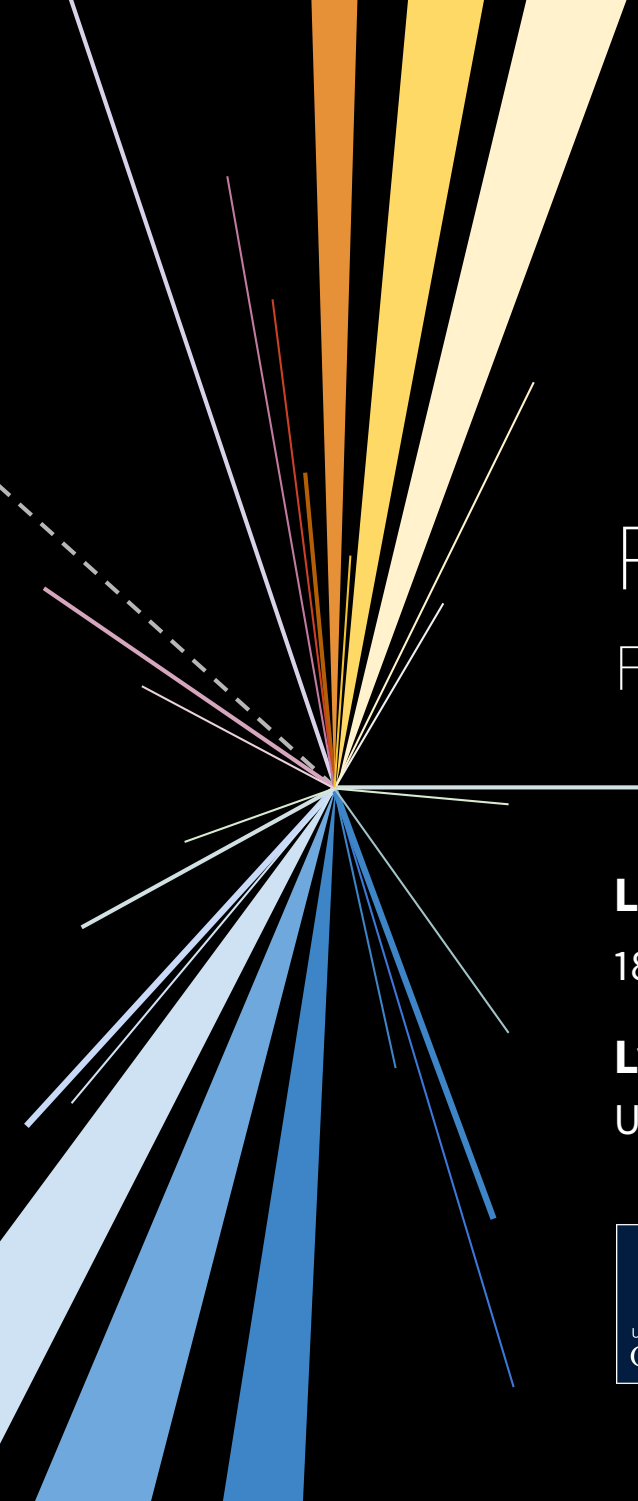


Photon Collider Opportunities

FOR NEW PHYSICS: SUSY & DARK MATTER

LHC Forward Physics Workshop

18 December 2018

Lydia Beresford & Jesse Liu

University of Oxford

Who we are & why we are here

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, $E_{\mathrm{T}}^{\mathrm{miss}}$.

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.

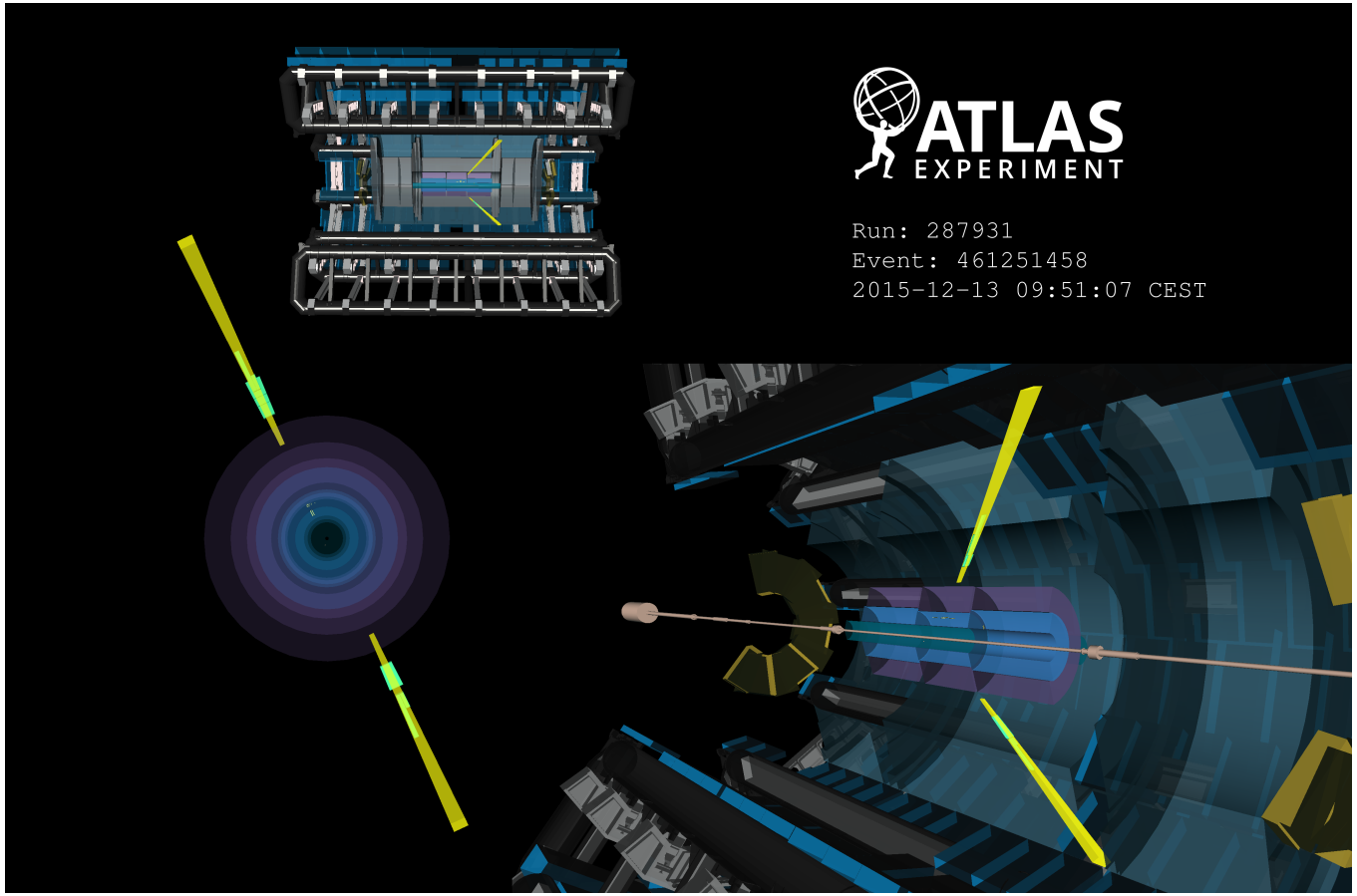
Modern view: SUSY/DM as signature generators to map sensitivity.

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



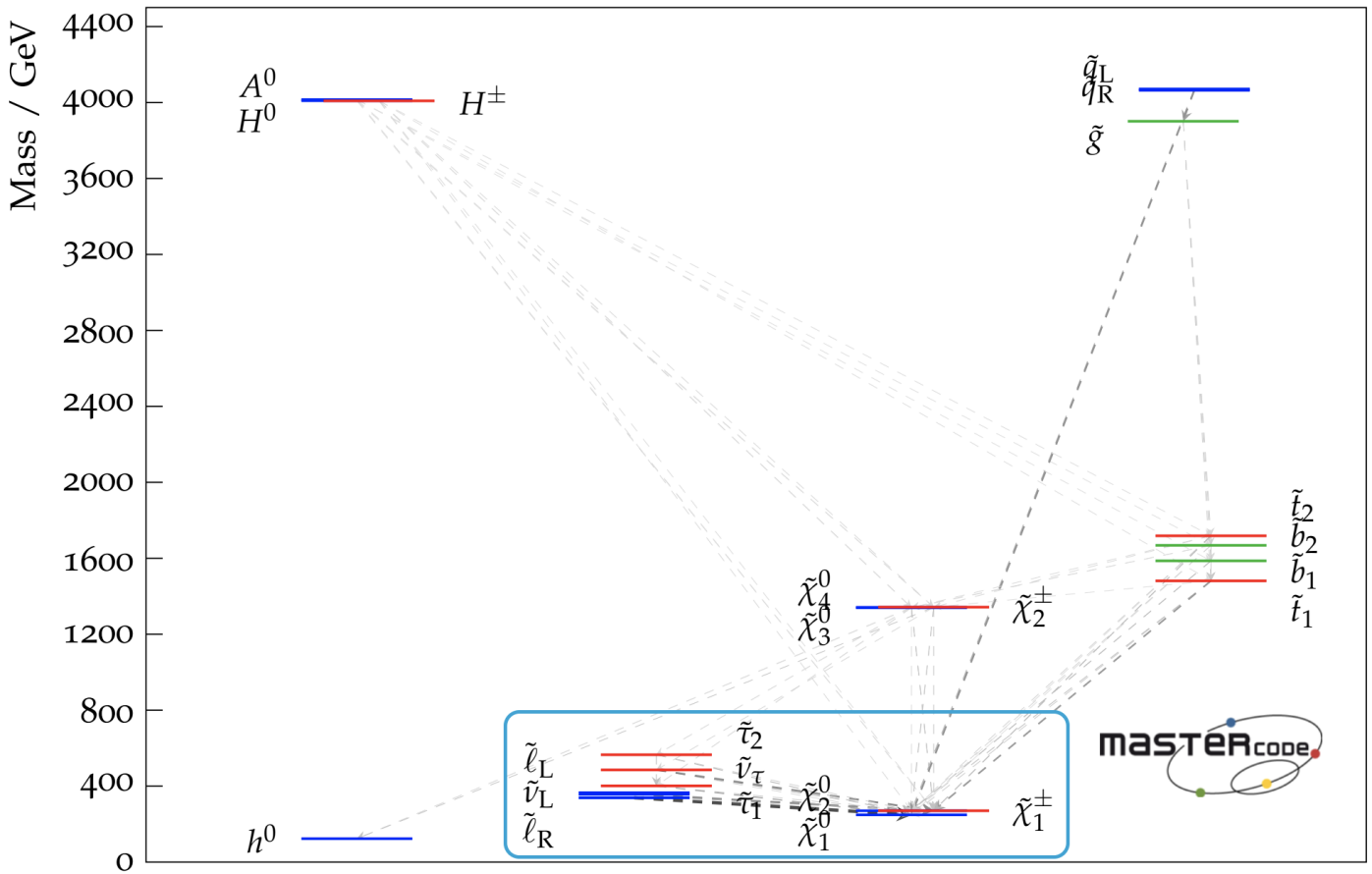
Searching for axion-like particles with ultra-peripheral heavy-ion collisions

Simon Knapen,[1,2] Tongyan Lin,[1,2] Hou Keong Lou,[1,2] and Tom Melia[1,2]

[1] *Department of Physics, University of California, Berkeley, California 94720, USA*
[2] *Theoretical 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 $\tilde{\ell}^{\pm}$

