Jet TMDs and Non-global logs
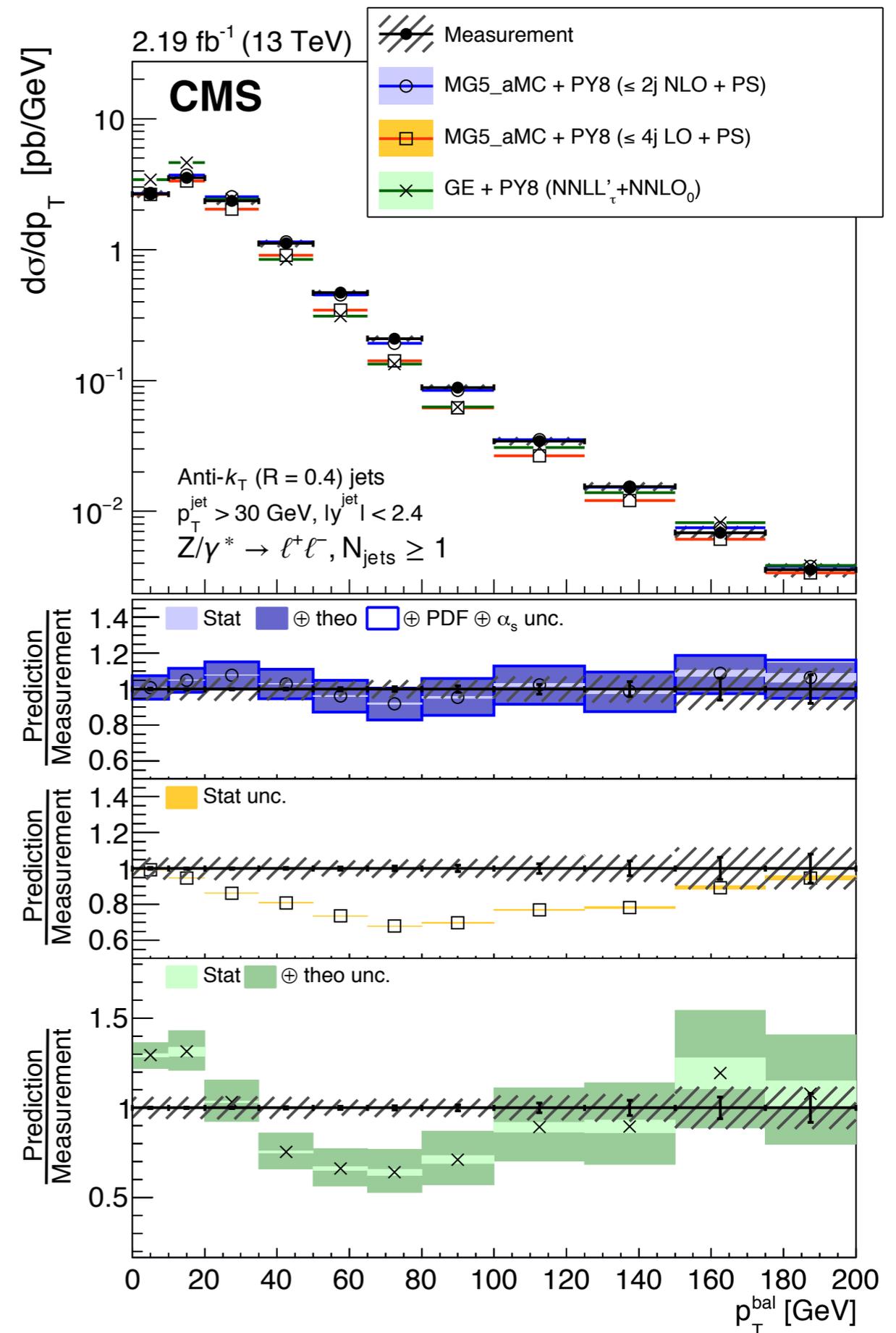
DingYu Shao
CERN, Theory department

TMD factorization and resummation

- **Drell-Yan processes: (Z, W, Higgs, VV, …)**

  - **the all order structure is first understood by CSS at 1985**

  - **computer codes: CUTE, DYRES/DYTurbo, MATRIX, NangaParbat, RADISH, RESBOS, reSolve, SCETlib ……**

  - **N^3LL for single-boson processes (CUTE, RADISH, SCETlib,…)**

  - **event-based automated framework (see Becher's talk); threshold and TMD joint resummatoin (see Hautmann's talk)**

- **Massive colored particles production: (ttbar, …)**

  - **Soft radiations from final states (Li, Li, DYS, Yang, Zhu '12 & Catani, Grazinni & Sargsyan '18)**

- **Jet processes: (jet substructures, jet distributions, …)**

  - **Jet pull (see Wu's talk); Jet shape (see Waalewijn's talk)**

  - **transverse momentum distribution of jets with the beam axis (this talk)**

Transverse momentum balance measurement

$$p_T^{bal} = |\vec{p}_T(Z) + \sum_{jets} \vec{p}_T(j_i)|$$

This observable can be used for jet calibration at pp & energy loss study at PbPb

CMS-SMP-16-015

Transverse momentum balance measurement

$$p_T^{\text{bal}} = |\vec{p}_T(Z) + \sum_{\text{jets}} \vec{p}_T(j_i)|$$

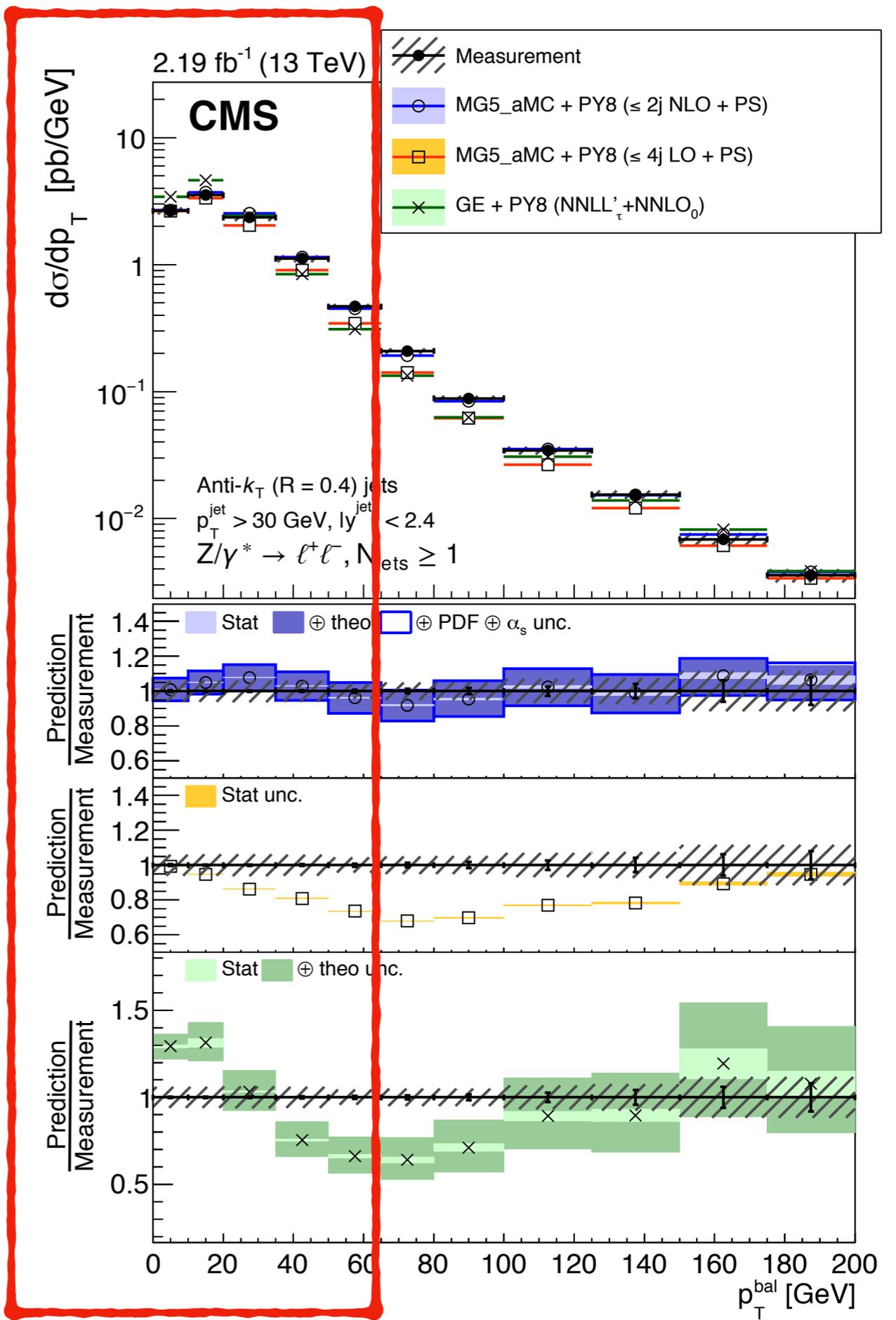**This observable can be used for jet calibration at pp & energy loss study at PbPb**

