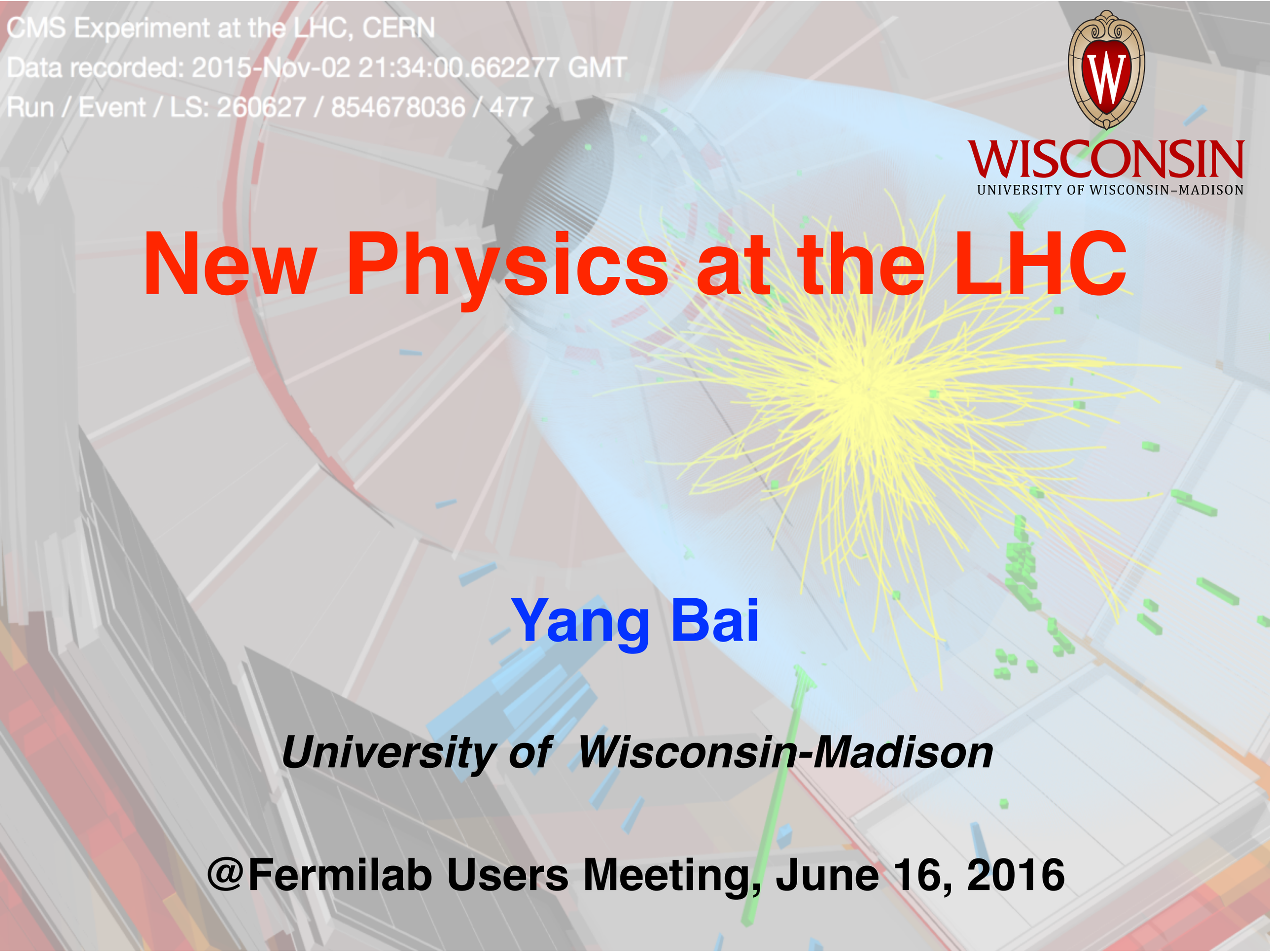


WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

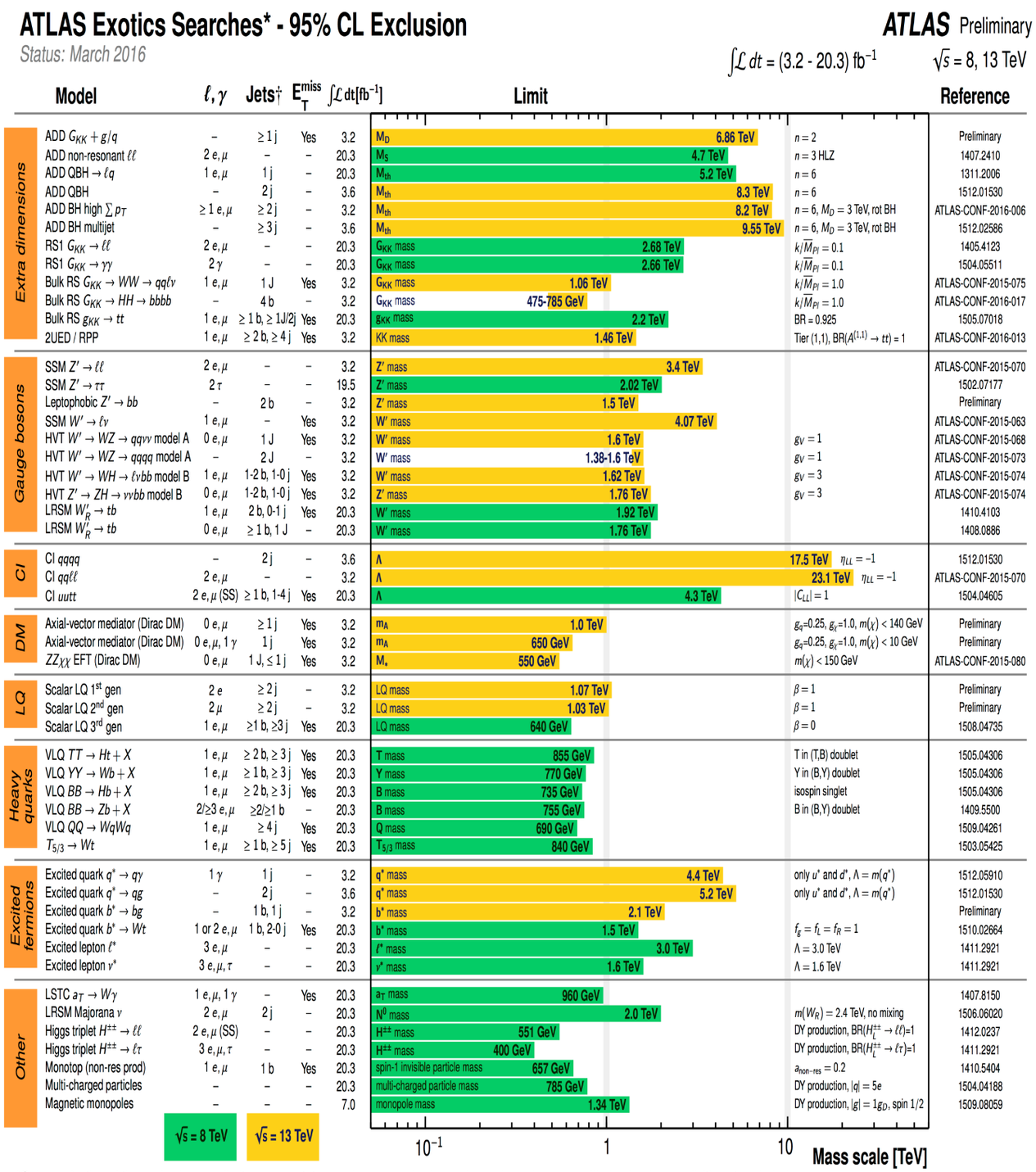
New Physics at the LHC

Yang Bai

University of Wisconsin-Madison

@Fermilab Users Meeting, June 16, 2016

Status Report



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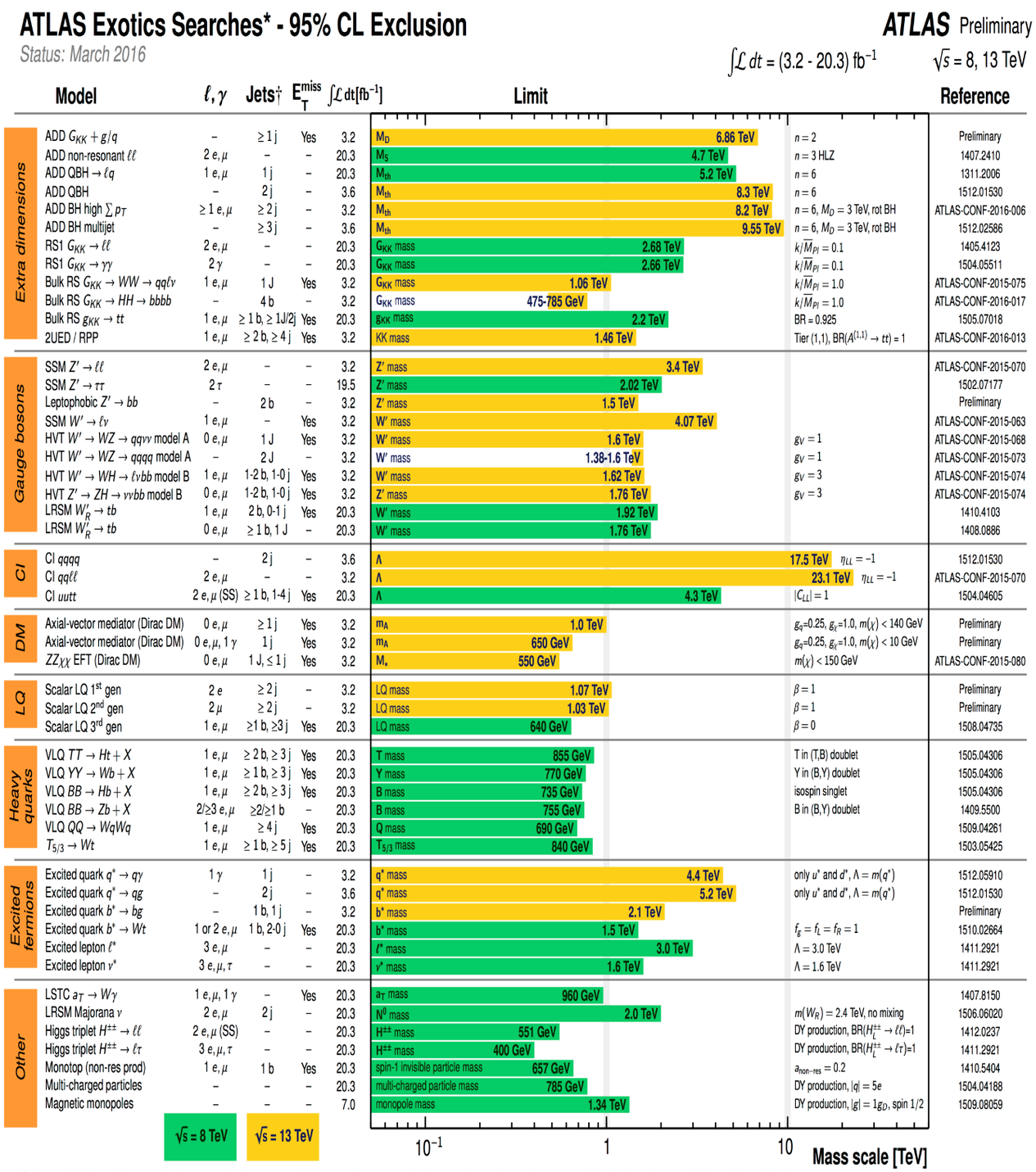

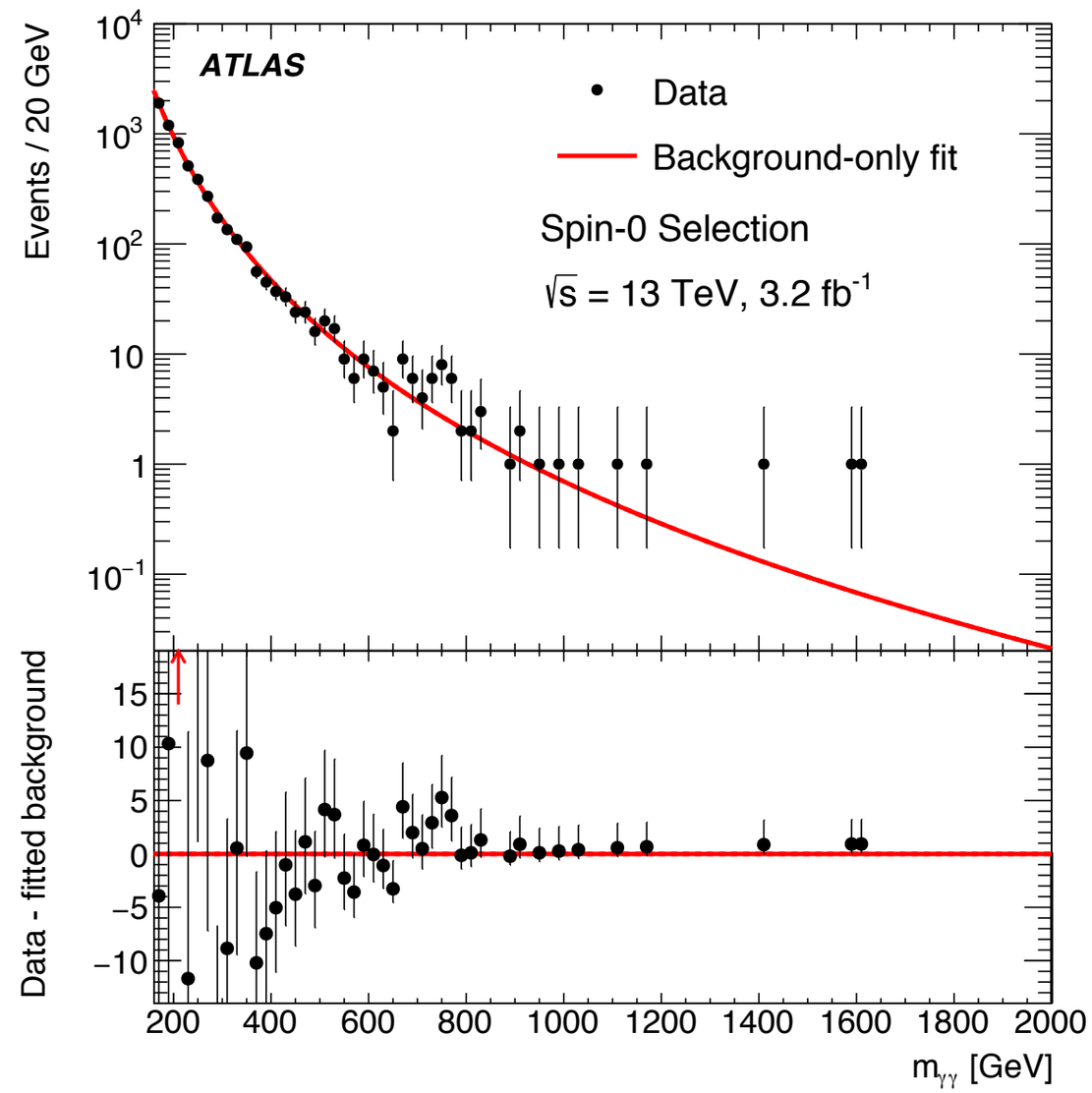

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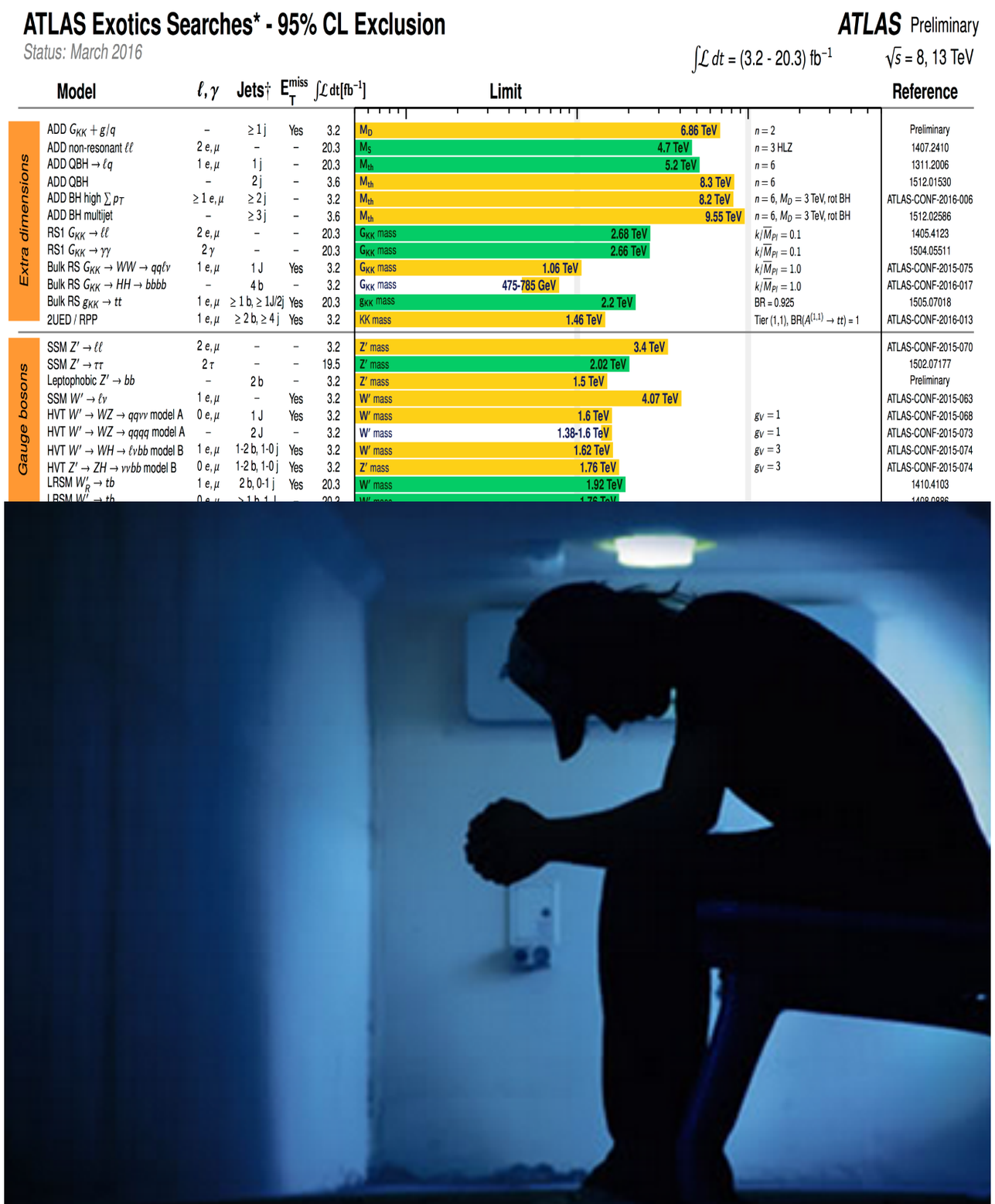

