QGSJET-III model: Physics & Preliminary Results

Sergey Ostapchenko
Frankfurt Institute for Advanced Studies

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Total cross section & jet production

- High energy hadron scattering ⇒ copious production of (mini-)jets *[e.g., Gaisser & Halzen, 1985]*
- Inclusive cross section for production jets of $p_{\rm t} > p_{\rm t}^{\rm cut}$:

$$\sigma_{pp}^{\rm jet}(s, p_{\rm t}^{\rm cut}) = \sum_{I,J=q,\bar{q},g} \int_{p_{\rm t}>p_{\rm t}^{\rm cut}} dp_t^2 \int dx^+ \, dx^- \, f_{I/p}(x^+, M_{\rm F}^2) \times \frac{d\sigma_{IJ}^{2\to 2}(x^+x^-s, p_t^2, M_{\rm F}^2)}{dp_t^2} \, f_{J/p}(x^-, M_{\rm F}^2)$$

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  - $\sigma_{pp}^{\mathrm{jet}}(s, Q_0) \propto \frac{1}{Q_0^2} s^{\Delta_{\mathrm{eff}}}$, $\Delta_{\mathrm{eff}} \simeq 0.3$
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  - $\sigma_{pp}^{\rm tot}(s) \propto \ln^2 s$
- $\Rightarrow$ multiple jet production required
  - $=$ multiparton interactions (MPIs)

MPIs & generalized parton distributions (GPDs)

- Usual PDFs $f_I(x, Q^2)$ insufficient to describe MPIs
  - multiparton GPDs $F^{(n)}_{I_1 \ldots I_n}(x_1, \ldots x_n, \vec{b}_1, \ldots \vec{b}_n, Q_1^2, \ldots Q_n^2)$ required

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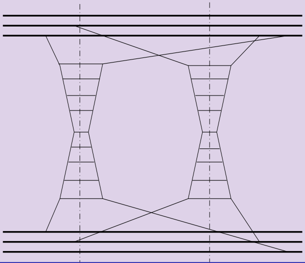
E.g., $F^{(2)}$ for double parton scattering (production of 2 dijets)

$$\sigma^{\rm 4jet(DPS)}_{pp}(s, p_{\rm t}^{\rm cut}) = \frac{1}{2} \int dx_1^+ dx_2^+ dx_1^- dx_2^- \int_{p_{\rm t_1}, p_{\rm t_2} > p_{\rm t}^{\rm cut}} dp_{\rm t_1}^2\, dp_{\rm t_2}^2 \sum_{I_1, I_2, J_1, J_2}$$

$$\times \frac{d\sigma^{2\to 2}_{I_1 J_1}}{dp_{\rm t_1}^2} \frac{d\sigma^{2\to 2}_{I_2 J_2}}{dp_{\rm t_2}^2} \int d^2 \Delta b\, F^{(2)}_{I_1 I_2}(x_1^+, x_2^+, M_{\rm F_1}^2, M_{\rm F_2}^2, \Delta b)\, F^{(2)}_{J_1 J_2}(x_1^-, x_2^-, M_{\rm F_1}^2, M_{\rm F_2}^2, \Delta b)$$



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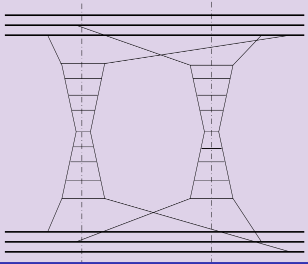
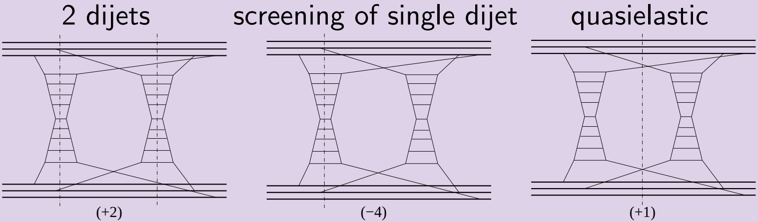
- standard simplification:
  neglect multiparton correlations
- $\Rightarrow F^{(n)}_{I_1\ldots I_n}(x_1,\ldots x_n,\vec{b}_1,\ldots\vec{b}_n,\ldots)=\prod_{i=1}^n G_{I_i}(x_i,\vec{b}_i,Q^2_i)$
- $\Rightarrow \sigma^{4\text{jet(DPS)}}_{pp}(s,p^{\rm cut}_{\rm t})=\frac{1}{2}\int d^2b\left[G_I\otimes\sigma^{2\to2}_{IJ}\otimes G_J\right]^2$



