HBB PRODUCTION
TOP QUARK MASS EFFECTS

Nicolas Deutschmann, ETH Zurich

Based on 1808.01660

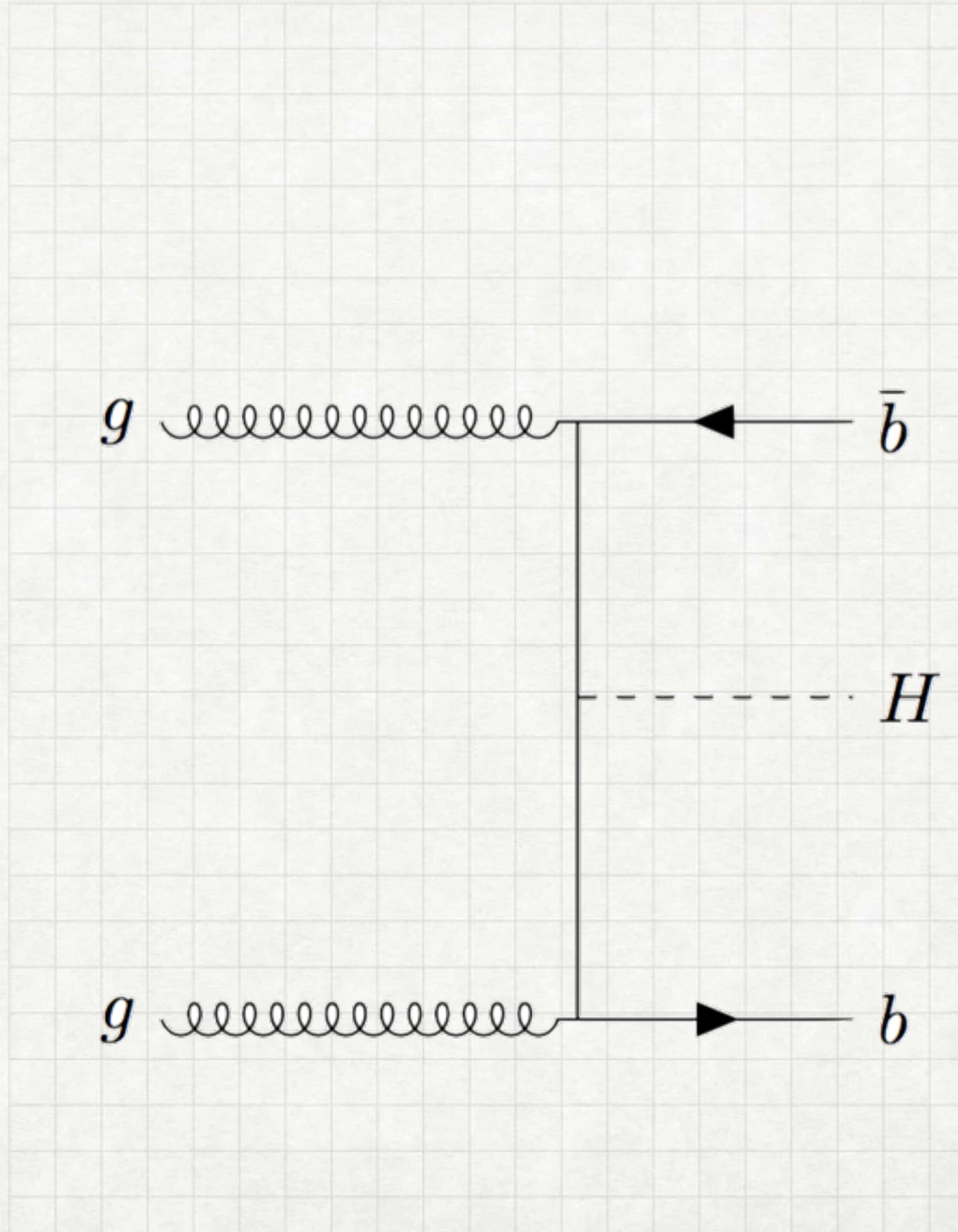
ND, Fabio Maltoni, Marco Zaro, Marius Wiesemann

GGI Workshop "Amplitudes in the LHC era"

MOTIVATION

- **Pheno:** another **direct** handle on Hbb couplings

- **TH:** toward a better description of g→bb splittings



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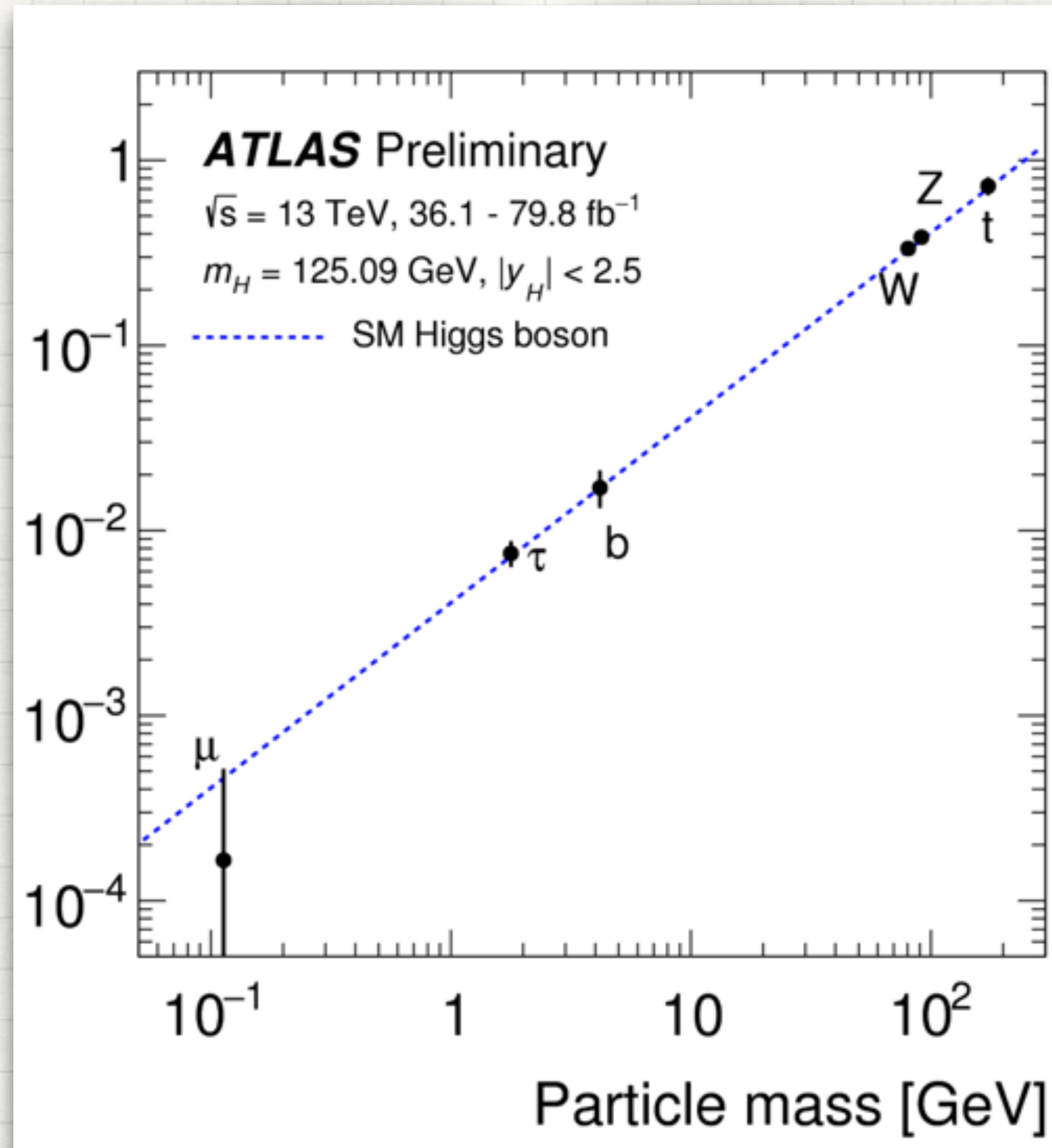
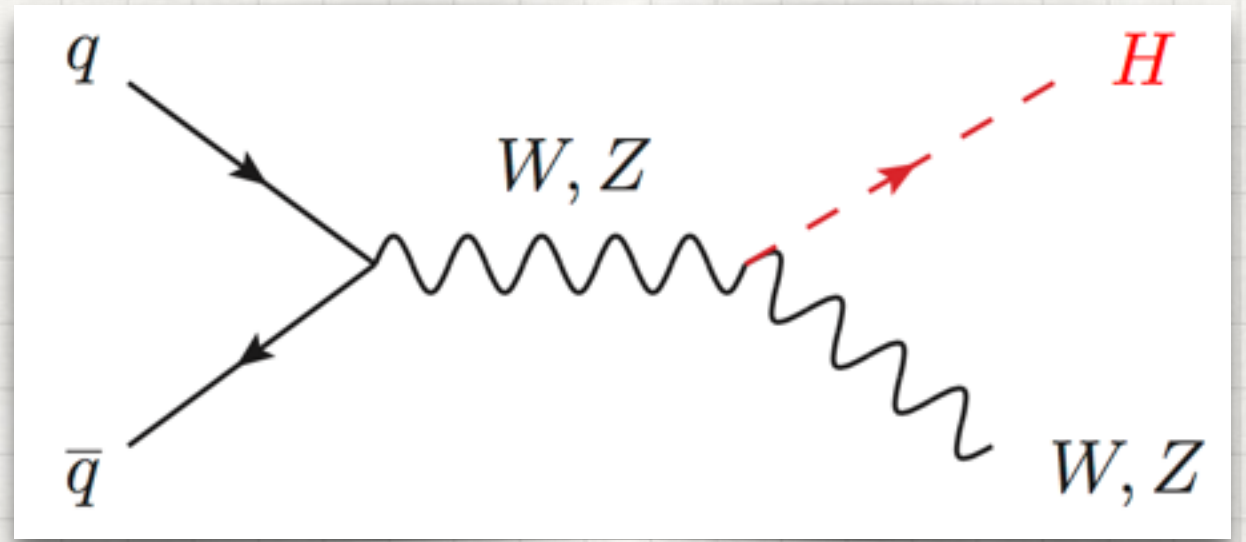


