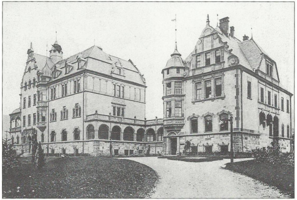
Cosmic Rays and Particle Physics

Michael Schmelling - MPI for Nuclear Physics

Outline

- Introduction
- Particle Physics Basics
- Air Showers and the Muon Puzzle
- Contributions by LHCb
- Summary

5th Graduate School on Astro-Particle Physics



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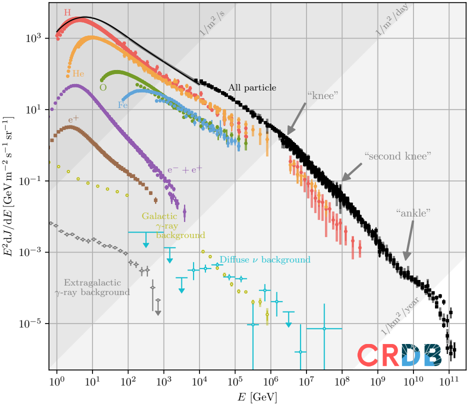
Hölterhoff-Stift around the time of the discovery of cosmic rays

❖ cosmic ray energy spectrum outside the atmosphere



- steeply falling spectrum
- huge energy range
- stable particles & nuclei
- open questions
  - acceleration mechanism
  - composition vs energy
- study of highest energies
  - ground based experiments
  - atmosphere as detector

The astroparticle physics connection

❖ cosmic rays = high energy elementary particles and nuclei

- production in extreme environments
  - supernova explosions
  - black-hole/neutron star mergers
  - high energy collisions in relativistic plasmas
- propagation
  - interstellar and intergalactic medium
  - interactions with EM fields, gas and dust
- detection by extensive air showers
  - cascade of electromagnetic and hadronic interactions
- modelling with knowledge of fundamental interactions: CRpropa, QGSjet, EPOS, . . .

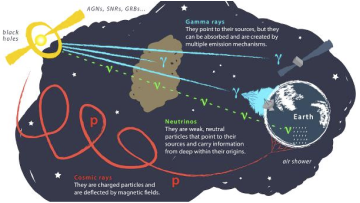
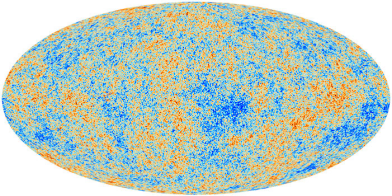
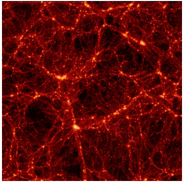


Image: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

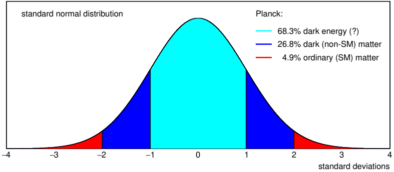
The cosmology connection

❖ results from cosmic microwave background & structure formation



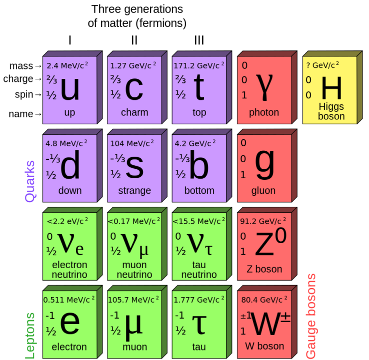


- the universe is “flat” (euclidean)
- “gaussian” sharing of energy content
  - 95% not understood
  - New (particle) Physics



The Standard Model of particle physics

❖ moderately small number of fundamental fields and interactions



plus antiparticles

- (unexplained) findings
  - 1 fundamental scalar
  - 2 types of fermions
  - 3 generations
  - 2 fermion doublets/generation
  - 3 gauge interactions

further questions ➜

❖ what determines the mass spectrum?

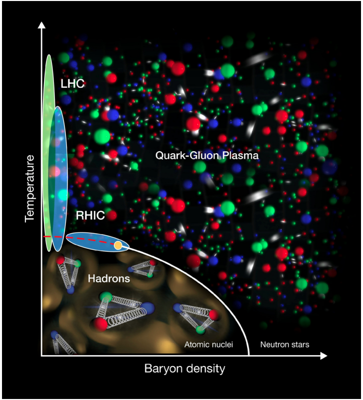
- the Higgs mechanism does not predict mass values
- understanding mass hierarchy requires New Physics (new particles & phenomenology)

❖ where is the antimatter?

(HST)

- no evidence for sizeable amounts of antimatter in the universe, i.e. lack of . . .
  - annihilation radiation
  - anti-nuclei in cosmic rays

❖ how does matter behave under extreme conditions?

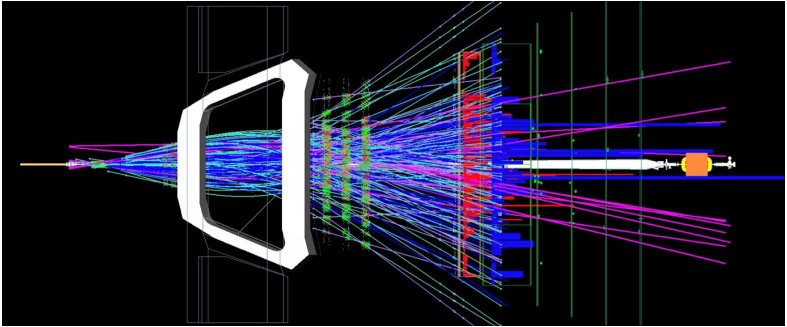


- what happens
  - at extreme densities
  - at extreme temperatures
- equation of state?
- phase transitions?
- critical point?

the tools of the trade ➜

2 Particle Physics Basics

❖ high-energy collisions among leptons, hadrons or nuclei

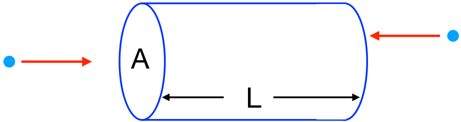


➜ creation of stuff that did not exist in the initial state?

describe and understand what's going on ➜

Cross-section – the fundamental quantity in particle physics

- consider two particles that interact in a cylindrical volume



  - A, L : area of the front faces and length of the volume
  - σ_X: cross-section for a scattering process X
  - the locations of both particles are drawn from a uniform PDF over A
- the probability of an interaction X is p_X

$$p_X = \frac{\sigma_X}{A}$$

➜ cross-section is measured in units of “area”

❖ exercise: how many electrons are scattered when ...

- the electron-hydrogen scattering cross-section $\sigma = 10^{-24}\,\text{cm}^2$
- a volume with $A = 100\,\text{cm}^2$ and $L = 100\,\text{cm}$ filled with H_2-gas
- the gas is at a pressure of 1 atm and at room temperature
- and a bunch of $N_e = 10^6$ electrons is shot into the volume?

