Exploring minijets beyond leading power

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based on:

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Introduction

Minijets in Pythia

- The rise of the total cross section with energy in hadron-hadron collision is due to minijets; in collinear factorization

$$d\sigma_{\mathrm{2jet}} = \sum_{a,b,c,d} \int \frac{dx_A}{x_A} \frac{dx_B}{x_B} \, d\hat{\sigma}_{ab\to cd}\left(x_A, x_B; \mu^2\right) f_{a/A}\left(x_A; \mu^2\right) f_{b/B}\left(x_B; \mu^2\right)$$

- $d\sigma_{\mathrm{2jet}}$ is divergent for $p_T \to 0$

$$\frac{d\sigma_{\mathrm{2jet}}}{dp_T^2} \sim \frac{\alpha_s\left(p_T^2\right)}{p_T^4}$$

- phenomenological regularization

[T. Sjostrand, M. van Zijl, Phys.Rev.D 36 (1987) 2019]

$$\frac{d\sigma'_{\mathrm{2jet}}}{dp_T^2} \sim \frac{\alpha_s\left(p_T^2 + p_{T0}^2(s)\right)}{\left(p_T^2 + p_{T0}^2(s)\right)^2},$$

with $p_{T0}(s) = p_{T0}\left(s/s_0\right)^{\lambda}$.

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Goal: calculate $p_{T0}(s)$ from some simple approach

- the $p_{T0}\,(s)$ regularization takes the collinear factorization out of the leading power approximation
- idea: use frameworks that have power corrections by including transverse momenta of incoming partons: High Energy (or k_T) Factorization (HEF) (or Color Glass Condensate, but saturation is not essential here)

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Plan

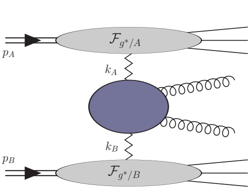
1. High Energy Factorization
2. Non-leading-power extension of DDT (Diakonov-Dokshitzer-Troyan) formula for dijet in *pp*
3. Direct study of minijet suppression
4. Hard dijet observable sensitive to $p_{T0}(s)$ cutoff
5. Summary

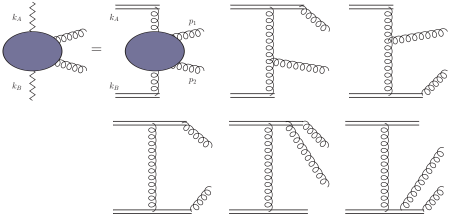
High Energy Factorization (HEF)

Gluon production in HEF

[S. Catani, M. Ciafaloni, F. Hautmann, Nucl.Phys. B366 (1991) 135-188]
[J.C. Collins, R.K. Ellis, Nucl.Phys. B360 (1991) 3-30]

$$d\sigma_{AB\to gg} = \mathcal{F}_{g^*/A}\left(x_A, k_{T\,A};\mu\right) \otimes d\hat{\sigma}_{g^*g^*\to gg}\left(x_A, x_B, k_{T\,A}, k_{T\,B};\mu\right) \otimes \mathcal{F}_{g^*/B}\left(x_B, k_{T\,B};\mu\right)$$





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[P.K. JHEP 1407 (2014) 128]

$\mathcal{F}_{g^*/H}\left(x_H, k_{T\,H};\mu\right)$ – Unintegrated Gluon Distribution (UGD)
$d\hat{\sigma}_{g^*g^*\to gg}$ – hard process with off-shell gauge invariant amplitude

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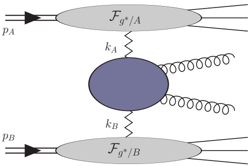

