Azimuthal correlations in J/ψ plus jet photoproduction

Speaker: Luca Maxia

University of Groningen - VSI

Synergies between LHC and EIC for quarkonium physics

STRONG 2020

12 July 2024

Based on:
LM, F. Yuan, arxiv.2403.02097 (2024)

Outline

- **Part I:** Motivation and physical content of the talk
- **Part II:** Soft gluon emission
    - **CS** and **CO** mechanisms
- **Part III:** Phenomenology
- **Conclusions**

Quarkonia & gluon TMDs

Cristian's Talk

Processes involving Quarkonia are **sensitive to gluons**

hadron collisions

Nanako's Talk (next one)

- $p + p \to \eta_Q + X$
- $p + p \to \chi_Q + X$

Jelle's Talk

- $p + p \to J/\psi + J/\psi + X$
- $p + p \to J/\psi + X$ **?**

ep **collisions**

- $e + p \to e' + J/\psi + X$
- $e + p \to e' + J/\psi + jet + X$

and more…

Two mechanisms: Color-Singlet and Color-Octet

The **NRQCD** cross-section combines the **CS** and **CO mechanisms**

Bodwin, Braaten, Lepage, PRD 51 (1997)

$$\mathrm{d}\sigma[\mathcal{Q}] = \sum_n \int \mathrm{d}\xi_i \, \mathrm{d}\xi_j \, f_i(\xi_i) f_j(\xi_j) \, \mathrm{d}\hat{\sigma}_{i+j\to Q\bar{Q}[n]+\ldots} \langle \mathcal{O}_{\mathcal{Q}}[n] \rangle$$

Long-Distance Matrix Elements (**universal** in principle)

Goal: Comprehending the significance of **CS** and **CO channels**

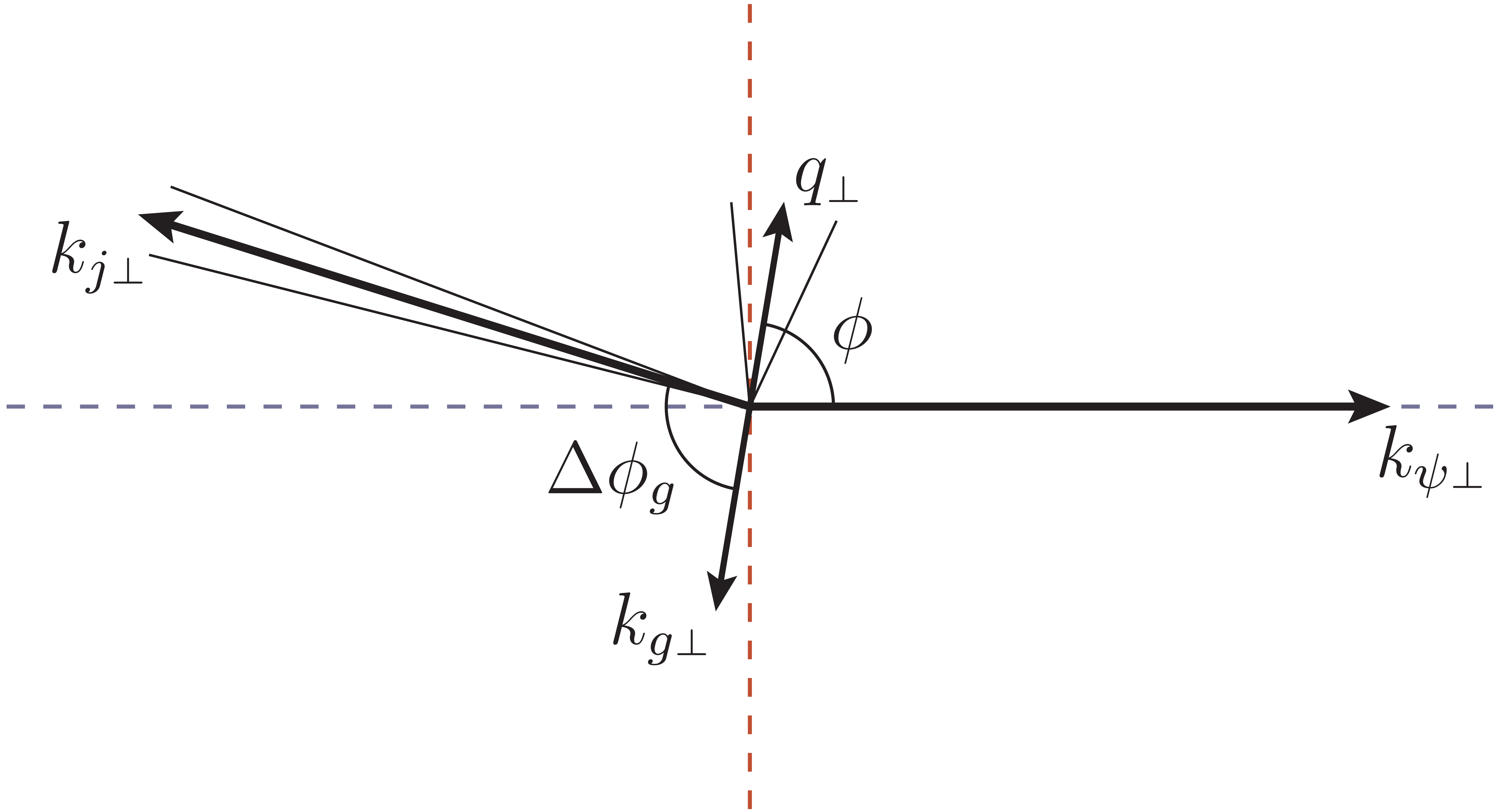
Opportunities: **Quarkonium polarization** D'Alesio, LM, Murgia, Pisano, Rajesh, PRD 107 (2023)

Onia vs open quark ratios Bacchetta, Boer, Pisano, Taels, EPJC 80 (2020); Boer, Pisano, Taels, PRD 103 (2021)

Averaged Azimuthal Asymmetries LM, Yuan, arxiv.2403.02097 (2024)

Correlation limit

transverse plane



Kinematics

(J/ψ and jet back-to-back)

$$q_\perp \ll P_\perp$$

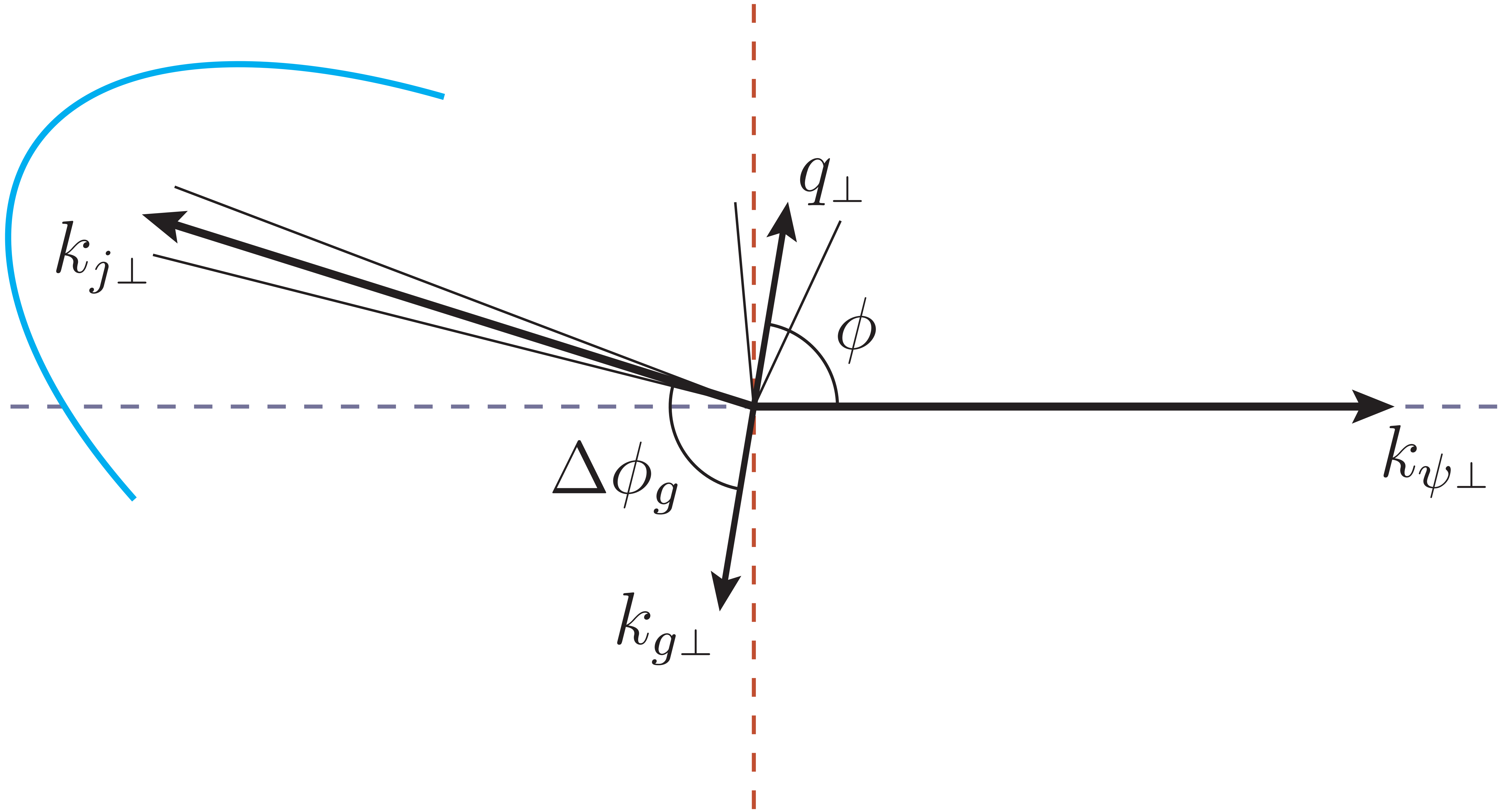
$$\vec{q}_\perp = \vec{k}_{\psi\perp} + \vec{k}_{j\perp}$$

