Hadronic collisions: cross sections, diffraction, and multi-parton interactions

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Particle Physics Phenomenology Workshop
devoted to the memory of Alexei B. Kaidalov

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Outline

1. Introduction: RFT approach & Quark-Gluon String model
2. Enhanced Pomeron diagrams
   - resummation
   - 'loops' & 'nets' – relative importance
   - non-eikonal rap-gap suppression & diffractive cross sections
3. QGSJET-II Monte Carlo model
   - 'semihard Pomeron'
   - enhanced graphs: assumptions & MC implementation
4. Inelastic diffraction
   - M_X-shape for high mass diffraction
   - LHC puzzles
5. Total cross section & multi-parton interactions
   - multi-Pomeron interactions & multi-parton correlations
   - contribution from perturbative splitting: how important?

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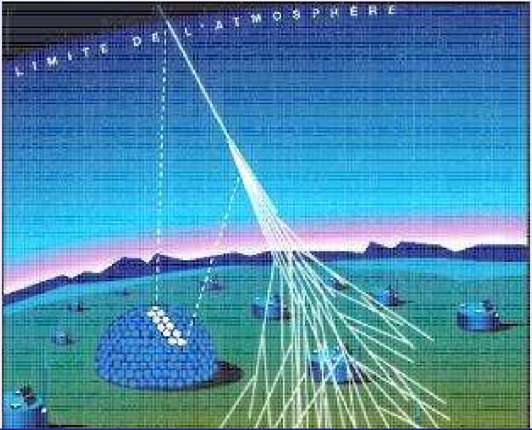
Cosmic ray studies with extensive air shower techniques



ground-based observations (= thick target experiments)

- primary CR energy $\Longleftrightarrow$ charged particle density at ground
- CR composition $\Longleftrightarrow$ muon density at ground

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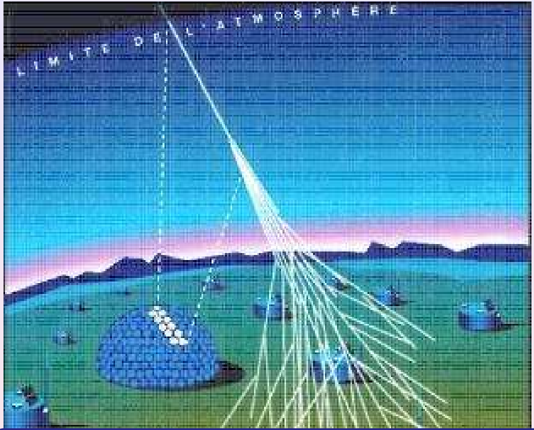

measurements of EAS fluorescence light

- primary CR energy $\Longleftrightarrow$ integrated light
- CR composition $\Longleftrightarrow$ shower maximum position $X_{\max}$

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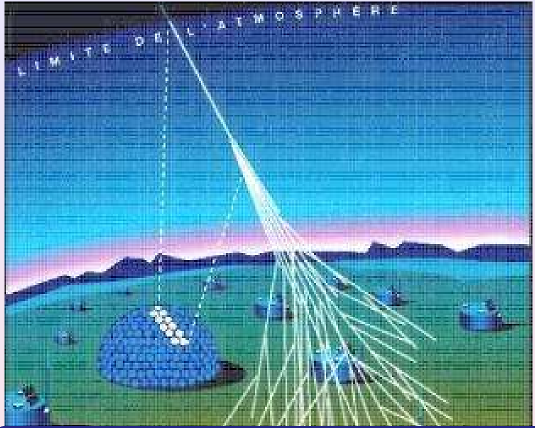

CR composition studies – most dependent on interaction models

- e.g. predictions for $X_{\max}$ depend on $\sigma^{\text{inel}}_{p-\text{air}}$, $\sigma^{\text{diffr}}_{p-\text{air}}$
- predictions for muon density – on the multiplicity $N^{\text{ch}}_{\pi-\text{air}}$

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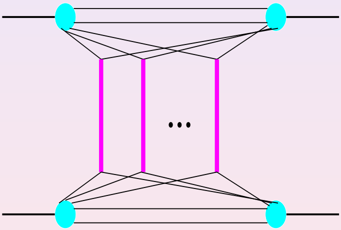

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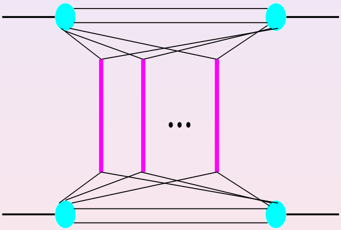

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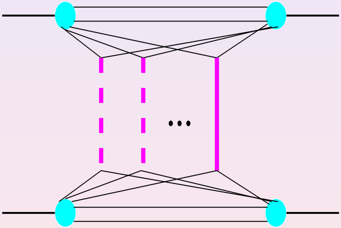

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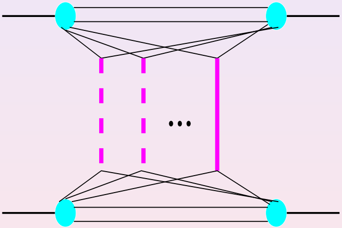

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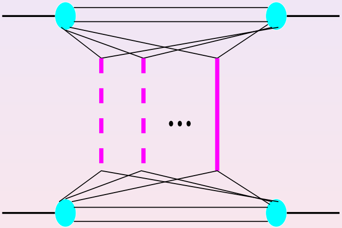

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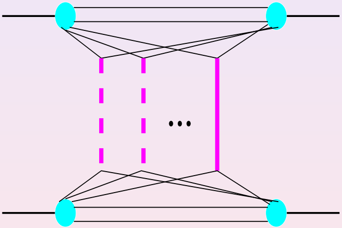

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- absorptive effects stronger at small b, weaker at large b
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  Pomeron-Pomeron interactions important
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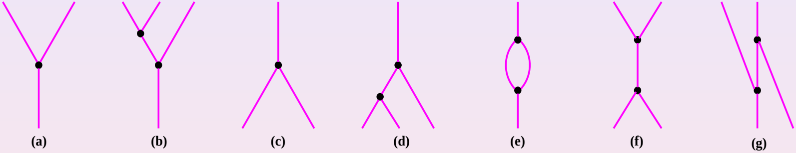

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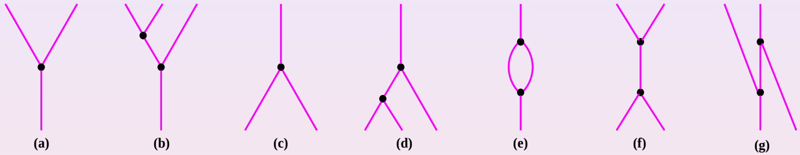

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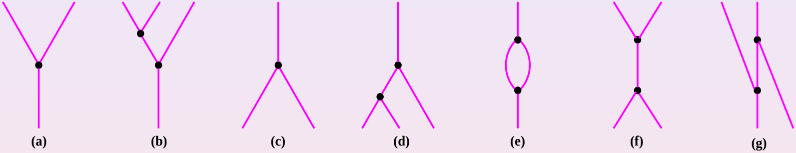

  - describe elastic re-scattering of intermediate partons off the projectile/target hadrons & off each other
- why all-order resummation?
  - higher order (wrt $G_{3\mathbb{P}}$) contributions rise quicker with energy
  - have altering signs

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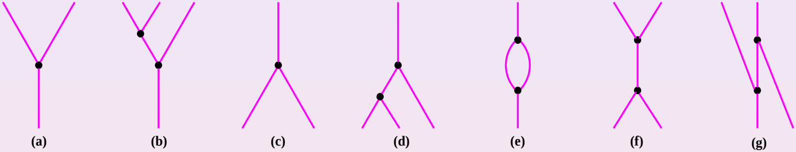

  - describe elastic re-scattering of intermediate partons off the

Diagrammatic resummation *[SO, 2006, 2008, 2010]*

- define some elementary 'building blocks'
- construct arbitrary enhanced graphs out of them
- correct for double (triple, etc.) counting
- similarly for cut diagrams (based on AGK-rules)

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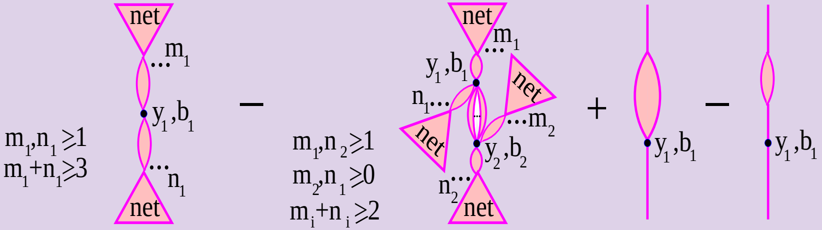
E.g. sum of irredicible contributions to elastic amplitude



