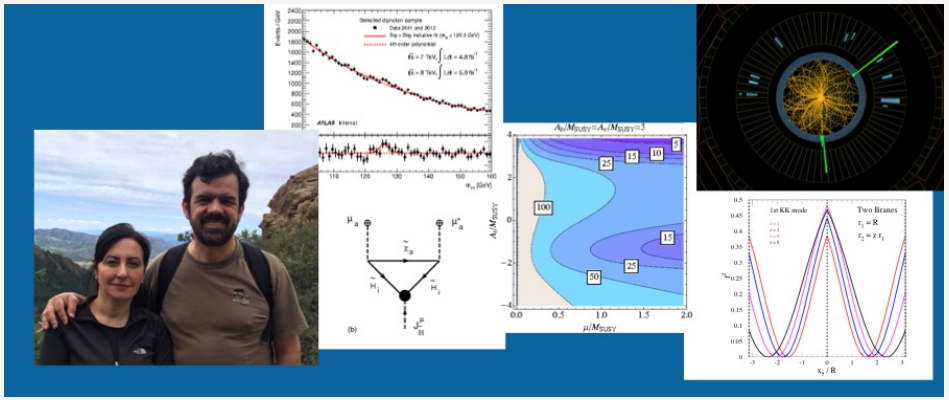
Supersymmetry
&
the Electroweak Phase Transition



Nausheen R. Shah

WAYNE STATE UNIVERSITY

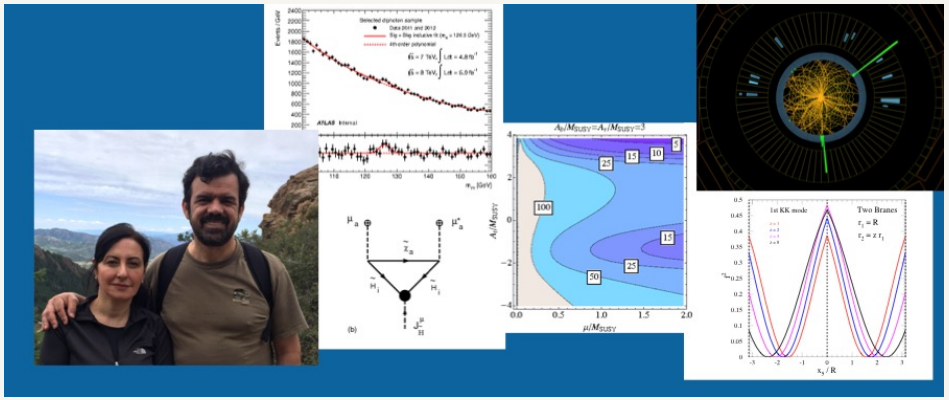
Beyond the SM:
From Colliders to the Early Universe

[Marcela-Carlos Fest 2023]

U. of Chicago & Fermilab

Supersymmetry

&



Life Transitions

Student 5

WAYNE STATE UNIVERSITY

Beyond the SM:
From Colliders to the Early Universe

[Marcela-Carlos Fest 2023]

U. of Chicago & Fermilab

Happy Birthday
60th
Marcela & Carlos

My physics mentors: SUSY, Electroweak phase transition, Higgs …

But SO MUCH MORE: My LIFE mentors

The Beginning (for me!)

(Already broke "First Golden Rule of Happiness" before I met Carlos)

NO SUSY!!

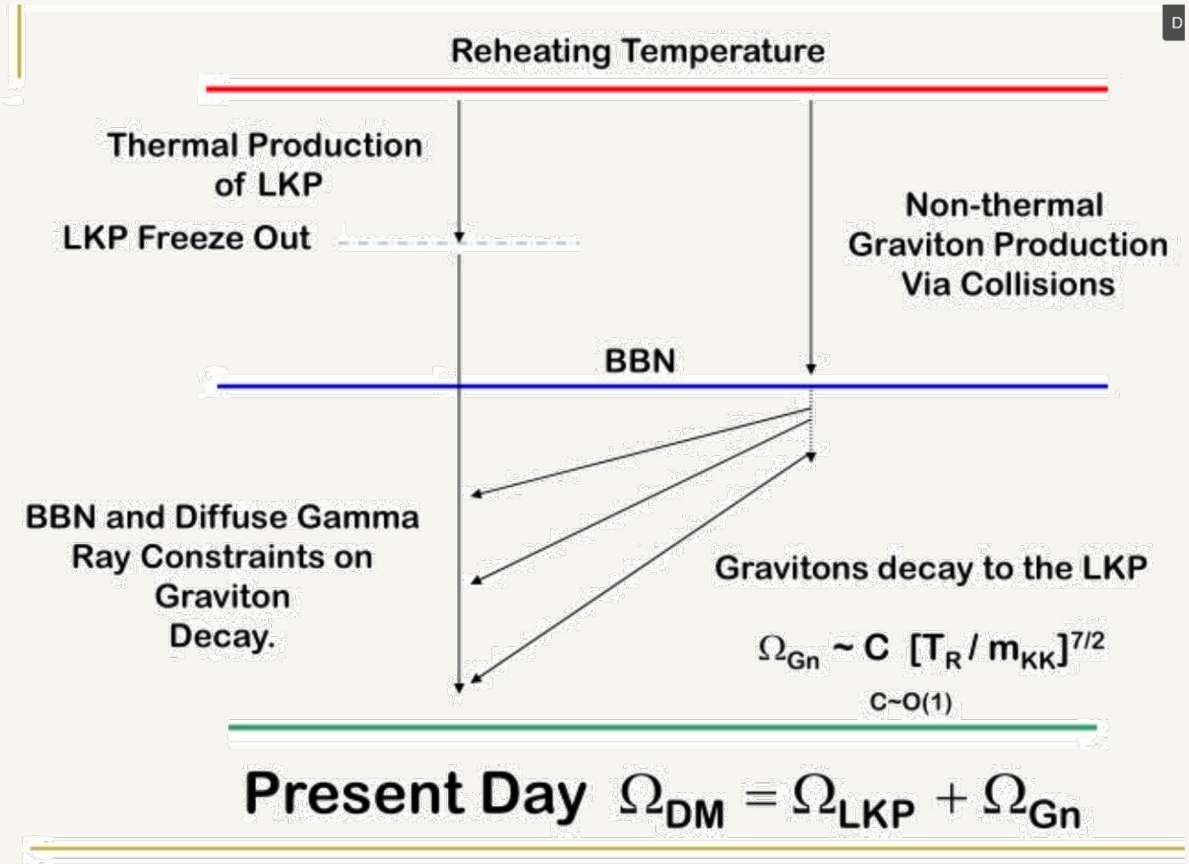
Extra Dimensions:

Universal → Warped
Dark Matter + Higgs
(Of Course!)

