

**The EPOS event generator :
collectivity in small systems, heavy flavour production
and recent developments**

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What is EPOS ?

Event generators are programs made to **compute models** in order to **simulate every step** of a **collision** (e.g. EPOS, PYTHIA ¹ ...).

Advantages : - **perfect detector**, as final-state particles are all listed (no uncertainties)
- **gives access** to the whole **history of the collision**

*(indeed, there are always some **flaws** : one has to be careful on the applicability, and phenomenological approaches generally requires parametrisation)*

Energy conserving quantum mechanical approach, based on

Partons, parton ladders, strings,

Off-shell remnants, and

Saturation of parton ladders

Event generator based on parton-based Gribov-Regge Theory (PBGRT) ².

Can simulate with the same formalism **any type of collision** consistently :

$$e^- + e^+$$

$$e^- + p$$

$$p + p$$

$$p + A$$

$$A + A$$

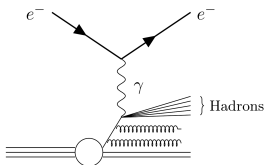
¹T. Sjöstrand et al., *Comput. Phys. Commun.* **191** (2015) 159-177

²K. Werner et al., *Phys. Rep.* **350** (2001) 93-289

The motivations behind the PBGRT

Parton model

Mainly used for inclusive cross-section calculations



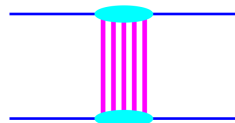
Deep Inelastic Scattering

Problems :

- can only calculate cross-section for hard processes \rightarrow not suitable alone for HIC

Gribov-Regge theory

EFT for Multiple *Pomeron* Interaction



(K. Werner et al., 2000)

Inconsistencies :

- energy conserved for particle production but NOT for cross-section calculations
- although multiple scattering approach, all interactions are not treated equally

Solution : merge both into a formalism treating consistently hard and soft scattering

\Rightarrow **Parton-based Gribov-Regge Theory !**

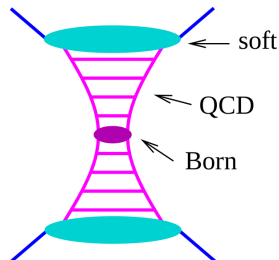
Main principle of PBGRT

Based on **S-matrix approach** where, from : $\langle f | \hat{S} | i \rangle = S_{fi} = \delta_{fi} + i(2\pi)^4 \delta(P_f - P_i) T_{fi}$
we got the total inelastic cross-section σ_{tot} with the optical theorem (see details [here](#))

$$\sigma_{tot} = \frac{1}{2s} (2\pi)^4 \delta(p_f - p_i) \sum_f |T_{fi}|^2$$

In the PBGRT, one **elementary interaction** is modeled as a **Pomeron**, each of them giving a contribution to the total T -matrix.

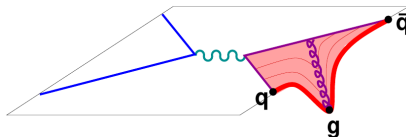
- **Soft process** ($Q^2 < 1 \text{ GeV}$) : mainly elastic scatterings, parametrised T-matrix (Regge poles)
- **Hard process** ($Q^2 > 1 \text{ GeV}$) : pQCD applicable, computed T-matrix (DGLAP equation)
- **Semi-hard process** ($Q^2 > 1 \text{ GeV}$ $q_{sea}/\bar{q}_{sea}/g$) : using both previous formalisms



The string model

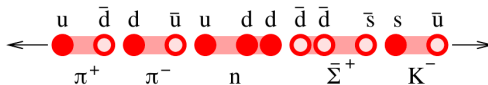
In the simplest system which is e^+e^- , the $q\bar{q}$ pair created is linked by a **color field**, forming what we call a **relativistic string**.

Such string can indeed have **transverse kinks**, caused by **gluon emission**, and **evolve** following the dynamics of a **gauge invariant Lagrangian**.



