"FROM THE LHC TO DARK MATTER AND BEYOND": THEORY SUMMARY

ANN NELSON, MARCH 25, 2017

PRE LHC EXPECTATION

aspen 2012: 3 susy theory talks

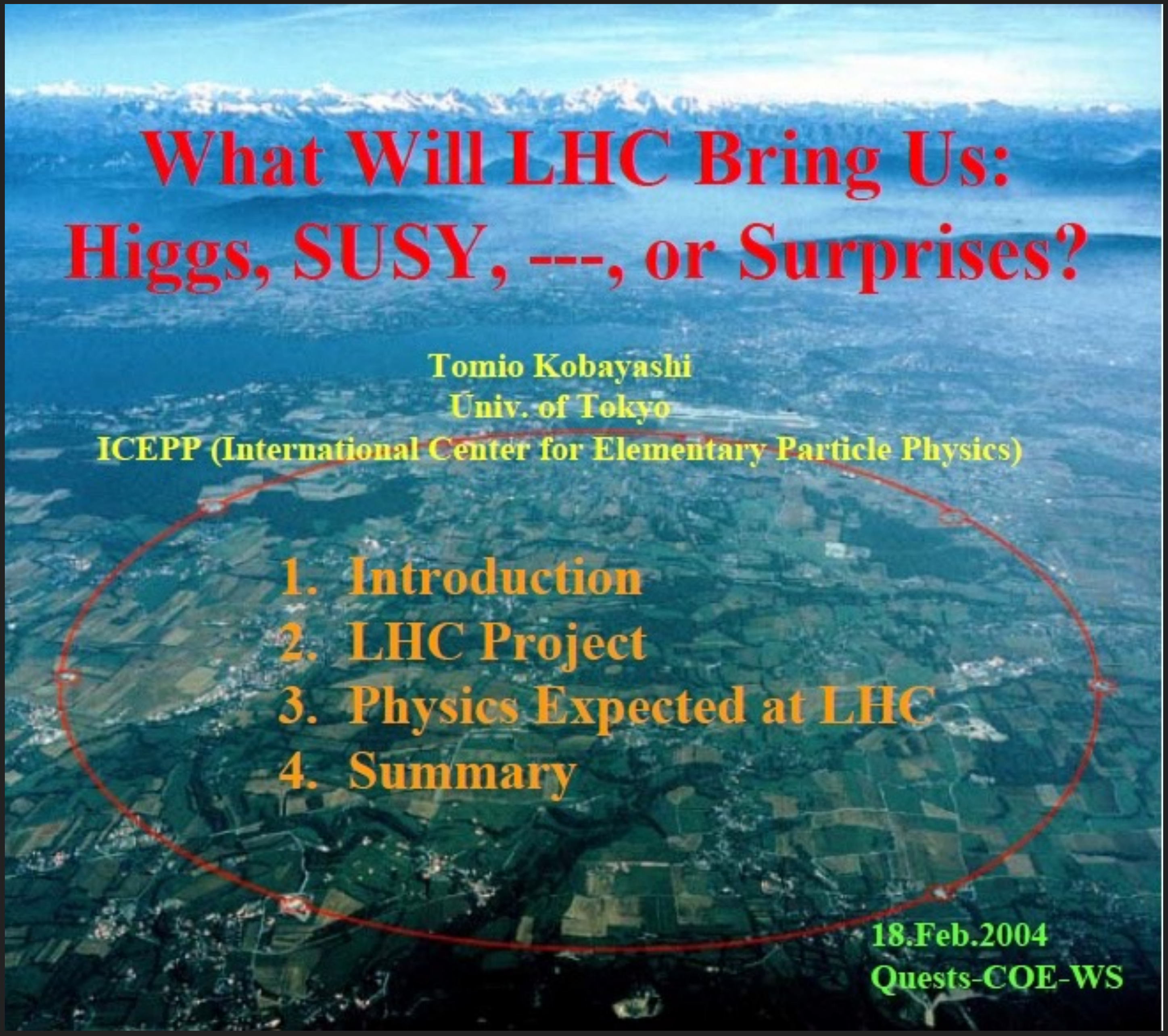
aspen 2013: 1 susy theory talk

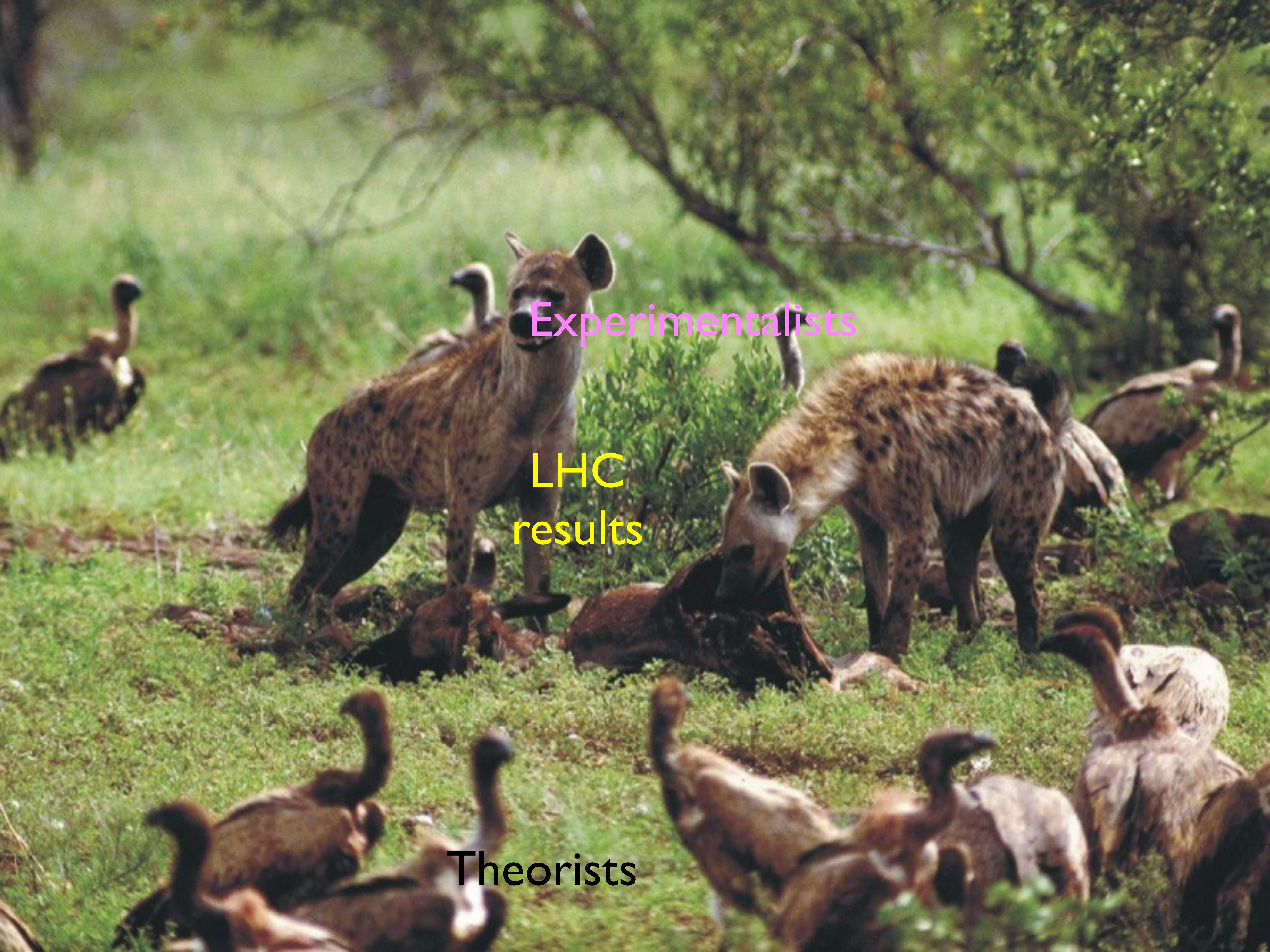
aspen 2014: 1 susy theory talk

aspen 2015: 1 susy theory talk

aspen 2016: 0 susy theory talks

aspen 2017: 1 (split) susy theory talks




Experimentalists
LHC
results
Theorists

PRE-LHC

- solution menu: SUSY, new dimensions, strong dynamics
  - ads/cft merged new dimensions/strong dynamics
  - Particle phenomenologists learn about CFTs
  - Georgi "unparticles"
  - a few adventurous theorists ventured into hidden valleys and other "non-standard" physics beyond the standard model
- Basic expectation among theorists (see inverse LHC problem games) was that signals would emerge and the issue would be figuring out the (likely SUSY) parameter space in BSM to fit them.

