# Recoil-free jet observable in heavy ion collisions


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# Motivations

# $\hat{q}$ and its conventional measurement

## $\hat{q}$ determines both $\langle p_\perp^2 \rangle$ and energy loss:

**Jet quenching parameter $\hat{q}$**

$$\frac{d}{dL}\langle p_\perp^2 \rangle = \hat{q}$$

$L$: the path length
$\perp$: the direction transverse to the (initial) jet direction.

**Medium-induced energy loss**

$$\frac{d}{dL}\Delta E = \frac{\alpha_s N_c}{6}\hat{q}L = \frac{\alpha_s N_c}{6}\langle p_\perp^2 \rangle.$$

Baier, Dokshitzer, Mueller, Peigne and Schiff, Nucl. Phys. B **484**, 265-282 (1997) [arXiv:hep-ph/9608322 [hep-ph]].

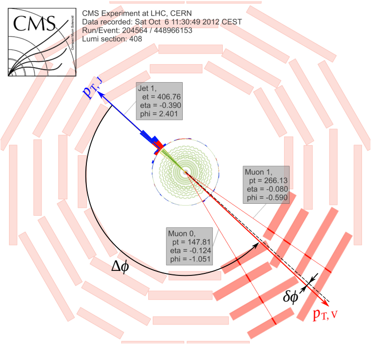
## $\hat{q}$ in AA collisions is mostly measured via jet quenching phenomena.

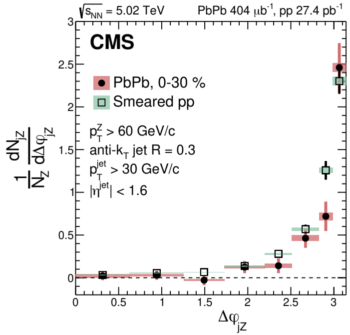
$$\hat{q} = (2-4)T^3$$

S. Cao *et al.* [JETSCAPE], Phys. Rev. C **104**, no.2, 024905 (2021) [arXiv:2102.11337 [nucl-th]].

# Boson-jet azimuthal decorrelation

Definition: $\Delta\phi \equiv |\phi_V - \phi_J|$ $(\delta\phi \equiv \pi - \Delta\phi)$



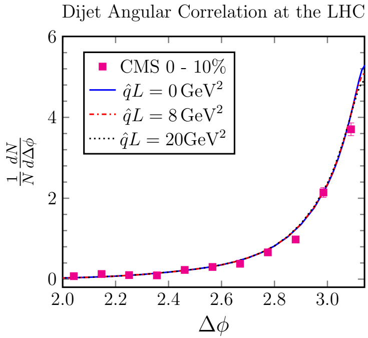

A. M. Sirunyan *et al.* [CMS], Phys. Rev. Lett. **119**, no.8, 082301 (2017) [arXiv:1702.01060 [nucl-ex]].

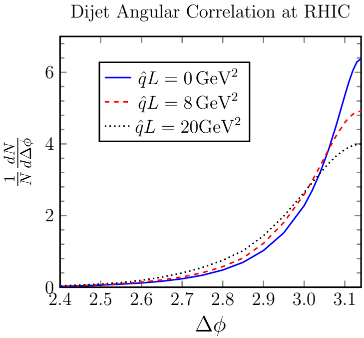
At lowest order, $d\sigma/d\delta\phi \propto \delta(\delta\phi)$ when terms of $O(\Lambda_{QCD}/p_T)$ is neglected!