$$\vec{P}_\perp = \frac{\vec{k}_{\psi\perp} - \vec{k}_{j\perp}}{2}$$

$\Delta\phi_g \approx \phi$ ➡ Azimuthal Imbalance

Correlation limit

transverse plane



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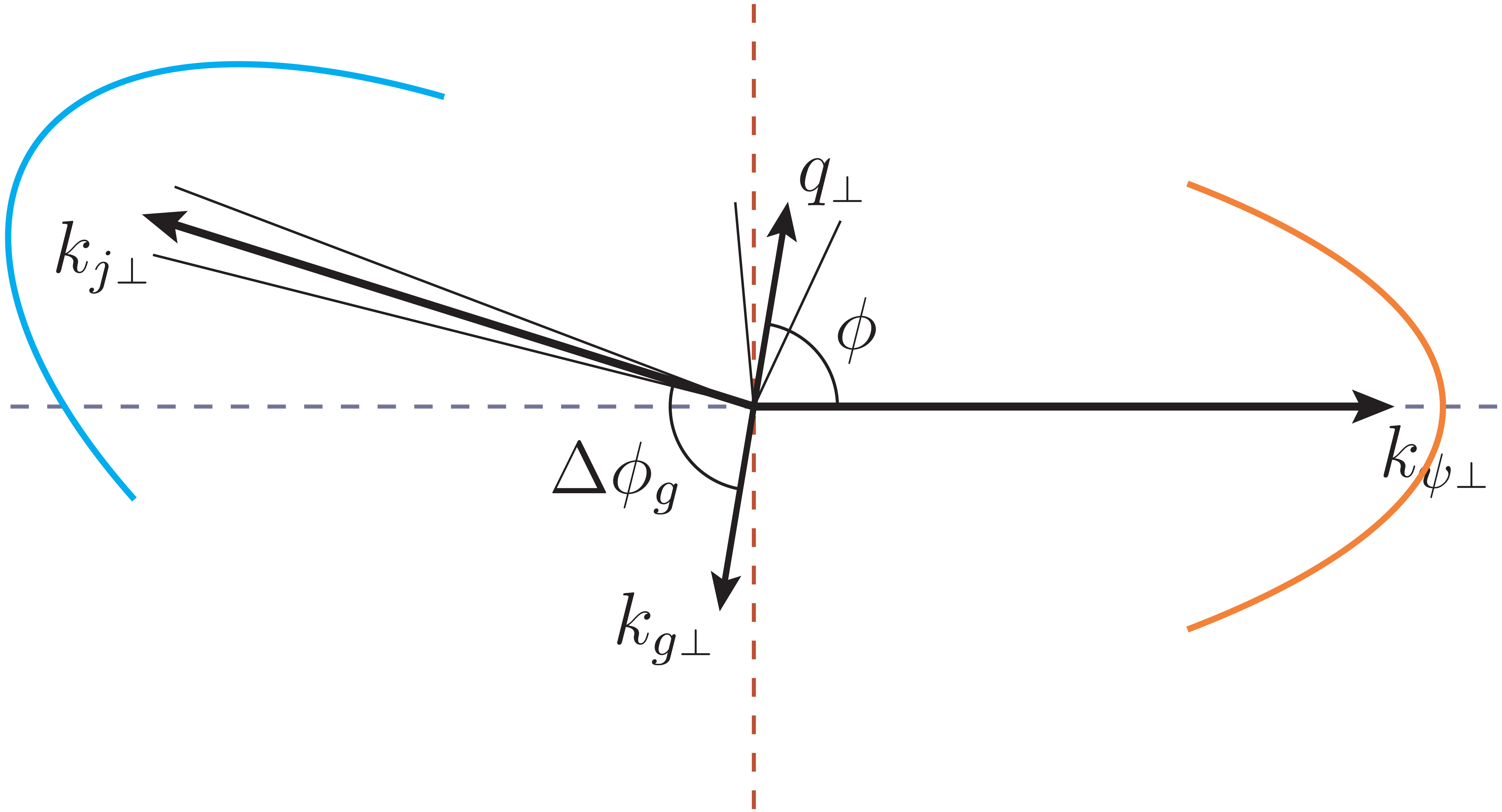

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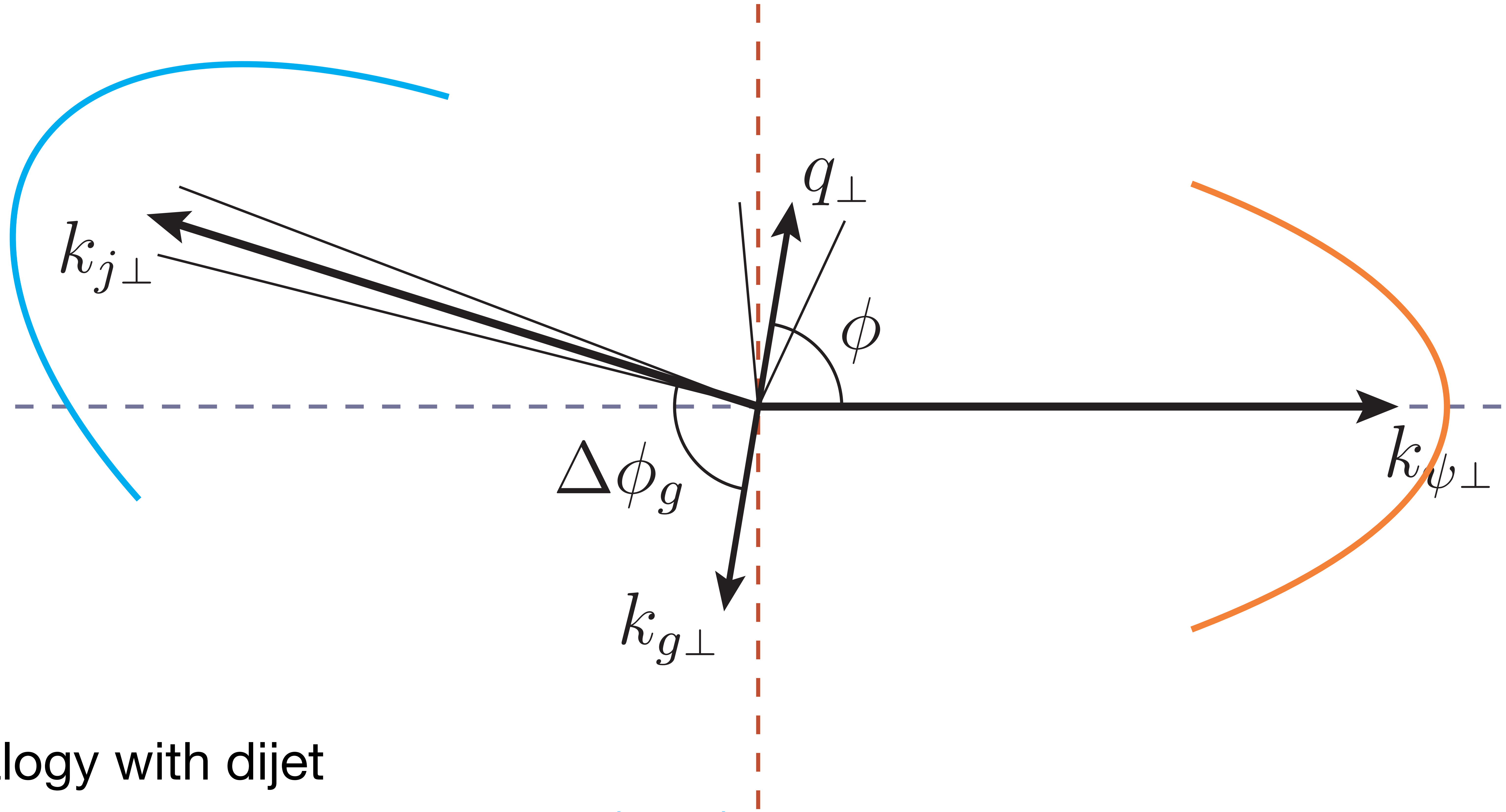
Correlation limit

transverse plane



Analogy with dijet
Hatta, Xiao, Yuan, Zhou, PRL 126 (2021)

Kinematics

(J/ψ and jet back-to-back)

$$q_\perp \ll P_\perp$$

$$\vec{q}_\perp = \vec{k}_{\psi\perp} + \vec{k}_{j\perp}$$

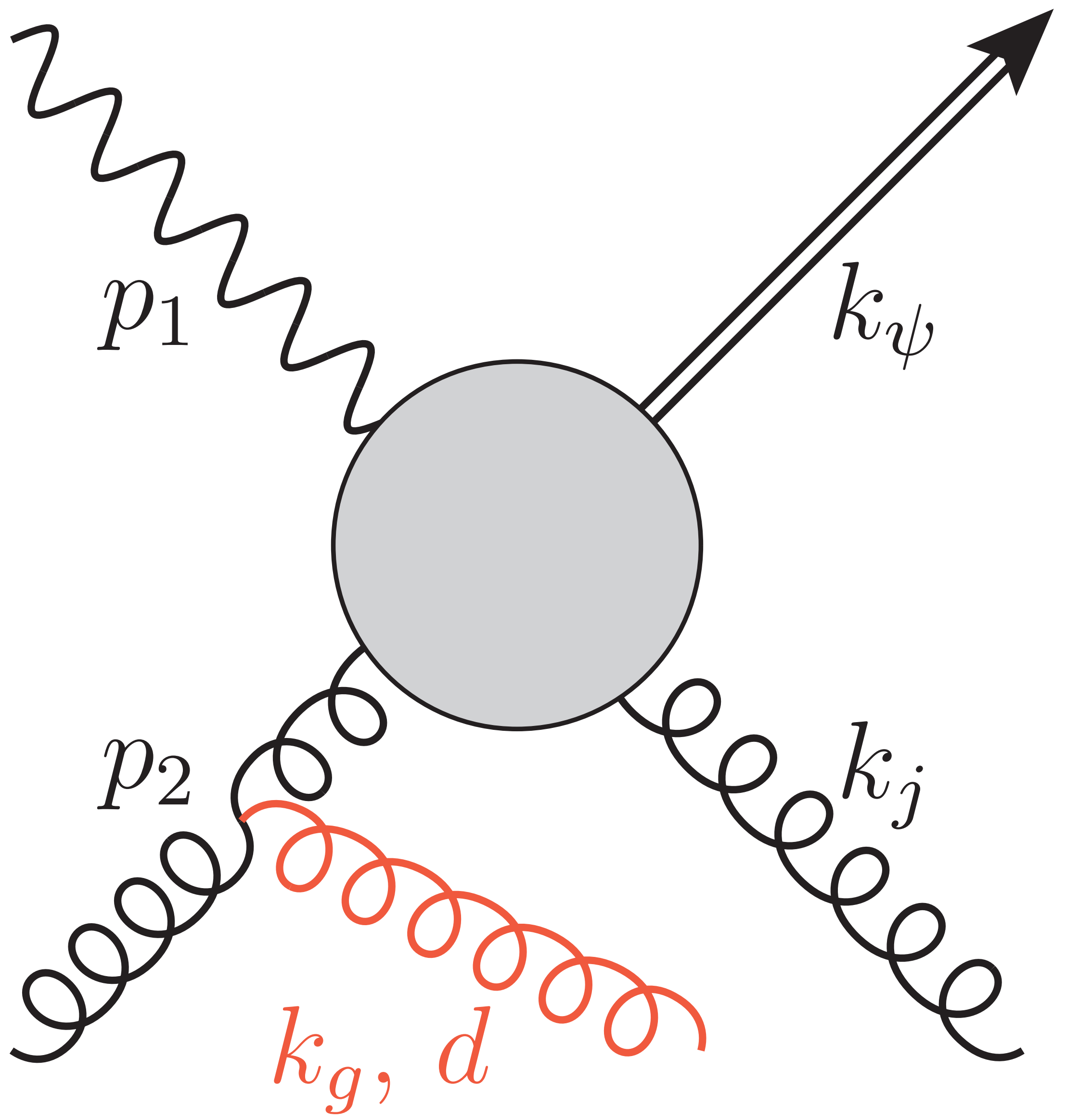
$$\vec{P}_\perp = \frac{\vec{k}_{\psi\perp} - \vec{k}_{j\perp}}{2}$$

