The strong CP problem: LHC and flavor

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The strong CP problem: LHC and flavor physics

Plan:

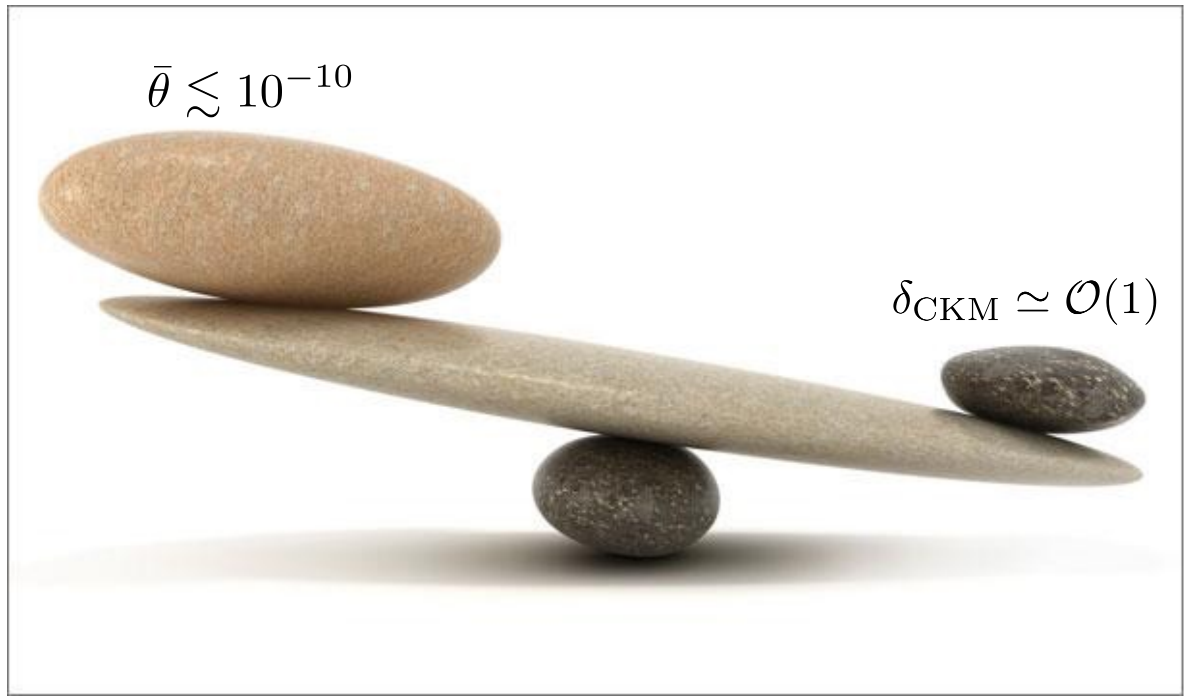
- learning from the Standard Model
- heavy axions @ colliders
- Nelson Barr and its challenges

Learning from the Standard Model I

2 phases in the SM C. Jarlskog '85

$$\bar{\theta} = \theta_0 - \arg\,\det Y_u Y_d$$

$$\begin{cases} Y_{u,d} \to e^{i\alpha} Y_{u,d} \\ \theta_0 \to \theta_0 + 6\alpha \end{cases}$$



$$J = \arg\,\det[Y_u Y_u^\dagger, Y_d Y_d^\dagger]$$

$$J = \mathrm{Im}(V_{ud} V_{cs} V_{us}^* V_{cd}^*)$$

$$\simeq A^2 \lambda^6 \eta \simeq 10^{-5} \eta$$

Lessons:
- there is a phase in the EW sector (3 generations)
- there is phase in the QCD sector (all quarks are massive)

Learning from the Standard Model I

2 phases in the SM

$$\bar{\theta} = \theta_0 - \arg\, \det Y_u Y_d$$

neutron dipole moment

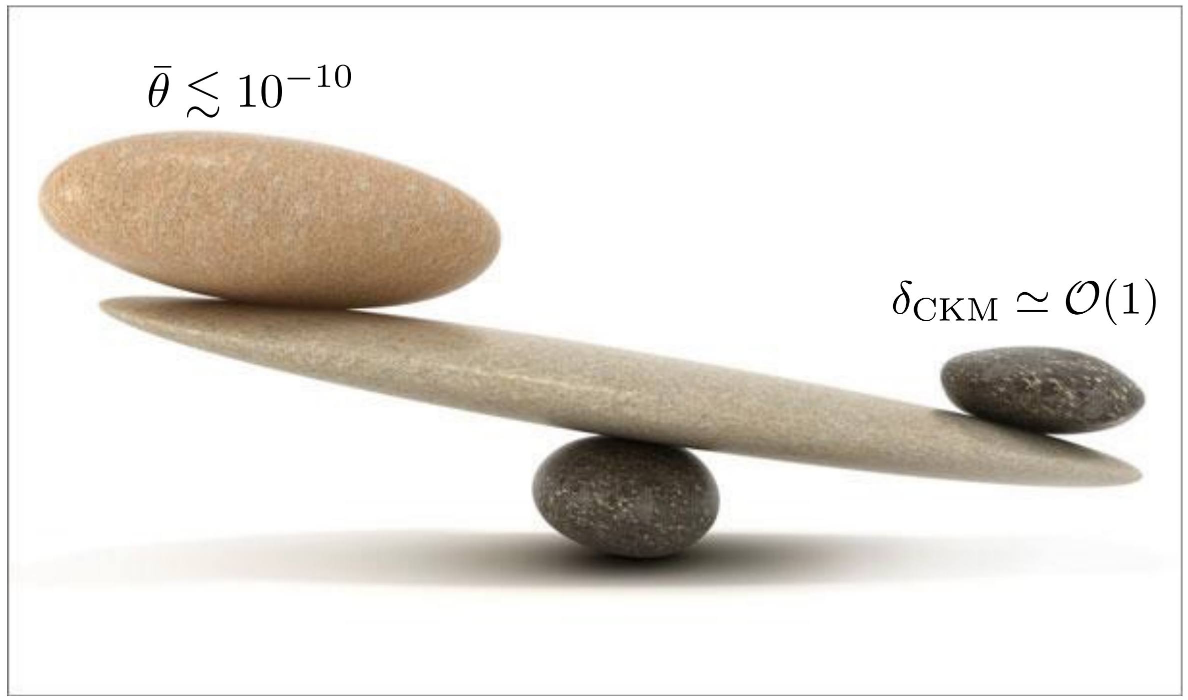
$$d_n \simeq e\,\bar{\theta}\,\frac{\overbrace{m_u}^{10^{-2}}}{m_n}\,\frac{g_n}{m_n}$$

experimentally

$$d_n \lesssim 10^{-12}\frac{e}{\text{GeV}}$$

$\downarrow$

$$\theta \lesssim 10^{-10}$$



$$J = \arg\, \det[Y_u Y_u^\dagger, Y_d Y_d^\dagger]$$

$$J = \text{Im}(V_{ud} V_{cs} V_{us}^* V_{cd}^*)$$

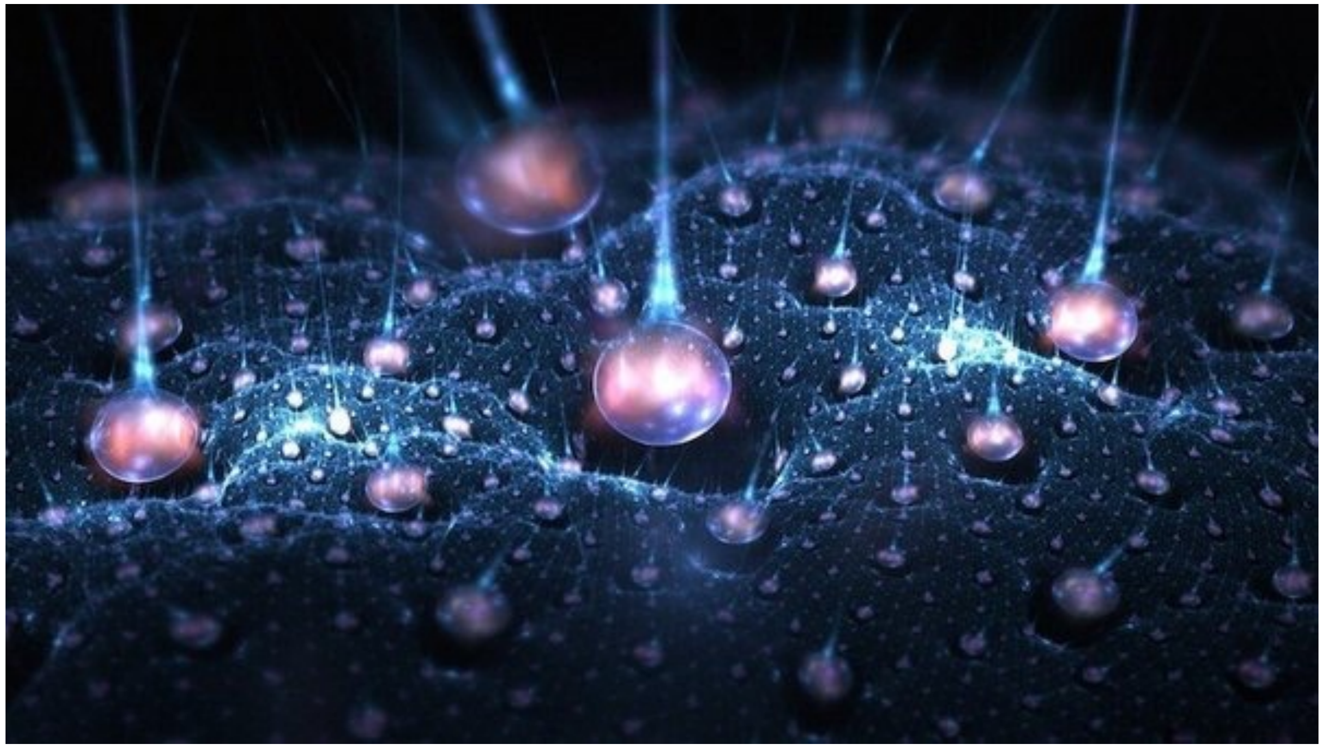
$$\simeq A^2 \lambda^6 \eta \simeq 10^{-5}\eta$$

experimentally

$$\eta \simeq 0.349$$

the tension between these 2 phases is what we call "strong CP problem"

we care even more now...



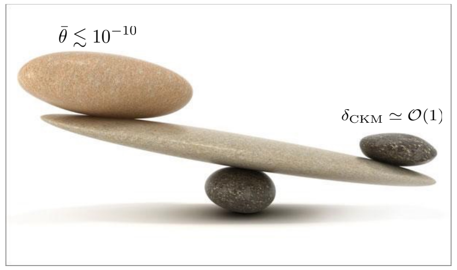
anthropic arguments in the multiverse might explain the dimensionful hierarchies

Arkani-Hamed, Dimopoulos, Kachru '05

most of the universes do not have large structures $\longleftrightarrow$ Λ_{CC} appears fine-tuned

most of the universes do not have complex nuclei $\longleftrightarrow$ v appears fine-tuned

only moderate anthropic bounds can be derived for θ! Ubaldi '08



Learning from the Standard Model II

the SM already has the 2 possible ingredients to solve the strong CP problem

Peccei Quinn-solution

if the up quark yukawa is zero $\longrightarrow$ $U(1)_{PQ}: \begin{cases} \theta \to \theta + \alpha \\ u \to e^{i\gamma_5 \alpha} u \end{cases}$

$U(1)_{PQ}$ spontaneously broken by $\langle u\bar{u}\rangle \simeq f_\pi^3$ $\longrightarrow$ η' is the pNGB

$U(1)_{PQ}$ is anomalous: $\mathcal{L}_{\eta'} \supset \dfrac{\alpha_s}{8\pi}\eta' G\tilde{G}$ $\longrightarrow$ $V(\eta') \approx \dfrac{1}{2} m_{\eta'}^2 f_\pi^2 (\dfrac{\eta'}{f_\pi} - \bar{\theta})^2 + \mathcal{O}(1/N_c^2)$

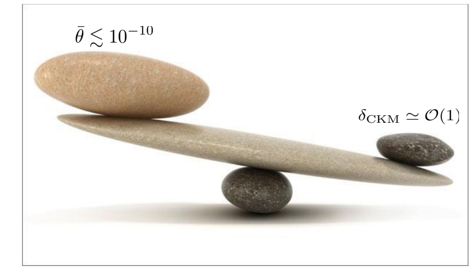
Veneziano '79, Witten '79, Witten '80

the strong CP phase is set to zero by the VEV of the pNGB of $U(1)_{PQ}$

CHALLENGE: $U(1)_{PQ}$ of very high "quality" $\longrightarrow$ $\Delta V \approx m_u f_\pi^3 \cos\dfrac{\eta'}{f_\pi}$

$\longrightarrow$ $\dfrac{\Delta\eta'}{f_\pi} \approx \dfrac{m_u}{m_{\eta'}}$

Learning from the Standard Model II



the SM already has the 2 possible ingredients to solve the strong CP problem

Nelson Barr-solution

if $\bar{\theta} = 0$ in the UV $\longrightarrow$ $\frac{d}{dt}\bar{\theta} \sim J$ in the SM

$J = \arg\det[Y_u Y_u^\dagger, Y_d Y_d^\dagger]$ $\longrightarrow$ $J \sim y^{12}$

$u \leftrightarrow d : \begin{cases} J \to -J \\ \bar{\theta} \to \bar{\theta} \end{cases}$

6 h-loops

+1 Y-loop

---

7 loops

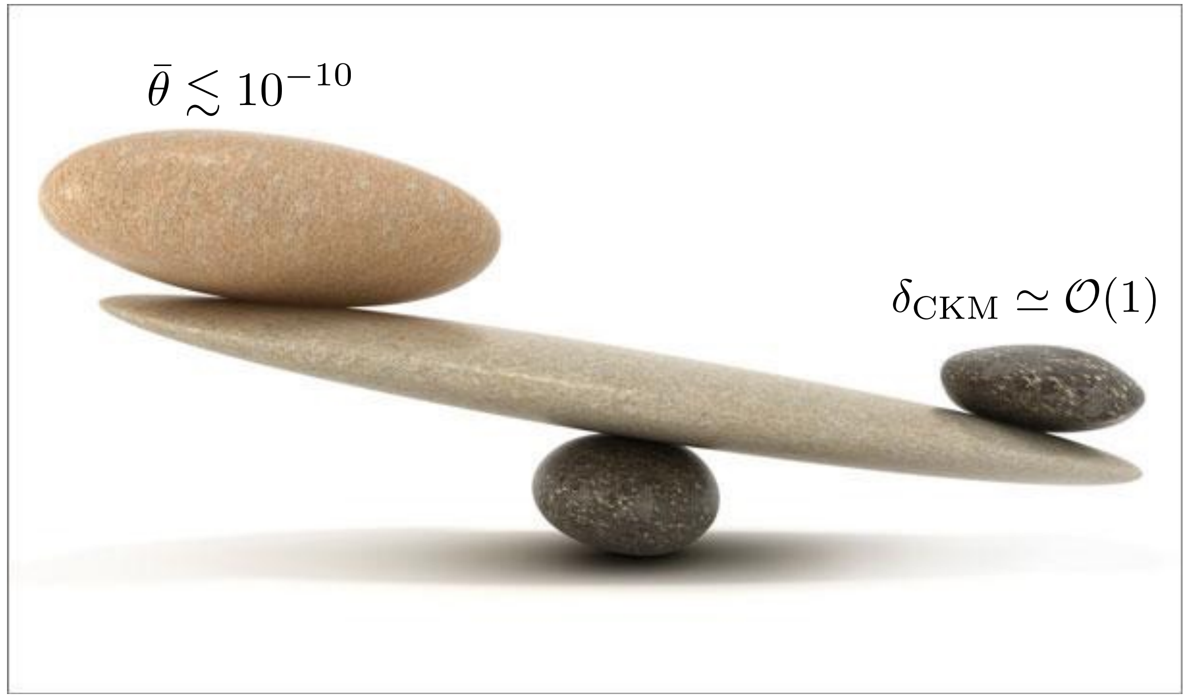
Ellis Galliard ’79

finite thresholds from heavy quarks more difficult to estimate systematically…

if the strong CP phase is set to zero in the UV is not generated within the SM

CHALLENGE: generate $\bar{\theta} = 0$ + the CKM phase

Learning from the Standard Model
Summary



Peccei Quinn-solution: spontaneously broken $U(1)_{PQ}$ with QCD anomaly can set $\bar{\theta} = 0$ dynamically

the $U(1)_{PQ}$ should be an accidental symmetry with very good accuracy

Nelson Barr-solution: the flavor structure of the SM makes $\bar{\theta} = 0$ radiatively stable

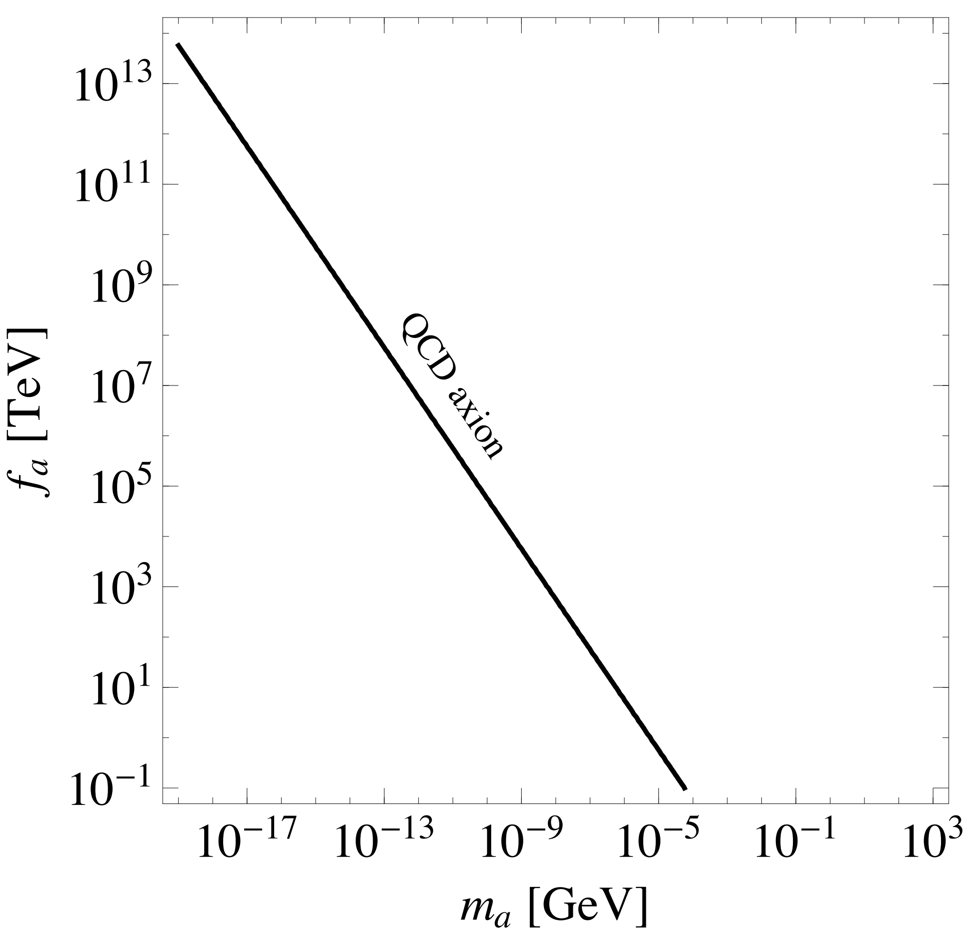
a UV mechanism should enforce this boundary condition + generate the CKM

Where do we bet?

