Forward physics at the LHC: within and beyond the SM

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São Miguel das Missões, RS, Brazil

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(*) arXiv:0708.0551 [hep-ex]
Why forward physics?

- Many interesting (mostly color-singlet) scattering process at the LHC are characterized by forward particle production:

  **QCD:** elastic, diffractive interactions

  ![QCD diagram](image)

  **QCD:** low-$x$

  ![QCD low-x diagram](image)

  **Higgs:** VBF, central exclusive

  ![Higgs diagram](image)

  **EWK:** excl. dileptons, gauge couplings

  ![EWK diagram](image)

  **Beyond SM:** MSSM Higgs, elastic grav., ...

  ![Beyond SM diagram](image)
Forward physics “menu”

1. Diffractive & elastic collisions:
   - Total cross-sections: elastic scatt., single/double diffraction
   - Soft: Gap survival dynamics, p-p underlying event, ...
   - Hard: dijets, vector-bosons, heavy-Q, QQbar, ...

2. Low-x QCD:
   - Parton saturation, non-linear QCD evolution, multi-parton scatt. … via:
     (i) forward QQ, jets (p-p, p-A), (ii) photoproduction (γ-p, γ-A interactions)

3. UHE Cosmic-rays physics:
   - Forward energy & particle flows (p-p, p-A, A-A)
   - Exotica: “Centauro” events (DCCs ?, strangelets ?)

4. EWK (two-photon, γ–W) interactions:
   - Absolute luminosity (~3% QED precision) via: pp → γγ → p ℓ+ℓ− p
   - Triple (quartic) gauge boson couplings via: pp → γp → pnW (γγ → ZZ,WW)

5. Higgs and beyond SM:
   - Vector-Boson-Fusion Higgs
   - Central exclusive (SM, MSSM) Higgs
Forward capabilities:
ATLAS, CMS/TOTEM,
ALICE, LHCb
The LHC experiments

- ALICE
- ATLAS
- CMS
- TOTEM / (FP420)
- LHCf / (FP420)
The LHC experiments: \((p_T, \eta)\) acceptance

- Particle production at LHC over \(\Delta \eta \sim 2 \times \ln(\sqrt{s})/m_p \sim 20\)
- All phase-space virtually covered (1\textsuperscript{st} time in a collider)

\[ p_T^{\text{max}} = \sqrt{s}/2 \exp(-\eta) \]

[plans to instrument also the \textit{TAS} (6.6<|\eta|<8.3) 20-cm slot with quartz-fibers]
Forward physics plans at the LHC

1. CMS (Forward-EOI submitted Jan.'04, CMS/TOTEM LOI LHCC-2006-039):
   • CASTOR, ZDCs, TAS (under consideration), +TOTEM
     ➔ Soft&hard diffraction (w/ TOTEM or rapgaps), low-x QCD, cosmic-rays, $\gamma-p$, $\gamma-A$, $\gamma-\gamma$

2. ATLAS (Forward-LOI submitted Mar.'04):
   • ALPHA RomanPots (240 m, LOI R&D), LUCID, ZDC (approved 2007)
     ➔ Total p-p cross-section, soft diffraction, $\gamma-A$, $\gamma-\gamma$

3. ALICE:
   • ZDCs, fwd. muon spectrometer
     ➔ Soft diffraction, low-x QCD

4. LHCb:
   • Forward muon spectrometer
     ➔ Low-x PDFs

5. TOTEM (approved LHCC July’04):
   • Roman pots (147m, 220 m), trackers (T1, T2)
     ➔ Elastic scattering, total p-p cross section, soft diffraction

6. LHCf (approved LHCC 2006):
7. FP420 (R&D collab. LHCC-2005-025):
   • EM Calo (ATLAS-TAN, 140 m)
     ➔ Cosmic-rays (forward $\gamma, \pi^0$)
   • Feasibility studies for near-beam dets. at 420m
     ➔ Exclusive Higgs, new physics, $\gamma\gamma$
The LHC experiments: zoom at IP5

CMS
TOTEM / (FP420)

Point 5

Point 4

Point 3.3

Point 3.2

Point 2

SPS

Point 1

Point 1.8

ALICE

ATLAS / LHCf / FP420

LHCb
• CMS+TOTEM+FP420: unique experimental setup
• All phase-space virtually covered (1\textsuperscript{st} time in a collider)
**CMS+TOTEM forward detectors**

