IMPLICATIONS OF A NEW LIGHT SCALAR NEAR THE BOTTOMONIUM REGIME

Matthew Baumgart (Carnegie Mellon University)

International Workshop on Heavy Quarkonium - April 25, 2013

IHEP, 北京

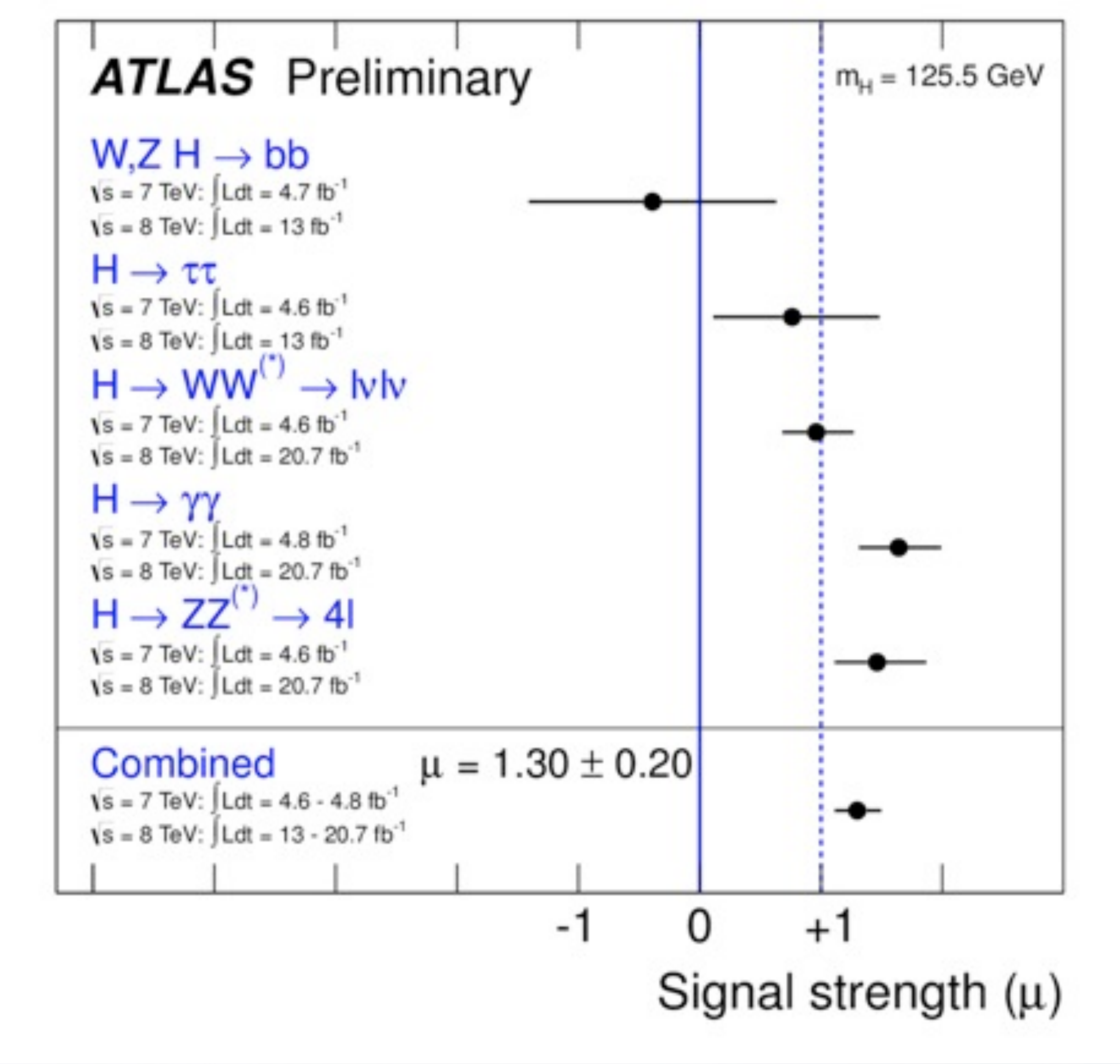
MB & Andrey Katz: 1204.6032 JHEP08(2012)133