DM & UED

Gravitons and dark matter in universal extra dimensions

Nausheen R. Shah and Carlos E. M. Wagner
Phys. Rev. D **74**, 104008 – Published 2 November 2006



FREEZE-IN *before* there was freeze-in!

(slide from one of the first talks I ever gave!!)

Sensitive Feet!

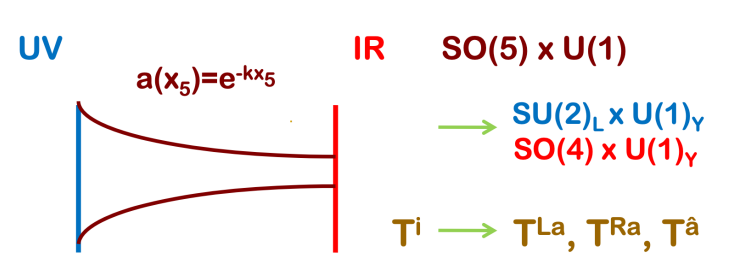
Before the age of smart phones!

First pictures I could find with Carlos

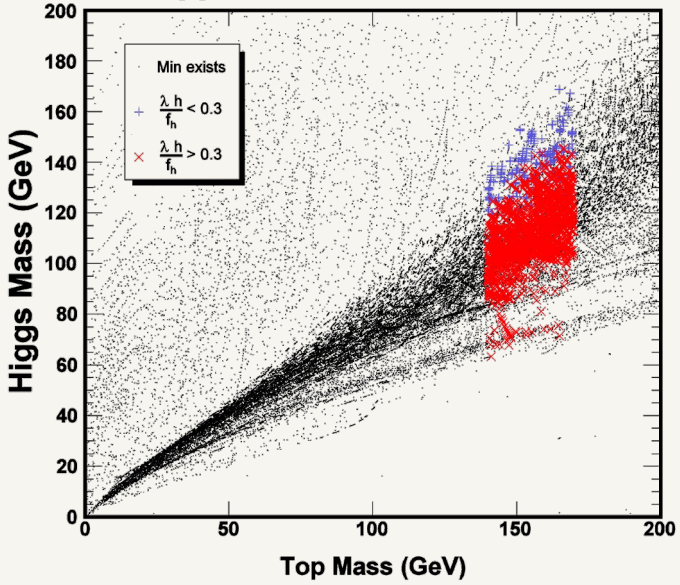
2009 – THE THESIS:

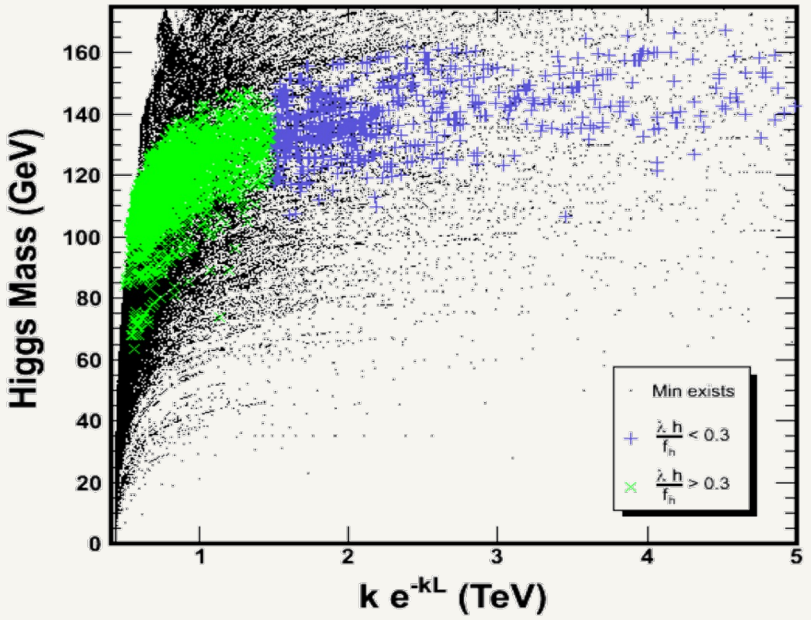
Carena, Medina, Panes, Shah, Wagner '07-'09

Gauge-Higgs Unification Phenomenology in Warped Extra Dimensions.



Top mass vs. Higgs Mass





SM Limit: $\lambda h / f_h \ll 1$

(Broke the “Second Golden Rule for Happiness”)

And there was a *little* SUSY…

Heavy Higgs boson with a light sneutrino next-to-lightest supersymmetric particle in the MSSM with enhanced $SU(2)$ D-terms

Anibal D. Medina, Nausheen R. Shah, and Carlos E. M. Wagner
Phys. Rev. D **80**, 015001 – Published 6 July 2009

UChicago → FNAL

FINALLY SUSY:

Renormalization Group Invariants in the MSSM (our most ignored masterpiece ☹)

