Pomeron Calculus: X-sections, Diffraction & MC

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Outline

- Optical theorem, unitarity & AGK cuts
- Enhanced Pomeron graphs: resummation
- Phenomenological approach - 2 Pomeron poles:

  total, elastic & diffractive x-sections

- 'Semihard Pomeron'
- MC approach (QGSJET II)

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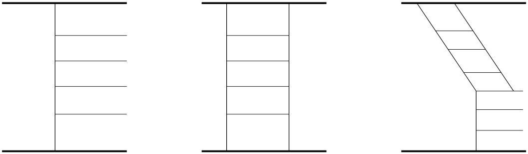
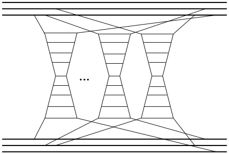
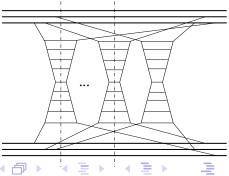
'Elementary' processes:

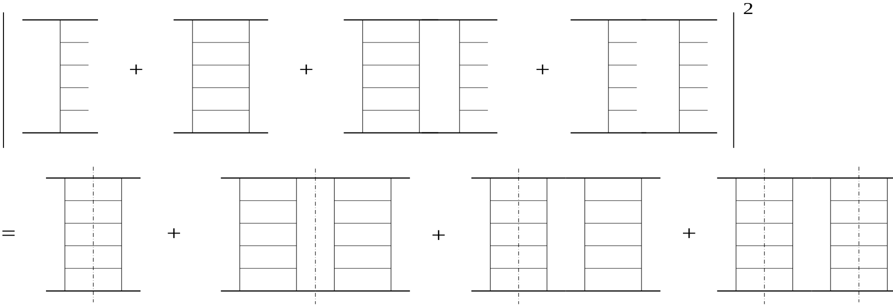
non-diffr. production   virtual rescattering   diffraction



- elastic scattering - coherence of the parton cascade preserved by the scattering process
- 'elementary' inel. process - coherence broken $\Rightarrow$ hadronization
- general interaction - multiple scattering:

$\sigma_{tot} = \mathrm{Im}$  $= \sum$ 

Optical theorem + AGK rules
⇒ relation between elastic amplitude & inelastic final states



- AGK rules: no interference between different topologies of final states
- ⇒ all possible final states - obtained via AGK-cuts of elastic scattering diagrams
- partial cross sections - expressed via amplitudes for 'elementary' scattering

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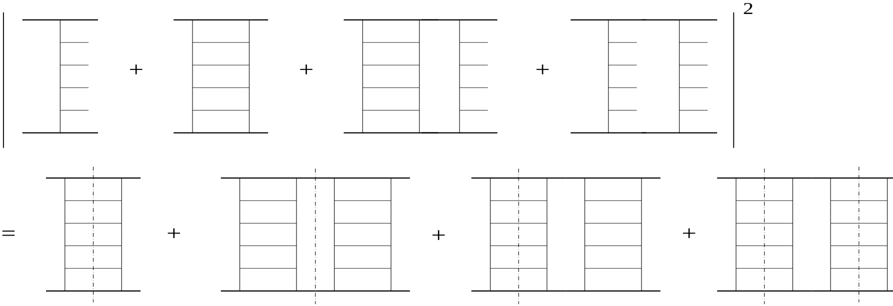

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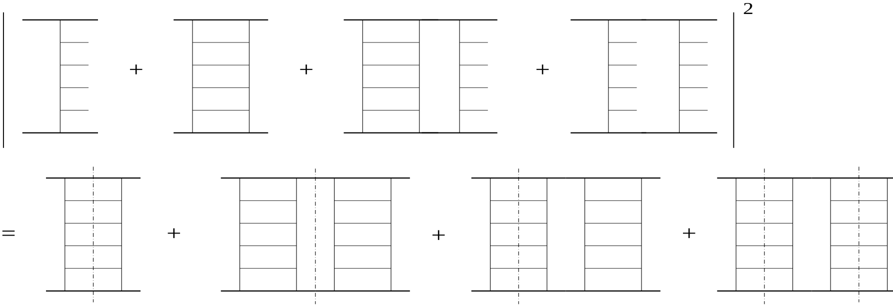

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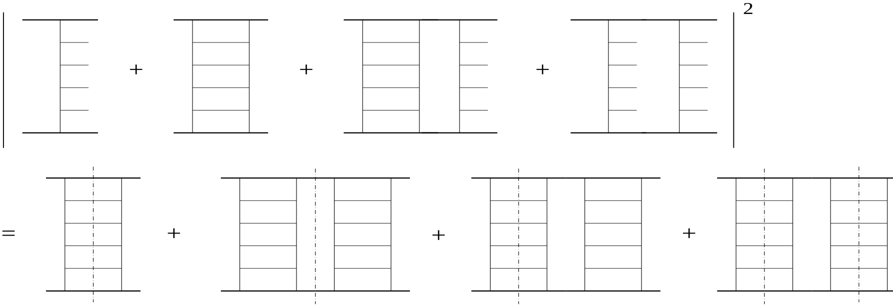

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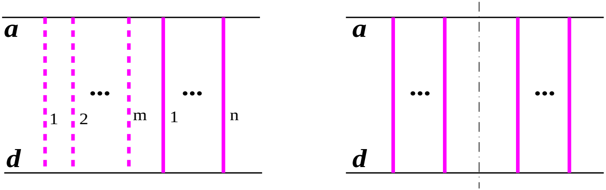
Schematic (elementary parton cascades $\equiv$ Pomerons):



- Pomeron amplitudes - various approaches possible (purely phenomenological, BFKL, ...)

Intermediate states between Pomeron exchanges include inelastic excitations: $\sum_i |X_i\rangle\langle X_i| = |p\rangle\langle p| + \sum_{i\neq p} |X_i\rangle\langle X_i|$

- Good-Walker-like scheme - use elastic scattering eigenstates:

$$|X_i\rangle \rightarrow \sum_j \sqrt{C_{j/X_i}}\, |j\rangle$$

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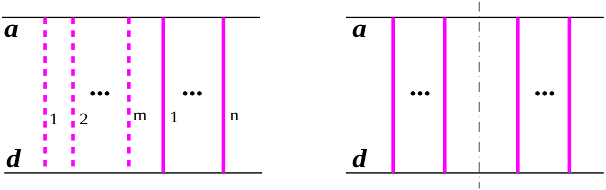

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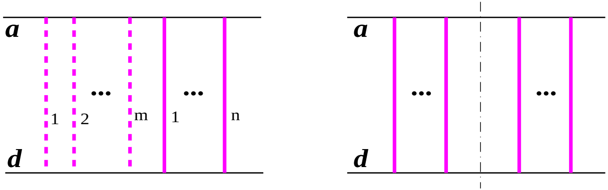

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E.g., using eikonal vertices for Pomeron emission:

$$f_{pp}(s,b) = i \sum_{j,k} C_{j/p} C_{k/p} \left[1 - e^{-\chi^{\mathbb{P}}_{jk}(s,b)} \right]$$

$\chi^{\mathbb{P}}_{jk} = \Im\mathfrak{m} f^{\mathbb{P}}_{jk}$ - eikonal for Pomeron exchange between $|j\rangle$ and $|k\rangle$

