

A 750 GeV Big Pion and its Companions

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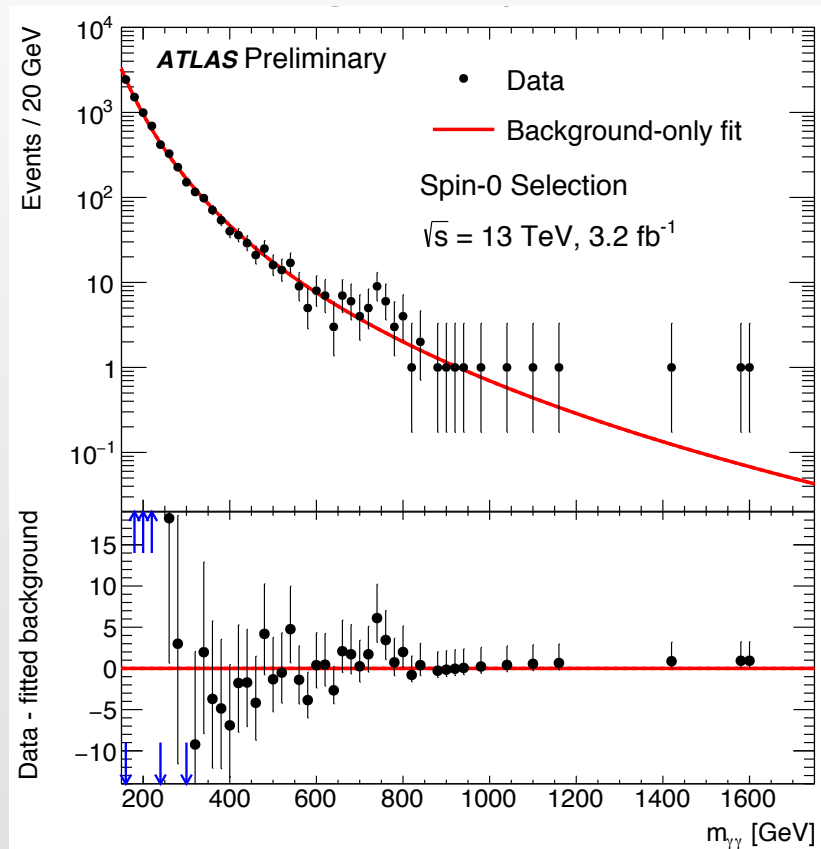
New Physics Interpretations at the LHC

@Argonne National Lab, May 3, 2016

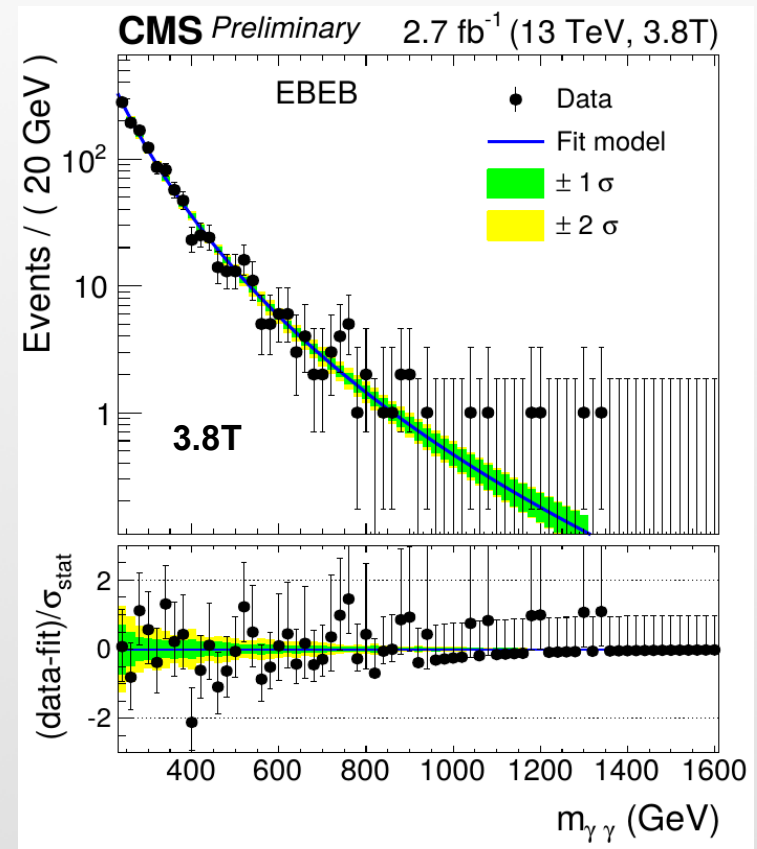
with Vernon Barger, Joshua Berger, Ran Lu, James Osborne, Ben Stefanek
arXiv:1512.05779, 1603.07335, 1604.07835 and in progress

Diphoton Resonance

ATLAS, Moriond EW, 2016



CMS, Moriond EW, 2016

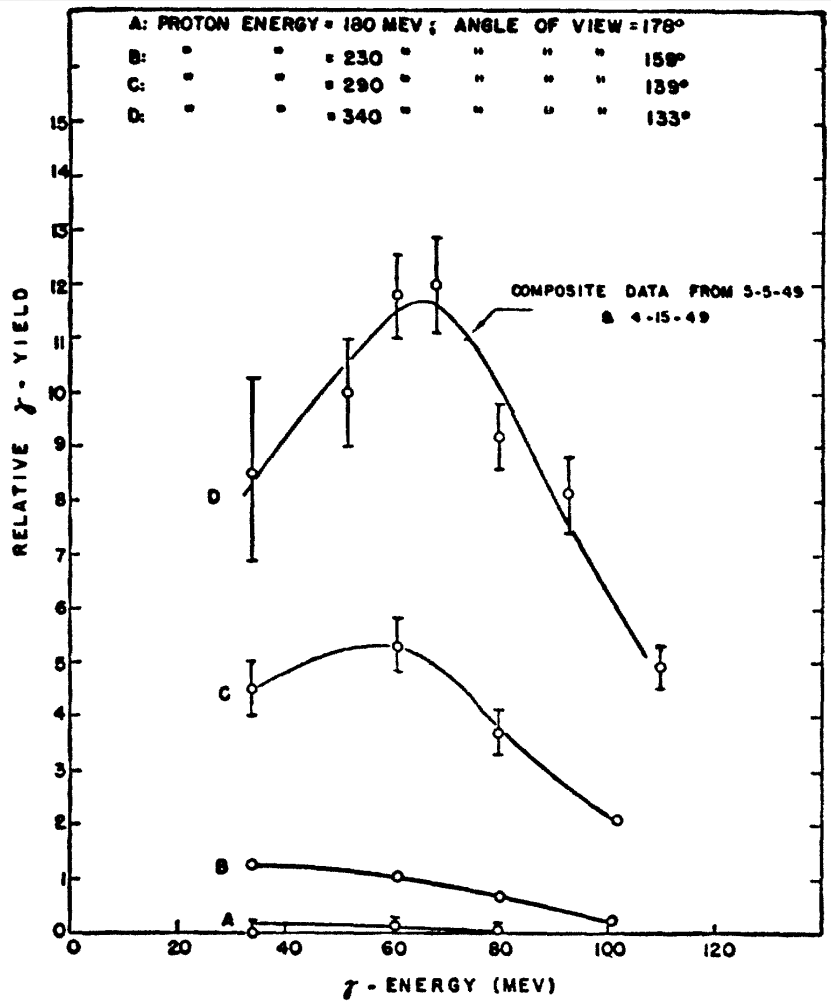


- ❖ The resonance mass is around 750 GeV and could be a narrow or a broad or two narrow ones
- ❖ The required cross section to explain the excess is around 5 fb

Diphoton Inverse Problem

- ❖ The first observed diphoton resonance is the neutral pion π^0 , composite particle from strong dynamics.