ATLAS-CONF-2018-031

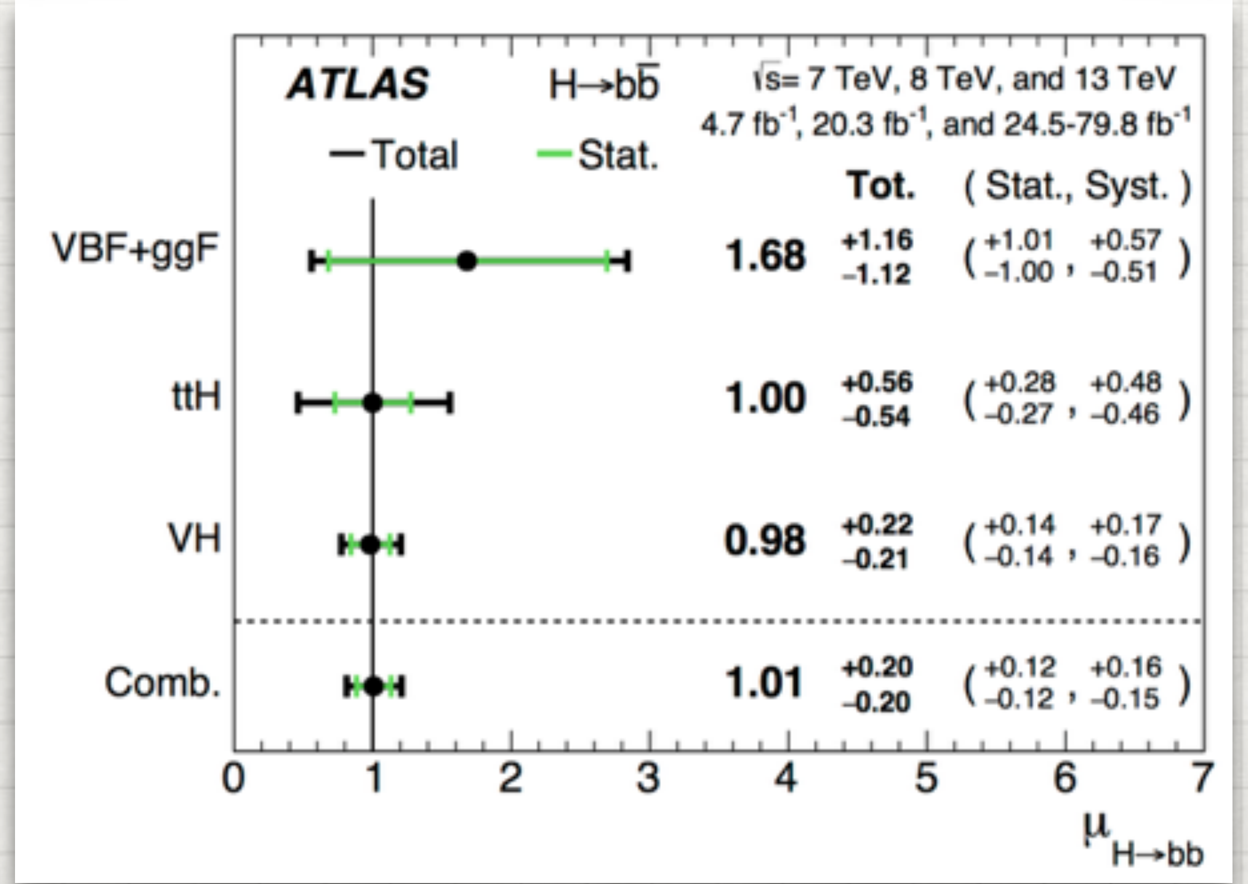
HIGGS DECAYS

WE ALREADY HAVE PROOF OF HBB COUPLING

- Higgs to bottom is the main decay channel (57%)
- Strong QCD background
- Searched in VBF and V+H: need a veto tool
- Observation by ATLAS in August through VH
- Decay has reduced sensitivity to yb due to width: $\Delta\mu = 0.2$ implies $\Delta\kappa = 0.3$



PDG [PRD 98, 030001]



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ATLAS [1808.08238]

PRODUCTION CHANNELS

INDIRECT PROBE THROUGH GLUON FUSION

- Main production channel is through gluon fusion
- Bottom loops account for 6% of the total cross section and 10% of the low pT region
- Already a good handle for fits: $\Delta\boldsymbol{\kappa}_b$= 20%
  ATLAS-CONF-2018-031
- Indirect constraint unsatisfying (slightly)
- Having a bbH measurement analogous to ttH would be nice
- Handle on SUSY at large **tanβ** (more relevant historically)

STATUS OF THE TH PREDICTIONS

- bbH has been a playground for the study of 5 flavor vs 4 flavor scheme discussion
  M. Lim, F. Maltoni, G. Ridolfi, and M. Ubiali [arXiv:1605.09411]
  M. Bonvini, A. S. Papanastasiou, and F. J. Tackmann [arXiv:1605.01733]
  S. Forte, D. Napoletano, and M. Ubiali [arXiv:1607.00389]

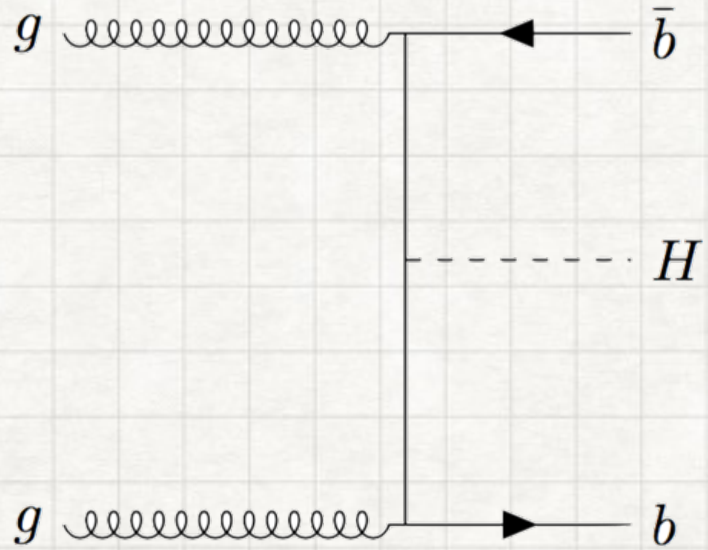
- For the 5 flavor scheme, predictions exist up to NNLO
  R. Harlander and M. Wiesemann [arXiv:1111.2182]
  S. Buhler, F. Herzog, A. Lazopoulos, and R. Muller [1204.4415]

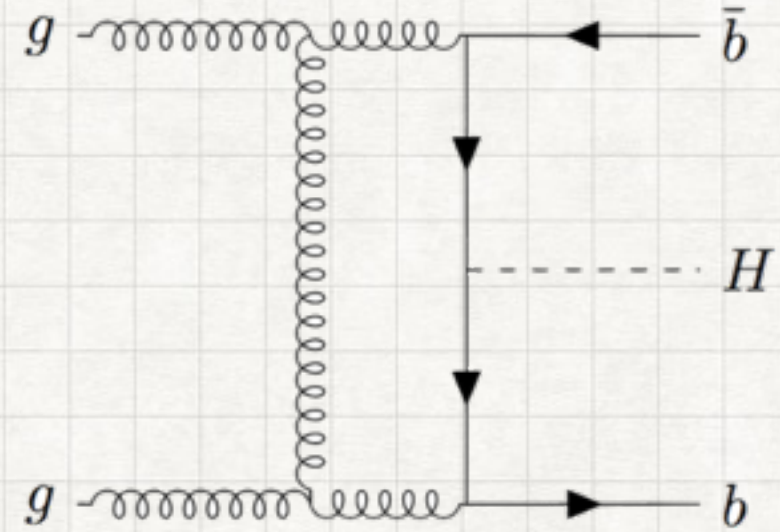
- For the 4 flavor, state of the art was NLO+PS, including top-bottom interference that appear first at NLO.
  B. Jager, L. Reina, and D. Wackeroth[arXiv:1509.05843].
  F. Krauss, D. Napoletano, and S. Schumann [arXiv:1612.04640]
  M. Wiesemann, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, and P. Torrielli [1409.5301]

- The systematic comparison of 4F and 5F schemes led to the recommendation of using the 4F scheme for most practical cases.

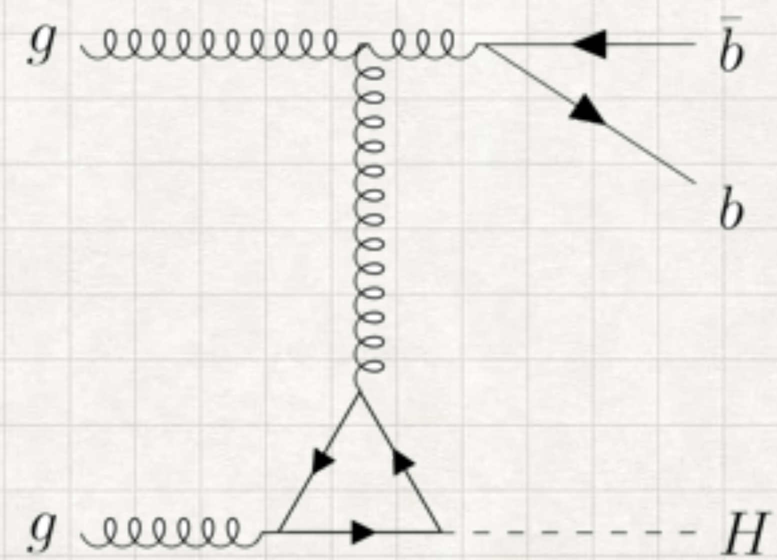
α_s α_s^2

y_b





y_t



CONTAINMATION BY GLUON FUSION

TOP QUARK EFFECTS ARE HUGE

	$\alpha_s^2 y_b^2$	$\alpha_s^2 y_b^2 + \alpha_s^3 y_b^2$	$\alpha_s^3 y_b y_t$	
σ [pb] (scale)	0.263 (57%)	0.405 (21%)	0.038 (65%)	
Δσ/Born	0	50 %	15 %	

CONTAMINATION BY GLUON FUSION

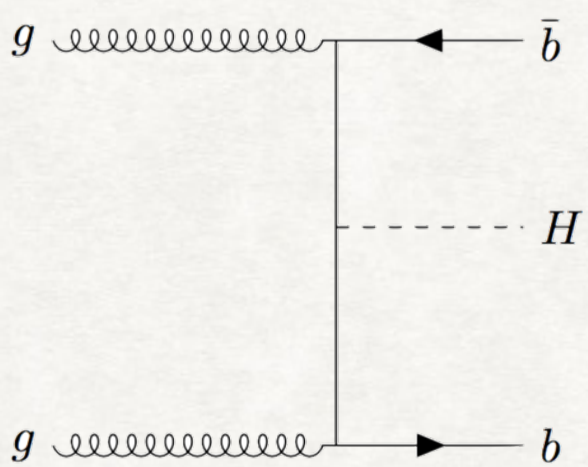
TOP QUARK EFFECTS ARE HUGE

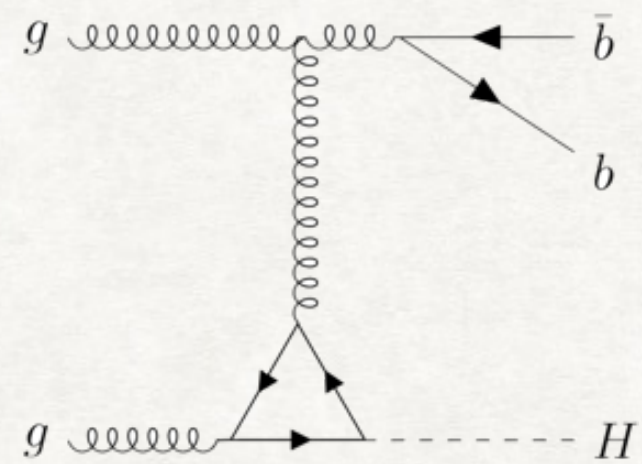
	$\alpha_s^2 y_b^2$	$\alpha_s^2 y_b^2 + \alpha_s^3 y_b^2$	$\alpha_s^3 y_b y_t$	$\alpha_s^4 y_t^2$
σ [pb] (scale)	0.263 (57%)	0.405 (21%)	0.038 (65%)	0.358 (74%)
Δσ/Born	0	50 %	15 %	**130 %**

