Physics of Future Circular Colliders

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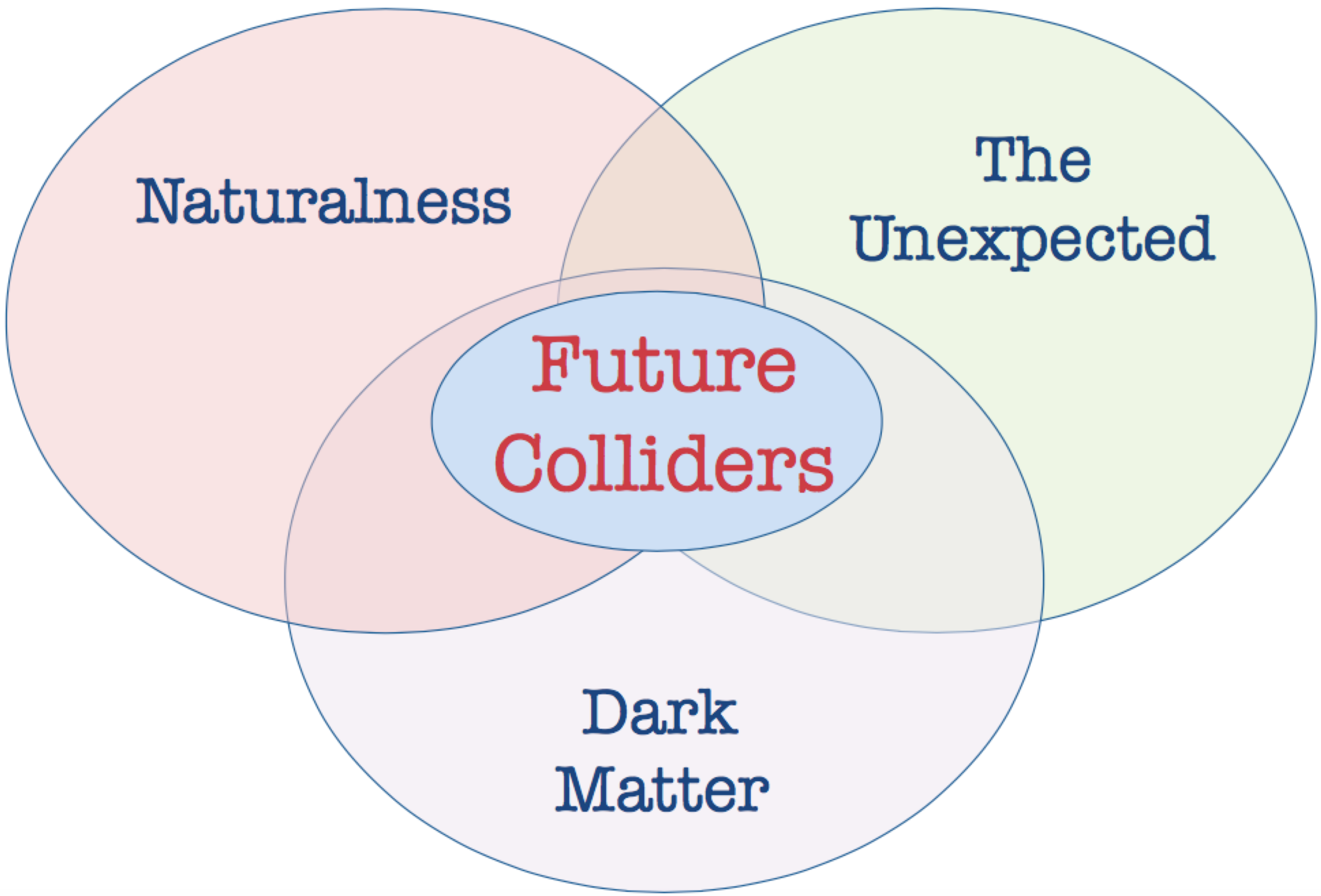


Dark Interactions – Perspectives from Theory and Experiment
Brookhaven National Laboratory, October 2016

Dawn of a New Age

- 2008 Nobel Prize in Physics

  "for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics"

- 2013 Nobel Prize in Physics

  "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Old and New Questions

- How to think of the vacuum as an “electroweak condensed state” ?
- How are the mysteries associated with a single, fundamental scalar field solved?
- What is the origin and nature of Dark Matter?
- What is the origin of the Baryon Asymmetry in the Universe?
- Why is Dark Energy so small but non-zero?
-
-

A Century of Particle Physics

- Success # 1: discovery of 6 quarks and 6 leptons
- 12 fundamental matter particles (and their antimatter counterparts) derived by combining quantum mechanics and special relativity

Quarks

$$\mathrm{u} < 1\ \mathrm{GeV} \quad \mathrm{c} \sim 1.5\ \mathrm{GeV} \quad \mathrm{t} \sim 175\ \mathrm{GeV}$$
$$\mathrm{d} < 1\ \mathrm{GeV} \quad \mathrm{s} < 1\ \mathrm{GeV} \quad \mathrm{b} \sim 4.5\ \mathrm{GeV}$$

But the intriguing pattern of mass values is not explained

Leptons

$$\nu_e < 1\ \mathrm{eV} \quad \nu_\mu < 0.17\ \mathrm{MeV} \quad \nu_\tau < 24\ \mathrm{MeV}$$
$$\mathrm{e}\ 0.5\ \mathrm{MeV} \quad \mu\ 106\ \mathrm{MeV} \quad \tau\ 1.8\ \mathrm{GeV}$$

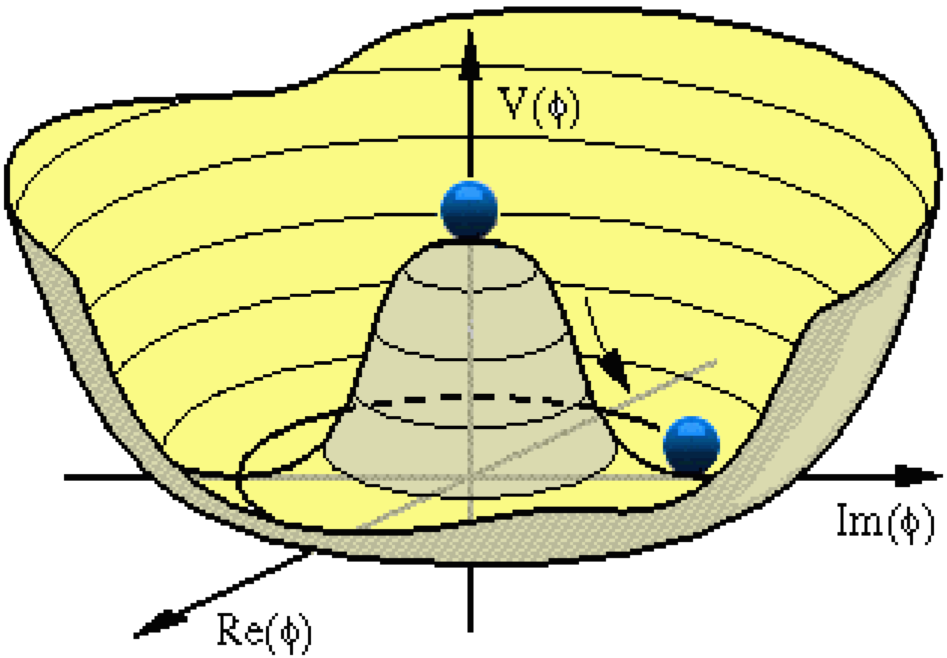
A Century of Particle Physics

- Success # 2: principle of gauge invariance for *predicting* the nature of fundamental forces
  - matter particles (quarks and leptons) transform in *curved* internal spaces
  - The equations of motion predict terms that describe particle interactions with force fields

Gauge sector $$L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}$$

Spontaneous Symmetry Breaking of Gauge Symmetry

- scalar Higgs field develops a vacuum expectation value (VeV) via spontaneous symmetry breaking
  - Goldstone modes appear as the new longitudinal modes of gauge bosons



- Phase transition → vacuum state possesses non-trivial quantum numbers
  - Dynamical origin of this phase transition is not known
  - Implies vacuum is a condensed, superconductor-like state

Fundamental *vs* Parametric Physics

- Fundamental principles lead to
  - Chiral fermions from irreducible representations of Lorentz group
    - fermions as spin ½ representations of Lorentz group
    - Fermi-Dirac statistics → Pauli Exclusion Principle
    - why matter occupies volume
  - Massless force mediators (gauge bosons) from gauge invariance
  - Massive gauge bosons and fermions from spontaneous breaking of gauge symmetry

- In comparison, the breaking of gauge symmetry by the Higgs VeV is parametrically induced
  - No dynamic or underlying principle behind it in the Standard Model

Why is Higgs Puzzling

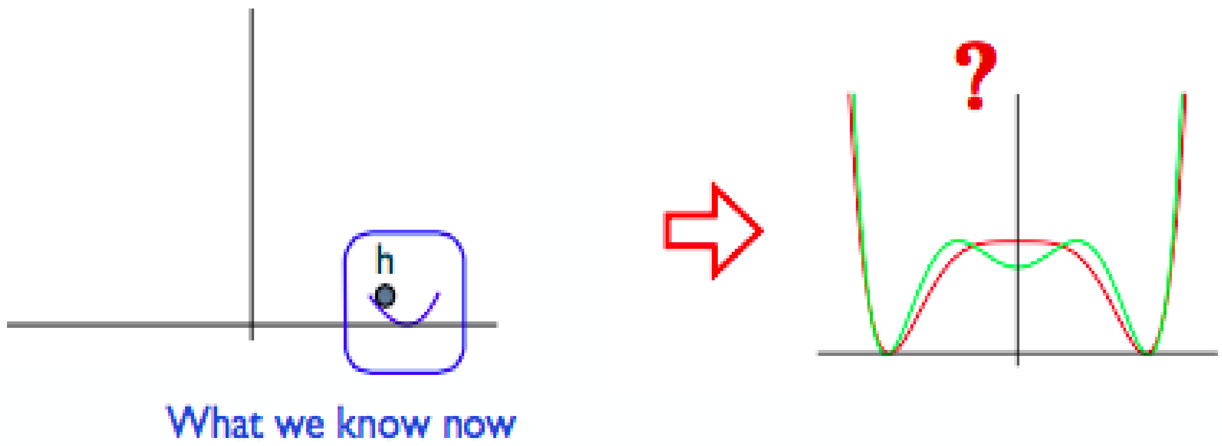
Gauge sector $$L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}$$

particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
Higgs	0

h: a new kind of
elementary particle

Higgs sector
$$L = \left(h_{ij}\bar{\psi}_i\psi_j H + \text{h.c.}\right) - \lambda|H|^4 + \mu^2|H|^2 - \Lambda_{CC}^4$$

Why is Higgs Puzzling



$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 \quad \text{or} \quad V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

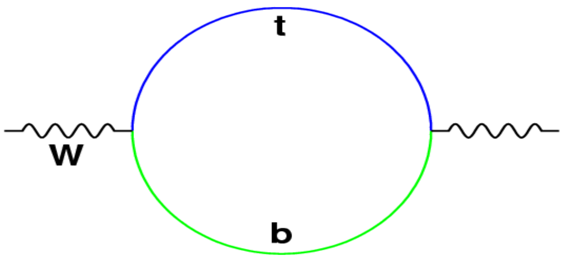
Ad-hoc potential, similar to and motivated by Landau-Ginzburg theory of superconductivity

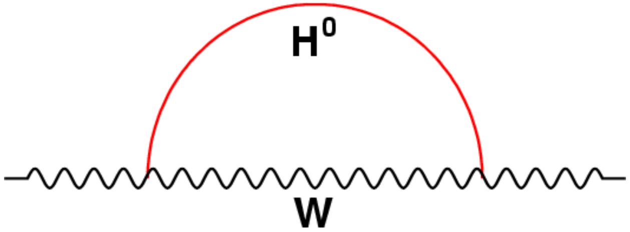
Higgs potential in SM can be extrapolated to Planck scale without additional parameters; but no a-priori reason for a parameterization to respect this condition

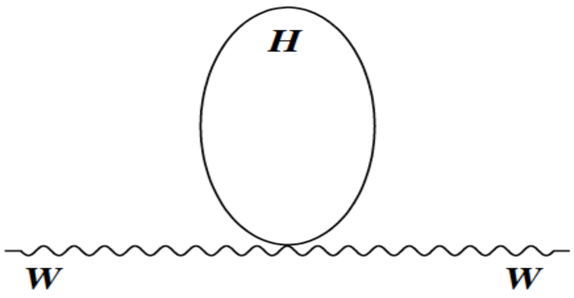
Radiative Stability of Higgs potential parameters

Test of Quantum Loops at High Energy – Example I

- W boson mass: radiative corrections due to heavy quark and Higgs loops



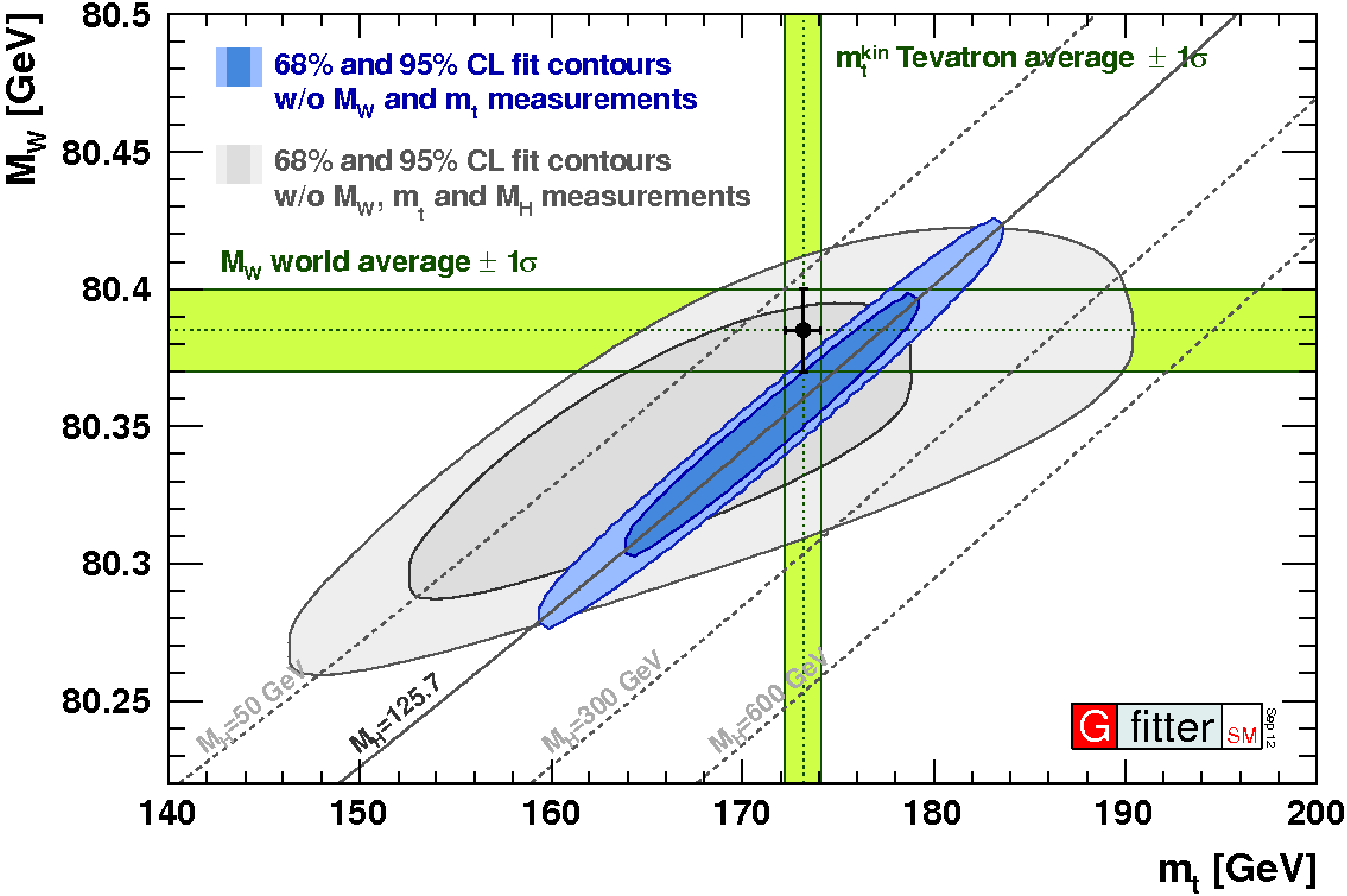




Motivate the introduction of the ρ parameter: $M_W^2 = \rho\,[M_W(\text{tree})]^2$
with the predictions $\Delta\rho \propto M_{top}^2$ and $\Delta\rho \propto \ln M_H$

- The top quark mass, the W boson mass and the mass of the Higgs boson provides a stringent test of the standard model at loop level

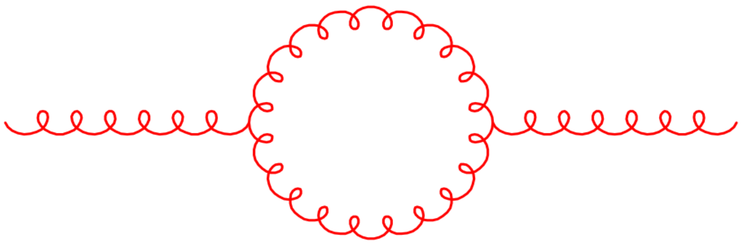
Test of Electroweak Quantum Loops at High Energy – Example I



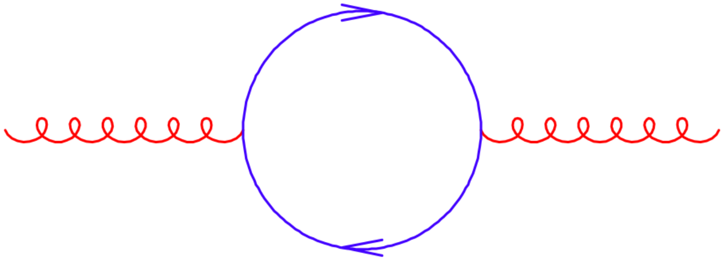
The top quark mass, the W boson mass and the mass of the Higgs boson provides a stringent test of the standard model at loop level

Example II - Asymptotic Freedom in QCD

QCD Lagrangian with no dimensionful parameters is scale-invariant classically
BUT quantum loops induce a distance (or momentum) scale dependence !