A NEW ERA OF ELECTROWEAK PHYSICS

- Higgs Physics IS Precision Electroweak Physics

- Smoking guns in SM channels haven't appeared

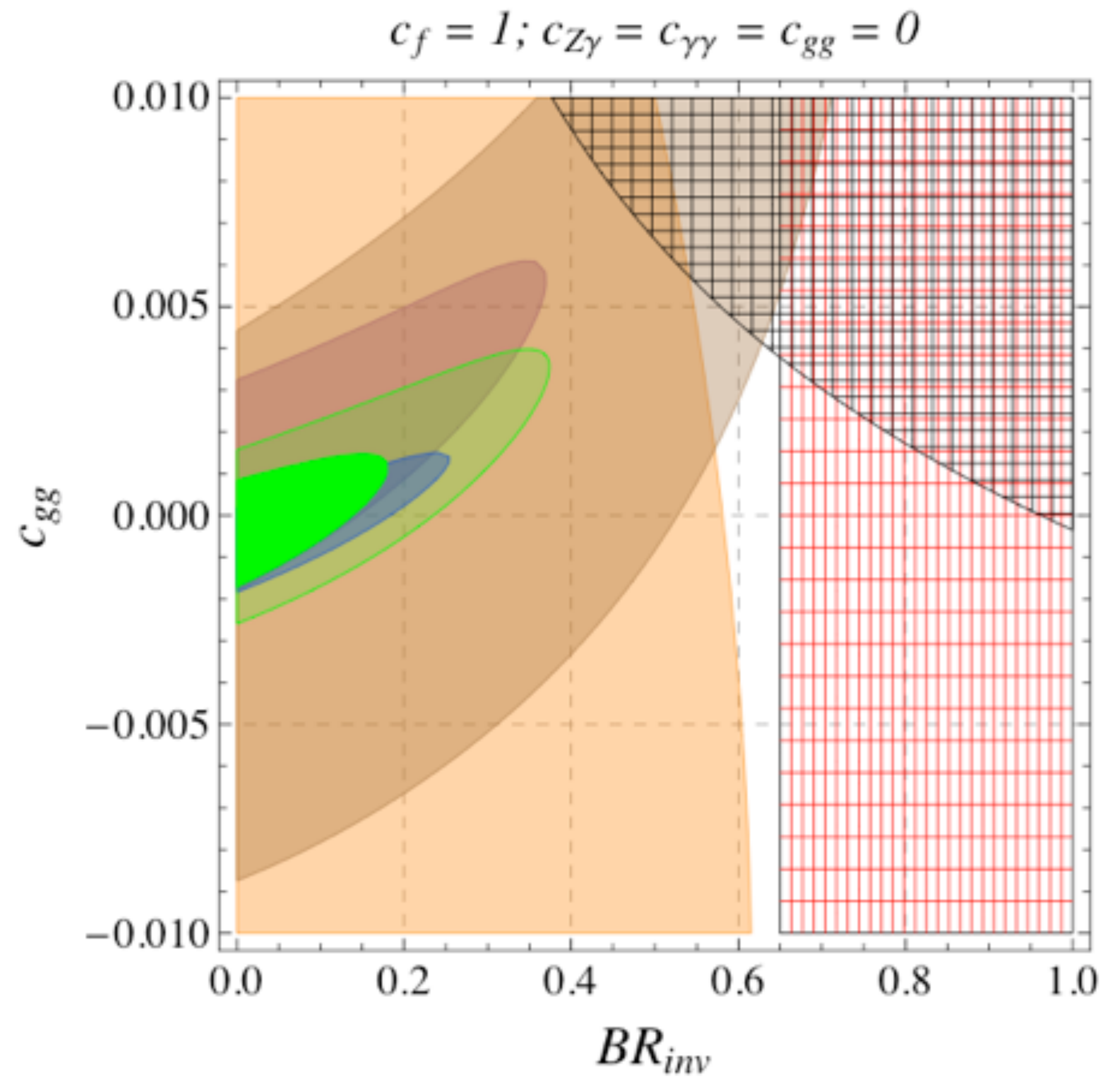
- Look for the Higgs to do something completely different from SM



*ATLAS-CONF-2013-034

H → INVISIBLE

- Could the Higgs be decaying in an unanticipated channel?
- Invisible Higgs width reduces rates into visible channels.
- Current limit is $BR_{inv} < 16\%$ (~40% if SM rate enhanced).
- Won't get much stronger than ~10%, even at LHC13



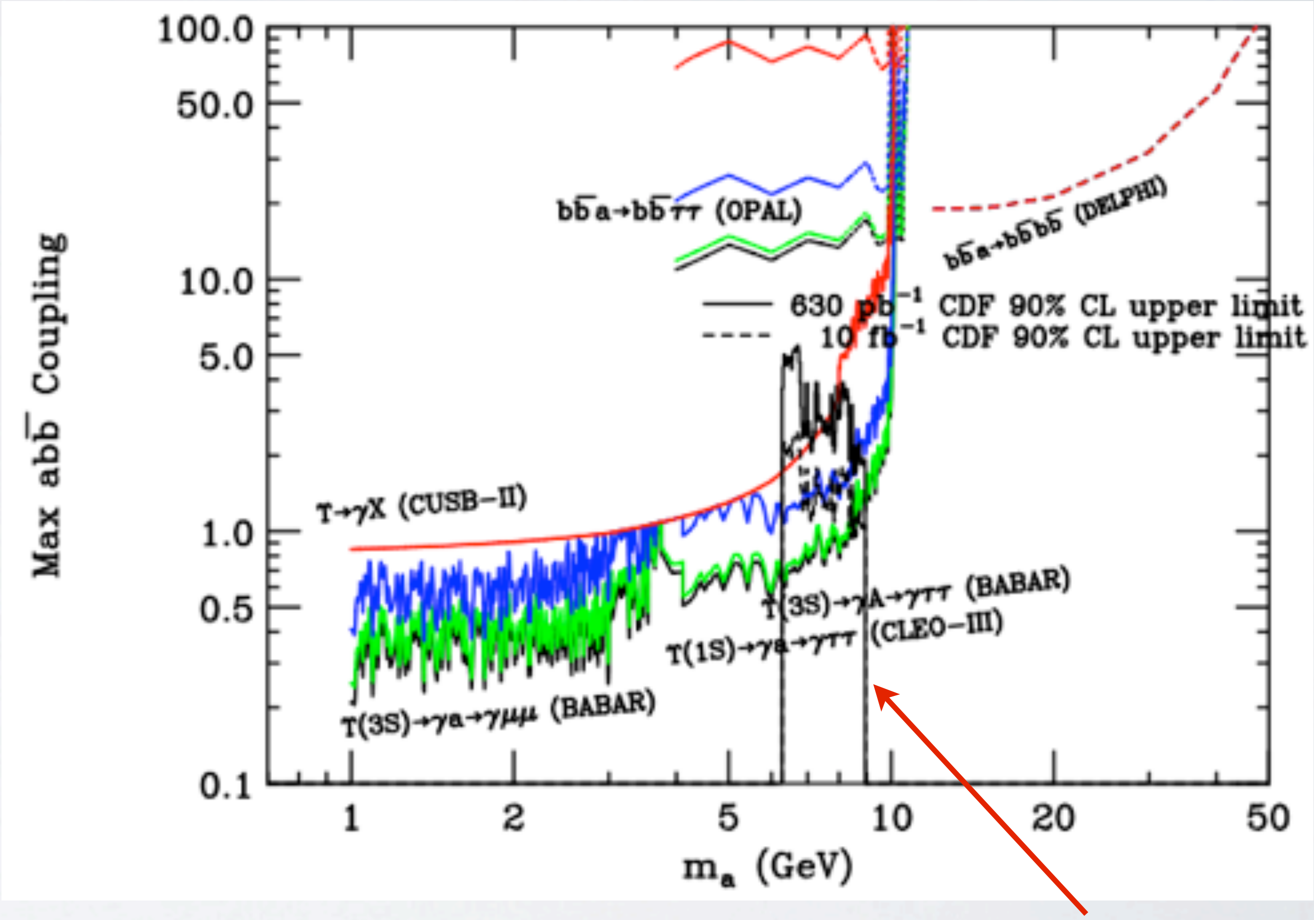
Green region allowed by observed visible rates.
Falkowski et al. [1303.1812]