In the small p_T^{bal} region, one needs all-order results ($\log(p_T^{\text{bal}}/Q)$ resummation)

The predictions from different event generators are not consistent !!!
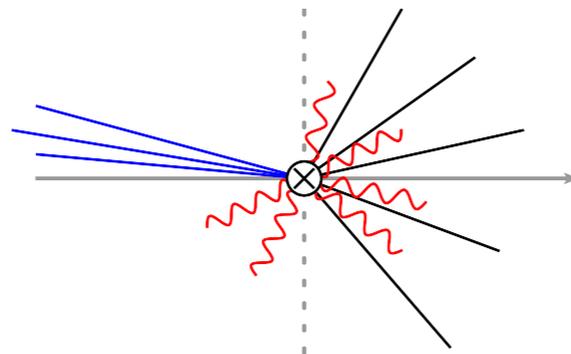

CMS-SMP-16-015

Jet TMDs and non-global logs

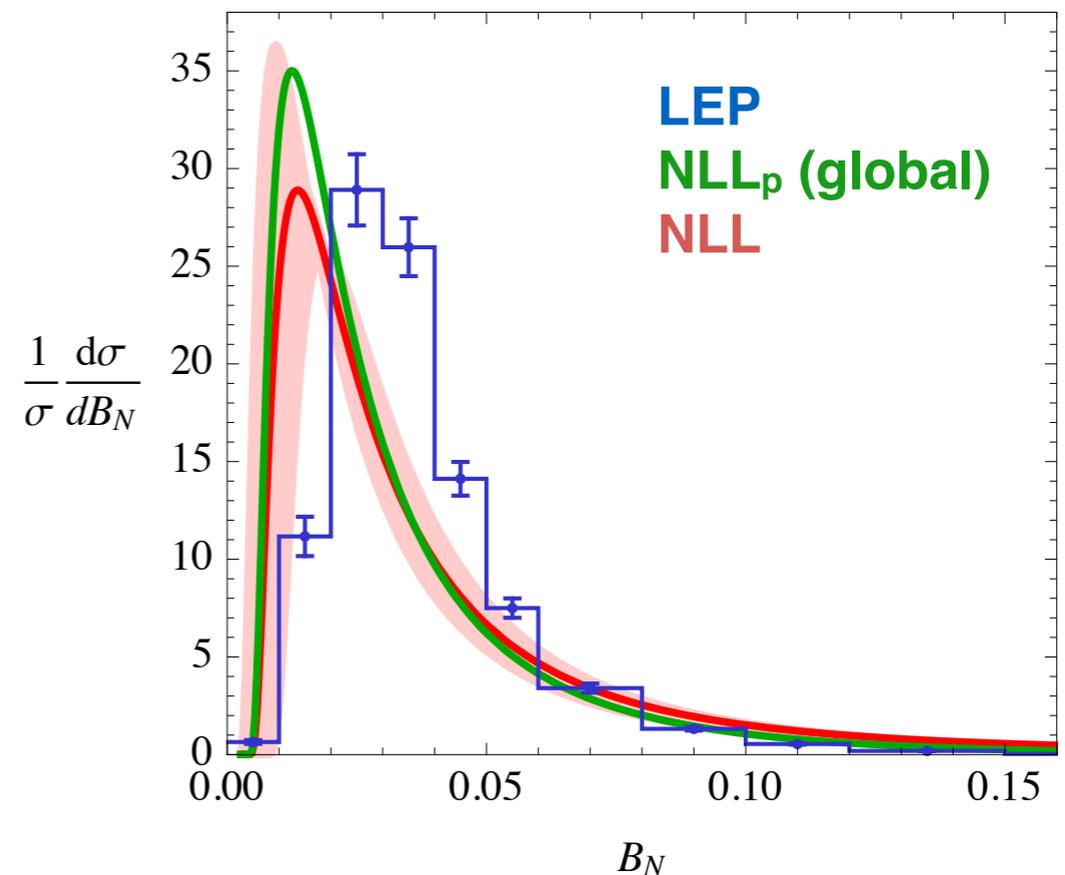- **Non-global logs in jet TMD resummation** (Banfi, Dasgupta & Delenda '08)

$$q_T = \left| \sum_{i \notin \text{ jets}} \vec{k}_{T,i} \right| + \mathcal{O}\left(k_T^2\right)$$

- sum over all soft partons not combined with hard jets

- deviation from $q_T=0$ are only caused by particle flow outside the jet regions

- non-global observables (Dasgupta & Salam '01)

- **E.g. narrow jet broadening resummation** (Becher, Rahn & DYS '17)

$$b_N = \sum_{i \in \text{jets}} \left| \vec{p}_i^\perp \right|$$

$$\frac{d\sigma}{db_L} = \sum_{f=q,\bar{q},g} \int db_L^s \int d^{d-2}p_L^\perp \mathcal{J}_f \left(b_L - b_L^s, p_L^\perp\right)$$

$$\times \sum_{m=1}^{\infty} \left\langle \mathcal{H}_m^f(\{\underline{n}\}, Q) \otimes \mathcal{S}_m\left(\{\underline{n}\}, b_L^s, -p_L^\perp\right) \right\rangle$$

$\frac{1}{\sigma}\frac{d\sigma}{dB_N}$

LEP
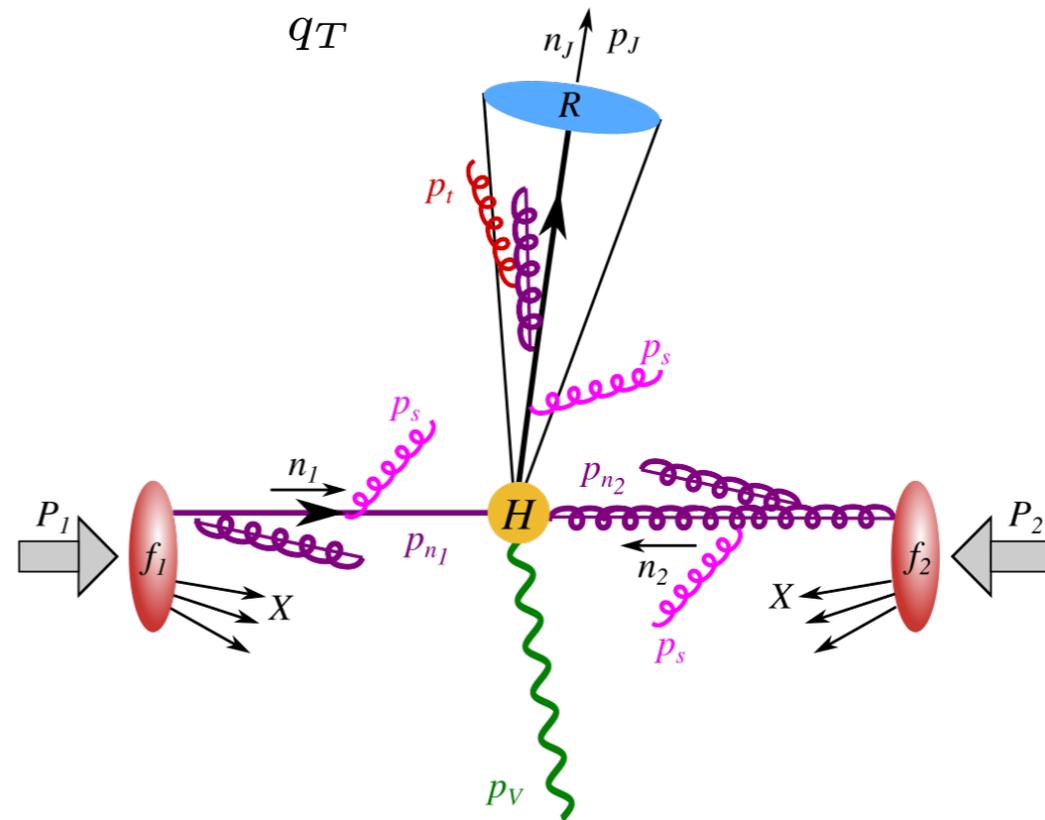NLL$_p$ (global)
NLL

B_N

$\frac{1}{\sigma}\frac{d}{d}$

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Previous works on the transverse momentum resummation for jet processes

- **CSS framework (NLL$_p$ log(qT/Q) w.o. non-global logs; partial log(R) resumed)**
  - **dijet** (Sun, Yuan & Yuan '14 & '15)
  - **jet + V** (Sun, Yuan & Yuan '18; Chen, Qin, Wang, Wei, Xiao, Zhang '18)
  - **lepton + jet (two-loop NGLs)** (Liu, Yuan & Felix '19)
  - **jet + top** (Cao, Sun, Yan, Yuan & Yuan '18 & '19)

- **SCET framework**
  - **photon + jet (NLL$_p$ log(qT/Q) & log(R); coft modes; w.o. non-global logs)** (Buffing, Kang, Lee & Liu '18)