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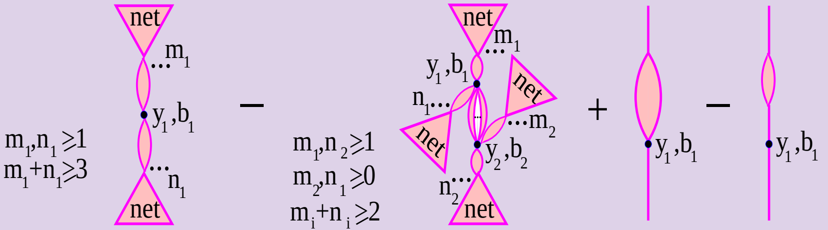
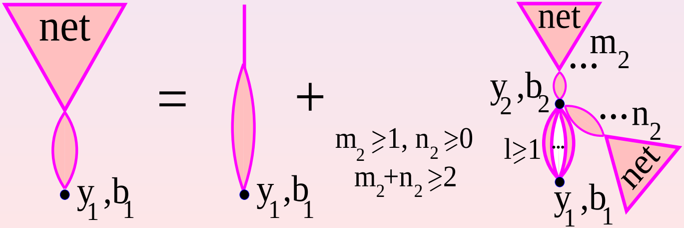


- expressed via 'net-fans' – 'reaction-dependent PDFs':



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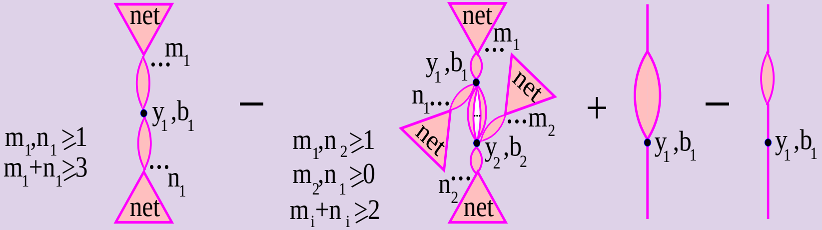
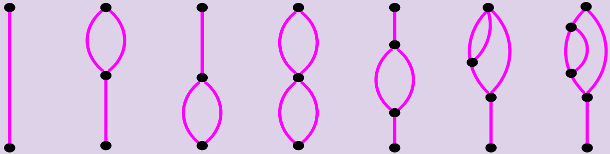


In turn, contain Pomeron 'loop' sequences (examples)



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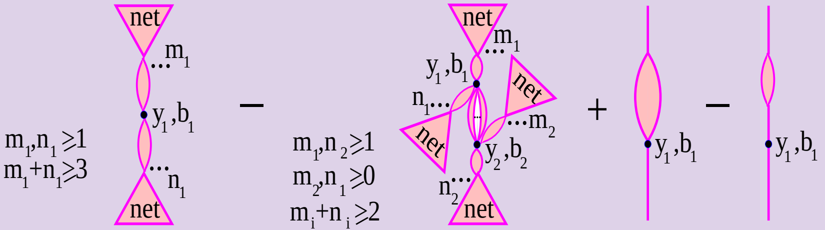

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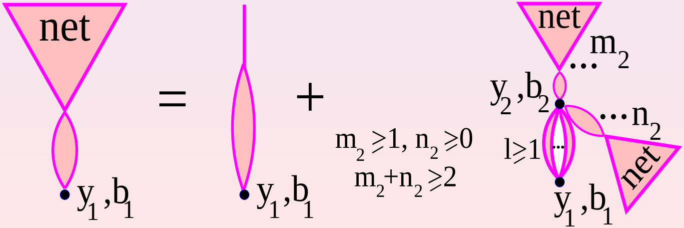

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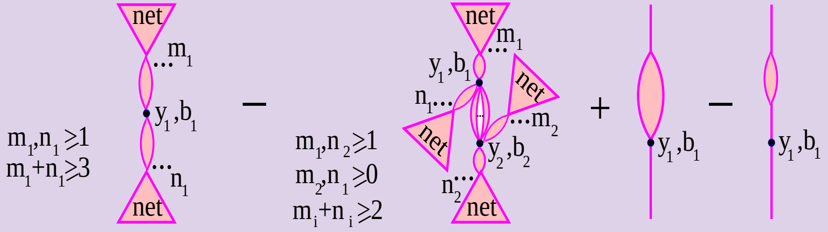

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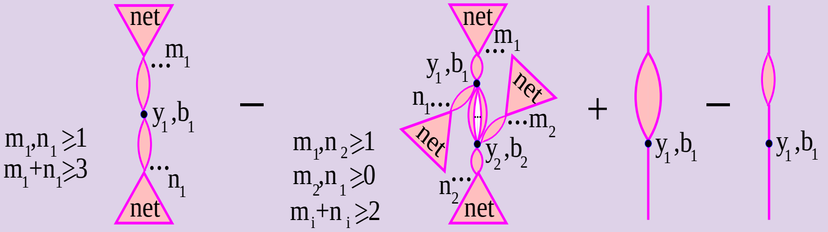

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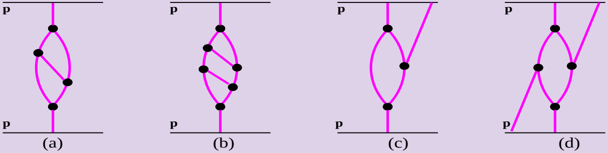
Examples of graphs not included in the procedure



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- $\Rightarrow$ positive-definite cross sections for various final states

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  - NB: applies for $\alpha_{\mathbb{P}}^{\rm ren} > 1$ only (for $G_{3\mathbb{P}}/\gamma_{\mathbb{P}} > \alpha_{\mathbb{P}} - 1$, $\sigma_{\rm tot}(s) \to {\rm const}$ for $s \to \infty$)
- $\Rightarrow$ positive-definite cross sections for various final states
- neglected contributions – negiligible (smaller than 1/mille)

Particular toy model *[SO, 2010]*

- interesting case – model with 2 Pomerons:
  - 'soft' Pomeron: smaller $\alpha_{\mathbb{P}\mathrm{soft}}$, larger $\alpha'_{\mathbb{P}\mathrm{soft}}$
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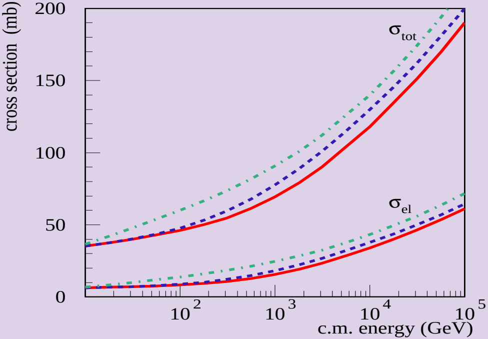
Relative importance of 'nets' & 'loops'



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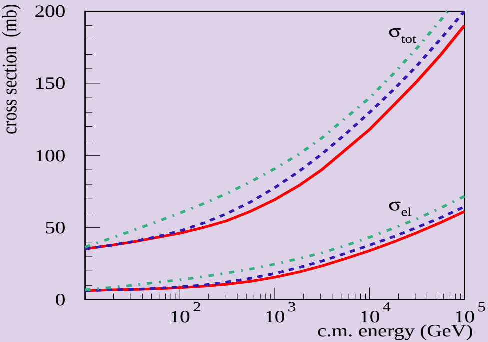

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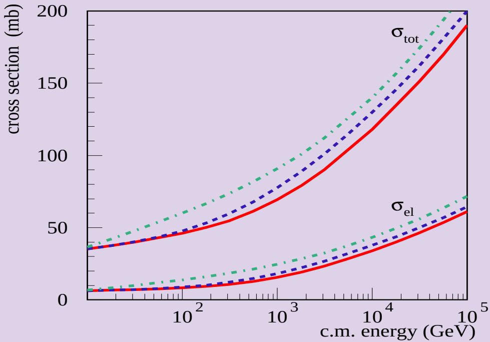

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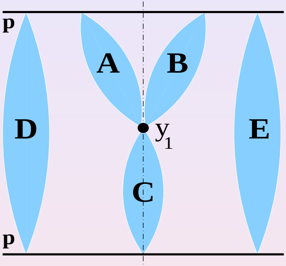
- NB: relative contribution of $\mathbb{P}$-loops strongly depends on $\alpha'_{\mathbb{P}}$
  - simpliest loop contribution $\propto G_{3\mathbb{P}}^2/\alpha'_{\mathbb{P}}$
  - $\Rightarrow \to \infty$ for $\alpha'_{\mathbb{P}} \to 0$ (assuming the slope for the $3\mathbb{P}$-vertex $\simeq 0$)
- in the above example, $\alpha'_{\mathbb{P}\text{soft}} = 0.14\,\text{GeV}^{-2}$ was used