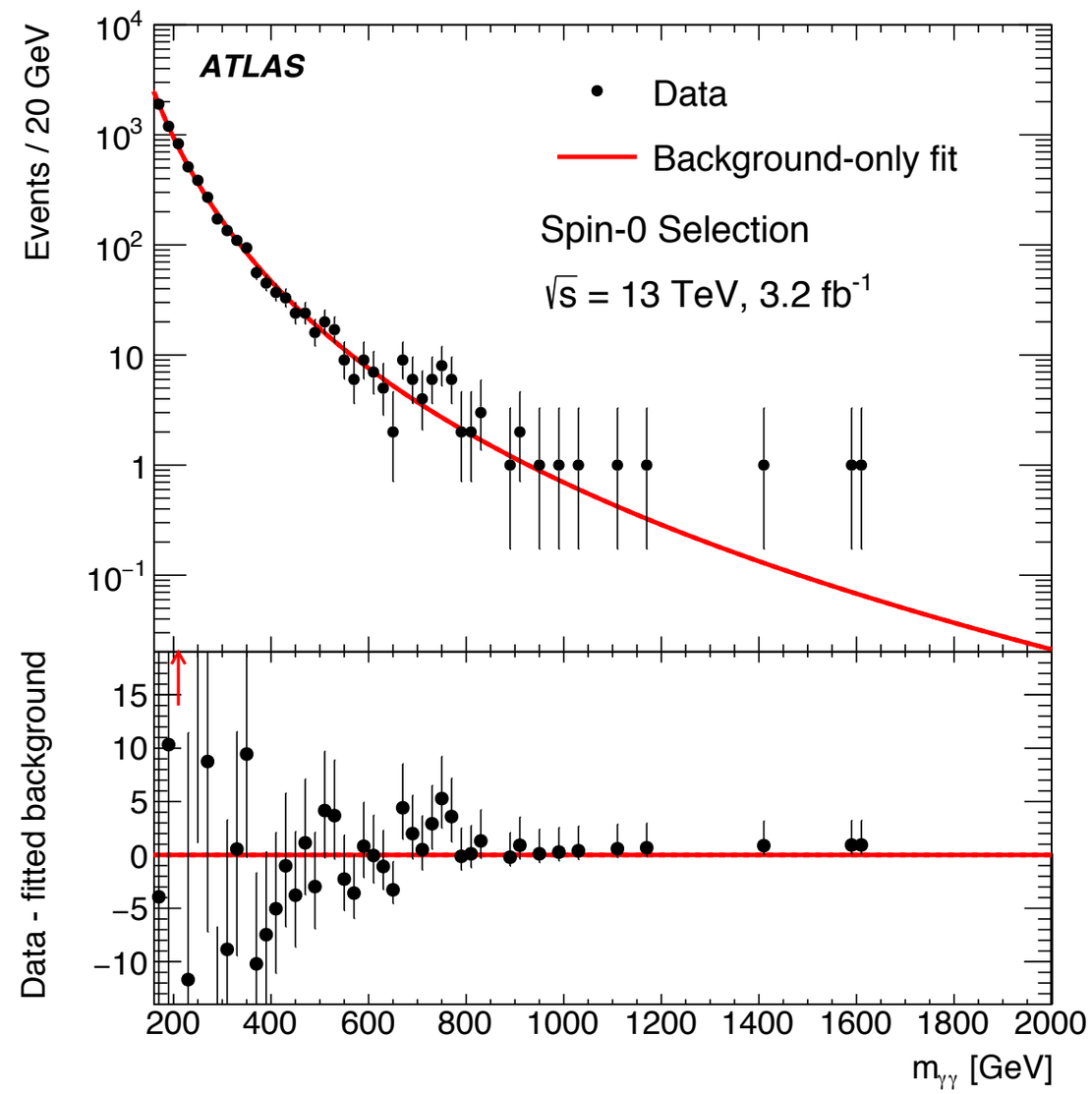

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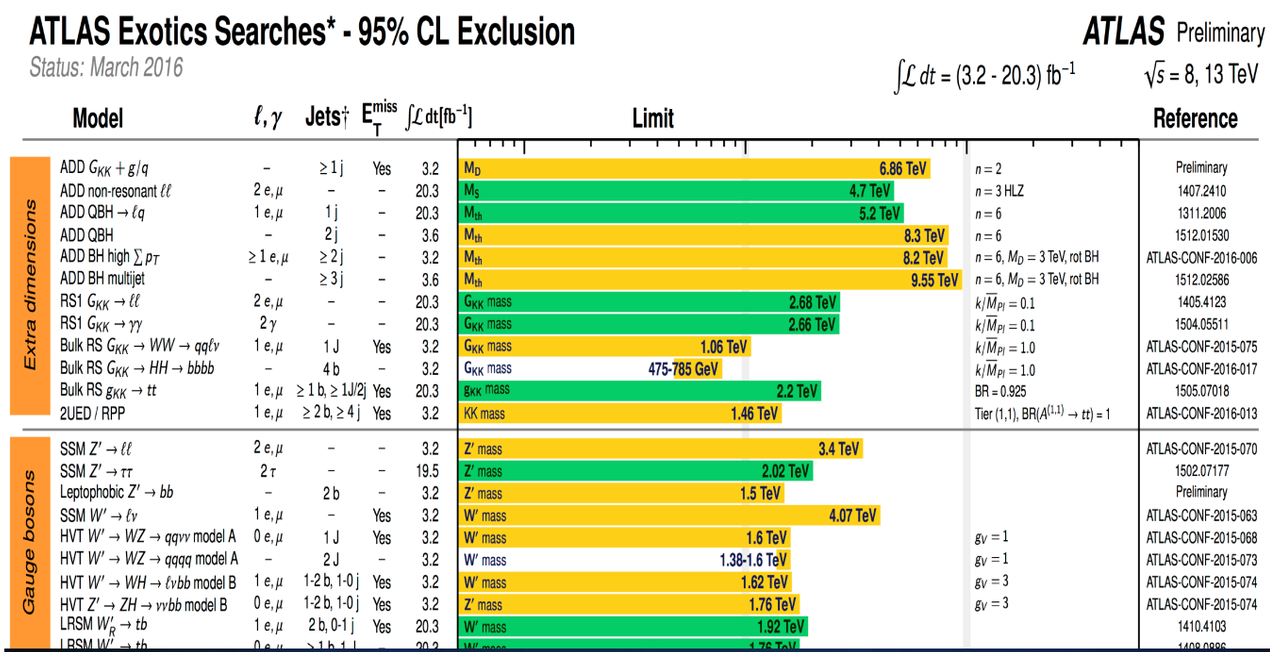
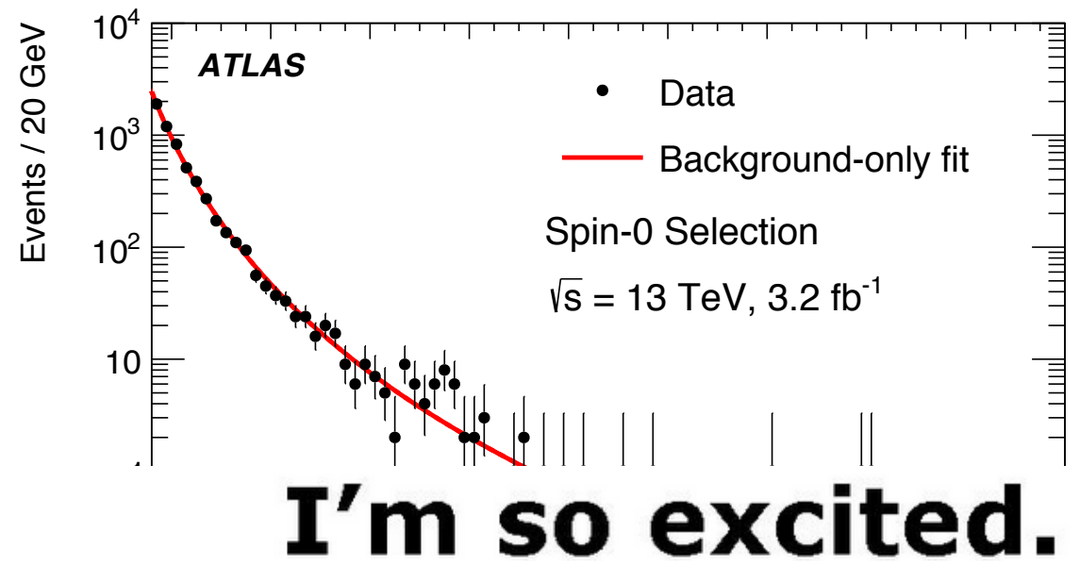


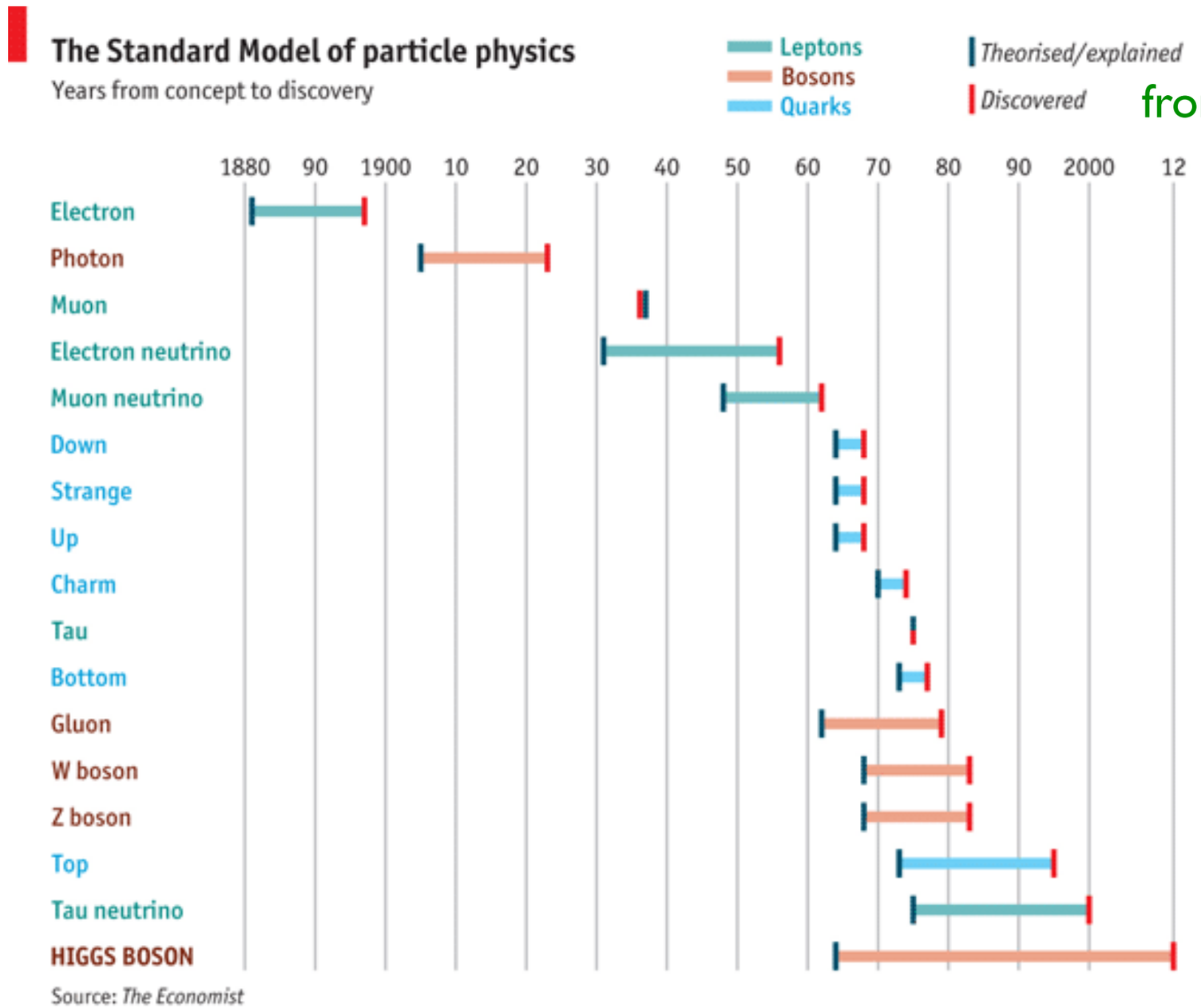


I'm so excited.

http://livethegoodlifewithsara.com

Next Particle from Colliders, When?

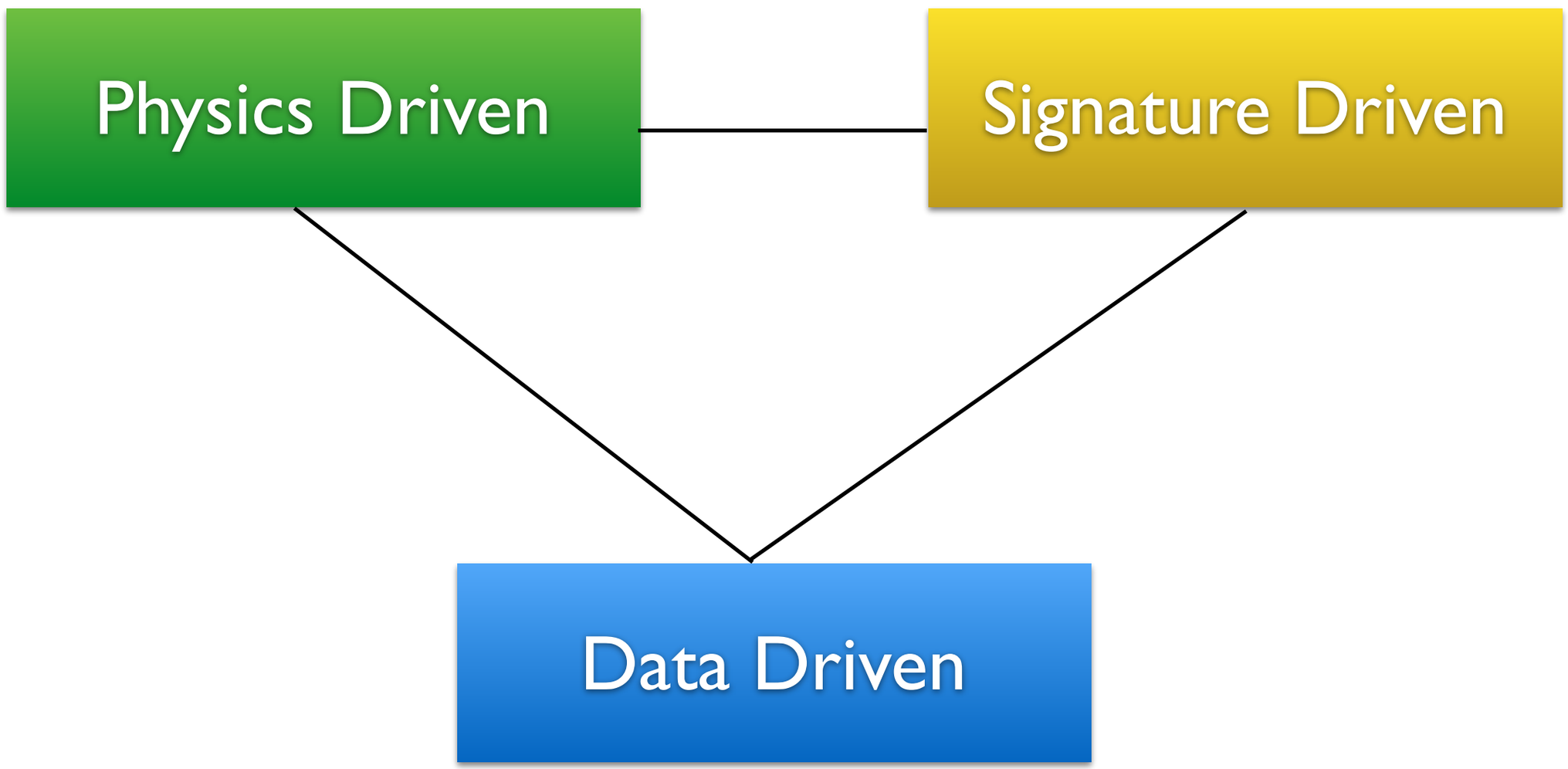
- **Longer time interval between theory and experiment.**



