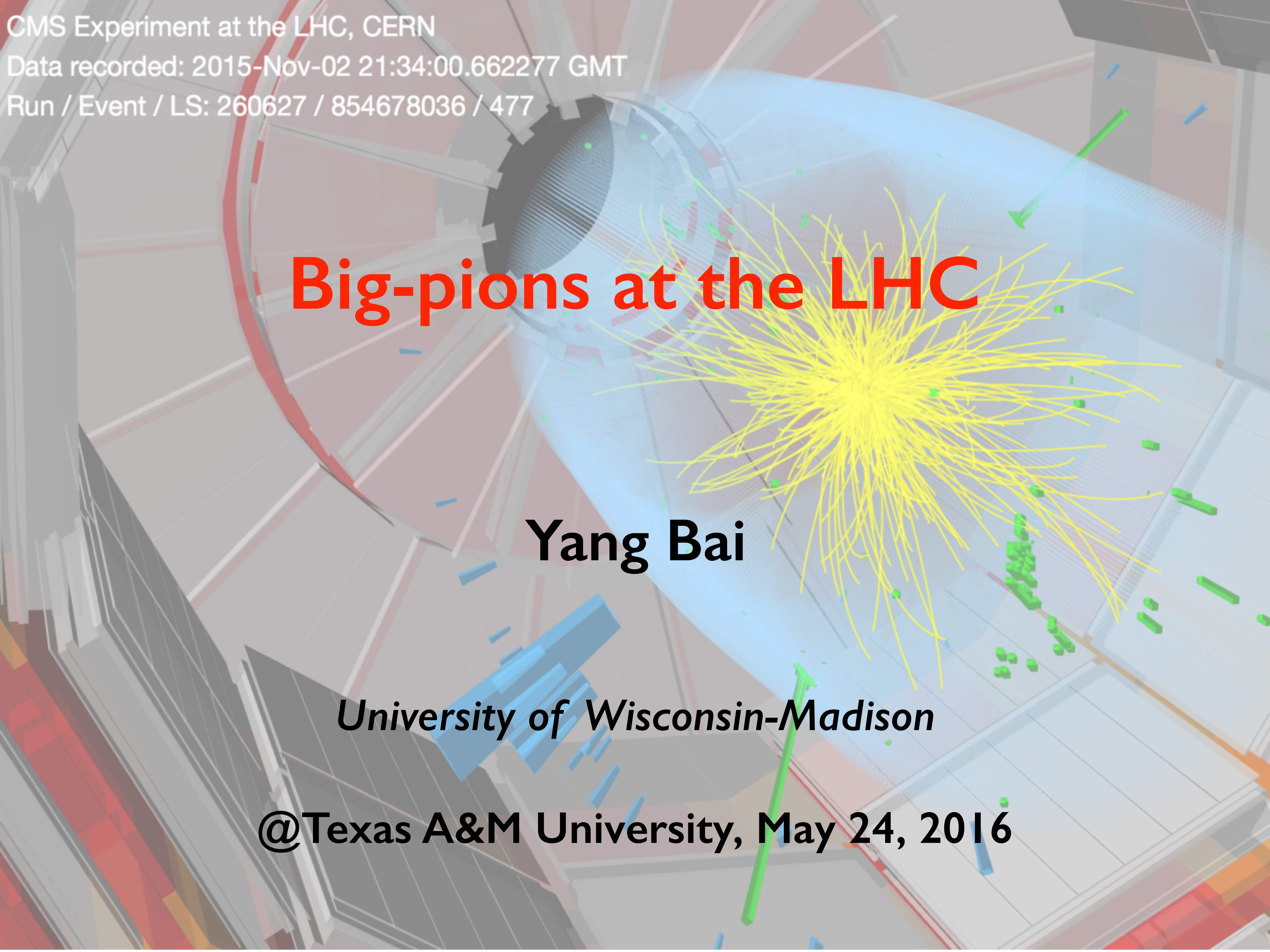
Big-pions at the LHC

Yang Bai

University of Wisconsin-Madison

@Texas A&M University, May 24, 2016



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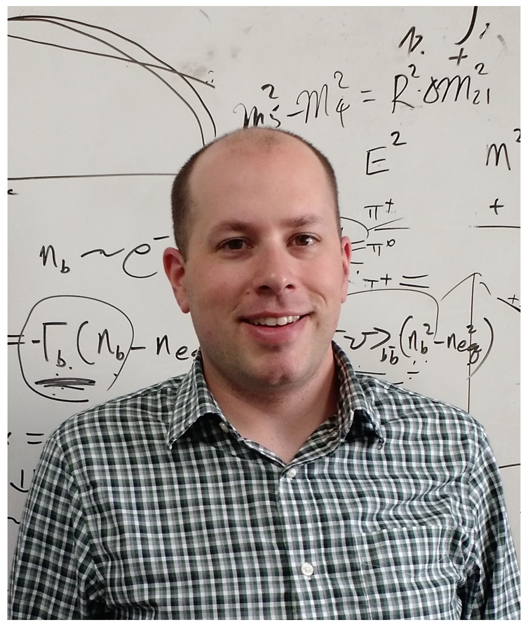
collaborators:

Vernon Barger



Joshua Berger

Ran Lu

James Osborne

Ben Stefanek

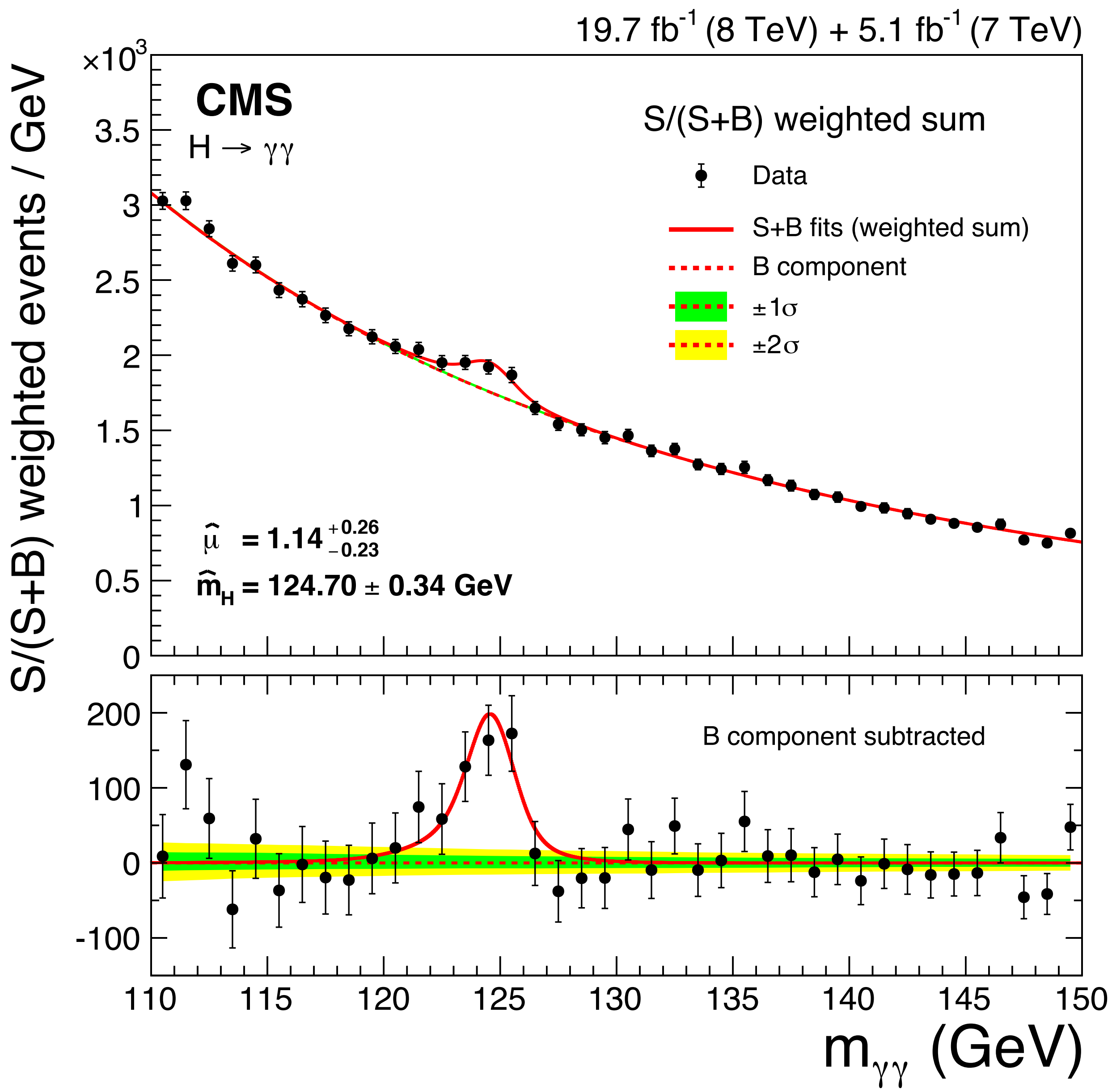
YB, Joshua Berger, Ran Lu, arXiv:1512.05779

