Some Theoretical Motivations for Long-lived Particle Search

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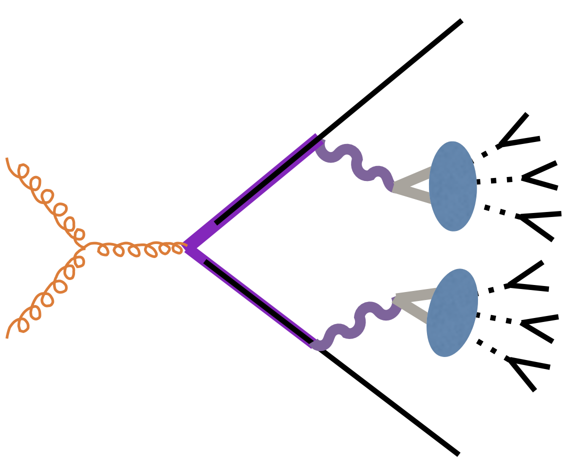
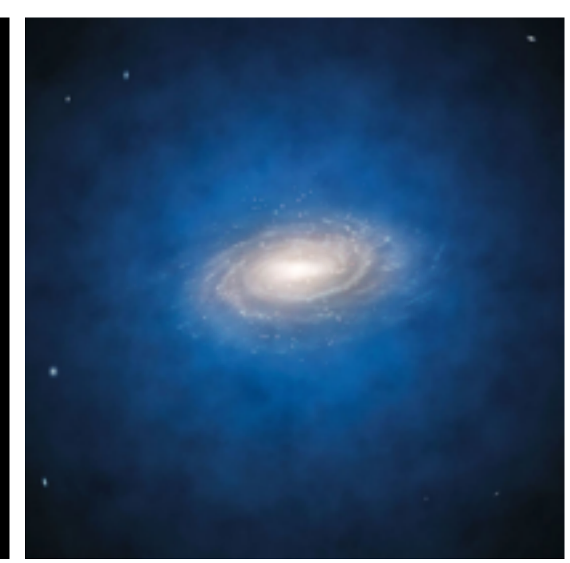
University of Maryland

New Physics with Displaced Vertices, NCTS, June 2018



h_{125}



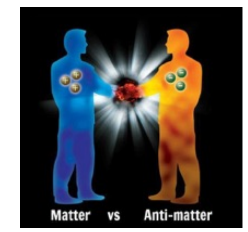
Why Long-lived Particles (LLP)?

Will discuss four examples that motive the LLP searches

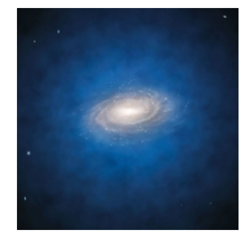
LLP in

Higgs hierarchy problem h_{125}

Matter / anti-matter asymmetry



Puzzles of DM halo structure



DM indirect detection signals

LLP and Higgs hierarchy problem

h125

SM-like dark sector helps to stabilize Higgs mass

LLP and Higgs hierarchy problem

h_{125}

SM-like dark sector helps to stabilize Higgs mass

=> dark-QCD, Higgs portal/photon mixing coupling

LLP and Higgs hierarchy problem

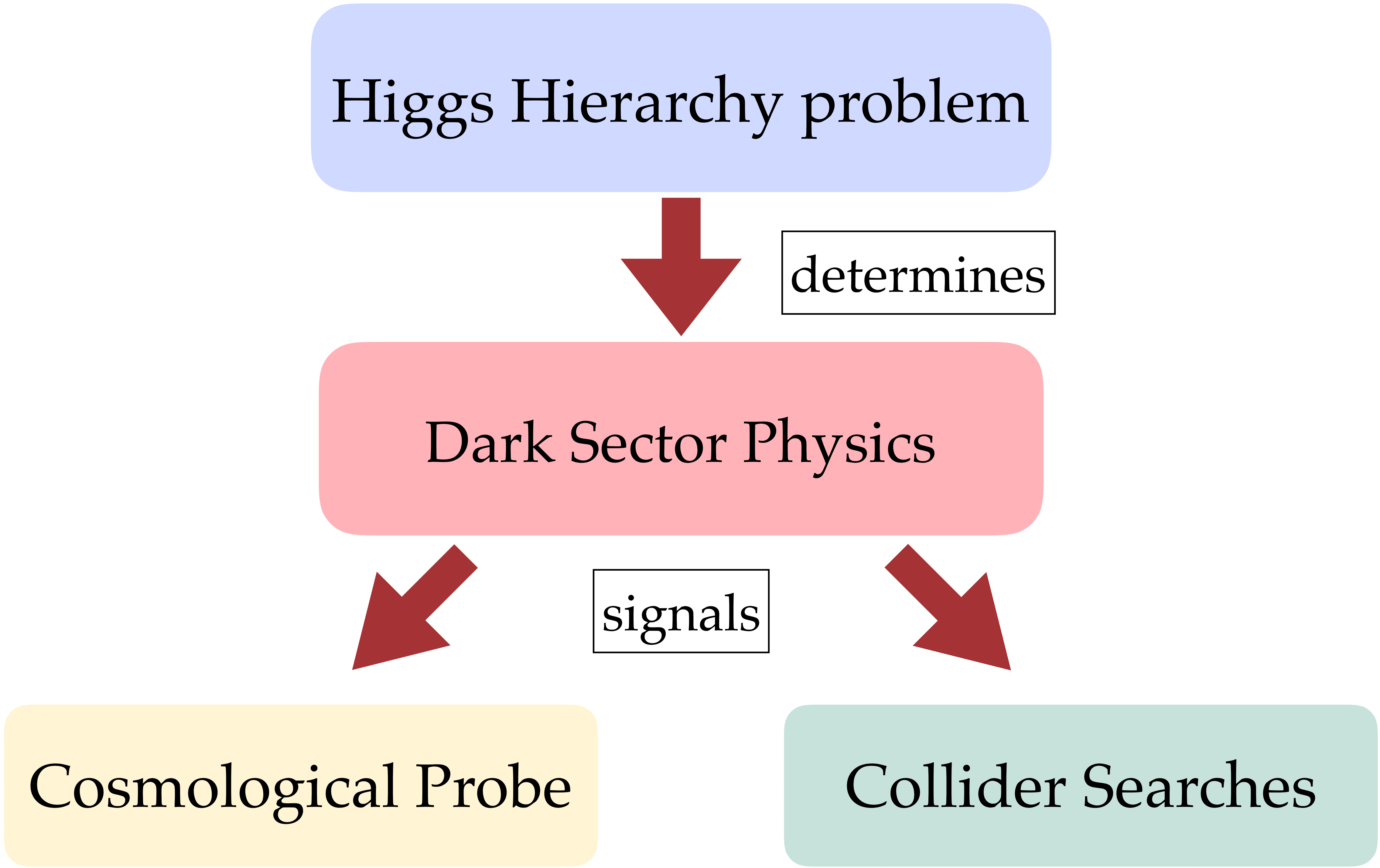
h_{125}

SM-like dark sector helps to stabilize Higgs mass

=> dark-QCD, Higgs portal/photon mixing coupling

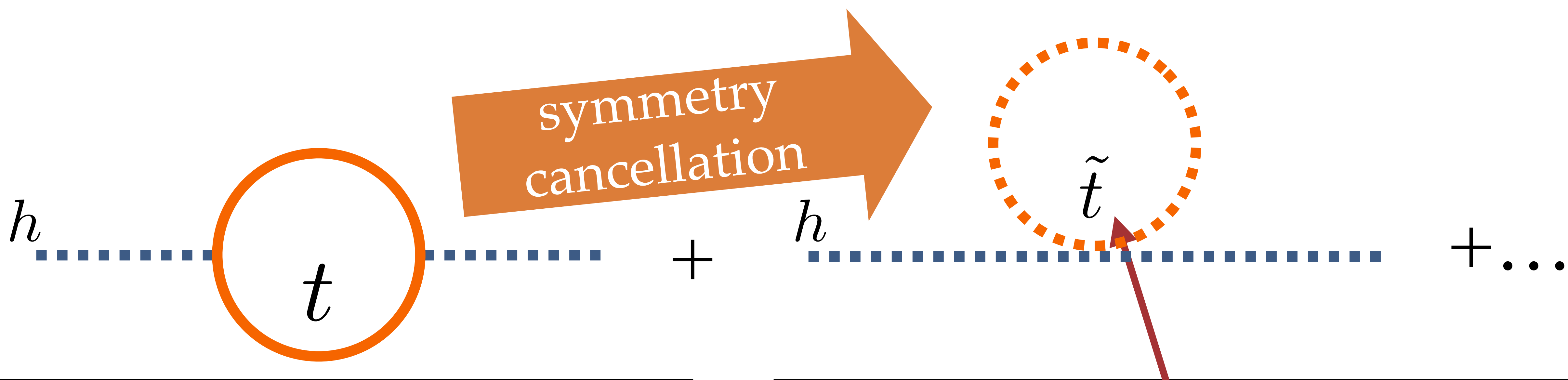
=> long-lived dark hadrons

Hidden Naturalness scenario



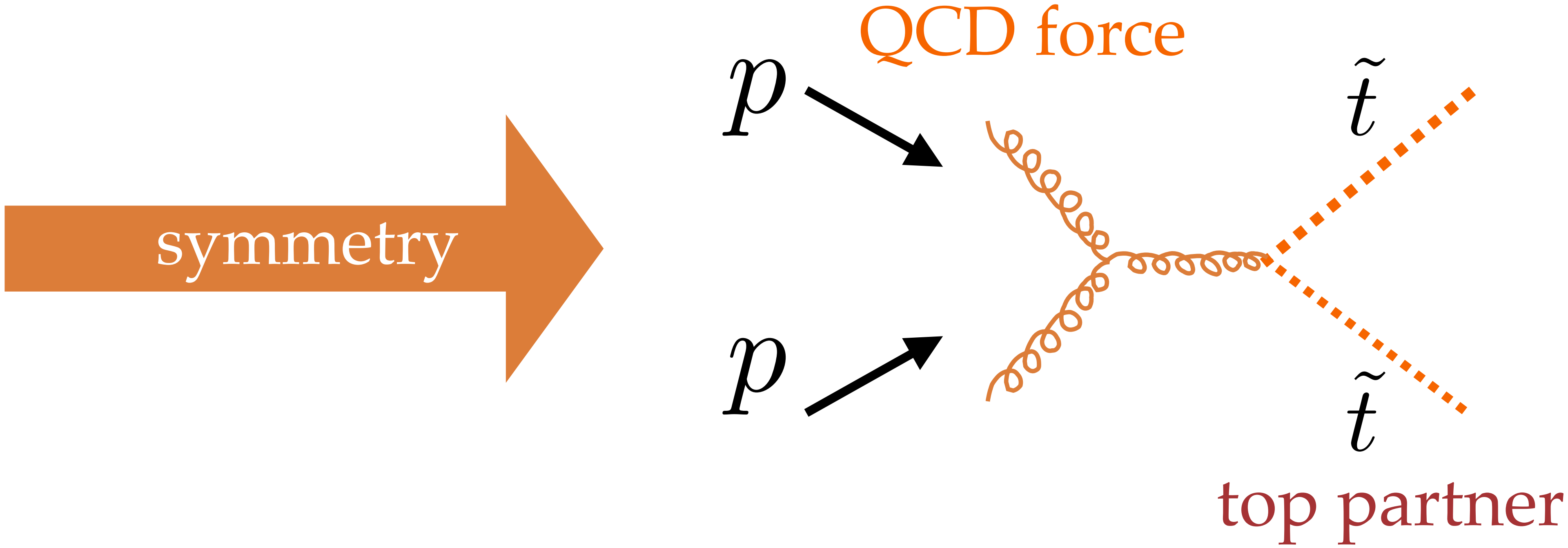
One solution to the hierarchy problem:
Supersymmetry