LIGHT CP-ODD HIGGS

- A motivated "invisible" scenario is the decay $h \to aa$, where a is a CP-odd Higgs in part of an extended Higgs sector
- **NMSSM**: Scalar potential can have exact $U(1)_R$ symmetry in limit of vanishing A-terms and gaugino masses. The CP-odd Higgs can be the pseudo-Goldstone of this symmetry
- **Little Higgs**: The whole Higgs sector are pGBs. Mass is protected by collective symmetry breaking and generated at loop level

"INVISIBLE" & BOTTOMONIA

- Natural "invisible" Higgs decay product to consider is a light CP-odd scalar: a
- As a "Higgs," coupling to 3rd generation and limits from b-quarks



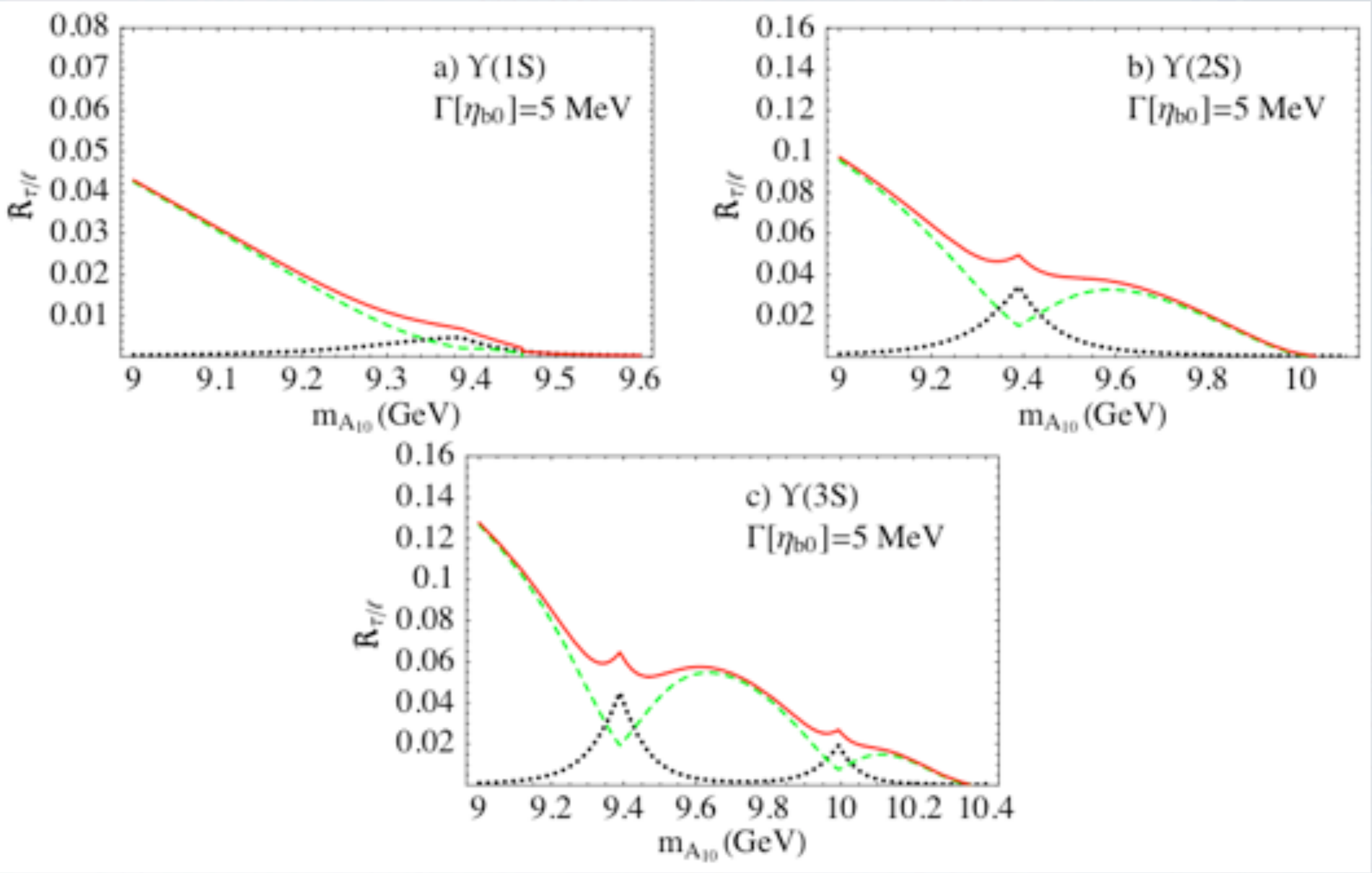
Notice Cutoff near 9GeV

Limits on m_a from Υ decay, and production followed by decay to bs or μs

Gunion and Dermisek [1002.1971]

BOTTOMONIUM OBSERVABLES FOR NEW PHYSICS

- Regardless of motivation or likelihood, we don’t want to miss a particle ~10 GeV
  - 1-9 GeV: As is done, look for rare ϒ decays
  - 9-11 GeV: Mixing effects with bottomonia
  - 11-15 GeV: Substantial decays TO bottomonia



Effect from a-η_b mixing on lepton universality of ϒ decays
Domingo et al. [0810.4736]

a NEAR THE BOTTOMONIA

- We assume a light (9-15 GeV) scalar with Higgs-like couplings to SM fermions

- We are interested in ITS decay rates:

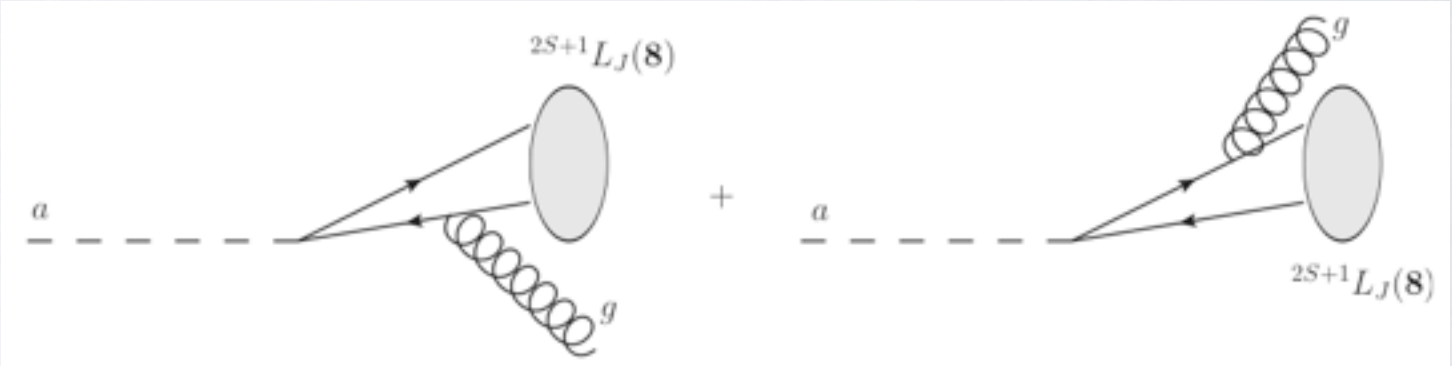
  - For $(m_a - m_{onia}) > m_b v$, ($m_a > 11$ GeV) we have straightforward semi-perturbative calculation in NRQCD

  - Below this region, we lose calculability, but use mixing formalism for order of magnitude estimates

PROBING BOUND STATE PHYSICS WITH A FUNDAMENTAL

- Independent of phenomenology, interesting field theory question to ask about decays to bound states vs. open flavor

- If mass splitting sufficiently large $O(m_b v)$, exploit separation of scales.



Leading diagrams that contribute to the process
a → bottomonia + X

(VERY) BRIEF INTRODUCTION TO NRQCD*

$$\mathcal{L}_{\text{heavy}} = \psi^\dagger \left(iD_t + \frac{\mathbf{D^2}}{2M} \right) \psi + \chi^\dagger \left(iD_t - \frac{\mathbf{D^2}}{2M} \right) \chi$$

Heavy quark kinetic term. Creation & Annihilation decoupled.

- NRQCD is an EFT with 3 effective scales
  - m_b
  - $m_b v$, scale of momentum transfer and size of bottomonium
  - $m_b v^2$, bottom kinetic energy scale and radial excitation splitting
- Parametrics give us factorization and power counting

*See e.g. Bodwin, Braaten, Le Page PRD51, 1125 (1995) hep-ph/9407339

FACTORIZATION AND QUARKONIUM PRODUCTION

- Splitting between m_b and bound quark momentum exchange ($m_b v$) lets us factorize production into:
  - For quark creation, perturbative QCD-like part with angular momentum and color decomposition
  - For binding through long-distance, nonperturbative physics, the expectation value of an NRQCD operator
- For our case of interest:

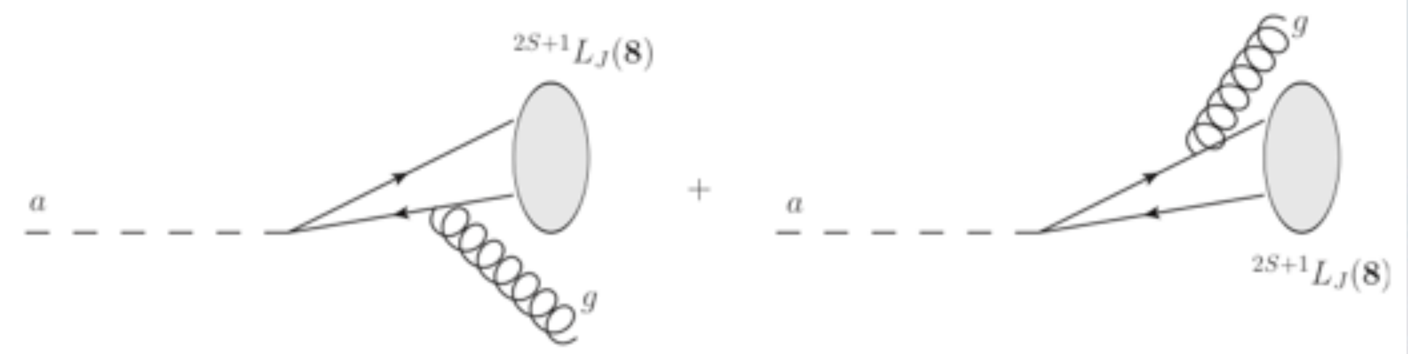
$$\Gamma[a \to H + X] = \sum_n \hat{\Gamma}[a \to b\bar{b}(n, \mathbf{8}) + g]\langle \mathcal{O}_n^H \rangle$$

HEAVY QUARK PRODUCTION THROUGH SCALAR DECAY

- We couple our particle, a, to b quarks:

$$\mathcal{L}_{a\bar{b}b} = y_b^+ \, a\, \bar{b}b + i\, y_b^- \, a\, \bar{b}\,\gamma^5\, b$$

- Nontrivial part is determining which operators contribute
- We get an infinite tower, but NRQCD power counting gives suppression by $\alpha_s^n v^m$



Interpreted through NRQCD factorization:
Blobs are nonperturbative matrix elements
Vertices are perturbative, but
Project onto color and angular momentum

FINDING THE MATRIX ELEMENTS OF INTEREST

- We emit a single perturbative gluon as other possibilities give α_s and three-body suppression
- This leads us to consider color-octet matrix elements
- Angular momentum simplified by "accidental" C-invariance, implies:

$$L + S = \mathrm{odd}$$

Γ(a →BOTTOMONIA+X)

