The Collider-Cosmology Interface III

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AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

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

HEP School, Lanzhou
8/1-8/18

Lecture III Goals

- *Introduce the key ideas for relating the electroweak phase transition and WIMP dark matter in the context of electroweak baryogenesis*
- *Provide general considerations regarding dark matter model building*
- *Explain how electroweak baryogenesis works*
- *Discuss simple EWPT-DM scenarios and their collider probes*
- *Invite questions !*

Lecture III Outline

I. Electroweak Phase Transition & Dark Matter: Overview

II. WIMP Dark Matter: Context & Properties

III. Electroweak Baryogenesis: How It Works

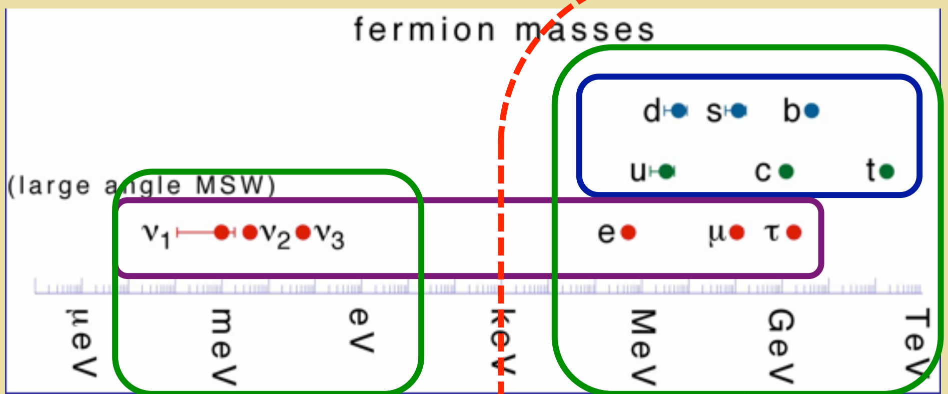
IV. EWPT & DM: Scenarios & Collider Probes

Selected References

- *M. Quiros, hep-ph/9901312*
- *S. Profumo, MJRM, G. Shaugnessy, 0705.2425 [hep-ph]*
- *H. Patel & MJRM, 1101.4665 [hep-ph]*
- *D. Morrissey & MJRM, 1206.2941 [hep-ph]*
- *K. Asamagan et al, 1604.05324 [hep-ph]*

I. EWPT & Dark Matter: Overview

Fermion Masses & Baryon Asymmetry



Partners

Partners

Something else ?

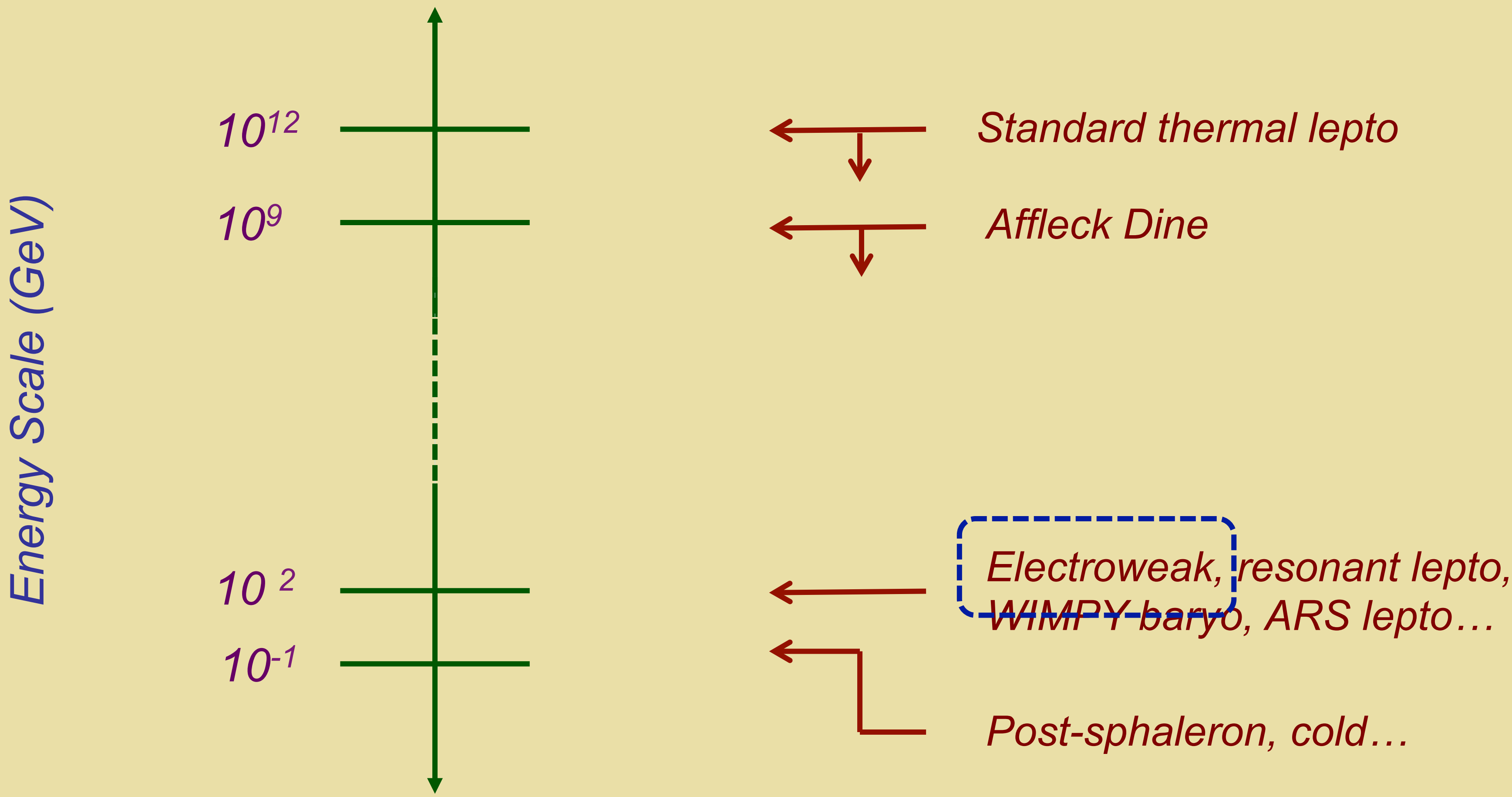
Higgs Mechanism

Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

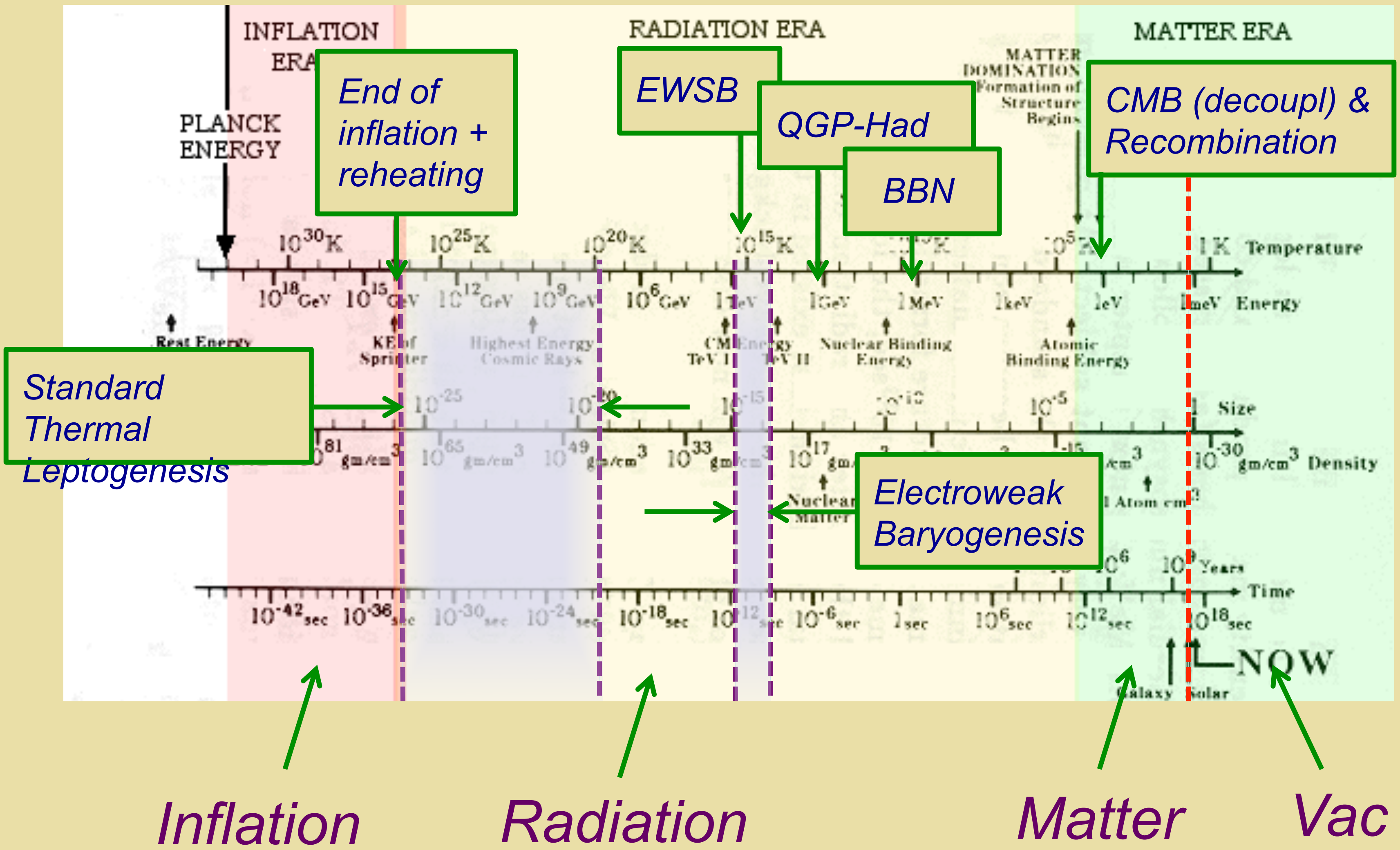
Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

This lecture

Baryogenesis Scenarios



Thermal History



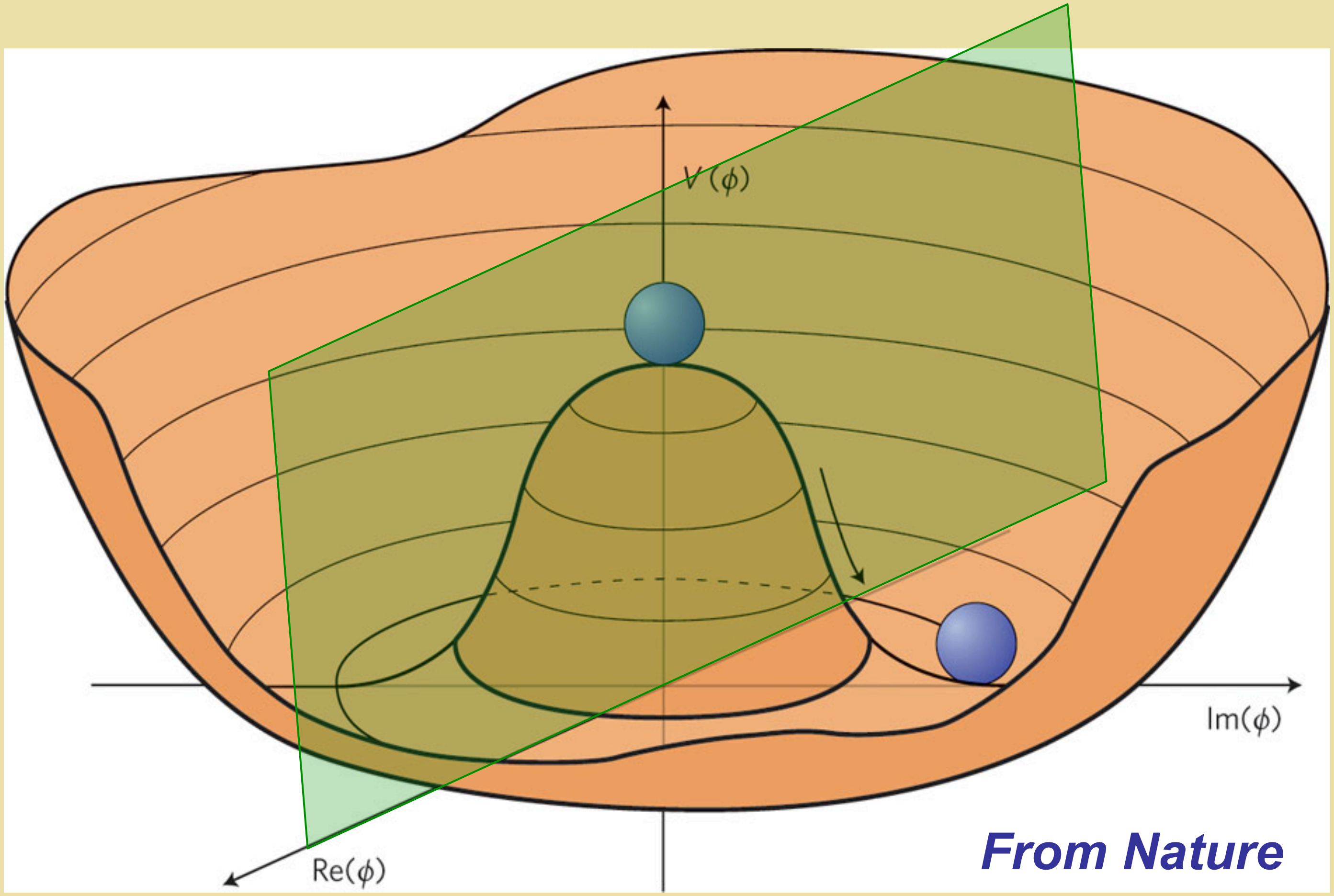
Ingredients for Baryogenesis

Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

	Standard Model	*BSM*
• *B violation (sphalerons)*	✔	✔
• *C & CP violation*	✖	✔
• *Out-of-equilibrium or CPT violation*	✖	✔

First order EWPT

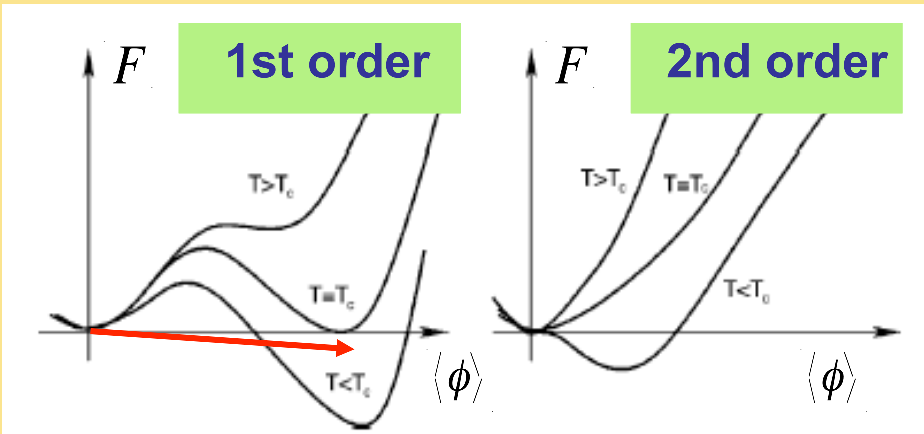
EWSB: The Scalar Potential



From Nature

What was the thermal history of EWSB ?

EW Phase Transition: St'd Model



Increasing m_h →

Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
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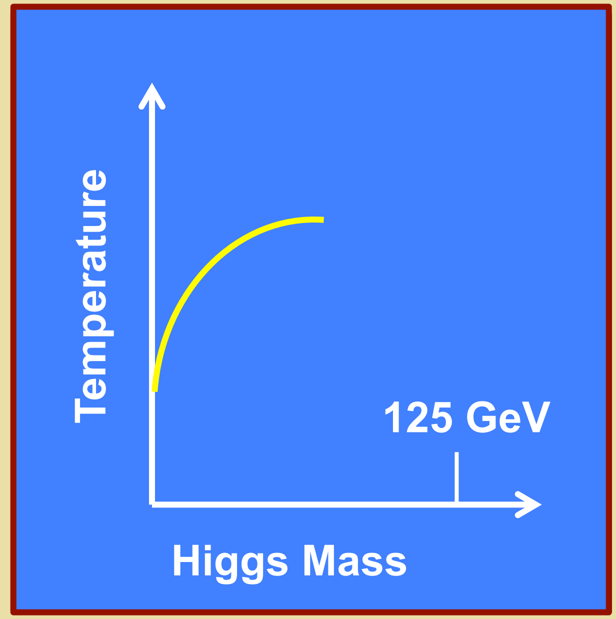
SM EW: Cross over transition



EW Phase Diagram

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

First Order EWPT from BSM Physics

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

EWPT & Dark Matter

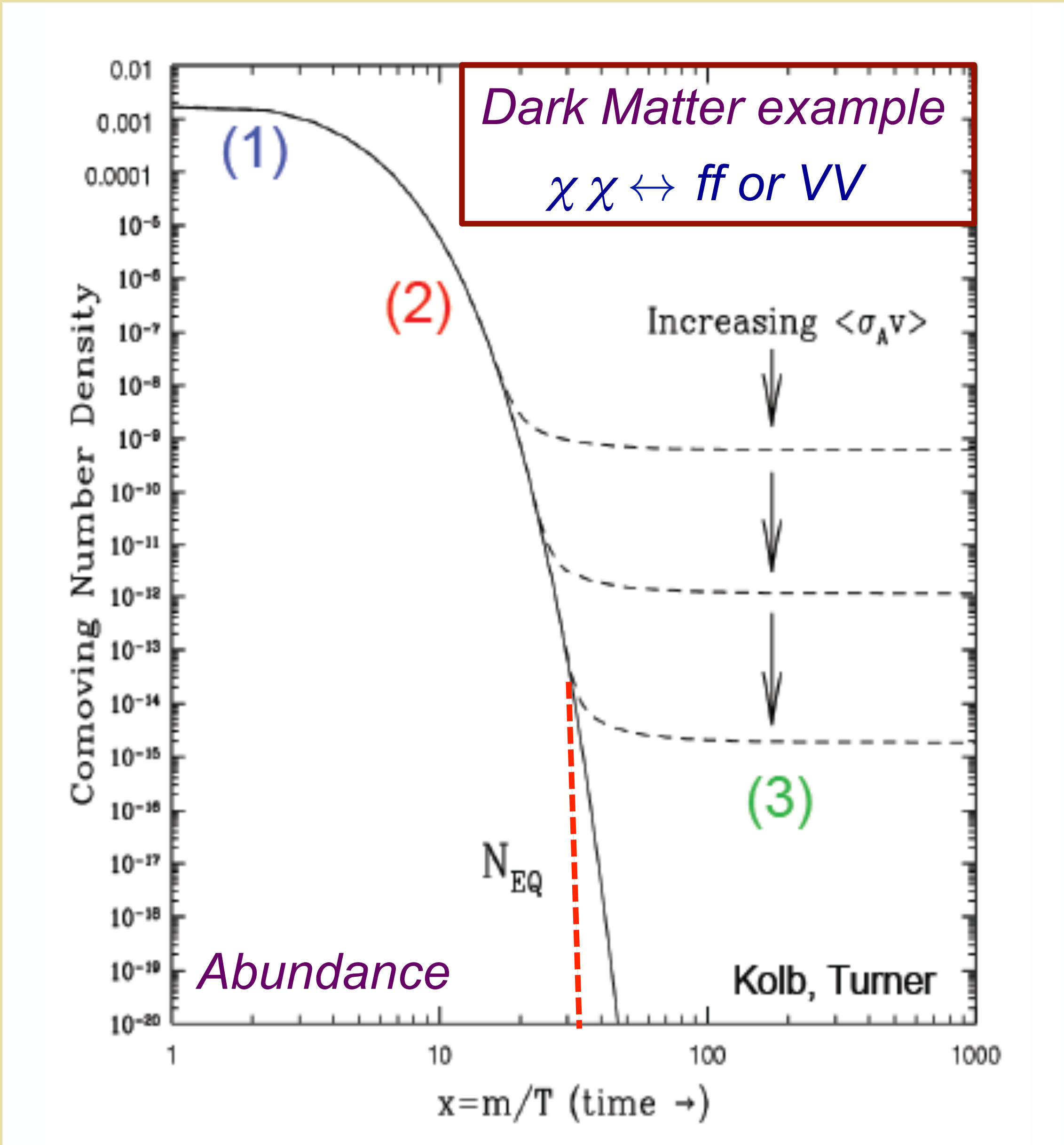
- ***Can the BSM particles that catalyze a first order EWPT also be viable dark matter candidates ?***

II. WIMP Dark Matter: Context & Properties

Dark Matter Properties

- Electrically neutral & colorless
- Stable on cosmological time scales
- “Cold”
- Thermal or Non-Thermal

Thermal Dark Matter



Boltzmann Eqs:

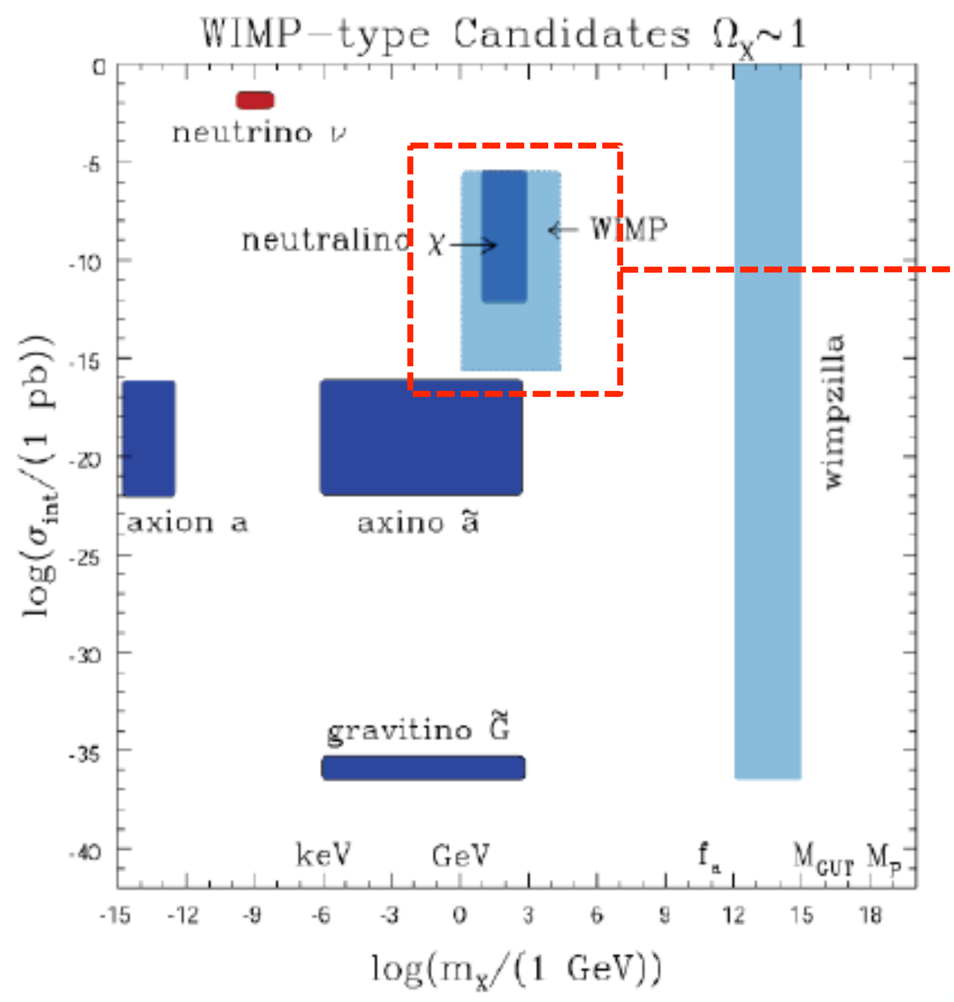
1) $N \sim N_{EQ}$
2) N starts to depart from N_{EQ}
3) N "freezes out" at x_f

$x_f \sim \mathcal{O}(10) \rightarrow$
$T \sim m / 10$

Dark Matter Interactions

- ***Gravitational***
- ***Non-grav interactions w/ St'd Model ?***
- ***Non-grav interactions w/ itself ?***

Particle Dark Matter Scenarios



L. Roszkowski, Particle Dark Matter **hep-ph/0404052**

Weakly Interacting Massive Particles: "WIMPS"

- $\sigma_{INT} \sim \sigma_{weak}$
- M_χ : *few GeV* $\rightarrow$ *few TeV*

Dark Matter Portals

Standard Model

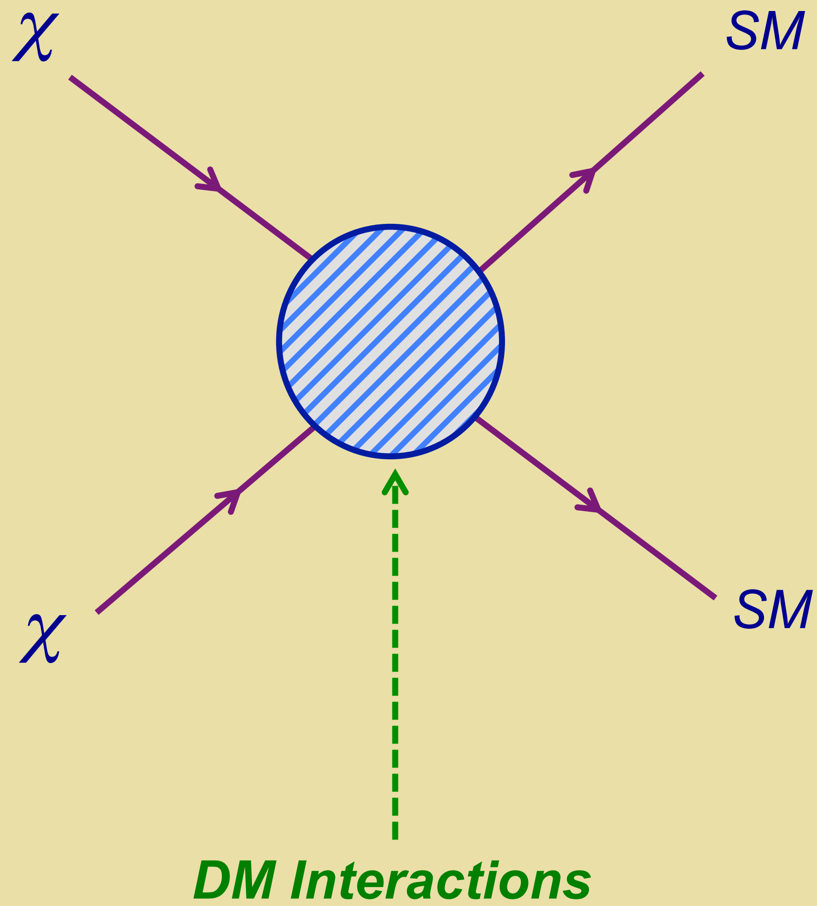
Hidden Sector

Dark Matter Portals

- ***Gauge sector (SUSY neutralinos)***
- ***Higgs portal (BSM scalars)***
- ***QCD portal (Axion)***
- ***Yukawa portal (neutrinos)***

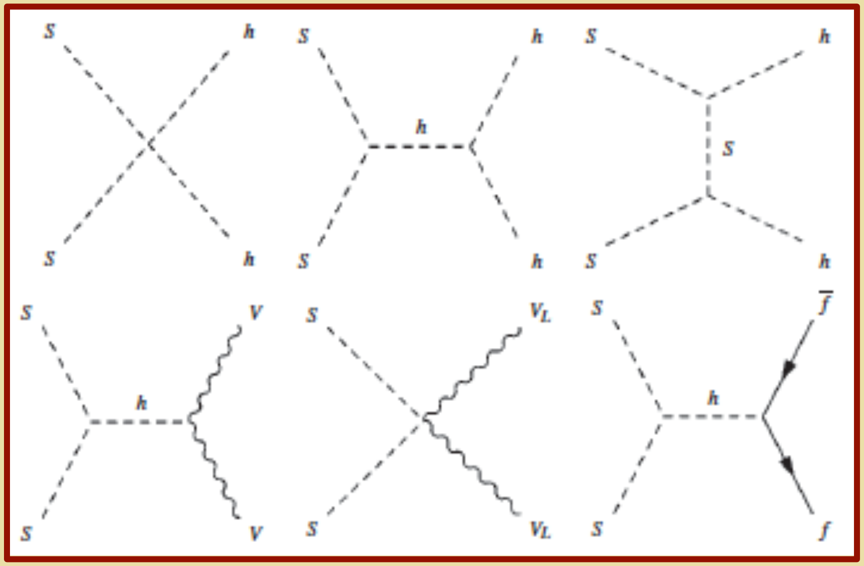
WIMP Dark Matter Probes

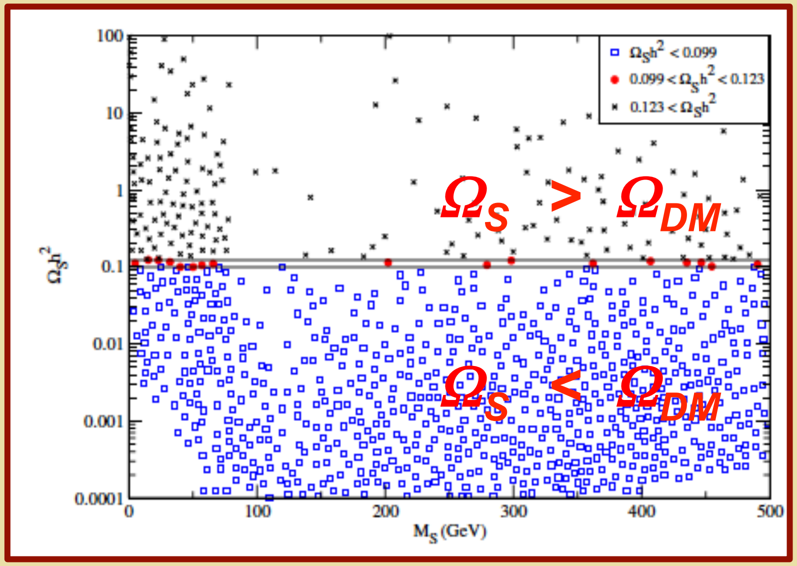
Thermal Abundance & Indirect Detection



WIMP DM: Ω_{DM} & Indirect Det

Real singlet exension: "xSM"

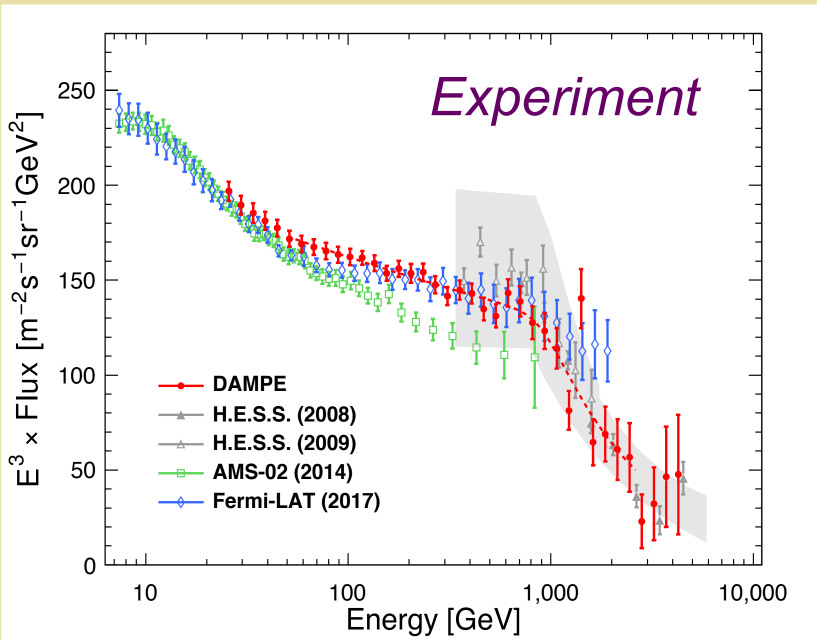


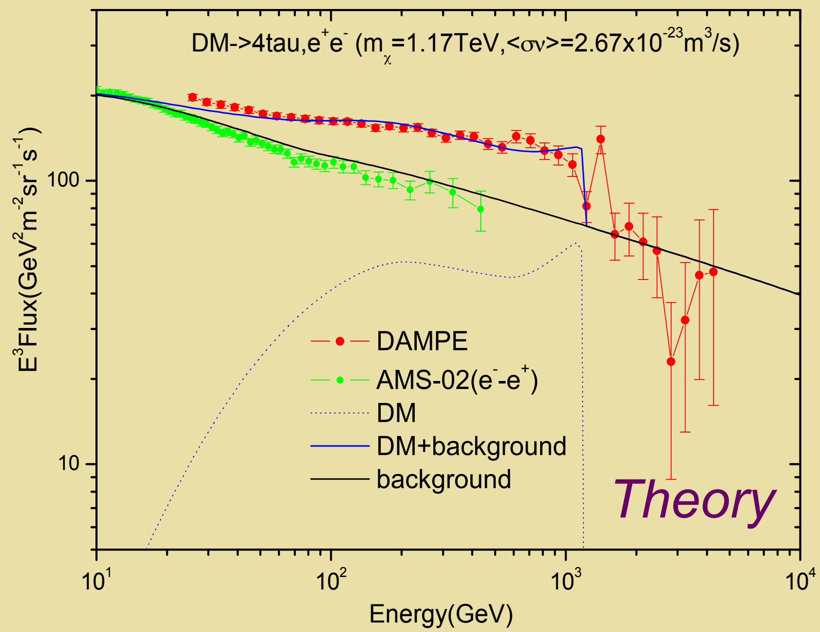


Barger, Langacker, McCaskey, MJRM, Shaugnessy 0706.4311 [hep-ph]

WIMP DM: Ω_{DM} & Indirect Det

Indirect detection



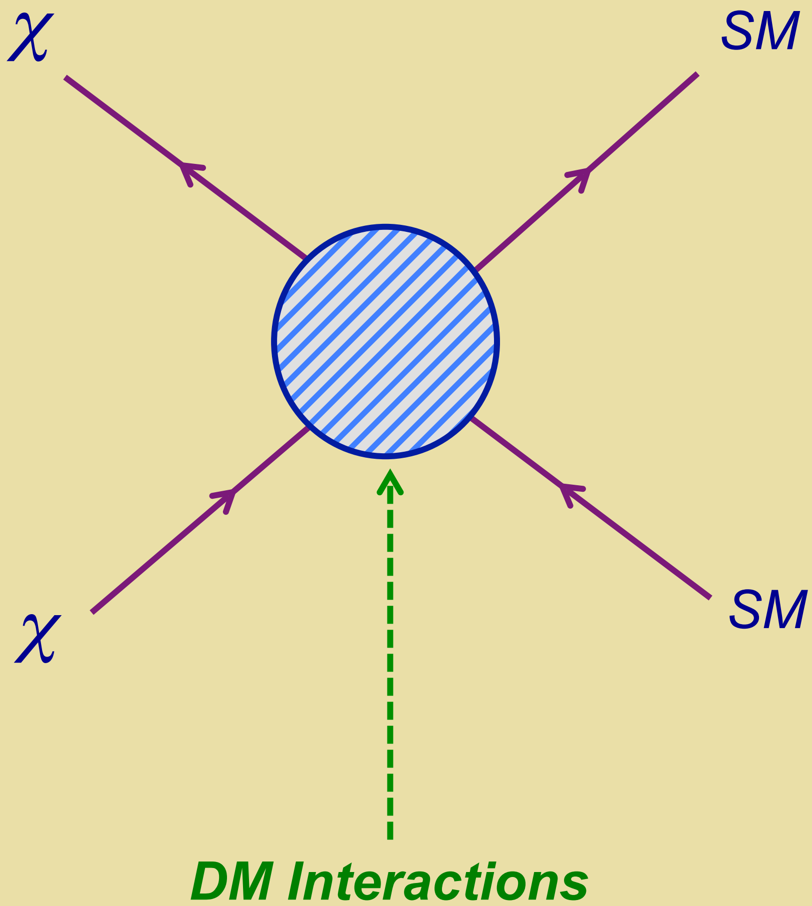


Ambrosi et al (DAMPE Collab) 1711.10981 [astro-ph]

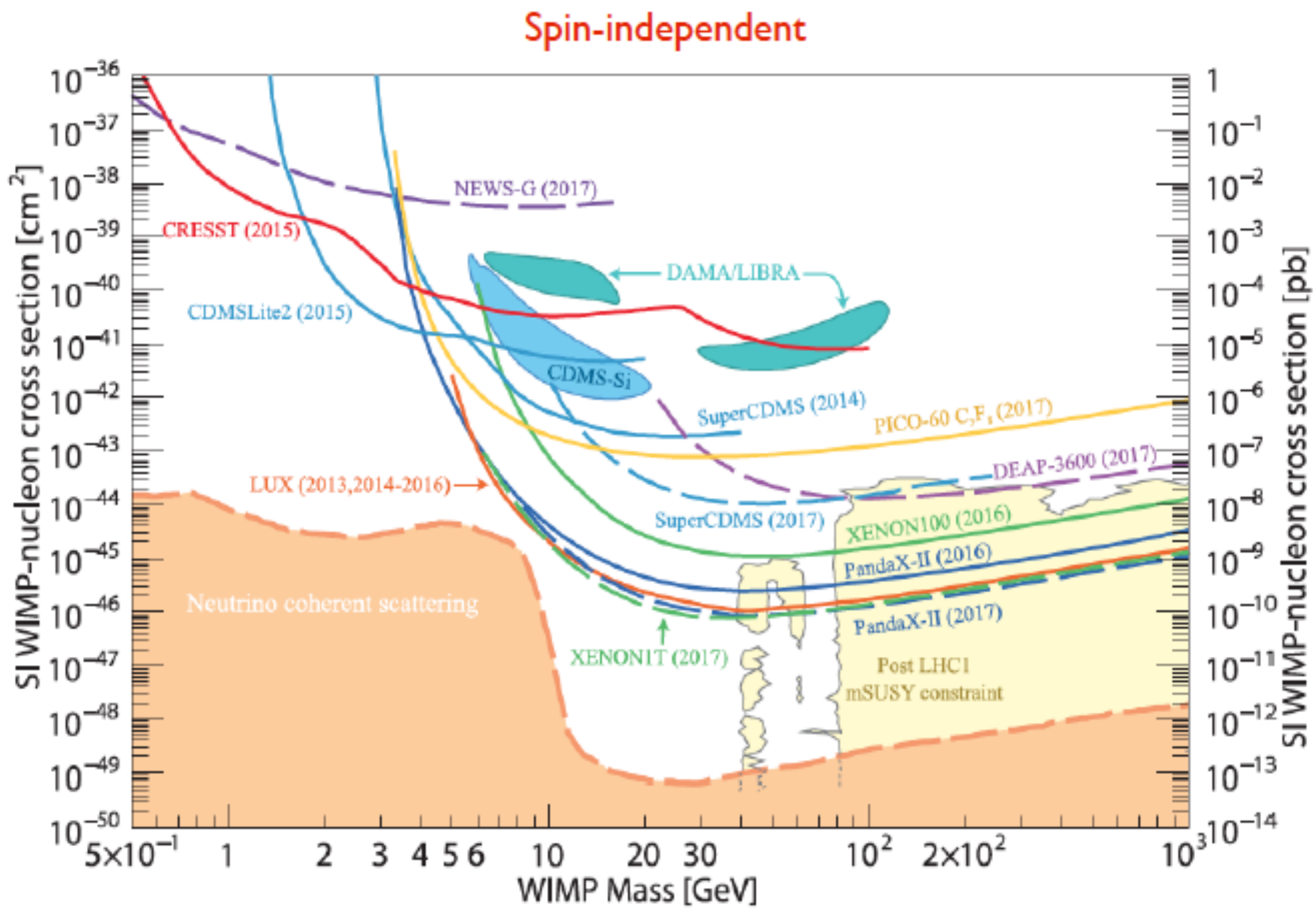
Jin, Yue, Zhang, Chen 1712.00362 [astro-ph]

WIMP Dark Matter Probes

Direct Detection: WIMP-Nucleus scattering



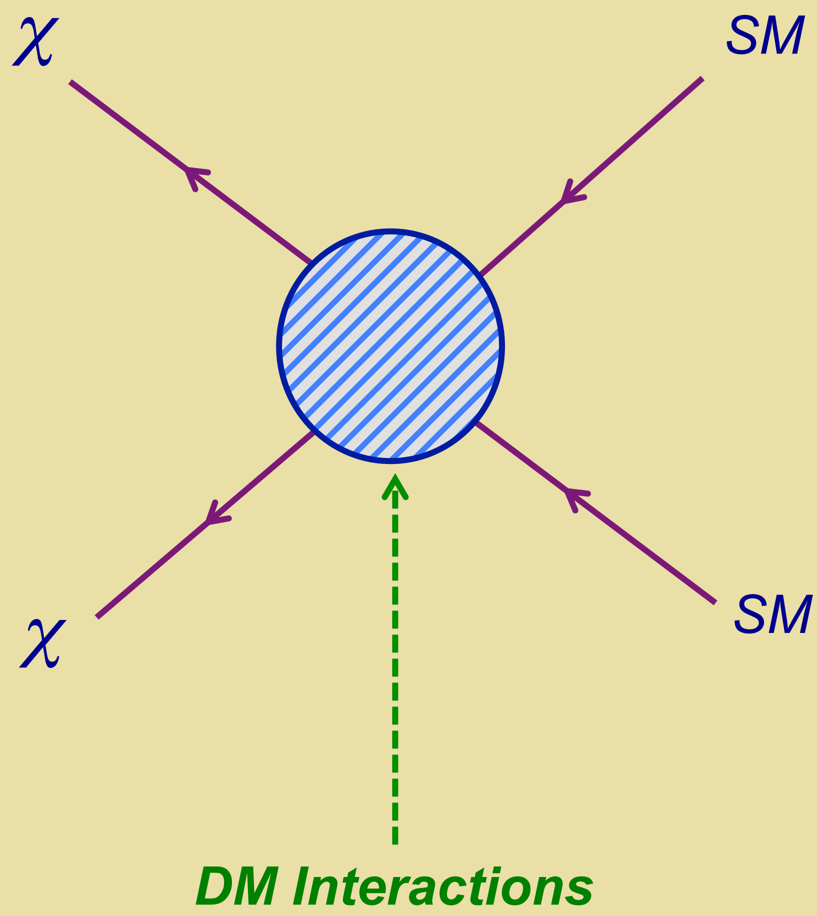
WIMP Dark Matter: Direct Detection



PDG 2018

WIMP Dark Matter Probes

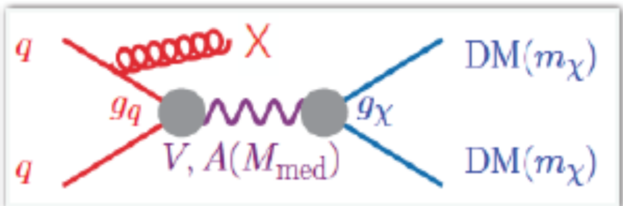
DM Production at Colliders



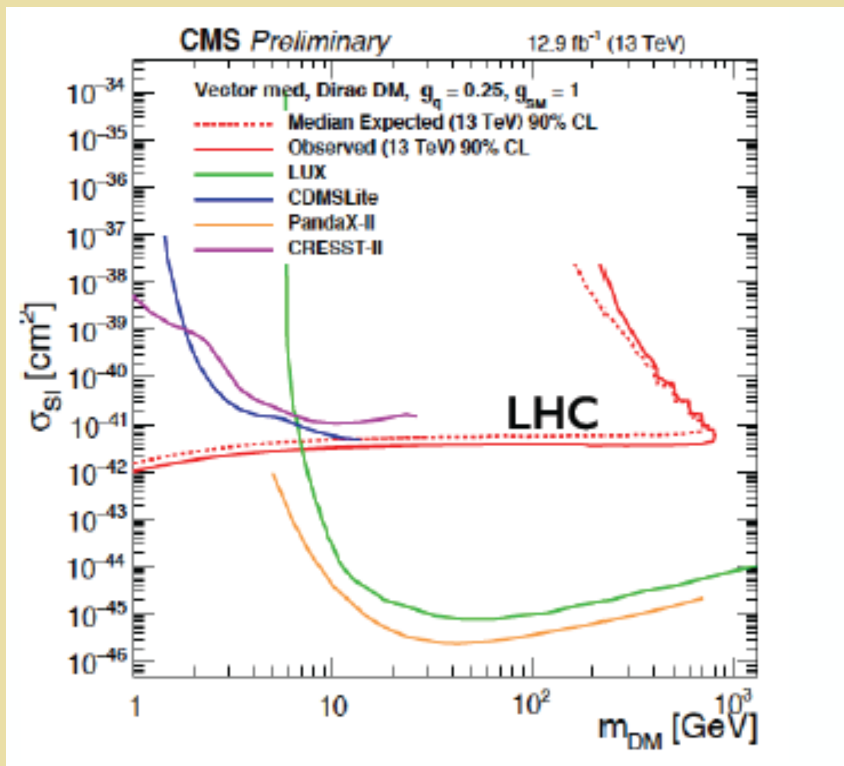
WIMP Dark Matter: Colliders

Signature: pp → X + missing E_T ("mono-X" searches)