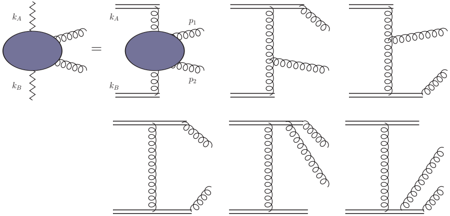

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$$d\sigma_{AB\to gg} = \frac{1}{64\pi^2}\int d^2\vec{k}_{TA} d^2\vec{k}_{TB} \int \frac{z_1 dz_1\, z_2 dz_2}{(z_1+z_2)^2} \int \frac{dp_T^2 d\phi}{\left[z_1\left(\vec{p}_T - \vec{K}_T\right)^2 + z_2 p_T^2\right]^2}$$

$$\mathcal{F}_{g^*/A}\left(z_1+z_2, k_{TA}\right)\mathcal{F}_{g^*/B}\left(\frac{1}{z_2 S}\left(\vec{p}_T - \vec{K}_T\right)^2 + \frac{1}{z_1 S}p_T^2, k_{TB}\right)\left|\overline{\mathcal{M}}\right|^2_{g^*g^*\to gg}\left(z_1, z_2, \vec{k}_{TA}, \vec{k}_{TB}\right)$$

Unintegrated Gluon Distributions (UGDs)

- Kimber-Martin-Ryskin (KMR) [M. Kimber, A. D. Martin, and M. Ryskin, Phys.Rev. D63, 114027 (2001)]

$$\mathcal{F}_{g^*/H}(x, k_T, \mu) = \frac{\partial}{\partial k_T^2}\left[f_{g/H}(x, k_T)\, T_g(k_T, \mu)\right]$$

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  BFKL + DGLAP corrections + kinematic constraint + running α_s

$$\mathcal{F}\left(x, k_T^2\right) = \mathcal{F}_0\left(x, k_T^2\right) + \frac{\alpha_s N_c}{\pi}\int_x^1 \frac{dz}{z}\int_{k_{T0}^2}^{\infty}\frac{dq_T^2}{q_T^2}\left\{\frac{q_T^2\mathcal{F}\left(\frac{x}{z}, q_T^2\right)\theta\left(\frac{k_T^2}{z} - q_T^2\right) - k_T^2\mathcal{F}\left(\frac{x}{z}, k_T^2\right)}{\left|q_T^2 - k_T^2\right|} + \frac{k_T^2\mathcal{F}\left(\frac{x}{z}, k_T^2\right)}{\sqrt{4q_T^4 + k_T^4}}\right\}$$

$$+ \frac{\alpha_s}{2\pi k_T^2}\int_x^1 dz\left\{\left(P_{gg}(z) - \frac{2N_c}{z}\right)\int_{k_{T0}^2}^{k_T^2} dq_T^2\mathcal{F}\left(\frac{x}{z}, q_T^2\right) + zP_{gq}(z)\,\Sigma\left(\frac{x}{z}, k_T^2\right)\right\}$$

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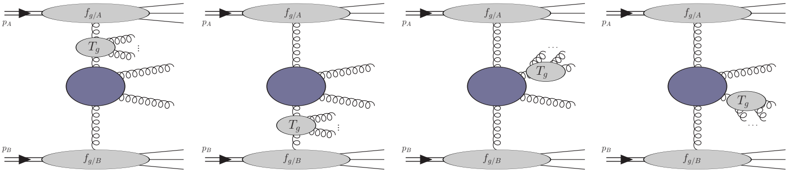
- CCFM
- ...

Non-leading-power extension of DDT

Dokshitzer-Diakonov-Troyan (DDT) formula (leading power)

[Y. Dokshitzer,D. Dyakonov, S. Troyan, Phys.Rep. 58 (1980) 269-395]

$$\frac{d\sigma_{2\text{jet}}}{dK_T^2} = \int \frac{dx_A}{x_A}\frac{dx_B}{x_B}\, d\hat{\sigma}_{gg\to gg}\left(x_A, x_B; \mu^2\right) \frac{\partial}{\partial K_T^2}\left\{f_{g/A}\left(x_A; K_T^2\right) f_{g/B}\left(x_B; K_T^2\right) T_g^4\left(K_T^2, \mu^2\right)\right\}$$



