PHOTON COLLIDERS

FOR THE FUTURE OF FUNDAMENTAL PHYSICS

YETI 2019

Durham University

8 January 2019

Jesse Liu

In collaboration with Lydia Beresford

University of Oxford

UNIVERSITY OF OXFORD

PROLOGUE : THE CRISIS

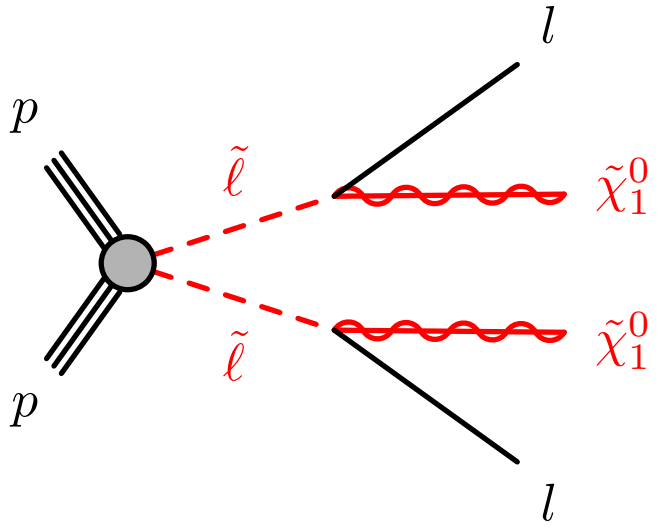
WHY HAVEN'T WE SEEN NEW PHYSICS?

Deepest experimental tragedy we must avoid:

Build a **dark matter factory** but **we could not detect it**

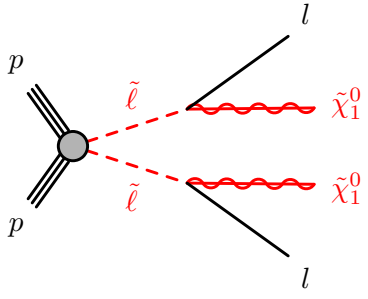
What do I mean by this?

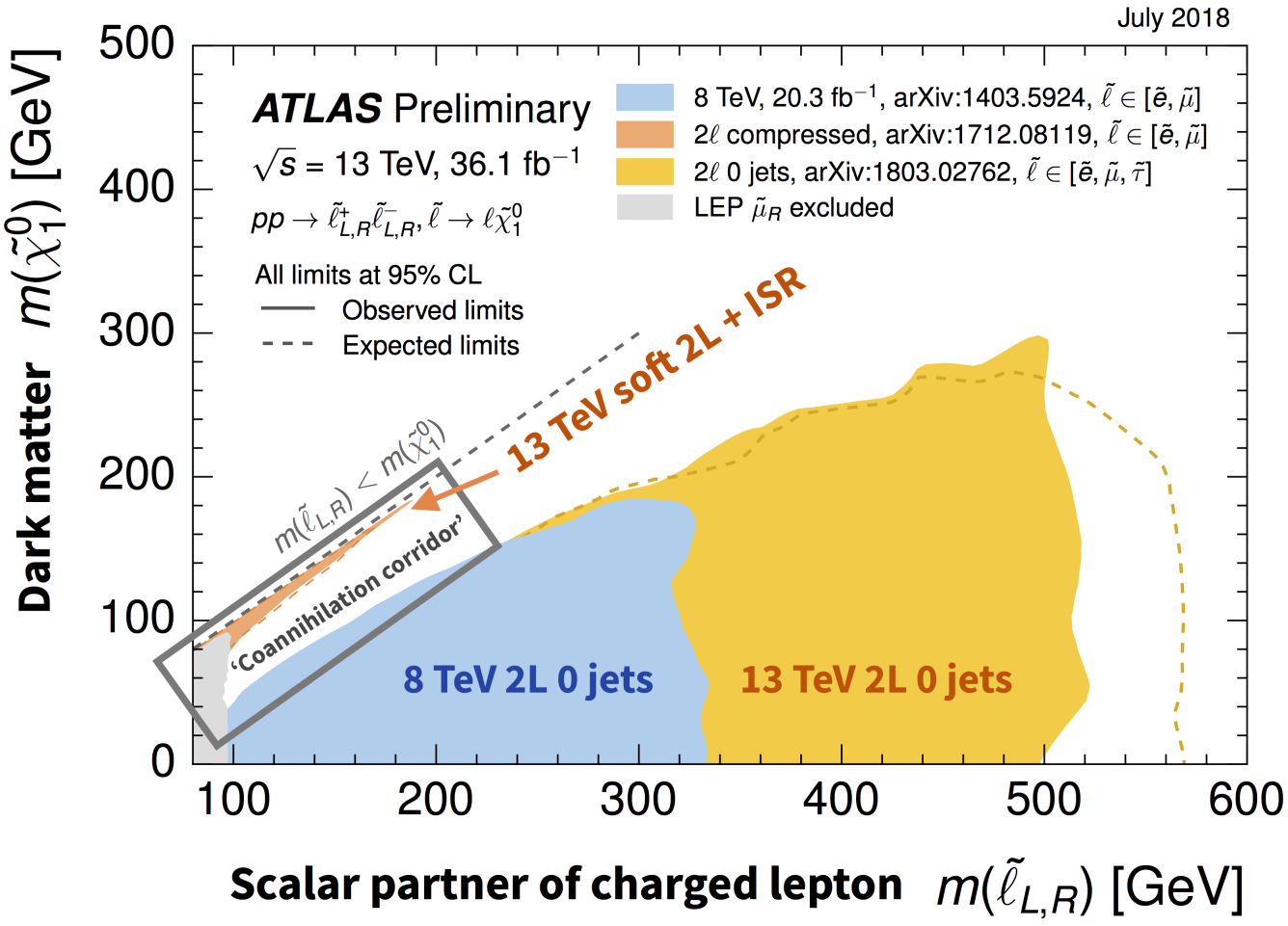
Case study: sleptons = spin 0 partners of leptons



