Future Colliders and the Cosmic Frontier
Part A: EWPT

M.J. Ramsey-Musolf

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My pronouns: he/him/his

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Tsung-Dao Lee Institute
上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

http://www.physics.umass.edu/acfi/

http://tdli.sjtu.edu.cn/web/yjxy/5130001.htm

Future Colliders Workshop
IFT Madrid, June-July 2019

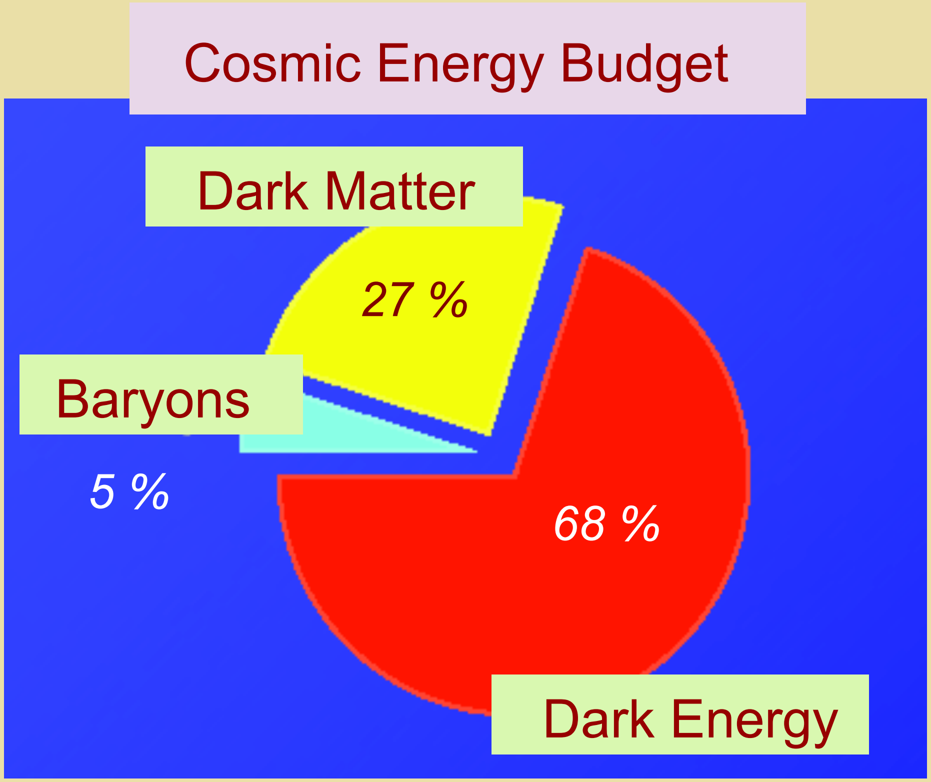
Feliz Fiesta del Orgullo

Cincuenta anos Stonewall

Questions for Future Colliders

- *What is the "value added" ?*
- *What are the synergies/complementarities involving the pp, ee, and ep colliders ?*
- *Are there well-defined targets in mass reach and precision that would definitively address key open questions ?*

The Origin of Matter



What can the LHC & future colliders teach us about open questions in cosmology ?

Themes for This Talk

- *The future collider program provides an opportunity to perform a comprehensive probe of the thermal history of EW symmetry breaking in BSM scenarios*
- *Many interesting aspects of dark matter/dark sector physics can be studied with future colliders → a comprehensive picture remains to be developed*

Disclaimer & Credits

- ***Disclaimer:*** *I am attempting to combine two topics into one longer talk → my apologies to anyone for omission of work that should be mentioned in a full one hour talk on either topic*
- ***Credits:*** *Many thanks to input I've received from week 1 speakers, Tim Tait who unfortunately had to cancel his visit, and my many collaborators*

Outline – Part A: EW Phase Transition

I. Context & Questions

II. Models & Phenomenology

- *MSSM*
- *Simplified Higgs Portal*

III. Theoretical Robustness

IV. Outlook

Outline – Part B: DM

I. Context

II. MSSM

III. Simplified Models

IV. EW Multiplets

V. QCD-Like DM

VI. Mediators

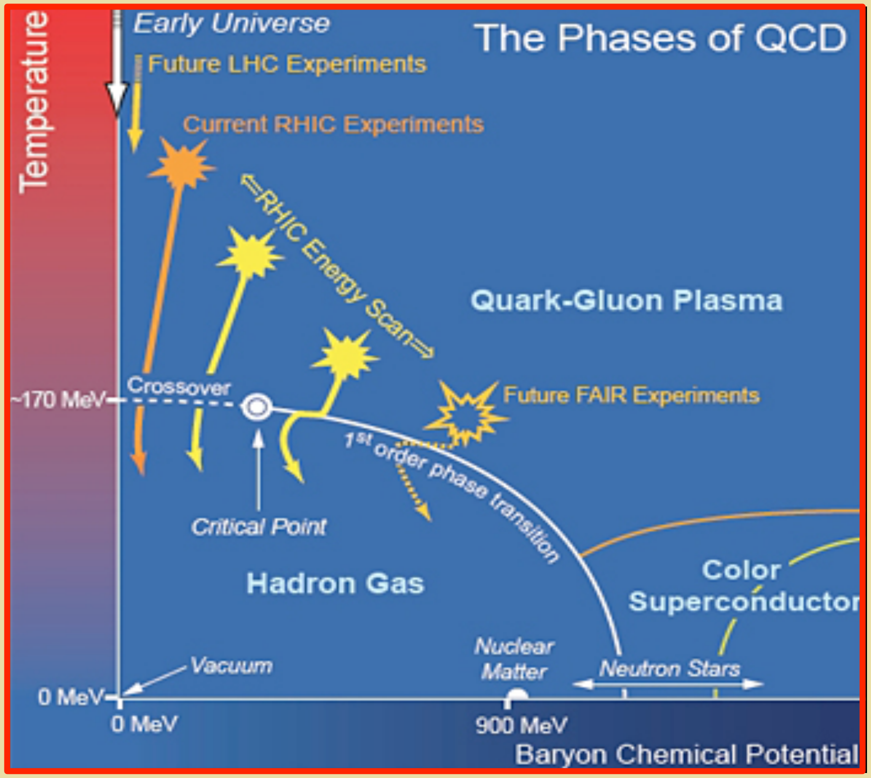
VII. Outlook

A-I. Context & Questions

Electroweak Phase Transition

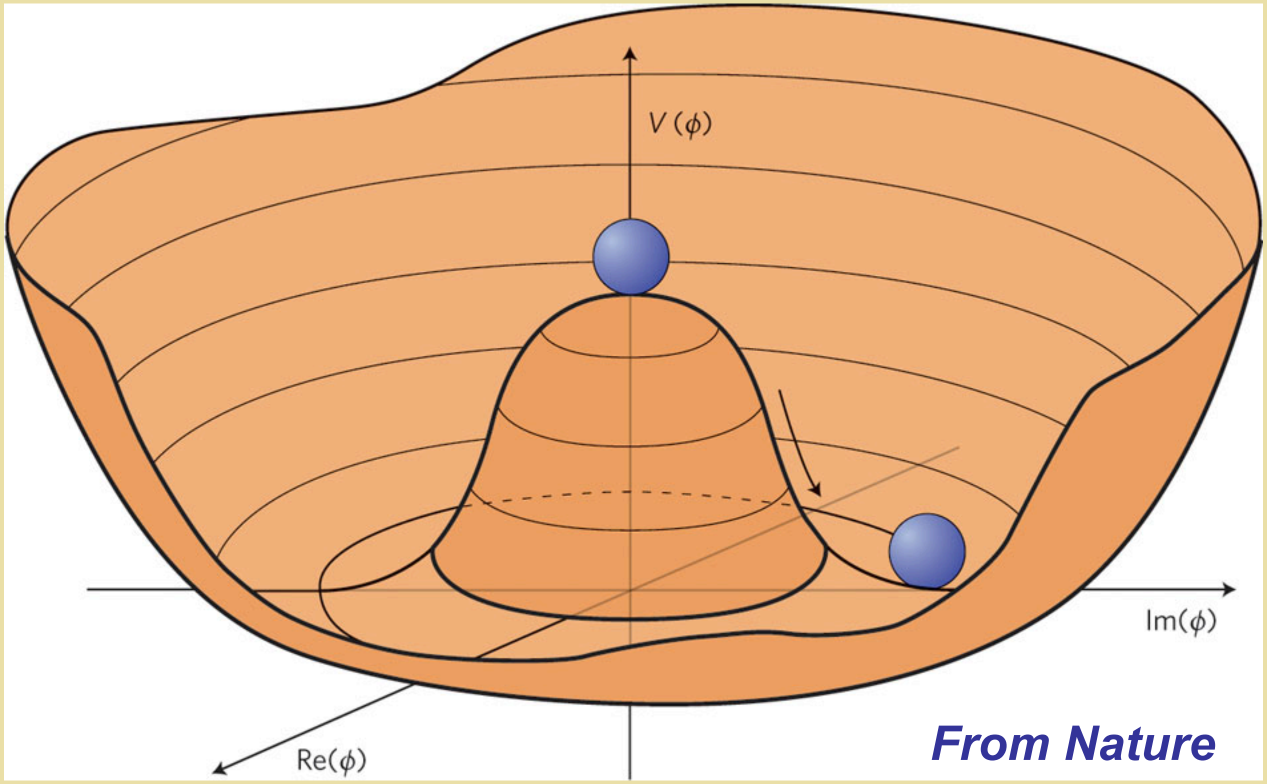
- *Higgs discovery $\rightarrow$ What was the thermal history of EWSB ?*

Thermal History of Symmetry Breaking



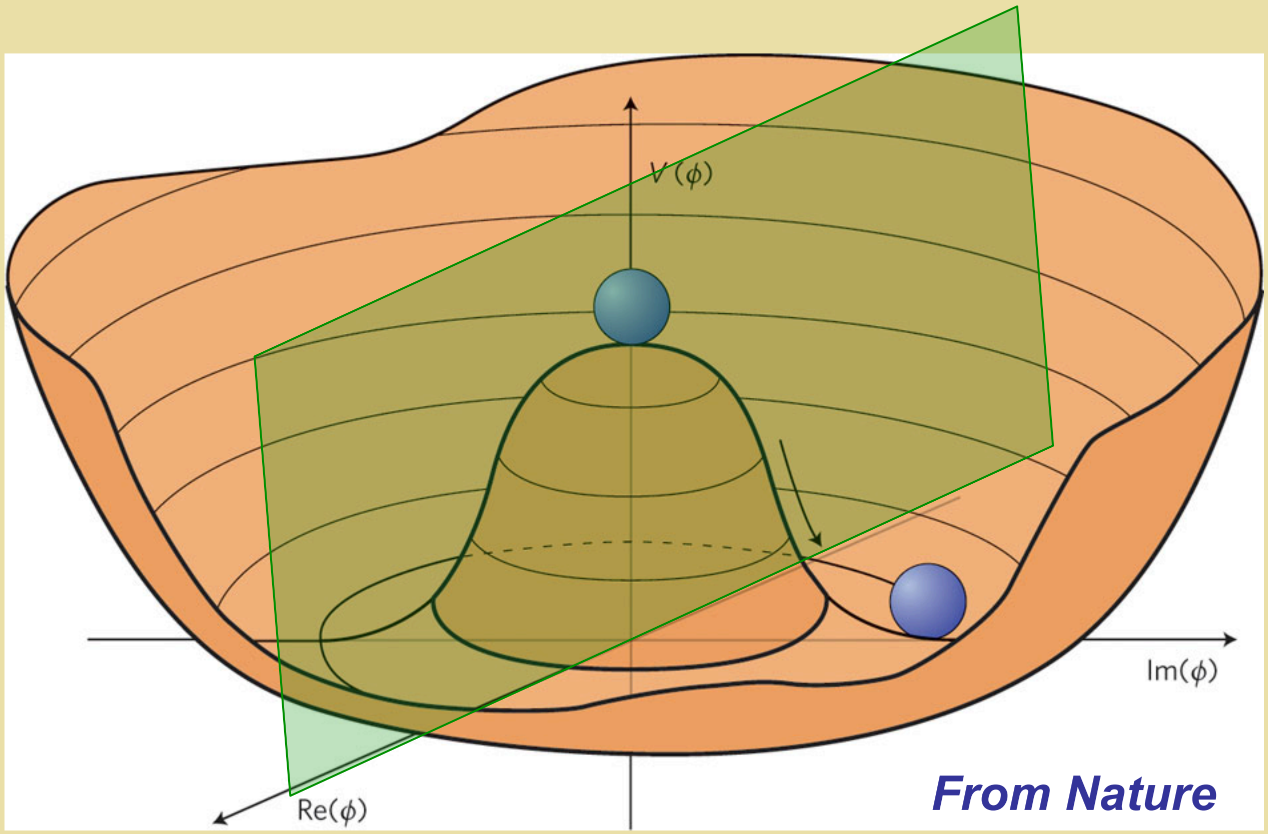
QCD Phase Diagram → EW Theory Analog?

EWSB: The Scalar Potential



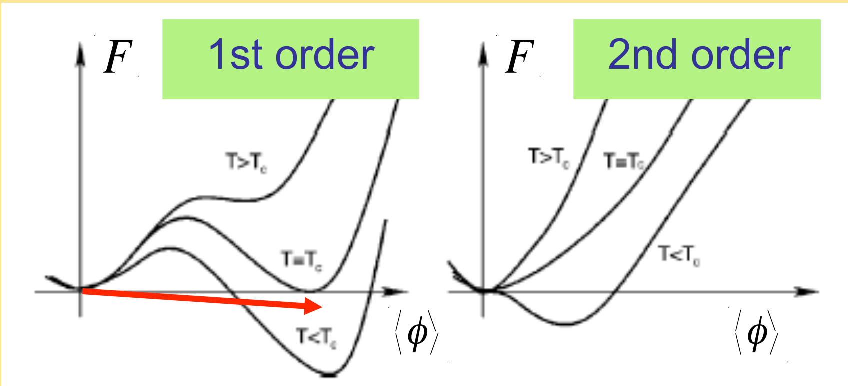
What was the thermal history of EWSB ?

EWSB: The Scalar Potential



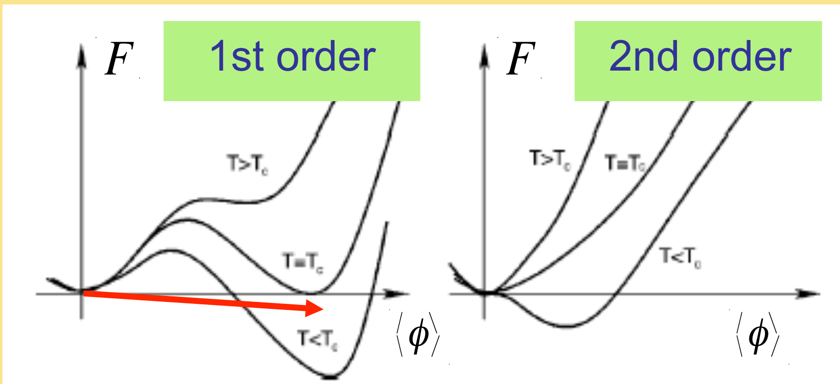
What was the thermal history of EWSB ?

EW Phase Transition: St'd Model



Increasing m_h →

EW Phase Transition: St'd Model



Increasing m_h →

Lattice	Authors	M_h^C (GeV)
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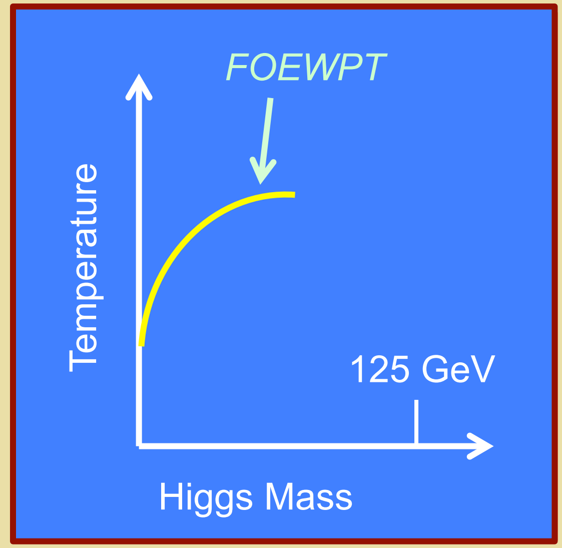
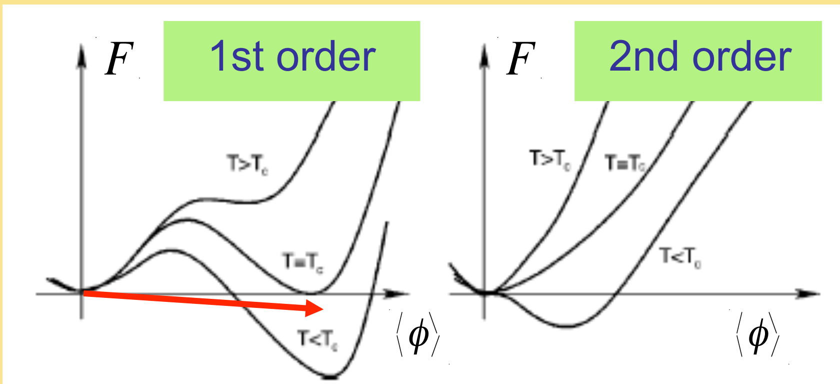
SM EW: Cross over transition



EW Phase Diagram

EW Phase Transition: St'd Model



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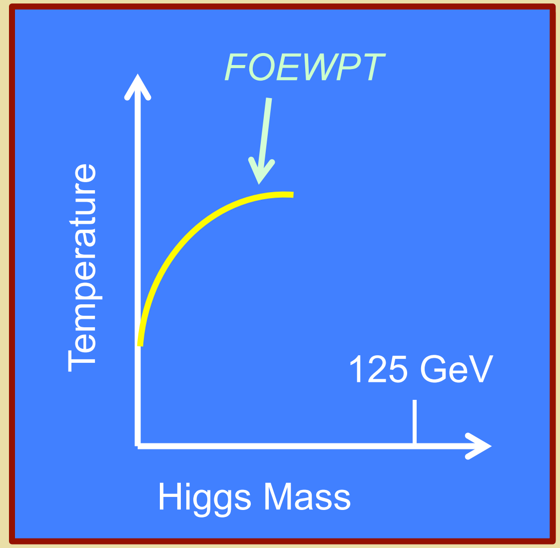
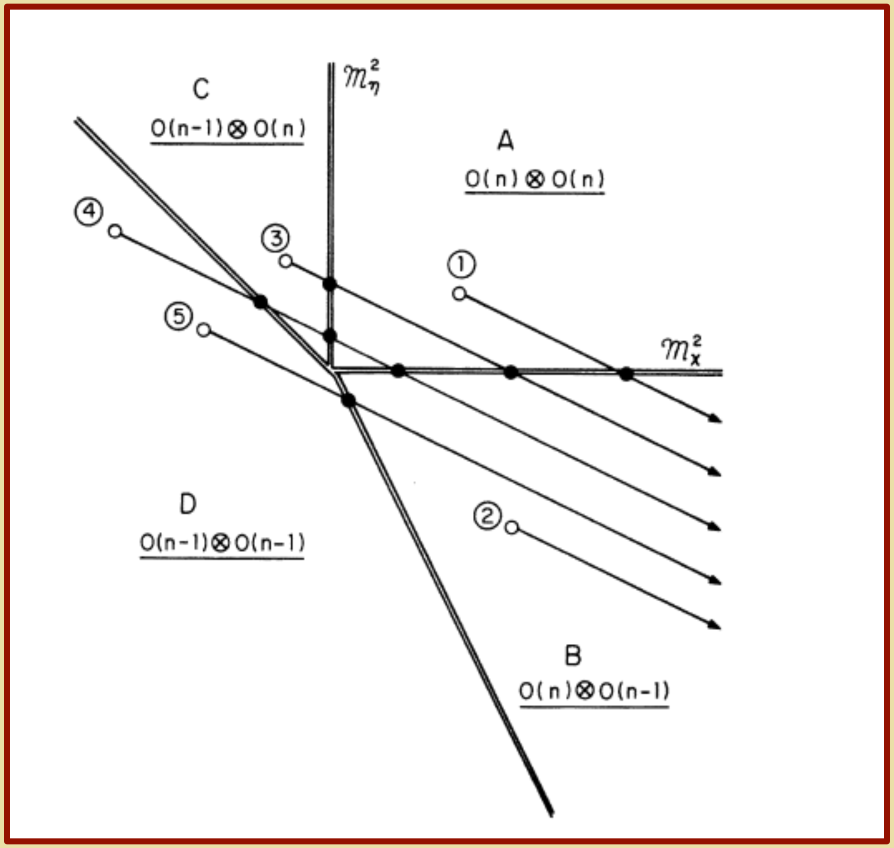


EW Phase Diagram

How does this picture change in presence of new TeV scale physics ? What is the phase diagram ? SFOEWPT ?

Patterns of Symmetry Breaking



S. Weinberg, PRD 9 (1974) 3357

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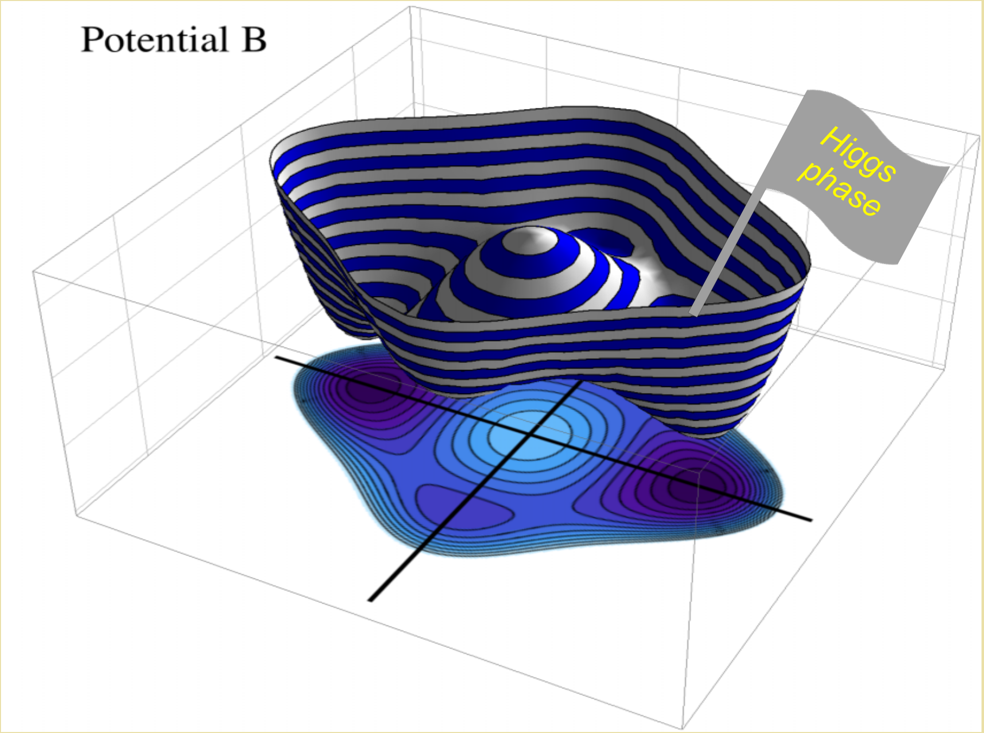

Extrema can evolve differently as T evolves →
rich possibilities for symmetry breaking

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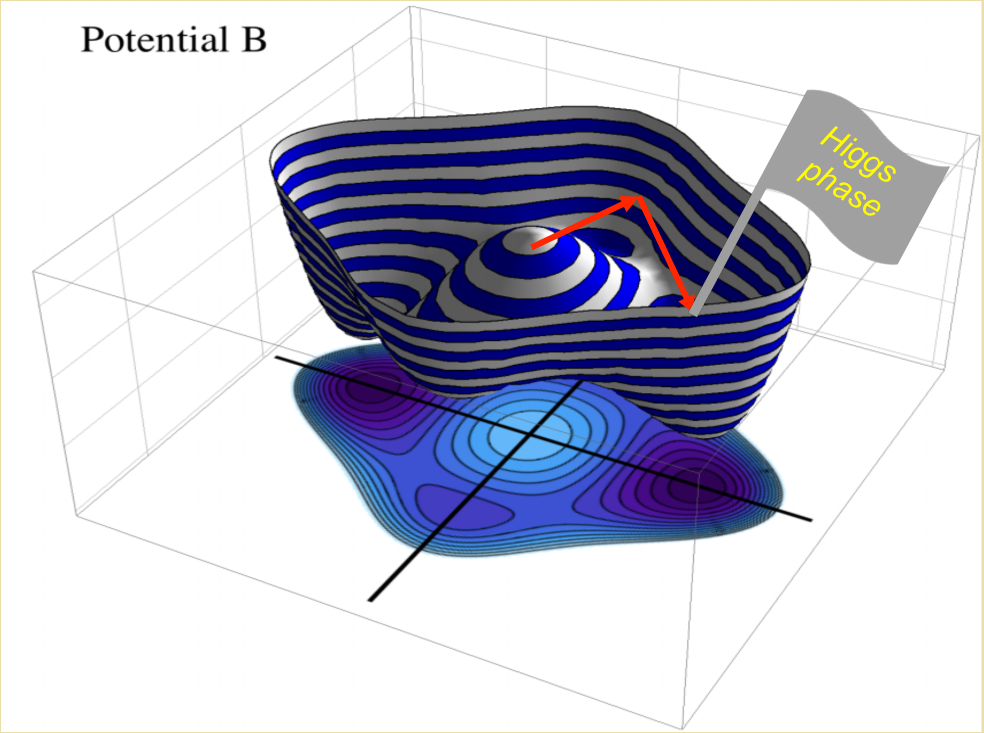

