Azimuthal decorrelation as a probe to QCD matter

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Nikhef Theory Seminar

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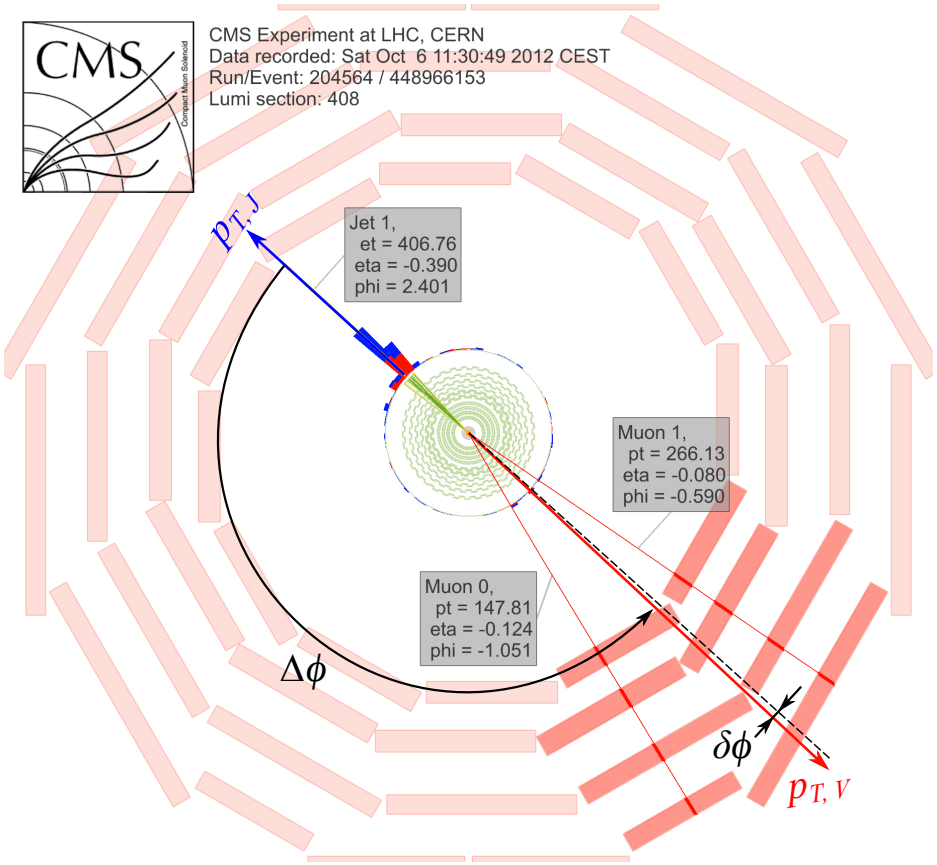
Motivations

Azimuthal decorrelation

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

In pp collisions: a stringent test of QCD



Precise predictions rely on

1. Fixed-order calculations

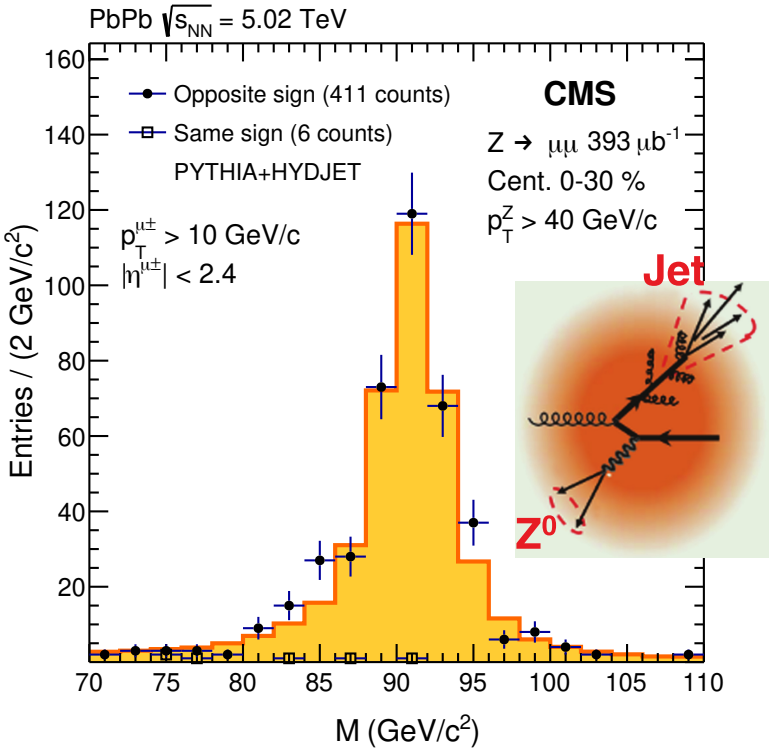
   NLO, NNLO,$\cdots$

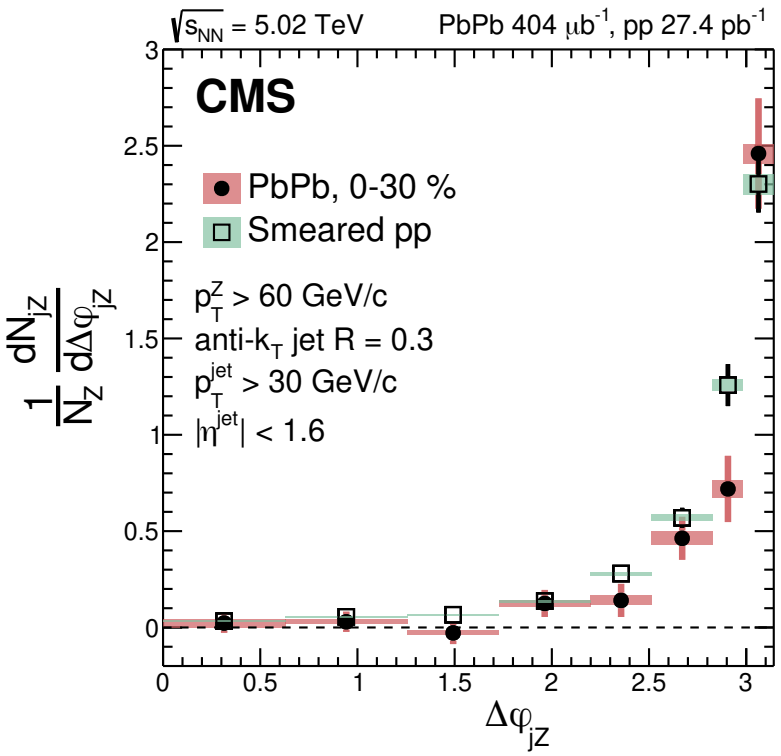
2. Resummation of $\ln \delta\phi$
   - Parton branching method
   - Pythia, Herwig,$\cdots$
   - TMD factorization
   - SCET

3. Validity of factorziation

   Is it broken by Glauber modes?

In high-energy nuclear collisions:

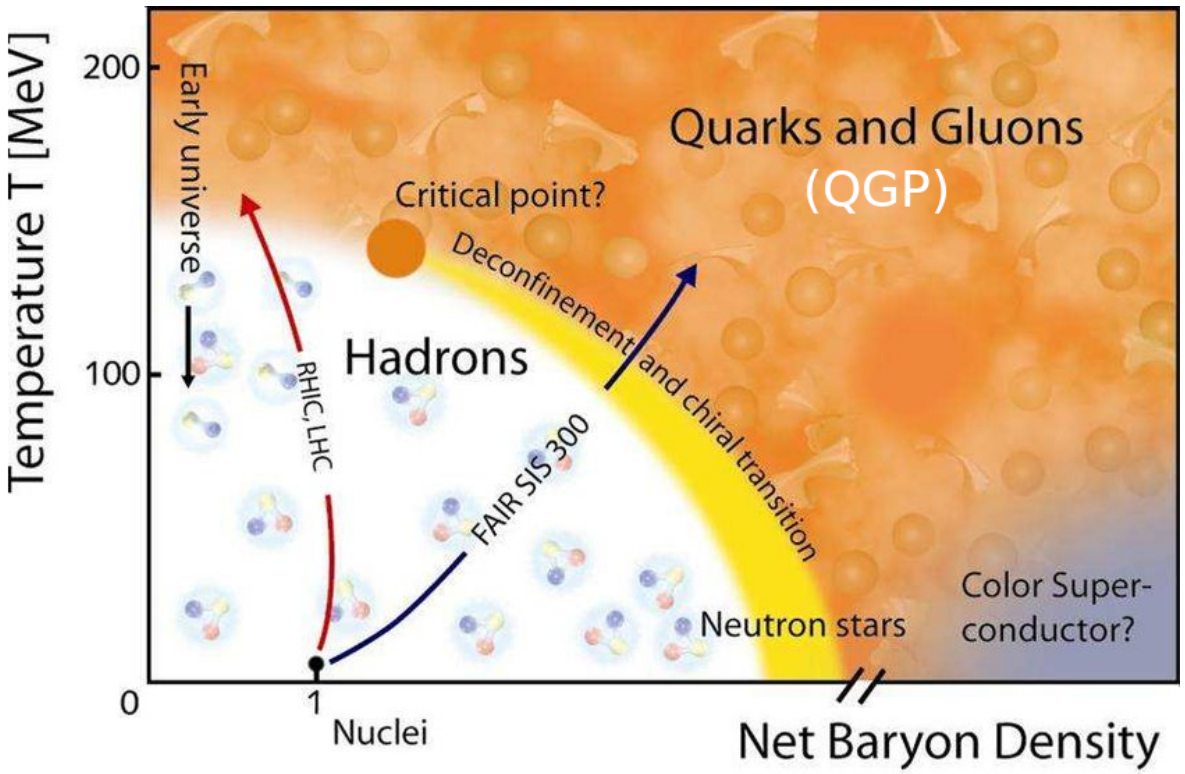




A. M. Sirunyan *et al.* [CMS], Phys. Rev. Lett. **119**, no.8, 082301 (2017) [arXiv:1702.01060 [nucl-ex]].

Properties of QCD matter are measured as deviation from pp collisions!