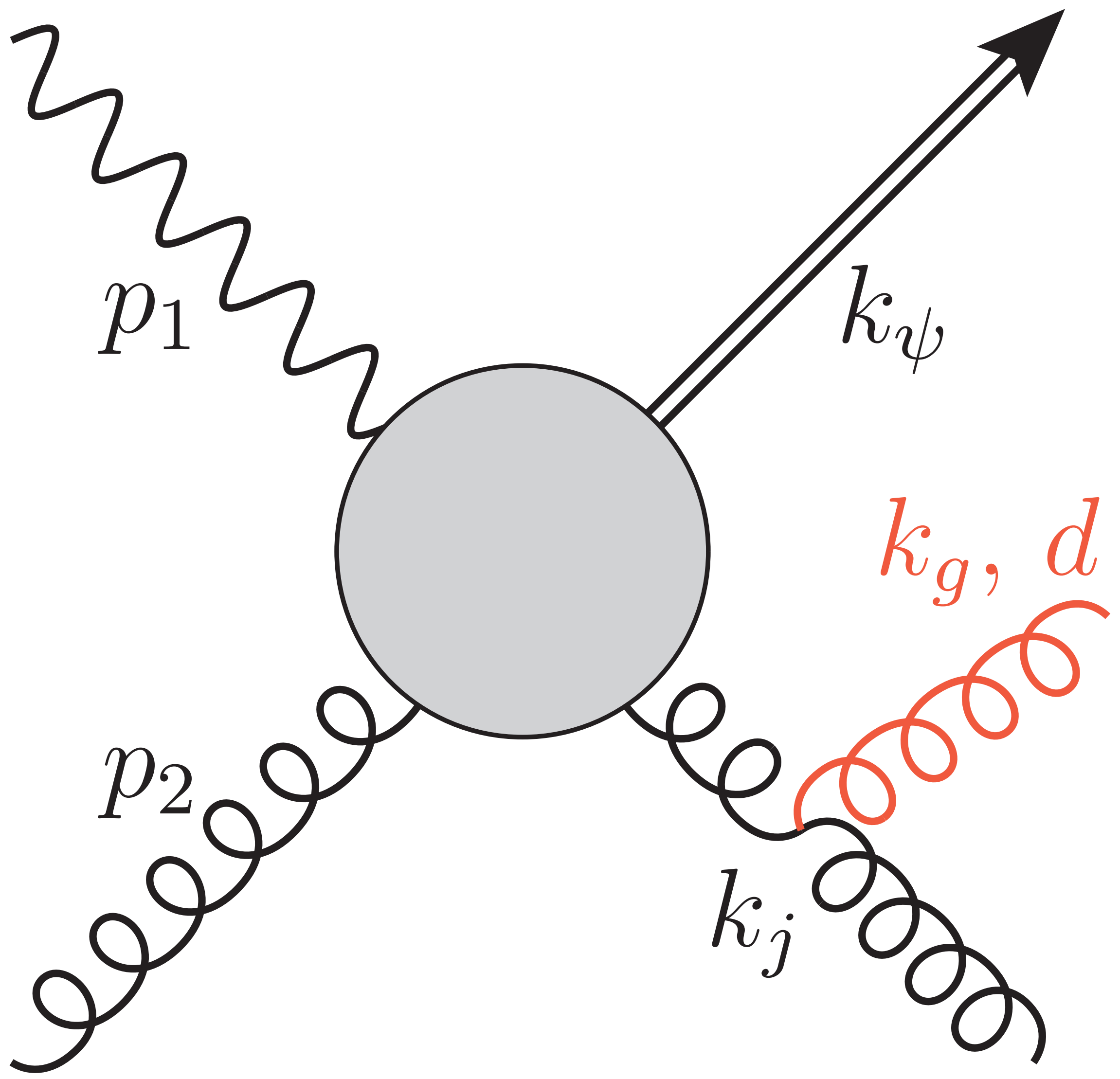
$\Delta\phi_g \approx \phi$ ➡ Azimuthal Imbalance

A diagrammatic point of view of soft gluon radiation

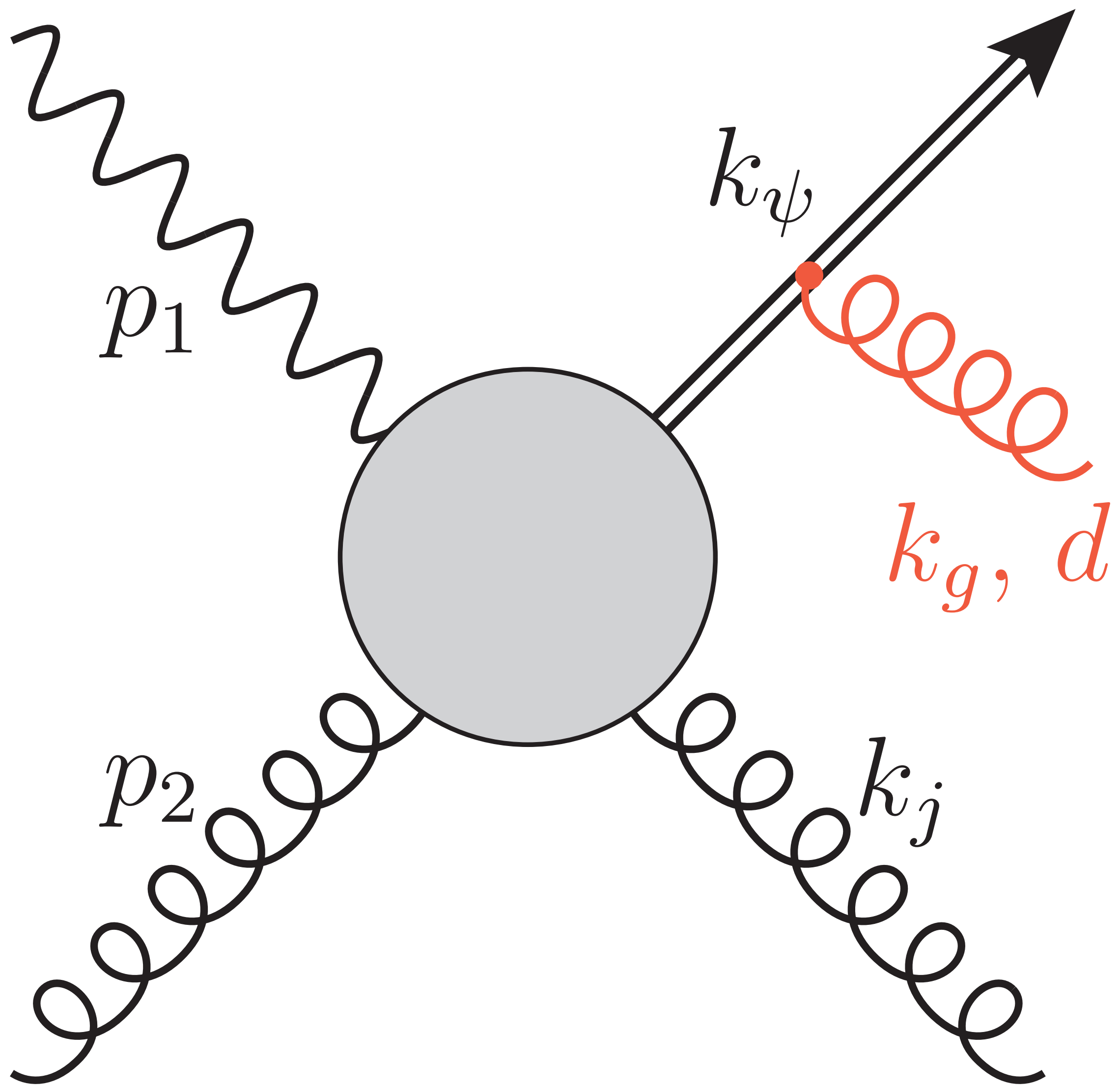
Three possibilities to emit a soft gluon from the Born amplitude

LM, Yuan, arxiv.2403.02097 (2024)





CS



CO

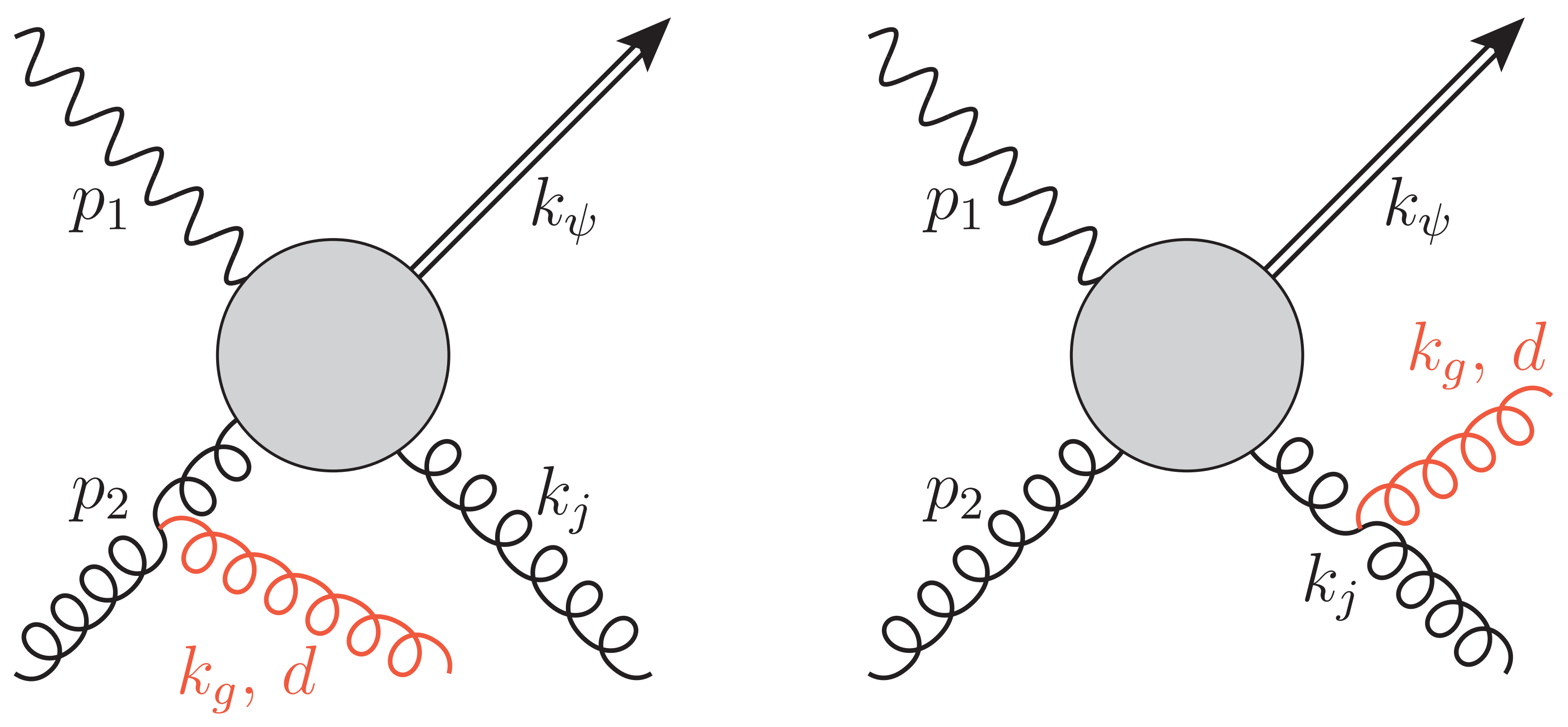
$$\epsilon^\mu(p_2) \to i\, g_s\, f_{aa'd} \frac{(p_2 \cdot \epsilon_g)}{(p_2 \cdot k_g)}\, \delta_\mu^{\mu'}\, \epsilon^\mu(p)$$

$$\epsilon^\mu(k_j) \to i\, g_s\, f_{cc'd} \frac{(k_j \cdot \epsilon_g)}{(k_j \cdot k_g)}\, \delta_\mu^{\mu'}\, \epsilon^\mu(k_j)$$

$$\Phi_{ij}(k_\psi, q) \to i\, g_s\, f_{bb'd} \frac{k_\psi \cdot \epsilon_g}{k_\psi \cdot k_g}\, \Phi_{ij}(k_\psi, q)$$

