Exclusive description on hadronic decays of the Higgs boson

Jun Gao
INPAC, Shanghai Jiao Tong University

based on 2101.08916 with YaLu Hu, ChuanLe Sun, Xiao-Min Shen

The 3rd Workshop of the CEPC Physics, Detector and Software, Yangzhou

April 16, 2021

上海交通大學 Shanghai Jiao Tong University
SHANGHAI JIAO TONG UNIVERSITY Department of Physics
INPAC INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

Higgs boson production and decays

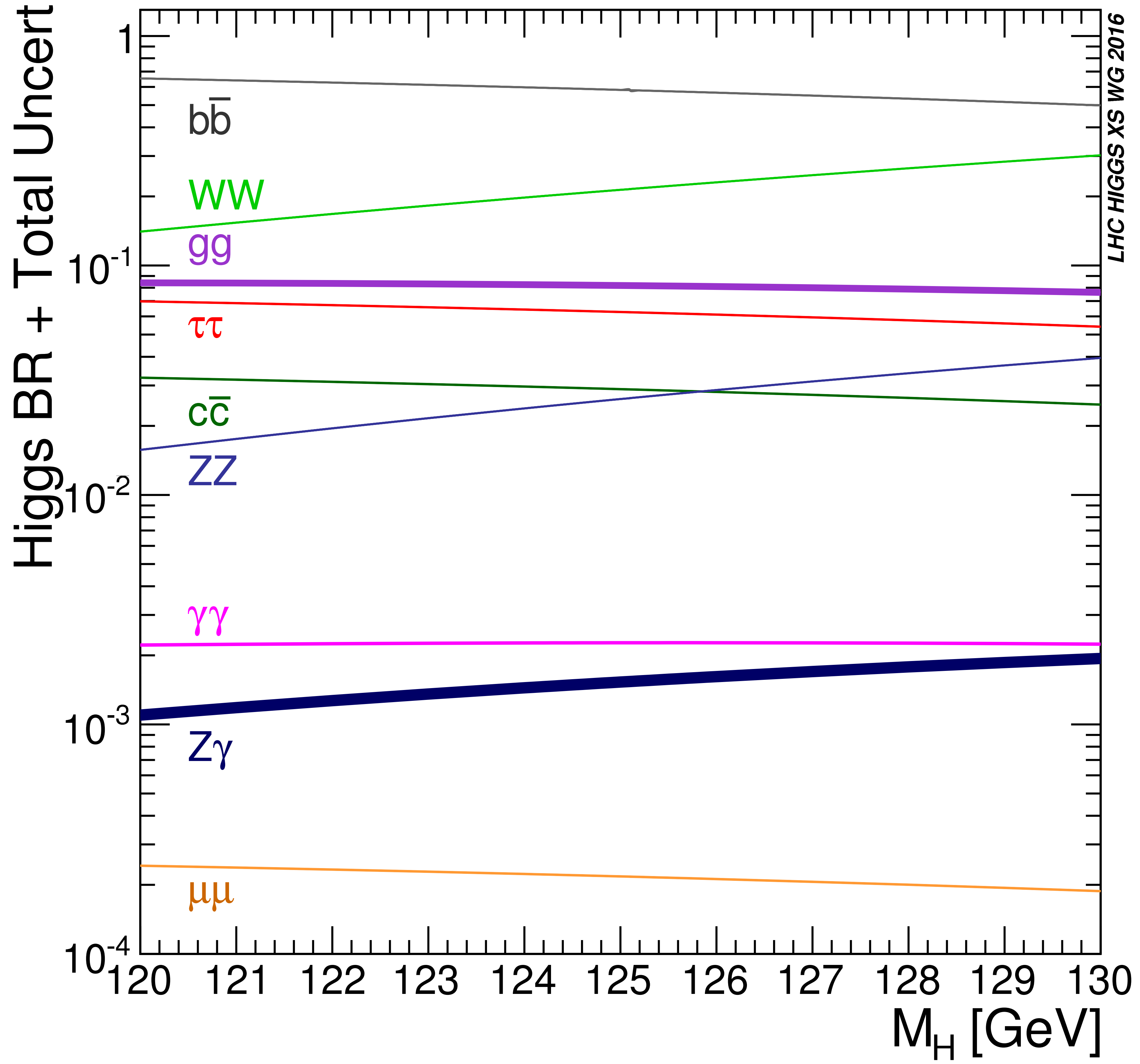
- The tiny width ($\Gamma/M \sim 3\times10^{-5}$) and 0-spin of the Higgs boson ensure a simple factorization of production and decay of the Higgs boson in most theory calculations

[Davies, Steinhauser, Wellmann, 2017]

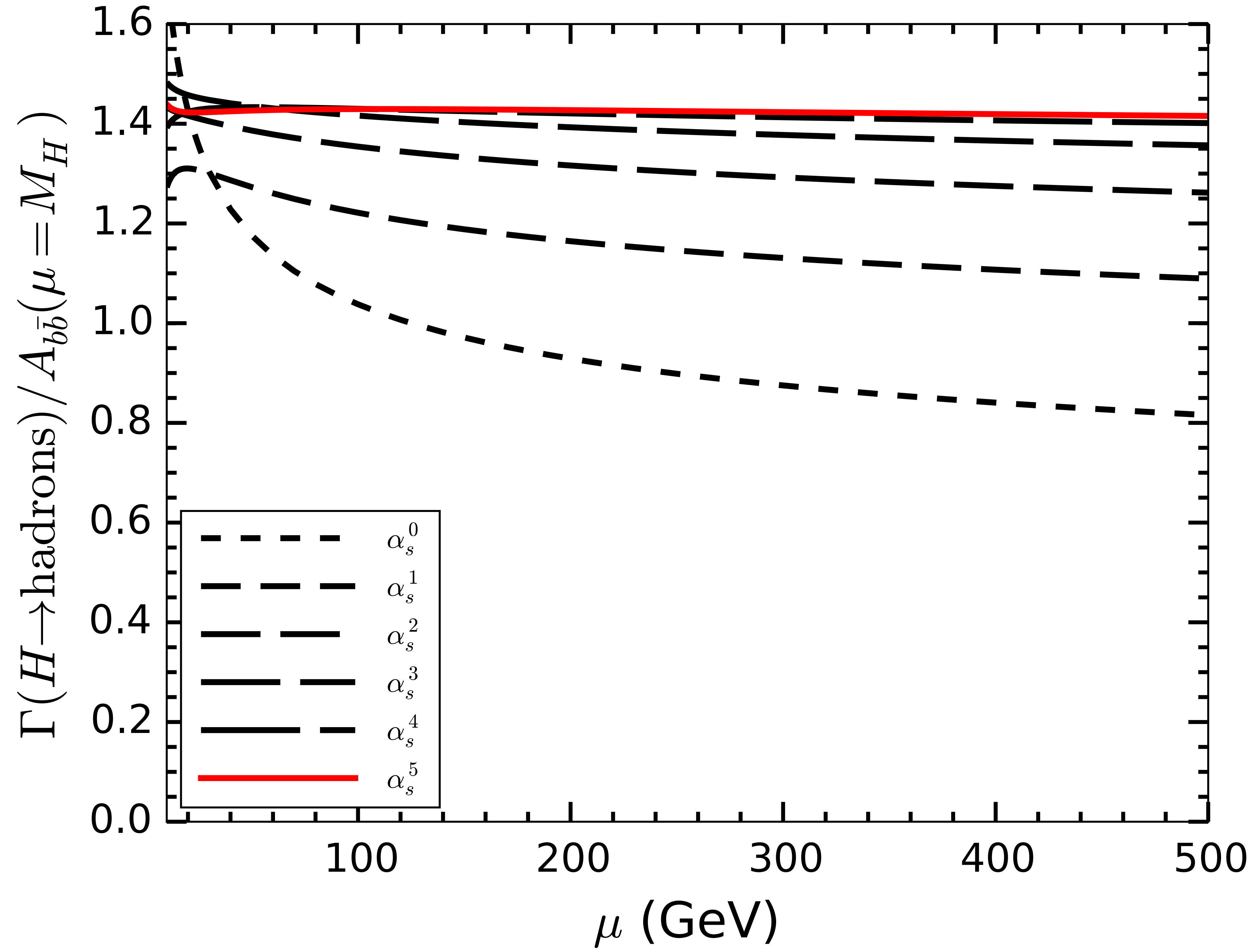
[LHCHXSWG]

[Herzog, Ruijl, Ueda, Vermaseren, Vogt, 2017]

decay branching ratios vs. mass



hadronic width of the Higgs boson vs QCD scale



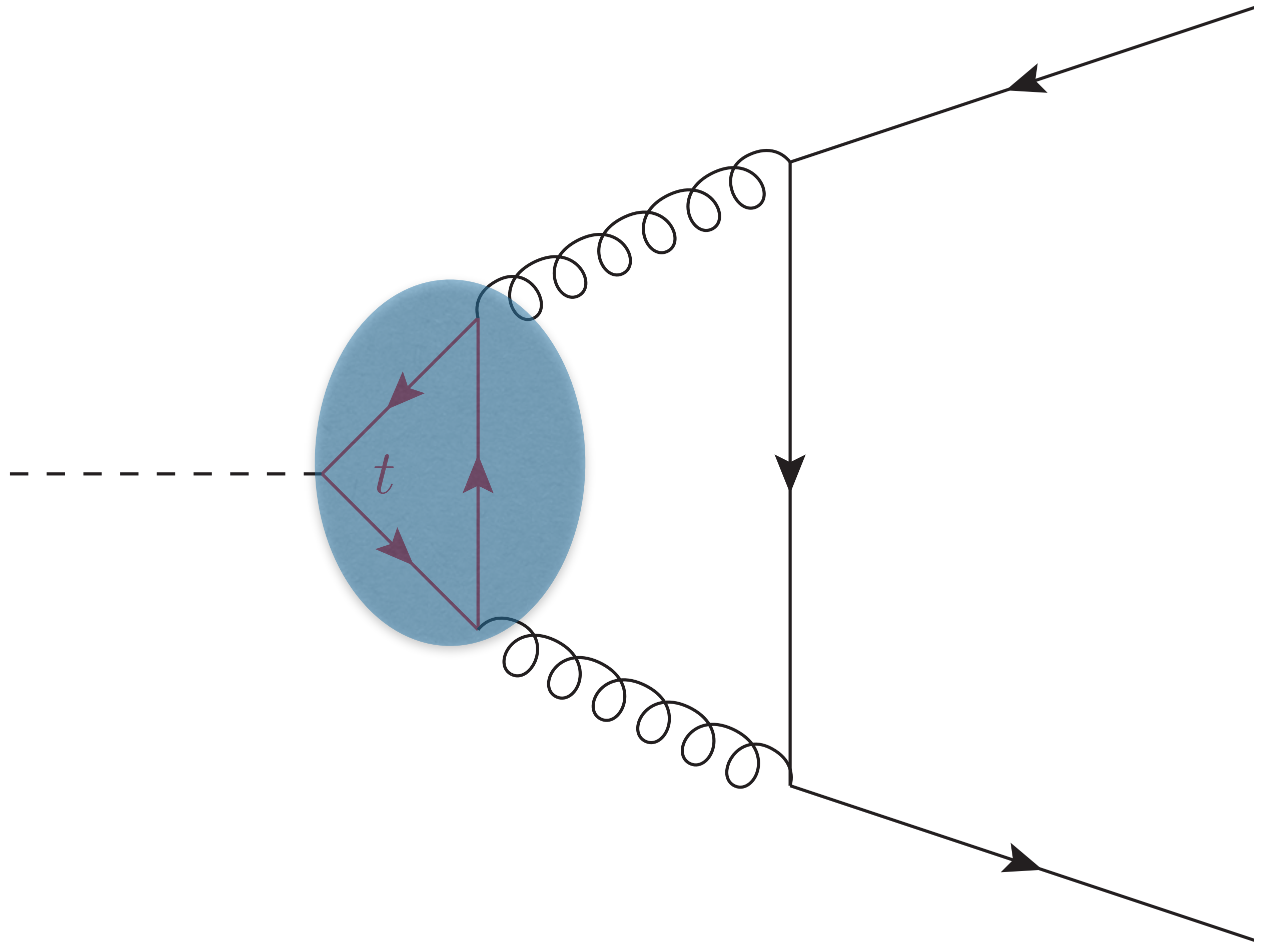
known to $O(\alpha_s^4)$ neglecting certain mass corrections from Higgs effective theory in heavy top limit