- For pseudoscalar:

$\xi = m_{onia}^2/m_a^2$

$$\Gamma(a \to \mathrm{i} + X) = \frac{32\,\alpha_s y_b^2}{m_a m_\mathrm{i}^3}\left((1-\xi)\,m_\mathrm{i}^2\langle\mathcal{O}_8^\mathrm{i}(^3S_1)\rangle + 4\frac{(1+\xi)^2}{1-\xi}\langle\mathcal{O}_8^\mathrm{i}(^1P_1)\rangle\right)$$

- Parity-even scalar

$$\Gamma(a_{\mathrm{P-even}} \to \mathrm{i} + X) = \frac{32\,\alpha_s y_b^2}{m_a m_\mathrm{i}^3}(1-\xi)\left[m_\mathrm{i}^2\langle\mathcal{O}_8^\mathrm{i}(^3S_1)\rangle + 4\,\langle\mathcal{O}_8^\mathrm{i}(^1P_1)\rangle\right]$$

- It remains to parametrize and justify matrix elements, but first...

SOFT ASIDE

- We notice an interesting structure in the decay rate formulas

$$\Gamma(\text{pseudo}, {}^1P_1) \propto \frac{(1+\xi)^2}{1-\xi}$$

- This diverges as $m_a \rightarrow m_{onium}$, but no other rate did
- This is a soft gluon divergence, as other channels require either finite gluon linear or angular momentum.
- Only for pseudoscalar by demands of 3-body parity:

$$P_{3-\text{body}} = P_1 P_2 P_3 (-1)^{\ell} (-1)^{L},$$

NRQCD POWER COUNTING*

- Perturbation theory shows that $^1P_1$ contribution important.
- Which quarkonia have overlap with this state?
- One example is the pseudosclar η_b:

$$|\eta_b\rangle = |b\bar{b}(^1S_0)_1\rangle + \mathcal{O}(v)\,|b\bar{b}(^1P_1)_8\,g\rangle + \mathcal{O}\left(v^{3/2}\right)|b\bar{b}(^3S_1)_8\,g\rangle + \mathcal{O}\left(v^2\right)|b\bar{b}(^1S_0)_{8/1}\,gg\rangle$$
$$+\ \mathcal{O}\left(v^2\right)|b\bar{b}(^1D_2)_{8/1}\,gg\rangle + \ldots$$

- Electric gluons bring factor of v, magnetic (spin flip) $v^{3/2}$.
- Other important states for $^1P_1$ are the $^1D_2$ O(v) and χ_{bJ} O($v^{3/2}$).

*We use the revised power counting of BBL, PRD51, 1125 (1995) hep-ph/9407339

POWER COUNTING FOR DECAY OPERATORS

- Need to convert matrix elements to numbers to compare decay rate
- Our states of interest are obscure, so we compare two methods
  - Straight power counting: $m_b^n v^m$
  - Scale up spin-flipped charmonium results

Factor	Origin
$(m_b v)^{-3}$	Volume factor from operator spatial integral
$(m_b v)^6$	4 heavy quark fields
v^2	Overlap of $b\bar{b}(^1P_1)_8$ with η_b Fock state
$(m_b v)^2$	D^i in operator
$m_b^5 v^7$	Total

Power counting for $O_8^{\eta_b}(^1P_1)$

$$\mathcal{O}_8^{\eta_b}(^1P_1) = \chi^\dagger \left(-\frac{i}{2}\overleftrightarrow{D}^i\right) t^a \psi \left(\sum_X |\eta_b + X\rangle\langle\eta_b + X|\right) \psi^\dagger \left(-\frac{i}{2}\overleftrightarrow{D}^i\right) t^a \chi$$

FROM MATRIX ELEMENTS TO NUMBERS

- We arrive at $\langle O_8^{\eta_b}(^1P_1)\rangle \sim m_b^5 v^7 \approx 1\ \text{GeV}^5$
- $O_8^{\eta_b}(^1P_1)$ related by spin flip to $\langle O_8^{J/\Psi}(^3P_0)\rangle \approx 10^{-2}\ \text{GeV}^5$

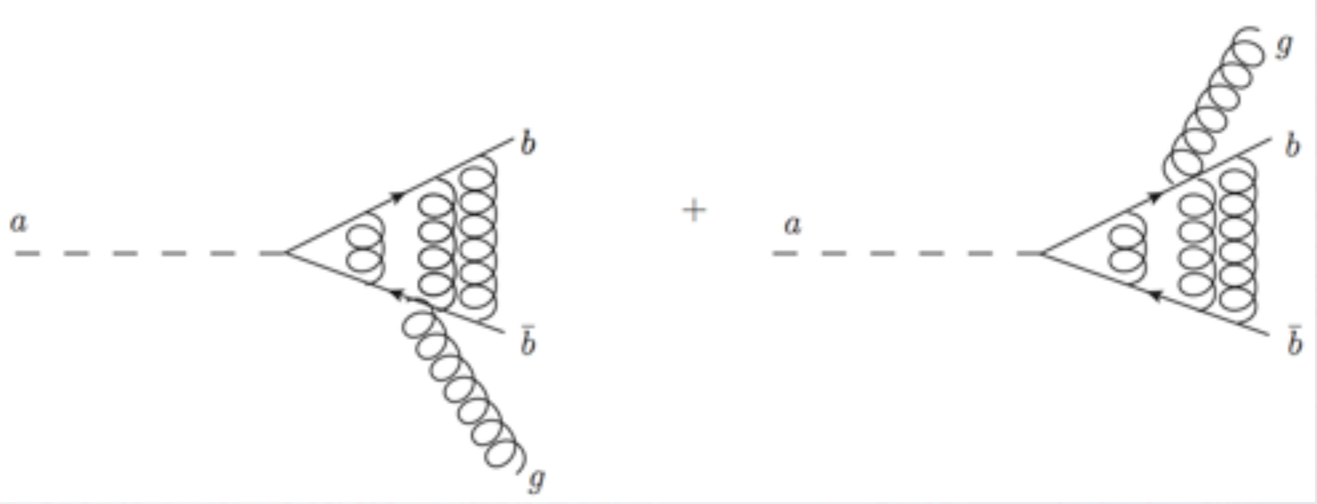
$$\langle \mathcal{O}_8^{\eta_b}(^1P_1)\rangle \approx \frac{m_b^5 v_b^7}{m_c^5 v_c^7}\langle \mathcal{O}_8^{\eta_c}(^1P_1)\rangle \approx 0.3\,\text{GeV}^5$$

