Forward physics at the LHC: within and beyond the SM\(^(*)\)

\(^\text{(*)}\) 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: low-x

  Higgs: VBF, central exclusive

  EWK: excl. dileptons, gauge couplings

  Beyond SM: MSSM Higgs, elastic grav., ...
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)
- LHCb

Large Hadron Collider

Lake Geneva
FRANCE
PA6
PA4

16.8 miles
5.3 miles
4.4 miles
1.4 miles

SWITZERLAND
Meyrin

II LAWHEP, 6/12/2007
David d'Enterria (CERN)
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 (1st time in a collider)

[plans to instrument also the 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, γ–p, γ–A, γ–γ

## 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, γ–A, γ–γ

## 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):
- EM Calo (ATLAS-TAN, 140 m)
  - Cosmic-rays (forward γ,π⁰)

## 7. FP420  
(R&D collab. LHCC-2005-025):
- Feasibility studies for near-beam dets. at 420m
  - Exclusive Higgs, new physics, γγ
The LHC experiments: zoom at IP5

CMS

TOTEM / (FP420)

ATLAS / LHCf / FP420

ALICE

LHCb
CMS+TOTEM forward detectors

- CMS+TOTEM+FP420: unique experimental setup
- All phase-space virtually covered (1st 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
The LHC experiments: zoom at IP1

- CMS
- TOTEM / (FP420)
- ALICE
- ATLAS / LHCf / FP420
- LHCb
ATLAS forward detectors

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

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

- **ALPHA** (Sci-Fi in RPs): ±240 m.
  Abs. lumi (elastic scatt. in Coulomb interf. region)
ALICE & LHCb forward detectors

- Forward muon spectrometers:

- Good capabilities for fwd. heavy-Q, QQ, gauge bosons measurements:
  (low-x PDFs)
Diffractive physics
Pomeron-induced processes

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

  - $\sigma_{\text{tot}}, \rho$: Test fundamental QM relations (Froisart bound, optical th., dispersion relat)

  - Soft diffraction ($X = $ 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-p events.

  - Hard diffraction ($X = $ 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)
Total p-p cross section, elastic scattering

- \( \sigma_{\text{tot}} \) predictions for LHC vary by \(+10\% - 20\%\).

- Luminosity measurement via optical theorem:
  \[
  \sigma_{\text{tot}} = \frac{16 \pi}{1 + \rho^2} \left( \frac{dN/dt}{|t|=0} \right) \times \frac{N_{\text{el}} + N_{\text{inel}}}{N_{\text{inel}}}
  \]

- E710/811–CDF 2.6\( \sigma \) disagreement
- COMPETE extrapolation for LHC:
  \[
  \sigma_{\text{tot}} = 111.5 \pm 1.2 \pm 4.1 - 2.1 \text{ mb}
  \]

- TOTEM goal: \(~1\%\) 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.:
    - \( Q^2 - \text{DGLAP} \): \( F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n \), \( Q_0^2 \sim 1 \text{ GeV}^2 \)
    - \( x - \text{BFKL} \): \( F_2(x) \sim \alpha_s \ln(1/x)^n \)
  - Linear equations (single parton radiation/splitting) cannot work at low-x: Unitarity violated (even for \( Q^2 \gg \Lambda^2 \)), 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

\(\text{pp} @ 14 \text{ TeV}:\)

(i) At \(y=0, x=2p_T/\sqrt{s} \sim 10^{-3}\) (domain probed at HERA, Tevatron). Go fwd. for \(x<10^{-4}\)

(ii) Saturation momentum: \(Q_s^2 \sim 1 \text{ GeV}^2 (y=0), 3 \text{ GeV}^2 (y=5)\)

(iii) Very large perturbative cross-sections:

- \(p(p_1) + p(p_2) \rightarrow \text{jet} + \gamma + X\) Prompt \(\gamma\)
- \(p(p_1) + p(p_2) \rightarrow \ell \ell + X\) Drell-Yan
- \(p(p_1) + p(p_2) \rightarrow \text{jet}_1 + \text{jet}_2 + X\) Jets
- \(p(p_1) + p(p_2) \rightarrow Q + \bar{Q} + X\) Heavy flavour
- \(p(p_1) + p(p_2) \rightarrow W/Z + X\) W,Z production

Fwd. production:

\[\begin{align*}
x_1 & \sim \frac{\sqrt{s}}{2} \\
x_2 & \sim \frac{p_T}{\sqrt{s}} \cdot e^{-y} = x_T \cdot e^{-y}
\end{align*}\]

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 $\sqrt{s} \Rightarrow$ 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 $Z_{\text{Pb}} = 82$ protons:
  - Equivalent flux of photons in EM (aka. Ultra-Peripheral, $b_{\text{min}} \sim 2R_A \sim 20$ fm) AA colls.:
    - Max. $\gamma$ energy: $E_{\gamma \text{max}} \sim 80$ GeV (PbPb-LHC)
    - $\gamma_{\text{Pb}}$: max. $\sqrt{s}_{\gamma\text{Pb}} \approx 1$ TeV $\approx 3. - 4. \times \sqrt{s}_{\gamma p}$ (HERA)
  - QQ diffractive photoprod. (neutron-tagging in ZDC) sensitive to $|xG|^2$

\[ xG_A(x,Q^2) \]

\[
y = 0: x(\Upsilon) = 2 \cdot 10^{-3}
\]
\[
y \sim 2: x(\Upsilon) \sim x(y=0) \cdot e^{-y} \sim 10^{-4}
\]
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- QQ diffractive photoprod. (neutron-tagging in ZDC) sensitive to $|xG|^2$