"Diagrammatic" view of a kinky string (*K. Werner, 2019*)

Eventually, it will **fragment** via production of $q(q) - \bar{q}(\bar{q})$ pairs, thus forming **hadrons**, following a so-called area law : $dP_{break} = \lambda \cdot dA$ (dA : infinitesimal area)



Meson and baryon production from string breaking

Initial conditions

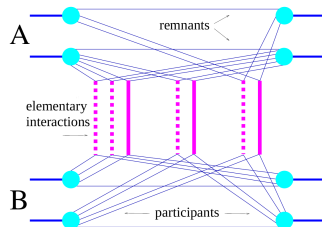
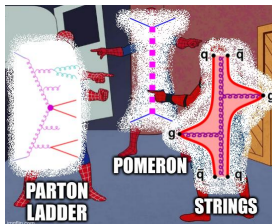
We show here the **complete formalism of EPOS 3³**, or how events are simulated for **hadronic collisions** (pp, pA or AA).

Primary interactions treated with PBGR

Nuclei (A and B) interact by the exchange of **multiple Pomerons** in parallel (= MPI).

Uncut Pomerons are important as they give **interference** terms to σ_{tot} :

$$\sigma_{tot} = \sum_i \sum_j \int (G_i^{cut} - G_j^{uncut}) \cdot d^2b$$



Schematic representation of a collision

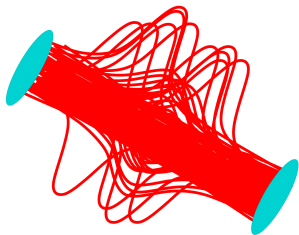
(K. Werner et al., 2000)

Cut Pomerons will be used for **particle production**.

They can be assimilated to **parton ladders** (= *physical picture*), or seen as **flux tubes** or **kinky strings** ($q - g - \dots - \bar{q}$), like introduced before.

³K. Werner et al., *Phys. Rev. C* **89** (2014), 064903

Core-corona procedure



Multiple interactions within the PBGRT
(K. Werner, 2018)

In most of the pp collisions, the string picture is sufficient to simulate correctly the events.

However, for **AA** events in particular (*but not only...*), the **density of strings** become **so important** that they **cannot decay independently**.

We separate then, at a time τ_0 :

- **core** = bulk matter from high string density region ($\rho > \rho_0$)
- **corona** = high p_T segments (jets) escaping the core

In particular, for the string segments **close to the surface** with a **local string density** ρ , we evaluate if they have enough p_T to **escape the core** with :

$$p_T^{\text{esc}} = p_T - f_{E_{\text{loss}}} \int_{\gamma} \rho \cdot dL$$

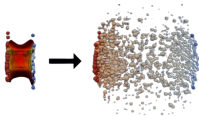
Medium evolution, hadronisation and re-scattering

Core evolution

Viscous 3D+1 hydrodynamics expansion
based on a cross-over transition EoS

+

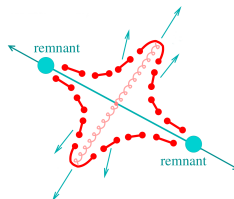
Statistical hadronisation of the medium
via Cooper-Frye procedure ⁴



(MADAI collaboration)

Corona evolution

Strings evolution + fragmentation
to produce hadrons



Re-scatterings between formed hadrons with the UrQMD model ⁵ until
chemical freeze-out, kinetic freeze-out

Final state particle

⁴F. Cooper & G. Frye, *Phys. Rev. D* **10** (1974), 186

⁵M. Bleicher et al., *J. Phys. G* **25** (1999), 1859-1896

Towards the next public release

We are currently working on the development of a new version, **EPOS 4**⁶, planned to be **released publicly during 2022**.

This new version include some **major changes** compare to elder versions :

- new developments on **parton saturation scale**, now depending on $N_{pom} + N_{part}$ (instead of a simple constant Q_0 originally)
- possibility to use a **new Equation of State** including a **critical point** and a **1st order phase transition**
- a **microcanonical decay** of the **core** part, replacing the grand-canonical Cooper-Frye procedure

and some minor/technical updates :

- **solving issues** in the list of **particles decay channels** (especially for some quarkonia)
- adding a **new output format** to make **EPOS usable with RIVET**

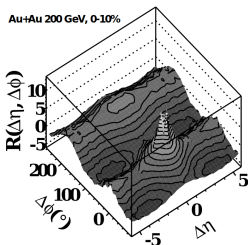
⁶K. Werner, et al., *Phys. Atom. Nucl.* **84** (2021), 1026–1029

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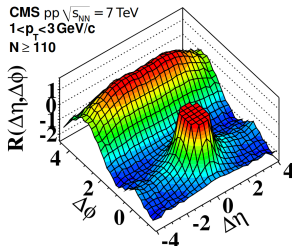
Motivation for a unified approach to treat all hadronic systems

Many measurements **since 10 years** indicate that there are **collective effects** in **high-multiplicity** events for **small systems** (pp, pA).