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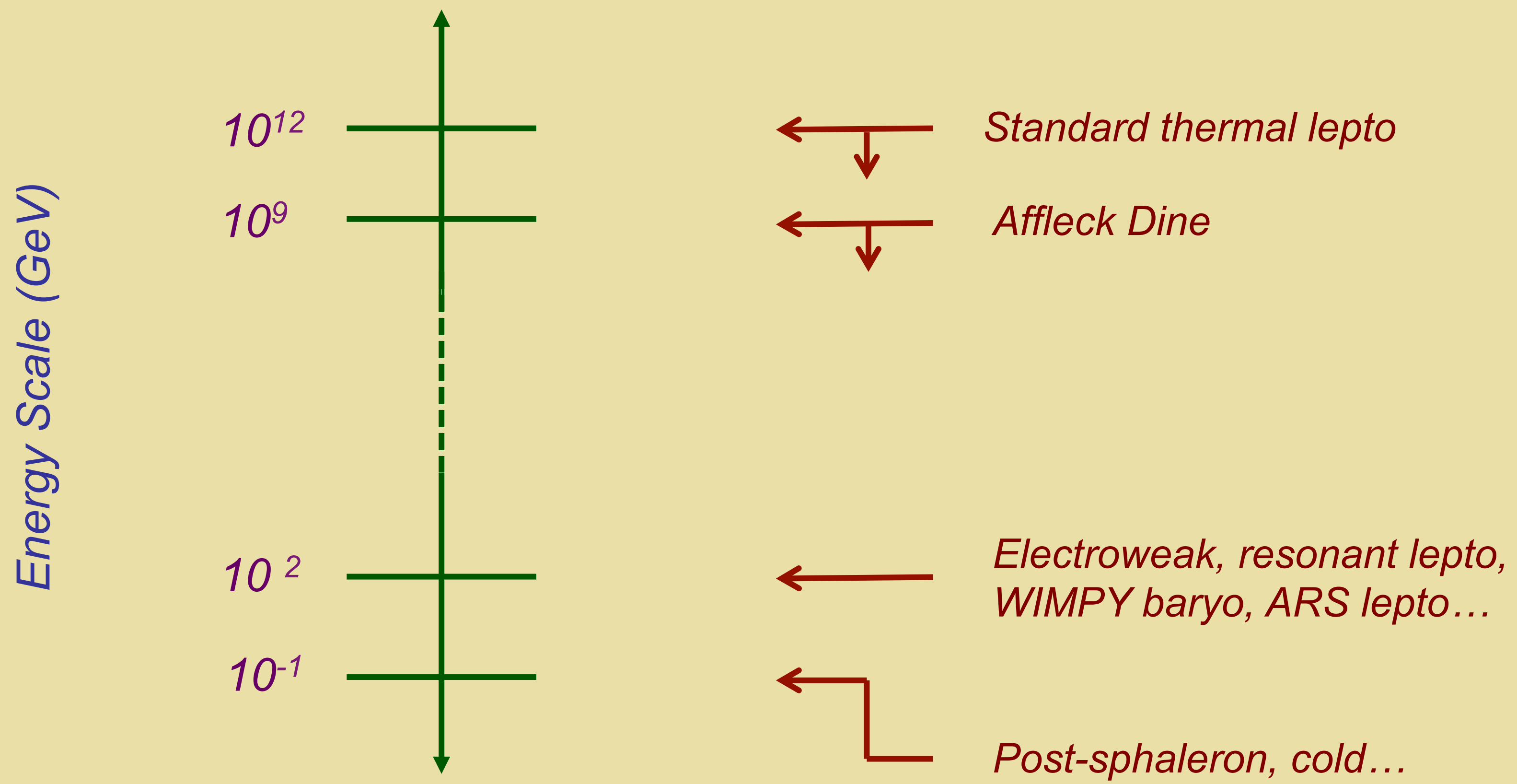
Electroweak Phase Transition

- *Higgs discovery $\rightarrow$ What was the thermal history of EWSB ?*

- *Baryogenesis $\rightarrow$ Was the matter-antimatter asymmetry generated in conjunction with EWSB (EW baryogenesis) ?*

Baryogenesis Scenarios



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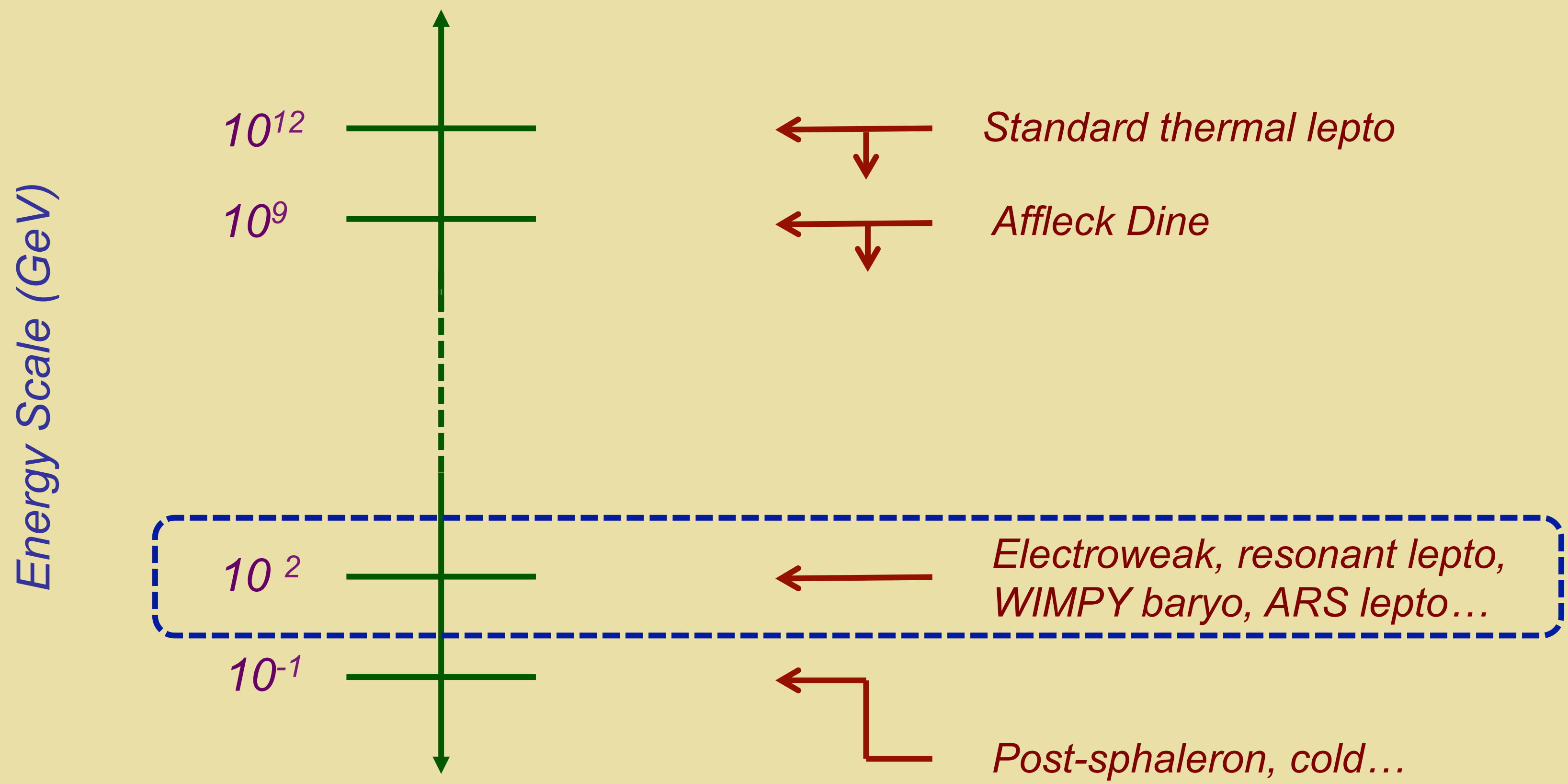
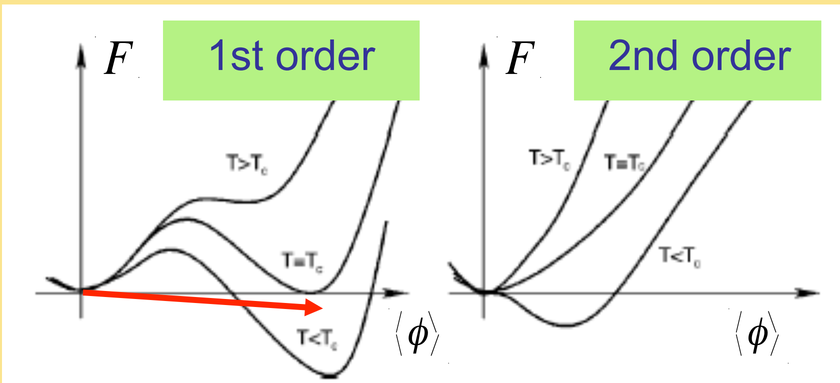


Era of EWSB: t_{univ} ~ 10 ps

EW Phase Transition: Baryogenesis



Increasing m_h →

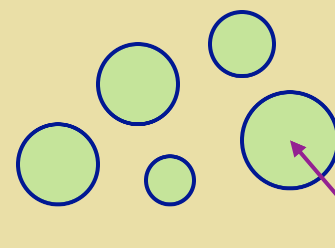
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

↓

Bubble nucleation



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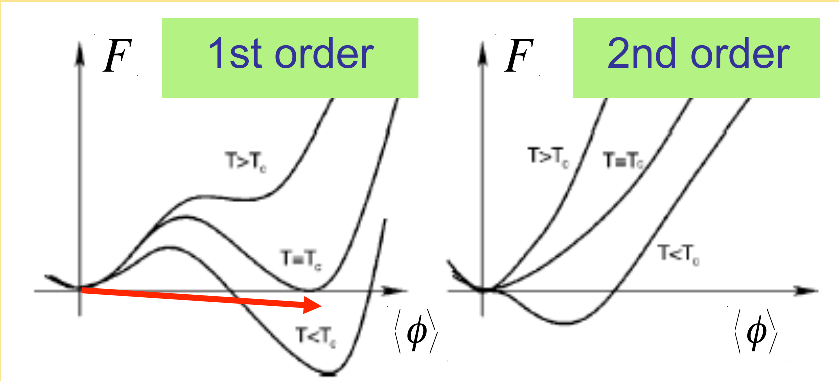

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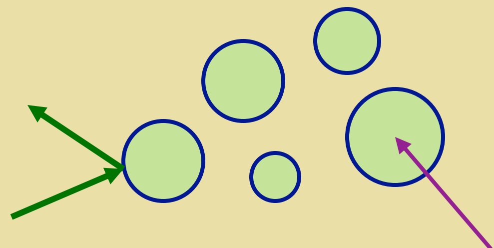
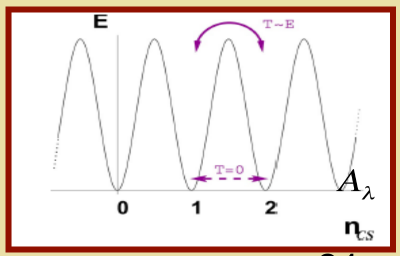


Y_B : CPV & EW sphalerons

EWSB



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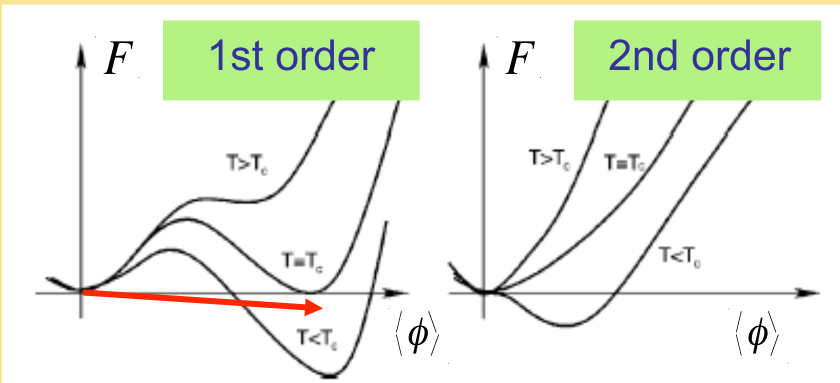

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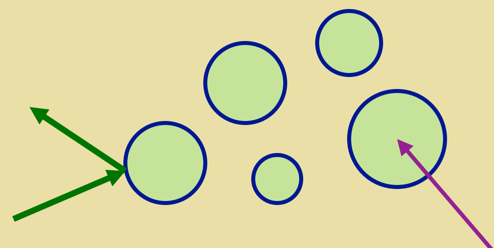
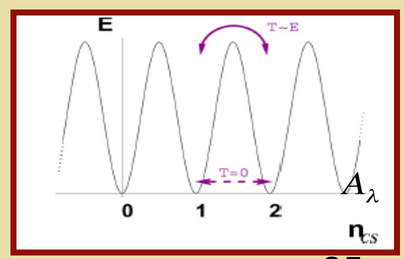


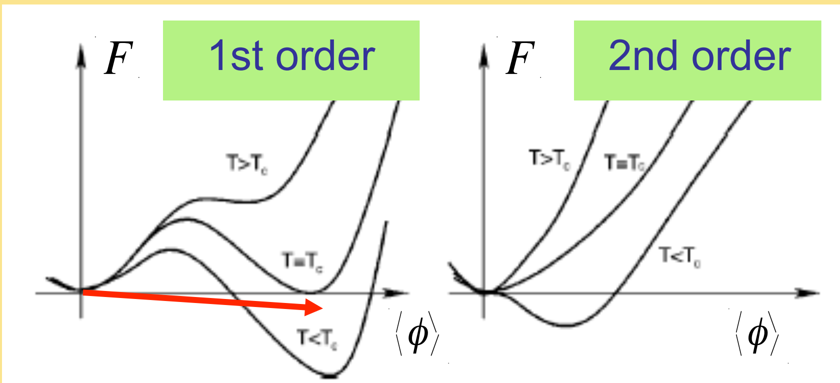
Y_B : CPV & EW sphalerons

EWSB

BSM



EW Phase Transition: Baryogenesis



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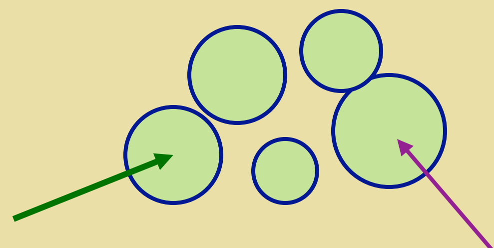
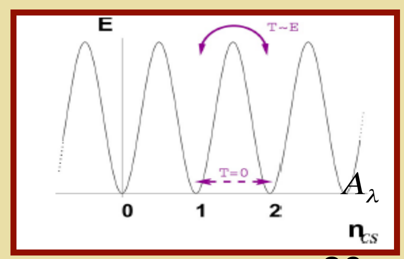
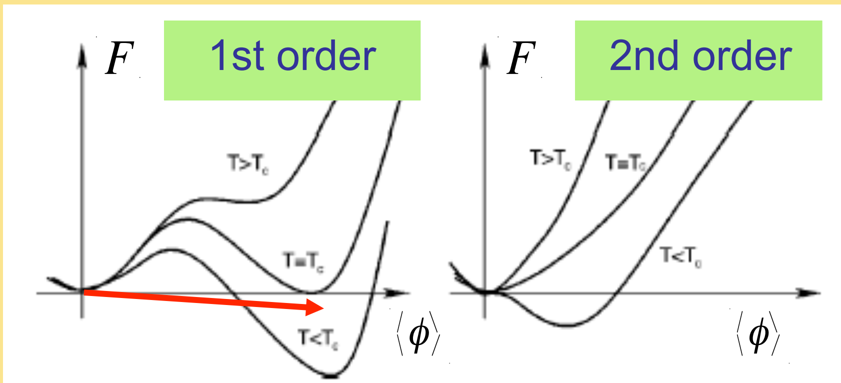


Y_B : diffuses into interiors

EWSB



EW Phase Transition: Baryogenesis



Increasing m_h →

← *New scalars*

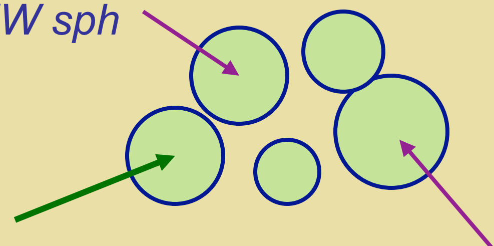
Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

Preserve $Y_B^{initial}$

Bubble nucleation

Quench EW sph



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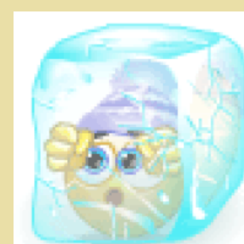
EWSB



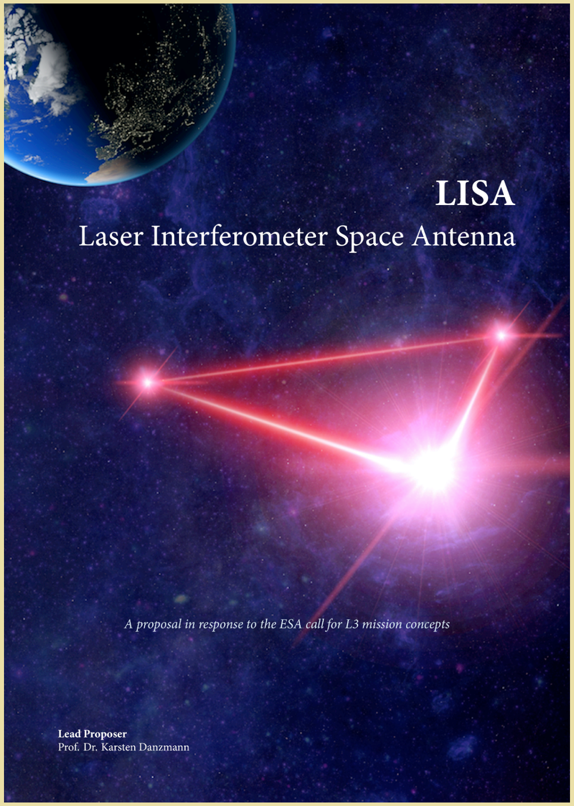
Electroweak Phase Transition

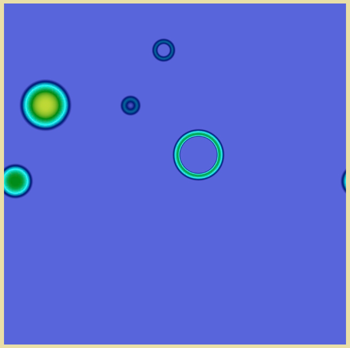
- *Higgs discovery $\rightarrow$ What was the thermal history of EWSB ?*

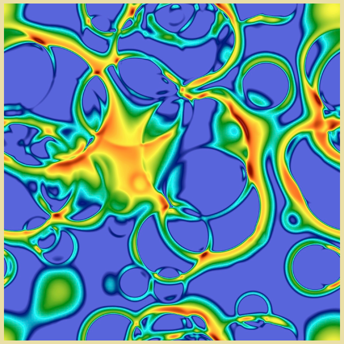
- *Baryogenesis $\rightarrow$ Was the matter-antimatter asymmetry generated in conjunction with EWSB (EW baryogenesis) ?*

- *Gravitational waves $\rightarrow$ If a signal observed in LISA, could a cosmological phase transition be responsible ?*

Gravitational Radiation



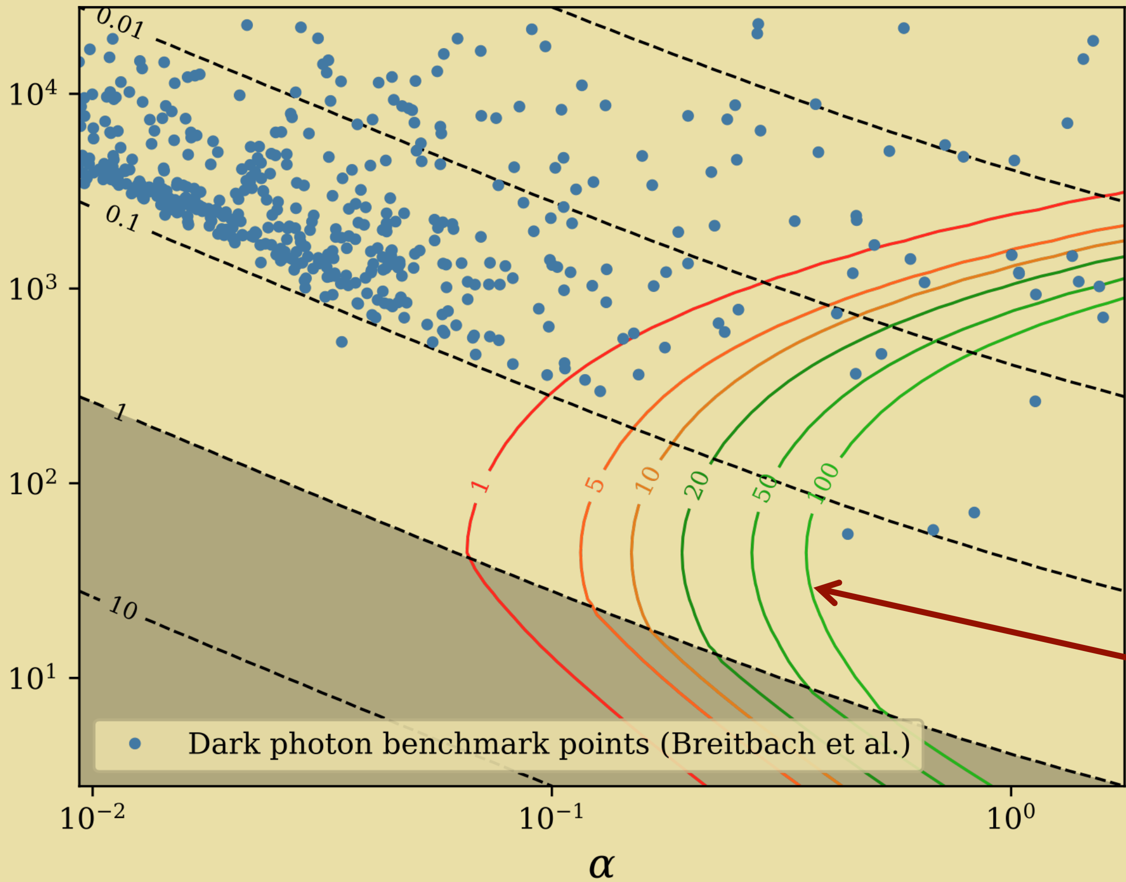




1. Bubbles nucleate and grow
2. Expand in a plasma - create reaction fronts
3. Bubbles + fronts collide - violent process
4. Sound waves left behind in plasma
5. Turbulence; damping

Thanks: D. Weir

Gravitational Radiation



"Duration"

LISA SNR

"Energy Release"

Thanks: D. Weir

A-II. Models & Phenomenology

Models & Phenomenology

What BSM Scenarios?

SM + Scalar Singlet	Espinosa, Quiros 93, Benson 93, Choi, Volkas 93, Vergara 96, Branco, Delepine, Emmanuel-Costa, Gonzalez 98, Ham, Jeong, Oh 04, Ahriche 07, Espinosa, Quiros 07, Profumo, Ramsey-Musolf, Shaughnessy 07, Noble, Perelstein 07, Espinosa, Konstandin, No, Quiros 08, Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy 09, Ashoorioon, Konstandin 09, Das, Fox, Kumar, Weiner 09, Espinosa, Konstandin, Riva 11, Chung, Long 11, Barger, Chung, Long, Wang 12, Huang, Shu, Zhang 12, Fairbairn, Hogan 13, Katz, Perelstein 14, Profumo, Ramsey-Musolf, Wainwright, Winslow 14, Jiang, Bian, Huang, Shu 15, Kozaczuk 15, Cline, Kainulainen, Tucker-Smith 17, Kurup, Perelstein 17, Chen, Kozaczuk, Lewis 17, Gould, Kozaczuk, Niemi, Ramsey-Musolf, Tenkanen, Weir 19...
SM + Scalar Doublet (2HDM)	Turok, Zadrozny 92, Davies, Froggatt, Jenkins, Moorhouse 94, Cline, Lemieux 97, Huber 06, Froome, Huber, Seniuch 06, Cline, Kainulainen, Trott 11, Dorsch, Huber, No 13, Dorsch, Huber, Mimasu, No 14, Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka 16, Dorsch, Huber, Mimasu, No 17, Bernon, Bian, Jiang 17, Andersen, Gorda, Helset, Niemi, Tenkanen, Tranberg, Vuorinen, Weir 18...
SM + Scalar Triplet	Patel, Ramsey-Musolf 12, Niemi, Patel, Ramsey-Musolf, Tenkanen, Weir 18 ...
MSSM	Carena, Quiros, Wagner 96, Delepine, Gerard, Gonzalez Felipe, Weyers 96, Cline, Kainulainen 96, Laine, Rummukainen 98, Carena, Nardini, Quiros, Wagner 09, Cohen, Morrissey, Pierce 12, Curtin, Jaiswal, Meade 12, Carena, Nardini, Quiros, Wagner 13, Katz, Perelstein, Ramsey-Musolf, Winslow 14...
NMSSM...	Pietroni 93, Davies, Froggatt, Moorhouse 95, Huber, Schmidt 01, Ham, Oh, Kim, Yoo, Son 04, Menon, Morrissey, Wagner 04, Funakubo, Tao, Yokoda 05, Huber, Konstandin, Prokopec, Schmidt 07, Chung, Long 10, Kozaczuk, Profumo, Stephenson Haskins, Wainwright 15...