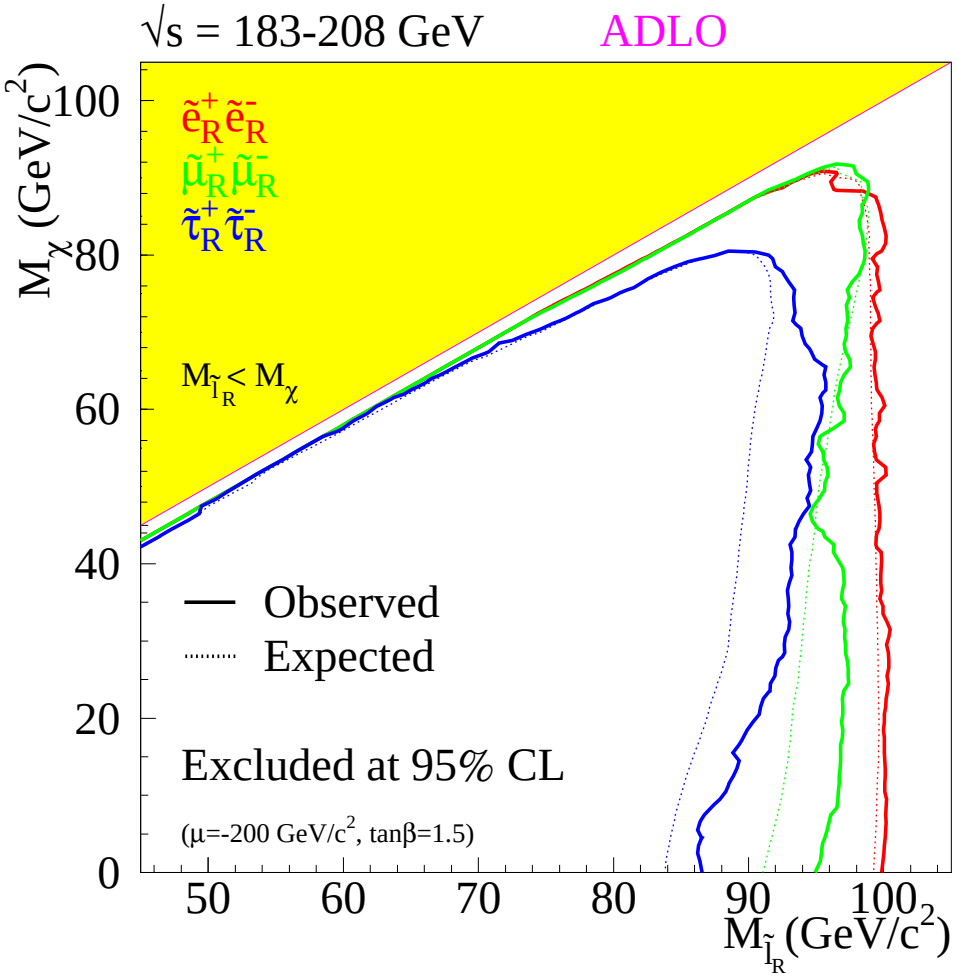
Scalar partners of the charged leptons

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

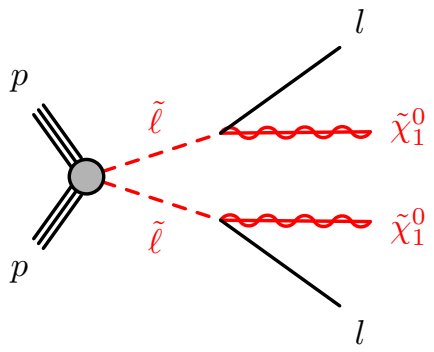
Scalar partners of charged leptons: LEP limits

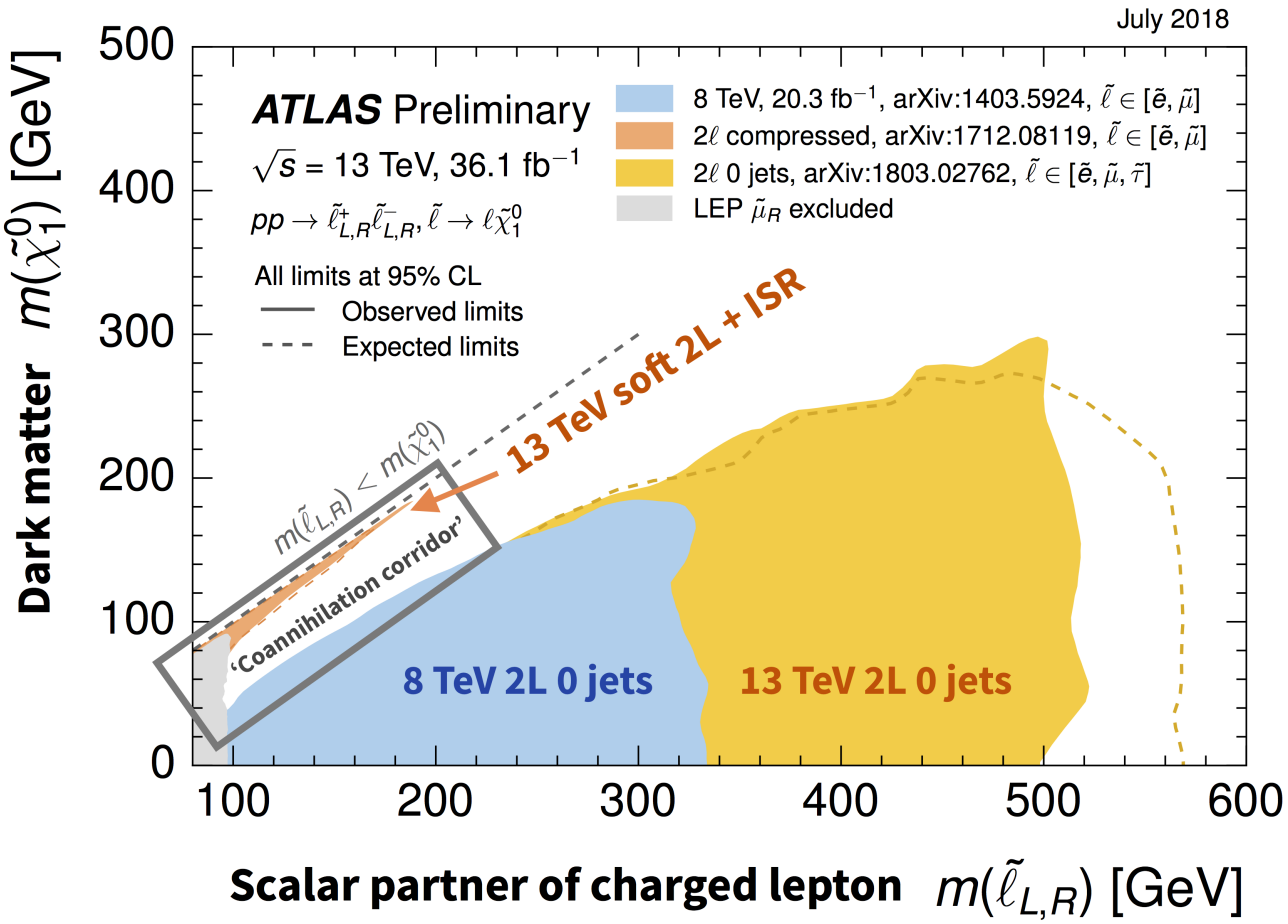


LEP searches extremely clean: mainly $\sqrt{s}$ limited, LEP SUSY Combination Group

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

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



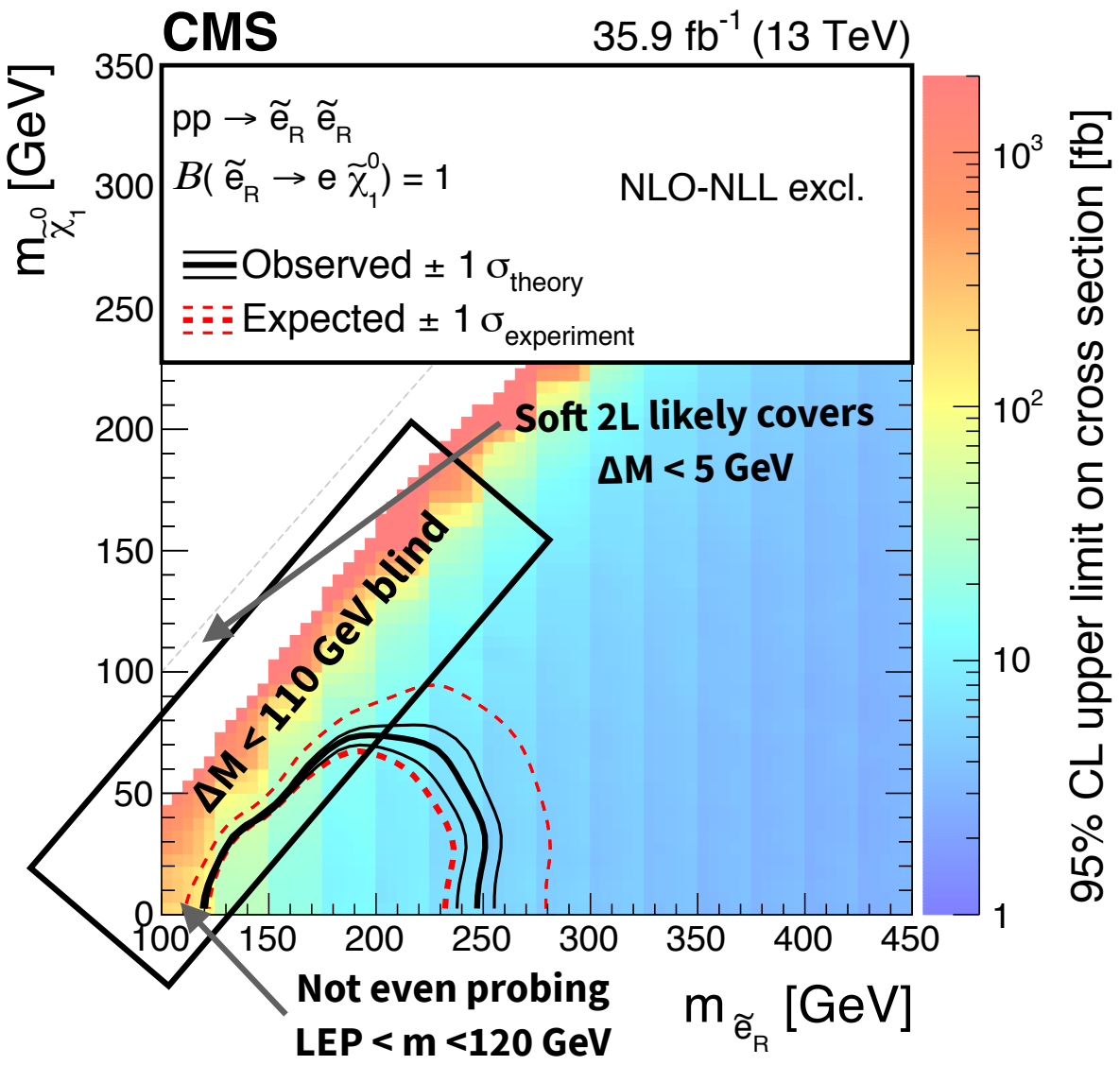


LHC could already be a dark matter factory and we'd have no idea

$m(\tilde{\ell}) \sim 100$ GeV: $\sigma(pp \to \tilde{\ell}\tilde{\ell}) \times \mathscr{L} \sim 730$ fb $\times$ 140 fb^{-1} $\sim$ 100 000 events