Hadronic decays of the Higgs boson

- The Higgs effective theory works well in calculations of hadronic decays of the Higgs boson due to the smaller Higgs mass comparing to the top quark

Higgs effective theory by integrating out top quarks

$$\mathcal{L}_{\text{eff}} = -\frac{H^0}{v^0}\left(C_1[\mathcal{O}'_1] + C_2[\mathcal{O}'_2]\right) + \mathcal{L}'_{\text{QCD}} \qquad \mathcal{O}'_1 = \left(G^{0\prime}_{a,\mu\nu}\right)^2 , \quad \mathcal{O}'_2 = m_b^{0\prime}\bar{b}^{0\prime}b^{0\prime}$$



- operator mixing at higher-orders in perturbation theory
- as a results the separation of bb/cc and gg channels/couplings is not uniquely defined
- when referring H->light quarks (s/u/d), assuming enhanced Yukawa (>>mq/v); mixing with O_1 can be neglected

$$\Gamma(H \to \text{hadrons}) = A_{b\bar{b}}\left[(C_2)^2(1+\Delta_{22}) + C_1C_2\Delta_{12}\right] + A_{gg}(C_1)^2\Delta_{11}$$

Theory uncertainty on Hadronic width

- Theory uncertainty can be under CEPC/FCC-ee precision goal, giving the projected improvement on SM input parameters and some straight forward works on the perturbative calculations

[FCC-ee theory, 1906.05379]

intrinsic/perturbative uncertainty on partial width vs. exp. precision

Partial width	QCD	electroweak	total	available order
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	N^{4}LO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$	–	$< 0.3\%$	$< 0.3\%$	— / NLO
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$	N^{3}LO / NLO
$H \to \gamma\gamma$	$< 0.1\%$	$< 1\%$	$<1\%$	NLO / NLO
$H \to Z\gamma$	$\lesssim 0.1\%$	$\sim 5\%$	$\sim 5\%$	LO / LO
$H \to WW/ZZ \to 4\mathrm{f}$	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	NLO/NLO

decay	intrinsic	FCC-ee prec.
$H \to b\bar{b}$	$\sim 0.2\%$	$\sim 0.8\%$
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1.4\%$
$H \to \tau^+\tau^-$	$< 0.1\%$	$\sim 1.1\%$
$H \to \mu^+\mu^-$	$< 0.1\%$	$\sim 12\%$
$H \to gg$	$\sim 1\%$	$\sim 1.6\%$
$H \to \gamma\gamma$	$< 1\%$	$\sim 3.0\%$
$H \to Z\gamma$	$\sim 1\%$	~13% for CEPC
$H \to WW$	$\lesssim 0.3\%$	$\sim 0.4\%$
$H \to ZZ$	$\lesssim 0.3\%^\dagger$	$\sim 0.3\%$

due to current available (not complete) QCD and EW corrections

only a few channels need some additional works

Theory uncertainty on Hadronic width

- Theory uncertainty can be under CEPC/FCC-ee precision goal, giving the projected improvement on SM input parameters and some straight forward works on the perturbative calculations

[FCC-ee theory, 1906.05379]

parametric uncertainty on partial width vs. exp. precision

decay	para. m_q (current)	para. α_s (current)	para. M_H (current)	para. m_q (projected)	para. α_s (projected)	para. M_H (projected)	FCC-ee prec.
$H \to bb$	1.4%	0.4%	–	0.6%	$< 0.1\%$	–	$\sim 0.8\%$
$H \to c\bar{c}$	4.0%	0.4%	–	$\sim 1\%$	$< 0.1\%$	–	$\sim 1.4\%$
$H \to \tau^+\tau^-$	–	–	–	–	–	–	$\sim 1.1\%$
$H \to \mu^+\mu^-$	–	–	–	–	–	–	$\sim 12\%$
$H \to gg$	$< 0.2\%$	3.7%	–		0.5% (0.3%)	–	$\sim 1.6\%$
$H \to \gamma\gamma$	$< 0.2\%$	–	–	–	–	–	$\sim 3.0\%$
$H \to Z\gamma$	–	–	2.1%	–	–	$\sim 0.1\%$	~13% for CEPC
$H \to WW$	–	–	2.6%	–	–	$\sim 0.1\%$	$\sim 0.4\%$
$H \to ZZ$	–	–	3.0%	–	–	$\sim 0.1\%$	$\sim 0.3\%$

current input parameters

$$\delta\alpha_s = 0.0015 \text{ and } \delta m_b = 0.03 \text{ GeV}$$

$$\delta m_c = 0.025 \text{ GeV}$$

$$\delta m_t = 0.85 \text{ GeV and } \delta M_H = 0.24 \text{ GeV}$$

projected input parameters

$$\delta\alpha_s = 0.0002 \text{ and } \delta m_b = 13 \text{ MeV}$$

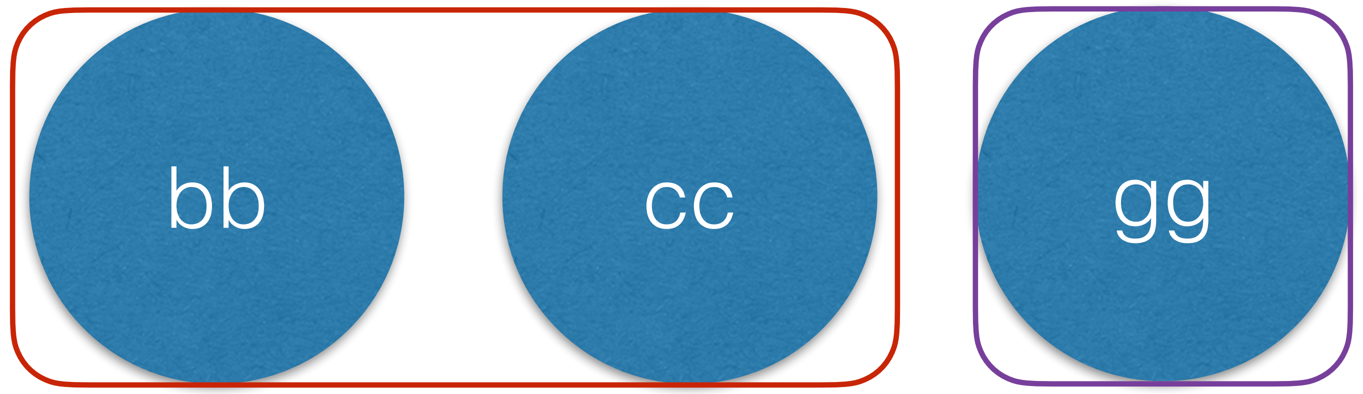
$$\delta m_c = 7 \text{ MeV}$$

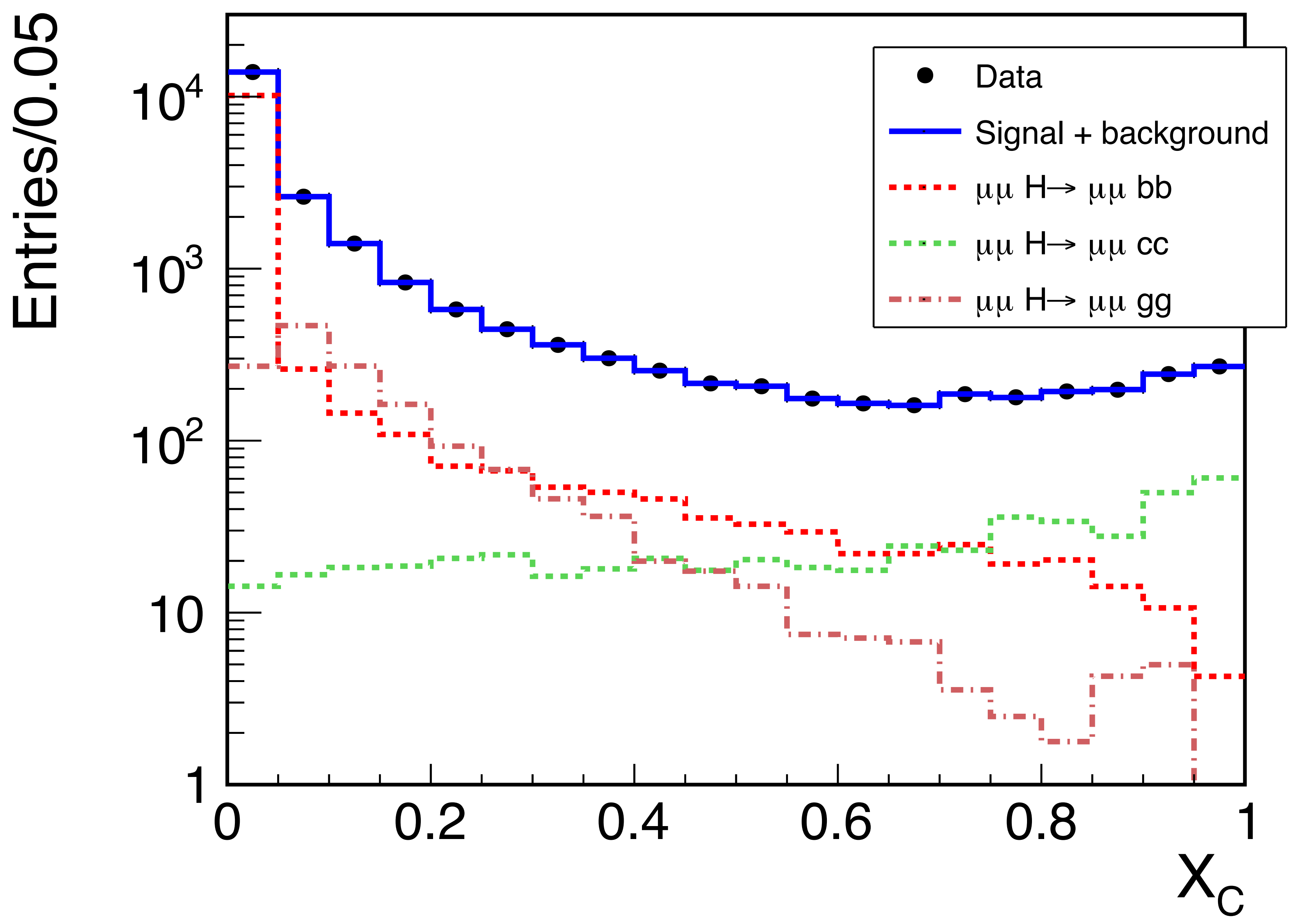
$$\delta m_t = 50 \text{ MeV} \quad \text{and } \delta M_H = 10 \text{ MeV}$$

Modeling on Hadronic decays

- Theoretical input of Higgs boson decay are more than numbers of partial width/BRs, modeling on kinematics and various NP QCD effects are mandatory for precision measurement of hadronic channels