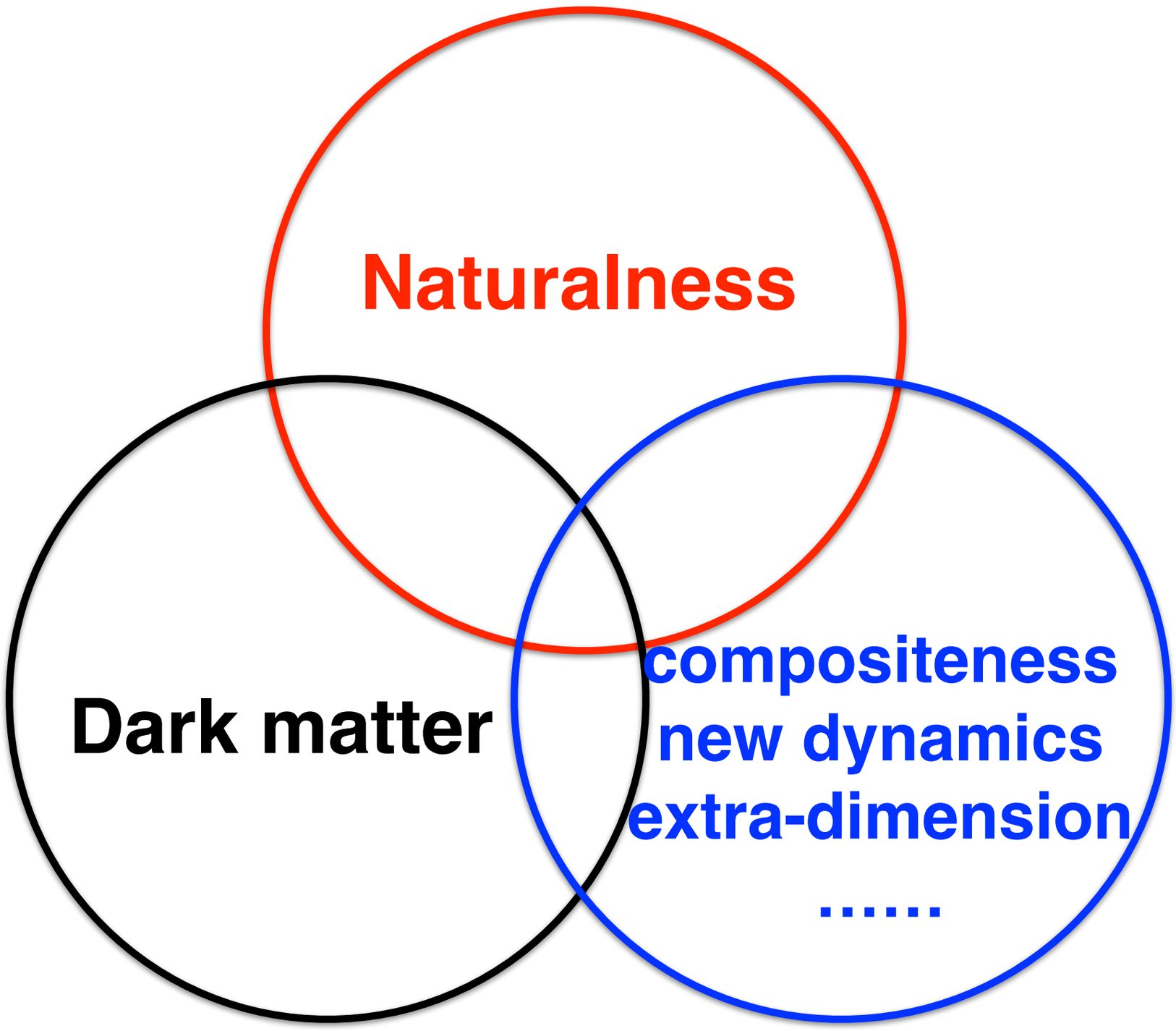
from "The Economist"

- **The LHC Run 2 just starts. Worth the wait.**

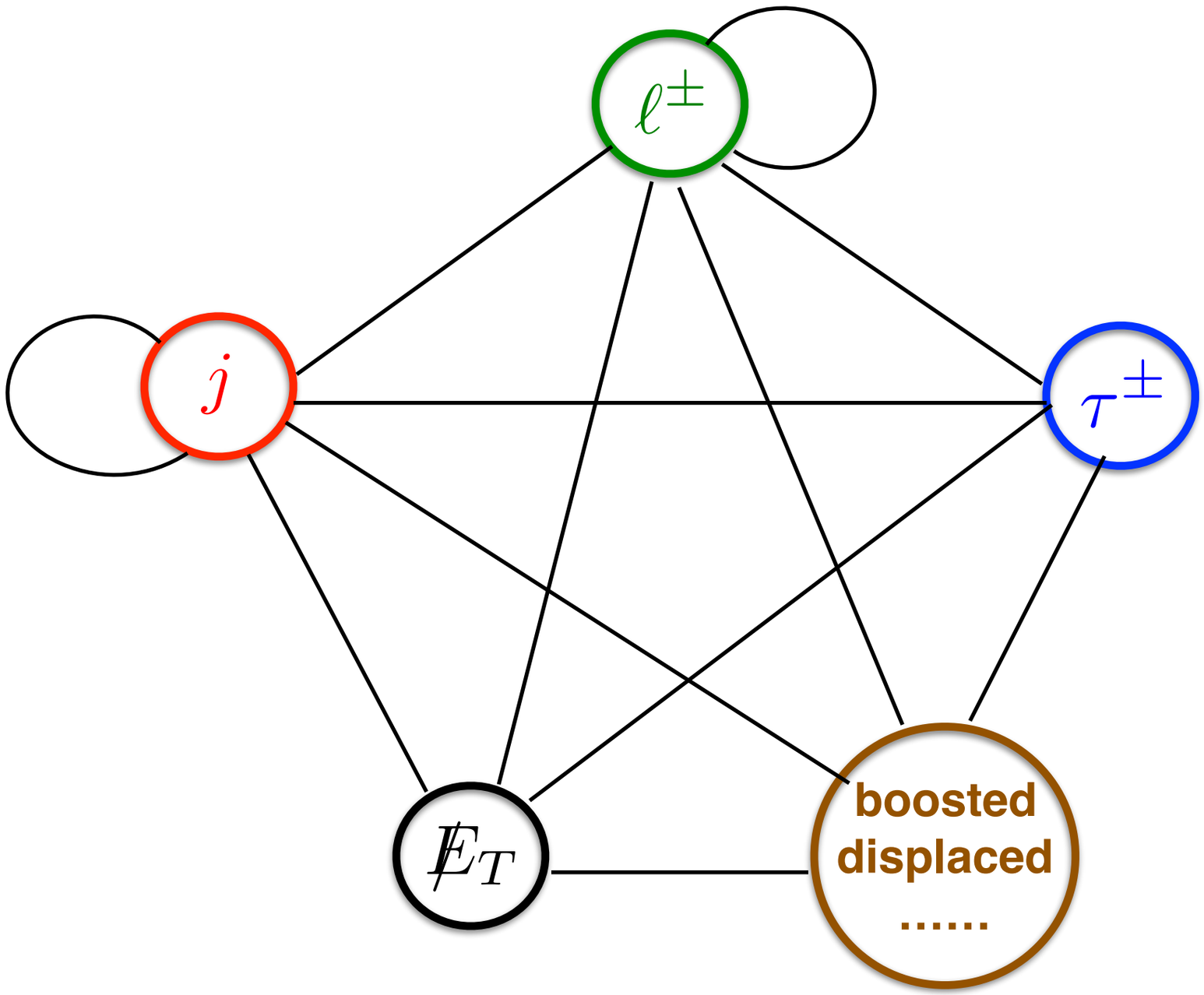
The Road to New Physics



Physics Driven



Signature Driven



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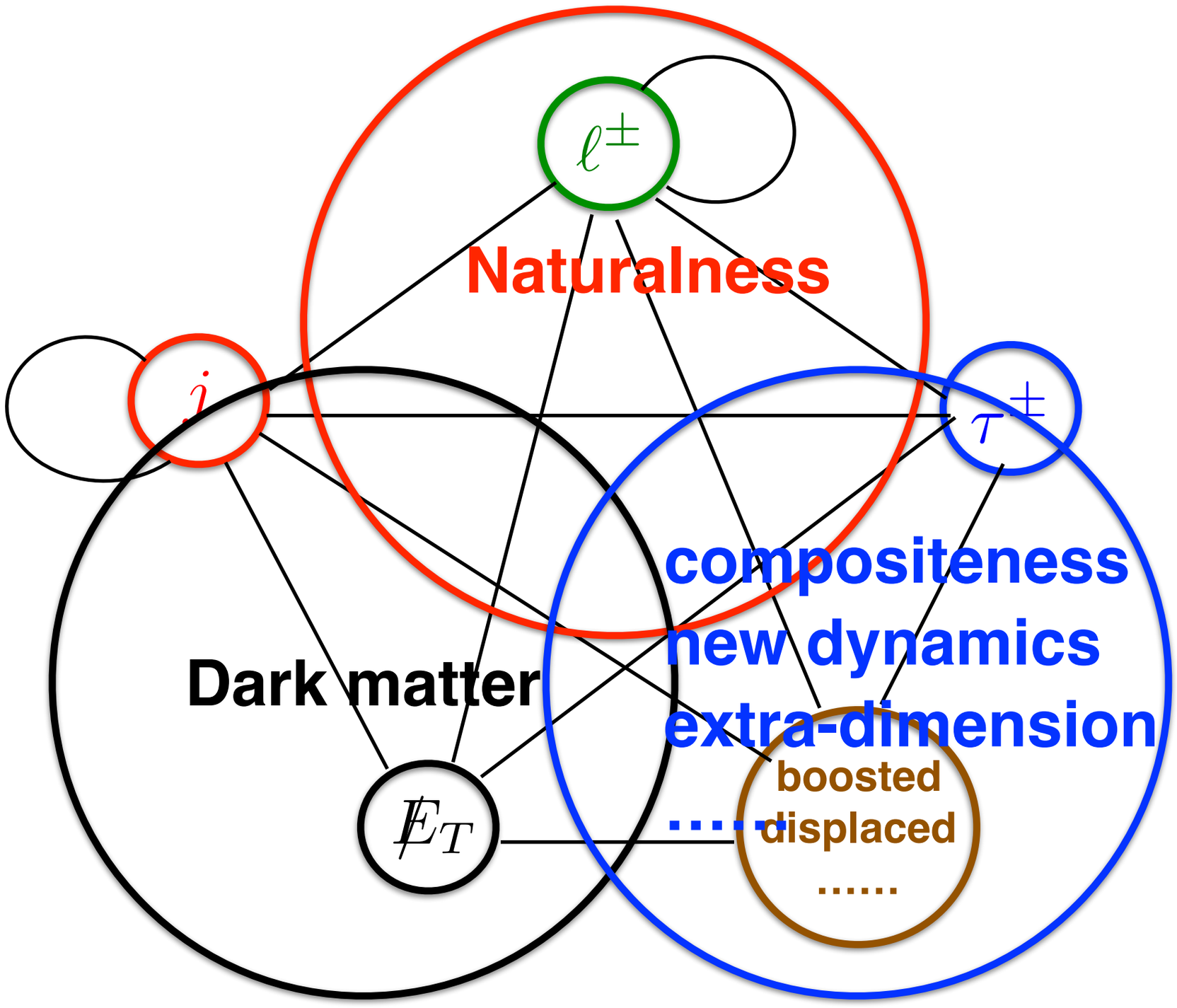
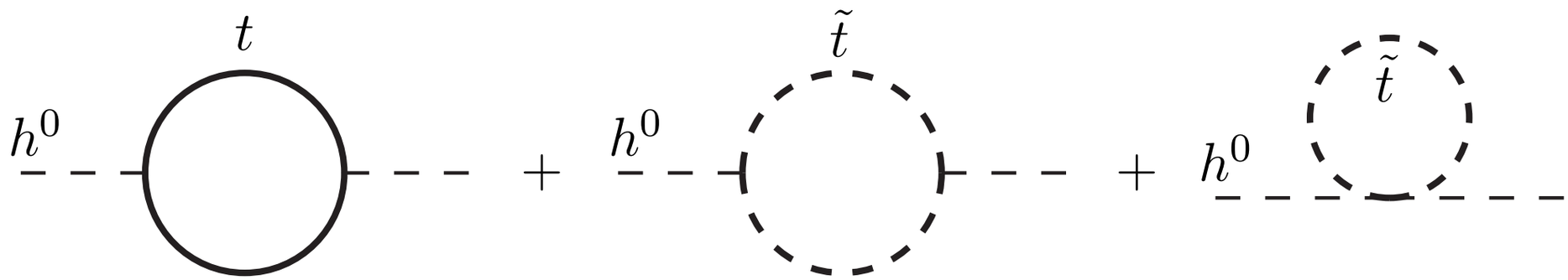
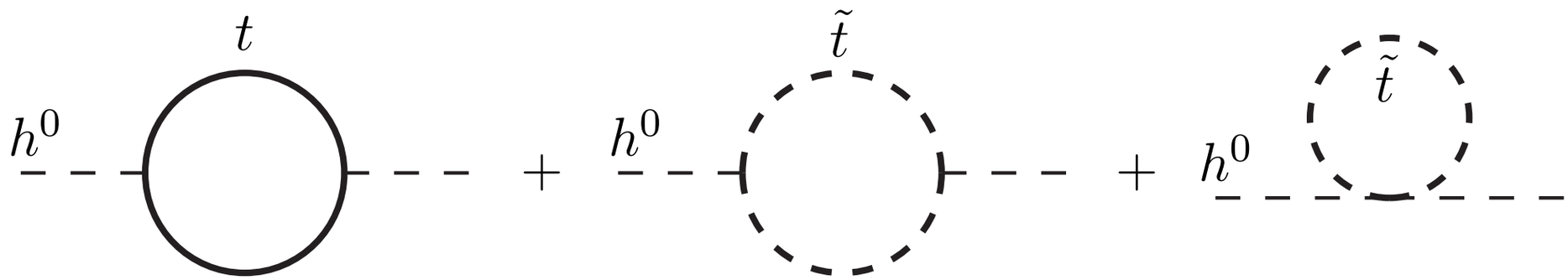


Naturalness



- **The new physics scale is generically at ~TeV**
- **The LHC Run 2 will be the right one to discover them**

Naturalness



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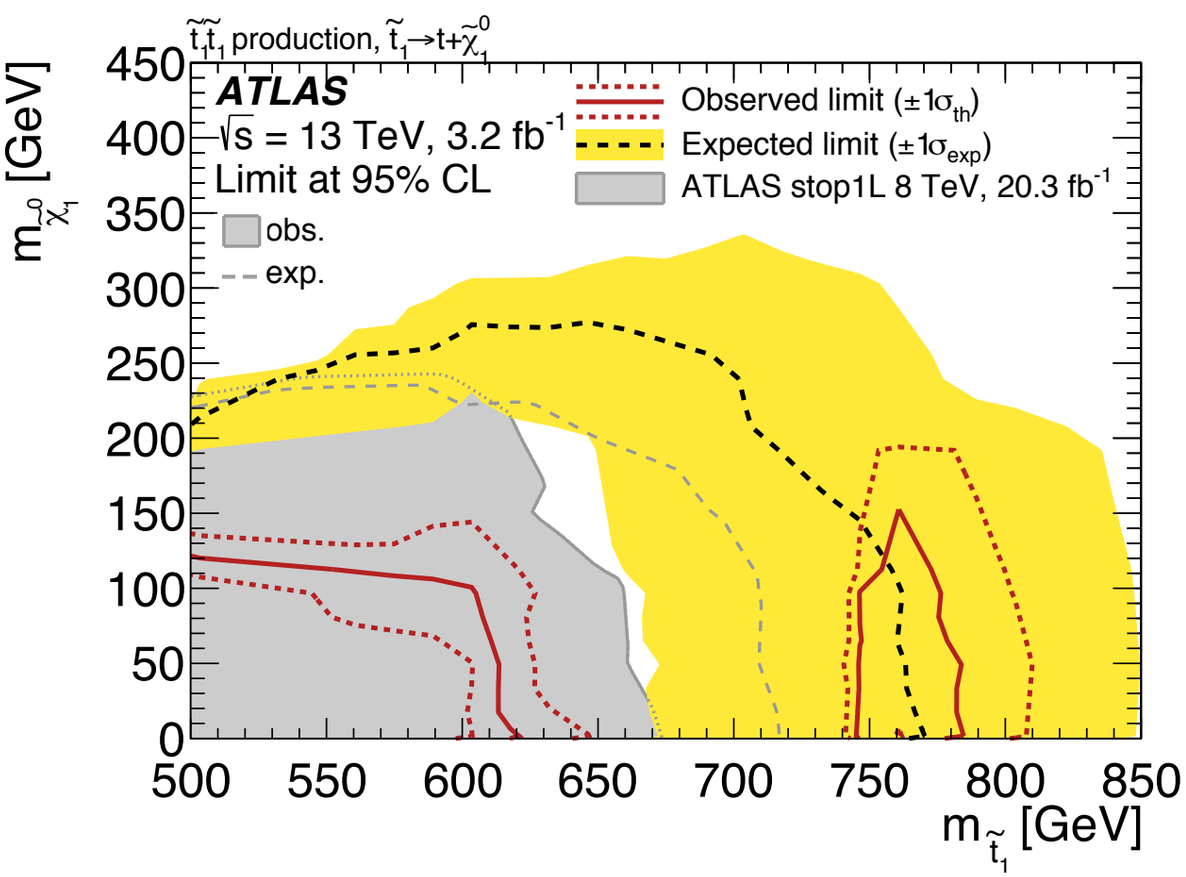

