LHCb/LHCf/TOTEM inputs for astrophysics

Valery Zhukov
on behalf of the LHCb collaboration
**LHC & Astrophysics**

**Physics:**
- BSM (DM)
- LFV, CPV...
- SM (QCD)

**Experiments:**
- ATLAS
- CMS
- TOTEM
- LHCb
- SMOG
- ZDC+ALFA
- Castor
- ALICE
- Others: SPS(NA49,58,61..), RHIC, HERA, Tevatron, ...

**Astro(Cosmic Rays):**
- DMA (BSM)
- CR spectra, composition, gamma, neutrino Sources, ...

**Space:**
- AMS02, FERMI, PAMELA, DAMPE, CALET,...

**EASground:**
- Auger, TA, HAWC, HiRes, Yakutsk, ...

**Cherenkov Arrays (CA):**
- Hess, Magic, Veritas, ...

**Neutrino:**
- IceCube, Antares, ...

**CR interactions = forward physics**
- soft: low $Q^2$, non pQCD contributions
- diffractions: large $x_F$ i.e. low-$x$(saturation) and large-$x$(gPDF)
- scalings violations: Bjorken, Feynman, KNO
- nuclear collective effects

1. Data parameterization.
   with some assumptions on factorization and scalings

2. Reggeon Field Theory (RFT) + pQDC
   - EPOS, QGSJET, SYBILL, DPMJET, ...
   - more solid theory motivations and predictions
   - Check parameterizations with RFT models that are verified with the LHC data
Two modes of operation:

**I. Collisions:** pp(\(\sqrt{s}=0.9, 7, 13\) TeV), pPb(5 TeV)

**II. Fixed Target** (LHCbSMOG) p(2.5, 4, 6.5 TeV) or Pb(2.5 TeV) beams: pHe(\(\sqrt{s}=87, 110\) GeV), pNe(69, 110), pAr(110), PbAr(69)

- **Beam1**
  - Fixed-target fiducial ~800 mm
  - Whole gas region ~40 m
  - Gas in the beam pipe ~2 \times 10^{-7} \text{ mbar of He, Ne, Ar...}

- **Beam2**
  - System for measuring the overlap with gas
  - Not all bunches are colliding
  - \(\mathcal{L} \sim 0.5 \text{ mb}^{-1}\text{s}^{-1}\) per non coll. bunch

- Gas pumped out

Collisions:
- pp(\(\sqrt{s}=13\) TeV) for ATLAS, CMS, ALICE
- p-SMOG(\(\sqrt{s}=110\) GeV)

Fixed Target:
- pHe \(\rightarrow\) pX

\[ x_F < 0 \] target fragmentation
\[ x_F > 0 \] projectile fragmentation
**Experiments: LHCf/TOTEM**

**LHCf**
- 2 arms
- Double-tower calorimeter: tungsten+GSO 44X₀, 1.6 λ
- 4 tracking layers (200μm)

**TOTEM**
- 2 arms
- Roman pots (RPS): Δ_{beam} ~1mm (Silicon)
- |η| > 8.4 neutral calorimetry and tracking:
  - γ: pγ > 100 GeV/c
  - π0 (2γ): p_{π0} > 200 GeV/c
  - n: p_{n} > 500 GeV/c
- Collisions:
  - pp √s = 0.9, 2.8, 7, 13 TeV
  - pPb √s = 5, 8 TeV
- Standalone and with ATLAS

- |η| > 3.1 tracking:
  - p_T > 40 MeV/c (T2)
- Collisions:
  - pp √s = 2.8, 7, 8, 13 TeV
  - Standalone and with CMS

**CERN-LHCC-2006-004**

**CERN-LHCC-2014-021**
Indirect Dark Matter searches

DM Annihilations:
\[ \chi \chi \rightarrow b \bar{b}, t \bar{t}, e^+ e^-, \mu^+ \mu^-, \tau^+ \tau^-, \nu \bar{\nu}, \gamma \gamma, W^+ W^-, ZZ, Z\gamma \ldots \]

Fluxes of secondary CR from AMS02:

DMA excess in secondary CR: \( \bar{p}, e^-, \gamma, \nu \)
- monopeaks for \( \nu \nu, \gamma \gamma, Z\gamma \)
- also antideuterons \( \bar{d} \) from DMA, via coalescence \( \bar{p} + \bar{n} \)