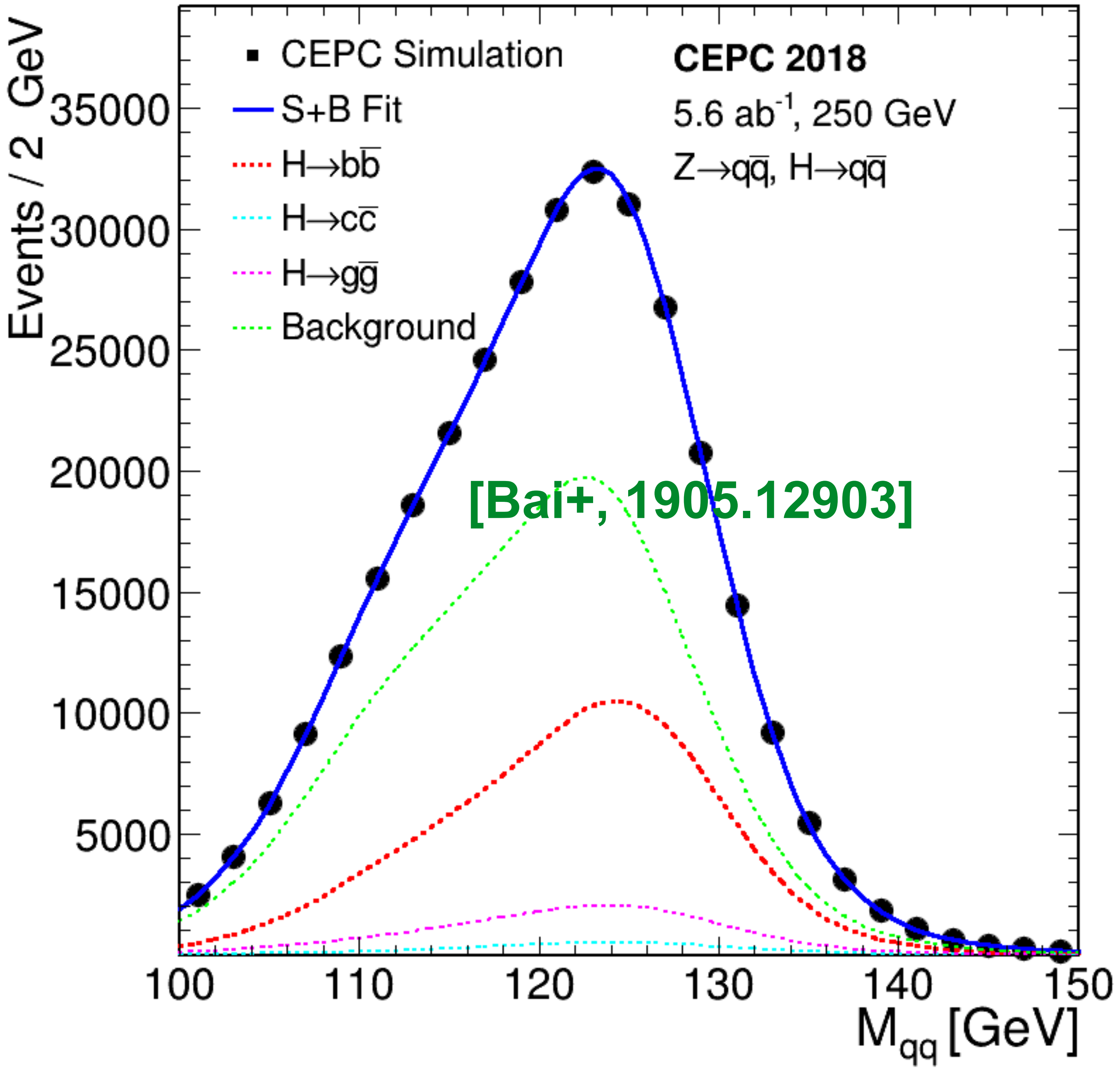
heavy-flavor tagging





charm-quark tagging

all hadronic channels and multi-jets final state

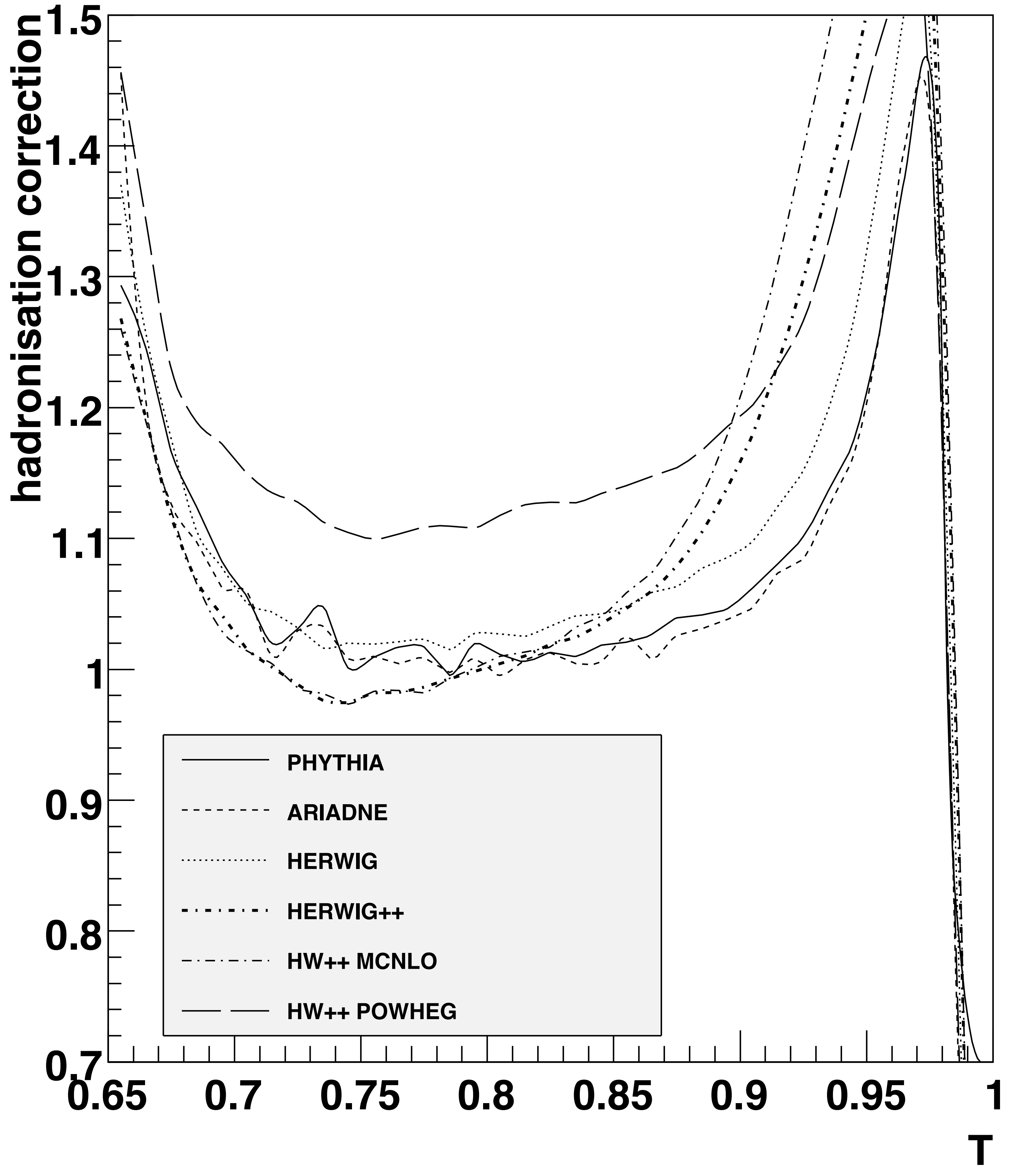


di-jet invariant mass

MC event generator

- A QCD MC event generator requires ingredients from both perturbative calculations (fixed-order and resummation) and non-perturbative modeling (tunned to data), and a consistent matching of the two

C=Hadron/Parton from MC



Event shapes

from NP models based on dispersion approach

$$\frac{1}{\sigma}\frac{d\sigma(y)}{dy}_{\text{corrected}} = \frac{1}{\sigma}\frac{d\sigma(y-\Delta y)}{dy}_{\text{pert}}$$

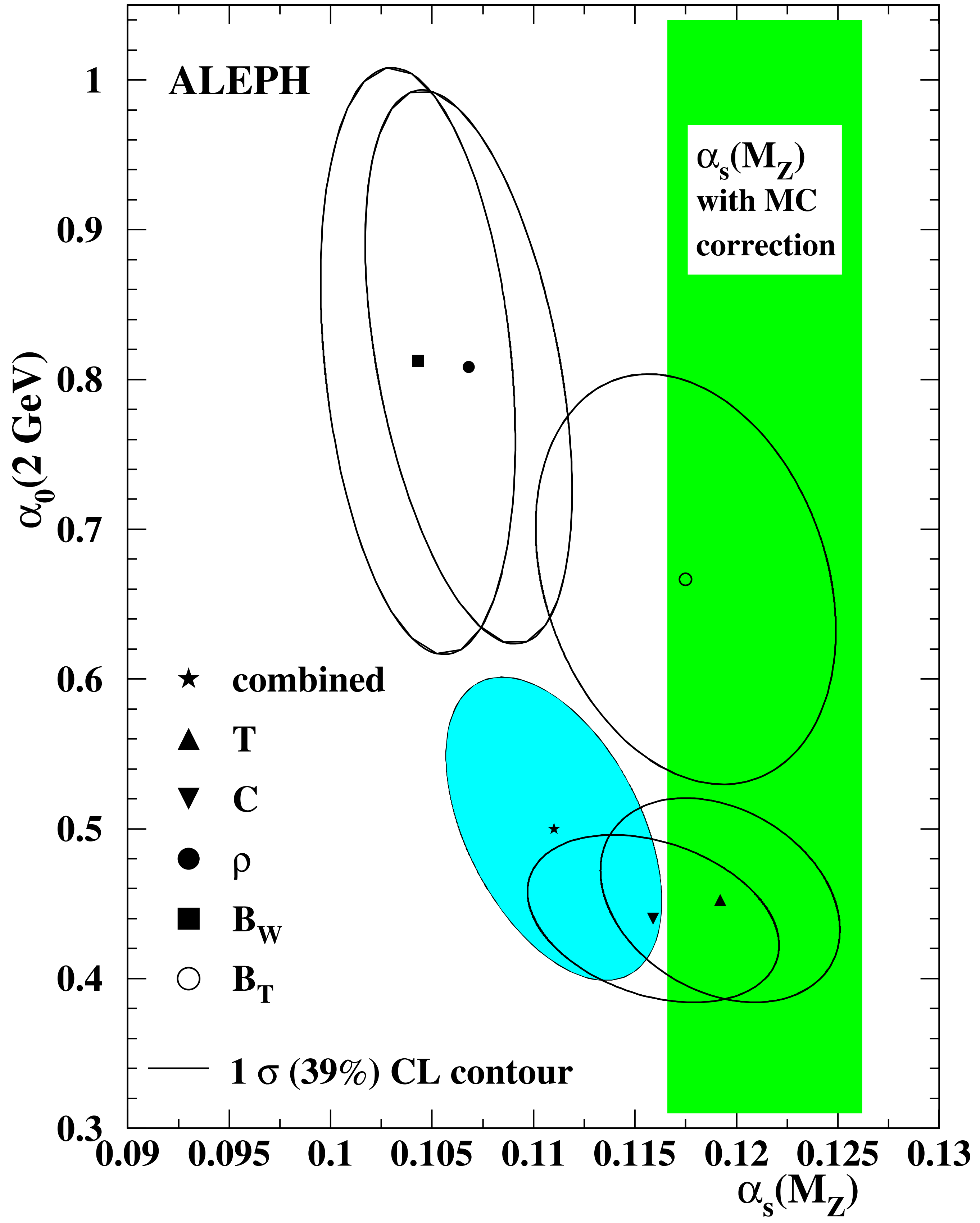
$$\Delta y = a_y \mathcal{P}$$

power suppressed NP

$$\alpha_0(\mu_I) = \frac{1}{\mu_I}\int_0^{\mu_I} dk_\perp \tilde{\alpha}_s(k_\perp^2)$$

[Dokshitzer+, hep-ph/9512336]

extracted strong coupling



[ALEPH, 2004]

POWHEG method

✦ Positive Weight Hardest Emission Generator for matching NLO QCD fixed-order predictions with parton shower MC **[Nason 2004]**, one of the two mostly used schemes at the LHC (POWHEG&MC@NLO)

POWHEG method in brief

$$\Delta(\Phi_n, p_T) = \exp\left(- \int \frac{[\mathrm{d}\Phi_{rad} R(\Phi_{n+1})\theta(k_T(\Phi_{n+1}) - p_T)]^{\bar{\Phi}_n = \Phi_n}}{B(\Phi_n)} \right)$$

Sudakov factor (k_T) with ME corrections

$$\bar{B}(\Phi_n) = [B(\Phi_n) + V(\Phi_n)] + \int \mathrm{d}\Phi_{rad} [R(\Phi_{n+1}) - C(\Phi_{n+1})]$$

