Damping the energy-rise of $\sigma_{pp}^{\rm tot}$: interplay of perturbative & nonperturbative effects

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Outline

1. Total cross section & multiple scattering
2. Total cross section & multi-parton interactions
   - multi-parton correlations & multi-Pomeron interactions
   - role of perturbative parton splitting
3. Dynamical higher twist corrections
   - discussion of a phenomenological approach

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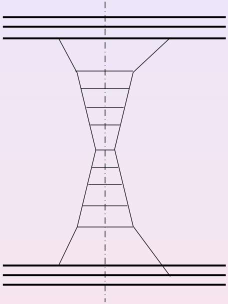
Total cross section & multiple scattering

- Production of (mini)jets dominates high energy collisions
- inclusive jet cross section $\sigma_{pp}^{\rm jet}(s, p_t^{\rm cut})$: steep energy rise ($\propto s^{\Delta_{\rm eff}}$, $\Delta_{\rm eff} \simeq 0.3$)
  - $\Rightarrow$ multiple parton scattering is a must ($\sigma_{pp}^{\rm jet}(s, p_t^{\rm cut}) > \sigma_{pp}^{\rm inel}(s)$)



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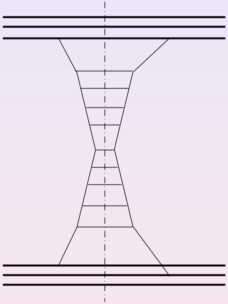


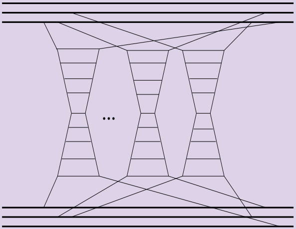
Total cross section & multiple scattering

Multiple parton scattering involves multiparton distributions

e.g., DPDs (^{2}GPDs) $F^{(2)}$ for double scattering:

$$\sigma_{pp}^{\text{4jet(DPS)}}(s, p_{\text{t}}^{\text{cut}}) = \frac{1}{2} \int dx_1^+ dx_2^+ dx_1^- dx_2^- \int_{p_{\text{t}_1}, p_{\text{t}_2} > p_{\text{t}}^{\text{cut}}} dp_{\text{t}_1}^2 \, dp_{\text{t}_2}^2 \sum_{I_1, I_2, J_1, J_2}$$

$$\times \frac{d\sigma_{I_1 J_1}^{2\to 2}}{dp_{\text{t}_1}^2} \frac{d\sigma_{I_2 J_2}^{2\to 2}}{dp_{\text{t}_2}^2} \int d^2 \Delta b \, F_{I_1 I_2}^{(2)}(x_1^+, x_2^+, M_{\text{F}_1}^2, M_{\text{F}_2}^2, \Delta b) \, F_{J_1 J_2}^{(2)}(x_1^-, x_2^-, M_{\text{F}_1}^2, M_{\text{F}_2}^2, \Delta b)$$



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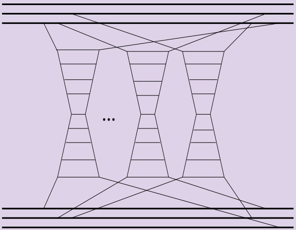
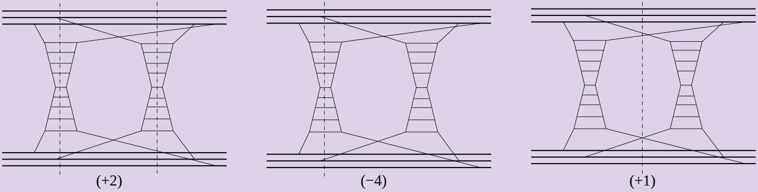
- standard simplification:
  neglect multiparton correlations
- $\Rightarrow F_{I_1 I_2}^{(2)}(x_1, x_2, \Delta b) =$
  $\int d^2 b\, f_{I_1}(x_1, b)\, f_{I_2}(x_2, |\vec{b} + \vec{\Delta b}|)$
- $\Rightarrow \sigma_{pp}^{\mathrm{4jet(DPS)}}(s, p_{\mathrm{t}}^{\mathrm{cut}}) =$
  $\frac{1}{2}\int d^2 b \left[f_I \otimes \sigma_{IJ}^{2\to 2} \otimes f_J\right]^2$