Scalar leptons $\tilde{\ell}$ decay to fermionic dark matter $\tilde{\chi}_1^0$

Striking blind spot: more data does not guarantee discovery



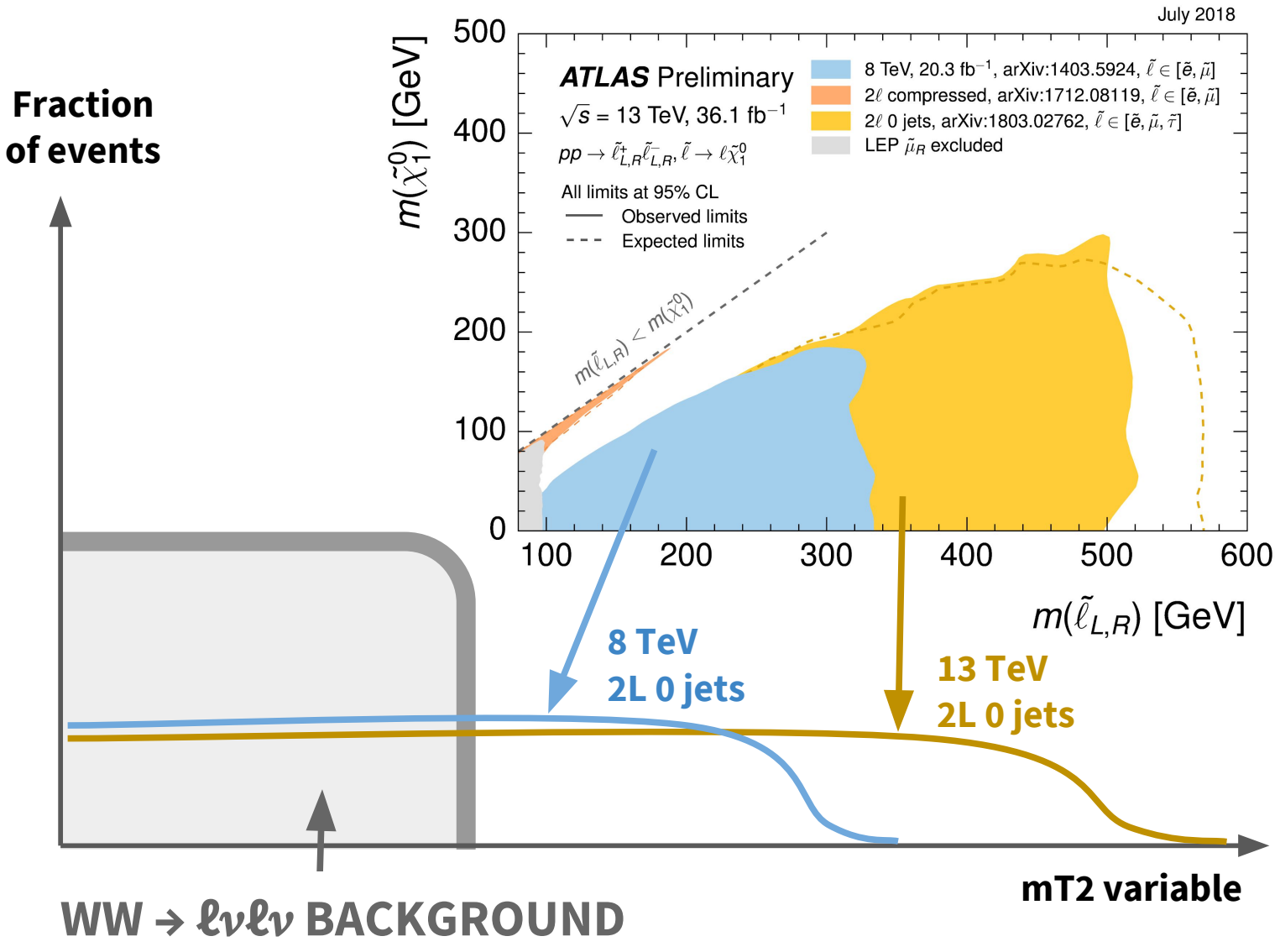


LHC could already be a dark matter factory and we'd have no idea!

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

ATLAS SUSY Summary Plots, LHC SUSY Cross-section Working Group

What's hindering sensitivity?



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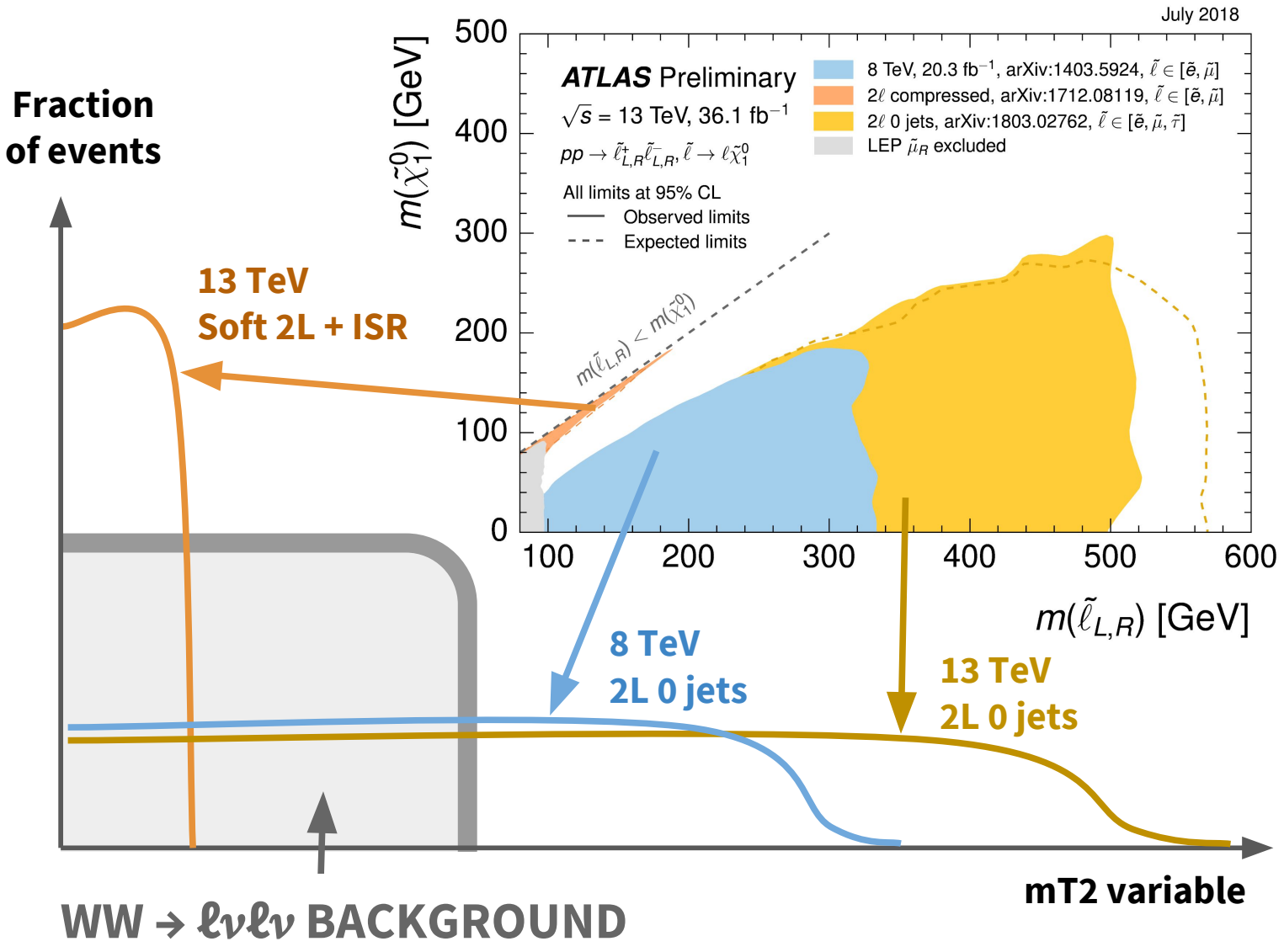

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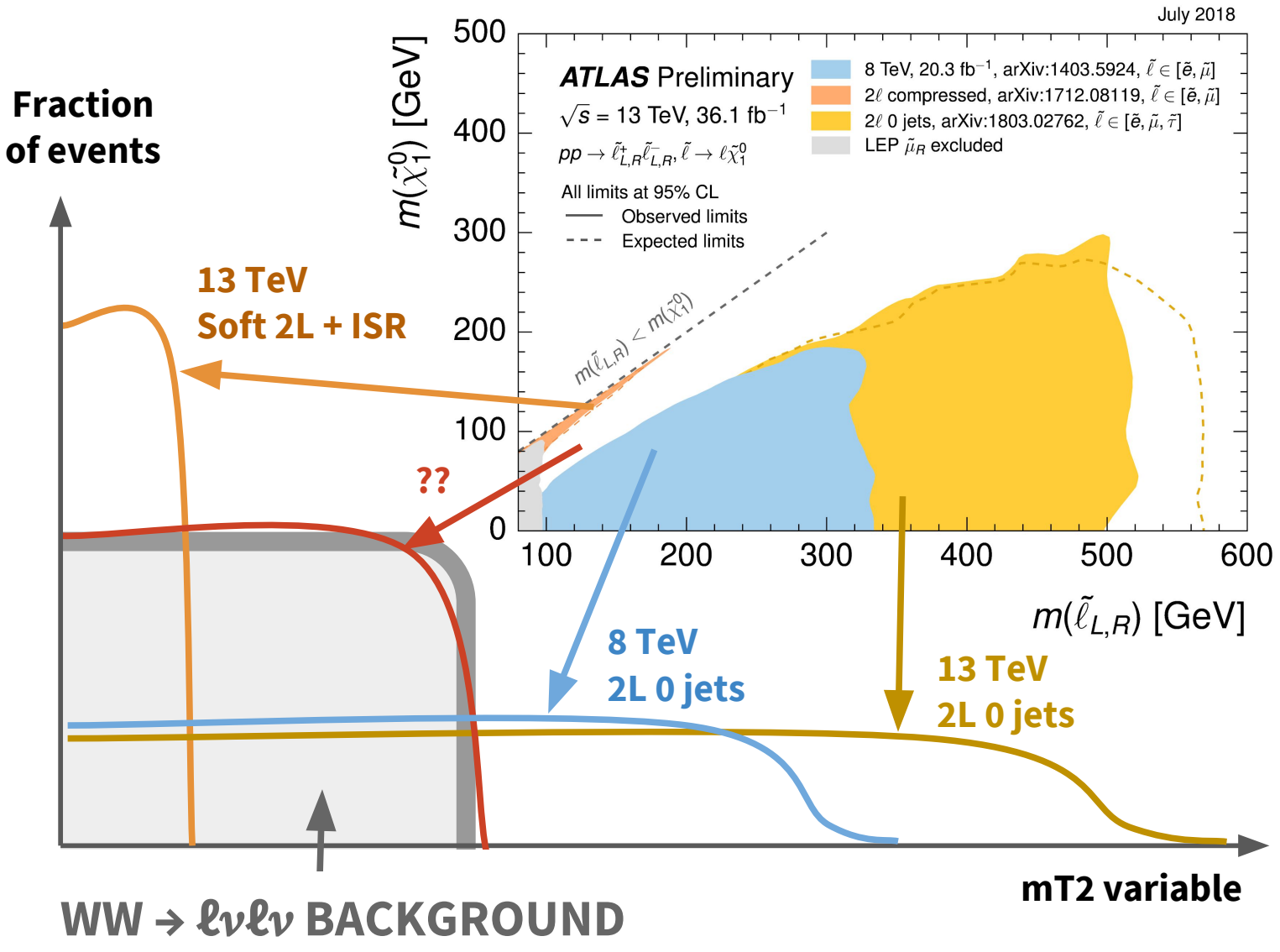