σ_{SD} & non-eikonal rap-gap suppression

- schematic diagram for single high mass diffraction:



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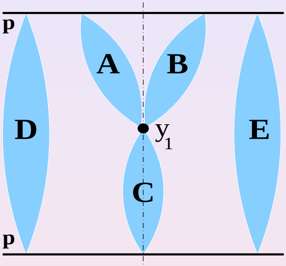

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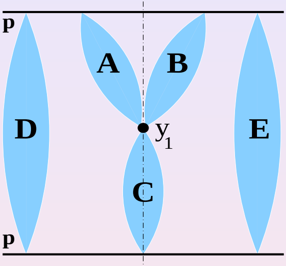

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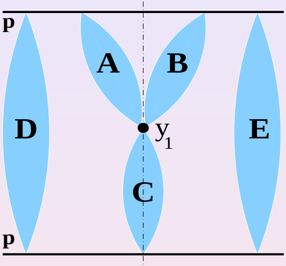

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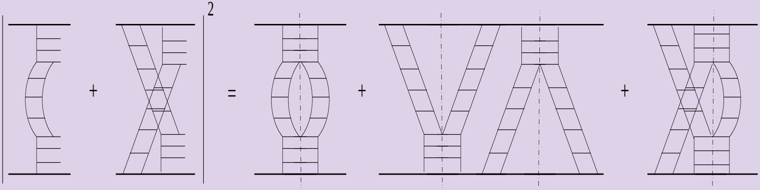
NB: generally, also multiple exchanges of the ABC subgraph

- e.g. required by *s*-channel unitarity for DD (at small b)



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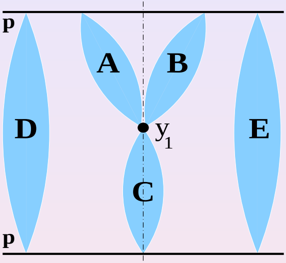

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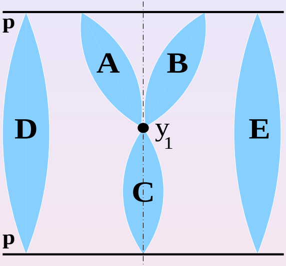

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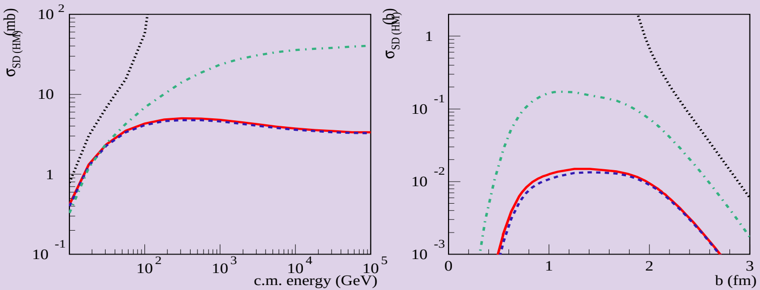
Impact on σ_{SD} (high mass) & diffraction profile at 14 TeV c.m.



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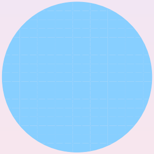

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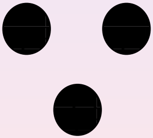

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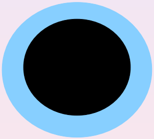

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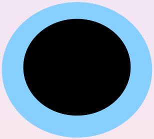

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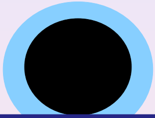

Phenomenological treatment *[Kalmykov & SO, 1994,1997]*

- soft Pomerons to describe soft (parts of) cascades $(p_t^2 < Q_0^2)$
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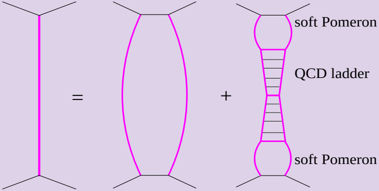

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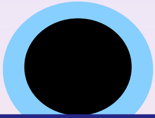

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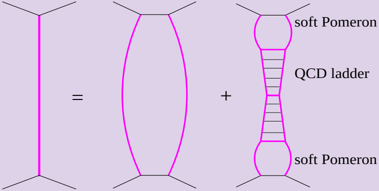

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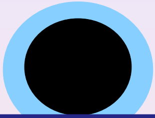

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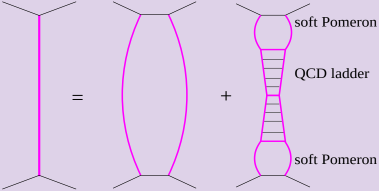

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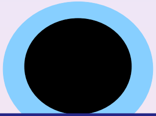

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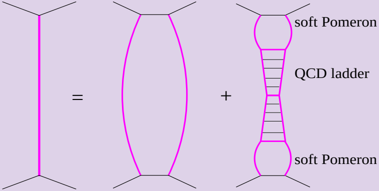

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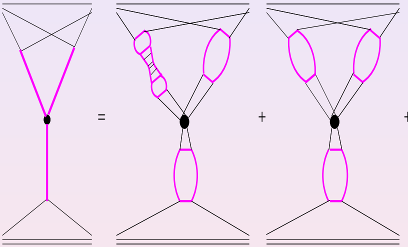

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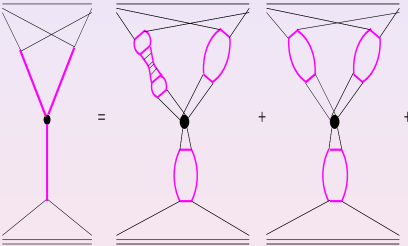

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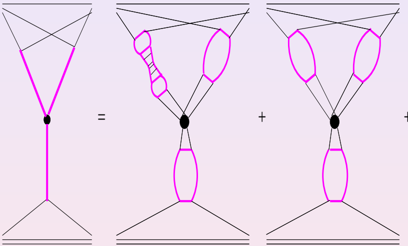

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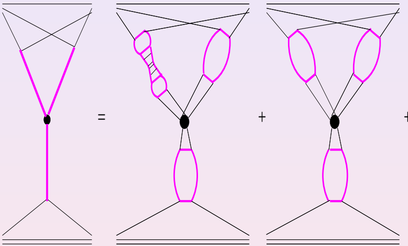

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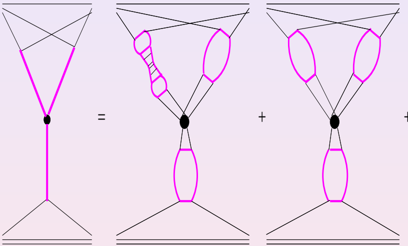

- $\Rightarrow$ undercritical soft $\mathbb{P}$ ($\Delta_{\mathbb{P}\rm soft} \equiv \alpha^{\rm ren}_{\mathbb{P}\rm soft} - 1 < 0$) in dense limit
  - 'shrinking' of soft cascades (& soft pieces of 'semihard' ones)
  - saturation of parton density at the Q_0-scale
  - but: no evolution for the saturation scale

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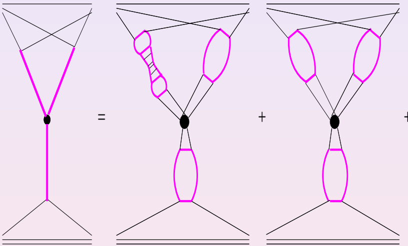

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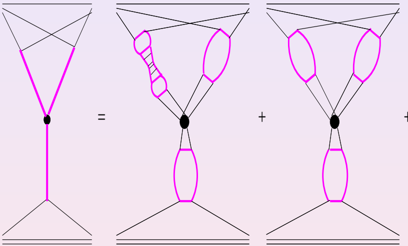

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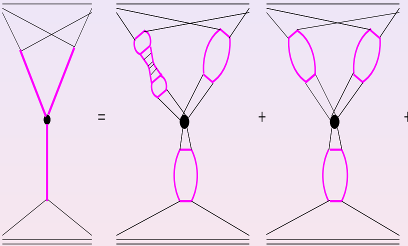

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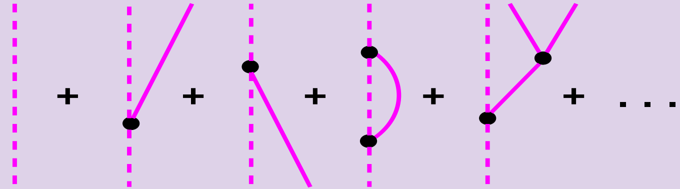