Super particle loops cancel the divergence



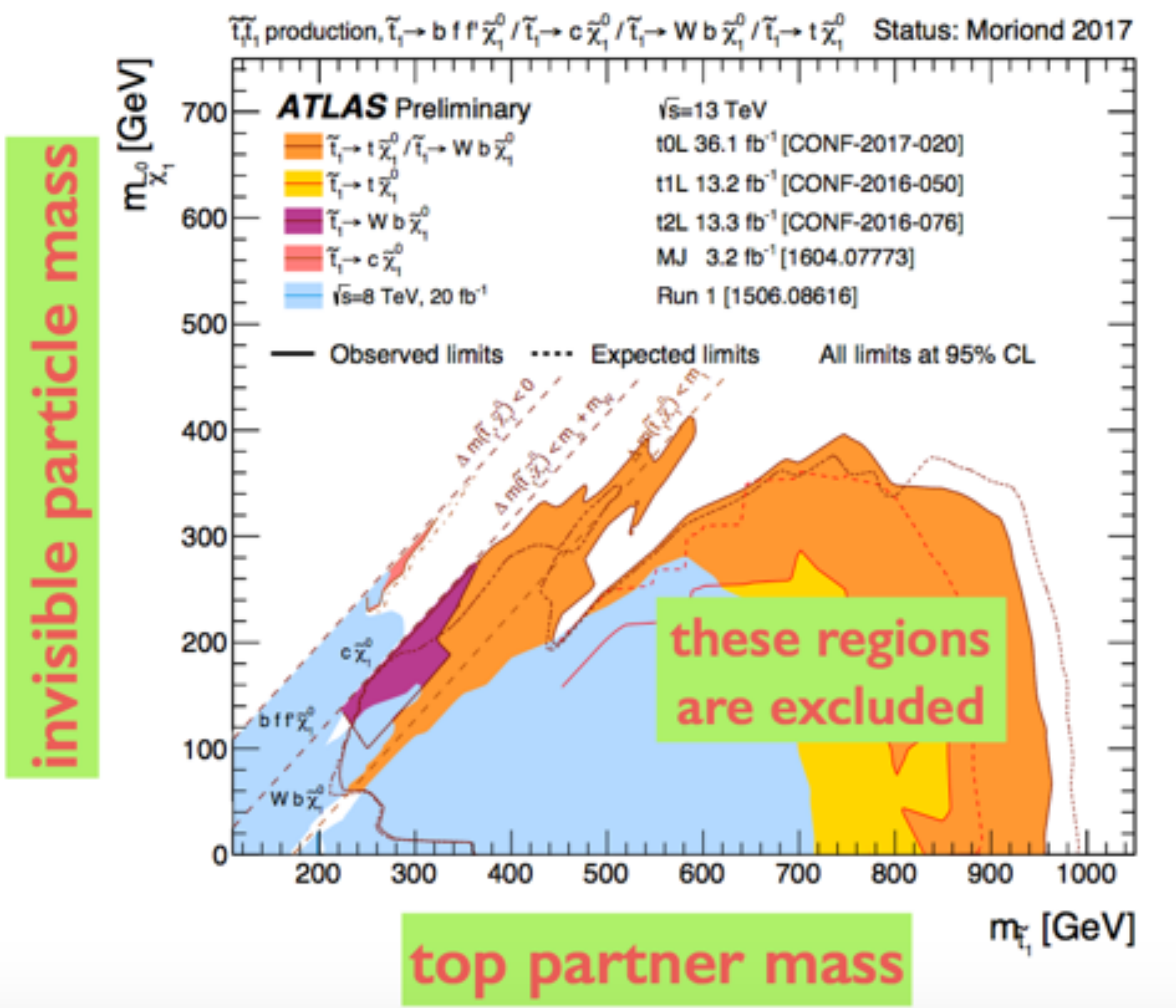
top quark
carry SM QCD charge

Top Partner
carry SM QCD charge



collider signal

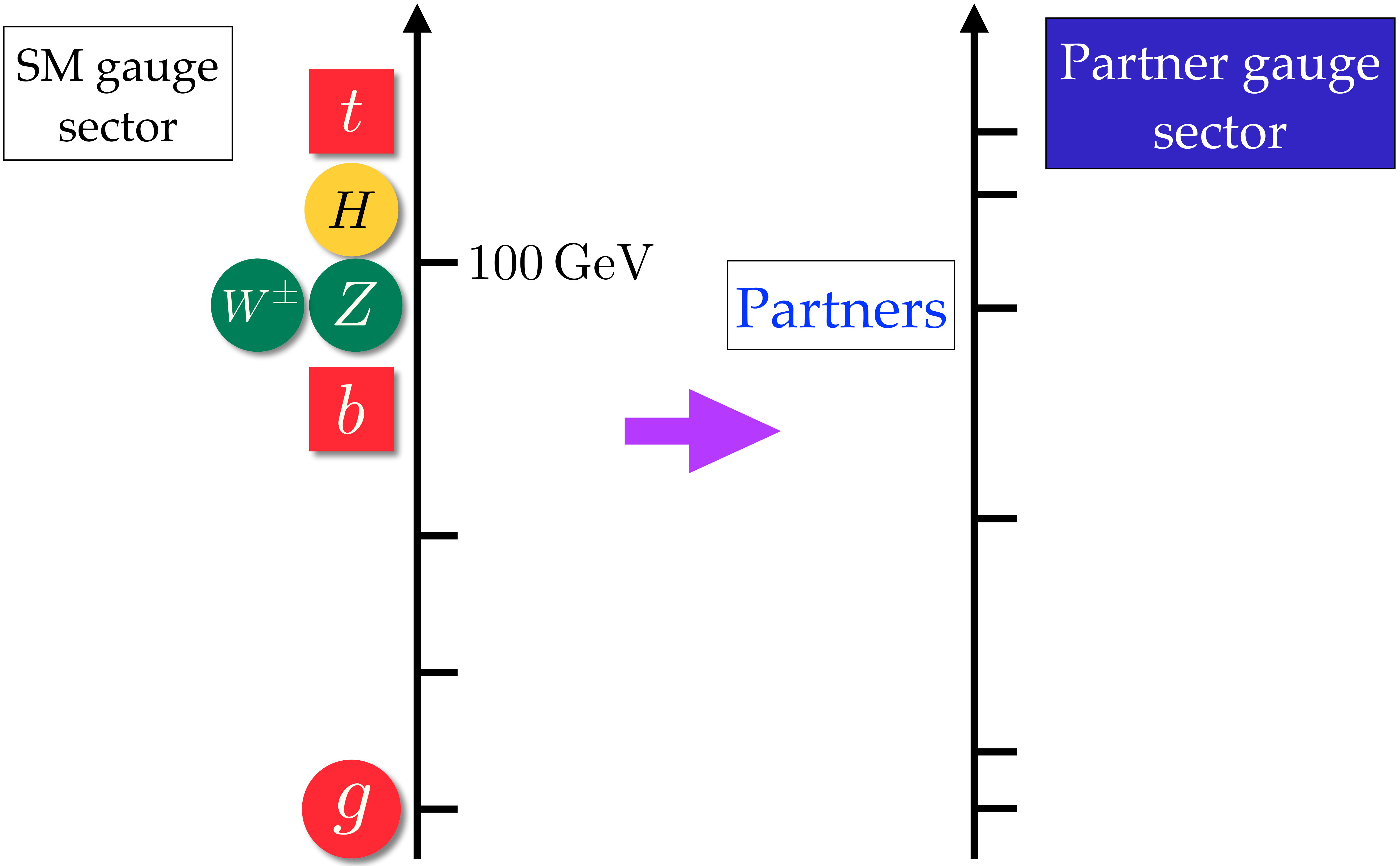
No SUSY so far…



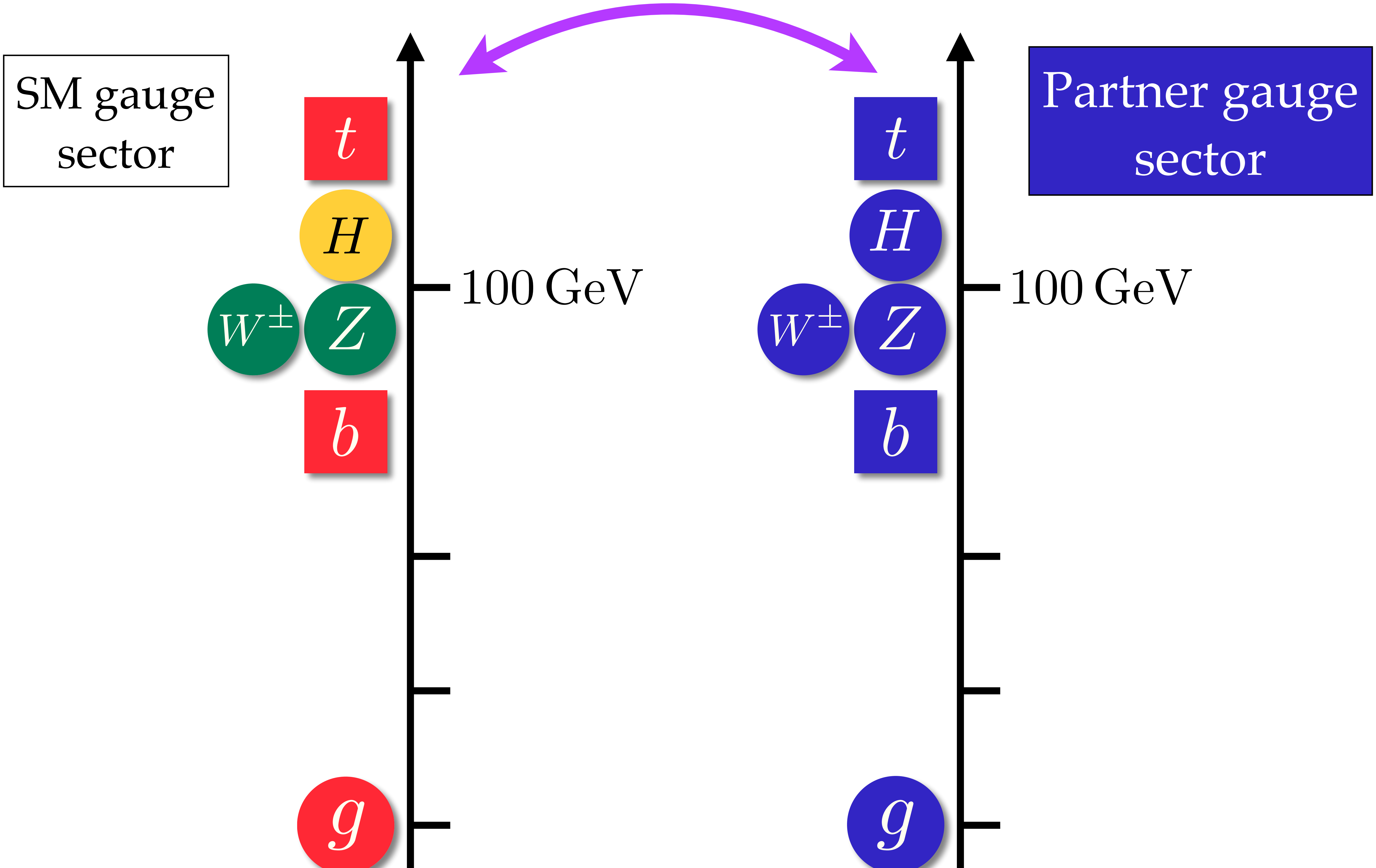
$$m_{\tilde{t}} \gg m_t$$

The hope for symmetry cancellation is fading…

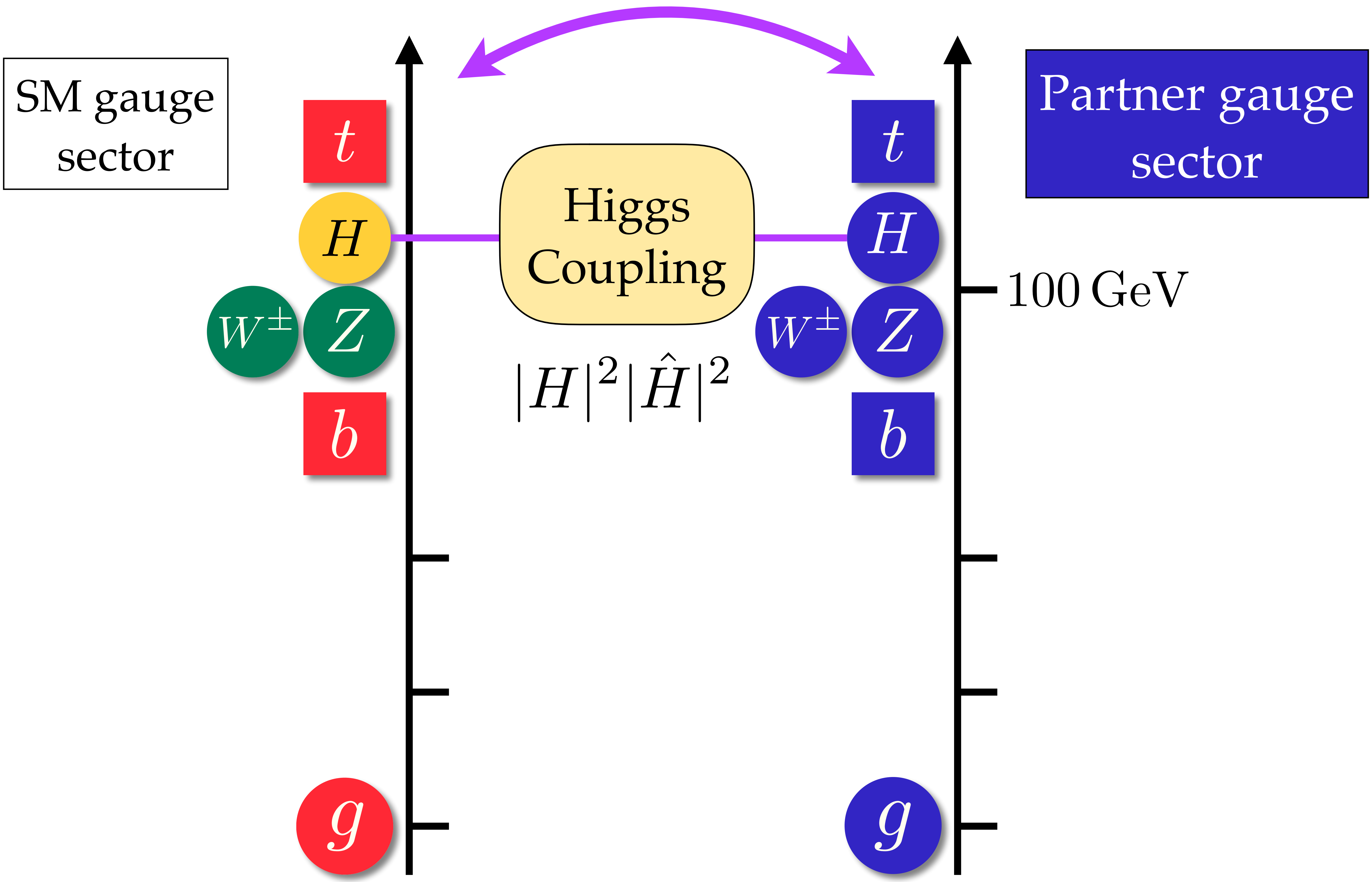
Partner fields in a different gauge sector



Related by a **Mirror Symmetry** Z_2

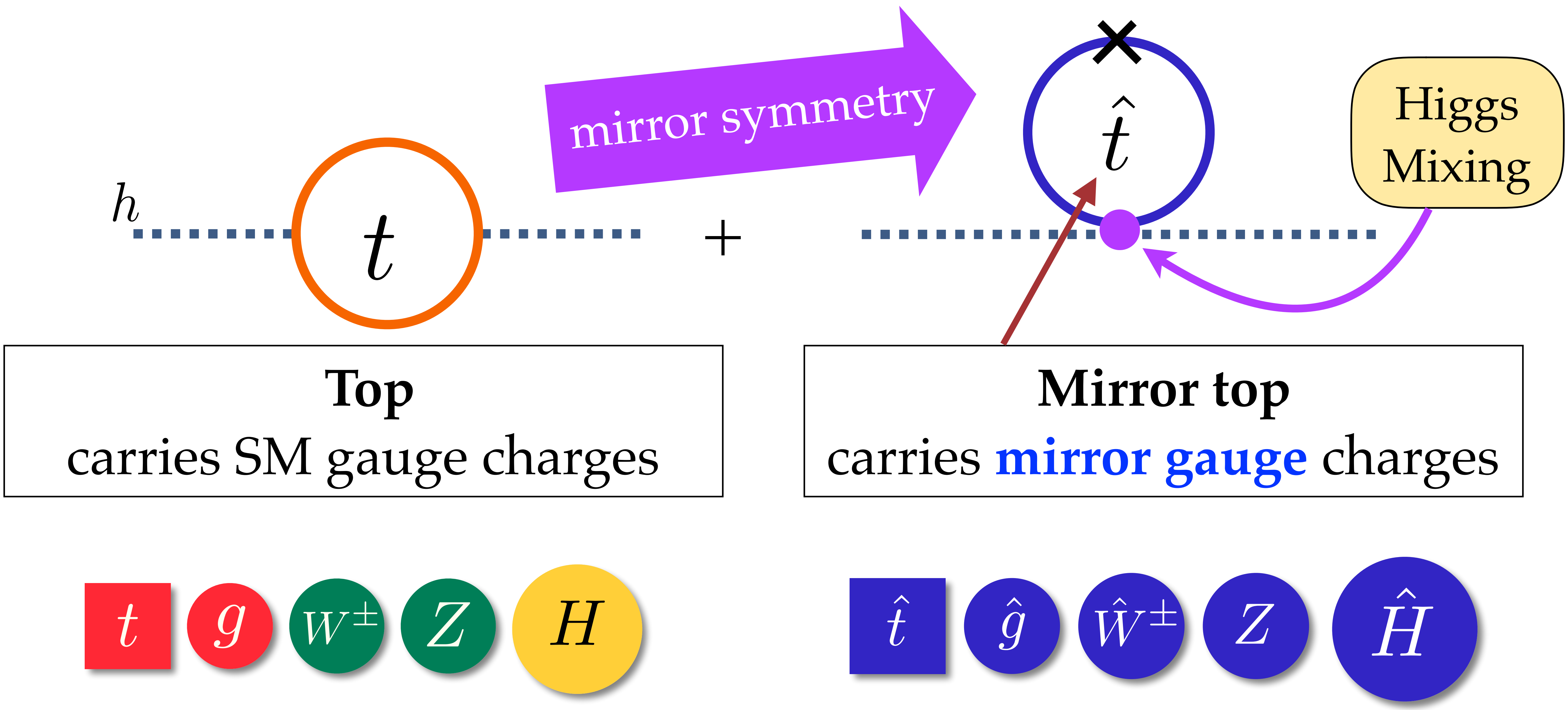


Related by a **Mirror Symmetry** Z_2

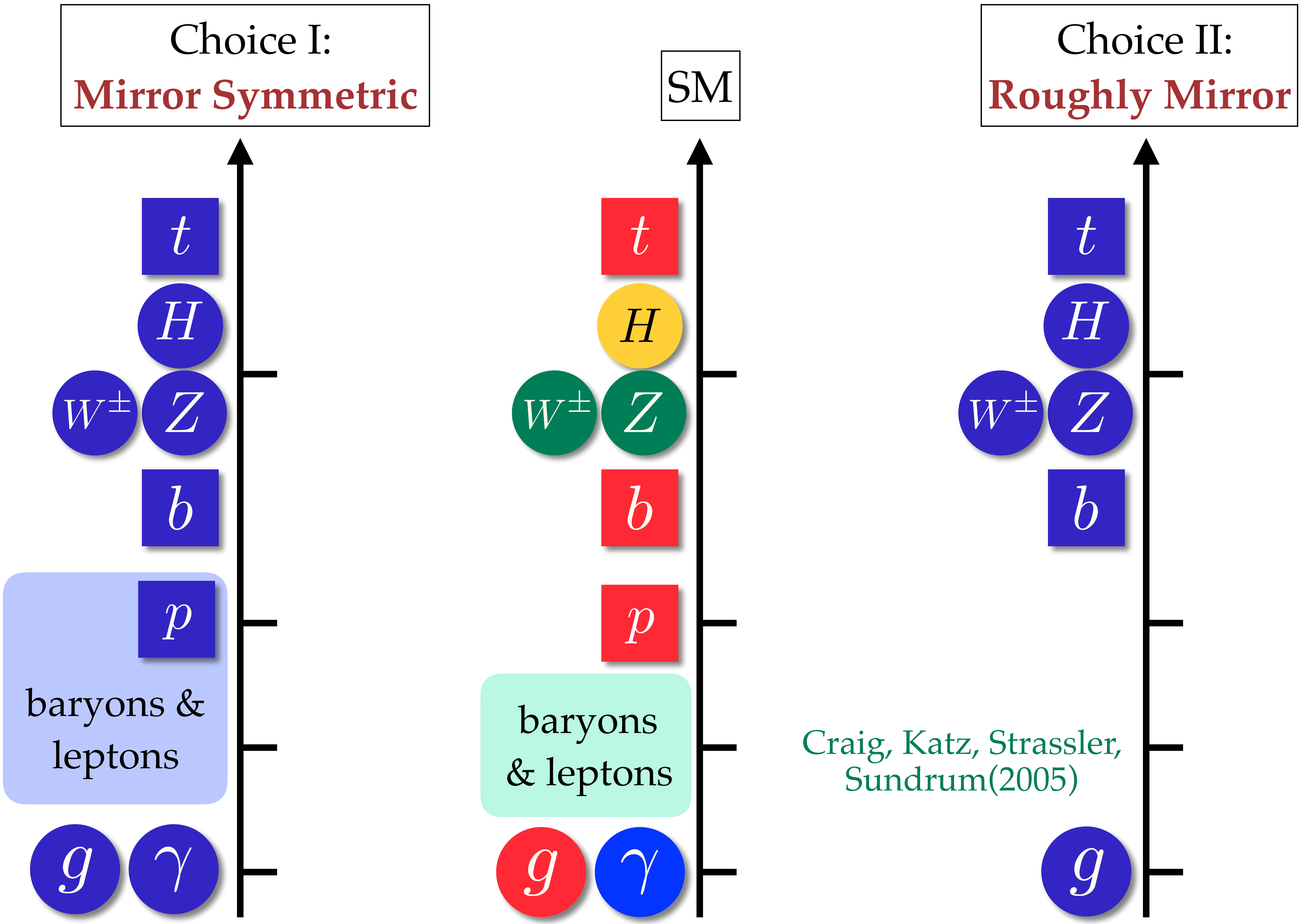


A concrete example: Twin Higgs

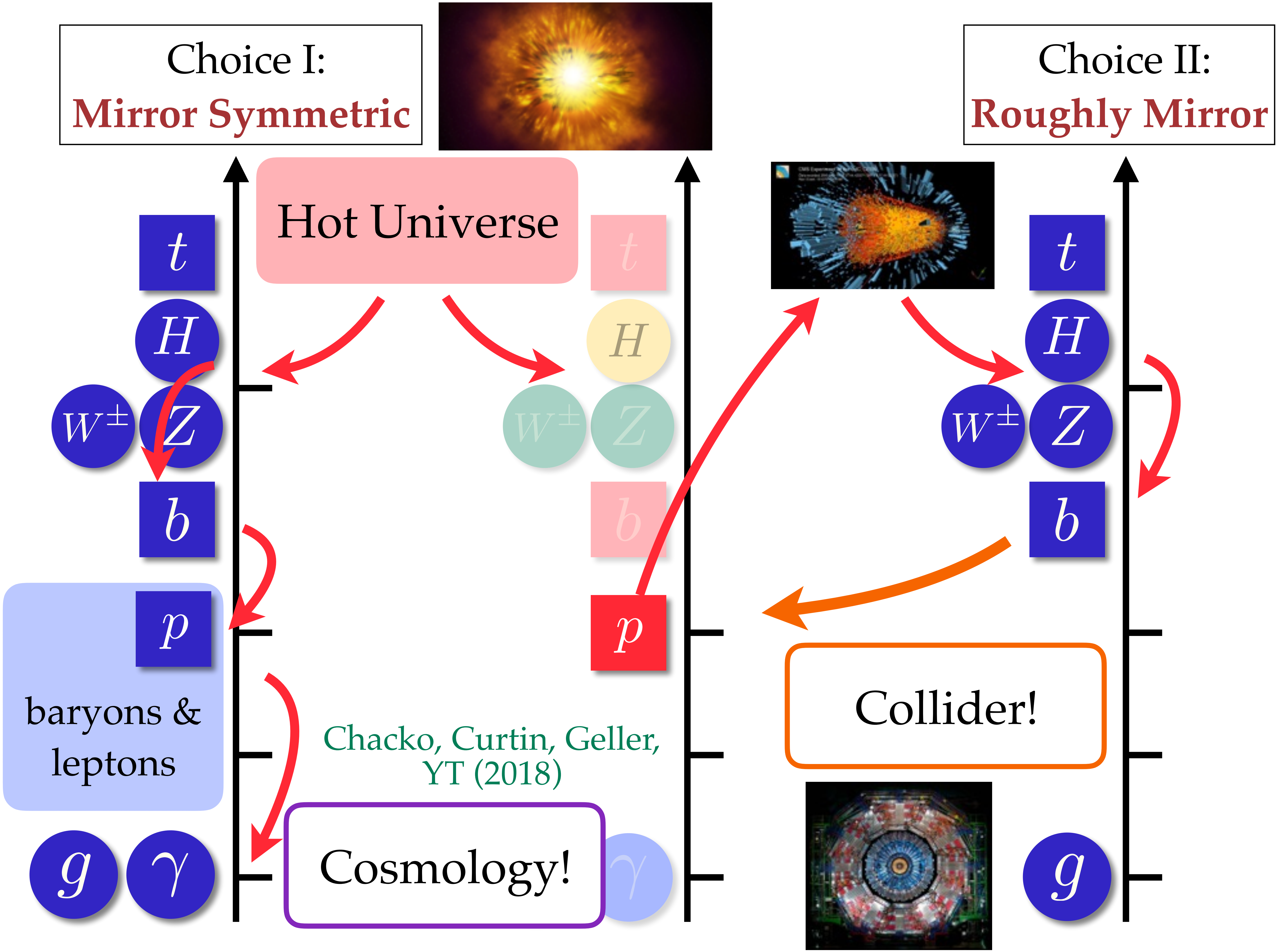
Chacko, Goh, Harnik (2005)



Mirror copy of the relevant particles

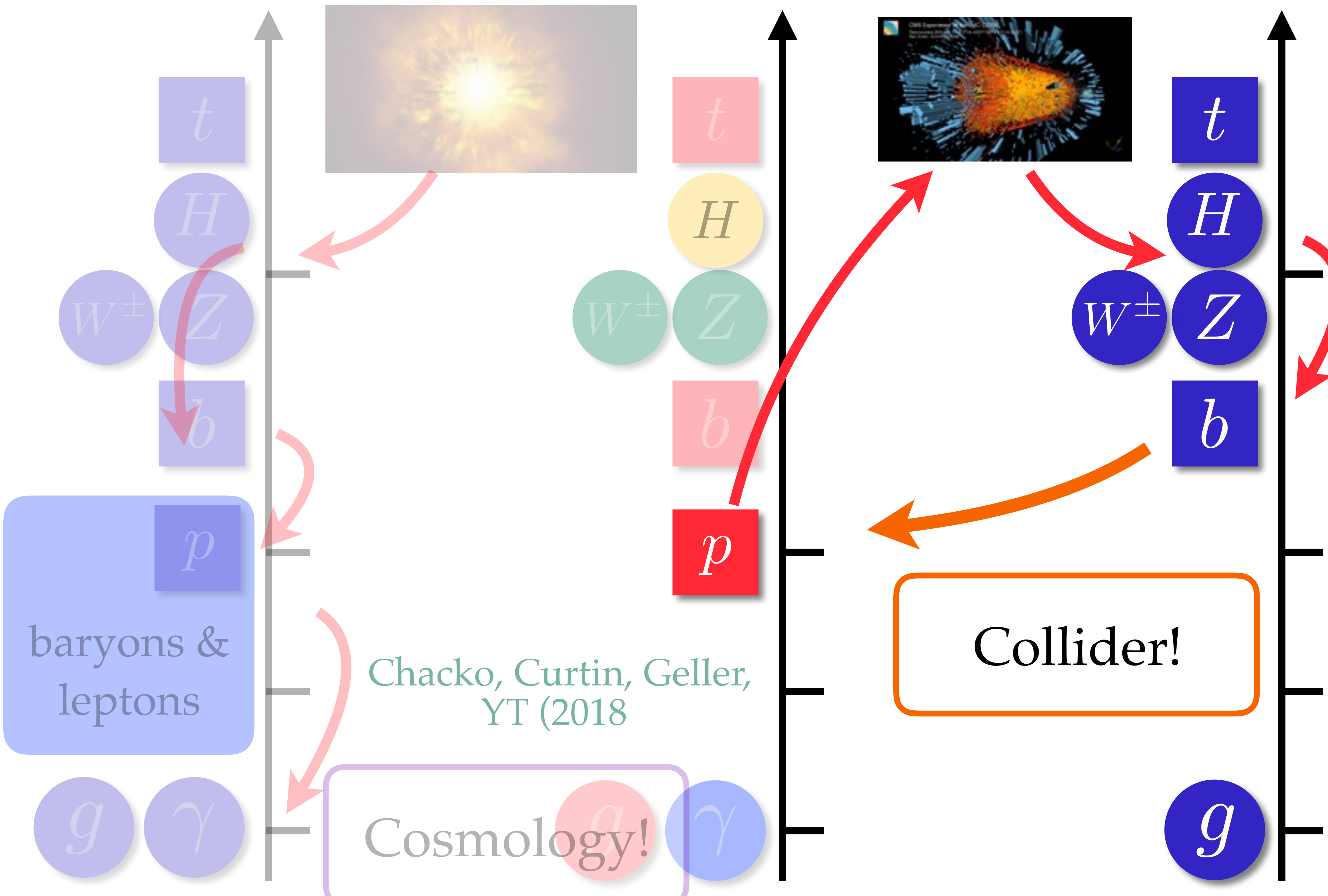


Choice I:
Mirror Symmetric
SM
Choice II:
Roughly Mirror
t
H
W±
Z
b
p
baryons & leptons
g
γ
Craig, Katz, Strassler, Sundrum(2005)