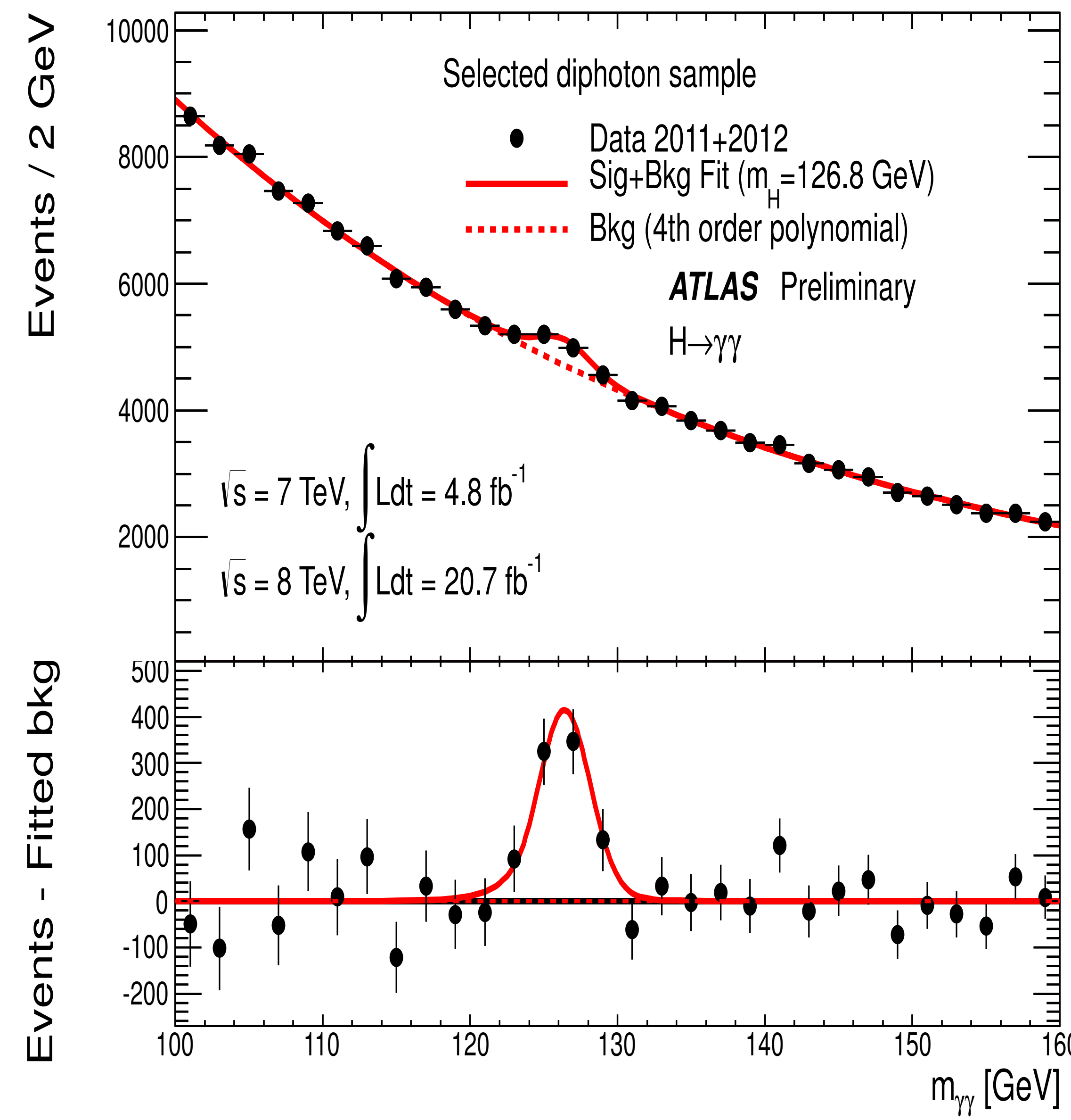
YB, Joshua Berger, arXiv:1603.07335

YB, Vernon Barger, Joshua Berger, arXiv:1604.07835

YB, Joshua Berger, James Osborne, Ben Stefanek, arXiv:1605.today

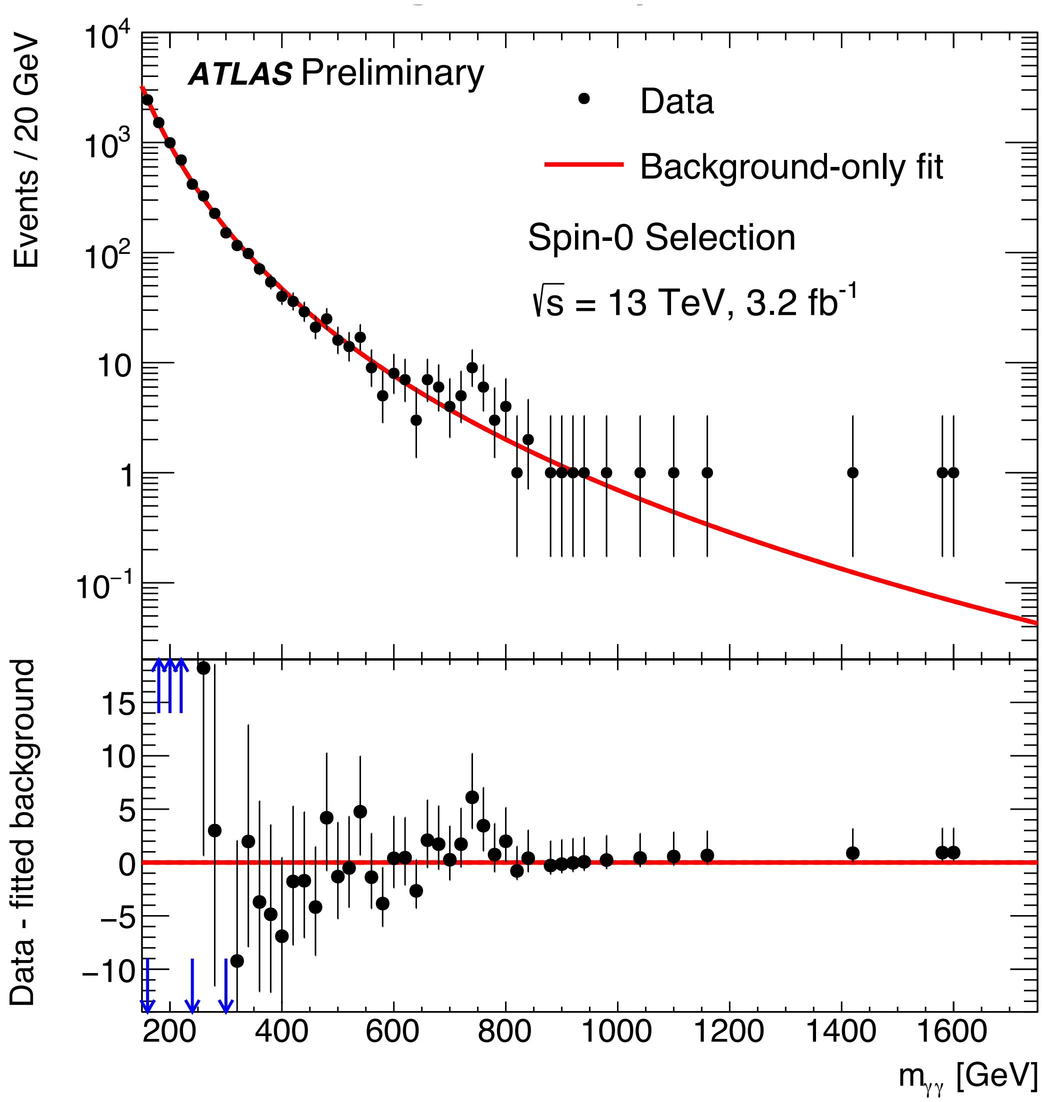
Higgs Discovery in Diphoton



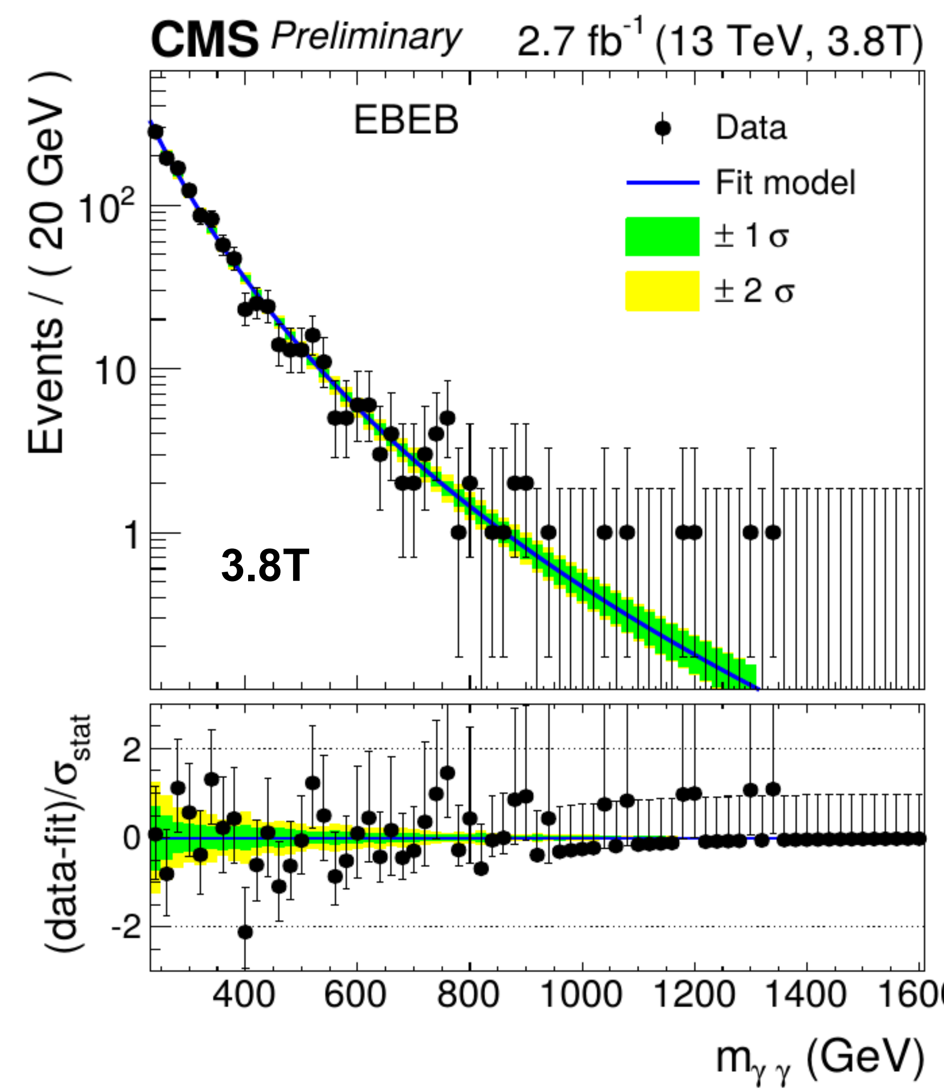


Hint of a Heavier Diphoton Resonance

ATLAS, Moriond EW, 2016



CMS, Moriond EW, 2016

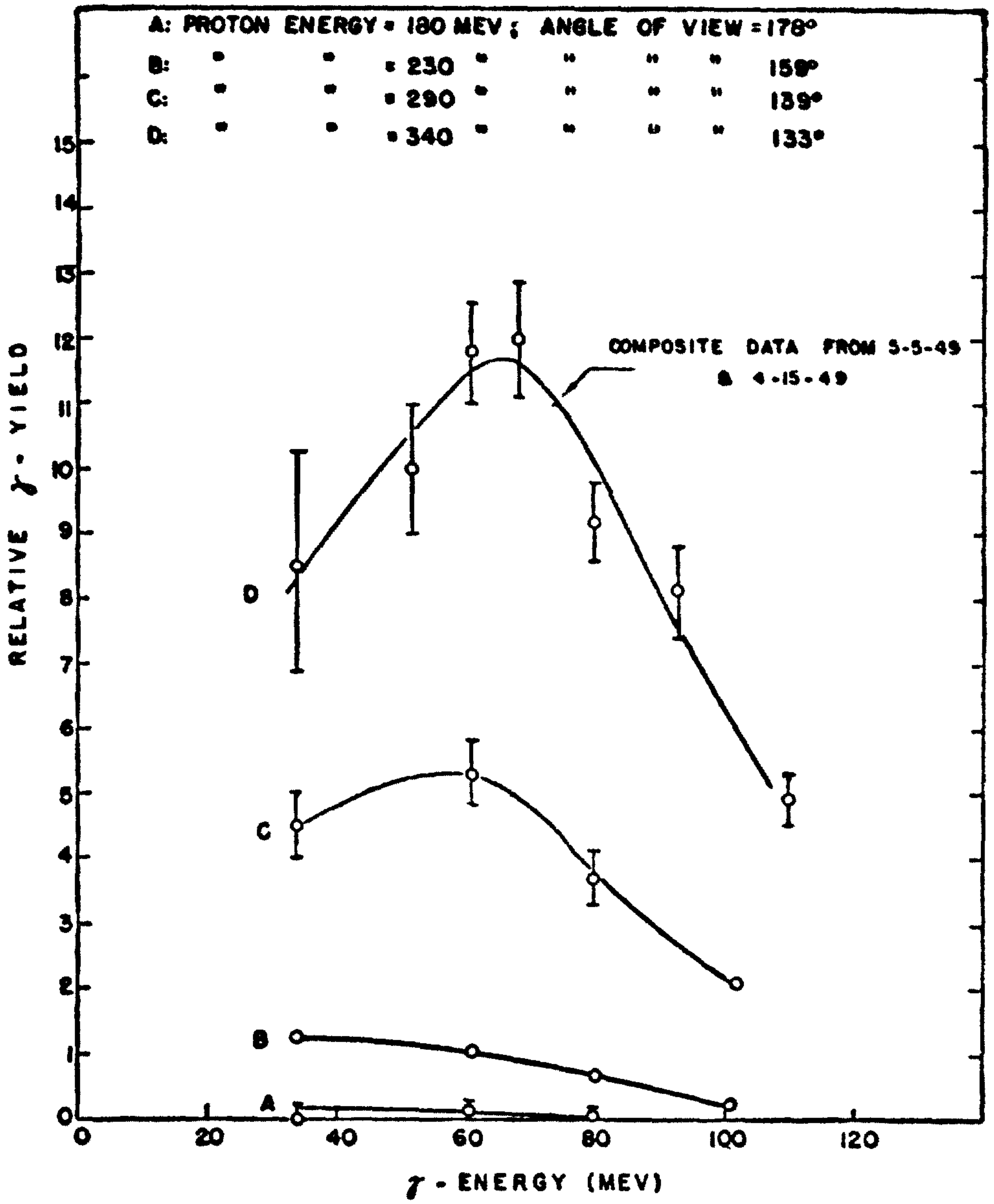


- The resonance mass is around 750 GeV and could be a narrow or a broad or two narrow ones
- The required cross section to explain the excess is around 5 fb

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

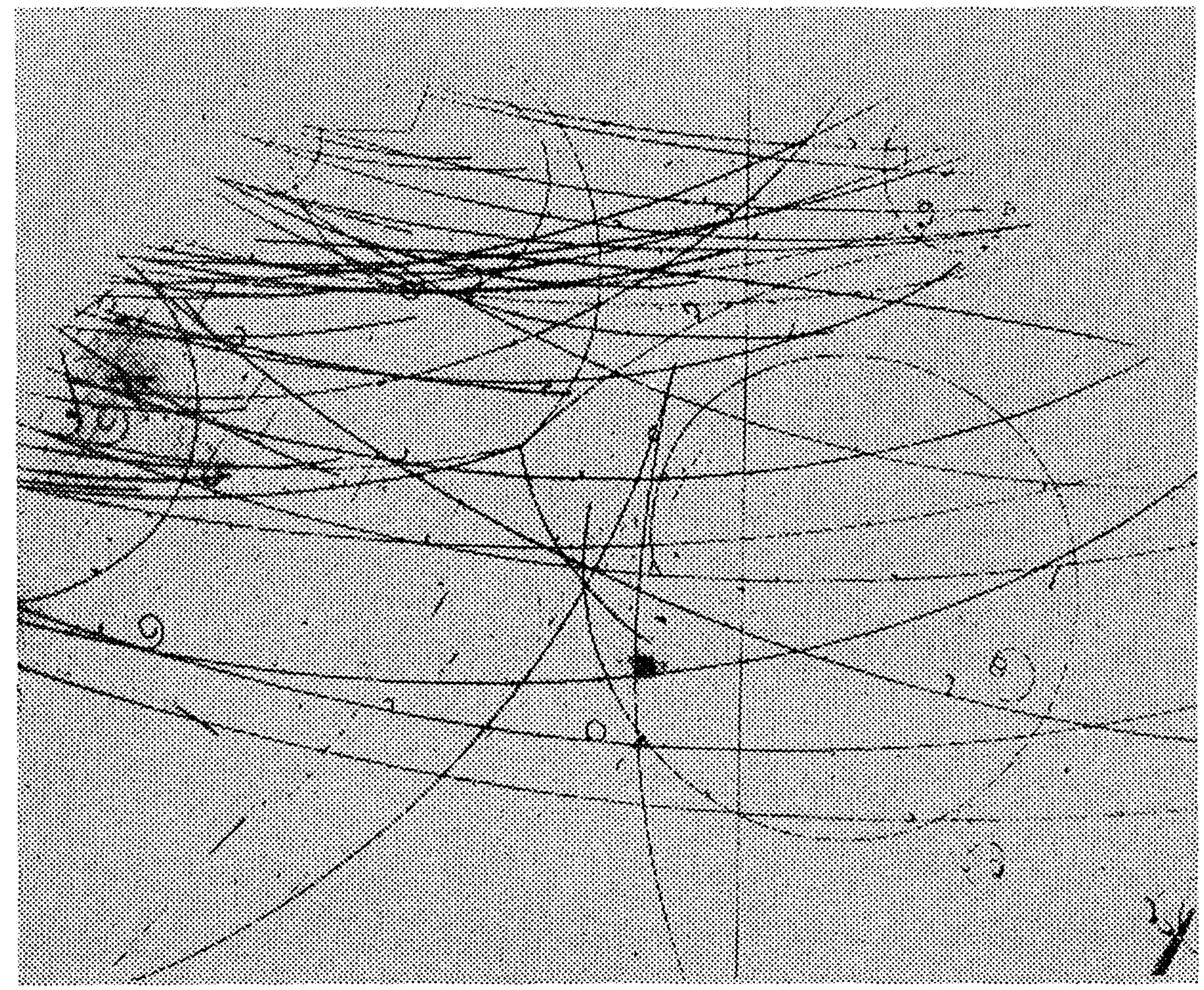
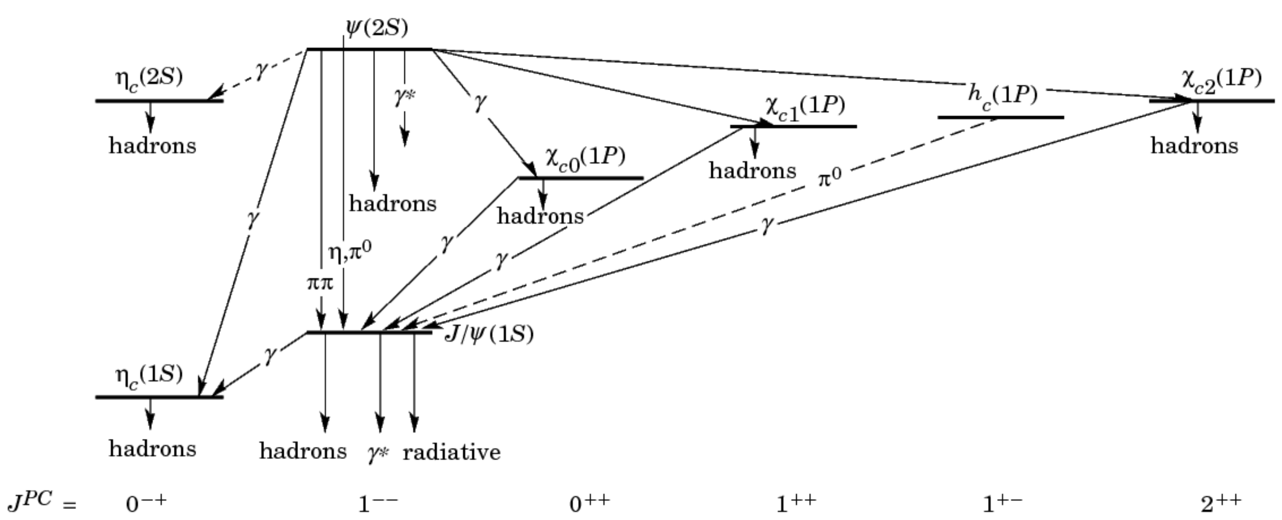


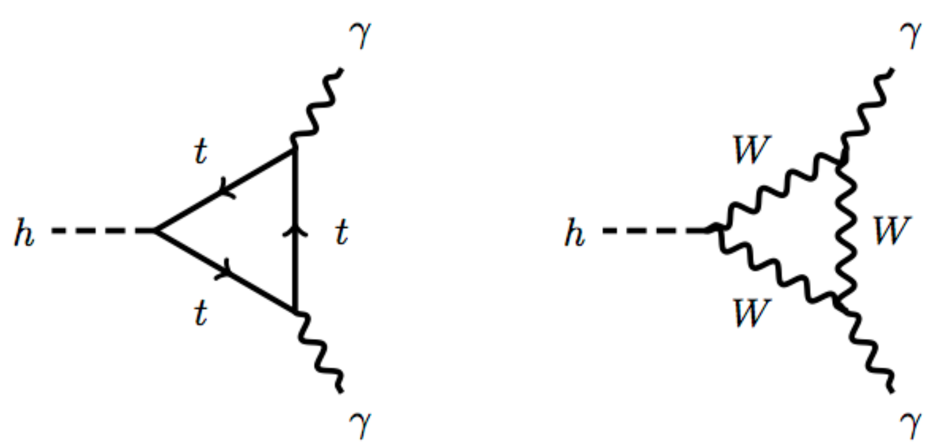
FIG. 1. Photograph of a typical double internal conversion.