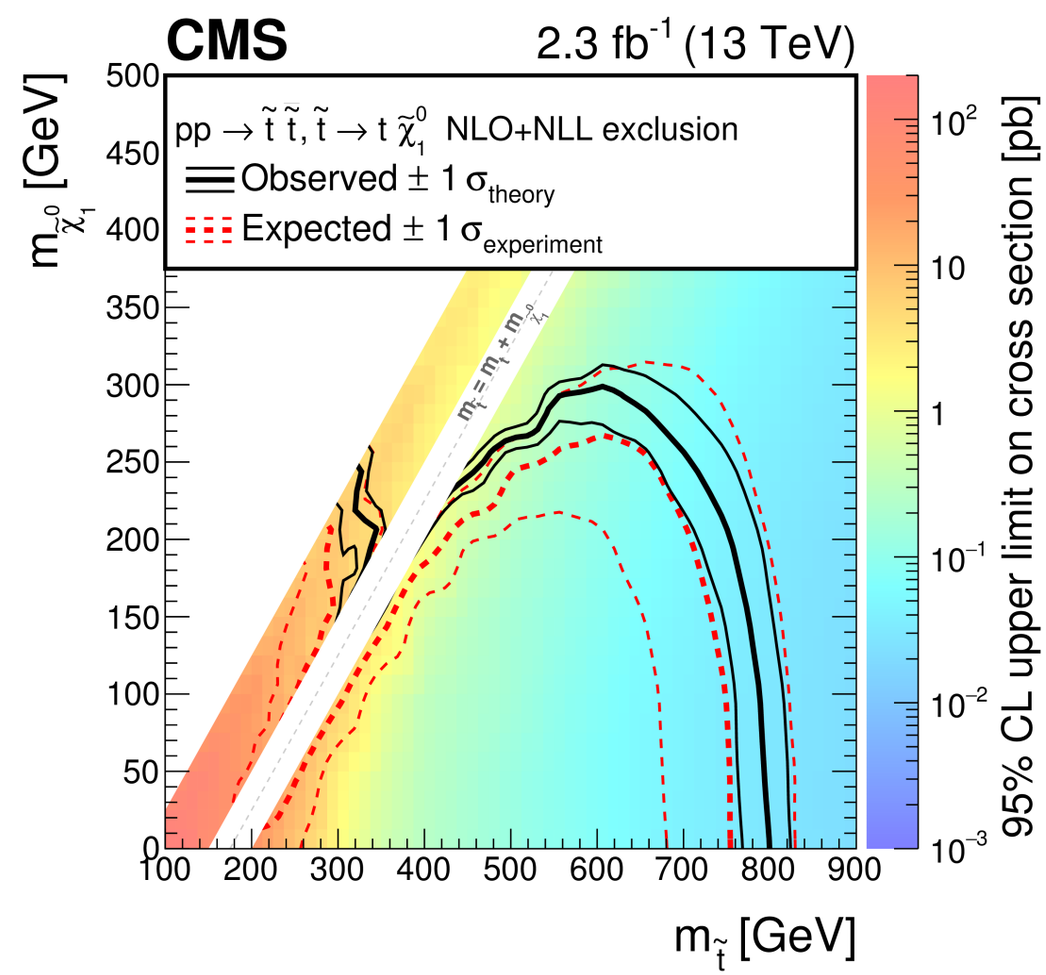

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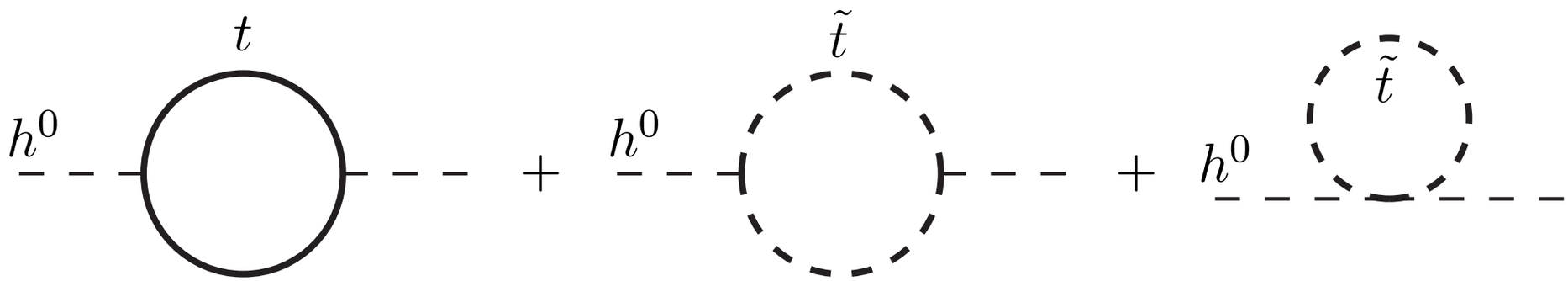

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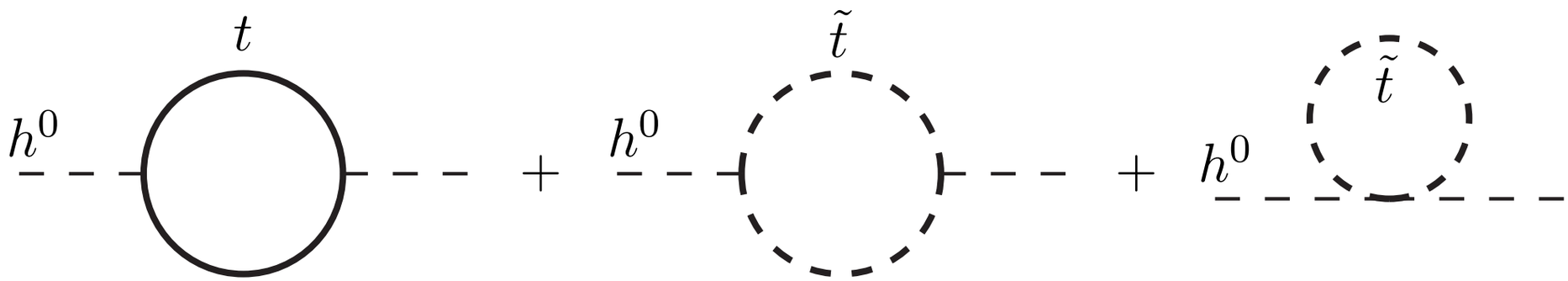
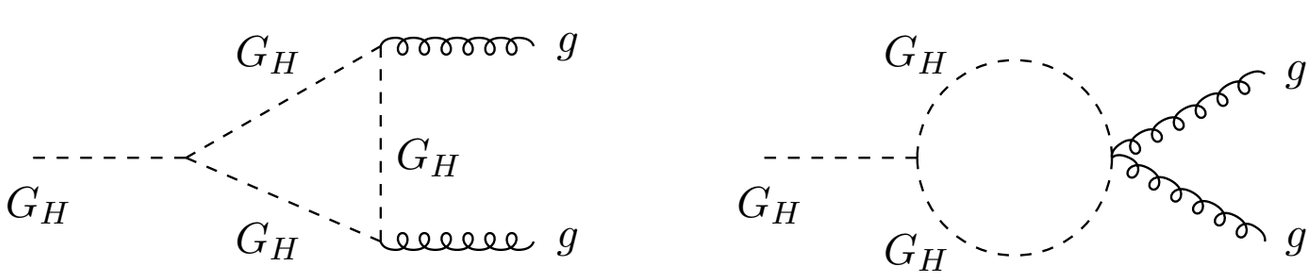


- **The new physics scale is generically at ~TeV**
- **The LHC Run 2 will be the right one to discover them**

- **Hope Nature will not have a meta tuning such that the LHC is just below the threshold**



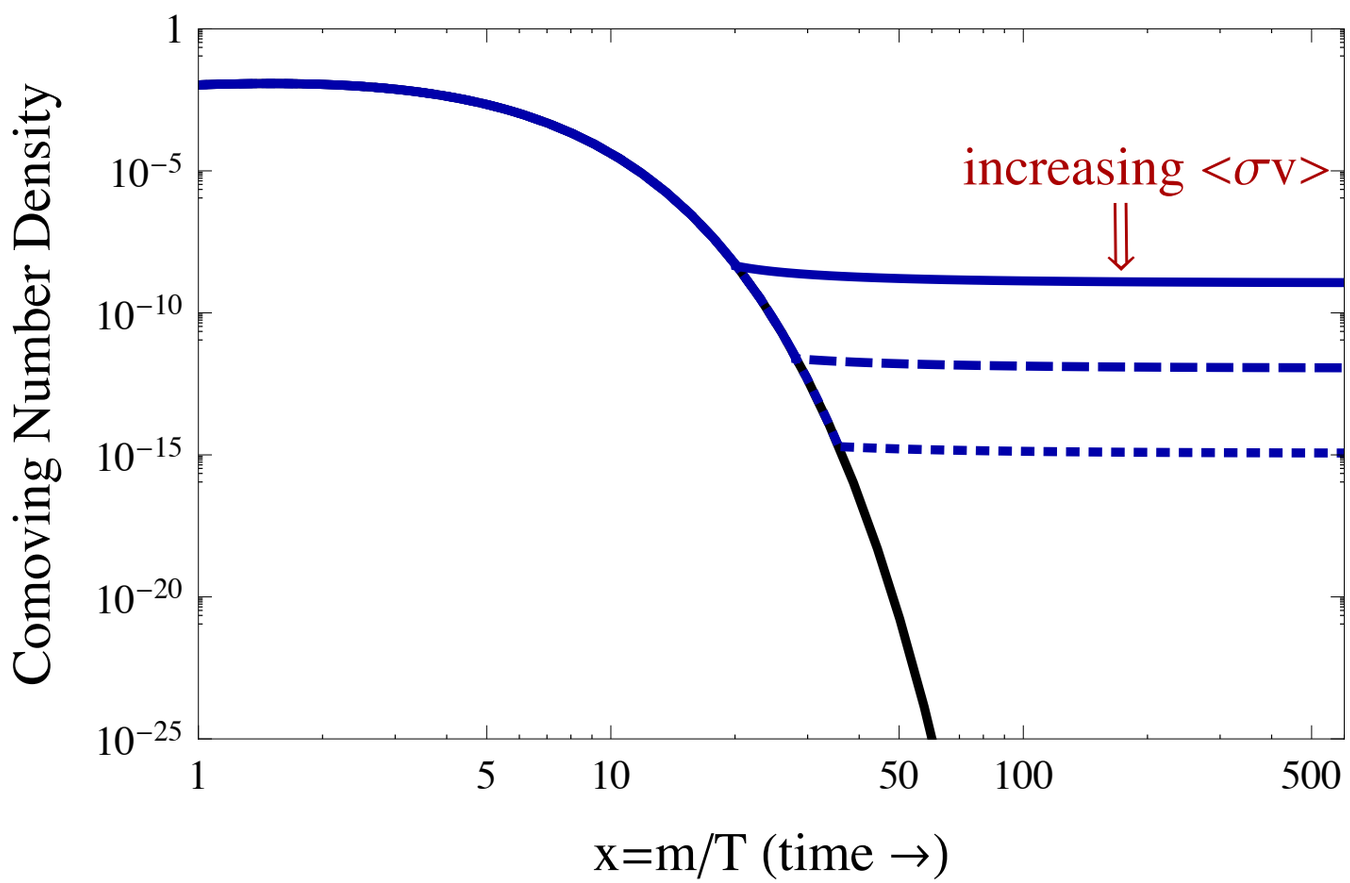
$$\Gamma_0(G_H \to gg) = \frac{15\,\alpha_s^2\,\mu_G^2}{128\,\pi^3\,M_{G_H}}\left(\frac{\pi^2}{9}-1\right)^2 = 0.0093$$

YB, Dobrescu, 1012.5814

1% tuning

Dark Matter — "WIMP Miracle"

- **WIMP miracle is well motived. The dark matter is related to the electroweak scale. The discrete symmetry making dark matter stable is a byproduct of solving other problems like proton decay or electroweak precision measurement.**



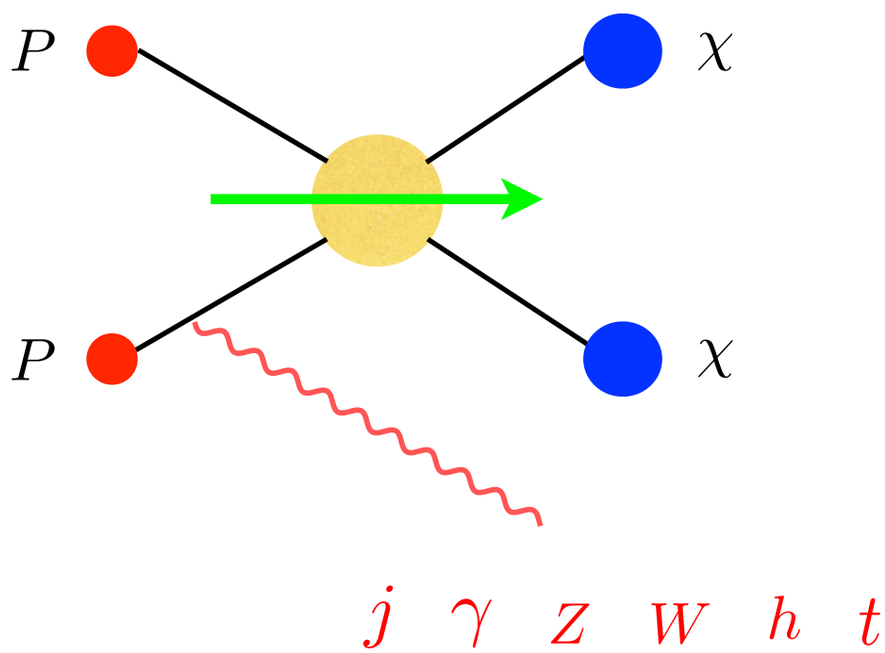
$$\Omega_{\rm DM} \sim \langle \sigma_A\, v \rangle^{-1} \;+\; \langle \sigma_A\, v \rangle \sim \frac{\alpha^2}{m_\chi^2}$$

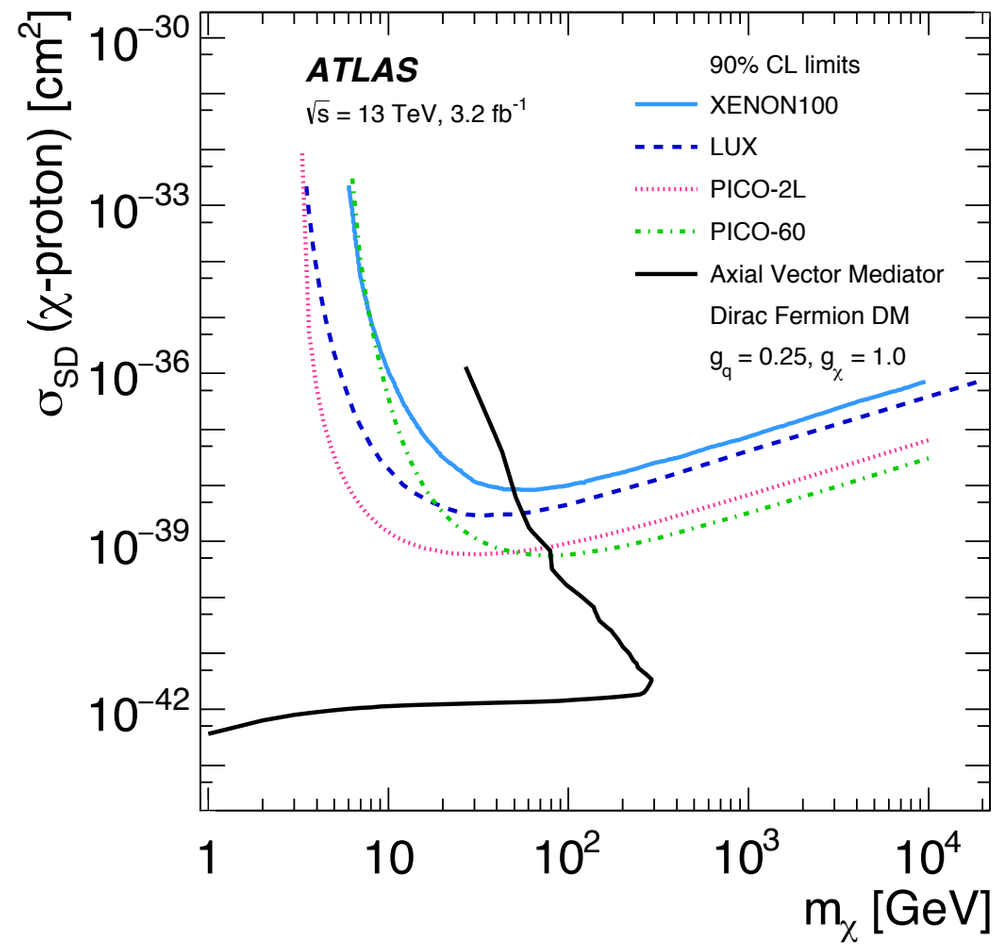
$$m_\chi \sim 100 \text{ GeV} \sim \text{W mass}$$

- **It does point out to a generic scale for dark matter mass and interactions.**

WIMP at the LHC

- **Mono-X + Missing Et as a generic signature.**



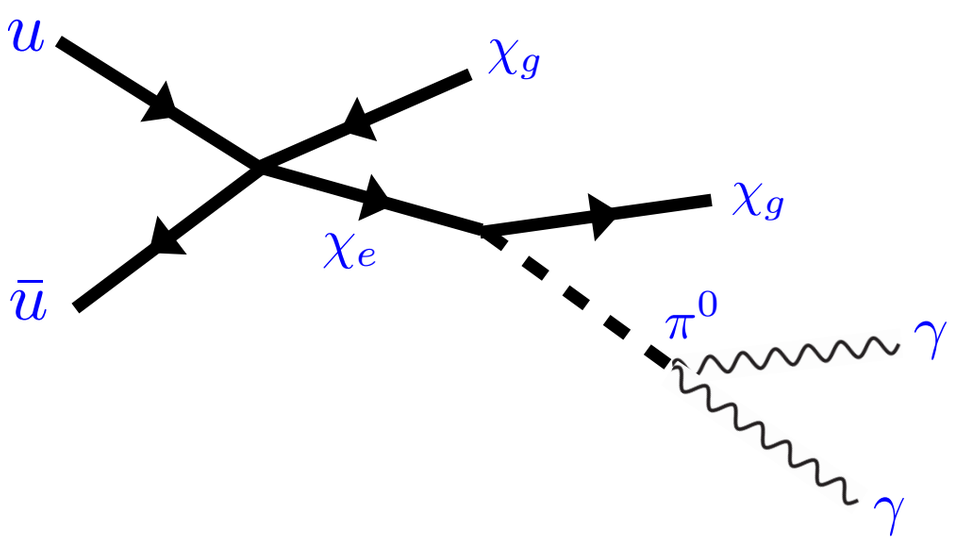


- **To have a better theoretic description, simplified dark matter models will be explored more at the LHC Run 2. See the report from ATLAS/CMS dark matter forum, 1507.00966.**