- total number of hydrogen atoms

$$N_H = 2N_A \frac{A \cdot L}{22\,400\,\text{cm}^3}$$

- expected number of scattering processes

$$n = N_e\, N_H\, \frac{\sigma}{A} = N_e\, N_A\, \frac{2\,L\,\sigma}{22\,400\,\text{cm}^3} = \frac{10^6 \cdot 6.022 \cdot 10^{23} \cdot 2 \cdot 100 \cdot 10^{-24}}{22\,400} \approx 5377$$

- only the length L of the target area matters
- the actual number of scattering processes is a binomial random variable
- for $p = 0.05377$ it can be approximated by a poisson distribution

Total and differential cross-sections

❖ total cross-section

- something happens – the final state is different from the initial state
- problem: "different" can be anything
  - change of momentum – always happens via EM and/or gravitational radiation
  - change of momentum larger than a certain threshold
    - without creation of new massive particles ➜ elastic cross-section
    - with creation of new massive particles ➜ inelastic cross-section

➤ further remarks

- "total cross-section" sounds simple but is a highly non-trivial concept
- requires observables that satisfy two conditions:
  1. experimentally accessible
  2. theoretically well defined

differential cross-section

- defined for a variable x that characterizes the final state
- measured by the total cross-section change $d\sigma$ in an infinitesimal range dx

$$\frac{d\sigma}{dx}$$

  - experimental definition: finite range Δx instead of dx

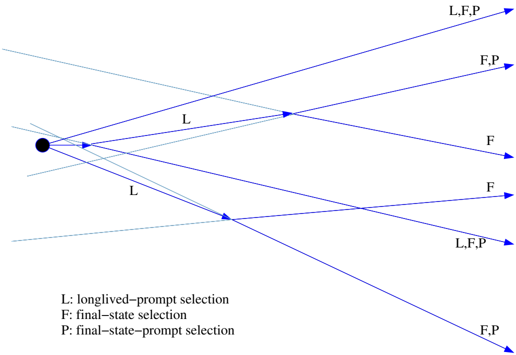
$$\left.\frac{d\sigma}{dx}\right|_{\mathtt{exp}} = \frac{\Delta\sigma}{\Delta x} = \frac{1}{\Delta x}\int_{\Delta x} dx\,\frac{d\sigma}{dx} \approx \frac{d\sigma}{dx}$$

  - the total cross-section σ is obtained integrating over all x
  - usually requires extrapolation for experimentally inaccessible regions

Definition of observables – the theory-experiment divide

- example: number of final state particles produced in a pp collision
  - L: “longlived-prompt”
    - all particles with a proper lifetime $\tau > \tau_0$ that have no ancestors with $\tau > \tau_0$
      - definition based only on particle properties – not on how the event evolved
      - experimental selection by e.g. impact parameter needs correction
  - F: “final-state”
    - all particles that did not decay within a fixed flight length
      - depends on flight length and Lorentz frame
      - extra random component since e.g. K_S^0 may or may not decay
  - P: “final-state-prompt”
    - all final-state particles that extrapolate within a certain distance to the PV
      - impact parameter is experimentally accessible
      - same caveats as method “F”

❖ example illustrate the different final state definitions

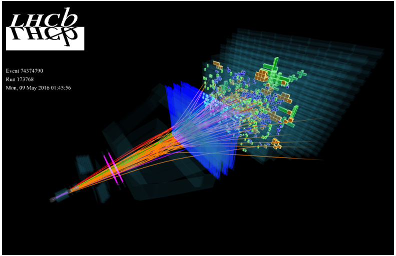


- method "L"
  - well defined final state
  - energy & charge conserved
  - little impact of secondary interactions if $\tau_0 = 30\,\mathrm{ps}$
- method "F"
  - actually surviving particles
  - energy & charge conservation violated by secondary interactions
- method "P"
  - decay kinematic dependent
  - energy & charge conservation violated

Kinematic and other variables – different windows to physics

❖ quantitative description of multi-particle final states

- cross-sections & cross-section ratios
- number of produced particles
- particle fractions
- multiplicity distribution(s)
- fluctuations in the particle production
- correlations between produced particles
- particle spins
- distributions in kinematic variables
  - rapidity and pseudorapidity
  - Feynman's x_F
  - transverse momentum



- $O(10^{3...4})$ dimensional phase space
- full exploration requires ML techniques

Lorentz transformations (in natural units c=1)

❖ boost to the lab from a system that moves with velocity $\beta = v/c$ in the lab

$$\begin{pmatrix} E \\ p_L \end{pmatrix} = \begin{pmatrix} \gamma & \gamma\beta \\ \gamma\beta & \gamma \end{pmatrix} \begin{pmatrix} E^* \\ p_L^* \end{pmatrix} \quad \text{and} \quad p_T = p_T^* \quad \text{with} \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

- E^*: energy in the moving system
- p_L^*: longitudinal momentum along the boost direction in the moving system
- p_T^*: transverse momentum w.r.t the boost direction in the moving system
- E, p_L, p_T: 4-momentum in the lab system

example: 4-momentum of a particle of mass m moving with velocity β

$$E^* = m \quad , \quad p_L^* = 0 \quad , \quad p_T^* = 0 \quad \rightarrow \quad E = \gamma m \quad , \quad p_L = \gamma\beta m \quad , \quad p_T = 0$$

$$\text{and thus} \qquad \gamma = \frac{E}{m} \quad , \quad \beta = \frac{p}{E} \quad \text{and} \quad \gamma\beta = \frac{p}{m}$$

Rapidity

❖ relativistic alternative to classical velocity

$$y = \frac{1}{2} \ln \frac{1+\beta}{1-\beta} \quad \in \quad [-\infty, +\infty]$$

- rapidity of a system moving with velocity β
- classical limit $\beta \to 0$

$$y = \frac{1}{2} \ln \frac{1+\beta}{1-\beta} \approx \frac{1}{2} \ln(1+\beta)^2 = \ln(1+\beta) \approx \beta$$

- rapidity of a particle with 4-momentum (E, p)

$$y = \frac{1}{2} \ln \frac{1+\beta}{1-\beta} = \frac{1}{2} \ln \frac{1+p/E}{1-p/E} = \frac{1}{2} \ln \frac{E+p}{E-p}$$

- rapidity with respect to a certain direction: p ➜ p_L
- rapidity axis = beam direction = boost direction between lab and center-of-mass

❖ exercise: improve the approximation $y \approx \beta$

solution: use the Taylor expansion of $\ln(1+x)$ at $x = 0$

$$\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \frac{x^5}{5} \ldots$$

it follows

$$\begin{aligned} y &= \frac{1}{2}(\ln(1+\beta) - \ln(1-\beta)) \\ &= \frac{1}{2}\left(\beta - \frac{\beta^2}{2} + \frac{\beta^3}{3} - \frac{\beta^4}{3} + \frac{\beta^5}{5} \ldots\right) - \frac{1}{2}\left(-\beta - \frac{\beta^2}{2} - \frac{\beta^3}{3} - \frac{\beta^4}{3} - \frac{\beta^5}{5} \ldots\right) \\ &= \beta + \frac{\beta^3}{3} + \frac{\beta^5}{5} + \ldots \end{aligned}$$

➜ only odd powers of β contribute

❖ behaviour under boost along the rapidity axis

rapidity of a particle in a reference system moving with velocity β

$$y^* = \frac{1}{2} \ln \frac{E^* + p_L^*}{E^* - p_L^*}$$

Lorentz boost

$$y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L} = \frac{1}{2} \ln \frac{(\gamma E^* + \gamma\beta p_L^*) + (\gamma p_L^* + \gamma\beta E^*)}{(\gamma E^* + \gamma\beta p_L^*) - (\gamma p_L^* + \gamma\beta E^*)}$$

$$= \frac{1}{2} \ln \frac{(E^* + p_L^*)(1+\beta)}{(E^* - p_L^*)(1-\beta)} = y^* + y_0 \quad \text{with} \quad y_0 = \frac{1}{2} \ln \frac{1+\beta}{1-\beta}$$

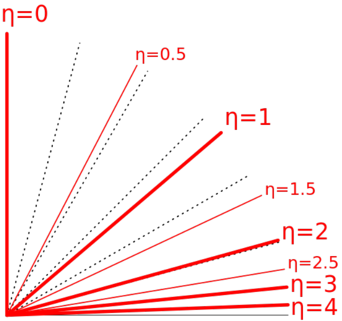
➜ rapidity differences are invariant under boost along the rapdity axis

Pseudorapidity

❖ rapidity of a massless particle

$$\eta = \frac{1}{2}\ln\frac{E(m=0)+p_L}{E(m=0)-p_L}$$
$$= \frac{1}{2}\ln\frac{p+p_L}{p-p_L}$$
$$= \frac{1}{2}\ln\frac{1+p_L/p}{1-p_L/p}$$
$$= \ln\sqrt{\frac{1+\cos\theta}{1-\cos\theta}}$$
$$= -\ln\tan\frac{\theta}{2}$$

► function of the polar angle to the rapidity axis

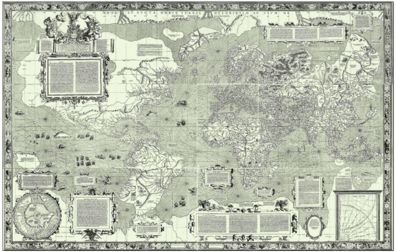


dashed lines at 15,30,45,60,75 degrees

Historical note: Who invented pseudorapidity?