V. Cirigliano

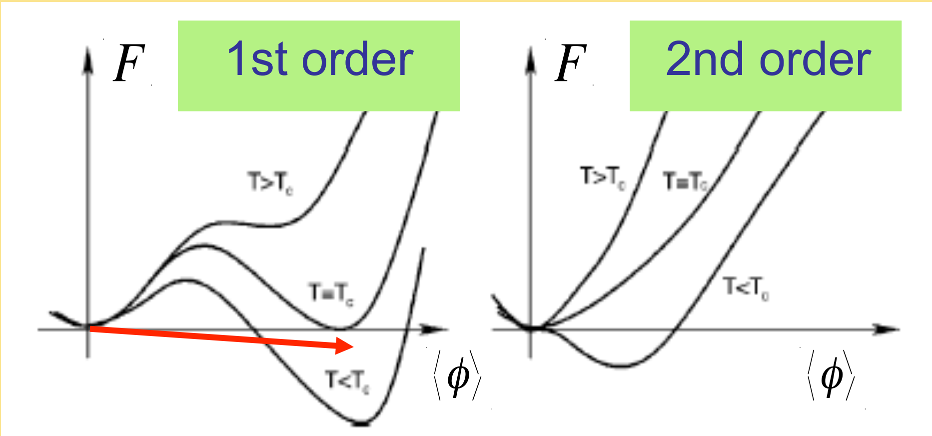


Irreducible background:
pp → Z (νν) + jets

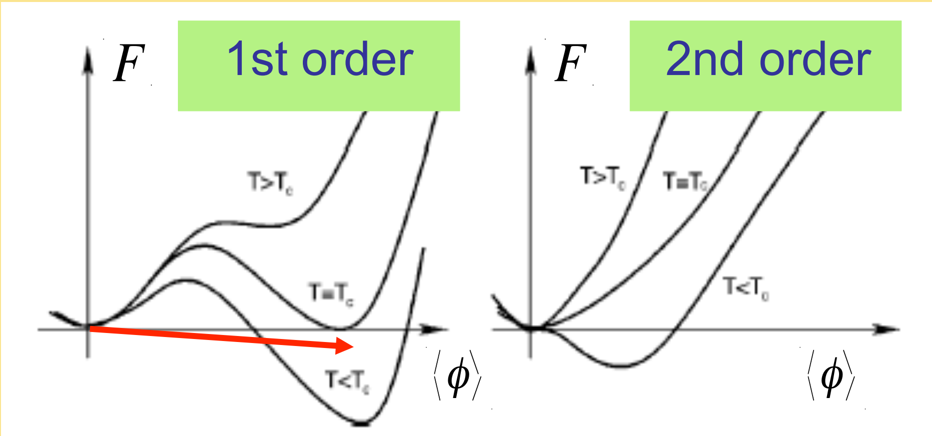


III. Electroweak Baryogenesis: How It Works

EW Phase Transition: New Scalars & CPV

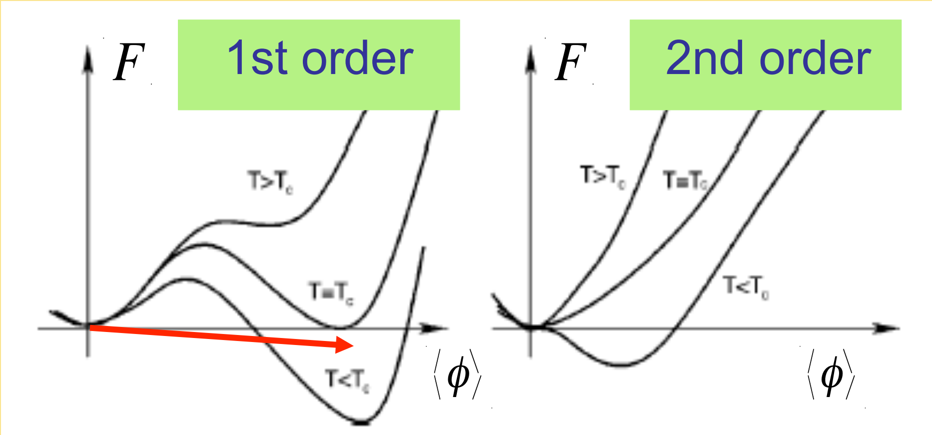


EW Phase Transition: New Scalars & CPV



Increasing m_h ⟶

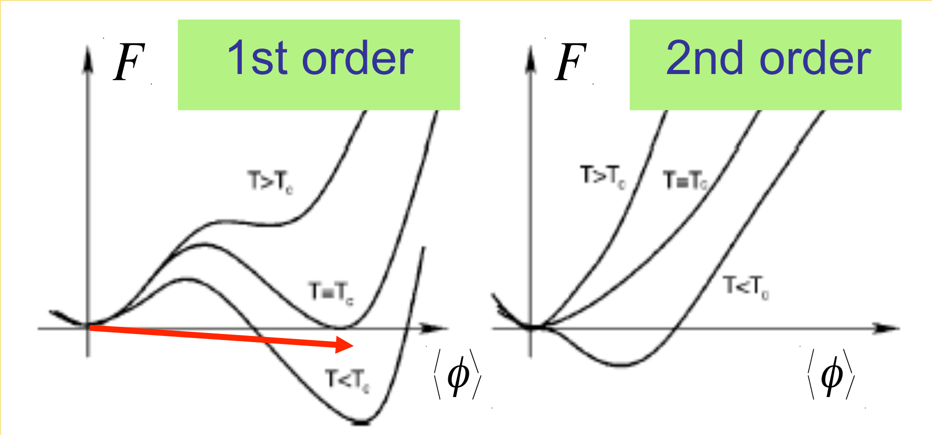
EW Phase Transition: New Scalars & CPV



Increasing m_h →

← *New scalars*

EW Phase Transition: New Scalars & CPV

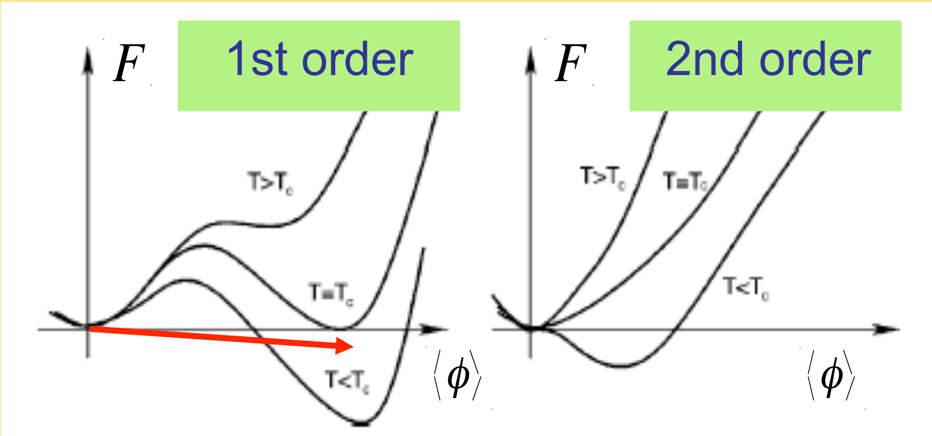


Increasing m_h ⟶

⟵ *New scalars*

- *Loop effects*
- *Tree-level barrier*

EW Phase Transition: New Scalars & CPV



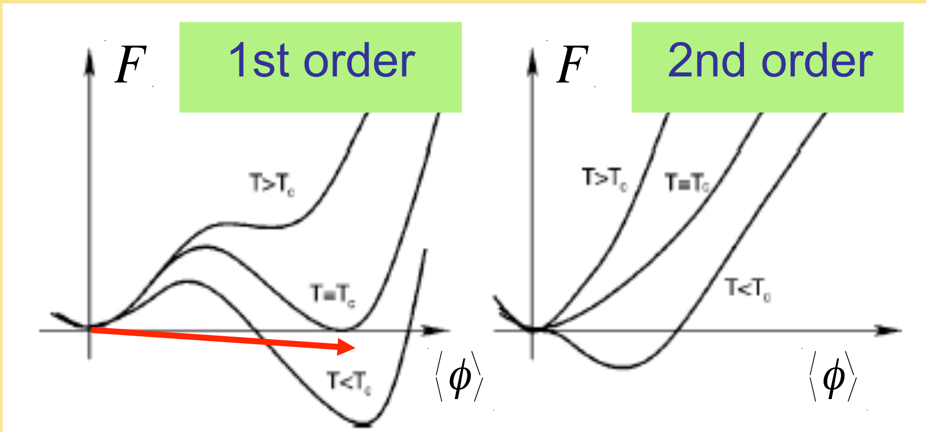
Increasing m_h →

← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

EW Phase Transition: New Scalars & CPV



Increasing m_h ⟶

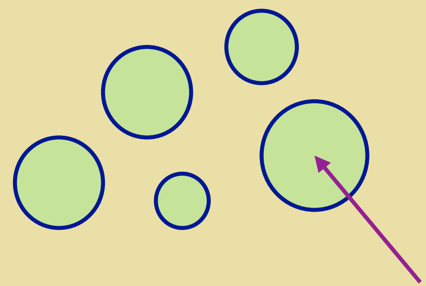
⟵ *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" *1^{st} order EWPT*

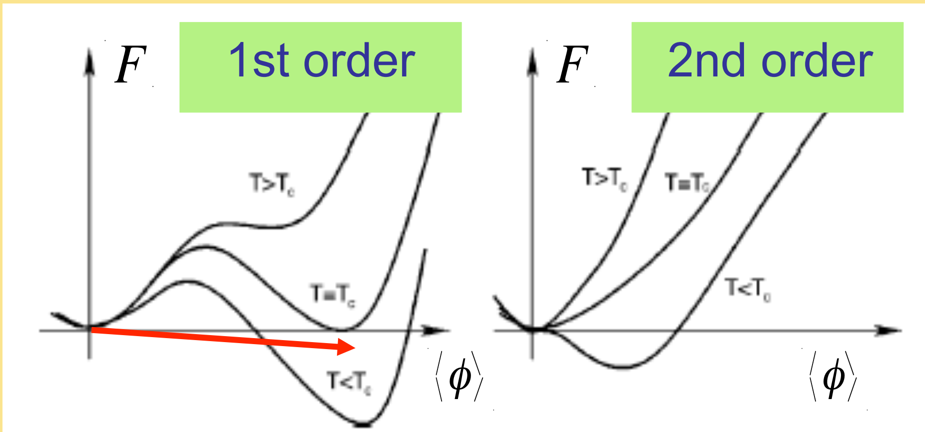
↓

Bubble nucleation



EWSB

EW Phase Transition: New Scalars & CPV



Increasing m_h →

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Gravity Waves
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"Strong" 1st order EWPT

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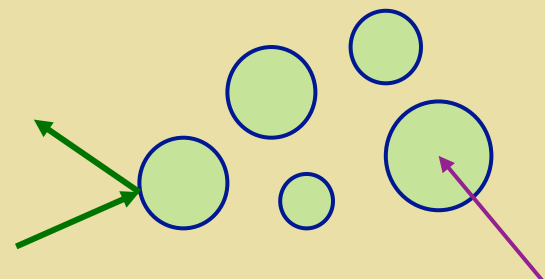
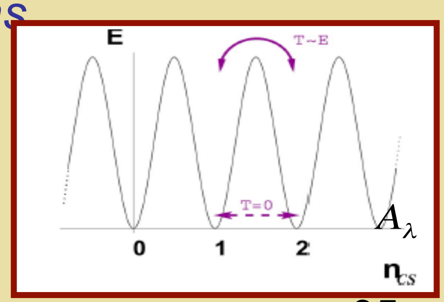
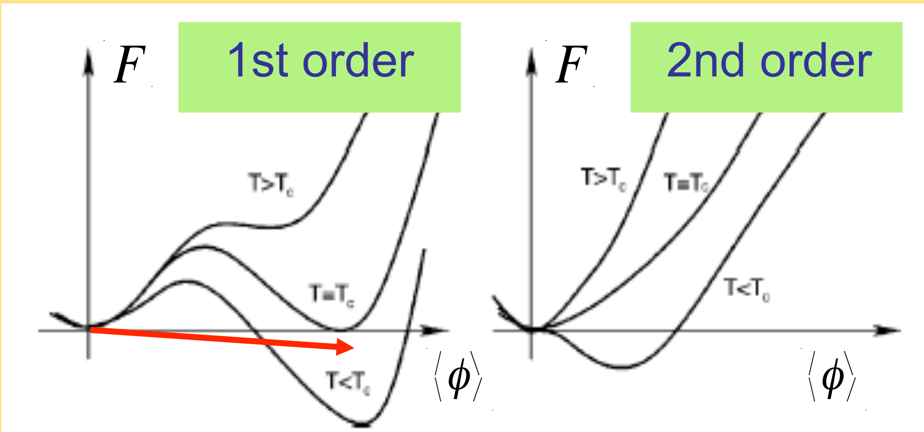


Y_B : CPV &
EW sphalerons

EWSB



EW Phase Transition: New Scalars & CPV



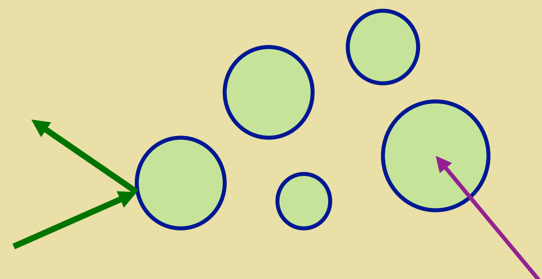
Increasing m_h ⟶

⟵ *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" *1^{st} order EWPT*

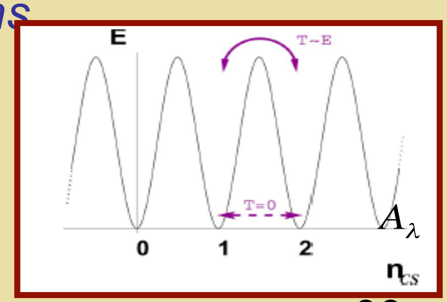
Bubble nucleation



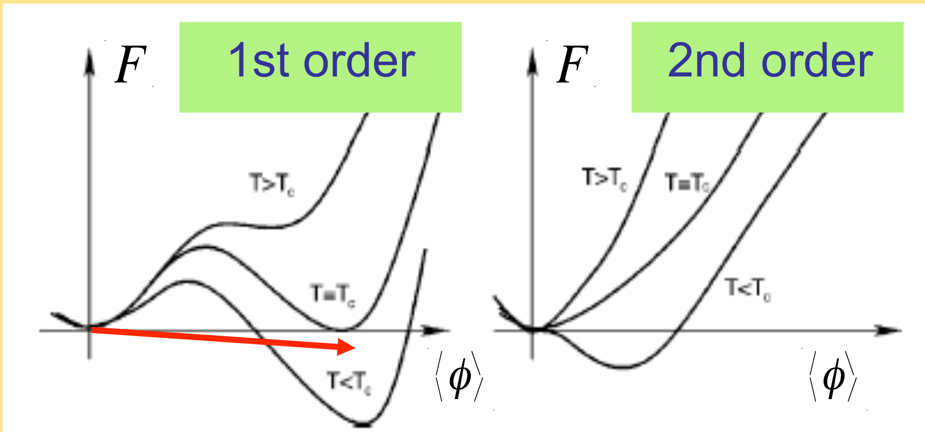
Y_B : CPV & EW sphalerons

EWSB

BSM



EW Phase Transition: New Scalars & CPV



Increasing m_h →

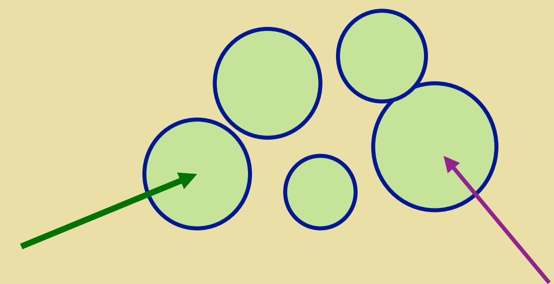
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" *1^{st} order EWPT*

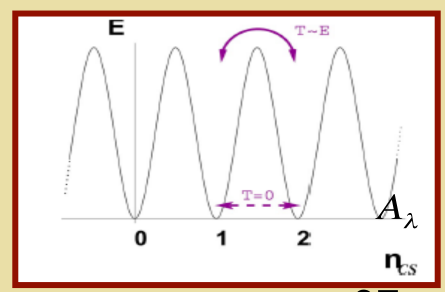
↓

Bubble nucleation

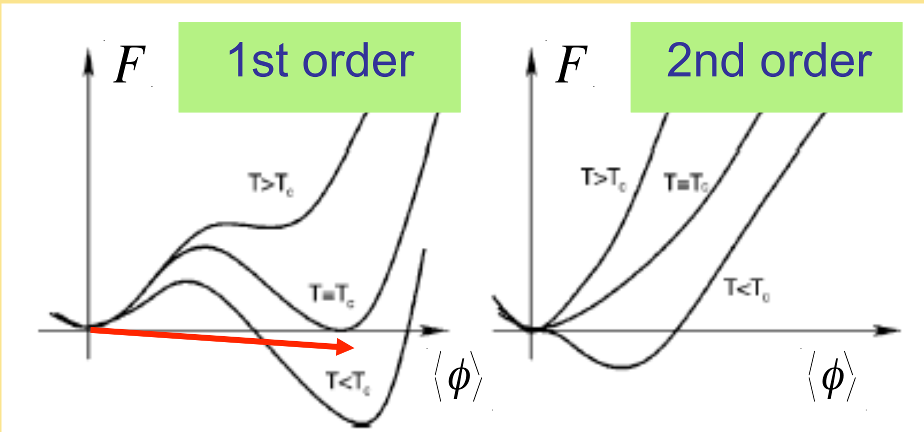


Y_B : diffuses into interiors

EWSB



EW Phase Transition: New Scalars & CPV



Increasing m_h →

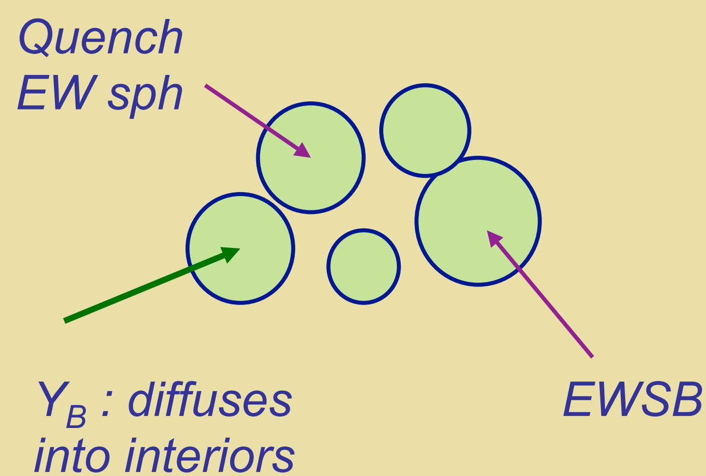
← New scalars

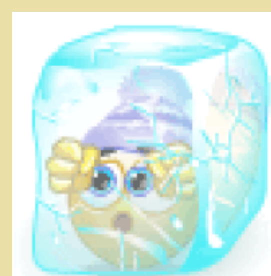
- Baryogenesis
- Gravity Waves
- Scalar DM
- LHC Searches

