Research Training Group Physics of the Heaviest Particles at the LHC | RWTH AACHEN UNIVERSITY

TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Complete NLO corrections to off-shell $t\bar{t}$ production in the $\ell + j$ channel

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In collaboration with Daniel Stremmer and Małgorzata Worek

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Collaborative Research Center TRR 257

PPH

Particle Physics Phenomenology after the Higgs Discovery

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Why $\ell + j$, and what was missing?

- $\ell + j$ is a clean, high-statistics decay mode, useful for precision differential measurements.
- One neutrino only ⇒ better reconstruction of the top system.
- Boosted regions need NLO QCD *and* EW corrections: EW Sudakov terms can be sizeable in tails. (Czakon et al., JHEP 10 (2017) 186).

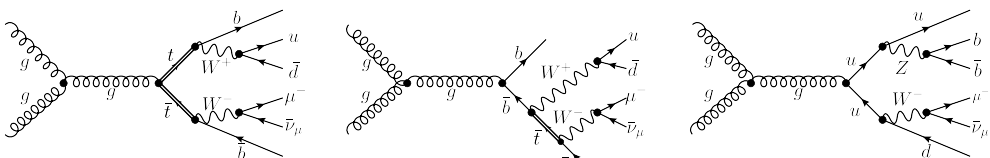
full off-shell = resonant + non-resonant
+interference + Breit-Wigner effects

This work

First **complete full off-shell NLO QCD+EW** calculation for the semi-leptonic channel, including all Born channels and all NLO coupling orders.

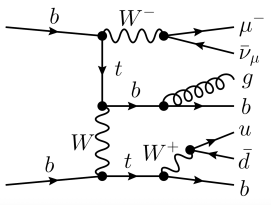
Main complication

Real QCD/EW radiation introduces photons and light jets in the same fiducial final state, so the jet definition has to be IR safe.

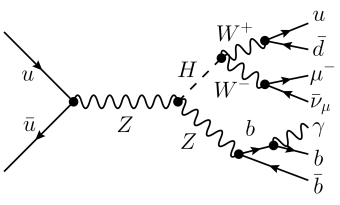


(Feynman diagrams done with FeynGame, Bündgen et al., Comput.Phys.Commun. 314 (2025) 109662)

Process Definition and Fiducial Phase Space



$$pp \to \ell^- \bar{\nu}_\ell \, j_b \, j_b \, j \, j + X$$



Final-state definition

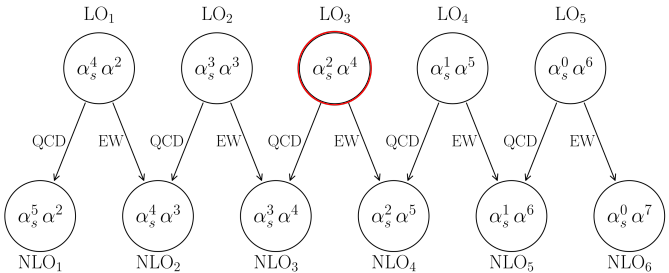
- j_b: b-tagged jets; j: light-flavour jets.
- X: extra QCD or EW radiation at NLO.
- Extra photons/jets in X are **not tagged**; they enter through the inclusive event definition.

Resonance-enhancing selection

- At least two b-jets and two light jets.
- Fiducial acceptance for jets and lepton.
- Resonance-enhancing cut:

$$Q_{\text{cut}}: \quad |M_{jj} - M_W| < 20 \text{ GeV}.$$

What “complete NLO” means



Dominant contributions

$$\mathrm{Born}_3 \quad \text{and} \quad \mathrm{NLO}_3$$

Complete NLO contributions

$$\mathrm{NLO} = \mathrm{Born}_1 + \cdots + \mathrm{Born}_5 + \mathrm{NLO}_1 + \cdots + \mathrm{NLO}_6$$

“Complete” means QCD-background terms, EW-induced pieces, photon-initiated channels and interferences are included together.