NLO cross sections projected onto Born phase space

$$d\Gamma = \bar{B}(\Phi_n) d\Phi_n \left(\Delta(\Phi_n, p_T^{min}) + \Delta(\Phi_n, k_T(\Phi_{n+1})) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \mathrm{d}\Phi_{rad} \right)$$

generation of first/hard radiation

☆ later passed to k_T ordered (or vetoed) shower program (SMC) for subsequent emissions below the first hard scale; not SMC specific, negligible fraction of events with negative weights; accuracy NLO+(N′)LL

POWHEG method

- Positive Weight Hardest Emission Generator for matching NLO QCD fixed-order predictions with parton shower MC **[Nason 2004],** one of the two mostly used schemes at the LHC (POWHEG&MC@NLO)

POWHEG method in brief

$$\Delta(\Phi_n, p_T) = \exp\left(- \int \frac{[\mathrm{d}\Phi_{rad} R(\Phi_{n+1}) \theta(k_T(\Phi_{n+1}) - p_T)]^{\bar{\Phi}_n = \Phi_n}}{B(\Phi_n)} \right)$$

Sudakov factor (k_T) with ME corrections

$$\bar{B}(\Phi_n) = [B(\Phi_n) + V(\Phi_n)] + \int \mathrm{d}\Phi_{rad} [R(\Phi_{n+1}) - C(\Phi_{n+1})]$$

NLO cross sections projected onto Born phase space

$$d\Gamma = \bar{B}(\Phi_n) d\Phi_n \left(\Delta(\Phi_n, p_T^{min}) + \Delta(\Phi_n, k_T(\Phi_{n+1})) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \mathrm{d}\Phi_{rad} \right)$$

generation of first/hard radiation

- later passed to k_T ordered (or vetoed) shower program (SMC) for subsequent emissions below the first hard scale; not SMC specific, negligible fraction of events with negative weights; accuracy NLO+(N′)LL

Our work: NNLO+PS based on POWHEG method and an unitarized merging of different multiplicities

Total partial width

- A NNLO calculation of the hadronic decays requires inputs of decays to 3-jets at NLO and the singular terms in the 2-jets limit up to NNLO; reproducing the known NNLO total partial widths of H->bb, gg, qq

[JG+, 2021]

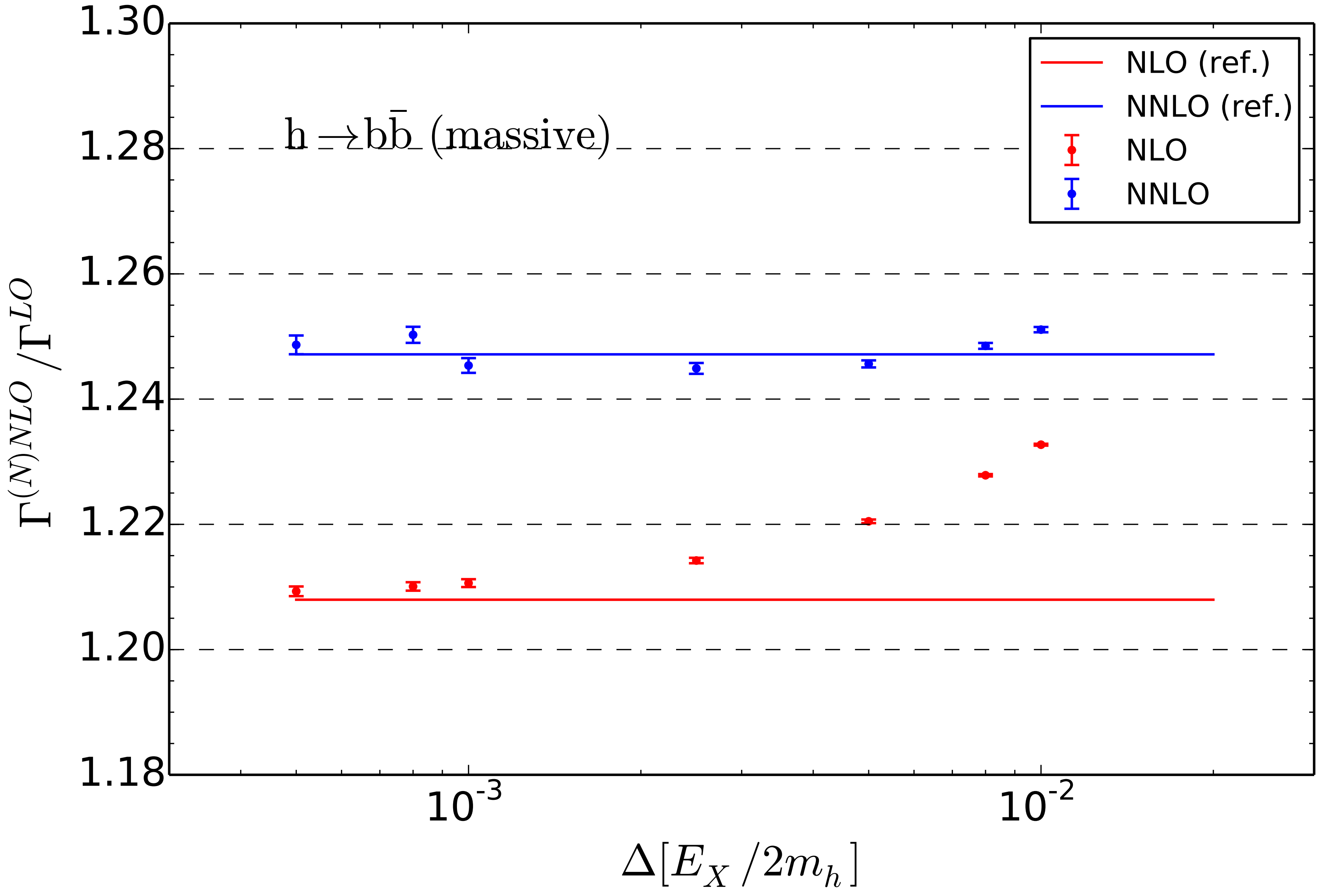
$$\frac{1}{\Gamma_0}\frac{d\Gamma}{dE_X} = H(Q^2, m_b^2, \mu)\int \mathrm{d}k S(k,\mu)\delta(E_X - k)$$

$$\Gamma_s(x) \equiv \int_0^x dx \frac{d\Gamma_s}{dx} = \Gamma_0(1 + \Gamma_s^{(1)}(x) + \Gamma_s^{(2)}(x))$$

$$\frac{d\Gamma_{3j}(x)}{dx} = \Gamma_0\left(\frac{d\Gamma_{3j}^{(1)}(x)}{dx} + \frac{d\Gamma_{3j}^{(2)}(x)}{dx}\right)$$

$$\Gamma^{NNLO} = \Gamma_s(\delta) + \int_\delta dx \frac{d\Gamma_{3j}(x)}{dx}$$

partial width of H->bb vs. resolution parameter



bottom-quark mass power corrections are small ~0.4% for total width

[MeV/GeV]	$\Gamma_{b\bar{b}}(m_b \neq 0)$	$\Gamma_{b\bar{b}}(m_b = 0)$	Γ_{gg}
$\mu = m_h/2$	2.314	2.320	0.3488
$\mu = m_h$	2.293	2.302	0.3437
$\mu = 2m_h$	2.252	2.263	0.3290