Heart of problem: fundamental obstruction of hadron collider physics

Desirable

Direct missing momentum & 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

Generic to Tevatron, LHC, HL-LHC, FCC-hh

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

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 discriminate *massless* neutrinos ν vs *massive* dark matter χ

Propose solution to long-standing open problem

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

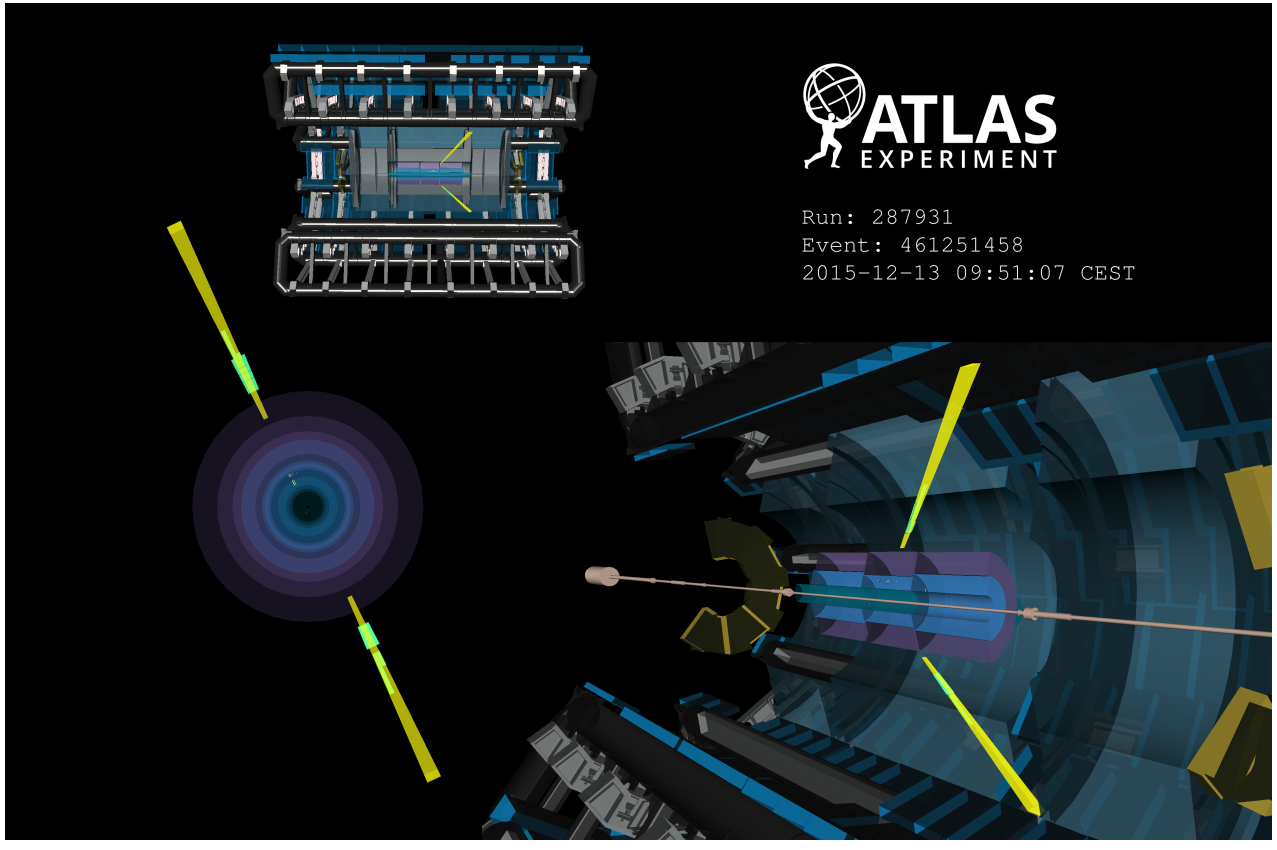
Lydia Beresford[1,*] and Jesse Liu[1,†]

[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]

Photon collisions (PbPb) as evidence for photon quantum self-interaction

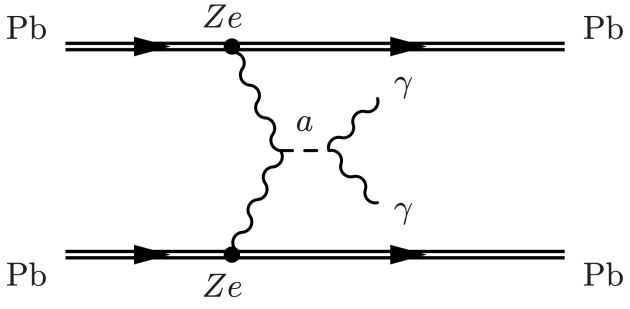


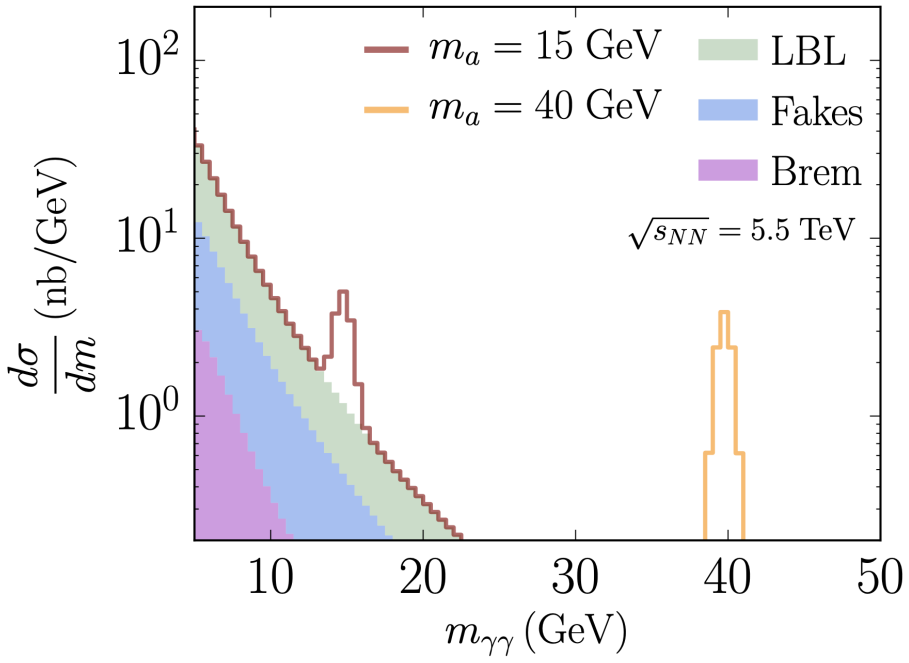
ARTICLES
PUBLISHED ONLINE: 14 AUGUST 2017 | DOI: 10.1038/NPHYS4208
nature physics
OPEN

Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

[1702.01625]

Photon collisions (PbPb) as bumphunt searches for new physics





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]

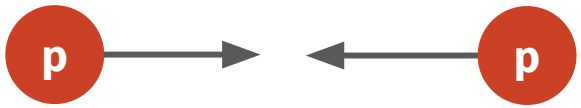
[1] *Department of Physics, University of California, Berkeley, California 94720, USA*
[2] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

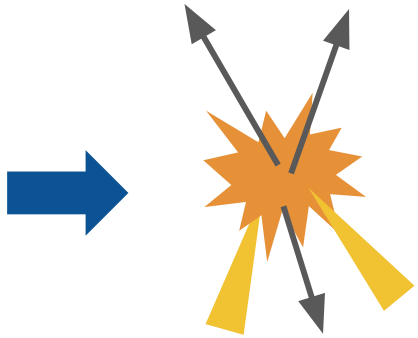
(Dated: May 5, 2017)

[1607.06083]