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**

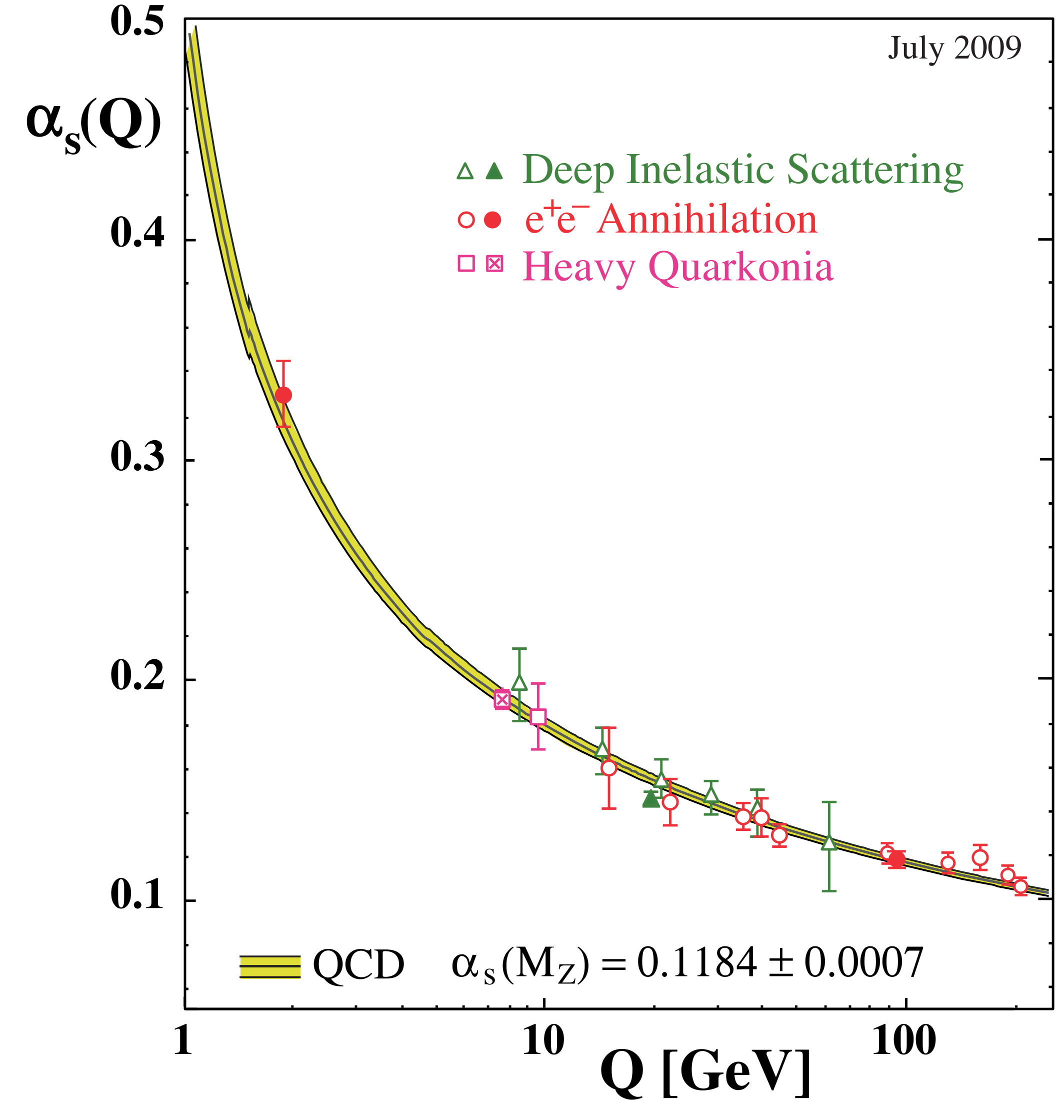


- Other than perturbative Landau pole argument for some perturbative models and additional top-down (GUT compatible) motivations, we need more experimental information to solve this nice inverse problem.

Intro. for Quantum Chromo-Dynamics

- The two faces of QCD:
  - asymptotic freedom at large momentum
  - confinement and chiral symmetry breaking at an infrared scale
- Below the QCD scale $\Lambda_{\rm QCD}$, descriptions change from quarks to mesons

	$SU(N_c)$	$U(1)_{EM}$
$u_{L,R}$	N_c	$\frac{2}{3}$
$d_{L,R}$	N_c	$-\frac{1}{3}$
$s_{L,R}$	N_c	$-\frac{1}{3}$

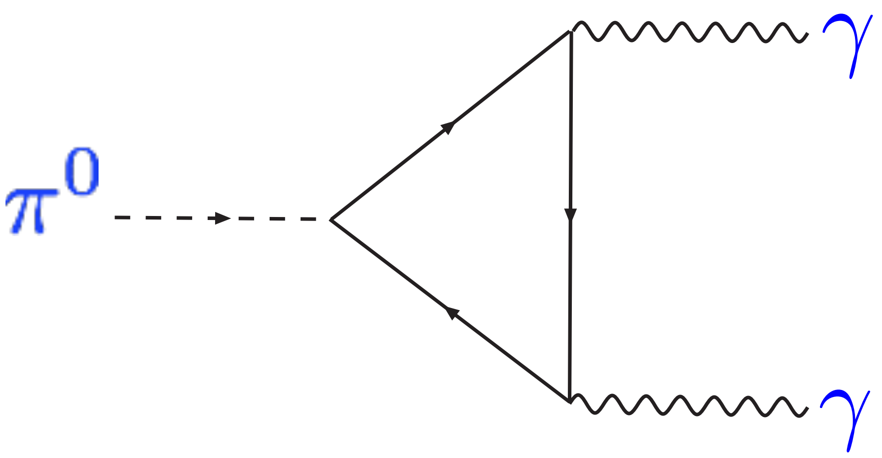


- The global chiral symmetry breaking is: $SU(3)_L \times SU(3)_R \to SU(3)_V$
- There are 8 PNGB's: $\pi^0, \pi^\pm, K^\pm, K^0, \overline{K}^0, \eta$

Neutral Pion Decay

- The charged pion decays with Gf suppressed interactions.

- **The neutral pion decays into two photons via triangle-anomaly, so it has a much shorter lifetime.**



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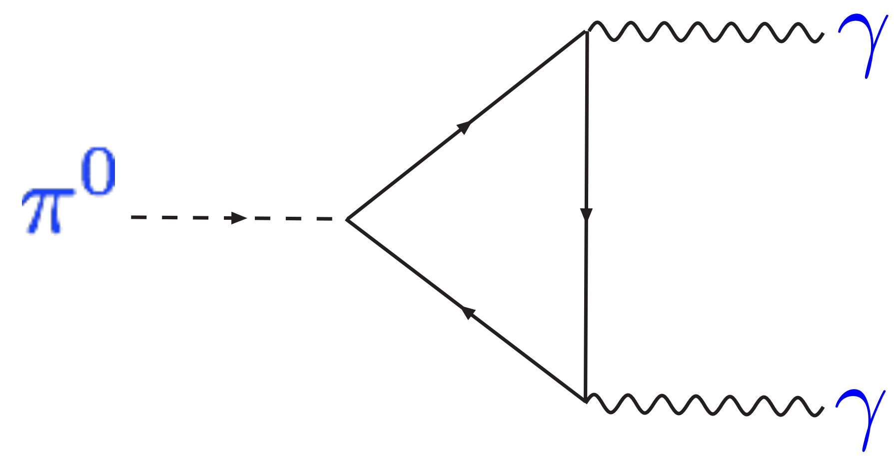


There is one less familiar discrete symmetry

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

$\boxed{\pi^0}$

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

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

G-parity

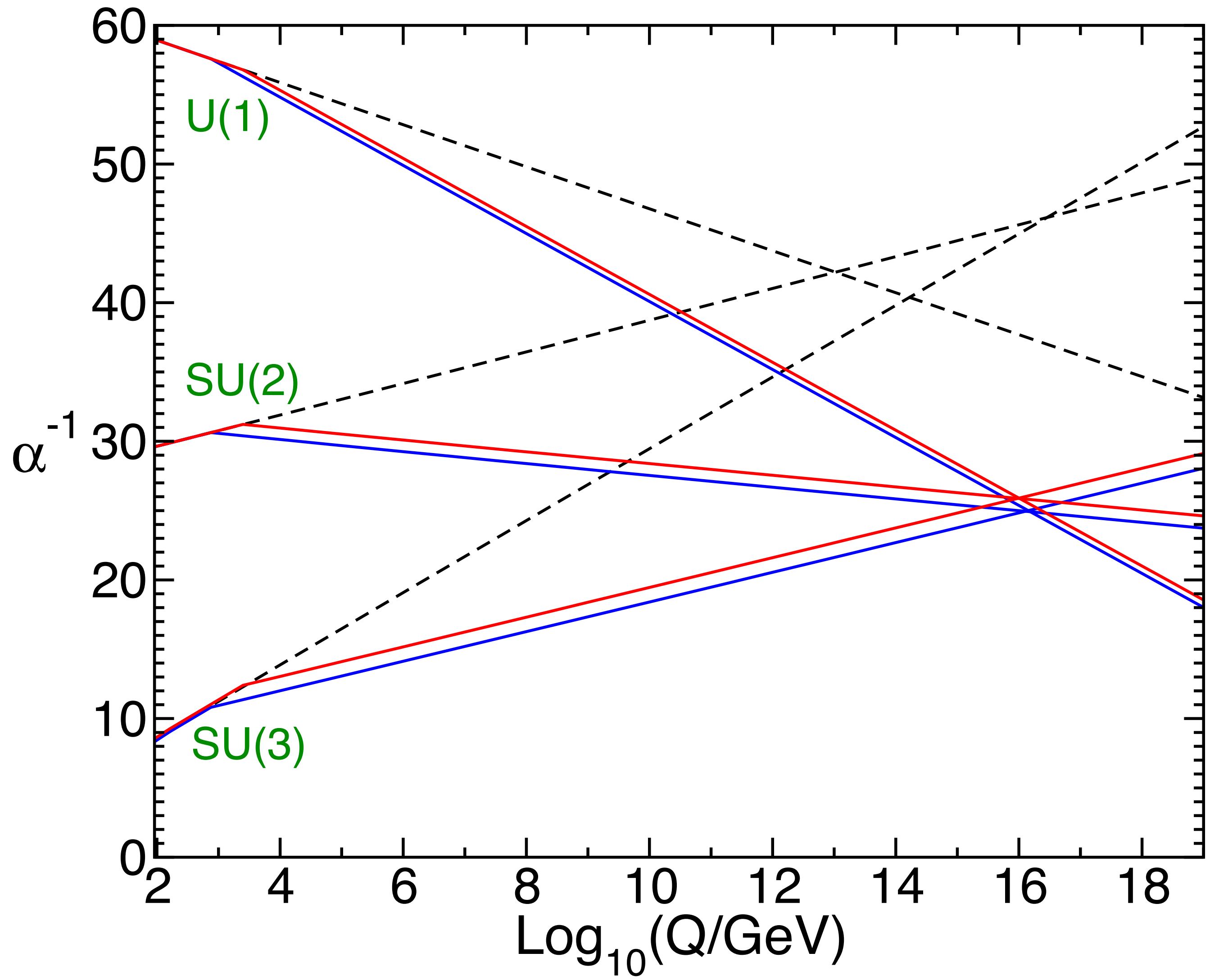
The G-parity is defined to be: $G = \mathcal{C}\exp[i\pi I_2]$

Michel '1953
Lee and Yang '1956

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

- The existence of a good G-parity forbids the neutral pion from decaying into two photons.
- 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 a later part of this talk, I will also discuss a new G-parity in a new strong-dynamics sector could be unbroken and provide us a stable dark matter candidate.**

Grand Unified Theory



$$SU(5)_{\rm GUT} \supset SU(3)_c \times SU(2)_W \times U(1)_Y$$

$$5 = (3,1)_{-1/3} + (1,2)_{1/2}$$

$$\overline{10} = (3,1)_{2/3} + (\bar{3},2)_{-1/6} + (1,1)_{-1}$$

750 GeV Resonance as a Big Pion

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

	$SU(N_b)$	$SU(5)_{\rm GUT}$
$(\psi_L^{\rm D},\ \psi_L^{\rm L})$	N_b	5
$(\psi_R^{\rm D},\ \psi_R^{\rm L})$	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: $SU(5)_L \times SU(5)_R \to SU(5)_V$

- There are 24 PNGB's or big-pions [$N_b = 2$ has 44 PNGB's]

