Implications of LHCb measurements and future prospects

Searching for new spin-0 resonances at LHCb

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mostly based on arXiv:1601.05110
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13/10/2016

Motivation

Scalar particles ⇔ symmetry breaking

- Examples: pions, Higgs, axions, dilaton…

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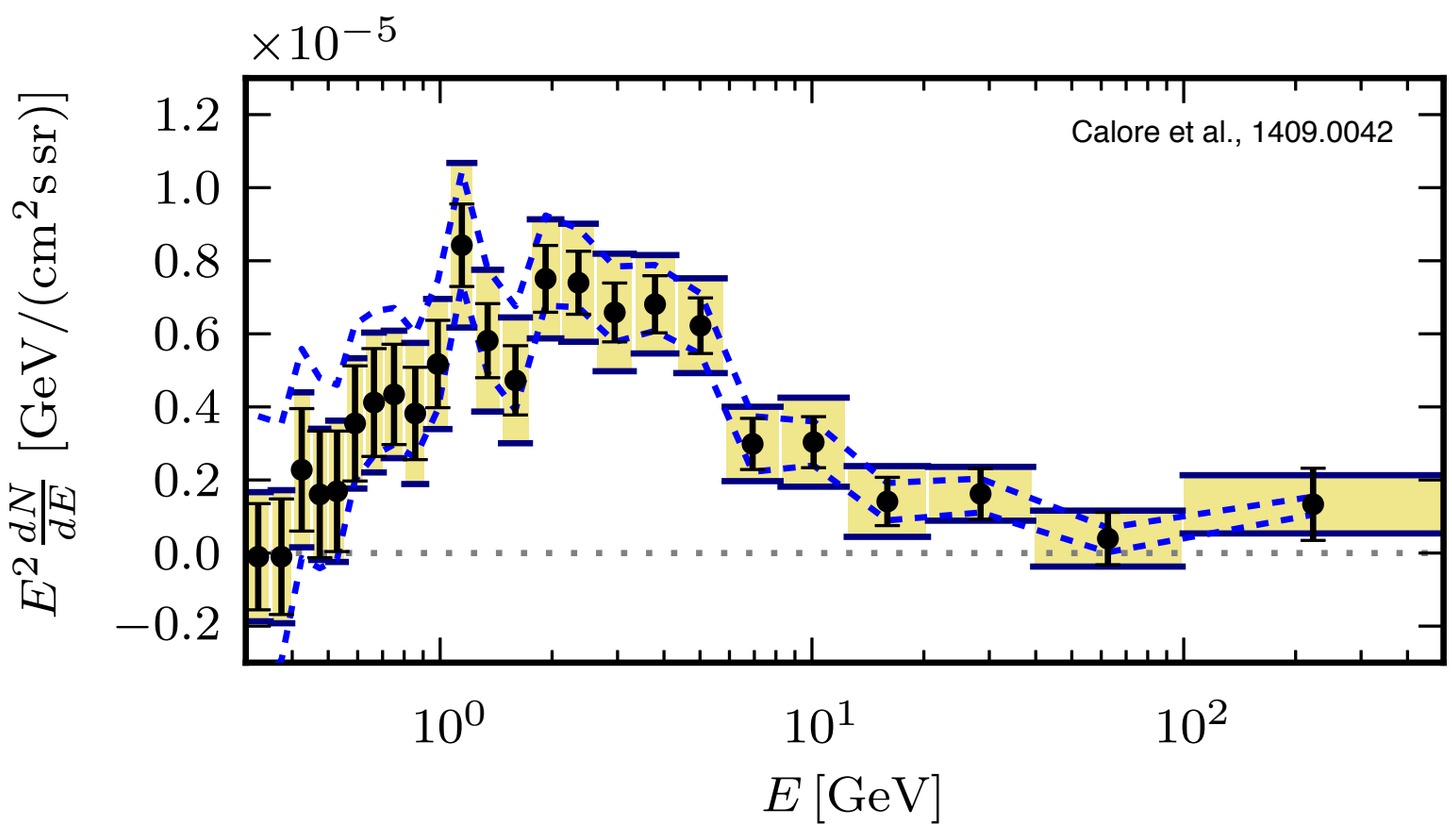
- Example: FERMI-LAT 1GeV excess



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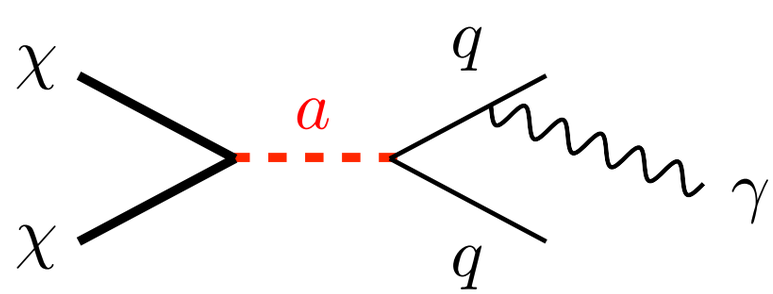
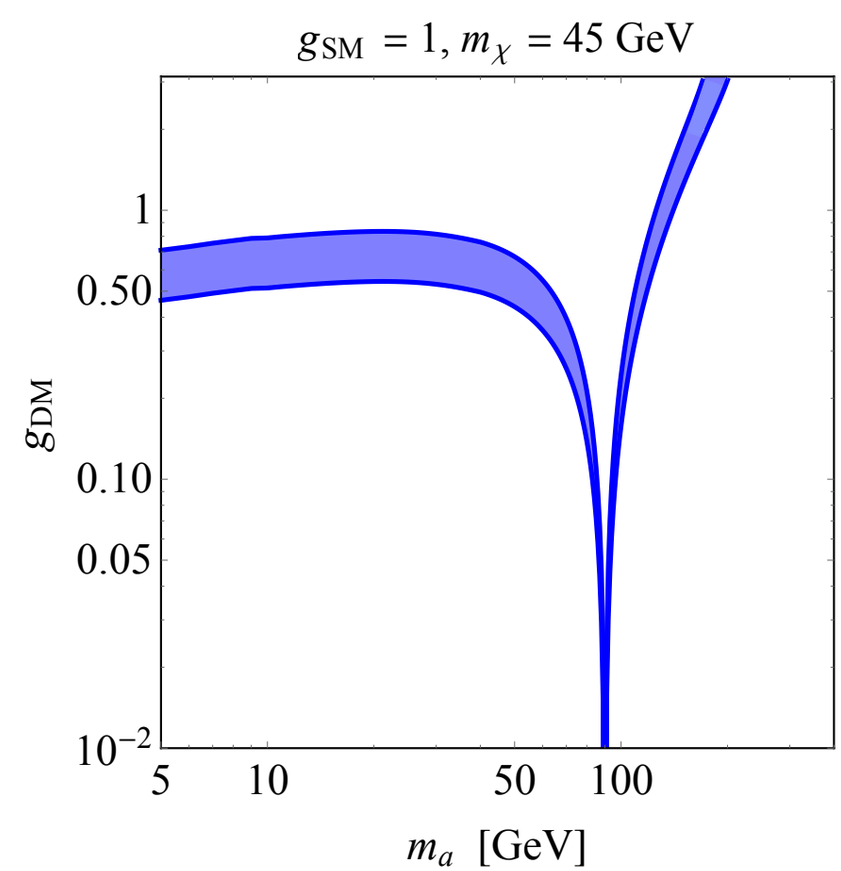
$$\mathcal{L} \supset -i g_{\rm DM}\, a\, \bar{\chi}\gamma_5\chi$$

$$-i g_{\rm SM} \sum_q \frac{m_q}{v}\, a\, \bar{q}\gamma_5 q$$





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Couplings to SM fermions break flavor - existing FCNC constraints imply special structure (~MFV, U(2))