- Rough agreement, so we use $\langle O_8^{\eta_b}(^1P_1)\rangle = 0.5\ \text{GeV}^5$

INTO THE BINDING REGIME

- Where can we apply our numerical results?
- $^1P_1$ divergence already a clue of IR complications
- We take as our cutoff:

$$m_a - m_{\text{onium}} \sim p(g) > m_b v \approx 1.4 \text{ GeV}$$



If radiated gluon at same scale as those involved in binding, no factorization of its emission

LOSING CONTROL: THE DETAILS

- We organize our operators in powers of v^2
- Squeezing amplitude support into region of width v^2 turns our expansion into $(v^2/\boldsymbol{\varepsilon})^n$
- For $(\Delta m = m_b v) \equiv (\Delta E = m_b v^2)$, we need to sum infinite towers based on our leading operators
- For $\boldsymbol{\varepsilon} << v^2$, even $v^n(v^2/\boldsymbol{\varepsilon})^m > 1$, all operators important

HOW TO PROCEED (IN PRINCIPLE)

- Intermediate mass splittings ($\Delta m \sim m_b v$) are tractable, in principle
- One possibility is to use OPE + Optical Theorem:
  - Compute
    $$\mathcal{T} = i \int d^4x \, T\Big(\mathcal{L}_{a\bar{b}b}(x)\mathcal{L}_{a\bar{b}b}(0)\Big)$$
    $$\Gamma^{a\to b\bar{b}-\mathrm{states}+X} = \frac{\mathrm{Im}\langle a|\mathcal{T}|a\rangle}{m_a}$$
  - OPE on ***T*** gives our infinite series summed into non-perturbative structure functions
- pNRQCD designed for scales < $m_b v$. Can calculate with binding gluons integrated out

MIXING EFFECTS

- For $m_{\eta b(1)} < m_a < m_{\eta b(6)}$, first principle calculation difficult
- However, we get strong, calculable mixing effects with η_b and we can use them to estimate rate.
- We account for three different decay channels by mixing
  - $a \rightarrow gg$
  - $a \rightarrow \eta_b + X$ (bottomonium hadronic transition)
  - $a \rightarrow$ b-bbar (open flavor)

a → gg

- We diagonalize the a-η_b mass matrix, accounting for the finite widths

- Both a and η_b have decays into gluons and we account for interference

- We use wavefunction at the origin for bottomonium decay

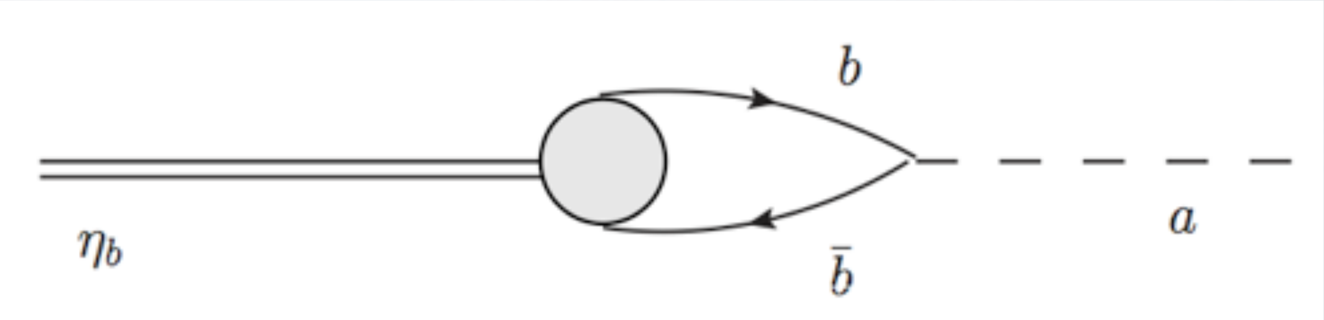


Diagram above leads to off-diagonal mass term

$$\delta m^2_{a-\eta_b(n)} = y_b \sqrt{\frac{3}{4\pi} m_{\eta_b(n)}} \, |R_{\eta_b(n)}(0)|,$$

$$\Gamma(\eta_b(n) \to gg) = \frac{\alpha_s(m_{\eta_b(n)})^2}{3\, m^2_{\eta_b(n)}} |R_{\eta_b(n)}(0)|^2.$$