❖ historical example where using the right variable makes a difference

- wanted: a map where a straight line corresponds to a fixed direction on the surface of the earth
- useful for navigation at sea: plotted and actual direction agree



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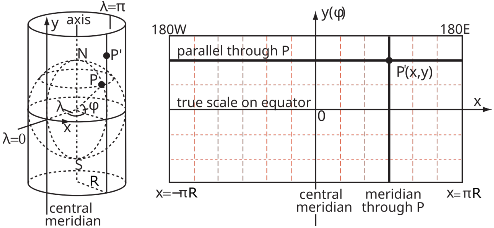
Gerardus Mercator (Gerhard Krämer), 1569

- ansatz: project earth surface on a cylinder that touches the earth at the equator



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- longitude $-\pi < \lambda < \pi$, latitude $-\pi/2 < \varphi < \pi/2$
- x-direction: parallel to equator, pointing east
- y-direction: parallel to axis of rotation, pointing north
- mapping: meridians parallel to the y-axis, parallels parallel to the x-axis,

$$x = \lambda \quad \text{and} \quad y = g(\varphi) \quad \text{with} \quad g(0) = 0$$

- construction of an angle-preserving projection from infinitesimal displacements
  - du, dv in local cartesian coordinates on earth, u pointing east, v pointing north
  - dx, dy displacements in the projection

$$du = \cos\varphi\, d\lambda \quad \text{and} \quad dv = d\varphi$$

$$dx = d\lambda \qquad\qquad \text{and} \quad dy = g'(\varphi)\, d\varphi$$

- condition for equal angles (slopes) in (x, y) and (u, v)

$$\frac{dy}{dx} = \frac{dv}{du} \quad \rightarrow \quad g'(\varphi) = \frac{1}{\cos\varphi}$$

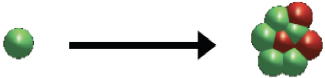
- unique solutions with $g(0) = 0$: Mercator projection

$$g(\varphi) = \ln\tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) = -\ln\tan\frac{\theta}{2} \quad \text{with polar angle} \quad \theta = \pi/2 - \varphi$$

➜ Mercartor-projection = mapping of parallels by $\eta(\theta)$

Feynman's x_F

❖ definition motivated by high-energy fixed target pA collisions



$$x_F = \frac{p_z}{p_z^{\text{max}}} = \frac{p_z}{p_z^{\text{beam}}}$$

- purely longitidinal variable
- behaviour under Lorentz boost $p_z' = \gamma(E + \beta p_z)$ when $\beta \to 1$ and $E \approx |p_z|$

$$x_F' = \frac{p_z'}{p_z'^{\,\text{max}}} \approx \frac{\gamma(|p_z| + p_z)}{\gamma(|p_z^{\text{max}}| + p_z^{\text{max}})} = \begin{cases} x_F & \text{for} \quad p_z > 0 \\ 0 & \text{for} \quad p_z < 0 \end{cases}$$

  - ► Lorentz-invariant variable for high-momentum forward going particles
  - ► frame dependence for backwards region

- alternative definition

$$x_F \approx \frac{E + p_z}{(E + p_z)_{\mathrm{max}}} \approx \sqrt{\frac{p_x^2 + p_y^2}{s}}\, \mathrm{exp}(y_{cm}) \;\in\; [0, 1]$$

- definition in centre-of-mass system

$$x_F = \frac{2p_z^{cm}}{\sqrt{s}} = 2\sqrt{\frac{m^2 + p_x^2 + p_y^2}{s}}\; \mathrm{sinh}\, y_{cm} \;\in\; [-1, +1]$$

  - ambiguity: proton-nucleon vs proton-nucleus centre-of-mass

➤ bottom line

$x_F \to 1$ Lorentz invariant and universal

$x_F \leqslant 0$ frame- and definition dependent

Transverse momentum p_T

❖ momentum orthogonal to the direction of the colliding particles

$$p_T = \sqrt{p_x^2 + p_y^2}$$

- Lorentz invariant for boosts along the beam direction
- small cross-sections for processes with large transverse momentum
  - most particles created in hadronic collisions have small transverse momenta
- transverse momentum scale set by the uncertainty relation

$$\Delta u \, \Delta p_u \sim \hbar \quad \text{with} \quad u = x, y$$

- calculate the p_T distribution for gaussian distributions of the components

$$\frac{dn}{dp_u} = \frac{1}{\sqrt{2\pi}\sigma} e^{-p_u^2/2\sigma^2} \qquad \sigma = \Delta p_u = \hbar / \Delta u$$

with transformation to polar coordinates ϕ and $q = \sqrt{p_x^2 + p_y^2}$ ➜

- result

$$\frac{dn}{dp_T} = \frac{1}{2\pi\sigma^2}\int dp_x\, dp_y\, e^{-(p_x^2+p_y^2)/2\sigma^2}\,\delta(p_T - \sqrt{p_x^2+p_y^2})$$

$$= \frac{1}{2\pi\sigma^2}\int d\phi\, dq\; q\; e^{-q^2/2\sigma^2}\,\delta(p_T - q) = \frac{1}{\sigma^2}\, p_T\; e^{-p_T^2/2\sigma^2}$$

➜ universal (phase space) behaviour $\propto p_T$ for $p_T \to 0$

- mean value

$$\langle p_T \rangle = \int_0^\infty dp_T\, p_T \frac{dn}{dp_T} = \sigma\sqrt{\frac{\pi}{2}} \quad \text{i.e.} \quad \langle p_T \rangle \propto \sigma$$

  - the average transverse momentum is defined size of the particle emitting region
  - localisation Δu determined by the Compton wavelength λ of a particle

$$\sigma \sim \frac{h}{\lambda} \quad \text{with} \quad \lambda = \frac{h}{m} \quad \Rightarrow \quad \langle p_T \rangle \sim m$$

➜ heavier particles are produced with larger transverse momentum

Remark: arguments using the uncertainty relation . . .

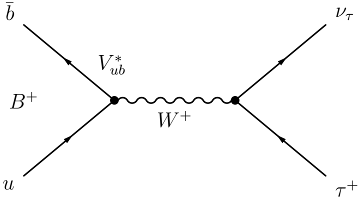
- . . . should always be taken with a grain of salt!
  - commonly seen:

$$\Delta E \, \Delta t \geqslant \hbar$$

This means that short time intervals energy-conservation can be violated.
Energy can be borrowed and returned as long as the above inequality holds.

