Medium-enhanced $g \to c\bar{c}$ radiation

M. Attems, J. Brewer, GMI, A. Mazeliauskas, S. Park, W. v.d. Schee, U. A. Wiedemann
arXiv.2203.11241, submitted to JHEP
arXiv.2209.13600, submitted to PRL

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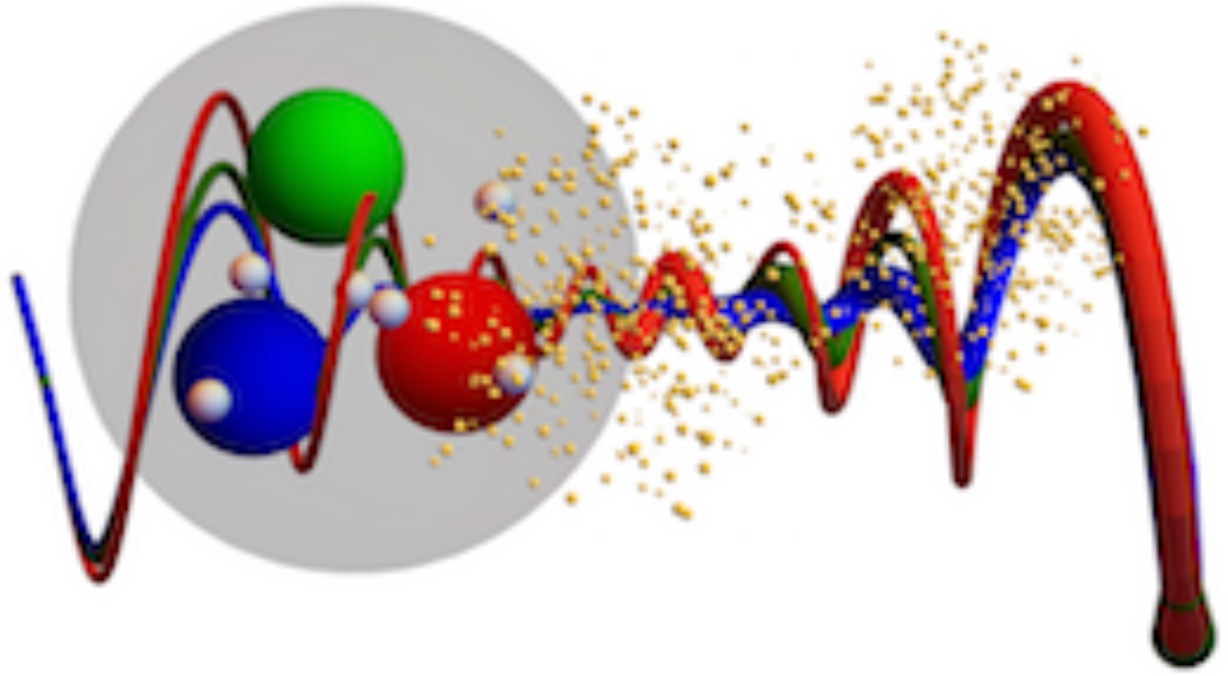
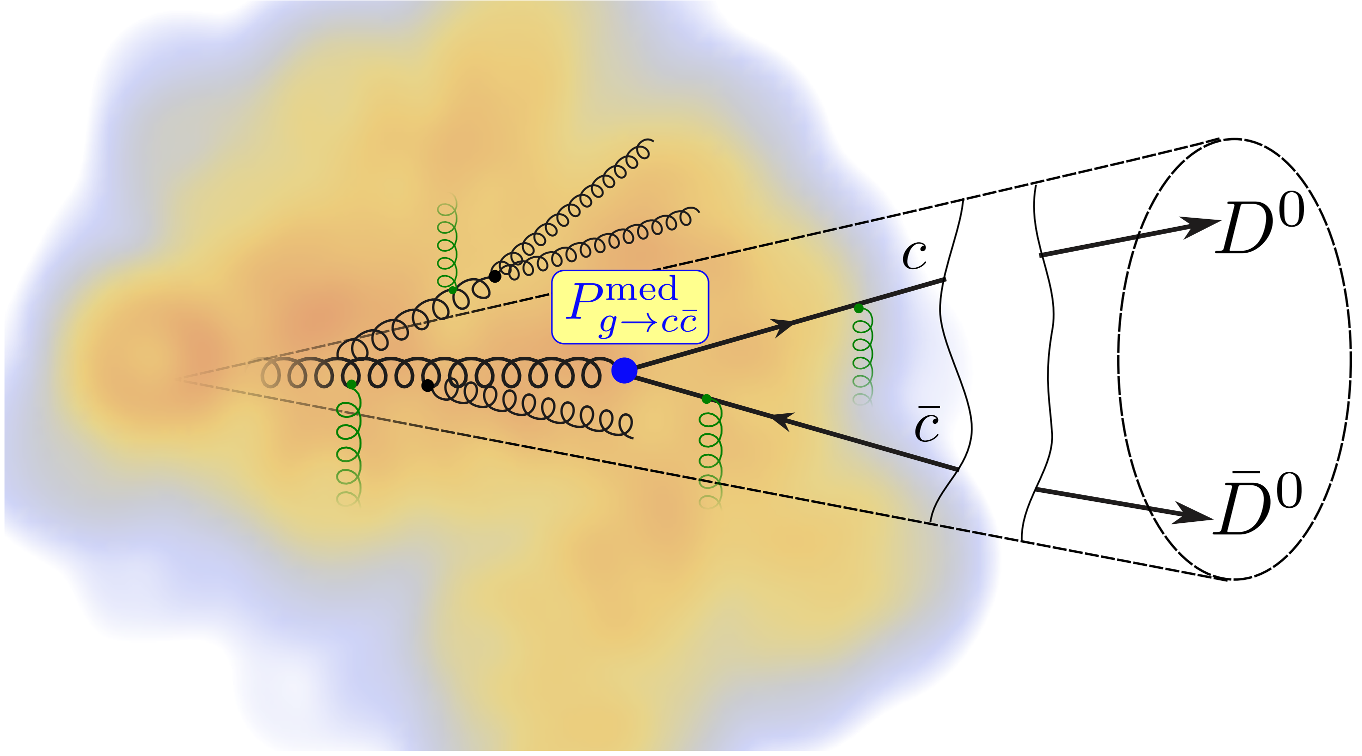


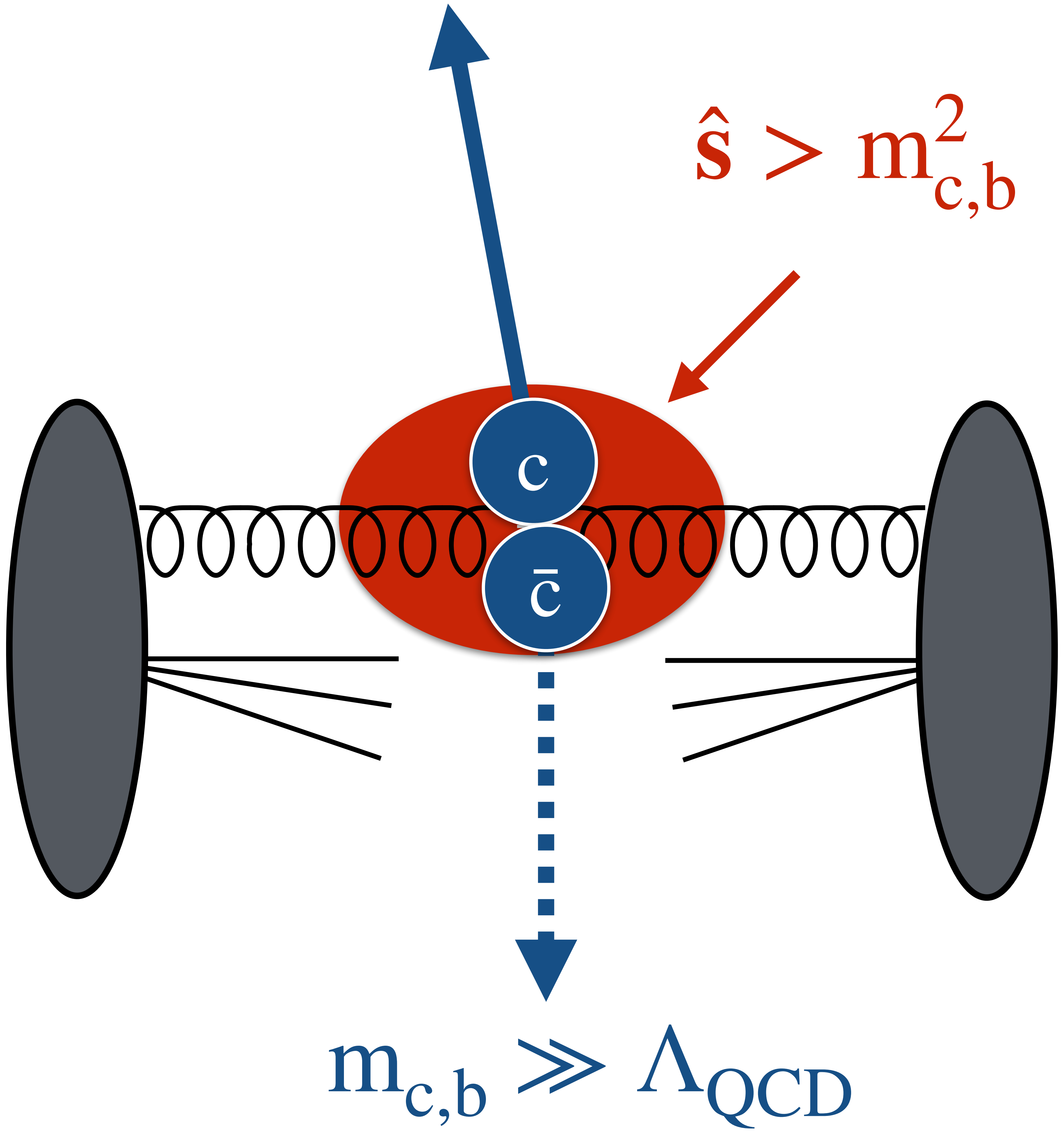
MPI@LHC 2022



Heavy flavors production in proton-proton collisions

→ **“schematic” picture**

$m_b \sim 4.18$ GeV
$m_c \sim 1.27$ GeV
$\Lambda_{QCD} \sim 200$ MeV



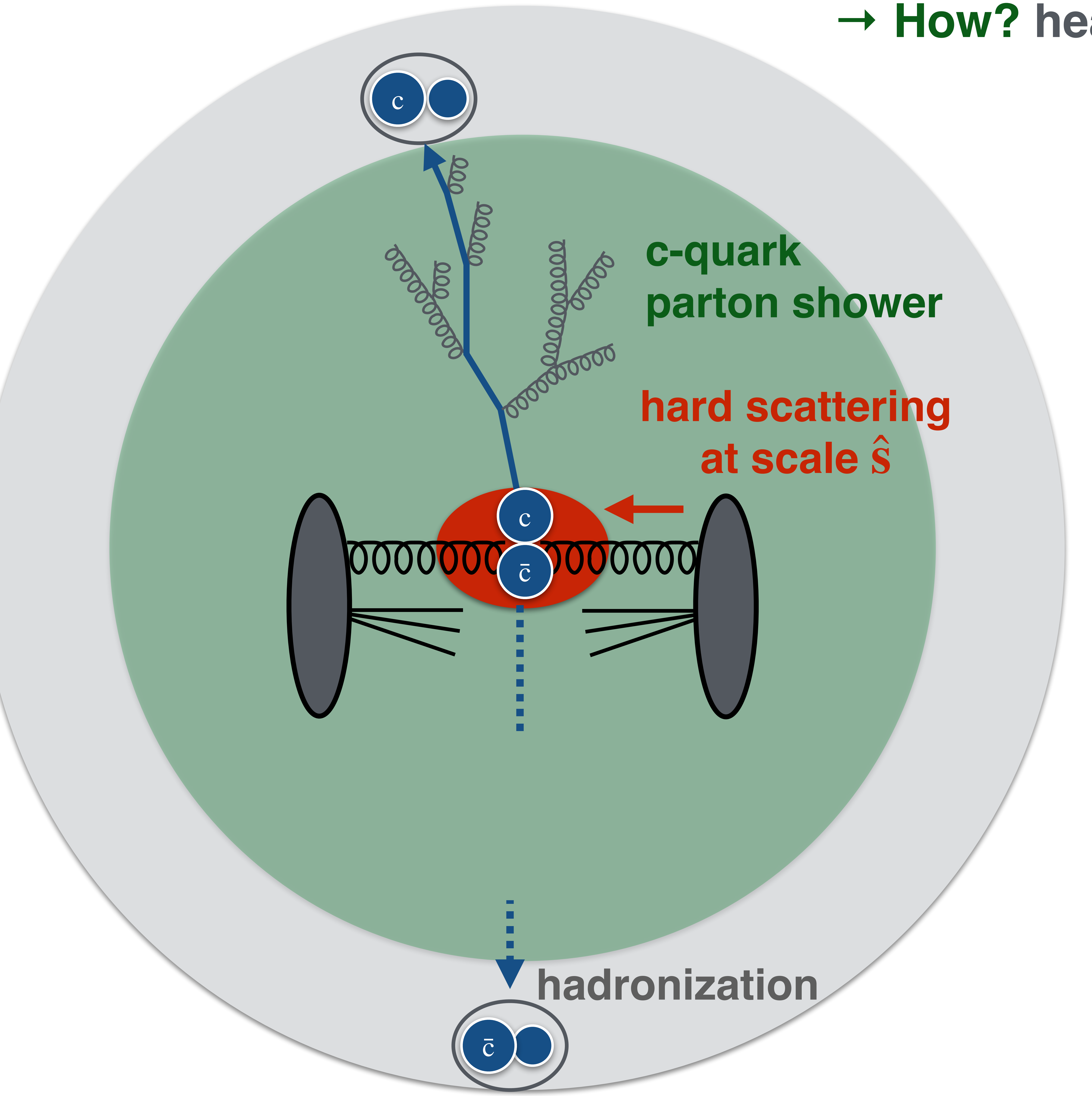
→ **short-distance** high-momentum transferred

→ **mass threshold removes many non-perturbative effects**
→ pQCD can predict the total heavy-flavour (HF) production

“Perturbative” cross-sections in elementary collisions:
→ set the yields for heavy-flavour production in heavy-ions
→ Quark Gluon Plasma only modifies the p_T distribution of heavy-quarks.

M. Cacciari et al., JHEP 10 (2012) 137

Dominant medium-modification of HQ in the QGP



→ **How? heavy quarks rescatter inside the QGP**

$m_b \sim 4.18$ GeV
$m_c \sim 1.27$ GeV
$T_{QGP} \sim 300$ MeV
$\Lambda_{QCD} \sim 200$ MeV

Modification of the parton shower:

- splitting function c→cg can be modified by the QGP

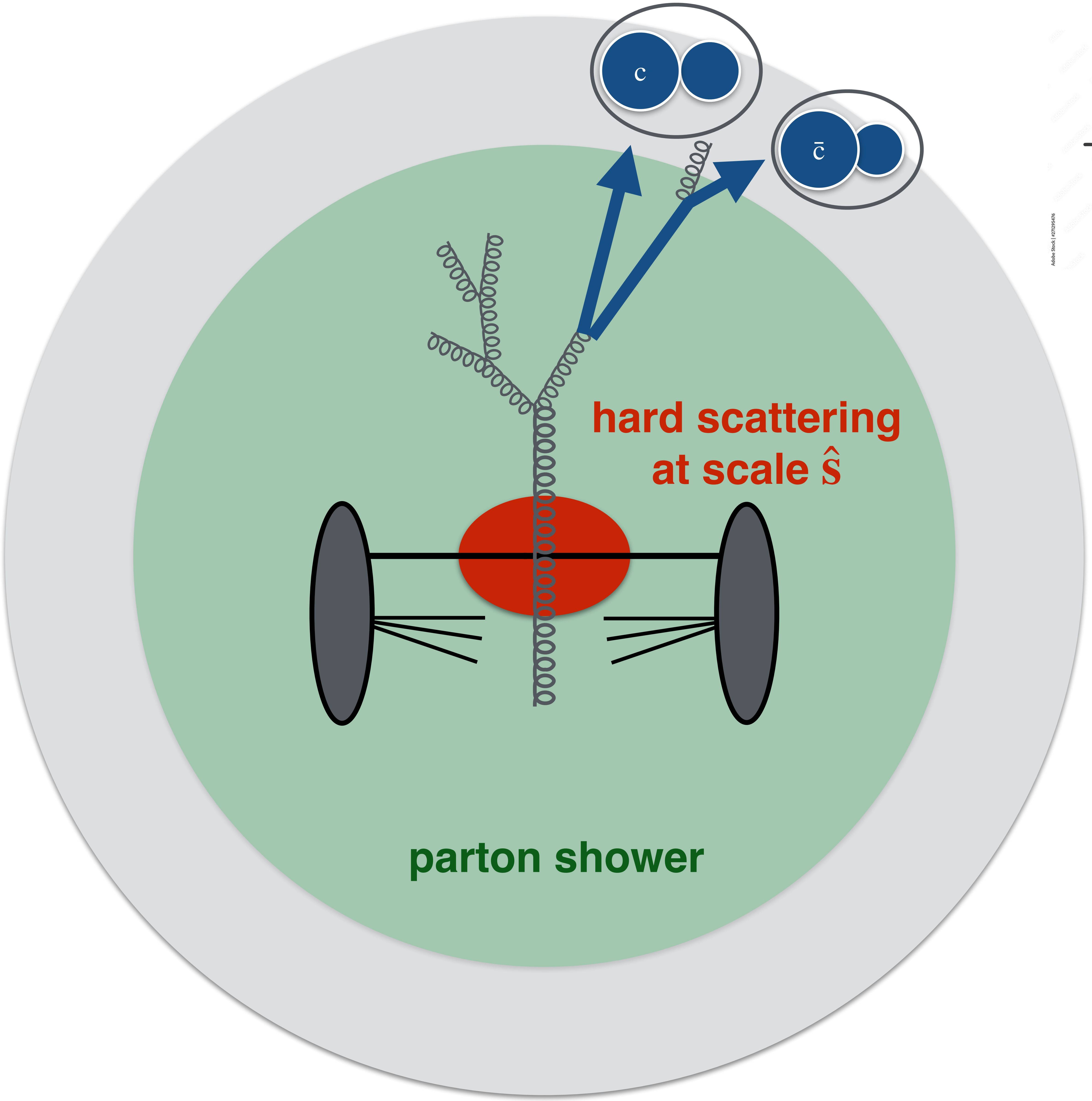
$$\tau_{hard} \ll \tau^{med}_{c\rightarrow cg} \ll \tau_{hadr}$$

→ **enhanced gluon radiation from c and b quarks**

→ **Observed experimentally** via modification of high-p_T spectra of heavy-flavour hadrons

BDMPS, Nucl.Phys., B484:265–282, 199
B.G. Zakharov, JETP Lett., 63:952–957, 1996.
Y.L. Dokshitzer, D.E Kharzeev, Phys.Lett. B 519, 199-206, 2001

Heavy-quark production from collinear $g \rightarrow c\bar{c}$

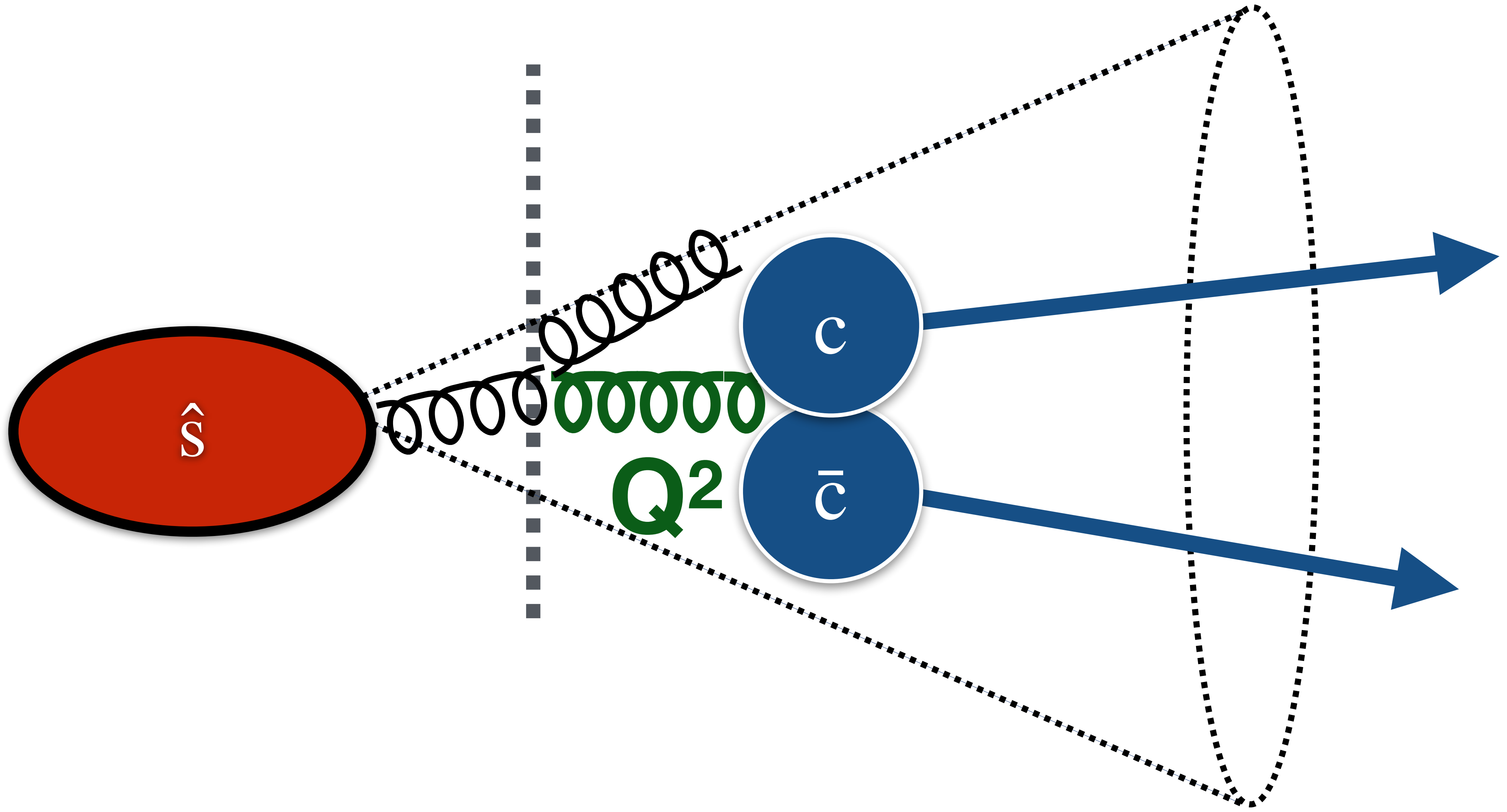


- **$g \rightarrow c\bar{c}$ splittings** originated in the parton shower of high-p_T gluon jets:
  → **long-distance process $\tau_{g\rightarrow c\bar{c}} \gg \tau_{hard}$**
  → **$g \rightarrow c\bar{c}$ splitting modified by the medium!**