NNLO partial width of H->bb, qq, gg

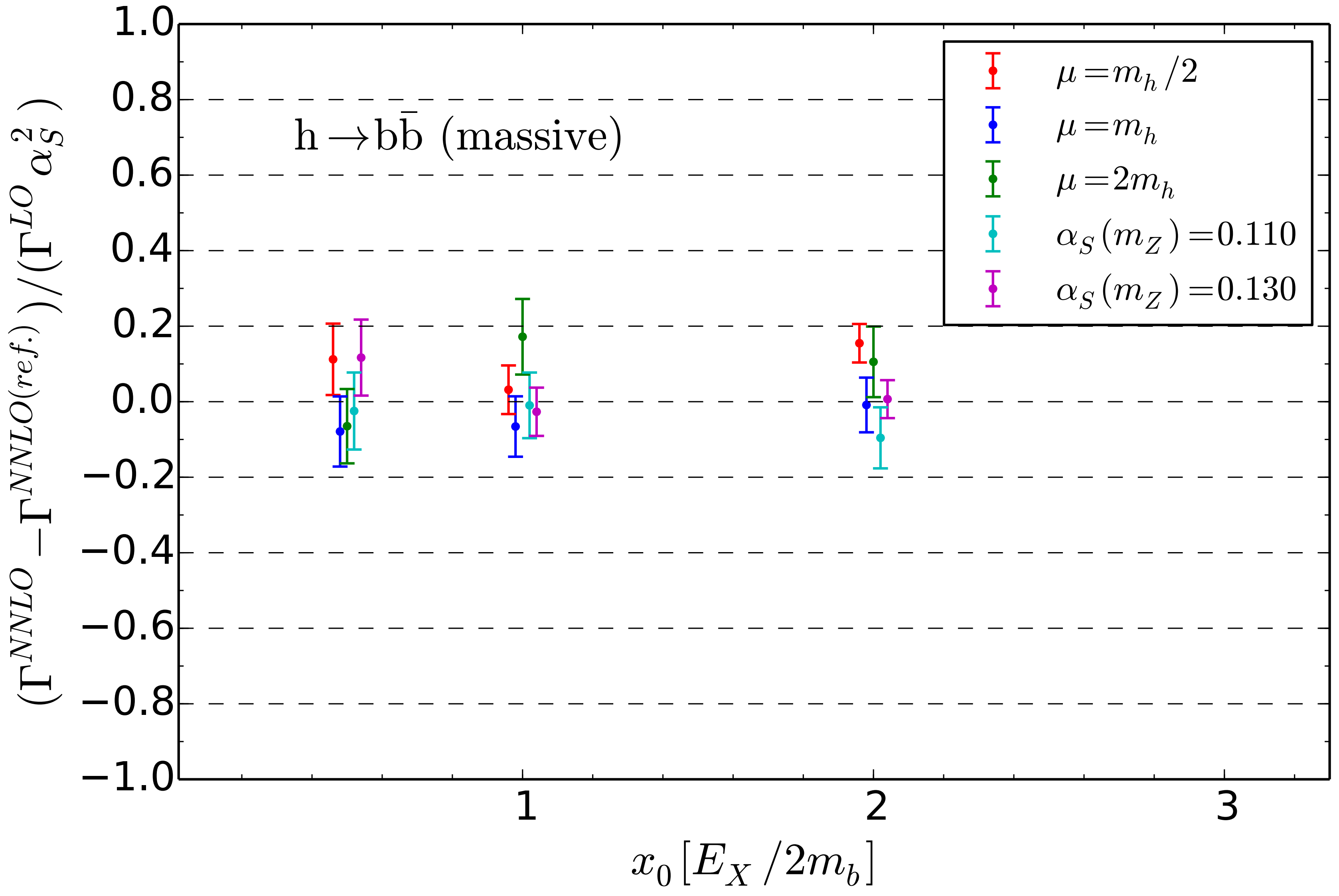
NNLOPS

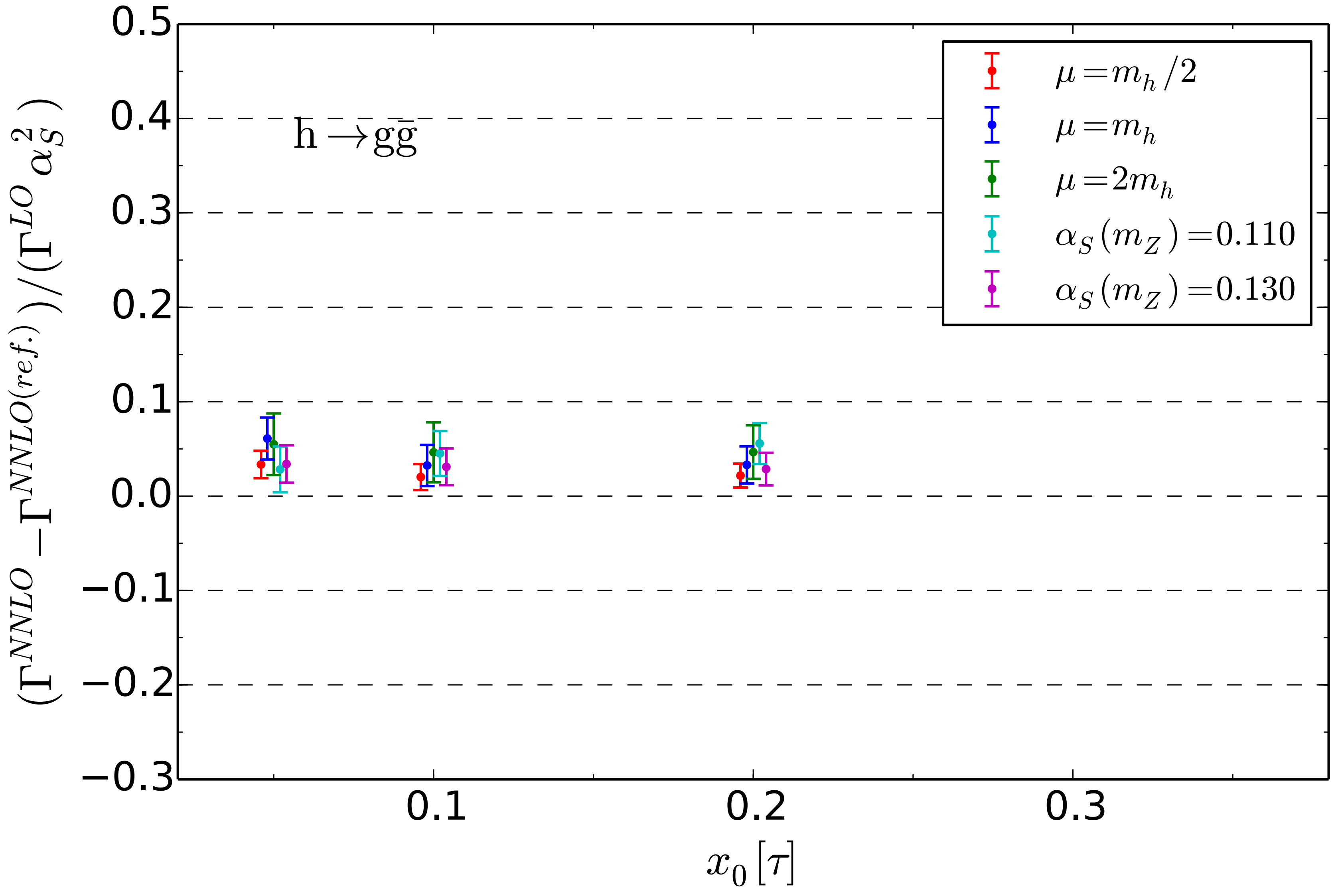
- Matching of NNLO calculations with parton shower for hadronic decays can be done through: 1. NLOPS for Higgs boson decaying into 3-jets; 2. followed by an unitarized merging with 2-jets sample

$$\bar{B}^*(\Phi_3) = \tilde{\mathcal{D}}(x(\Phi_3))[B(\Phi_3)(1 - \tilde{D}^{(1)}(x(\Phi_3))) + V(\Phi_3)] + \int \mathrm{d}\Phi_{rad}[\tilde{\mathcal{D}}(x(\Phi_4))R(\Phi_4) - \tilde{\mathcal{D}}(x(\Phi_3))C(\Phi_4)].$$

POWHEG implementation of NLOPS for H->3 jets with damping on Born phase space

$$\mathcal{D}(x) = \exp\left[\Gamma_s^{(1)}(x) + \Gamma_s^{(2)}(x) - (\Gamma_s^{(1)}(x))^2/2\right]$$



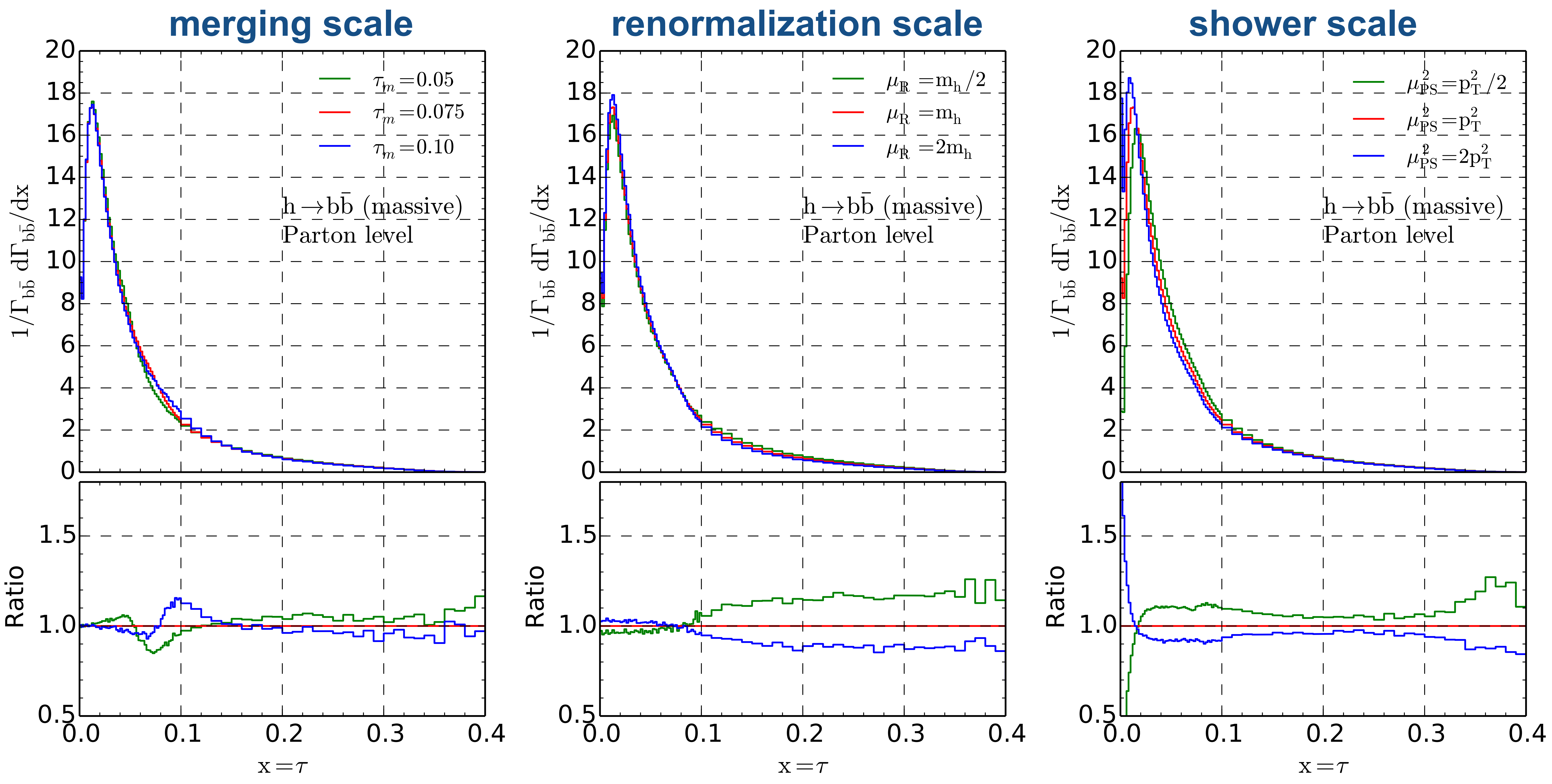


$$d\Gamma = \bar{B}^*(\Phi_3)\theta(\tau(\Phi_3) - \tau_m)d\Phi_3\left(\Delta(\Phi_3, p_T^{min}) + \Delta(\Phi_3, k_T(\Phi_4))\frac{R(\Phi_4)}{B(\Phi_3)}\mathrm{d}\Phi_{rad}\right) + \bar{B}^*(\Phi_3)\theta(\tau_m - \tau(\Phi_3))d\Phi_3.$$

unitarized merging using thrust as the resolution parameter and vetoed shower

Perturbative uncertainties

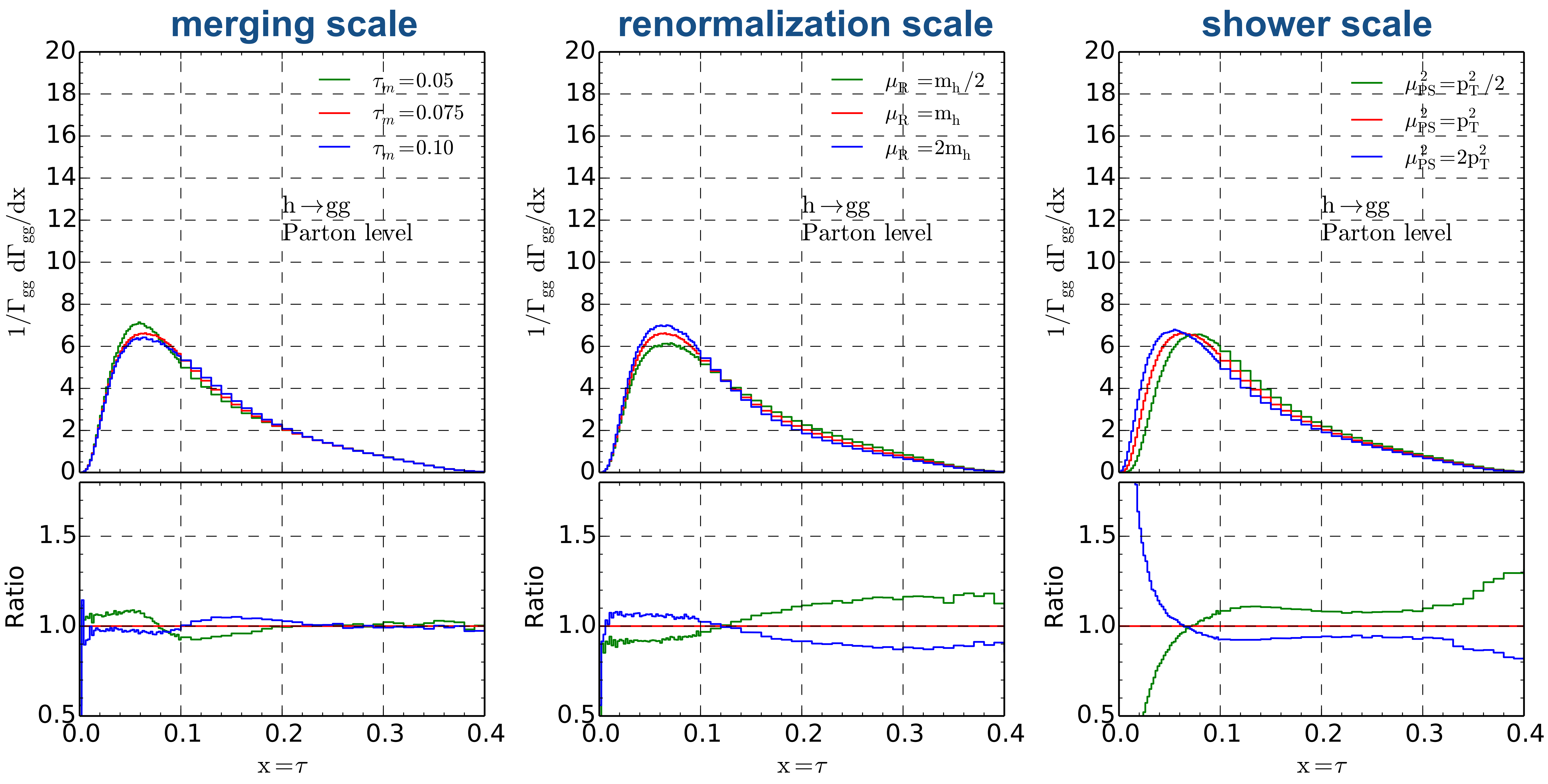
- Perturbative uncertainties of H->bb/qq/gg can be estimated by varying the merging scale, renormalization scale, and QCD scale in parton showers, each responsible for its designed kinematic region