Carena, Draper, Lykken, Sekmen, Shah, Wagner, '10 -'12

Table I: 1-Loop RG Invariants in the MSSM

RGI	Definition in Terms of Soft Masses	MGM(M)	GGM(M)	CMSSM+NUHM(M)
$D_{B_{13}}$	$2(m^2_{\tilde{Q}_1} - m^2_{\tilde{Q}_3}) - m^2_{\tilde{u}_1} + m^2_{\tilde{u}_3} - m^2_{\tilde{d}_1} + m^2_{\tilde{d}_3}$	0	0	0
$D_{L_{13}}$	$2(m^2_{\tilde{L}_1} - m^2_{\tilde{L}_3}) - m^2_{\tilde{e}_1} + m^2_{\tilde{e}_3}$	0	0	0
D_{X1}	$3(3m^2_{\tilde{d}_1} - 2(m^2_{\tilde{Q}_1} - m^2_{\tilde{L}_1}) - m^2_{\tilde{u}_1}) - m^2_{\tilde{e}_1}$	0	0	$5m_0^2$
$D_{Y_{13H}}$	$m^2_{\tilde{Q}_1} - 2m^2_{\tilde{u}_1} + m^2_{\tilde{d}_1} - m^2_{\tilde{L}_1} + m^2_{\tilde{e}_1}$ $-\frac{10}{13}\left(m^2_{\tilde{Q}_3} - 2m^2_{\tilde{u}_3} + m^2_{\tilde{d}_3} - m^2_{\tilde{L}_3} + m^2_{\tilde{e}_3} + m^2_{H_u} - m^2_{H_d}\right)$	$-\frac{10}{13}(\delta_u - \delta_d)$	$-\frac{10}{13}(\delta_u - \delta_d)$	$-\frac{10}{13}(\delta_u - \delta_d)$
D_Z	$3(m^2_{\tilde{d}_3} - m^2_{\tilde{d}_1}) + 2(m^2_{\tilde{L}_3} - m^2_{H_d})$	$-2\delta_d$	$-2\delta_d$	$-2\delta_d$
$I_{Y\alpha}$	$\left(m^2_{H_u} - m^2_{H_d} + \sum_{gen}(m^2_{\tilde{Q}} - 2m^2_{\tilde{u}} + m^2_{\tilde{d}} - m^2_{\tilde{L}} + m^2_{\tilde{e}})\right)/g_1^2$	$(\delta_u - \delta_d)/g_1^2$	$(\delta_u - \delta_d)/g_1^2$	$(\delta_u - \delta_d)/g_1^2$
I_{B_i}	M_i/θ_i^2	B	B_i	$m_{1/2}/\theta_i^2$
I_{M_1}	$M_1^2 - \frac{33}{8}(m^2_{\tilde{d}_1} - m^2_{\tilde{u}_1} - m^2_{\tilde{e}_1})$	$\frac{38}{5}g_1^4B^2$	$g_1^4\left(B_1^2 + \frac{33}{10}A_1\right)$	$m^2_{1/2} + \frac{33}{8}m_0^2$
I_{M_2}	$M_2^2 + \frac{1}{24}\left(9(m^2_{\tilde{d}_1} - m^2_{\tilde{u}_1}) + 16m^2_{\tilde{L}_1} - m^2_{\tilde{e}_1}\right)$	$2g_2^4B^2$	$g_2^4\left(B_2^2 + \frac{1}{2}A_2\right)$	$m^2_{1/2} + \frac{5}{8}m_0^2$
I_{M_3}	$M_3^2 - \frac{3}{16}(5m^2_{\tilde{d}_1} + m^2_{\tilde{u}_1} - m^2_{\tilde{e}_1})$	$-2g_3^4B^2$	$g_3^4\left(B_3^2 - \frac{3}{2}A_3\right)$	$m^2_{1/2} - \frac{15}{16}m_0^2$
I_{g_2}	$1/g_1^2 - 33/(5g_2^2)$	≈ -10.9	≈ -10.9	≈ -10.9
I_{g_3}	$1/g_1^2 + 11/(5g_3^2)$	≈ 6.2	≈ 6.2	≈ 6.2

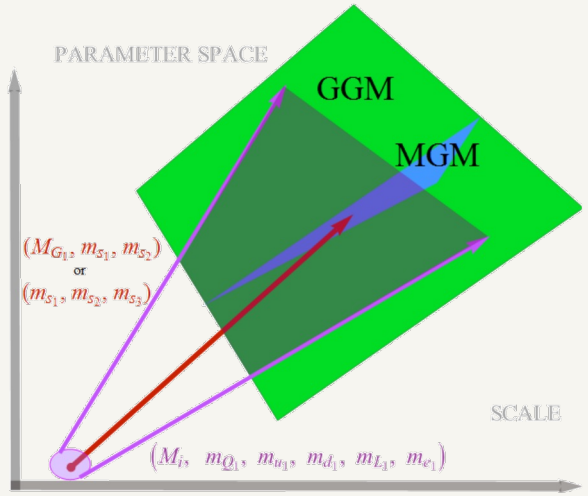
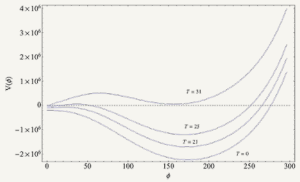


Figure 1: The green (light grey) region is GGM parameter space, extending over different A_r, B_r, δ_u, δ_d, and M. The blue (medium grey) region denotes the MGM subspace of GGM, with universal A_r and B_r constrained to satisfy the relationship $A = 2B^2$. Using the RGIs and assuming a high scale MGM structure, low scale experimental measurements of only 3 soft masses (small red circle at low scale), including at least 2 scalar masses, can determine consistent B and messenger scale values (middle red arrow). Low scale measurement of all the gauginos and the first generation masses (purple shaded oval at low scale), on the other hand, leads to the determination of a consistent region of GGM parameter space (shaded region between outer purple arrows).



PHASE TRANSITIONS

Marcela & Carlos: ~20 papers on Elctroweak phase transitions/Baryogenesis.

Light Dark Matter and the Electroweak Phase Transition in the NMSSM

#33

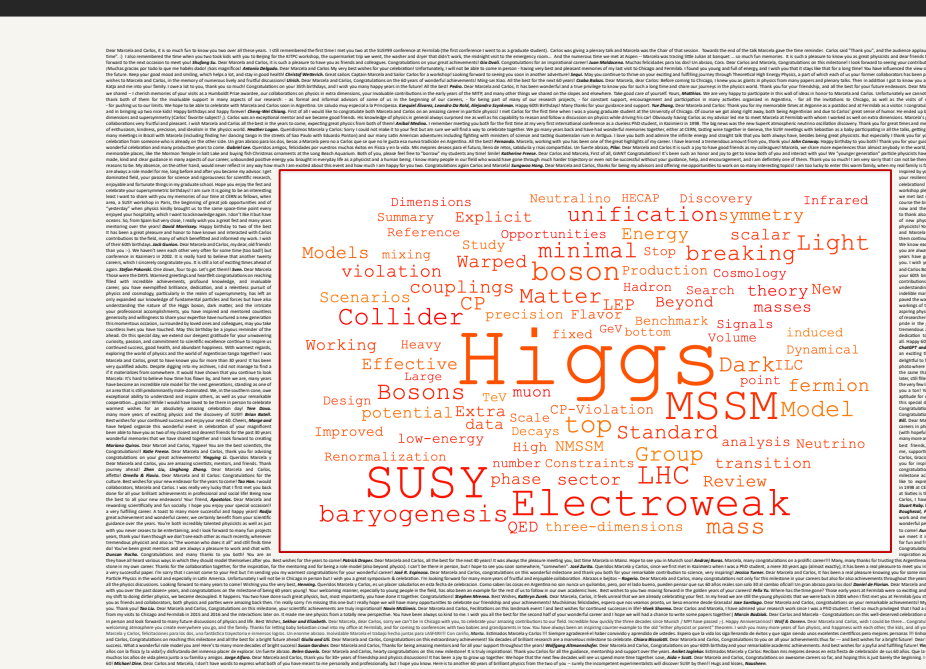
Marcela Carena (Fermilab and Chicago U., EFI), Nausheen R. Shah (Fermilab), Carlos E.M. Wagner (Argonne and Chicago U., EFI and Chicago U., KICP) (Oct, 2011)

