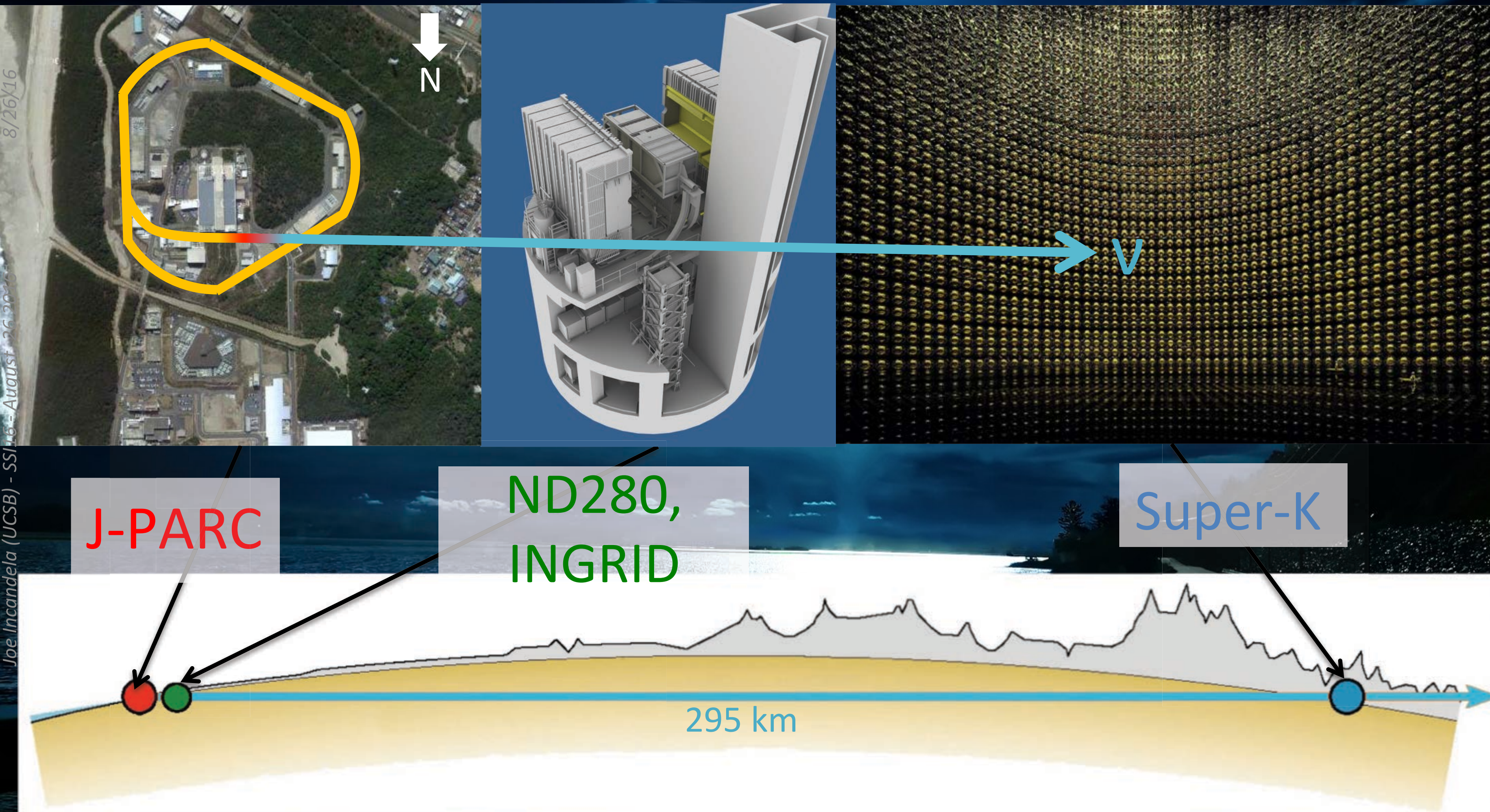
Most sensitive channels 120 < m < 130 GeV:
H→ ZZ*→ 4l, H→ γγ, H→ WW*→ lνlν
H→ ττ and V+H with H→ $b\bar{b}$

Increase sensitivity - measure as many channels as possible:
- e.g. events with two forward jets → Enhances Vector Boson Fusion (VBF)
- e.g. events with additional leptons, missing Energy → Enhances V + H contribution etc.