- $\Rightarrow$ allows to calculate X-sections for various final states:

$$\sigma^{(n)}_{ad}(s) = \sum_{j,k} C_{j/p} C_{k/p} \int d^2b \, \frac{[2\chi^{\mathbb{P}}_{jk}(s,b)]^n}{n!} e^{-2\chi^{\mathbb{P}}_{jk}(s,b)}$$

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Higher diffraction = more asymmeric eigenstates

smaller σ_{tot} (σ_{inel}) - inelastic screening

bigger fluctuations of multiplicity / of N_{part} in pA (AA)

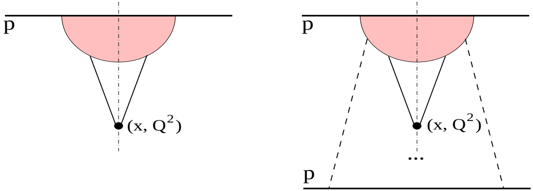
Non-linear effects

Pomeron-Pomeron interactions $\Rightarrow$ rich physics

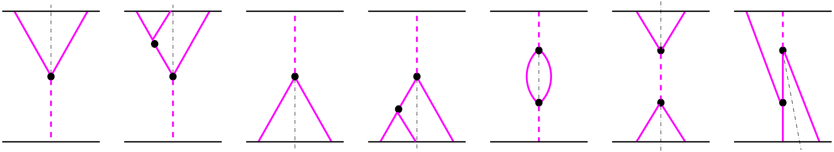
- e.g. final states with jets:

'fan' diagrams - low-x PDFs as 'seen' in DIS & inclusive cross sections

'net fans' - 'reaction-dependent PDFs' (depend on rescattering on the partner hadron))



High mass diffraction from enhanced diagrams:



- sign-indefinite contributions
- higher orders - increasingly important with energy
- $\Rightarrow$ all order resummation needed
- same applies to other final states

General solution to the problem (e.g. MC implementation) requires:

- knowledge of the Pomeron amplitude
- knowledge of multi-Pomeron vertices
- complete resummation of enhanced diagrams:
  for elastic scattering amplitude & for particular final states

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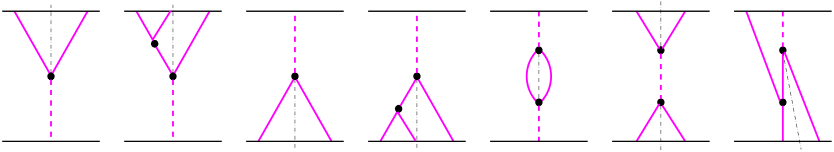

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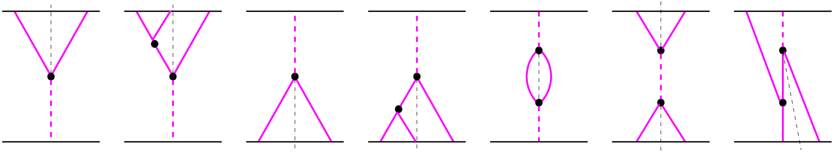

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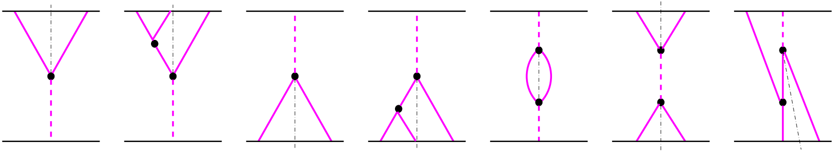

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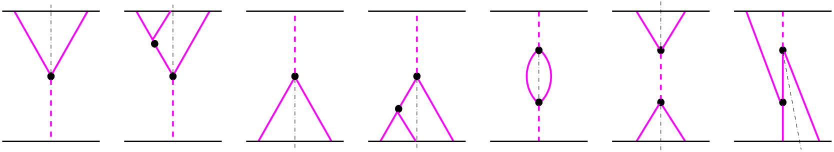

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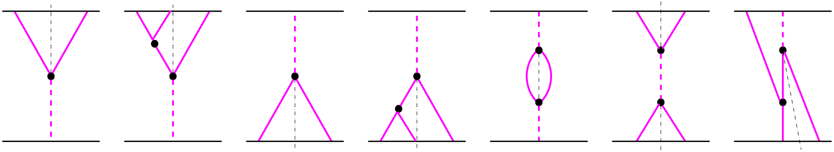

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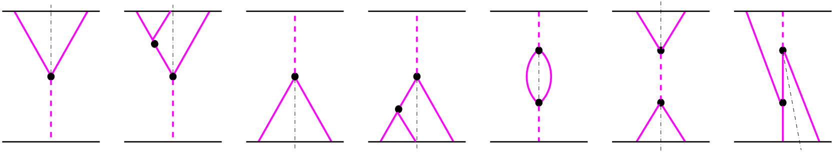

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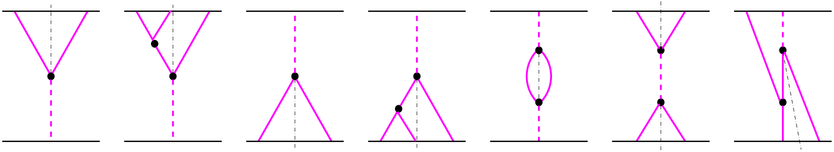

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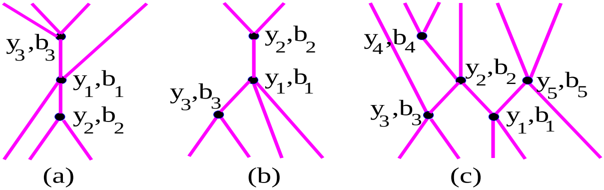
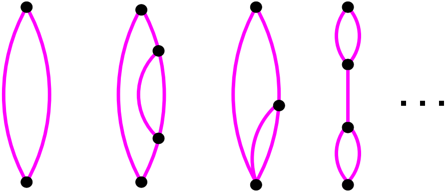
Diagrammatic resummation

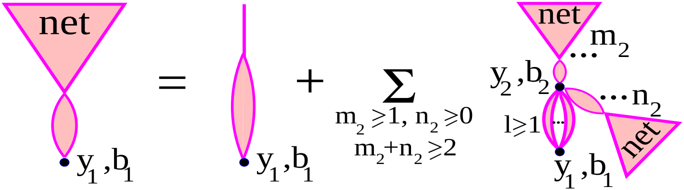
Without Pomeron 'loops' one would have 'net'-like graphs:



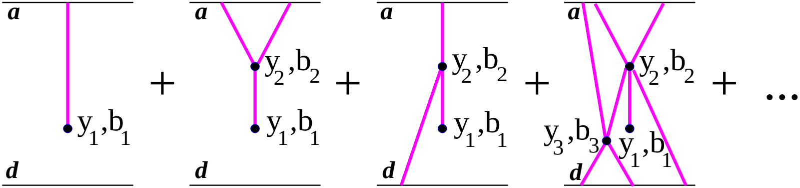
In reality, any 'intermediate' Pomeron may be replaced by 'loops':



Introduce 'net fan' contributions via Schwinger-Dyson equation:



- correspond to arbitrary Pomeron 'nets' coupled to given vertex (for simplicity, loops not shown)



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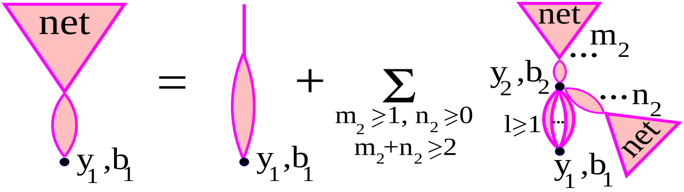

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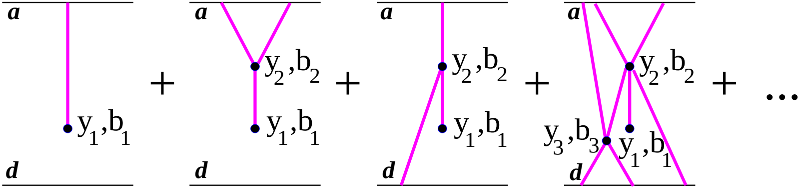

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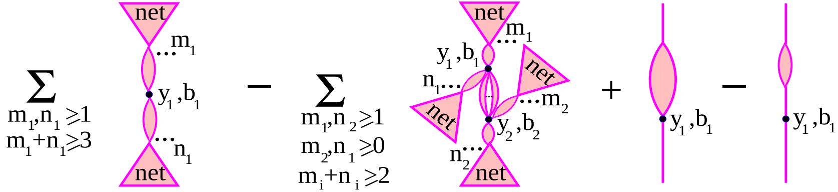
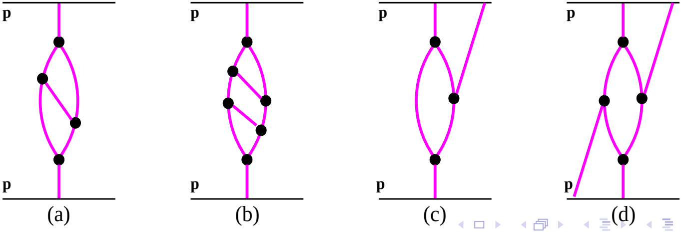
Sum of (almost) all irredicible contributions to elastic amplitude ($\Omega_{pp(jk)}(s,b)$):



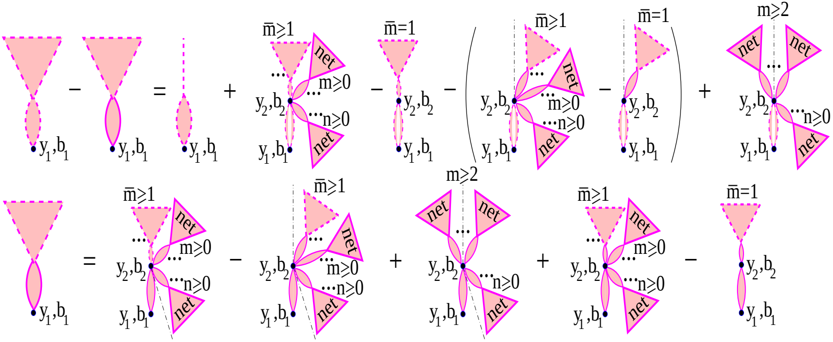
examples of graphs which are not included in this scheme:



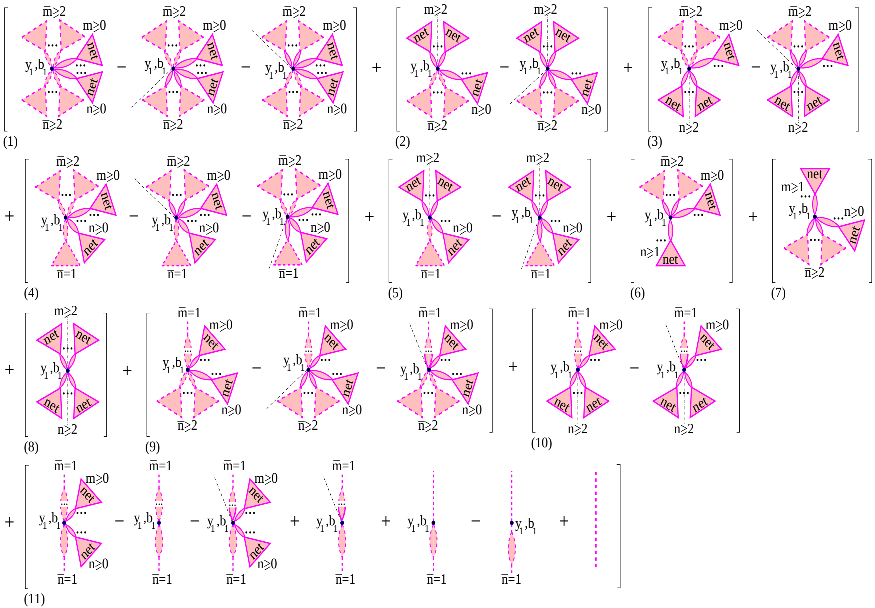
Knowing the amplitude one can calculate $\sigma_{\rm tot}$, $d\sigma_{\rm el}/dt$, etc.

However, to describe the structure of final states one needs the complete set of partial cross sections

- one assumes the validity of AGK cutting rules
- one starts from 'building blocks': AGK-cuts of 'net fans' - defined by Schwinger-Dyson equations



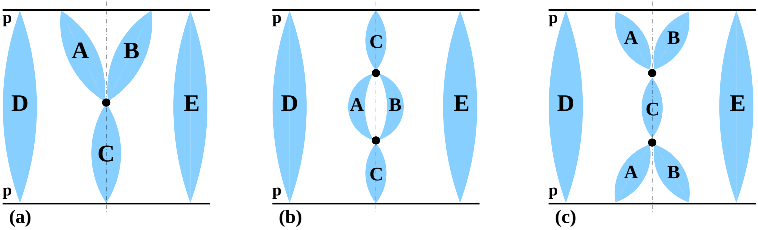
One obtains the complete system of cuts:



Obtained contributions satisfy s-channel unitarity (completness):

$$\sum_{i=1}^{11} \bar{\Omega}^{(i)}_{pp(jk)}(s,b) = \Omega_{pp(jk)}(s,b)$$

- allow to derive x-sections for various topologies of final states
- e.g., diffractive cuts:



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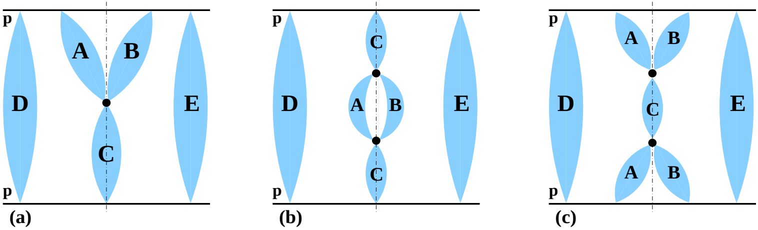