- features of the in-medium calculation of $g \rightarrow c\bar{c}$ splitting function with BDMPS-Z

- One **experimental** signature for $g \rightarrow c\bar{c}$ modifications: $D^0\overline{D}^0$ production in high-p_T jets

$c\bar{c}$ pairs in high-p_T gluon jets



ŝ = center of mass energy of partonic scattering

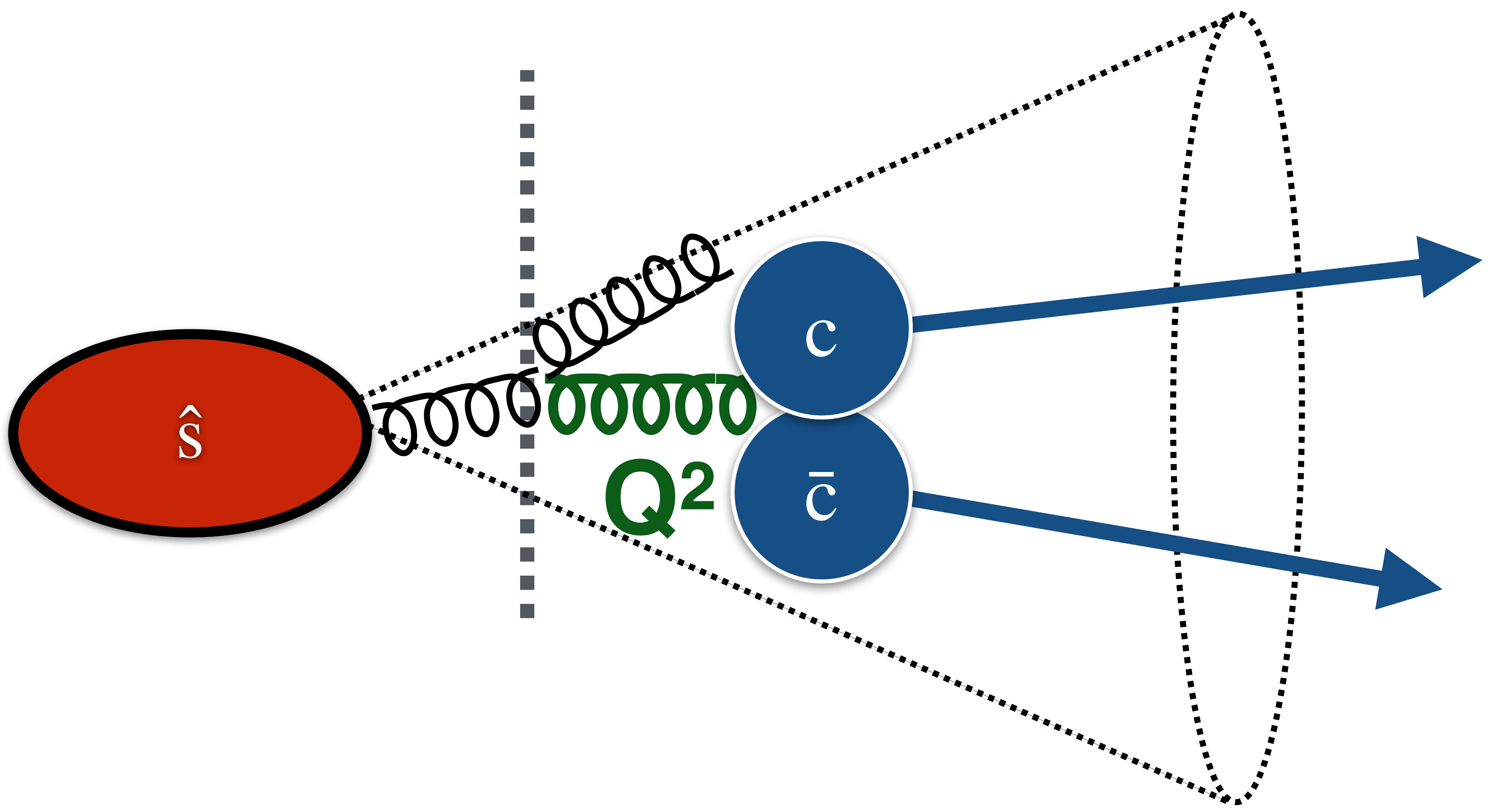
$$Q^2 \ll \hat{s}$$

→ preferentially select g → $c\bar{c}$ splittings

→collinear limit of QCD

$$\hat{\sigma}^{g\,g \to c\,\bar{c}\,X} \xrightarrow{Q^2 \ll \hat{s}} \hat{\sigma}^{g\,g \to g\,X} \otimes \frac{\alpha_s}{2\pi} \frac{1}{Q^2} P_{g \to c\bar{c}}(z)$$

$c\bar{c}$ pairs in high-p_T gluon jets



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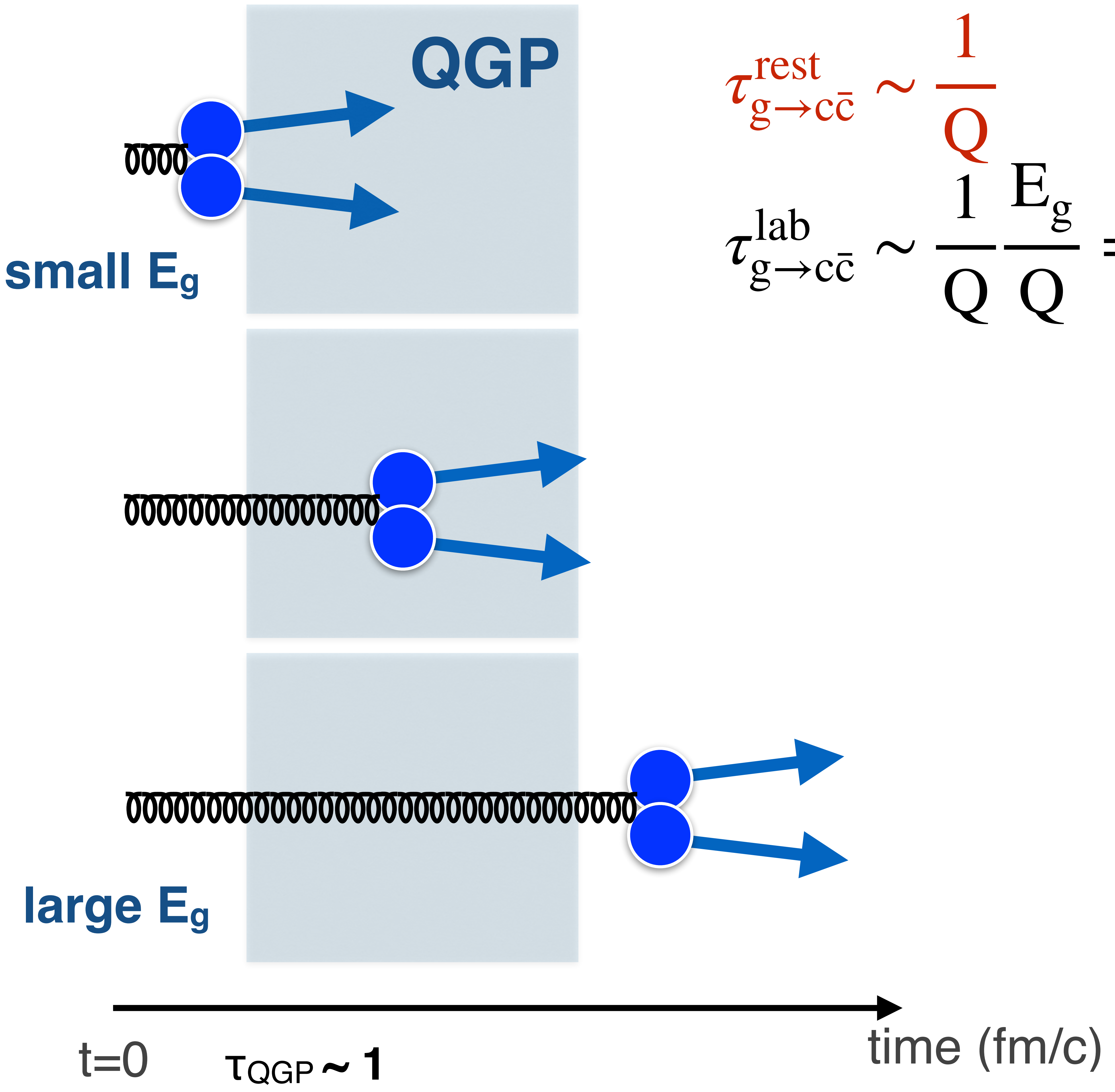
$$\hat{\sigma}^{g\,g\rightarrow c\,\bar{c}\,X} \xrightarrow{Q^2 \ll \hat{s}} \hat{\sigma}^{g\,g\rightarrow g\,X} \otimes \frac{\alpha_s}{2\pi}\frac{1}{Q^2}P_{g\rightarrow c\bar{c}}(z)$$

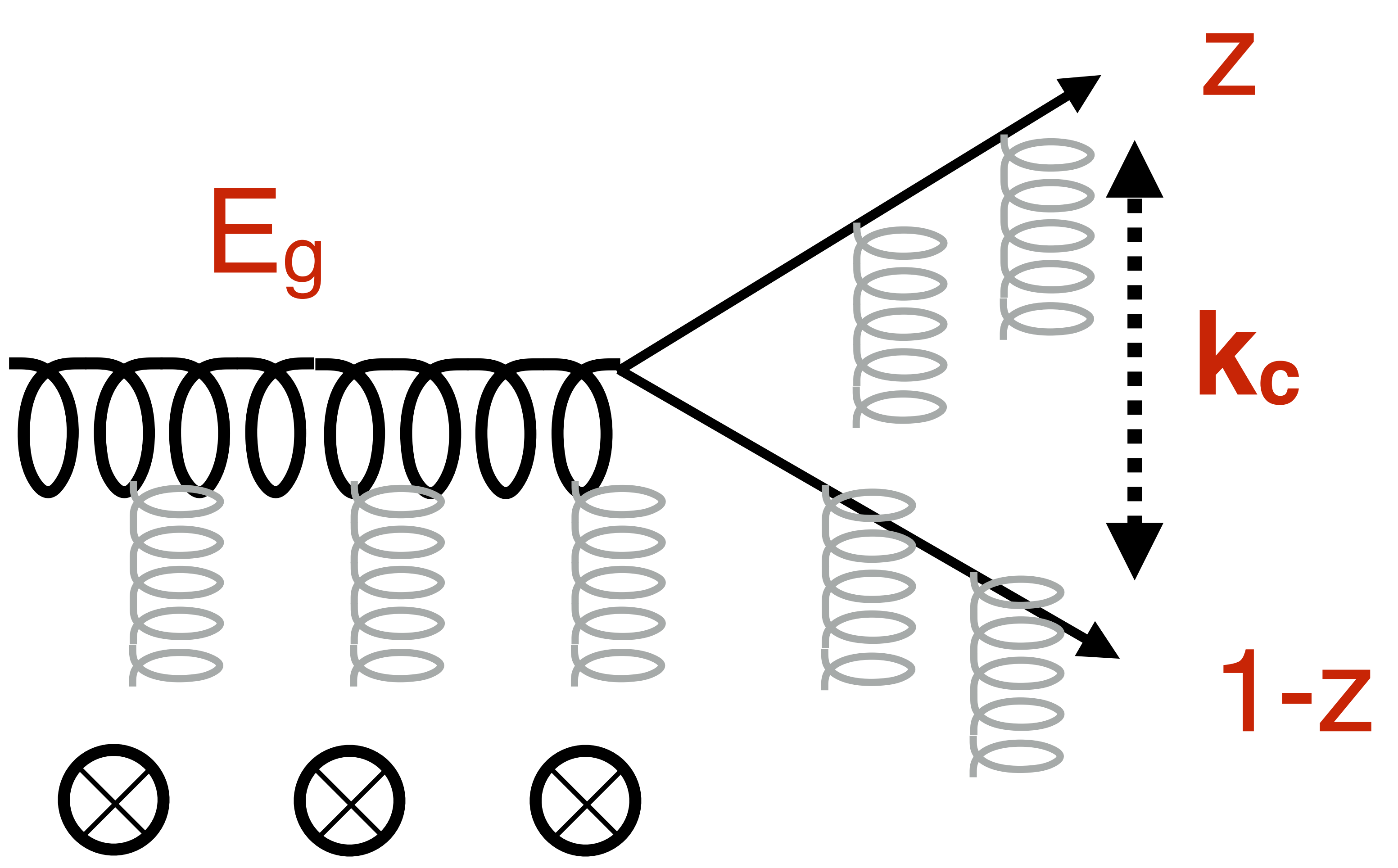


$$\tau^{rest}_{g\rightarrow c\bar{c}} \sim \frac{1}{Q}$$

$$\tau^{lab}_{g\rightarrow c\bar{c}} \sim \frac{1}{Q}\frac{E_g}{Q} = \frac{E_g}{Q^2}$$

In-medium g → c$\bar{c}$ splitting function

arXiv:2203.11241 → **BDMPS-Z formalism to calculate in-medium** $P_{g \to c\bar{c}} = P_{g \to c\bar{c}}(E_g, k_c, z, \hat{q}, L)$



Medium properties and **g → c$\bar{c}$ kinematics:**

- $\hat{q}$ average squared transverse momentum
- L medium length

$$\left(\frac{1}{Q^2} P_{g\to c\bar{c}}\right)^{\text{tot}} = \left(\frac{1}{Q^2} P_{g\to c\bar{c}}\right)^{\text{vac}} + \left(\frac{1}{Q^2} P_{g\to c\bar{c}}\right)^{\text{med}}$$

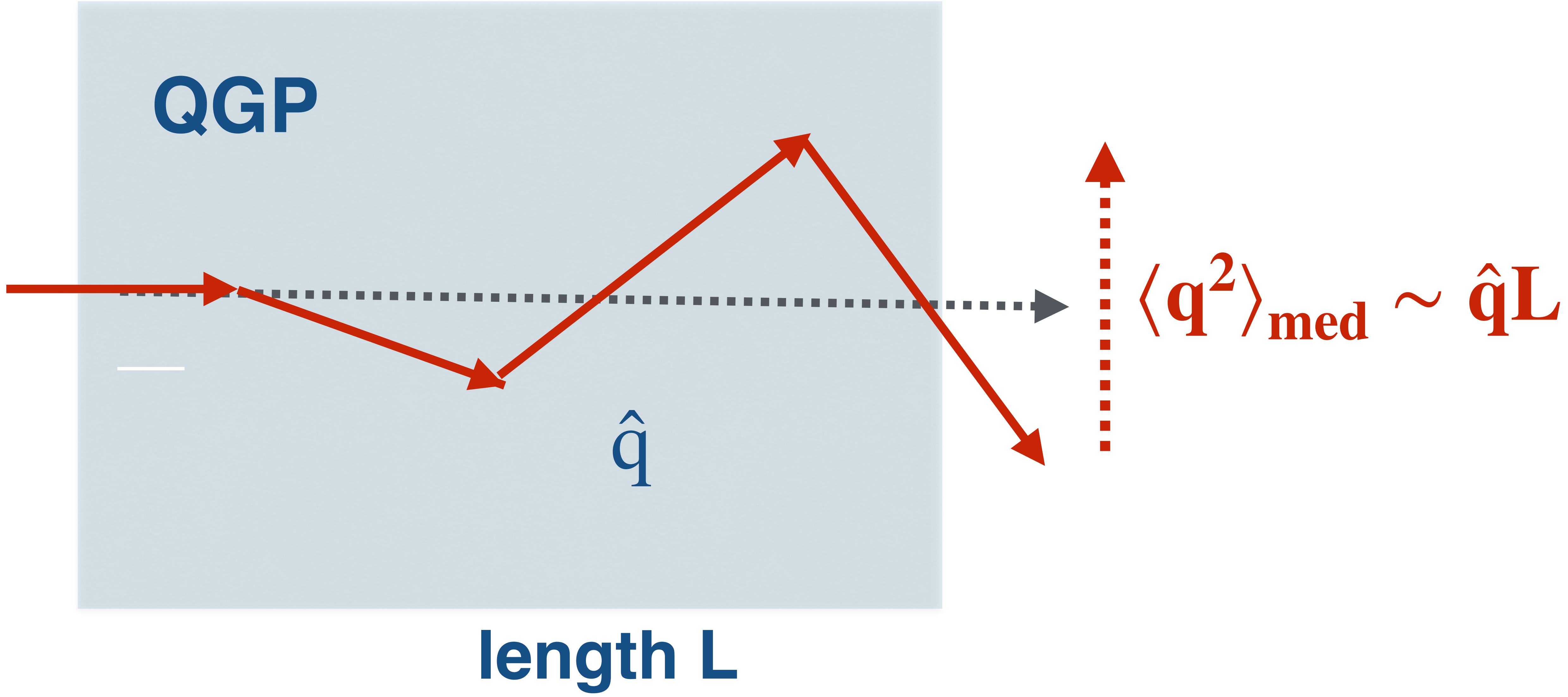
$$= 2\,\mathfrak{Re}\,\frac{1}{8\,E_g^2}\int_0^\infty dt \int_t^\infty d\bar{t} \int d\mathbf{r}$$

$$\times\; e^{i\frac{m_c^2}{2E_g z(1-z)}(t-\bar{t})-\epsilon|t|-\epsilon|\bar{t}|}\; e^{-\frac{1}{4}\int_{\bar{t}}^{\infty} d\xi\, \hat{q}(\xi,z)\,\mathbf{r}^2}\; e^{-i\,\boldsymbol{\kappa}\cdot\mathbf{r}} \qquad (3)$$

$$\times \left[\frac{m_c^2}{z(1-z)} + \frac{z^2+(1-z)^2}{z(1-z)}\frac{\partial}{\partial \mathbf{x}}\cdot\frac{\partial}{\partial \mathbf{r}}\right]\mathcal{K}\left[\mathbf{x}=0, t; \mathbf{r}, \bar{t}\right]\,.$$

$P^{med}_{g\to c\bar{c}}$: **"magnitude"** of the in-medium modification

$\langle \mathbf{q}^2 \rangle_{\mathbf{med}} \sim \hat{\mathbf{q}}\mathbf{L}$ average squared transverse momentum that a parton acquire in a medium of length L



From the calculation:

→ $P^{med}_{g\to c\bar{c}} \sim \mathcal{O}\left(\frac{\langle \mathbf{q}^2 \rangle_{med}}{Q^2}\right)$

From model extraction in central PbPb data:

$\langle q^2 \rangle_{med} = \hat{q}L$ from 1 to 8 GeV² (conservative)