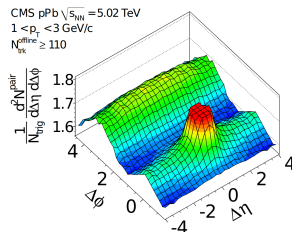
First evidence : the "ridges" observed at $\Delta\phi = 0$ over many units in $\Delta\eta$



(PHOBOS collaboration, 2008)



(CMS collaboration, 2010)



(CMS collaboration, 2012)

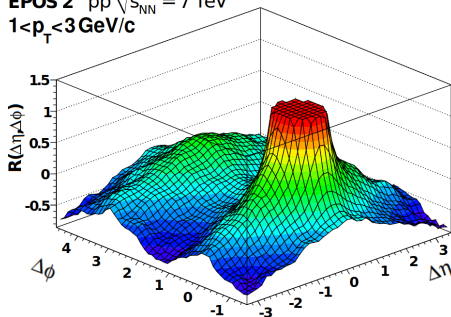
Even though the **question** about whether it is **QGP** or not is **still unclear**, the use of **hydrodynamics enables** to **reproduce well** the **experimental results**...

The "ridge" in pp and pPb

This ridge feature means that **charged particles** are **strongly correlated** in their **azimuthal distribution** over a **large η -range**.

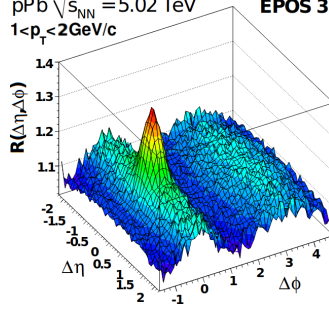
EPOS is **only able to reproduce** it when using **hydrodynamical evolution** of the core for **high-multiplicity pp collisions**, as well as in **pPb collisions**.

EPOS 2 pp $\sqrt{s_{NN}} = 7$ TeV
 $1 < p_T < 3$ GeV/c



(K. Werner et al., 2011)

EPOS 3 pPb $\sqrt{s_{NN}} = 5.02$ TeV
 $1 < p_T < 2$ GeV/c

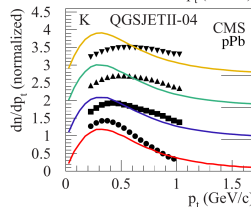
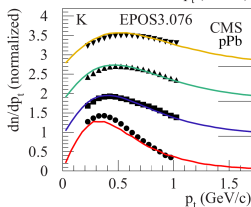
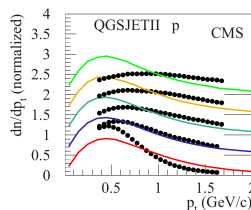
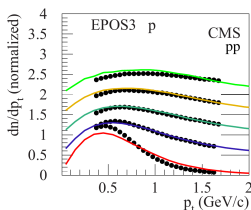


(K. Werner et al., 2013)

Identified particles p_T spectra

The **hardening** of the p_T spectra with the **event multiplicity** for identified particles seems also to **originate from flow**.

⇒ **clear** when **comparing EPOS 3 to QGSJET II** (*no flow features*)



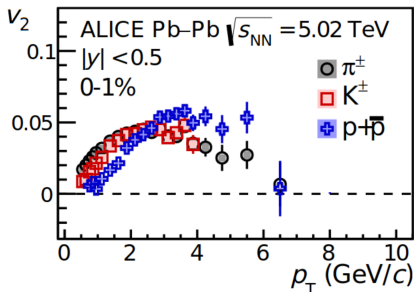
N.B. : centrality classes (\uparrow) $\langle N_{ch} \rangle = 7, 40, 75, 98, 131$ (pp) – 8, 84, 160, 235 (pPb) (*K. Werner et al., 2013*)

Mass ordering in elliptic flow

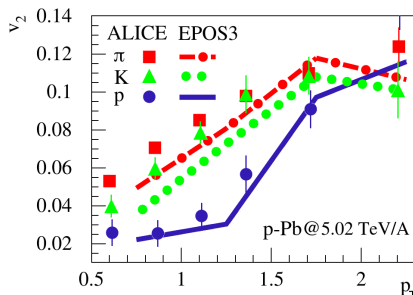
In **AA collisions**, we observe a **mass ordering with p_T** of the v_2 of hadrons at low- p_T , due to the fact that **all hadrons originate from the same fluid**, hence formed with the **same initial velocity**.