Thanks: J. M. No

EWPT: Theory & Phenomenology

- *What models can lead to a (strong) first order electroweak phase transition (EW baryogenesis & gravitational waves) ?*
- *Can they also yield contributions to Ω_{DM} ?*
- *How can they be tested experimentally ?*
- *How reliably can we compute phase transition properties & make the connection with phenomenology ?*

First Order EWPT from BSM Physics

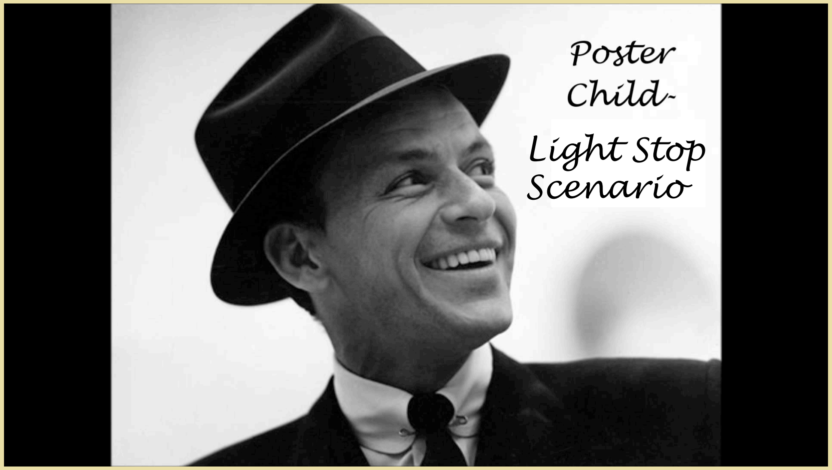
- *Thermal loops involving new bosons*
- *T=0 loops (CW Potential)*
- *Change tree-level vacuum structure*

Why T_{EW} Sets a Scale for Colliders

- ***Thermal loops involving new bosons***
- ***T=0 loops (CW Potential)***
- ***Change tree-level vacuum structure***

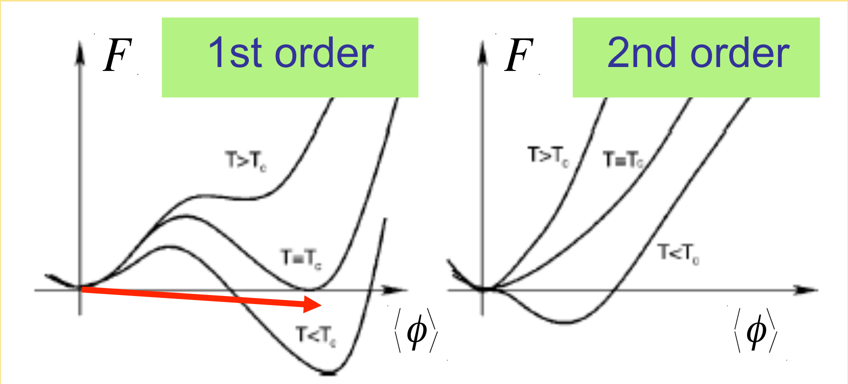
Blackboard Discussion

EWPT "Poster Child": MSSM Light Stop Scenario



Thermal loops

EW Phase Transition: SUSY



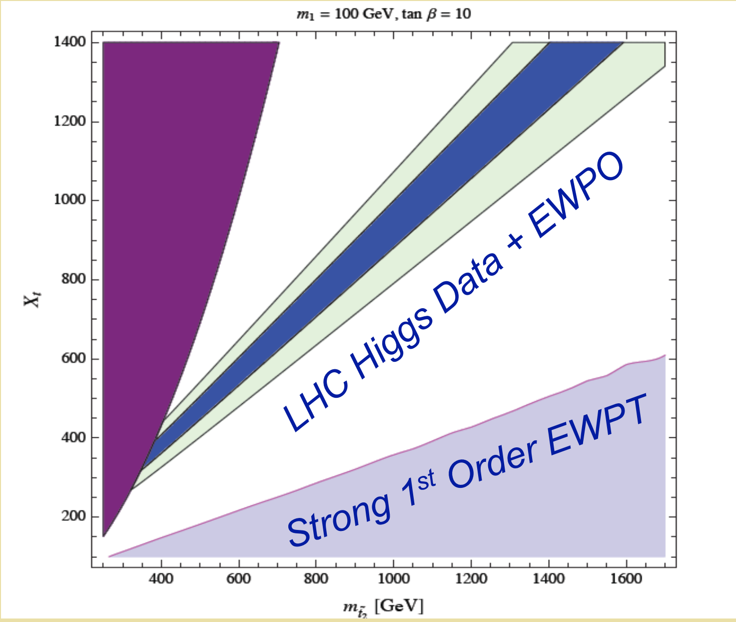
Increasing m_h →

← *New scalars*

Light RH stops also affect Higgs properties

Curtin, Jaiswal, Meade 1203.2932

MSSM + $\delta\lambda_4\,(H_u^\dagger H_u)^2$



Katz, Perelstein, R-M, Winslow 1509.02934

Strong 1st Order EWPT

Definitive probe of the possibilities → LHC + next generation colliders

Higgs Portal: Simple Scalar Extensions

Extension	DOF	EWPT	DM
Real singlet: ~~Z_2~~	1	✔	✖
Real singlet: Z_2	1	✔	✔
Complex Singlet	2	✔	✔
EW Multiplets	3+	✔	✔

May be low-energy remnants of UV complete theory & illustrative of generic features

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Simplest Extension

Standard Model + real singlet scalar

Singlet Driven EW Phase Transition

(lots of) Motivation

⇒ Neutral Naturalness

⇒ Higgs Portal (Dark Sectors)

⇒ Non-minimal SUSY (e.g. NMSSM)

⇒ Warped Extra Dim (dilaton...)

...

Thanks: J. M. No

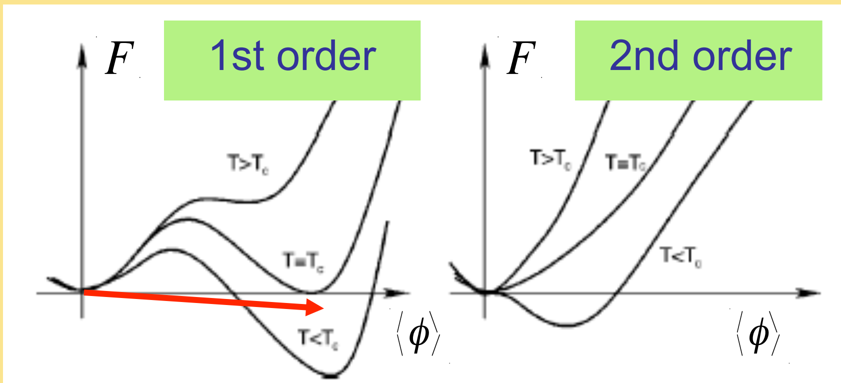
Simplest Extension

Standard Model + real singlet scalar

$$V_{\rm HS} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

- *Strong first order EWPT*
- *Two mixed singlet-doublet states*

EW Phase Transition: New Scalars

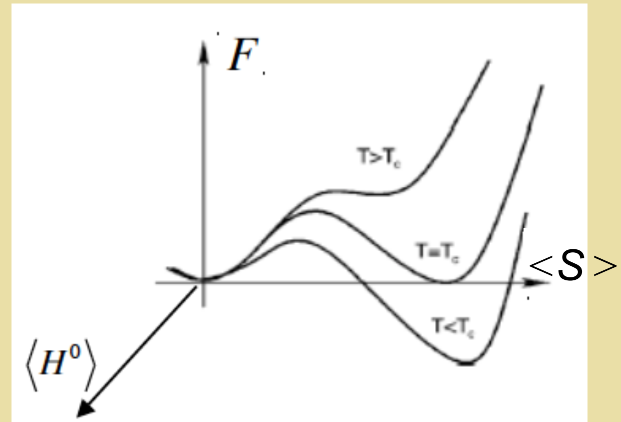


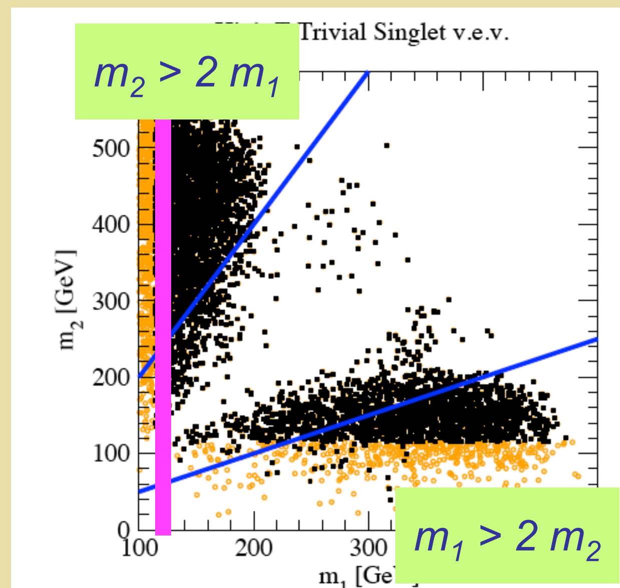
Increasing m_h →

← *New scalars*

Real Singlet: $\phi \to S$

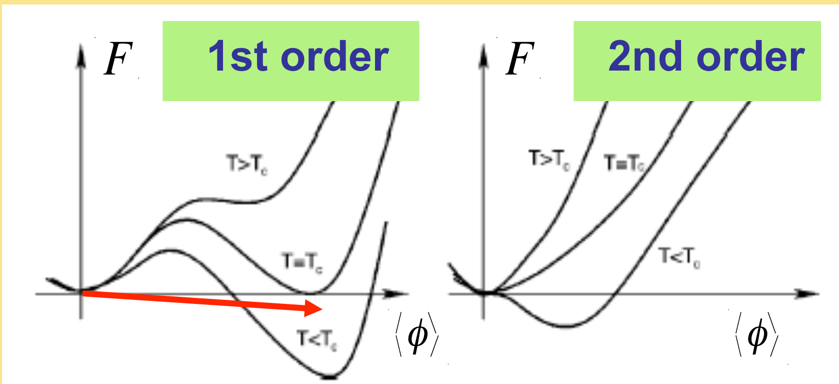
Simplest Extension:
two states h_1 & h_2





Profumo, R-M, Shaugnessy JHEP 0708 (2007) 010
Espinosa, Konstandin, Riva NPB 854 (2012) 592

EW Phase Transition: Singlet Scalars



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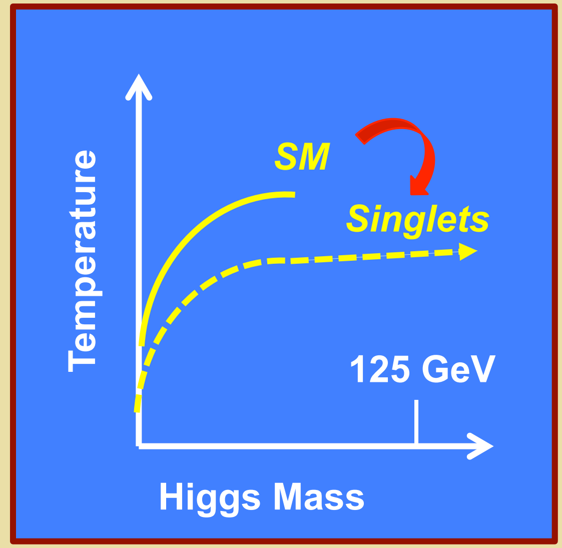

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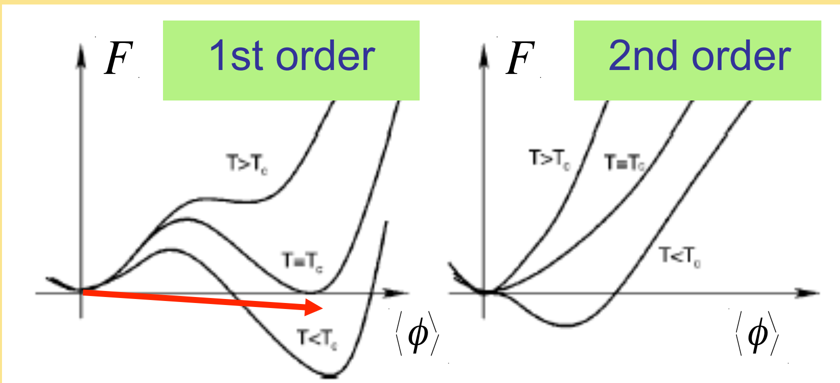

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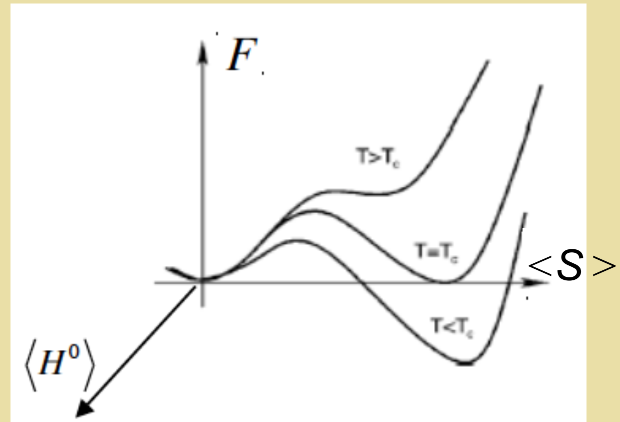
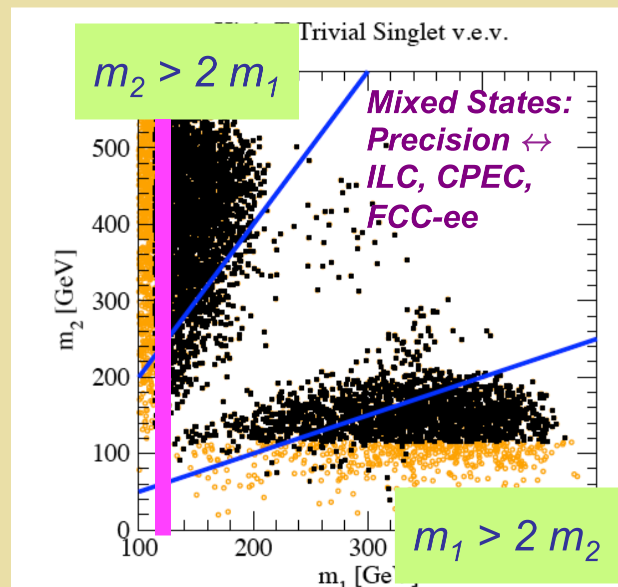
Real Singlet: $\phi \rightarrow S$

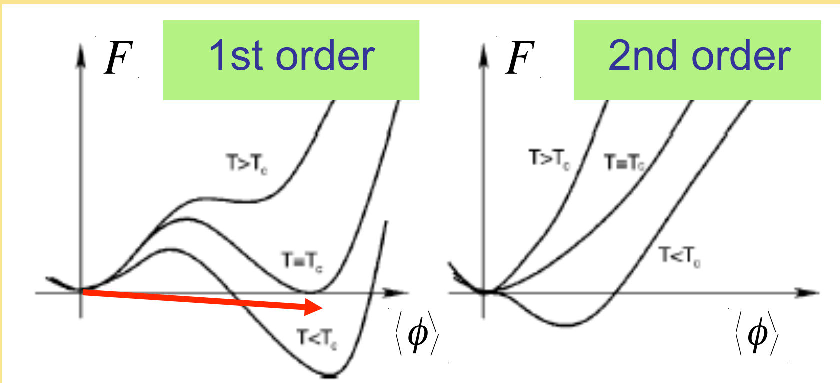
Simplest Extension: two states h_1 & h_2 – h,S mixtures

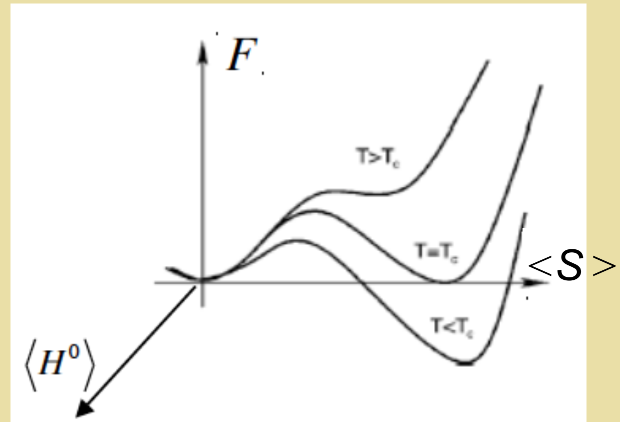




Profumo, MJRM, Shaugnessy '07

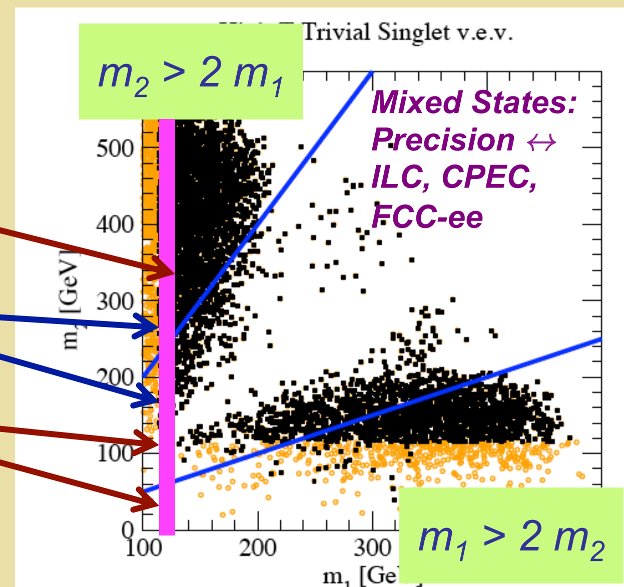
EW Phase Transition: Singlet Scalars





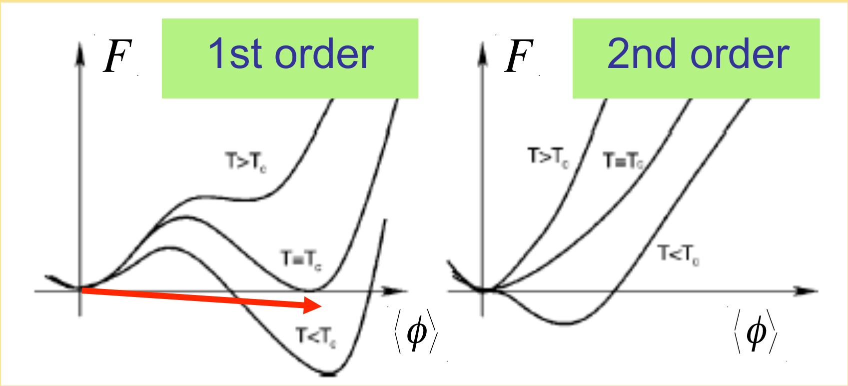
Collider probes

- *Resonant di-Higgs production*
- *Precision Higgs measurements*
- *Non-resonant di-Higgs & exotic Higgs decays*



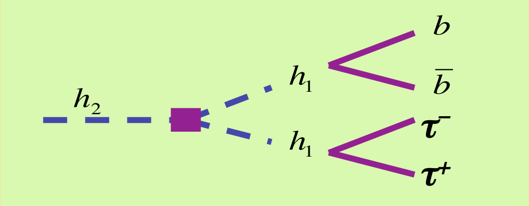
Profumo, MJRM, Shaugnessy '07

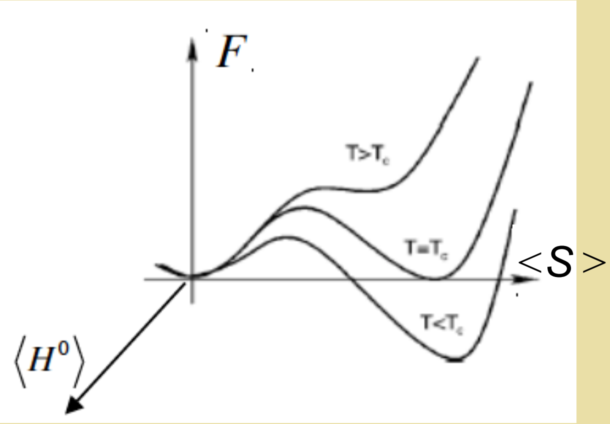
EW Phase Transition: New Scalars

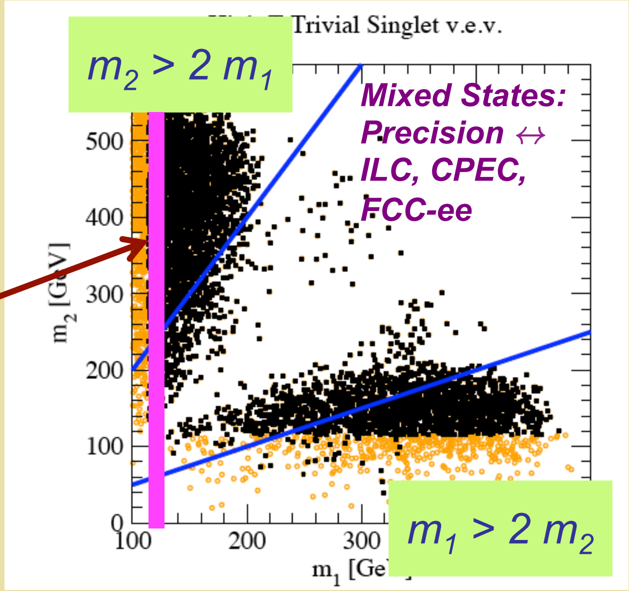


Increasing m_h →

Resonant di-Higgs production



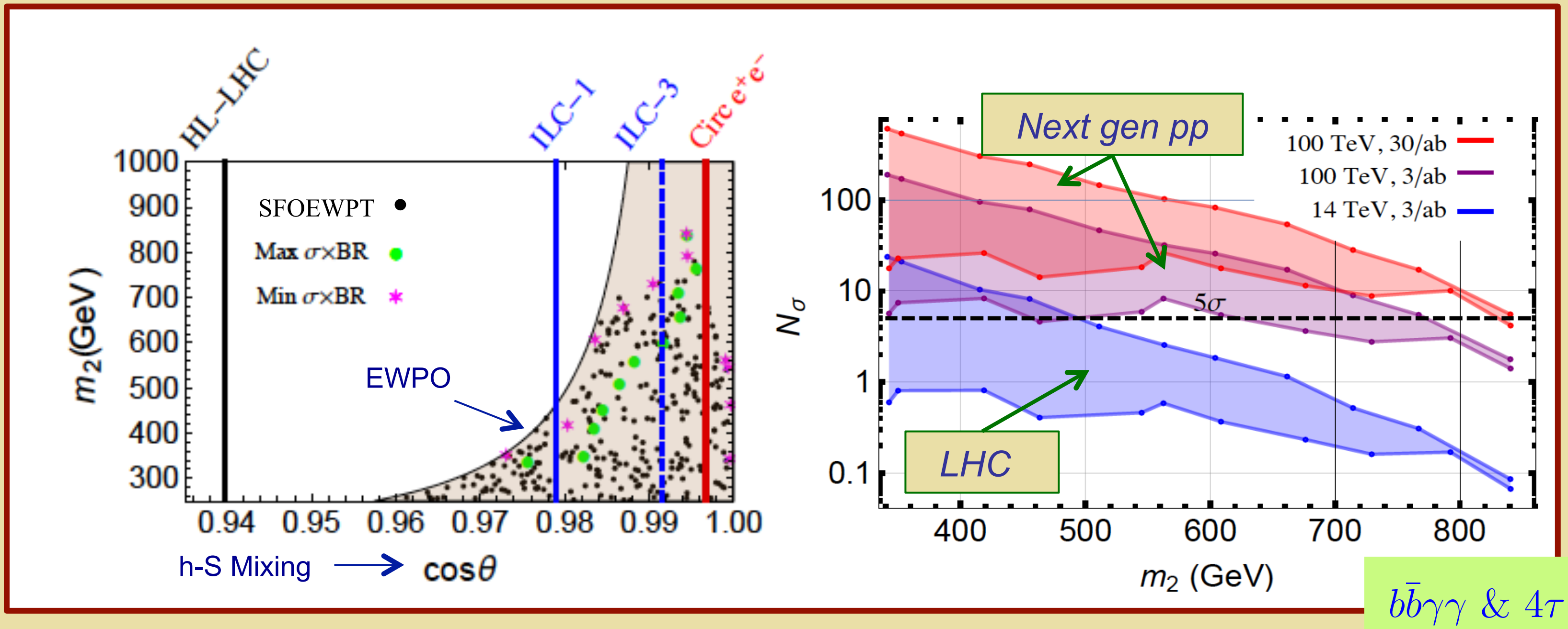




No & RM, arXiv:1310.6035 : ***LHC Discovery w/ 100 fb^{-1}***

EW Phase Transition: Singlet Scalars

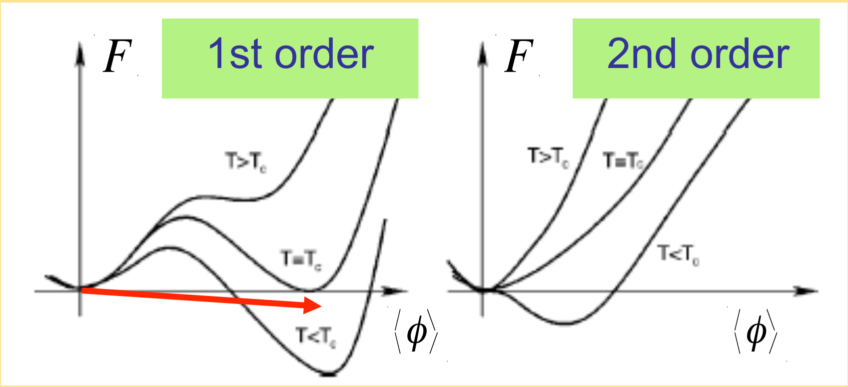
SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