Diffusive Gamma FermiLAT:

Uncertainties in secondary CR fluxes, \( \gamma, \nu \):
- nuclear interactions
  - CR source spectra
  - Propagation
  - InterStellarMedia:
    - InterStellarGas(ISG) + InterStellarRadiationField(ISRF)
- Astrophysical uncertainties can be constrained by using other CR fluxes and astro data (+nuclear uncertainties for propagation and Elosses)
Antiprotons in CR: nuclear uncertainties

Interaction of CR(p,He,C,...) with ISG(H1,HII,H2+ 10% He):

\[ CR + ISG \rightarrow \bar{p} + X \]

Many parameterizations of \( \sigma_{pp(\bar{p}X)} \):
- Tan and Ng 1983 (Galprop)
- Duperray et al., 2003
- Di Mario et al, 2014
- Tomassetti, Oliva 2017
- Winkler 2017
- or MC RFT, eg. QGSJET, EPOS:
  - Kacherliess et al, 2015

using mostly ISR data at \( \sqrt{s} \sim 17 \) GeV

Assumptions in parameterizations:
- scaling violations (\( \sigma_{\text{inel}}, n_{\bar{p}}, p_{\text{T}} \))
- \( \bar{p} \) from hyperons \( \Lambda, \Sigma \) (hyperon/prompt ~0.3)
- \( n \) production, isospin invariance (\( n/\bar{p} \sim 1 \)) ....

correlations in parameterization can be missed...

Need validation of parametrization and RFT models with data at high energies
Prompt antiprotons LHCbSMOG

in \( pHe\rightarrow \bar{p}+X \) at \( \sqrt{s}=110.4 \text{ GeV} \)

### Ratio of LHCb data to different model predictions for prompt \( \bar{p} \) in \( p_\perp-p \) plane

**LHCb-CONF-2017-002**

Underestimation of prompt \( \bar{p} \) production in EPOS-LHC, but overall higher CR \( \bar{p} \) flux due to isospin violation

eg., see Feng, et al. arXiv:1701.02263

AMS02 CR antiprotons and RW parameterization with the fit to B/C for propagation
No DMA.

- **Increase of \( \bar{p} \) production** and reduction of nuclear uncertainties to \( \sim 10\% \), little room for DM
- **Good agreement between QGSJETII-4m and RW parametrization**

Only prompt \( \bar{p} \) is measured, still need: \( pHe\rightarrow \bar{\Lambda} \)

Isospin symmetry violation \( \Delta_{IS}=\bar{n}/\bar{p}-1 \), need Deuterium target

big uncertainties; 0.1(NA49), 0.4(Fermilab), \( \) in EPOS-LHC (0.5)?
**Diffusive galactic gamma rays: nuclear uncertainties**

**CR+ISG → π₀(γγ)+X**

dominant contribution for galactic plane region \(|b|<10^o\) and \(E_γ<10^9\) eV
Inverse Compton for larger \(b\) and \(E\)
\(e^±+ISRF → e^±+γ\)

Parameterizations of \(σ_{pp(πX)}\):
- Stephens, Badhwar 1980 (Galprop)
- Dermer 1986
- Kamae et al., 2006 (used in Fermi)
- Huang et al., 2007
- Sato et al, 2012 (with LHC data)
- Kafexhiu et al 2016
- or MC, e.g. QGSJET:
  - Kacherliess, Ostapchenko 2014

Delta(1232) \(→ γ+X\), RFT models are not reliable in resonance region <10 GeV, parameterization is better
hadronization of diffraction(~20%) is not well parameterized, RFT models should be better

>30% uncertainties in \(pp(π_0)\) in emissivity
The uncertainties in \(F_γ^{CR} \otimes I\) are large due to uncertainties in the \(F_γ^{CR}\) galactic CR (p,e,..) spectral shapes

Fermi excess (bubble) hard to explain with \(π_0(γγ)\) uncertainties... But:
- The \(π_0\) is important for \(E_γ=0.1-1000\) GeV in dense ISG regions.
- Check of galactic model: can constrain remote galactic \(F_γ^{CR}: F_γ^{CR} \otimes σ_γ \otimes ISM\)
and compare with local \(F_γ^{LIS}_{CR}\)
Gamma with LHCf