A lot of money on the Peccei-Quinn solution

$$\frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G}$$

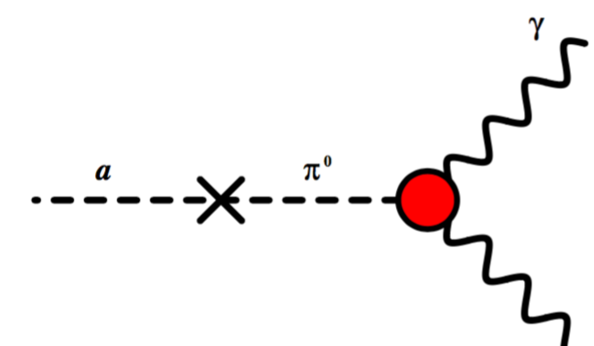
anomaly matching → light axion @ low energy



IR potential after confinement → $V_{\rm QCD} \approx \bar{m}_a^2 f_a^2 \cos(\frac{a}{f_a} - \theta)$

$$\bar{m}_a \approx \frac{m_\pi f_\pi}{f_a}$$

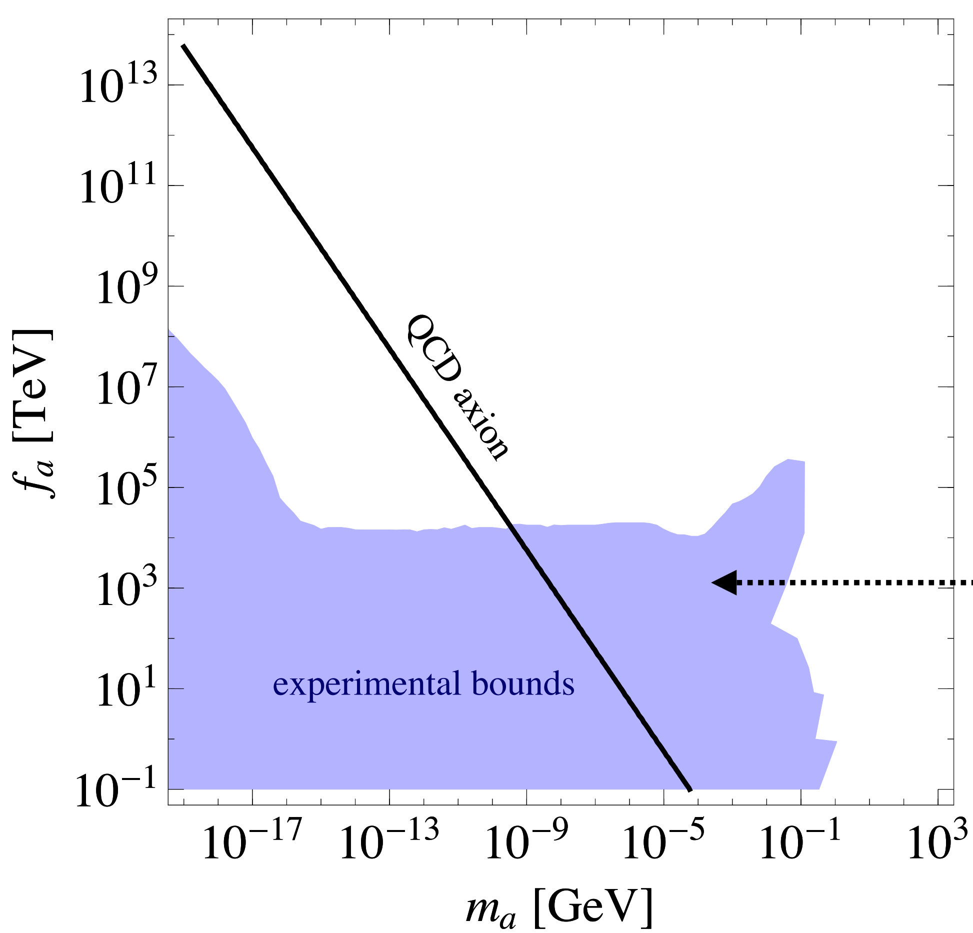
IR coupling to photons →



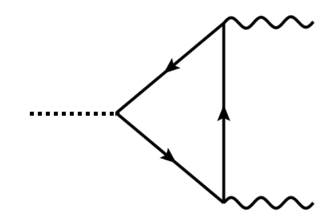
The simplest model: the KSVZ axion

$$\mathcal{L}_{\rm KSVZ} = |\partial\Phi|^2 - V(\Phi) + g_* \bar{\Psi}_L \Psi_R \Phi + h.c.$$

$\Phi = \dfrac{f_a}{\sqrt{2}} e^{ia/f_a}$ spontaneously broken $U(1)_{PQ}$



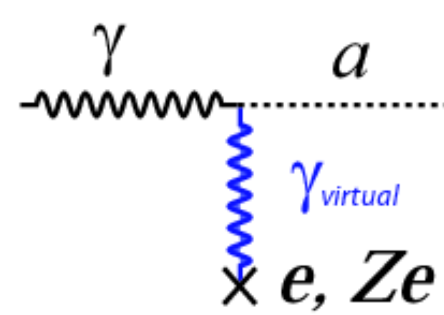
below $g_* f_a$ one gets $\dfrac{\alpha_s}{8\pi}\dfrac{Na}{f_a} G\tilde{G}$ for N fermions

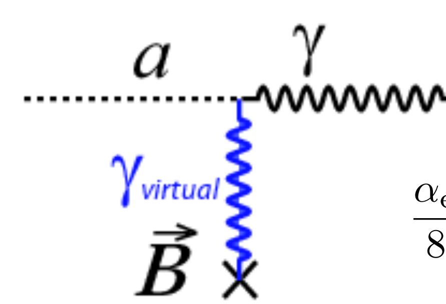


generically one also gets a UV coupling to photons $\dfrac{\alpha_{\rm em}}{8\pi}\dfrac{Ea}{f_a} F\tilde{F}$

(E/N=8/3 for GUT multiplets)

Astrophysical bounds force high scale PQ breaking...





$$\frac{\alpha_{\rm em}}{8\pi}\frac{Ea}{f_a} F\tilde{F} \to \frac{\alpha_{\rm em}}{8\pi}\frac{Ea}{f_a} \vec{E}\cdot\vec{B}$$

The large scale separation $g_* f_a \gg \Lambda_{\rm QCD}$ requires more PQ "quality"

Explicitly in the KSVZ model $\Delta V_{P\!\!\!/Q} = \lambda_\Delta \dfrac{\Phi^\Delta}{\Lambda_{\rm UV}^{\Delta-4}} + \text{h.c.}$, $\lambda_\Delta = |\lambda_\Delta| e^{i\delta_\Delta}$

The accidental PQ symmetry is broken at the scale $\Lambda_{\rm UV}$

by an operator of dim. Δ

with generic phase δ_Δ

with O(1) strength λ_Δ

$\delta_\Delta \sim \arg \det Y_u Y_d$

$$V_a = \Lambda_{\rm QCD}^4 \cos \frac{Na}{f_a} + \frac{|\lambda_\Delta| f_a^\Delta}{\Lambda_{\rm UV}^{\Delta-4}} \cos \frac{\Delta a + \delta_\Delta}{f_a} \,.$$

solution of the strong CP | *upper bound on the decay constant*

$$\langle Na/f_a \rangle \lesssim 10^{-10} \longleftrightarrow f_a \lesssim \Lambda_{\rm UV} \left[\frac{10^{-10}}{|\lambda_\Delta| \tan \delta_\Delta} \cdot \frac{N}{\Delta} \cdot \left(\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm UV}} \right)^4 \right]^{1/\Delta}$$

Let's give numbers...

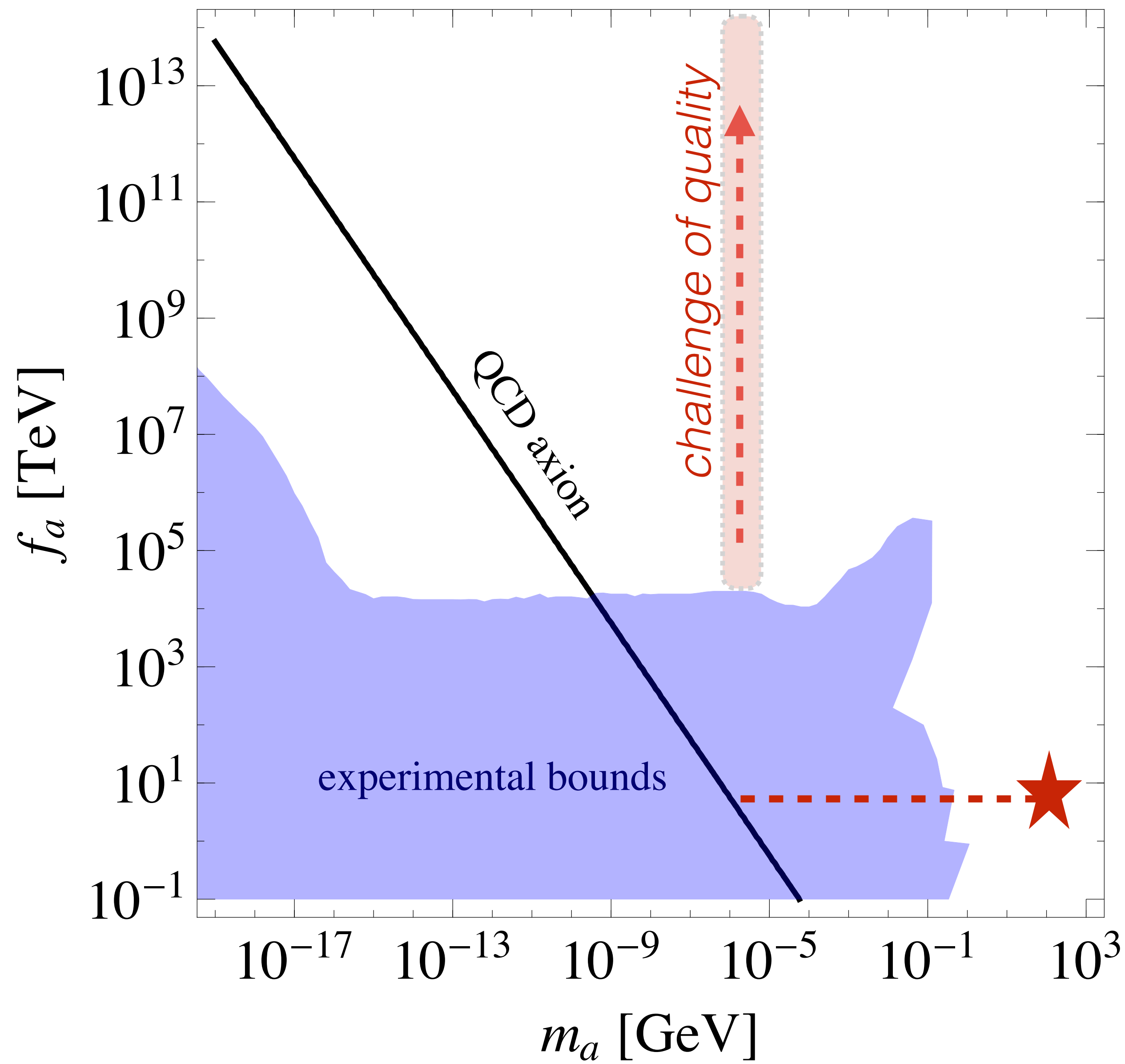
In the best case scenario the PQ is only broken by $1/M_{Pl}$ operators

Kamionkowski and March-Russell '92 etc…

$\Delta = 5 \qquad f_a \lesssim 10 \text{ GeV}$

$\Delta = 6 \qquad f_a \lesssim 5 \text{ TeV}$

$\dots \qquad \dots$

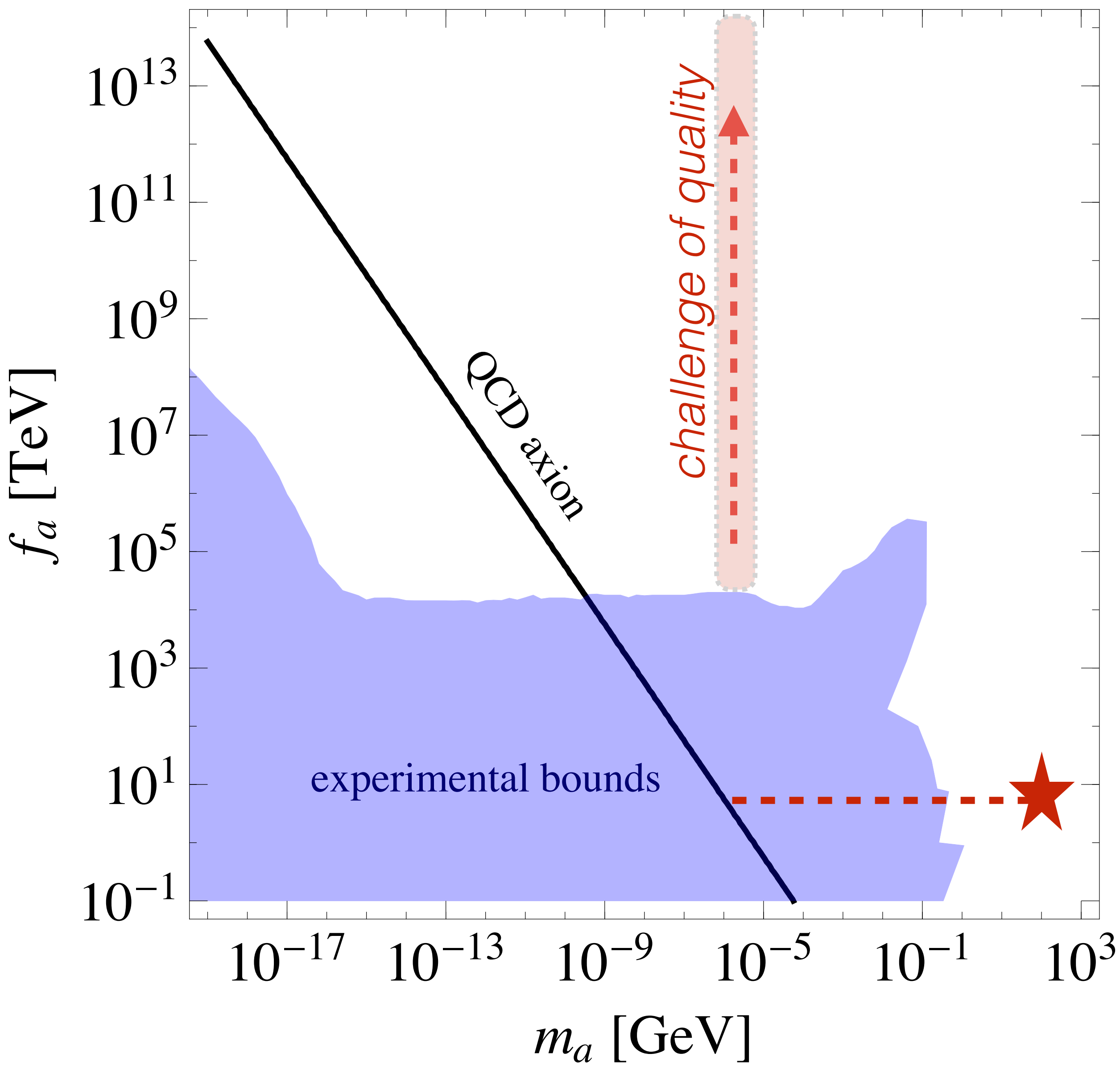


Can we have an axion with TeV decay constant?

This would make the PQ very similar to the SM baryon number

Above 1 GeV the axion bounds disappear…

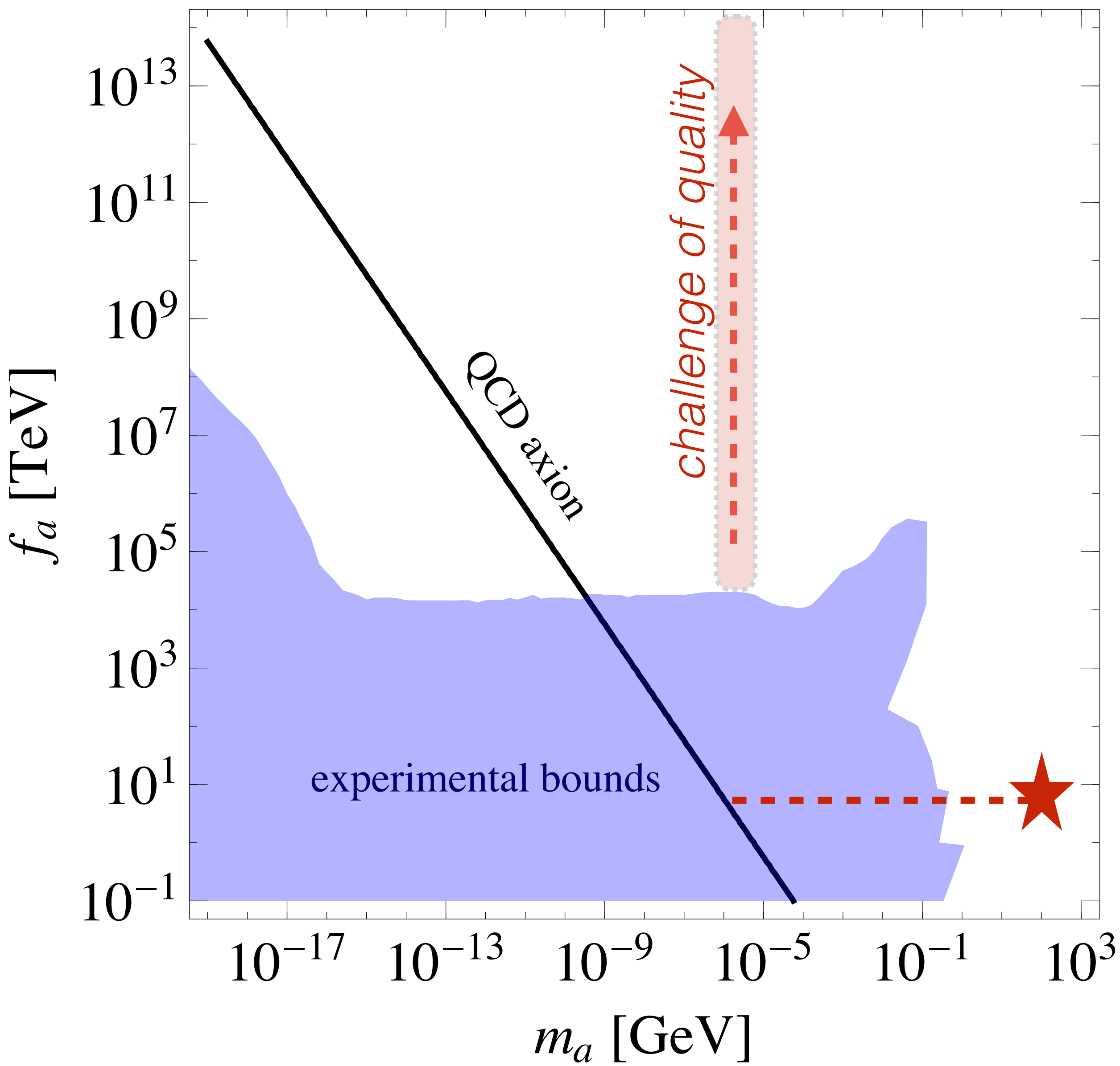
Then the idea is to raise the axion mass without spoiling the strong CP



- 2 QCD's +1axion
  alignment from mirror symmetry
  (Rubakov '97, Berezhiani et al.'00,
  Hook '14 -'16, Yanagida et al '15.)
- N QCD's + N axions
  alignment from UV instantons
  (Agrawal Howe '17)
- …

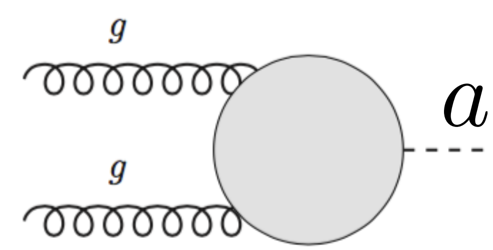
I can tell more about these models if you want…

