Are there monojets in proton-nucleus collisions at high energy?

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Are there monojets in high-energy proton-nucleus collisions?

A proton colliding on a heavy nucleus produces a gluon with a high transverse momentum $k_\perp$.

How many collisions did the gluon undergo in the nucleus? of what kind?

— many soft collisions (monojet)?

— one hard scattering accompanied by soft collisions (dijet)?

Within the Color Glass Condensate framework, one can compute the probability to have n collisions above a given threshold $k_\perp^{\min}$, their momentum distribution, study the dependence on $k_\perp$, $k_\perp^{\min}$ and Q_s...

And answer the question!

N.Borghini & F.Gelis, Phys. Rev. D **74** (2006) 054025

Gluon production in pA collisions

The Color Glass Condensate framework provides an analytical formula for the number of gluons produced per unit transverse momentum and rapidity in the high-energy collision between a small projectile (= a weak color source which only contributes to 1st order) and a large nucleus (= classical Yang-Mills fields):

cf. François on Thursday!

$$\frac{\mathrm{d}N_g}{\mathrm{d}\mathbf{p}_\perp \mathrm{d}y} = \frac{1}{16\pi^3 p_\perp^3} \int \frac{\mathrm{d}^2\mathbf{k}_\perp}{(2\pi)^2} k_\perp^2 C(\mathbf{k}_\perp) \underbrace{\varphi_p(\mathbf{p}_\perp - \mathbf{k}_\perp)}$$

"non-integrated gluon distribution" in the proton

which includes all multiple scatterings of the gluon on the nucleus.

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$C(\mathbf{k}_\perp)$, which is the Fourier transform of a correlator of Wilson lines, admits a transparent interpretation à la Glauber when the distribution of color sources in the nucleus has Gaussian correlations, either local (McLerran-Venugopalan model) or non-local (in the regime reached after evolution to large rapidities): $C(\mathbf{k}_\perp) = \sum_n \mathfrak{C}_n(\mathbf{k}_\perp)$.

number of collisions of the gluon on the nucleus ↗ n

Gluon production in pA collisions

$C(\mathbf{k}_\perp) = \sum_n \mathfrak{C}_n(\mathbf{k}_\perp)$ probability that the gluon acquire the momentum $\mathbf{k}_\perp$ while going though the nucleus.

☞ $P_n(\mathbf{k}_\perp) \equiv \mathfrak{C}_n(\mathbf{k}_\perp)/C(\mathbf{k}_\perp)$ probability that the gluon acquire the momentum $\mathbf{k}_\perp$ while undergoing n collisions on the nucleus.

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One further step: probability $P_n(\mathbf{k}_\perp|\mathbf{k}_\perp^{\min})$ that the gluon acquire the momentum $k_\perp$ while undergoing n collisions with momentum transfers $q_\perp \geq k_\perp^{\min}$ in traversing the nucleus:

$$P_n(\mathbf{k}_\perp|\mathbf{k}_\perp^{\min}) = \frac{\mathrm{e}^{-\mu_0^2\sigma_{\mathrm{tot}}}}{C(\mathbf{k}_\perp)} \sum_{p=0}^{+\infty} \rho^{p+n} \int_0^L \mathrm{d}z_1 \int_{z_1}^L \mathrm{d}z_2 \cdots \int_{z_{p+n-1}}^L \mathrm{d}z_{n+p}$$
$$\times \int_\Lambda^{k_\perp^{\min}} \frac{\mathrm{d}^2\mathbf{k}_{1\perp}}{(2\pi)^2} \cdots \frac{\mathrm{d}^2\mathbf{k}_{p\perp}}{(2\pi)^2} \int_{k_\perp^{\min}} \frac{\mathrm{d}^2\mathbf{k}_{p+1\perp}}{(2\pi)^2} \cdots \frac{\mathrm{d}^2\mathbf{k}_{p+n\perp}}{(2\pi)^2}$$
$$\times (2\pi)^2 \delta(\mathbf{k}_{1\perp} + \cdots + \mathbf{k}_{p+n\perp} - \mathbf{k}_\perp)\sigma(\mathbf{k}_{1\perp}) \cdots \sigma(\mathbf{k}_{p+n\perp})$$

which can be computed (here using a generating function of the P_n).

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density of color charges $\Leftrightarrow Q_s$

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density of scattering centers per unit area $\Updownarrow$ Q_s

which can be computed (here using a generating function of the P_n).

Probability of having n collisions with $q_\perp \geq k_\perp^{\min}$ balancing $k_\perp$

Instead of calculating each $P_n(k_\perp|k_\perp^{\min})$ individually, we compute the generating function $F(z,k_\perp|k_\perp^{\min}) \equiv \sum_{n=0}^{\infty} P_n(k_\perp|k_\perp^{\min})\, z^n$ which gives all the probabilities $P_n(k_\perp|k_\perp^{\min})$ at once, as well as the average number of scatterings $N(k_\perp|k_\perp^{\min}) = \sum_{n=0}^{\infty} n P_n(k_\perp|k_\perp^{\min}) = \frac{\mathrm{d}F}{\mathrm{d}z}(z=1,k_\perp|k_\perp^{\min})$.

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We use two models with different gluon-scattering center differential cross sections:

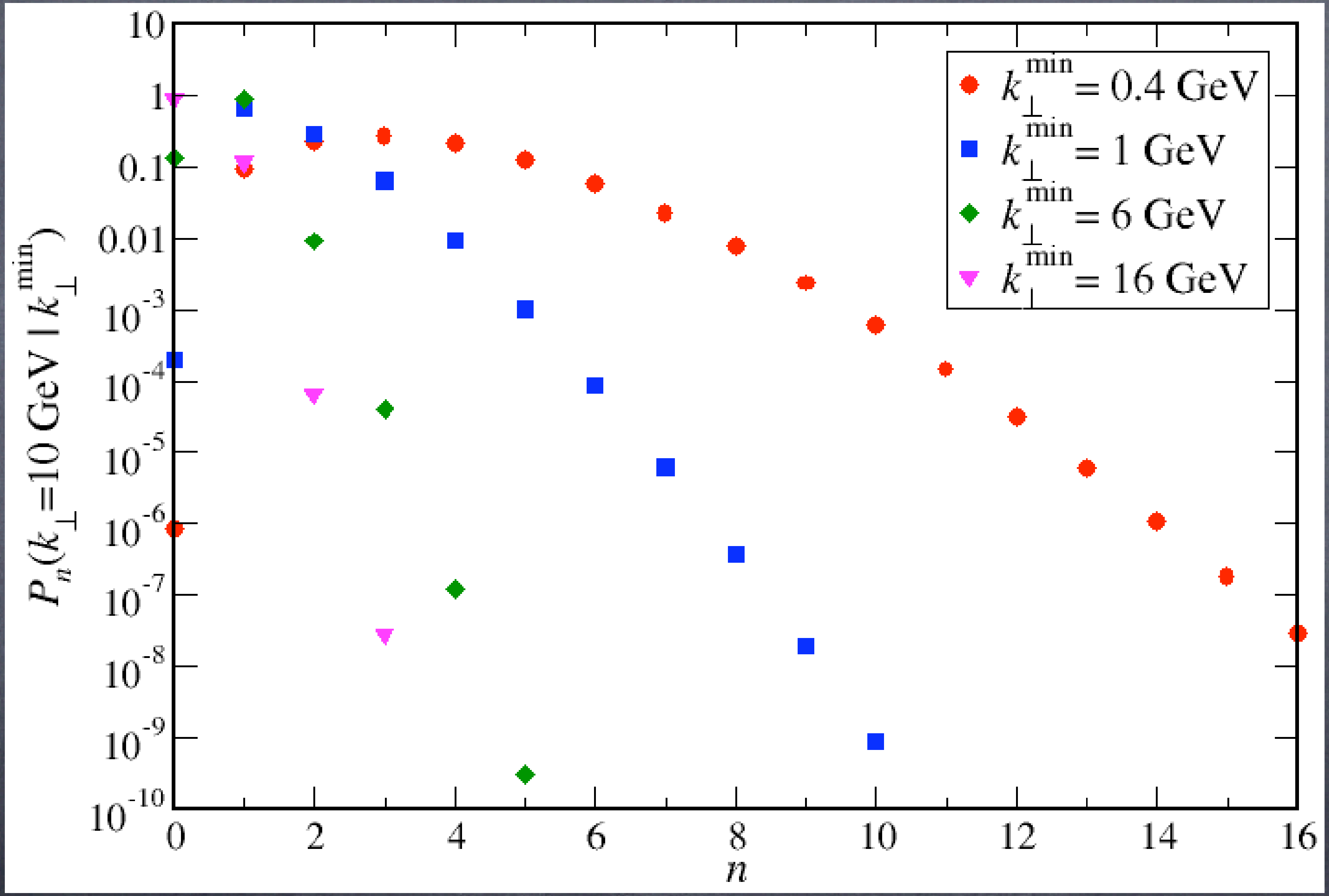
– McLerran-Venugopalan model (no shadowing): $\sigma(q_\perp) = \frac{g^4 N_c}{2\, q_\perp^2}$

– a Gaussian effective theory with leading-twist shadowing:

$$\mu_0^2 \sigma(q_\perp) = \frac{2\pi}{\gamma c} \frac{Q_s^2}{q_\perp^2} \ln\left[1 + \left(\frac{Q_s^2}{q_\perp^2}\right)^\gamma\right] \quad \text{with} \quad c \approx 4.84, \gamma \approx 0.64$$

Probability of having n collisions with $q_\perp \geq k_\perp^{\min}$ balancing $k_\perp$ = 10 GeV

Q_s^2 = 2 GeV²



The width decreases with increasing threshold $k_\perp^{\min}$.