Conjectured QCD phase diagram

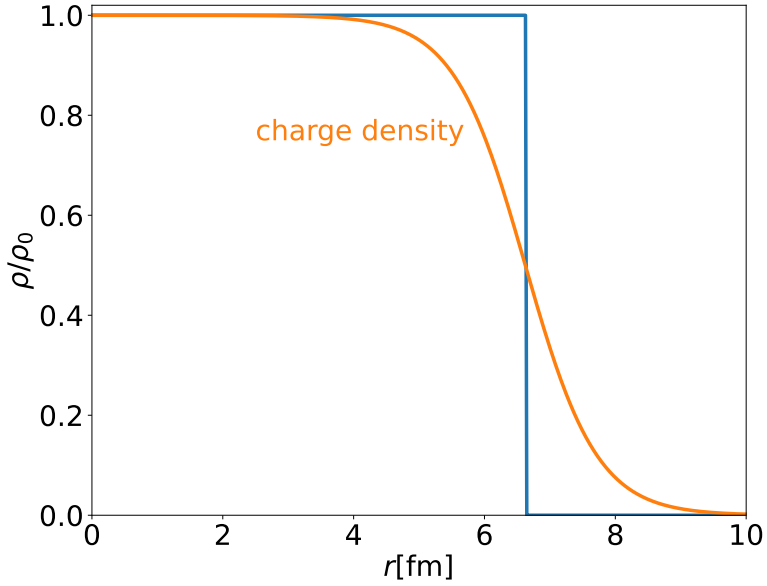


In collider physics, we can study

- **Cold nuclear matter:** substructure of p, Cu, Xe, Au, Pb $\cdots$
- **Hot nuclear matter:** the quark-gluon plasma (QGP)

Substructure of Heavy-nuclei

As seen by a low-energy electron:



$$\rho(r)/\rho_0 = \frac{1}{1+e^{\frac{r-R_{ws}}{a}}} \qquad \text{with } R_{ws} = 6.62 \text{ fm and } a = 0.55 \text{ fm for } {}^{208}\text{Pb}.$$

C. W. De Jager, H. De Vries and C. De Vries, Atom. Data Nucl. Data Tabl. **14** (1974), 479-508.

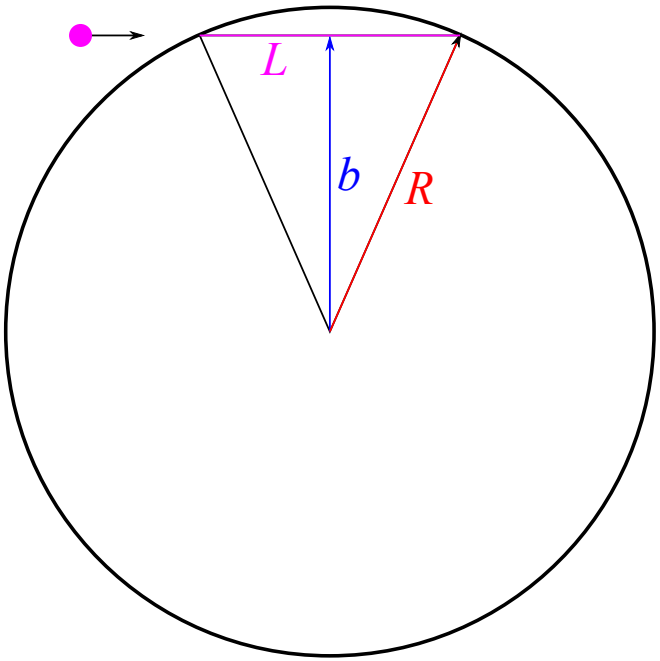
Idealized heavy nuclei: a perfect sphere of R with $\rho_0 = 0.16$ fm^{-3}

$$A = \frac{4\pi}{3} R^3 \rho_0 \Rightarrow R = 1.14 A^{\frac{1}{3}} \text{ fm} \qquad \text{with } A \text{ the mass number}$$

Underlying event in nucleus-nucleus (AA) collisions

Mean free path of a nucleon in a heavy-nucleus:

$$\lambda = \frac{1}{\rho_0 \sigma_{pp}} \approx 1 \text{ fm} \qquad \text{with inelastic } \sigma_{pp} \approx 62.8 \text{ mb at } \sqrt{s_{NN}} = 2.76 \text{ TeV}$$



$$L = 2\sqrt{R^2 - b^2}$$

$$\Rightarrow L \geq \lambda \text{ for } b < 6.75 \text{ fm}$$

Note $R = 6.77$ fm For ^{208}Pb

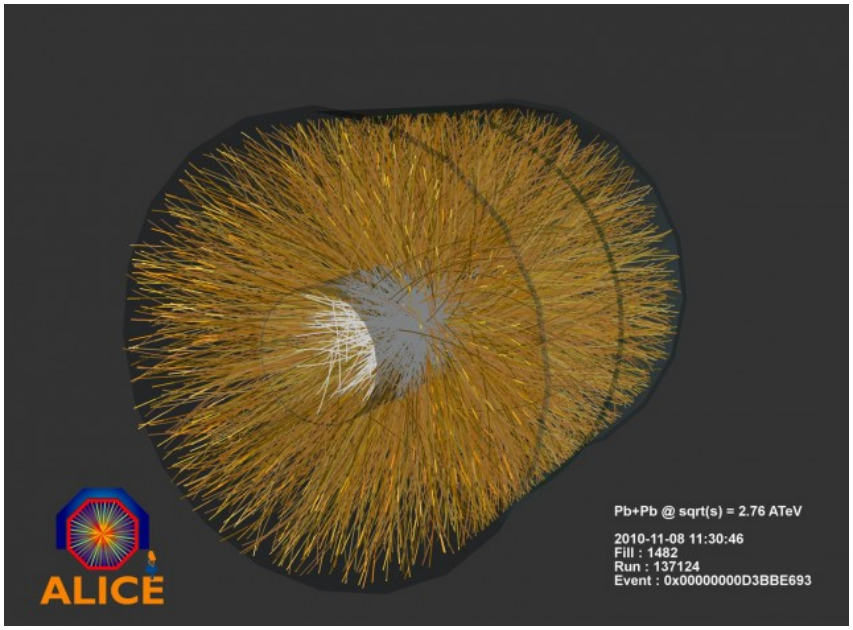
$\Rightarrow$The number of participants

$$N_{\text{part}} \approx 2A$$

for central collisions

AA collisions can be roughly viewed as $\sim A$ pairs of pp collisions!

QCD matter in central AA collisions



Trajectories of charged hadrons in PbPb collisions

Parametric estimates:

In pp collisions at the LHC

$$\frac{dN_{pp}}{d\eta} \sim 10, \quad \langle p_T \rangle \sim 1 \text{ GeV at } \eta \sim 0$$

In central AA collisions

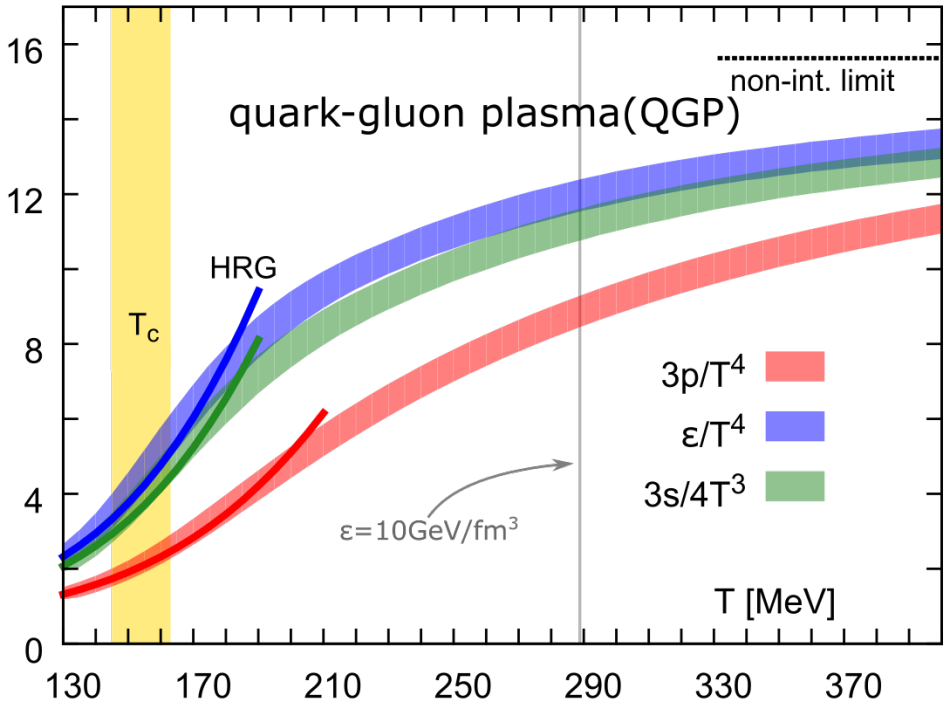
$$\frac{dN_{AA}}{d\eta} \sim A\frac{dN_{pp}}{d\eta} \sim 10^3 \text{ at } \eta \sim 0$$

$$\varepsilon(t = 1\ fm/c) \sim \langle p_T \rangle \frac{dN_{AA}}{d\eta}\frac{1}{tR^2} \sim 10 GeV/fm^3.$$

$\varepsilon(t = 1\ fm/c) = 14\ GeV/fm^3$ based on measurement in CMS: Phys. Rev. Lett. **109**, 152303 (2012) [arXiv:1205.2488 [nucl-ex]]

The quark-gluon plasma (QGP)