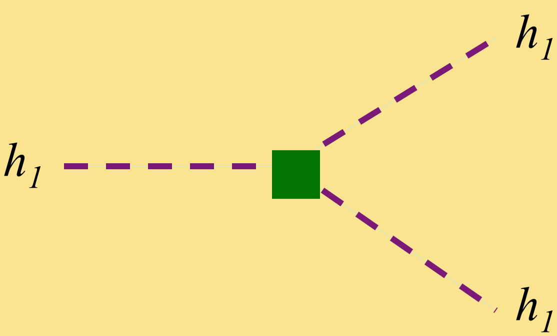
Kotwal, No, R-M, Winslow 1605.06123

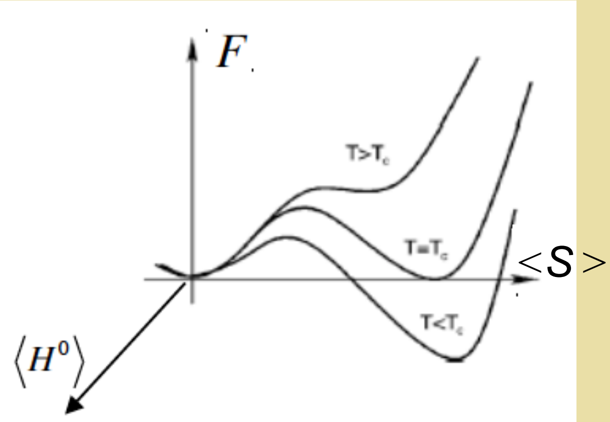
See also: Huang et al, 1701.04442;
Li et al, 1906.05289

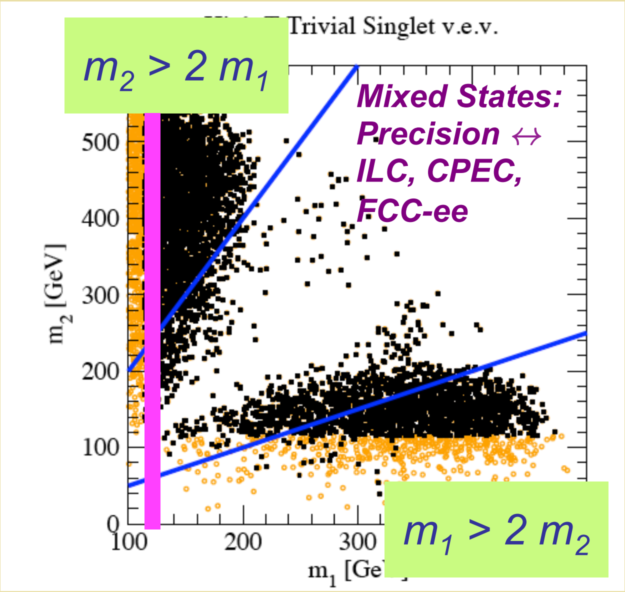
EW Phase Transition: New Scalars



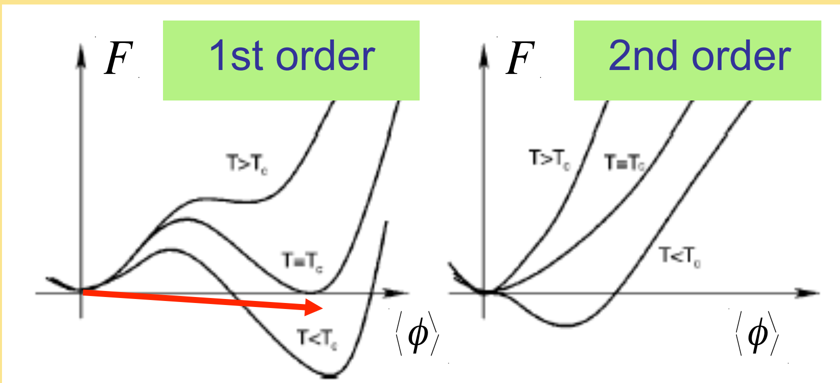
Modified Higgs Self-Coupling

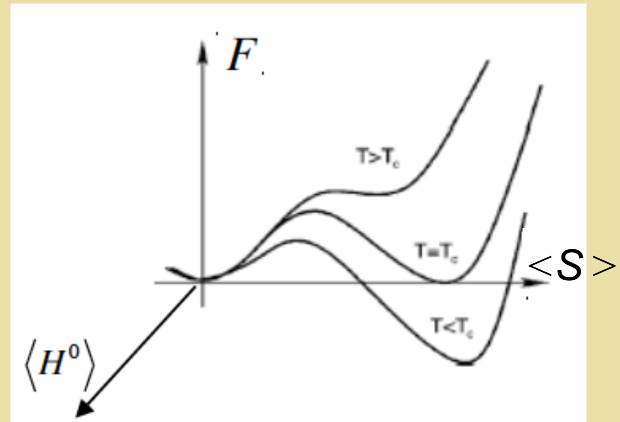






EW Phase Transition: Singlet Scalars





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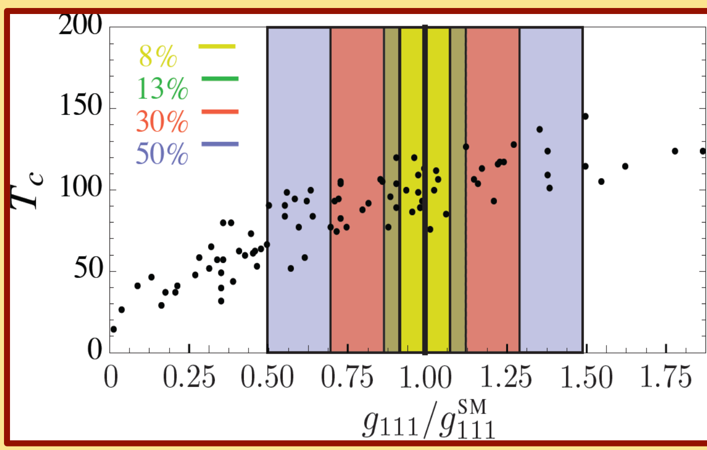
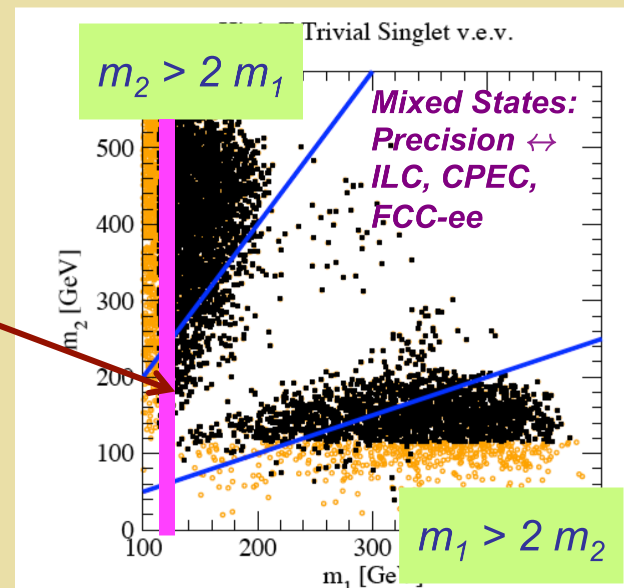
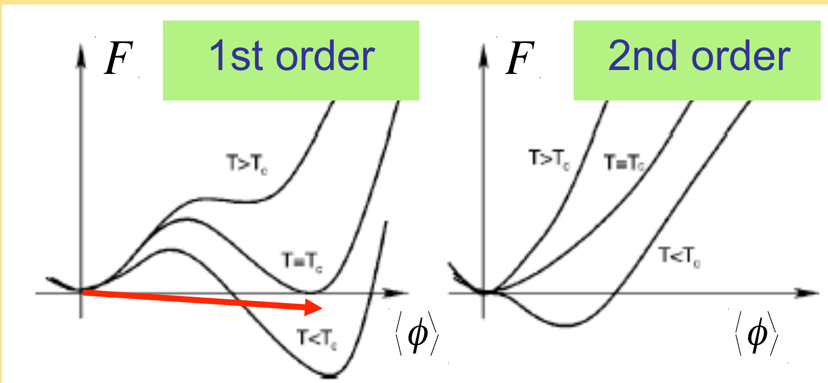
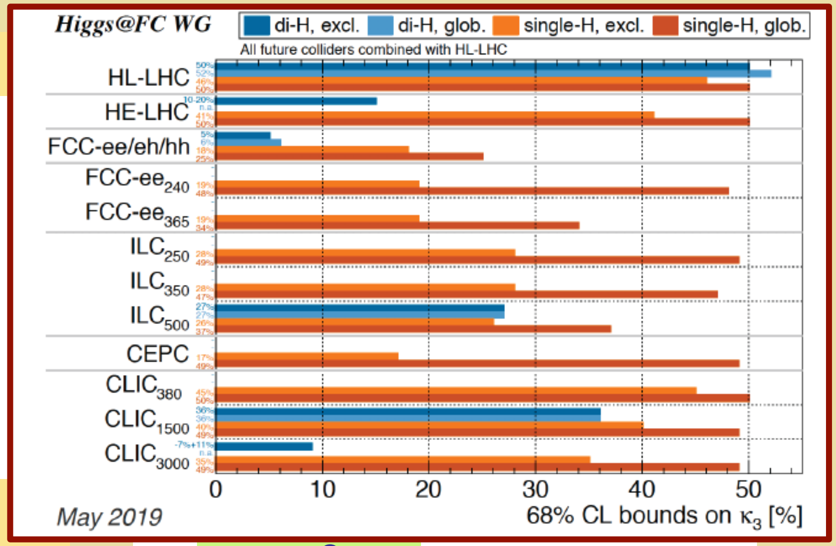




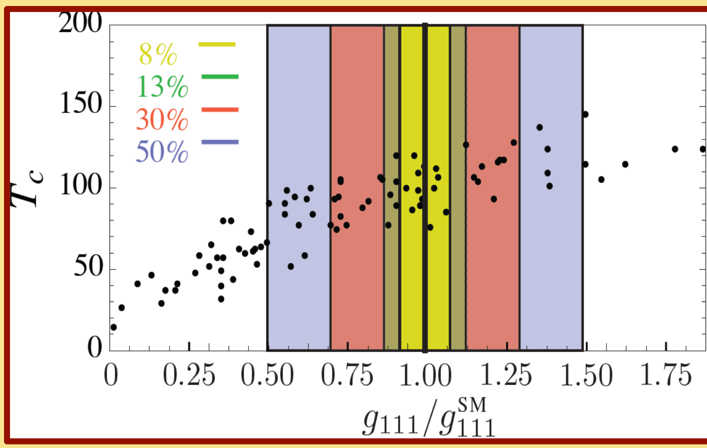
Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

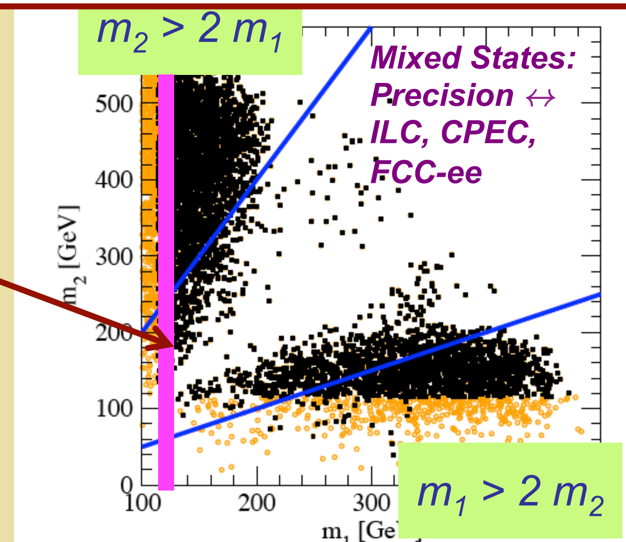
EW Phase Transition: Singlet Scalars





Modified Higgs Self-Coupling





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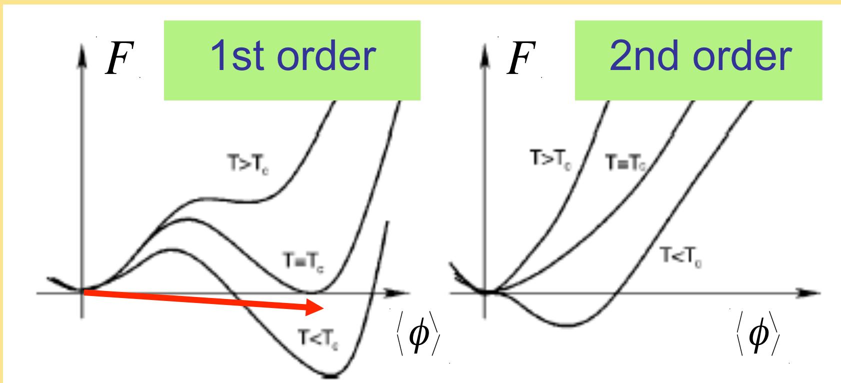
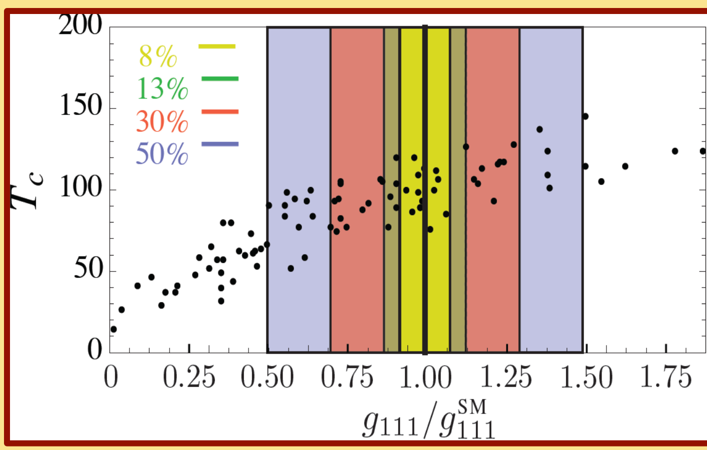
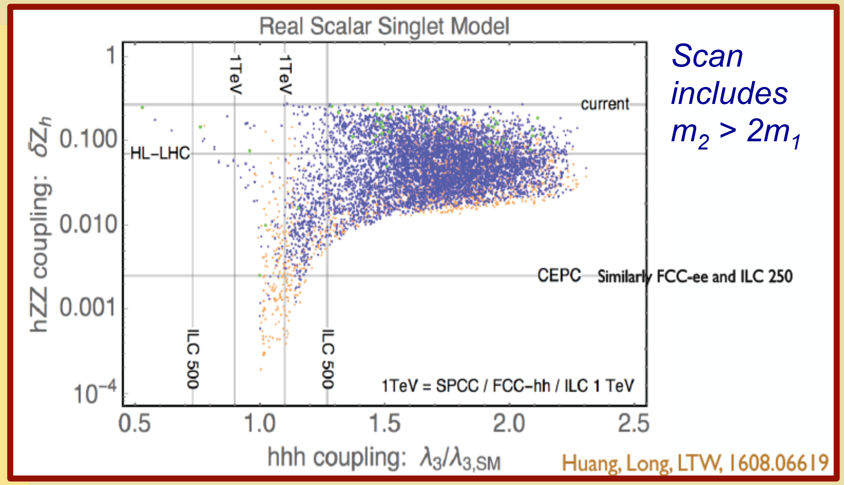
Thanks: M. Cepeda

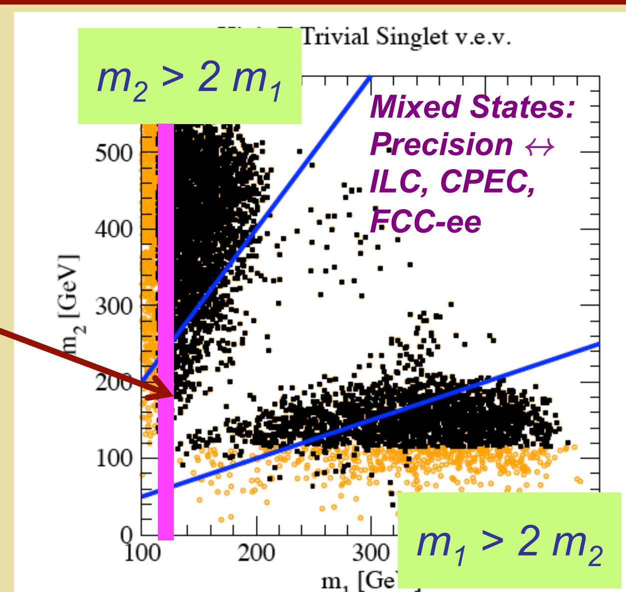
EW Phase Transition: Singlet Scalars



Modified Higgs Self-Coupling







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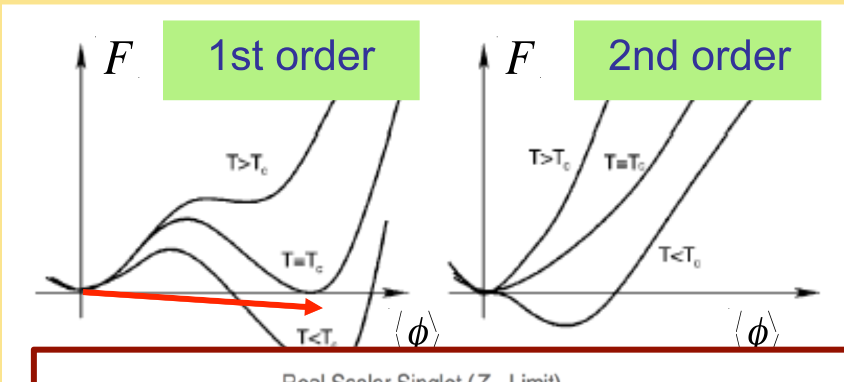
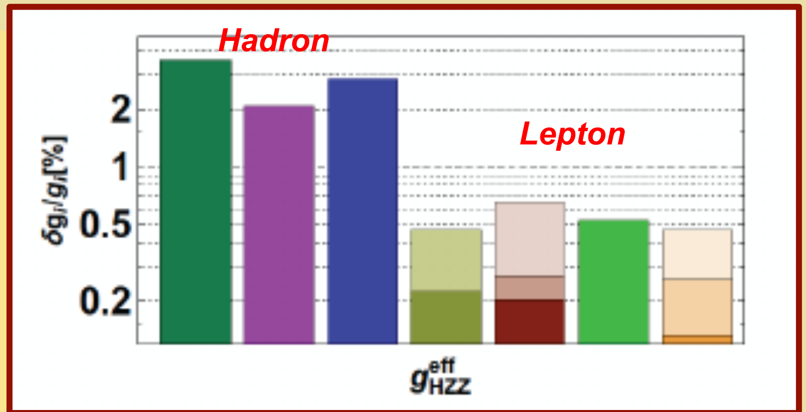
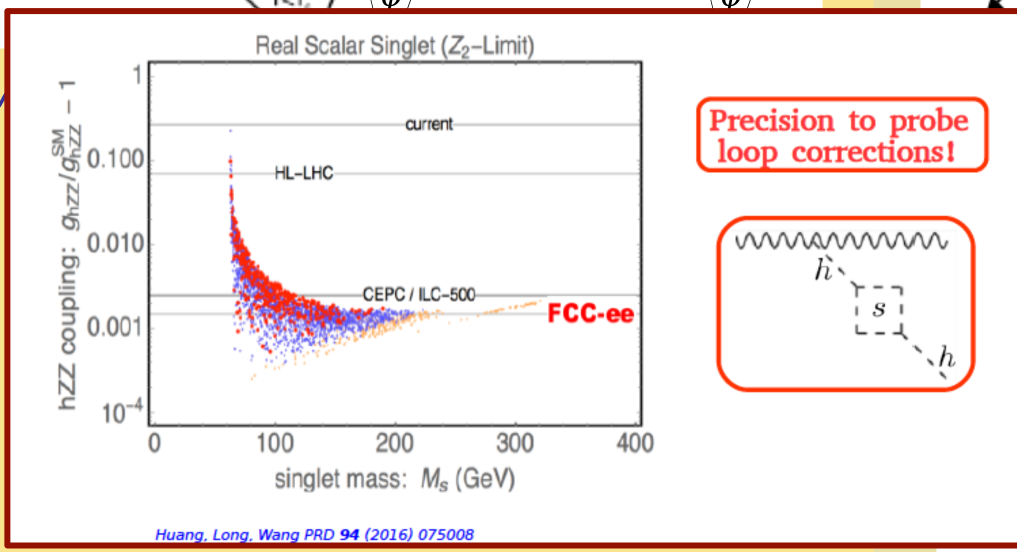
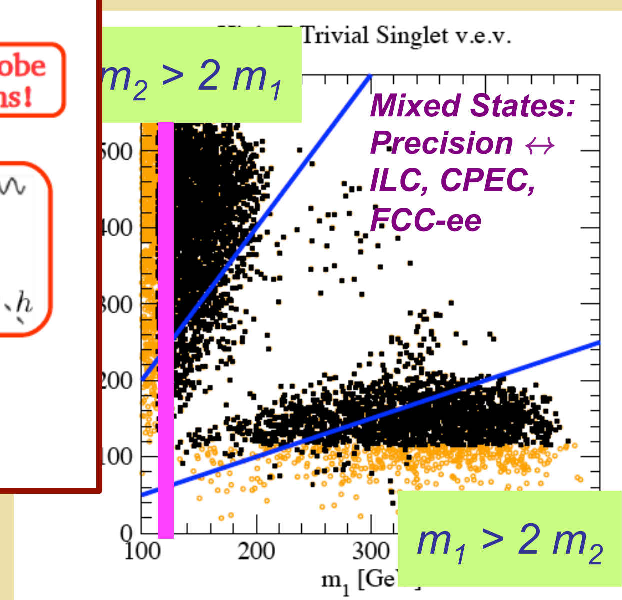
EW Phase Transition: New Scalars