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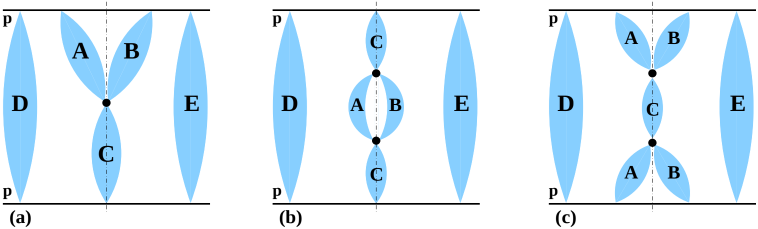

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Particular (simple) model

Let us assume eikonal multi-$\mathbb{P}$ vertices: $G^{(m,n)} = r_{3\mathbb{P}}\,\gamma_{\mathbb{P}}^{m+n-3}$

- 2-component ('soft' +'hard') Pomeron:

$$D^{\mathbb{P}}(s,t) = 8\pi i \left[s^{\alpha_{\mathbb{P}(s)}}\; e^{\alpha'_{\mathbb{P}(s)} \ln s\, t} + r_{h/s}\, s^{\alpha_{\mathbb{P}(h)}}\; e^{\alpha'_{\mathbb{P}(h)} \ln s\, t} \right]$$

- dipole form factor for proton elastic eigenstates $|j\rangle$:

$$F_j^{\mathbb{P}}(t) = \frac{\gamma_j}{(1-\Lambda_j t)^2}; \quad \gamma_j = \gamma(1 \pm \kappa),\, j = 1,2$$

- Pomeron eikonal:
$\chi_{jk}^{\mathbb{P}}(s,b) = \frac{1}{8\pi^2 is} \int d^2q\; e^{-i\vec{q}\vec{b}}\, F_j^{\mathbb{P}}(q^2)\, F_k^{\mathbb{P}}(q^2)\, D^{\mathbb{P}}(s,q^2)$
- $\mathbb{P}$ exchange between a proton and a multi-$\mathbb{P}$ vertex $(y,\vec{b})$:

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Particular (simple) model

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- 2-component ('soft' +'hard') Pomeron:

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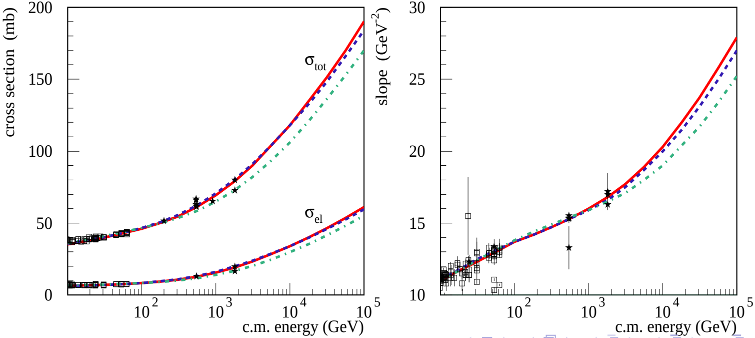
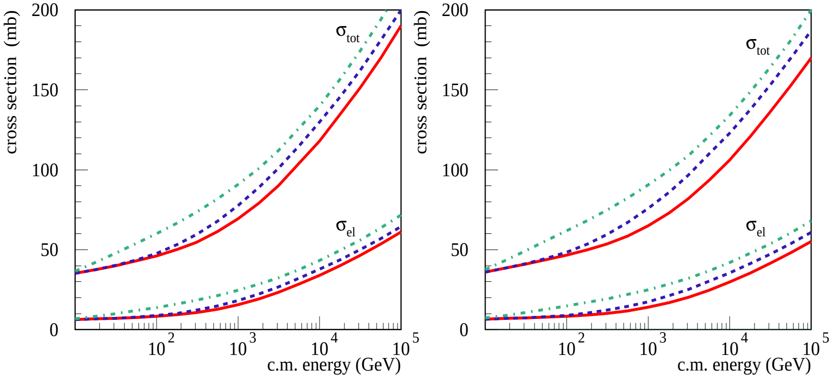
Few parameter sets differ by the fit to CDF/E710 at $\sqrt{s}$=1800 GeV and by the $\mathbb{P}$ mass cutoff ($\xi = \ln M^2_{\min}$): $\xi = 2$ - A, C; $\xi = 1.5$ - B

	$\alpha_{\mathbb{P}(s)}$	$\alpha_{\mathbb{P}(h)}$	$\alpha'_{\mathbb{P}(s)}$, GeV^{-2}	$\alpha'_{\mathbb{P}(h)}$, GeV^{-2}	γ, GeV^{-1}	η	$r_{h/s}$	Λ_1, GeV^{-2}	Λ_2, GeV^{-2}	$r_{3\mathbb{P}}$, GeV^{-1}	$\gamma_{\mathbb{P}}$, GeV^{-1}
(A)	1.145	1.35	0.13	0.075	1.65	0.6	0.06	1.06	0.3	0.14	0.5
(B)	1.15	1.35	0.165	0.08	1.75	0.6	0.065	1.03	0.3	0.15	0.5
(C)	1.14	1.31	0.14	0.085	1.6	0.5	0.09	1.1	0.4	0.14	0.5

- total / elastic cross sections and elastic slope



Using only 'net'-like (blue) / 'loop'-like (green) enhanced graphs:



- $\Rightarrow$ none of the two classes can be neglected
- $\mathbb{P}$-loops only - far insifficient for cross section calculations
- relative importance of $\mathbb{P}$-loops - higher for smaller $\mathbb{P}$-slope and for non-eikonal multi-$\mathbb{P}$ vertices (e.g. in QCD)

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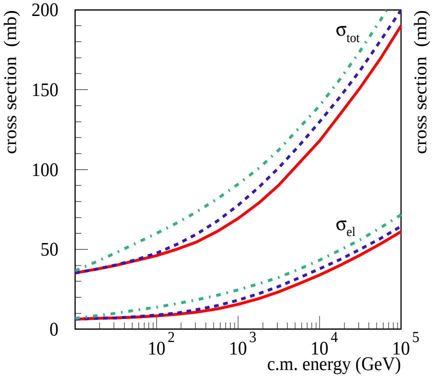

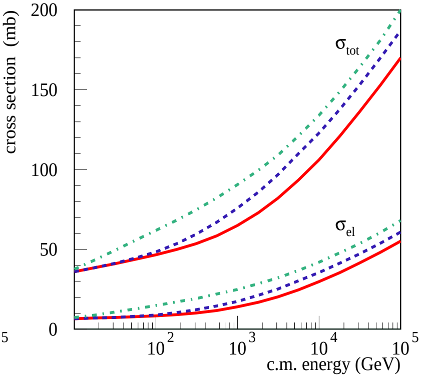

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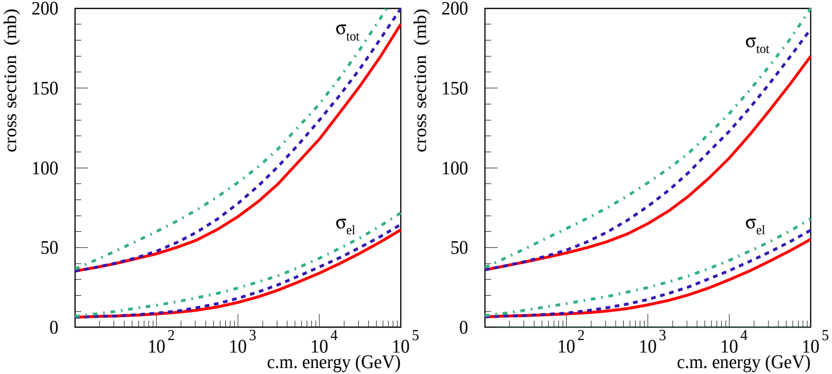

