Modelling of air showers:
theoretical basis of interaction models

CMS

Sergey Ostapchenko (NTNU)

CERN, February 11-12, 2013

LHCb

ATLAS

ALICE

]

Outline of the talk

Outline of the talk

Outline of the talk

Outline of the talk

Outline of the talk

Outline of the talk

Outline of the talk

Outline of the talk

Outline of the talk

- Cascade of hadron-air interactions – backbone of EAS
  - starts from the primary particle interaction
  - proceeds with secondary sub-cascades (mostly $\pi^{\pm}$)
  - production of π^0 – works like a sink
    (negligible feed back from e/m cascades)

- Cascade of hadron-air interactions – backbone of EAS
    - starts from the primary particle interaction
    - proceeds with secondary sub-cascades (mostly $\pi^{\pm}$)
    - production of π^0 – works like a sink
      (negligible feed back from e/m cascades)

- Cascade of hadron-air interactions – backbone of EAS
  - starts from the primary particle interaction
  - proceeds with secondary sub-cascades (mostly $\pi^{\pm}$)
  - production of π^0 – works like a sink
    (negligible feed back from e/m cascades)

- Cascade of hadron-air interactions – backbone of EAS
  - starts from the primary particle interaction
  - proceeds with secondary sub-cascades (mostly $\pi^\pm$)
  - production of π^0 – works like a sink
    (negligible feed back from e/m cascades)

- Cascade of hadron-air interactions – backbone of EAS
  - starts from the primary particle interaction
  - proceeds with secondary sub-cascades (mostly $\pi^{\pm}$)
  - production of π^0 – works like a sink
    (negligible feed back from e/m cascades)

- CR composition studies – depend strongly on interaction model predictions
  (nature of a primary particle is best viewed via its interactions)

Introduction: EAS development & hadronic interactions

- Cascade of hadron-air interactions – backbone of EAS
  - starts from the primary particle interaction
  - proceeds with secondary sub-cascades (mostly $\pi^{\pm}$)
  - production of π^0 – works like a sink
    (negligible feed back from e/m cascades)

- CR composition studies – depend strongly on interaction model predictions
  (nature of a primary particle is best viewed via its interactions)

- most important observable – shower maximum position X_{max}
  - most sensitive to primary particle interaction
  - especially to σ_{inel} and σ_{diffr} (also to the relative energy loss)

- Cascade of hadron-air interactions – backbone of EAS
  - starts from the primary particle interaction
  - proceeds with secondary sub-cascades (mostly $\pi^{\pm}$)
  - production of π^0 – works like a sink
    (negligible feed back from e/m cascades)
- CR composition studies – depend strongly on interaction model predictions
  (nature of a primary particle is best viewed via its interactions)
- most important observable – shower maximum position X_{max}
  - most sensitive to primary particle interaction
  - especially to σ_{inel} and σ_{diffr} (also to the relative energy loss)

Introduction: EAS development & hadronic interactions

- Cascade of hadron-air interactions – backbone of EAS
  - starts from the primary particle interaction
  - proceeds with secondary sub-cascades (mostly $\pi^{\pm}$)
  - production of π^0 – works like a sink
    (negligible feed back from e/m cascades)

- CR composition studies – depend strongly on interaction model predictions
  (nature of a primary particle is best viewed via its interactions)

- most important observable – shower maximum position X_{max}
  - most sensitive to primary particle interaction
  - especially to σ_{inel} and σ_{diffr} (also to the relative energy loss)

- Cascade of hadron-air interactions – backbone of EAS
  - starts from the primary particle interaction
  - proceeds with secondary sub-cascades (mostly $\pi^{\pm}$)
  - production of π^0 – works like a sink
    (negligible feed back from e/m cascades)

- CR composition studies – depend strongly on interaction model predictions
  (nature of a primary particle is best viewed via its interactions)

- most important observable – shower maximum position X_{max}
  - most sensitive to primary particle interaction
  - especially to σ_{inel} and σ_{diffr} (also to the relative energy loss)

- for ground-based studies: EAS muon content is important
  - probs the cascade process (mostly via pion-air collisions)

- Cascade of hadron-air interactions – backbone of EAS
  - starts from the primary particle interaction
  - proceeds with secondary sub-cascades (mostly $\pi^{\pm}$)
  - production of π^0 – works like a sink
    (negligible feed back from e/m cascades)

- CR composition studies – depend strongly on interaction model predictions
  (nature of a primary particle is best viewed via its interactions)

- most important observable – shower maximum position X_{max}
  - most sensitive to primary particle interaction
  - especially to σ_{inel} and σ_{diffr} (also to the relative energy loss)

- for ground-based studies: EAS muon content is important
  - probs the cascade process (mostly via pion-air collisions)

- Cascade of hadron-air interactions – backbone of EAS
  - starts from the primary particle interaction
  - proceeds with secondary sub-cascades (mostly $\pi^{\pm}$)
  - production of π^0 – works like a sink
    (negligible feed back from e/m cascades)

- CR composition studies – depend strongly on interaction model predictions
  (nature of a primary particle is best viewed via its interactions)

- most important observable – shower maximum position X_{max}
  - most sensitive to primary particle interaction

Crucial requirement to the models – predictive power

- very desirable: coherent formalism for treating cross sections & particle production

- also important: generalizability from pp (hp) to pA & AA

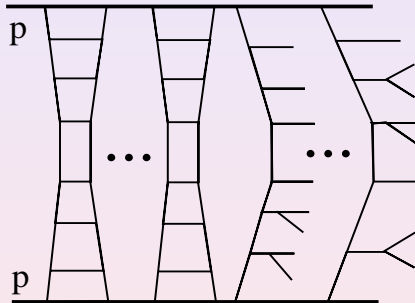# Introduction: EAS development & hadronic interactions

- Cascade of hadron-air interactions – backbone of EAS
  - starts from the primary particle interaction
  - proceeds with secondary sub-cascades (mostly $\pi^{\pm}$)
  - production of π^0 – works like a sink
    (negligible feed back from e/m cascades)

- CR composition studies – depend strongly on interaction model predictions
  (nature of a primary particle is best viewed via its interactions)

- most important observable – shower maximum position $X_{\max}$
  - most sensitive to primary particle interaction

Crucial requirement to the models – predictive power

- very desirable: coherent formalism for treating cross sections & particle production

- also important: generalizability from pp (hp) to pA & AA
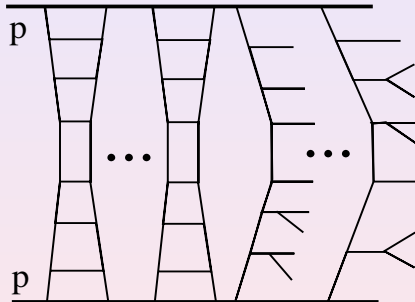
- QCD-inspired: interaction mediated by parton cascades

- multiple scattering (many cascades in parallel)

- real cascades
  ⇒ particle production

- vitual cascades
  ⇒ elastic rescattering
  (just momentum transfer)

- QCD-inspired: interaction mediated by parton cascades

- multiple scattering (many cascades in parallel)

- real cascades
  $\Rightarrow$ particle production

- vitual cascades
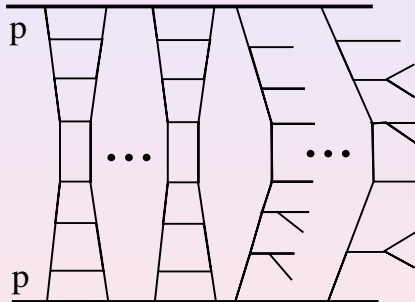 $\Rightarrow$ elastic rescattering
  (just momentum transfer)

- QCD-inspired: interaction mediated by parton cascades

- multiple scattering (many cascades in parallel)

- real cascades
  ⇒ particle production

- vitual cascades
  ⇒ elastic rescattering
  (just momentum transfer)

- QCD-inspired: interaction mediated by parton cascades

- multiple scattering (many cascades in parallel)

- real cascades
  $\Rightarrow$ particle production

- vitual cascades
  $\Rightarrow$ elastic rescattering
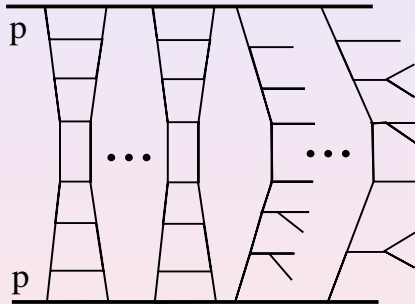 (just momentum transfer)

Hadronic interactions – qualitative picture

- QCD-inspired: interaction mediated by parton cascades

- multiple scattering (many cascades in parallel)

