Photoproduction and CR showers:
Post-LHC updates of Photoproduction total cross section at ultra high energies and shower development from cosmic ray photons

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AdA – First charging
21st February 1961

AdA – Positron run
12-13th February 1963
Photon 2017, CERN
Photons in cosmic rays

• CR Composition not yet well known
• Photon content still unclear
• Showers development can give information

• Input in MC depends on Hadronic Interaction Model
  – i.e. QSGJET-II in AIRES
  – \( \gamma p \rightarrow X \rightarrow \gamma \rightarrow \text{air} \)

• Data for \( \gamma p \) are only up to \( \sqrt{s} = 210 \text{ GeV} \) (HERA)
  – \( E_{lab} \approx 10^{19} \text{eV} \rightarrow 10-100 \text{ TeV} \) yet unexplored in photoproduction
  – Models for \( \gamma p \rightarrow X \) differ at very high energies
Total hadronic cross-sections

Post-LHC update of Godbole, Grau, GP, Srivastava (GGPS) 2009 figure
Updating
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• Results of simulations of photon showers with AIRES from

• 2 Models for $\gamma p$ total cross-section at very high energies
    $\rightarrow$ present in AIRES
  – Godbole, Grau, Pancheri, Srivastava (GGPS)
    $\rightarrow$ Bloch-Nordsieck (BN) model implemented in AIRES by Sciuto and Garcia-Canal
A selection of models for $\gamma p$

- Block and Halzen: 2001
  \[ \ln^2 \left( \frac{E}{m_p} \right) \]
- GGPS for photons 2008
  - Fletcher Gaisser Halzen for $\gamma p \rightarrow X$
  - Eikonal minijet driven with Infrared gluons for $pp$ (see slides later)
- Eikonal minijet with form factors
- Aspen model PRD 1999 “QCD inspired”
  Block, Gregores, Halzen, GP

Extension of mini-jet model to photoproduction


\[ \sigma_{\text{tot}}^{\gamma p} = 2P_{\text{had}} \int d^2b \left[ 1 - e^{-n_{\gamma p}(b,s)/2} \right] \]

\[ n_{\gamma p}(b, s) = n_{\gamma p}^{\text{soft}}(b, s) + n_{\gamma p}^{\text{hard}}(b, s) \]

Fletcher, Gaisser, Halzen, Phys.Rev. D45 (1992) 377

\[ P_{\text{had}} = \sum_{V=\rho,\omega,\phi} \frac{4\pi\alpha}{f^2_V} \]

Mimics details of photon fluctuation into a hadron

\[ n_{\gamma p}^{\text{hard}}(b, s) = A_{BN}(b, s)\sigma_{\text{jet}}^{\gamma p}(s)/P_{\text{had}} \]

LO current PDFs

resummation

Input from our pp model with infrared gluon resummation for mini-jet
The model for pp

• Mini-jets with pQCD $\rightarrow$ DGLAP LO PDFs
  Grau,GP,Srivastava PRD1999
  Godbole, Grau,GP, Srivastava PRD2004

• A (democratic) resummation scheme to probe the infrared limit for soft gluons
  Corsetti, Grau,GP,Srivastava 1996
  Grau, GP, Srivastava PRD 1999

• Maximally allowed singularity
  Nakamura, GP, Srivastava PLB 1984
All total cross-sections rise... but not too much (Froissart dixit)

What generates the rise? Low-x parton collisions

\[ S^\varepsilon \quad \varepsilon \sim 0.3 \]

How to go from hard to soft?

What tames the rise into a Froissart-like behavior?

A cut off obtained by [embedding into the eikonal]
the acollinearity induced by IR kt-emission

Cline, Halzen & Luthe 1973
Gaisser, Halzen, Stanev 1985
G.P., Y.N. Srivastava 1986
Durand, Pi 1987
Sjostrand, van Zijl 1987
...