Jet radius and q_T joint resummation for boson-jet correlation

$$N_1(P_1) + N_2(P_2) \to \underbrace{\text{boson}(p_V) + \text{jet}(p_J)}_{q_T} + X$$

$p_h \sim Q(1,1,1)$

$p_{n_J} \sim p_T^J (R^2, 1, R)_{n_J \bar{n}_J}$

$p_{n_1} \sim (q_T^2/Q, Q, q_T)_{n_1 \bar{n}_1}$

$p_s \sim (q_T, q_T, q_T)$

$p_t \sim q_T (R^2, 1, R)_{n_J \bar{n}_J}$

- **Coft modes:** $p_t^\mu \sim q_T(R^2, 1, R)_{n_J \bar{n}_J}$ **for the jet radius R resummation** (Becher, Neubert, Rothen & DYS '15; Chien, Hornig & Lee '15; Kolodrubetz, Pietrulewicz, Stewart, Tackmann & Waalewijn '16; ……)

- **Multi-Wilson-Line operators describe radiations along the jet direction for NGLs resummation** (Caron-Hout '15; Becher, Neubert, Rothen & DYS '15; ……)

Jet radius and q_T joint resummation for boson-jet correlation

(Chien, DYS & Wu 1905.01335)

$$N_1(P_1) + N_2(P_2) \rightarrow \underbrace{\text{boson}(p_V) + \text{jet}(p_J)}_{q_T} + X$$

$p_h \sim Q(1,1,1)$

$p_{n_J} \sim p_T^J \left(R^2, 1, R\right)_{n_J \bar{n}_J}$

$p_{n_1} \sim (q_T^2/Q, Q, q_T)_{n_1 \bar{n}_1}$

$p_s \sim (q_T, q_T, q_T)$

$p_t \sim q_T \left(R^2, 1, R\right)_{n_J \bar{n}_J}$

Factorization formula (neglecting glauber modes):

$$\frac{d\sigma}{d^2 q_T d^2 p_T d\eta_J dy_V} = \sum_{ijk} \int \frac{d^2 x_T}{(2\pi)^2} e^{i\vec{q}_T \cdot \vec{x}_T} \mathcal{S}_{ij \rightarrow Vk}(\vec{x}_T, \epsilon) \mathcal{B}_{i/N_1}(\xi_1, x_T, \epsilon) \mathcal{B}_{j/N_2}(\xi_2, x_T, \epsilon)$$

$$\times \mathcal{H}_{ij \rightarrow Vk}(\hat{s}, \hat{t}, m_V, \epsilon) \sum_{m=1}^{\infty} \langle \mathcal{J}_m^k(\{\underline{n_J}\}, R\, p_J, \epsilon) \otimes \mathcal{U}_m^k(\{\underline{n_J}\}, R\, \vec{x}_T, \epsilon) \rangle$$

- **Coft modes:** $p_t^\mu \sim q_T(R^2, 1, R)_{n_J \bar{n}_J}$ **for the jet radius R resummation** (Becher, Neubert, Rothen & DYS '15; Chien, Hornig & Lee '15; Kolodrubetz, Pietrulewicz, Stewart, Tackmann & Waalewijn '16; ......)

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RG evolution and resummation

- **Resummation formula:**

$$\frac{d\sigma}{d^2 q_T d^2 p_T d\eta_J dy_V} = \sum_{ijk} \int \frac{d^2 x_T}{(2\pi)^2} e^{i\vec{q}_T \cdot \vec{x}_T} e^{\int_{\mu_h}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \Gamma^{\mathrm{H}_{ij \to Vk}}(\bar{\mu})} \mathcal{H}_{ij \to Vk}(\hat{s}, \hat{t}, m_V, \mu_h)$$

$$\times \left(\frac{x_T^2 \hat{s}}{b_0^2} \right)^{-(C_i + C_j) F_\perp(\mu)} e^{\int_{\mu_b}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \Gamma^{\mathrm{W}_{ij \to Vk}}(\bar{\mu})} S_{ij \to Vk}(\vec{x}_T, \mu_b) B_{i/N_1}(\xi_1, x_T, \mu_b) B_{j/N_2}(\xi_2, x_T, \mu_b)$$

$$\times e^{\int_{\mu_t}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \Gamma^{\mathrm{U}_k}(\bar{\mu}) + \int_{\mu_j}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \Gamma^{\mathrm{J}_k}(\bar{\mu})} U_{\mathrm{NG}}^k(\mu_t, \mu_j),$$

- **Typical scales:** $\mu_h \sim Q,$ $\qquad \mu_b \sim b_0/x_T,$ $\qquad \mu_j \sim R \, p_T,$ $\qquad \mu_t \sim R \, b_0/x_T,$

- **NGL resummation:** (Becher, Neubert, Rothen & DYS '15)

$$U_{\mathrm{NG}}(\mu_t, \mu_j) \equiv \sum_{l=1}^{\infty} \left\langle \boldsymbol{\mathcal{J}}_l(\{\underline{n}'\}, R \, p_T, \mu_j) \otimes \sum_{m \geq l}^{\infty} \boldsymbol{U}_{lm}(\{\underline{n}\}, \mu_t, \mu_j) \hat{\otimes} \, \boldsymbol{\mathcal{U}}_m(\{\underline{n}\}, R \, \vec{x}_T, \mu_t) \right\rangle$$

- **At the NLL(LR) level and large Nc limit the evolution factor reduces to Dasgupta-Salam shower and BMS equation**

$$U_{\mathrm{NG}}(\mu_t, \mu_j) \xrightarrow{\mathrm{NLL}} \sum_{m \geq 1}^{\infty} \left\langle \boldsymbol{U}_{1m}(\{\underline{n}\}, \mu_t, \mu_j) \hat{\otimes} \, \mathbf{1} \right\rangle$$

RG evolution and resummation

- **Resummation formula:** **Logs from different scales**

$$\frac{d\sigma}{d^2 q_T d^2 p_T d\eta_J dy_V} = \sum_{ijk} \int \frac{d^2 x_T}{(2\pi)^2} e^{i\vec{q}_T \cdot \vec{x}_T} \boxed{e^{\int_{\mu_h}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \Gamma^{\mathrm{H}}_{ij \to Vk}(\bar{\mu})}} \mathcal{H}_{ij \to Vk}(\hat{s}, \hat{t}, m_V, \mu_h)$$

$$\times \left(\frac{x_T^2 \hat{s}}{b_0^2}\right)^{-(C_i + C_j) F_\perp(\mu)} \boxed{e^{\int_{\mu_b}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \Gamma^{\mathrm{W}}_{ij \to Vk}(\bar{\mu})}} S_{ij \to Vk}(\vec{x}_T, \mu_b) B_{i/N_1}(\xi_1, x_T, \mu_b) B_{j/N_2}(\xi_2, x_T, \mu_b)$$

$$\times \boxed{e^{\int_{\mu_t}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \Gamma^{\mathrm{U}k}(\bar{\mu}) + \int_{\mu_j}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \Gamma^{\mathrm{J}k}(\bar{\mu})}} U_{\mathrm{NG}}^k(\mu_t, \mu_j),$$

- **Typical scales:** $\mu_h \sim Q, \qquad \mu_b \sim b_0/x_T, \qquad \mu_j \sim R\, p_T, \qquad \mu_t \sim R\, b_0/x_T,$

- **NGL resummation:** (Becher, Neubert, Rothen & DYS '15)

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Rapidity logs resummation

$$\times \left(\frac{x_T^2 \hat{s}}{b_0^2}\right)^{-(C_i + C_j) F_\perp(\mu)} e^{\int_{\mu_b}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \Gamma^{\mathrm{W}_{ij \to Vk}}(\bar{\mu})} S_{ij \to Vk}(\vec{x}_T, \mu_b) B_{i/N_1}(\xi_1, x_T, \mu_b) B_{j/N_2}(\xi_2, x_T, \mu_b)$$