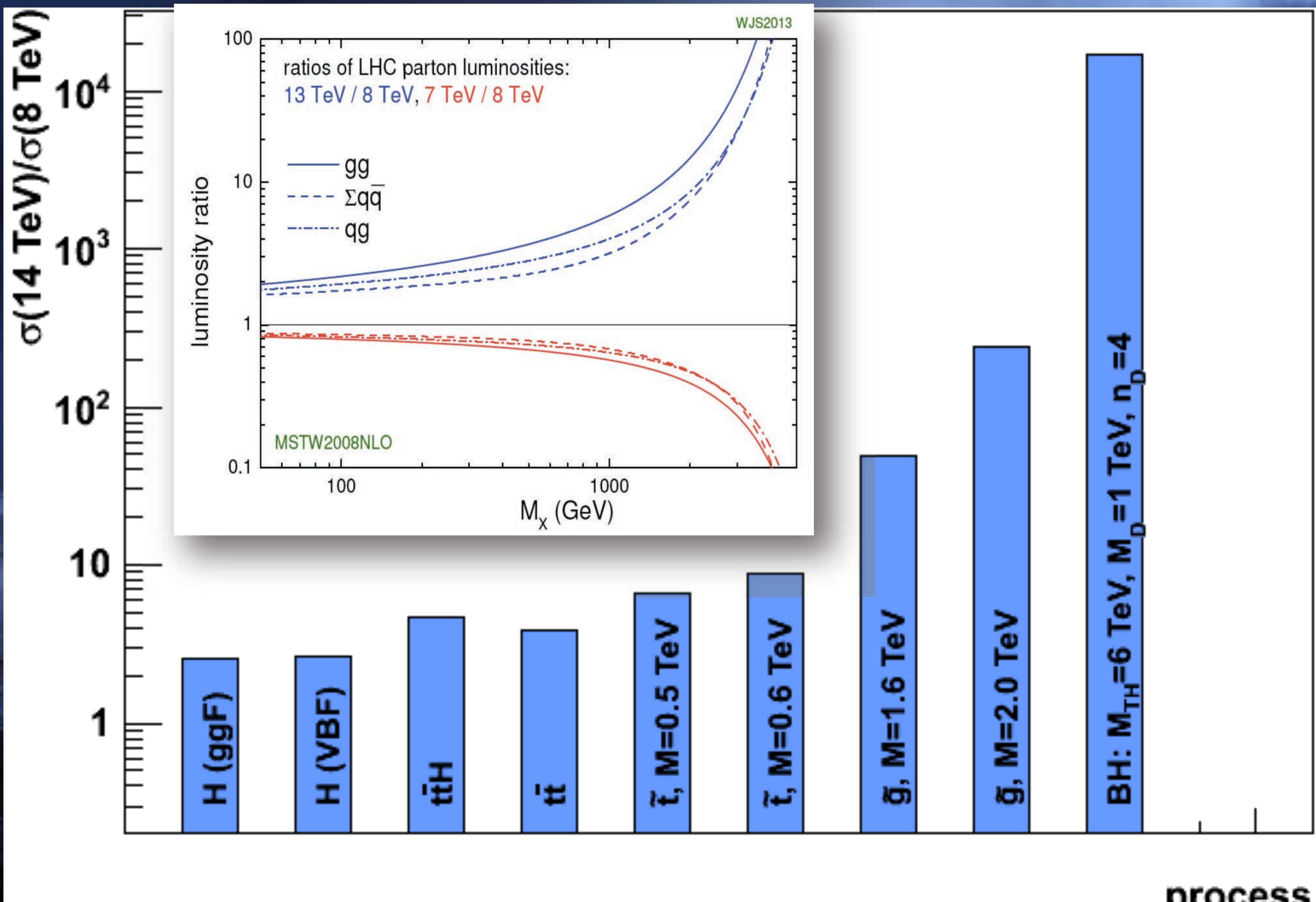
NOvA


NOνA Far Detector (Ash River, MN)
810 km baseline
Lake Superior
Wisconsin
Lake Michigan
Milwaukee
Fermilab
Chicago

