Physics at the FCC: Workshop Overview Part II (BSM)

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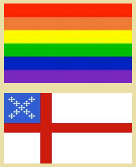
U Mass Amherst



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

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

VLHC Seminar
September 2017

FCC Physics Week

Jan 16-20 2017 https://indico.cern.ch/event/550509/

1st FCC Physics Workshop

Follow up to M. Mangano's talk

16-20 January 2017
CERN
Europe/Zurich timezone

Topics:

- Higgs
- QCD
- EW precision measurements
- Top and flavour
- BSM searches
- Relation with cosmology: DM and neutrino mass probes
- Experimental opportunities at the FCC and novel techniques
- Physics with Heavy Ion collisions
- Physics at beam dumps, injectors, or forward region detectors

199 registered participants

Goals For This Talk

- *Give a flavor of important BSM opportunities presented at workshop*
- *Give my own perspective on status so far*
- *Invite discussion and input*

Outline

I. Context

II. Naturalness & EWSB

III. Cosmology

IV. Neutrinos

V. Outlook

Disclaimer: not all talks included, some interesting topics omitted due to time, mostly focused on material presented at workshop & not comprehensive review of recent work…

I. Context

Future Circular Colliders

lepton collider parameters

parameter	FCC-ee (400 MHz)					LEP2
Physics working point	Z		WW	ZH	tt_{bar}	
energy/beam [GeV]	45.6		80	120	175	105
bunches/beam	30180	91500	5260	780	81	4
bunch spacing [ns]	7.5	2.5	50	400	4000	22000
bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7	4.2
beam current [mA]	1450	1450	152	30	6.6	3
luminosity/IP x 10^{34}cm^{-2}s^{-1}	210	90	19	5.1	1.3	0.0012
energy loss/turn [GeV]	0.03	0.03	0.33	1.67	7.55	3.34
synchrotron power [MW]	100					22
RF voltage [GV]	0.4	0.2	0.8	3.0	10	3.5

identical FCC-ee baseline optics for all energies

FCC-ee: 2 separate rings, LEP: single beam pipe

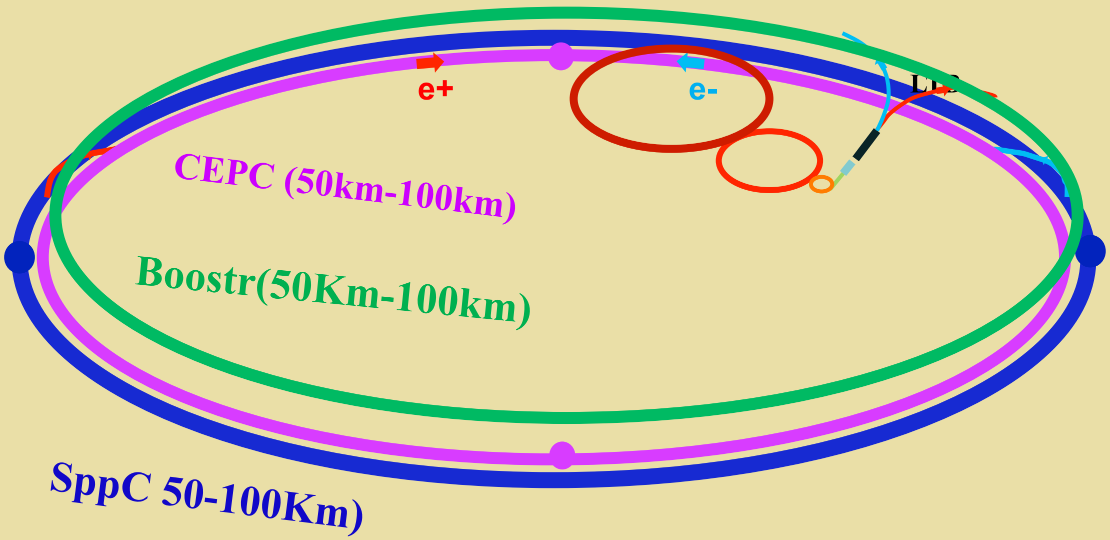
FCC-he & HE-LHC-ep parameters

parameter	FCC-he	ep at HE-LHC	ep at HL-LHC	LHeC
E_p [TeV]	50	12.5	7	7
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	**3.5**	**1.7**	1.3	1.3
bunch spacing [ns]	25	25	25	25
protons / bunch [10^{11}]	1	2.5	2.2	1.7
$\gamma\epsilon_p$ [μm]	2.2	2.5	2.0	3.75
electrons / bunch [10^9]	2.3	2.3	2.3	1.0
electron current [mA]	15	15	15	6.4
IP beta function β_p* [m]	15	10	7	10
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
proton-ring filling factor	0.8	0.8	0.8	0.8
luminosity [10^{33} cm^{-2}s^{-1}]	**11**	**9**	8	1.3

Hadron collider parameters

parameter	FCC-hh		HE-LHC* (*tentative)	(HL) LHC
collision energy cms [TeV]	100		>25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		3.6	(0.35) 0.18

CEPC



Q. Qin, PANIC 2017, Beijing

Parameter	Design Goal
Particles	e+, e-
Center of mass energy	2 x 120 GeV
Peak Luminosity	>2 x $10^{34}/cm^2/s$
No. of IP	2

SppC

Parameter	Unit	Value		
		PreCDR	CDR	Ultimate
Circumference	km	54.4	100	100
C.M. energy	TeV	70.6	75	125-150
Dipole field	T	20	12	20-24
Injection energy	TeV	2.1	2.1	4.2
Number of IPs		2	2	2
Nominal luminosity per IP	$cm^{-2}s^{-1}$	$1.2x10^{35}$	$1.0x10^{35}$	-
Beta function at collision	m	0.75	0.75	-
Circulating beam current	A	1.0	0.7	-
Bunch separation	ns	25	25	-
Bunch population		$2.0x10^{11}$	$1.5x10^{11}$	-
SR power per beam	MW	2.1	1.1	-
SR heat load per aperture @arc	W/m	45	13	-

Questions for the FCC

- *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 ?*

Fundamental Questions

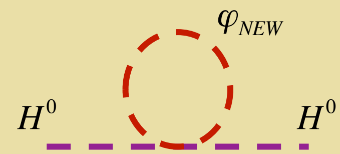
MUST *answer*

SHOULD *answer*

Fundamental Questions

***MUST** answer*

***SHOULD** answer*



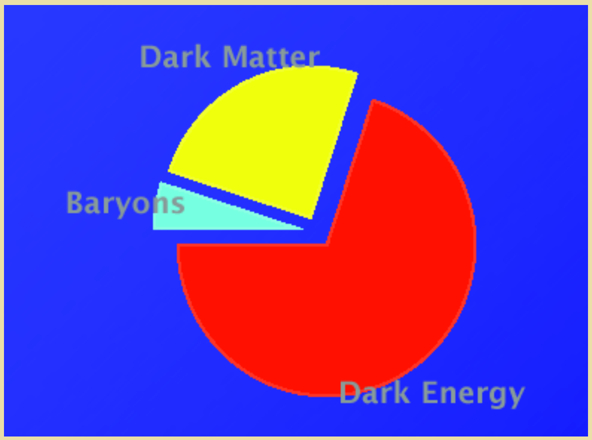
$\Delta m^2 \sim \lambda \Lambda^2$

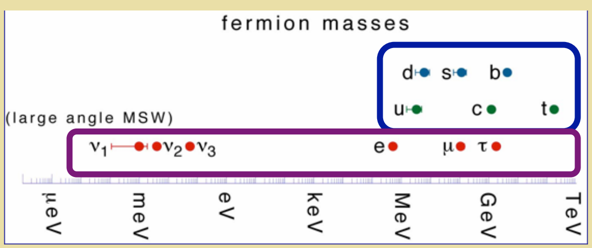
$\Lambda_{Cosmological}$

θ_{QCD} , parity, unification...

Fundamental Questions

***MUST** answer*

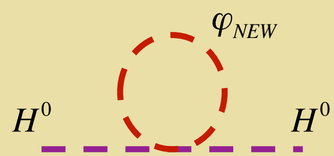




Origin of m_ν

flavor…

***SHOULD** answer*



$\Delta m^2 \sim \lambda \Lambda^2$

$\Lambda_{Cosmological}$

θ_{QCD} , parity, unification...

Scenarios

- *Extended scalar sector*
  - *Singlets*
  - *Un-colored EW multiplets*
  - *Colored scalars*
- *Extended gauge sector*
  - *U(1)'*
  - *Mirror SU(N)*
  - *GUTS*
- *Additional fermions*
  - *Vector-like*
  - *Heavy N_R*
  - *Gauginos*

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	Naturalness	Cosmology	Neutrino mass
Singlets		✔	
Un-colored EW multiplets	✔	✔	✔
Colored scalars	✔		
U(1)'		✔	
Mirror SU(N)	✔		✔
GUTS			✔
Vector-like	✔	✔	
Heavy N_R		✔	✔
Gauginos	✔	✔	

✔ **Naturalness**

✔ **Cosmology**

✔ **Neutrino mass**

Signatures & Reach

- *New states*
  - *Higher energy*
  - *Higher parton luminosity*
  - *More statistics & bknd reduction*
  - *New detectors (LLPs…)*

- *Modifications of SM properties*
  - *Precision, precision, precision*
  - *“Clean” signals*
  - *More statistics*

- *New interactions*
  - *Symmetry tests: CP, lepton number & flavor, baryon number…*

II. Naturalness & EWSB

Naturalness

Scenarios

	Scalar Top Partner	Fermion Top Partner
All SM Charges	SUSY	pNGB/RS
EW Charges	Folded SUSY	Quirky Little Higgs
No SM Charges	???	Twin Higgs

Signatures

- Higgs coupling deviations
  - Tree level vs. loop level
- Probing the UV completion
- Exotic Higgs Decays
- Direct top partner production
  - Higgs Portal
  - Drell-Yan for EW charged partners

Naturalness

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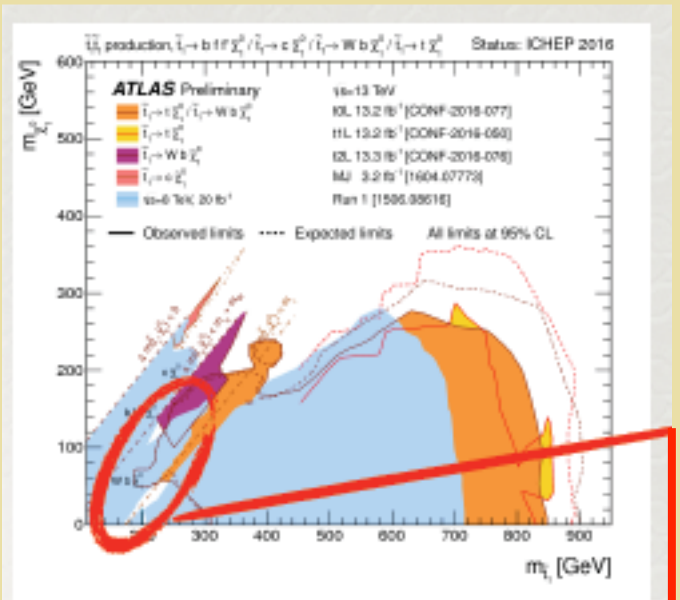
Naturalness: SUSY & Compositeness

SUSY: Look for the cracks…



The cracks are here, even in the small mass regime, and they can possibly survive the HL LHC.

Compressed regions are also hard.

Minimal Composite Higgs: Modified W, Z couplings

$$r_{W,Z} = \sqrt{1 - \left(\frac{v}{f}\right)^2}$$

- *LHC: $(v/f)^2 \sim 0.1$*
- *FCC-ee: $(v/f)^2 \sim 0.01$*

A. Katz

Naturalness: SUSY & Higgs

What Does SUSY Do to the SM Higgs?

The simplest SUSY SM extension demands two Higgs doublets, making sure that it is a type II 2HDM — expect deviations in the Higgs couplings like in 2HDM

In the decoupling large tan β limit of the type II 2HDM the first couplings to be affected are couplings of the Higgs to the down type sector.

$$r_d = -\frac{\sin\alpha}{\cos\beta} \approx \left(1 + \frac{m_h^2}{m_A^2}\right)\left(1 + \frac{m_Z^2 \sin^2\beta}{m_A^2}\right)$$

Assuming 1% precision in these measurements, this means that heavy higgses as heavy as 2 TeV might leave imprints in FCC-ee

Another promising direction — looking for the new Higgses.*

**See talk by Shufang Su for more details*

A. Katz

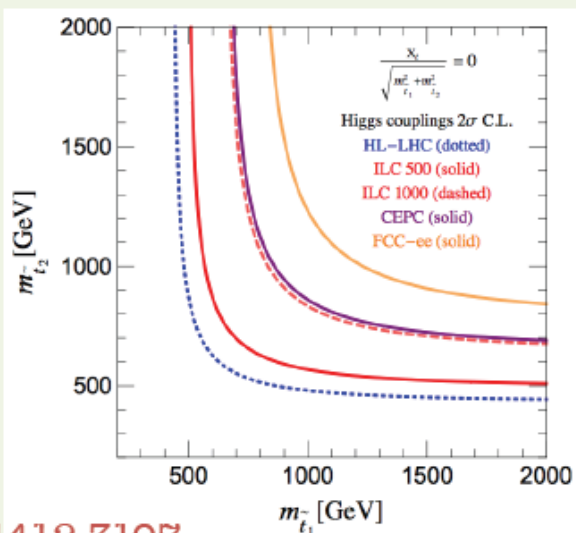
Naturalness & SUSY

Stop-induced hgg coupling modificaiton

$$r_g - 1 \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_1}^2} - \frac{X_t^2 m_t^2}{m_{\tilde{t}_1}^2 m\tilde{t}_2^2}\right)$$

FCC-ee

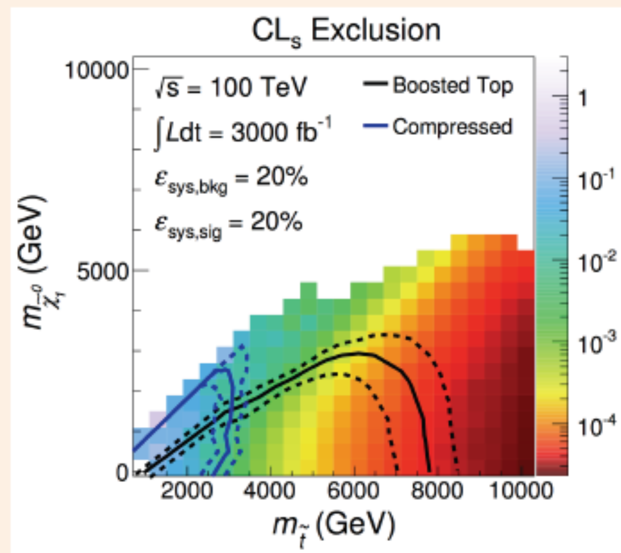
Coloured and charged, stops modify Higgs couplings:



1412.3107

FCC-hh

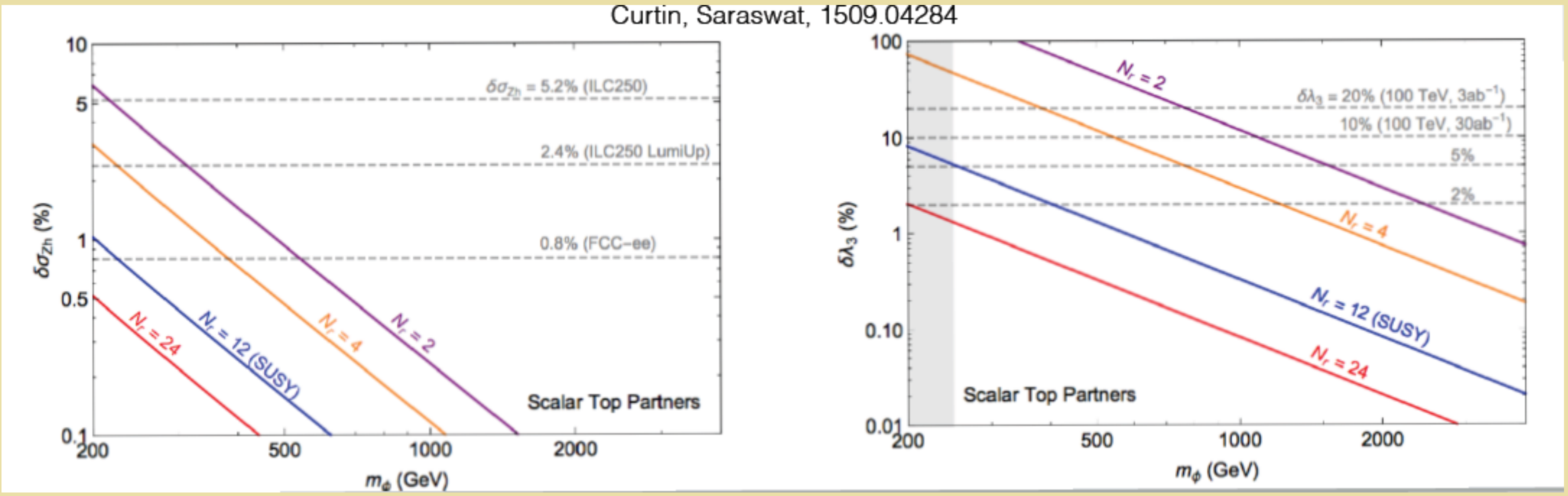
And show up directly at hadron colliders:



M. McCullough

Naturalness

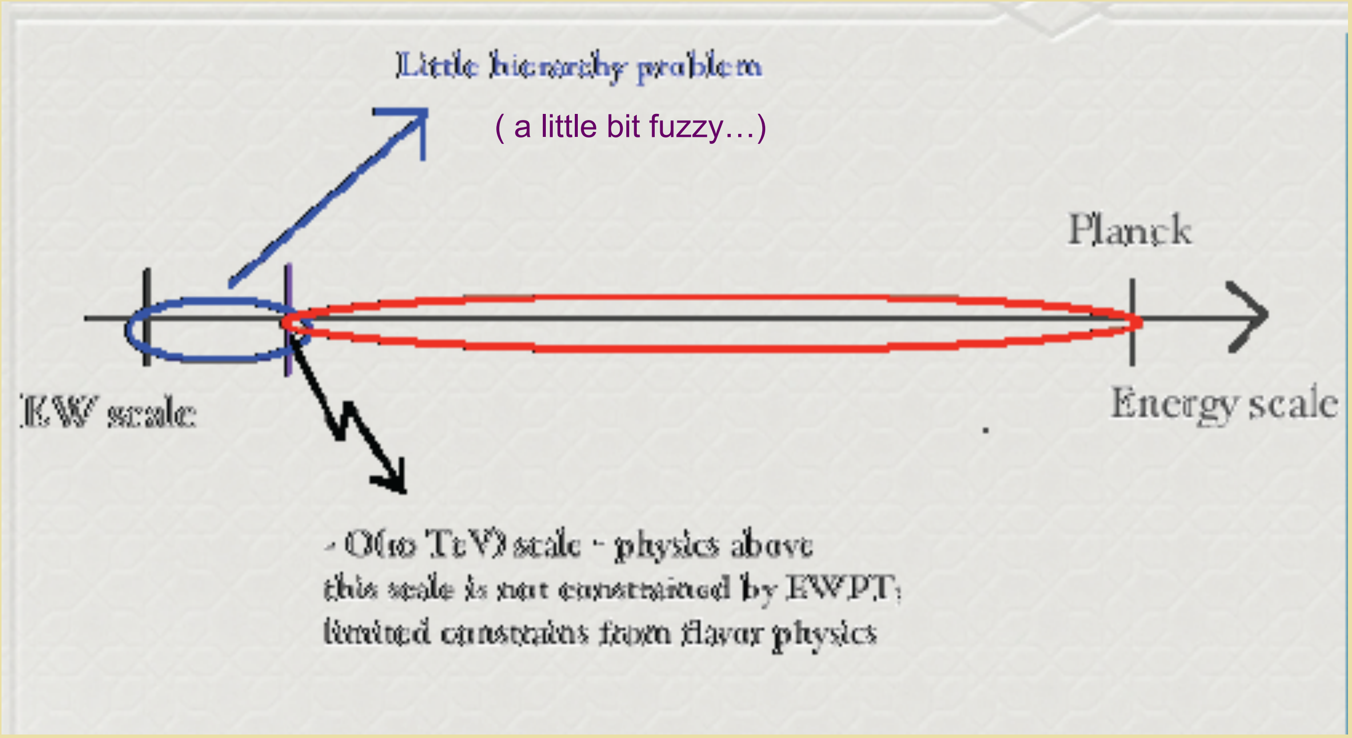
Higgs coupling deviations



ZZh coupling

hhh coupling

Naturalness: Little Hierarchy



A. Katz

Naturalness

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Neutral Naturalness

Neutral Naturalness Prototype Models

Fermionic partners — Twin Higgs	Bosonic partners — Folded SUSY
Largely along the lines of the little Higgs. Higgs is an approximate pGB of a large global symmetry SO(8)/SO(7). Trick: up to 5 TeV cutoff this structure can be maintained by imposing a discrete mirror symmetry, top partners are not charged under the SM color	***It is not SUSY!!*** An extended symmetry SU(3)×SU(3)×SU(2)×U(1) with the scalar top partners are charged under a non-SM color SU(3). Descends from a 10 TeV SUSY orbifold, which insures that the couplings have the right strength.

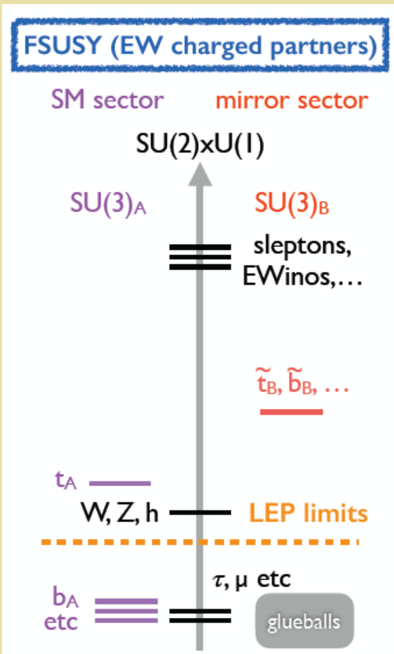
A. Katz

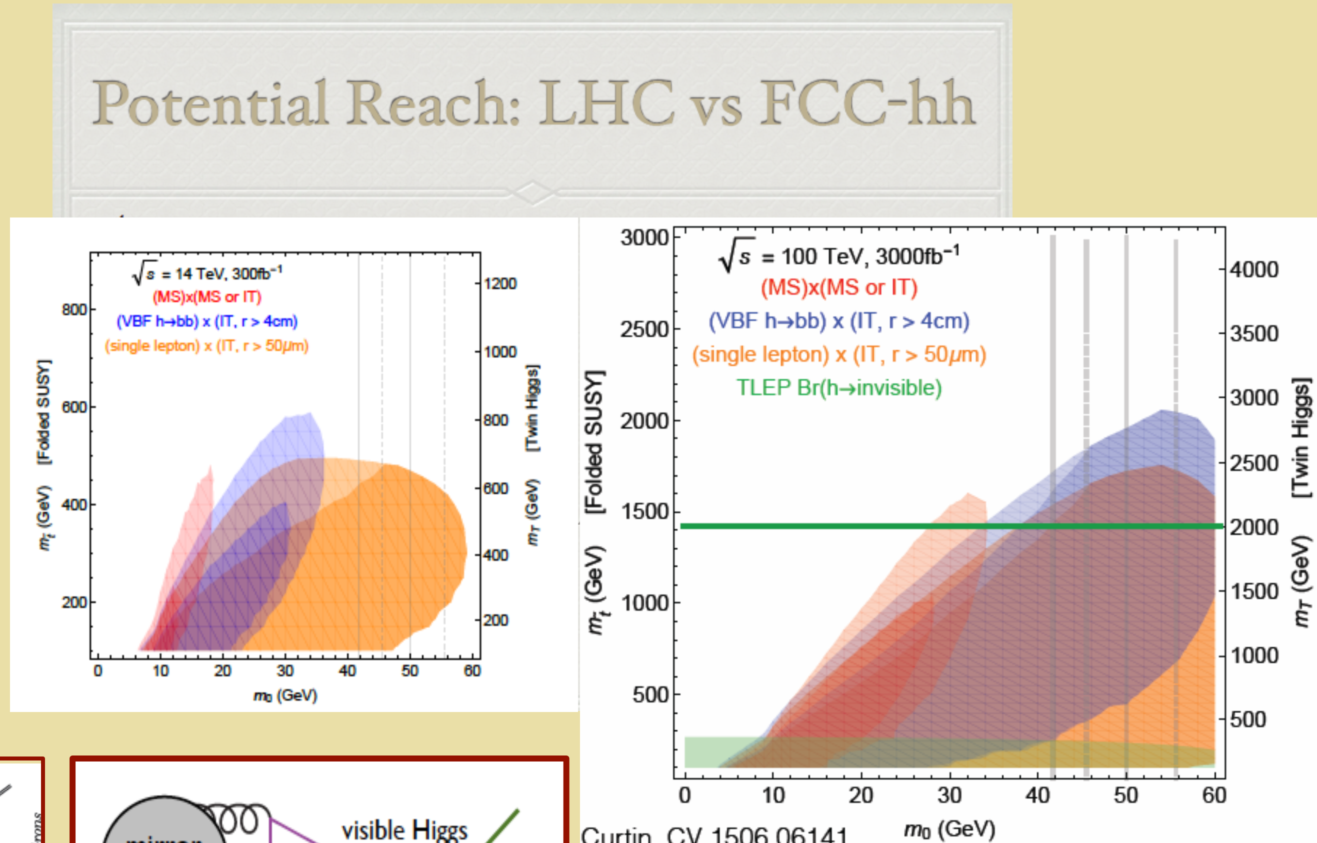
Neutral Naturalness

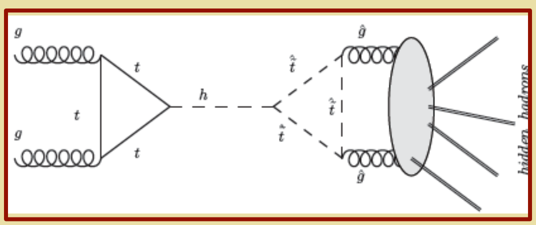
- FCC-ee
  - Tree level Higgs couplings (pNGB Higgs models)
  - Loop level σ_{Zh} (All, best for SM neutral non-pNGB)
- FCC-hh
  - Direct EW production (EW charged)
  - Direct Higgs portal production (All, best for SM neutral)
  - Exotic Higgs Decays (No light states)
  - Higgs Self coupling (All, best for scalar top partners, depends on number)
  - UV states (All known)

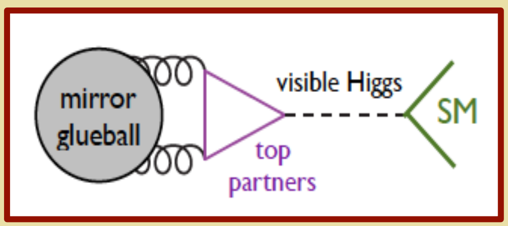
Neutral Naturalness

Exotic Higgs decays





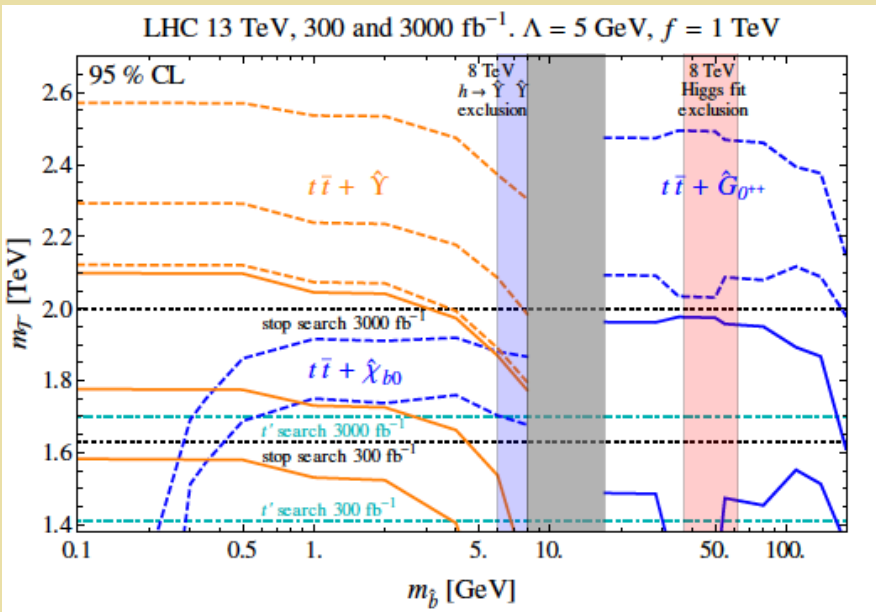


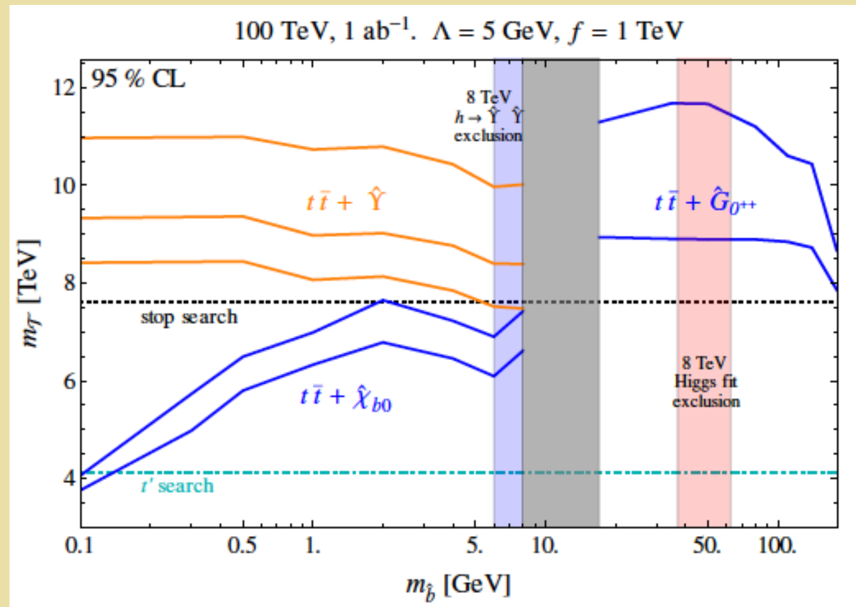


Exotic Higgs decays: $h \to 0^{++}\,0^{++}$
w/ 2 DV's or 1 DV +…

Neutral Naturalness: UV States

$$pp \to (\mathcal{T} \to tZ_B)(\overline{\mathcal{T}} \to \bar{t}Z_B) \to t\bar{t} + (\text{twin Hadron} \to \text{Displaced Vertex})$$





$$\begin{pmatrix} u^A_{3R} \\ \tilde{u}^A_{3R} \end{pmatrix} = \begin{pmatrix} -c_R & s_R \\ s_R & c_R \end{pmatrix} \begin{pmatrix} t_R \\ \mathcal{T}_R \end{pmatrix}, \qquad \begin{pmatrix} u^A_{3L} \\ \tilde{u}^A_{3L} \end{pmatrix} = \begin{pmatrix} -c_L & s_L \\ s_L & c_L \end{pmatrix} \begin{pmatrix} t_L \\ \mathcal{T}_L \end{pmatrix}$$

$$- y_t H^\dagger_A \overline{u}^A_{3R} q^A_{3L} - y_t H^\dagger_B \overline{u}^A_{3R} \tilde{q}^A_{3L} - \tilde{M} \overline{\tilde{q}}^A_{3R} \tilde{q}^A_{3L} + \text{h.c.}$$

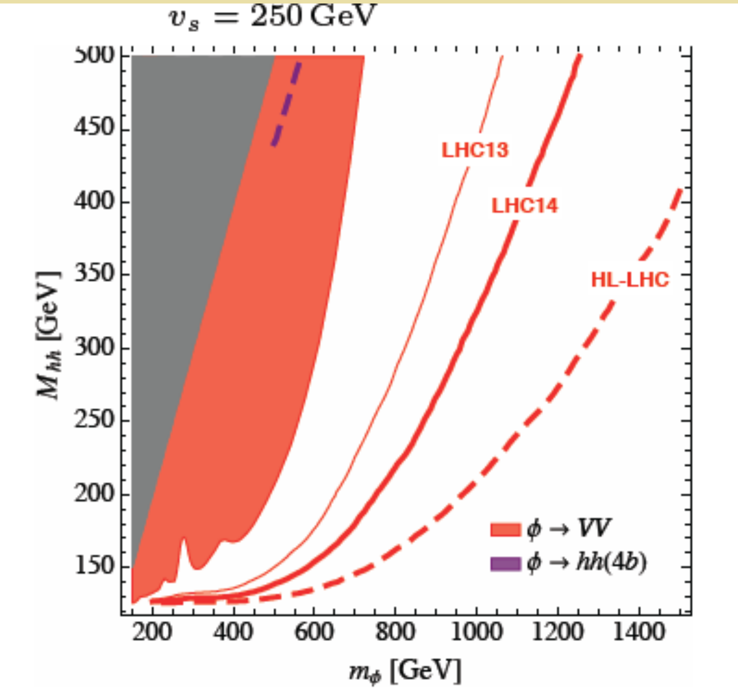
Cheng et al
1512.02647

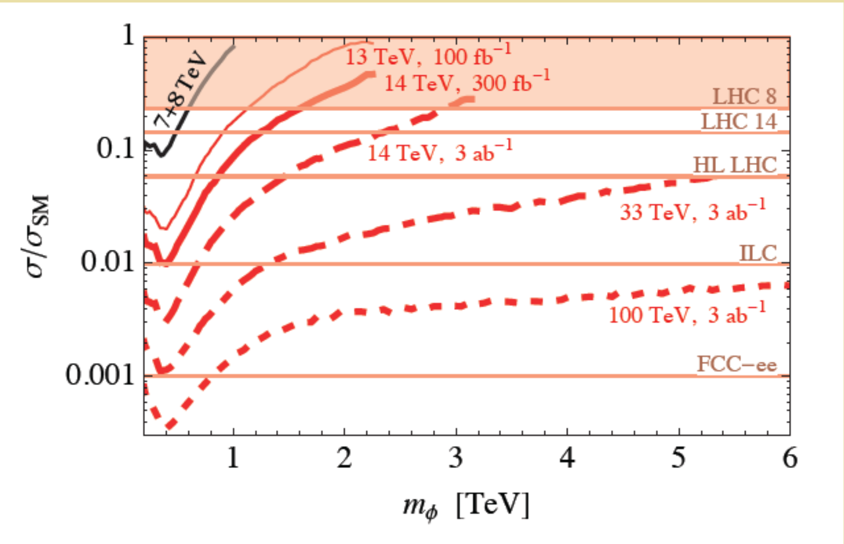
C. Verhaaren

Neutral Naturalness & Higgs Portal

SM gauge singlet scalars (illustrative of reach)

$$V = \mu_H^2 |H|^2 + \lambda_H |H|^4 + \lambda_{HS} |H|^2 S^2 + a_H |H|^2 S + \mu_S^2 S^2 + a_S S^3 + \lambda_S S^4$$





D. Buttazzo

EWSB: BSM Higgs

2HDM

Why 2HDM?

Models with extended Higgs sector: arise in natural theories of EWSB

- Higgs sector of MSSM/NMSSM
- Generic 2HDM
- Little Higgs, twin Higgs ...
- Composite Higgs models ...