$pp \rightarrow \gamma X$ at 7 and 13 TeV, and different models

Diffraction: ratio of Gamma with ATLAS charged veto($|\eta|<2.5$)/all

arXiv:1703.07678
pp → π₀X with LHCf

π₀(γγ) p_T at 7TeV

Scalings of π₀ production in forward region

- Good agreement of forward pp → γX spectra and π₀ distributions with QGSJETII and EPOS-LHC
- Some deviations for diffractive contribution, important for γ emissivity, QGSJETII4 looks underestimated (unexpected)
- Large uncertainties for harder γ and more central regions, more data needed.
- Forward scaling holds at ~20% accuracy in 0.6-7TeV range compatible with QGSJETII and EPOS-LHC evolutions
Atmospheric Neutrino: nuclear uncertainties

Intrinsic Charm (IC)
non pQCD charm contribution
to PDF at large $x>0.1$, eg.:
BHPS model Brodsky et al, 1980
SEA model Dulat et al, 2013
Observations: EMC, ISR, Tevatron, HERA...
EMC, NPB461, 181, 1996
D0, PLB719, 354, 2013
CDF, PRL111, 2013....

but no clear evidence

Low-x with charm in pp collisions at LHCb
Large-x at LHC, two possibilities:
• in pp collisions via Z/W+c (ongoing)
• in LHCbSMOG via open charm $D, \Lambda_c$

Update of atmospheric $\nu$ flux calculations
(using LHCb charm and bottom production)
Interactions of astrophysical $\nu$ with ISG
(low-$x$ gPDF improvement, with LHCb)
Intrinsic Charm contribution in atmospheric $\nu$
(disentangle IC and CNM effects by simultaneous observation of the charmonium $J/\Psi$ and open charm $D, \Lambda_c$)

At high energy open charm production is the main source of uncertainties (>50%)
Neutrino and low-\(x\) physics with LHCb

Update atmospheric \(\nu\) production using LHCb charm and bottom production

**Open charm LHCb measurements 13TeV**

\[
\sigma(pp \to c\bar{c}X) \text{ [\(\mu b\)]}
\]

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Atmospheric neutrino flux at NLO QCD (color dipole, BFKL,nPDF) using LHCb charm production (with different CR spectra)

30% reduction of atmospheric \(\nu_\mu\) (i.e larger astro \(\nu_\mu\) signal)

**Interactions of UHE CR \(\nu\):** \(\nu + ISG \rightarrow lX\): \(x \sim M_w^2/m_p E_\nu\), i.e. low-\(x\) PDF

\(gPDF\) (HERAPDF) fit with HERA data and with \(D,B\) mesons LHCb 7-13TeV

**LHCb:** Charm, Bottom production in pp
\(x - M_c^2/s < 10^{-5}\)

Still to be included:
Low mass DY (LHCb, arXiv:1511.07302)
CentralExclusiveProduction (LHCb-CONF-2012-013)
also see arXiv:1409.4785 for CEP

Uncertainties for \(gPDF\) \(x < 10^{-5}\) are down to \(\sim 10\%\)

**PROSA NLO FFNS fit: HERA DIS**

**PROSA NLO FFNS fit: HERA DIS + LHCb norm.**

**Recombination:** \(gg \rightarrow g\)

**Splitting:** \(g \rightarrow gg\)

Before LHC, arXiv:0806.0418

Bhattacharya et al arXiv:1607.00193

BPL

30% reduction of atmospheric \(\nu_\mu\) (i.e larger astro \(\nu_\mu\) signal)

**atmospheric \(\nu_\mu\) production using LHCb charm and bottom production**

**Open charm LHCb measurements 13TeV**

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Intrinsic Charm with LHCbSMOG in pAr at $\sqrt{s}=110.4$ GeV

**D^0**

- LHCb preliminary
- $\sqrt{s_{NN}} = 110$ GeV pAr
- $x_2 = \frac{M_{D^0}}{\sqrt{s}} \exp(-y^*)$
- LHCb data
- Pythia8 CT09MCS (no IC)

**J/$\Psi$**

- LHCb preliminary
- $\sqrt{s_{NN}} = 110$ GeV pAr
- $x_2 = \frac{M_{J/\Psi}}{\sqrt{s}} \exp(-y^*)$
- LHCb data
- Pythia8 CT09MCS (no CNM)