Total cross section & multiple scattering

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



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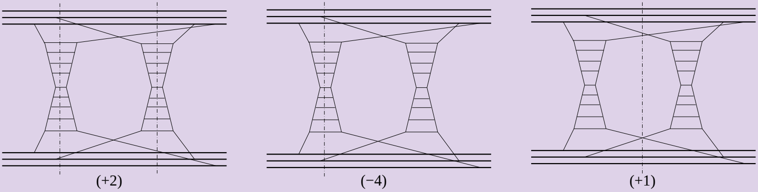

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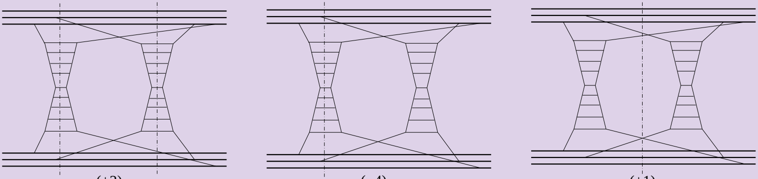

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- this leads to the usual 'minijet' ansatz:
  $\sigma_{pp}^{\rm tot}(s) = 2\int d^2b \left[1 - \exp(-\chi_{pp}^{\rm jet}(s,b,p_{\rm t}^{\rm cut}))\right]$
  $(\ \chi_{pp}^{\rm jet}(s,b,p_{\rm t}^{\rm cut}) = \frac{1}{2}\sum_{I,J} f_I \otimes \sigma_{IJ}^{2\to 2} \otimes f_J\ )$

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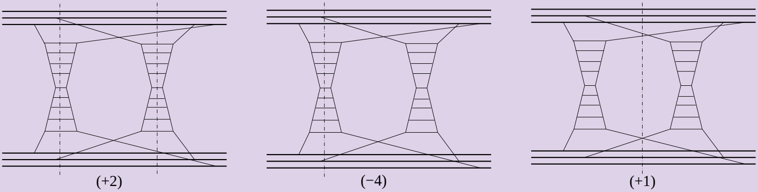

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NB: absorptive (screening) corrections to $\sigma_{pp}^{\mathrm{tot}}$ – closely related to the strength of multiple scattering

- stronger screening $\Rightarrow$ larger multiplicity tails

Total cross section & multiple scattering

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- this will be in variance with measured $d\sigma_{pp}^{\rm el}/dt$ & $B_{pp}^{\rm el} \propto \langle b^2 \rangle$
- this signals the breakdown of the uncorrelated parton picture!
- NB: in MC-generators the problem is 'cured' by using energy-dependent cutoff for jet production: $p_{\rm t}^{\rm cut} = p_{\rm t}^{\rm cut}(s)$

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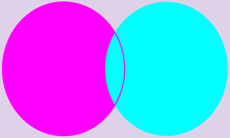
Where is the problem and how to cure it?

- double (multiple) hard scattering results from independent cascades
  - $\Rightarrow$ mostly in central collisions



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Where is the problem and how to cure it?

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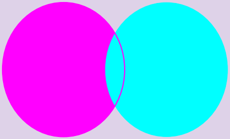
- one has to create parton 'clumps' to enhance peripheral multiple scattering (without changing the transverse profile)
  - can be done via 'soft' & 'hard' parton splitting mechanisms



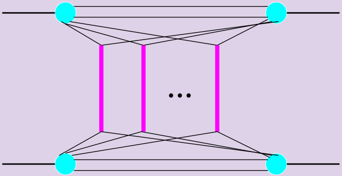
Multi-parton correlations & multi-Pomeron interactions

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

Multi-parton correlations & multi-Pomeron interactions

Multiple scattering processes = multi-Pomeron exchanges

- 'elementary' parton cascade = Pomeron



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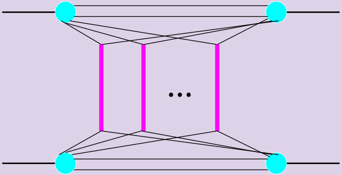
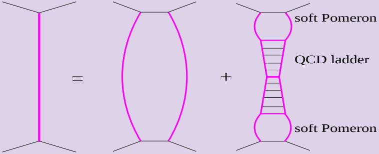


Hard processes included using 'semihard Pomeron' approach *[Drescher et al., 2001]*

- soft Pomerons to describe soft (parts of) cascades ($p_t^2 < Q_0^2$)
  - ⇒ transverse expansion governed by (small) Pomeron slope
- DGLAP for hard cascades
- taken together:
  'general Pomeron'