The T2K Experiment



13 & 14 TeV vs 8 TeV Cross Sections



Constraints on MSSM spectrum

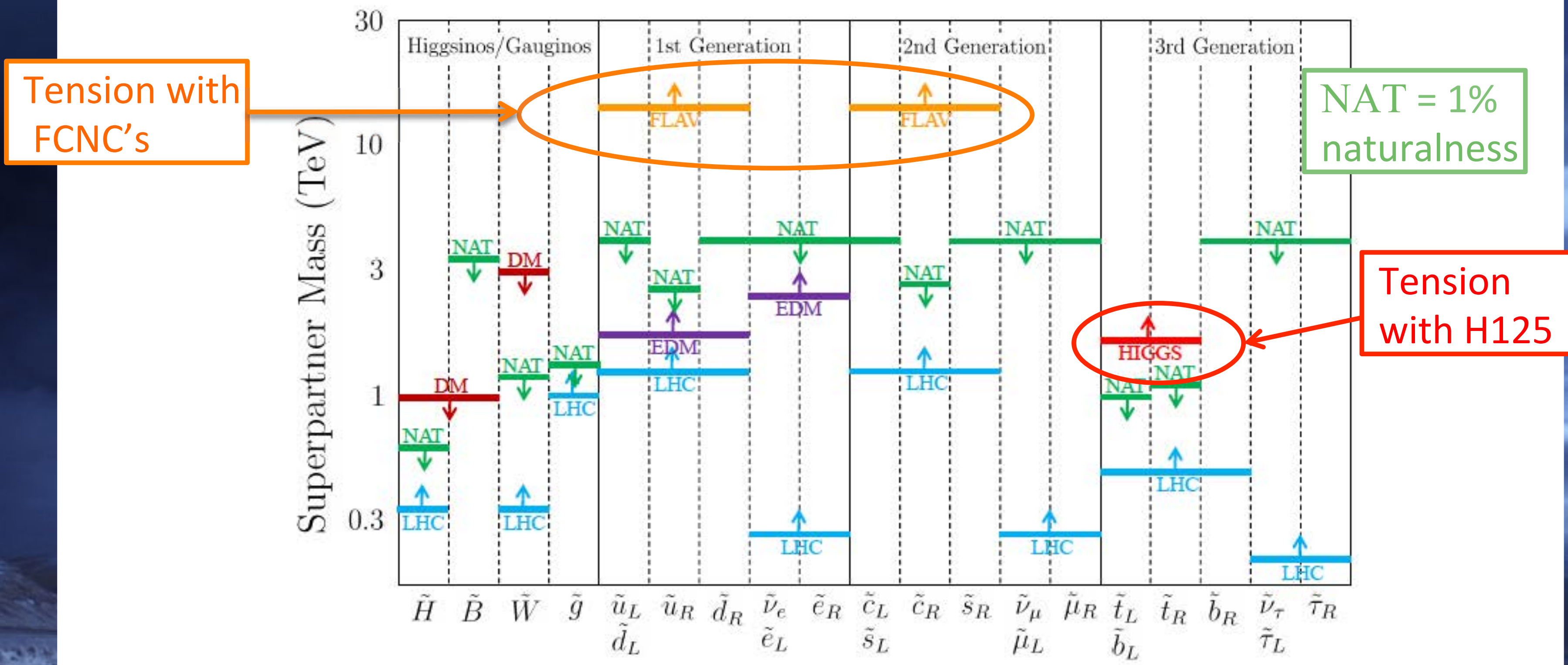
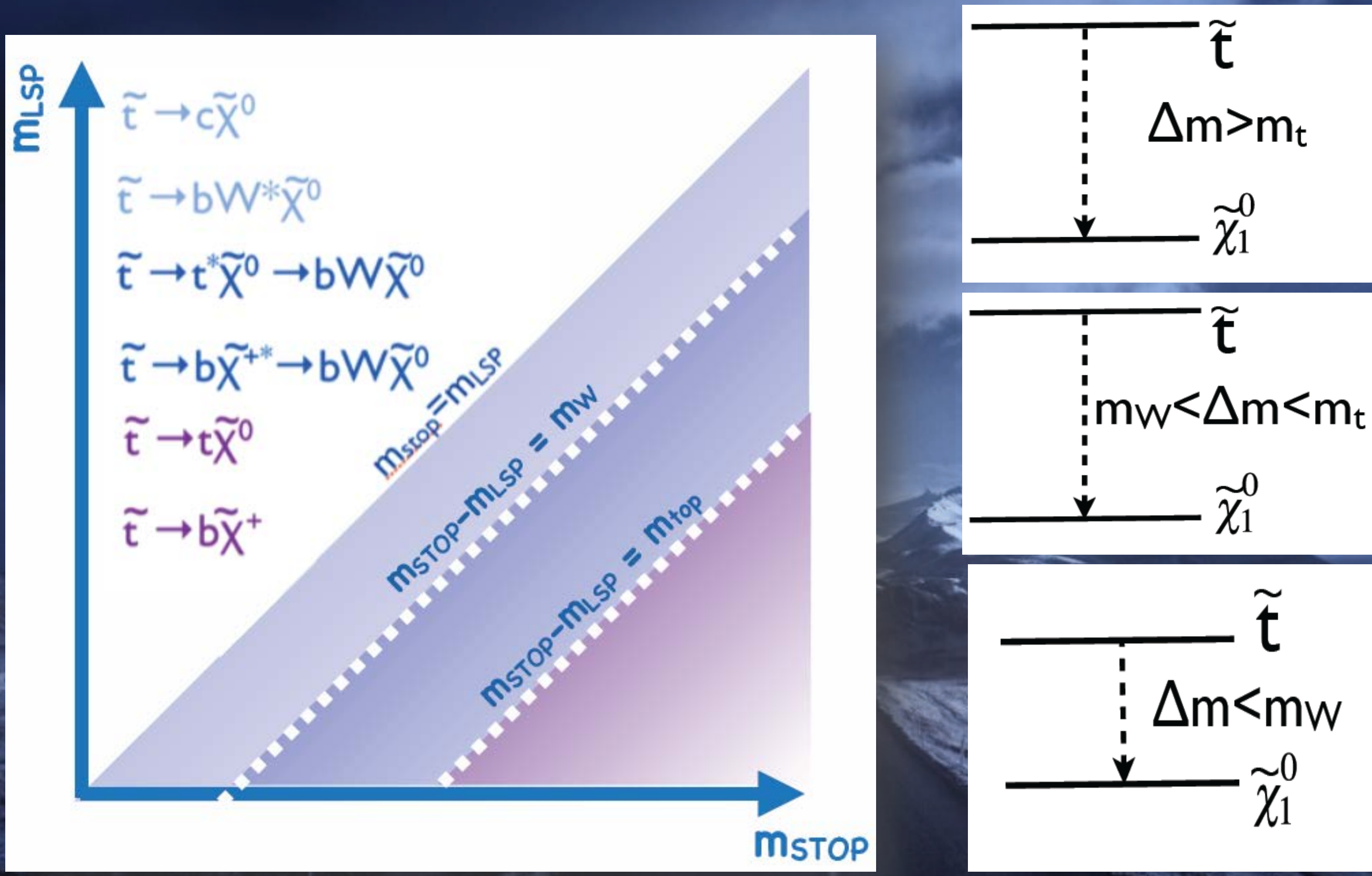