TESTING STRONG CP PROBLEM @ colliders

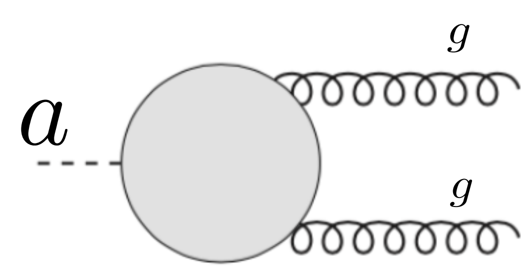


The coupling to gluons is unavoidable to address strong CP

and has drastic pheno consequences:



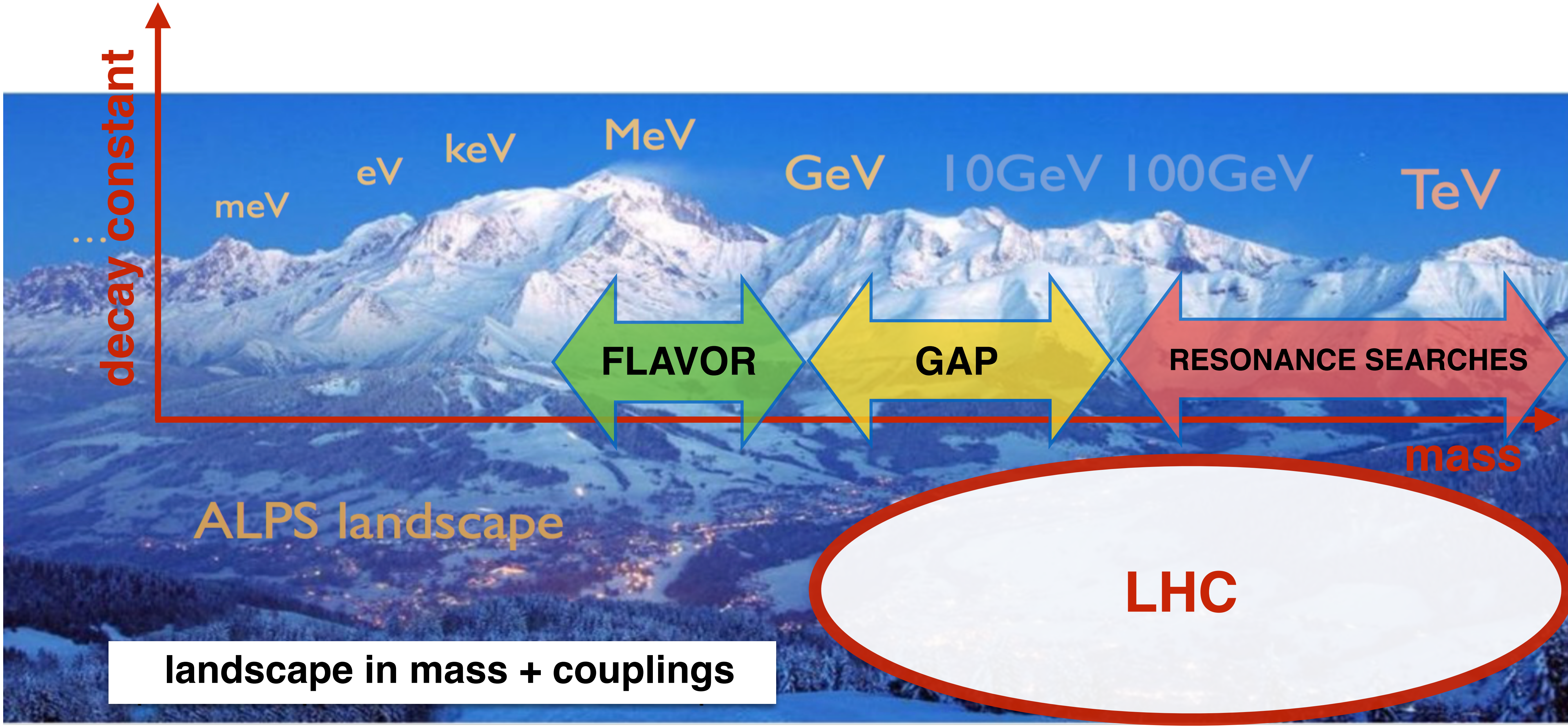
gluon fusion



promptly decay

$m_a \gtrsim 3m_\pi$

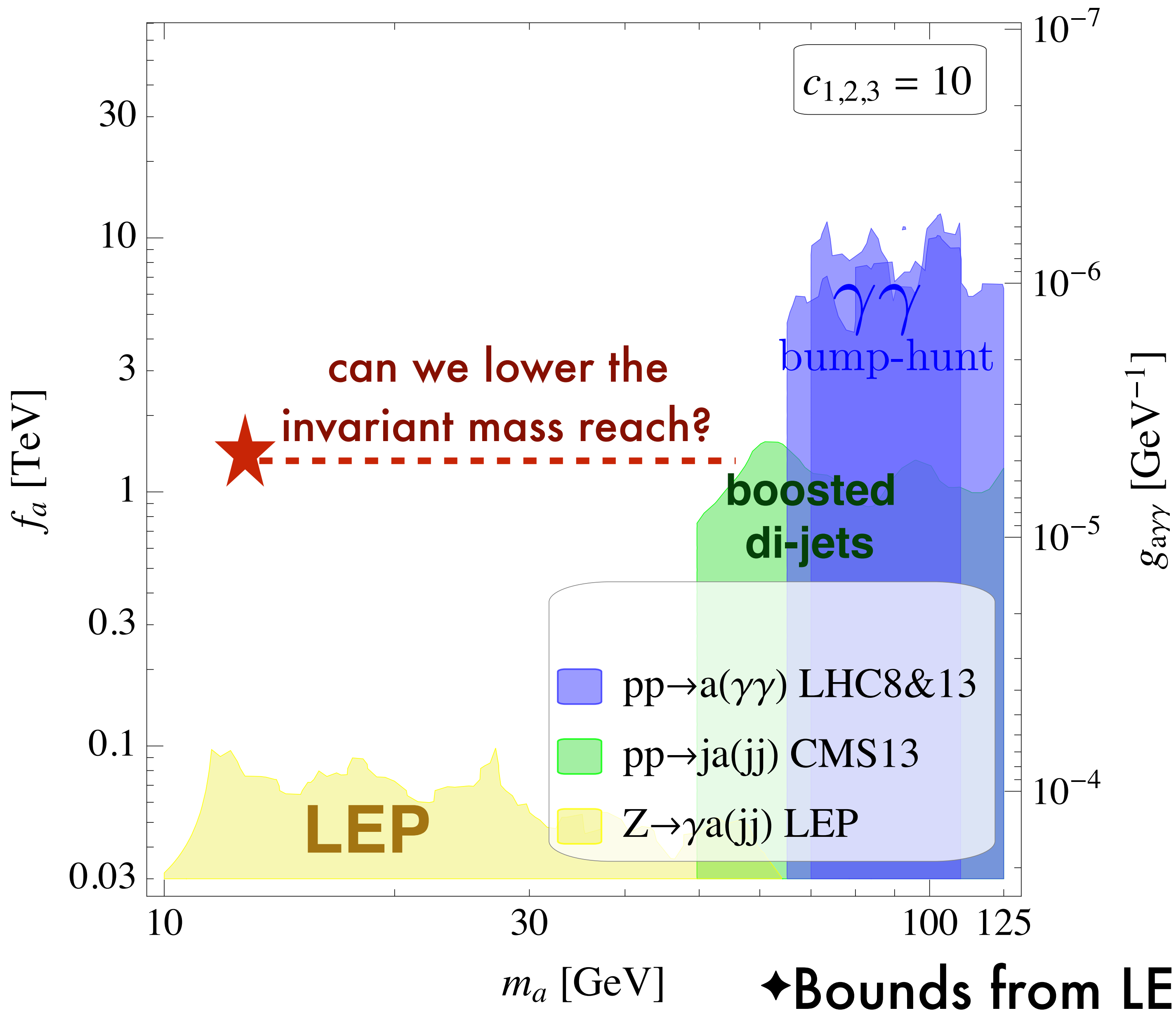
How much can we test axions at colliders?



the strong CP problem *motivates low mass resonance searches*

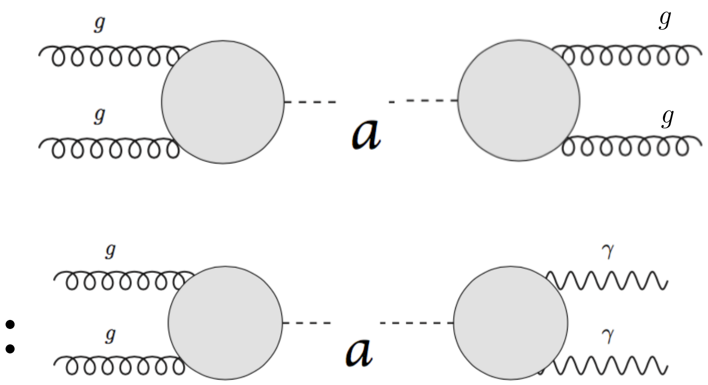
select a slice of coupling in the ALP landscape

status above 10 GeV...



dijets:

diphotons:



comments:

✦Bounds from LEP 1 $\mathrm{BR}(Z \to a\gamma) \cdot \mathrm{BR}(a \to jj) \lesssim 10^{-5}$

✦Photon BR suppressed $\mathrm{BR}(a \to \gamma\gamma) \sim \frac{1}{8}\left(\frac{\alpha_{\rm em}}{\alpha_s}\right)^2 \sim 5 \cdot 10^{-4}$

✦bounds based on EW couplings not relevant

Lowering the invariant mass reach?

$$m_{\gamma\gamma} > \Delta R \sqrt{p_{T_1}^{\min} p_{T_2}^{\min}}$$

- Lower pT cuts
- CHALLENGE: *trigger & background from MC*

- Lower photon ISO $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$
- CHALLENGE: *mass resolution*

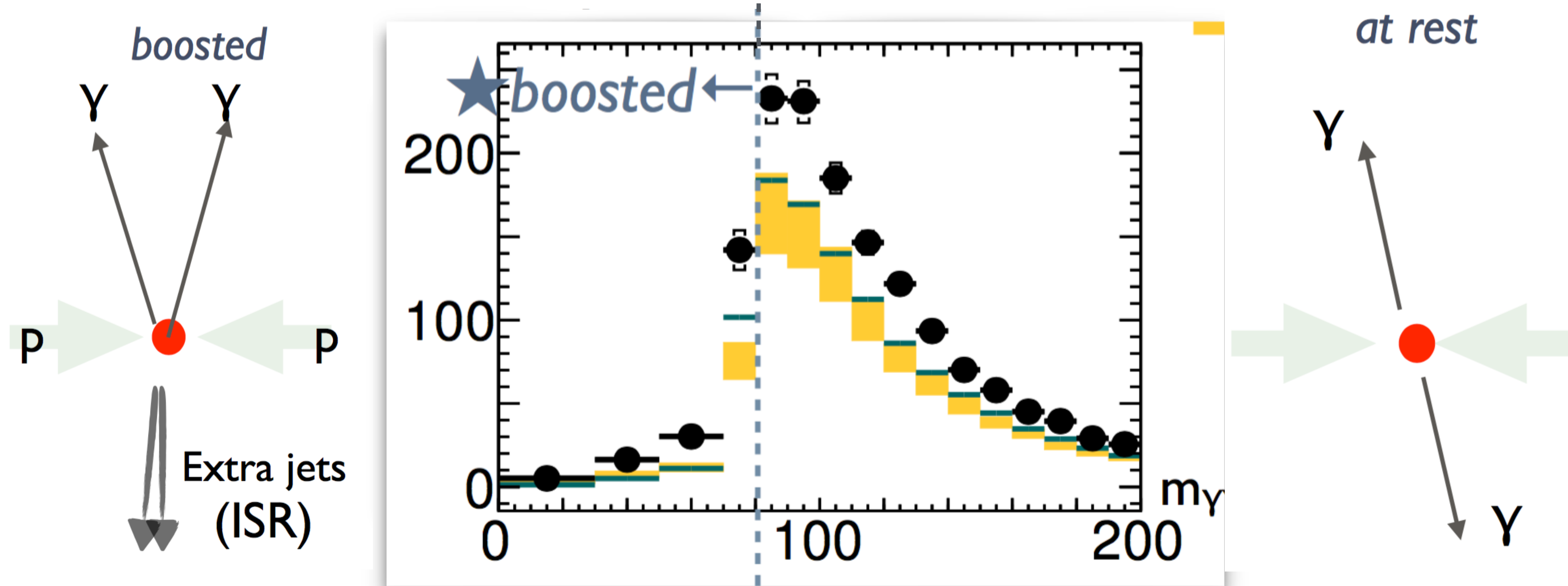
The *lowest* invariant mass for *diphoton trigger*

$$m_{\gamma\gamma} > \Delta R \sqrt{p_{T_1}^{\min} p_{T_2}^{\min}}$$

$p_{T_1}^{\min} = 40\ \mathrm{GeV}$
$p_{T_2}^{\min} = 30\ \mathrm{GeV}$

below pT cuts
the background has a *structure*

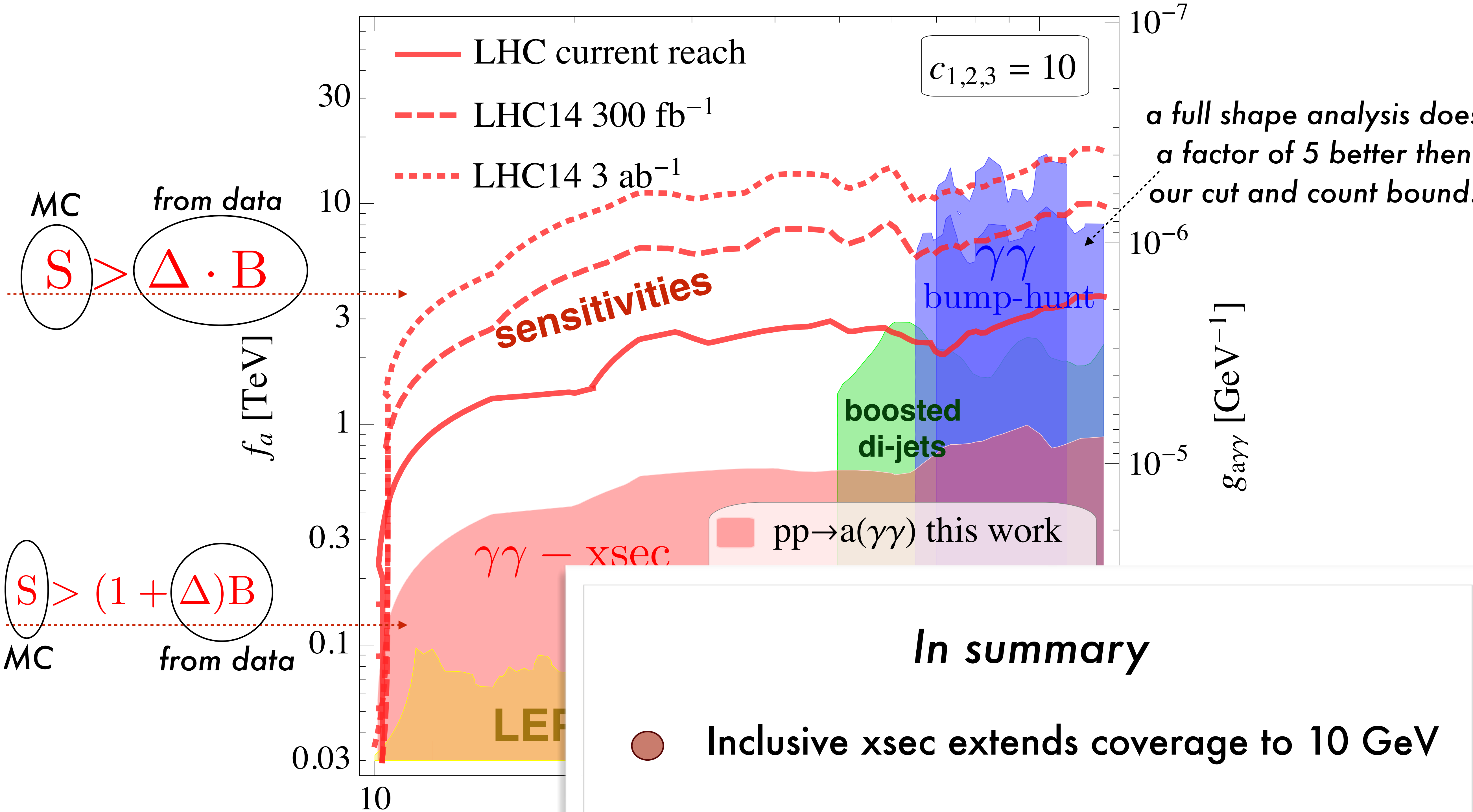
above pT cuts
the background is *smooth*



the signal efficiency does not drop to zero below the pT cuts!

Final results

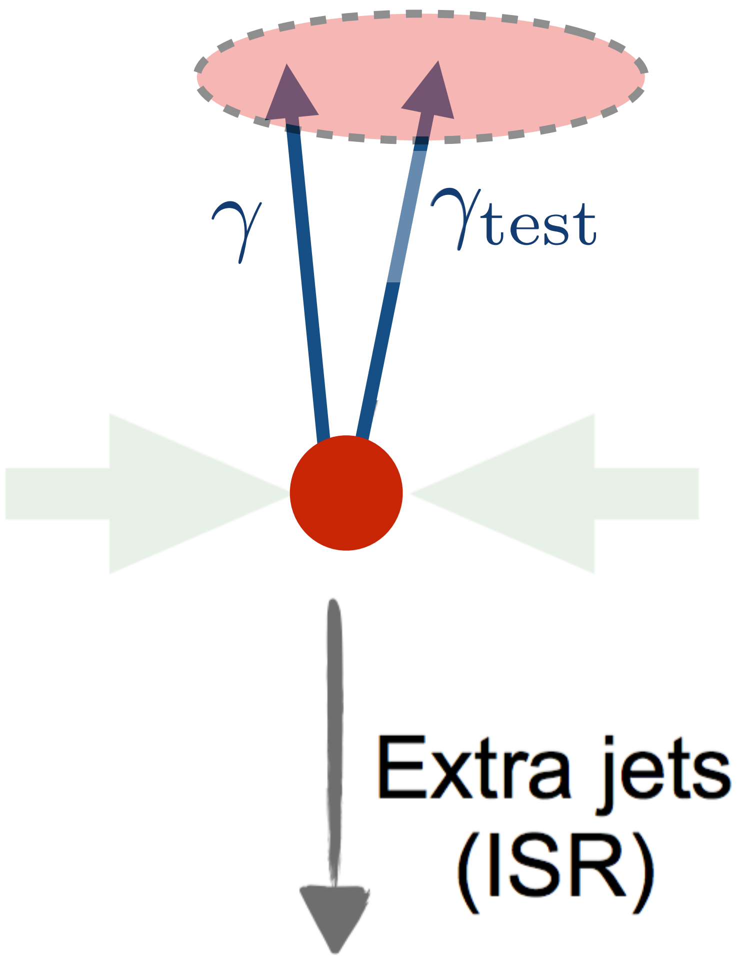
Mariotti, Tobioka, D.R., Sala '17



In summary

- Inclusive xsec extends coverage to 10 GeV
- MC uncertainties limit discovery potential

Modifying standard photon isolation



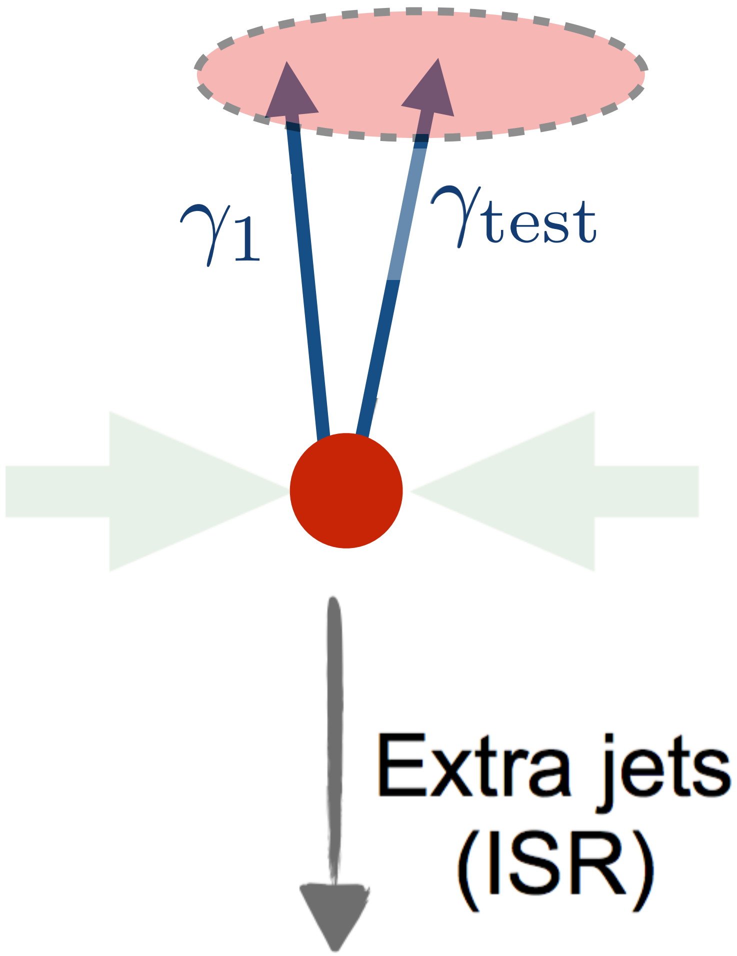
- boosting the system against a hard jet
- $\Delta R \simeq \frac{2m_a}{p_T^a}$ the two photons get collimated
- standard isolation would reject the signal

$$\sum_{i \neq \gamma_{\text{test}}}^{\Delta R < R_{\text{iso}}} p_{T,i} < \#$$

$$\sum_{i \neq \gamma_{\text{test}}}^{\Delta R < R_{\text{iso}}} p_{T,i} \Big/ E_{T,\gamma_{\text{test}}} < \#$$

CAN WE MODIFY THIS KEEPING JET-FAKES UNDER CONTROL?