Photon collider (pp) cross-sections make this interesting today

Usual head-on proton–proton collisions

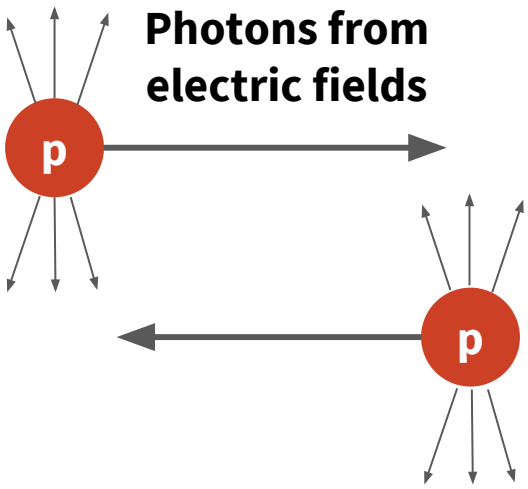


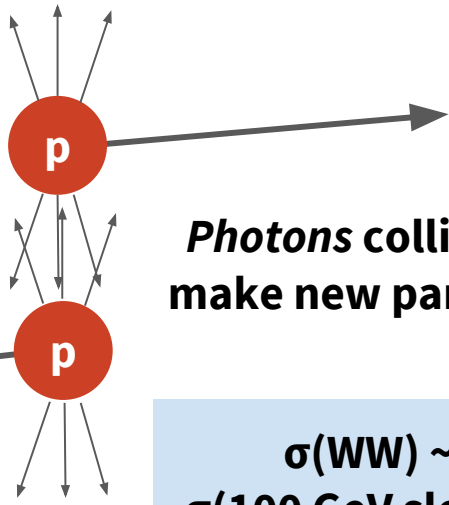


Partons **collide to make new particles**

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

Photons from electric fields



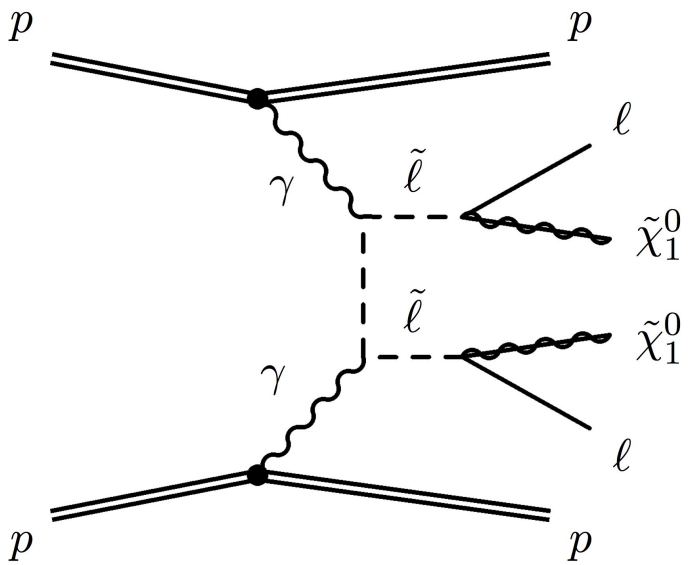


Photons **collide to make new particles**

Protons remain intact & deflected by LHC dipole magnets

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

QED production of slepton pairs



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

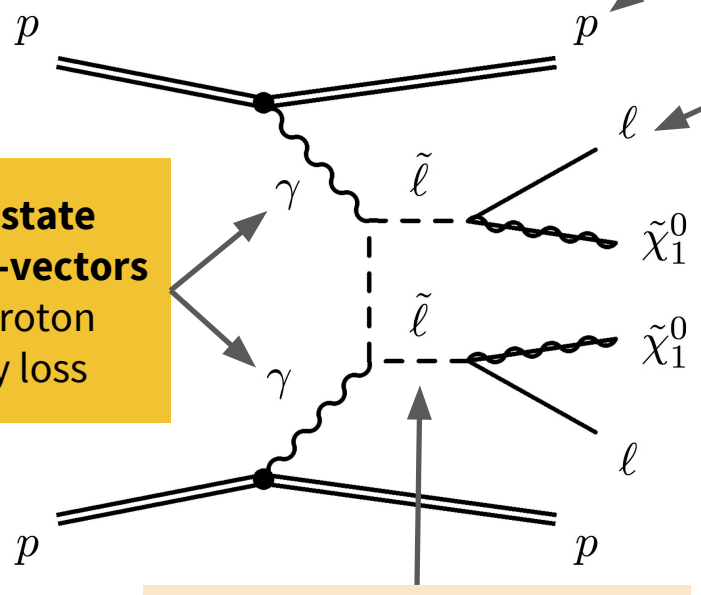
Beam energy known

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

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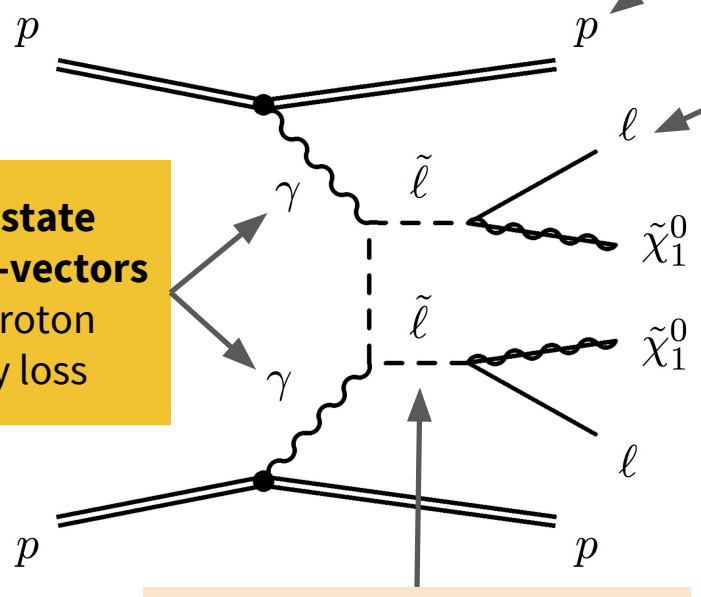
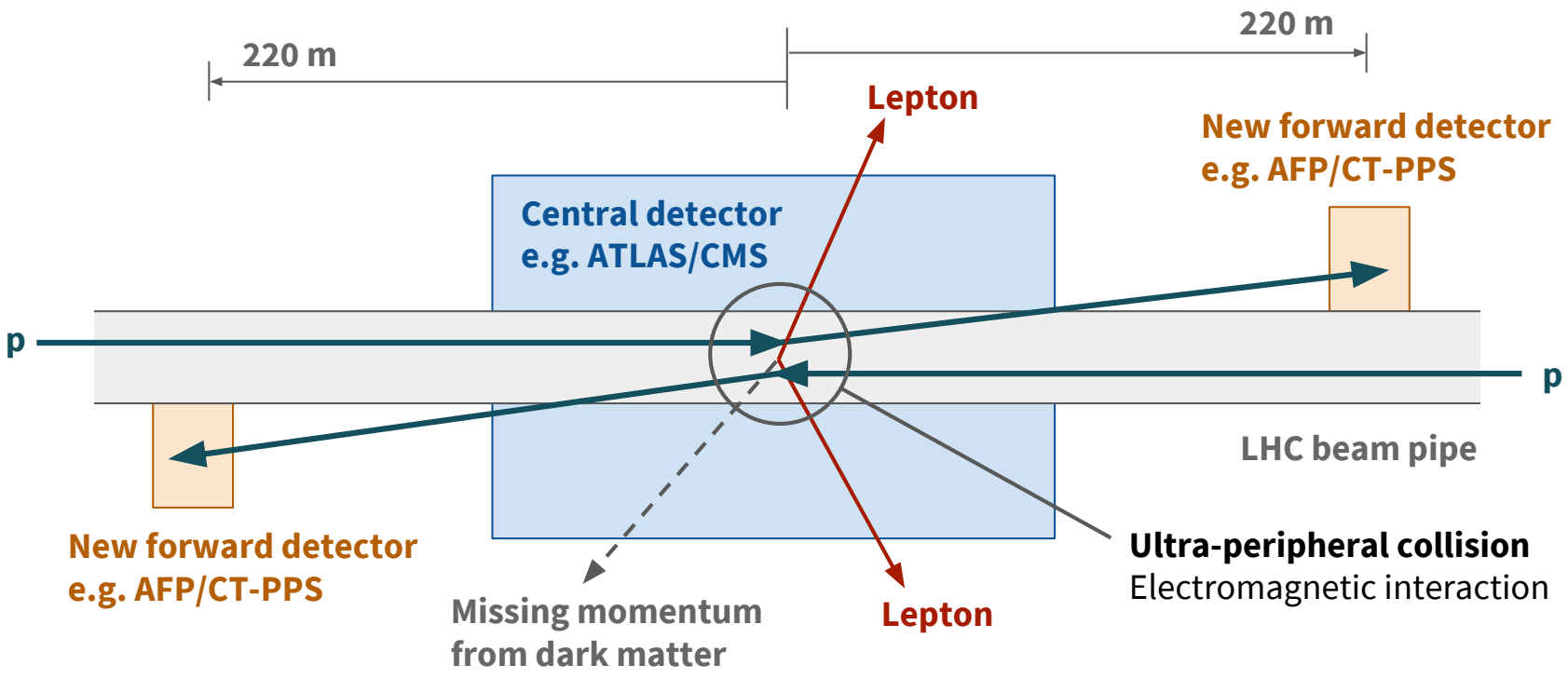