MOTIVATION FOR BEYOND THE STANDARD MODEL IS SUPER-ROBUST

- Hierarchy Problem
- Flavor
- Dark Matter
- Inflation
- Baryogenesis
- Neutrino mass
- Strong CP
- Self consistency/definition of Chiral Gauge Theory
- Consistency with Quantum Gravity
- Dark Energy
- Phenomenology exploration: e.g. Hidden Sectors+portals

SO WHERE IS THE NEW PHYSICS

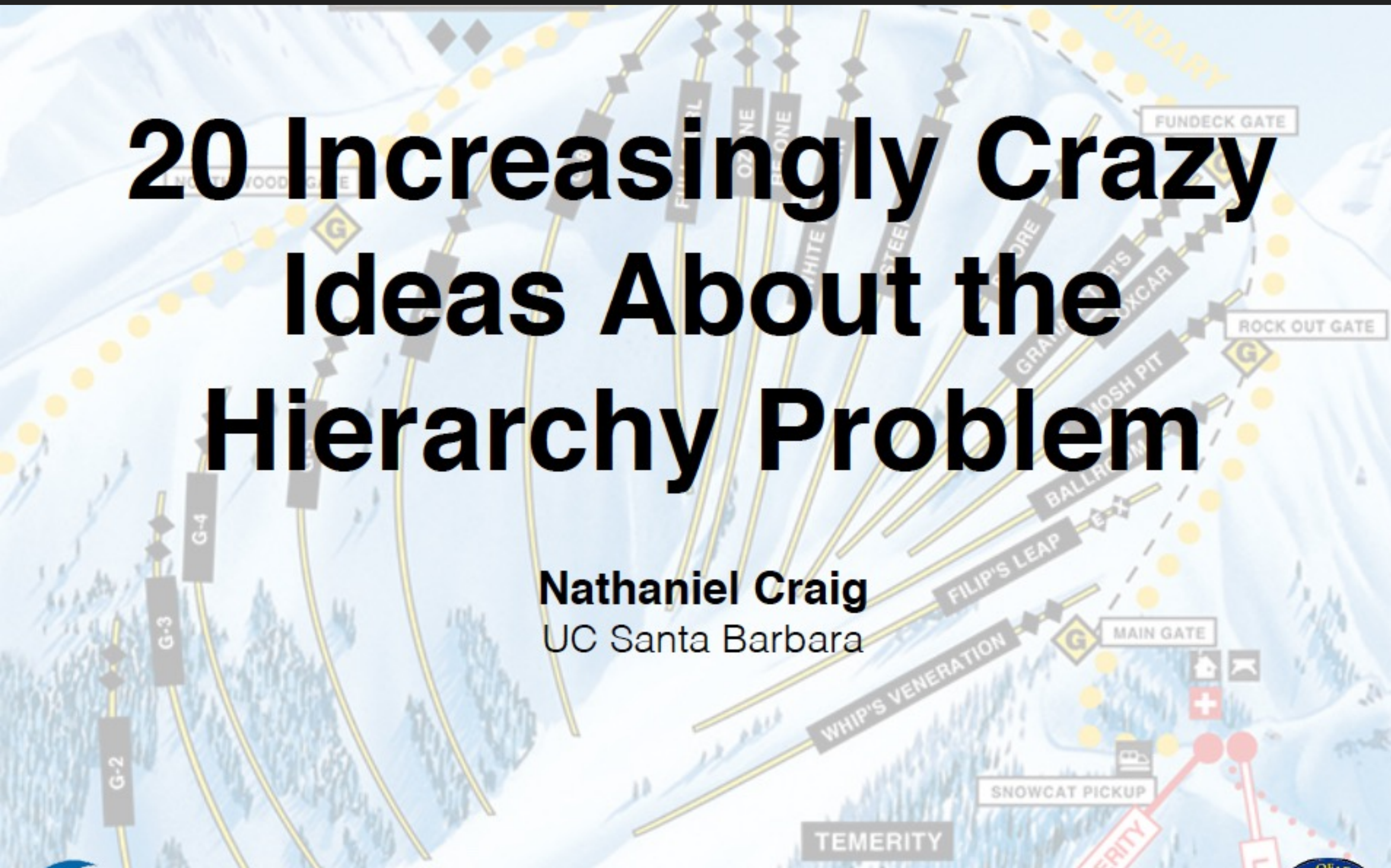
A MOVING TARGET–THERE HAVE BEEN MAJOR DISCOVERIES

- 1998: ν oscillations!
  - Wikipedia: no longer BSM “In particular, an interesting new model should address questions left unanswered in the Standard Model which has, including three massive neutrinos, 28 free parameters. “
- 1998: Dark Energy!
  - Wikipedia:”Standard cosmological model" redirects here. Lambda-CDM model
- 2012: LHC discovered the Higgs!
  - Every talk at this workshop: Higgs is not BSM
  - c. 1980 “the origin of electroweak symmetry breaking” considered mysterious, with a single fundamental scalar doublet considered one possible, not especially favored option.
- also, many CMB, lensing etc confirmations that dark matter IS something very new, extremely likely a new kind of particle

LHC SUPPOSED TO GIVE US CLUES

- (and has done)
  - A standard model(-like) Higgs at 125 GeV!
  - a big clue to what lies beyond standard model
  - lots of constraints
  - things should be settling down, theoretically

WHAT HAVE THEORISTS DONE WITH THESE CLUES?



THEORISTS HAVE BEEN RETOOLING

- exploring many ideas that used to be the playground of "formal" theorists
- proposing new experiments
- developing new jet techniques, new methods to analyze collider data, new tools to analyze data from the sky, new collider searches, even proposing new detectors and leading new experimental collaborations
- improving old ideas with new insights

"STILL ALIVE?"