normalized differential width vs. 1-Thrust, at parton level, for H->bb

Perturbative uncertainties

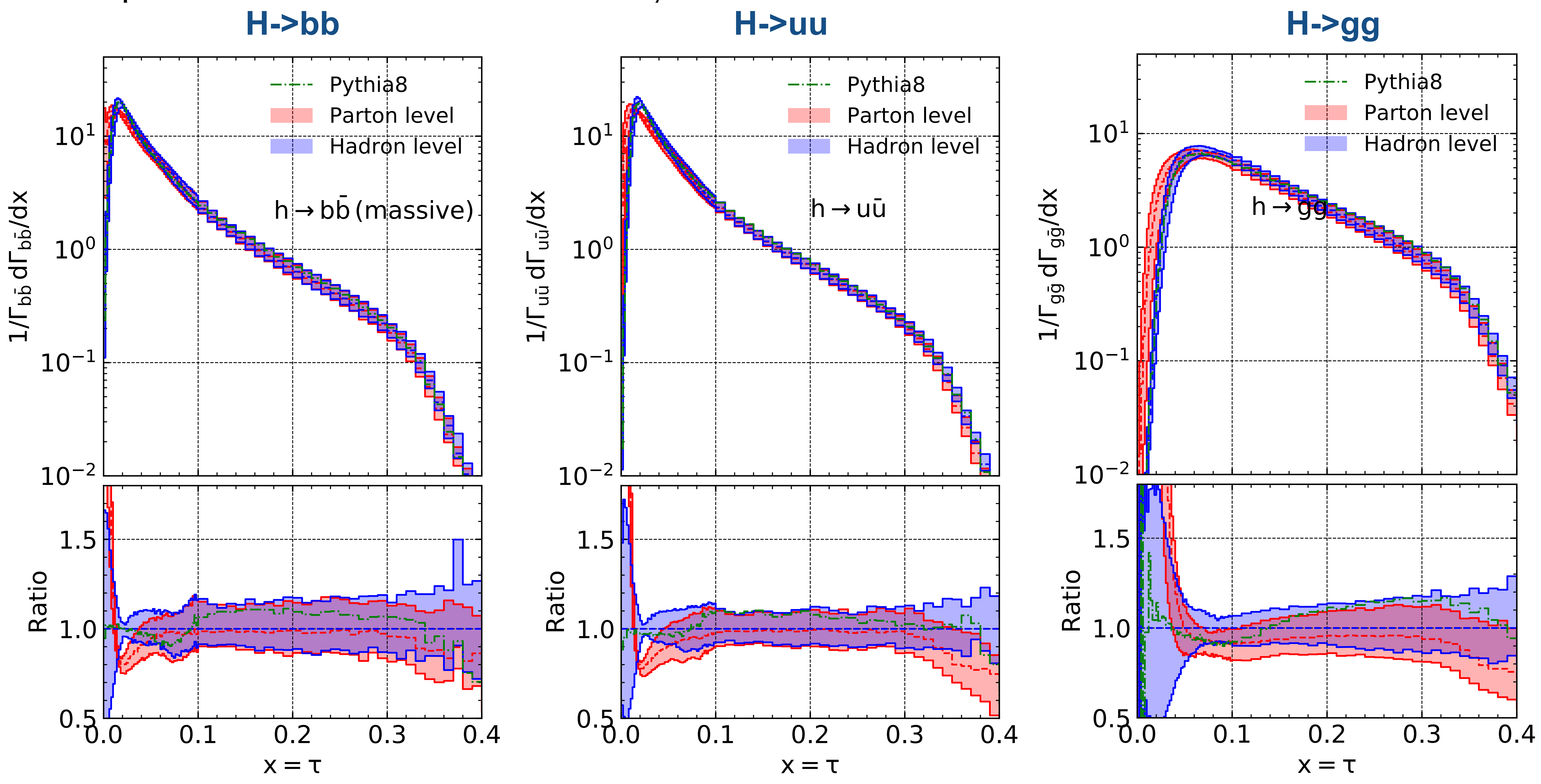
- Perturbative uncertainties of H->bb/qq/gg can be estimated by varying the merging scale, renormalization scale, and QCD scale in parton showers, each responsible for its designed kinematic region



normalized differential width vs. 1-Thrust, at parton level, for H->gg

Complete results

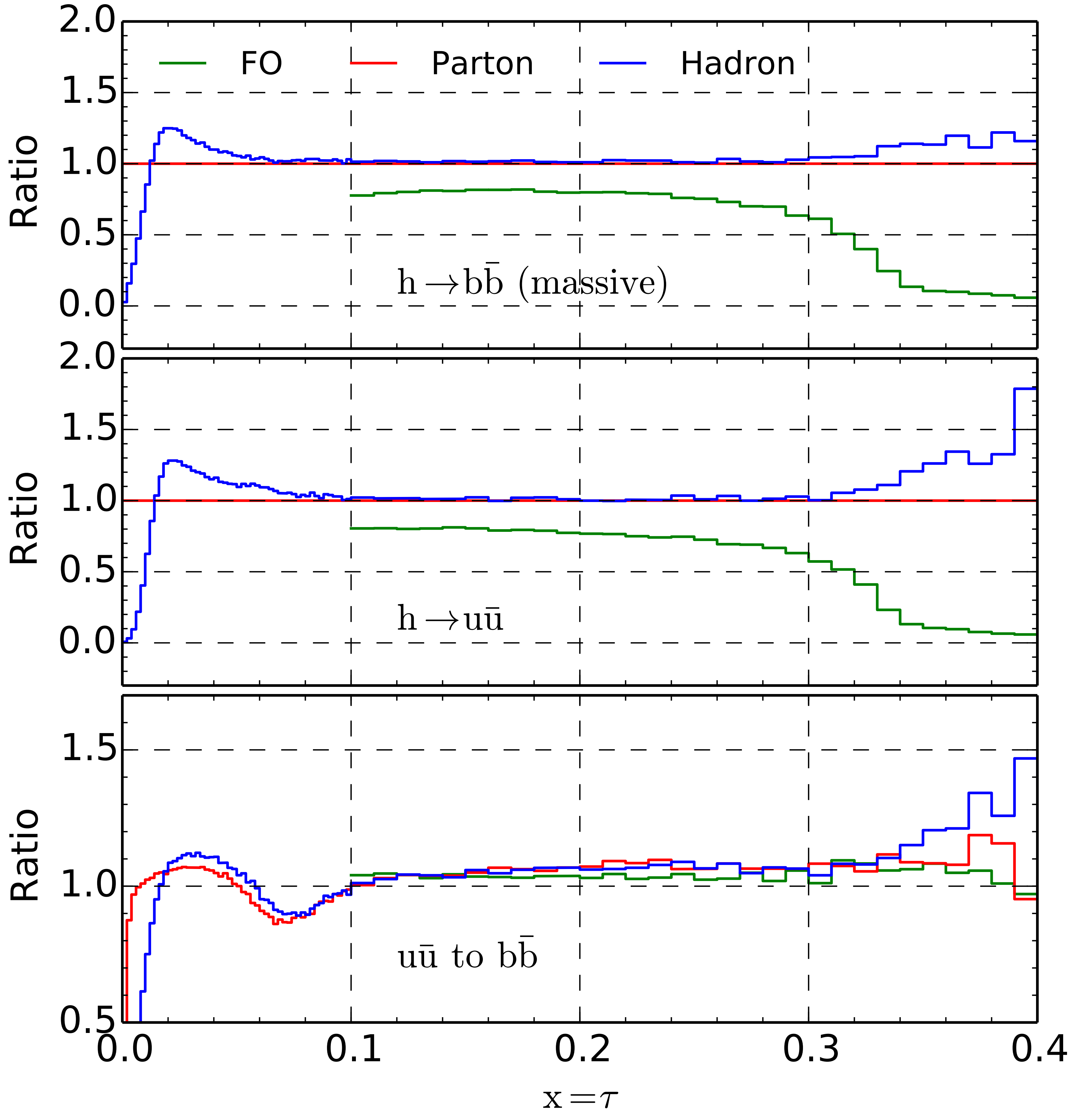
- Comparison of predictions at parton and hadron level with full perturbative uncertainties, also shown are PYTHIA 8 predictions, for all hadronic decay channels



normalized differential width vs. 1-Thrust, at parton/hadron level, for H->bb, uu, gg

Hadronization and mass corrections

- Further comparison of H->bb and H->uu, including the size of hadronization corrections, their fixed-order predictions, and the quark-mass power corrections



ratio of normalized differential width vs. 1-Thrust

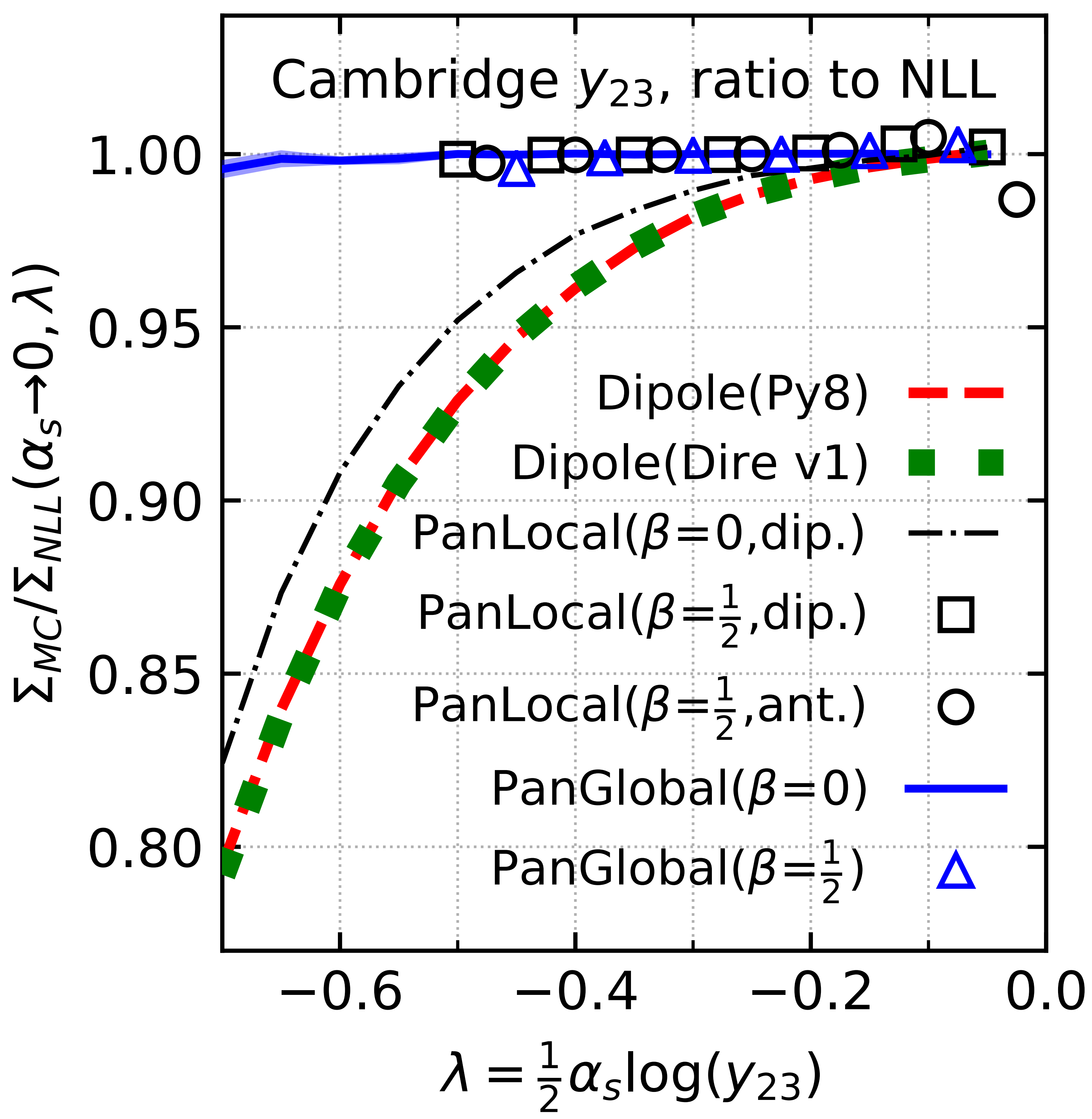
- Hadronization corrections are significant at peak/tail region
- PS matched predictions are larger by 20% comparing to FO in the 3-jet region
- The bottom quark mass lead to a 5% suppression comparing to light quarks in the 3-jet region