Bjorklund, et. al., PR 77, 1950



Samios, et. al., PR 126, 1962

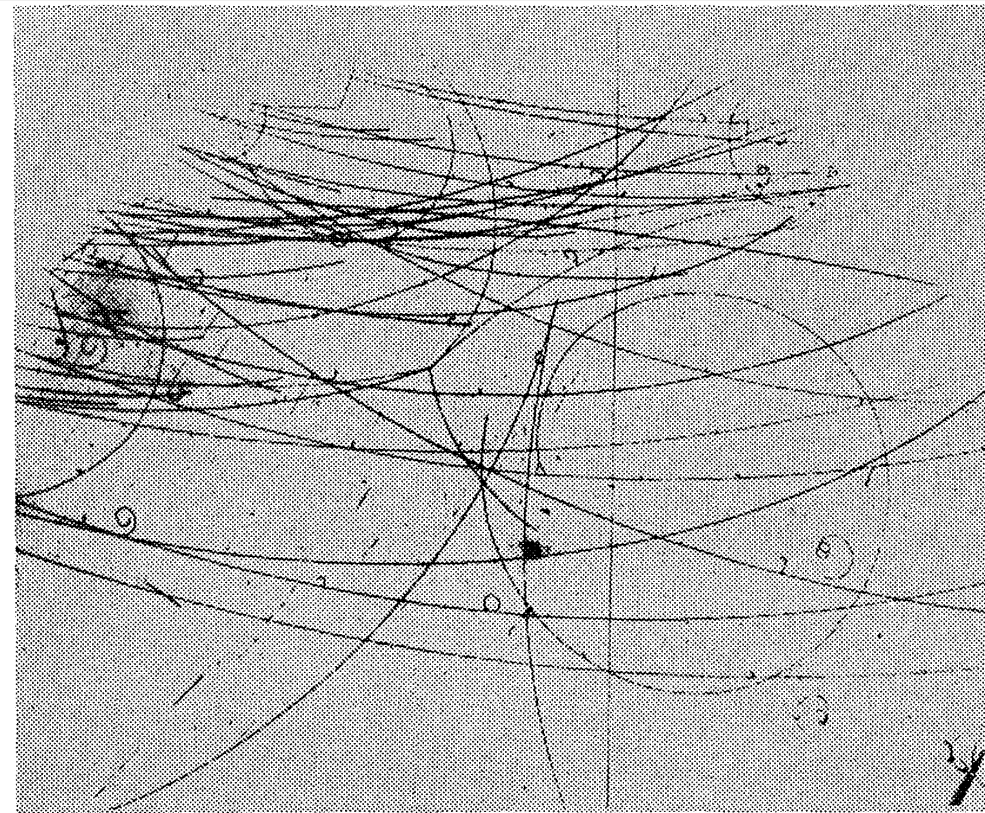
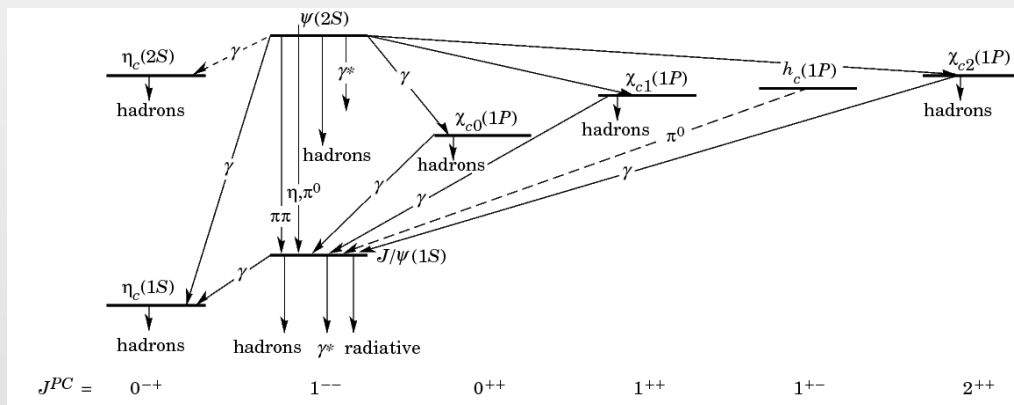


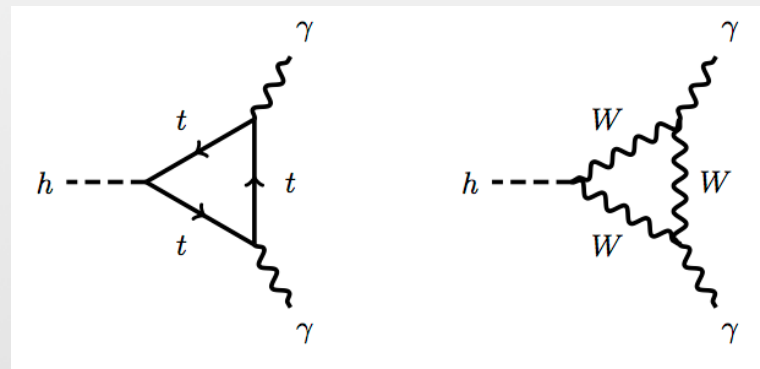
FIG. 1. Photograph of a typical double internal conversion.

Diphoton Inverse Problem

- ❖ The second example is charmonium, η_c , non-relativistic bound state



- ❖ The third example is the SM Higgs boson, perturbative elementary particle



- ❖ Other than perturbative Landau pole argument for some perturbative models and additional top-down (GUT compatible) motivations, we need more experimental information to solve this nice inverse problem.

750 GeV Resonance as a Big Pion

- ❖ The minimal model $D \oplus L$ to compatible with GUT, could be

	$SU(N_b)$	$SU(5)_{\text{GUT}}$
(ψ_L^D, ψ_L^L)	N_b	5
(ψ_R^D, ψ_R^L)	N_b	5

- ❖ The rank of **big-color** group is required to have no SM gauge coupling Landau pole below GUT scale: $2 \leq N_b \leq 10$
- ❖ The symmetry breaking pattern is simply: $SU(5)_L \times SU(5)_R \rightarrow SU(5)_V$
- ❖ There are 24 PNGB's or big-pions

$$24 = (8, 1)_0 + (3, 2)_{-5/6} + (\bar{3}, 2)_{5/6} + (1, 3)_0 + (1, 1)_0$$

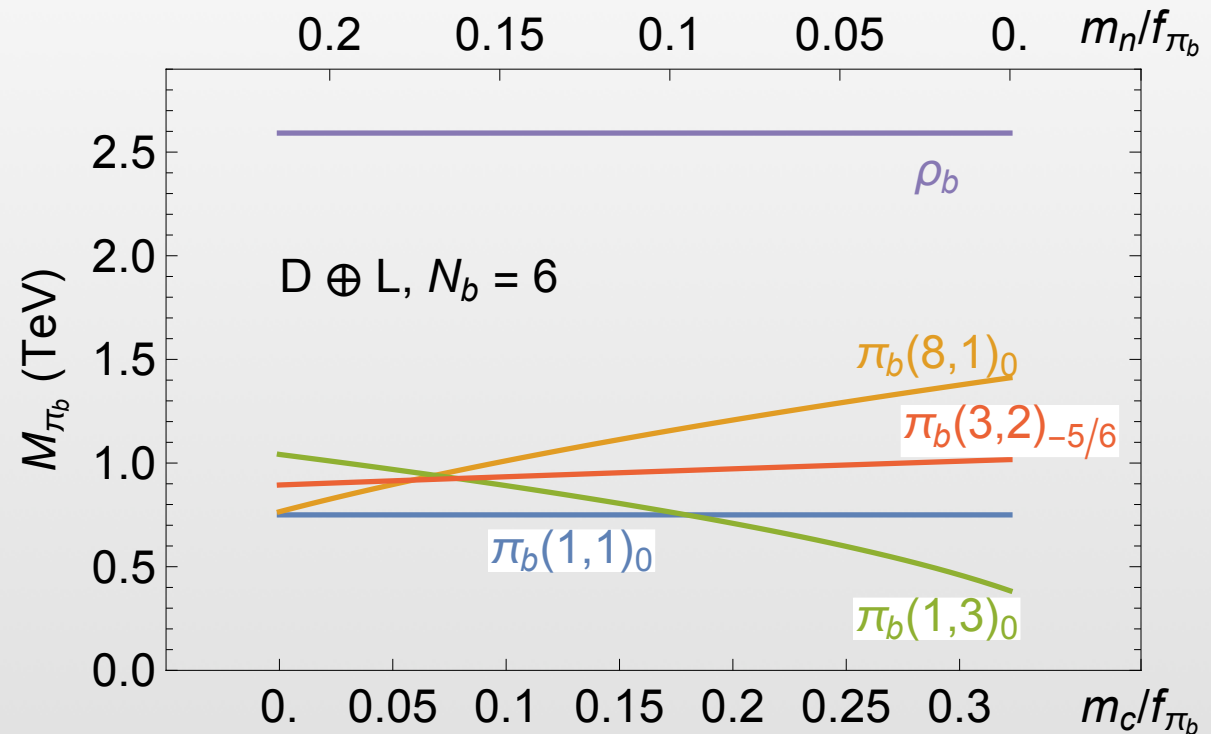
- ❖ The SM-singlet $(1, 1)_0$ could be the 750 GeV resonance