→ $\langle q^2 \rangle_{med} \sim m_c^2$

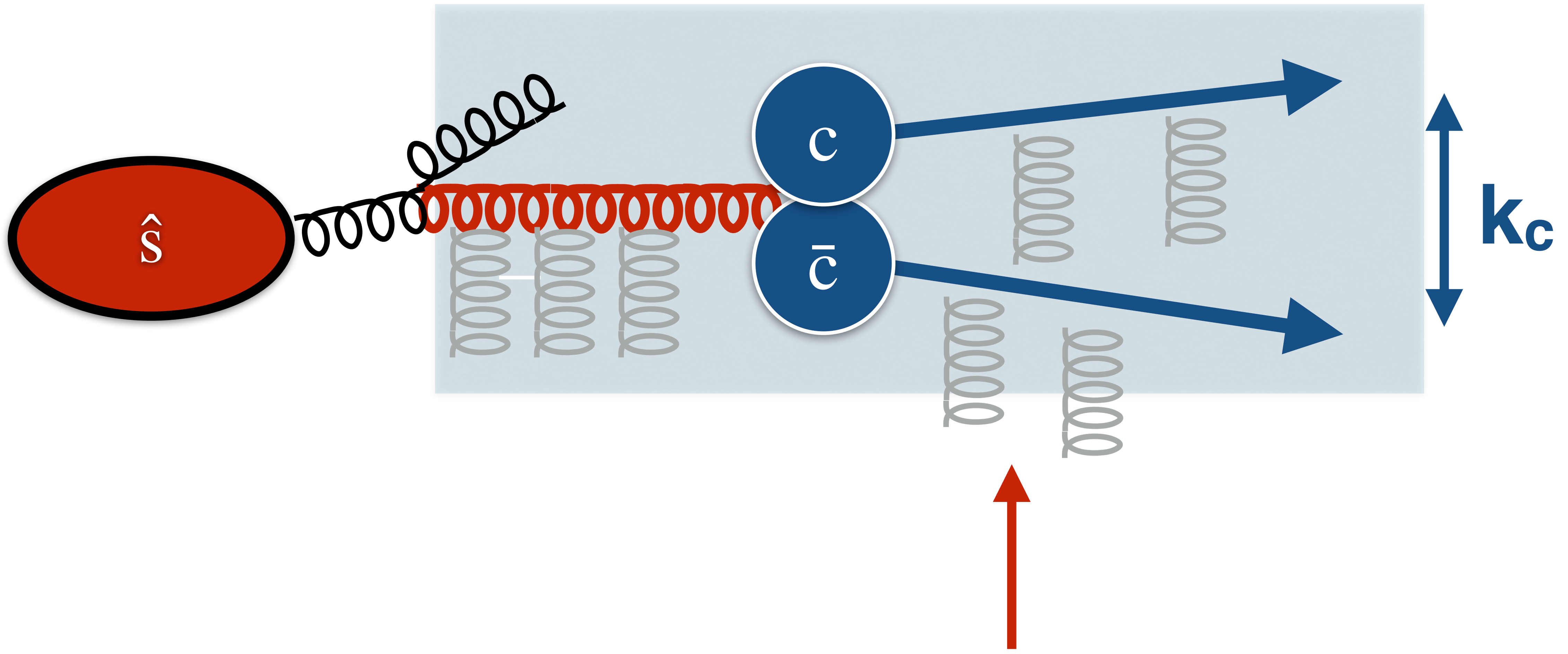
→ $P^{med}_{g\to c\bar{c}} \sim \mathcal{O}\left(\frac{m_c^2}{Q^2}\right)$ $P^{vac}_{g\to c\bar{c}}(z) = z^2 + (1-z)^2 + 2\frac{m_c^2}{Q^2}$

- $P^{med}_{g\to c\bar{c}}$ has same "magnitude" of the mass term of $P^{vac}_{g\to c\bar{c}}$, known to give origin to sizeable effects

→ **effect of $P^{med}_{g\to c\bar{c}}$ likely to be relevant**

$P^{med}_{g\to c\bar{c}}$: $c\bar{c}$ **broadening** and $c\bar{c}$ **enhancement**

QGP with length L



k_c → relative transverse momentum of the $c\bar{c}$ pair

increases of k^2_c due to transverse momentum broadening on the individual quarks:
→ conserves splitting probability

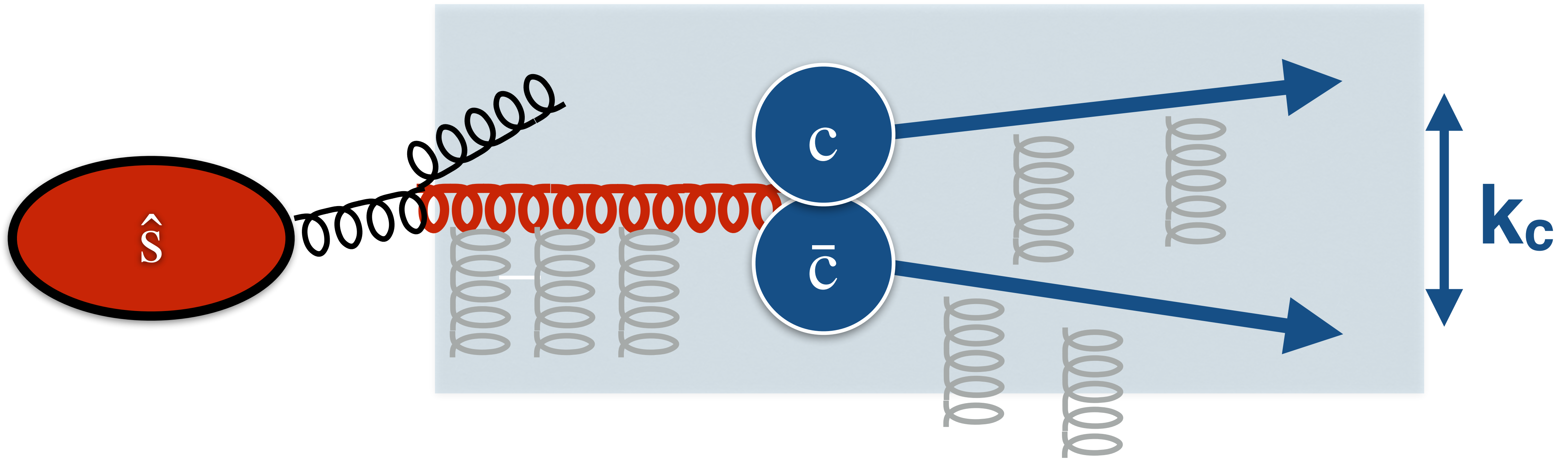
Enhancement of g → $c\bar{c}$ splittings

→ Gluons which would not split in vacuum can split if in-medium scatters occurs

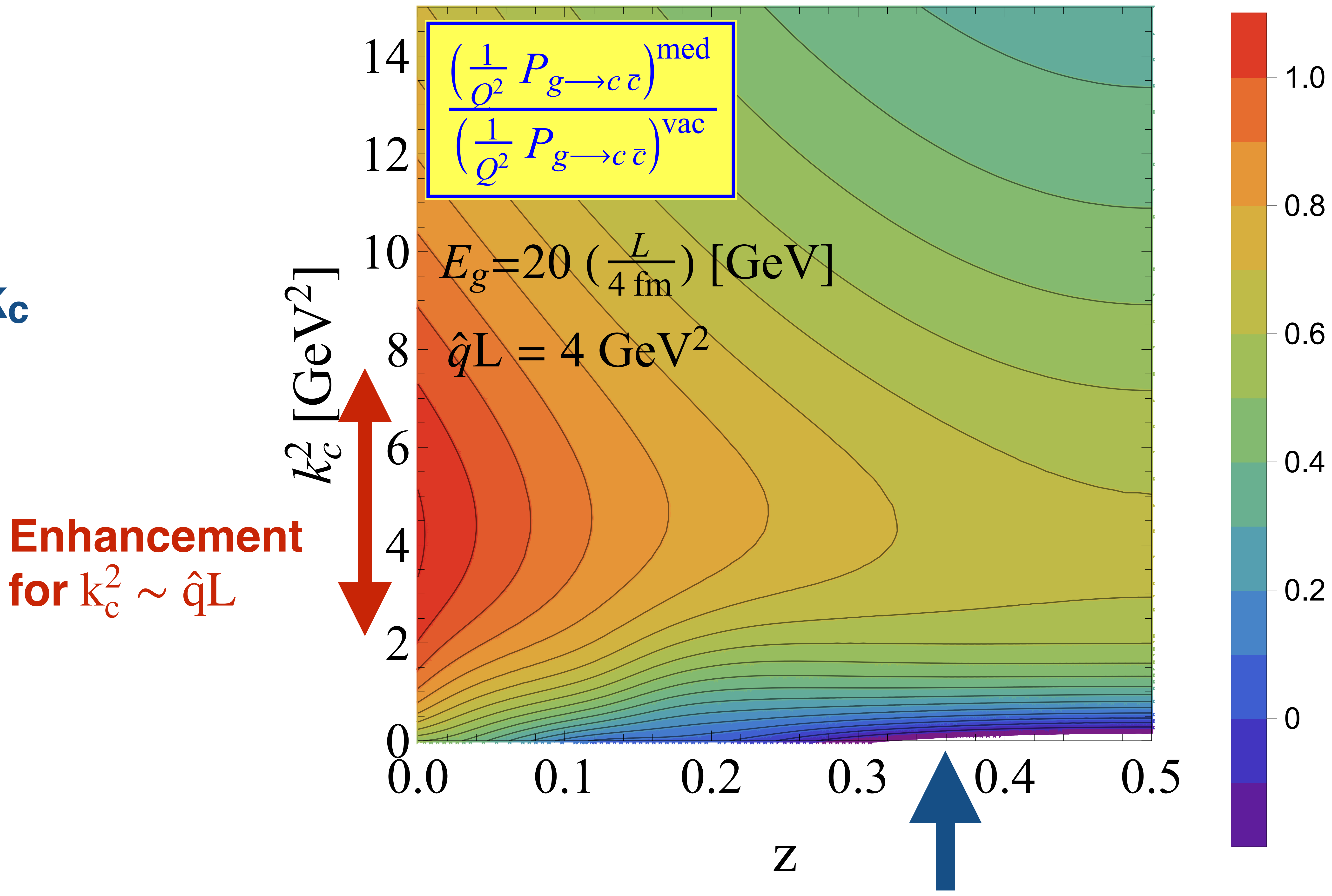
→ increase of a "conserved"and "traceable" quantity via interaction with the medium

Numerical results for $P^{med}_{g\to c\bar{c}}$ / $P^{vac}_{g\to c\bar{c}}$

→ Multiple soft-scattering approximation
→ QGP brick with $\hat{q}L$ = 4 GeV²

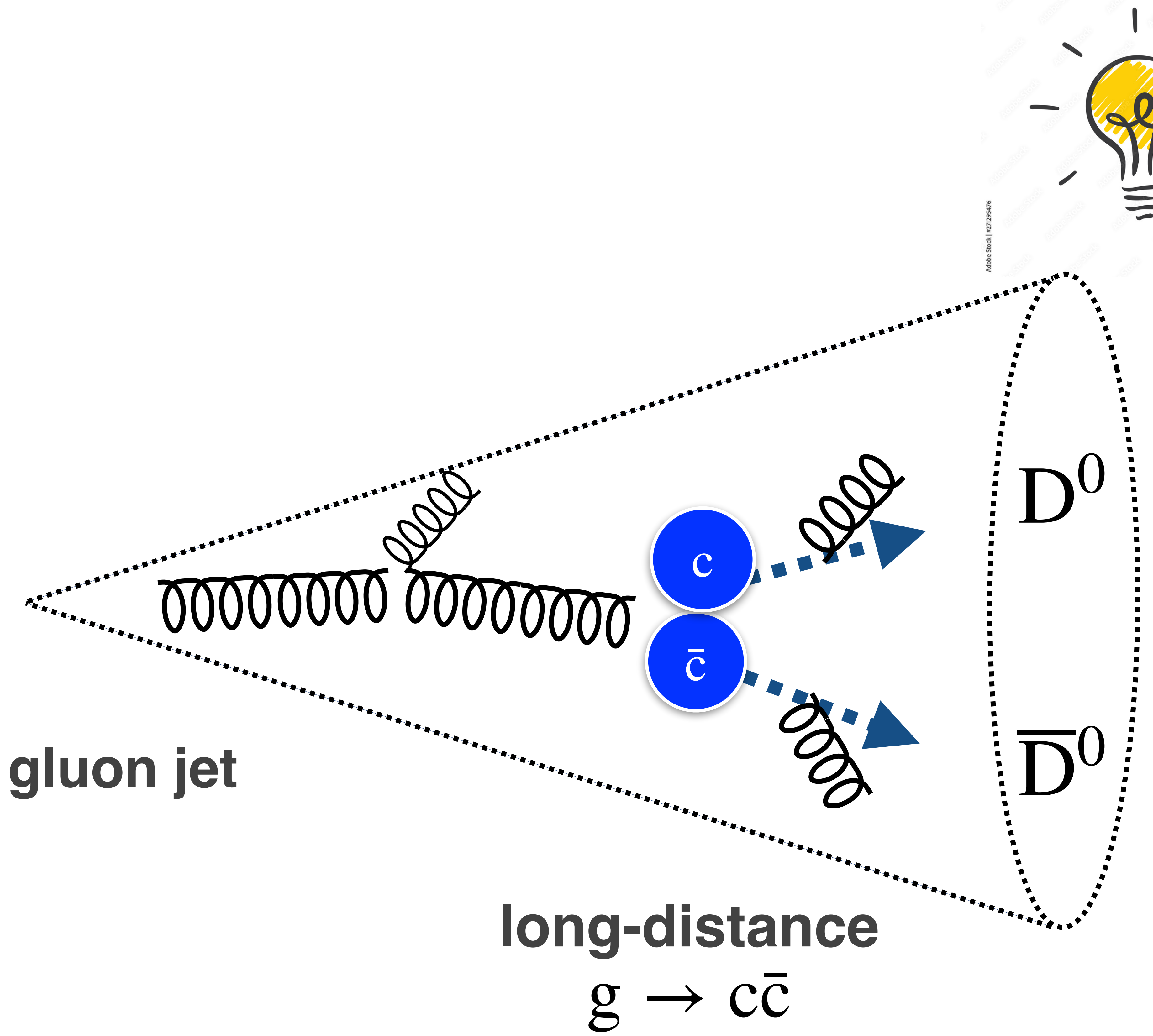


→ **magnitude of in-medium modification**
$P^{med}_{g\to c\bar{c}} \sim P^{vac}_{g\to c\bar{c}}$



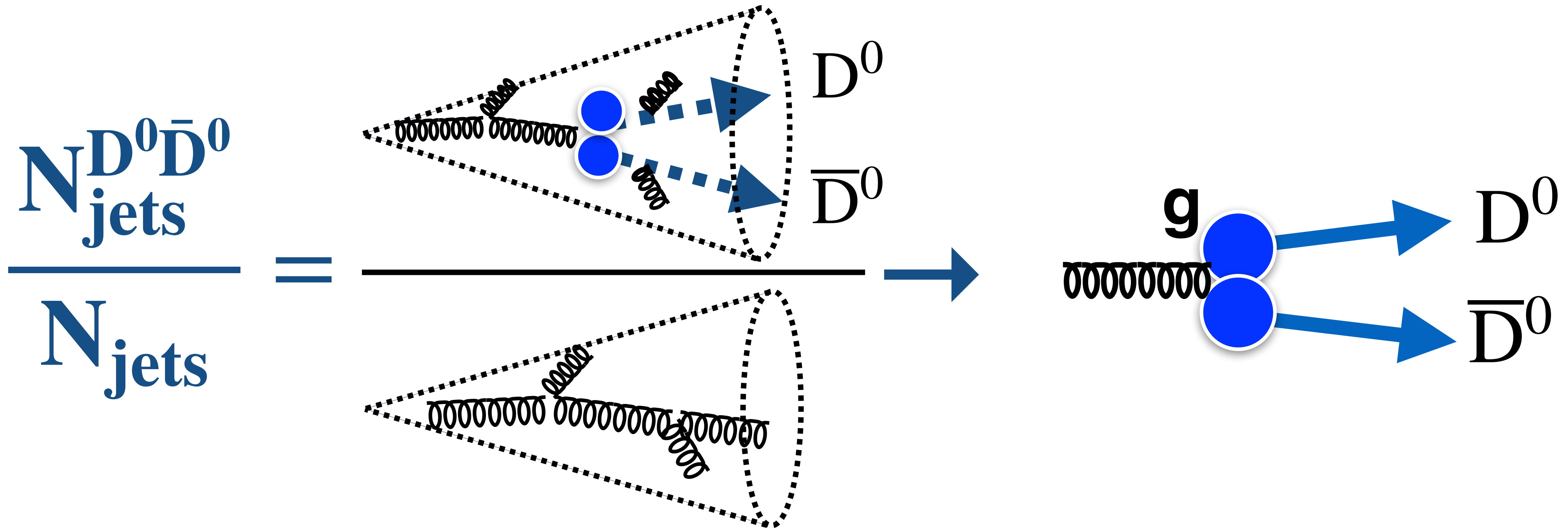
→ the formalism that describes enhanced gluon radiation in the QGP also predicts a **sizeable** enhancement of the $c\bar{c}$ radiation

Experimental strategy for g→$c\bar{c}$ enhancement



High-p_T jets with a $D^0\overline{D}^0$ pair inside the jet code:

- <u>D-meson reconstruction</u>
  - constraints on the charm-quarks kinematics
  - accessible down to low p_T in heavy-ions

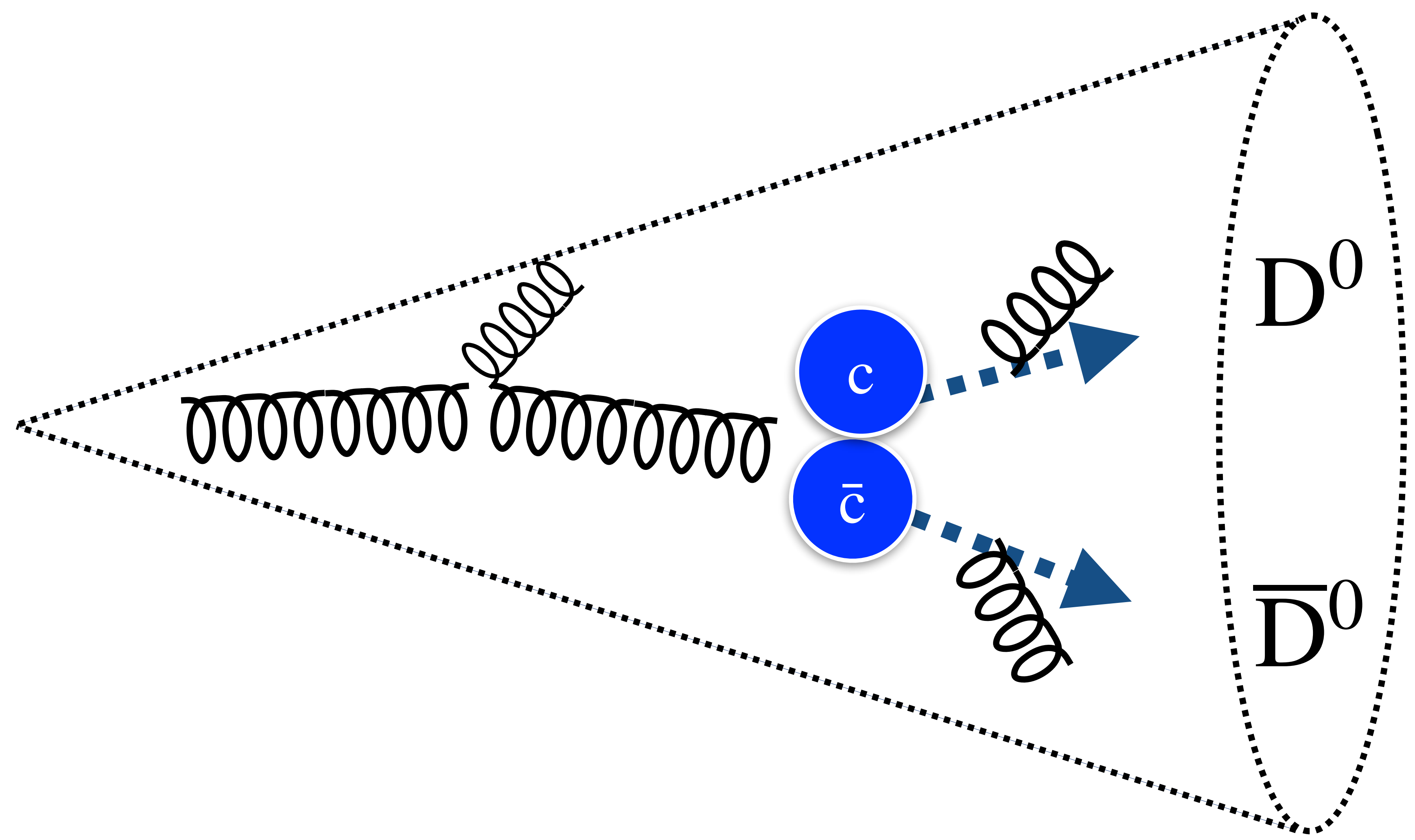


Due to $g\to c\bar{c}$ enhancement, a larger fraction of $D^0\overline{D}^0$-tagged jets expected in heavy-ions