Joe Lykken, BSM review talk at DPF 2002, compares strongly couples EWSB with Rolling Stones

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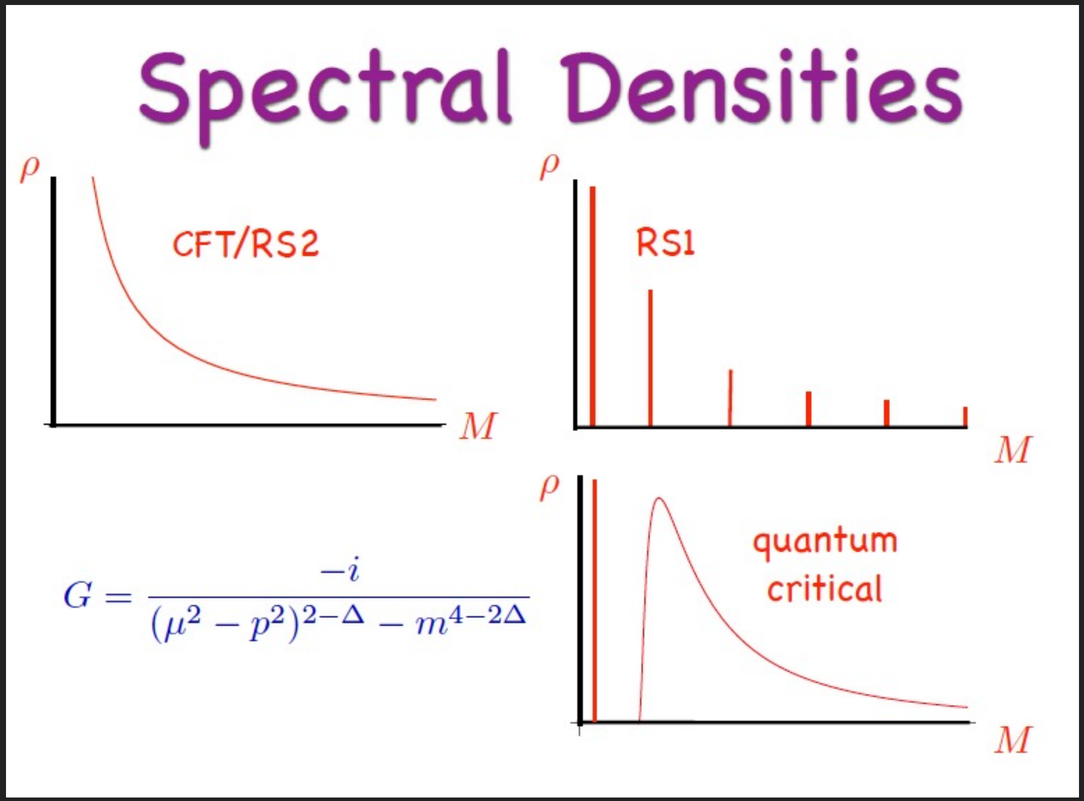
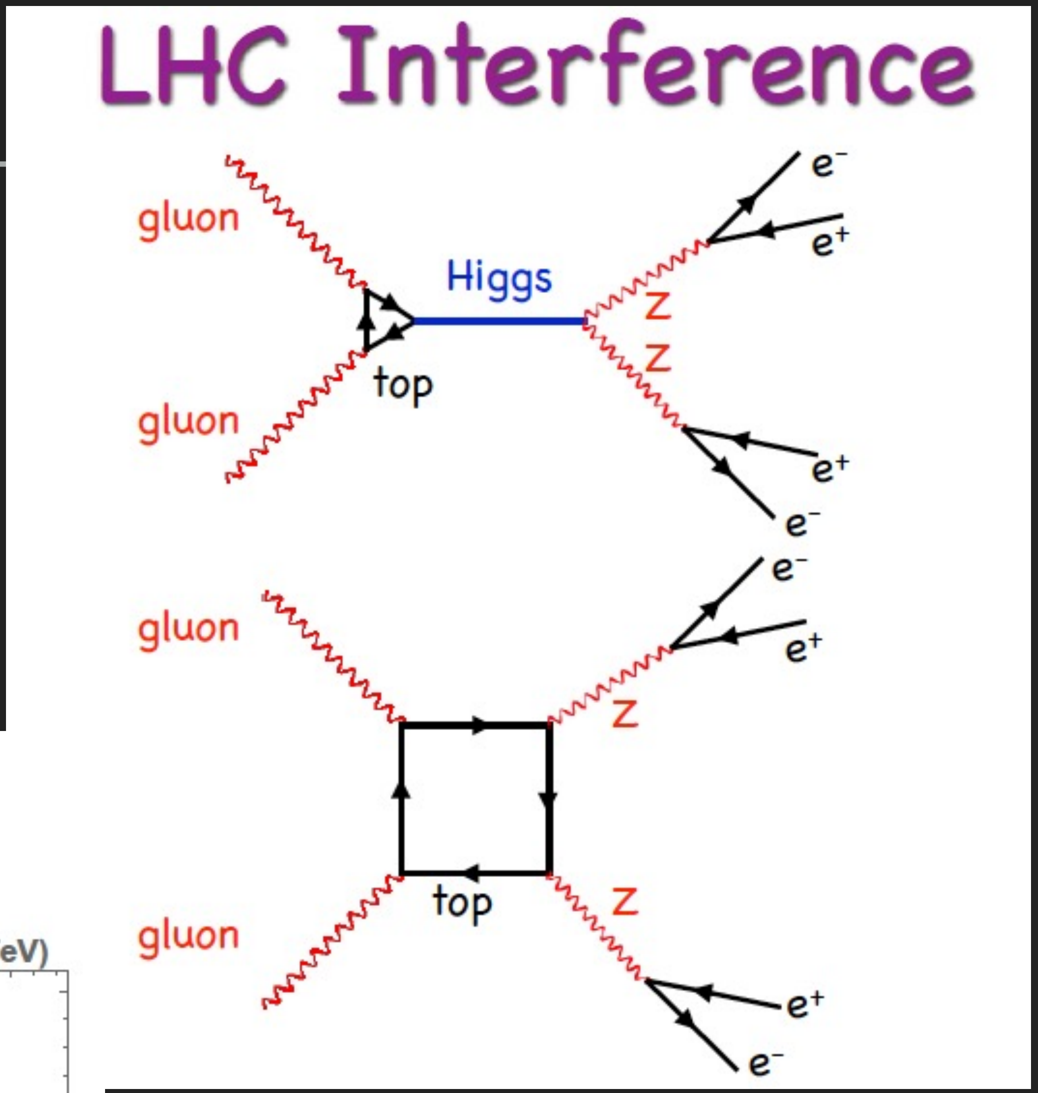
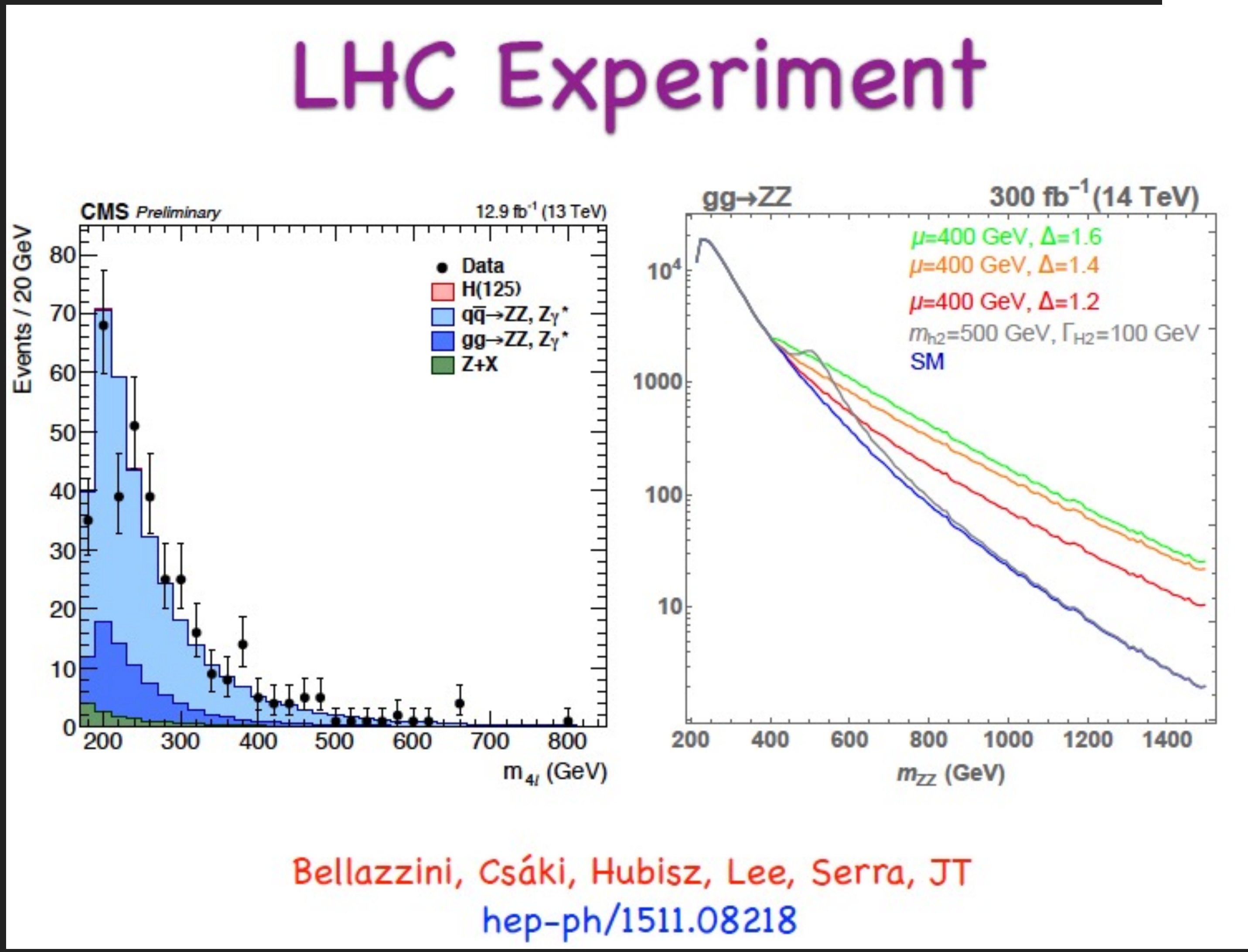
LOOKING BETTER THESE DAYS