**This observable is directed related to $\langle p_\perp^2 \rangle$ in AA collisions!**

# Provide an alternative to measure $\hat{q}$

**Using $\Delta\phi$ in dijets:** $\delta\phi \sim \frac{\sqrt{\hat{q}L}}{p_{T,J}}$ (in a static medium)




A. H. Mueller, BW, B. W. Xiao and F. Yuan, Phys. Lett. B **763**, 208-212 (2016) [arXiv:1604.04250 [hep-ph]]. .

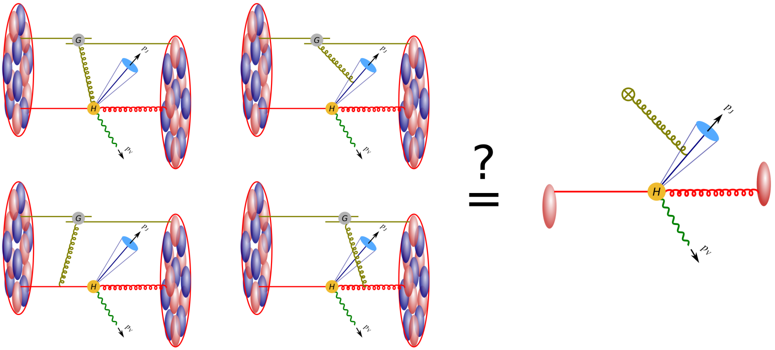
**Using $\Delta\phi$ in boson-jet:**

$$\hat{q}_0 = (4 - 8)\ \mathrm{GeV}^2/\mathrm{fm}\ \text{for}\ T_0 = 509\ \mathrm{MeV}\ \text{at}\ \sqrt{s_{NN}} = 5.02\ \mathrm{TeV}.$$

L. Chen, S. Y. Wei and H. Z. Zhang, PoS **HardProbes2020**, 031 (2021).

**Can we provide more precise calculations?**

# Ingredients for precise calculations




N. Armesto, C. A. Salgado, F. Cougoulic and BW, work in progress.

**Assuming below bulk matter only modifies the final-state distribution:**

1. High precision calculations in vacuum radiation (pp collisions)
2. Interplay of vacuum and medium-induced radiation

**We will see the recoil-free jet definition facilitates this task!**

# What is a recoil-free jet definition?

**A recombination scheme** ⇒the momentum of two combined particles $i, j$

- $p_T^n$ recombination scheme for $n > 1$

$$\begin{aligned} p_{T,r} &= p_{T,i} + p_{T,j}, \\ \phi_r &= (p_{T,i}^n \phi_i + p_{T,j}^n \phi_j)/(p_{T,i}^n + p_{T,j}^n), \\ y_r &= (p_{T,i}^n y_i + p_{T,j}^n y_j)/(p_{T,i}^n + p_{T,j}^n) \end{aligned}$$

M. Cacciari, G. P. Salam and G. Soyez, Eur. Phys. J. C **72**, 1896 (2012) [arXiv:1111.6097 [hep-ph]]. .

In the limit $n \to \infty$, one has

- **Winner-Take-All (WTA)-$p_T$ scheme:**

$$p_{T,r} = p_{T,i} + p_{T,j}, \qquad (y_r, \phi_r) = (y, \phi) \text{ of larger } p_T$$

Salam, "$E_t^\infty$ Scheme." unpublished; Bertolini, Chan and Thaler, JHEP **04**, 013 (2014) [arXiv:1310.7584 [hep-ph]].

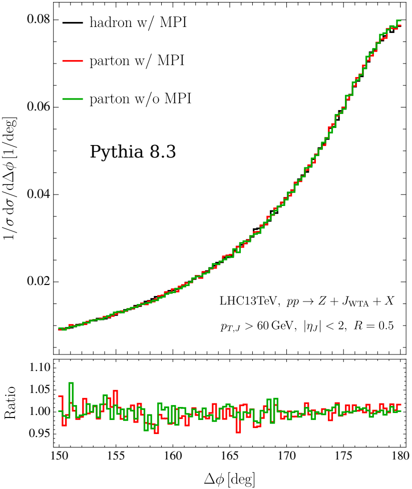
For comparison: $p^\mu = p_i^\mu + p_j^\mu$ for SJA.

**Jet definition:** a jet algorithm, e.g., anti-$k_t$ with $p_T^n$ scheme

**Below take for example the WTA: anti-$k_t$ with WTA-$p_T$ scheme**

# Why WTA (in pp collisions)?

## Very robust to hadronization and the underlying event




Chien, Rahn, Shao, Waalewijn and BW, JHEP **02**, 256 (2023) [arXiv:2205.05104 [hep-ph]].