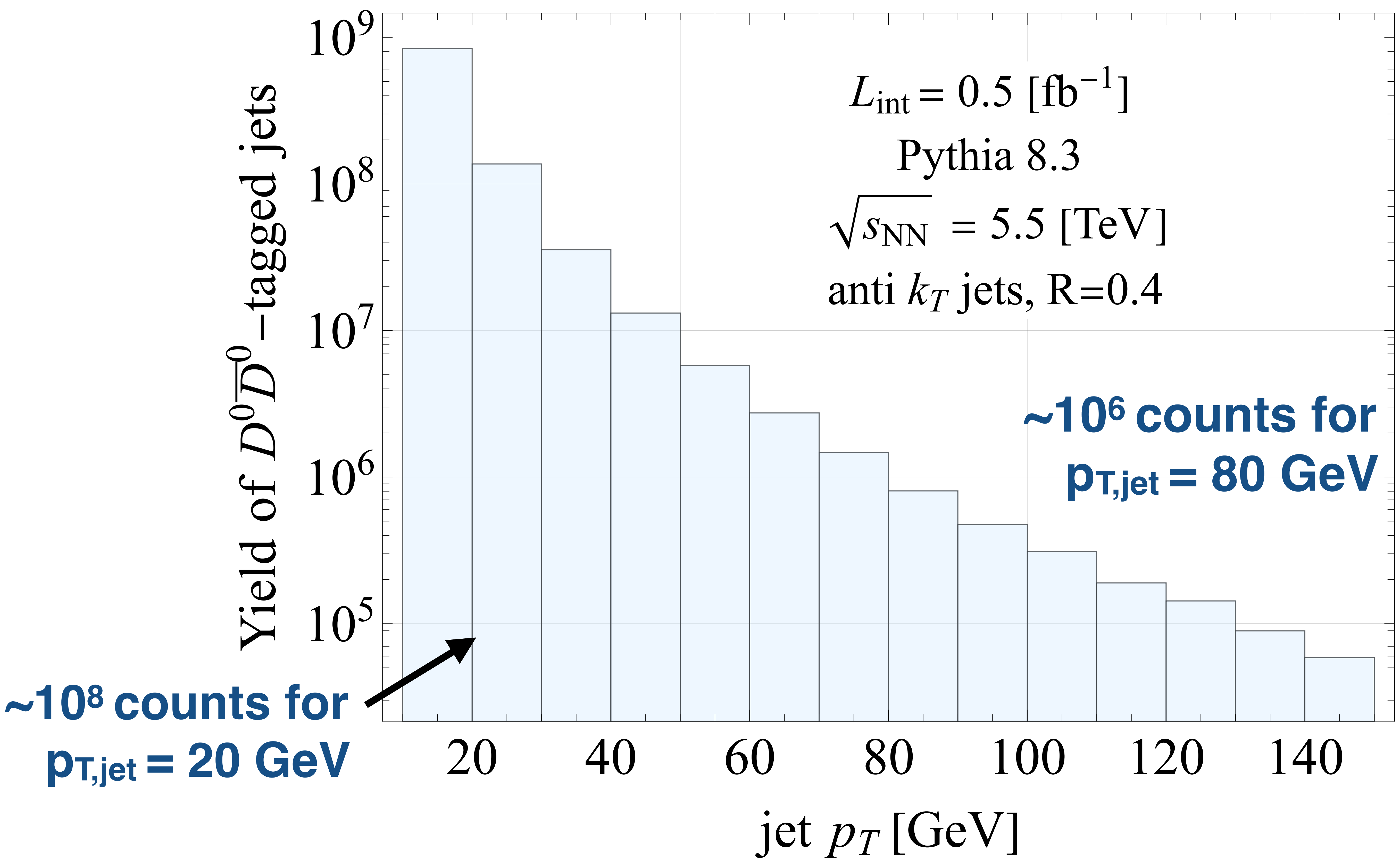
→ dedicated MC study to provide a first assessment of the feasibility of such measurement

Monte Carlo study with Pythia

- Anti-k_T "full" jets with FastJet (R=0.4)
- one $D^0\overline{D}^0$ per jet
- only prompt D^0 contribution considered ($c \rightarrow D^0$)



L_{int} = 0.5 fb^{-1} pp ~ 10 nb^{-1} PbPb (no quenching)



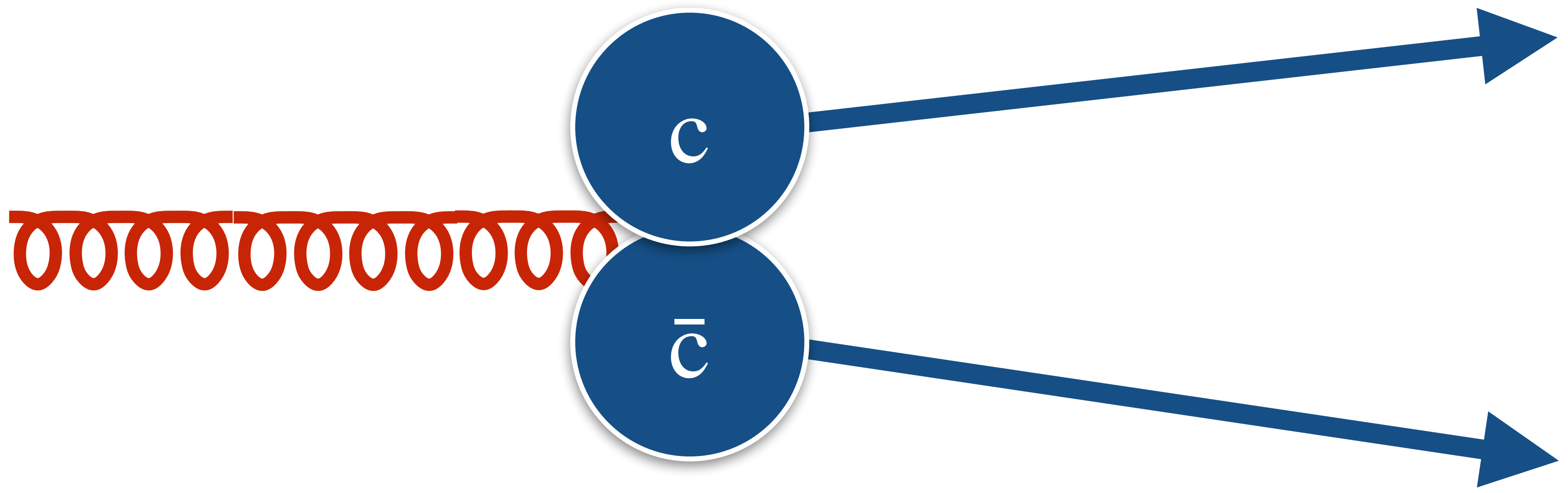
- Fully reconstructed hadronic D^0 decays
- **<u>But also</u>** $c\bar{c}$-tagging techniques high-p_T jets or tagging of semi-leptonic charm decays → **sample ~ entire $c\bar{c}$ statistics**

Challenging measurement:

→ Based on expected yields, the measurement could be within reach with HL-LHC

Embedding $P^{med}_{g\to c\bar{c}}$ in the parton shower

→ **ideal strategy:** include all modified splitting functions in the parton shower (currently not available)



$$p_g = p_c + p_{\bar{c}}$$

A simplified procedure:

- identify and reconstruct the $g \to c\bar{c}$ kinematics in Pythia
- **"reweigh" each splitting to accounts for modified $g \to c\bar{c}$ probability**

$$w^{med}_{g\to c\bar{c}}(E_g, k_c^2, z) = 1 + \frac{\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\rm med}(E_g, k_c^2, z)}{\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\rm vac}(k_c^2, z)}$$

This simplified strategy relies on few realistic assumptions/approximations (arXiv:2203.11241)

→ **captures the qualitative features of the in-medium $g \to c\bar{c}$ modifications**

$N_{jets}^{D^0\bar{D}^0}/N_{jets}$ as a function of jet p_T

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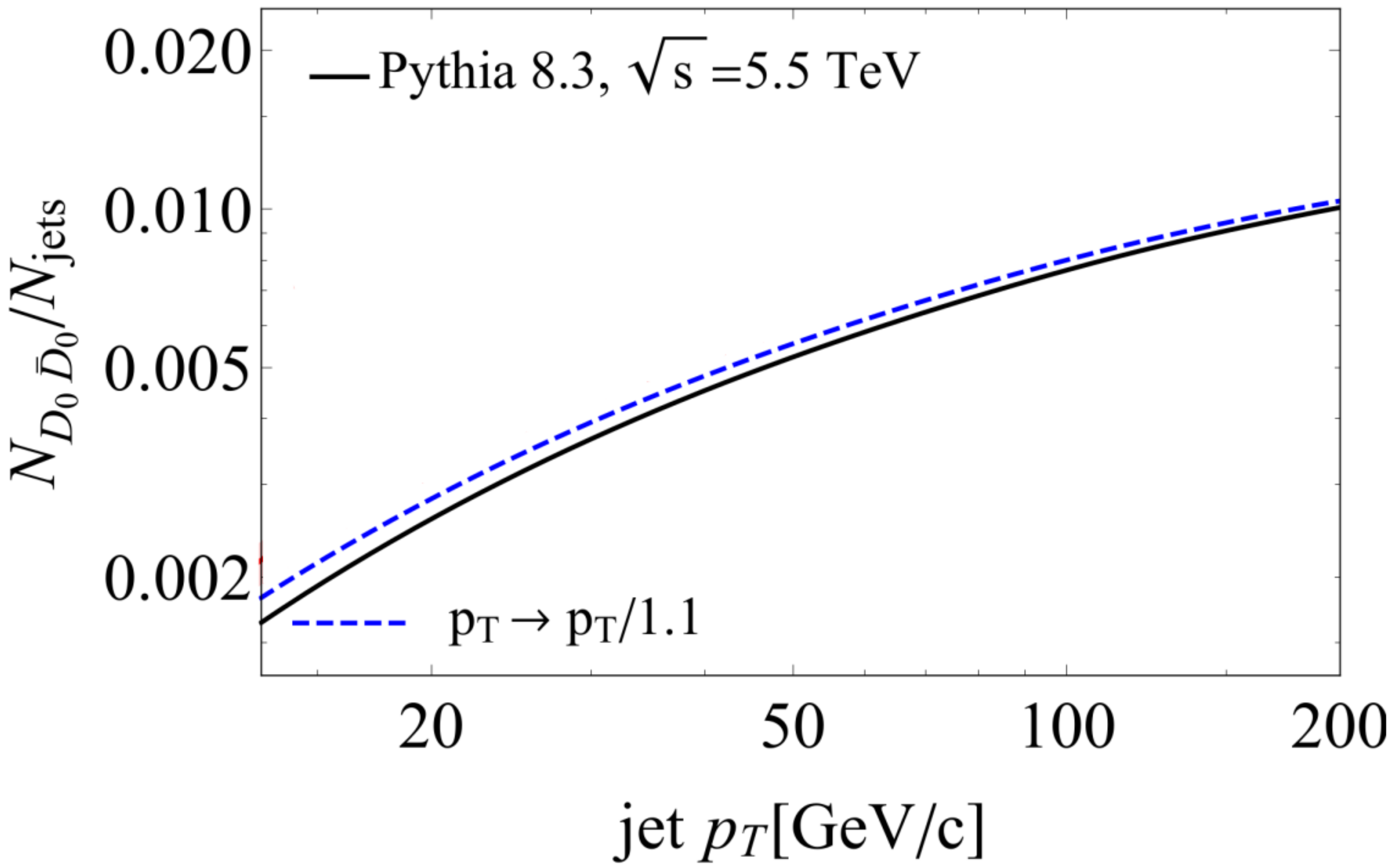

Parton shower in vacuum (Pythia pp)

Corrected for jet quenching:

- 10% p_T shift for both $D^0\overline{D}^0$-tagged and inclusive jets
  → baseline to establish the effect of $P^{med}_{g\to c\bar{c}}$

$N^{D^0\bar{D}^0}_{jets}/N_{jets}$ as a function of jet p_T

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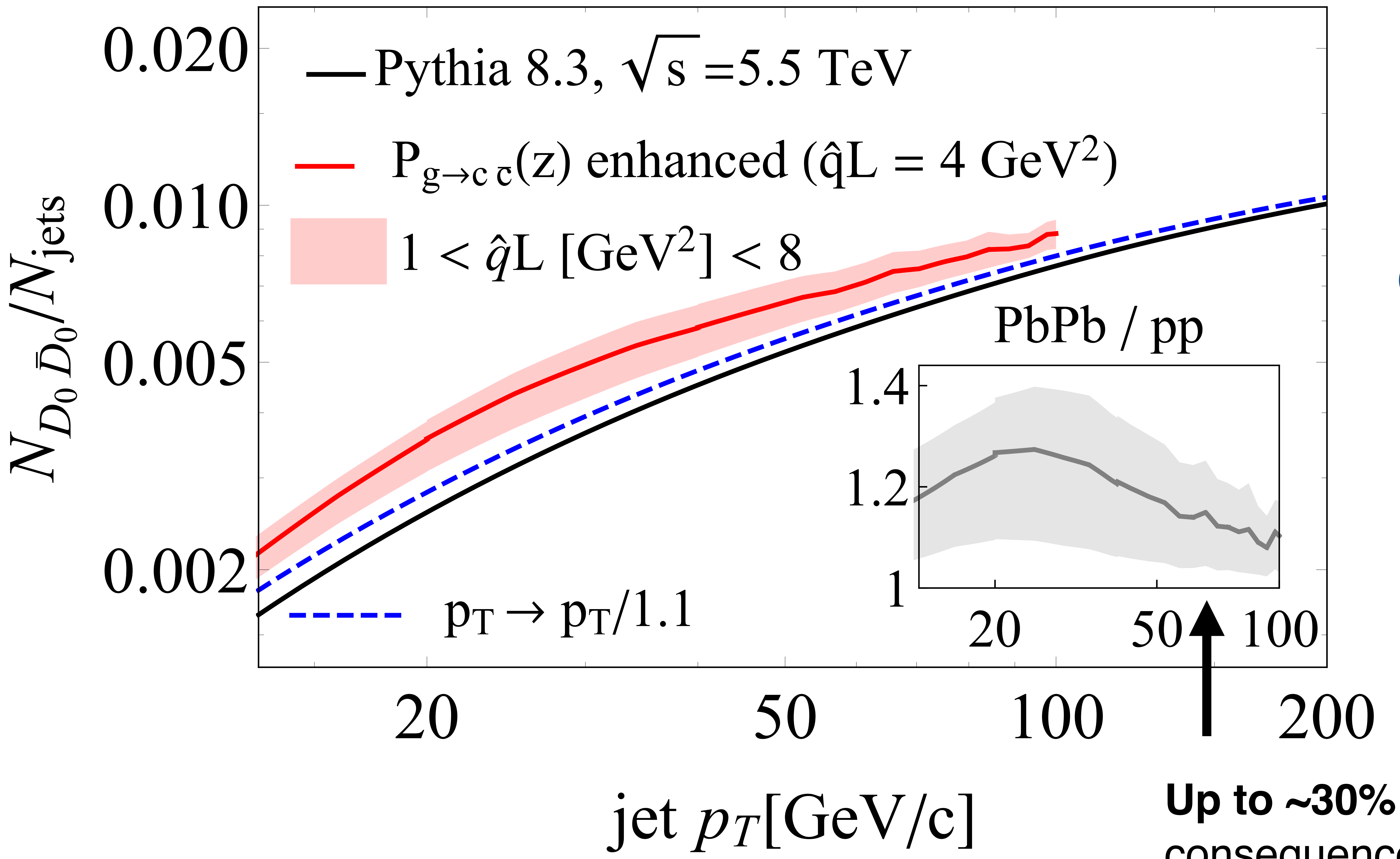


Parton shower in vacuum (Pythia pp)

Corrected for jet quenching:

- 10% p_T shift for both $D^0\overline{D}^0$-tagged and inclusive jets
  → baseline to establish the effect of $P^{med}_{g\to c\bar{c}}$

Up to ~30% increase in the rate of $D^0\overline{D}^0$ tagged jets as a consequence of modified $g \to c\bar{c}$ splitting function

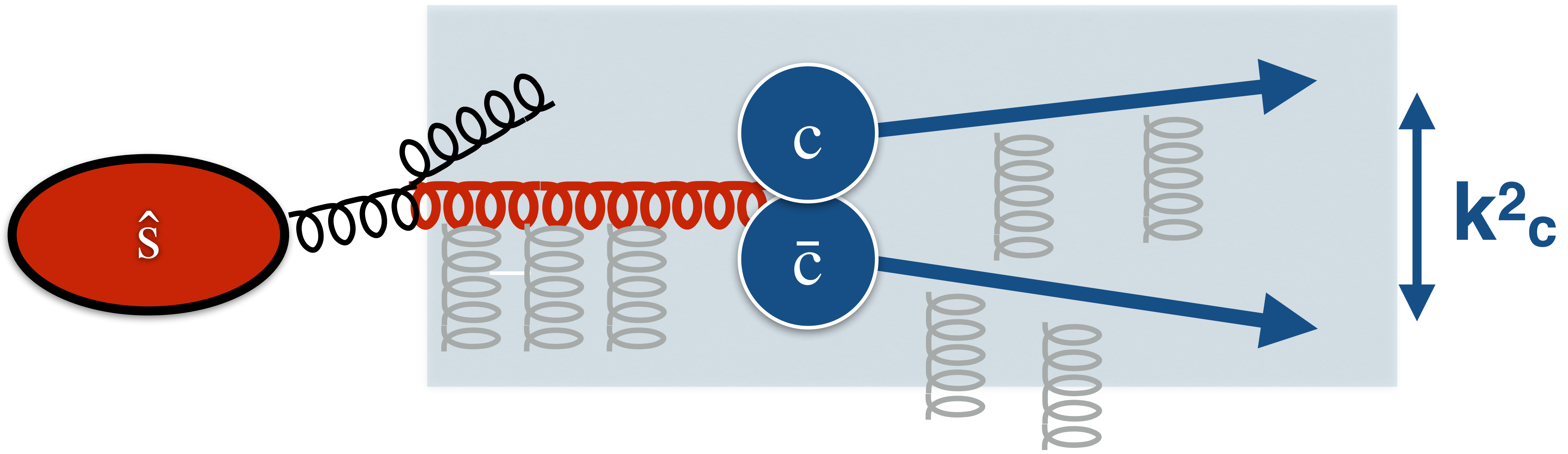
Reweighed to account for modified $g \to c\bar{c}$ splitting function:
→magnitude of the effect likely to increase with more differential observables

Conclusions

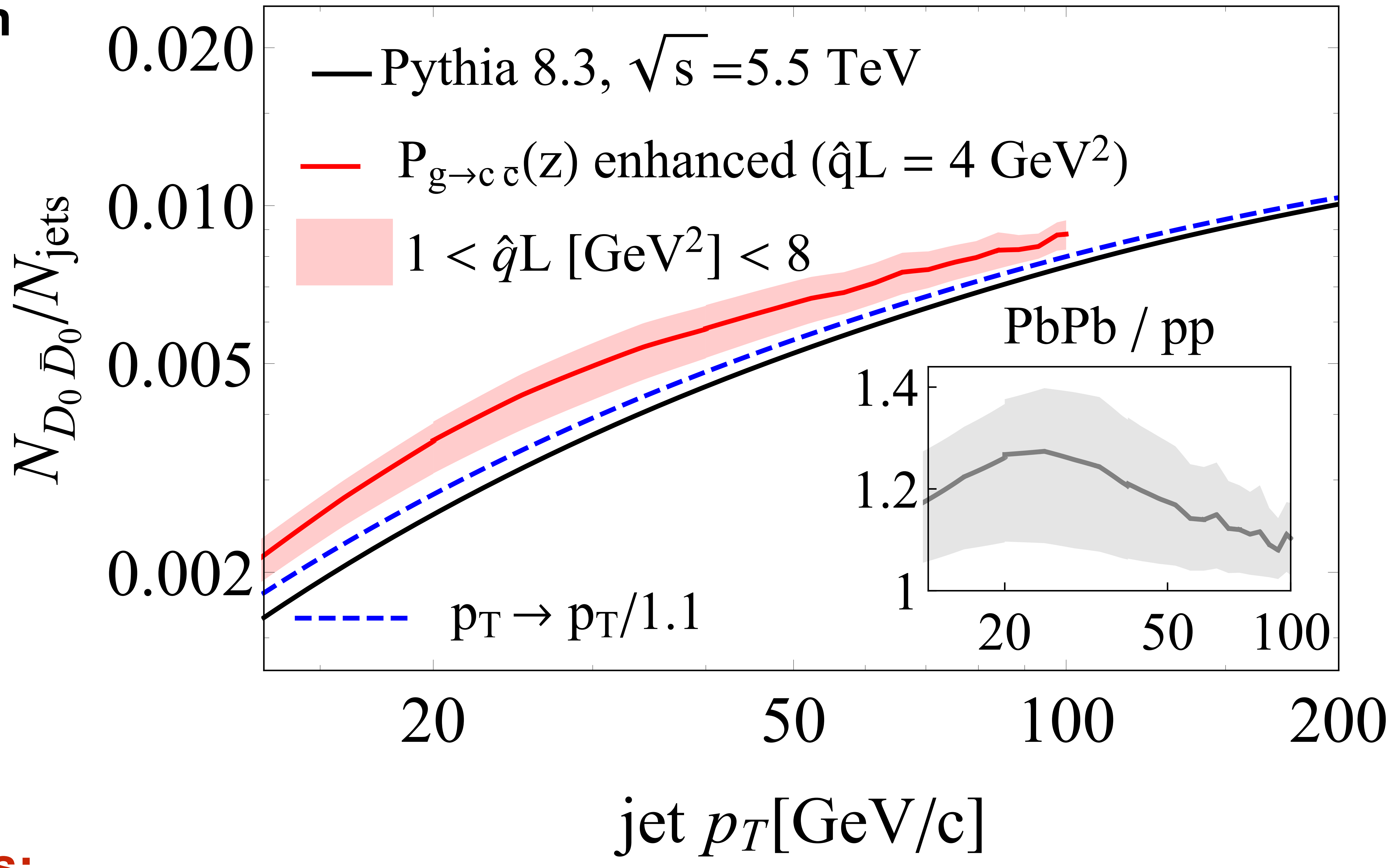
→ g → $c\bar{c}$ for "in-medium" production of heavy quarks

g → $c\bar{c}$ splitting function with BDMPS-Z:
- broadening of $c\bar{c}$ pairs and **enhancement of $c\bar{c}$ radiation**

QGP with length L



Experimental strategy for g → $c\bar{c}$ enhancement:
- challenging but potentially measurable signal



Push for new theoretical and experimental developments:
- parton showers including the in-medium modifications of all splitting functions → more differential observables
- high-luminosity heavy-ion runs, improved detector capabilities and new analysis techniques

ALICE 3 Letter of Intent, CERN-LHCC-2022-009, arXiv:2211.02491

Conclusions

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Thank you for your attention!