$$\times e^{\int_{\mu_t}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \Gamma^{\mathrm{U}_k}(\bar{\mu}) + \int_{\mu_j}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \Gamma^{\mathrm{J}_k}(\bar{\mu})} U_{\mathrm{NG}}^k(\mu_t, \mu_j),$$
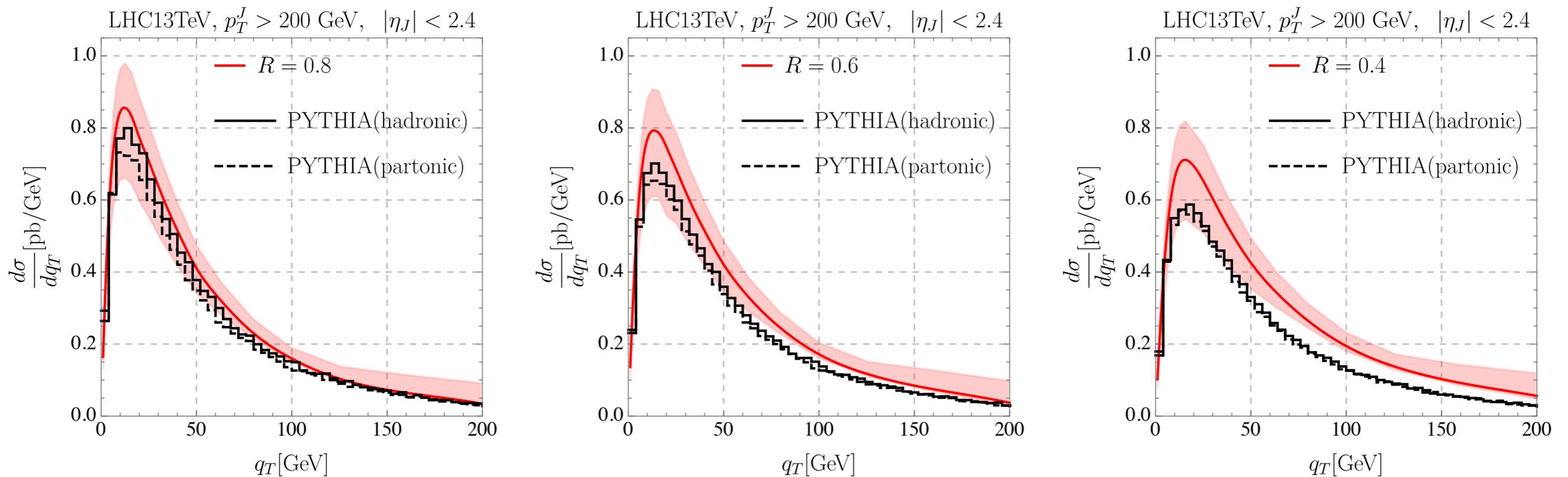
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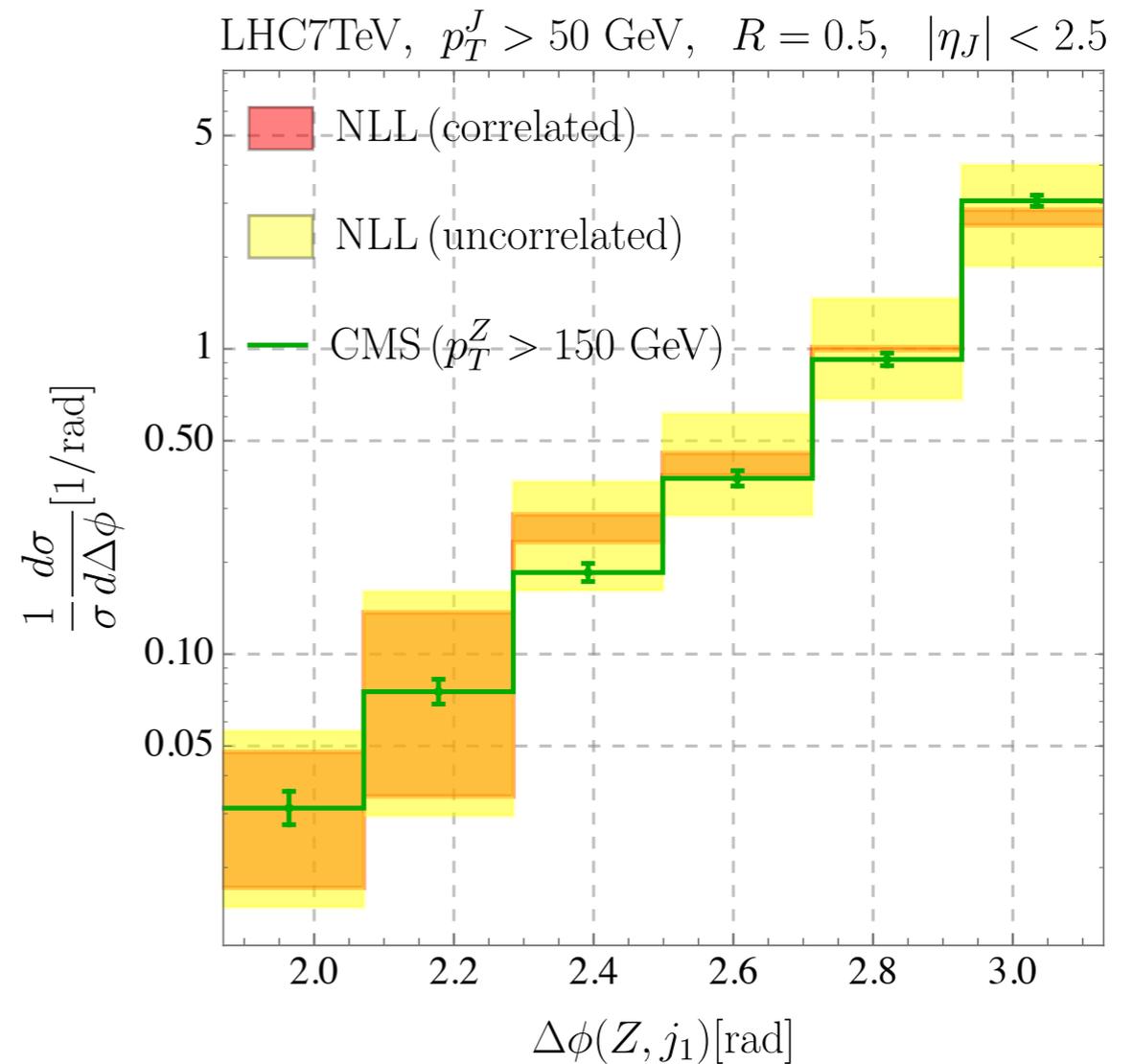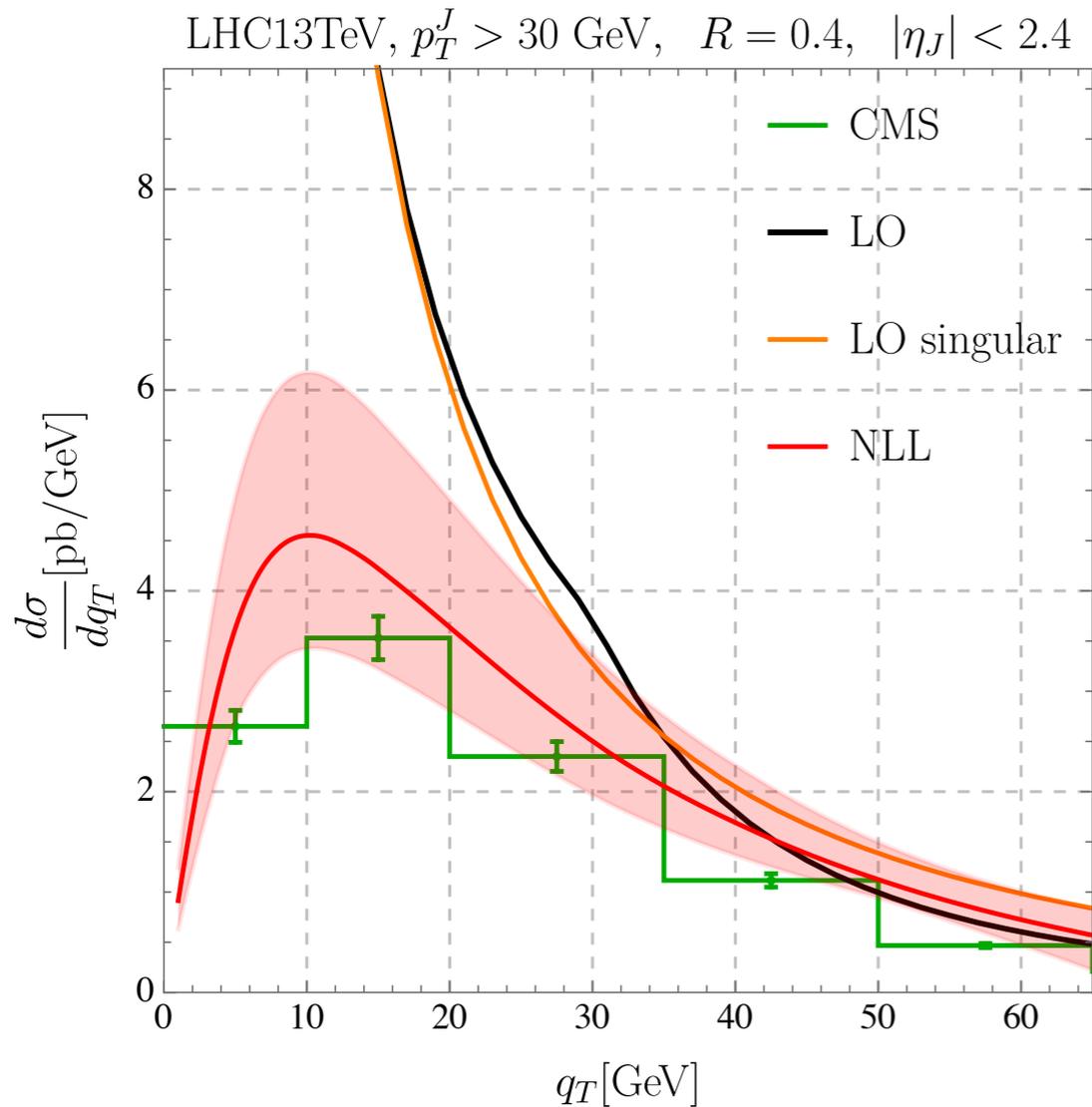
$$U_{\mathrm{NG}}(\mu_t, \mu_j) \xrightarrow{\mathrm{NLL}} \sum_{m \geq 1}^{\infty} \left\langle U_{1m}(\{\underline{n}\}, \mu_t, \mu_j) \hat{\otimes} \mathbf{1} \right\rangle$$

Numerical results

- **Resummation is "consistent" with pythia (discrepancy in normalization)**
- **At NLL theoretical uncertainties mainly come from scale variations**
- **Non-perturbative corrections mainly comes from MPI contributions**

Numerical results

- **NLL resummation is consistent with the LHC data (q_T & $\Delta\Phi$)**

- **q_T distribution can be a clean probe of *factorization violation*** (Collins & Qiu '07, Rogers & Mulders '10, ...)