Thermodynamics of QGP: color deconfined state of QCD matter



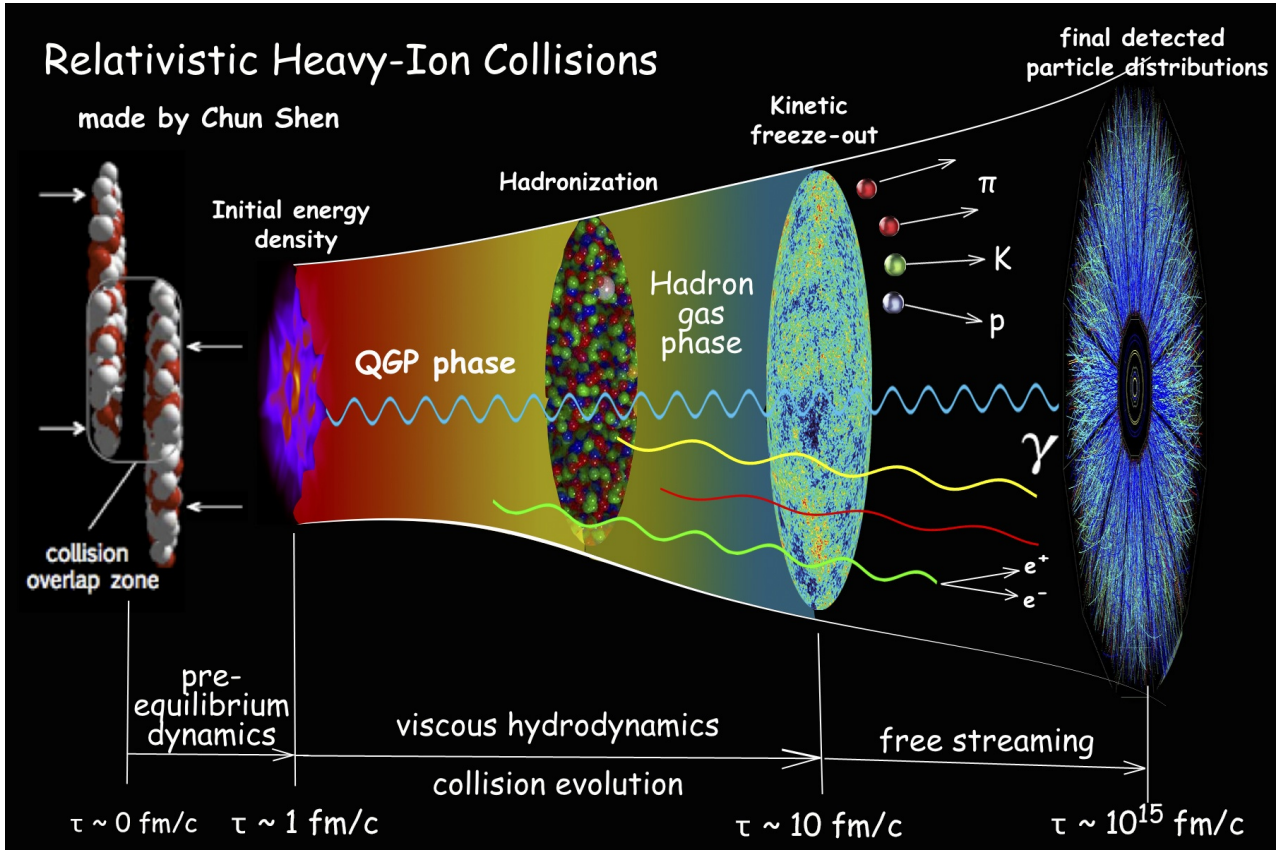
Lattice QCD: Phys. Rev. D **90**, 094503 (2014) [arXiv:1407.6387 [hep-lat]].

QGP dominated the early universe at

$$t \approx 1/T_{MeV}^2 \approx 10\mu s$$

Real-time dynamics of AA collisions

Bulk matter $\neq$ QGP in thermal equilibrium



I only focus on the evolution of jets in QCD medium of size ~ 10 fm!

Jets in QCD medium

Do they hadronize in it?

$$t_{\text{hadr}} \sim \frac{1}{\Lambda_{QCD}} \frac{E}{\Lambda_{QCD}} \sim \frac{E}{\Lambda_{QCD}} \text{ fm.}$$

As long as $E \gg 10\Lambda_{QCD}$, they typically don't.

Do jets develop in it?

$$t_{\text{jet}} \sim \frac{1}{m_J} \frac{E_J}{m_J} \sim \frac{1}{R^2 E_J} \qquad \text{with } R \text{ jet radius.}$$

They do (as long as $E_J \gg 10^{-2} R^{-2}$ GeV)

Main medium effects on jet evolution:

1. $p_\perp$-broadening ($p_\perp$ is transverse to the jet momentum)
2. Medium-induced radiation

$p_\perp$-broadening and radiative energy loss

Jet quenching parameter $\hat{q}$

$$\langle p_\perp^2 \rangle = \hat{q} L$$

with L the path length.

Medium-induced energy loss

$$\Delta E = \frac{\alpha_s N_c}{12} \hat{q} L^2 = \frac{\alpha_s N_c}{12} \langle p_\perp^2 \rangle L.$$

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.

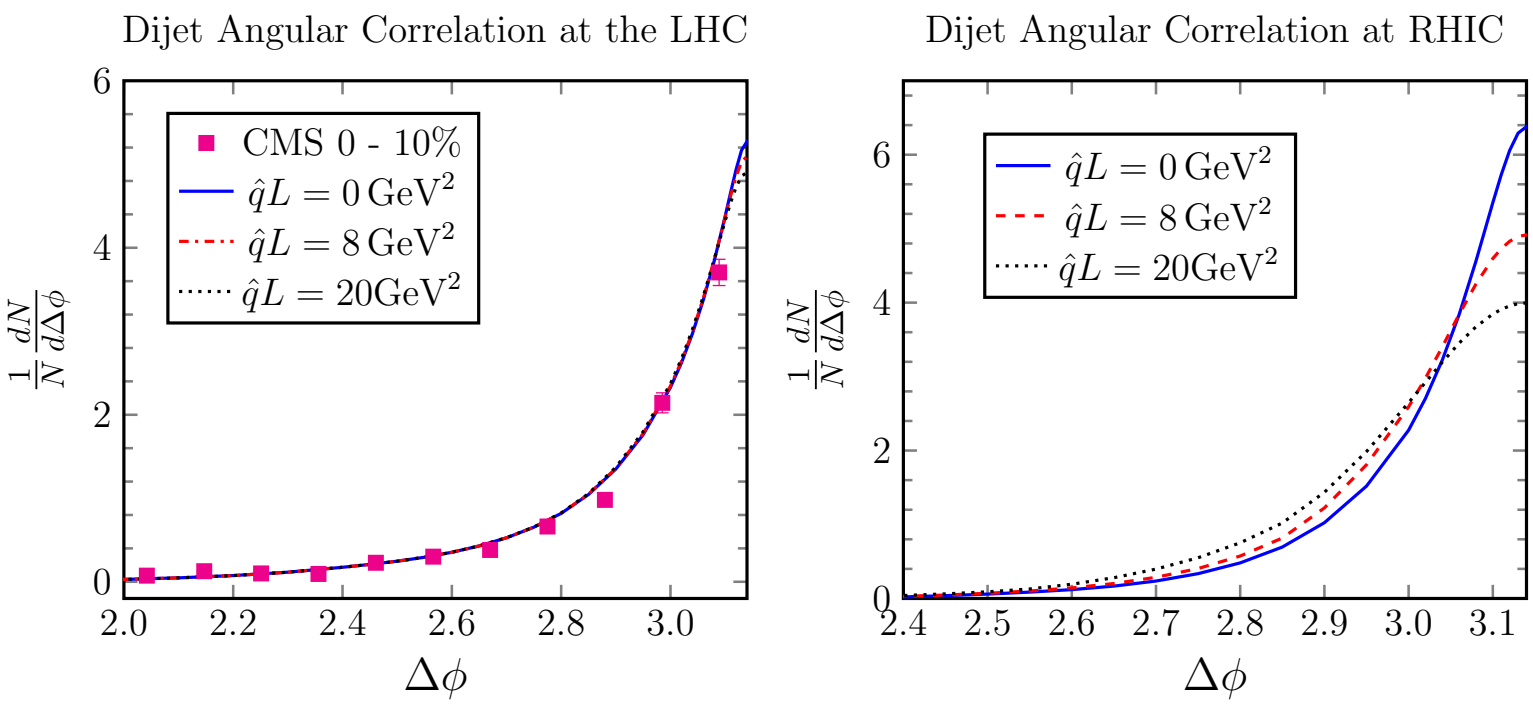
$$\hat{q} = (2-4) T^3$$

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

An alternative way to measure $\hat{q}$: $\delta\phi \sim \frac{\sqrt{\hat{q}L}}{p_{T,J}}$

Measurement of $\hat{q}$ via $\Delta\phi$

Using dijets: NLL resummation of Sudakov logs + tree-level medium effects



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

Using boson-jet:

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

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

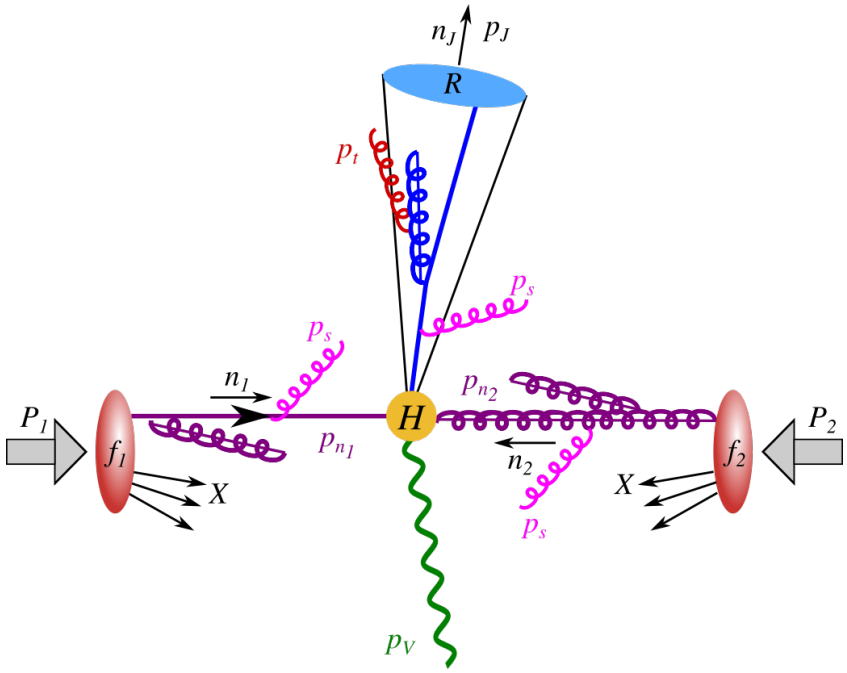
Main topics: going beyond NLL resummation and LO medium effects!

Boson-jet correlation in pp collisions

Resummation using standard jet axis

Standard jet axis (SJA): $p_J = \sum_{i \in \text{jet}} p_{J,i}$

An all-order resummation formula (with Glauber modes neglected):



Hard function: $\mathcal{H}_{ij\to Vk}$

Beam functions: $\mathcal{B}_{i/N_1}, \mathcal{B}_{j/N_2}$

Soft function: $\mathcal{S}_{ij\to Vk}$

Jet function: $\mathcal{J}^k$ contains NGLs!