- **TOTEM-T1** (CSC telescope): $3.1 < |\eta| < 4.7$
- **TOTEM-T2** (GEM telescope): $5.3 < |\eta| < 6.7$
  Soft diffraction (SD,DPE), MB/UE/MPI
- **CASTOR** (W/Q-fiber calo): $5.1 < |\eta| < 6.6$
  Higgs, $M_{E_T}$, diffract., low-x QCD, MB/UE/MPI, heavy-ions (L1 trigger, centrality, ...), CRs
- **ZDC** (W/Q-fiber calo): $|\eta| > 8.3$ (neutral)
  CRs, heavy-ions (L1 trigger, centrality, $\gamma$-$A$, ..)
- **TOTEM Roman Pots** (Si): $\pm 147$, $\pm 220$ m
  Leading $p$: $\sigma_{tot}$, elastic scatt., diffraction
ATLAS forward detectors

- **LUCID** (Cerenkov Tubes): 17 m, $5.4 < |\eta| < 6.1$
  Relative luminosity, diffraction (rap-gaps)

- **ZDC** (W/Q-fiber calo): 140m, $|\eta| > 8.3$ (neutral)
  $n, \gamma$ detection: relative lumi, CRs, heavy-ions
  (L1 trigger, centrality, photoprod, ...)

- **ALPHA** (Sci-Fi in RPs): $\pm 240$ m.
  Abs. lumi (elastic scatt. in Coulomb interf. region)
The LHC experiments: zoom at IP2, IP8

- CMS
- TOTEM / (FP420)
- ATLAS / LHCf / FP420
- ALICE
- LHCb
Forward muon spectrometers:

- ZDCs also at ±7m, ±100m

- 2 < η < 5

- 4.8 < |η| < 5.7

Good capabilities for fwd. heavy-Q, QQ, gauge bosons measurements:

- (low-x PDFs)
Diffractive physics
Pomeron-induced processes

- Diffract./Elastic scatt. ($\sim 40\% p\cdot p \sigma_{tot}$): $p$ intact (Roman Pots), rapidity gap(s). Colourless exchange with vacuum quantum-numbers:

- Diffract./Elastic scatt. ($\sim 40\% p\cdot p \sigma_{tot}$): $p$ intact (Roman Pots), rapidity gap(s). Colourless exchange with vacuum quantum-numbers:

  - Soft diffraction ($X = \text{anything}$): Dominated by soft QCD $\rightarrow$ SD, DPE vs. $s, t, M_X$ provide valuable info of non-perturb. QCD. Contributions to pile-up $p\cdot p$ events.

  - Hard diffraction ($X = \text{jets, W's, Z's ...}$): Calculable (in principle) in pQCD $\rightarrow$ Info on proton structure (dPDFs, GPDs), multi-parton interactions, discovery physics (DPE Higgs, beyond SM)

- $\sigma_{tot,p}$: Test fundamental QM relations (Froisart bound, optical th., dispersion relat)
Total $p$-$p$ cross section, elastic scattering

- $\sigma_{\text{tot}}$ predictions for LHC vary by $\frac{+10}{-20}$%.
- Luminosity measurement via optical theorem:

$$\sigma_{\text{tot}} = \frac{16 \pi}{1 + \rho^2} \times \left( \frac{dN/dt}{|t=0} \right)$$

- $\sigma_{\text{tot}} = 111.5 \pm 1.2^{+4.1}_{-2.1}$ mb
- $E710/811$–CDF $2.6\sigma$ disagreement
- COMPETE extrapolation for LHC:
- $\beta^* = 90 \text{ m}$ optics needed (acceptance at low $|t|$)
- TOTEM goal: $\sim 1\%$ precision

(for $\beta^* = 1500\text{m}$)
Low-x QCD physics
Parton saturation & evolution at low-x

➢ Strong rise at low-x of gluons (HERA):
➢ Radiation controlled by QCD evolution eqs.:

\[ Q^2 \text{- DGLAP: } F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n, \quad Q_0^2 \sim 1 \text{ GeV}^2 \]

\[ x \text{- BFKL: } F_2(x) \sim \alpha_s \ln(1/x)^n \]