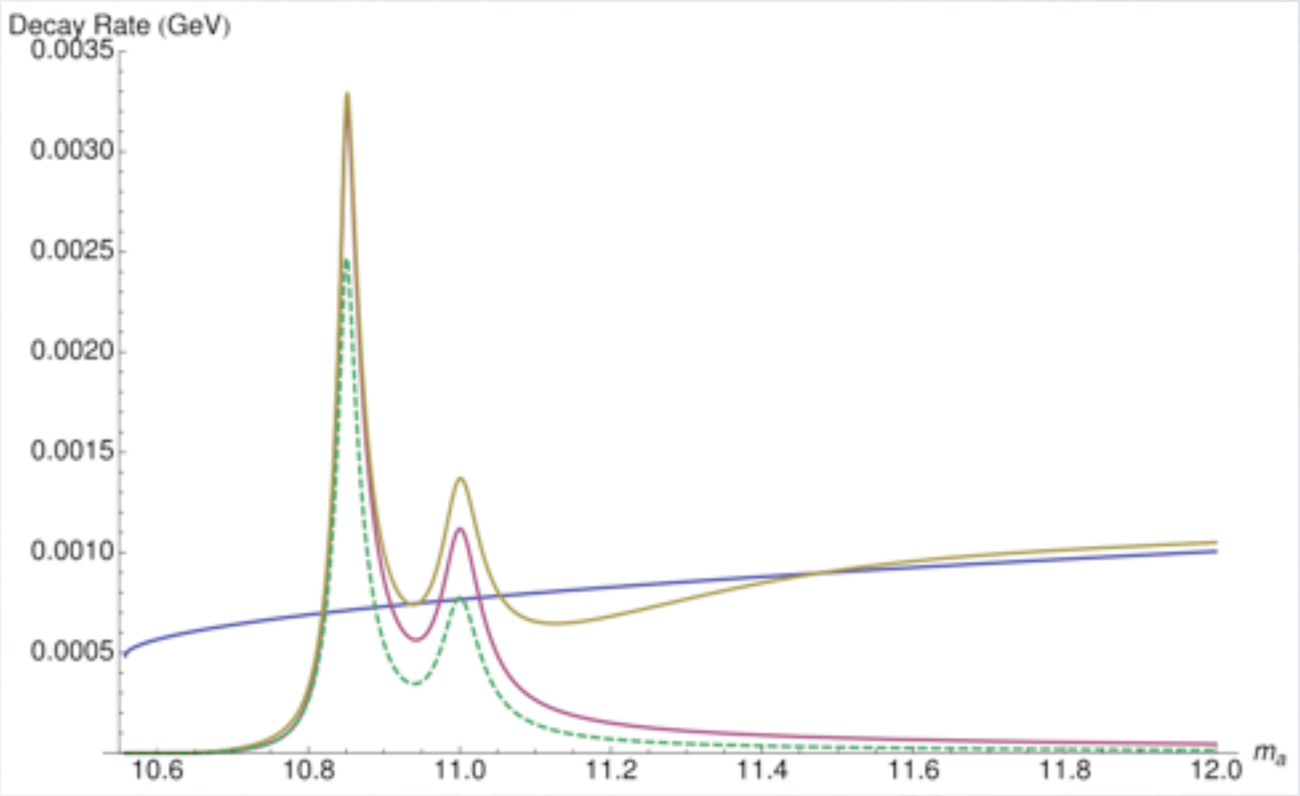
$a \to \eta_b + X$ (hadronic transition)

- Just like the Υ, the η_b transition among themselves hadronically, principally $\eta_b(n) \to \eta_b(m)\pi\pi$. We thus compute $a \to \eta_b(m)\pi\pi$ by mixing.
- We lack data for the η_b, but use the Υ.
  - For the lower-lying $\eta_b(1\text{-}3,4)$, this step justified by multipole expansion
  - For $\Upsilon(5,6)$, multipole expansion fails badly. Possible enhancement by Z_b ($\Upsilon(n) \to Z_b\pi$, $Z_b \to \Upsilon(m)\,\pi$). Spin symmetry predicts analogous W_{b0} for η_b.* We again use Υ rates.

*Bondar et al. [1105.4473], Voloshin [1105.5829], Mehen & Powell [1009.3479]

a→b-bbar (open flavor)

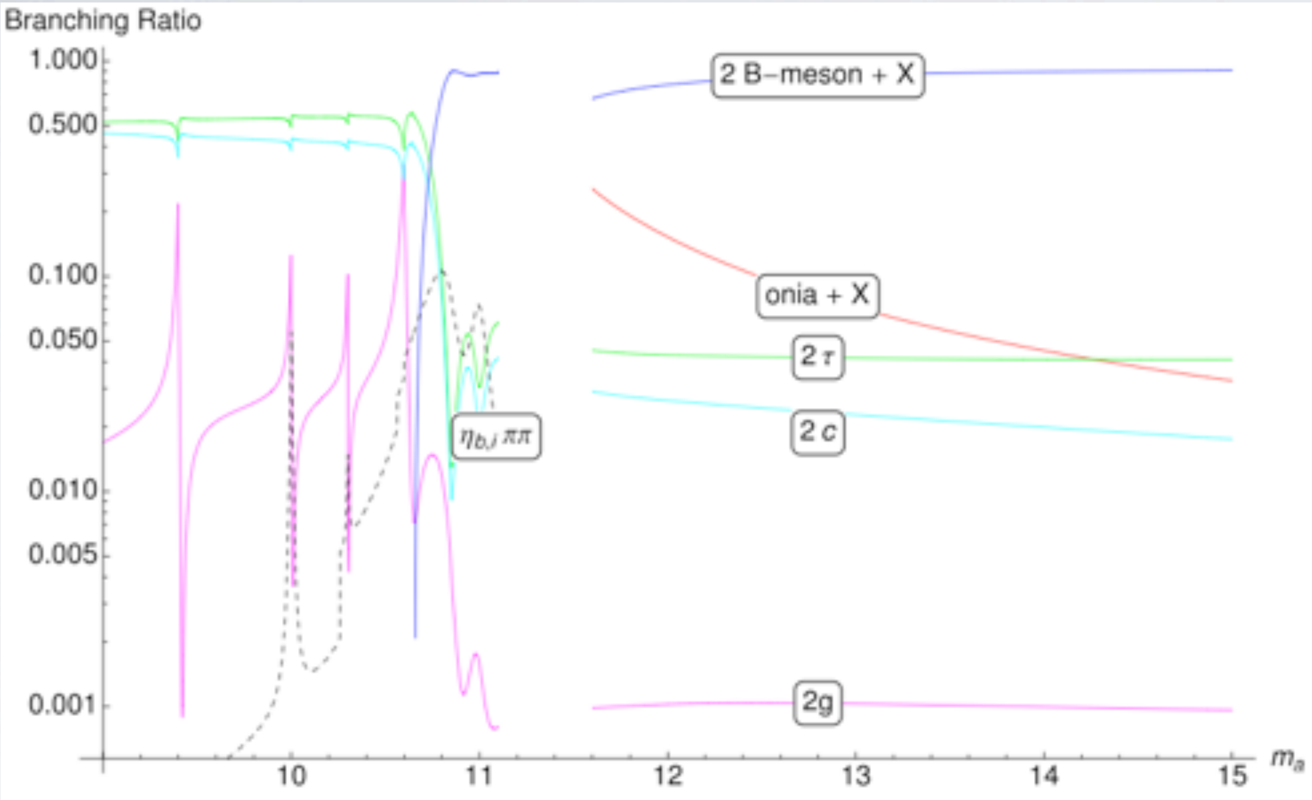
- m_a sufficiently large will decay to open-flavor b-bbar.
- Highest two states $\eta_b(5,6)$ can decay to B mesons and we must understand mixing*
- Pseudoscalar decay into b-quarks is S-wave, but decay to lightest B mesons is P-wave