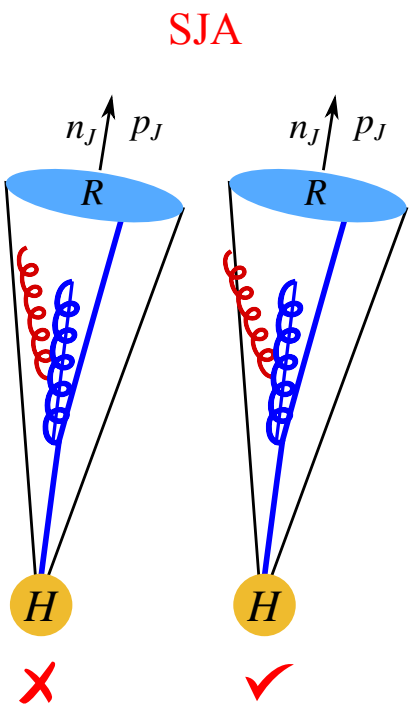
$$\frac{d\sigma}{d^2p_T^J d^2p_T^V d\eta_J dy_V} = \sum_{ijk} \int \frac{d^2x_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{x}_T} \mathcal{S}_{ij\to Vk}(\vec{x}_T,\epsilon)\mathcal{B}_{i/N_1}(\xi_1,x_T,\epsilon)\mathcal{B}_{j/N_2}(\xi_2,x_T,\epsilon)$$

$$\times \mathcal{H}_{ij\to Vk}(\hat{s},\hat{t},m_V,\epsilon)\mathcal{J}^k(p_J^2,\vec{x}_T,\epsilon)$$

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

Non-global logarithm and SJA

An non-global observable:



For $\delta\phi > 0$

- In-jet soft radiation does not contribute
- Only out-jet soft radiation contributes

$\Rightarrow$ NGL $\propto \alpha_S C_A \alpha_s C_k L^2$

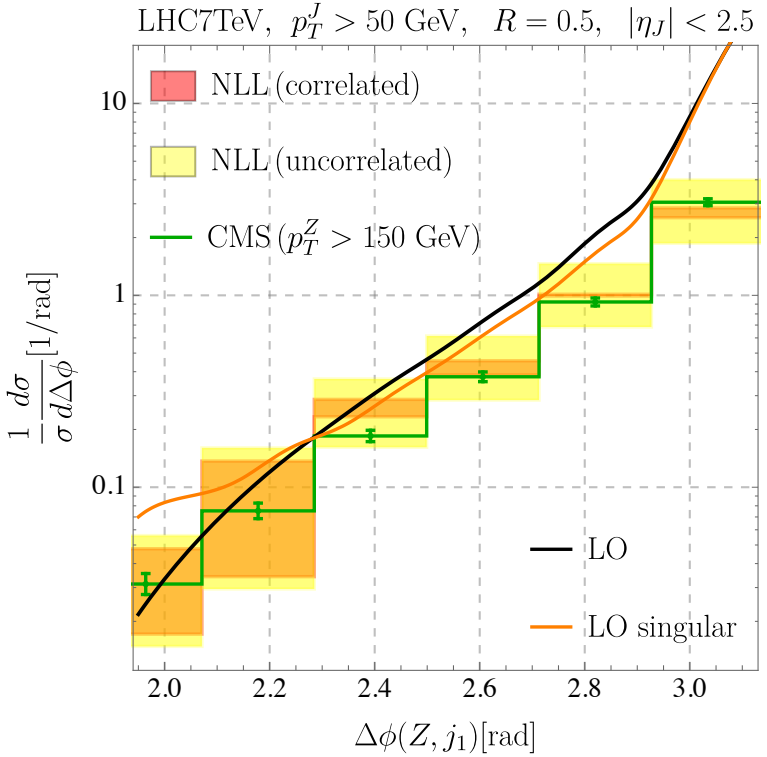
starting as NLL terms with $\alpha_s L \sim 1$.

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

Resummation of NGLs is very difficult

NLL resummation using SJA

NLL resummed results with NGLs: relatively large uncertainties

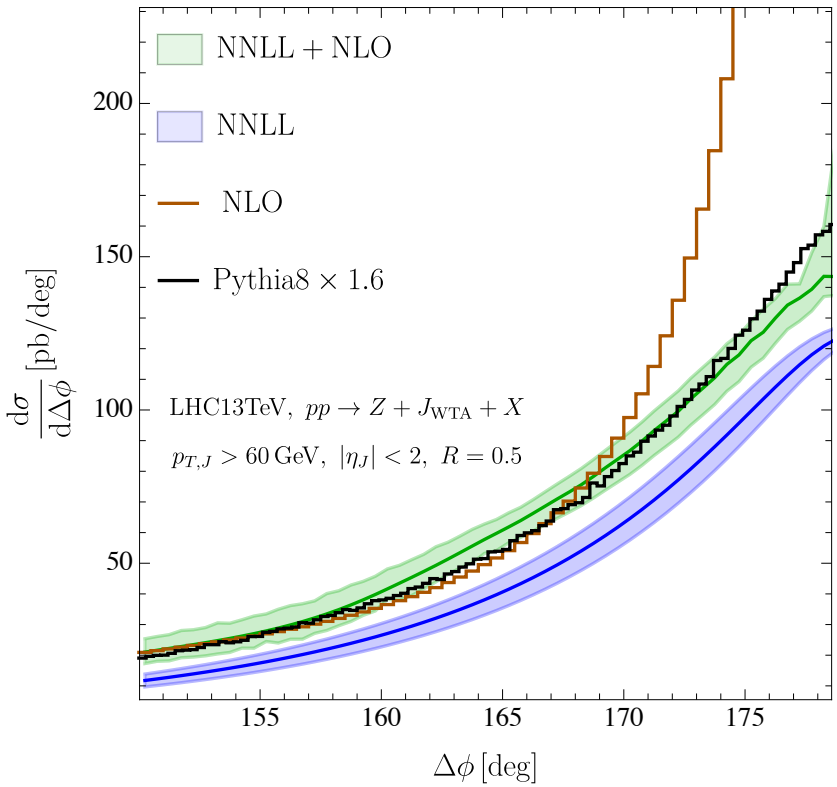


Y. T. Chien, D. Y. Shao and BW, JHEP **11**, 025 (2019) [arXiv:1905.01335 [hep-ph]].

precision predictions ⇔ going beyond NLL

NNLL resummation using SJA has not been achieved in any frameworks!

NNLL resummation in $\delta\phi$



The "minor" change: SJA $\to$ Winner-Take-All (WTA) axis

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, [arXiv:2205.05104 [hep-ph]].

What is WTA?

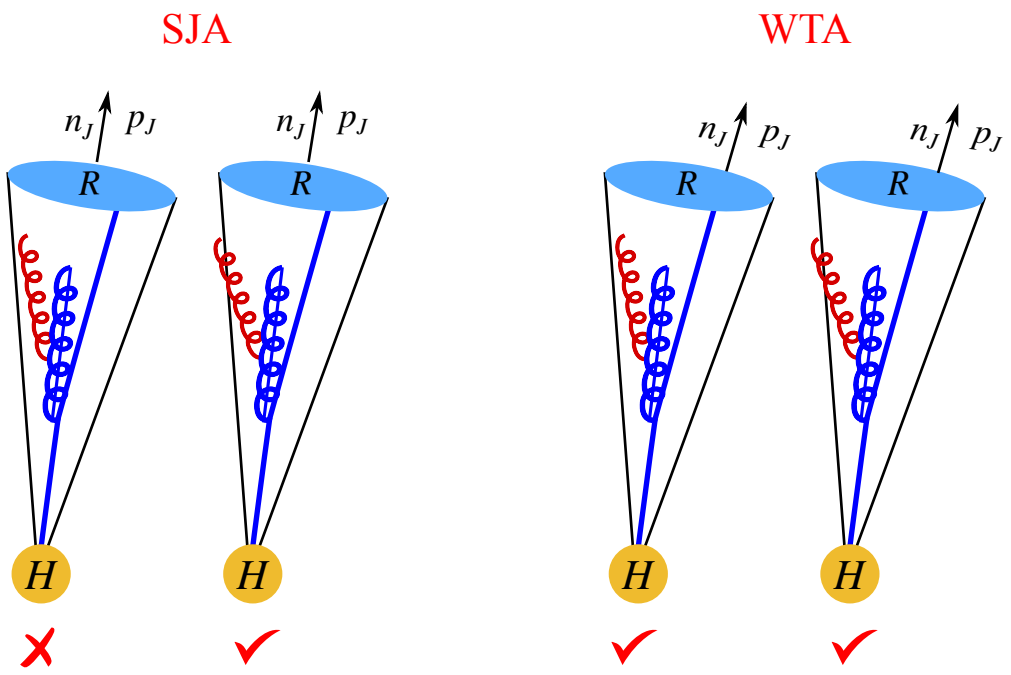
WTA-p_T scheme:

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

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

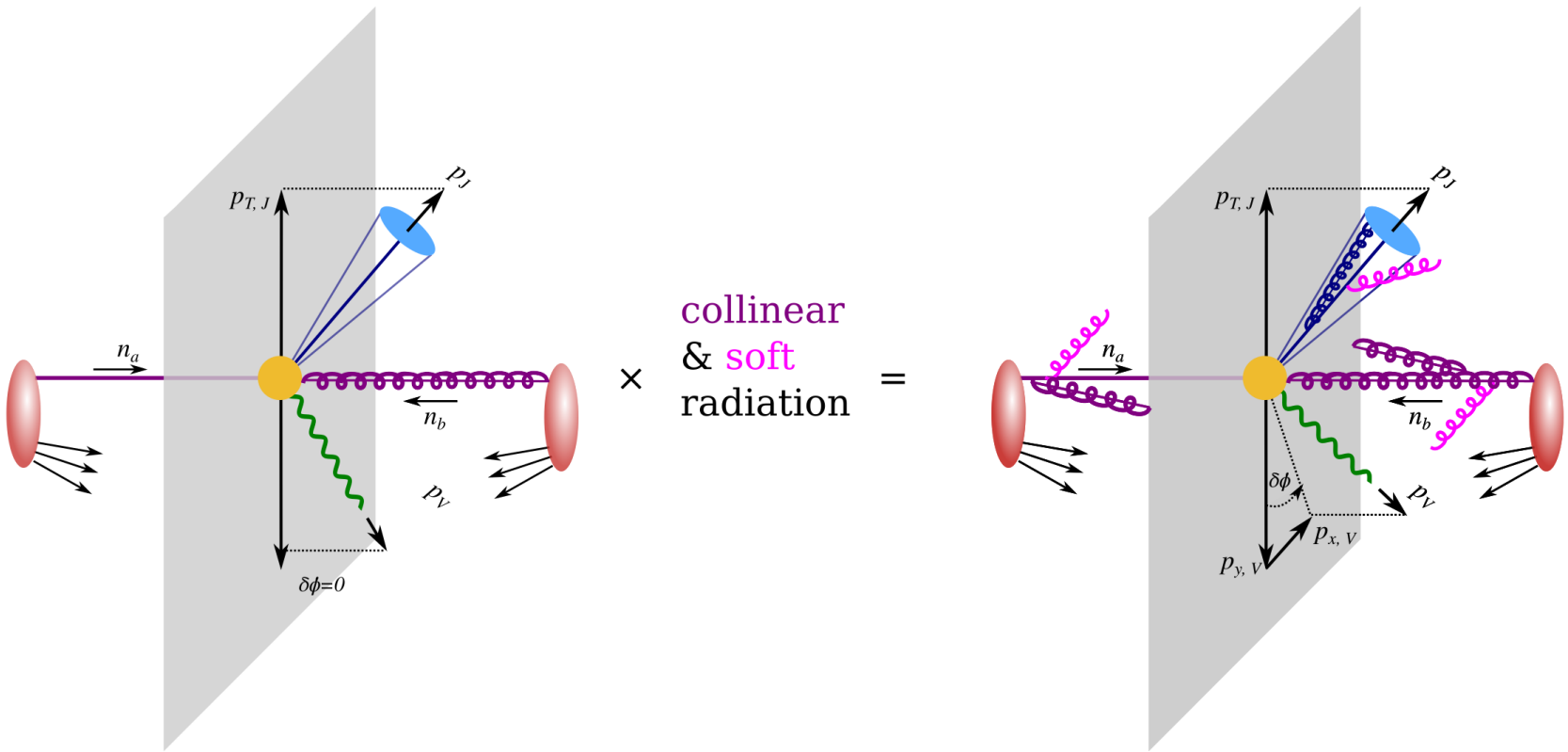
Jet definition: anti-k_t algorithm with WTA-p_T scheme