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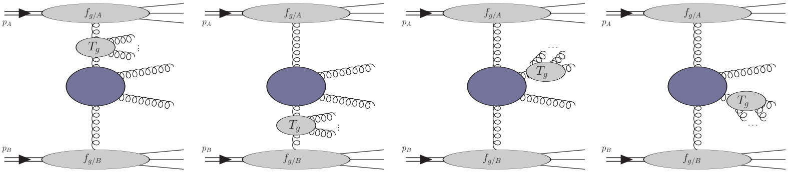

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Improved DDT (IDDT) formula (beyond leading power) [P.K., A. Stasto, M. Strikman, arXiv:1608.00523]

$$d\sigma_{2\text{jet}}^{(\text{IDDT})} = d\sigma_{2\text{jet}}^{(\text{IS})} + d\sigma_{2\text{jet}}^{(\text{FS})}$$

$$d\sigma_{2\text{jet}}^{(\text{IS})} = 2\,\mathcal{F}_{g^*/A}\left(x_A, K_T, \mu\right) \otimes d\hat{\sigma}_{g^*g\to gg}\left(x_A, x_B, \vec{K}_T\right) \otimes f_{g/B}\left(x_B, K_T^2\right) \otimes T_g^3\left(K_T^2, \mu^2\right)$$

$$d\sigma_{2\text{jet}}^{(\text{FS})} = 2\, f_{g/A}\left(x_A; K_T^2\right) \otimes d\hat{\sigma}_{gg\to gg^*}\left(x_A, x_B, \vec{K}_T\right) \otimes f_{g/B}\left(x_B; K_T^2\right) \otimes \mathcal{T}_g\left(K_T^2, \mu^2\right) \otimes T_g^3\left(K_T^2, \mu^2\right)$$

where $\mathcal{T}_g\left(K_T^2, \mu^2\right) = \partial T_g\left(K_T^2, \mu^2\right)/\partial K_T^2$. There is a restriction $K_T \le \mu$.

Direct study of minijet suppression

Inclusive dijets with Pythia: anti-k_T with $R = 0.5$, rapidity $[-4, 4]$

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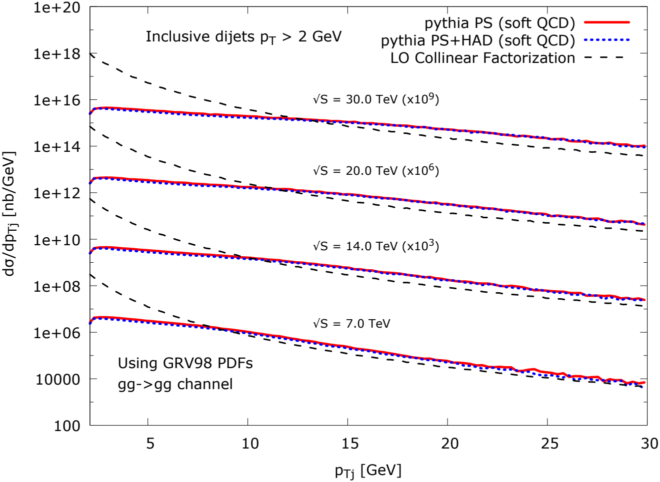
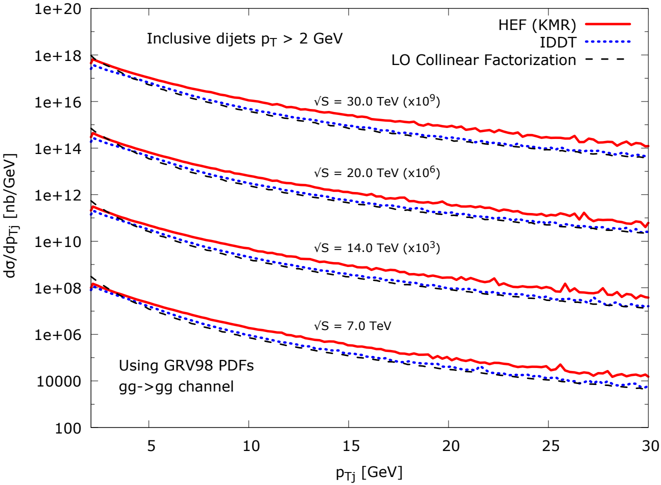