**Nuclear modification Pb of gluon nPDF**

- $R_{Pb}(x,Q^2 = 10 \text{ GeV}^2)$
- EMC
- nCTEQ15
- EPPS16

No significant IC contribution

ongoing comparison with theory
Cross sections with TOTEM

\[ \sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}} \{ \sigma_{\text{diff}}(SD+DD+CD) + \sigma_{\text{NonDiff}} \} \]

**TOTEM decisive measurements with 3 methods**

<table>
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<th>Method</th>
<th>Measurements at ( \sqrt{s} = 7 \text{ TeV} )</th>
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<tr>
<td>( \sigma_{\text{tot}} )</td>
<td>![Graph showing total cross section]</td>
</tr>
<tr>
<td>( \sigma_{\text{el}} )</td>
<td>![Graph showing elastic cross section]</td>
</tr>
<tr>
<td>( \sigma_{\text{inel}} )</td>
<td>![Graph showing inelastic cross section]</td>
</tr>
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</table>

Increasing rise driven by pomeron \( \epsilon = 0.08 \text{ (1 TeV)} \rightarrow \sim 0.12 \text{ (10 TeV)} \)

\[ \sigma_{\text{tot}} \sim \sigma_{\text{p}} s^{-0.5} + \sigma_{\text{p}} s^\epsilon \] Donnachie, Landshoff, 1992

\[ \sigma_{\text{tot}} = c + a s^{-0.5} + b \ln^2(s) \] COMPETE fit triplepole RRP, and more...

\[ \sigma_{\text{el}} / \sigma_{\text{tot}} \] will at stop at black disk ½ limit?

\[ \sigma_{\text{el}} / \sigma_{\text{tot}} \] will at stop at black disk ½ limit?

**Big improvement for all models after TOTEM** \( \sigma_{\text{tot}}, \sigma_{\text{inel}}, \sigma_{\text{el}} \) is important for all exclusive productions in all models, increase secondary CR yields baryons/mesons inelasticity, nuclear effects

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Diffraction with TOTEM

Diffraction contributes ~50% for $x_F \rightarrow 1$ in CR interactions, important hard to simulate, important source of models uncertainties.

Pseudorapidity: Inclusive and SD enhanced in TOTEM+CMS

Diffraction versus forward RG $\Delta \eta^F$ ATLAS(arXiv:1201.2808) and model

d$x/d\Delta \eta^F$ (mb)

KMR, arXiv:1402.2778
$\sqrt{s}=7$ TeV

Diffraction extrapolated by Pythia8-MBR from visible $\lg \xi_y [-5.5,-2.5]$ to larger mass range:

CMS, arXiv:1503.08689 $\xi_y<0.05$:

$\sigma_{DD} = 5.17 \pm 0.08$ (stat) $^{+1.62}_{-0.51}$ (extrap) mb,

$\sigma_{SD} = 8.84 \pm 0.08$ (stat) $^{+1.17}_{-0.37}$ (extrap) mb

TOTEM(preliminary Kaspar, ISMD17) $\xi_y<0.02$:

$\sigma_{SD} = (9.1 \pm 2.9)$ mb.

agreement on SD in extrapolated mass range, but low-mass diffraction(LMD) is neglected in P8MBR

Large underestimation of $d\sigma_{SD}/d\eta$ for QGSJETII or RG contamination?

Extrapolation with P8-MBR and QGSJET

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More diffraction

LHCf: Neutrons

Comparison of CMS SD and QGSJETII SD and SD+DD in the visible mass range

Ostapchenko, arXiv:1402.5084

\[
\frac{d\sigma}{dE} \left( \text{mb/GeV} \right)
\]

CMS
SD QGSJET
SD+DD QGSJET

KMR, arXiv:1402.2778

<table>
<thead>
<tr>
<th>Mass interval (GeV)</th>
<th>(3.4, 8)</th>
<th>(8, 350)</th>
<th>(350, 1100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prelim. TOTEM data</td>
<td>1.8</td>
<td>3.3</td>
<td>1.4</td>
</tr>
<tr>
<td>CMS data</td>
<td>4.3</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>Present model</td>
<td>2.3</td>
<td>4.0</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Tension between CMS, TOTEM and models on SD in the measured mass range