FIG. 7: A sample of constraints on the superpartner spectrum from naturalness (NAT), dark matter (DM), collider searches (LHC), the Higgs boson mass (HIGGS), flavor violation (FLAV), and EDM constraints (EDM). The constraints assume a moderate value of $\tan\beta = 10$. The naturalness constraints derive from a bottom-up analysis and scale as $(\mathcal{N}_{\max}/100)^{1/2}$, where $\mathcal{N}_{\max}$ is the maximally allowed naturalness parameter; see Sec. IV. All of the constraints shown are merely indicative and subject to significant loopholes and caveats; see the text for details.

see J.L. Feng arXiv 1302.6587v2

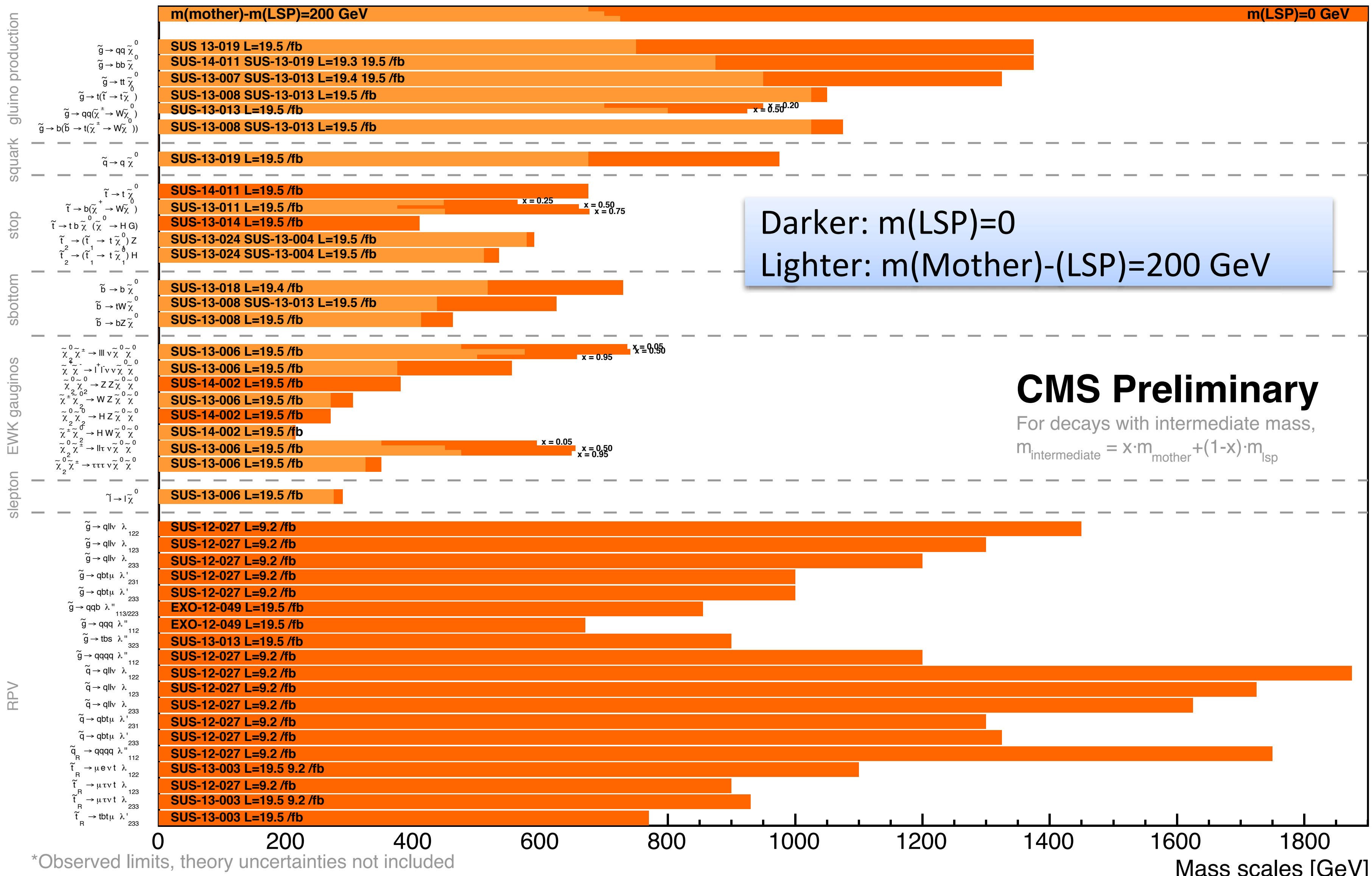
SUSY-top searches: final states



Joe Incandela (UCSB) - SSI16 - August, 26 2016 8/26/16

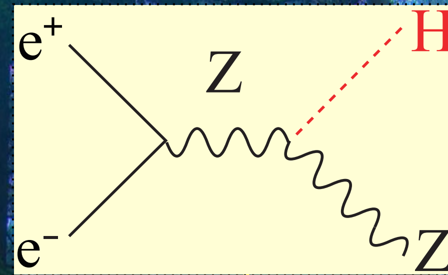
Slide courtesy M. Pierini

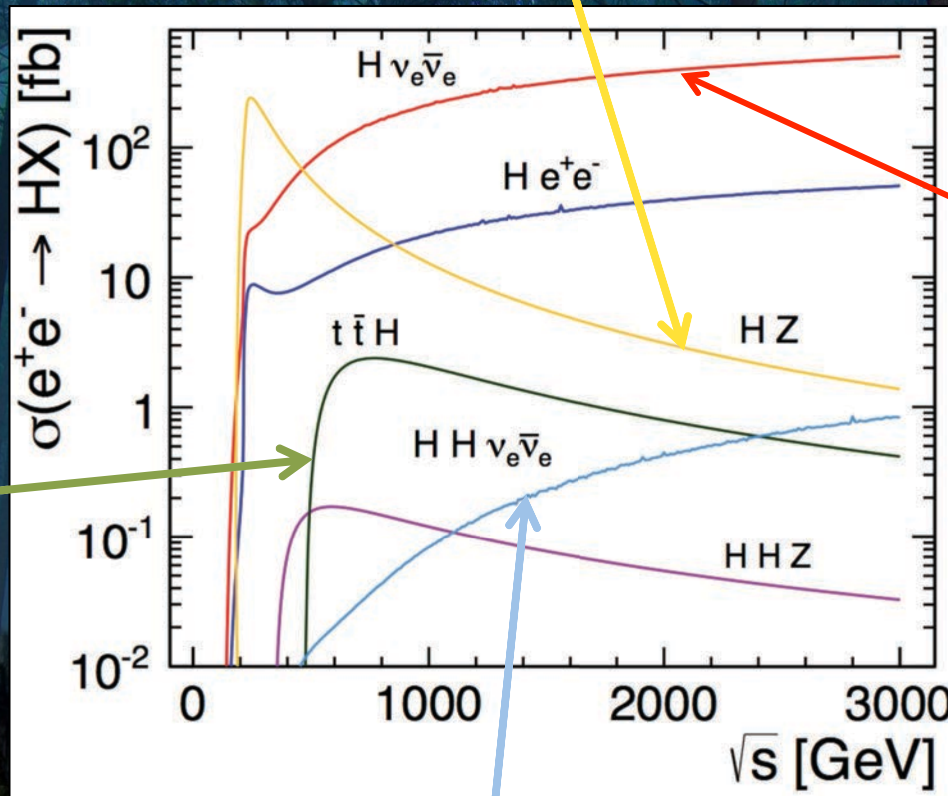
Summary of CMS SUSY Results* in SMS framework

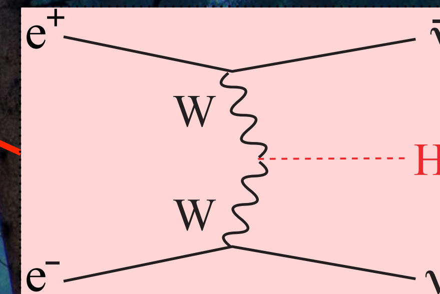


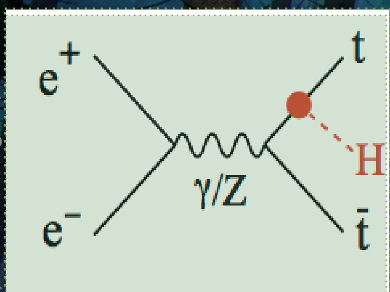
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