Sample Meson Spectrum

- With vector-like quark masses: $m_c \bar{\psi}_c \psi_c + m_n \bar{\psi}_n \psi_n$, all big-pions are massive

- The SM charged pions receive additional loop contributions:

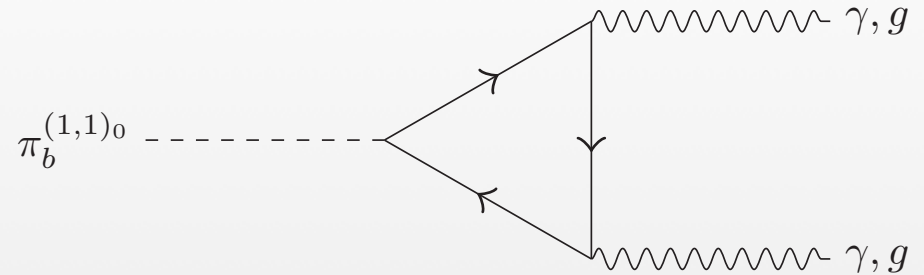
$$\Delta m^2 = \sum_{i=1,2,3} \frac{C_2(r_i) \alpha_i(f_\Pi)}{\alpha(f_\pi)} \frac{f_\Pi^2 \Delta m_\pi^2}{f_\pi^2}$$



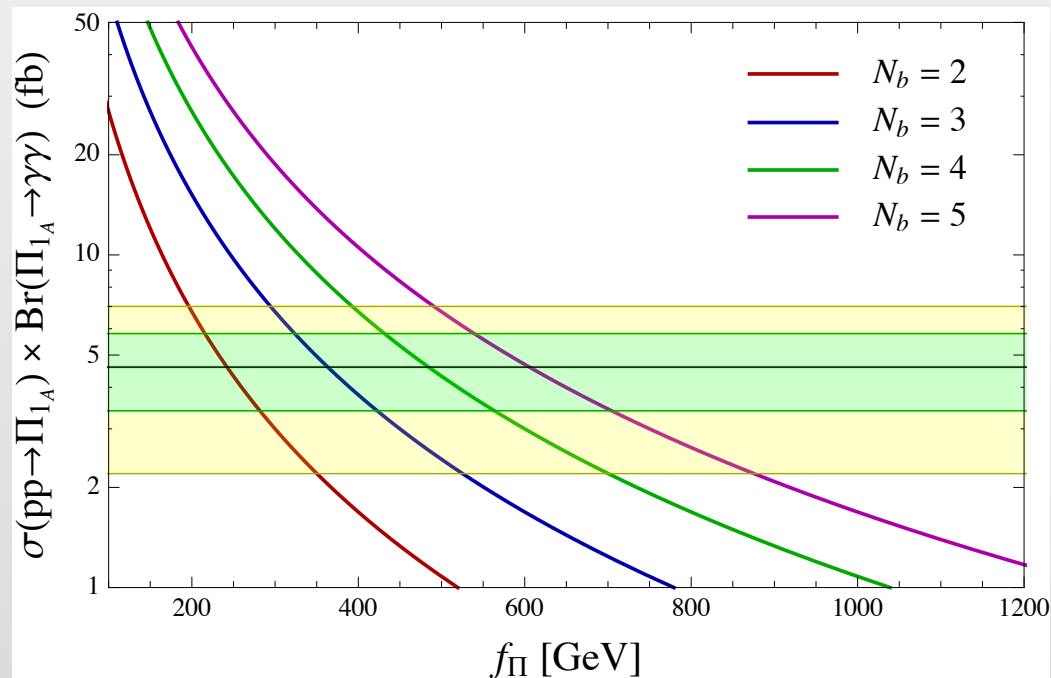
- For instance, the color-octet pion should have a mass below around 2.8 TeV for all ranges of N_b and for the 750 GeV diphoton signal around 5.0 fb.
- The vector ρ_b meson must be below around 5 TeV.

Fit to 750 GeV Diphoton Signal

- ❖ The big-pion $\pi_b^{(1,1)_0} \equiv \Pi_{1_A}$ couples to two gluons and two photons through triangular anomalies



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



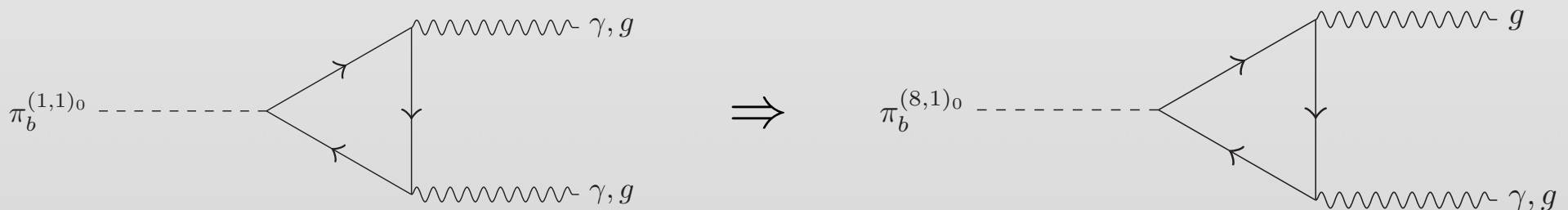
- ❖ Increasing the big-color rank can increase the decay constant and increase the some meson masses.

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:

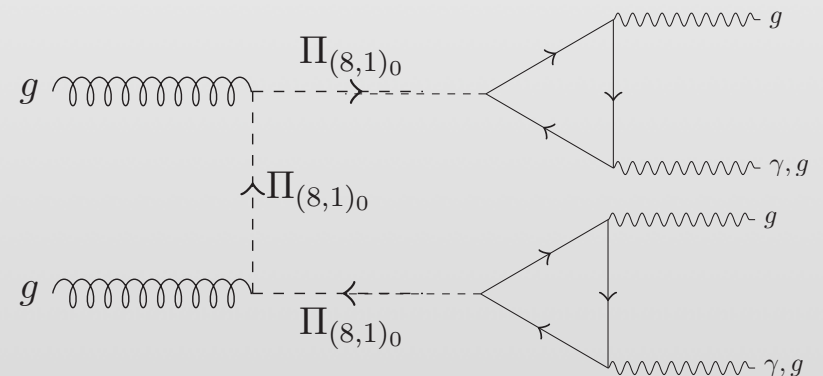
$$-\frac{\alpha_s}{8\pi f_\Pi} \frac{N_d}{2} d^{abc} \Pi^{8a} \epsilon_{\mu\nu\rho\sigma} G^{\mu\nu b} G^{\rho\sigma c} + 2 \frac{\sqrt{\alpha_Y \alpha_s}}{8\pi f_\Pi} \frac{N_d}{3} \Pi^{8a} \epsilon_{\mu\nu\rho\sigma} G^{\mu\nu a} B^{\rho\sigma}$$

- ❖ The branching ratio to gluon+photon is simply

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

- ❖ 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.