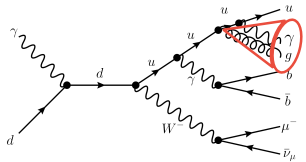
IR safety I: democratic clustering and $q \to q\gamma$

Problem

With photons and jets in the same event, a photon–parton pair can be clustered together (**democratic clustering**). The photon energy fraction is

$$z_\gamma = \frac{E_\gamma}{E_\gamma + E_{\text{jet}}}.$$

If $z_\gamma > z_{\gamma,\text{cut}}$, the cluster is treated as a photon and the event is rejected. This removes part of the $q \to q\gamma$ collinear phase space.



Fix

Restore the missing collinear contribution with a quark-to-photon fragmentation term (Denner et al., JHEP 01 (2015) 094):

$$d\hat{\sigma}^{\text{finite}}_{\text{jet}+\gamma} = d\hat{\sigma}^{\text{demo}}_{\text{jet}+\gamma} - \sum_j d\hat{\sigma}^{\text{Born}}_j \otimes D^B_{j\to\gamma}.$$

IR-safe ingredient

$$D^B_{j\to\gamma} = D_{j\to\gamma}(\mu_{\text{Fr}}) - \frac{\alpha}{2\pi}\Gamma^{(0)}_{j\to\gamma} + \mathcal{O}(\alpha^2)$$

IR safety II: $\gamma \to q\bar{q}$ clustered as a jet

Problem

A collinear $q\bar{q}$ pair can originate from a photon splitting and be clustered into a light jet. The virtual counterpart would live in an underlying Born state with an identified photon, which is not part of the process definition.

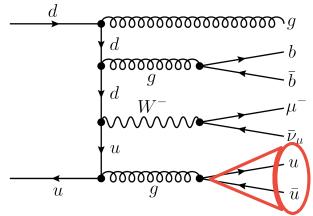
Fix

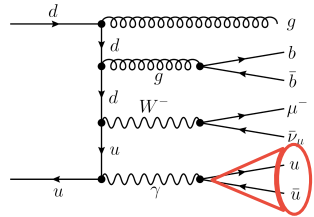
Add the photon-to-jet conversion contribution (Denner et al., Phys.Lett.B 798 (2019) 134951):

$$d\sigma^{\text{finite}}_{X+q\bar{q}} = d\sigma^{\text{pert}}_{X+q\bar{q}} + d\sigma^{\text{LO}}_{X+\gamma} \int_0^1 dz\, D^B_{\gamma\to\text{jet}}(z).$$

Outcome

Standard NLO subtraction + quark-to-photon fragmentation + photon-to-jet conversion
$\Rightarrow$ IR-safe complete-NLO prediction.





Integrated rates: subleading complete-NLO terms are small

With Q_{cut} : $|M_{jj} - M_W| < 20$ GeV

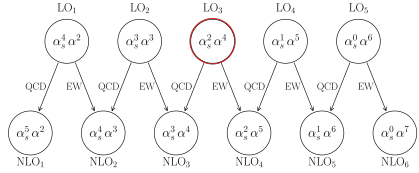
Prediction	σ [pb]	Scale variation
Born_3	31.264(4)	$^{+30.7\%}_{-22.0\%}$
Born	31.634(4)	$^{+30.7\%}_{-22.0\%}$
NLO_{QCD}	29.72(2)	$^{+1.4\%}_{-6.0\%}$
NLO	30.16(2)	$^{+1.5\%}_{-5.6\%}$

$$\sigma_{\text{NLO}} - \sigma_{\text{NLO}_{\text{QCD}}} \simeq +1.5\% \times \sigma_{\text{NLO}_{\text{QCD}}}.$$