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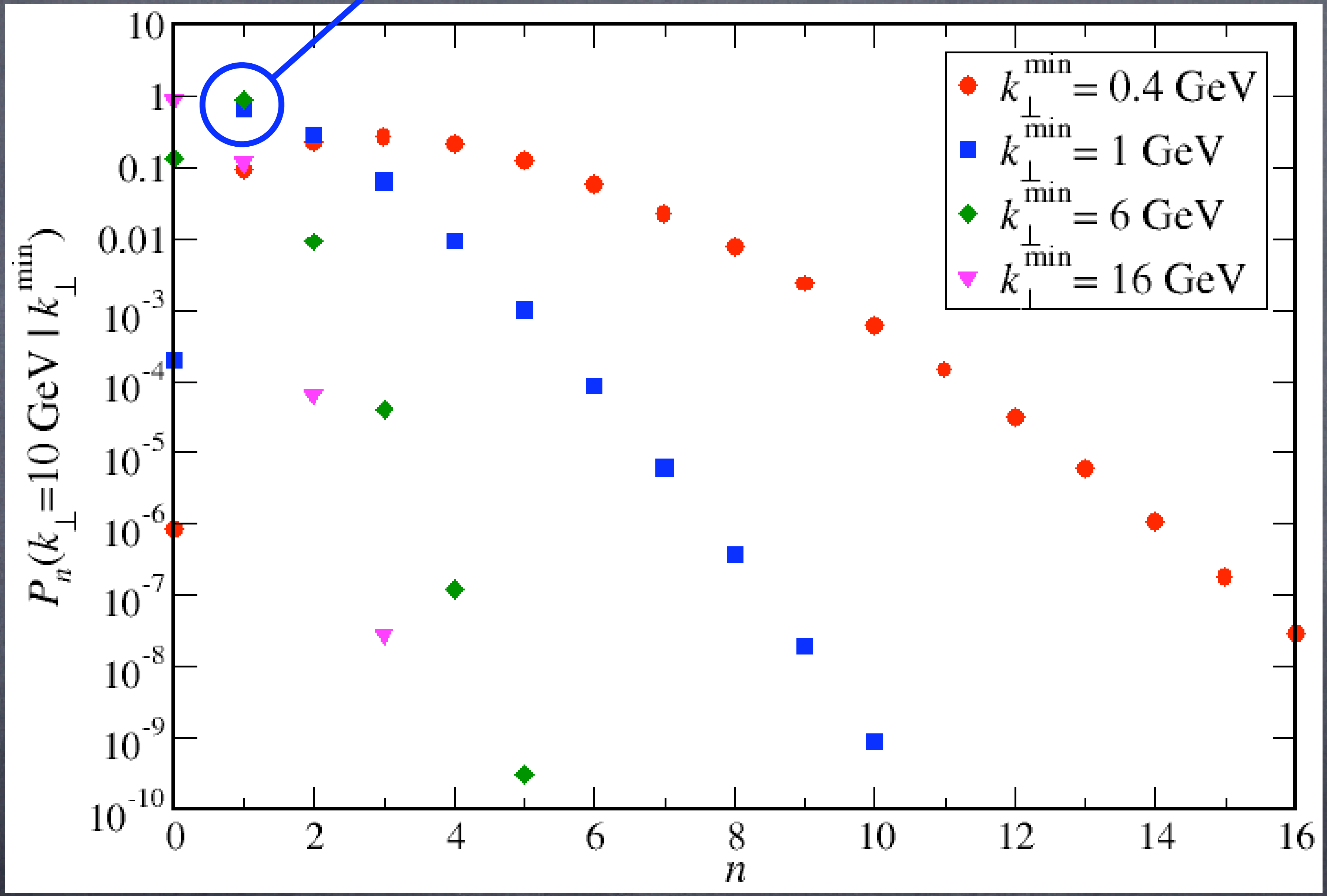
for $Q_s \lesssim k_\perp^{\min} \lesssim k_\perp,\ n = 1$ is most probable



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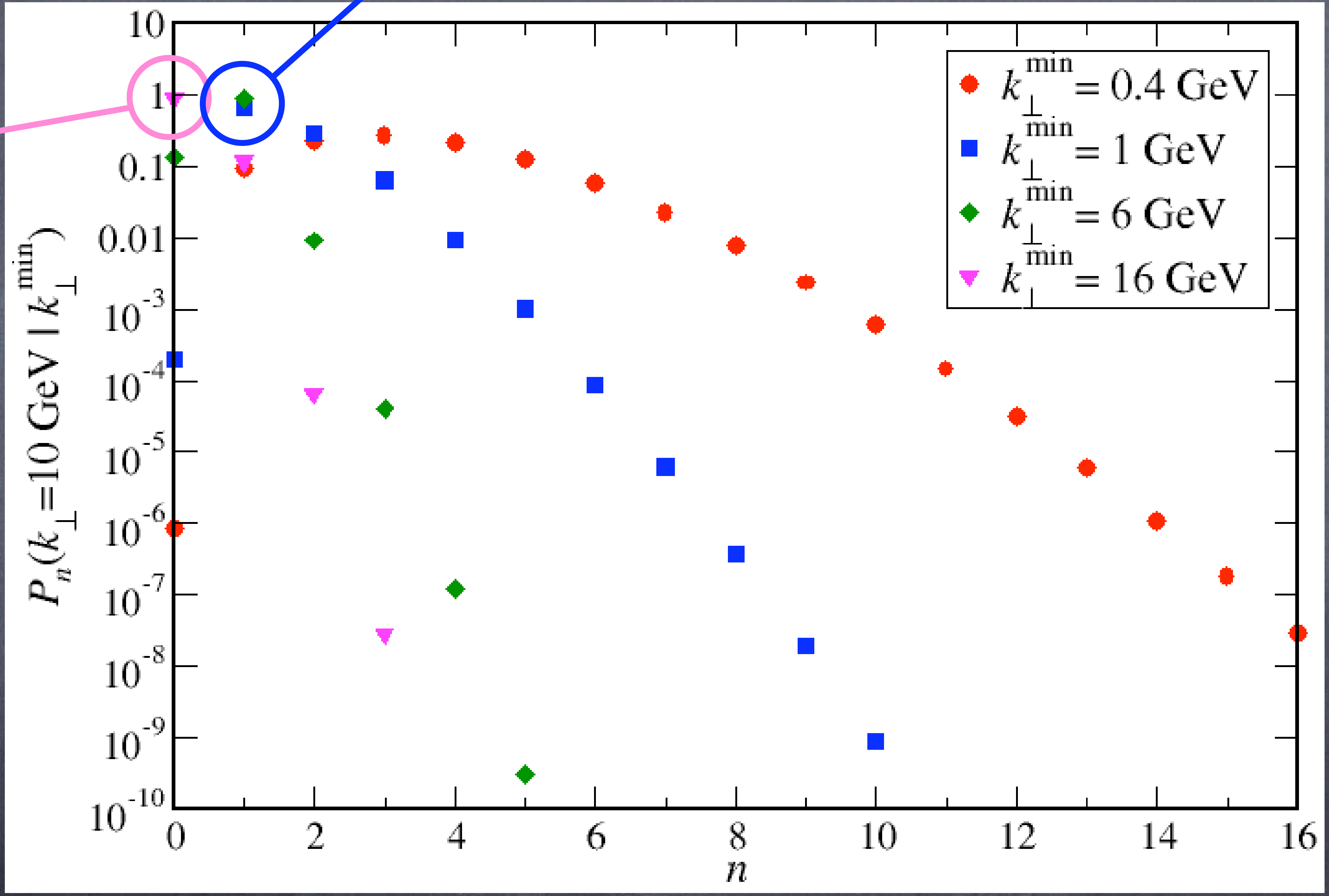
$k_\perp^{\min} > k_\perp$
$n = 0$ most probable