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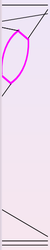

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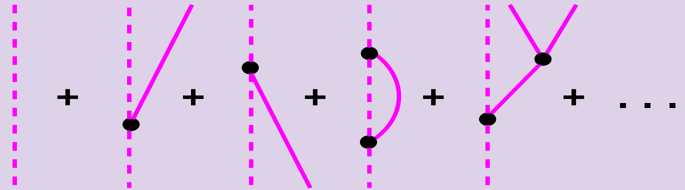

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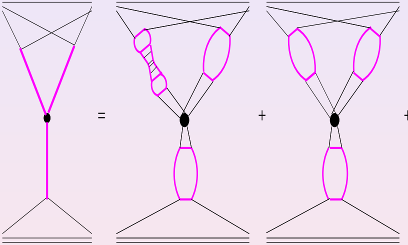

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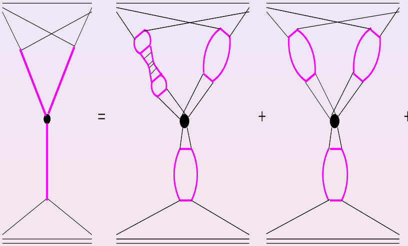

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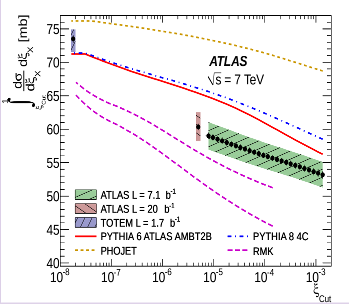

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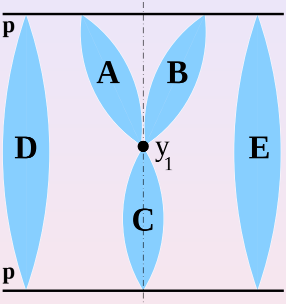

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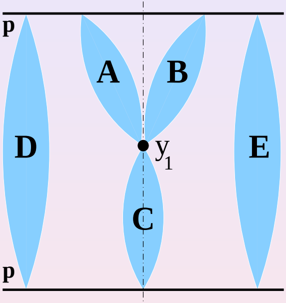

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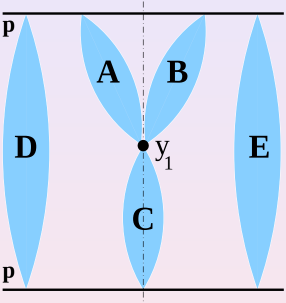

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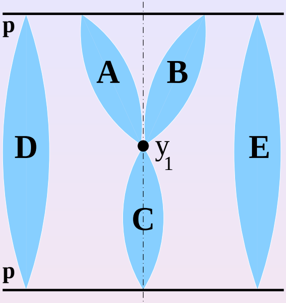

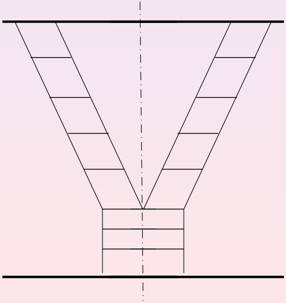

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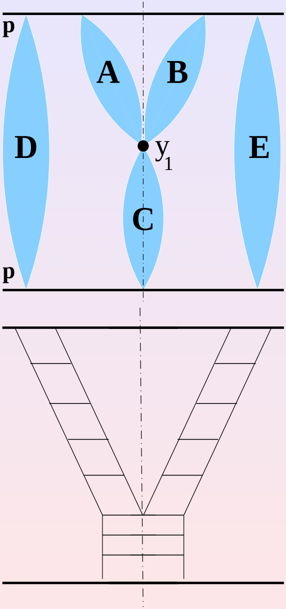

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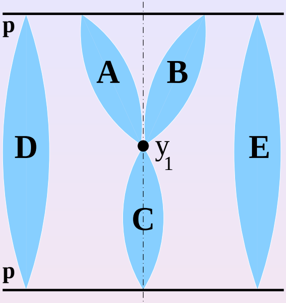

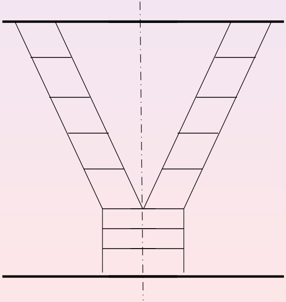

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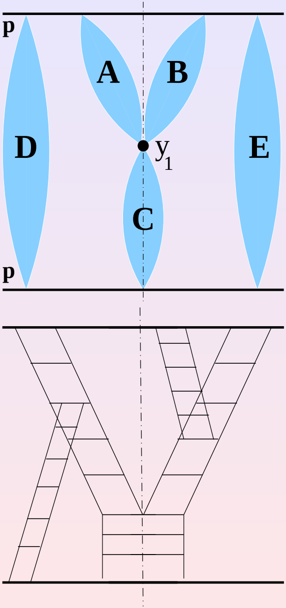

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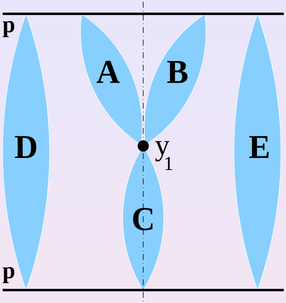

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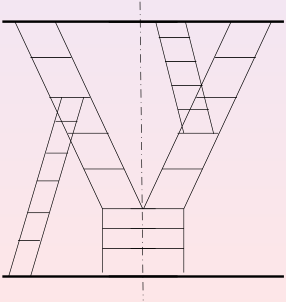

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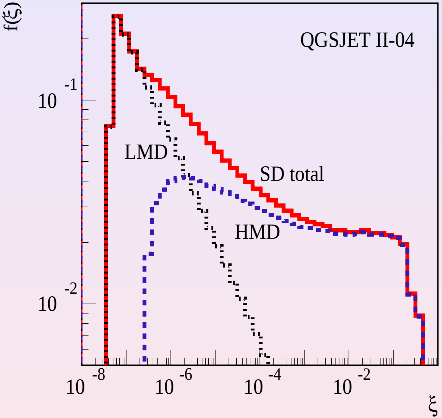

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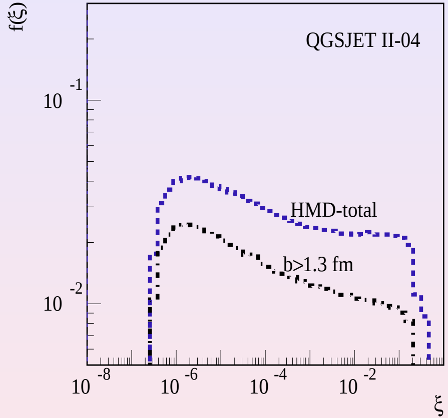

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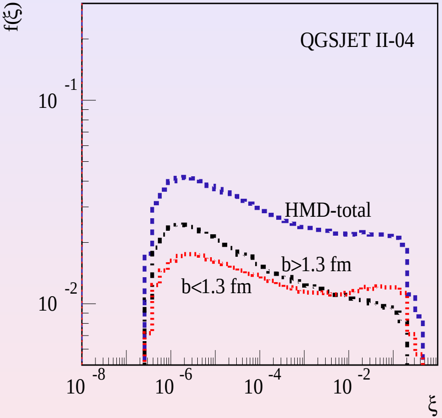

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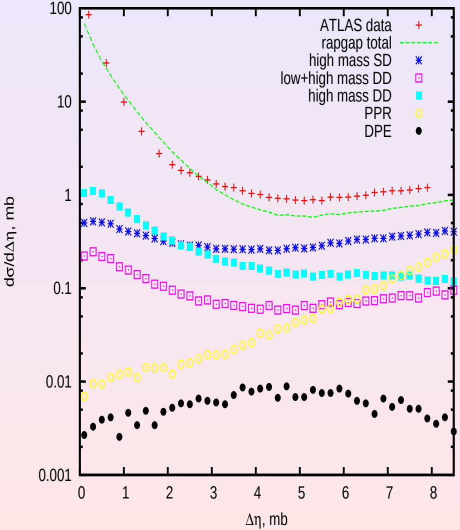
- forward rap-gap (η_F) distribution: QGSJET-II-04 wrt ATLAS