"Strong" 1st order EWPT

"Strong" → Preserve $Y_B^{initial}$

1st order EWPT → Bubble nucleation

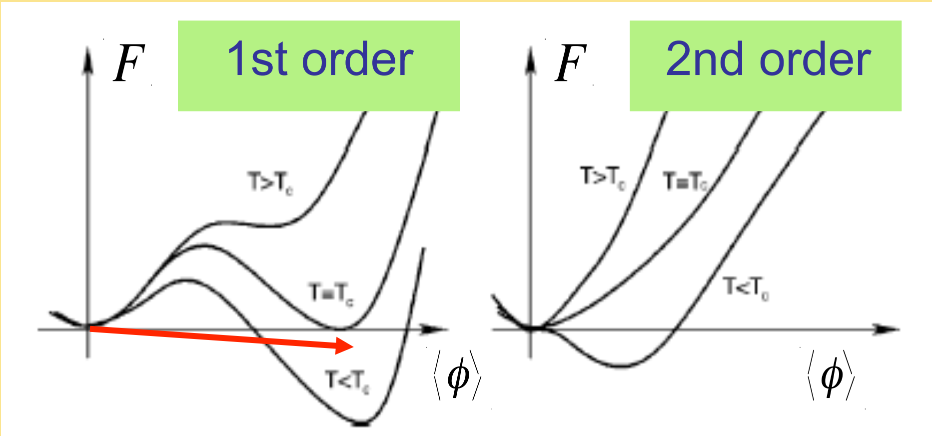




IV. EWPT & DM: Scenarios & Collider Probes

Higgs Portal DM & EWPT

EW Phase Transition: Higgs Portal



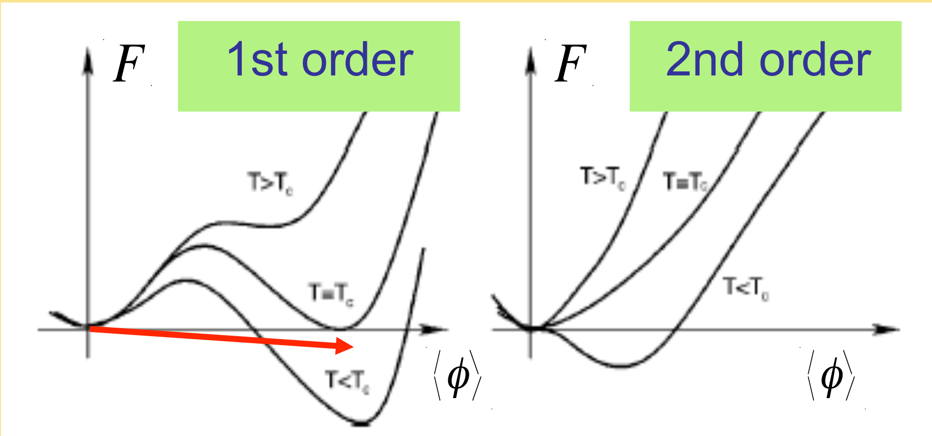
Increasing m_h →

← *New scalars*

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

+…

EW Phase Transition: Higgs Portal



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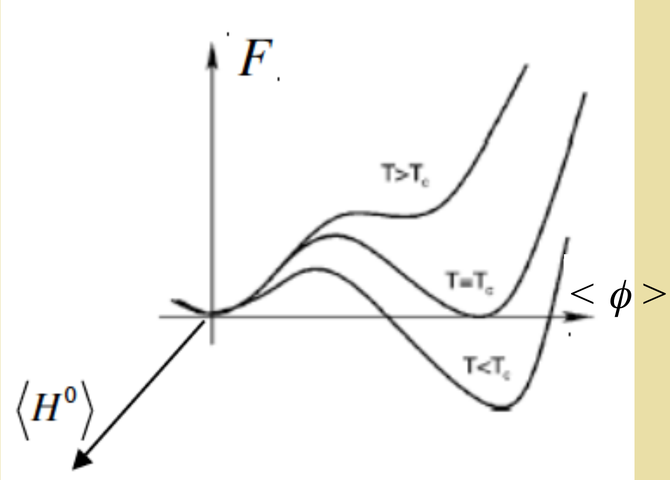

- *Renormalizable*
- *ϕ : singlet or charged under $SU(2)_L$ x $U(1)_Y$*
- *Generic features of full theory (NMSSM, GUTS…)*
- *More robust vacuum stability*
- *Novel patterns of SSB*

Higgs Portal: Simple Scalar Extensions

Extension	DOF	EWPT	DM
Real singlet: $\not{Z}_2$	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

Higgs Portal: Simple Scalar Extensions

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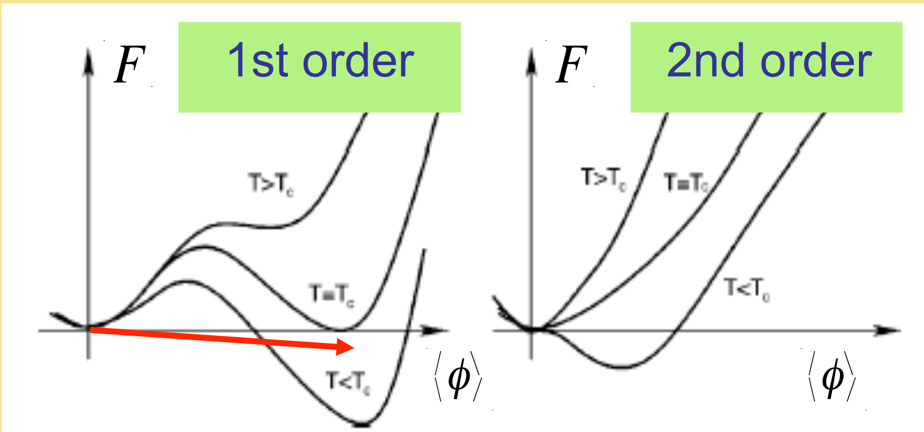
EW Phase Transition: New Scalars

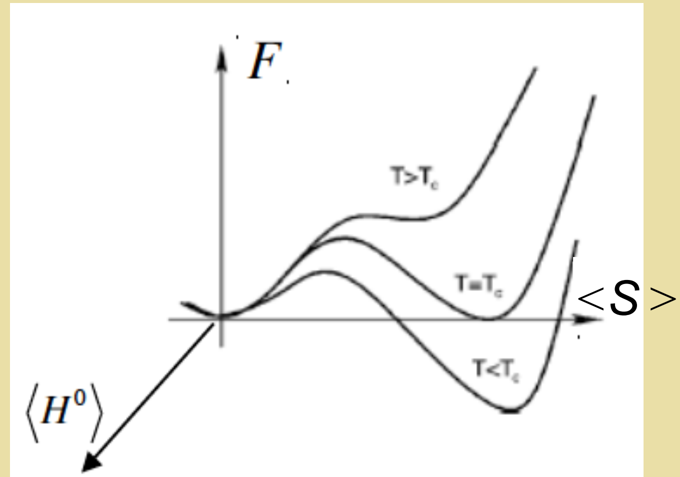


Increasing m_h →

← *New scalars*

Real Singlet: $\phi \to S$

Simplest Extension:
two states h_1 & h_2



Profumo, R-M, Shaugnessy JHEP 0708 (2007) 010

Simplest Extension

Standard Model + real singlet scalar

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

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

Simplest Extension

Standard Model + real singlet scalar

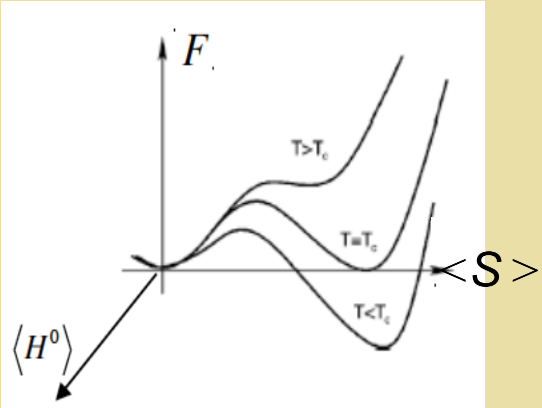
$$V_{\rm HS} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

Phenomenology

$$h_1 = \sin\theta\ s + \cos\theta\ h$$
$$h_2 = \cos\theta\ s - \sin\theta\ h$$

$m_{1,2}$; θ ; $h_i\ h_j\ h_k$ couplings

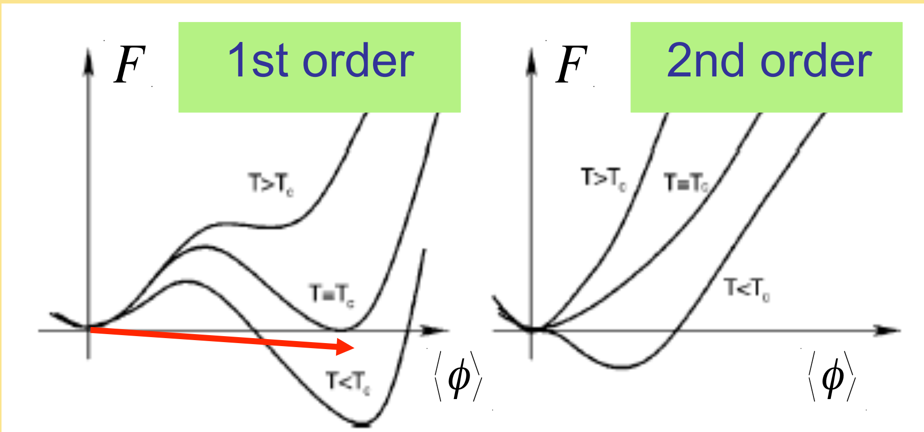
EWPT



T_C , Γ_N , Γ_{sph} , …

Profumo, R-M, Shaugnessy JHEP 0708 (2007) 010

EW Phase Transition: New Scalars



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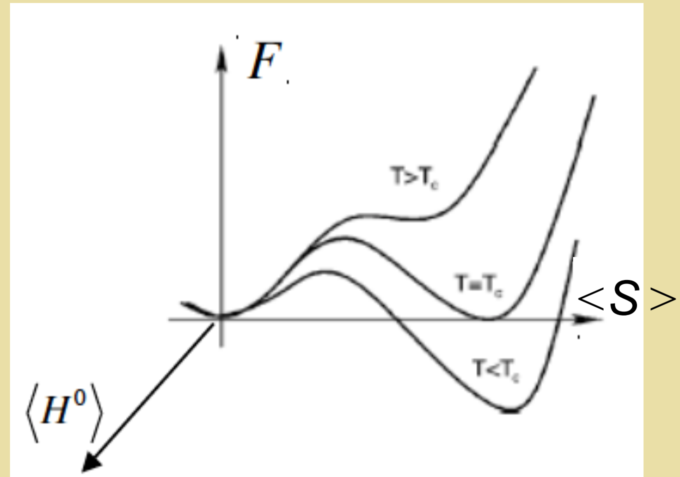
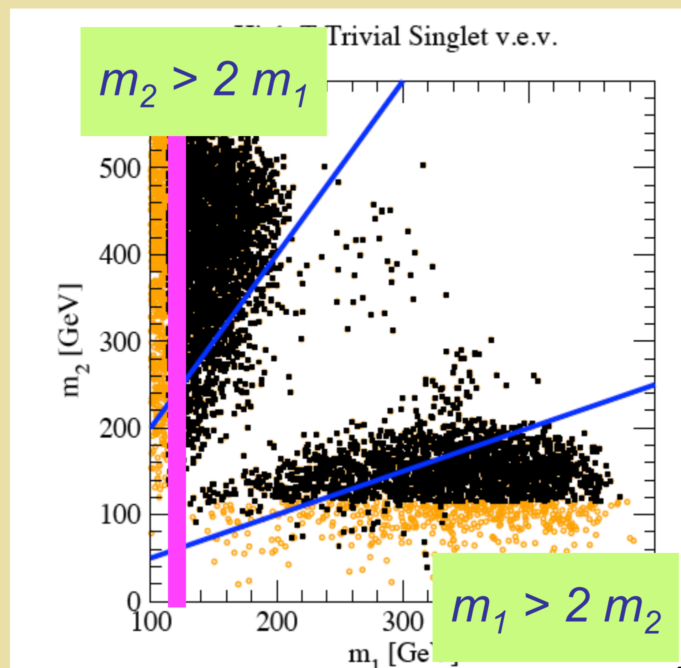
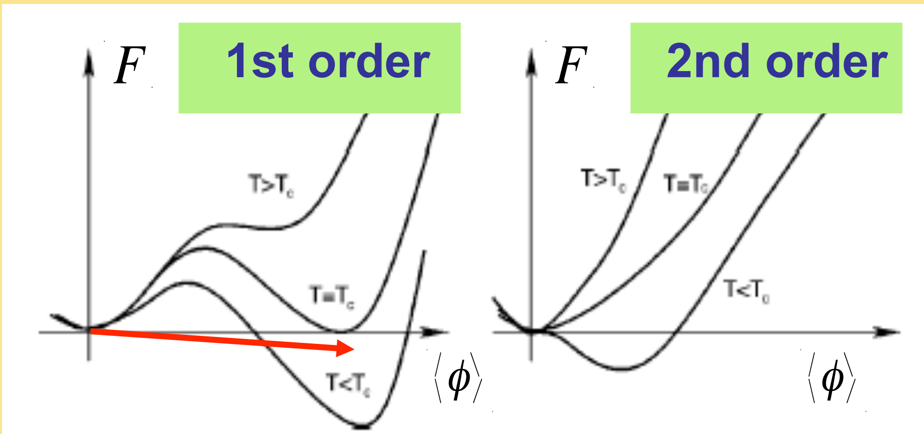


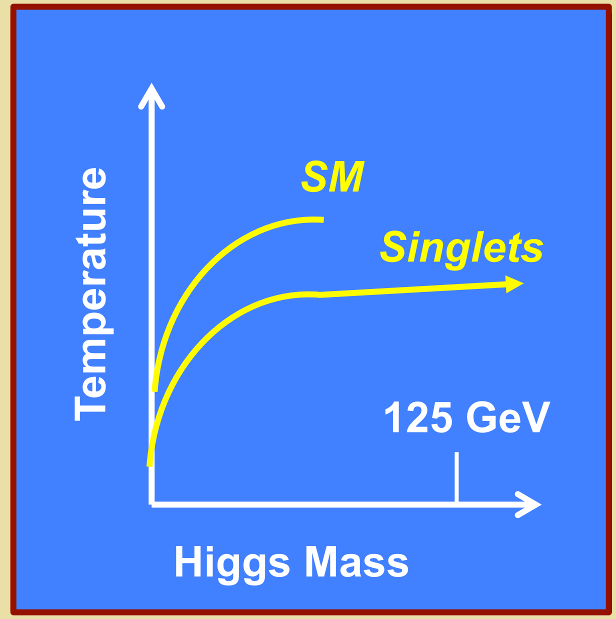


Profumo, R-M, Shaugnessy JHEP 0708 (2007) 010

EW Phase Transition: Singlet Scalars



Increasing m_h →



EW Phase Diagram

Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
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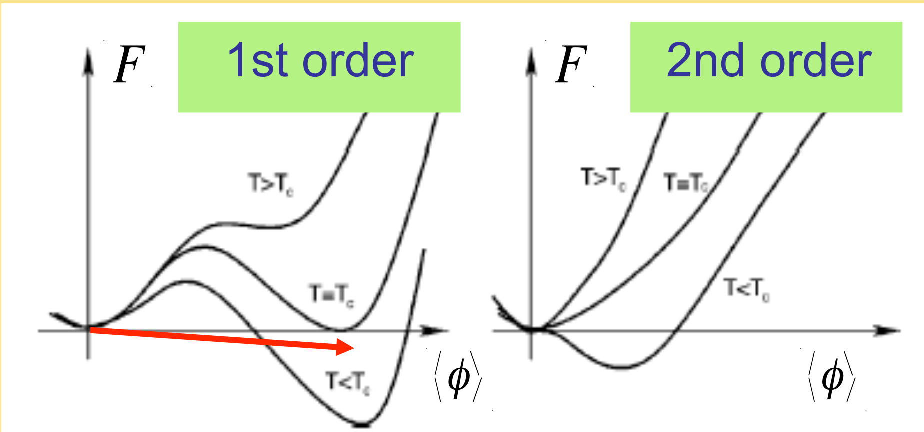
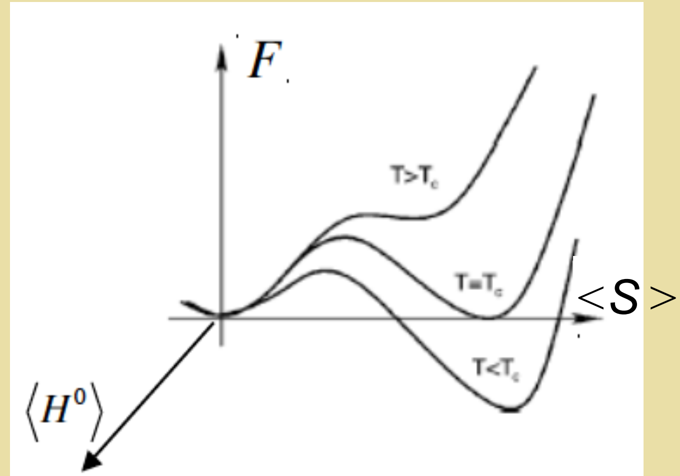
How does this picture change in presence of new TeV scale physics ? What is the phase diagram ?

SM EW: Cross over transition

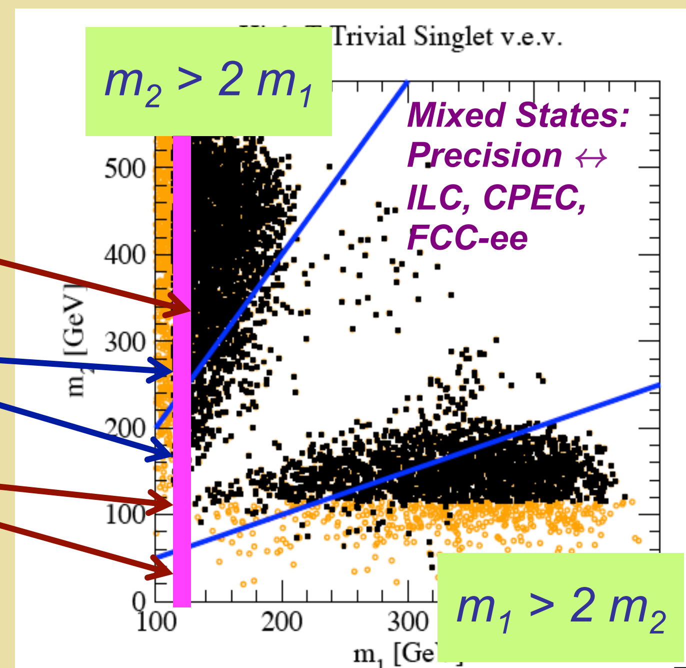
EW Phase Transition: Singlet Scalars





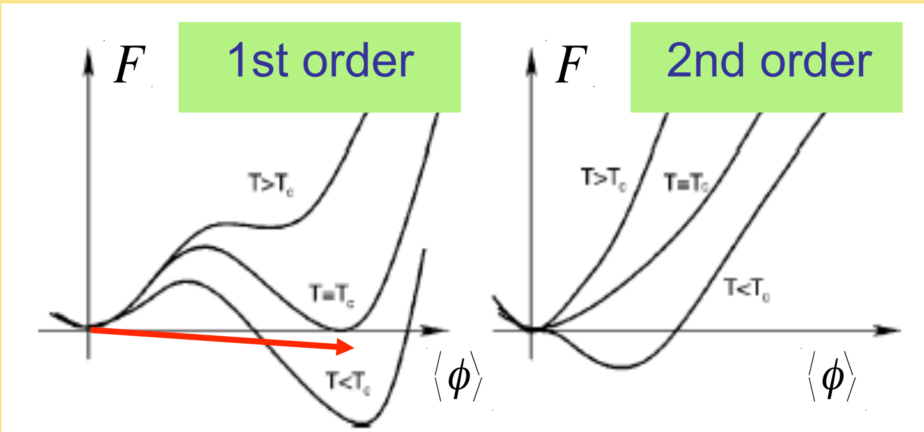
Collider probes

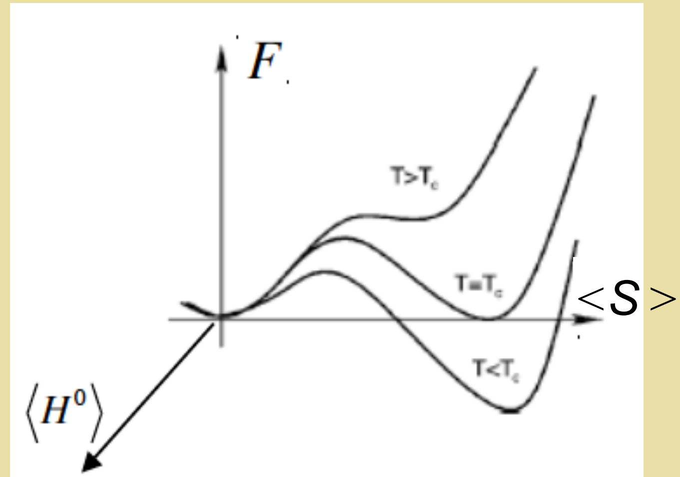
- Resonant di-Higgs production
- Precision Higgs measurements
- Non-resonant di-Higgs & exotic Higgs decays