Photon 2017, CERN
Soft gluon emission introduces acollinearity

Acollinearity reduces the collision cross-section as partons do not scatter head-on any more, also explained as the gluon cloud becoming too thick for partons to see each other: *gluon saturation*
Our model for pp

1. Mini-jet cross-sections
   $\text{Pt} \sim 1 \text{ GeV}$

2. Dress with Initial State
   Infrared Radiation

3. Eikonalize
   \[ \sigma_{total} = 2 \int d^2 b \left[ 1 - e^{-\chi(b,s)} \right] \]
The infrared region in hadronic collisions → large distance QCD

- To access the infrared region and tame the rise of total x-sections from minijets contributions, we use a resummation procedure different from the usual LLA or Sudakov

- The Bloch and Nordsieck theorem on infinite “photon” emission + Energy Momentum Conservation

- Maximally allowed divergence of the coupling of soft gluons to quarks
From Bloch Norsdieck (1937) (B-N) theory of emission from a classical source to our proposal for maximally allowed infrared singularity in QCD (1984)

- F. Bloch and A. Nordsieck
  - Neglecting recoil \( \rightarrow \) Poisson distribution of soft photons (gluons) emitted
    \[
    \frac{[\bar{n}_k]^n_k}{n_k!} e^{-\bar{n}_k}
    \]
    - Only emission of infinite number of soft photons (gluons) is finite

- B. Touschek
  - 1952 with W. Thirring : covariant formulation
  - 1968 (with E.Etim+GP) : summation to all orders

\[
d^4 P(K) = \sum_k P(\{n_k\}) \delta^4(\sum_k k n_k - K) d^4 K
\]

\[
\delta^4(\sum_{n_k} n_k k - K) = \int \frac{d^4 x}{(2\pi)^4} e^{-i K \cdot x} e^{\sum n_k k \cdot x}
\]

- Exchange Sum (in k) with Product (on \( n_k \))
Semi-classical and democratic (no branching or ordering) summation

\[ d^4 P(K) = \frac{1}{(2\pi)^4} \int d^4 x \, e^{-h(x) - iK \cdot x} \]

\[ h(x) = \sum_k (1 - e^{i k \cdot x}) \bar{n}_k \rightarrow \int d^3 \bar{n}_k [1 - e^{i k \cdot x}] \]

→ Integrate over \( K_0 \) and \( K_3 \)

\[ \Pi(K_t, s) = d^2 K_t \int d^2 b e^{-iK_t \cdot b - h(b, s)} \]

→ \( h(b, s) \) ?

QED or QCD: integrand can be finite or singular but to be finite → integrable is the basic condition
Applied to K-t resummation in QCD

\[ h^{(PP)}(b, s) = \frac{4}{3\pi^2} \int_{M^2}^{Q^2} d^2 k_\perp [1 - e^{ik_\perp \cdot b}] \alpha_s(k_\perp^2) \frac{\ln(Q^2/k_\perp^2)}{k_\perp^2} \]

Our Proposal (ZPC 1984)

\[ M^2 \to 0 \]
\[ \alpha_{IR}(k_t) \propto \left[ \frac{\Lambda}{k_t} \right]^{2p} \]
\[ p < 1 \]

G. Parisi R. Petronzio 1979 and Dokshitzer, Diakonov, Trojan 1978
With Asymptotic Freedom

Dropped in DDT, Phys. Lett. B79, 269
We model the impact parameter distribution as the Fourier-transform of ISR soft $k_t$ distribution and thus obtain a cut-off at large distances: Froissart bound?

$$A_{BN}(b, s) = N \int d^2K_\perp \ e^{-iK_\perp \cdot b} \frac{d^2P(K_\perp)}{d^2K_\perp} = \frac{e^{-h(b,q_{\text{max}})}}{\int d^2b \ e^{-h(b,q_{\text{max}})}}$$

$$h(b, E) = \frac{16}{3\pi} \int_0^{q_{\text{max}}} \frac{dk_t}{k_t} \alpha_{\text{eff}}(k_t) \ln\left(\frac{2q_{\text{max}}}{k_t}\right)[1 - J_0(bk_t)]$$

$$\alpha_{\text{eff}}(k_t \to 0) \sim k_t^{-2p}$$

$$A_{BN}(b, s) \sim e^{-(b\bar{\Lambda})^{2p}}$$

$q_{\text{max}}$ fixed by single gluon emission kinematics
1. Calculate mini-jet cross-section
Choosing densities and ptmin

\[ \sigma_{mini-jet} \sim s^\epsilon \]
\[ \epsilon \sim 0.3 - 0.4 \]

2. Calculate qmax: single soft gluon upper scale, for given PDF, ptmin

\[ q_{max} \sim p_{tmin} \]
\[ \lesssim 2 - 3 \text{ GeV} \]

3. Calculate impact parameter distribution for given qmax and given infrared parameter p

\[ \chi(b, s) = \chi_{low\ energy} + A(b, q_{max})\sigma_{jet} \]

4. Eikonalize

\[ \sigma_{total} = 2 \int d^2b[1 - e^{-\chi(b, s)}] \]
The total cross-sections in pp