Color-charge *anti-screening* due to quark loops



Color-charge screening due to quark loops

Running of coupling constant induces an energy scale $\Lambda \sim 0.2$ GeV where coupling becomes large

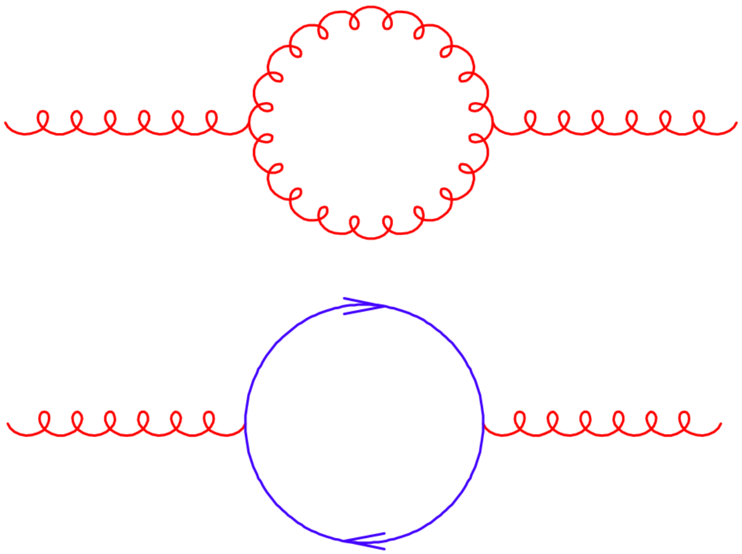
$$\alpha_s = \frac{6\pi}{(33 - 2N_f)\ln(\mu/\Lambda)}$$

N_f = Number of quark flavors

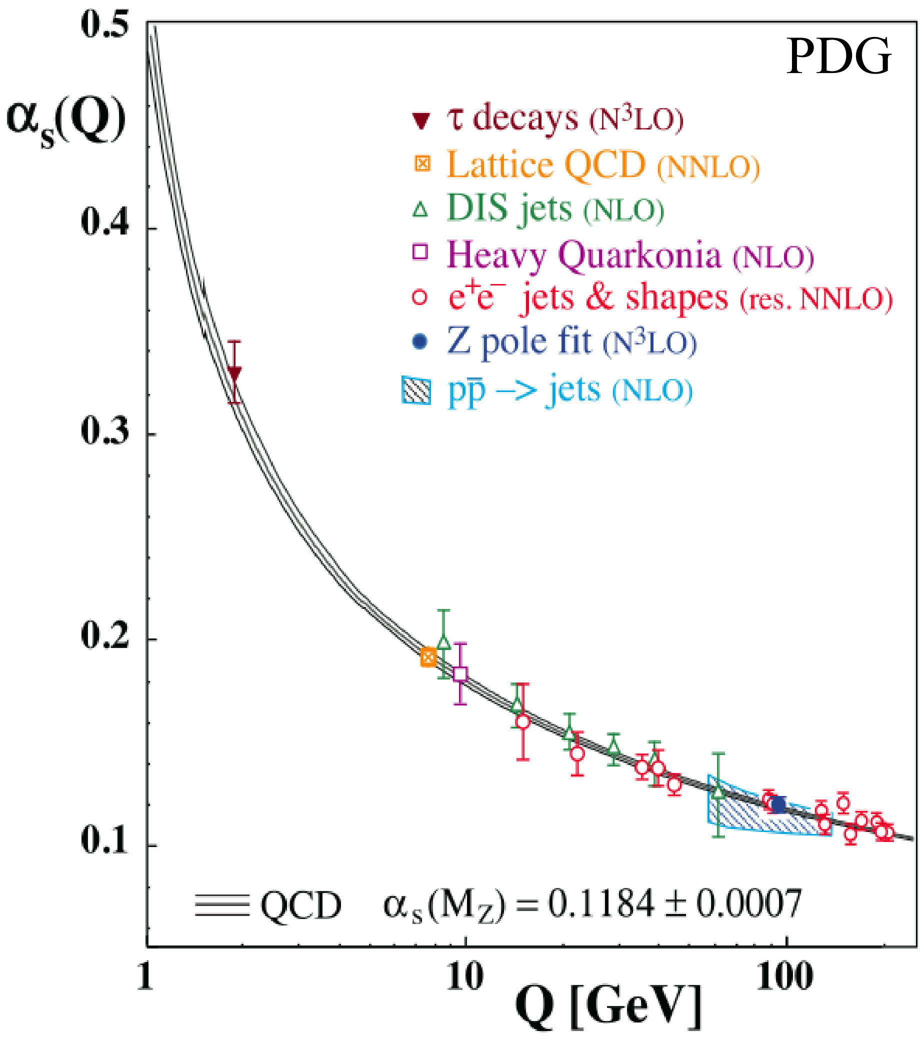
$\alpha_s \rightarrow 0$ as $\mu \rightarrow \infty$: asymptotic freedom

(2004 Nobel Prize for Gross, Wilczek, Politzer)

Example II - Test of QCD Quantum Loops at High Energy

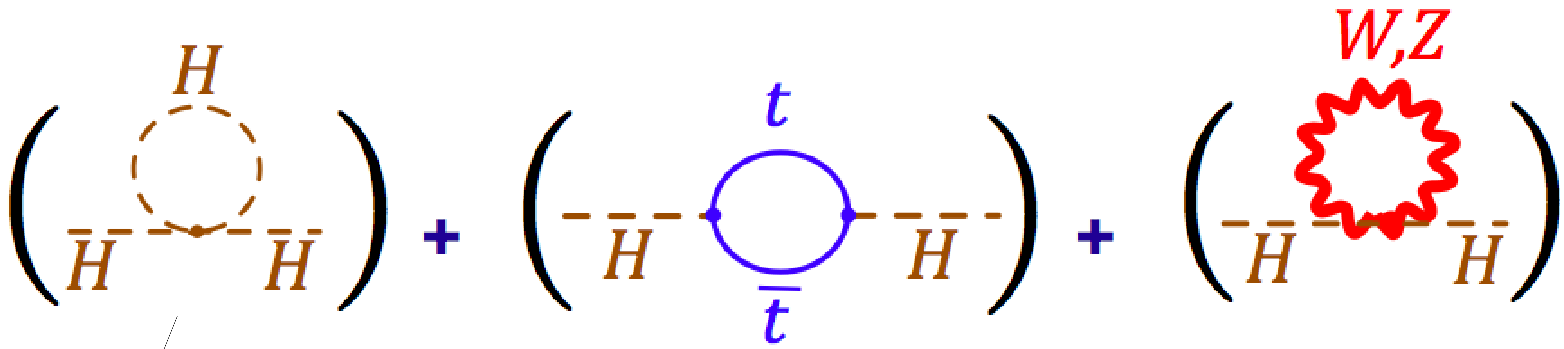


Running of strong coupling
has been confirmed experimentally



Why is the Higgs Boson so Light?

$m_H^2 - m_{\text{bare}}^2 =$



$$\lambda \int^{\Lambda} \mathrm{d}^4 k \, (k^2 - m_{\mathrm{H}}^2)^{-1} \;\sim\; \Lambda^2 \lambda$$

For the first time, we have additive corrections to parameters which are quadratically divergent

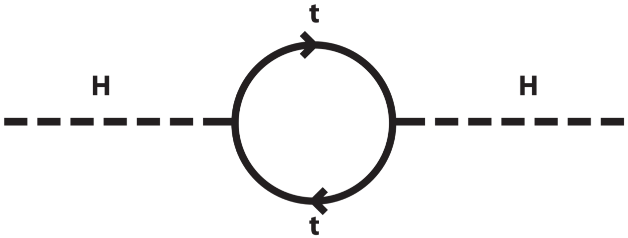
The Higgs boson ought to be a very heavy particle, naturally

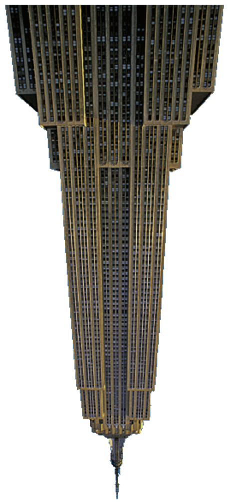
However, observed $m_{\mathrm{H}} << \Lambda$

Fine-tuning Problem of Higgs Boson Mass

- The divergent integral in this quantum loop must be regulated by a high-momentum cutoff, Λ, which could be the gravitational Planck energy scale $M_{planck} \sim 10^{19}$ GeV
  - Loop calculation gives Higgs boson mass correction $\sim M^2_{planck}$

Top quark loop



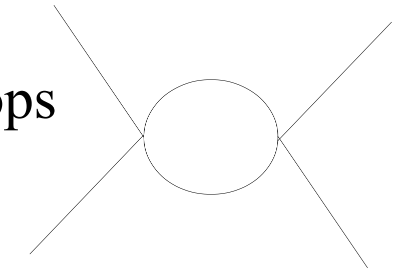


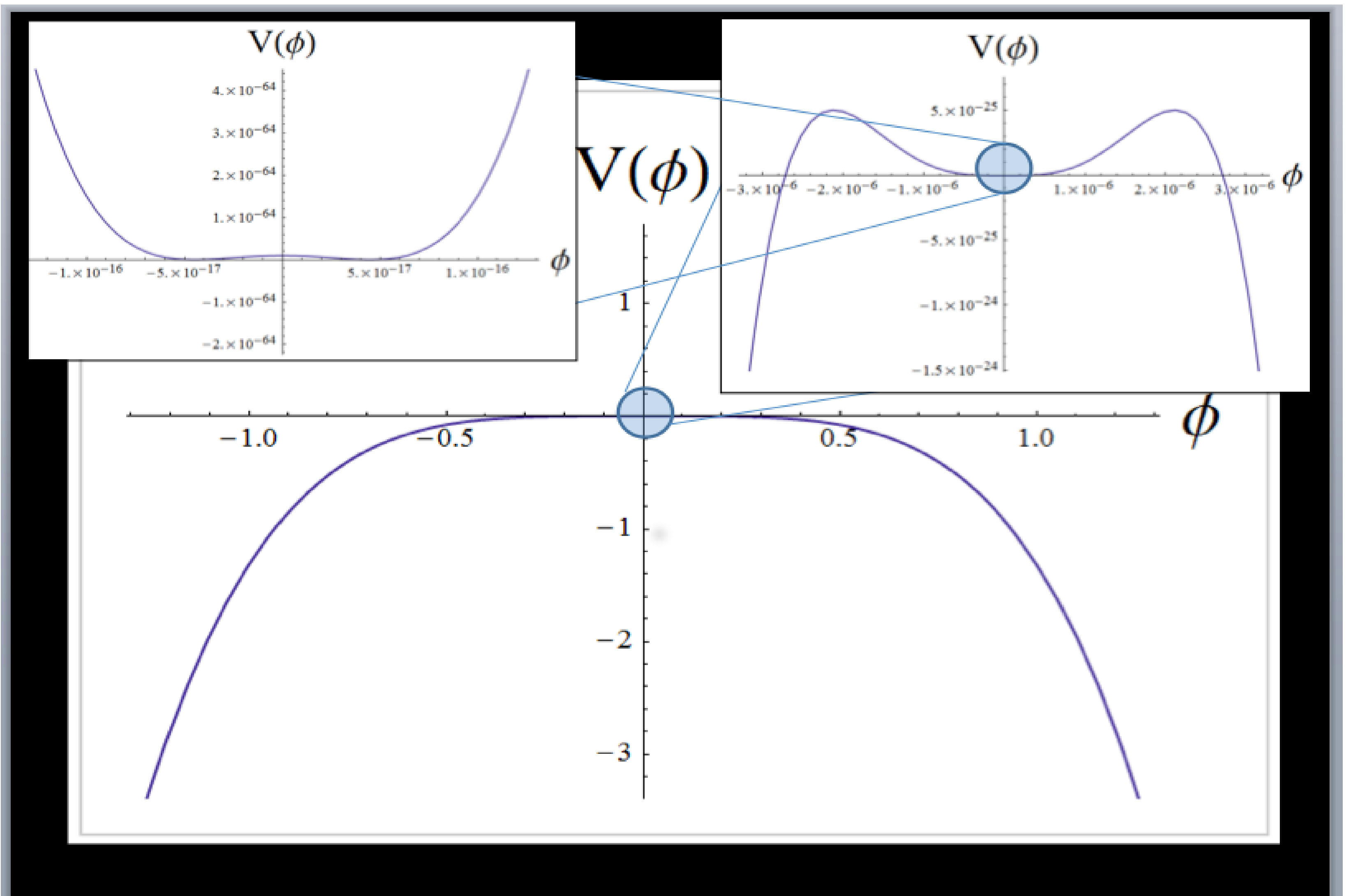
- physical Higgs boson mass ~ 125 GeV

- Therefore need extreme "fine-tuning" of bare lagrangian parameters at high energy

Radiative Corrections to Higgs Self-Coupling

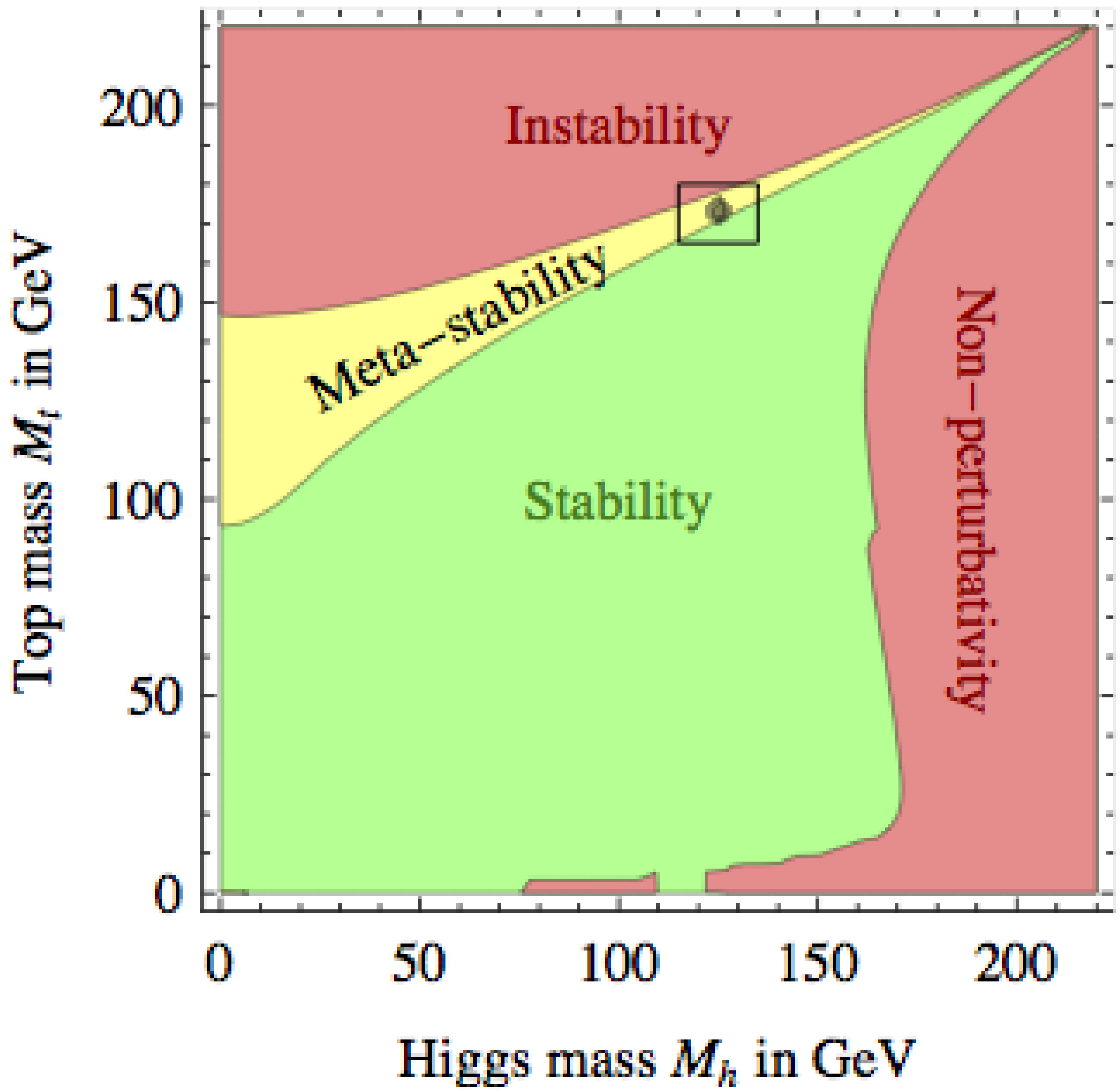
- $\lambda|\phi|^4$ receives radiative corrections from Higgs and top-quark loops