Linear equations (single parton radiation/splitting) cannot work at low-x: Unitarity violated (even for \( Q^2 >> \Lambda^2 \)), collinear & k_T factorization invalid

➢ Gluon-gluon fusion balances parton branchings below “saturation scale”: \( Q_s^2 \sim 1 \text{GeV}^2 \) (LHC)

➢ Enhanced in nuclei \( (A^{1/3} \sim 6) \): \( Q_s^2 \sim 5 \text{ GeV}^2 \)

➢ CGC = effective-field theory describes hadrons as classical fields below \( Q_s \)

➢ Non-linear JIMWLK/BK evolution eqs.
**Low-x proton PDF studies**

- **pp @ 14 TeV:**
  1. At $y=0$, $x=2p_T/\sqrt{s}\sim 10^{-3}$ (domain probed at HERA, Tevatron). Go fwd. for $x<10^{-4}$
  2. Saturation momentum: $Q_s^2 \sim 1 \text{ GeV}^2 (y=0), 3 \text{ GeV}^2 (y=5)$
  3. **Very large perturbative cross-sections:**

$$
p(p_1) + p(p_2) \rightarrow \text{jet} + \gamma + X \quad \text{Prompt } \gamma
\quad \begin{align*}
p(p_1) + p(p_2) &\rightarrow l\bar{l} + X \quad \text{Drell-Yan} \\
p(p_1) + p(p_2) &\rightarrow \text{jet}_1 + \text{jet}_2 + X \quad \text{Jets} \\
p(p_1) + p(p_2) &\rightarrow Q + \bar{Q} + X \quad \text{Heavy flavour} \\
p(p_1) + p(p_2) &\rightarrow W/Z + X \quad \text{W,Z production}
\end{align*}
$$

Fwd. production:

$$
x_1 \sqrt{s}/2 \quad x_2 \sqrt{s}/2
$$

- $x_2^{\text{min}} \sim p_T/\sqrt{s} \cdot e^{-y} = x_T \cdot e^{-y}$
- Every 2-units of $y$, $x^{\text{min}}$ decreases by $\sim 10$
Low-x nuclear PDF studies

- PbPb @ 5.5 TeV, pPb @ 8.8 TeV:
  (i) Very high $\sqrt{s}$ ⇒ Bjorken $x = 2p_T/\sqrt{s}$~30-45 times lower than AuAu,dAu @ RHIC !
  (ii) Saturation momentum ($A^{1/3} \sim 6$) : $Q_s^2 \sim [5 \text{ GeV}^2] e^{(0.3y)}$
  (iii) Very large perturbative cross-sections.

Ratio of Pb/p gluon densities:

Nuclear $xG(x,Q^2)$ unknown for $x<10^{-3}$!
Case-study I: $\Upsilon$ photoproduction in CMS (Pb-Pb)

- High energy heavy-ions produce **strong electromagnetic fields** due to the coherent action of $Z_{Pb} = 82$ protons:

- Equivalent flux of photons in EM (aka. Ultra-Peripheral, $b_{min} \sim 2R_A \sim 20$ fm) AA colls.:
  - Max. $\gamma$ energy: $E_{\gamma \max} \sim 80$ GeV (PbPb-LHC)
  - $\gamma$ Pb: $\max. \sqrt{s_{\gamma Pb}} \approx 1. \text{ TeV} \approx 3 - 4 \times \sqrt{s_{\gamma p}}$ (HERA)

- QQ diffractive photoprod. (neutron-tagging in ZDC) sensitive to $|xG|^2$
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$\Upsilon \rightarrow e^+e^-$

$\Upsilon \rightarrow \mu^+\mu^-$

$\sim 500 \ Upsilon/0.5 \ nb^{-1}$ expected in CMS
Case-study II: Forward $Q\bar{Q}$ in ALICE (p-p)

- $J/\psi$ measurement in $\mu$-spectrometer ($2.5 < \eta < 4$): $xg(x)$ at $x_2 \sim 10^{-5}$

$log_{10}(x)$

$J/\psi$

$log_{10}(x)$

$\gamma$

$pp \ @ \ 14$ TeV

$d\sigma/dy$ $J/\psi$: NLO CEM w/ varying PDFs

QQbar: Sensitive to diff. PDFs and DGLAP vs non-linear evolutions

[D. Stocco - ALICE]
Case-study III: Forward (di)jets in CMS (p-p)

- **Forward “soft” jets** ($E_T \sim 20$-100 GeV):

  \[ p + p \rightarrow \text{jet}_1 + \text{jet}_2 + X \] (VBF-Higgs trigger)

  Jets in HF's sensitive to: \( x_2 \sim 10^{-4} \)

  Jets in CASTOR (5.1 < |\eta| < 6.6): \( x_2 \sim 10^{-6} \)!