Outlook

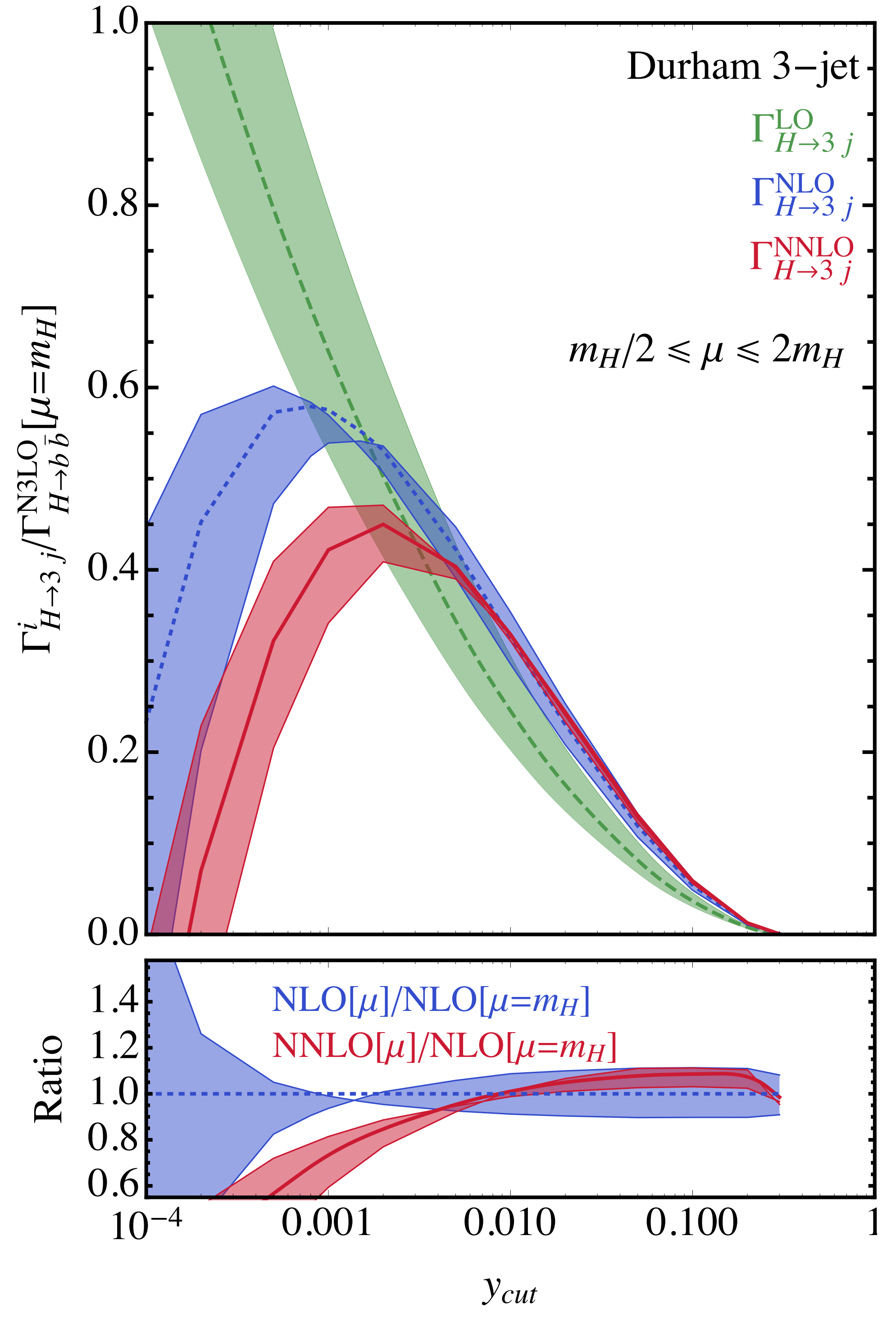
- Better understanding on the perturbative uncertainties; possible improvements on various perturbative inputs, e.g., with N3LO matrix elements and parton shower of NLL accuracy

  - comparison with the GENEVA generator (for H->gg, qq), (a NNLOPS with further resummed contributions from SCET)
  - matching with parton shower MCs at NLL accuracy, available in PanLocal/PanGlobal
  - incorporating N3LO matrix element corrections, exist for long times

[Salam+, 2020]



[Mondini, Williams, 2019]



Outlook

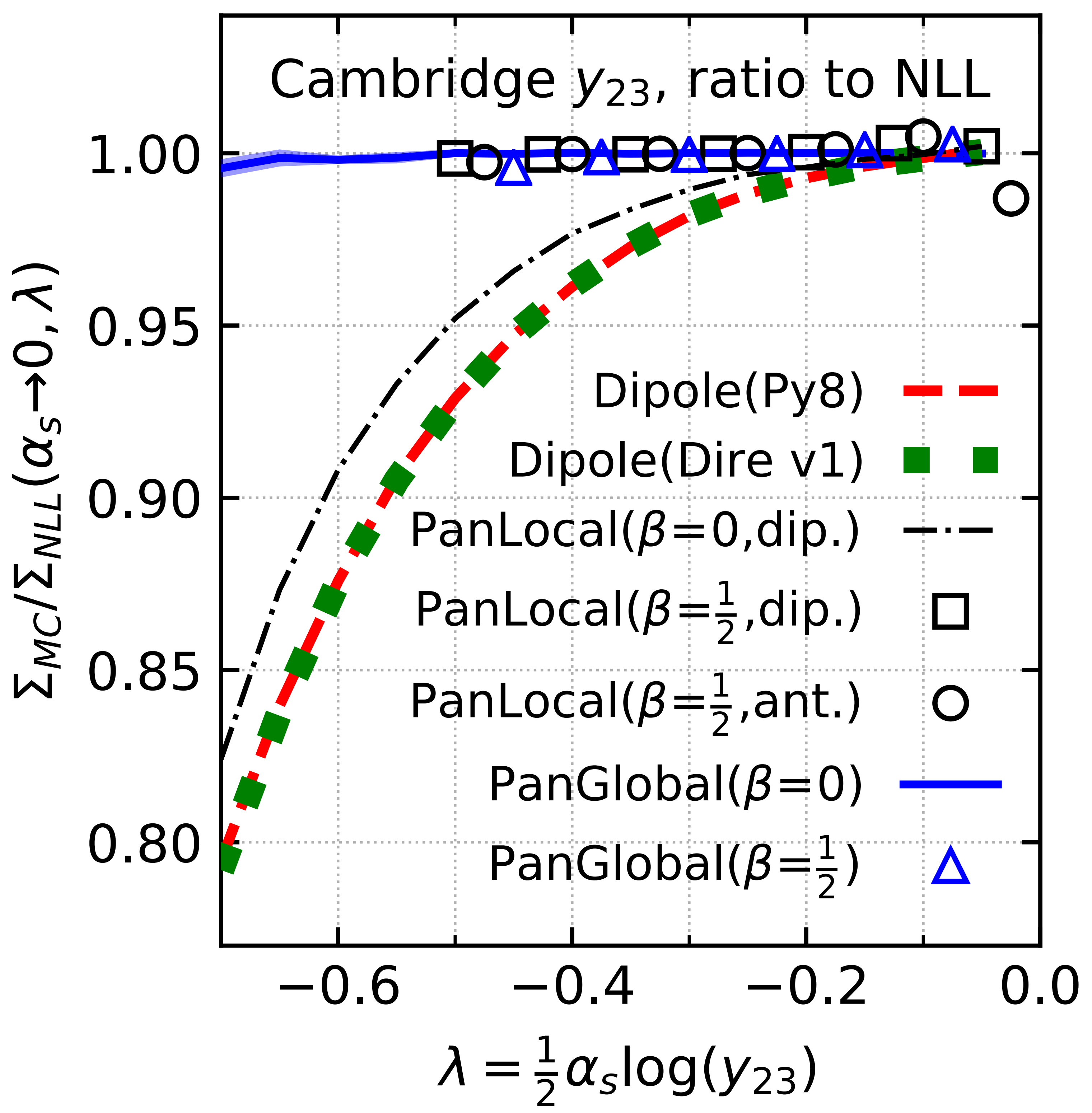
- Better understanding on the perturbative uncertainties; possible improvements on various perturbative inputs, e.g., with N3LO matrix elements and parton shower of NLL accuracy

  - comparison with the GENEVA generator (for H->gg, qq), (a NNLOPS with further resummed contributions from SCET)

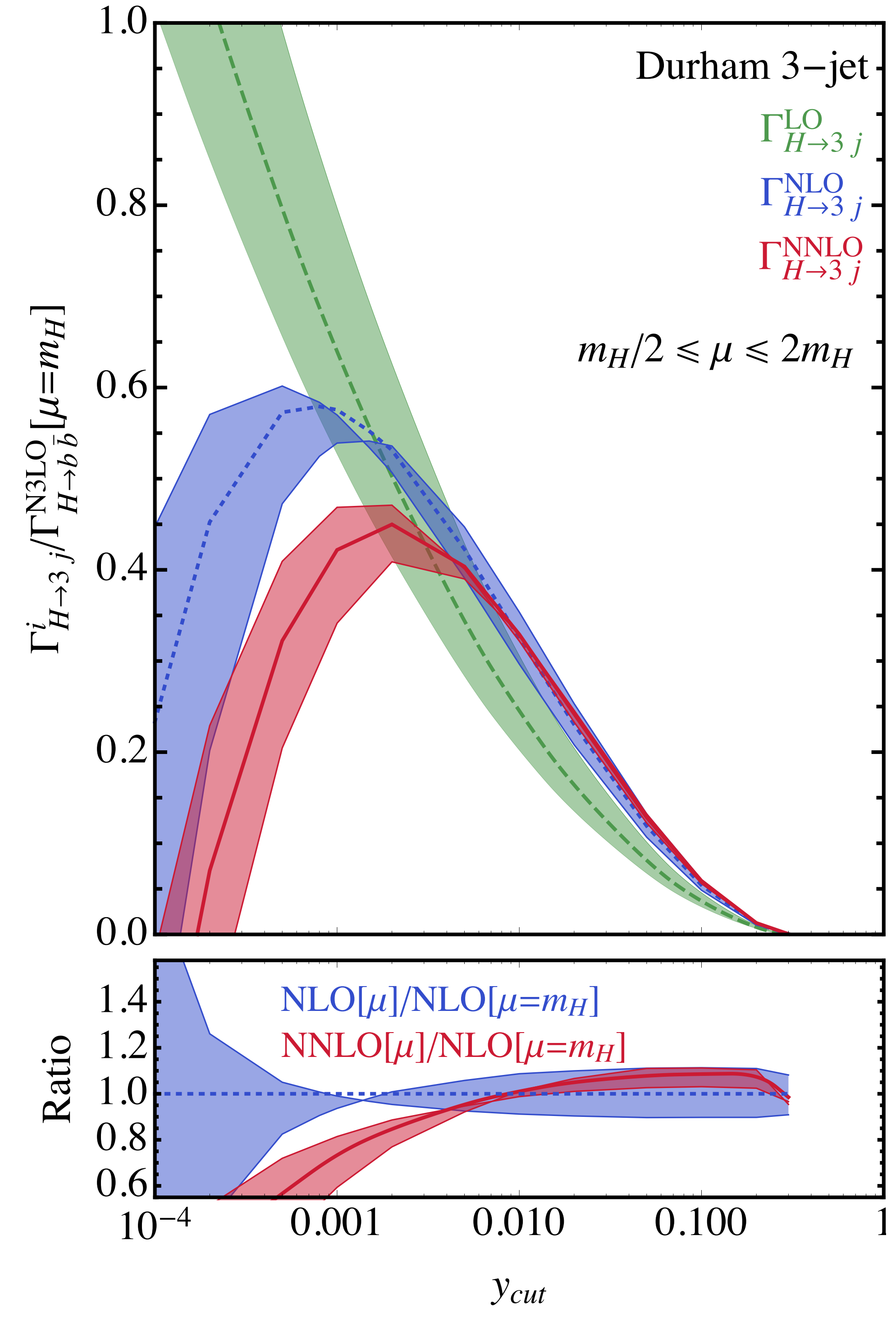
  - matching with parton shower MCs at NLL accuracy, available in PanLocal/PanGlobal