Profumo, MJRM, Shaugnessy '07

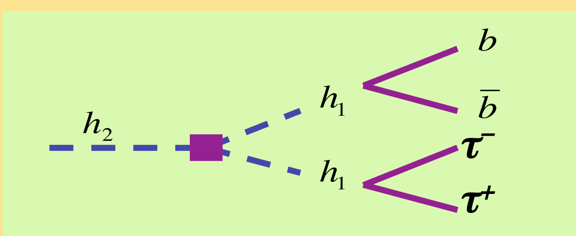
EW Phase Transition: New Scalars

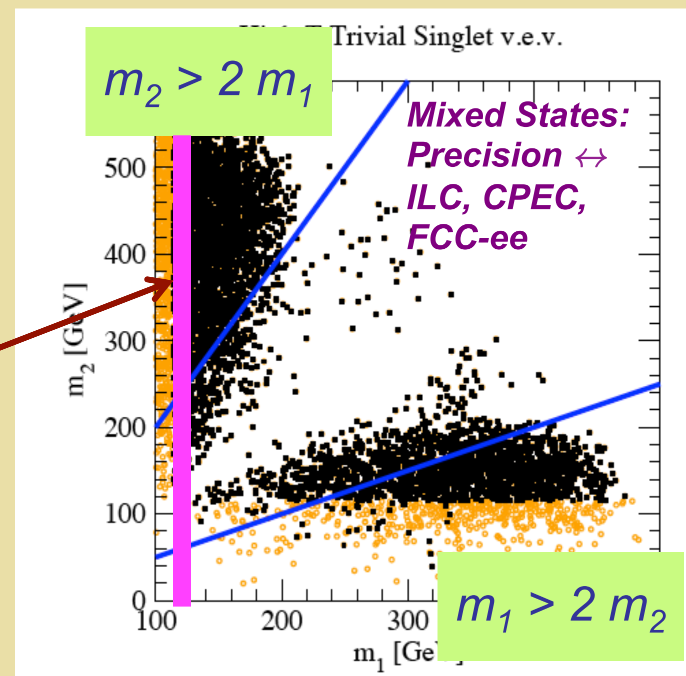




Increasing m_h →

Resonant di-Higgs production

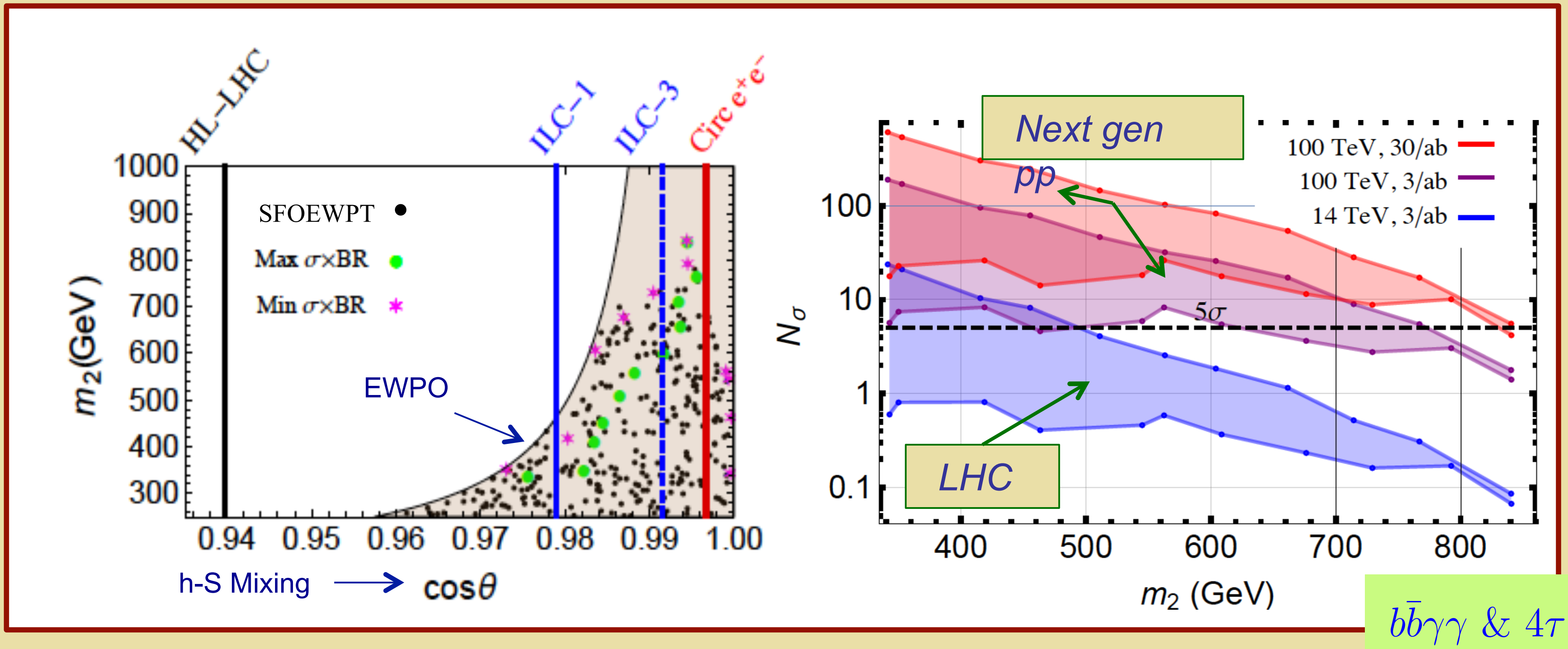




No & RM, arXiv:1310.6035 : **LHC Discovery w/ 100 fb^{-1}**

EW Phase Transition: Singlet Scalars

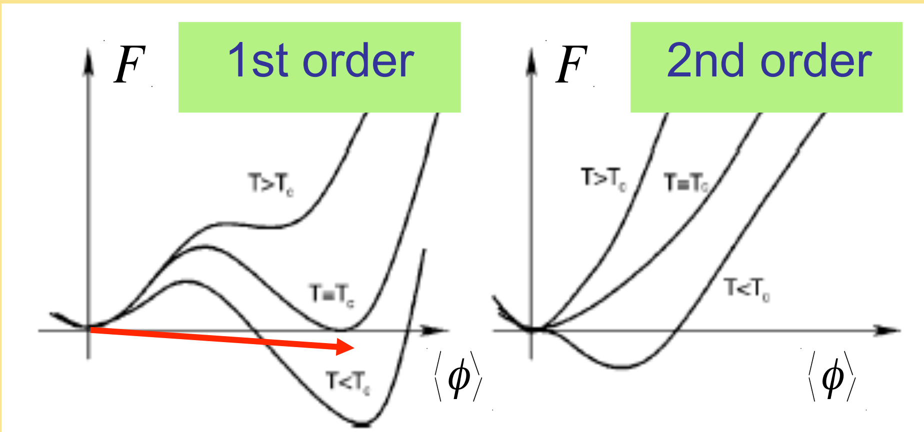
SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies

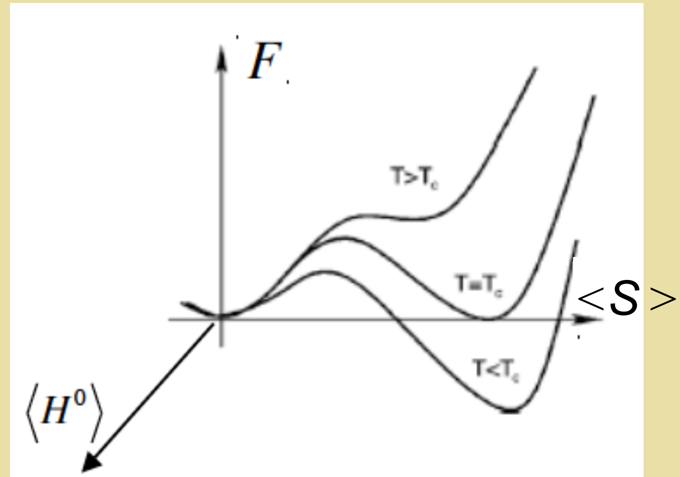


Kotwal, No, R-M, Winslow 1605.06123

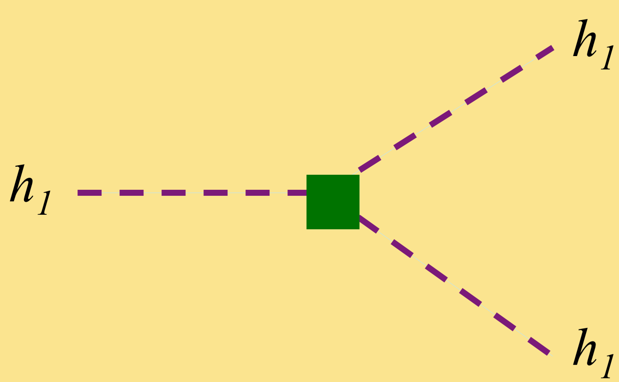
See also: Huang et al, 1701.04442

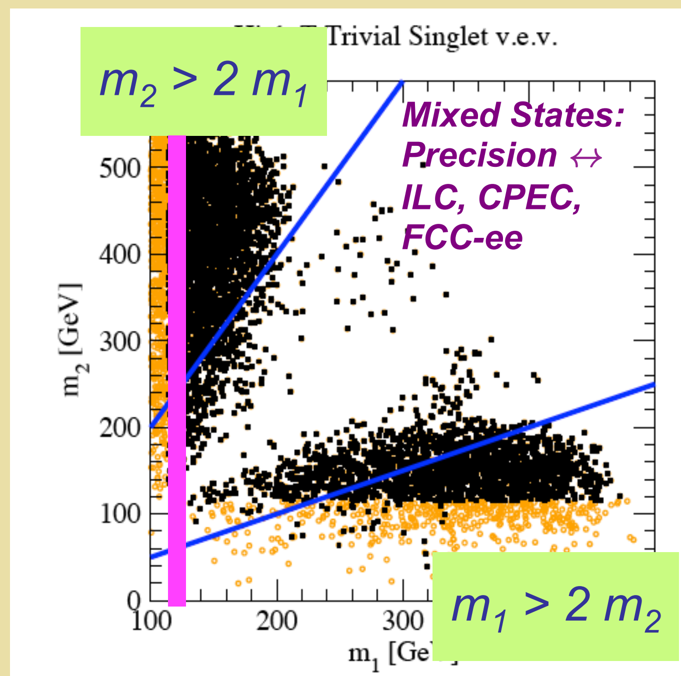
EW Phase Transition: New Scalars



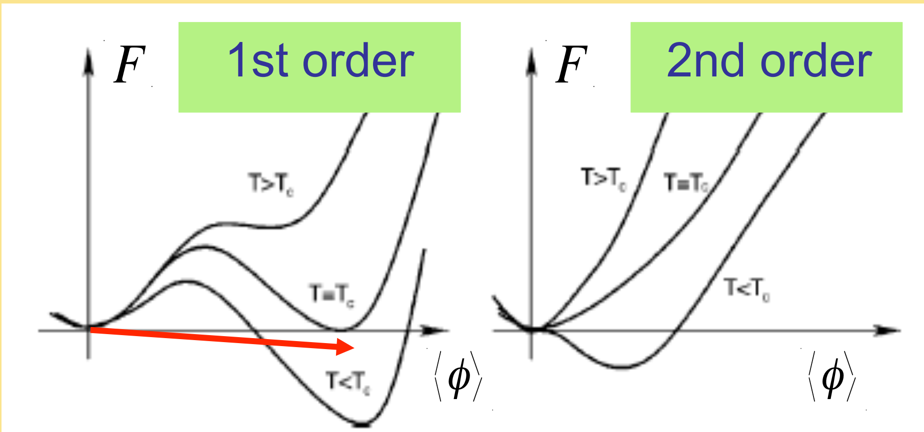


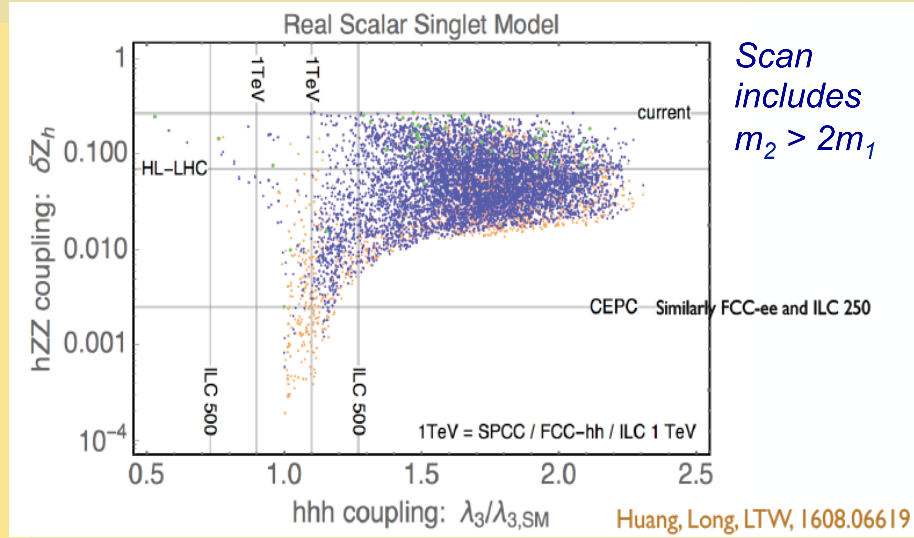
Modified Higgs Self-Coupling





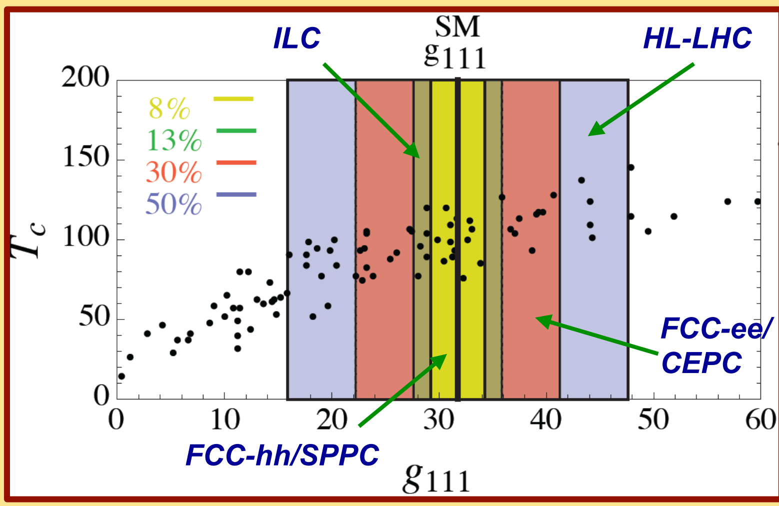
EW Phase Transition: Singlet Scalars

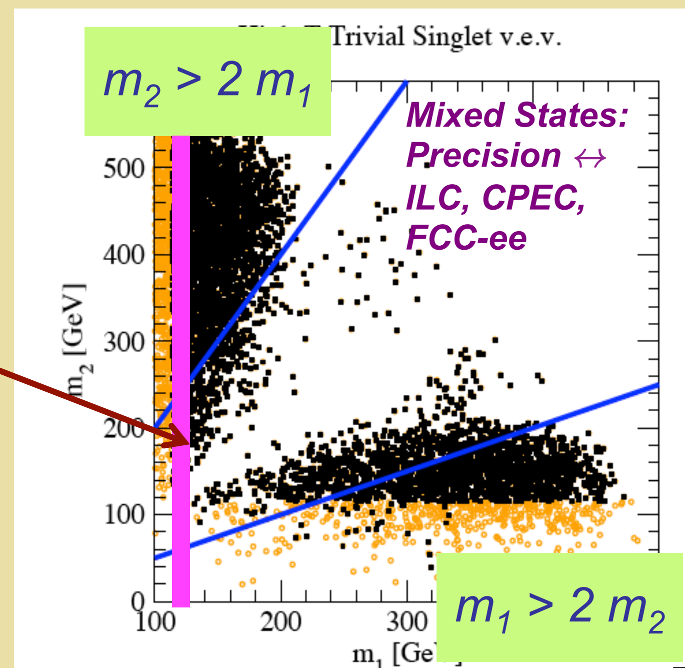




Scan includes $m_2 > 2m_1$

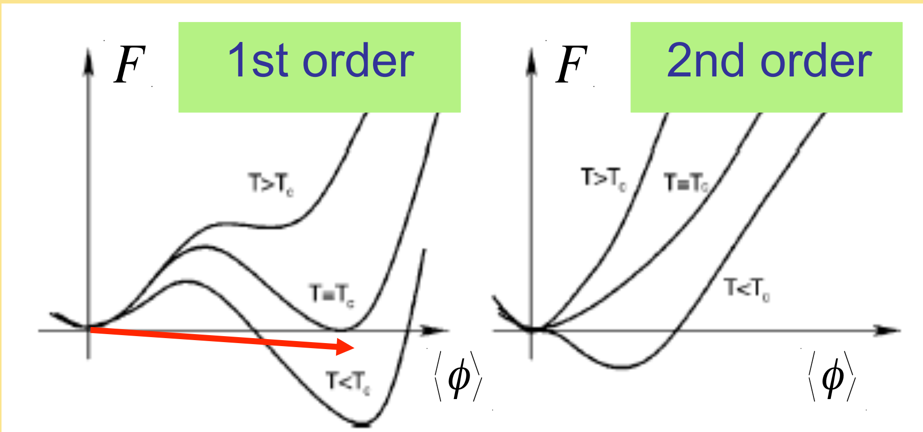
Modified Higgs Self-Coupling

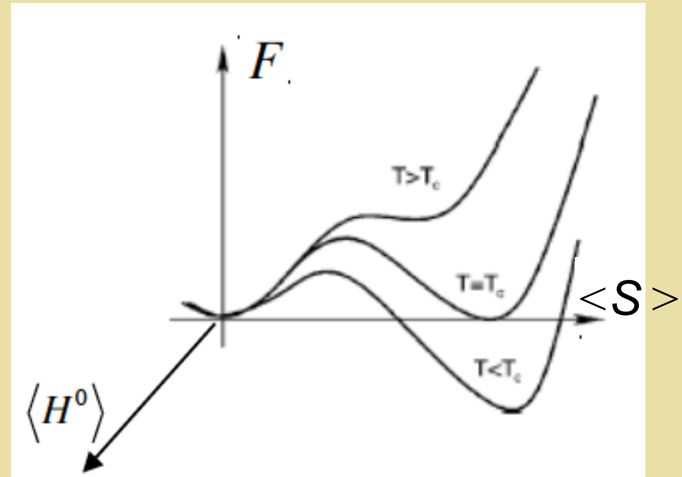




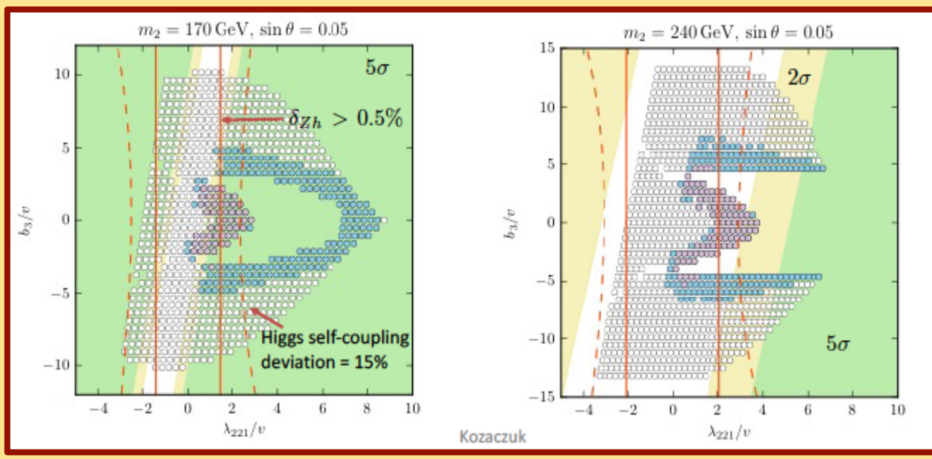
Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

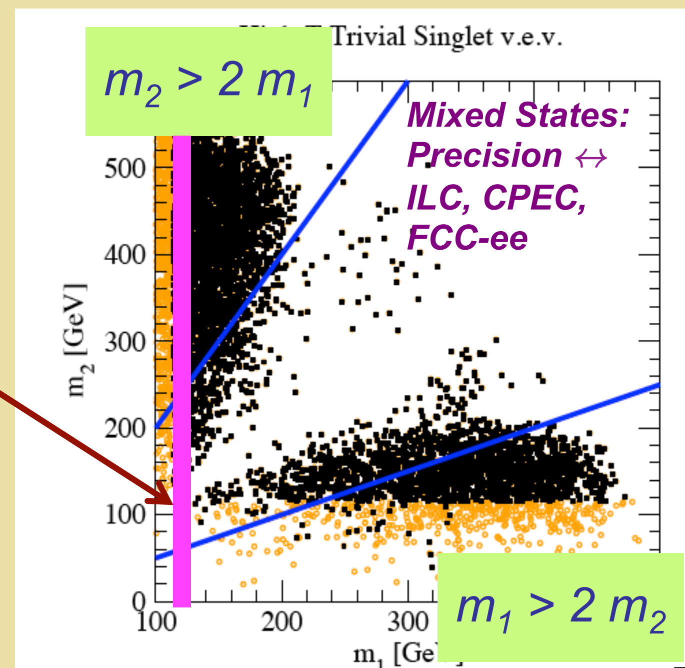
EW Phase Transition: Singlet Scalars





Singlet-like pair production





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

Dark Matter Stability:

- *Invariance under $S \to -S$*
- $\langle S \rangle = 0$
- $\theta_{hs} = 0$

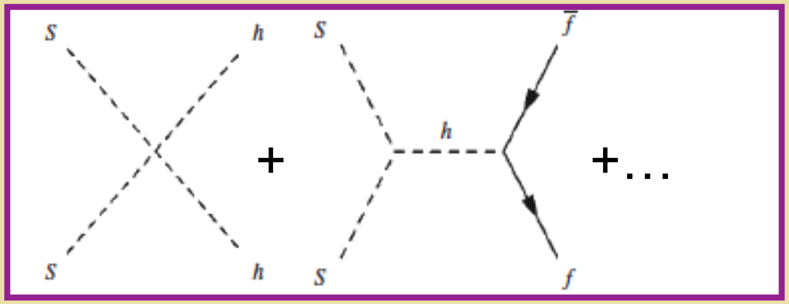
"Z_2 Symmetry"

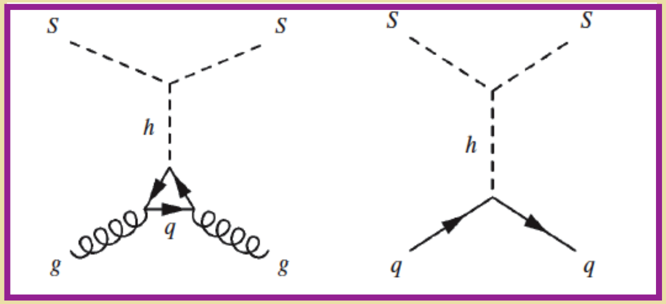
The Simplest Extension

DM Scenario

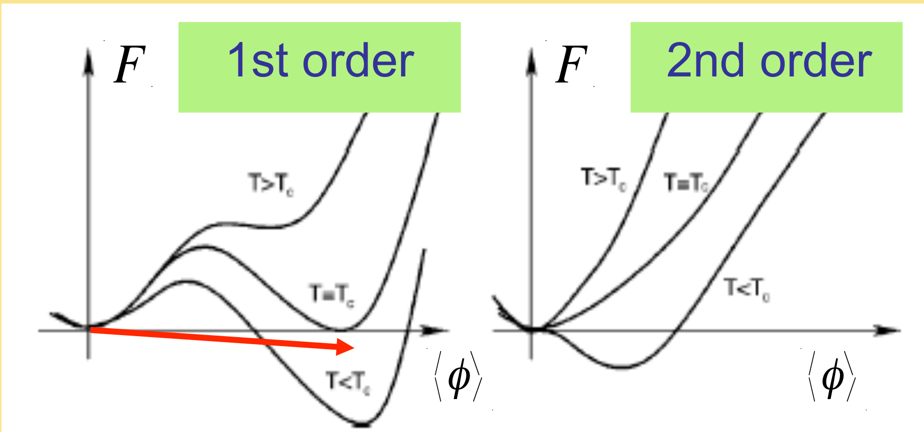
$$V_{\rm HS} = \quad + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