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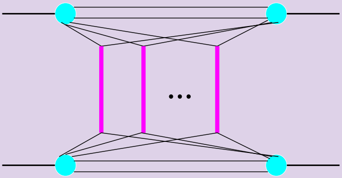

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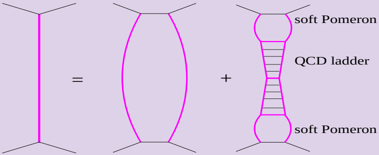

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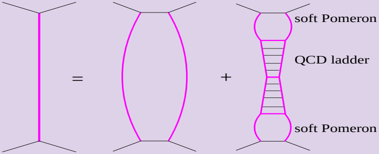
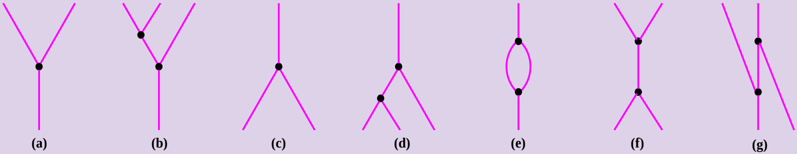


Nonlinear processes: Pomeron-Pomeron interactions (scattering of intermediate partons off the proj./target hadrons & off each other)



thick lines = Pomerons = 'elementary' parton cascades

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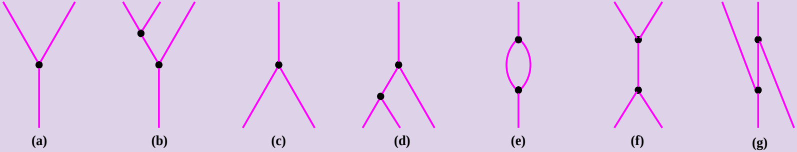

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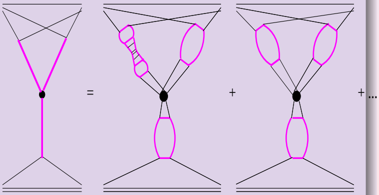
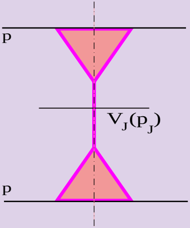
Pomeron-Pomeron interaction: a closer look

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



Inclusive jet production - a closer look

- described in RTF by Kancheli-Mueller graphs
- projectile & target 'triangles' generally contain absorptive corrections



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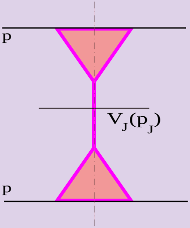
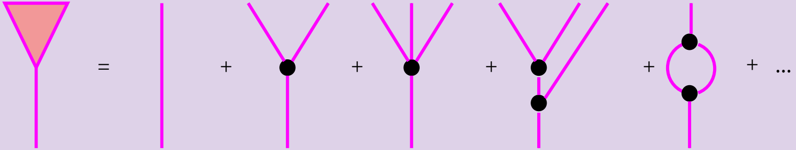


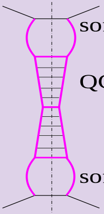
Examples of graphs hidden in the 'triangles'



Inclusive jet production - a closer look

Dijet cross section (neglecting absorption)

$$\sigma_{pp}^{2\mathrm{jet(no\,abs)}}(s,p_{\mathrm{t}}^{\mathrm{cut}}) = \sum_{i,j} C_i\, C_j \int d^2b'\, d^2b''$$
$$\times \sum_{I,J} \int \frac{dx^+}{x^+}\frac{dx^-}{x^-}\; \sigma_{IJ}^{\mathrm{QCD}}(x^+x^-s, Q_0^2, p_{\mathrm{t}}^{\mathrm{cut}})$$
$$\times \chi_{(i)I}^{\mathbb{P}_{\mathrm{soft}}}(s_0/x^+, b')\, \chi_{(j)J}^{\mathbb{P}_{\mathrm{soft}}}(s_0/x^-, b'')$$



- $\sigma_{IJ}^{\mathrm{QCD}}$ - contribution of DGLAP ladder with leg parton virtualities Q_0^2
- $\chi_{(i)I}^{\mathbb{P}_{\mathrm{soft}}}$ - eikonal for soft Pomeron coupled to eigenstate $|i\rangle$ of the proton & parton I