- Terning: "Quantum critical Higgs"
  - RS 2 with soft IR brane
  - Higgs scalar +
- if within LHC reach do not use eft expansion
- LHC can test critical exponents
- Weiler, Geller: PNB Composite Higgs coupled to partially composite fermions
  - old ideas of Kaplan, improved ingredients from Randall-Sundrum, Little Higgs
  - "Good ideas can take a long time to mature"
    - (old examples of good ideas that took a while to figure out how they work: quarks, Yang-Mills, Spontaneous symmetry breaking)
- These theories look good because they look pretty close to standard model but with new physics which is still viable
- Can still avoid fine-tuning
- Weiler: dark matter too!

QUANTUM CRITICAL POINT





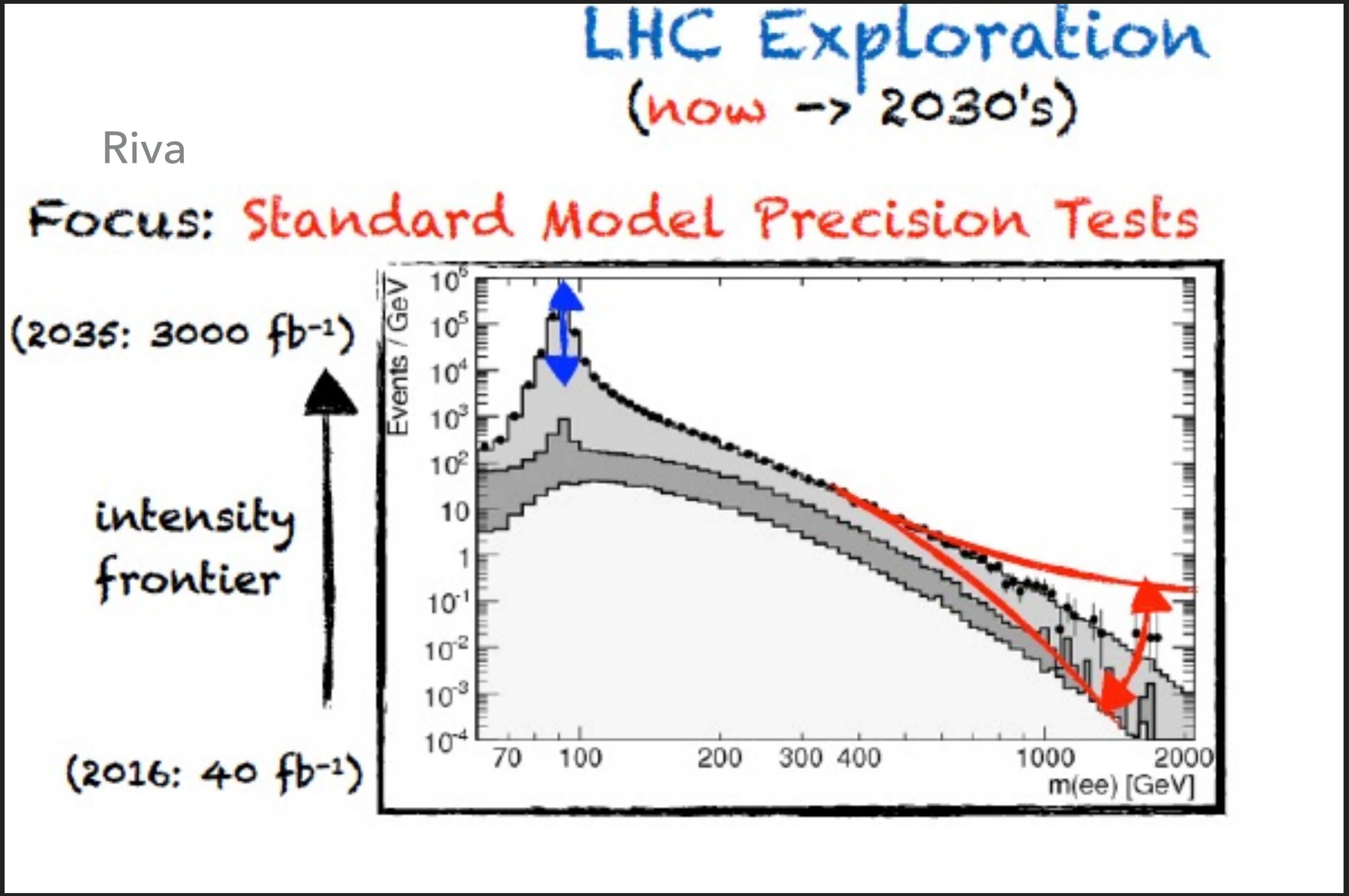
SUSY AND THE MSSM NO LONGER RULE THE BSM PLAYGROUND

- Composite higgs
- partially composite fermions
- "Randall Sundrum"/CFT UV completion
- minimal models/effective theories
- lattice explorations of conformal and nearly conformal theories

EXPLORATIONS

- Nathaniel Craig-20 ways from easy to difficult (less well understood theoretically/experimentally)
  - conformal symmetry/little conformal symmetry
  - no UV cutoff/scale (must unify at 10 TeV)?
- Matt Low-quirks (charged particles carrying new nonabelian gauge charge) search at CMS for curved tracks with magnet off. Even with limited data nearly competetive with other constraints

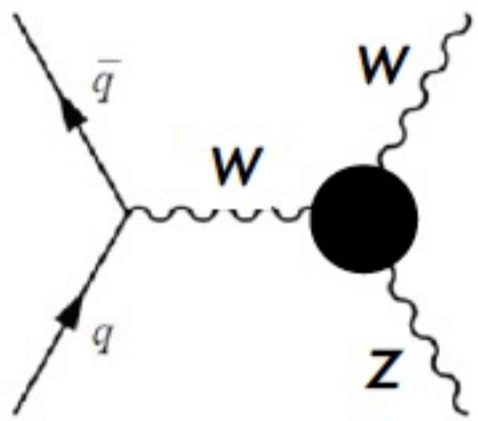
PRECISION LHC PHYSICS!



