TMD cross-section factorization for dijet production at the EIC

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Outline

Dijet production

- Kinematic region
- Cross-section factorization
- New TMD Soft Function

ζ-prescription & evolution

Plots

Based on the work published by
Rafael F. del Castillo, Miguel G. Echevarría, Yiannis Makris & Ignazio Scimemi
https://arxiv.org/abs/2008.07531v4

...and following work soon to be published

Motivation

- Gluon transverse momentum dependent distributions (TMDs) are difficult to access due to the lack of clean processes where the factorization of the cross-section holds and incoming gluons constitute the dominant effect.

- We consider two processes which are presently attracting increasing attention

$$\ell + h \to \ell' + J_1 + J_2 + X \qquad \ell + h \to \ell' + H + \bar{H} + X$$

Dijet — Heavy-meson

Dominguez, Xiao, Yuan, 2013

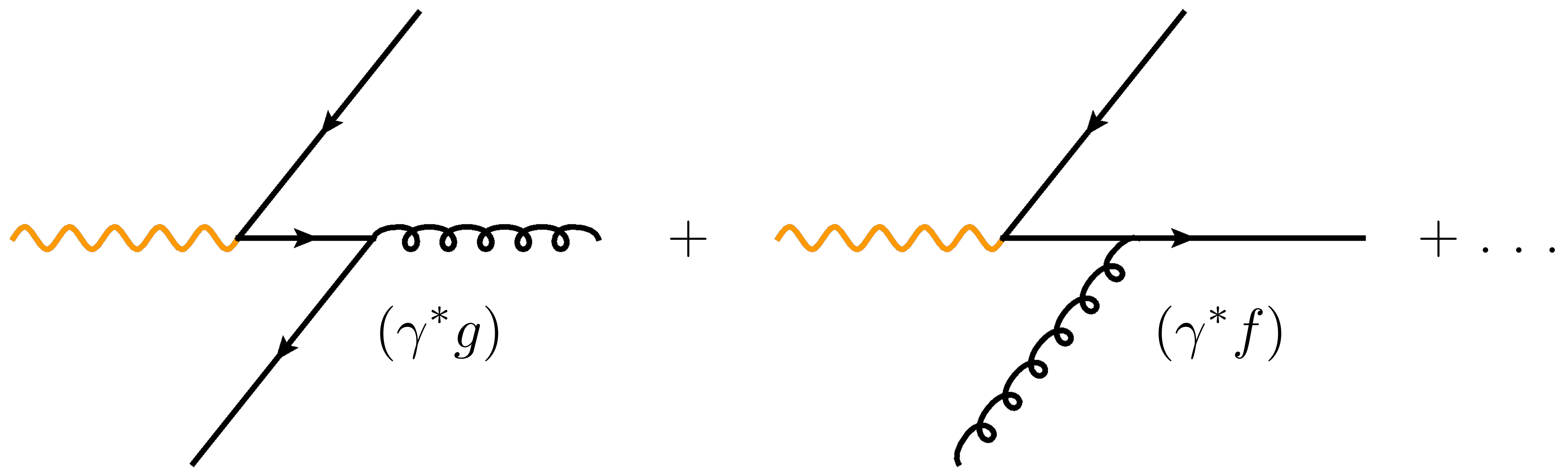
Boer, Brodsky, Mulders, Pisano, 2011

Zhang, 2017

Dijet production

$$\ell + h \to \ell' + J_1 + J_2 + X$$

dijet LO process:



- Sensitive of polarized and unpolarized TMDPDFs
- Experimental observation should be possible in the future EIC Page, Chu, Aschenauer, 2020
- Jets here described have $p_T \in [2, 40]$ GeV and are found in the central rapidity region
- Factorization within SCET