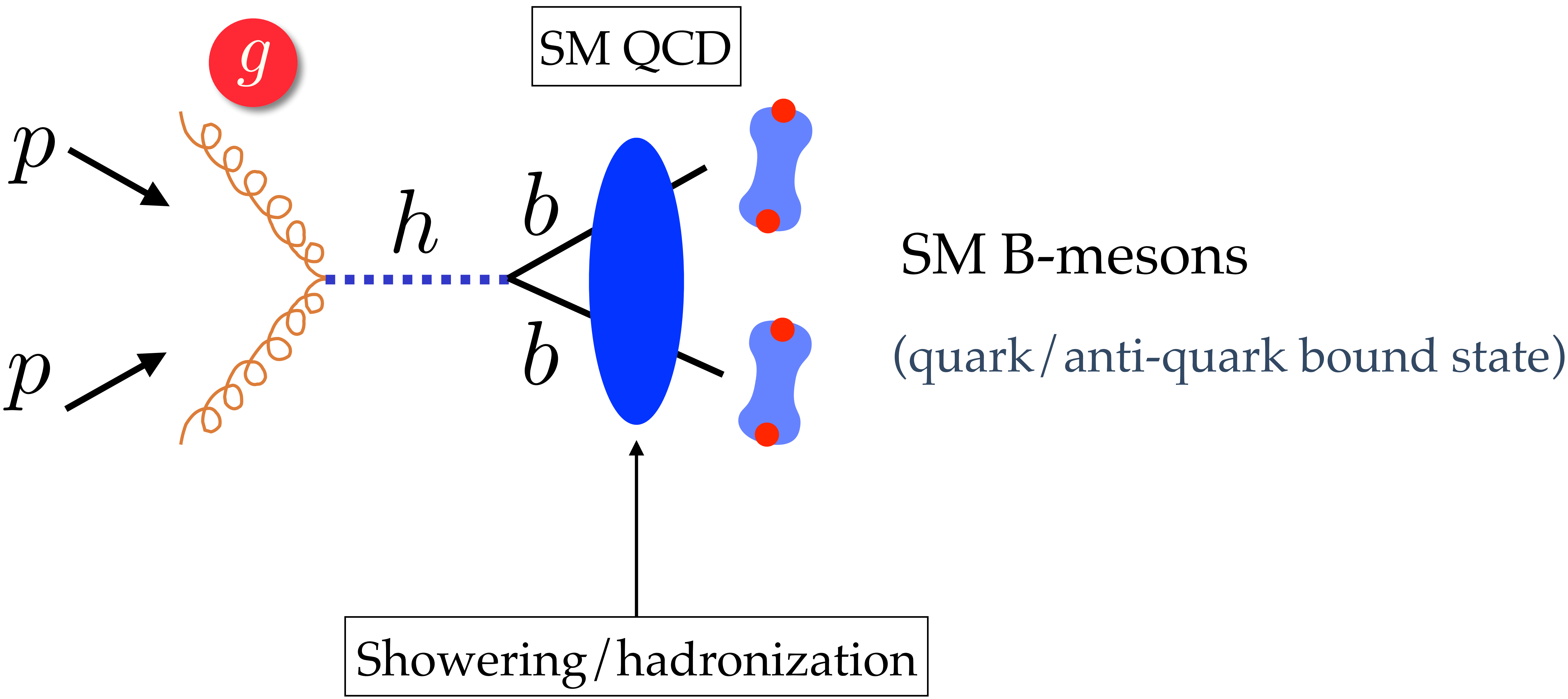


Choice I:
Mirror Symmetric
Choice II:
Roughly Mirror
Hot Universe
t
H
W±
Z
b
p
baryons &
leptons
g
γ
Chacko, Curtin, Geller,
YT (2018)
Cosmology!
Collider!

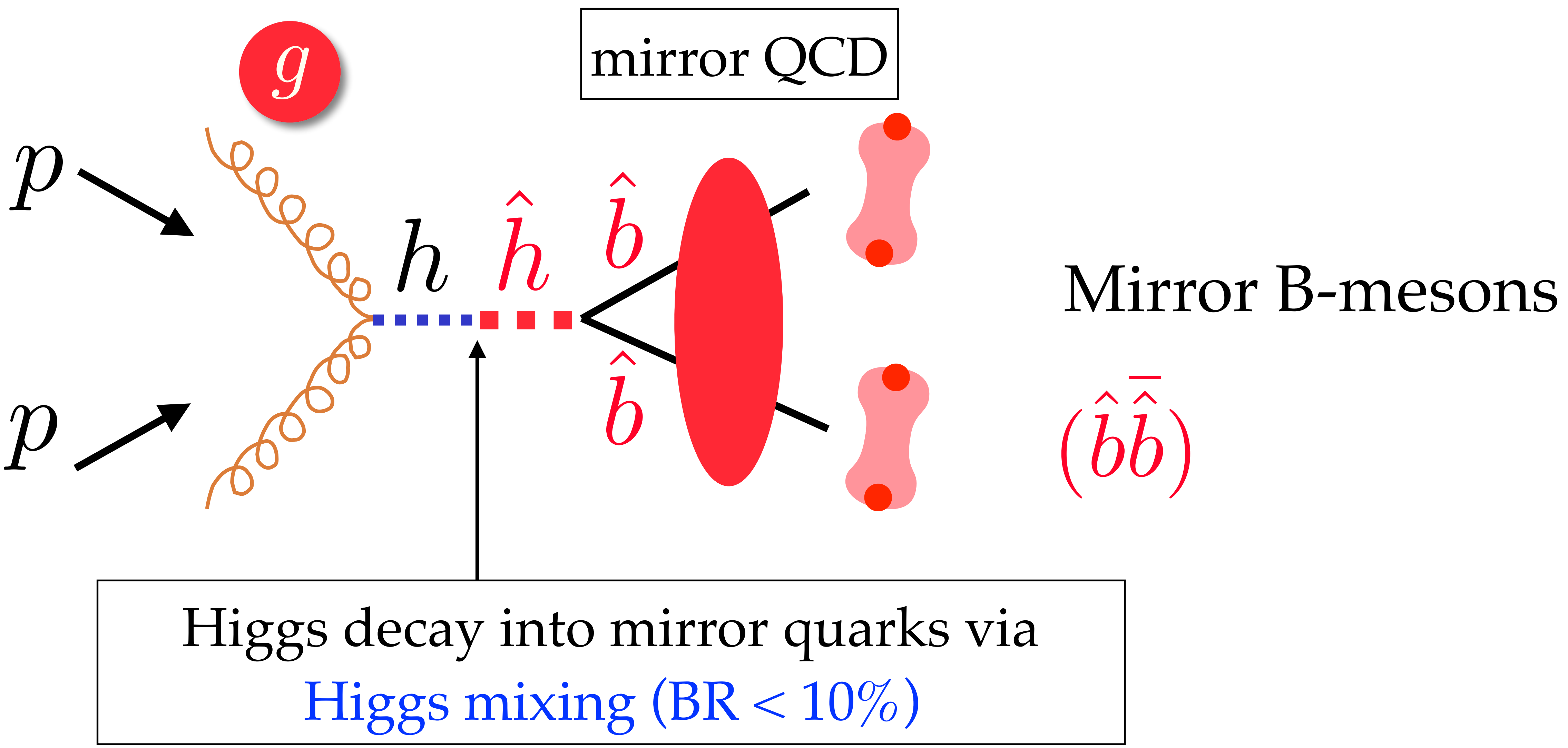
Collider Signature from Hidden Naturalness



Production & decay of SM Higgs @ LHC

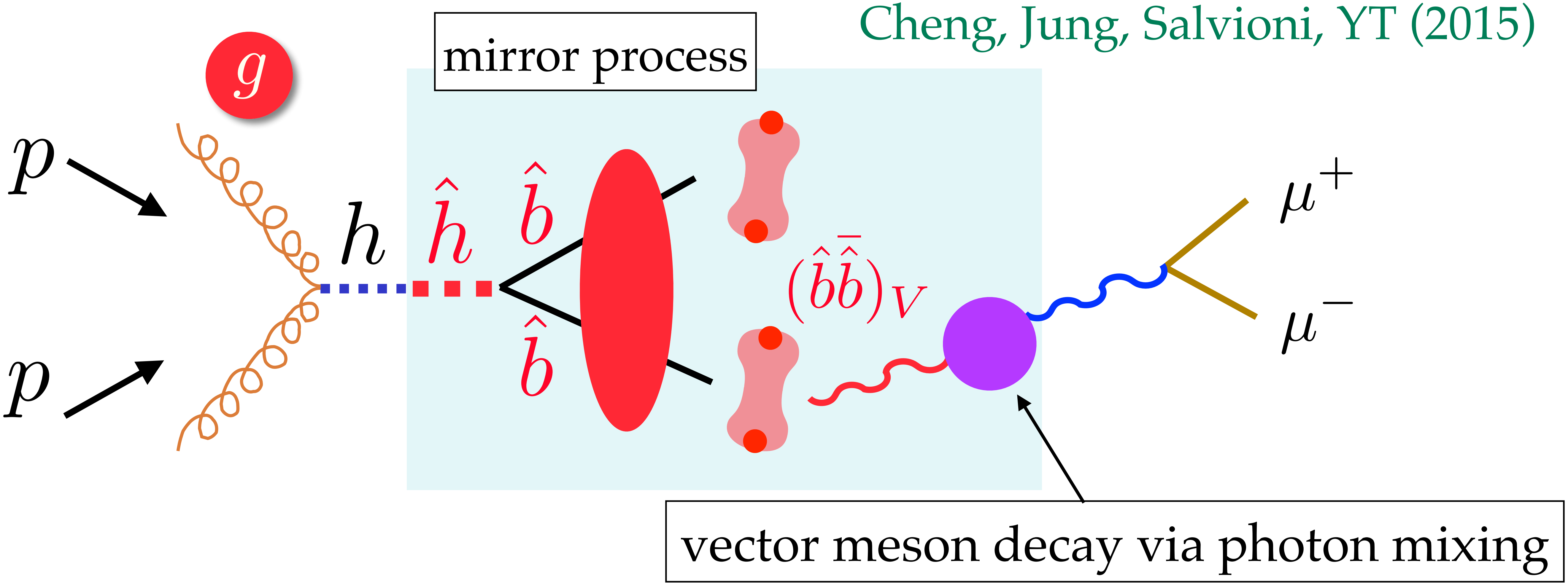


Higgs decay into mirror particles



Higgs decay into mirror particles

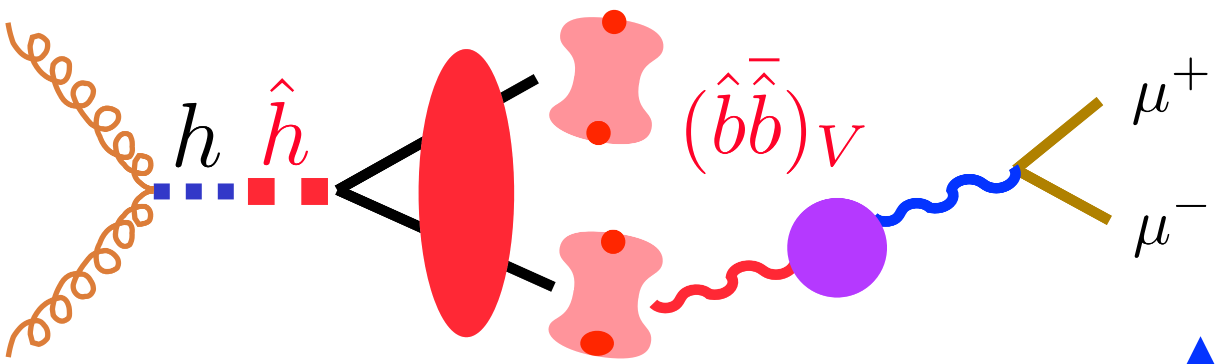
Cheng, Jung, Salvioni, YT (2015)



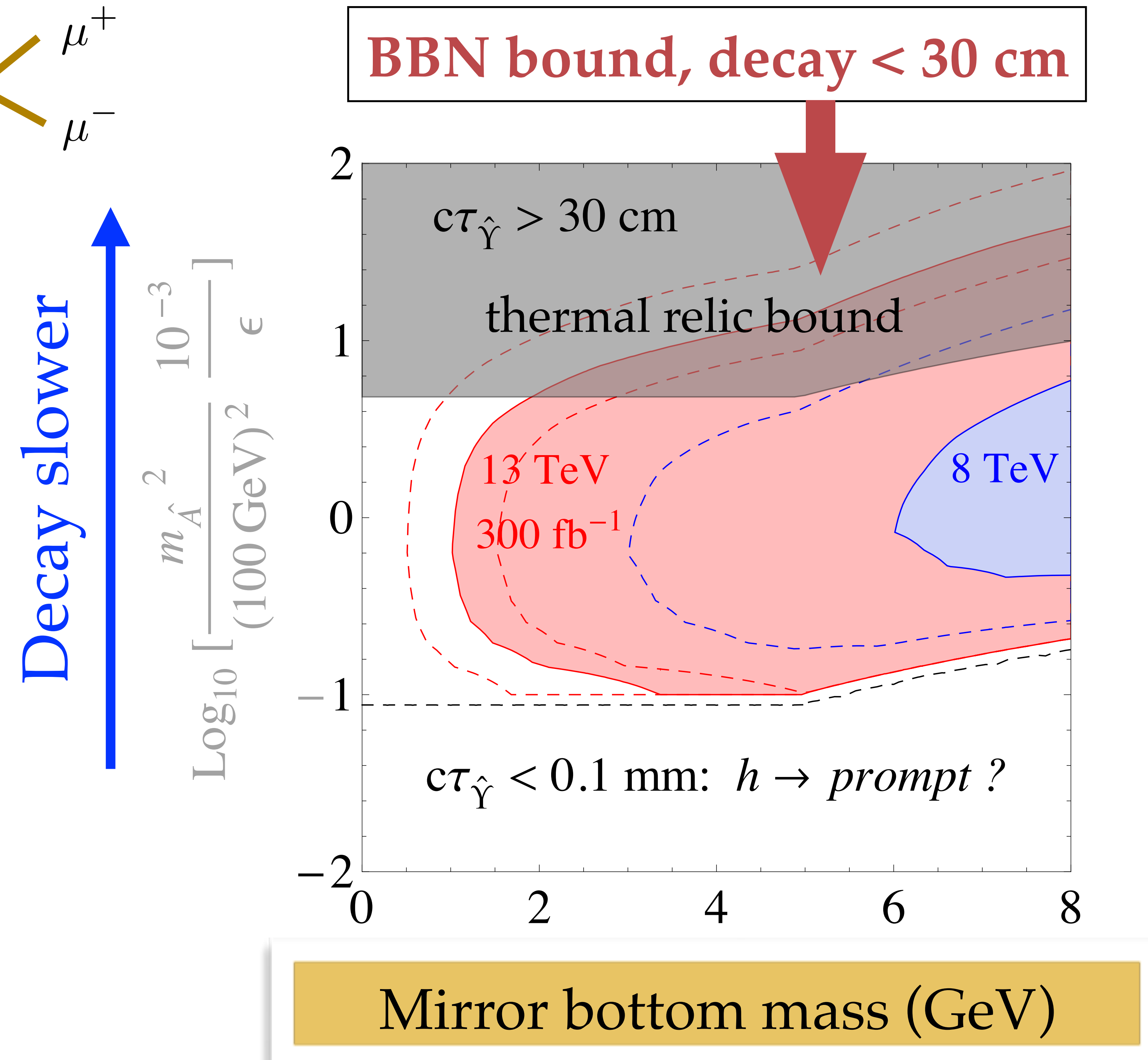
Mirror mesons **SLOWLY** decay into SM particles

LHC search of displaced muon pairs

Cheng, Jung, Salvioni, YT (2015)



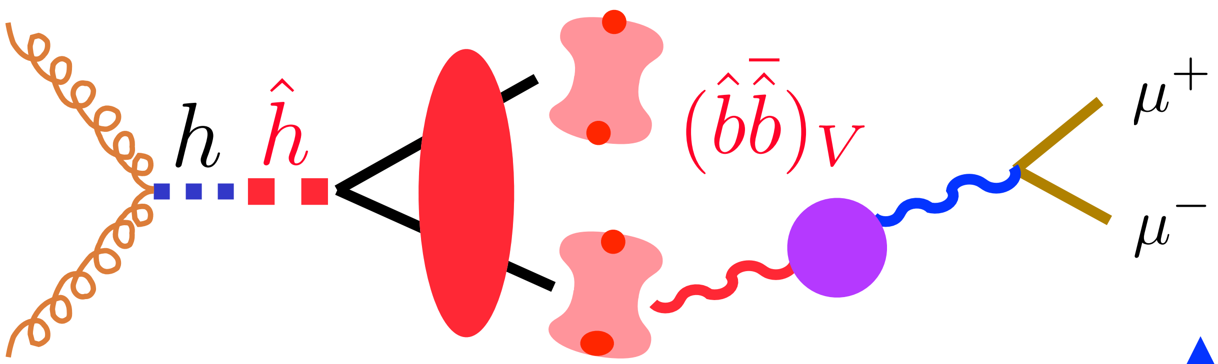
Using CMS displaced di-muon search (1411.6977)



LHC search of displaced muon pairs

Cheng, Jung, Salvioni, YT (2015)

We showed the whole param-space is accessible!



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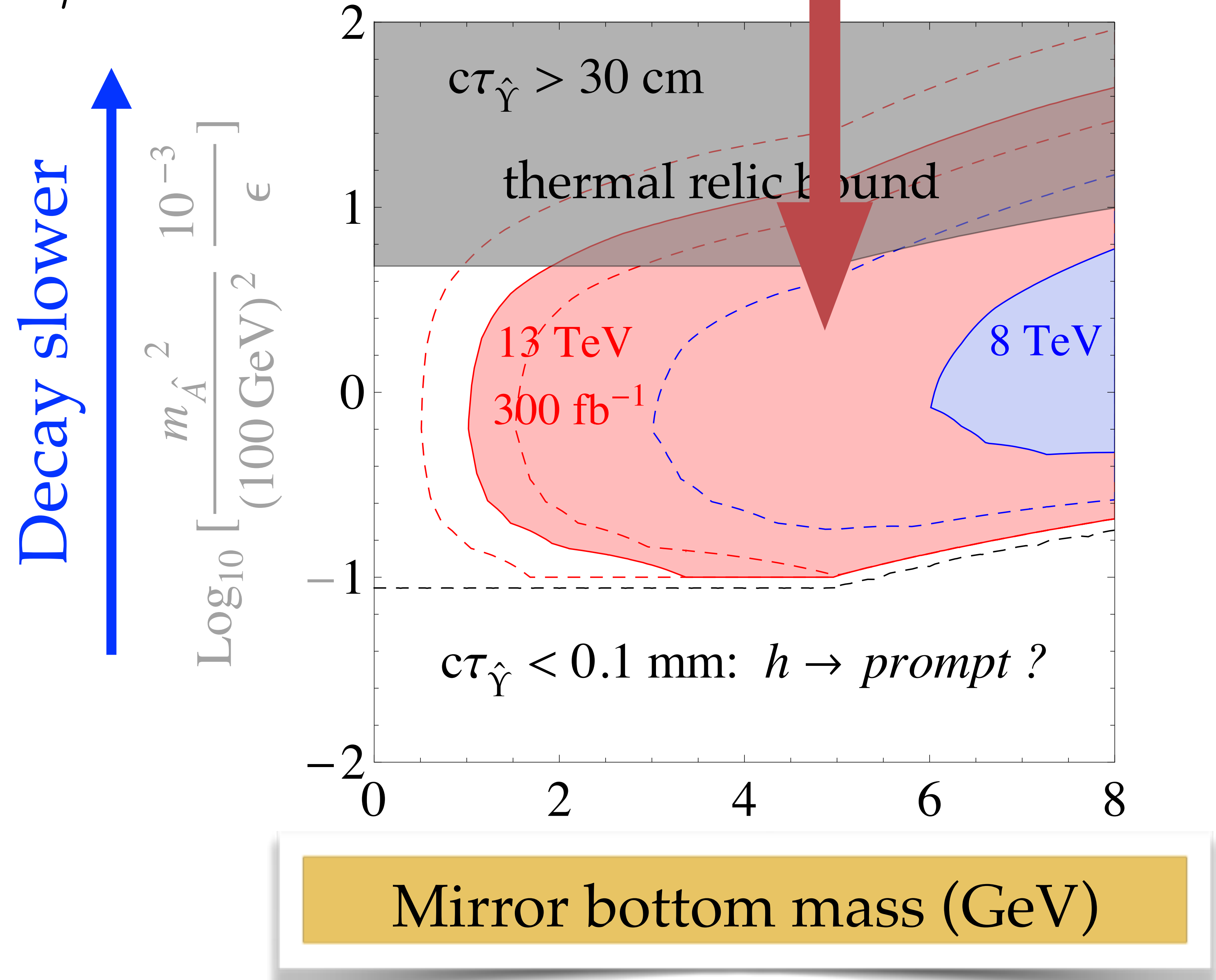
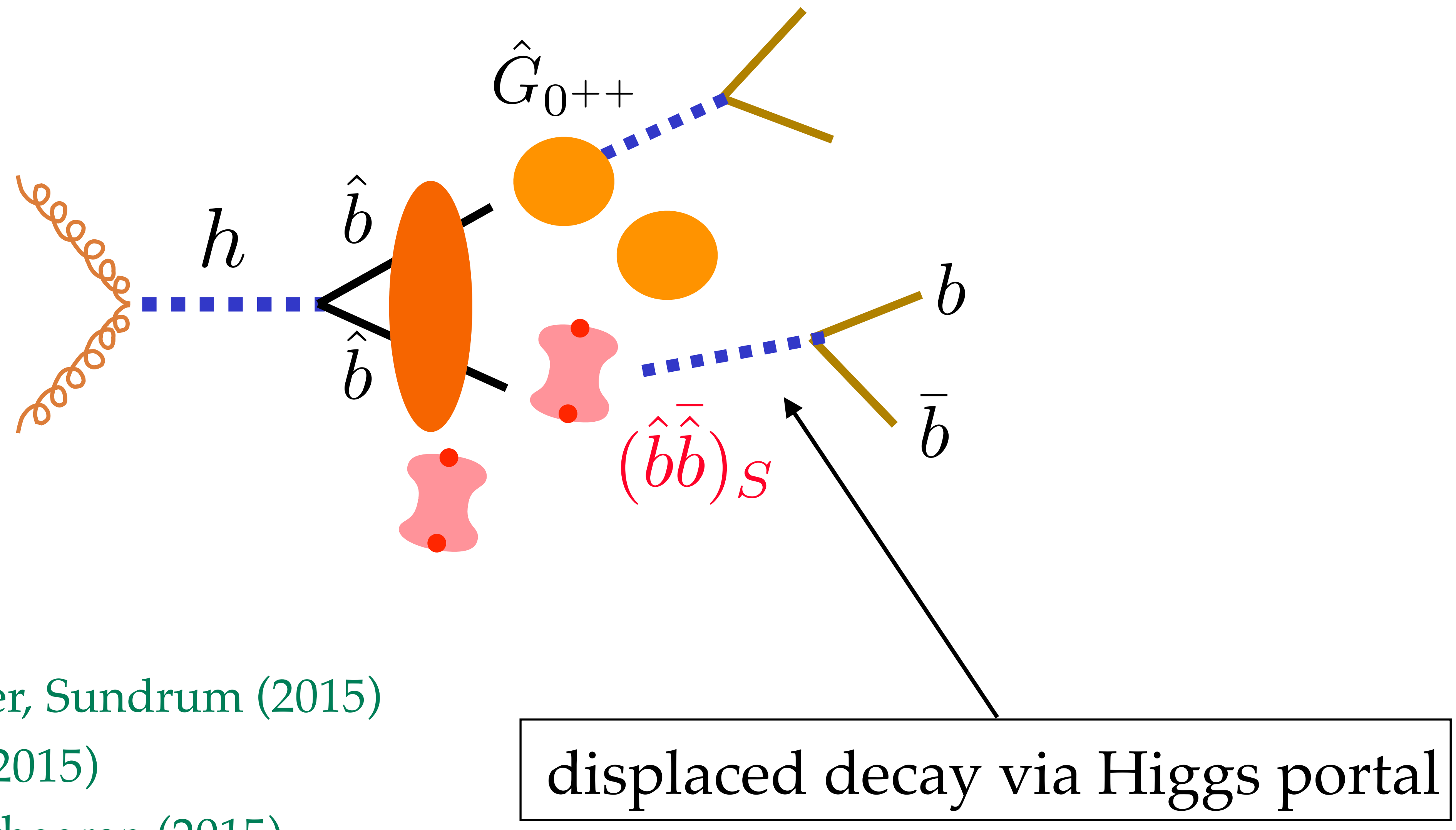