Ω_{DM} & σ_{SI}





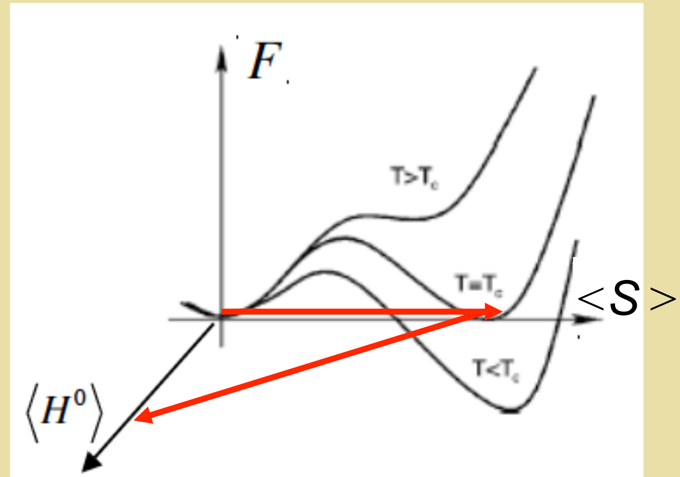
EW Phase Transition: Two-Step



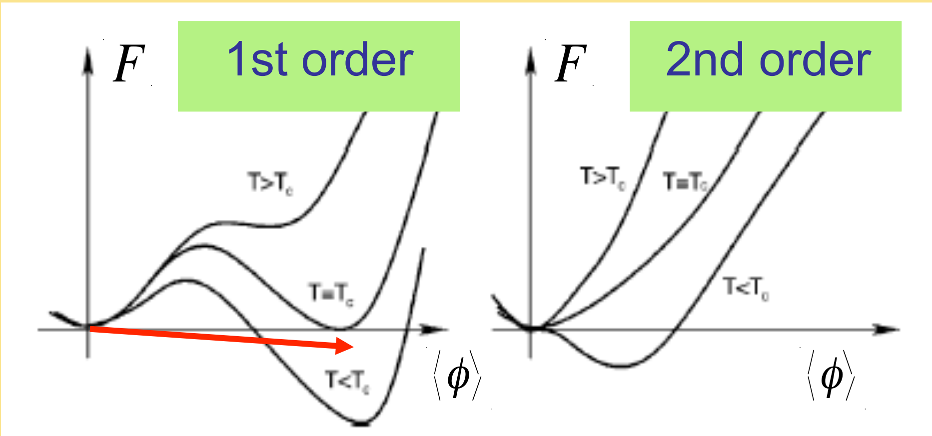
Profumo, R-M, Shaugnessy 2007

Curtain, Meade, Yu: arXiv: 1409.0005

Jiang, Bian, Huang, Shu 1502.07574



EW Phase Transition: Singlet Scalars



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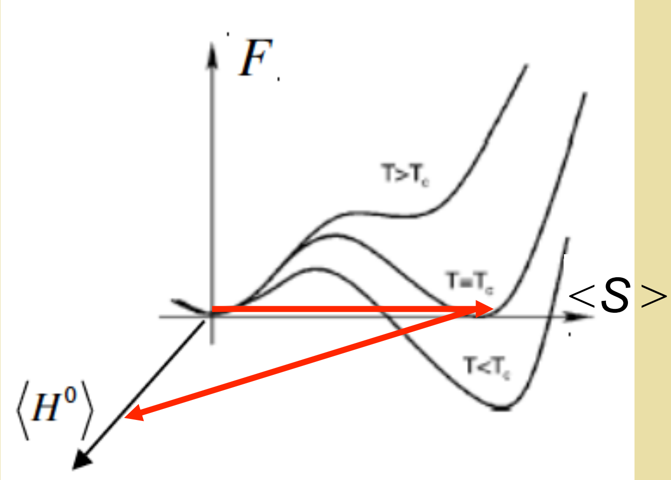
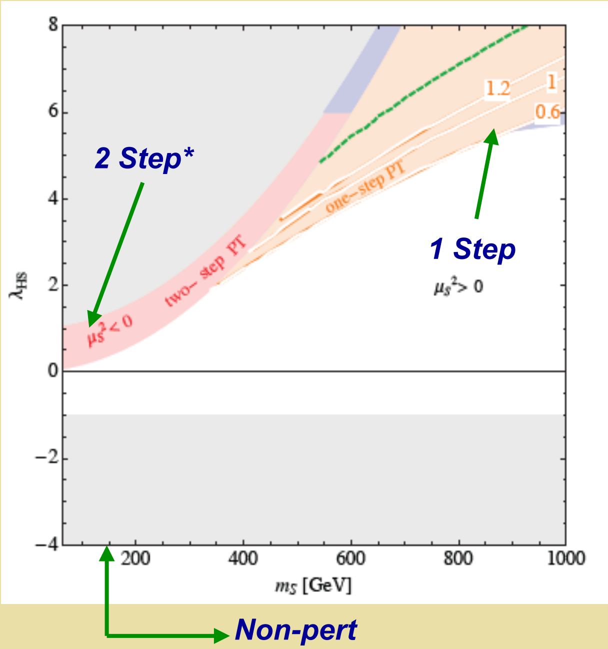


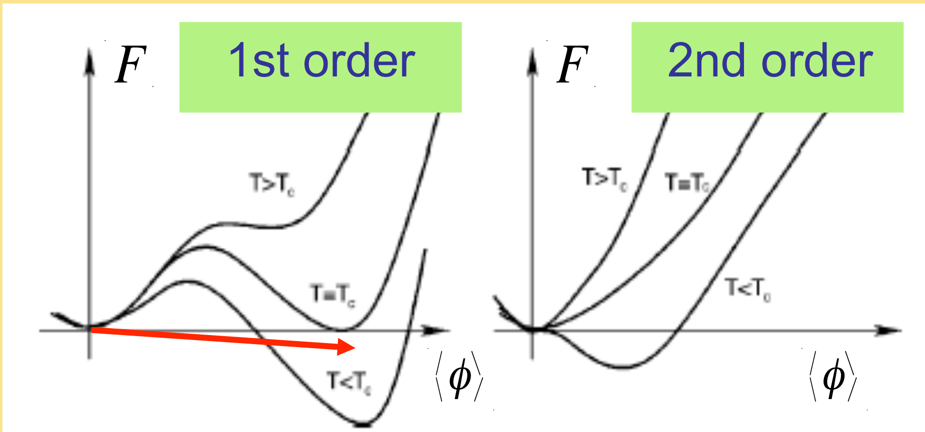
Z_2 symmetric real singlet extension

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



* Singlet two step: see also Profumo, R-M, Shaugnessy 2007

EW Phase Transition: Singlet Scalars



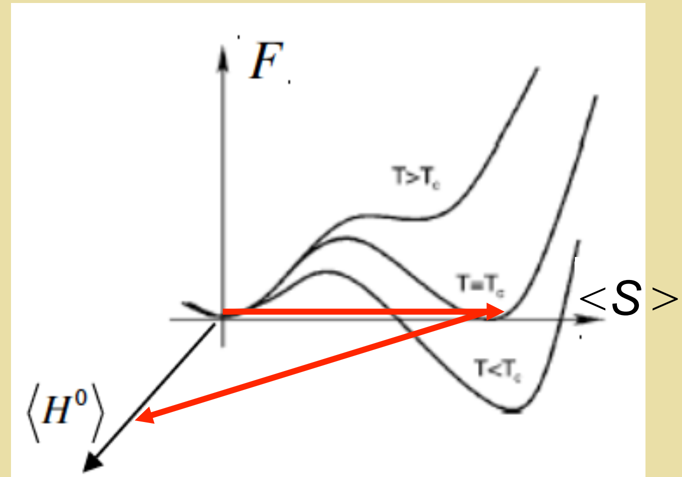
Curtain, Meade, Yu: arXiv: 1409.0005

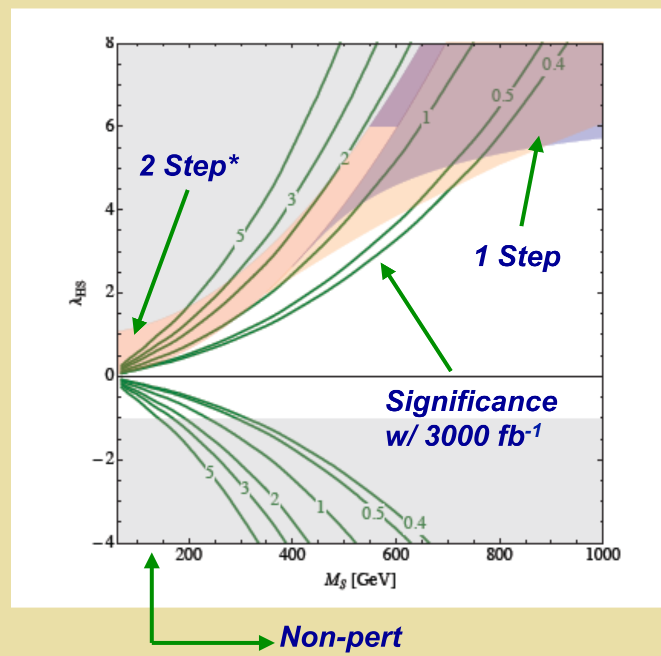
Z_2 symmetric real singlet extension

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

VBF @ 100 TeV pp:

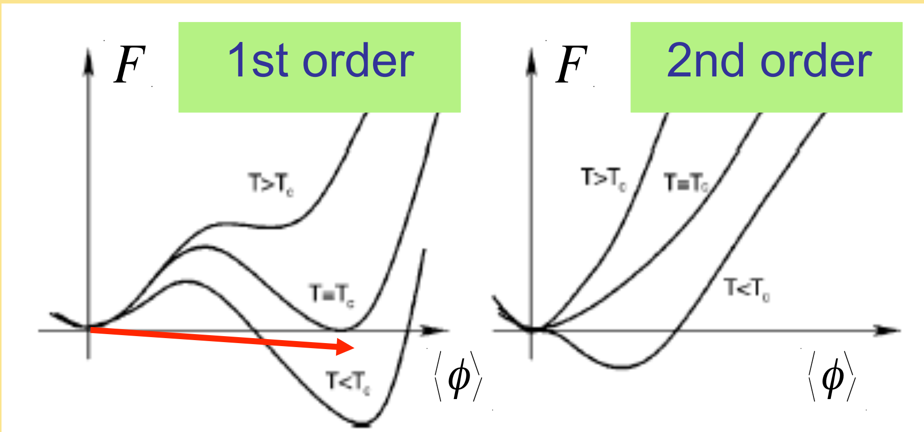
$pp \rightarrow h\,jj$, $h \rightarrow$ invis





* Singlet two step: see also Profumo, R-M, Shaugnessy 2007

EW Phase Transition: DM Direct Detection

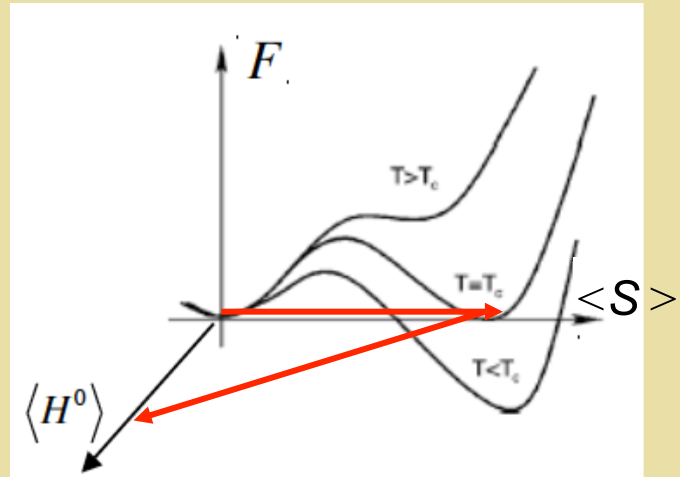


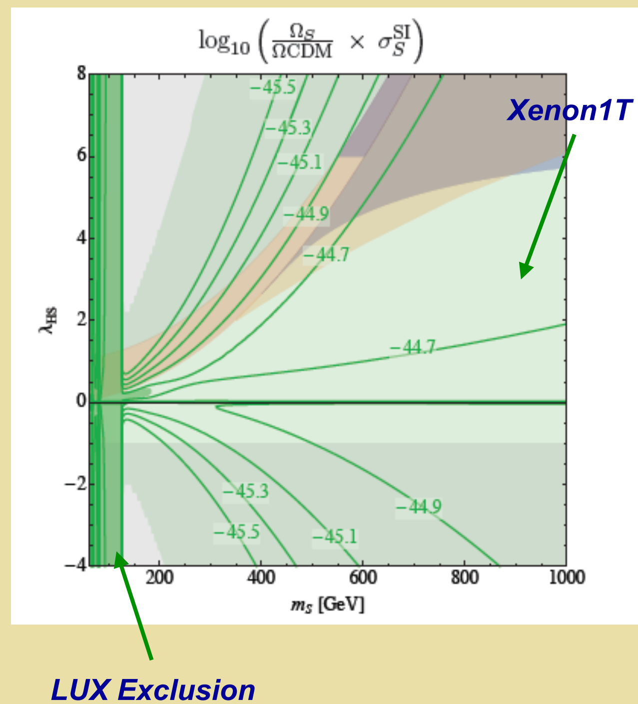
Curtain, Meade, Yu: arXiv: 1409.0005

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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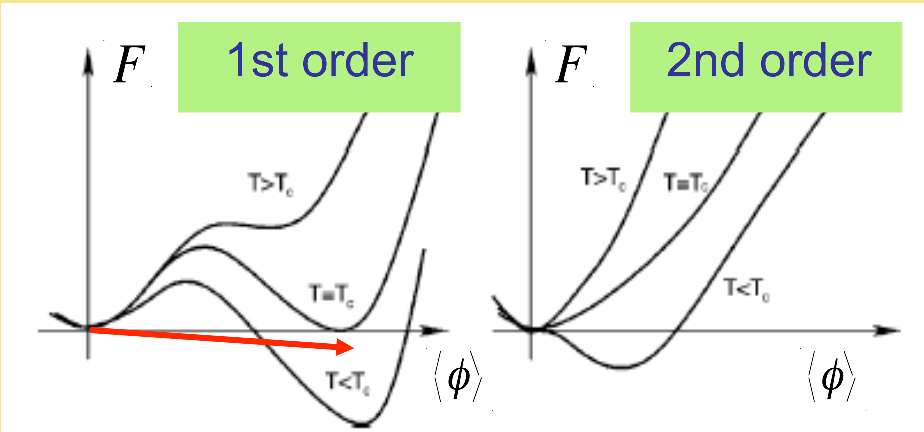
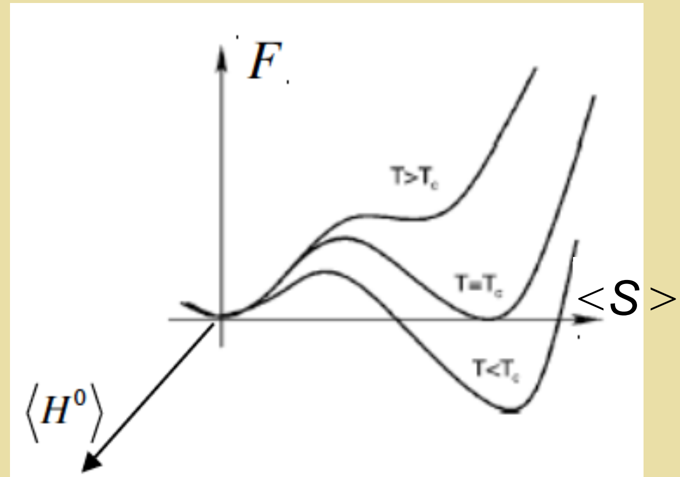
EW Multiplets	3+	✔	✔

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

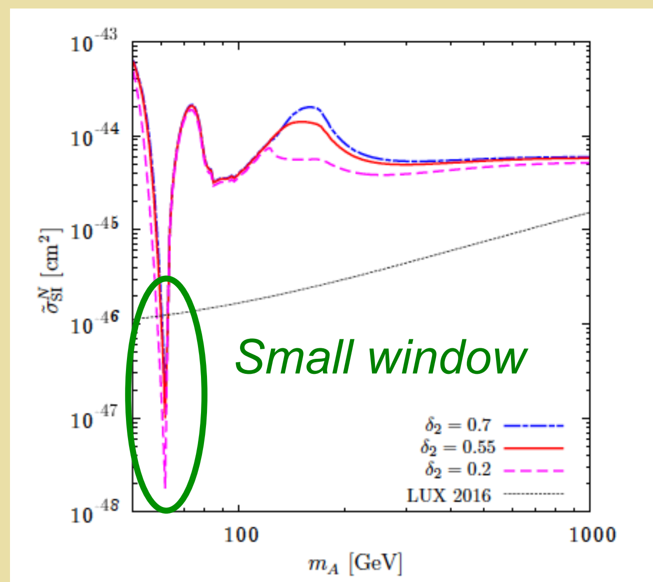
EWPT: Complex Singlet Scalars





SFOEWPT-viable parameters

- *DM: Spontaneously & softly-broken global U(1)*
- *Possibility of SFOEWPT & DM candidate*



Chiang, MJRM, Senaha '17

Higgs Portal: Simple Scalar Extensions

Extension	DOF	EWPT	DM
Real singlet: $\not{Z}_2$	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

Real Triplet

Σ^0, Σ^+, Σ^- ~ (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: $a_1 = 0$ & $\langle \Sigma^0 \rangle = 0$

Small: ρ-param

Real Triplet

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

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

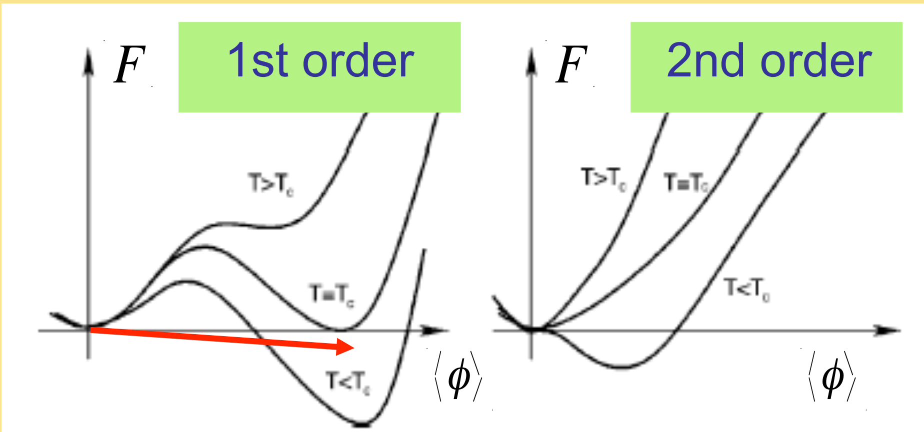
$$V_{H\Sigma} = \qquad + \frac{a_2}{2} H^\dagger H \, \mathrm{Tr}\, \Sigma^2$$

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

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

DM Stability

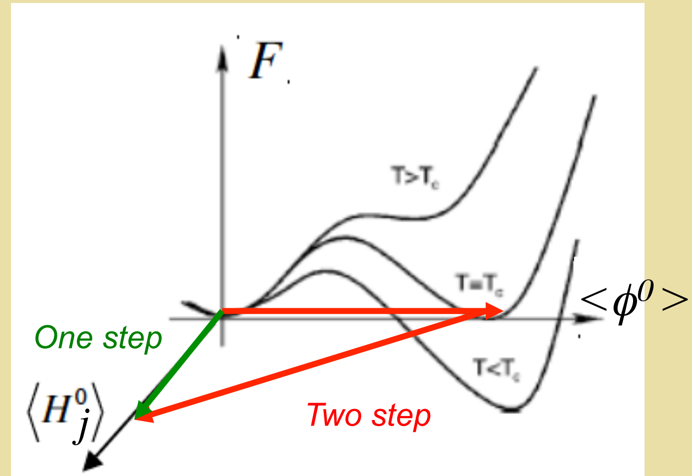
EW Multiplets: Two-Step EWPT

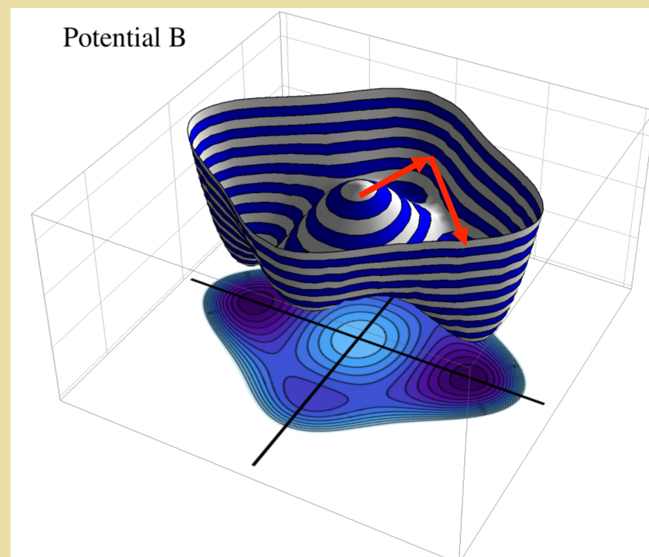


Increasing m_h →

← *New scalars*

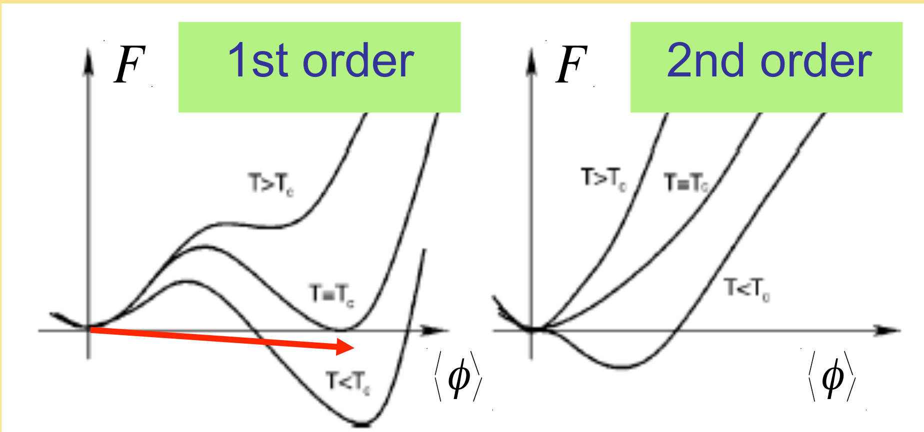
- *Step 1: thermal loops*
- *Step 2: tree-level barrier*





