Probing light quark Yukawa couplings through angularities in Higgs boson decay

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Institute of High Energy Physics

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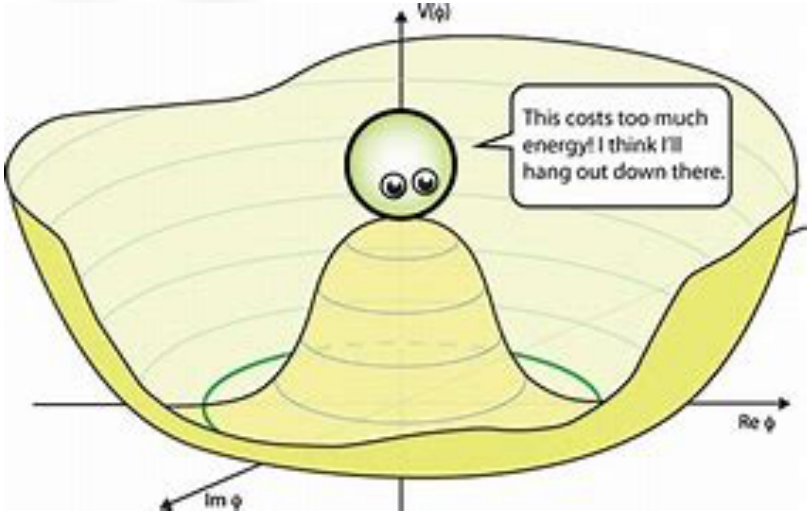
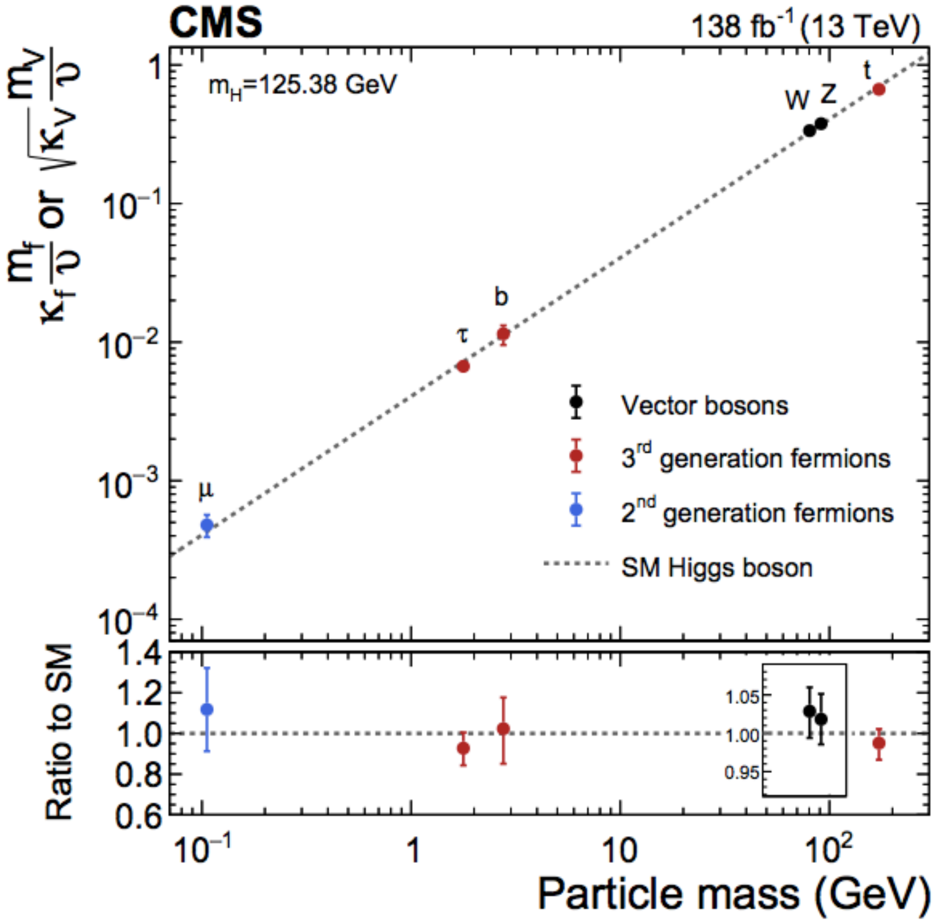
In collaboration with: Christopher Lee

Higgs couplings and EWSB





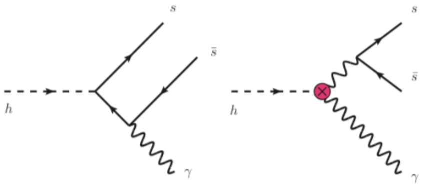
All fundamental particles get their mass from Higgs boson vev

How about light quarks?

Does Higgs mechanism still work?

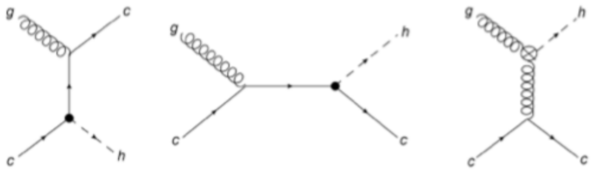
Light quark Yukawa couplings@LHC

A. Rare decay: $h \to J/\Psi\gamma \; (\phi\gamma, \rho\gamma, \omega\gamma)$

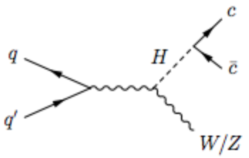


G. T. Bodwin, F. Petriello, S. Stoynev, M. Velasco, PRD88 (2013) 5, 053003
A. L. Kagan, G. Perez, F. Petriello, Y. Soreq, S. Stoynev, PRL114 (2015) 10,101802

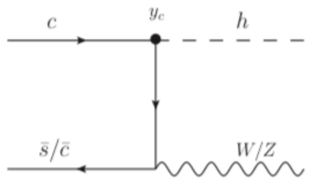
B. Higgs+charm production or Higgs decay



I. Brivio, F. Goertz, G. Isidori, PRL115 (2015)21,211801



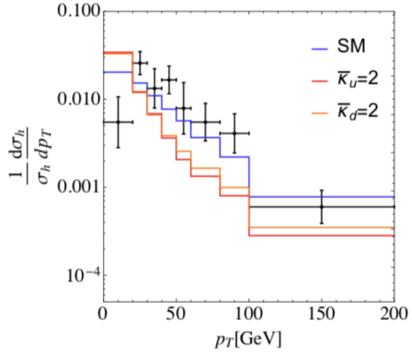
C. Higgs data global analysis:



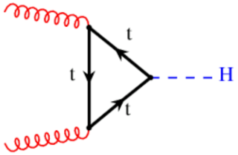
G. Perez, Y. Soreq, E. Stamou, K. Tobioka, PRD92(2015)3,033016, PRD93(2016)1,013001
Y. Zhou, PRD93(2016) 1,013019

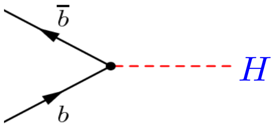
D. Higgs p_T analysis:

Soft gluon radiation

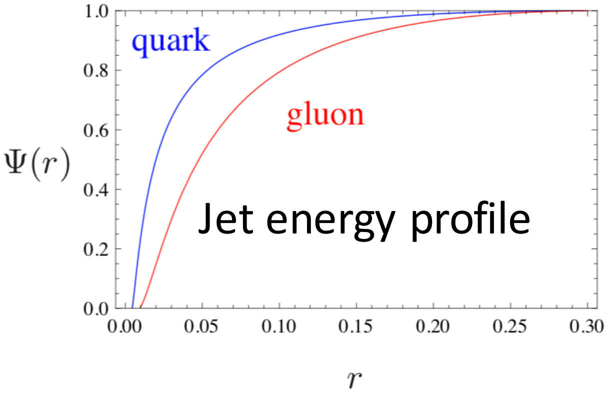


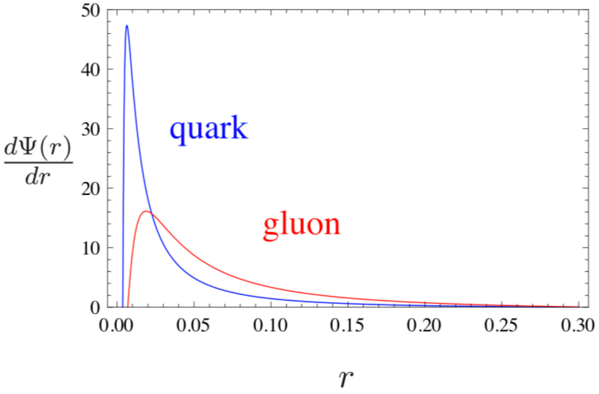
Y. Soreq, H.X. Zhu, J. Zupan, JHEP 12(2016)045
F. Bishara, U. Haisch, P. F. Monni, E. Re, PRL 118(2017)12,121801
G. Bonner, H. E. Logan, 1608.04376



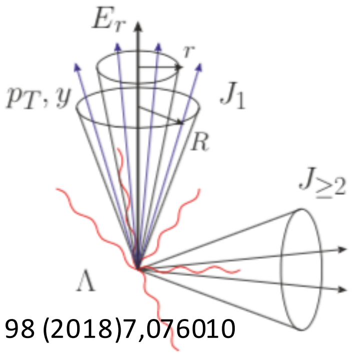


Light quark Yukawa couplings@ e^+e^-

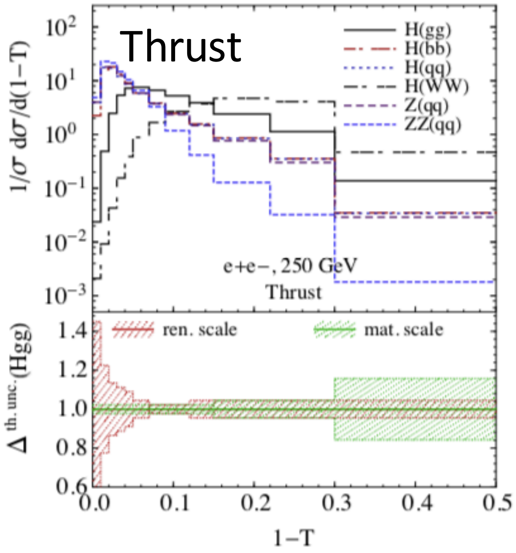


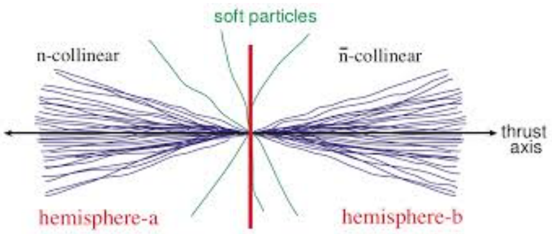


$$\Psi_J(r) = \frac{\sum_{i,d_{i,\hat{n}}<r} E_T^i}{\sum_{i,d_{i,\hat{n}}<R} E_T^i}$$