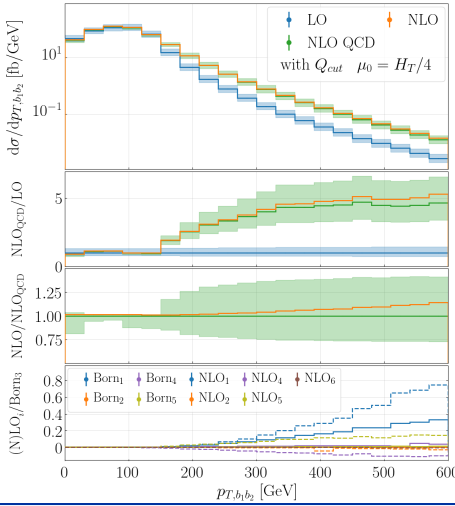
Integrated subleading NLO effects are small after applying Q_{cut}.

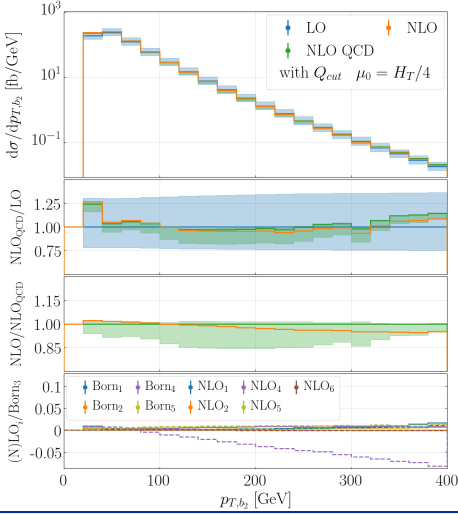
Interpretation

- Born_3 and NLO_3 dominate the fiducial rate.
- Individual subleading NLO orders are at the per-cent level or below.
- The Q_{cut} suppresses QCD background-like configurations.



Differential tails: subleading terms can matter locally





- p_{T,b_1b_2} tail: subleading QCD-background contribution $\mathrm{NLO}_1 \sim +75\%$; EW Sudakov-type term $\mathrm{NLO}_4 \sim -11\%$.
- p_{T,b_2}: EW Sudakov logarithm, NLO_4 -8%, less affected by QCD corrections.

Take-home message

1. Complete and finite

Full off-shell semi-leptonic $t\bar{t}$ with all Born orders and all NLO QCD/EW coupling orders can be defined in an IR-safe way.

2. Integrated rates

With the Q_{cut} cut, the fiducial cross section is dominated by Born_3 and NLO_3; subleading complete-NLO terms are small.

3. Differential tails

In selected high-p_T regions, subleading QCD, EW Sudakov and photon-induced effects can become visible and can cancel each other.

The complete NLO framework shows that IR-safe predictions can be obtained, and identifies where the full set of QCD/EW effects is phenomenologically relevant.

BACKUP

Setup and cuts

Setup

- pp collisions at $\sqrt{s} = 13.6$ TeV.
- 5FS, massless b quarks, diagonal CKM.
- G_μ scheme.
- Photon PDFs included consistently with NLO EW corrections.

Jet algorithm and fiducial cuts

- anti-k_T, $R = 0.4$.
- Democratic clustering, $z_{\gamma,\text{cut}} = 0.7$.
- $p_T > 25$ GeV and $|y| < 2.5$ for charged lepton, b-jets and light jets.
- $\Delta R > 0.4$ among identified objects.
- Optional Q_{cut} : $|M_{jj} - M_W| < 20$ GeV.