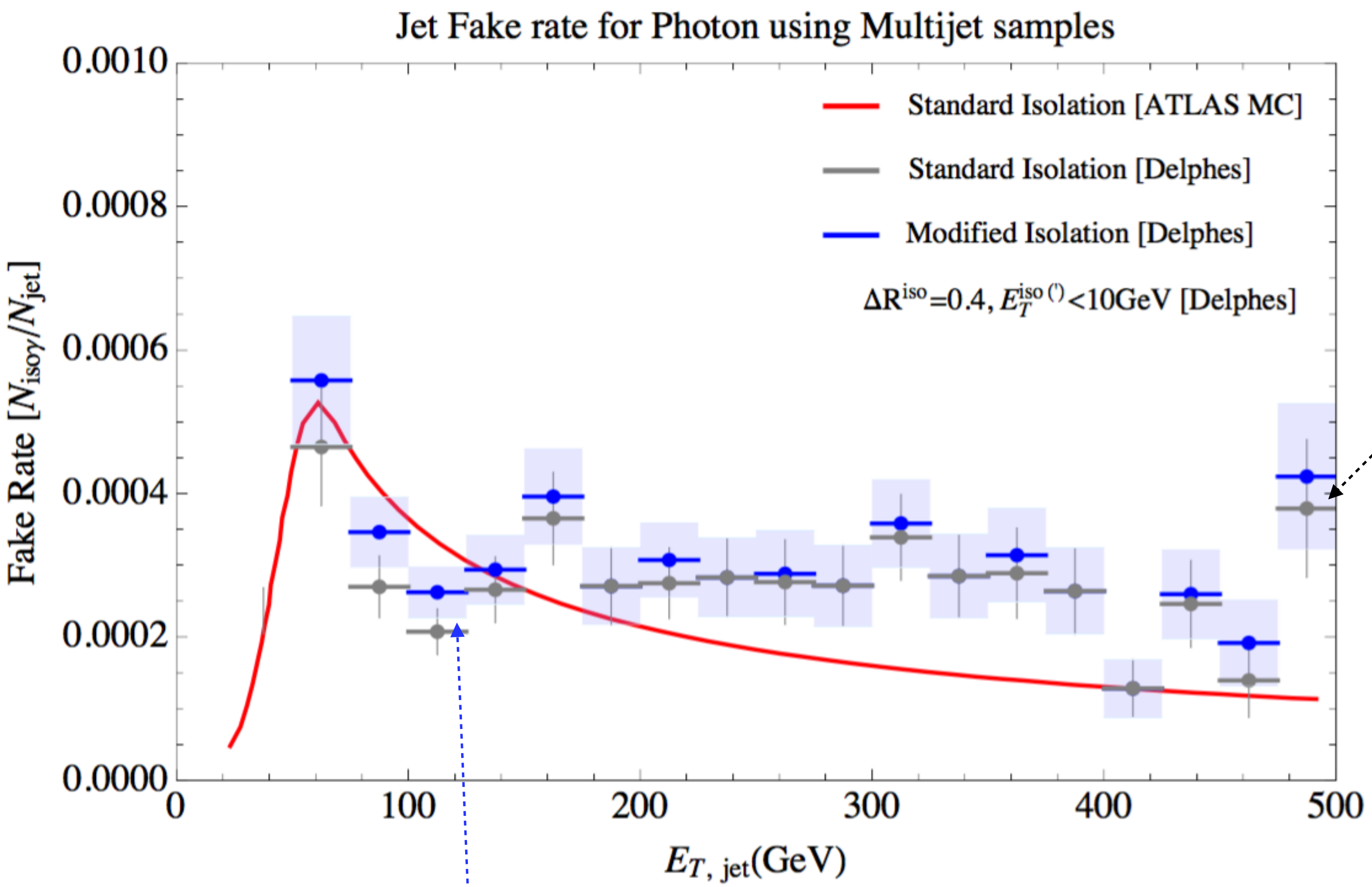
Modifying standard photon isolation



- boosting the system against a hard jet (Ht>500 GeV)
- $\Delta R \simeq \frac{2m_a}{p_T^a}$ the two photons get collimated
- NEW ISOLATION

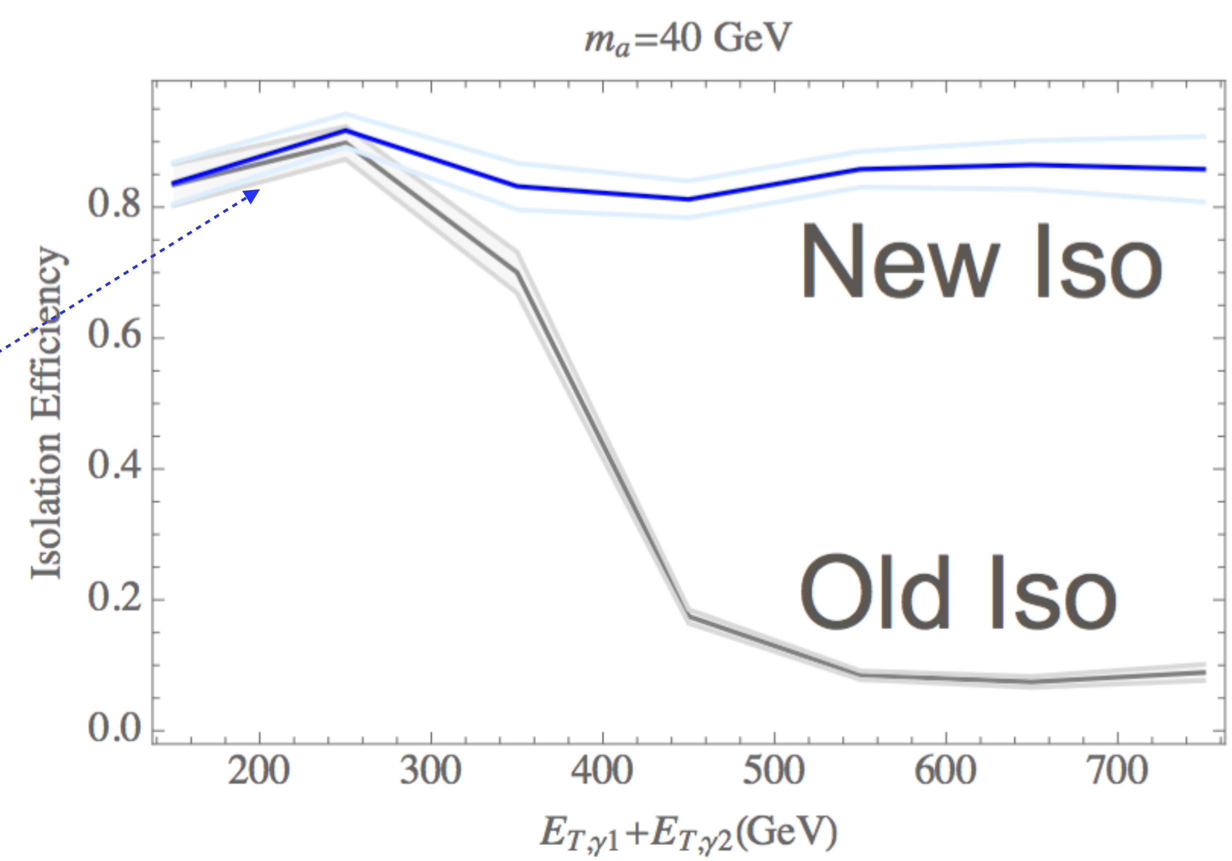
$$\sum_{i \neq \gamma_{\text{test}}, \gamma_1}^{\Delta R < R_{\text{iso}}} p_{T,i} \qquad \sum_{i \neq \gamma_{\text{test}}, \gamma_1}^{\Delta R < R_{\text{iso}}} p_{T,i} \Big/ E_{T,\gamma_{\text{test}}}$$

Rejecting the pions (jet activity) keeping the hard photon γ_1



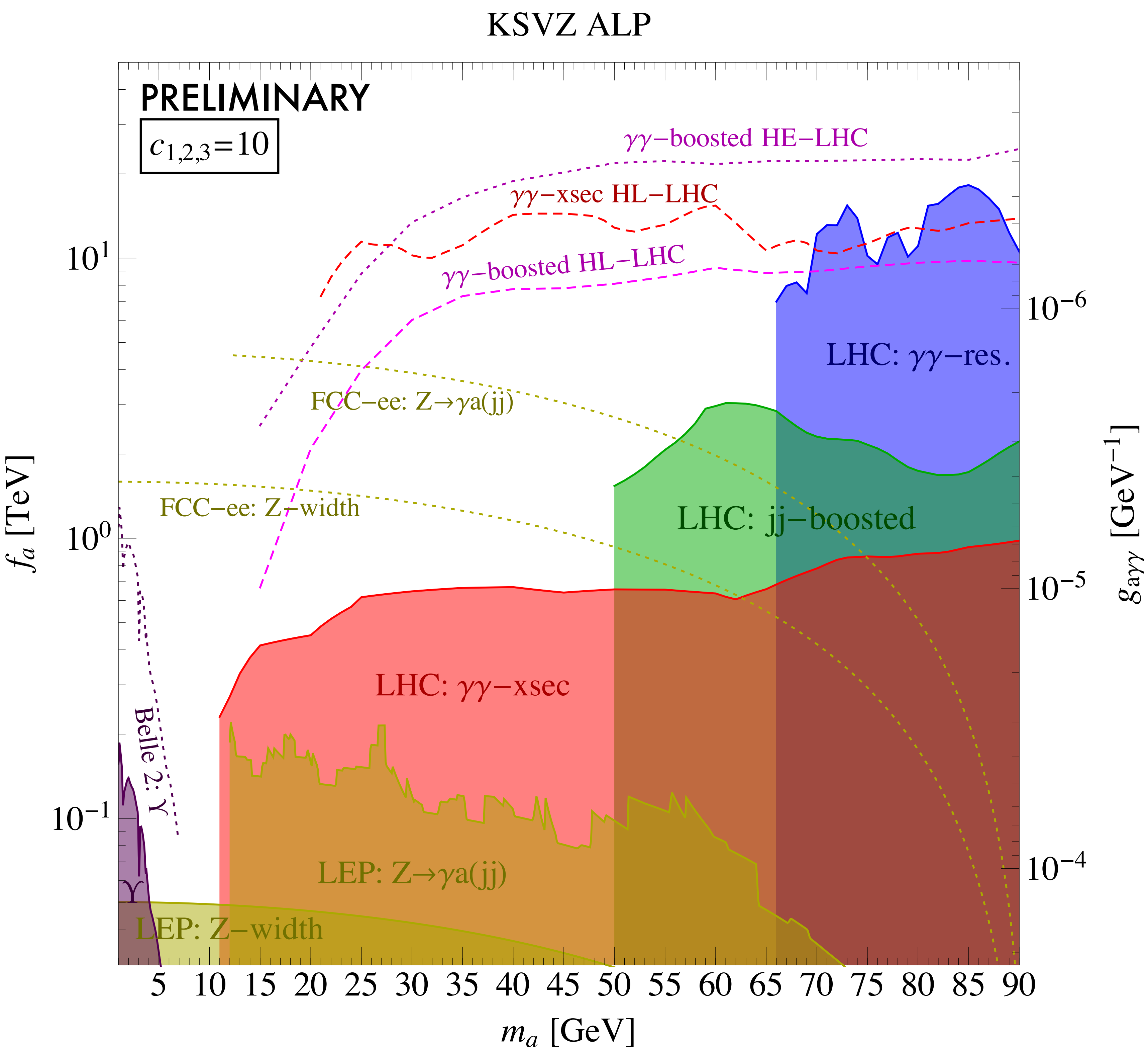
fast-sim with Delphes capture the fake rate normalization

our new ISO does as good as the standard one!



it keeps most of the signal!

Low, Mariotti, Tobioka, D.R., Sala *to appear*



$$\Delta R \simeq \frac{2m_a}{p_T^a}$$

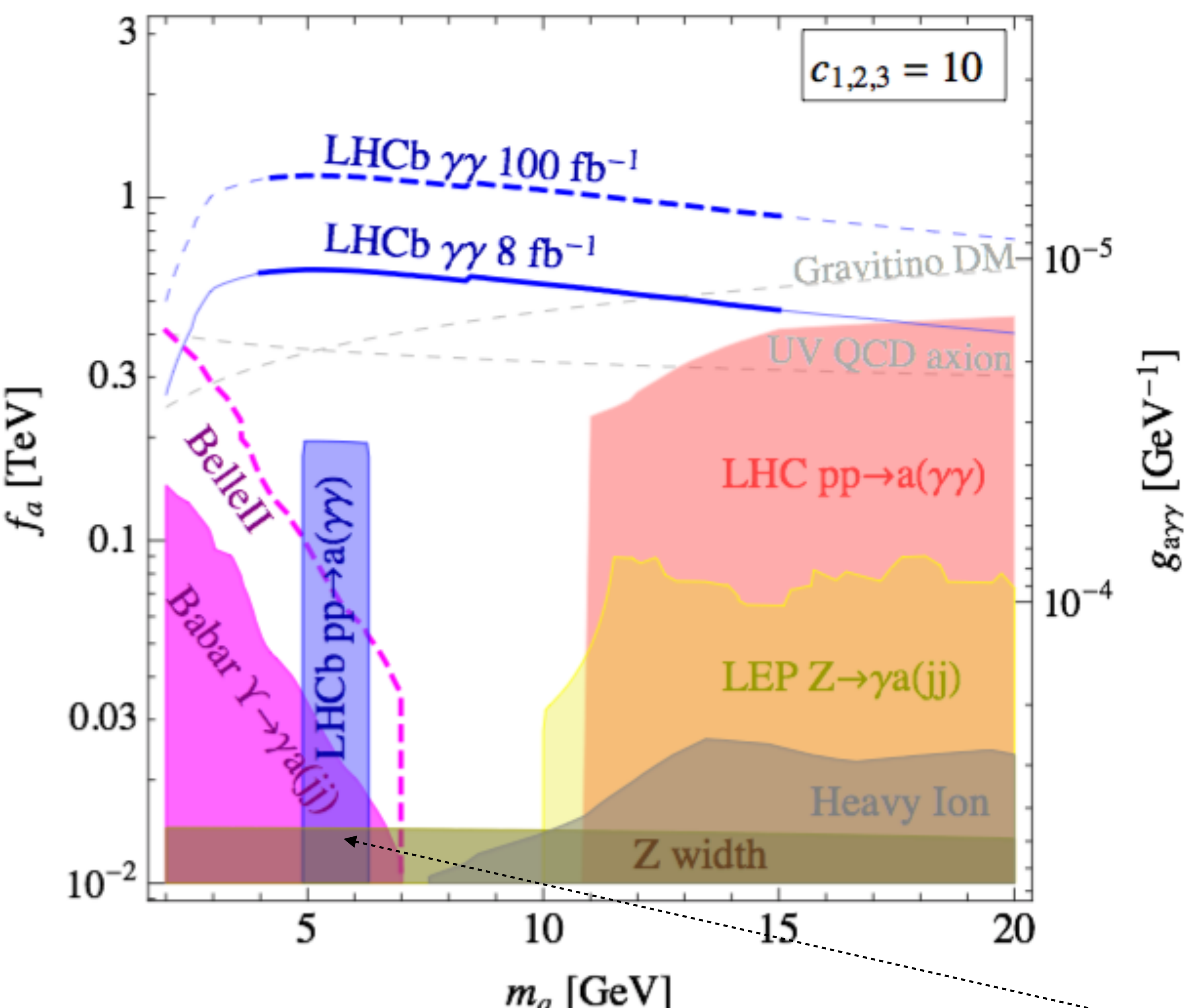
$\Delta R \gtrsim 0.1$ PID

$p_T^a \gtrsim 500$ GeV jet trigger

boosted diphoton searches will probe 10 TeV decay constants down to 10 GeV masses

what can we do below 10 GeV?