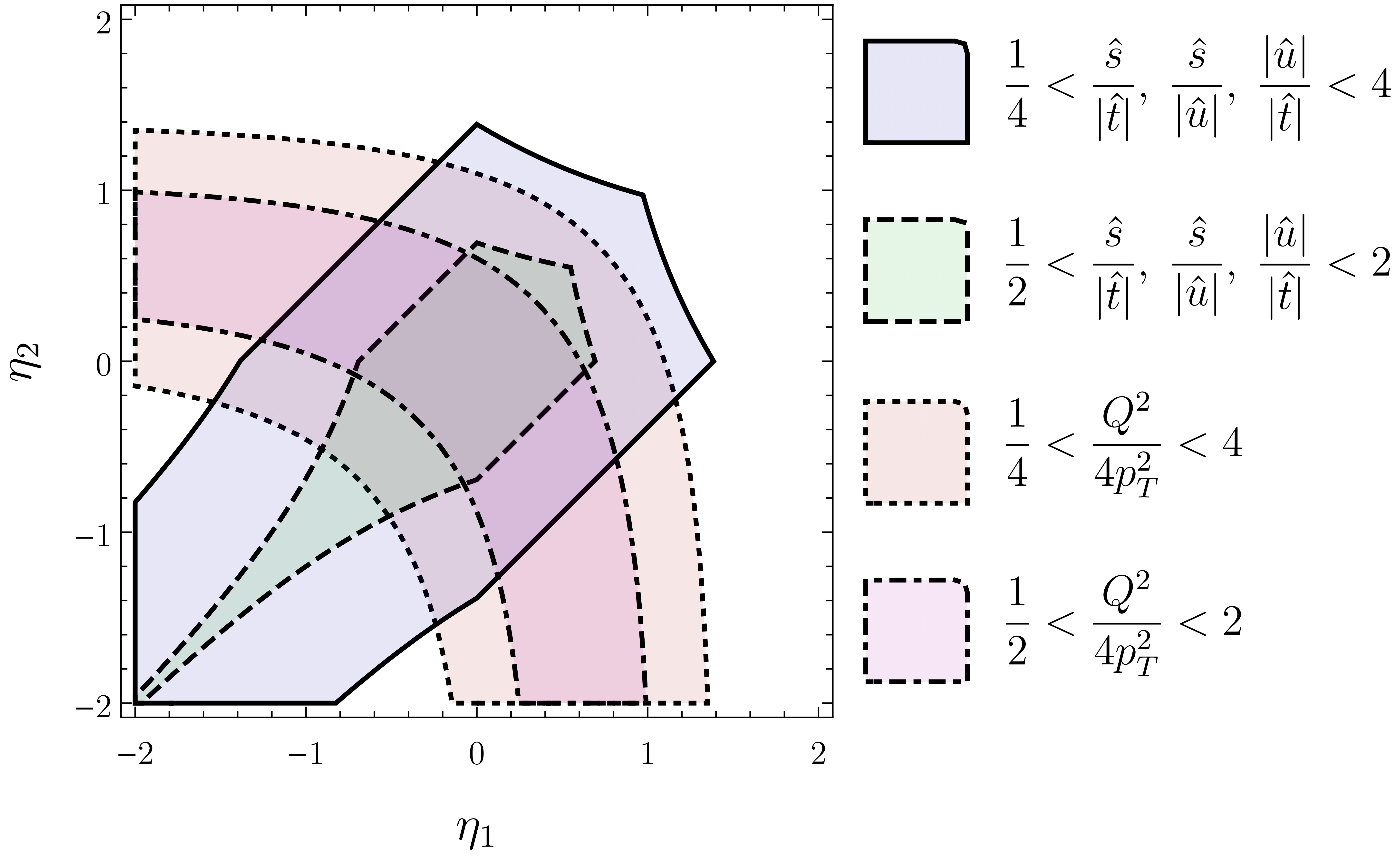
Kinematic region

Dijet production

$$\boldsymbol{r}_T = \boldsymbol{p}_{1T} + \boldsymbol{p}_{2T}$$

$$p_T = \frac{|\boldsymbol{p}_{1T}| + |\boldsymbol{p}_{2T}|}{2}$$

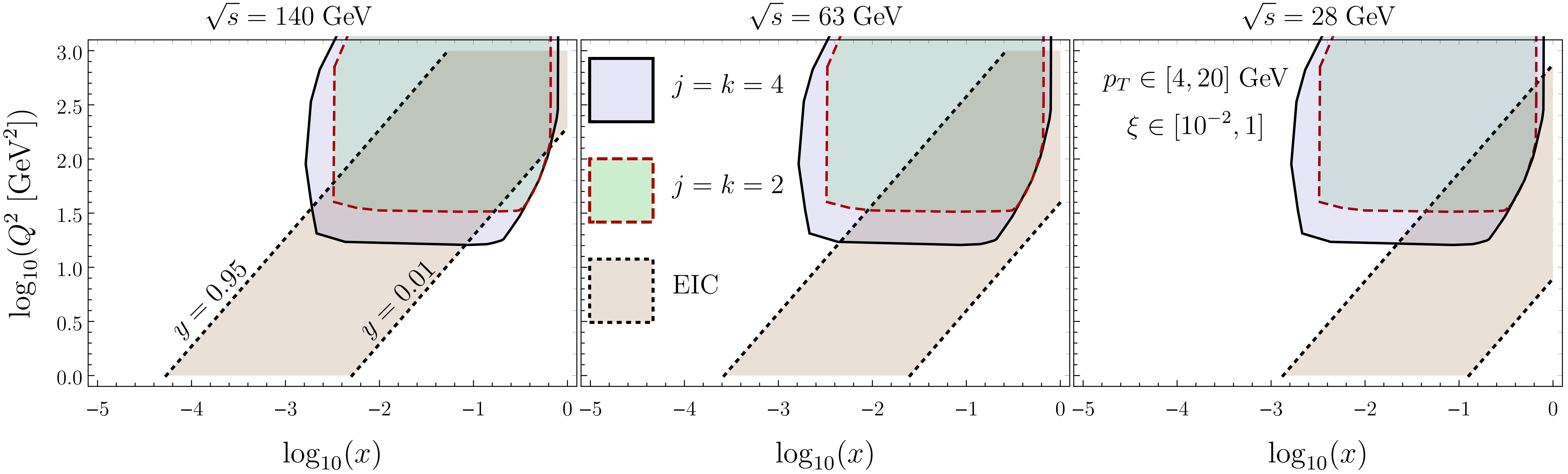
$$|\boldsymbol{r}_T| \ll p_T$$



Factorization holds for $|\boldsymbol{r}_T| \ll p_T$ and for the central rapidity region

Kinematic region vs EIC coverage

Dijet production



$$\frac{1}{j} < \frac{\hat{s}}{|\hat{t}|}, \frac{\hat{s}}{|\hat{u}|}, \frac{|\hat{u}|}{|\hat{t}|} < j \qquad \frac{1}{k} < \frac{Q^2}{4p_T^2} < k$$

Overlapping increases with higher beam energies

Cross-section factorization

Dijet production

$$\frac{d\sigma}{dx d\eta_1 d\eta_2 dp_T d\boldsymbol{r}_T}$$

We measure over

- x Bjorken variable
- η_i jet pseudorapidity
- p_T transverse momentum
- $\boldsymbol{r}_T$ transverse momentum imbalance

$(\gamma^* g)$