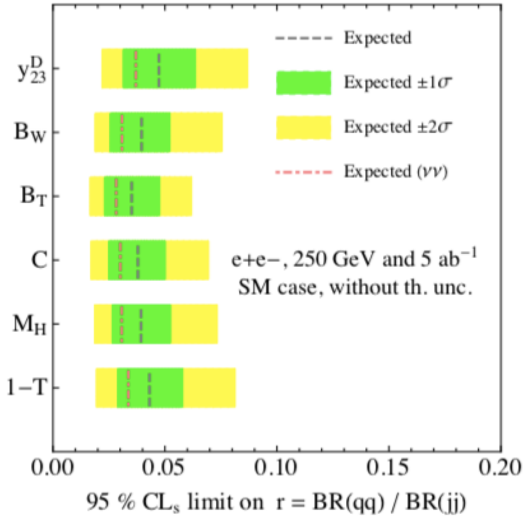
H. N. Li, Z. Li and C.-P. Yuan, PRL 107 (2011)152001; Y. T. Chien, I. Vitev, JHEP 12(2014)061
J. Isaacson, H.N. Li, Z. Li and C.-P. Yuan, PLB 771 (2017)619-623; G. X. Li, Z. Li, Y.D. Liu, Y. Wang, X. R. Zhao, PRD 98 (2018)7,076010





$$T = \max_{\vec{n}} \left(\frac{\sum_i |p_i \cdot \vec{n}|}{\sum_i |p_i|} \right)$$

$$y_{u,d,s}/y_b < 0.091$$



J. Gao, JHEP 01 (2018) 038

Event shapes

One class of event shapes:

$$e(X) = \frac{1}{Q}\sum_{i\in X} |p_\perp^i| f_e(\eta_i)$$

Examples:

Thrust $f_{1-T}(\eta) = e^{-|\eta|}$ Brandt, Peyrou, Sosnowski, Wroblewski,64; Farhi, 77

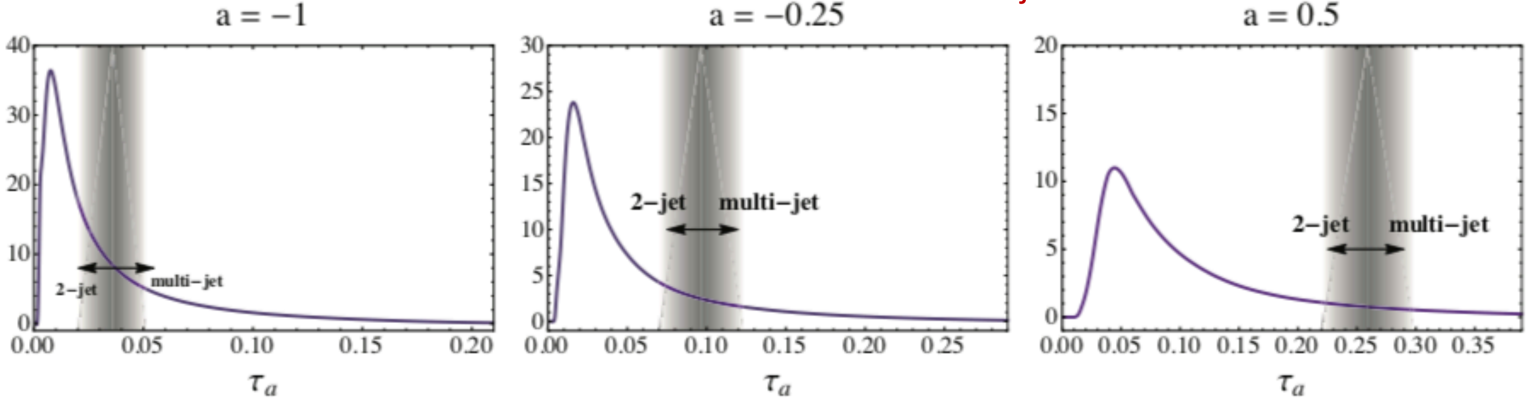
Jet broadening $f_B(\eta) = 1$ Catani, Turnock, Webber, 92

C-Parameter $f_C(\eta) = \frac{3}{\cosh(\eta)}$ Ellis, Ross, Terrano, 81

Angularities $f_{\tau_a}(\eta) = e^{-|\eta|(1-a)}$ Berger, Kucs, Sterman, 03 (relatively new)

G. Bell, A. Hornig, C. Lee, J. Talbert, JHEP01(2019)147

The proportions of two jet-like and three-or-more jet like events



Why Event shapes?

One class of event shapes:

$$e(X) = \frac{1}{Q}\sum_{i\in X} |p_\perp^i| f_e(\eta_i)$$

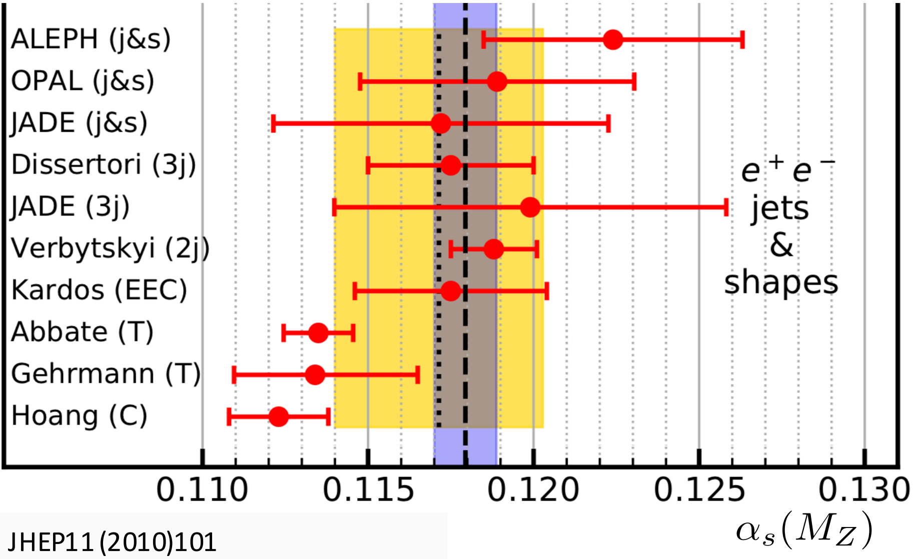
A. Tests the PQCD

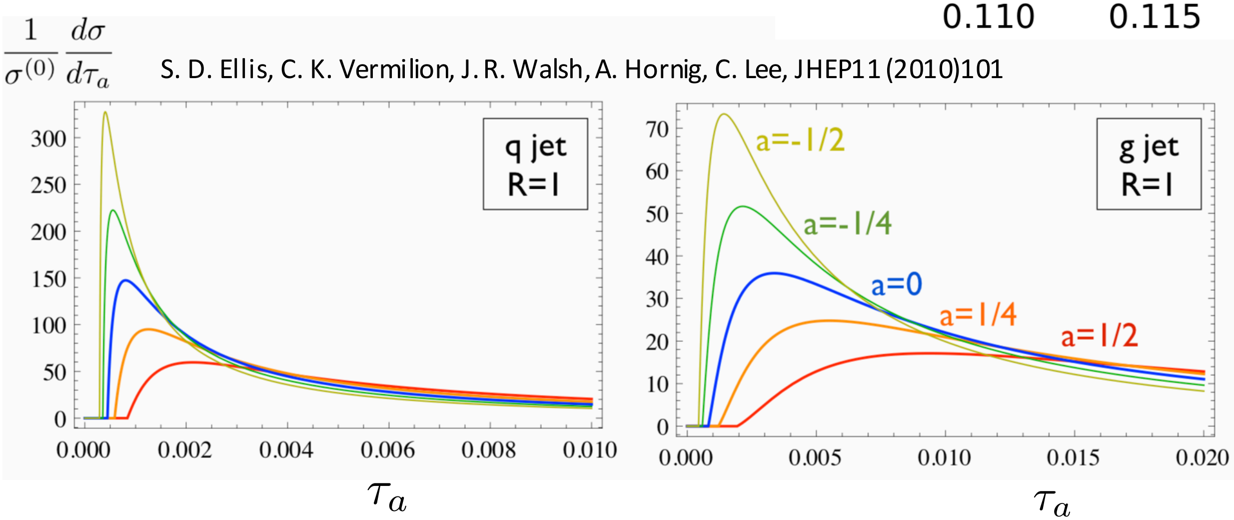
B. Extractions of strong couplings

C. Substructure of jets

D. Quark-gluon discriminations

PDG2019




S. D. Ellis, C. K. Vermilion, J. R. Walsh, A. Hornig, C. Lee, JHEP11 (2010)101

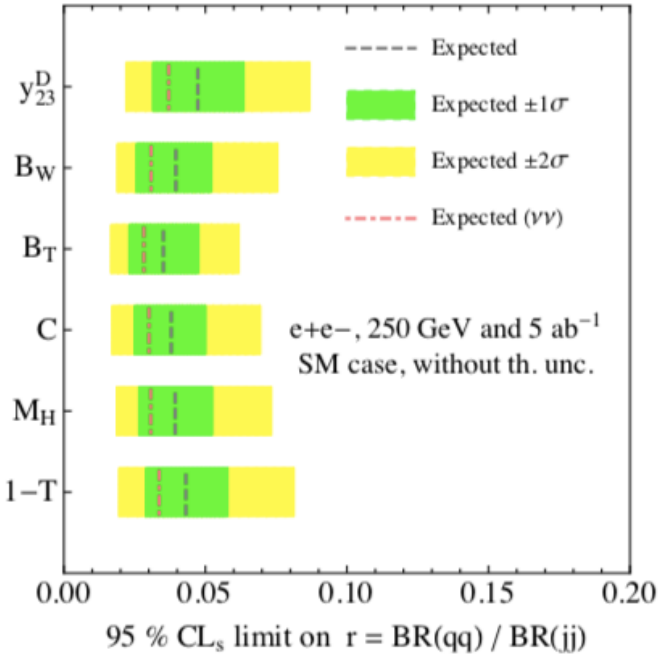
The peak:
Approximate CA/CF scaling

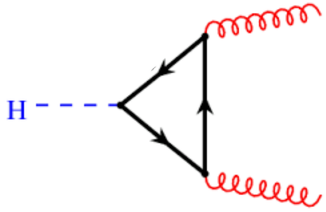
Jet Angularities

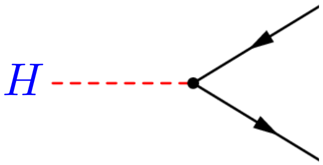
$$f_{\tau_a}(\eta) = e^{-|\eta|(1-a)}$$

Event shapes and Yukawa couplings

J. Gao, JHEP 01 (2018) 038

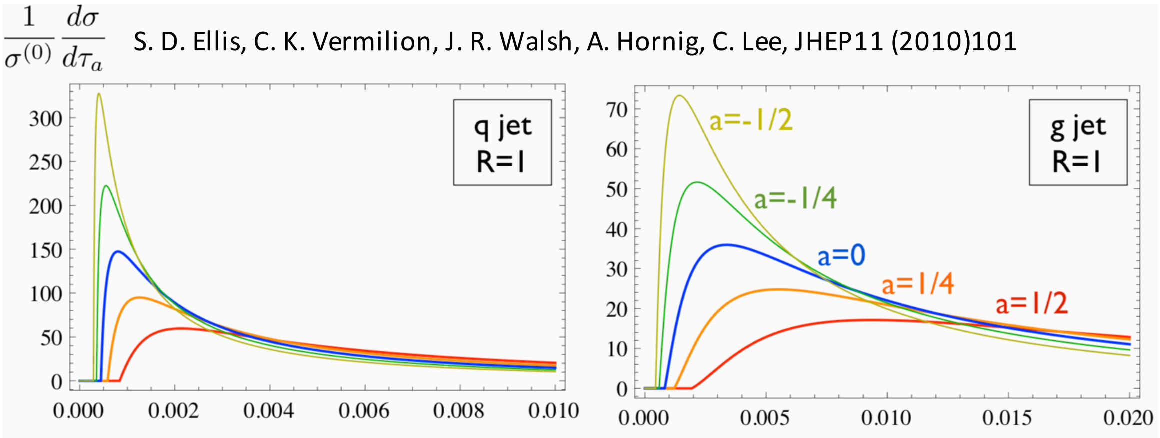






Event shapes could give a strong constraint for the light quark Yukawa couplings

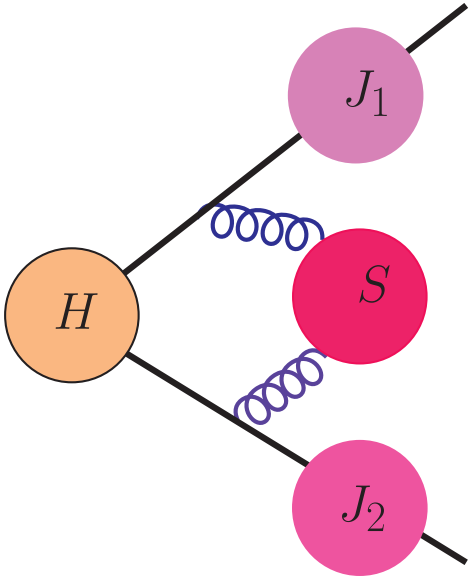
Angularities also show strong discriminatory power for quark and gluon jets


S. D. Ellis, C. K. Vermilion, J. R. Walsh, A. Hornig, C. Lee, JHEP11 (2010)101

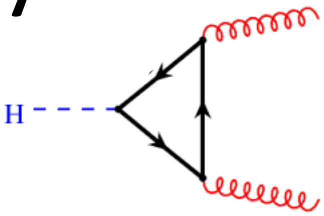
What's the impact of **angularities** for the Yukawa coupling measurements?

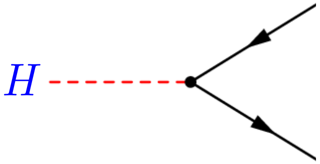
Factorization for event shapes in Higgs decay

Fleming, Hoang, Mantry, Stewart (2007)
Bauer, Fleming, Lee, Sterman (2008)



$\tau_a \ll 1$

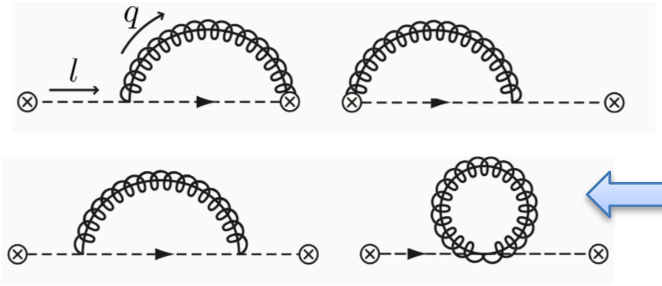




$$\frac{d\Gamma^i_H}{\Gamma^i_{H0}\, d\tau_a} = H^i(m_H,\mu) J_n(\tau_n) \otimes J_{\bar{n}}(\tau_{\bar{n}}) \otimes S(\tau_s)$$

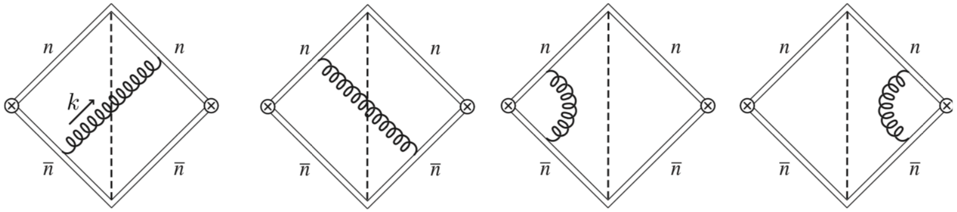
Hard function, the matching from SCET to QCD

Jet function, Collinear gluon emissions



e.g. Quark Jet function

Hornig, Lee, Ovanesyan (2009)



Soft function, Soft gluon radiation

Accuracy counting

Accuracy	Γ_{cusp}	$\gamma_F, \gamma_\Delta^\mu, \gamma_R$	β	$H, \tilde{J}, \tilde{S}, \delta_a$
LL	α_s	1	α_s	1
NLL	α_s^2	α_s	α_s^2	1
NNLL	α_s^3	α_s^2	α_s^3	α_s
N^{3}LL	α_s^4	α_s^3	α_s^4	α_s^2

Accuracy	$H, \tilde{J}, \tilde{S}, \delta_a$
NLL$'$	α_s
NNLL$'$	α_s^2
N^{3}LL$'$	α_s^3

Matching	$r^n(\tau_a)$
$+\mathcal{O}(\alpha_s)$	α_s
$+\mathcal{O}(\alpha_s^2)$	α_s^2
$+\mathcal{O}(\alpha_s^3)$	α_s^3

G. Bell, R. Rahn, and J. Talbert, NPB936(2018)520-541; JHEP 07 (2019) 101

From NLL' to NNLL accuracy:

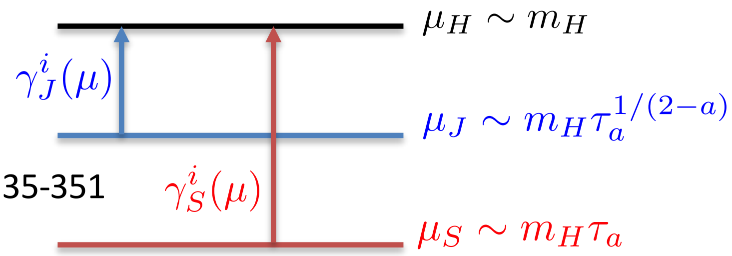
Two-loop soft anomalous dimensions provided by SoftSERVE

Two-loop jet anomalous dimension obtained from consistency relations

Non-Perturbative Model

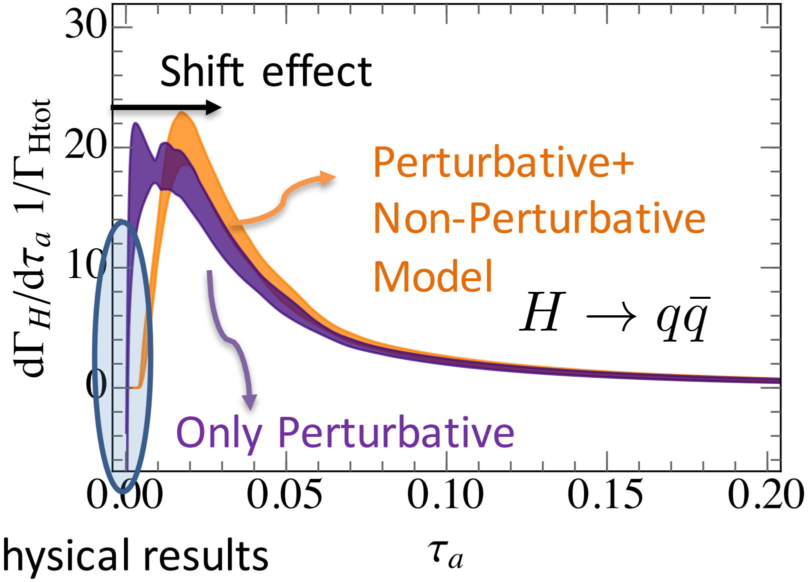
Soft function as convolution of Perturbative and Non-Perturbative parts:

$$S^i(k,\mu) = \int dk' S^i_{\mathrm{PT}}(k-k',\mu) f^i_{\mathrm{mod}}(k' - 2\bar{\Delta}^i_a).$$



Korchemsky, hep-ph/9806537; Korchemsky and Sterman, NPB555(1999)335-351
Hoang, Stewart, PLB660(2008) 483-493

The Non-Perturbative function will give a shift of the angularity distributions



Unphysical results

Bell, Hornig, Lee, Talbert, JHEP01(2019)147

$$\frac{d\Gamma^i_H}{d\tau_a} \to \frac{d\Gamma^i_H}{d\tau_a}\left(\tau_a - c_{\tau_a}\frac{\Omega_1}{m_H}\right)$$

$$c_{\tau_a} = \frac{2}{1-a}$$

Universal non-perturbative parameter

Lee, Sterman, PRD75(2007)014022

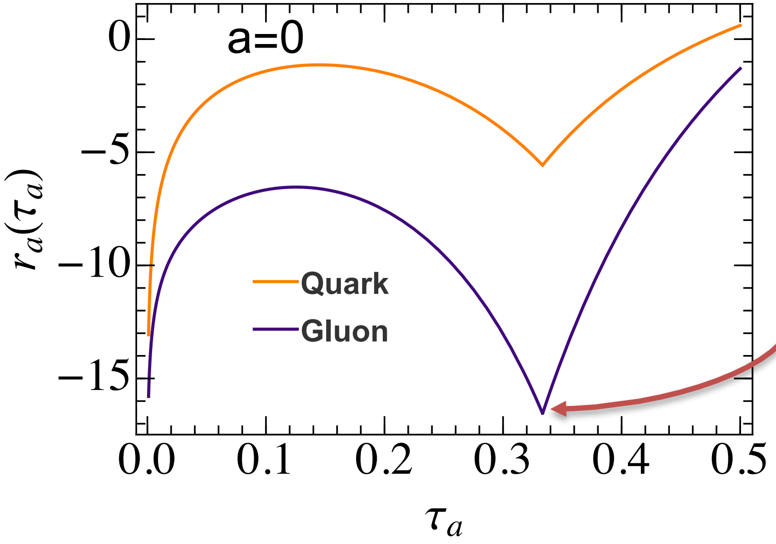
Matching to Fixed order

Factorization is only valid: $\tau_a \ll 1$

$$\frac{d\Gamma^i_H}{\Gamma^i_{H0}d\tau_a} = H^i(m_H,\mu)J_n(\tau_n)\otimes J_{\bar{n}}(\tau_{\bar{n}})\otimes S(\tau_s)$$

Matching to Fixed order:

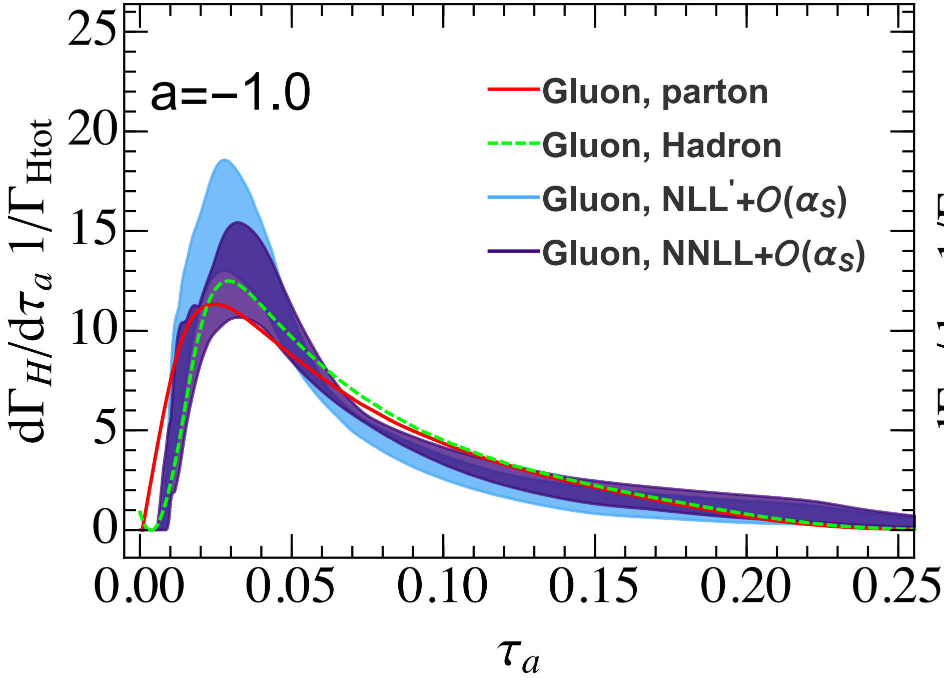
$$\frac{1}{\Gamma^i_{H0}}\frac{d\Gamma^i_H}{d\tau_a} = \underbrace{\frac{1}{\Gamma^i_{H0}}\frac{d\Gamma^{i,\text{resum}}_H}{d\tau_a}}_{\text{Resummation}} + \underbrace{\underbrace{\frac{1}{\Gamma^i_{H0}}\frac{d\Gamma^{i,\text{FO}}_H}{d\tau_a}}_{\text{Fixed order}} - \underbrace{\frac{1}{\Gamma^i_{H0}}\frac{d\Gamma^{i,\text{sing}}_H}{d\tau_a}}_{\text{Singular part}}}_{\text{Non-singular/ remainder function}}$$



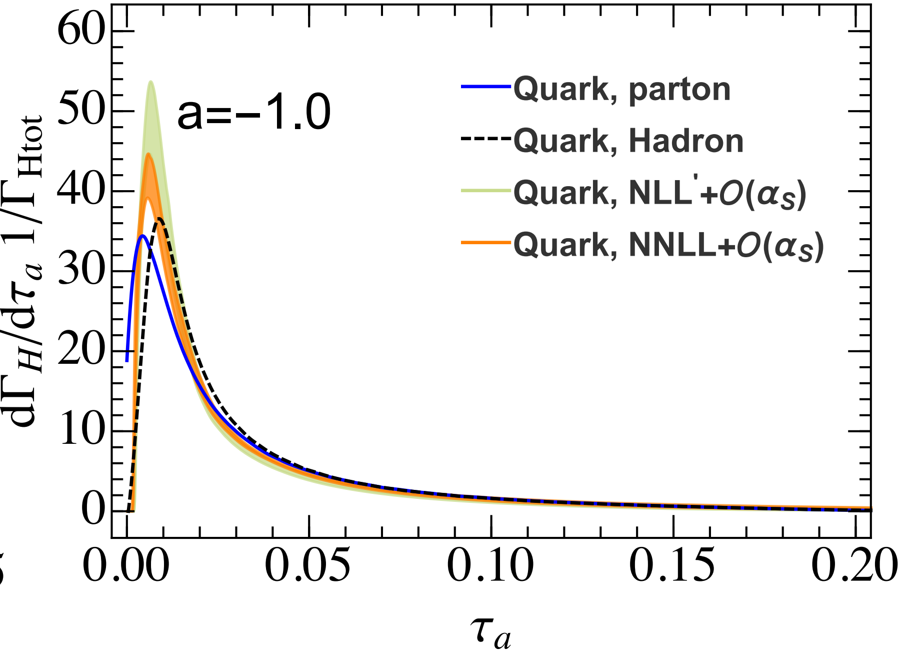
Fixed order =0
Only singular part

Resummaton and Pythia

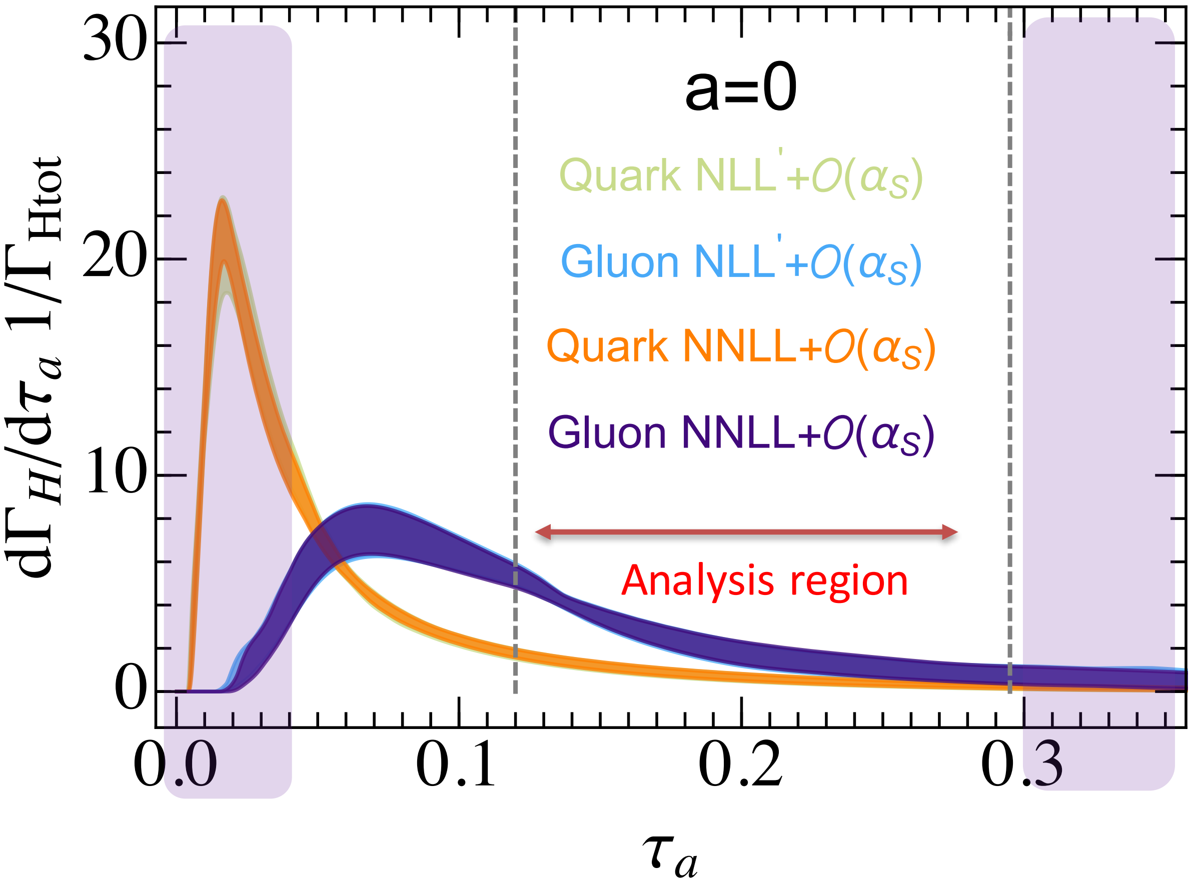
$\Omega_1^g = C_A/C_F\Omega_1^q$



$\Omega_1^q = 0.4$



Light quark Yukawa couplings



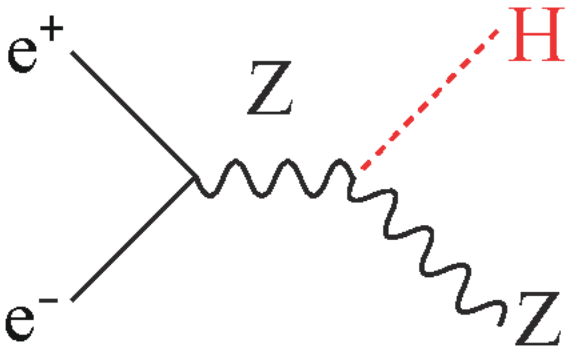
Sensitive to Non-perturbative assumptions

Sensitive to multijet events

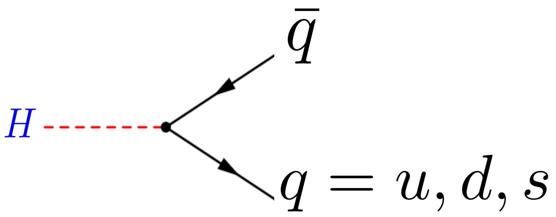
Angularity distributions are very different for quark and gluon final state

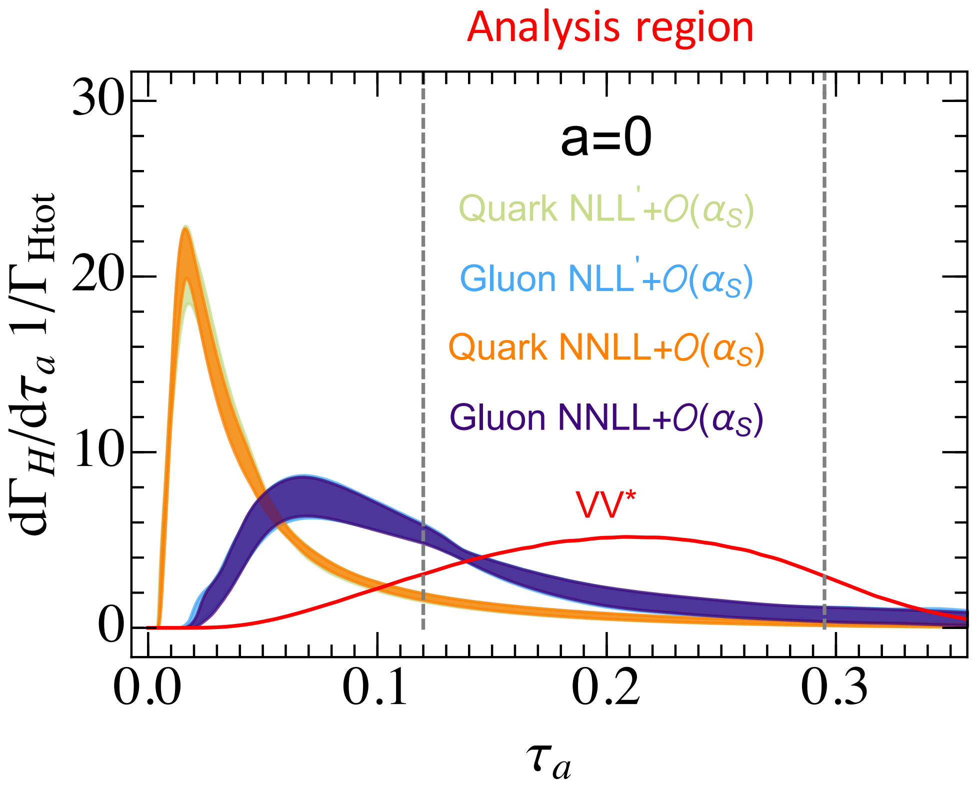
Probing the light quark Yukawa couplings.