Displaced jets from twin glueball decay

Scalar mesons/glueballs can decay into heavy quark paris



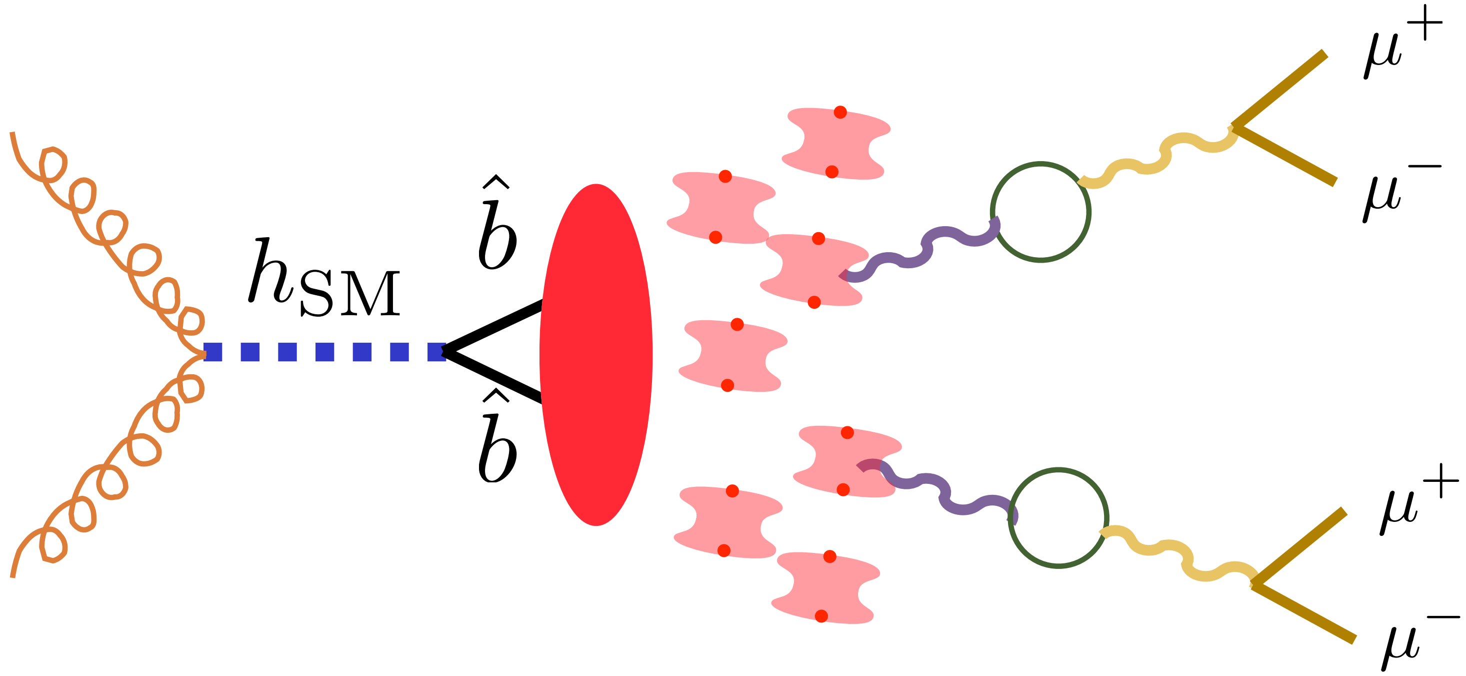
Craig, Katz, Strassler, Sundrum (2015)

Curtin, Verhaaren (2015)

Chacko, Curtin, Verhaaren (2015)

Cheng, Jung, Salvioni, YT (2015)

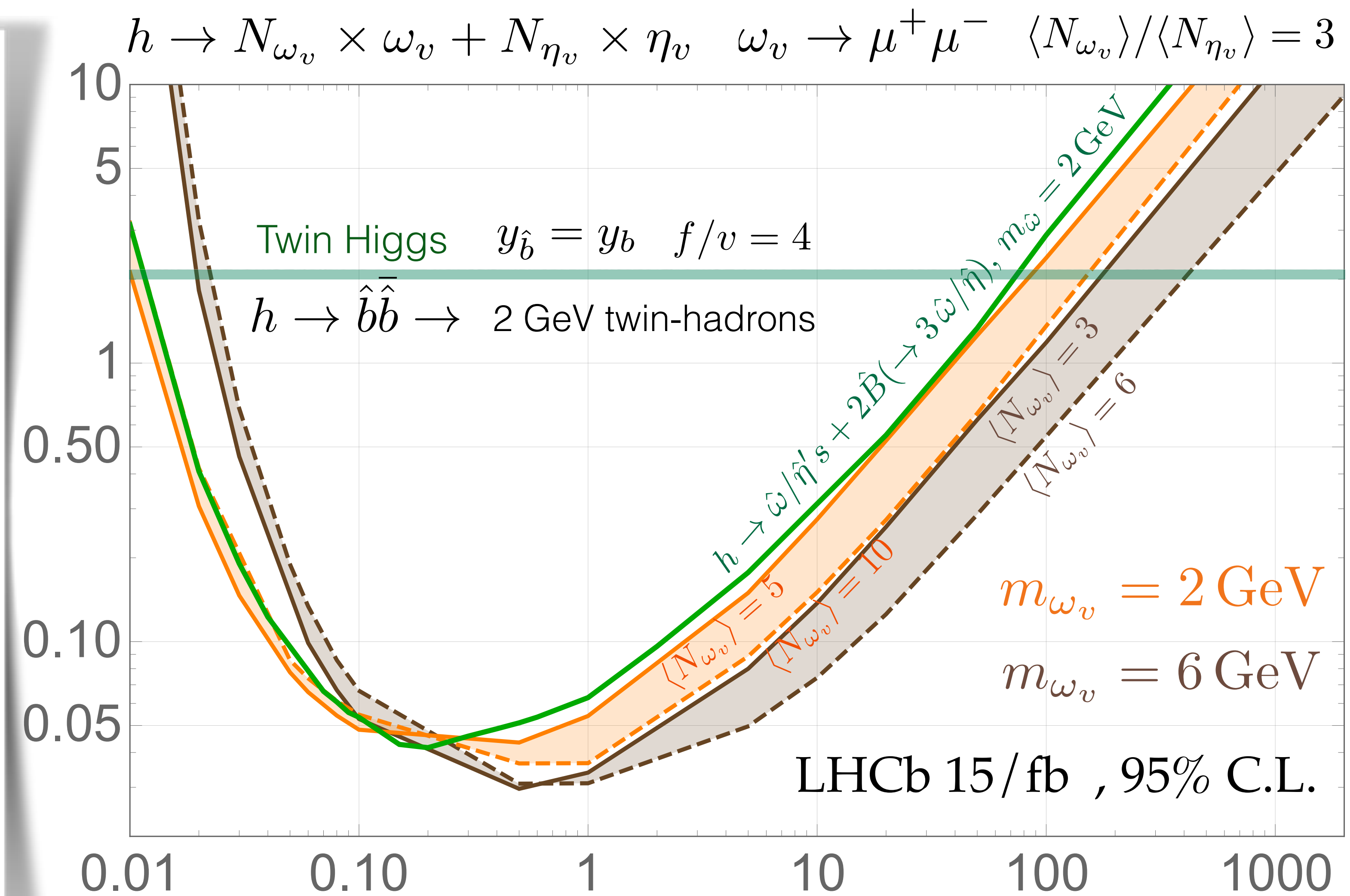
Challenge: LLP with low mass & low energy



If produce many mirror mesons, average muon pT ~ few GeV

LHCb constraint on the exotic Higgs decay

Probability of Higgs Decay into Mirror Mesons

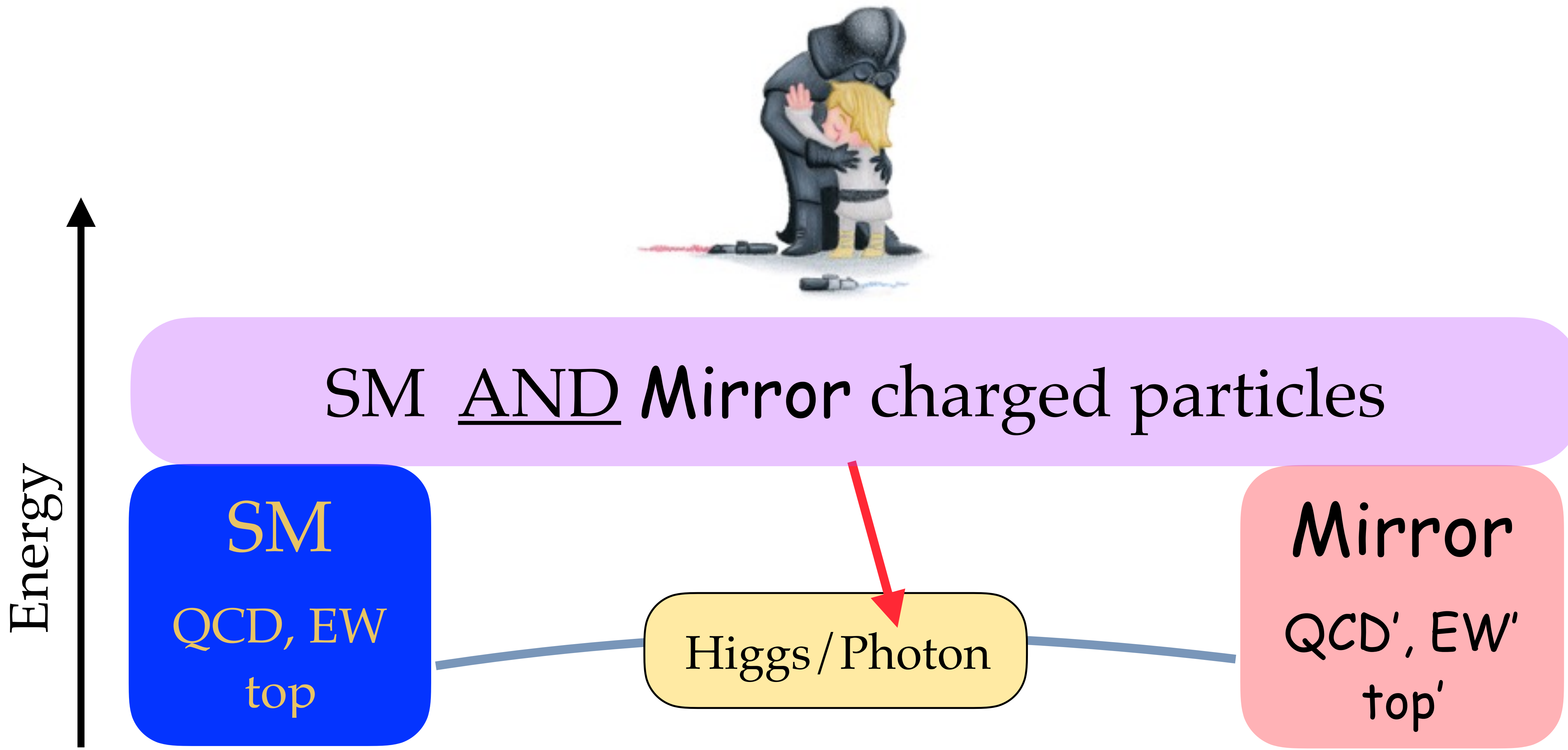


Average Decay Length (cm)

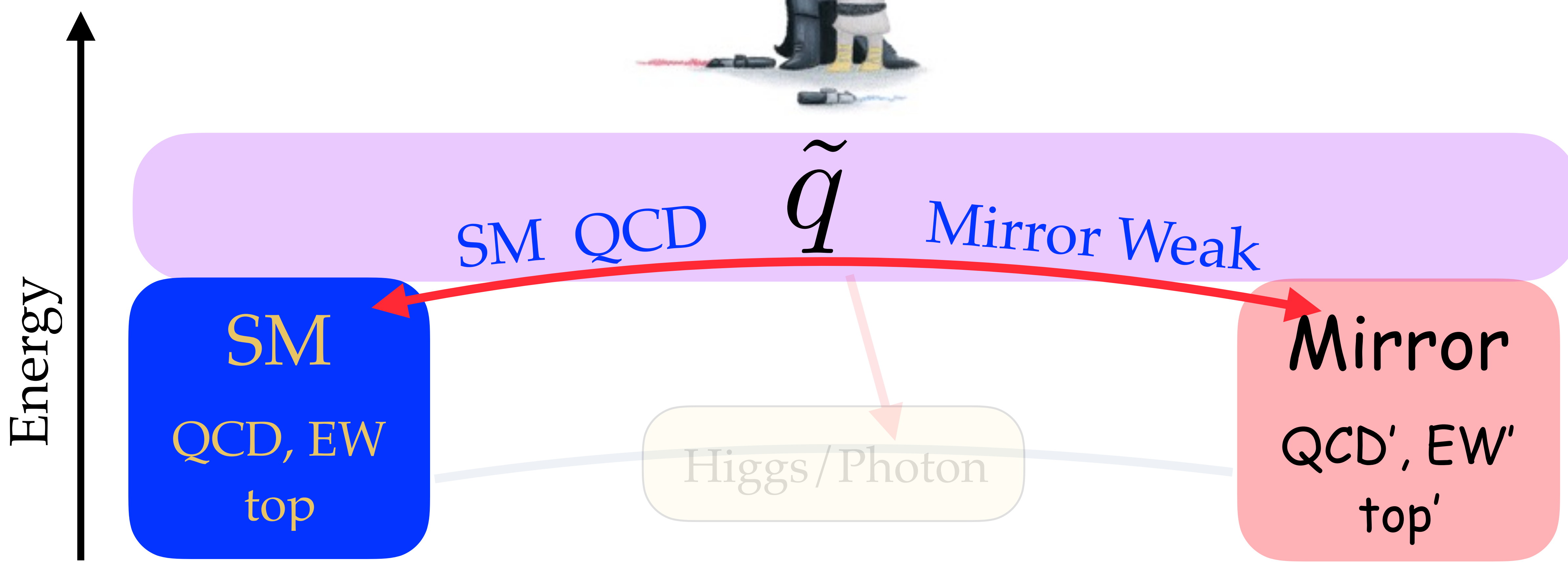
Pierce, Shakya, YT, Zhao (2017)

LHCb can play important roles in more mirror-symmetric twin Higgs model

Probing the Light-Dark unification!



Probing the Light-Dark unification!



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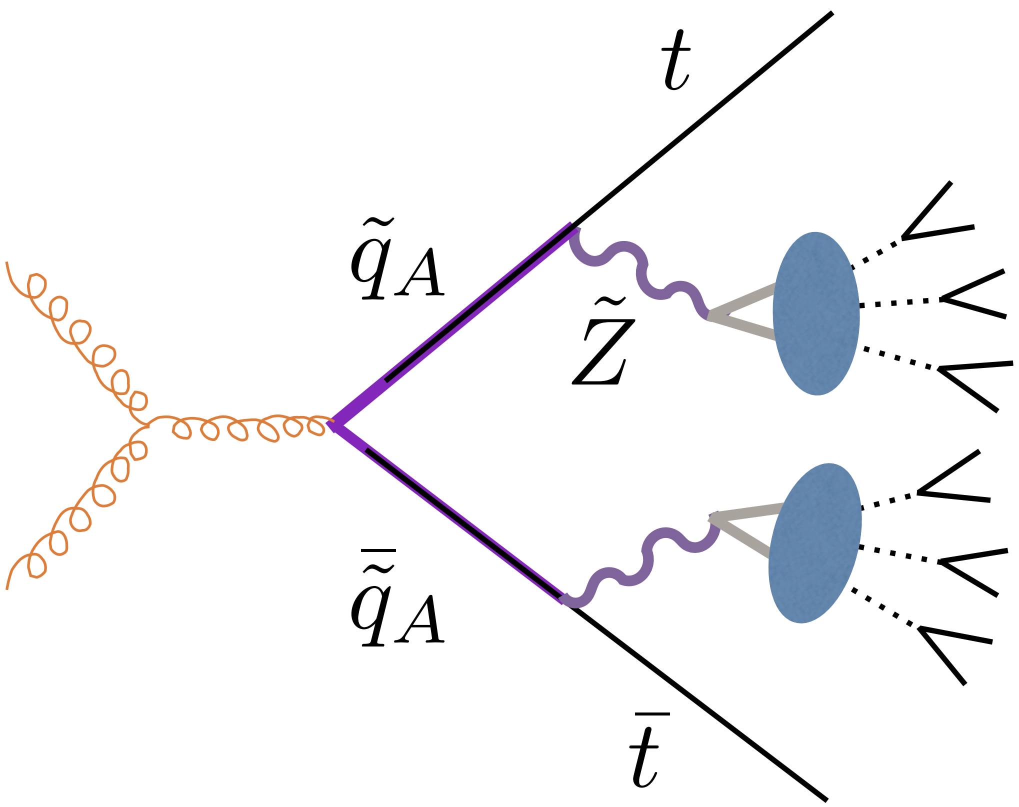
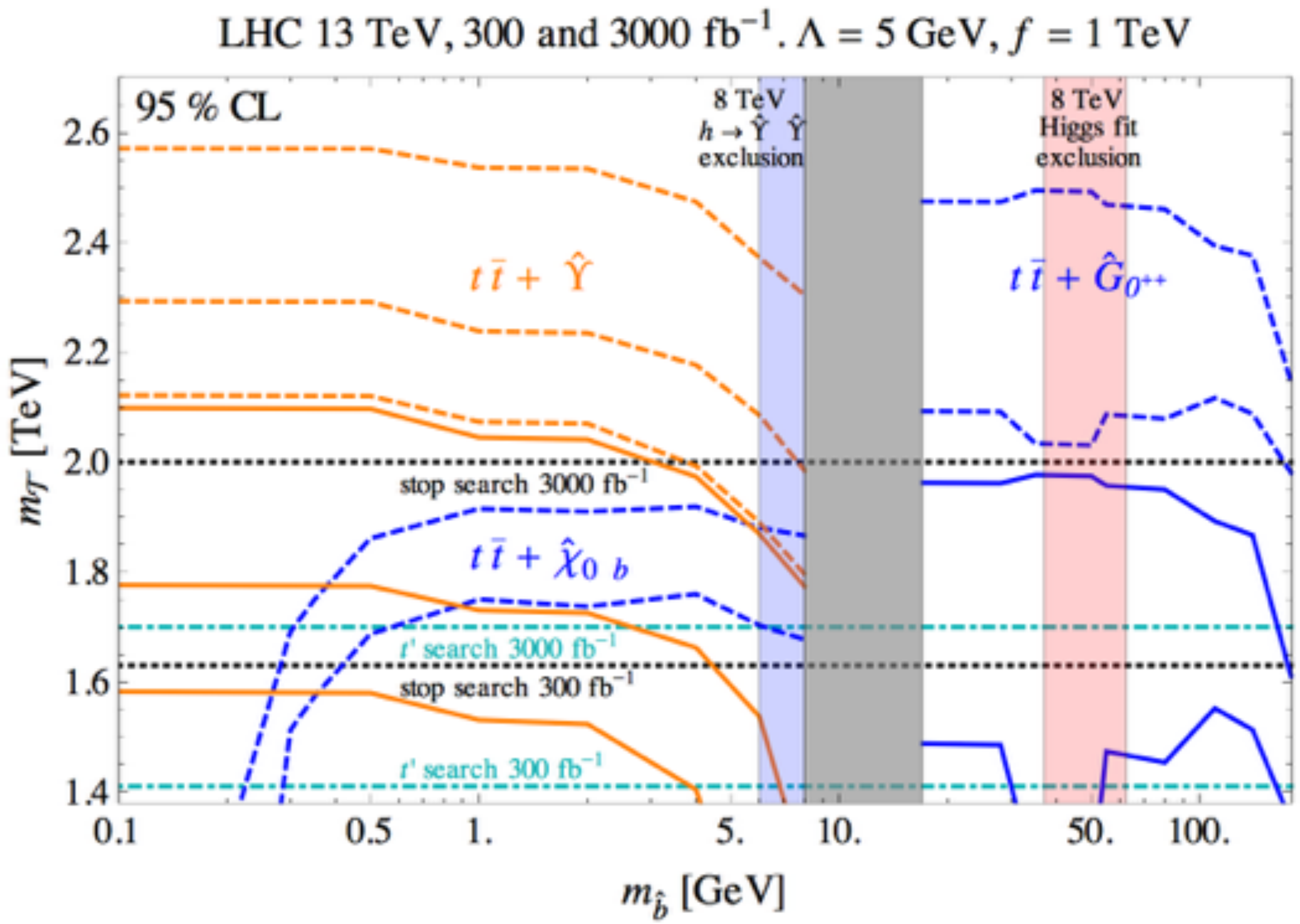