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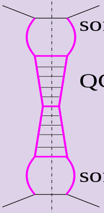


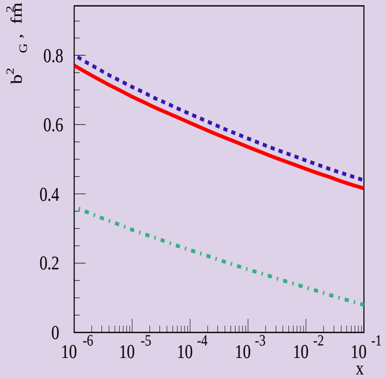
Including absorption $\chi_{(i)I}^{\mathbb{P}_{\mathrm{soft}}}(s_0/x,b)$ is replaced by the solution of 'fan' diagram equation, $x\tilde{f}_I^{(i)}(x,b)$

- $\tilde{f}_I^{(i)}(x,b)$ may be interpreted as GPDs $G_I^{(i)}(x,Q_0^2,b)$ at the virtuality scale Q_0^2; higher scales - DGLAP-evolved:

$$G_I^{(i)}(x,Q^2,b) = \sum_{I'} \int_x^1 \frac{dz}{z}\, E_{I'\to I}^{\mathrm{DGLAP}}(z,Q_0^2,Q^2)\, \tilde{f}_{I'}^{(i)}(x/z,b)$$

Inclusive jet production - a closer look

Impact of transverse diffusion on $\langle b^2 \rangle$ of gluons at $Q_0^2 = 3$ GeV^2

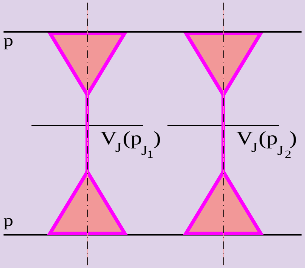


- $\langle b^2 \rangle$ - dominated by the largest size Fock state
- quick spread with energy

DPS production of 2 dijets

Production of 2 dijets by independent parton cascades ('2v2')

$$\sigma_{pp}^{\text{4jet(2v2)}}(s, p_{\text{t}}^{\text{cut}}) = \frac{1}{2}\sum_{i,j} C_i C_j \int d^2b$$
$$\times \left[\int dx^+ dx^- \sum_{I,J} \sigma_{IJ}^{\text{QCD}}(x^+x^-s, Q_0^2, p_{\text{t}}^{\text{cut}})\right.$$
$$\left.\times \int d^2b' \tilde{f}_I^{(i)}(x^+, b')\tilde{f}_J^{(j)}(x^-, |\vec{b}-\vec{b}'|)\right]^2$$

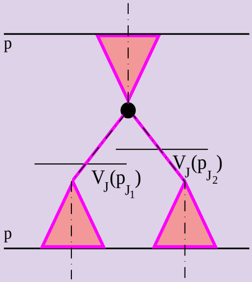


- NB: two dijet processes for the same b & eigenstates $|i\rangle$, $|j\rangle$

DPS production of 2 dijets

'Soft parton splitting' ('2v1s')

$$\sigma_{pp}^{4\text{jet}(2\text{v}1)_s}(s, p_t^{\text{cut}}) = \frac{1}{2}\sum_{i,j} C_i\, C_j$$
$$\times G_{3\mathbb{P}} \int d^2b' \int \frac{dx'}{x'} \left[1 - e^{-\chi^{\text{fan}}_{(i)}(s_0/x', b')}\right]$$
$$\times \int d^2b \left[\int \frac{dx^+}{x^+} \int dx^- \sum_{I,J} \sigma^{\text{QCD}}_{IJ}(x^+x^-s, Q_0^2, p_t^{\text{cut}})\right.$$
$$\left.\times \int d^2b''\, \chi^{\mathbb{P}_{\text{soft}}}_{\mathbb{P}I}(s_0\, x'/x^+, b'')\, \tilde{f}^{(j)}_J(x^-, |\vec{b} - \vec{b}''|)\right]^2$$



- small $\alpha'_{\mathbb{P}}$ $\Rightarrow$ two hard processes are closeby in b-space
- involves triple-Pomeron coupling $r_{3\mathbb{P}}$ ($G_{3\mathbb{P}} \propto r_{3\mathbb{P}}$)
- neglecting absorptive corrections $\to$ triple-Pomeron graph