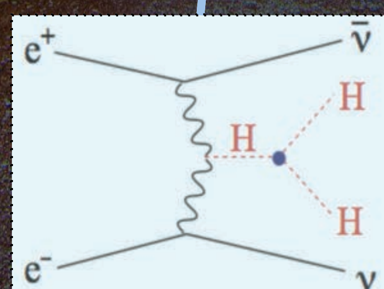
Higgs Production in e+e- colliders





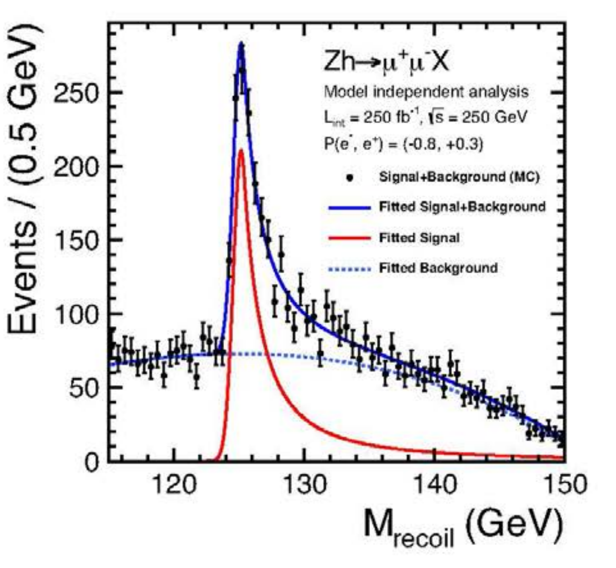






F. Gianotti, Higgs Hunting, LAL, Orsay, 1/8/2015

ILC Example: Higgs and Top

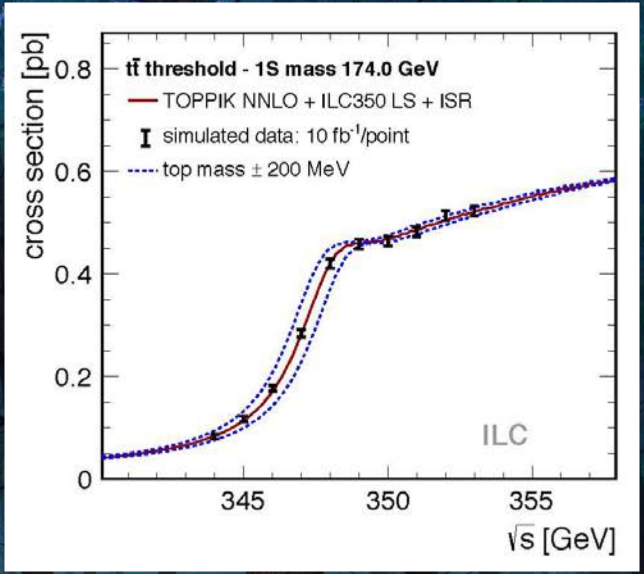


Higgs mass via recoil in Zh→ μμX events:

- σ_M < 30MeV
- xsec uncertainty <1%

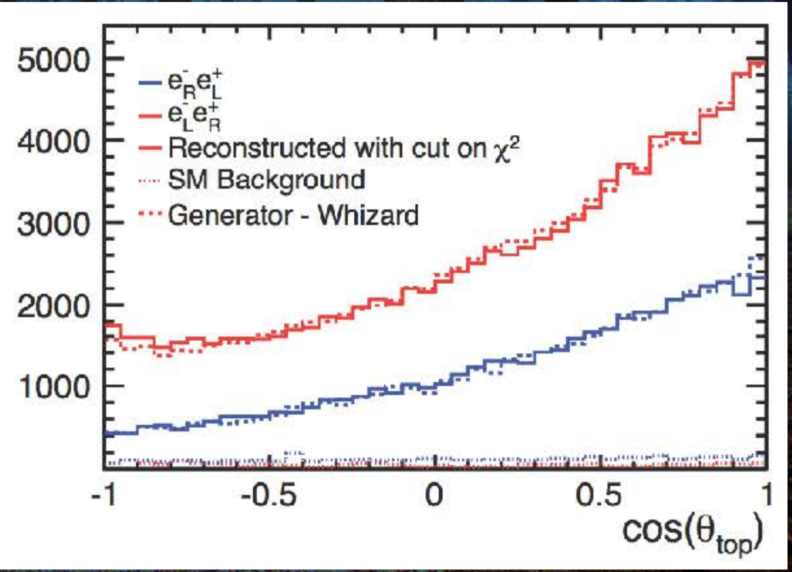
Top mass via 3-param fit to threshold, stat. errors:

- Mass ± 17MeV
- Γ_t ± 26MeV
- λ_t ± 4%



$t\bar{t}$ via s-channel γ and Z diagrams

- O(1) interference, constructive/destructive, depending on beam polarizations and top quark polarizations → Forward/Backward and polarization asymmetries



*arXiv:1506.05992