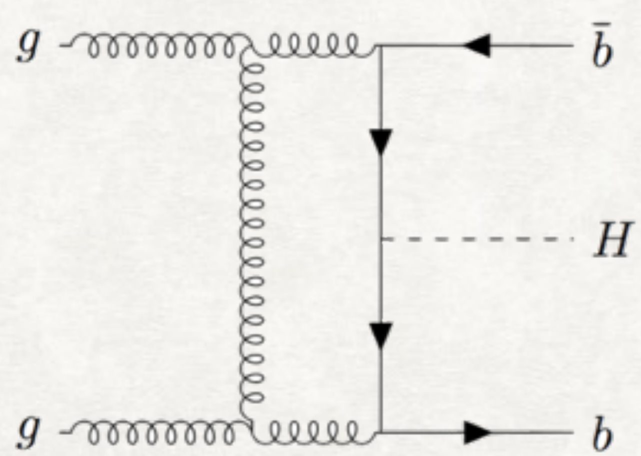
Enormous scale uncertainty: need for higher orders

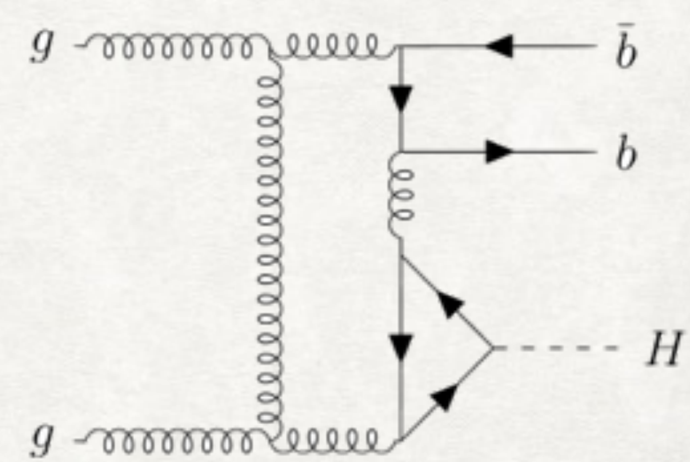
ORGANIZING THE CROSS SECTION

$$\sigma = y_b^2\,\alpha_s^2\left(\Delta^{(0)}_{y_b^2} + \alpha_s\Delta^{(1)}_{y_b^2}\right) + y_t y_b\,\alpha_s^3\left(\Delta^{(0)}_{y_b\,y_t} + \alpha_s\Delta^{(1)}_{y_b\,y_t}\right) + y_t^2\,\alpha_s^4\left(\Delta^{(0)}_{y_t^2} + \alpha_s\Delta^{(1)}_{y_t^2}\right)$$



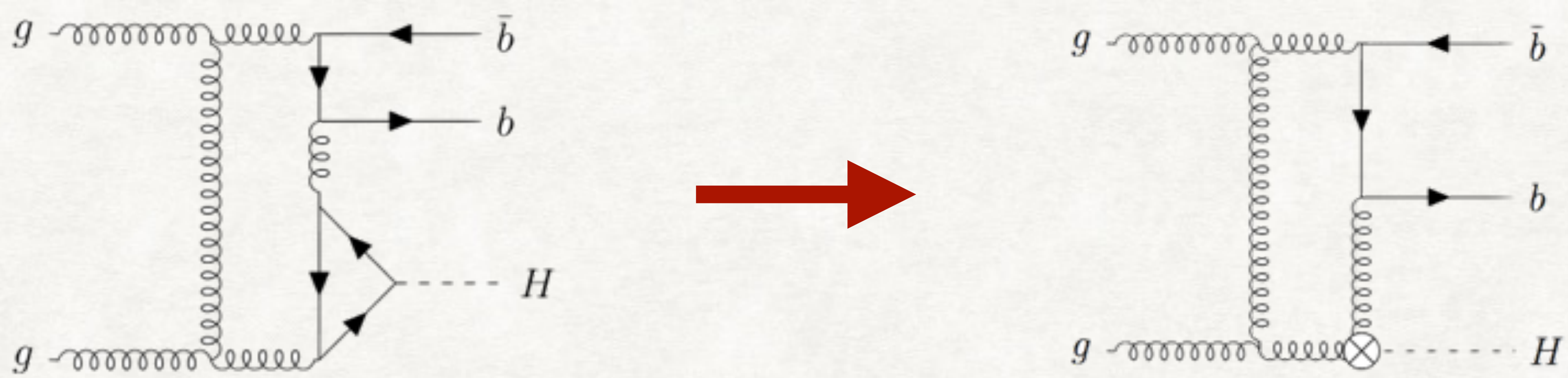


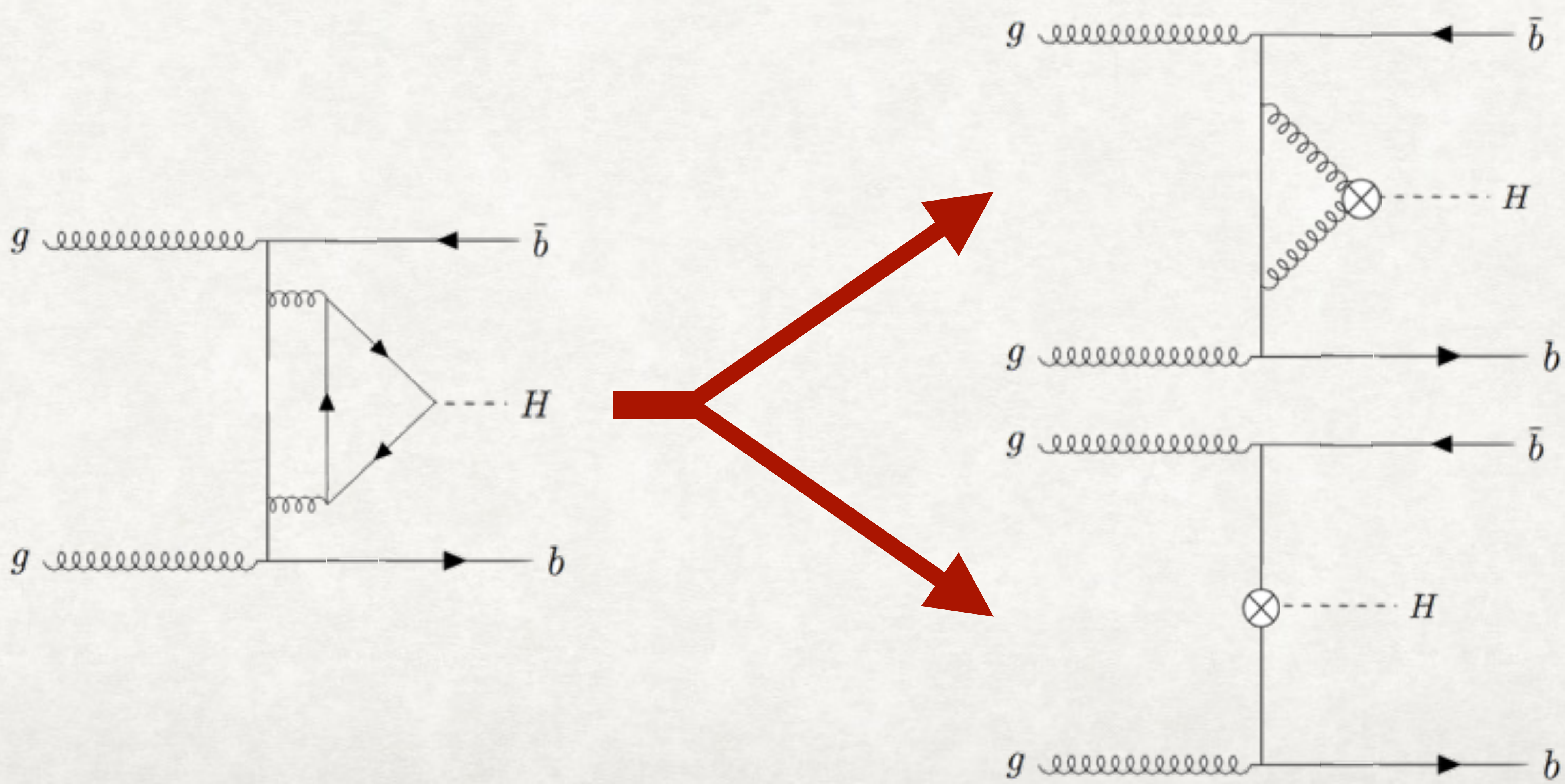




LARGE TOP MASS LIMIT

ONE LOOP FEWER





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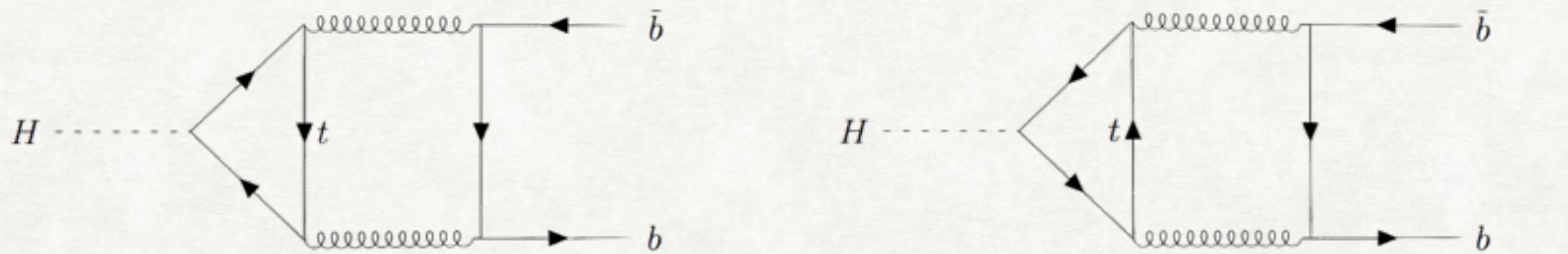
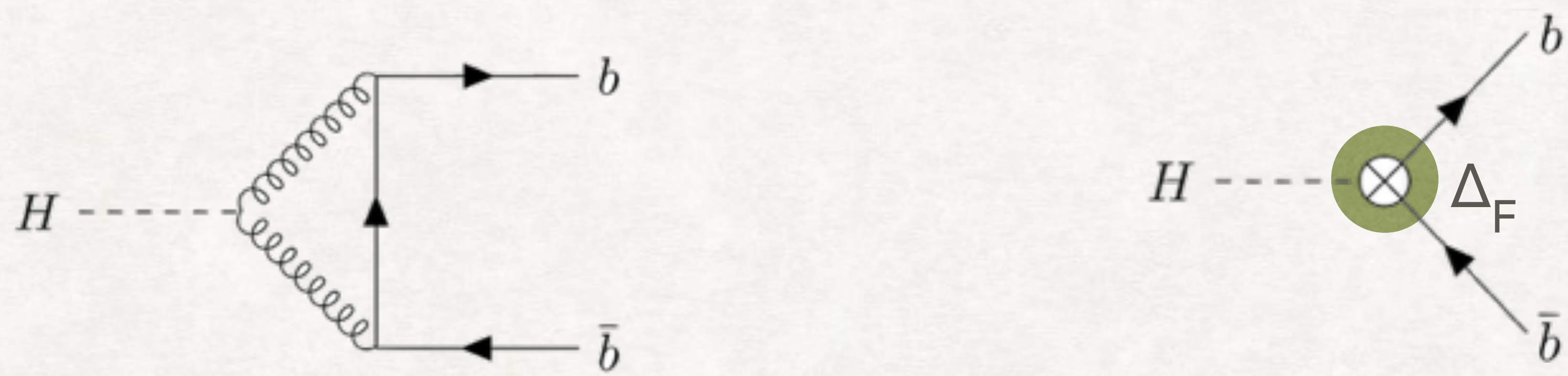
MATCHING THE EFT TO THE SM