Total cross section & multiple scattering

Relation to σ_{pp}^{tot} and σ_{pp}^{inel} comes from the AGK cutting rules



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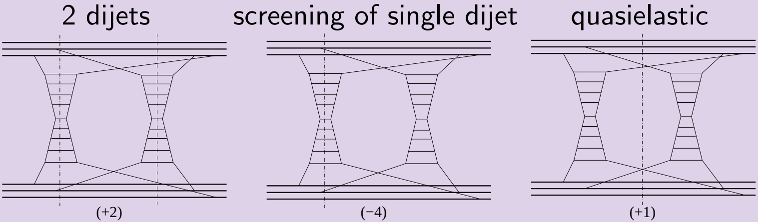

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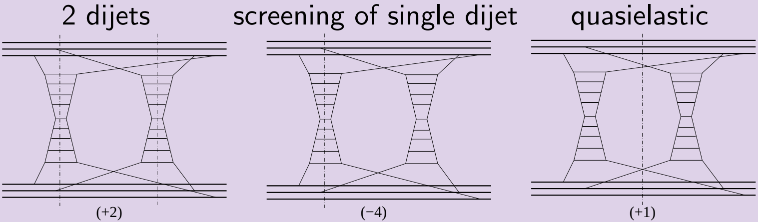

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- $\Rightarrow \Delta^{(2)}\sigma_{pp}^{\rm tot} = -\frac{1}{2}\sigma_{pp}^{\rm 4jet(DPS)}$ (similarly for $n > 2$ dijets)
- this leads to the usual 'minijet' ansatz:
  $\sigma_{pp}^{\rm tot}(s) = 2\int d^2b \left[1 - \exp(-\chi_{pp}^{\rm jet}(s,b,p_{\rm t}^{\rm cut}))\right]$
  $\left(\ \chi_{pp}^{\rm jet}(s,b,p_{\rm t}^{\rm cut}) = \frac{1}{2}\sum_{I,J} G_I \otimes \sigma_{IJ}^{2\to 2} \otimes G_J\ \right)$

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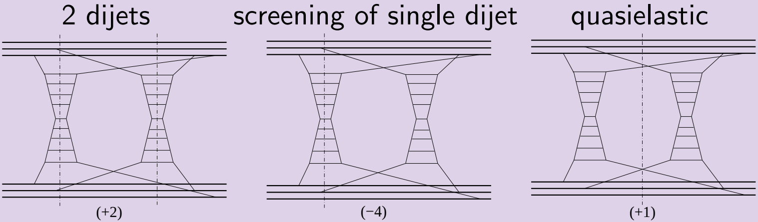

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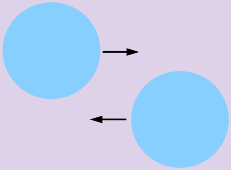
NB: inclusive jet cross section – unmodified by such MPIs

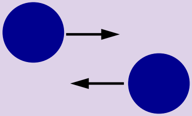
- e.g., summary contribution of the 3 processes: $2*(+2)+1*(-4)+0*(+1)=0$
- $\Rightarrow$ collinear factorization holds: $\frac{d\sigma_{pp}^{jet}}{dp_t^2} = \sum_{I,J} f_I \otimes \frac{d\sigma_{IJ}^{2\to 2}}{dp_t^2} \otimes f_J$

Main message: to reduce σ_{pp}^{tot}, enhance MPIs

Simpliest way to regulate the rise of σ_{pp}^{tot}: denser parton 'packing'



- larger proton size
  $\Rightarrow$ larger σ_{pp}^{tot}
- smaller parton density
  $\Rightarrow$ smaller MPI rate



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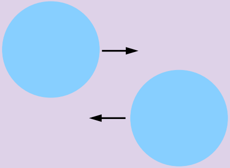

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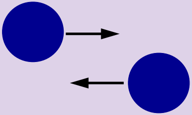

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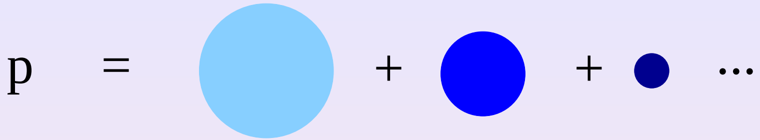
- Unfortunately, not a solution:
  proton size is constrained by data on $B_{pp}^{el}(s) \propto \langle b^2(s) \rangle$
- more generally, $d\sigma_{pp}^{el}/dt$ is related to the transverse profile of the proton (thanks to data of TOTEM & ATLAS ALFA)