- **NLL result has 20-30% scale uncertainties. Higher-order resummation is necessary**

NLL'(LR') resummation of the jet mass

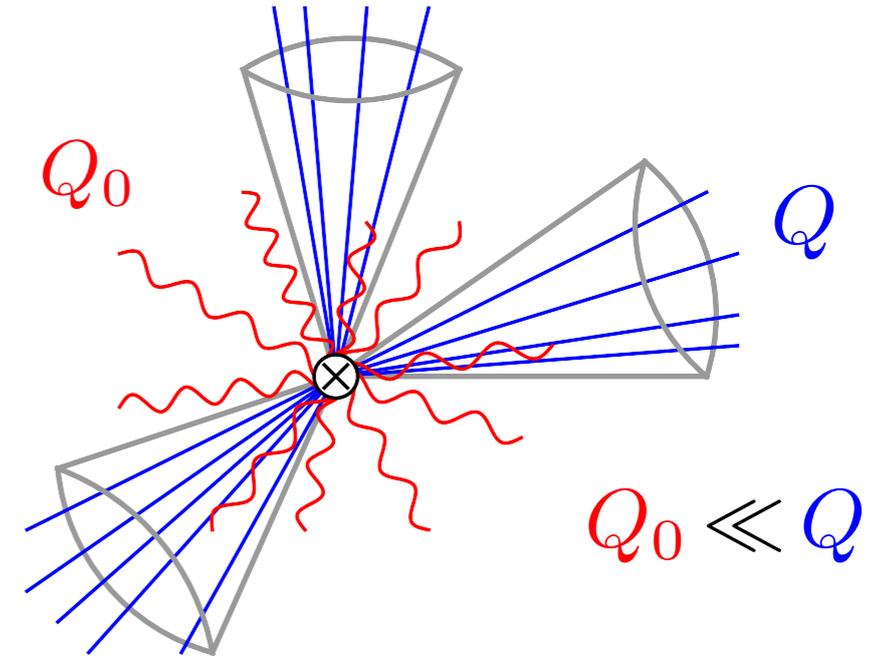**Balsiger, Becher & DYS (JHEP04(2019)020)**

Factorization in SCET

(Becher, Neubert, Rothen & DYS '15)

- **Energy flow outside jet (single log observable)**

$$d\sigma(Q, Q_0) = \sum_{m=k}^{\infty} \big\langle \boldsymbol{\mathcal{H}}_m(\{\underline{n}\}, Q, \mu) \otimes \boldsymbol{\mathcal{S}}_m(\{\underline{n}\}, Q_0, \mu) \big\rangle$$

$$\{\underline{n}\} = \{n_1, n_2, \cdots, n_m\}$$

- **Soft function:**

$$\boldsymbol{\mathcal{S}}_m(\{\underline{n}\}, Q_0, \mu) = \sum_{X_s} \langle 0 | \, \boldsymbol{S}_1^\dagger(n_1) \, \ldots \, \boldsymbol{S}_m^\dagger(n_m) \, |X_s\rangle\langle X_s| \, \boldsymbol{S}_1(n_1) \, \ldots \, \boldsymbol{S}_m(n_m) \, |0\rangle \, \theta(Q_0 - E_{\text{out}})$$
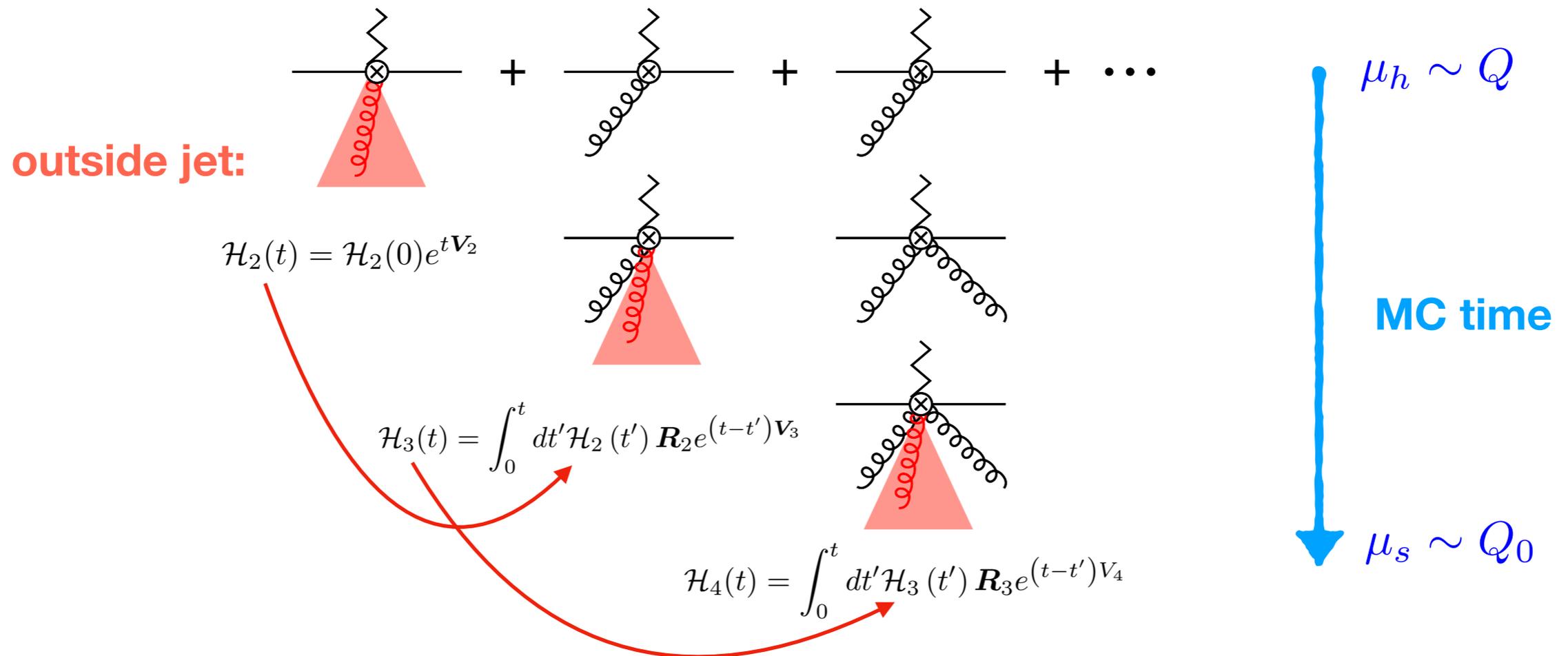
- **Hard function: integrating over the energies of the hard particles, while keeping their direction fixed**

$$\boldsymbol{\mathcal{H}}_m(\{\underline{n}\}, Q, \mu) = \frac{1}{2Q^2} \sum_{\text{spins}} \prod_{i=1}^{m} \int \frac{dE_i \, E_i^{d-3}}{(2\pi)^{d-2}} \, |\mathcal{M}_m(\{\underline{p}\})\rangle\langle\mathcal{M}_m(\{\underline{p}\})| (2\pi)^d \, \delta\Big(Q - \sum_{i=1}^{m} E_i\Big) \, \delta^{(d-1)}(\vec{p}_{\text{tot}}) \, \Theta_{\text{in}}(\{\underline{p}\})$$

- $\otimes$ **indicates integration over the direction of the energetic partons**