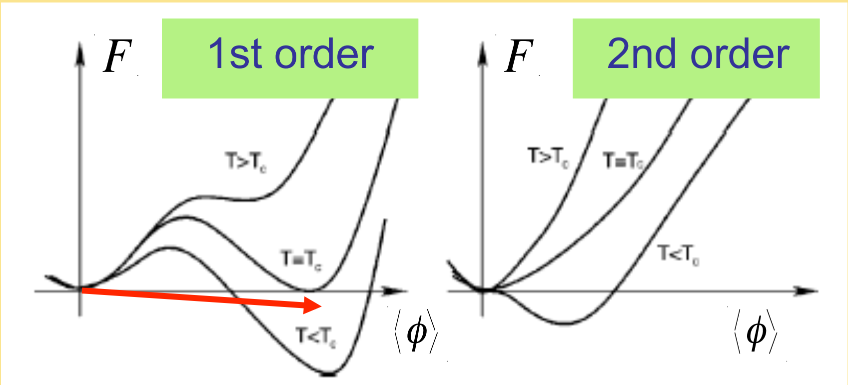


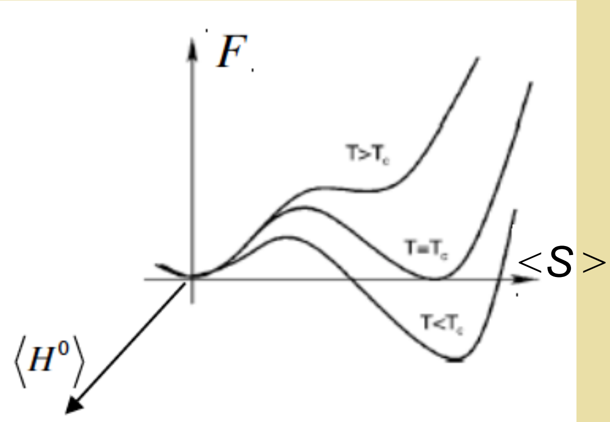




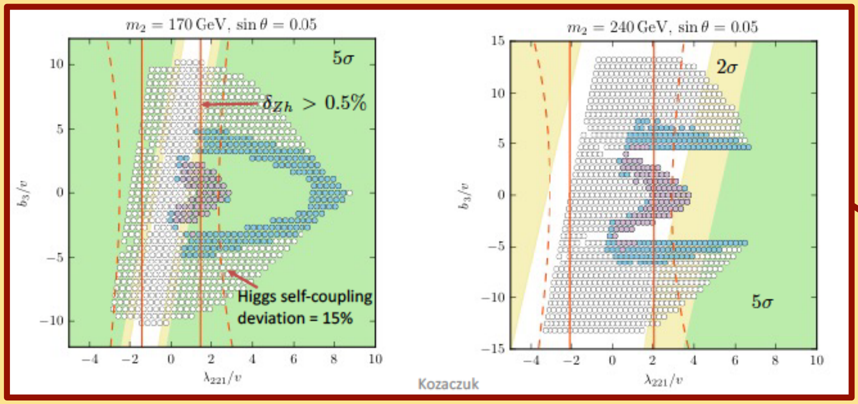
Thanks: J. M. No, M. Cepeda

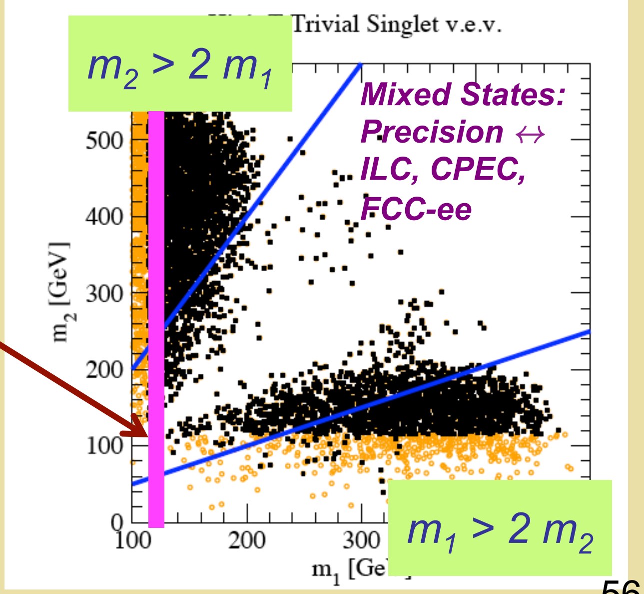
EW Phase Transition: Singlet Scalars





Singlet-like pair production (off shell)





Chen, Kozaczuk, Lewis 2017

Higgs Portal: Simple Scalar Extensions

Extension	DOF	EWPT	DM
Real singlet: ~~Z_2~~	1	✔	✖
Real singlet: Z_2	1	✔	✔
Complex Singlet	2	✔	✔
EW Multiplets	3+	✔	✔

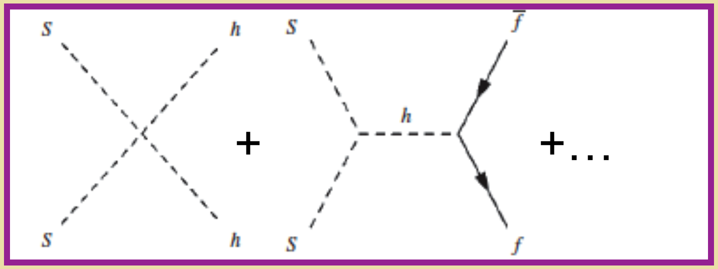
May be low-energy remnants of UV complete theory & illustrative of generic features

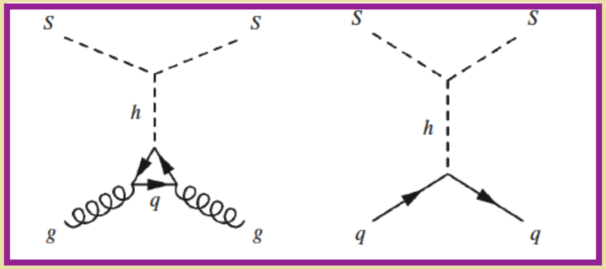
The Simplest Extension

DM Scenario

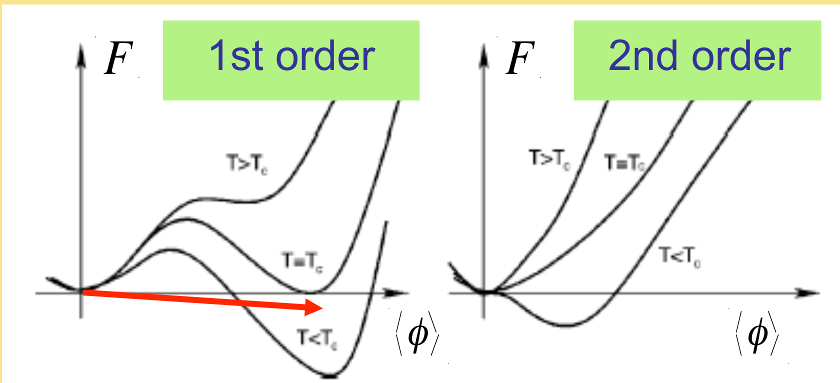
$$V_{\mathrm{HS}} = \quad + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

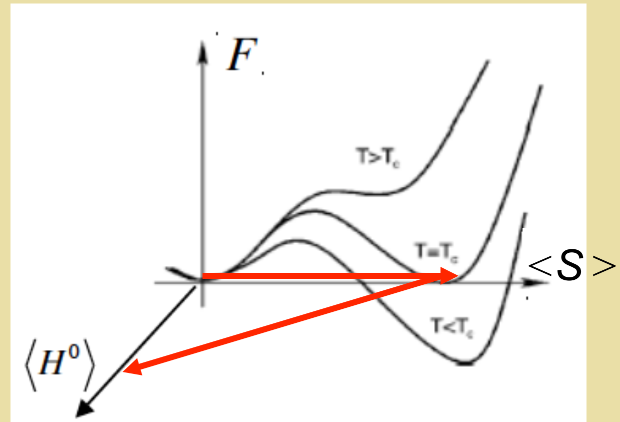
Ω_{DM} & σ_{SI}





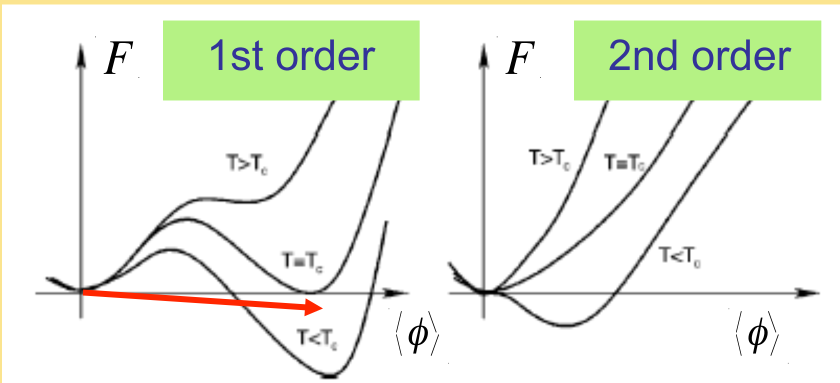
EW Phase Transition: Two-Step





Profumo, R-M, Shaugnessy 2007
Epsinosa, Konstandin, Riva 2011
Curtain, Meade, Yu: arXiv: 1409.0005
Jiang, Bian, Huang, Shu 1502.07574

EW Phase Transition: Singlet Scalars



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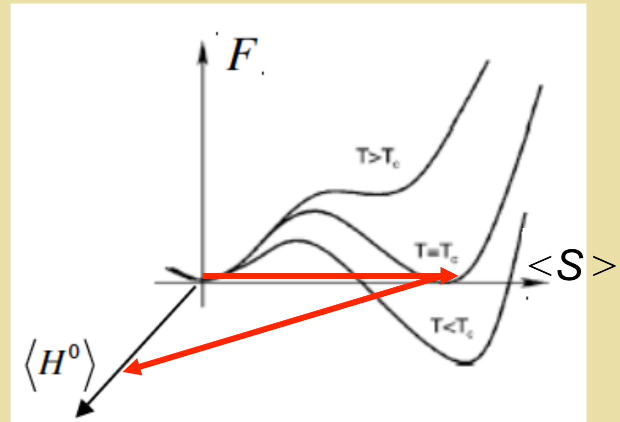
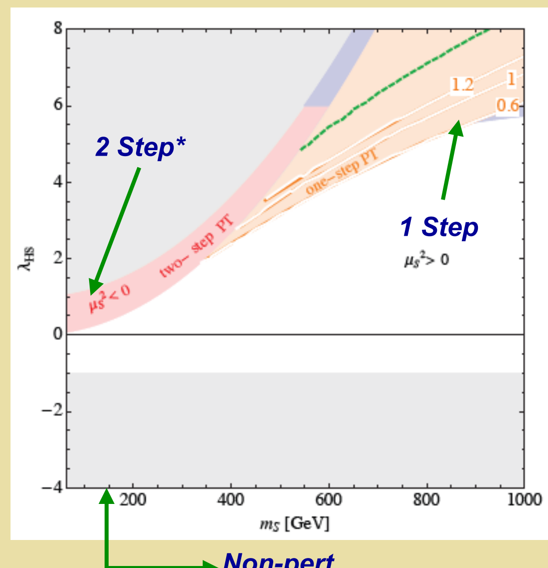
Z_2 symmetric real singlet extension

- *Loop-induced 1-step transition*
- *2-step transition for $\mu_S^2 < 0$*





** Singlet two step: see also Profumo, R-M, Shaugnessy 2007, Epsinosa, Konstandin, Riva 2011*

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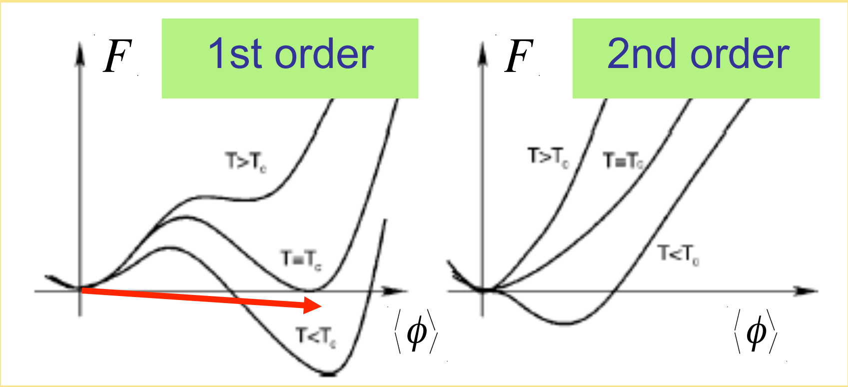

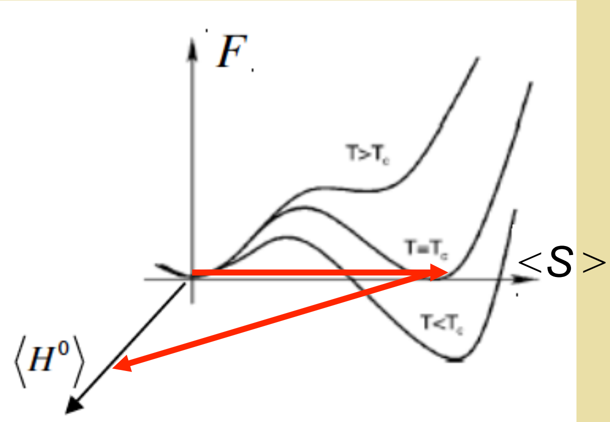

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Z_2 symmetric real singlet extension

- *Loop-induced 1-step transition*
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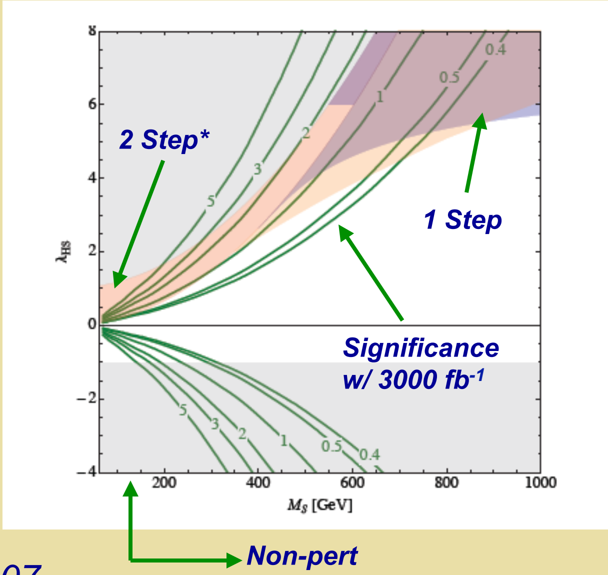
VBF @ 100 TeV pp:

pp → h jj , h → invis



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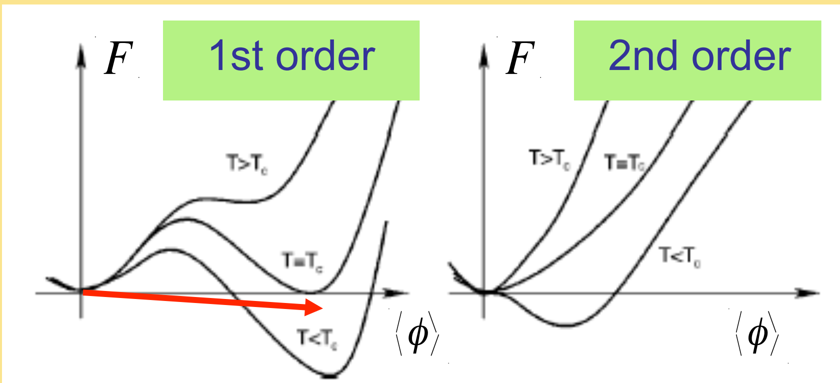
EW Phase Transition: DM Direct Detection

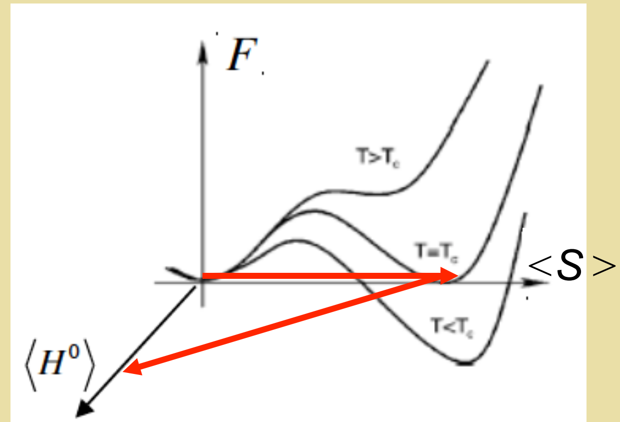


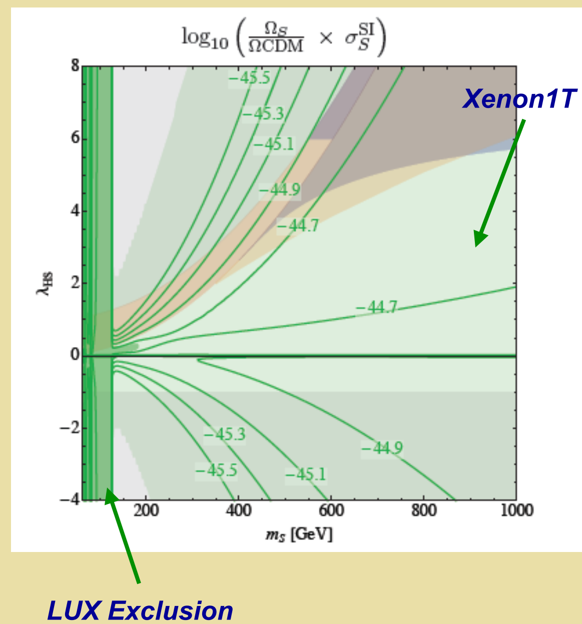
Curtain, Meade, Yu: arXiv: 1409.0005

Z_2 symmetric real singlet extension

- *Loop-induced 1-step transition*
- *2-step transition for $\mu_S^2 < 0$*

Scalar singlet DM: direct detection





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May be low-energy remnants of UV complete theory & illustrative of generic features

Real Triplet

$\Sigma^0, \Sigma^+, \Sigma^-$ ~ (1, 3, 0)

Fileviez-Perez, Patel, Wang, R-M: PRD 79: 055024 (2009); 0811.3957 [hep-ph]

$$V_{H\Sigma} = \frac{a_1}{2} H^\dagger \Sigma H + \frac{a_2}{2} H^\dagger H \ \mathrm{Tr}\ \Sigma^2$$

EWPT: $a_{1,2} \neq 0$ & $\langle\Sigma^0\rangle \neq 0$

DM & EWPT: $a_1 = 0$ & $\langle\Sigma^0\rangle = 0$

Real Triplet

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EWPT: $a_{1,2} \neq 0$ & $\langle\Sigma^0\rangle \neq 0$

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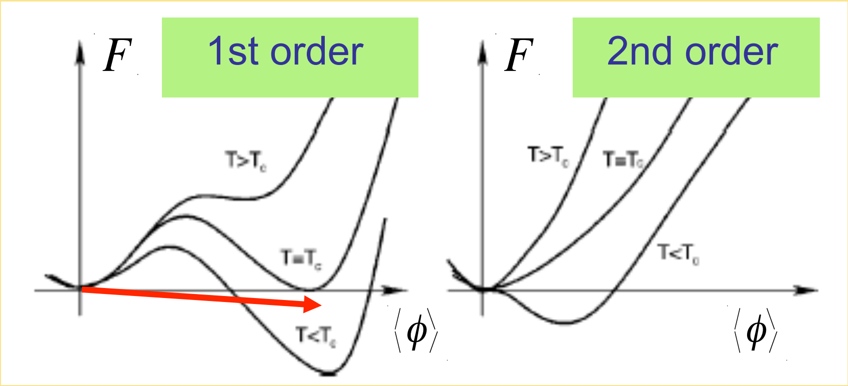
DM Stability

EW Multiplets: EWPT

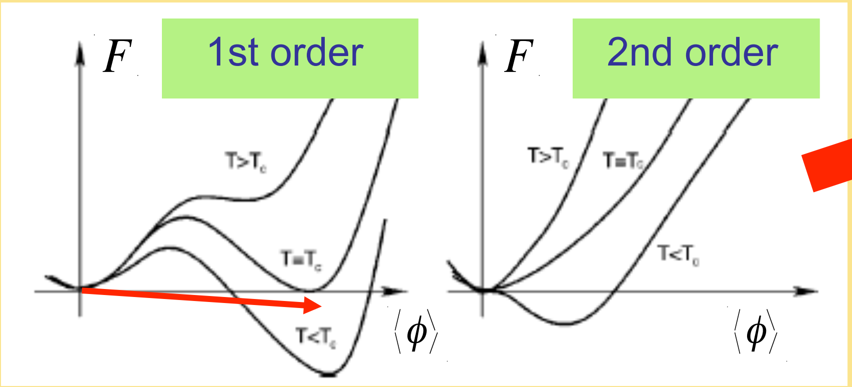


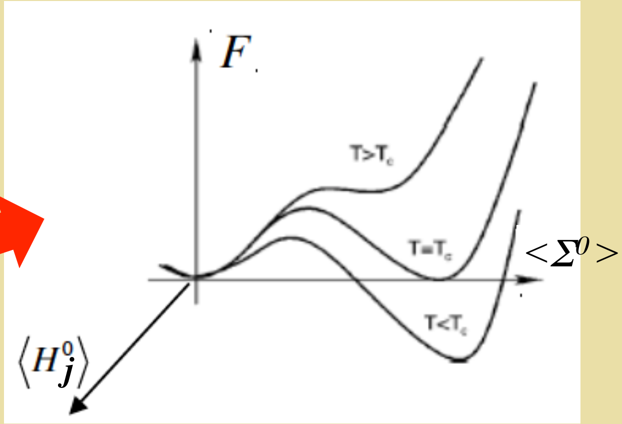
Increasing m_h →

← *New scalars*

Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

EW Multiplets: EWPT





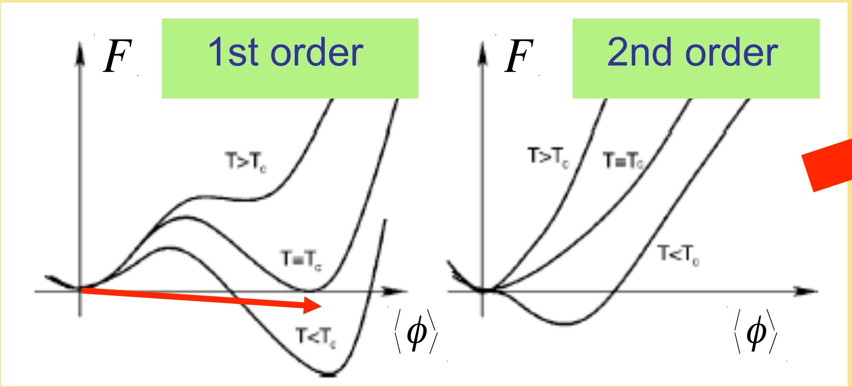
Increasing m_h →

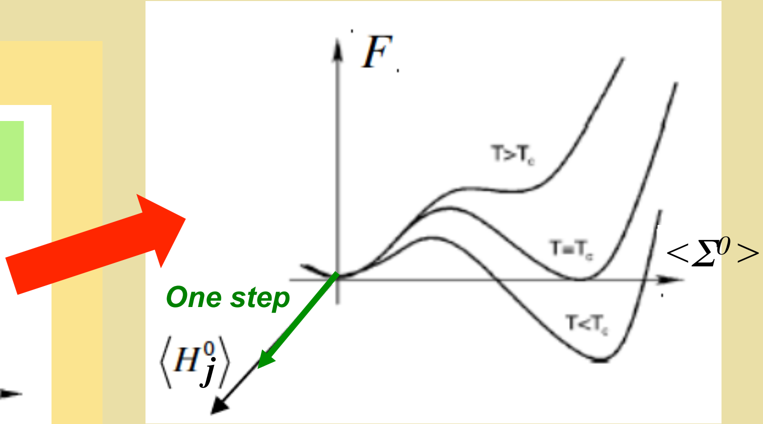
← *New scalars*

- *Thermal loops*
- *Tree-level barrier*

Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

EW Multiplets: One-Step EWPT





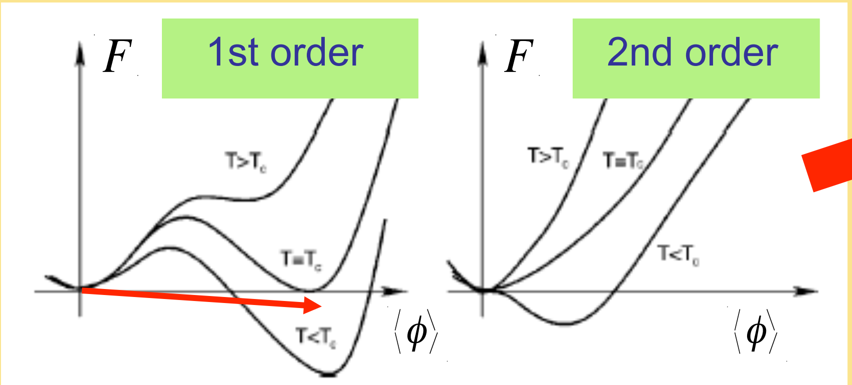
Increasing m_h →

← *New scalars*

- *One-step: Sym phase → Higgs phase*

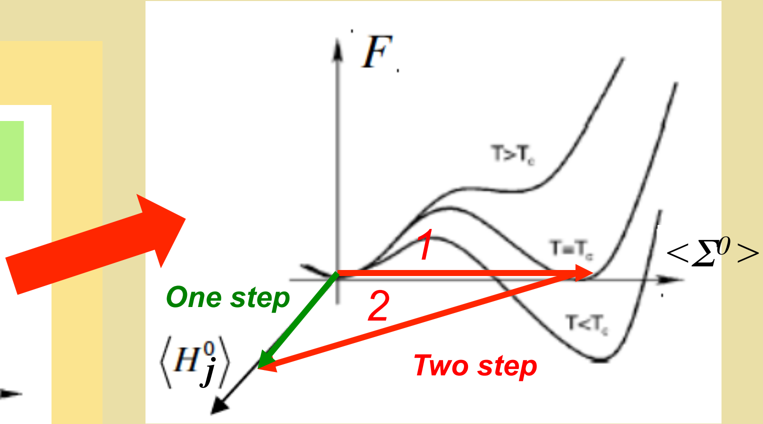
Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