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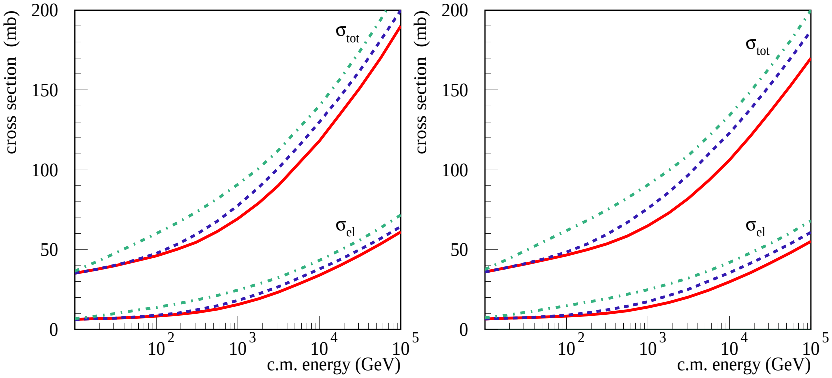

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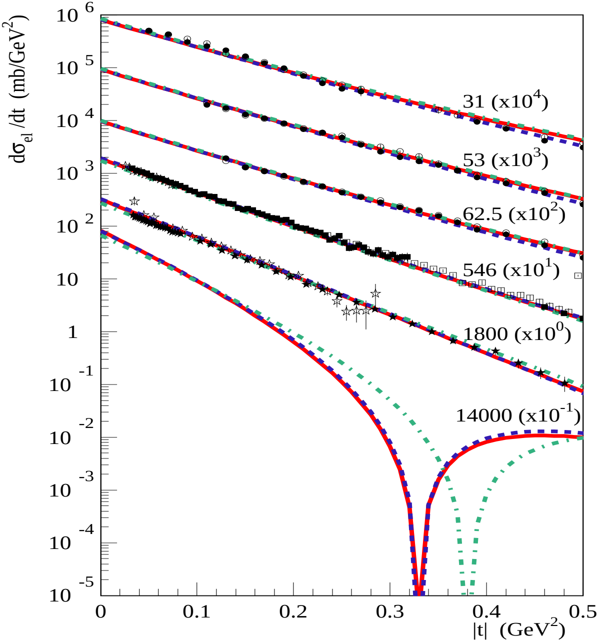
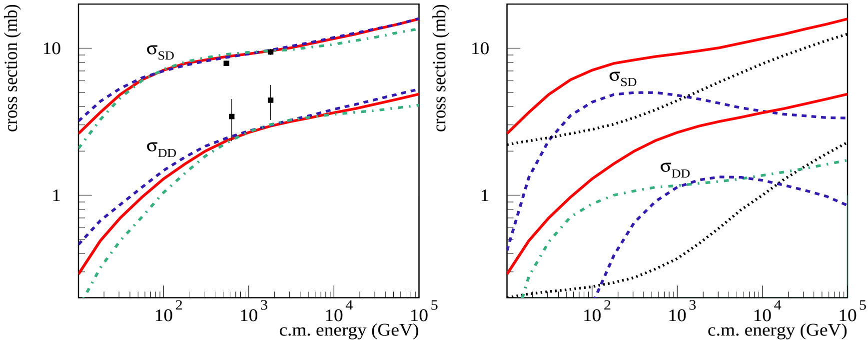
Differential elastic cross section



Diffractive cross sections

Single ($M_X^2/s < 0.15$) and double ($y_{\rm gap}^{(0)} \geq 3$) diffraction x-sections



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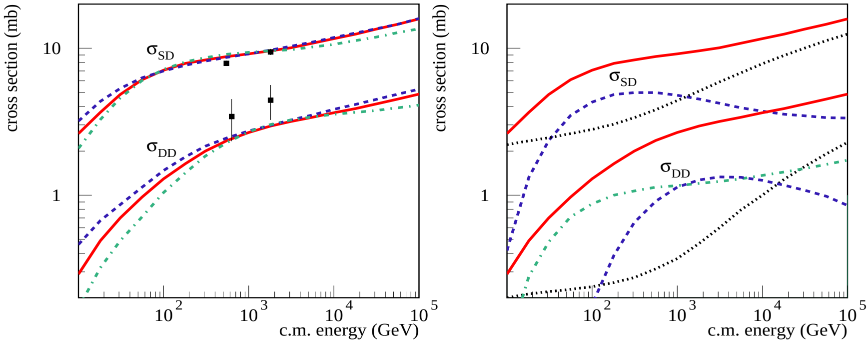

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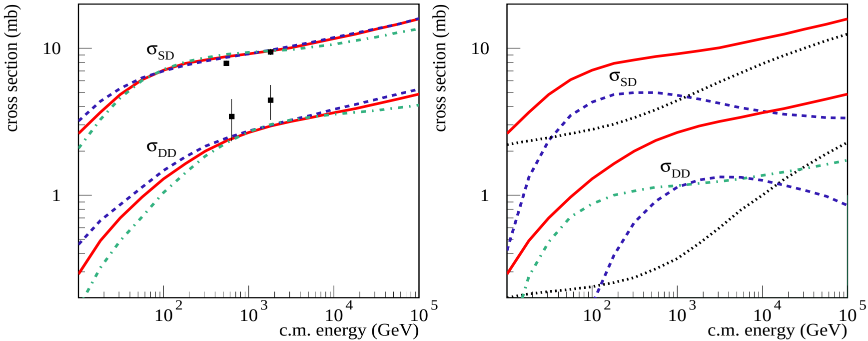

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Examples - partiall resummations of higher order graphs

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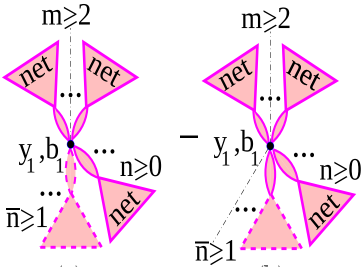

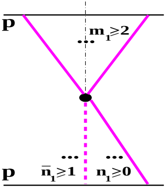

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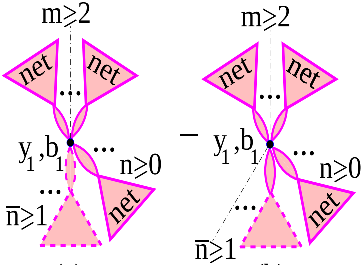

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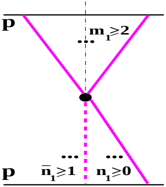