+ quark channel

Soft gluon emission: CS mechanism



:

$$|\overline{\mathscr{A}_1^{(1)}}|^2 = g_s^2 C_A\, S_g(p_2, k_j)\, |\overline{\mathscr{A}_0^{(1)}}|^2$$

$$S_g(v_a, v_b) = \frac{2\,(v_a \cdot v_b)}{(v_a \cdot k_g)(v_b \cdot k_g)}$$

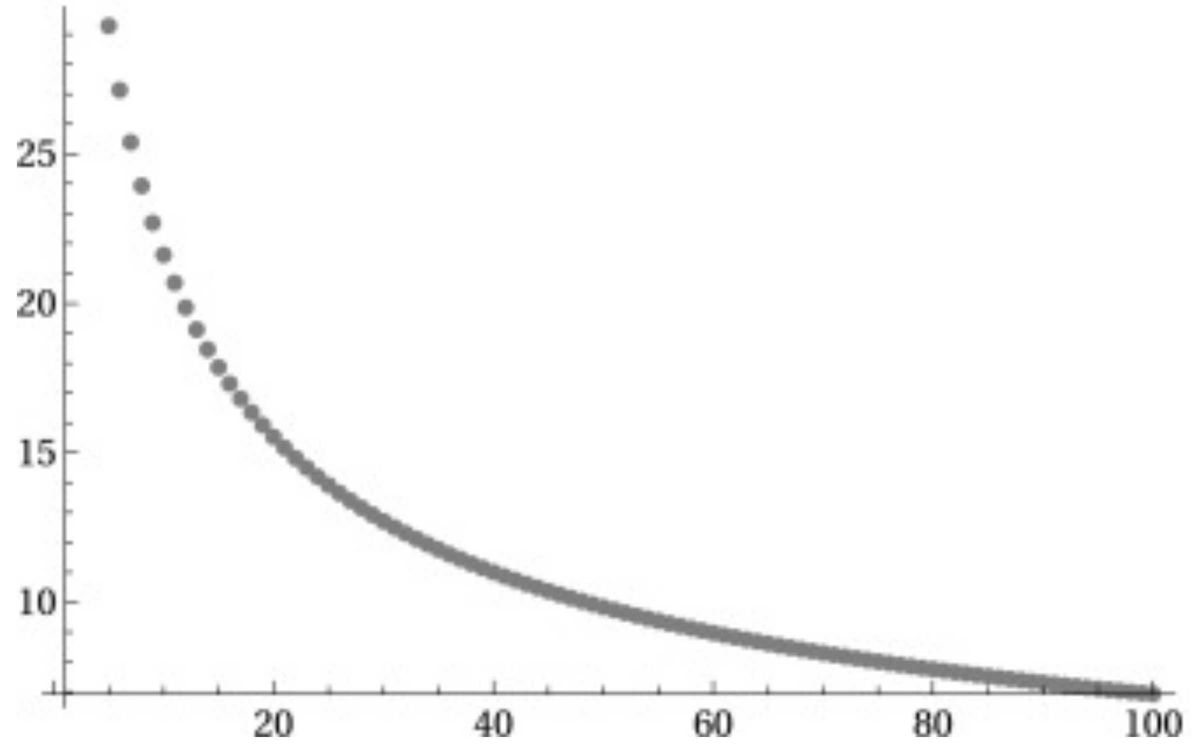
Integration of the extra *dof*

$$\int \frac{\mathrm{d}^3 k_g}{(2\pi)^3 2E_{k_g}} |\overline{\mathscr{A}_1^{(1)}}|^2\, \delta^{(2)}(q_\perp + k_{g\perp}) = \frac{\alpha_s C_A}{2\pi^2 q_\perp^2} |\overline{\mathscr{A}_0^{(1)}}|^2 \left[\ln \frac{\hat{s}}{q_\perp^2} + \ln \frac{\hat{t}}{\hat{u}} + I_j(R, \phi) \right]$$

Soft gluon emission: CS mechanism - II

$$\int \frac{\mathrm{d}^3 k_g}{(2\pi)^3 2E_{k_g}} |\overline{\mathscr{A}_1^{(1)}}|^2 \delta^{(2)}(q_\perp + k_{g\perp}) = \frac{\alpha_s C_A}{2\pi^2 q_\perp^2} |\overline{\mathscr{A}_0^{(1)}}|^2 \left[\ln\frac{\hat{s}}{q_\perp^2} + \ln\frac{\hat{t}}{\hat{u}} + I_j(R,\phi) \right]$$

- $\ln\frac{\hat{s}}{q_\perp^2}$: dominant behavior at low $q_\perp$



- $\ln\frac{\hat{t}}{\hat{u}}$: related to jet rapidity $y_j = \frac{1}{2}\ln\frac{k_j^+}{k_j^-}$

- $I_j(R,\phi)$: subject under investigation

Azimuthal Distribution: CS

$$I_j(R,\phi) = C_0^{(j)}(R) + 2\sum_{n=1}^{\infty} C_n^{(j)}(R)\,\cos(n\phi)$$

R is the jet cone radius → Arises by removing collinear divergences

$I_j(R,\phi)$ was already encountered in other works

Dijet

- Hatta, Xiao, Yuan, Zhou, PRL 126 (2021)
- Hatta, Xiao, Yuan, Zhou, PRD 104 (2021)
- Sun, Yuan, Yuan, PRL 113 (2014)
- Sun, Yuan, Yuan, PRD 92 (2015)

Lepton-jet

- Liu, Ringer, Vogelsang, Yuan, PRL 122 (2019)
- Liu, Ringer, Vogelsang, Yuan, PRD 102 (2020)

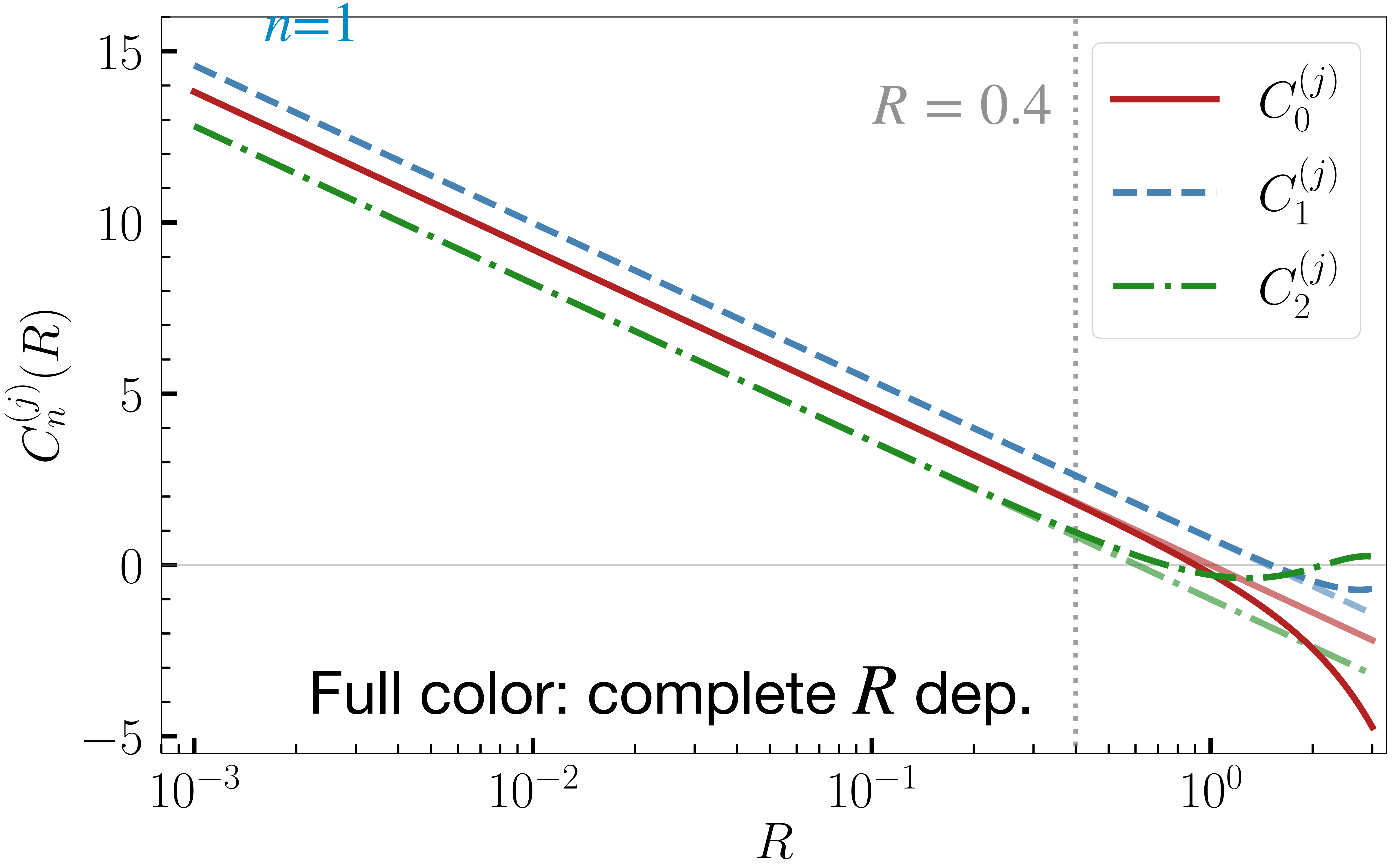
…

Azimuthal Distribution: CS - II

$$I_j(R,\phi) = C_0^{(j)}(R) + 2\sum_{n=1}^{\infty} C_n^{(j)}(R)\,\cos(n\phi)$$

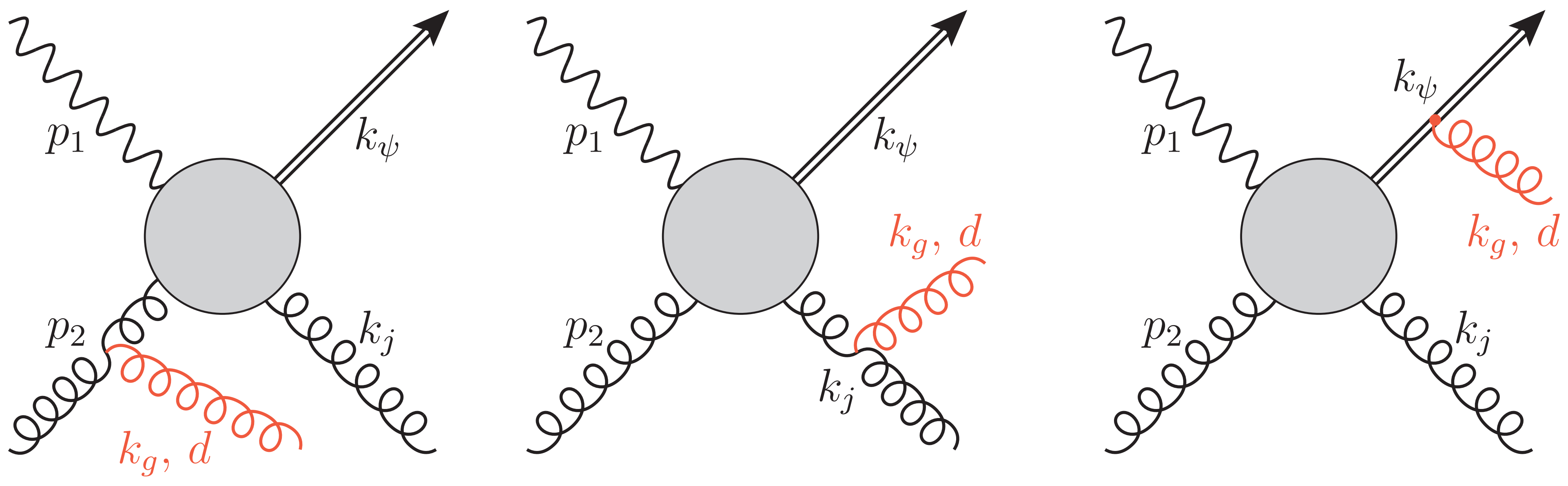
Small-R limit:

$$I_j(R,\phi) = \ln\frac{1}{R^2}$$
$$+2\cos(\phi)\left(\ln\frac{1}{R^2} + 2\ln(4) - 2\right)$$
$$+2\cos(2\phi)\left(\ln\frac{1}{R^2} - 1\right) + \cdots$$