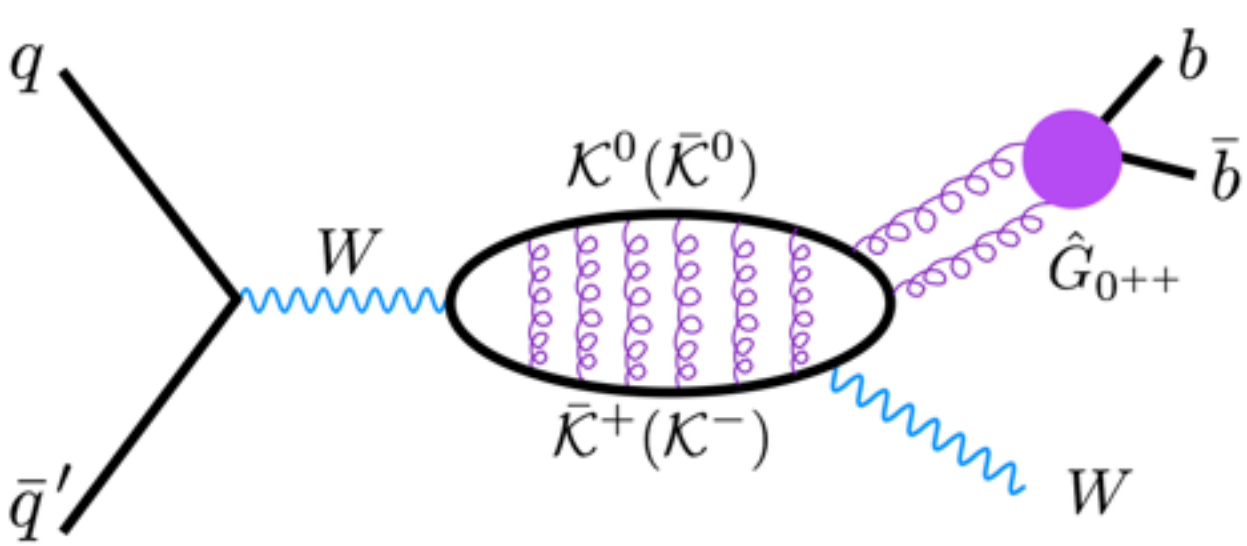


Cheng, Jung, Salvioni, YT (2015)

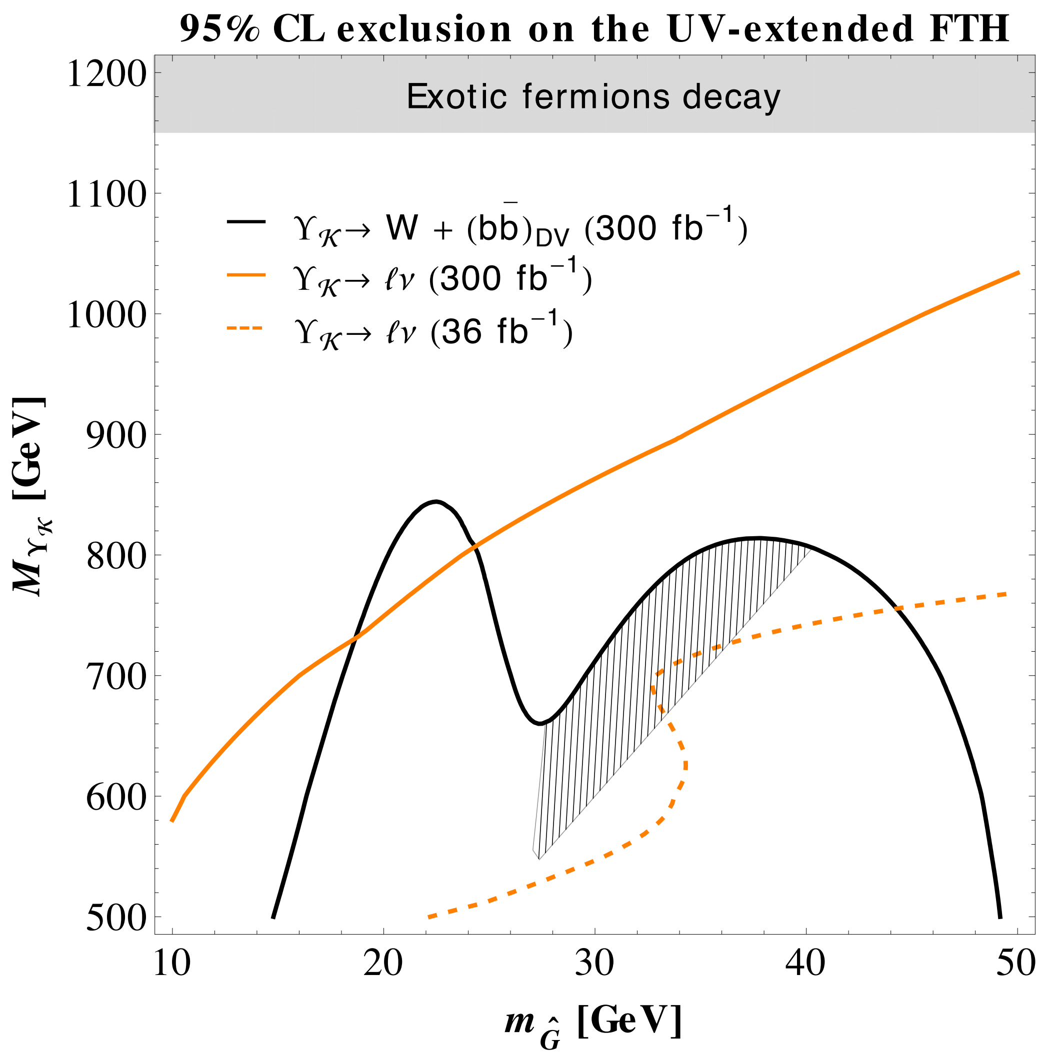
Can probe the twin structure up to ~ 20x Higgs mass scale!

DV from a decay of EW-charged bound state

Resonance decays into SM + DV



Trigger using the hard lepton



EW-charged bound state from twin QCD binding force (can produce more than one G_0's)

Cheng, Salvioni, YT (2016) Li, Salvioni, YT, Zheng (2017)

DV signals from Neutral Naturalness models

Signal_Neutral Naturalness Models: Twin Higgs (TH), Fraternal TH (FTH), Folded-SUSY (FSUSY), Quirky Little Higgs (QLH) **Exotic Higgs Decay, Heavy Resonance Decay, Pair Production & Decay**	**Paper**	**LLP Mass**	**LLP Multiplicity**	**ctau** Higgs portal Kinetic mixing	**SM contents** Higgs portal Kinetic mixing	**Trigger**
h > ***glueball*** (FTH, FSUSY), signal: DV bb	**1501.05310, 1506.06141**	10-60 GeV	2-4	micro m - km	DV bb, tautau	monojet, VBF, single lepton, tau(?),MuRoI
h > ***twin bottomonia*** (FTH), signal: DV bb or mumu	**1501.05310,1512.02647**	10-60 GeV	2-4	~< m (twin upsilon, assume heavy twin photon & cosmo bound), 0.01mm - 1m (twin chi, SM/5 < twin yb < SM)	DV bb, tautau, mumu	monojet, VBF, single lepton, tau(?),MuRoI
h > ***lighter twin hadrons*** (~MTH), signal: DV mumu, cc, tautau	**1708.05389**	1-10 GeV	2-8	~< m (twin omega, assume heavy twin photon & cosmo bound), Higgs portal too slow	DV cc, tautau, mumu	multi-muon, MuRoI, mono-jet, tau(?)
Exotic fermion bound state > SM W + ***twin glueball*** (FTH), DV to bb	**1612.03176, 1710.06437**	10-60 GeV	1-2 (T=0.3-0.5 TeV)	micro m - km	DV bb, tautau + prompt lepton	prompt lepton (pT > 100 GeV)
Quirky bound state > ***glueball*** (FSUSY), signal: DV bb	**1512.05782**	10-60 GeV	2-8 (T=0.5-1 TeV)	micro m - km	DV bb, tautau	monojet, VBF, single lepton, tau(?),MuRoI
Quirky bound state > ***glueball*** (QLH), signal: DV bb	**1512.05782**	10-60 GeV	2-8 (T=0.5-1 TeV)		DV bb, tautau	monojet, VBF, single lepton, tau(?),MuRoI
Heavy Higgs > ***glueball*** (FTH), signal: DV bb	**1711.03107**	10-60 GeV	20-30 (H=1-2.5 TeV)	micro m - km	DV bb, tautau	monojet, VBF, single lepton, tau(?),MuRoI
2 Exotic fermion, each decay into SM t + twin Z, and twin Z decay into ***twin glueballs***, signal: prompt lepton + DV bb (FTH)	**1512.02647**	10-60 GeV	2-8 from a twin Z = 270-450 GeV, 4-16 from both twin Z's	micro m - km	DV bb, tautau, mumu + prompt lepton	prompt lepton (pT > 100 GeV)
2 Exotic fermion, each decay into SM t + twin Z, and twin Z decay into ***twin bottomonia***, signal: prompt lepton + DV bb or mumu (FTH)	**1512.02647**	10-60 GeV	2-8 from one twin Z = 270-450 GeV, 4-16 from both twin Z's	~< m (twin upsilon, assume heavy twin photon & cosmo bound), 0.01mm - 1m (twin chi, SM/5 < twin yb < SM)	DV bb, tautau, mumu + prompt lepton	prompt lepton (pT > 100 GeV)

Lots of assumptions in the mass/multiplicity/lifetime estimation

See the reference for details

LLP and Baryogenesis

WIMP baryogenesis: One solution to TWO puzzles

LLP and Baryogenesis

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=> baryon asymmetry + why baryon density $\sim$ DM

LLP and Baryogenesis

WIMP baryogenesis: One solution to TWO puzzles

=> baryon asymmetry + why baryon density $\sim$ DM

=> B-number violating decay happens after freeze out

LLP and Baryogenesis

WIMP baryogenesis: One solution to TWO puzzles

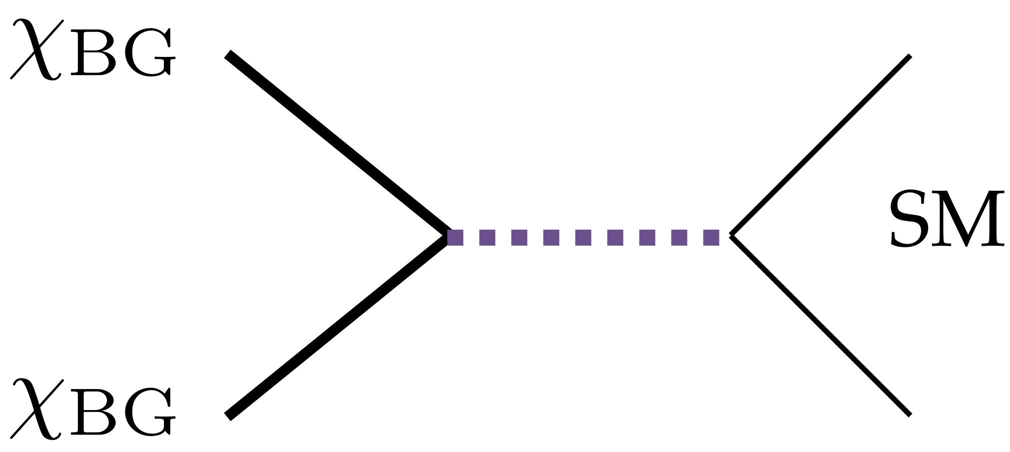
=> baryon asymmetry + why baryon density $\sim$ DM

=> B-number violating decay happens after freeze out

=> slow decay into baryons

WIMP Baryogenesis

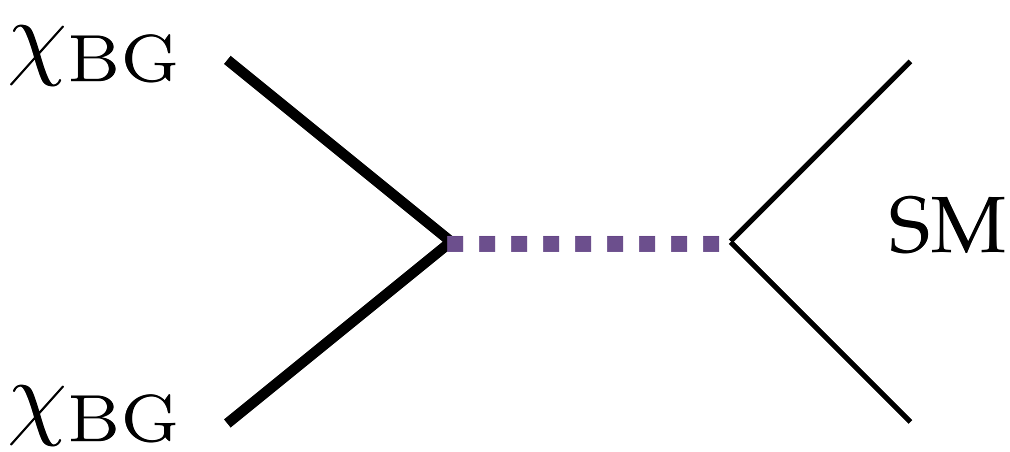
Cui, Sundrum (2012)



baryogenesis (BG) particles
annihilate into SM and freeze out

WIMP Baryogenesis

Cui, Sundrum (2012)



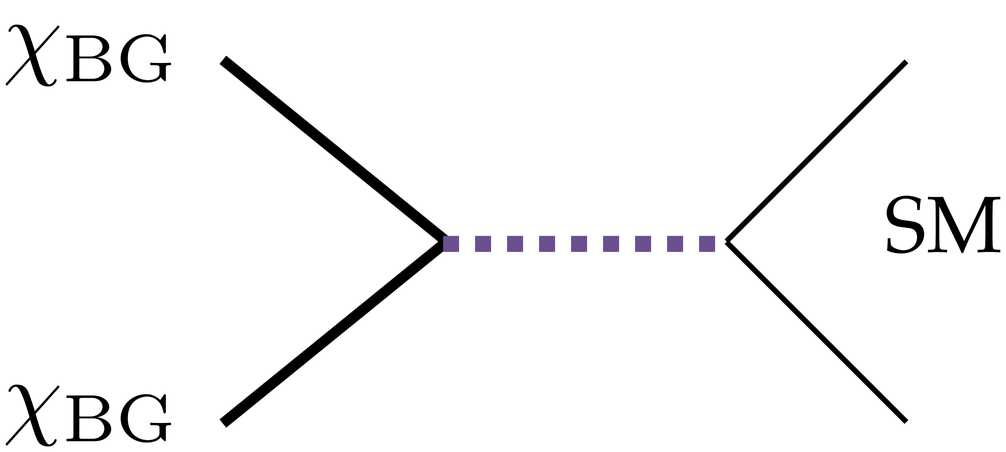
baryogenesis (BG) particles annihilate into SM and freeze out

(WIMP miracle) if all the particles are around EW energy scale

$$n_{\rm BG} \sim n_{\rm DM}$$

WIMP Baryogenesis

Cui, Sundrum (2012)



baryogenesis (BG) particles annihilate into SM and freeze out

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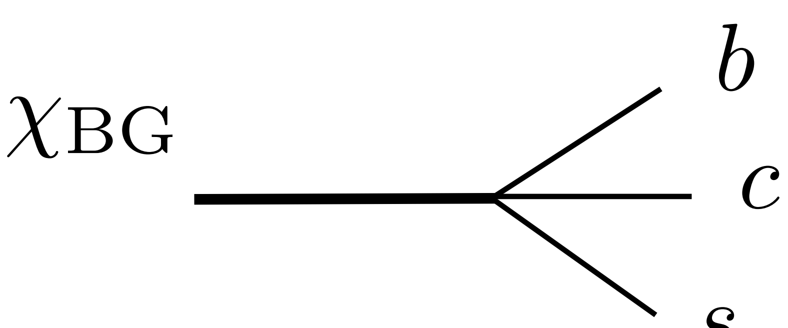
$$n_{\rm BG} \sim n_{\rm DM}$$



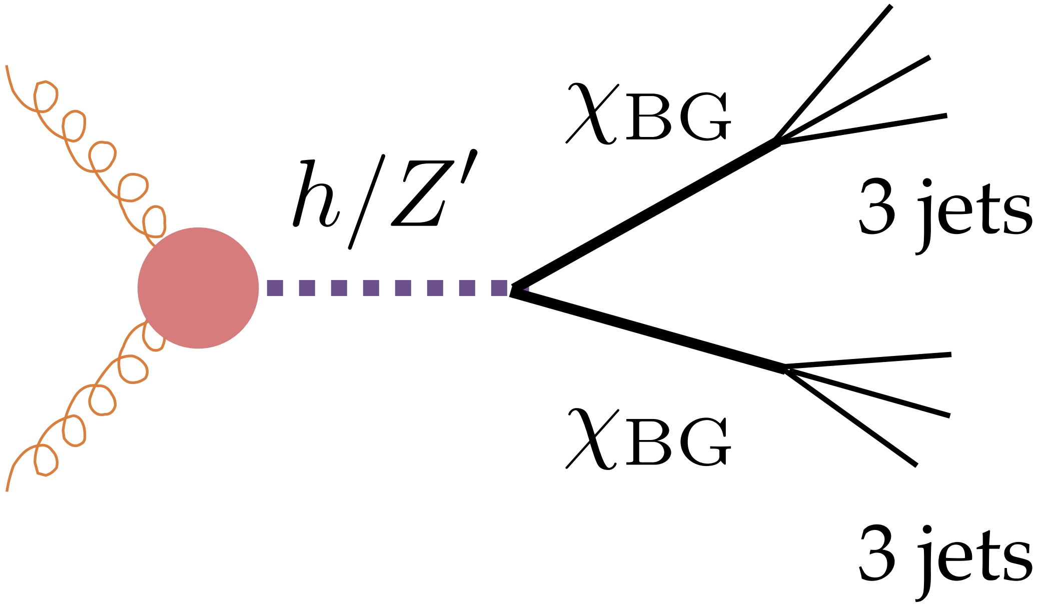
CP-violation decay dominantly into baryon (but not anti-baryon)

$$n_b \sim n_{\rm DM} \Rightarrow \rho_b \sim \rho_{\rm DM}$$

CPV decay needs to happen after freeze-out

Cui, Sundrum (2012)

$$\Gamma_{\chi_{\rm BG}\to udd} < H(T \sim T_{\rm freeze\ out}) \Rightarrow c\tau_{\chi_{\rm BG}\to udd} > {\rm cm}$$