$$\frac{d\sigma(\gamma^* g)}{dx d\eta_1 d\eta_2 dp_T d\boldsymbol{r}_T} = \sum_f H^{\mu\nu}_{\gamma^* g \to f\bar{f}}(\hat{s},\hat{t},\hat{u},\mu) \int \frac{d^2\boldsymbol{b}}{(2\pi)^2} \exp(i\boldsymbol{b}\cdot\boldsymbol{r}_T) F_{g,\mu\nu}(\xi,\boldsymbol{b},\mu,\zeta_1)$$
$$\times S_{\gamma g}(\boldsymbol{b},\eta_1,\eta_2,\mu,\zeta_2)\Big(\mathcal{C}_f(\boldsymbol{b},R,\mu)J_f(p_T,R,\mu)\Big)\Big(\mathcal{C}_{\bar{f}}(\boldsymbol{b},R,\mu)J_{\bar{f}}(p_T,R,\mu)\Big)$$

$(\gamma^* f)$

$$\frac{d\sigma^U(\gamma^* f)}{dx d\eta_1 d\eta_2 dp_T d\boldsymbol{r}_T} = \sigma_0^{fU} \sum_f H^U_{\gamma^* f \to g\bar{f}}(\hat{s},\hat{t},\hat{u},\mu) \int \frac{d^2\boldsymbol{b}}{(2\pi)^2} \exp(i\boldsymbol{b}\cdot\boldsymbol{r}_T) F_f(\xi,\boldsymbol{b},\mu,\zeta_1)$$
$$\times S_{\gamma f}(\boldsymbol{b},\zeta_2,\mu)\Big(\mathcal{C}_g(\boldsymbol{b},R,\mu)J_g(p_T,R,\mu)\Big)\Big(\mathcal{C}_{\bar{f}}(\boldsymbol{b},R,\mu)J_{\bar{f}}(p_T,R,\mu)\Big)$$