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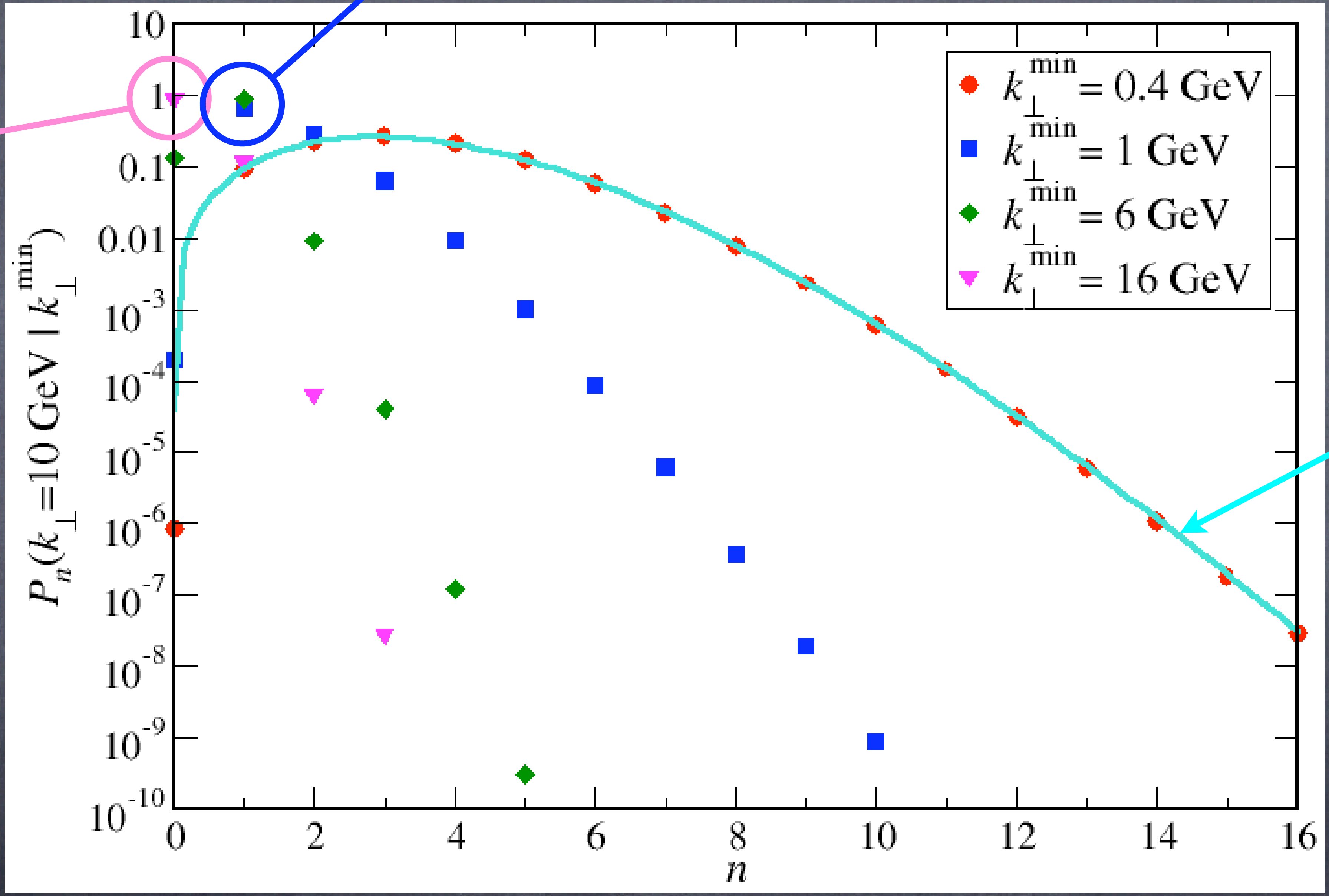

$$\frac{\bar{n}^{n-1}}{(n-1)!}\,\mathrm{e}^{-\bar{n}}$$

P_n shifted Poisson distribution: $\left\{ \begin{array}{l} 1 \text{ "compulsory" scattering} \\ n-1 \text{ independent scatterings} \end{array} \right.$

Number of recoils with $q_\perp \geq k_\perp^{\min}$ balancing $k_\perp$

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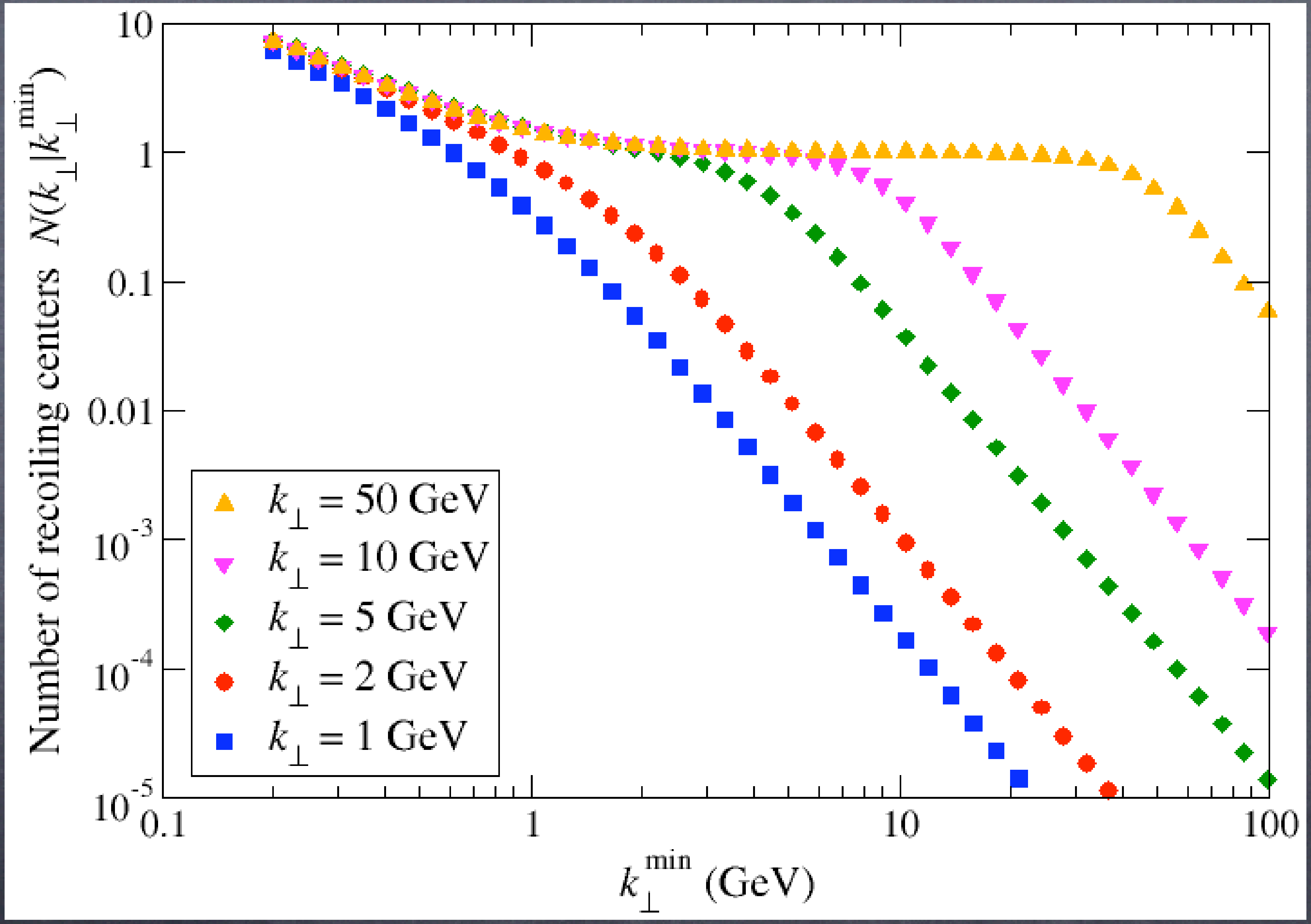

