Decoding Higgs Boson Branching Ratios from Event Shape Variables

based on:
Knobbe, Krauss, DR, Schumann EPJC 84 (2024) 1, 83 [arXiv:2306.03682]
Gehrmann-de Ridder, Preuss, DR, Schumann [arXiv:2403.06929]

Daniel Reichelt, 9 July 2024

This Talk…

Part I:

alternative ideas for Measurements of Higgs Boson Branching ratios based on event shapes [Knobbe, Krauss, DR, Schumann ‘23]

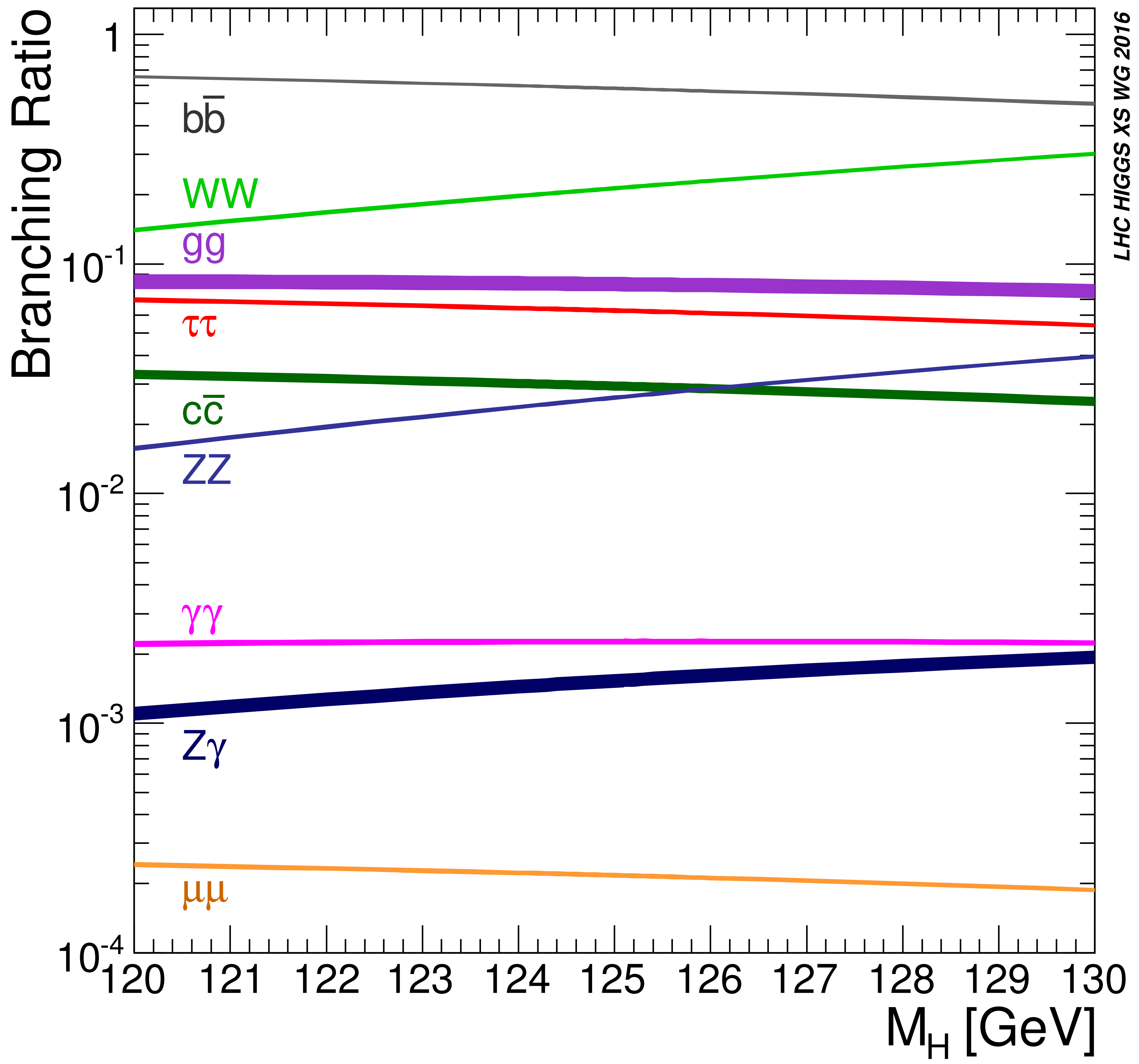
make use of clean environment in FCC-ee setting

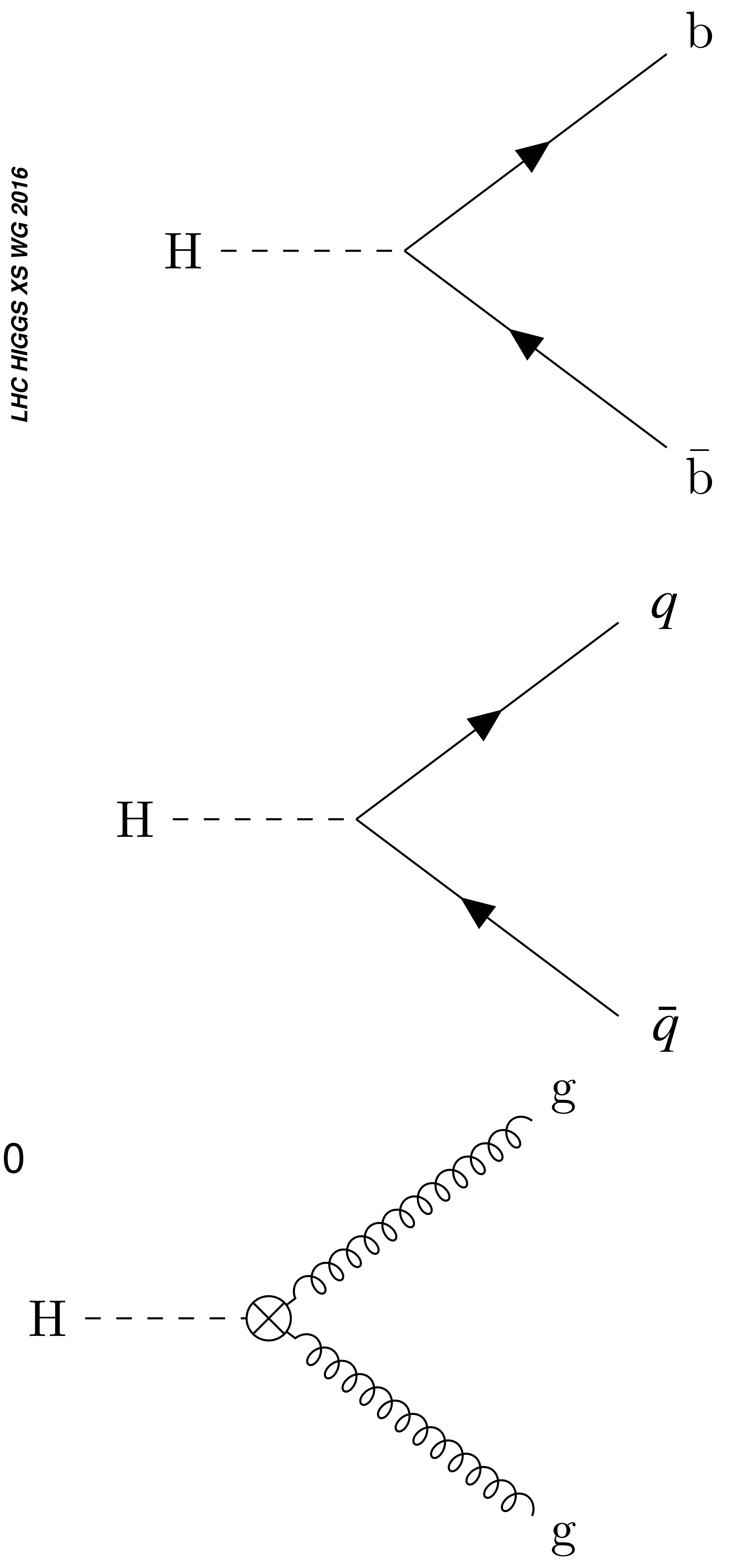
Part II:

precision calculations for event shapes in Higgs decays with EERAD [Coloretti, Gehrmann-de Ridder, Preuss ’22] [Gehrmann-de Ridder, Preuss, Williams ‘23] and resummation in Sherpa-CAESAR framework [Gehrmann-de Ridder, Preuss, DR, Schumann ’24]

Hadronic Higgs Decays

- Higgs with $m_H = 125\ \mathrm{GeV}$:
  - dominant decay into b-quarks (observed ATLAS/CMS in Run 2)
  - tiny c-quark (first limits)
  - substantial into gluons
  - suppressed light (s-quark) BR





