Theory summary

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U. Chicago

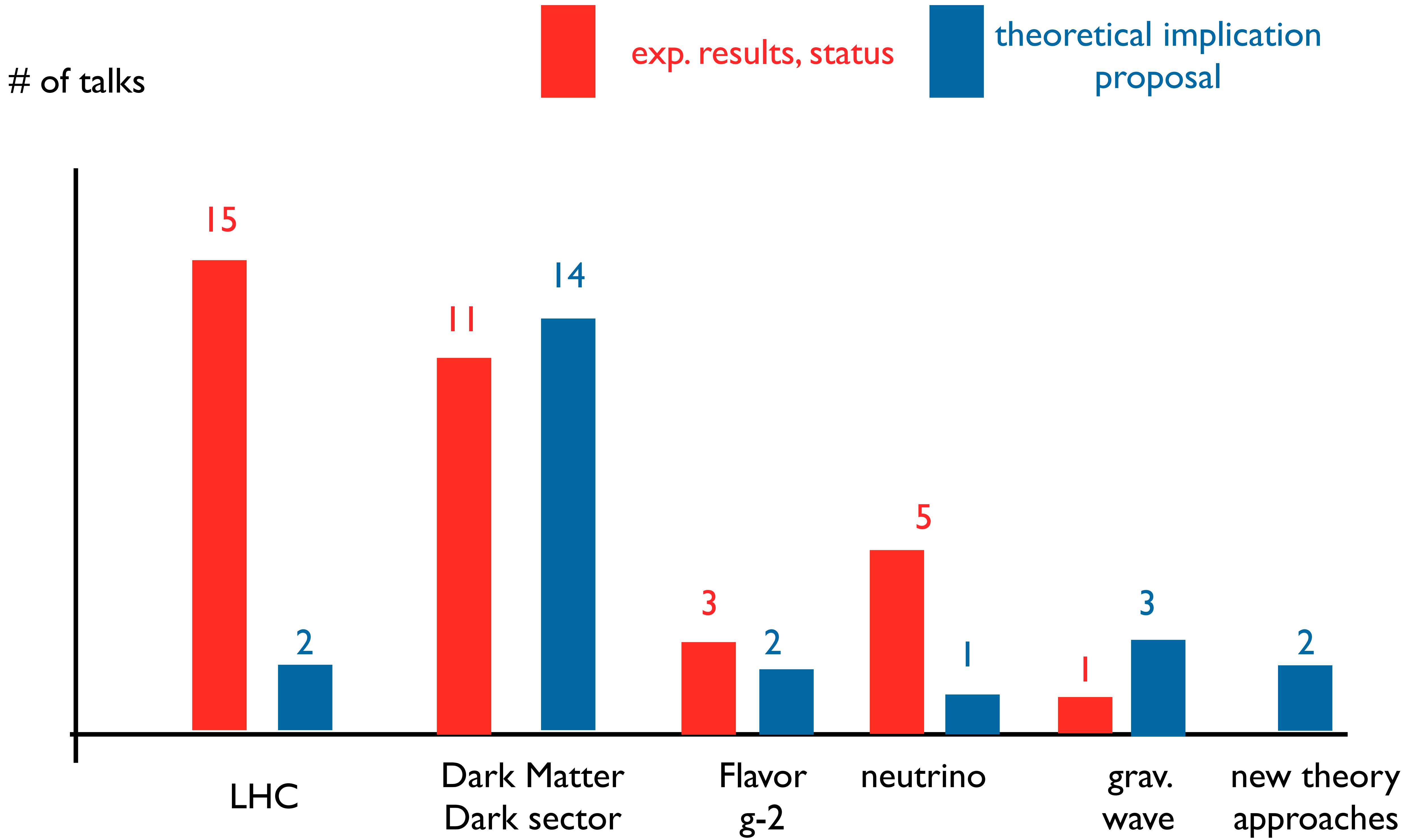
Aspen Winter Conference. March 31, 2018

Won't be able to properly summarize everything.

Lack of time and expertise.

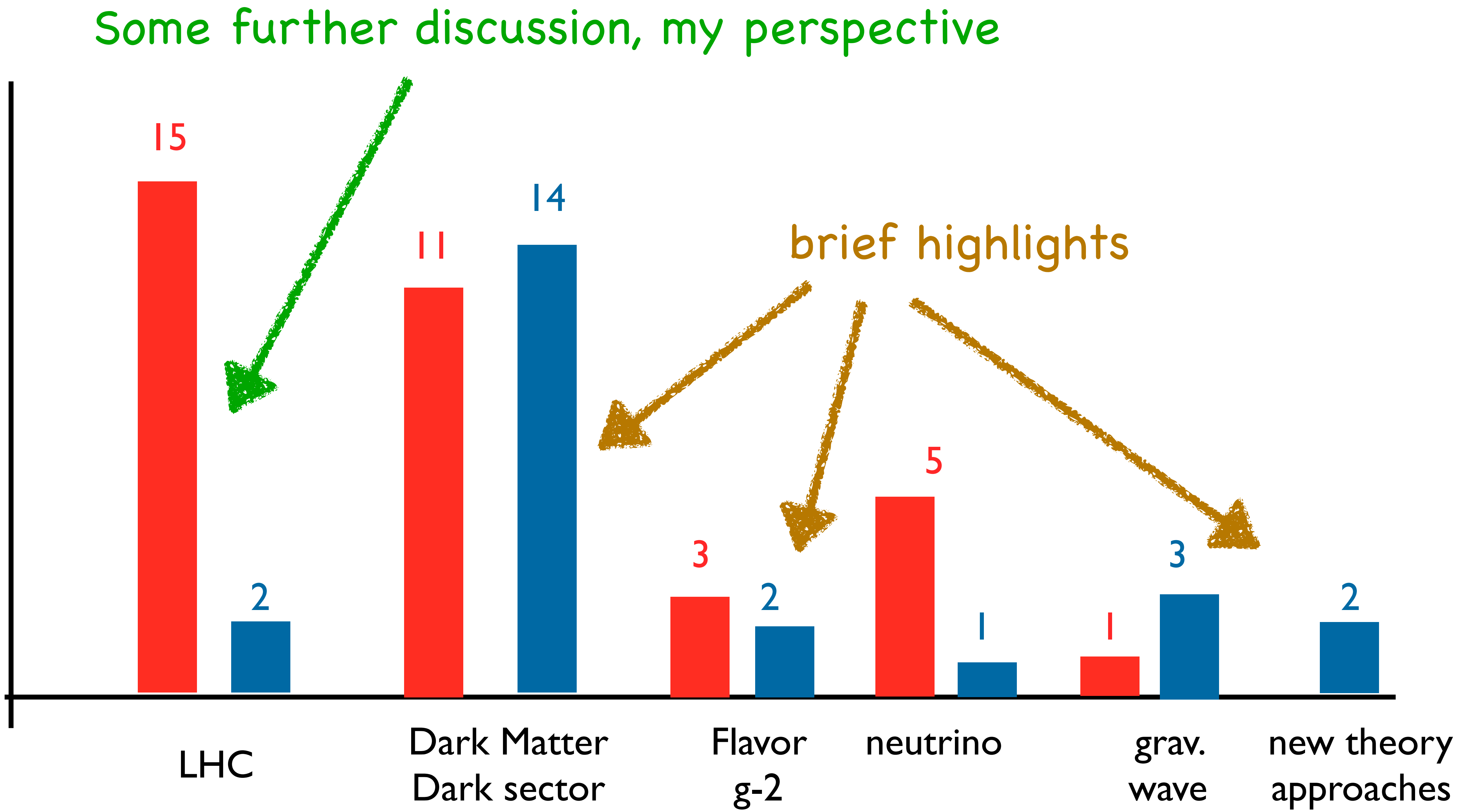
My apologies for omissions and misrepresentations.

This conference



A reflection of trend in theory (?).

This talk



Some further discussion, my perspective
brief highlights
15
2
11
14
3
2
5
1
1
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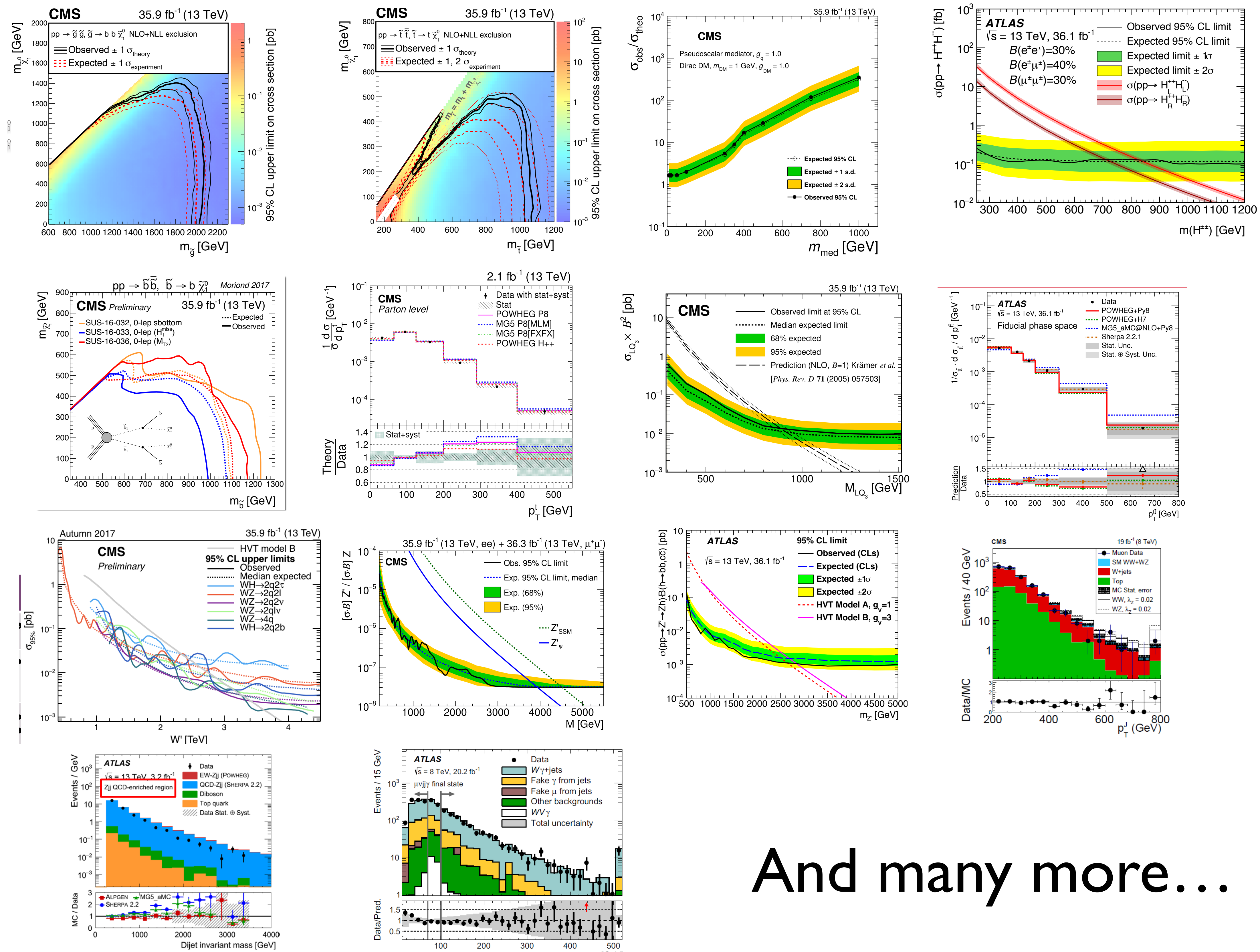
2
LHC
Dark Matter
Dark sector
Flavor
g-2
neutrino
grav.
wave
new theory
approaches

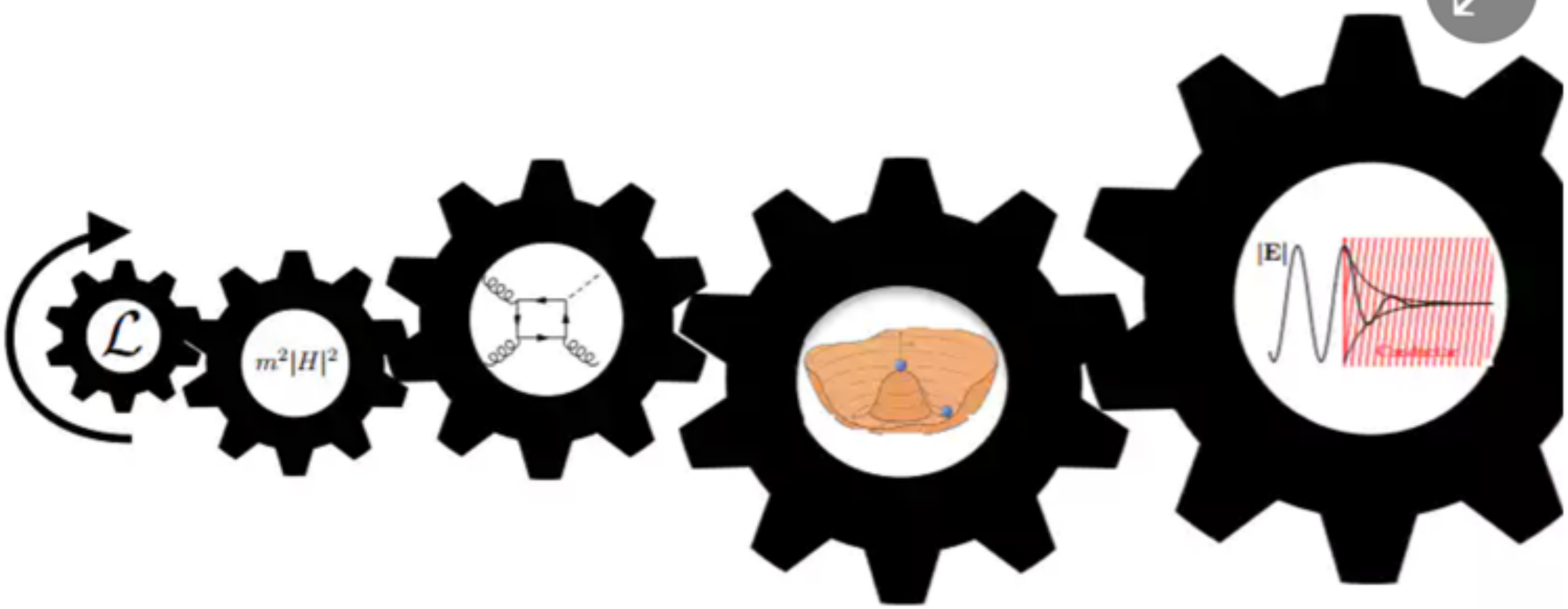
Many LHC results presented here



And many more…

From gravity to the Higgs we're still waiting for new physics

Annual physics jamboree Rencontres de Moriond has a history of revealing exciting results from colliders, and this year new theories and evidence abound



Guardian

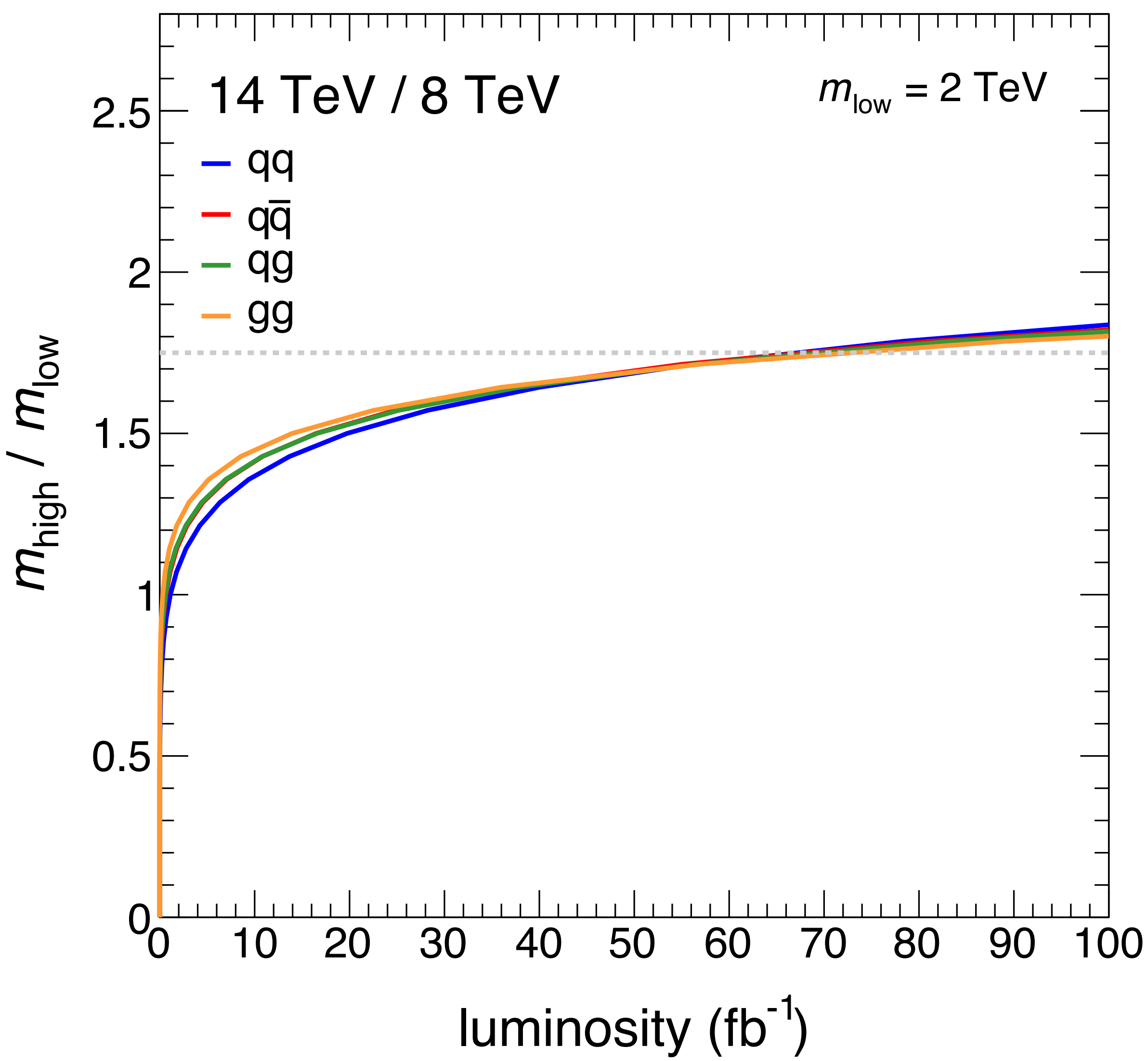
Road ahead:

LHC is pushing ahead.

Exp. collaborations are pursuing a broad and comprehensive physics program.

As data accumulates

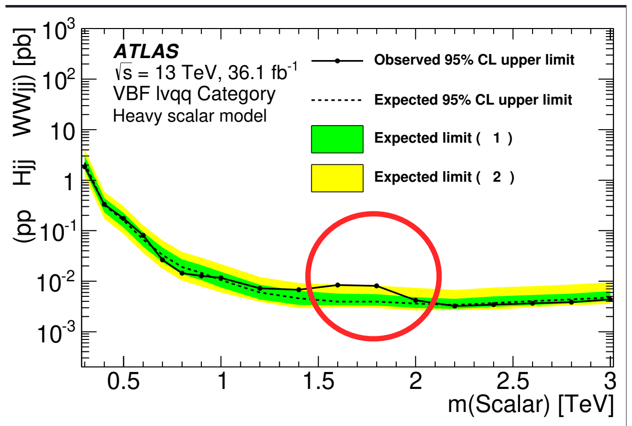
Run 1 limit 2 TeV, e.g. pair of 1 TeV gluino.

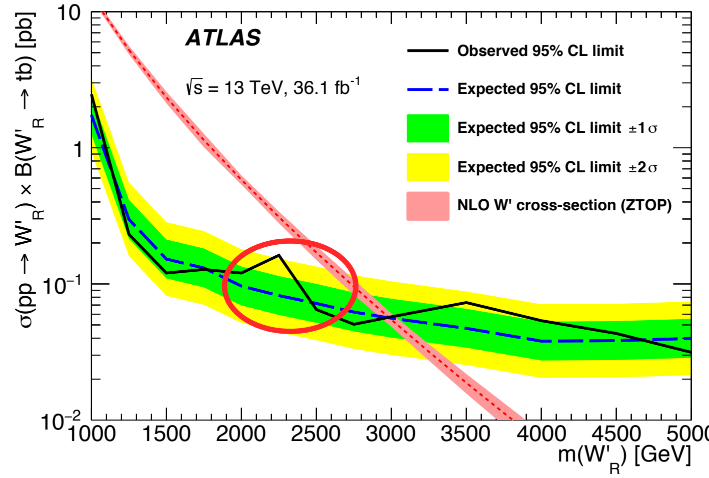


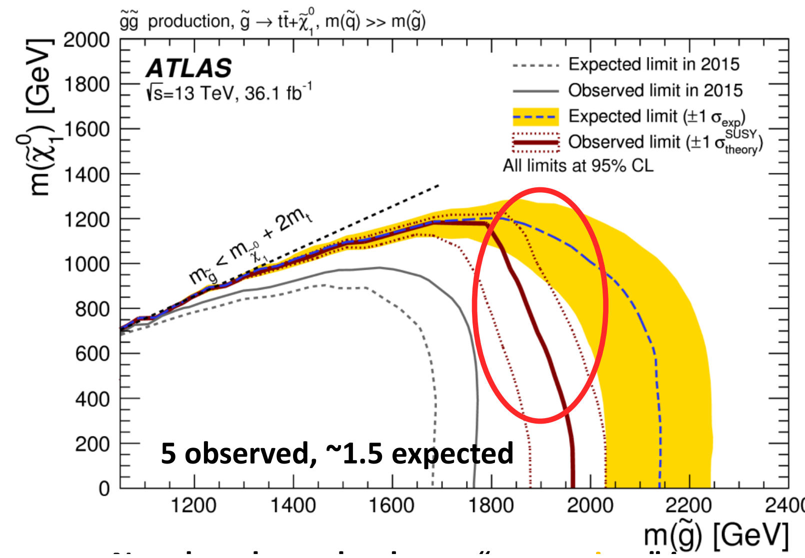
Rapid gain initial 10s fb^{-1}, slow improvements afterwards.

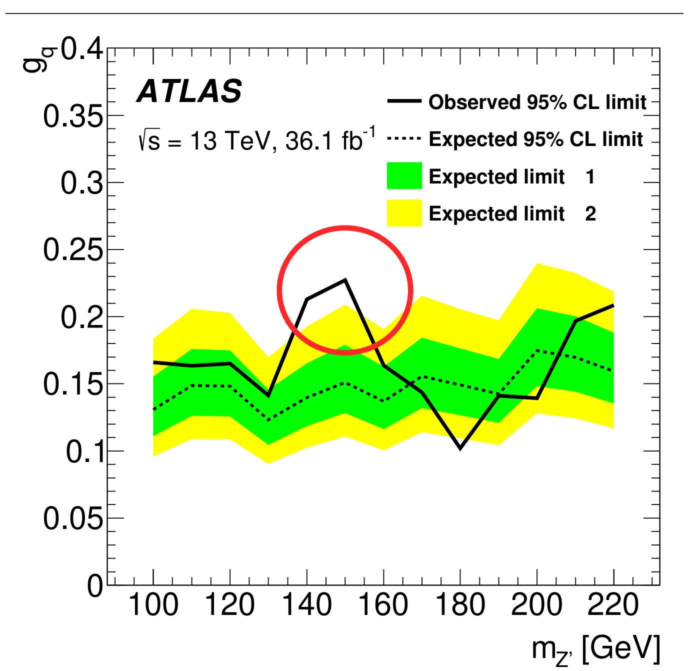
Progress will become slower, harder

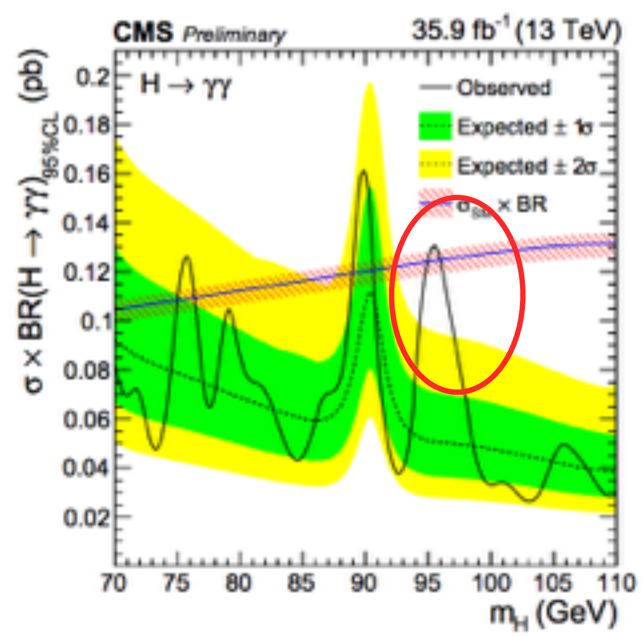
Things to watch?



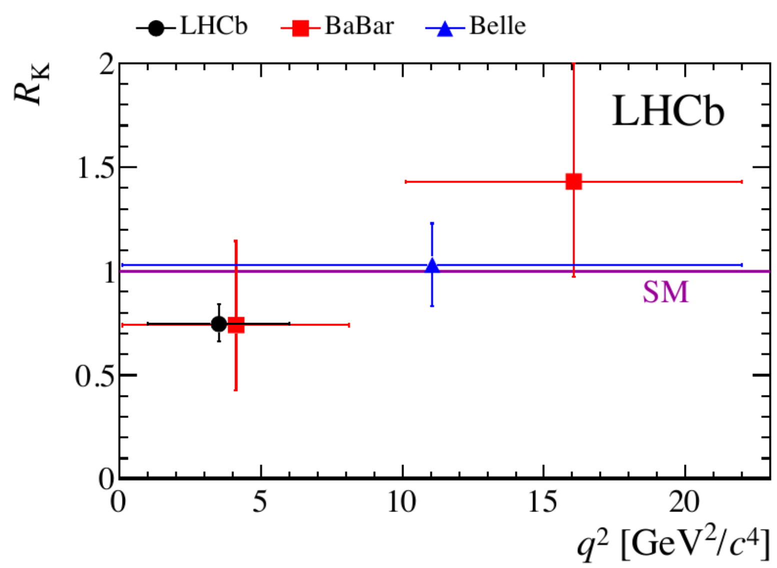


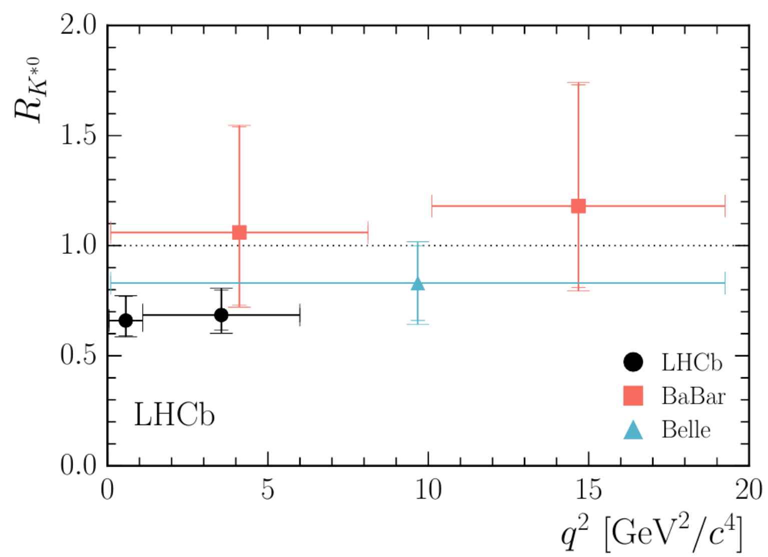






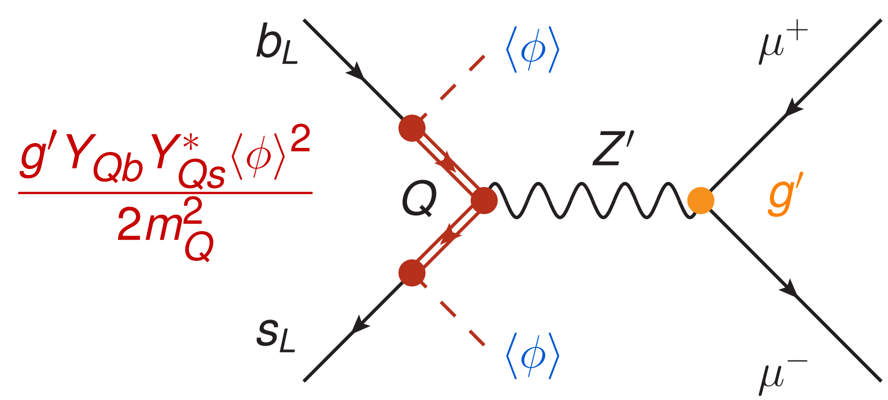
Maybe?





Z' based on gauging $L_\mu - L_\tau$
with effective flavor violating couplings to quarks

WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009



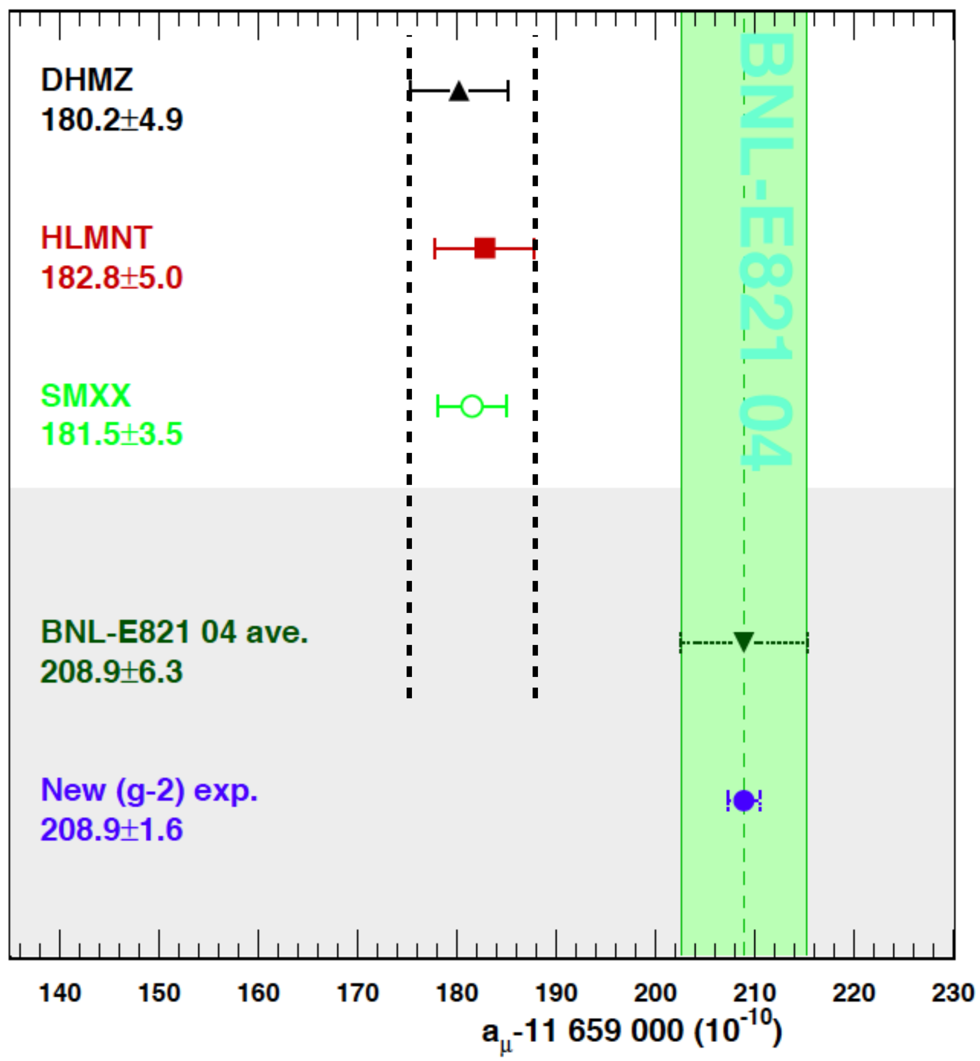
predicted Lepton Universality Violation!