(from Paul Steinhardt)

Stability of Electroweak Vacuum



Higgs boson puzzles

- First fundamental (?) scalar field to be discovered
- Spontaneous symmetry breaking by development of a VeV
  - But VeV is induced parametrically by ad-hoc Higgs potential, no dynamics
- Parameters of Higgs potential are not stable under radiative corrections
  - First time that the radiative correction to a particle mass is additive and quadratically divergent
  - Gauge boson masses are protected by gauge invariance
  - Fermion masses are protected by chiral symmetry of massless fermions

- Single scalar Higgs field is a strange beast, compared to fermions and gauge bosons
- Additional symmetries and/or dynamics strongly motivated by Higgs discovery

A Toy Model for Strongly-Interacting Higgs Sector

- Consider a term coupling the Higgs to a singlet scaler *S*: $f\,\phi^\dagger\phi S$
- Via *S* exchange, can mediate scattering process: $\phi\phi \rightarrow \phi\phi$

$[\Box - m_S^{\,2}]^{-1} \sim m_S^{\,-2}[1 + \Box/m_S^{\,2}]$

- For energies << m_S, induces effective field theory operators:
  - Dimension-4: $(f/m_S)^2(\phi^\dagger\phi)^2$
  - Dimension-6: $O_{\phi d} = (f^2/m_S^{\,4})\,\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$
  - This is one of the operators predicted in strongly-interacting light Higgs models
  - alters Higgs couplings compared to SM

Next Steps for Electroweak Measurements

- Electroweak observables access all the mechanisms that can stabilize / explain the light Higgs mass
  - Is it stabilized by a symmetry such as SuperSymmetry ?
  - Is the Higgs boson a pseudo Nambu-Goldstone Boson?
  - Is there new strong dynamics ?
  - Do extra-dimensional models bring the Planck scale close to Electroweak scale?
- Motivation for a W/Z/Higgs factory (electron-positron collider)

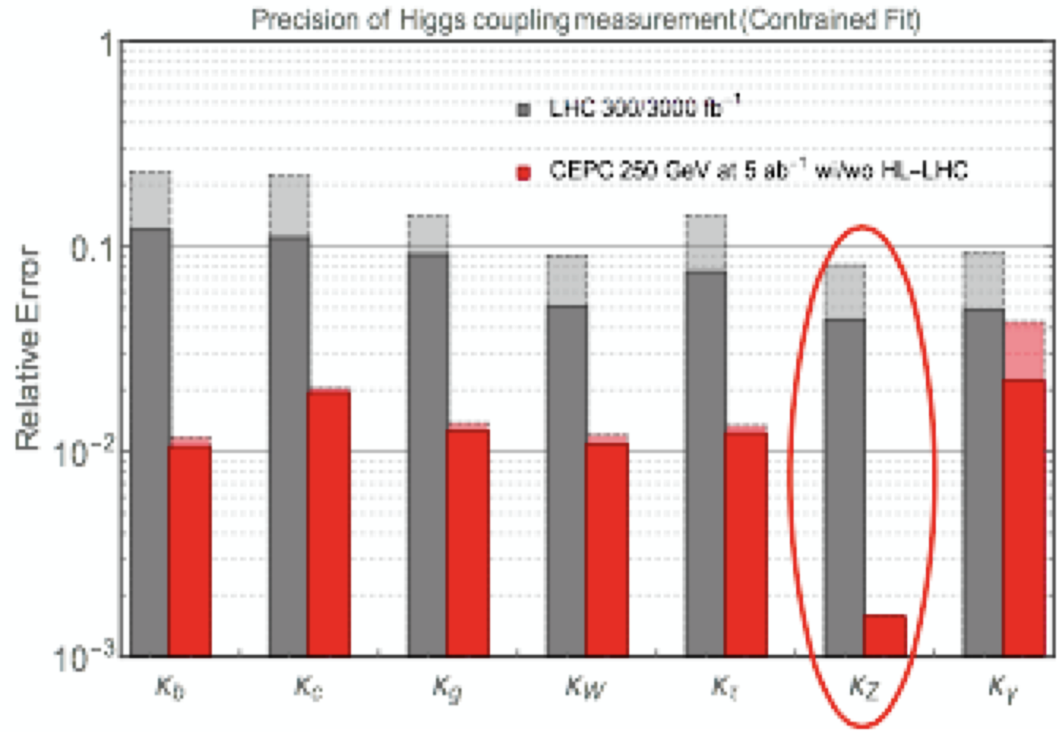
Circular Electron-Positron Collider

Circular e^+e^- Collider Physics Goals

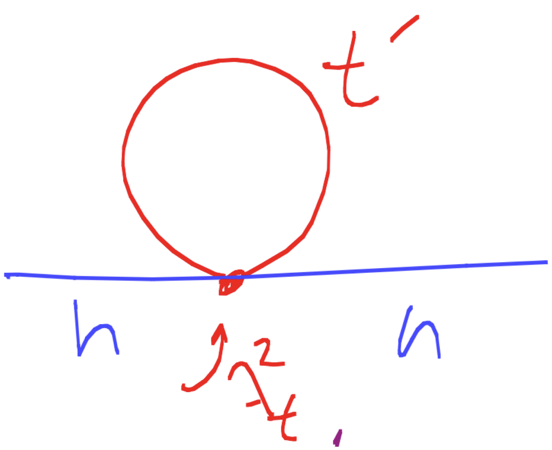
- 100 billion (CEPC) to 1 trillion Z bosons (FCC-ee)
  - 10K to 100K more statistics than LEP
  - 100 times smaller statistical errors
  - Potential for probing 10 times higher mass scales in loops
  - Current electroweak precision observables already probing new physics at the few TeV scale through dim-6 operators

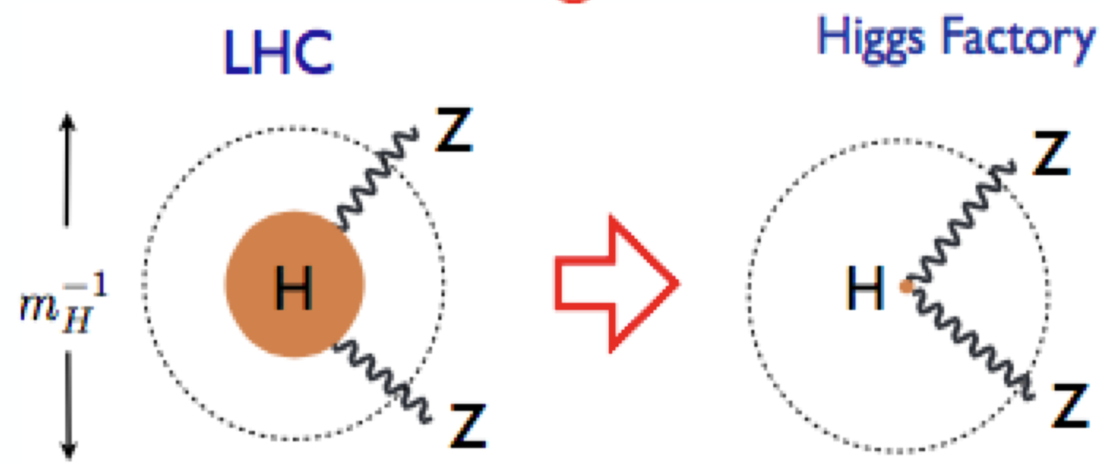
- 0.1-0.5 MeV W mass measurement from WW threshold scan
- 1-2 million Higgs boson events
  - 1% - 0.1% precision on many Higgs branching ratios
  - Model-independent extraction of Higgs couplings
  - Invisible Higgs branching ratio to 0.3% precision
  -
- Using $t\bar{t}$ threshold scan, top quark mass with <100 MeV precision (10 MeV statistical error) and measure top-electroweak couplings using angular distributions

Precision of Higgs Coupling Measurements



$$\kappa_Z = \frac{g_{hZ}(\text{Measured})}{g_{hZ}(\text{SM})}$$





Effective Field Theory Analysis of Precision EWK and Higgs observables

J.Ellis, T.You, arXiv:1510.04561

Ops directly affecting EW precision observables

$$\mathcal{L}_{\text{dim-6}}^{\text{EWPT}} \supset \frac{1}{2}\frac{(\bar{c}_W + \bar{c}_B)}{m_W^2}(\mathcal{O}_W + \mathcal{O}_B) + \frac{\bar{c}_T}{v^2}\mathcal{O}_T + \frac{\bar{c}_{LL}^{(3)l}}{v^2}\mathcal{O}_{LL}^{(3)l} + \frac{\bar{c}_R^e}{v^2}\mathcal{O}_R^e, \qquad \bar{c}_i = c_i\frac{M^2}{\Lambda^2} \qquad M \equiv v, m_W$$

Ops directly affecting Higgs properties and Triple gauge boson couplings

$$\mathcal{L}_{\text{dim-6}}^{\text{Higgs+TGC}} \supset \frac{1}{2}\frac{(\bar{c}_W - \bar{c}_B)}{m_W^2}(\mathcal{O}_W - \mathcal{O}_B) + \frac{\bar{c}_{HW}}{m_W^2}\mathcal{O}_{HW} + \frac{\bar{c}_{HB}}{m_W^2}\mathcal{O}_{HB} + \frac{\bar{c}_g}{m_W^2}\mathcal{O}_g + \frac{\bar{c}_\gamma}{m_W^2}\mathcal{O}_\gamma + \frac{\bar{c}_H}{v^2}\mathcal{O}_H + \frac{\bar{c}_f}{v^2}\mathcal{O}_f$$

<table>
<tr><th>EWPTs</th><th>Higgs Physics</th><th>TGCs</th></tr>
<tr><td colspan="3">$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$</td></tr>
<tr><td colspan="2">$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$</td><td>$\mathcal{O}_{3W} = g\frac{\epsilon_{abc}}{3!}W^{a\,\nu}_{\mu}W^b_{\nu\rho}W^{c\,\rho\mu}$</td></tr>
<tr><td>$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$</td><td colspan="2">$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$</td></tr>
<tr><td>$\mathcal{O}_{LL}^{(3)l} = (\bar{L}_L\sigma^a\gamma^\mu L_L)(\bar{L}_L\sigma^a\gamma_\mu L_L)$</td><td colspan="2">$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$</td></tr>
<tr><td>$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$</td><td>$\mathcal{O}_g = g_s^2|H|^2 G^A_{\mu\nu}G^{A\mu\nu}$</td><td></td></tr>
<tr><td>$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$</td><td>$\mathcal{O}_\gamma = g'^2|H|^2 B_{\mu\nu}B^{\mu\nu}$</td><td></td></tr>
<tr><td>$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$</td><td>$\mathcal{O}_H = \frac{1}{2}(\partial^\mu|H|^2)^2$</td><td></td></tr>
<tr><td>$\mathcal{O}_L^{(3)q} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$</td><td>$\mathcal{O}_f = y_f|H|^2\bar{F}_L H^{(c)} f_R + \text{h.c.}$</td><td></td></tr>
<tr><td>$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$</td><td>$\mathcal{O}_6 = \lambda|H|^6$</td><td></td></tr>
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Sensitivity Reach for Dimension-6 Operators

J.Ellis, T.You, arXiv:1510.04561

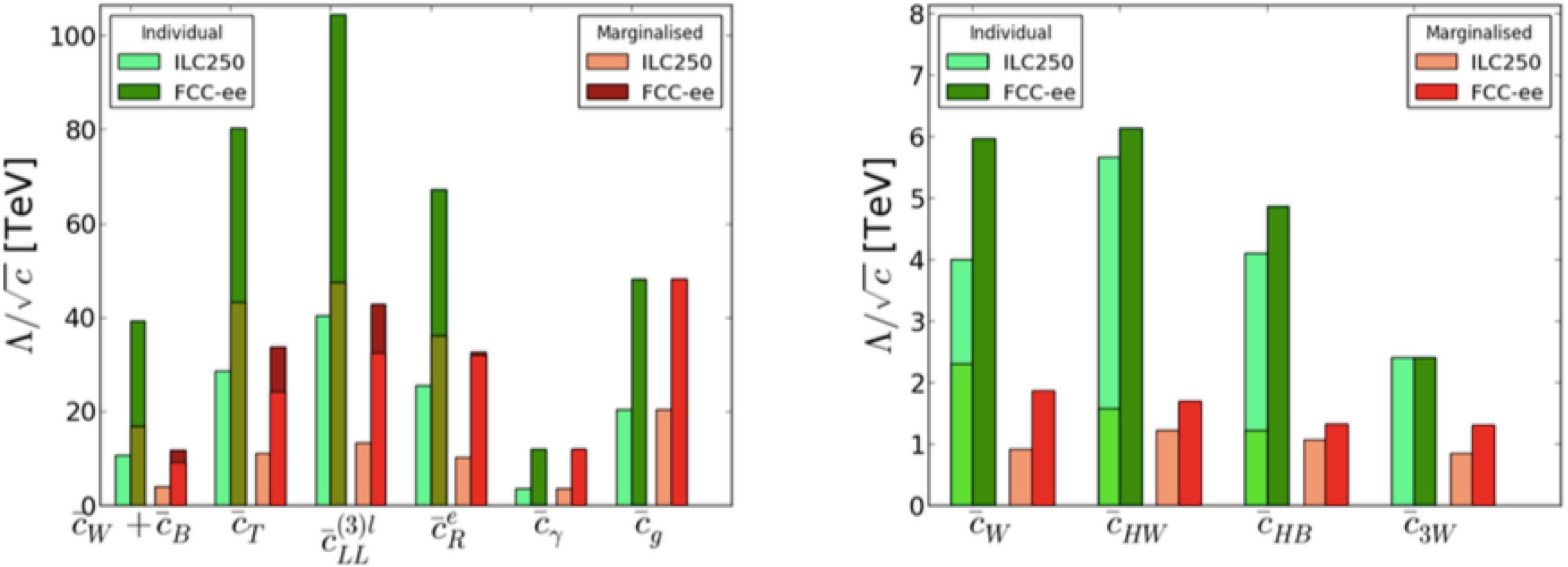


Figure 9: *Summary of the reaches for the dimension-6 operator coefficients with TeV scale sensitivity, when switched on individually (green) and when marginalised (red), from projected precision measurements at the ILC250 (lighter shades) and FCC-ee (darker shades). The left plot shows the operators that are most strongly constrained by EWPTs and Higgs physics, where the different shades of dark green and dark red represent the effects of EWPT theoretical uncertainties at FCC-ee. The right plot is constrained by Higgs physics and TGCs, and the different shades of light green demonstrate the improved sensitivity when TGCs are added at ILC250.*