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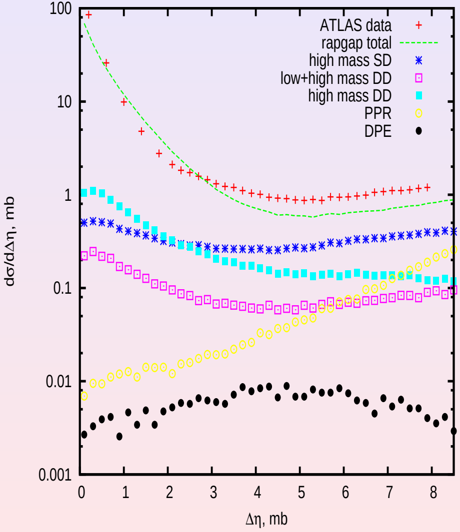

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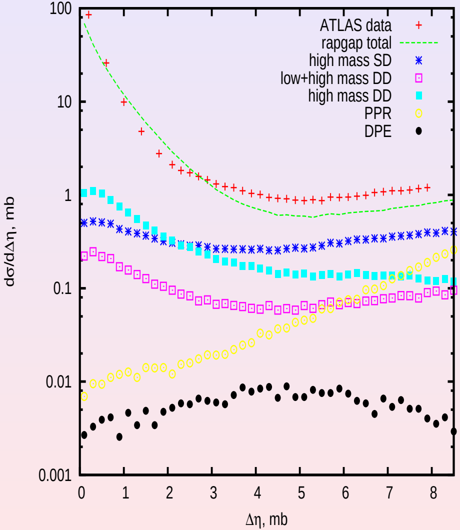

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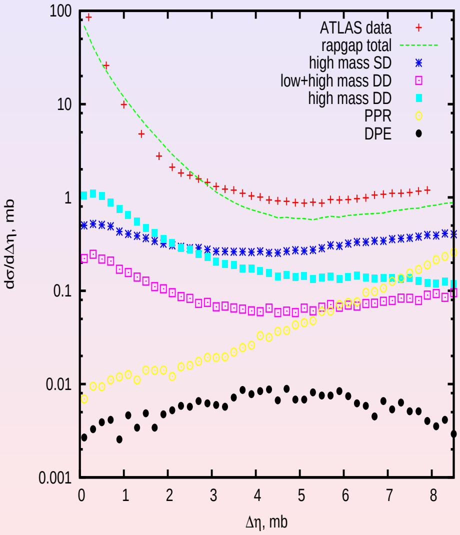

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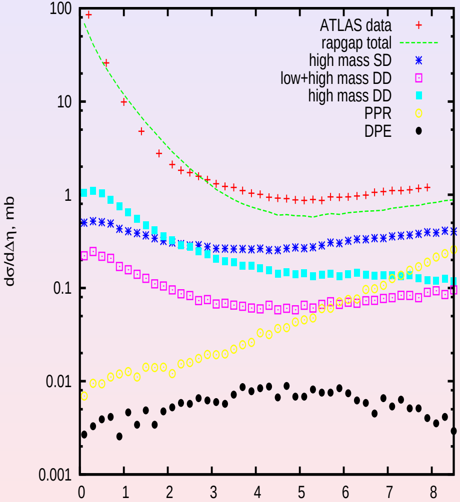

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But: the model misses $\sim 30\%$ of HMD seen by ATLAS!

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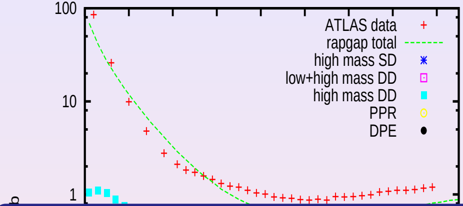

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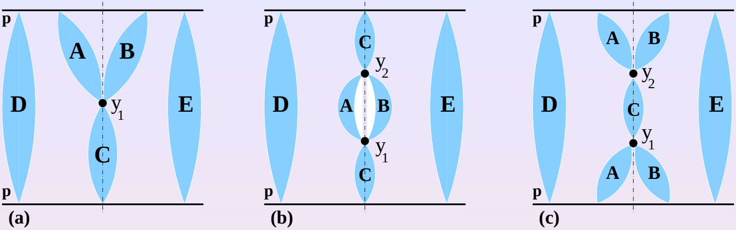
Comparison to preliminary TOTEM results for SD

M_X, GeV ξ_X	$3.4-7$ $(2.4-10)\cdot 10^{-7}$	$7-350$ $10^{-6}-2.5\cdot 10^{-3}$	$350-1100$ $(2.5-25)\cdot 10^{-3}$
TOTEM	1.8	3.3	1.4
model	2.3	4.8	1.6
model/data	1.3	1.5	1.2

- overall trend – similar
- but: rate in variance with ATLAS

SD, DD, CD: b-profiles



- DD contribution (b) – comparable to SD (a)
  - at lowest order: Pomeron 'loop'
  - $\sim G_{3\mathbb{P}}^2/\alpha'_{\mathbb{P}} \sim G_{3\mathbb{P}}$
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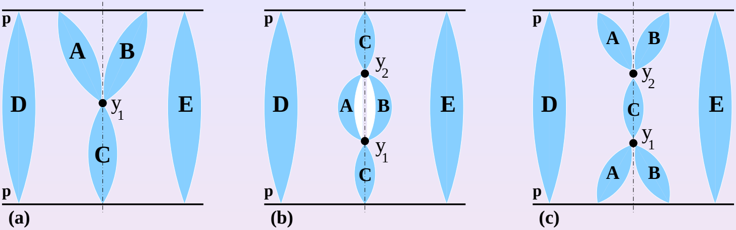

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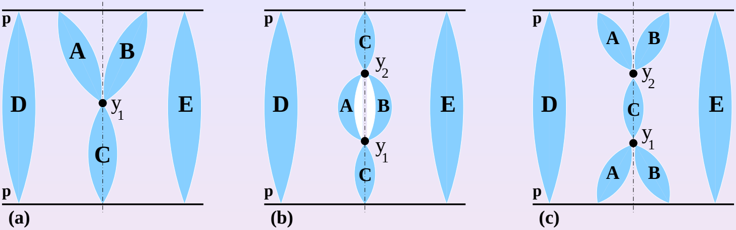

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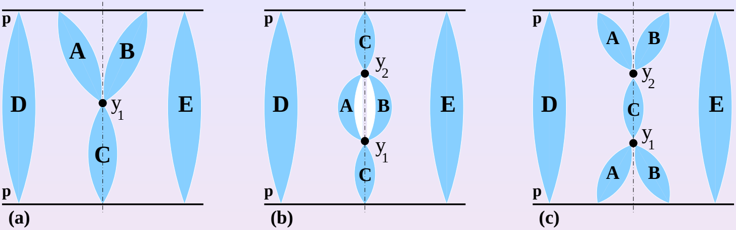

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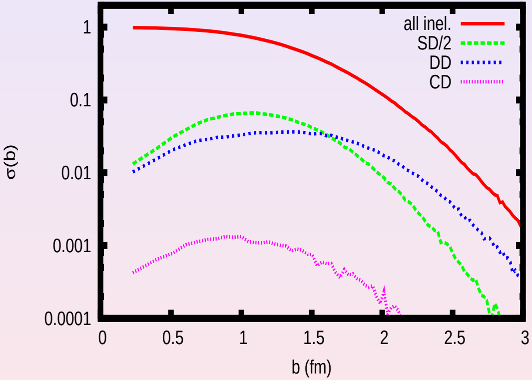
Example: b profiles for pp at $\sqrt{s} = 5$ TeV:



- σ_{SD}: $\sim 15\%$ of σ_{inel}
- σ_{DD}: $\sim 7\%$
- σ_{CD}: $\sim 0.1\%$

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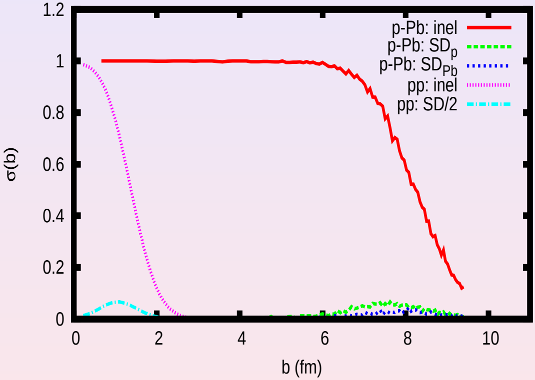
Cf.: b profiles for $p-Pb$ at $\sqrt{s}=5$ TeV:



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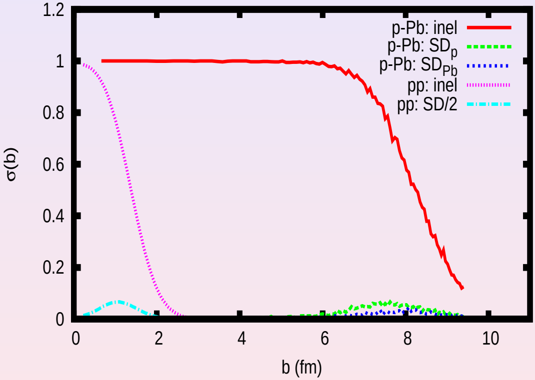

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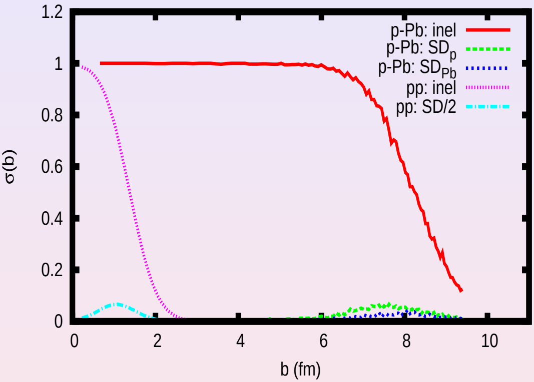

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Diffraction on nuclear target – comparable to the *pp* case

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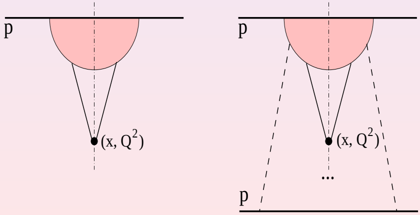

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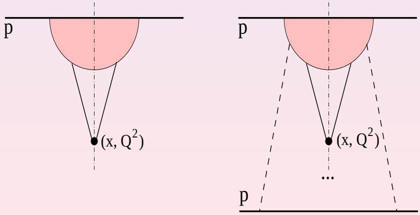

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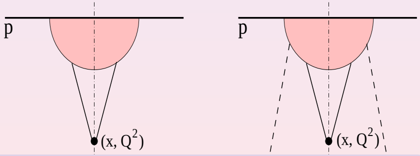

non-inclusive observables can't be described with universal PDFs
(additional screening corrections are process-dependent)

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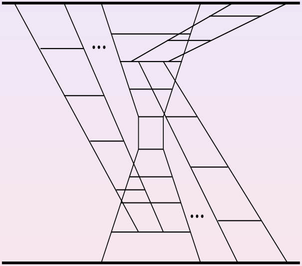

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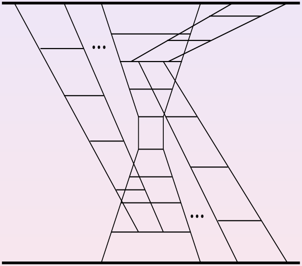

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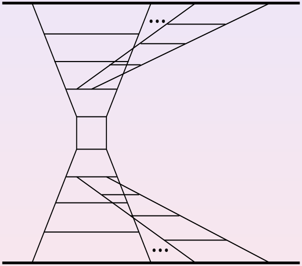

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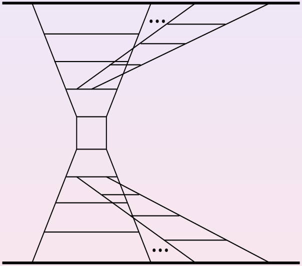

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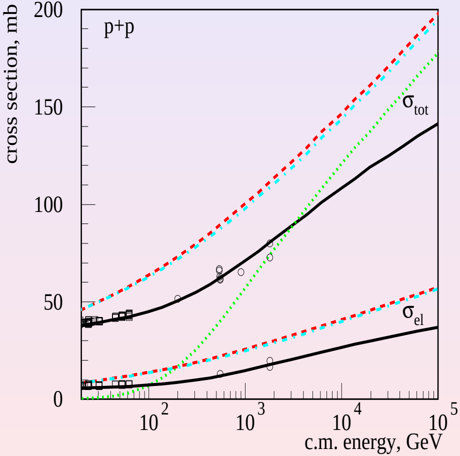

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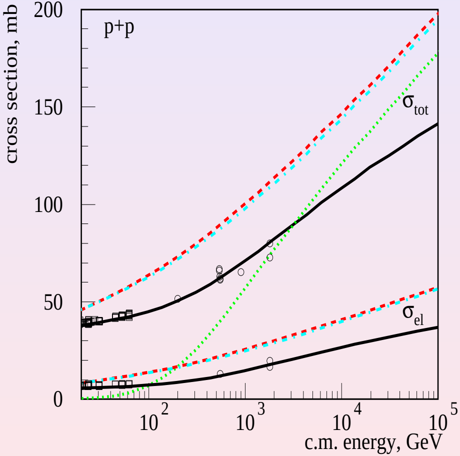

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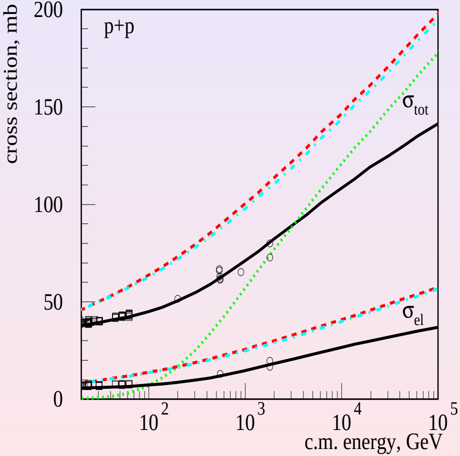

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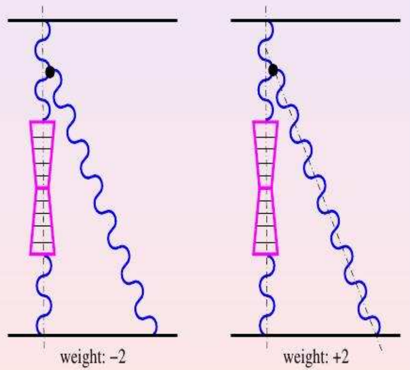

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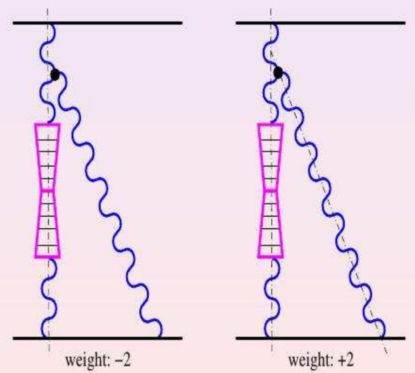

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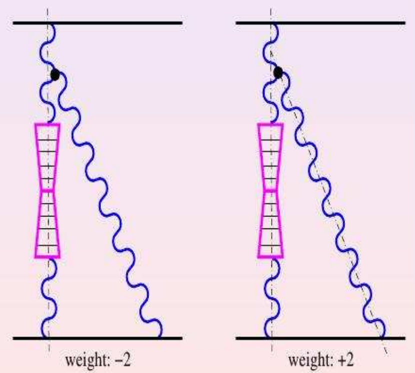

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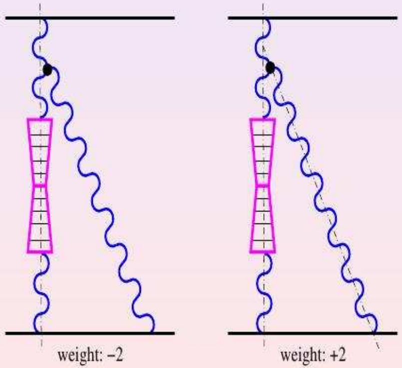

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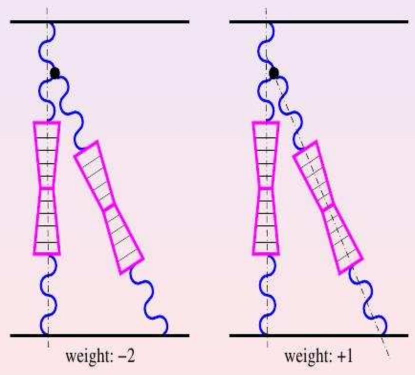

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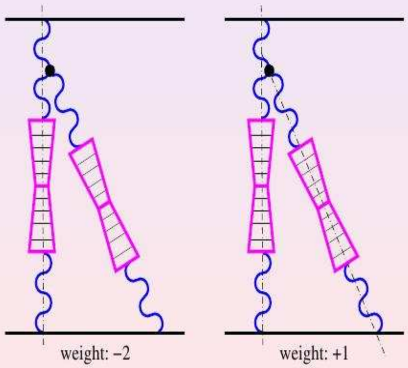