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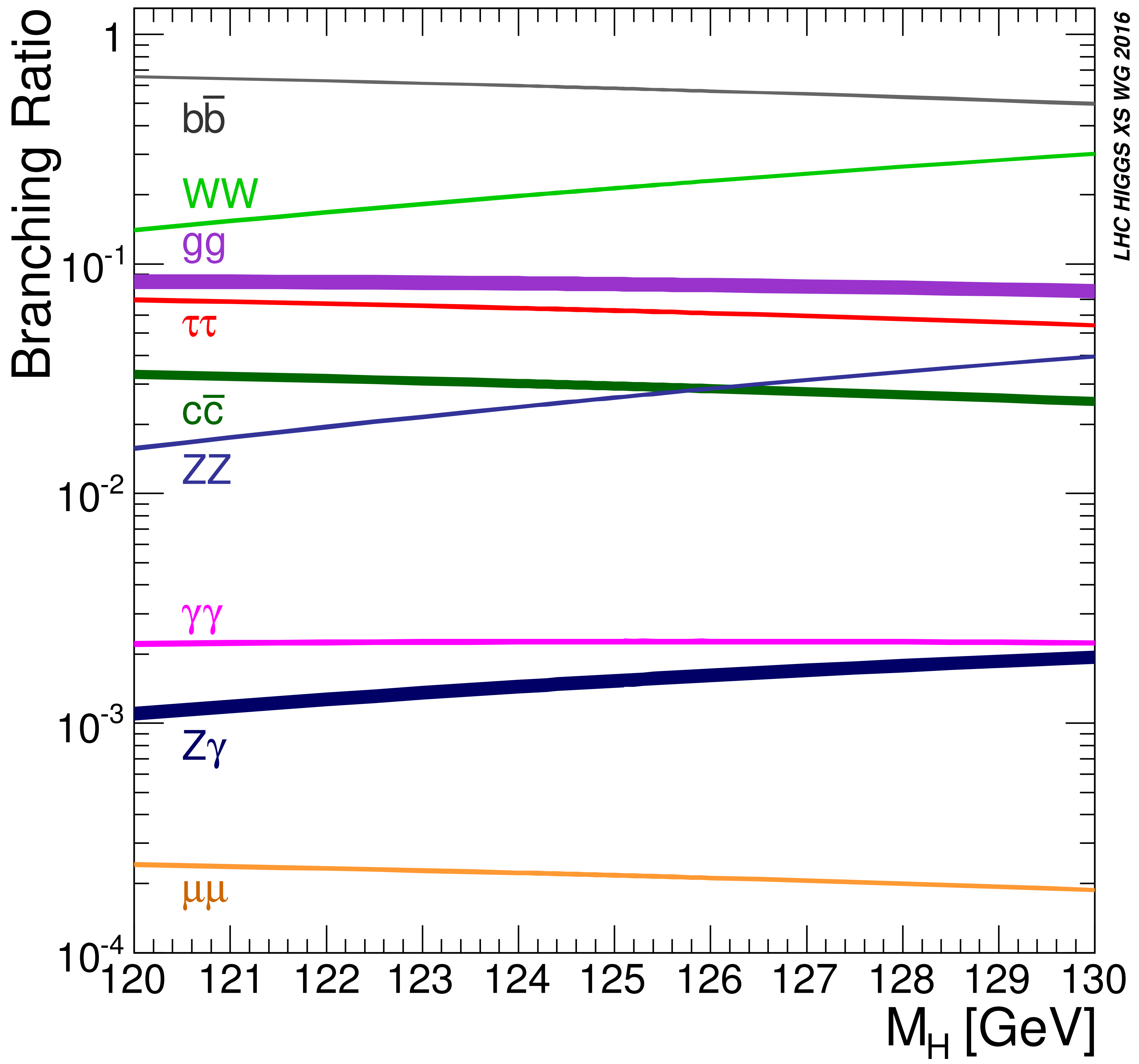
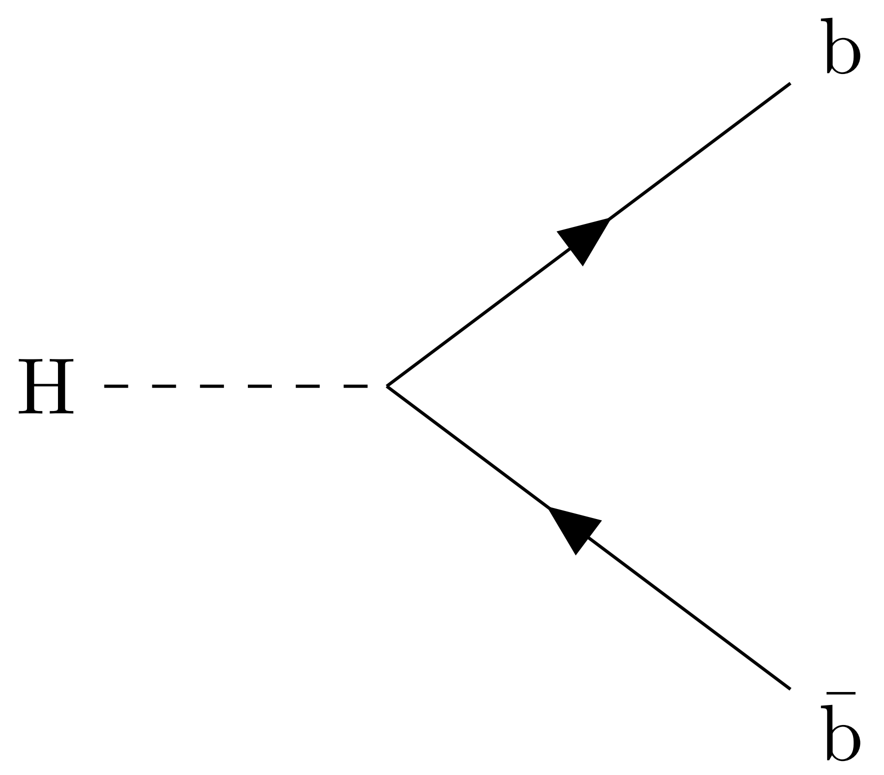
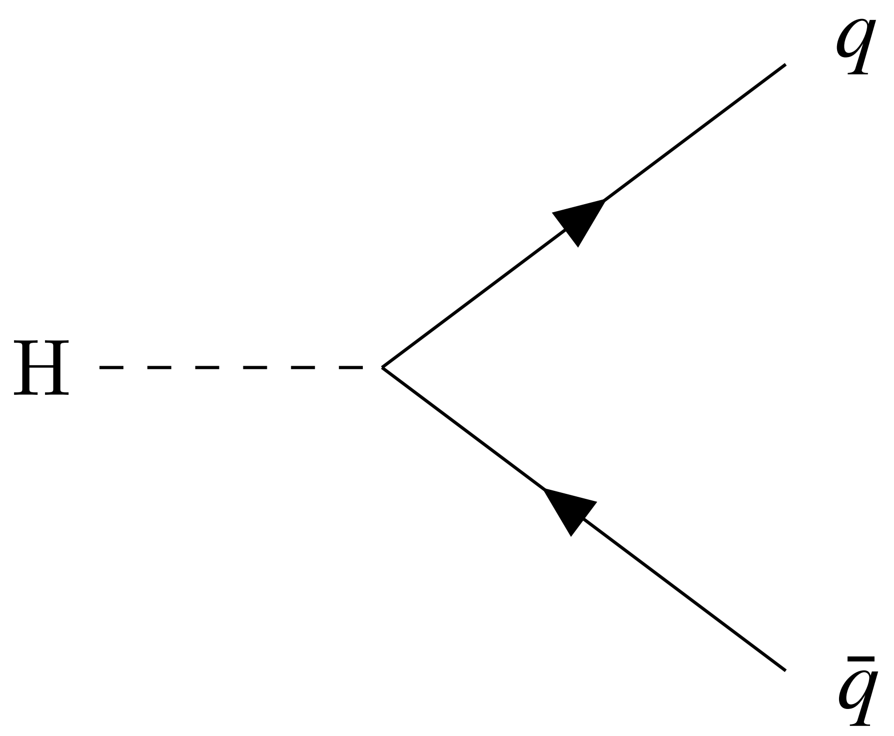
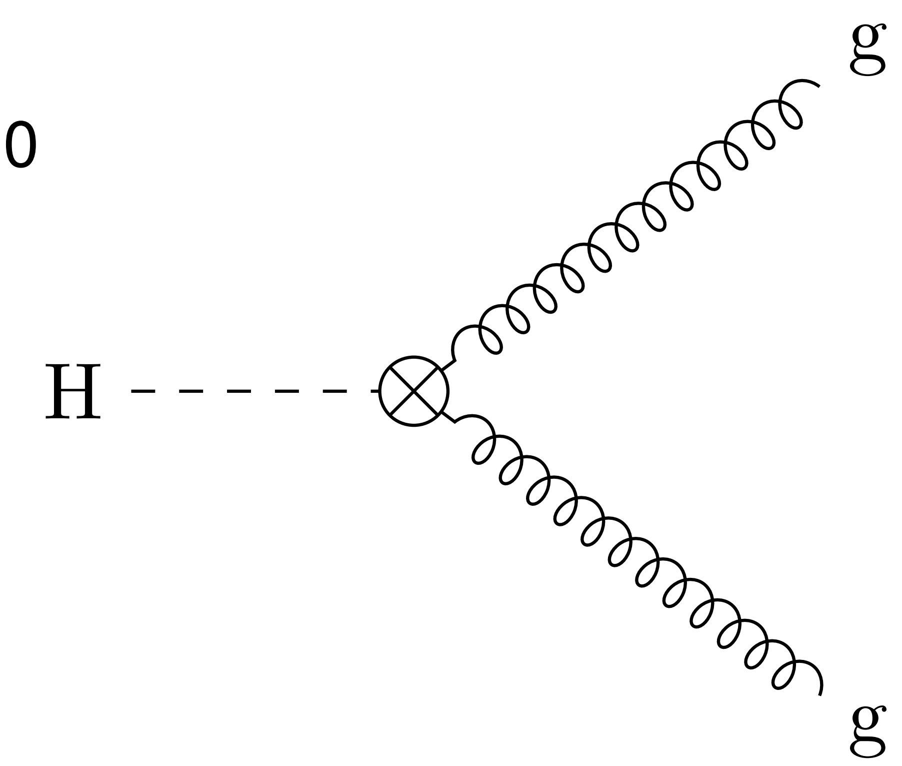


