Photon Collider Opportunities
FOR NEW PHYSICS: SUSY & DARK MATTER

LHC Forward Physics Workshop
18 December 2018

Lydia Beresford & Jesse Liu
University of Oxford
Who are we
We’re from the community searching for new BSM particles at the LHC. Principally search for SUSY, DM, Higgs with jets, leptons, $E_T^{\text{miss}}$. We are not forward physics experts – we’re here to learn :)

Why we are here
We’ll share why we are suddenly interested in forward physics!
I’ll review more model-dependent SUSY viewpoint.
Lydia will discuss more model-agnostic search opportunities.
We present our phenomenology paper [1811.06465] in wider context.
See also Valery Khoze’s talk
Motivation: big picture experimental landscape

LHC is a once-in-a-generation collider:
The only one capable of discovery SUSY for another $\gtrsim 2$ decades!
What is data telling us? Dark matter, $(g - 2)_\mu$ tensions.

Deepest experimental tragedy we must avoid:
Build a SUSY/dark matter factory but we’re incapable of detecting them.
Modern view: SUSY/DM as signature generators to map sensitivity.

Startling realisation: we could already be in this situation!
ATLAS+CMS revealing where we are blind.
Review where they are even for the most vanilla simplified models.
Photon collisions exciting venue for LHC search programme

Searching for axion-like particles with ultra-peripheral heavy-ion collisions

Simon Knapen,¹,² Tongyan Lin,¹,² Hou Keong Lou,¹,² and Tom Melia¹,²

¹Department of Physics, University of California, Berkeley, California 94720, USA
²Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Dated: May 5, 2017)

ATLAS 1702.01625, Knapen et. al. 1607.06083, Baldenegro et. al. 1803.10835
Light electroweak SUSY favoured by state-of-the-art global fits

Best fit point of 11-dim MSSM to all data gives light electroweak SUSY
Mastercode collaboration 1710.11091, see also GAMBIT 1705.07917
New charged scalars: sleptons $\tilde{\ell}^{\pm}$

Scalar partners of the charged leptons

Selectrons $\tilde{e}$, smuons $\tilde{\mu}$, staus $\tilde{\tau}$

Please see backup p37 for striking gaps in charged fermions (charginos $\tilde{\chi}^{\pm}$)

Won’t discuss charged Higgs bosons but generic in two Higgs doublet models (2HDM) & MSSM
Scalar partners of charged leptons: LEP limits

\[ \sqrt{s} = 183-208 \text{ GeV} \quad \text{ADLO} \]

LEP searches extremely clean: mainly $\sqrt{s}$ limited, LEP SUSY Combination Group

Critical open problem: how will LHC surpass LEP for all $\Delta M(\tilde{\ell}, \tilde{\chi})$?

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Selectrons & smuons: striking gap $15 \lesssim \Delta M \lesssim 60$ GeV

LHC could already be a dark matter factory and we’d have no idea
$m(\tilde{\ell}) \sim 100$ GeV: $\sigma(pp \to \tilde{\ell}\tilde{\ell}) \times \mathcal{L} \sim 730$ fb $\times 140$ fb$^{-1} \sim 100$ 000 events
See backup for striking gaps in charged fermion (chargino) production

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Relax mass degeneracy: just $\tilde{e}_R$ blind corridor is truly striking

CMS

$pp \rightarrow \tilde{e}_R \tilde{e}_R$

$B(\tilde{e}_R \rightarrow e \chi^0_1) = 1$

NLO-NLL excl.

Observed $\pm 1 \sigma_{\text{theory}}$

Expected $\pm 1 \sigma_{\text{experiment}}$

CMS 1806.05264, see also ATLAS 1403.5294

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Half empty or half full

Blind spots = limitations of existing strategies
Blind spots = exciting opportunities for new ideas

**Opportunity for forward proton programme**

**Could be important discovery window**
What’s hindering sensitivity in the gap?

Fraction of events

**Compressed ΔM \lessgtr 15 GeV signals**
- Signal peaks at low mT2
- Signal endpoint
- Success: *ATLAS soft 2L ISR strategy*

**Large ΔM \gtrsim 60 GeV signals**
- Signal is rising tail at high mT2
- Background endpoint
- Success: *ATLAS 2L 0 jets strategy*

**Moderate 15 \lessgtr ΔM \lessgtr 60 GeV signals**
- Difficult to distinguish from WW shape
**Desirable**

Direct missing momentum 4-vector & missing mass reconstruction

\[ p_{\text{miss}} = \sum_{\text{initial}} p_i - \sum_{\text{final}} p_{\text{visible}} \Rightarrow m_{\text{miss}}^2 = p_{\text{miss}}^2 \]