Next possibility: color fluctuations in the proton



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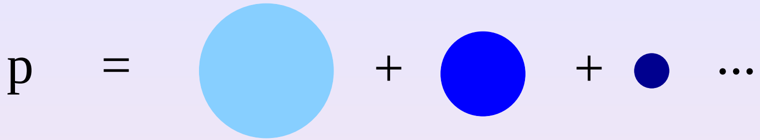

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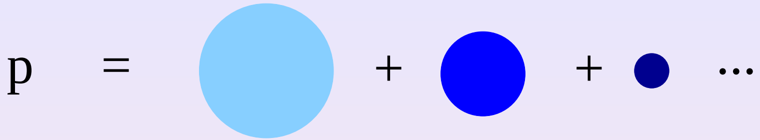

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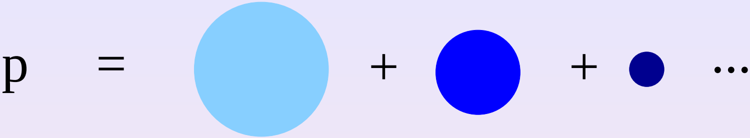

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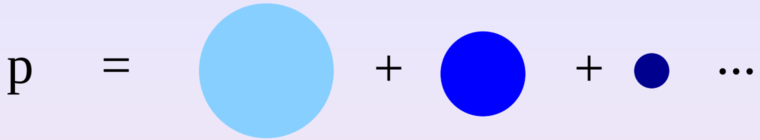

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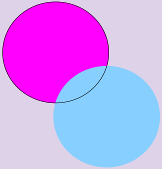
- but: would yield a high cross section for low mass diffraction
  - NB: $\sigma_{pp}^{\rm SD(LM)}$ – constrained by TOTEM & LHCf data

Nearly last possibility: introduce parton 'clumps'

What is wrong with the uncorrelated parton picture?

- double (multiple) hard scattering results from independent cascades
  - ⇒ mostly in central collisions



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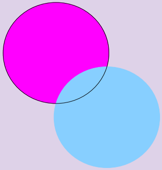
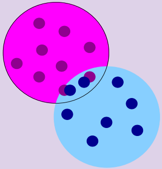


How multiparton correlations help?

- one has to create parton 'clumps' to enhance peripheral multiple scattering (without changing the transverse profile)
  - can be done via 'soft' & 'hard' parton splitting mechanisms



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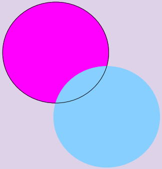

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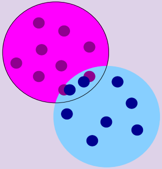
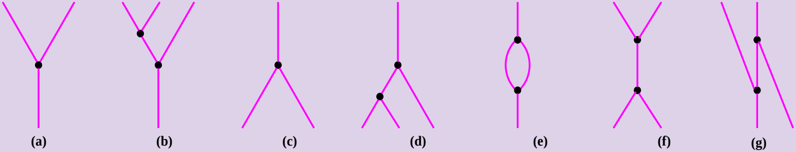


- 'soft parton splitting' naturally emerges in enhanced Pomeron framework in QGSJET-II *[SO, 2006, 2011]*

QGSJET-II: interactions between parton cascades

Nonlinear processes: Pomeron-Pomeron interactions (scattering of intermediate partons off the proj./target hadrons & off each other)



thick lines = Pomerons = 'elementary' parton cascades

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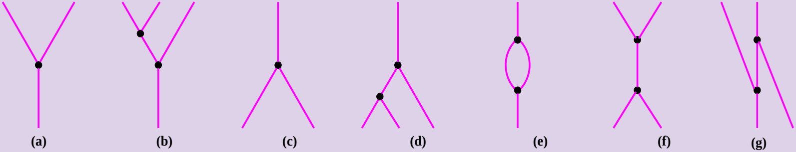

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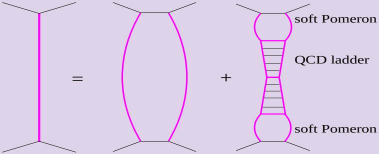
'General Pomerons' contain both soft & hard processes ('semihard Pomeron' approach) *[Drescher et al., 2001]*

- soft Pomerons to describe soft (parts of) cascades $(p_t^2 < Q_0^2)$
  - $\Rightarrow$ transverse expansion governed by (small) Pomeron slope