Published in: *Phys.Rev.D* 85 (2012) 036003 • e-Print: 1110.4378 [hep-ph]

pdf links DOI cite claim reference search 72 citations

We analyze the stability of the vacuum and the electroweak phase transition in the NMSSM close to the Peccei-Quinn symmetry limit. This limit contains light Dark Matter (DM) particles with a mass significantly smaller than the weak scale and also light CP-even and CP-odd Higgs bosons. Such light particles lead to a consistent relic density and facilitate a large spin-independent direct DM detection cross section, that may accommodate the recently reported signatures at the DAMA and CoGeNT experiments. Studying the one-loop effective potential at finite tem-

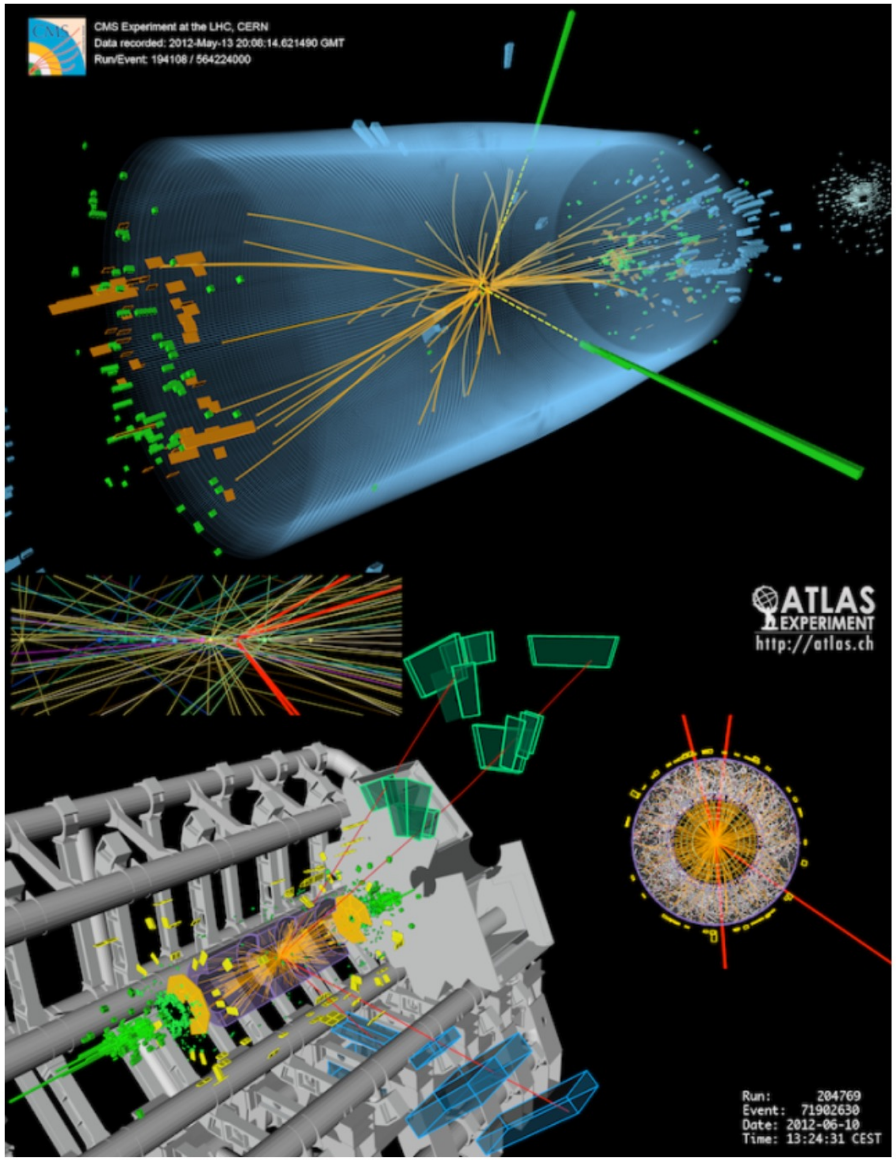
Unfortunately excess didn't survive ☹



You may have noticed a certain preoccupation with ...

HIGGS

https://home.cern/science/physics/higgs-boson/how



Candidate Higgs boson events from collisions between protons in the LHC. The top event in the CMS experiment shows a decay into two photons (dashed yellow lines and green towers). The lower event in the ATLAS experiment shows a decay into four muons (red tracks) (Image: CMS/ATLAS/CERN)

Higgs DISCOVERY!!

Dec 2011: Hints of enhanced H --> γγ!!!

July 2012: Higgs!!!

Light Stops

Light Staus

Light Stops AND Staus!!