Unpolarized & linearly polarized cross-section

Dijet production

$$F_g^{\mu\nu}(\xi,\boldsymbol{b}) = f_1(\xi,\boldsymbol{b})\frac{g_T^{\mu\nu}}{d-2} + h_1^{\perp}(\xi,\boldsymbol{b})\left(\frac{g_T^{\mu\nu}}{d-2}+\frac{b^\mu b^\nu}{\boldsymbol{b}^2}\right)$$

$$H^{\mu\nu}_{\gamma^* g\to f\bar{f}} = \sigma_0^{gU}\, H^U_{\gamma^* g\to f\bar{f}}\frac{g_T^{\mu\nu}}{d-2} + \sigma_0^{gL}\, H^L_{\gamma^* g\to f\bar{f}}\left(-\frac{g_T^{\mu\nu}}{d-2}+\frac{v_{1T}^\mu\, v_{2T}^\nu + v_{2T}^\mu\, v_{1T}^\nu}{2\; v_{1T}\cdot v_{2T}}\right)$$

Unpolarized cross-section

$$\frac{d\sigma^U(\gamma^* g)}{dx\,d\eta_1 d\eta_2 dp_T d\boldsymbol{r}_T} = \sigma_0^{gU}\sum_f H^U_{\gamma^* g\to f\bar{f}}(\hat{s},\hat{t},\hat{u},\mu)\int\frac{d^2\boldsymbol{b}}{(2\pi)^2}\exp(i\boldsymbol{b}\cdot\boldsymbol{r}_T)\, f_1(\xi,\boldsymbol{b},\mu,\zeta_1)$$
$$\times\, S_{\gamma g}(\boldsymbol{b},\zeta_2,\mu)\left(\mathcal{C}_f(\boldsymbol{b},R,\mu)J_f(p_T,R,\mu)\right)\left(\mathcal{C}_{\bar{f}}(\boldsymbol{b},R,\mu)J_{\bar{f}}(p_T,R,\mu)\right)$$

Linearly polarized cross-section

$$\frac{d\sigma^L(\gamma^* g)}{dx\,d\eta_1 d\eta_2 dp_T d\boldsymbol{r}_T} = \sigma_0^{gL}\sum_f H^L_{\gamma^* g\to f\bar{f}}(\hat{s},\hat{t},\hat{u},\mu)\int\frac{d^2\boldsymbol{b}}{(2\pi)^2}\exp(i\boldsymbol{b}\cdot\boldsymbol{r}_T)\, h_1^{\perp}(\xi,\boldsymbol{b},\mu,\zeta_1)$$
$$\times\,\frac{s_{\boldsymbol{b}}^2-c_{\boldsymbol{b}}^2}{2}\, S_{\gamma g}(\boldsymbol{b},\zeta_2,\mu)\left(\mathcal{C}_f(\boldsymbol{b},R,\mu)J_f(p_T,R,\mu)\right)\left(\mathcal{C}_{\bar{f}}(\boldsymbol{b},R,\mu)J_{\bar{f}}(p_T,R,\mu)\right)$$

New soft function

n - incoming beam direction

v_1 - jet 1 direction

v_2 - jet 2 direction

Soft function

$$\hat{S}_{\gamma g}(\boldsymbol{b}) = \frac{1}{C_F C_A}\langle 0|\mathcal{S}_n^\dagger(\boldsymbol{b},-\infty)_{ca'}\mathrm{Tr}\Big[S_{v_2}(+\infty,\boldsymbol{b})T^{a'}S_{v_1}^\dagger(+\infty,\boldsymbol{b}) \times S_{v_1}(+\infty,0)T^a S_{v_2}^\dagger(+\infty,0)\Big]\mathcal{S}_n(0,-\infty)_{ac}|0\rangle$$