- DGLAP for hard cascades

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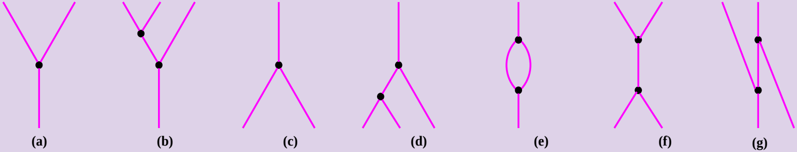

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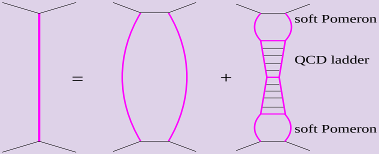

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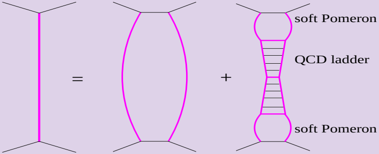
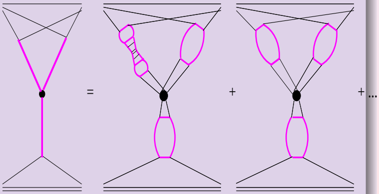


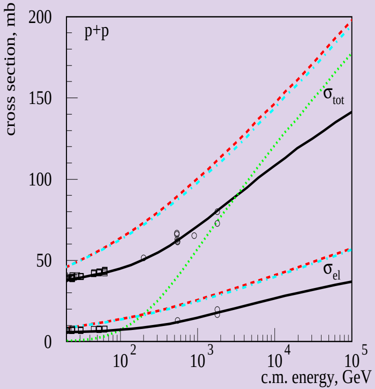
Pomeron-Pomeron interaction: a closer look

- basic assumption: multi-$\mathbb{P}$ vertices – dominated by soft ($|q^2| < Q_0^2$) parton processes



Taking into account interactions between parton cascades substantially reduces the impact of jet production on σ_{pp}^{tot}

- e.g., a reasonable fit of σ_{pp}^{tot} was obtained for a low cutoff $Q_0^2 = 1$ GeV^2 *[SO, 2006]*
- though stricter constraints from particle production: $Q_0^2 = 3$ GeV^2 in QGSJET-II-04



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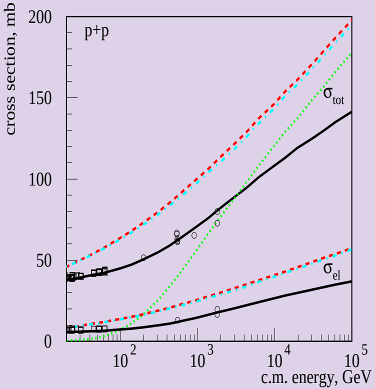
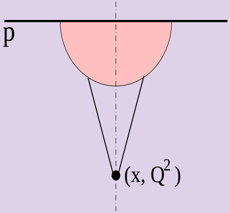


- these results can be explained in 2 different ways

1st explanation: rescattering of intermediate partons reduces effective parton density

For independent parton cascades, one uses universal PDFs (GPDs)

- those contain rescattering of intermediate partons off the parent hadron only (hidden in the 'blob')



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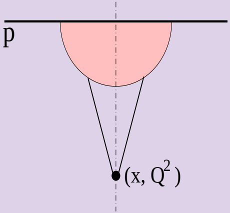
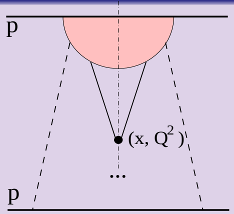


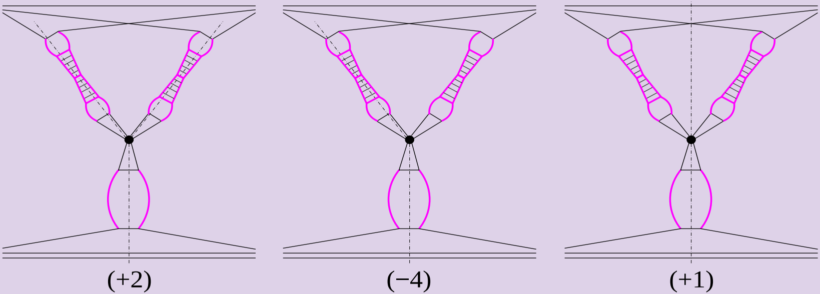
In enhanced framework, parton density is influenced by the collision

- intermediate partons scatter off the partner proton in addition
  - this dynalically reduces the effective parton density for an exclusive process (stronger effect for higher s, smaller b)



2nd explanation: 'clumping' due to 'soft parton splitting'