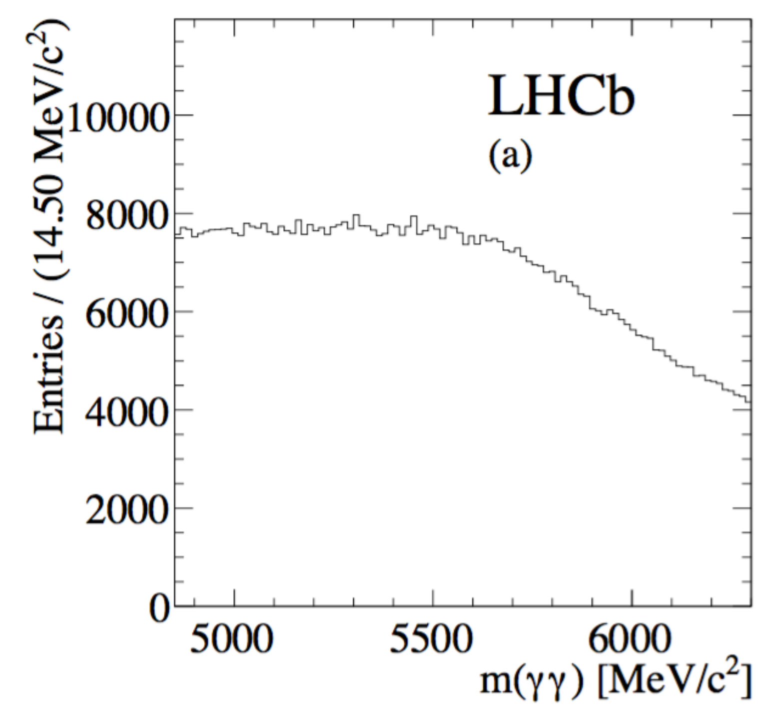
Mariotti, Tobioka, D.R., Sala ***to appear***



estimate bound from Y-decay

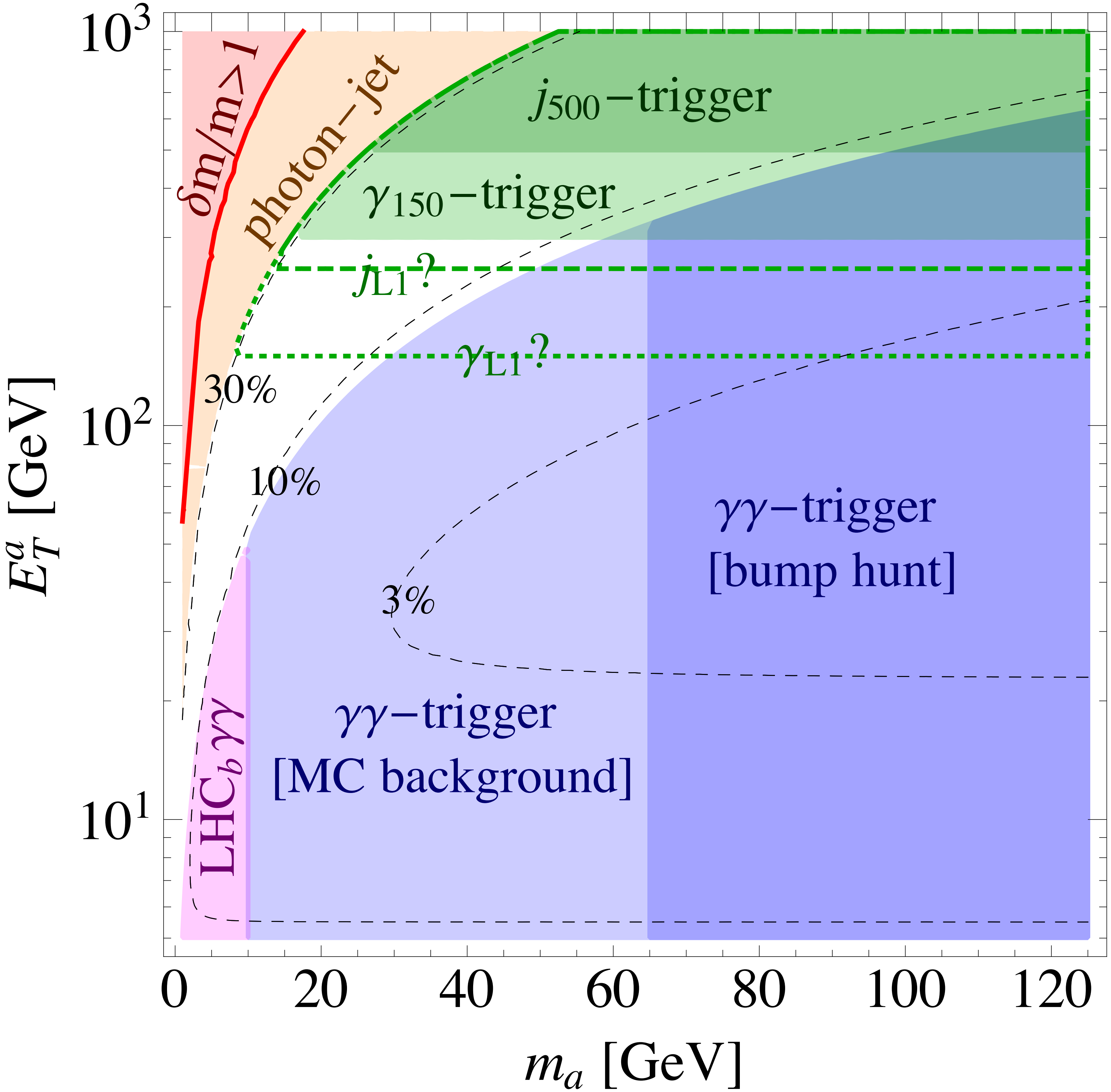
$$\Upsilon \to \gamma a$$

NEW bound from LHCb



bound from real data published by LHCb to motivate a diphoton trigger in the $B_s \to 2\gamma$ range

summary of the strategies with photons



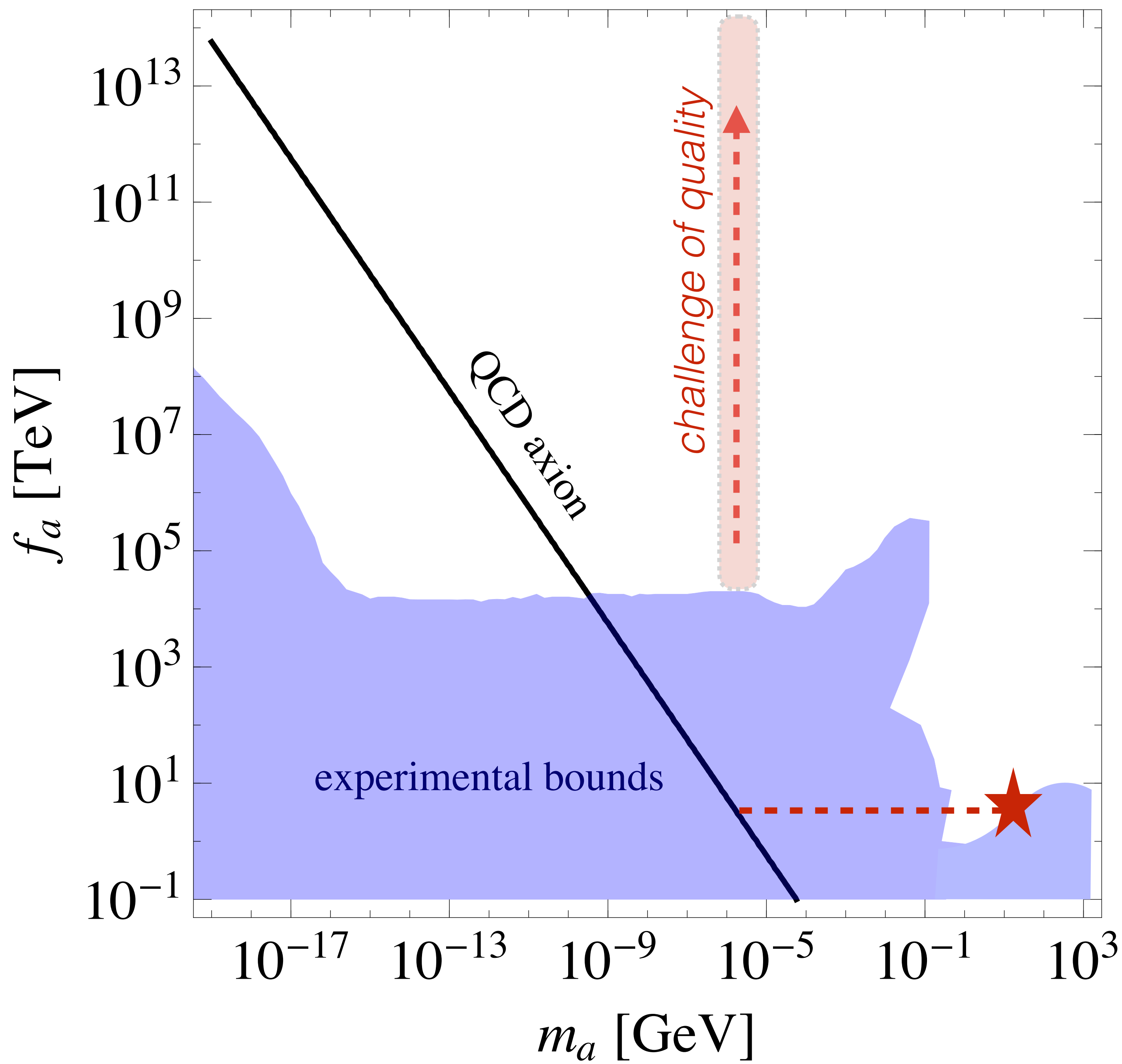
The 2 photon showers are still separated

The 2 photon showers merge

Invariant mass resolution

$$\left.\frac{\delta m_{\gamma\gamma}}{m_{\gamma\gamma}}\right|_{\text{boosted}} = \left[\sqrt{2}\frac{\delta E_T^a}{E_T^a} \oplus \frac{E_T^a}{2m_a}\delta\Delta R\right]$$

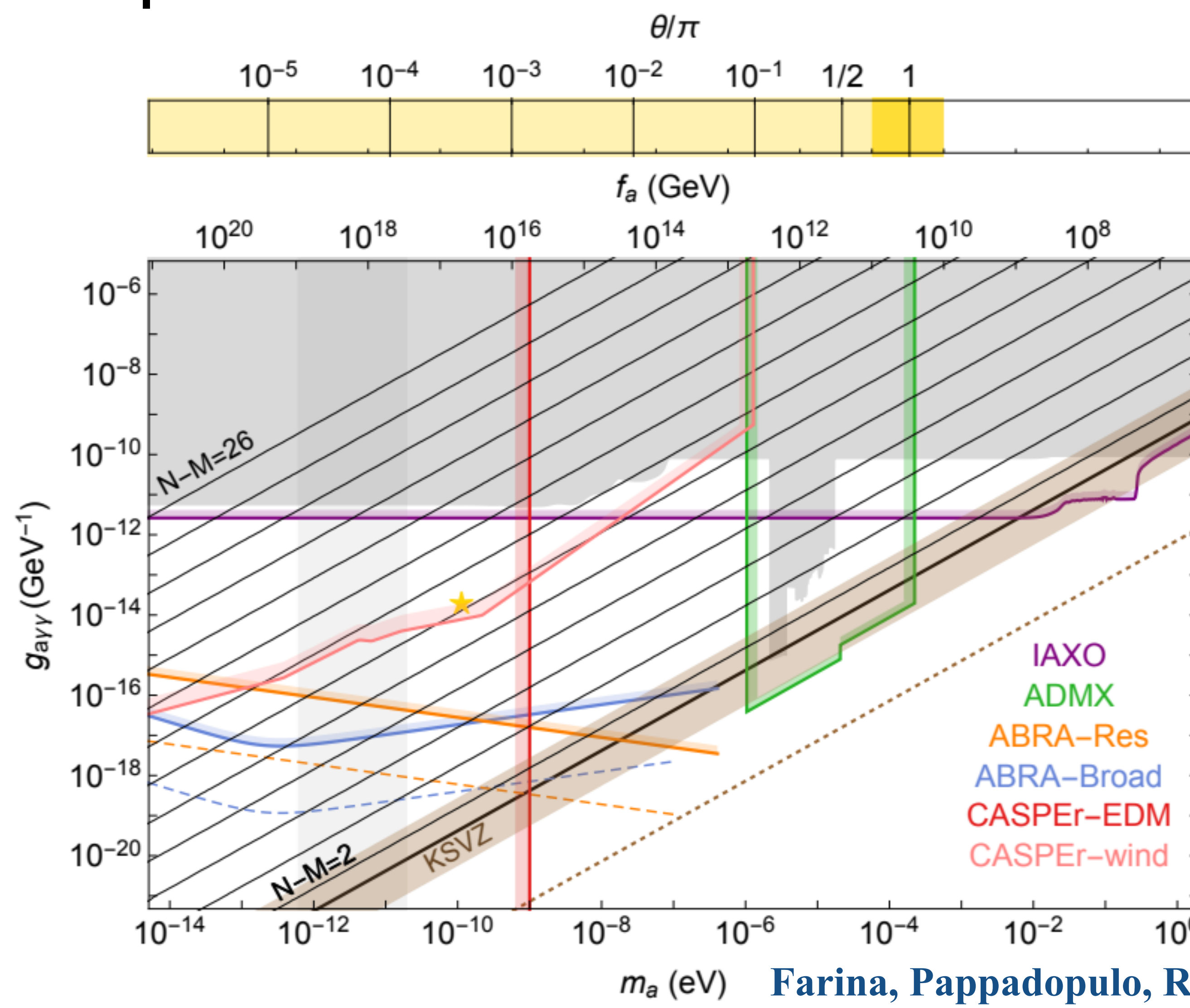
very simple summary of all this effort...



collider searches can probe PQ symmetries with the quality of baryon number

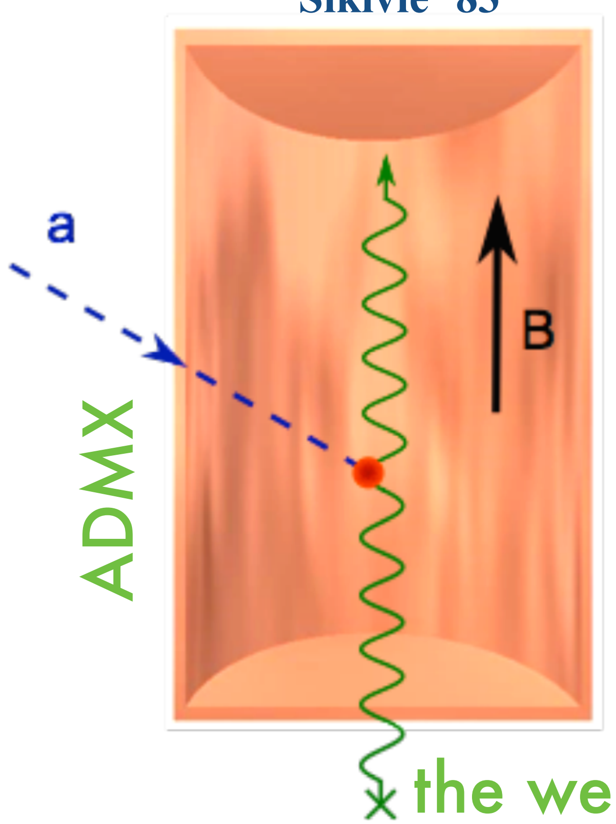
Where do we bet?

We will probe axion Dark Matter in the near future!



Farina, Pappadopulo, Rompineve, Tesi '16

Sikivie '83

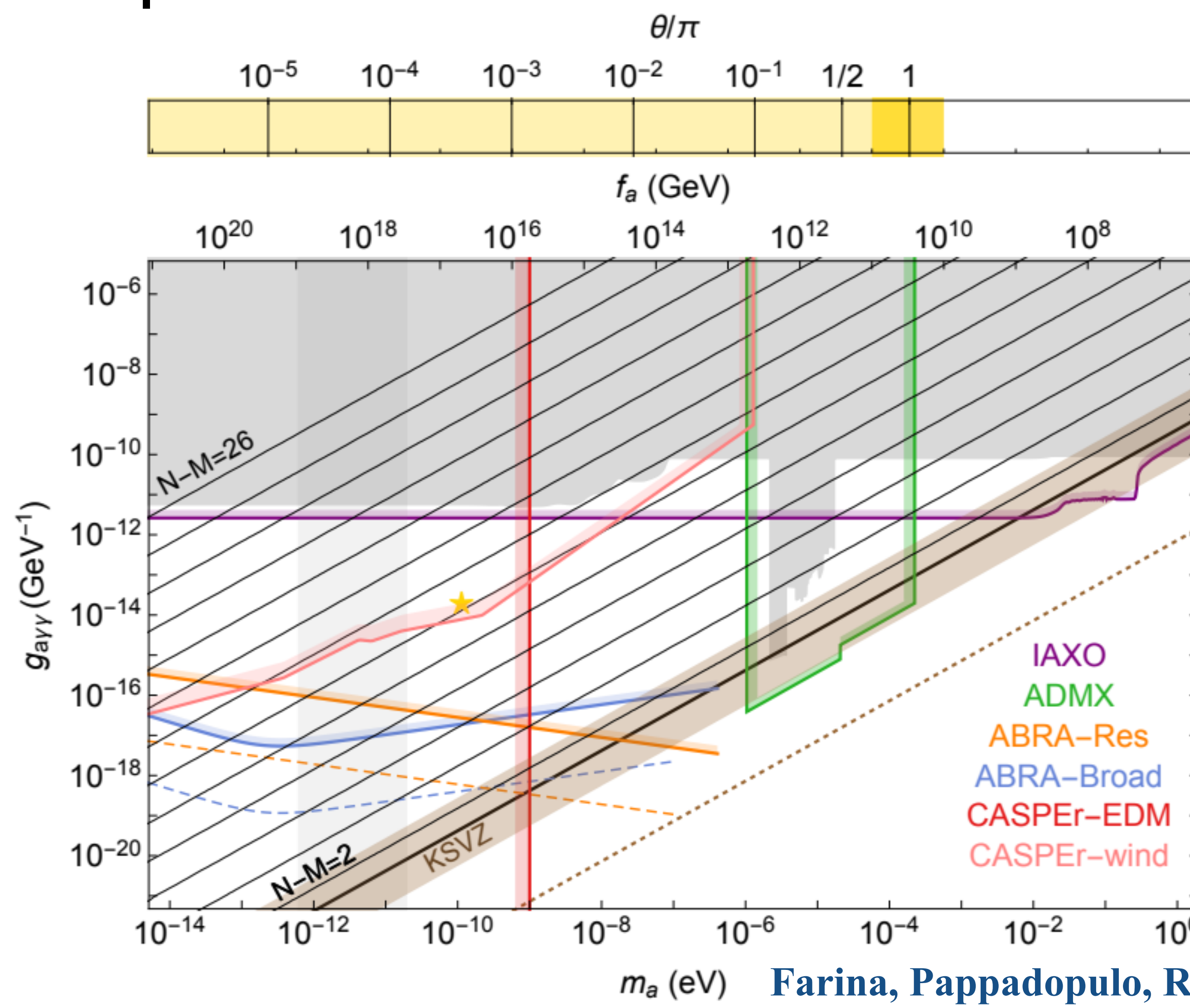


the weak axion signal is enhanced by resonator with a huge Q factor

$$P_{axion} = 1.9\times10^{-22}\,\mathrm{W}\left(\frac{V}{136\ \mathrm{L}}\right)\left(\frac{B}{6.8\ \mathrm{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_a}{0.45\ \mathrm{GeV\ cm^{-3}}}\right)\left(\frac{f}{650\ \mathrm{MHz}}\right)\boxed{\left(\frac{Q}{50,000}\right)}$$

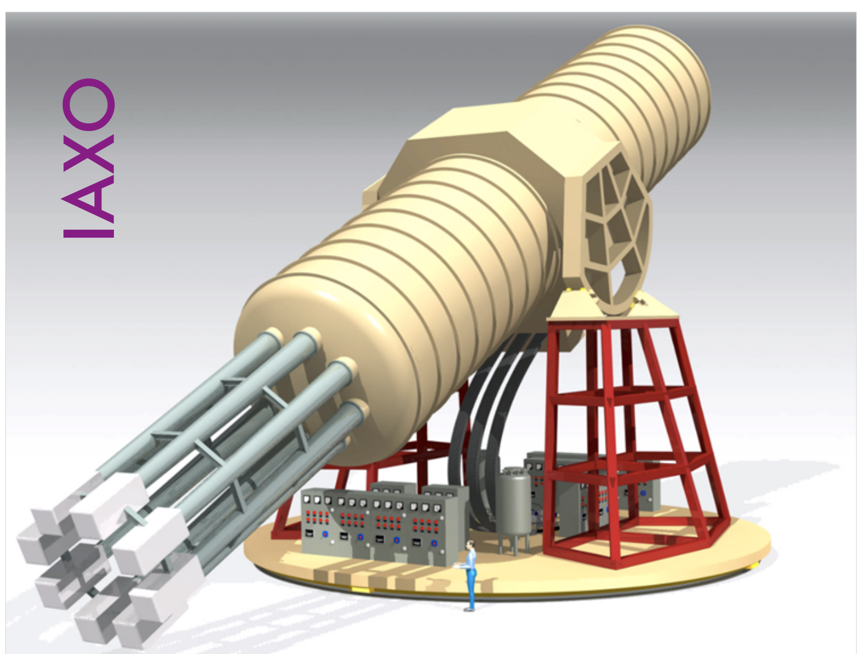
Where do we bet?