EW Multiplets: Two-Step EWPT



Increasing m_h →

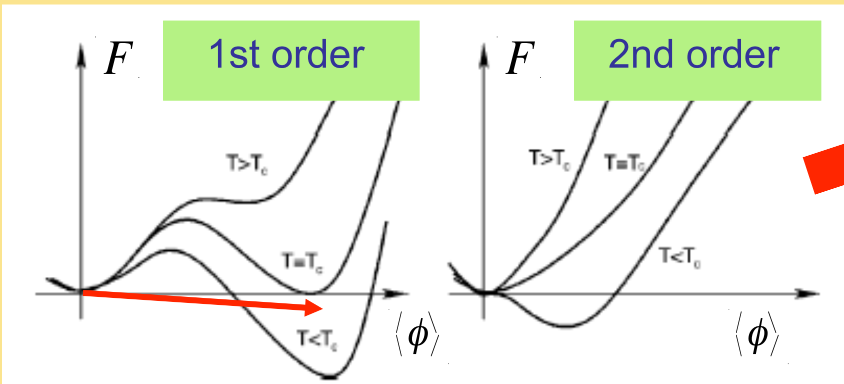
← *New scalars*



- *One-step: Sym phase → Higgs phase*
- *Two-step: successive EW broken phases*

Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

EW Multiplets: Two-Step EWPT



Increasing m_h →

← *New scalars*

- *One-step: Sym phase → Higgs phase*
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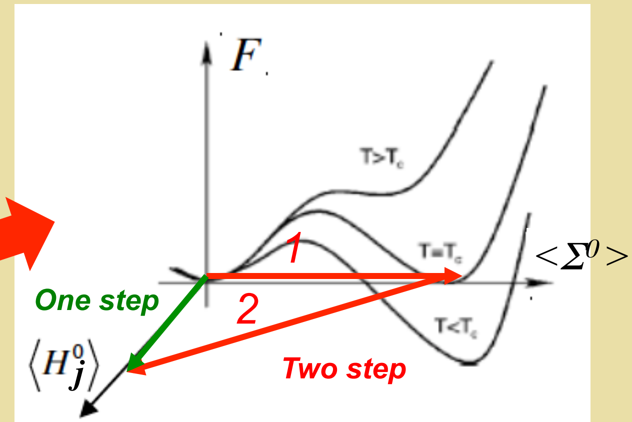

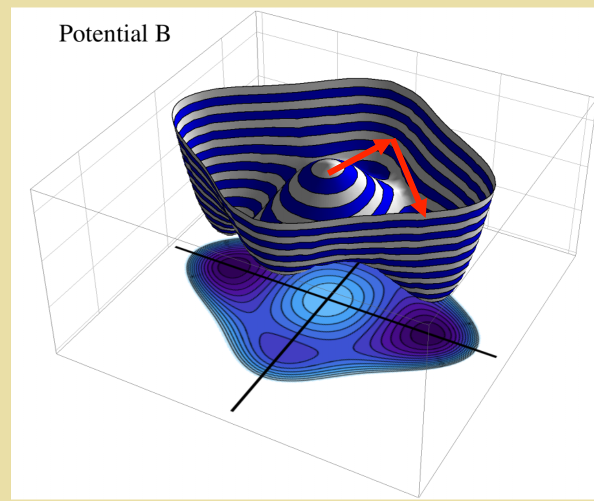

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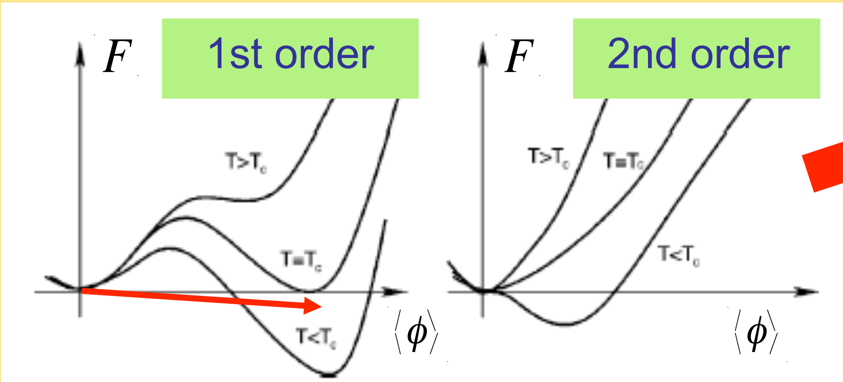
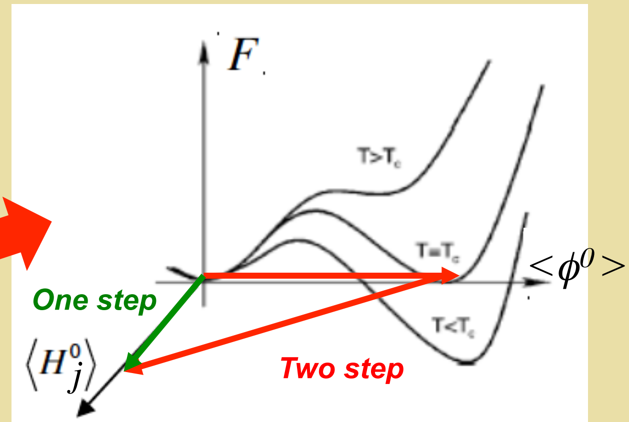
EW Multiplets: Two-Step EWPT

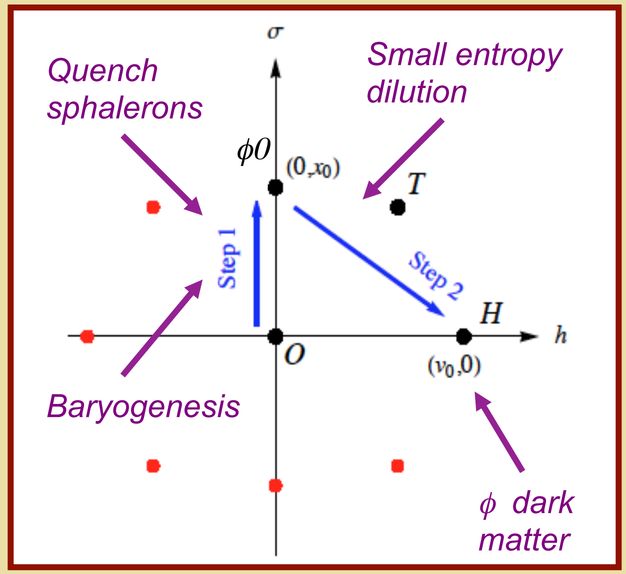




Increasing m_h →

← New scalars

- Step 1: thermal loops
- Step 2: tree-level barrier



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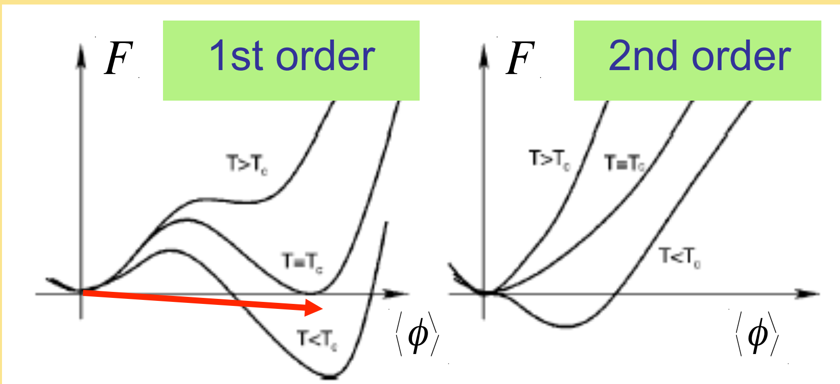
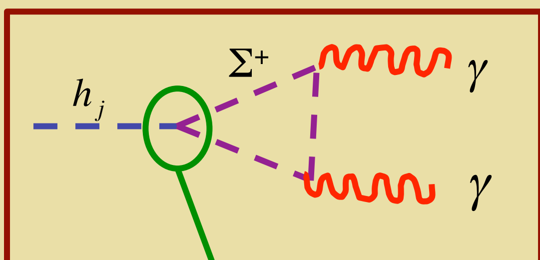
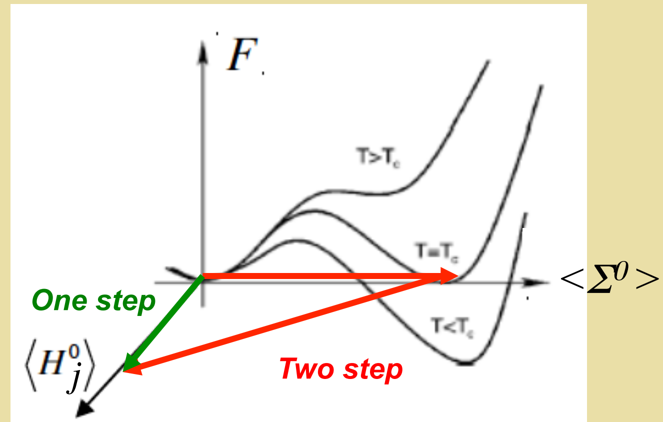
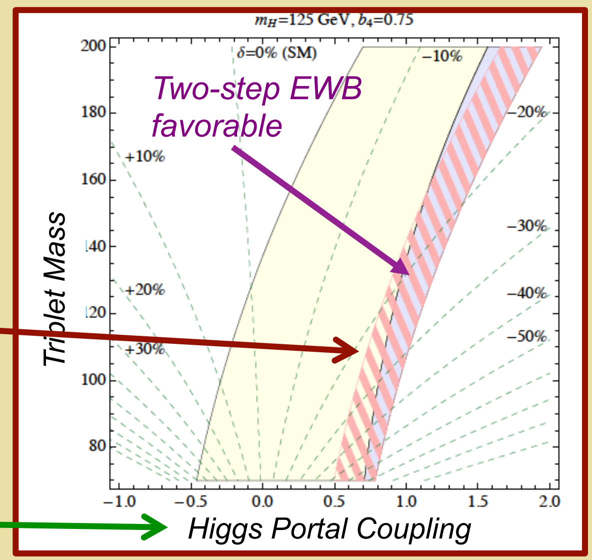
EW Multiplets: Two-Step EWPT



Increasing m_h →

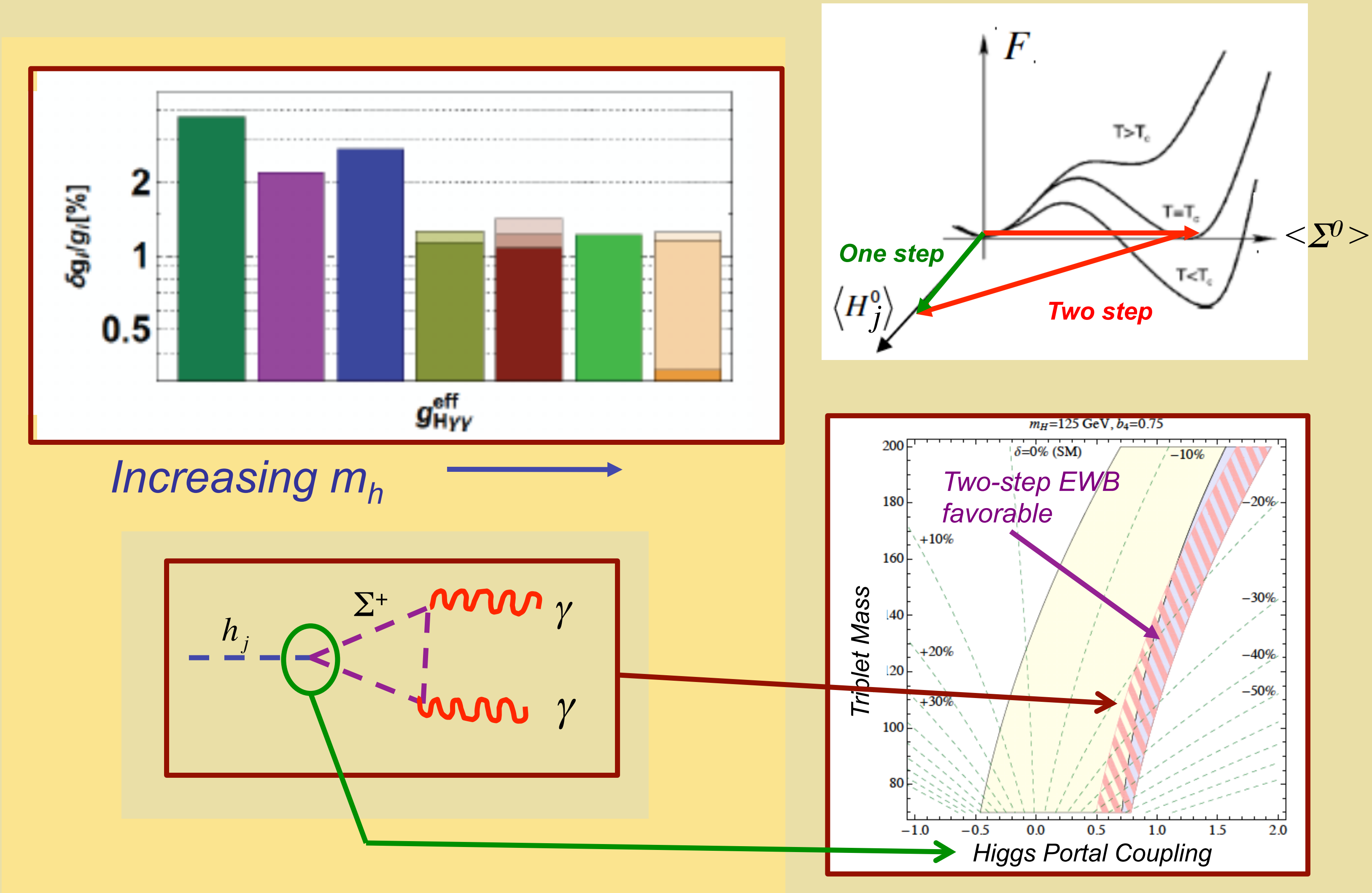






Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

EW Multiplets: Two-Step EWPT



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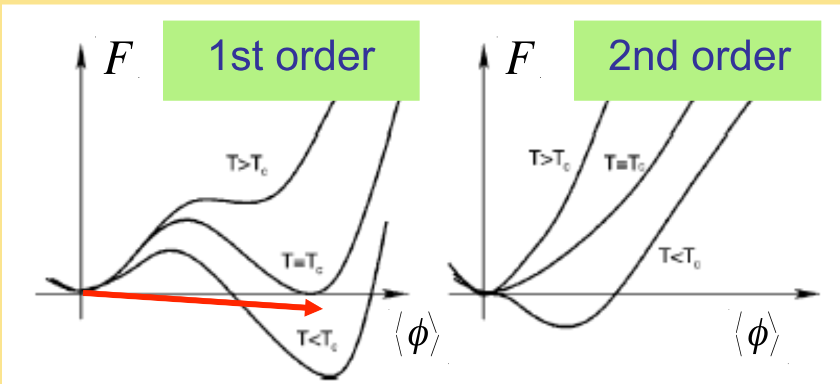
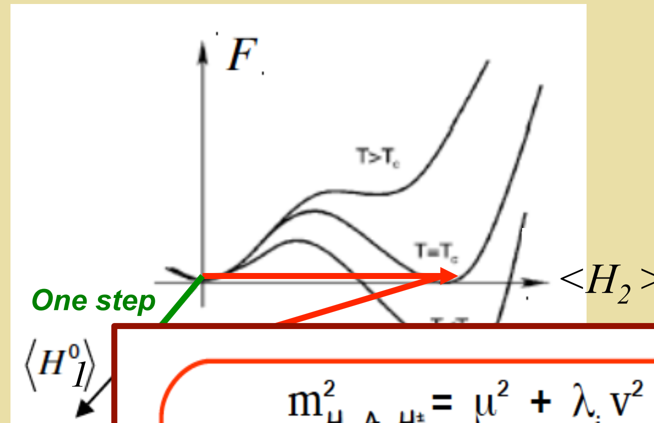
Thanks: M. Cepeda

EW Multiplets: 2HDM



Increasing m_h →



$$m^2_{H_0, A_0, H^\pm} = \mu^2 + \lambda_i v^2$$

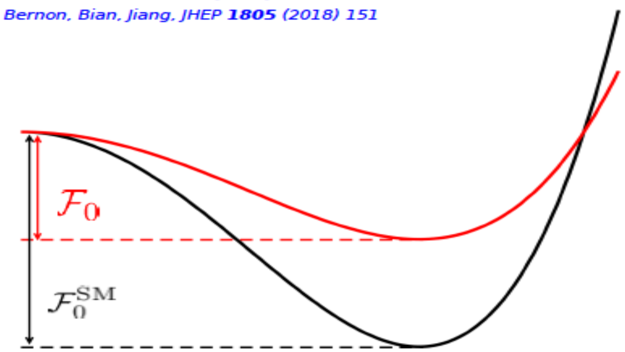
Difference between Symmetric - Broken phase in CW piece guaranteed for large BSM mass splitting!

$$m_{A_0} - m_{H_0}$$

Nature of EWPT dominantly controlled by T=0 Vacuum energy difference

Dorsch, Huber, Mimasu, JMN, JHEP **1712** (2017) 086

Bernon, Bian, Jiang, JHEP **1805** (2018) 151



$$\Delta\mathcal{F} \equiv \mathcal{F}_0 - \mathcal{F}_0^{\rm SM} = -\frac{v^2}{8}\cos(\beta-\alpha)^2(m^2_{H_0} - m_h^2) + \left[\sum_s \frac{m_s^4}{64\pi^2}\left(\log\frac{|m_s^2|}{Q^2} - \frac{1}{2}\right)\right]\Bigg|_v - \left[\sum_s \frac{m_s^4}{64\pi^2}\left(\log\frac{|m_s^2|}{Q^2} - \frac{1}{2}\right)\right]\Bigg|_0$$

Broken — Symmetric

1-loop (Coleman-Weinberg)

Thanks: J. M. No

See S. Huber Talk

A-III. Theoretical Robustness

Theory Meets Phenomenology

A. Non-perturbative

- *Most reliable determination of character of EWPT & dependence on parameters*
- *Broad survey of scenarios & parameter space not viable*

B. Perturbative

- *Most feasible approach to survey broad ranges of models, analyze parameter space, & predict experimental signatures*
- *Quantitative reliability needs to be verified*

Theory Meets Phenomenology

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Benchmark pert theory

- Most feasible approach to survey broad ranges of models, analyze parameter space, & predict experimental signatures
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EWPT & Perturbation Theory

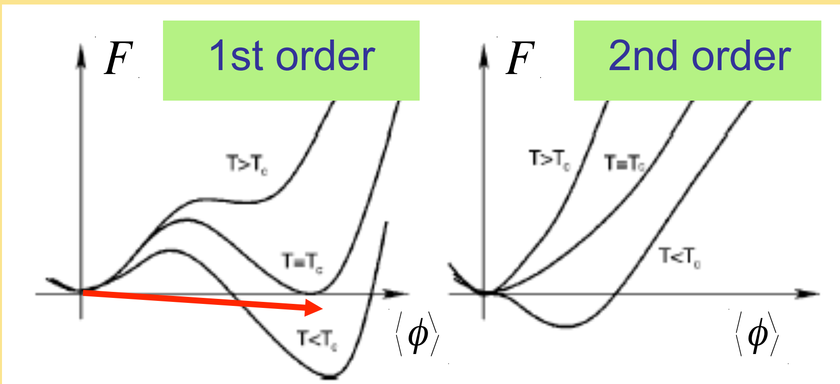
Expansion parameter

Gauge coupling in finite-T theory (→ g_3^2)

$$g_{\mathrm{eff}} \equiv \frac{g_3^2}{\pi m_T(\varphi)}$$

SM lattice studies: *g_{eff} ~ 0.8 in vicinity of EWPT for m_H ~ 70 GeV*

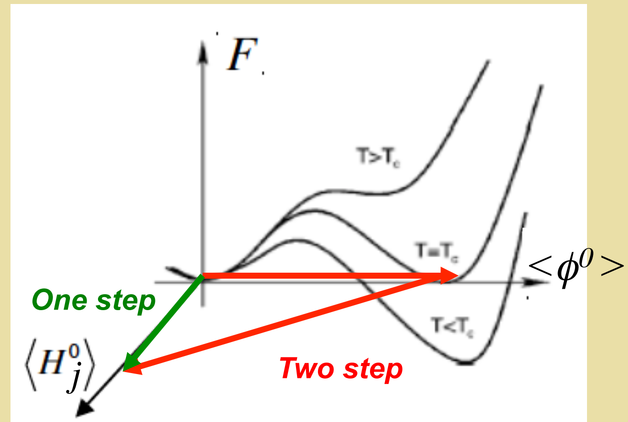
EW Multiplets: One-Step EWPT ?

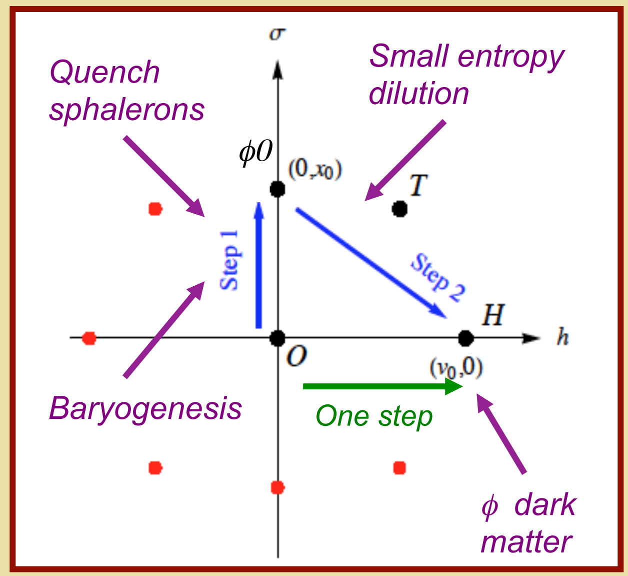


Increasing m_h ⟶

⟵ *New scalars*

- *One-step: thermal loops*





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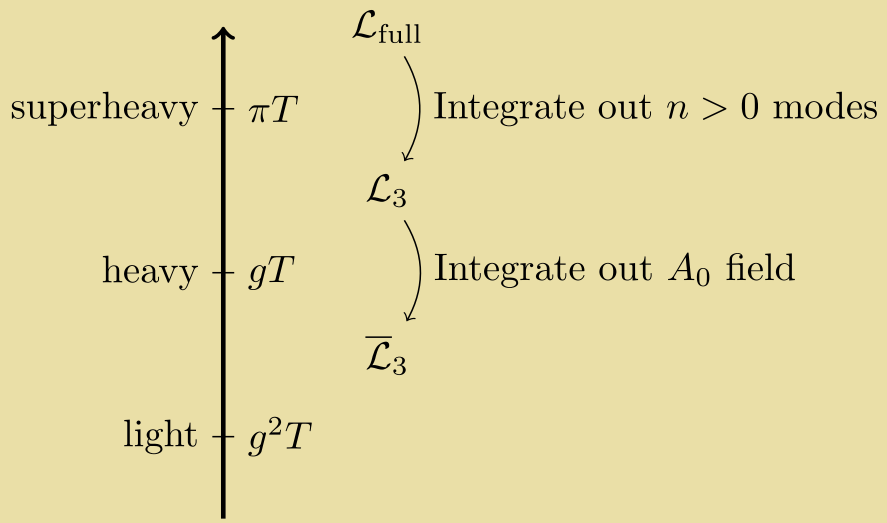
Benchmarking PT: Recent Progress

Meeting ground: 3-D high-T effective theory



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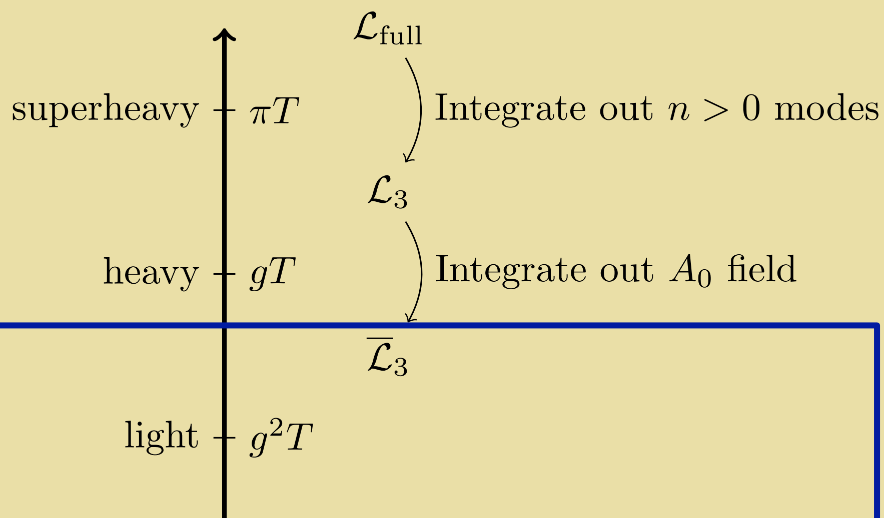

$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

Lattice simulations exist

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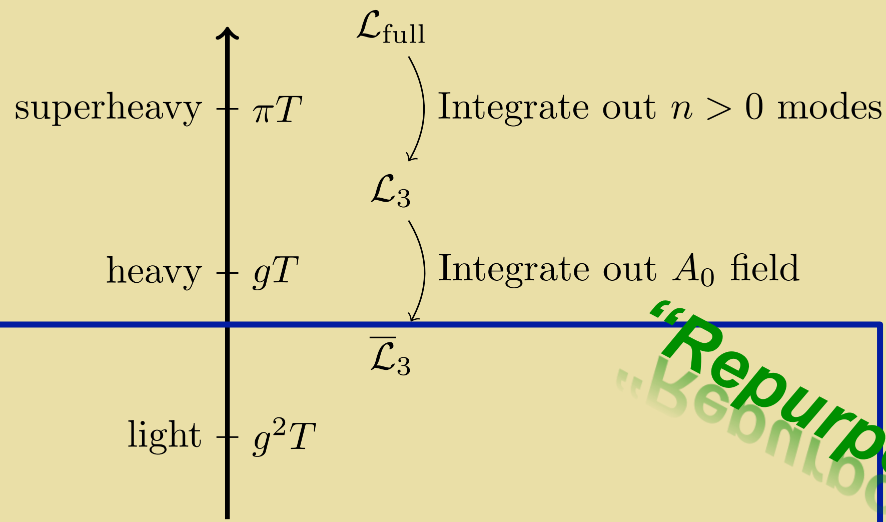