Number of recoils with $q_\perp \geq k_\perp^{\min}$ balancing $k_\perp$

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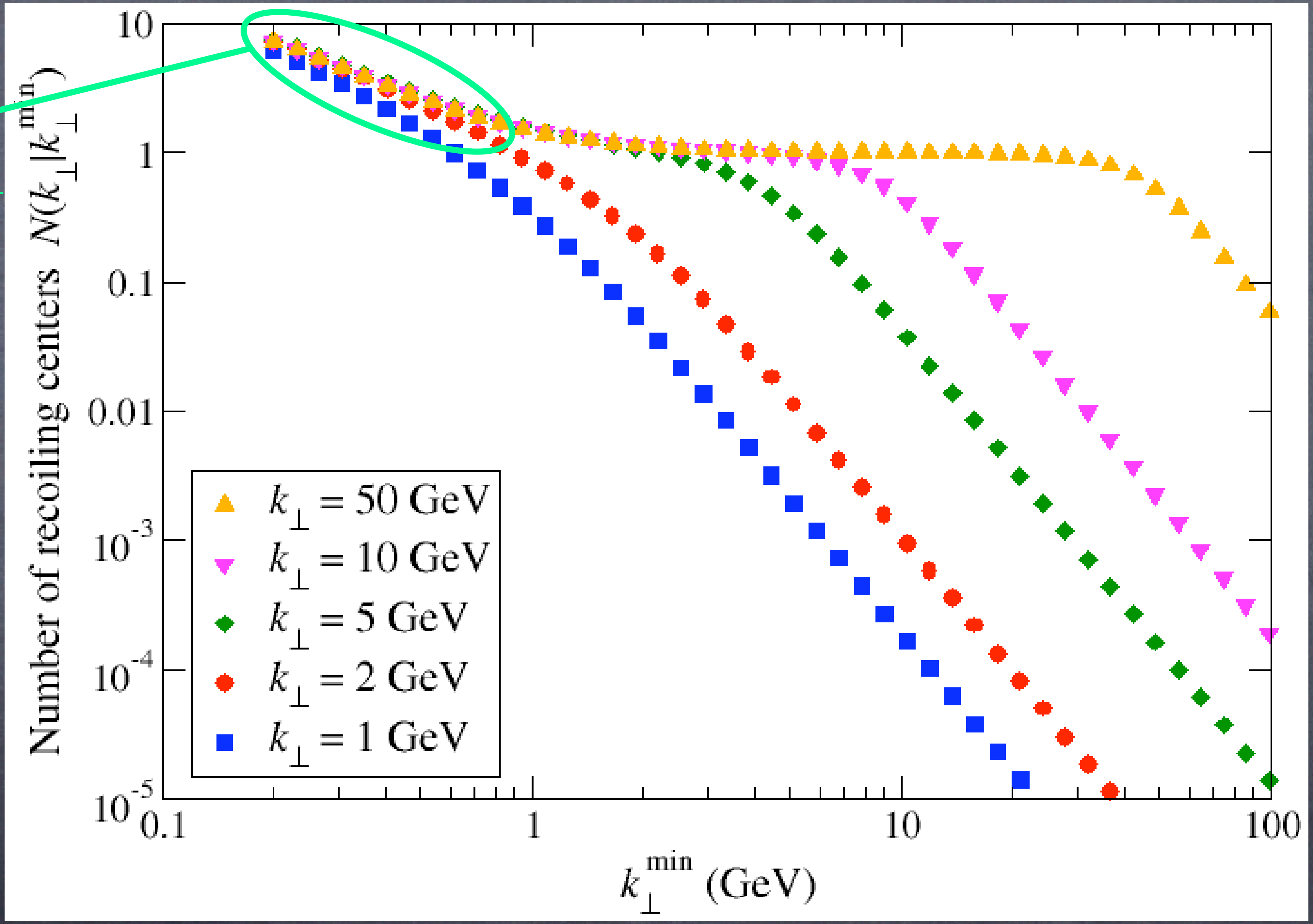
universal for $k_\perp^{\min}, Q_s \ll k_\perp$



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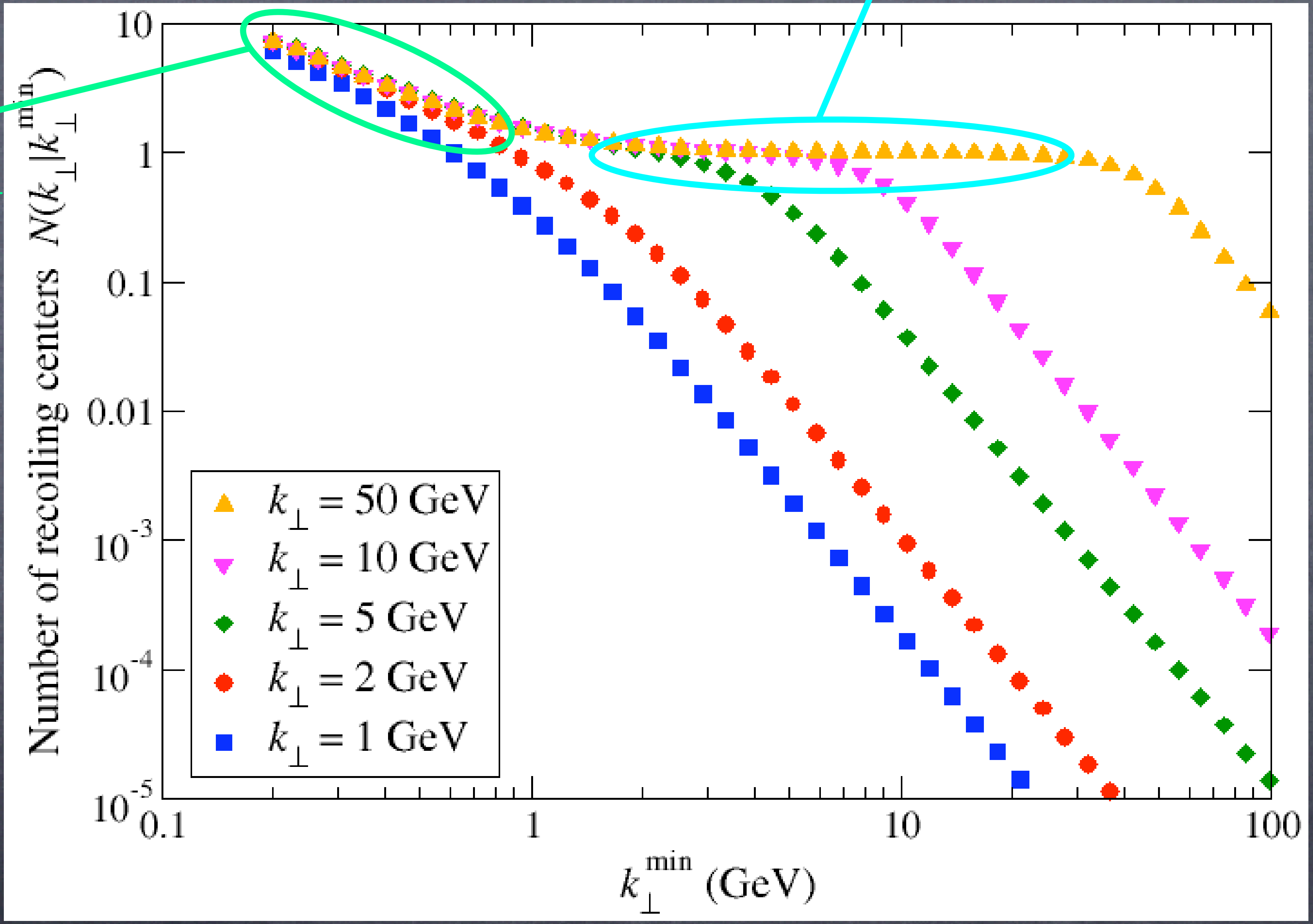