Backup: Detailed integrated cross sections with Q_{cut}

		σ_i [pb]	Ratio to Born_3
Born_1	$\mathcal{O}(\alpha_s^4\alpha^2)$	0.138(2)	0.44%
Born_2	$\mathcal{O}(\alpha_s^3\alpha^3)$	0.0002(1)	0.00%
Born_3	$\mathcal{O}(\alpha_s^2\alpha^4)$	31.264(4)	100.00%
Born_4	$\mathcal{O}(\alpha_s\alpha^5)$	0.1336(1)	0.43%
Born_5	$\mathcal{O}(\alpha^6)$	0.0968(1)	0.31%
NLO_1	$\mathcal{O}(\alpha_s^5\alpha^2)$	$+0.144(4)$	$+0.46\%$
NLO_2	$\mathcal{O}(\alpha_s^4\alpha^3)$	$-0.0022(4)$	-0.01%
NLO_3	$\mathcal{O}(\alpha_s^3\alpha^4)$	$-1.90(2)$	-6.10%
NLO_4	$\mathcal{O}(\alpha_s^2\alpha^5)$	$+0.112(2)$	$+0.36\%$
NLO_5	$\mathcal{O}(\alpha_s\alpha^6)$	$+0.1864(6)$	$+0.60\%$
NLO_6	$\mathcal{O}(\alpha^7)$	$+0.00228(2)$	$+0.01\%$

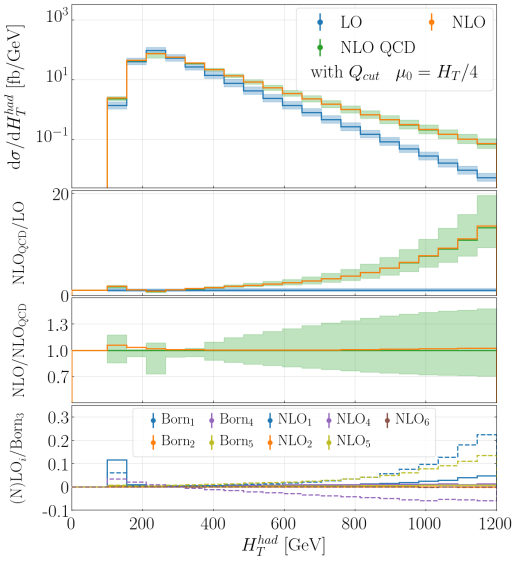
	σ_i [pb]	Ratio
LO	$27.241(2)^{+30.7\%}_{-22.0\%}$	0.87
Born	$31.634(4)^{+30.7\%}_{-22.0\%}$	1.01
NLO_{QCD}	$29.72(2)^{+1.4\%}_{-6.0\%}$	0.95
NLO	$30.16(2)^{+1.5\%}_{-5.6\%}$	0.96

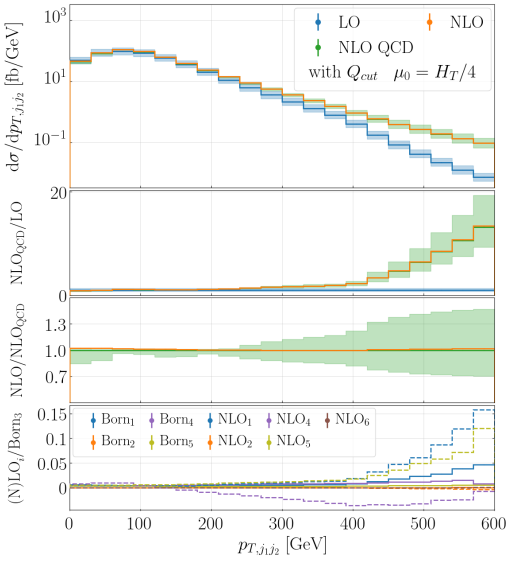
Backup: Detailed integrated cross sections