A 125 GeV SM-like Higgs in the MSSM and the $\gamma\gamma$ rate

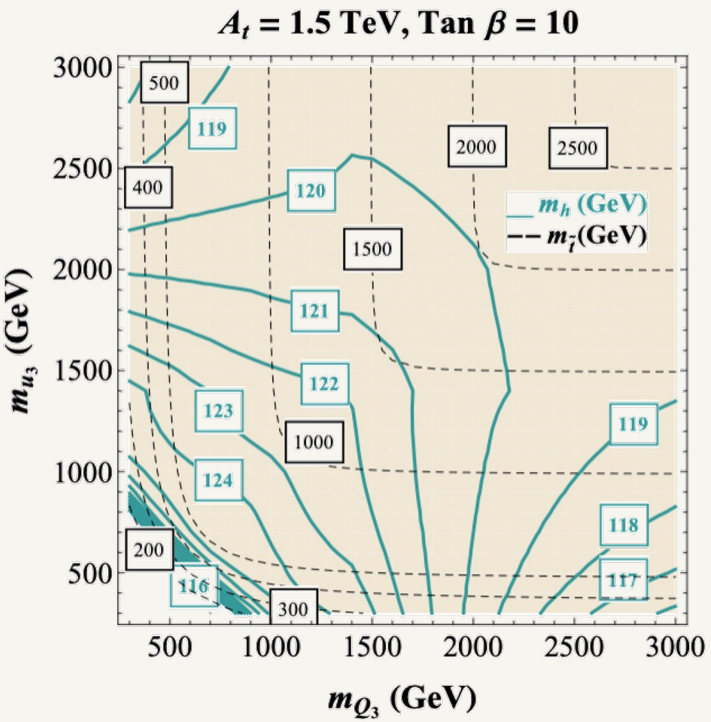
#32

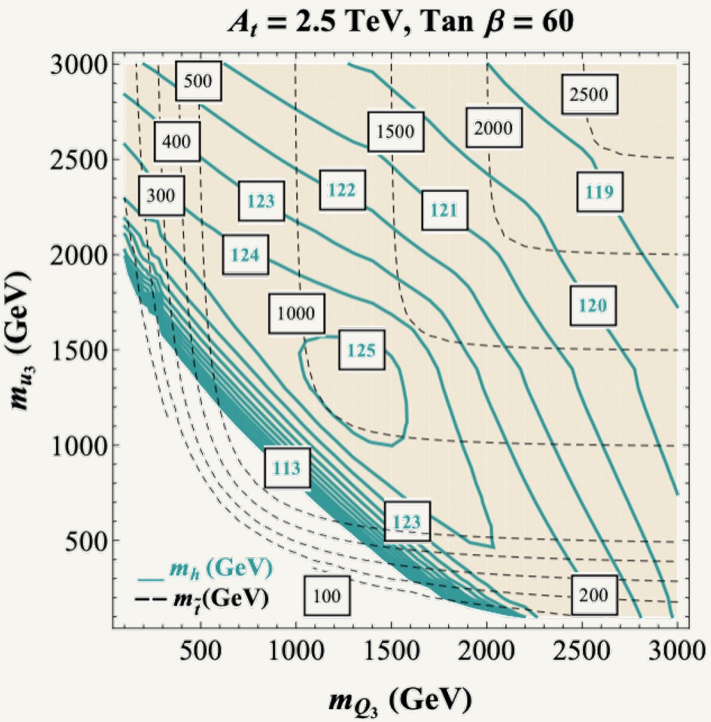
Marcela Carena (Chicago U., EFI and Fermilab), Stefania Gori (Chicago U., EFI and Argonne), Nausheen R. Shah (Fermilab), Carlos E.M. Wagner (Chicago U., EFI and Argonne and Chicago U., KICP) (Dec, 2011)

Published in: *JHEP* 03 (2012) 014 • e-Print: 1112.3336 [hep-ph]

pdf links DOI cite claim reference search 428 citations

Stefania and I didn't sleep for a week!!





50th!!

Cannot find pics of Marcela's awesome 50th Bday party celebration

Or Higgs Discovery party at 4 am!!

(Marcela & Carlos house!!)

Light Stops, Light Staus and the 125 GeV Higgs

#27

Marcela Carena (Fermilab and Chicago U., EFI and Chicago U., KICP), Stefania Gori (Argonne and Chicago U., EFI), Nausheen R. Shah (Michigan U., MCTP), Carlos E.M. Wagner (Chicago U., EFI and Chicago U., KICP and Argonne), Lian-Tao Wang (Chicago U., EFI and Chicago U., KICP) (Mar 18, 2013)

Published in: *JHEP* 08 (2013) 087 • e-Print: 1303.4414 [hep-ph]

pdf links DOI cite claim reference search 61 citations

Light Stops

Indirect Probes of the MSSM after the Higgs Discovery

#28

Wolfgang Altmannshofer (Fermilab), Marcela Carena (Chicago U., KICP and Chicago U., EFI and Fermilab), Nausheen R. Shah (Michigan U., MCTP), Felix Yu (Fermilab) (Nov, 2012)

Published in: *JHEP* 01 (2013) 160 • e-Print: 1211.1976 [hep-ph]

pdf links DOI cite claim reference search 123 citations

Light Staus

Vacuum Stability and Higgs Diphoton Decays in the MSSM

#29

Marcela Carena (Fermilab and Chicago U., EFI and Chicago U., KICP), Stefania Gori (Argonne and Chicago U., EFI), Ian Low (Argonne and Northwestern U. and Santa Barbara, KITP), Nausheen R. Shah (Michigan U., MCTP), Carlos E.M. Wagner (Chicago U., EFI and Chicago U., KICP and Argonne) (Nov, 2012)

Published in: *JHEP* 02 (2013) 114 • e-Print: 1211.6136 [hep-ph]

pdf links DOI cite claim reference search 93 citations

Light Stops AND Staus!!

Light Stau Phenomenology and the Higgs $\gamma\gamma$ Rate

#30

Marcela Carena (Chicago U., EFI and Fermilab), Stefania Gori (Chicago U., EFI and Argonne), Nausheen R. Shah (Fermilab), Carlos E.M. Wagner (Chicago U., EFI and Argonne and Chicago U., KICP), Lian-Tao Wang (Chicago U., EFI and Chicago U., KICP) (May, 2012)

Published in: *JHEP* 07 (2012) 175 • e-Print: 1205.5842 [hep-ph]

pdf links DOI cite claim reference search 209 citations

And Heavy Higgs


ES&H

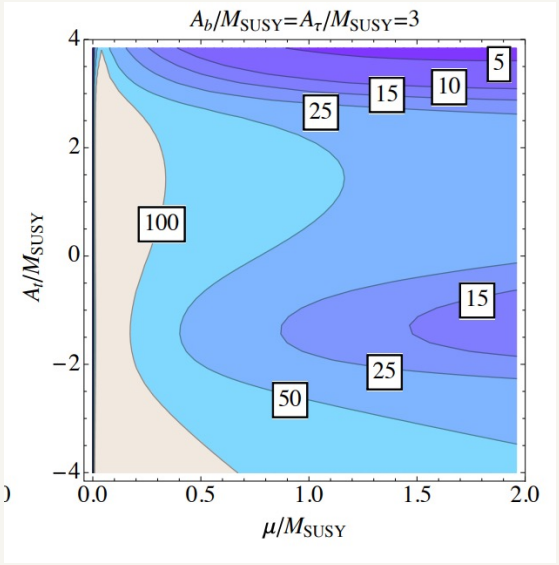
FNAL
Daycare
Graduate!!

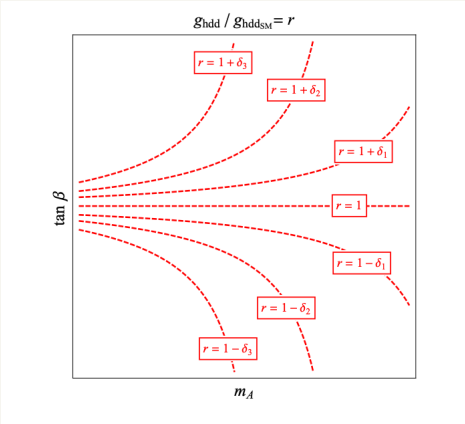
FAMILY!