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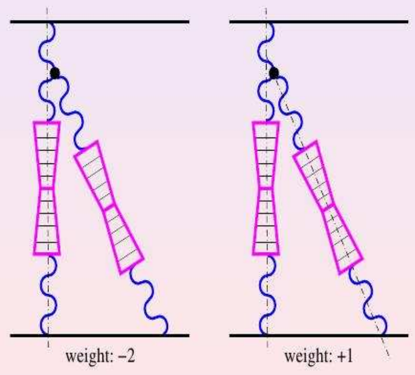

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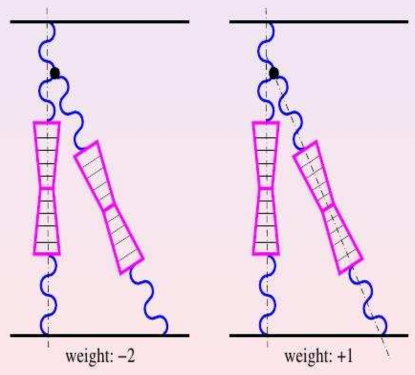

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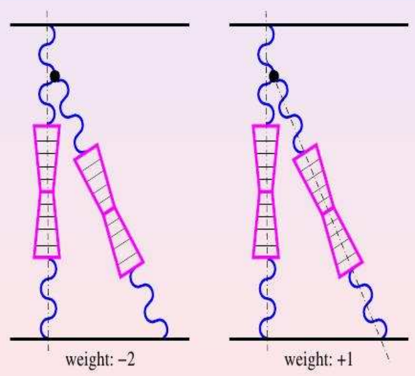

additional screening caused by multi-parton correlations

- two hard parton cascades originate from the same soft parent

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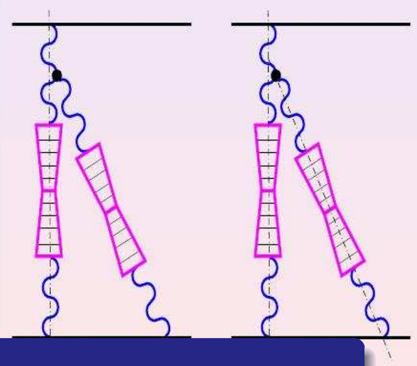

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- double hard scattering from independent cascades: mostly in central collisions
- correlated partons are close-by in b-space (two sub-cascades start from the same $\vec{b}$)
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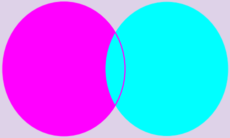

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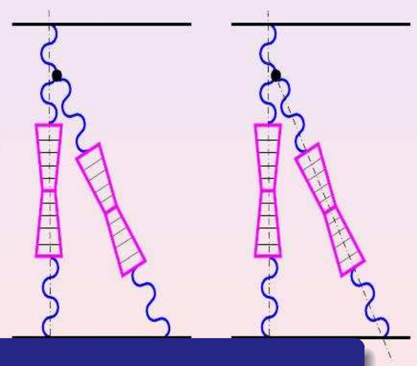

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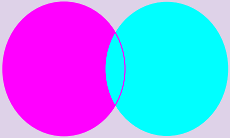

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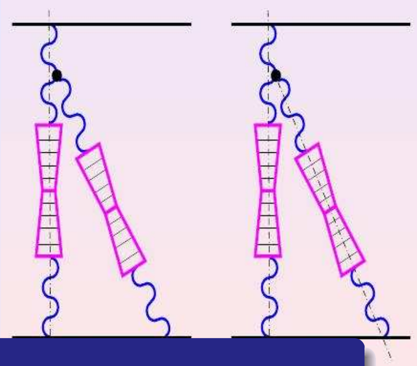

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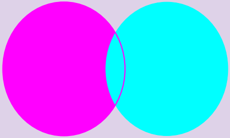

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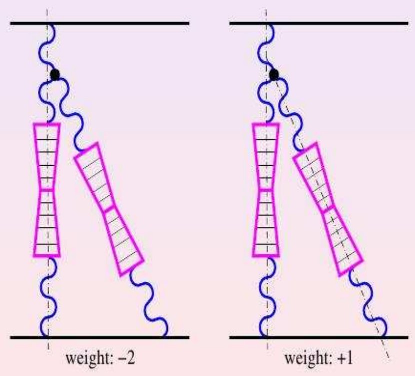
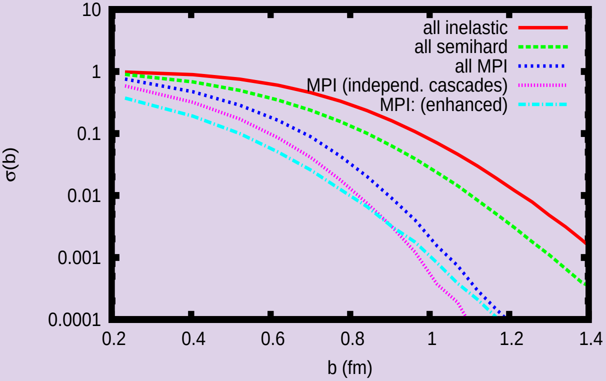


$\Rightarrow$ multi-parton interactions provide a key to understand σ_{pp}^{tot}
(and vice versa)

- now hard screening

Illustration: b-profiles for MPI for pp at 14 TeV c.m. (QGSJET-II)

- NB: more stringent limits on Q_0 from $N_{\rm ch}$ data
  - $\Rightarrow Q_0^2 = 3$ GeV^2 used
  - $\Rightarrow$ factor of 10 weaker effect here



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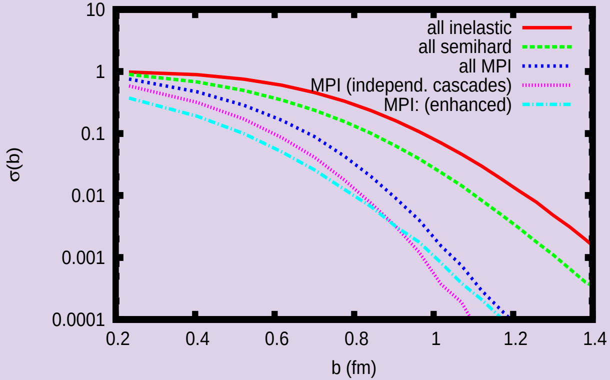

Multi-parton interactions: perturbative splitting

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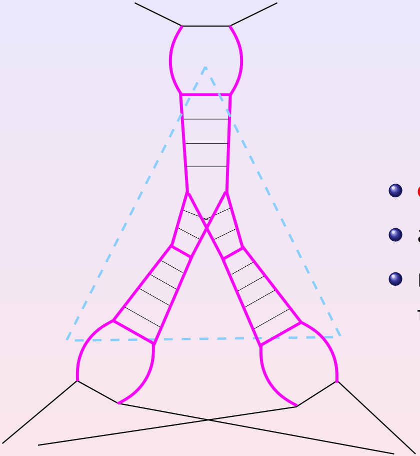

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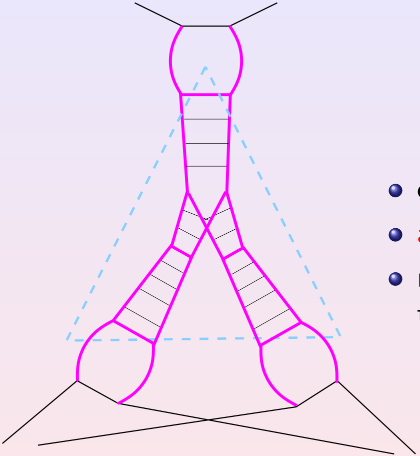

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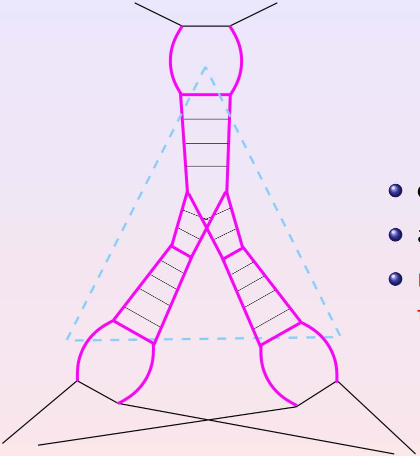

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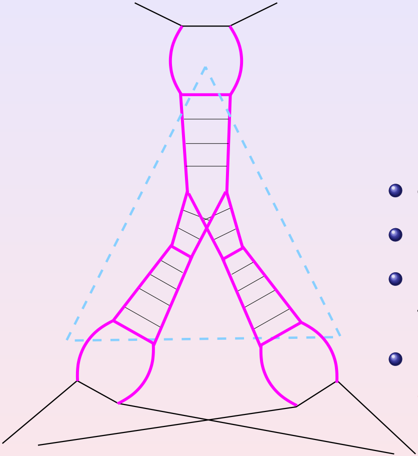

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- neglect b-size of the 'hard triangle' wrt soft evolution
- $\Rightarrow$ 'hard triangle' works as an effective $3\mathbb{P}$-vertex

- 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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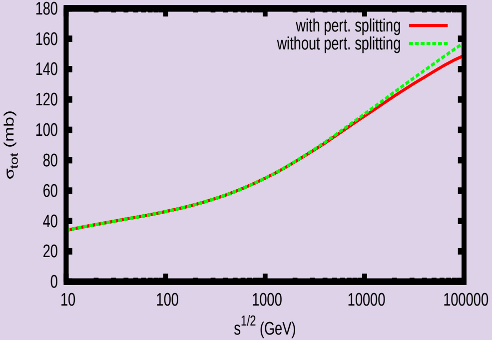
σ_{pp}^{tot} with/without pert. splitting



- effect seen at the highest energies
- but: too weak in the LHC energy range
- mostly nonpert. origin for parton correlations?