See backup for striking gaps in charged fermion (chargino) production

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



CMS 1806.05264, see also ATLAS 1403.5294

Half empty or half full

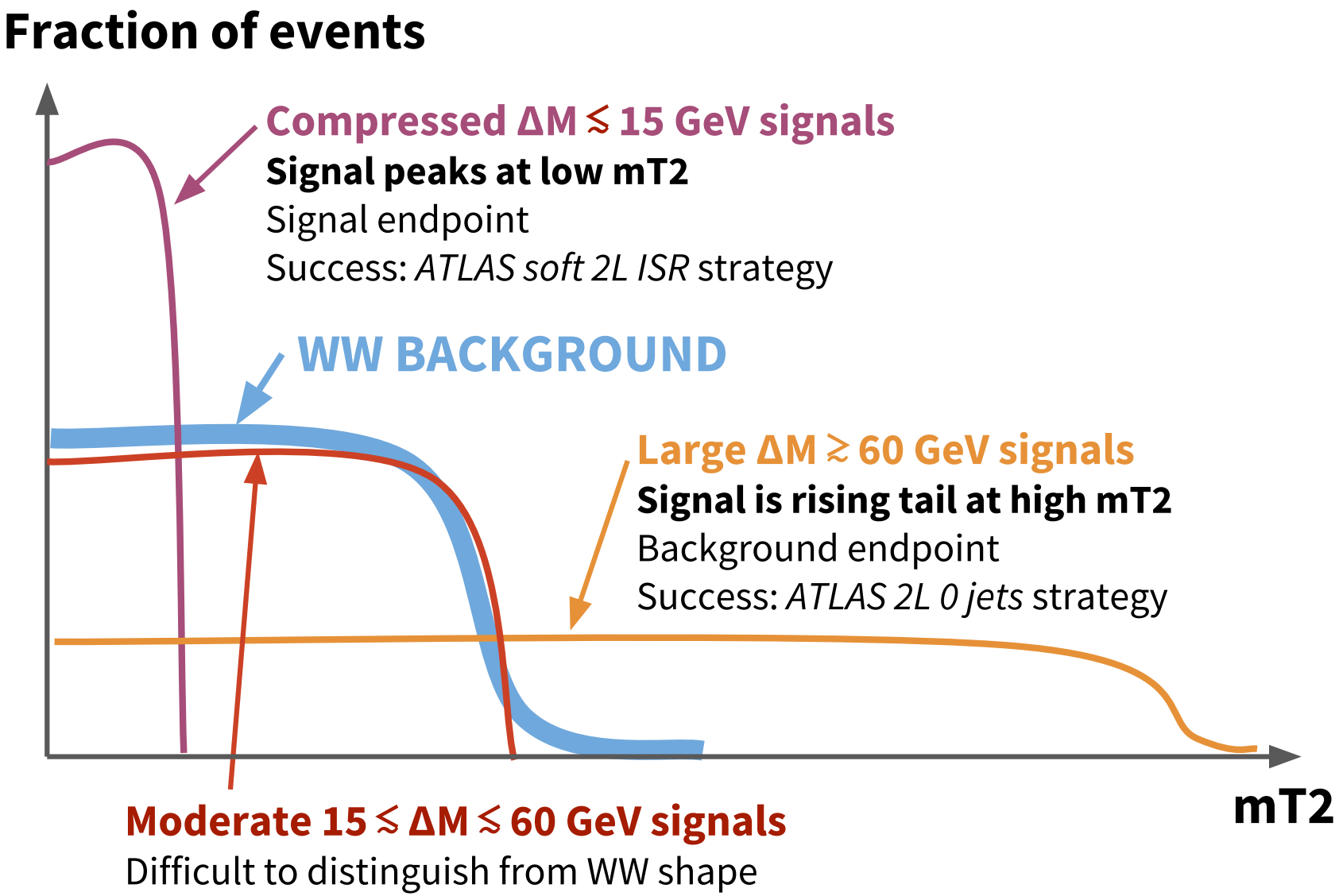
Blind spots = limitations of existing strategies

Blind spots = exciting opportunities for new ideas

Opportunity for forward proton programme

Could be important discovery window

What's hindering sensitivity in the gap?



Heart of problem: fundamental obstruction of hadron collider physics

Desirable

Direct missing momentum 4-vector & missing mass reconstruction

$$p_{\text{miss}} = \sum_{\text{initial}} p_i - \sum_{\text{final}} p_f^{\text{visible}} \Rightarrow \quad m_{\text{miss}}^2 = p_{\text{miss}}^2$$

Obstruction

Per event initial state parton kinematics immeasurable at hadron colliders

$$p_{\text{initial}}(\text{quarks \& gluons}) \quad \text{immeasurable}$$

Consequence

Only transverse component $\mathbf{p}_{\text{T}}^{\text{miss}}$ measurable: lost information

$$\mathbf{p}_{\text{T}}^{\text{miss}} = \mathbf{0} - \sum_{\text{final}} \mathbf{p}_{\text{T}}^{\text{final}}$$

Cannot use neutrino vs DM mass for discrimination

Build physics case: photon collider as solution to pressing problem

Photon collider search strategy for sleptons and dark matter at the LHC

Lydia Beresford[1,*] and Jesse Liu[1,†]

[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^{-1} of 13 TeV proton collisions. We encourage the LHC collaborations to open this forward frontier for discovering new physics.

[arXiv:1811.06465]

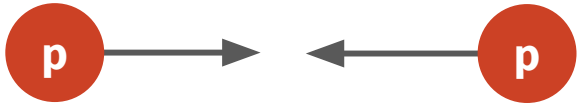
Strategic goal: establish comprehensive & compelling physics case

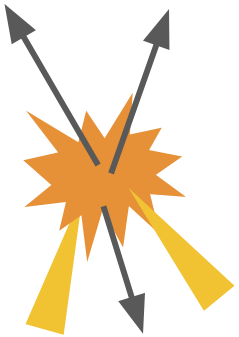
to build critical mass of people & funding for confronting experimental challenges

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

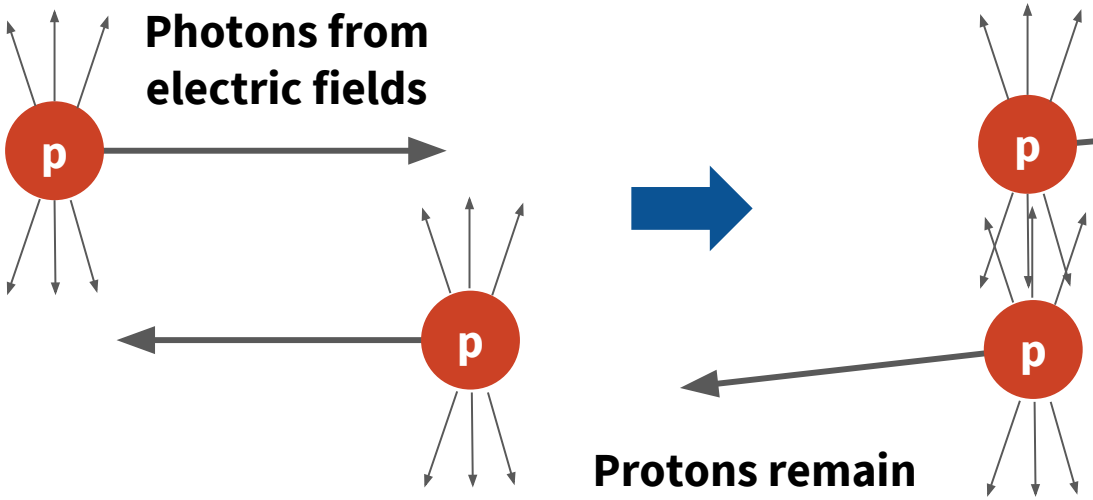




Partons **collide to make new particles**

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

Photons from electric fields

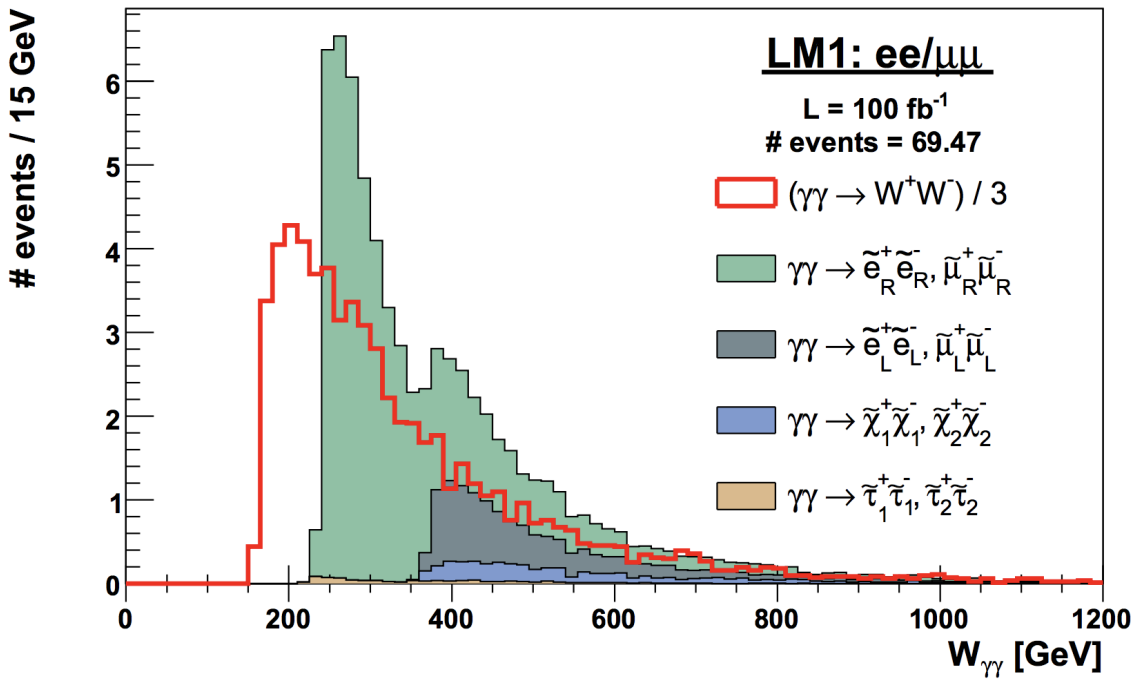


Photons **collide to make new particles**

Protons remain intact & deflected by LHC dipole magnets

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

Photon collider production of sleptons studied 10 years ago



High energy photon interactions at the LHC

J. de Favereau de Jeneret, V. Lemaître, Y. Liu[a], S. Ovyn, T. Pierzchała, K. Piotrzkowski, X. Rouby[b], N. Schul, and M. Vander Donckt[c]

Université catholique de Louvain, Center for Particle Physics and Phenomenolgy (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

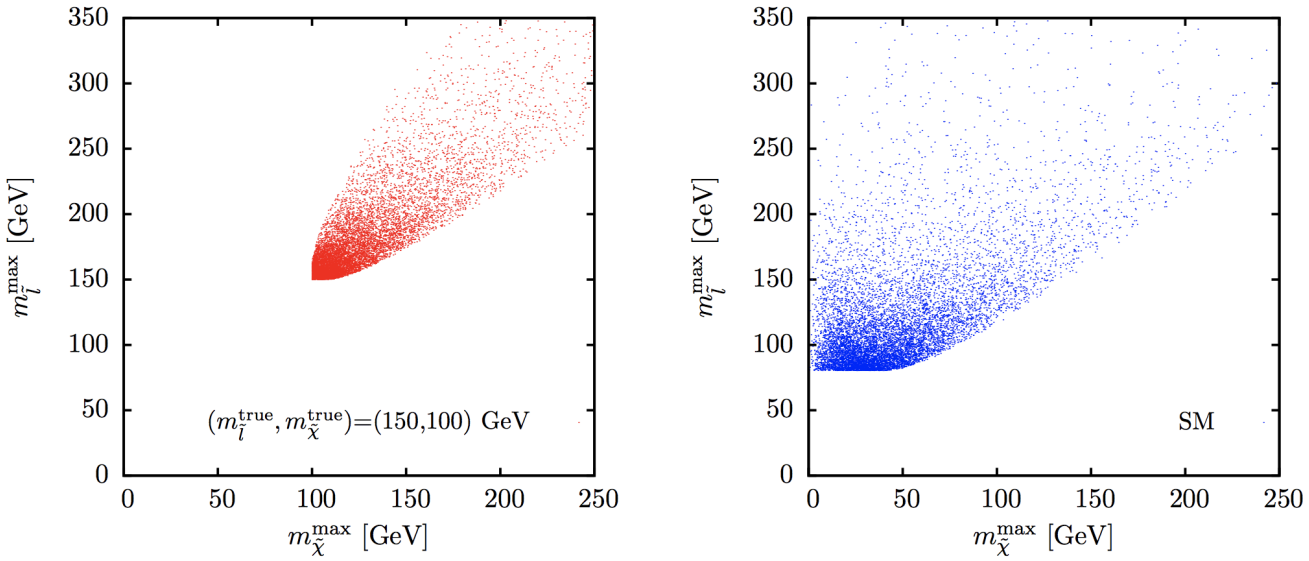


Figure 3: Scatter plots showing the $(m_{\tilde{l}}^{\max}, m_{\tilde{\chi}}^{\max})$ values consistent with each event. Left: SUSY $(m_{\tilde{l}}^{\text{true}}, m_{\tilde{\chi}}^{\text{true}}) = (150, 100)$ GeV. Right: SM. Each plot contains 10,000 events. No detector smearing is included.