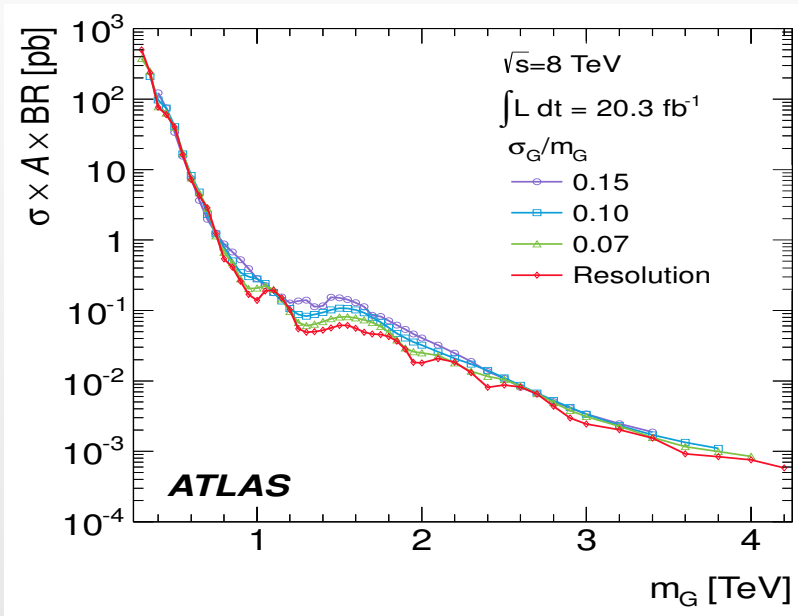
Single Production of Color-octet Pion

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

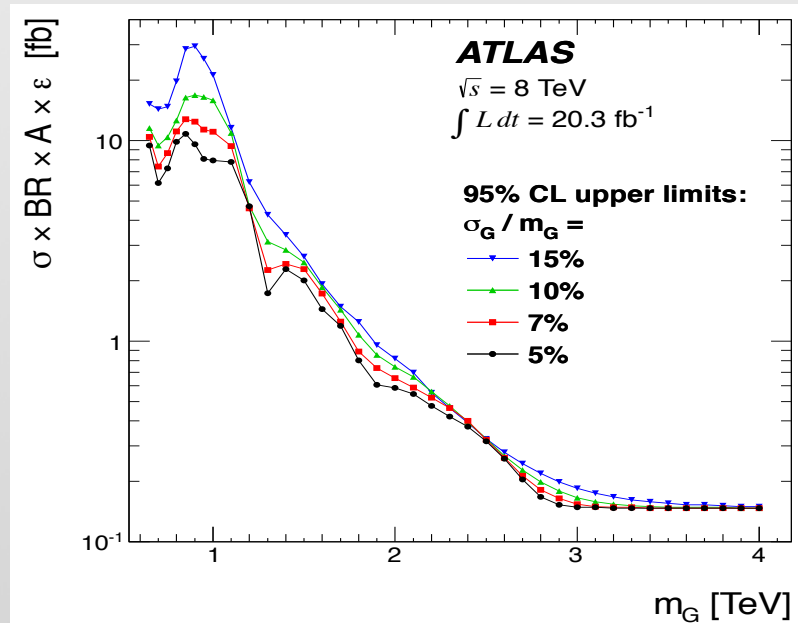
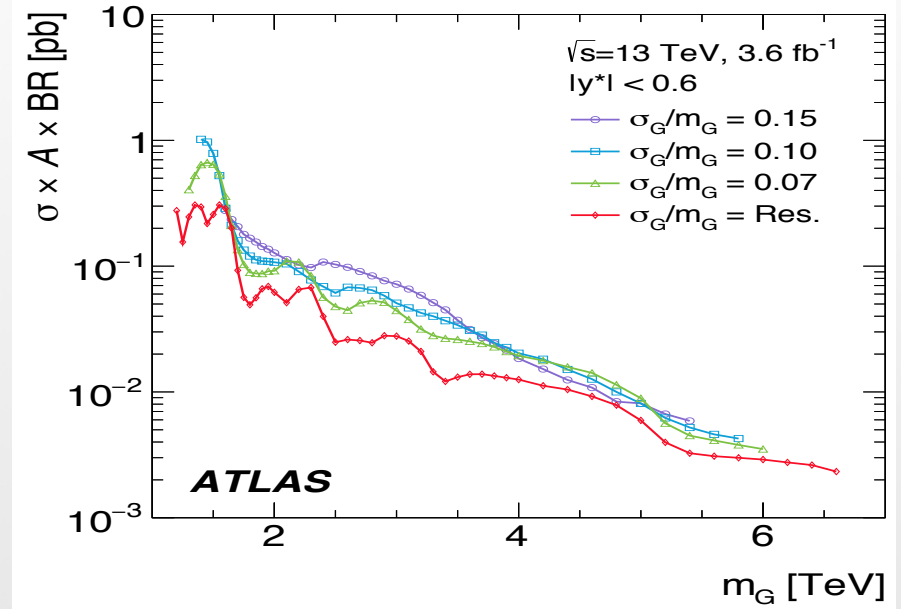
$$\frac{\sigma[gg \rightarrow \Pi_{(8,1)_0}]}{\sigma[gg \rightarrow \Pi_{(1,1)_0}]} = \frac{25}{4} \frac{m_{\Pi_8}^2 \delta(s - m_{\Pi_8}^2)}{m_{\Pi_1}^2 \delta(s - m_{\Pi_1}^2)}$$

- ❖ The decay constant and the big-color rank are factored out.
- ❖ For a given model or known branching ratios, the constraints on color-octet production cross section can be directly translated into the 750 GeV heavy pion diphoton rate.
- ❖ The existing search for dijet and jet+photon resonances can be applied to constrain the color-octet states.
- ❖ The usual motivations for those searches are excited quarks with a larger width. The color-octet pion has a width much smaller than the detector-resolution-generated widths.