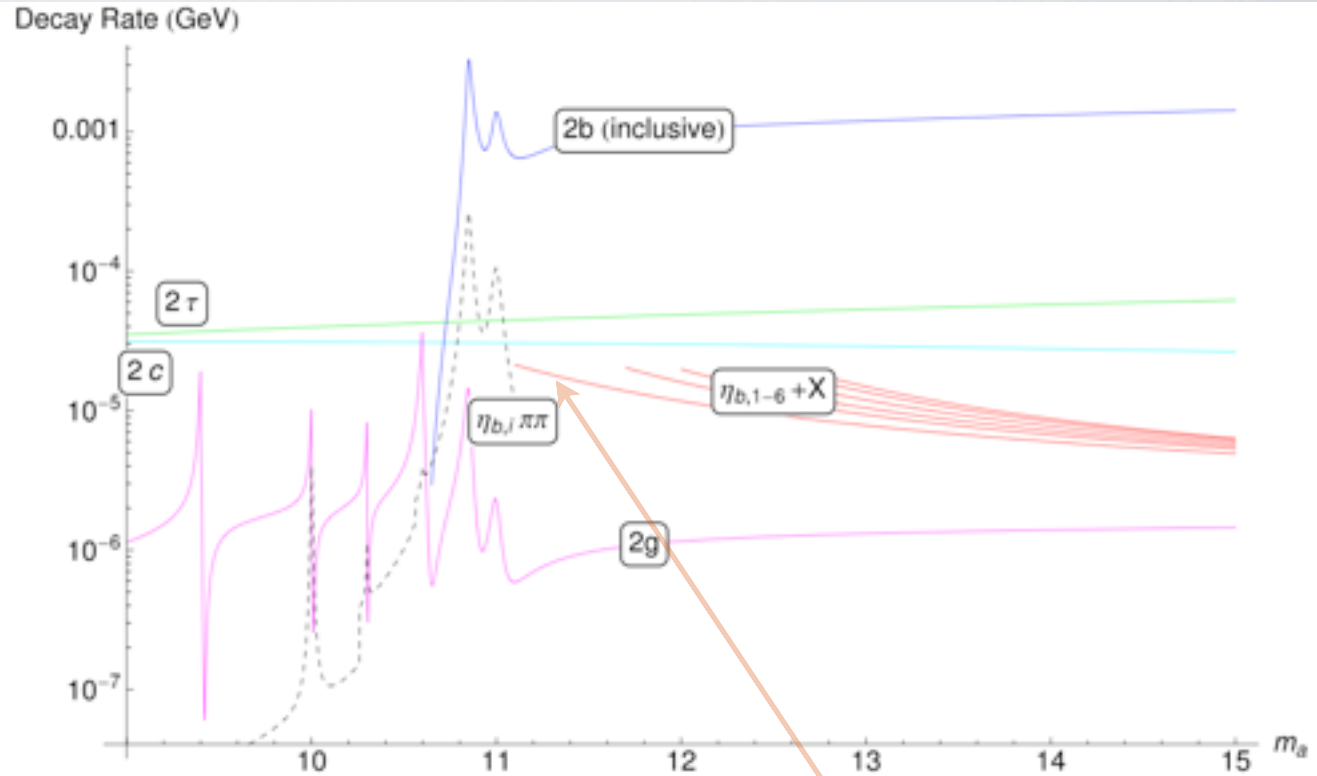
Open flavor decay of pseudoscalar.
(Blue) Naive decay to fermions
(Red) Decay to B mesons through mixing
(Yellow) Phenomenological interpolation
(Green) Omits B_s

*We use mixing formalism of Drees & Hikasa PRD41, 1547 (1990)

RESULTS



We omit the region where NRQCD isn't reliable and mixing effects are negligible



For computing decay rate, we couple the a with SM Higgs Yukawa couplings

*While nowhere dominant, we see that decays to bottomonia can be an important subleading decay

*Despite our many approximations, we see that NRQCD and mixing agree at order of magnitude level

PHENOMENOLOGY

- The η_b decays primarily by annihilation to two gluons
- We may worry about such a jetty final state, but there are handles for the **case $h \rightarrow aa$**:
    - "Jetty" Higgses are handled by (cf. Butterworth et al. [0802.2470])
        - look for boosted Higgses
        - make a fat, Higgs-jet, look for substructure
    - Different radiation pattern from QCD jets (no color until a decay), η_b decay is "sparse"
    - Can reconstruct bottomonium mass
    - Exploit other decay channels by looking for e.g. $\tau^+\tau^-$ or open-flavor b-bbar in other a-decay
- Could also look for a's produced in charged Higgs decay, or radiated off b-bbar/t-tbar

CONCLUSIONS

- "Invisible" decays of the SM Higgs may be our last best hope for striking new physics in the Higgs sector
- A light CP-odd Higgs offers a motivated invisible channel
- For ma from 9-15 GeV, we get interesting, observable interplay with bottomonia
- A couple challenges:
  - For m_a-m_{onium} ~ $m_b v$, it is an interesting, hard, but tractable problem to compute its decays
  - Since (a→onium+X) is proportional to matrix element expectation values, does thought-experiment of coupling this state to b's constrain their positivity?
- Were nature to give us such a state, we would gain access to a trove of new information about bottomonia.