# Why WTA (in pp collisions)?

## Very robust to jet definition with all or charged only hadrons:

In experiments (track-based measurements):

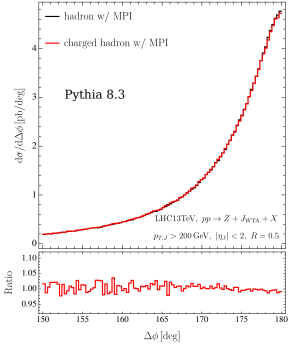
- Limitation of (calorimeter) jet measurements:

  granularity $\sim 0.1$ rad $\approx 6^\circ$

- LHC trackers have superior angular resolution

  e.g., CMS layer 1 at r=4.4 cm with resolution 23 $\mu$m $\Rightarrow \delta\phi \sim 5 \times 10^{-4}$ rad

- Naturally robust to pile-up




Pythia simulations: using tracks has a minimal effect on $\Delta\phi$ distribution!

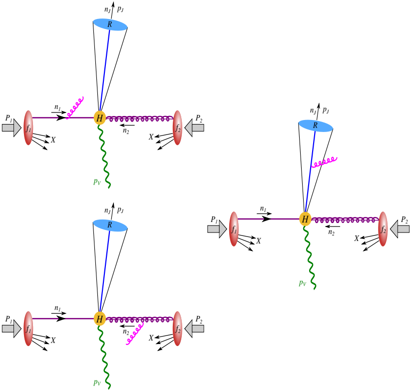
Track-based jets: a means to access the resummation region!

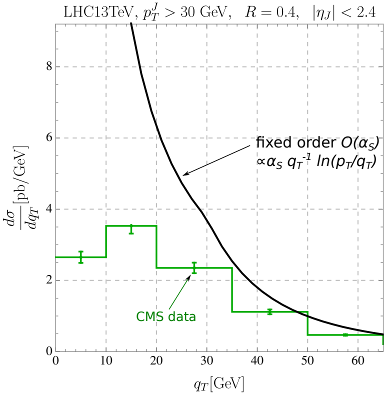
Chien, Rahn, Shao, Waalewijn and BW, JHEP **02**, 256 (2023) [arXiv:2205.05104 [hep-ph]].

# Precision calculations in pp collisions

# Fixed-order calculations fail at small $\delta\phi$

Here, $q_T = |\vec{p}_J + \vec{p}_V| \approx\ p_T \delta\phi$



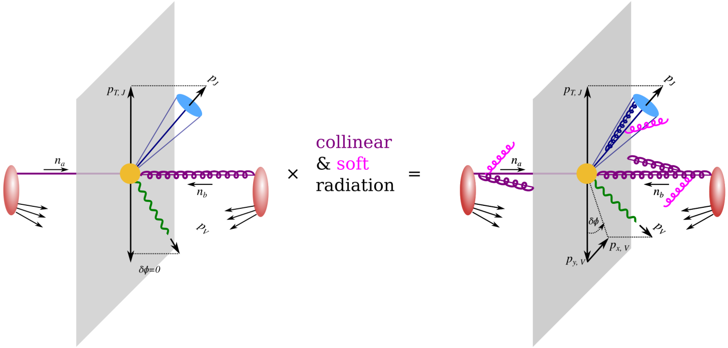




Data is taken from A. M. Sirunyan *et al.* [CMS], Eur. Phys. J. C **78**, no.11, 965 (2018) [arXiv:1804.05252 [hep-ex]].

There are (Sudakov) logs in $p_T/q_T$ along the beam and jet directions.

# Resummation of large logarithms

Resum logs up to all orders in $O(\alpha_s)$

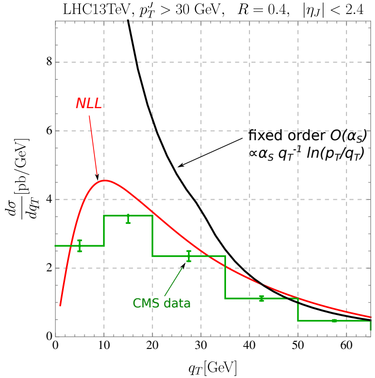



$$\Rightarrow \ln \Sigma(\delta\phi) \equiv \ln\left(\int_0^{\delta\phi} \frac{d\sigma}{d\delta\phi}\right) \sim \underbrace{L(\alpha_s L)}_{\text{Leading Log } (LL)} + \underbrace{(\alpha_s L)}_{\text{Next to LL } (NLL)} + \underbrace{\alpha_s(\alpha_s L)}_{\text{Next to NLL } (NNLL)} + \cdots$$

$$\text{with } L = \ln\delta\phi \text{ and } \alpha_s L \sim 1 \Rightarrow \underbrace{NLL}_{\text{a must}} \sim O(\alpha_s^0), NNLL \sim O(\alpha_s)\cdots$$