		σ_i [pb]	Ratio to Born_3
Born_1	$\mathcal{O}(\alpha_s^4\alpha^2)$	$0.778(4)$	2.40%
Born_2	$\mathcal{O}(\alpha_s^3\alpha^3)$	$0.0021(1)$	0.01%
Born_3	$\mathcal{O}(\alpha_s^2\alpha^4)$	$32.388(4)$	100.00%
Born_4	$\mathcal{O}(\alpha_s\alpha^5)$	$0.1365(2)$	0.42%
Born_5	$\mathcal{O}(\alpha^6)$	$0.09980(6)$	0.31%
NLO_1	$\mathcal{O}(\alpha_s^5\alpha^2)$	$+0.220(6)$	$+0.68\%$
NLO_2	$\mathcal{O}(\alpha_s^4\alpha^3)$	$-0.0172(8)$	-0.05%
NLO_3	$\mathcal{O}(\alpha_s^3\alpha^4)$	$+16.56(2)$	$+51.15\%$
NLO_4	$\mathcal{O}(\alpha_s^2\alpha^5)$	$+0.192(2)$	$+0.59\%$
NLO_5	$\mathcal{O}(\alpha_s\alpha^6)$	$+0.276(1)$	$+0.85\%$
NLO_6	$\mathcal{O}(\alpha^7)$	$+0.00235(2)$	$+0.01\%$

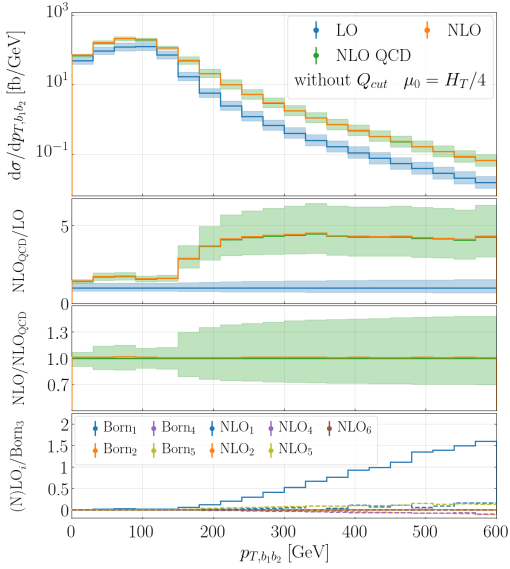
	σ_i [pb]	Ratio
LO	$28.896(2)^{+31.2\%}_{-22.2\%}$	0.89
Born	$33.404(4)^{+31.2\%}_{-22.2\%}$	1.03
$\mathrm{NLO}_{\mathrm{QCD}}$	$49.98(2)^{+15.1\%}_{-13.5\%}$	1.54
NLO	$50.64(2)^{+14.2\%}_{-13.2\%}$	1.56

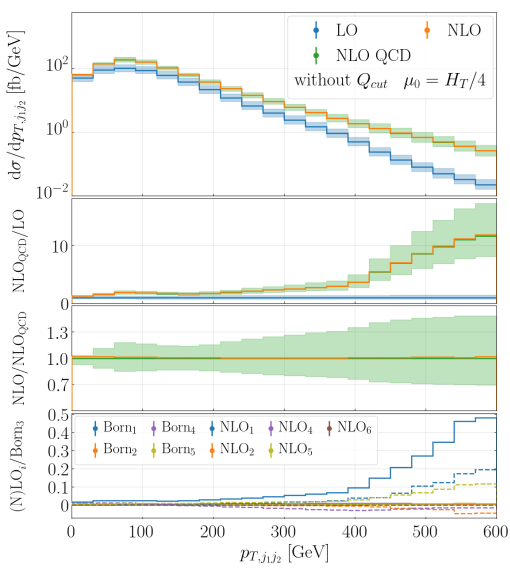
Additional differential examples with Q_{cut}