- Examples: Higgs-singlet mixing, THDM I,II,X…

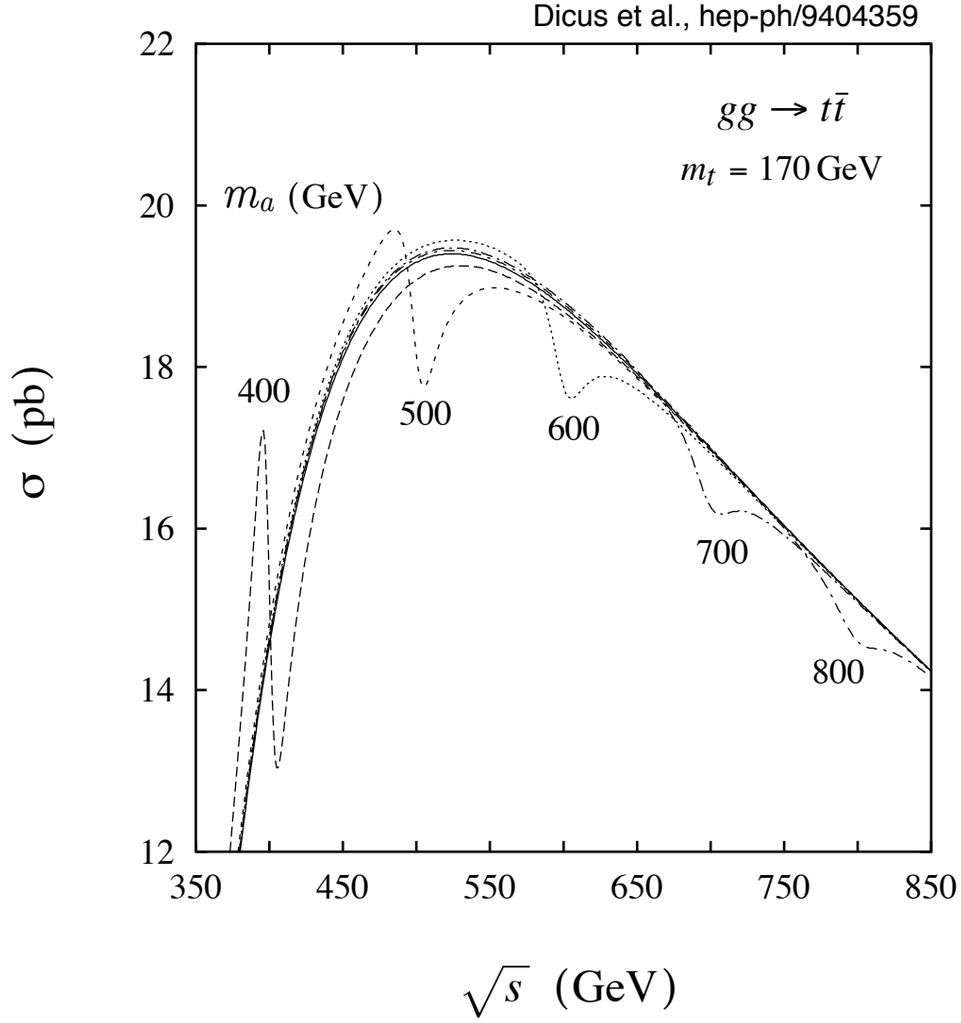
Scalar resonance searches at LHC

Decays to SM final states:

$m_a \gtrsim 350\mathrm{GeV}$: tt resonances (challenging)

Gori et al., 1602.02782
Carena & Liu, 1608.07282
Craig et al., 1605.08744

Dicus et al., hep-ph/9404359



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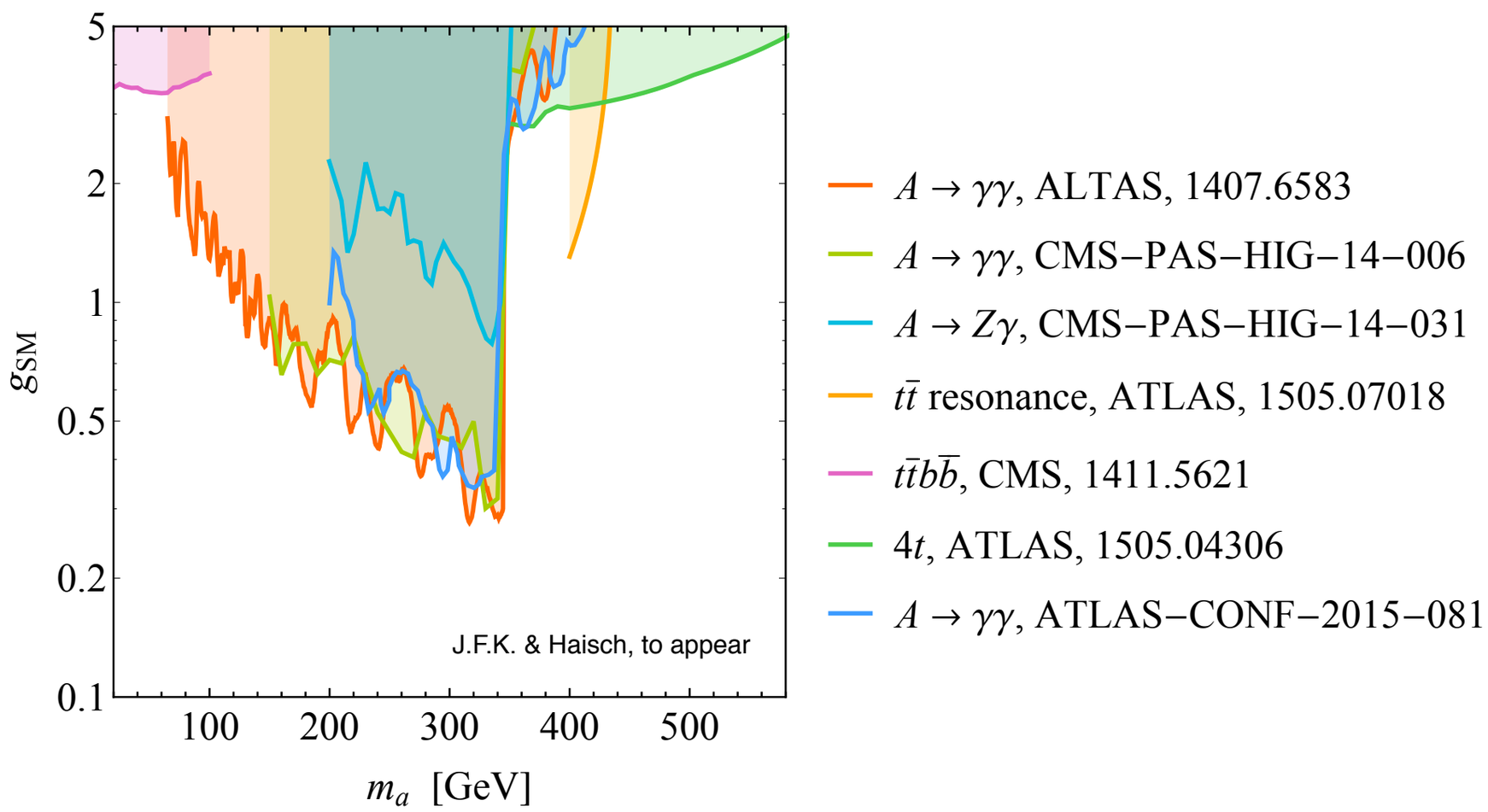