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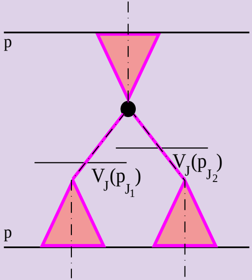
$$\times \int d^2b \left[\int \frac{dx^+}{x^+} \int dx^- \sum_{I,J} \sigma_{IJ}^{\mathrm{QCD}}(x^+x^-s, Q_0^2, p_t^{\mathrm{cut}})\right.$$

$$\left.\times \int d^2b''\, \chi_{\mathbb{P}I}^{\mathbb{P}_{\mathrm{soft}}}(s_0\, x'/x^+, b'')\, \tilde{f}_J^{(j)}(x^-, |\vec{b}-\vec{b}''|)\right]^2$$



We may compare this with the standard DPS formula

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

$$\times \frac{d\sigma_{I_1J_1}^{2\to 2}}{dp_{t_1}^2} \frac{d\sigma_{I_2J_2}^{2\to 2}}{dp_{t_2}^2} \int d^2\Delta b\, F_{I_1I_2}^{(2)}(x_1^+, x_2^+, M_{F_1}^2, M_{F_2}^2, \Delta b)\, F_{J_1J_2}^{(2)}(x_1^-, x_2^-, M_{F_1}^2, M_{F_2}^2, \Delta b)$$

DPS production of 2 dijets

We may compare this with the standard DPS formula

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

$$\times \frac{d\sigma_{I_1J_1}^{2\to 2}}{dp_{\rm t_1}^2}\frac{d\sigma_{I_2J_2}^{2\to 2}}{dp_{\rm t_2}^2}\int d^2\Delta b\, F_{I_1I_2}^{(2)}(x_1^+,x_2^+,M_{\rm F_1}^2,M_{\rm F_2}^2,\Delta b)\, F_{J_1J_2}^{(2)}(x_1^-,x_2^-,M_{\rm F_1}^2,M_{\rm F_2}^2,\Delta b)$$

The two contributions (2v2 & 2v1s) correspond to ${}_2$GPDs

$$F_{I_1I_2}^{(2)}(x_1,x_2,Q_0^2,Q_0^2,\Delta b) = \sum_i C_i \int d^2b' \left\{ \tilde{f}_{I_1}^{(i)}(x_1,b')\tilde{f}_{I_2}^{(i)}(x_2,|\vec{b}'-\vec{\Delta b}|) \right.$$

$$\left. + \frac{G_{3\mathbb{P}}}{x_1x_2}\int \frac{dx'}{x'}\left[1-e^{-\chi_{(i)}^{\rm fan}(s_0/x',b')}\right]\int d^2b''\, \chi_{\mathbb{P}I_1}^{\mathbb{P}_{\rm soft}}(\frac{s_0x'}{x_1},b'')\, \chi_{\mathbb{P}I_2}^{\mathbb{P}_{\rm soft}}(\frac{s_0x'}{x_2},|\vec{b}''-\vec{\Delta b}|) \right\}$$

- 2nd term generates short range two-parton correlations in *b*-space

DPS production of 2 dijets

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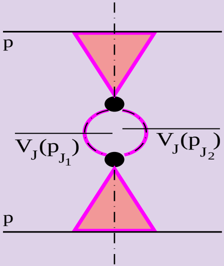
$$F^{(2)}_{I_1 I_2}(x_1, x_2, Q_0^2, Q_0^2, \Delta b) = \sum_i C_i \int d^2b' \left\{ \tilde{f}^{(i)}_{I_1}(x_1, b') \tilde{f}^{(i)}_{I_2}(x_2, |\vec{b}' - \vec{\Delta b}|) \right.$$

$$\left. + \frac{G_{3\mathbb{P}}}{x_1 x_2} \int \frac{dx'}{x'} \left[1 - e^{-\chi^{\rm fan}_{(i)}(s_0/x', b')} \right] \int d^2b'' \, \chi^{\mathbb{P}_{\rm soft}}_{\mathbb{P}I_1}(\frac{s_0 x'}{x_1}, b'') \, \chi^{\mathbb{P}_{\rm soft}}_{\mathbb{P}I_2}(\frac{s_0 x'}{x_2}, |\vec{b}'' - \vec{\Delta b}|) \right\}$$