- problematic aspects
  - the uncertainty relation holds between operators, but there is no time operator
    - excuse: relativity tells us that there is a space-time continuum, and if there is an uncertainty relation involving space, there should also be one for time
  - we always emphasize that energy and momentum must be conserved
  - by the above equation indefinite loans should be allowed . . .

example: weak decay of $B^+ \to \tau^+ \nu_\tau$



By means of the uncertainty relation the 5.279-GeV B^+-particle can briefly borrow the energy to turn into a 80.4-GeV W^+ that decays into the tau and its neutrino

➤ what we actually do when we calculate the process

- at each vertex the 4-momentum is conserved; energy conservation is never violated
- the W-boson has an invariant mass equal to the B^+ mass
- the uncertainty relation relates to the fact that short lived particles can be off-shell

4-fold differential cross-section

$$\frac{d^4\sigma}{d^4p'} = \frac{d^4\sigma}{d^4p}\left|\frac{\partial p}{\partial p'}\right| = \frac{d^4\sigma}{d^4p} \quad \text{with} \quad d^4p = dp_x\,dp_y\,dp_z\,dE$$

- the differential cross-section is invariant under Lorentz transformations

- mass constraint for physical particles

$$E^2 - p^2 - m^2 = 0 \quad \text{with} \quad p^2 = p_x^2 + p_y^2 + p_z^2 \quad \text{and} \quad E > 0$$

- physical 3-fold differential invariant phase-space element

$$dp_x\,dp_y\,dp_z \int dE\,\delta(E^2 - p^2 - m^2) = \frac{dp_x\,dp_y\,dp_z}{2E} \quad \text{with} \quad E = \sqrt{m^2 + p^2}$$

follows from $\int dx\; g(x)\,\delta(f(x)) = \frac{g(x_0)}{f'(x_0)}$ with $f(x_0) = 0$

❖ equivalent representations of the Lorentz invariant phase space element

$$\frac{1}{2E}\,dp_x\,dp_y\,dp_z = \frac{1}{2E}\,p_T\,dp_T\,dp_z\,d\phi = \frac{1}{4E}\,dp_T^2\,dp_z\,d\phi = \frac{1}{4}\,dp_T^2\,dy\,d\phi$$

- the last expression follows because

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{\sqrt{m^2+p_x^2+p_y^2+p_z^2}+p_z}{\sqrt{m^2+p_x^2+p_y^2+p_z^2}-p_z} \quad \text{implies} \quad \frac{dp_z}{E} = dy$$

- particles produced according to phase space, are
  - uniformly distributed in ϕ – symmetry around the beam direction
  - uniformly distributed in y – approximately realized in data
  - uniformly distributed in p_T^2 – true for $p_T \to 0$

putting things to work ➜

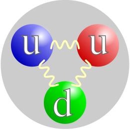
Modelling the structure of hadrons

- global quantum numbers described by the quark model
- (strong) interaction between constituents leads to parton model with valence quarks, gluons and virtual, mostly light, quark-antiquark pairs
- parametrisation by "Parton Density Functions" (PDFs) for each parton-type k

parton density: $$\rho_k(x) \sim x^{\alpha_k - 1}\,(1-x)^{\beta_k}$$

momentum density: $$x\rho_k(x) \sim x^{\alpha_k}\,(1-x)^{\beta_k}$$

momentum conservation: $$\sum_k \int_0^1 dx\; x\,\rho_k(x) = 1$$



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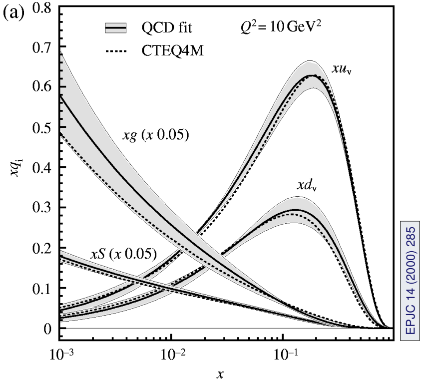
- $x \in [0, 1]$: 4-momentum fraction carried by a parton
- power-law behaviour at the phase space limits
- $\alpha_k > -1$ needed for normalisation (momentum conservation)

❖ global fit result for parton densities of the proton



- $x \to 0$: gluon density dominates
- $x \to 1$: valence quark density dominates

parametrisation for $x \to 0$:

$$x\rho(x) = A \cdot x^{\alpha}$$

parton	A	α
gluon	1.32	−0.26
valence quark	1.57	0.63
sea quark	0.14	−0.15

pp collisions at large centre-of-mass energies

❖ basic process: collision of two massless & collinear partons

kinematics in pp center of mass

$$E_{1,2} = \frac{\sqrt{s}}{2} x_{1,2} \qquad \text{and} \qquad p_{1,2} = \pm \frac{\sqrt{s}}{2} x_{1,2}$$

total energy and momentum

$$E = E_1 + E_2 = \frac{\sqrt{s}}{2}(x_1 + x_2) \qquad \text{and} \qquad p = p_1 + p_2 = \frac{\sqrt{s}}{2}(x_1 - x_2)$$

invariant mass and rapidity of the two-parton system:

$$m^2 = E^2 - p^2 = s\, x_1 x_2 \qquad \text{and} \qquad y = \frac{1}{2} \ln \frac{E+p}{E-p} = \frac{1}{2} \ln \frac{x_1}{x_2}$$

phenomenology ➜

❖ cross-section to create of a system with $M > m$

- reminder: $x_1 x_2 = m^2/s$
- assume small-x scattering and thus that gluon-gluon scattering dominates
- use $m \to m_\pi$ to estimate the total inelastic cross-section σ_{inel}

$$\sigma \propto \int_0^1 dx_1 \int_0^1 dx_2\, \rho(x_1)\rho(x_2)\, \Theta\left(x_1 x_2 - \frac{m^2}{s}\right) \quad \text{with} \quad \rho(x) \propto x^{\alpha-1}, \alpha < 0$$

$$= \int_{m^2/s}^1 dx_1\, x_1^{\alpha-1} \int_{m^2/sx_1}^1 dx_2\, x_2^{\alpha-1}$$

$$= \frac{1}{\alpha^2} + \frac{1}{|\alpha|}\left(\frac{s}{m^2}\right)^{|\alpha|}\left(1 + \ln\frac{s}{m^2}\right) \quad \rightarrow \quad \sigma \sim \left(\frac{s}{m^2}\right)^{|\alpha|} \ln\frac{s}{m^2} \quad \text{for} \quad m \to m_\pi$$

- ▶ growth of gluon density for $x \to 0$ leads to growth of σ_{inel} with s
- ▶ dominated by power-law term

❖ rapidity distribution of particles with mass m produced in gg collisions

$$\frac{d\sigma}{dy} \propto \int_0^1 dx_1 \int_0^1 dx_2 \; \rho(x_1)\, \rho(x_2)\, \delta\left(y - \frac{1}{2}\ln\frac{x_1}{x_2}\right)\, \delta\left(x_1 x_2 - \frac{m^2}{s}\right)$$

- result from integration over δ-functions:

$$\frac{d\sigma}{dy} \propto \rho(x_1)\, \rho(x_2) \quad \text{with} \quad x_1 = \frac{m}{\sqrt{s}} e^{y} \quad \text{and} \quad x_2 = \frac{m}{\sqrt{s}} e^{-y}$$

- explicit form for $\rho(x) \propto x^{\alpha-1}(1-x)^{\beta}$ with $\alpha < 0$, $\beta > 0$

$$\frac{d\sigma}{dy} \propto \left(\frac{s}{m^2}\right)^{|\alpha|+1-\beta/2} \left(1 - \frac{\cosh y}{\cosh y_m}\right)^{\beta} \quad \text{with} \quad y_m = \ln\frac{\sqrt{s}}{m}$$

  - ► uniform distribution in the center
  - ► power-law growth with energy of density and thus of final state particle multiplicity

❖ exercise: show that

$$\int_0^1 dx_1 \int_0^1 dx_2 \, \rho(x_1)\, \rho(x_2)\, \delta\left(y - \frac{1}{2}\ln\frac{x_1}{x_2}\right)\, \delta\left(x_1 x_2 - \frac{m^2}{s}\right) \propto \rho\left(\frac{m}{\sqrt{s}}e^{y}\right)\rho\left(\frac{m}{\sqrt{s}}e^{-y}\right)$$

straightforward calculation shows that for

$$x_1 = \frac{m}{\sqrt{s}}e^{y} \quad \text{and} \quad x_2 = \frac{m}{\sqrt{s}}e^{-y}$$