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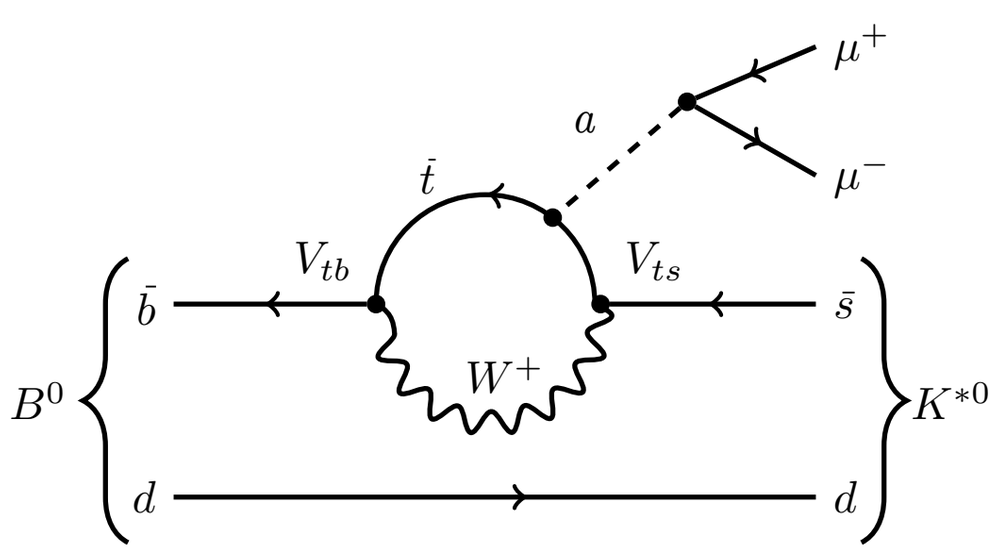
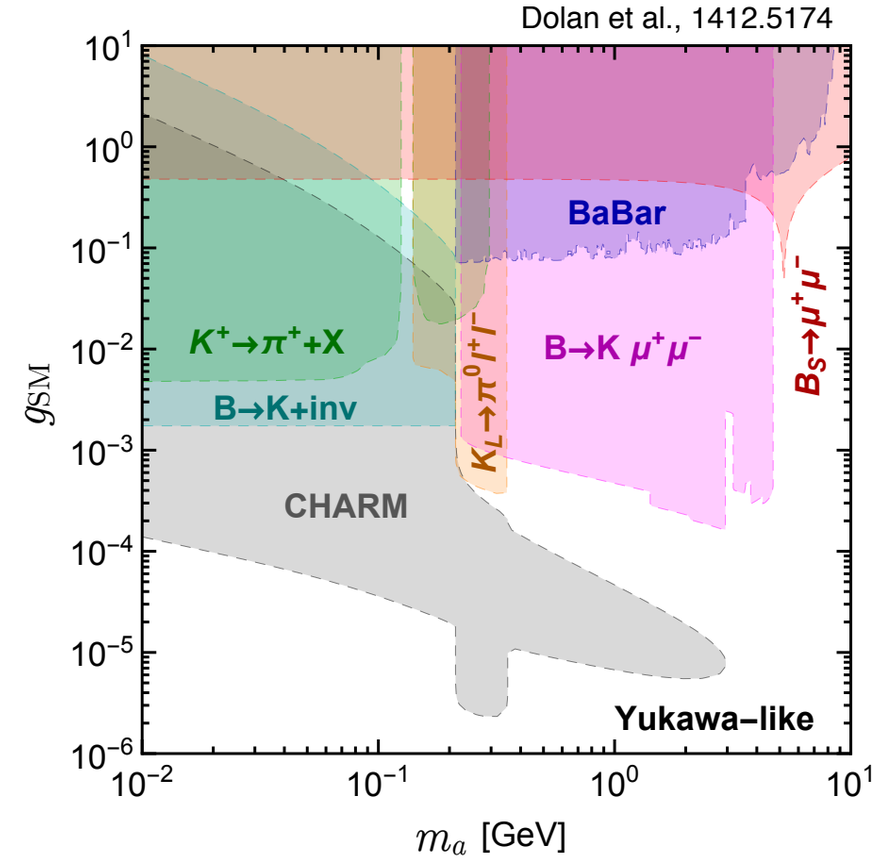
$m_a \lesssim 10\mathrm{GeV}$: rare quarkonium, meson decays,…



Dolan et al., 1412.5174



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$m_a \lesssim 10\mathrm{GeV}$: rare quarkonium, meson decays,…

$10\mathrm{GeV} \lesssim m_a \lesssim 50\mathrm{GeV}$ region poorly constrained!