The same trend has been **observed also** by ALICE in **pPb collisions**

⇒ typical from flow !



(ALICE collaboration, 2018)

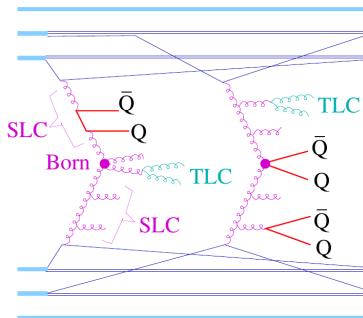


(ALICE collaboration, 2013 + K. Werner et al., 2019)

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Heavy flavour production in EPOS

Implemented since EPOS 3, **heavy quarks** ($Q = c, b$) are produced during **primary interactions**, like light quarks, but with $m_Q \neq 0$.



They can be produced in any ladder :

- during **space-like cascades** (SLC)
- during **time-like cascades** (TLC)
- in the **Born process** ($2 \rightarrow 2$)

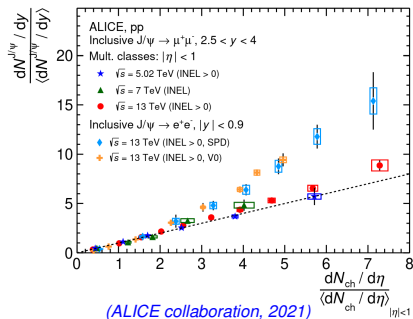
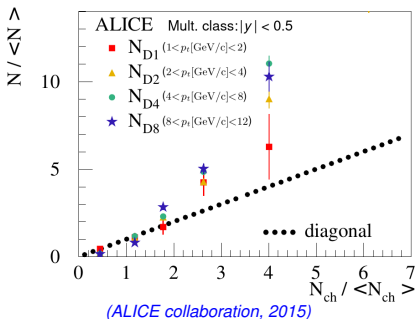
$\Rightarrow m_Q$ plays a role in **matrix elements**
+ **ladder kinematics** (splitting conditions)

HQs production in parton ladders (*K. Werner, 2018*)

Important : No HQs appears in the **initial hadrons** that collide, in **string fragmentation** nor during the **hadronisation of the core** (\approx QGP)

Charm multiplicity vs. event activity

Results from ALICE collaboration have shown a **more than linear increase** of **D mesons** and **J/Ψ multiplicity** with the **charged particle multiplicity** in pp collisions at central rapidity.



What could explain this ?

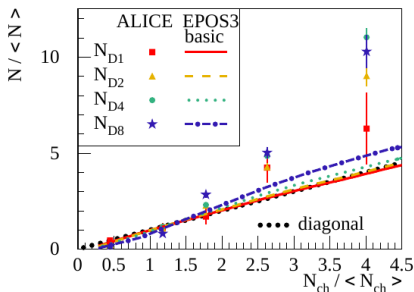
Each ladder having the **same contribution** to both **charged particles** and **charm** production (on average), we would **naively expect** : $N_D \propto N_{ch}$

Charm multiplicity vs. event activity

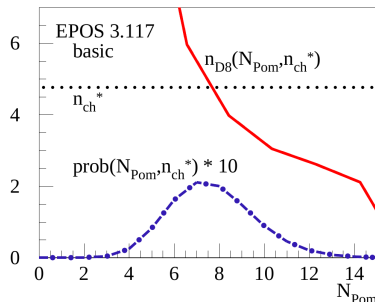
Impact from parton saturation

This is what we observe for low p_T ($n_{D_1, D_2} \approx n_{ch}$), but not for high p_T ($n_{D_4, D_8} > n_{ch}$) :
we observe a hierarchy at high multiplicity : $n_{D_1} < n_{D_2} < n_{D_4} < n_{D_8}$.

$$N.B. : n_i = \frac{N_i}{\langle N_i \rangle}$$



(K. Werner et al., 2016)



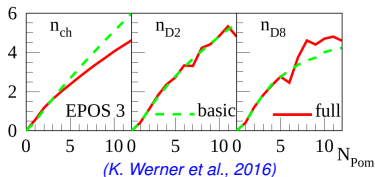
In fact, when **increasing the multiplicity**, the saturation scale Q_s **increase**
which cause to **suppress low- p_T production**