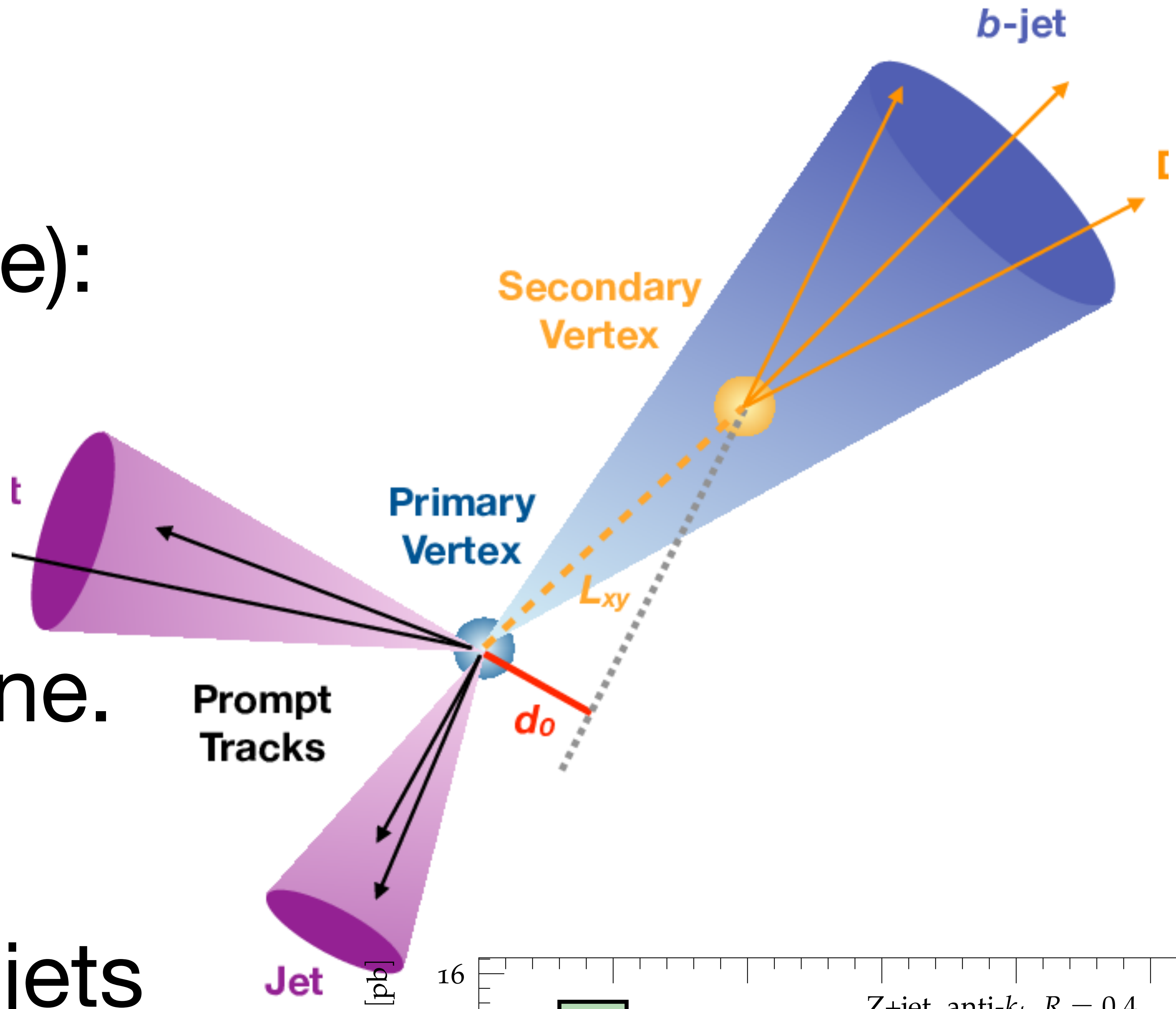


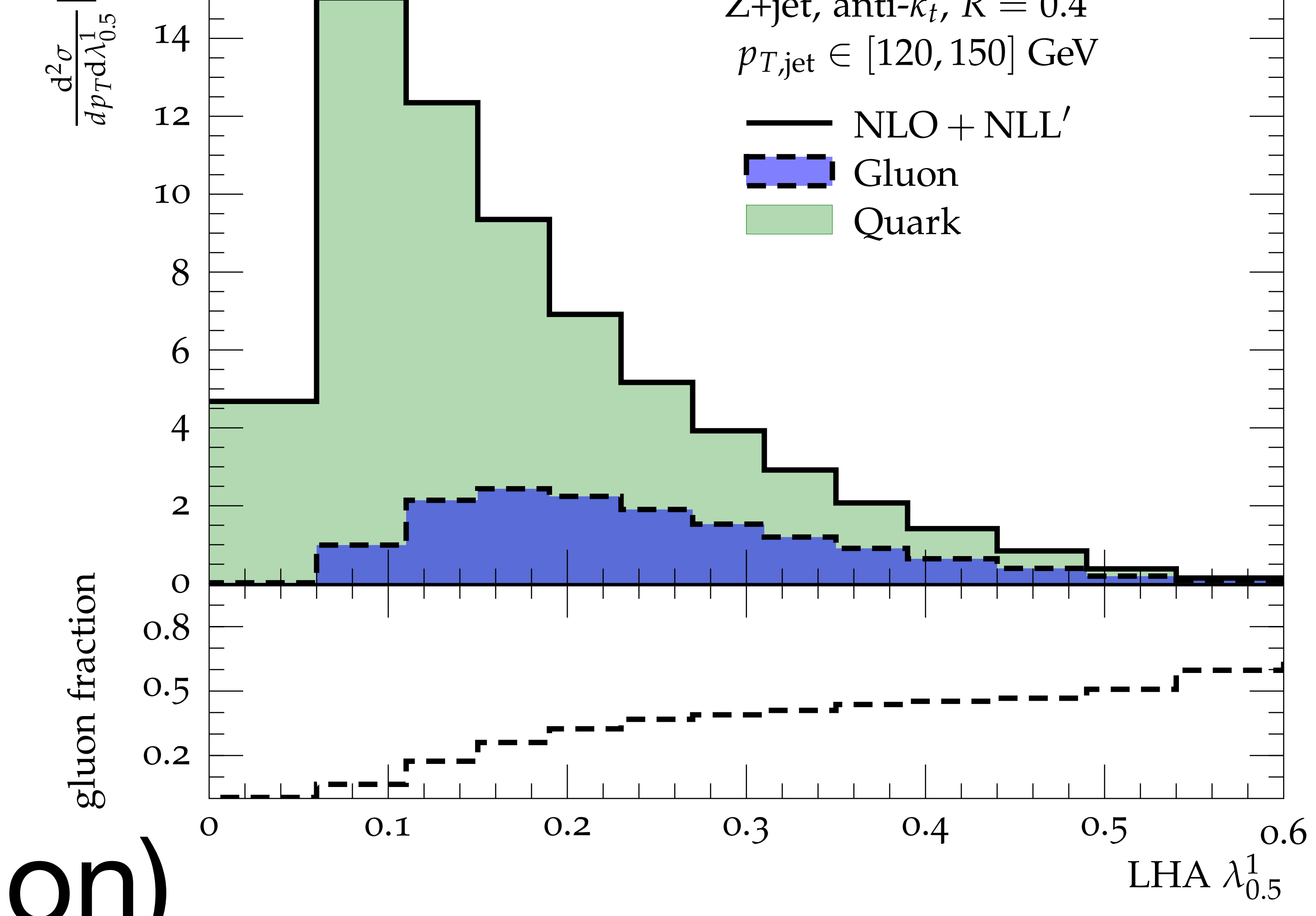




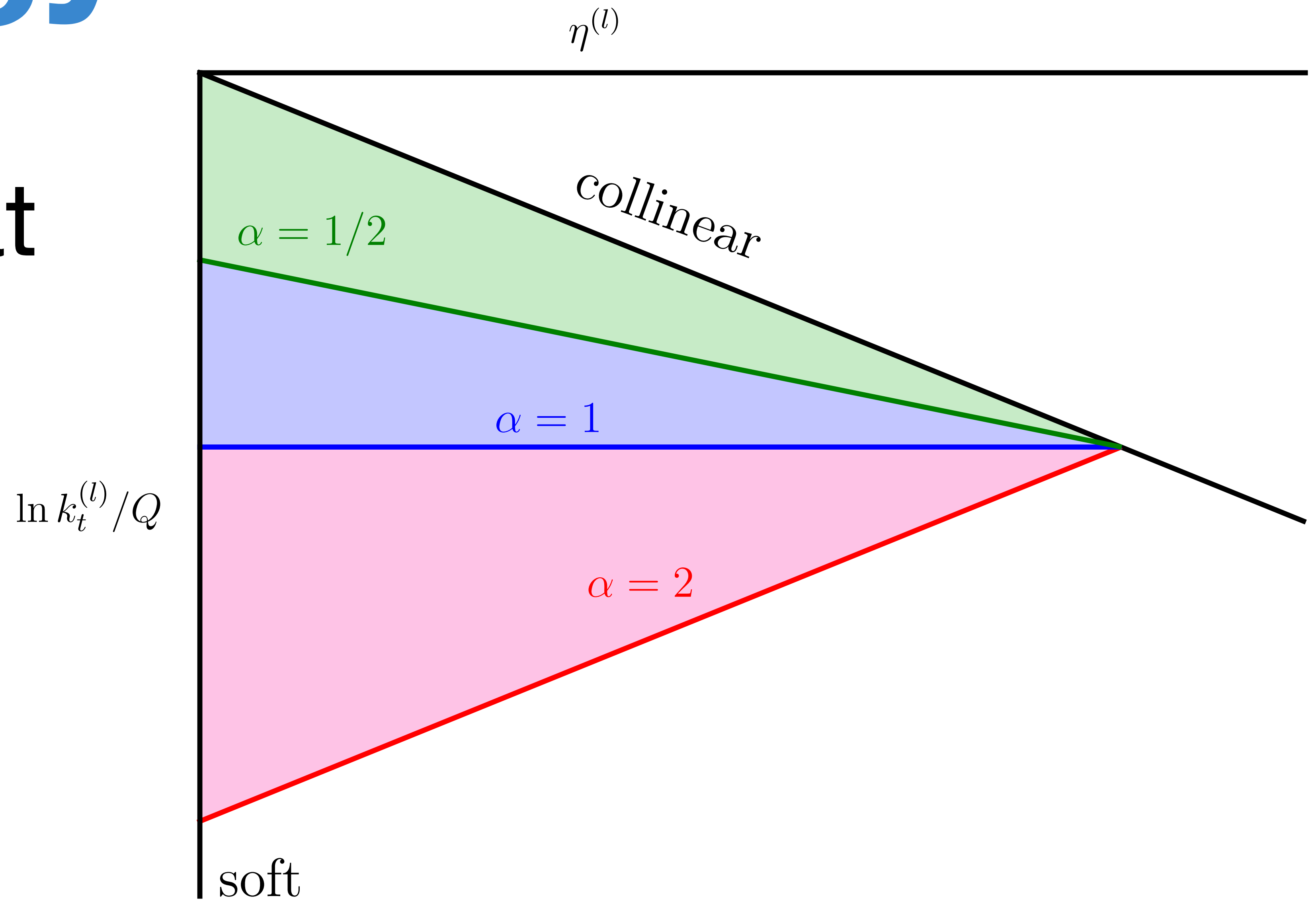
Event/Jet Shapes as taggers

- tagging in experiment (from a theorists perspective):
  - look for displaced vertex, identify with decaying hadron (~ heavy parton)
  - improvable with various techniques from machine. learning etc.
  - application to H decays → just count b tagged jets
- great performance, but often hard to gain theoretical understanding
  - theory study with event or jet shapes → not necessarily most performant taggers, but accurate understanding possible (i.e. well defined FO, resummation)
  - can we apply this to H decays (challenge: without any vertex info)?





Event Shapes - Fractional Energy Correlations



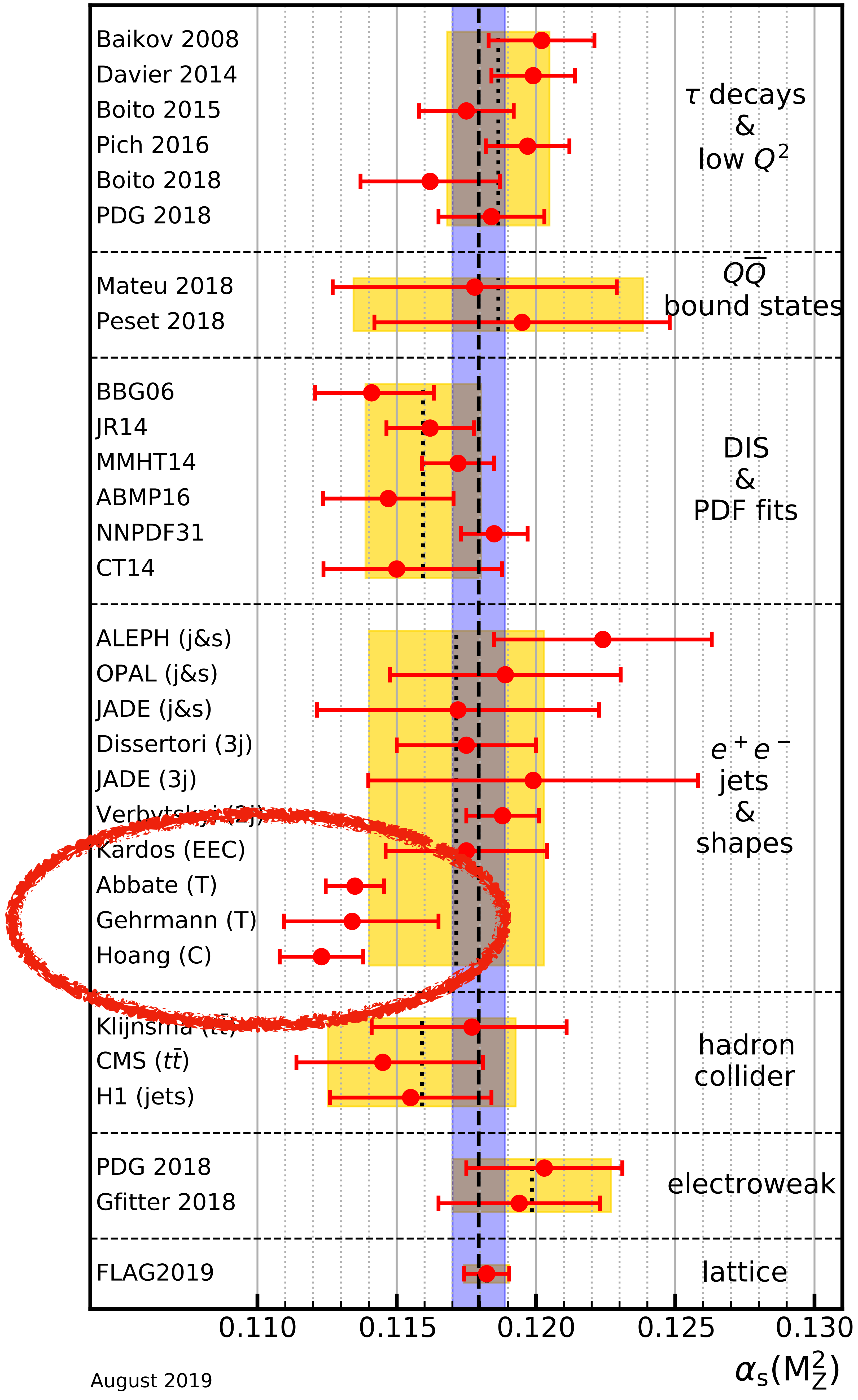
- class of observables, typically normalised such that
  - $FC_x \to 0 \Rightarrow$ pencil-like event (little radiation),
  - $FC_x \to FC_x^{\max} < 1 \Rightarrow$ spherical event (a lot of radiation)

$$\mathrm{FC}_x \equiv \sum_{i \neq j} \frac{E_i E_j |\sin\theta_{ij}|^x (1 - |\cos\theta_{ij}|)^{1-x}}{(\sum_i E_i)^2} \Theta\left[(\vec{q}_i \cdot \vec{n}_T)(\vec{q}_j \cdot \vec{n}_T)\right]$$