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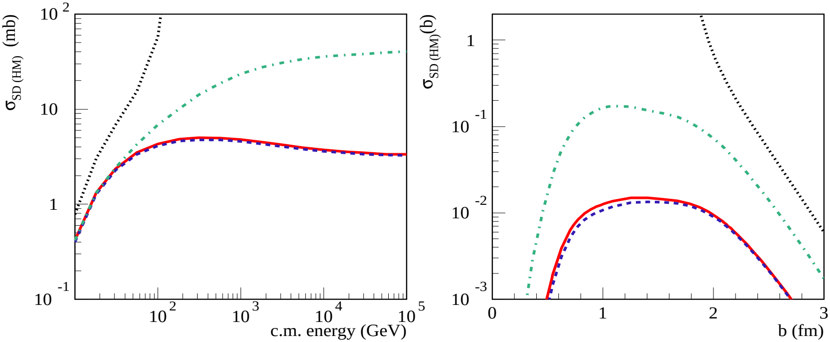
Impact on high mass part of $\sigma_{\rm SD}$ and diffraction profile (at 14 TeV):



- using dominant contributions only - coincides with the full re-summation within 5%
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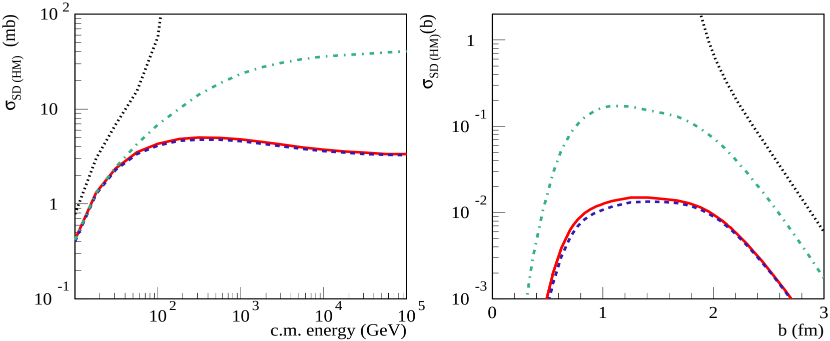

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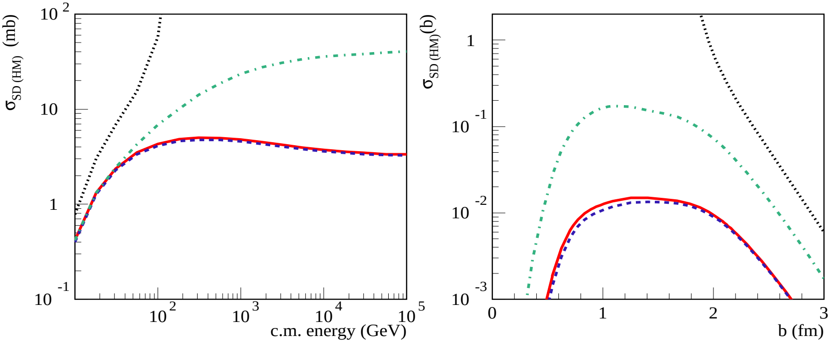

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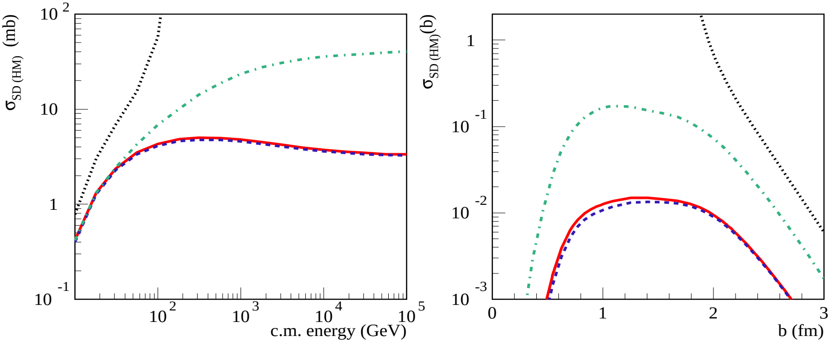

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From the Tevatron to the LHC

1.8 TeV	σ^{tot}	σ^{el}	σ^{SD}	σ^{DD}	σ^{SD}_{HM}	σ^{DD}_{HM}	σ^{DD}_{LHM}	σ^{DPE}
Set (A)	79.3	19.3	9.62	3.62	4.52	1.95	1.20 (1.17)	0.19
Set (B)	80.5	19.9	9.84	4.06	4.78	2.37	1.24 (1.20)	0.23
Set (C)	72.8	16.4	10.5	3.84	5.74	2.01	1.42 (1.36)	0.28
KMR	73.7	16.4	13.8		9.7			
GLM	73.3	16.3	9.76	5.36	1.2			

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KMR	91.7	21.5	19.0		14.1			
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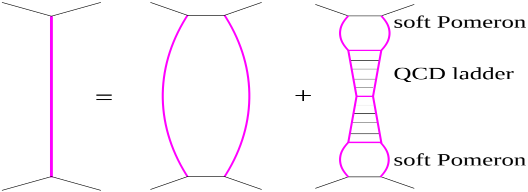
Parton cascades start at low virtualities ⇒

- Q_0^2 - cutoff between 'soft' and perturbative physics
- 'Soft' interactions (all $|q^2|$ - small $\Rightarrow \alpha_s(q^2) > 1$):
  - pQCD is inapplicable ⇒'soft' Pomeron amplitude
- 'Semihard' processes ($|q^2| > Q_0^2 \Rightarrow \alpha_s(q^2) \ll 1$)
  - 'soft' Pomeron for $\left|p_t^2\right| < Q_0^2$
  - DGLAP ladder for $\left|p_t^2\right| > Q_0^2$
- general interaction ⇒ 'general Pomeron':



- same multi-$\mathbb{P}$ vertices: $G^{(m,n)} = r_{3\mathbb{P}}\,\gamma_{\mathbb{P}}^{m+n-3}$
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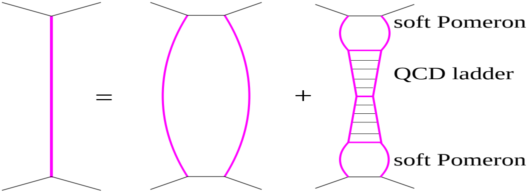

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Monte Carlo approach (QGSJET-II)

MC procedure:

- choose between low mass diffraction or multiple production
- sample impact parameter & elastic scattering eigenstates
- sample a particular 'macro-configuration' of the interaction
- for each cut 'net-fan': generate (recursively) all cut Pomerons & rapidity gaps
- perform energy partition between all cut Pomerons
- for each cut 'semihard Pomeron': reconstruct the perturbative 'piece' (hard process, ISR, FSR)
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Like in the linear (quasi-eikonal) scheme

- interaction configurations are defined by Regge cuts of elastic diagrams
- the procedure generalizes to hA (AA) in a parameter-free way

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Like in the linear (quasi-eikonal) scheme

- interaction configurations are defined by Regge cuts of elastic diagrams
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Monte Carlo approach (QGSJET-II)

MC procedure:

- choose between low mass diffraction or multiple production
- sample impact parameter & elastic scattering eigenstates
- sample a particular 'macro-configuration' of the interaction
- for each cut 'net-fan': generate (recursively) all cut Pomerons & rapidity gaps
- perform energy partition between all cut Pomerons
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- higher soft/hard cutoff: $Q_0^2 = 3\,\mathrm{GeV}^2$ ($Q_0^2 = 2.5\,\mathrm{GeV}^2$ in II-03)

corresponds to $p_{\perp,\mathrm{hard}}^{\mathrm{min}} = 2Q_0 \simeq 3.4$ GeV for the chosen factorization scale in the model: $M_{\mathrm{F}}^2 = p_\perp^2/4$