(Far future: $4t$, $2t2b$ searches)

Goncalves & Lopez-Val, 1607.08614

Scalar resonance searches at LHC

Decays to SM

$m_a \gtrsim 350\text{GeV}$

$50\text{GeV} \lesssim m_a$

$m_a \lesssim 10\text{GeV}$:

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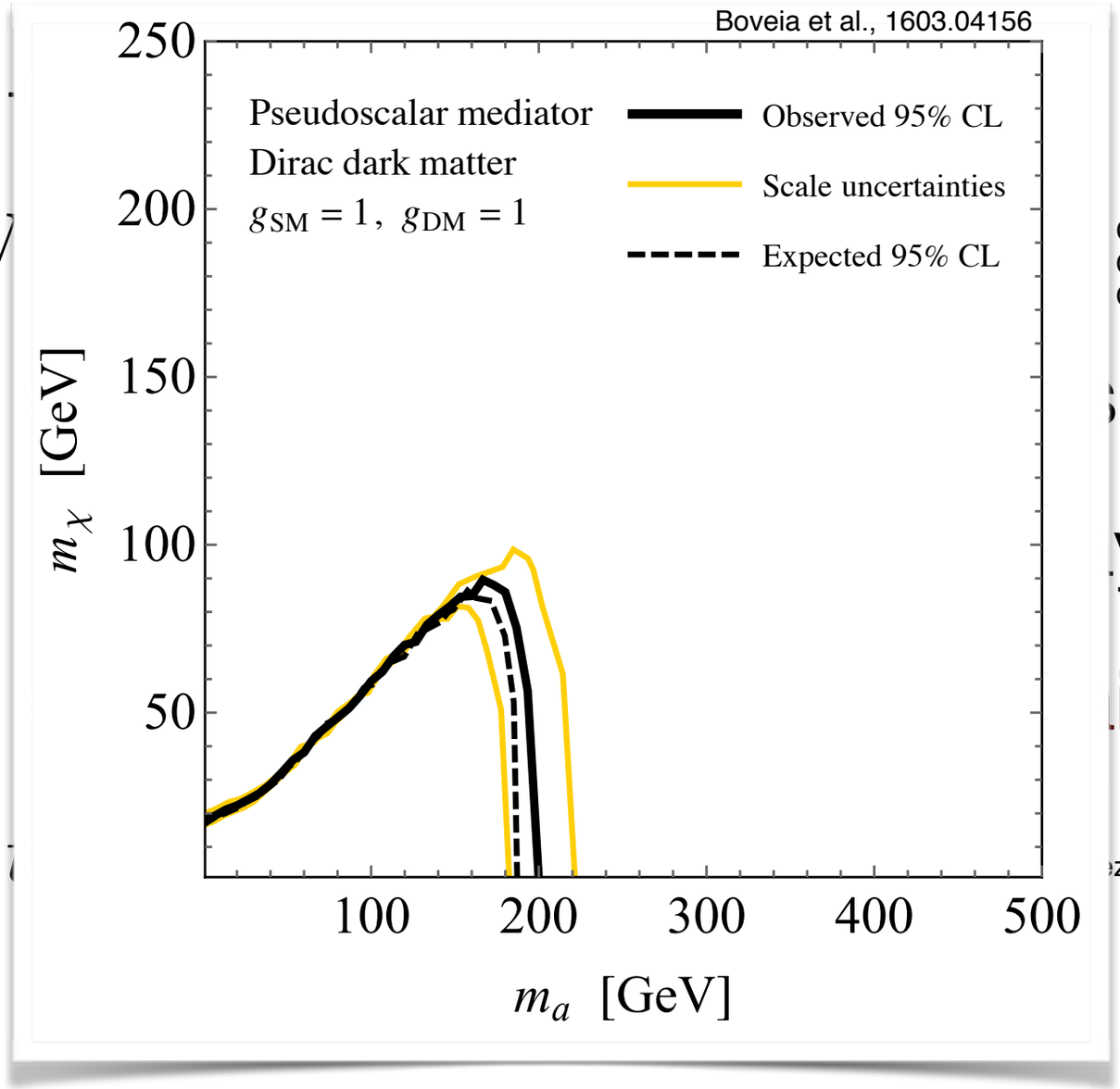
(Far future: 4



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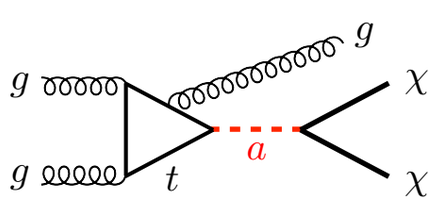
z-Val, 1607.08614

Mono-$(b,t,\ldots)$-jets, Higgs - probe decays to hidden sector



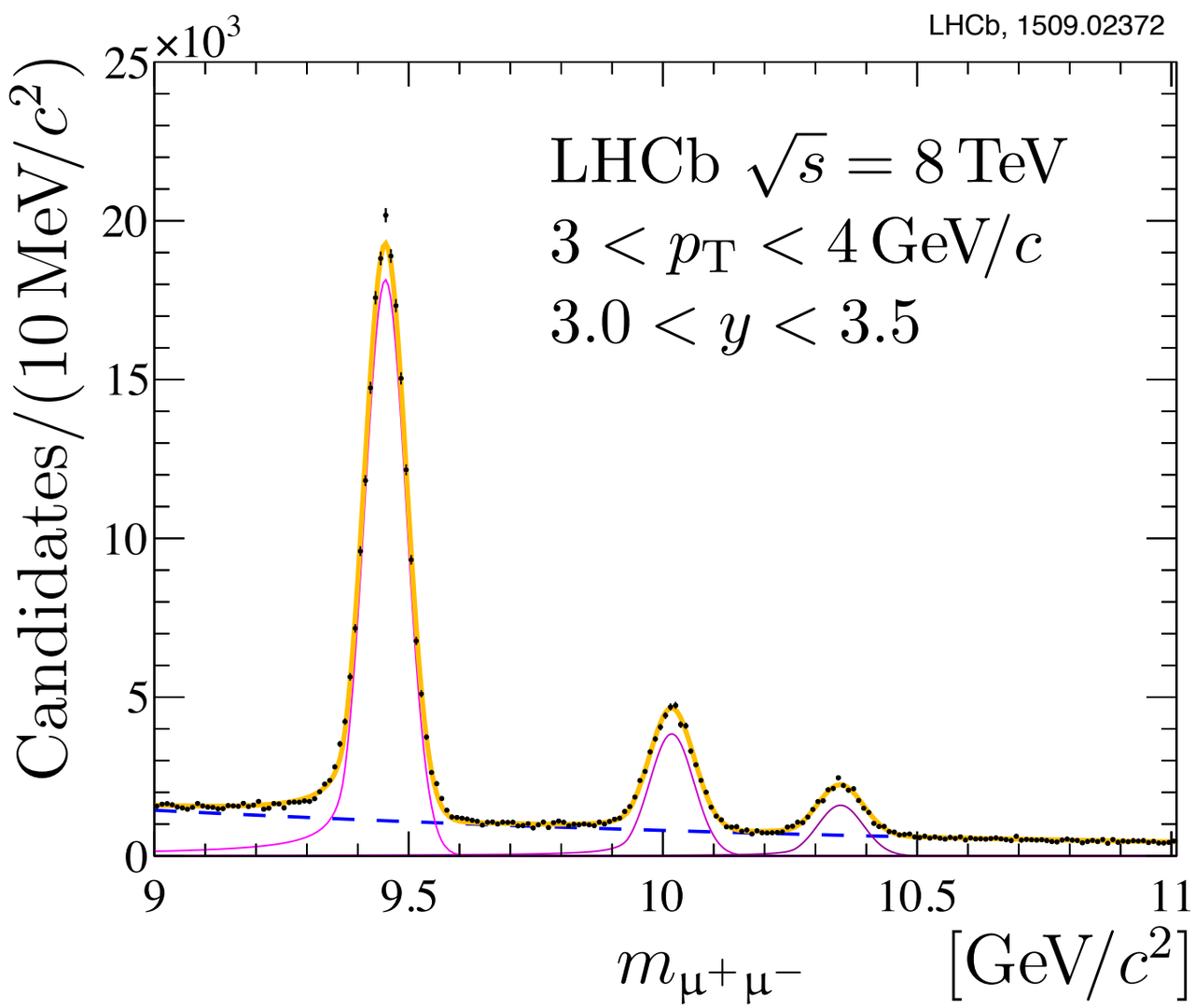
Can LHCb add something?