- parameter x determines weight of collinear emissions
- analogous to angularities at the LHC ($\alpha \sim 2 - x$)

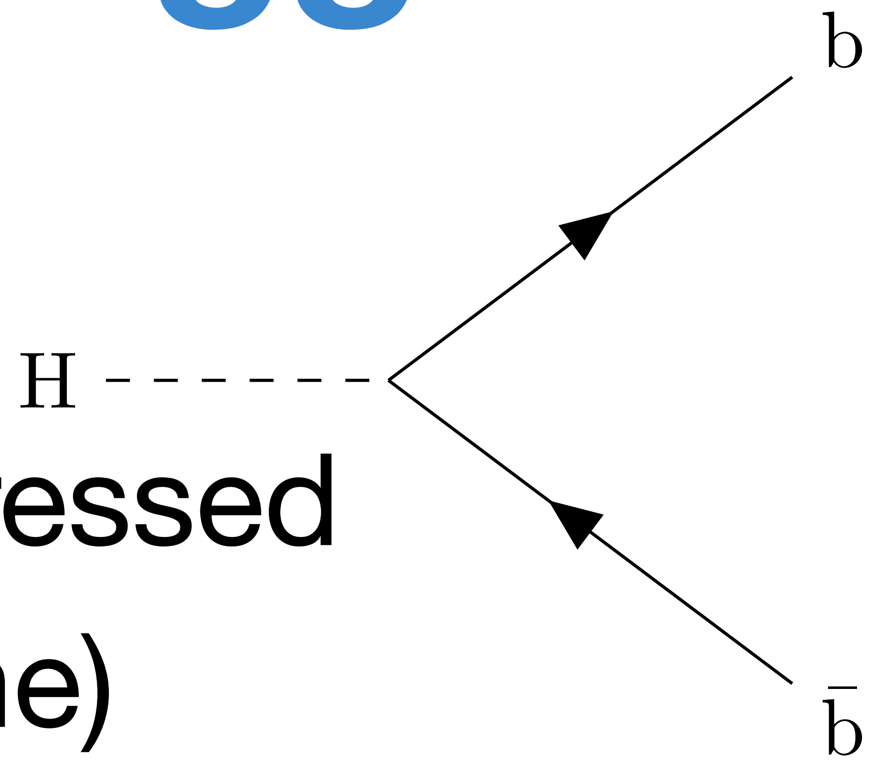
Event Shapes and α_s

- one traditional way to extract strong coupling constant:
  - high accuracy (NNLO+NNLL) of event shapes (Thrust, C-Parameter etc.) fitted to LEP data at the Z-pole
  - simple 1 or 2 parameter fit, can be pushed by theorists long after experiments are done

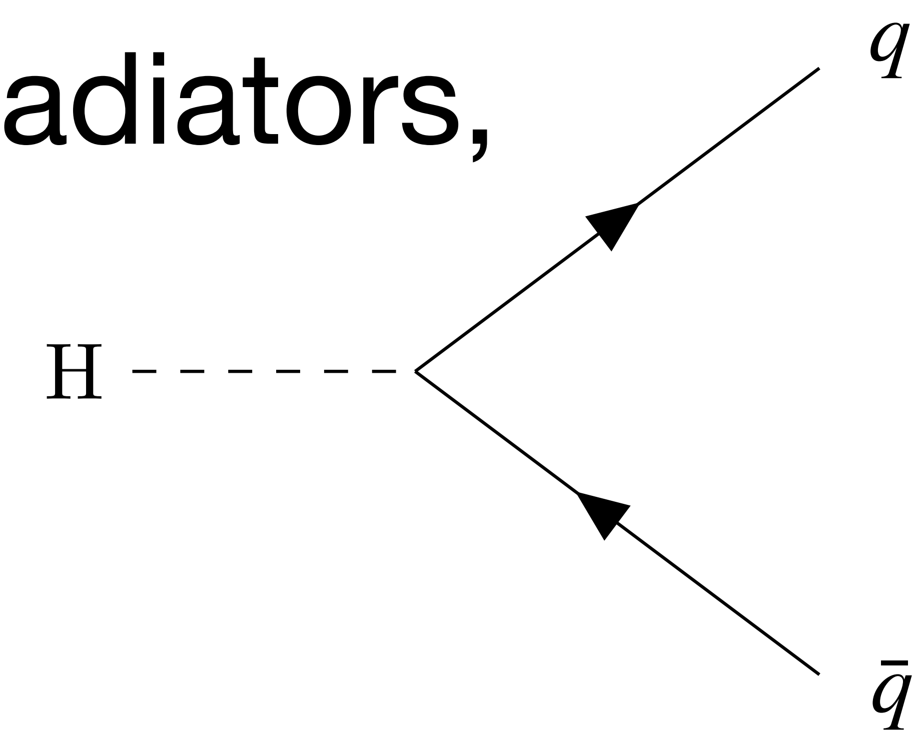


Event Shapes in Higgs Decays

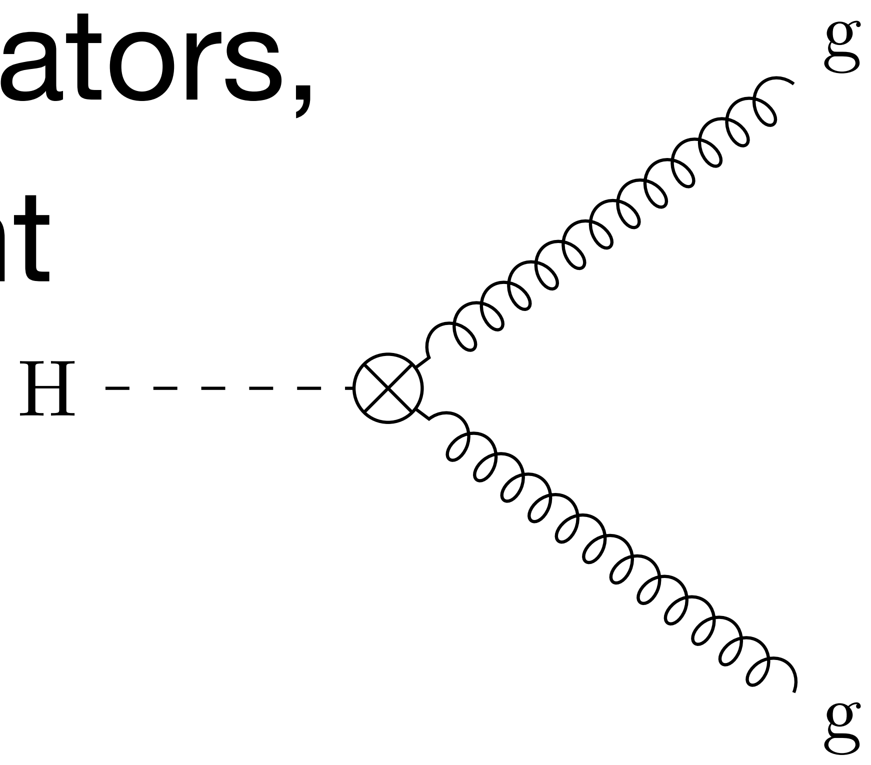
- naive picture
  - b-quarks: radiation suppressed due to masses (dead-cone)