**Obstruction**

Per event initial state parton kinematics immeasurable at hadron colliders

\[ p_{\text{initial}}(\text{quarks & gluons}) \text{ immeasurable} \]

**Consequence**

Only transverse component \( p_{T}^{\text{miss}} \) measurable: lost information

\[ p_{T}^{\text{miss}} = 0 - \sum_{\text{final}} p_{T}^{\text{final}} \]

Cannot use neutrino vs DM mass for discrimination
Photon collider search strategy for sleptons and dark matter at the LHC

Lydia Beresford\textsuperscript{1,*} and Jesse Liu\textsuperscript{1,†}

\textsuperscript{1}Department of Physics, University of Oxford, Oxford OX1 3RH, UK

We propose a search strategy using the LHC as a photon collider to open sensitivity to scalar lepton (slepton $\tilde{\ell}$) production with masses around 15 to 60 GeV above that of neutralino dark matter $\tilde{\chi}_1^0$. This region is favored by relic abundance and muon $(g-2)_\mu$ arguments. However, conventional searches are hindered by the irreducible diboson background. We overcome this obstruction by measuring initial state kinematics and the missing momentum four-vector in proton-tagged ultra-peripheral collisions using forward detectors. We demonstrate sensitivity beyond LEP for slepton masses of up to 220 GeV for $15 \lesssim \Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \lesssim 60$ GeV with 100 fb\textsuperscript{-1} of 13 TeV proton collisions. We encourage the LHC collaborations to open this forward frontier for discovering new physics.

[arXiv:1811.06465]

\textbf{Strategic goal: establish comprehensive & compelling physics case}

to build critical mass of people & funding for confronting experimental challenges

See also Ohnemus et. al. hep-ph/9402302, de Favereau de Jeneret et. al. 0908.2020, Harland-Lang et. al. 1110.4320, Khoze et. al. 1702.05023 Harland-Lang et. al. 1812.04886
Photon collider: exceptionally clean QED production

Usual head-on proton–proton collisions

Partons collide to make new particles

σ(WW) ~ 140 pb
σ(100 GeV slep) ~ 0.73 pb

Photons from electric fields

Photons collide to make new particles

σ(WW) ~ 93 fb
σ(100 GeV slep) ~ 2.5 fb

Protons remain intact & deflected by LHC dipole magnets
High energy photon interactions at the LHC

J. de Favereau de Jeneret, V. Lemaitre, Y. Liu\textsuperscript{a}, S. Ovyn, T. Pierzchała, K. Piotrzkowski, X. Rouby\textsuperscript{b}, N. Schul, and M. Vander Donckt\textsuperscript{c}

Université catholique de Louvain, Center for Particle Physics and Phenomenology (CP3), 1348 Louvain-la-Neuve, Belgium

August 14, 2009

de Favereau de Jeneret et. al. [0908.2020]

\[ m(\tilde{\ell}_R, \tilde{\ell}_L, \tilde{\tau}_1, \tilde{\chi}_1^0) = (118, 184, 109, 97) \text{ GeV} \]
Mass measurement study 8 years ago

Figure 3: Scatter plots showing the \((m_i^{\text{true}}, m_{\tilde{\chi}}^{\text{true}})\) values consistent with each event. Left: SUSY \((m_i^{\text{true}}, m_{\tilde{\chi}}^{\text{true}}) = (150, 100)\) GeV. Right: SM. Each plot contains 10,000 events. No detector smearing is included.

Measuring the masses of a pair of semi-invisibly decaying particles in central exclusive production with forward proton tagging

L. A. Harland-Lang, a C. H. Kom, a,b,c K. Sakurai a,b,c,d,e and W. J. Stirling a

Harland-Lang et. al. [1110.4320]

Chose masses very difficult to discover via current electroweak searches!
New kinematic info: initial state & full missing momentum 4-vector

Beam energy known

Outgoing proton energy measured by forward detectors

Central detectors measure lepton 4-vectors

Initial state photon 4-vectors from proton energy loss

Missing momentum 4-vector from photon & lepton 4-vectors → Directly reconstruct DM mass

New mediators only need to carry electric charge

Direct measurement of initial state & missing momentum 4-vector Impossible in usual LHC collisions
How can we fully exploit this facility & confront challenges?