Cui, Shuve (2015)

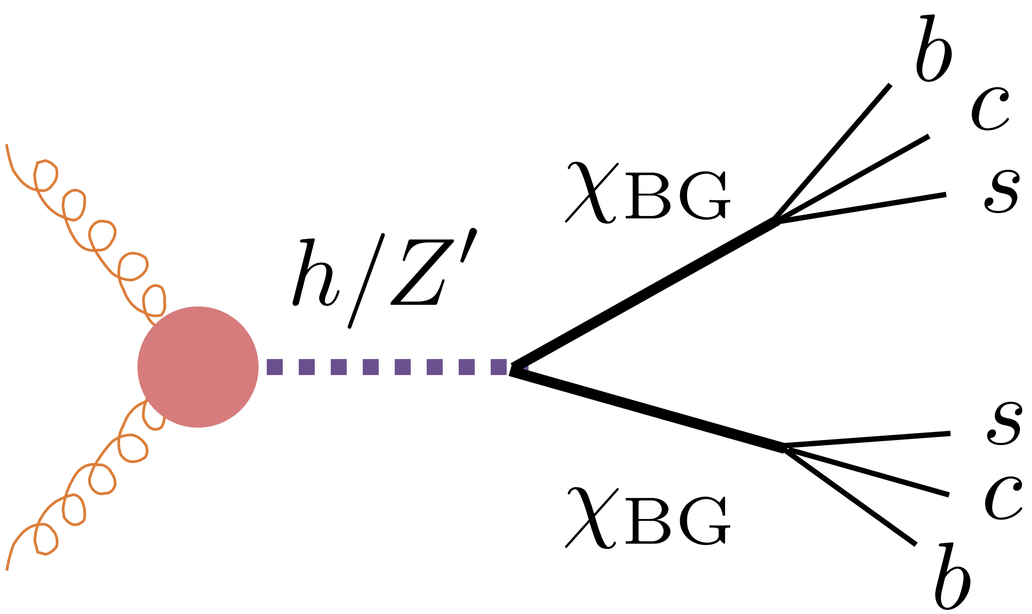
Two displaced jets

e.g. ATLAS displaced di-jets
(CMS-PAS-EXO-12-038)
Trigger: total jet HT > 300 GeV,
2 displaced jets, each pT > 60 GeV

CPV decay needs to happen after freeze-out

Cui, Sundrum (2012)

$$\Gamma_{\chi_{\rm BG}\to udd} < H(T \sim T_{\rm freeze\ out}) \Rightarrow c\tau_{\chi_{\rm BG}\to udd} > {\rm cm}$$

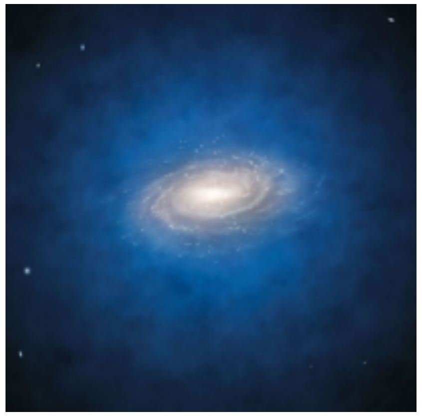


Two displaced jets

flavor tagging the CPV decays?

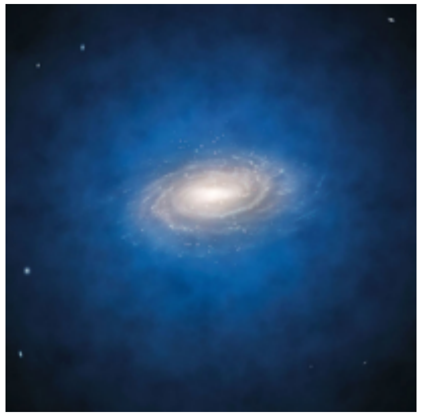
Cui, Joglekar, Shuve, YT (in progress)

LLP and Halo structure puzzles



Self-interacting DM addresses mass deficit problems

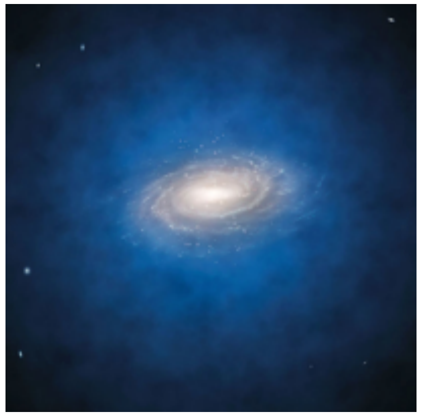
LLP and Halo structure puzzles



Self-interacting DM addresses mass deficit problems

=> light dark force mediator for DM scattering

LLP and Halo structure puzzles

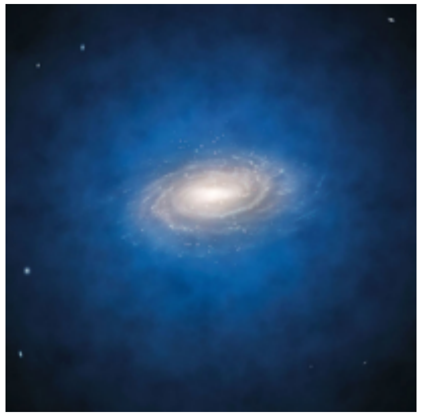


Self-interacting DM addresses mass deficit problems

=> light dark force mediator for DM scattering

=> force mediator decays into SM eventually

LLP and Halo structure puzzles



Self-interacting DM addresses mass deficit problems

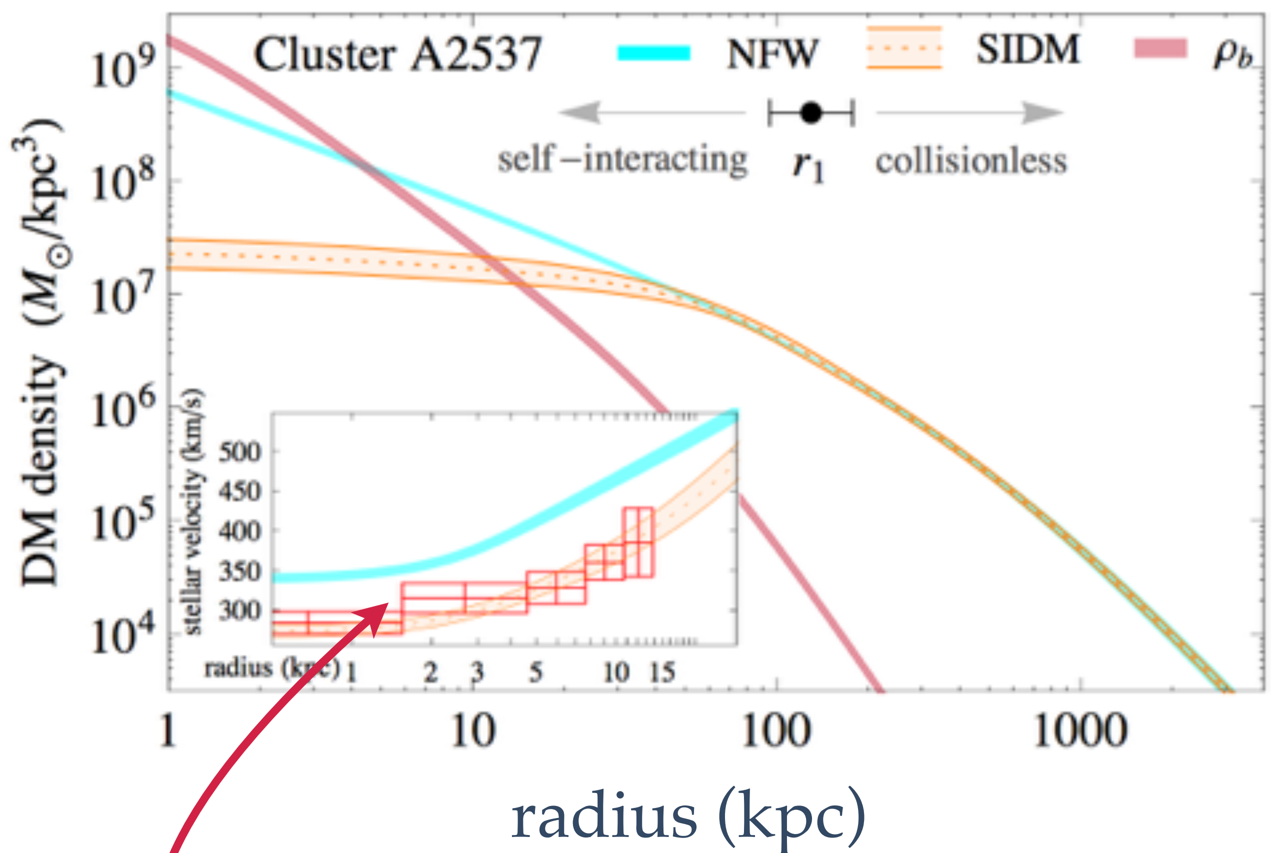
=> light dark force mediator for DM scattering

=> force mediator decays into SM eventually

=> DM bound state decays into long-lived mediators

Self-interacting DM & the mass deficit problem

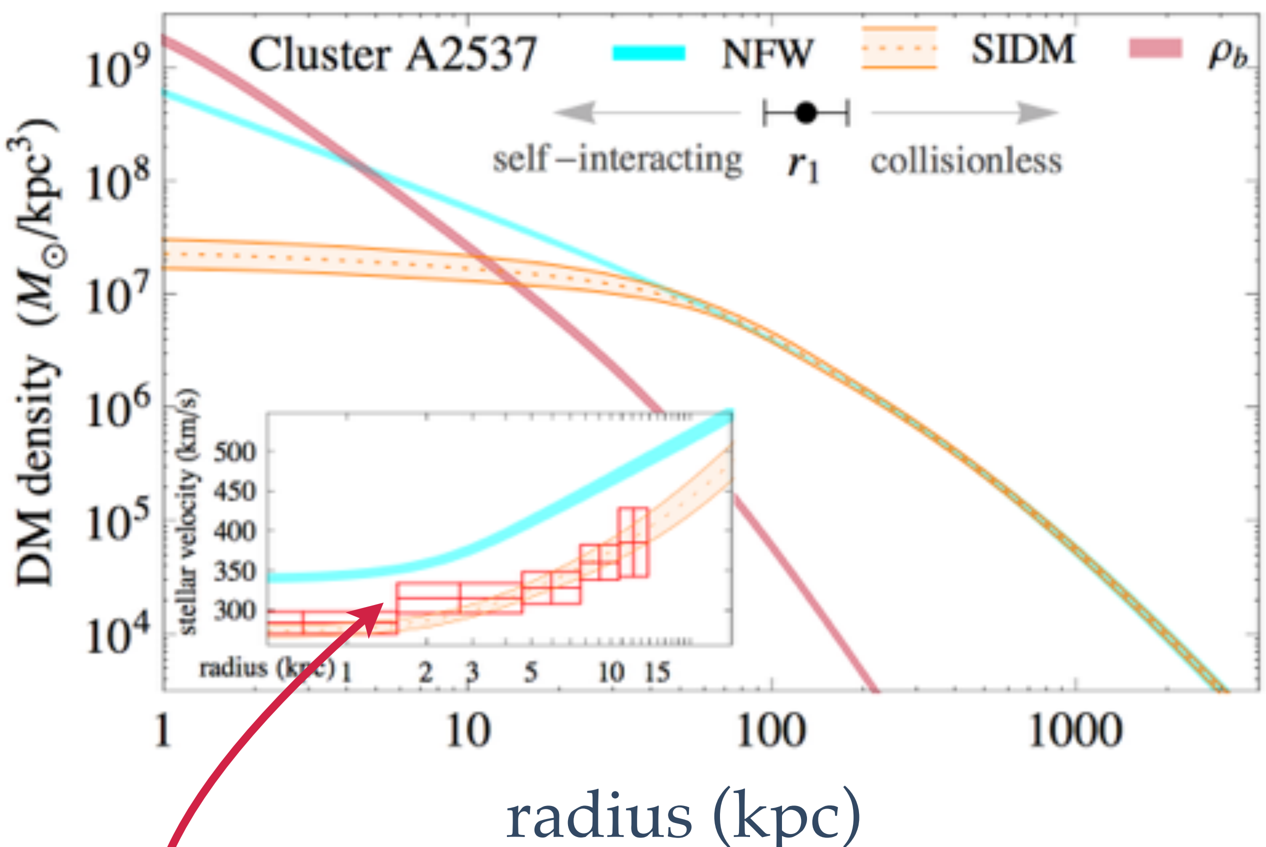
Kaplinghat, Tulin, Yu (2015)

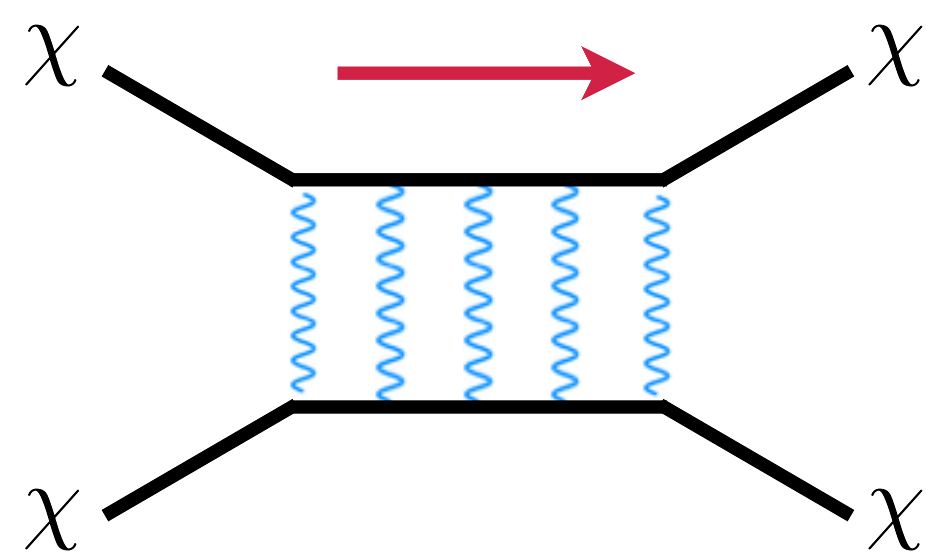


stars move slower, lower mass density than collisionless DM prediction

Self-interacting DM & the mass deficit problem

Kaplinghat, Tulin, Yu (2015)





Tulin, Yu, Zurek (15')

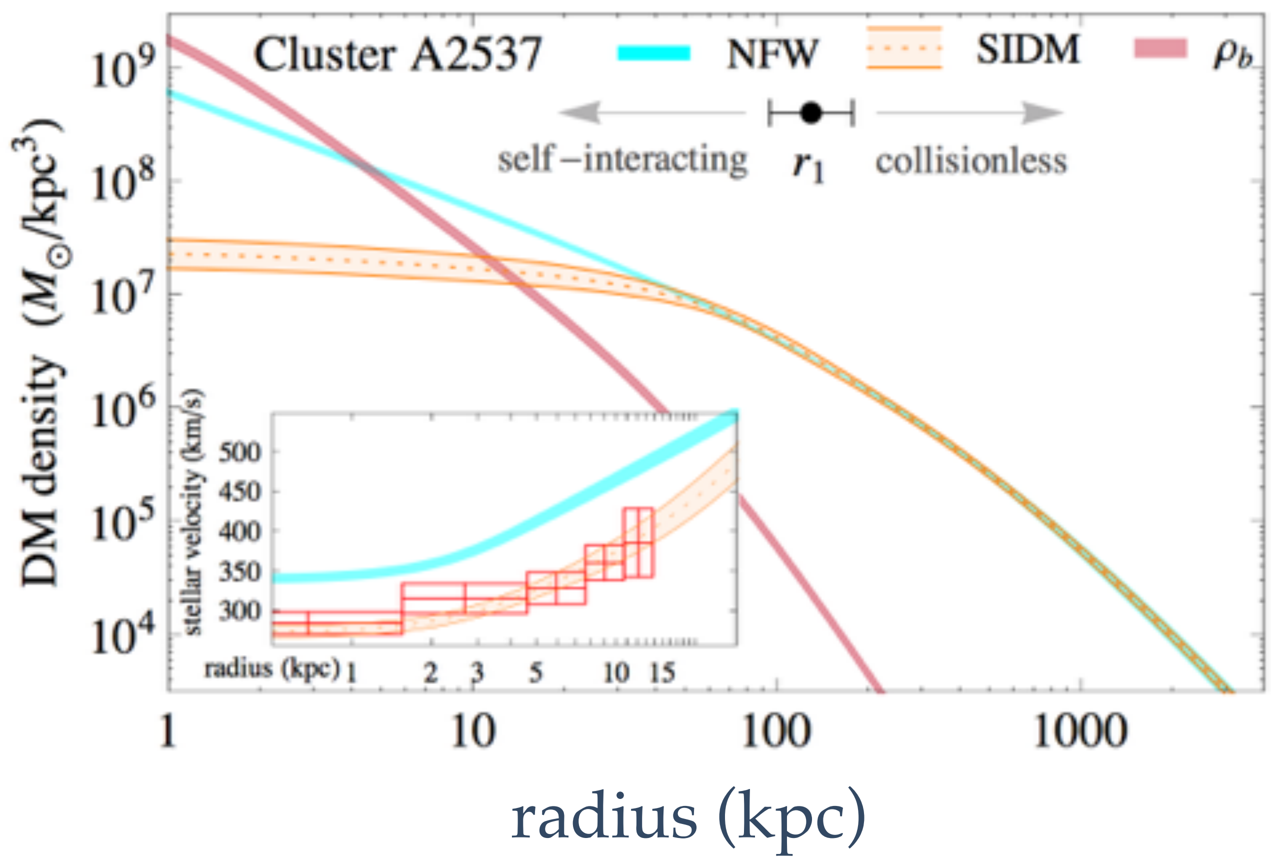
Kaplinghat, Tulin, Yu (13')

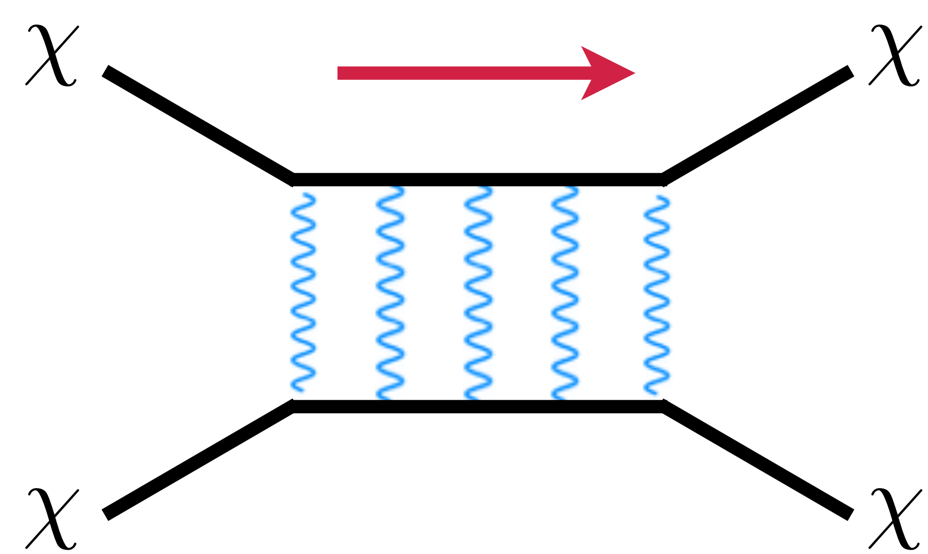
For a review: Tulin, Yu (17')

stars move slower, lower mass density than collisionless DM prediction

Self-interacting DM & the mass deficit problem

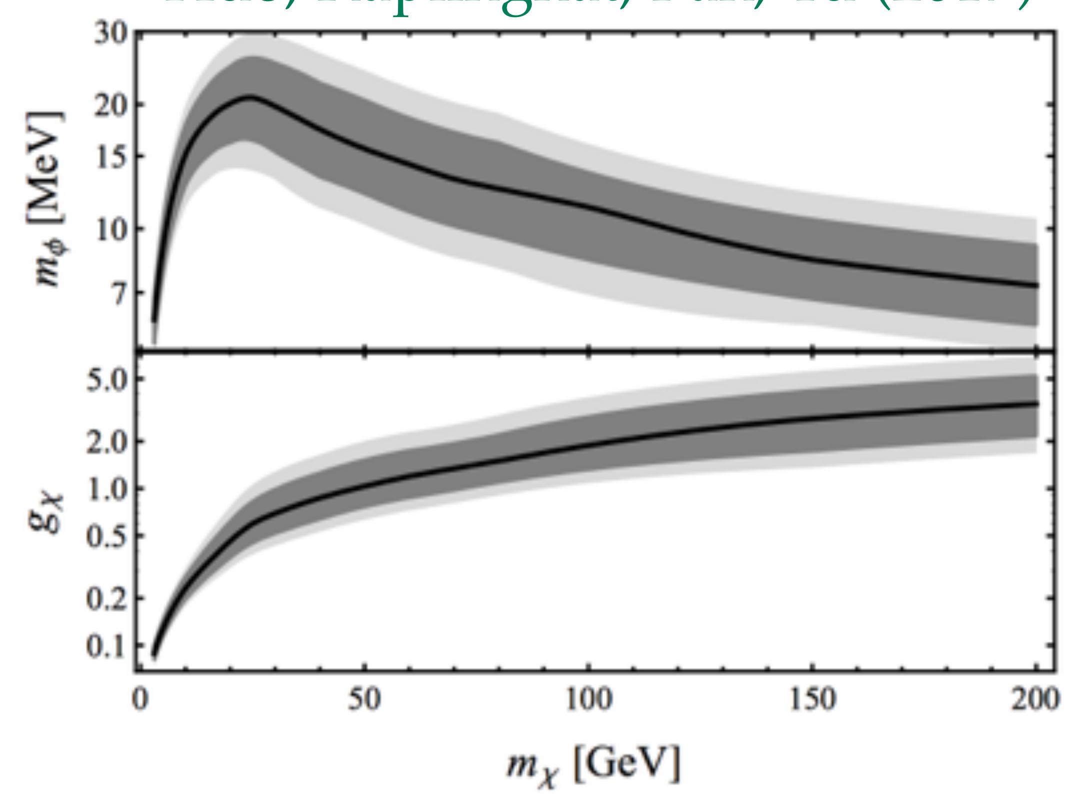
Kaplinghat, Tulin, Yu (2015)