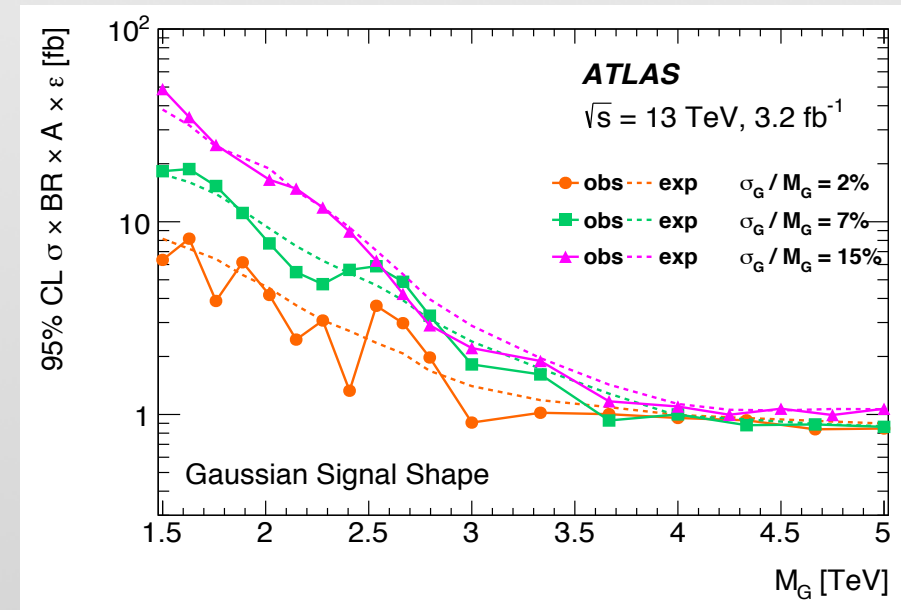
Dijet and photon+jet Narrow Resonance



dijet

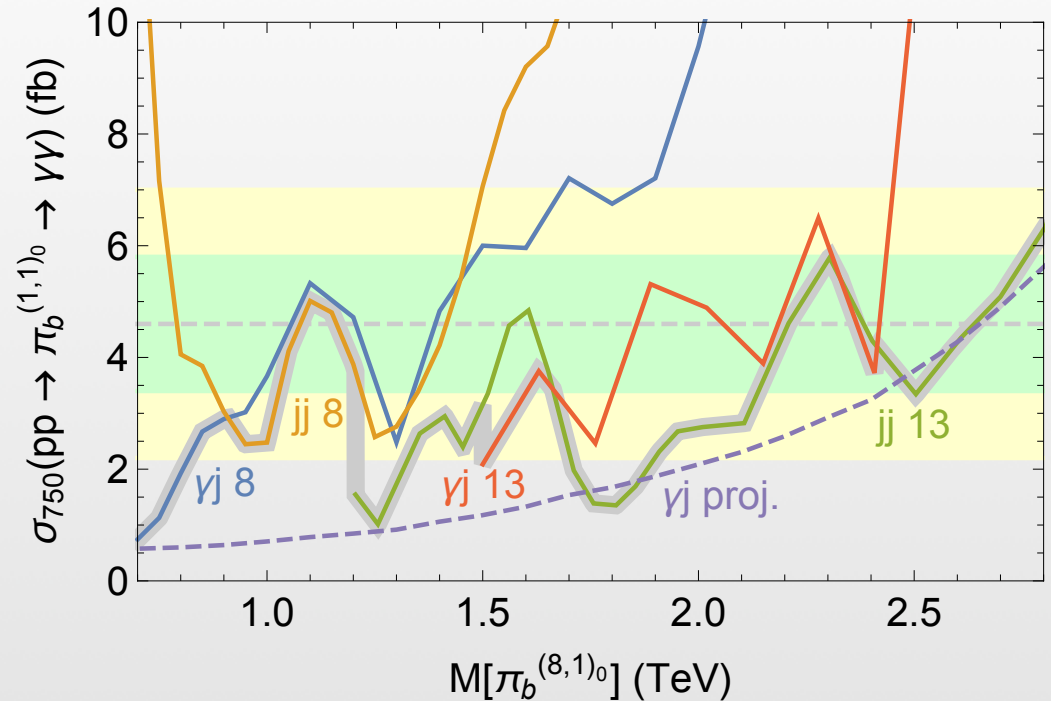


$j + \gamma$



Color-octet Correlated Bound on 750 GeV Diphoton Rate

- ❖ For the allowed range of color-octet masses, the diphoton rate is constrained to be below 5-6 fb for this D+L model.
- ❖ The weakest bound happens at around 1.1 TeV, 1.6 TeV, 2.2 TeV, due to small excesses for narrow dijet and γj resonance searches at 8 TeV.



- ❖ The projected gamma+jet resonance searches with 20/fb and 1% systematic error can further constraint the 750 GeV diphoton rate.
- ❖ So, if the 750 GeV is due to a QCD-like strong dynamics, **this summer we should see the evidence of the color-octet heavy pion.**
- ❖ One could also look for narrow dijet resonance below 2 TeV (emphasized also by [Dobrescu&Yu 1306.2629](#)) by solving the trigger issue like data scouting: [CMS 1604.08907](#).

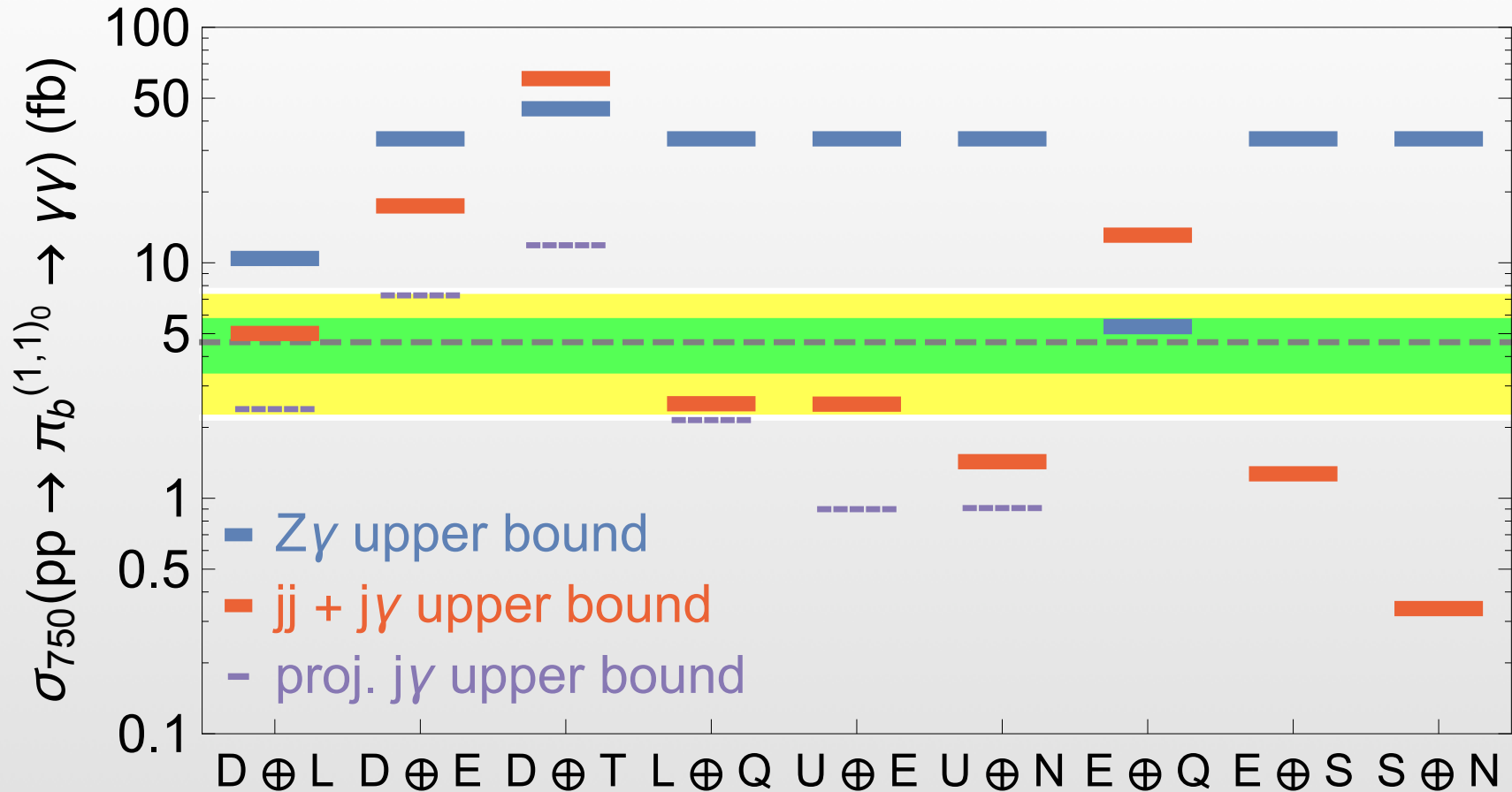
More Composite Models

Model	Big-Quark	Big-pion
D ⊕ 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 ⊕ 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 ⊕ 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 ⊕ 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 ⊕ 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 ⊕ 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 ⊕ 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 ⊕ 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 ⊕ 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: I 602.07297](#)

- ❖ 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.

