Монте-Карло генераторы событий для дифракционных адронных и ядерных соударений при высоких энергиях: Pythia, EPOS-LHC и QGSJET-II

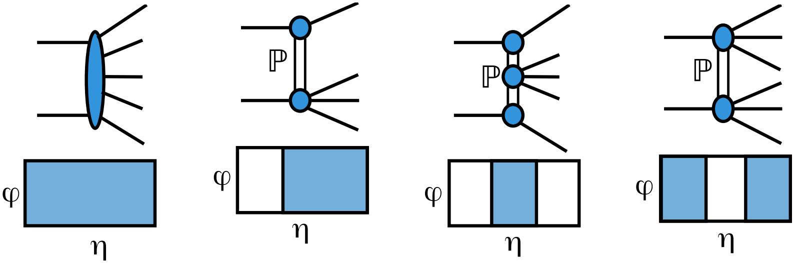
Соснов Дмитрий

Семинар ОФВЭ,
25 января 2022 г.

Contents

Soft QCD

Types of processes:



Non-Diffractive | Single Diffraction | Central Diffraction | Double Diffraction

- Diffractive collisions are defined as special inelastic collisions in which vacuum quantum numbers are exchanged between colliding particles
- A diffractive process is characterized by a Rapidity Gap, which is caused by t-channel pomeron(s) exchange
  (and also by t-channel γ-exchange)

Proton-Nuclear collisions

- Most important problems of QCD which can be studied with diffraction:
  - Nature of the pomeron in QCD
  - Small-x problem and "saturation" of parton densities
  - Color transparency
- Cross sections of inelastic diffractive processes are very sensitive to nonlinear saturation effects, especially for nuclei.

The main generators used in proton-nuclear high energy physics:

- Pythia 8 [Sjöstrand et.al., Comput. Phys. Commun., 191:159–177, 2015]
- EPOS-LHC [Pierog et.al, Phys. Rev. C, 92:034906, 2015]
- QGSJET-II [Ostapchenko, Phys. Rev. D, 83:014018, 2011]

Contents

Pythia: elastic and diffractive cross section

Based on : Effective reggeon field theory by V. Gribov [Gribov, JETP Lett., 41:667, 1961]
Hadronization : Lund string model [Andersson, Cambridge University Press, 7 2005]

- $\sigma_{tot}(s) = X^{AB}s^{\epsilon} + Y^{AB}s^{-\eta}$, $\eta = 0.0808$, $\eta = 0.4525$
- $\frac{d\sigma_{el}}{dt} = (1+\rho^2)\frac{\sigma^2_{tot(s)}}{16\pi}exp(B_{el}(s)t)$
- $\frac{d\sigma_{XB}(s)}{dtdM_X^2} = \frac{g_{3\mathbb{P}}}{16\pi}\frac{\beta_{A\mathbb{P}}(s)\beta^2_{B\mathbb{P}}(s)}{M_X^2}exp(B_{XB}(s)t)F_{SD}(M_X^2, s)$
- $\frac{d\sigma_{AX}(s)}{dtdM_X^2} = \frac{g_{3\mathbb{P}}}{16\pi}\frac{\beta^2_{A\mathbb{P}}(s)\beta_{B\mathbb{P}}(s)}{M_X^2}exp(B_{AX}(s)t)F_{SD}(M_X^2, s)$
- $\frac{d\sigma_{XY}(s)}{dtdM_X^2dM_Y^2} = \frac{g_{3\mathbb{P}}}{16\pi}\frac{\beta_{A\mathbb{P}}(s)\beta_{B\mathbb{P}}(s)}{M_X^2M_Y^2}exp(B_{XY}(s)t)F_{DD}(M_X^2, M_Y^2, s)$

- $B_{el} = 2b_A + 2b_B + 4s^{\epsilon} - 4.2$
- $B_{XB} = 2b_B + 2\alpha'_{\mathbb{P}}ln\left(\frac{s}{M_X^2}\right)$
- $B_{AX} = 2b_A + 2\alpha'_{\mathbb{P}}ln\left(\frac{s}{M_X^2}\right)$
- $B_{XY} = 2\alpha'_{\mathbb{P}}ln\left(e^4 + \frac{s/\alpha'_{\mathbb{P}}}{M_X^2M_Y^2}\right)$
- $b_x = 2.3$ for p, $\bar{p}$; $\alpha'_{\mathbb{P}} = 0.25$ GeV^{-2}