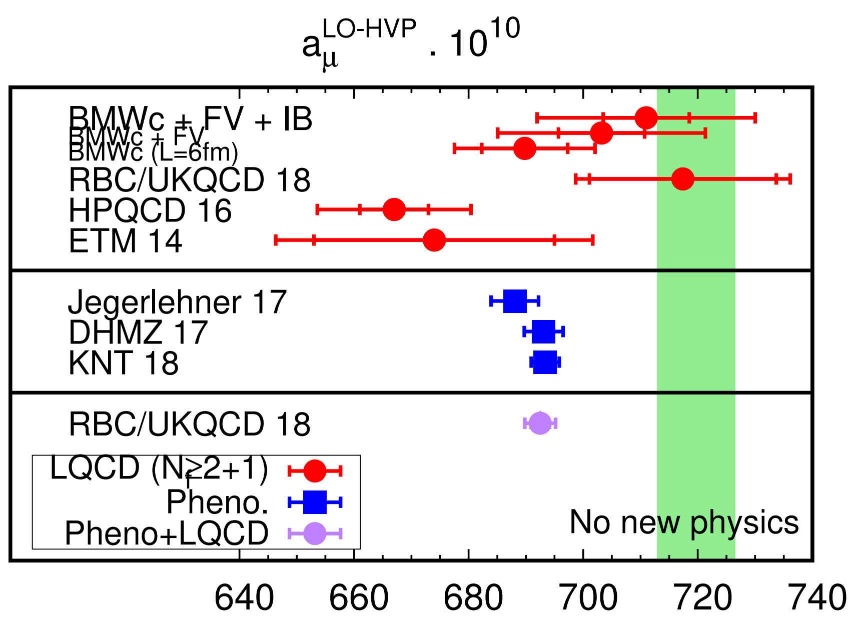
W. Altermannshofer

Or, some lepto-quark

Or, perhaps

T. Blum et al. (arXiv:1311.2198)





$$a_\mu^{\mathrm{HLbL}} = (5.35 \pm 1.35) \times 10^{-10}$$

A. El-Khadra

New results from Fermilab soon!

Rapid progress in Lattice QCD conquering th. uncertainties

Personal note: my first ambulance chasing paper, 2001

- If any of these materialize, certainly will open up a new exciting direction for particle physics.
  - Time will tell.
- However, we are not just hoping some anomaly to pop up to surprise us. We have goals.
- SM is not a complete theory, it does not answer many important questions.
  - New physics searches will help us answer that.

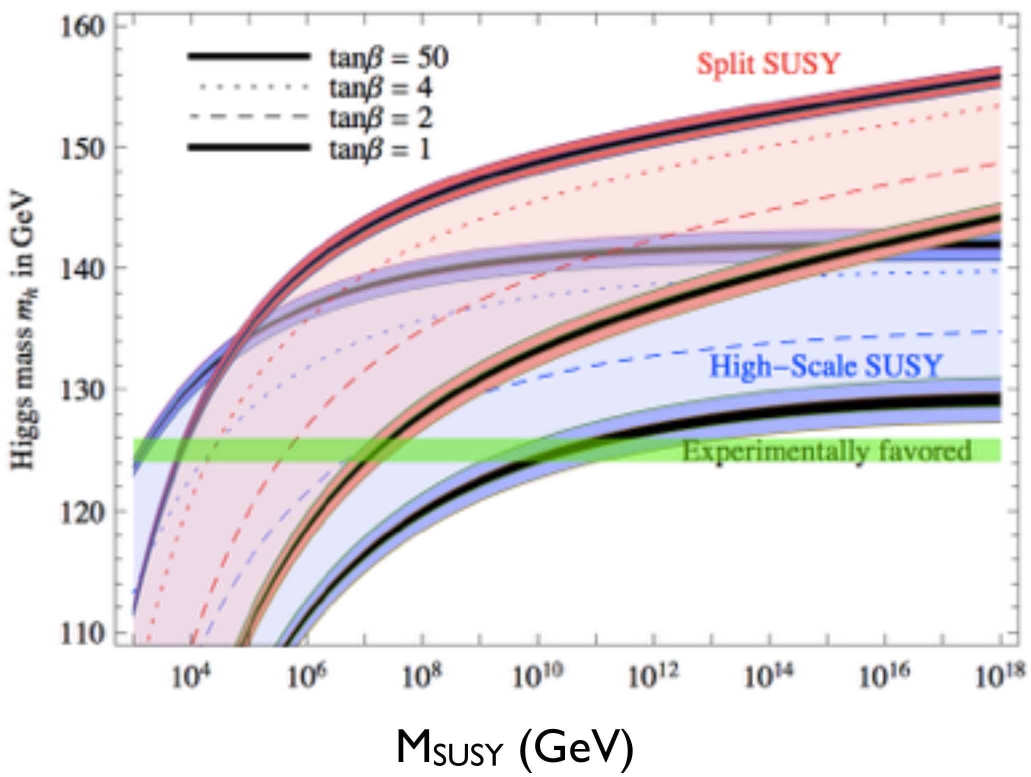
Big questions in particle physics

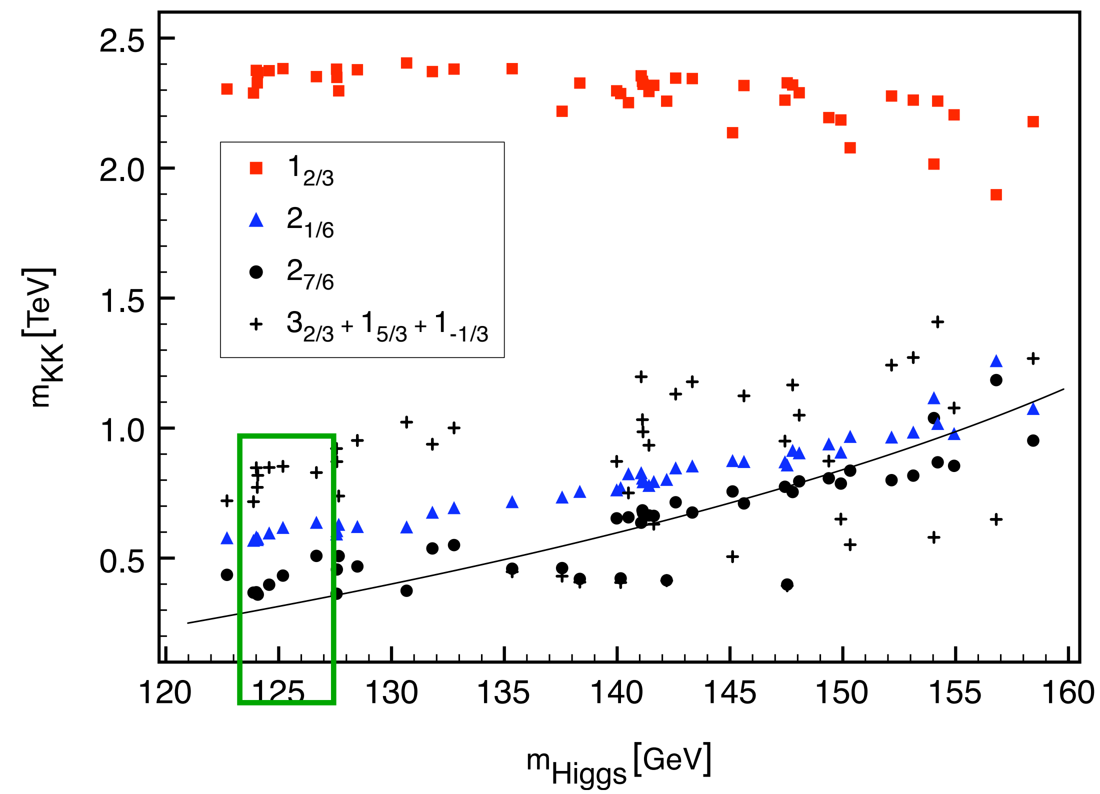
- Origin of the electroweak scale.
- Identity of dark matter.
- Origin of flavor.
- Matter and anti-matter asymmetry.
- ...

Electroweak

Origin of electroweak scale.
Why so different from the Planck scale?

A confusing picture.





Supersymmetry
Stop too heavy to be natural

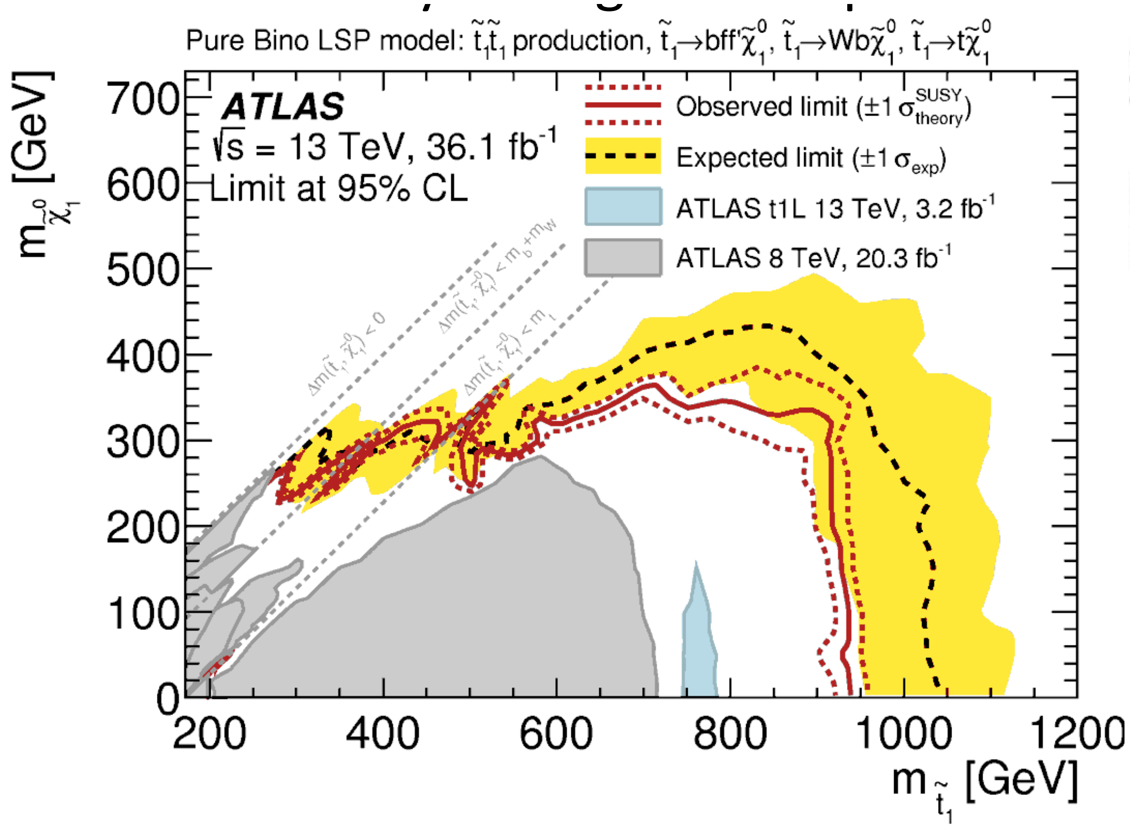
Composite top partner
too light, excluded

Such conclusions too simplistic, “work around” available.
A bit uncomfortable, hurt feeling of theorists, yes.

But, certainly not time to give up.

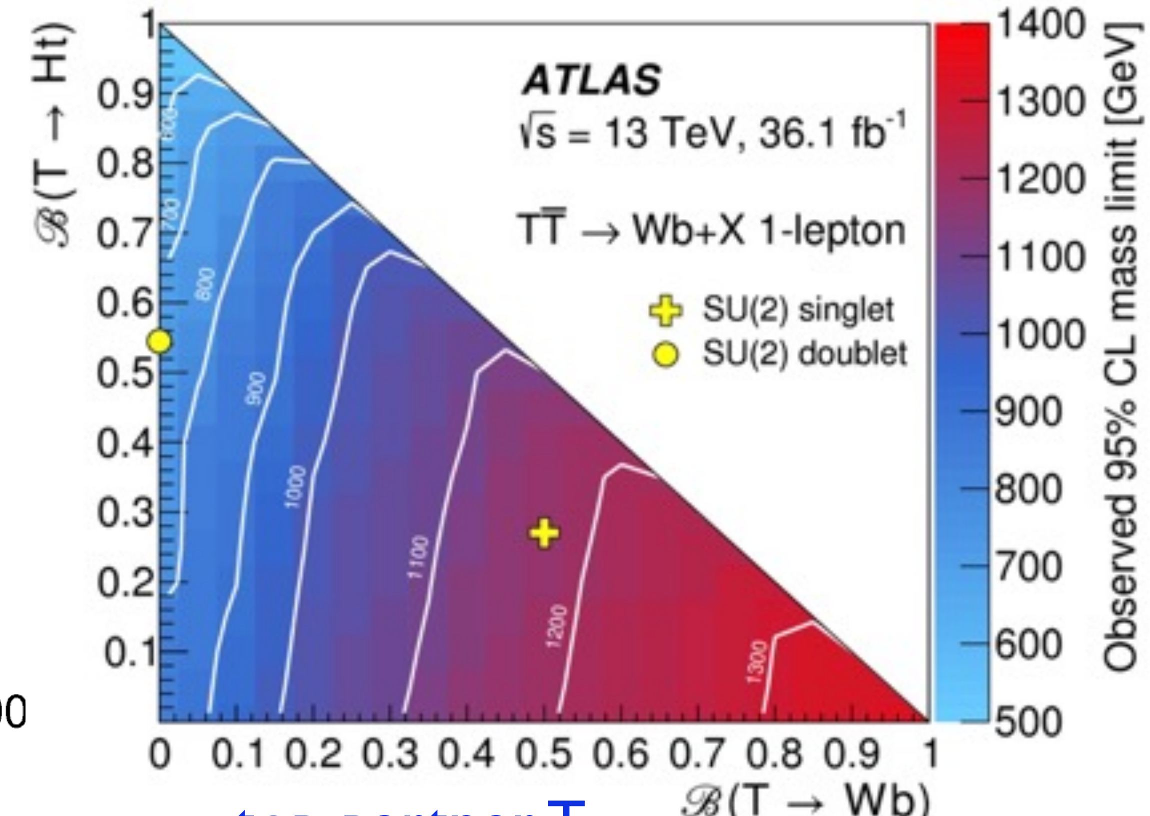
Impressive experimental progresses

Supersymmetry



stop

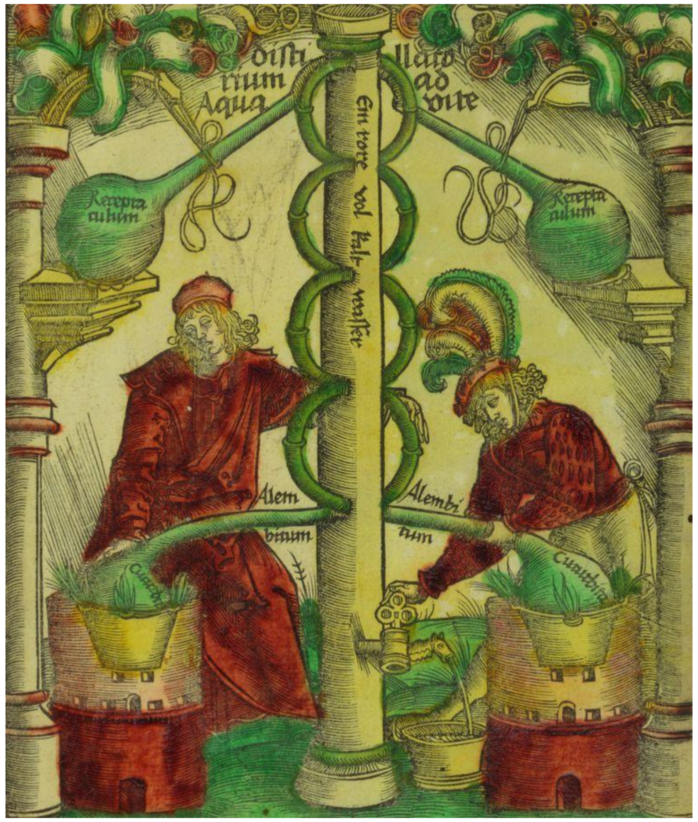
Composite Higgs



top partner, T

Good targets for searches.

Lack of theory work (talk) ≠ less motivated



"philosopher's stone" enables:

- creation of an elixir of immortality
- transmutation of common substances into gold

A. Paramonov

G. Landsberg

We theorists don't think SUSY in quite the same way

But, we are equally enthusiastic.

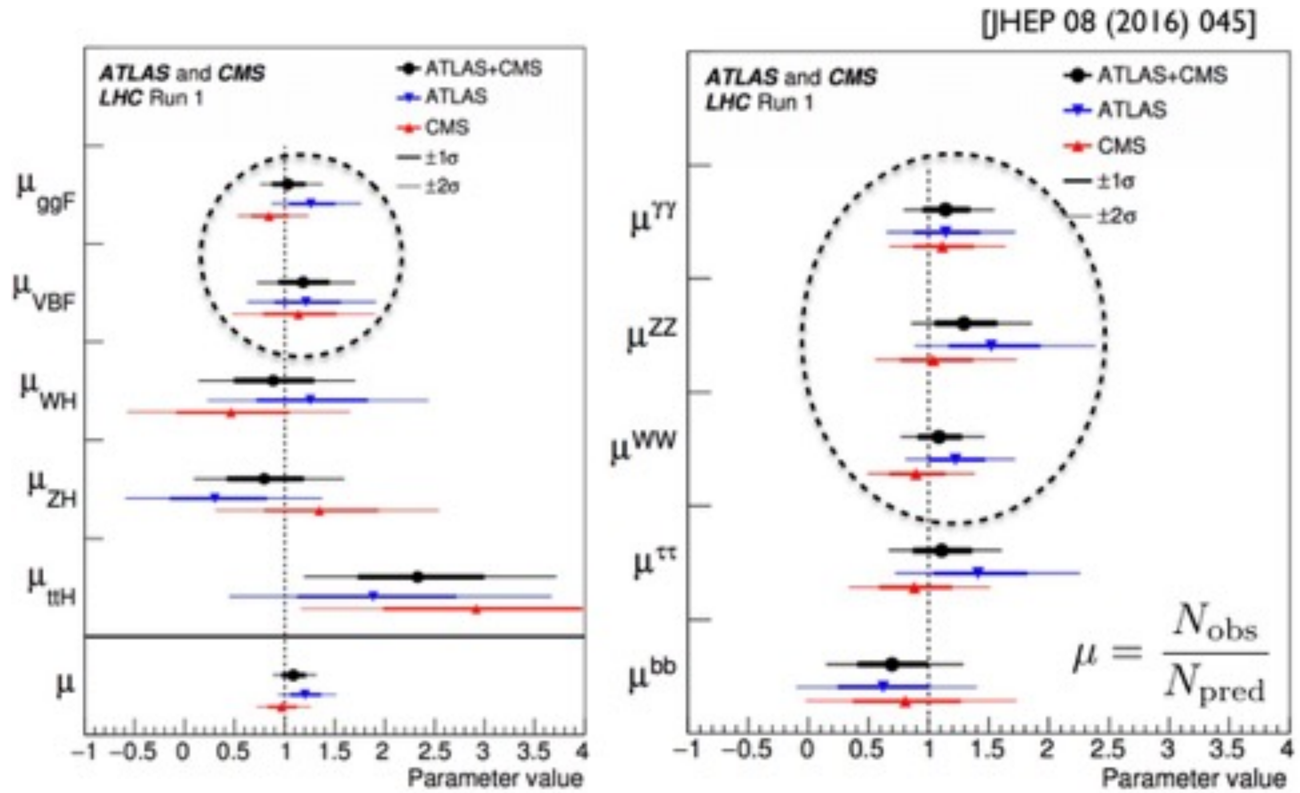
LHC will carry on this comprehensive searches for new physics.
SUSY, composite, extraD, ...

At the same time,
LHC enters precision era

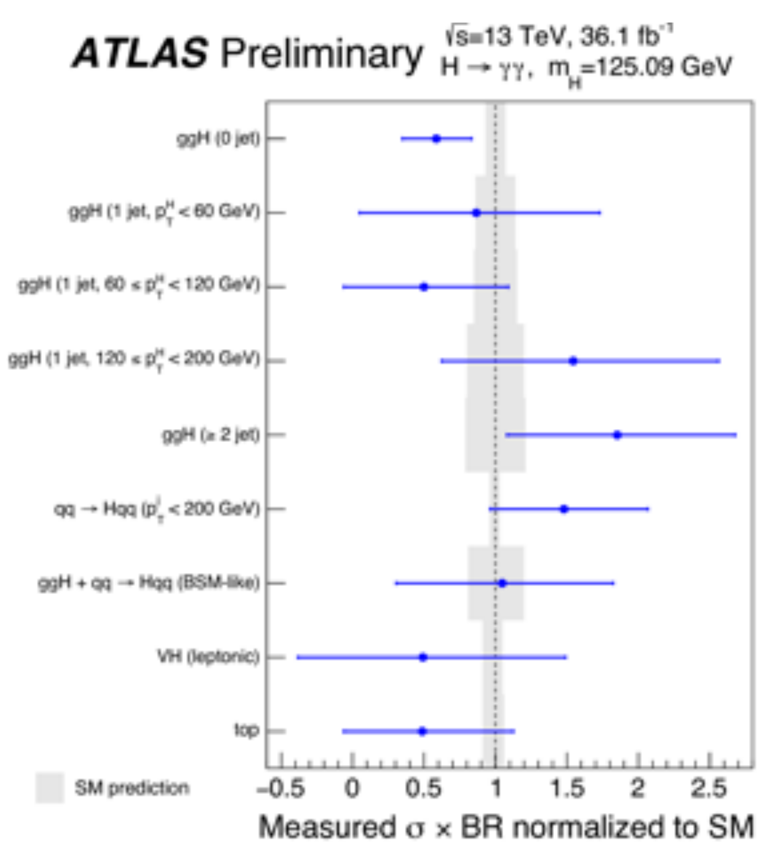
Importance of precision measurement

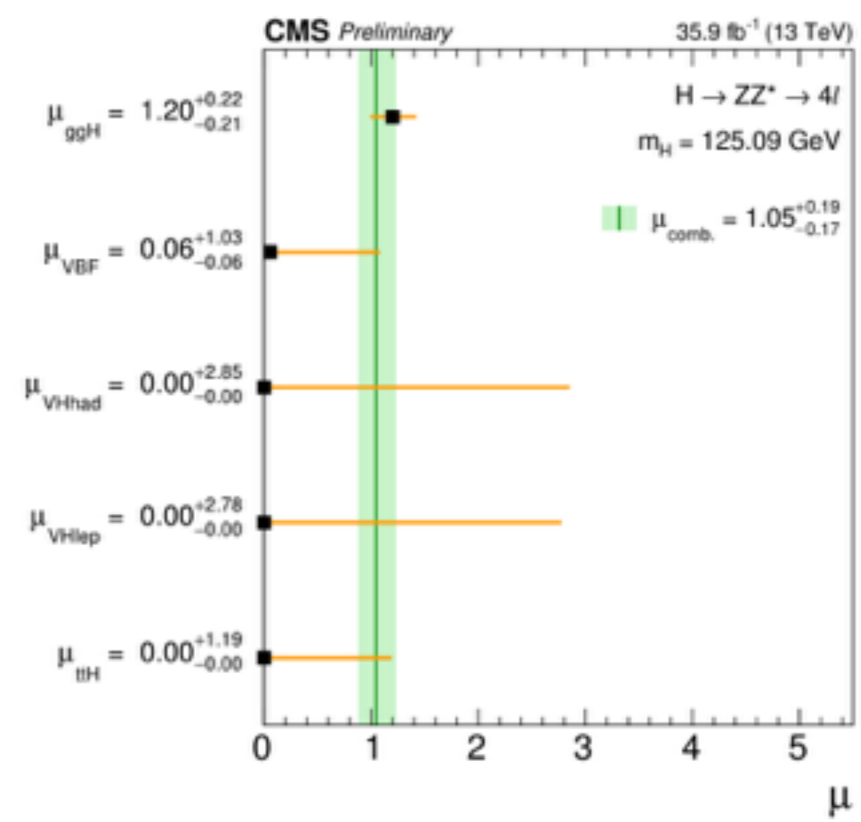
- Naturalness is the most pressing question of EWSB.
- We may not have the right idea. No confirmation of any of the proposed models.
- More creative ("crazy") ideas.
- Crucially, need experiment!
- Fortunately, with important players in EWSB W/Z/Higgs and top, we know where to look.
- And, the clue could show up in such precision measurement.

Higgs Standard Model-like



Agree to about 10-20%





Not entirely surprising

- In general, deviation induced by new physics is of the form

$$\delta \simeq c \frac{v^2}{M_{\rm NP}^2}$$

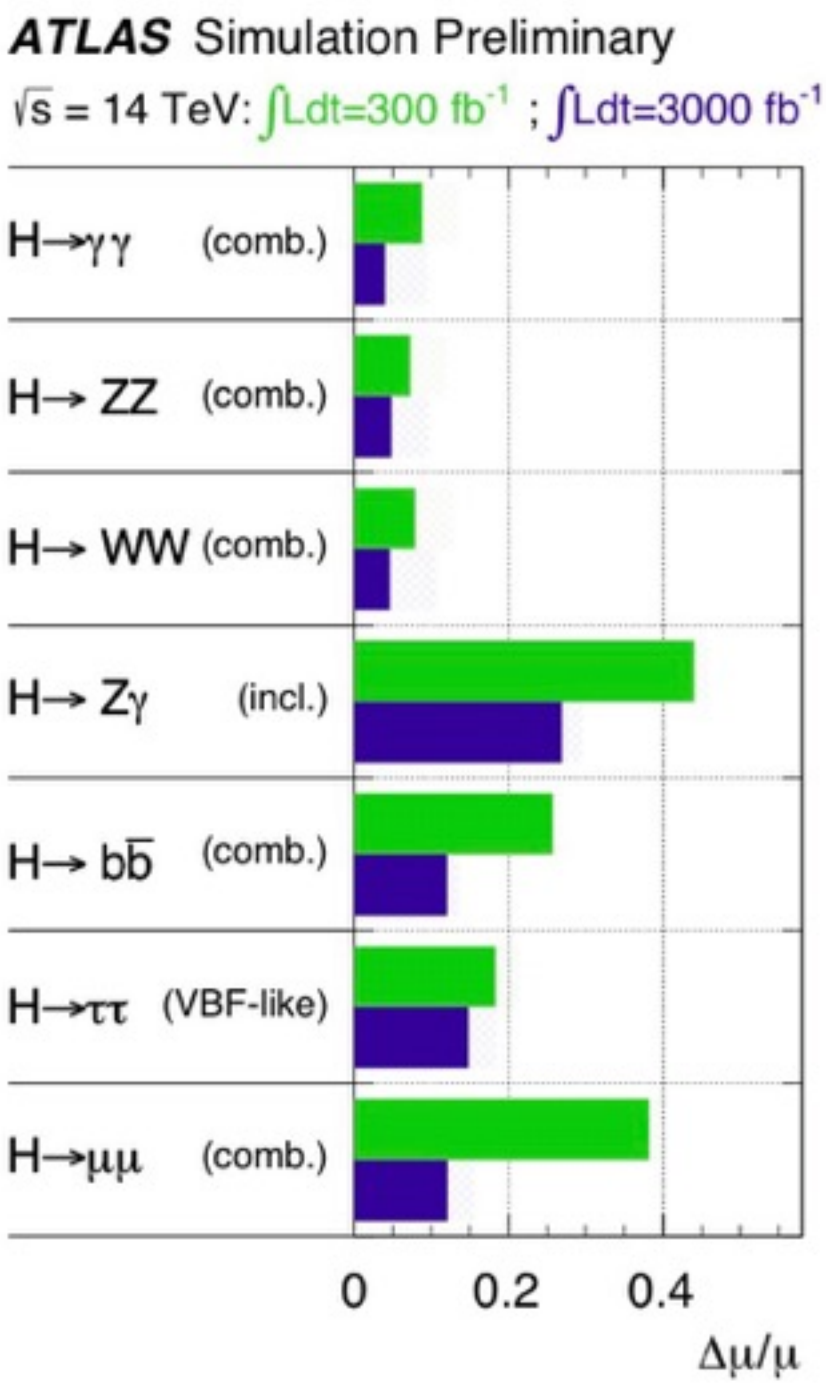
M_{NP} : mass of new physics
c: $O(1)$ coefficient

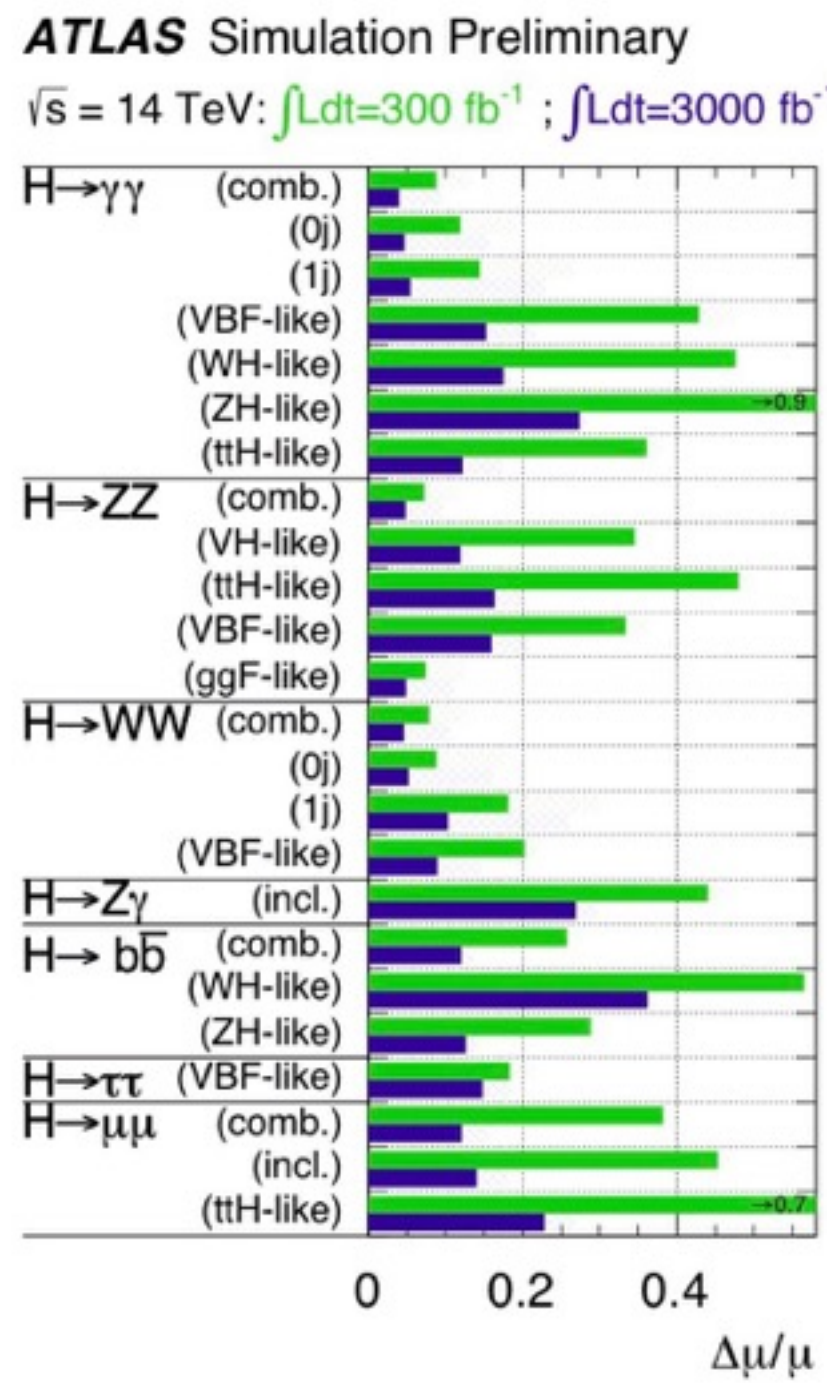
- Current LHC precision: 10%
  $\Rightarrow$ sensitive to M_{NP} < 500-700 GeV

- At the same time, direct searches constrain new physics below TeV already.