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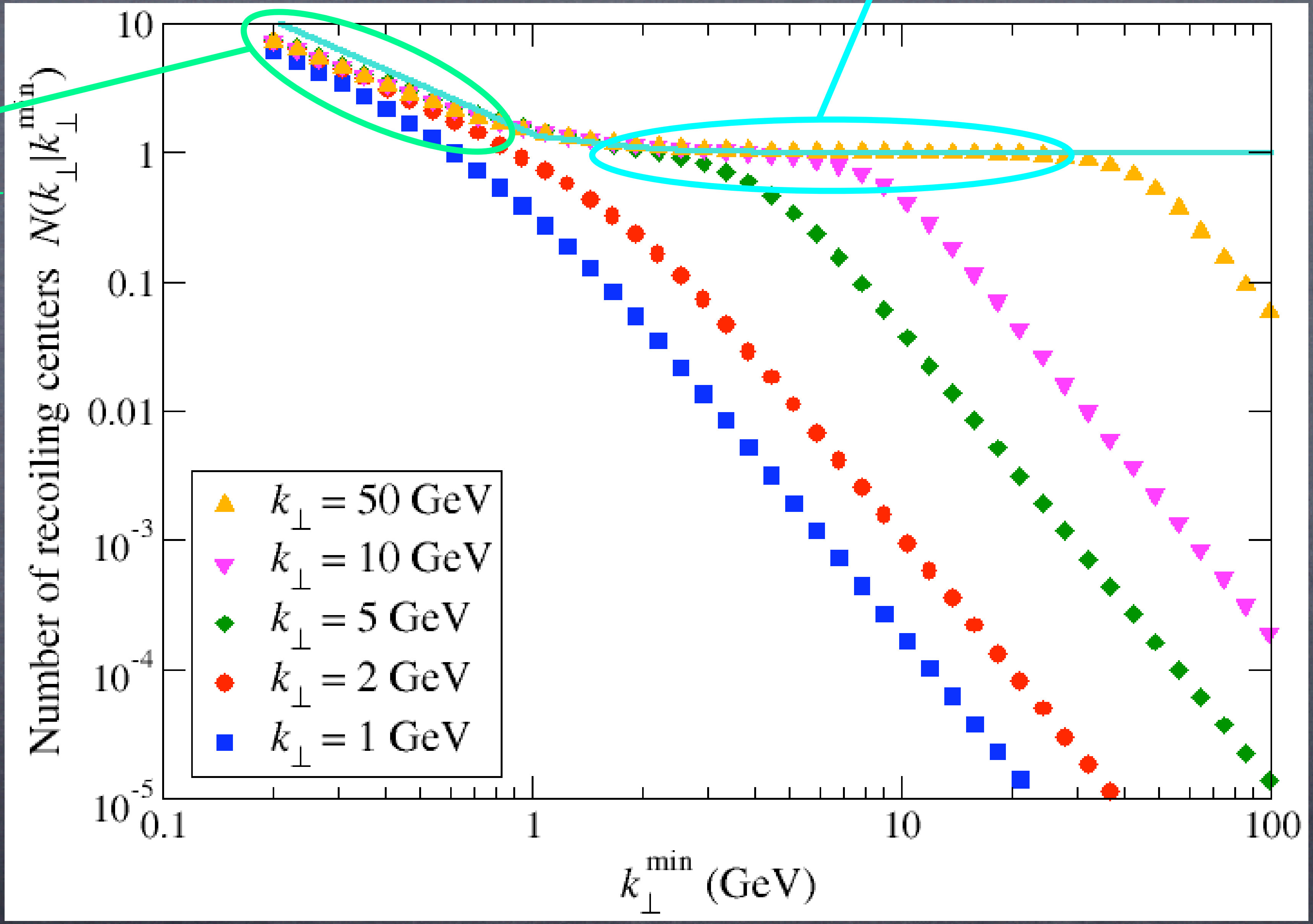
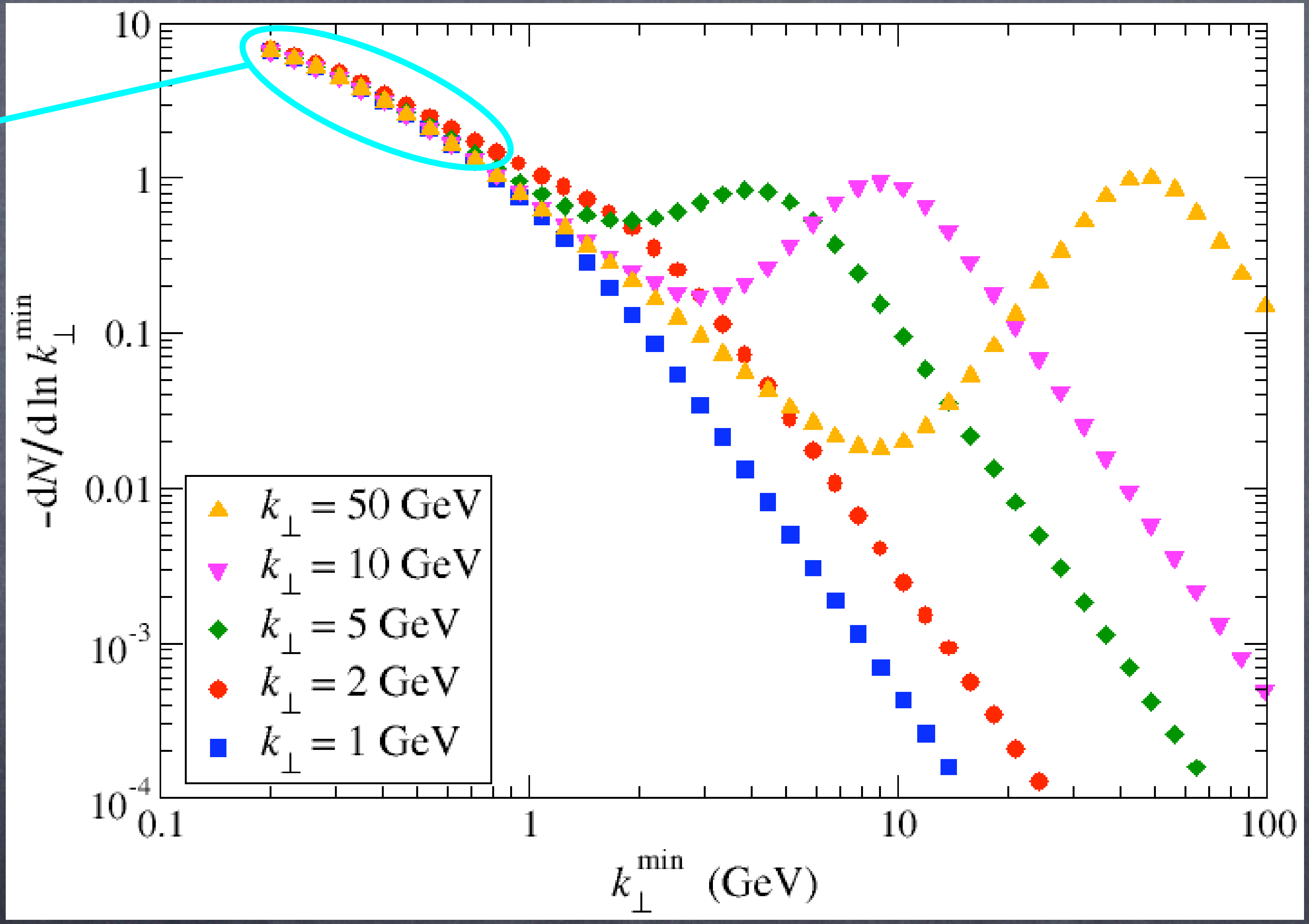


Shifted Poisson distribution: $N(k_\perp|k_\perp^{\rm min}) = 1 + \bar{n}$ with $\bar{n} \propto 1/(k_\perp^{\rm min})^2$.

Momentum distribution of recoils with $q_\perp \geq k_\perp^{\min}$ balancing $k_\perp$

Q_s^2 = 2 GeV²

universal for $k_\perp^{\min} \lesssim Q_s$



Shifted Poisson distribution: $-\dfrac{dN}{d\ln k_\perp^{\min}} \approx 2\bar{n} \propto 1/(k_\perp^{\min})^2.$

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unit-area peak centered around $k_\perp^{\rm min} \simeq k_\perp$ for $k_\perp \gg Q_s$

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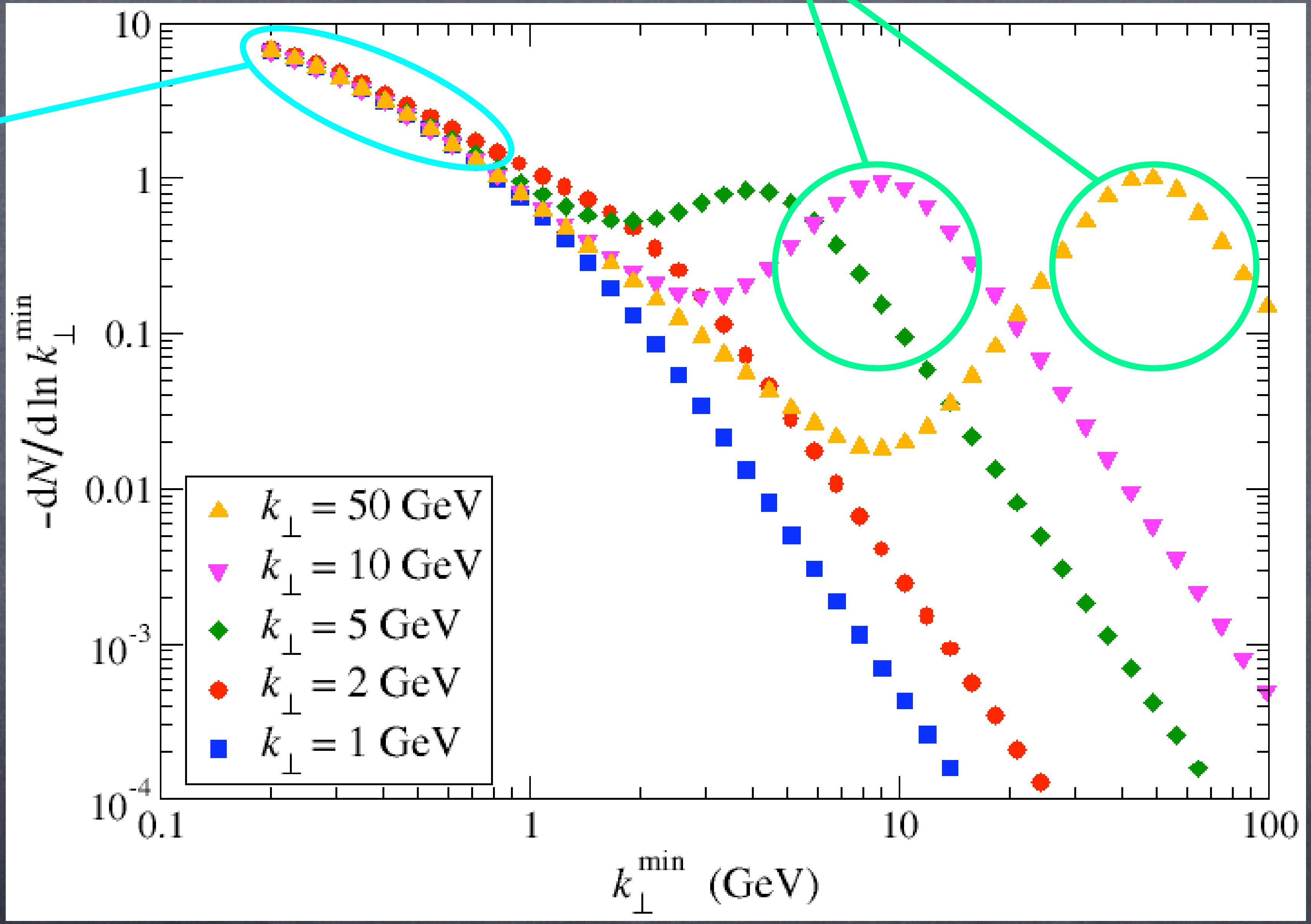