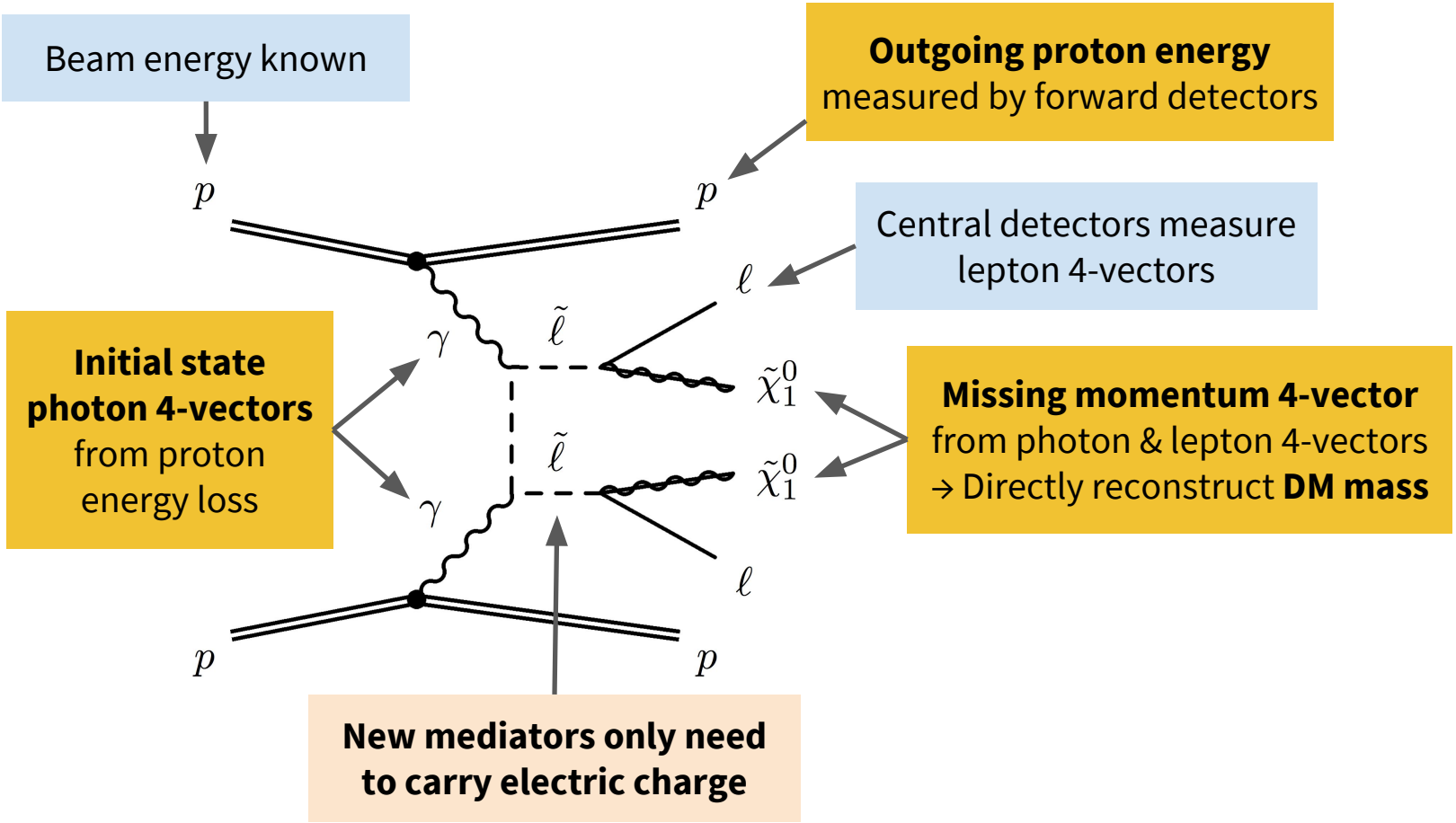
Measuring the masses of a pair of semi-invisibly decaying particles in central exclusive production with forward proton tagging

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

Harland-Lang et. al. [1110.4320]

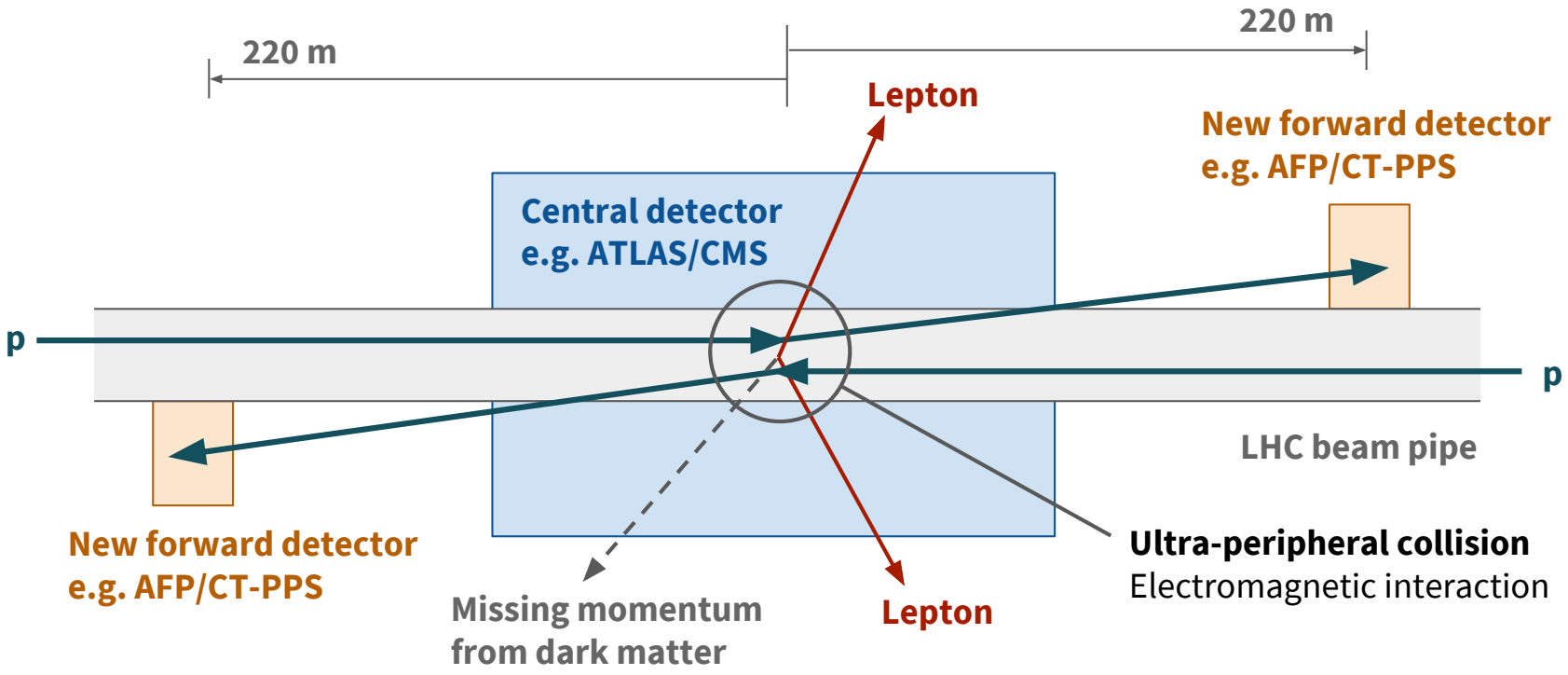
Chose masses very difficult to discover via current electroweak searches!

New kinematic info: initial state & full missing momentum 4-vector



Direct measurement of initial state & missing momentum 4-vector
Impossible in usual LHC collisions

How can we fully exploit this facility & confront challenges?



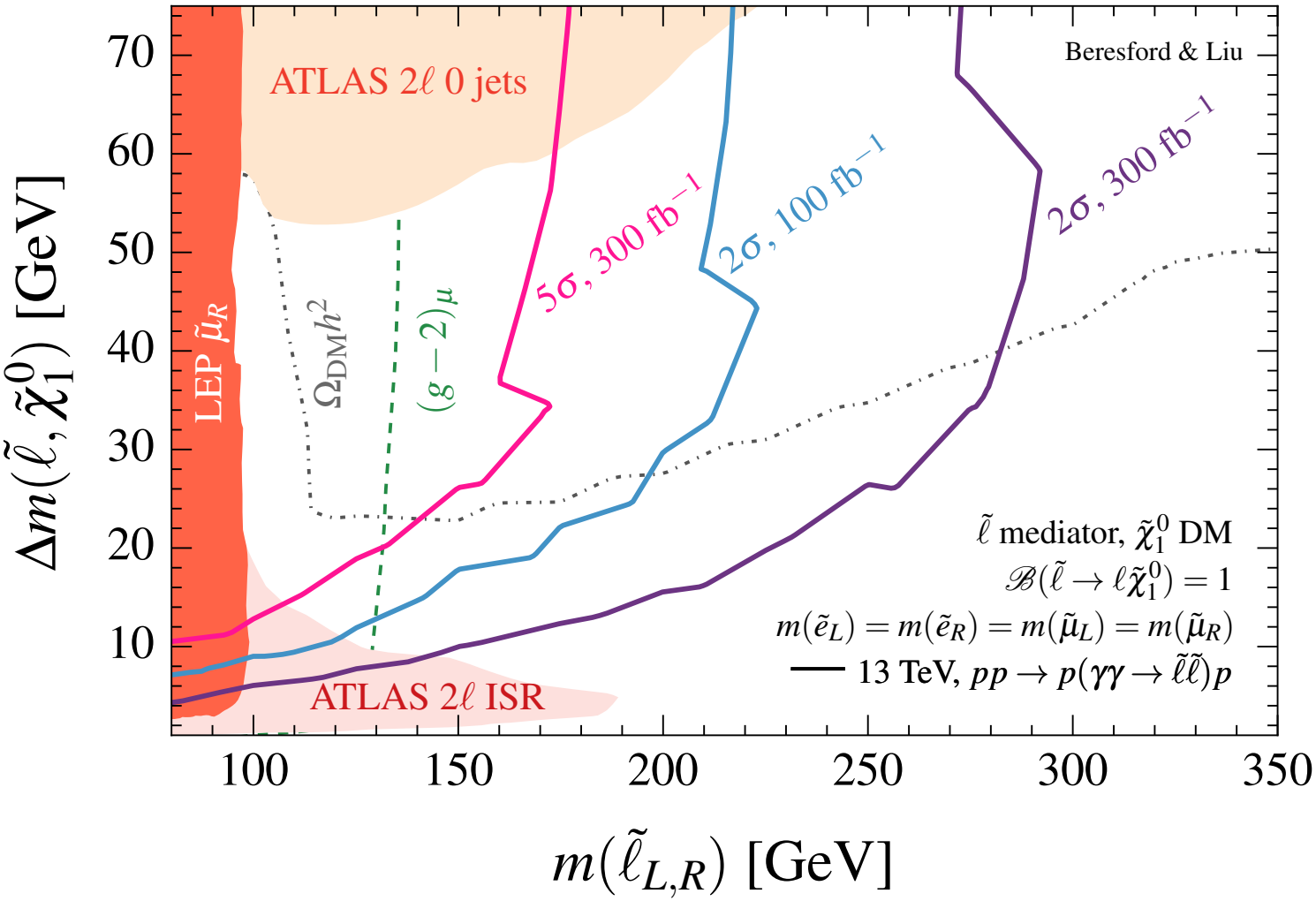
ATLAS Forward Proton, **CMS–TOTEM Precision Proton Spectrometer**

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 $p_{\text{T}}^{\ell} > 15$ GeV: fine for $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \gtrsim 15$ GeV gaps

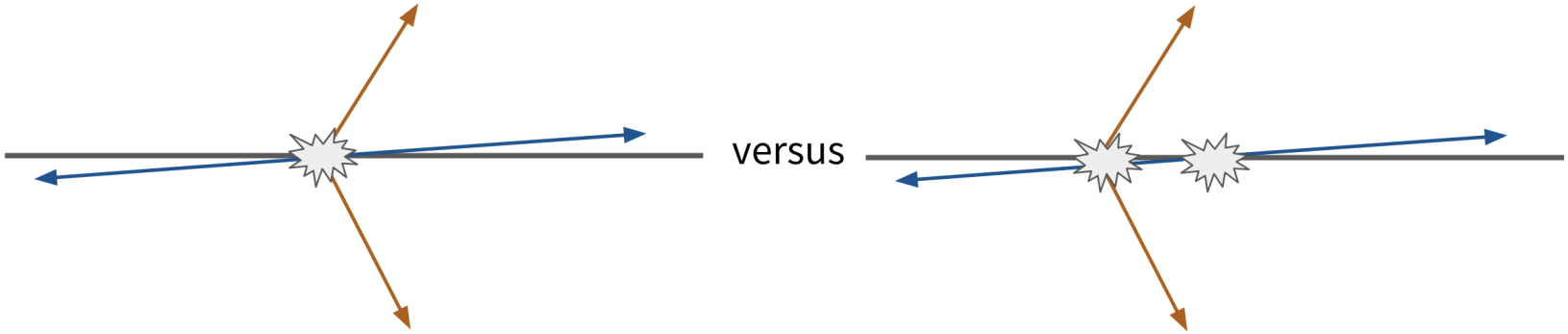
Key plot: central inclusive vs forward exclusive sensitivity



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

Accompanying landmark measurement of $p_{\rm miss}$ at hadron collider

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[1*], V.A. Khoze[2,3†], M.G. Ryskin[3‡] and M. Tasevsky[4§]

1812.04886

What if?