- Pomarol/Riva/Ruderman:
- Focus on SM deviations that grow with energy
- (cases where BSM in Dim 8> Dim 6> SM
- e.g. di-bosons sensitive to NP
- e.g. qq->ll
- longitudinal W and Z couplings– HLLHC needed
- “s-parameter of LHC in WWZ coupling” from 10% deviation in WZ m(WZ) > 300 GeV

DI-BOSON SENSITIVITY

Testing universal theories



$$\frac{\delta \mathcal{M}_{00}}{\mathcal{M}_{00}^{\rm SM}} = 1 - \frac{\hat{s}}{m_Z^2}\delta g_1^Z$$

Shift of the SM **WWZ-coupling**

Franceschini,Panico,AP,Riva,Wulzer

"The S-parameter of the LHC"

$(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$ → δg_1^Z, S

Composite Higgs: $\delta g_1^Z \simeq -\frac{\hat{S}}{2\cos^2\theta_W}$

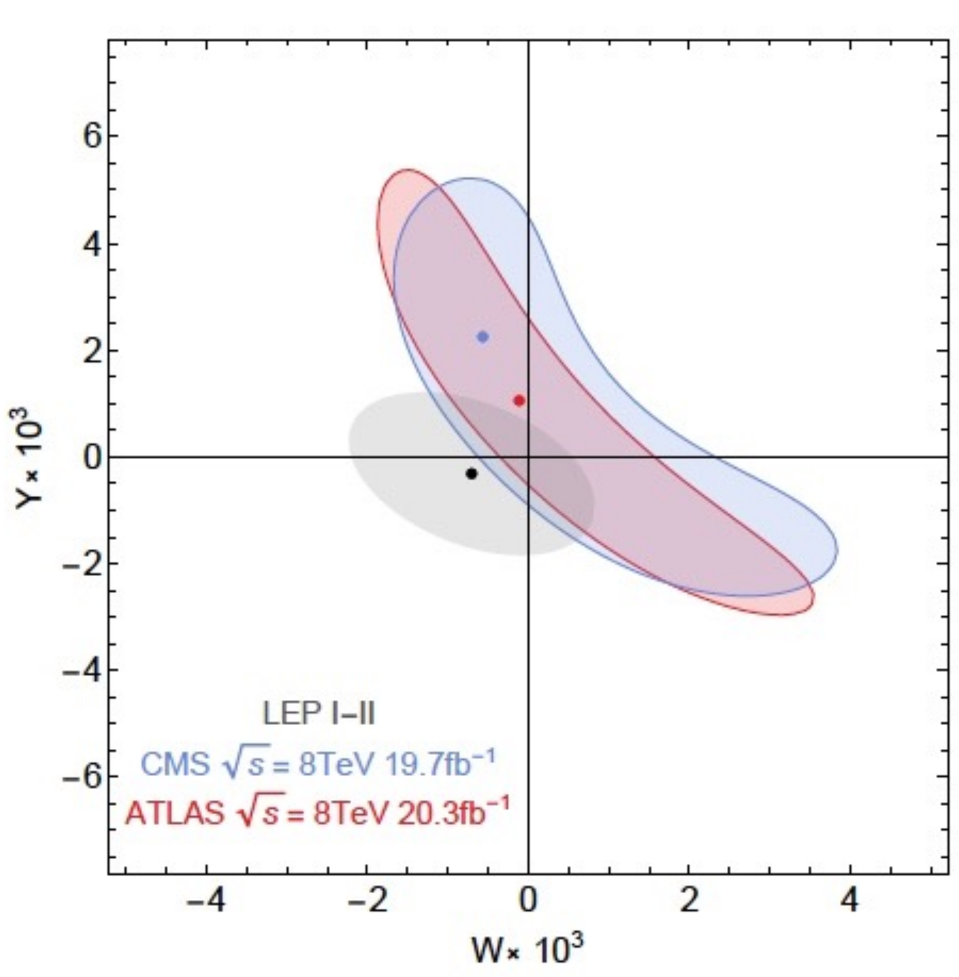
Sequential W': $\delta g_1^Z \simeq -\frac{\hat{S}}{\cos^2\theta_W}$

PRECISION LHC PHYSICS

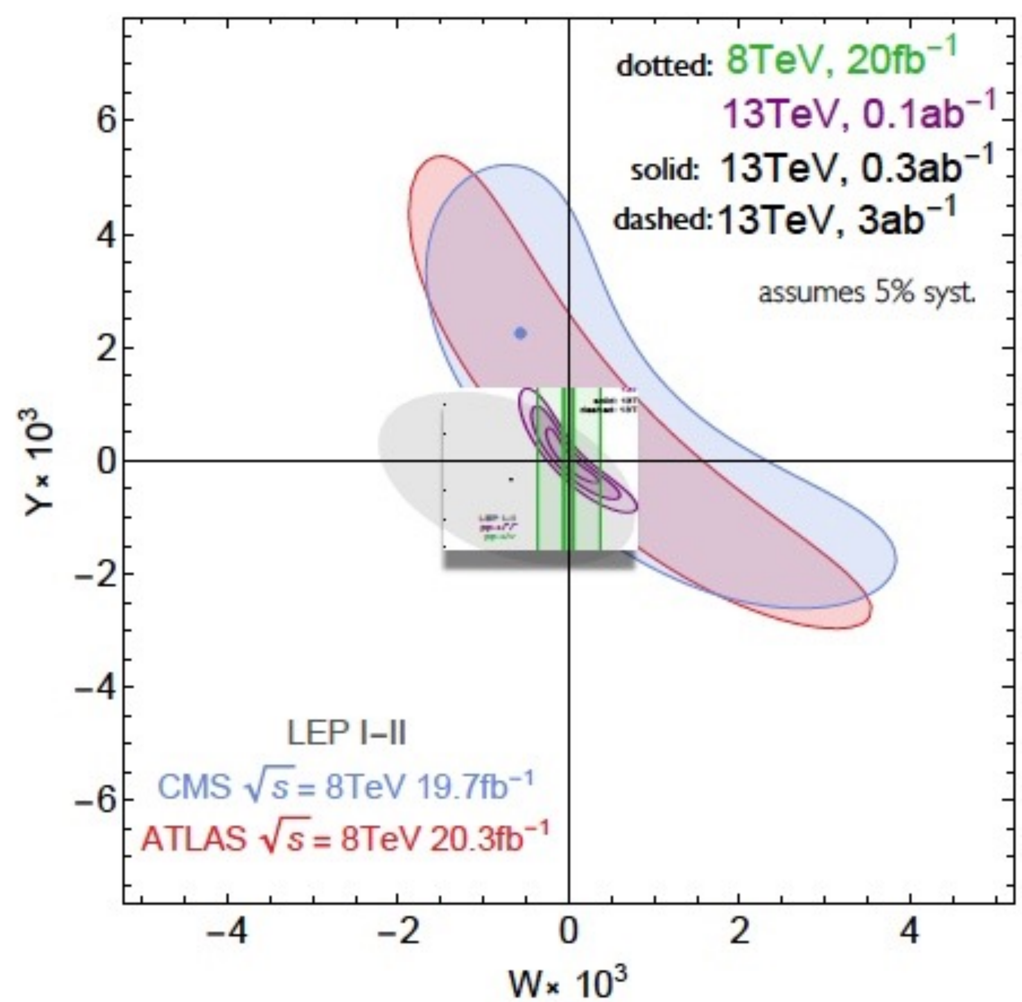
- Ruderman: oblique parameters STWY at LEP VS LHC. Focus on WY effects ("gauge boson compositeness") as these grow with energy so LHC can compete with and beat LEP. Equivalent to 4-fermi current-current operator.
- could arise from heavy sequential gauge bosons
- Interference with SM gives LHC good sensitivity