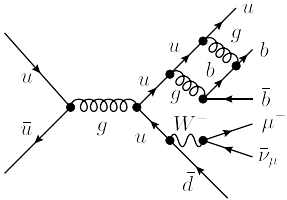


Differential examples without Q_{cut}

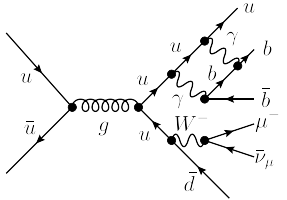




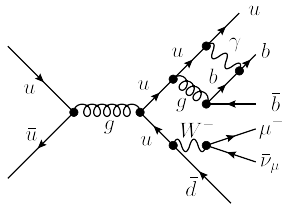
Loop Contributions and Real Radiation



QCD loops

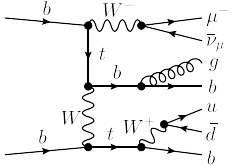


EW loops

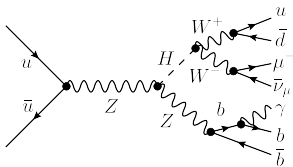


Mixed loops

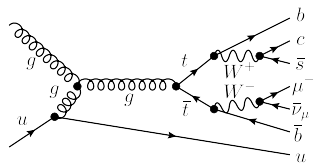
$\Rightarrow$ include EW corrections for consistency



NLO gluon radiation



NLO photon radiation



init./final state splitting

Fragmentation Function and Collinear Divergence Cancellation

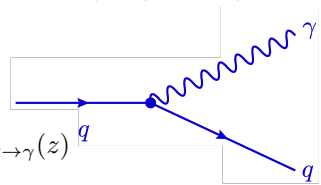
$$d\hat{\sigma}_{\text{jet}+\gamma} = d\hat{\sigma}^{\text{demo}}_{\text{jet}+\gamma} - \sum_j d\hat{\sigma}^{\text{Born}}_j \otimes D^B_{j\to\gamma}$$

- Collinear photon singularity is canceled by the **convolution of the Born-level cross section** with the bare fragmentation function (Denner et al., JHEP 01 (2015) 094).

$$D^B_{q\to\gamma}(z) = D_{q\to\gamma}(z, \mu^2_{Fr}) - \frac{\alpha}{2\pi}\Gamma^{(0)}_{q\to\gamma}(z, \mu^2_{Fr}) + \mathcal{O}(\alpha^2)$$

- The **bare fragmentation function** is split into:
  - a finite, non-perturbative part from experiment (ALEPH, Z.Phys.C 69 (1996) 365-378)
  - and a singular part (from factorization)
- μ_{Fr} dependence handled via **RG evolution**

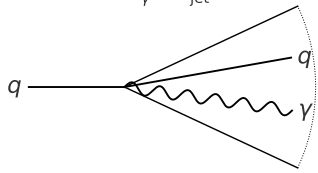
$$\Gamma^{(0)}_{q\to\gamma}(z, \mu^2_{Fr}) = -\frac{1}{\epsilon} Q_q^2 \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{\mu^2_R}{\mu^2_{Fr}}\right)^\epsilon P_{q\to\gamma}(z)$$



- $\Gamma^{(0)}$: **factorization kernel** with the DGLAP splitting function
- Cancels the collinear divergence from real photon emission

Non-perturbative contribution to fragmentation function

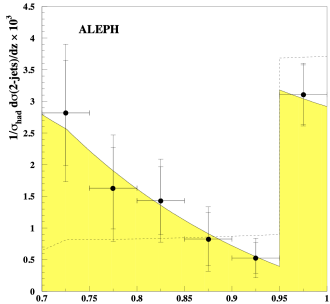
$$z_\gamma = \frac{E_\gamma}{E_\gamma + E_{\text{jet}}}$$



- Non-perturbative part fit to data from ALEPH, $e^+e^- \to \text{jets} + \gamma$ (ALEPH, Z.Phys.C 69 (1996) 365-378)
- At least one jet with a large photonic energy fraction, $z_\gamma > 0.7$

$$D_{q\to\gamma}^{\text{ALEPH},\,\overline{\text{MS}}}(1-z,\mu_F) = \frac{\alpha Q_q^2}{2\pi}\left[\frac{1+z^2}{1-z}\ln\left(\frac{\mu_{Fr}^2}{z^2\mu_0^2}\right) + C\right]$$

$$\mu_0 = 0.14 \text{ GeV}, \qquad C = -13.26$$



Taken from (ALEPH, Z.Phys.C 69 (1996) 365-378)