THE TOP PART OF THE BOTTOM YUKAWA

- Compute the amplitude for the decay H→bb in the SM



- Compute its EFT corresponding diagrams



- Matching: the renormalized amplitudes must be equal up to O(mt)

Thanks to Claude Duhr for his help and advice for this calculation

CALCULATING THE AMPLITUDES

- Two loop amplitude expressed as a combination of 17 master integrals using LiteRed.
- Computed as a series expansion in $\frac{1}{m_t}$ using ASY
- Direct integration is sufficient as the most complicated integral is the one loop triangle of the EFT amplitude

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  R. N. Lee [1310.1145]

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  B. Jantzen, A. V. Smirnov, V. A. Smirnov [1206.0546]

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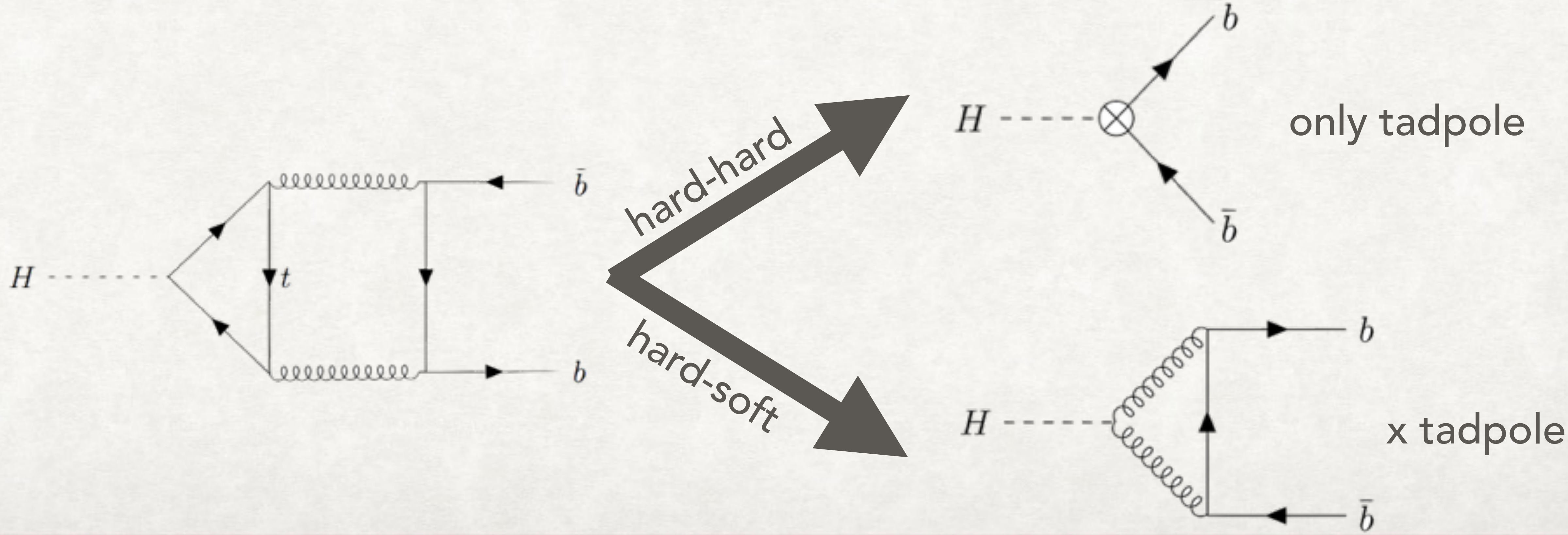

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$$\mathcal{A}_{\mathrm{SM}} = i y_t^R \left(\alpha_s^R\right)^2 C_A C_F \left(\frac{m_b}{m_t}\right) \frac{m_b^2}{36\sqrt{2}\pi^2} \frac{(2r+1)}{r(r+1)} \Big(6G(0,-1,r) + 6G(0,0,r) - 6G(-1,-1,r) - 6G(-1,0,r) + 36\,(2r+1)\log\left(\frac{m_b}{m_t}\right) - 78r + 4\pi^2 - 39\Big)$$

$$\mathcal{A}^{\mathrm{HEFT}}_{H\to b\bar{b}}\big|_{y_t\alpha_s^2} = i y_t^R \left(\frac{\alpha_s^R}{\pi}\right)^2 C_A C_F \left(\frac{m_b}{m_t}\right) m_b^2 \frac{(2r+1)}{r(r+1)18\sqrt{2}} \Big(3G(0,-1,r) + 3G(0,0,r) - 3G(-1,-1,r) - 3G(-1,0,r) + 9(1+2r)\log\left(\frac{m_b^2}{\mu^2}\right) - 24r + 2\pi^2 - 12\Big) + i y_t^R \left(\frac{\alpha_s}{\pi}\right)^2 \left(\frac{m_b}{m_t}\right) C_A \frac{m_b^2}{\sqrt{2}} \frac{(2r+1)^2}{r(r+1)} \Delta_F$$

$$r = \frac{\sqrt{\tau}\sqrt{\tau+4} - r}{2\tau}, \text{ with } \tau = -\frac{m_H^2}{m_b^2}$$

RESULT OF THE MATCHING

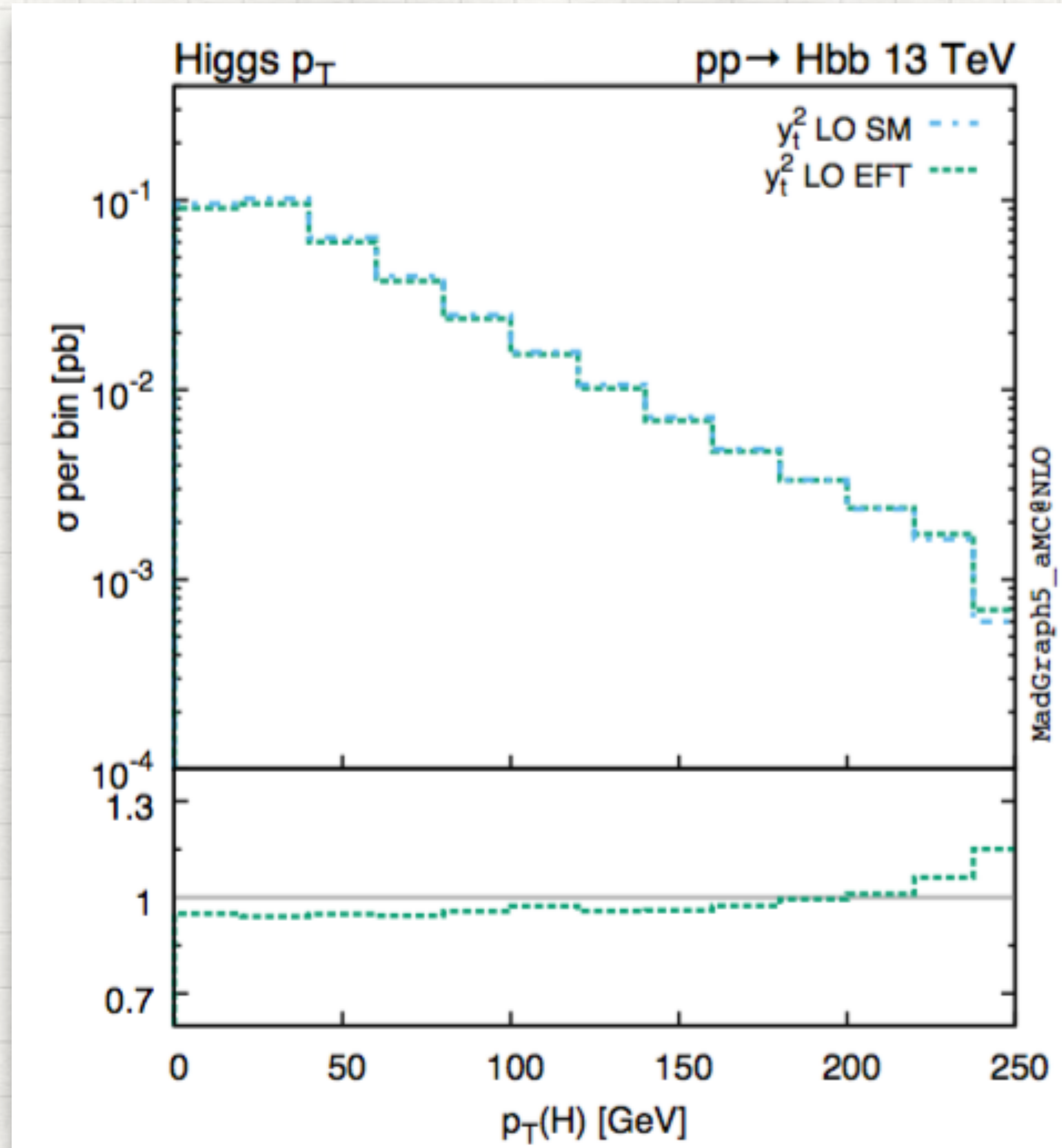
A tiny effect

$$y_b^{\mathrm{HEFT}} = y_b^{\mathrm{SM}} - y_t \left(\frac{\alpha_s}{\pi}\right)^2 \frac{m_b}{m_t} \left(\frac{5}{24} - \frac{1}{4}\log\left(\frac{\mu_R^2}{m_t^2}\right)\right)$$

$$\frac{y_b^{\mathrm{SM}} - y_b^{\mathrm{HEFT}}}{y_b^{\mathrm{SM}}} \simeq 10^{-4} \sim 10^{-3}$$