  Stats. \( \sim 10^7/1 \text{ pb}^{-1} \) (ongoing full jet reco studies)

- **Mueller-Navelet dijets** separated by large \( \Delta y \): very sensitive to non-DGLAP evolution

\[ \sim 10^4 \text{ dijets (HF}^\pm, E_T > 30 \text{ GeV): enough stats. for detailed studies of } \Delta y\text{-evolution} \]
Cosmic-rays physics
UHE cosmic-rays via extended air-showers

Cosmic-ray energy spectrum:

- Only "indirect" measurements (EAS) above $E_{\text{lab}} \sim 100$ TeV
- CR energy & mass determined via hadronic MC simulations:
  Shower development dominated by fwd, soft QCD interactions.
- Uncertain $\times 10^6$ extrapolations from SppS, Tevatron to GZK limit.

LHC: $\sqrt{s} = 14$ TeV $\leftrightarrow E_{\text{lab}} = 10^{17}$ eV

- LHCf experiment:
  n, $\gamma$ detection
  140 m from IP2
  Sci-fiber/W calo + Silicon strip det.
Calibration & tuning of hadronic models

- Model predictions of particle multiplicity, energy flow, sigma-tot, ... differ by large factors:

- ZDCs, LHCf: Measurement of leading baryon (n), neutral meson ($\pi^0$, $K^0_s$) in pp, pA, AA at $E_{\text{lab}} \sim 100$ PeV: Strong EAS model constraint

[CRs collisions: p-Air, $\alpha$-Air, Fe-Air]
Cosmic-rays “exotica”

- $E \sim 10^{15}-10^{17}$ eV cosmic-rays (“Centauro”) events observed:
  1. Anomalous number of $(N \sim 0)$ electromagnetic secondaries
  2. Forward “long-flying” (i.e. non-interacting) component

“strangelets”?
“DCCs”?

Figure 2.5: Diagram of the number of hadrons and hadronic energy fraction: Chacaltaya events with the total visible energy greater than 100 TeV [38]: (o) Centauro, (x) Mini-Centauro, (*) others; (x) C-K [36].

CMS-CASTOR (longitud. segmentation) can access this research programme.
EWK ($\gamma-\gamma$, $\gamma-W$, ...) physics
Two-photon, $\gamma$-W interactions

➢ Exclusive $l^+l^-$ ($e^+e^-, \mu^+\mu^-$) production

$\gamma \rightarrow l^+l^-$ ($e^+e^-$ in T2/CASTOR)

$\gamma \rightarrow l^-l^-$ ($\mu^+\mu^-$ in muon-chambers)

(fwd. proton in RPs)

QED process: $\sigma$ known precisely (LPAIR)

Signature: back-to-back leptons

RPs: reco of proton $\xi$ w/ resol. of $10^{-4}$

~300 evts./100 pb$^{-1}$ after CMS $\mu$ trigger

➢ Absolute p-p luminosity within ~3% (theo)

➢ Cross-calibration of FP420, TOTEM dets.

➢ W-photoproduction:

Triple (anomalous?) gauge couplings

$\gamma \rightarrow W$

$\gamma \rightarrow W$

$\gamma \rightarrow W$

$\gamma \rightarrow W$

$\gamma \rightarrow W$

$\gamma \rightarrow W$

$\gamma \rightarrow W$

$\gamma \rightarrow W$

$\gamma \rightarrow W$

n,p tagging in ZDC/RPs

~50 evts./100 pb$^{-1}$ in p-p 14 TeV

[Also quartic couplings via $\gamma\gamma \rightarrow WW, ZZ$]
Higgs & beyond SM
Vector-Boson-Fusion Higgs

- **qq→qqH** accompanied by forward jets:
  - 2 jets ($p_T \approx 20-60$ GeV)
  - w/ large $\Delta \eta \approx 5$ separation