$\Upsilon \rightarrow e^+e^-$

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

$\sim 500 \ Upsilon/0.5 \ nb^{-1}$ 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 $x_2 \sim 10^{-5}$

$$xg(x) \quad \text{at} \quad x_2 \sim 10^{-5}$$

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

$Q\bar{Q}bar$: Sensitive to diff. PDFs and DGLAP vs non-linear evolutions

$pp @ 14$ TeV

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

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

  Jets in HF sensitive to: $x_2 \sim 10^{-4}$

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

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

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

- $\sim 10^4$ dijets (HF$^\pm$, $E_T > 30$ GeV): enough stats. for detailed studies of $\Delta y$-evolution

[D.d'E hep-ex/0703024]

\[ \log_{10}(x_{1,2}) \]

\[ \text{jet}_1 \quad \Delta y \sim 10 \quad \text{jet}_2 \]

\[ \text{Increased azimuth. decorrelation} \]

\[ \Delta \phi \]

\[ \text{BFKL NLL} S4 \]

\[ Q>5 \text{ GeV, R}=1 \]

\[ \Delta \eta = 6 \quad \Delta \eta = 8 \quad \Delta \eta = 10 \quad \Delta \eta = 11 \]
Cosmic-rays physics
UHE cosmic-rays via extended air-showers

Cosmic-ray energy spectrum:

- Only "indirect" measurements (EAS) above $E_{\text{lab}} \approx 100$ TeV
- CR energy & mass determined via hadronic MC simulations:
  - Shower development dominated by fwd, soft QCD interactions.
- Uncertain $x10^6$ extrapolations from SppS, Tevatron to GZK limit.
  
  **LHC:** $\sqrt{s} = 14$ TeV $\iff E_{\text{lab}} = 10^{17}$ 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:
  
  (i) anomalous number of $(N \sim 0)$ electromagnetic secondaries

  (ii) forward “long-flying” (i.e. non-interacting) component

  \[\text{“strangelets”?} \quad \text{“DCCs”?}\]

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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-Centaur, (●) others; (●) C-K [36].

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

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

\[
\begin{array}{cccc}
| & | & | & | \\
\text{p} & \gamma & \text{l}^+ & \text{p} \\
| & | & | & | \\
\text{p} & \gamma & \text{l}^- & \text{p} \\
\end{array}
\]

$(e^+e^- \text{ in T2/CASTOR})$

$(\mu^+\mu^- \text{ in muon-chambers})$

$(\text{fwd. proton in RPs})$

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

Signature: back-to-back leptons

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

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

- Absolute p-p luminosity within $\sim 3\%$ (theo)

- Cross-calibration of FP420, TOTEM dets.

$\gamma$-photoproduction:

Triple (anomalous?) gauge couplings

\[
\begin{array}{cccc}
| & | & | & | \\
\gamma & \text{W} & | & | \\
| & | & | & | \\
\text{p} & | & \text{n} \\
\end{array}
\]

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

$n,p$ tagging in ZDC/RPs

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

- $qq \rightarrow qqH$ accompanied by forward jets:
  - 2 jets ($p_T \sim 20-60$ GeV)
  - with large $\Delta \eta \sim 5$ separation

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

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: $pp \rightarrow p\ H\ p$

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

$\sigma_H = 3-10 \text{ fb (SM)}, x10(0) \text{ in MSSM}$
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 $\tan\beta$)

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

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

**Novel technologies:**

(i) **Moving beampipe** in cold LHC area

(ii) **Very fast ($\tau \sim 10$ ps) Cerenkov detectors:**
    - GASTOF (gas), Quartic (Quartz)

precise leading protons time-difference needed:

to isolate $pp \rightarrow p \, H \, p$ vertex in high luminosity ($\sim 20$ pp colls.) conditions

Where $\xi_{1,2}$ are the fractional momentum losses of the outgoing protons
many BSM ... Transplanckian effects

Once you pass the Planck scale \( \sqrt{s} \gg M_D \ldots \)

Processes with small momentum transfer e.g.:

Elastic transplanckian colls.:

Study gravity propagation in ED’s

Signal: dijets with large \( \Delta y \), \( M_{jj} \)

Large rapidity separation of 2 jets

Giudice, Rattazzi, Wells, NPB 630 (2002) 293
Summary: forward instrumentation @ LHC

- ATLAS LUCID
- CMS CASTOR
- ALICE ZDCs
- CMS ZDCs
- ATLAS ZDCs
- ATLAS ALFA
- TOTEM T1
- TOTEM T2
- TOTEM RPs
- LHCf
- FP420

David d'Enterria (CERN)
Summary: forward physics @ LHC

- **p-p \( \sigma_{\text{tot}} \), elastic scatt.**
- **hard diffraction**
- **VM photoprod.**
- **exclusive Higgs**

- **gluon saturation, CGC**
- **low-x PDFs**
- **BFKL**
- **EWK (\( \gamma-\gamma,\gamma-W,... \))**

- **MB/UE/MPI**
- **UHE cosmic-rays**
Backup slides