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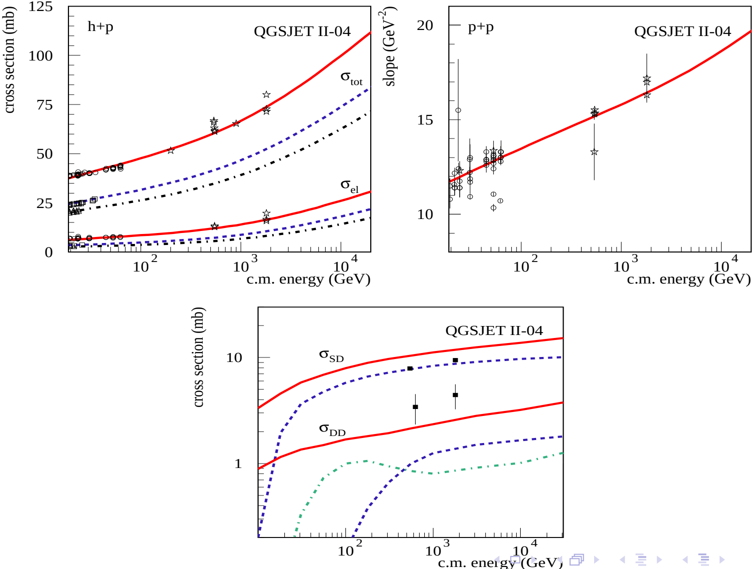
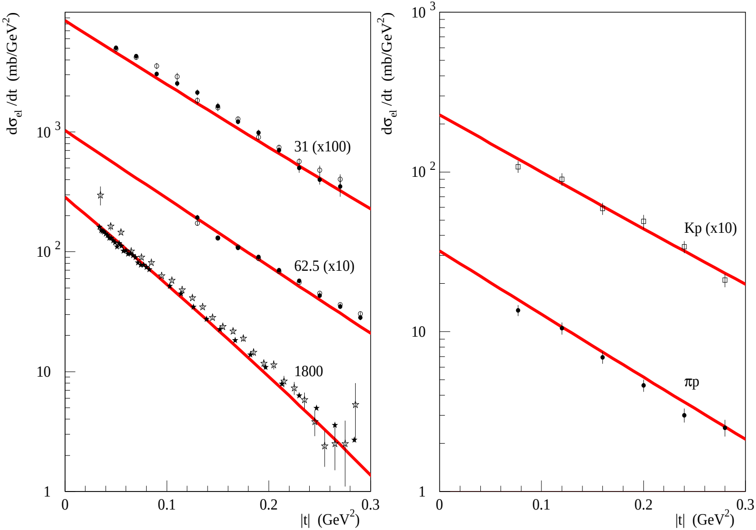
Differences between the two versions for particle production: at fine-tuning level (no drastic modifications induced by LHC)

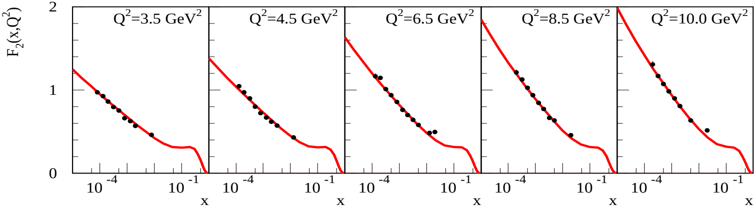
Total, elastic & diffractive X-sections / slope



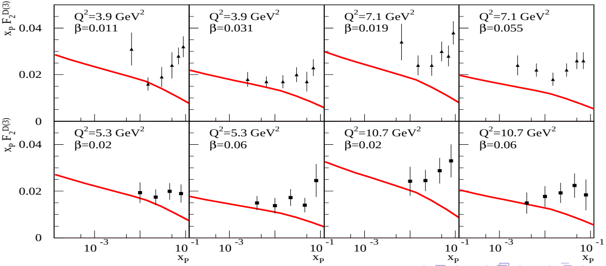
$d\sigma^{\rm el}_{hp}/dt$ - only for small $|t|$ (Gaussian form-factor used)



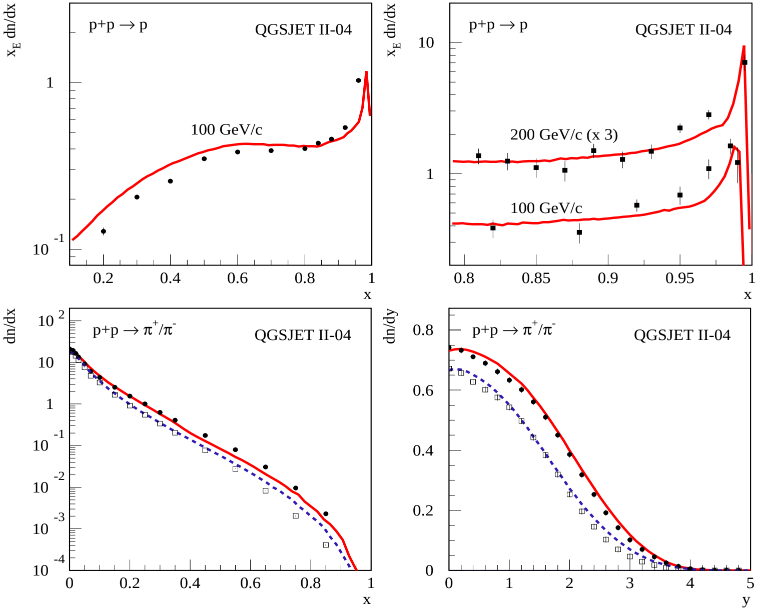
$F_2, F_2^{\mathrm{D}(3)}$



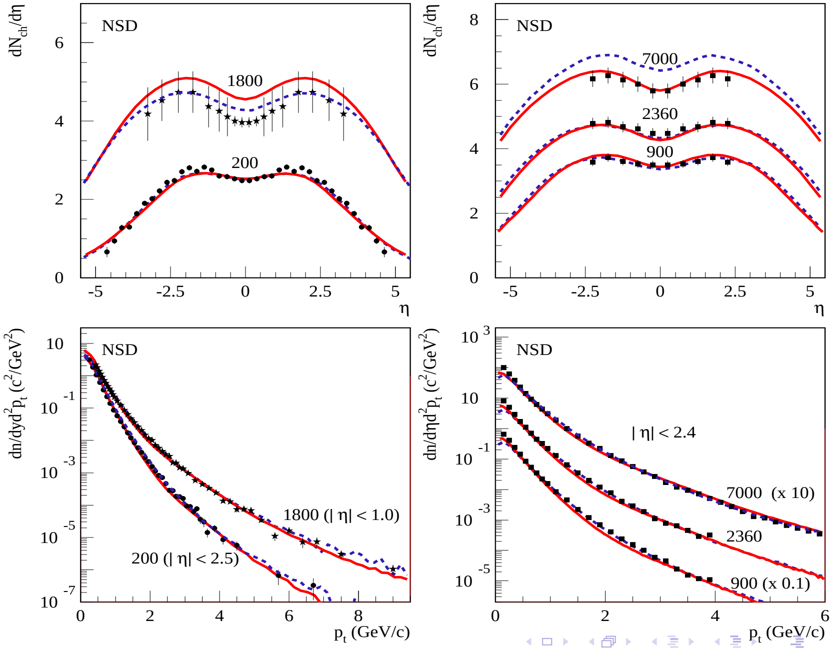
$F_2^{\mathrm{D}(3)}$ - upper limit on $r_{3\mathbb{P}}$ ($\mathbb{RRP}$ & $\bar{q}q$ contributions neglected)