New mediators only need to carry electric charge

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

Creativity: using the LHC beyond its original design



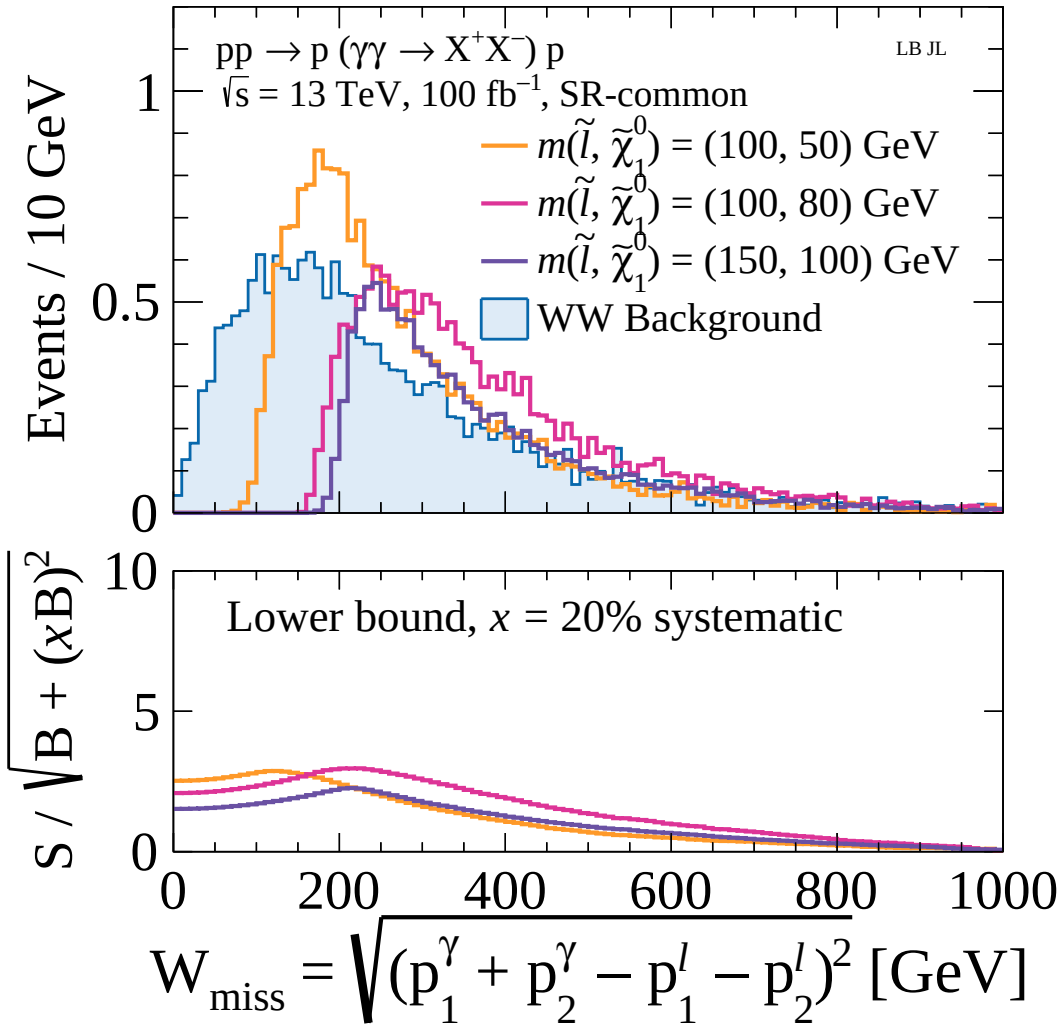
ATLAS Forward Proton, **CMS–TOTEM Precision Proton Spectrometer**

Forward detectors inserted within mm of beam, already collected ~ 100 fb^{-1}

Intact protons detectable when $150 \lesssim E^{\text{loss}}_{\text{proton}} \lesssim 1000$ GeV

Use lepton triggers $p^{\ell}_{\text{T}} > 15$ GeV: ok for $\Delta m(\tilde{\ell}, \tilde{\chi}^0_1) \gtrsim 15$ GeV gaps

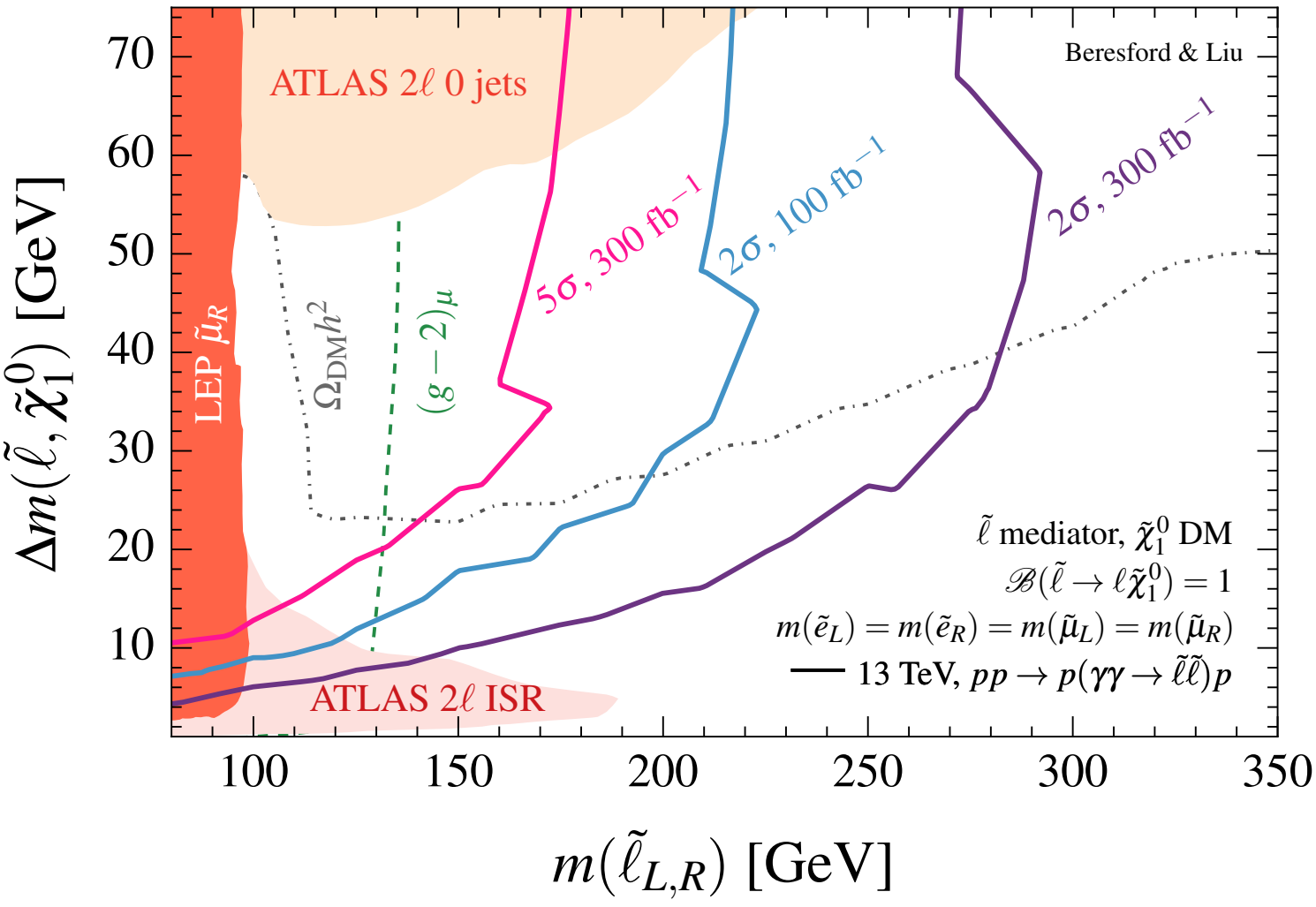
Missing mass: new Lorentz invariant impossible in conventional collisions



Directly reconstruct dark matter mass: $W^2_{\text{miss}} = p^2_{\text{miss}} \geq (2m_{\tilde{\chi}_1^0})^2$

Next: add data points for landmark LHC measurement of p_{miss} & W_{miss}

Success: photon collider (lines) surpasses existing strategies (shaded)



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

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.