Soft gluon emission: CO mechanism

LM, Yuan, arxiv.2403.02097 (2024)



:

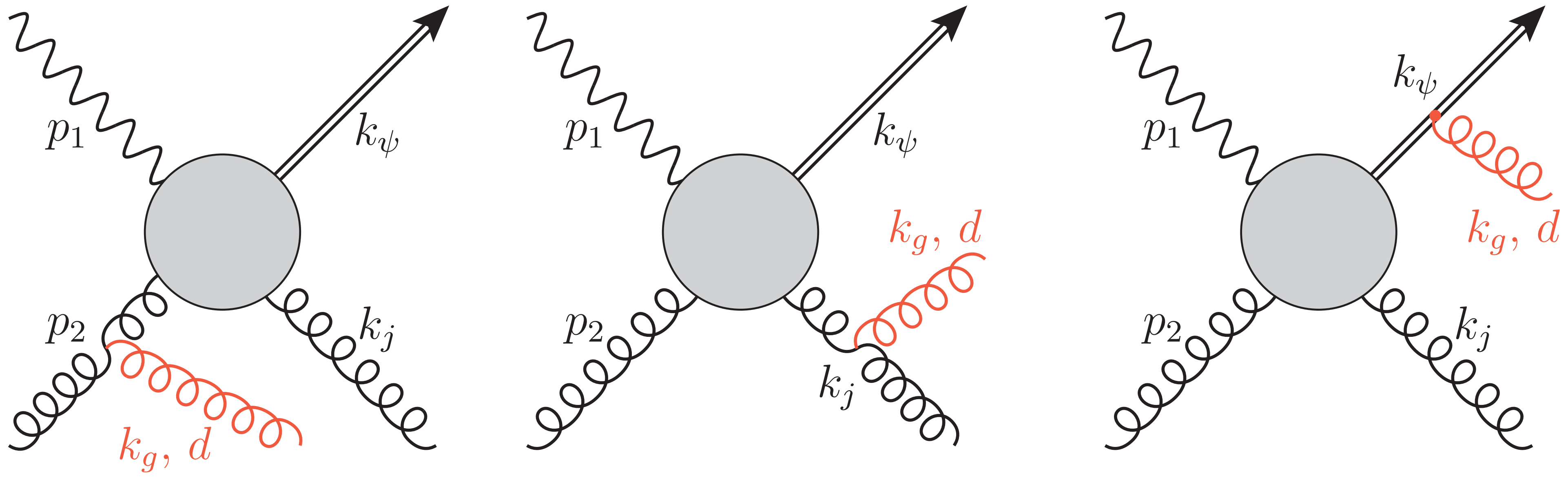
$$|\overline{\mathscr{A}_1^{(8)}}|^2 = \frac{1}{2} g_s^2 C_A \Big[S_g(p_2, k_j) + S_g(p_2, k_\psi) - S_g(k_\psi, k_\psi) + S_g(k_j, k_\psi) \Big] |\overline{\mathscr{A}_0^{g,(8)}}|^2$$

+ quark channel

Valid for all (relevant) CO states

Soft gluon emission: CO mechanism

LM, Yuan, arxiv.2403.02097 (2024)



:

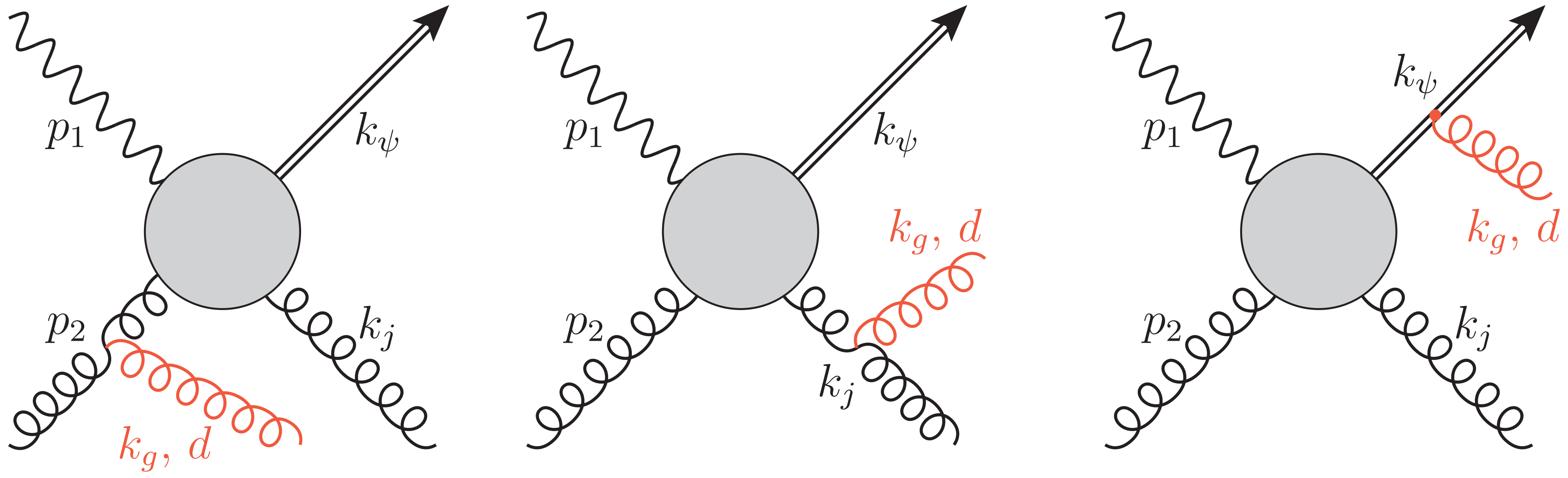
$$|\overline{\mathscr{A}_1^{(8)}}|^2 = g_s^2 C_A |\overline{\mathscr{A}_0^{g,(8)}}|^2 \Big[S_g(p_2, k_j) + \frac{1}{2}\Big(S_g(p_2, k_\psi) - S_g(k_\psi, k_\psi) + S_g(k_j, k_\psi) - S_g(p_2, k_j) \Big) \Big]$$

+ quark channel

J/ψ related contribution

Soft gluon emission: CO mechanism

LM, Yuan, arxiv.2403.02097 (2024)



: $$|\overline{\mathscr{A}_1^{(8)}}|^2 = g_s^2 C_A |\overline{\mathscr{A}_0^{g,(8)}}|^2 \Big[S_g(p_2, k_j) + \frac{1}{2}\Big(S_g(p_2, k_\psi) - S_g(k_\psi, k_\psi) + S_g(k_j, k_\psi) - S_g(p_2, k_j) \Big) \Big]$$

+ quark channel

J/ψ related contribution

Integration of the extra *dof*

$$\int \frac{\mathrm{d}^3 k_g}{(2\pi)^3 2E_{k_g}} |\overline{\mathscr{A}_1^{(8)}}|^2 \delta^{(2)}(q_\perp + k_{g\perp}) = \frac{\alpha_s C_A}{2\pi^2 q_\perp^2} |\overline{\mathscr{A}_0^{g,(8)}}|^2 \Big[\ln\frac{\hat{s}}{q_\perp^2} + \frac{1}{2}\ln\frac{1 - M_\psi^2/\hat{u}}{1 - M_\psi^2/\hat{t}} + I_j(R,\phi) + I_\psi(m_{\psi\perp},\phi) + \frac{1}{2} I_{\psi\text{-}j}(m_{\psi\perp},\Delta y, 2\phi) - \frac{1}{2} I_\psi^{\text{jet}}(R, m_{\psi\perp}, \Delta y, \phi) \Big]$$

Soft gluon emission: CO mechanism - II

$$\int \frac{d^3k_g}{(2\pi)^3 2E_{k_g}} |\overline{\mathscr{A}_1^{(8)}}|^2 \delta^{(2)}(q_\perp + k_{g\perp}) = \frac{\alpha_s C_A}{2\pi^2 q_\perp^2} |\overline{\mathscr{A}_0^{g,(8)}}|^2 \left[\ln \frac{\hat{s}}{q_\perp^2} + \frac{1}{2} \ln \frac{1 - M_\psi^2/\hat{u}}{1 - M_\psi^2/\hat{t}} + I_j(R,\phi) + I_\psi(m_{\psi\perp},\phi) + \frac{1}{2} I_{\psi\text{-}j}(m_{\psi\perp},\Delta y, 2\phi) - \frac{1}{2} I_\psi^{\text{jet}}(R, m_{\psi\perp}, \Delta y, \phi) \right]$$

LM, Yuan, arxiv.2403.02097 (2024)

- $\ln \frac{\hat{s}}{q_\perp^2}$ and $I_j(R,\phi)$ do not vary from CS case
- $\frac{1}{2} \ln \frac{1 - M_\psi^2/\hat{u}}{1 - M_\psi^2/\hat{t}}$: related to jet and J/ψ rapidities
- $I_\psi(m_{\psi\perp},\phi)$, $I_{\psi\text{-}j}(m_{\psi\perp},\Delta y, 2\phi)$, $I_\psi^{\text{jet}}(R, m_{\psi\perp}, \Delta y, \phi)$ under study

Azimuthal Distribution: CO

LM, Yuan, arxiv.2403.02097 (2024)

$I_\psi(m_{\psi\perp}, \phi)$ → Contributions from $S_g(p_2, p_\psi)$ and $S_g(p_\psi, p_\psi)$

($I_{\psi\text{-}p}(m_{\psi\perp}, \phi)$) ($I_{\psi\text{-}\psi}(m_{\psi\perp}, \phi)$)

$I_{\psi\text{-}j}(m_{\psi\perp}, \Delta y, 2\phi)$ → Included in J/ψ - jet correlation $S_g(p_j, p_\psi)$

(R dependence removed by $S_g(p_2, p_j)$)

$\boldsymbol{m_{\psi\perp}} = \dfrac{M_\psi}{k_{j\perp}}$ → Replaces R (acts like a regulator)

Each distribution is expanded in Fourier

$$I_{[\psi]}(K, \phi) = C_0^{([\psi])}(K) + 2\sum_{n=1}^{\infty} C_n^{([\psi])}(K)\,\cos(n\phi)$$

Azimuthal Distribution: CO

LM, Yuan, arxiv.2403.02097 (2024)