- $\langle \cdots \rangle$ **taking the color trace**
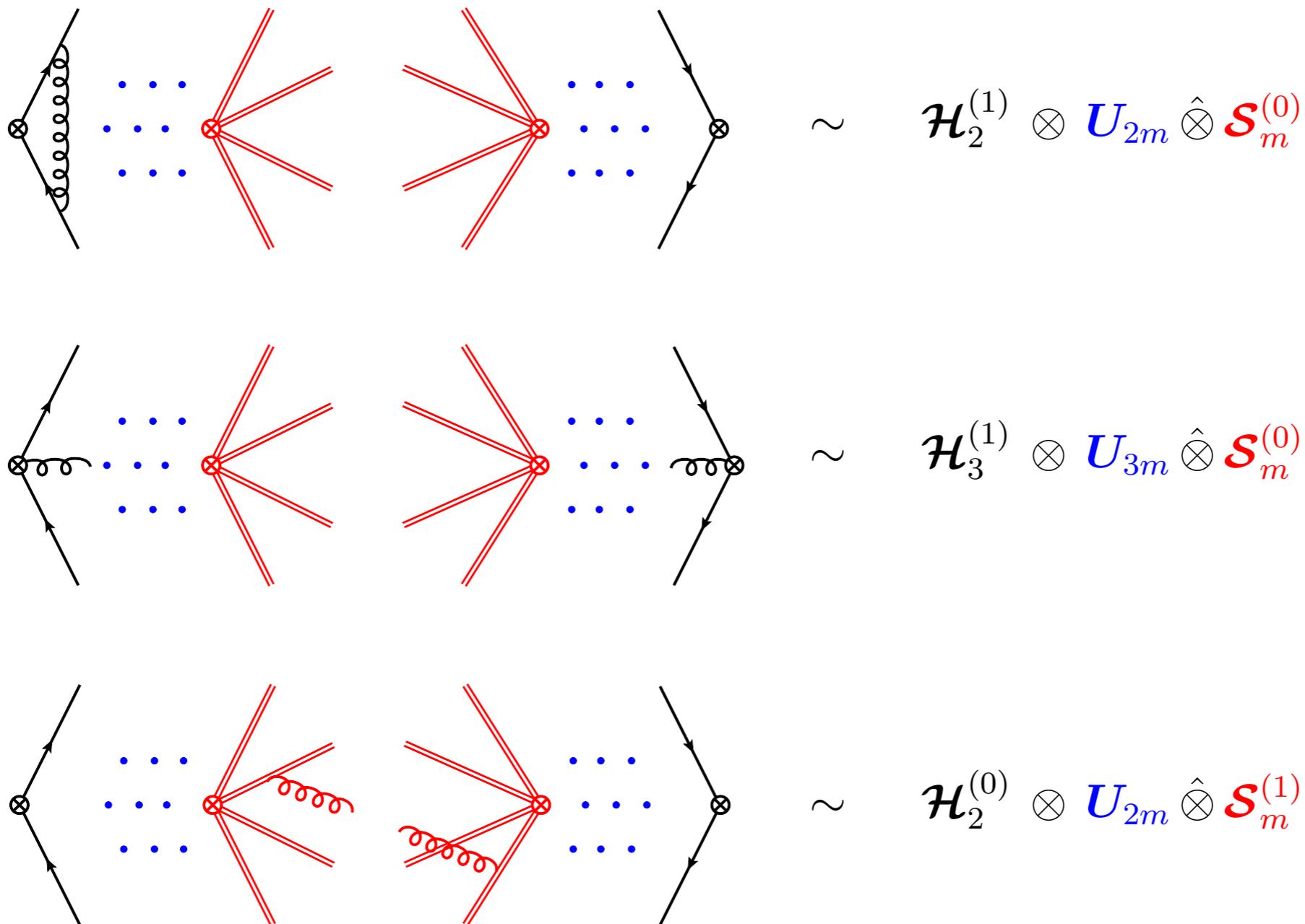
A brief review of the leading log resummation

$$\sigma^{\mathrm{LL}}(Q, Q_0) = \sum_{m=2}^{\infty} \left\langle \boldsymbol{\mathcal{H}}_2(\{n_1, n_2\}, Q, \mu_h) \otimes \boldsymbol{U}_{2m}(\{\underline{n}\}, \mu_s, \mu_h) \,\hat{\otimes}\, \boldsymbol{1} \right\rangle$$

outside jet:

$\mathcal{H}_2(t) = \mathcal{H}_2(0) e^{t \boldsymbol{V}_2}$

$\mathcal{H}_3(t) = \int_0^t dt' \, \mathcal{H}_2(t') \, \boldsymbol{R}_2 e^{(t-t') \boldsymbol{V}_3}$

$\mathcal{H}_4(t) = \int_0^t dt' \, \mathcal{H}_3(t') \, \boldsymbol{R}_3 e^{(t-t') V_4}$

$\mu_h \sim Q$

MC time

$\mu_s \sim Q_0$

1. start at $t = 0$ with initial event $E = \{n_1, n_2\}$ and weight $w = 1$
2. increase Δt according to $V_E \exp(-V_E t)$
3. choose a dipole $\{n_i, n_j\}$ with probability V_{ij}/V_E
4. generate a new vector, if it's inside the jet, add it to the event, and return step 2. Otherwise, stop and go to step 1

LL'(LR') resummation

$\mu_h \sim Q \quad \longrightarrow \quad \mu_s \sim Q_0$

$\sim \quad \boldsymbol{\mathcal{H}}_2^{(1)} \otimes \boldsymbol{U}_{2m} \,\hat{\otimes}\, \boldsymbol{\mathcal{S}}_m^{(0)}$

$\sim \quad \boldsymbol{\mathcal{H}}_3^{(1)} \otimes \boldsymbol{U}_{3m} \,\hat{\otimes}\, \boldsymbol{\mathcal{S}}_m^{(0)}$

$\sim \quad \boldsymbol{\mathcal{H}}_2^{(0)} \otimes \boldsymbol{U}_{2m} \,\hat{\otimes}\, \boldsymbol{\mathcal{S}}_m^{(1)}$

Soft corrections

One-loop soft function corrections:

$$\sum_{m=2}^{\infty} \langle \boldsymbol{\mathcal{H}}_m(t) \,\hat{\otimes}\, \boldsymbol{\mathcal{S}}_m^{(1)} \rangle = \langle \boldsymbol{\mathcal{H}}_2(t) \boldsymbol{\mathcal{S}}_2^{(1)} + \int \frac{d\Omega_1}{4\pi} \boldsymbol{\mathcal{H}}_3(t) \boldsymbol{\mathcal{S}}_3^{(1)} + \int \frac{d\Omega_1}{4\pi} \int \frac{d\Omega_2}{4\pi} \boldsymbol{\mathcal{H}}_4(t) \boldsymbol{\mathcal{S}}_4^{(1)} + \dots \rangle$$

Definition:

$$\frac{\alpha_s}{4\pi} \boldsymbol{\mathcal{S}}_m^{(1)}(\{\underline{n}\}, Q_0, \epsilon) = -g_s^2 \, \tilde{\mu}^{2\epsilon} \sum_{(ij)} \boldsymbol{T}_{i,L} \cdot \boldsymbol{T}_{j,R} \int \frac{d^d k}{(2\pi)^{d-1}} \delta(k^2)\theta(k^0) \frac{n_i \cdot n_j}{n_i \cdot k \, n_j \cdot k} \Theta_{\text{out}}(n_k)\theta(Q_0 - E_k)$$

$$\boldsymbol{T}_{i,L} \cdot \boldsymbol{T}_{j,R} \to -\frac{N_c}{2} \delta_{i,j\pm1}$$ **c.m. frame of parent dipole** (n_i, n_j)

$$\boldsymbol{\mathcal{S}}_m^{(1)}(\{\underline{n}\}, Q_0, \mu) = \frac{N_c}{2} \sum_{i,j=1}^{m} \delta_{i,j\pm1} \int d\hat{y} \int_0^{2\pi} \frac{d\hat{\phi}}{2\pi} \left[-4\ln\frac{\mu}{Q_0} + 4\ln\frac{2\,|\sin\hat{\phi}|}{f_{ij}(\hat{\phi},\hat{y})} \right] \Theta_{\text{out}}^{\text{lab}}(\hat{y}, \hat{\phi})$$

weight factor

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Soft corrections

One-loop soft function corrections:

$$\sum_{m=2}^{\infty} \langle \boldsymbol{\mathcal{H}}_m(t) \,\hat{\otimes}\, \boldsymbol{\mathcal{S}}_m^{(1)} \rangle = \langle \boldsymbol{\mathcal{H}}_2(t) \boldsymbol{\mathcal{S}}_2^{(1)} + \int \frac{d\Omega_1}{4\pi} \boldsymbol{\mathcal{H}}_3(t) \boldsymbol{\mathcal{S}}_3^{(1)} + \int \frac{d\Omega_1}{4\pi} \int \frac{d\Omega_2}{4\pi} \boldsymbol{\mathcal{H}}_4(t) \boldsymbol{\mathcal{S}}_4^{(1)} + \dots \rangle$$