  - incorporating N3LO matrix element corrections, exist for long times

[Salam+, 2020]



[Mondini, Williams, 2019]

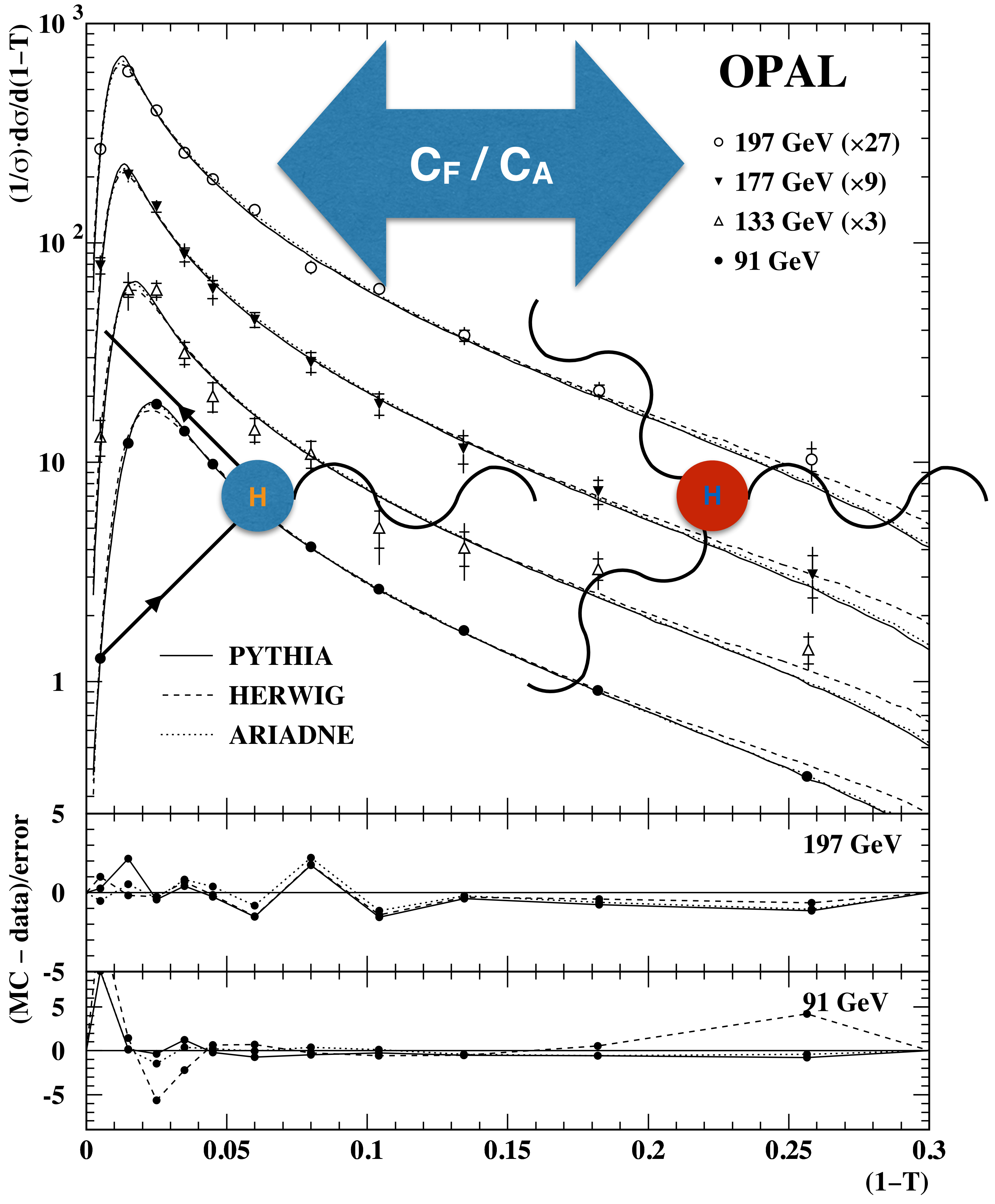


Thank you for your attention!

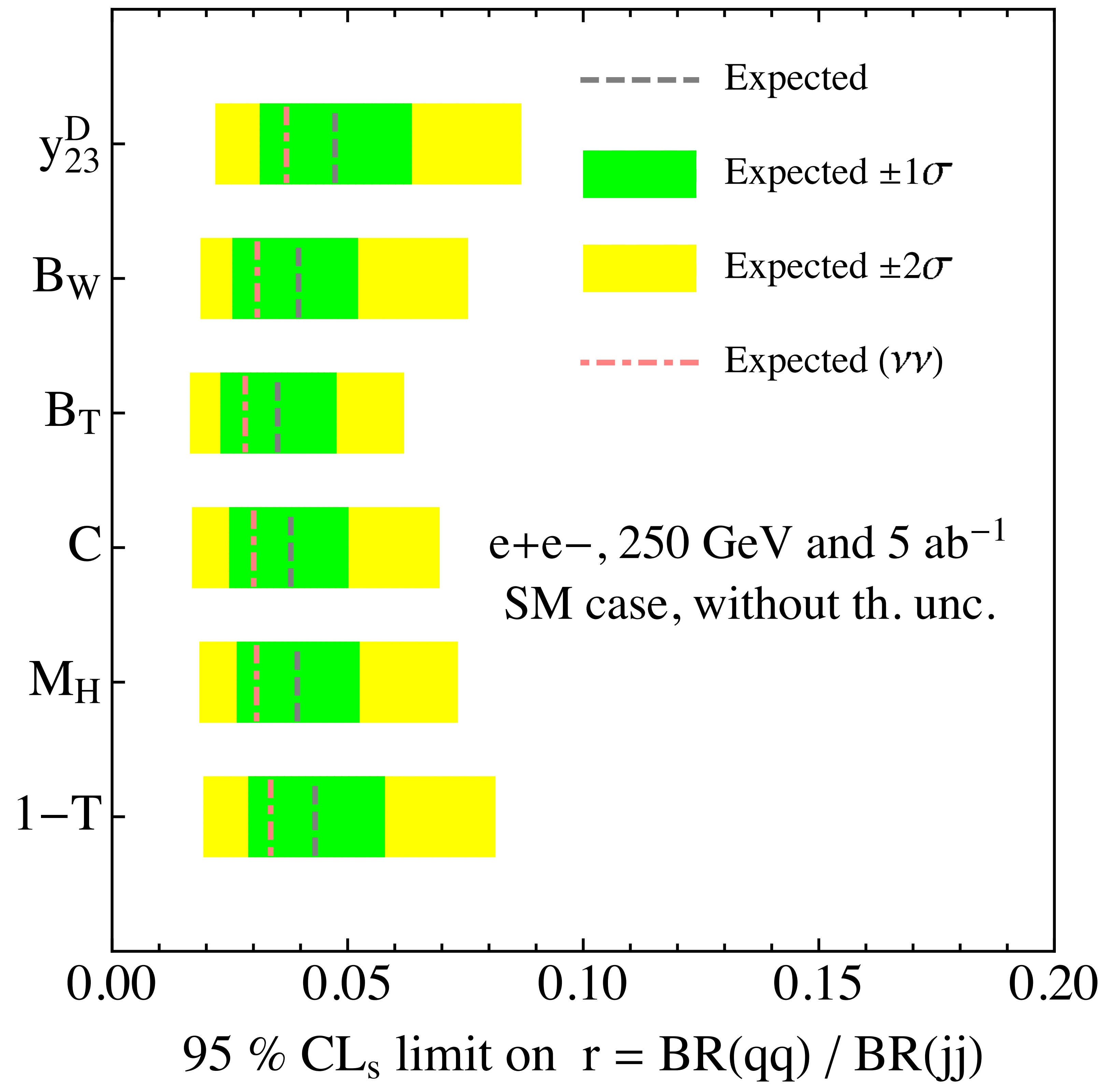
Modeling on Hadronic decays

- Also important for direct search of new physics, e.g., looking for light-quark decay modes from enhanced Yukawa couplings via event shapes, exotic decays into heavy quarks **[JG, 2016]**

discrimination of gg and qq channels



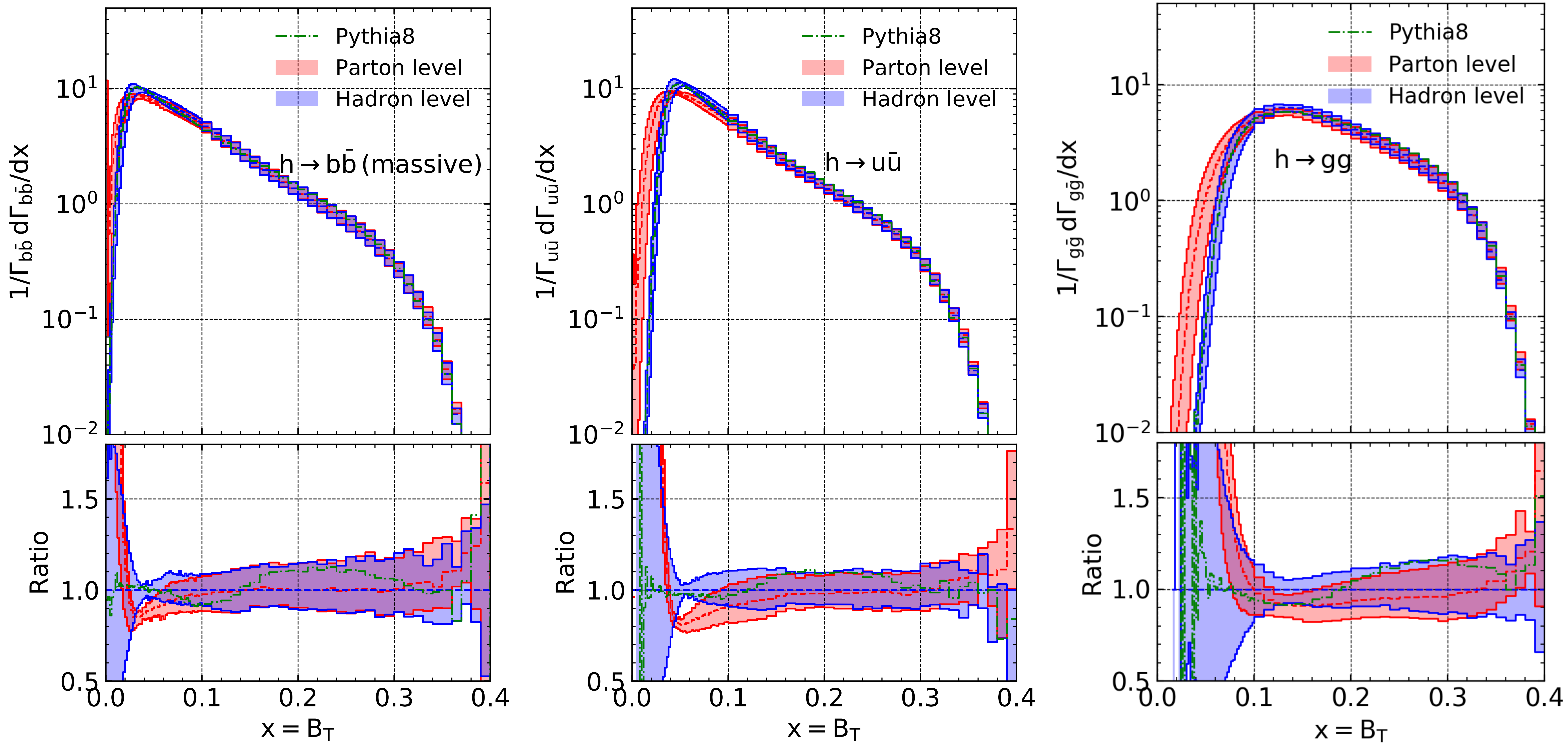
expected exclusion limit on BRs to light quarks normalized to BR to gluons



from various event shapes

Full results for total broadening

- Comparison of predictions at parton and hadron level with full perturbative uncertainties, also shown are PYTHIA 8 predictions, for all hadronic decay channels



normalized differential width vs. total jet broadening, at parton/hadron level, for H->bb, uu, gg