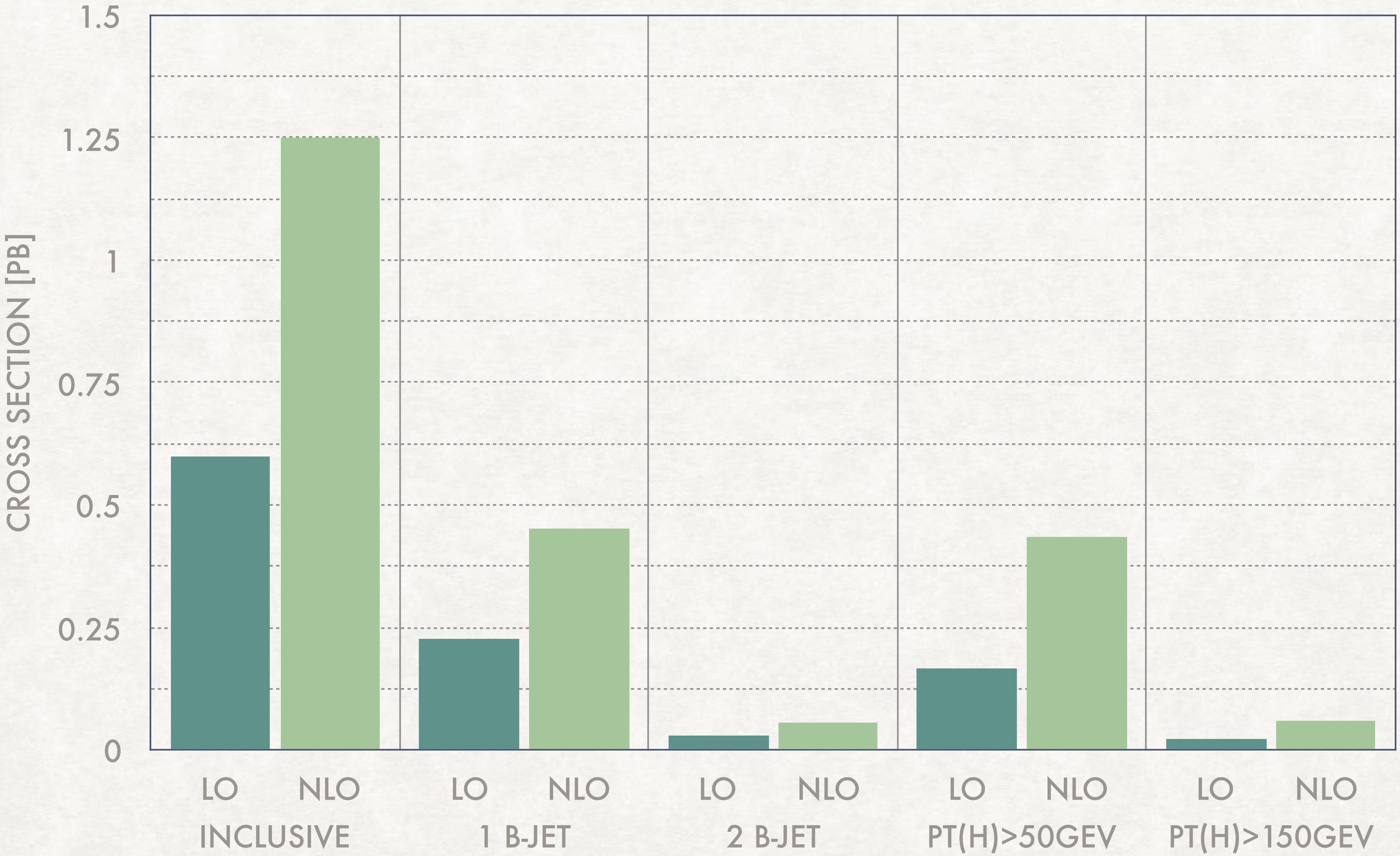
EFT VALIDATION AT LO

- Comparing MG5_aMC@NLO loop-induced LO with the EFT model
- X-section: 5% agreement
- Pretty similar picture to gg→H(j) for the distributions: approximation works well up to pT~200GeV
- Comparison of rescaled EFT vs exact NLO for H+j give good expectations for the larger pT region (Jones, Kerner, Luisoni [1802.00349])
- "Best" prediction: LO exact + NLO reweighted EFT



TOTAL NLO CROSS SECTIONS

ALL CONTRIBUTIONS



Scale uncertainties: 65% at LO, 35% at NLO

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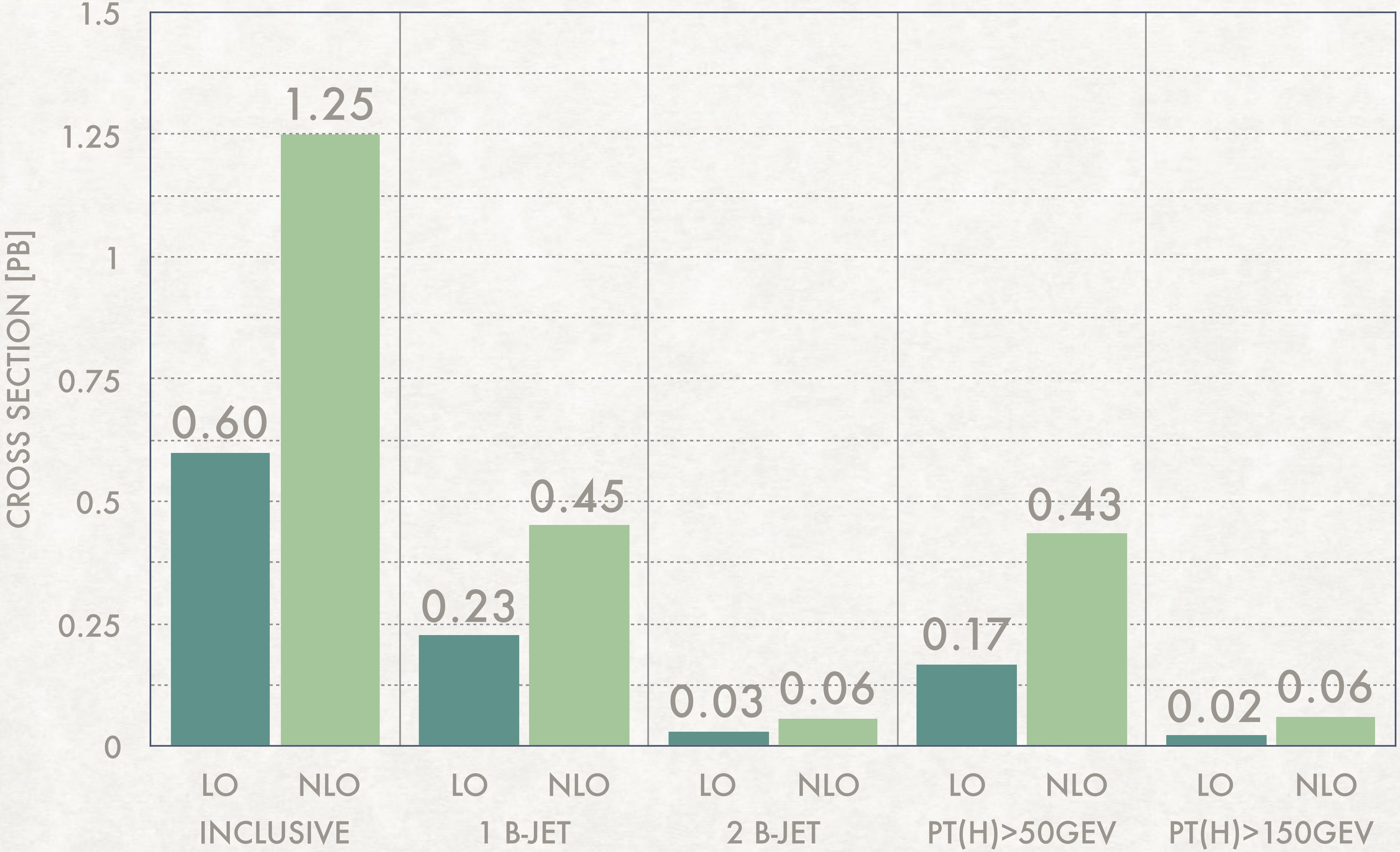