F functions introduced to dampen large mass systems

Central diffraction

$$\sigma_{CD}(s) = \sigma_{CD}^{ref}\frac{ln^{1.5}\left(\frac{0.06s}{s_{min}}\right)}{ln^{1.5}\left(\frac{0.06s_{ref}}{s_{min}}\right)},$$ where $\sigma_{CD}^{ref} = 1.5$ mb,

$s_{ref} = 4$ TeV^2, $s_{min} = 1$ GeV^2

Modification of cross-section (from Tevatron to LHC)

$$\sigma_i^{mod}(s) = \frac{\sigma_i^{old}(s)\sigma_i^{max}}{\sigma_i^{old}(s) + \sigma_i^{max}}$$

Regimes

Diffractive event generation is split to three regimes:

- Very low mass diffraction
- Low mass diffraction
- High mass diffraction

Probability to apply high mass description

$$P_{pert} = 1 - exp\left(-\frac{max(0, M_X - m_{min})}{m_{width}}\right)$$

- where m_{min}, m_{width} – free parameters.
- Default values: 10 GeV for both, m_{min} and m_{width}

Very low mass diffraction

$$M_X \leq m_B + 1\text{GeV}$$

The system is allowed to decay to a two-body system

Pythia: types of diffraction events

Regimes

Diffractive event generation is split to three regimes:

- Very low mass diffraction
- Low mass diffraction
- High mass diffraction

Probability to apply high mass description

$$P_{pert} = 1 - exp\left(-\frac{max(0, M_X - m_{min})}{m_{width}}\right)$$

- where m_{min}, m_{width} – free parameters.
- Default values: 10 GeV for both, m_{min} and m_{width}

Low mass diffraction

$\mathbb{P}$ kicking-out qualk or gluon from proton with probabilities:

$$\frac{P(q)}{P(g)} = \frac{N}{M_X^{\rho}}$$

Default values for free parameters:

- $N = 5$, $\rho = 1$

Quark kicked-out

String between quark and diquark

Gluon kicked-out

String quark and diquark through gluon

Pythia: types of diffraction events

Regimes

Diffractive event generation is split to three regimes:

- Very low mass diffraction
- Low mass diffraction
- High mass diffraction

Probability to apply high mass description

$$P_{pert} = 1 - exp\left(-\frac{max(0, M_X - m_{min})}{m_{width}}\right)$$

- where m_{min}, m_{width} – free parameters.
- Default values: 10 GeV for both, m_{min} and m_{width}

High mass diffraction

Diffraction cross-section calculated from:

- Pomeron flux
- Pomeron-proton cross-section
- Proton form-factor

The $\mathbb{P}$ parton distribution functions (PDFs) are introduced like for a hadron $\rightarrow$ hadron-hadron iteraction.

Pythia: types of diffraction events

Regimes

Diffractive event generation is split to three regimes:

- Very low mass diffraction
- Low mass diffraction
- High mass diffraction

Probability to apply high mass description

$$P_{pert} = 1 - exp\left(-\frac{max(0, M_X - m_{min})}{m_{width}}\right)$$

- where m_{min}, m_{width} – free parameters.
- Default values: 10 GeV for both, m_{min} and m_{width}

High mass diffraction

Diffraction cross-section calculated from:

- Pomeron flux
- Pomeron-proton cross-section
- Proton form-factor

The $\mathbb{P}$ parton distribution functions (PDFs) are introduced like for a hadron $\rightarrow$ hadron-hadron iteraction.

Reproducing non-diffractive collision

Tuning performed by selection average number of multiple parton interactions (MPI) to reproduce pp diffraction.