1. **start at** $t = 0$ **with initial event** $E = \{n_1, n_2\}$ **and weight** $w = 1$
2. **increase** Δt **according to** $V_E \exp(-V_E t)$
3. **choose a dipole** $\{n_i, n_j\}$ **with probability** V_{ij}/V_E
4. **generate a new vector, if it's inside the jet, add it to the event, and return step 2. Otherwise, add the** **weight factor** **at time t, go to step 1**

$$\mathcal{S}_m^{(1)}(\{\underline{n}\}, Q_0, \mu) = \frac{N_c}{2} \sum_{i,j=1}^{m} \delta_{i,j\pm1} \int d\hat{y} \int_0^{2\pi} \frac{d\hat{\phi}}{2\pi} \left[-4\ln\frac{\mu}{Q_0} + 4\ln\frac{2\,|\sin\hat{\phi}|}{f_{ij}(\hat{\phi}, \hat{y})} \right] \Theta_{\text{out}}^{\text{lab}}(\hat{y}, \hat{\phi})$$
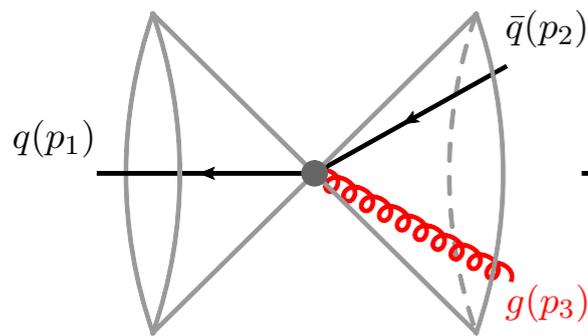
weight factor

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Hard corrections

Virtual corrections to $\mathcal{H}_2$ **give trivial refactors** $\quad H_2(Q^2, \mu) = 1 + \frac{\alpha_s}{4\pi} C_F \left[-8 \ln^2 \frac{\mu}{Q} - 12 \ln \frac{\mu}{Q} - 16 + \frac{7}{3} \pi^2 \right]$

$$\sum_{m=2}^{\infty} \left\langle \mathcal{H}_2(\{n_1, n_2\}, Q, \mu_h) \otimes \boldsymbol{U}_{2m}(\{\underline{n}\}, \mu_s, \mu_h) \hat{\otimes} \boldsymbol{1} \right\rangle = \sigma_0 H_2(Q, \mu_h) \left\langle \boldsymbol{U}_{2m}(\{\underline{n}\}, \mu_s, \mu_h) \hat{\otimes} \boldsymbol{1} \right\rangle$$

$\mathcal{H}_3$ **is a distribution of two angles:** $\quad \mathcal{H}_3 \left[\delta(u), \delta(v), \left(\frac{1}{v} \right)_+, \left(\frac{\log v}{v} \right)_+, \cdots \right]$
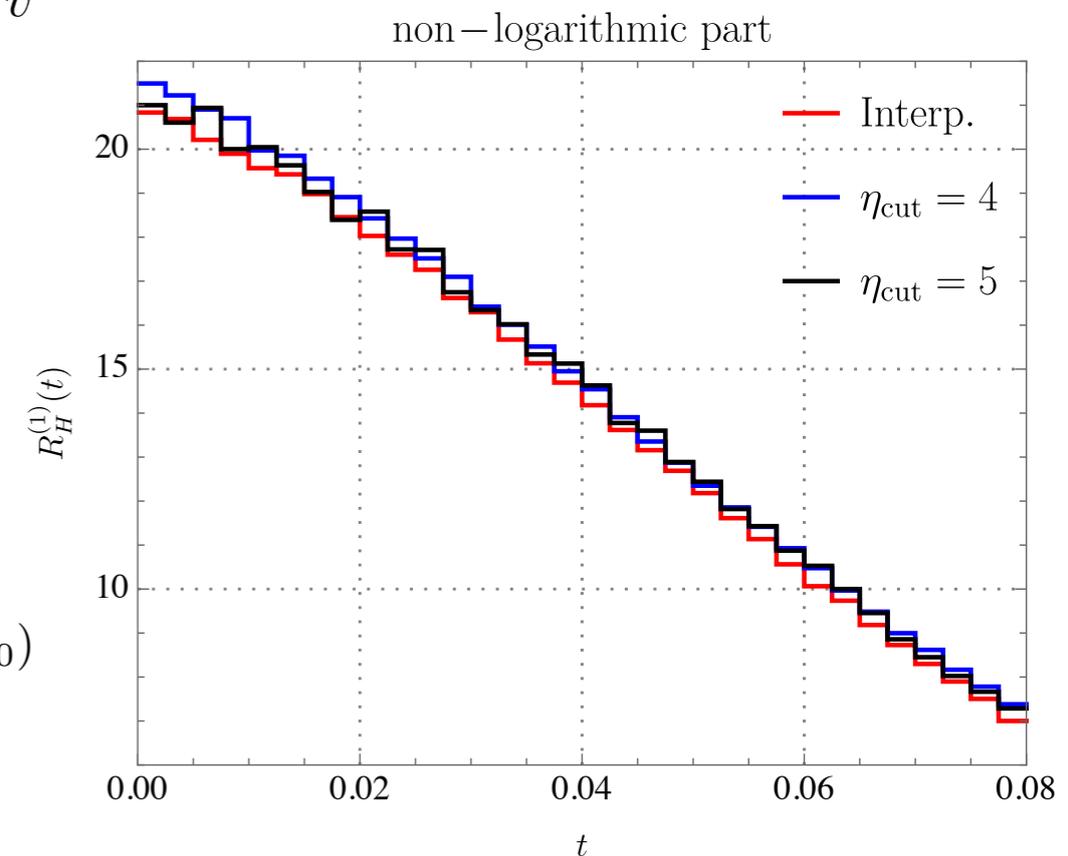

$\hat{\theta}_2 \equiv \tan \frac{\theta_2}{2} = u\, v, \qquad \hat{\theta}_3 \equiv \tan \frac{\theta_3}{2} = v$

$$\int_0^1 du \int_0^1 dv \langle \mathcal{H}_3^{(1)}(u, v, Q, \mu_h) \sum_{m=3}^{\infty} \boldsymbol{U}_{3m}(\{\underline{n}\}, \mu_s, \mu_h) \hat{\otimes} \boldsymbol{1} \rangle$$
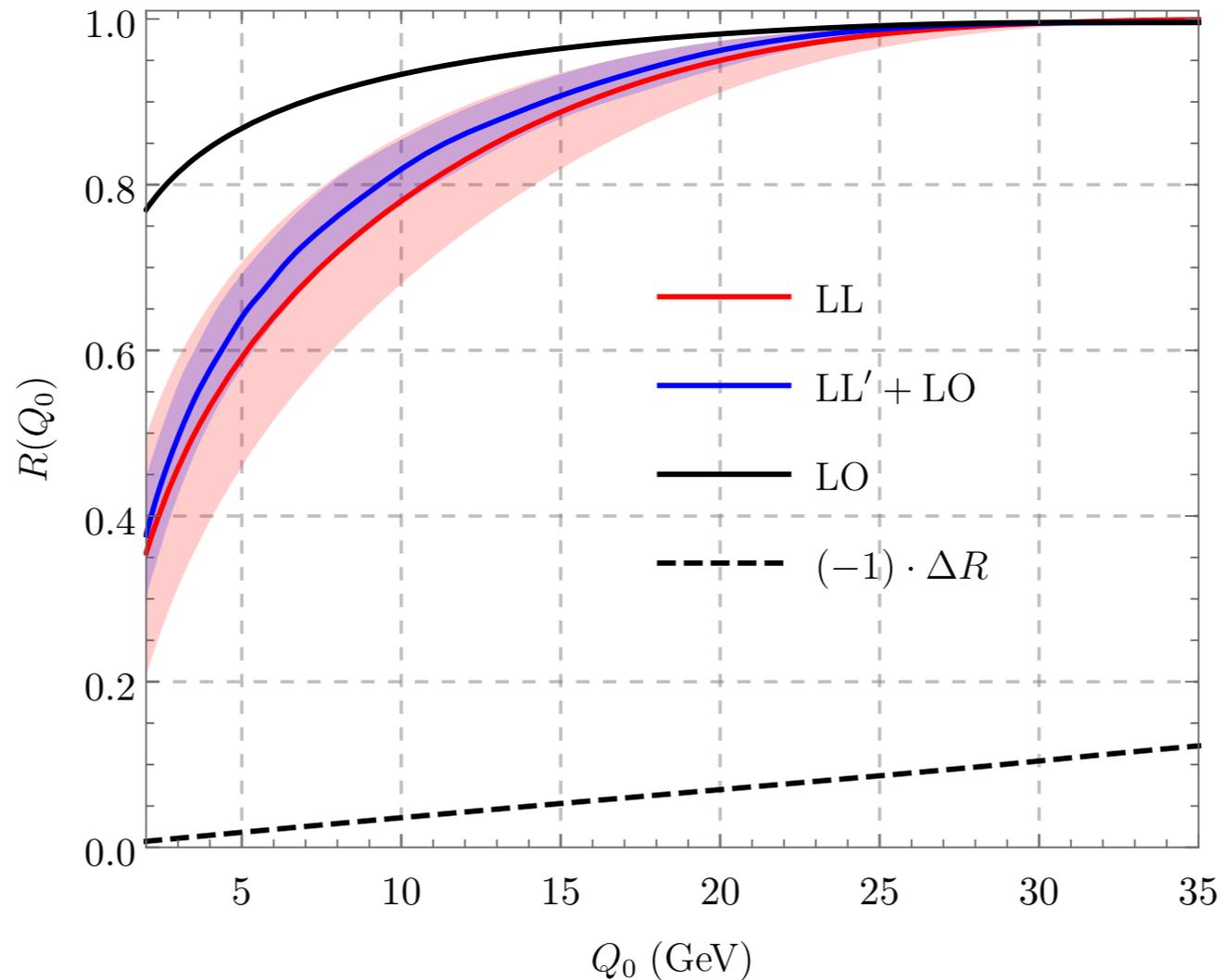
Slicing method:

$$\int_0^1 dv \left[\frac{1}{v} \right]_+ \widehat{\mathcal{S}}_3(v) = \int_0^1 \frac{dv}{v} \left[\widehat{\mathcal{S}}_3(v) - \widehat{\mathcal{S}}_2 \right] = \int_{v_0}^1 \frac{dv}{v} \widehat{\mathcal{S}}_3(v) + \ln v_0\, \widehat{\mathcal{S}}_2 + \mathcal{O}(v_0)$$