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

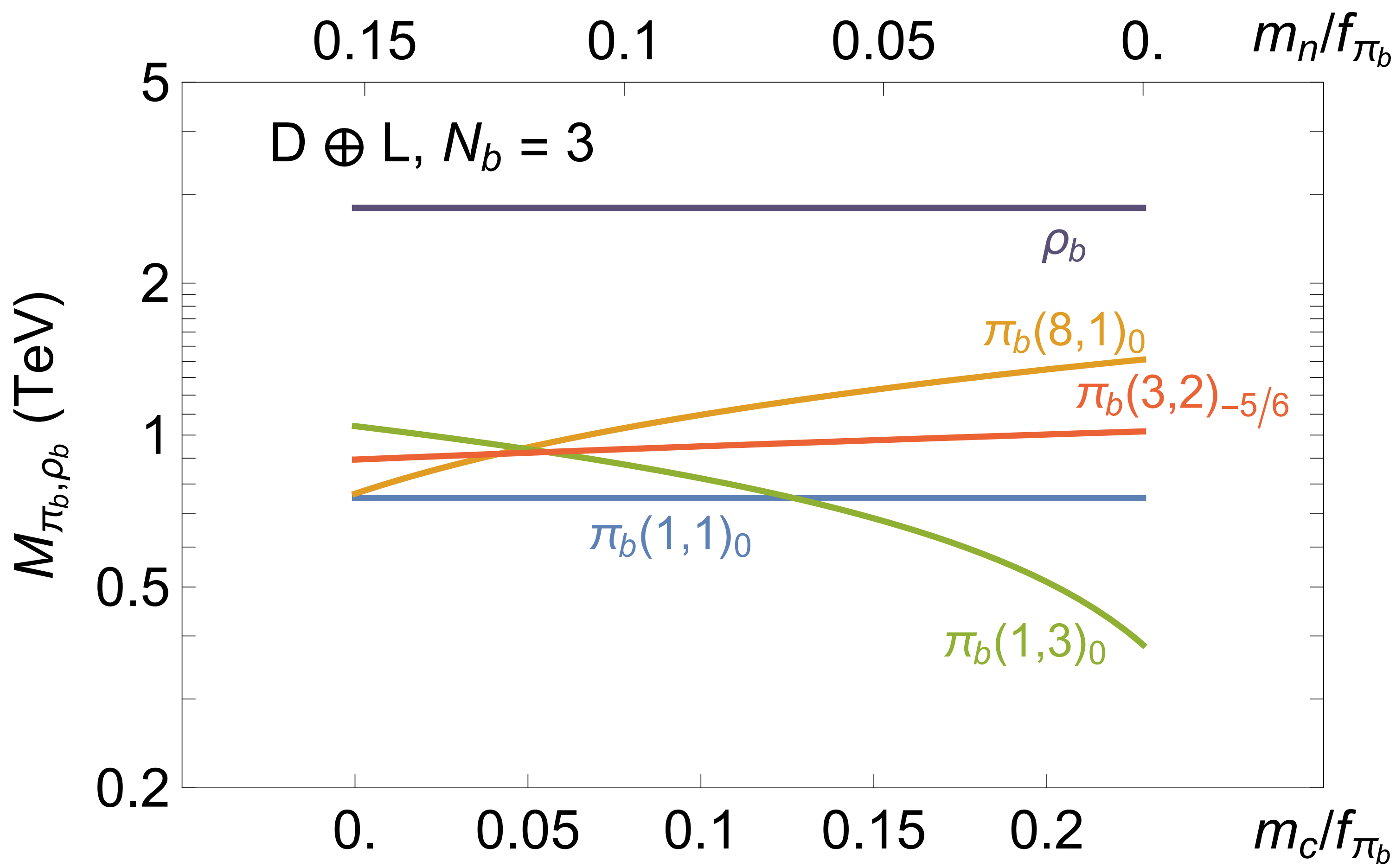
- **The SM-singlet $(1,1)_0$ could be the 750 GeV resonance**

Sample Meson Spectrum

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

- The SM charged pions receive additional loop contributions:

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

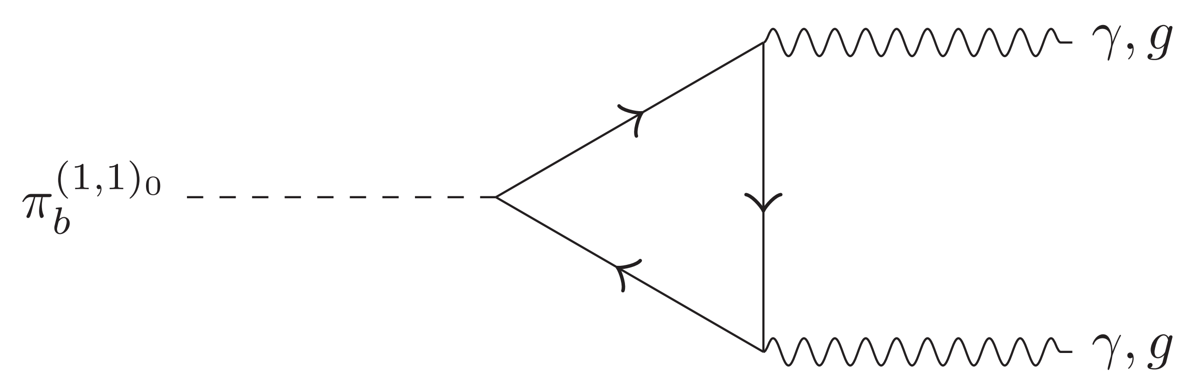


- **For instance, the color-octet pion should have a mass below around 2.8 TeV for all ranges of N_b and for the 750 GeV diphoton signal around 5.0 fb.**

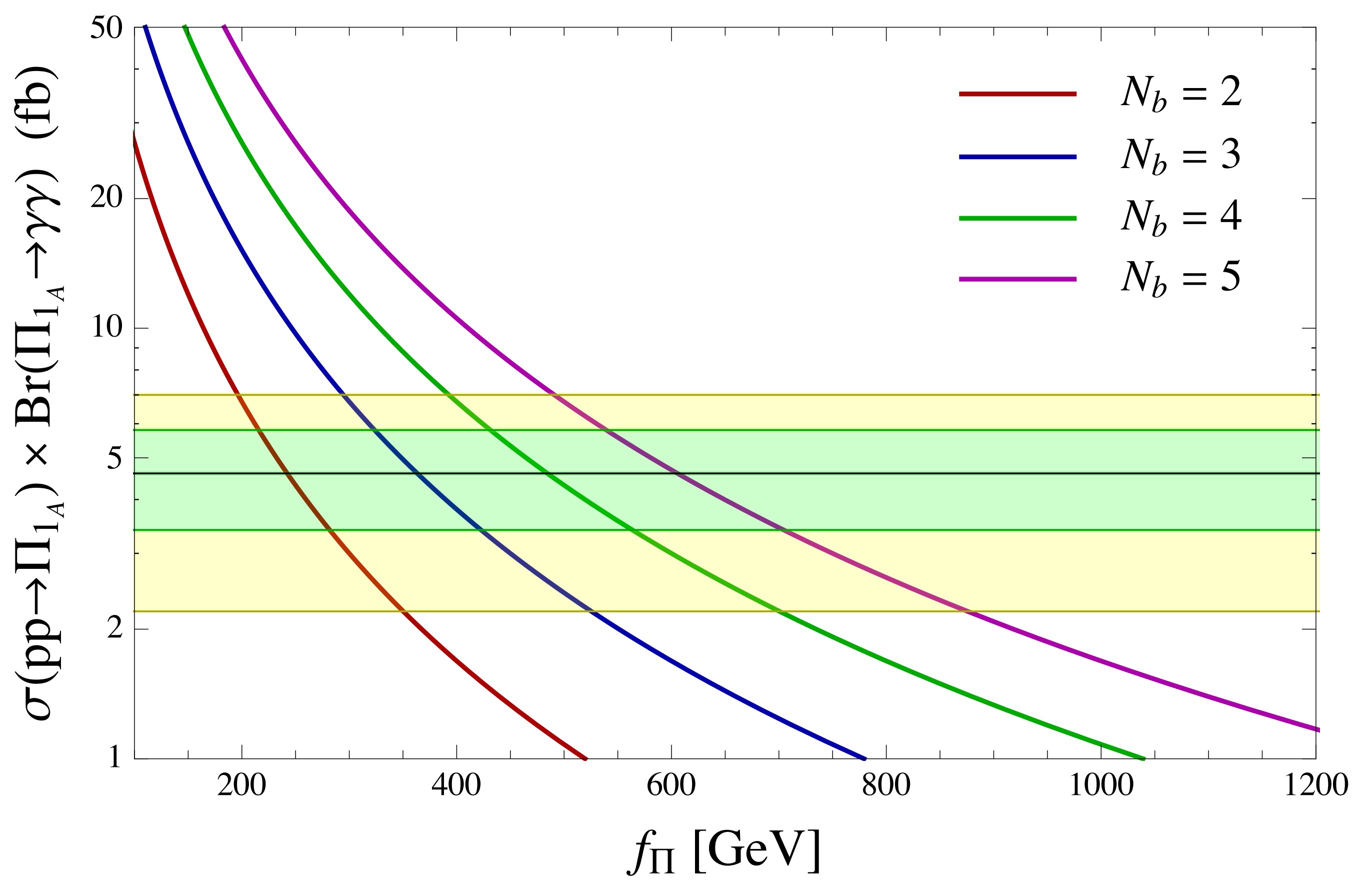
- The vector ρ_b meson must be below around 5 TeV.

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.

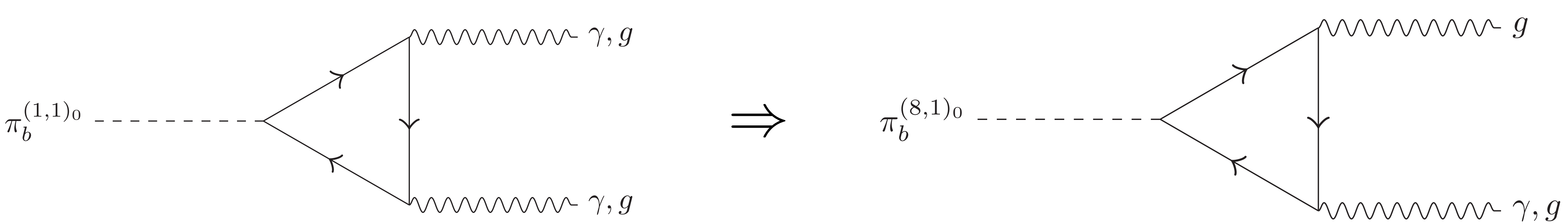
Other Things to Look For

- 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:

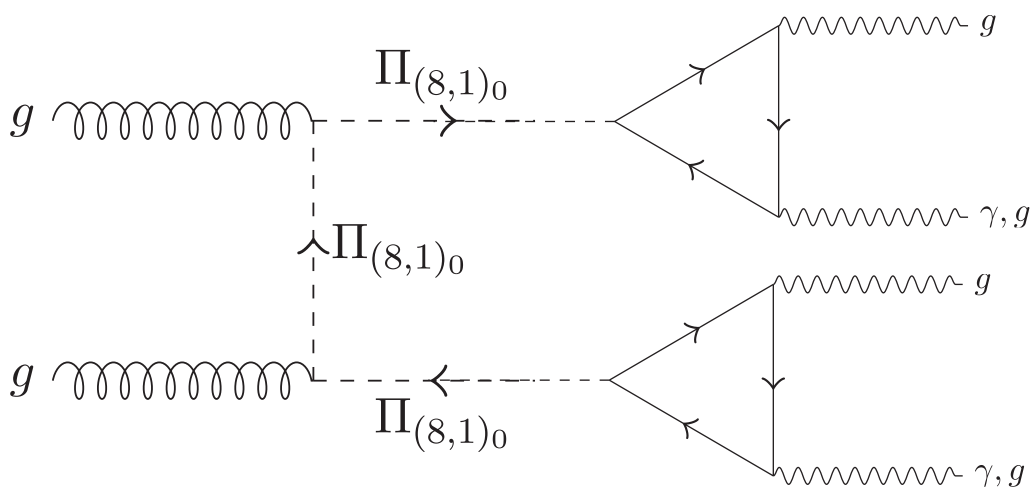
$$-\frac{\alpha_s}{8\pi\, f_\Pi}\,\frac{N_d}{2}\, d^{abc}\,\Pi^{8\,a}\,\epsilon_{\mu\nu\rho\sigma}\,G^{\mu\nu\,b}\,G^{\rho\sigma\,c} + 2\,\frac{\sqrt{\alpha_Y\,\alpha_s}}{8\pi\, f_\Pi}\,\frac{N_d}{3}\,\Pi^{8\,a}\,\epsilon_{\mu\nu\rho\sigma}\,G^{\mu\nu\,a}\,B^{\rho\sigma}$$

- 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:

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

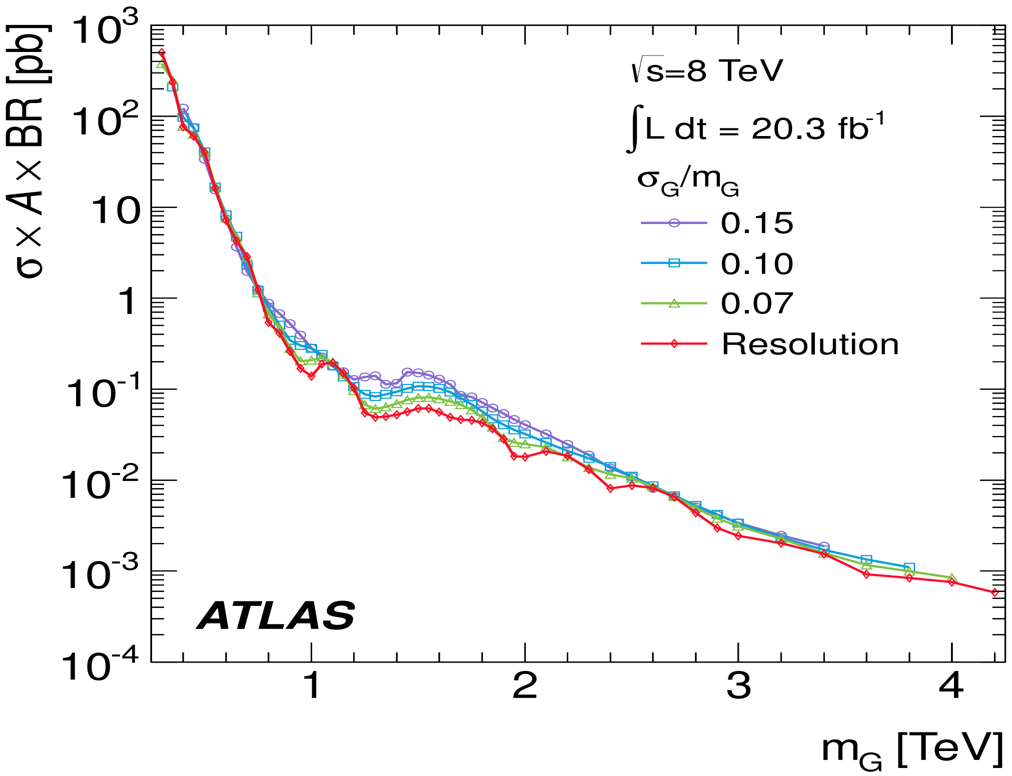
- **The decay constant and the big-color rank are factored out.**