E P I L O G U E

WHAT CRISIS?

"We are struggling to find clear indications that can point us in the right direction.
Some people see in this state of crisis a source of frustration.
I see a source of excitement because
***new ideas have always thrived in moments of crisis**."*

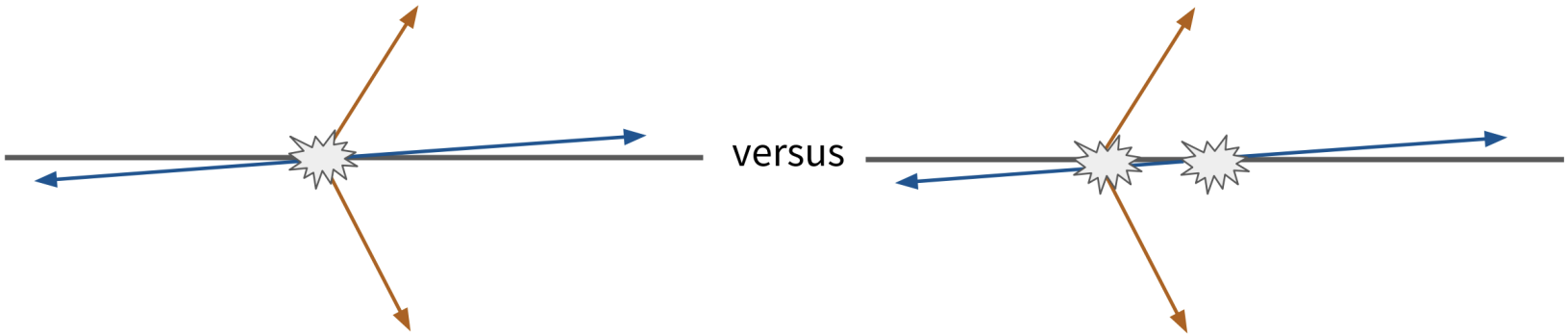
— Gian Giudice

Acknowledgements

Many thanks Alan Barr, Moritz Backes, Till Eifert, Will Fawcett, Barak Gruberg, Lucian Harland–Lang, 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

Example challenge: pileup mitigation



Proton arrival time matched with **lepton** vertex
⇒ ULTRAPERIPHERAL

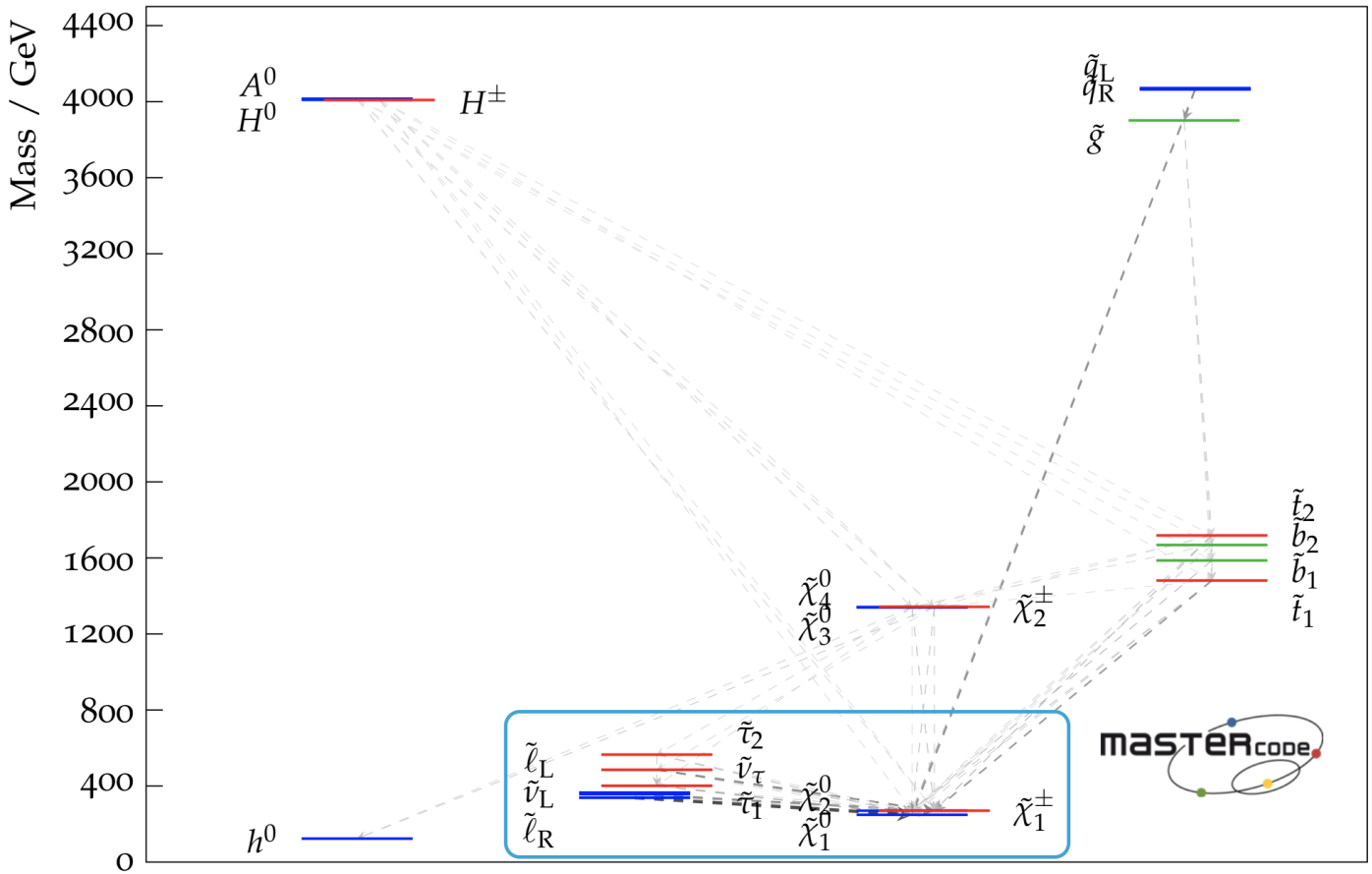
Proton arrival time NOT matched with **lepton** vertex
⇒ PILEUP

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 is the big picture data telling us?



Light sleptons favoured by global fits: best fit point of 11-parameter MSSM

Mastercode collaboration 1710.11091, see also GAMBIT 1705.07917

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

THE SEARCHLIGHT IS SHIFTING
from spectacular to subtle discoveries

Opportunities & challenges for
soft, rare, quirky signals

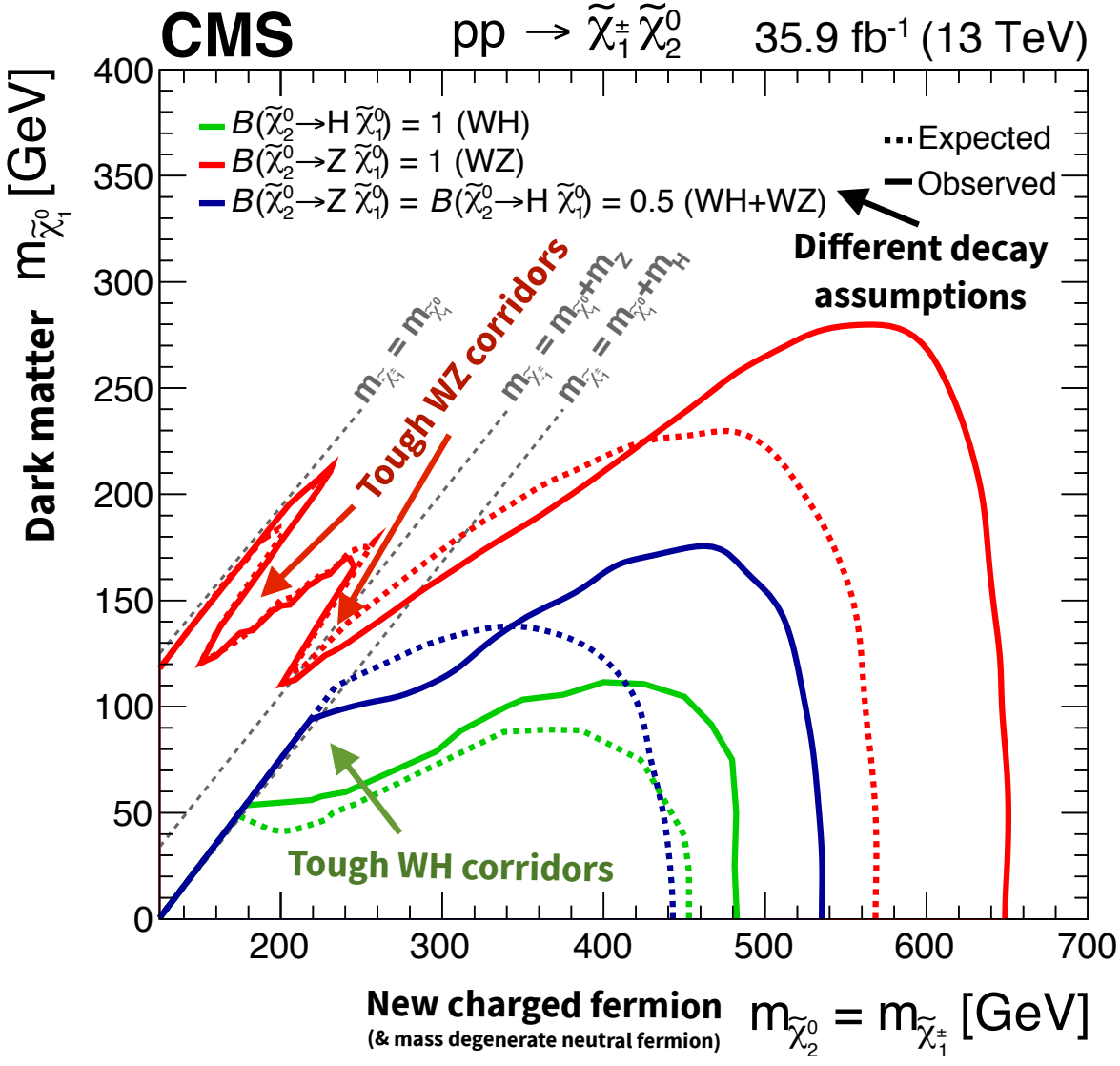
Soft stuff
Particle identification
Trigger thresholds