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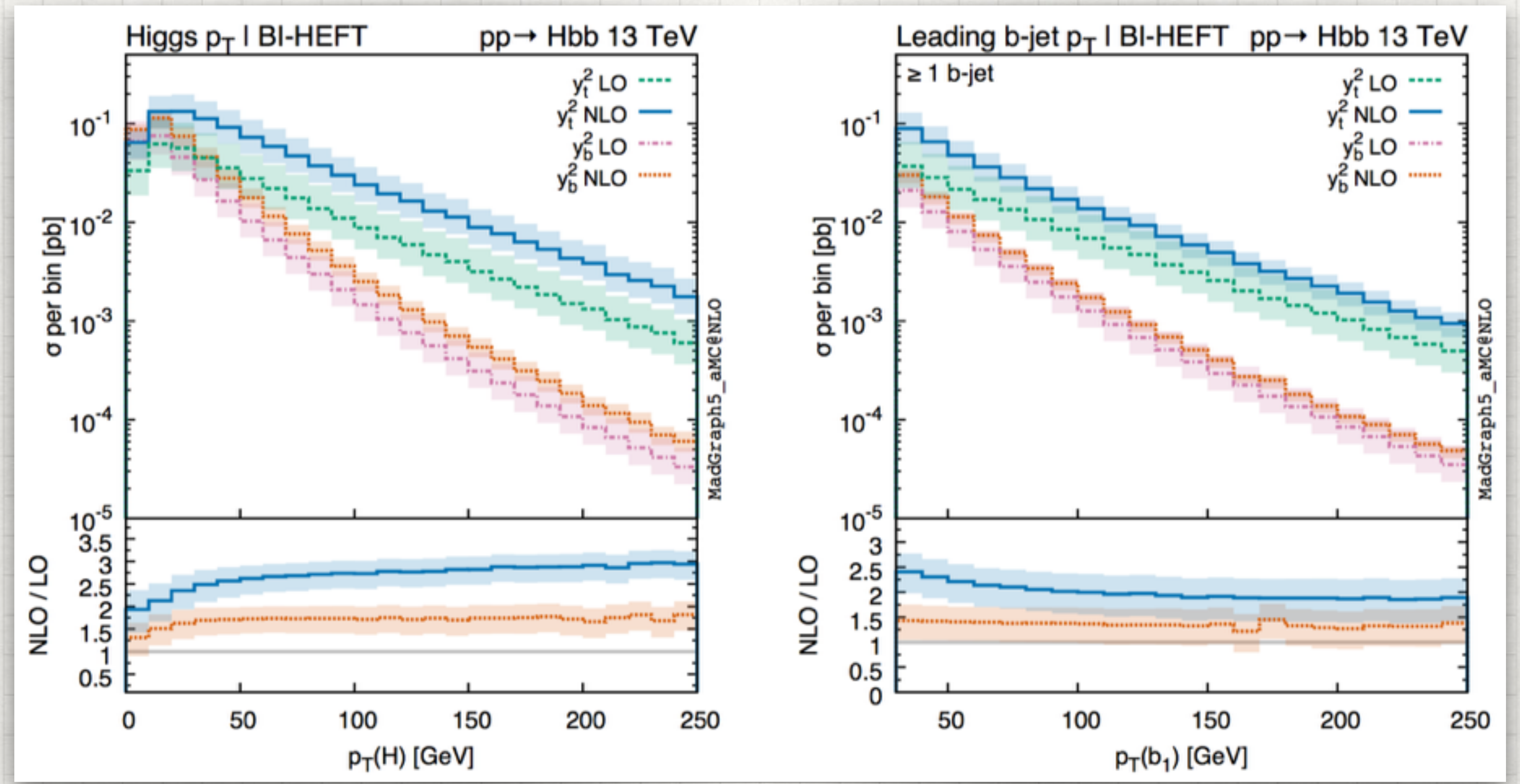
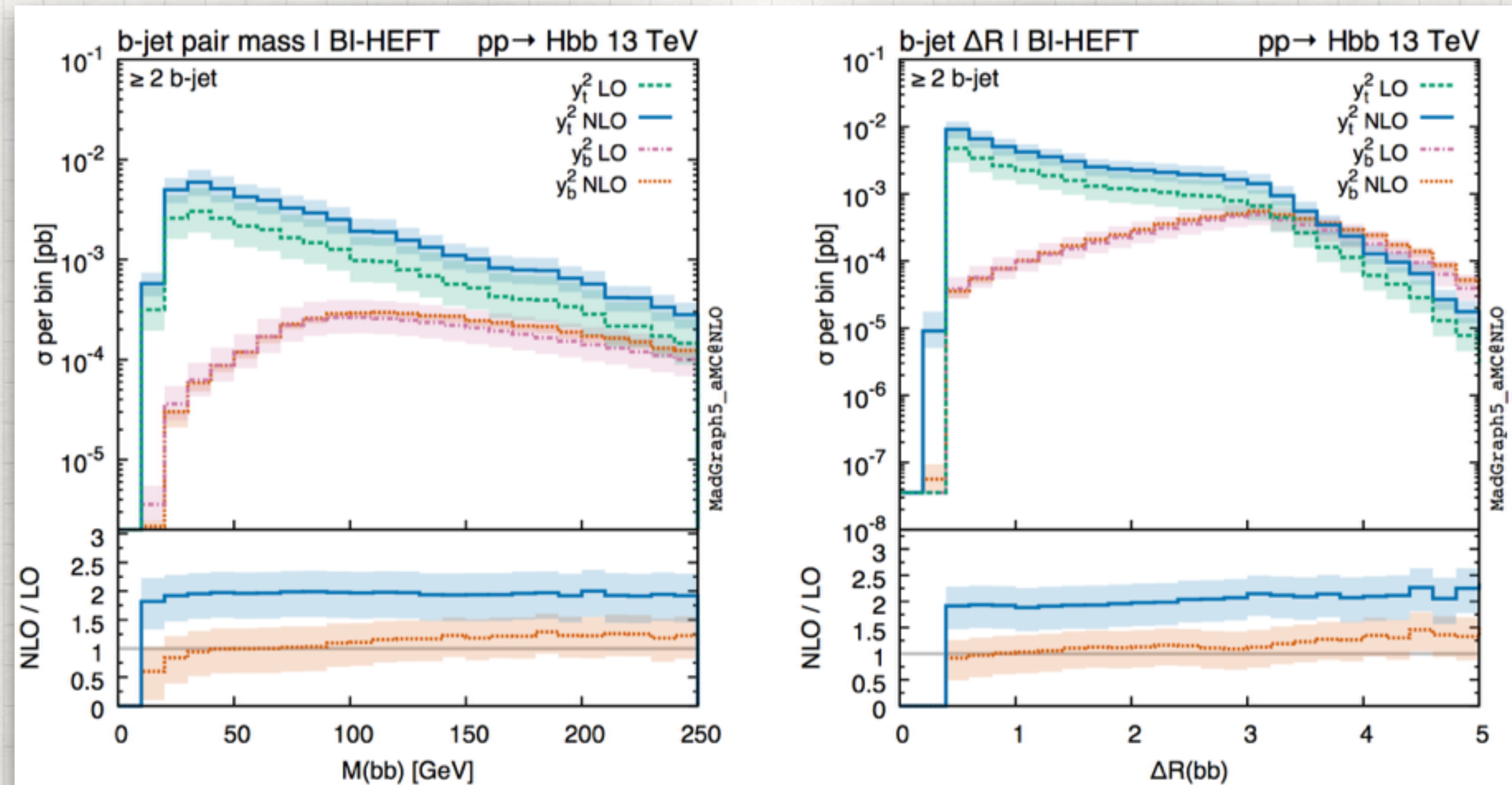
K-FACTORS