- SM+singlet: parametrized by a simple mixing parameter
- 2HDM: covers board class of known models
- Allow for convenient parametrization
- Many features shared by many extended EWSB sectors

S. Su 3

S. Su

EWSB: BSM Higgs

2HDM

New channels open up for non-SM Higgs decay

neutral Higgs	HH type	(bb/ττ/WW/ZZ/γγ)(bb/ττ/WW/ZZ/γγ)	$h_{SM} \to AA$, $H \to h_{SM} h_{SM}$, $H \to AA$,
	H^+H^- type	(τν/tb)(τν/tb)	$H \to H^+H^-$
	$WH^\pm$ type	(lν/qq') (τν/tb)	$H/A \to WH^\pm$
	ZH type	(ll/qq/νν)(bb/ττ/WW/ZZ/γγ)	$H \to ZA$, $A \to ZH$, Zh
charge Higgs	WH type	(lν/qq')(bb/ττ)	$tH^\pm$ production, $H^\pm \to WH$ $H^\pm \to WA$

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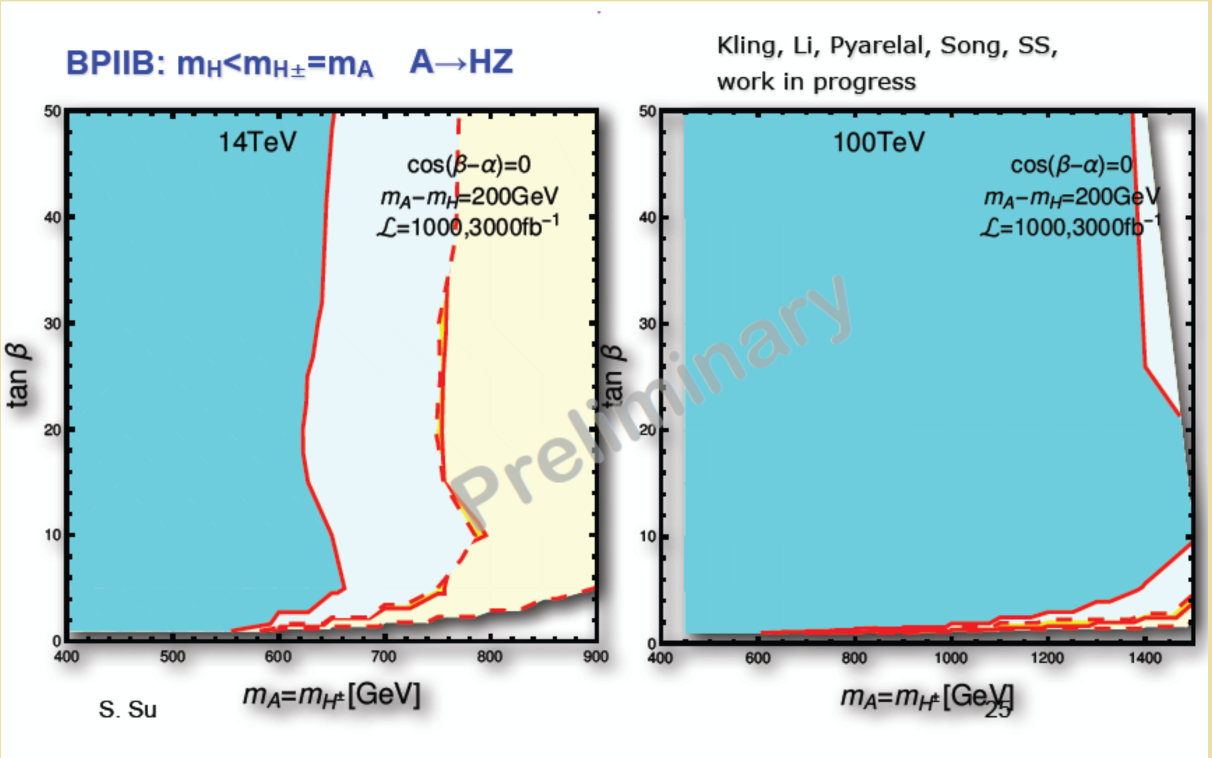
EWSB: BSM Higgs

2HDM



Naturalness

- *Value added*

Extend reach significantly beyond HL-LHC

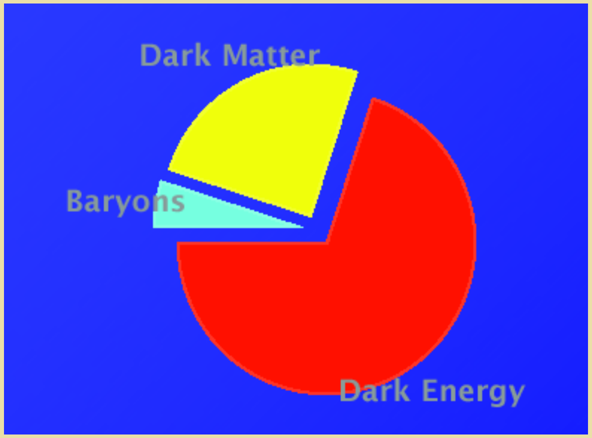
- *Synergy/complementarity*

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

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

Assumptions about "acceptable" fine tuning…

III. Cosmology



Dark Sector

- ***What is the dark matter ?***
  - *Fermions*
  - *Scalars*
  - *…*

- ***What are its interactions ?***
  - *Scalar mediators*
  - *Vector mediators*
  - *Contact interactions*

Dark Sector

P. Harris

Targeting Dark matter

- Currently there are 3 industries looking for DM
  - Direct detection
  - Indirect detection
  - Collider searches
- For each of these approaches :
  - Benchmarks have been established to drive search
    - For collider this is not as well formed
- For collider searches :
  - New benchmark to be established based precision SM
    - Turns out DM search is best way to measure high p_T V prod
  - This talk looks at this benchmark for the 100 TeV

Dark Sector

P. Harris

Beyond Mono-jet + MET

What about the cross sections?

- The relative rate to all processes is similar
  - σ(100 TeV/14 TeV) : ggH : 14.7
  - σ(100 TeV/14 TeV) : VBF : 18.6
  - σ(100 TeV/14 TeV) : WH : 9.8
  - σ(100 TeV/14 TeV) : ZH : 12.5
  - σ(100 TeV/14 TeV) : ttH : 60.8
  - σ(100 TeV/14 TeV) : bbH : 14.8
  - σ(100 TeV/14 TeV) : HH : 42.0
  - Except for ttH
- Means we expect VBF to give similar improvement
- Benchmarking agains ggH means ttH/VBF have a lot of room to gain

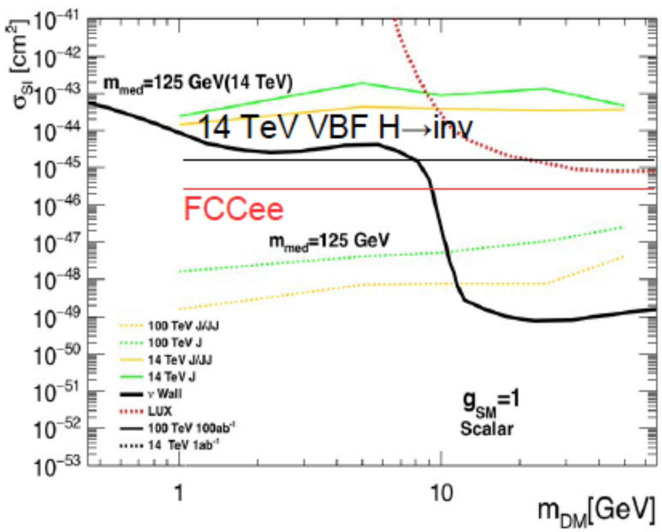
Dark Sector

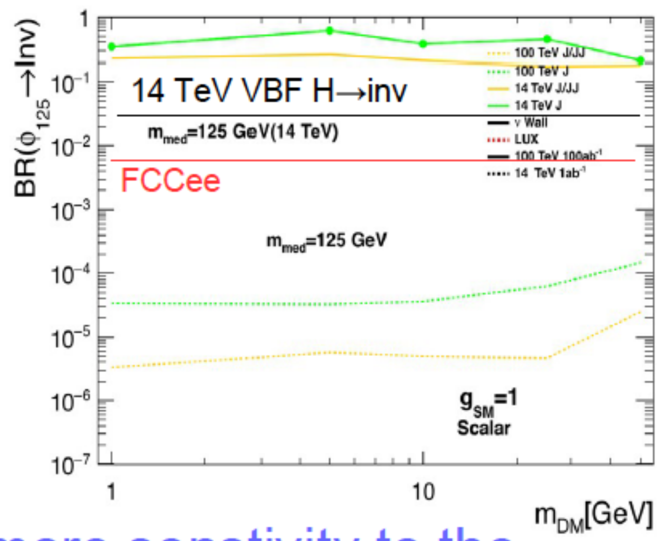
P. Harris

Beyond Mono-jet + MET

Higgs to invisible

- A nice benchmark is the Higgs invisible:





100 TeV machine has far more senstivity to the invisible decays of a Higgs

https://arxiv.org/abs/1603.07739
https://indico.cern.ch/event/438866/contributions/1085169/attachments/1258088/1858101/FCCwe
k_Hinv_MDG_14042016.pdf

Dark Sector: EW Multiplets

Cirelli & Strumia '05

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM can decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Events at LHC $\int \mathcal{L}\, dt = 100/\text{fb}$	σ_{SI} in $10^{-45}\,\text{cm}^2$
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
3	0	1/2	LH	2.4 ± 0.06	166	$0.8 \div 4.0$	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12
5	0	1/2	–	4.4 ± 0.1	166	$\ll 1$	12
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46

Siganture: Disappearing charge track $S^+ \to S_{DM} + \pi^+$ *(soft)*

Dark Sector: EW Multiplets

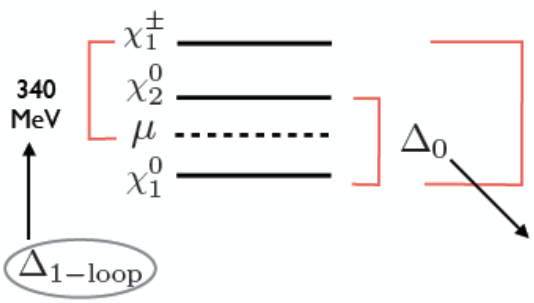
Disappearing charged tracks

J.F. Zurita

Simplified Bino/Higgsino (S/D)

$$M = \begin{pmatrix} M_1 & -mc_\beta & ms_\beta \\ -mc_\beta & 0 & \mp\mu \\ ms_\beta & \mp\mu & 0 \end{pmatrix} \qquad m = m_Z s_W \approx 43.8 \text{ GeV}$$

Expanding in μ/M_1



$$\Delta_+ = \Delta_{1-\text{loop}} + \frac{96 \text{ MeV}(1 \mp s_{2\beta})}{(M_1/10 \text{ TeV})} + \mathcal{O}\left(\frac{|\mu|}{M_1}, \frac{m}{M_1}\right)$$

$$\Delta_0 = \frac{192 \text{ MeV}}{(M_1/10 \text{ TeV})} + \mathcal{O}\left(\frac{|\mu|}{M_1}, \frac{m}{M_1}\right)$$

Limiting cases:

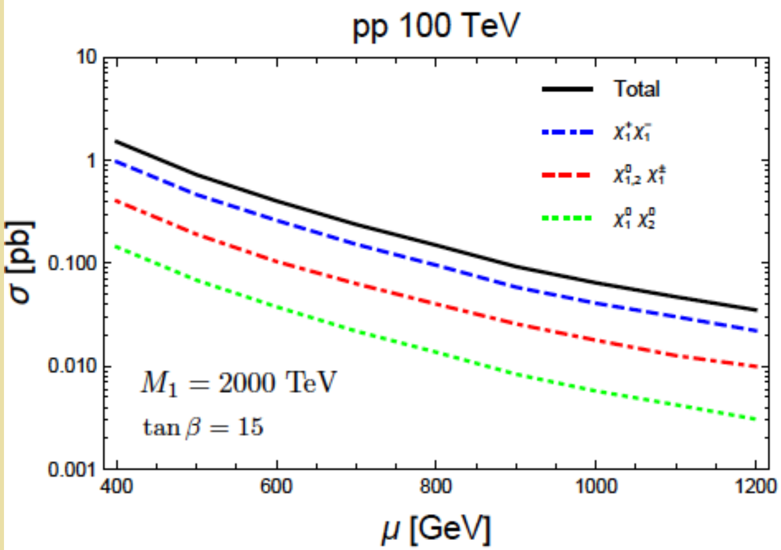
1. $\Delta_0 \geq \Delta_+$: decay open only to first neutralino $\longrightarrow$ only for $M_1 \lesssim 3|\mu|$.
2. $\Delta_0 = 0$, $\Delta_+ = 340$ MeV: decays to both, lifetime reduced by half.

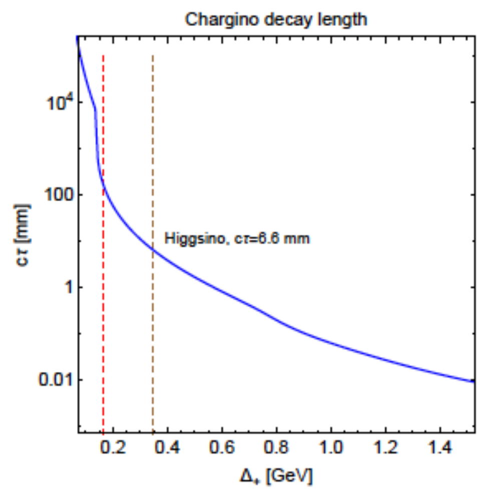
Δ_0 < 100 KeV gives inelastic scattering @ DD ➜ M_1 < 20 PeV.

Dark Sector: EW Multiplets

Disappearing charged tracks — *J.F. Zurita*

Cross sections and decay lengths





$\sigma(1.1\ \mathrm{TeV})[\mathrm{fb}] = 47.23\ (39.05)\ \ \mathrm{NLO\ (LO)}\,.$

PROSPINO Beenakker, Klasen, Krämer, Plehn, Spira, Zerwas, hep-ph/9906298

Decays formulae (mostly) from
Chen, Drees, Gunion: hep-ph/951230, 9607421, 9902302.

$\Delta_+ = 340\ \mathrm{MeV}$ ➡ $\mathrm{BR}\ (\chi_1^\pm \to \pi^\pm \chi_0^{(1)}) \sim 97\%\,.$

Dark Sector: EW Multiplets

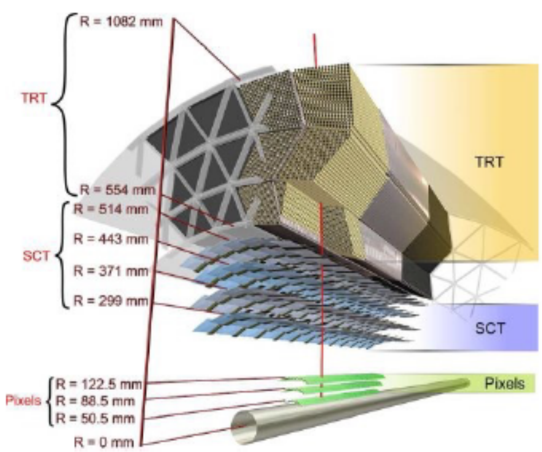
Disappearing charged tracks

J.F. Zurita

Disappearing tracks @ LHC

ATLAS: CERN-PH-EP-2013-155 [CMS: CERN-PH-EP-2013-037]

- Charged particle (track) decays into neutral + SM (unreconstructed): disappeared!!!
- Event selection requires:
  - 1 "good quality"* (isolated, well reconstructed) track with large pT.
  - large missing transverse energy (MET > O(100 GeV)).
  - 1 hard jet, pT > 100 GeV (from initial state radiation, to trigger the event).
  - ΔΦ(jet,MET) > 1.0 (0.5) @ ATLAS (CMS) : kills mismeasured QCD multijets.



* Quality track

- At least 3 hits in pixel detectors.
- At least 2 hits in the SCT.
- Less than 5 hits in the TRT**

$d_{min} \approx 30$ cm

- pT > 15 GeV, 0.1 < |η| < 1.9 (hard and central)

** SM particle leaves (on average) 32 hits in TRT

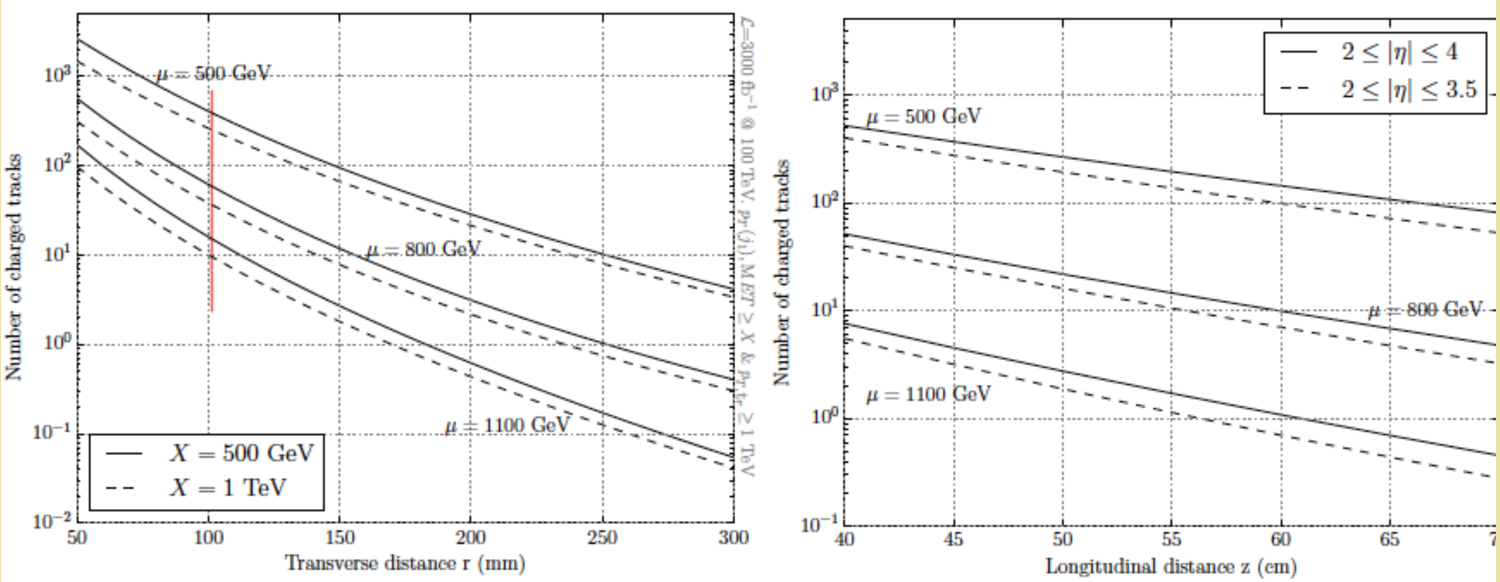
Dark Sector: EW Multiplets

Disappearing charged tracks

J.F. Zurita

Charged tracks in r-z

100 TeV, $3ab^{-1}$



r=10 cm gives 10 events for 1.1 TeV charginos with 1 TeV pT cut.