$$\hat{S}_{\gamma f} = \hat{S}_{\gamma g}(n \leftrightarrow v_2)$$

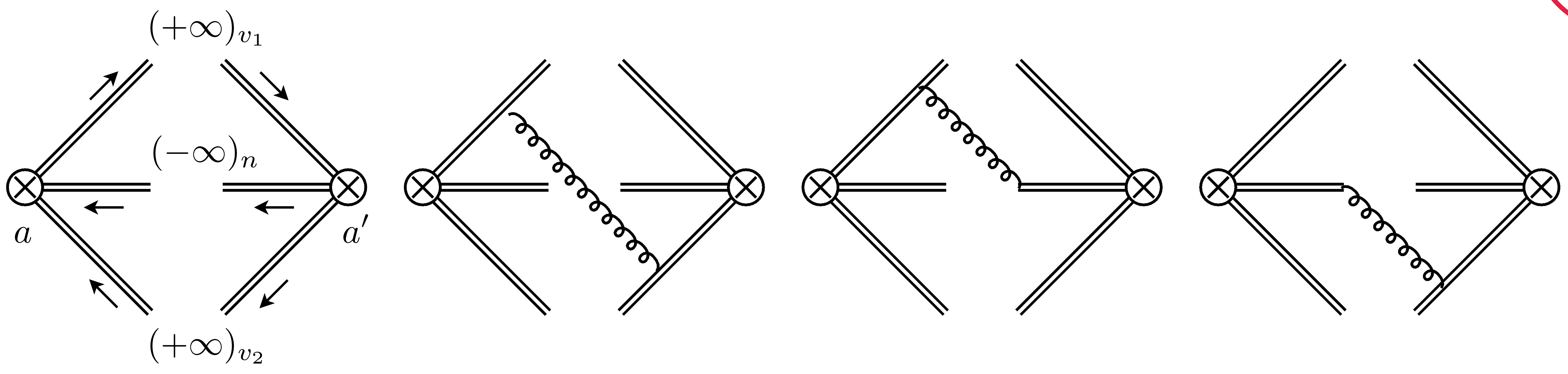
Wilson lines

$$S_v(+\infty,\xi) = P\exp\Big[-ig\int_0^{+\infty} d\lambda\; v\cdot A(\lambda v+\xi)\Big] \qquad S_{\bar{v}}^\dagger(+\infty,\xi) = P\exp\Big[ig\int_0^{+\infty} d\lambda\; \bar{v}\cdot A(\lambda\bar{v}+\xi)\Big]$$

$$S_n(+\infty,\xi) = \lim_{\delta^+\to 0} P\exp\Big[-ig\int_0^{+\infty} d\lambda\; n\cdot A(\lambda n+\xi)e^{-\delta^+\lambda}\Big]$$

δ - regulator !!!