LHCb detector has excellent invariant-mass & vertex resolution as well as unique particle-identification & real-time data-analysis capabilities

These features allow to probe unexplored new-physics territory via dimuon searches:

- Hidden-sector bosons in $B \to K^* \mu^+ \mu^-$ [Freytsis et al., 0911.5355; LHCb, 1508.04094]
- Light spin-0 s-channel mediators [Haisch & J.F.K., 1601.05110]
- Dark photons through $A' \to \mu^+ \mu^-$ [Ilten et al., 1603.08926]

Υ production at LHCb



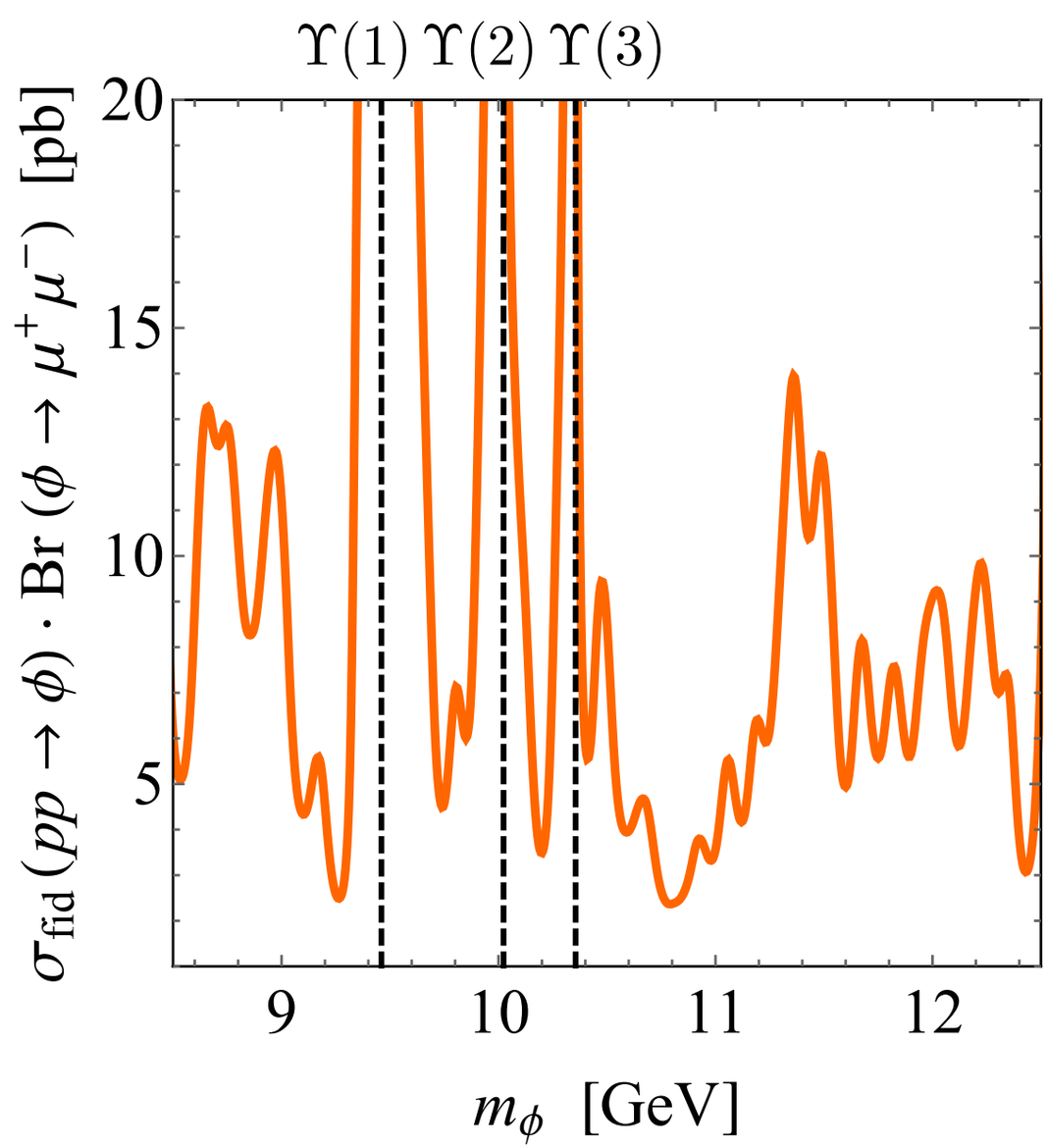
Precision measurement of dimuon spectrum for invariant masses in the Υ region with only 3% of 8 TeV data set

Bound on $\sigma_{\rm fid}(pp \to \phi)\cdot{\rm Br}(\phi \to \mu^+\mu^-)$

Signal: light spin-0 dimuon resonance ϕ

Acceptances: $A = 0.23$ for $|\eta| \in [2,\, 4.5]$ & $p_T < 30$ GeV independent of ϕ mass; final acceptance A_f in $|\eta| \in [3,\, 3.5]$ & $p_T \in [3,\, 4]$ GeV depends mildly on m_ϕ

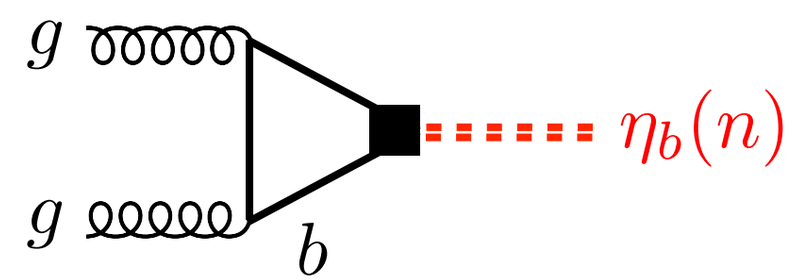
Recast: inject ϕ signal & refit LHCb data on Υ production



Example SM application

Consider bottomonium pseudoscalar production in NRQCD

$$\sigma\left(pp \to \eta_b(n)\right) = \left(391^{+174}_{-68}\right) \left|R_{\eta_b(n)}(0)\right|^2 \frac{\text{nb}}{\text{GeV}^3}$$