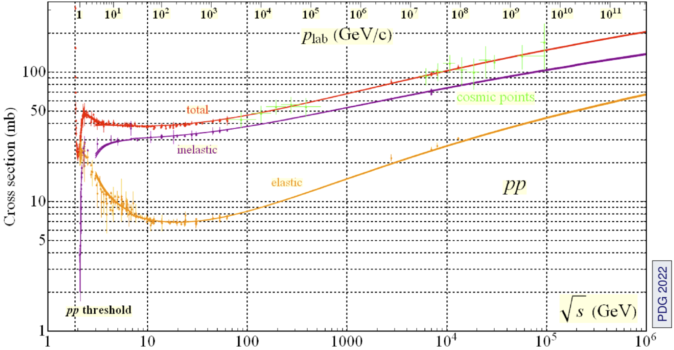
the arguments to both delta-functions are zero. It remains to consider the derivatives of the arguments to the delta functions. Using the integral over x_1 (x_2) to get rid of the first (second) delta function one picks up the jacobians

$$\left|\frac{d}{dx_1}\left(y - \frac{1}{2}\ln\frac{x_1}{x_2}\right)\right| = \frac{1}{2x_1} \quad \text{and} \quad \left|\frac{d}{dx_2}\left(x_1 x_2 - \frac{m^2}{s}\right)\right| = x_1$$

The product is constant, which proves the proposition.

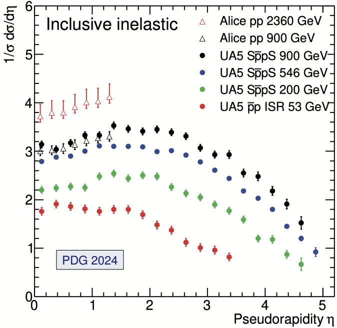
Experimental findings

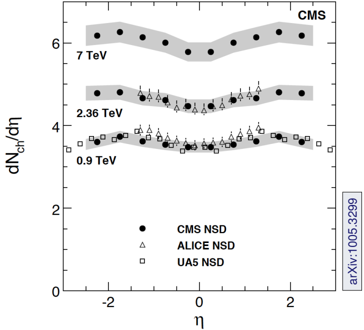
❖ total inelastic pp cross-section



➜ energy dependence at high energies can be described by a power-law

❖ (pseudo) rapidity distributions

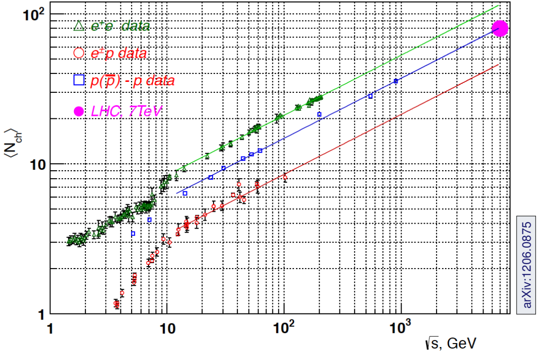




- pseudorapidity used as a proxy for rapipity
- $dn/d\eta < dn/dy$ in the central region because of mass effects

➜ approximately uniform rapidity distribution in the central region

❖ total charged-particle multiplicities



- universal power laws
- fit for $\sqrt{s} > 11\,\mathrm{GeV}$

$$\langle n_{\rm ch} \rangle = N_0 \left(\frac{s}{m_p^2} \right)^{1/5}$$

- $N_0(pp, p\bar{p}) = 2.32$
- $N_0(e^{\pm}p) = 1.32$
- $N_0(e^+e^-) = 3.32$

- universal phenonmenology in multi-particle production
- qualitative understanding relatively simple

Hadronic interactions in a nutshell

❖ nucleon-nucleon center-of-mass energy

collider: $\sqrt{s_{NN}} = 2E_{\rm beam}$ fixed target: $\sqrt{s_{NN}} = \sqrt{2E_{\rm beam}\, m_N}$

► $\sqrt{s_{NN}} = 10$ TeV pp at LHC $\Leftrightarrow$ $E_{\rm beam} = 5 \cdot 10^7$ GeV CR protons on earth

❖ rule-of-thumb bulk properties of hadronic interactions

- exponential spectrum $\propto p_T \exp(-ap_T)$ with $\langle p_T \rangle = O(0.4)$ GeV
- uniform (pseudo)rapidity ($\eta \approx y$) distribution with $O(10)$ particles/unit
- ranges covered

collider: $y \in [-y_{\rm max}, +y_{\rm max}]$ fixed target: $y \in [0, 2y_{\rm max}]$ with $y_{\rm max} = \ln \frac{\sqrt{s_{NN}}}{m_N}$

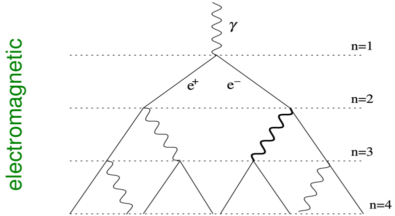
► e.g. $y_{\rm max}(10\,\text{TeV}) = 9.2$ and $y_{\rm max}(100\,\text{GeV}) = 4.6$

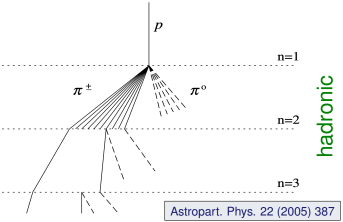
► weak center-of-mass dependency of particle density

Beyond soft QCD – heavy flavours

- production cross-sections increase at high energies
  - heavy flavours contribute a larger share of the total particle production
- contribution to large p_T processes in EAS
  - understanding of lateral extent of air showers
  - extra contributions to high-energy neutrinos
- phenomenology with large CP-asymmetries
  - help understanding the baryon-asymmetry of the universe
- heavy long-lived quarks are ideal tracers in hot QCD media
  - melting of bound states in QGP
  - probing differences between free nucleons and nuclear matter
- more reliable theoretical calculations
  - better sensitivity to New Physics

❖ Heitler/Mattews-type toy models for extensive air showers





- branchings after splitting length $\lambda_r \ln 2$
  - $\gamma \to e^+ e^-$
  - $e^\pm \to \gamma e^\pm$
- equal sharing of energy in all branchings
- termination when $E < E_c^r$

- branchings after interaction length λ_I
  - $h \to M(\pi^+\pi^-\pi^0)$ with $M = 5$
  - EM sub-cascades from $\pi^0 \to \gamma\gamma$
- equal sharing of energy in all processes
- termination when $E < E_c^h$
  - pions decay to muons

❖ predictions of the toy model for a primary photon of energy E_0

- number of final state particles N

$$N = \frac{E_0}{E_c^r}$$

- number of splittings n

$$N = 2^n \quad \text{and thus} \quad n = \frac{\ln N}{\ln 2} = \frac{\ln E_0/E_c^r}{\ln 2}$$

- depth of the shower maximum

$$X_{\text{max}} = n\lambda_r \ln 2 = \lambda_r \ln \frac{E_0}{E_c^r}$$

  - ▶ the number of produced particles is proportional to the primary energy E_0
  - ▶ the depth of shower maximum grows proportional to $\ln E_0$

❖ predictions of the toy model for a primary hadron of energy E_0

- total number of pions after n branchings

$$N_n = (2M)^n$$

- total energy carried by pions and energy E_n per pion

$$N_n E_n = \left(\frac{2}{3}\right)^n E_0 \quad \text{and thus} \quad E_n = \left(\frac{2}{3}\right)^n \frac{1}{(2M)^n} E_0$$

- number of branchings until shower maximum

$$E_c^h = E_n = \left(\frac{1}{3M}\right)^n E_0 \quad \text{and thus} \quad n = \frac{\ln E_0/E_c^h}{\ln 3M} \quad \text{at} \quad X_{\max} = n\lambda_I$$