Need sub-GeV mediator
to explain the puzzles from
dwarf galaxies to galaxy clusters

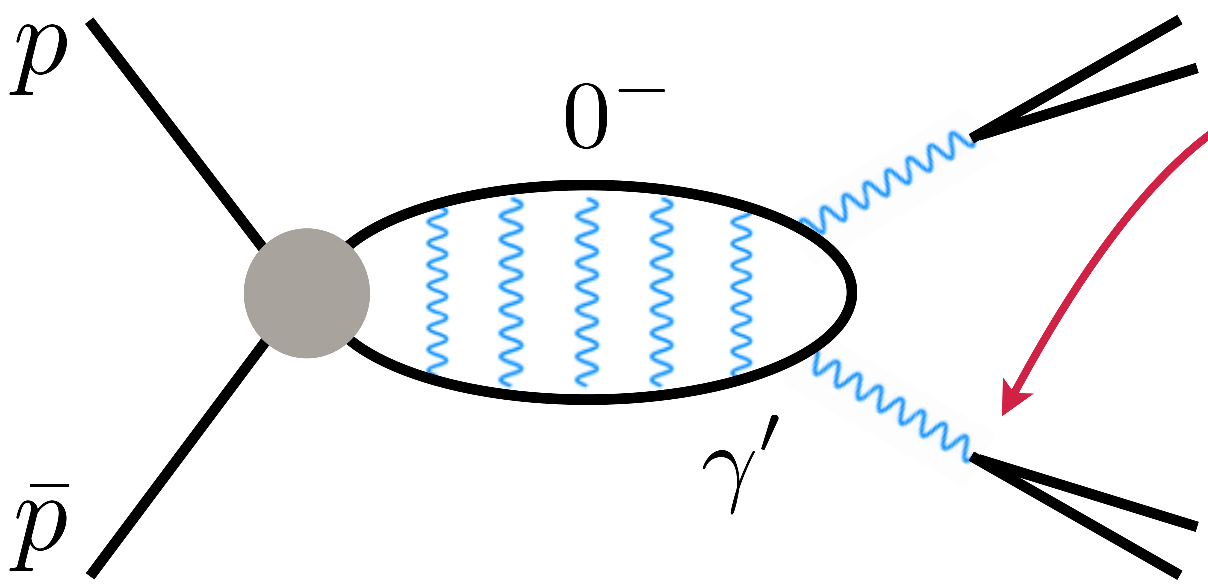
Huo, Kaplinghat, Pan, Yu (2017)



DM annihilation at the LHC

YT, Wang, Zhao (2015)

light mediator + strong coupling => DM bound state $m_{\gamma'} \leq \frac{\alpha_\chi m_\chi}{2}$



kinetic mixing to SM photon

$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$

two displaced lepton-jets from a resonance decay

$$c\tau_{\gamma' \to e^+e^-} \simeq \gamma_{\gamma'} \left(\frac{e^2 \epsilon_{\gamma'}^2 m_{\gamma'}}{12\pi} \right)^{-1}$$
$$\simeq 0.08\,\text{mm} \times \gamma_{\gamma'} \left(\frac{100\,\text{MeV}}{m_{\gamma'}} \right) \left(\frac{10^{-4}}{\epsilon_{\gamma'}} \right)^2$$

DLJ search of dark photon

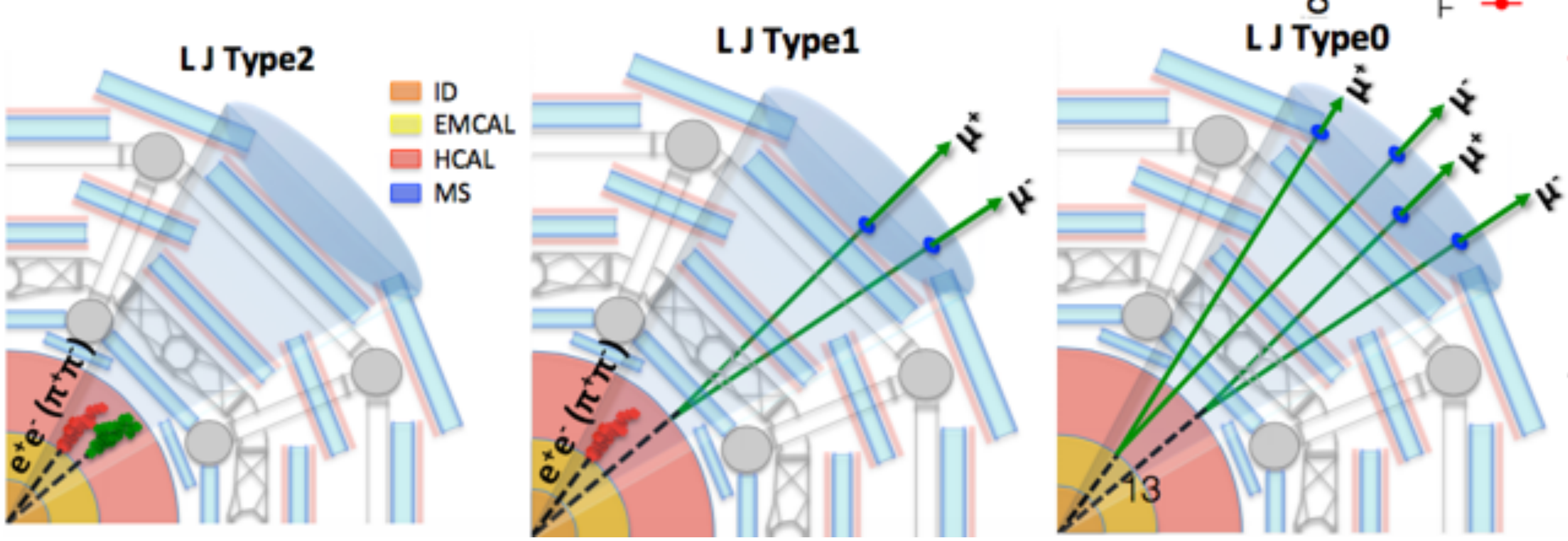
Look for displaced decay in the detector volume

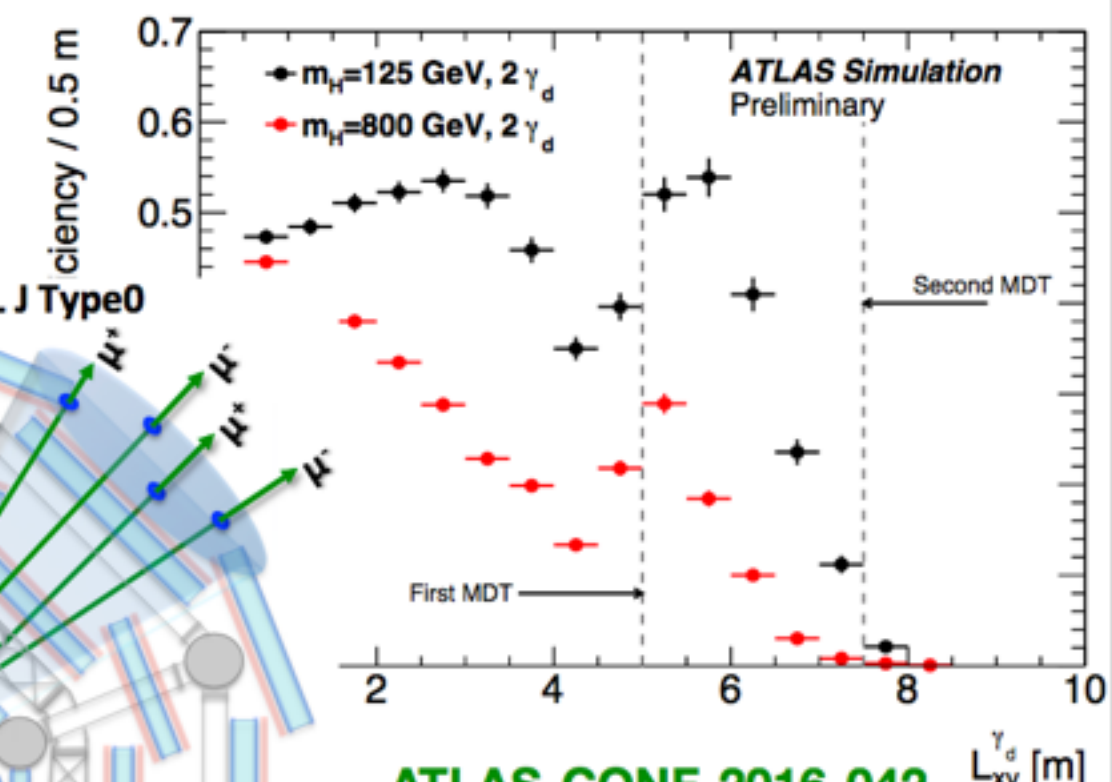
- Scan Muon trigger for $\phi \to \mu\mu$ in HCAL, find one hard μ first
- CAL Ratio trigger for $\phi \to ee$ in HCAL, find jet-like object

DV location and efficiency in our simulation

	$\|\eta_\phi\| \leq 1.5$	$1.5 \leq \|\eta_\phi\| \leq 2.4$
$\phi \to e^+e^-$	barrel: 2.2 – 3.7 [m]; P=0.7	endcap: 4.3 – 6.0 [m]; P=0.5
$\phi \to \mu^+\mu^-$	barrel: 2.2 – 6.0 [m]; P=0.5	endcap: 4.3 – 10.0 [m]; P=0.6

SM background free





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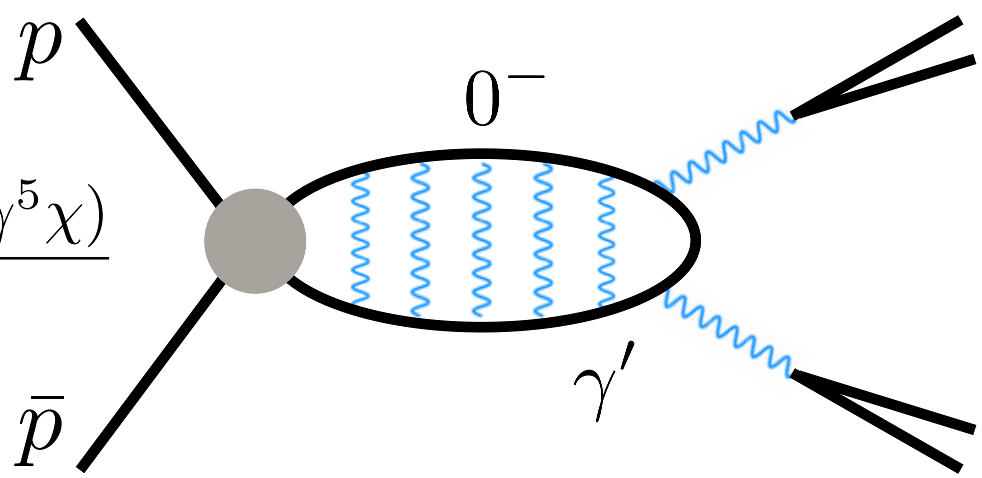
Future coverage on SIDM production

$$\frac{m_q(\bar{q}\gamma^5 q)(\bar{\chi}\gamma^5\chi)}{v\,M_*^2}$$



$$(\phi = \gamma')$$

Trigger first ϕ

The second ϕ should satisfy

$$p_T^\phi \geq 20 \text{ GeV}$$

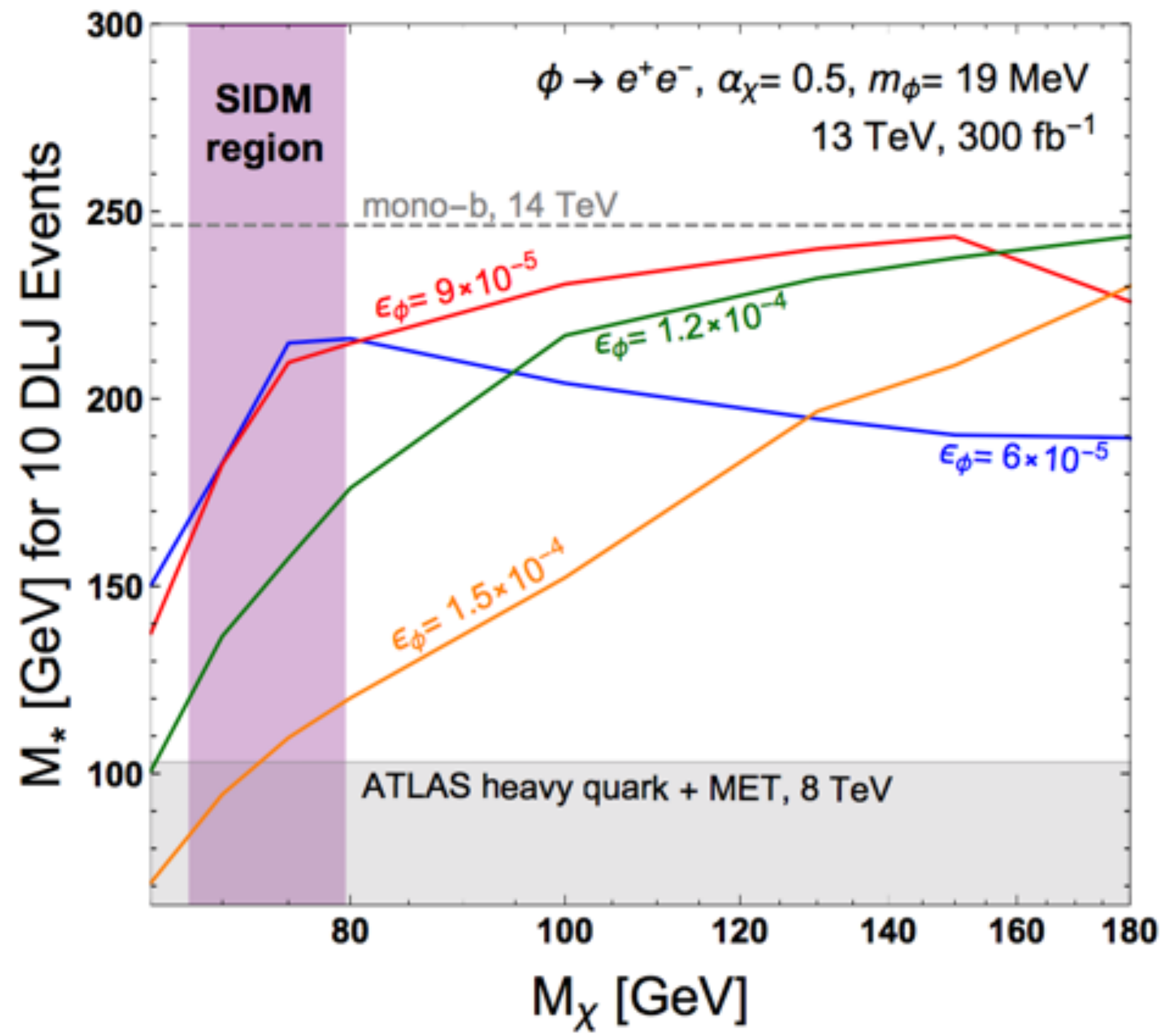
Kinematic cuts

$$|\eta^\ell| \leq 2.4$$

$$\Delta R_{1,2}^{\bar{\ell}\ell} \leq 0.5$$

$$p_T^\phi \geq 30 \text{ GeV}$$

Ren, YT, Yu, Xu (preliminary, in progress)



LLP and DM indirect detection signals

Cosmic ray with broad & soft energy spectrum

LLP and DM indirect detection signals

Cosmic ray with broad & soft energy spectrum

=> can come from dark showering + light mesons

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=> need to be pretty isolated from us

LLP and DM indirect detection signals

Cosmic ray with broad & soft energy spectrum

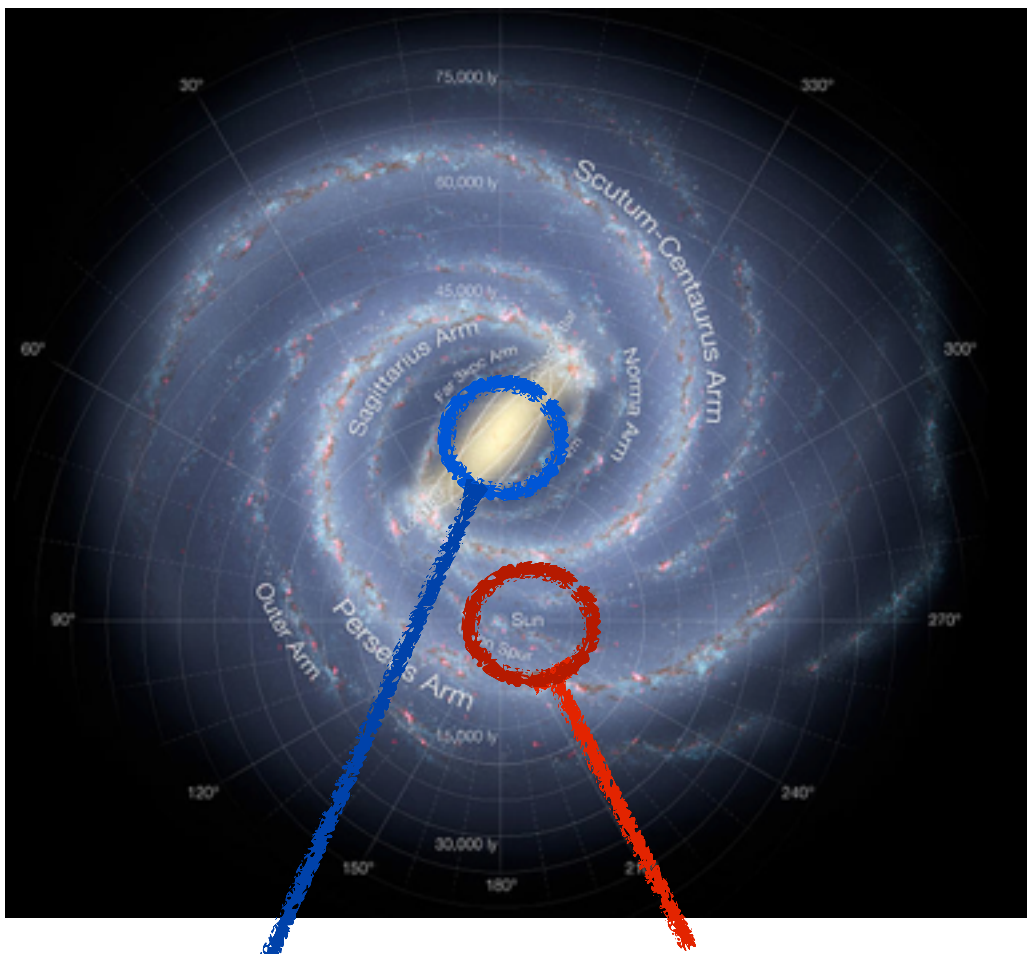
=> can come from dark showering + light mesons