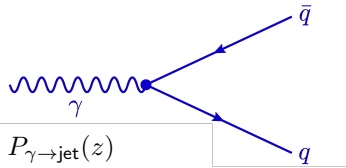
Photon-to-Jet Conversion and Divergence Cancellation

$$\mathrm{d}\sigma_{X+q\bar{q}} = \mathrm{d}\sigma^{\text{pert}}_{X+q\bar{q}} + \mathrm{d}\sigma^{\text{LO}}_{X+\gamma} \int_0^1 \mathrm{d}z\, D^B_{\gamma\to\text{jet}}(z)$$

- Collinear EW divergence from $\gamma \to q\bar{q}$ is canceled by the **convolution of the bare photon-to-jet conversion function** with the underlying Born process (Denner et al., Phys.Lett.B 798 (2019) 134951).

$$D^B_{\gamma\to\text{jet}}(z) = D_{\gamma\to\text{jet}}(z, \mu^2_{Fr}) - \frac{\alpha}{2\pi}\Gamma^{(0)}_{\gamma\to\text{jet}}(z, \mu^2_{Fr}) + \mathcal{O}(\alpha^2)$$

- The **bare conversion function** is split into:
  - a finite, non-perturbative part from experiment (Keshavarz 114025)
  - and a singular part (from factorization)
- μ_{Fr} dependence handled via **RG evolution**

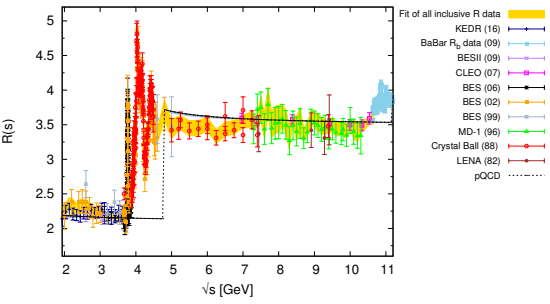


$$\Gamma^{(0)}_{\gamma\to\text{jet}}(z, \mu^2_{Fr}) = -\frac{1}{\epsilon} N_c \sum_q Q^2_q \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{\mu^2_R}{\mu^2_{Fr}}\right) P_{\gamma\to\text{jet}}(z)$$

- $\Gamma^{(0)}$: **factorization kernel** includes sum over all light quark flavors, color factor N_c, and DGLAP splitting function.
- Cancels the collinear divergence from $\gamma \to q\bar{q}$ splitting.

Non-perturbative contribution to photon-to-jet conversion function in form of $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$

- Photon vacuum polarization from $q\bar{q}$ loops drives the running of $\alpha(M_Z^2)$; non-perturbative at low s.
- Use experimental $R(s) = \frac{\sigma(e^+e^-\to\text{hadrons})}{\sigma(e^+e^-\to\mu^+\mu^-)}$ in a dispersion relation to compute $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$.
- Integrate $R(s)$: data at low s + pQCD at high $s \Rightarrow$ precise $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$.



Taken from (Keshavarzi et al., Phys.Rev.D 97 (2018) 11, 114025)

$$\int_0^1 \mathrm{d}z\, D_{\gamma\to\text{jet}}(z,\mu_F) = \Delta\alpha^{(5)}_{\rm had}(M_Z^2) + \sum_q N_{c,q}\frac{Q_q^2\alpha}{3\pi}\left[\ln\left(\frac{\mu_F^2}{M_Z^2}\right) + \frac{5}{3}\right]$$

$$\Delta\alpha^{(5)}_{\rm had}(M_Z^2) = (276.11 \pm 1.11)\times 10^{-4}$$