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

EW Multiplets: Two-Step EWPT



Increasing m_h →

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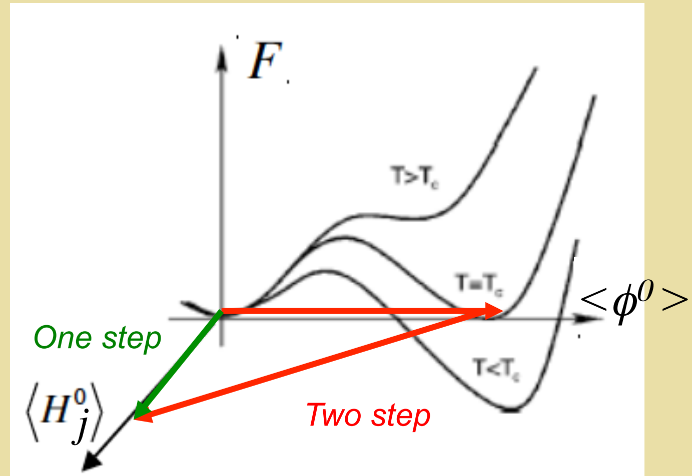

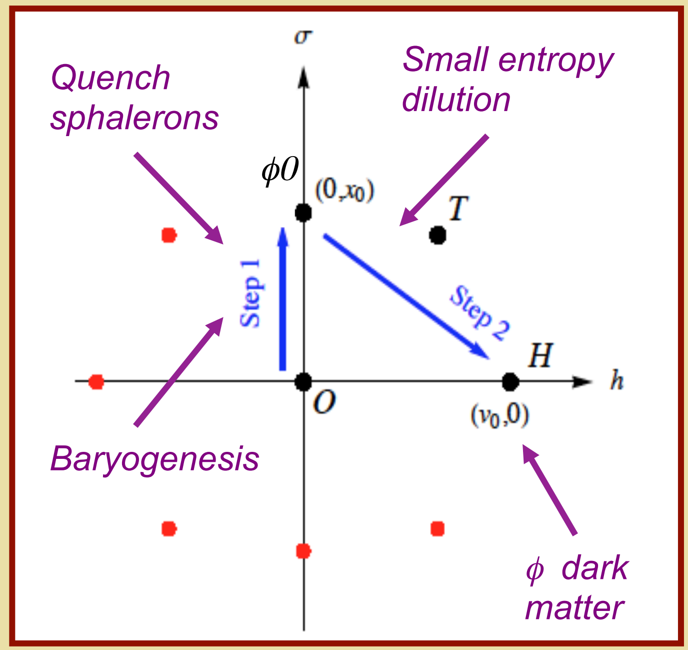

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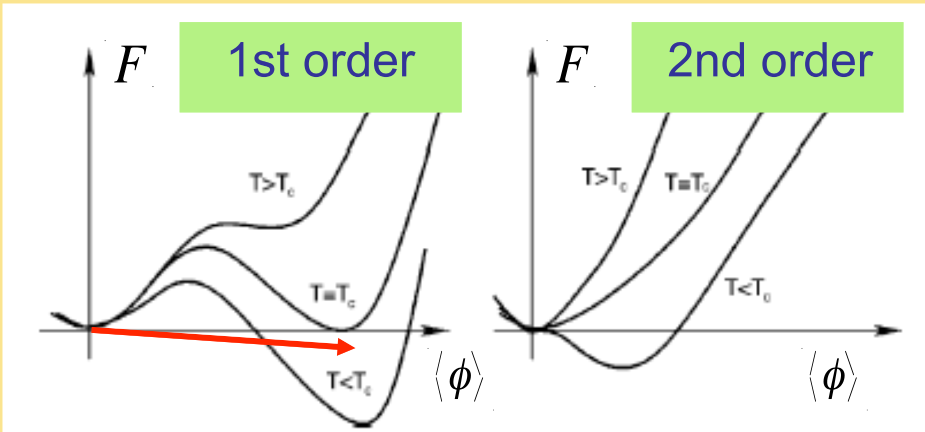
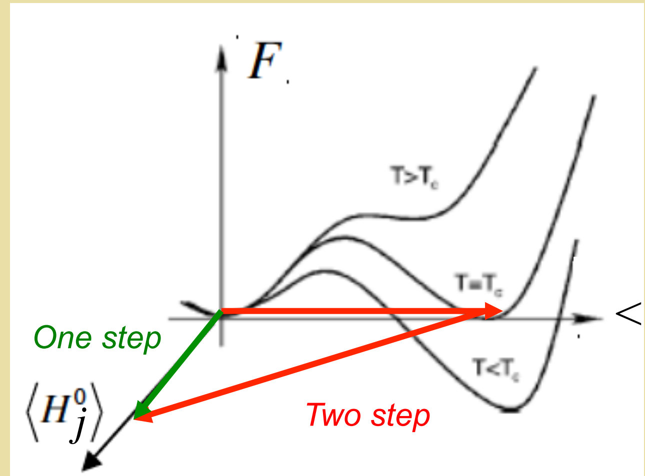
EW Multiplets: Real Triplet

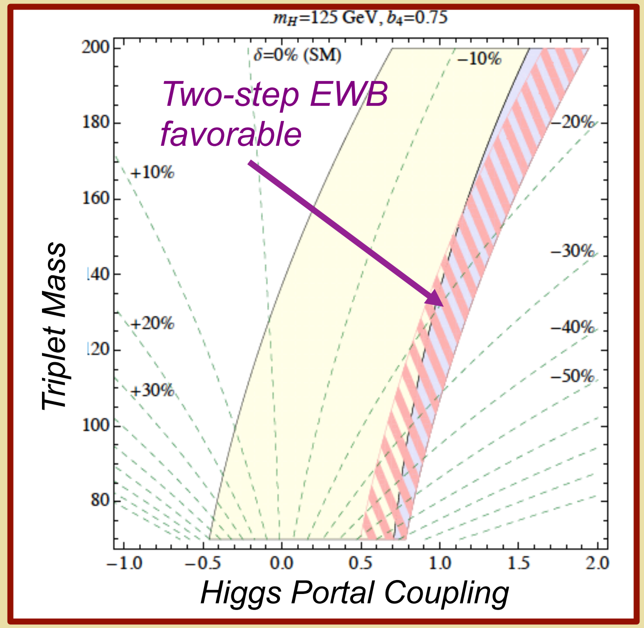


Increasing m_h →

← *New scalars*

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





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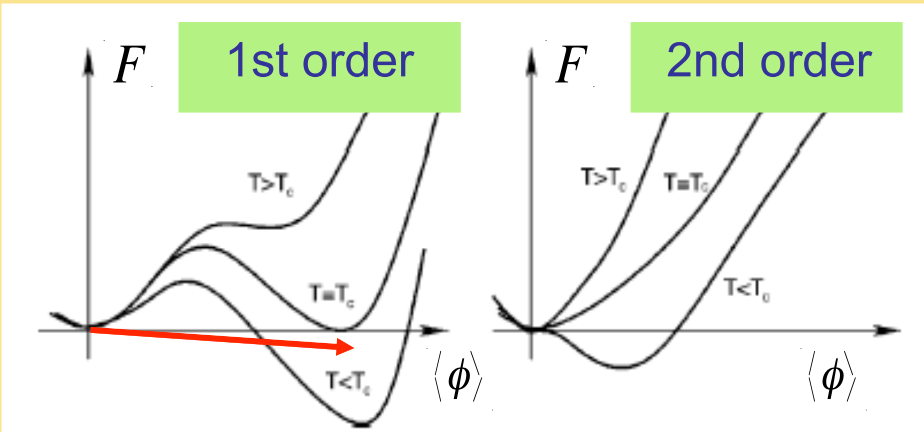
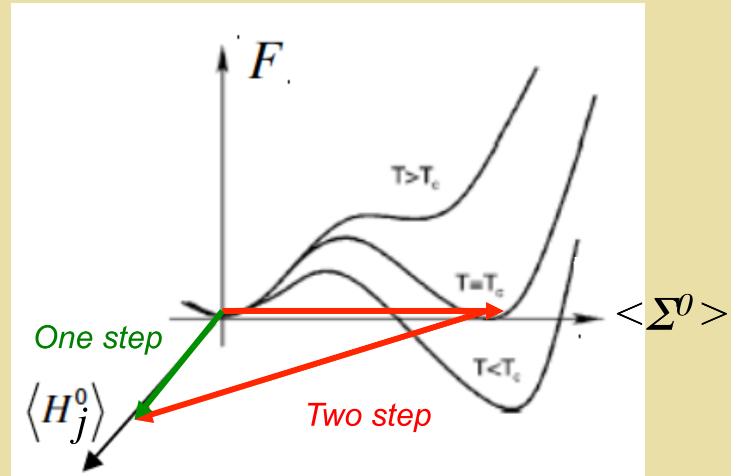
EW Multiplets: Real Triplet





Increasing m_h →

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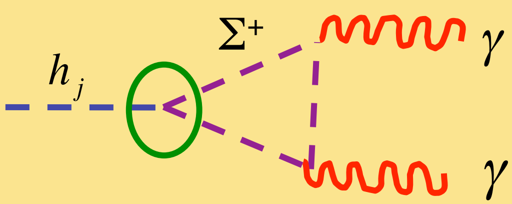
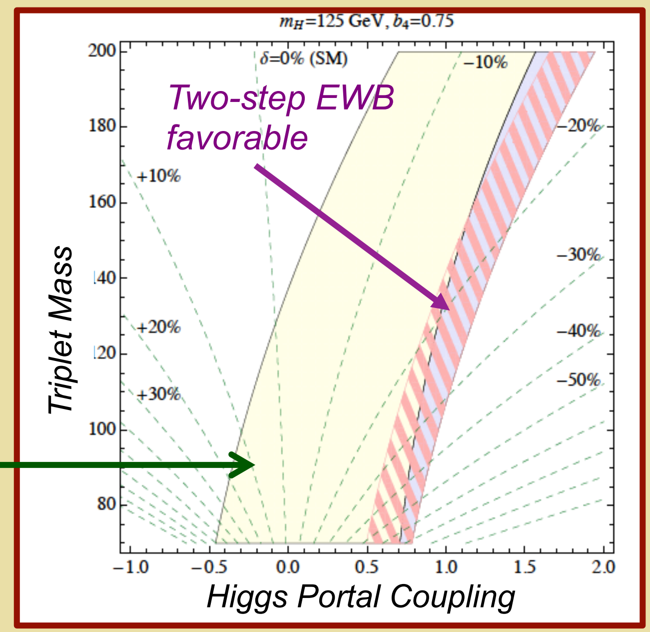




Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

EW Multiplets: Two-Step EWPT

Using BR(H→ZZ*) from FCC-ee (known at ~0.3% from δg_{HZZ}~0.15%), production ratios σ(H→XY)/σ(H→ZZ*) for p_T>100 GeV return the following stat precision on the **absolute value** of rare BRs

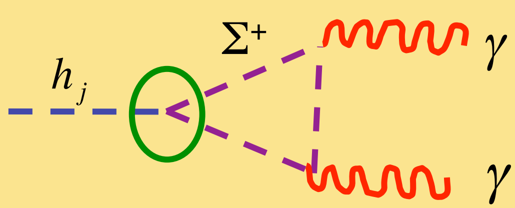
	γγ	Zγ	μμ
δ BR	**~0.5%**	**~1%**	**~1%**

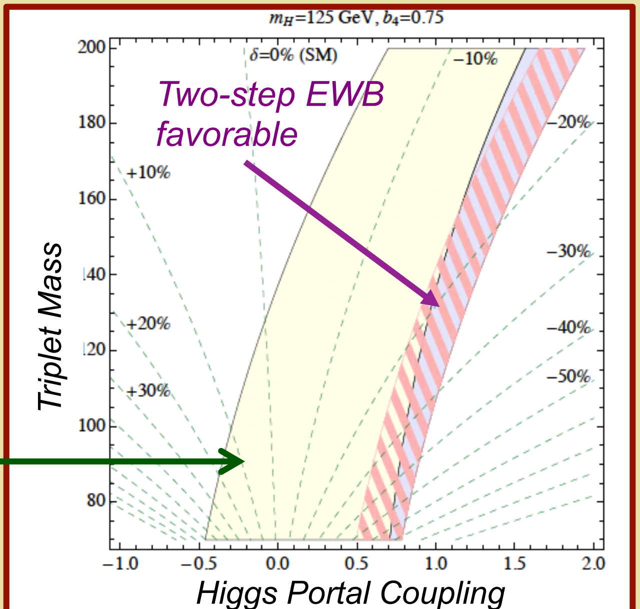
M. Mangano

FCC-ee: < 2% on $\delta_{H\gamma\gamma}$

Increasing m_h →

← *New scalars*





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

Lecture III Key Ideas

- *Role of 1st order EWPT in electroweak baryogenesis*
- *Thermal WIMP dark matter: relic density, indirect & direct detection signatures, collider probes*
- *Higgs portal EWPT & dark matter: simplest singlet & electroweak multiplet scalar sector extensions; Z_2 symmetry; multi-step EW symmetry breaking*
- *Collider implications: resonant di-Higgs production; modified Higgs self-coupling, Higgs signal strengths (mixing), Higgs di-photon decay*

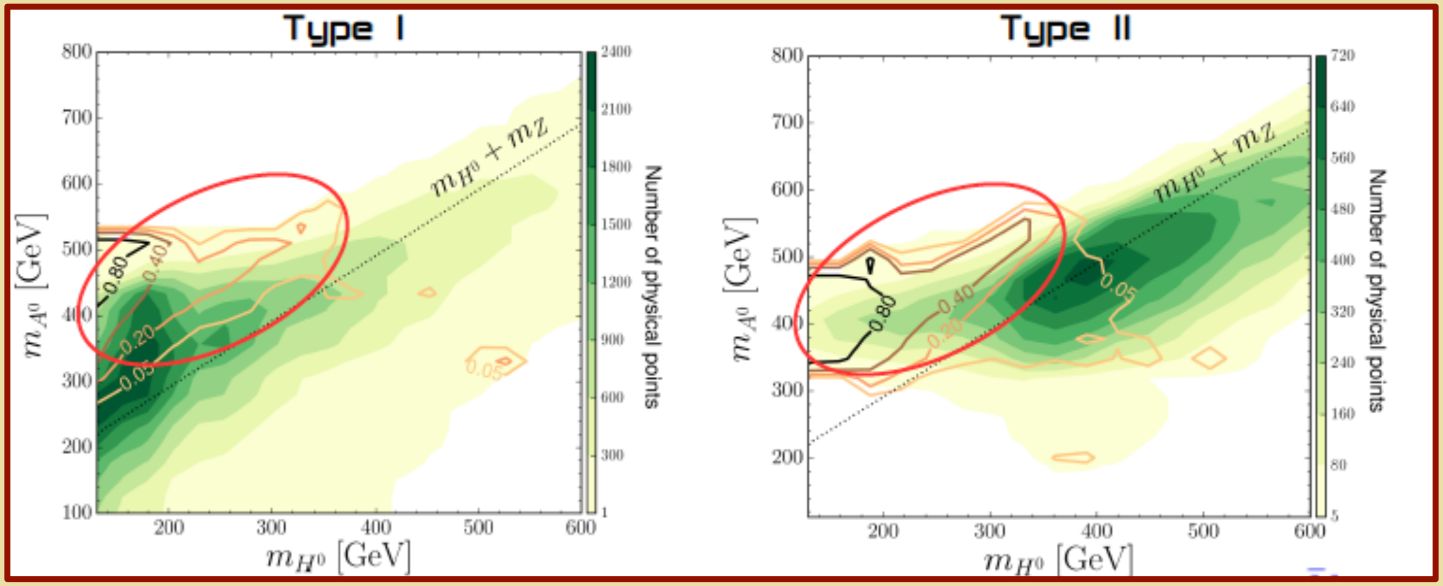
Research Opportunities

- *Finite T, out-of-equilibrium quantum field theory*
- *Model building*
- *Collider phenomenology*
- *Inter-frontier connections: high-energy, cosmic, & high sensitivity*