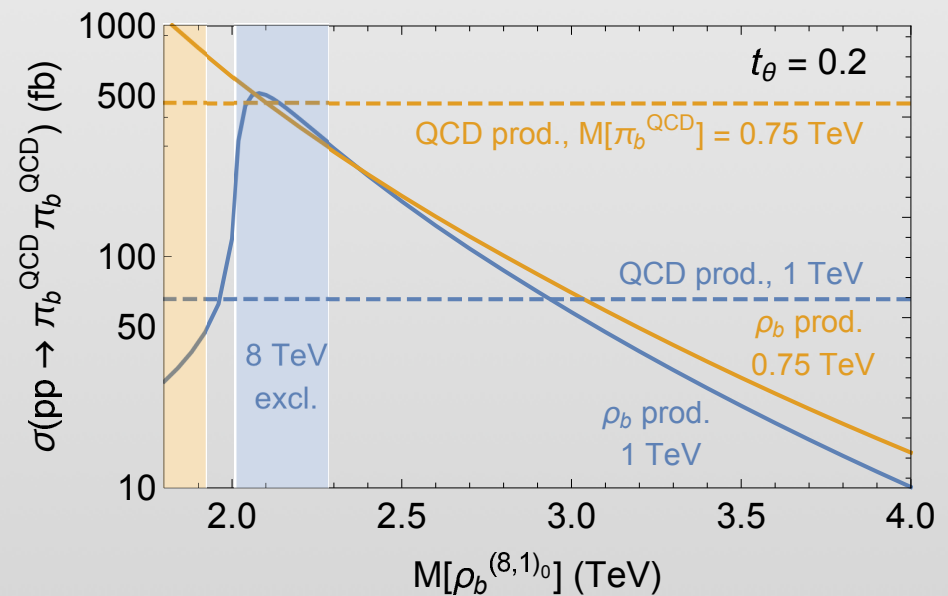
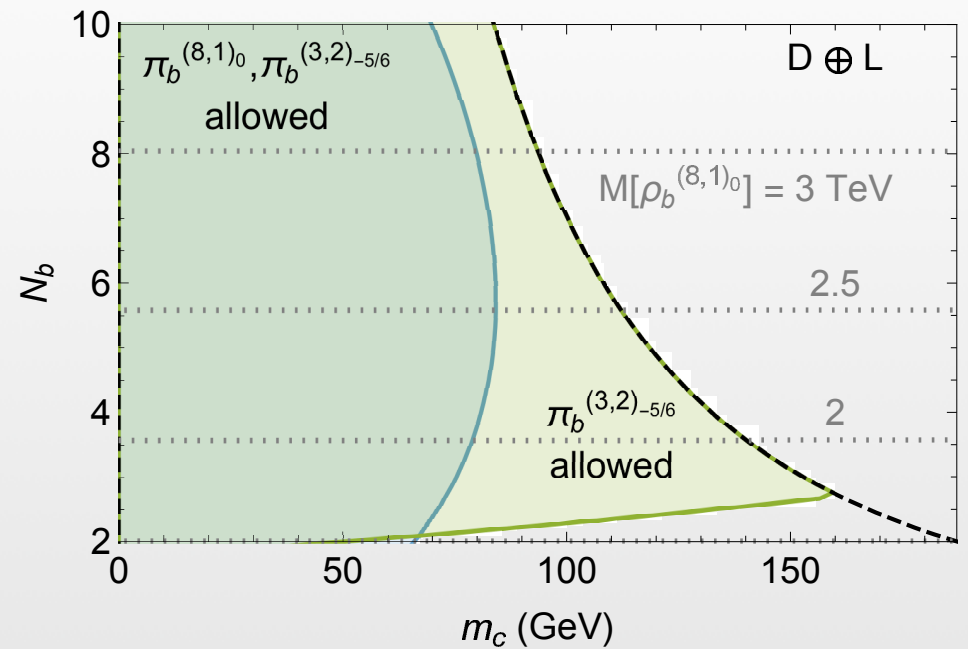
Status for More Composite Models



- ❖ 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.

Color-octet ρ -meson

- ❖ Similar to the SM, the rho-meson mainly decays into two pions.
- ❖ The majority of parameter space in our models have color-octet vector meson (coloron) decay into two QCD-charged pions
- ❖ For a 3 TeV rho-meson, its width is at $O(500 \text{ GeV})$, so a very broad resonance.
- ❖ Directly search for ρ_b^8 is challenging.
- ❖ We could notice their existence from its contribution to pair-production of QCD-charged pions.



Questions about the Two Scales

- ❖ Why is the confinement scale $\Lambda_b \sim 4\pi f_\Pi$ for the new strong dynamics sector around a few TeV?
- ❖ Why is the bare-fermion mass for the vector-like big-quark around 100 GeV?
- ❖ For the first question, it will be nice if the new sector has something to do with the electroweak symmetry sector. It is not obvious how to build this connection.
- ❖ For the second question, it will also be nice if the Higgs VEV can provide the bare-fermion masses. However, this will mess up the SM Higgs properties.
- ❖ I will show two directions to answer those two questions, but not in a combined way.

WIMP could justify the TeV Confinement Scale

- ❖ A simple guess: WIMP and the 750 GeV particle could come from the same strong dynamics.
- ❖ When we have the 750 GeV interaction with two gluons and two photons, it is very likely that the WIMP could have similar interactions in pair.

$$c_G \frac{g_s^2 N_b}{\Lambda_b^2} \Pi_{1-} \Pi_{1-} G^{\mu\nu a} G_{\mu\nu}^a \qquad c_F \frac{e^2 N_b}{\Lambda_b^2} \Pi_{1-} \Pi_{1-} F^{\mu\nu} F_{\mu\nu}$$

- ❖ The dark matter chromo-Rayleigh interaction could be the dominant one to explain its thermal relic abundance.

$$\langle \sigma v \rangle (\Pi_{1-} \Pi_{1-} \rightarrow gg) = \frac{64 c_G^2 g_s^4 M_{\Pi_{1-}}^2}{\pi \Lambda_b^4} + \mathcal{O}(v^2) \approx 1.0 \text{ pb} \cdot c$$

- ❖ For a dark matter mass around 750 GeV, the scale Λ_b is required to be around $4\pi \times 500$ GeV to have the thermal annihilation rate.

One Realization: dark-G-parity-odd WIMP

- ❖ This is just one example that can use the WIMP to explain the confinement scale. More models along this line should be studied.
- ❖ The pure SM QCD sector (turning off the electroweak interactions) has an unbroken G-parity, which is a combination of charge-conjugation and second-isospin rotation. Similar thing could happen for the new strong dynamics sector by choosing proper matter content.
- ❖ Double the matter content and have the same bare-fermion mass for ψ_1 and ψ_2 .
- ❖ One then has an unbroken and independent G-parity: dark G-parity. **YB, R. Hill: 1003.3006**

	$SU(N_b)$	$SU(5)_{\text{GUT}}$
$(\psi_{1,L}^D, \psi_{1,L}^L)$	N_b	5
$(\psi_{1,R}^D, \psi_{1,R}^L)$	N_b	5
$(\psi_{2,L}^D, \psi_{2,L}^L)$	N_b	$\bar{5}$
$(\psi_{2,R}^D, \psi_{2,R}^L)$	N_b	$\bar{5}$

Dark-G-even and odd Heavy Pions

- There totally 99 new heavy pions:

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

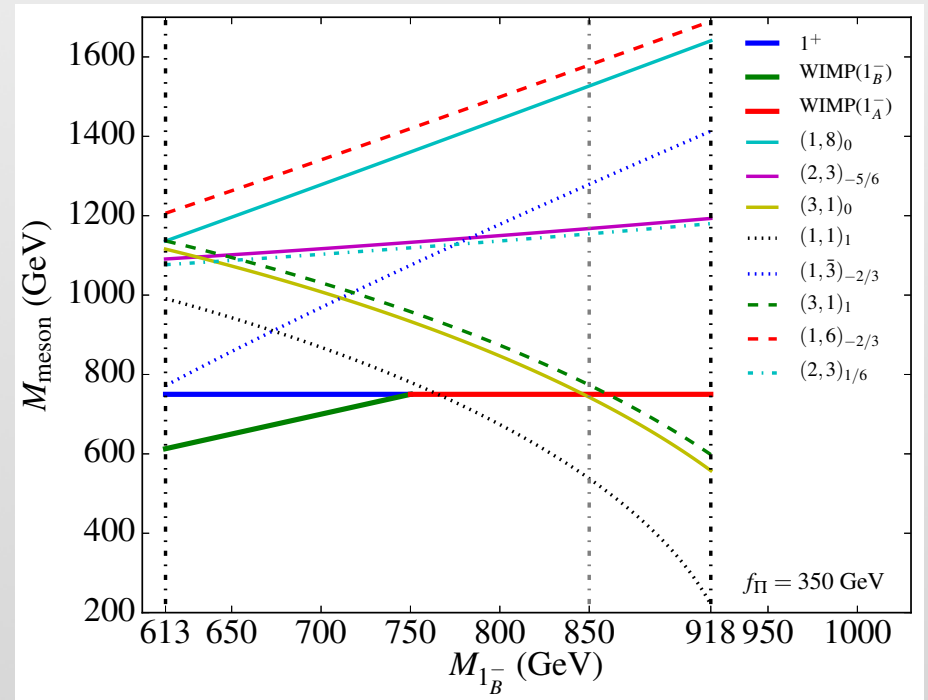
$$24^+ = (1, 1)_0^+ + (3, 1)_0^+ + (2, 3)_{-5/6}^+ + (2, \overline{3})_{5/6}^+ + (1, 8)_0^+$$

$$24^- = (1, 1)_0^- + (3, 1)_0^- + (2, 3)_{-5/6}^- + (2, \overline{3})_{5/6}^- + (1, 8)_0^-$$