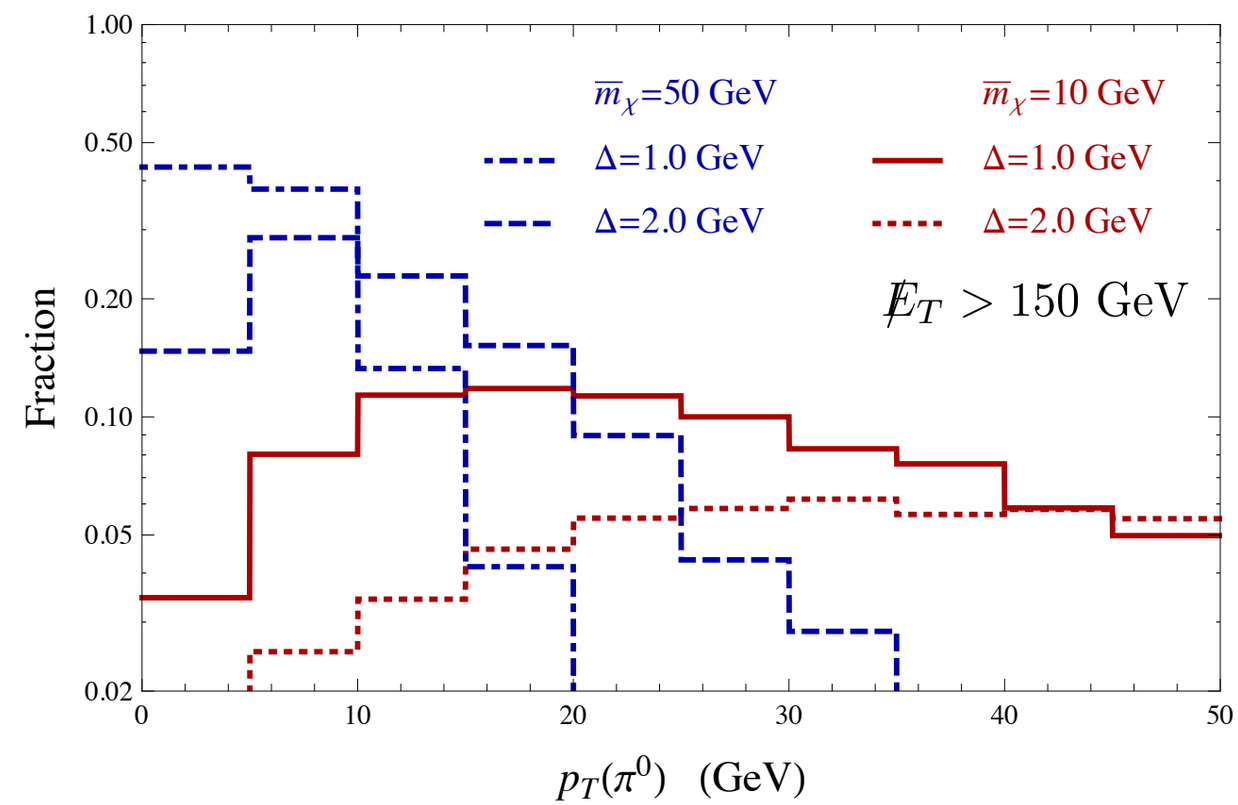
Inelastic Dark Matter

- **Inelastic dark matter: the dark matter interacts with SM together with its excited state. If the mass splitting is above 1 MeV, there is no direct detection signal, but the LHC can still search for it.**

$$\frac{\bar{u}\,\gamma_\mu\gamma_5\,u\,\bar{\chi}_e\,\gamma^\mu\gamma_5\,\chi_g}{\Lambda_1^2}$$



YB, Tait, 1109.4144
Izaguirre, Krnjaic, Shuve, 1508.03050

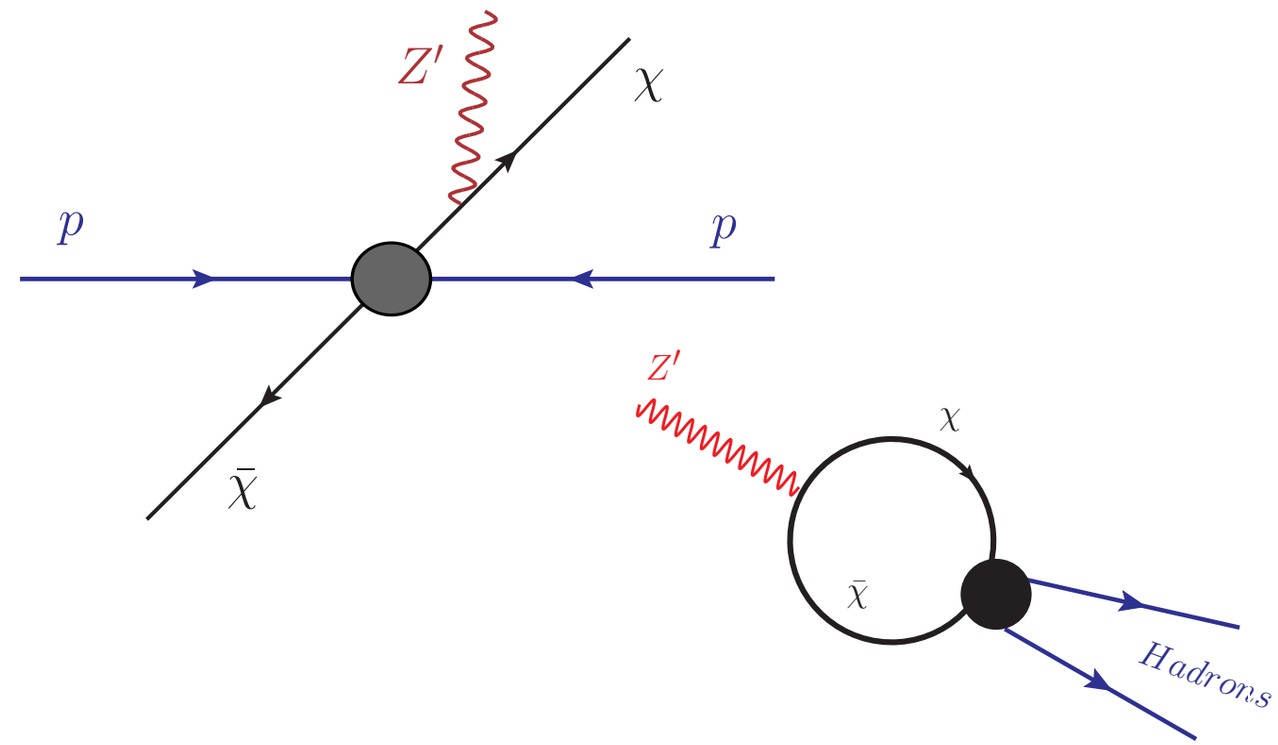


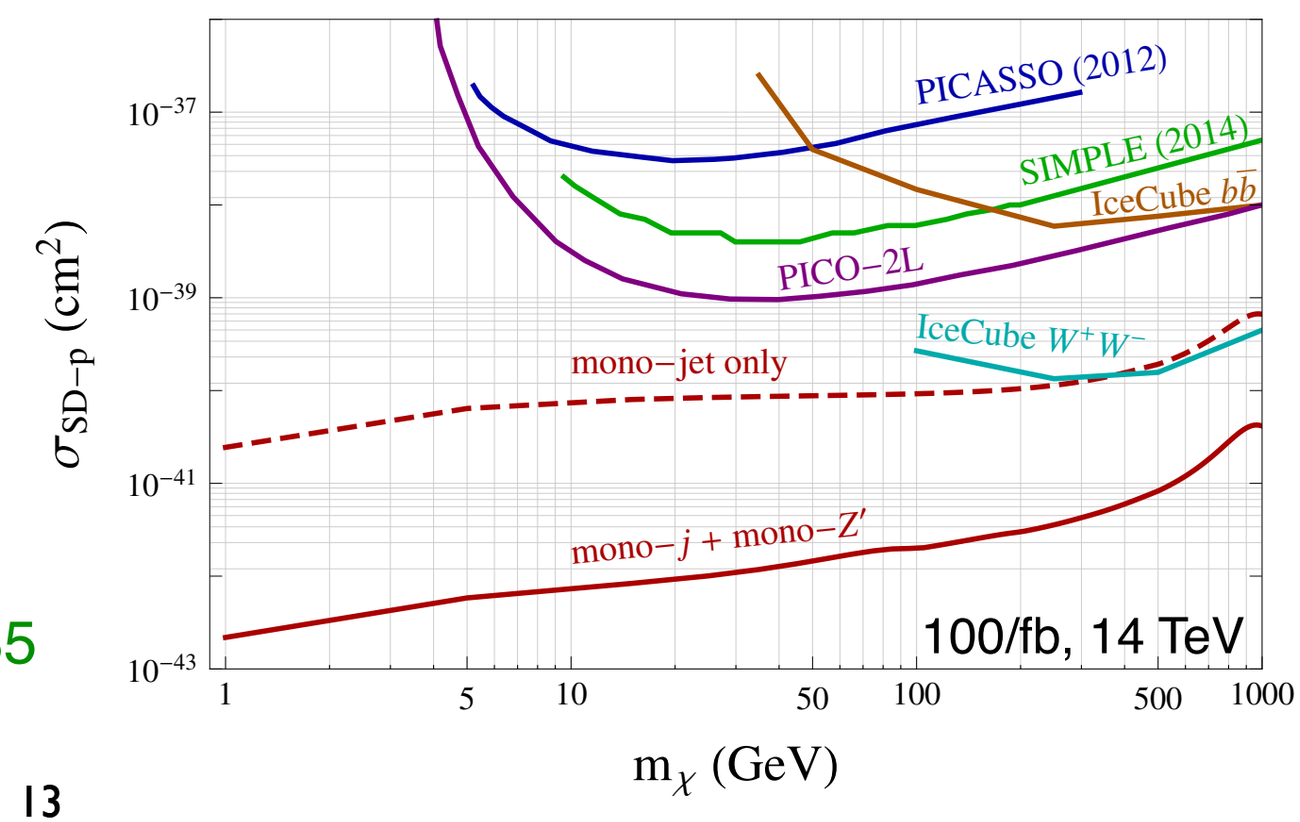
- **The signature is mono-jet plus displaced pions**

Dark Matter FSR

- Dark matter may have its own forces. It can radiate its force carrier from final state radiation.
- Given the hope that dark matter can be produced at the LHC and couple to Z'. The corresponding Z' must decay into hadrons.
- For a light Z', one could search for mono-Zprime jet.

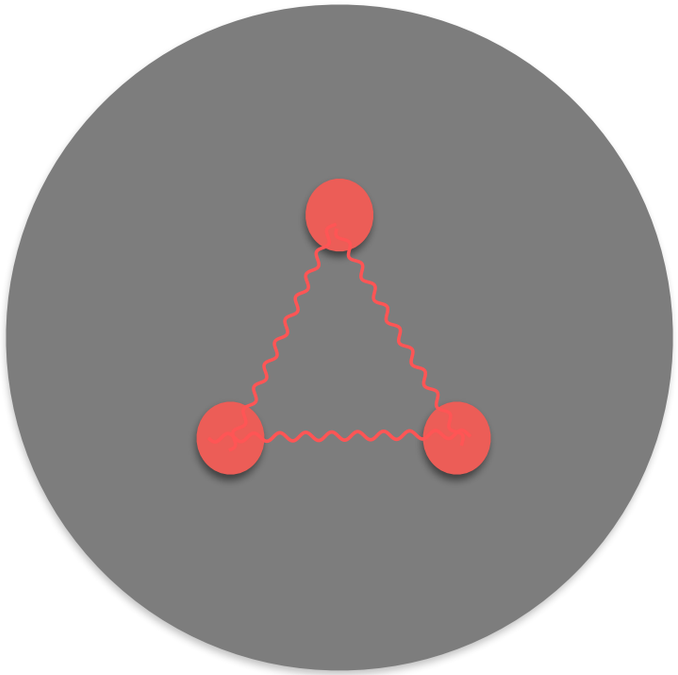
YB, Bourbeau, Lin, 1504.01395
Gupta, Primulando, Saraswat, 1504.01385

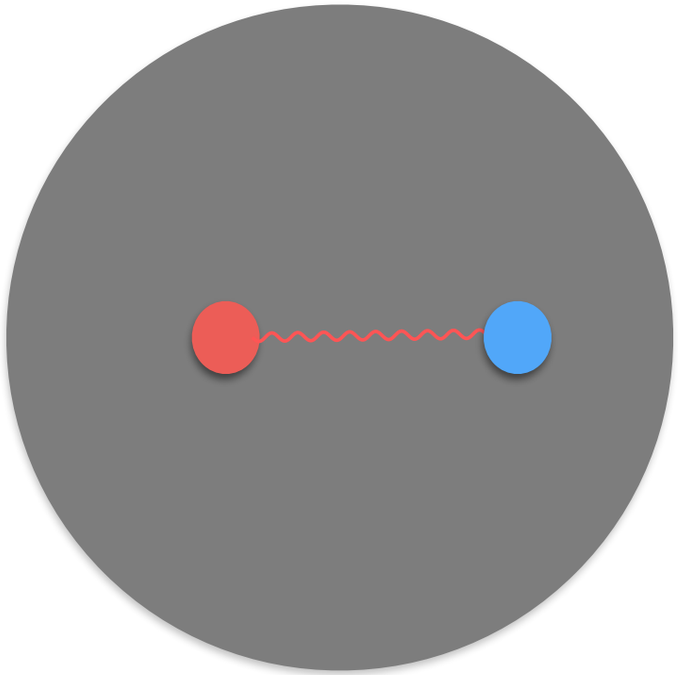




Composite Dark Matter

- **The ordinary matter has proton and neutron as composite particles. QCD is responsible for around 95% of ordinary matter mass.**
- **The dark matter sector could also have its own QCD-like dynamics. The dark matter could be an (asymmetric) dark baryon or a (symmetric) dark pion.**





Nussinov ’1985; Bahr, Chivukula, Fahre ’1990; …; YB, Schwaller, 1306.4676; Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727; Appelquist et.al. (LSD), 1503.04203; Antipin, Redi, Strumia, Vigiani, 1503.08749; Kribs, Neil, 1604.04627

Dark Baryon

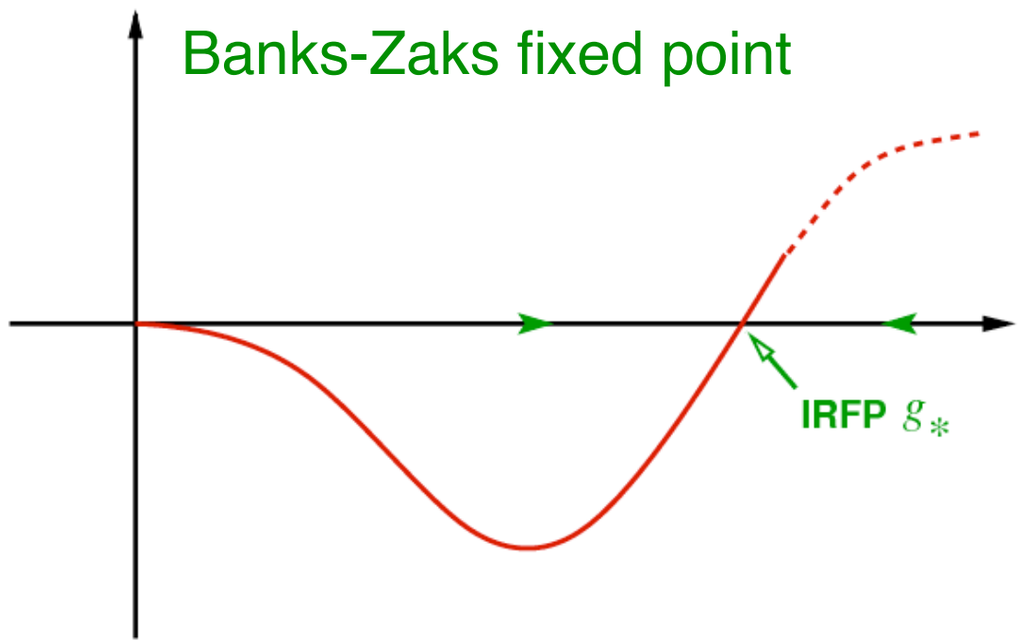
$$\frac{\Omega_{\rm DM}}{\Omega_{\rm Baryon}} = \frac{m_{\rm DM} n_{\rm DM}}{m_{\rm p} n_p} \approx 5 \sim 6$$