E.g., double dijet production from soft Pomeron splitting



- small slope for soft Pomeron ⇒ two hard processes are closeby in b-space
  - ≡ having a parton 'clump' in the target proton
- ⇒ enhanced MPI rate in peripheral collisions

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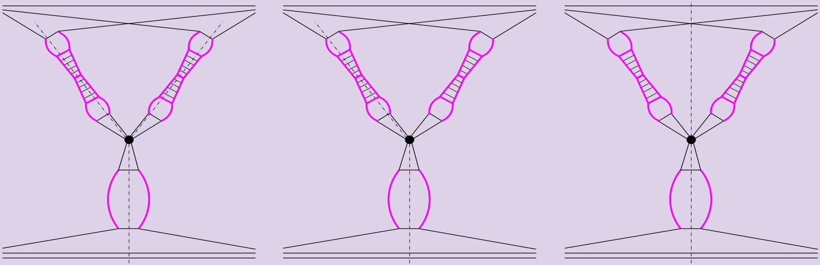

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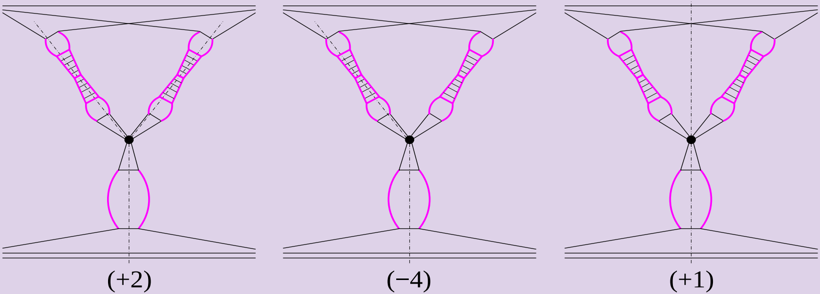

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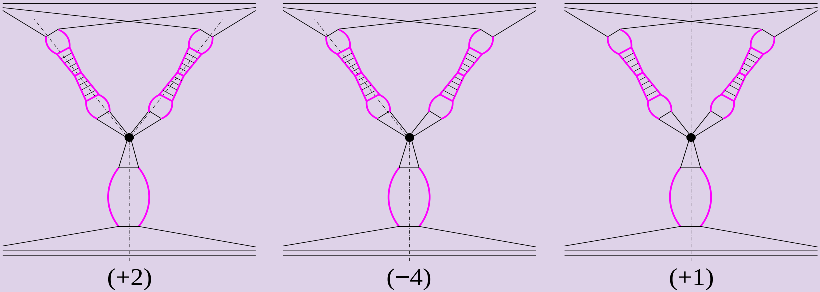

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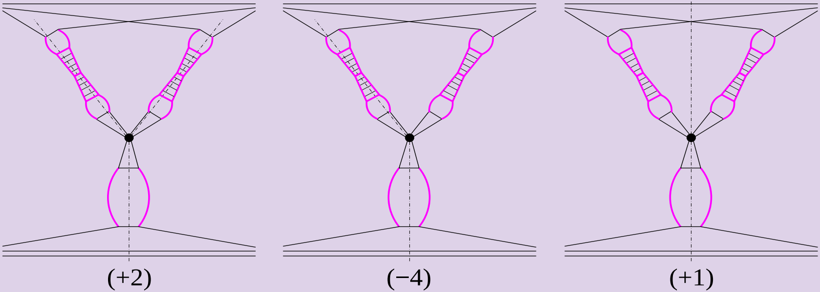

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Generic property: thanks to AGK cancellations, collinear factorization holds for inclusive jet cross section

$$\frac{d\sigma_{pp}^{\rm jet}}{dp_t^2} = \sum_{I,J} f_I \otimes \frac{d\sigma_{IJ}^{2\to 2}}{dp_t^2} \otimes f_J$$

General major problem with hadron multiplicity rise

Applies to any model which respects collinear factorization

- $\sigma_{pp}^{\rm jet}(s,Q_0) \propto \frac{1}{Q_0^2}\, s^{\Delta_{\rm eff}}$, $\Delta_{\rm eff} \simeq 0.3$
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- wanted: a perturbative mechanism to suppress low p_{t} jet production, without a strong impact on PDFs

Dynamical higher twist corrections as a potential solution?