The WTA axis eliminates NGLs: insensitive to soft radiation



Factorization formula

An all-order resummation formula using the WTA axis:

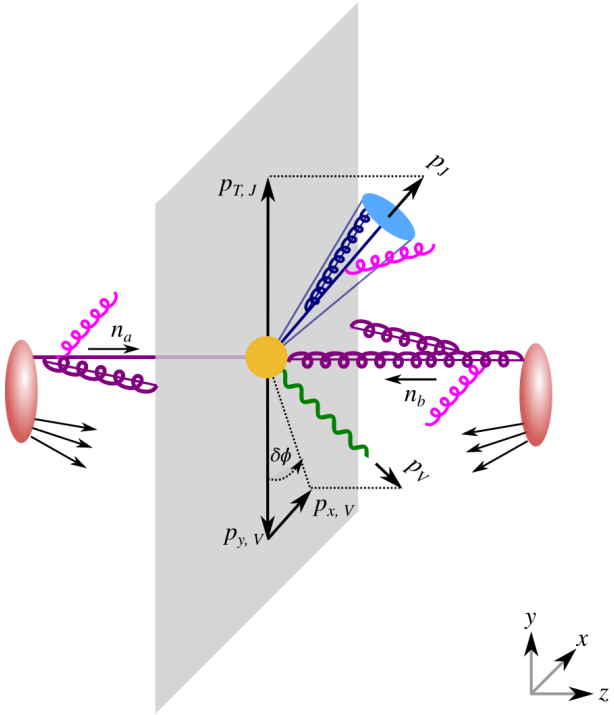


$$\Rightarrow \ln \Sigma(\delta\phi) \equiv \ln\left(\int_0^{\delta\phi} \frac{d\sigma}{d\delta\phi}\right) \sim \underbrace{L(\alpha_s L)}_{LL} + \underbrace{(\alpha_s L)}_{NLL} + \cdots + \underbrace{\alpha_s^{i-1}(\alpha_s L)}_{N^i LL}$$

with $L = \ln \delta\phi$ as $\delta\phi \to 0$.

Factorization formula

An all-order resummation formula using the WTA axis:



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!

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

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]].

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

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

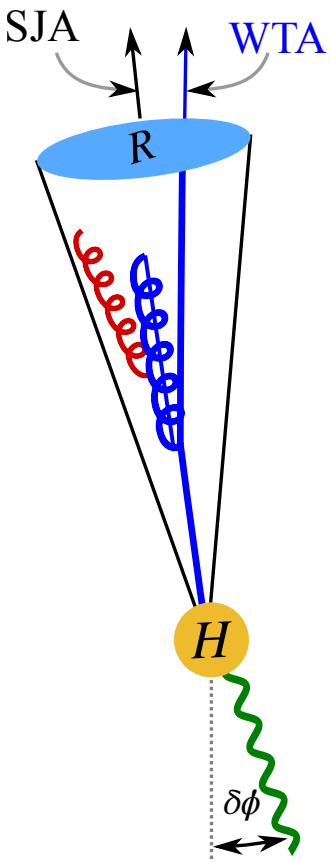
with

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

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]].

Track-based measurements

In experiments:

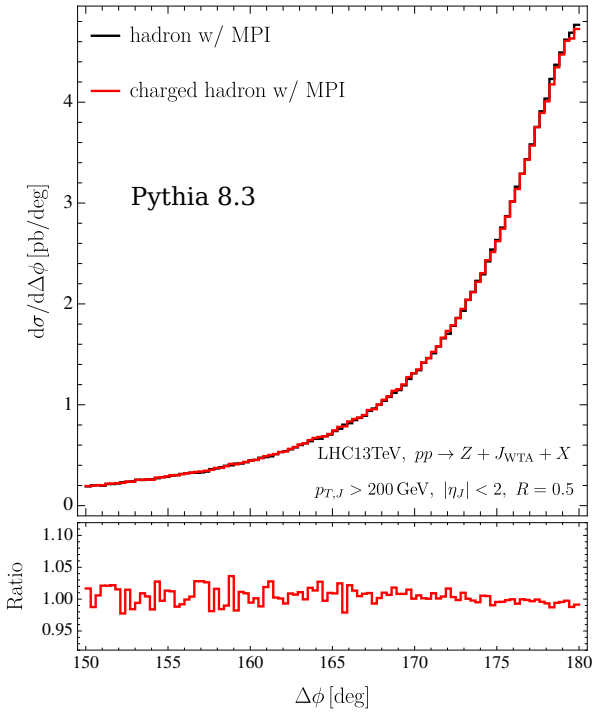
- Limitation of (calorimeter) jet measurements:

$$\text{granularity} \sim 0.1 \text{ rad} \approx 6^\circ$$

- LHC trackers have superior angular resolution

In theory, for track-based jets using WTA

- Only jet functions need to be modified!
- Naturally robust to pile-up

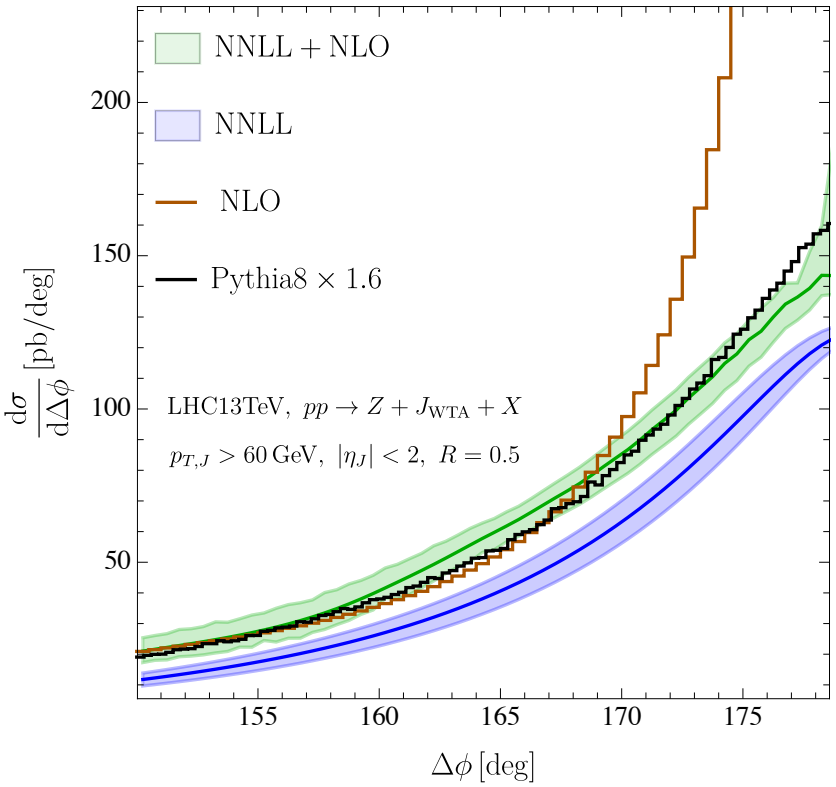


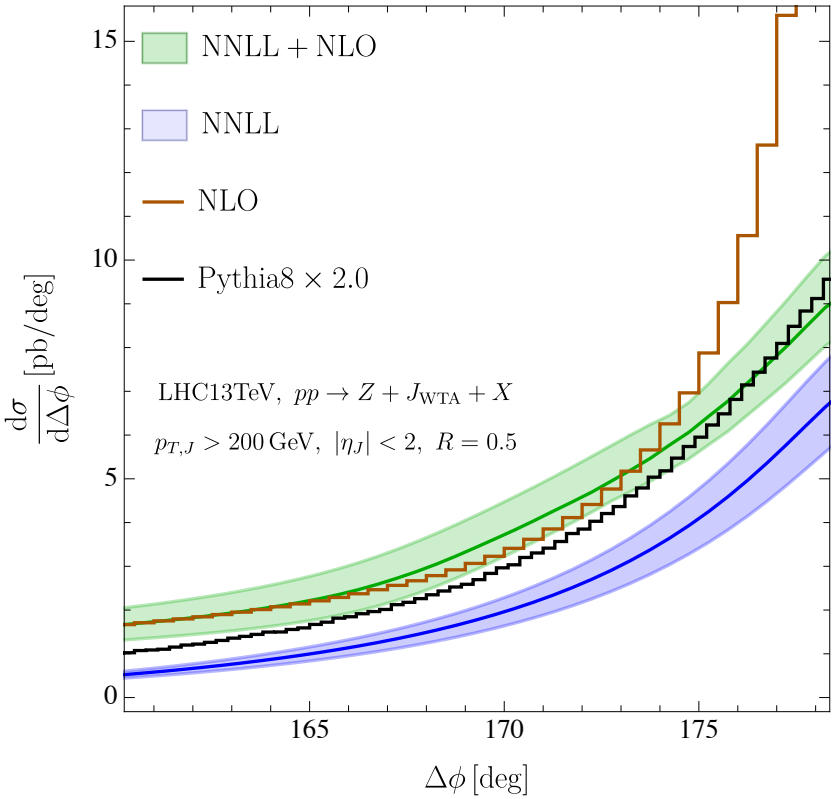
Pythia simulations: using tracks has a minimal effect on $\Delta\phi$ distribution!