Forward (η) extension from 3.5 to 4 gives a factor 2 enhancement.

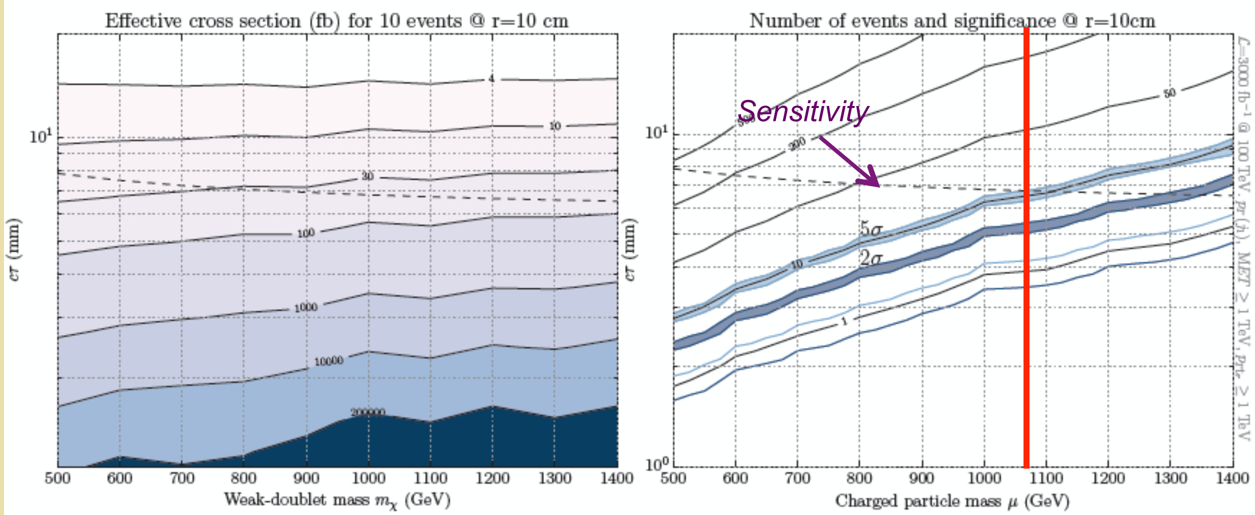
Dark Sector: EW Multiplets

Disappearing charged tracks

J.F. Zurita

Sensitivity (*r*=10cm)

100 TeV, 3ab^{-1}



m < 1065 (1286) GeV for discovery (exclusion) for pure Higgsino, 50% systematics.

Scaling with di-jets (gg). If using Z+jets (q-qbar), the reach moves to 1.5 (1.6) TeV.

Is M_{DM} ~ 2-3 TeV reachable ?

Dark Sector: EW Multiplets

Mono-Z

J.F. Zurita

Potential advantages for mono-Z at FCC:

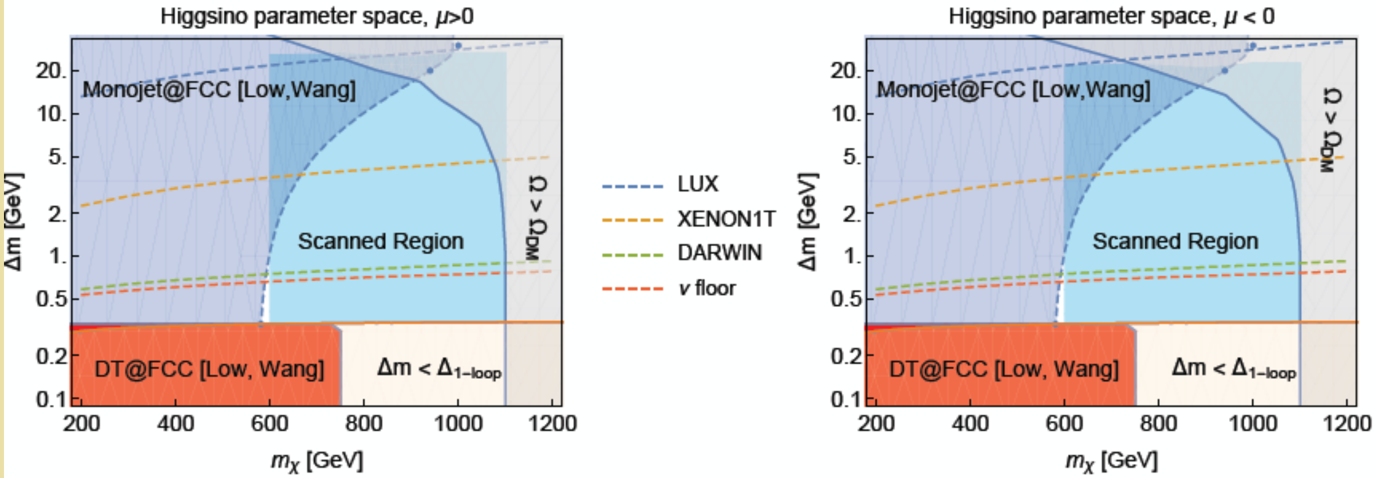
- Soft leptons might not be viable (depend on pT thresholds).
- Weak coupling stronger at FCC energies.
- Weak effects in PDFs are important (Rojo, 1605.08302)
- EW Sudakovs can have a large impact (Becher, Garcia i Tormo, 1305.4202 1509.01961).
- Very different systematics (crucial to estimate the sensitivity).

Dark Sector: EW Multiplets

Mono-Z

J.F. Zurita

The parameter space



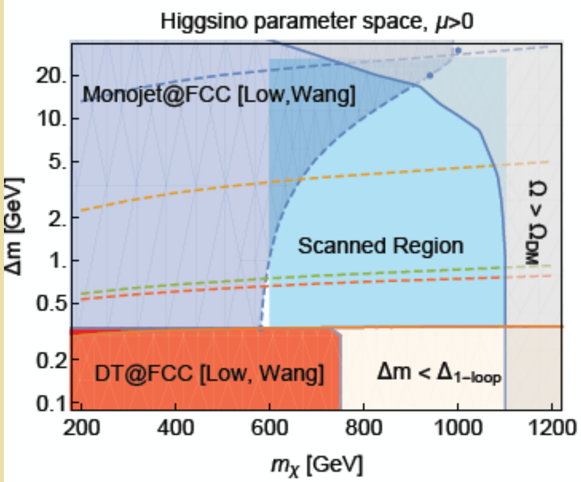
- Xenon 1-T forces splittings below 2-5 GeV.
- LHC 95% C.L bounds give m_χ > 200 GeV.
- FCC monojet bounds: m_χ > 600 GeV for nominal splitting.
- Relic density forces m_χ < 1100 GeV.
- Scanned region: $|\mu|$ = 600, 750, 900, 1000, 1100 ; t_β = 15, M_1 scans Δ_+.

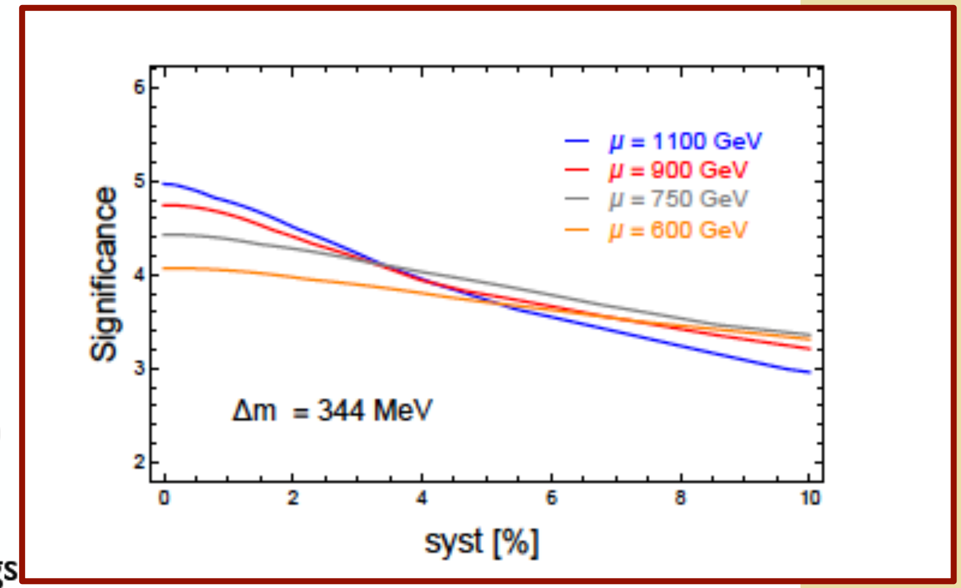
Dark Sector: EW Multiplets

Mono-Z

J.F. Zurita

The parameter space





- Xenon 1-T forces splittings
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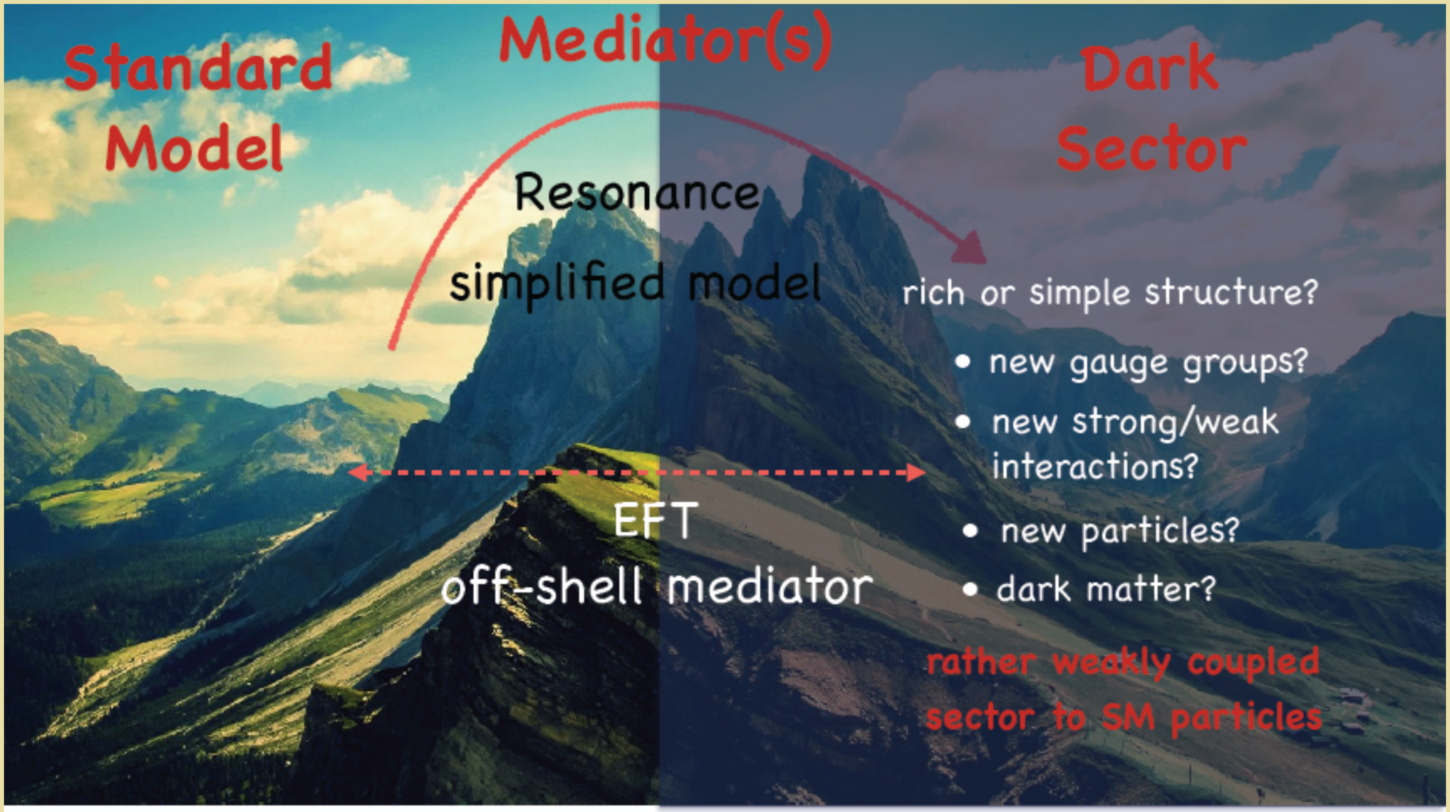
Dark Sector: Mediators



Resonant phenomenology rather one-directional
- its difficult to excite particles in the dark sector directly

How to study structure of dark sector?

M. Spannowsky

Dark Sector: Mediators

Incomplete list how to receive echoes from dark sectors

It depends on **nature of mediator** and **dark sector structure**

Gravity	• **direct**, e.g. Planck, velocity of galaxies • **indirect**, e.g. grav. waves from first-order phase transition
vector mediator (new gauge group)	• **direct**, e.g. hidden valley phenomenology, comp. dark matter, ... • **indirect**, e.g. running of gauge coupling
scalar mediator	• **direct**, e.g. hidden valley phenomenology, ... • **indirect**, e.g. running of mixing angles,...

See talks by D. Curtin, S. Iwamoto, A. Katz, M. McCullough, J. Zurita

Dark Sector: Mediators

Direct dark sector spectroscopy at e+e- colliders

- Can we access the quantum numbers of the mediator and dark sector particle, e.g. spin or masses?

[Dreiner, Huck, Kraemer, Schmeier, Tattersall '12]
[Andersen, Rauch, MS '13]
[Chacko, Cui, Hong '13]

- Let us pick a benchmark simplified model

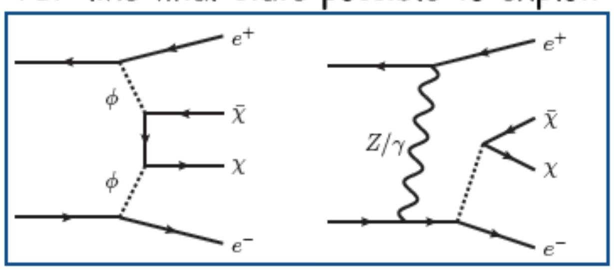
assume mediator couples between electron and dark sector particle

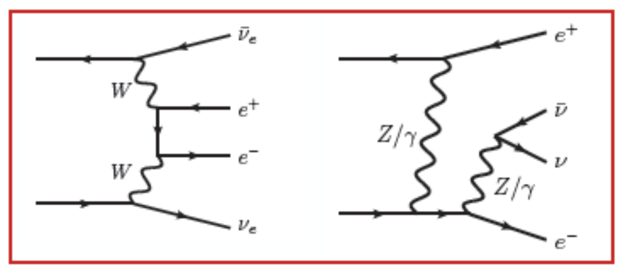
	scalar	vector
e	$i\, g_{ee\phi,S}\ \bar{e}e\ \phi_S$	$i\, g_{ee\phi,V}\ \bar{e}\gamma_\mu e\ \phi_V^\mu$
χ	$i\, g_{\chi\chi\phi,S}\ \bar{\chi}\chi\ \phi_S$	$i\, g_{\chi\chi\phi,V}\ \bar{\chi}\gamma_\mu\chi\ \phi_V^\mu$

$$M_* = \frac{M_\phi}{\sqrt{g_{ee\phi}\, g_{\chi\chi\phi}}}$$

model	mediator mass	mediator spin	WIMP mass	M_*
LSL	8 GeV	0 (scalar)	5 GeV	30 GeV
LVL	8 GeV	1 (vector)	5 GeV	30 GeV
LSH	8 GeV	0 (scalar)	120 GeV	27.4 GeV
LVH	8 GeV	1 (vector)	120 GeV	21 GeV
HSL	200 GeV	0 (scalar)	5 GeV	1250 GeV
HVL	200 GeV	1 (vector)	5 GeV	1250 GeV
HSH	200 GeV	0 (scalar)	120 GeV	332.4 GeV
HVH	200 GeV	1 (vector)	120 GeV	511.8 GeV

- In VBF-like final state possible to exploit kinematic distributions





M. Spannowsky

Dark Sector: Mediators

Direct dark sector spectroscopy at e+e- colliders

- The **spin of the mediator** can be probed directly in this multi-Regge kinematic limit, where the invariant mass bigger than prop. momentum $s_{ij} \gg |\bar{t}_i|$

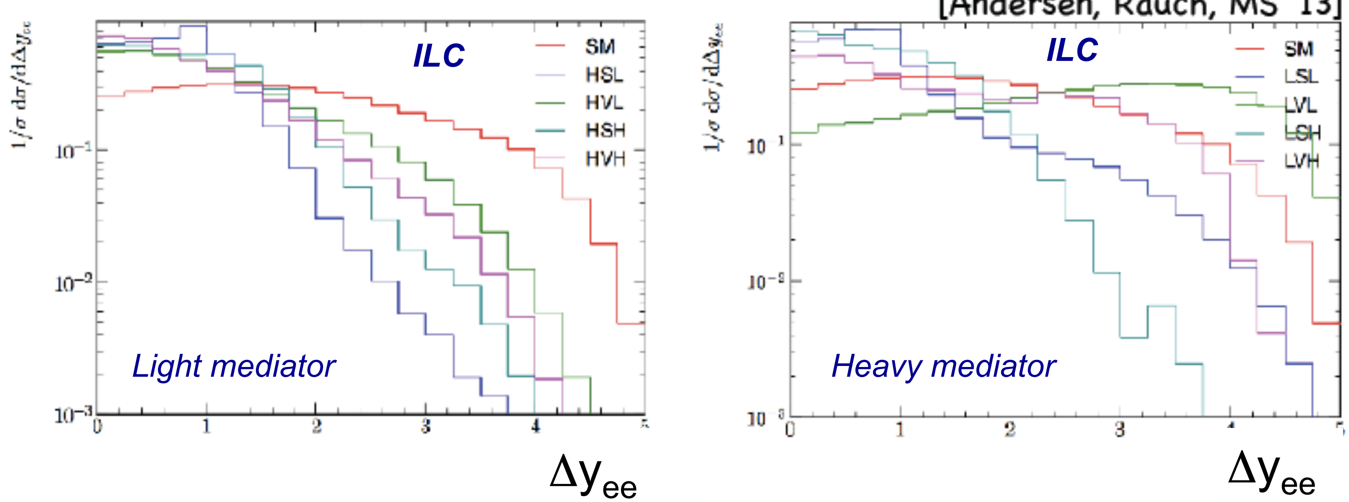
Behaviour of 2->n scattering is for rapidity ordered momenta p determined by