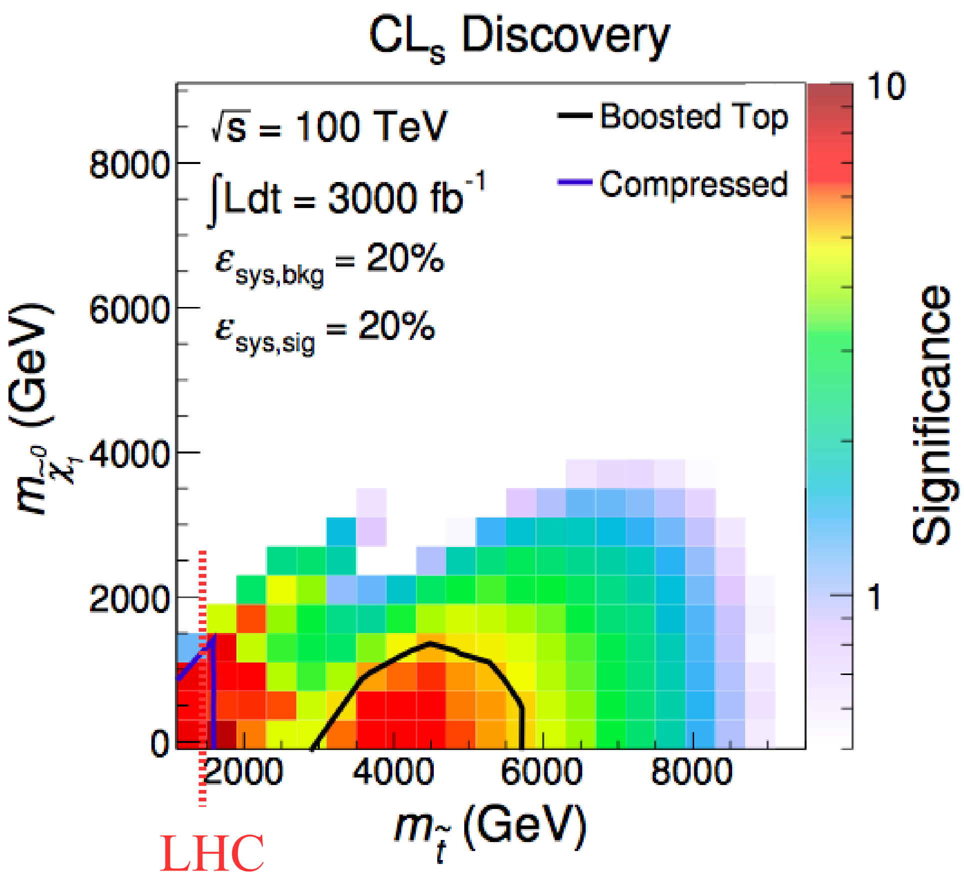
Circular *pp* Collider

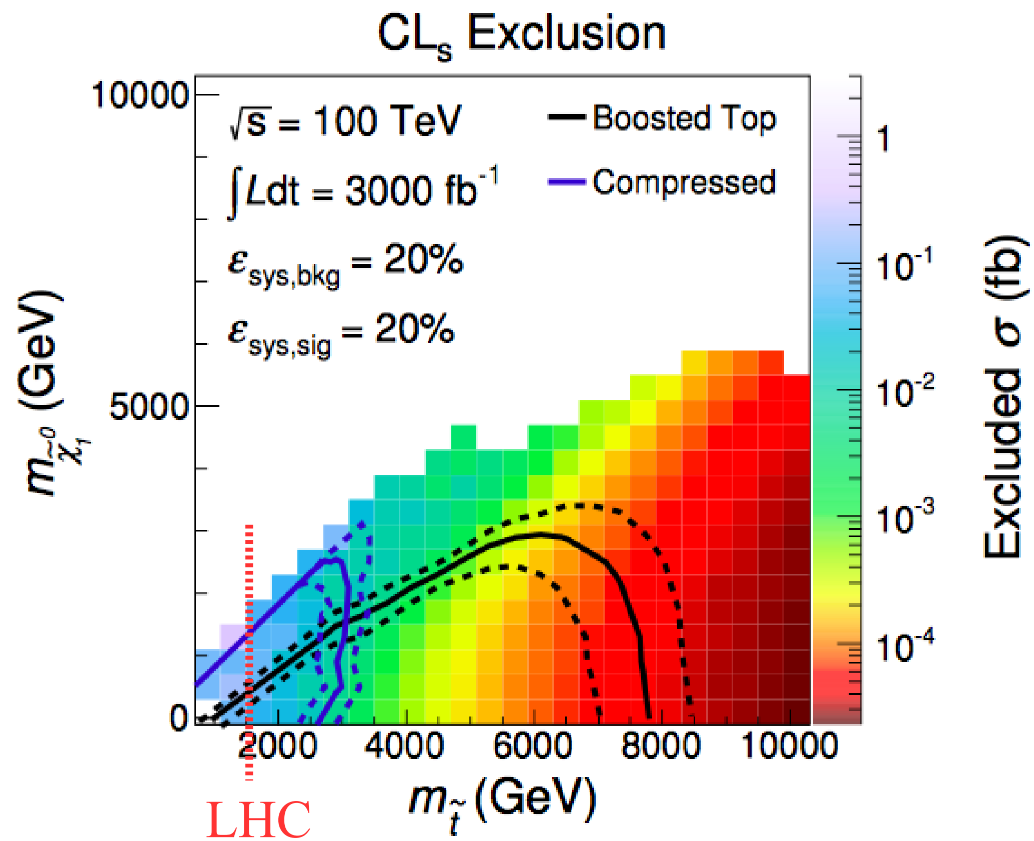
Circular *pp* Collider Physics Goals

- Testable reasons why the Standard Model must be incomplete
  - Dark Matter could be
    - Weakly-interacting particles
    - Particles interacting through Higgs portal
    - Interacting with SM particles through gravity
  - Electroweak Baryogenesis
    - Can the electroweak phase transition (formation of Higgs VeV) provide the out-of-equilibrium condition needed for matter-antimatter asymmetry observed?
  - Can the parameter space of new physics be a bounded parameter space?
    - Can it be fully covered with a 100-TeV scale *pp* collider?
- Naturalness – the need to explain the lightness of the Higgs mass – testing Naturalness at 10^{-4}

Supersymmetric Colored Top Partner Sensitivity

(Cohen *et al*, 2014)



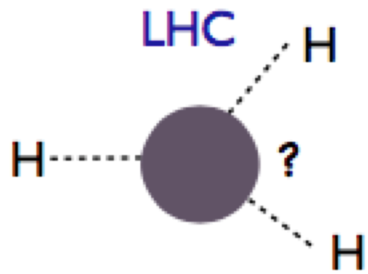


Fine-tuning $\sim m_{stop}^{\ 2} \sim 10^{-4}$

A big jump beyond LHC

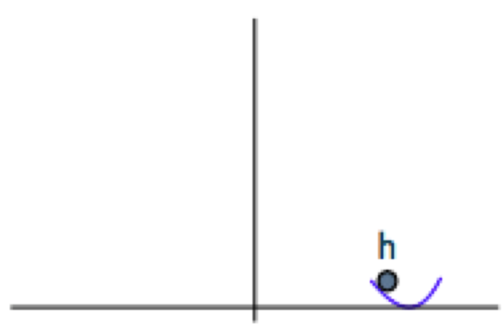
Discovering or eliminating “natural” low-energy SUSY

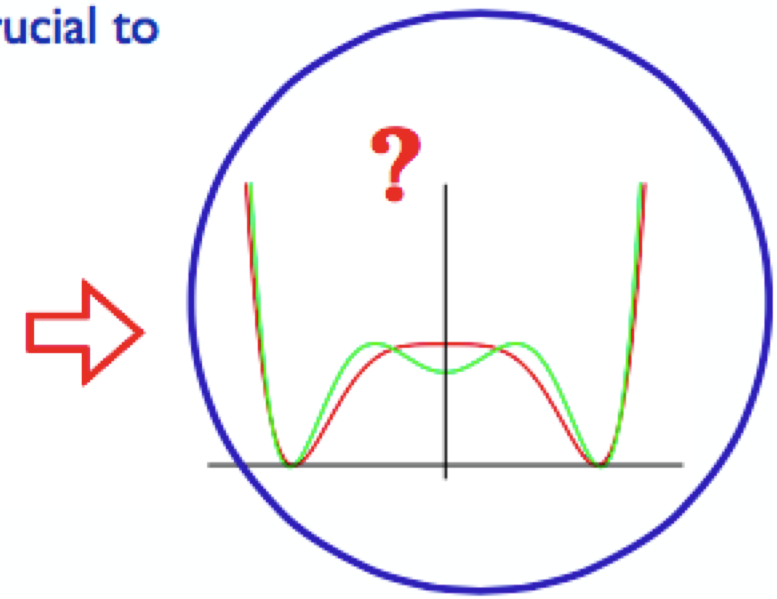
Higgs Self-Coupling



Unique type of coupling for spin-0 scalars
Not seen before in nature!

Measuring it well is crucial to answer this question.





Expect $O(1)$ deviations from SM in self-coupling coefficient

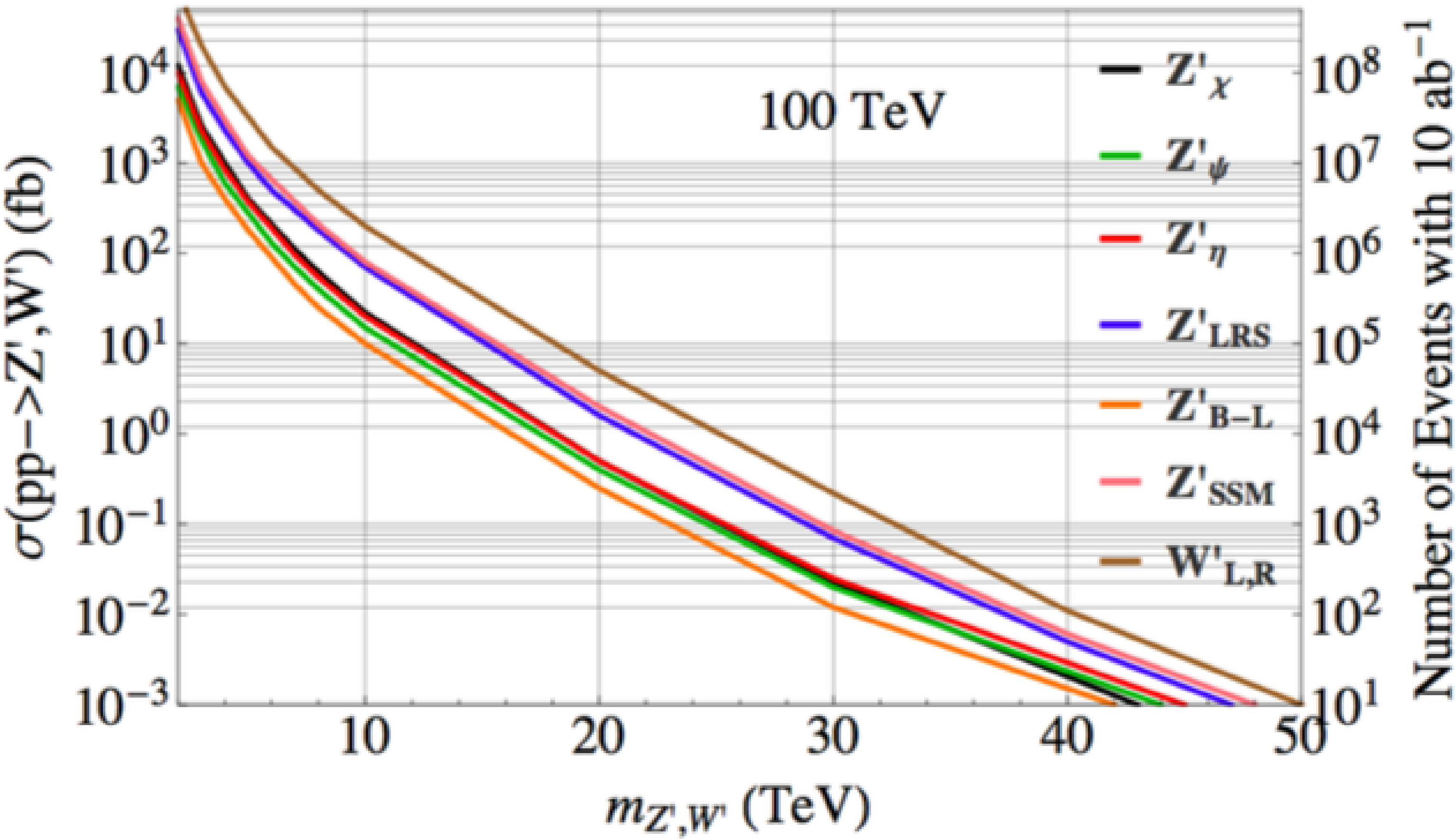
Measuring the Higgs Self-Coupling

- gg→HH (most promising?) , qq→HHqq (via VBF)
- Reference benchmark process: HH→bb γγ
- Goal: 5% (or better) precision for SM selfcoupling

$HH \rightarrow b\bar{b}\gamma\gamma$	Barr,Dolan,Englert,Lima, Spannowsky JHEP 1502 (2015) 016	Contino, Azatov, Panico, Son arXiv:1502.00539	He, Ren Yao arXiv:1506.03302
$\mathrm{FCC}_{@100\mathrm{TeV}}$ 3/ab	30~40%	30%	15%
$\mathrm{FCC}_{@100\mathrm{TeV}}$ 30/ab	10%	10%	5%
$S/\sqrt{B}$	8.4	15.2	16.5
Details	✓ λ_{HHH} modification only ✓ $c \rightarrow b$ & $j \rightarrow \gamma$ included ✓ Background systematics ○ $b\bar{b}\gamma\gamma$ not matched ✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV	✓ Full EFT approach ○ No $c \rightarrow b$ & $j \rightarrow \gamma$ ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV ✓ Jet /W_{had} veto	✓ λ_{HHH} modification only ✓ $c \rightarrow b$ & $j \rightarrow \gamma$ included ○ No marginalization ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV

Work in progress to compare studies, harmonize performance assumptions, optimize, etc
⇒ ideal benchmarking framework

Exploring New Territory - New Weak Gauge Interactions



Model	1 ab^{-1}	10 ab^{-1}	100 ab^{-1}
SSM	23.8	33.3	41.3
LRM	22.6	31.5	39.5
ψ	20.1	29.1	37.2
χ	22.7	30.6	38.2
η	20.3	29.8	38.0
I	22.4	29.2	36.2

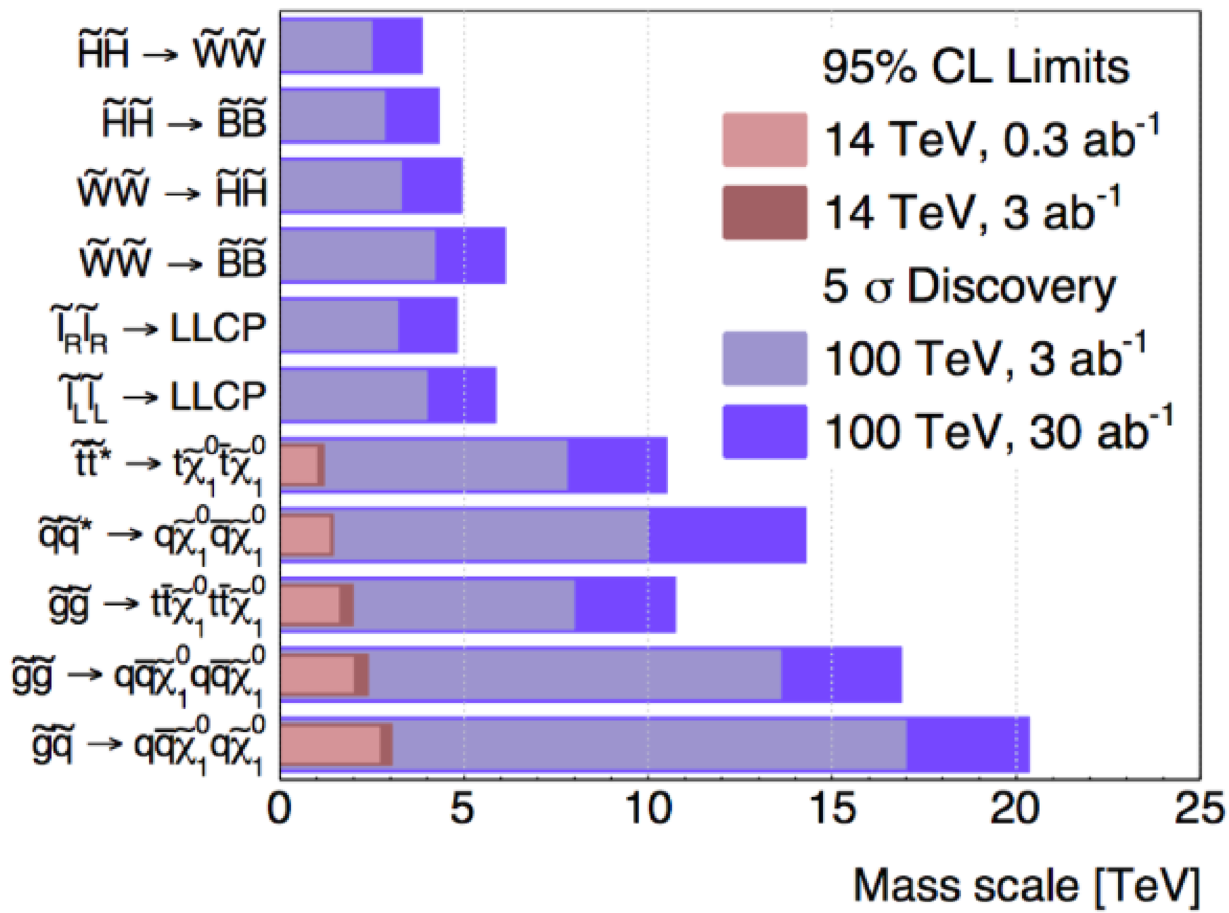
Discovery reach

T.Rizzo, arXiv:1403.5465

10-fold increase in luminosity
→ ~7 TeV increase in mass reach

Exploring New Territory – Squarks and Gluinos

Summary from FCC Report:

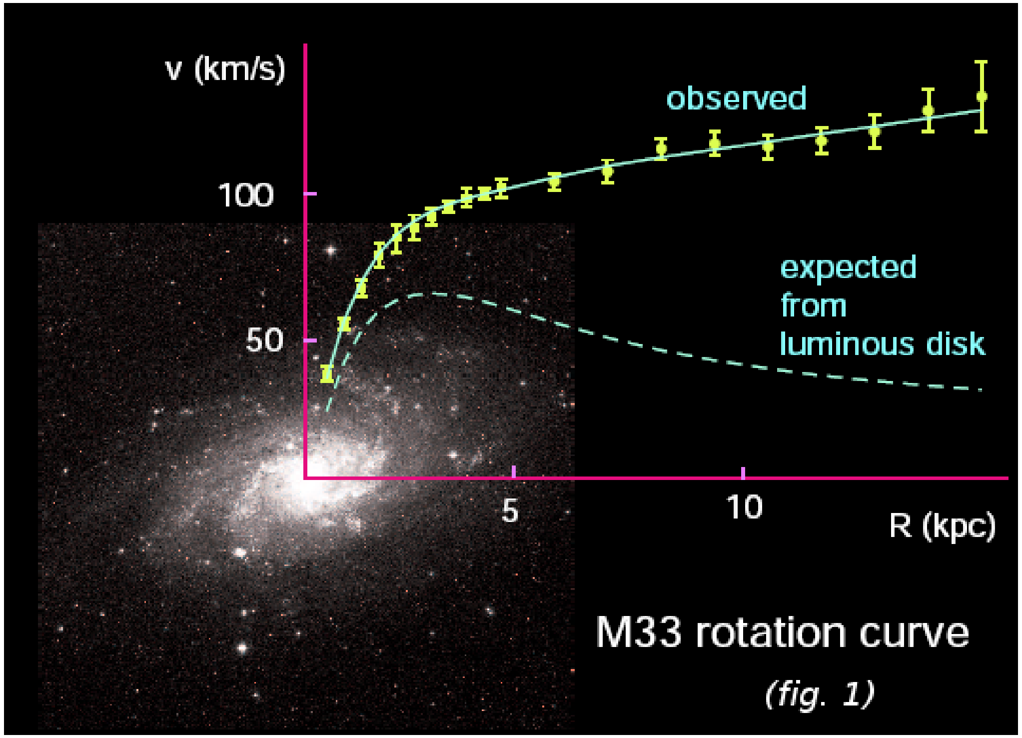


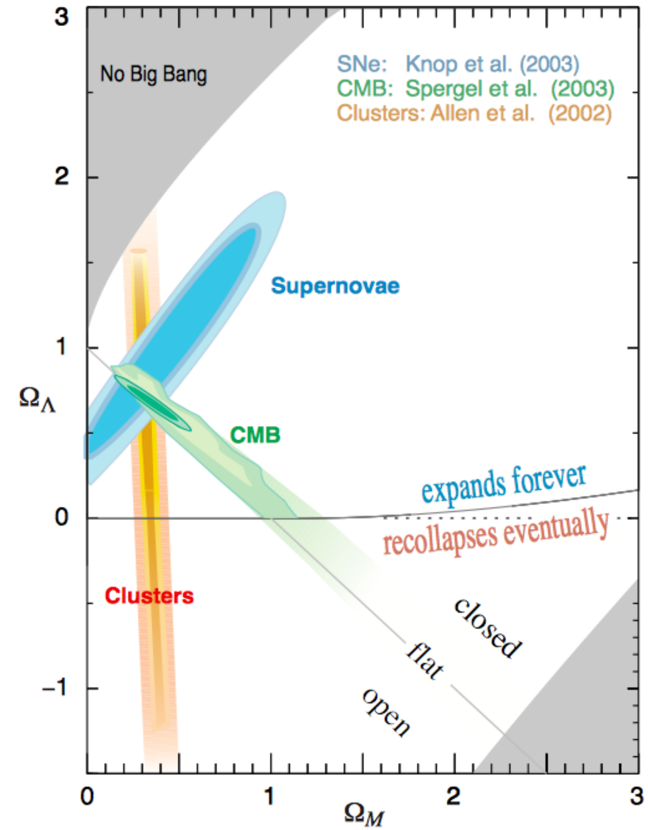
Squark & gluino discovery potential up to 10-20 TeV

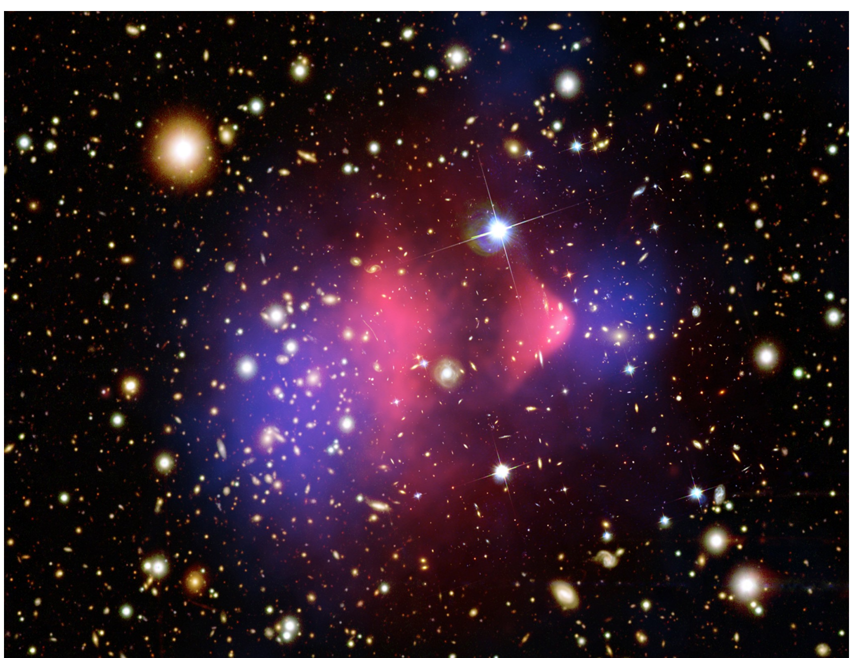
Full exploration of "low-scale" SUSY

Dark Matter

Dark Matter Particles

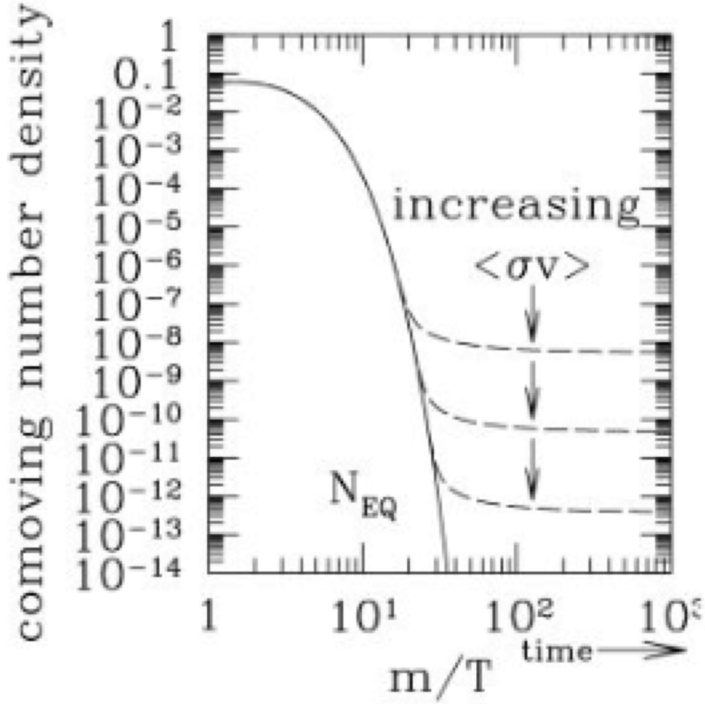


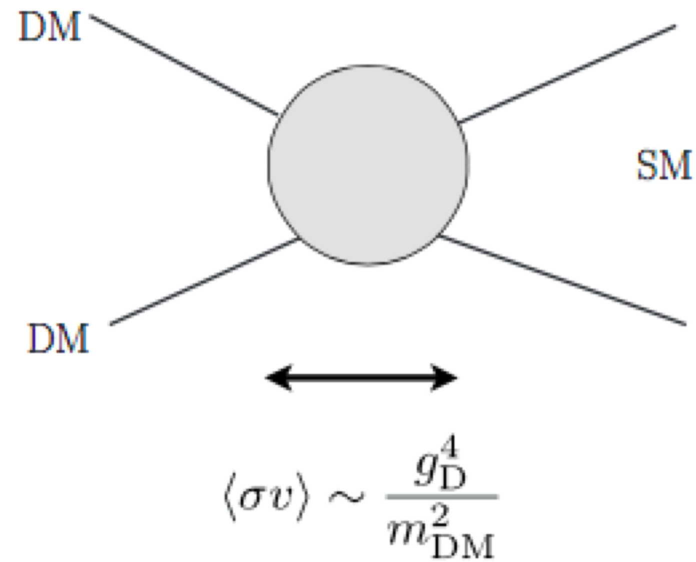




A consistent hypothesis is the existence of non-relativistic particles beyond the Standard Model

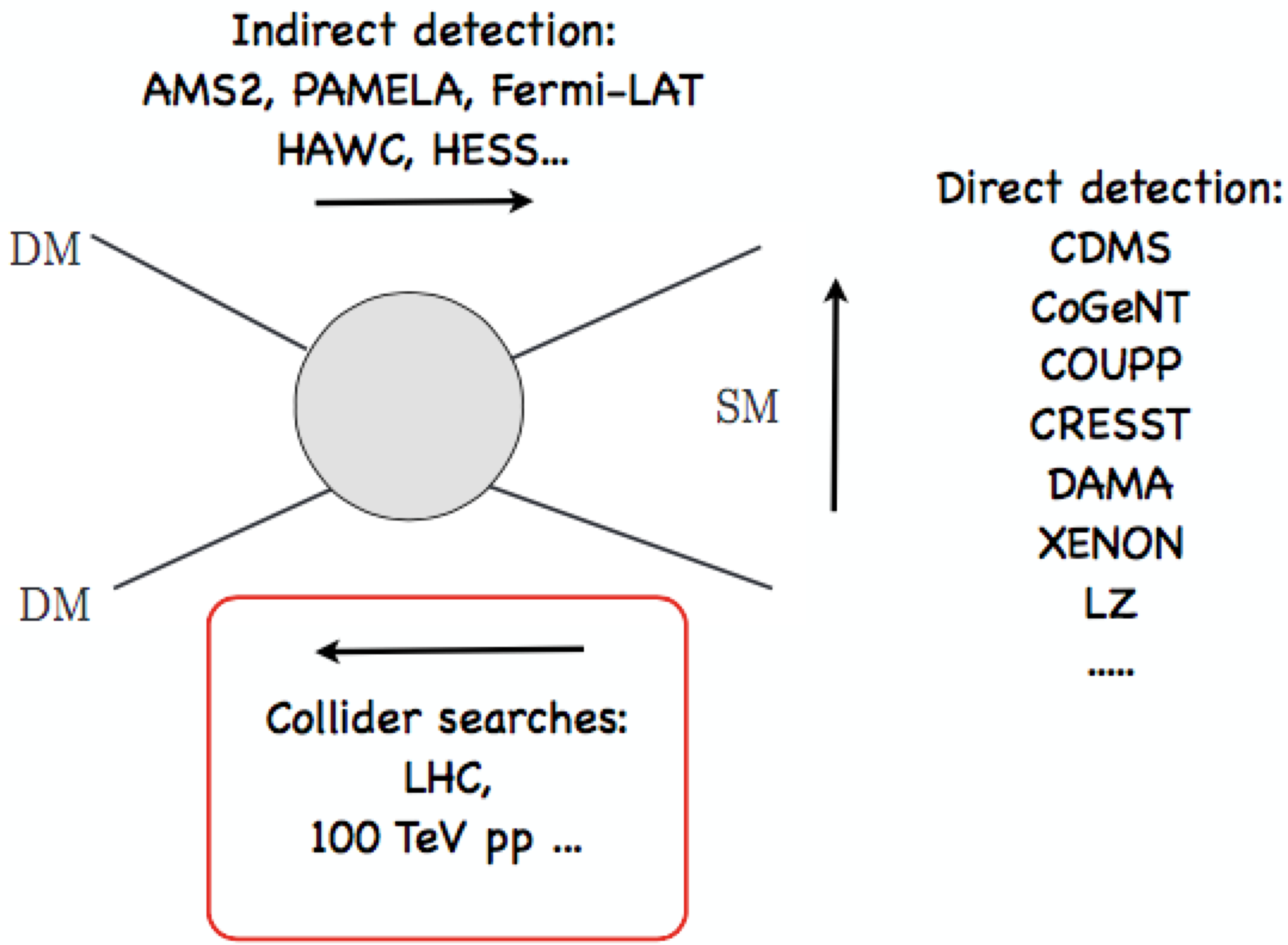
WIMP Miracle



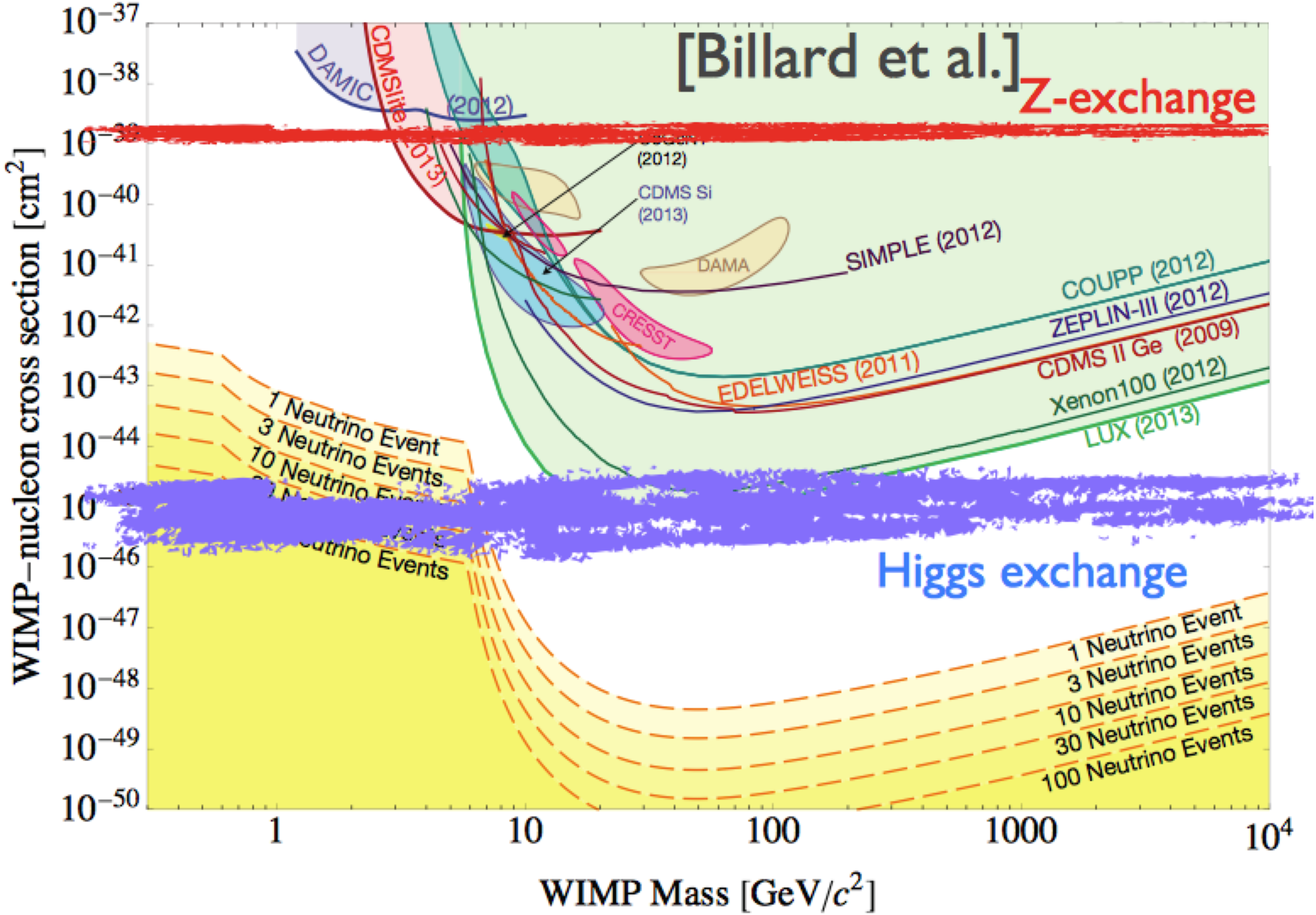


- Thermal equilibrium in the early universe.
- If $g_D \sim 0.1$ $M_D \sim$ 10s GeV - TeV
  - We get the right relic abundance of dark matter.
- Major hint for weak scale new physics!