PT DISTRIBUTIONS



K-FACTORS

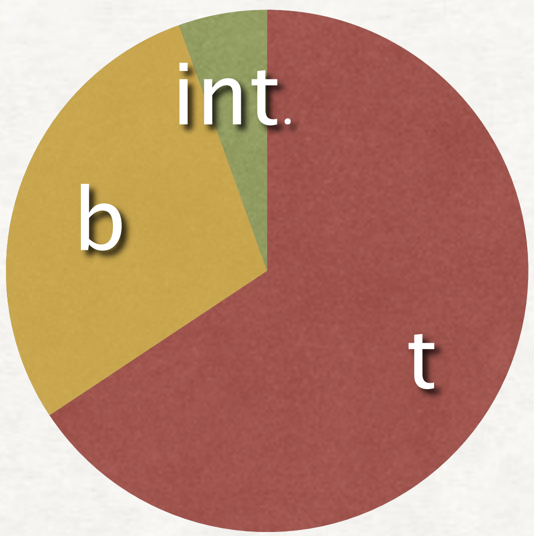
B-JET SEPARATION



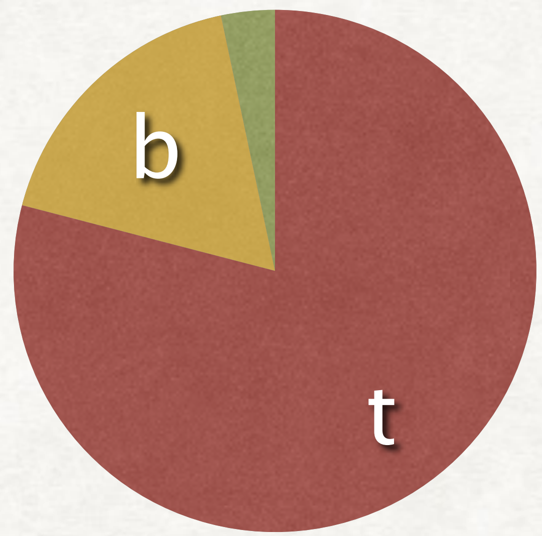
TOTAL NLO CROSS SECTIONS

YUKAWA BREAKDOWN

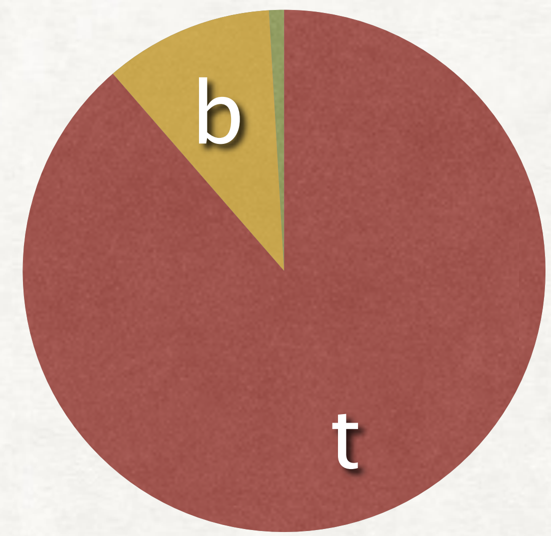
INCLUSIVE



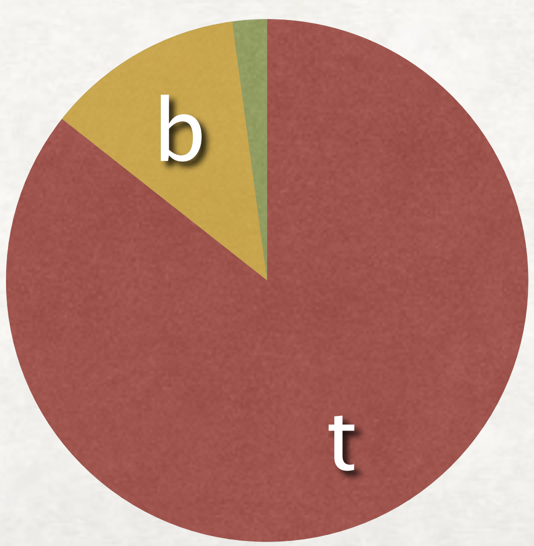
1 B-JET



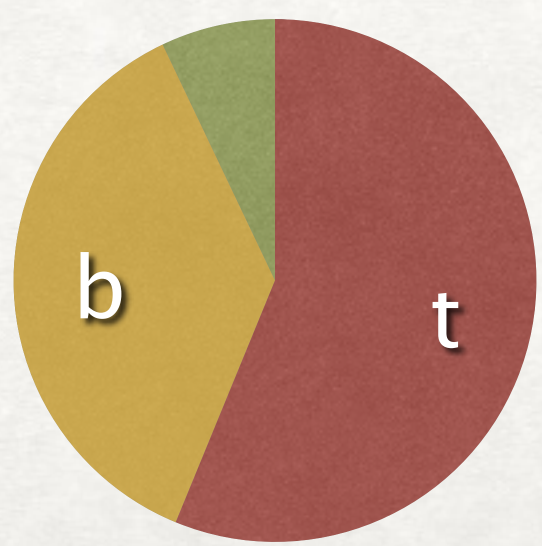
2 B-JETS



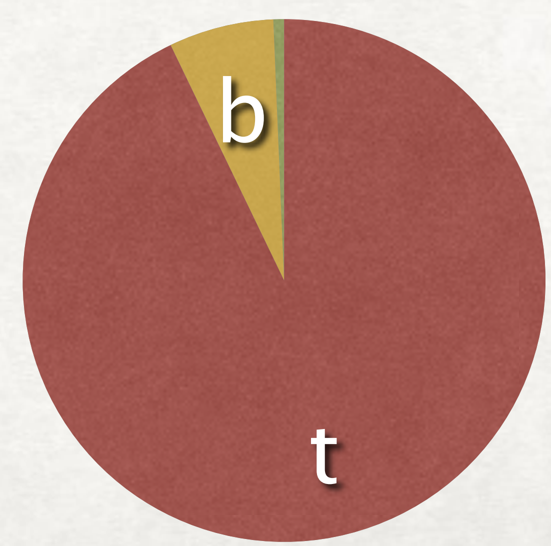
1 BB-JET



PT<50GEV

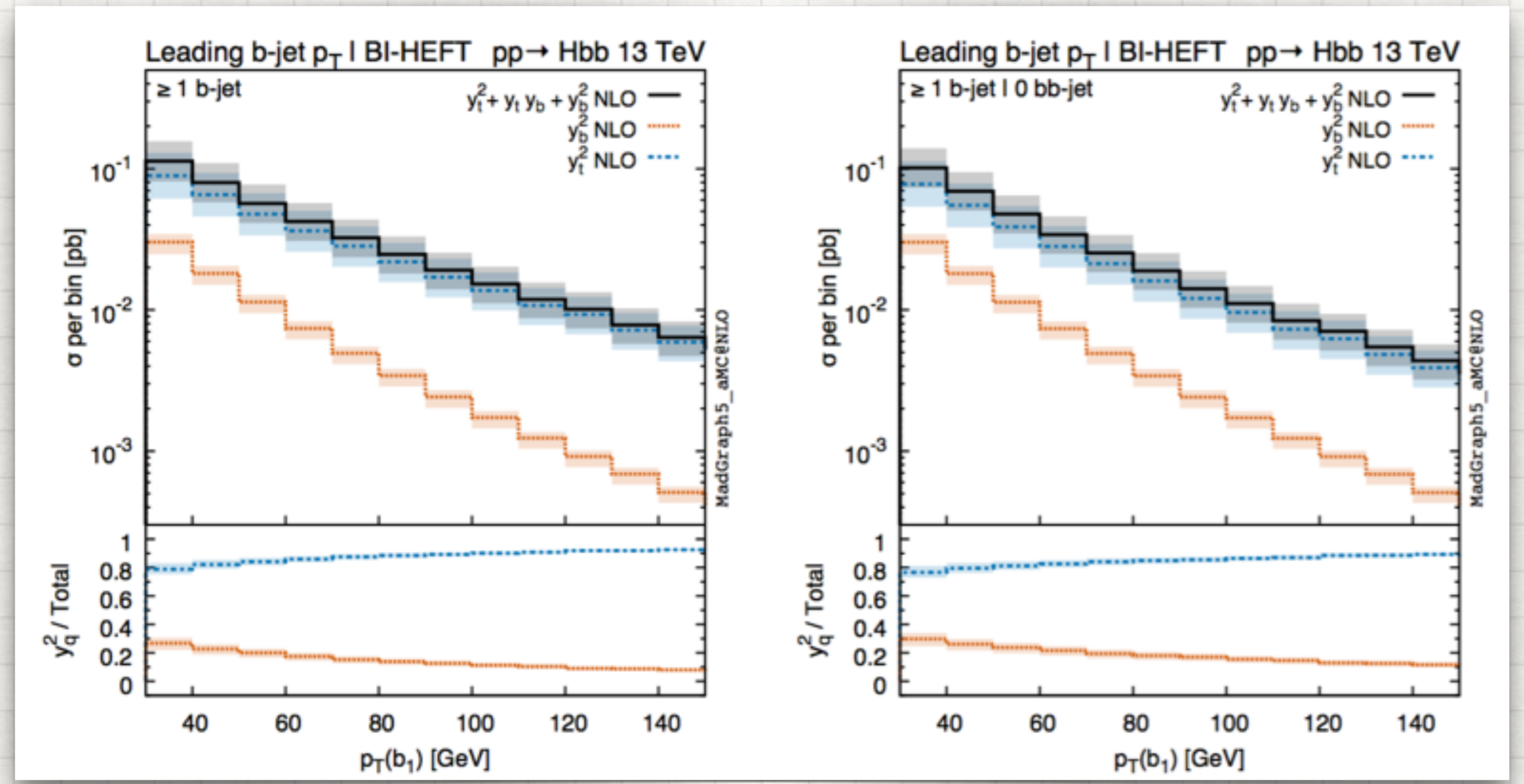


PT>150GEV



DISTRIBUTIONS

EXTRACTING MORE B THROUGH CUTS



Single b observables are not very good at discriminating yb and yt

DISTRIBUTIONS

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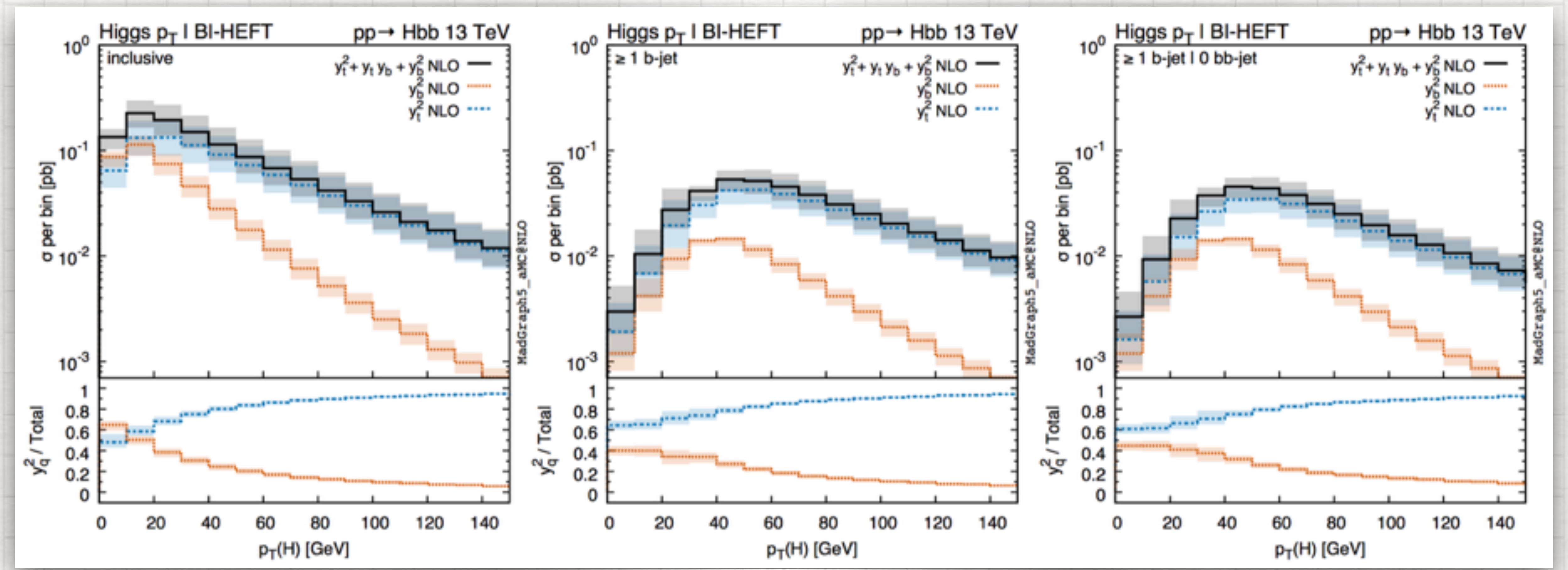
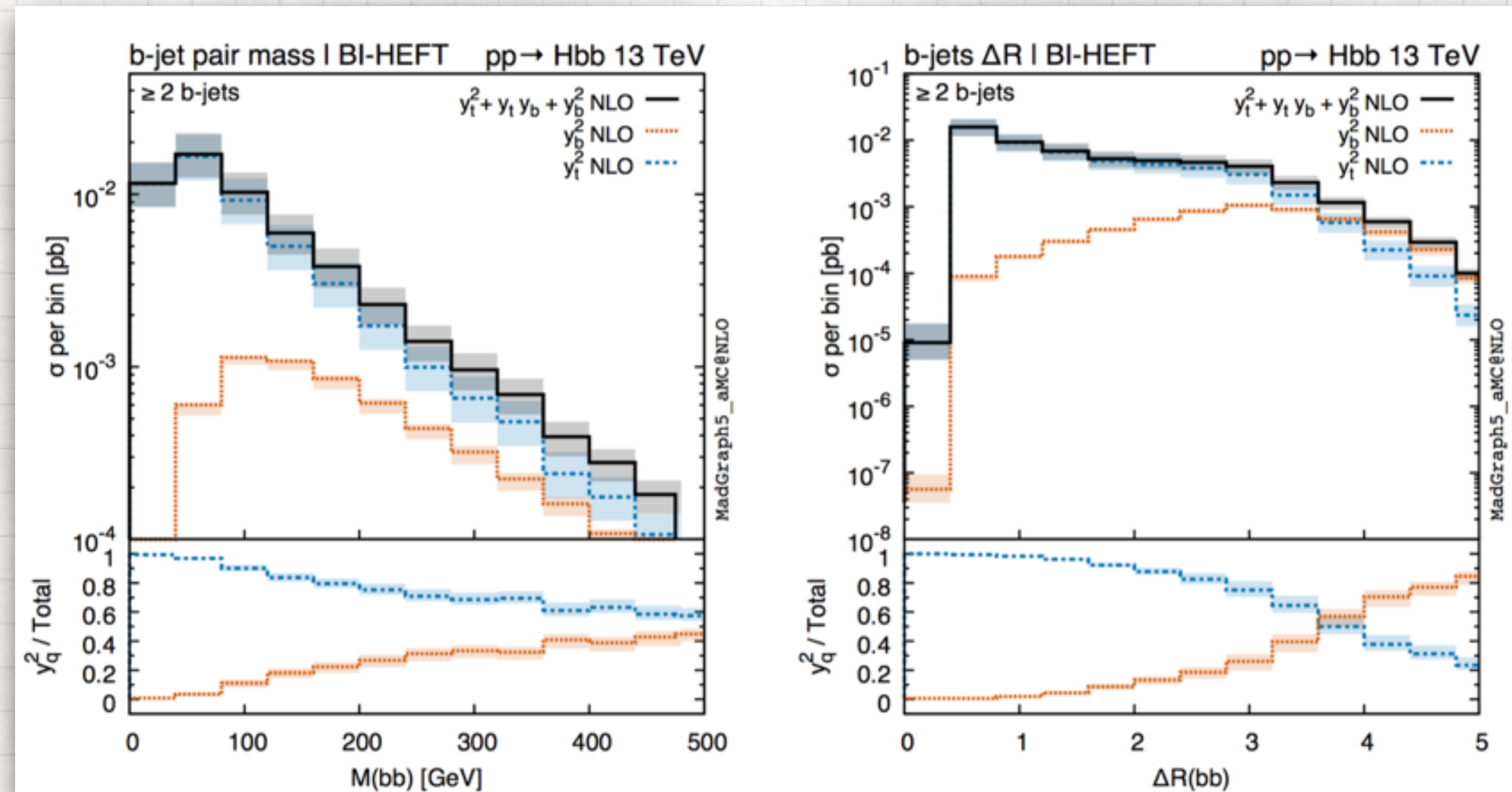


- Low Higgs pT improves yb fraction
- Tagging reduces signal
- Excluding jets with two b slightly improves