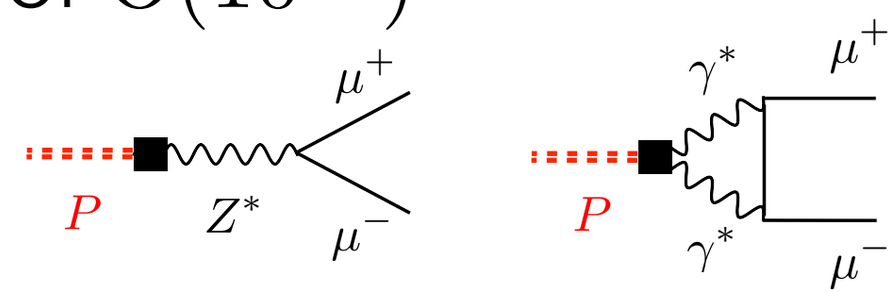


From bound on $\sigma(pp \to \phi)\cdot\text{Br}(\phi \to \mu\mu)$, one finds

$$\text{Br}\left(\eta_b(1) \to \mu^+\mu^-\right) < \frac{38.4\,\text{pb}}{\sigma\left(pp \to \eta_b(1)\right) A} = 1.9 \cdot 10^{-4}$$

- factor of 50 better than current PDG bound
- SM dimuon η_b branching ratios of $\text{O}(10^{-10})$

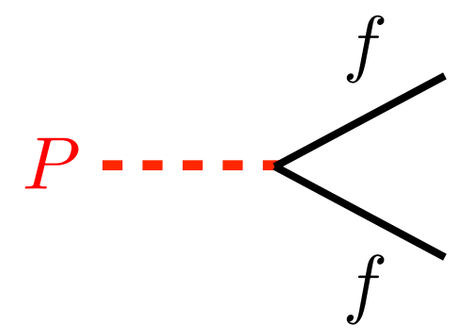
[Similar results for scalar $\chi_b(n)$ states.]



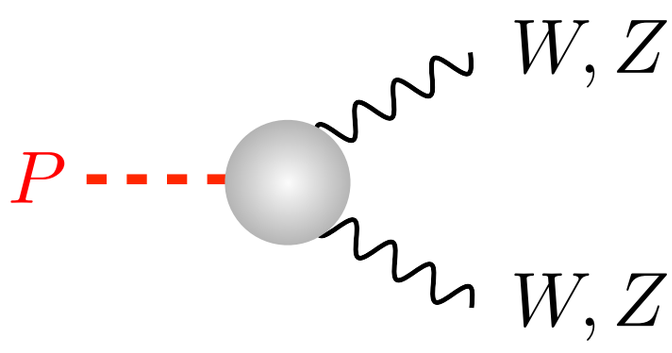
Example BSM application

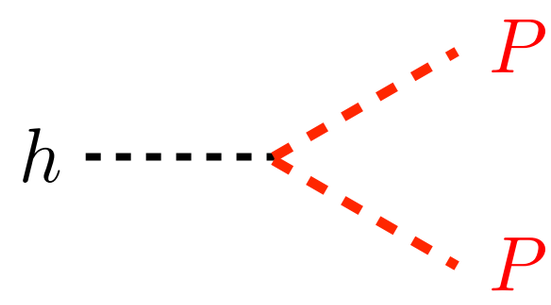
Pseudoscalar P with Higgs-like couplings to fermions

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial P)^2 - \frac{1}{2}m_P^2 P^2 - \sum_f \frac{m_f}{v}\, i\kappa_P^f P \bar{f}\gamma_5 f$$



- Avoids flavour & CPV constraints by construction (MFV).
- Couplings to WW or ZZ loop suppressed.
- Interactions with SM Higgs depend on potential details.

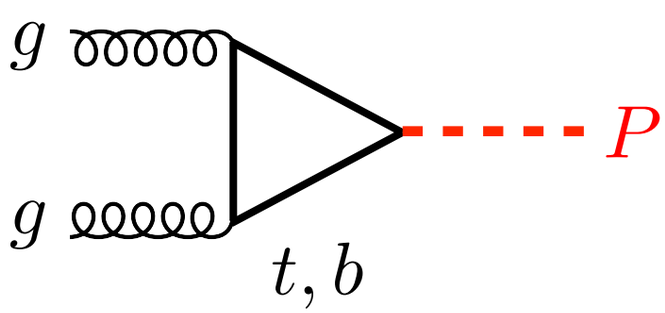


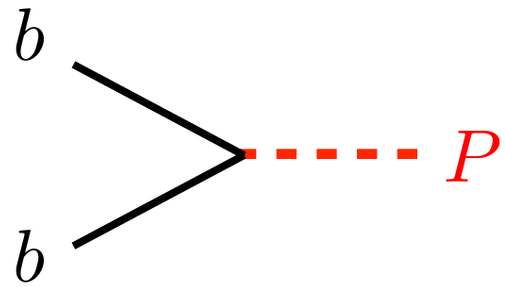


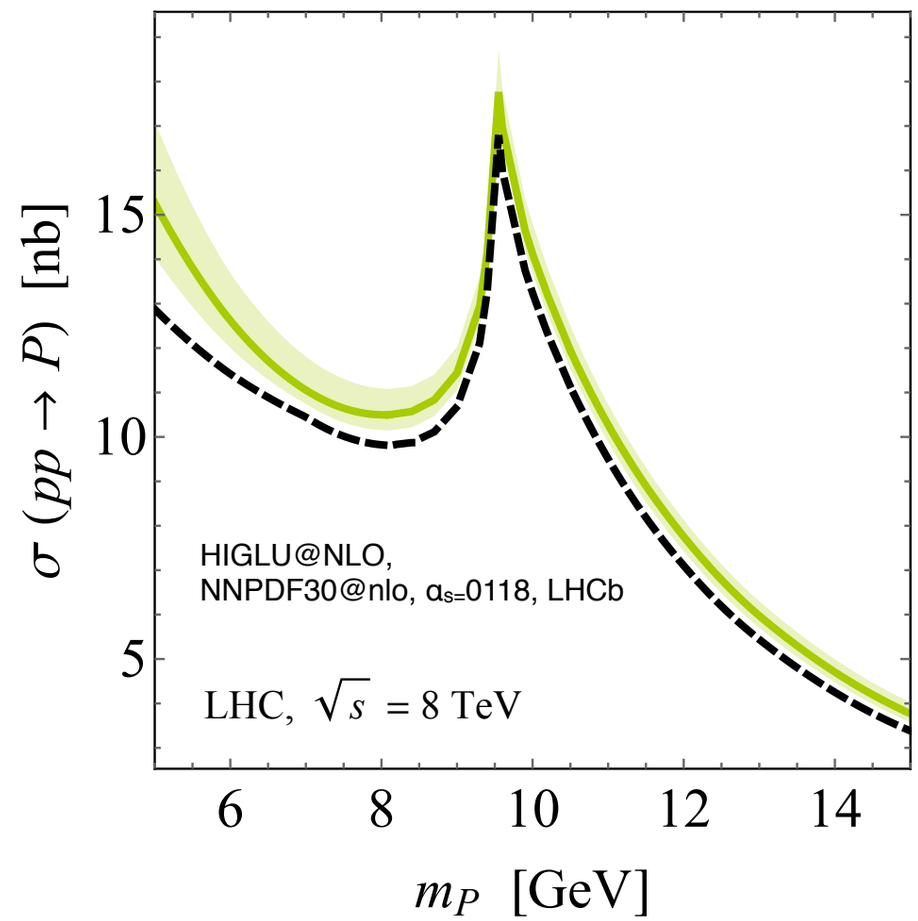
Restrict analysis to couplings of P to fermions