- Good QCD background rejection:
  - $H \rightarrow WW (\rightarrow l^\pm j j \nu)$
  - vs. $tt\bar{t}, WW$
  - $H \rightarrow \tau \tau$ vs. $Z+nj, W+nj, tt\bar{t}$

CMS: Combined HF+CASTOR extends VBF jet tagging efficiency

- $m_H \sim 120$ GeV
- $m_H \sim 200$ GeV

Background jets at central rapidities
Central exclusive SM Higgs

- Central exclusive Higgs production: $pp \rightarrow p\ H\ p$

![Graph showing exclusive DPE Higgs production at LHC](image)

$\sigma_H = 3\text{-}10\ fb\ (SM),\ \times10(0)\ in\ MSSM$

- Motivations:
  - **Quantum numbers**: central system is approx. $J^{PC} = 0^{++}$ (selection rule)
  - **Excellent mass resolution**: from protons, indep. of central decay products.
  - **Enhanced S/B**: Reduced QCD background. $H \rightarrow b\bar{b}$ channel accessible
  - **CP violation** in Higgs sector: directly measurable from protons azimuthal asymm.
  - **Discovery channel**: in certain regions in MSSM
Central exclusive SUSY Higgs

- MSSM $h^0, H^0, A^0, H^+, H^-$: Tagged proton channel can be the discovery channel in various MSSM scenarios (for similar masses of the 3 neutral Higgs & large $\tan\beta$)

![Graph showing discovery channel](image_url)

[Heinemann et al. arXiv:0708.3052]
Central exclusive Higgs: FP-420 project

- For $m_H < 200 \text{ GeV}$, proton tagging acceptance needed at $\pm 420 \text{ m}$
- FP420 R&D collaboration (ATLAS/CMS under discussion)

- Novel technologies:
  (i) Moving beampipe in cold LHC area
  (ii) Very fast ($\tau \sim 10 \text{ ps}$) Cerenkov detectors: GASTOF (gas), Quartic (Quartz)

  precise leading protons time-difference needed:
  to isolate $pp \rightarrow p \ H \ p$ vertex in high luminosity ($\sim 20 \text{ pp colls.}$) conditions
many BSM ... Transplanckian effects

Once you pass the Planck scale $\sqrt{s} \gg M_D$...

Processes with small momentum transfer e.g.:
Elastic transplanckian colls.:
Study gravity propagation in ED’s
Signal: dijets with large $\Delta y$, $M_{jj}$

Giudice, Rattazzi, Wells, NPB 630 (2002)293

Large rapidity separation of 2 jets
Summary: forward instrumentation @ LHC

- ATLAS LUCID
- CMS CASTOR
- TOTEM T1
- CMS ZDCs
- TOTEM T2
- ATLAS ALFA
- CMS ZDCs
- TOTEM RPs
- ATLAS ZDCs
- LHCf
- ALICE ZDCs
- FP420
Summary: forward physics @ LHC

- **p-p σ_{tot}, elastic scatt.**
- **Hard diffraction**
  - EWK (γ-γ, γ-W, ...)
  - UHE cosmic-rays
- **Exclusive Higgs**
- **MB/UE/MPI**
- **Low-x PDFs**
- **Gluon saturation, CGC**

**Graphs and Diagrams:**
- Graph showing p-p cross-section with statistical error bands and total error bands from models.
- Graph of F_{dijets} vs. t (per. t).
- Diagram of multiple parton interactions.
- Diagram of UHE cosmic rays.
- Diagram of exclusive Higgs production.
- Diagram of hard diffraction and EWK processes.
Backup slides
All phase-space virtually covered at the LHC (first time in a collider)

Ongoing plans to instrument the only current "hole": TAS (6.6<|\eta|<8.3) [20 cm slot with quartz-fibers]
CMS (Castor + ZDC) + TOTEM + FP420:

1. Total p-p x-section precision of ~1%

2. Elastic p-p scatt.: $10^{-3} < t = (p\theta)^2 < 10 \text{ GeV}^2$

3. Leading protons: $2 \times 10^{-3} < \xi < 2 \times 10^{-1}$

4. Particle flows, rap gaps: $|\eta| < 6.6$
CMS (central, CASTOR, ZDC)+TOTEM: largest acceptance ever at a collider
Total p-p cross section, elastic scattering