BACKUP SLIDES

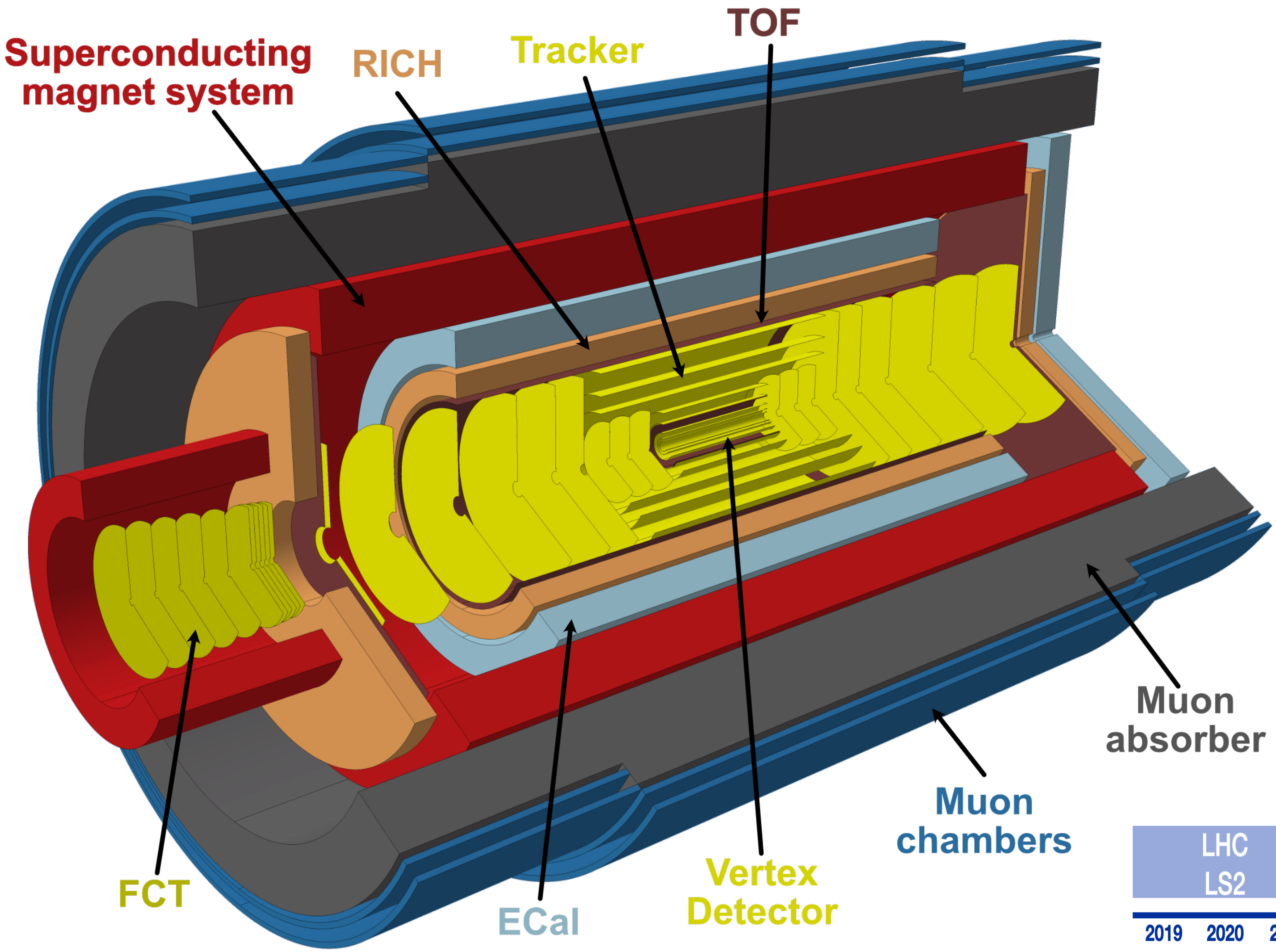
ALICE 3 for Run 5 and 6

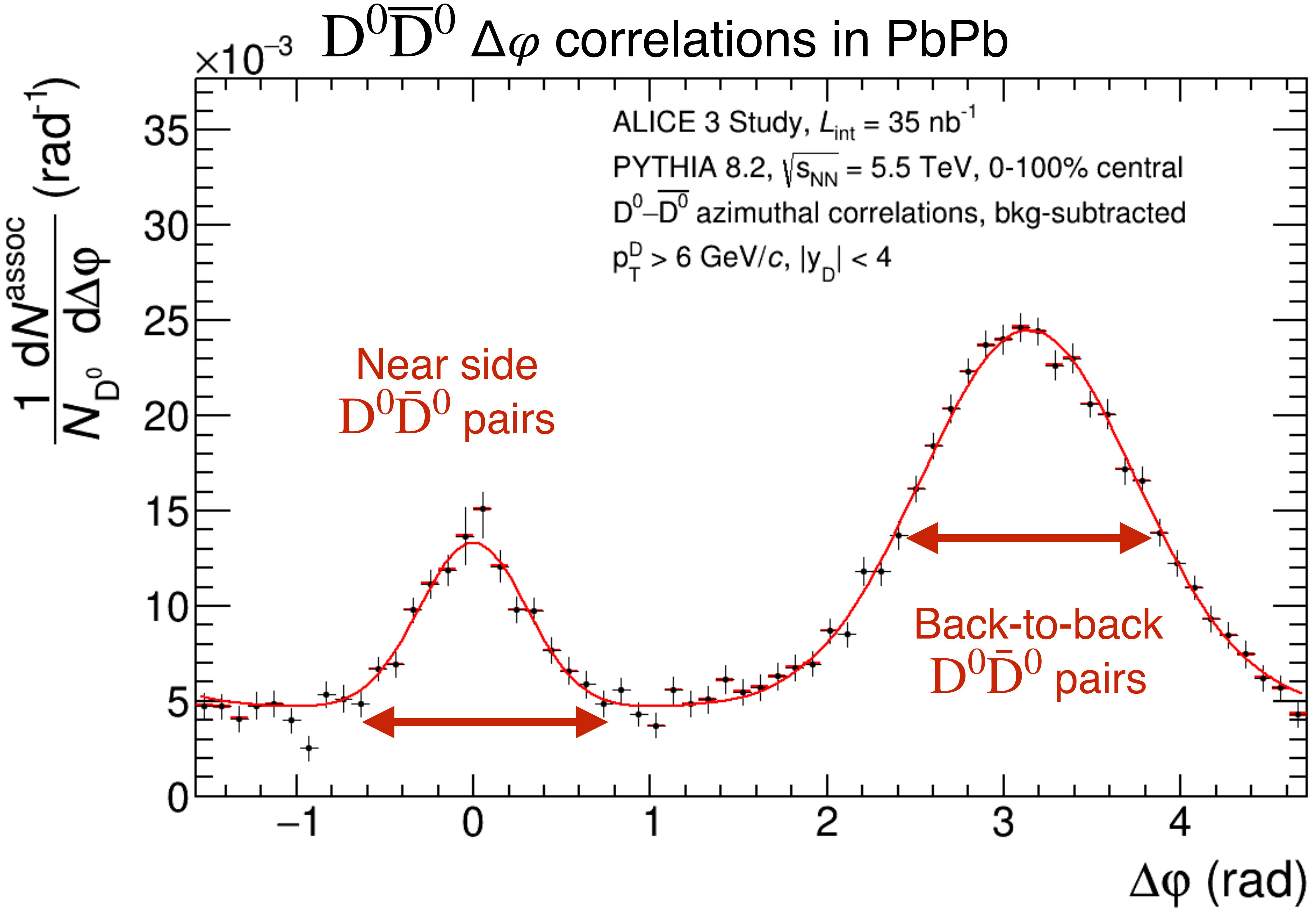
ALICE 3 Letter of Intent, CERN-LHCC-2022-009, arXiv:2211.02491
LoI submitted in October ’21
Review concluded in March ’22

To exploit this physics program → designed the ultimate HI detector at the LHC

- Ultra-light pixel layers, also inside the beam pipe → **~μm DCA resolution, crucial for HF at low p_T**
- PID from low to high momentum and tracking over $|\eta|<4$
- $\mathscr{L}_{int}$= 35 nb^{-1} PbPb in Run 5/6

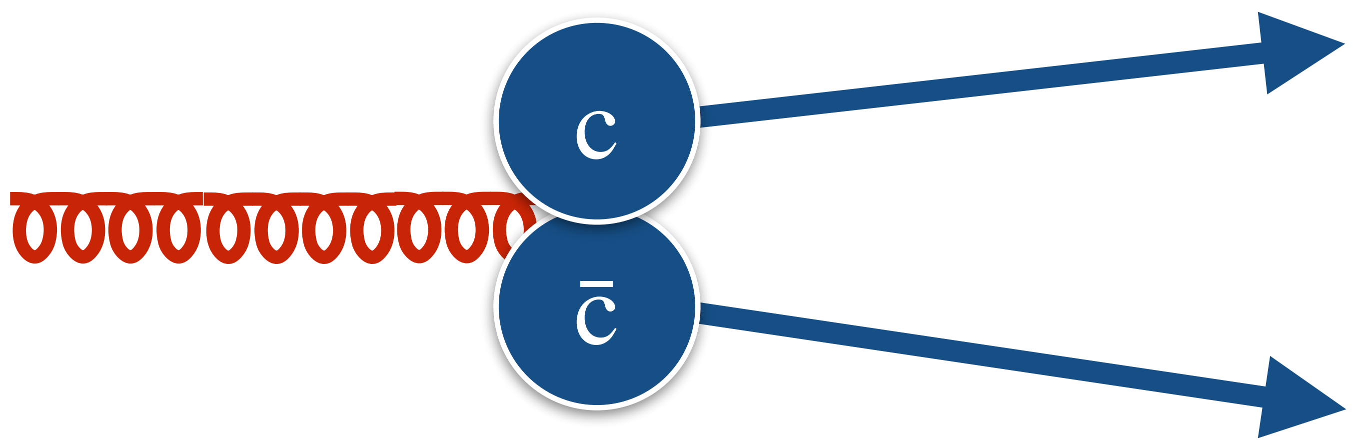
→ **ALICE 3 makes this unique experimental program possible!**





Embedding $P^{med}_{g\to c\bar{c}}$ in the parton shower

→ **ideal strategy:** include all modified splitting functions in the parton shower (currently not available)



$p_g = p_c + p_{\bar{c}}$

A simplified procedure

- identify and reconstruct the $g \to c\bar{c}$ kinematics in Pythia
- **"reweigh" each splitting to accounts for modified $g \to c\bar{c}$ probability**

$$w^{med}_{g\to c\bar{c}}(E_g, k_c^2, z) = 1 + \frac{\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\text{med}}(E_g, k_c^2, z)}{\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\text{vac}}(k_c^2, z)}$$

This simplified strategy relies on few realistic assumptions/approximations:

- $g \to c\bar{c}$ splitting function is small (→ Sudakov factor can be "linearized")
- Energy loss of gluon prior to splitting (not included) would likely increase the magnitude of the enhancement

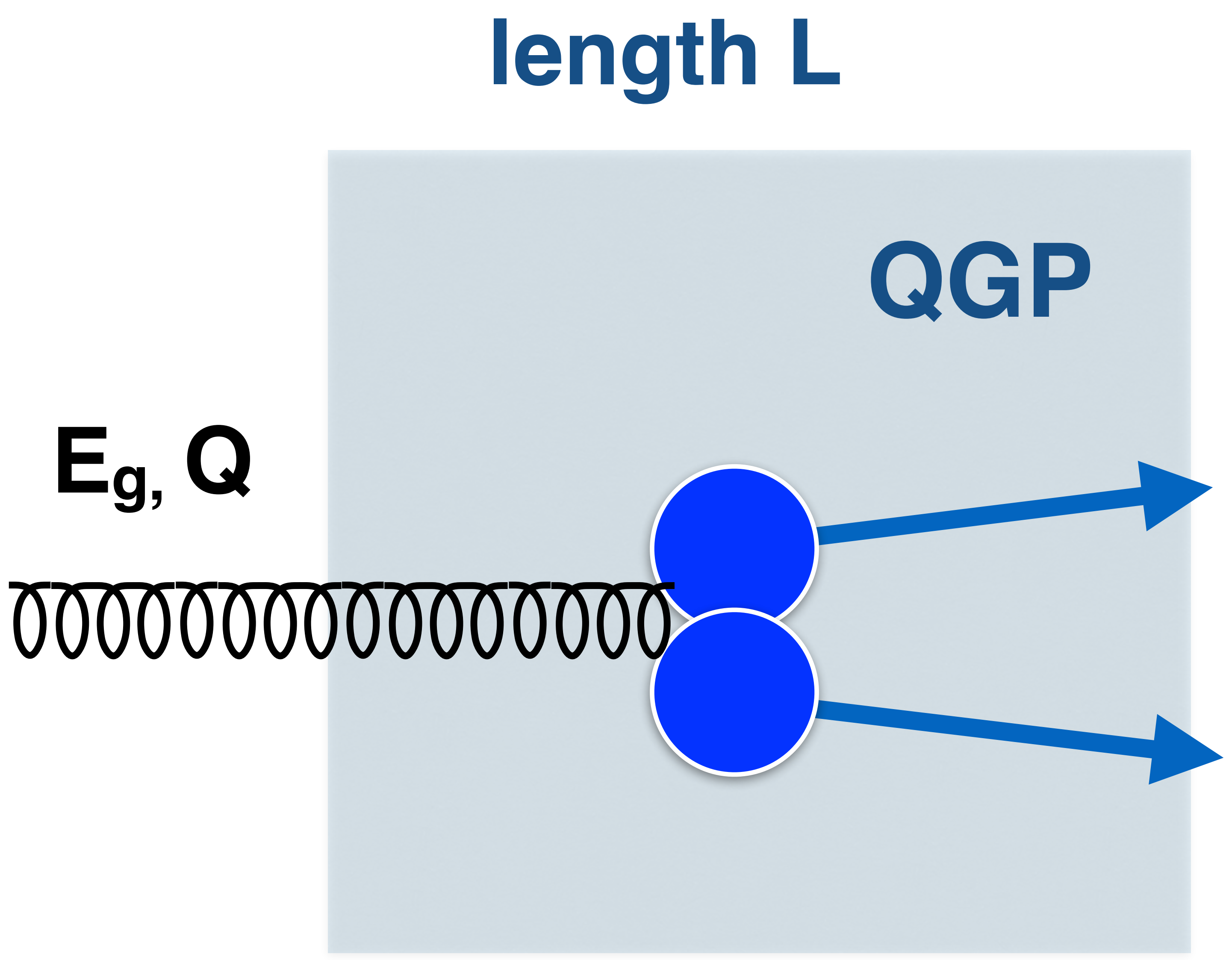
→ **Modifications of $c \to cg$ splittings not relevant for this observable (integrated in D^0, $\overline{D}^0$ pT)**

$P^{med}_{g\to c\bar{c}}$: formation time

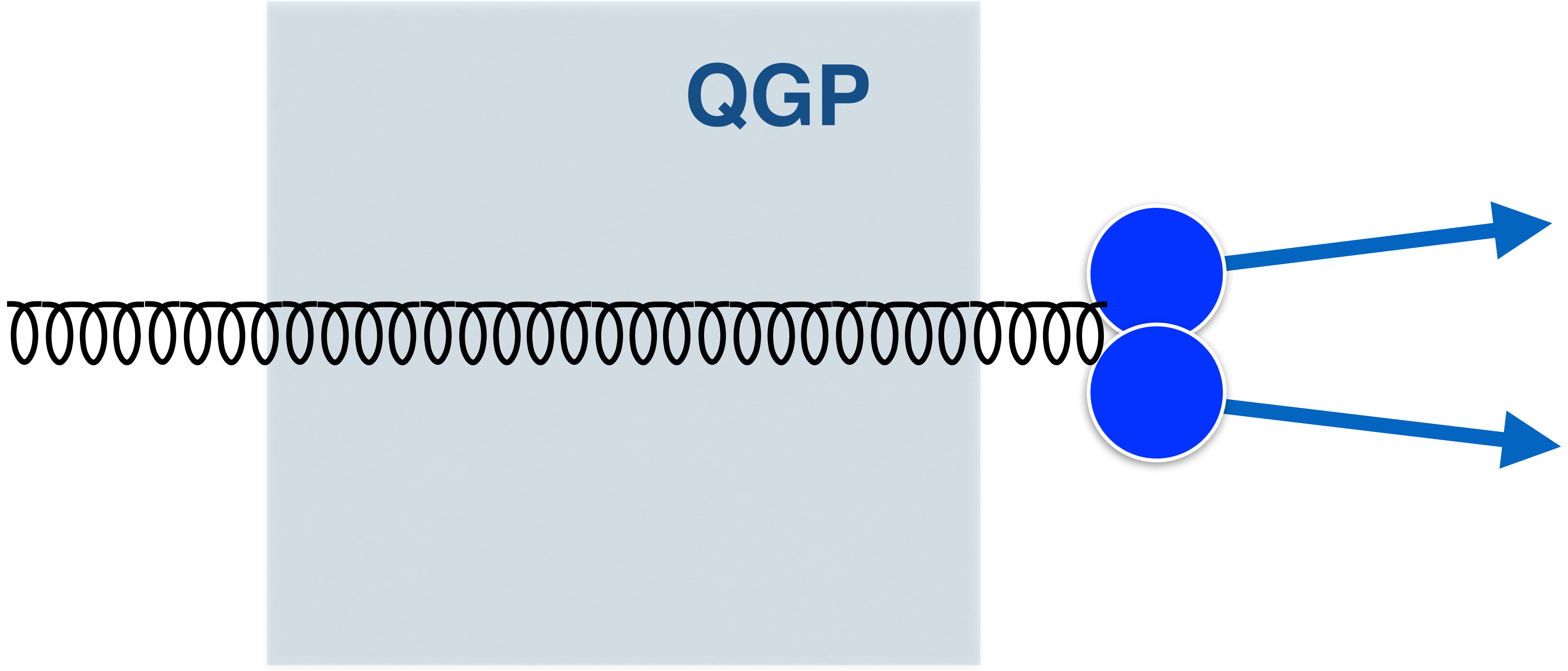
The BDMPS-Z calculation of $P^{med}_{g\to c\bar{c}}$ reveals the same formation-time argument:

$$\tau^{rest}_{g\to c\bar{c}} \sim \frac{1}{Q}$$ → **"formation time"**

$$\tau^{lab}_{g\to c\bar{c}} \sim \frac{1}{Q}\frac{E_g}{Q} = \frac{E_g}{Q^2}$$

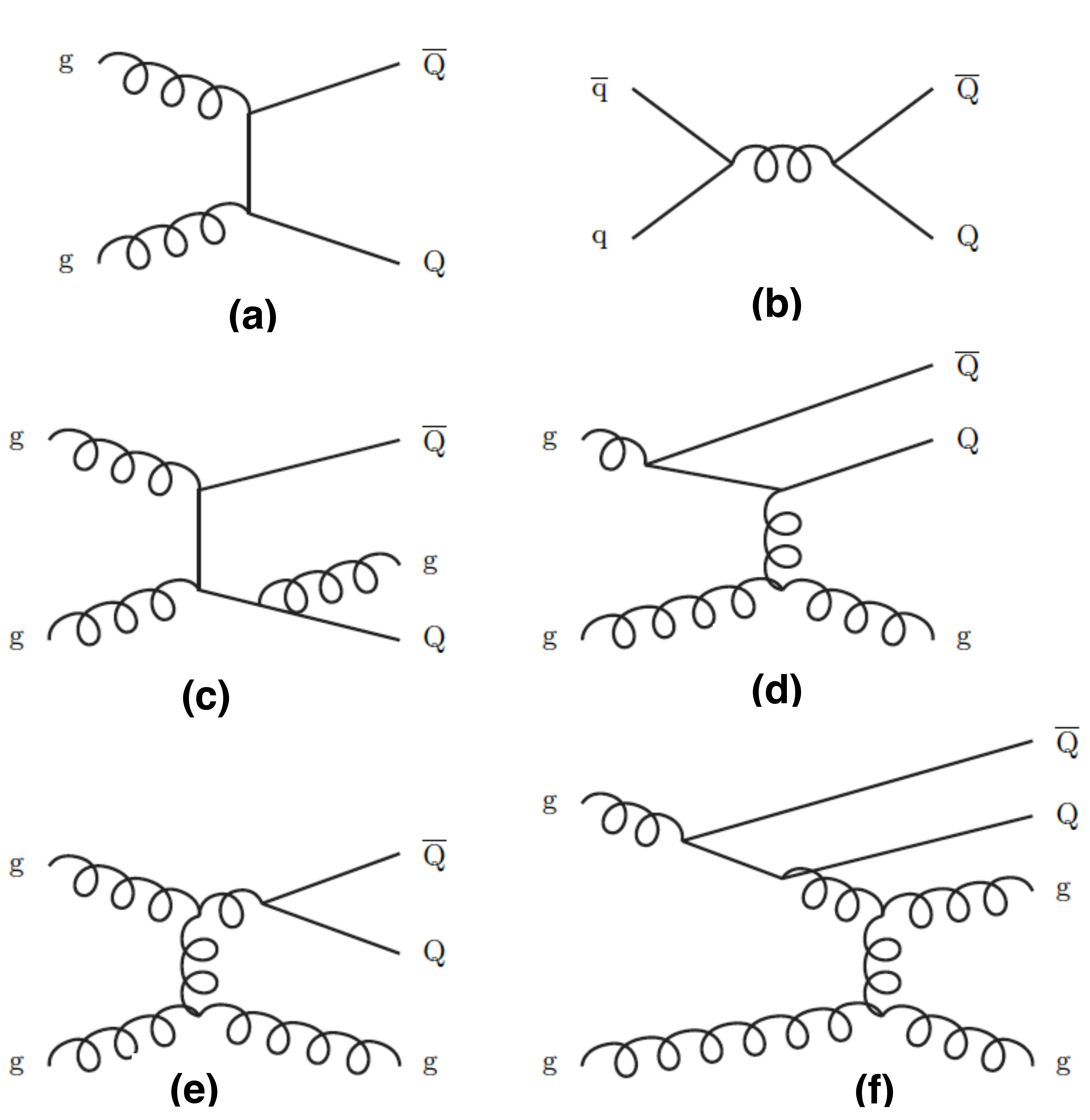


$$P^{med}_{g\to c\bar{c}} \neq P^{vac}_{g\to c\bar{c}}$$



$$P^{med}_{g\to c\bar{c}} \xrightarrow{\tau_{g\to c\bar{c}} \gg L} P^{vac}_{g\to c\bar{c}}$$

Heavy-flavour production in the parton shower approach



E. Norrbin, T. Sjöstrand, Eur. Phys. J. C17, 137–161

Not an exact $\mathcal{O}(\alpha_s^3)$, but it catches the leading-log aspects of the multiple-parton-emission phenomenon.