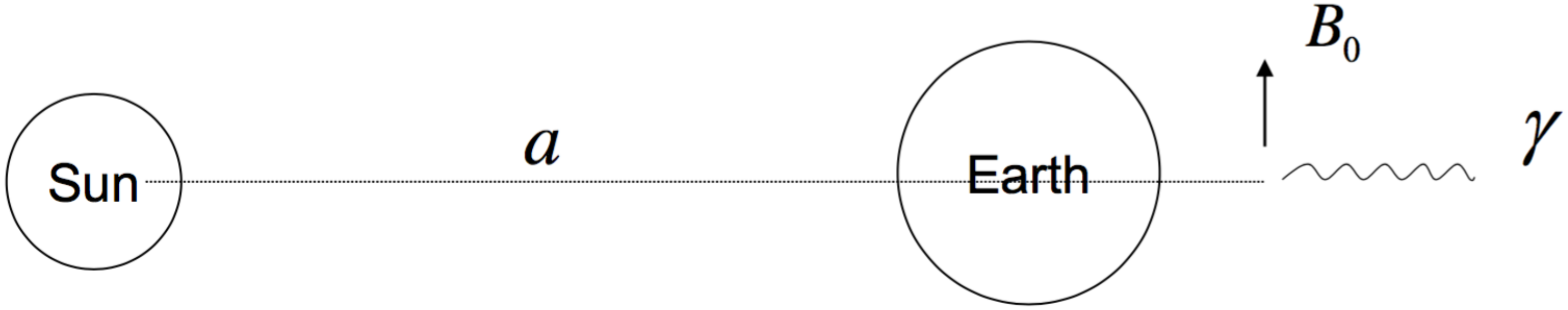
We will probe axion Dark Matter in the near future!



Farina, Pappadopulo, Rompineve, Tesi '16

Davoudiasl and Huber '05

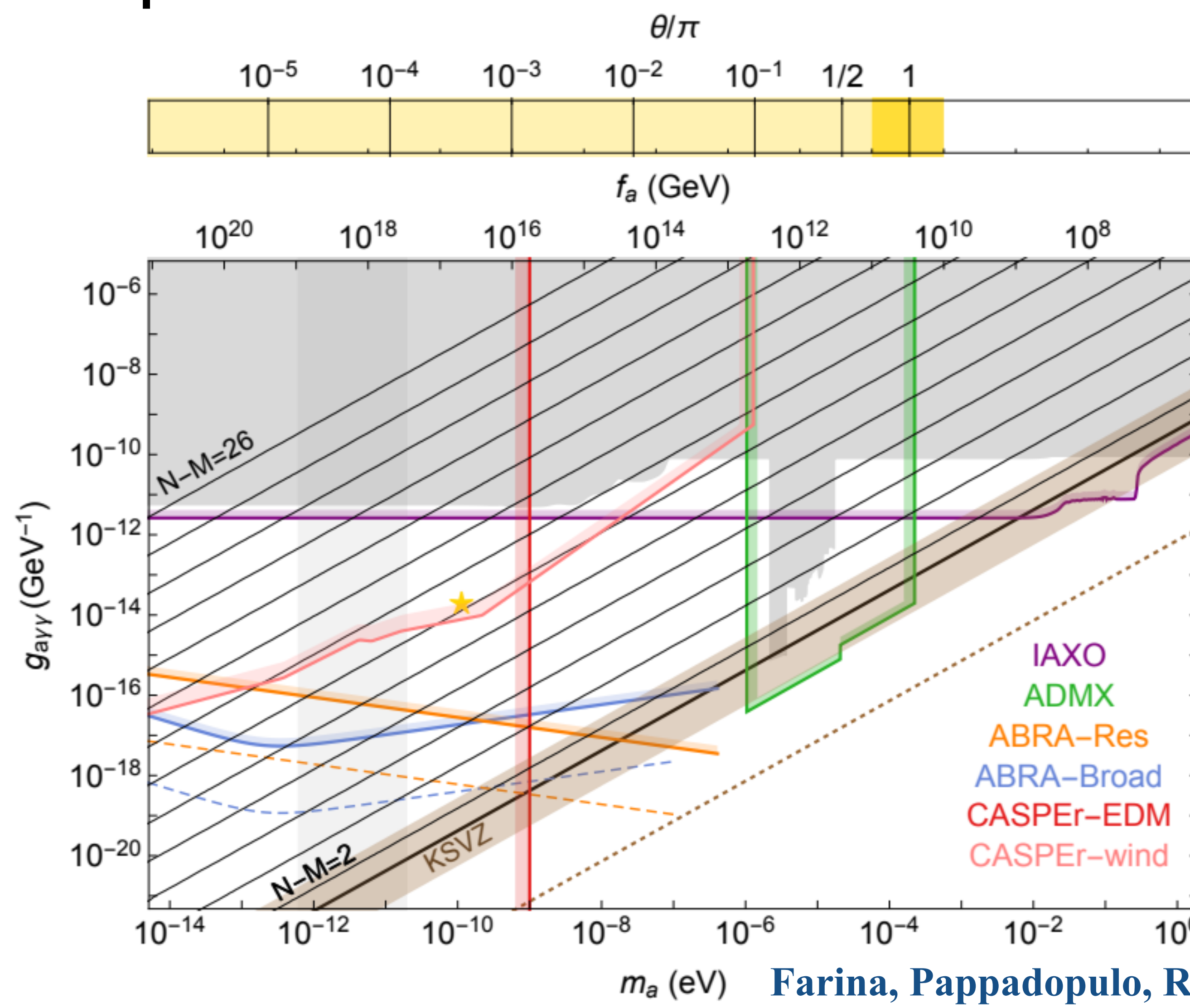




conversion of solar axions in the Earth magnetic field

Where do we bet?

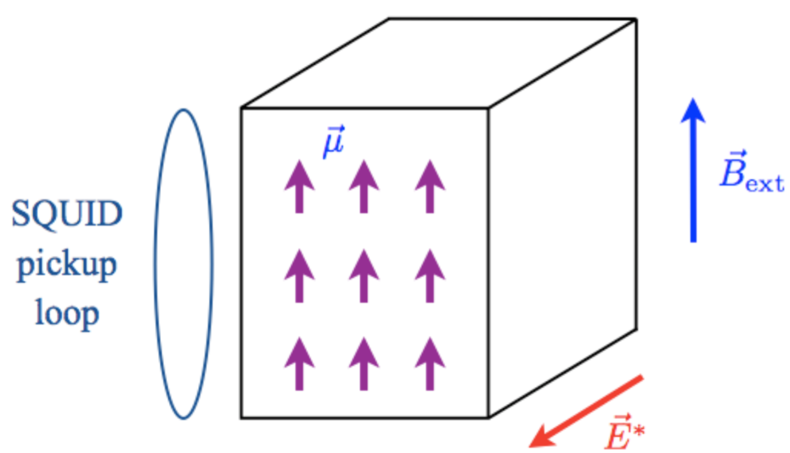
We will probe axion Dark Matter in the near future!



Farina, Pappadopulo, Rompineve, Tesi ‘16

Budker, Graham, Ledbetter, Rajendran ‘14

CASPER EDM

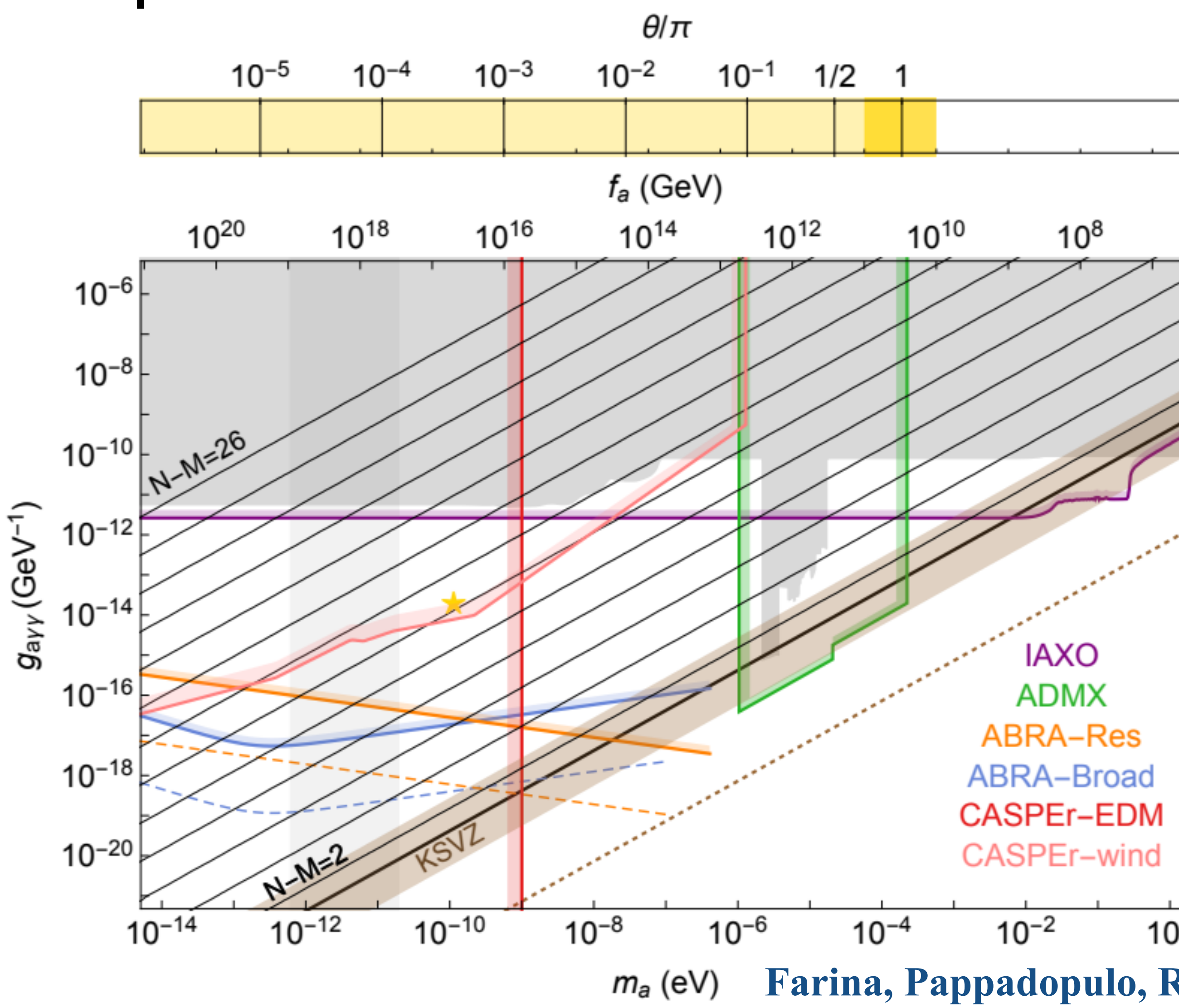


The axion field induces an oscillating EDM

$$d_n = 1.2 \times 10^{-16}\,\frac{a}{f_a}\,\mathrm{e}\cdot\mathrm{cm} \longleftrightarrow a(t) = a_0 \cos\left(m_a t\right)$$

Where do we bet?

We will probe axion Dark Matter in the near future!



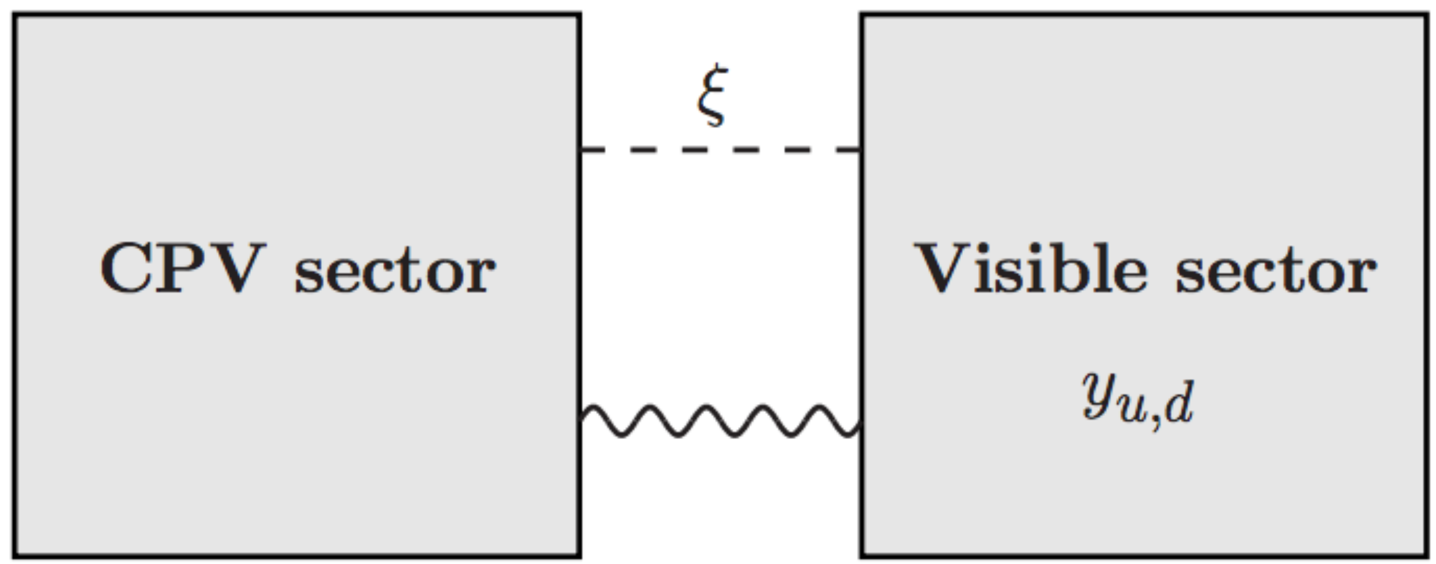
Farina, Pappadopulo, Rompineve, Tesi '16

What if we don't find the axion?

As theorists we should also bet on the Nelson-Barr solution…

CHALLENGE: generate $\bar{\theta} = 0$ + the CKM phase

The prototype setup



Vecchi, '12

CP is only spontaneously broken (all couplings are real)

CP-violation is mediated to the SM to generate CKM but screen $\bar{\theta}$

The prototype model

new pair of vector-like quarks

$$\mathcal{L}_{\text{NB}} = \Big[\underbrace{y_i^{\psi}\Phi_N + \tilde{y}_i^{\psi}\Phi_N^*}_{B_i \in 3_u}\Big]\psi u_i^c + \mu\psi\psi^c + \text{h.c.}$$

Bento, Branco, Parada '91, Dine, Draper '15

Z_2- symmetry: $\begin{cases} [\Phi_N] = [\psi] = [\psi^c] = \text{odd} \\ [\text{SM}] = \text{even} \end{cases}$

$\cancel{\Phi_N \bar{\psi}\psi^c}$

$$M^u = \begin{pmatrix} (\mu)_{1\times 1} & (B)_{1\times 3} \\ (0)_{3\times 1} & (vY^u)_{3\times 3} \end{pmatrix}$$

$\cancel{HQ\psi^c}$

exact CP assumption

discrete symm. @ work

$$\theta_{\text{QCD}}^{\text{tree}} = \text{Arg}(\det M^d) + \text{Arg}(\mu \cdot \det vY^u) = 0$$

The prototype model

$$\mathcal{L}_{\rm NB} = \Big[\overbrace{y_i^{\psi}\Phi_N + \tilde{y}_i^{\psi}\Phi_N^*}^{B_i}\Big]\psi u_i^c + \mu\psi\psi^c + {\rm h.c.}$$

Bento, Branco, Parada '91, Dine, Draper '15

Integrating out the heavy mode we get

$$\left[M_{\rm eff}^u M_{\rm eff}^{u\dagger}\right]_{ij} \sim v^2 Y_{ik}^u Y_{jk}^{u*} - \frac{v^2 Y_{ik}^u B_k^* B_\ell Y_{j\ell}^{u*}}{\mu^2 + |B|^2}$$

The matrix diagonalizing this matrix leads to the CKM phase! $B_i \sim \mu$

The RGE's are under control: $B_i \in 3_u \quad J = {\rm Im}\left(B^\dagger \underbrace{[Y_u^\dagger Y_u, Y_u^\dagger Y_d^\dagger Y_u Y_d]}_{\text{anti-symmetric}} B\right)$

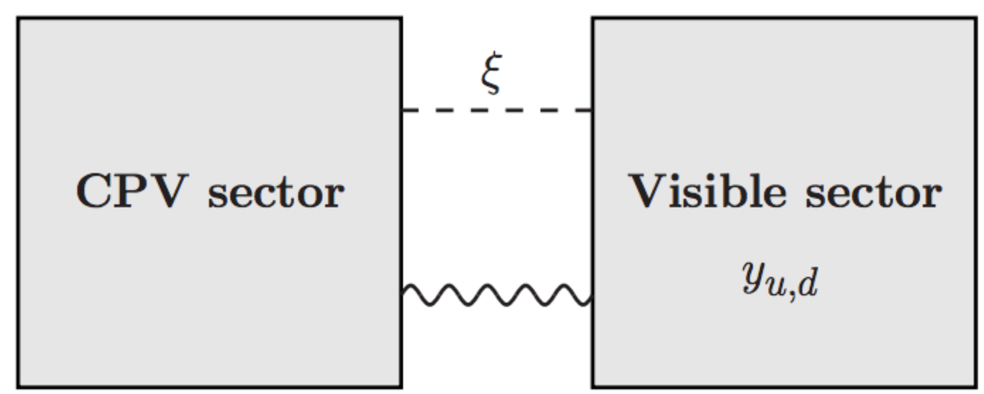
$$\frac{d}{dt}\bar{\theta} \sim J \text{ 4-loops !}$$

The flavor structure can take care of the RGE

$$\frac{d}{dt}\bar{\theta} \sim J \qquad J = \mathrm{Im}\left(B^\dagger \underbrace{[Y_u^\dagger Y_u, Y_u^\dagger Y_d^\dagger Y_u Y_d]}_{\text{anti-symmetric}} B\right)$$

New thresholds are always suppressed by $(v/B)^{\#}$

They decouple for $B \gg v$



2 THEORY CHALLENGES:

Can we make CP violation dynamical?

in progress...

Can we make the symmetry of the portal accidental?

WHERE DO WE BET for strong CP?

The PQ solution is highly testable

We saw that it is strong physics case for light resonance searches at colliders

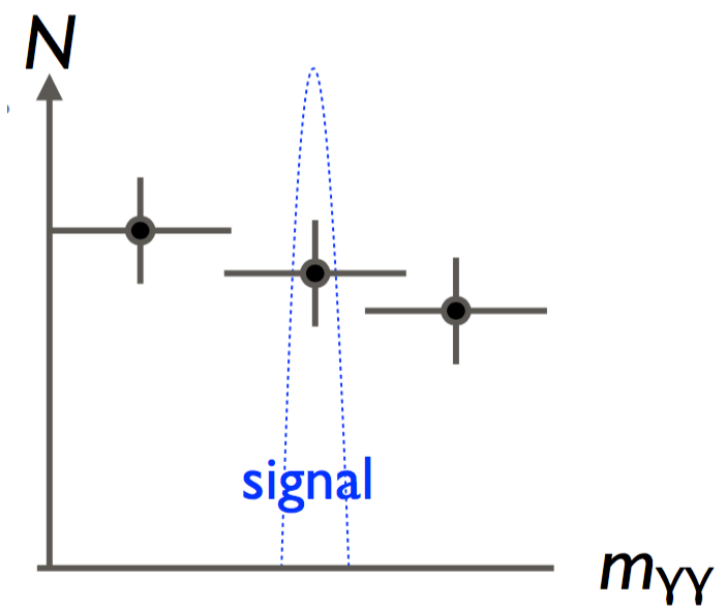
Nelson-Barr has interesting connection with flavor but it might be difficult to test...

maybe an interesting bet for the future?

Rien ne va plus!