- Unlikely to see O(1) deviation.

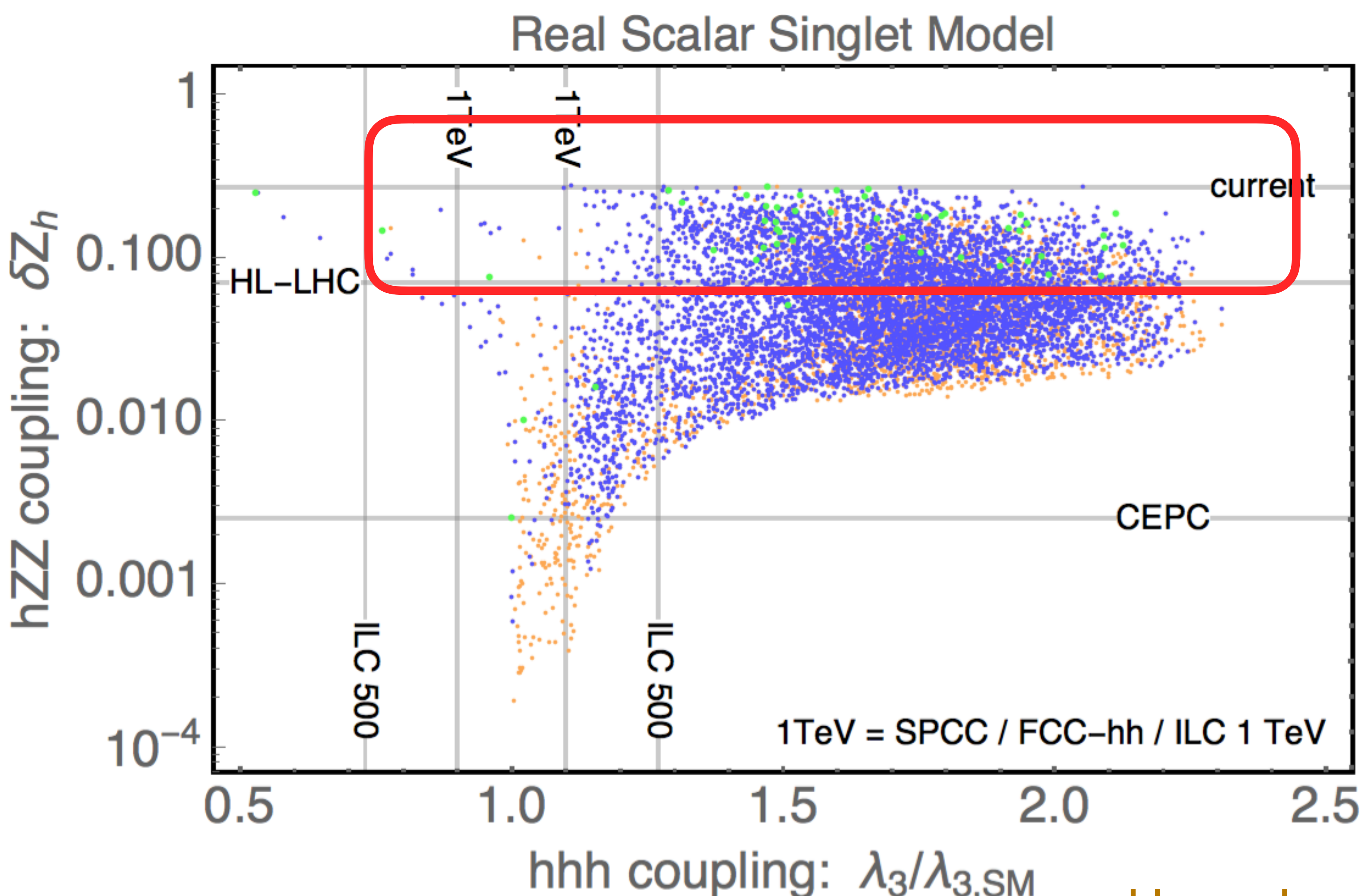
Significant improvement with high lumi





4-5% on Higgs coupling, reach TeV new physics

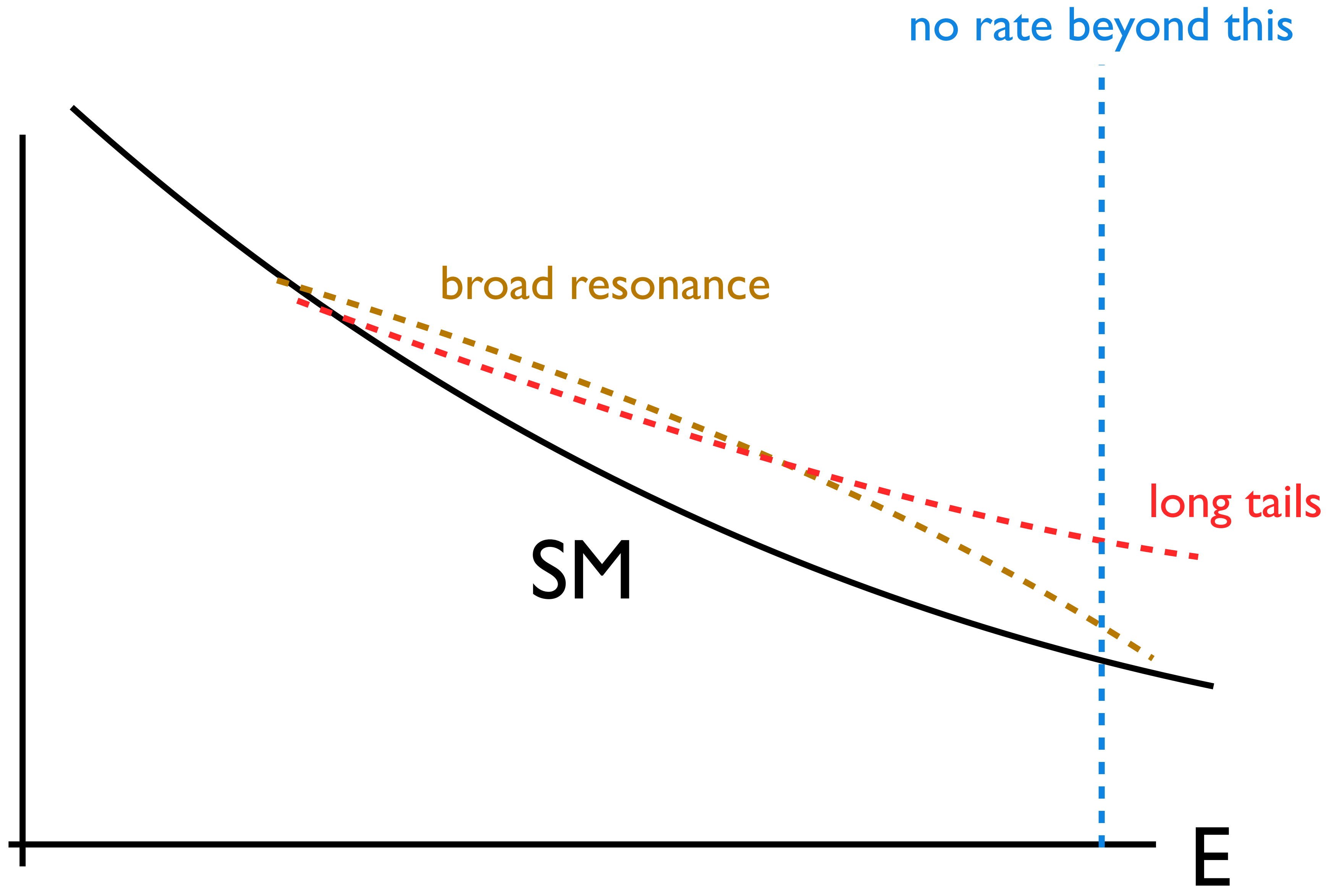
Probing EW phase transition



Huang, Long, LTW, 1608.06619

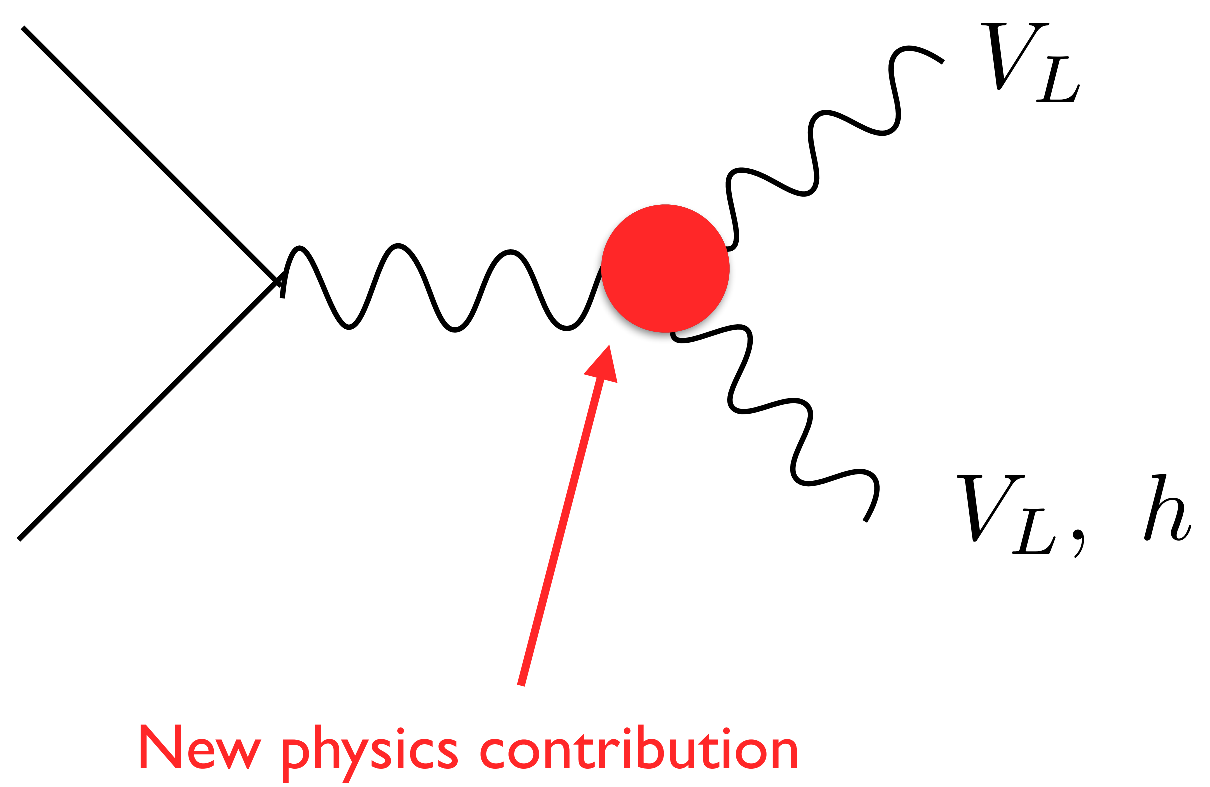
Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

Precision measurement with distribution



Diboson production at the LHC

$$q\bar{q} \to VV, \quad V = W, Z, h.$$



New physics effect encoded in the non-renormalizable operators:

$$\frac{1}{\Lambda^2}\mathcal{O}$$

$\Lambda:$ new physics scale

Precision measurement at the LHC possible?

LEP precision tests probe NP about 2 TeV

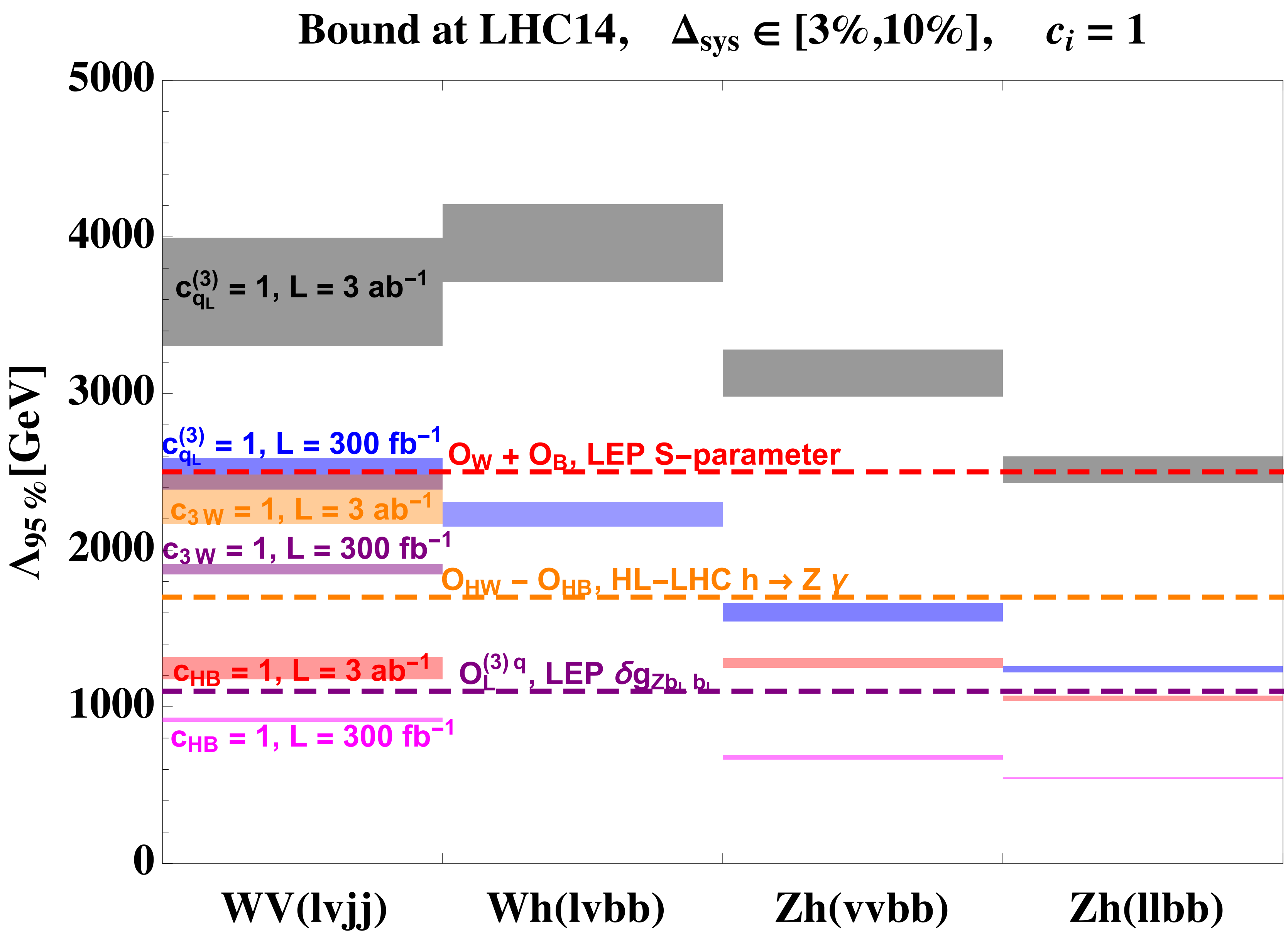
$$\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{m_W^2}{\Lambda^2} \sim 2\times 10^{-3} \quad \to \Lambda \geq 2 \text{ TeV}$$

At LHC, new physics effect grows with energy

$$\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{E^2}{\Lambda^2} \sim 0.25 \qquad E \sim 1 \text{ TeV},\ \Lambda \sim 2 \text{ TeV}$$

LHC needs to make a 20% measurement to beat LEP
LHC has potential.

Projections



Possible to reach 4 TeV.

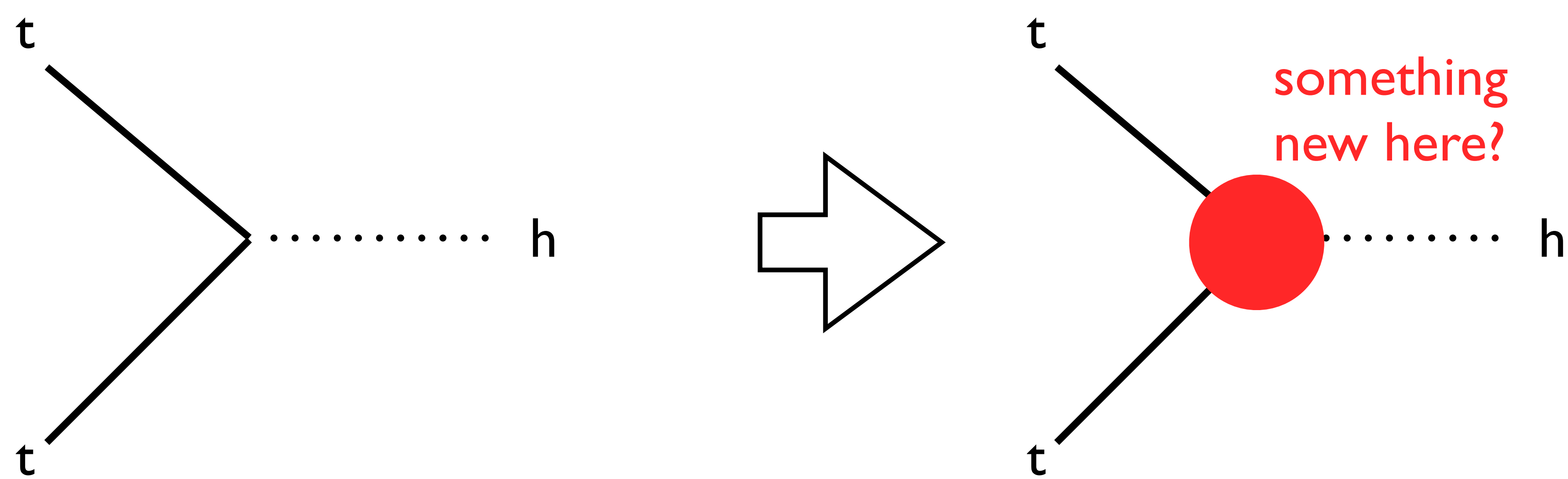
D. Liu, LTW

Better than LEP, and many LHC direct searches

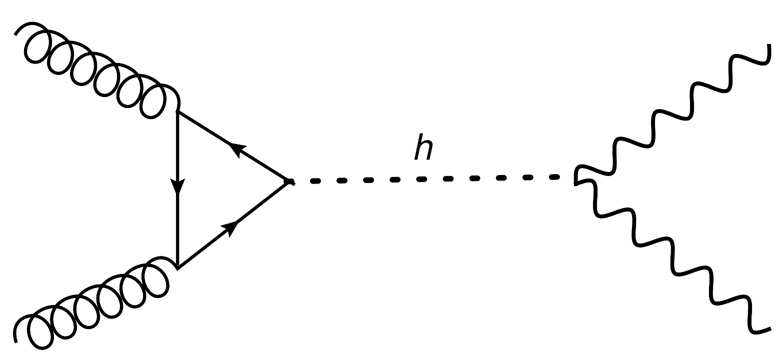
See also: Alioli, Farina, Pappadopulo, Ruderman, Franceschini, Panico, Pomarol, Riva, Wulzer, Azatov, Elias-Miro, Regimuaji, Venturini

tth, at higher energies

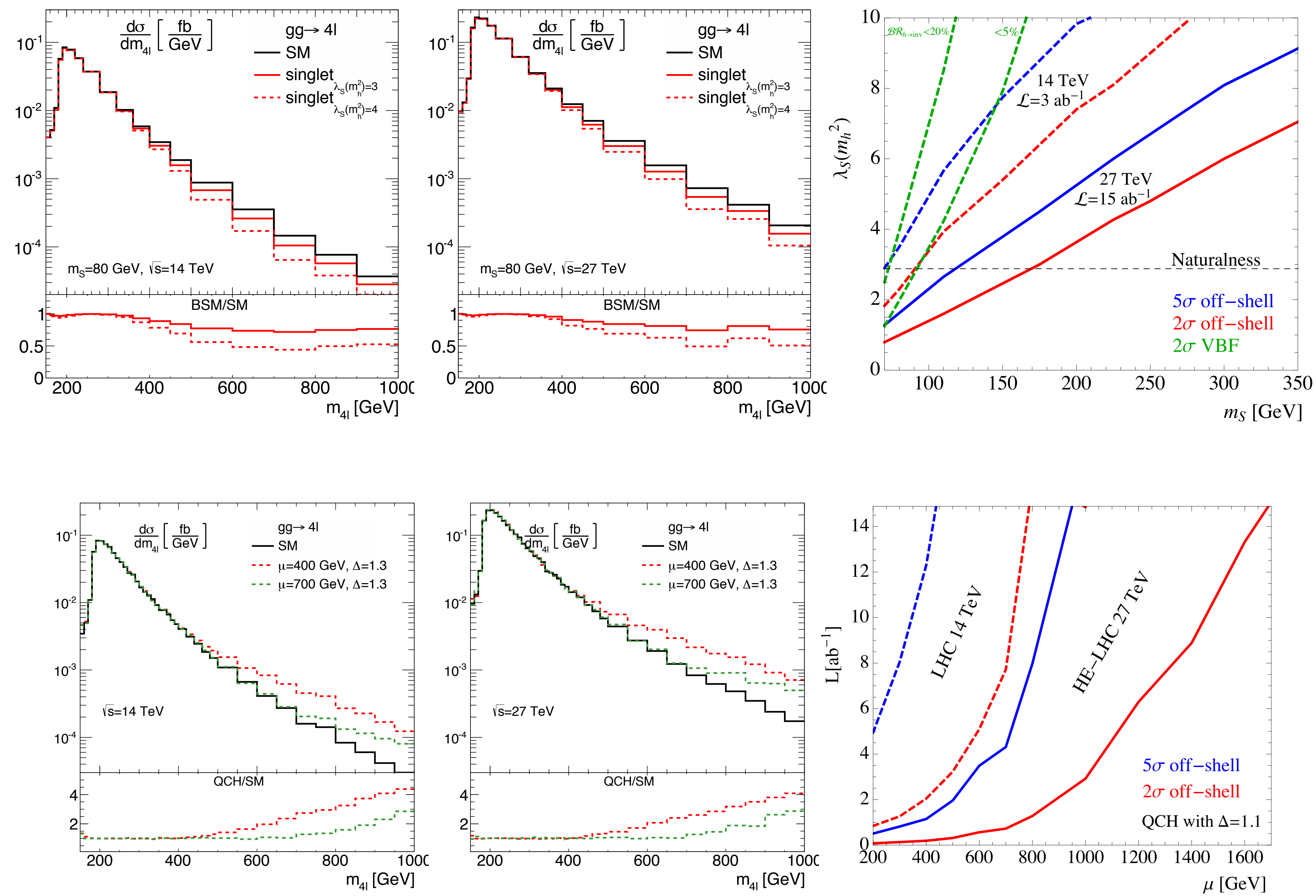
T. Han



Rather model independently, this can be probed
by precisely measuring tth coupling.
High energy = off-shell Higgs, can have better sensitivity.



tth, at higher energies

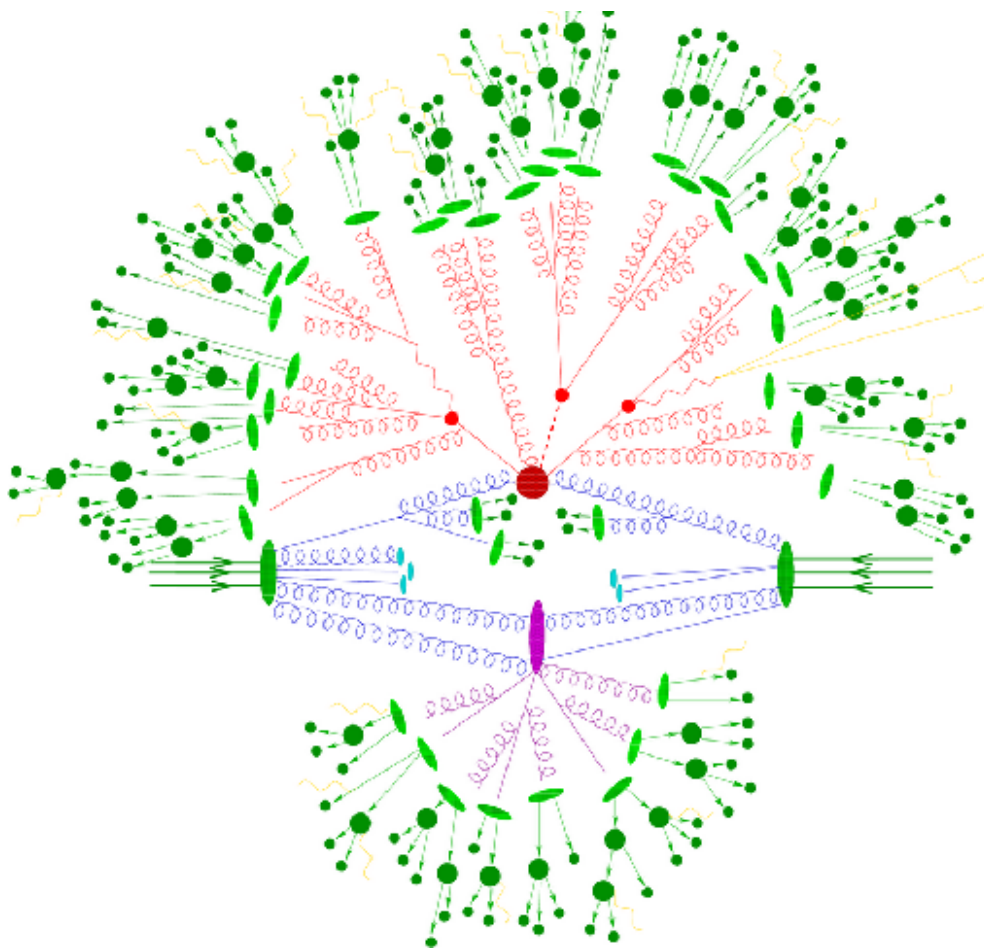


T. Han

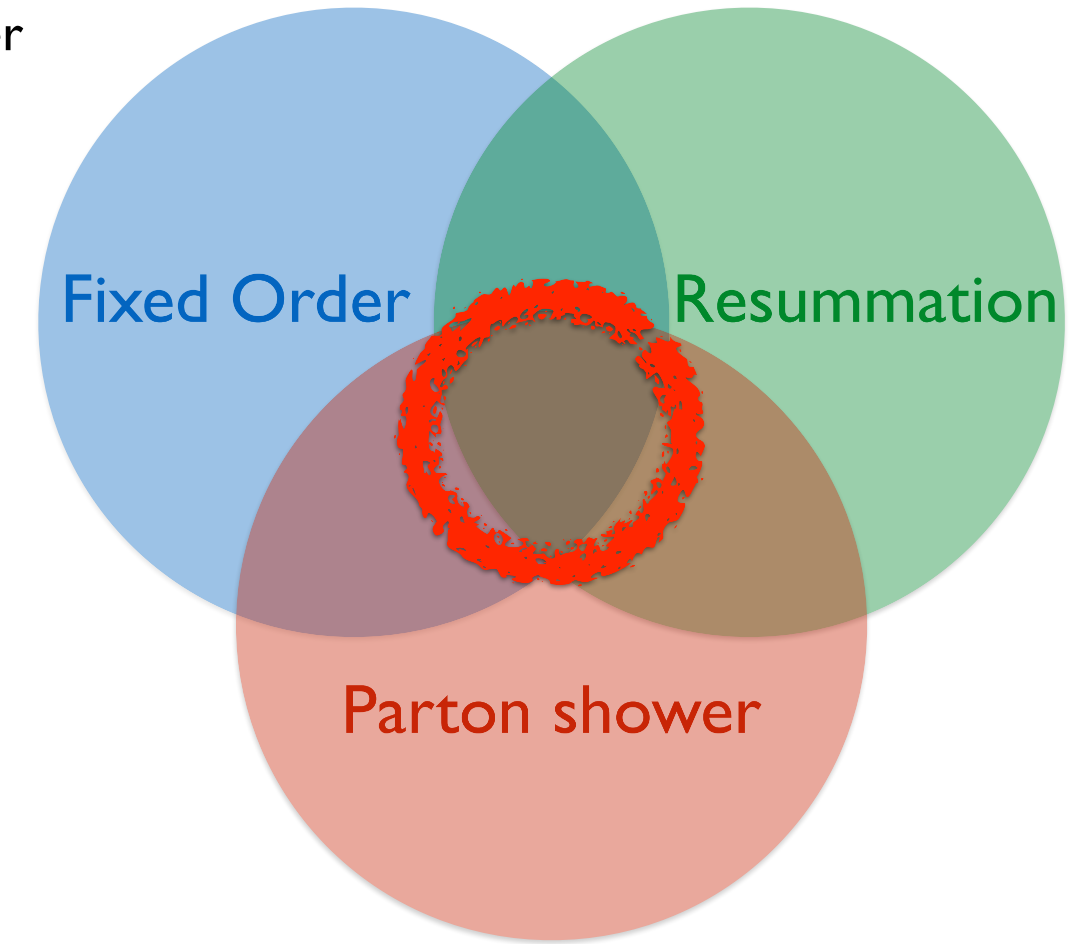
Precision is difficult

- Small S/B.
  - For example, in Wh: LHC @ 8 TeV : $\sigma_b^{red}/\sigma_{SM}^{Wh} \sim 200 - 10$
  - New techniques such polarization tagging, jet substructure can be instrumental.
- Improve on exp. systematics.
- Better modeling of background crucial.