Light quark Yukawa couplings@CEPC



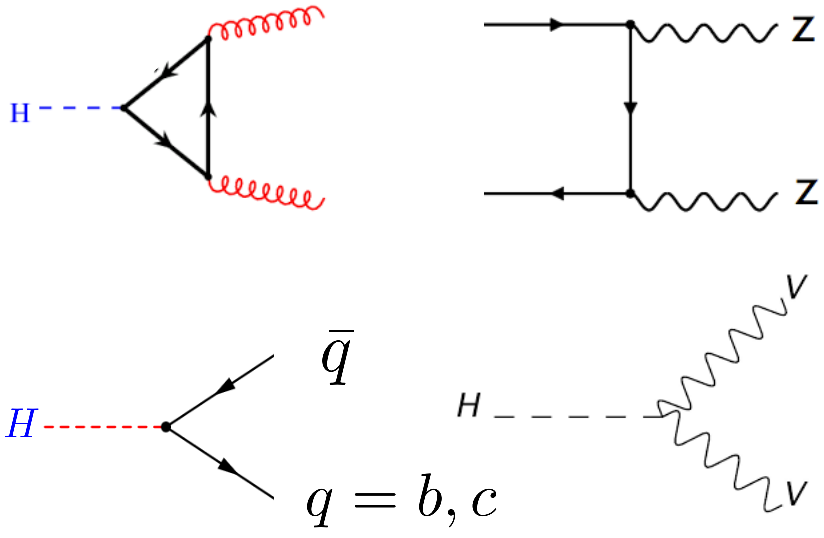
Signal:





Backgrounds:

C. Bell, A. Hornig, C. Lee and J. Talbert, 19': NNLL'+NNLO



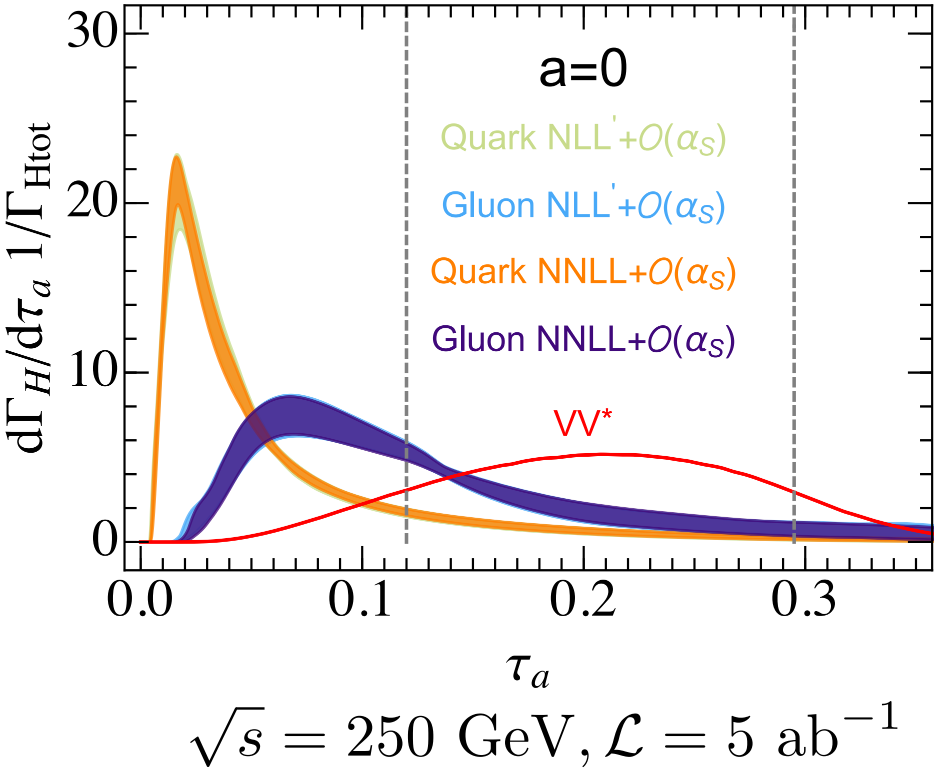
Light quark Yukawa couplings

Likelihood analysis:

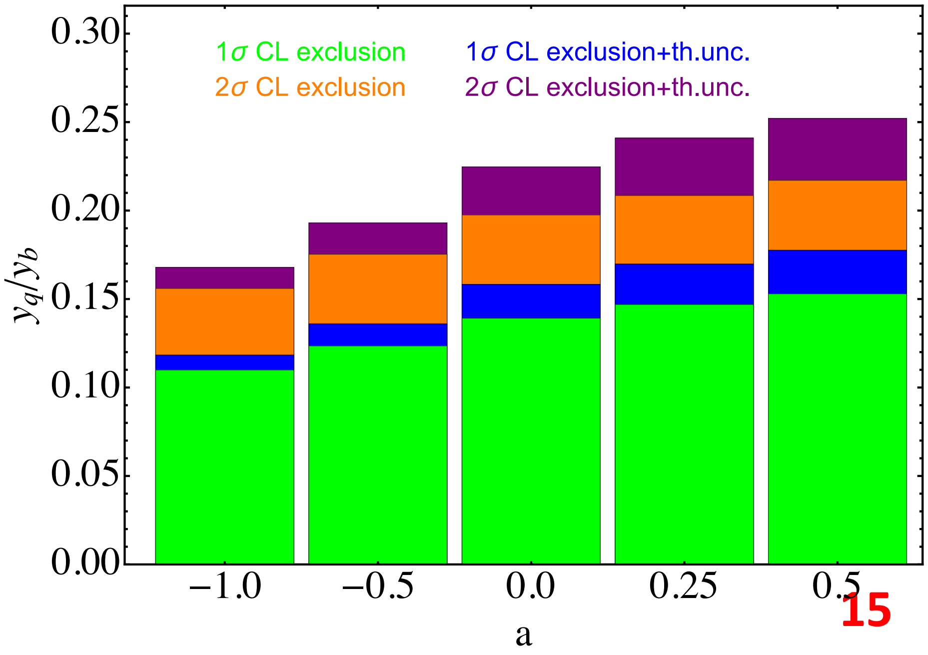
$$L(R_q) = \prod_{i=1}^{N_{\rm bin}} \frac{(s_i(R_q)+b_i)^{n_i}}{n_i!} e^{-s_i(R_q)-b_i}$$

Analysis region

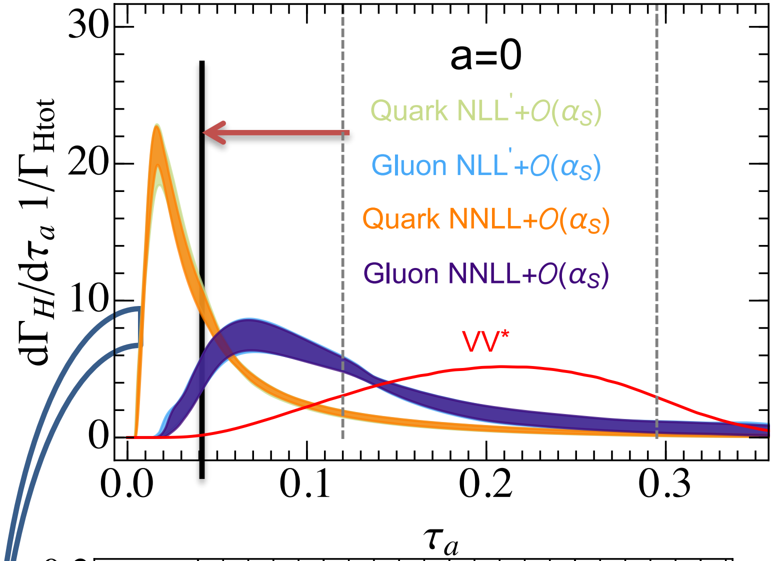
$$R_q = \frac{\mathrm{BR}(H \to q\bar{q})}{\mathrm{BR}(H \to gg)}$$



$\sqrt{s} = 250 \text{ GeV}, \mathcal{L} = 5 \text{ ab}^{-1}$



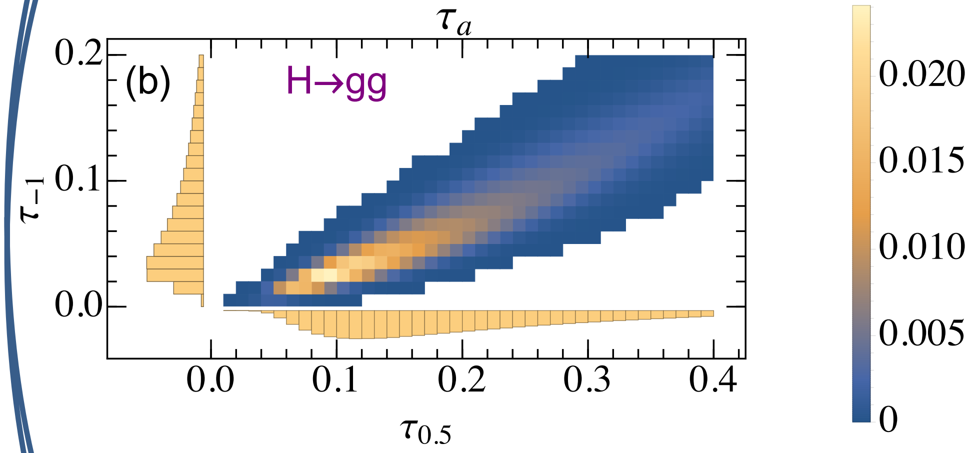
How to improve results?