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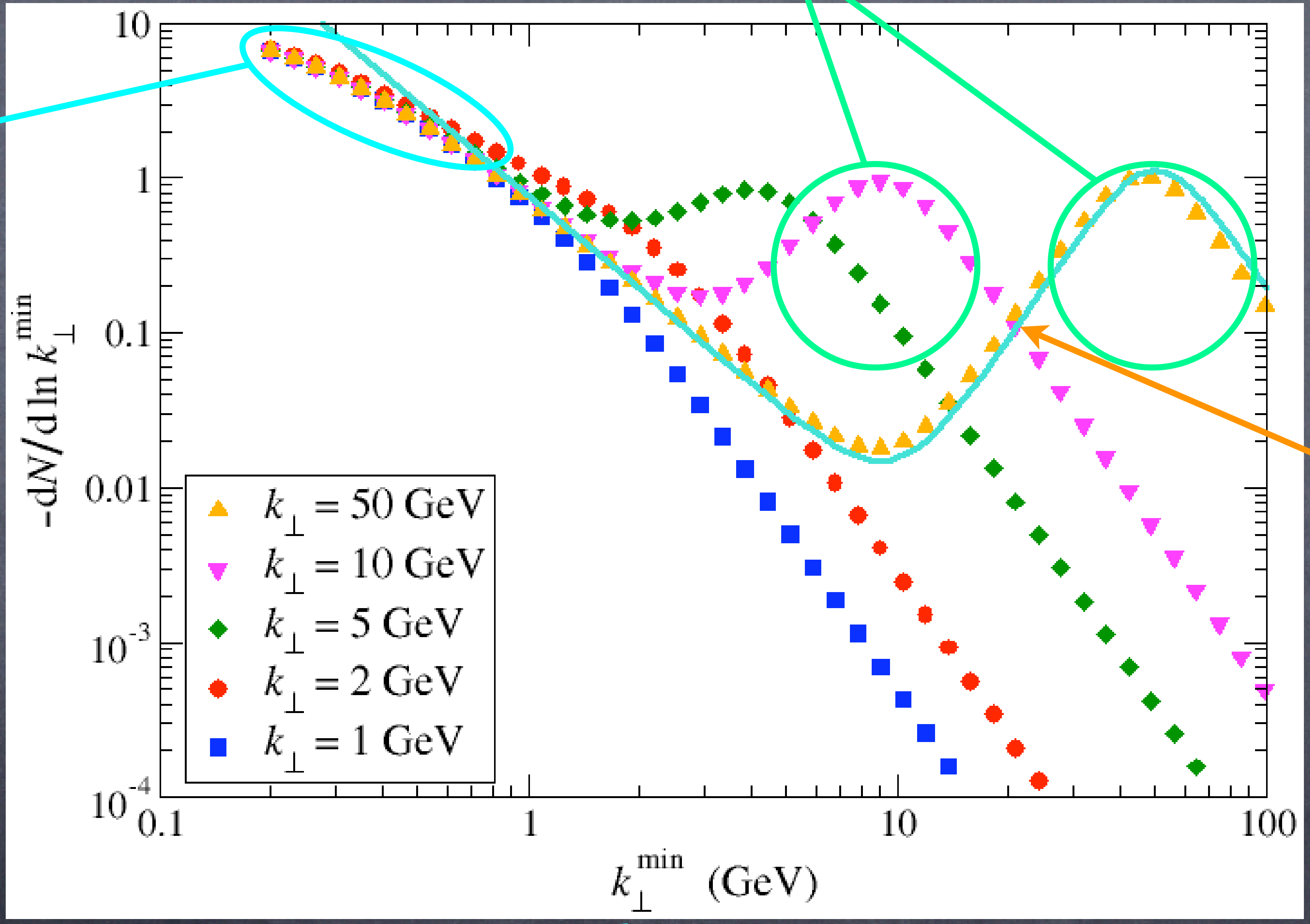

shape due to cutoff function

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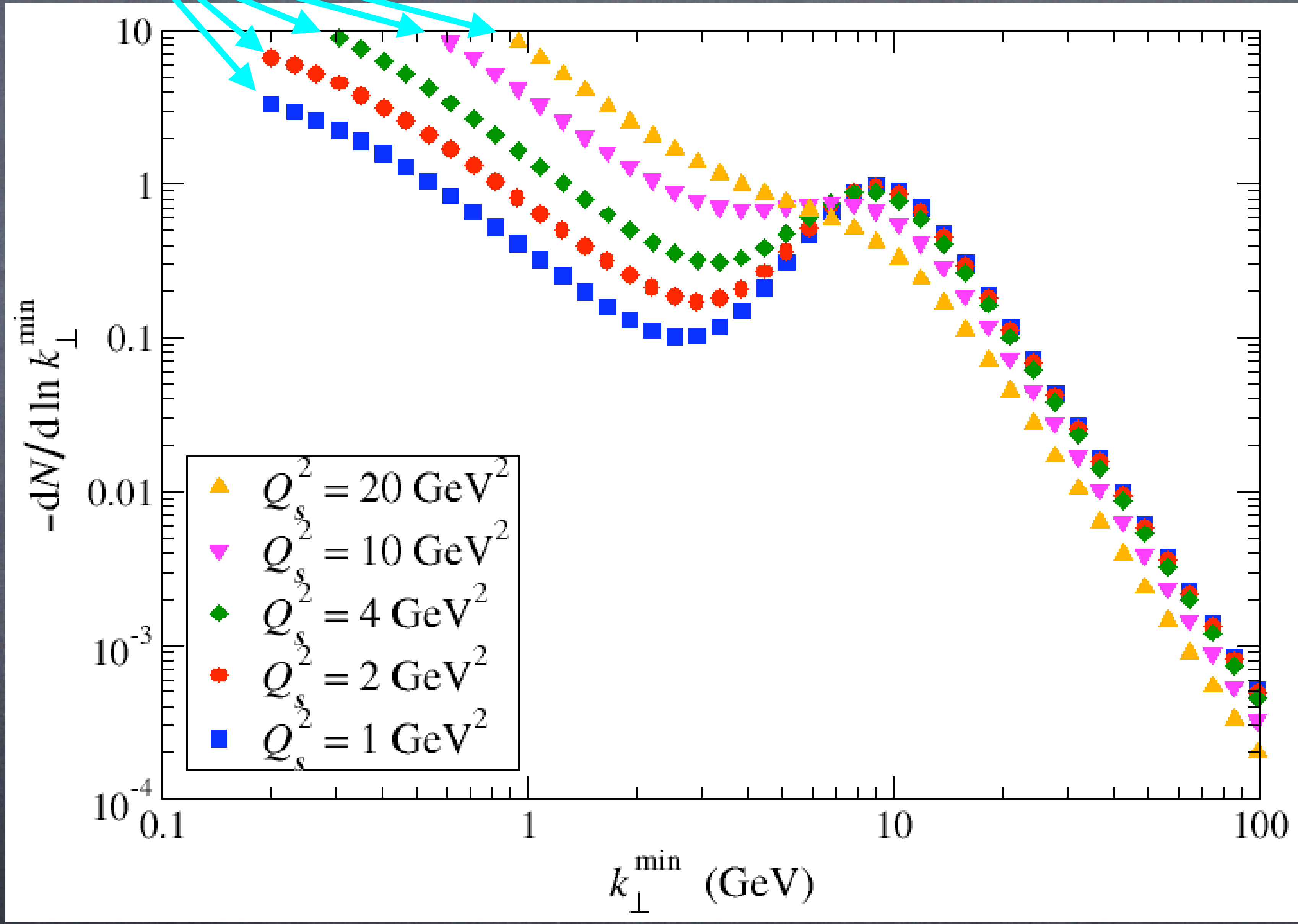
Momentum distribution of recoils with $q_\perp \geq k_\perp^{\min}$ balancing $k_\perp = 10$ GeV