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?

The Dream

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:

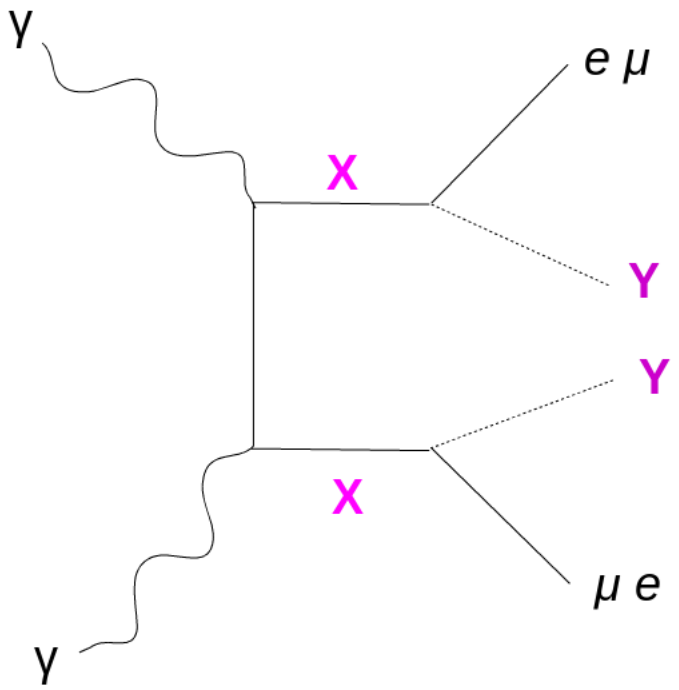
- Inclusive in signal decay mode → Inclusive in bkg decay mode
- Triggering challenging using only forward proton tag
- Pile-up is issue without object to identify interaction vertex
- Need to consider both pomeron-production & photo-production

Exotics: The ultimate lepton + X search

Lepton + X signature is still extremely model-independent & solves many experimental challenges!

Anything charged with a lepton in decay chain

- Can be broad resonance

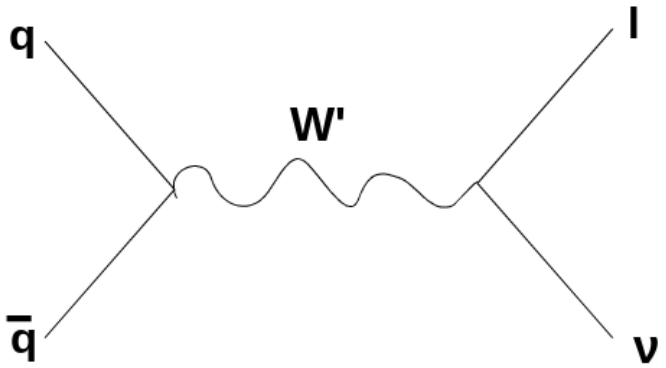


Anything which couples to leptons & X

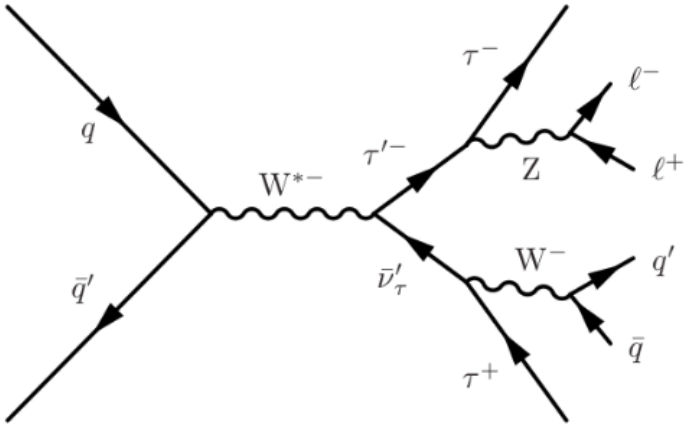
- Can be invisible
- Can be a cascade

Exotics: The ultimate lepton + X search

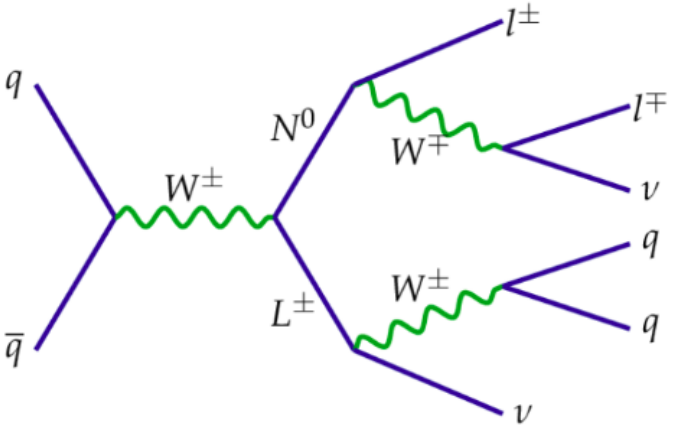
W' Heavy version of W boson



Vector-like Leptons



Seesaw Models with Majorana Neutrinos

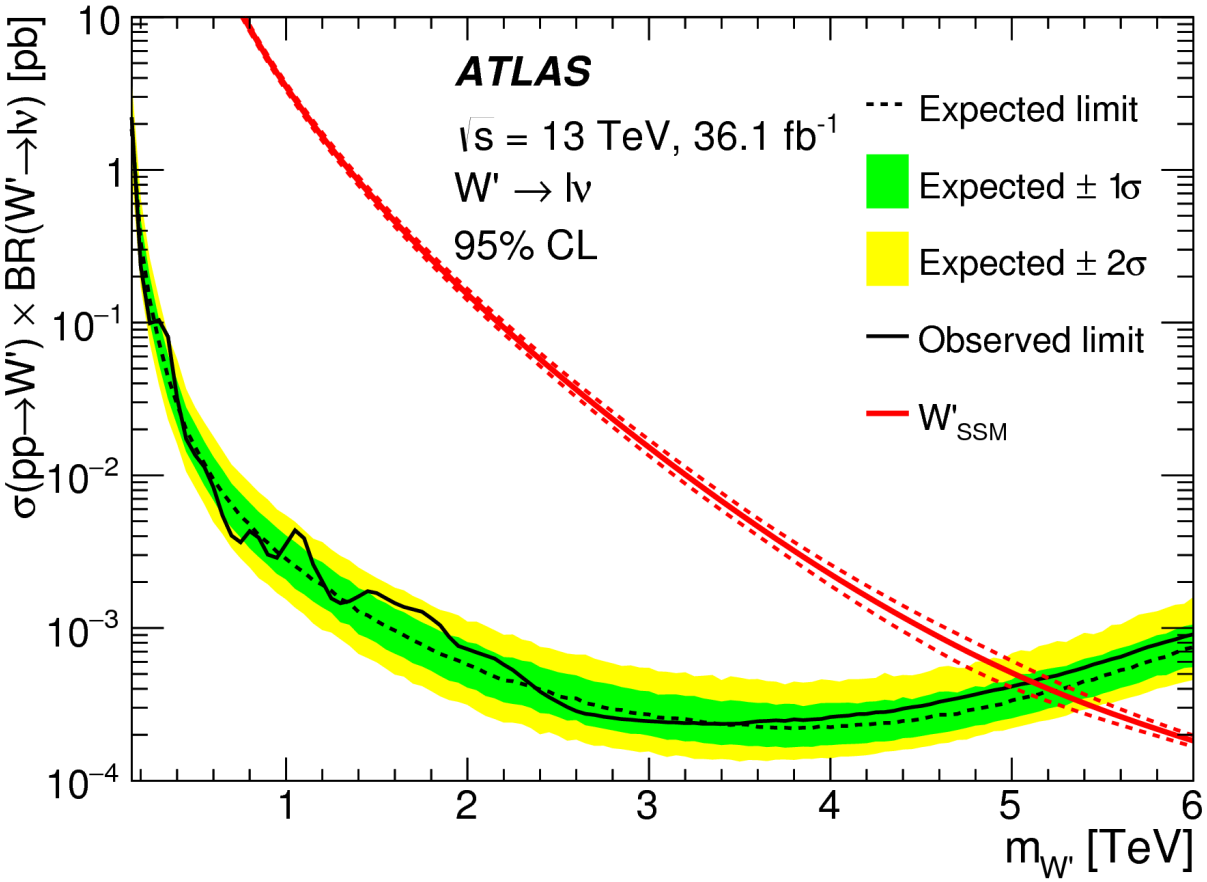


?

Using slepton signals as illustrative example in following plots

Exotics example

Example limit for SSM W' 1706.04786



Observed limit weakens at lower masses due to huge SM backgrounds

Beautiful Variables - Mediator Mass

Scan mass of central system for excesses/thresholds

$\rightarrow \min(m_{\gamma\gamma}) = 2 \times m_X$

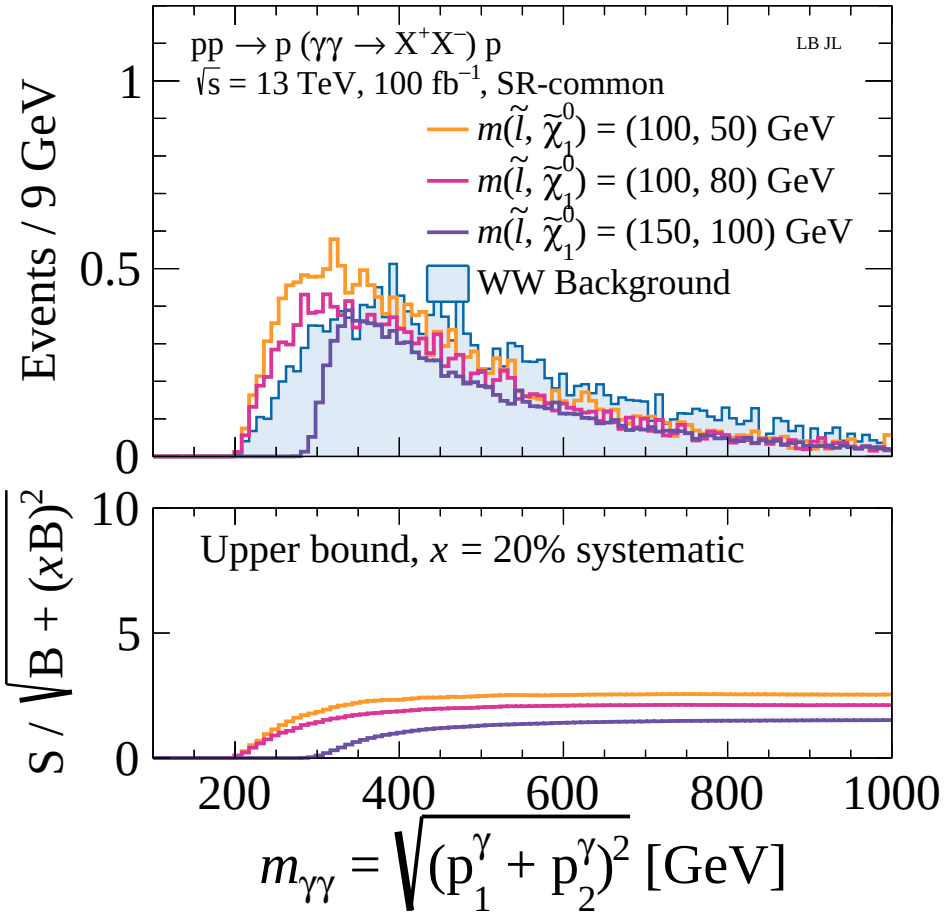
Search for any charged mediator with ≥ 1 lepton in decay chain

$\rightarrow$ 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

$\rightarrow$ Sensitivity to soft lepton scenarios which might otherwise be missed!