Power corrections seem to fit in the demand

- can (in principle and to some extent) be treated perturbatively
- come into play at relatively small $p_{\rm t}$ (suppressed as $1/(p_{\rm t}^2)^n$)
- appeared to be significant for nuclear targets
  - hence, may be important for pp as well

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- contributions involve many unknown mutiparton correlators
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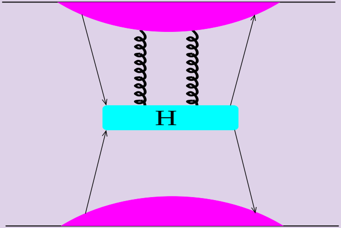
- $\Rightarrow$ brave (wild?) assumptions may be needed

Dynamical higher twist corrections: brave assumptions

Basic assumptions (qq'-scattering as an example)

- restrict oneself with rescattering on soft ($x_g \simeq 0$) gluons
- neglect color octet contributions



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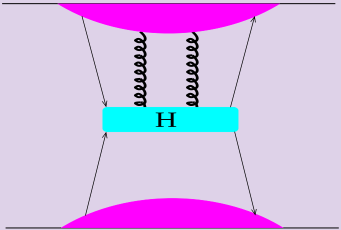

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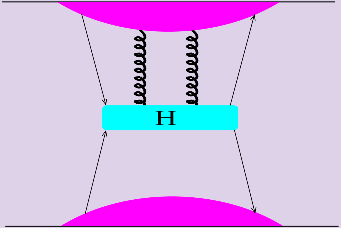

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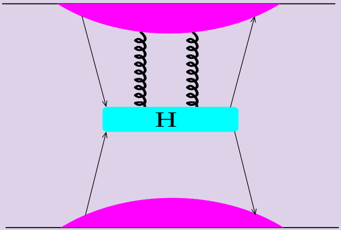

Some justifications

- dominant contributions in the small x limit usually from gluons
- soft gluon contributions proved important for p_t-broadening and suppression of SFs & jet spectra on nuclear targets *[Guo, 1998; Guo & Qiu, 2000; Qiu & Vitev, 2004, 2006]*
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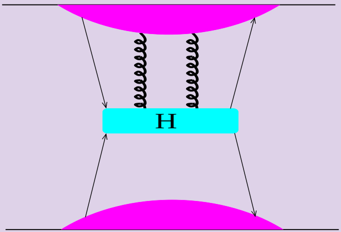

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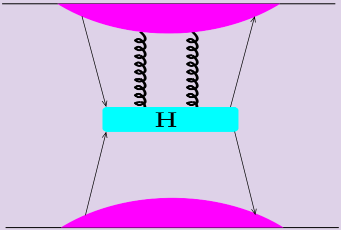

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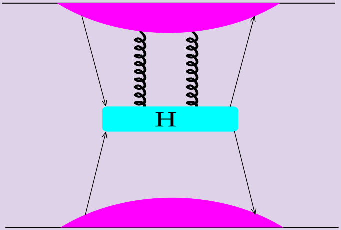

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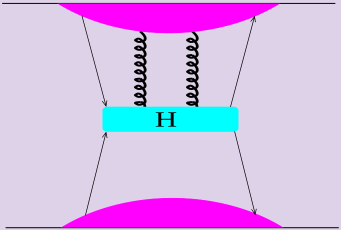

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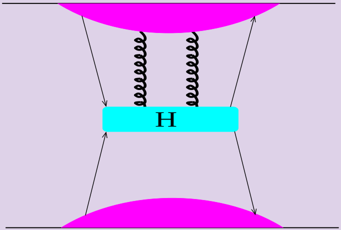

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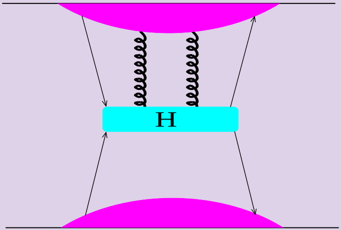

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- describe low x GPDs by Pomeron asymptotics
- account for multiparton correlations due to the "soft splitting" mechanism
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- i.e., incorporate the mechanism in the Pomeron framework
    - NB: AGK rules not applicable for HT contributions

Dynamical higher twist corrections: hevristic reasoning

Consider as an example corrections to qq' scattering in LC gauge

Twist 4 contribution to the cross section:

$$\Delta\sigma_{\mathrm{HT}}(s) = \frac{1}{2s}\int \frac{d^4k_q}{(2\pi)^4}\frac{d^4k_{q'}}{(2\pi)^4}\frac{d^4k_{g_1}}{(2\pi)^4}\frac{d^4k_{g_2}}{(2\pi)^4}\,H^{\alpha\beta}_{ijkl}(k_q,k_{q'},k_{g_1},k_{g_2})$$
$$\times\left[\int d^4z_q d^4z_{g_1} d^4z_{g_2}\, e^{ik_qz_q+ik_{g_1}z_{g_1}-ik_{g_2}z_{g_2}}\langle p|\bar\psi_j(0)A_\alpha(z_{g_2})A_\beta(z_{g_1})\psi_i(z_q)|p\rangle\right]$$
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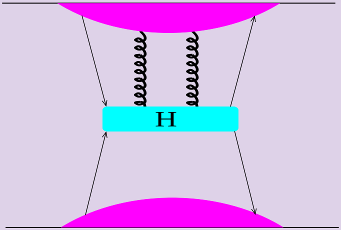