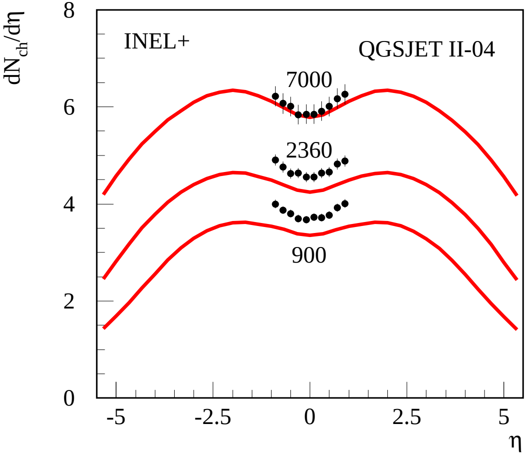
Some results at fixed target energies



Versions II-04 (solid) / II-03 (dashed) at $\sqrt{s} = 0.2 \div 7$ TeV



But: the influence of detector effects unclear in CMS results
E.g., contradiction with ALICE 'inel>0' selection:



Outlook

QGSJET-II is based on

- optical theorem & *s*-channel unitarity
- all-order resummation of enhanced Pomeron graphs
- complete set of partial *x*-sections (for all possible final states)
- self-consistent MC implementation
- 'semihard Pomeron' scheme for hard processes
- phenomenological soft Pomeron ($\Rightarrow$ strings) for soft processes
- phenomenological vertices for Pomeron-Pomeron interactions

Main drawbacks:

- neglects energy-momentum correlations (at amplitude level) in multiple scattering
- neglects 'hard' ($|q^2| > Q_0^2$) Pomeron-Pomeron coupling

$\Rightarrow$ no evolution of saturation scale above $Q_0^2 = 3\,\mathrm{GeV}^2$

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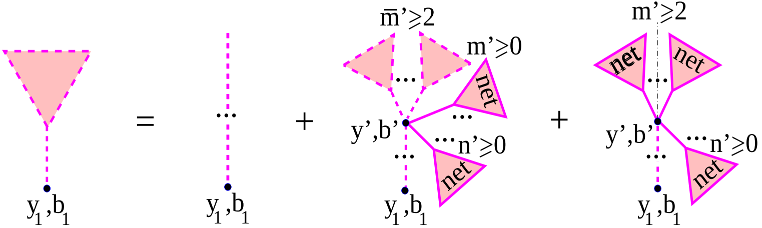
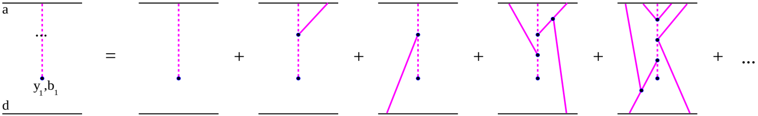
Backup

Procedure for a 'cut net-fan' reconstruction
(for simplicity, illustrated without Pomeron loops)



- at each step, one checks if the remaining piece is just a single cut Pomeron (with all the absorptive effects included):



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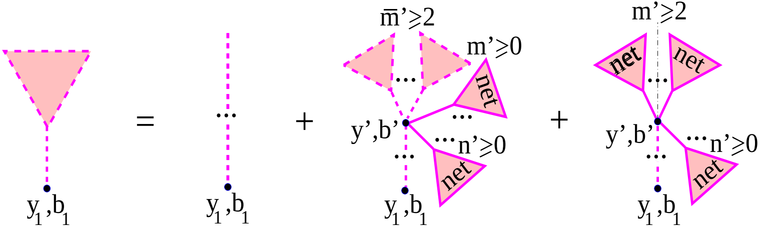

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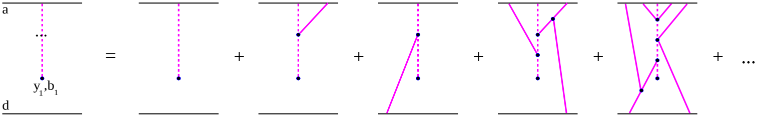

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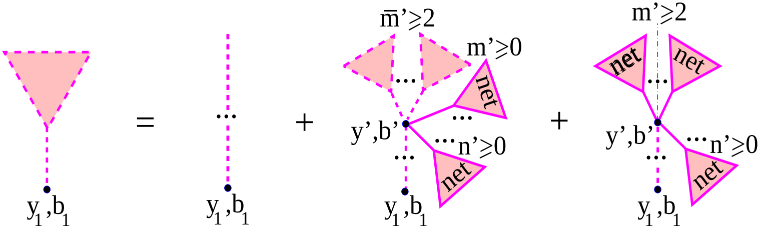

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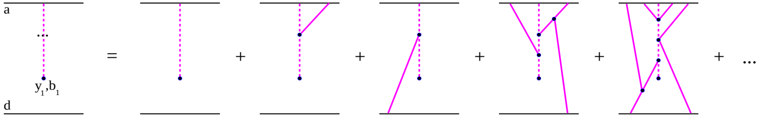

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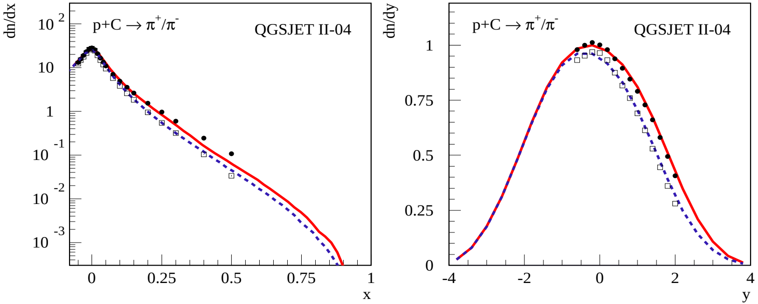
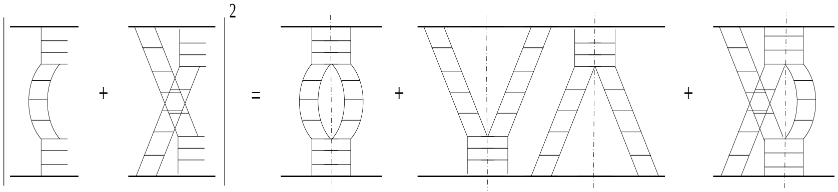
Fixed target pC-collision



Interferention between double diffraction and double single diffraction

Example: double high mass diffraction at the lowest order



Comparison with heavy ions (QGSJET-II-03 - previous version)