Beautiful Variables - Missing Mass

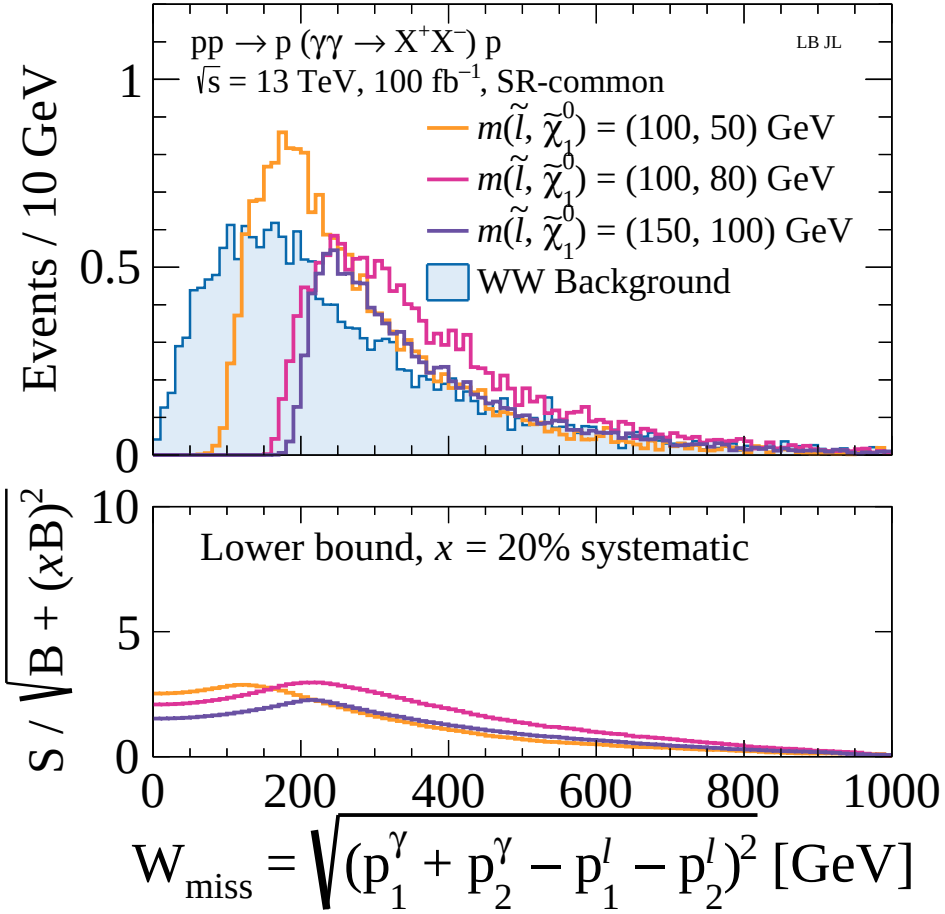
Scan missing mass for excesses/thresholds

$\rightarrow \min(W_{miss}) = 2 \times m_{\gamma}$

Search for anything coupling to leptons & charged mediator

$\rightarrow$ Even invisible particles or particle cascades! Notoriously challenging with central only info!

Missing mass provides powerful discrimination against WW bkg with $\sim$ massless ν & allows mass determination



Beautiful Variables - Mass Splitting

Scan mass splitting for excesses/peaks

→ peaks at 2 x $m_{splitting}$

Could do 2D bumpHunt in $m_{\gamma\gamma}$ and W_{miss}

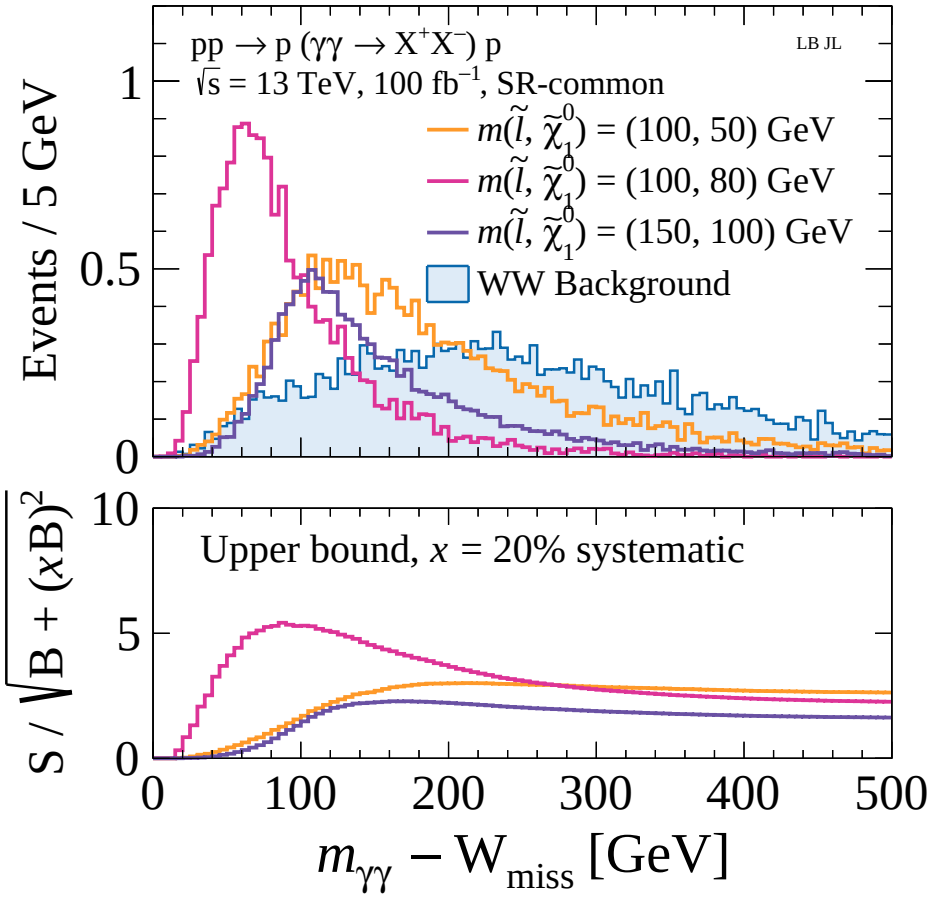
→ Too sparse at low lumi?

Can also combine information: $m_{\gamma\gamma} - W_{\text{miss}}$

→ Simple alternative

→ Retain stats as 1D

→ Great signal & bkg separation enhances significance!!



Just the tip of an iceberg of world firsts @ hadron collider

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: $\gamma\gamma \to WW$ guaranteed SM search.

New reconstruction: decay-independent mass measurement of parent.

New outreach: using light to reveal the darkness.

Acknowledgements

Many thanks Moritz Backes, Alan Barr, Till Eifert, Will Fawcett, Barak Gruberg, Phil Harris, Ian Hinchliffe, Valery Khoze, Markus Klute, Tommaso Lari, Larry Lee, Zach Marshall, Simone Pagan Griso, Santiago Paredes, Christoph Paus, Andy Pilkington, Jesse Thaler, Haichen Wang for interesting discussions.

EXTRAS

THE SEARCHLIGHT IS SHIFTING
from spectacular to subtle discoveries

Opportunities & challenges for
soft, rare, quirky signals

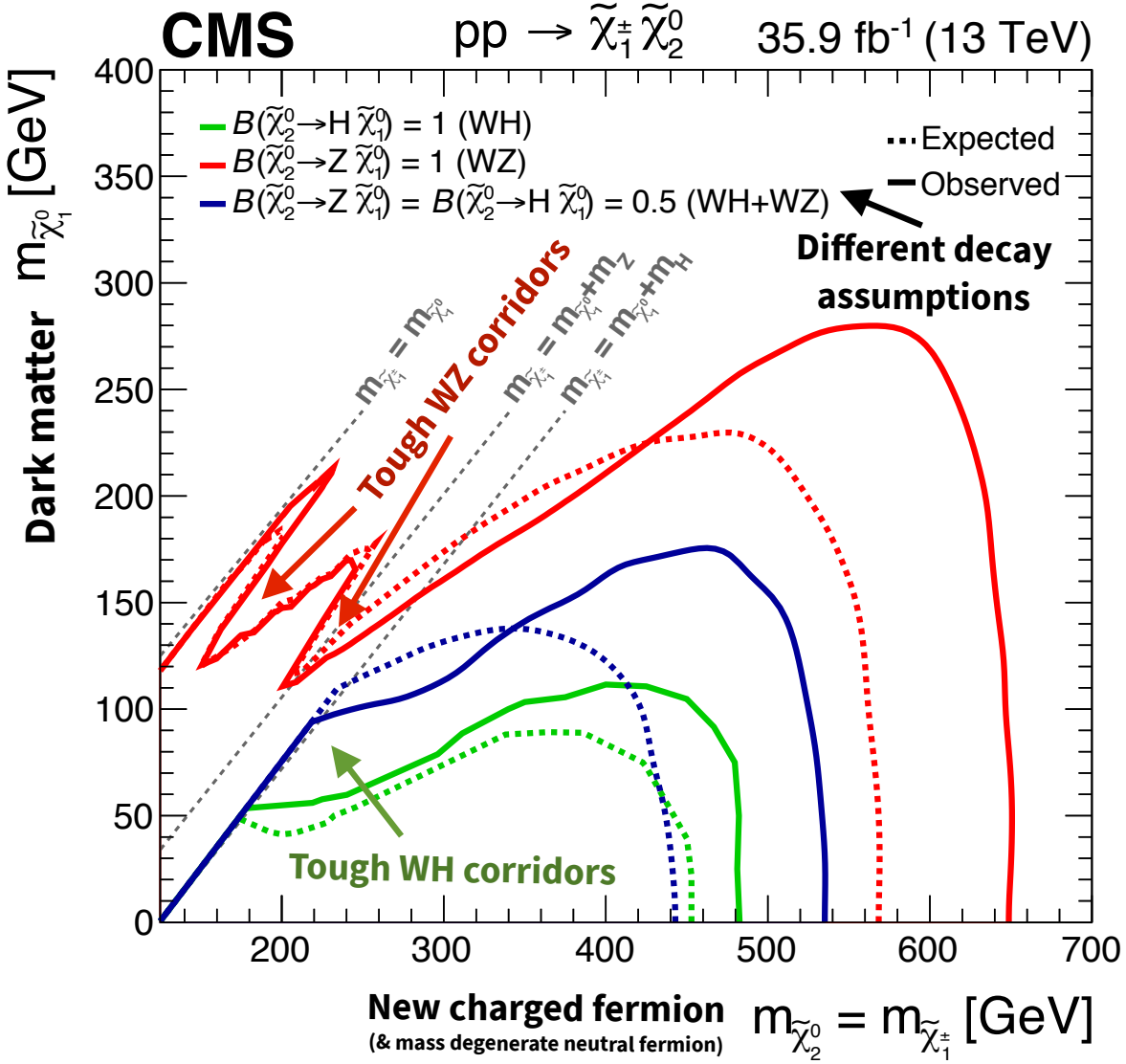
Soft stuff
Particle identification
Trigger thresholds