- real cascades
  $\Rightarrow$ particle production

- vitual cascades
  $\Rightarrow$ elastic rescattering
  (just momentum transfer)

universal interaction mechanism

- different hadrons (nuclei) $\Rightarrow$ different initial conditions (parton Fock States) but same mechanism

- energy-evolution of the observables (e.g. σ_{pp}^{tot}): due to a larger phase space for cascades to develop
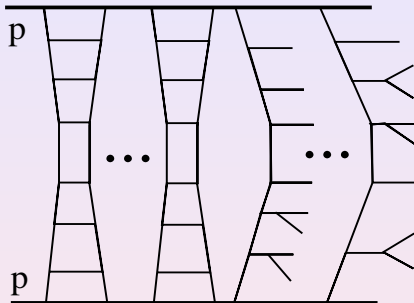
Hadronic interactions – qualitative picture

- QCD-inspired: interaction mediated by parton cascades

- multiple scattering (many cascades in parallel)

- real cascades
  $\Rightarrow$ particle production

- vitual cascades
  $\Rightarrow$ elastic rescattering
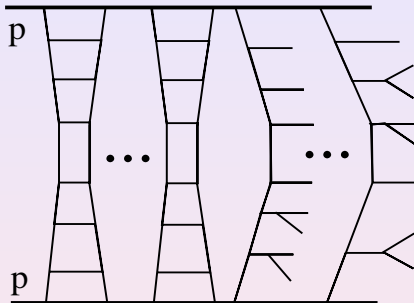 (just momentum transfer)



universal interaction mechanism

- different hadrons (nuclei) $\Rightarrow$ different initial conditions (parton Fock States) but same mechanism

- energy-evolution of the observables (e.g. σ_{pp}^{tot}):
  due to a larger phase space for cascades to develop

Constraints from pQCD & problems

- pQCD: collinear factorization applies for inclusive spectra
  $$\frac{d^3\sigma_{pp\to h}}{dp^3} = \sum_{i,j,k} f_{i/p} \otimes \sigma_{ij\to k} \otimes f_{j/p} \otimes D_{h/k}$$

- separates short- & long-distance dynamics

- pQCD predicts evolution of PDFs ($f_{i/p}$) & FFs ($D_{h/k}$)

- $\Rightarrow$ allows to simulate perturbative (high p_t) part of parton cascades (initial & final state emission)

- pQCD: collinear factorization applies for inclusive spectra
  $\frac{d^3\sigma_{pp\to h}}{dp^3} = \sum_{i,j,k} f_{i/p} \otimes \sigma_{ij\to k} \otimes f_{j/p} \otimes D_{h/k}$

- separates short- & long-distance dynamics

- pQCD predicts evolution of PDFs ($f_{i/p}$) & FFs ($D_{h/k}$)

- $\Rightarrow$ allows to simulate perturbative (high p_t) part of parton cascades (initial & final state emission)

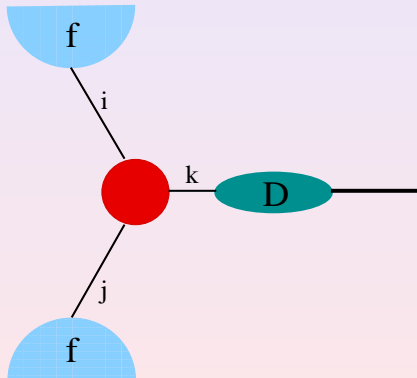- pQCD: collinear factorization applies for inclusive spectra
  $\frac{d^3\sigma_{pp\to h}}{dp^3} = \sum_{i,j,k} f_{i/p} \otimes \sigma_{ij\to k} \otimes f_{j/p} \otimes D_{h/k}$

- separates short- &
  long-distance dynamics

- pQCD predicts evolution of
  PDFs ($f_{i/p}$) & FFs ($D_{h/k}$)

- $\Rightarrow$ allows to simulate
  perturbative (high p_t) part
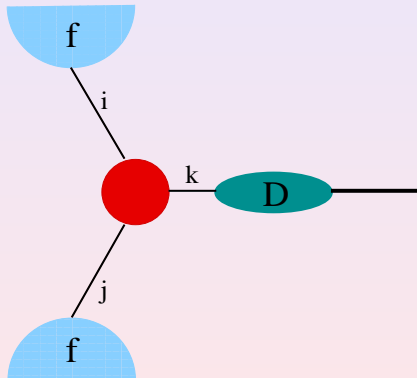 of parton cascades (initial
  & final state emission)
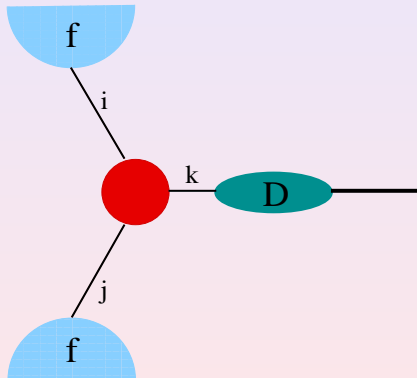
- pQCD: collinear factorization applies for inclusive spectra
  $\frac{d^3\sigma_{pp\rightarrow h}}{dp^3} = \sum_{i,j,k} f_{i/p} \otimes \sigma_{ij\rightarrow k} \otimes f_{j/p} \otimes D_{h/k}$

- separates short- & long-distance dynamics

- pQCD predicts evolution of PDFs ($f_{i/p}$) & FFs ($D_{h/k}$)

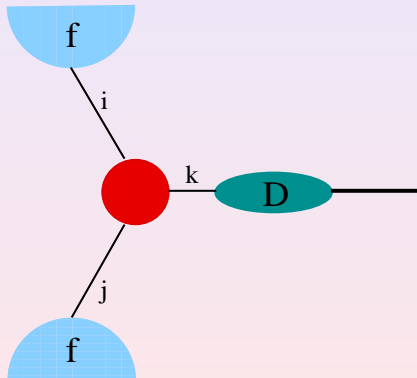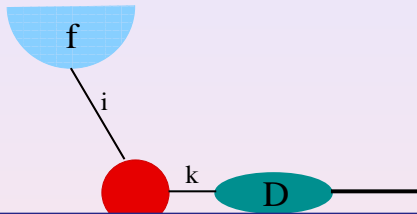- $\Rightarrow$ allows to simulate perturbative (high p_t) part of parton cascades (initial & final state emission)

Constraints from pQCD & problems

- pQCD: collinear factorization applies for inclusive spectra
  $\frac{d^3\sigma_{pp\to h}}{dp^3} = \sum_{i,j,k} f_{i/p} \otimes \sigma_{ij\to k} \otimes f_{j/p} \otimes D_{h/k}$

- separates short- & long-distance dynamics

- pQCD predicts evolution of PDFs ($f_{i/p}$) & FFs ($D_{h/k}$)

Problems beyond pQCD – require phenomenological treatment

- nonperturbative (low p_t) parton evolution ('soft' rescatterings; very initial stage of 'semihard' cascades)

- structure of Fock states & hadron 'remnants'

- multiple scattering aspect

- nonlinear effects (interactions between parton cascades)

Constraints from pQCD & problems

- pQCD: collinear factorization applies for inclusive spectra
  $$\frac{d^3\sigma_{pp\to h}}{dp^3} = \sum_{i,j,k} f_{i/p} \otimes \sigma_{ij\to k} \otimes f_{j/p} \otimes D_{h/k}$$

- separates short- &
  long-distance dynamics

- pQCD predicts evolution of
  PDFs ($f_{i/p}$) & FFs ($D_{h/k}$)

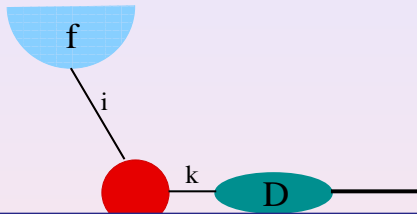## Problems beyond pQCD – require phenomenological treatment

- nonperturbative (low p_t) parton evolution
  ('soft' rescatterings; very initial stage of 'semihard' cascades)

- structure of Fock states & hadron 'remnants'

- multiple scattering aspect

- nonlinear effects (interactions between parton cascades)

Constraints from pQCD & problems

- pQCD: collinear factorization applies for inclusive spectra
  $\frac{d^3\sigma_{pp\to h}}{dp^3} = \sum_{i,j,k} f_{i/p} \otimes \sigma_{ij\to k} \otimes f_{j/p} \otimes D_{h/k}$

- separates short- &
  long-distance dynamics

- pQCD predicts evolution of
  PDFs ($f_{i/p}$) & FFs ($D_{h/k}$)