- **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.**

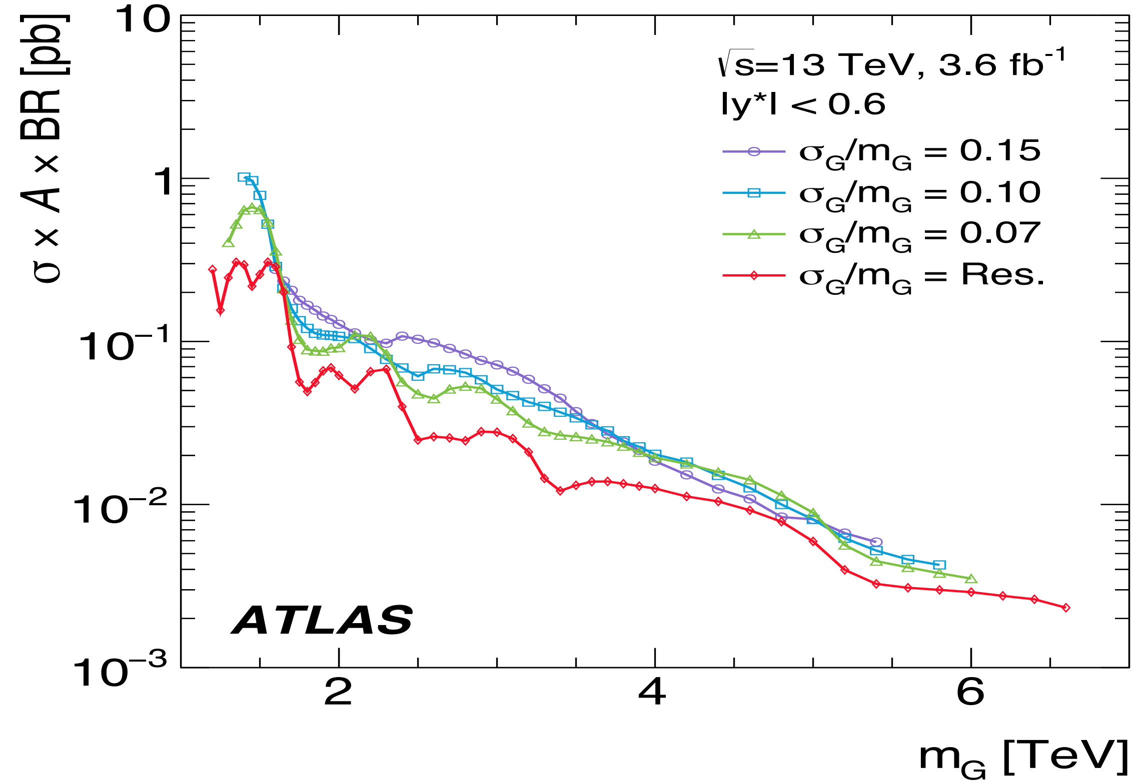
- **The existing search for dijet and jet+photon resonances can be applied to constrain the color-octet states.**

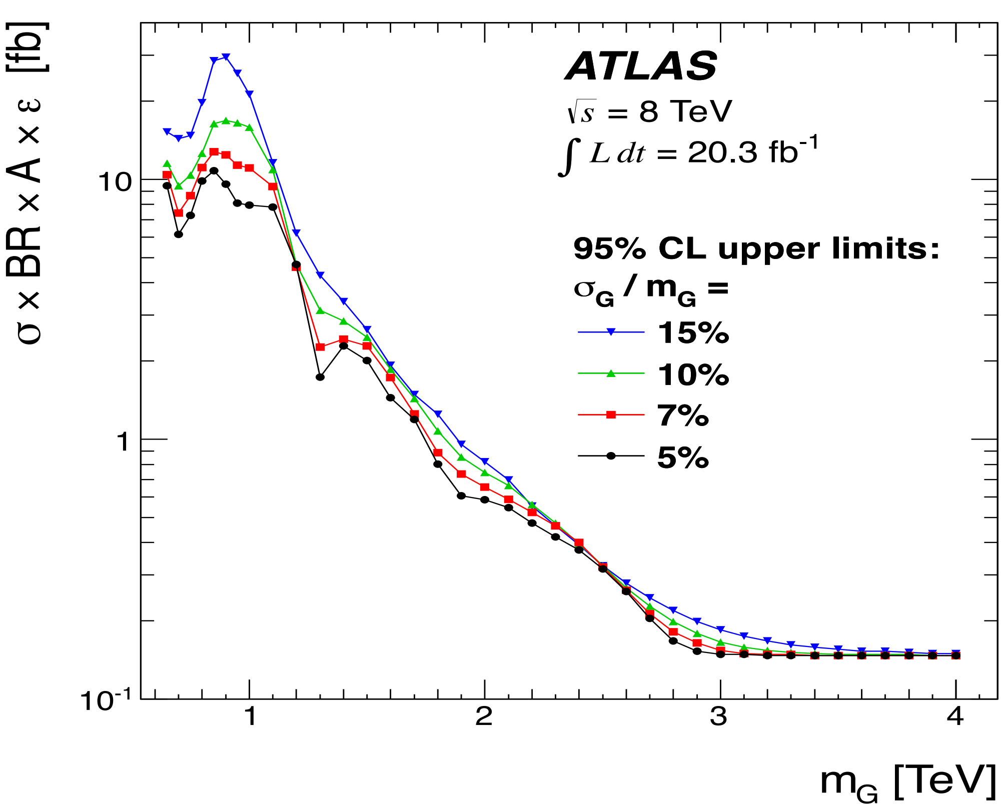
- The usual motivations for those searches are excited quarks with a larger width. The color-octet pion has a width much smaller than the detector-resolution-generated widths.

Dijet and photon+jet Narrow Resonance

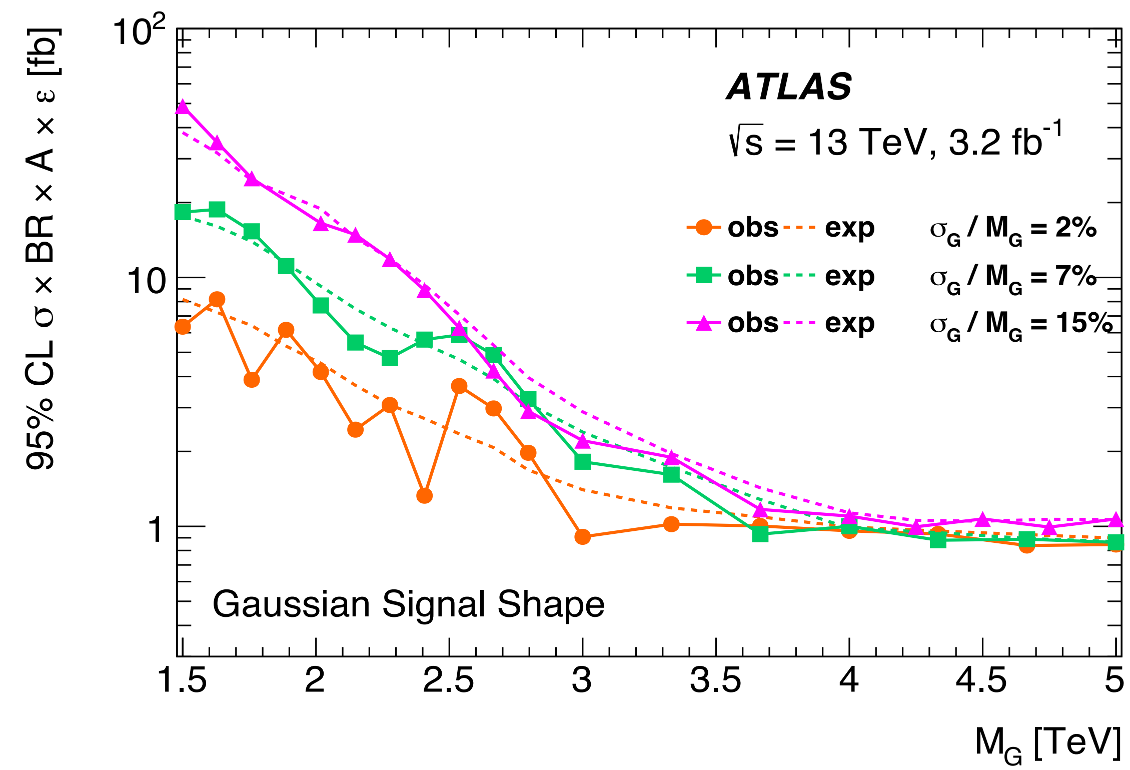


dijet

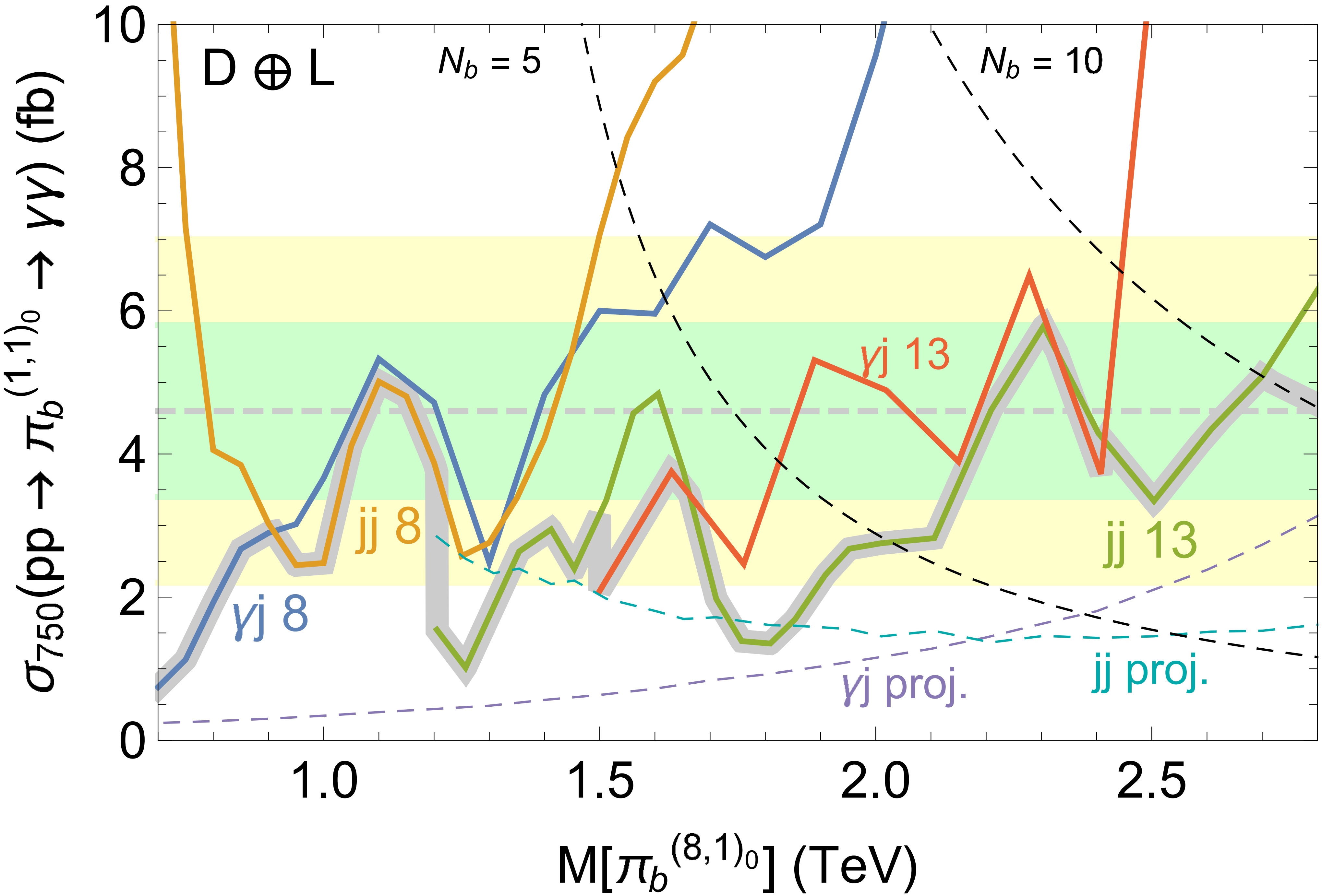




$j + \gamma$

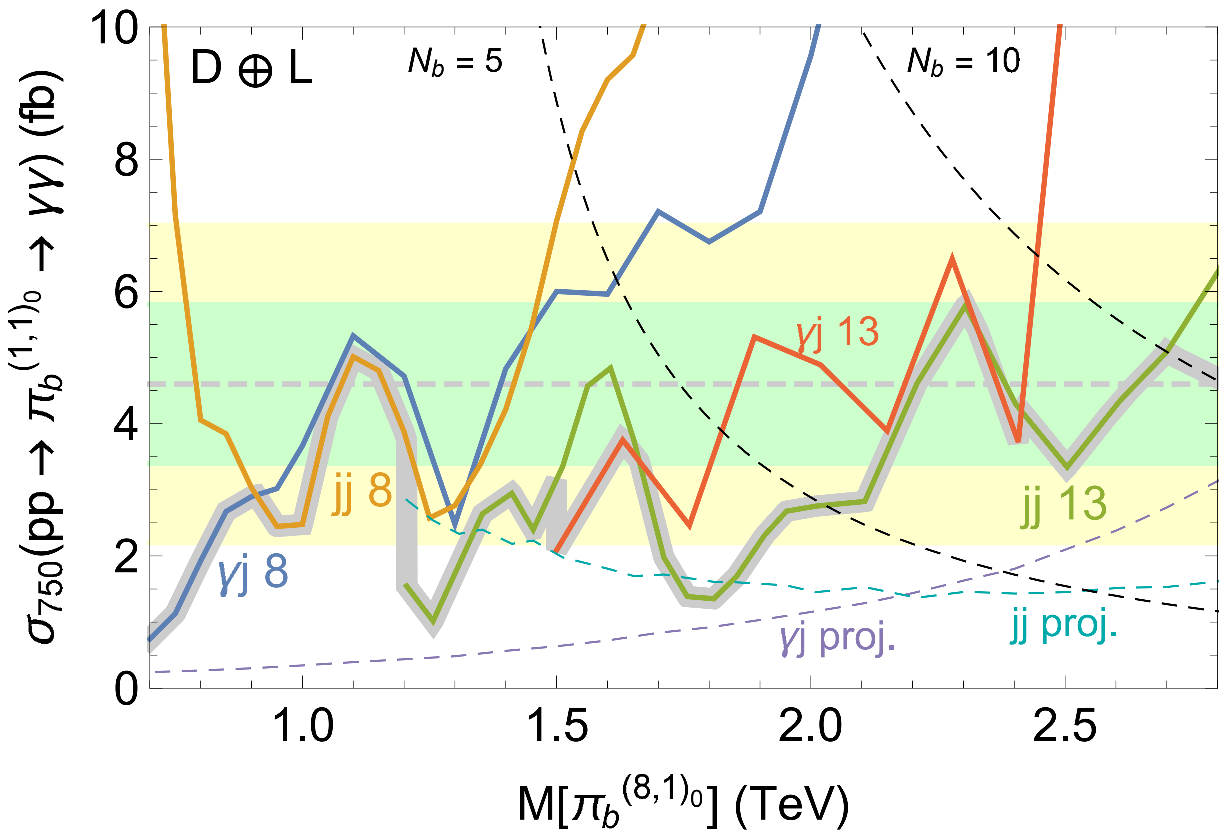


Color-octet Correlated Bound on 750 GeV Diphoton Rate



Color-octet Correlated Bound on 750 GeV Diphoton Rate

- **For the allowed range of color-octet masses, the diphoton rate is constraints 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.