Backup Slides: xsec measurement

Extend the bump searches using xsec. measurements



1) **conservative bound** (no *bkd* knowledge)

$$\sigma^{\mathrm{S}}(m_a)\cdot\epsilon_S(m_a) < m_{\gamma\gamma}^{\mathrm{Bin}}\cdot\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\gamma\gamma}}\cdot(1+2\Delta)$$

2) **sensitivity** (*bkd* dominated by SM diphotons)

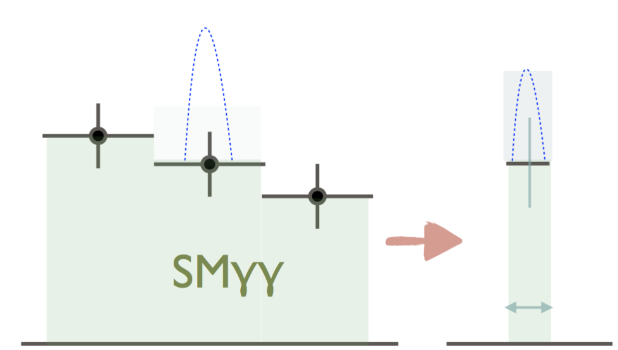
$$\sigma^{\mathrm{S}}(m_a)\cdot\epsilon_S(m_a) < m_{\gamma\gamma}^{\mathrm{Bin}}\cdot\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\gamma\gamma}}\cdot 2\Delta$$

$\Delta =$ error on measure

$m_{\gamma\gamma}^{\mathrm{Bin}}\cdot\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\gamma\gamma}} =$ bin size • measure

$\epsilon_S =$ signal efficiency

3) **rebinning** (shrinking the bin S/B increases)

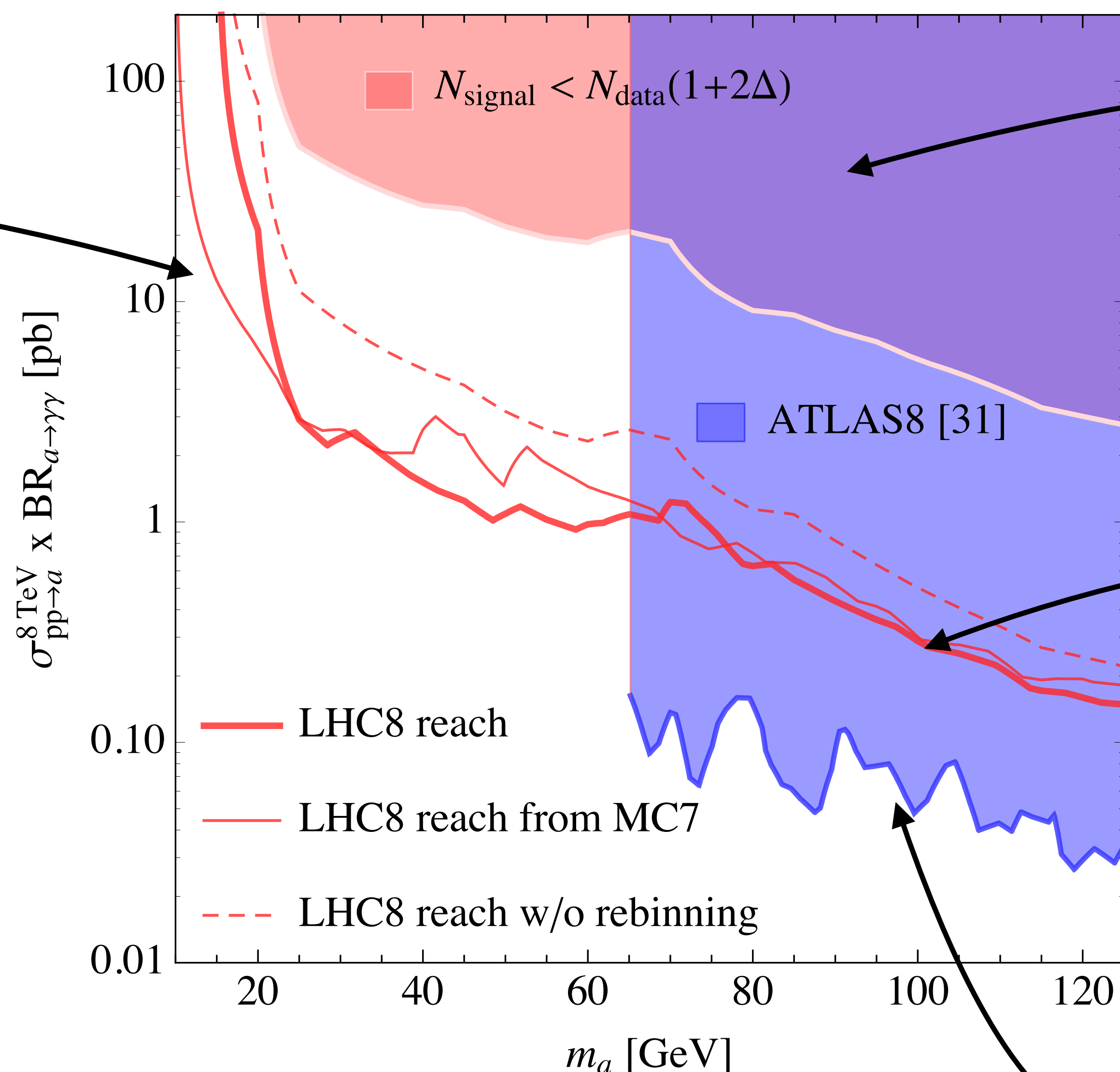


projection $(\sqrt{s}_{\rm low}, L_{\rm low}) \to (\sqrt{s}_{\rm high}, L_{\rm high})$

$$\frac{\sigma_{\rm high}}{\sigma_{\rm high}} = \sqrt{\frac{L_{\rm low}}{L_{\rm high}} \cdot \frac{\sigma_{\rm high}}{\sigma_{\rm low}} \cdot \frac{\epsilon^{\rm low}}{\epsilon^{\rm high}}}$$

7 TeV reach
projected at 8 TeV

low mass reach
9.4 GeV
13.9 GeV
14.2 GeV



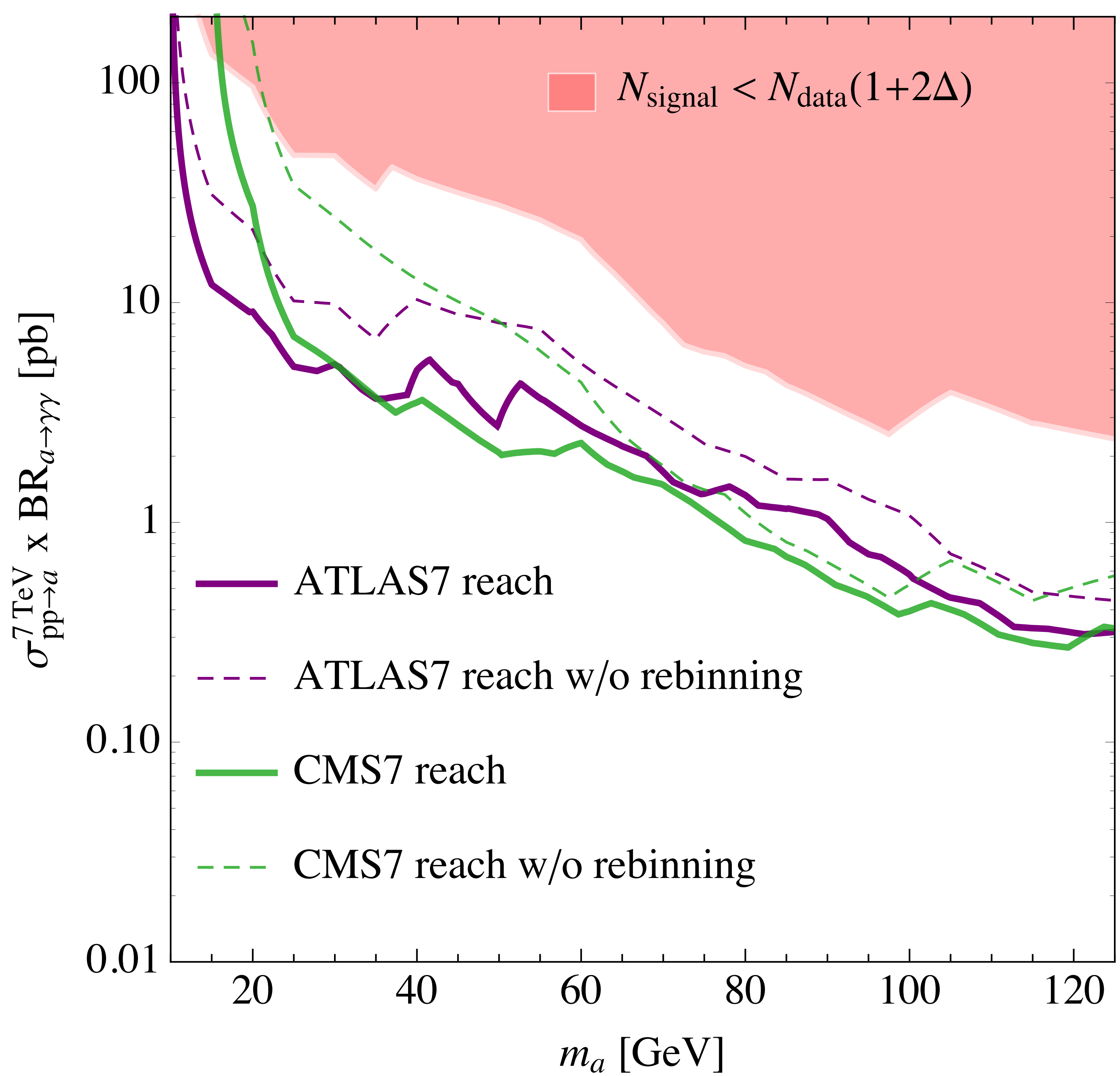
conservative bound
from 8 TeV data

rebinning
with ECAL resolution

$$\frac{\delta E_\gamma}{E_\gamma} = 10\% \cdot \left(\frac{\rm GeV}{E_\gamma}\right)^{1/2}$$

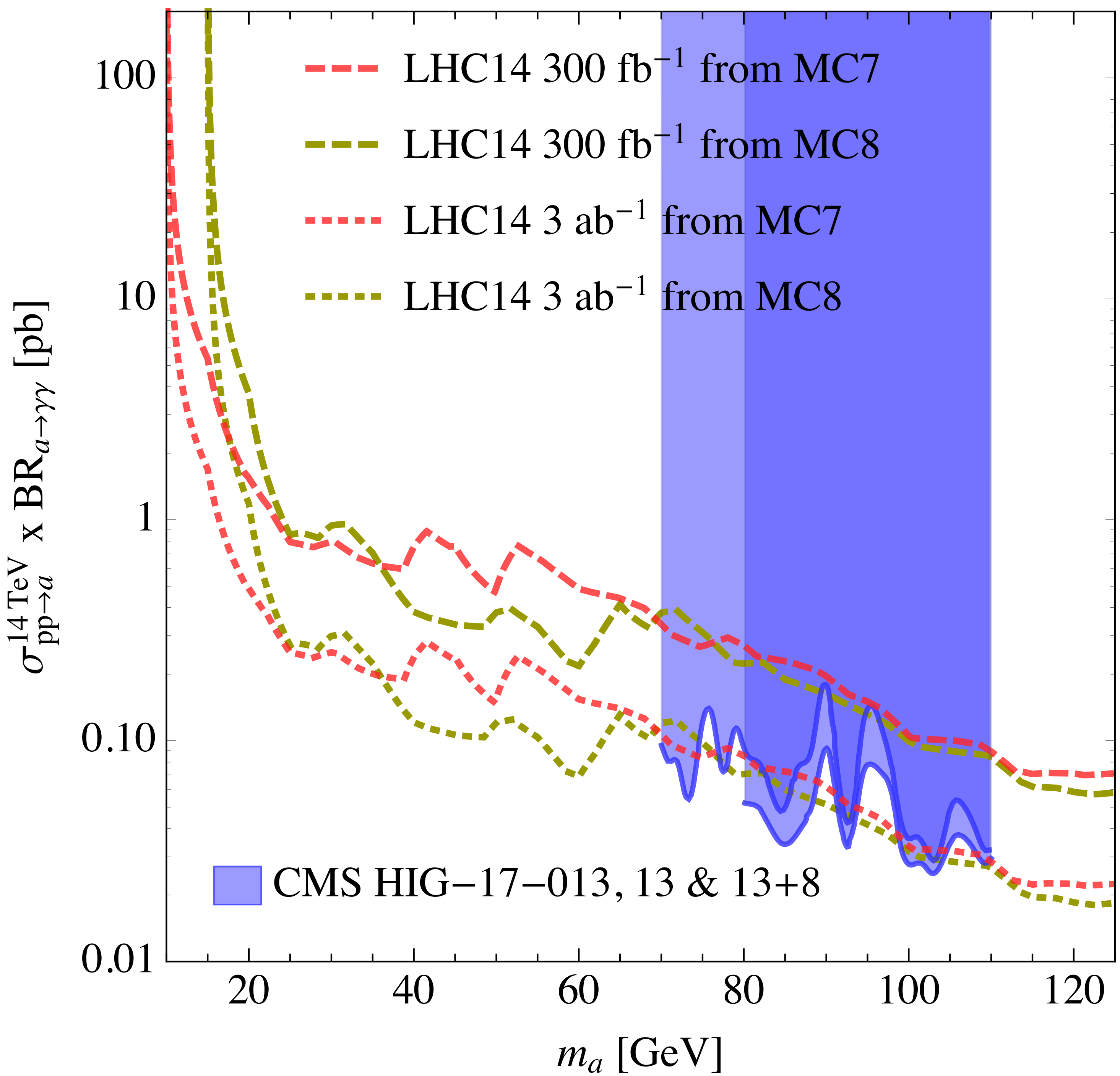
N.B. An unbinned shape analysis still does ~5 better!

7 TeV data



$N_{\text{signal}} < N_{\text{data}}(1+2\Delta)$
ATLAS7 reach
ATLAS7 reach w/o rebinning
CMS7 reach
CMS7 reach w/o rebinning
100
10
1
0.10
0.01
20
40
60
80
100
120
$\sigma^{7\,\text{TeV}}_{pp\to a}$ x $\text{BR}_{a\to\gamma\gamma}$ [pb]
m_a [GeV]

14 TeV projections



Did we dig carefully enough in old data?

Experiment	Process	Lumi	$\sqrt{s}$	low mass reach	ref.
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma jj$	12 pb^{-1}	Z-pole	10 GeV	[25]
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma\gamma\gamma$	78 pb^{-1}	Z-pole	3 GeV	[26]
LEPII	$e^+e^- \to Z^*, \gamma^* \to \gamma a \to \gamma jj$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[27]
LEPII	$e^+e^- \to Z^*, \gamma^* \to \gamma a \to \gamma\gamma\gamma$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[27, 28]
LEPII	$e^+e^- \to Z^*, \gamma^* \to Za \to jj\gamma\gamma$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[27]
D0/CDF	$p\bar{p} \to a \to \gamma\gamma$	7/8.2 fb^{-1}	1.96 TeV	100 GeV	[29]
ATLAS	$pp \to a \to \gamma\gamma$	20.3 fb^{-1}	8 TeV	65 GeV	[30]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	80 GeV	[31]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	150 GeV	[32]
CMS	$pp \to a \to \gamma\gamma$	35.9 fb^{-1}	13 TeV	70 GeV	[33]

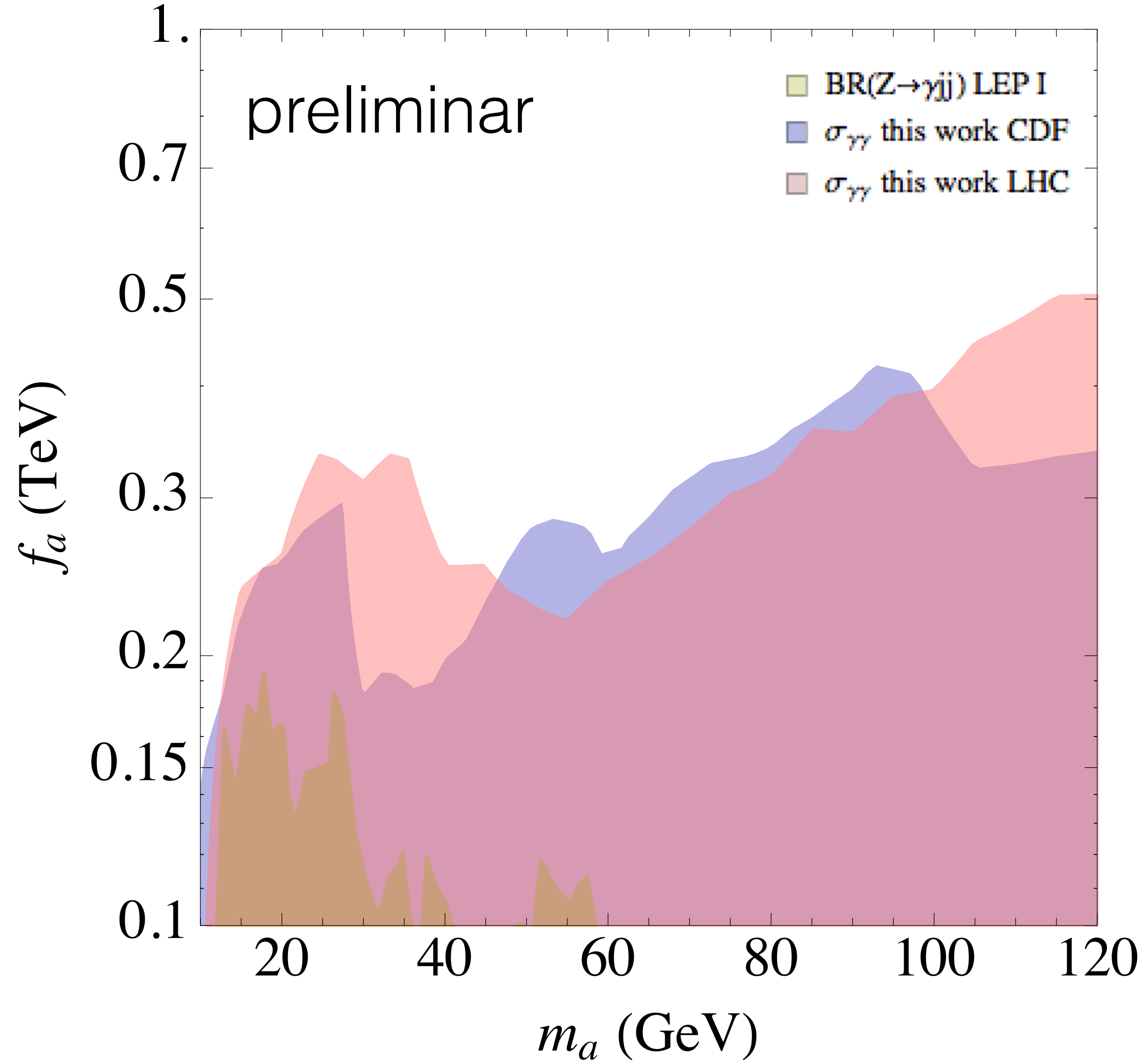
UA2	$p\bar{p} \to a \to \gamma\gamma$	13.2 pb^{-1}	0.63 TeV	17.9 GeV	[34]
D0	$p\bar{p} \to a \to \gamma\gamma$	4.2 fb^{-1}	1.96 TeV	8.2 GeV	[35]
CDF	$p\bar{p} \to a \to \gamma\gamma$	5.36 fb^{-1}	1.96 TeV	6.4 GeV	[36]
ATLAS	$pp \to a \to \gamma\gamma$	4.9 fb^{-1}	7 TeV	9.4 GeV	[8]
ATLAS	$pp \to a \to \gamma\gamma$	20.2 fb^{-1}	8 TeV	13.9 GeV	[9]
CMS	$pp \to a \to \gamma\gamma$	5.0 fb^{-1}	7 TeV	14.2 GeV	[10]

UA2? looked only at almost back to back photons

$$m_{\gamma\gamma}^2 = 2\underbrace{p_{T_1} p_{T_2}}_{\gtrsim (9\ \mathrm{GeV})^2} \underbrace{(\overbrace{\cosh \Delta\eta}^{\gtrsim 1} - \overbrace{\cos \Delta\phi}^{\lesssim -0.7})}_{\gtrsim 1.7} \gtrsim (18\ \mathrm{GeV})^2$$

Tevatron? It is comparable with LHC now!

$$\sigma^{\mathrm{S}}(m_a)\cdot\epsilon_S(m_a) < m_{\gamma\gamma}^{\mathrm{Bin}}\cdot\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\gamma\gamma}}\cdot(1+2\Delta)$$