W, Y FROM $q\bar{q} \to \ell\bar{\ell}, \ell\bar{\nu}$:

8 TeV LHC already competitive w
high-precision LEP measurement



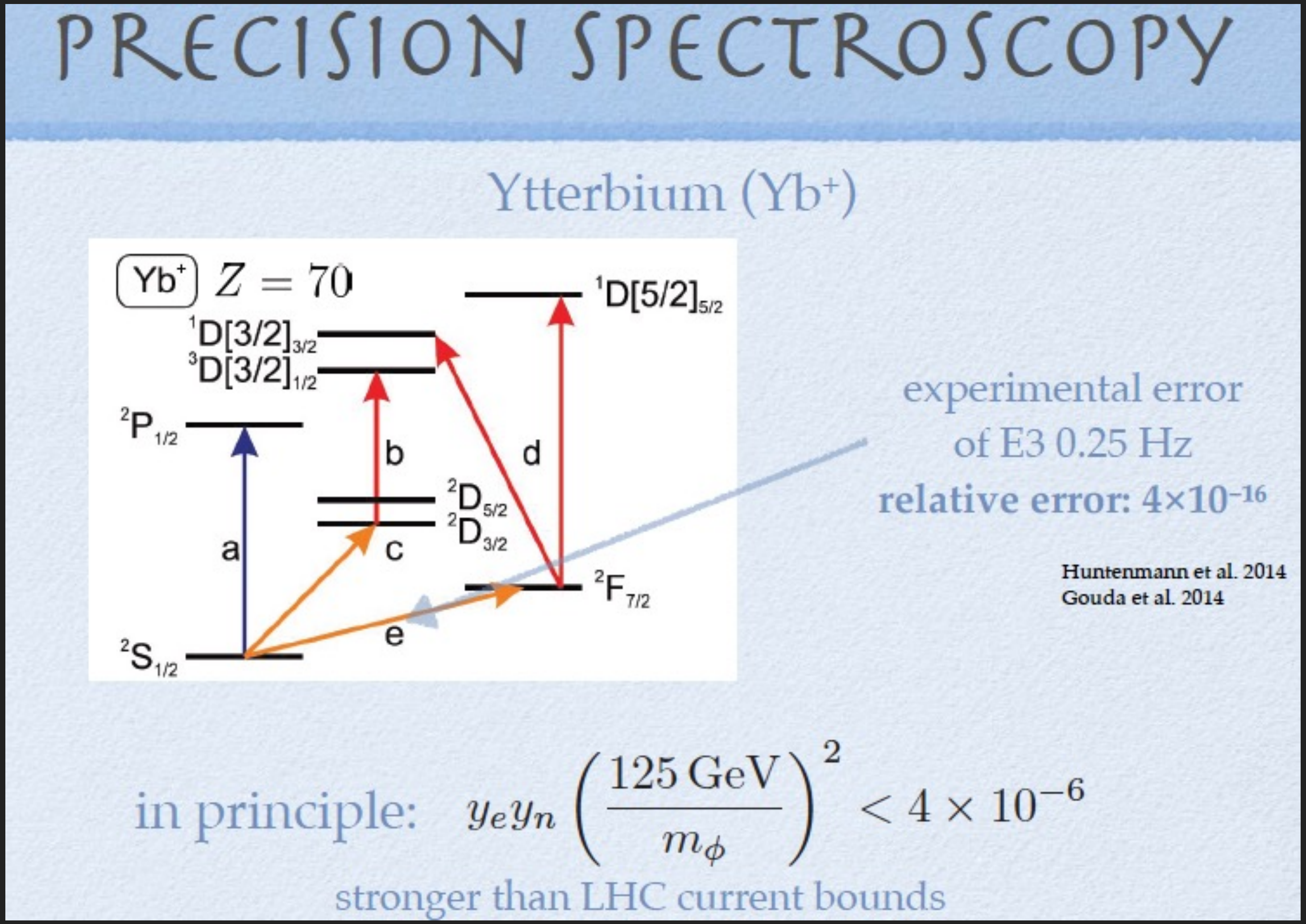
Improving by an order of magnitude for the 13 TeV 300/fb



M.Farina, G.Panico, D.Pappadopulo, J.T.Ruderman, R.Torre, A.Wulzer
arXiv:1609.08157

ISOTOPE SHIFT

- Yotam Soreq: constraining light new bosons with couplings to e and n



“just when you think you can forget something it becomes important”

- Belle II will probe new physics with 50 times previous B physics data~2.5 times higher energy
- Ligeti: B-> $D^{(*)}$ τ ν anomaly (3.9 σ). Sizable lepton universality violation? theory uncertainty is under control using heavy quark symmetry + corrections+ lattice theory + e, μ channels
  - tree level effect, new particle(s) at weak scale
  - scalar or vector lepto-quark? W’? scalar doublet?
  - suppress e, μ modes? (CKM changes)
  - 10% violation of e, μ universality allowed experimentally
  - look at B-> D^{**} τ ν

TOP

- Kamenik: NP reach in top sector (4t production, Htt, boosted)

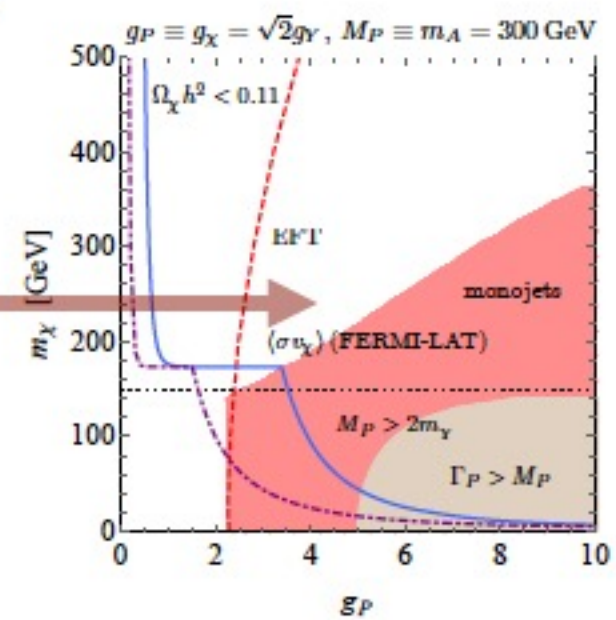
Simplified DM model with (pseudo)scalar mediator

$$\mathcal{L}_{\rm DM} = i\, g_\chi\, A\, \bar{\chi}\gamma^5\chi + \sum_{f=q,\ell,\nu} i\, g_f\, A\, \bar{f}\gamma^5 f$$