Similarity with gamma, overestimated low-mass SD and underestimated high-mass SD

S. Ostapchenko, ISMD15

LHCf and CMSTOTEM results on diffraction are important for CR interaction and EAS modeling, but diffractive mass distribution is puzzling.

more measurements on SD, DD, especially in the low mass range are very needed, decomposition of different contributions using vetos
Nucleus interactions in CR

**Cold Nuclear Matter effects:**
- Initial state energy losses
- $k_T$ spread ('Cronin' effect)
- Final state interactions
- Collective effects
  - Shadowing, antishadowing, EMC, Fermi motion

**CR:** Peripheral interactions (high $b$, low centrality, low $Q^2$), forward (low-$x$/high-$x$), light targets

**LHC:** Central collisions, heavy ions (Pb), high density, good for QGP

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**LHCb modification factors vs $y$ for prompt $J/\psi$, $\psi$, and $D^0$ in $pPb(PbP)$**

- Some advance in nPDF for heavy ions
  - but not much data on low centrality and light targets, large uncertainties
- Collective effects in RFT models: some are included (EPOS-LHC)

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**Comparison of nPDF of preLHC EPPS09**

- $p_T < 10$ GeV/$c$
- $p_T > 14$ GeV/$c$

**Experimental data:**
- DIS and DY in $p,l,\nu+A$ (NMC, SLAC, FNAL, RHIC) → EPPS09
- $W,Z$, dijets in $pPb$ (CMS, ATLAS, ALICE) → EPPS16
- Charms in $pPb$, $pA$ FT (LHCb, SMOG) →?

- More data, more uncertainties....
Summary

Forward measurements in LHCb/LHCf/TOTEM are used to largely reduce uncertainties in antiprotons, gamma and neutrino production in CR interactions, relevant for indirect (and direct) DM searches, and Cosmic Ray physics. Mostly used to improve exclusion DMA limits in antiprotons and gamma.

- reduced uncertainties in prompt $pA \rightarrow \bar{p}X$
- improvement of $pA \rightarrow \pi_0 X$ prediction
- improvement of $pA \rightarrow \nu X$ calculations
- verification of forward scaling
- constrained intrinsic charm contribution
- improved low-x gPDF fit
- constrained diffraction contribution at high energies
- improvement of RFT models for EAS simulations
- ...

ongoing:
- $p$ from hyperons
- isospin n/p asymmetry
- (anti)baryons/mesons ratios
- charm production in diffraction
- diffraction puzzle
- nuclear effects on lighter targets
- ...

More measurements on diffraction and light ions can be expected with LHCbSMOG+HeRS HC eL and TOTEM with Run2 data.
Backups
Models

EPOS
Werner, Liu & Pierog, PRC74 (2006) 044902

- Gribov-Regge based models for hard and soft (Pomeron) parts
- DGLAP for hard part, own PDF
- Enhanced diagrams, multipomeron interactions, screenings
- Can be used to simulate soft and hard up to high energies in central and forward regions

- Tuning to data, parameterizations
- MPI with energy conservation
- Collective effects for nucleus
- Special treatment for diffraction and nonlinear effects
- Resonance production included

QGSJET-II
Ostapchenko, PRD83 (2011) 0114018

- Theory motivated, almost no parameters ($Q_0$ cutoff scale)
- Diffraction, elastic and inelastic unified approach
- High and low mass diffractions
- Not (many) resonance production

SIBYLL
Ahn, Engel, Gaisser, Lipari & Stanev, PRD80 (2009)

- RFT based, for cross sections, used for EAS.
- Separate hard and soft treatment, String fragmentation (similar to Pythia), external PDF
- Only high mass diffraction
- Non linear effects via running $Q(s)$
- Mostly for central production
- Limited to light ions

DPMJET
S. Roesler, R. Engel, J. Ranft

- RFT based, Separate hard-soft, external PDF,
- Limited collective effects, used in GEANT, and HI

complimentary approaches and cross checks
LHCbSMOG

LHCbSMOG+HeRSCHeL
HighRapidityShowerCounterforLHCb
up/downstream veto scintillators

Primary vertex z reconstructed with Beam1(be), Beam2(eb), Collisions(bb), and without beams(ee)

Rosenbluth pe- elastic scattering cross section (<1% accuracy):