strongly Q_s-dependent

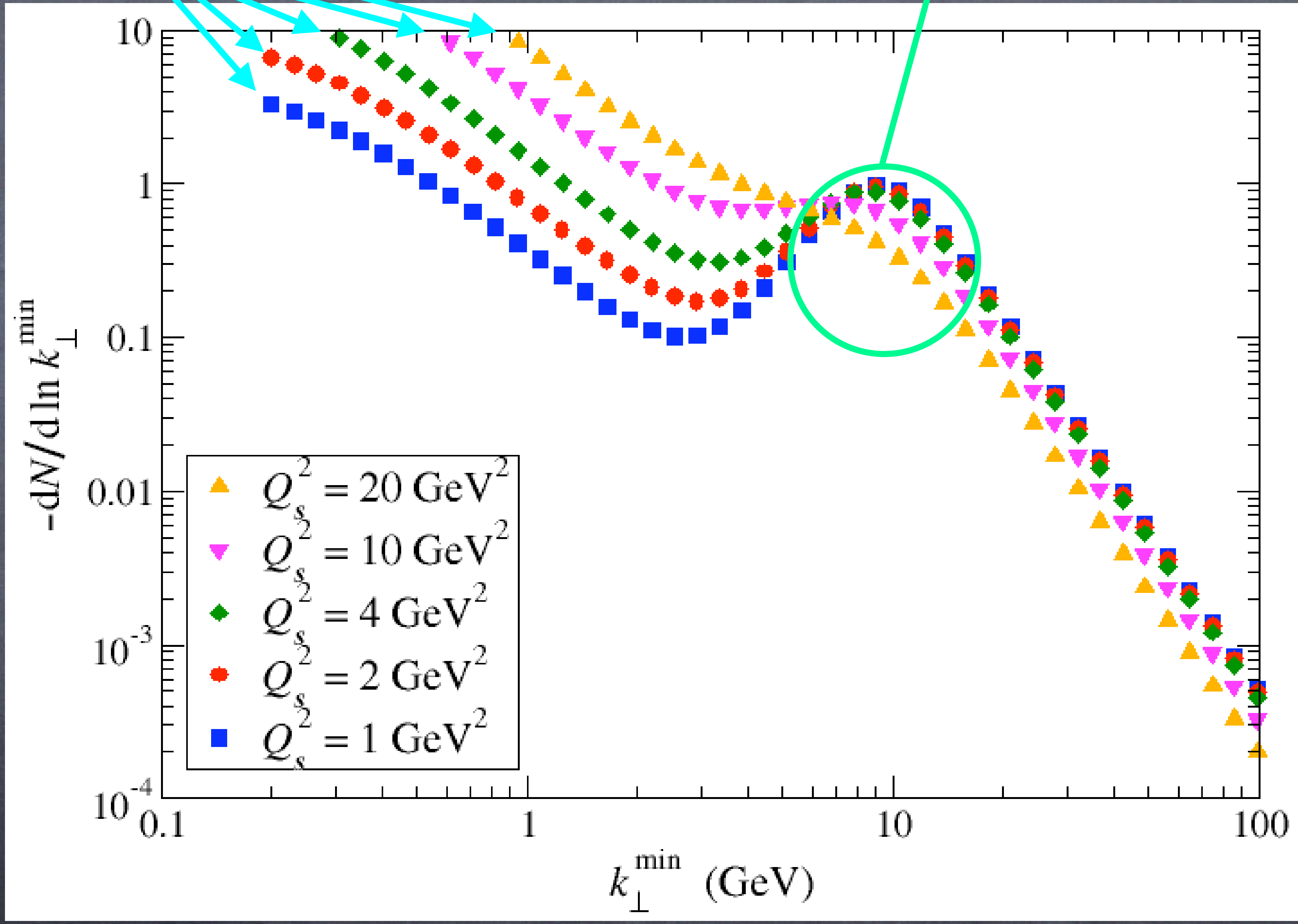


☞ the number of semi-hard scatterings gives access to Q_s.

Momentum distribution of recoils with $q_\perp \geq k_\perp^{\min}$ balancing $k_\perp = 10$ GeV

strongly Q_s-dependent

unchanged as long as $Q_s \ll k_\perp$



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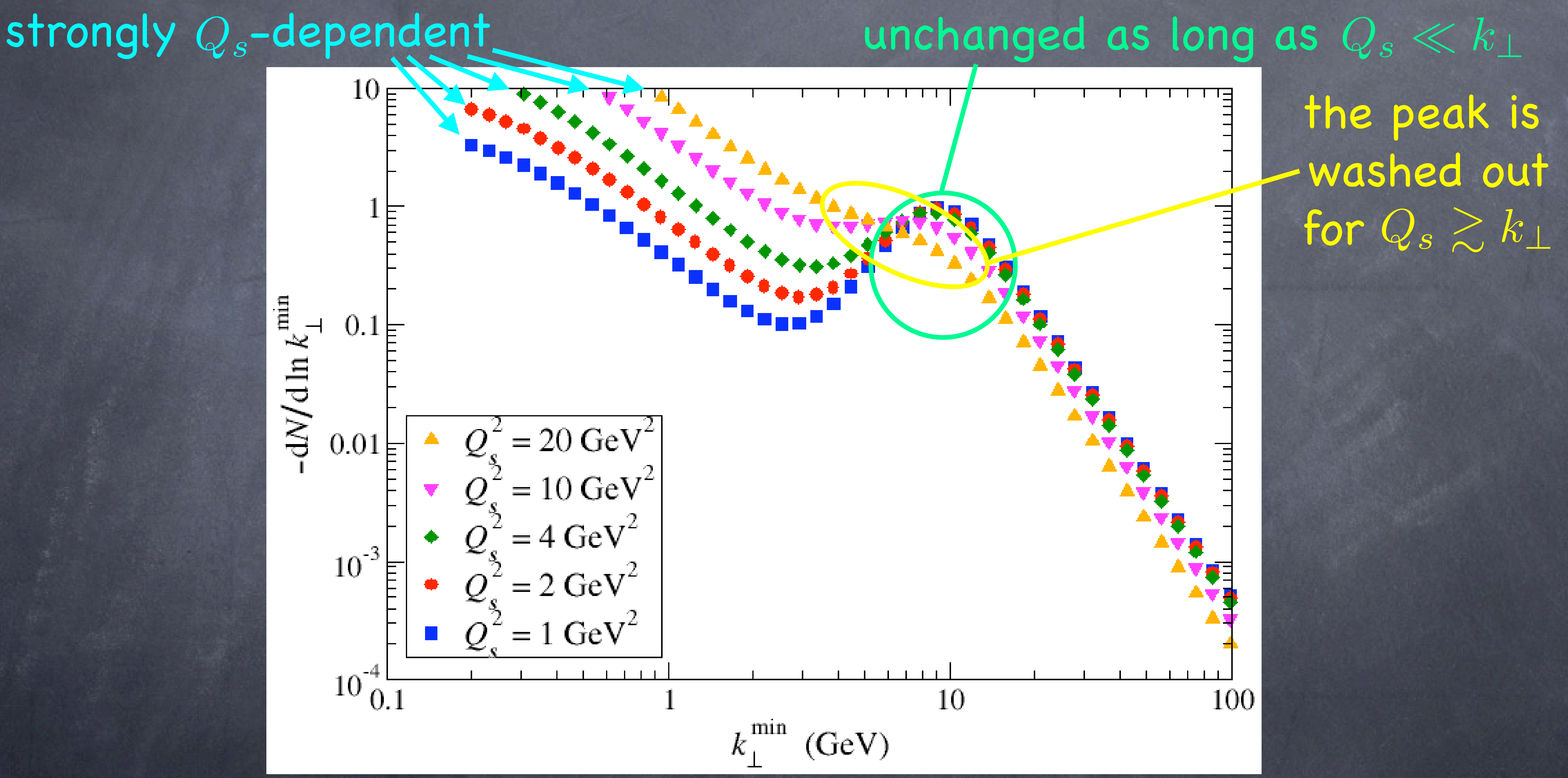