[Regge 1959]

$$\mathcal{M}^{p_a p_b \to p_1 p_2 p_3 p_4} \to s_{12}^{\alpha_1(t_1)} \; s_{23}^{\alpha_2(t_2)} \; s_{34}^{\alpha_3(t_3)} \; \gamma.$$

Powers determined by spin $\alpha_i = J_i$ → can probe spin in mjj or yjj

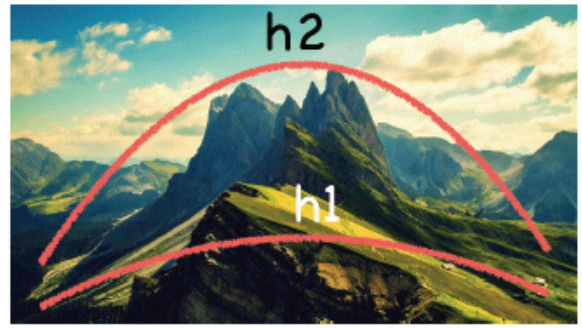
[Andersen, Rauch, MS '13]

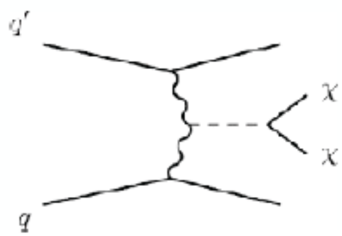


Dark Sector: Mediators

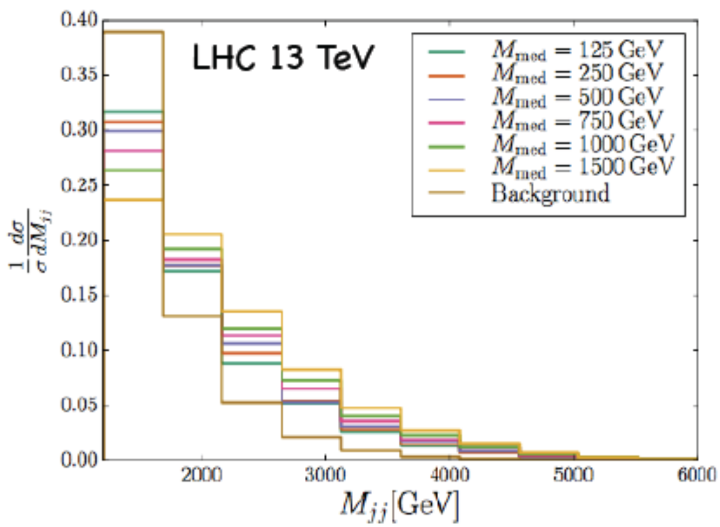
[Khoze, Ro, MS '15]

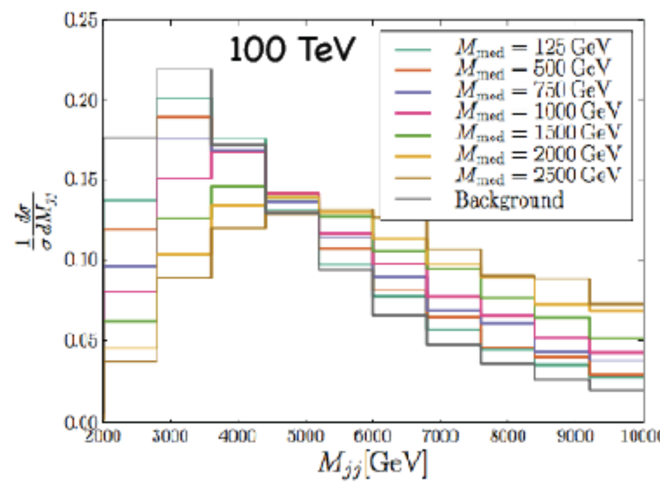
Measuring the mediator mass at the LHC





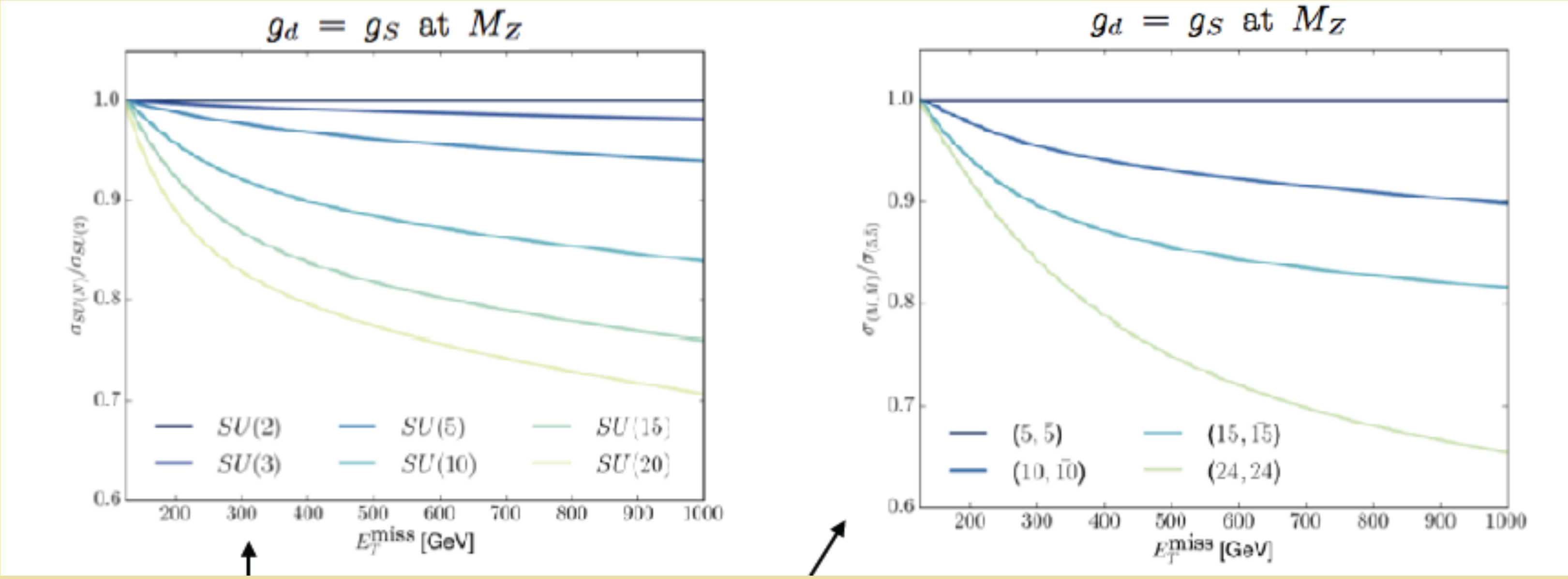
$$\mathcal{L} = \sqrt{\kappa}\left(\frac{2M_W^2}{v}W_\mu^+W^{-\mu} + \frac{M_Z^2}{v}Z_\mu Z^\mu - \sum_f \frac{m_f}{v}\bar{f}f\right)\phi - g_{\rm DM}\bar{\chi}\chi\phi - \frac{1}{2}M_{\rm med}^2\phi^2 - m_\chi\bar{\chi}\chi$$





Dark Sector: Mediators

Coupling evolution



M. Spannowsky

Dark Sector

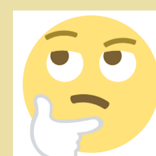
- *Value added*

Extend reach significantly beyond HL-LHC

- *Synergy/complementarity*

Discovery (hh mode) and interactions (ee and hh modes)

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



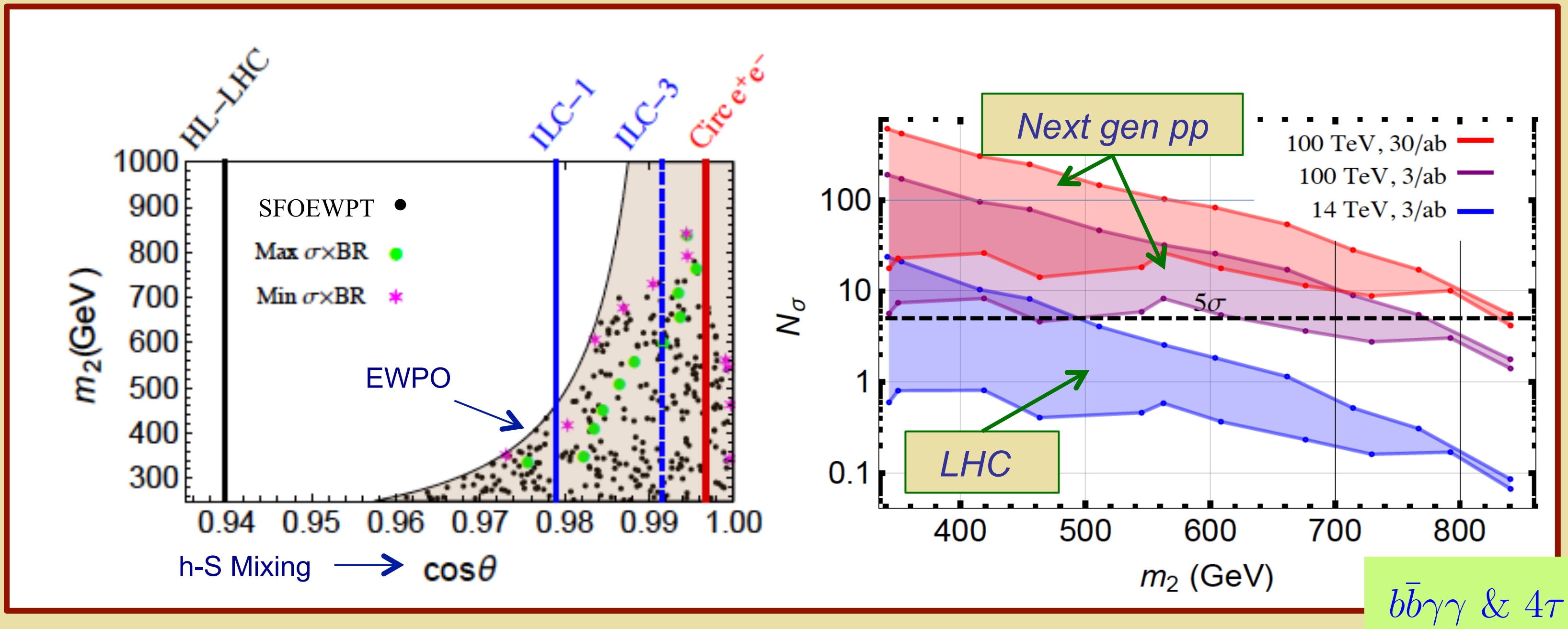
EW multiplets: M_{DM} ~ 2-3 TeV

Baryogenesis

- ***Baryon number violation ?***
- ***BSM CPV ?***
- ***Out of Equilibrium ?***

EW Phase Transition: Singlet Scalars

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



Next gen pp: Kotwal, No, R-M, Winslow 1605.06123

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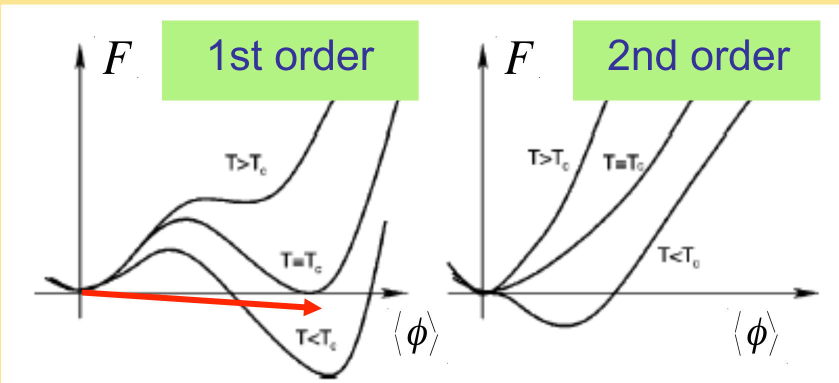
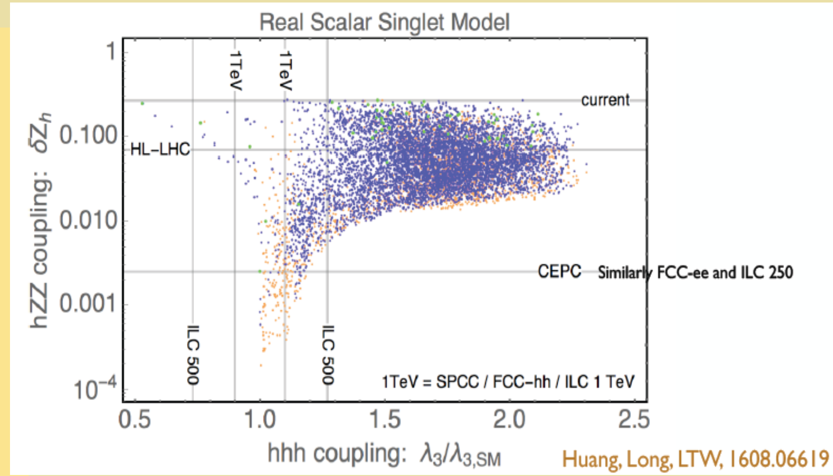
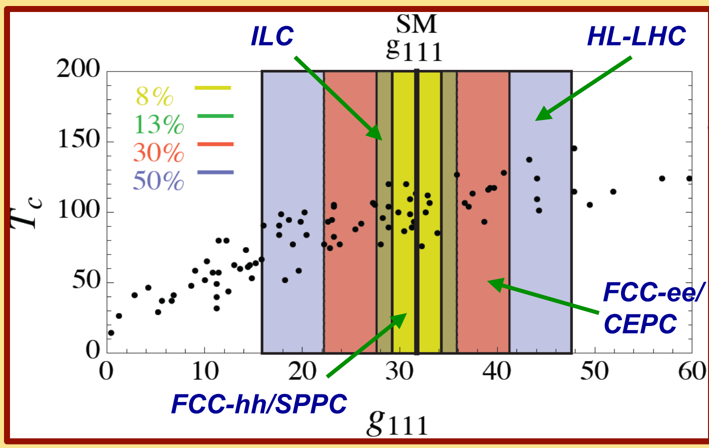
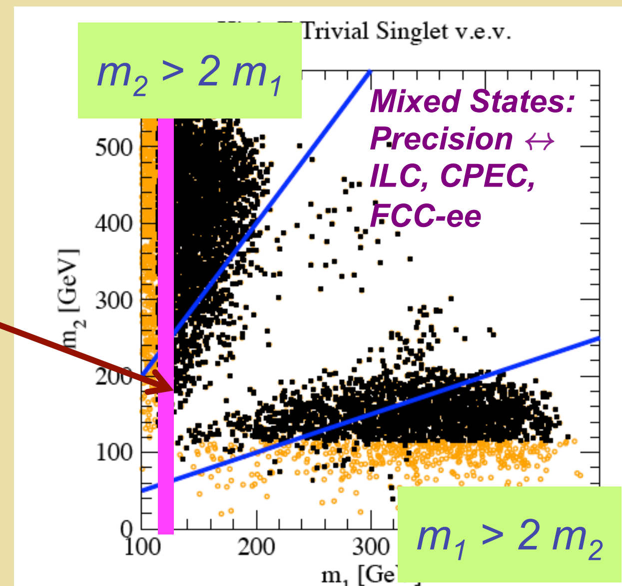
EW Phase Transition: Singlet Scalars





Modified Higgs Self-Coupling





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

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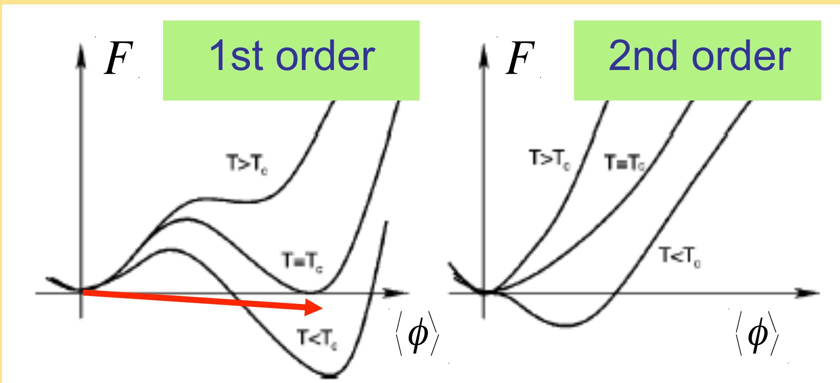
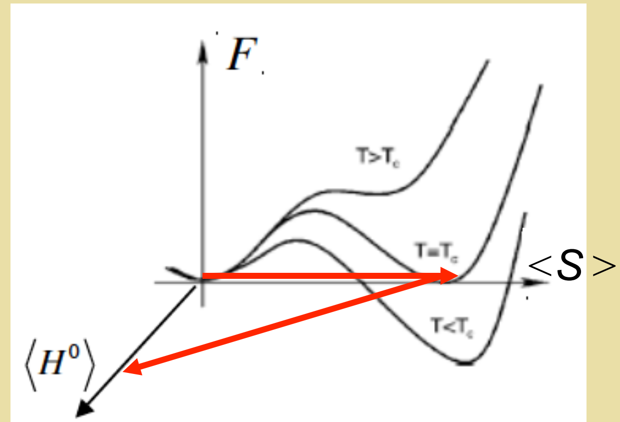
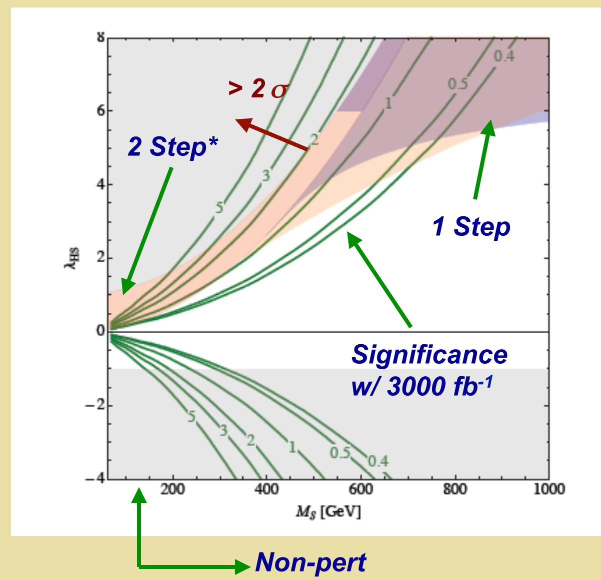
EW Phase Transition: Singlet Scalars