# NLL resummation

Using Standard Jet Axis (SJA), only NLL resummation has been done

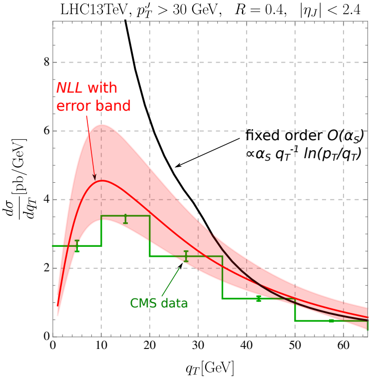



With NGLs: Y. T. Chien, D. Y. Shao and BW, JHEP **11**, 025 (2019) [arXiv:1905.01335 [hep-ph]].

See also (without NGLs): P. Sun, B. Yan, C. P. Yuan and F. Yuan, Phys. Rev. D **100**, no.5, 054032 (2019) [arXiv:1810.03804 [hep-ph]].

# Uncertainties for NLL resummation

NLL resummation has large uncertainties of $O(\alpha_s)$



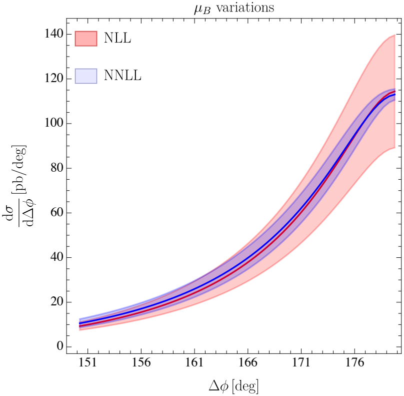

Y. T. Chien, D. Y. Shao and BW, JHEP **11**, 025 (2019) [arXiv:1905.01335 [hep-ph]].

Note uncertainties for *LL* is even larger $\sim\ O(\alpha_s^0)$

**More precision predictions requires going beyond NLL**

# NNLL resummation

## The most precise prediction:




NNLL requires a "minor" change: SJA $\rightarrow$ recoil-free jet axis

More precise like N$^3$LL resummation is also possible!

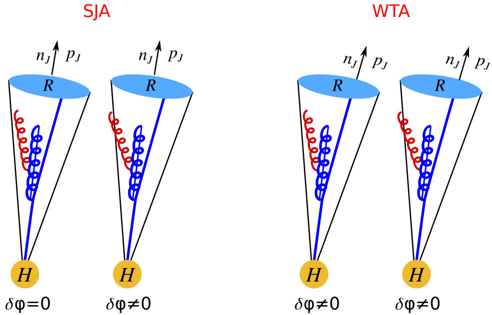

Chien, Rahn, Schrijnder van Velzen, Shao, Waalewijn and BW, Phys. Lett. B **815**, 136124 (2021) [arXiv:2005.12279 [hep-ph]].

Chien, Rahn, Shao, Waalewijn and BW, JHEP **02**, 256 (2023) [arXiv:2205.05104 [hep-ph]].

# Why WTA again?

## No Non-Global Logarithms (NGLs):

The WTA axis eliminates NGLs: insensitive to soft radiation

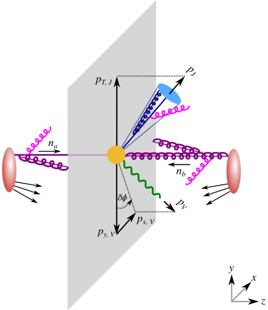



Definition of NGLs: M. Dasgupta and G. P. Salam, Phys. Lett. B **512**, 323-330 (2001) [arXiv:hep-ph/0104277 [hep-ph]].