- $<n>= f_{\mathbb{P}}/\sigma^{eff}_{\mathbb{P}p}$ or $<n>= f_p/\sigma^{ND}_{pp}$
- where $f_{\mathbb{P}}$ and f_p – PDF
- $\sigma^{eff}_{\mathbb{P}p}$ – main (mass-dependent) tuning parameter

Pythia: Multi-parton interactions (MPI)

Subprocess cross-section

- $d\sigma_{2j} \propto \frac{dt}{t^2} = \frac{dp_\perp^2}{p_\perp^4}$
- $\sigma_{2j} = \langle n \rangle \, (p_{\perp min})\sigma_{tot}$,
- where $\langle n \rangle \, (p_{\perp min})$ – average of the number of parton-parton interactions above $p_{\perp min}$ per hadron-hadron collision

Solving problem at $p_{\perp min} \to 0$

- Energy-momentum conservation:
  multiple interactions are ordered in $p_{\perp min}$ and constructed to have $\sum x <= 1$
- Screening (at low $p_{\perp min}$): exchanged particle becoming larger than a typical colour-anticolour separation distance
- Saturation: reducing increasing of the parton densities at low x

Pythia: Fritiof model

**Fritiof model: extension of Pythia
for soft iteraction for hadron-nucleus collisions**

The proton-proton model extended to hadron-nucleus and nucleus-nucleus collisions: assuming that a nucleus just a a package of free nucleons
[Pi, Comput. Phys. Commun., 71:173–192, 1992].

Angantyr model (incorporated since Pythia 8.230)

Angantyr [Bierlich et.al., JHEP, 10:134, 2018] – global upgrade of Pythia for extending to ions, inspired by Fritiof 7.0

Angantyr model (incorporated since Pythia 8.230)

Angantyr [Bierlich et.al., JHEP, 10:134, 2018] – global upgrade of Pythia for extending to ions, inspired by Fritiof 7.0

Cross-section calculation

Estimation for cross-section from

- $P(r) = \frac{r^{k-1} e^{-r/r_0}}{\Gamma(k) r_0^k}$ – radius of nucleon
- $T(b, r_p, r_t) = T_0(r_p + r_t)\Theta\left(\sqrt{\frac{(r_p+r_t)^2)}{2T_0}} - b\right)$ – elastic amplitude
- $T_0(r_p + r_t) = (1 - exp(-\pi(r_p + r_t)^2/\sigma_t))^\alpha$ – opacity of the semi-transparent disk
- σ_t, α, k, r_0 – free parameters.

The reasonable fit to cross-sections (calculated from T) and elastic slope parameter ($B = -dln\sigma_{el}^{NN}/dt|_{t=0}$) is obtained

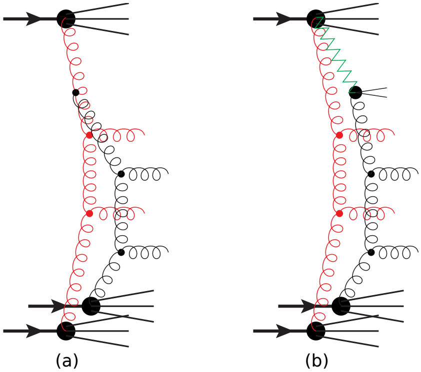
Pythia: Angantyr (since Pythia 8.230)

Multi-parton interactions in a pA collision

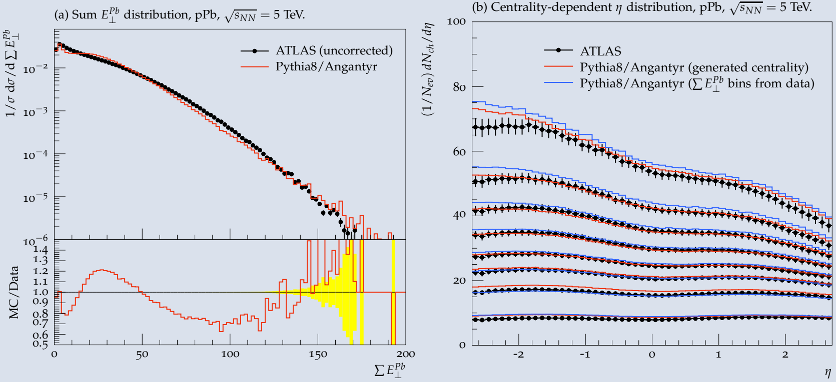
- Primary scattering – between the projectile and one of the target nucleons
- Secondary scattering – between the projectile and the other target nucleon
- The same distribution of particles as if the second sub-scattering was a separate single diffractive excitation event
- A secondary nucleon contributes to the final state as if the final state particles were produced in a single diffractive excitation
- Additional parton scatterings – as multiple scatterings in the Pomeron–proton system