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

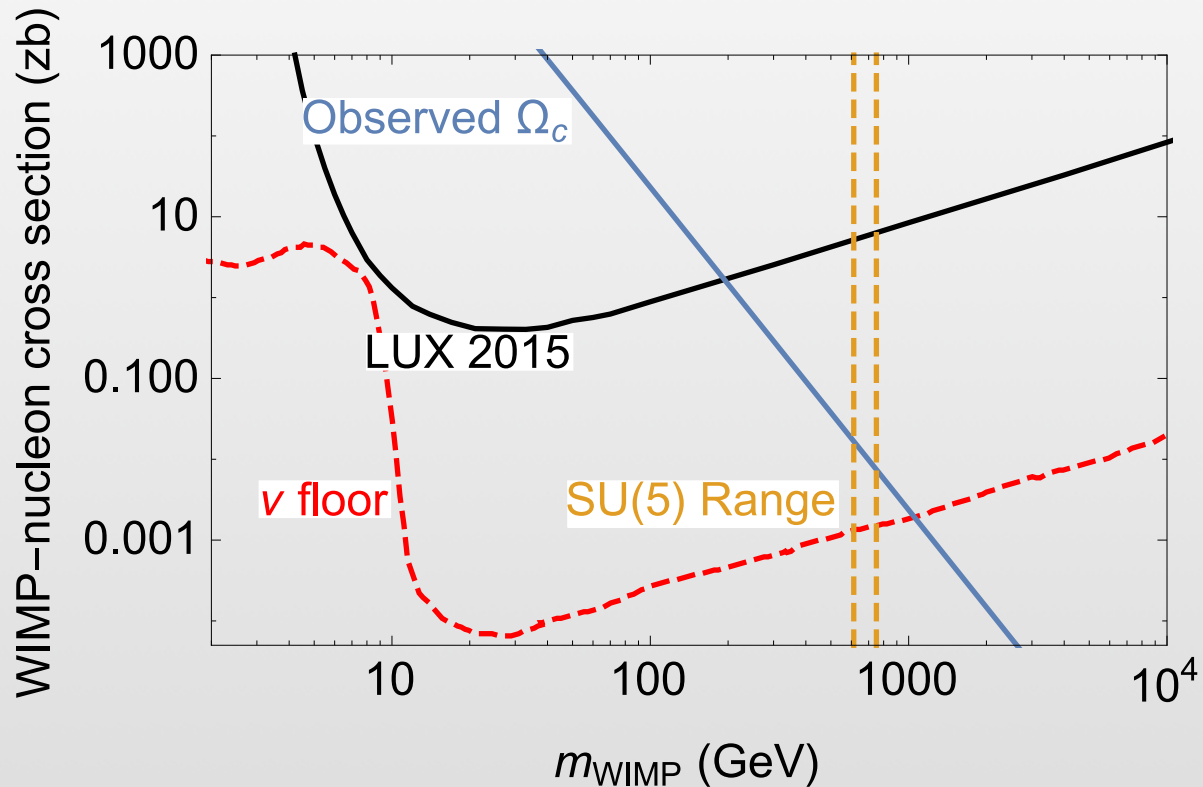
- The WIMP sits in the (612, 750) GeV mass window, with the lower bound just from group structure:

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



Direct Detection of the LGP

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



- ❖ The predicted cross sections for the 5+5bar model is around two orders of magnitude below the current constraints, but should be above the neutrino floor.

Questions about the Two Scales

- ❖ Why is the confinement scale $\Lambda_b \sim 4\pi f_\Pi$ for the new strong dynamics sector around a few TeV?
- ❖ Why is the bare-fermion mass for the vector-like big-quark around 100 GeV?

A Chiral Composite Model

- ❖ The new big-quarks could be vector-like under Standard Model gauge group, but chiral under a new $U(1)'$ or other new gauge group.

	$SU(N_b)$	$SU(5)_{\text{GUT}}$	$U(1)'$
$(\psi_{1,L}^D, \psi_{1,L}^L)$	N_b	5	q_1
$(\psi_{1,R}^D, \psi_{1,R}^L)$	N_b	5	q_2
$(\psi_{2,L}^D, \psi_{2,L}^L)$	N_b	$\bar{5}$	$-q_1$
$(\psi_{2,R}^D, \psi_{2,R}^L)$	N_b	$\bar{5}$	$-q_2$

- ❖ The big-color confinement can also generate $U(1)'$ spontaneously breaking, such that the big-quark mass could be tied together with the confinement scale.
- ❖ The detailed model also requires additional four-fermion-like operators to give all masses to pseudo Nambu-Goldstone bosons.

New Decays for 750 GeV and color-octet Pions

- ❖ We have new decay channels for the 750 GeV particle and the color-octet pion. For $g' = 0.2$ and $M_{Z'} \approx 306$ GeV

Π_{1A} decays

Mode	gg	$\gamma\gamma$	$Z\gamma$	ZZ	WW	$Z'\gamma$	$Z'Z$
Branching ratio	0.90	0.0045	0.0075	0.019	0.059	0.0024	0.0007
Γ_{tot}	$73 \text{ MeV} \left(\frac{N_d}{4}\right)^2 \left(\frac{685 \text{ GeV}}{f_\Pi}\right)^2$						

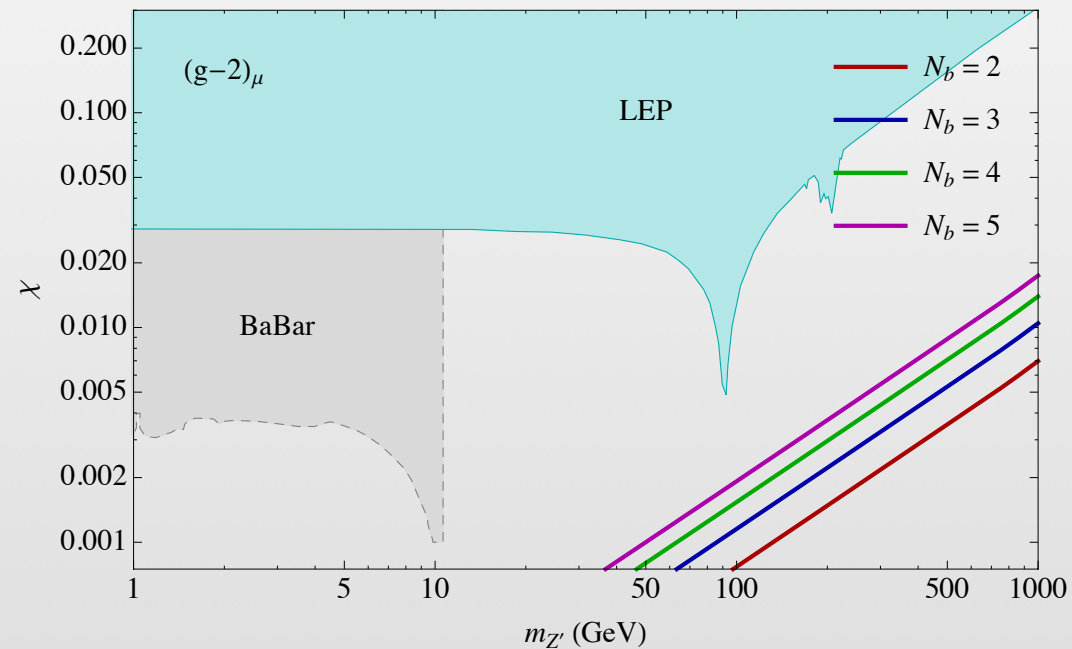
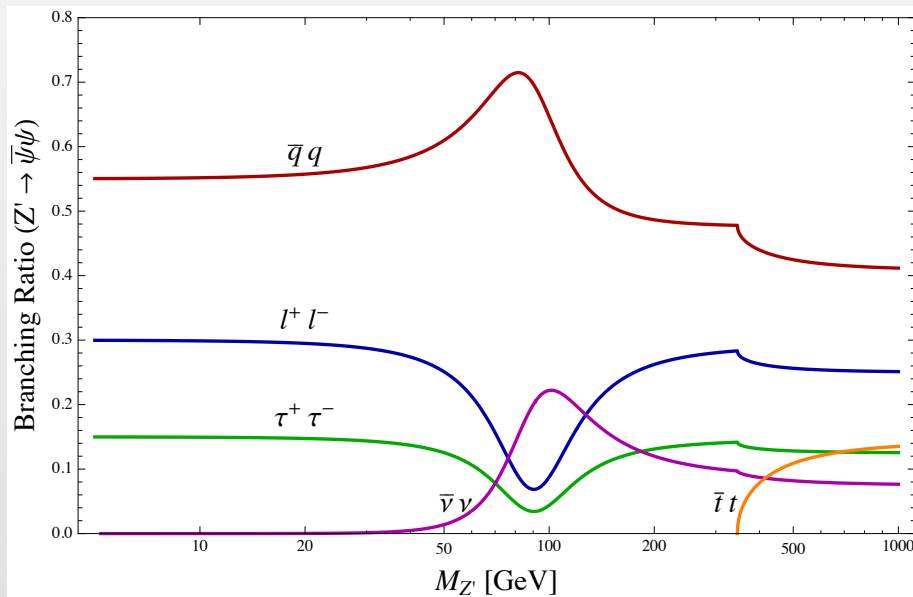
Π^8 decays