Resummation of NGLs is difficult and NNLL has NOT be achieved using SJA

# Factorization in pp collisions

Factorization formula, excluding Glauber modes, for recoil-free jets using SCET:




Hard function: $\mathcal{H}_{ij\to Vk} \leftarrow$ parton-level $\hat{\sigma}$

Beam functions: $\mathcal{B}_i, \mathcal{B}_j \leftarrow$ TMDs in hadrons

Soft function: $S_{ijk} \leftarrow$ soft radiation

Jet function: $\mathcal{J}_k$ does NOT contain NGLs!

$$\frac{d\sigma}{dq_x\, dp_{T,V}\, dy_V\, d\eta_J} = \int \frac{db_x}{2\pi} e^{b_x q_x} \sum_{ijk} \mathcal{H}_{ij\to Vk}(p_{T,V}, y_V - \eta_J)\mathcal{B}_i(x_a, b_x)B_j(x_b, b_x)\mathcal{J}_k(b_x)S_{ijk}(b_x, \eta_J)$$

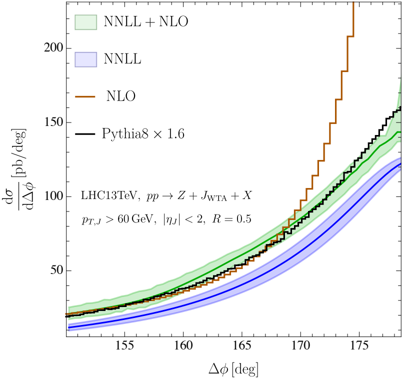
Glauber modes do not spoil factorization up to NNLO!

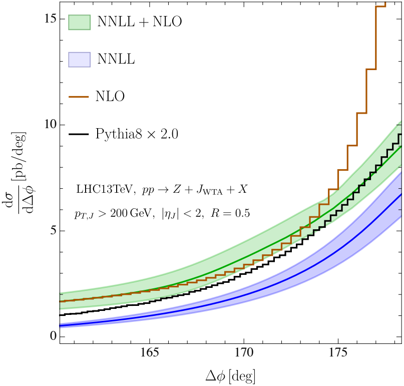
Resummation via the RG equation: for each function above denoted by $F$

$$\frac{d}{d\ln\mu}F(\mu) = \gamma^F F(\mu) \text{ with } \gamma^F \text{ anomalous dimension of } F$$

# Most precise prediction at $O(\alpha_s)$

At NNLL + NL0 (2→3) accuracy




Source of the difference between our prediction and PYTHIA:

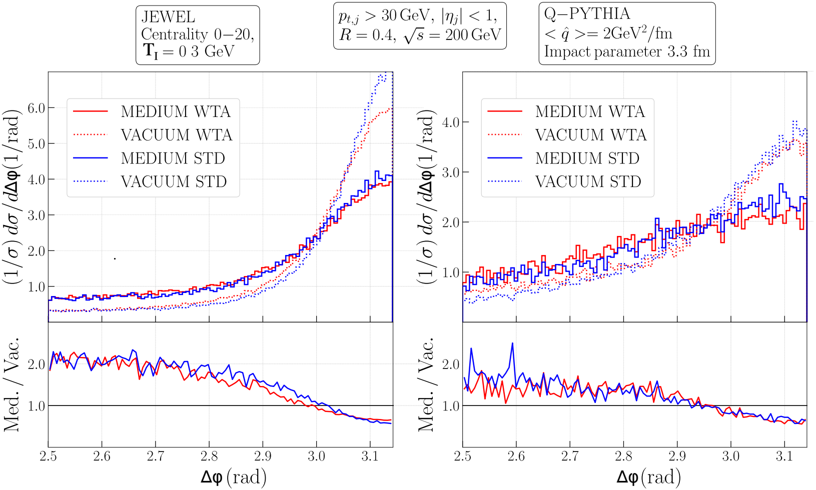
Emission of boson off dijets is NOT included in PYTHIA simulations!

Chien, Rahn, Shao, Waalewijn and BW, JHEP **02**, 256 (2023) [arXiv:2205.05104 [hep-ph]].

# Vacuum vs medium-induced radiation

# Interplay of vacuum and medium-induced radiation

Simulations with JEWEL and Q-PYTHIA:




It looks promising to measure $\hat{q}$ given the small error band in our pp results.