- hard scattering, short-distance, 2→2 process
- three classes of events: pair creation, flavour excitation, gluon splitting

(a,b) Leading order $\mathcal{O}(\alpha_s^2)$ flavour creation:

- $gg \rightarrow Q\bar{Q}$, $q\bar{q} \rightarrow Q\bar{Q}$
- $gg \rightarrow Q\bar{Q}$ dominant LO mechanism at LHC energies
  → **back-to-back $\mathrm{Q\bar{Q}}$ pairs**

(c) Pair creation (with gluon emission)

(d) Flavour excitation (with gluon emission): HF from the PDF of one beam particle is put on mass shell by scattering against a parton of the other beam. ~ DGLAP $g \rightarrow Q\bar{Q}$ process.

- hard scale of the scattering $Q^2 \gtrsim m^2_c$
  → **~ uniform ΔΦ distribution of $\mathrm{Q\bar{Q}}$ pairs**

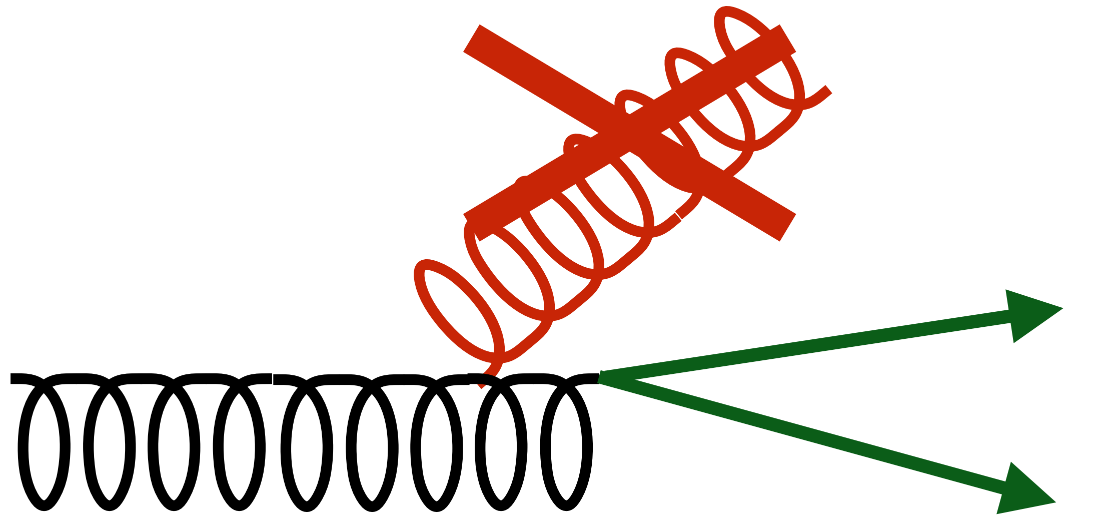
(e) gluon splitting
→ **peaked at ΔΦ = 0**

(f) Events classified as gluon splitting but of flavour-excitation character: a gluon first branches to QQ and the Q later emits another gluon that is the one to enter the hard scattering

Embedding $P^{\mathrm{med}}_{g\to c\bar{c}}$ in Pythia parton showers

Parton showers use parton splitting functions to evaluate branching probabilities at each splitting:

→ **reweighting procedure based on modification of the Sudakov factor *S* (→no splitting probability)**



$\mathbf{S^{tot}_{g\to X}}$

No-splitting probability g→X

$\mathbf{(1 - S^{tot}_{g\to c\bar{c}})}$

Splitting probability g → c$\bar{c}$

$$\frac{P^{medium}_{g\to c\bar{c}}}{P^{vacuum}_{g\to c\bar{c}}} = \frac{(1 - S^{tot}_{g\to c\bar{c}})\, S^{tot}_{g\to X}}{(1 - S^{vac}_{g\to c\bar{c}})\, S^{vac}_{g\to X}} \sim 1 + \frac{\int dQ^2 \int dz \left(\frac{1}{Q^2} P_{g\to c\bar{c}}\right)^{\mathrm{med}}}{\int dQ^2 \int dz \left(\frac{1}{Q^2} P_{g\to c\bar{c}}\right)^{\mathrm{vac}}}$$

$\frac{S^{tot}_{g\to X}}{S^{vac}_{g\to X}}$ → $1 - \mathcal{O}(\alpha_s)$

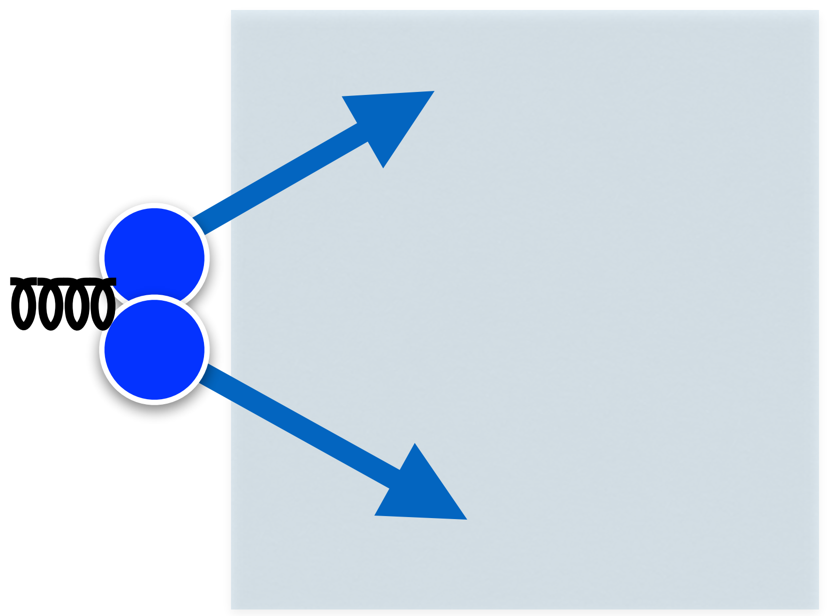
$P^{\mathrm{medium}}_{g\to c\bar{c}}$, $P^{\mathrm{medium}}_{g\to c\bar{c}}$ are small

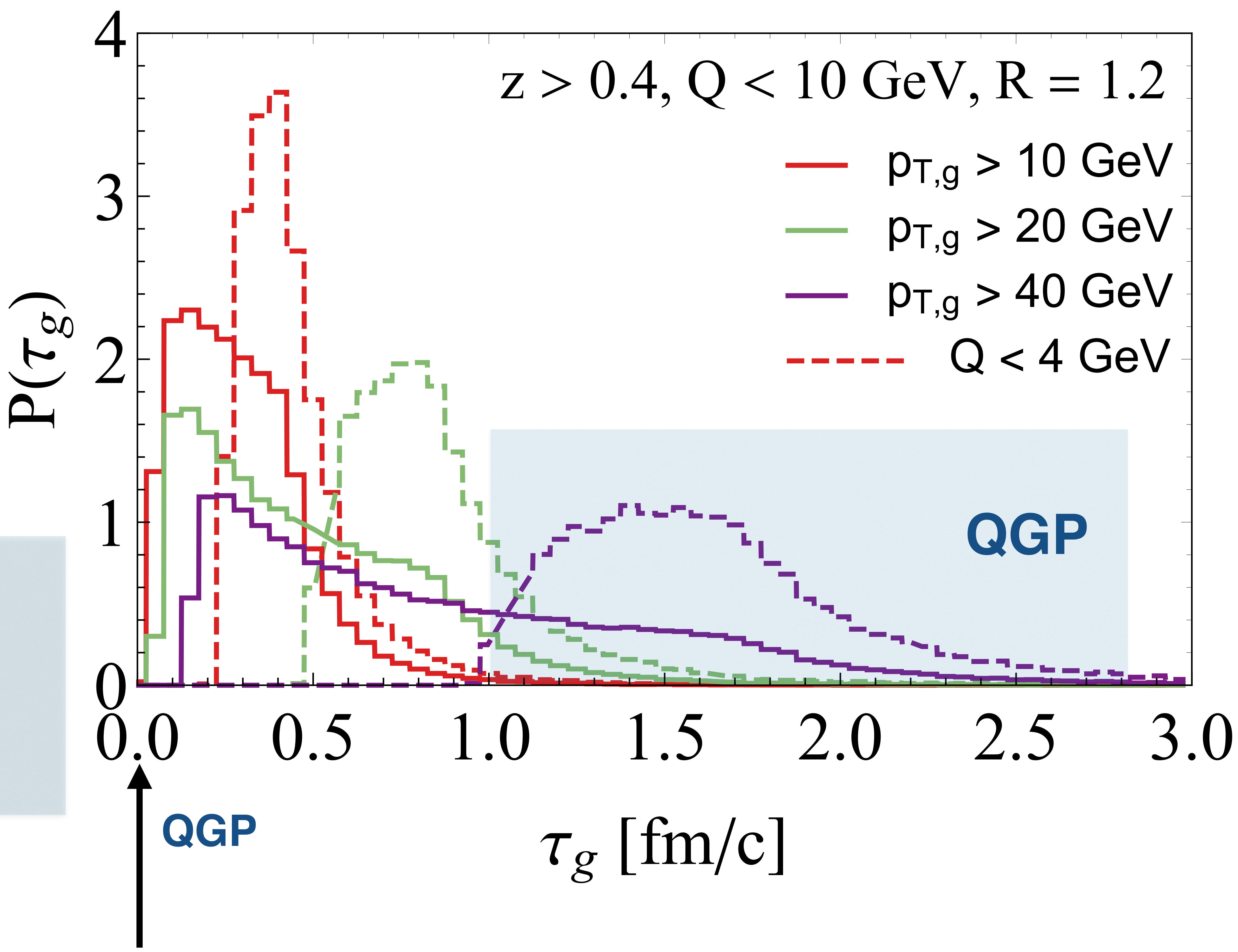
$$w^{med}_{g\to c\bar{c}}(E_g, k_c^2, z) = 1 + \frac{\left(\frac{1}{Q^2} P_{g\to c\bar{c}}\right)^{\mathrm{med}}(E_g, k_c^2, z)}{\left(\frac{1}{Q^2} P_{g\to c\bar{c}}\right)^{\mathrm{vac}}(k_c^2, z)}$$

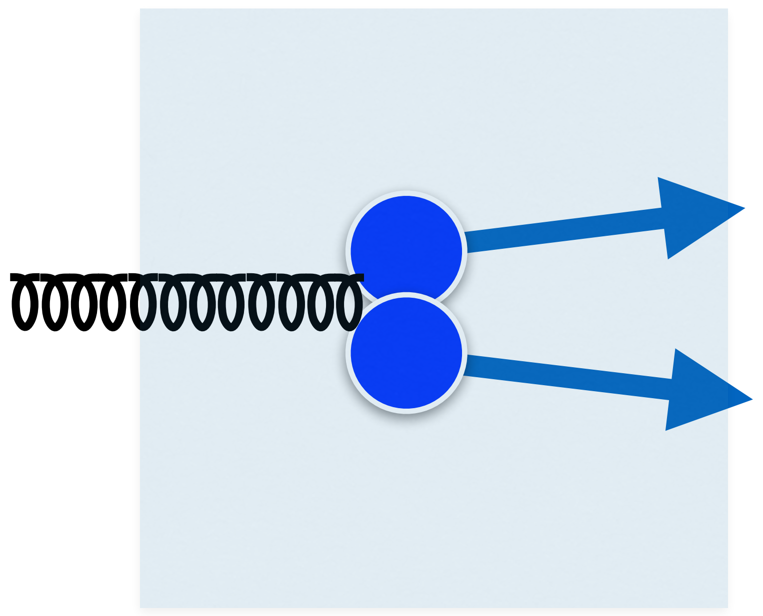
For each g → c$\bar{c}$ splitting:

- reconstruct the gluon kinematics via $c\bar{c}$ pair (e.g. $\mathrm{E_g} = \mathrm{E_c} + \mathrm{E_{\bar{c}}}$)
- calculated and apply $w^{med}_{g\to c\bar{c}}(E_g, k_c^2, z)$ to each splitting
  → **N.B. it does not account for c-quark energy loss**

Formation time of $g \to c\bar{c}$ splittings





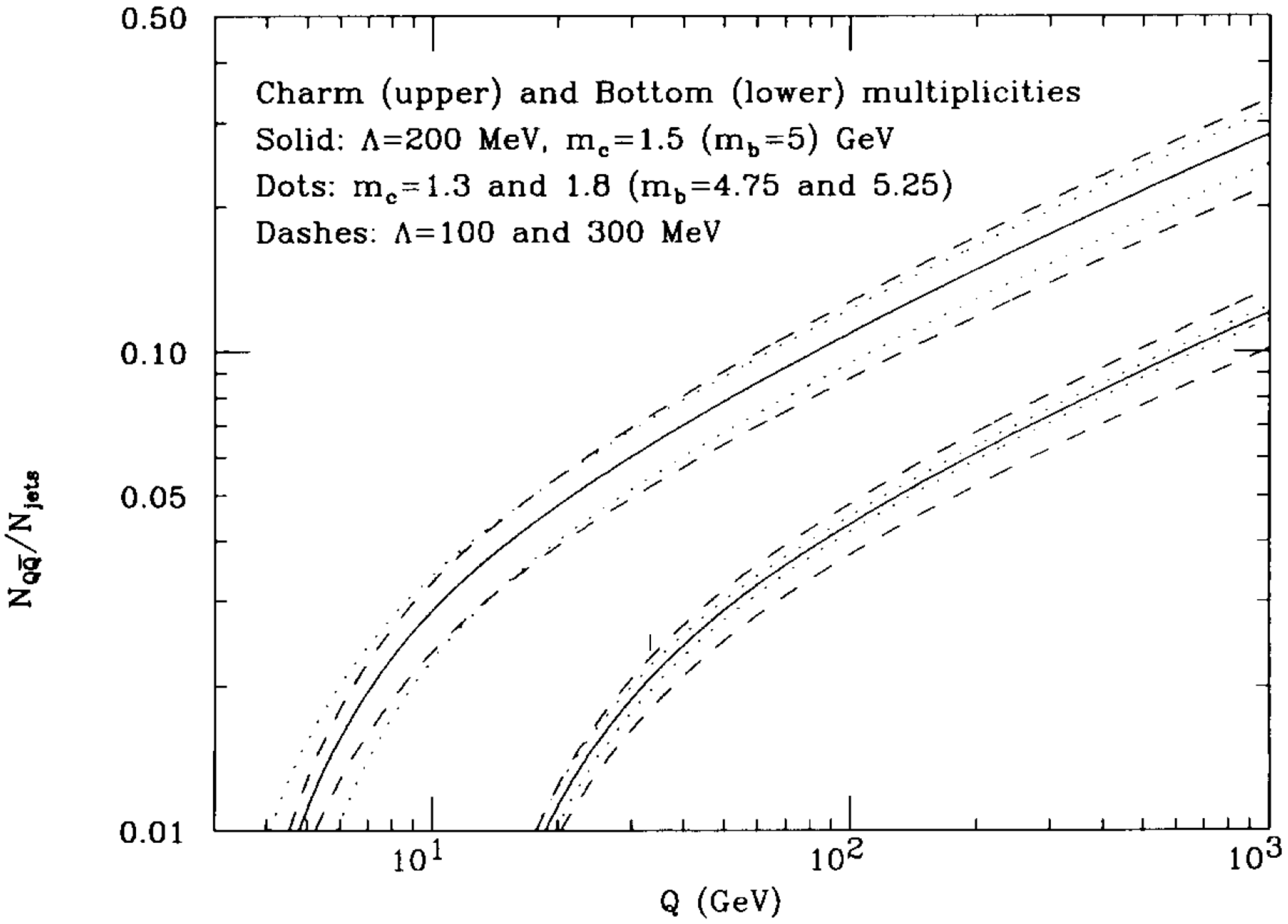


Dominant HQ production mechanisms are short-distance

- At threshold $\tau_g \sim 1/2m_c = 0.07$ fm/c

$N^{c\bar{c}}_{jets}/N_{jets}$ to constrain charm mass in pQCD

M. Mangano, P. Nason, Physics Letters B 285 (1992) 160-166



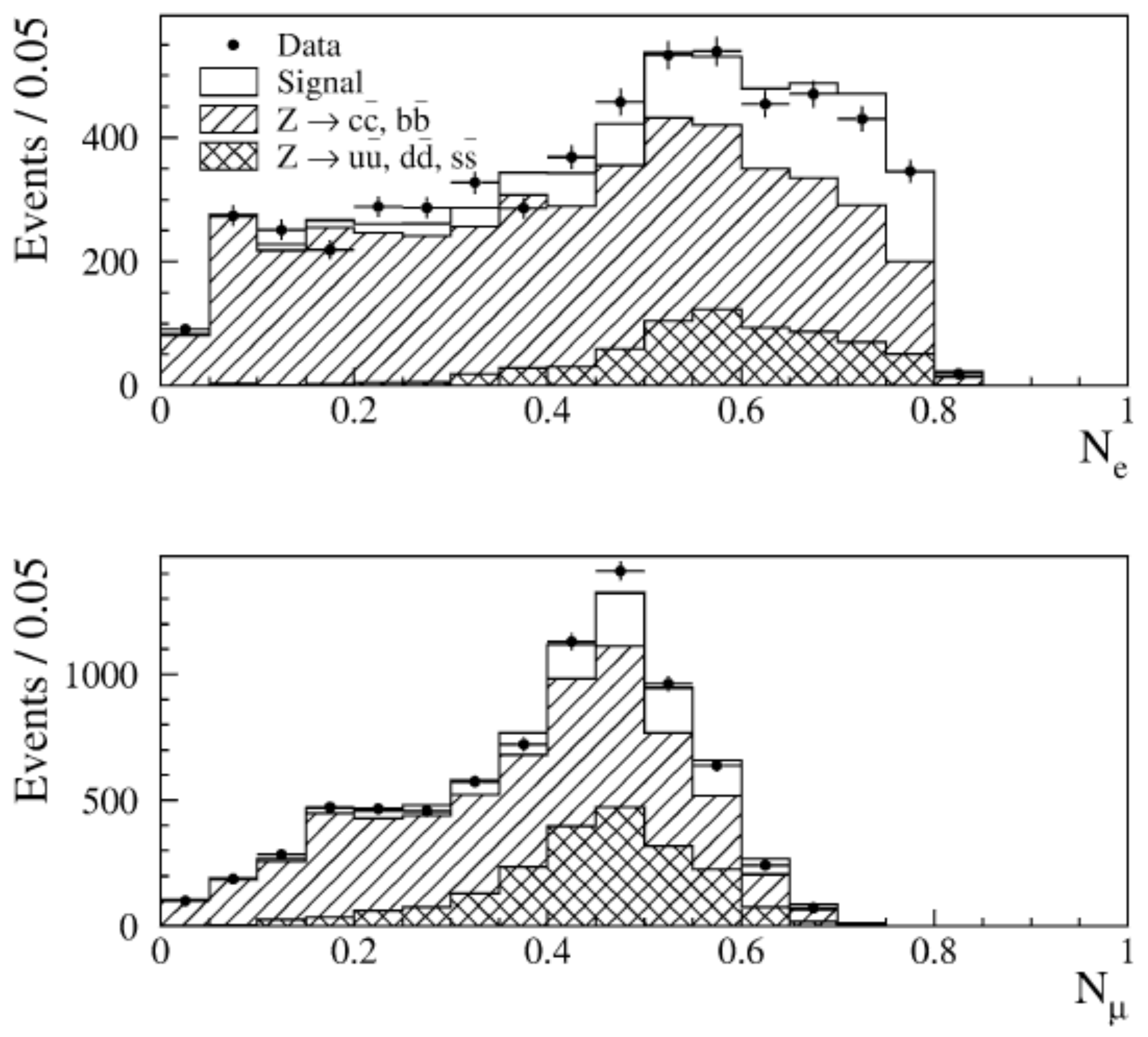
$g \to c\bar{c}$ splitting rate in ALEPH

→ measurement of the production rate of $c\bar{c}$ pairs from gluons in hadronic Z decays

ALEPH, Phys. Lett. B 561:213-224 (2003)

$$g_{c\bar{c}} = \frac{N(Z \to q\bar{q}g),\, g \to c\bar{c}}{N(Z \to \text{hadrons})}$$

ALEPH Collaboration / Physics Letters B 561 (2003) 213–224



- $g_{c\bar{c}}$ is an important test of perturbative QCD at the Z scale
- $g \to c\bar{c}$ is a background for heavy-quark analyses and for Higgs-boson searches
- $g_{c\bar{c}}$ was at that time predicted to be large, from 1.4% to 2.5%