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

Theoretical predictions

At NNLL + NL0 accuracy

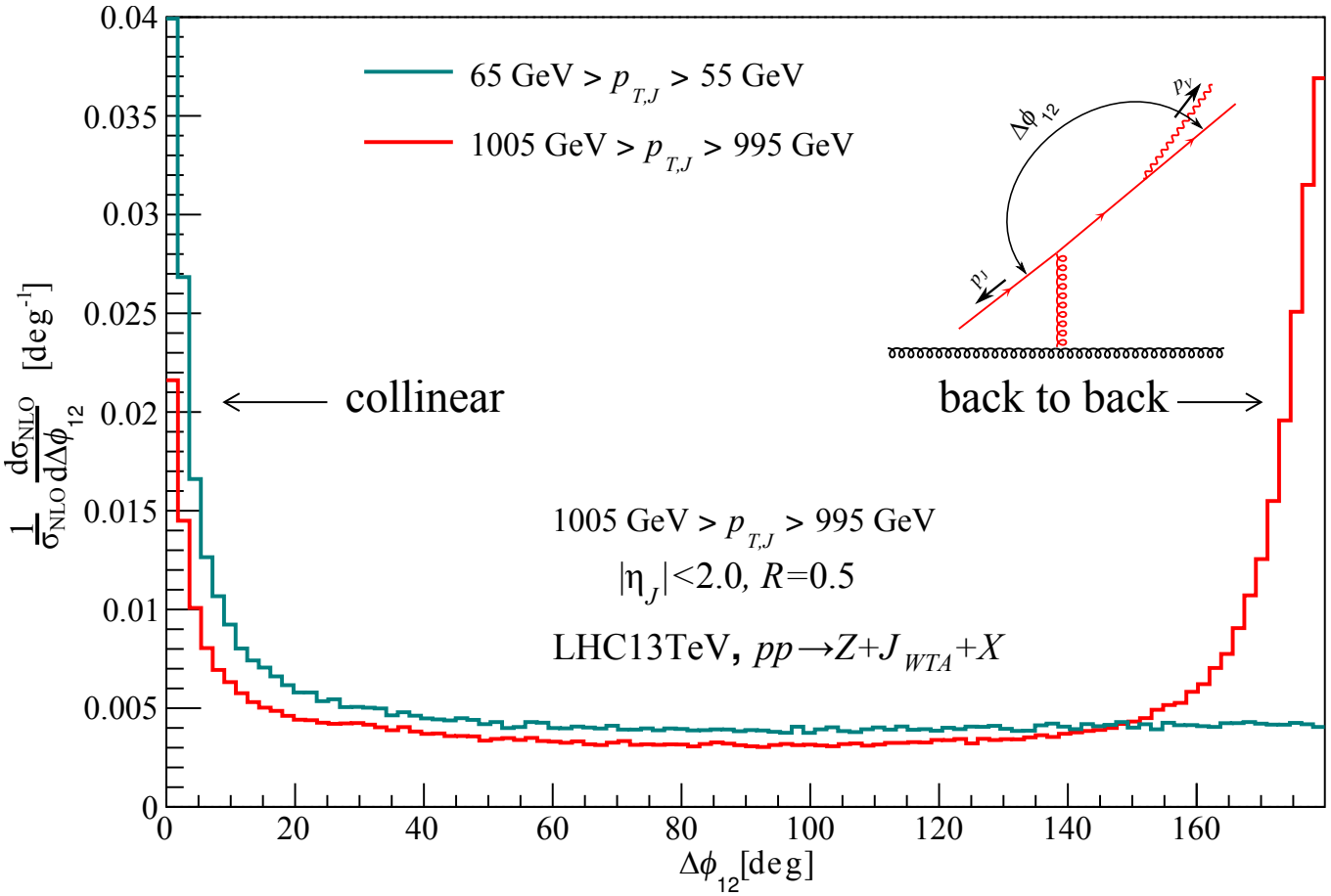




Large nonsingular corrections are not accounted for in Pythia simulations!

Large nonsingular corrections even at small $\delta\phi$?

Matching: emission of boson off dijets

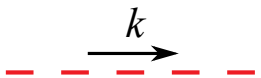


- For $p_{T,J} \gg m_V$: Large contribution for $\delta\phi \gtrsim m_V/p_{T,J}$
- For $p_{T,J} \ll m_V$: finite corrections independent of $\delta\phi$

Can be removed by Z isolation!

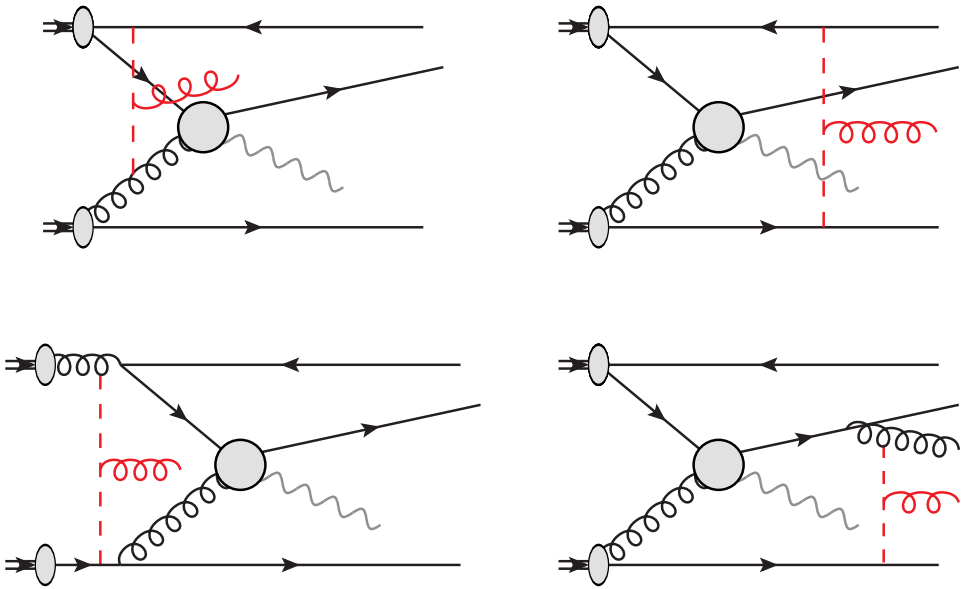
Factorization breaking?

Glauber exchange: instantaneous interaction



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

Glauber topologies:



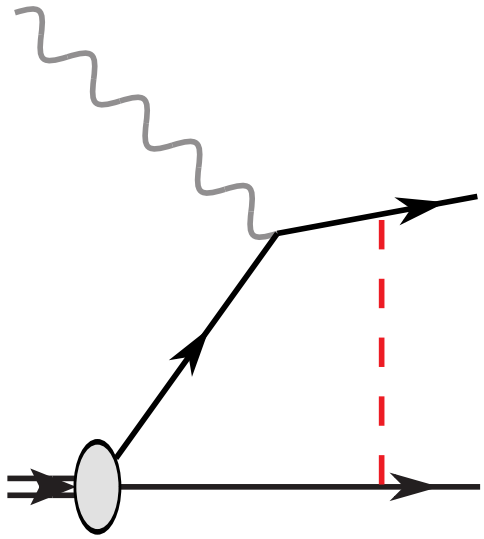
Don't spoil factorization up to and including $O(\alpha_s^3)$

$p_\perp$-broadening in nuclear collisions

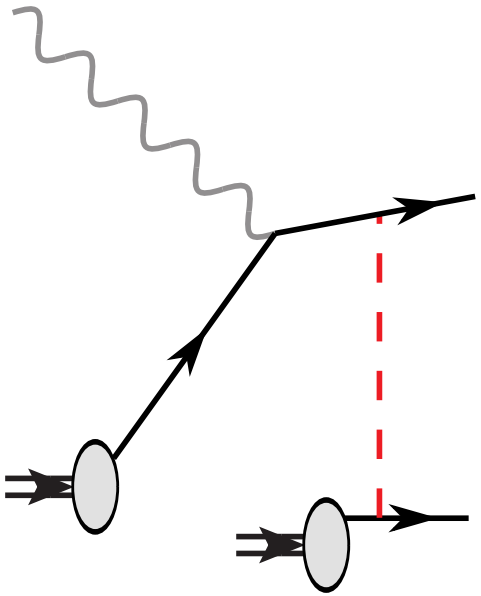
What if the proton is replaced by a nucleus?

Let us focus on DIS for simplicity.

Glauber topologies:



(a) *ep*: a pure phase



(b) *eA*

Glauber modes could contribute at $O(\alpha_s^2)$ in eA.

Quark production at LO

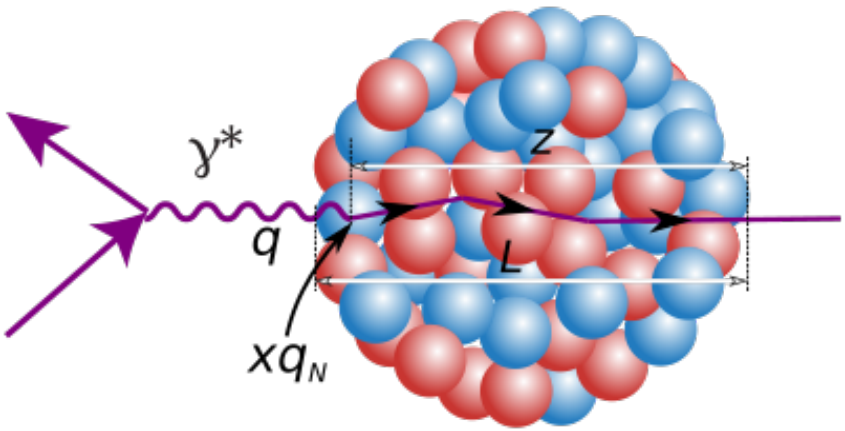
Frame: (sometimes the nucleus is shown at rest)

virtual photon: $$q_\mu = \left(q_+, q_- = \frac{Q^2}{2q_+}, q_\perp = 0\right)$$

the nucleus: $$P_\mu = \left(\frac{m_A^2}{2P_-}, P_-, P_\perp = 0\right)$$

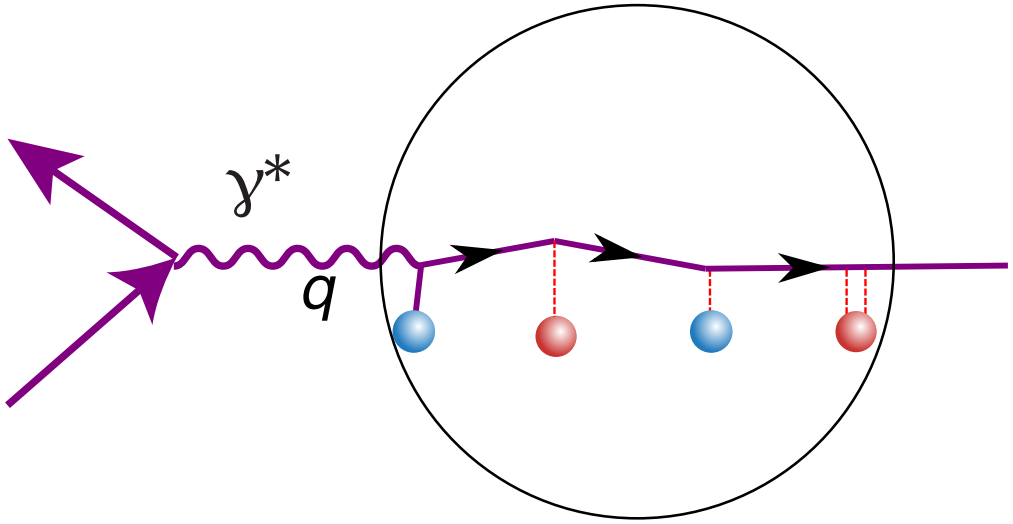
where q_+ and P_- are large.