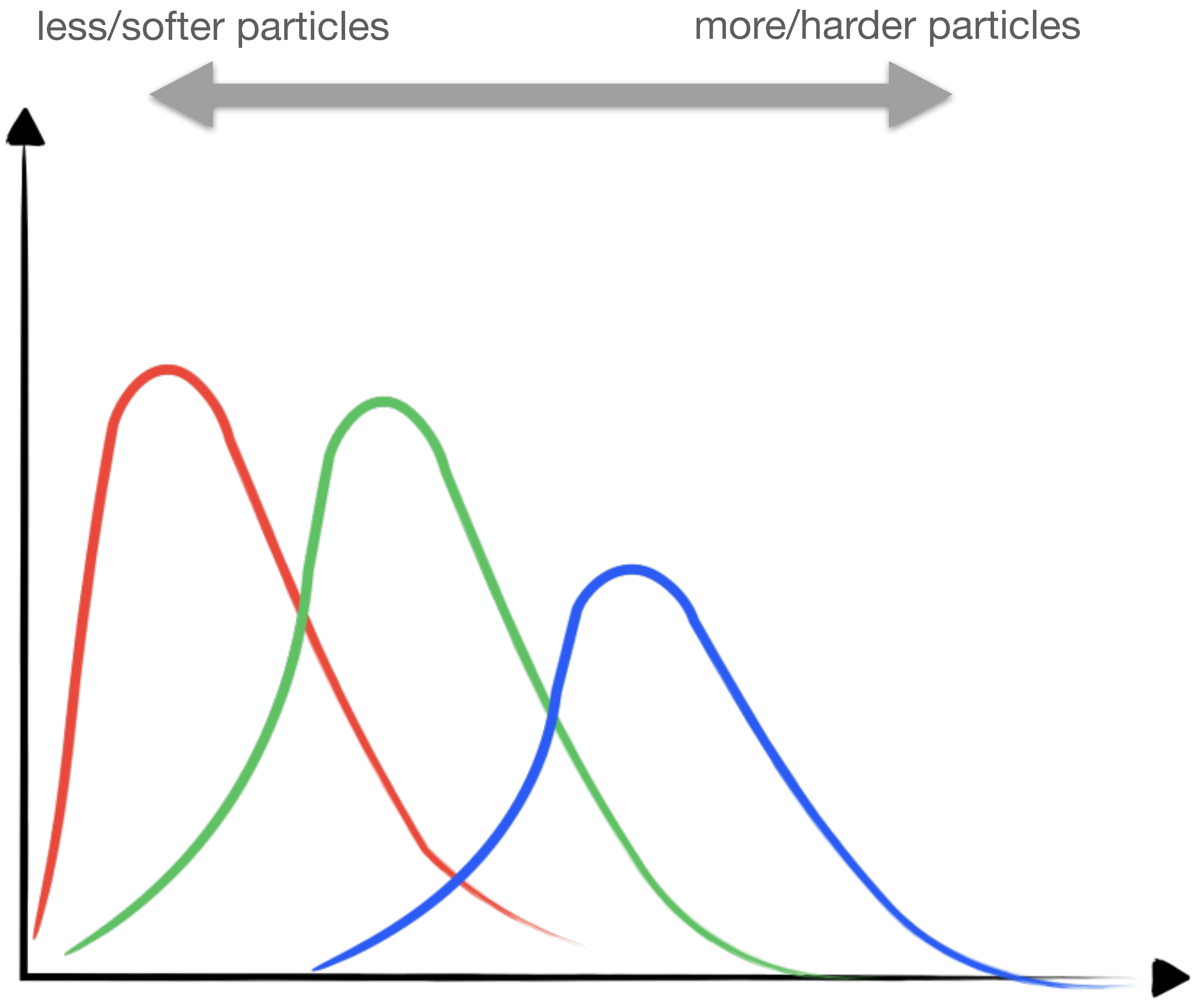


  - light quarks: massless radiators, collinear enhancement $\propto C_F = 4/3$



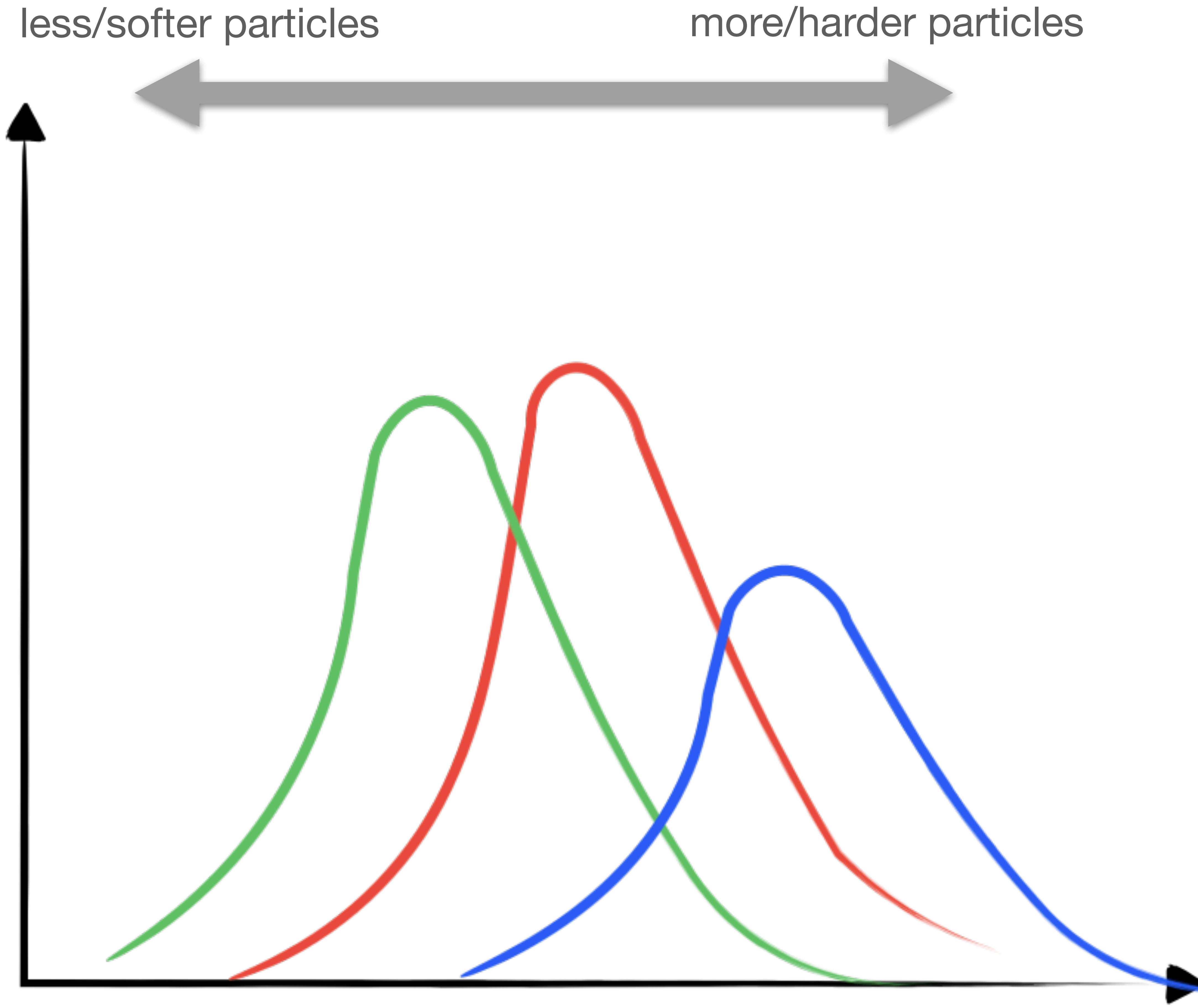
  - gluons: massless radiators, collinear enhancement $\propto C_A > C_F$





Event Shapes in Higgs Decays

- naive picture, at hadron level
  - b-quarks: radiation suppressed due to masses (dead-cone), **high mass decay**
  - light quarks: massless radiators, collinear enhancement $\propto C_F = 4/3$
  - gluons: massless radiators, collinear enhancement $\propto C_A > C_F$



Effect of Yukawa couplings

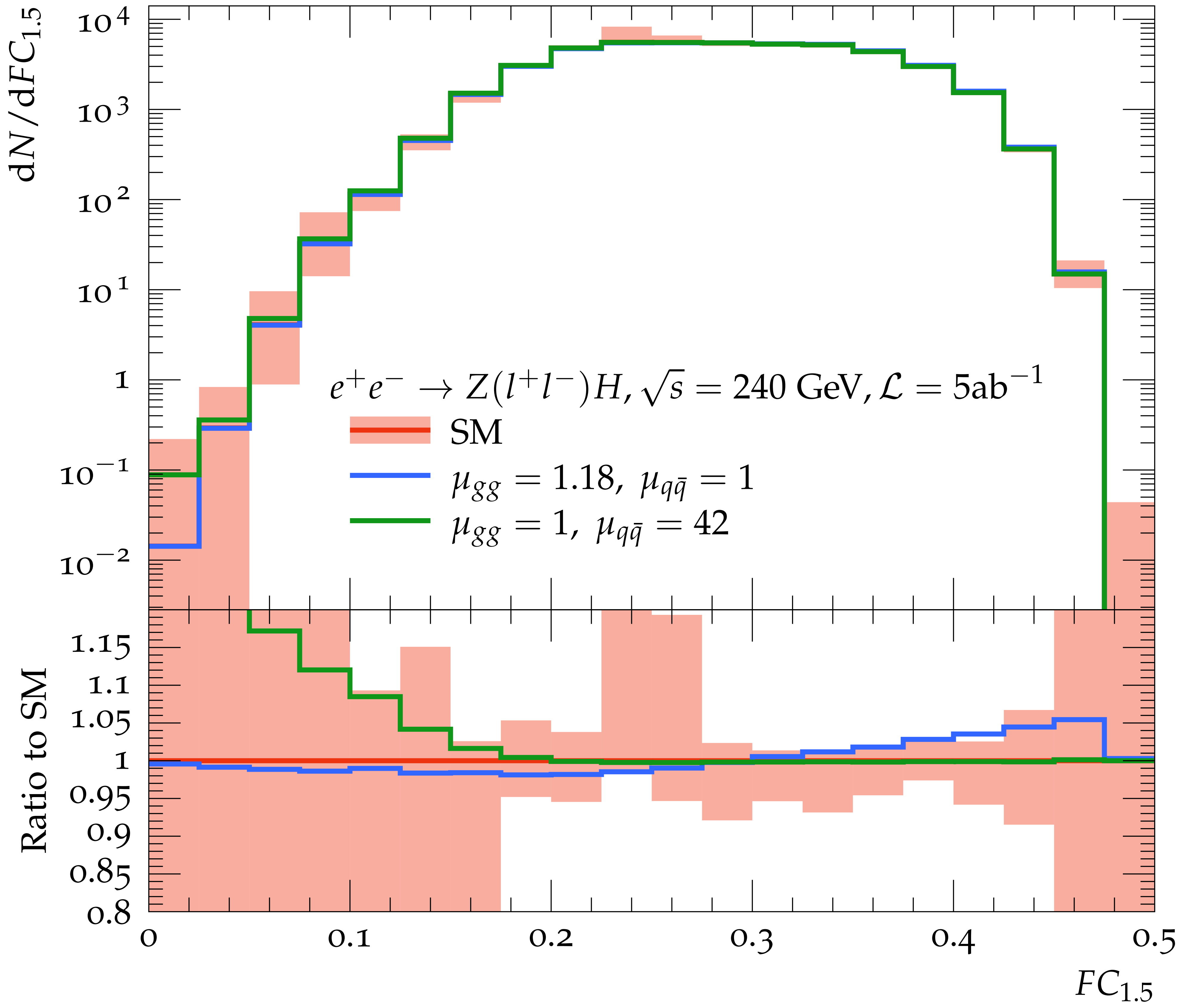
- overall distribution is sum over hadronic decay channels

$$\frac{d\sigma}{dv} = \sum_{i\in\{q\bar{q},c\bar{c},b\bar{b},gg,WW,ZZ\}} \mu_i \frac{d\sigma_i}{dv} + \frac{d\sigma_{ZZ}}{dv}$$

- can determine relative contribution of each channel (here 2 parameters, $\mu_{gg}, \mu_{q\bar{q}}$)

- boundary condition

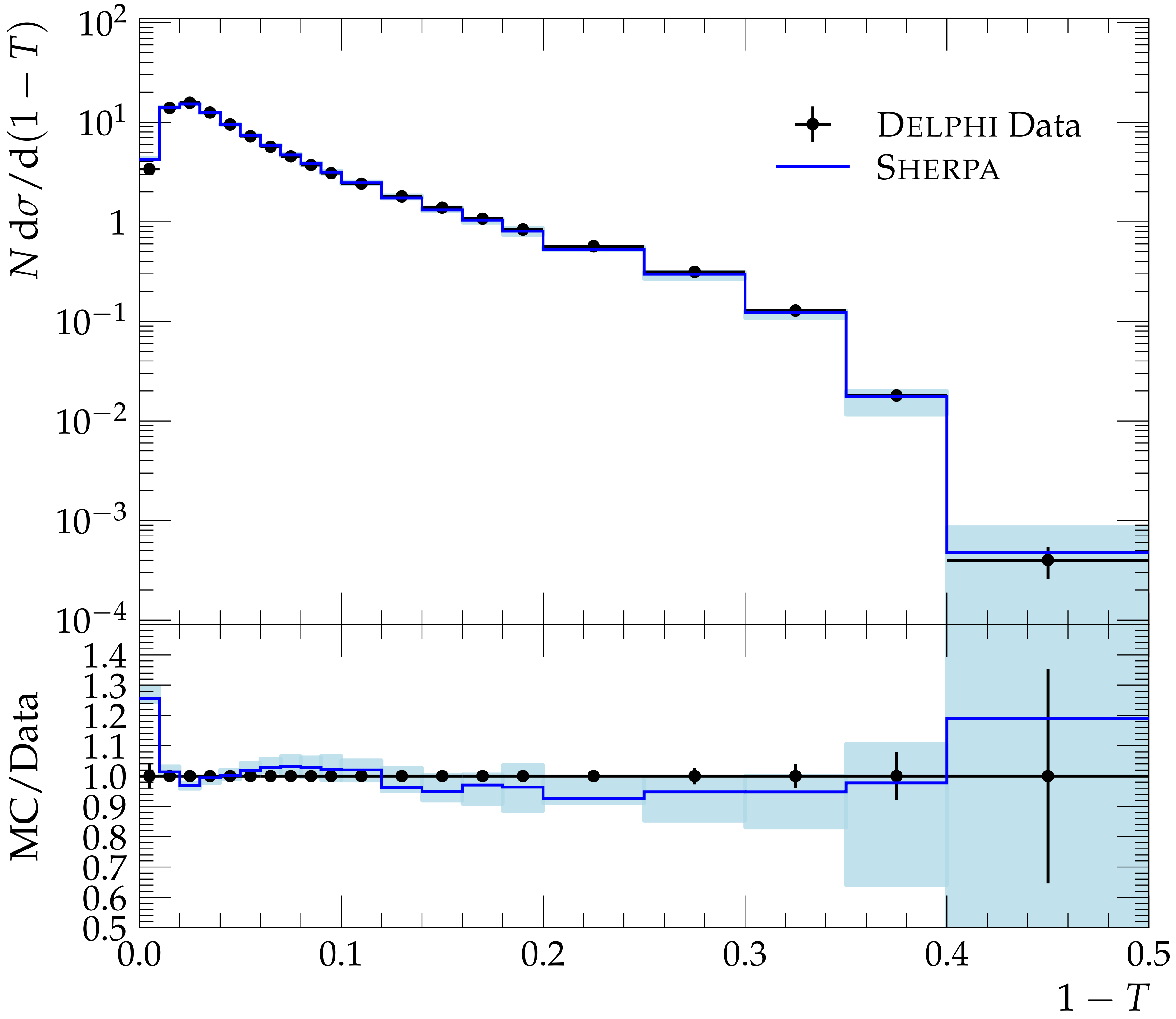
$$\mu_{b\bar{b}} = 1 - (\mu_{gg} - 1)\frac{\sigma_{gg}}{\sigma_{b\bar{b}}} - (\mu_{q\bar{q}} - 1)\frac{\sigma_{q\bar{q}}}{\sigma_{b\bar{b}}}$$