Photon - Pomeron interference \( \propto \rho \)

Multigluon ("Pomeron") exchange \( \propto e^{-B |t|} \)

\[ \beta^* = 1540 \text{ m} \]
\[ L = 1.6 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1} \]

\[ \beta^* = 18 \text{ m} \]
\[ L = 3.6 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \]

BSW = Bourrely, Soffer and Wu

\[ B(s) = B_0 + 2\alpha_p' \ln (s/s_0) \approx 20 \text{ GeV}^{-2} \text{ at LHC} \]

Multigluon ("Pomeron") exchange \( \propto e^{-B |t|} \)

\[ B(s) = B_0 + 2\alpha_p' \ln (s/s_0) \approx 20 \text{ GeV}^{-2} \text{ at LHC} \]

BSW model

\[ \beta^* = 18 \text{ m} \]
\[ L = 3.6 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \]

Wide range of predictions

~1 day

(1) (3)
Central exclusive SM Higgs

- Central exclusive Higgs production: $pp \rightarrow p \ H \ p$

**Generator studies with detector cuts**

**b jets:**
- $M_H = 120 \text{ GeV}; \quad = 2 \text{ fb}$ (uncertainty factor $\sim 2.5$)
- $M_H = 140 \text{ GeV}; \quad = 0.7 \text{ fb}$

$M_H = 120 \text{ GeV}$: 11 signal / O(10) background in 30 fb$^{-1}$

with detector cuts

Note: This H decay channel is impossible in non-CEP production!

**WW$^*$:**
- $M_H = 120 \text{ GeV}; \quad = 0.4 \text{ fb}$
- $M_H = 140 \text{ GeV}; \quad = 1 \text{ fb}$

$M_H = 140 \text{ GeV}$: 8 signal / O(3) background in 30 fb$^{-1}$

with detector cuts

Note: Use semi-leptonic decays for measurement
Central exclusive SUSY Higgs ($h_0, H_0, A_0, H^+, H$)

- Intense coupling regime: similar masses of the 3 neutral Higgs bosons and $\tan\beta$ is large

$\gamma\gamma, WW^*, ZZ^*$ suppressed

$gg \rightarrow \phi$ enhanced

$0^{++}$ selection rule suppresses $A$ production:

CEDP ‘filters out’ pseudo-scalar production, leaving pure $H$ sample for study

$m_A = 130$ GeV, $\tan \beta = 50$

$m_h = 124$ GeV : $S/B = 70 / (3-10)$ in 30 fb$^{-1}$

$m_H = 135$ GeV : $S/B = 125 / (2-5)$ in 30 fb$^{-1}$

$m_A = 130$ GeV : $S/B = 3 / (2-5)$ in 30 fb$^{-1}$

- Tagged proton channel may well be the discovery channel, and is certainly a powerful spin/parity filter
Case-study IV: Forward DY in CMS (p-p)

- Drell-Yan feasibility studies with CMS (CASTOR) + TOTEM (T2):
- Sensitive to low-x quark densities

**PDF parametrizations**

TOTEM T2 tracker + CASTOR needed to deal w/ large QCD (& QED) bckgd
Experimental probes of gluon PDF ($\gamma^*(p,pp,\gamma^*(A,AA))$

- Perturbative processes:
  - Prompt $\gamma$, (di)jets ($\gamma^*(p, pp, AA)$):
    - Perturbative processes:
      - Prompt $\gamma$, (di)jets ($\gamma^*(p, pp, AA)$):
        - Diffractive $Q\bar{Q}$, heavy-Q ($\gamma^*(p, \gamma^*(A)$):
          - Forward production:
            - $x_1 \sqrt{s}/2$
            - $x_2 \sqrt{s}/2$
            - $x_2^{\text{min}} \sim p_T/\sqrt{s} \cdot e^{-y} = x_T \cdot e^{-y}$
            - Every 2-units of $y$, $x^{\text{min}}$ decreases by $\sim 10$
Small-\(x\) → \(\text{Forward rapidities}\)

- \(2 \rightarrow 2\) parton kinematics:
  \[x = 0: \ x_1 \sim x_2 \sim x_T = 2p_T/\sqrt{s}\]