When $\frac{1}{q^-} \ll L$:



Quark production at LO

When $\frac{1}{q^-} \ll L$:

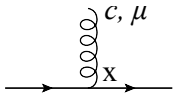


$$\frac{dN}{d^2b d^2k_\perp} = \int \frac{d^2x_\perp}{(2\pi)^2} e^{-ik_\perp \cdot x_\perp} \rho_0 x q_N(x) \int_0^L dz \underbrace{e^{-\frac{1}{4}\hat{q}x_\perp^2 z}}_{S(x_\perp, z)}$$

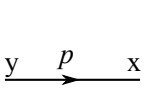
Kovchegov and Mueller, Nucl. Phys. B **529**, 451 (1998).

Feynman rules

Eikonal approximation on the quark line:

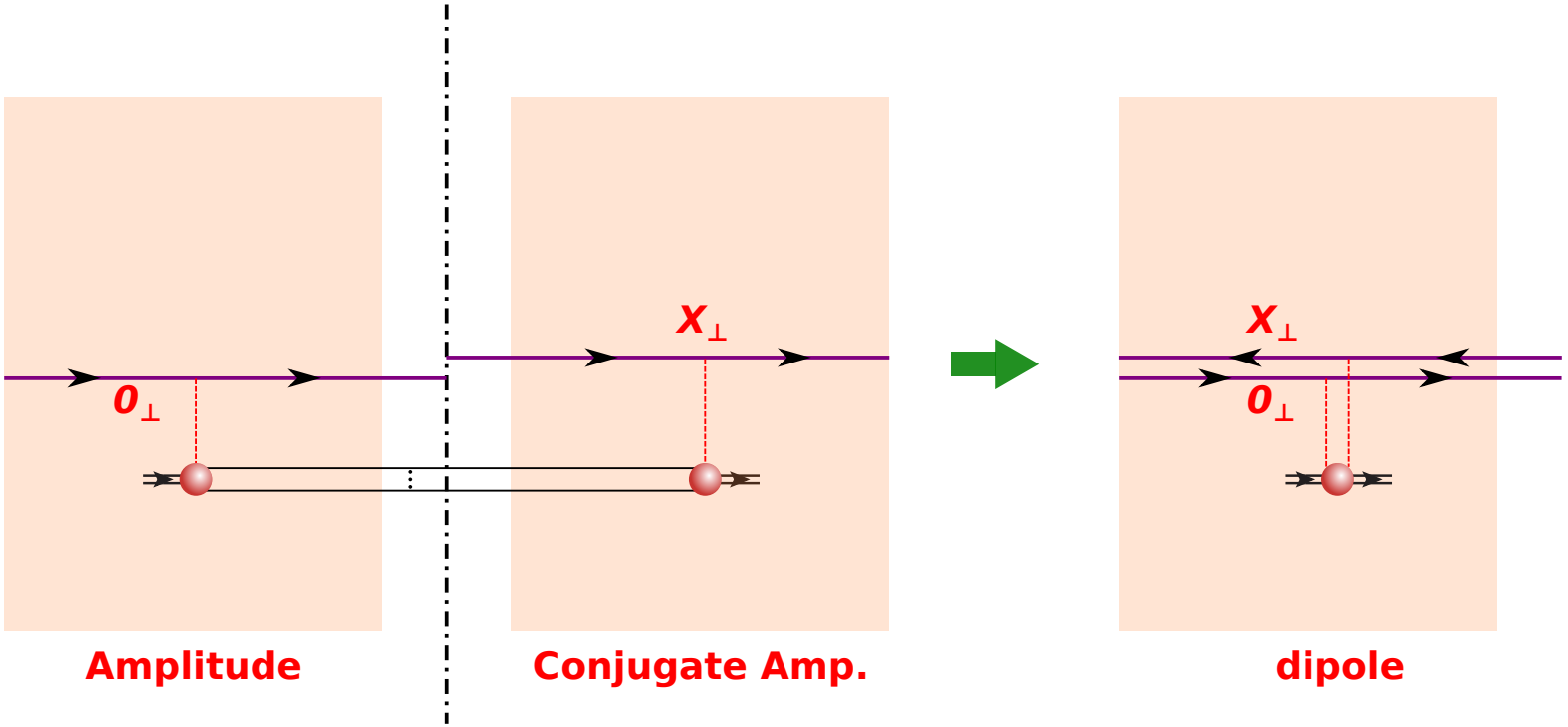


$$= -igt^c \frac{\not{\bar{n}}}{2} n^\mu \int d^2\mathbf{x}$$



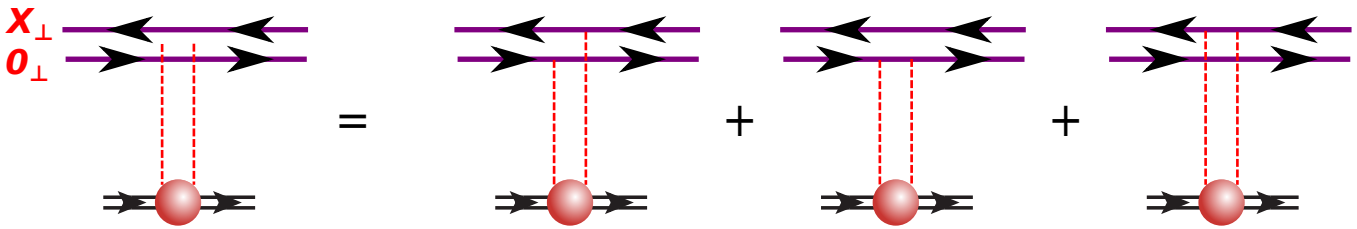
$$= \frac{i\frac{\not{\bar{n}}}{2}\delta^{(2)}(\mathbf{x}-\mathbf{y})}{n\cdot p + i\bar{n}\cdot p\ \epsilon}$$

Dipole picture:



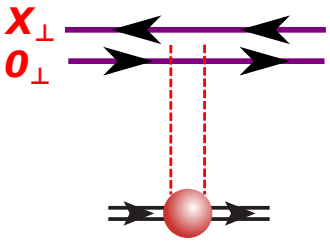
Dipole cross section

Single scattering:



$$= \int \frac{d^2 l_\perp}{(2\pi)^2} \frac{d\sigma_{qN}}{d^2 l_\perp} (e^{i\vec{l}_\perp \cdot x_\perp} - 1)$$

Leading-log approximation:



$$\approx -\frac{1}{2} \int_{l_\perp^2 < \frac{1}{x_\perp^2}} \frac{d^2 l_\perp}{(2\pi)^2} \frac{d\sigma_{qN}}{d^2 l_\perp} (\vec{l}_\perp \cdot x_\perp)^2$$

$$= -\frac{1}{4} x_\perp^2 \int_{l_\perp^2 < \frac{1}{x_\perp^2}} \frac{d^2 l_\perp}{(2\pi)^2} l_\perp^2 \frac{d\sigma_{qN}}{d^2 l_\perp}$$

Jet quenching parameter $\hat{q}$

Physical meaning: $p_\perp$-broadening per unit path length!

$$\hat{q}(1/x_\perp^2) \equiv \rho_0 \int\limits_{p_\perp^2 < \frac{1}{x_\perp^2}} d^2p_\perp \frac{d\sigma_{qN}}{d^2p_\perp} p_\perp^2$$

$$= \frac{1}{\lambda} \int\limits_{p_\perp^2 < \frac{1}{x_\perp^2}} d^2p_\perp \frac{1}{\sigma_{qN}} \frac{d\sigma_{qN}}{d^2p_\perp} p_\perp^2$$

$$= \frac{\langle p_\perp^2 \rangle}{\lambda} = \frac{d}{dz} \langle p_\perp^2(z) \rangle$$

Definition:

$$\boxed{\hat{q}(1/x_\perp^2) = \frac{4\pi^2 \alpha_s C_F}{N_c^2 - 1} \rho_0 x G(x, 1/x_\perp^2)}$$

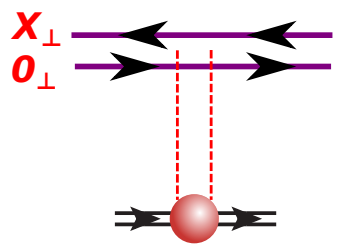
Baier, Dokshitzer, Mueller, Peigne and Schiff, Nucl. Phys. B **484**, *265 (1997).*

Dipole cross section

Multiple scatterings:

$$S(x_\perp, z) = \int d^2p_\perp e^{ip_\perp \cdot x_\perp} \frac{dN}{d^2p_\perp}$$

$$= \exp\Bigg($$



$$\Bigg) = e^{-\frac{1}{4}\hat{q}x_\perp^2 z}$$

Time-dependent medium (QGP):

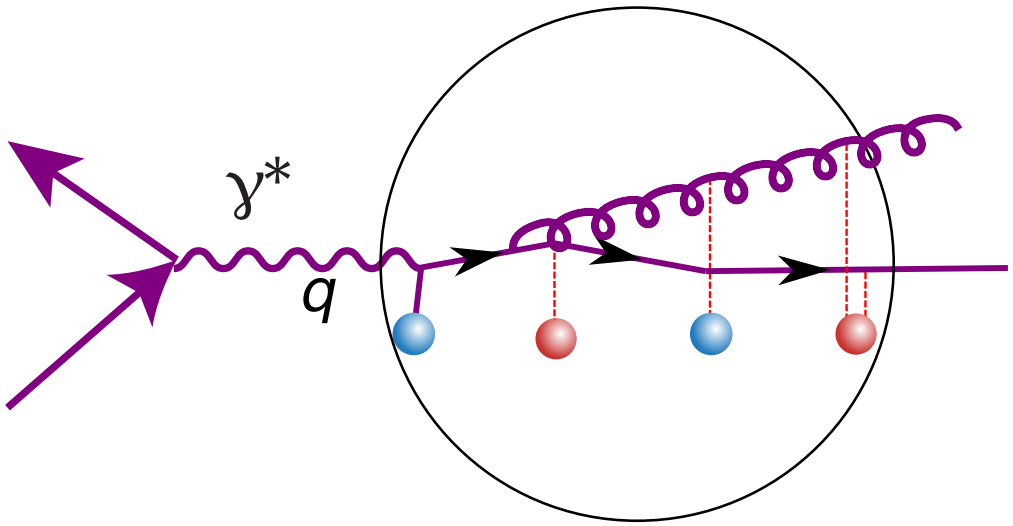
$$S(x_\perp, z_i, z_f) = e^{-\frac{1}{4}x_\perp^2 \int_{z_i}^{z_f} dz\hat{q}(z)}$$