Direct study of minijet suppression

Inclusive dijets with HEF and IDDT



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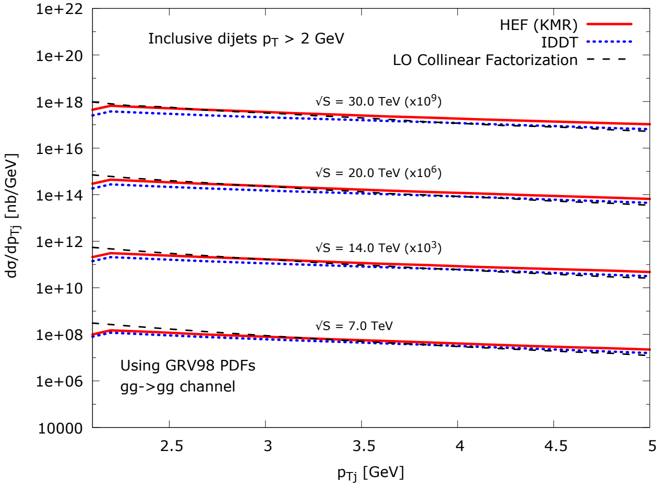

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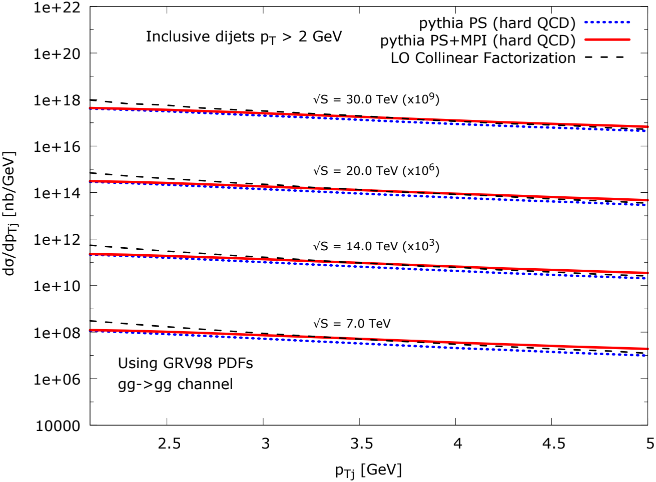
Inclusive dijets with Pythia 'hard'



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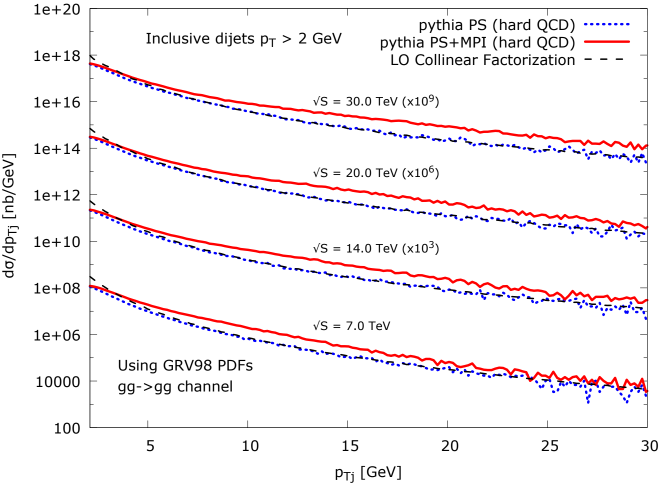