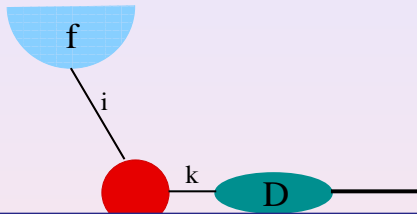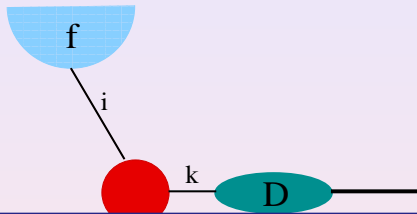## Problems beyond pQCD – require phenomenological treatment

- nonperturbative (low p_t) parton evolution
  ('soft' rescatterings; very initial stage of 'semihard' cascades)

- structure of Fock states & hadron 'remnants'

- multiple scattering aspect

- nonlinear effects (interactions between parton cascades)

Constraints from pQCD & problems

- pQCD: collinear factorization applies for inclusive spectra
  $\frac{d^3\sigma_{pp\to h}}{dp^3} = \sum_{i,j,k} f_{i/p} \otimes \sigma_{ij\to k} \otimes f_{j/p} \otimes D_{h/k}$

- separates short- & long-distance dynamics

- pQCD predicts evolution of PDFs ($f_{i/p}$) & FFs ($D_{h/k}$)

Problems beyond pQCD – require phenomenological treatment

- nonperturbative (low p_t) parton evolution ('soft' rescatterings; very initial stage of 'semihard' cascades)

- structure of Fock states & hadron 'remnants'

- multiple scattering aspect

- nonlinear effects (interactions between parton cascades)

- Basic ingredient: treatment of an individual parton cascade

  - scattering amplitude
  - hadronization procedure

- Basic ingredient: treatment of an individual parton cascade

  - scattering amplitude
  - hadronization procedure

- Basic ingredient: treatment of an individual parton cascade
  - scattering amplitude
  - hadronization procedure

- Basic ingredient: treatment of an individual parton cascade

  - scattering amplitude
  - hadronization procedure

- important: transverse development of the cascade
  ($\Delta b^2 \sim 1/\Delta q^2$)

- Basic ingredient: treatment of an individual parton cascade

    - scattering amplitude
    - hadronization procedure

- important: transverse development of the cascade
  $(\Delta b^2 \sim 1/\Delta q^2)$

- e.g. for soft cascades:
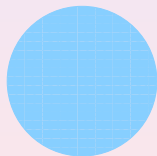 quick transverse spread & low parton density
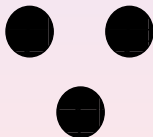
Single parton cascade

- Basic ingredient: treatment of an individual parton cascade
    - scattering amplitude
    - hadronization procedure

- important: transverse development of the cascade
  $(\Delta b^2 \sim 1/\Delta q^2)$

- e.g. for soft cascades quick transverse spread
  & low parton density

- hard cascades: frozen in transverse space but
  high density rise

Single parton cascade

- Basic ingredient: treatment of an individual parton cascade

    - scattering amplitude
    - hadronization procedure

- important: transverse development of the cascade
  ($\Delta b^2 \sim 1/\Delta q^2$)

- e.g. for soft cascades quick transverse spread
  & low parton density

- hard cascades: frozen in transverse space but
  high density rise

- semihard cascades: quick expansion during
  'soft preevolution' followed by the density rise

    - $\Rightarrow$ dominant in high energy limit

Single parton cascade

- Basic ingredient: treatment of an individual parton cascade

    - scattering amplitude
    - hadronization procedure

- important: transverse development of the cascade
  $(\Delta b^2 \sim 1/\Delta q^2)$

- e.g. for soft cascades quick transverse spread
  & low parton density

- hard cascades: frozen in transverse space but
  high density rise

- semihard cascades: quick expansion during
  'soft preevolution' followed by the density rise

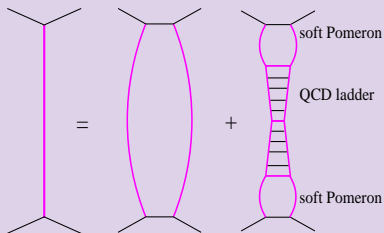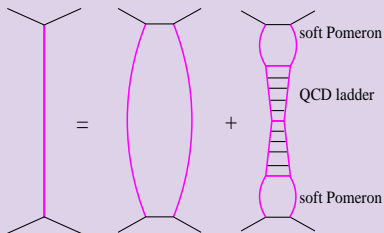   - $\Rightarrow$ dominant in high energy limit

Single parton cascade

- Basic ingredient: treatment of an individual parton cascade

  - scattering amplitude
  - hadronization procedure

- important: transverse development of the cascade
  $(\Delta b^2 \sim 1/\Delta q^2)$

Phenomenological: 'semihard Pomeron' (in QGSJET & EPOS)

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

- DGLAP for hard cascades

- taken together:
  'general Pomeron'

- hadronization:
  string procedures

Single parton cascade

- Basic ingredient: treatment of an individual parton cascade
    - scattering amplitude
    - hadronization procedure

- important: transverse development of the cascade
  $(\Delta b^2 \sim 1/\Delta q^2)$
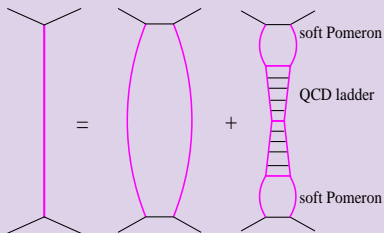
Phenomenological: 'semihard Pomeron' (in QGSJET & EPOS)

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

- DGLAP for hard cascades

- taken together:
  'general Pomeron'

- hadronization:
  string procedures

Single parton cascade

- Basic ingredient: treatment of an individual parton cascade

  - scattering amplitude
  - hadronization procedure

- important: transverse development of the cascade
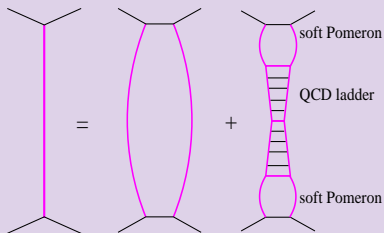 $(\Delta b^2 \sim 1/\Delta q^2)$

Phenomenological: 'semihard Pomeron' (in QGSJET & EPOS)

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

- DGLAP for hard cascades

- taken together:
  'general Pomeron'

- hadronization:
  string procedures

Single parton cascade

- Basic ingredient: treatment of an individual parton cascade

  - scattering amplitude
  - hadronization procedure

- important: transverse development of the cascade
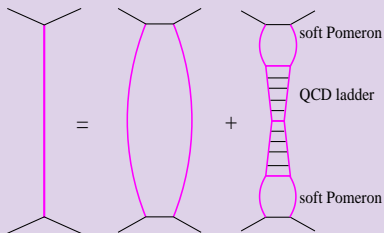 $(\Delta b^2 \sim 1/\Delta q^2)$

Phenomenological: 'semihard Pomeron' (in QGSJET & EPOS)

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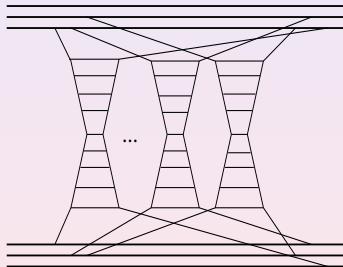 - $\Rightarrow$ transverse expansion governed by Pomeron slope

- DGLAP for hard cascades

- taken together:
  'general Pomeron'

- hadronization:
  string procedures

Single parton cascade

- Basic ingredient: treatment of an individual parton cascade
  - scattering amplitude
  - hadronization procedure

- important: transverse development of the cascade
  $(\Delta b^2 \sim 1/\Delta q^2)$

Phenomenological: 'semihard Pomeron' (in QGSJET & EPOS)

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

- DGLAP for hard cascades

- taken together:
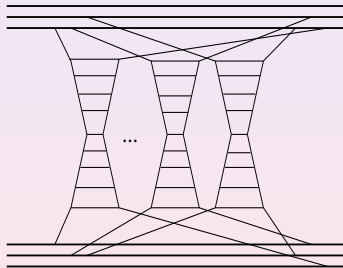 'general Pomeron'

- hadronization:
  string procedures

Multiple scattering & RFT approach

- Treatment of multiple scattering – presently beyong pQCD (dominated by small momentum transfer along the cascades)

- the only viable approach so far: Reggeon Field Theory (RFT) *[Gribov, 1967]*

  - allows to calculate: cross sections & partial probabilities of final states

- important assumption: validity of AGK cutting rules (no interference between different configurations of final states)
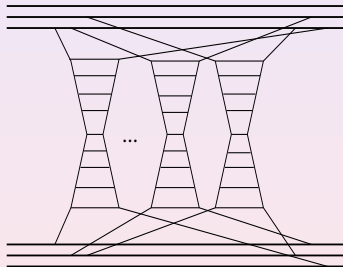
Multiple scattering & RFT approach