DISTRIBUTIONS

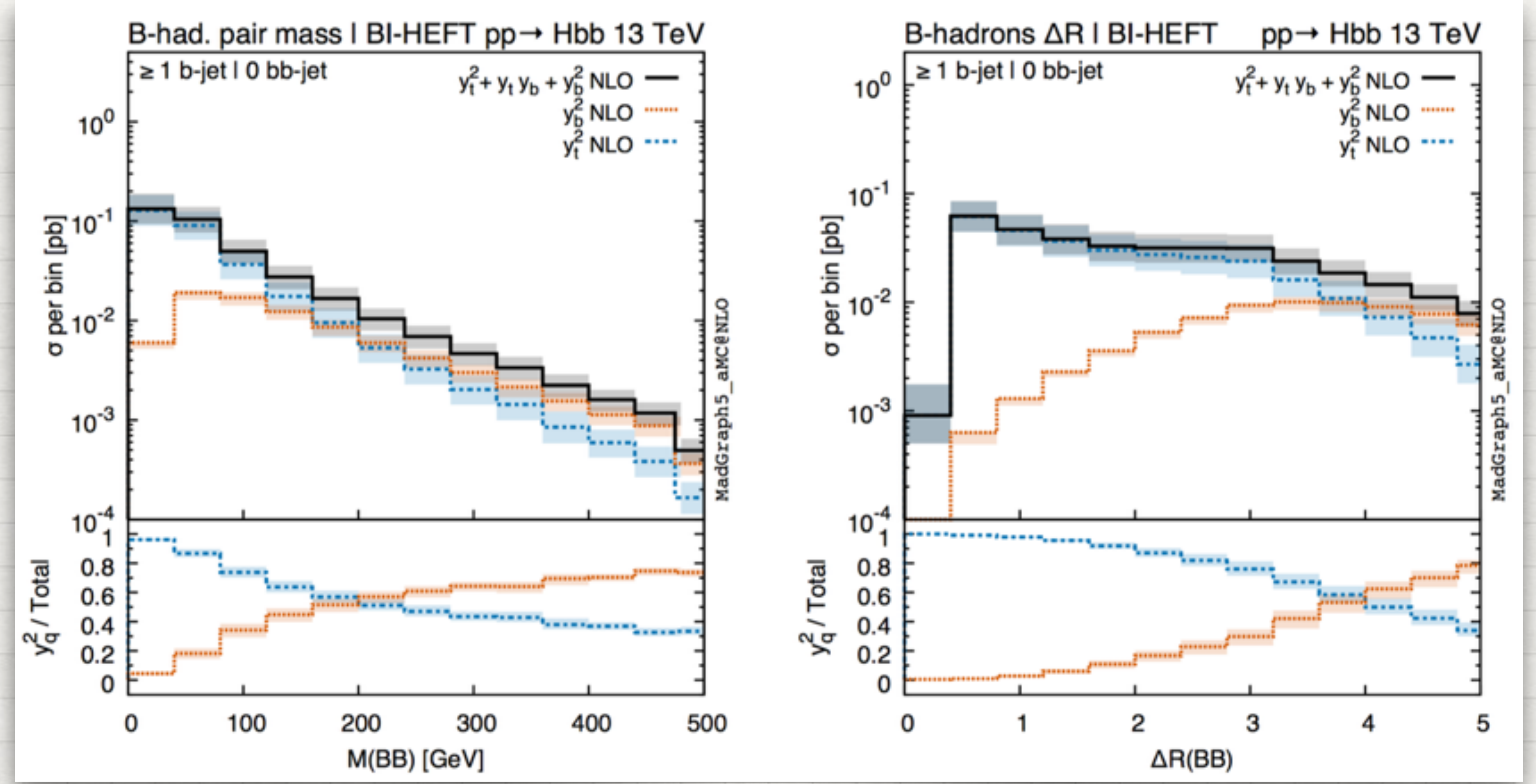
EXTRACTING MORE B THROUGH CUTS



- **Very clear characteristic of Hbb interaction: well separated b-jets**

DISTRIBUTIONS

THEORIST DREAMS



- Well separated, hard B-hadrons would be even better
- As usual, TH solution killed by EXP reality

LESSONS LEARNED

GOOD NEWS FOR OBSERVATION, LESS FOR MEASUREMENT

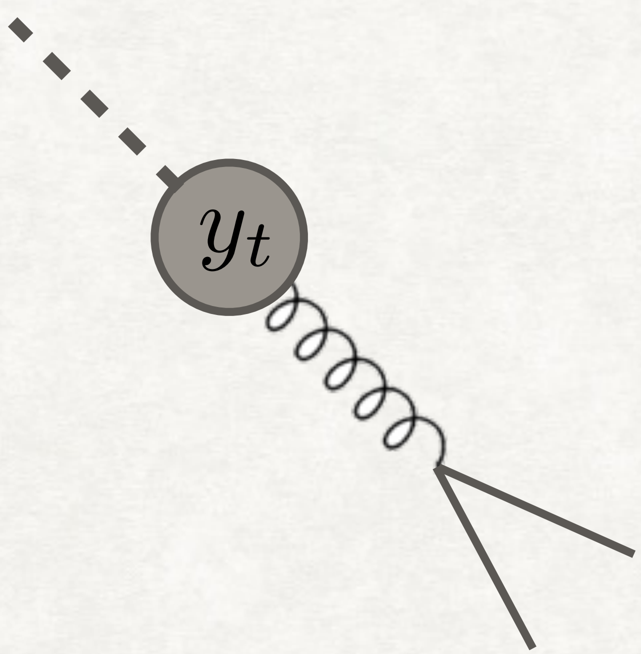
- Very large contamination of the bbH from gluon fusion
- True bbH coupling part is reduced by tagging
- Better signal now
- Less interesting physics in it

- The top-induced signal is enhanced in the high pT and collinear bb regions (enhancement due to g→bb splitting)
- Might be possible to veto "2-prong b-jets"
- Further developments: use this process to better characterize g→bb splittings

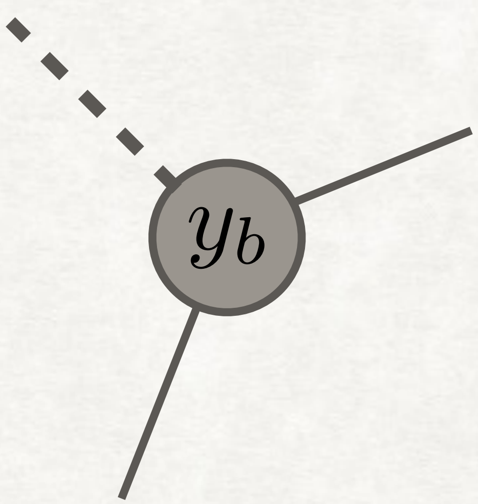
ANATOMY OF A BBH EVENT

AN OVERLY SIMPLISTIC PICTURE

top-events



bottom-events

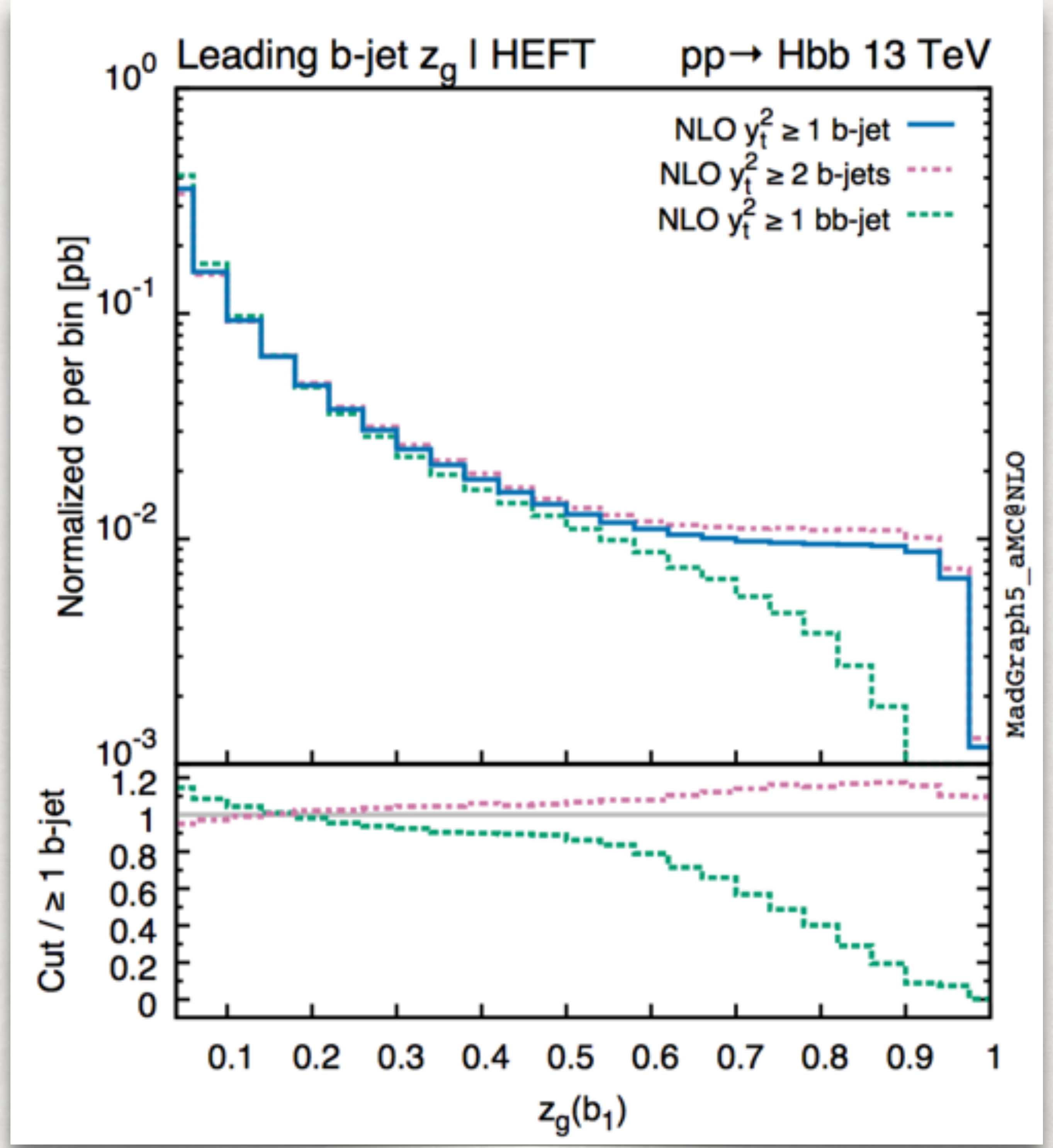


In practice all of the relevant phase space is dominated by tops

Correct statement: regions of phase space where the cross section has an enhanced dependence on either Yukawa

GLUON SPLITTINGS

- Processes for the backgrounds of ttH such as ttbb suffer from uncertainties related to g→bb
- Large log(pt/mb) for 4FS
- Large MC dependence when in the 5FS
- Hbb yt is a good testing ground as large pT(H) selects these splittings
- We could already illustrate the enhancements with soft b in jets



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