- \(2 \rightarrow 1\) (gluon fusion) CGC kinematics: much lower \(x\) allowed (\(x_2 \sim x_2^{\text{min}}\))

\[
x_{1,2}^{\rightarrow 1} = \frac{p_T}{\sqrt{s}} (e^{\pm y})
\]

\[
x_{1,2}^{\rightarrow 2} = \frac{p_T}{\sqrt{s}} (e^{\pm y} + e^{\pm y'})
\]

\[
x_2^{\text{min}} = \frac{x_T e^{-\eta}}{2 - x_T e^\eta}
\]

- e.g. LHC, \(p_T = 10\ \text{GeV/c}\)
- \(\theta \sim 10^{-3}\) \((\eta \sim 7): x_\text{min} \sim 10^{-6}\)

Every 2-units of \(y\), \(x_2\) decreases by \(\sim 10\)

\[
x_2^{2 \rightarrow 1} = \frac{p_T}{\sqrt{s}} (e^{\pm y})
\]

CGC: \(x(y=4) \sim 10^{-4}\)

pQCD: \(x(y=4) \sim 10^{-2}\)

(RHIC energies)

[Accardi,nucl-th/0405046]
Saturation hints at HERA?

➢ DGLAP fits most of ep data … Saturation models explain better a few cases:

“Geometric scaling”

flat $\sigma_{\text{diss}}/\sigma_{\text{tot}}$ vs energy

Longitudinal struc. funct.

Inclusive DIS x-section depends on single scale $Q^2/Q_s^2$ for $x < 0.01$

Diffract. & total x-sections similar $W$ dependence ≠ pQCD: $\sigma_{\text{tot}} \sim W^{2\lambda} \neq \sigma_{\text{diff}} \sim W^{4\lambda}$

Gluon ($F_L$) at NLO becomes negative for $Q^2 \sim 2$ GeV$^2$ at low-x

Golec-Biernat-Wusthoff
PRD60 114023 (1999)
Case-study III: Forward jets in CMS \((3 < |\eta| < 5)\)

- Forward “soft” jets \((E_T \sim 20-100 \text{ GeV})\):
  
  \[ p + p \rightarrow \text{jet1} + \text{jet2} + X \]  
  (VBF-Higgs trigger)

  Sensitive to partons with: \(x_2 \sim 10^{-4}\)

  Jets in CASTOR \((5.3 < |\eta| < 6.6)\): \(x_2 \sim 10^{-6}\)

- Inclusive fwd. jet reconstruction (HF):
  
  - PYTHIA 6.4. min-bias (hard&soft QCD)
  - MC-level proof-of-principle only
  - HF grid: \(\Delta \eta \times \Delta \phi = 0.175 \times 0.175\)
  - Iterative cone, \(R=0.5\), \(E_{\text{thresh}}=10 \text{ GeV}\), \(E_{\text{seed}}=3 \text{ GeV}\)
  - Missing important corrections: underlying-evt.
    
    (PYTHIA CMS-Tune), hadronization (cluster vs. Lund)
  - Large yields. Low-\(E_T\) uncertainties to be determined.

\[ p + p \rightarrow \text{jet1} + \text{jet2}, \sqrt{s} = 14 \text{ TeV} \]

\(\text{jet}_{1,2} \text{ in } 3.0 < |\eta| < 5.0\)

\(\text{PYTHIA 6.4: } p + p \rightarrow \text{jet1} + \text{jet2}, \sqrt{s} = 14 \text{ TeV}\)

\(\text{jet}_{1,2} \text{ in } 3.0 < |\eta| < 5.0\)

\(\text{PYTHIA} \sim \text{NLO} \text{ [Vogelsang]}\)

\(\text{Dd'E, hep-ex/0703024}\)
Case-study V: Mueller-Navelet dijets in CMS-HF

- Mueller-Navelet dijets separated by large $\Delta y$: very sensitive to non-DGLAP evolution