Study Setup

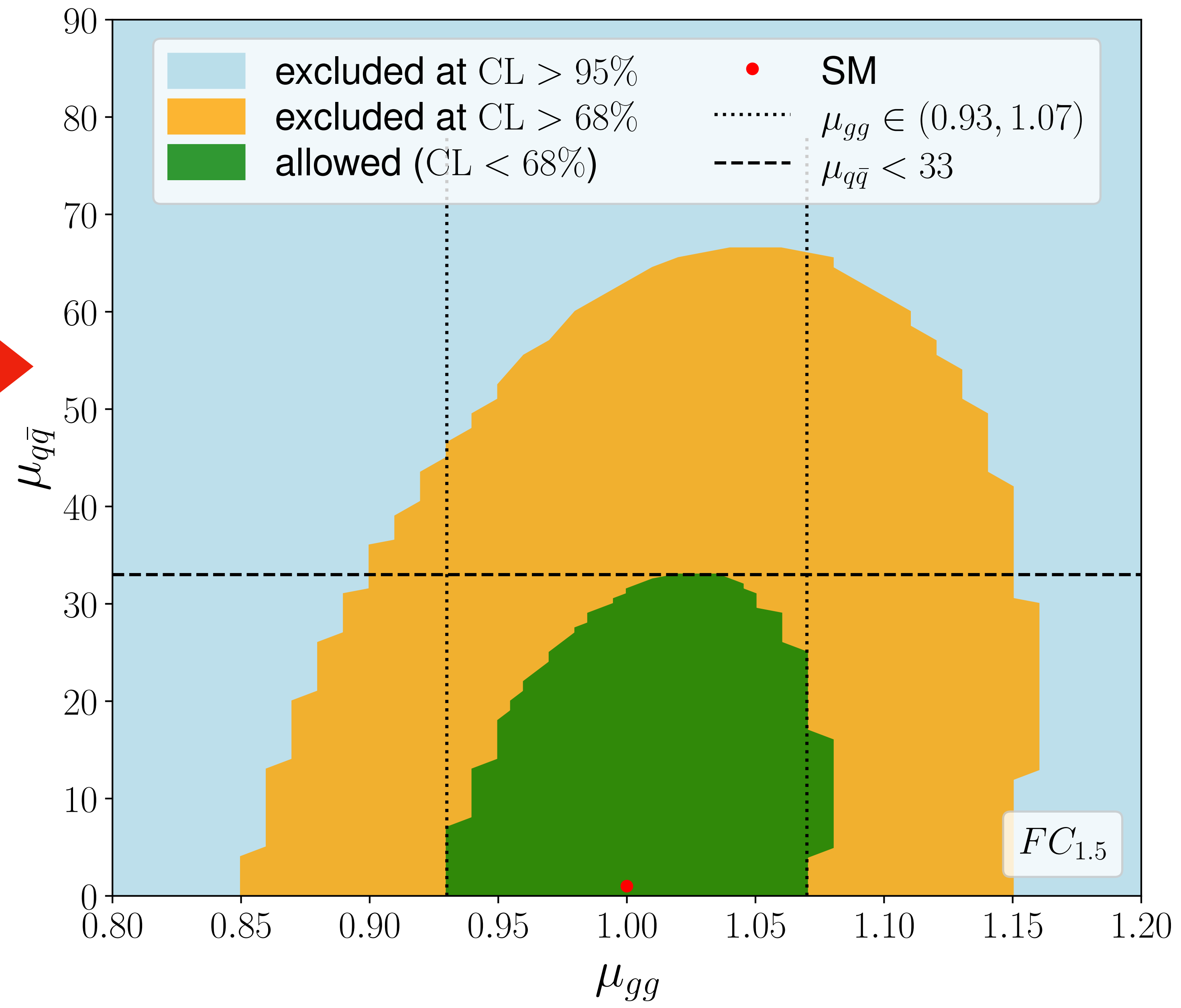
Sherpa 3.0.0
now released,
see talk by
F. Siegert

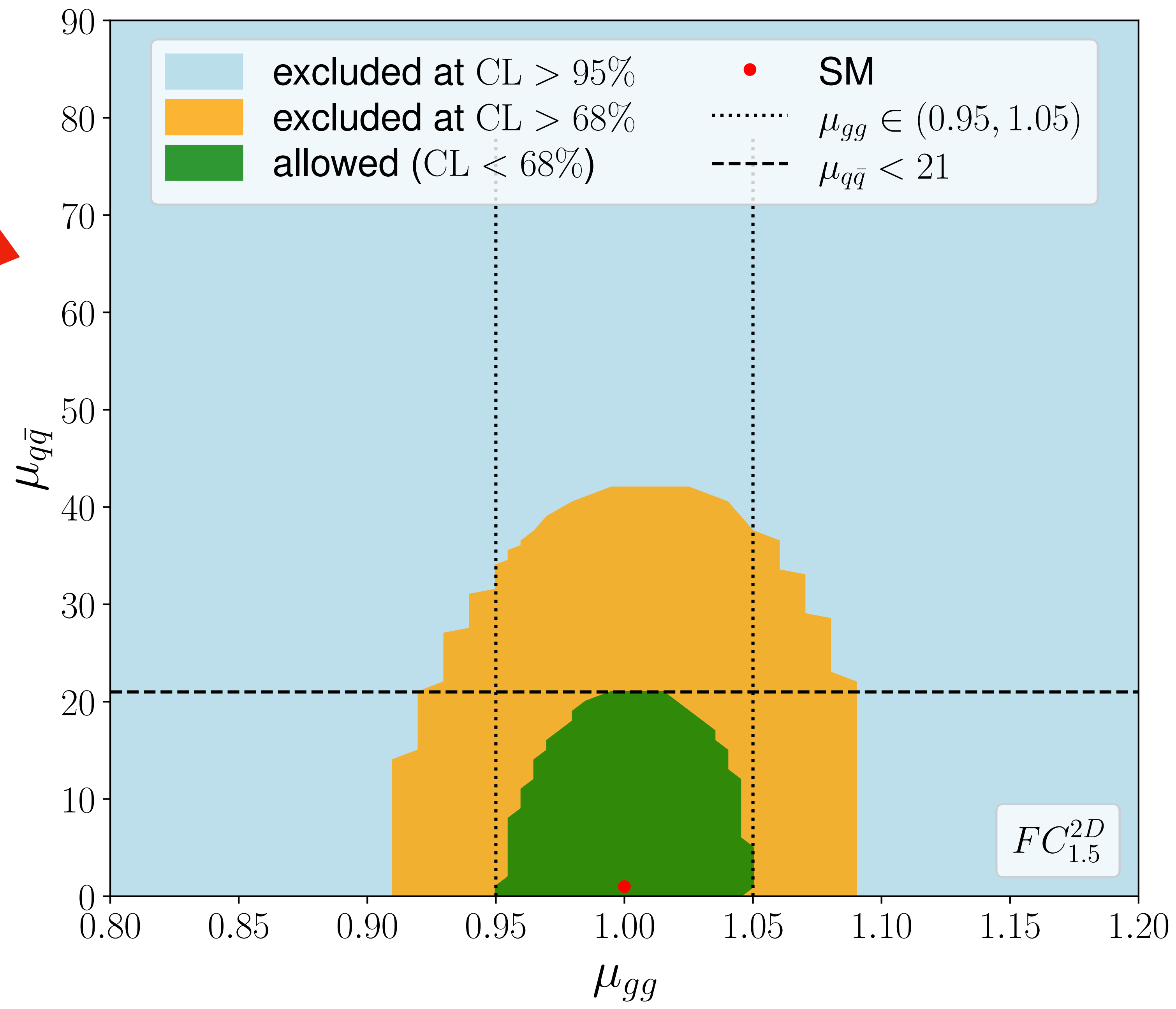
- run $e^+e^- \to HZ(\to l^+l^-)$ at $\sqrt{s} = 240 \text{ GeV}$ with Sherpa $3.0.\alpha$
- assume luminosity of 5ab^{-1}
- follow cuts from [Azzi, Bernet, Botta, et. al. '12]
- fragmentation: tune to LEP data
- replica tunes: well defined variations of fragmentation parameters,
  allow systematic study of uncertainties
  (see also [Knobbe, DR, Schumann '23])



Results

- generally best limit from $FC_{1.5}$ (higher weight on collinear emissions)
- slight improvement from taking into account correlated distribution in each jet
- limit of the same orders as tagging techniques, though not quite competitive (but provides independent methodology)

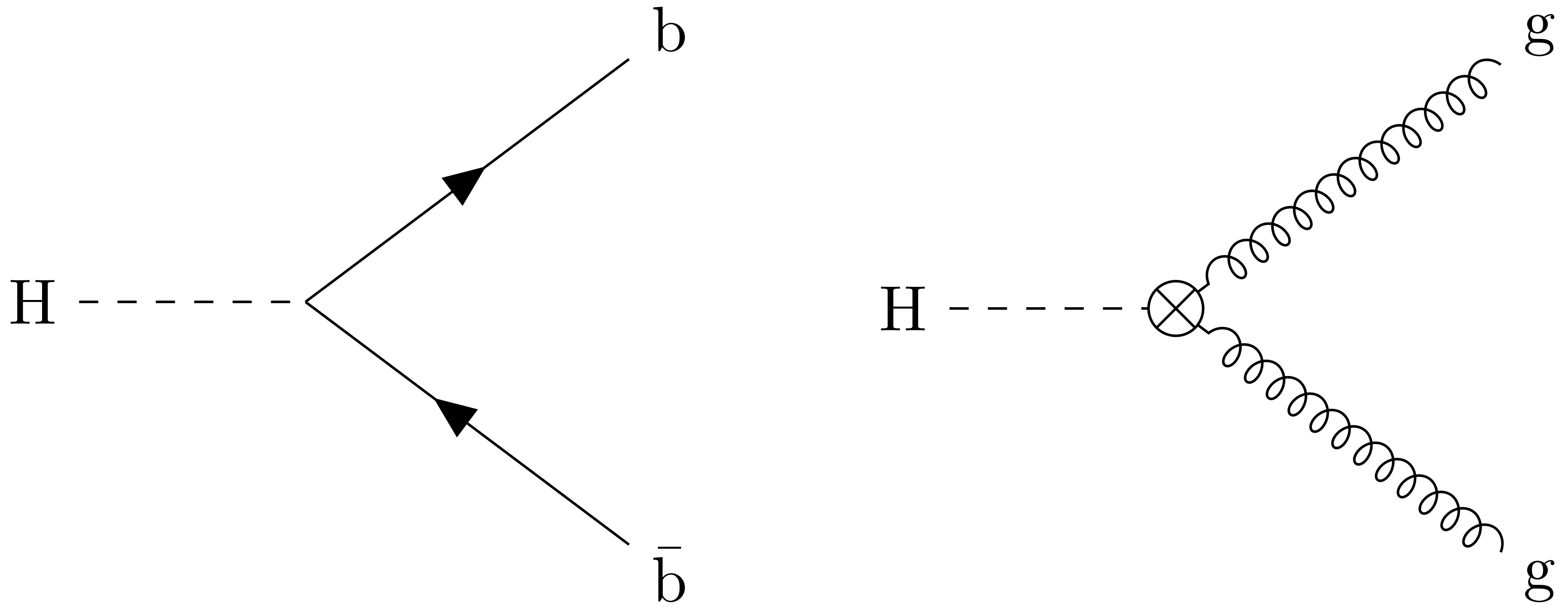




Part II - precision calculations for event shapes

Precision calculations - Fixed Order

- From [Coloretti, Gehrmann-de Ridder, Preuss ’22]: two types of Higgs decays, to (massless) quarks and gluons via effective vertex, implemented in EERAD3