ATLAS Forward Proton, CMS–TOTEM Precision Proton Spectrometer
First high-luminosity proton-tagged dilepton observation [arXiv:1803.04496]
Nominal proton acceptance: $0.015 \lesssim \xi \lesssim 0.15$, where $\xi = 1 - E_{\text{forward}}/E_{\text{beam}}$
Use lepton triggers $p_T^\ell > 15$ GeV: fine for $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \gtrsim 15$ GeV gaps

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Decisive sensitivity in region favoured by dark matter & \((g - 2)_{\mu}\) data

Accompanying landmark measurement of \(p_{\text{miss}}\) at hadron collider

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Example challenge: pileup mitigation

Proton arrival time matched with lepton vertex
⇒ ULTRAPERIPHERAL

Proton arrival time NOT matched with lepton vertex
⇒ PILEUP

LHC Searches for Dark Matter in Compressed Mass Scenarios:
Challenges in the Forward Proton Mode

L.A. Harland-Lang\textsuperscript{1*}, V.A. Khoze\textsuperscript{2,3†}, M.G. Ryskin\textsuperscript{3‡}
and M. Tasevsky\textsuperscript{4§}

1812.04886
What if New Physics ...

- Doesn’t couple to quarks?
- Is invisible to detector?
- Decays to a cascade of particles?
- Produces soft decay products?
- Is a broad resonance?
- Long-lived particles?
Mass of central system $m_{\gamma\gamma}$ is dream exotics variable!

Search inclusively for new particle regardless of decay channel!!

BUT ... very challenging experimentally if don’t require central object:

- Inclusive in signal decay mode → Inclusive in bkg decay mode
- Triggering challenging using only forward proton tag
- Pile-up is issue without object to identify interaction vertex
- Need to consider both pomeron-production & photo-production
Lepton + X signature is still extremely model-independent & solves many experimental challenges!

Anything charged with a lepton in decay chain

- Can be broad resonance

Anything which couples to leptons & X

- Can be invisible
- Can be a cascade
Exotics: The ultimate lepton + X search

W' Heavy version of W boson

Vector-like Leptons

Seesaw Models with Majorana Neutrinos

Using slepton signals as illustrative example in following plots
Exotics example

Example limit for SSM $W'$

\[ \text{Observed limit weakens at lower masses due to huge SM backgrounds} \]
Scan mass of central system for excesses/thresholds

\[ \rightarrow \min(m_{\gamma\gamma}) = 2 \times m_x \]

Search for any charged mediator with \( \geq 1 \) lepton in decay chain

\[ \rightarrow \text{Even broad resonances!} \]

Search inclusive of all decay modes which include 1 lepton & discriminate with mediator mass

Proton tag trigger allows lower lepton \( p_T \) threshold

\[ \rightarrow \text{Sensitivity to soft lepton scenarios which might otherwise be missed!} \]
Scan missing mass for excesses/thresholds

\[ \rightarrow \min(W_{\text{miss}}) = 2 \times m_{\gamma} \]

Search for anything coupling to leptons & charged mediator

\[ \rightarrow \text{Even invisible particles or particle cascades! Notoriously challenging with central only info!} \]

Missing mass provides powerful discrimination against WW bkg with \(~\) massless \(\nu\) & allows mass determination

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Scan mass splitting for excesses/peaks
→ peaks at $2 \times m_{\text{splitting}}$

Could do 2D bumpHunt in $m_{\gamma\gamma}$ and $W_{\text{miss}}$
→ Too sparse at low lumi?

Can also combine information:
$m_{\gamma\gamma} - W_{\text{miss}}$
→ Simple alternative
→ Retain stats as 1D
→ Great signal & bkg separation enhances significance!!

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New physics: not just complementary but essential to LHC discovery program.

New observables: initial state & complete missing momentum 4-vector.

New windows: QED for charginos, $W'$, stops, staus, vector-like leptons…

New detectors: ATLAS Forward Proton still commissioning.

New environment: extremely clean, nothing but pileup & detector noise.

New triggers: forward proton trigger independent of central detector.

New timing: dedicated detectors match proton with primary vertices.

New invariants: direct measurement of invisible system mass.

New measurements: $\gamma\gamma \rightarrow WW$ guaranteed SM search.

New reconstruction: decay-independent mass measurement of parent.