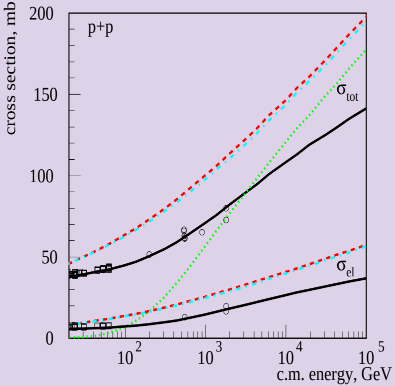
- 2nd term generates short range two-parton correlations in b-space

- NB: such $_2$GPDs would also produce a 'loop' contribution



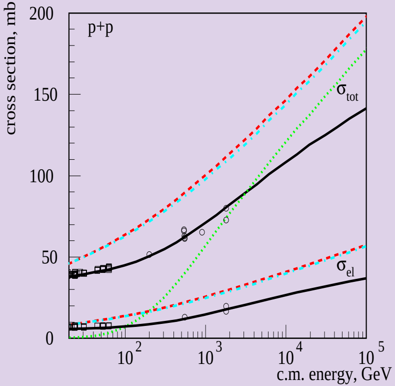
Example of the fit of σ_{pp}^{tot}

- in this framework, reasonable fit of σ_{pp}^{tot} was obtained for a low cutoff $Q_0^2 = 1$ GeV^2 *[SO, 2006]*



Example of the fit of σ_{pp}^{tot}

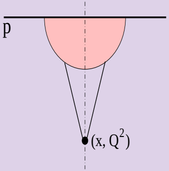
- in this framework, reasonable fit of σ_{pp}^{tot} was obtained for a low cutoff $Q_0^2 = 1$ GeV^2 *[SO, 2006]*
- with constraints from particle production, much higher value is required ($Q_0^2 = 3$ GeV^2 is used in QGSJET-II)

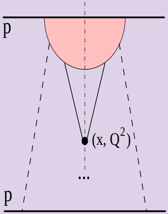


A different view on the problem: nonuniversality of PDFs

Universal PDFs insufficient for noninclusive observables in pp

- in DIS: rescattering of intermediate partons off the parent hadron
- in pp: rescattering off the target hadron in addition





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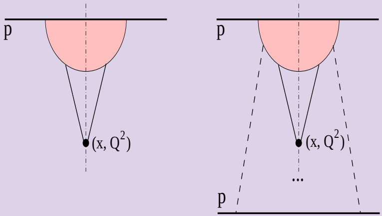

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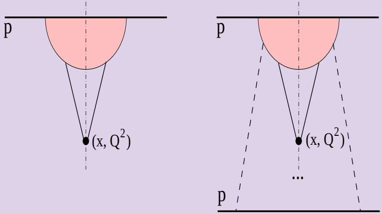
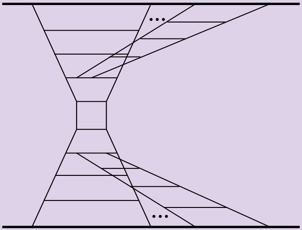


Some enhanced graphs are contained in PDFs

- namely, the ones describing rescattering off the parent hadron



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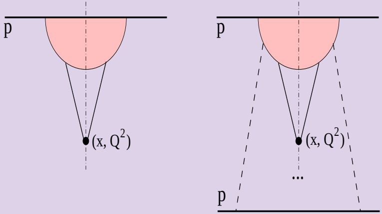
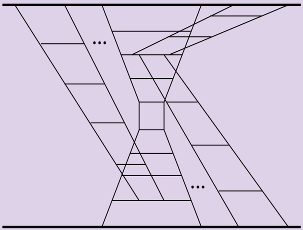


Others are responsible for nonfactorizable corrections

- those prove to be the most important ones



Multi-parton interactions: perturbative splitting

- $3 \to 4$ contrib. to double parton scatt.: collinearly enhanced *[Blok et al., 2011]*
- may also impact $\sigma_{pp}^{\rm tot}$?
- $\Rightarrow$ included in a test version of the model

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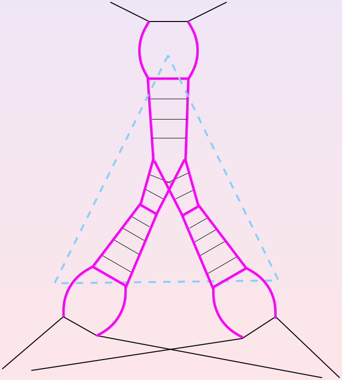