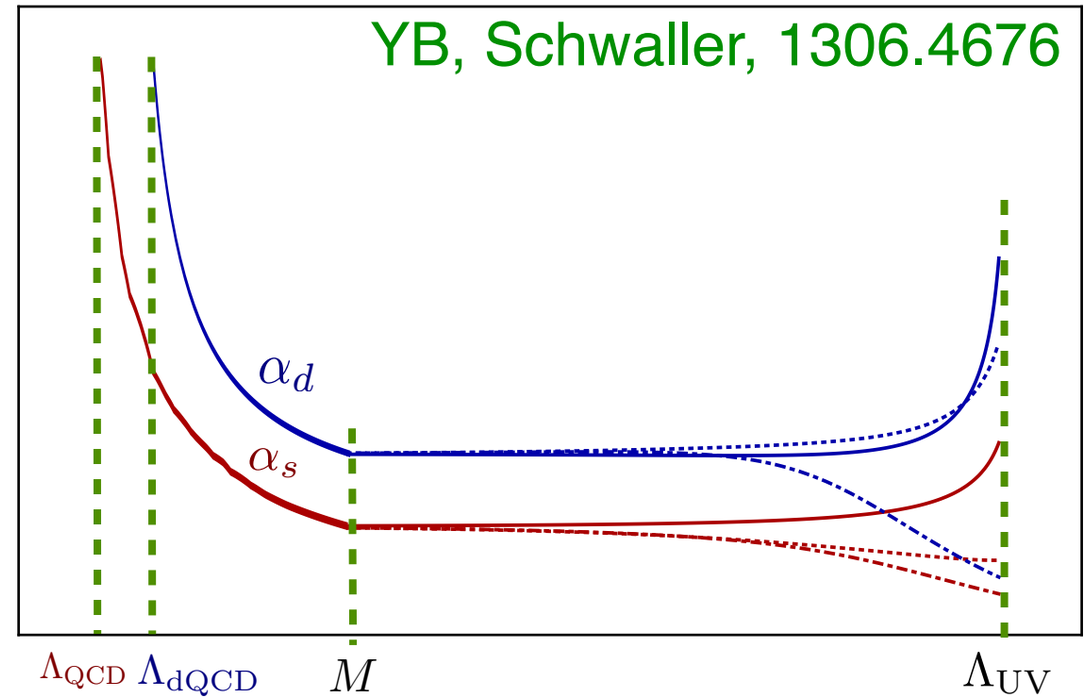
- **Need to satisfy two conditions: (1)** $n_{\rm DM} \sim n_p$ **(2)** $m_{\rm DM} \sim m_p$
- **The first condition can be satisfied by high-scale physics like Leptogenesis to generate similar asymmetries for baryon and dark baryon.**
- **For (2) and if dark matter is a "dark baryon", we need to explain**

$$\Lambda_{\rm dQCD} \sim \Lambda_{\rm QCD} \sim v_{\rm EW}/100$$

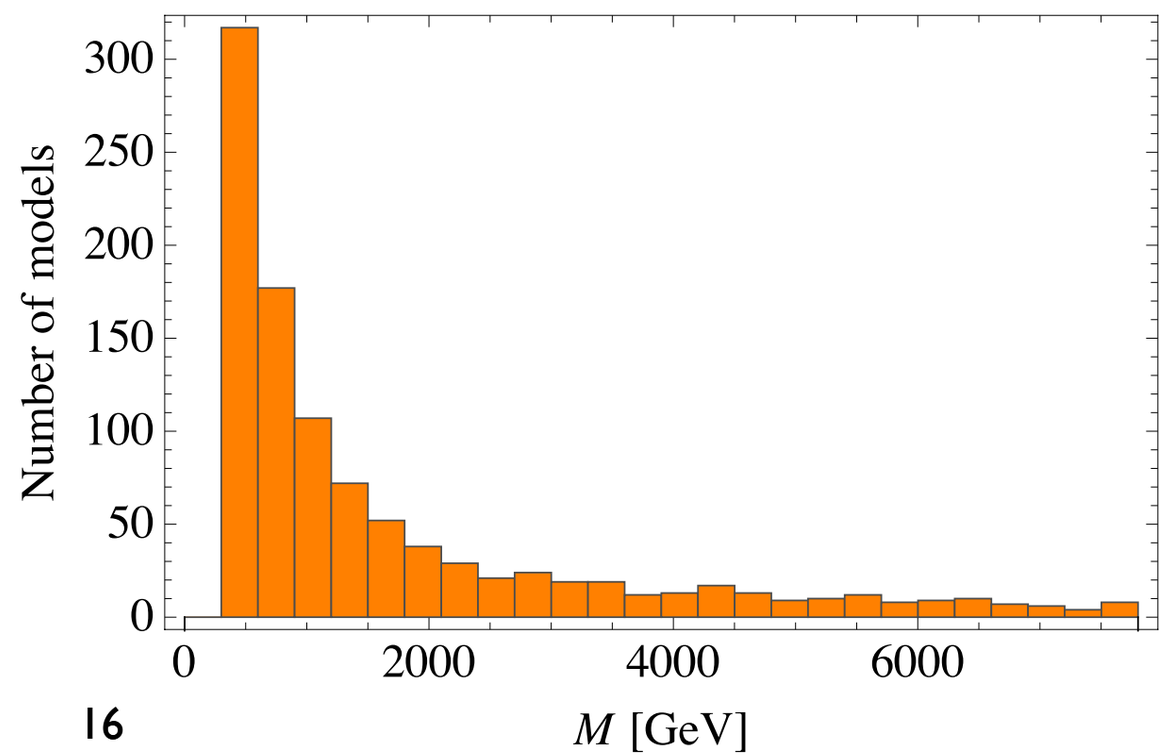
- **Need to have QCD and dQCD gauge couplings related to each other and similar confinement scales.**
- **Or, the dark QCD gauge coupling running knows the electroweak scale.**

Infrared Fixed Point to Relate QCD and dQCD Scales





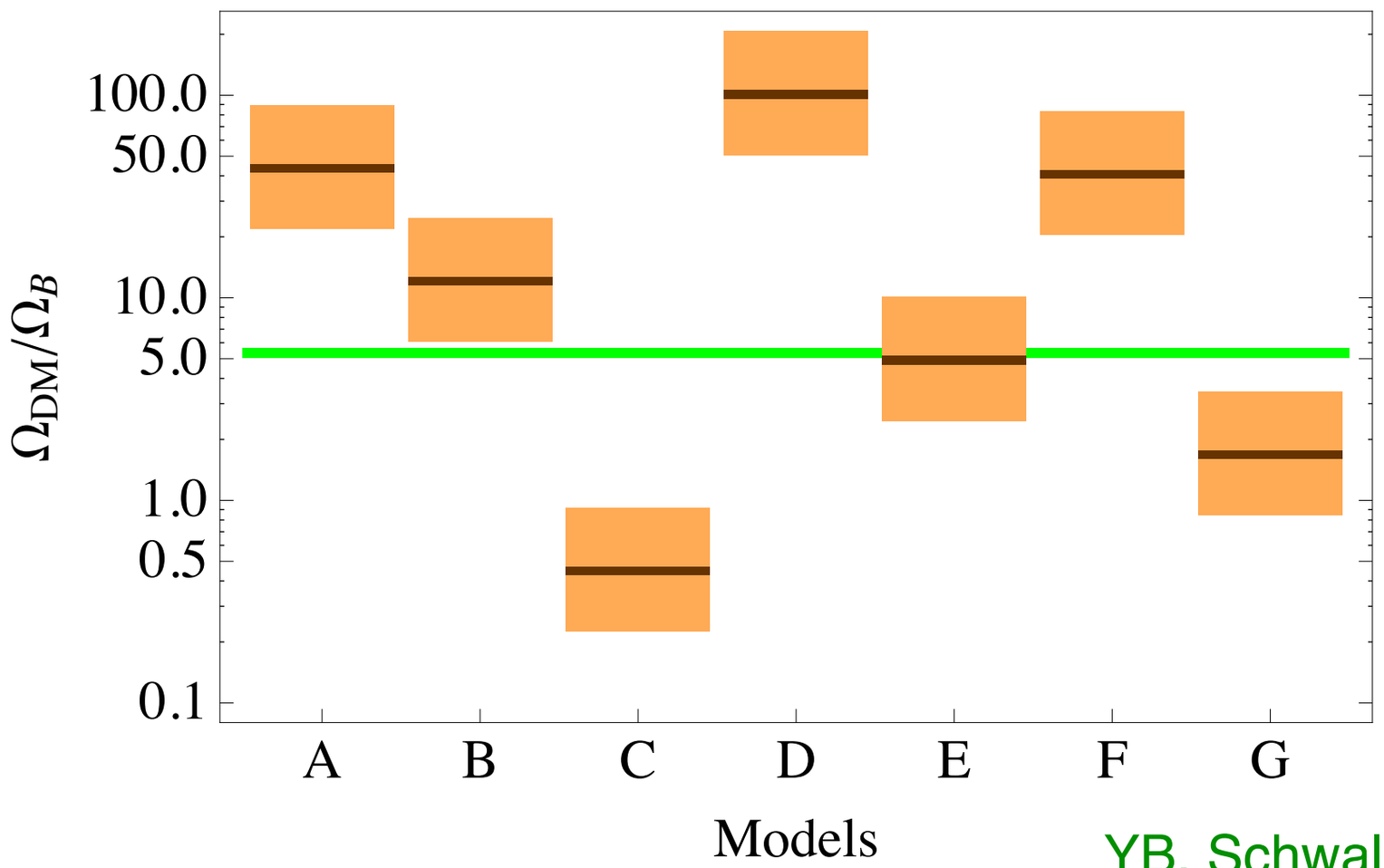
- **The particles bi-fundamental of QCD and dark QCD prefers to have masses below 2 TeV**



Ratios of Energy Densities

- **The bi-fundamental particles can also be used to share the baryon and the dark baryon asymmetries.**

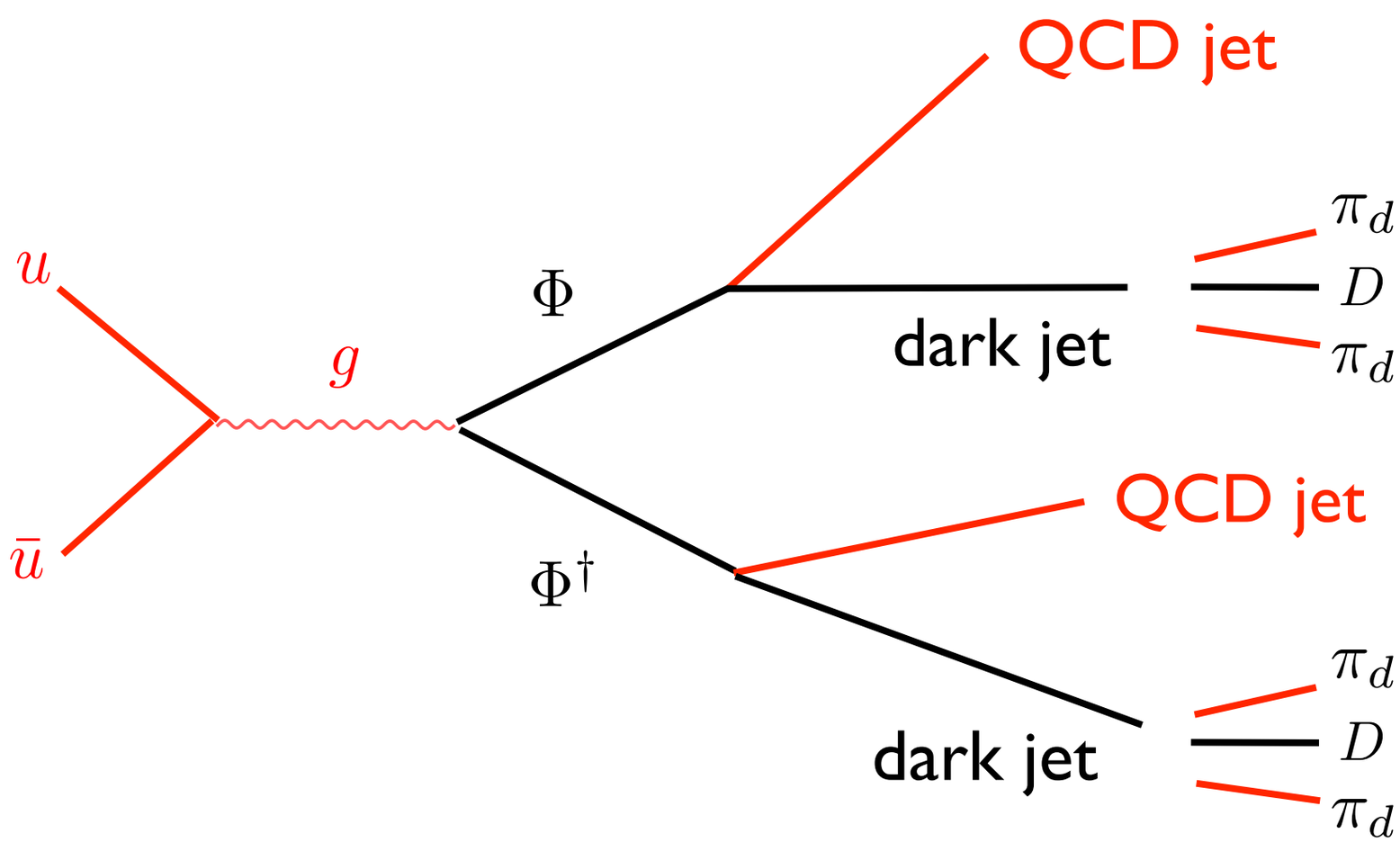
$$\frac{\Omega_{\rm DM}}{\Omega_{\rm Baryon}} = \frac{n_D m_D}{n_B m_p} \approx \frac{79}{56}\frac{m_D}{m_p}$$



YB, Schwaller, 1306.4676

Signatures at the LHC

- **The bi-fundamental particles also mediates the interactions between the two sectors.**



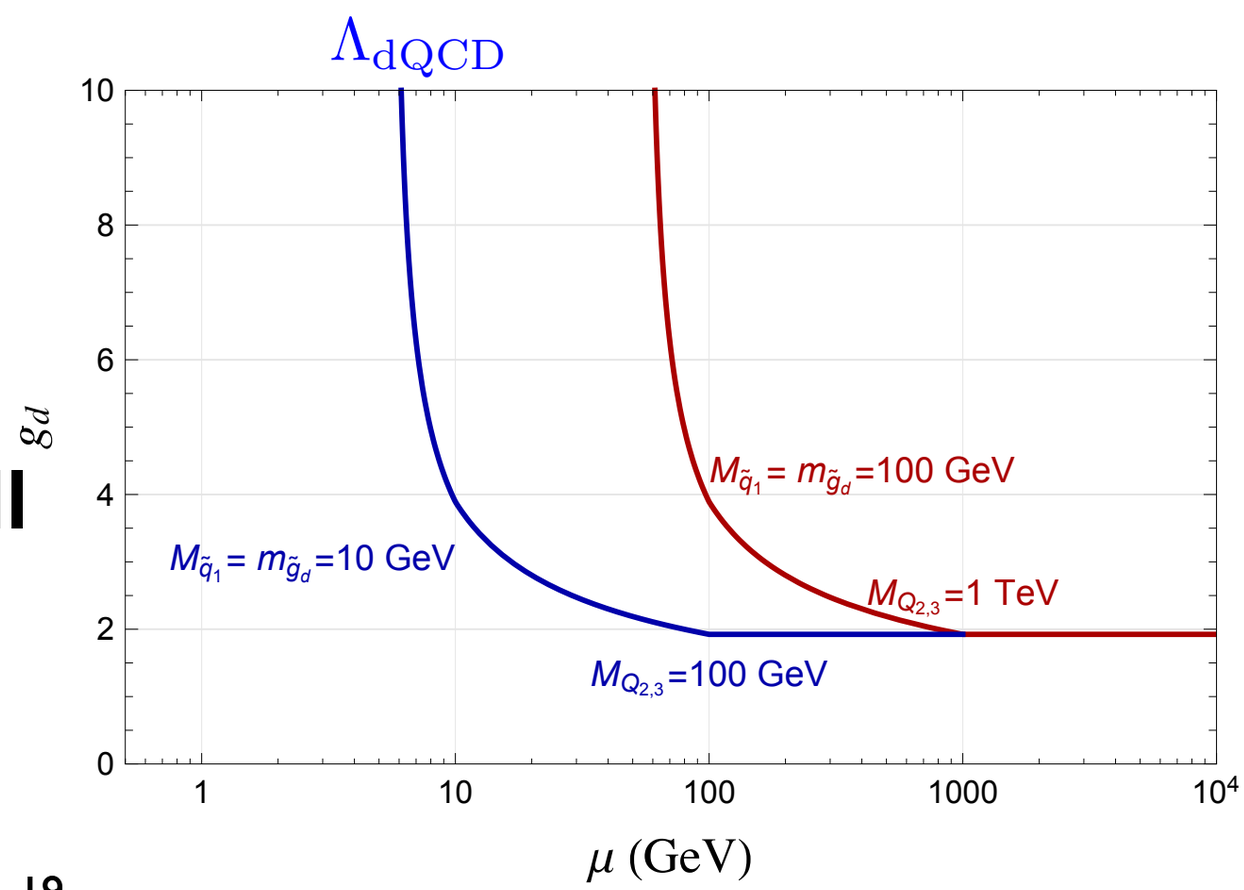
- **The dark pions can decay back to SM particles and are generically long-lived.**

a detailed collider study: Schwaller, Stolarski, Weiler, 1502.05409

Related to the Electroweak Scale

- **The visible sector is NMSSM to accommodate the 125 GeV Higgs boson mass.**
- **The dark matter sector is SUSY-QCD and superconformal at a UV scale. For instance, Nd=3 and Nf=8, the infrared fixed point gauge coupling is known. Some flavors of SQCD get their masses similar to the μ-term in NMSSM.**
- **The SQCD gauge coupling only starts to run below $\mu \sim v_{\rm EW}$**
- **The singlet, S, in NMSSM will be the portal to dark SQCD.**

YB, Joshua Berger, work in progress



Dark Pion as a WIMP

- **Different from the dark baryon case, an additional symmetry is needed to make one or more dark pion stable.**

There is one less familiar discrete symmetry

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

π^0

$$I^G(J^{PC}) = 1^-(0^{-+})$$

Mass $m = 134.9766 \pm 0.0006$ MeV (S = 1.1)
$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV
Mean life $\tau = (8.4 \pm 0.6) \times 10^{-17}$ s (S = 3.0)
$c\tau = 25.1$ nm

The G-parity is defined to be:

$$G = \mathcal{C} \exp[i\pi I_2]$$

$$\pi^0 \xrightarrow{G} -\pi^0 \qquad \pi^\pm \xrightarrow{G} -\pi^\pm$$

Michel '1953
Lee and Yang '1956

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Michel '1953
Lee and Yang '1956

$$\pi^0 \xrightarrow{G} -\pi^0 \qquad \pi^\pm \xrightarrow{G} -\pi^\pm$$

- **In the SM, the specific hypercharge or EW charge assignment explicitly breaks the G-parity in our QCD sector. So, the neutral pion can decay into two photons. In the dQCD, the G-parity could be unbroken.**

YB, Hill, 1003.3006

Dark Pion as a WIMP

- **The dark G-parity is charge-conjugation times** $\psi_1 \leftrightarrow \psi_2$
- **Below the confinement or chiral symmetry breaking scale, we anticipate dark pions in the low-energy spectrum.**

	$SU(N_b)$	$SU(5)_{\rm GUT}$
$(\psi^{\rm D}_{1,L},\ \psi^{\rm L}_{1,L})$	N_b	5
$(\psi^{\rm D}_{1,R},\ \psi^{\rm L}_{1,R})$	N_b	5
$(\psi^{\rm D}_{2,L},\ \psi^{\rm L}_{2,L})$	N_b	$\overline{5}$
$(\psi^{\rm D}_{2,R},\ \psi^{\rm L}_{2,R})$	N_b	$\overline{5}$