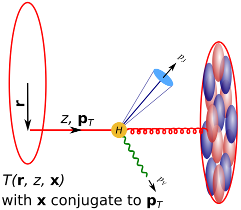
# Contributions from initial states in AA collisions

The impact-parameter dependent cross section in QFT

$$\frac{d\sigma}{d^2\mathbf{b}dO} = \int \prod_f [d\Gamma_{p_f}]\, \delta(O - O(\{p_f\})\langle\phi_1\phi_2|\hat{S}^\dagger|\{p_f\}\rangle\langle\{p_f\}|\hat{S}|\phi_1\phi_2\rangle$$

where $O(\{p_f\})$ defines an observable $O(=\Delta\phi)$ as a function of $\{p_f\}$.

**Expanding at high $p_T$ leads to Thickness Beam function $\mathcal{T}(\mathbf{r}, z, \mathbf{x})$:**




$\mathcal{T}(\mathbf{r}, z, \mathbf{x}) \approx$ Fourier Transform of Transverse phase space (TPS) PDF

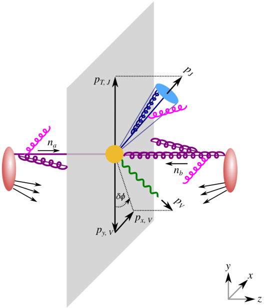
In the Glauber model: $\mathcal{T}(\mathbf{r}, z, \mathbf{x}) \to \underbrace{T(\mathbf{r})}_{\text{thickness function}} \times \underbrace{\mathcal{B}(z, \mathbf{x})}_{\text{nucleon beam function}}$

BW, JHEP **07**, 002 (2021) [arXiv:2102.12916 [hep-ph]].

# (Conjectured) factorization in AA collisions

$$\frac{d\sigma}{dq_x\, dp_{T,V}\, dy_V\, d\eta_J\, d^2\mathbf{b}} = \int d^2\mathbf{r} \int \frac{dx}{2\pi} e^{xq_x} \sum_{ijk} \mathcal{H}_{ij\to Vk}(p_{T,V}, y_V - \eta_J)$$
$$\times\, \mathcal{T}_i(\mathbf{r}-\mathbf{b}, z_a, x)\, \mathcal{T}_j(\mathbf{r}, z_b, x)$$
$$\times\, \mathcal{J}_{\mathrm{med},k}(\mathbf{r}, \mathbf{b}, x)\, \mathcal{S}_{\mathrm{med},ijk}(\mathbf{r}, \mathbf{b}, x, \eta_J)$$

where




Hard function: $\mathcal{H}_{ij\to Vk} \leftarrow$ parton-level $\hat{\sigma}$

Thickness beam functions: $\mathcal{T}_i, \mathcal{T}_j \leftarrow$ TPS PDFs in nuclei

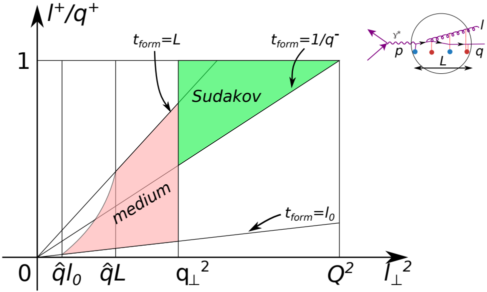
Medium-modified soft function: $\mathcal{S}_{\mathrm{med},ijk}$

Medium-modified jet function: $\mathcal{J}_{\mathrm{med},k}$

Chien, Rahn, Shao, Waalewijn and BW, work in progress.

# LL resummation in AA collisions

**Factorization at LL in Deep Inelastic Scattering on nuclei:**




Mueller, BW, Xiao and Yuan, Phys. Rev. D **95**, no.3, 034007 (2017) [arXiv:1608.07339 [hep-ph]].

**Medium-induced double log**: $\langle p_\perp^2 \rangle_{rad} = \frac{\alpha_s N_c}{8\pi} \hat{q} L \log^2 \left( \frac{L}{r_0} \right)^2$

Here $r_0$ the nucleon size or $1/T$ (See Weitz's talk for an update near $r_0$).