Searching for WIMP Dark Matter

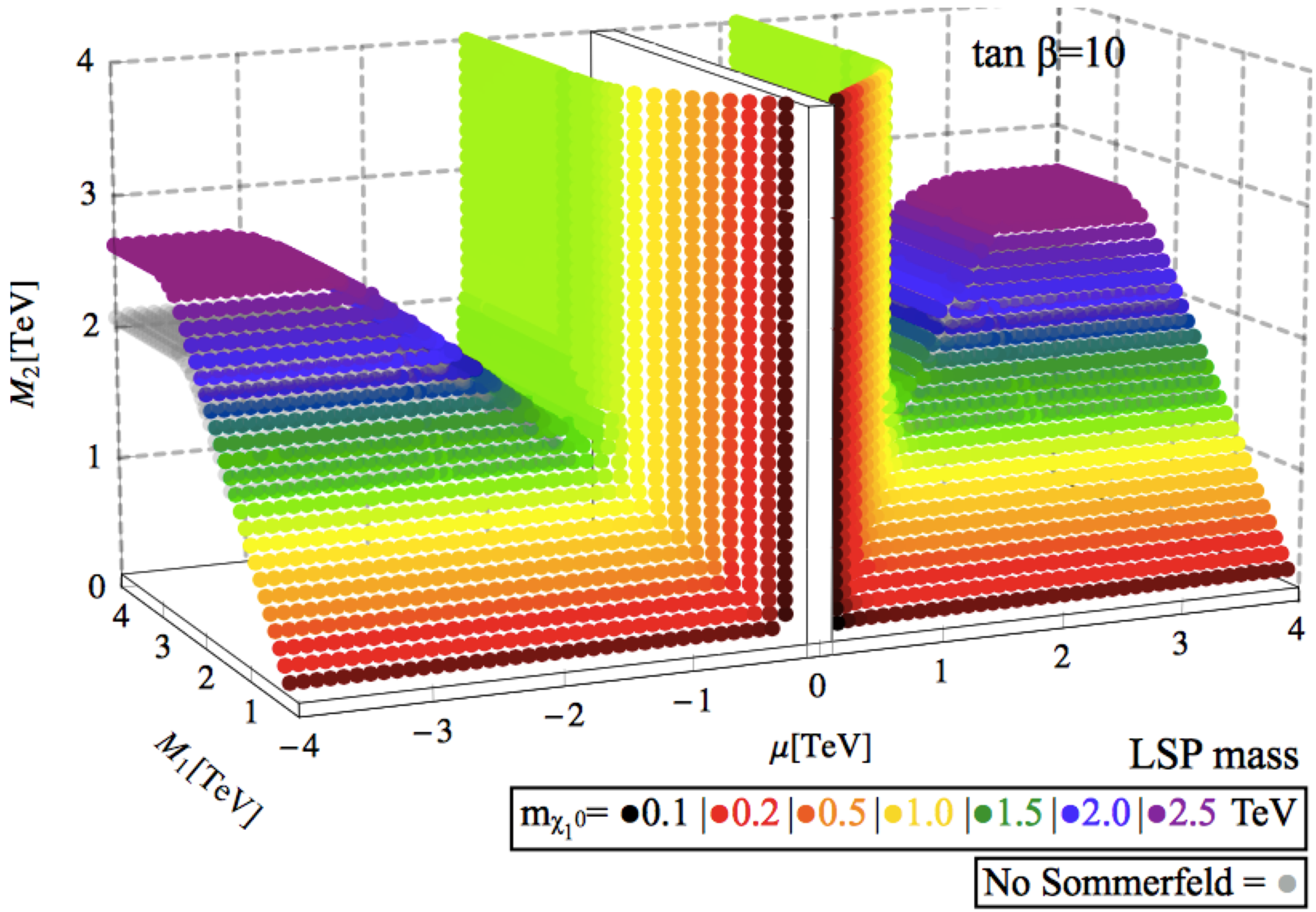


Direct Searches for Dark Matter



SUSY Neutralino Relic Surface

- Combinations of Neutralino mass parameters that produce the correct relic abundance, along with Dark Matter particle (LSP) mass



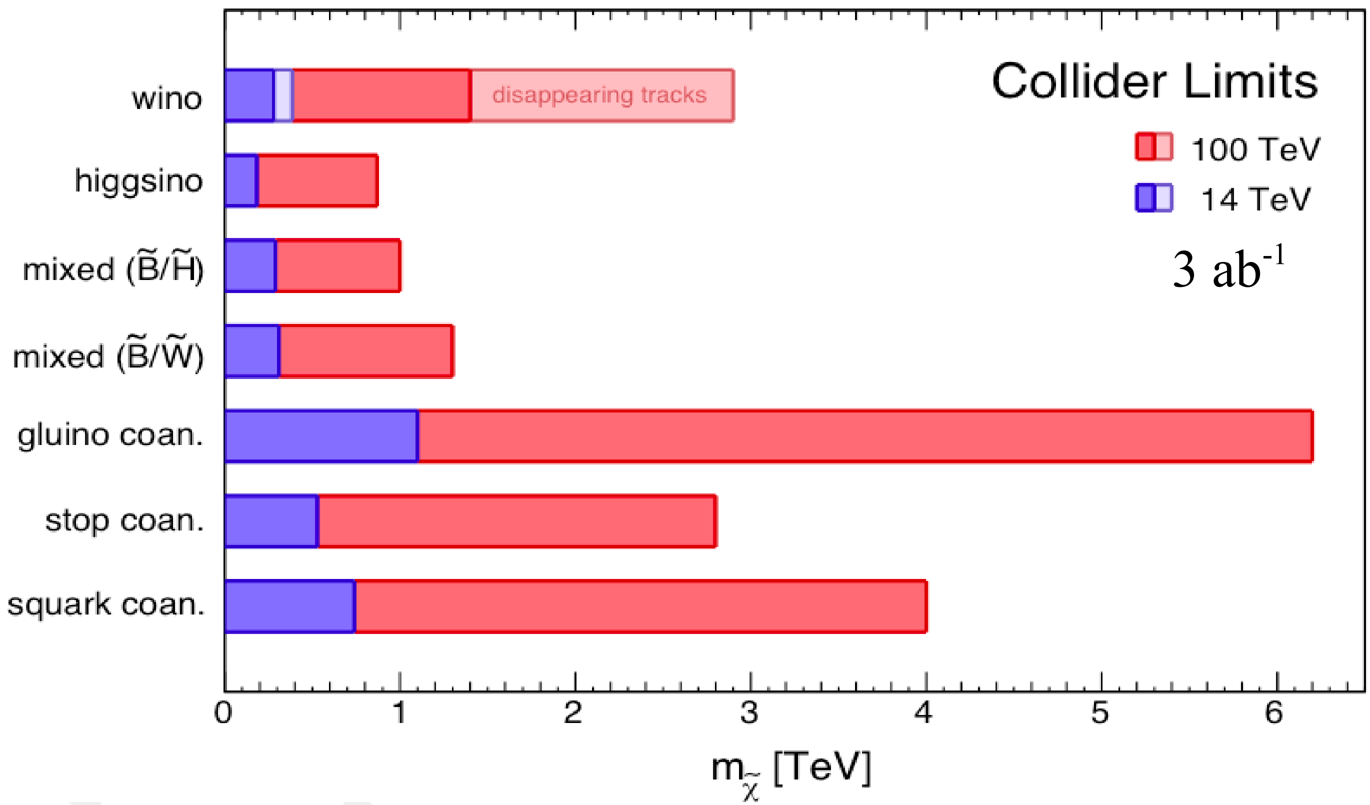
Bramante *et al,*

ArXiv:1510.03460

(in the limit that other SUSY is heavy and decoupled)

WIMP Dark Matter

- $M_{\text{Dark Matter}} < 1.8$ TeV $(g_{DM}{}^2/0.3)$ based on WIMP thermal relic hypothesis



M. Low, L-T Wang,

ArXiv:1404.0682

(mono-jet channel)

100 TeV *pp* collider covers most of the parameter space

Can double mass reach with 30 ab^{-1}

Collider vs Direct Detection Complementarity

Common ground (almost)

- Axial-Vector mediator

  DD and collider are equal in overall sensitivity but probe different regions of parameter space!

- Scalar mediator

  DD and collider are equal in overall sensitivity but probe different regions of parameter space!

Exclusive domains (almost)

- Vector mediator

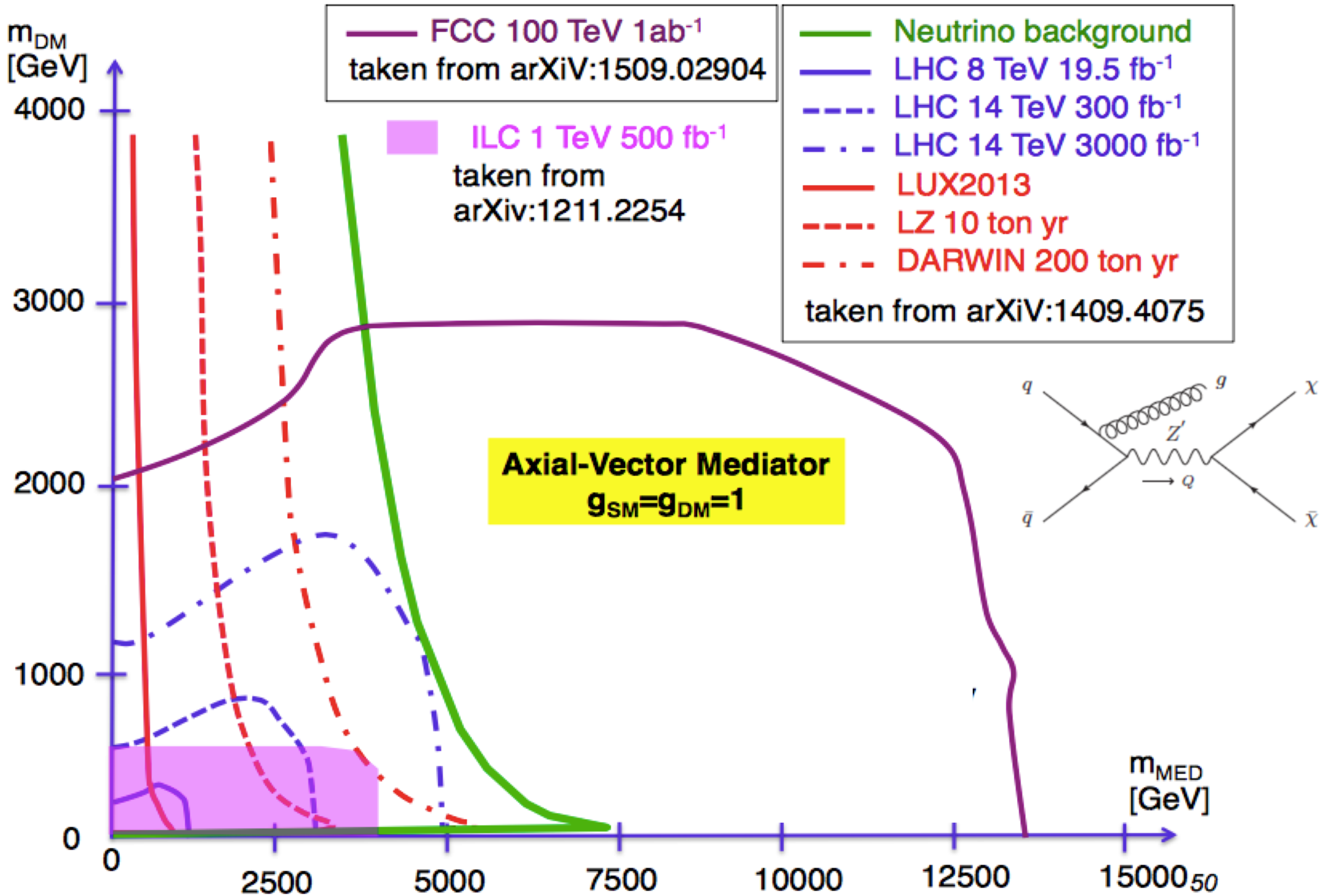
  Besides very low DM masses DD wins clearly over collider

- Pseudo-Scalar mediator

  No competitive limits from DD (only from indirect detection). Collider provides limits similar in sensitivity to scalar limits

 (from O. Buchmuller)

Collider Searches – Large Mediator Mass



Origin of Matter-Antimatter Asymmetry

Origin of Baryon Asymmetry

POSSIBLE EXPLANATIONS...

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$ (from BBN)

⇨ **Baryogenesis at EW Scale** → **TESTABLE!**

⇨ ...

SAKHAROV CONDITIONS *(for dynamical generation of baryon asymmetry)*

B Violation ✓ *Sphalerons*

*V. A. Kuzmin, V. A. Rubakov, M. Shaposhnikov, Phys. Lett. B**155** (1985) 36*

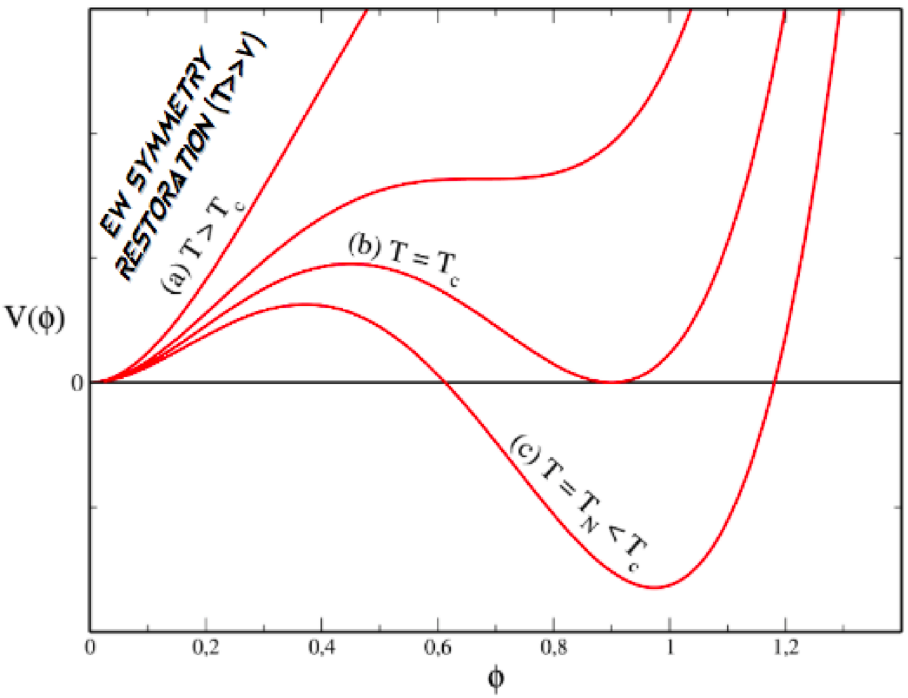
C/CP Violation ✗ *not enough*

Departure from Thermal Equilibrium ✗ *not enough*

Baryon Asymmetry and Electroweak Phase Transition

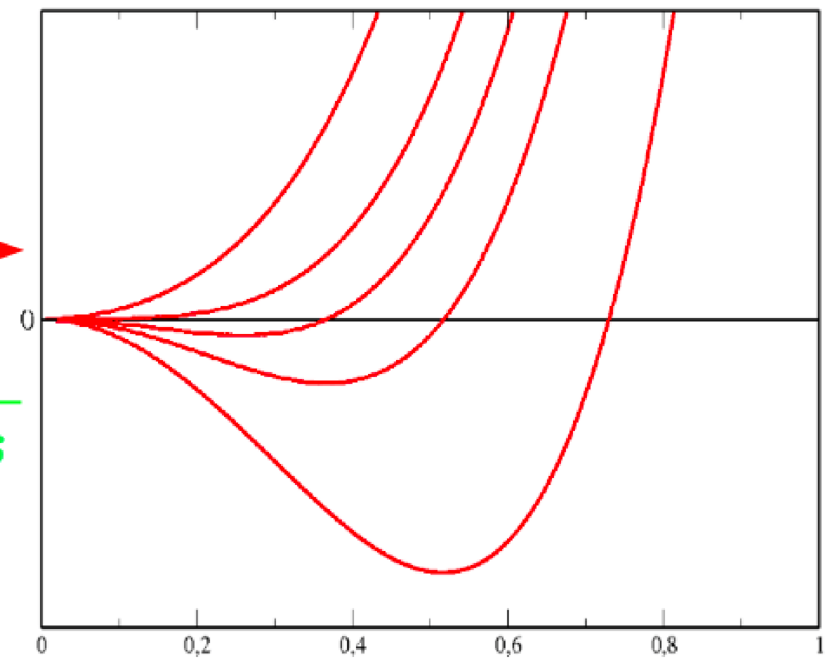
1st Order:

$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Discontinuous



2nd Order:

$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Continuous



LARGER M_H →

← NEW BOSONS

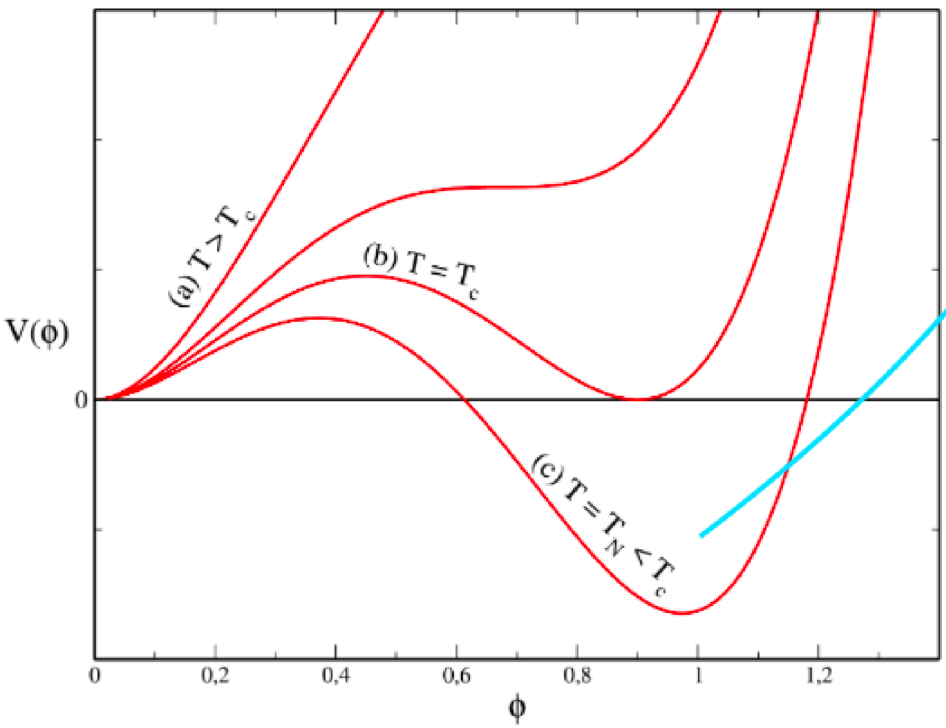
In the SM (m_h = **125 GeV**) EW Phase Transition Smooth CrossOver

*K. Kajantie, M. Laine, K. Rummukainen, M. Shaposhnikov, Phys. Rev. Lett. **77** (1996) 2887*