Multi-parton interactions in a AA collision

- For AA the primary collisions generated firstly,
- Secondary (one of the nucleons already wounded) later
- The final state for a secondaryinteraction is then added to a primary sub-event



Comparison Pythia 8 to data



Contents

EPOS-LHC: Diffraction cross section

Based on : Effective reggeon field theory by V. Gribov [Gribov, JETP Lett., 41:667, 1961] with Abramovsky-Gribov-Kancheli cutting rules [Abramovsky, Gribov, Kancheli, Sov. J. Nucl. Phys. 18 (1974) 308.]

Hadronization : Based on Lund string model [Andersson, Cambridge University Press, 7 2005)]

Amplitude

- $G_0(\hat{s}, b) = \alpha_0(b)\hat{s}^{\beta_0}$ – soft contribution
- $G_1(\hat{s}, b) = \alpha_1(b)\hat{s}^{\beta_1}$ – non-soft contribution
- $\hat{s} = sx^+x^-$ – fraction of energy carried by the pomeron
- Total amplitude: $G = \sum_i G_i$

EPOS-LHC: Low mass diffraction

Low mass diffraction

- A low mass diffractive event will be produced if only the remnants are excited and no inelastic (i.e. cut) pomeron is exchanged
- To have it consistently produced by EPOS, G2 is added
- G2 not produce central strings
- $G_2(x, s, b) = \alpha_2 x^{-\alpha_{diff}} exp\left(-\frac{b^2}{\delta_2(s)}\right)$
- To have the same as soft pomeron, $\delta_2 = 4 \cdot 0.0389 \cdot (R_{diff}^{proj} + R_{diff}^{tar} + \alpha'_{diff} lns)$
- $\alpha_{diff} = 1$ to have $1/M^2 = \hat{s}^{-\alpha_{diff}}$
- Free parameters: α_2, α'_{diff}

Low mass diffraction

- Soft diffraction: only G_2 is exchanged
- G_2 can be produced together with G_0 and/or G_1

EPOS-LHC: Diffraction cross section

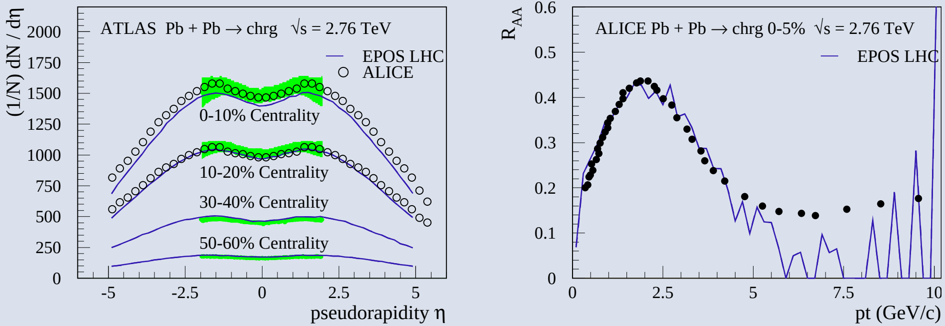
Inclusive cross-section

- $\Phi(x^{proj} = 1, x^{tar} = 1, s, b)$ – probability to have only elastic pomeron exchange without any new particles produced
- $\sigma_{inel}(s) = \int d^2 b(1 - \Phi(1, 1, s, b))$
- $\sigma_{el}(s) = \int d^2 b(1 - \sqrt{\Phi(1, 1, s, b)})^2$
- Elastic slope B can be expressed with Φ, $\rightarrow$ free parameters in G and Φ for tuning cross-sections.