- number of muons

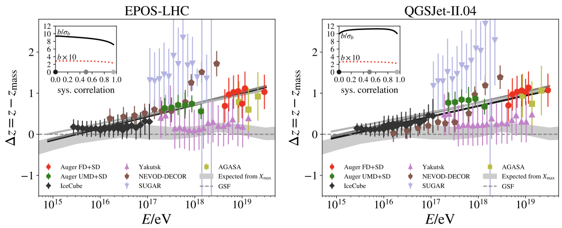
$$N_\mu = N_n = (2M)^{\frac{\ln E_0/E_c^h}{\ln 3M}} = \left(\frac{E_0}{E_c^h}\right)^{\frac{\ln 2M}{\ln 3M}} \overset{M=5}{\approx} \left(\frac{E_0}{E_c^h}\right)^{0.85}$$

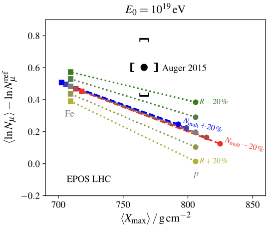
findings

- qualitatively similar behaviour for electromagnetic and hadronic showers
- accurate prediction of muon flux requires understanding of
  - chemical composition of primary cosmic rays
  - hadronic interaction length λ_I
  - final states multiplicities
  - energy fraction into electromagnetic cascades
- input from particle physics
  - inelastic cross-sections $\sigma_{\mathrm{inel}}(E)$ for pp, pA, AA interactions
  - number and types of produced particles
  - kinematics
  - nuclear modification factors

The Muon Puzzle

❖ discrepancy between expected and measured muon flux in air showers





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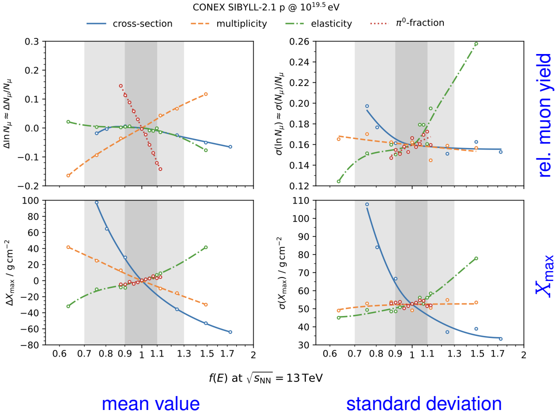
compare normalized muon yield:

$$z = \frac{\ln \langle N_\mu \rangle - \ln \langle N_\mu \rangle_p^{MC}}{\ln \langle N_\mu \rangle_{Fe}^{MC} - \ln \langle N_\mu \rangle_p^{MC}}$$

- works for any experimental measure of N_μ
- MC accounts for different experimental conditions
- normalization handles composition dependence

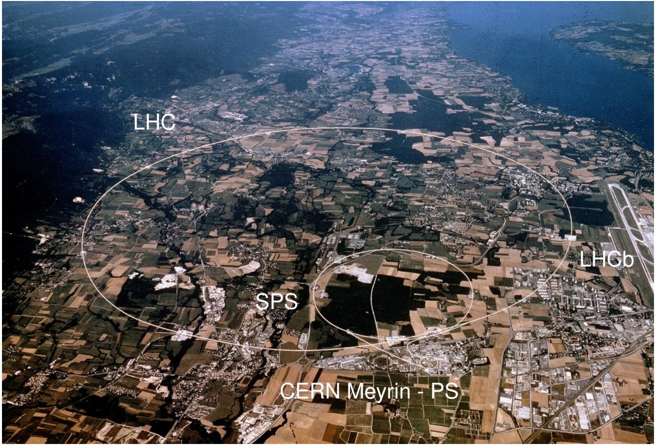
➜ at high energies all models predict to few muons

❖ sensitivity studies

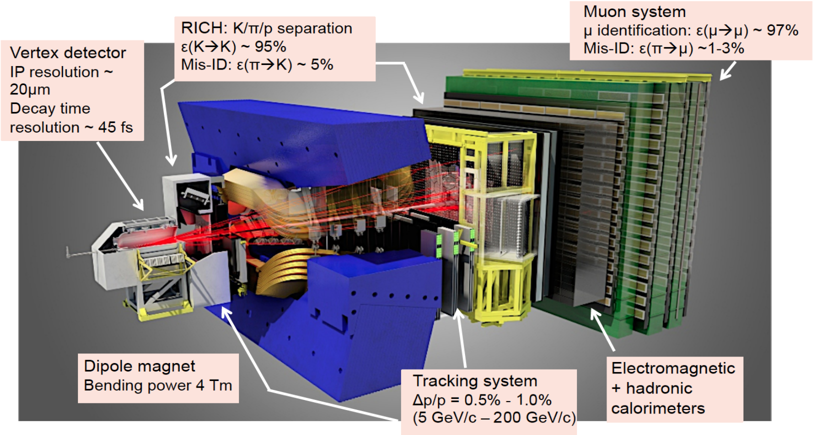


- vary model parameters adjusted at $\sqrt{s} = 13$ TeV
- predict N_μ and X_{max} at $\sqrt{s} = 10^{7.5}$ TeV
- X_{max} driven by σ_{inel}
- N_μ rises with multiplicity and drops with EM fraction

4 Contributions by LHCb

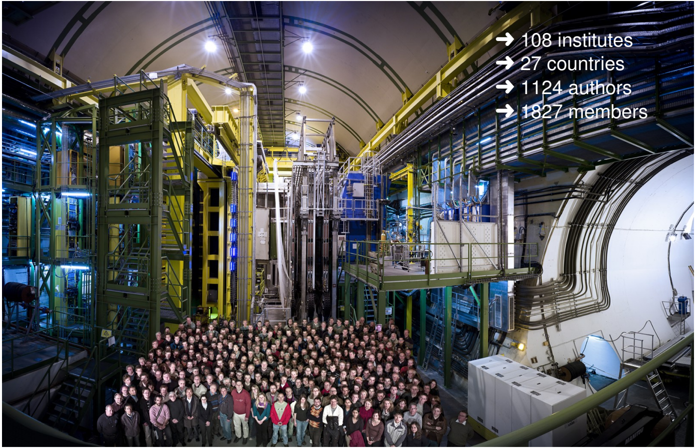


The Run 1 / Run 2 LHCb detector



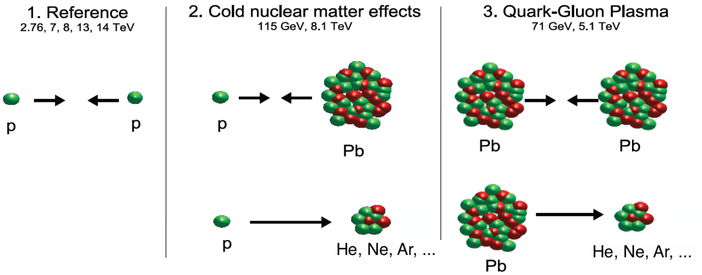
JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

The LHCb collaboration

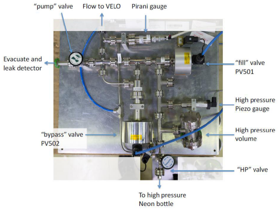


LHCb beam configurations

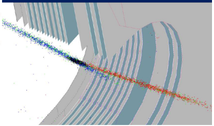
- possibility to study hadronic collisions. . .
  - as a function of the centre-of-mass energy
  - for different combinations of collision partners
  - colliding beam and fixed target mode

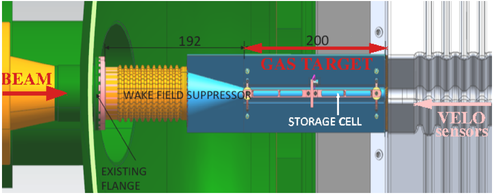


Fixed target mode – the SMOG systems



- injection of gas into interaction region
- very simple robust system
- used for a precise luminosity determination