[Discussion restricted to pseudoscalar P; analogous results for scalar S]

P production at LHC



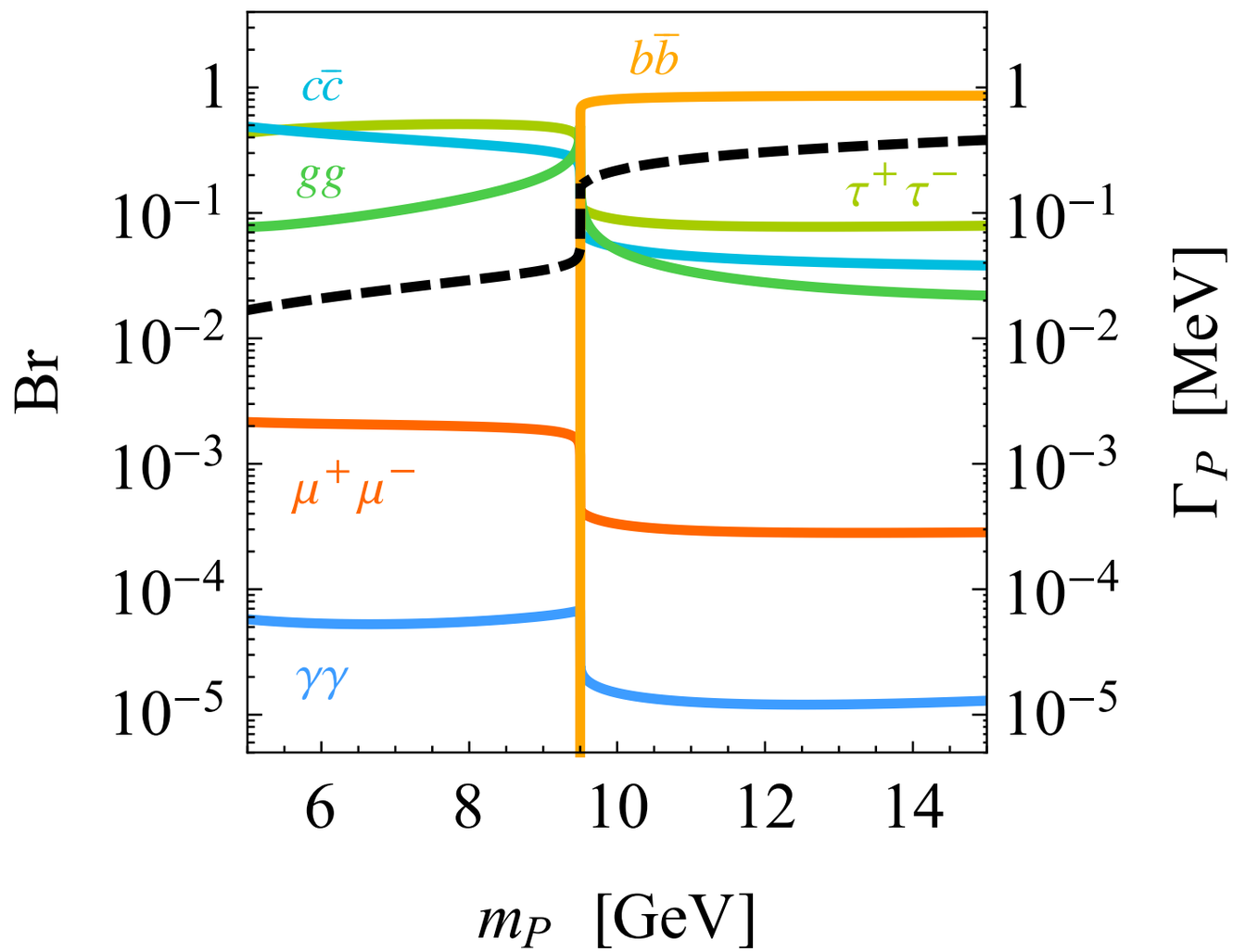




For $m_P \simeq 10$ GeV & $\varkappa_f = 1$ cross sections of $\mathrm{O}(10\mathrm{nb},\ 20\mathrm{nb})$ at 8TeV, 13TeV.

Production via bottom-quark annihilation negligible.

P width & branching ratios



For $|\varkappa_P| = \mathrm{O}(1)$, total decay width of P below $1\ \mathrm{MeV}$.

Dimuon branching ratios of $2{\cdot}10^{-3}$ $(3{\cdot}10^{-4})$ below (above) bb threshold

Mass-mixing of P with $\eta_b(n)$

Drees & Hikasa, PRD 41, 1547 (1990); Baumgart & Katz, 1204.6032

Since P & $\eta_b(n)$ carry the same quantum numbers, the states can mix:

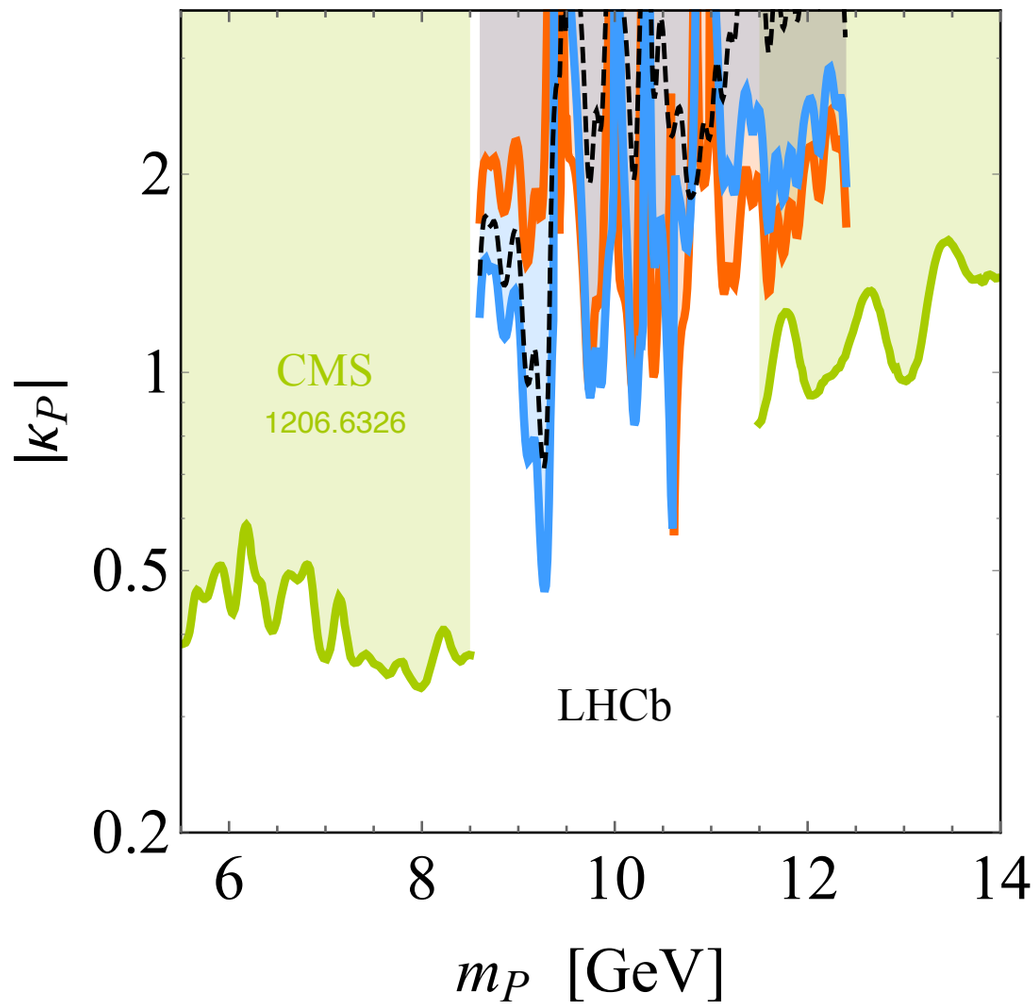
$$\delta m^2_{P\eta_b(n)} = \kappa^b_P \sqrt{\frac{3}{4\pi v^2} m^3_{\eta_b(n)}} \left| R_{\eta_b(n)}(0) \right|$$

Effects most pronounced if P & $\eta_b(n)$ are mass degenerate.

Interference pattern arising from mass-mixing depends on sign of couplings $\varkappa_P$. To illustrate model dependence consider both cases.

Close to bottom threshold P decays to B^*B via P-wave. This suppresses (enhances) dibottom (dimuon) rate of P.

Constraints on universal $\varkappa_P$



For $m_P \in [8.6,\ 11.5]$ GeV recast of LHCb Υ data allows to set first $\mathrm{O}(1)$ limits on $|\varkappa_P|$.

Above 11.5 GeV CMS low-mass dimuon search superior.

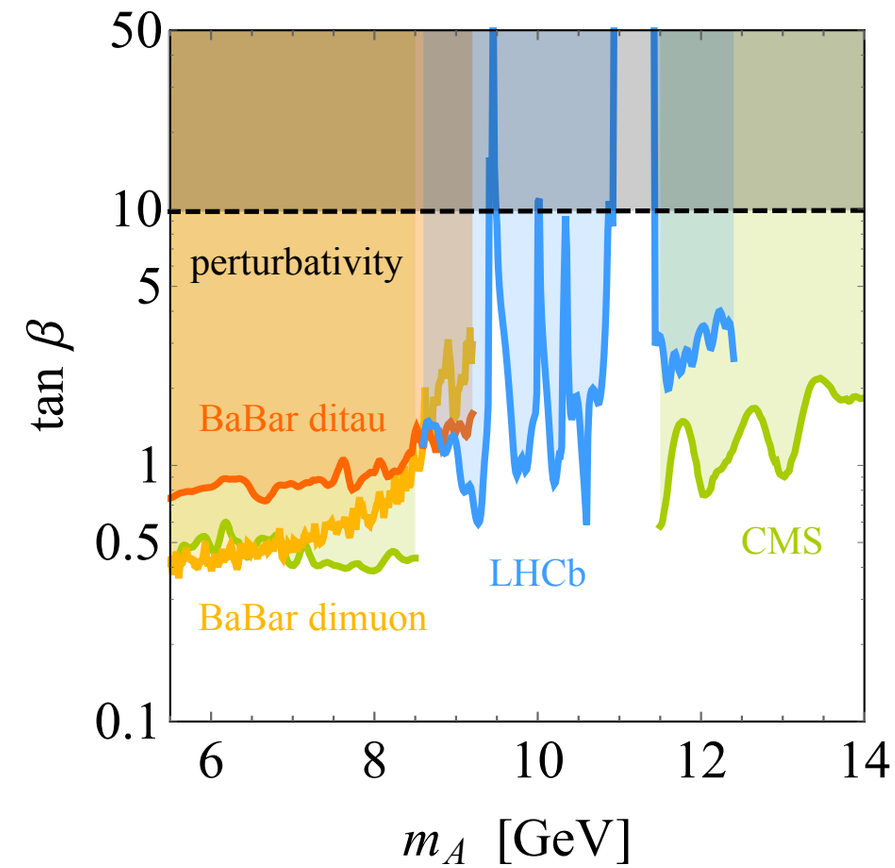
Constraints on THDM II

Can also set limits on pseudoscalar A within decoupling limit of THDMII:

$$\mathcal{L} \supset \frac{1}{2}(\partial A)^2 - \frac{1}{2} m_A^2 - \sum_f \frac{m_f}{v} i\kappa_A^f A \bar{f} \gamma_5 f$$

$$\kappa_A^{e,\mu,\tau,d,s,b} = \tan\beta$$

$$\kappa_A^{u,c,t} = \cot\beta$$



LHCb provides best bound for $m_A \in [8.6, 11]$ GeV. Mass region [11,11.5] GeV remains unconstrained, due to strong mixing effects

Conclusions & outlook

- Efficient triggering & excellent invariant mass resolution of LHCb allow to test unexplored parameter space in simplified models of spin-0 di-muon resonances
- Dedicated LHCb analysis of full Run I data set is expected to significantly improve shown limits, can be extended to larger invariant masses.
- May also be possible to search for spin-0 resonances in exclusive invariant mass spectra of heavy flavoured hadrons (D^+D^-, B^+B^-,...)
- Feasibility of di-tau, di-photon searches at LHCb?

Backup

Bottomonium parameters

	$m_{\eta_b(n)}$	$\left\lvert R_{\eta_b(n)}(0)\right\rvert$	$m_{\chi_b(n)}$	$\left\lvert R'_{\chi_b(n)}(0)\right\rvert$
$n=1$	9.4	2.71 ± 0.07	9.86	1.28 ± 0.11
$n=2$	10.0	1.92 ± 0.11	10.23	1.34 ± 0.15
$n=3$	10.3	1.66 ± 0.11	10.51	1.36 ± 0.20
$n=4$	10.6	1.43 ± 0.09	—	—
$n=5$	10.85	1.42 ± 0.53	—	—
$n=6$	11.0	0.91 ± 0.17	—	—

Masses of $\eta_b(n)$ $\chi_b(n)$ states given in units of GeV and corresponding values of radial wave functions at the origin (their derivatives) in units of $\mathrm{GeV}^{3/2}$ ($\mathrm{GeV}^{5/2}$)