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- doing collinear factorization, one obtains *[Ellis et al., 1982; Qiu, 1990]*

$$\Delta\sigma_{\rm HT}(s) = \int dx_{q'}\,dx_q\,dx_{g_1}\,dx_{g_2}$$
$$\times\quad q(x_{q'})\,T_{qg}(x_q,x_{g_1},x_{g_2})$$
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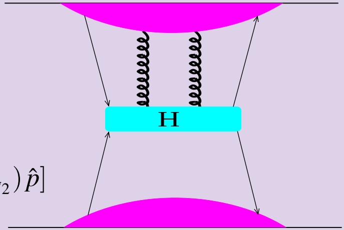

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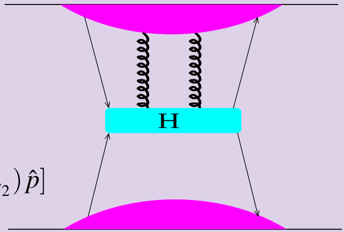

- here the quark-gluon correlation function:

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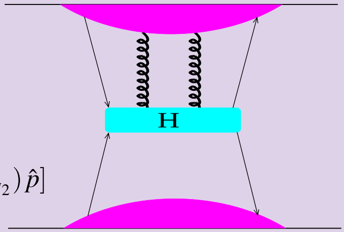

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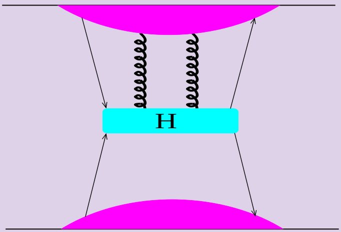
- now: assume the integrals to be dominated by $x_{g_1}, x_{g_2} \simeq 0$
  - e.g., converting $1/x_{g_i}$ into poles & doing residies *[Guo & Qiu, 2001]*

Dynamical higher twist corrections: hevristic reasoning

Most radical assumptions

- observe that $\lim_{x_{g_{1,2}}\to 0} x_{g_1} x_{g_2} T_{qg}(x_q, x_{g_1}, x_{g_2}) \propto \lim_{x_g \to 0} x_g F^{(2)}_{qg}(x_q, x_g, \Delta b = 0)$



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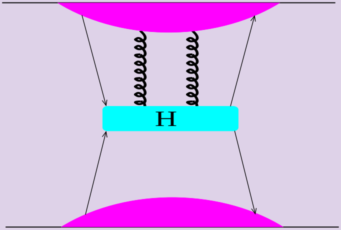

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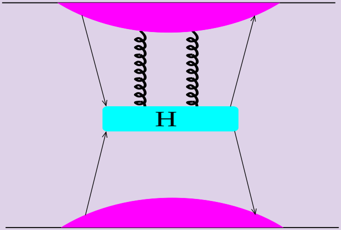

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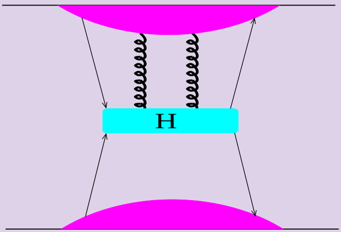

- observe that
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- Currently, implementation of the HT-effects is the main difference to QGSJET-II-04
  - now twice smaller cutoff for hard processes: $Q_0^2 = 1.5$ GeV^2 ($\Rightarrow p_{\rm t}^{\rm cut} \simeq 2.4$ GeV)
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- what about using even a smaller cutoff?
  - generally possible but would require higher order corrections (multiple exchanges of soft gluons)
  - $\Rightarrow$ additional assumptions

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$\sqrt{s}$-dependence of $\sigma_{pp}^{tot/el}$: different effects