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"Repurpose" lattice results

Lattice simulations exist

Benchmarking PT: Recent Progress

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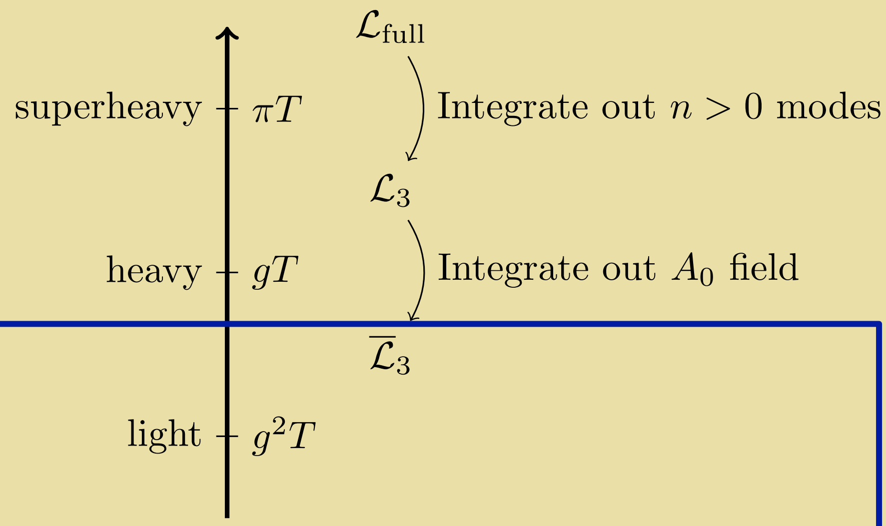

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Lattice simulations exist (e.g., Kajantie et al ‘95)

- *Assume BSM fields are “heavy” or “supeheavy” : integrate out*
- *Effective “SM-like” theory parameters are functions of BSM parameters*
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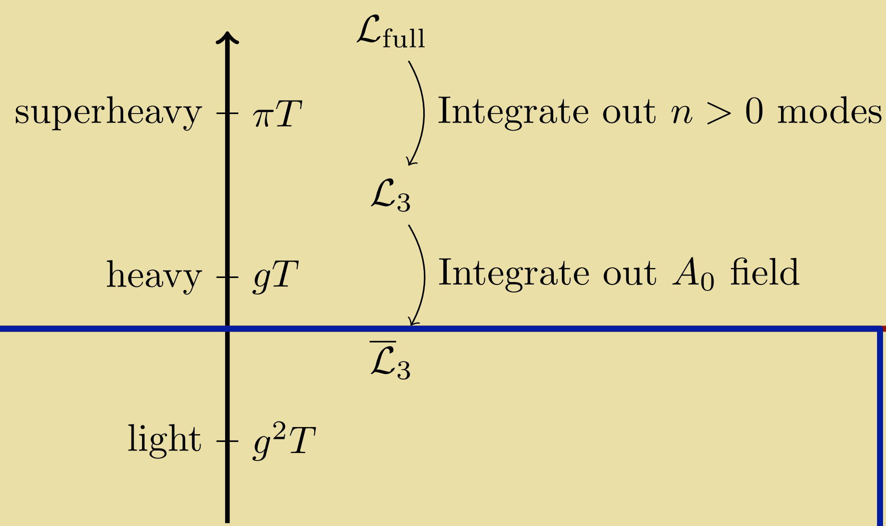

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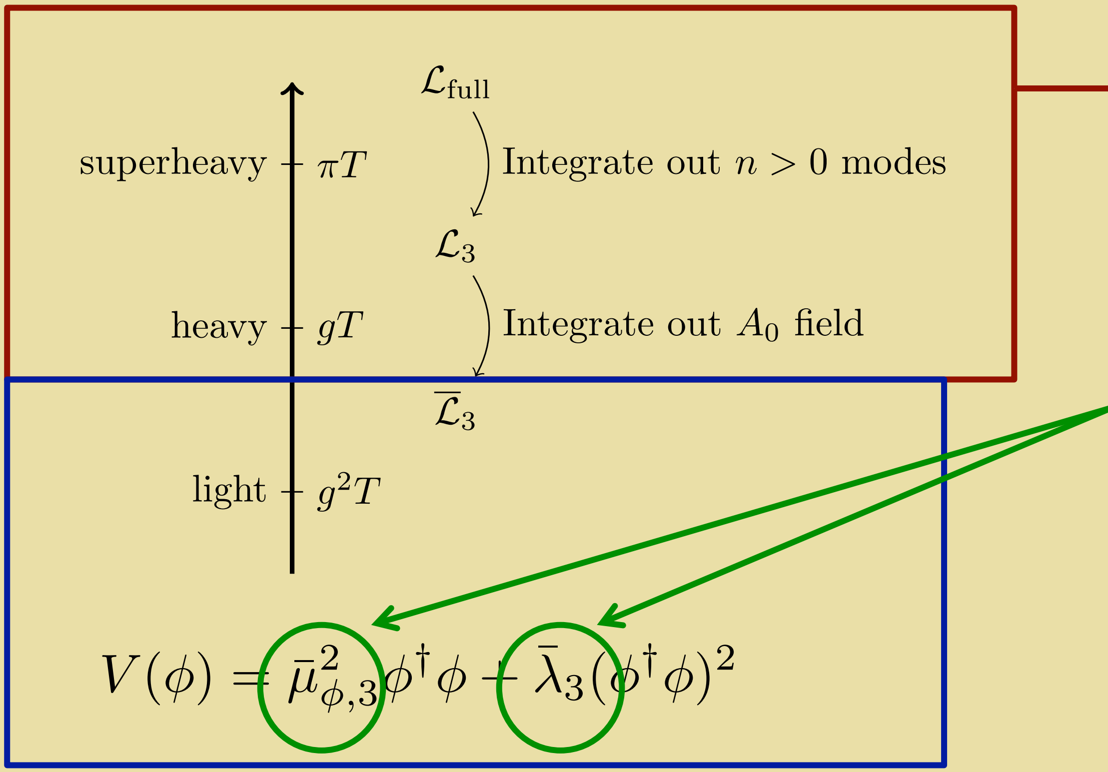

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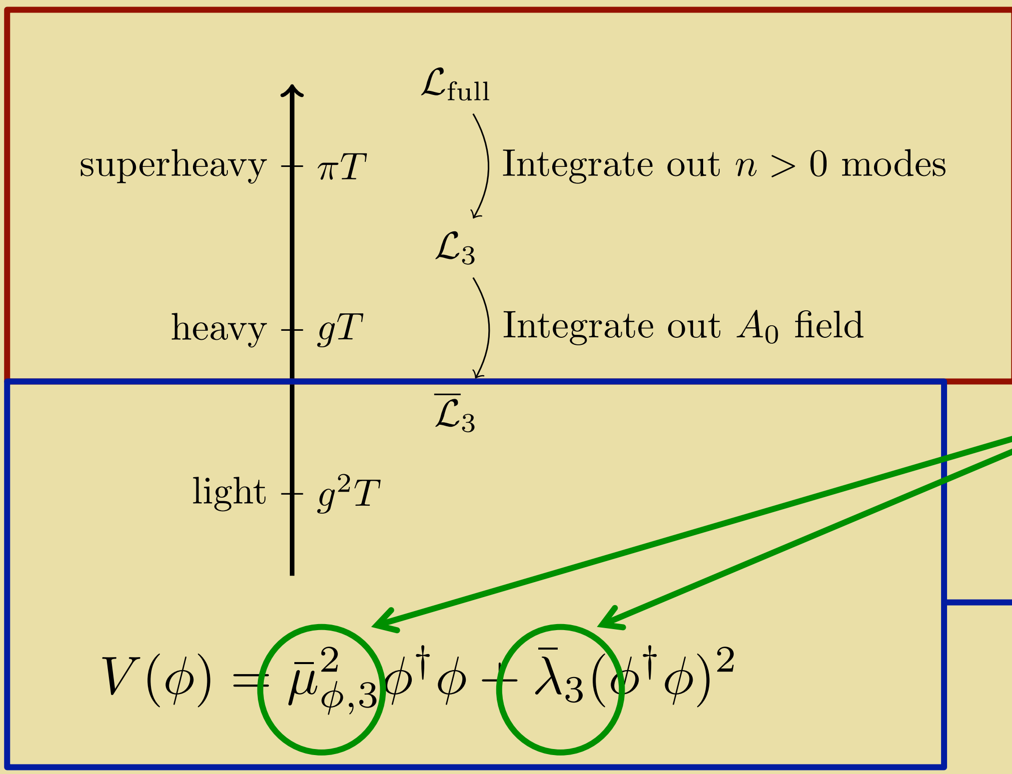

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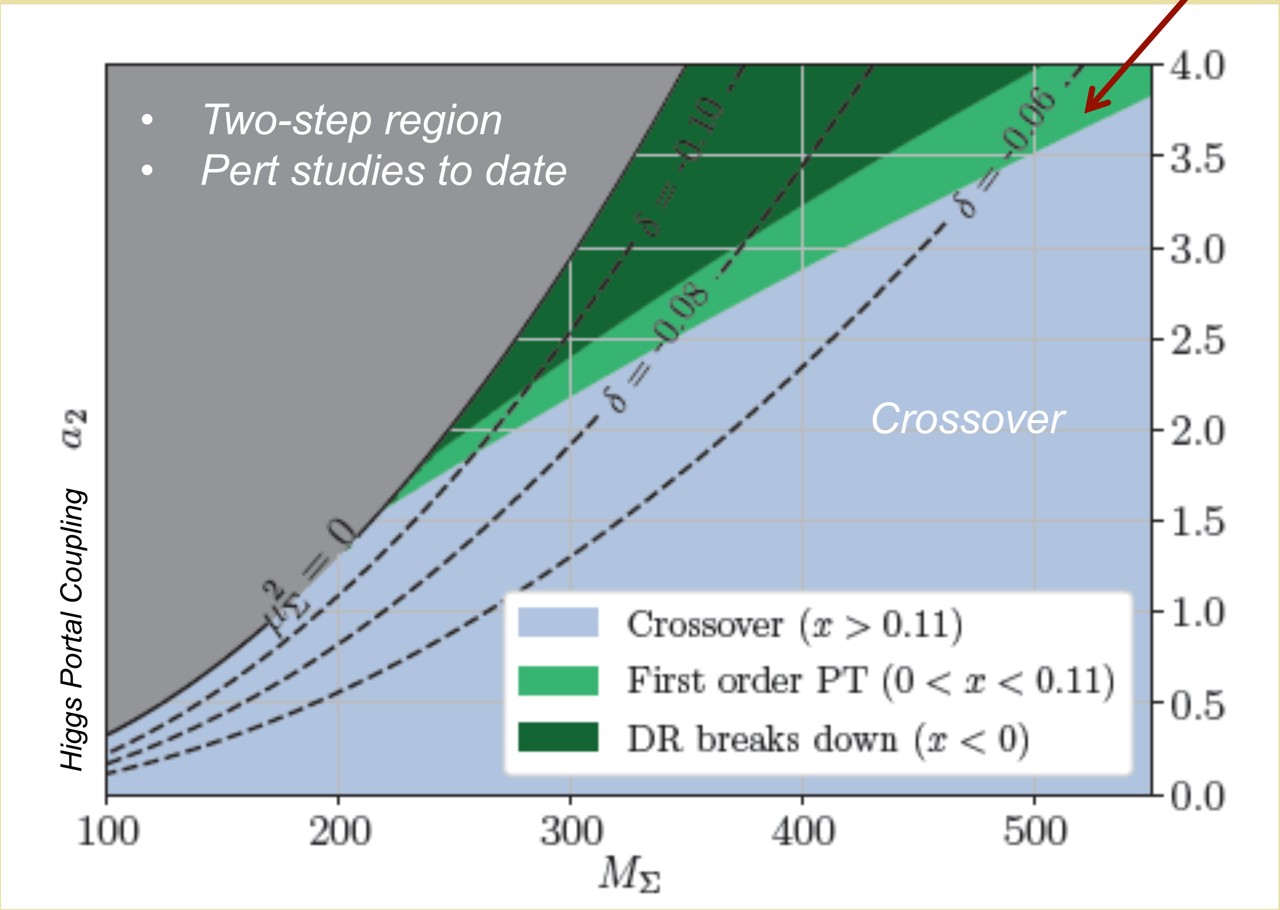
Real Triplet & EWPT

FOEWPT



- One-step
- Non-perturbative

Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet & EWPT

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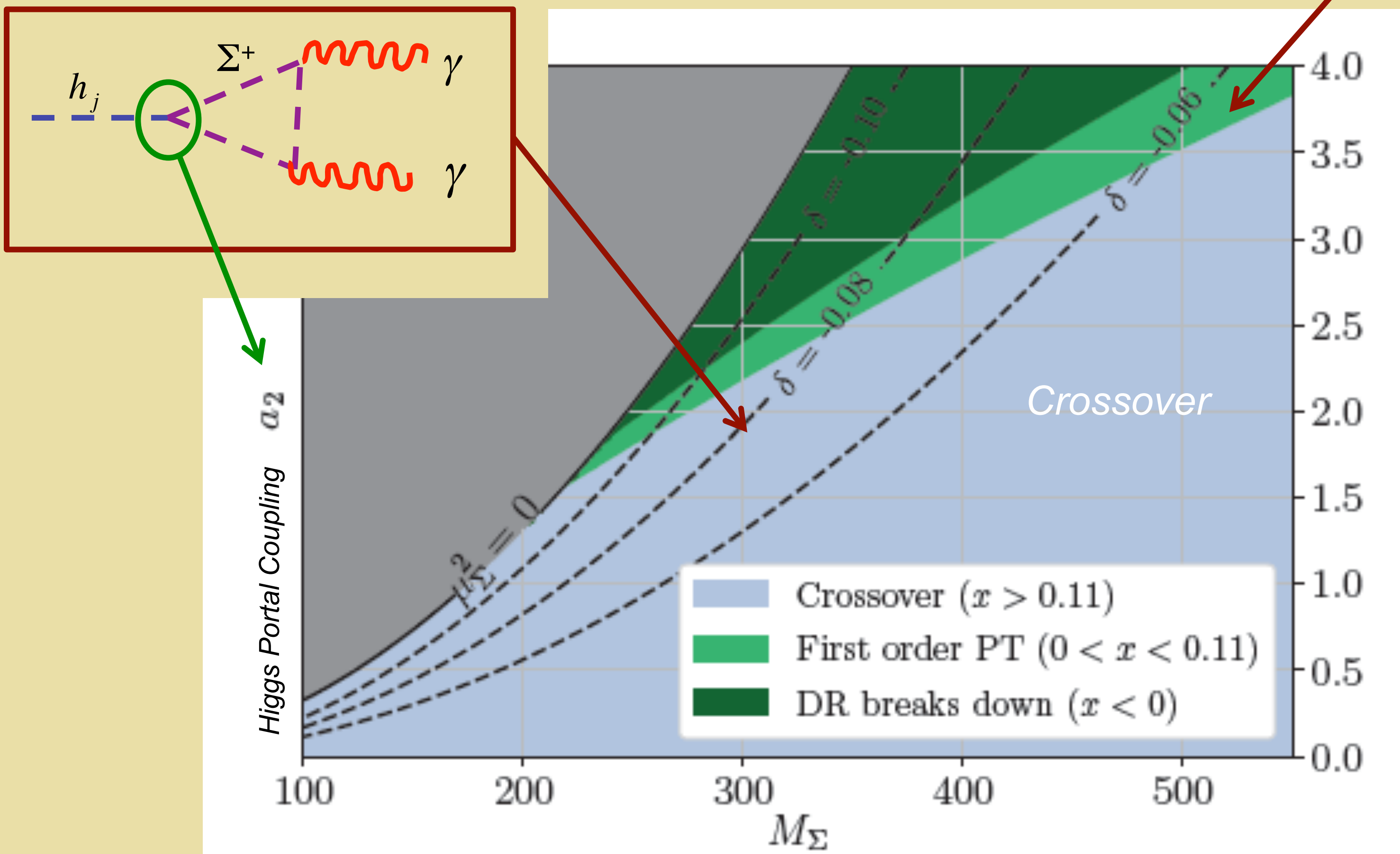

Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

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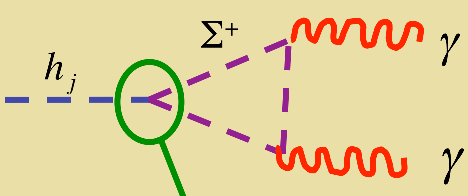
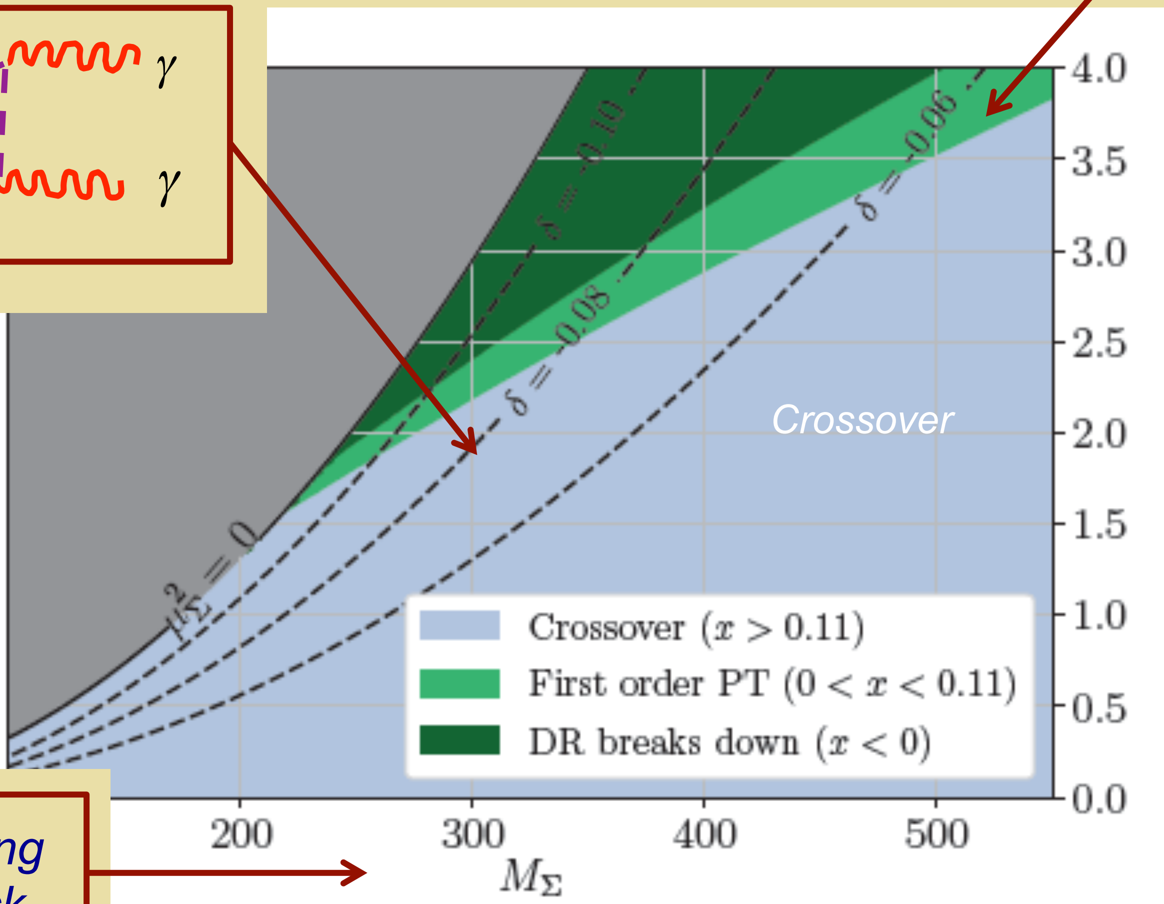
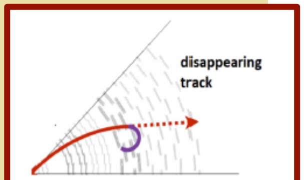


FOEWPT





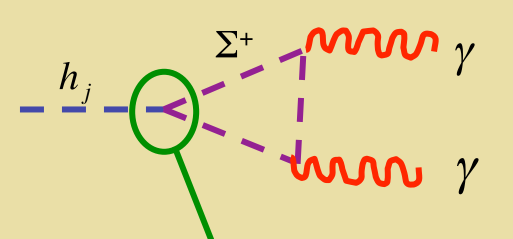
Disappearing charge track

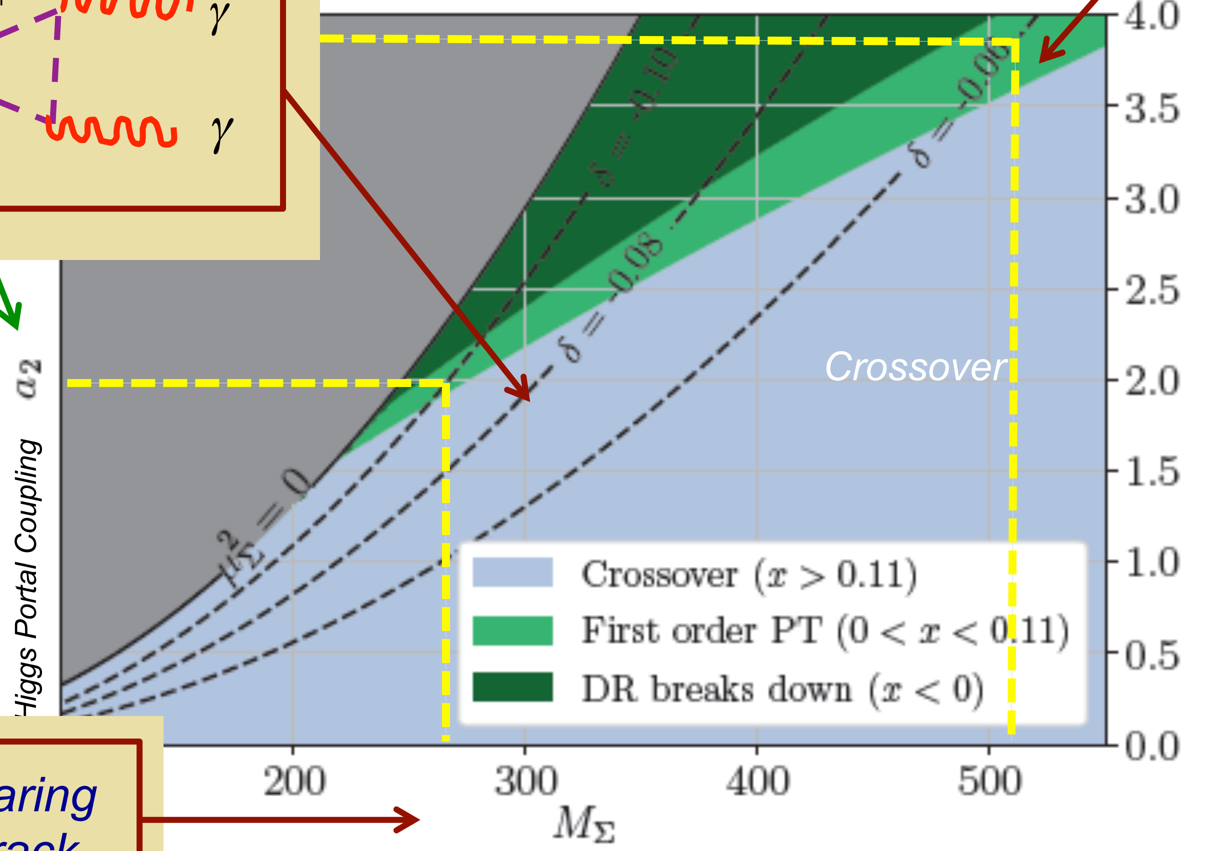
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

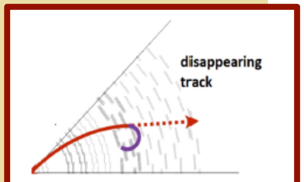
- One-step
- Non-perturbative

Real Triplet & EWPT

FOEWPT







Disappearing charge track

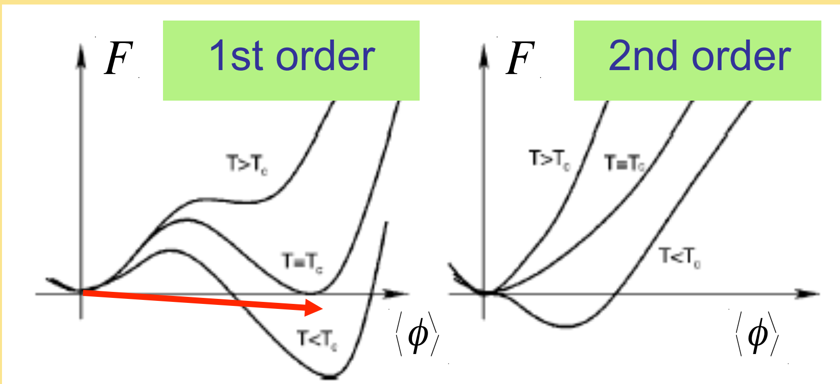
- *One-step*
- *Non-perturbative*

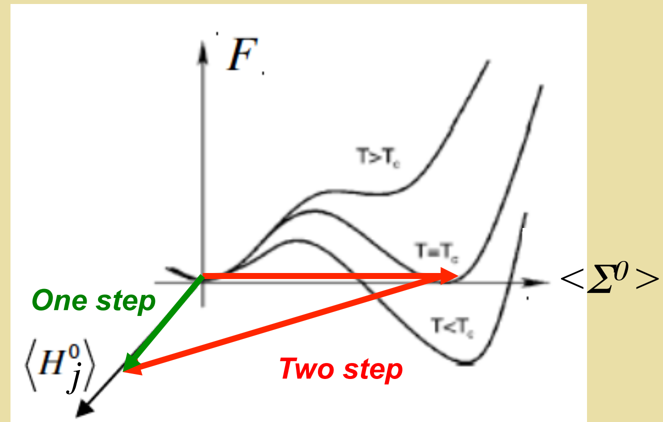
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet Example: Lessons