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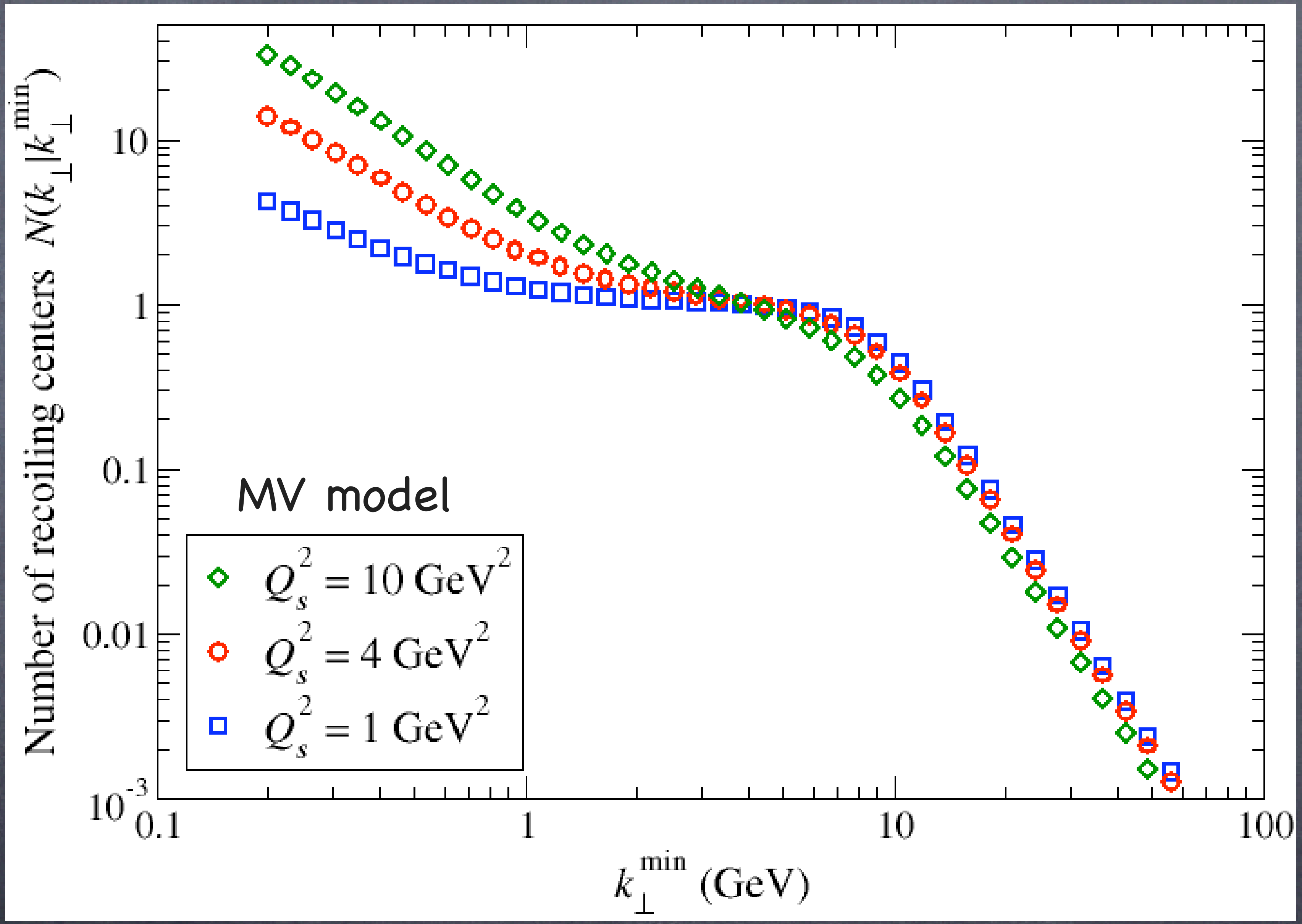
Influence of shadowing on the number of recoils

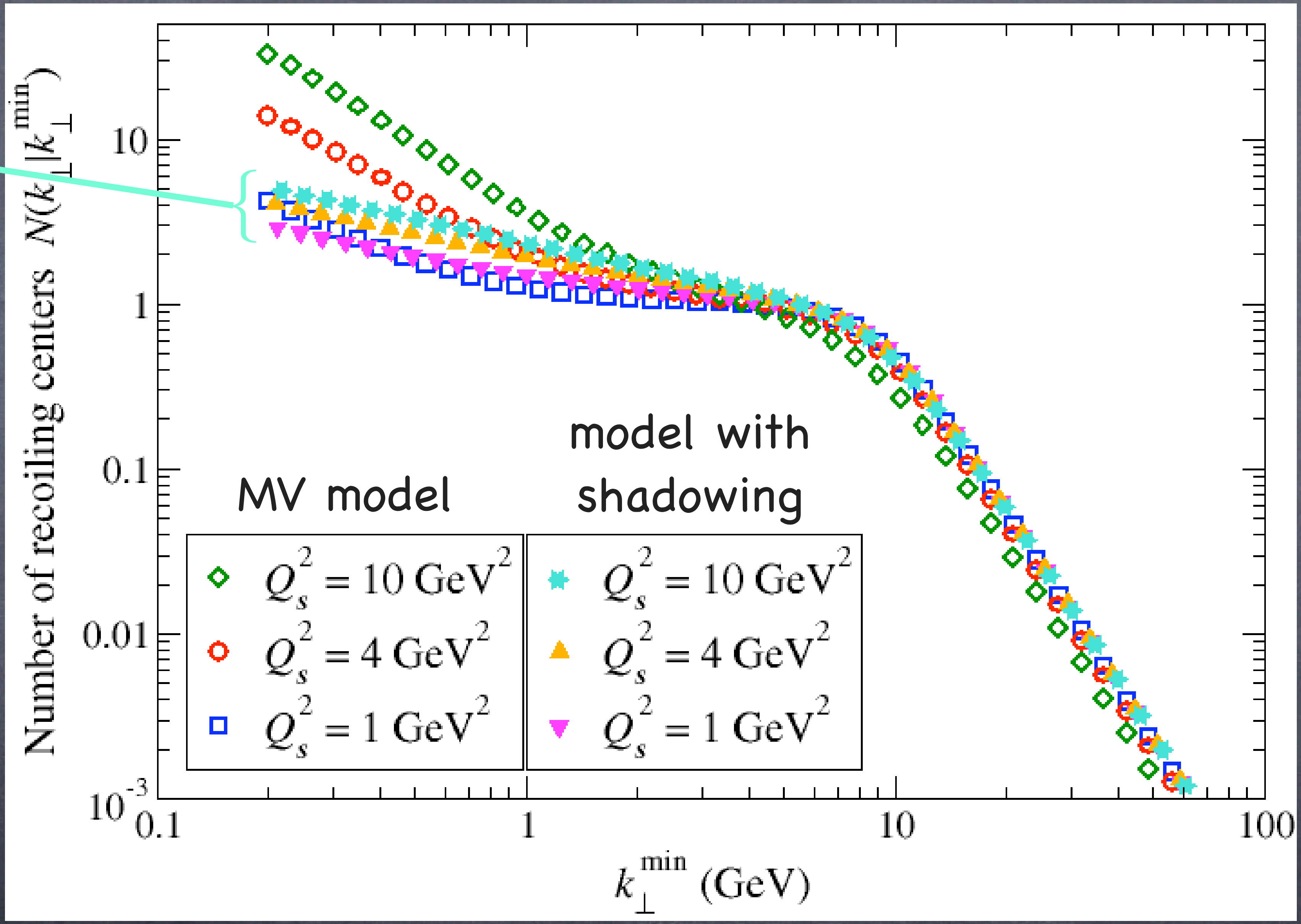
$k_\perp$ = 10 GeV



Influence of shadowing on the number of recoils

$k_\perp$ = 10 GeV

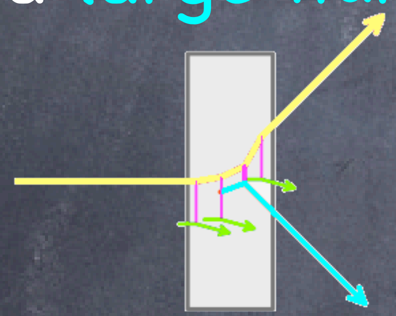
weaker Q_s dependence



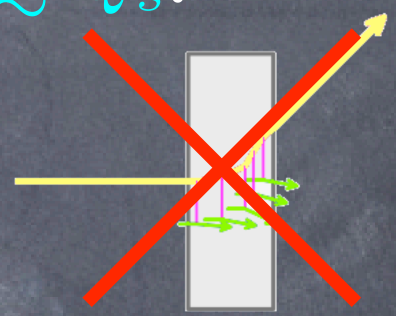
Shadowing ⇒ "charge screening" { less soft & semi-hard collisions; weak sensitivity on charge density }

Are there monojets in high-energy proton-nucleus collisions?

In a proton-nucleus collision, if a gluon is produced with a transverse momentum $k_\perp$ larger than the saturation scale Q_s, this momentum is mostly provided by a single hard scattering with $q_\perp \approx k_\perp$, accompanied by a large number of independent scatterings with $q_\perp \lesssim Q_s$.



☛ dijets, rather than monojets



In a model that includes leading-twist shadowing, which describes the regime of very small x, the number of scatterings with $q_\perp \lesssim Q_s$ is significantly smaller than in the absence of shadowing.

The separation between the contributions of semi-hard ($q_\perp \sim Q_s$) and soft ($q_\perp \ll Q_s$) scatterings is less marked than in the shadowing-free McLerran–Venugopalan model.