Echevarría, Scimemi, Vladimirov, 2016

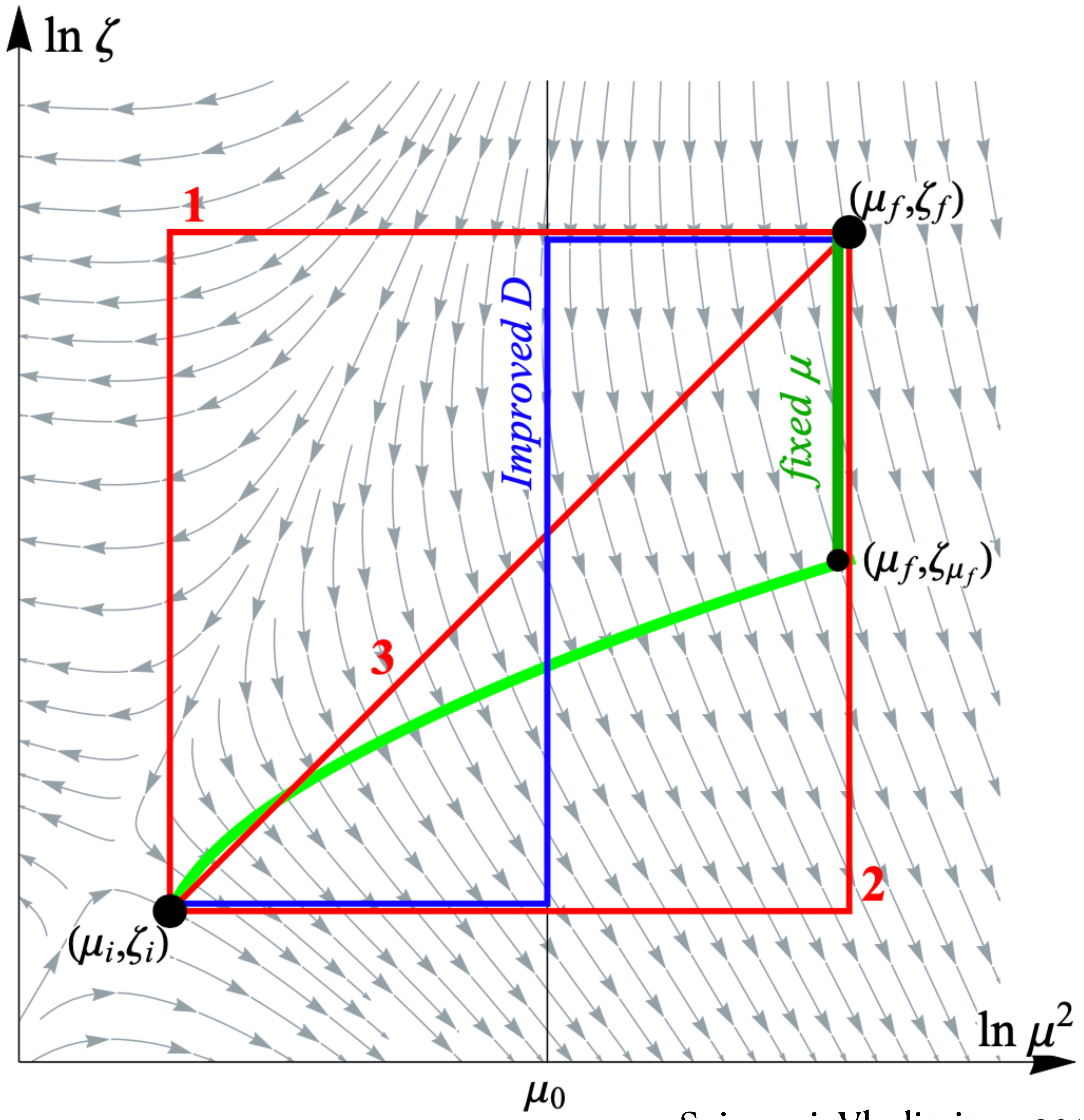


+ virtual diagrams

at one-loop order...

Evolution, double-scale evolution

fixed μ evolution



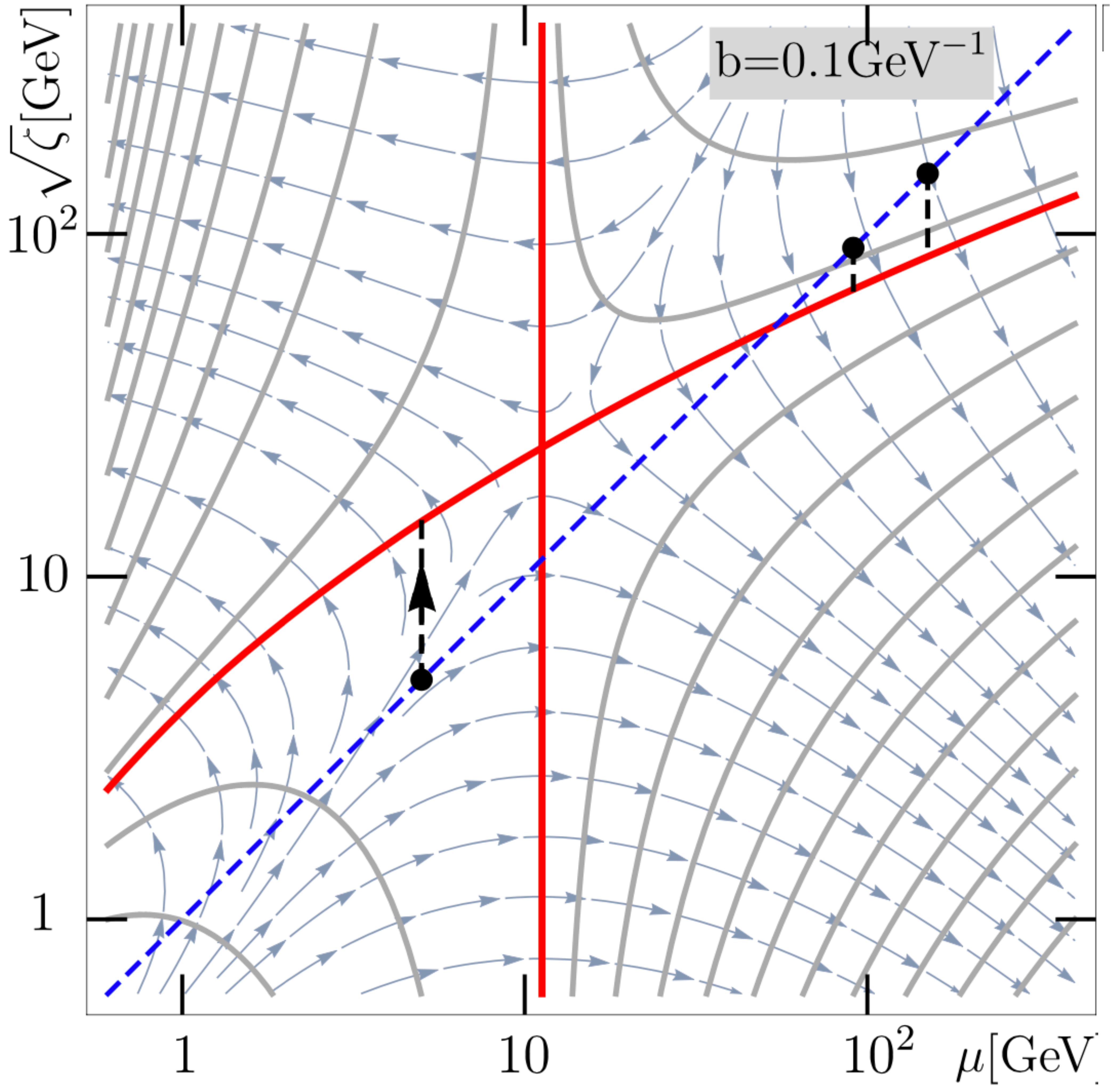
Scimemi, Vladimirov, 2018
Scimemi, Vladimirov, 2020