- Treatment of multiple scattering – presently beyong pQCD (dominated by small momentum transfer along the cascades)

- the only viable approach so far:
  Reggeon Field Theory (RFT)
  [Gribov, 1967]

    - allows to calculate:
      cross sections & partial
      probabilities of final states

- important assumption:
  validity of AGK cutting rules
  (no interference between different
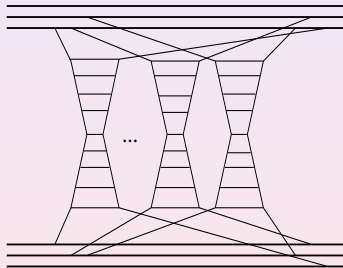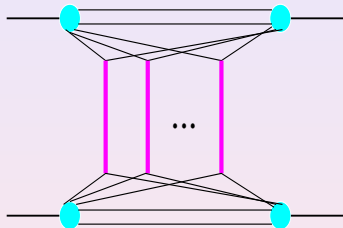 configurations of final states)

Multiple scattering & RFT approach

- Treatment of multiple scattering – presently beyong pQCD (dominated by small momentum transfer along the cascades)

- the only viable approach so far: Reggeon Field Theory (RFT) *[Gribov, 1967]*

  - allows to calculate: cross sections & partial probabilities of final states

- important assumption: validity of AGK cutting rules (no interference between different configurations of final states)
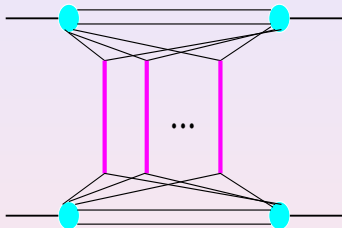
Multiple scattering & RFT approach

- Treatment of multiple scattering – presently beyong pQCD (dominated by small momentum transfer along the cascades)

- the only viable approach so far:
  Reggeon Field Theory (RFT)
  [Gribov, 1967]

  - allows to calculate:
    cross sections & partial
    probabilities of final states

- important assumption:
  validity of AGK cutting rules
  (no interference between different
  configurations of final states)

Multiple scattering & RFT approach

- Treatment of multiple scattering – presently beyong pQCD (dominated by small momentum transfer along the cascades)

- the only viable approach so far: Reggeon Field Theory (RFT)

- e.g. elastic amplitude in the Pomeron scheme
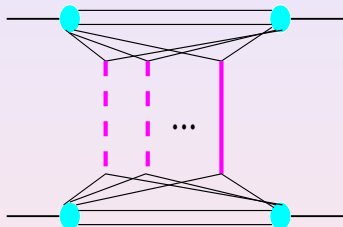 - requires Pomeron amplitude & Pomeron-hadron vertices
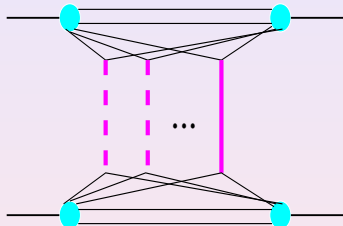
Multiple scattering & RFT approach

- Treatment of multiple scattering – presently beyong pQCD (dominated by small momentum transfer along the cascades)

- the only viable approach so far: Reggeon Field Theory (RFT)

- e.g. elastic amplitude in the Pomeron scheme

  - requires Pomeron amplitude & Pomeron-hadron vertices

- Treatment of multiple scattering – presently beyong pQCD (dominated by small momentum transfer along the cascades)

- cross sections for final states: from 'cut' diagrams

- e.g. using the 'semihard Pomeron': consistent with collinear factorization for inclusive spectra
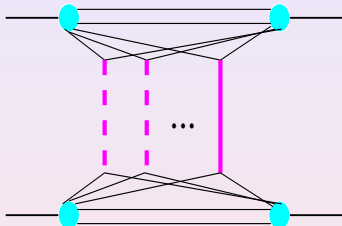
- Treatment of multiple scattering – presently beyong pQCD (dominated by small momentum transfer along the cascades)

- cross sections for final states: from 'cut' diagrams

- e.g. using the 'semihard Pomeron': consistent with collinear factorization for inclusive spectra
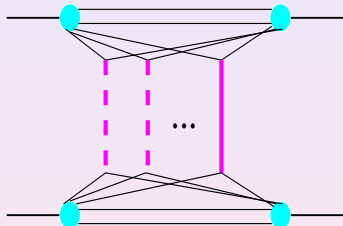
Multiple scattering & RFT approach

- Treatment of multiple scattering – presently beyong pQCD (dominated by small momentum transfer along the cascades)

- cross sections for final states: from 'cut' diagrams

- e.g. using the 'semihard Pomeron': consistent with collinear factorization for inclusive spectra

- particularly simple expressions when using eikonal approximation (independent Pomeron emissions)
  - standard practice but not self-consistent
  - energy-momentum sharing between multiple rescatterings addressed in EPOS
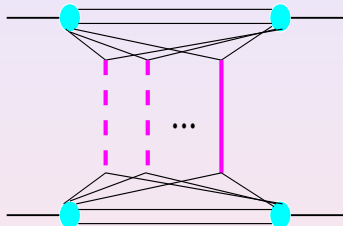
Multiple scattering & RFT approach

- Treatment of multiple scattering – presently beyong pQCD (dominated by small momentum transfer along the cascades)

- cross sections for final states: from 'cut' diagrams

- e.g. using the 'semihard Pomeron': consistent with collinear factorization for inclusive spectra

- particularly simple expressions when using eikonal approximation (independent Pomeron emissions)
  - standard practice but not self-consistent
  - energy-momentum sharing between multiple rescatterings addressed in EPOS

Multiple scattering & RFT approach

- Treatment of multiple scattering – presently beyong pQCD (dominated by small momentum transfer along the cascades)

- cross sections for final states: from 'cut' diagrams

- e.g. using the 'semihard Pomeron': consistent with collinear factorization for inclusive spectra

- particularly simple expressions when using eikonal approximation (independent Pomeron emissions)
    - standard practice but not self-consistent
    - energy-momentum sharing between multiple rescatterings addressed in EPOS
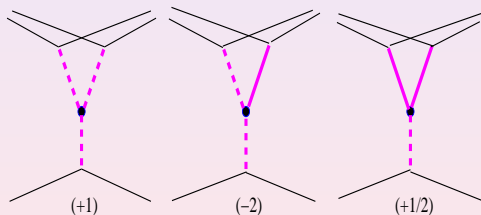
- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
  - described in RFT by enhanced ($\mathbb{PP}$-interaction) graphs

- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
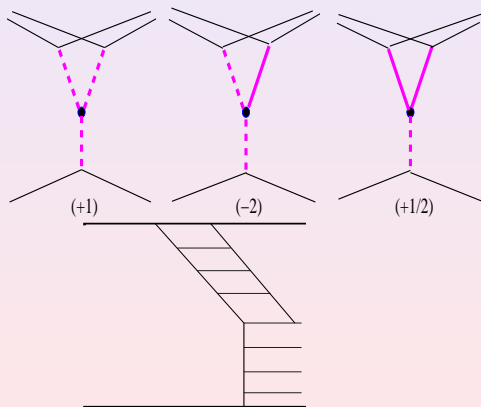 - described in RFT by enhanced ($\mathbb{P}\mathbb{P}$-interaction) graphs

- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
  - described in RFT by enhanced ($\mathbb{PP}$-interaction) graphs

- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
  - described in RFT by enhanced ($\mathbb{PP}$-interaction) graphs

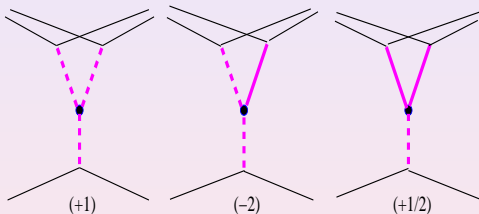- consider simplest (cut) enhanced diagrams to illustrate important consequences
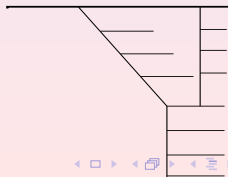

(+1)   (–2)   (+1/2)

Nonlinear effects

- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
  - described in RFT by enhanced ($\mathbb{P}\mathbb{P}$-interaction) graphs