Direct study of minijet suppression

Summary:

- HEF/IDDT do not produce significant small p_T suppression, despite the internal gluon k_T
- The suppression is very similar to the one produced by Pythia with the 'hard' events (this is actually quite intuitive)
- For larger p_T the enhancement in HEF (but not IDDT) with respect to collinear result is very similar to Pythia with MPIs

  $\Rightarrow$ MPIs are power corrections which are present in HEF (where this enhancement comes from $K_T > \overline{p}_T$), where $\overline{p}_T = (p_{T1} + p_{T2})/2$

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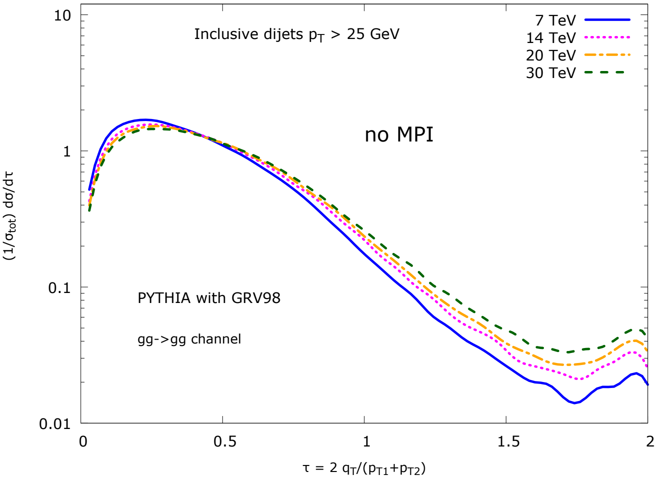
Idea: study sensitivity to large dijet imbalance to look for MPI effects

- define $\tau = K_T/\overline{p}_T$ and simply consider $d\sigma/d\tau$
- p_T of dijets $> 25\,\mathrm{GeV}$ (to be within the hard regime)
- study an impact of MPIs (by playing with $p_{T0}\,(s)$)

Indirect study of minijet suppression

$(1/\sigma)\ d\sigma/d\tau$ in Pythia



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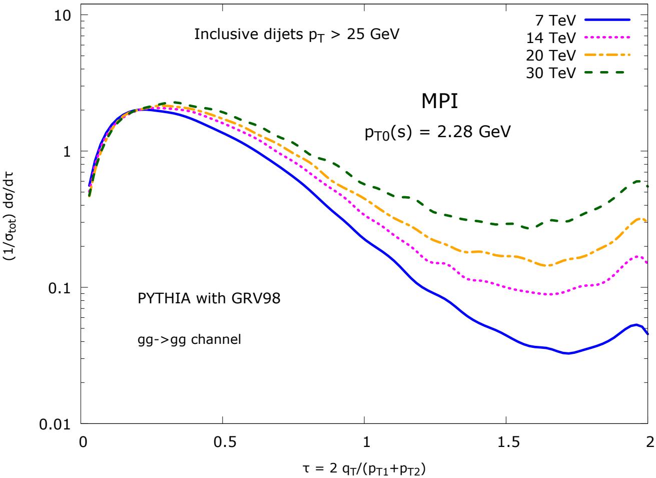

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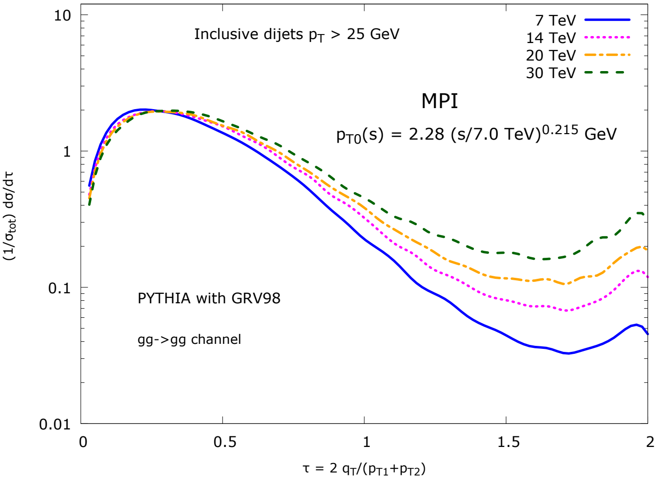