❖ inital setup

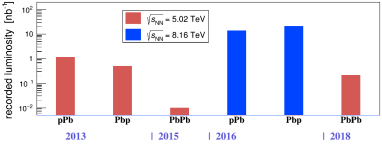
- beam-gas imaging for luminosity measurement
- inject noble gases into VELO
- pressure $O(10^{-7})$ mbar

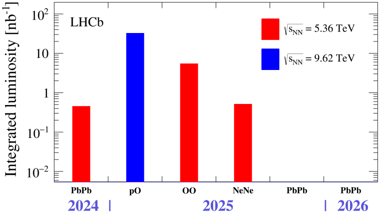
❖ SMOG2

- dedicated storage cell
- O(100) times higher pressure
- joint running with collider mode

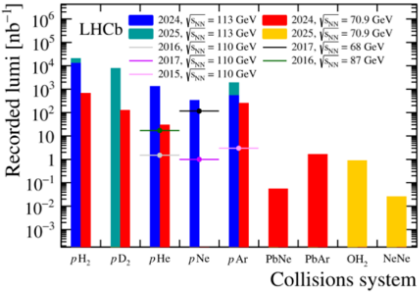
Data sets

❖ collider mode ion physics





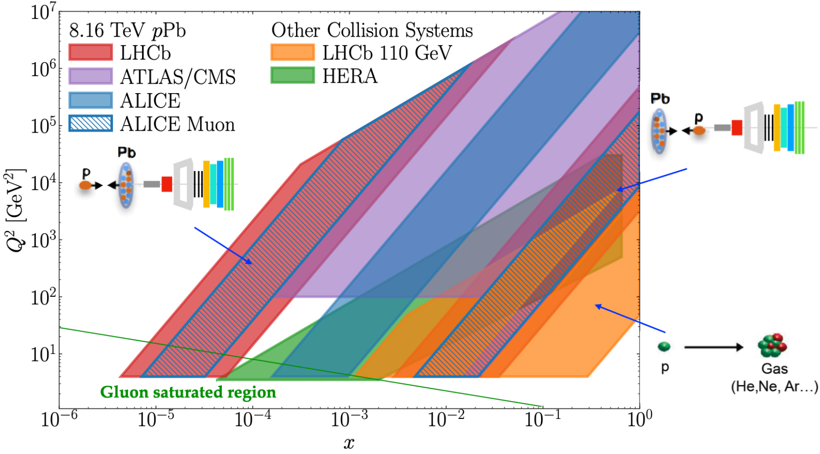
❖ fixed target mode ion physics



❖ collider mode pp physics

0.9, 2.76, 5, 7, 8, 13, 13.6 TeV

Probing the structure of a nucleon inside a nucleus



Some selected results

- basic measurements of multi-particle production
  - inelastic cross-section
  - inclusive particle production cross-sections
  - multiplicities
  - hadronization studies
- probing the structure of the nucleon, the nucleus, and the nucleon inside a nucleus
  - nuclear modification factors in pA collisions
  - probing nuclear shapes in ion-ion collisions
- specific measurements
  - antimatter production in light ion collisions

Measurement of the inelastic pp cross-section

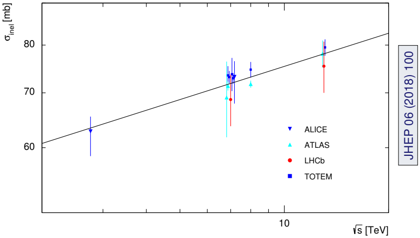
- fiducial cross-section $\sigma_{\rm acc}$ at $\sqrt{s} = 13\,\mathrm{TeV}$
  $\geqslant 1$ long-lived prompt charged particle with $p > 2\,\mathrm{GeV}$ and $2 < \eta < 5$
  produced directly in the interaction or from decays of short-lived ancestors
  with "short-lived" defined as $\tau < 30\,\mathrm{ps}$

$$\sigma_{\rm acc} = 62.2 \pm 0.2 \pm 2.5\,\mathrm{mb}$$

- extrapolation to full phase space

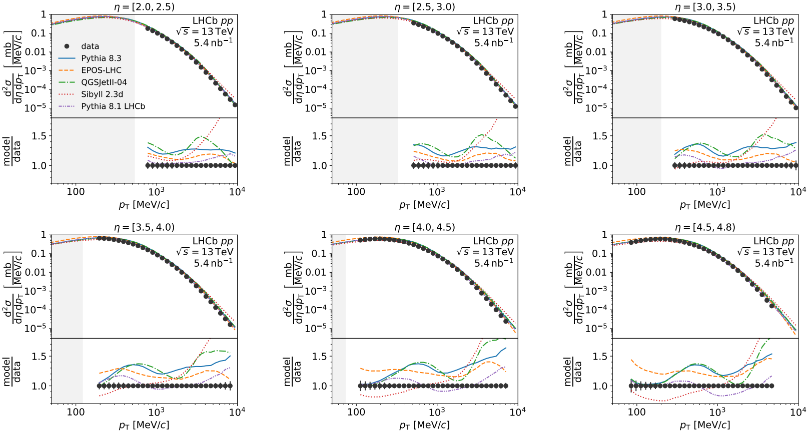
$$\sigma_{\rm inel} = 75.4 \pm 3.0 \pm 4.5\,\mathrm{mb}$$

- dominant uncertainties
  - systematics
  - luminosity
  - extraploation



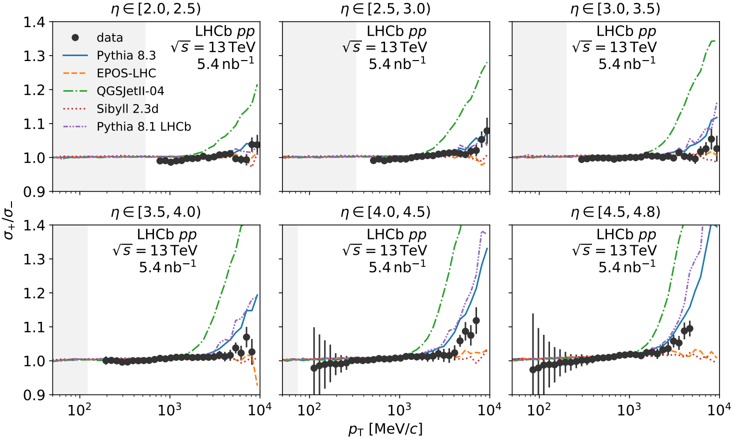
LHC results with a power-law fit

Inclusive charged particle production cross-sections $\sqrt{s} = 13\,\mathrm{TeV}$



JHEP 01 (2022) 166

Charge ratios at $\sqrt{s} = 13\,\text{TeV}$



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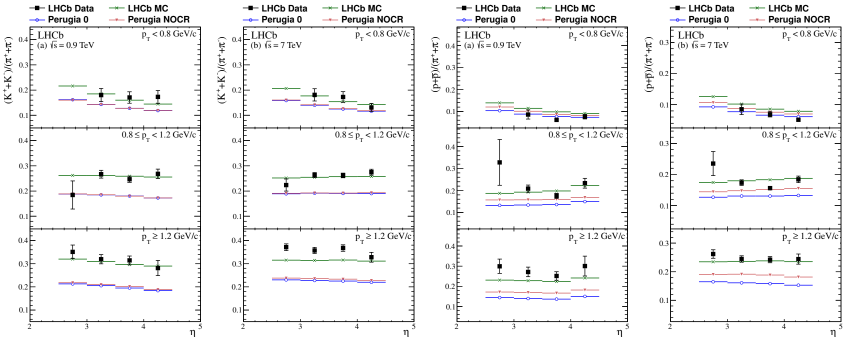
Strangeness and baryon suppression at $\sqrt{s} = 0.9$ and 7 TeV