BUT THE HIGGS …

… IT LOOKS SM - LIKE …

The Story of ALIGNMENT





KITP (Santa Barbara) → Aspen
2013 -- 2016

Impersonating the Standard Model Higgs Boson: Alignment without Decoupling #25

Marcela Carena (Fermilab and Chicago U., EFI and Chicago U., KICP), Ian Low (Santa Barbara, KITP and Argonne and Northwestern U.), Nausheen R. Shah (Michigan U., MCTP), Carlos E.M. Wagner (Chicago U., EFI and Chicago U., KICP and Argonne) (Oct 8, 2013)

Published in: *JHEP* 04 (2014) 015 • e-Print: 1310.2248 [hep-ph]

pdf links DOI cite claim reference search 250 citations

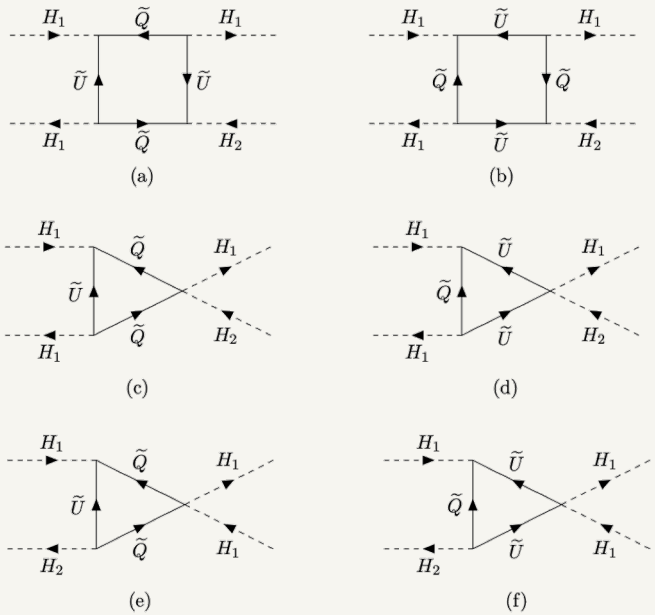
Complementarity between Nonstandard Higgs Boson Searches and Precision Higgs Boson Measurements in the MSSM

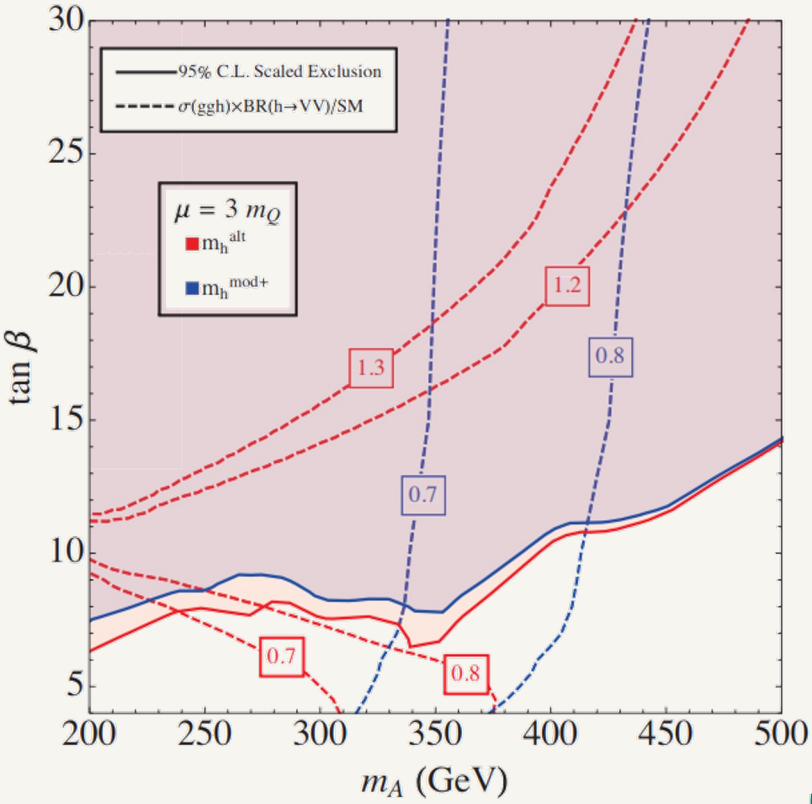
#23

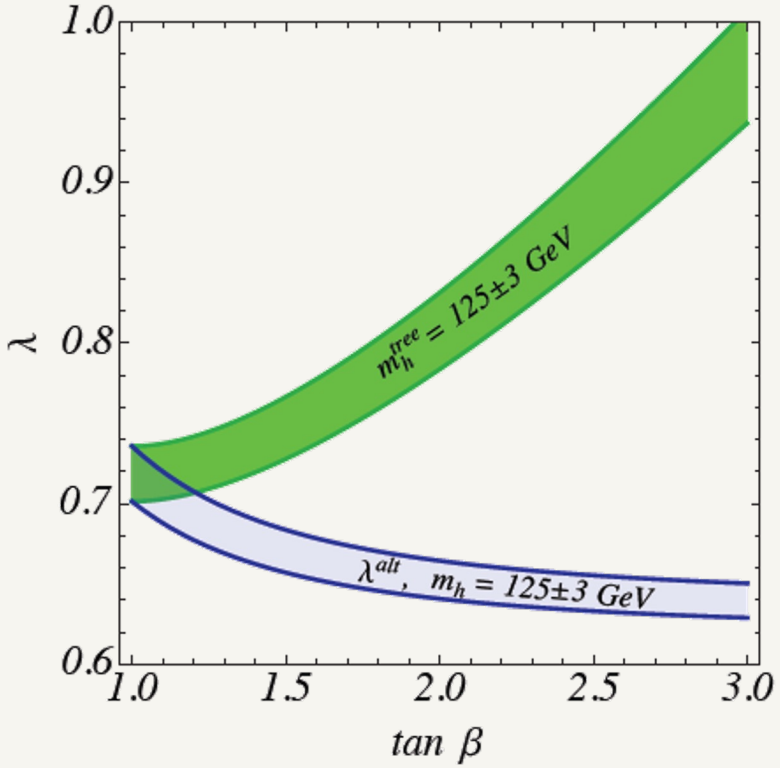
Marcela Carena (Fermilab and Chicago U., EFI and Chicago U., KICP), Howard E. Haber (UC, Santa Cruz, Inst. Part. Phys. and LBNL, Berkeley), Ian Low (Argonne and Northwestern U.), Nausheen R. Shah (Michigan U., MCTP), Carlos E. M. Wagner (Chicago U., EFI and Chicago U., KICP and Argonne) (Oct 18, 2014)