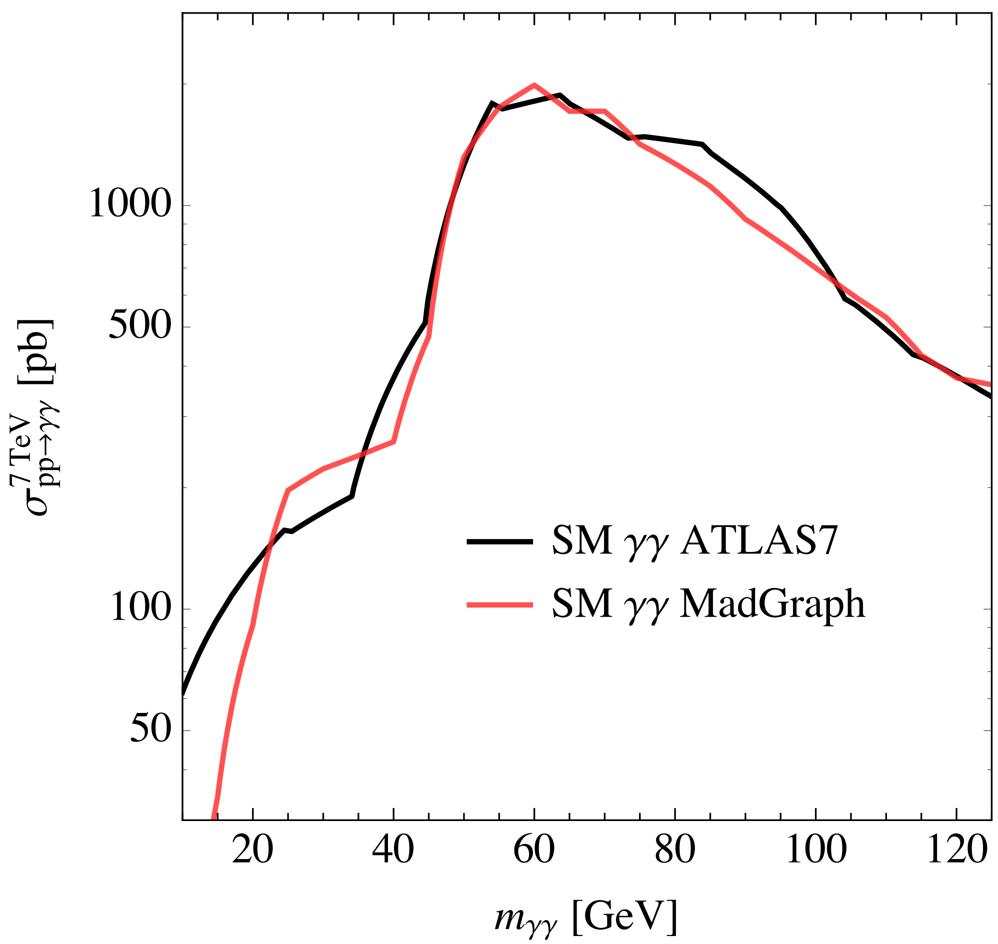
however this is an artifact of our conservative bound

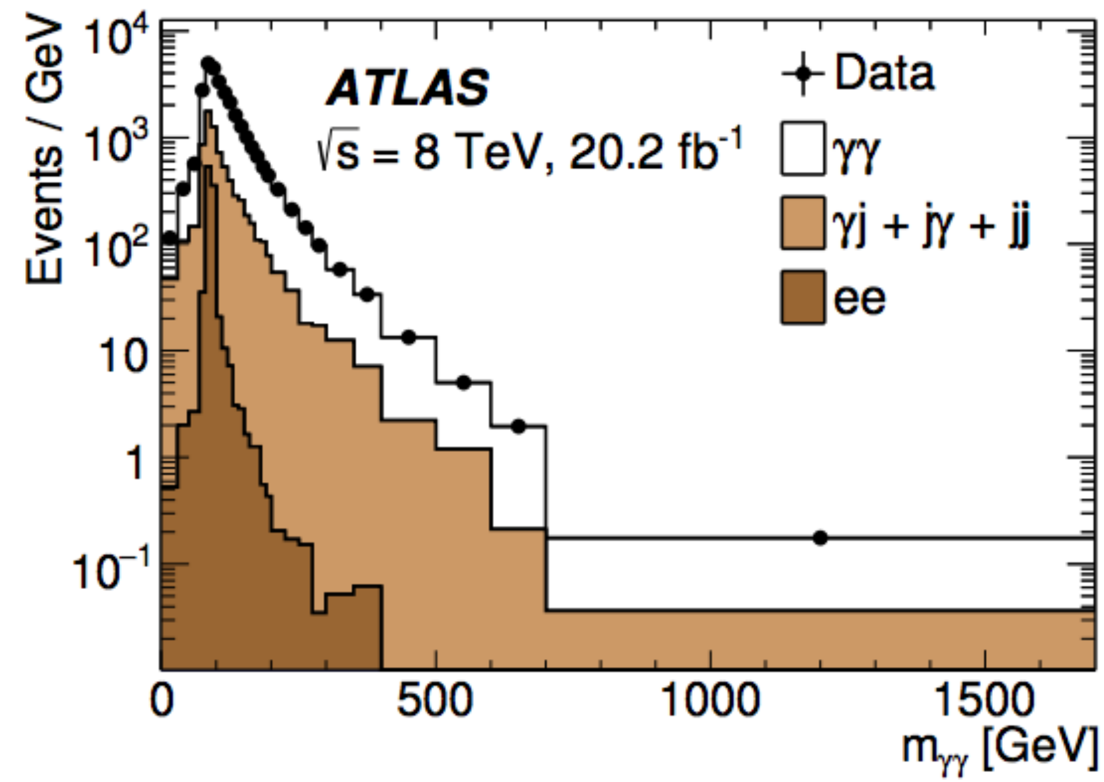
systematics went down by a factor ~3-4 depending on the mass

LHC has better sensitivity! EXTRA REASON TO DO THIS!

diphoton backgrounds

we validated only the one from real photons

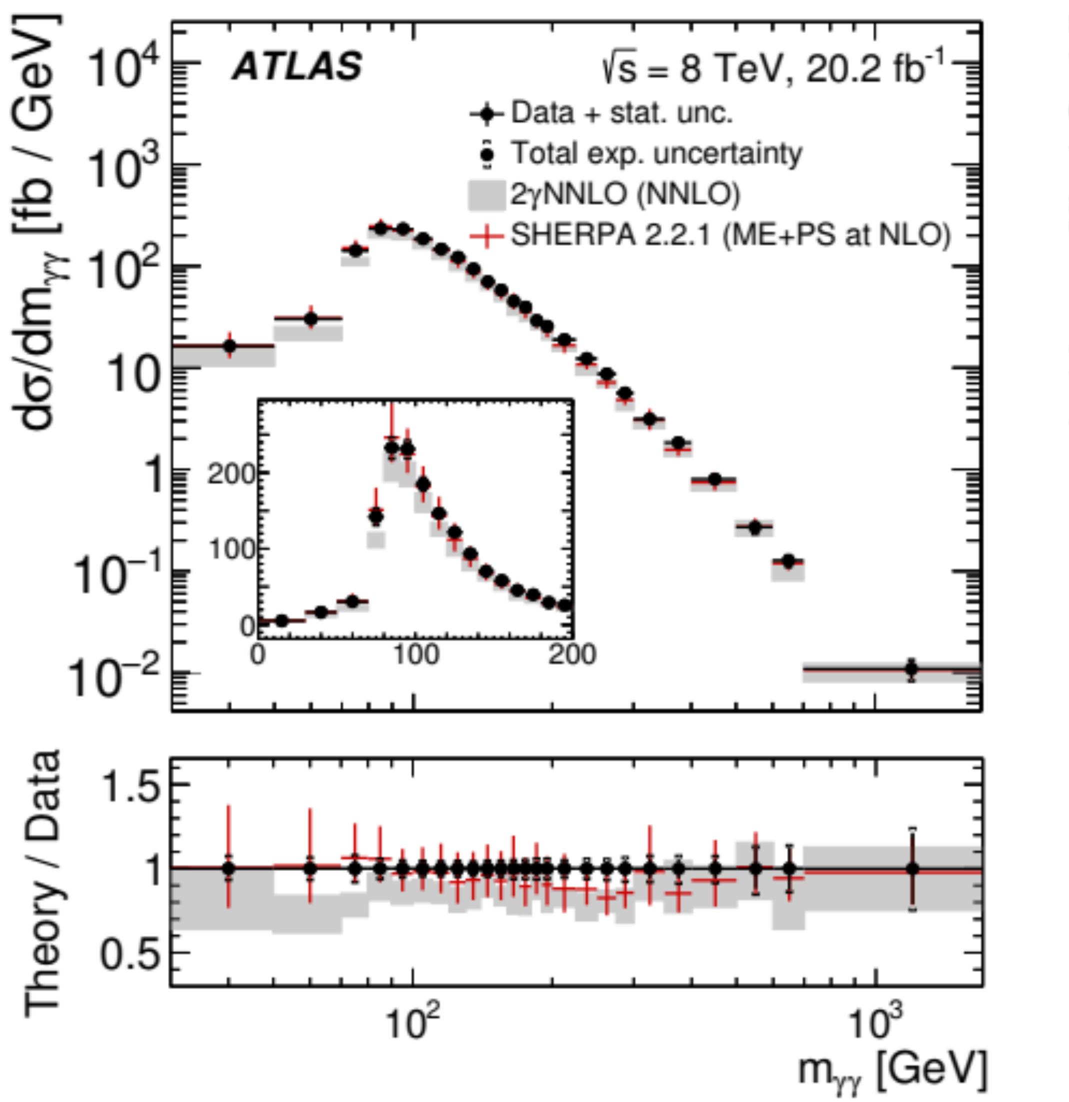




photon+jet is ~ 30% of the background but it does not modify the shape significantly

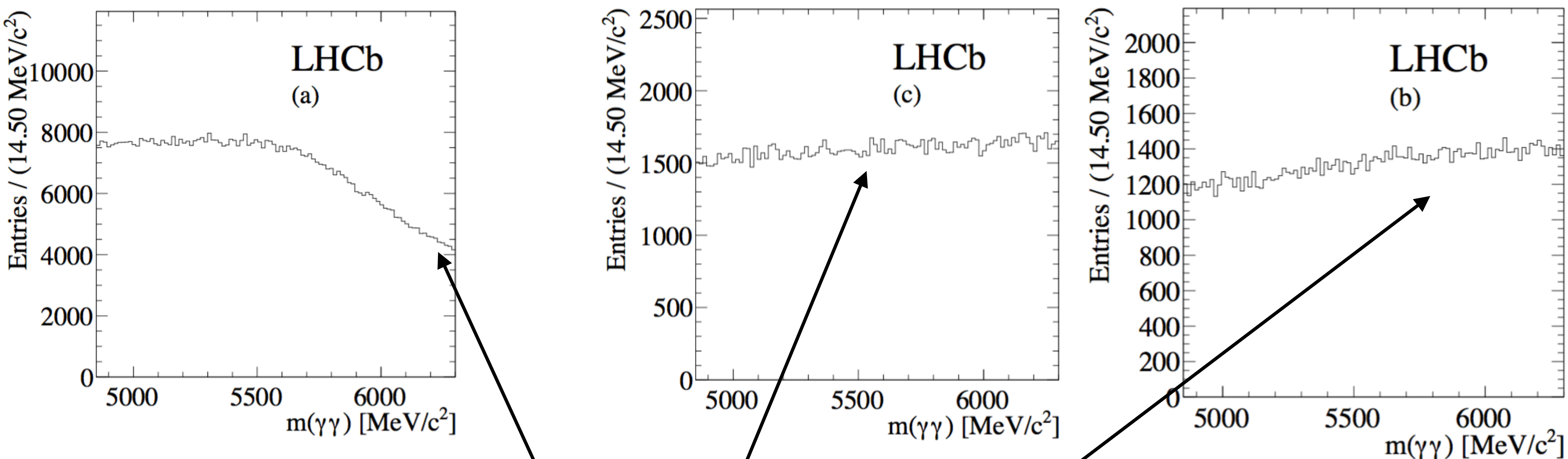
jet+jet is irrelevant

the challenge of background modelling

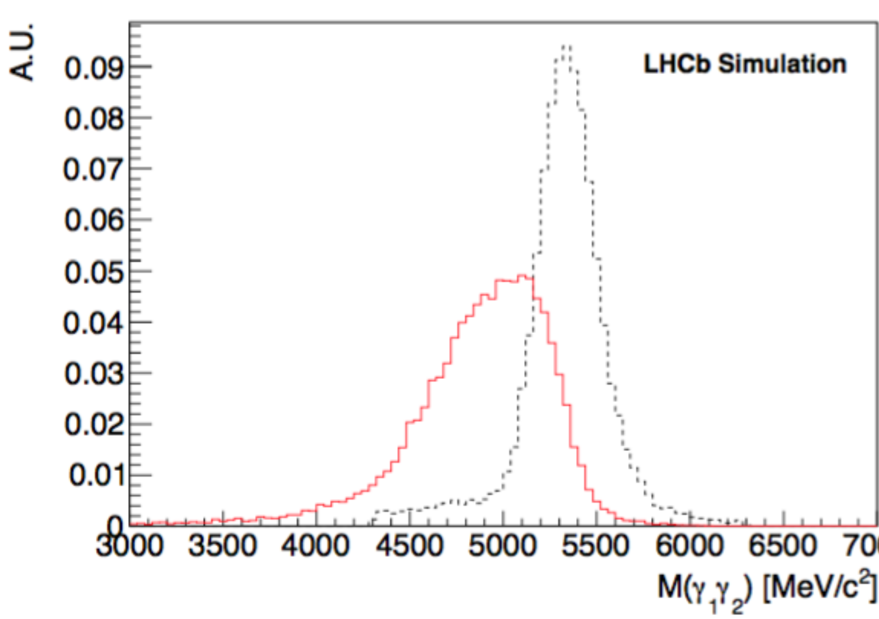


modeling of the calorimeter isolation variable in simulated samples. Predicted cross sections from fixed-order QCD calculations implemented in DIPHOX and RESBOS at next-to-leading order, and in 2γNNLO at next-to-next-to-leading order, are about 36%, 28% and 16% lower than the data, respectively. The relative errors associated to the predictions from DIPHOX (2γNNLO) are 10–15% (5–10%).

Backup Slides: LHCb

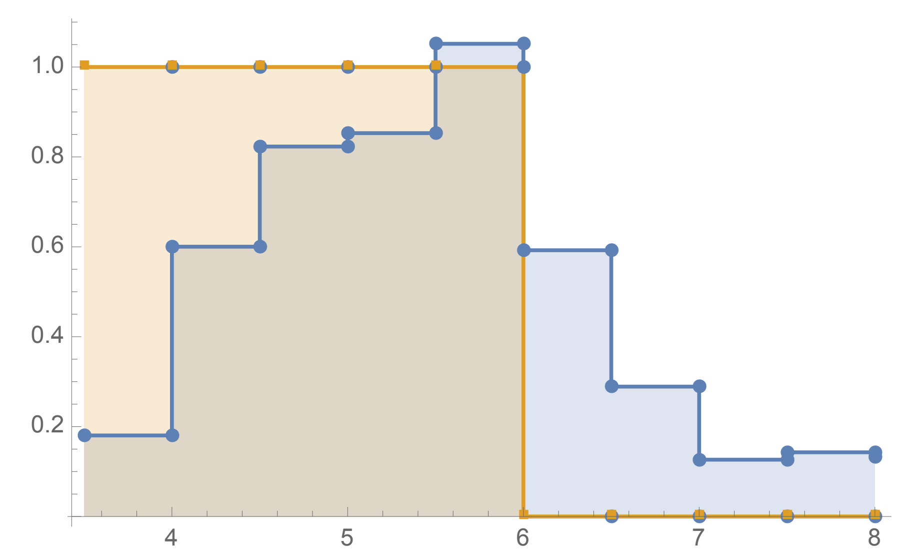


background feature not present in CV categories



bin migration from 2x2 cluster cells

to 3x3 cluster cells



Backup Slides: boosted searches

Backup Slides: Heavy Axion models

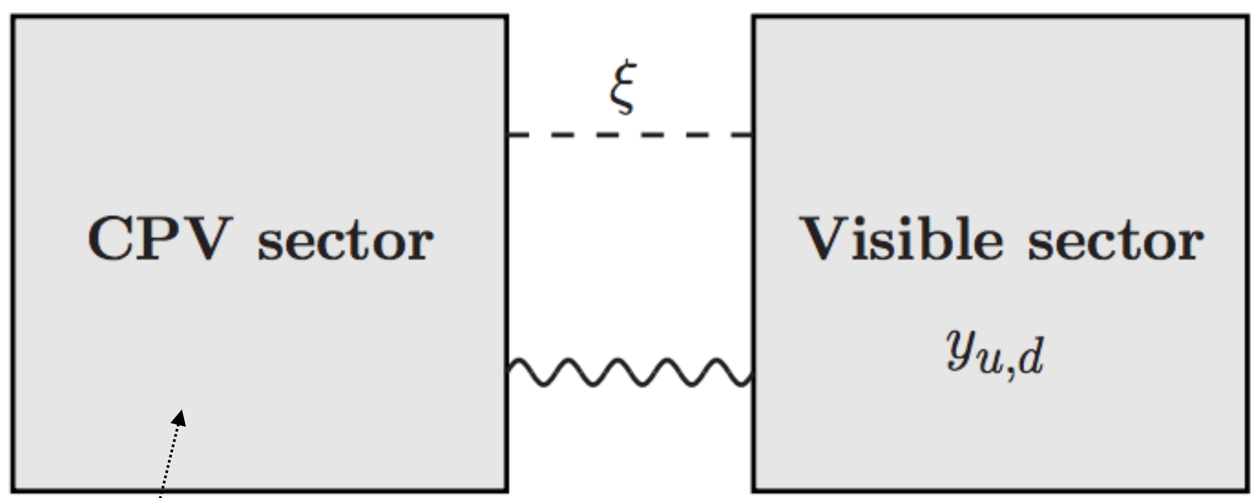
Mirror Axions

UV instantons

Backup Slides: NB models

Can we make CP violation dynamical?

in progress with G. Perez and A. Shalit



Breaking CP from the dynamics of a confining sector

We need a gauge theory which has a CP-breaking vacuum   Gaiotto, Komargodski, Seiberg '18

$$\mathcal{L} \supset \begin{array}{l} -m_\chi \sum_{a=1,2} \chi_{(a)}\tilde{\chi}_{(a)} + \sum_{a=1,2} \left[\lambda_a \varphi + \hat{\lambda}_a \varphi^*\right] \chi_{(a)}\tilde{\chi}_{(a)} \\ -m_\psi \psi\tilde{\psi} + \left[y_i^\psi \varphi + \hat{y}_i^\psi \varphi^*\right] \psi \tilde{d}_i \end{array}$$

Can we make the symmetry of the portal accidental?

in progress

gauging $U(3)_{Q_L} \otimes U(3)_{U_R} \otimes U(3)_{D_R}$ Grinstein, Redi, Villadoro '10

	$SU(3)_{Q_L}$	$SU(3)_{U_R}$	$SU(3)_{D_R}$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_L	3	1	1	3	2	1/6
U_R	1	3	1	3	1	2/3
D_R	1	1	3	3	1	-1/3
Ψ_{uR}	3	1	1	3	1	2/3
Ψ_{dR}	3	1	1	3	1	-1/3
Ψ_u	1	3	1	3	1	2/3
Ψ_d	1	1	3	3	1	-1/3
Y_u	$\bar{3}$	3	1	1	1	0
Y_d	$\bar{3}$	1	3	1	1	0
H	1	1	1	1	2	1/2

we get the NB structure!

$$\lambda_u \, \overline{Q}_L \tilde{H} \Psi_{uR} + \lambda_u' \, \overline{\Psi}_u Y_u \Psi_{uR} + M_u \, \overline{\Psi}_u U_R$$

generate the Yukawas & the phases from the vacuum structure