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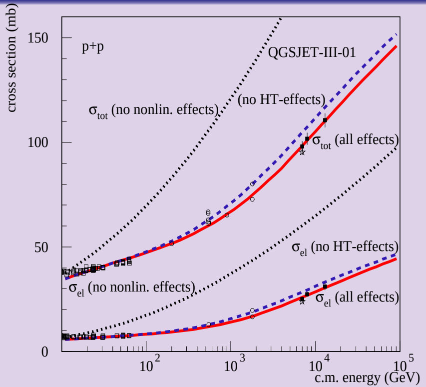

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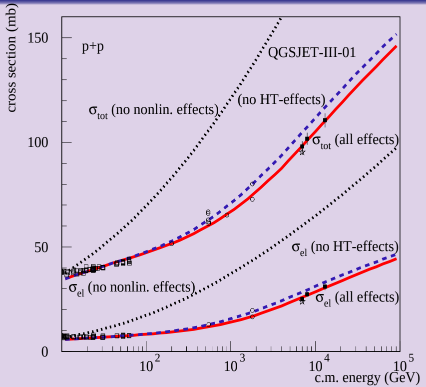

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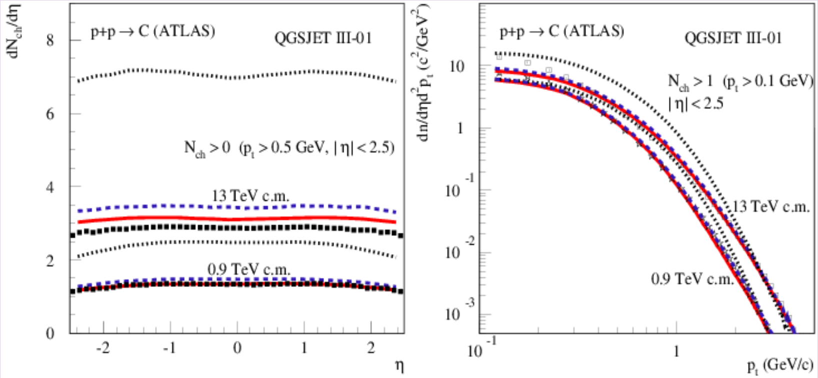
$\sqrt{s}$-dependence of $dN_{\rm ch}/d\eta$ & $dN_{\rm ch}/dp_{\rm t}$



- soft production: mostly affected by enhanced diagrams (shadowing & saturation of soft ($p_{\rm t} < p_{\rm t}^{\rm cut}$) parton cascades)
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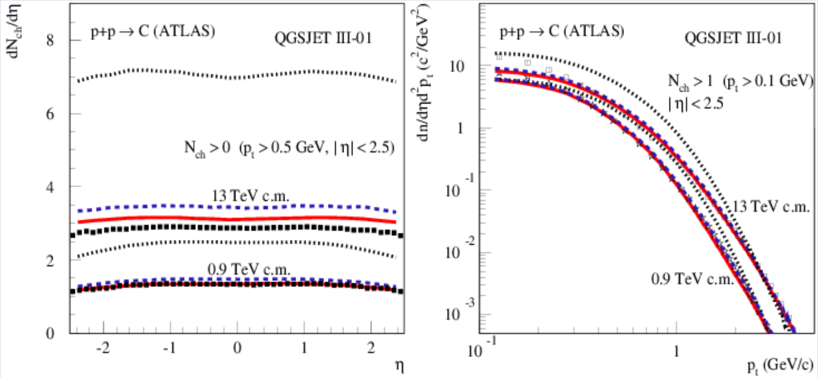

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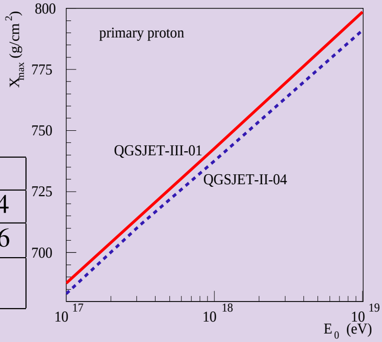
E.g., $\simeq 5$ g/cm^2 shift of $X_{\max}$ – mostly due to higher diffraction

- not sure about it because of the CMS-TOTEM tension:

	TOTEM	CMS
M_X range, GeV	$7-350$	$12-394$
$\sigma_{pp}^{SD}(\Delta M_X)$, mb	$\simeq 3.3$	4.3 ± 0.6
$\frac{d\sigma_{pp}^{SD}}{dy_{gap}}$, mb	0.42	0.62



Outlook

1. Treatment of nonlinear effects due to enhanced Pomeron graphs remains the key element of the model
   - with 2 adjustable parameters, provides a very rich formalism
   - plays central role for timing the energy-rise of cross sections & soft hadron production
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