**In AA using WTA:** $\Sigma(q_x) = e^{-\frac{\alpha_s}{\pi}\left[(C_i+C_j+C_k)\log^2\left(\frac{p_T}{q_x}\right)\right]-\frac{q_x^2}{\hat{q}_t L}}$

where medium-induced double logs are included in $\hat{q}_t$ (for a static medium)

# Interplay of vacuum and medium-induced radiation

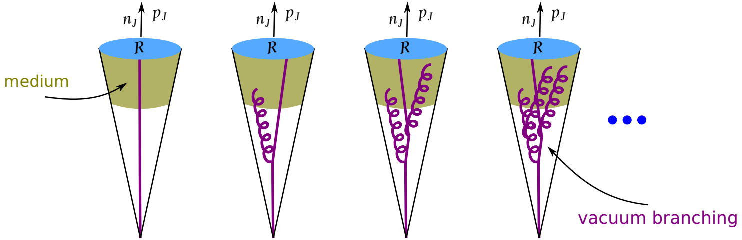
## The central problem to be solved:

how to reconcile the RG equation and the time-evolution of jets?

For example, the vacuum logs can be resummed by

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\mathcal{J}(\mu) = \gamma^{J}\mathcal{J}(\mu)$$

Even assuming medium modification comes only after vacuum branching:




Much more complicated than LBT, Hybrid, MARTINI, PyQUEN ...

# Summary

1. Azimuthal decorrealtion provides an alternative to measure $\hat{q}$

   A test of the classical relation between $\langle p_\perp^2 \rangle$ and energy loss

2. Using the recoil-free jet definition has the following advantages:
   - Robust to hadronization, underlying event and charged hadrons
   - Amenable to high precision prediction (for pp thus far)

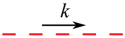
3. Interplay of vacuum and medium-induced radiation in AA has been studied:
   - at LL where vacuum Sudakov and medium-induced double logs factorize
   - by simulations using JEWEL and Q-PYTHIA,

4. Resummation and time evolution of jet observables will be reconciled!

# Backup slides

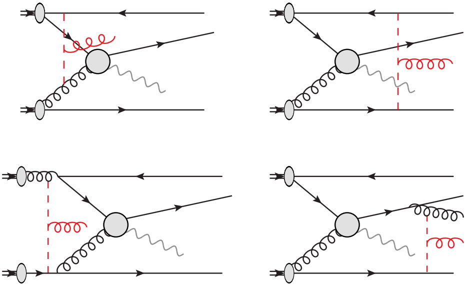
# Factorization breaking?

Glauber exchange: instantaneous interaction




$\propto \frac{1}{k_\perp^2}$

Glauber topologies:



Don't spoil factorization up to and including $O(\alpha_s^3)$

# Parton TMD distributions

Linearly-polarized beam functions start to contribute to $\delta\phi$ at NLO/NNLL:

$$B_g^L(x, b_x) = \frac{d-2}{d-3}\left(\frac{1}{d-2}g_T^{\alpha\alpha'} + \frac{b_T^\alpha b_T^{\alpha'}}{\vec{b}_T^2}\right)B_{\alpha\alpha'}(x, b_x)$$
$$= \mathcal{O}(\alpha_s),$$

where

$$\mathcal{B}^{\alpha'\alpha}(x, b_x) \equiv 2x\bar{n}\cdot P\int\frac{dt}{2\pi}e^{-i\xi t\bar{n}\cdot p}\langle P|\mathcal{B}_{n\perp}^{a\alpha'}(t\bar{n}+b_x)\mathcal{B}_{n\perp}^{a\alpha}(0)|P\rangle$$

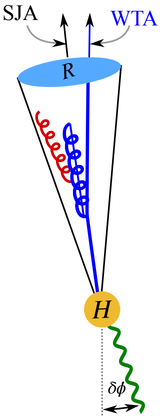
with

$$\mathcal{B}_n^\alpha = \frac{1}{\bar{n}\cdot\mathcal{P}}W_n^\dagger i\bar{n}_\nu F^{\nu\mu}W_n$$

They contribute to Higgs production starting only at NNLO!

Gutierrez-Reyes, Leal-Gomez, Scimemi and Vladimirov, JHEP **11**, 121 (2019) [arXiv:1907.03780 [hep-ph]].

# TMD in jets




TMD jet function: offset of the WTA axis w.r.t SJA

Gutierrez-Reyes, Scimemi, Waalewijn and Zoppi, Phys. Rev. Lett. **121**, 162001 (2018).