LL'(LR') + LO resummation
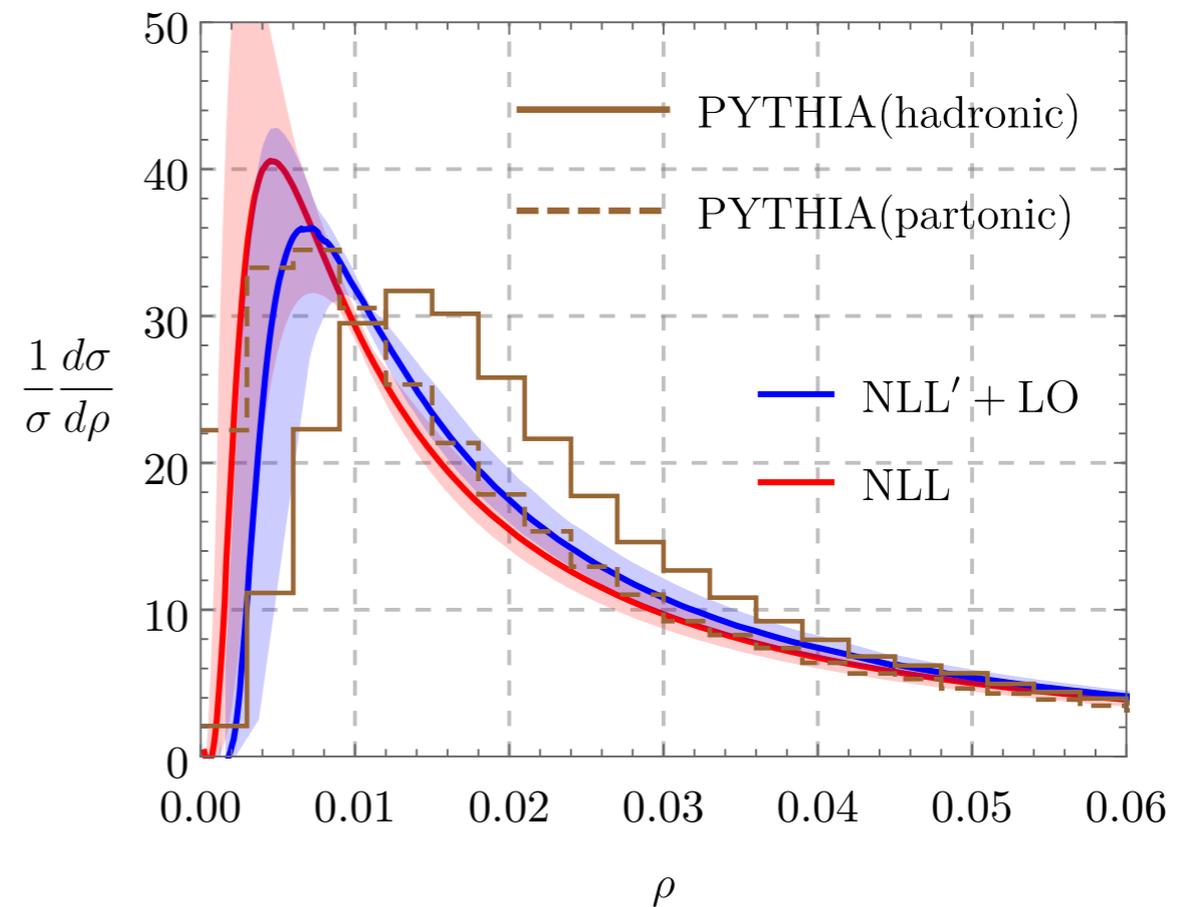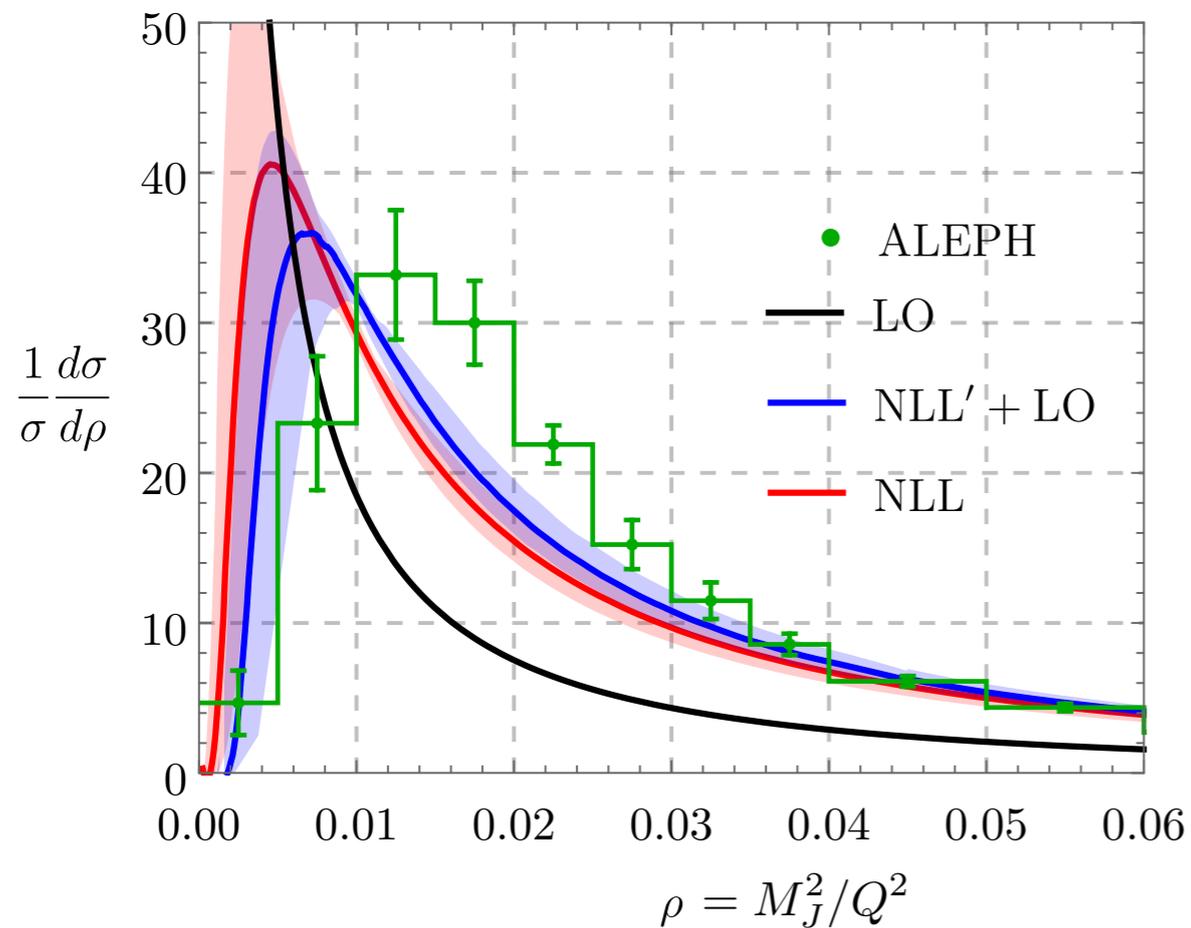
(Balsiger, Becher, DYS,'19)

$$\sigma(Q,Q_0)/\sigma$$

- **We match LL' to LO and use a profile function to switch off resummation**
- **No Exp. data**

NLL'(LR') resummation for the jet mass

(Balsiger, Becher, DYS,'19)

- **Peak at** $\rho \sim 0.006$ **corresponds to** $\mu_s \sim 0.5\,\mathrm{GeV}$. **Non-perturbative effects are important and shift the peak**

- **Partonic PYTHIA is close to NLL'+LO**

Conclusions

- **Jet radius and q_T joint resummation for boson-jet correlation**

  - **including NGLs resummation**

  - **small N.P. corrections, perturbative predictions are reliable**

  - **the winner-take-all axis? glauber modes? factorization violation effects?**

- **First results for non-global observables which go beyond the (N)LL (LR) accuracy**

  - **full one-loop corrections to matching coefficients**

  - **implemented in Monte-Carlo framework**

  - **higher order corrections improve results significantly**

Thank you!