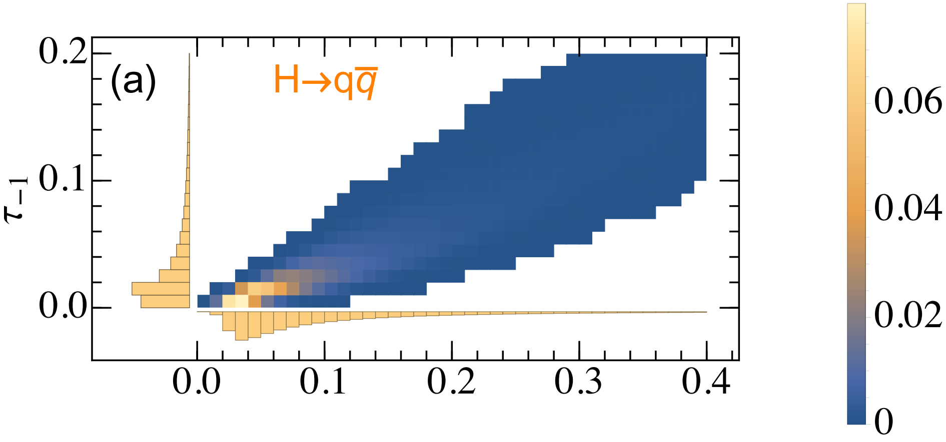


A. Moving to small angularities regions? Soft-Drop?

B. Multiple angularities?

C. NNLL’ predictions? Matching to NNLO





$\frac{y_q}{y_b}$

a	-1.0	-0.5	0.0	0.25	0.5
$[\tau_{\rm min}(a), \tau_{\rm max}(a)]$	0.16	0.18	0.20	0.21	0.22
$[t_0(a), \tau_{\rm max}(a)]$	0.087	0.091	0.091	0.090	0.089

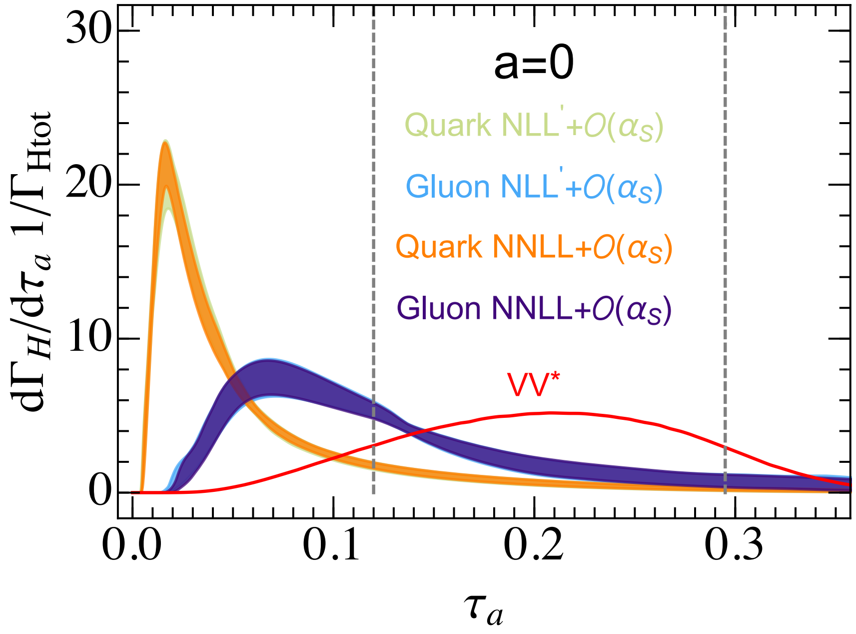
Summary

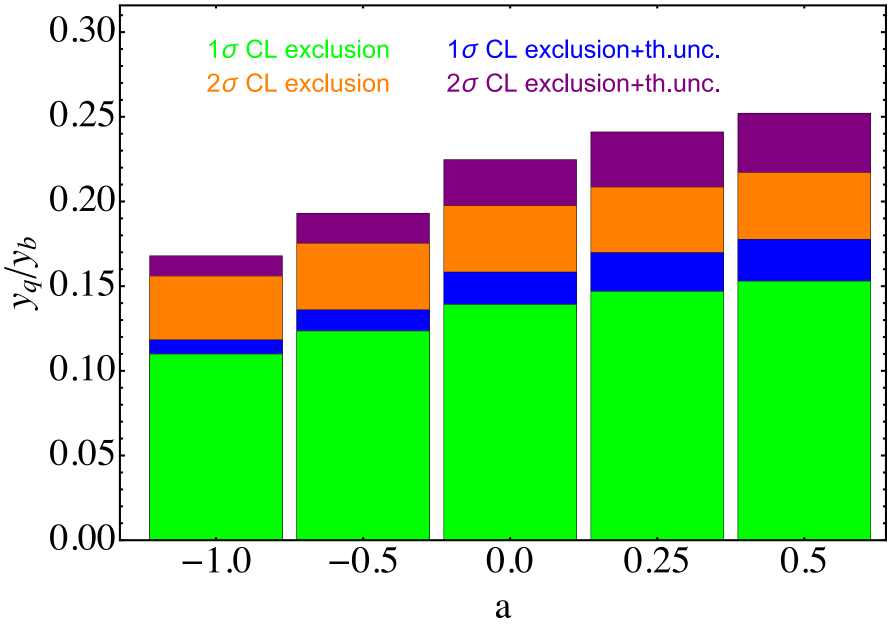
A. Light quark Yukawa couplings are important for us to verify the electroweak symmetry breaking mechanism ;

B. Event shapes are powerful tool to suppress the gluon background;

C. We use angularities from Higgs decay to constrain the light quark Yukawa couplings.

Analysis region

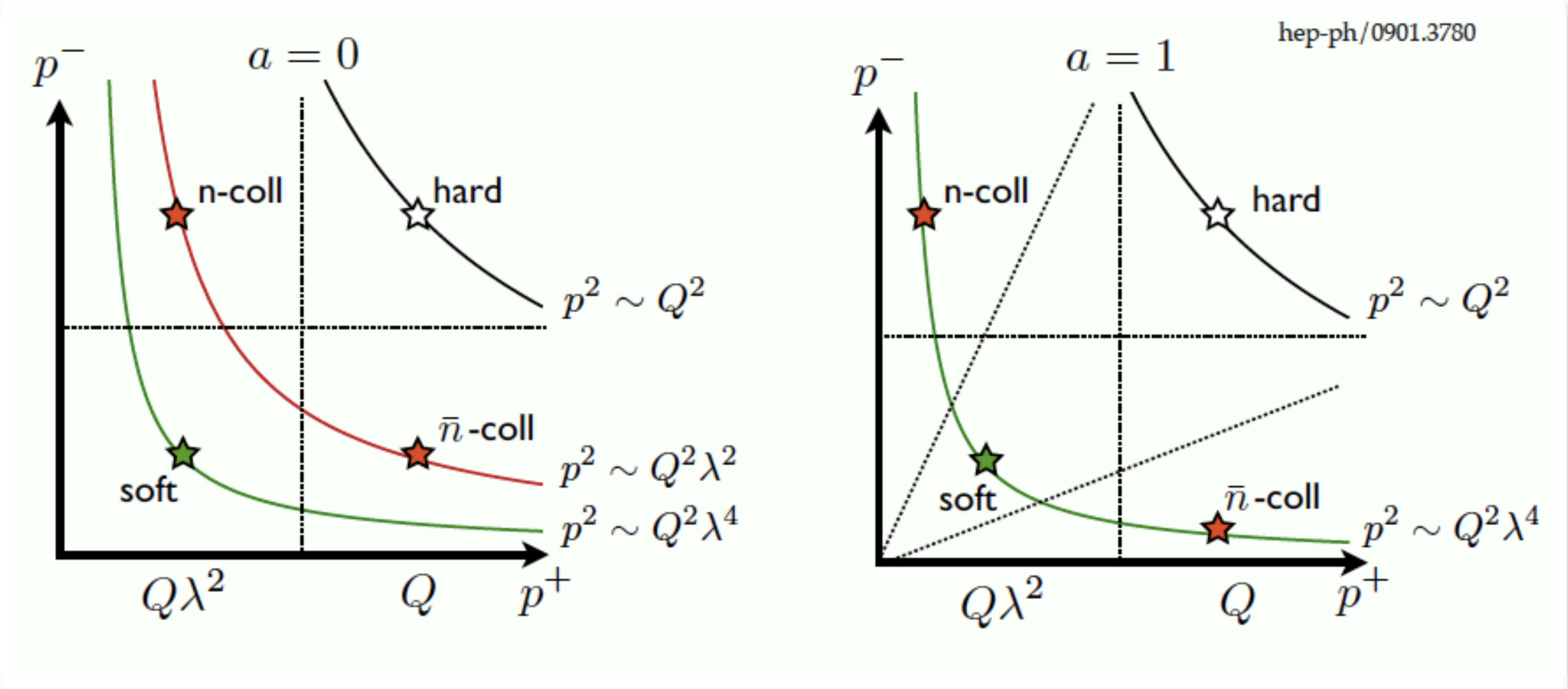




Thank you!

Backup

SCET$_{\text{I}}$ & SCET$_{\text{II}}$ — a virtual(ity) contest



hep-ph/0901.3780

Thrust ***Broadening***

Angularity distributions map between thrust and jet broadening, i.e. between SCET$_{\text{I}}$ and SCET$_{\text{II}}$

Hard, jet and soft function@1 Loop

Hard function:

Berger, Marcantonini, Stewart, Tackmann, Waalewijn, 2011

$$H^q(m_H,\mu) = 1 - \frac{\alpha_s C_F}{2\pi}\left[\ln^2\frac{\mu^2}{m_H^2} + 3\ln\frac{\mu^2}{m_H^2} - 2 + \frac{7\pi^2}{6}\right],$$

$$H^g(m_H,\mu) = 1 - \frac{\alpha_s}{2\pi}\left[C_A\ln^2\frac{\mu^2}{m_H^2} + \beta_0\ln\frac{\mu^2}{m_H^2} - (5+\frac{7\pi^2}{6})C_A + 3C_F\right]$$

Jet function:

Hornig, Lee, Ovanesyan (2009)

$$J_n^i(\tau_a^n,\mu) = \delta(\tau_a^n)\left[1 + \frac{\alpha_s}{2\pi}\left(\frac{2-a}{2(1-a)}C_i\ln^2\frac{\mu^2}{m_H^2} + \gamma_i\ln\frac{\mu^2}{m_H^2} + f_i(a)\right)\right] - \frac{\alpha_s}{2\pi}C_i\left[\left(\frac{\gamma_i}{1-a/2} + \frac{2C_i}{1-a}\ln\frac{\mu}{m_H(\tau_a^n)^{1/(2-a)}}\right)\left(\frac{\theta(\tau_a^n)}{\tau_a^n}\right)\right]_+$$

Soft function:

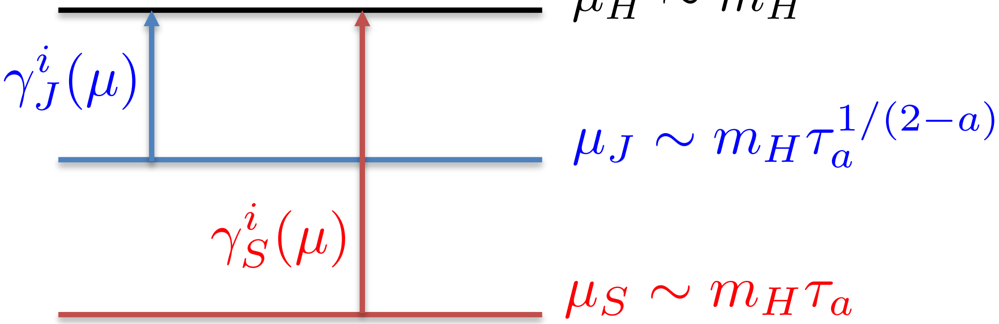
Hornig, Lee, Ovanesyan (2009)

$$S^i(\tau_a^s,\mu) = \delta(\tau_a^s)\left[1 - \frac{\alpha_s C_i}{\pi(1-a)}\left(\frac{1}{2}\ln^2\frac{\mu^2}{m_H^2} - \frac{\pi^2}{12}\right)\right] + \frac{2\alpha_s C_i}{\pi(1-a)}\left[\frac{\theta(\tau_a^s)}{\tau_a^s}\ln\frac{\mu^2}{(m_H\tau_a^s)^2}\right]_+$$