Mode	gg	gZ'	$g\gamma$	gZ
Branching ratio	0.91	0.037	0.041	0.013
Γ_{tot}	$854 \text{ MeV} \left(\frac{N_d}{4}\right)^2 \left(\frac{685 \text{ GeV}}{f_\Pi}\right)^2$			

Z' Properties

- ❖ The Z' has kinetic mixing with the hypercharge gauge boson from new big-quark running in the loop.

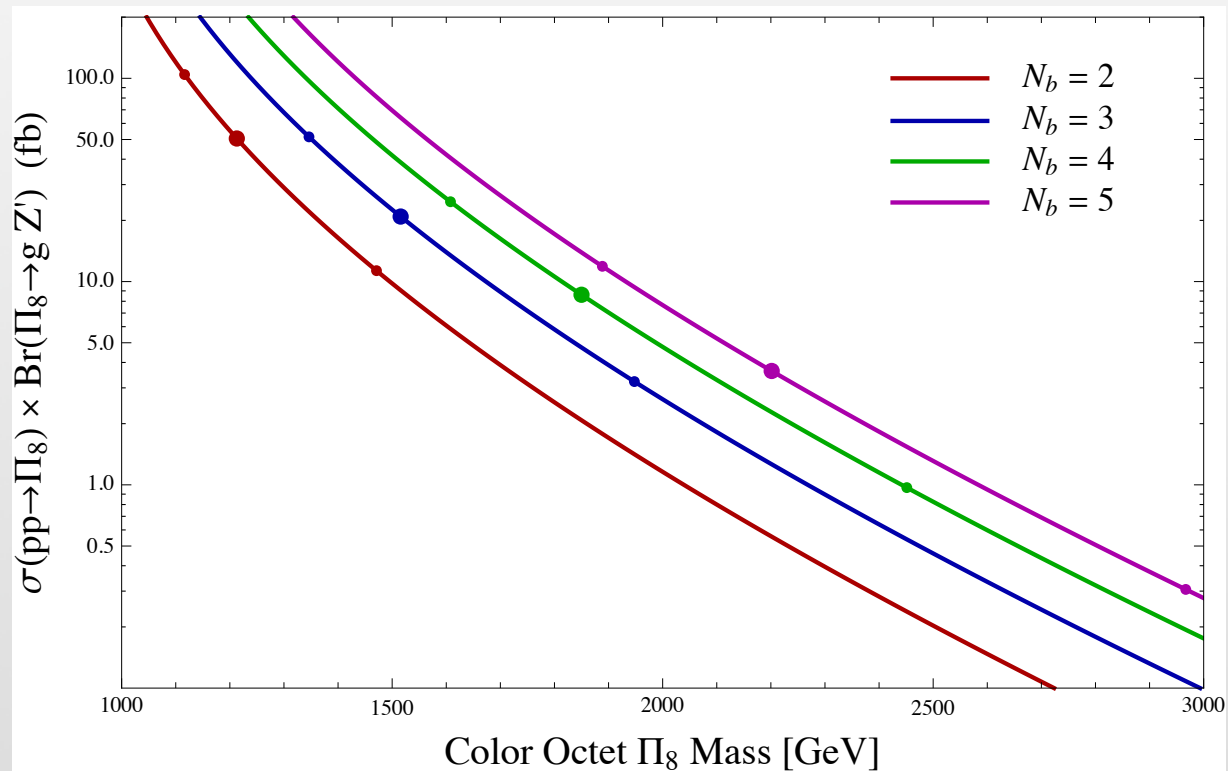
$$\frac{\sin \chi}{2} \hat{B}_{\mu\nu} \hat{Z}'^{\mu\nu}$$



- ❖ For a mass above around 200 GeV, there are also small Z' decay branchings to two $Z+h$ and WW .
- ❖ The SM Higgs boson could decay into $Z'+Z$ for a small range of parameters space.

$\ell^+ \ell^- j$ Resonance

- ❖ The Z' has larger leptonic decay branching ratio than the SM Z boson. One could look for a narrow resonance decaying into two leptons plus one jet.



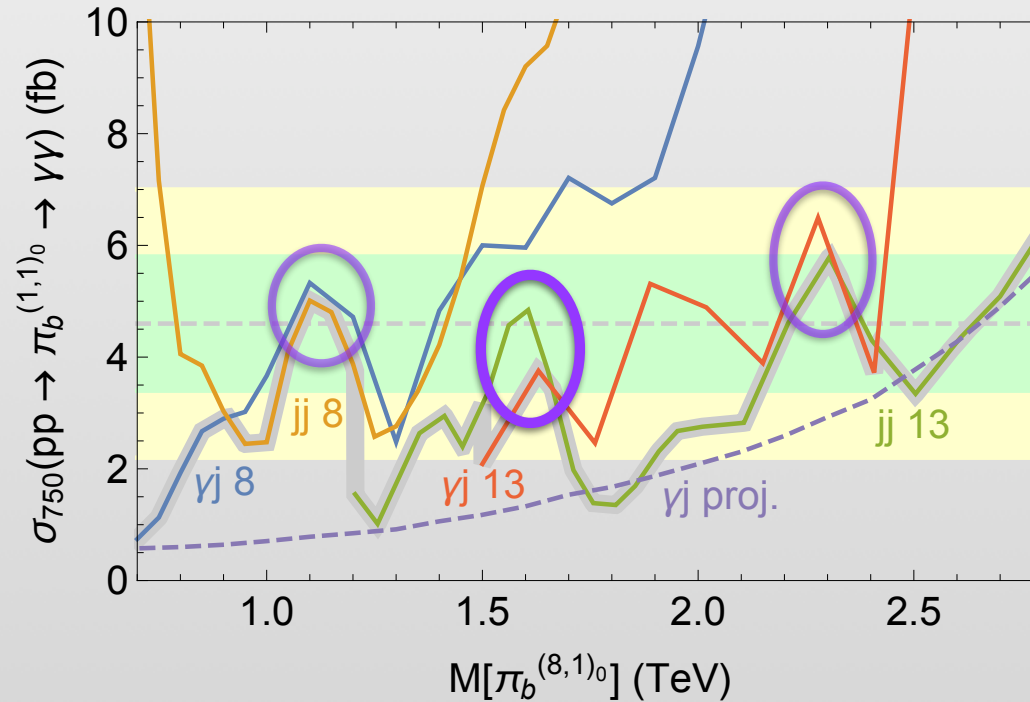
- ❖ The signature could be interesting by itself.

Conclusion

- ❖ The composite models to explain 750 GeV diphoton excess will be concretely tested this summer.
- ❖ The associated color-octet big-pion can be searched for in the dijet and photon+jet channels.

Conclusion

- ❖ The composite models to explain 750 GeV diphoton excess will be concretely tested this summer.
- ❖ The associated color-octet big-pion can be searched for in the dijet and photon+jet channels.
- ❖ For the minimal 5+5bar model, the color-octet may have already shown their hints. My bet is $1.6 \text{ TeV} > 2.2 \text{ TeV} > 1.1 \text{ TeV}$.



Thanks!