$I_\psi(m_{\psi\perp}, \phi)$ → Contributions from $S_g(p_2, p_\psi)$ and $S_g(p_\psi, p_\psi)$

($I_{\psi\text{-}p}(m_{\psi\perp}, \phi)$) ($I_{\psi\text{-}\psi}(m_{\psi\perp}, \phi)$)

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Azimuthal Distribution: CO - II

LM, Yuan, arxiv.2403.02097 (2024)

$$I_{\psi\text{-}p}(m_{\psi\perp},\phi) = C_0^{(\psi\text{-}p)}(m_{\psi\perp}) + 2\sum_{n=1}^{\infty} C_n^{(\psi\text{-}p)}(m_{\psi\perp})\cos(n\phi)$$

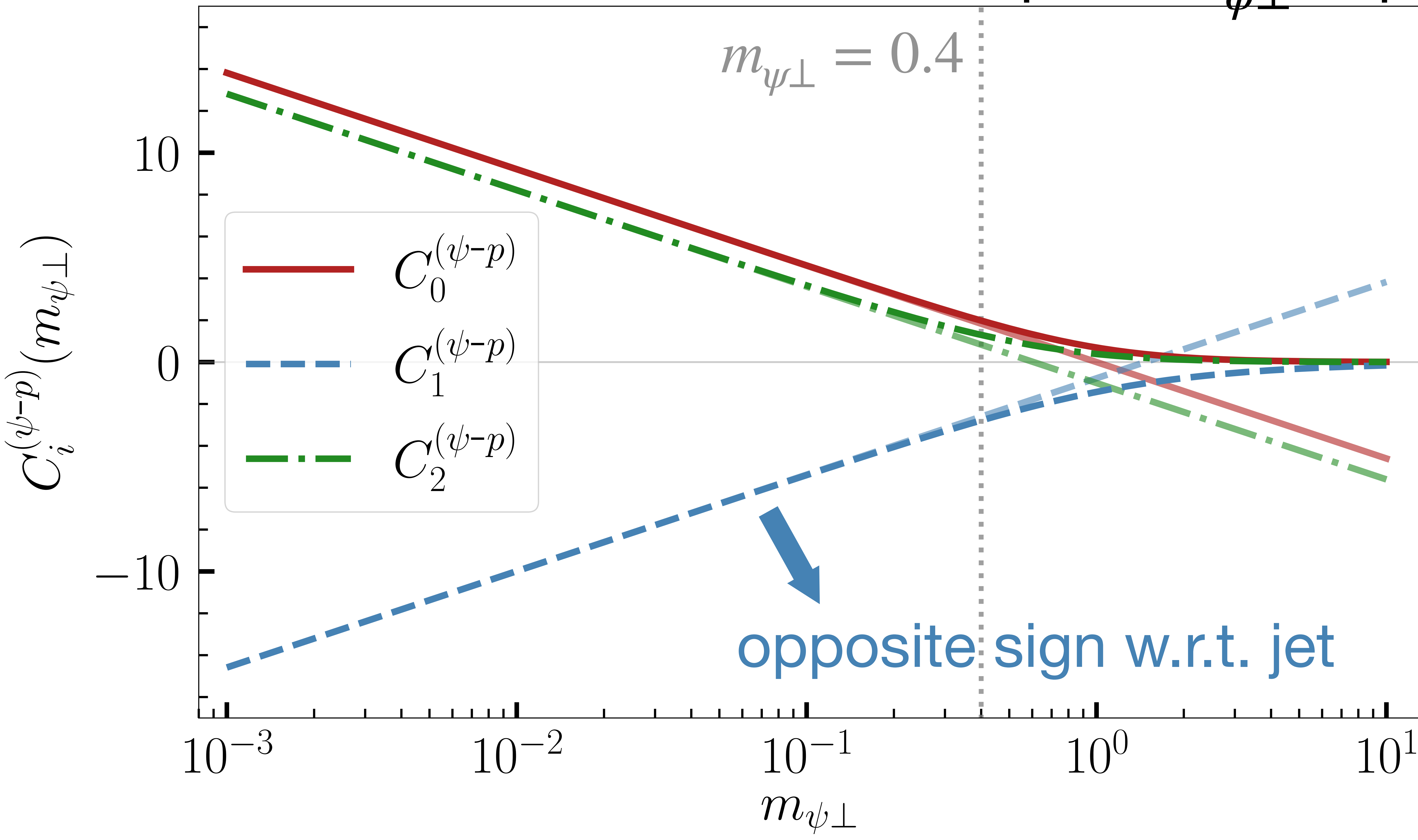
Small-$m_{\psi\perp}$ limit:

$$I_\psi(m_{\psi\perp},\phi) = \ln\frac{1}{m_{\psi\perp}^2}$$

$$-2\cos(\phi)\left(\ln\frac{1}{m_{\psi\perp}^2} + 2\ln(4) - 2\right)$$

$$+2\cos(2\phi)\left(\ln\frac{1}{m_{\psi\perp}^2} - 1\right) + \cdots$$

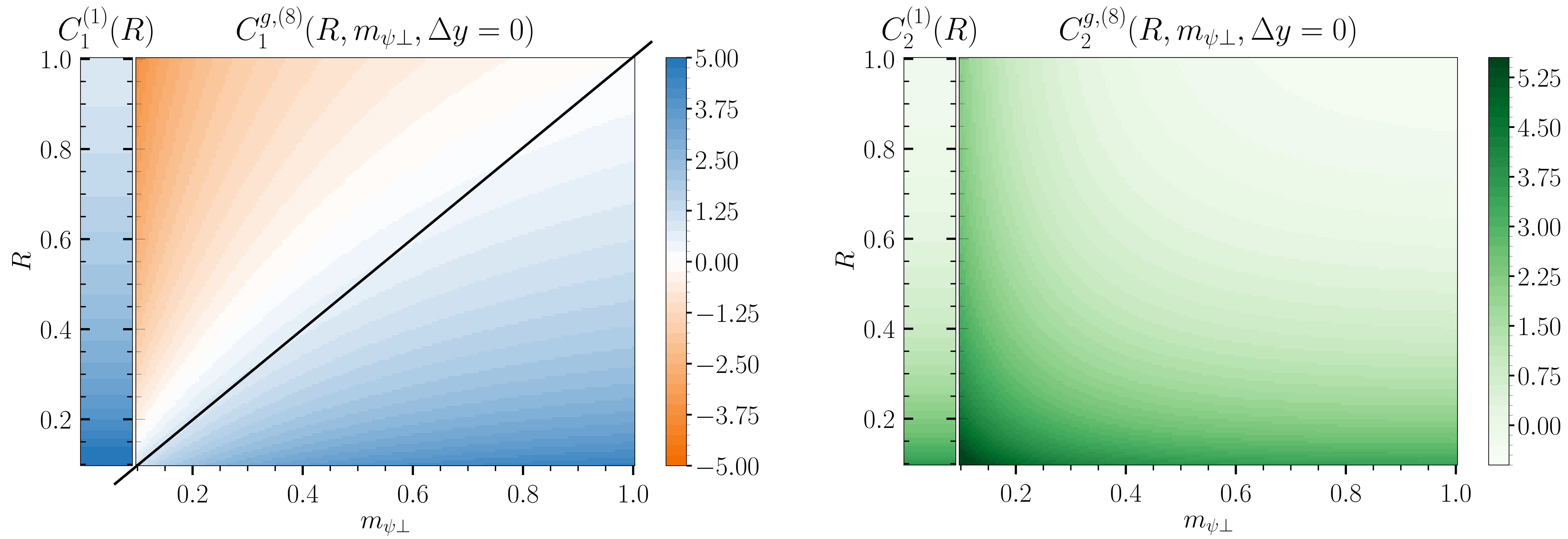
Full color: complete $m_{\psi\perp}$ dep



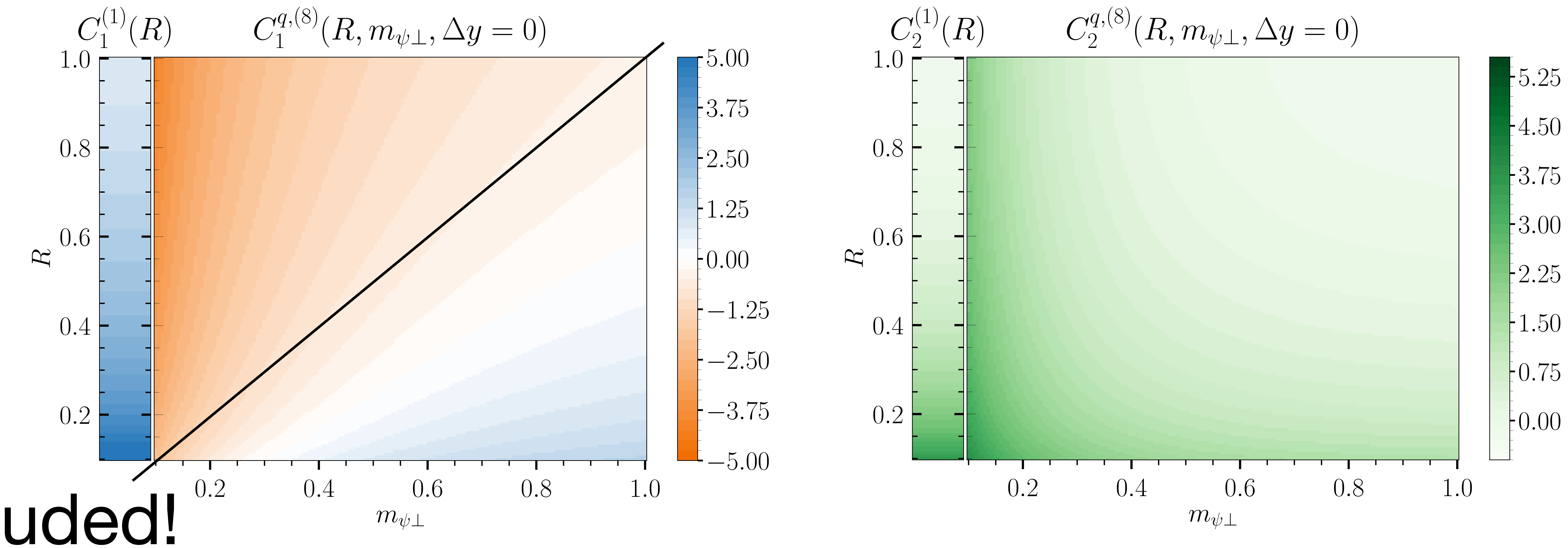
Coefficients dependences

LM, Yuan, arxiv.2403.02097 (2024)

Gluon channel:



Quark channel:



All distributions are included!