Evolution and Resummation

$$\mu \frac{dH^i}{d\mu} = \gamma_H^i(\mu) H^i \qquad \mu \frac{d\tilde{J}^i}{d\mu} = \gamma_J^i(\mu) \tilde{J}^i \qquad \mu \frac{d\tilde{S}^i}{d\mu} = \gamma_S^i(\mu) \tilde{S}^i$$

Laplace space



$\gamma_J^i(\mu)$

$\gamma_S^i(\mu)$

$\mu_H \sim m_H$

$\mu_J \sim m_H \tau_a^{1/(2-a)}$

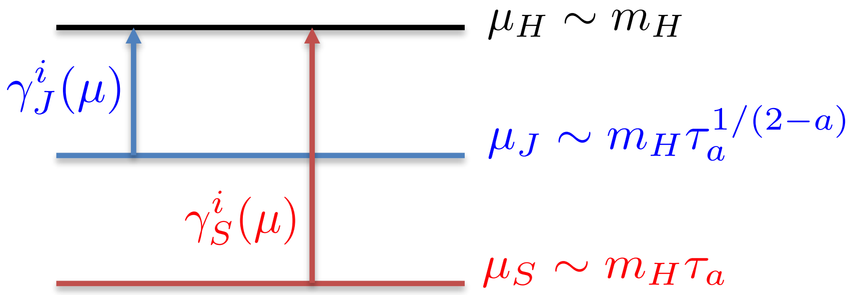
$\mu_S \sim m_H \tau_a$

$$\Gamma_{Hc}^i = \int_0^{\tau_a} d\tau_a' \frac{d\Gamma_H^i}{d\tau_a'}.$$

$$\frac{\Gamma_{Hc}^i}{\Gamma_{H0}^i} = e^{\widetilde{K}^i(\mu_H,\mu_J,\mu_S,m_H)+K_\gamma^i(\mu_H,\mu_J,\mu_S)} \left(\frac{1}{\tau_a}\right)^{\Omega^i(\mu_J,\mu_S)} H^i(m_H,\mu_H)$$
$$\times \widetilde{J}^i \left(\partial_{\Omega^i} + \ln \frac{\mu_J^{2-a}}{m_H^{2-a}\tau_a}, \mu_J\right)^2 \widetilde{S}^i \left(\partial_{\Omega^i} + \ln \frac{\mu_S}{m_H \tau_a}, \mu_S\right) \frac{e^{\gamma_E \Omega^i}}{\Gamma(1-\Omega^i)}.$$

Profile scales and their variation

Typical scales:



$\mu_H \sim m_H$

$\gamma_J^i(\mu)$

$\mu_J \sim m_H \tau_a^{1/(2-a)}$

$\gamma_S^i(\mu)$

$\mu_S \sim m_H \tau_a$

Peak Region:

$$\mu_H \gg \mu_J \gg \mu_S \sim \Lambda_{QCD}$$

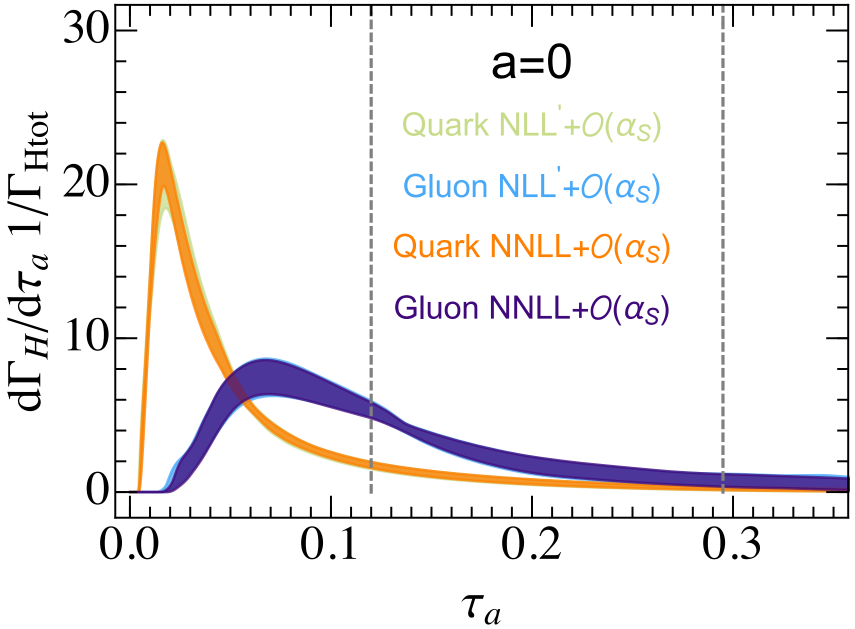
Tail Region:

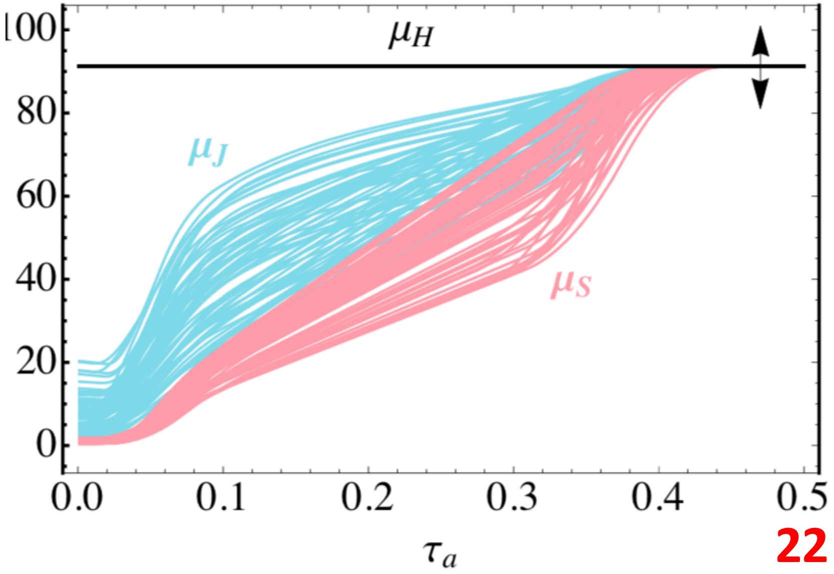
$$\mu_H \gg \mu_J \gg \mu_S \gg \Lambda_{QCD}$$

Far Tail Region:

$$\mu_H = \mu_J = \mu_S \gg \Lambda_{QCD}$$

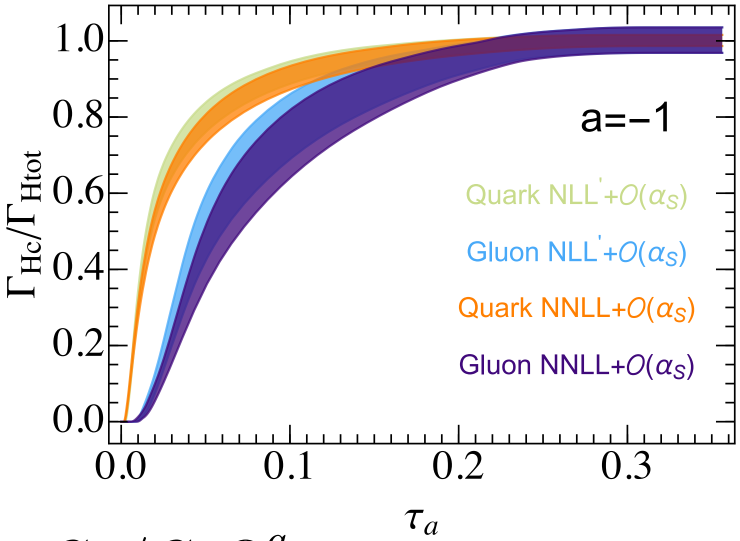
G. Bell, A. Hornig, C. Lee and J. Talbert, *JHEP* 01 (2019) 147