Diffractive cross-section

- $\sigma_{diff}(s) = \Phi(1, 1, s, b)\left[exp\left(\int dx^+ dx^- G_2(x^+, x^-, s, b)\right) - 1\right]$
- R_{pro} and R_{tar} – probability to have projectile or target excitation
- $\sigma_{sd}(s) = R_{pro} \cdot (1 - R_{tar}) \cdot \sigma_{diff}(s) + (1 - R_{pro}) \cdot R_{tar} \cdot \sigma_{diff}(s)$
- $\sigma_{dd}(s) = R_{pro} \cdot R_{tar} \cdot \sigma_{diff}(s)$
- $\sigma_{cd}(s) = (1 - R_{pro}) \cdot (1 - R_{tar}) \cdot \sigma_{diff}(s)$

Comparison EPOS-LHC to data



Contents

QGSJET-II

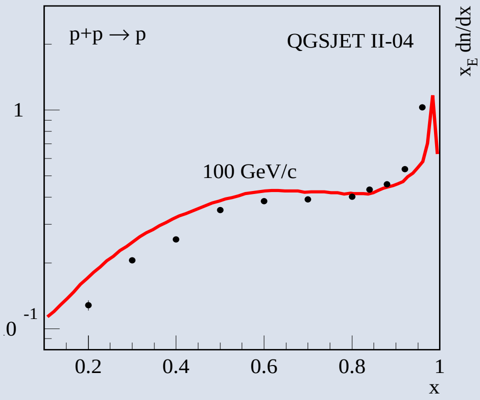
Based on : Kaidalov-Ter-Martirosyan color tube model [Kaidalov, Ter-Martirosyan, Sov. J. Nucl. Phys., 40:135–140, 1984]

Hadronization : independent model

QGSJET-II

- Two types of pomerons:
  - soft ($|q^2| < Q_0^2$)
  - semi-hard ($|q^2| > Q_0^2$)
- Total and elastic cross sections calculated for pp (pA, AA) scattering
- From total and elastir cross-section – partial cross sections can be calculated

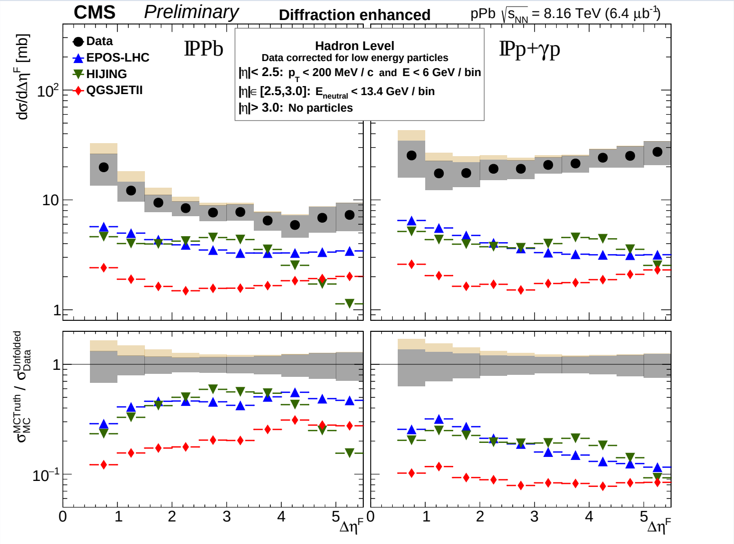
Comparison QGSJET-II to data



Feynman x spectra of secondary protons in proton-proton collisions

Contents

Comparison with first pA diffraction result at LHC



- On the left part: predictions of both, EPOS-LHC (blue) and QGSJET-II (red) below the data
- On the right part: all generators underestimate cross-section
- Used generators have no γ-exchange implemented
- That indicates of significant contribution of γ-exchange events

Contents

Summary

Summary

- The three Monte-Carlo generators used for high energy proton-nuclear and nuclei-nuclear collisions were considered
- All three generators based on Gribov's reggeon theory, but uses different implementations
- EPOS-LHC and QGSJET-II generators compared to the first proton-nuclear diffraction results at LHC
- Both used generators underestimate cross-section
- There is significant contribution of γ-exchange events

Спасибо за внимание!