- Proof-of-principle study in CMS: MC-level dijet reconstruction applying MN kinematics cuts to PYTHIA pp-14 TeV:
  - $E_{T,i} > 20$ GeV
  - $|E_{T,1} - E_{T,2}| < 2.5$ GeV (similar virtuality, to minimise DGLAP-evolution)
  - $3 < |\eta_{1,2}| < 5$ (both jets in HF)
  - $\eta_1 \cdot \eta_2 < 0$ (each jet in a different HF)
  - $|\eta_1| - |\eta_2| < 0.25$ (almost back-to-back in pseudo-rapidity)

\[
\frac{d^2\sigma}{d\eta dQ} = \frac{N_{jets}}{\Delta\eta \Delta Q} \frac{1}{\int \mathcal{L} dt} \cdot Q = \sqrt{E_{T,1} \cdot E_{T,2}}
\]
Case-study V: Mueller-Navelet dijets in CMS-HF

Mueller-Navelet dijets separated by large $\Delta y$: very sensitive to non-DGLAP evolution

PYTHIA rates with M-N kin. cuts: $\sim 10^4$ dijets [$E_T \sim 30$ GeV] in $\mathcal{L} \sim 1$ pb$^{-1}$ (low luminosity run): enough stats. for detailed studies of $\Delta y$-evolution.

Dd'E, hep-ex/0703024
Onset of non-linear QCD when gluons are numerous enough (low-x) & “large” enough (low-\(Q^2\)) to overlap:

\[
Q_s^2 \sim \alpha_s \frac{x G_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3}(x^{-\lambda} \sim A^{1/3}(\sqrt{s})^\lambda \sim A^{1/3} e^{\lambda y} \quad \lambda \sim 0.3
\]

Nucleus (larger parton tranverse density) amplifies saturation effects:

\[
Q_s^2 \sim A^{1/3} \sim 6
\]

\(Q_s^2 \sim 1 \text{ GeV}^2\) (HERA,p)

\(Q_s^2 \sim 2 \text{ GeV}^2\) (e)RHIC (Au), 5 GeV² (LHC,Pb)
UHE cosmic-rays via extended air-showers

Knowledge of the energy and particle flow in high-energy p+N,O, Fe+N,O collisions is crucial for cosmic ray showers >100 PeV:

Determination of $E$, mass of cosmic rays depends on hadronic MC. Forward region poorly known. Models differ by factor 2 or more. Need forward particle/energy measurements: $dN/dh$, $dE_{(T)}/d\eta$, particle ID ...
Photoproduction ($\gamma A$) in UPC AA collisions

- Heavy-ions (charge $Z$) produce strong EM fields (coherent action of all protons):
- Equivalent flux of photons in electromagnetic (aka. Ultra-Peripheral, $b_{\text{min}} \sim 2R_A$) A+A:
  \[
  \frac{dN_\gamma}{dE}(b > b_{\text{min}}) \propto \frac{\alpha_\text{em} Z^2}{\pi} \frac{1}{E} \quad \text{(soft bremsstrahlung $\gamma$ spectrum)}
  \]
- Photon beams:
  - **Flux** $\sim Z^2$ ($\sim 7 \cdot 10^3$ for Pb).
  - “Coherence condition”: $\gamma$ wavelength $> \text{nucleus size}$
  - Maximum $\gamma$ energy: $\omega < \omega_{\text{max}} \approx \frac{\gamma}{R} \sim 80 – 160$ GeV (Pb,Ca)
  - Center of mass-energies (LHC): $\sqrt{s_{\gamma A}} \approx 0.7 – 2.$ TeV $\approx (3 – 10) \times \sqrt{s_{\gamma p}}$ (HERA)
  - Bjorken $x$ range in nucleus:
    - (y=0): $x(J/\Psi) \sim 3 \cdot 10^{-3}$, $x(\Upsilon) \sim 10^{-2}$
    - (y=3): $x(J/\Psi) \sim 2 \cdot 10^{-5}$, $x(\Upsilon) \sim 10^{-4}$
  - **Forward neutron-tagging (ZDC)**: $\sim 50\%$ UPC colls. lead to nuclear breakup.
CMS: TOTEM-2 and CASTOR (5.2 < |\eta| < 6.6)

- TOTEM GEM ("Gas Electron Multiplier")
  - Telescope detector: electron polar angle

- CASTOR (W/-Q-fiber calo): electromag. shower identification
  - Tungsten plates + quartz fibres
  - Cherenkov sampling calorimeter
  - Light-guides + APDs readout
  - Azimuth segmented (8 octants)
  - EM section: 11.2 cm ~ 19 X_0
  - HAD+EM sections: 136 cm~ 10\lambda_i
  - 192 channels