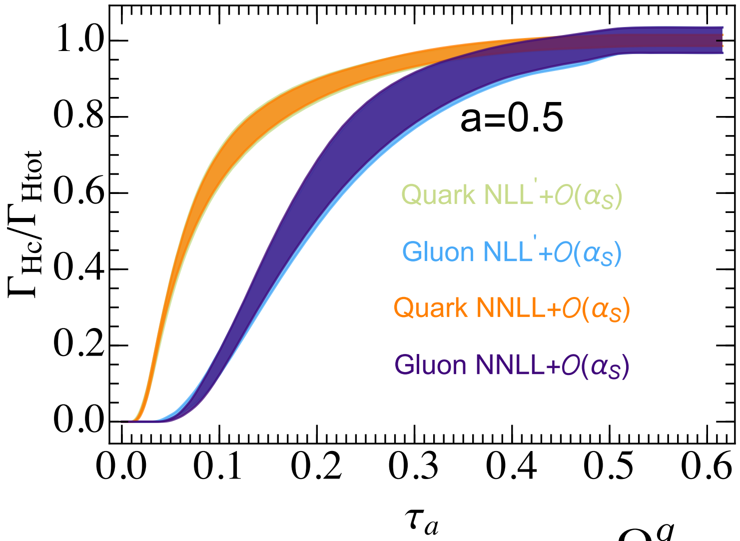




$$\Gamma^i_{Hc} = \int_0^{\tau_a} d\tau'_a \frac{d\Gamma^i_H}{d\tau'_a}.$$

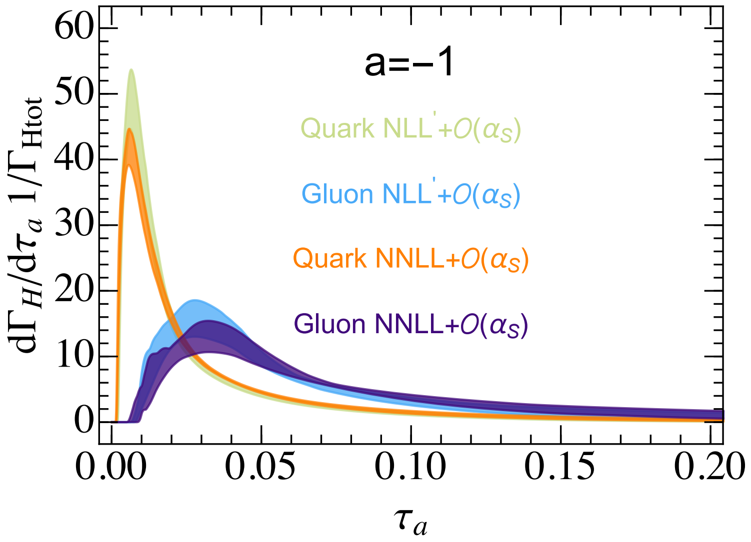
Numerical Results

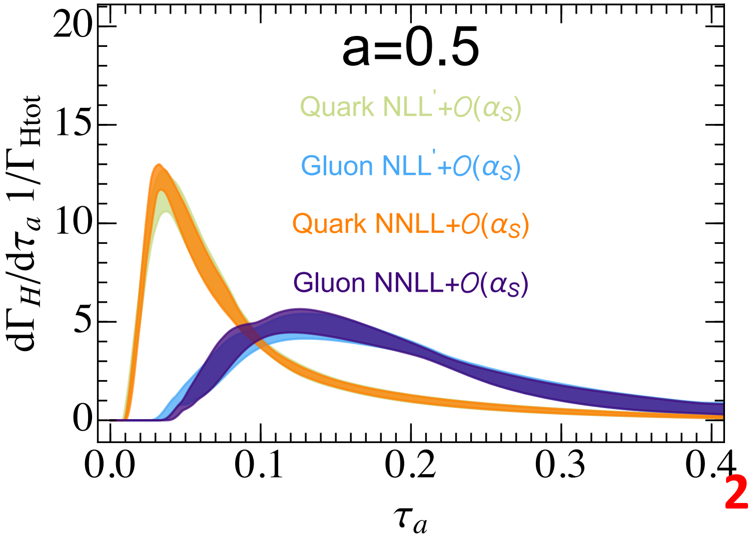




$$\Omega_1^g = C_A/C_F \Omega_1^q$$

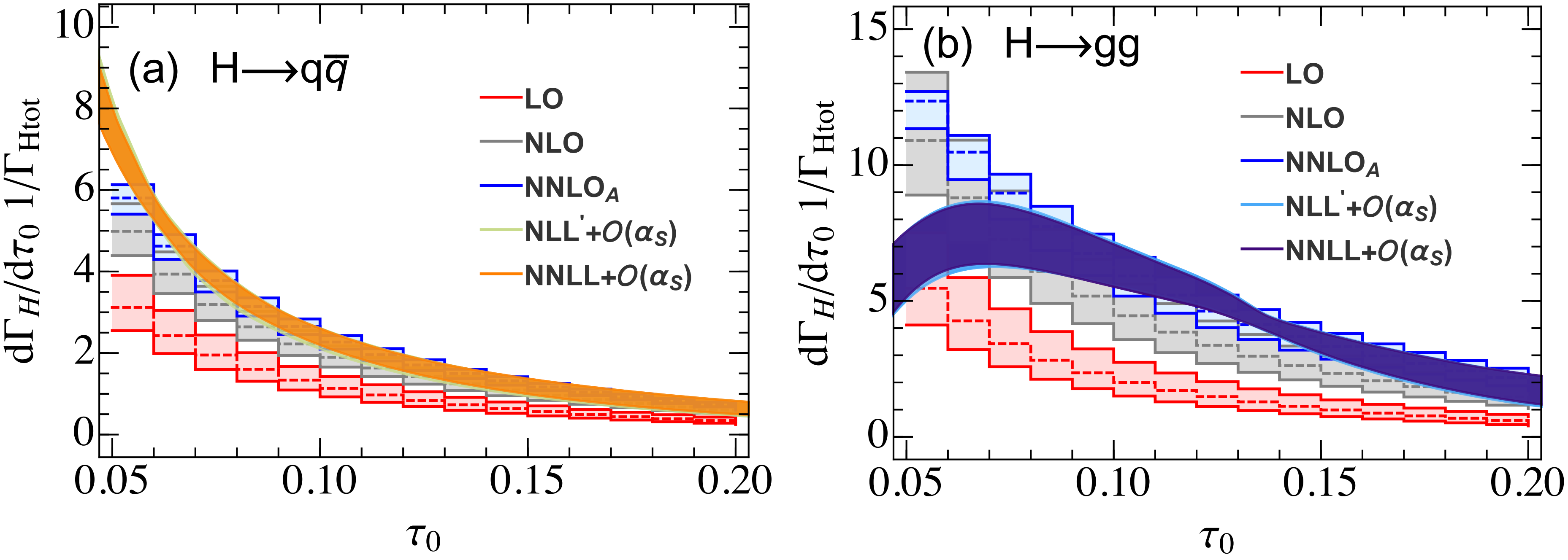
$$\Omega_1^q = 0.4$$





Resummation and fixed order

Thrust



NNLOA: approximate NNLO

Fixed order prediction is from, Gao, Gong, Ju, Yang, JHEP03(2019)030

Profile function

Smooth transition between different scale regions:

$$\mu_H = e_H m_H,$$

$$\mu_S(\tau_a) = \left[1 + e_S \theta(t_3 - \tau_a)\left(1 - \frac{\tau_a}{t_3}\right)^2\right]\mu_{\rm run}(\tau_a),$$

$$\mu_J(\tau_a) = \left[1 + e_J \theta(t_3 - \tau_a)\left(1 - \frac{\tau_a}{t_3}\right)^2\right]\mu_H^{\frac{1-a}{2-a}}\mu_{\rm run}(\tau_a)^{\frac{1}{2-a}},$$

$$\mu_{\rm run} = \begin{cases} \mu_0, & \tau_a \le \tau_0, \\ \xi\left(\tau_a; \{t_0, \mu_0, 0\}, \{t_1, 0, \frac{r}{\tau_a^{\rm sph}\mu_H}\}\right), & t_0 \le \tau_a \le t_1, \\ \frac{r}{\tau_a^{\rm sph}}\mu_H \tau_a, & t_1 \le \tau_a \le t_2, \\ \xi\left(\tau_a; \{t_2, 0, \frac{r}{\tau_a^{\rm sph}\mu_H}\}, \{t_3, \mu_H, 0\}\right), & t_2 \le \tau_a \le t_3, \\ \mu_H, & \tau_a \ge t_3. \end{cases}$$

$$\xi\left(\tau_a; \{t_0, y_0, r_0\}, \{t_1, y_1, r_1\}\right) = \begin{cases} a + r_0(\tau_a - t_0) + c(\tau_a - t_0)^2, & \tau_a \le \frac{\tau_0 + \tau_1}{2} \\ A + r_1(\tau_a - t_1) + C(\tau_a - t_1)^2, & \tau_a \ge \frac{\tau_0 + \tau_1}{2} \end{cases},$$

$$a = y_0 + r_0 t_0, \quad A = y_1 + r_1 t_1, \quad c = 2\frac{A - a}{(t_0 - t_1)^2} + \frac{3r_0 + r_1}{2(t_0 - t_1)}, \quad C = 2\frac{a - A}{(t_0 - t_1)^2} + \frac{3r_1 + r_0}{2(t_1 - t_0)}.$$

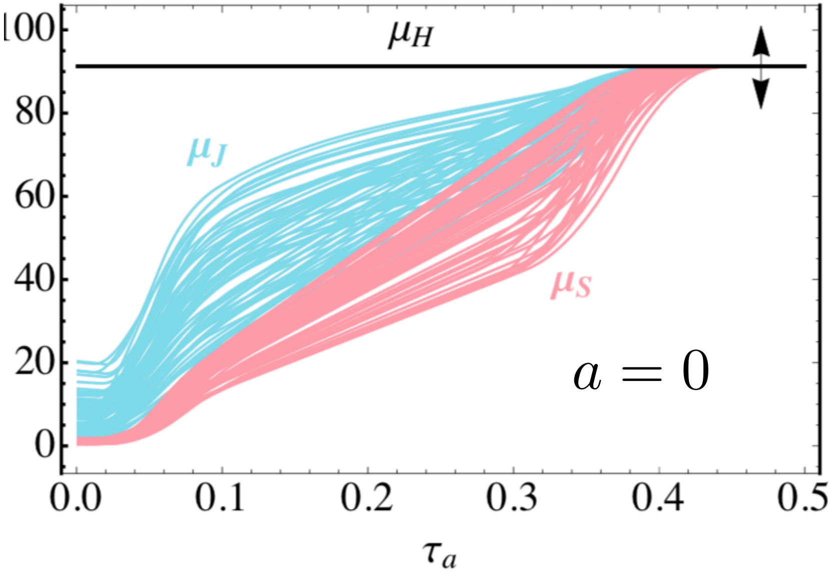
$$t_0 = \frac{n_0}{m_H}3^a, \qquad t_1 = \frac{n_1}{m_H}3^a, \qquad t_2 = n_2 \times 0.295^{1-0.637a}, \qquad t_3 = n_3 \tau_a^{\rm sph}$$

Non-singular part:

$$\mu_{\rm ns}(\tau_a) = \begin{cases} \frac{1}{2}(\mu_H + \mu_J(\tau_a)), & n_s = 1 \\ \mu_H, & n_s = 0 \\ \frac{1}{2}(3\mu_H - \mu_J(\tau_a)), & n_s = -1 \end{cases}$$

Theoretical uncertainty

e_H	e_J	e_S	$n_0(q)$	$n_0(g)$
$0.5 \leftrightarrow 2$	$-0.5 \leftrightarrow 0.5$	0	$1 \leftrightarrow 2$ GeV	$2.8 \leftrightarrow 3.5$ GeV
$n_1(q)$	$n_1(g)$	n_2	n_3	$\mu_0(q)$
$8.5 \leftrightarrow 11.5$ GeV	$25 \leftrightarrow 28$ GeV	$0.9 \leftrightarrow 1.1$	$0.8 \leftrightarrow 0.9$	$0.8 \leftrightarrow 1.2$ GeV
$\mu_0(g)$	$R_0(q)$	$R_0(g)$	r	
$2.2 \leftrightarrow 3.0$ GeV	$\mu_0(q) - 0.4$ GeV	$\mu_0(g) - 1.8$ GeV	$0.75 \leftrightarrow 1.33$	



Evolution and Resummation

$$\widetilde{K}_\Gamma^i(\mu, \mu_F, Q) = \int_{\mu_F}^{\mu} \frac{d\mu'}{\mu'} \Gamma_{\text{cusp}}^i[\alpha_s(\mu')] \ln \frac{\mu'}{Q}.$$

$$\eta_\Gamma^i(\mu, \mu_F) = \int_{\mu_F}^{\mu} \frac{d\mu'}{\mu'} \Gamma_{\text{cusp}}^i[\alpha_s(\mu')], \qquad K_{\gamma_F}^i(\mu, \mu_F) = \int_{\mu_F}^{\mu} \frac{d\mu'}{\mu'} \gamma_F^i[\alpha_s(\mu')].$$

$$\begin{aligned}
\Omega^i \equiv \Omega^i(\mu_J, \mu_S) &= -2\kappa_J \eta_\Gamma^i(\mu, \mu_J) - \kappa_S \eta_\Gamma^i(\mu, \mu_S), \\
K_\gamma^i(\mu_H, \mu_J, \mu_S) &\equiv K_{\gamma_H}^i(\mu, \mu_H) + 2K_{\gamma_J}^i(\mu, \mu_J) + K_{\gamma_S}^i(\mu, \mu_S), \\
\widetilde{K}^i(\mu_H, \mu_J, \mu_S, Q) &\equiv -4\widetilde{K}_\Gamma^i(\mu, \mu_H, Q) - 2j_J \kappa_J \widetilde{K}_\Gamma^i(\mu, \mu_J, Q) - \kappa_S \widetilde{K}_\Gamma^i(\mu, \mu_S, Q).
\end{aligned}$$

Event number

$$\sqrt{s} = 250\ \mathrm{GeV}, \mathcal{L} = 5\ \mathrm{ab}^{-1}$$

J. Gao, JHEP 01 (2018) 038

A. Two non-b/c jets in final state

B. Recoil mass constraint

$$N_b^g = 3070,\ \ N_b^{\mathrm{HF}} = 0.1 N_b^g,\ \ N_b^{ZZ} = 0.2 N_b^g,\ \ N_b^{4q} = 0.6 N_b^g$$