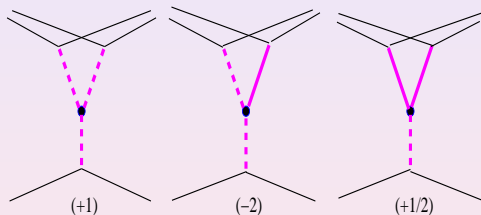- consider simplest (cut) enhanced diagrams to illustrate important consequences

(+1)　　(−2)　　(+1/2)
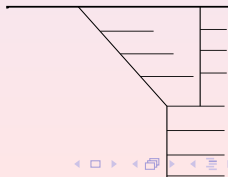
- high mass diffraction

Nonlinear effects

- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
  - described in RFT by enhanced ($\mathbb{PP}$-interaction) graphs

- consider simplest (cut) enhanced diagrams to illustrate important consequences

(+1)   (–2)   (+1/2)

- high mass diffraction
- multi-parton interactions

Nonlinear effects

- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
  - described in RFT by enhanced ($\mathbb{PP}$-interaction) graphs

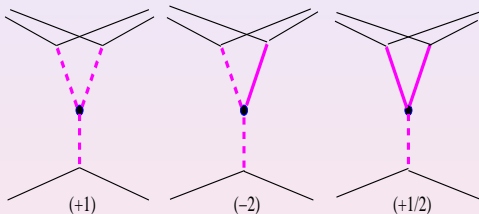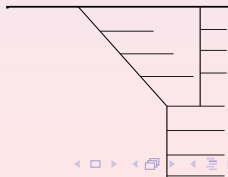- consider simplest (cut) enhanced diagrams to illustrate important consequences

(+1)   (–2)   (+1/2)

- high mass diffraction
- multi-parton interactions
- parton density shadowing

Nonlinear effects

- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
  - described in RFT by enhanced ($\mathbb{PP}$-interaction) graphs

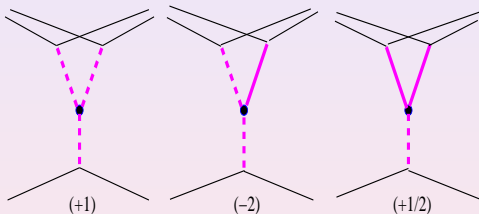- consider simplest (cut) enhanced diagrams to illustrate important consequences

- high mass diffraction
- multi-parton interactions
- parton density shadowing
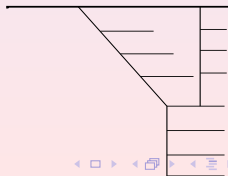- larger fluctuations

$(+1)$ (-2) $(+1/2)$

Nonlinear effects

- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
  - described in RFT by enhanced ($\mathbb{PP}$-interaction) graphs

- consider simplest (cut)
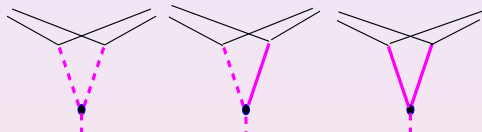 enhanced diagrams
  to illustrate important
  consequences

(+1)   (–2)   (+1/2)

- high mass diffraction
- multi-parton interactions
- parton density shadowing
- larger fluctuations
- 'softening' of forward spectra

- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
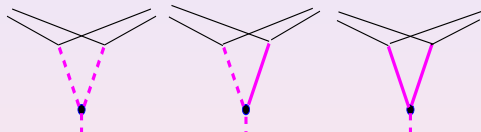 - described in RFT by enhanced ($\mathbb{PP}$-interaction) graphs

- consider simplest (cut) enhanced diagrams

Different approaches in models

- effective 'saturation scale' as energy-dependent cutoff $Q_0(s)$
- effective treatment of lowest order graphs + collective hadronization (EPOS)
- full resummation of enhanced graphs (QGSJET-II)
  - but: assuming 'soft' multi-Pomeron coupling

Nonlinear effects

- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
  - described in RFT by enhanced ($\mathbb{PP}$-interaction) graphs
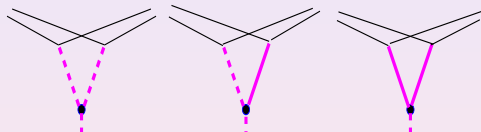
- consider simplest (cut) enhanced diagrams

Different approaches in models

- effective 'saturation scale' as energy-dependent cutoff $Q_0(s)$
- effective treatment of lowest order graphs + collective hadronization (EPOS)
- full resummation of enhanced graphs (QGSJET-II)
  - but: assuming 'soft' multi-Pomeron coupling

Nonlinear effects

- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
  - described in RFT by enhanced ($\mathbb{PP}$-interaction) graphs

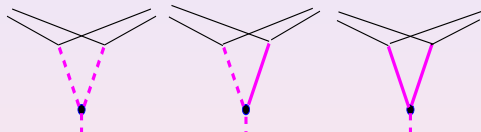- consider simplest (cut)
  enhanced diagrams

Different approaches in models

- effective 'saturation scale' as energy-dependent cutoff $Q_0(s)$
- effective treatment of lowest order graphs + collective hadronization (EPOS)
- full resummation of enhanced graphs (QGSJET-II)
  - but: assuming 'soft' multi-Pomeron coupling

Nonlinear effects

- Crucial at high energies: interactions between parton cascades

  - become increasingly important at higher E & smaller b
  - described in RFT by enhanced ($\mathbb{PP}$-interaction) graphs

- consider simplest (cut) enhanced diagrams

Different approaches in models

- effective 'saturation scale' as energy-dependent cutoff $Q_0(s)$
- effective treatment of lowest order graphs + collective hadronization (EPOS)
- full resummation of enhanced graphs (QGSJET-II)
  - but: assuming 'soft' multi-Pomeron coupling

- 'Marry' slow energy rise of σ_{pp}^{tot} and the steep increase of F_2?

  - next to impossible in the eikonal picture
    (independent parton cascades)

  - $\Rightarrow$ nonlinear parton dynamics – crucial

  - generally believed: cured by parton saturation effects
    (for small Q^2, $xG(x, Q^2) \to$ const as $x \to 0$)

  - mimicked in models by energy-dependent cutoff: $Q_0 = Q_0(s)$

  - however strong saturation not seen at HERA?

  - what is different in pp compared to DIS?

- 'Marry' slow energy rise of σ_{pp}^{tot} and the steep increase of F_2?
    - next to impossible in the eikonal picture
      (independent parton cascades)
    - $\Rightarrow$ nonlinear parton dynamics – crucial
    - generally believed: cured by parton saturation effects
      (for small Q^2, $xG(x, Q^2) \rightarrow$ const as $x \rightarrow 0$)
    - mimicked in models by energy-dependent cutoff: $Q_0 = Q_0(s)$
    - however strong saturation not seen at HERA?
    - what is different in pp compared to DIS?

- 'Marry' slow energy rise of σ_{pp}^{tot} and the steep increase of F_2?
  - next to impossible in the eikonal picture
    (independent parton cascades)
  - $\Rightarrow$ nonlinear parton dynamics – crucial
  - generally believed: cured by parton saturation effects
    (for small Q^2, $xG(x, Q^2) \rightarrow \text{const}$ as $x \rightarrow 0$)
  - mimicked in models by energy-dependent cutoff: $Q_0 = Q_0(s)$
  - however strong saturation not seen at HERA?
  - what is different in pp compared to DIS?

- 'Marry' slow energy rise of σ_{pp}^{tot} and the steep increase of F_2?

    - next to impossible in the eikonal picture (independent parton cascades)

    - $\Rightarrow$ nonlinear parton dynamics – crucial

    - generally believed: cured by parton saturation effects (for small Q^2, $xG(x, Q^2) \to \text{const}$ as $x \to 0$)

    - mimicked in models by energy-dependent cutoff: $Q_0 = Q_0(s)$

    - however strong saturation not seen at HERA?

    - what is different in pp compared to DIS?
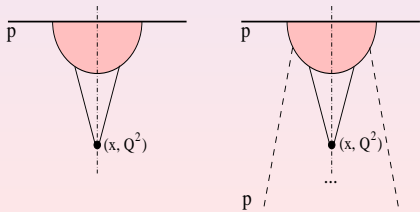
- 'Marry' slow energy rise of σ_{pp}^{tot} and the steep increase of F_2?
  - next to impossible in the eikonal picture (independent parton cascades)
  - $\Rightarrow$ nonlinear parton dynamics – crucial
  - generally believed: cured by parton saturation effects (for small Q^2, $xG(x,Q^2) \to \text{const}$ as $x \to 0$)
  - mimicked in models by energy-dependent cutoff: $Q_0 = Q_0(s)$
  - however strong saturation not seen at HERA?
  - what is different in pp compared to DIS?

- 'Marry' slow energy rise of σ_{pp}^{tot} and the steep increase of F_2?