- produces coefficients A, B for IR safe event shape O:

$$\frac{1}{\Gamma^n(s,\mu_R)}\frac{d\Gamma(s,\mu_R,O)}{dO} = \frac{\Gamma^0(\mu_R)}{\Gamma^n(s,\mu_R)}\left(\frac{\alpha_s(\mu_R)}{2\pi}\right)\frac{dA(s)}{dO} + \frac{\Gamma^0(\mu_R)}{\Gamma^n(s,\mu_R)}\left(\frac{\alpha_s(\mu_R)}{2\pi}\right)^2\frac{dB(s,\mu_R)}{dO}$$

- needs addition of all orders (resummed) calculation

Resummation - CAESAR in Sherpa

- CAESAR formalism for soft gluon resummation at NLL [Banfi, Salam, Zanderighi ’04]
- available as implementation in Sherpa [Gerwick, Höche, Marzani, Schumann ’15] [Baberuxki, Preuss, DR, Schumann ’19]
- multiplicative matching (⇒ NLL’ accurate)
- necessary extensions for jet observables… :
  - modified wide angle behaviour [Dasgupta, Khelifa-Kerfa, Marzani, Spannowski ‘12] [Caletti, Fedkevych, Marzani, DR, Schumann, Soyez, Theeuwes ’21] [DR, Caletti, Fedkevych, Marzani, Schumann, Soyez ‘22]
  - non-global logs [Dasgupta, Salam ’01]
- … and for soft drop grooming [Larkoski, Marzani, Soyez, Thaler ’14]
  - CEASAR style formulas available [Baron, DR, Schumann, Schwanemann, Theeuwes ‘20]

Precision Calculations - Resummation with CAESAR

- master formula for rIRC save observable: [Banfi, Salam, Zanderighi ’04]

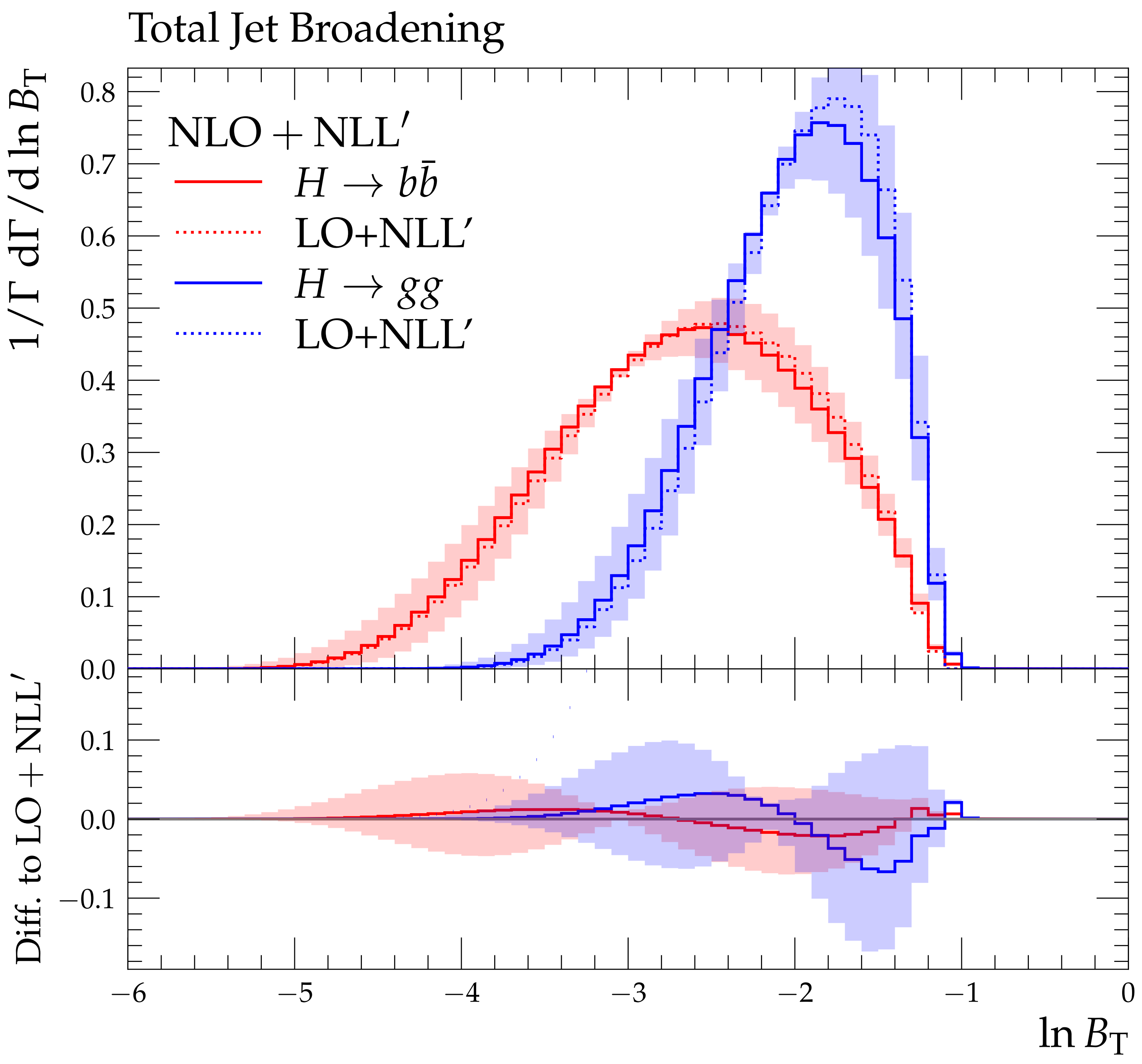
$$\Sigma^{\delta}_{\rm res}(v) = \int d\mathcal{B}_\delta \frac{d\sigma_\delta}{d\mathcal{B}_\delta} \exp\left[-\sum_{l\in\delta} R_l^{\mathcal{B}_\delta}(L)\right] \mathcal{P}^{\mathcal{B}_\delta}(L)\mathcal{S}^{\mathcal{B}_\delta}(L)\mathcal{F}^{\mathcal{B}_\delta}(L)\mathcal{H}^{\delta}(\mathcal{B}_\delta)$$

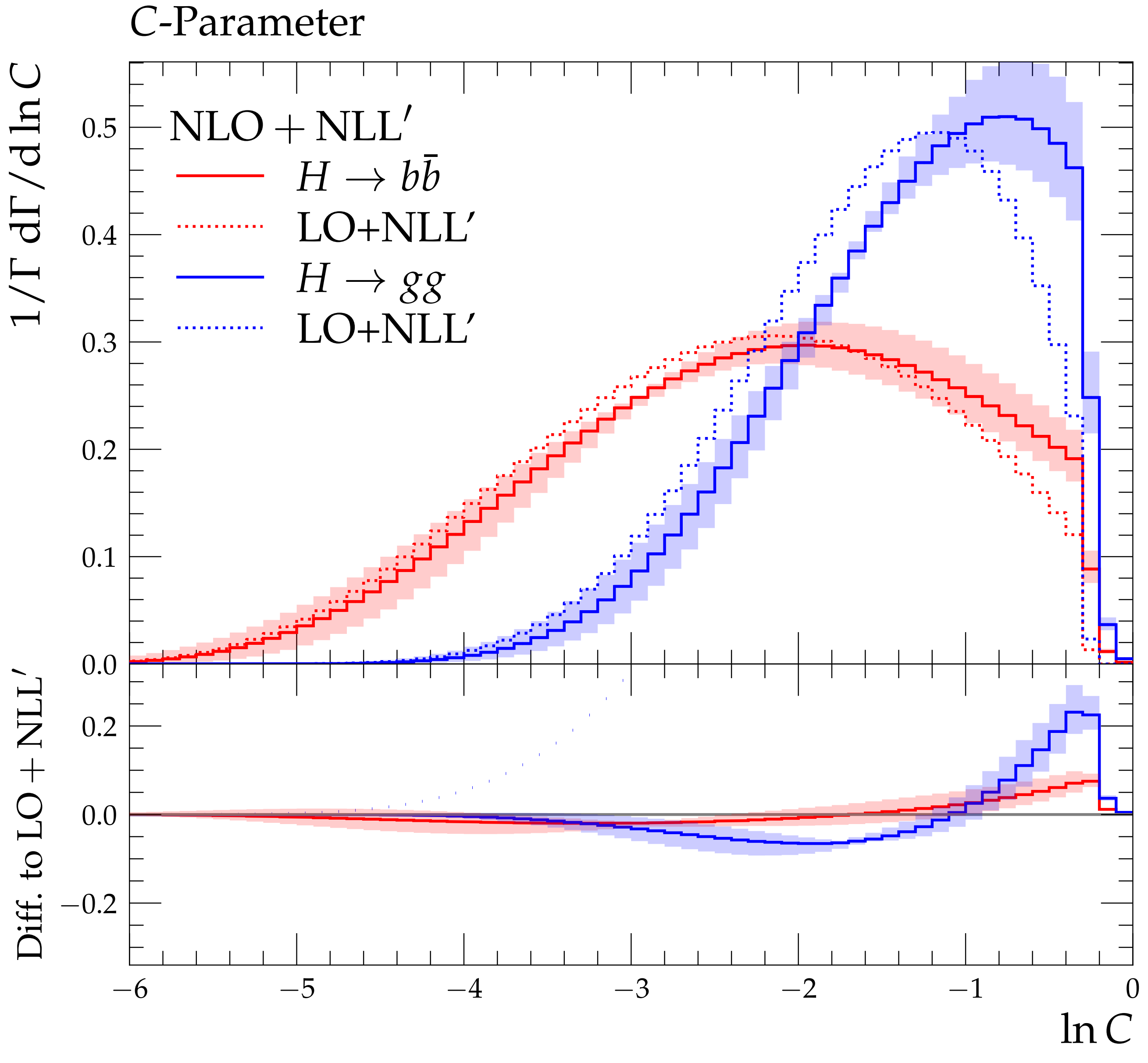
- ingredients known analytically in our cases
- matching: $\Sigma_{\rm matched} = \Sigma_{\rm res}\left(1 + \frac{\Sigma^{(1)}_{\rm fo} - \Sigma^{(1)}_{\rm res}}{\sigma^{(0)}} + \frac{\Sigma^{(2)}_{\rm fo} - \Sigma^{(2)}_{\rm res}}{\sigma^{(0)}} - \frac{\Sigma^{(1)}_{\rm res}}{\sigma^{(0)}}\frac{\Sigma^{(1)}_{\rm fo} - \Sigma^{(1)}_{\rm res}}{\sigma^{(0)}}\right)$
- here for the first time, handle external (to Sherpa) fixed order calculation, given in terms of A, B distributions for matching:

$$\frac{1}{\Gamma^n(s,\mu_{\rm R})}\frac{{\rm d}\Gamma(s,\mu_{\rm R},O)}{{\rm d}O} = \frac{\Gamma^0(\mu_{\rm R})}{\Gamma^n(s,\mu_{\rm R})}\left(\frac{\alpha_{\rm s}(\mu_{\rm R})}{2\pi}\right)\frac{{\rm d}A(s)}{{\rm d}O} + \frac{\Gamma^0(\mu_{\rm R})}{\Gamma^n(s,\mu_{\rm R})}\left(\frac{\alpha_{\rm s}(\mu_{\rm R})}{2\pi}\right)^2\frac{{\rm d}B(s,\mu_{\rm R})}{{\rm d}O}$$