→ **semileptonic (e,μ) decays of the c quarks from gluon splitting in the lowest energy jet of a three jet event**

$$g^{e}_{c\bar{c}} = \big(3.32 \pm 0.28(\text{stat}) \pm 0.42(\text{syst})\big)\%$$

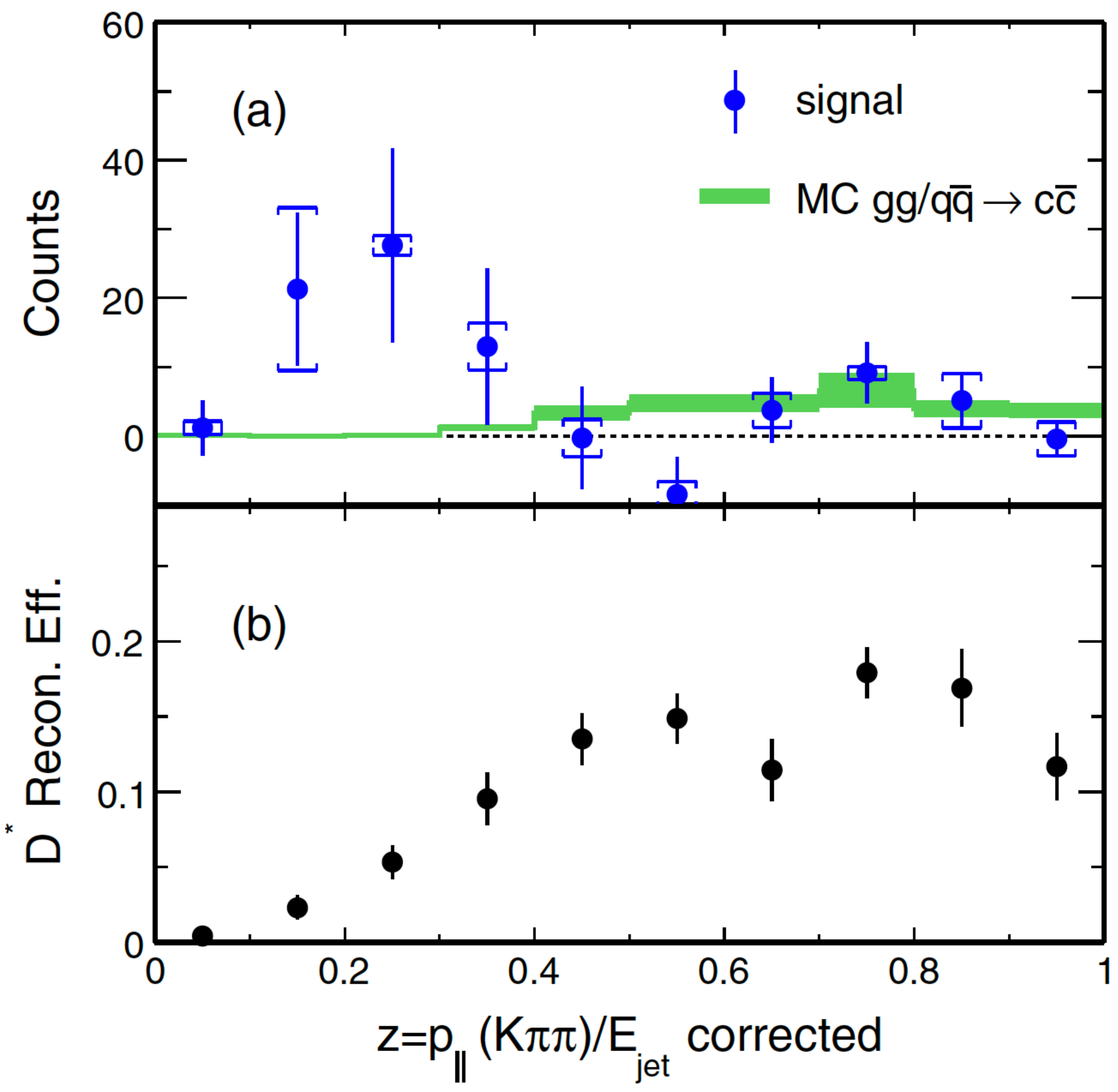
$$g^{\mu}_{c\bar{c}} = \big(2.99 \pm 0.38(\text{stat}) \pm 0.72(\text{syst})\big)\%$$

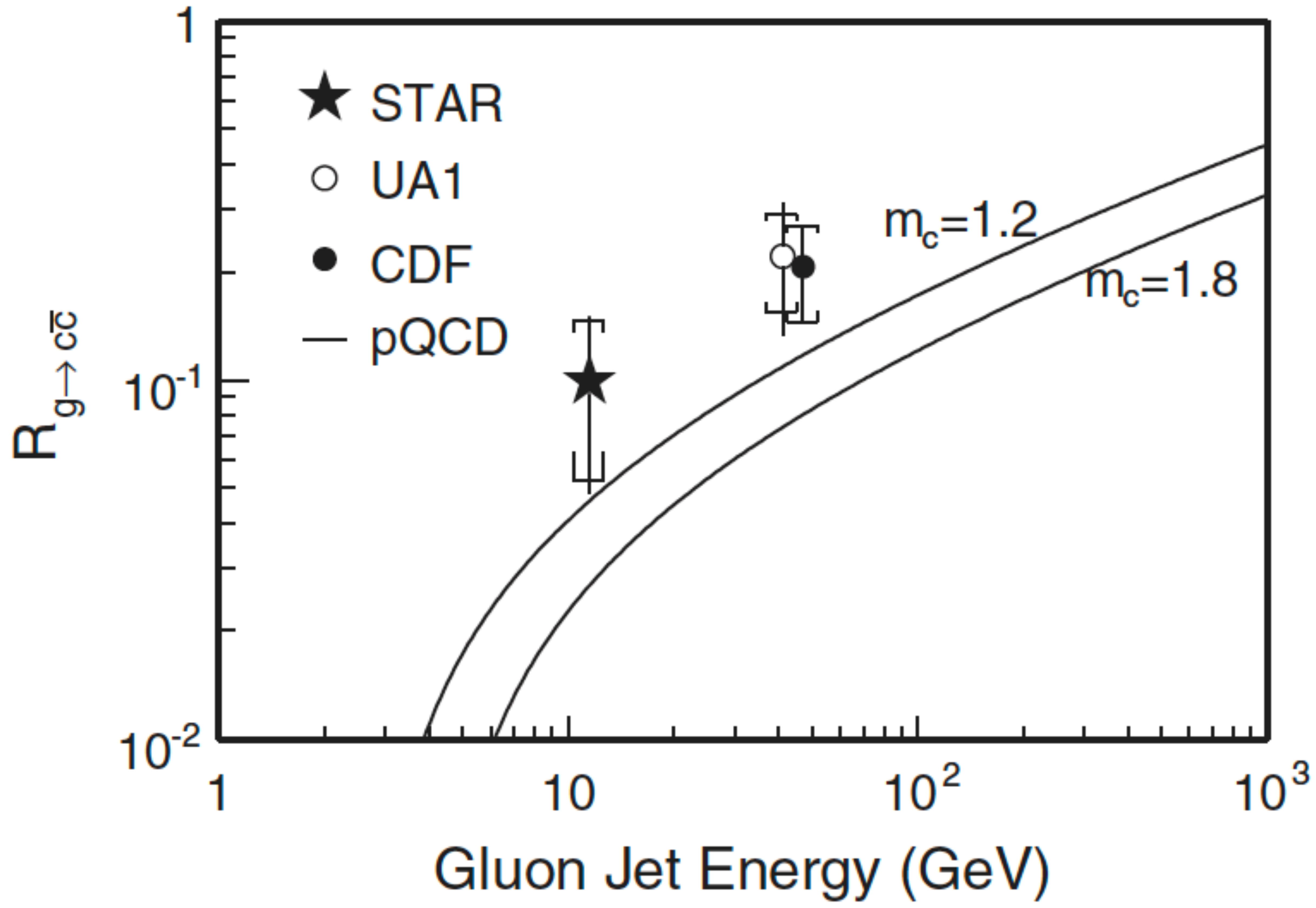
$$g_{c\bar{c}} = \big(3.26 \pm 0.23(\text{stat}) \pm 0.42(\text{syst})\big)\%$$

D* and lepton → **OPAL**, Eur. Phys. J. C 13 (2000) 1
D* → **ALEPH**, Eur. Phys. J. C 16 (2000) 597
lepton/event shape → **L3**, Phys. Lett. B 476 (2000) 243

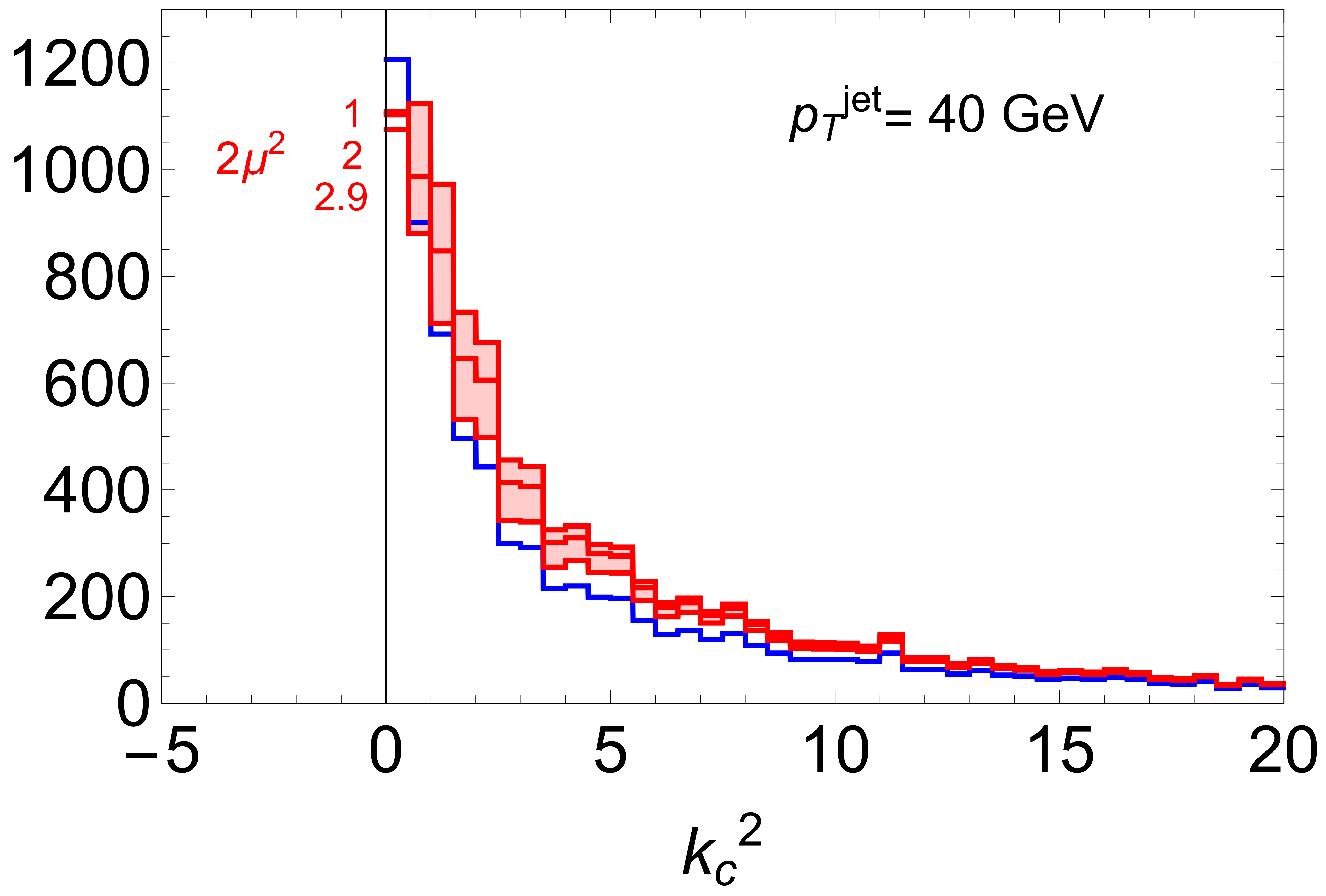
$R_{g\to c\bar{c}}$ in pp collisions at RHIC

STAR Collaboration, Phys.Rev.D79:112006 (2009)





In-medium broadening of g → $c\bar{c}$

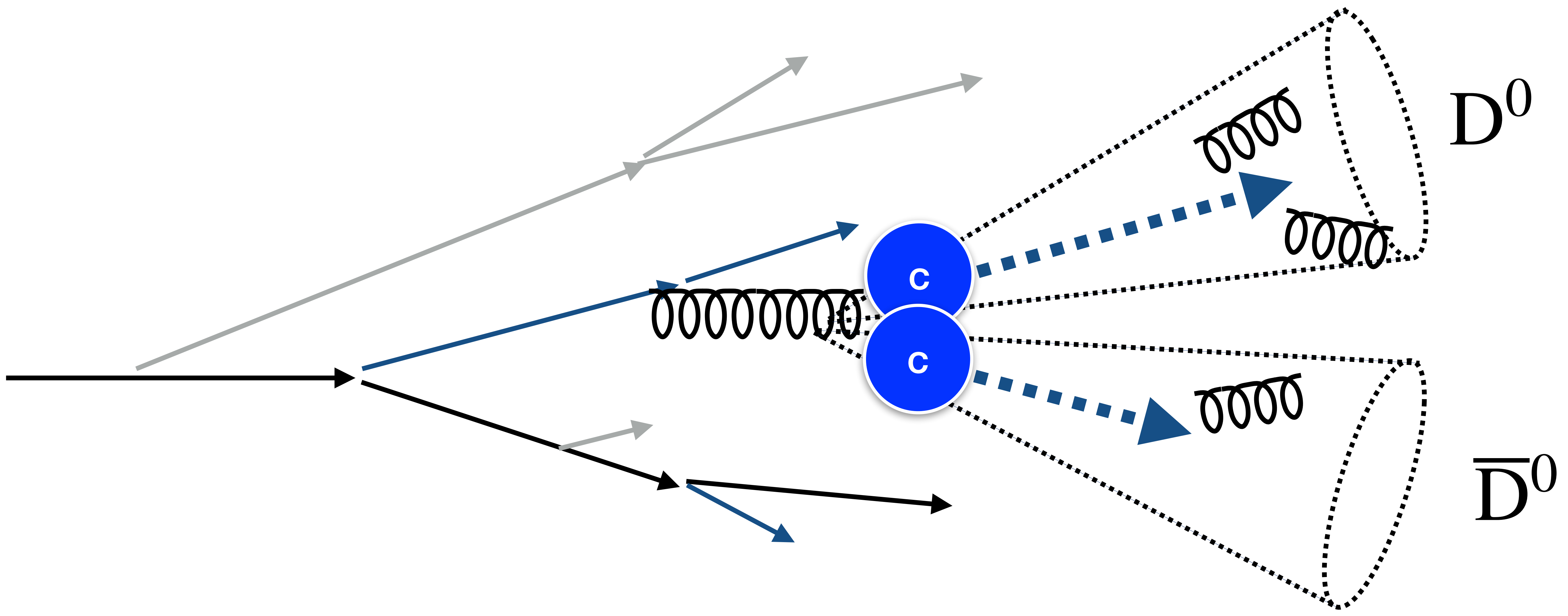


→ **in-medium path length dependence of transverse momentum broadening (<k^2_c> ~ $\hat{\bar{q}}$L)**

→ Paper in preparation!

Modified $c\bar{c}$-yields in parton showers

Parton showers use parton splitting functions to evaluate branching probabilities at each splitting:
→ **ideal setup:** parton-shower simulation that include all in-medium modified splitting functions



$$P^{vac}_{g\to gg}(z),\quad P^{vac}_{q\to qg}(z),\quad P^{vac}_{g\to q\bar{q}}(z),\quad P^{vac}_{g\to c\bar{c}}(z)$$

$$\downarrow$$

$$P^{med}_{g\to gg}(z),\quad P^{med}_{q\to qg}(z),\quad P^{med}_{g\to q\bar{q}}(z),\quad P^{med}_{g\to c\bar{c}}(z)$$

Under the following hypotheses:

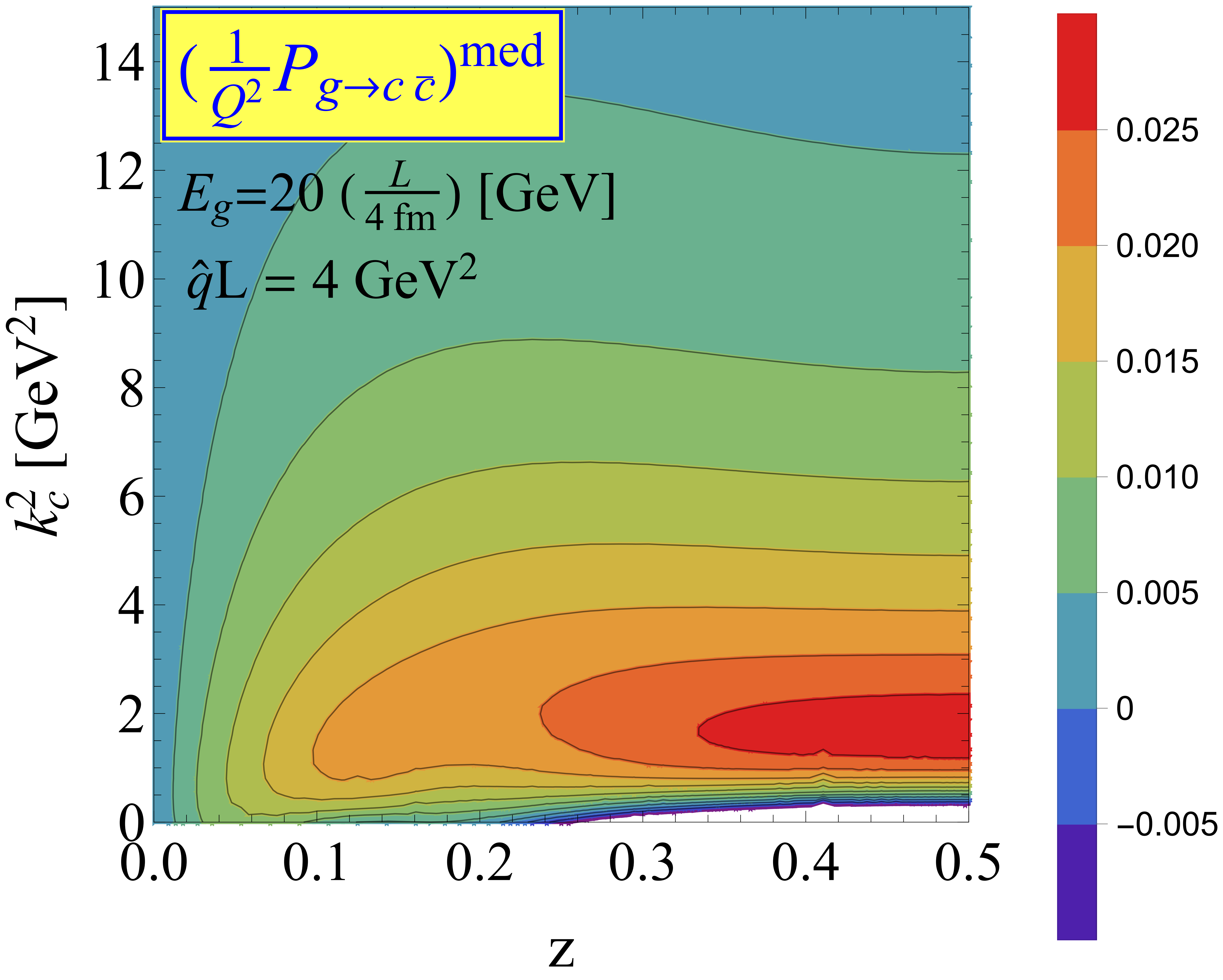
- $g \to c\bar{c}$ is a negligible process for the global shower evolution
  → **ignore modifications to other splitting functions**
- induced gluon radiation is "small"
  → **effect on gluons before the splitting is negligible**
- limit to charm p_T-integrated observables
  → **ignore the energy loss of individual quarks**