Rare SUSY
Colourless sparticles
Dark sector

Quirky creatures
Displaced difficulties
Long-lived exotica

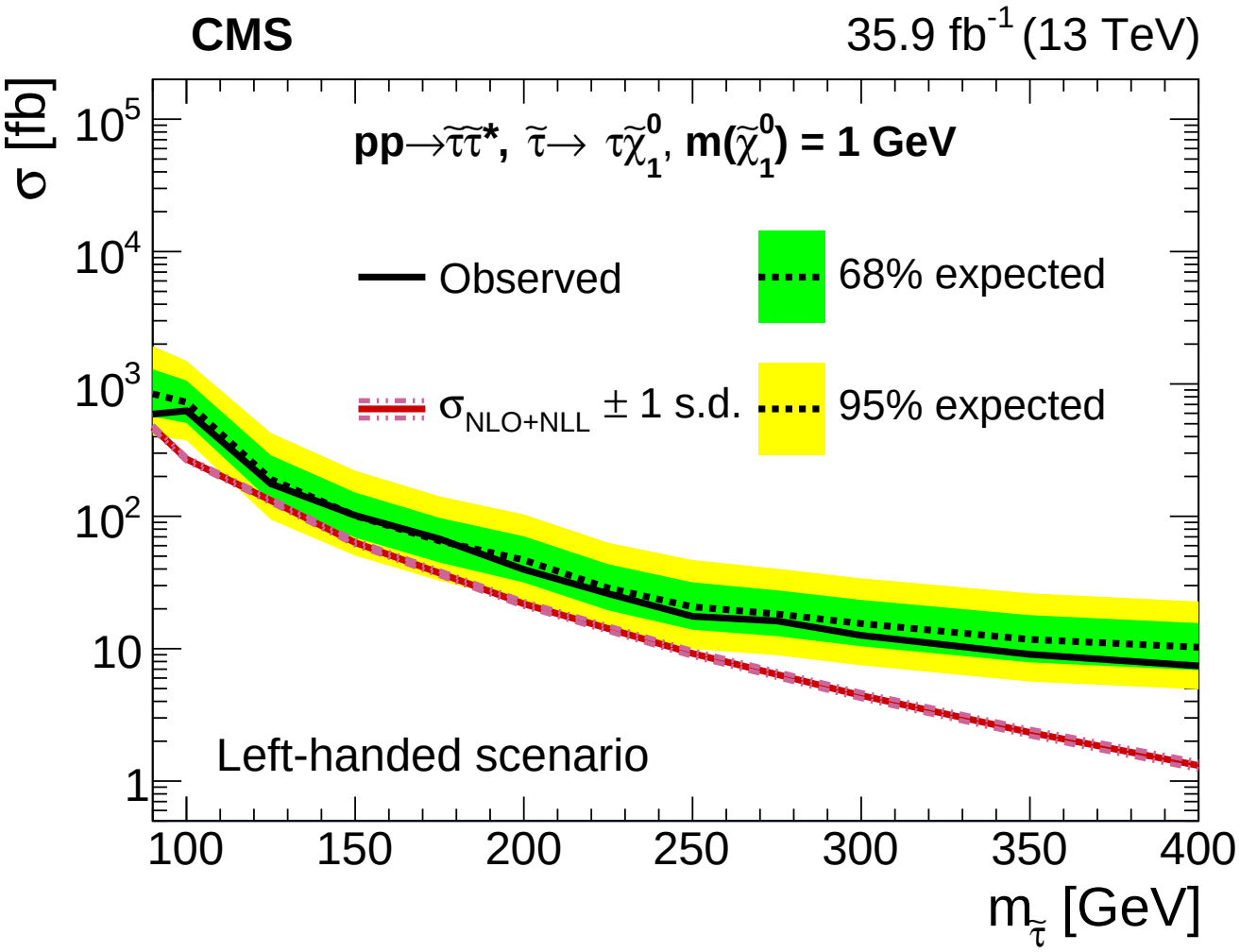
Case study
Electroweak SUSY

Chargino–neutralino production: tough corridors due to SM backgrounds



CMS 1801.03957, see also ATLAS 1803.02762

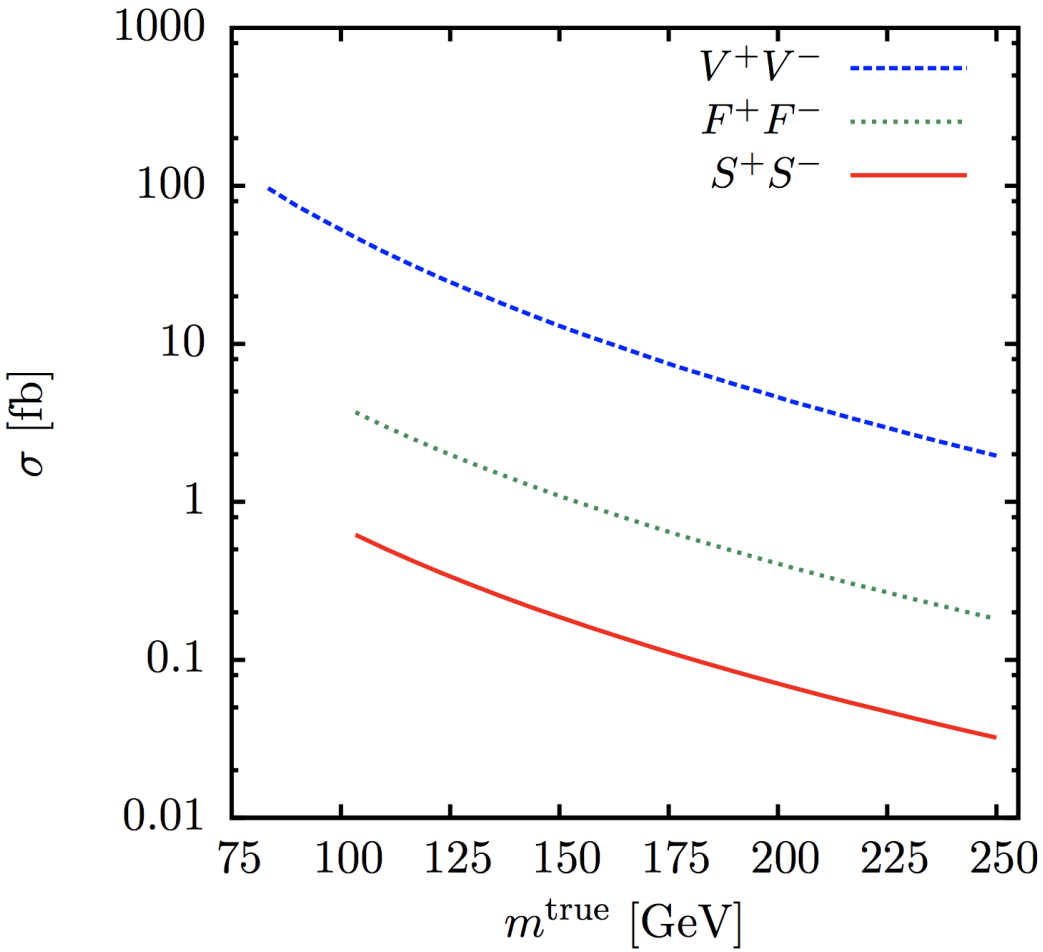
Staus: currently no LHC sensitivity even in most optimistic scenario



CMS 1807.02048 hadronic & lepton tau analysis

Expect full Run 2 dataset results soon. Will not discuss staus further today.

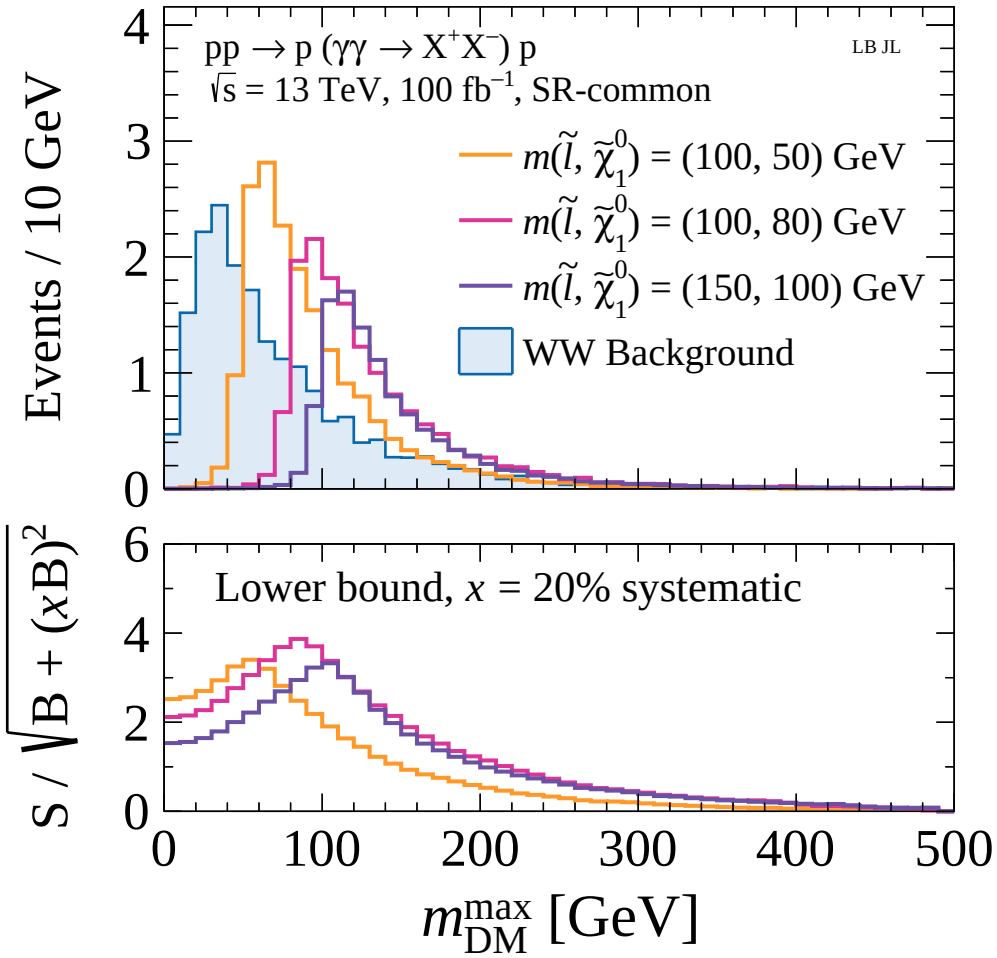
14 TeV cross-sections $pp \to p(\gamma\gamma \to X^+X^-)p$



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



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

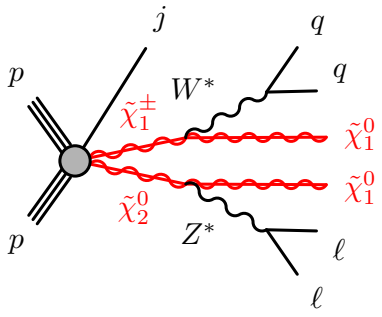
Variable from Harland–Lang et. al. [arXiv:1110.4320]

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

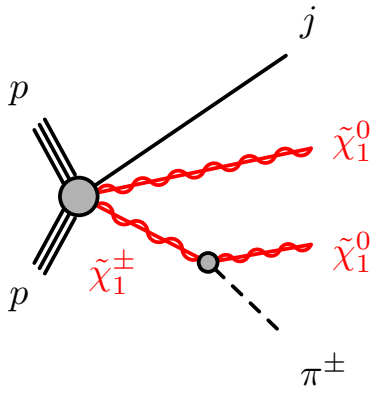
Sub-100 GeV Higgsino dark matter: the 'prompt–long-lived gap'