Results

- example: jet/hemisphere broadening
- expected separation between quark and gluon final states
    - gluons dominate much “harde configurations than quarks
- expected “Sudakov shoulder” for observables like C-parameter





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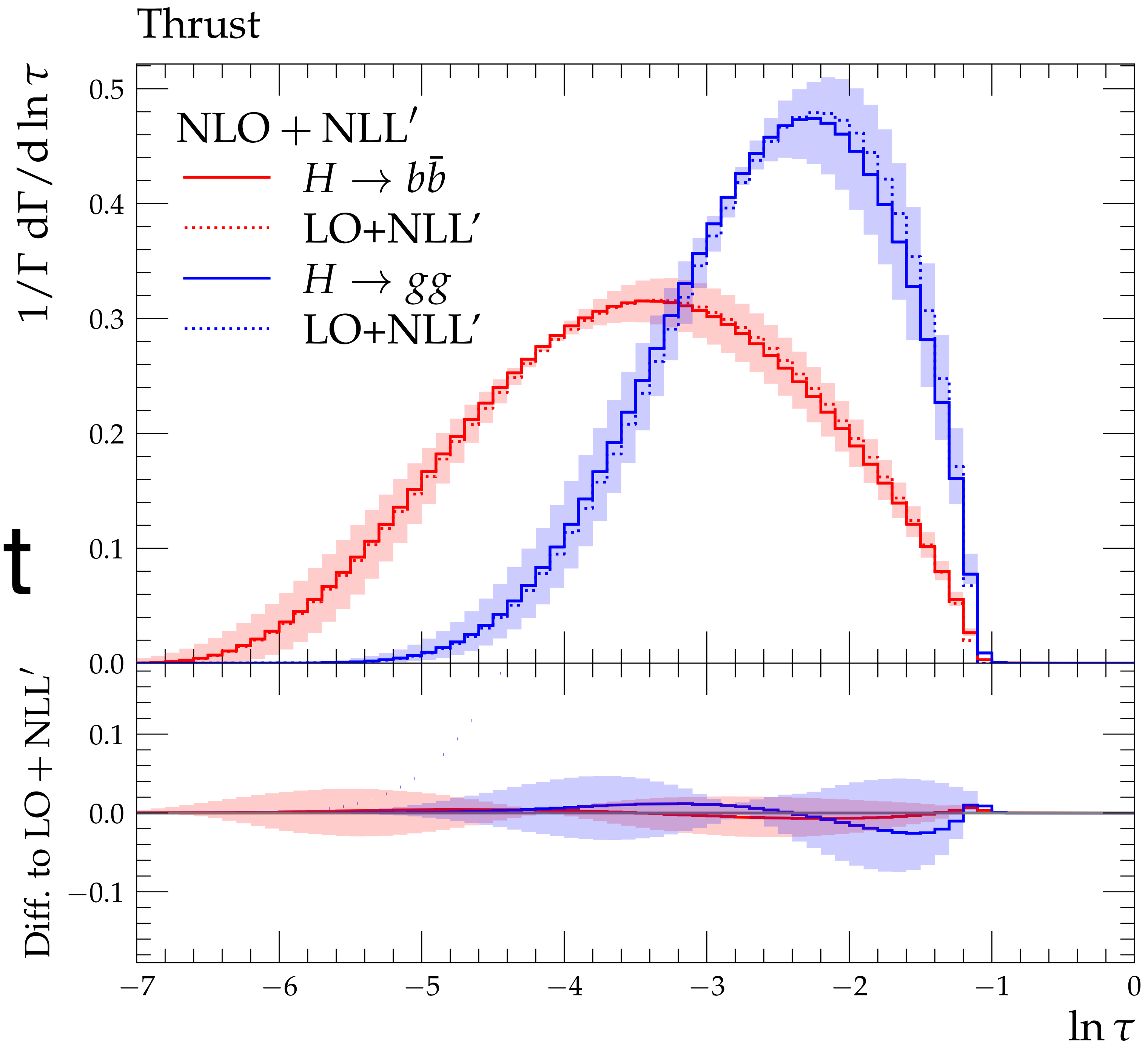
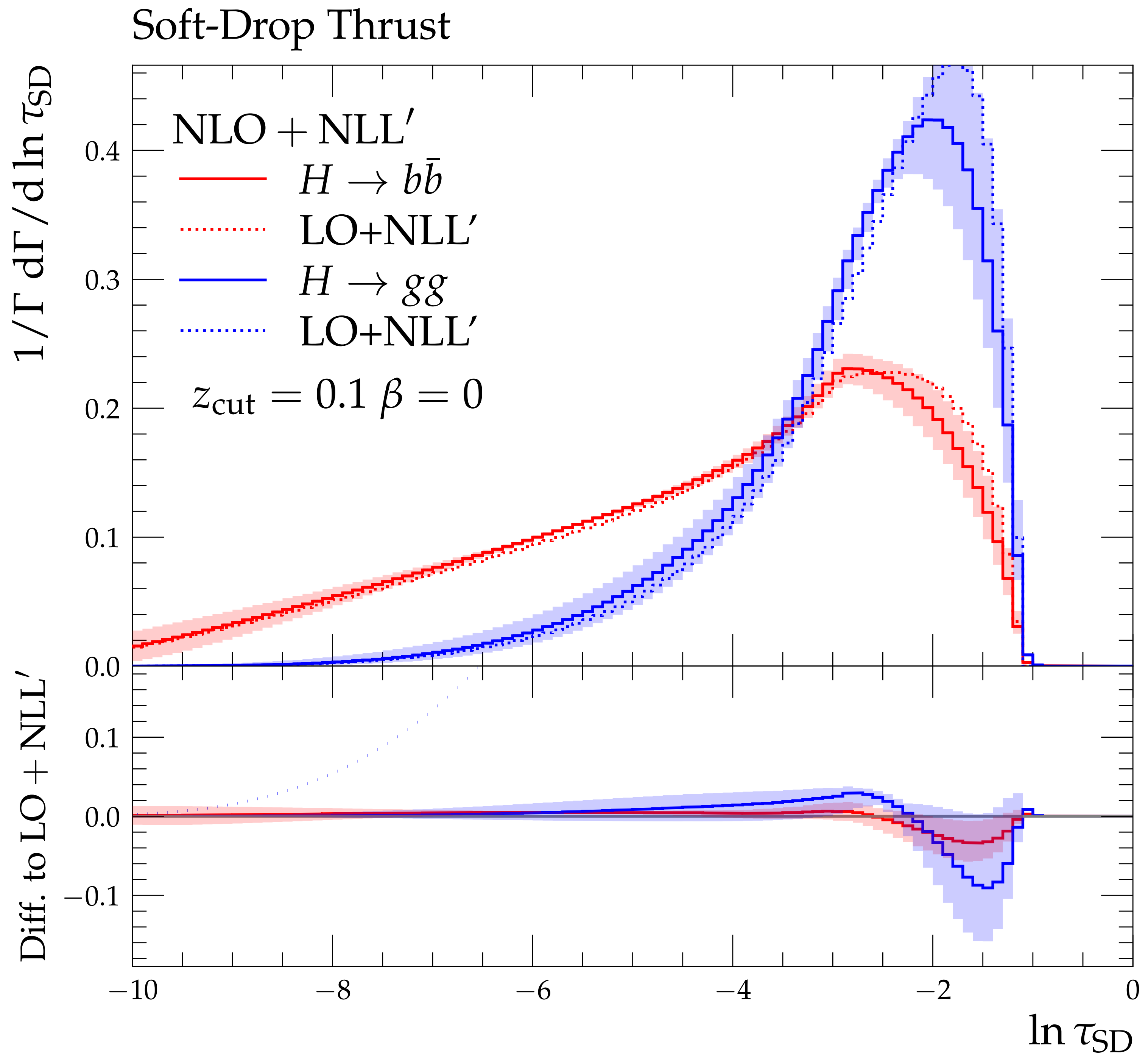
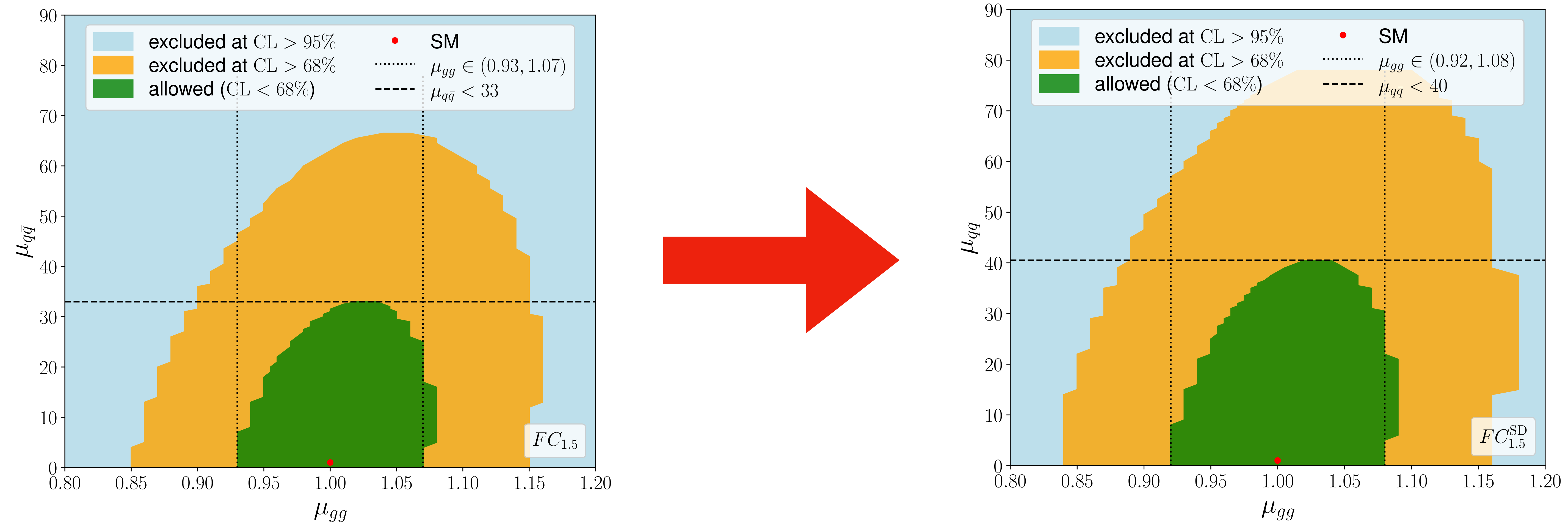




- example: Thrust and Soft-Drop groomed thrust
- no grooming: well separated distributions
- with grooming: overlap of Sudakov peak for gluons with transition region of quark distribution, possible explanation for limited additional separation power



Summary

- Event shapes as theoretically well controllable taggers
  - applicable to hadronic Higgs decays
  - enables measurement with minimal (possibly without) modelling input
  - strongest limits for $FC_{1.5}$ observable, in particular 2D version
- accompanied by precision calculation of event shapes
  - NLO+NLL' almost trivially available
  - NNLO+NNLL in principle available
- outlook: studies with next generation of NLL dipole showers (see for example Alaric talk on Wednesday)