It's messy.



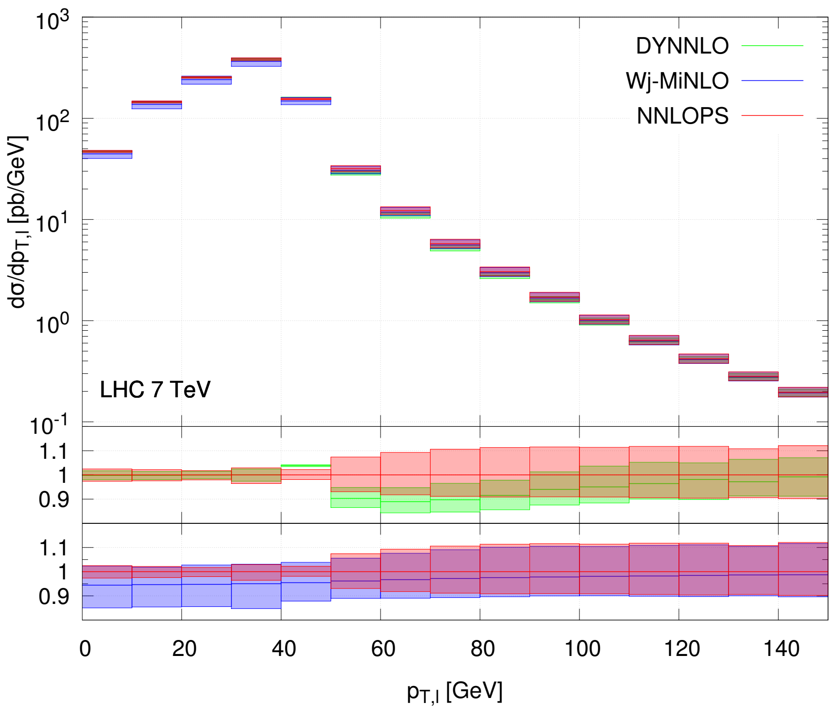
C. Bauer



- We have learned a lot how to deal with it.
- Yet, to achieve precision, we need to do better.

There are three main methods available at this point

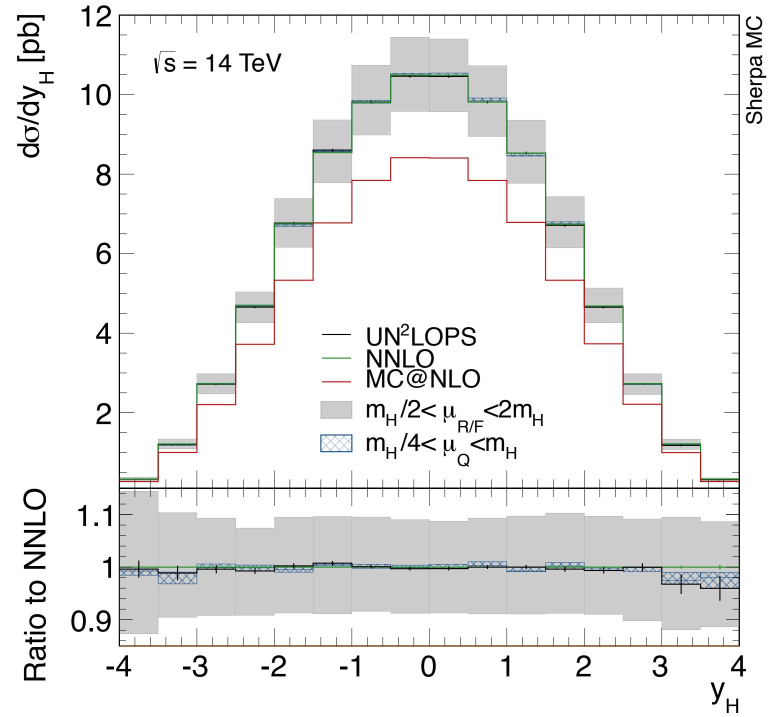
MINLO-NNLOPS



Hamilton, et al '13 - '16

MINLO improved NLO reweighted to NNLO

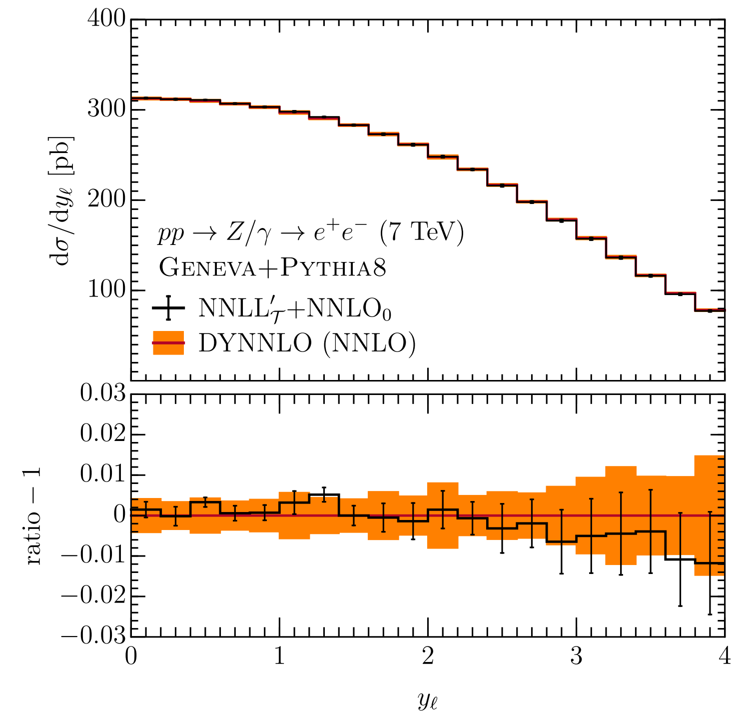
UNNLOPS



Hamilton, et al '14 - '16

N-jettiness slicing and Unitarity

Geneva



Alioli, CWB et al, et al '13 - '16

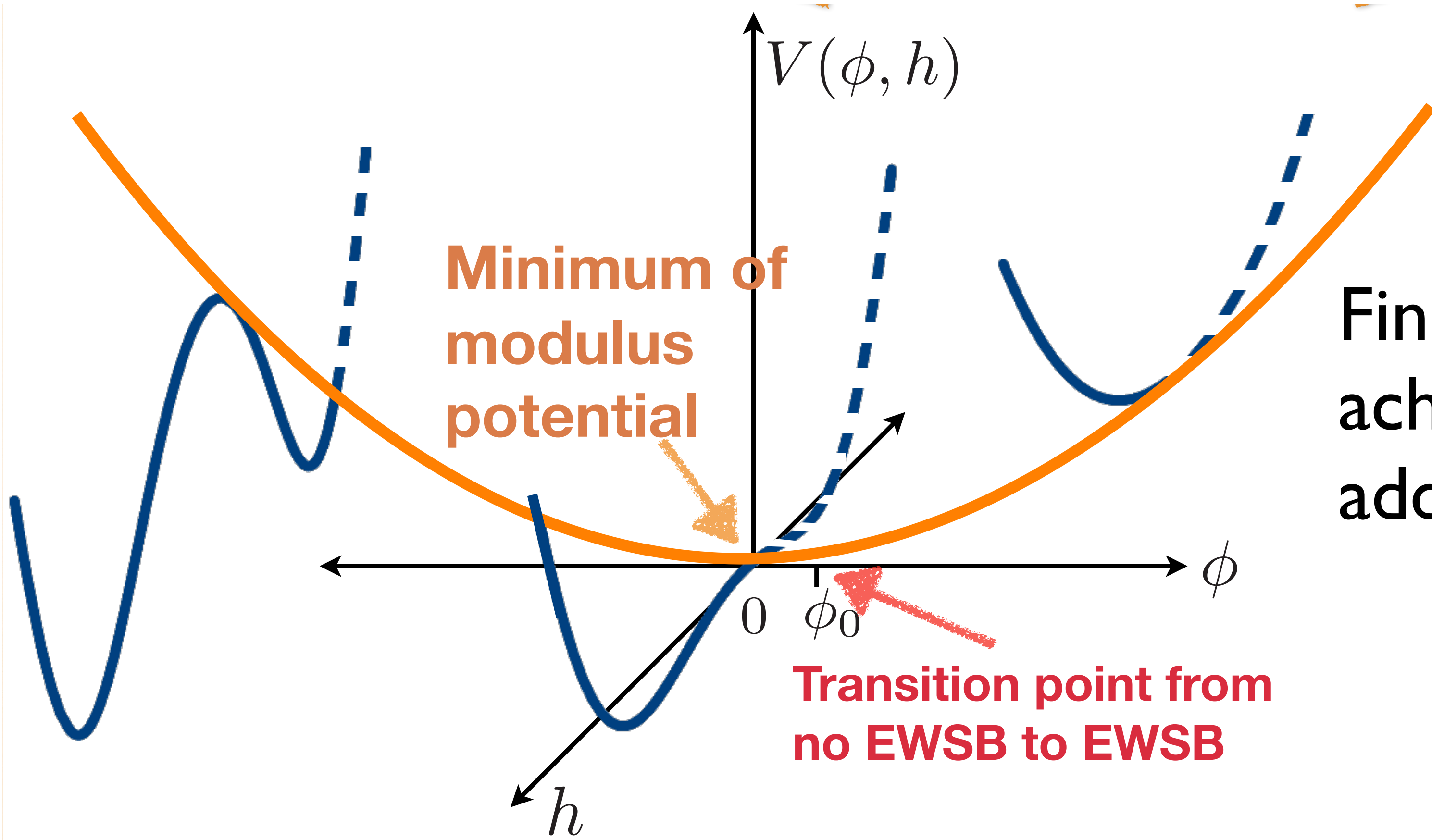
N-jettiness slicing and NNLL' resummation

C. Bauer

- Many progresses recently.

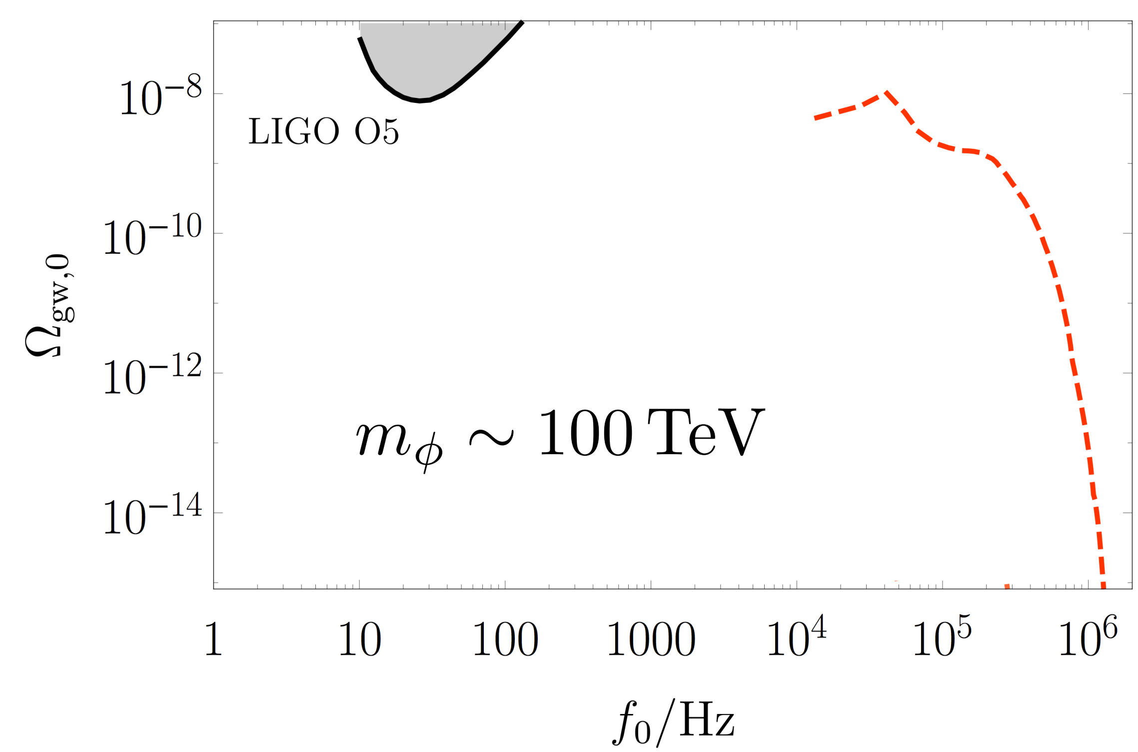
Cosmic imprint of fine-tuning?

J. Fan



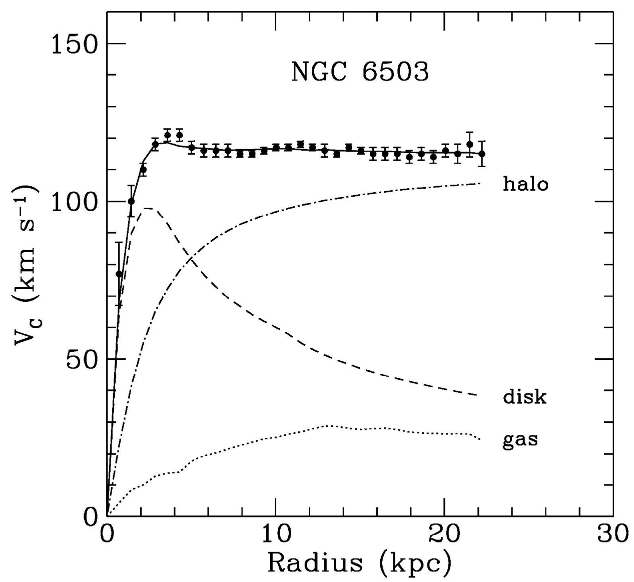
Fine-tuning of Higgs mass achieved with coupling to some additional scalar field (moduli).

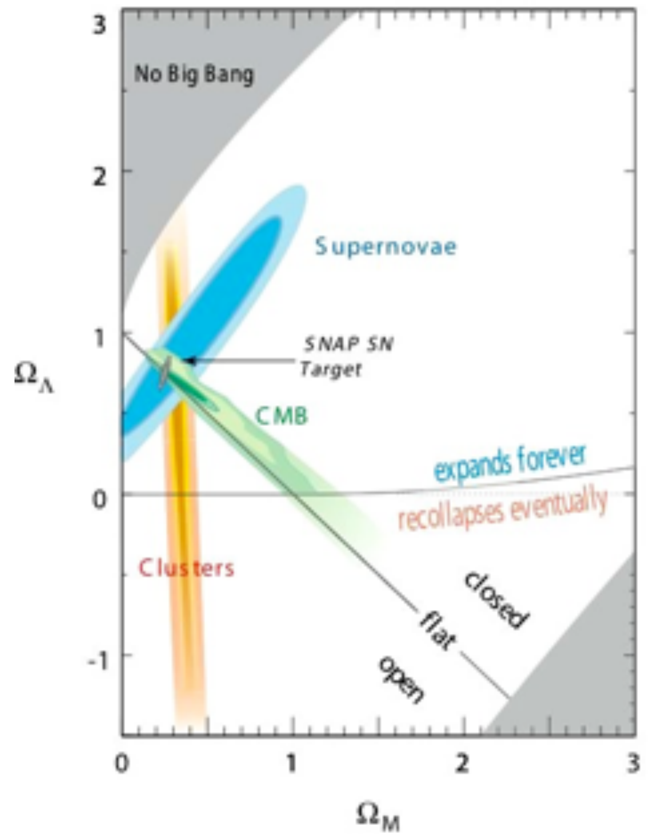
Coupling affects the dynamics of scalar fields, leads to gravitational wave production.

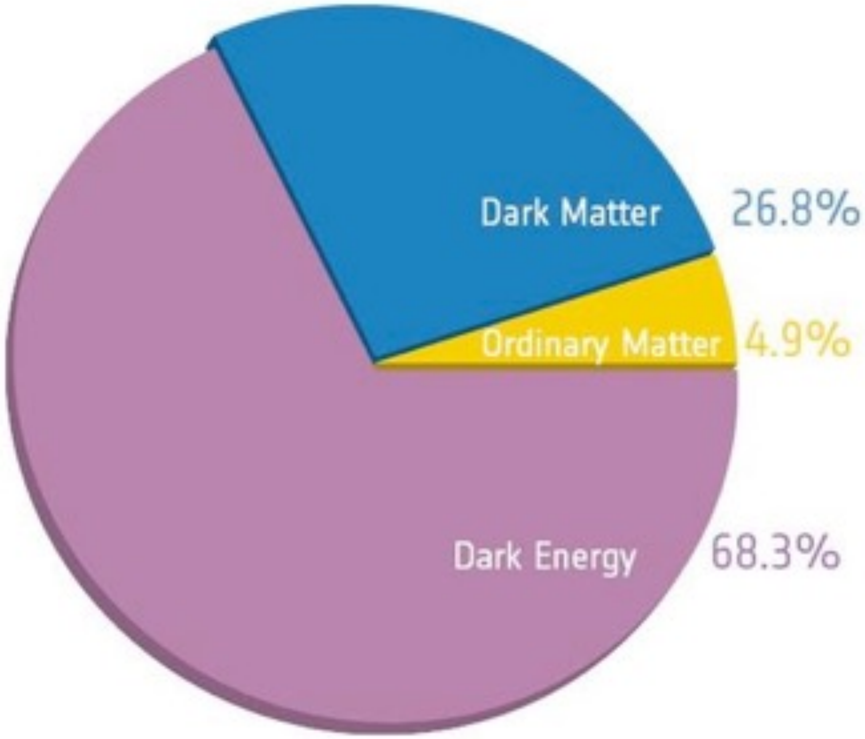


Dark matter
Dark sector

Dark matter



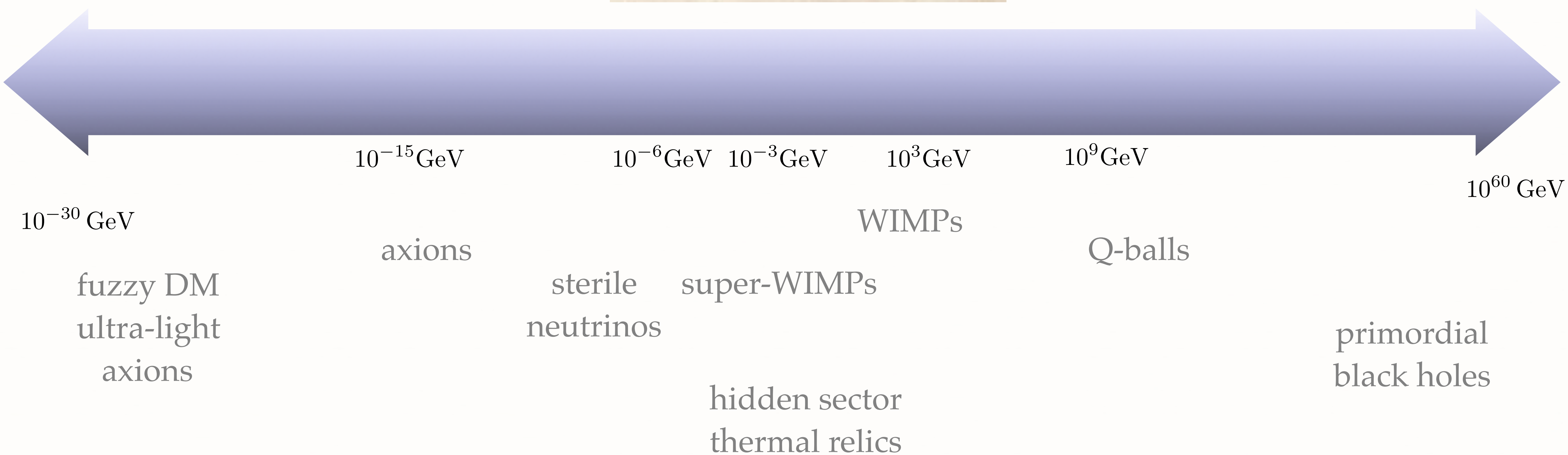




It is there.
Only seen its gravitational interaction.

We have to understand them better.

Vast range of possibilities



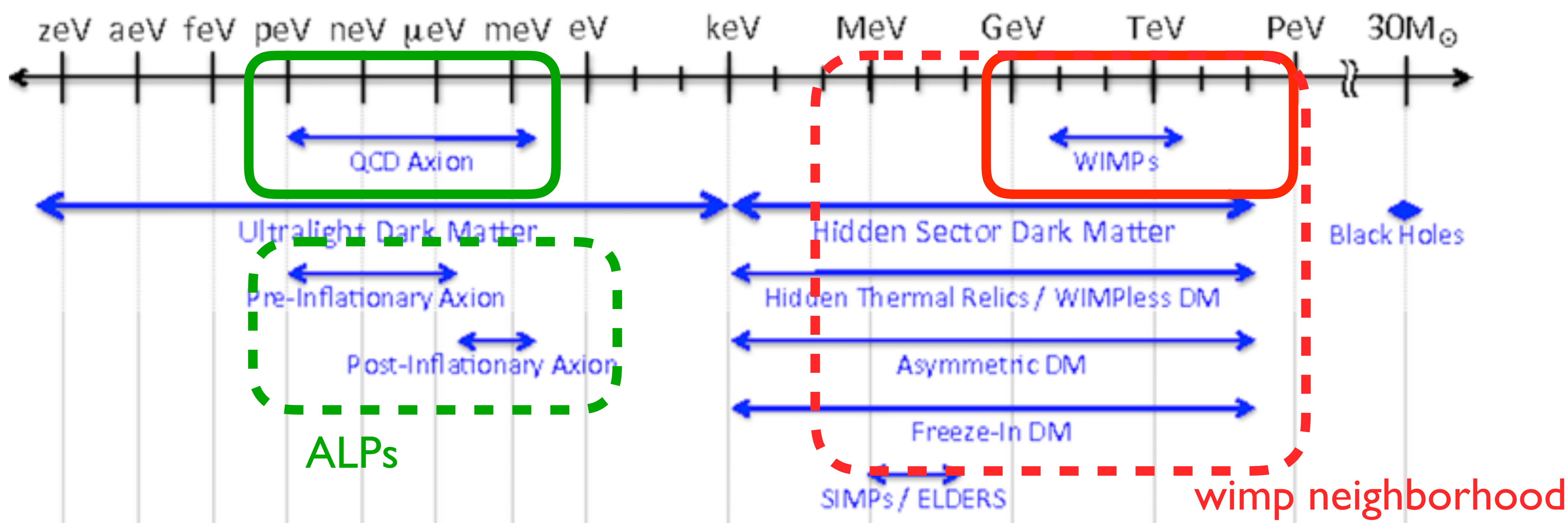
J. Shelton

Search under lamppost, by definition

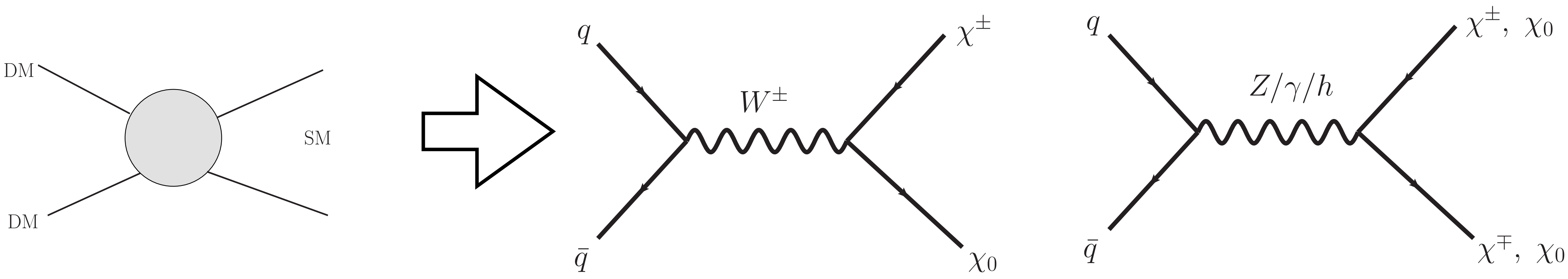
J. Shelton

- Need good stories (lampposts) about couplings to the Standard Model.

Only a few good stories.

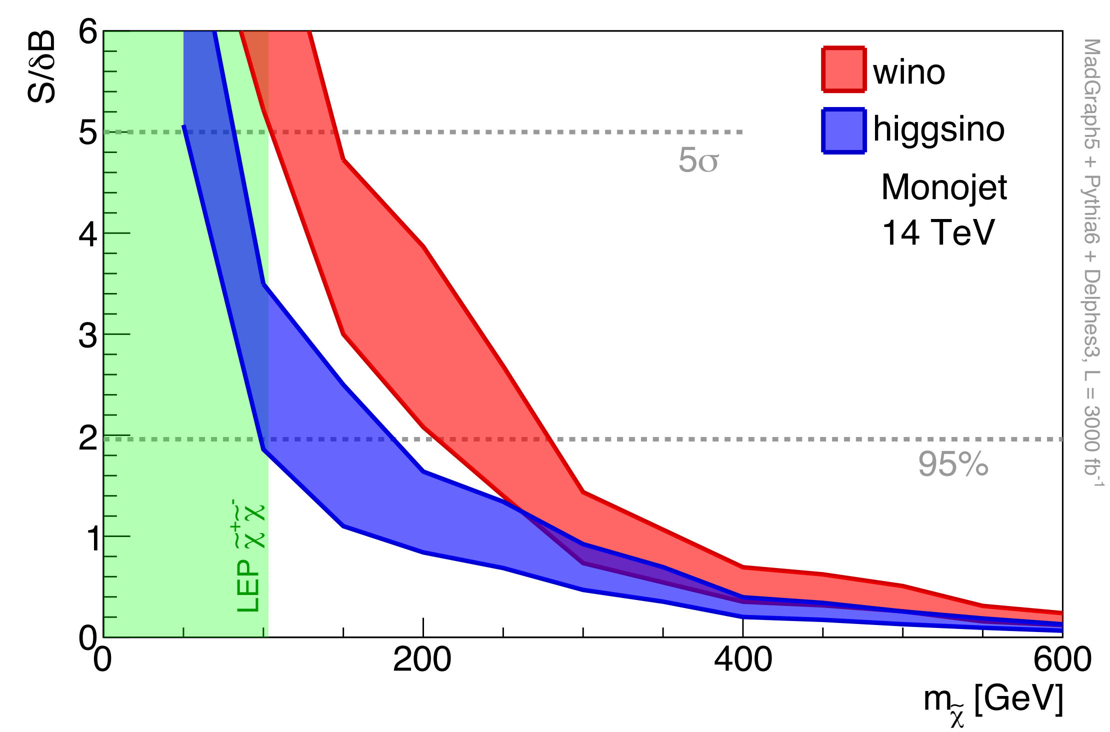


Simplest WIMP: part of weak multiplet

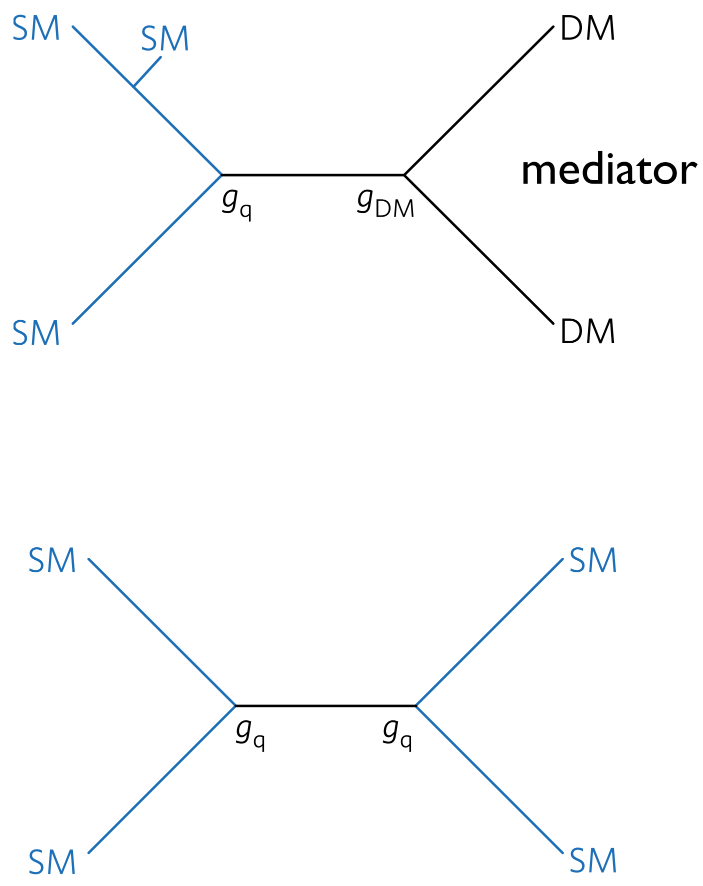


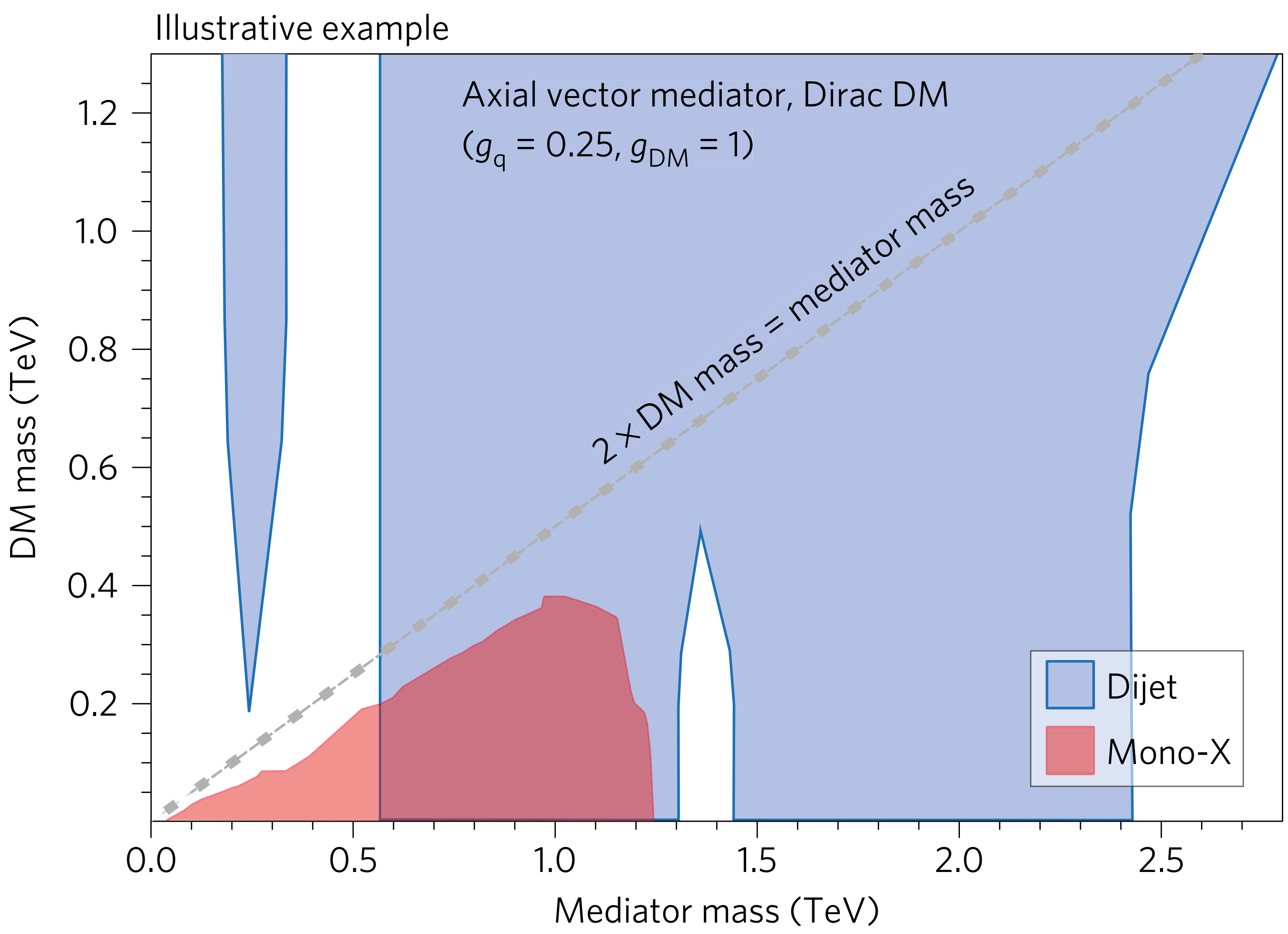
$$M_{\rm WIMP} \leq 1.8\ {\rm TeV}\ \left(\frac{g^2}{0.3}\right)$$

- Mediated by W/Z/h.
- Very challenging at the LHC.