⇒ **harder Pomerons** producing **more high- p_T / large mass particles**
in particular when **fewer but harder Pomerons**

Charm multiplicity vs. event activity

Impact from hydrodynamical evolution

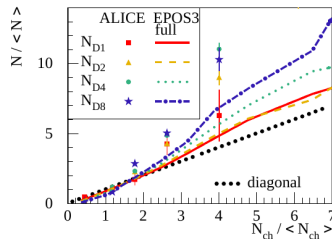
The **second effect** responsible for the increase of charm multiplicity with event activity is the presence of **hydrodynamical expansion**.



Whether **hydro** is used ("full") or not ("basic") has **no impact on D mesons multiplicities**, because it **doesn't affect D meson production**.

Nevertheless, **hydro** evolution of the core **reduces the charged particles multiplicity**, because part of the **energy** goes into **flow instead of particle production**.

⇒ n_{ch} increase is slower with hydro expansion while n_D increase is unchanged



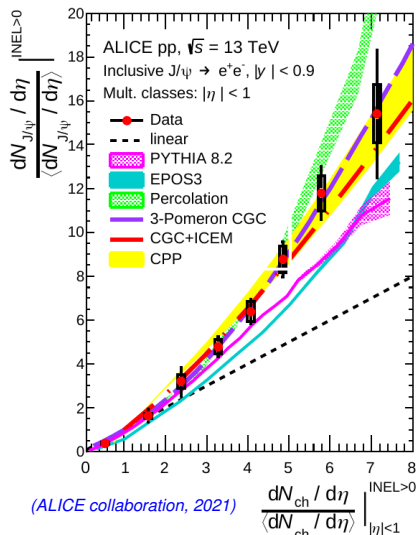
N.B. : the magnitude of these effects might have changed in more recent versions of EPOS

Charm multiplicity vs. event activity

The **trend** is also **pretty well reproduced** when compared to recent ALICE results on **central J/Ψ production**.

Disclaimer : keep in mind that EPOS and PYTHIA are multi-purpose event generators, whereas other models are (more or less) dedicated to such study

N.B. : again, result might change with EPOS 4, due to recent developments on saturation



EPOS-HQ

Project initiated in collab. with P.B. Gossiaux and J. Aichelin (*based on MC@shQ⁷*).

Main motivation : study **correlations** between **heavy flavours** and **light hadrons**, by using the **EPOS dynamical evolution** as a **background** for the **E_{loss} model**
(time-dependent temperature and velocity fields used to sample thermal scattering partners for HQs)

Key ingredients of the E_{loss} model :

- ① based on Monte-Carlo treatment of the **Boltzmann equation for heavy quarks**
 - ② **collisional part** based on a **HTL+semihard approach**,
 i.e. **pQCD-fashion** calculation including a **running coupling constant $\alpha_{eff}(t)$** and an **IR regulator** using a **reduced Debye screening mass**
 - ③ **radiative part** based on a **Gunion-Bertsch distribution** (extended to **$m_Q \neq 0$**) for induced gluon radiation, with inclusion of **LPM/BDMPS effect**
- + a **K factor** (*same for RHIC and LHC*) to **fit $\sigma_{el/inel}$** on **experimental data**

N.B. : taken from P.B. Gossiaux, 2018

⁷P.B. Gossiaux & J. Aichelin, *Phys. Rev. C* **78** (2008) 014904

From MC@sHQ+EPOS2 to EPOS-HQ

Ingredient	MC@sHQ+EPOS 2	EPOS-HQ
hydro	vHLLE (0 viscosity)	Viscous vHLLE
Init cond (soft)	EPOS	EPOS
Init state fluctuations	Yes	Yes
hadronization	Covar. Inst. Coal + frag	Same
HQ production	FONLL (p) + EPOS (space): position of NN interactions	EPOS 3
CNM	EPS09	EPOS 3
Hadronic interaction	None	URQMD

(P.B. Gossiaux, 2018 ; see also the proceeding ⁸)

Current status : project in standby because of problem found in EPOS (c/b production, factorisation...), which might be resolved by now