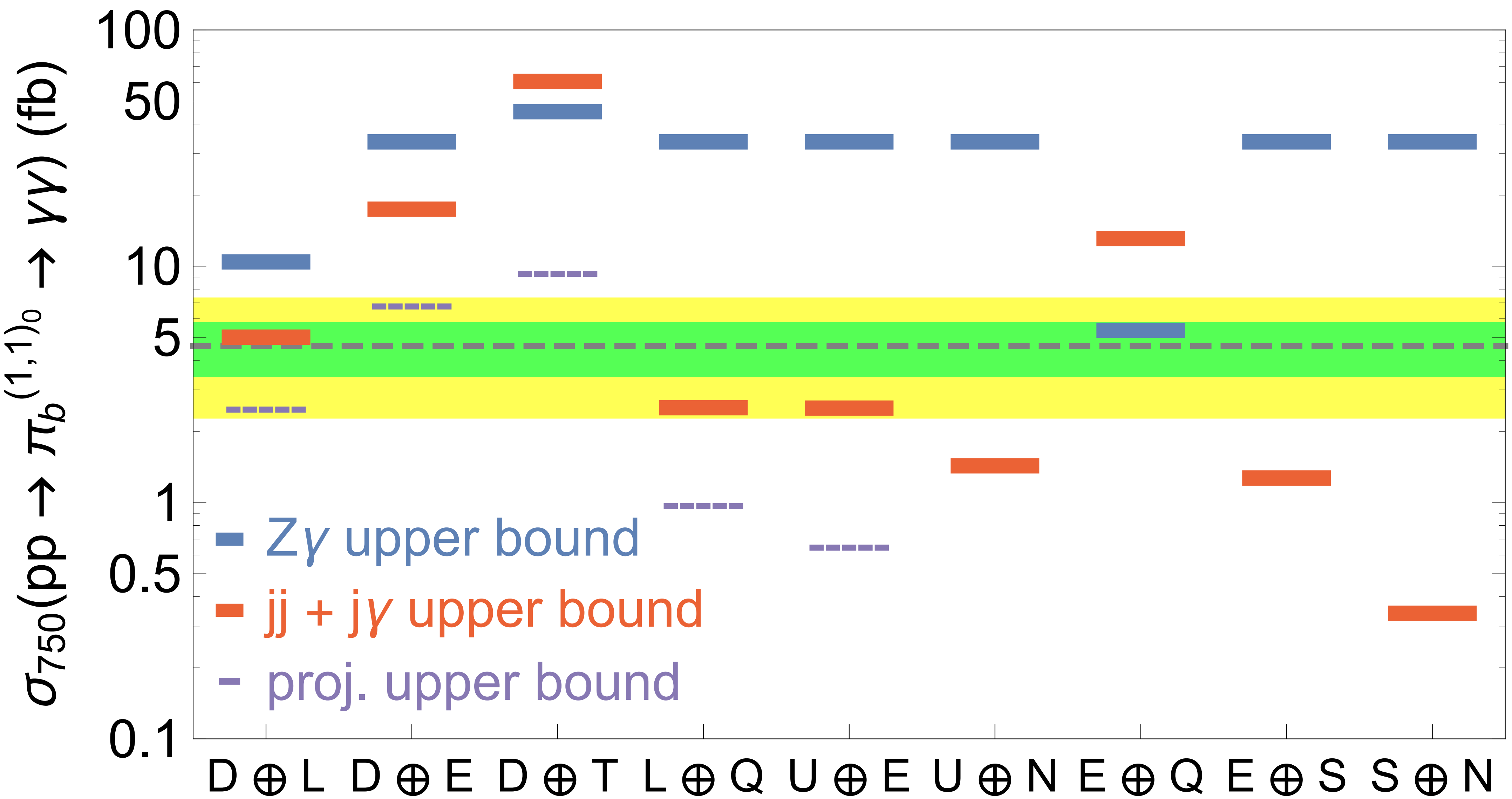
More Composite Models

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: 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.

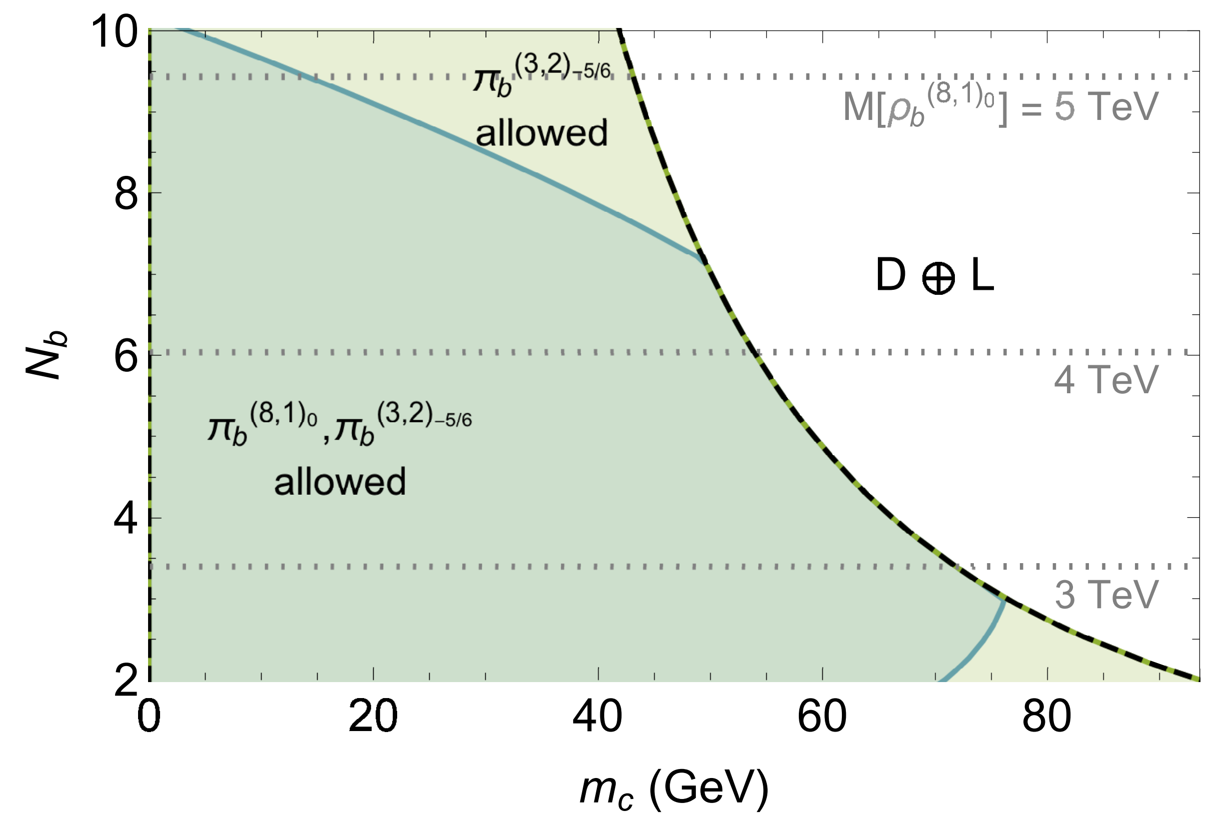
Status for More Composite Models

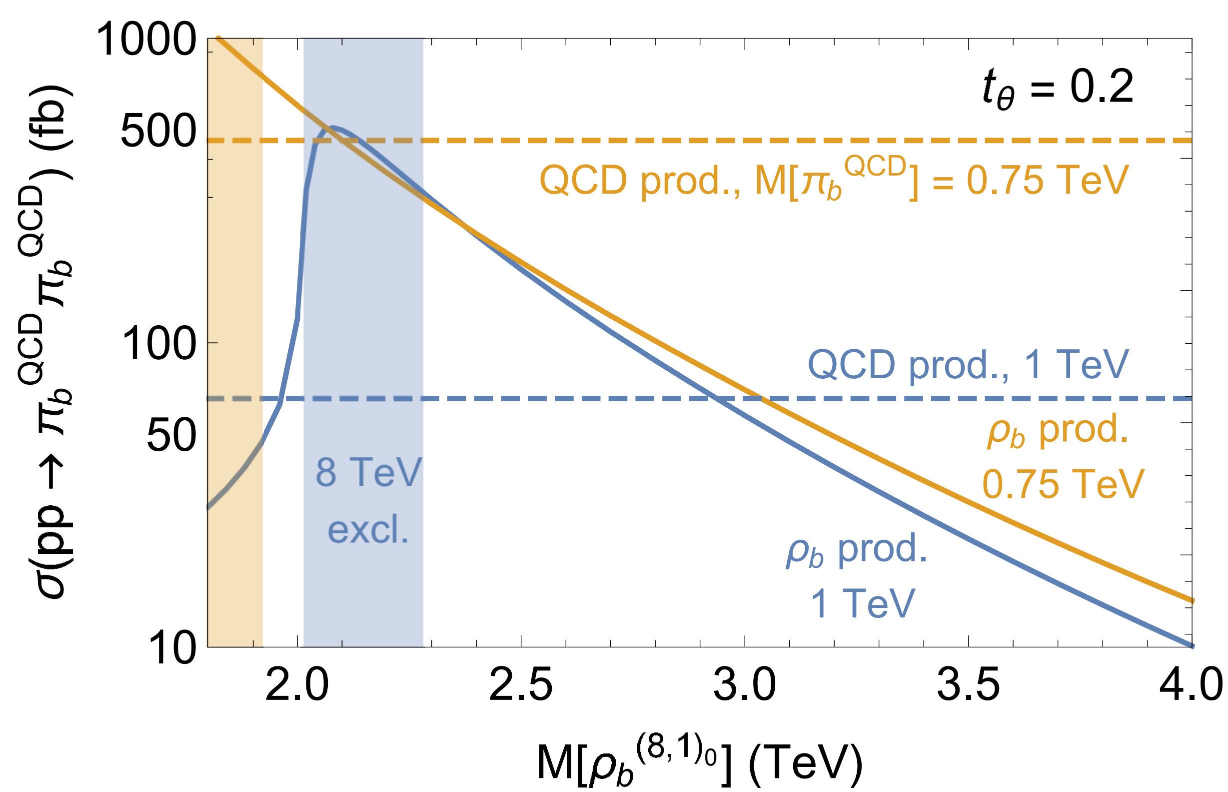


- More than a half of models are constrained by their color-octet (color-27) state properties.
- For the D+E and D+T models, one could look for the color-triplet pions via their leptoquark or diquark decays.

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 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.

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

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

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

- 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

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

see also 0906.0577 by Kilic, Okui, Sundrum

Dark-G-even and odd Heavy Pions

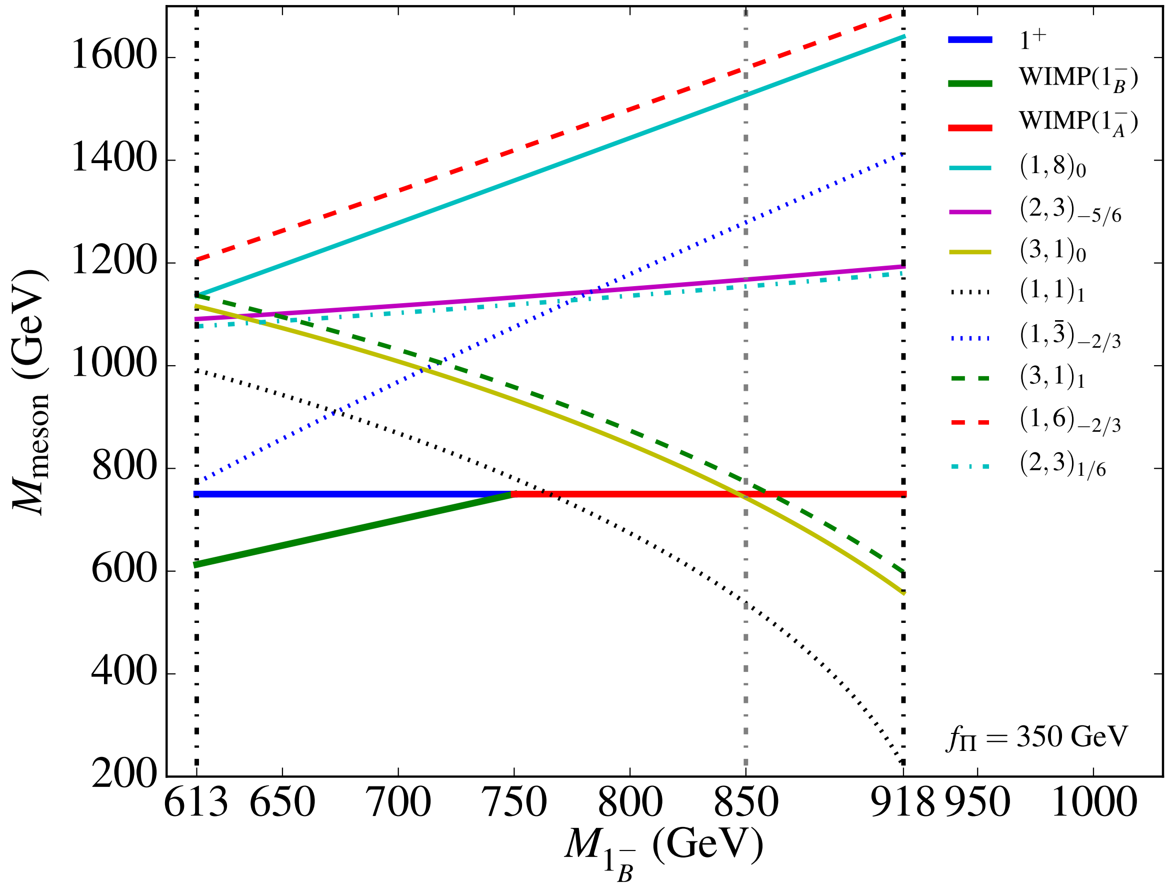
- There totally 99 new heavy pions:

$$\begin{aligned} \mathbf{10} \times \mathbf{10} - \mathbf{1} &= \mathbf{24}^{+} + \mathbf{24}^{-} + \mathbf{1}^{-} + \mathbf{10} + \mathbf{15} + \overline{\mathbf{10}} + \overline{\mathbf{15}} \\ \mathbf{24}^{+} &= (\mathbf{1},\mathbf{1})_{\mathbf{0}}^{+} + (\mathbf{3},\mathbf{1})_{\mathbf{0}}^{+} + (\mathbf{2},\mathbf{3})_{-\mathbf{5}/\mathbf{6}}^{+} + (\mathbf{2},\bar{\mathbf{3}})_{\mathbf{5}/\mathbf{6}}^{+} + (\mathbf{1},\mathbf{8})_{\mathbf{0}}^{+} \\ \mathbf{24}^{-} &= (\mathbf{1},\mathbf{1})_{\mathbf{0}}^{-} + (\mathbf{3},\mathbf{1})_{\mathbf{0}}^{-} + (\mathbf{2},\mathbf{3})_{-\mathbf{5}/\mathbf{6}}^{-} + (\mathbf{2},\bar{\mathbf{3}})_{\mathbf{5}/\mathbf{6}}^{-} + (\mathbf{1},\mathbf{8})_{\mathbf{0}}^{-} \end{aligned}$$

- 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.**

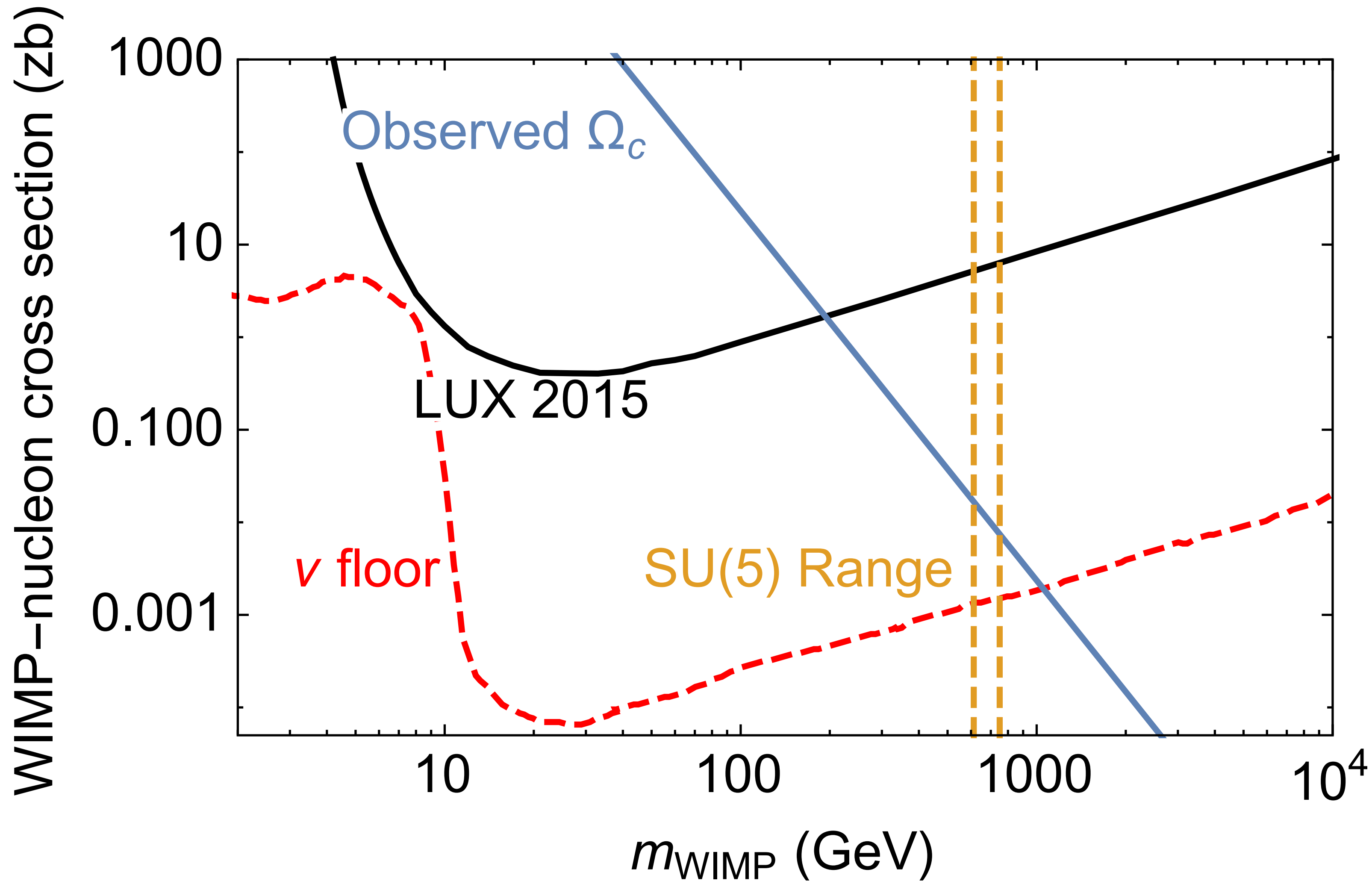
- **The WIMP sits in the (612, 750) GeV mass window**, with the lower bound just from group structure:

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



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**.

	$SU(N_b)$	$SU(5)_{\rm GUT}$	$U(1)'$
$(\psi^{\rm D}_{1,L},\ \psi^{\rm L}_{1,L})$	N_b	5	q_1
$(\psi^{\rm D}_{1,R},\ \psi^{\rm L}_{1,R})$	N_b	5	q_2
$(\psi^{\rm D}_{2,L},\ \psi^{\rm L}_{2,L})$	N_b	$\overline{5}$	$-q_1$
$(\psi^{\rm D}_{2,R},\ \psi^{\rm L}_{2,R})$	N_b	$\overline{5}$	$-q_2$

- 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 $M_{Z'} \approx 310$ GeV

Π_{1_A} decays

Mode	gg	$\gamma\gamma$	$Z\gamma$	ZZ	WW	$Z'\gamma$	$Z'Z$
Branching ratio	0.90	0.0046	0.0079	0.0196	0.062	0.0025	0.0007
Γ_{tot}	$67.4\ \text{MeV} \left(\frac{N_b}{4}\right)^2 \left(\frac{695\ \text{GeV}}{f_\Pi}\right)^2$						

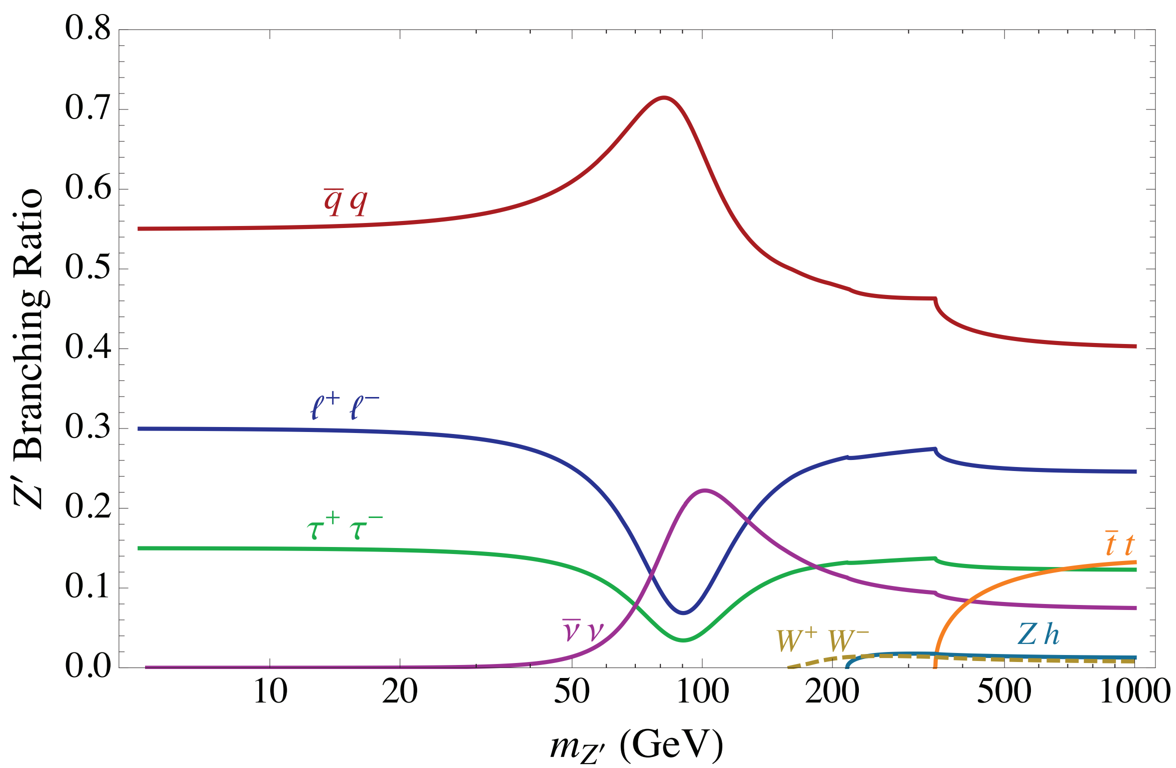
Π^8 decays

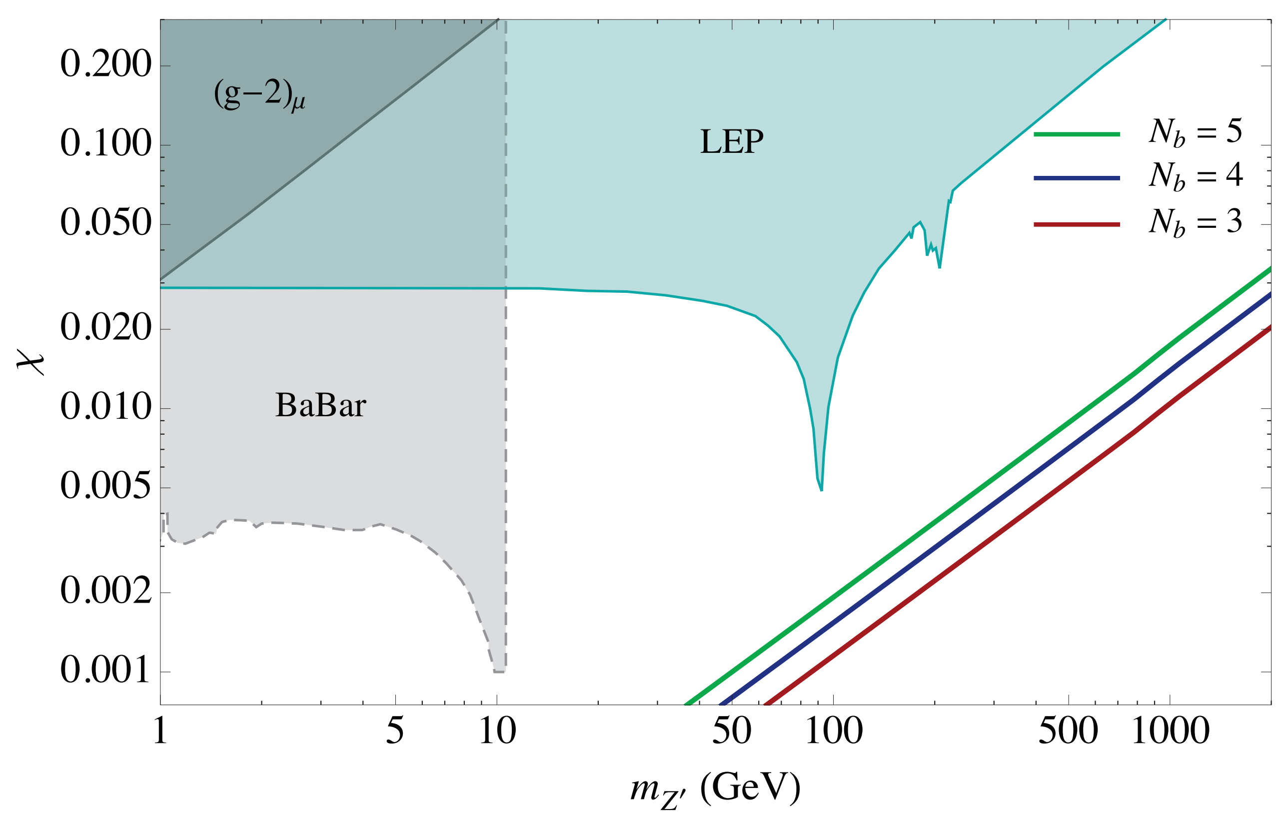
Mode	gg	gZ'	$g\gamma$	gZ
Branching ratio	0.91	0.038	0.042	0.013
Γ_{tot}	$793\ \text{MeV} \left(\frac{N_d}{4}\right)^2 \left(\frac{695\ \text{GeV}}{f_\Pi}\right)^2$			