  - next to impossible in the eikonal picture
    (independent parton cascades)

  - $\Rightarrow$ nonlinear parton dynamics – crucial

  - generally believed: cured by parton saturation effects
    (for small Q^2, $xG(x, Q^2) \to \text{const}$ as $x \to 0$)

  - mimicked in models by energy-dependent cutoff: $Q_0 = Q_0(s)$

  - however strong saturation not seen at HERA?

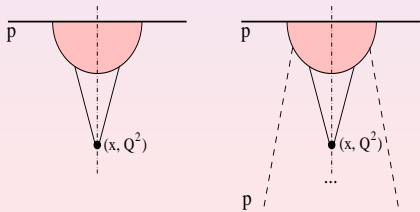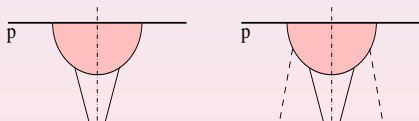 - what is different in pp compared to DIS?

- 'Marry' slow energy rise of σ_{pp}^{tot} and the steep increase of F_2?
  - next to impossible in the eikonal picture (independent parton cascades)
  - $\Rightarrow$ nonlinear parton dynamics – crucial
  - generally believed: cured by parton saturation effects (for small Q^2, $xG(x, Q^2) \to \text{const}$ as $x \to 0$)
  - mimicked in models by energy-dependent cutoff: $Q_0 = Q_0(s)$
  - however strong saturation not seen at HERA?
  - what is different in pp compared to DIS?

From SFs to σ_{pp}^{tot}: saturation or parton correlations?

- 'Marry' slow energy rise of σ_{pp}^{tot} and the steep increase of F_2?
  - next to impossible in the eikonal picture
    (independent parton cascades)
  - $\Rightarrow$ nonlinear parton dynamics – crucial
  - generally believed: cured by parton saturation effects
    (for small Q^2, $xG(x, Q^2) \to$ const as $x \to 0$)
  - mimicked in models by energy-dependent cutoff: $Q_0 = Q_0(s)$
  - however strong saturation not seen at HERA?
  - what is different in pp compared to DIS?

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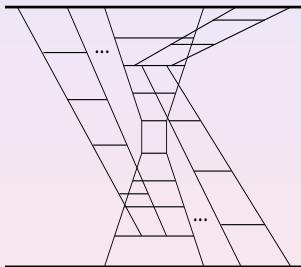 intermediate partons off
  the parent hadron

- in pp: rescattering off the
  target hadron in addition

From SFs to σ_{pp}^{tot}: saturation or parton correlations?

- 'Marry' slow energy rise of σ_{pp}^{tot} and the steep increase of F_2?
    - next to impossible in the eikonal picture (independent parton cascades)
    - $\Rightarrow$ nonlinear parton dynamics – crucial
    - generally believed: cured by parton saturation effects (for small Q^2, $xG(x, Q^2) \to$ const as $x \to 0$)
    - mimicked in models by energy-dependent cutoff: $Q_0 = Q_0(s)$
    - however strong saturation not seen at HERA?
    - what is different in pp compared to DIS?

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

- in pp: rescattering off the target hadron in addition

- 'Marry' slow energy rise of σ_{pp}^{tot} and the steep increase of F_2?

  - next to impossible in the eikonal picture
    (independent parton cascades)

  - $\Rightarrow$ nonlinear parton dynamics – crucial

  - generally believed: cured by parton saturation effects
    (for small Q^2, $xG(x, Q^2) \to \text{const}$ as $x \to 0$)

  - mimicked in models by energy-dependent cutoff: $Q_0 = Q_0(s)$

  - however strong saturation not seen at HERA?

  - what is different in pp compared to DIS?

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

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

- How strong is the effect?

- How strong is the effect?

- consider σ_{pp}^{tot} including all corrections (also rescattering off the partner hadron)
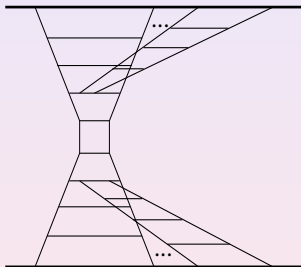
- with both soft and semihard contributions included

- How strong is the effect?

- consider σ_{pp}^{tot} including all corrections (also rescattering off the partner hadron)

- with both soft and semihard contributions included

- How strong is the effect?

- or just corrections to PDFS (factorizable contributions)

- and neglecting soft processes

- How strong is the effect?

- or just corrections to PDFS (factorizable contributions)

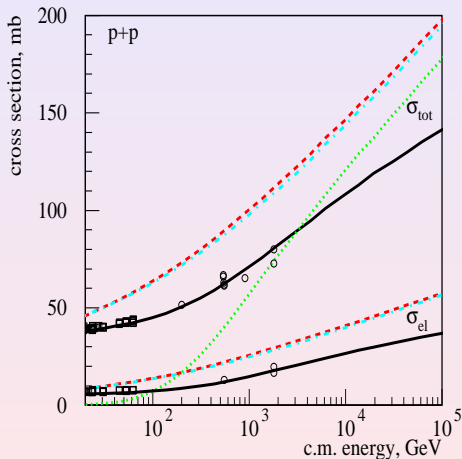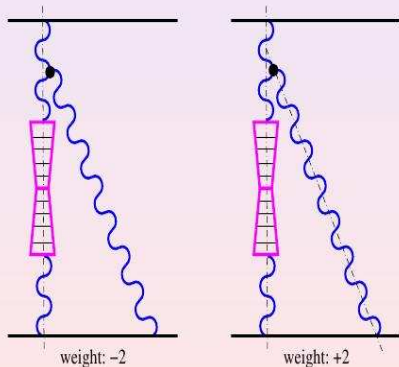- and neglecting soft processes

- How strong is the effect?

- nonfactorizable corrections dominate! [SO, 2006]

- why and how?!

- related to multi-parton correlations [Rogers & Strikman, 2010]

- How strong is the effect?

- nonfactorizable corrections dominate! [SO, 2006]
- why and how?!
- related to multi-parton correlations [Rogers & Strikman, 2010]

- How strong is the effect?

- nonfactorizable corrections dominate! [SO, 2006]

- why and how?!

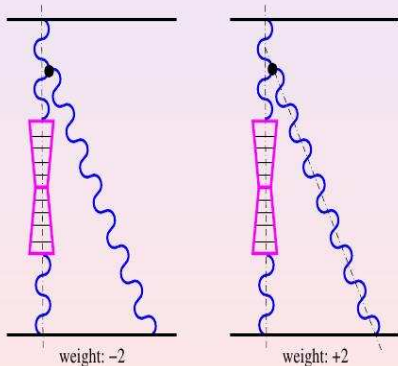- related to multi-parton correlations [Rogers & Strikman, 2010]

- corrections to single hard process due to soft rescattering

- soft screening
  (soft elastic rescattering)
- and double (soft + hard)
  scattering (particle production)
- equal weights $\Rightarrow$ zero effect
  for inclusive spectra & σ_{pp}^{tot}
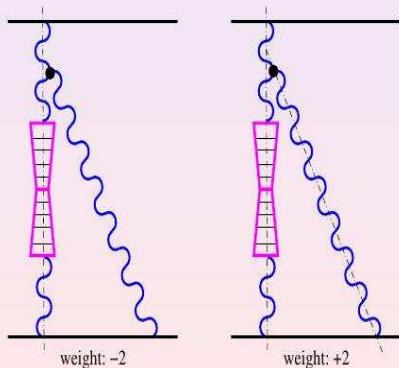 ('soft' can't screen 'hard'!)

weight: -2 weight: $+2$

- corrections to single hard process due to soft rescattering

- soft screening
  (soft elastic rescattering)
- and double (soft + hard)
  scattering (particle production)
- equal weights $\Rightarrow$ zero effect
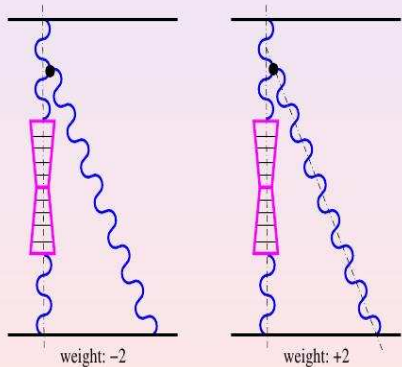 for inclusive spectra & σ_{pp}^{tot}
  ('soft' can't screen 'hard'!)

weight: −2

weight: +2

- corrections to single hard process due to soft rescattering

- soft screening
  (soft elastic rescattering)

- and double (soft + hard)
  scattering (particle production)