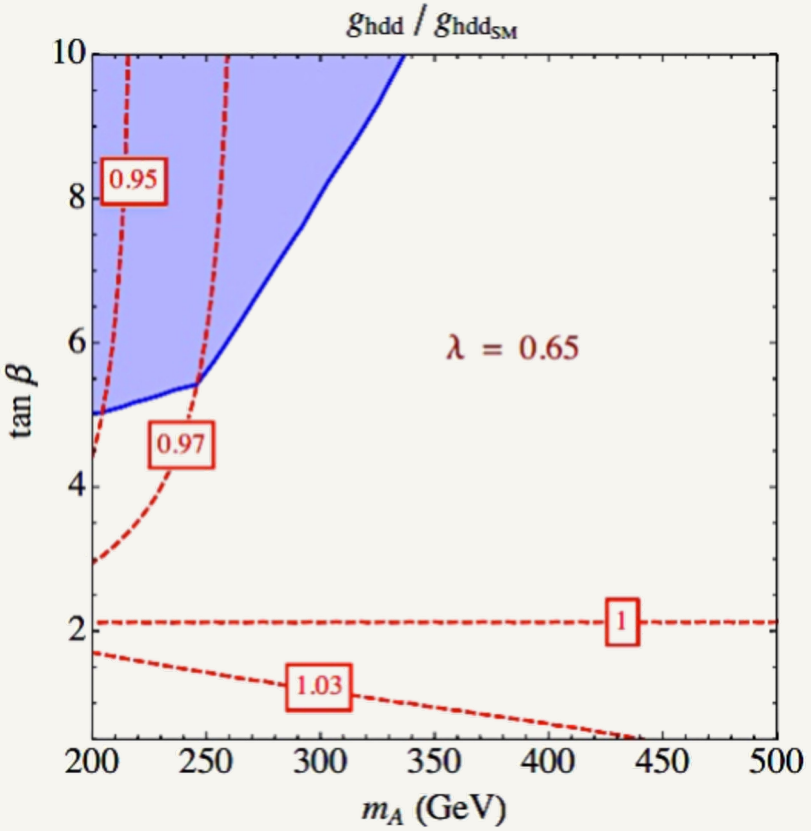
Published in: *Phys.Rev.D* 91 (2015) 3, 035003 • e-Print: 1410.4969 [hep-ph]

pdf links DOI cite claim reference search 96 citations









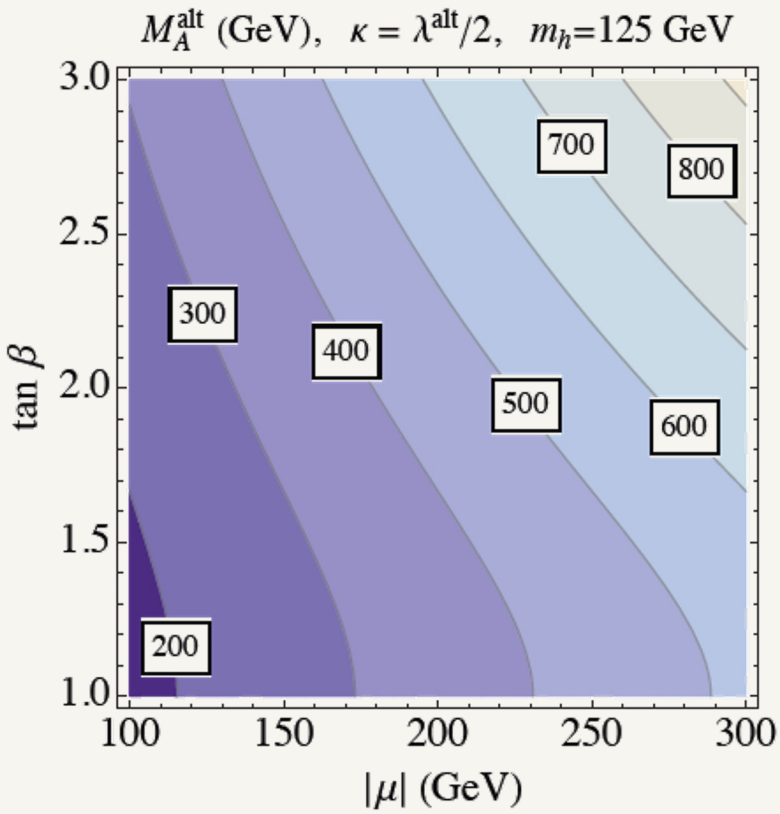
Alignment limit of the NMSSM Higgs sector

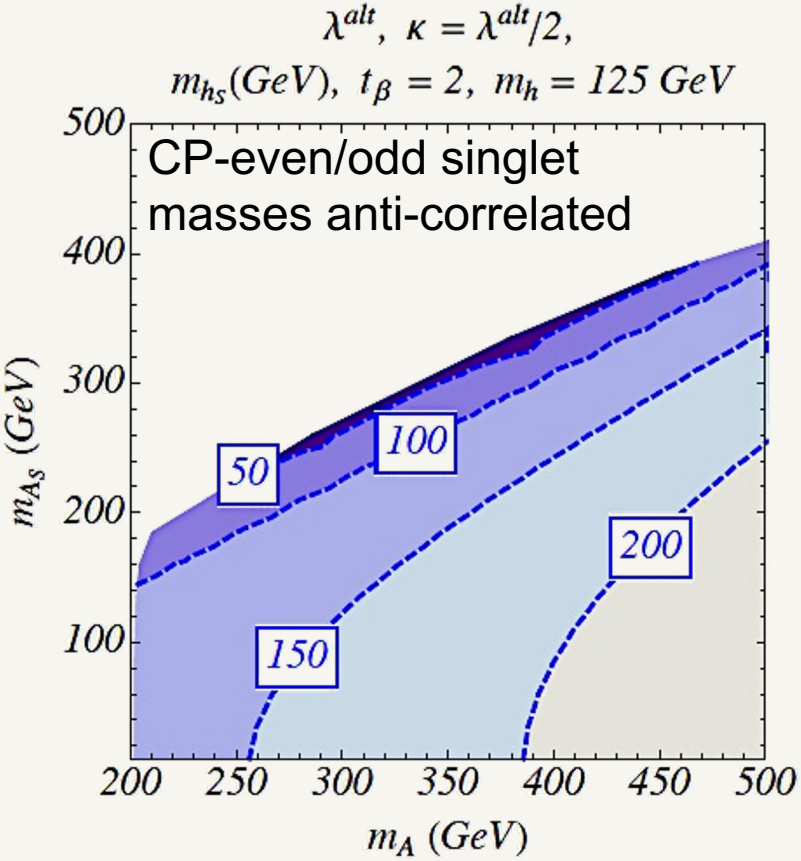
#20

Marcela Carena (Chicago U., EFI and Chicago U., KICP and Fermilab), Howard E. Haber (UC, Santa Cruz, Inst. Part. Phys.), Ian Low (Argonne and Northwestern U.), Nausheen R. Shah (Michigan U., MCTP and Wayne State U.), Carlos E. M. Wagner (Argonne and Chicago U., KICP and Chicago U., EFI) (Oct 30, 2015)

Published in: *Phys.Rev.D* 93 (2016) 3, 035013 • e-Print: 1510.09137 [hep-ph]

pdf links DOI cite claim reference search 85 citations





$$1 - \frac{m_A^2}{4\mu^2} s_{2\beta}^2 - \frac{\kappa}{2\lambda} s_{2\beta} = 0$$

Singlet Alignment

$h_{125} = H_{SM}$

LIGHT SPECTRUM

Singlino: **$2\,\kappa\,\mu/\lambda \sim < \mu$**

Aspen Higgs working Group 2015
(missing Ian ☹)

Ooops

UMich → Wayne State

Therein breaking "Third and FINAL Golden Rule" for happiness!!