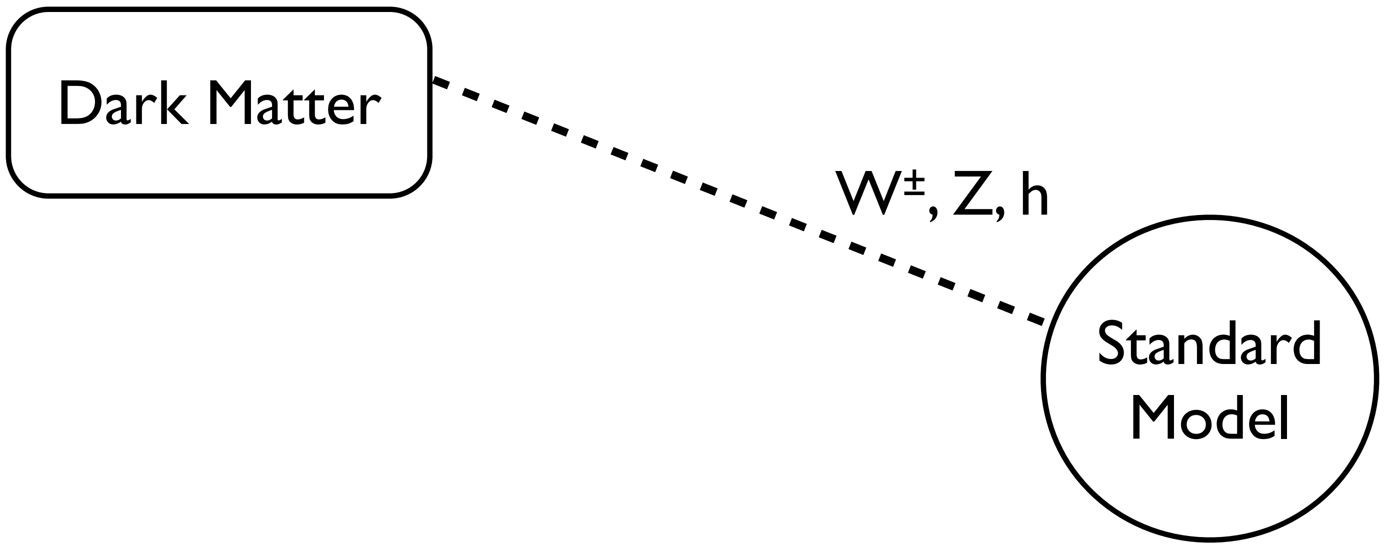
Simplified models



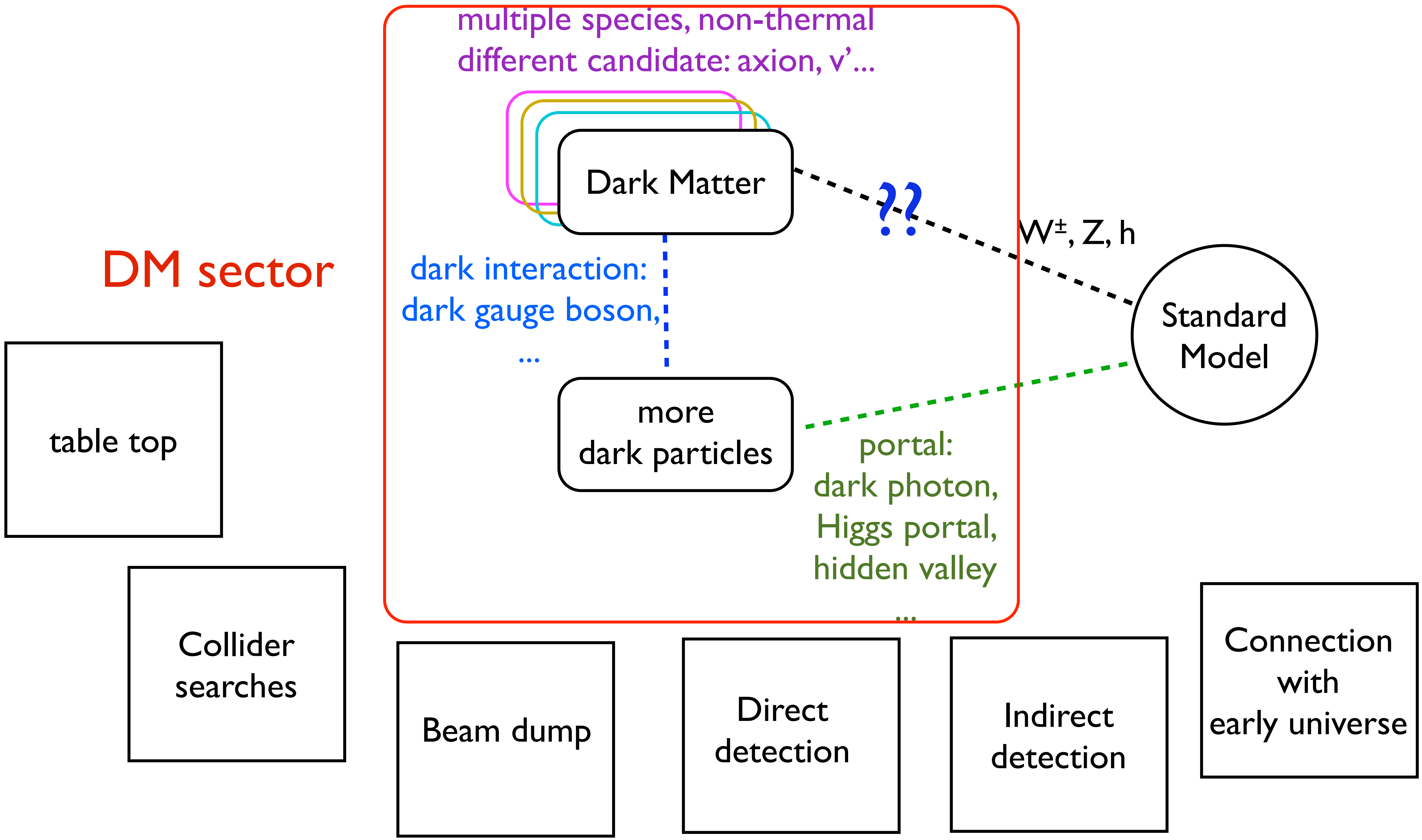


- LHC can cover these models well.

Dark sector



Dark sector

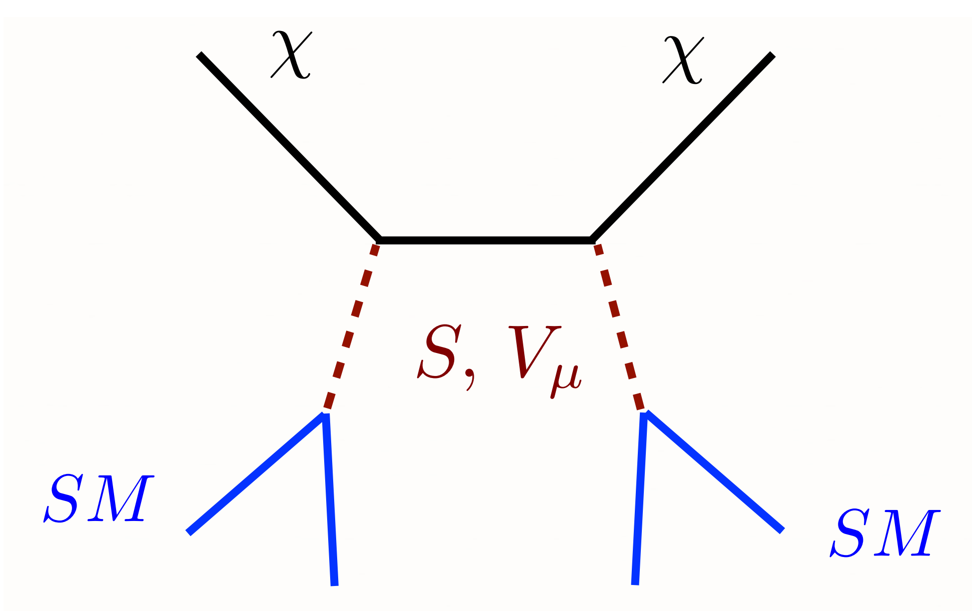


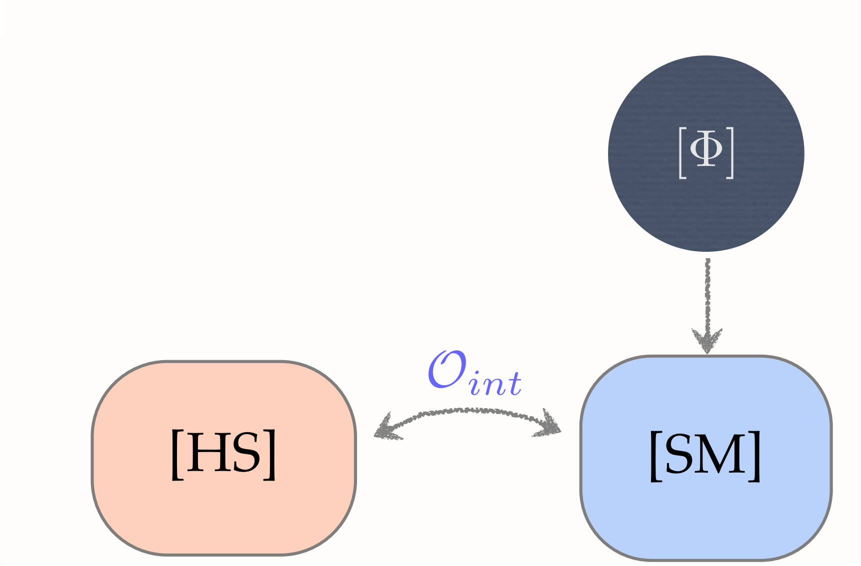
Richer dynamics, new signals.

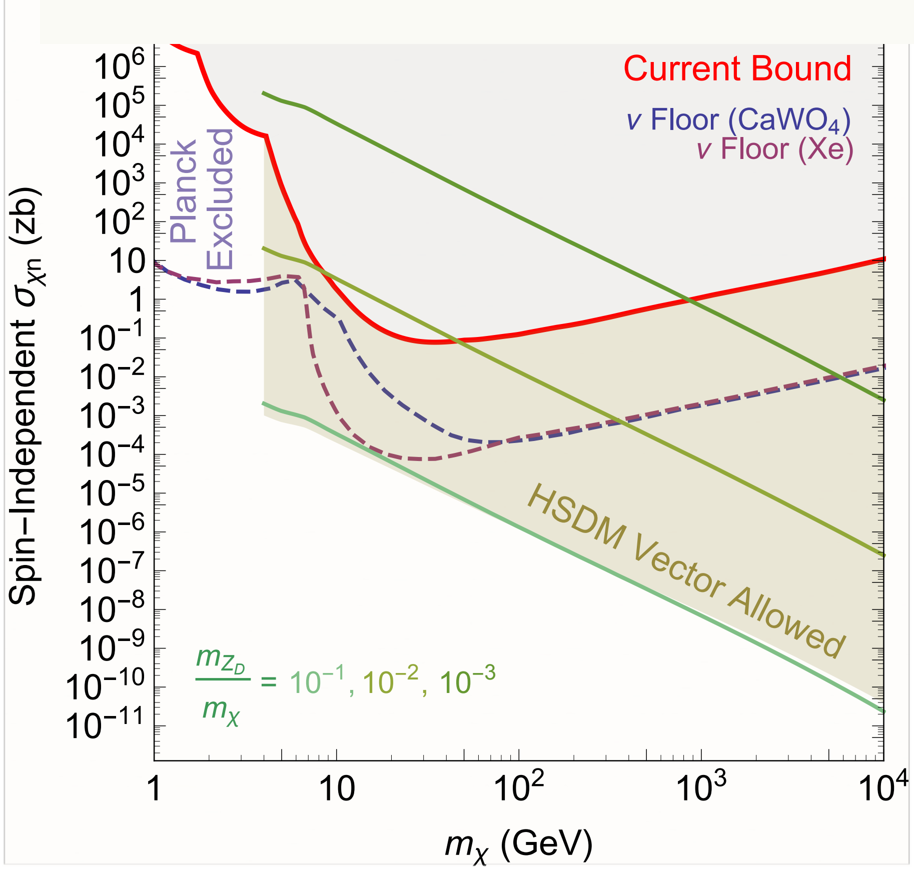
DM may not be the first dark sector discovery.

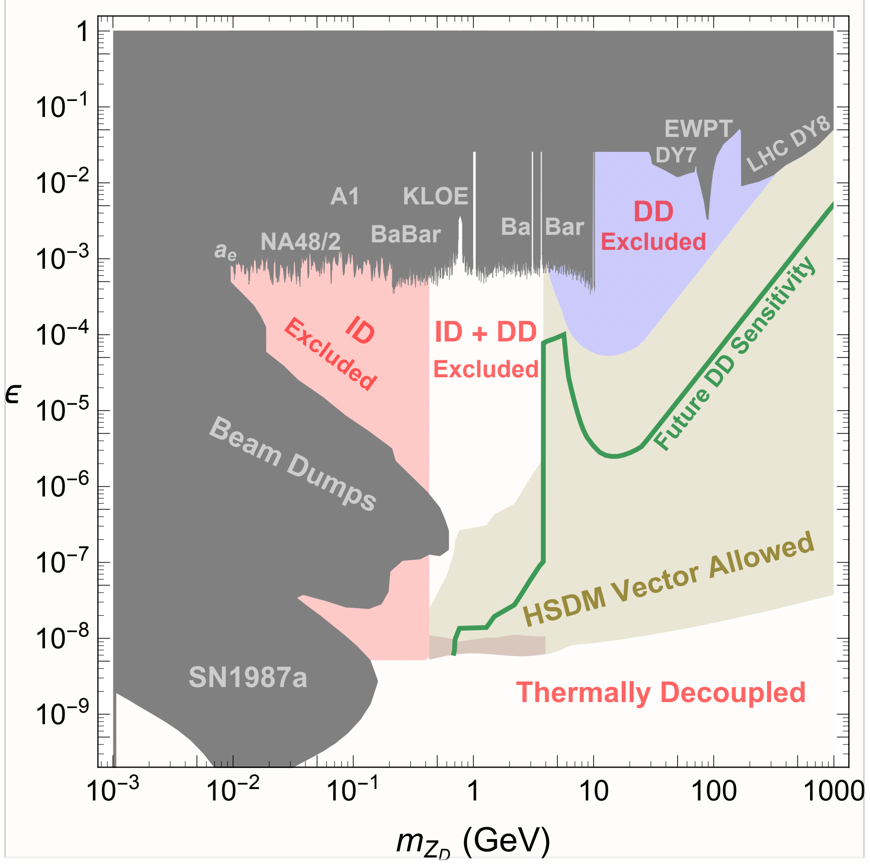
WIMP “next door”

J. Shelton





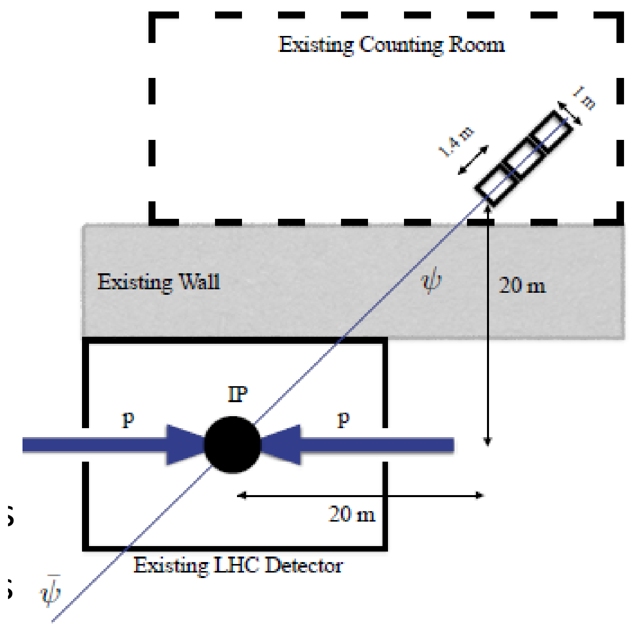


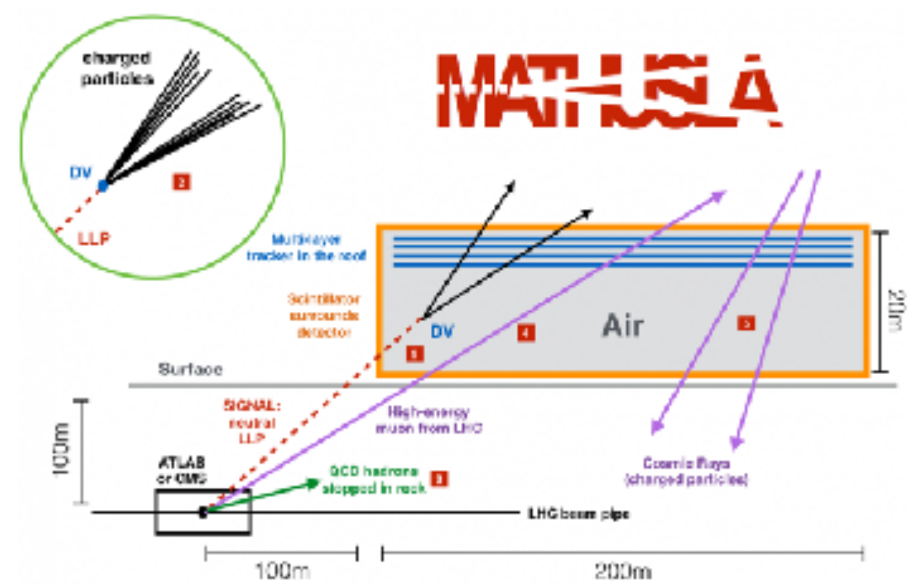


Long Lived Particles (LLP)

- Dark sector has tiny coupling with SM.
- Going through "portals": dark photon, Higgs, ...
- Can be produced at the LHC through the decay of SM particles: Higgs, Z, ... or directly.
- Long Lived Particle (LLP) searches at the LHC.

Far detectors





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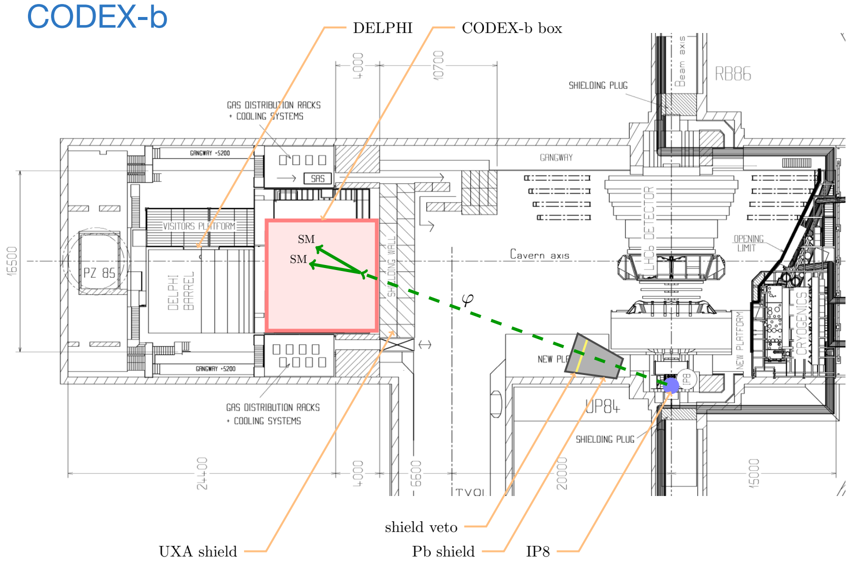
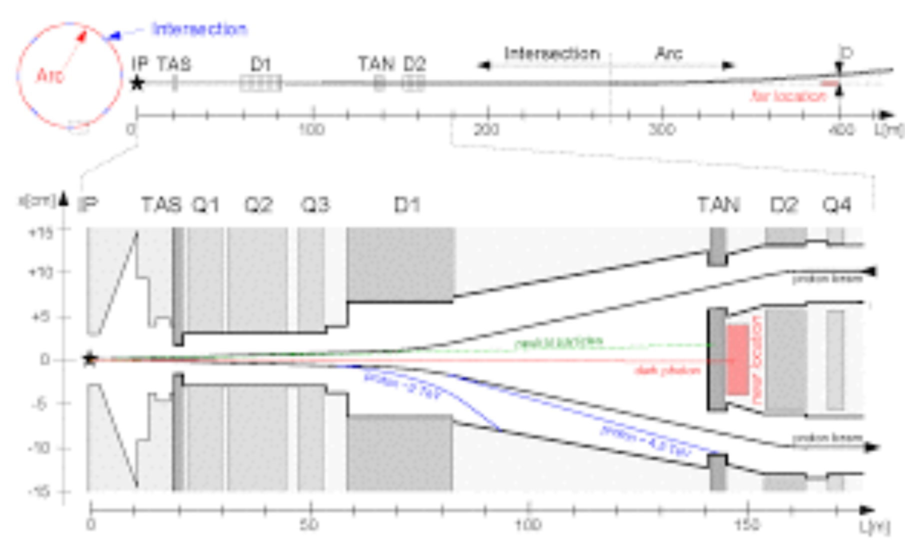
CODEX-b



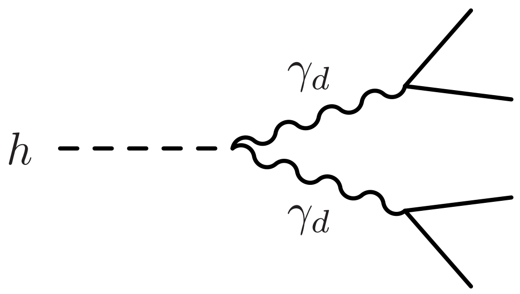


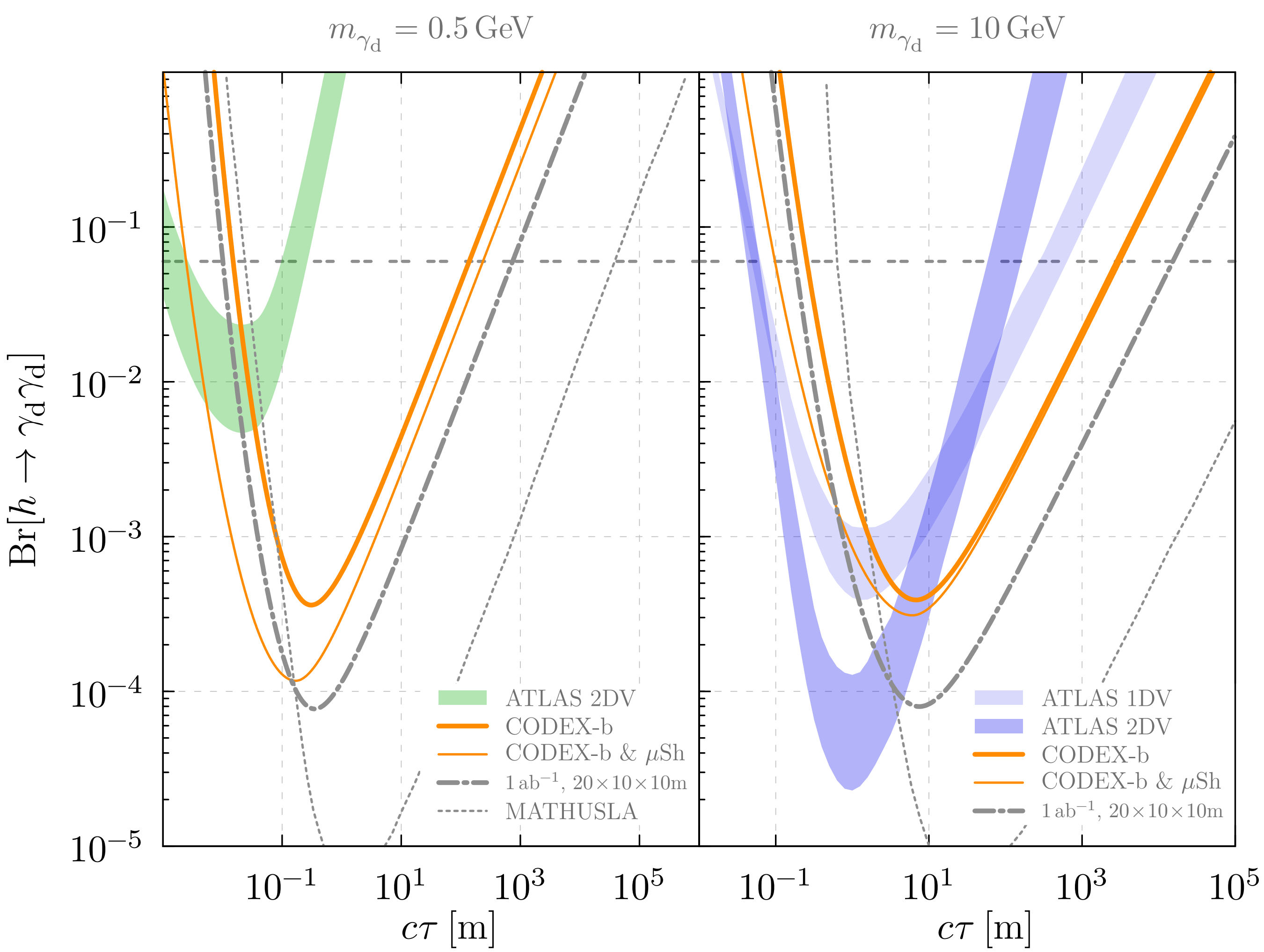
FASER

Far detector panel on Monday.