- **There totally 99 new heavy pions:** YB, Lu, Berger, 1512.05779

$$\mathbf{10} \times \mathbf{10} - \mathbf{1} \;=\; \mathbf{24}^+ + \mathbf{24}^- + \mathbf{1}^- + \mathbf{10} + \mathbf{15} + \overline{\mathbf{10}} + \overline{\mathbf{15}}$$

$$\mathbf{24}^+ \;=\; (\mathbf{1},\mathbf{1})^+_{\mathbf{0}} + (\mathbf{3},\mathbf{1})^+_{\mathbf{0}} + (\mathbf{2},\mathbf{3})^+_{\mathbf{-5/6}} + (\mathbf{2},\overline{\mathbf{3}})^+_{\mathbf{5/6}} + (\mathbf{1},\mathbf{8})^+_{\mathbf{0}}$$

$$\mathbf{24}^- \;=\; (\mathbf{1},\mathbf{1})^-_{\mathbf{0}} + (\mathbf{3},\mathbf{1})^-_{\mathbf{0}} + (\mathbf{2},\mathbf{3})^-_{\mathbf{-5/6}} + (\mathbf{2},\overline{\mathbf{3}})^-_{\mathbf{5/6}} + (\mathbf{1},\mathbf{8})^-_{\mathbf{0}}$$

- **The dark-G-even SM singlet,** $(1,1)^+_0$ **, could be the 750 GeV diphoton resonance.**
- **There are two dark-G-odd SM singlets, either of them could be the WIMP.**

G-parity-odd Dark Pion

YB, Lu, Berger, 1512.05779

- **The WIMP sits in the (612, 750) GeV mass window**, with the lower bound just from group structure:

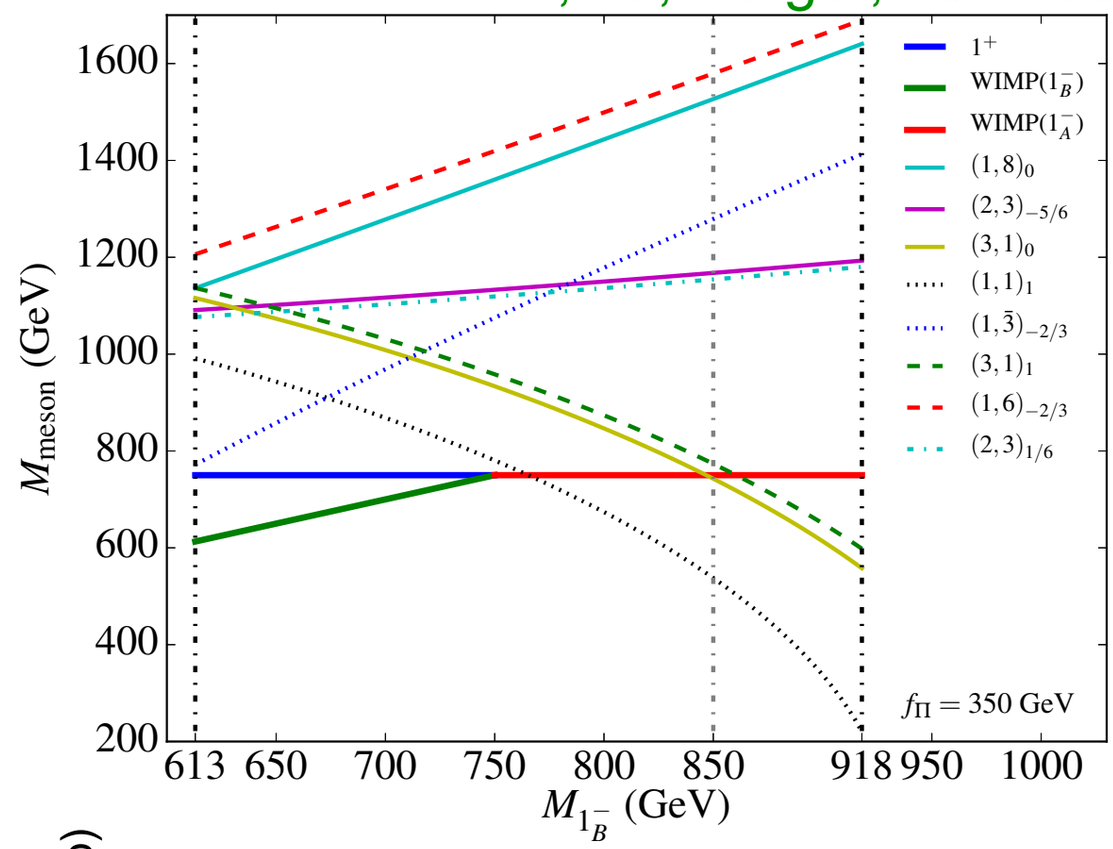
$$\sqrt{2/3} \times 750 = 612$$

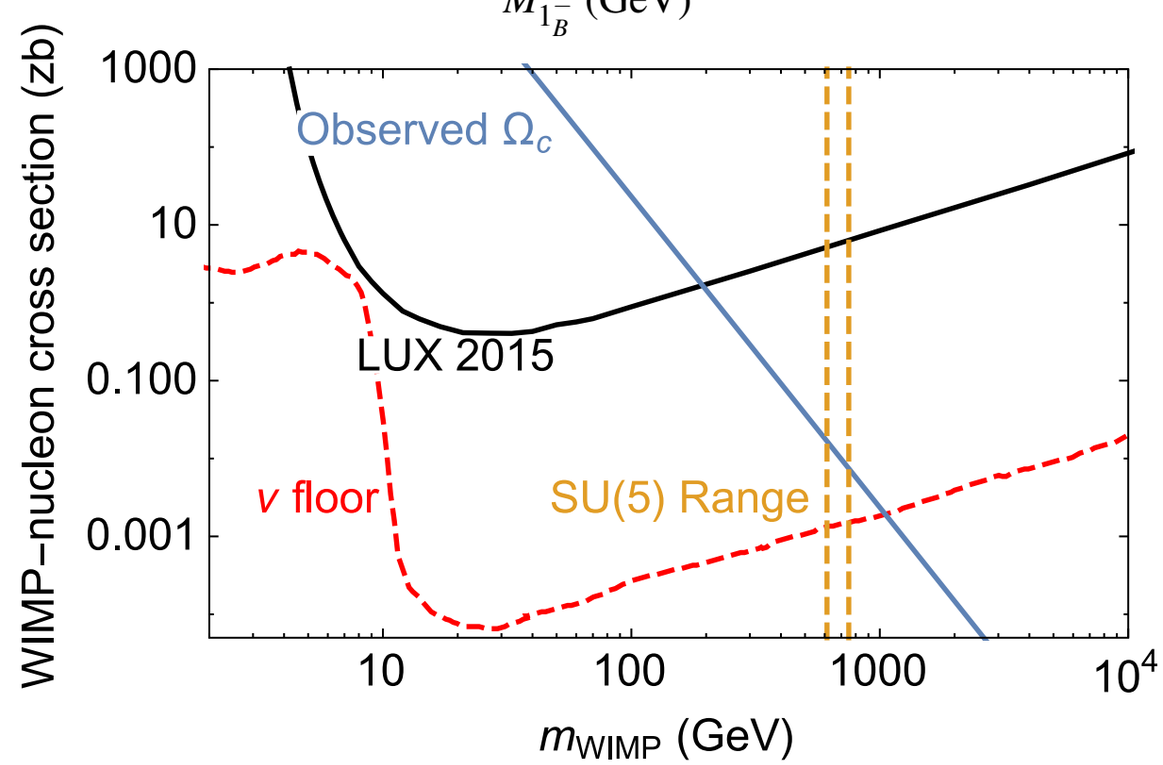
- **The WIMP candidate in our model has its dark matter phenomenology depend on its chromo-Rayleigh interaction.**

$$c_G \frac{g_s^2 N_b}{\Lambda_b^2} \Pi_{1^-} \Pi_{1^-} G^{\mu\nu\, a} G^a_{\mu\nu}$$

$$c_F \frac{e^2 N_b}{\Lambda_b^2} \Pi_{1^-} \Pi_{1^-} F^{\mu\nu} F_{\mu\nu}$$

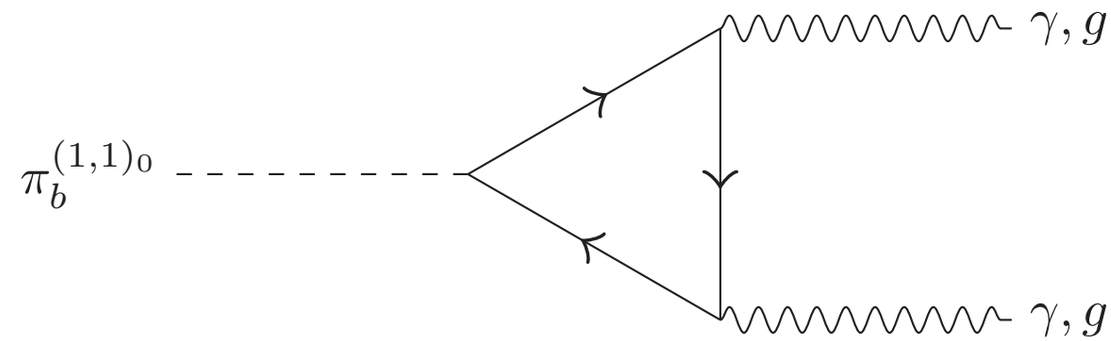
YB, Osborne, 1506.07110
Godbole, Mendiratta, Tait, 1506.01408



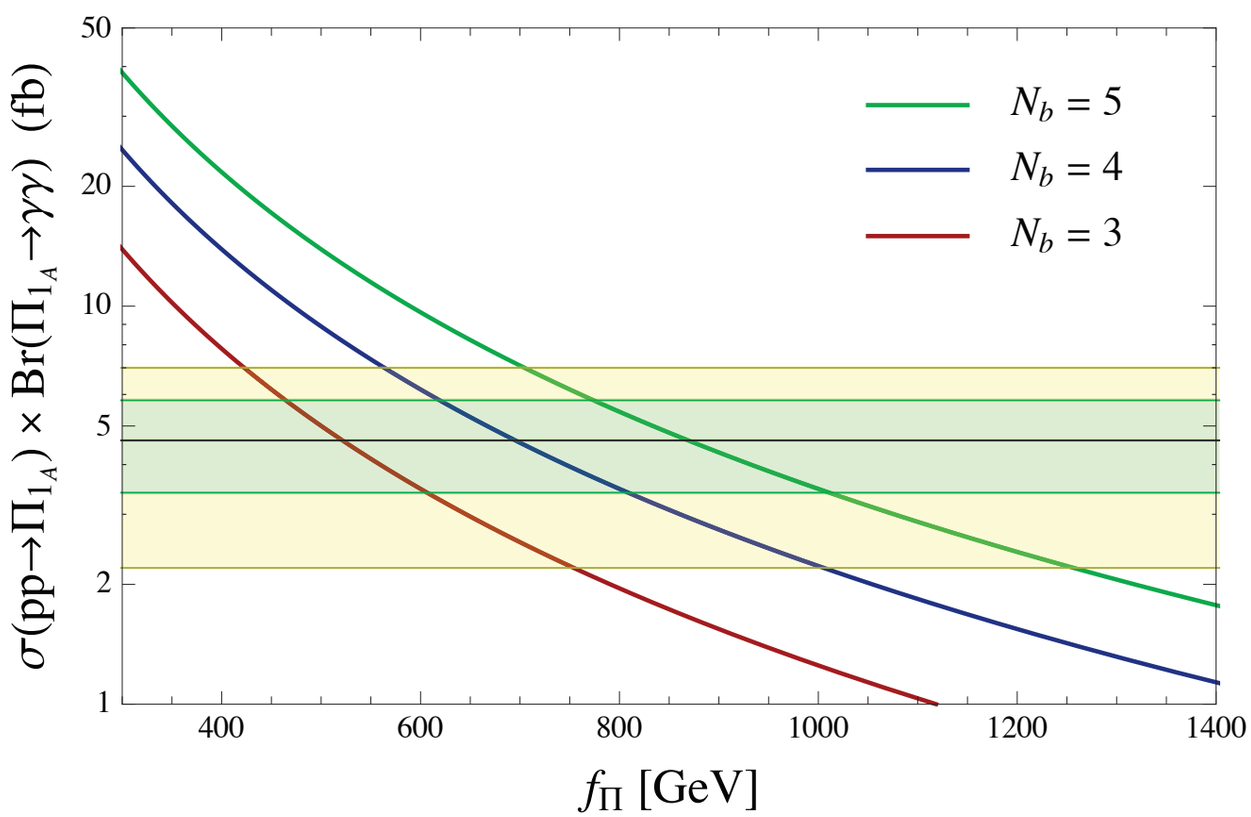


750 GeV G-parity-even Pion

- **The G-parity-even pion couples to two gluons and two photons through triangular anomalies**



- **The gluon parton inside proton can produce the singlet pion.**



YB, Lu, Berger, 1512.05779
Harigaya, Nomura, 1512.04850
Nakai, Sato, Tobioka, 1512.04924
Franceschini, et. al., 1512.04933
Bian, Chen, Liu, Shu, 1512.05759
Low, Tesi, Wang, 1512.05328
……

- Increasing the big-color rank can increase the decay constant and increase the some meson masses.

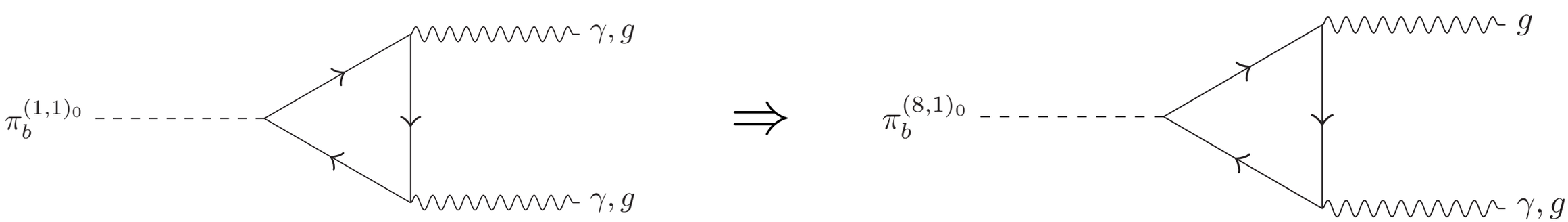
Other Things to Look For

- Additional decay branchings for the very narrow (width~50 MeV) 750 GeV singlet

Mode	gg	$\gamma\gamma$	$Z\gamma$	ZZ	WW
Branching ratio	0.90	0.0046	0.0083	0.021	0.065

- **Especially, searching for $Z\gamma$ is important to confirm this minimal 5+5bar model.**

- For all composite models with the 750 GeV heavy pions coupling to both gluons and photons, the color-octet pion and rho meson are a universal prediction.



Color-octet Pion

- Single-particle couplings of the color-octet pion:

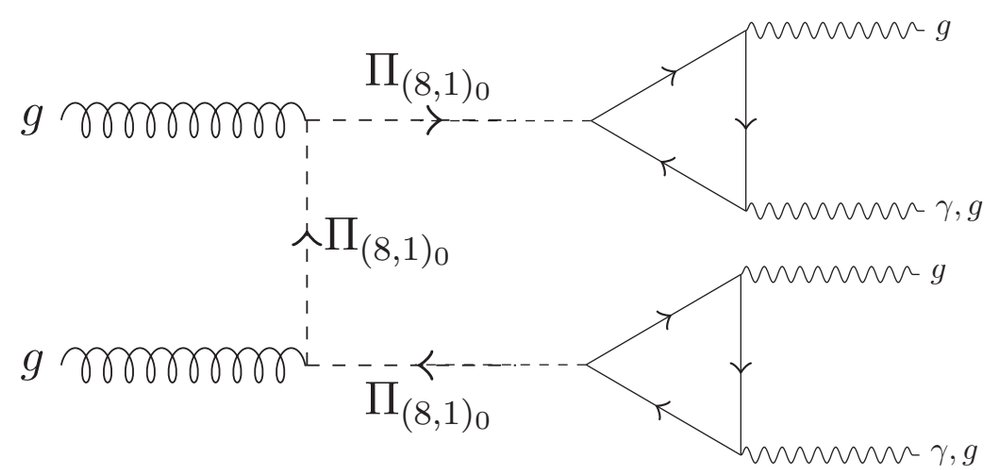
$$-\frac{\alpha_s}{8\pi\, f_\Pi}\,\frac{N_d}{2}\, d^{abc}\,\Pi^{8\,a}\,\epsilon_{\mu\nu\rho\sigma}\,G^{\mu\nu\,b}\,G^{\rho\sigma\,c} + 2\,\frac{\sqrt{\alpha_Y\,\alpha_s}}{8\pi\, f_\Pi}\,\frac{N_d}{3}\,\Pi^{8\,a}\,\epsilon_{\mu\nu\rho\sigma}\,G^{\mu\nu\,a}\,B^{\rho\sigma}$$

- The branching ratio to gluon+photon is simply

$$\frac{\mathrm{Br}[\Pi^8 \to g+\gamma]}{\mathrm{Br}[\Pi^8 \to 2\,g]} = \frac{8\,\alpha}{15\,\alpha_s} \approx 0.046$$

- The branching ratio into gluon+Z is smaller and is 0.013. The total width is O(100 MeV).

- For pair-production of the color-octet pion via its QCD interactions, one could look for a pair of dijet resonances. The current best limit has a lower mass around 700 GeV from CMS (1412.7706). One could also look for the related channels:



YB, Martin: 1003.3006;
Dobrescu, Krnjaic: 1104.2893.