Rare SUSY
Colourless sparticles
Dark sector

Quirky creatures
Displaced difficulties
Long-lived exotica

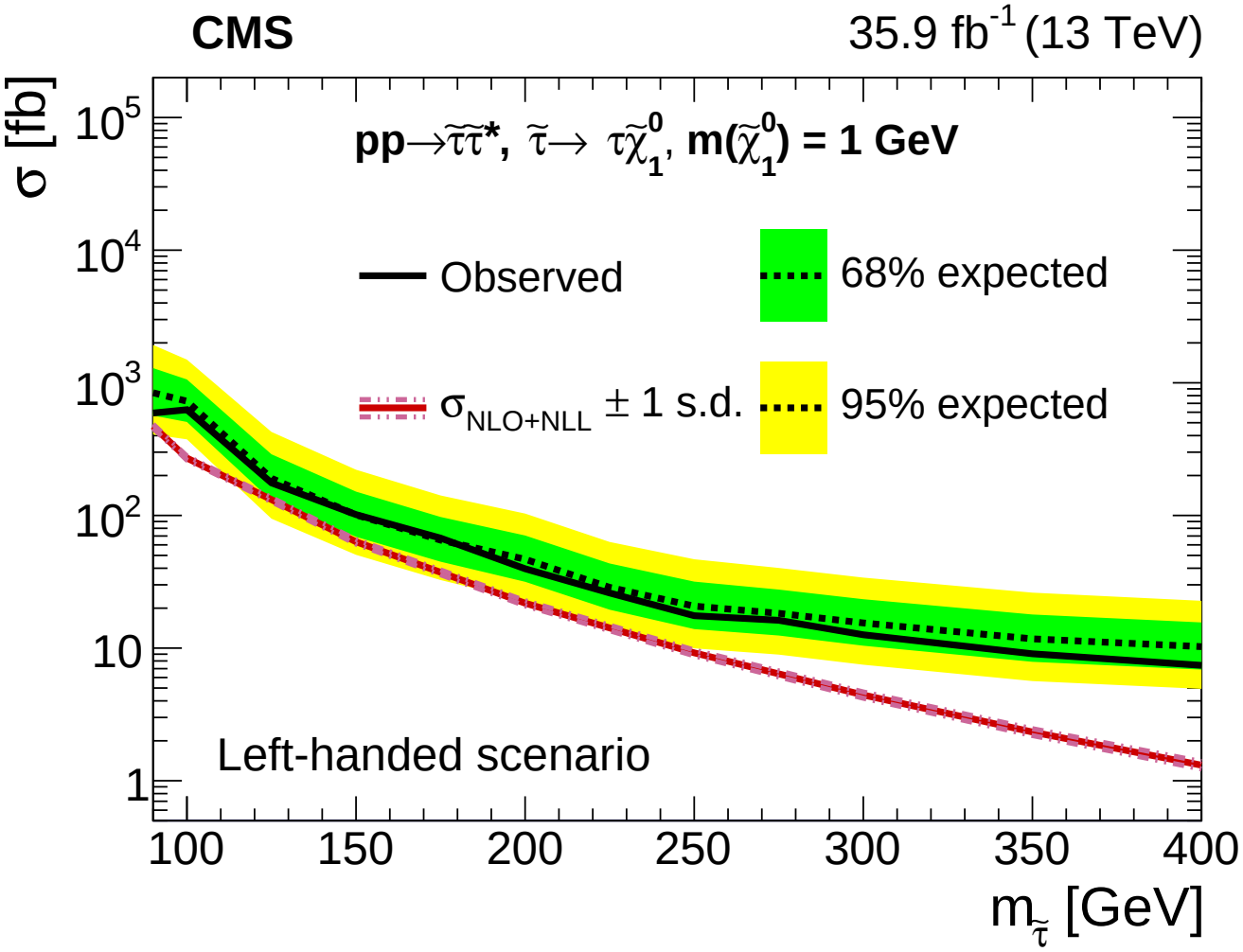
Case study
Electroweak SUSY

Chargino–neutralino production: tough corridors due to SM backgrounds



CMS 1801.03957, see also ATLAS 1803.02762

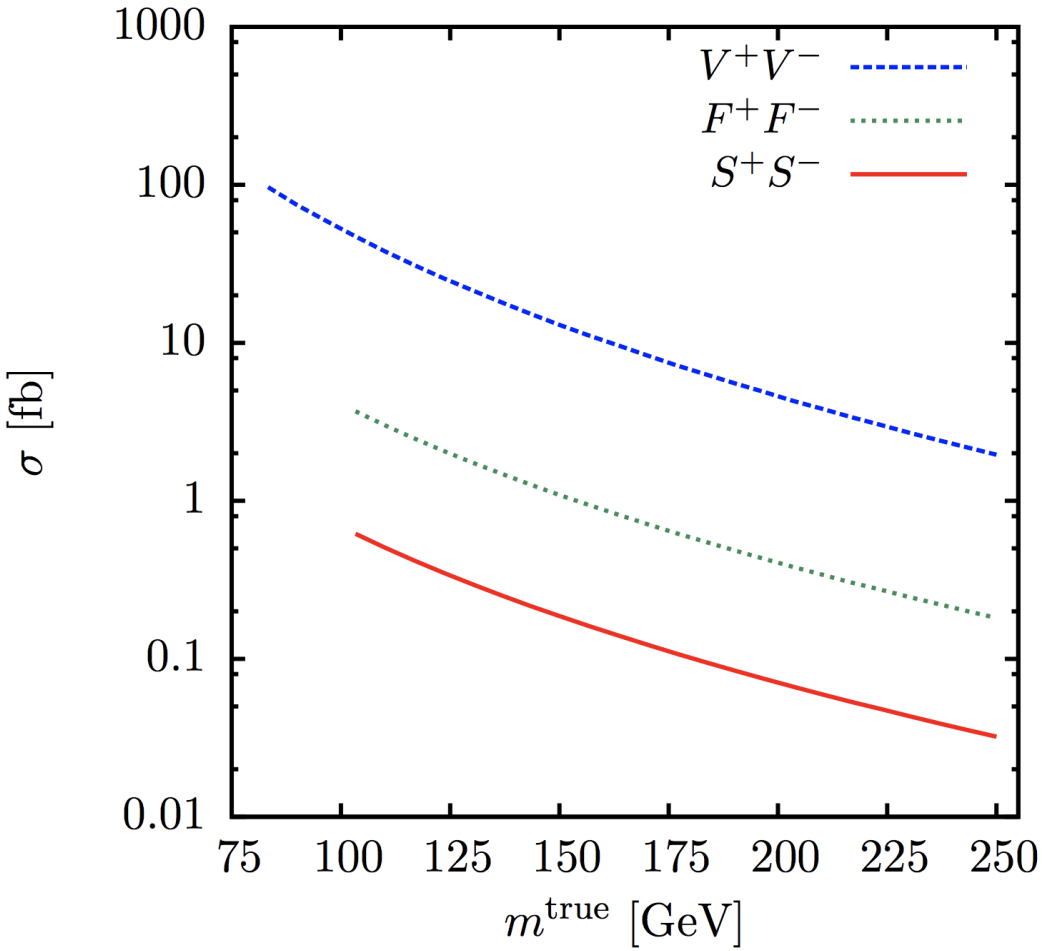
Staus: currently no LHC sensitivity even in most optimistic scenario