Could reach $\tau \approx 10^{4\text{-}5}$ m

Exotic Higgs decays





Application:
Neutral Naturalness
(See back-up material)

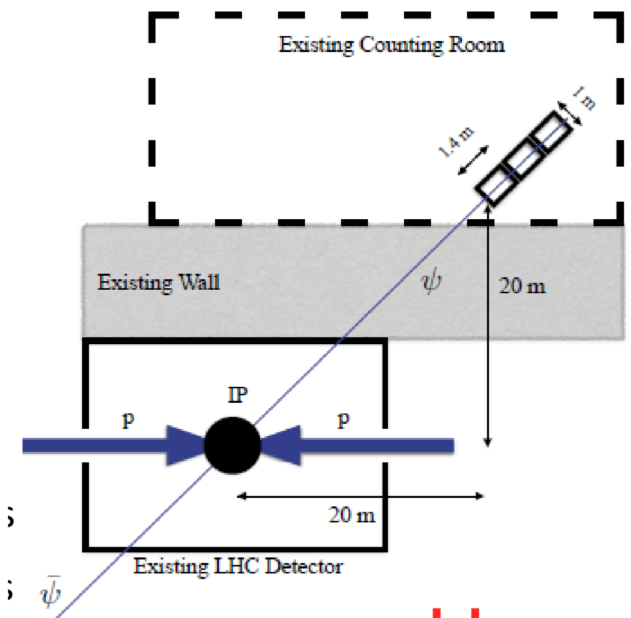
For low masses, ATLAS/CMS are background limited, CODEX-b & MATHUSLA have an edge

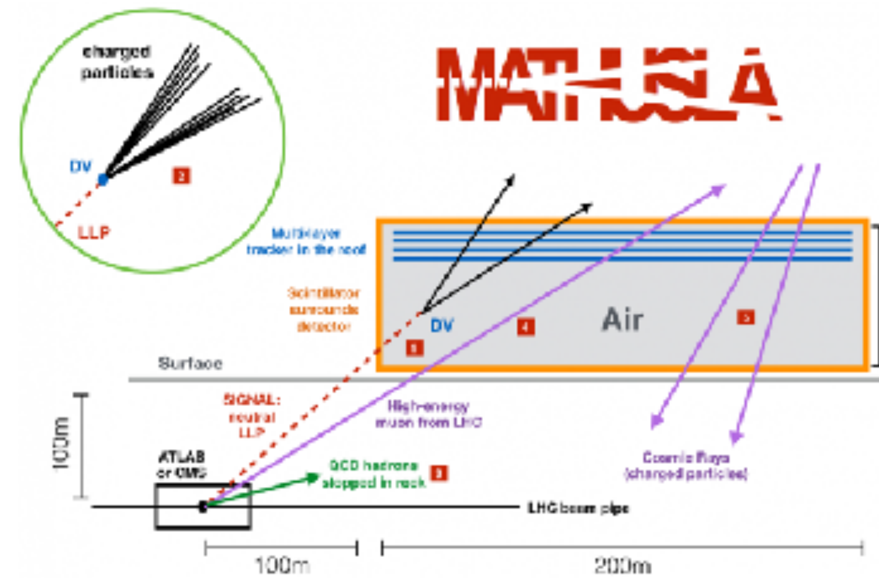
V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243

ATLAS reach: A. Coccaro, et al.: 1605.02742

S. Knapen

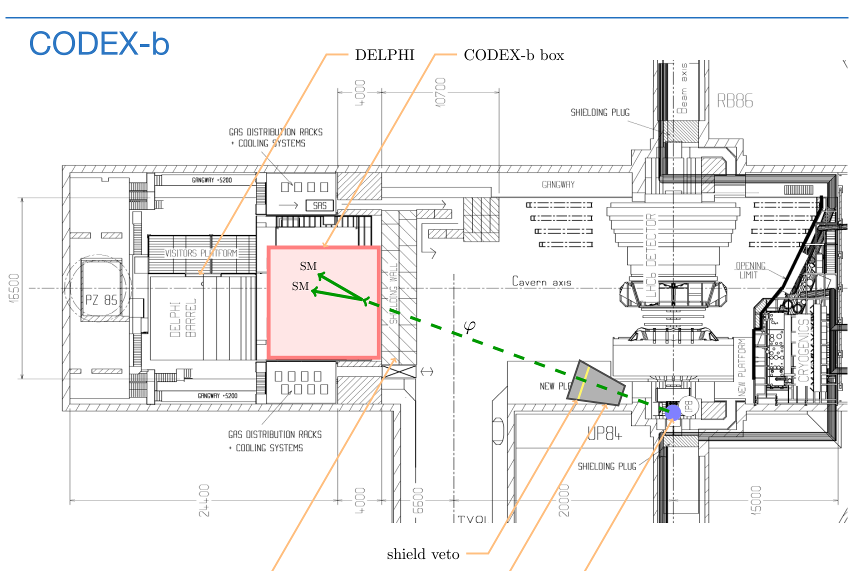
Far detectors

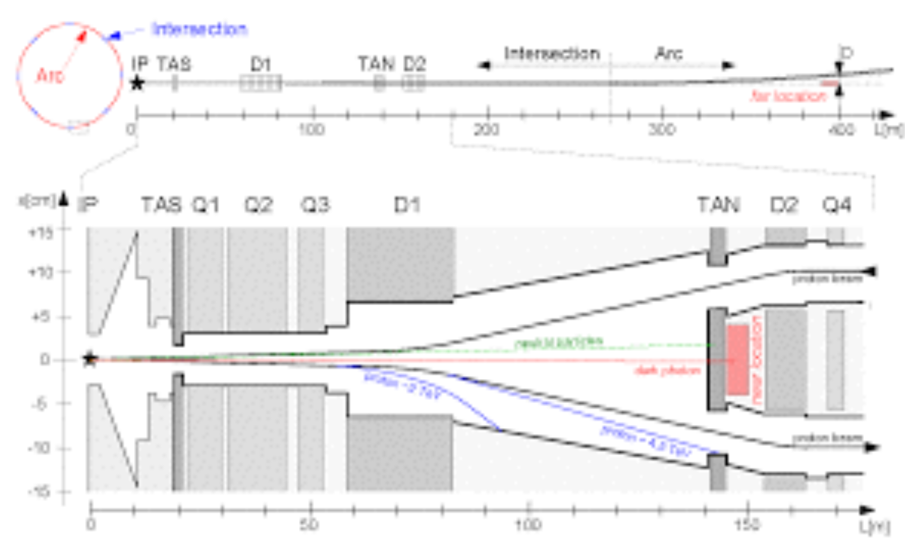




MATHUSLA

Have we fully optimized LLP searches at the interaction points ATLAS, CMS, LHCb?



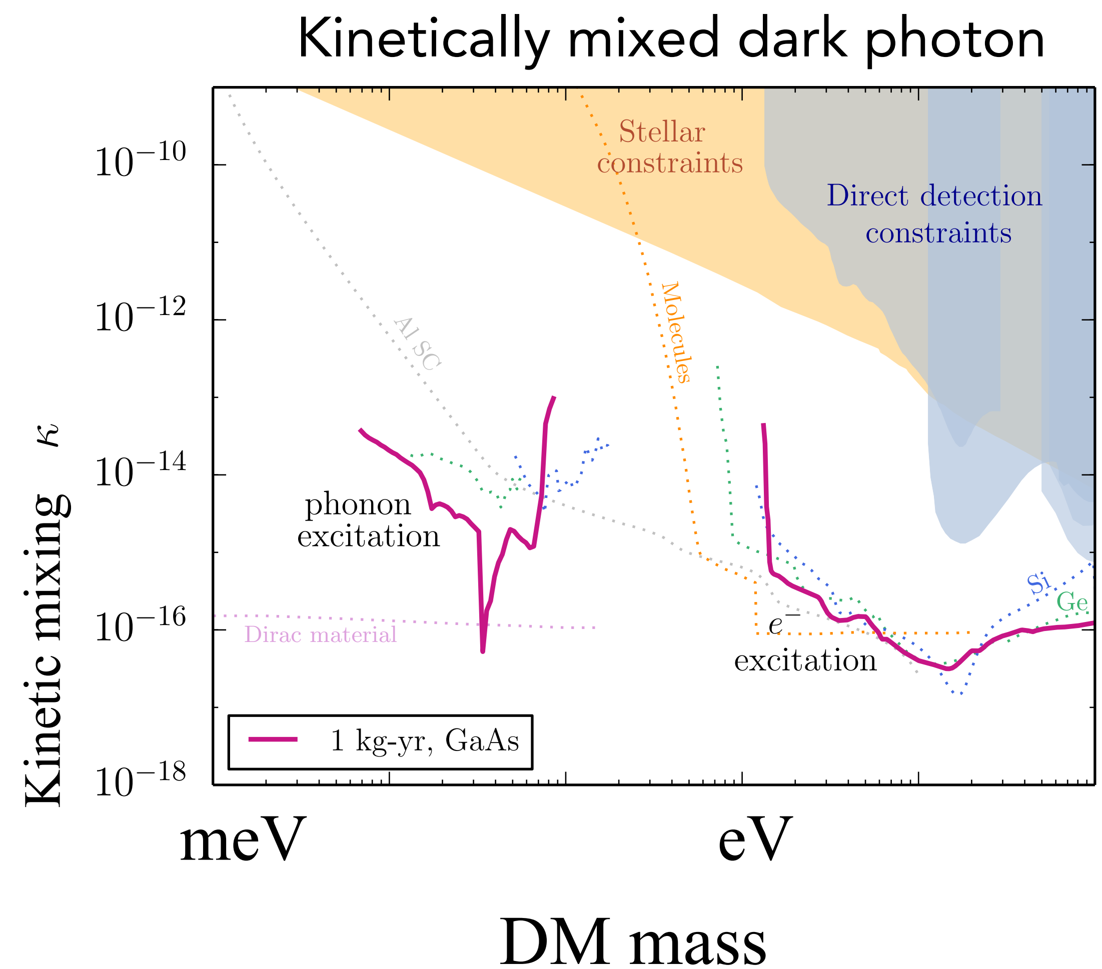


FASER

Small scale proposals, for example

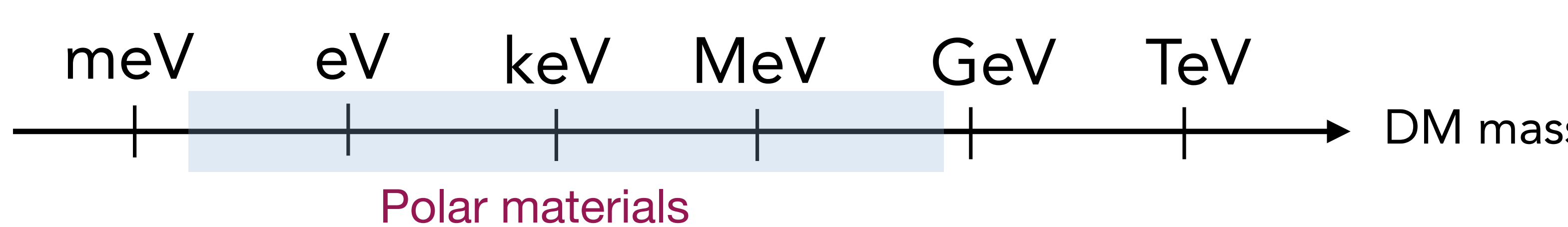
Dark matter absorption

T. Lin



- Dark photon is all of the dark matter
- Mono-energetic absorption signal

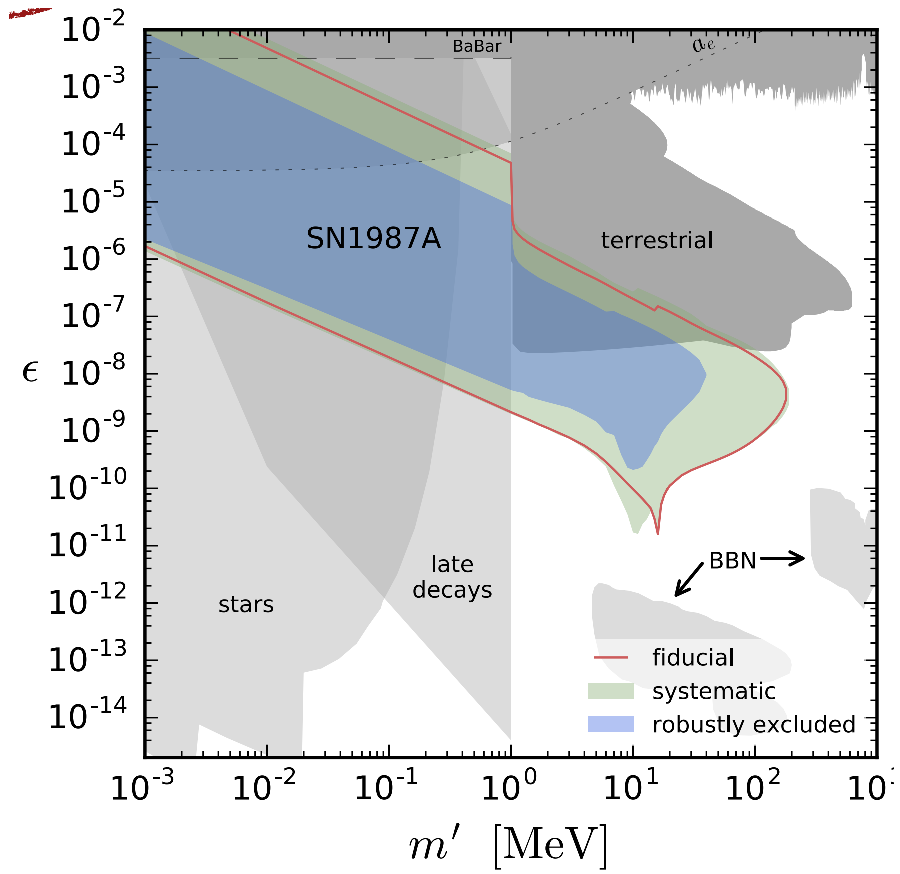
Hochberg, TL, Zurek 2016+2017
DAMIC: Chavarria et al. 2017
An, Pospelov, Pradler 2013, 2014

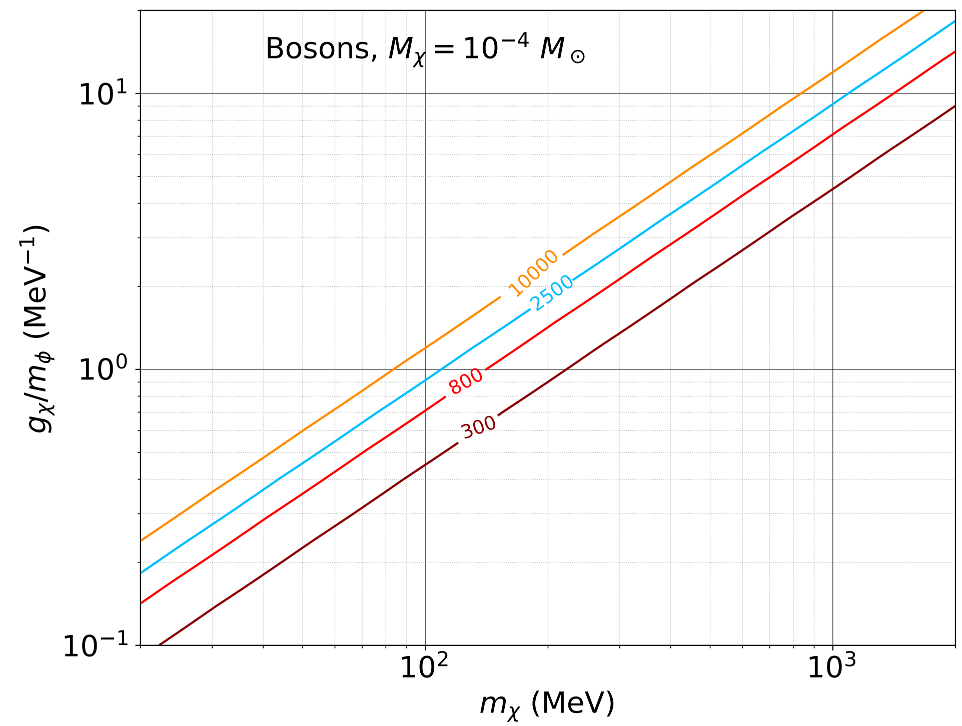


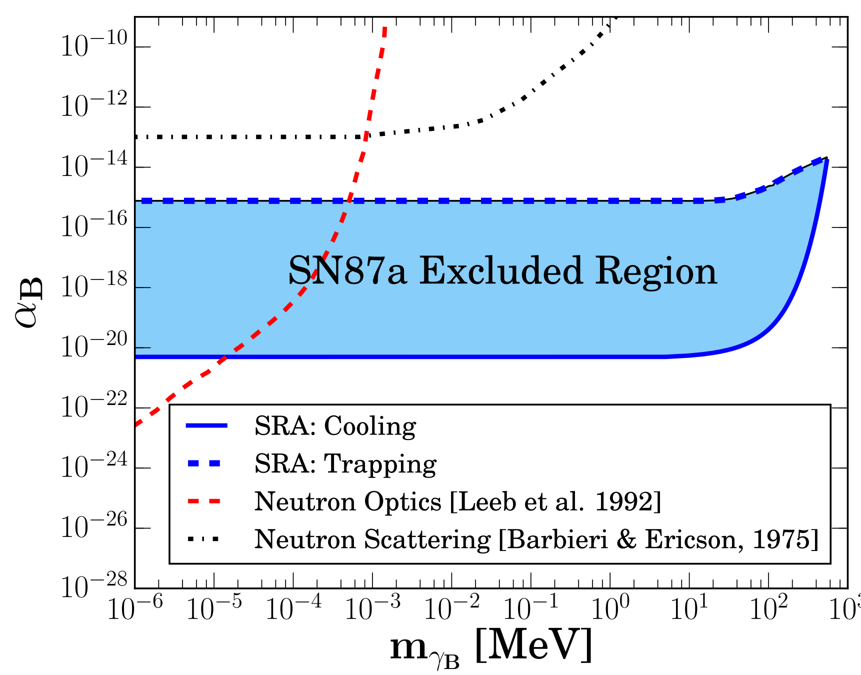
See also panel discussion on Tuesday.