$(K^+ + K^-)/(\pi^+ + \pi^-)$ $(\bar{p} + p)/(\pi^+ + \pi^-)$

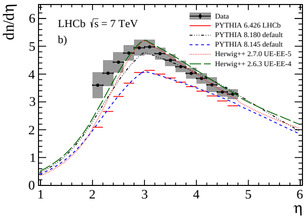
$\sqrt{s} = 0.9$ TeV $\sqrt{s} = 7$ TeV $\sqrt{s} = 0.9$ TeV $\sqrt{s} = 7$ TeV

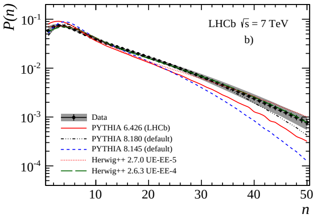


Eur.Phys.J. C72 (2012) 2168

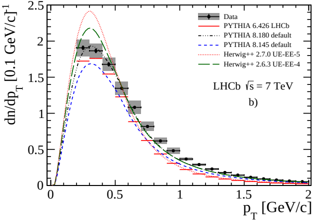
➜ LHCb MC based on Pythia 6 works best

Particle densities and multiplicity distribution at 7 TeV





Eur.Phys.J. C27 (2012) 1947



➤ charged particles

$p_T > 0.2\,\text{GeV}$, $p > 2\,\text{GeV}$, $2.0 < \eta < 4.8$

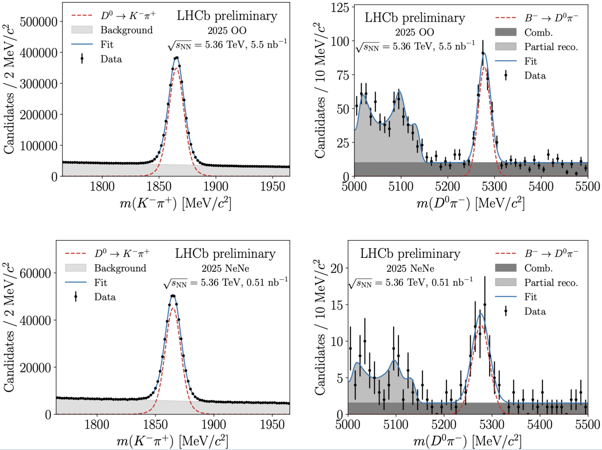
produced directly or from decays of ancestors with $\sum \tau < 10\,\text{ps}$

- none of the models is perfect
- satisfactory modelling by PYTHIA8 and Herwig++

Heavy flavour production in ion-ion collisions

OO

NeNe

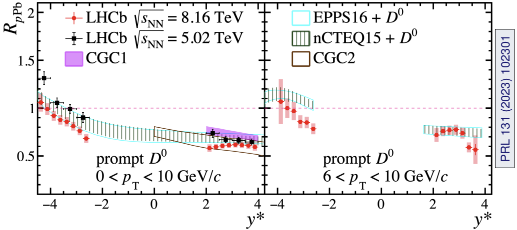


LHCb-FIGURE-2025-017

Probing nuclear PDFs by nuclear modification factors

❖ compare pp and pA collisions

$$R_{pA} = \frac{1}{A} \cdot \frac{d\sigma_{pA}/dy^*}{d\sigma_{pp}/dy^*}$$



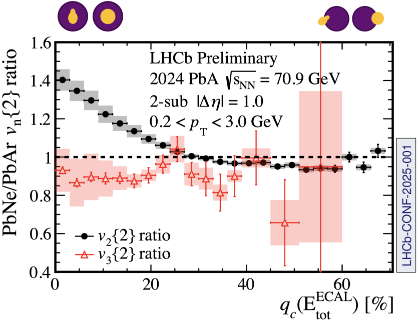
- sensitivity to x

$$x_{1,2} \sim e^{\pm y^*} \frac{M}{\sqrt{s}}$$

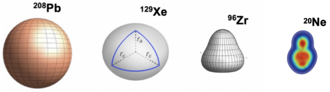
- M: mass of heavy system created in a collision
- y^*: center-of-mass rapidity
- less dilution of sensitivity to x due to fragmentation and decays for heavy particles

Probing nuclear shapes

- study collisions of a Pb beam on Ar/Ne nuclei at rest
  - transverse flow of secondary particles depends on overlap of shapes
    - central collisions: shape affects the flow pattern 
    - peripheral collisions: universal flow pattern 



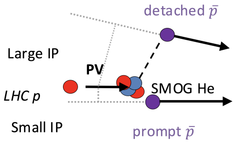
- study Fourier coefficents of transverse flow
  - Pb and Ar: round nuclei
  - Ne: bowling-pin shape
- results match theoretical expectation



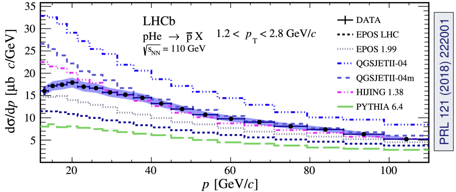
Antiproton production in pHe collisions at $\sqrt{s_{NN}} = 110\,\text{GeV}$

➤ distinguish prompt and non-prompt contributions by impact parameter (IP)

- PID-system to identify antiprotons
- cross-section normalization from pe scattering
- direct measurement of prompt component
- template fit of IP distribution for non-prompt $\bar{p}$

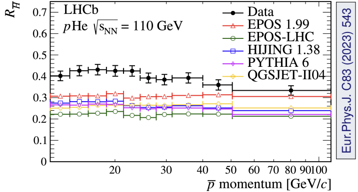


prompt $\bar{p}$ cross-section



➜ large reduction in uncertainty

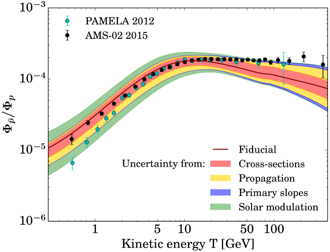
non-prompt fraction



➜ all models too low

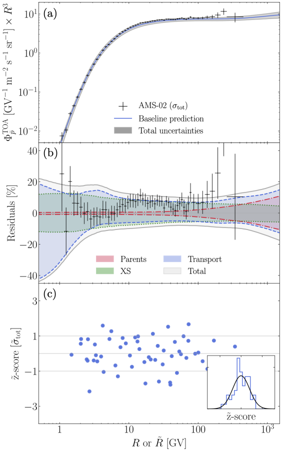
Impact on cosmic ray physics

initial prediction of AMS-02 $\bar{p}/p$ flux ratio



JACP 09 (2015)023

improved model ➜



Phys.Rev.Res.2 (2020) 2,023022

- tension with Standard Model reduced
- uncertainty still dominated by cross-section
- new input expectd from pH and pD data

5 Summary

❖ particle and cosmic ray physics are two sides of the same medal

- accelator based particle physics benefits from controlled conditions
- cosmic rays probes the entire phase space
- many particle physics results are directly relevant for astroparticle physics
  - understanding the propagation of CR particles
  - understanding hadronic interactions in CR induced air-showers (“Muon puzzle”)
- details of hadronic interactions are intricate but qualitative properties are simple

➔ further reading

A Heitler model of extensive air showers,
Astroparticle Physics 22 (2005) 387, https://doi.org/10.1016/j.astropartphys.2004.09.003

The Muon Puzzle in cosmic-ray induced air showers and its connection to the LHC,
Astrophysics and Space Science 3 (2022) 367, https://doi.org/10.1007/s10509-022-04054-5

Global tuning of hadronic interaction models with accelerator-based and astroparticle data,
Nature Reviews Physics 2025, https://doi.org/10.1038/s42254-025-00897-3