- equal weights $\Rightarrow$ zero effect
  for inclusive spectra & σ_{pp}^{tot}
  ('soft' can't screen 'hard'!)

weight: −2   weight: +2

- corrections to single hard process due to soft rescattering

- soft screening
  (soft elastic rescattering)
- and double (soft + hard)
  scattering (particle production)
- equal weights $\Rightarrow$ zero effect
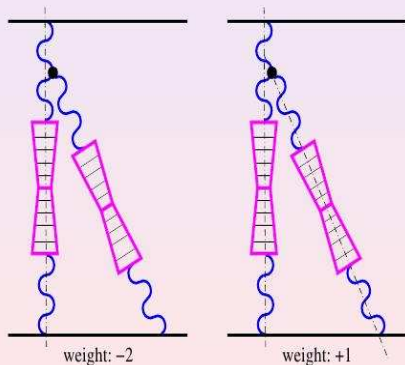 for inclusive spectra & σ_{pp}^{tot}
  ('soft' can't screen 'hard'!)

weight: −2   weight: +2

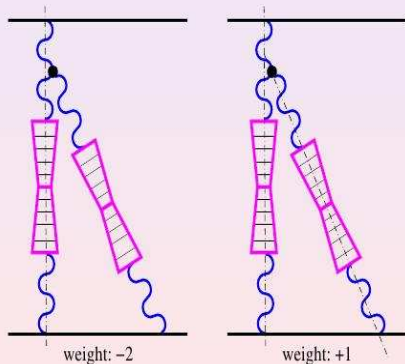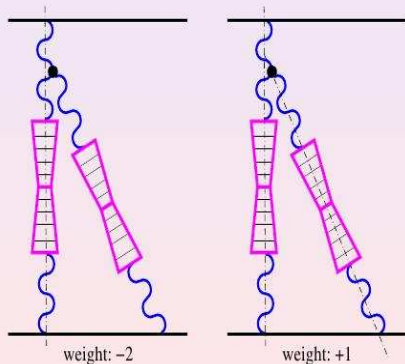# From SFs to σ_{pp}^{tot}: saturation or parton correlations?

- now hard screening
  (hard elastic rescattering)

- and double hard scattering
  (production of 2 jet pairs)

- no effect for inclusive jet spectra
  $[(-2) \times 1 + (+1) \times 2 = 0]$

- but: screening correction for σ_{pp}^{tot}
  $[(-2) + (+1) = -1]$

weight: -2   weight: +1

- now hard screening
  (hard elastic rescattering)

- and double hard scattering
  (production of 2 jet pairs)

- no effect for inclusive jet spectra
  $[(-2) \times 1 + (+1) \times 2 = 0]$

- but: screening correction for σ_{pp}^{tot}
  $[(-2) + (+1) = -1]$

weight: -2   weight: +1

- now hard screening
  (hard elastic rescattering)

- and double hard scattering
  (production of 2 jet pairs)

- no effect for inclusive jet spectra
  $[(-2) \times 1 + (+1) \times 2 = 0]$

- but: screening correction for σ_{pp}^{tot}
  $[(-2) + (+1) = -1]$

weight: −2   weight: +1

- now hard screening
  (hard elastic rescattering)

- and double hard scattering
  (production of 2 jet pairs)

- no effect for inclusive jet spectra
  $[(-2) \times 1 + (+1) \times 2 = 0]$

- but: screening correction for σ_{pp}^{tot}
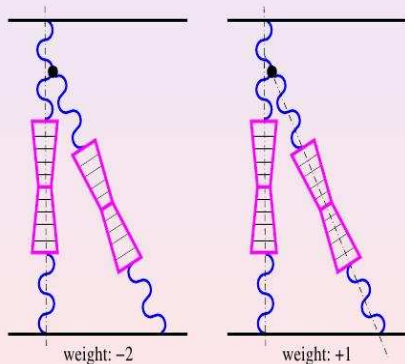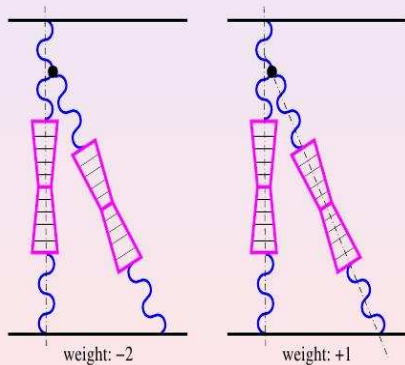 $[(-2) + (+1) = -1]$

weight: −2   weight: +1

From SFs to σ_{pp}^{tot}: saturation or parton correlations?

- now hard screening
  (hard elastic rescattering)

- and double hard scattering
  (production of 2 jet pairs)

- no effect for inclusive jet spectra
  $[(-2) \times 1 + (+1) \times 2 = 0]$

- but: screening correction for σ_{pp}^{tot}
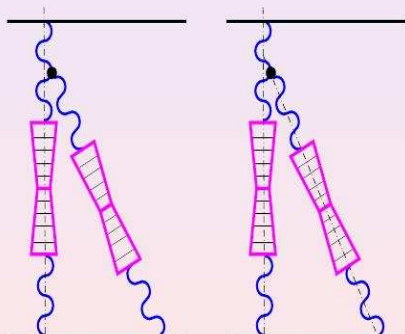 $[(-2) + (+1) = -1]$

weight: −2   weight: +1

additional screening caused by multi-parton correlations

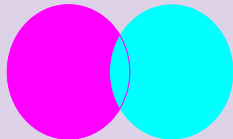- two hard parton cascades originate from the same soft parent

From SFs to σ_{pp}^{tot}: saturation or parton correlations?

- now hard screening
  (hard elastic rescattering)

- and double hard scattering
  (production of 2 jet pairs)

- no effect for inclusive jet spectra
  $[(-2) \times 1 + (+1) \times 2 = 0]$
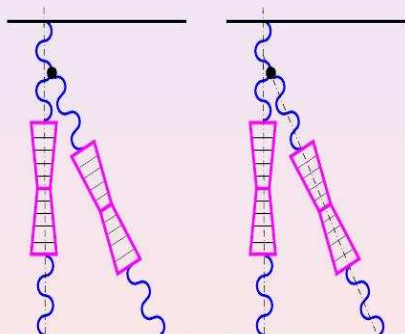
- but: screening correction for σ_{pp}^{tot}

why the effect so strong?

- 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 $\vec{b}$)

- $\Rightarrow$ also in peripheral collisions

From SFs to σ_{pp}^{tot}: saturation or parton correlations?

- now hard screening
  (hard elastic rescattering)

- and double hard scattering
  (production of 2 jet pairs)

- no effect for inclusive jet spectra
  $[(-2) \times 1 + (+1) \times 2 = 0]$

- but: screening correction for σ_{pp}^{tot}

why the effect so strong?

- 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 $\vec{b}$)
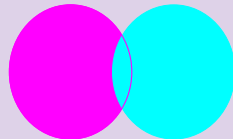
- $\Rightarrow$ also in peripheral collisions

From SFs to σ_{pp}^{tot}: saturation or parton correlations?

- now hard screening
  (hard elastic rescattering)

- and double hard scattering
  (production of 2 jet pairs)

- no effect for inclusive jet spectra
  $[(-2) \times 1 + (+1) \times 2 = 0]$
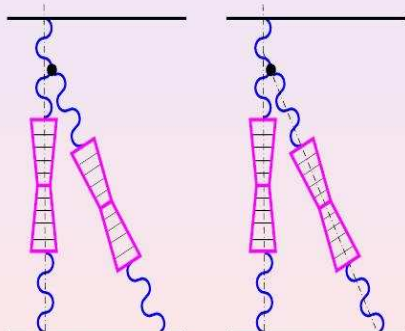
- but: screening correction for σ_{pp}^{tot}

why the effect so strong?

- 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 $\vec{b}$)
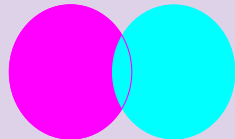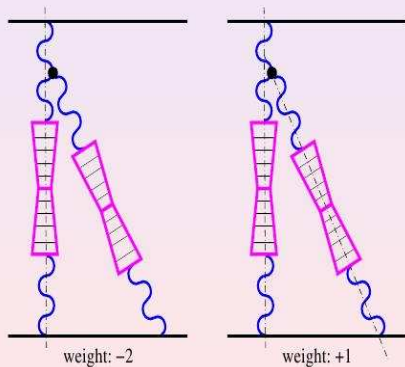
- $\Rightarrow$ also in peripheral collisions

From SFs to σ_{pp}^{tot}: saturation or parton correlations?