$\mathcal{L} = \frac{N_e}{Z_{He} \times \sigma_{p-e^-} \times \epsilon}$

~6% accuracy in absolute Lumi

SD high-mass on light targets at ~110 GeV
Charm with LHCbSMOG and IC in $\nu$

Other charm resonances in the pAr SMOG data sample (data17h)

$LHCb$-CONF-2017-001

**D**$^+$
(c$\bar{d}$)

~1000 candidate

$\Lambda_c^+$
(udc)

~50

**D**$^{*+}$
(c$\bar{d}$)

~2300

**D**$^+_s$
(c$\bar{s}$)

~130

---

**Effect of IC on atmospheric neutrino flux**

IceCube
HE neutrino cant be explained by IC of Atmospheric contribution

S.Brodsky et al. arXiv:1607.08240

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$\Lambda_c^+ \rightarrow p K^- \pi^+$

$D^+_s \rightarrow K^- K^+ \pi^+$

$D^+ \rightarrow K^- \pi^+ \pi^-$

$D^* \rightarrow D^0 \pi^+$

$D^0 \rightarrow K^- \pi^+ \pi^-$

$D^+_s \rightarrow K^- K^+ \pi^+$

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**Effect of IC in $D$ and $\Lambda_c$**

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Energy Flow with LHCf and LHCb

Energy flow **gamma** LHCf pp 13TeV

Energy flow **charged** LHCb pp 7TeV and preLHC models

Energy flow **neutrons** LHCf pp 13TeV

Energy flow **neutrons** LHCf pp 7TeV

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Energy flow vs. $\eta$ distr. of p-p $\sqrt{s}=7$[TeV]

MC QGSJETII
LHCf pions spectra and cross sections

Forward $\pi^0$ Pz and $P_T$ LHCf pp 7TeV

LHCf, arXiv1507.08764

Cross sections $\pi^0$ in $P_T$-$P_Z$ LHCf pp 7 TeV and EPOS-LHC, QGSJETII4, and SYBILL2.1

Ratios MC/Data

$LHCf$, T.Sako, ISVHECRI2016

Good agreement for QGSJETII-4
Antiprotons: $\sigma_{pp(\bar{p}X)}$ parameterizations and DMA

Scaling violations for $\bar{p}$ in RW parameterization

Winkler
JCAP 1702 (2017)

RW parameterizations n/p and $\Lambda/p$

EPOS and QGSJET for $p$ CR prediction

AMS02 $\bar{p}/p$ total uncertainties and different DMA mass hypothesis $M_{dm} = 500$-$1500$ GeV

Massi, xsrc2017
**Diffraction**

TOTEM and CMS SD extrapolated

How to extrapolate to different mass regions?

Comparison of **QGSJETII-04**, **EPOS-LHC** and **PYTHIA8-MBR** (tuned to CMS data no LMD)

Mass distribution $M^{3/2}/s$ for low and high mass SD

$\xi < 0.05$

Kaspar, ISMD17

Ostapchenko, arXiv1103.5684

**pp 7 TeV**

RG in minimum bias events or fluctuation of hadronization in inelastic production?
EAS models

EAS simulations:
- CR spectra and composition for $E > 10^{12}\,\text{eV}$ important for CR model and DMA search
- Test of interaction models: $\bar{X}_{\text{max}}$, $\bar{X}^\text{nl}_{\text{max}}$, $\sigma(X_{\text{max}})$ degeneracy of interactions and composition

$\bar{X}_{\text{max}}$ data and prediction for $p$ and Fe CR composition

Muon excess in EAS $>10^{17}\,\text{eV}$

large improvement on $\sigma_{\text{inel}}$ and less for $\sigma_{\text{diffr}}$, $K_{\text{inel}}$, and pp to pA recalculations

$X_{\text{max}}$ deeper than $X^\mu_{\text{max}}$ (heavier composition with $X^\mu_{\text{max}}$) can be due to large p/n production and/or larger $\pi$-air diffraction. Larger inelasticity, i.e. smaller diffraction for pions would shift $X^\mu_{\text{max}}$ to heavier component.
Cross sections

$\sigma_{\text{total}}$ (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
- $pp$ accelerator data
- $\bar{p}p$ accelerator data

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

arXiv:1610.100038