Chasing Anomalies …

Double peak searches for scalar and pseudoscalar resonances at the LHC

Marcela Carena (Chicago U., EFI and Chicago U., KICP and Fermilab), Peisi Huang (Chicago U., EFI and Argonne), Ahmed Ismail (Argonne and Illinois U., Chicago and Santa Barbara, KITP), Ian Low (Argonne and Northwestern U.), Nausheen R. Shah (Wayne State U.) et al. (Jun 21, 2016)

Published in: *Phys.Rev.D* 94 (2016) 11, 115001 • e-Print: 1606.06733 [hep-ph]

Supersymmetry and LHC Missing Energy Signals

Marcela Carena (Fermilab and Chicago U., EFI and Chicago U., KICP), James Osborne (Wayne State U.), Nausheen R. Shah (Wayne State U.), Carlos E.M. Wagner (Chicago U., EFI and Chicago U., KICP and Argonne) (Sep 28, 2018)

Published in: *Phys.Rev.D* 98 (2018) 11, 115010 • e-Print: 1809.11082 [hep-ph]

Return of the WIMP: Missing energy signals and the Galactic Center excess

Marcela Carena (Chicago U., EFI and Chicago U., KICP and Fermilab), James Osborne (Wayne State U.), Nausheen R. Shah (Wayne State U.), Carlos E.M. Wagner (Argonne and Chicago U., EFI and Chicago U., KICP) (May 9, 2019)

Published in: *Phys.Rev.D* 100 (2019) 5, 055002 • e-Print: 1905.03768 [hep-ph]

The tiny (g-2) muon wobble from small-μ supersymmetry

Sebastian Baum (Stanford U., ITP), Marcela Carena (Fermilab and Chicago U., EFI and Chicago U., KICP), Nausheen R. Shah (Wayne State U.), Carlos E.M. Wagner (Chicago U., EFI and Chicago U., KICP and Argonne) (Apr 7, 2021)

Published in: *JHEP* 01 (2022) 025 • e-Print: 2104.03302 [hep-ph]

And Other Cool Things …

Higgs portals for thermal Dark Matter. EFT perspectives and the NMSSM

#15

Sebastian Baum (Royal Inst. Tech., Stockholm and Stockholm U., OKC and Nordita), Marcela Carena (Fermilab and Chicago U., EFI and Chicago U., KICP), Nausheen R. Shah (Wayne State U.), Carlos E.M. Wagner (Chicago U., EFI and Chicago U., KICP and Argonne) (Dec 28, 2017)

Published in: *JHEP* 04 (2018) 069 • e-Print: 1712.09873 [hep-ph]

ν solution to the strong CP problem

#10

Marcela Carena (Fermilab and Chicago U., EFI and Chicago U., KICP), Da Liu (Argonne), Jia Liu (Chicago U., EFI and Chicago U., KICP), Nausheen R. Shah (Wayne State U.), Carlos E.M. Wagner (Chicago U., EFI and Chicago U., KICP and Argonne) et al. (Apr 10, 2019)

Published in: *Phys.Rev.D* 100 (2019) 9, 094018 • e-Print: 1904.05360 [hep-ph]

Nucleation is more than critical: A case study of the electroweak phase transition in the NMSSM

Yikun's Talk

Sebastian Baum (Stanford U., ITP), Marcela Carena (Fermilab and Chicago U., EFI and Chicago U., KICP), Nausheen R. Shah (Wayne State U.), Carlos E.M. Wagner (Chicago U., EFI and Chicago U., KICP and Argonne), Yikun Wang (Fermilab and Chicago U., EFI and Chicago U., KICP) (Sep 22, 2020)

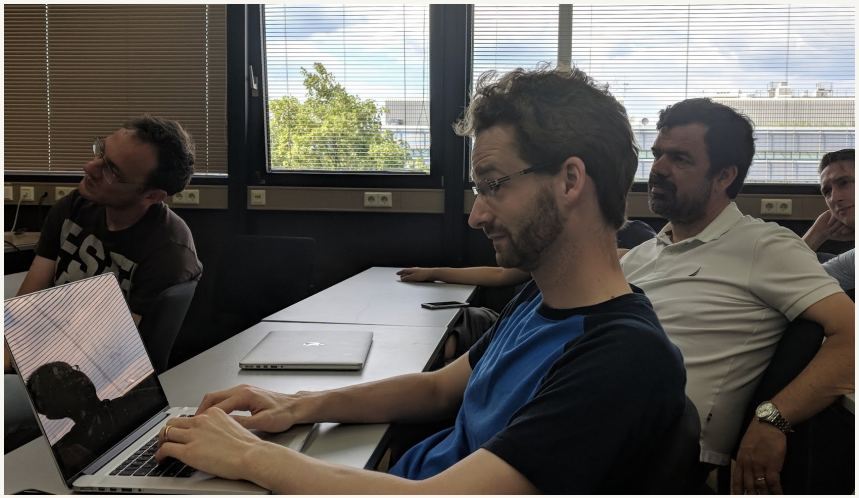
Published in: *JHEP* 03 (2021) 055, *JHEP* 03 (2021) 055 • e-Print: 2009.10743 [hep-ph]

Lighting up the LHC with Dark Matter

Sebastian Baum (Stanford U., ITP), Marcela Carena (Fermilab and Chicago U., EFI and Chicago U., Astron. Astrophys. Ctr. and Chicago U., KICP), Tong Ou (Chicago U., EFI), Duncan Rocha (Chicago U., EFI), Nausheen R. Shah (Wayne State U.) et al. (Mar 2, 2023)

e-Print: 2303.01523 [hep-ph]


ller-H



"Dear Carlos and Marcela, I don't have words to express what both of you have meant to me personally and professionally, but I hope you know. Here is to another 60 years of brilliant physics from the two of you -- surely the incompetent experimentalists will discover SUSY by then!! Hugs and kisses,"

Nausheen.