CS and CO predictions

LM, Yuan, arxiv.2403.02097 (2024)

$$\frac{d^4\sigma^{(c)}}{dPS} = \sigma_0^{g,(c)} \int \frac{|\vec{b}_\perp| \, d|\vec{b}_\perp|}{(2\pi)} \left[J_0(|\vec{b}_\perp||\vec{q}_\perp|)\, \widetilde{W}_0^{(c)}(|\vec{b}_\perp|) + 2\, J_n(|\vec{b}_\perp||\vec{q}_\perp|)\, \widetilde{W}_n^{(c)}(|\vec{b}_\perp|) \cos(n\phi) \right]$$

+quarks

$$\widetilde{W}_0^{(c)}(|\vec{b}_\perp|) = x f_g(x, \mu_b)\, e^{-S^{(c)}(P_\perp, b_\perp)}$$

→ Sudakov resummation ($S = S_{\text{pert.}} + S_{\text{NP}}$)

$$\widetilde{W}_n^{(c)}(|\vec{b}_\perp|) = \frac{C_A \alpha_s}{n\pi} C_n^{(c)}\, \widetilde{W}_0^{(c)}(|\vec{b}_\perp|)$$

→ higher-order double logs corrections

Catani, Grazzini, Torre, Nucl. Phys. B 890 (2014)

$$S_{\text{pert.}}^{(c)} = \int_{\mu_{b_*}^2}^{\hat{s}} \frac{d\mu^2}{\mu^2} \frac{\alpha_s C_A}{2\pi} \left[\ln\frac{\hat{s}}{\mu^2} - 2\beta_0 + 2\, C_0^{(c)} \right]$$

$$S_{\text{NP}} = \frac{C_A}{C_F} \left[0.106\, b_\perp^2 + 0.42 \ln\frac{P_\perp}{Q_0} \ln\frac{b_\perp}{b_*} \right] + g_\Lambda^{\text{jet}} b_\perp^2 + g_\Lambda^{\psi} b_\perp^2$$

b_* prescription

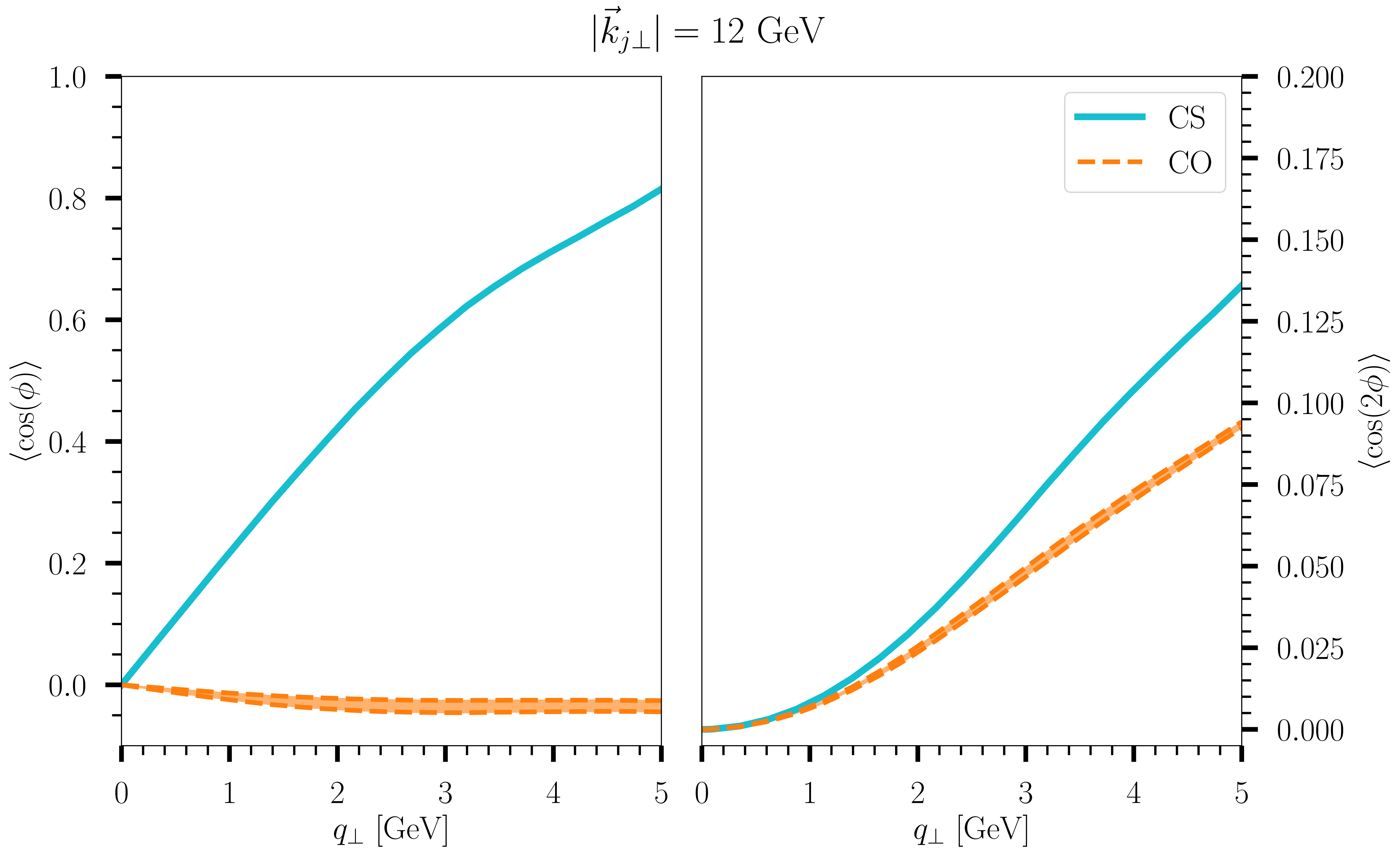
Isotropic term
depends on the prod. mechanism

Produkin, Sun, Yuan, Phys. Lett. B 750 (2015)

only CO

CS vs CO predictions - II

[LM, Yuan, arxiv.2403.02097 (2024)](#)



$k_{j\perp} = 12$ GeV

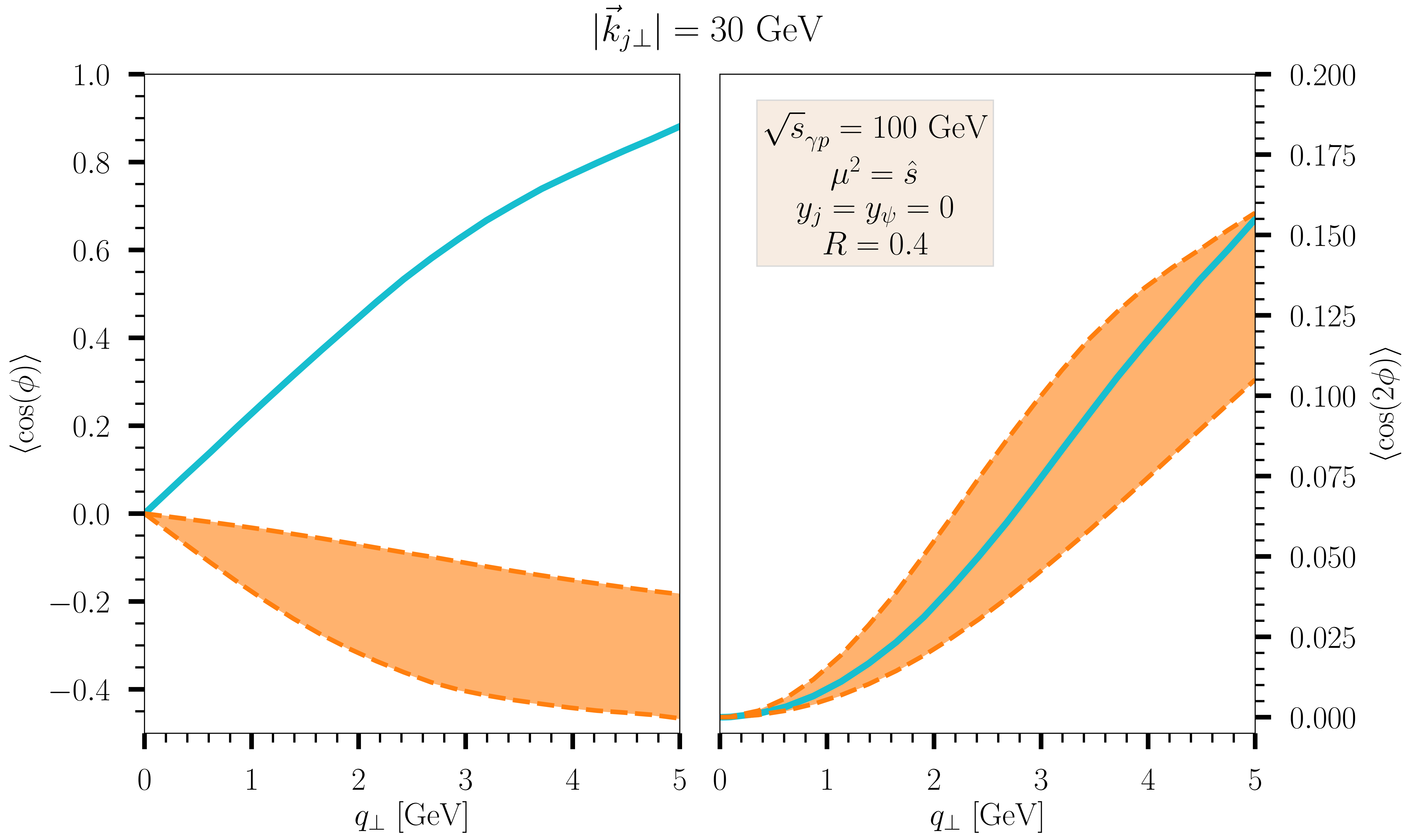
Dominance of gluon channel

$\cos\phi$ strongly suppressed for CO

$k_{j\perp} = 30$ GeV

Quarks and gluons are approx same size

Clear change of $\cos\phi$ sign for CO



CSM vs NRQCD predictions

LM, Yuan, arxiv.2403.02097 (2024)

NRQCD prediction is mostly **driven by** the **CO channel** for all the LDME sets considered

Phys. Rev. D 84 (2011)