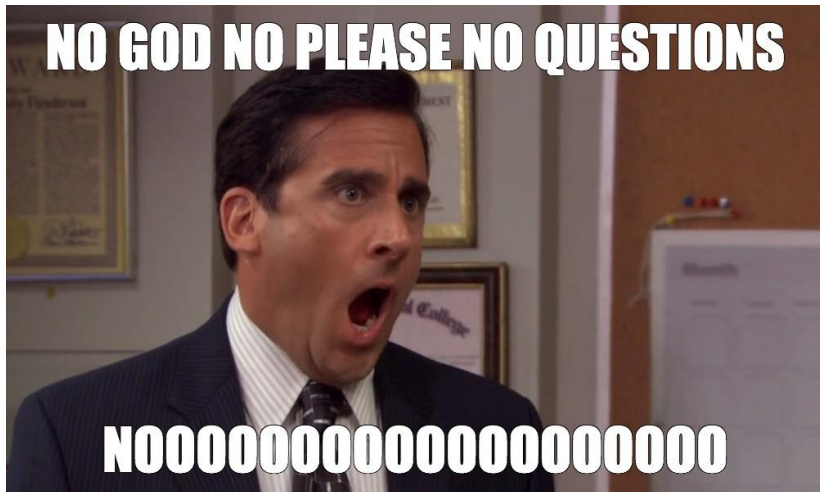
⁸P.B. Gossiaux et al., *Proc. of Sci. Hard Probes 2018* (2019) 169

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Summary

- **EPOS** uses a **unique approach** to treat **ALL systems** (pp, pA, AA) :
 - **primary interactions** treated with a Gribov-Regge-based multiple scattering approach, including parton saturation effects
 - **secondary interactions** based on a core-corona separation of jet hadrons and fluid, which expands using viscous hydrodynamical, with final-state hadronic cascades
- Reproduces naturally many **flow-like features in small systems**
- Includes **heavy flavours** production (since EPOS 3), enabling sophisticated coupling to an energy-loss model (**EPOS-HQ**) to study interaction of HQs with a dynamical fluid evolution
- **EPOS 4** under validation, **coming soon**
(many improvements on saturation, hadronisation...)

Thanks for your attention !



... or later on 😊

A bit more about EPOS...

More references about EPOS :

- [primary interactions & hydrodynamics in EPOS](#)
- [hydrodynamics in EPOS](#)
- [heavy flavours in EPOS](#) (see also [here \[French\]](#)),
- [EPOS-HQ project](#)
- [jet-fluid interaction in EPOS](#)

Recent developments for EPOS 4 :

- [parton saturation](#) (*not the final version though*)
- [BEST equation of state](#) inclusion (see work from [M. Stefaniak](#))
- [microcanonical decay](#)

Stay tuned ! More papers to come...

N.B. : click on the [words in blue](#) to open the hyperlinks leading to the corresponding webpages

Toward the next public release : EPOS 4

As a part of my Ph.D., I am involved in the **development of EPOS 4**,
a **new version** planed to be **released publicly in 2022**.

Concretely, I worked on :

- ① adding a **new output format** to enable **EPOS usage with RIVET**, which is a simple and standardised tool made to automatise comparison between event generators simulations and experimental data from papers
⇒ **makes it more user-friendly**
+ **integrating RIVET** to the **online EPOS analysis framework**
⇒ **provides huge and constantly growing library of data and analyses**
- ② **searching for experimental data** of basic observables and **writing** the **corresponding analyses** (*when not available in RIVET*)
⇒ **useful for validation of the new EPOS version**
- ③ **solving problems** found in the list of the **particles decay channels** (*some particles had a sum of decay branching ratios $\neq 1$*)
⇒ **ensures no inconsistencies of particle decays during simulations**

Updating the particle decay list

Inconsistencies in our list of particle decays :

we realised that some **sum of branching ratios** for some particles decay were **deviating from one**, with non-negligible differences.

⇒ I was in charge to **correct** those inconsistencies **from PDG website** mainly, also deleting in some cases particles treated twice in the file

Problem with the decay of some neutral vector mesons & quarkonia :

because some channels were defined such as $X \rightarrow gg(g)$, we found some **gluons in the final state** (no routine to hadronise them in EPOS).

⇒ had to find a simple and the most general way possible to correct this, i.e. replacing each gluon by any possible combination of $q\bar{q}$ pair (respecting kinematics) that will be hadronised thereafter.

(A topic on its own ! Work to be continued soon by a Master student, in order treat those decays with a more elaborated approach)