Describe evolution of functions depending on two scales

TMDPDF | TMDFF | Dijets SF

μ scale	Renormalization scale	ε regulator (DR)
ζ scale	Rapidity scale	δ regulator

Evolution, ζ-prescription



Scimemi, Vladimirov, 2018
Scimemi, Vladimirov, 2020

fixed μ evolution

Evolution kernel is given by

Saddle point

$$S(\boldsymbol{b};\mu_f,\zeta_{2,f}) = \exp\left[\int_P (\gamma_S(\mu,\zeta_2)\,d\ln\mu - \mathcal{D}_S(\mu,b)d\ln\zeta_2)\right] S(\boldsymbol{b};\overbrace{\mu_0,\zeta_{2,0}})$$

$$\left.\begin{aligned}\frac{d}{d\ln\mu}S(\boldsymbol{b};\mu,\zeta) &= \gamma_S(b;\mu,\zeta)S(\boldsymbol{b};\mu,\zeta)\\ \frac{d}{d\ln\zeta}S(\boldsymbol{b};\mu,\zeta) &= -\mathcal{D}_S(b,\mu)S(\boldsymbol{b};\mu,\zeta)\end{aligned}\right\} \longrightarrow \boxed{\boldsymbol{\nabla}F = \boldsymbol{E}F}$$

$$\boldsymbol{E} = (\gamma_S(b,\mu,\zeta), -\mathcal{D}_S(b,\mu))$$

Equipotential (null-evolution) line is given by $\gamma_S = 2\mathcal{D}_S\dfrac{d\ln\zeta_\mu}{d\ln\mu^2}$

gluon channel solution $\zeta_{2,\mu}^{\gamma^* g}(\boldsymbol{b},\mu) = \left(\dfrac{\mu}{\mu_0}\right)^{\frac{2C_F}{C_A}}\zeta_{2,0}e^{v_S(\boldsymbol{b},\mu)}$

perturbative

$$R_S((\mu_0,\zeta_{2,0})\to(\mu_f,\zeta_f)) = \left(\frac{\zeta_f}{\zeta_{2,\mu}(\boldsymbol{b},\mu_f)}\right)^{-D_S(\boldsymbol{b},\mu_f)}$$

Plots for phenomenological analysis

https://teorica.fis.ucm.es/artemide/
https://github.com/vladimirovalexey/artemide-public."