$\sigma_{\text{total}}$ (blue), $\sigma_{\text{inel}}$ (red), $\sigma_{\text{el}}$ (green), $\sigma_{\text{SD}}$ (purple) and $\sigma_{\text{DD}}$ (black) data

- Telescope Array
- Auger
- ALICE
- ATLAS
- TOTEM (L-indep.)
- CMS
- Cosmic Ray data
- $p\bar{p}$ accelerator data
- $pp$ accelerator data

BN-model-one-channel

Top MSTW08: $p_{t\text{min}}=1.3\ GeV, p=0.66$

Bottom GRV: $p_{t\text{min}}=1.2\ GeV, p=0.69$

$\sigma_{\text{tot,inel,el}}$: empirical model

PRD 88 (2013) 094019
\( \gamma p \) and \( \gamma - \text{air} \)

Photoproduction data before HERA
- ZEUS 96
- H1 94
- ZEUS BPC 95
- Vereshkov 03

BN-\( \gamma \) model, \( p_{\text{min}} = 1.3 \text{ GeV} \)
- Top: GRS(\( \gamma \)), MRST(\( p \)), \( p = 0.6 \)
- GRS(\( \gamma \)), GRV(\( p \)), \( p = 0.71 \)
- Lower: GRS(\( \gamma \)), GRV94(\( p \)), \( p = 0.75 \)

Updated with newer PDFs

5/24/17

Photon 2017, CERN
Longitudinal development from $10^{19}$ eV photon showers

--- standard cross sections implemented in AIRES

Electrons and positrons  muons

![Graph showing electron and positron distribution](image1)

![Graph showing muon distribution](image2)
Longitudinal shower development of hadrons from our model input and comparison with Block Halzen fit

**RED**: Using central curve from our model for proton - γ cross-section into AIRES simulation

**GREEN**: BH model lower fit (both fit are consistent with present HERA data)

**GREY**: pre-LHC QSGJET-II

For BN

Green: standard cross sections implemented in AIRES
Kaon longitudinal development, 60 degrees inclined – a difference confirmed by new simulations

Using QGSJET post-LHC.
Work in progress

• CR :
  – Update the simulations
  – Inspect transition \( \gamma p \rightarrow \gamma - air \)

• Model for survival probabilities in pp
• Diffraction?

• Photon-photon \( \rightarrow \) see Rohini’s talk
Studying showers with this model and post-LHC Aires

- Kaon Longitudinal development indicates a difference:
- QGSJET pre-LHC: 20% difference between simulations with BH and our model
- QGSJET post-LHC: simulated spectrum still shows difference between using our gamma-p or BH model
A maximally allowed singular expression for coupling of zero momentum gluons

$$\alpha_{strong}(k_t^2) = \frac{1}{\ln[1 + \left(\frac{k_t^2}{\Lambda^2}\right)^{b_0}]}$$

Photon 2013

arXiv:1403.8050

D. Fagundes, A. Grau, GP O. Shekhovtsova and YSrivastava
Muon longitudinal development, 60 and 80 degrees inclination

- Green is BH with post-LHC
- Red is BN with post-LHC QGSJET
- Grey is BN with pre–LHC QGSJET

→ no change in simulation of longitudinal development for muons for BN
→ BN model gives higher number of particles both pre-LHC and post-LHC
Pion longitudinal development, 60 degrees

- Green is BH post-LHC
- Red is BN with post-LHC QGSJET
- Grey is BN with pre-LHC QGSJET

→

- Slightly higher for pre-LHC
- Still BN higher than BH
Shapes of shower observables

With F. Cornet, C.A. Garcia Canal, A. Grau and S. Sciutto

Photon-proton

Photon-air

Photoproduction data before HERA
- ZEUS 96
- H1 94
- ZEUS BPC 95
- Vereshkov 03

BN-\(\gamma\) model, \(p_{\text{min}}=1.3\) GeV
Top: GRS(\(\gamma\)), MRST72(p), \(p=0.6\)
GRS(\(\gamma\)), GRV(p), \(p=0.71\)
Lower: GRS(\(\gamma\)), GRV94(p), \(p=0.75\)

Block-Halzen \(\log^2\left(\frac{E_{\gamma}}{m_p}\right)\)
fit1 (upper) and fit2 (lower)

“old” = standard cross sections implemented in AIRES and other SP
How does our (GGPS) pp model for the total cross-section differ from other models?