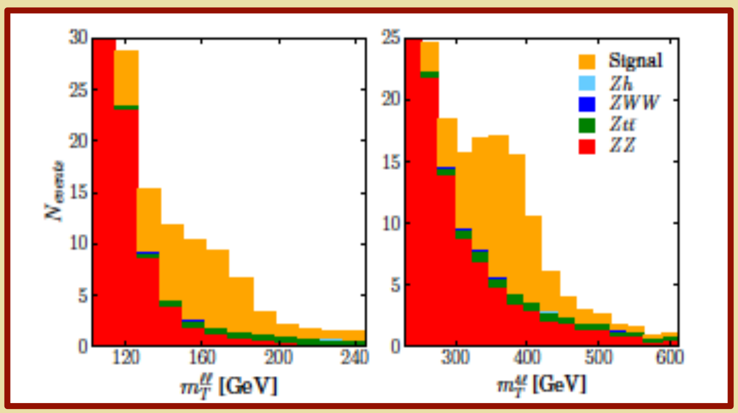
谢谢

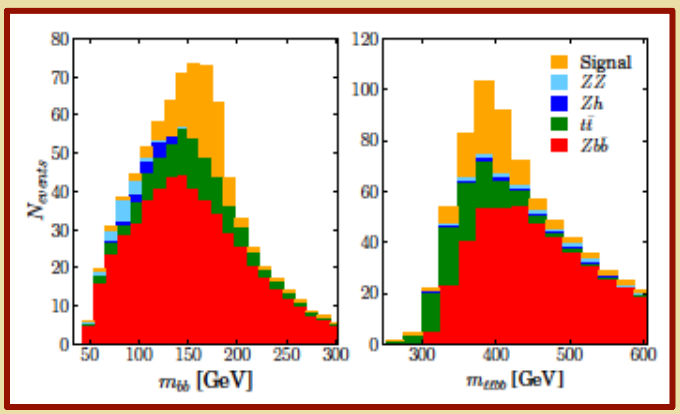
Back Up Slides

EW Multiplets: 2HDM



$A^0 \to Z\,H^0$ Signature





SFOEWPT testable w/ LHC

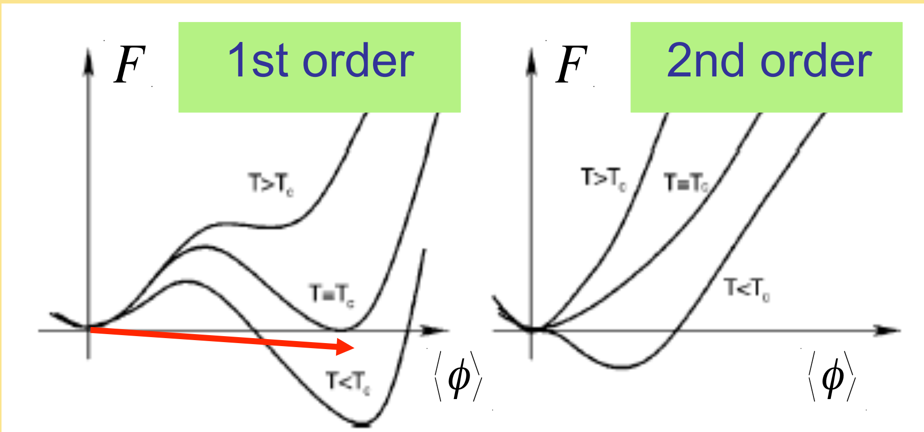
bb ll : 5σ for 40 fb^{-1}

4l + MET: 5σ for 60 fb^{-1}

Dorsch et al

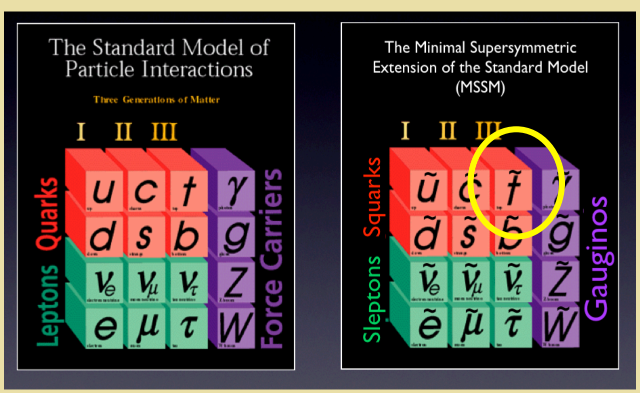
See S. Su talk

EW Phase Transition: SUSY



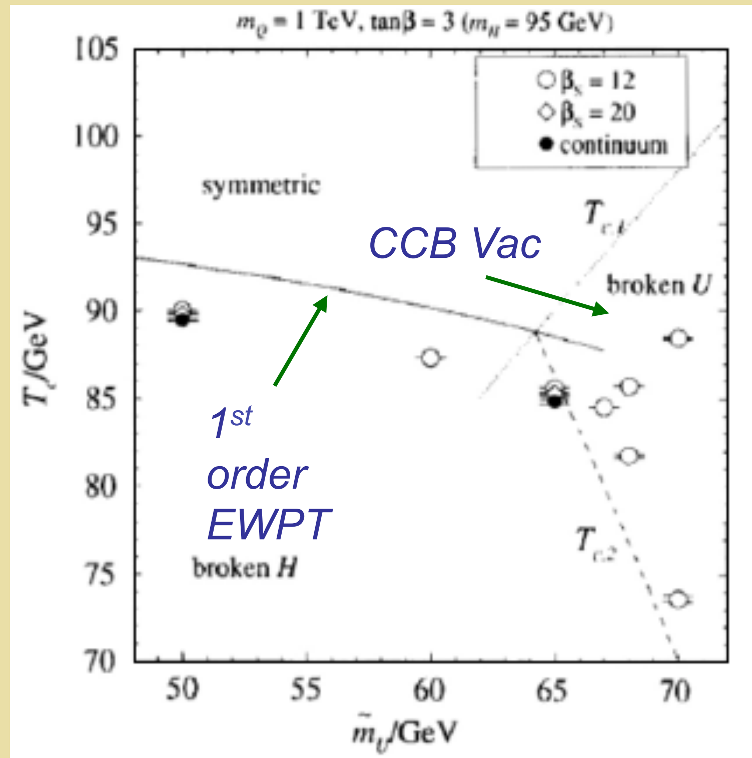
Increasing m_h →

← *New scalars*



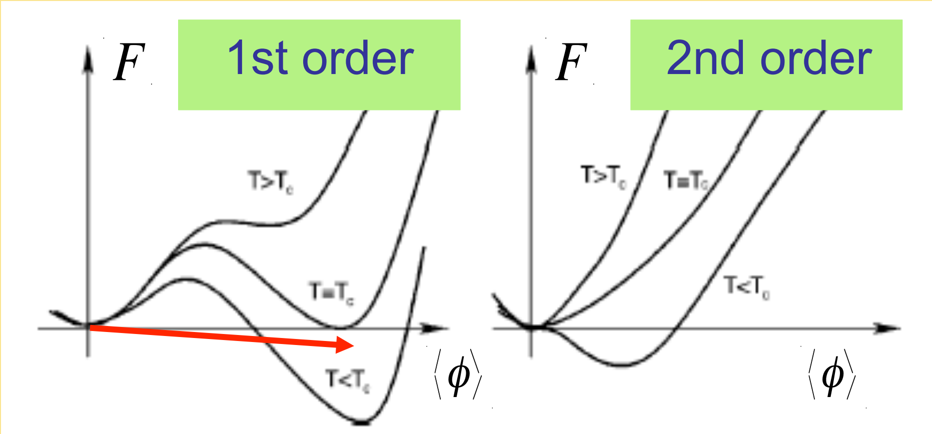
MSSM: Light Stop Scenario

Lattice: Laine, Rummukainen



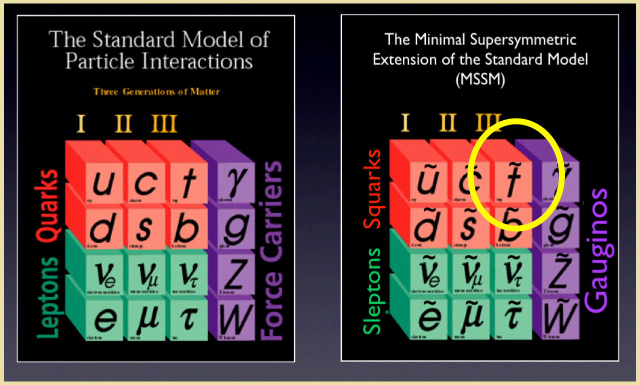
Decreasing RH stop mass →

EW Phase Transition: SUSY



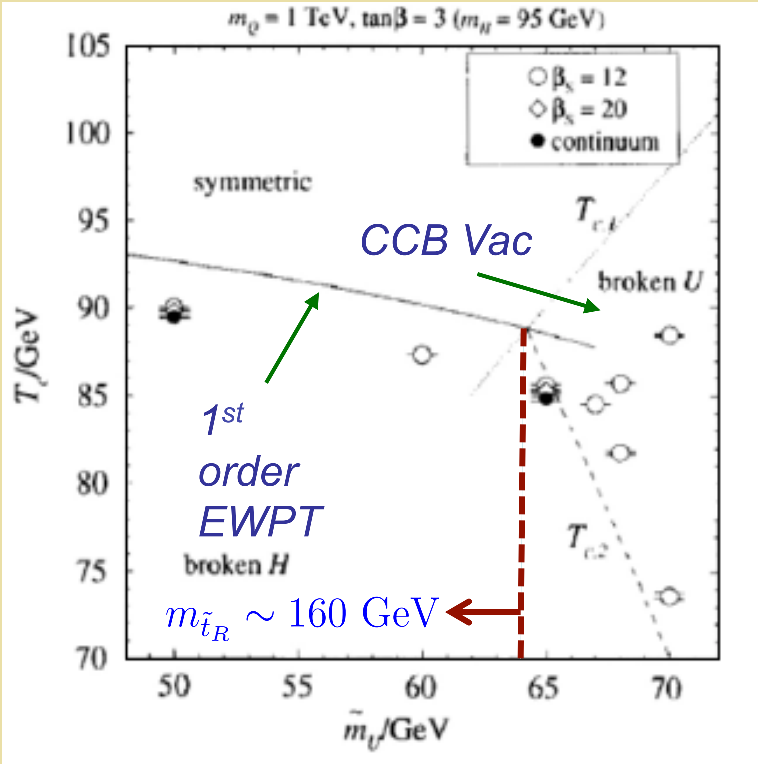
Increasing m_h →

← New scalars



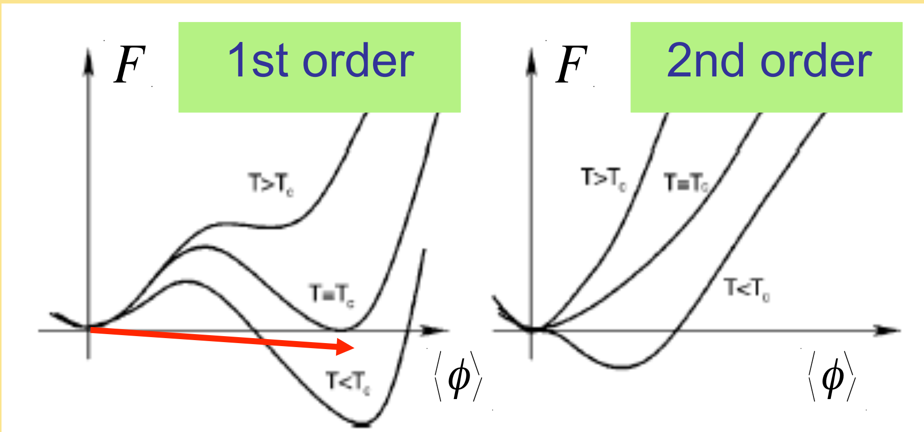
MSSM: Light Stop Scenario

Lattice: Laine, Rummukainen



Decreasing RH stop mass →

EW Phase Transition: SUSY



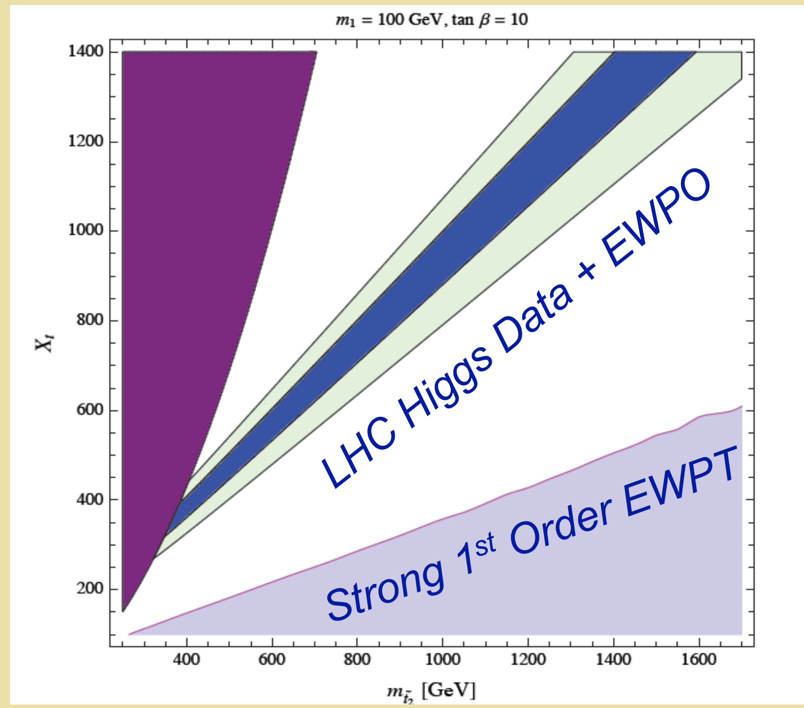
Increasing m_h →

← *New scalars*

Light RH stops also affect Higgs properties

Curtin, Jaiswal, Meade 1203.2932

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

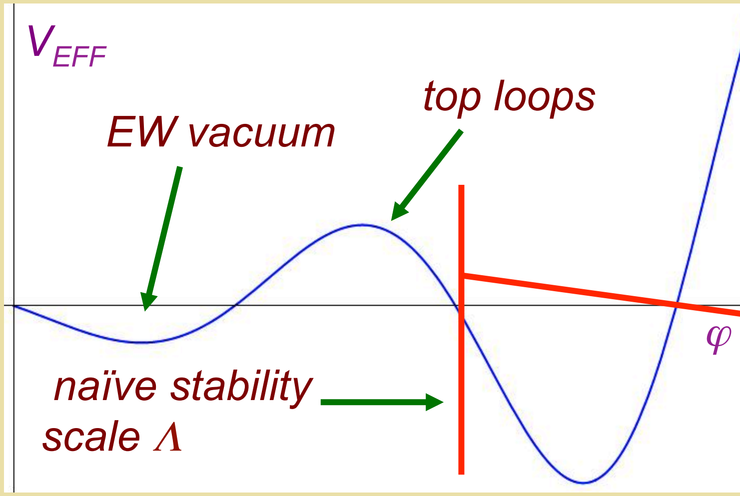


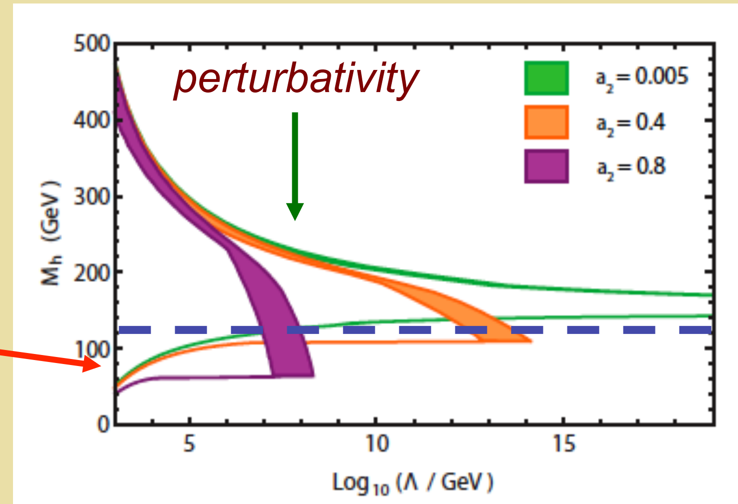
Katz, Perelstein, R-M, Winslow 1509.02934

Vacuum Stability & Perturbativity

Preserving EW Min

"Funnel plot"





m_H ?

$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda^2 + 12a_2^2 - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2g'^2 + \frac{27}{4}g^4\right)$$

DM-H coupling

top loops

Gonderinger, Li, Patel, R-M

Temperature Dependence of V(ϕ)

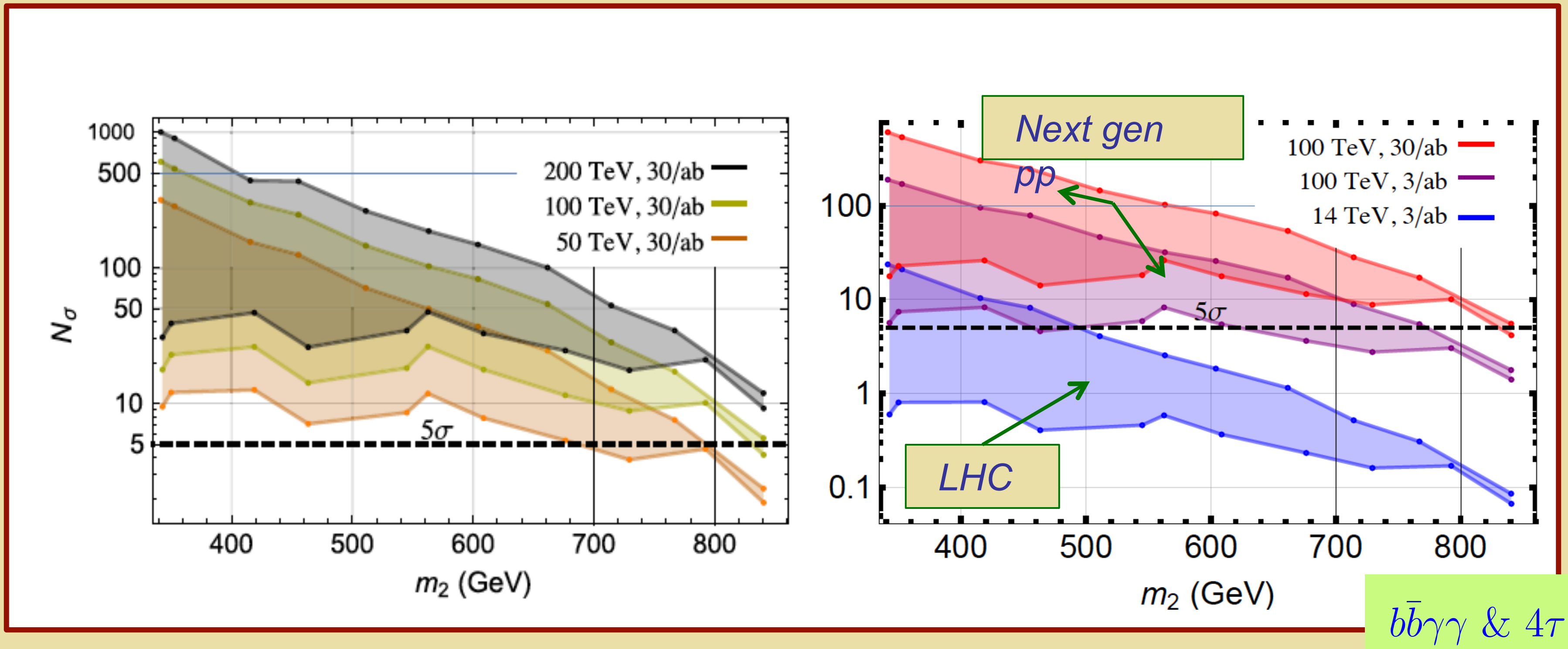
Standard Model Effective Potential: High-T expansion

$$V_{\text{eff}}(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\bar{\lambda}}{4}\phi^4 + \ldots .$$

- *Potential is gauge-dependent*
- *T_C is gauge-independent: Nielsen identities*
- *Detailed discussion: H. Patel & MJRM: 1101.4665 [hep-ph]*

EW Phase Transition: Singlet Scalars

SFOEWPT Benchmarks: Resonant di-Higgs

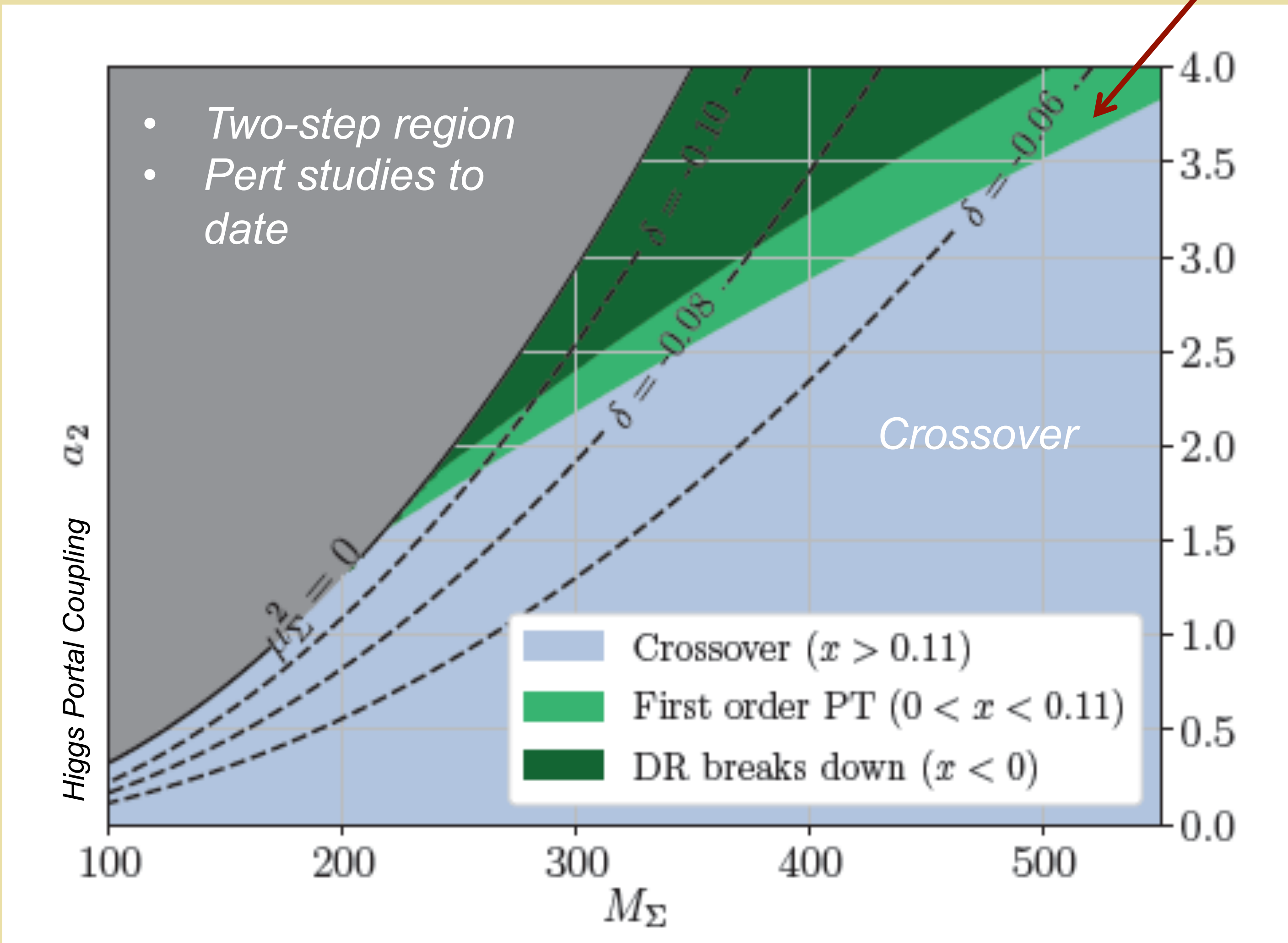


Kotwal, No, R-M, Winslow 1605.06123

See also: Huang et al, 1701.04442

Real Triplet & EWPT

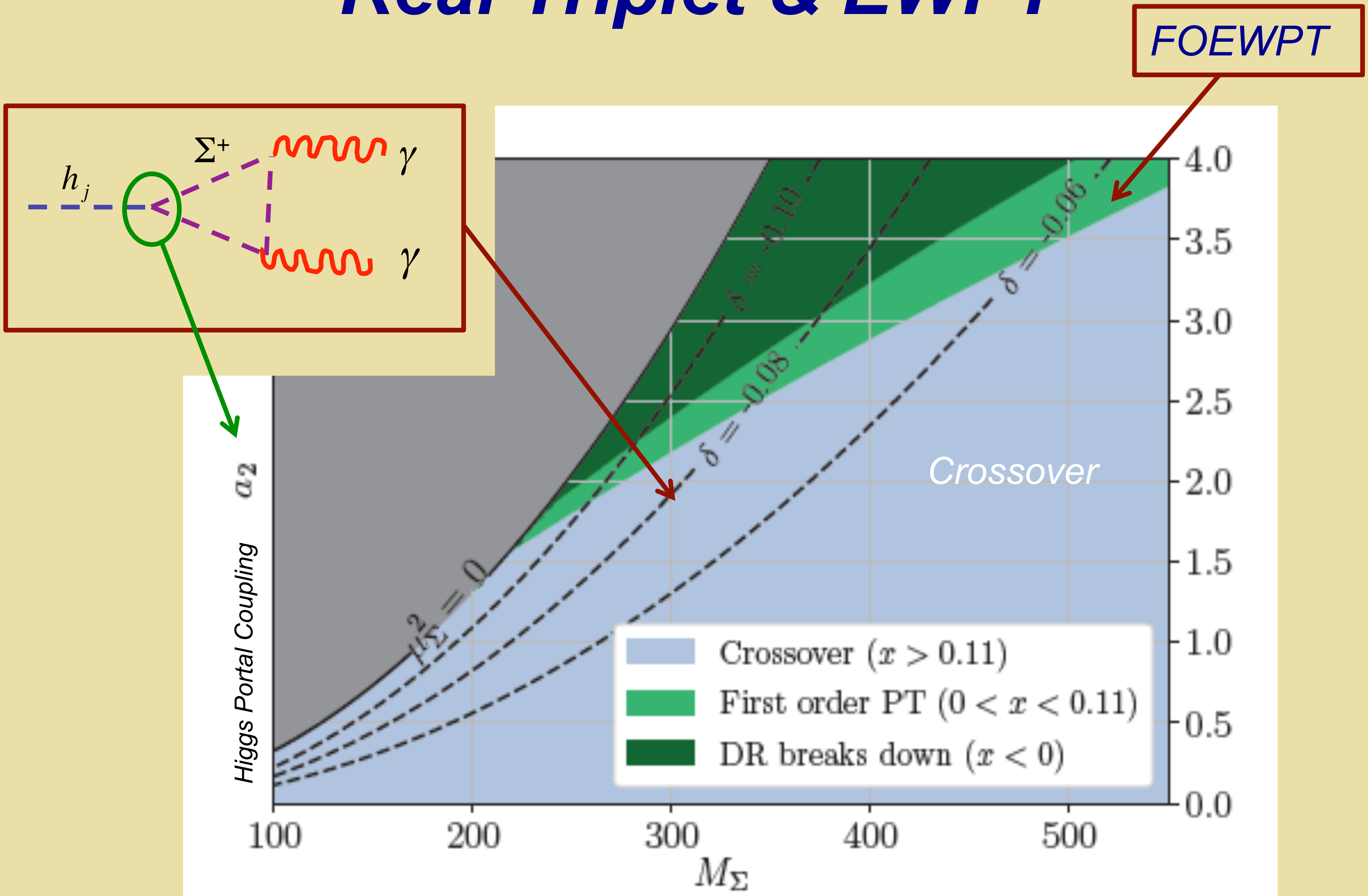
FOEWPT



- One-step
- Non-perturbative

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

Real Triplet & EWPT



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

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