Neutron star

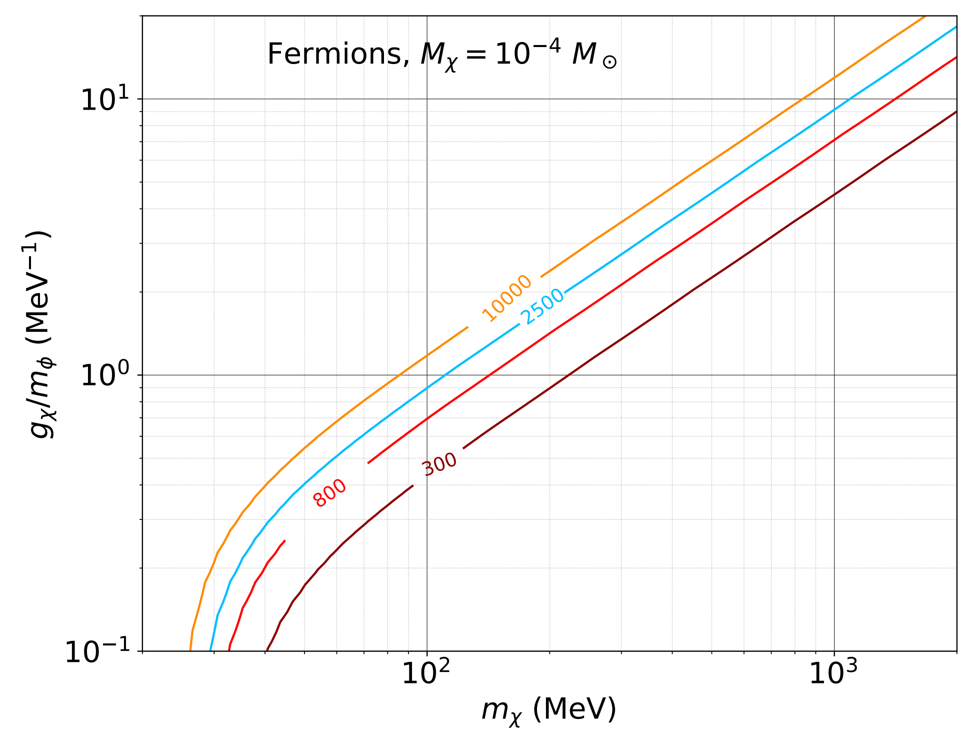
S. Reddy







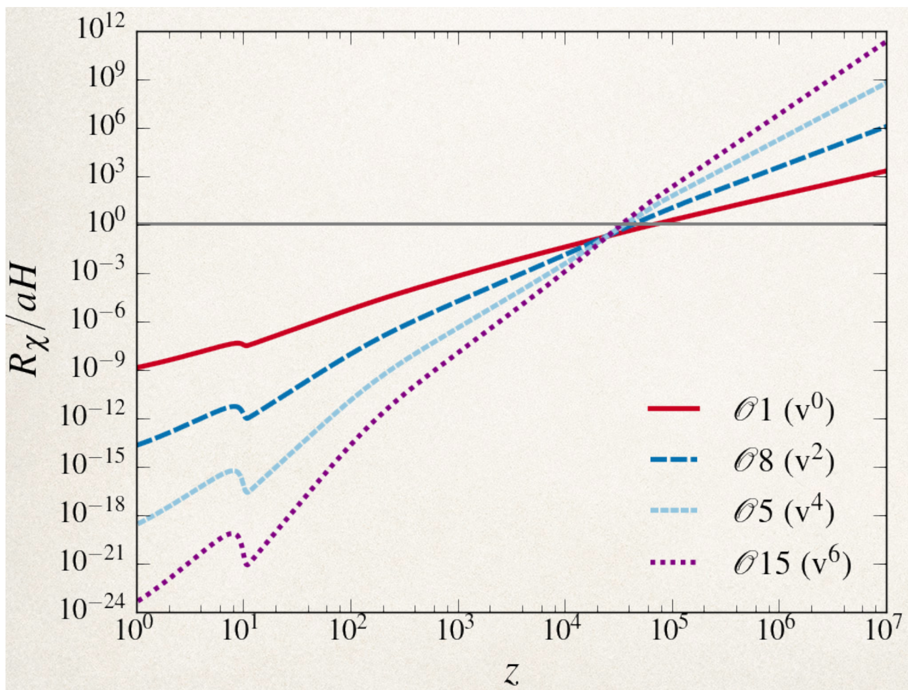
cooling

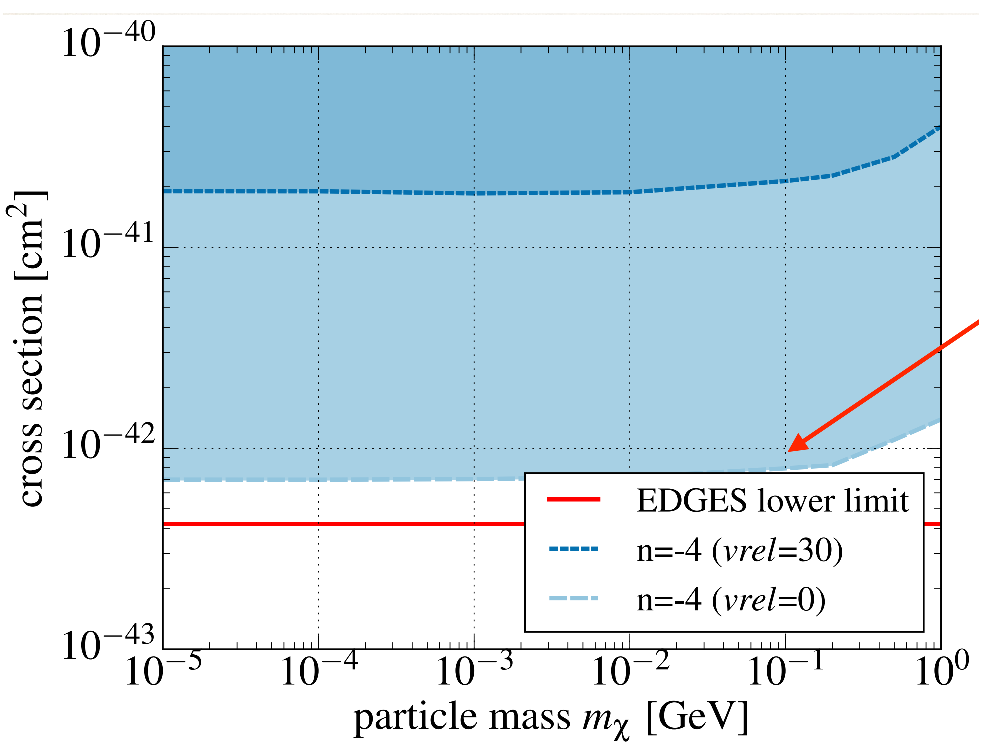


GW170817

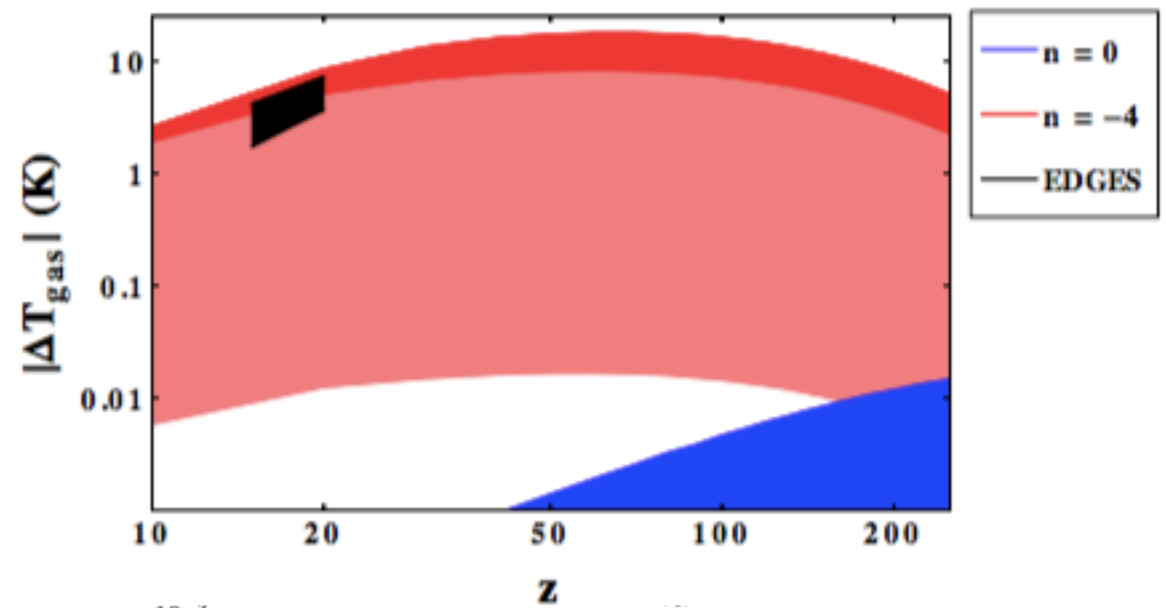
Early Universe: CMB. LSS

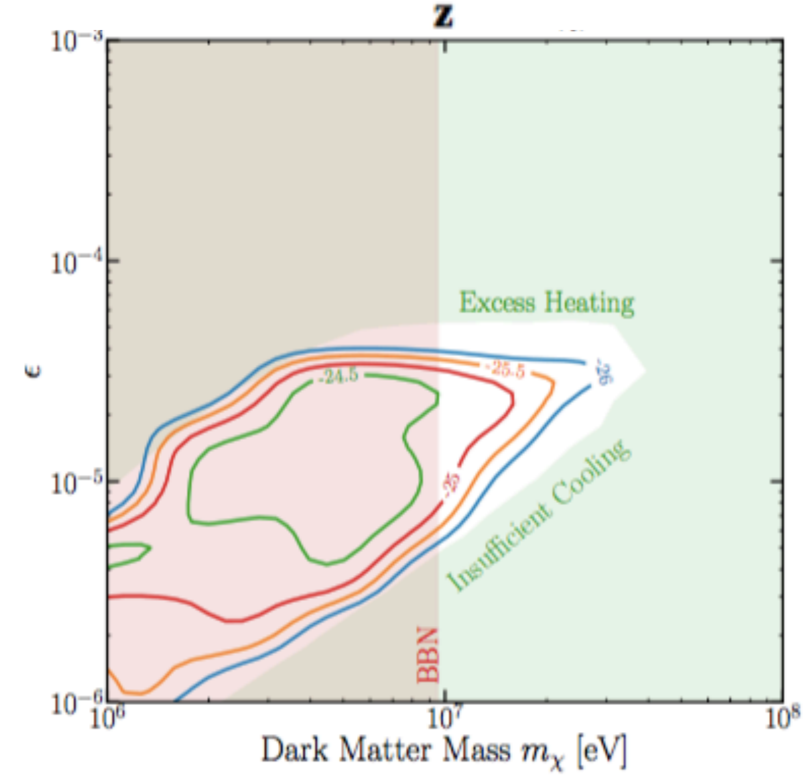
DM SM velocity dependent scattering





K. Boddy

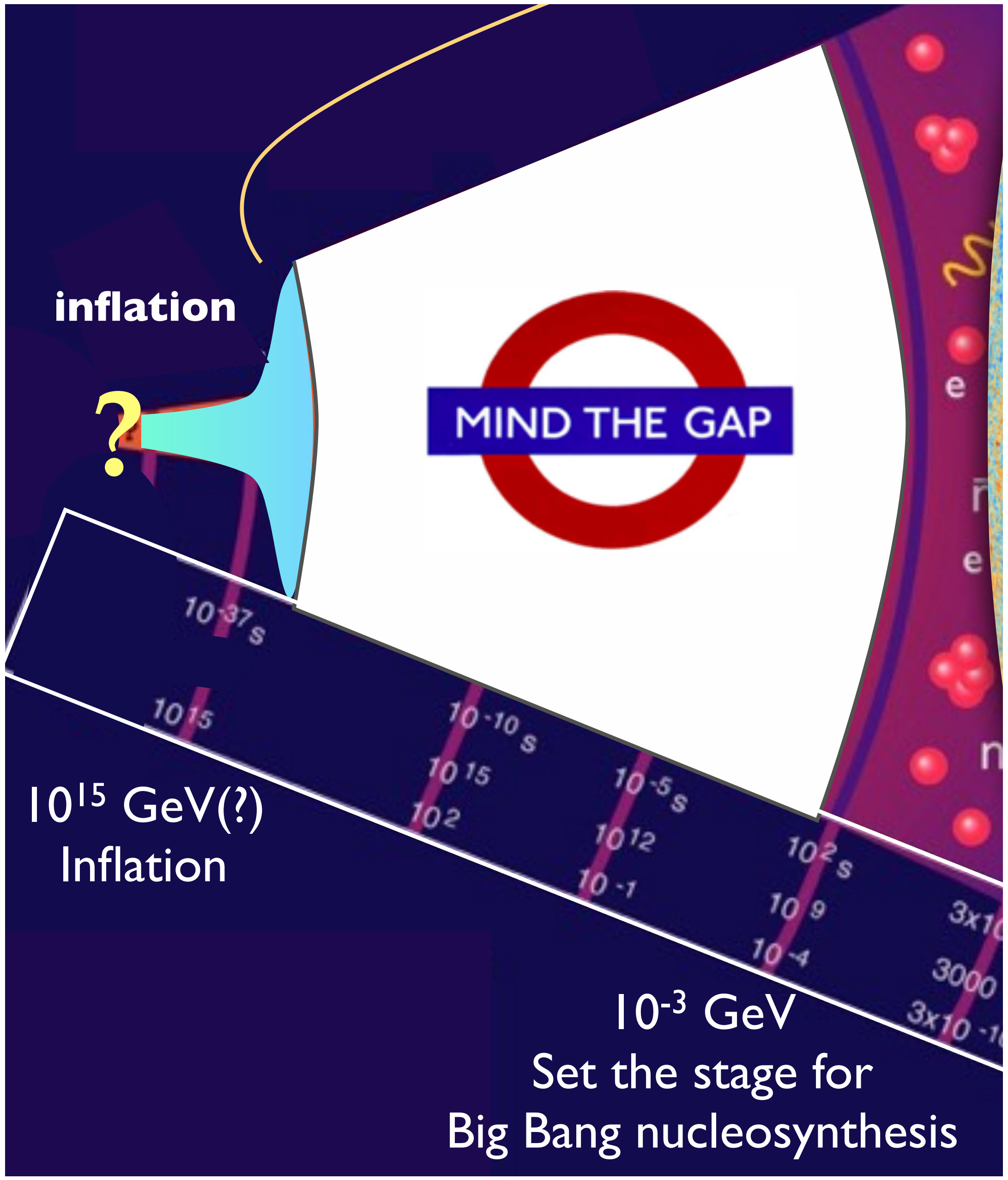


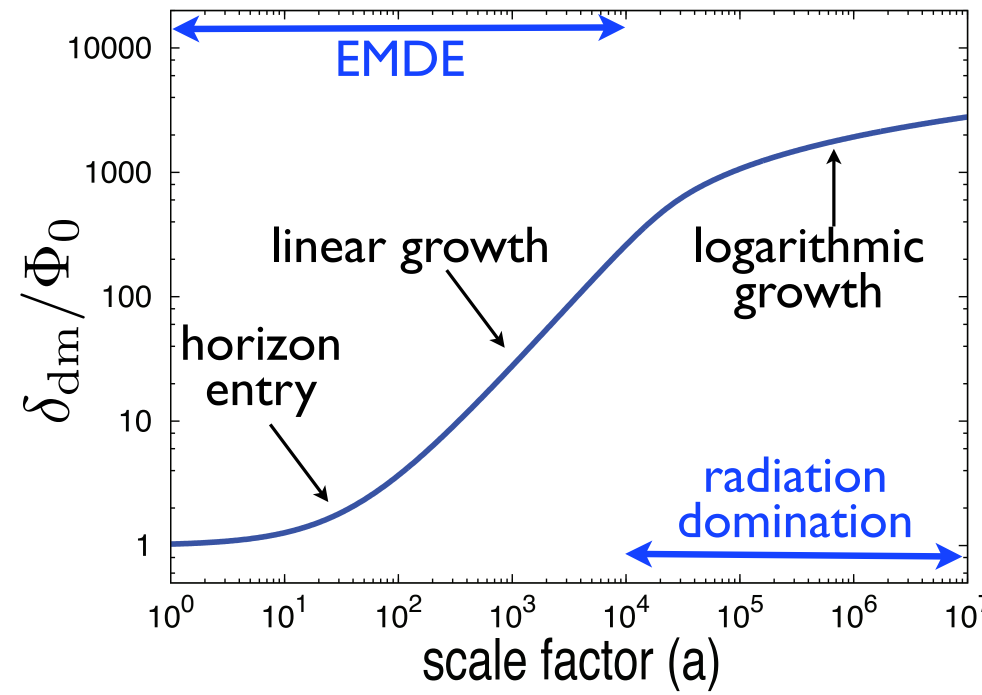


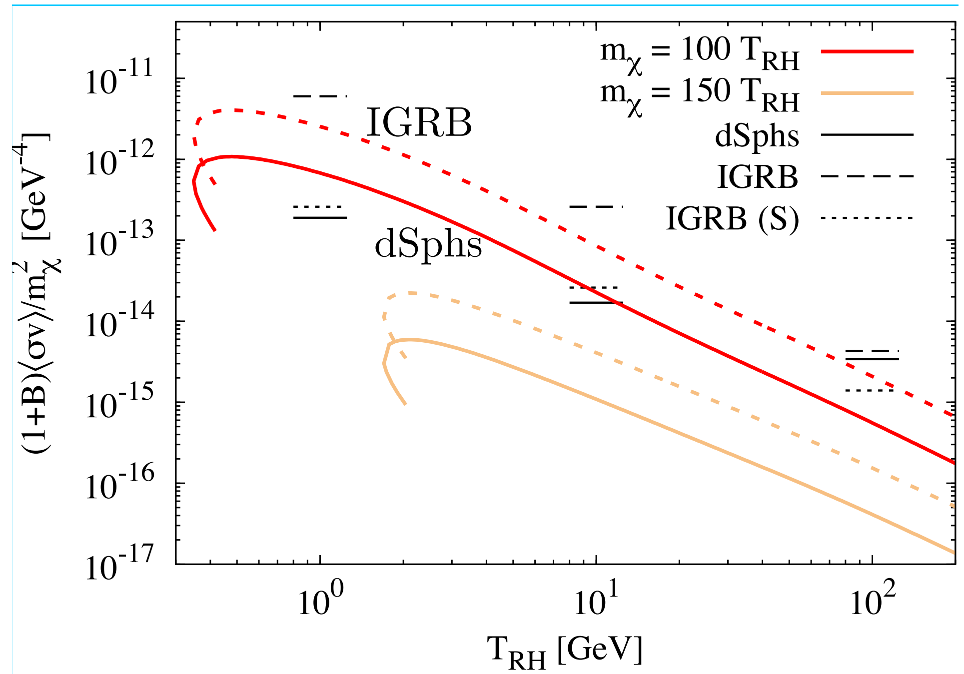
T. Slatyer

Interplay with early evolution

A. Erickcek







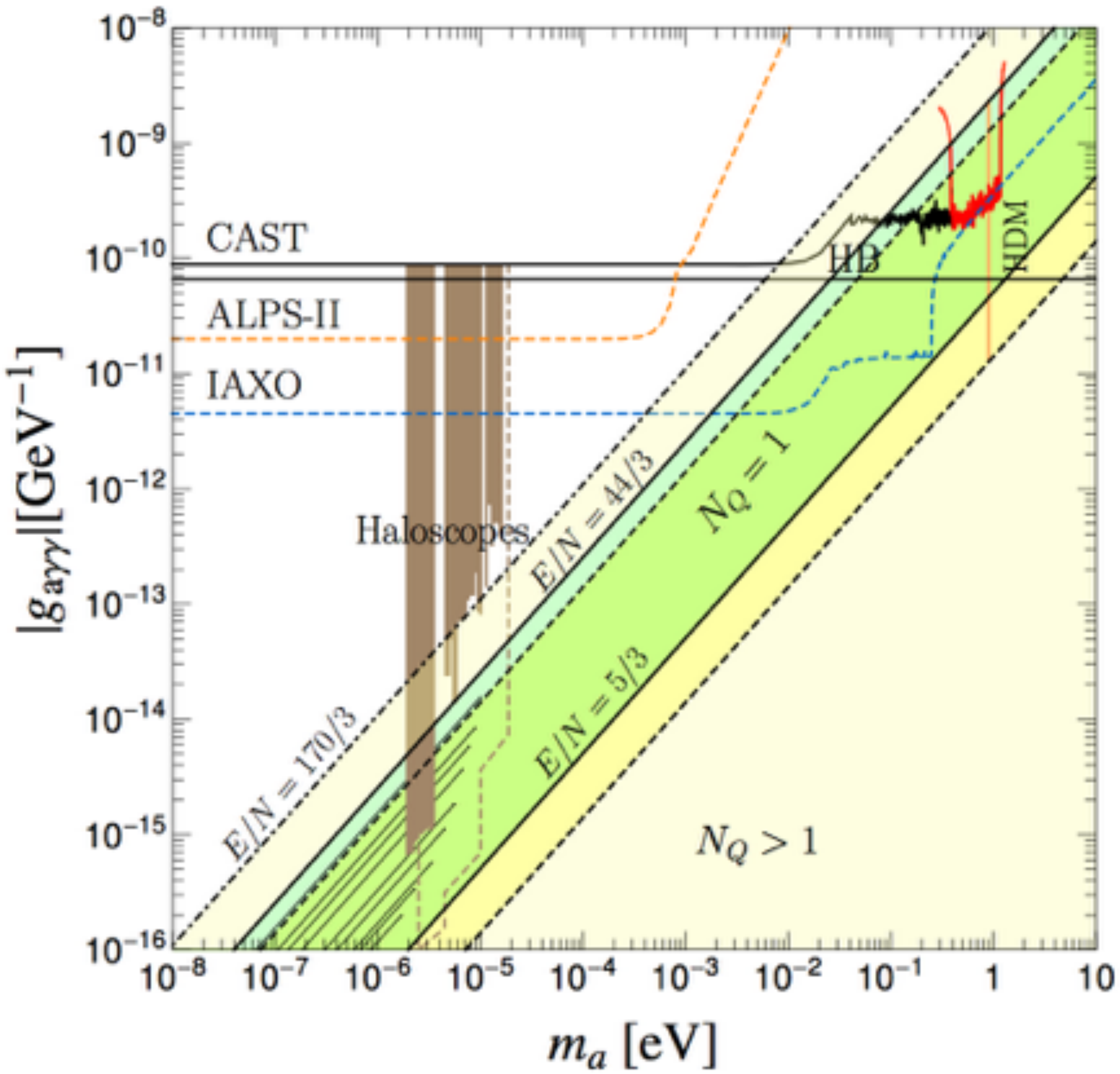
IGRB: $B = 75,000 \quad k_{\rm cut} = 40 k_{\rm RH}$

dSphs: $B = 20,000 \quad k_{\rm cut} = 20 k_{\rm RH}$

$z_f = 400$

Example: Early matter domination forming minihalos.

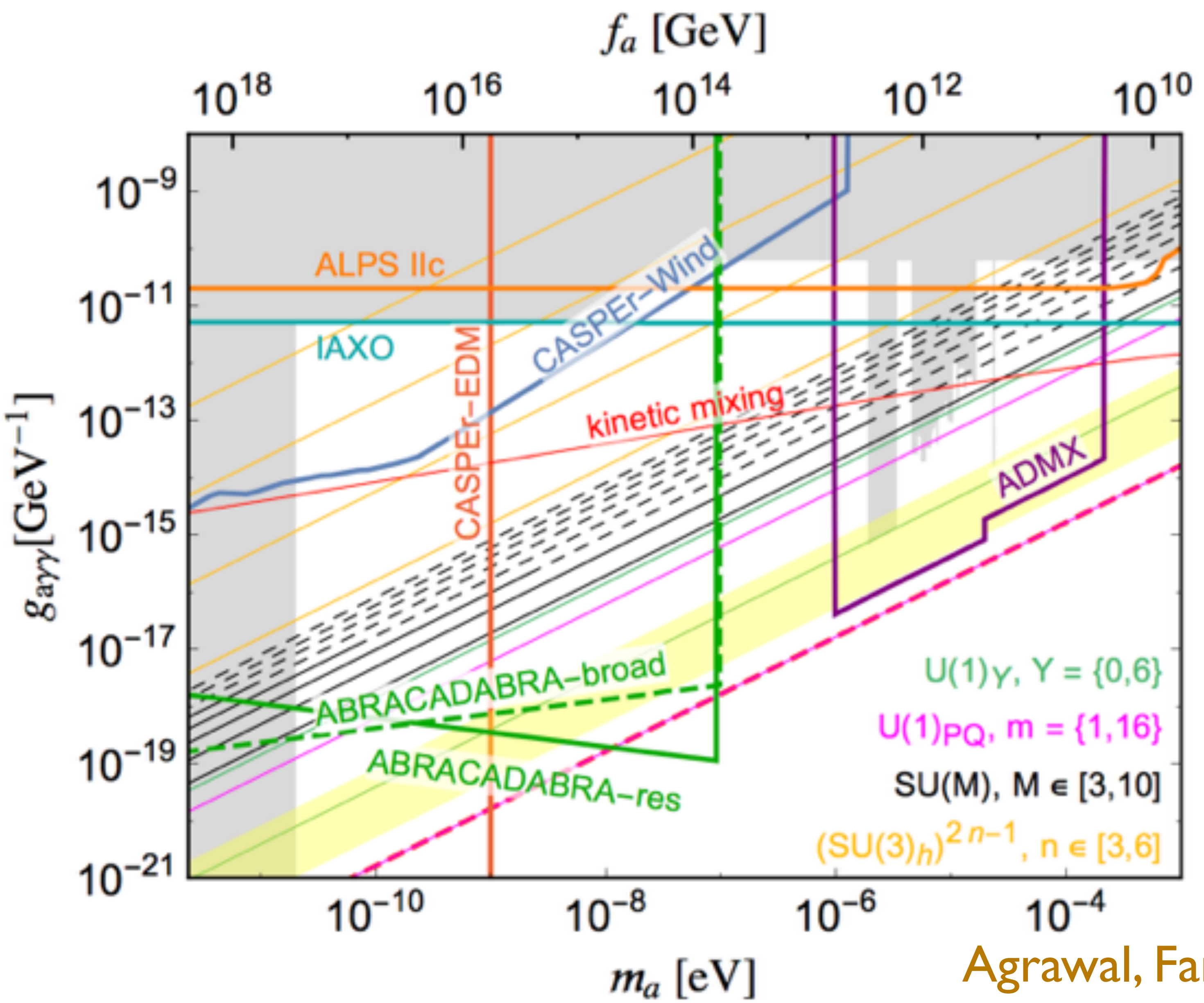
Axion: the old story



Remains interesting benchmarks, and exp. probes

Excited to hear new ADMX results in 2 weeks!

Much broader view



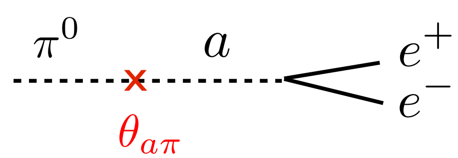
Agrawal, Fan, Reece, LTW

A much larger variety of models.

Many new exp. proposals as well.

A gap for MeV axion? D. Alves

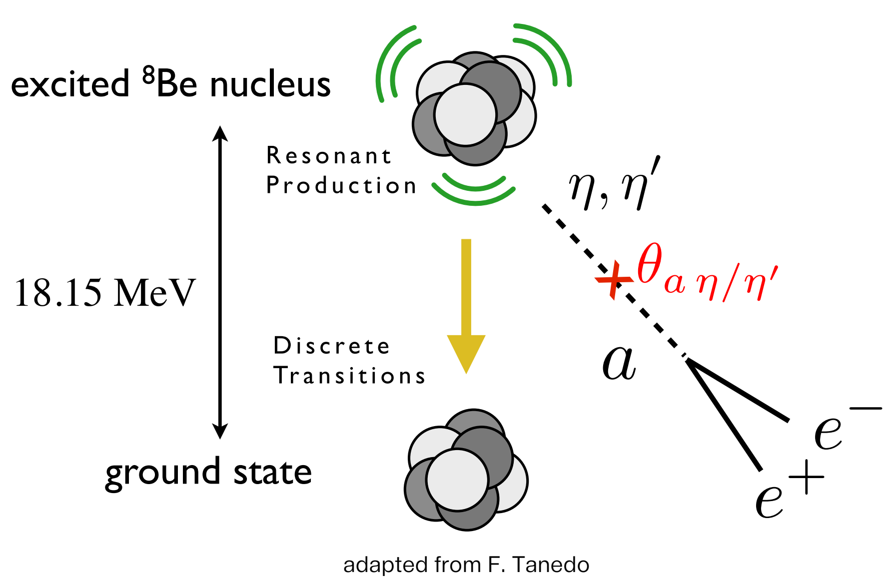
$$\textcolor{red}{2\times}\frac{m_u}{f_a}\,a\,\bar{u}\gamma_5 u \;+\; \textcolor{red}{1\times}\frac{m_d}{f_a}\,a\,\bar{d}\gamma_5 d \;+\; \textcolor{red}{Q_e\times}\frac{m_e}{f_a}\,a\,\bar{e}\gamma_5 e$$

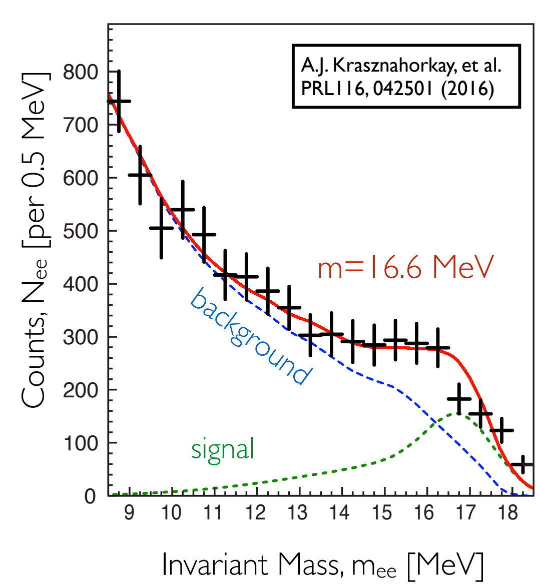


"KTeV anomaly":
measurement high relative to theoretical estimates by ~15% (3σ)

Suggests $\theta_{a\pi} \approx \frac{(0.6 \pm 0.2) \times 10^{-4}}{Q_e\ (\mathrm{GeV}/f_a)}$

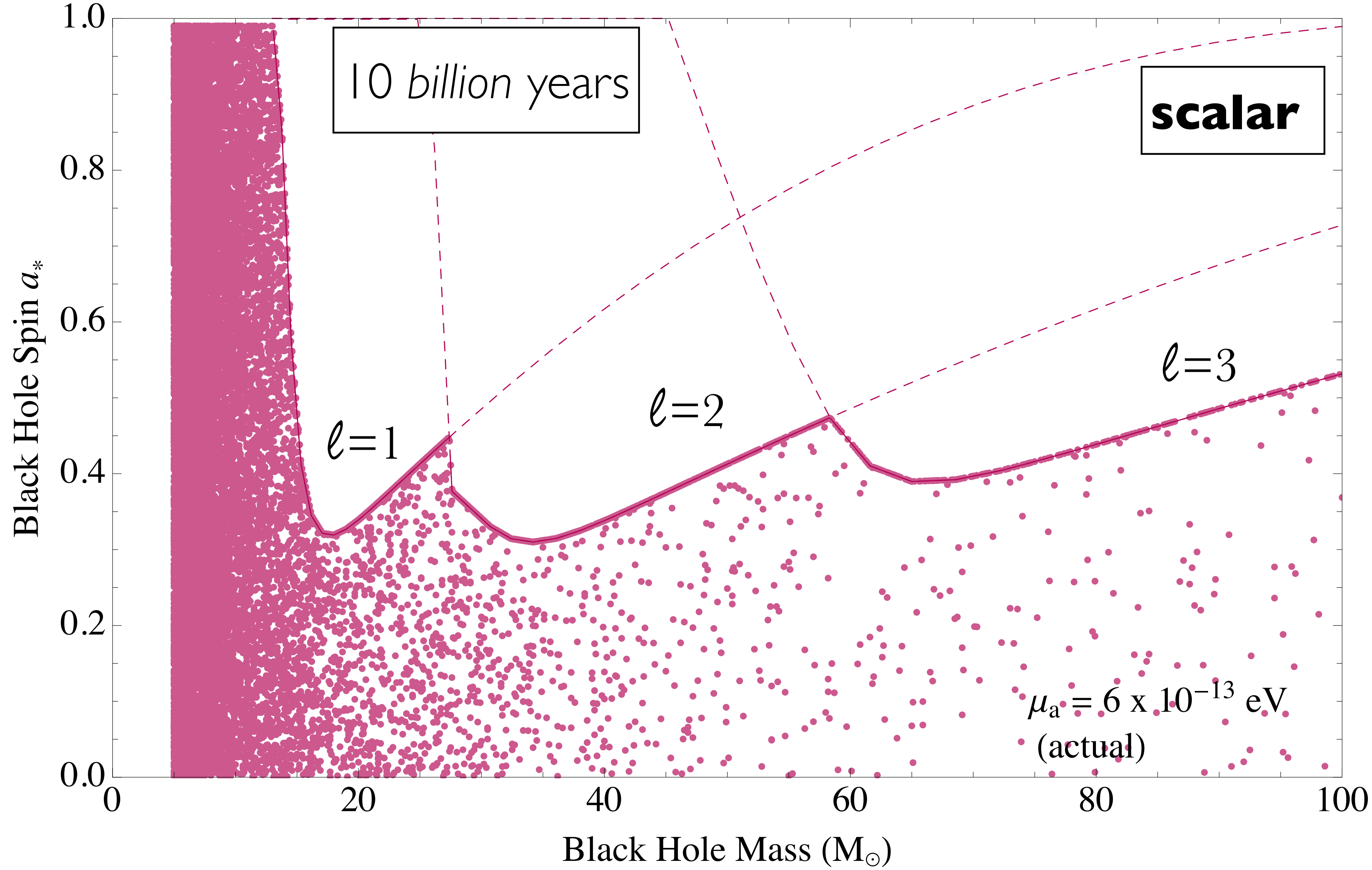
Interesting.
Complete model seems to be challenging.





New probes: superradiance

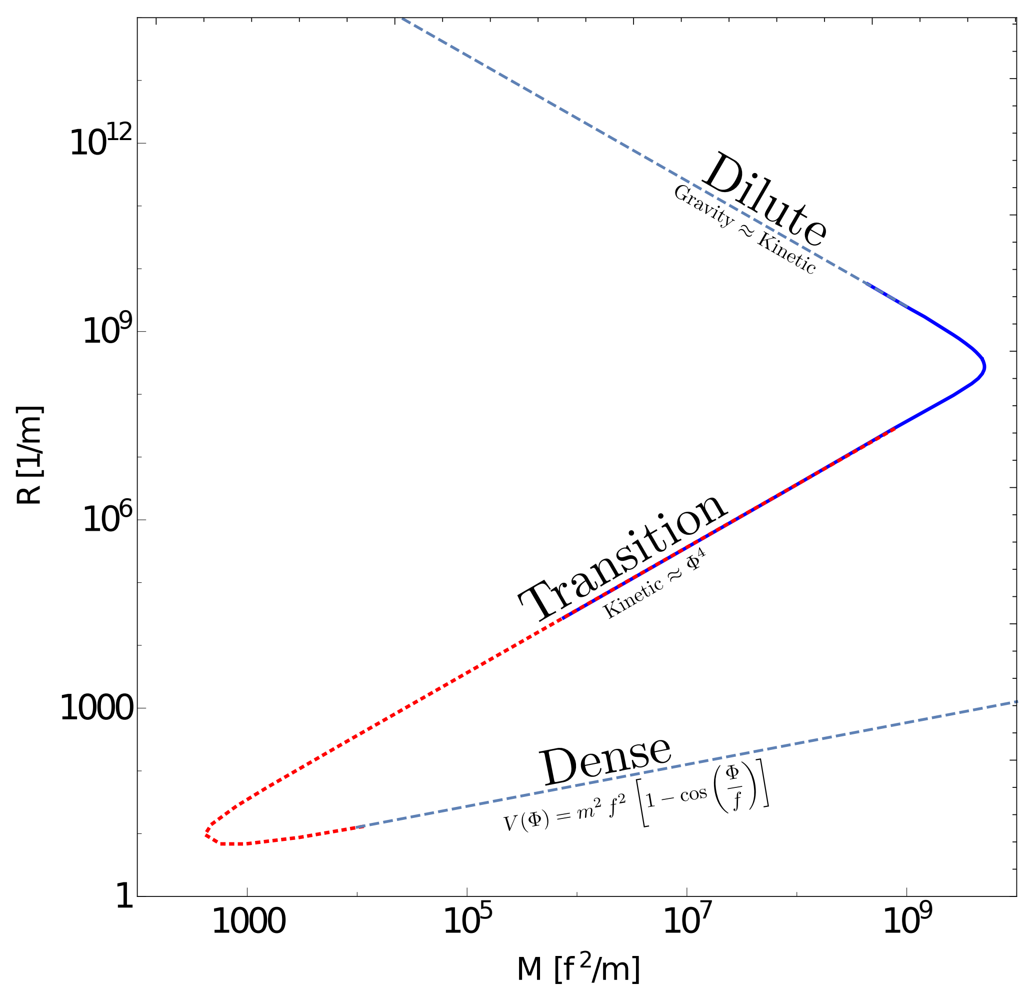
M. Baryakhtar



Can be probed by LIGO

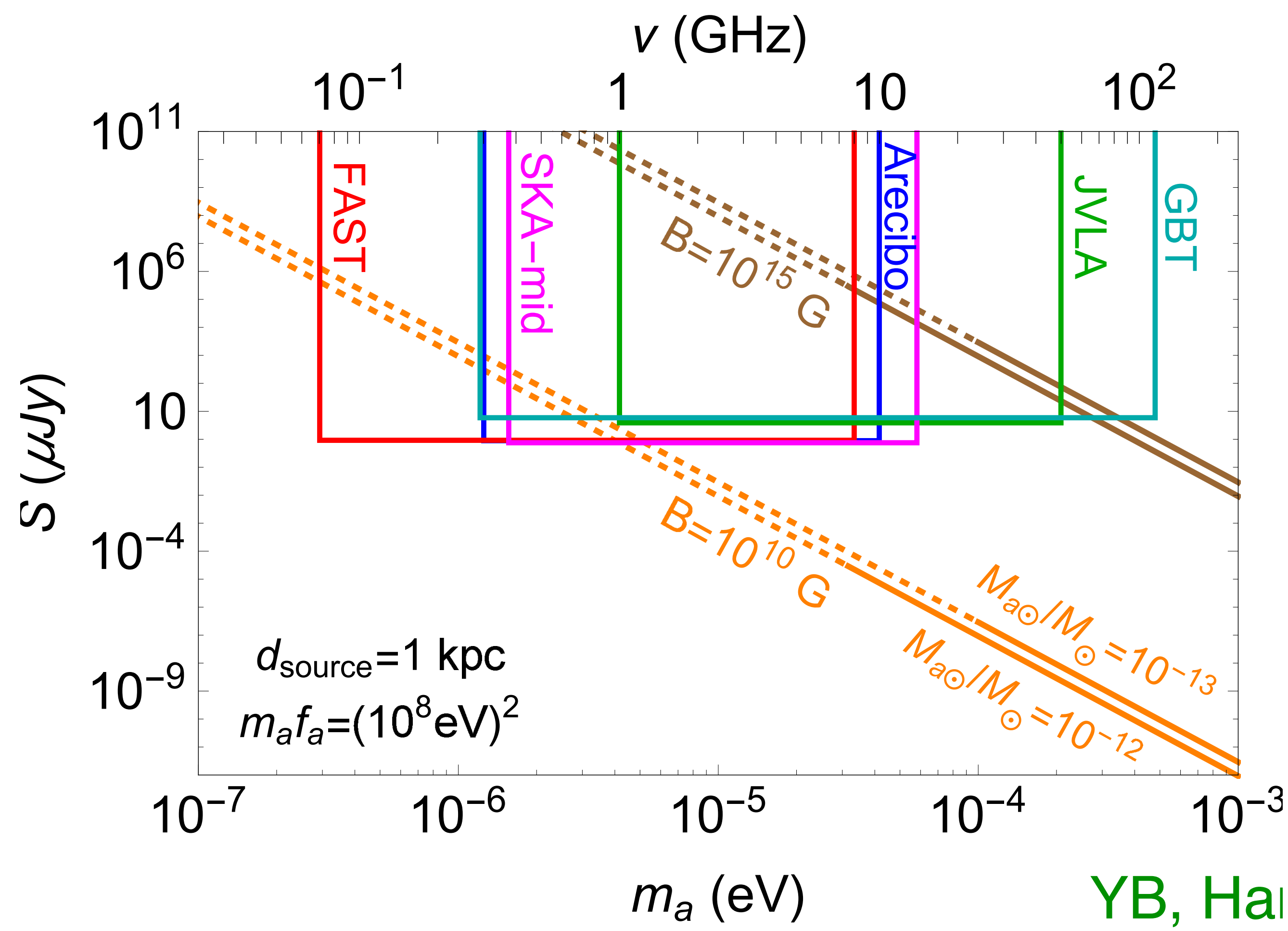
New probes: axion star?

J. Eby



Is dense axion star stable?

Y. Bai



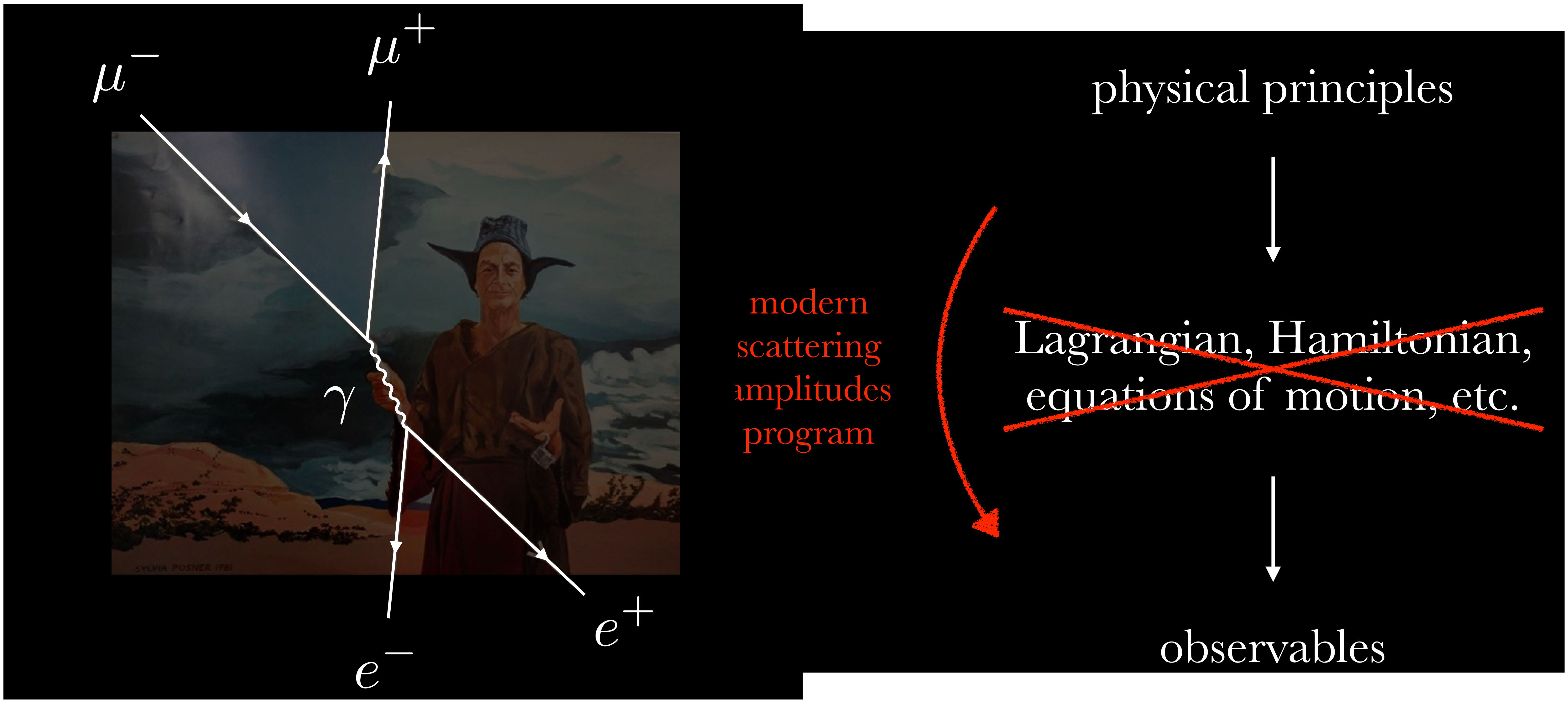
YB, Ha

neutron star encounter

New theory directions

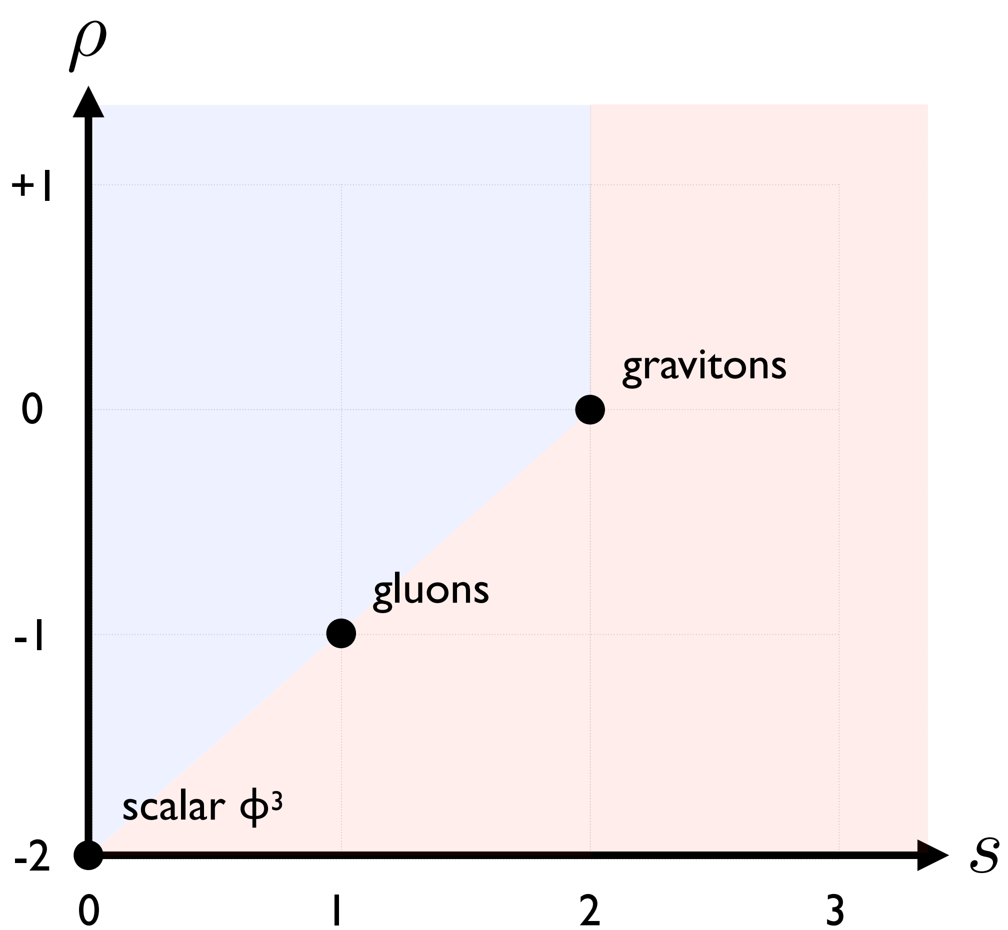
Perhaps we are not doing field theory the right way?