New outreach: using light to reveal the darkness.
EXTRAS
Opportunities & challenges for soft, rare, quirky signals

Minimality
Unification
Naturalness
Colourful states
Light gluino & stops
WIMP dark matter
Energetic jets + MET

Phenomenology
Parton level processes
Final state predictions

THE SEARCHLIGHT IS SHIFTING
from spectacular to subtle discoveries

Case study
Electroweak SUSY

Soft stuff
Particle identification
Trigger thresholds

Rare SUSY
Colourless sparticles
Dark sector

Quirky creatures
Displaced difficulties
Long-lived exotica

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Chargino–neutralino production: tough corridors due to SM backgrounds

\[
\text{CMS} \quad pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \quad 35.9 \text{ fb}^{-1} (13 \text{ TeV})
\]

- \(B(\tilde{\chi}_2^0 \rightarrow H \tilde{\chi}_2^0) = 1\) (WH)
- \(B(\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_2^0) = 1\) (WZ)
- \(B(\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_2^0) = B(\tilde{\chi}_2^0 \rightarrow H \tilde{\chi}_2^0) = 0.5\) (WH+WZ)

Expected \quad Observed

Different decay assumptions

\[
m_{\tilde{\chi}_2} = m_{\tilde{\chi}_1} \quad m_{\tilde{\chi}_2} = m_{\tilde{\chi}_1} + m_Z
\]

CMS 1801.03957, see also ATLAS 1803.02762
Staus: currently no LHC sensitivity even in most optimistic scenario

\[ \text{CMS } 35.9 \text{ fb}^{-1} (13 \text{ TeV}) \]

\[ \text{pp} \rightarrow \tilde{\tau} \tilde{\tau}^*, \tilde{\tau} \rightarrow \tau \tilde{\chi}^0_1, m(\tilde{\chi}^0_1) = 1 \text{ GeV} \]

- Observed
- 68% expected
- \( \sigma_{\text{NLO+NLL}} \pm 1 \text{ s.d.} \)
- 95% expected

Left-handed scenario

CMS 1807.02048 hadronic & lepton tau analysis

Expect full Run 2 dataset results soon. Will not discuss staus further today.
14 TeV cross-sections \( pp \rightarrow p(\gamma\gamma \rightarrow X^+X^-)p \)

QED: fixed by mass & spin: V (spin 1), F (spin 1/2), S (spin 0)
Our MadGraph cross-sections consistent with plot above from [arXiv:1110.4320]
New possibility: directly reconstruct dark matter mass

\[
\frac{S}{\sqrt{B + (xB)^2}}
\]

Related to \( m_{\text{miss}} = \sqrt{p_{\text{miss}}^2} = \sqrt{(p_{\gamma_1} + p_{\gamma_2} - p_{\ell_1} - p_{\ell_2})^2} \) but tails more steeply falling

Variable from Harland–Lang et. al. [arXiv:1110.4320]

\[
\frac{pp \rightarrow p (\gamma\gamma \rightarrow X^+X^-) p}{\sqrt{s} = 13 \text{ TeV}, 100 \text{ fb}^{-1}, \text{SR-common}}
\]

\[
m(\tilde{\ell}, \tilde{\chi}_1^0) = (100, 50) \text{ GeV}
\]

\[
m(\tilde{\ell}, \tilde{\chi}_1^0) = (100, 80) \text{ GeV}
\]

\[
m(\tilde{\ell}, \tilde{\chi}_1^0) = (150, 100) \text{ GeV}
\]

\[
\chi \sim \ell \sim (m) = (100, 80) \text{ GeV}
\]

\[
\chi \sim \ell \sim (m) = (150, 100) \text{ GeV}
\]

\[
\chi \sim \ell \sim (m) = (100, 50) \text{ GeV}
\]

\[
\chi \sim \ell \sim (m) = (150, 100) \text{ GeV}
\]
New charged fermions: charginos $\tilde{\chi}^\pm$

Charged fermionic partners of the gauge and Higgs bosons

Neutralinos $\tilde{\chi}^0$ are neutral eigenstates — lightest one can be dark matter
Sub-100 GeV Higgsino dark matter: the ‘prompt–long-lived gap’

$\tilde{\chi}^\pm_1, \tilde{\chi}^0_1$ (Higgsino)

Disappearing track
Pixel tracklets

Soft $2\ell$
$p_T(\ell, \nu) > 4.5, 4$ GeV

Disappearing track
Pixel tracklets

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Chargino pair production: no LHC sensitivity for off-shell W bosons

\[ m(\tilde{\chi}_1^\pm) = 105 \text{ GeV}: \sigma(pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp) \sim 10 \text{ pb} \times 100 \text{ fb} \Rightarrow 1 \text{ million events!} \]

But blind due to formidable SM \( WW \rightarrow \ell \nu \ell \nu \) background
Slepton $E_\gamma > 200$ GeV ($0.03 \lesssim \xi \lesssim 0.15$)

Sensitivity even if lower bound proton energy loss is less ideal $0.015 \rightarrow 0.03$