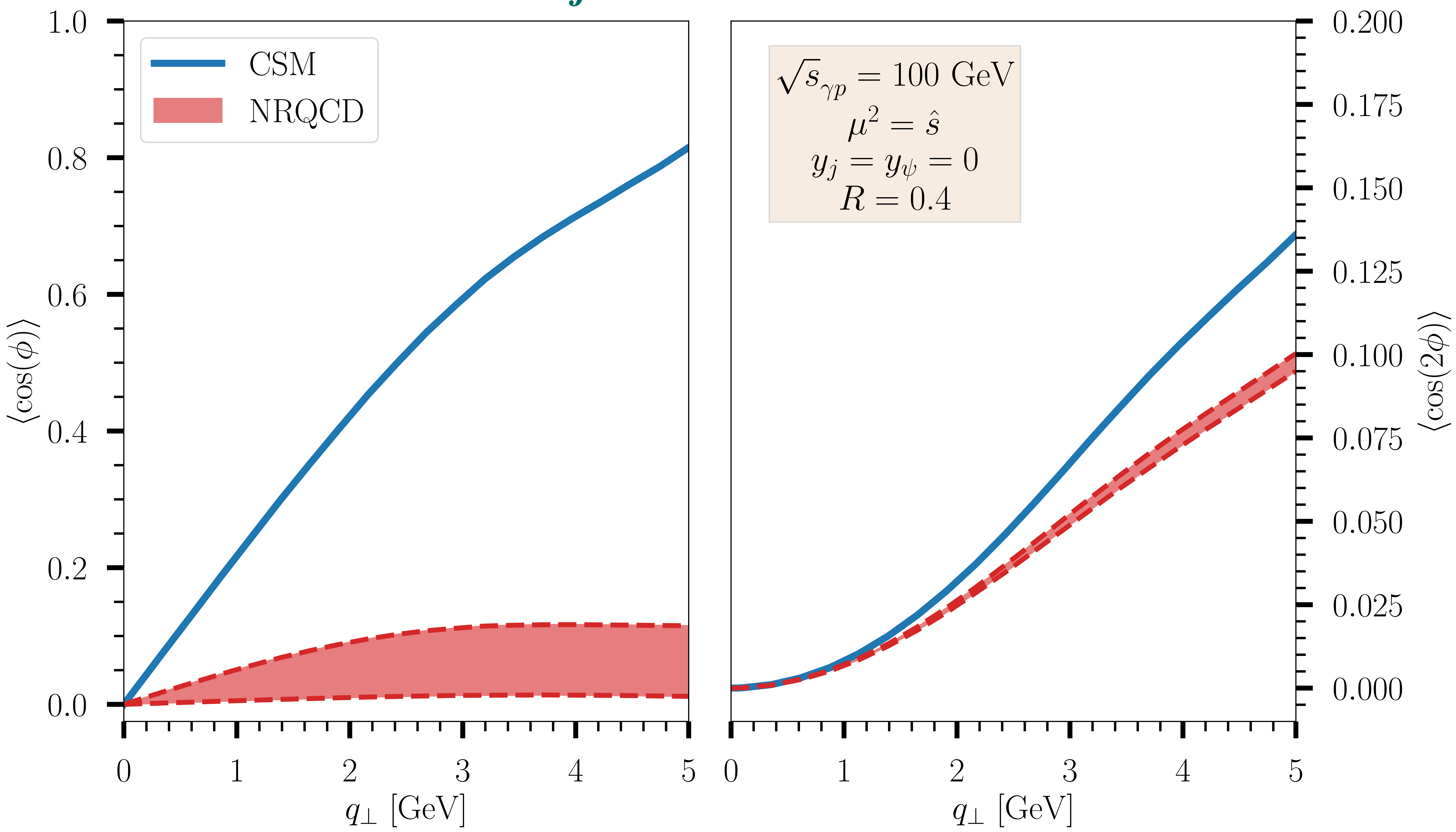
Phys. Rev. Lett. 108 (2012)

Phys. Rev. Lett. 110 (2013)

Phys. Rev. C 87 (2013)

Phys. Rev. D 105 (2022)

$k_{j\perp} = 12$ GeV



Summary of the talk

- Quarkonia can be used to extract the gluon TMD information

- Azimuthal correlations (and in particular $\langle \cos\phi \rangle$) can be used to disentangle between CO and CS mechanisms

Take-out message: within CS $\langle \cos\phi \rangle$ is sizeable independently of $k_{j\perp}$, whereas for CO it will always be a combination of $k_{j\perp}$ and R such that $\langle \cos\phi \rangle$ is suppressed

- J/ψ plus jet Photoproduction at the EIC or even hadron production at the LHC are an unique opportunity to shed a light on the production mechanism of quarkonia

Azimuthal correlation in J/ψ plus jet photoproduction

Back-up slides

Jet azimuthal distribution

$$I_j(R,\phi) = \int \mathrm{d}\Delta y_{gj} \left[\frac{\cos(\phi)}{\cosh(\Delta y_g) - \cos(\phi)} - \frac{k_{g\perp}^2}{2} \left(S_g(p_2, k_j)\, \Theta\left(\Delta_{k_g k_j} < R^2\right)\right)\right]$$

Divergent at $\phi = 0$

$$R \approx \sqrt{\Delta \bar{y}_{gj}^2 - \phi^2}$$

$$\Delta y_{gj} = y_g - y_j$$

soft gluon

jet

J/ψ - gluon azimuthal distribution

$$I_{\psi\text{-}j}(m_{\psi\perp}, \phi) = \int \mathrm{d}\Delta y_{g\psi} \left[\frac{\cos(\phi)}{\sqrt{1 + m_{\psi\perp}^2} \cosh(\Delta y_{g\psi}) + \cos(\phi)} \right]$$

No ϕ divergences

$$\Delta y_{g\psi} = y_g - y_\psi$$

soft gluon

J/ψ

J/ψ - jet azimuthal distribution

$$S_g(k_j, k_\psi) = \frac{2}{|\vec{k}_{g\perp}|^2} \frac{\sqrt{1+m_{\psi\perp}^2}\,\cosh(\Delta y) + 1}{\left[\cosh(\Delta y_g) - \cos(\phi)\right]\left[\sqrt{1+m_{\psi\perp}^2}\,\cosh(\Delta y_{g\psi}) + \cos(\phi)\right]}$$

$$= \frac{2}{|\vec{k}_{g\perp}|^2}\left(\frac{\cos(\phi)}{\cosh(\Delta y_g) - \cos(\phi)} - \frac{\cos(\phi)}{\sqrt{1+m_{\psi\perp}^2}\,\cosh(\Delta y_{g\psi}) + \cos(\phi)} + \hat{S}_g(k_j, k_\psi)\right)$$

Produces $I_j(R, \phi)$

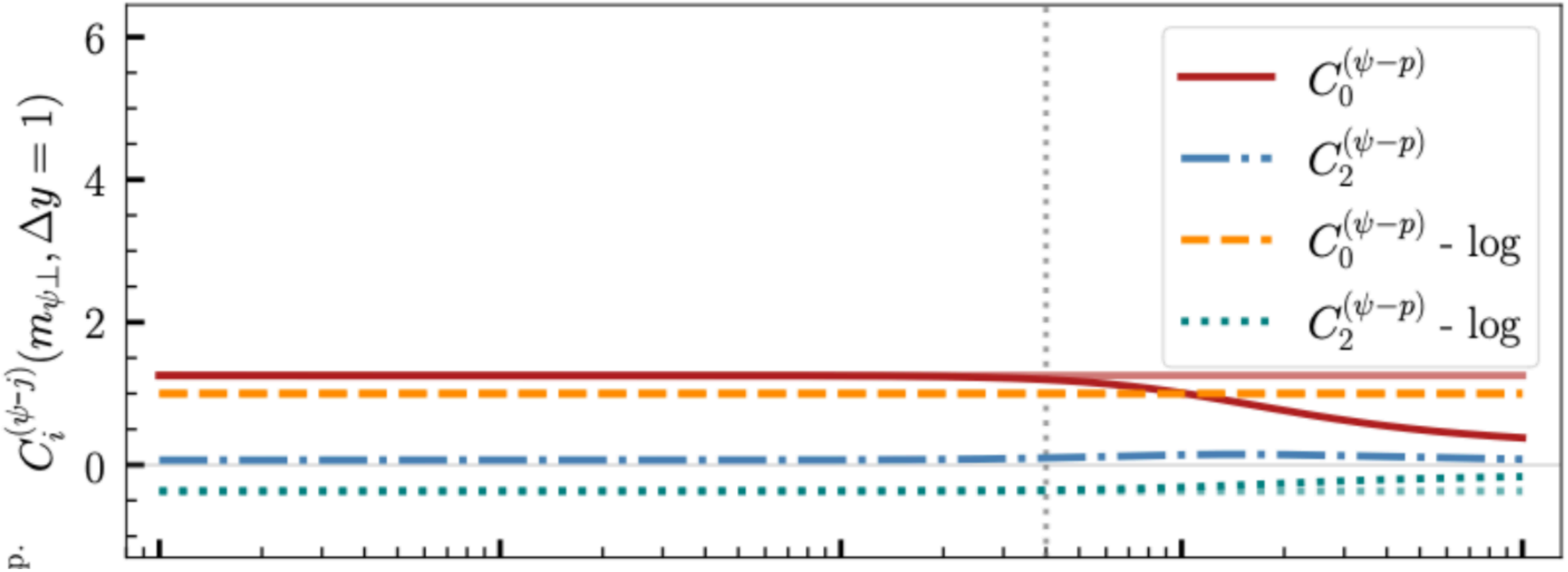
Produces $I_{\psi\text{-}p}(m_{\psi\perp}, \phi)$

Produces $I_{\psi\text{-}j}(m_{\psi\perp}, \Delta y, 2\phi)$

J/ψ - jet azimuthal distribution

There is no contribution to C_1

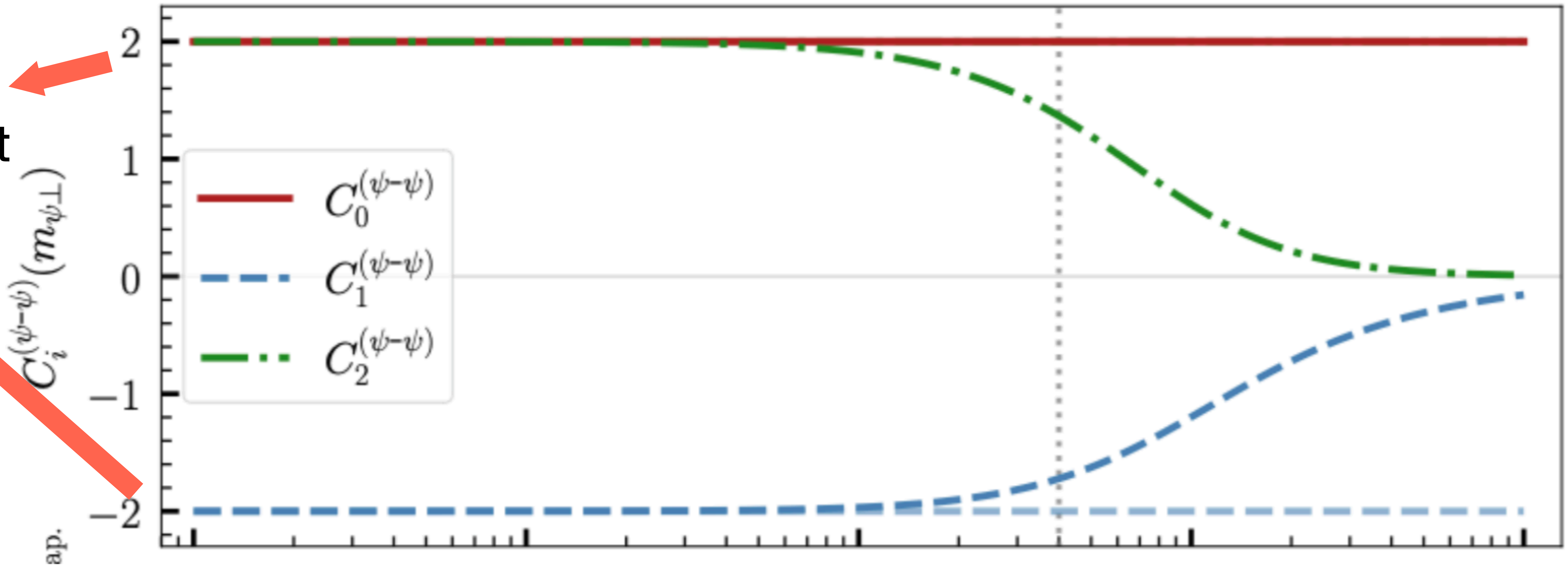
Depending on the difference $\Delta y = y_\psi - y_j$ we have a contribution to single logs



J/ψ - J/ψ azimuthal distribution

$$I_{\psi\text{-}\psi}(m_{\psi\perp}, \phi) = \int \mathrm{d}\Delta y_{g\psi} \left[\frac{m_{\psi\perp}^2}{\left(\sqrt{1 + m_{\psi\perp}^2}\cosh(\Delta y_{g\psi}) + \cos(\phi)\right)^2} \right]$$

Mostly constant



Normalized differential cross section

Normalized cross section displays a different behavior between CS and CO channels

Quarks subdominant to gluons