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

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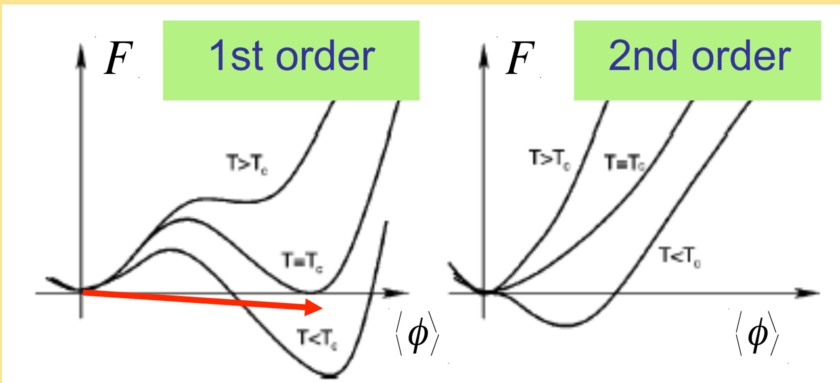
EW Phase Transition: DM Direct Detection

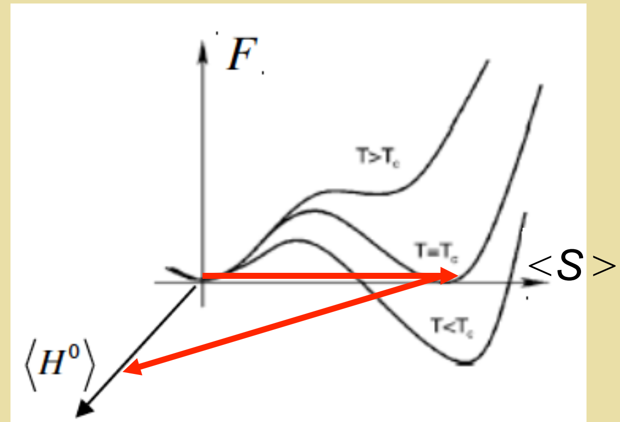


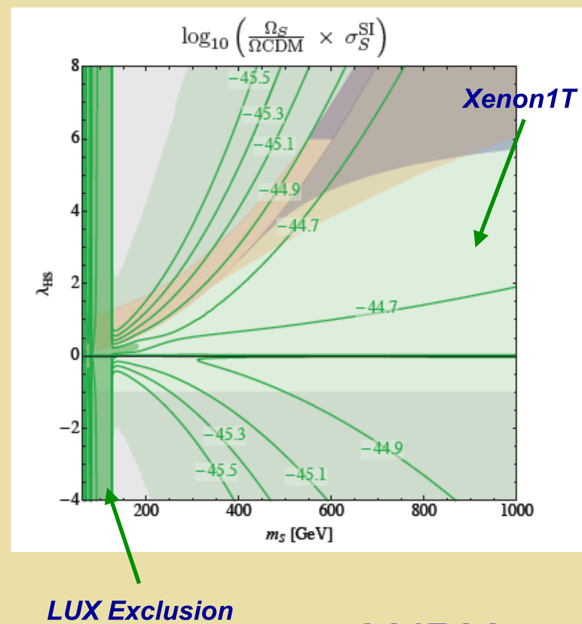
Curtain, Meade, Yu: arXiv: 1409.0005

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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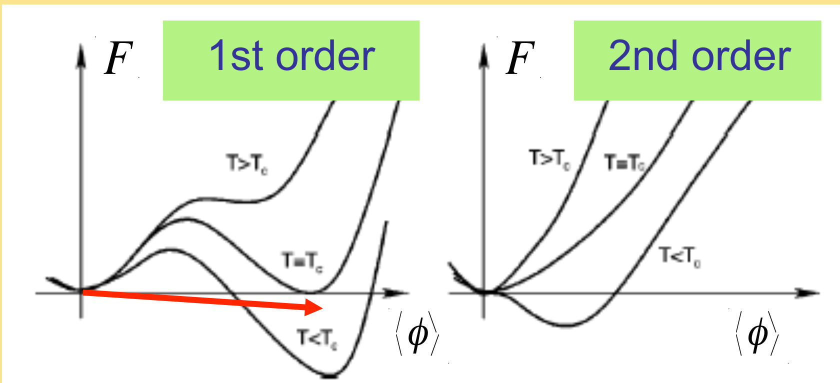
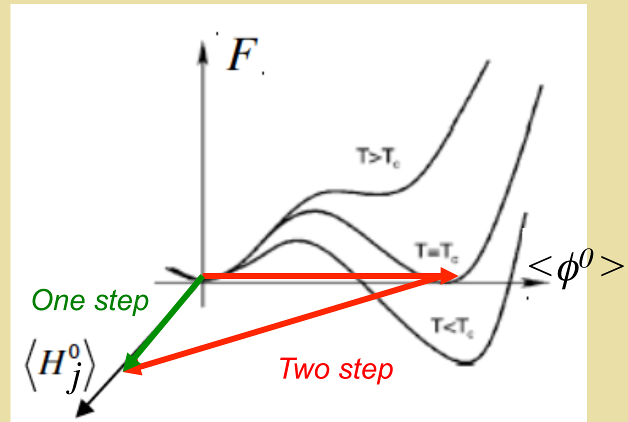
EW Multiplets: Two-Step EWPT

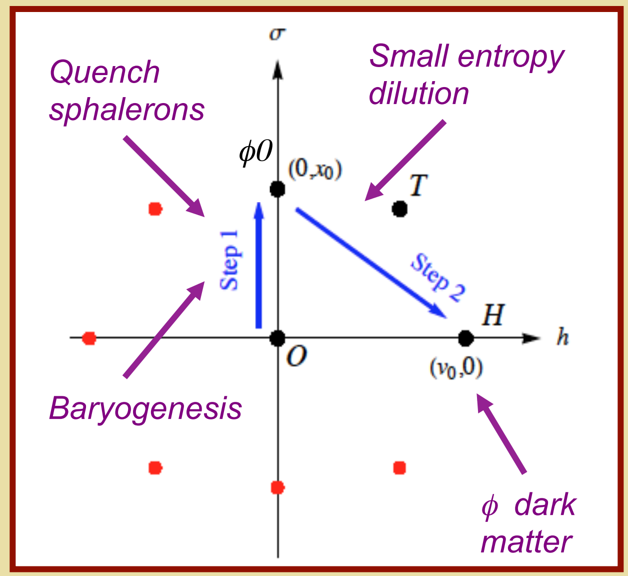


Increasing m_h →

← New scalars

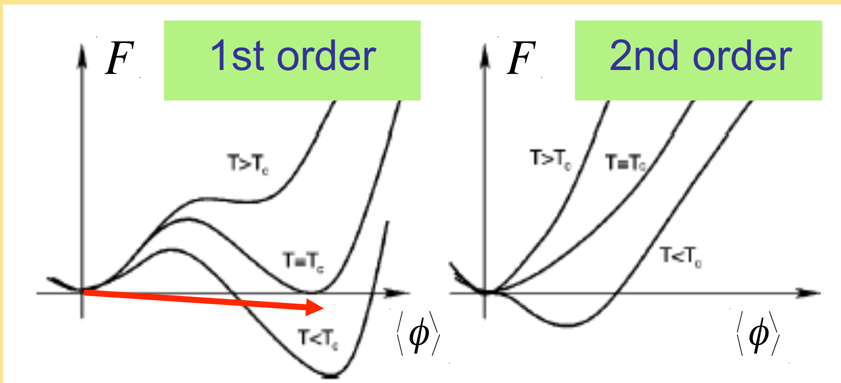
- Step 1: thermal loops
- Step 2: tree-level barrier

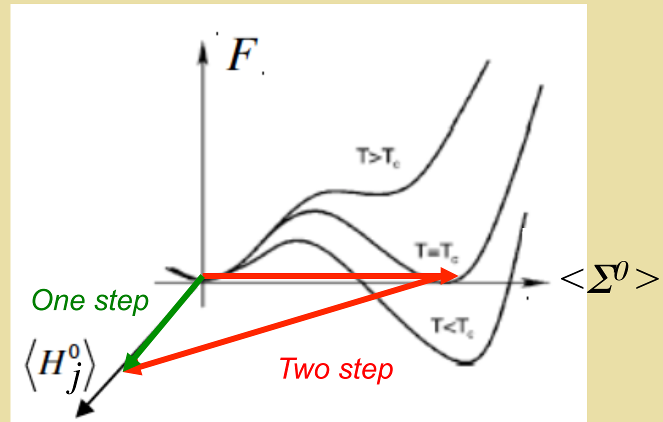




Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1505.05195

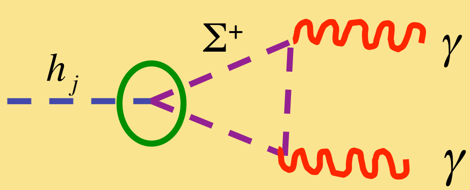
EW Multiplets: Two-Step EWPT

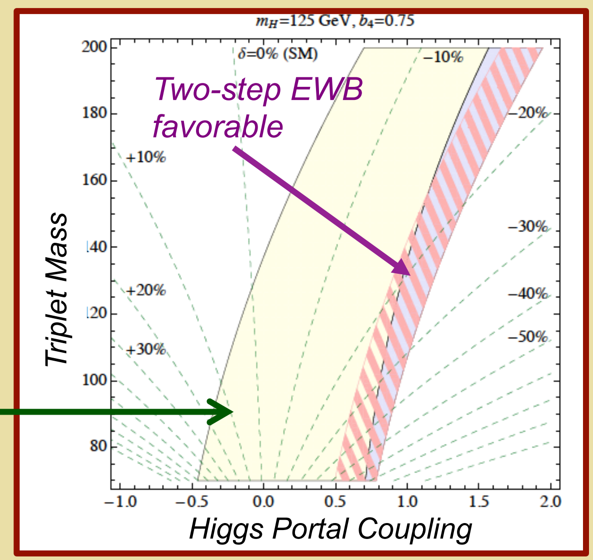




Increasing m_h

New scalars





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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

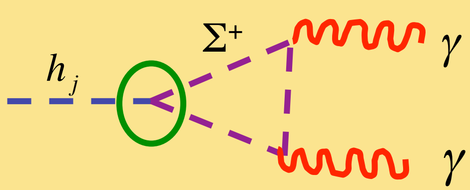
	γγ	Zγ	μμ
δ BR	~0.5%	~1%	~1%

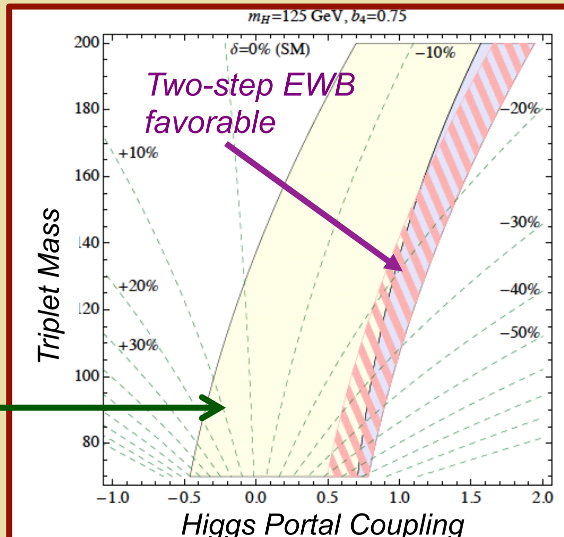
M. Mangano

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

Increasing m_h →

← *New scalars*





Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1505.05195

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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*

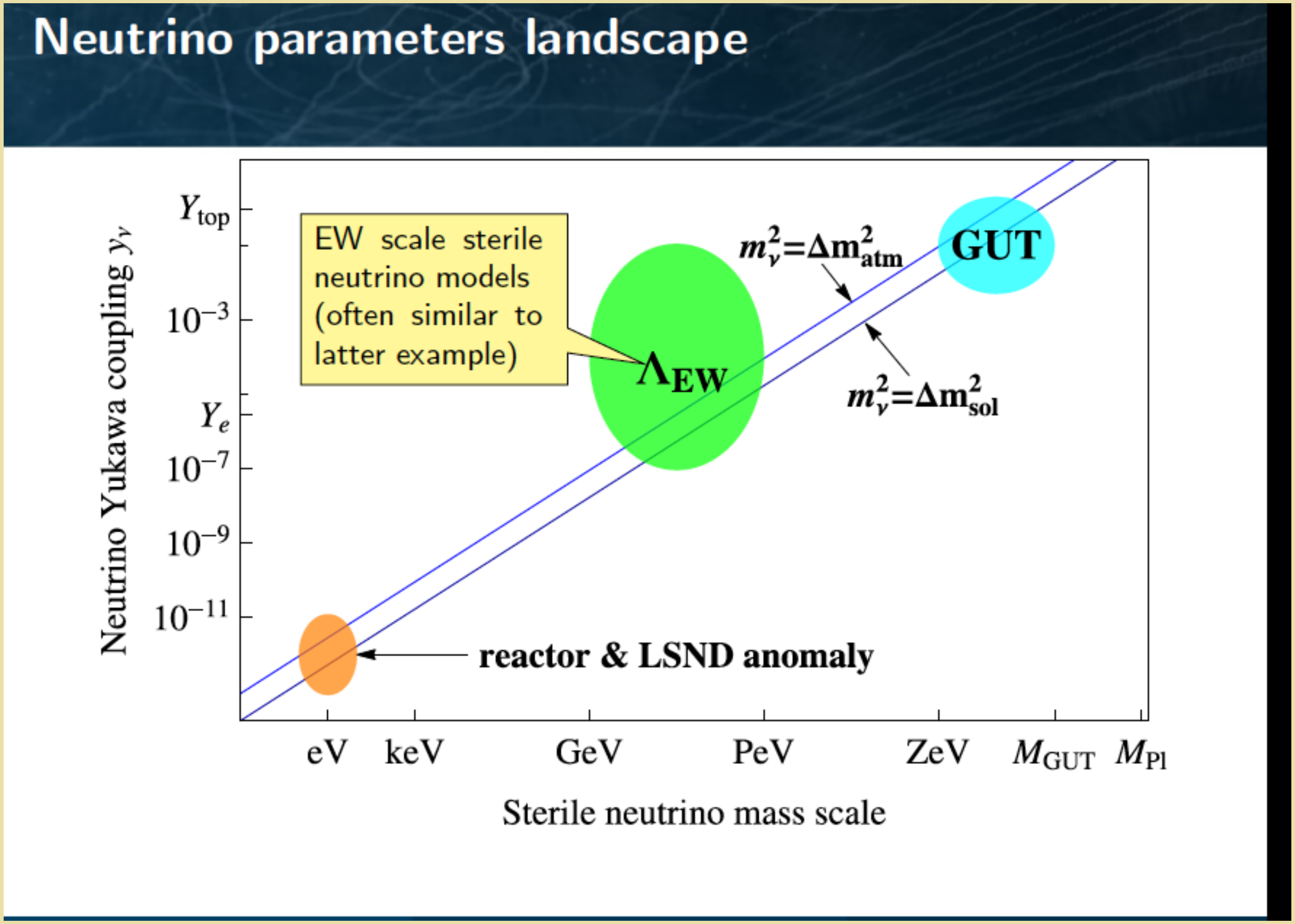
Singlets: 100 TeV + 30 ab^{-1}
EW Multiplets: < 10% on $h\gamma\gamma$

IV. Neutrino Mass

- ***RH neutrinos (type I & II see-saw)***
- ***New scalars (LRSM, raditive see-saw)***
- ***Lepton number violation (another day)***

ACFI workshop July '17: http://www.physics.umass.edu/acfi/seminars-and-workshops/neutrinos-at-the-high-energy-frontier

RH Sterile Neutrinos



RH Sterile Neutrinos

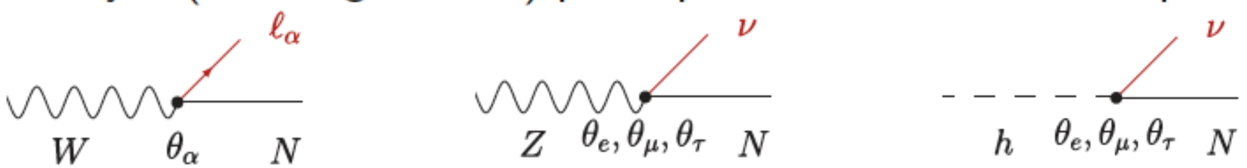
- The leptonic mixing matrix to leading order in θ_α

Mixing matrix of the light ν $\equiv U_{\text{PMNS}}$

$$\mathcal{U} = \begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{i}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu1} & \mathcal{N}_{\mu2} & \mathcal{N}_{\mu3} & -\frac{i}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau1} & \mathcal{N}_{\tau2} & \mathcal{N}_{\tau3} & -\frac{i}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{i}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) \end{pmatrix}$$