Baryon Asymmetry and Electroweak Phase Transition

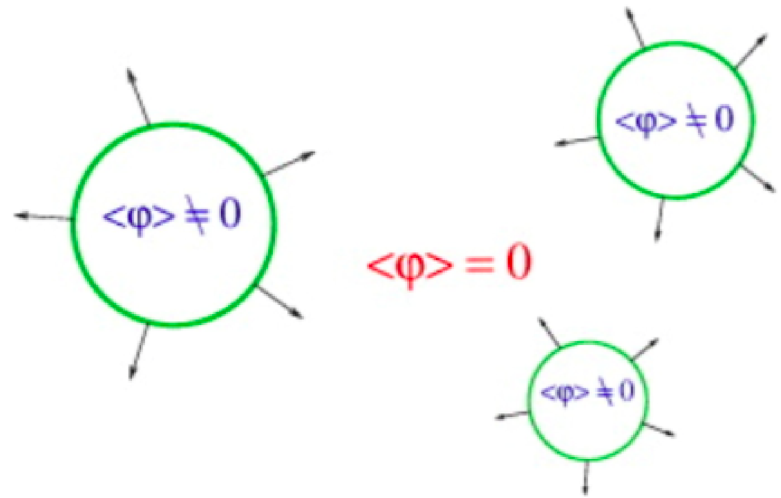
1^{st} Order:

$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Discontinuous



Nucleation of True Vacuum Bubbles
(in False Vacuum Sea)

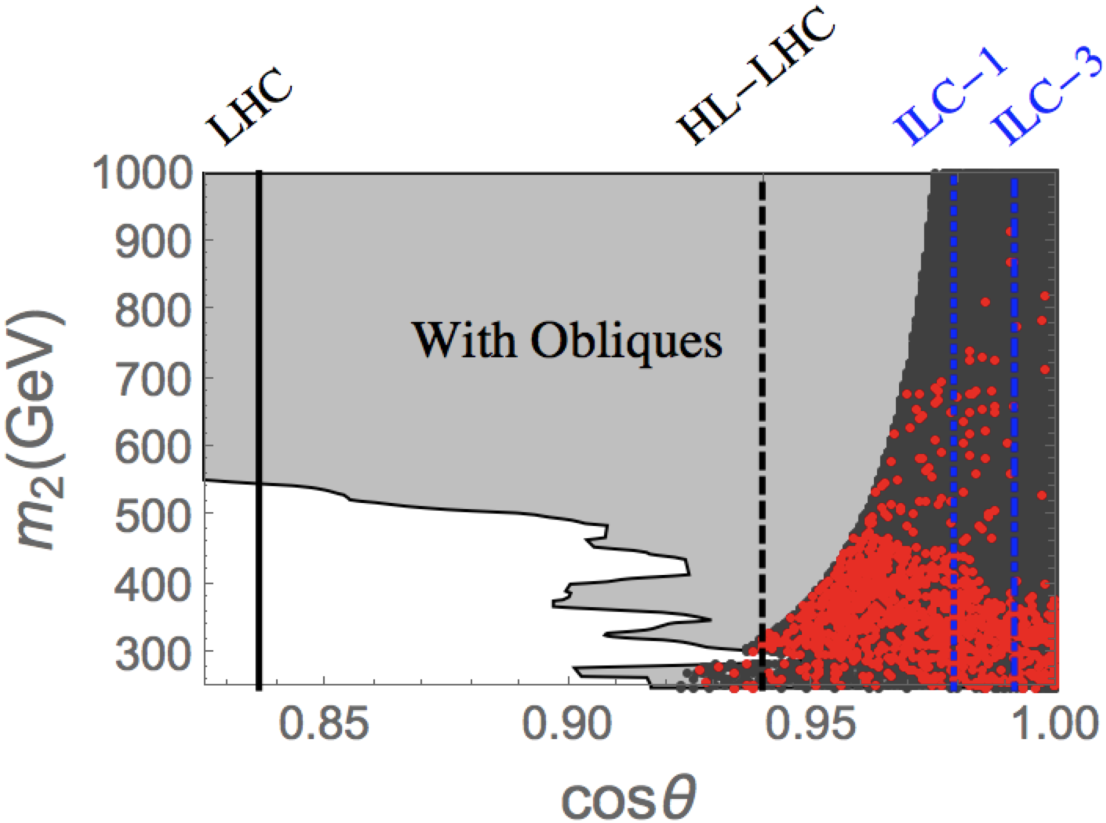
J. S. Langer, Ann. Phys. ***54*** *(1969) 258*
S. R. Coleman, Phys. Rev. D ***15*** *(1977) 2929*
A. D. Linde, Nucl. Phys. B ***216*** *(1983) 421*



SUDDEN CHANGE IN HIGGS VEV

First Order Phase Transition

$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$



(from P. Winslow)

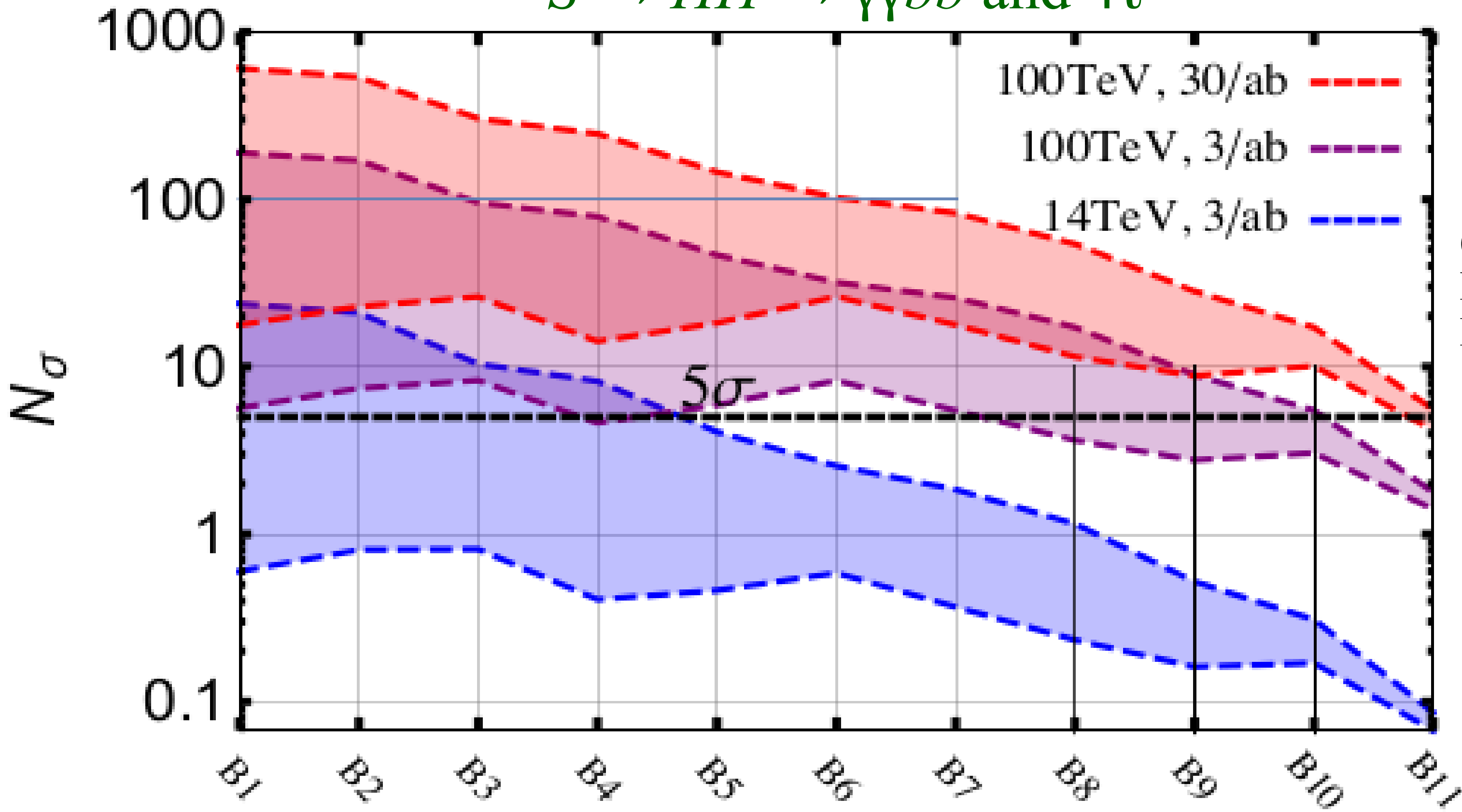
S. Profumo, M. J. Ramsey-Musolf, C. L. Wainwright and P. Winslow, arXiv:1407.5342

Can TeV-scale new physics associated with 1st order phase transition be completely covered by a *pp* collider?

Inducing First-Order Electroweak Phase Transition

$$V(H,S) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right) S$$
$$+ \frac{a_2}{2}\left(H^\dagger H\right) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

$S \to HH \to \gamma\gamma bb$ and 4τ



300 GeV ← benchmark m_S → 900 GeV

(AVK, P.Winslow, J.M. No, M.J.Ramsey-Musolf, PRD 94, 035022 (2016))

Discovery potential across entire parameter space

Conclusions

- Circular electron-position colliders (at very high luminosity) and proton-proton colliders (at very high energy) provide unprecedented discovery potential

- New territory explored with precision measurements and direct searches is strongly motivated for
  - Solving the mysteries associated with the Higgs boson
  - Discovering WIMP Dark Matter
  - Understanding the electroweak phase transition and discovering the conditions for electroweak bryogenesis

- Potential for big surprises and discovery of unexpected new principles of nature

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

http://cepc.ihep.ac.cn/preCDR/volume.html

http://tlep.web.cern.ch

http://lhec.web.cern.ch

Backup Slides

Target lum and statistics for the FCC-ee programme

This is an evolving issue, the table below is the latest documented assessment, from D. d'Enterria, (EPS talk), arXiv:1601.06640

$\sqrt{s}$ (GeV):	90 (Z)	125 (eeH)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350 (VV $\to$ H)
$\mathcal{L}$/IP (cm^{-2} s^{-1})	$2.2{\cdot}10^{36}$	$1.1{\cdot}10^{36}$	$3.8{\cdot}10^{35}$	$8.7{\cdot}10^{34}$	$2.1{\cdot}10^{34}$	$2.1{\cdot}10^{34}$
$\mathcal{L}_{\rm int}$ (ab^{-1}/yr/IP)	22	11	3.8	0.87	0.21	0.21
cross sections	43 nb	0.29 fb	4 pb	200 fb	0.5 pb	30 fb
Events/year (4 IPs)	$3.7{\cdot}10^{12}$	$1.3{\cdot}10^{4}$	$6.1{\cdot}10^{7}$	$7.0{\cdot}10^{5}$	$4.2{\cdot}10^{5}$	$2.5{\cdot}10^{4}$
Years needed (4 IPs)	2.5	1.5	1	3	0.5	3

'able 1: *Target luminosities, events/year, and years needed to complete the W, Z, H an op programs at FCC-ee. [$\mathcal{L}$ = 10^{35} cm^{-2} s^{-1} corresponds to $\mathcal{L}_{\rm int}$ = 1 ab^{-1}/yr for 1 yr = 10^7 s].*

SM parameters from FCC-ee

M. Bicer et al, "TLEP Physics Case", arXiv:1308.6176v3

M. Dam, arXiv:1601.03849

	Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
	M_Z [MeV]	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
	Γ_Z [MeV]	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
	R_ℓ	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
	R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \to b\bar{b}$
	N_ν	Peak	2.984 ± 0.008	0.00004	0.004	Lumi meast.
	$A_{FB}^{\mu\mu}$	Peak	0.0171 ± 0.0010	0.000004	< 0.00001	E_{beam} meast.
*	$\alpha_s(M_Z)$	R_ℓ	0.1190 ± 0.0025	0.000001	0.00015	New Physics
**	$1/\alpha_{QED}(M_Z)$	$A_{FB}^{\mu\mu}$ around peak	128.952 ± 0.014	0.004	0.002	EW corr.
	M_W [MeV]	Threshold scan	80385 ± 15	0.3	< 1	QED corr.
	N_ν	$e^+e^- \to \gamma Z(\text{inv.})$	2.92 ± 0.05	0.0008	< 0.001	?
*	$\alpha_s(M_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	$B_{had} = 67.41 \pm 0.27$	0.00018	0.00015	CKM Matrix
	m_{top} [MeV]	Threshold scan	173200 ± 900	10	10	QCD

* α_S workshop, d'Enterria, Skands eds, et al, arXiv:1512.05194

** P. Janot, arXiv:1512.05544

Rate comparisons at 8, 14, 100 TeV

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg\to H$	16 G	4.2×10^4	110
VBF	1.6 G	5.1×10^4	120
WH	320 M	2.3×10^4	66
ZH	220 M	2.8×10^4	84
ttH	760 M	29×10^4	420
$gg\to HH$	28 M		280

$N_{100} = \sigma_{100\,\text{TeV}} \times 20\ ab^{-1}$

$N_8 = \sigma_{8\,\text{TeV}} \times 20\ fb^{-1}$

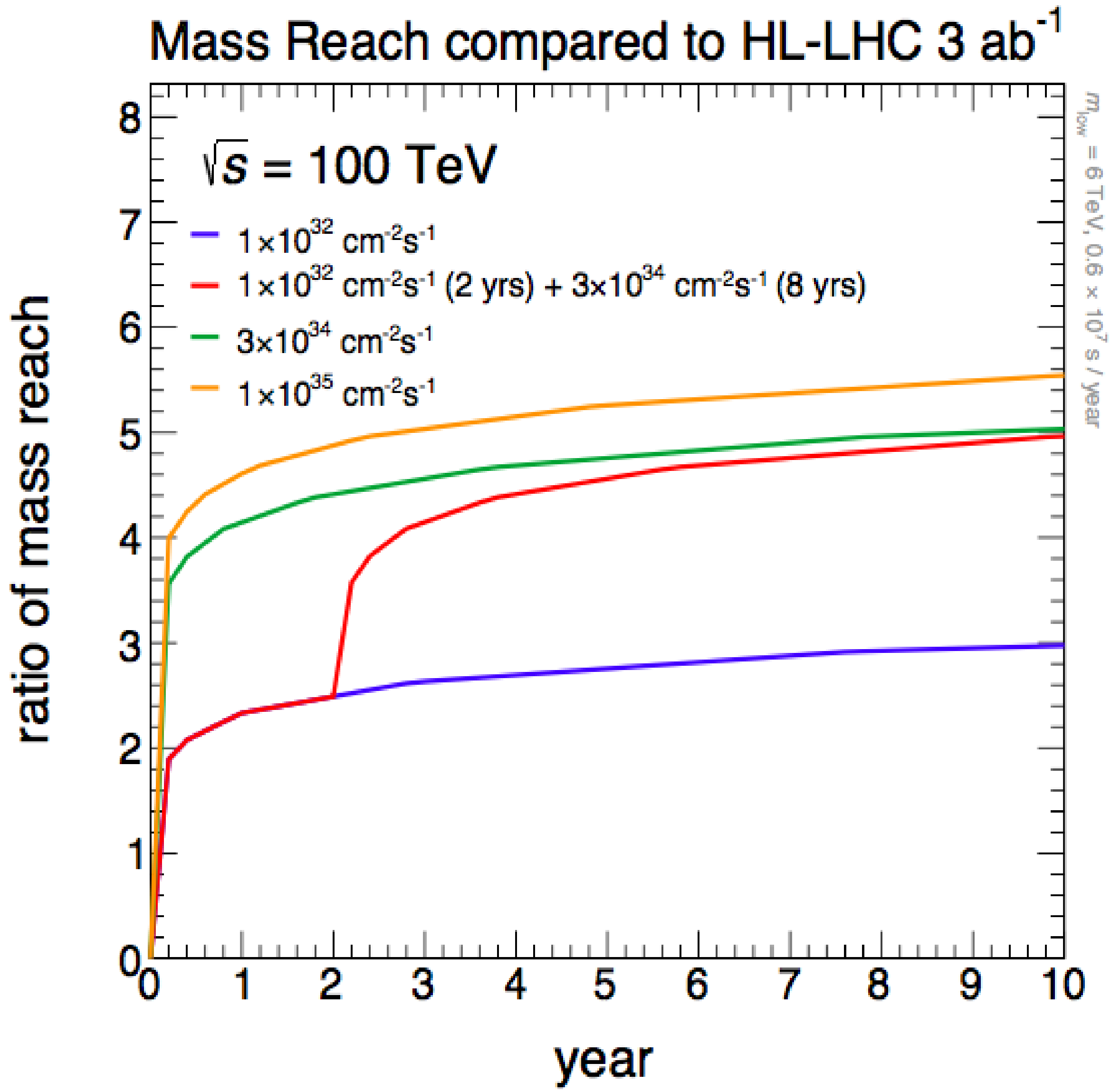
$N_{14} = \sigma_{14\,\text{TeV}} \times 3\ ab^{-1}$

Statistical precision:

- O(100 - 500) better w.r.t Run 1
- O(10 - 20) better w.r.t HL-LHC

Collider Luminosity and Energy

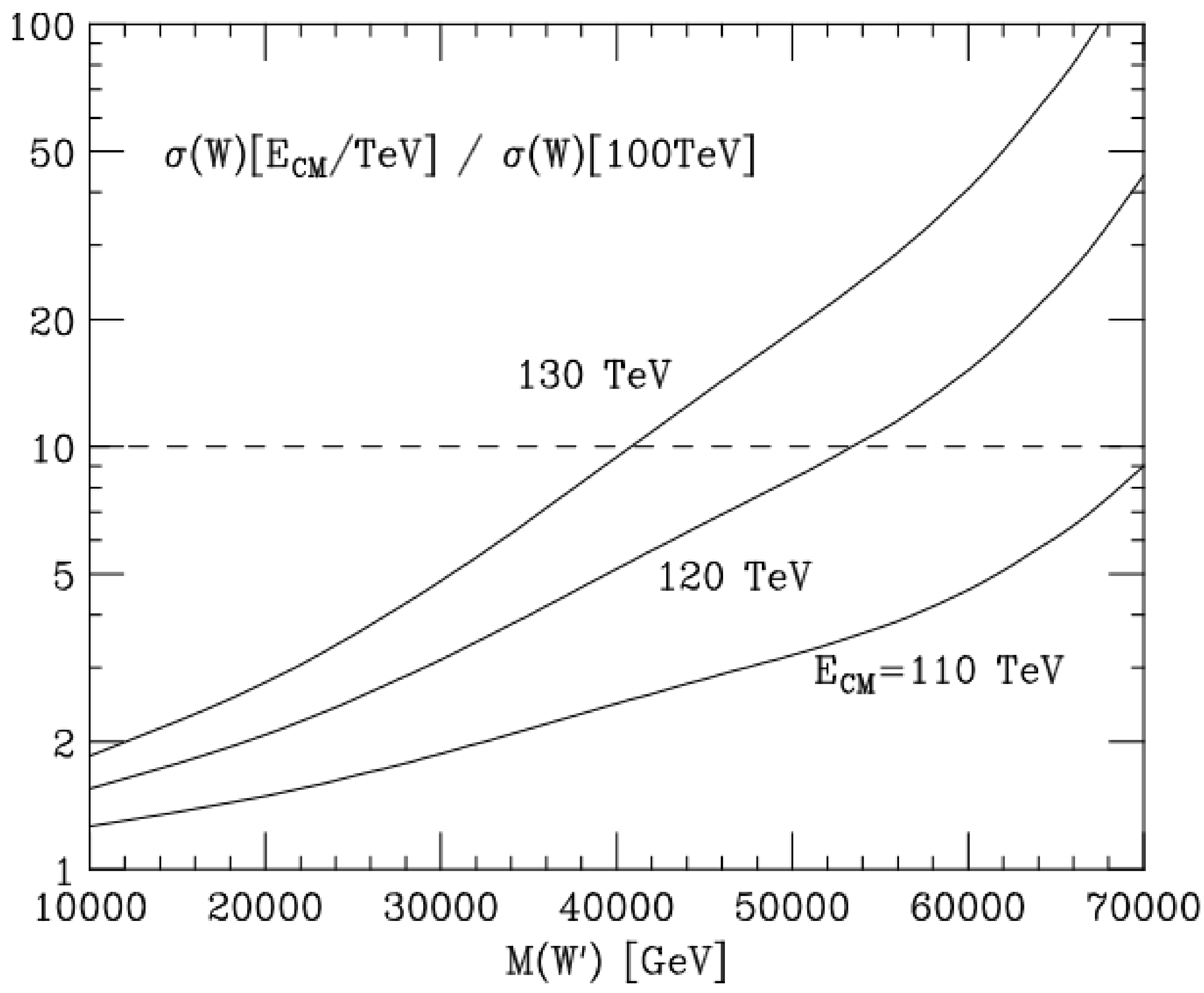
- Collider luminosity evolution for high-mass reach



(from L-T. Wang)

Collider Luminosity and Energy

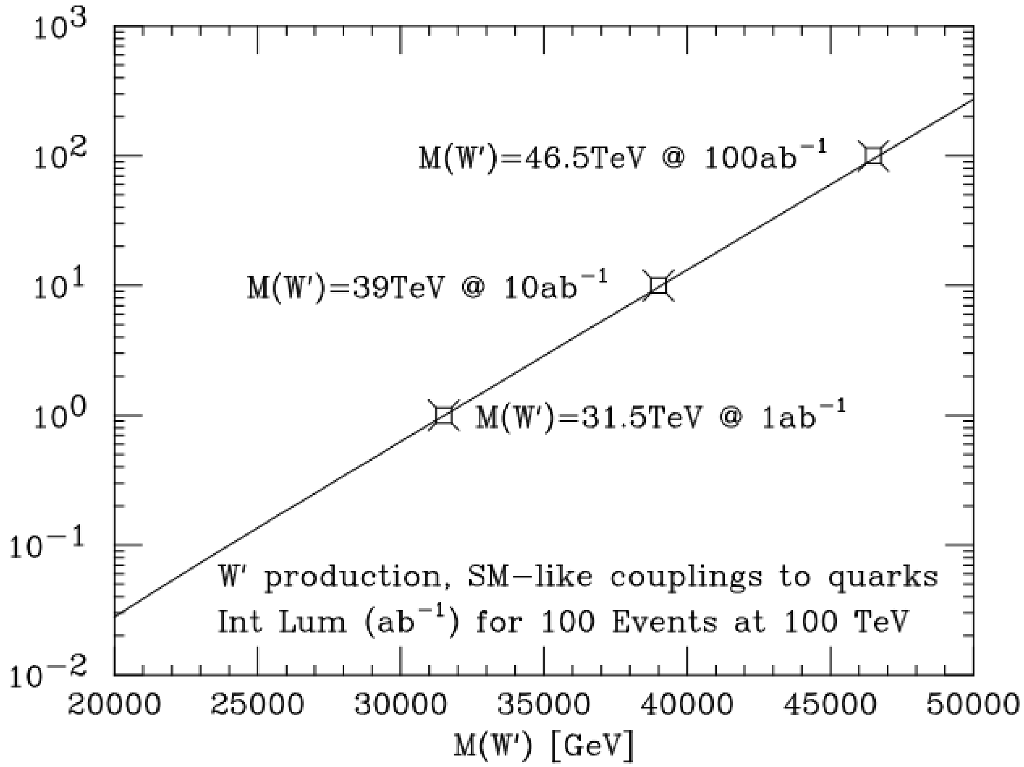
- Collider energy wins rapidly at higher masses

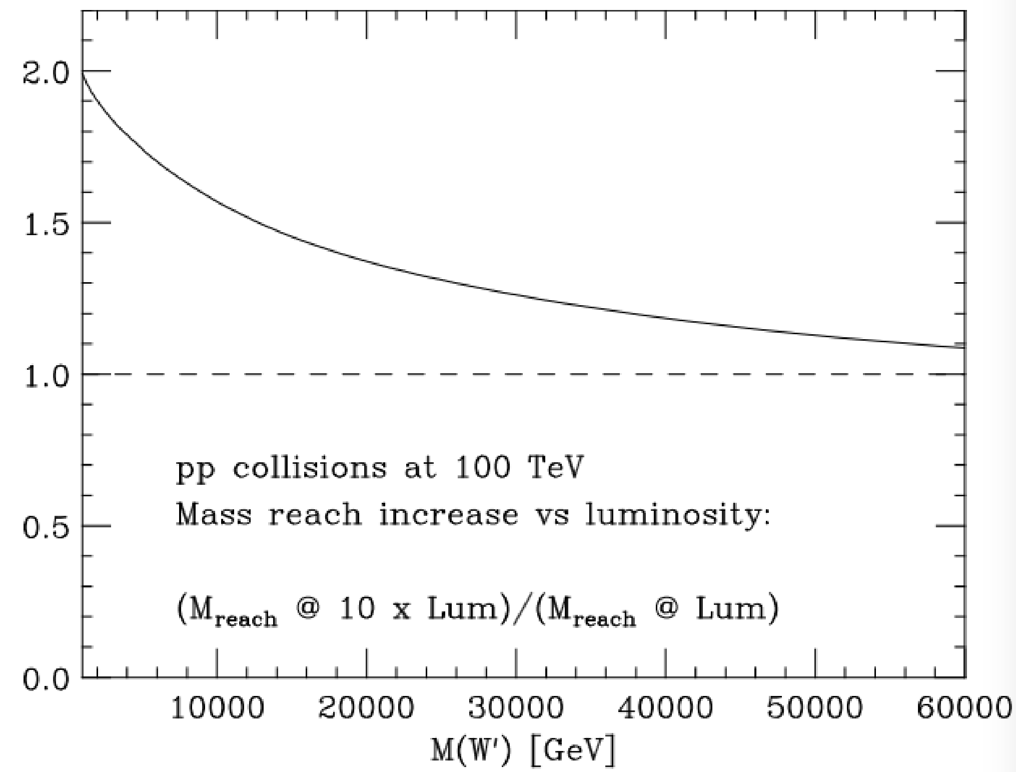


(from M. Mangano)

Collider Luminosity and Energy

- With 100 TeV collider, 7 TeV increase in mass reach for ten-fold increase in luminosity





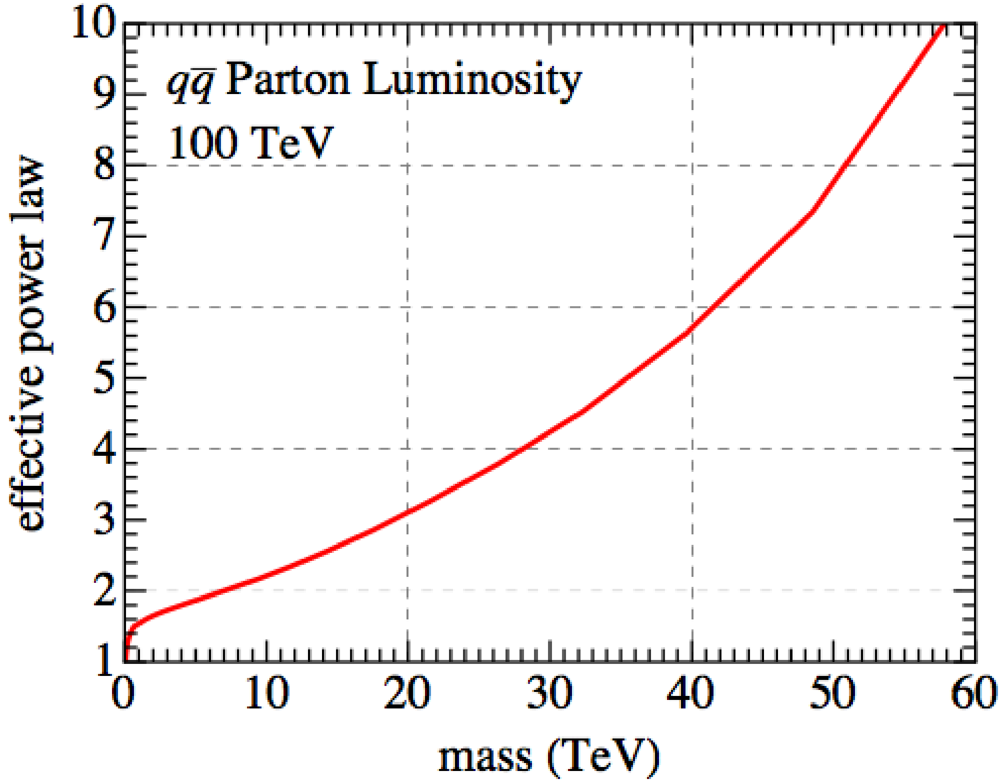
(from M. Mangano)

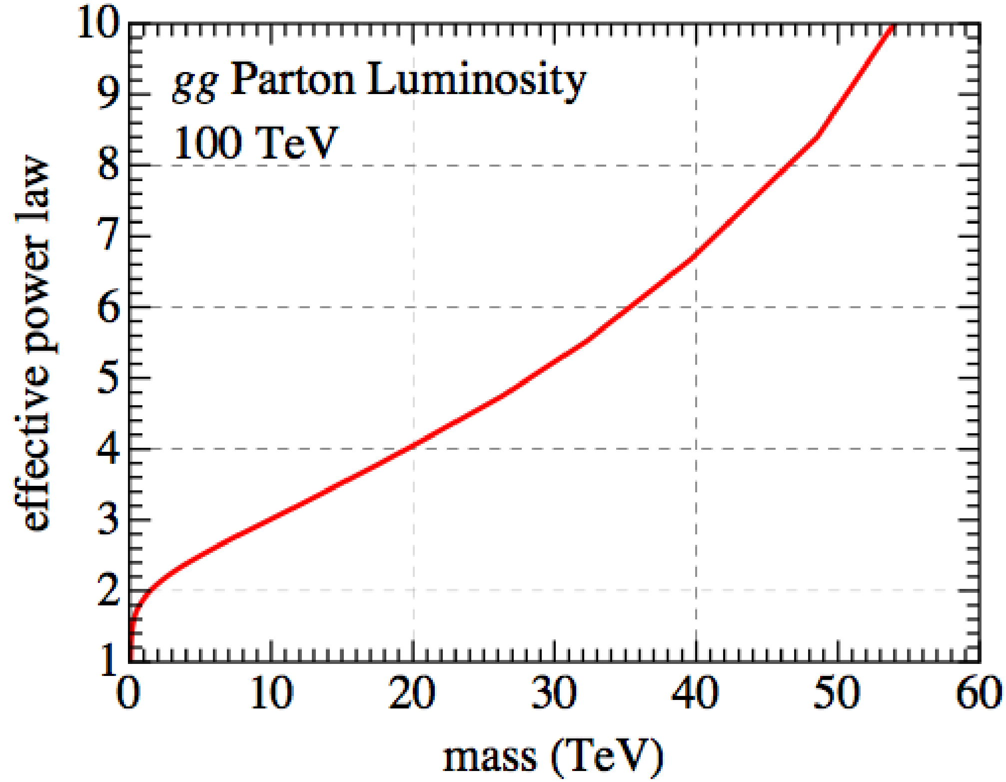
Collider Luminosity and Energy

- Collider luminosity more important for low-mass, low cross-section physics

$$\sigma \sim L_{\mathrm{p}} \cdot \hat{\sigma}$$
$$\sim \frac{1}{\tau^a}\hat{\sigma},$$

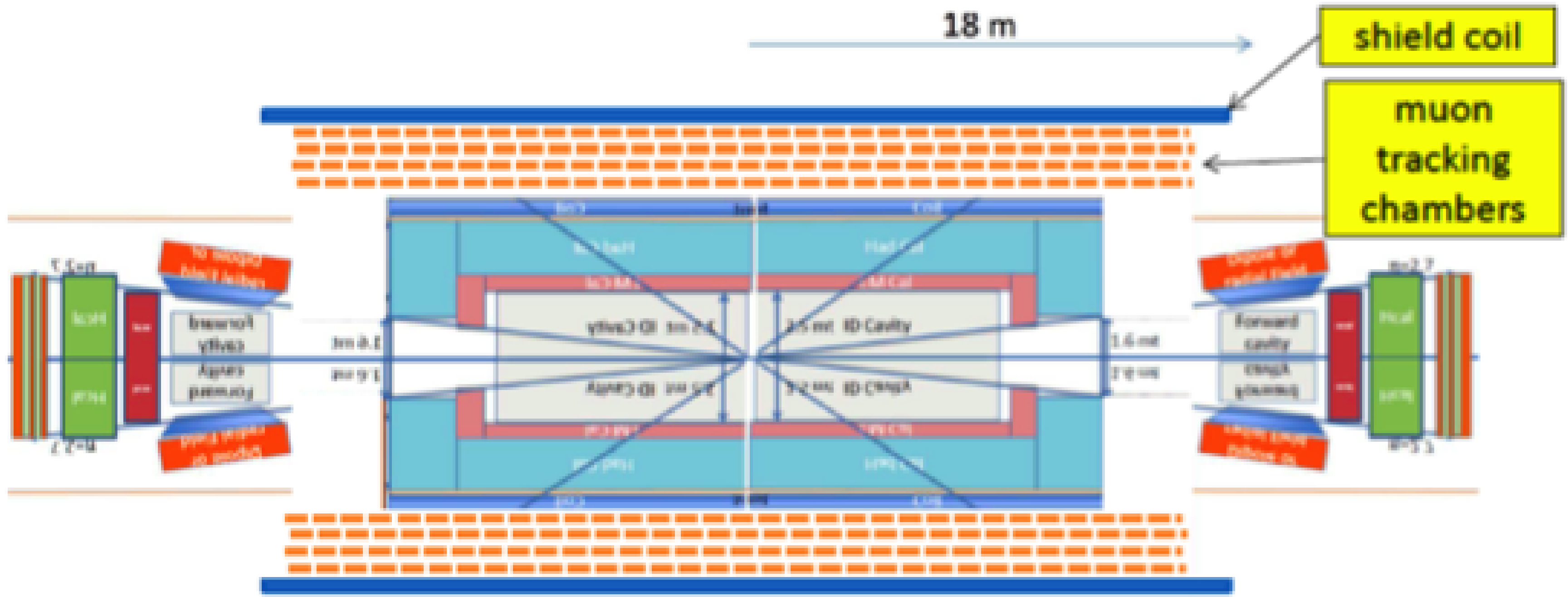
(from L-T Wang)





The dependence of power a on mass scale $M = \sqrt{\hat{s}} = \sqrt{s\tau}$

2. Option 2: Twin Solenoid + Dipoles



Twin Solenoid: a 6 T, 12 m dia x 23 m long main solenoid + an active shielding coil

Important advantages:

- ✓ **Nice Muon tracking space:** area with 2 to 3 T for muon tracking in 4 layers.
- ✓ **Very light:** 2 coils + structures, ≈ 5 kt, only ≈ 4% of the option with iron yoke!
- ✓ **Much smaller:** system outer diameter is significantly less than with iron .

Setting the Stage – USA Department of Energy Report (2014)

- Science Drivers
  - Use the Higgs boson as a new tool for discovery
  - Pursue the physics associated with neutrino mass
  - Identify the new physics of dark matter
  - Under stand cosmic acceleration: dark energy and inflation
  - Explore the unknown: new particles, interactions, and physical principles