=> need to be pretty isolated from us

=> dark meson is long-lived

``IF" galactic center gamma-ray excess is DM

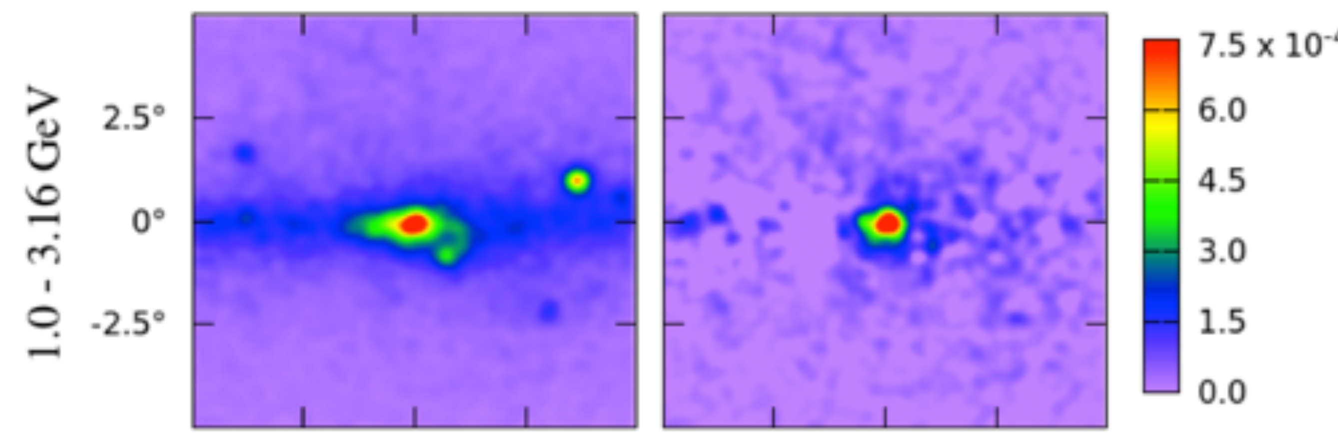
Still many debates, take it as an example for our LLP discussion

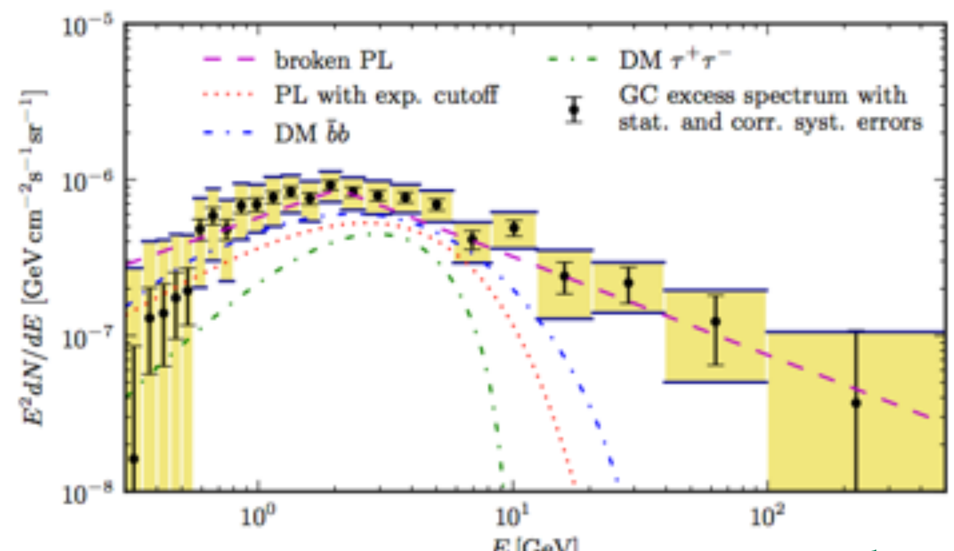


DM??

Fermi

signal ~ spherically distributed

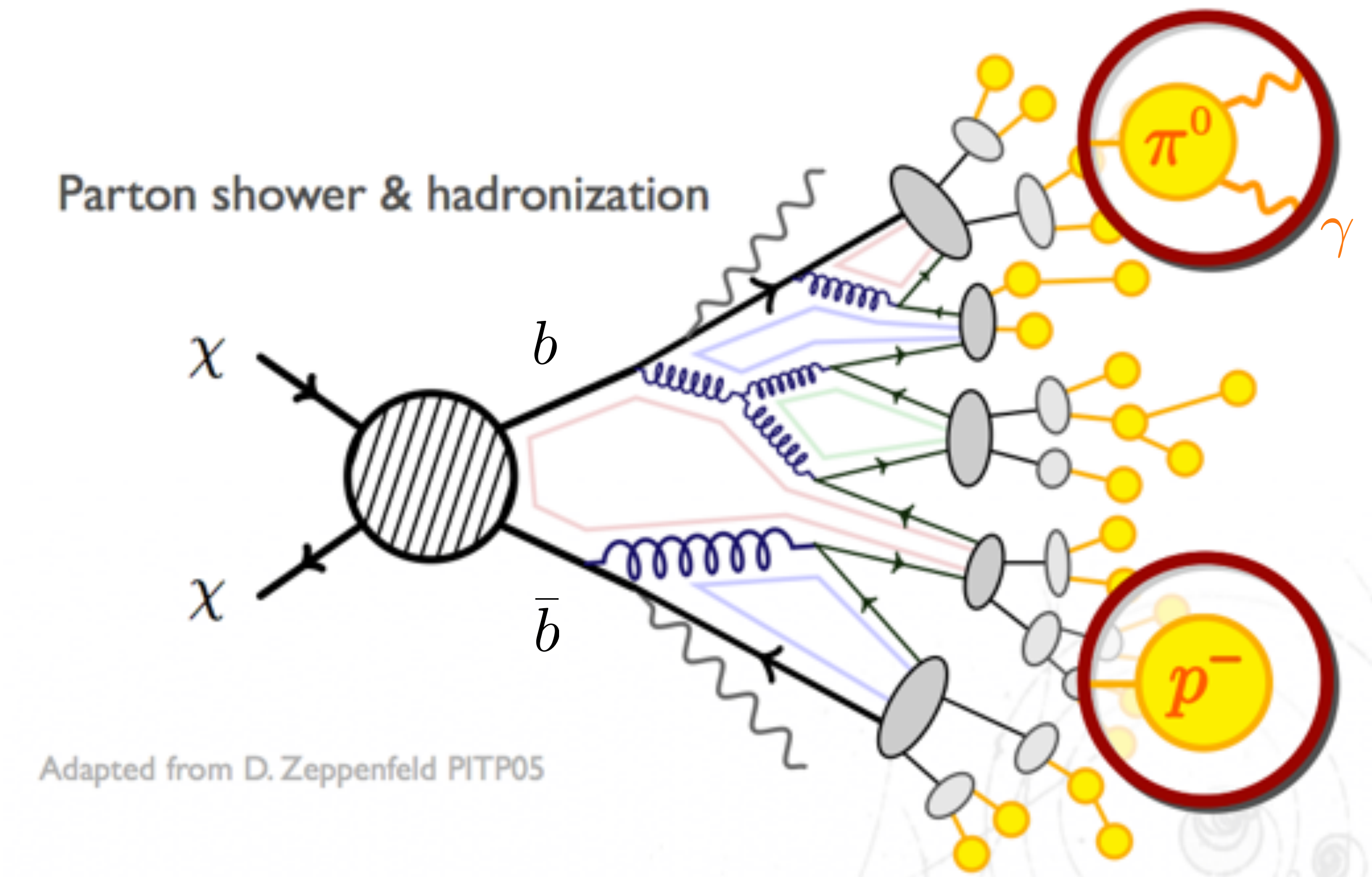




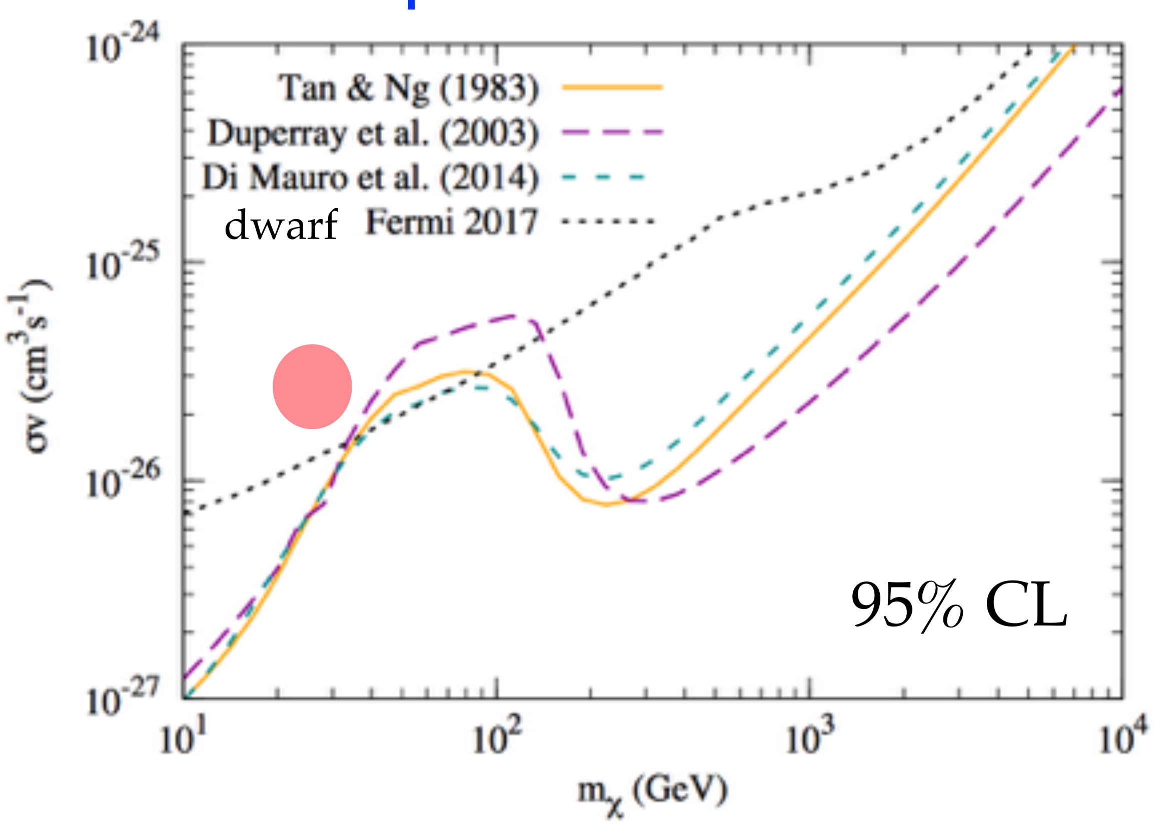
Calore, Cholis, Weniger (2014)

Goodenough & Hooper (0910.2998, 1010.2752), Hooper & Linden (1110.0006), Abazajian et al. (1011.4275, 1207.6047, 1402.4090), Boyarsky et al. (1012.5839); Gordon & Macias (1306.5725); Daylan et al. (1402.6703); Calore et al. (1409.0042)…

May come from DM annihilation & showering



anti-proton constraint

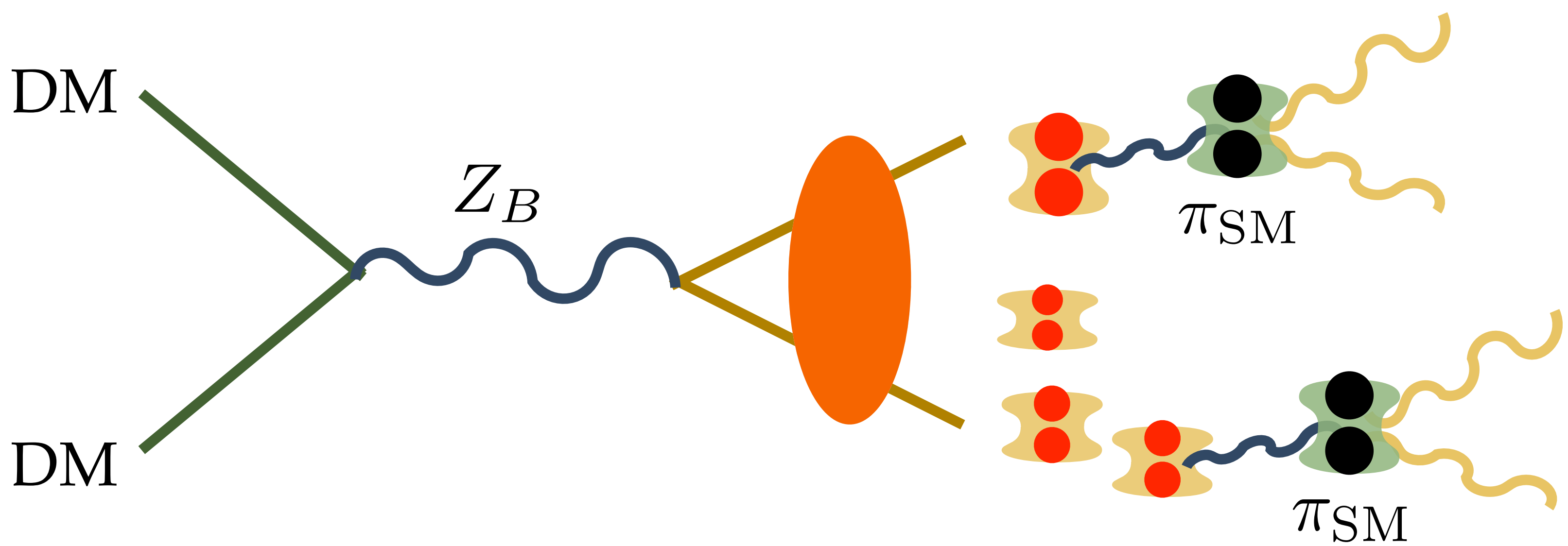


Cui, Yuan, Tsai, Fan (2017)

However, SM showering also produce anti-proton
that is well constrained by other searches

Idea: showering in the dark

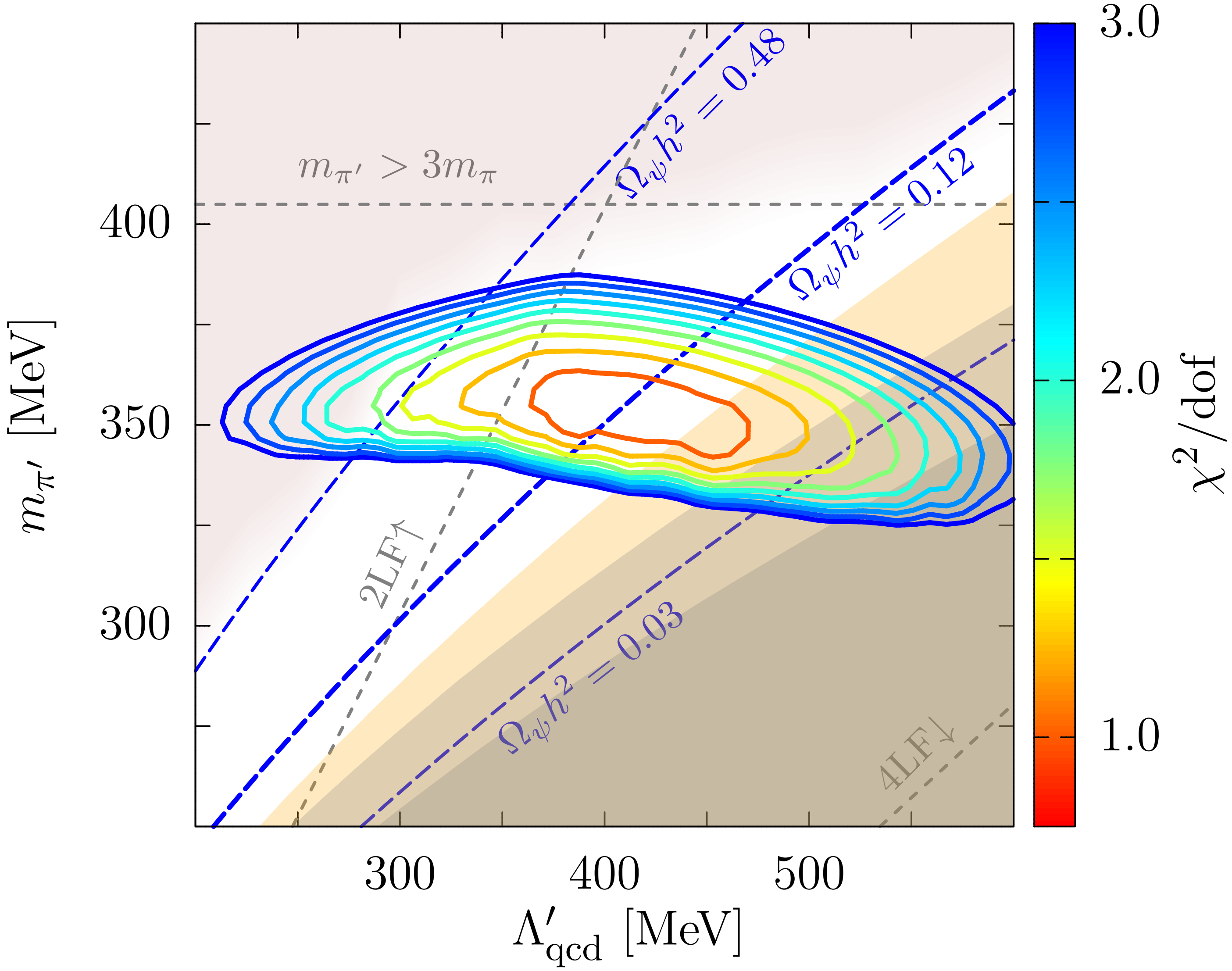
Freytsis, Robinson, YT (2014) Freytsis, Knapen, Robinson, YT (2016)



Can even come from Twin Higgs model (doesn't have to)

Data prefer light dark mesons

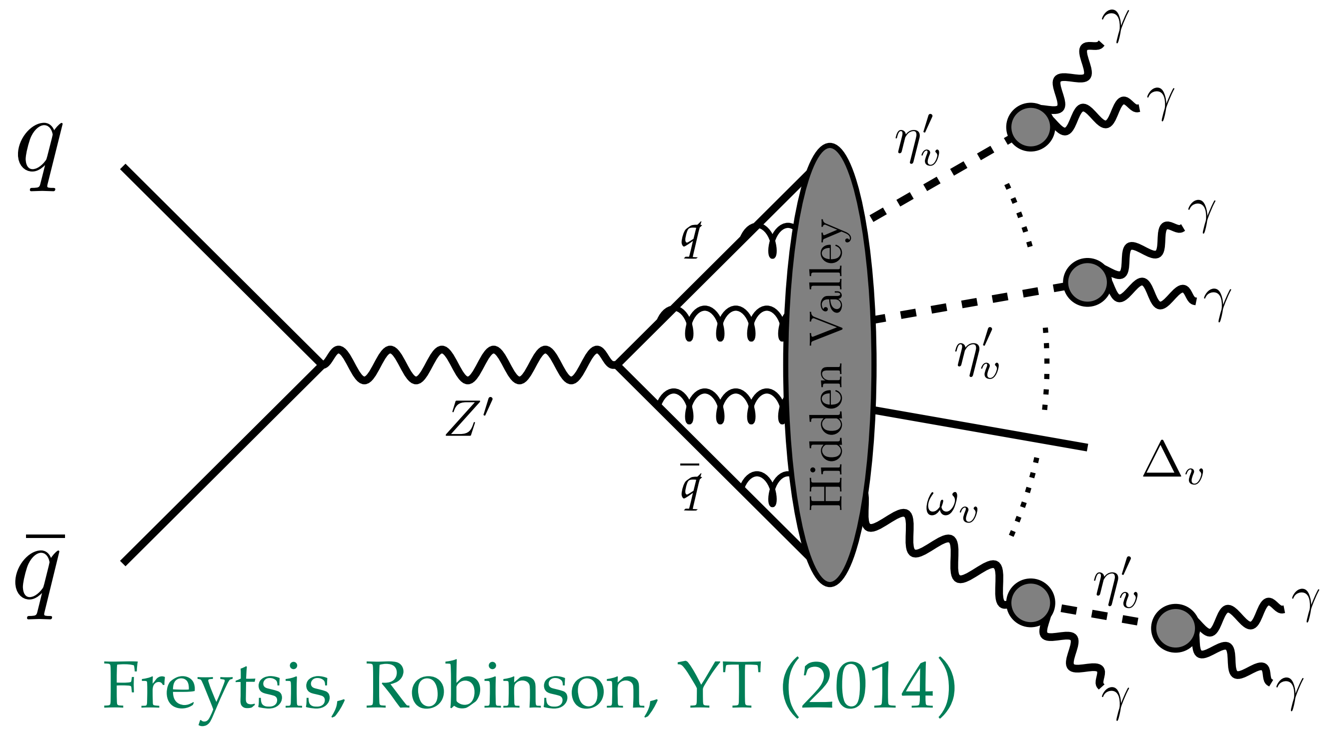
Freytsis, Knapen, Robinson, YT (2016)



Can provide the observed photon signals, while satisfying all the direct/indirect detection constraints

Displaced / delayed photon signals

Considering various existing constraints, sub-GeV dark meson decay into photons has lifetime > 100 m (at least)



Freytsis, Robinson, YT (2014)

However, if we don't focus on the Fermi-anomaly, detector-size decay length can be easily achieved

Summary and outlook

- LLP signatures show up in many physics scenarios
- their collider signatures can be quite different
- some signals (few displaced decays into muons/jets) are covered by existing searches
- some signals (multiple final state, low energy, light LLP, photon) require different searching strategies
- definitely worth the effort! once seeing the signal, we learn much more than simply missing energy signatures