- *Initial non-perturbative studies using 3d EFT reveals regions of FOEWPT & crossover transition not evident in PT*
- *Next generation circular e+e- and pp colliders likely necessary to access these region: a first order transition $\rightarrow$ Observable shift in h$\rightarrow \gamma\gamma$ rate*
- *Next generation colliders will have needed sensitivity*

EW Multiplets: Two-Step EWPT

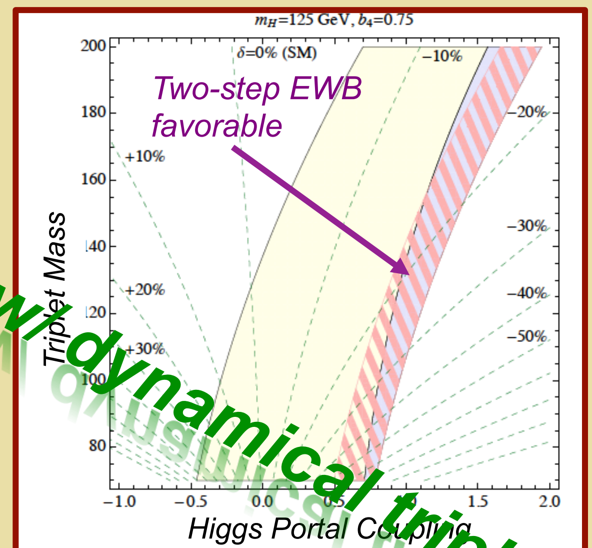




Increasing m_h →

← New scalars

$$\mathcal{O}_4 = \lambda_{\phi H}\ \phi^\dagger\phi\ H^\dagger H$$

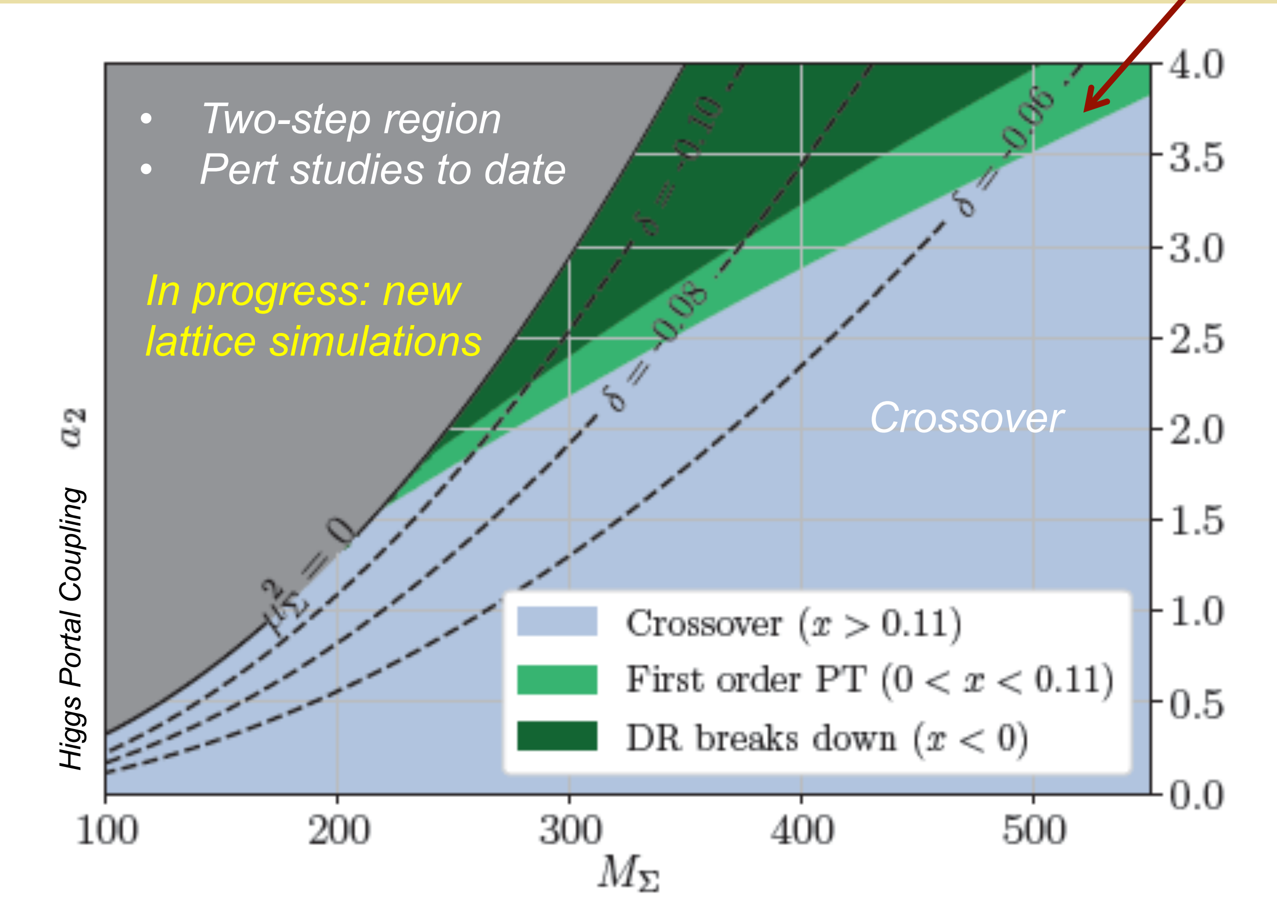


Lattice w/ dynamical triplet

Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

Real Triplet & EWPT

FOEWPT

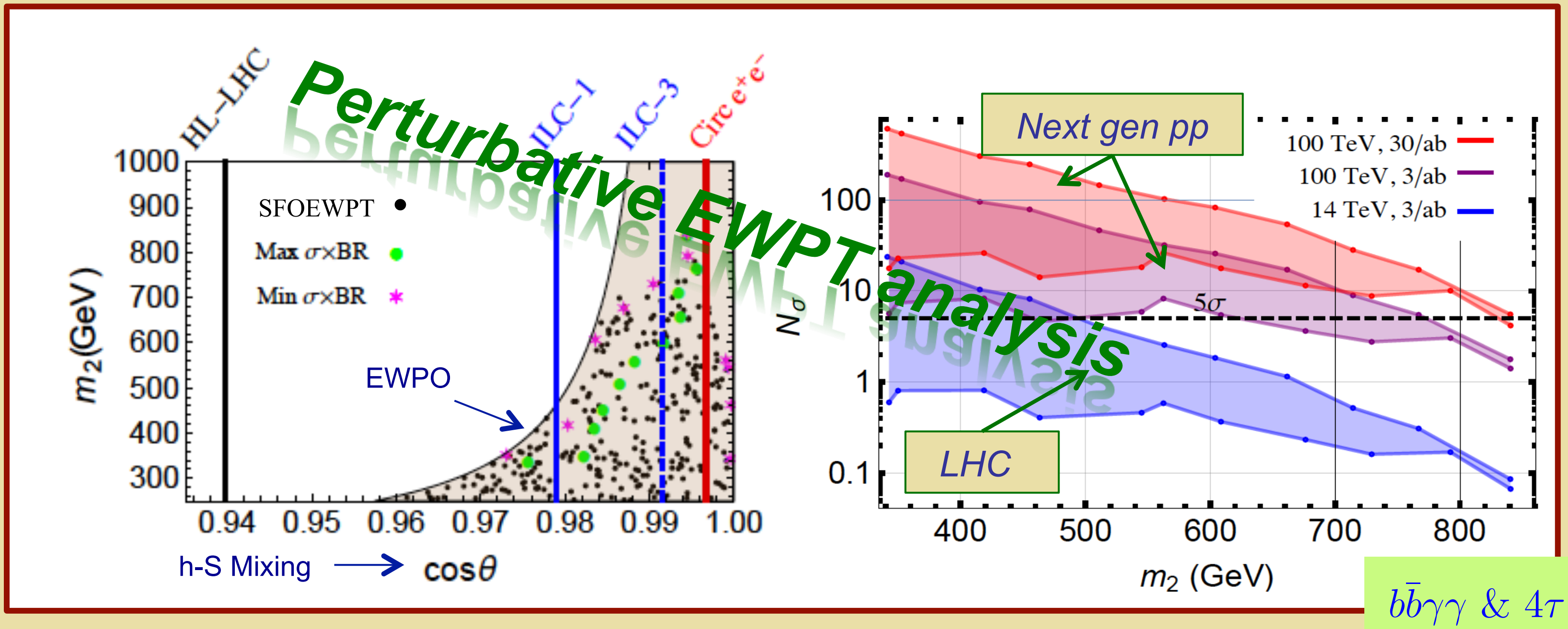


Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

- *One-step*
- *Non-perturbative*

Scalar Singlets & EWPT: Collider Reach

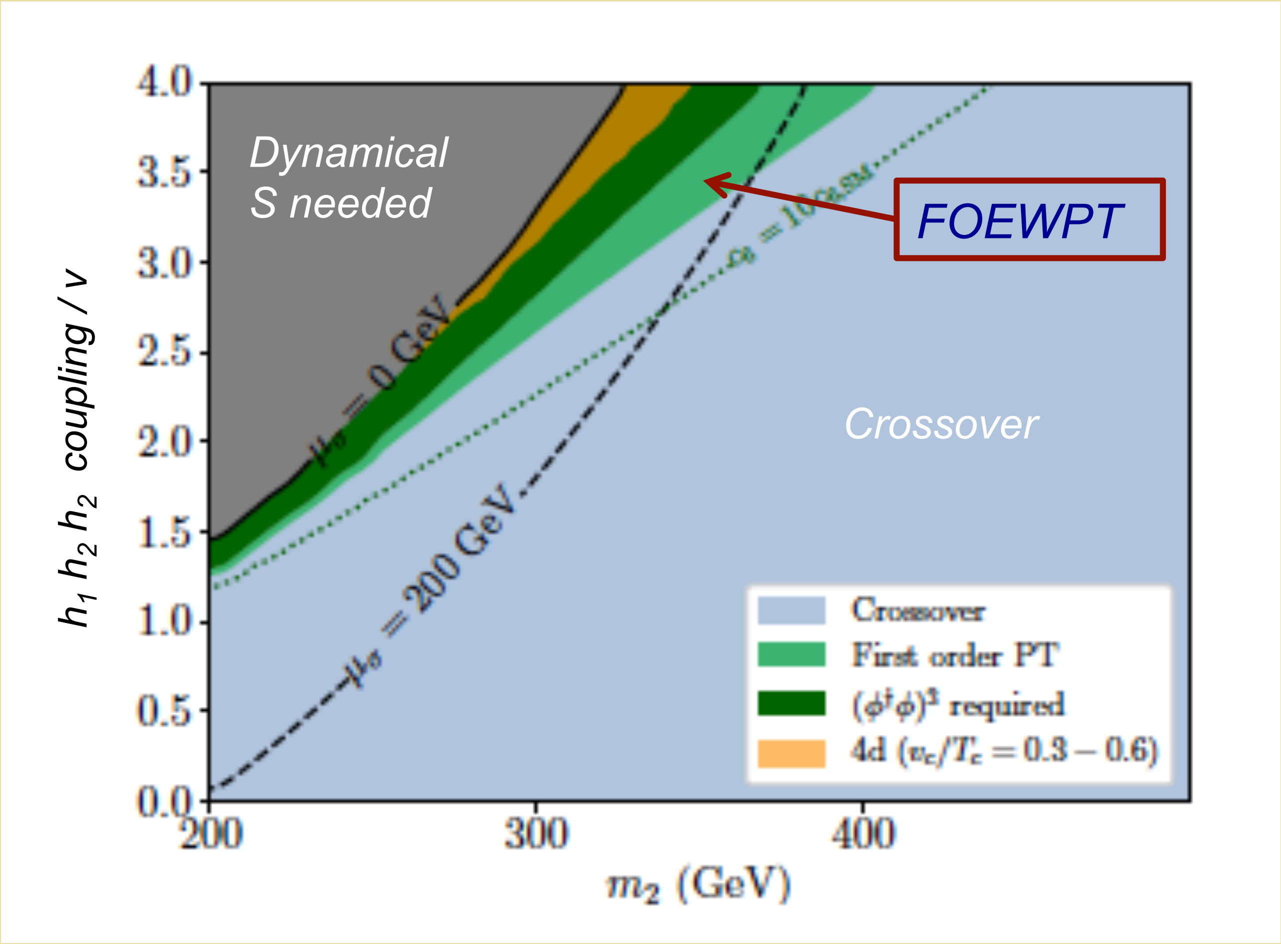
SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



Kotwal, No, R-M, Winslow 1605.06123

See also: Huang et al, 1701.04442

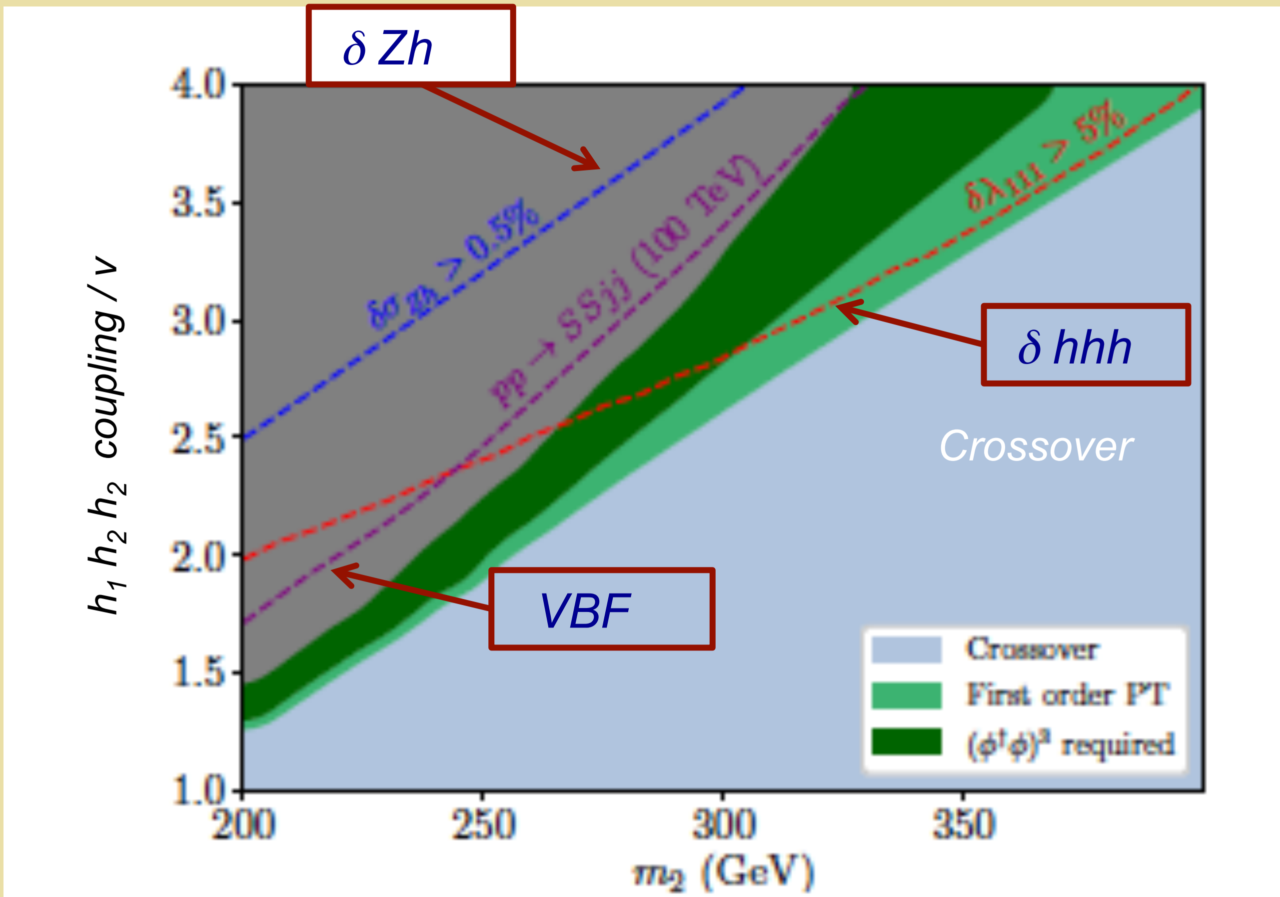
Real Singlet & EWPT: Lattice "Repurpose"



Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

- *One-step*
- *Non-perturbative*

Heavy Real Singlet & EWPT: Probes



Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

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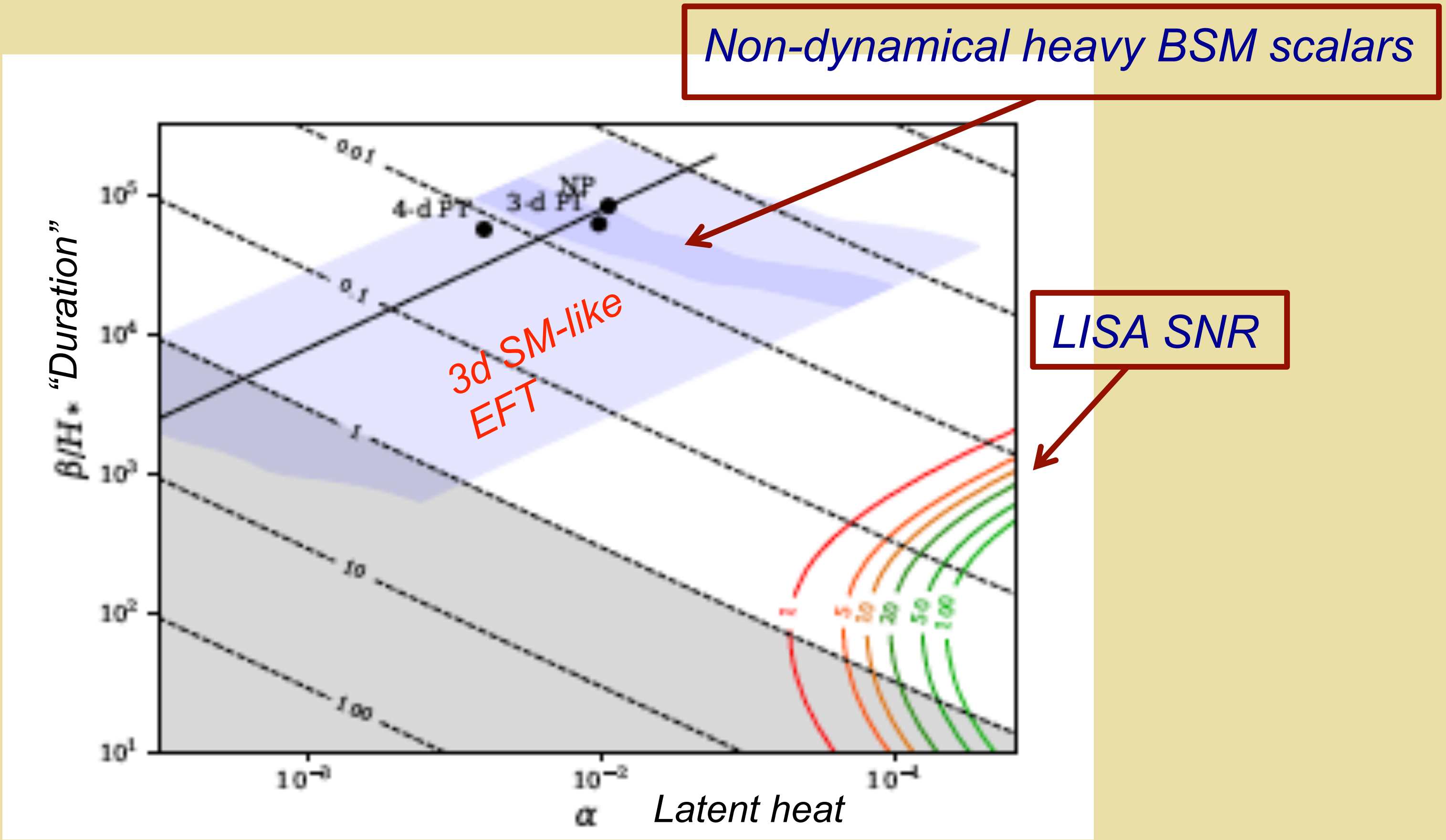
Heavy Real Singlet: EWPT & GW



Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

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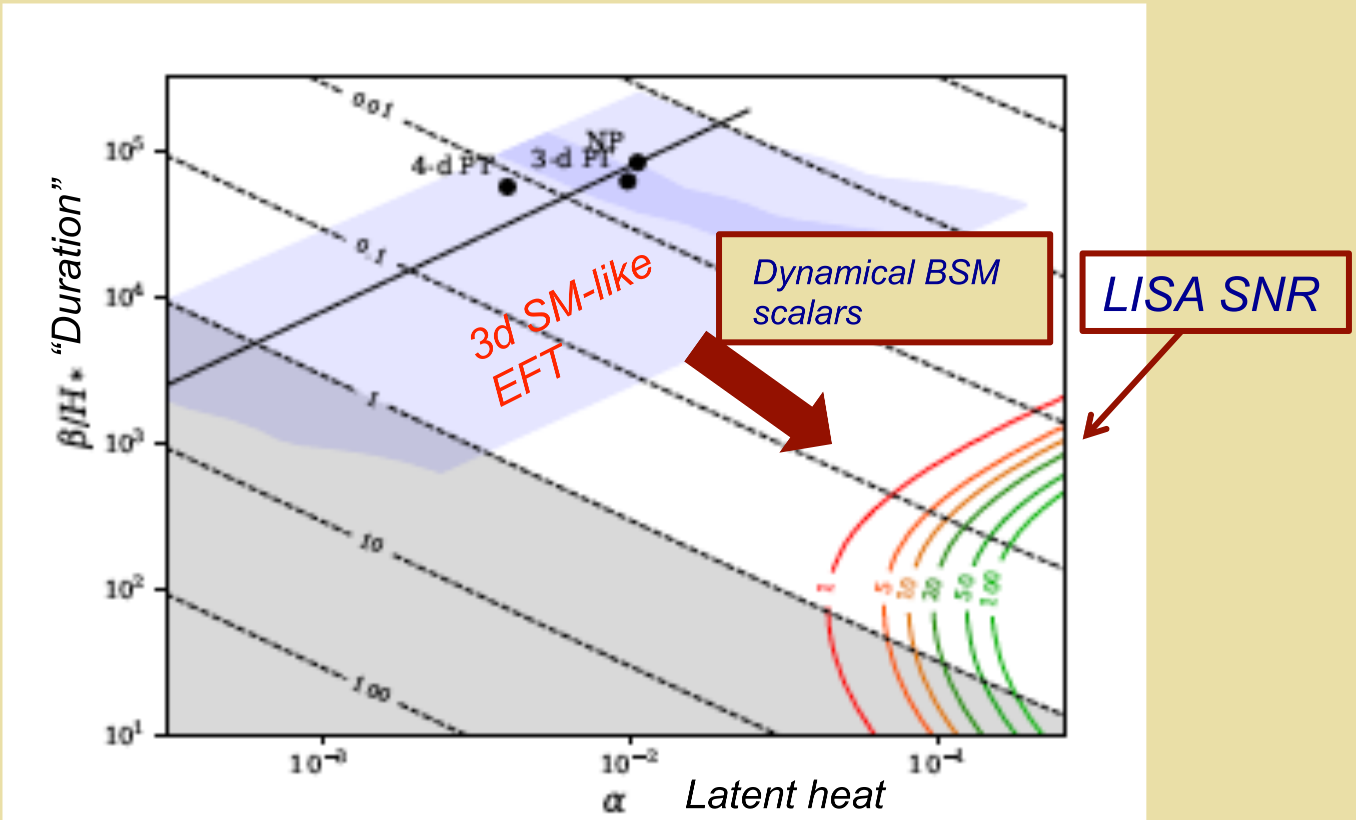
Heavy Real Singlet: EWPT & GW



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- *Non-perturbative*

A-IV. EWPT Outlook

Questions for Future Colliders

- *What is the "value added" ?*
- *What are the synergies/complementarities involving the pp, ee, and ep colliders ?*
- *Are there well-defined targets in mass reach and precision that would definitively address key open questions ?*

EWPT

- *Value added*

Extend reach significantly beyond HL-LHC

- *Synergy/complementarity*

Look for correspondence between new states (hh mode) and modified Higgs couplings (ee & hh modes)

- *Well-defined target in mass and/or precision*

Singlets: 100 TeV + 30 ab^{-1}
EW Multiplets: < 10% on h$\gamma\gamma$