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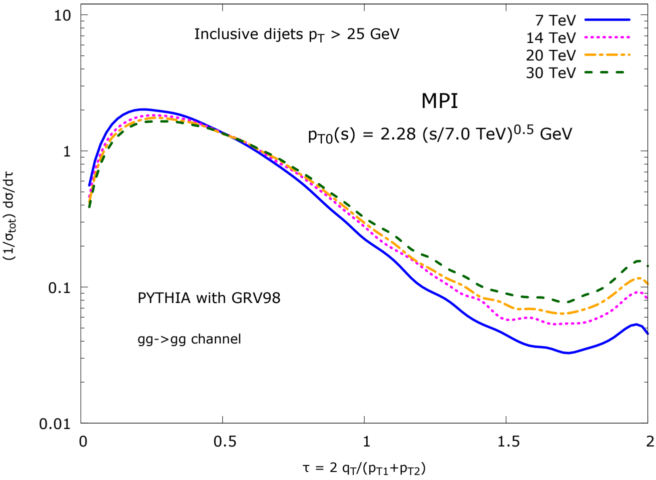

Indirect study of minijet suppression

Bimodality coefficient for Pythia

$$b = \frac{\gamma^2 + 1}{\kappa}\,, \text{ where } \gamma = \frac{\mu_3}{\sigma^3}\,,\ \kappa = \frac{\mu_4}{\sigma^4} \text{ with } \mu_n \text{ central moments}$$

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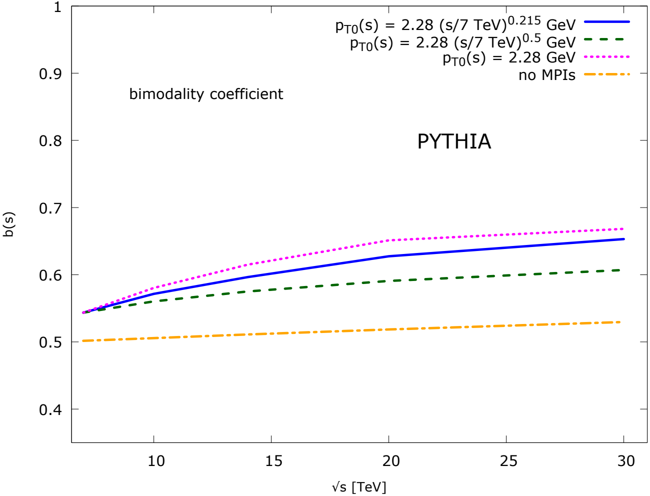
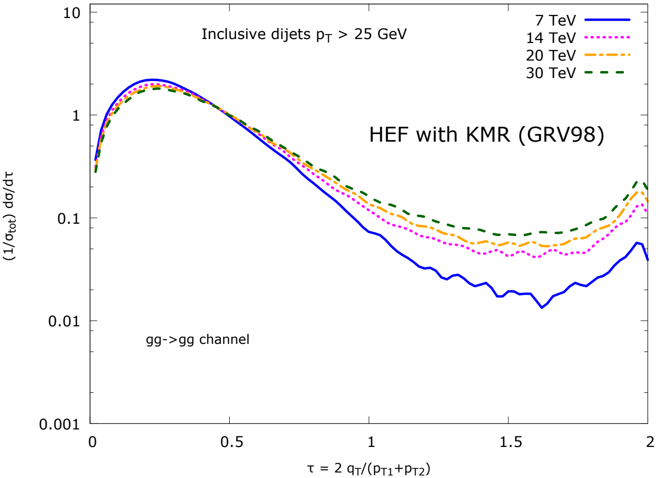