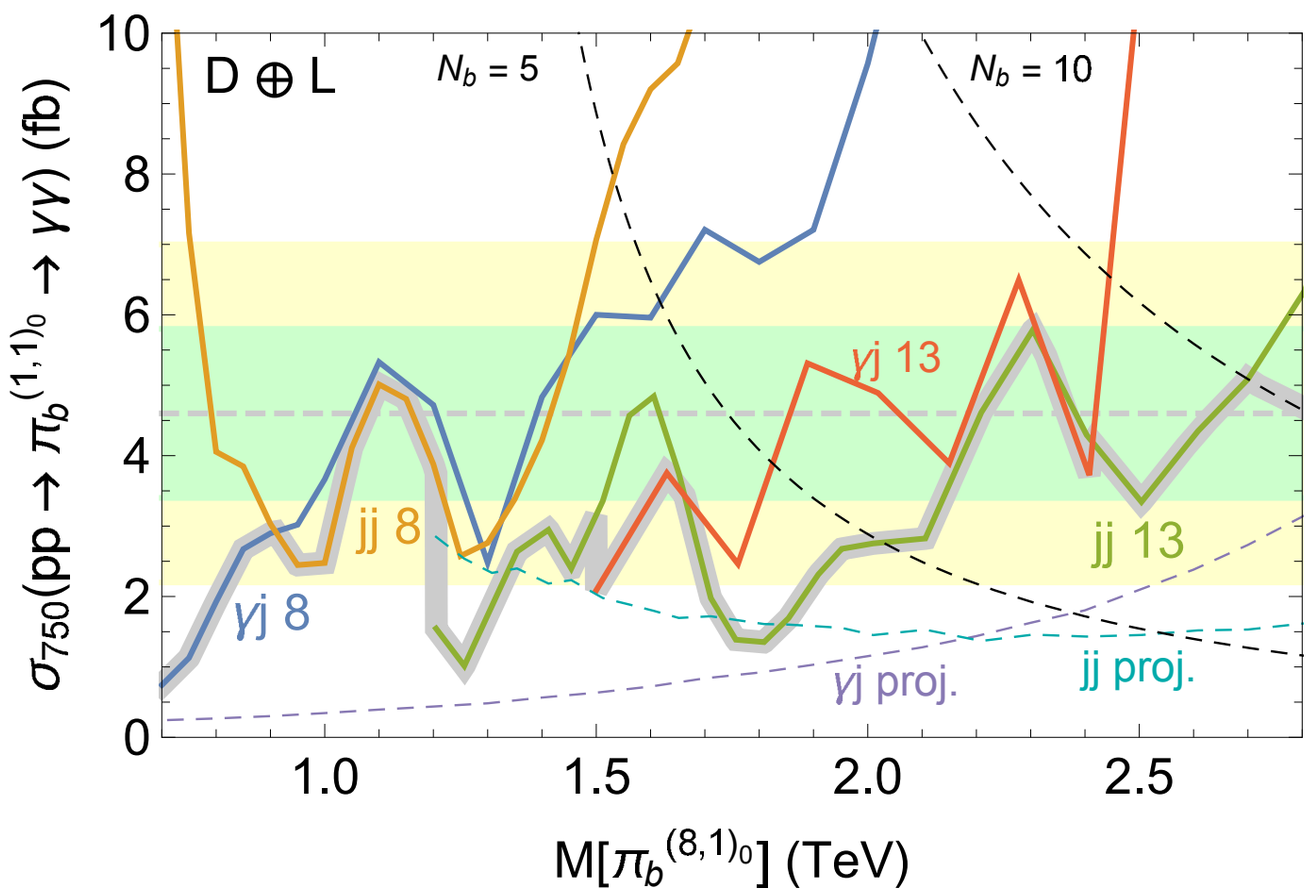
Single Production of Color-octet Pion

- **One could search for single productions of the color-octet pion via dijet or jet+photon channels. For color-octet and SM-singlet pions, the ratio of production cross sections is simply:**

$$\frac{\sigma[gg \to \Pi_{(8,1)_0}]}{\sigma[gg \to \Pi_{(1,1)_0}]} = \frac{25}{4}\,\frac{m^2_{\Pi_8}\delta(s - m^2_{\Pi_8})}{m^2_{\Pi_1}\delta(s - m^2_{\Pi_1})}$$

- **The existing search for dijet and jet+photon resonances can be applied to constrain the color-octet states.**

- **So, if the 750 GeV resonance stays and is due to a QCD-like strong dynamics, this summer we should see the evidence of the color-octet heavy pion.**



YB, Barger, Berger, 1604.07835

Conclusions

- A new kinematic region will be probed by the LHC Run 2. The TeV scale new physics related to the hierarchy problem will be tested very well in next few years.

- There are more signatures related to the WIMP dark matter at the LHC, including two-state inelastic dark matter and dark matter radiating its own force carrier.

- The composite dark matter model requires additional explanations for the mass scale close to the QCD or electroweak scales.

- The example models suggest interesting signatures associated with the dark QCD dynamics. In most of the cases, long-lived particles are anticipated.

- The 750 GeV resonance (a heavy pion) can naturally emerge in the composite dark matter models. Additional color-octet heavy pions are key to confirm this class of explanations.

Hope the weasle will not eat our 750 GeV egg!

Thanks!

More Composite Models

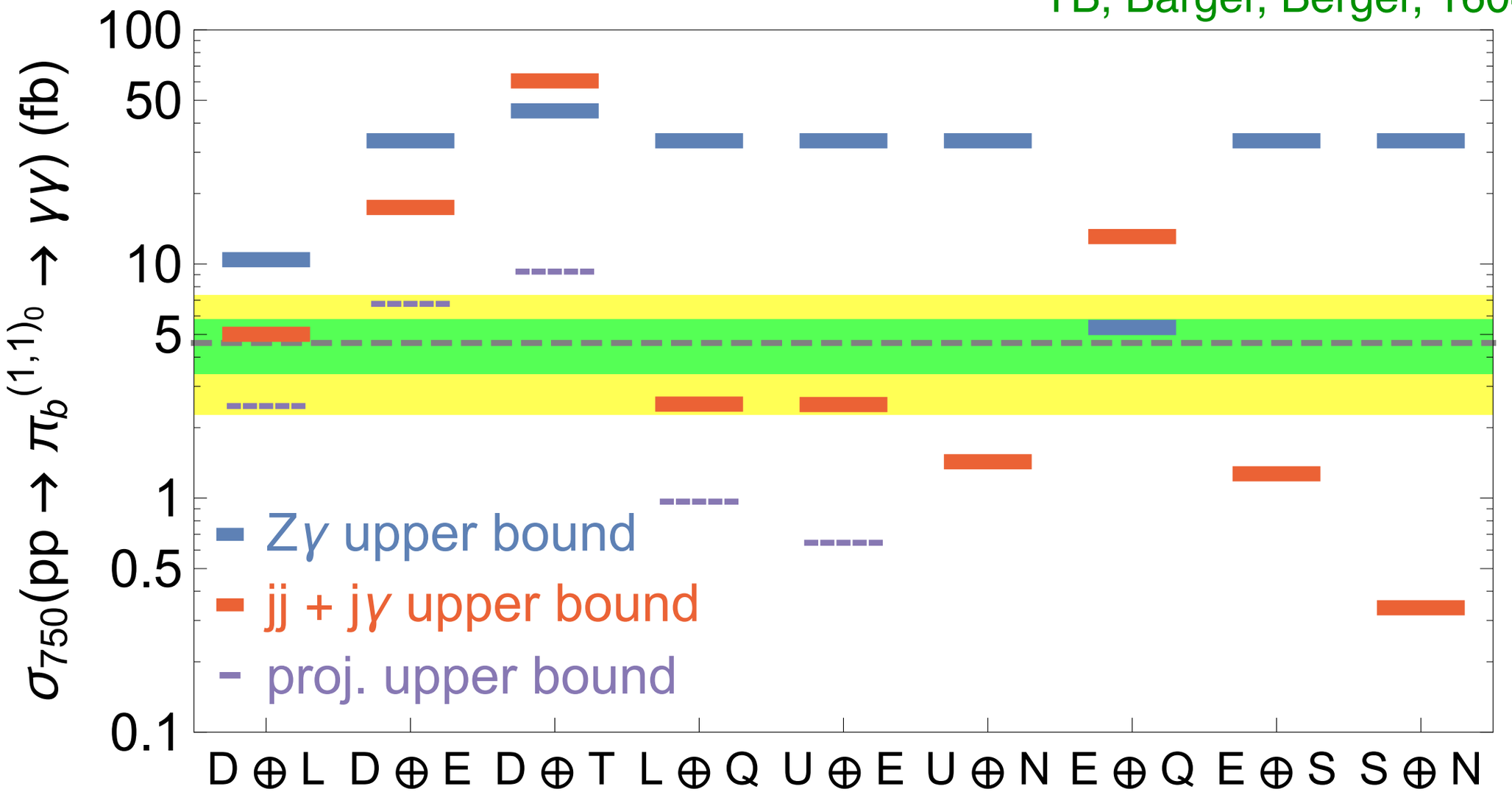
Model	Big-Quark	Big-pion
D $\oplus$ L	$(3,1)_{-1/3} \oplus (1,2)_{1/2}$	$(8,1)_0 \oplus (3,2)_{-5/6} \oplus (\bar{3},2)_{5/6} \oplus (1,3)_0 \oplus (1,1)_0$
D $\oplus$ E	$(3,1)_{-1/3} \oplus (1,1)_1$	$(8,1)_0 \oplus (\bar{3},1)_{4/3} \oplus (3,1)_{-4/3} \oplus (1,1)_0$
D $\oplus$ T	$(3,1)_{-1/3} \oplus (1,3)_1$	$(8,1)_0 \oplus (\bar{3},3)_{-2/3} \oplus (3,3)_{2/3} \oplus (1,5)_0 \oplus (1,3)_0 \oplus (1,1)_0$
L $\oplus$ Q	$(1,2)_{1/2} \oplus (\bar{3},2)_{-1/6}$	$(8,3)_0 \oplus (8,1)_0 \oplus (3,3)_{2/3} \oplus (\bar{3},3)_{-2/3} \oplus$
		$(3,1)_{2/3} \oplus (\bar{3},1)_{-2/3} \oplus 2 \times (1,3)_0 \oplus (1,1)_0$
U $\oplus$ E	$(3,1)_{2/3} \oplus (1,1)_{-1}$	$(8,1)_0 \oplus (\bar{3},1)_{-5/3} \oplus (3,1)_{5/3} \oplus (1,1)_0$
U $\oplus$ N	$(3,1)_{2/3} \oplus (1,1)_0$	$(8,1)_0 \oplus (\bar{3},1)_{-2/3} \oplus (3,1)_{2/3} \oplus (1,1)_0$
E $\oplus$ Q	$(1,1)_{-1} \oplus (3,2)_{1/6}$	$(8,3)_0 \oplus (8,1)_0 \oplus (\bar{3},2)_{5/6} \oplus (3,2)_{-5/6} \oplus (1,3)_0 \oplus (1,1)_0$
E $\oplus$ S	$(1,1)_{-1} \oplus (6,1)_{2/3}$	$(27,1)_0 \oplus (8,1)_0 \oplus (\bar{6},1)_{1/3} \oplus (6,1)_{-1/3} \oplus (1,1)_0$
S $\oplus$ N	$(6,1)_{2/3} \oplus (1,1)_0$	$(27,1)_0 \oplus (8,1)_0 \oplus (\bar{6},1)_{-2/3} \oplus (6,1)_{2/3} \oplus (1,1)_0$

see the list of models in Redi, Strumia, Tesi, Vigiani: 1602.07297

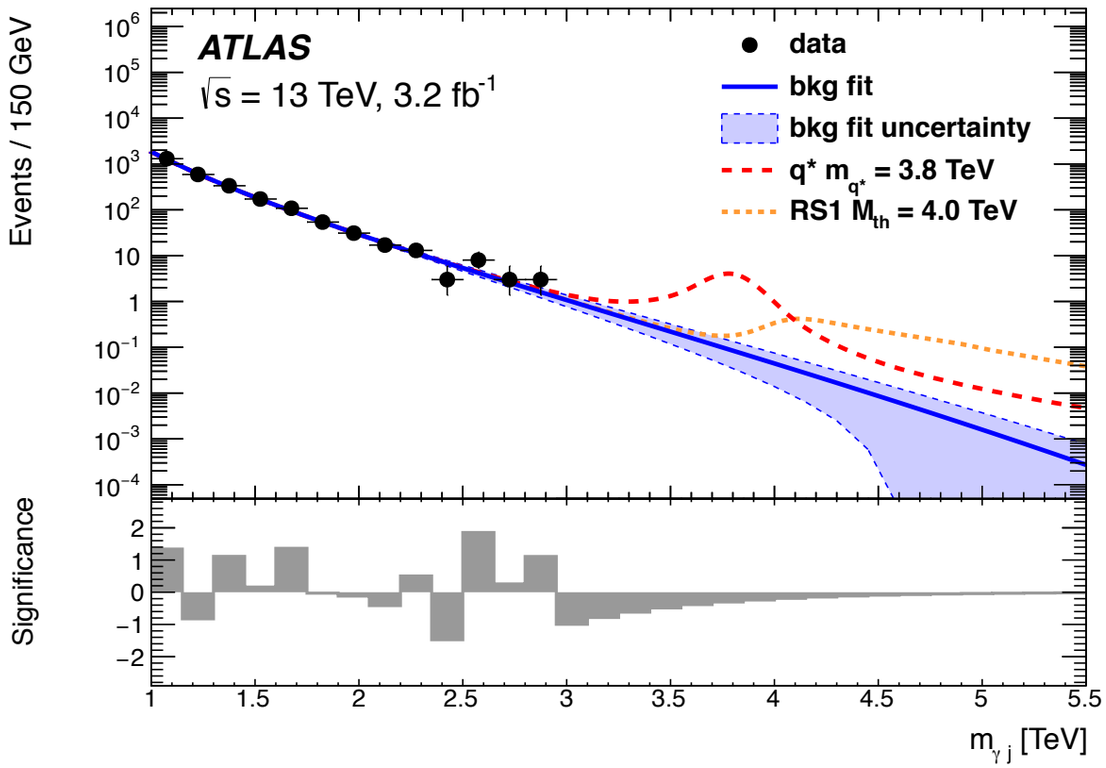
- Models like D+T has a double-charged particle. The 750 GeV diphoton branching is large, so the correlated constraints from color-octet are weaker.
- The last two models with color-sextet big-quarks have color-27 pions, which also couple to two gluons via triangle-anomaly. Their productions are enhanced by a large color-factor.

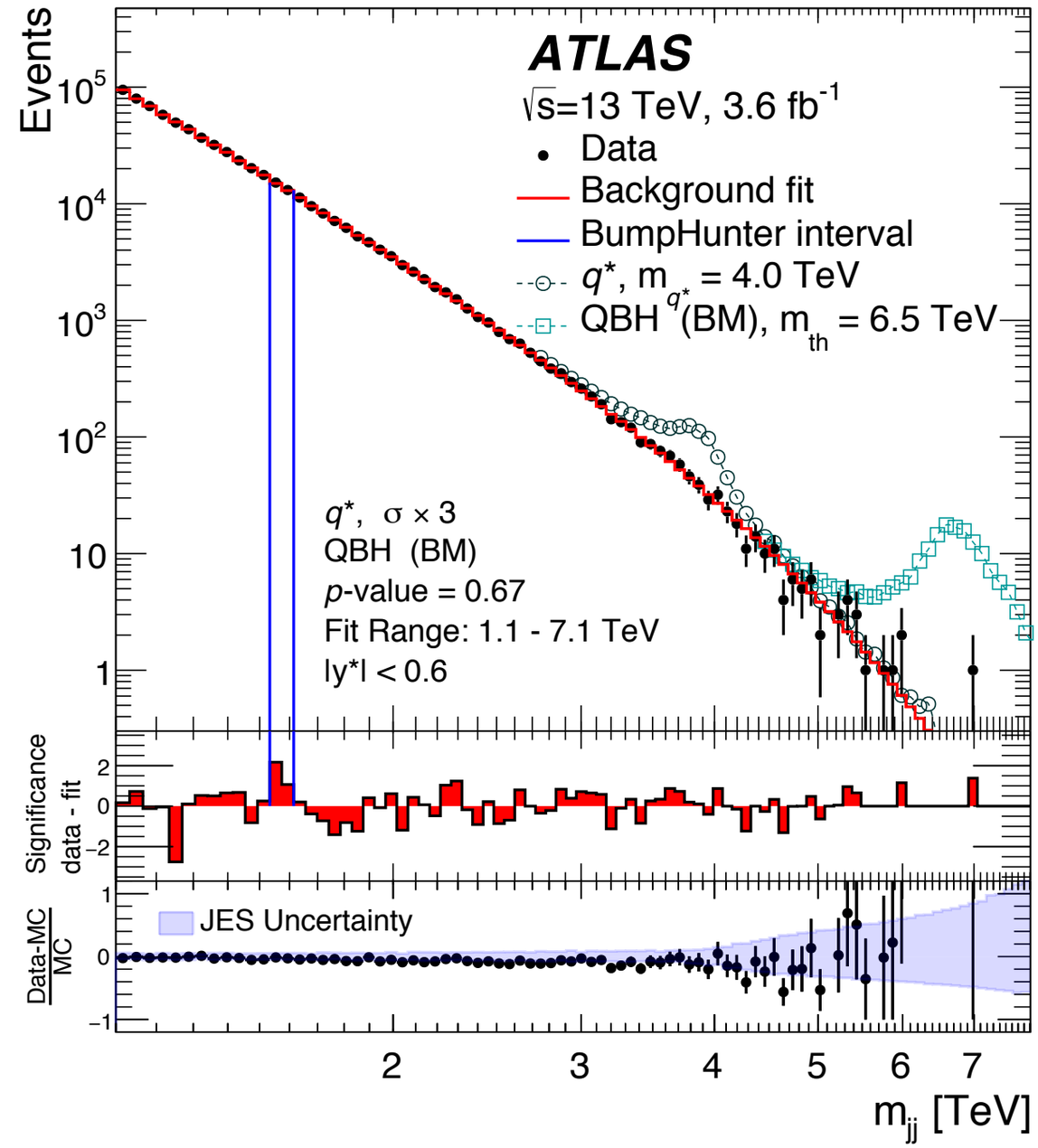
Status for More Composite Models

YB, Barger, Berger, 1604.07835



- More than a half of models are constrained by their color-octet (color-27) state properties.
- For the D+E and D+T models, one could look for the color-triplet pions via their leptoquark or diquark decays.


ATLAS
√s = 13 TeV, 3.2 fb-1
data
bkg fit
bkg fit uncertainty
q* m q* = 3.8 TeV
RS1 M th = 4.0 TeV
Events / 150 GeV
Significance
m γ j [TeV]


ATLAS
√s=13 TeV, 3.6 fb-1
Data
Background fit
BumpHunter interval
q*, m q* = 4.0 TeV
QBH (BM), m th = 6.5 TeV
q*, σ × 3
QBH (BM)
p-value = 0.67
Fit Range: 1.1 - 7.1 TeV
|y*| < 0.6
Events
Significance
data - fit
Data-MC / MC
JES Uncertainty
m jj [TeV]