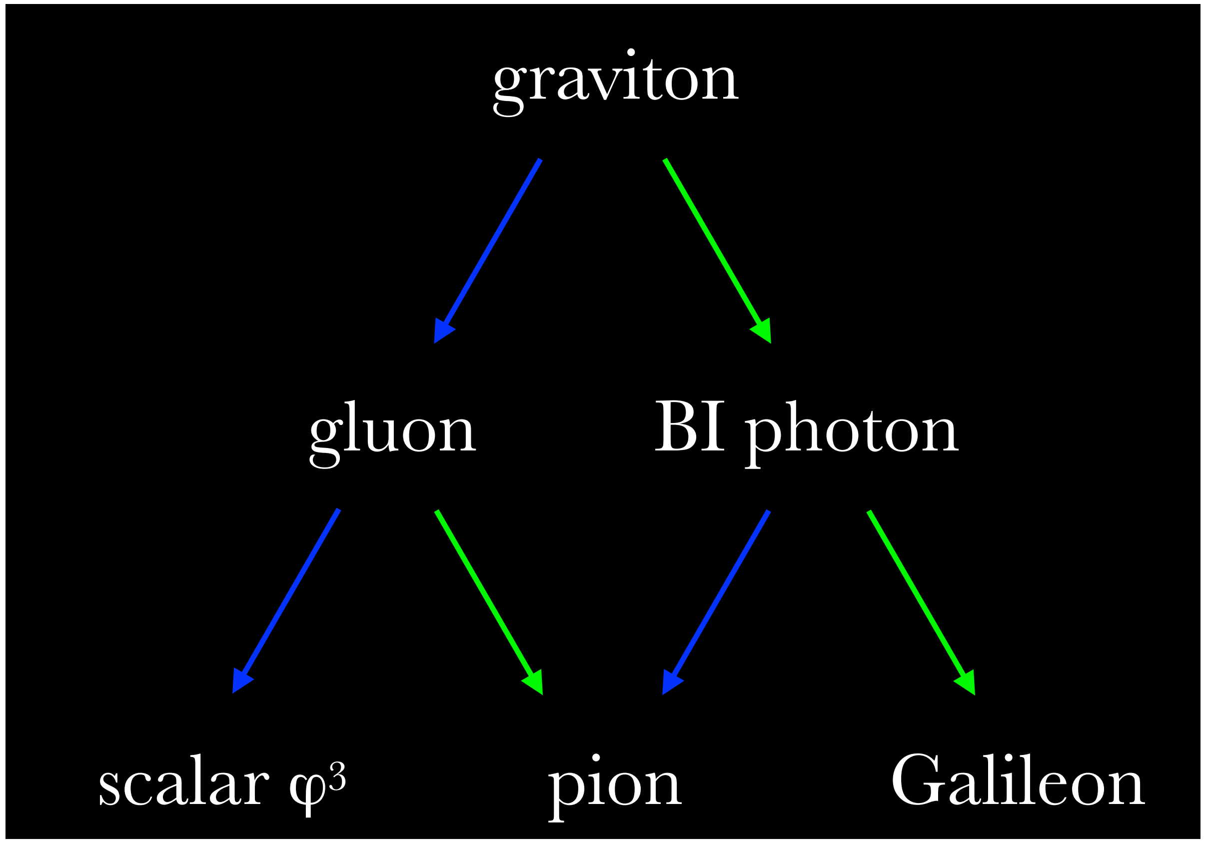
C. Cheung



Interesting progress in scattering amplitude.

C. Cheung





Deeper structure?

Connection to big questions in particle physics?

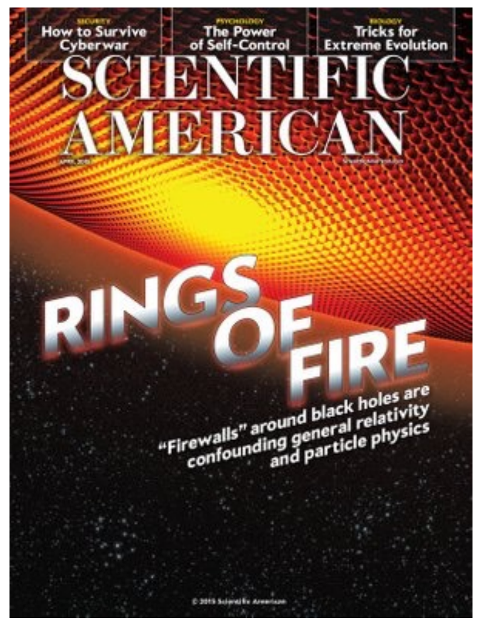
Blackhole information puzzle

S. Giddings

Various "extreme" proposals:

Firewalls

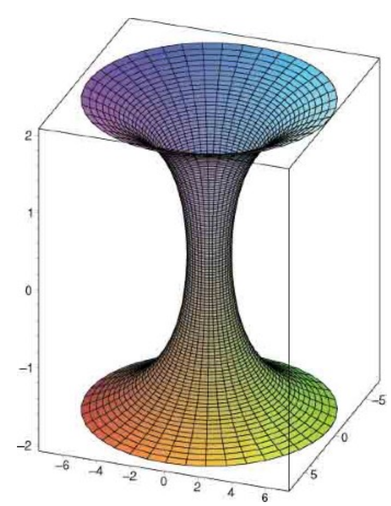
(Almheiri, Marolf, Polchinski, Sully)



Fuzzballs (starlike stringy object; Mathur, …)

ER=EPR
(Maldacena, Susskind; van Raamsdonk)

$$|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle \quad =$$

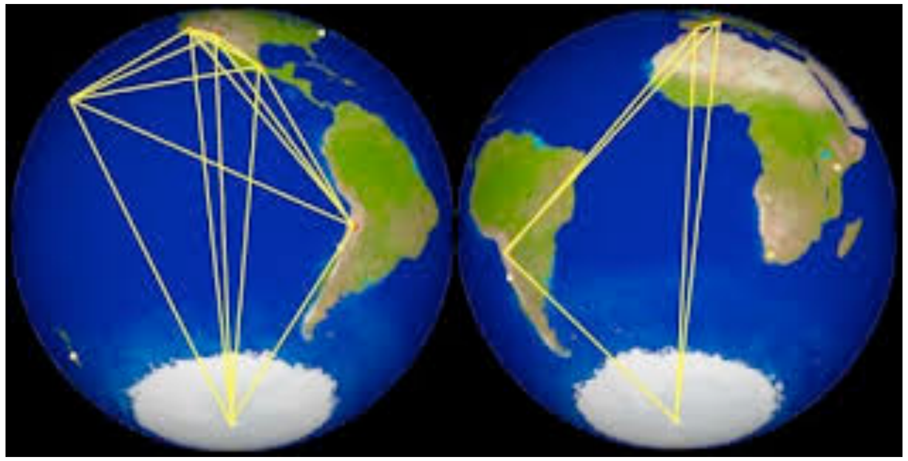


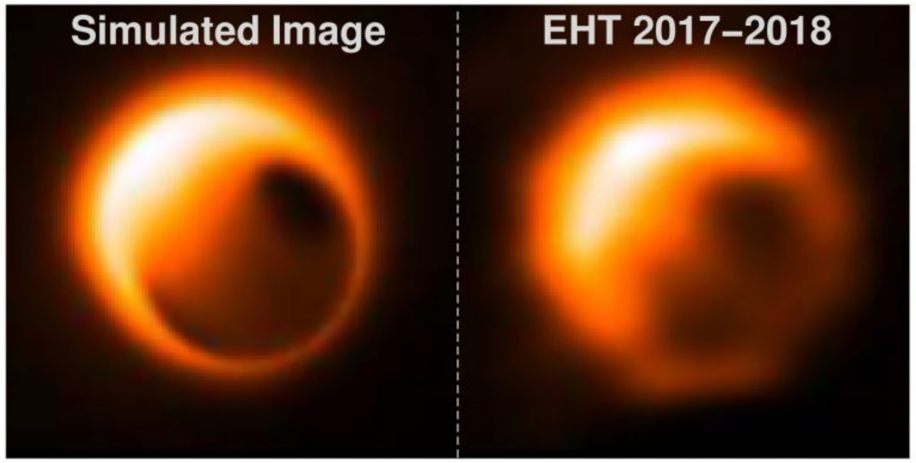
Most involve new physics on scales $\gtrsim$ R (not $l_{\rm Pl}$)

R= horizon radius

Could be testable!

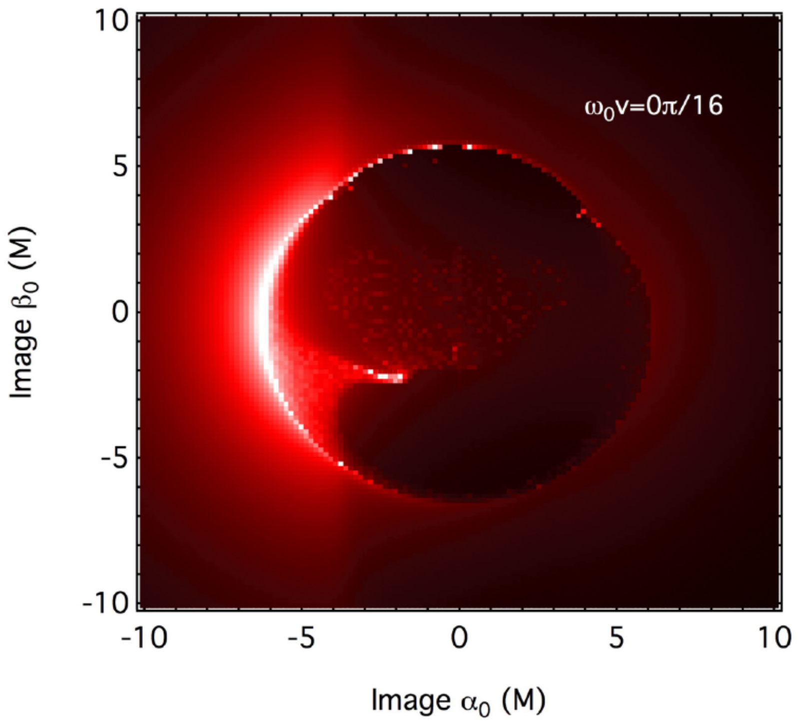
Event Horizon Telescope   Sgr A*, M87



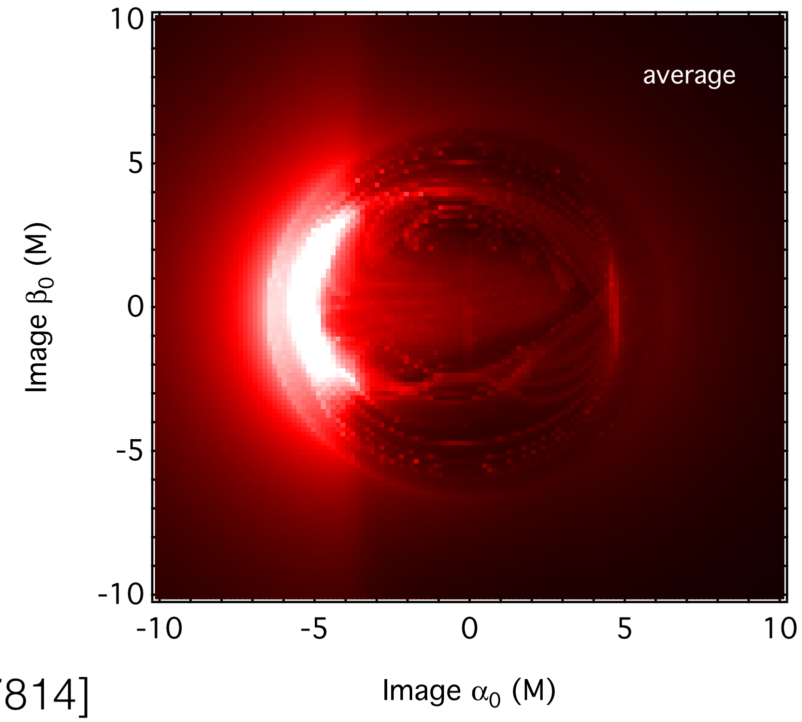


[Fish et al, 1409.4690]

E.g. Nonviolent unitarization, strong:



[SG/Psaltis, 1606.07814]

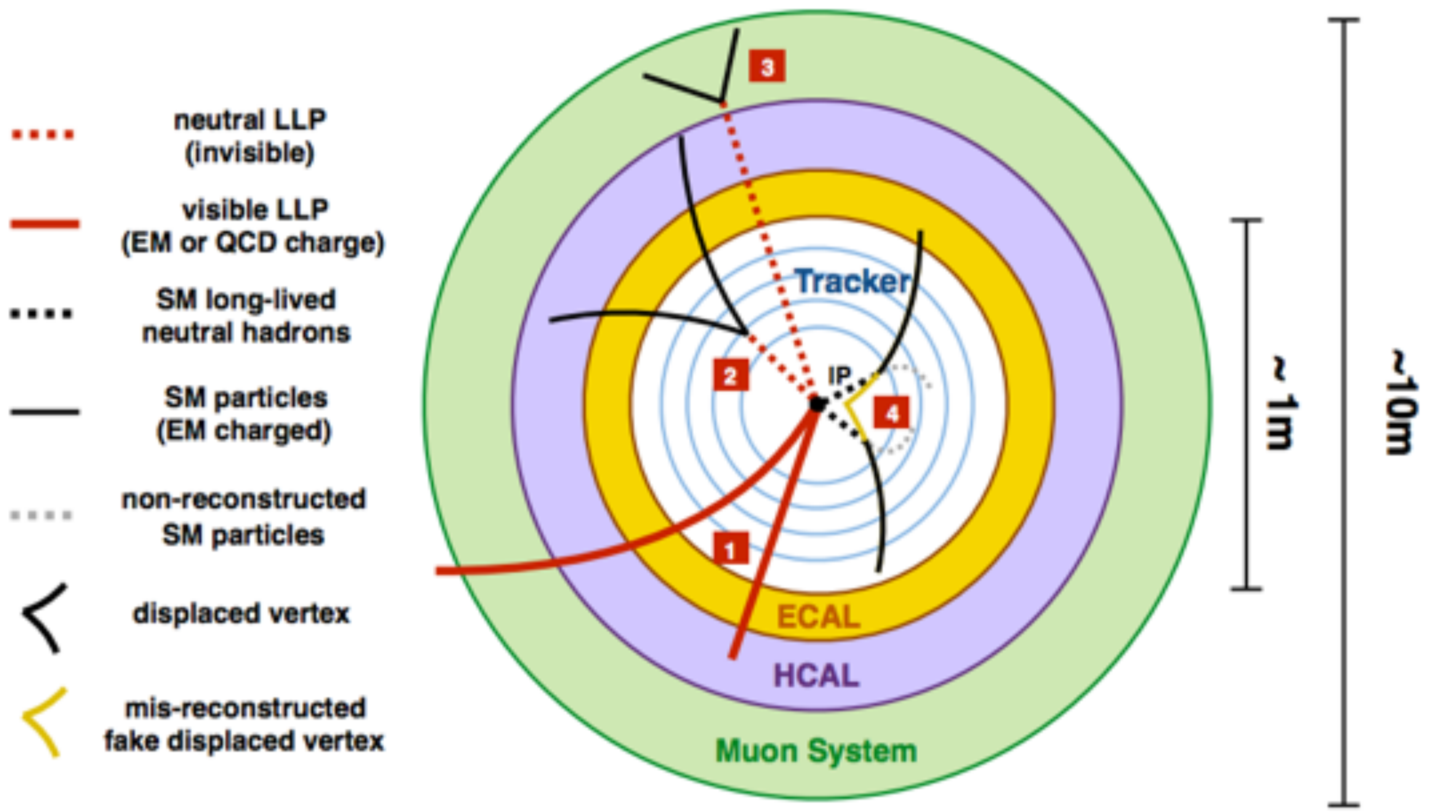


My wish for Aspen 2019 Winter Conference.

We will be talking about something completely different!

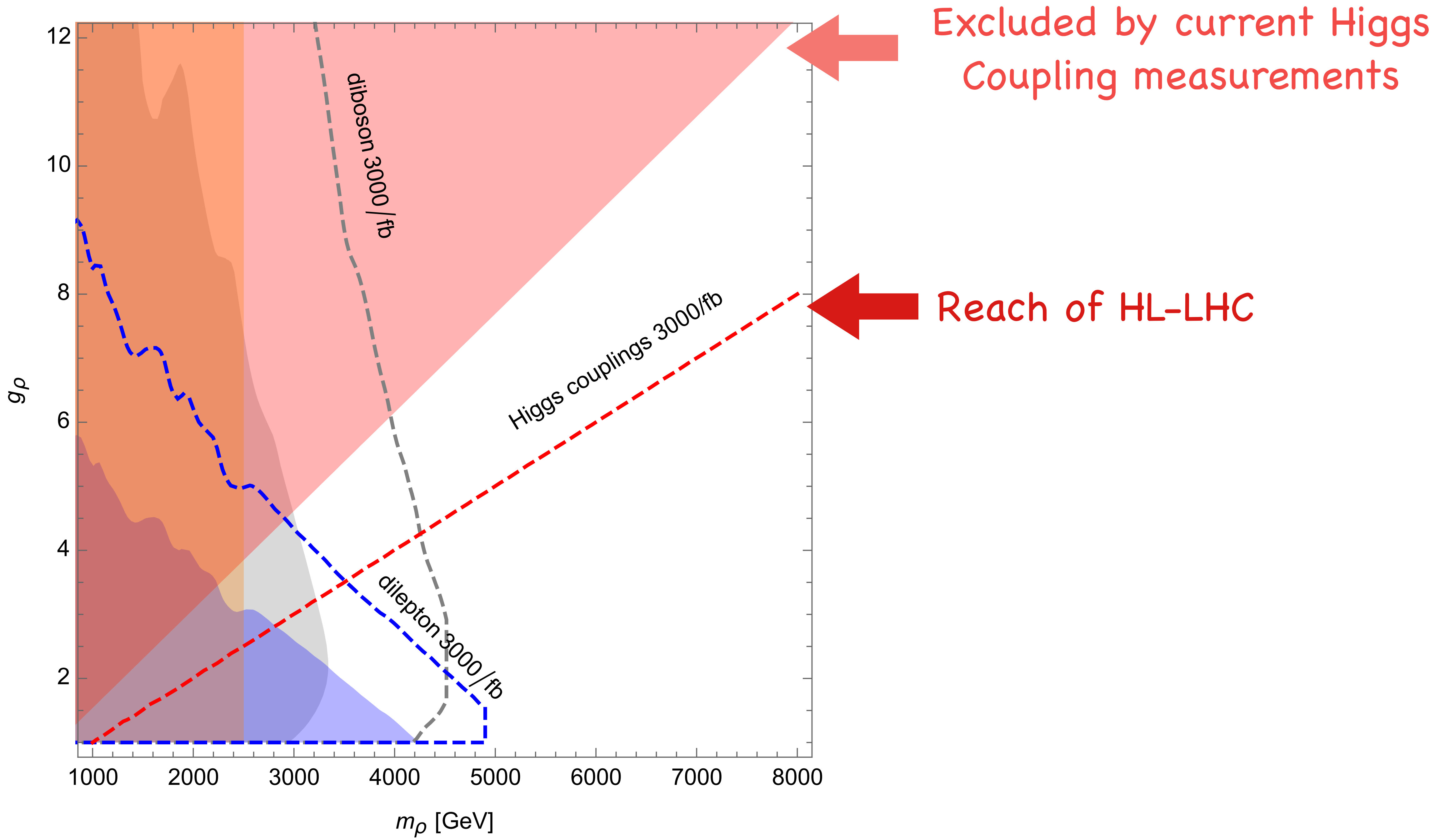
More dark-stuff searches

- Looking for dark sector. Very weakly coupled to the SM.
  - Connection with dark matter, neutrino, etc.
  - Many have not been searched for yet.
- Can come from Higgs portal, but could be more general.
- Displaced-Long lived, soft, kink, ...

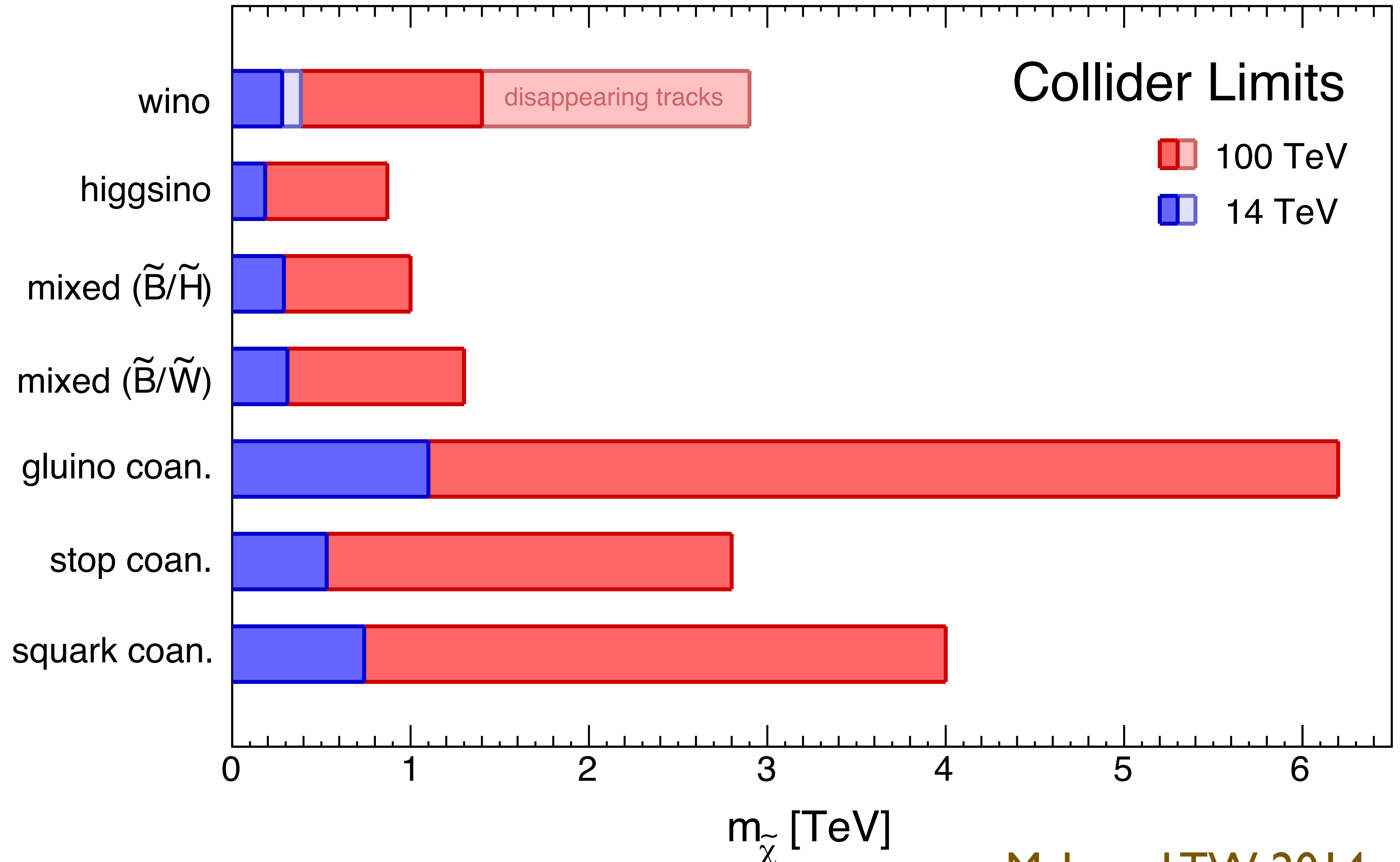


Curtin and Sundrum

Higgs coupling vs direct search



At 100 TeV pp collider



M. Low, LTW 2014

$$M_{\rm WIMP} \leq 1.8\ {\rm TeV}\ \left(\frac{g^2}{0.3}\right)$$

Will be challenging

SM WW, WZ processes are dominated by transverse modes

$$\sigma_{SM}^{total}/\sigma_{SM}^{LL} \sim 15 - 50$$

New technique such as polarization tagging of W/Z crucial

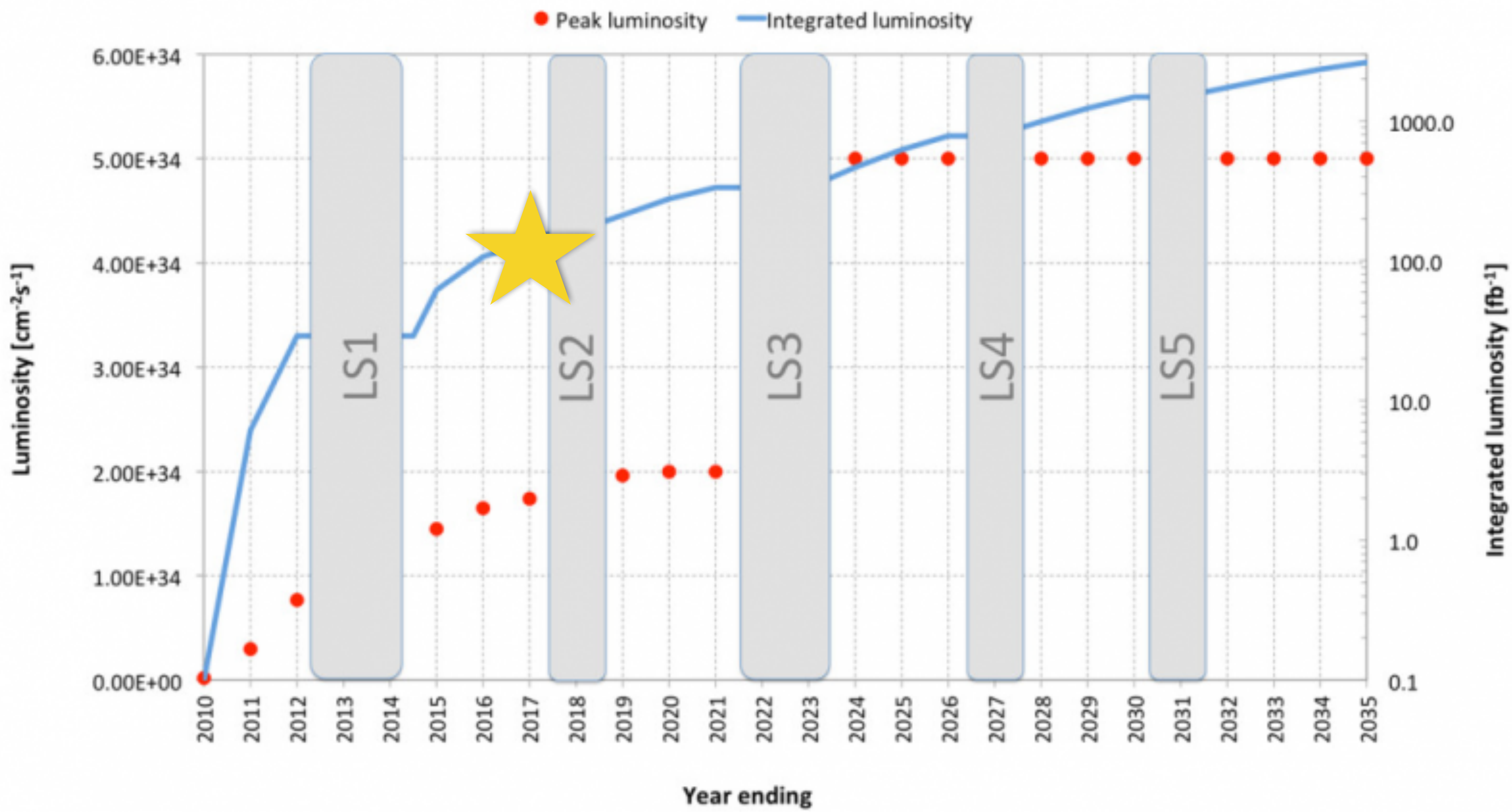
Wh/Zh(bb) channels have large reducible background

$$\text{LHC @ 8 TeV}: \qquad \sigma_b^{red}/\sigma_{SM}^{Wh} \sim 200 - 10$$

Difficult measurement. Large improvement needed.
Room for developing new techniques

Operators: d=6

name	structure	coefficient (power counting)
$\mathcal{O}_H$	$\frac{1}{2}\left(\partial_\mu \lvert H\rvert^2\right)^2$	c_H/f^2
$\mathcal{O}_y$	$y\bar{Q}_L H u_R \lvert H\rvert^2$	c_y/f^2
$\mathcal{O}_W$	$ig\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$	c_W/m_*^2
$\mathcal{O}_B$	$ig'\left(H^\dagger \overleftrightarrow{D}^\mu H\right) D^\nu B_{\mu\nu}$	c_B/m_*^2
$\mathcal{O}_{HW}$	$ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$c_{HW}/m_*^2 \times (g_*/4\pi)^2$
$\mathcal{O}_{HB}$	$ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$c_{HB}/m_*^2 \times (g_*/4\pi)^2$
O^q_L	$ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{Q}_L \gamma^\mu Q_L$	$c_q/m_*^2 \times \epsilon_q^2$
$O^{q,3}_L$	$ig^2\left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)\bar{Q}_L \sigma^a \gamma^\mu Q_L$	$c_{q,3}/m_*^2 \times \epsilon_q^2$
O^u_R	$ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{u}_R \gamma^\mu u_R$	$c_u/m_*^2 \times \epsilon_u^2$
O^u_R	$ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{d}_R \gamma^\mu d_R$	$c_d/m_*^2 \times \epsilon_d^2$
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	c_T/f^2
$\mathcal{O}_6$	$\lvert H\rvert^6$	λ_3/f^2



Peak luminosity
Integrated luminosity
6.00E+34
5.00E+34
4.00E+34
3.00E+34
2.00E+34
1.00E+34
0.00E+00
Luminosity [cm-2s-1]
1000.0
100.0
10.0
1.0
0.1
Integrated luminosity [fb-1]
LS1
LS2
LS3
LS4
LS5
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Year ending