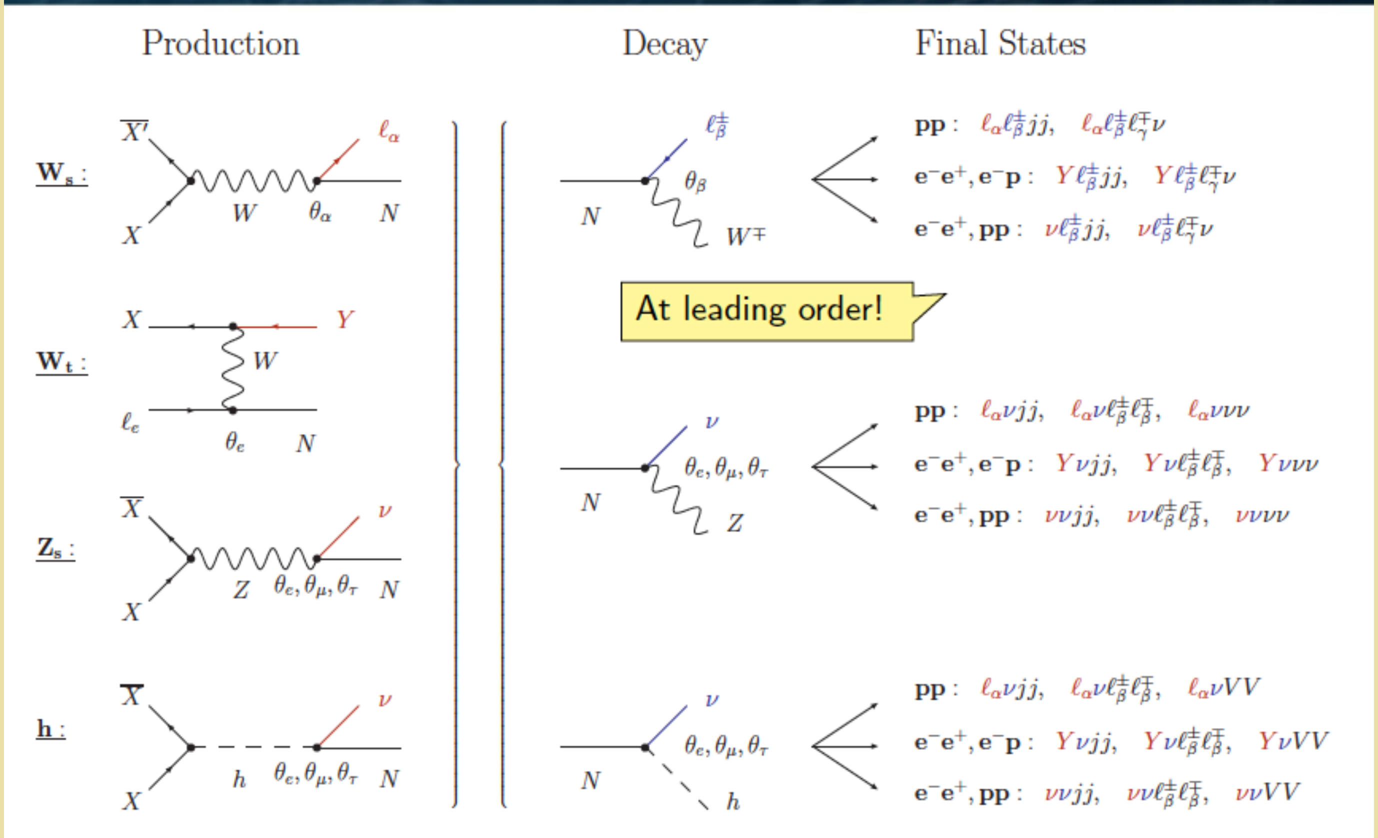
Sterile ν mix with active ones

$\Rightarrow$ Heavy ν (mass eigenstates) participate in weak interaction processes:



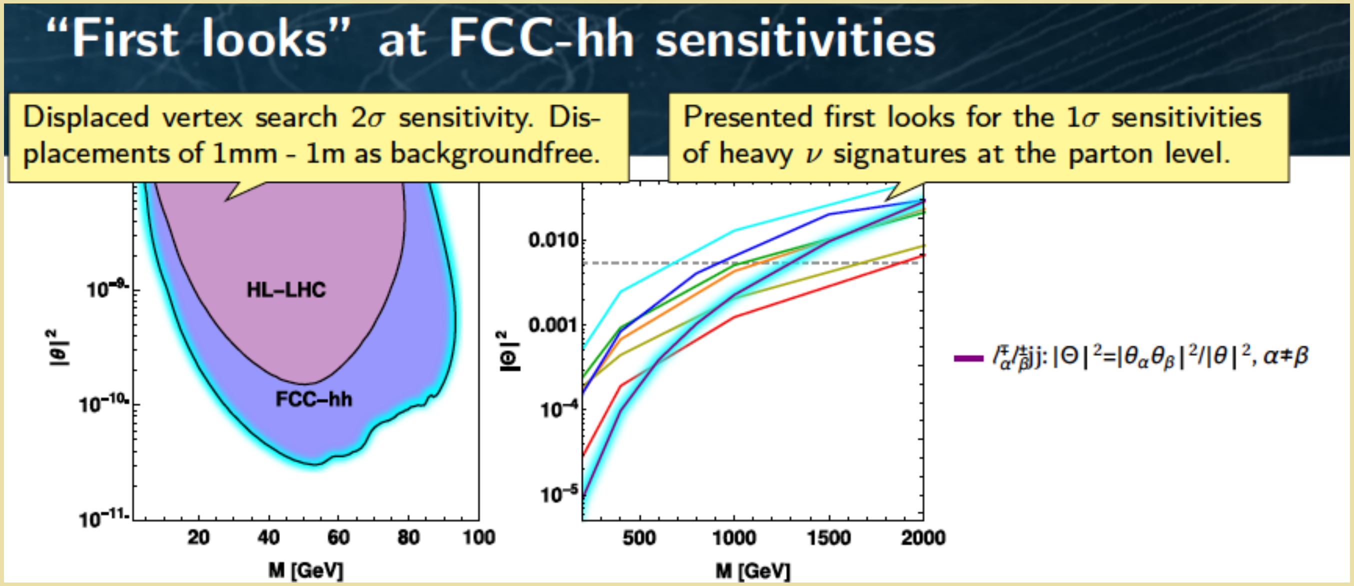
RH Sterile Neutrinos

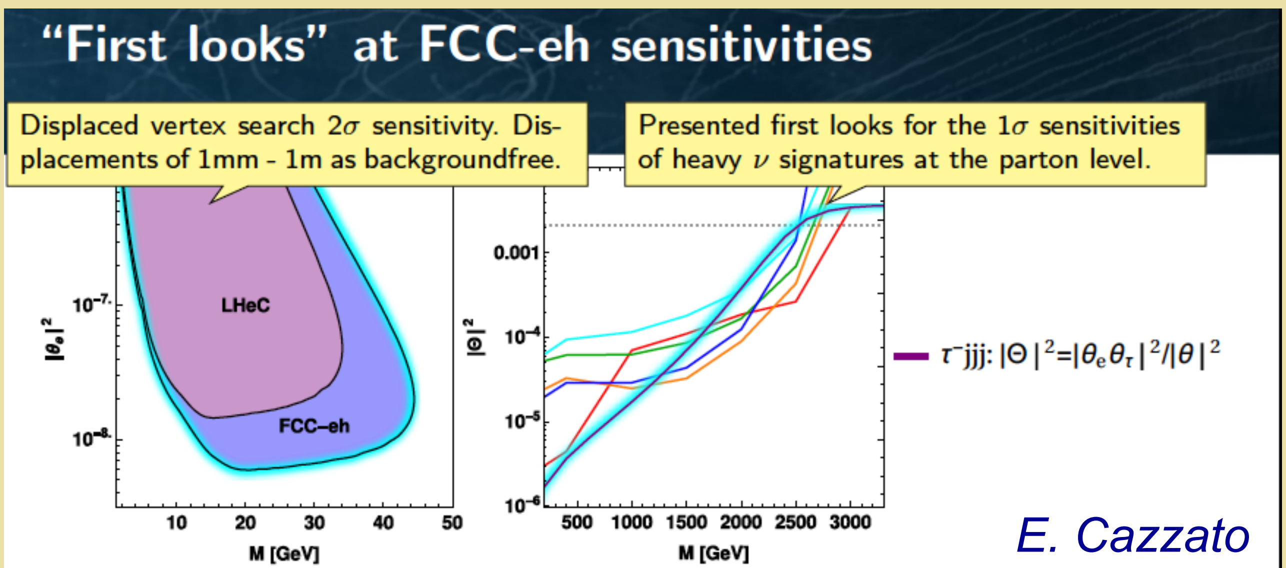
Systematic assessment of heavy neutrino signatures at colliders



E. Cazzato

RH Sterile Neutrinos



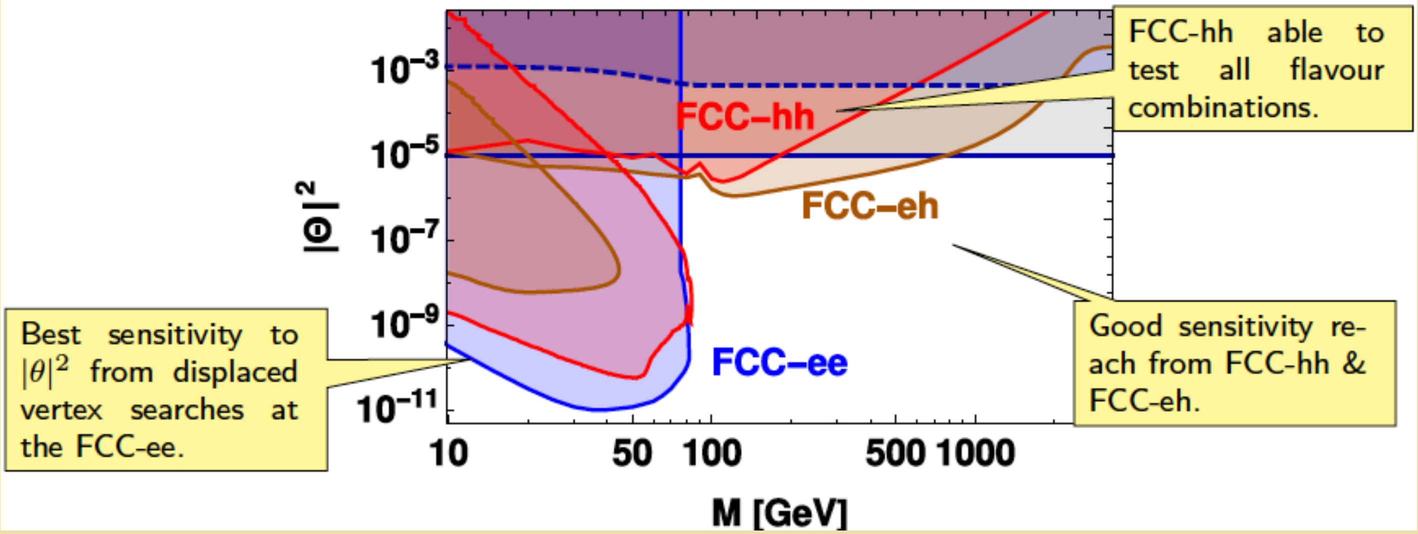


E. Cazzato

RH Sterile Neutrinos

Summary

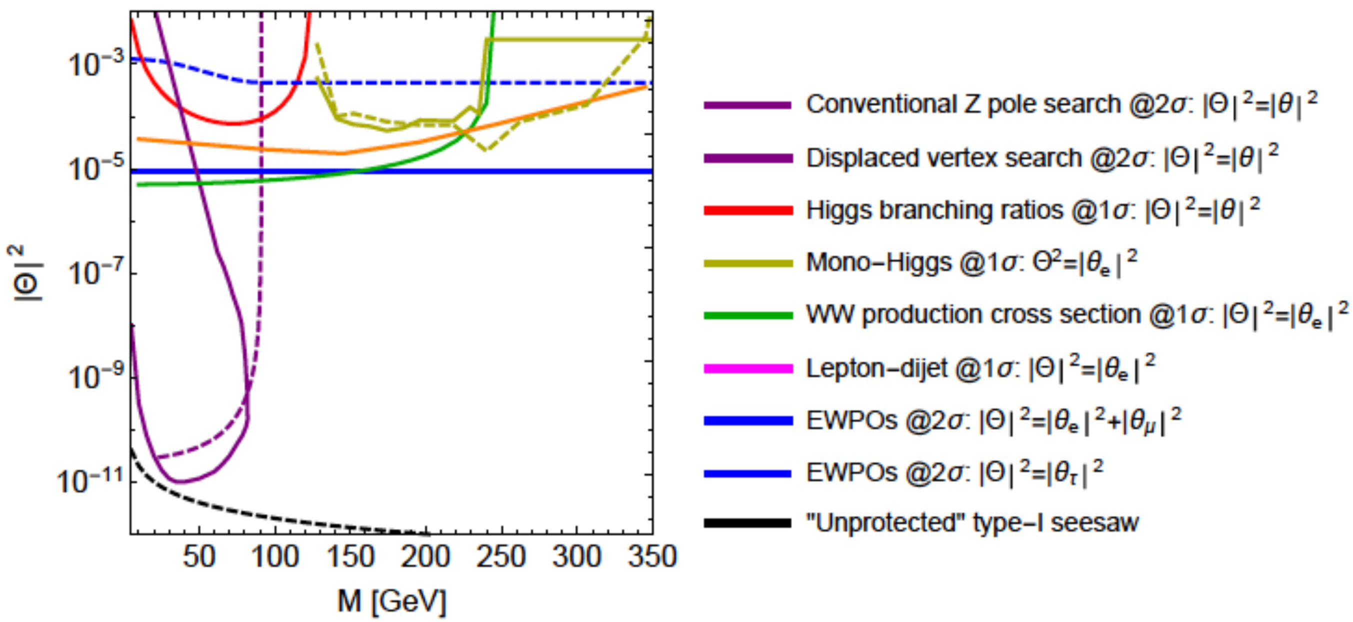
- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search



E. Cazzato

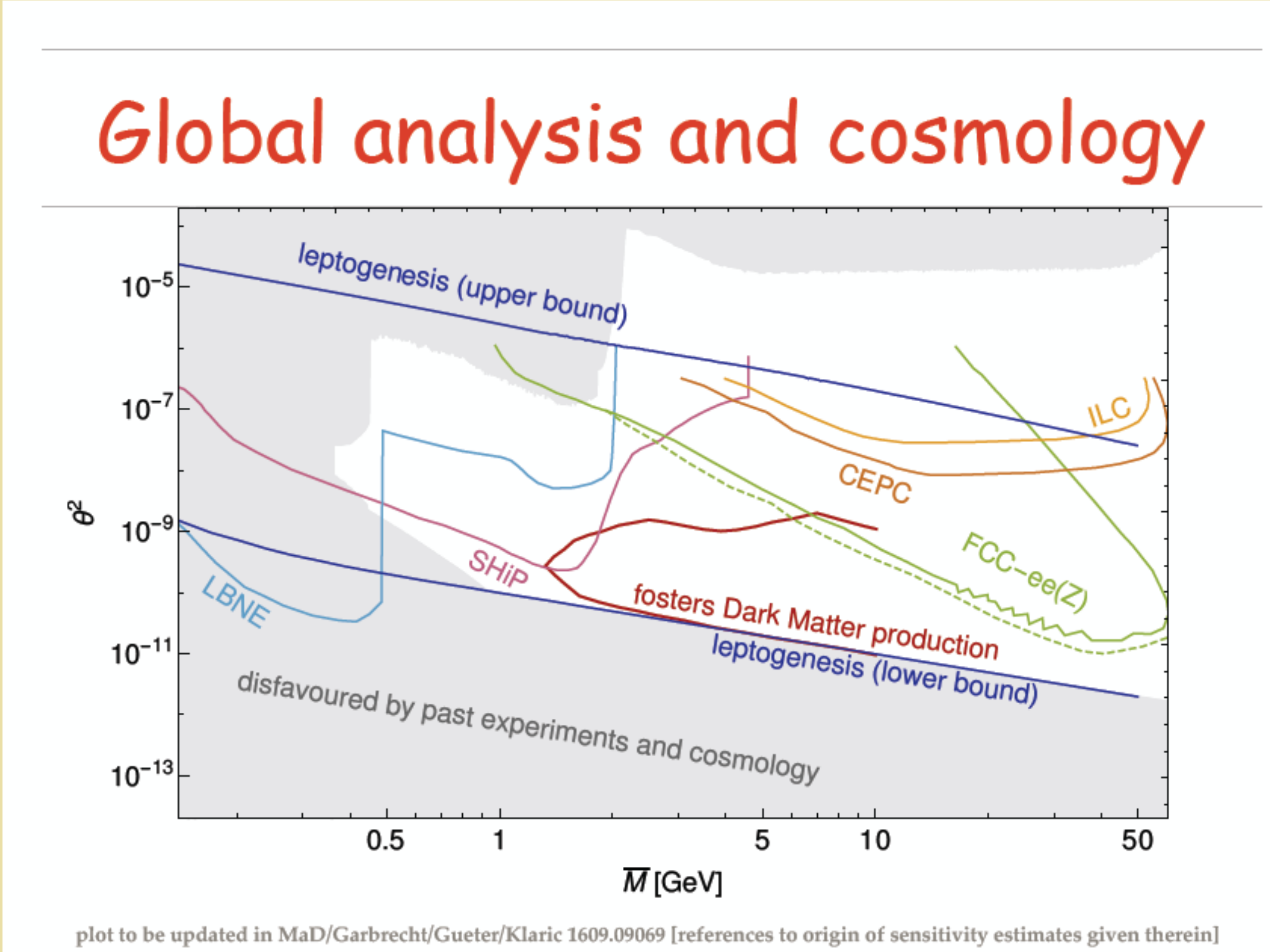
RH Sterile Neutrinos

Summary: FCC-ee sensitivities



- Displaced vertex searches test $|\theta|^2 \sim 10^{-11}$ for $M \leq m_W$.
- EWPOs test $|\theta|^2 \sim 10^{-5}$ up to $M \sim 60$ TeV with $\mathcal{O}(1)$ Yukawa couplings.