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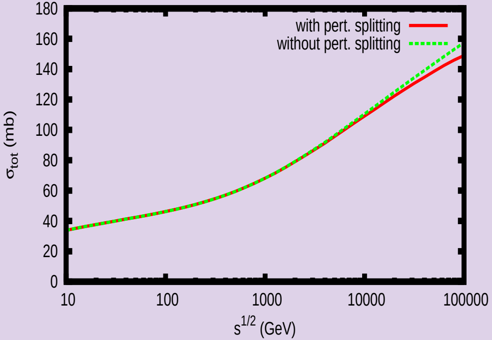

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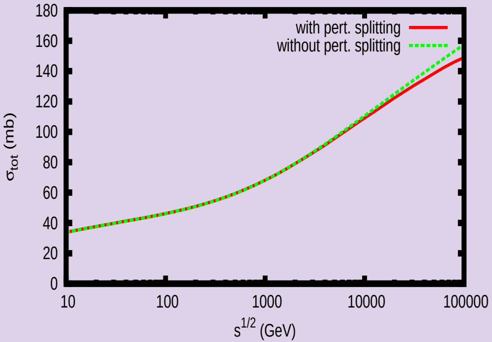

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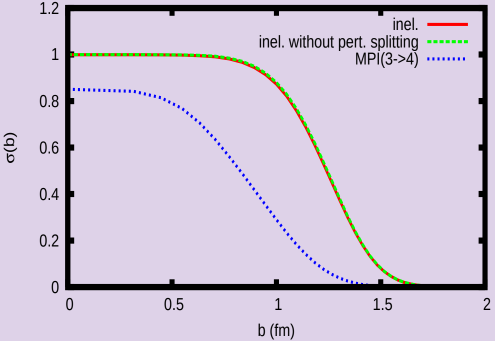

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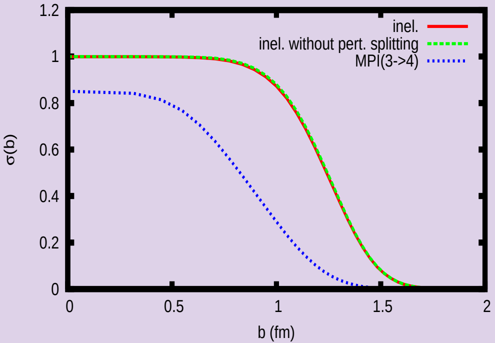

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Backup

Double Pomeron exchange (DPE) & CDF data

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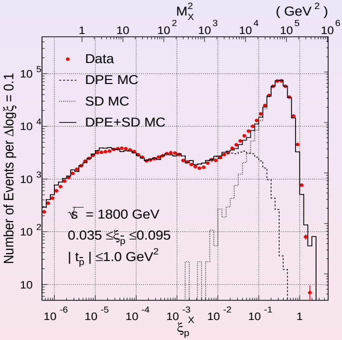

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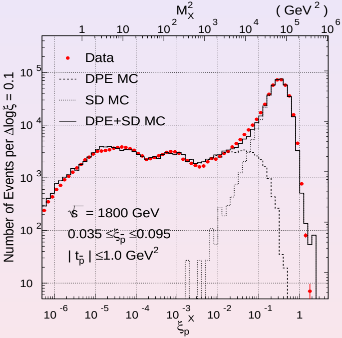

- sample with $0.035 < \xi_{\bar{p}} < 0.095$: assumed to consist of SD(p) & DPE events
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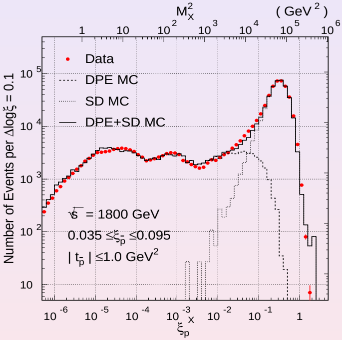

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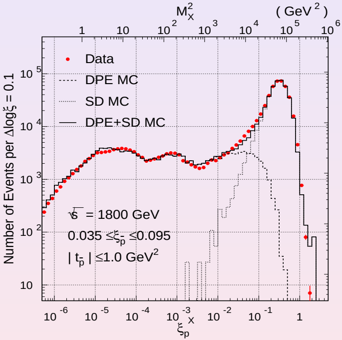

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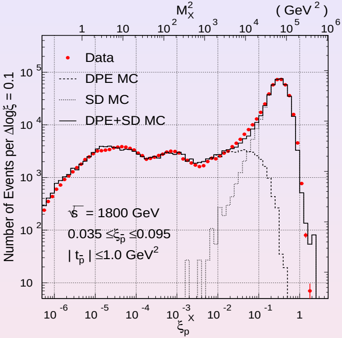

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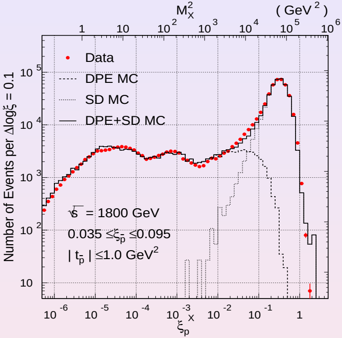

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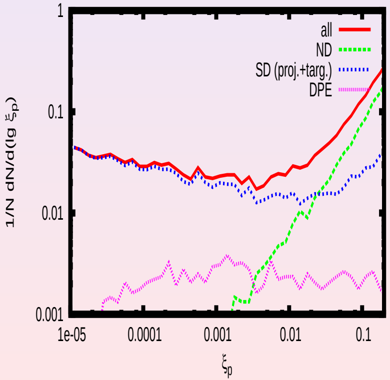

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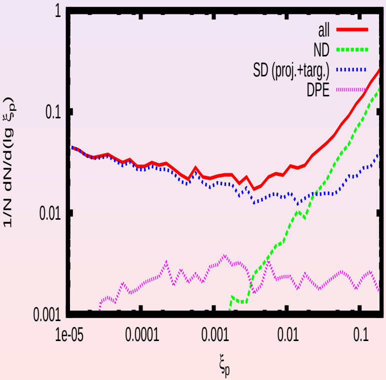

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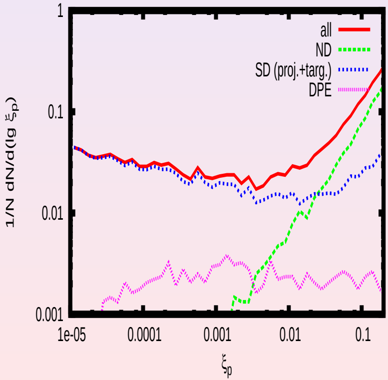

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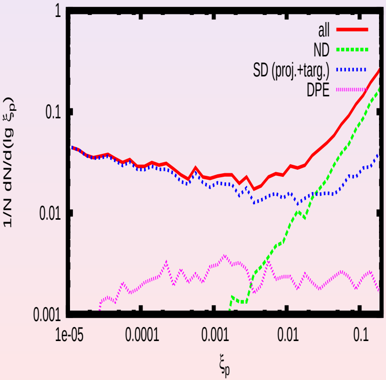

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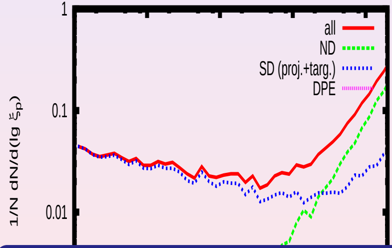

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Bottom line:

- accurate studies of t-dependence necessary for a reliable determination of DPE cross section