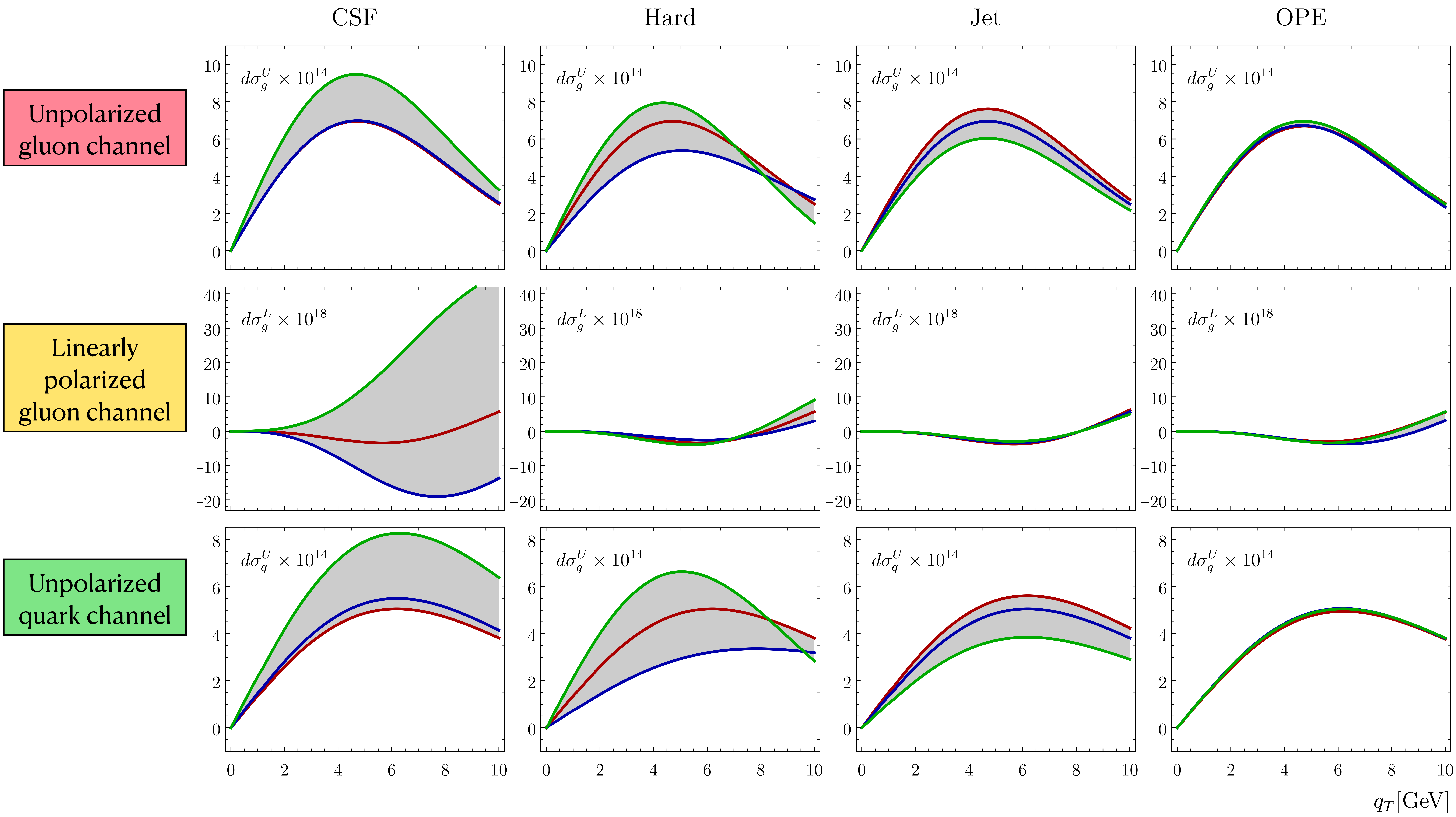
- We use arTeMiDe to obtain the plots
- TMDPDF and TMDFF structure and evolution is included arTeMiDe
- SF double-scale evolution and jet functions included as new modules

$p_T = 20\,\text{GeV} \quad (p_T \sim Q)$

$\sqrt{s} = 140\,\text{GeV}$

Integrated over x

Central rapidity region



CSF
Hard
Jet
OPE
Unpolarized gluon channel
Linearly polarized gluon channel
Unpolarized quark channel
$d\sigma_g^U \times 10^{14}$
$d\sigma_g^L \times 10^{18}$
$d\sigma_q^U \times 10^{14}$
q_T[GeV]

Conclusion

- We have established factorization for dijet production
- Can be potentially observed in the future EIC
- We have been able to compute the new TMD Soft Function up to NLO and its anomalous dimension up to three-loops
- Rapidity structure of this new SF allows us to use the ζ-prescription
- The presence of the new SF makes the gluon TMDPDF extraction non-trivial
- Analysis of the numerical result for the cross-section shows the effect of linearly polarized gluon TMDs can be neglected compared to unpolarized gluon TMDs

Thank you for listening!