Z' Properties

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

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

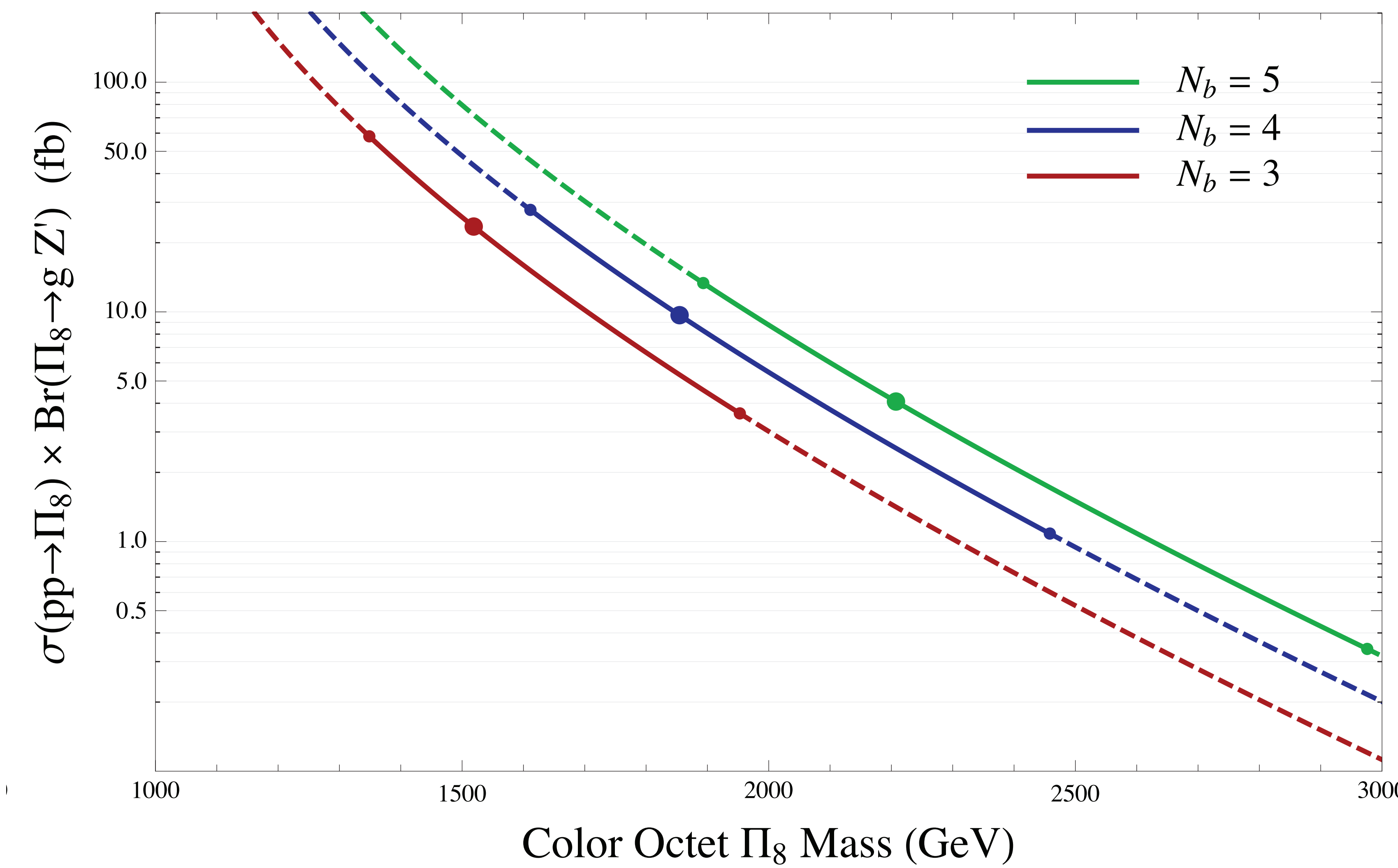




- For a mass above around 200 GeV, there are also small Z' decay branchings to two Z+h and WW.
- The SM Higgs boson could decay into Z'+Z for a small range of parameters space.

$\ell^+\ell^- j$ 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.

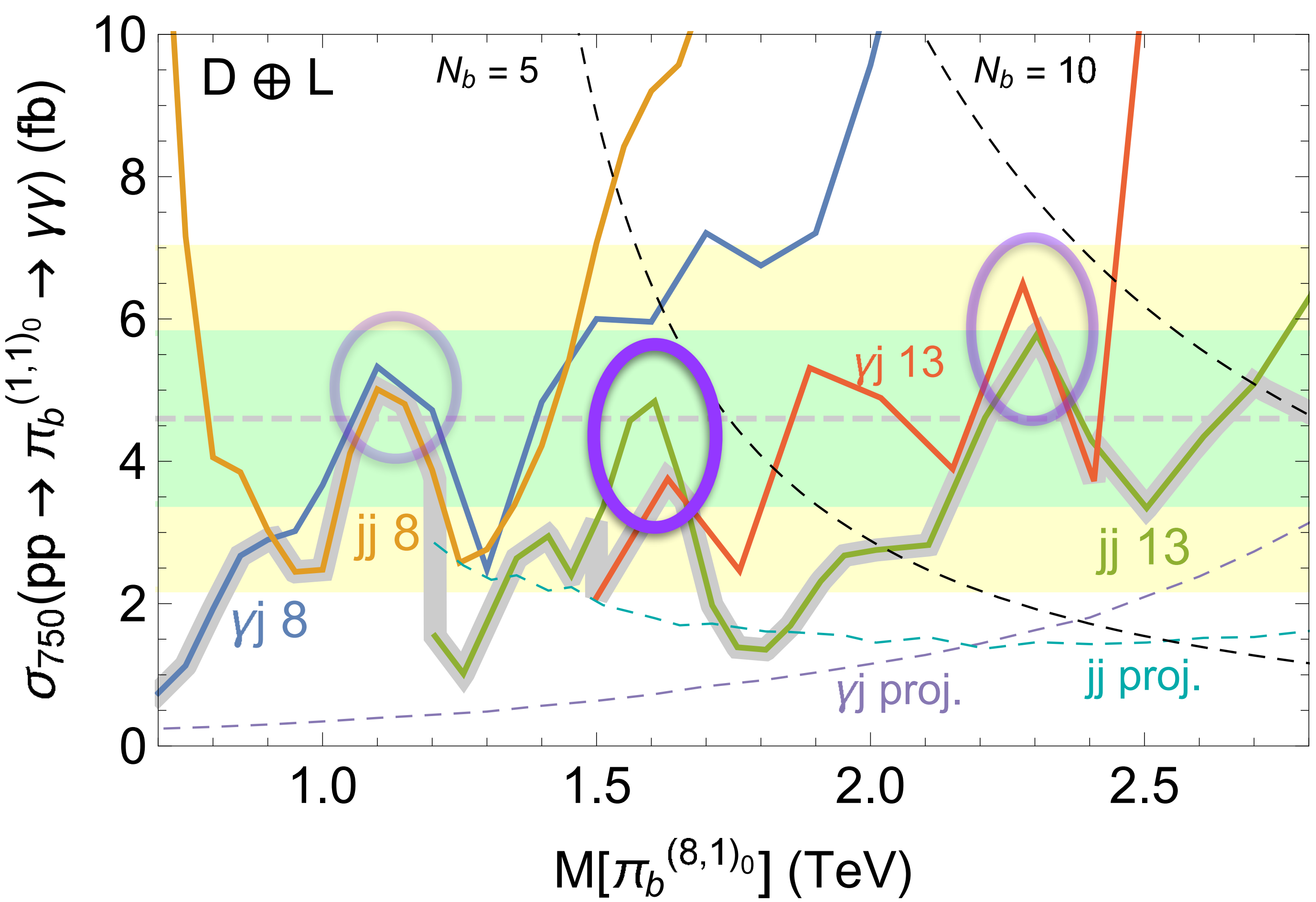
Conclusion

- The composite models to explain 750 GeV diphoton excess will be concretely tested this summer.

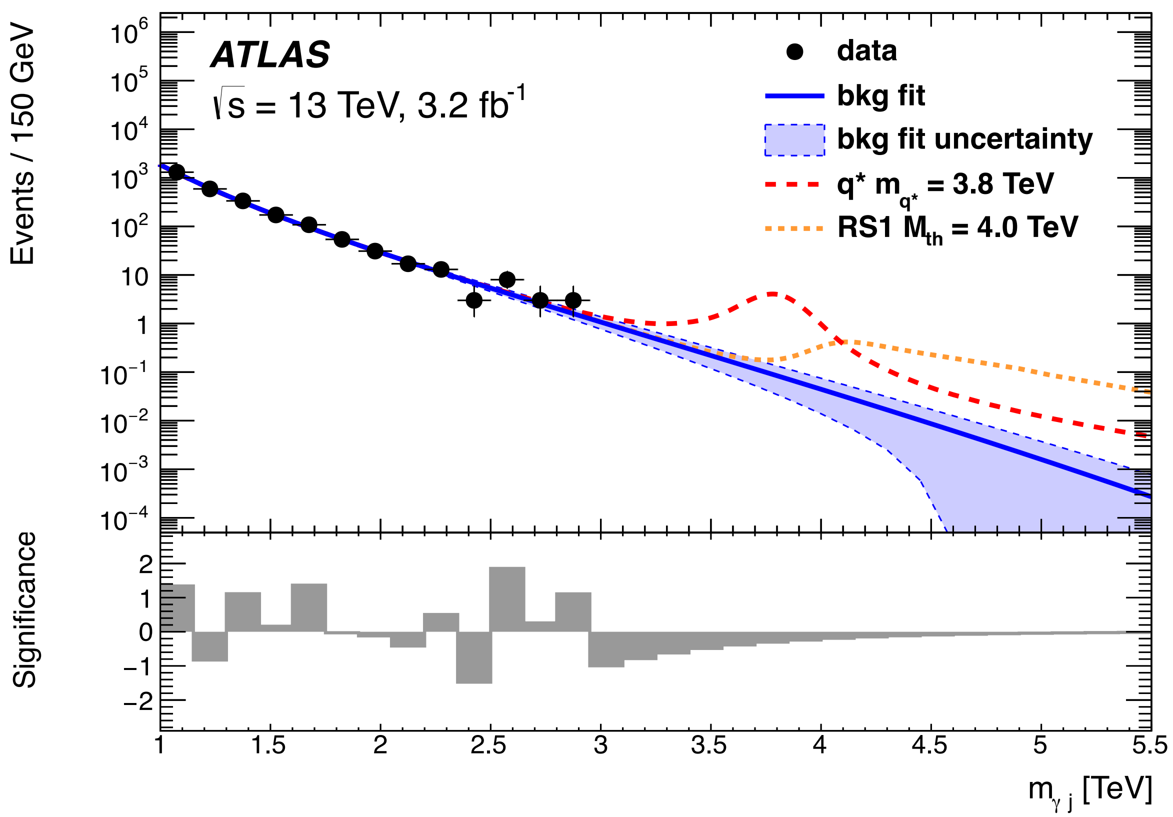
- The associated color-octet big-pion can be searched for in the dijet and photon+jet channels.

Conclusion

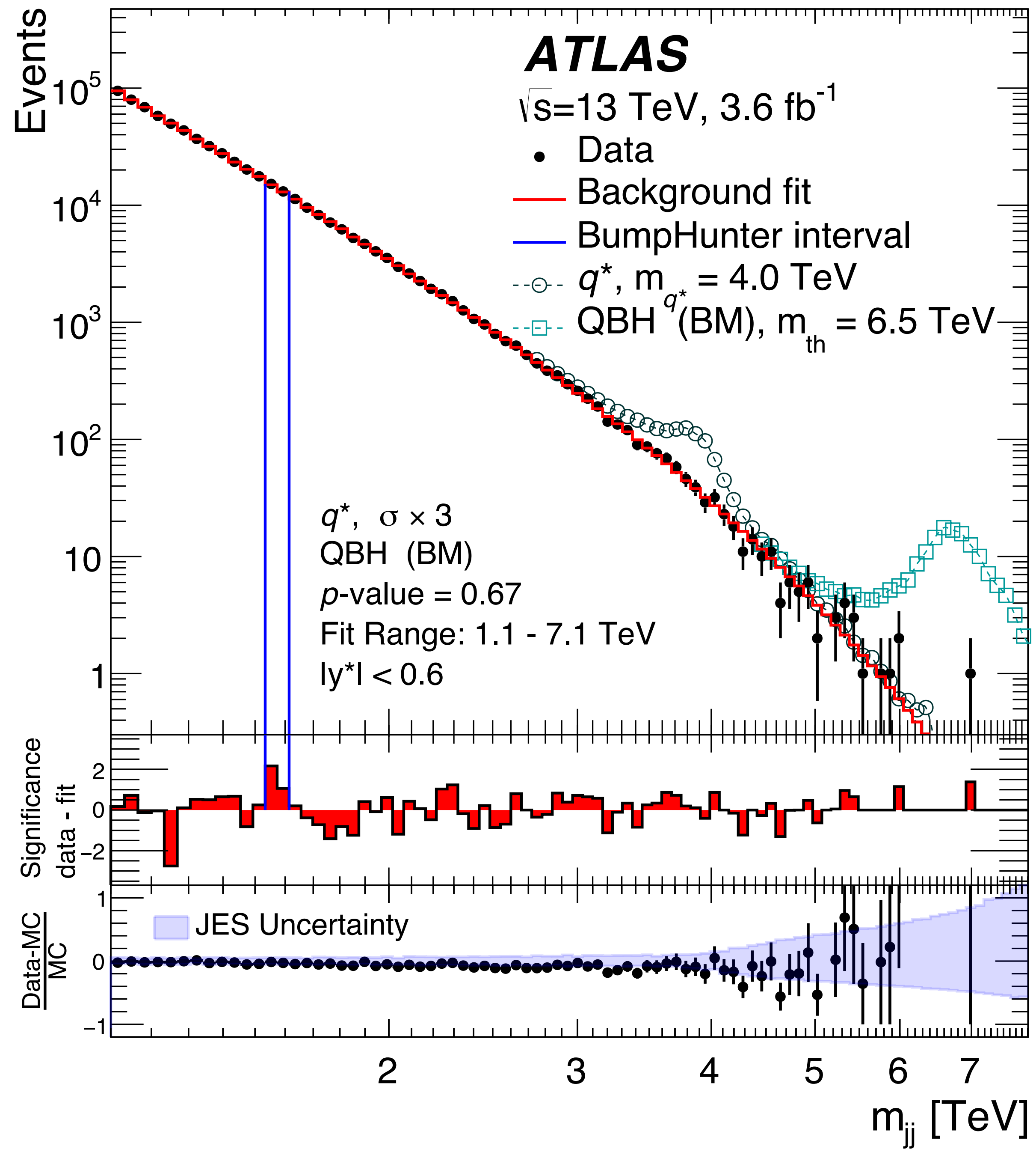
- **The composite models to explain 750 GeV diphoton excess will be concretely tested this summer.**
- **The associated color-octet big-pion can be searched for in the dijet and photon+jet channels.**
- **For the minimal 5+5bar model, the color-octet may have already shown their hints. My bet is 1.6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



Thanks!



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]