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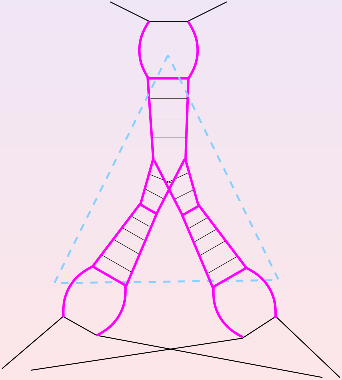

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- assume AGK rules
- neglect b-size of the 'hard triangle' wrt soft evolution
- $\Rightarrow$ 'hard triangle' works as an effective $3\mathbb{P}$-vertex

Multi-parton interactions: perturbative splitting

- for $Q_0^2 = 3$ GeV^2: negligible effect
- $\Rightarrow$ choose $Q_0^2 = 2$ GeV^2 and refit the model parameters (using $\sigma_{pp}^{\mathrm{tot/el}}$, F_2, $F_2^{D(3)}$)

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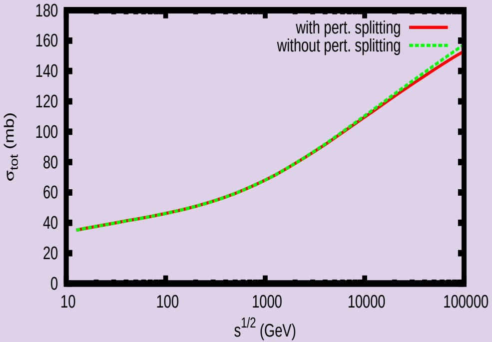

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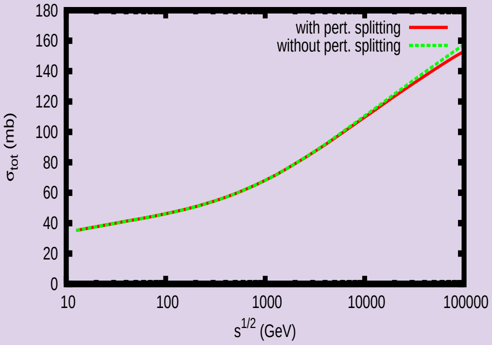

- effect seen at the highest energies
- but: too weak in the LHC energy range
- only nonperturbative parton correlations relevant for $\sigma_{pp}^{\mathrm{tot}}$

Perturbative splitting: cross-check with contributions to DPS rates *[SO & Bleicher, 2016]*

Relative importance of the soft and hard parton splittings

- 'soft splitting': large correction for small p_t^{cut}
  - small for high p_t^{cut}
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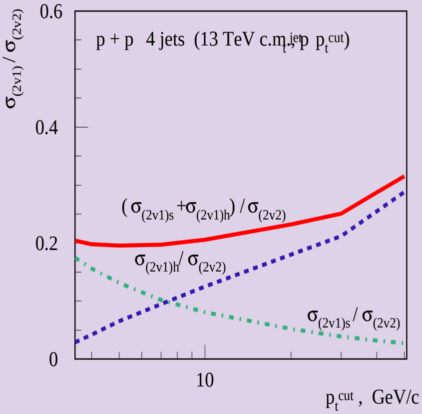

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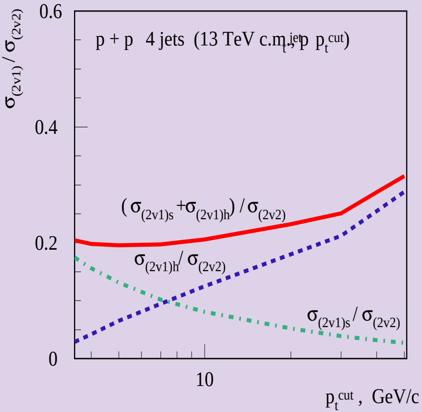
- hard splitting: dominant for high p_t^{cut}
  - vanishes for $p_t^{cut} \to Q_0$
  - irrelevant for minimum bias events



Dynamical higher twist corrections

Motivation: the situation is yet far from being satisfactory

- present fit of the model parameters is a marginary one
  - e.g., multiplicity distribution is broader than observed
- most worrysome: the p_t-cutoff plays a crucial role in the fit
  - moreover, a rather large value (3 GeV^2) is used

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- possible hint: energy-dependent p_t-cutoff in MC generators – is it possible have a perturbative mechanism behind?

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Power corrections seem to fit in the demand

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- come into play at relatively small p_t
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