→

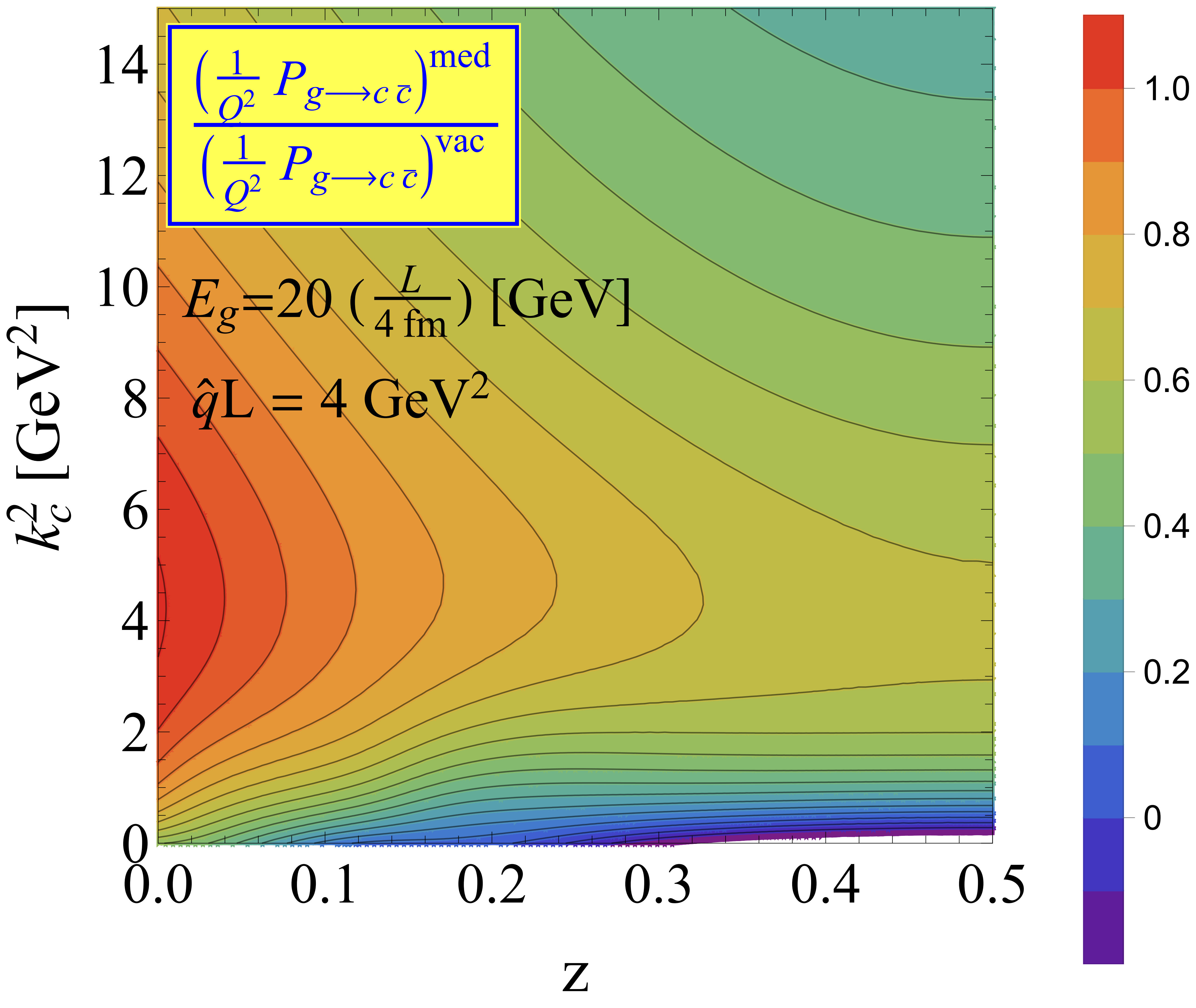
Reweight only the properties of the $g \to c\bar{c}$ splittings:

$$P^{medium}_{g\to c\bar{c}} = 1 + \boxed{P^{mod}_{g\to c\bar{c}}/P^{vac}_{g\to c\bar{c}}}$$

$P^{med}_{g\to c\bar{c}}$: broadening and enhancement



Numerical values for $\mathrm{P^{med}_{g\to c\bar{c}}/P^{vac}_{g\to c\bar{c}}}$



$\mathrm{P^{med}_{g\to c\bar{c}}}$ **in multiple soft scattering limit expressed in terms of:**

- $\hat{q}L$ → dimension of a squared momentum [GeV^2]
- $e_g, z, \tilde{m}_c{}^2, \tilde{k}_c{}^2$ → dimensionless

$$e_g = \frac{2E_g}{\hat{q}L^2}\,, \quad \tilde{m}_c^2 = \frac{m_c^2}{\hat{q}L}\,, \quad \tilde{k}_c^2 = \frac{k_c^2}{\hat{q}L}\,, \quad \tilde{\Omega} = \Omega L\,, \quad \tilde{\mu} = \frac{\mu}{\hat{q}L^2}$$

- To facilitate the physics interpretation of the result we present them at a given $\hat{q}L$, and for Eg=(20 L/4fm)

As an example

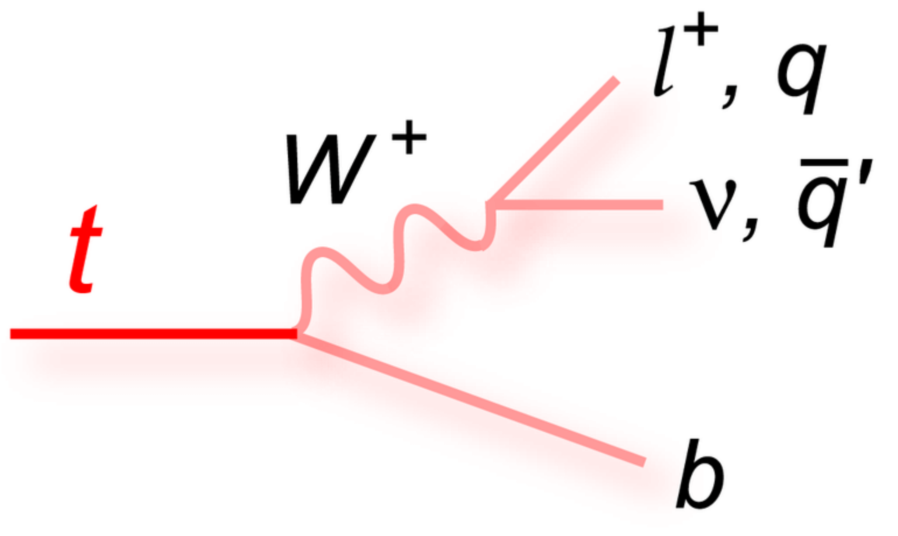
- $\hat{q}$=1(2) GeV^2
- L =4(2) GeV^2 ⟶ **E_g= 20(10) GeV**
- $\hat{q}$L=4(4) GeV^2
- $\hat{q}L^2$= 8 GeV^2

Yoctosecond structure of the QGP with top quarks

→ study differentially the space-time evolution of the medium created in heavy ion collisions

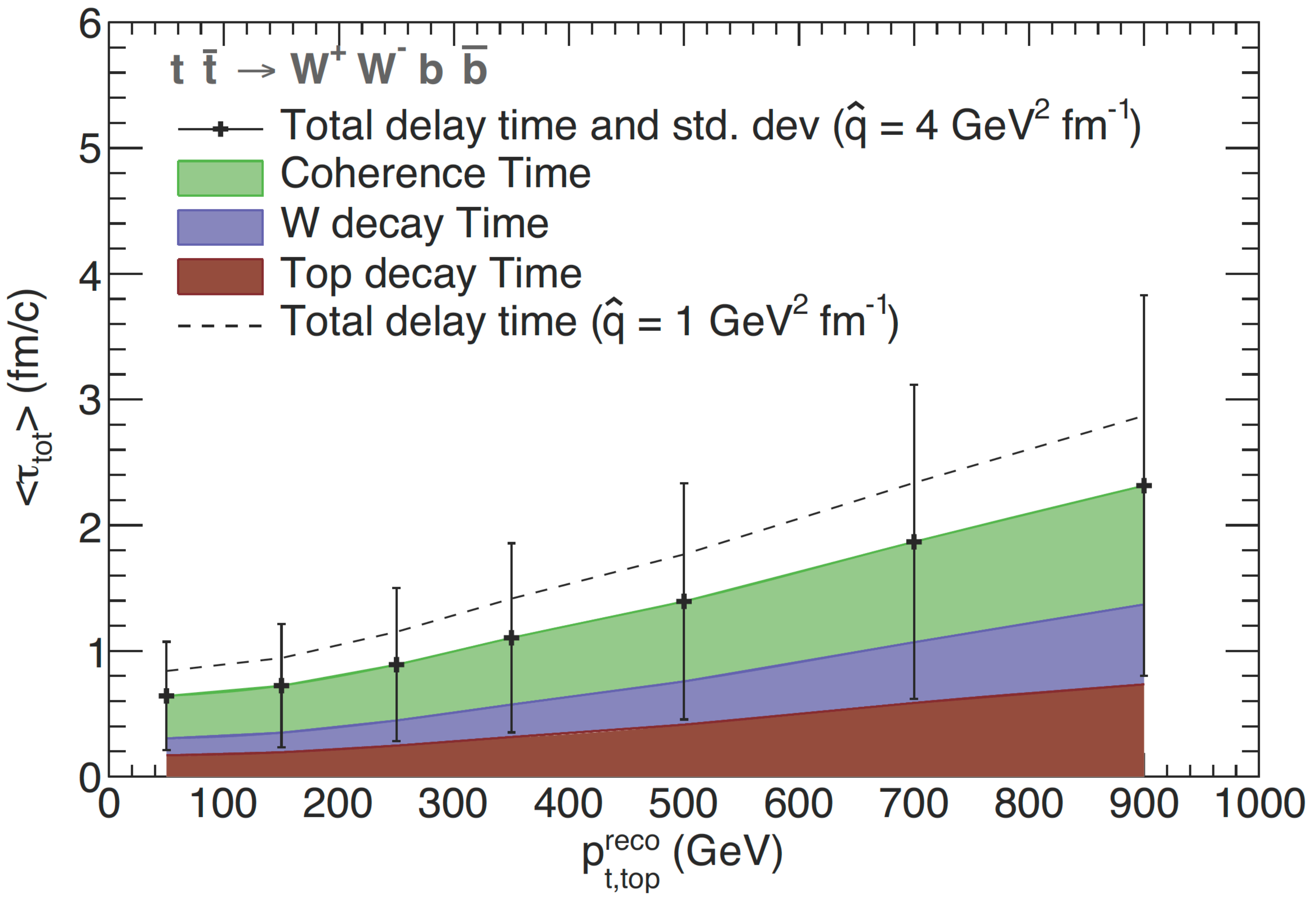
L. Apolinário, J.G. Milhano, G. P. Salam, C. A. Salgado,
Phys. Rev. Lett. 120, 232301 (2018)

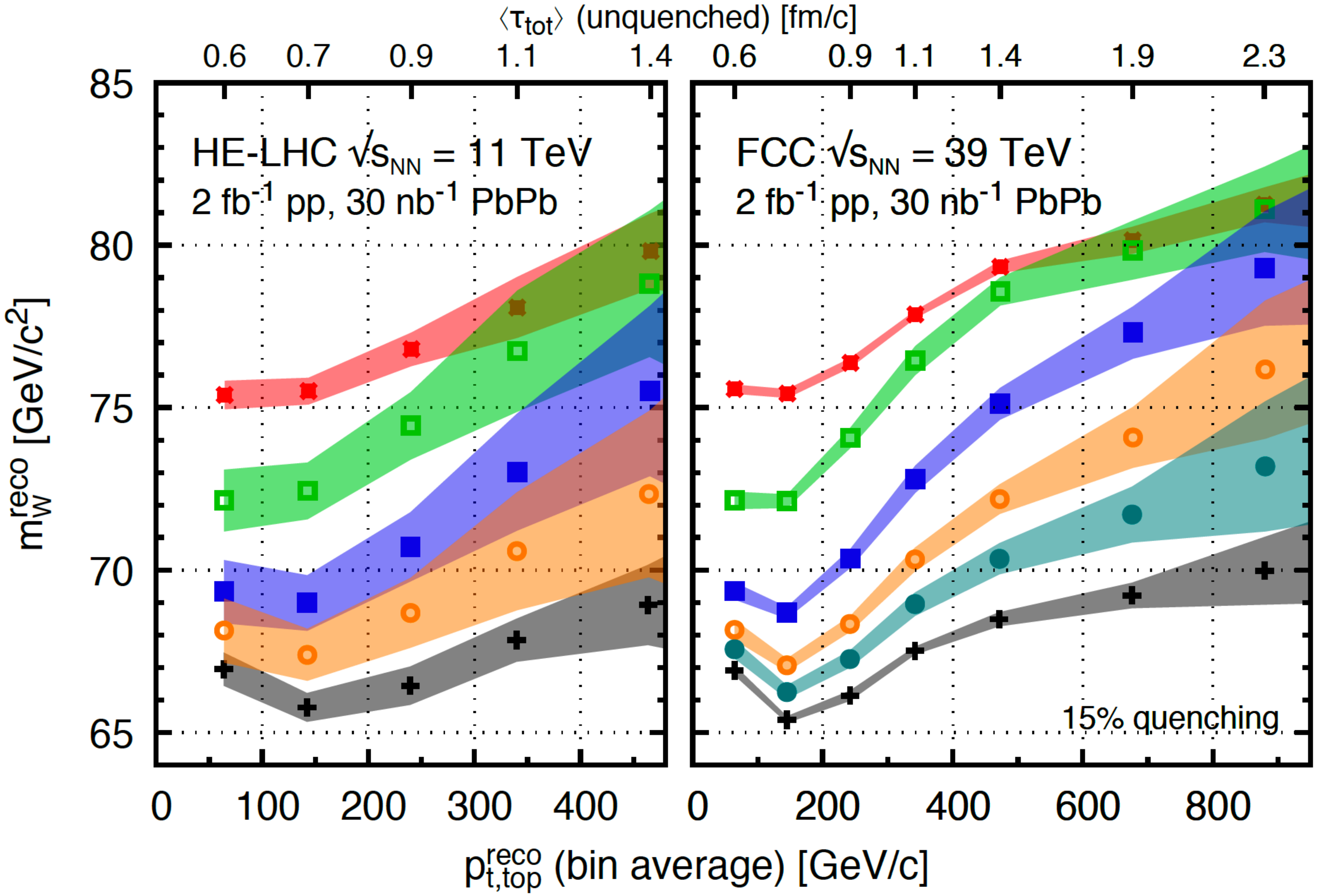
$$\langle \tau_{\rm tot} \rangle = \gamma_{t,\rm top}\tau_{\rm top} + \gamma_{t,W}\tau_W + \tau_d$$



$$\tau_d = \left(\frac{12}{\hat{q}\theta^2_{q\bar{q}}}\right)^{1/3}$$

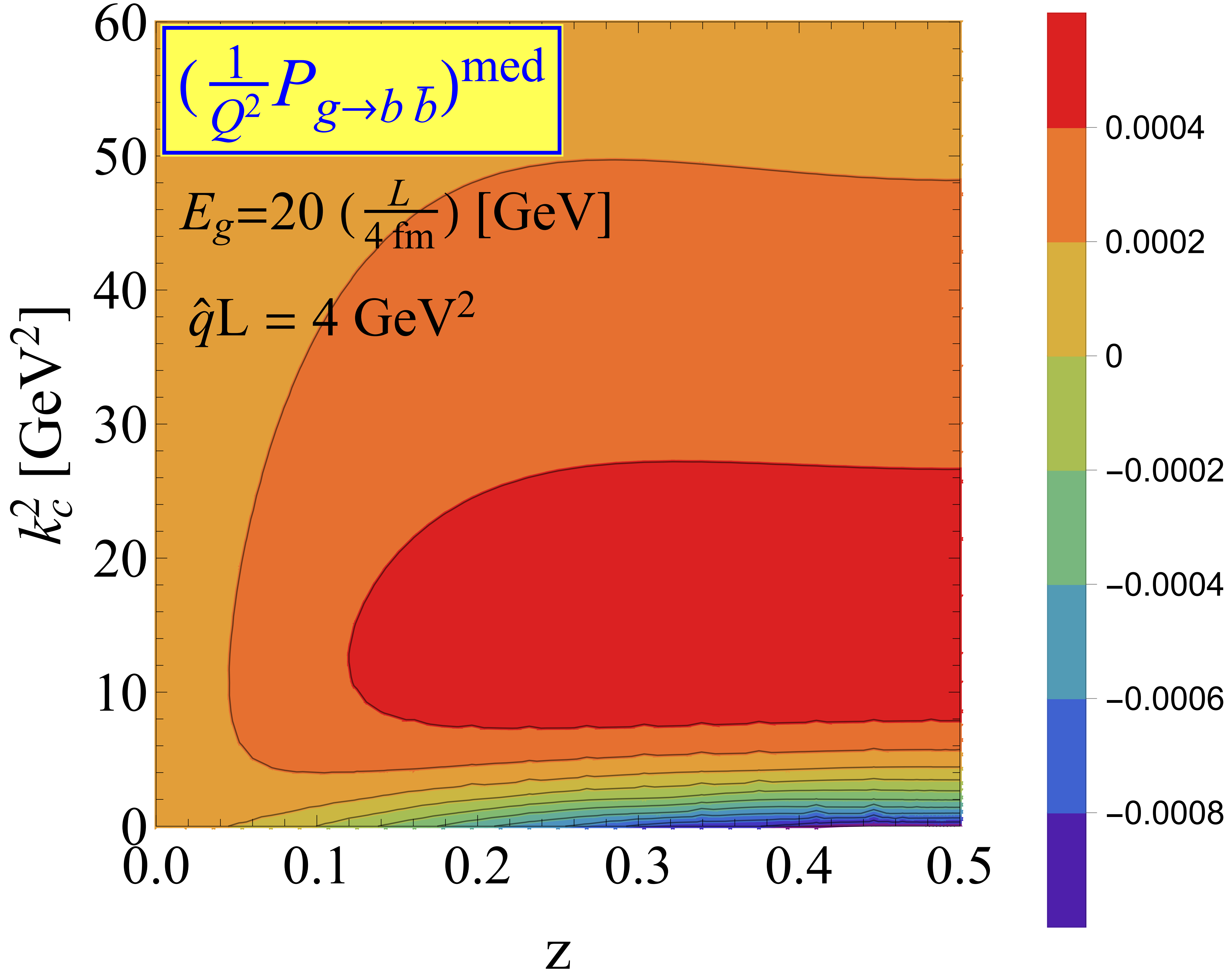
decoherence time of the $q\bar{q}$ singlet

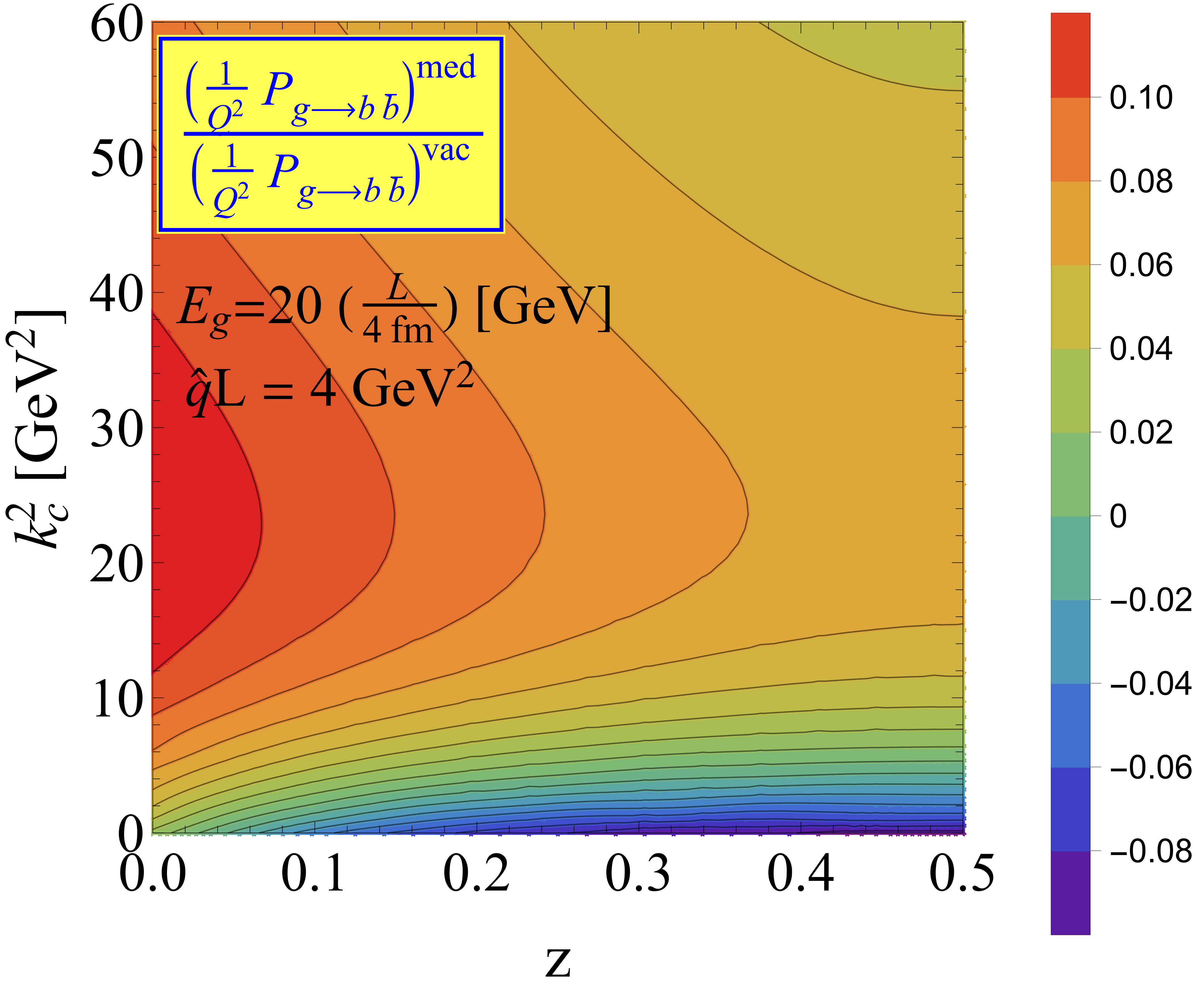




→ **effect of quenching observed via the shift in the invariant mass of the m_{jj} of the diet decays**

$g\rightarrow b\bar{b}$ splittings





$$\frac{P^{med}_{g\to b\,\bar{b}}}{P^{vac}_{g\to b\,\bar{b}}} \sim \frac{m_c^2}{m_b^2}\frac{P^{med}_{g\to c\,\bar{c}}}{P^{vac}_{g\to c\,\bar{c}}}$$

$D^0\overline{D}^0$ correlations in ALICE 3

ALICE 3 Letter of Intent, LHCC-I-038