Linearly-polarized TMD jet function starts to contribute

$$\mathcal{J}_g^T = \frac{-g_\perp^{\mu\nu}}{d-2}\mathcal{J}_{g\,\mu\nu} = 1 + \mathcal{O}(\alpha_s),$$

$$\mathcal{J}_g^L = \frac{1}{(d-2)(d-3)}\left[g_\perp^{\alpha'_J\alpha_J} + (d-2)\frac{b_\perp^{\alpha'_J}b_\perp^{\alpha_J}}{\vec{b}_\perp^2}\right]\mathcal{J}_{g\,\mu\nu}$$

$$= \frac{\alpha_s}{4\pi}\left(-\frac{1}{3}C_A + \frac{2}{3}T_F n_f\right) + O(\alpha_s^2)$$

with

$$\mathcal{J}_g^{\mu\nu} = \frac{2(2\pi)^{d-1}}{N_c^2-1}\bar{n}\cdot p_J\langle 0|\mathcal{B}_{n\perp}^{a\mu}(0)e^{\delta_x b_x}\delta(\bar{n}\cdot p_J - \bar{n}\cdot p_c)\delta^{(d-2)}(\vec{p}_{\perp,c})\mathcal{B}_{n\perp}^{a\nu}(0)|0\rangle$$

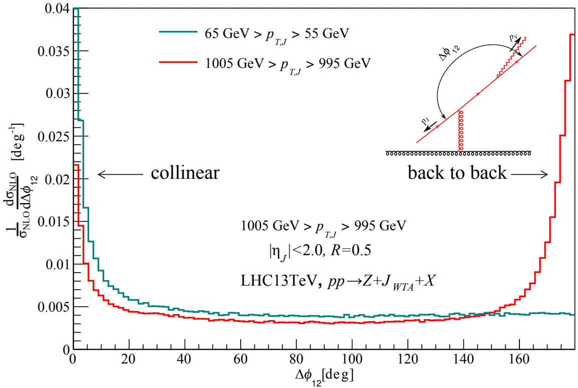
and $\delta_x \equiv p_{x,c} - p_{x,J}$.

TMD in jets contributes to $\delta\phi$ using WTA!

Chien, Rahn, Schrijnder van Velzen, Shao, Waalewijn and BW, Phys. Lett. B **815**, 136124 (2021) [arXiv:2005.12279 [hep-ph]].

Chien, Rahn, Shao, Waalewijn and BW, [arXiv:2205.05104 [hep-ph]].

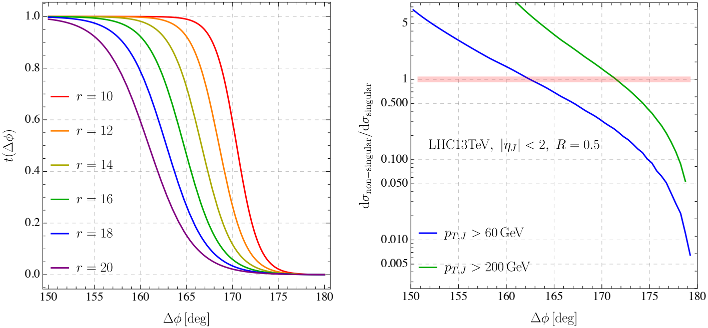
# Matching: emission of boson off dijets




- For $p_{T,J} \gg m_V$: Large contribution for $\delta\phi \gtrsim m_V/p_{T,J}$
- For $p_{T,J} \ll m_V$: finite corrections independent of $\delta\phi$

# Matching to the fixed-order cross section

The $O(\alpha_s)$ formula for a wide range of $\Delta\phi$:




$$\boxed{\mathrm{d}\sigma(\mathrm{NLO} + \mathrm{NNLL}) = [1 - t(\Delta\phi)] \times (\mathrm{NNLL} + \text{nonsingular part of NLO}) + t(\Delta\phi) \times (\mathrm{NLO})}$$

where $t(\Delta\phi) = \frac{1}{2} - \frac{1}{2}\tanh\left[4 - \frac{240(\pi - \Delta\phi)}{r}\right]$ with $r = 20(10)$ for $p_{T,J} > 60(200)$ GeV.