Soft 2ℓ

$p_T(e,\mu) > 4.5, 4$ GeV

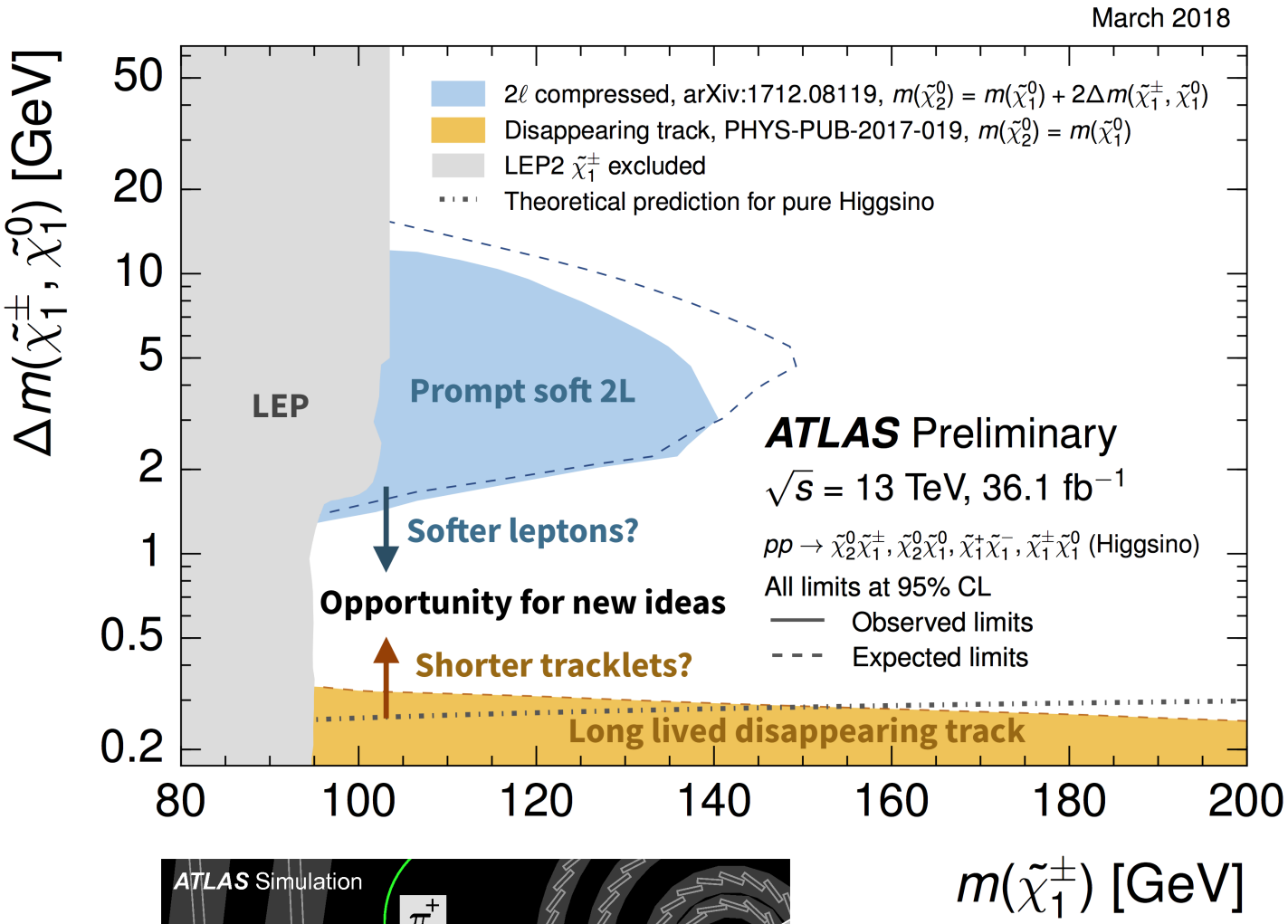
[1712.08119]

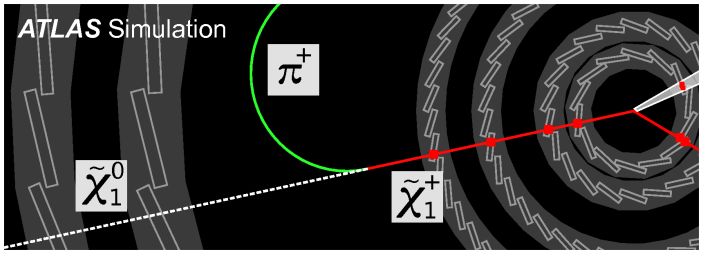


Disappearing track

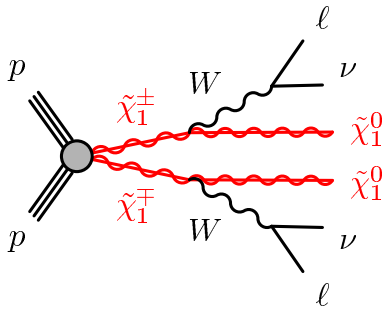
Pixel tracklets

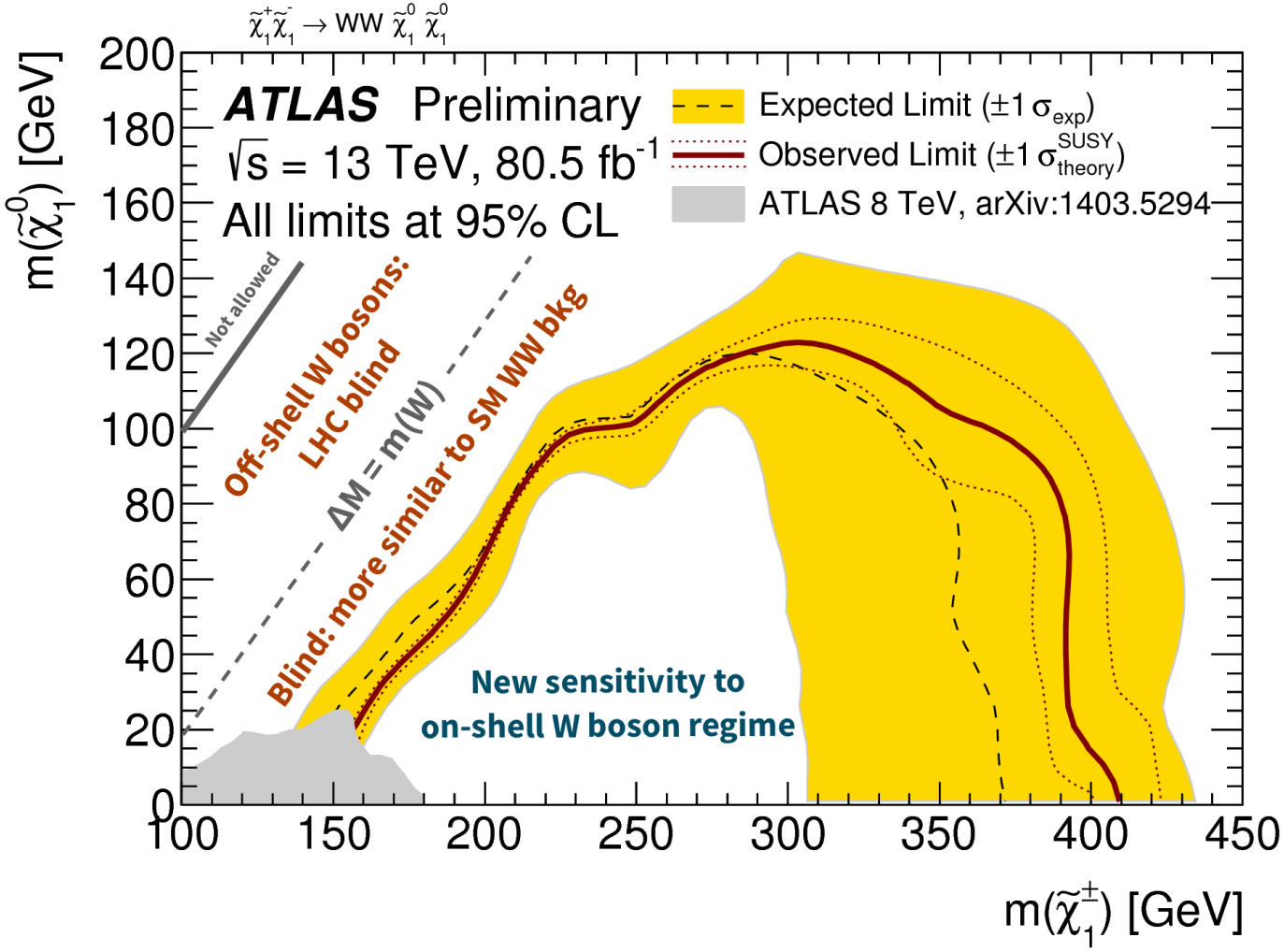
[1712.02118, PUB-2017-019]





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



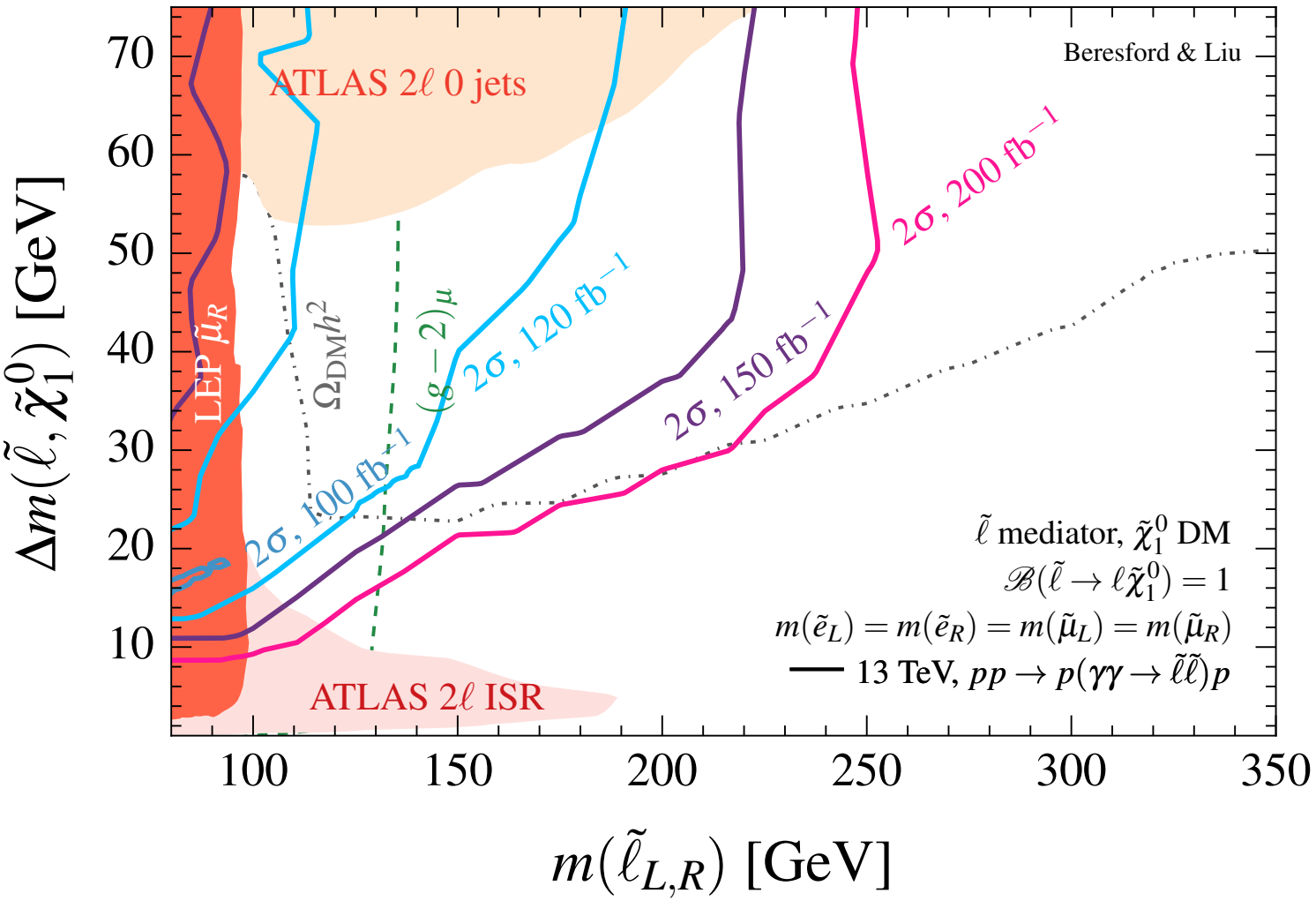


ATLAS-CONF-2018-042 (80 fb^{-1}), see also CMS 1807.07799 (36.1 fb^{-1})

$m(\tilde{\chi}_1^{\pm}) = 105$ GeV: $\sigma(pp \to \tilde{\chi}_1^+\tilde{\chi}_1^-) \sim 10$ pb $\times 100$ fb $\Rightarrow$ 1 million events!

But blind due to formidable SM $WW \to \ell\nu\ell\nu$ 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 → 0.03