$p_\perp$-broadening from multiple scattering

$$\langle p_\perp^2 \rangle \equiv \int d^2p_\perp p_\perp^2 dN d^2p_\perp = -\nabla^2 S(x_\perp, z)\Big|_{x_\perp=0}$$

Quark production at NLO

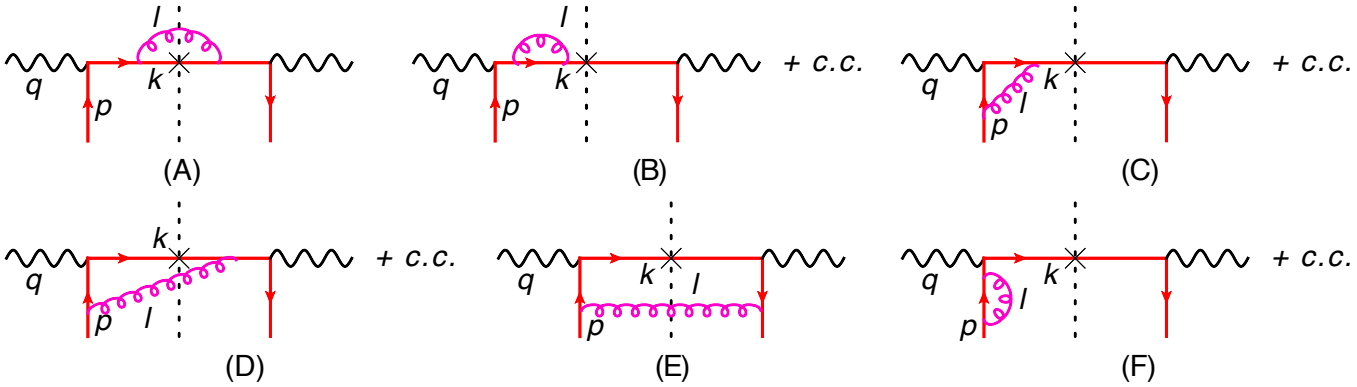
One gluon emission with multiple scatterings



There are both Sudakov and medium-dependent double logarithms!

Quark production at NLO

Sudakov double logs (in $A^+ = 0$ gauge): the $\hat{q} \to 0$ limit



$$A + B \approx -\frac{\alpha_s C_F}{\pi} \rho_0 x q_N \int_{k_\perp^2}^{Q^2} \frac{dl_\perp^2}{l_\perp^2} \int_0^{q^+} \frac{dl^+}{l^+}, \qquad E + F \approx 0$$

$$C + D \approx \frac{\alpha_s C_F}{\pi} \rho_0 x q_N \int_{k_\perp^2}^{Q^2} \frac{dl_\perp^2}{l_\perp^2} \int_{l^- > q^-} \frac{dl^+}{l^+} = \frac{\alpha_s C_F}{\pi} \rho_0 x q_N \int_{k_\perp^2}^{Q^2} \frac{dl_\perp^2}{l_\perp^2} \int_0^{q^+ \frac{l_\perp^2}{Q^2}} \frac{dl^+}{l^+},$$

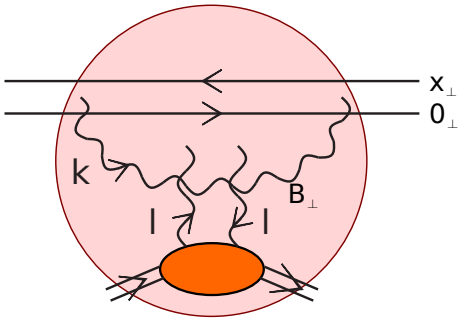
$$A + B + C + D \approx -\frac{\alpha_s C_F}{2\pi} \rho_0 x q_N \ln^2 \frac{Q^2}{k_\perp^2}.$$

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

Medium-dependent radiative correction

Medium-induced double log

$$\langle p_\perp^2 \rangle_{rad} =$$



$$= \frac{\alpha_s N_c}{\pi} \hat{q} L \int_{l_0}^{L} \frac{dz}{z} \int_{\hat{q} z^2}^{\hat{q} L z} \frac{d\omega}{\omega}$$

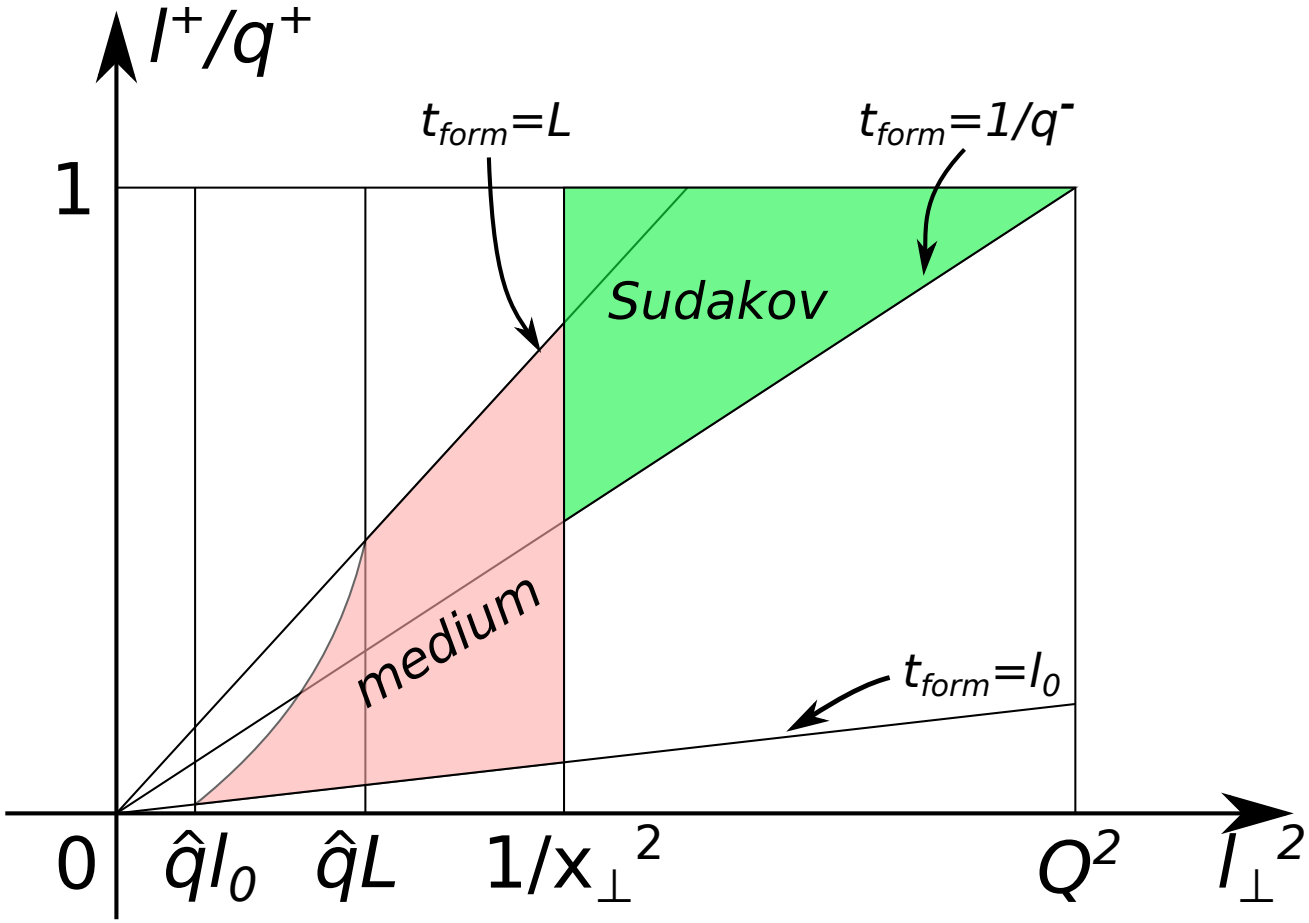
$$= \frac{\alpha_s N_c}{8\pi} \hat{q} L \log^2 \left(\frac{L}{r_0} \right)^2$$

with r_0 the nucleon size.

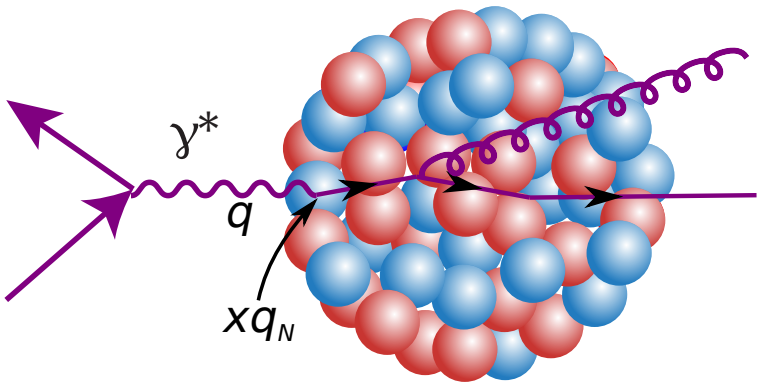
Liou, Mueller and BW, Nucl. Phys. A **916**, 102-125 (2013) [arXiv:1304.7677 [hep-ph]].

Factorization at LL

Two double log regions are separated in phase space:



LL resummation



$$\frac{dN}{d^2b d^2k_\perp} = \int \frac{d^2x_\perp}{(2\pi)^2} e^{-ik_\perp\cdot x_\perp} \rho\, xq_N\left(x, \frac{1}{x_\perp^2 + 1/Q^2}\right)$$
$$\times \int_0^L dz \exp\left[\underbrace{-\frac{1}{4}\hat{q}_t x_\perp^2 z}_{\text{medium-induced}} \underbrace{-\frac{\alpha_s C_F}{2\pi}\ln^2\left(Q^2 x_\perp^2\right)}_{\text{vacuum radiation}}\right]$$

where medium-induced double logs are included in $\hat{q}_t$.

Summary

Azimuthal decorrelation in pp collisions

- NNLL resummation in boson-jet events has been accomplished
- No factorization breaking up to and including $O(\alpha_s^3)$
- The results above hold for general p_T^n recombination scheme:

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

  with $n > 1$. WTA corresponds to the limit $n \to \infty$

Azimuthal decorrelation in high-energy nuclear collisions

- Azimuthal decorrelation has been used to measure $\hat{q}$
- The factorization formula for the transverse momentum distribution has been only derived up to leading log in DIS