- Direct DM detection (spin, momentum) suppressed $\sigma^N_{\rm SD} \propto \frac{q^4}{m_N^4}$
- Naturally SM Yukawa-like couplings: $g_f = \sqrt{2}\, g_Y\, m_f/v$
  - DM becomes effectively 'top-philic'
  - ➡ Reduced LHC mono-X sensitivity

Haisch & Re, 1503.00691

- Suppressed missing E_T signals for $m_\chi > m_A/2$



DARK SECTORS

- Gori: displaced vertices with Seaquest
  - 120 GeV proton beam fixed target 10^{18}POT
    - O(1) mesons/proton
  - displaced vertices from dark
  - iDM with dark photon
  - extend with ShiP ~2026

DARK SECTORS

- Lisanti, Pradler-direct detection of ~ keV-GeV dark matter
  - thermal dark matter
  - electron scattering
  - photons from nuclear recoils
  - semimetal and semiconductor targets
  - PTOLEMY-G3 directional dark matter

DARK STARS

- Freese
- first stars powered by dark matter (WIMP) annihilation,
- mechanism for supermassive stars,
- very large, cool, luminous, long lived
- observable with JWT (indirect evidence for WIMPS)
  - future program of constraining dark matter properties

EARLY UNIVERSE TO LHCB

- Wei Xue
  - thermal dark matter MeV-10 TeV
  - focus on MeV-GeV range (Not Forbidden Dark Matter (mx~<1.5A' mass 3<->2 processes dominate in early universe, can change thermal relic and still survive)
    - (if annihilates via vector portal to e+e- ruled out by CMB)
    - LHC can explore nonruled out parameters for dark phton to e+e- D*-> D γ*,inclusive dimuon

STRUCTURE FORMATION, CMB

- Cyr-Racine
- ETHOS (Effective Theory Of Structure formation) classifying DM models by their structure formation properties (small number of parameters)
    - small scales
    - initial conditions (warm
    - structure formation (self interacting
- CMB-fraction of dark matter which does not cluster is small
- subdominant components will be constrained by (ν mass)

DATA FROM THE SKY IS LEADING TO WAY TO NEW PHYSICS

- now with neutrinos too! ICECUBE! (note Halzen is theorist)
- inflation tests (Flauger)
  - and models (e.g. Tangarife)
- Green: CMB, large scale structure gives very powerful way to constrain long lived/light particles and ν mass indirect detection/ constraints on Dark Matter (Safdi)
- But we still must do everything possible in lab, including neutrino mass measurements (new ν properties/interactions can mean model dependence in comparison of lab and sky results)

STILL DO NOT FULLY UNDERSTAND COSMOLOGY OF AXIONS

- Prescod-Weinstein: BEC? implications?
    - need simulations with quantum effects included to see how many axions end up in mini-structures and what sizes

LATE BARYOGENESIS FROM OSCILLATIONS

- McKeen: Baryogenesis at ~10 MeV from oscillating neutral hadrons
  - either “mesinos” (quark-anti-squark) or heavy flavor baryons (e.g.bcd, bcs, css)
  - produce via late decay of neutralino, then oscillate and decay
  - baryon violation in $\Delta B=2$, Δc or $\Delta b=2$ operators (not very constrained by stability of matter)
  - CPV in oscillations give baryogenesis

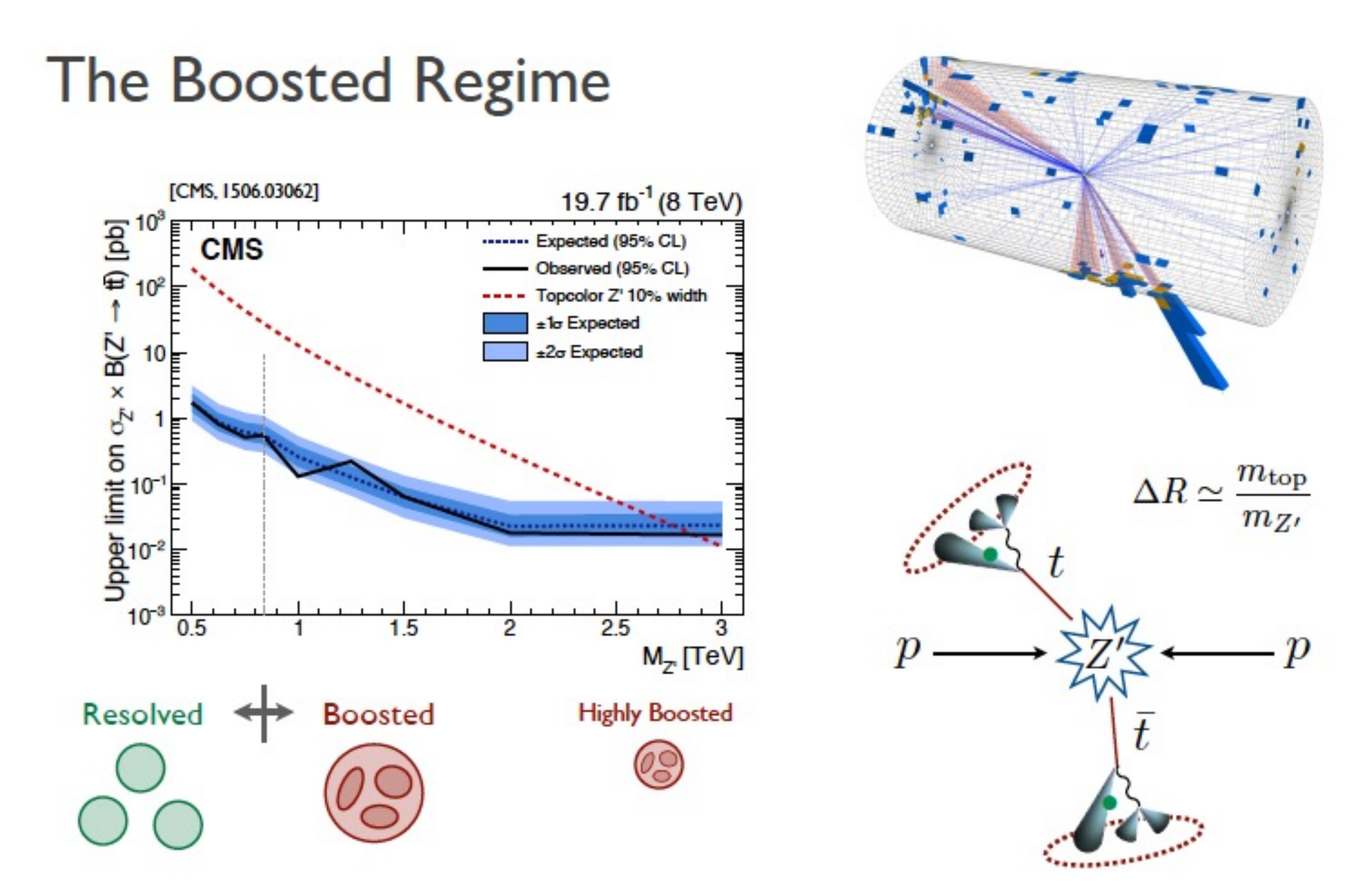
HIGGS RELAXATION

- Pearce
- 125 GeV Higgs-> flat potential-> large initial Higgs field expectation value->"era of Higgs relaxation"-> post inflation departure from thermal equilibrium
- uses Cohen-Kaplan "spontaneous baryogenesis mechanism. CPV and departure from equilibrium (still need to provide L violation)

$$\mathcal{O}_6 \propto -\frac{1}{\Lambda_n^2}(\partial_\mu \phi^2) j^\mu_{\mathrm{B+L}}$$

JET SUBSTRUCTURE–E.G. BOOSTED TOP TAGGING

- Thaler: techniques getting technical! machine learning, combinations of different strategies,