Indirect study of minijet suppression

$(1/\sigma)\ d\sigma/d\tau$ in HEF



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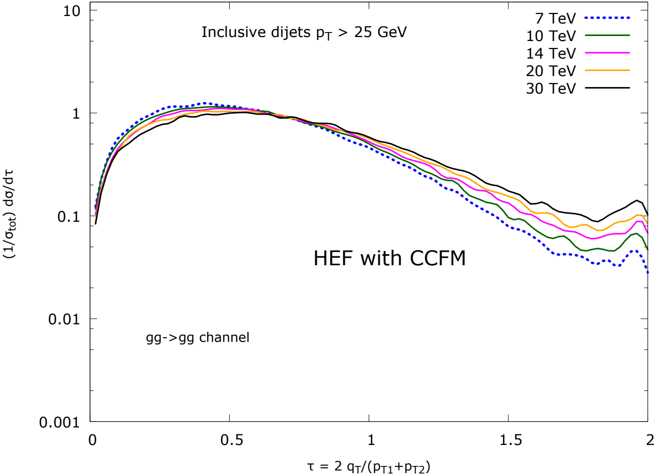

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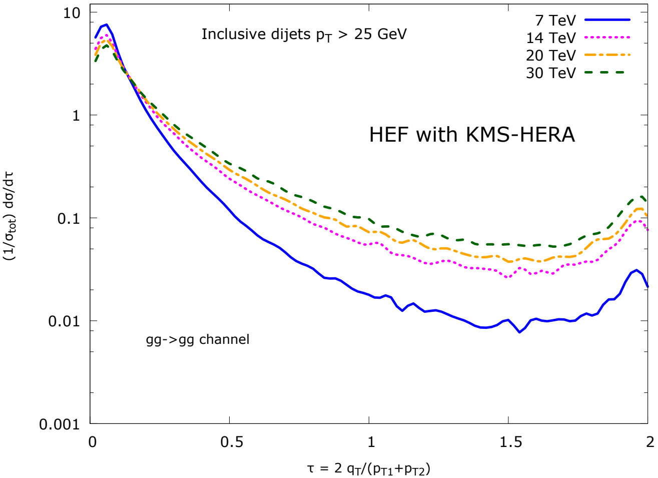

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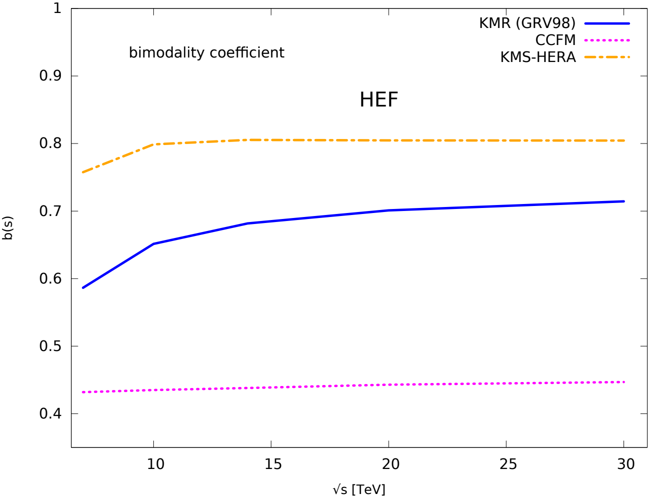

Conclusions

- The τ distribution is sensitive to MPIs
- The suppression of MPIs can be characterized by the bimodality coefficient which reflects the behavior of the p_{T0} cutoff
- HEF contains power corrections mimicking MPIs
- The energy dependence of the minijet p_T cutoff is related to the small x evolution of unintegrated gluon distribution