RH Sterile Neutrinos



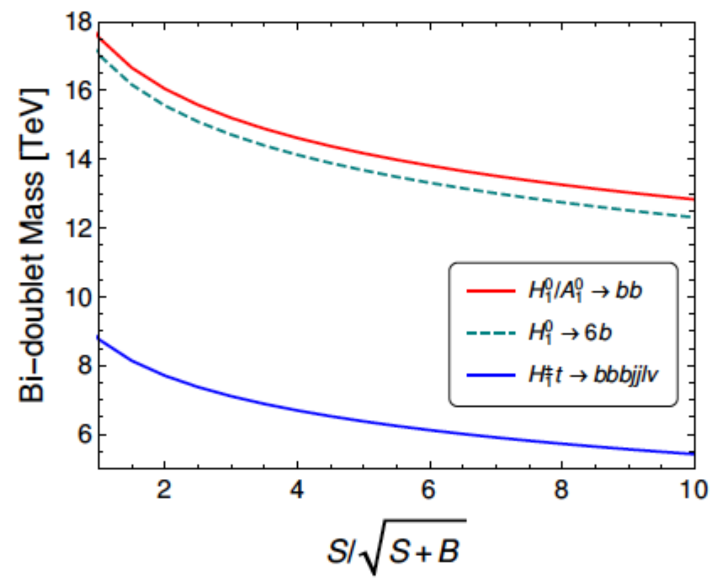
New Scalars & m_ν

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \;\Big\Downarrow\; \Delta_R\,(\mathbf{1},\mathbf{3},2) \quad \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}}\Delta_R^+ \end{pmatrix} \Rightarrow H_3^0,\, H_2^{\pm\pm}$$

$$SU(2)_L \times U(1)_Y \;\Big\Downarrow\; \Phi\,(\mathbf{2},\mathbf{2},0) \quad \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow h,\, H_1^0,\, A_1^0,\, H_1^\pm$$

$$U(1)_{\mathrm{EM}}$$

$\sqrt{s} = 100$ TeV, $\mathcal{L} = 30$ ab^{-1}



3σ sensitivities: $\{15.2\,\mathrm{TeV},\ 14.7\,\mathrm{TeV},\ 7.1\,\mathrm{TeV}\}$

New Scalars & m_ν

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \;\Big\Downarrow\; \Delta_R(\mathbf{1},\mathbf{3},2) \qquad \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}}\Delta_R^+ \end{pmatrix} \Rightarrow H_3^0,\, H_2^{\pm\pm}$$

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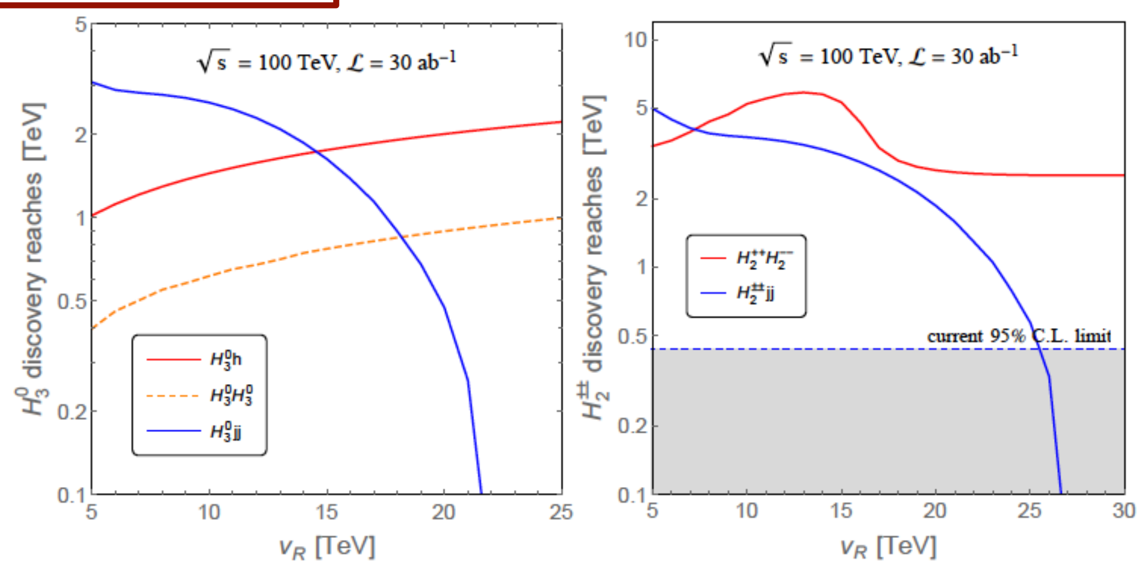
$$U(1)_{\rm EM}$$

Majorana mass



- Probable at the few-TeV scale, depending on the RH scale v_R.
- The SM Higgs portal production of H_3^0 depends also on the quartic couplings.
- Bump structure in the right panel: $\Rightarrow Z_R$ resonance.

Y. Zhang

Neutrino Mass

- *Value added*

Extend reach significantly beyond HL-LHC

- *Synergy/complementarity*

Probe different regions of (M_N , θ) space; produce new scalars; LNV & LFV @ FCC-hh

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

Leptogenesis-viable region ?

V. Outlook - 1

- ***FCC will provide an exciting opportunity to significantly extend the reach in mass scale and precision, addressing key open questions in fundamental physics***

- ***Different modes (pp, e^+e^-, e^-p) are richly complementary***

- ***There is considerable room for additional theoretical and experimental study***

V. Outlook - 2

Complementarity table to be completed and revised!

Proposed physics topics to be used in the study of synergy/complementarity among experiments at FCC-hh/ee/eh

Subject		ee	hh	he
Higgs Physics	precision studies higher dimension operators composite Higgs rare and exotic decays multiple Higgs production extra Higgs bosons			
Interface with Cosmology	Dark matter baryogenesis right-handed/(almost) sterile neutrinos			
Electroweak Sym. Breaking	WW scattering supersymmetry extra dimensions composite models			
Flavour Changing	rare H,Z,W,top decays lepton flavor violation			
Extensions of the SM	extra vector-like fermions $SU(2)_R$ models leptoquarks			
QCD	Perturbation theory, structure functions Modelling final states			
EW/SM precision issues	precision measts (m_Z,m_W,m_t,α,$\alpha_s(m_Z)$,$\sin^2\theta_W$.R_b... higher-order EW corrections W,Z triple and quadruple couplings top (anomalous) couplings charm/bottom flavor studies			

V. Outlook - 2

Complementarity — table to be completed and revised!

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We are starting to fill in the blanks !

A. Blondel

V. Outlook - 2

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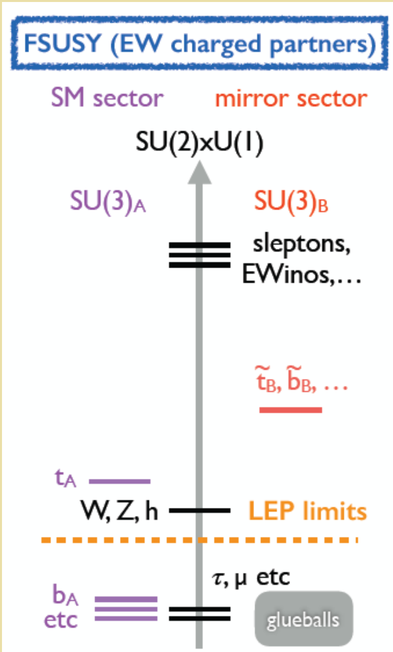
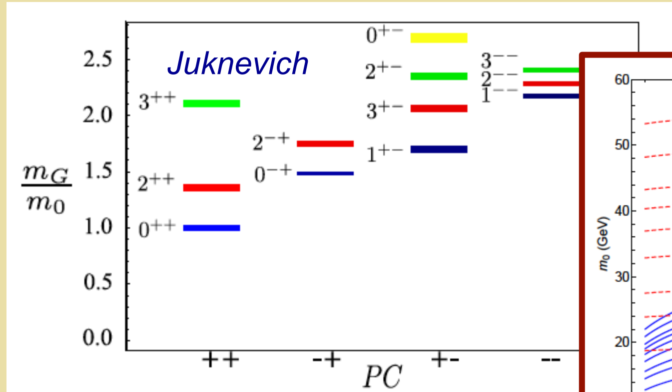
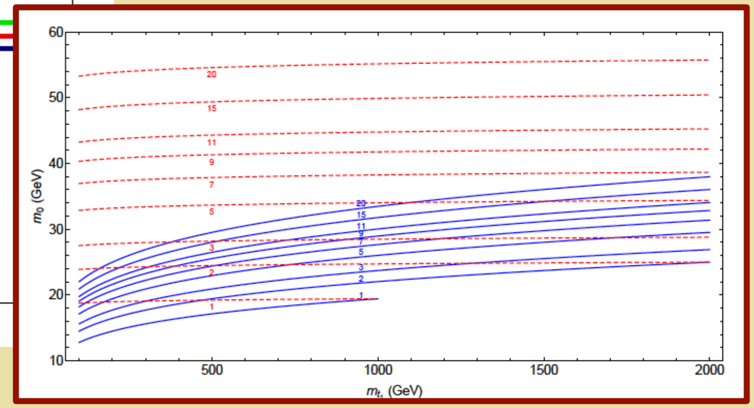
We are starting to fill in the blanks !
New contributions welcome !

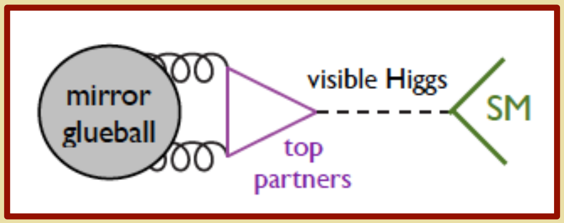
Back Up

Solutions w/ LLP's: Neutral Naturalness

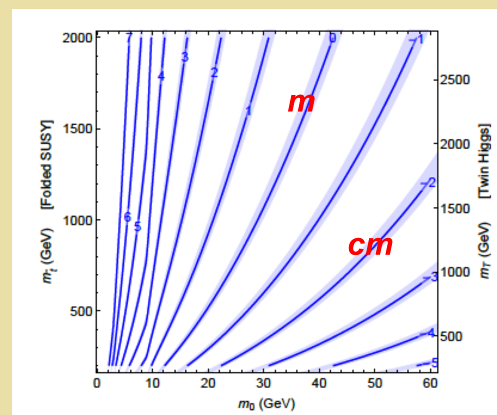






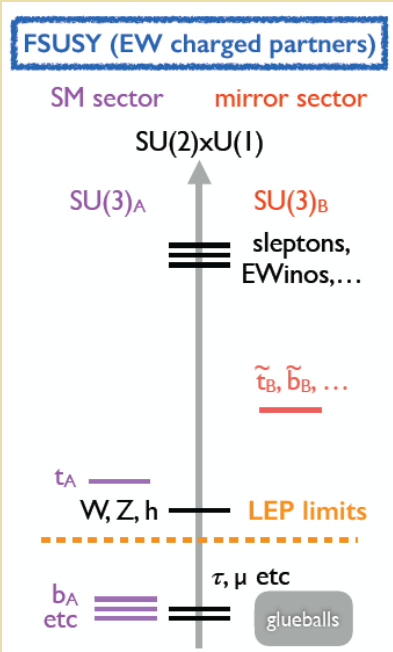


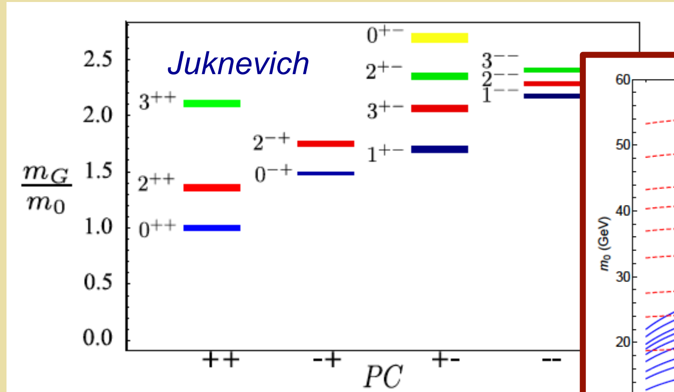
$$\Gamma_{0++} \sim m_0^7/(M^4 m_h^2)$$

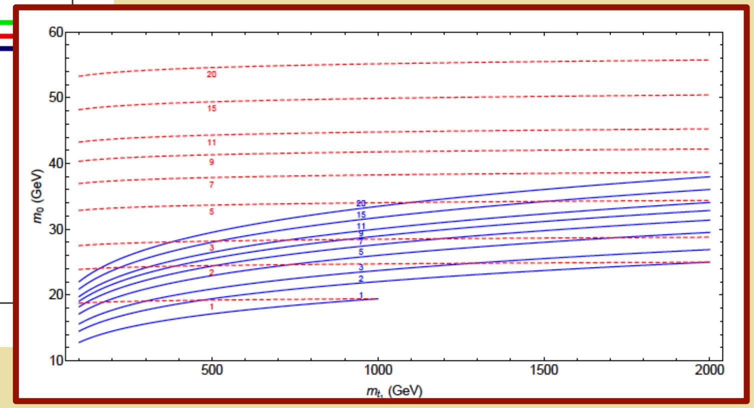


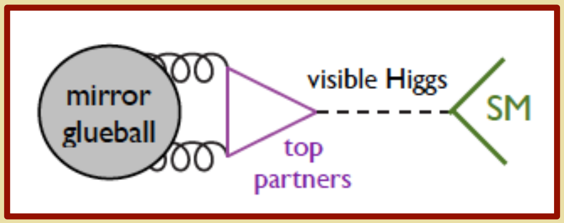
D. Curtin, C. Verhaaren

Solutions w/ LLP's: Neutral Naturalness

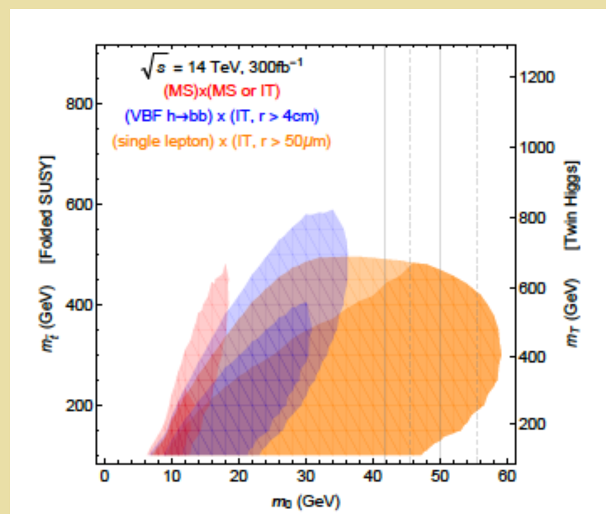






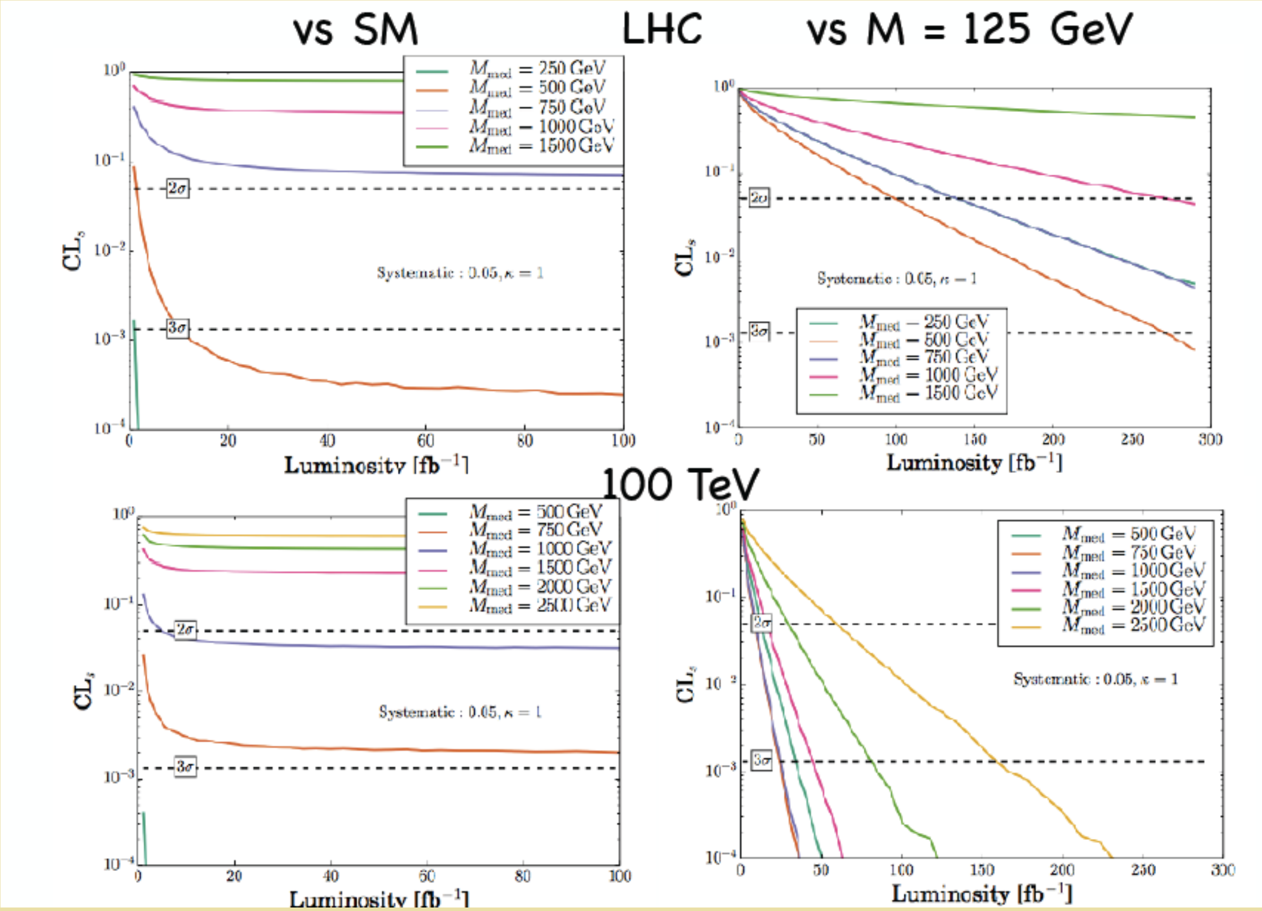


Exotic Higgs decays: $h \to 0^{++}\,0^{++}$
w/ 2 DV's or 1 DV +…



D. Curtin,
C. Verhaaren

Dark Sector: Mediators



M. Spannowsky