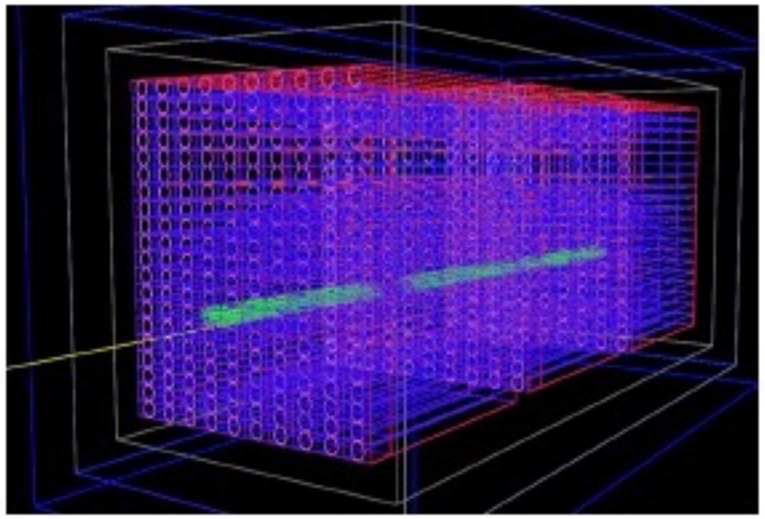
LIFETIME FRONTIER

- Curtin-Long Lived Particles generic and motivated, require new techniques
- MilliQan-new LHC detector to search for particles with tiny charge
- MATHUSLA-new LHC detector to search for particles which decay outside the main detectors

MILLI-CHARGE

- Is there more than 1 photon?
- "Hidden U(1)"
- Kinetic mixing give standard photon milli-coupling to hidden charges.

MilliQan



An Expression of Interest to Install a Milli-charged Particle Detector at LHC P5

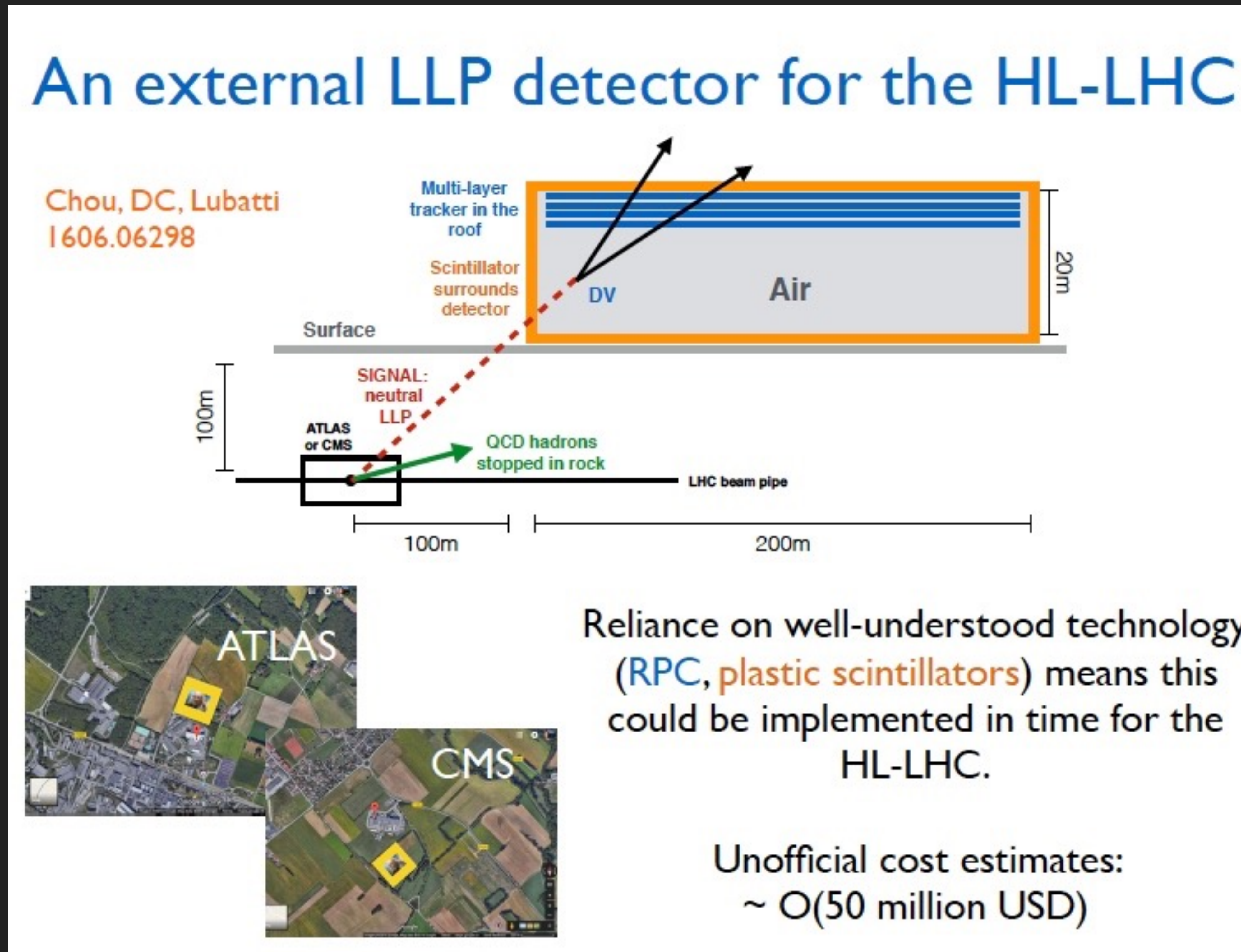
Austin Ball,[1] Jim Brooke,[2] Claudio Campagnari,[3] Albert De Roeck,[1] Brian Francis,[4] Martin Gastal,[1] Frank Golf,[3] Joel Goldstein,[2] Andy Haas,[5] Christopher S. Hill,[4] Eder Izaguirre,[6] Benjamin Kaplan,[5] Gabriel Magill,[7,6] Bennett Marsh,[3] David Miller,[8] Theo Prins,[1] Harry Shakeshaft,[1] David Stuart,[3] Max Swiatlowski,[8] and Itay Yavin[7,6]

Latest schedule for ENGINEERING RUN 2017:
Summer (TS1)- install support structure, cables, services, etc. in tunnel
Fall (TS2) - install 12 PMTs/scintillators, electronics, perform calibrations
Take data with beam through the end of 2017, and in 2018!

Install full detector in 2018-20 in time for Run3 (300/fb).

MATHUSLA

- explore lifetimes up to the BBN bound ($c\tau<10^8$m)
- measure masses, lifetimes
- is MET dark matter?



MIRROR FERMIONS IN STANDARD MODEL?

- Kaplan–using “gradient flow” to decouple mirror fermions
  - “fluffy” mirror fermions only couple to ultra long wavelengths of gauge field.
  - still couples to topology
  - fluffy massless quark=non-local extension of standard model to solve strong-CP?

Proposal is to get hide mirrors by making them infinitely fluffy, but could fluffiness be finite? (fluff=matter which couples only via very soft form factor but does not have light excitations)

WHERE IS THE NEW PHYSICS HANGING OUT?

- To help find out, theory is getting both weirder and more ‘exotic’
- simulataneously more bottom-up, data driven, using new ideas simplify old ones and make work better rather than add epicycles.
- Theorists are helping drive new experiments, new search strategies
- Even our condensed matter colleagues are helping! (new dark matter detection techniques, new ideas)