- now hard screening
  (hard elastic rescattering)

- and double hard scattering
  (production of 2 jet pairs)

- no effect for inclusive jet spectra
  $[(-2) \times 1 + (+1) \times 2 = 0]$

- but: screening correction for σ_{pp}^{tot}
  $[(-2) + (+1) = -1]$

weight: -2   weight: +1

$\Rightarrow$ multi-parton interactions provide a key to understand σ_{pp}^{tot}
(and vice versa)
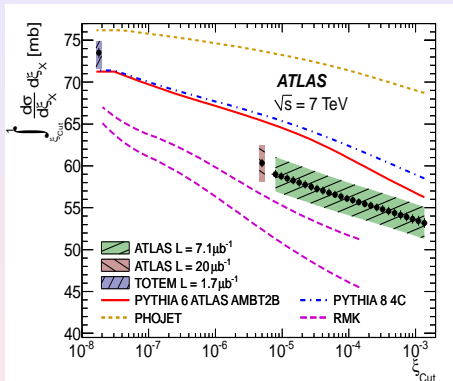
- from σ_{vis} to σ_{inel}?
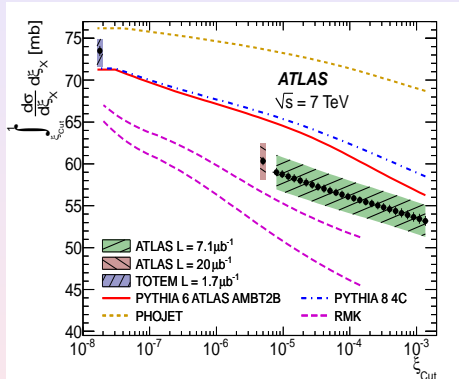- LMD or nontrivial shape for HMD?
- why and how?

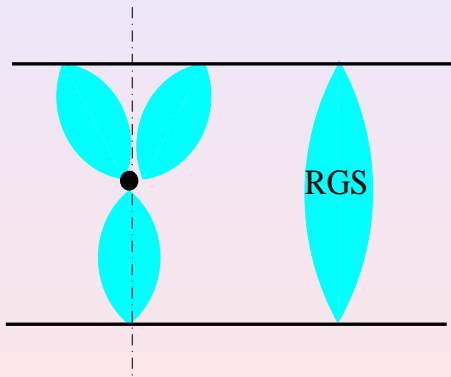# High mass diffraction dissociation

- from σ_{vis} to σ_{inel}?
- LMD or nontrivial shape for HMD?
- why and how?

- single HMD: eikonal rap-gap suppression doesn't impact distribution

- $\Rightarrow$ absorptive corrections to triple-$\mathbb{P}$ graph

- stronger at small $b \Rightarrow$ flatter M_X dependence

- weaker at large $b \Rightarrow$ closer to $3\mathbb{P}$ lmit

High mass diffraction dissociation

- single HMD: eikonal rap-gap suppression doesn't impact distribution

- $\Rightarrow$ absorptive corrections to triple-$\mathbb{P}$ graph

- stronger at small b $\Rightarrow$ flatter M_X dependence

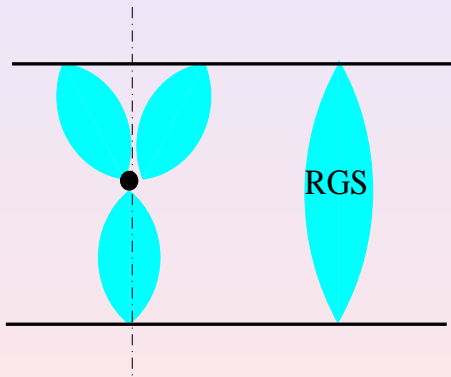- weaker at large b $\Rightarrow$ closer to $3\mathbb{P}$ lmit

RGS

High mass diffraction dissociation

- single HMD: eikonal rap-gap suppression doesn't impact distribution

- $\Rightarrow$ absorptive corrections to triple-$\mathbb{P}$ graph

- stronger at small b $\Rightarrow$ flatter M_X dependence

- weaker at large b $\Rightarrow$ closer to $3\mathbb{P}$ lmit
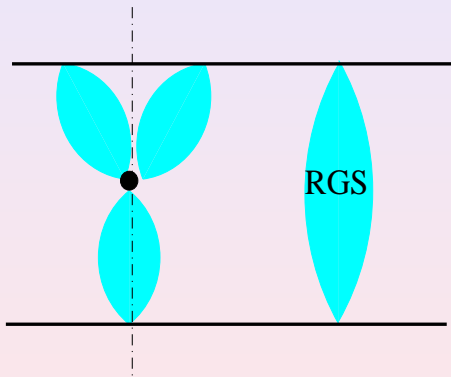

RGS

High mass diffraction dissociation

- single HMD: eikonal rap-gap suppression doesn't impact distribution

- $\Rightarrow$ absorptive corrections to triple-$\mathbb{P}$ graph

- stronger at small b $\Rightarrow$ flatter M_X dependence

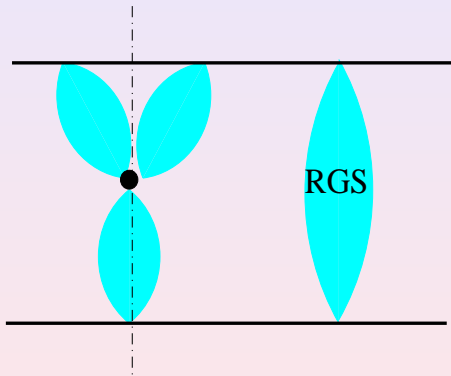- weaker at large b $\Rightarrow$ closer to 3$\mathbb{P}$ lmit
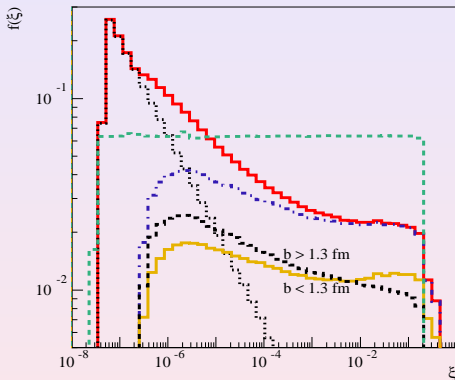

RGS

- $\xi = M_X^2/s$ distribution in SIBYLL 2.1 & QGSJET-II-04 *[SO, 2011]*
- relative contributions of LMD & HMD

- $\xi = M_X^2/s$ distribution in SIBYLL 2.1 & QGSJET-II-04 [SO, 2011]
- relative contributions of LMD & HMD

Summary

1. Models of hadronic interactions – important ingredient for CR studies

2. Important constraints from pQCD for inclusive observables:
   - collinear factorization
   - DGLAP evolution for PDFs

3. However: crucial issues treated phenomenologically

4. Most challenging problem: treatment of nonlinear effects
   - has important impact on hadronic cross sections, multiparton interactions & structure of diffractive final states

Summary

1. Models of hadronic interactions – important ingredient for CR studies

2. Important constraints from pQCD for inclusive observables:
   - collinear factorization
   - DGLAP evolution for PDFs

3. However: crucial issues treated phenomenologically

4. Most challenging problem: treatment of nonlinear effects
   - has important impact on hadronic cross sections, multiparton interactions & structure of diffractive final states

Summary

1. Models of hadronic interactions – important ingredient for CR studies

2. Important constraints from pQCD for inclusive observables:
   - collinear factorization
   - DGLAP evolution for PDFs

3. However: crucial issues treated phenomenologically

4. Most challenging problem: treatment of nonlinear effects
   - has important impact on hadronic cross sections, multiparton interactions & structure of diffractive final states

1. Models of hadronic interactions – important ingredient for CR studies

2. Important constraints from pQCD for inclusive observables:
   - collinear factorization
   - DGLAP evolution for PDFs

3. However: crucial issues treated phenomenologically

4. Most challenging problem: treatment of nonlinear effects
   - has important impact on hadronic cross sections, multiparton interactions & structure of diffractive final states

Summary

1. Models of hadronic interactions – important ingredient for CR studies

2. Important constraints from pQCD for inclusive observables:
   - collinear factorization
   - DGLAP evolution for PDFs

3. However: crucial issues treated phenomenologically

4. Most challenging problem: treatment of nonlinear effects
   - has important impact on hadronic cross sections, multiparton interactions & structure of diffractive final states

Summary

1. Models of hadronic interactions – important ingredient for CR studies

2. Important constraints from pQCD for inclusive observables:
   - collinear factorization
   - DGLAP evolution for PDFs

3. However: crucial issues treated phenomenologically

4. Most challenging problem: treatment of nonlinear effects
   - has important impact on hadronic cross sections, multiparton interactions & structure of diffractive final states