CMS 1807.02048 hadronic & lepton tau analysis

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

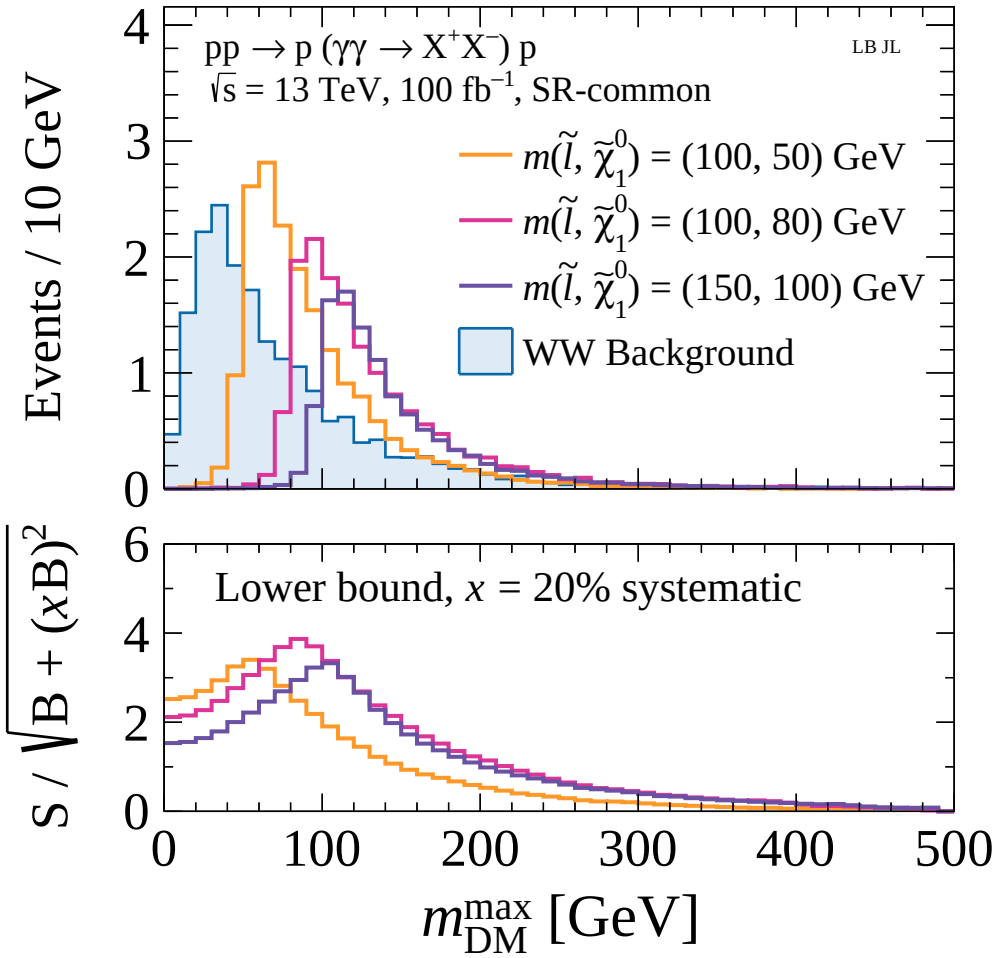
14 TeV cross-sections $pp \to p(\gamma\gamma \to X^+X^-)p$



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

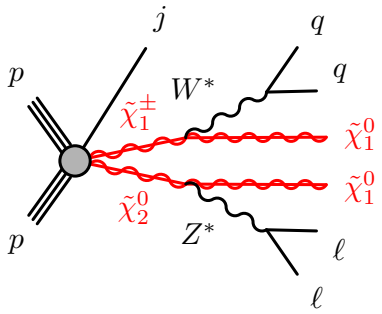
Variable from Harland–Lang et. al. [arXiv:1110.4320]

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

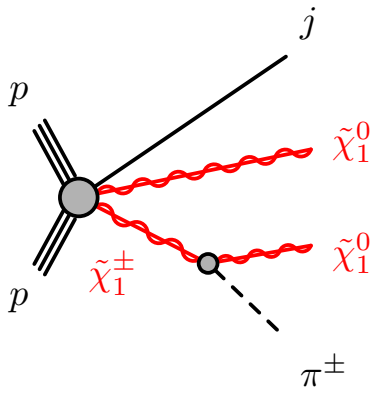
Sub-100 GeV Higgsino dark matter: the ‘prompt–long-lived gap’



Soft 2ℓ

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

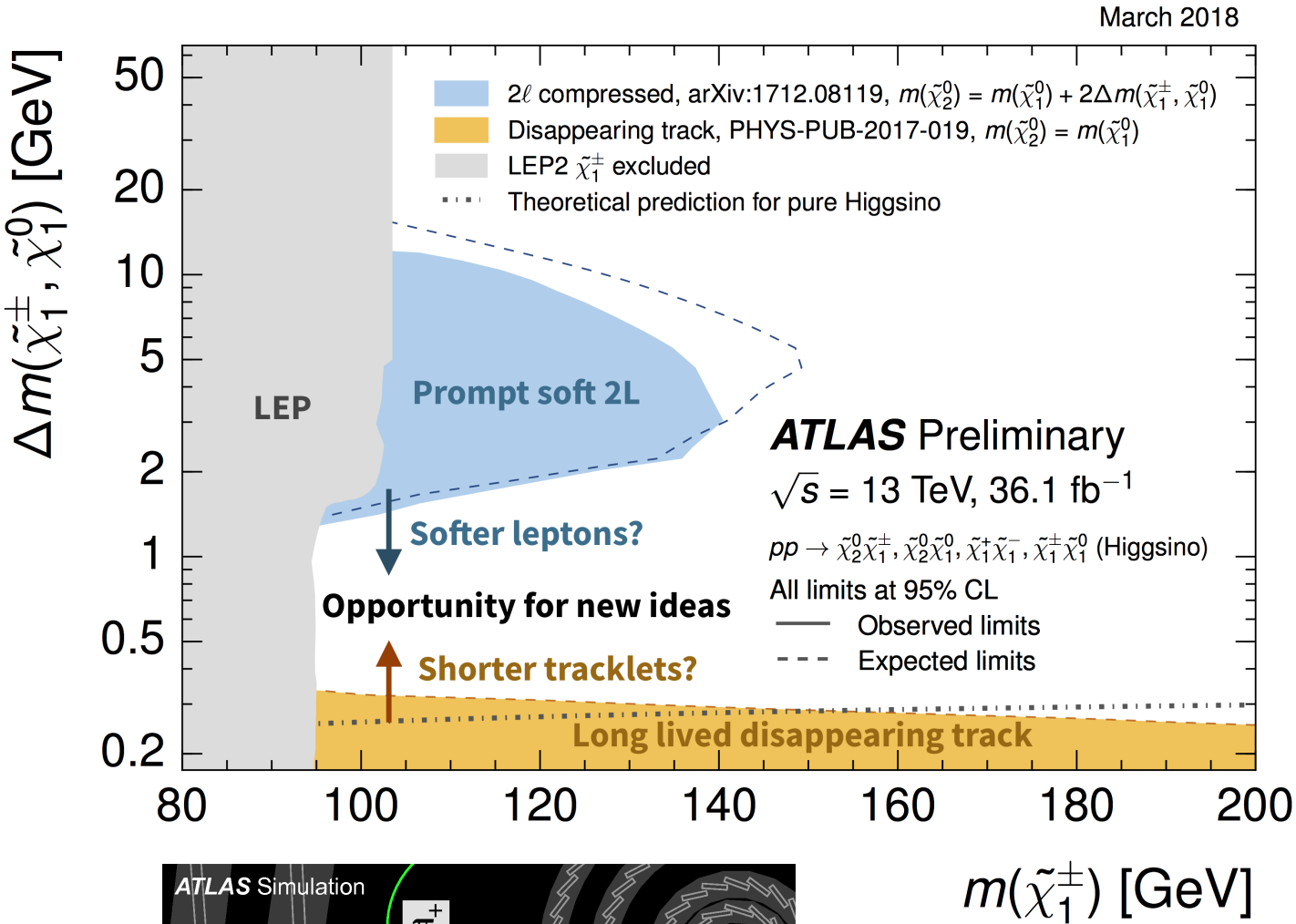
[1712.08119]

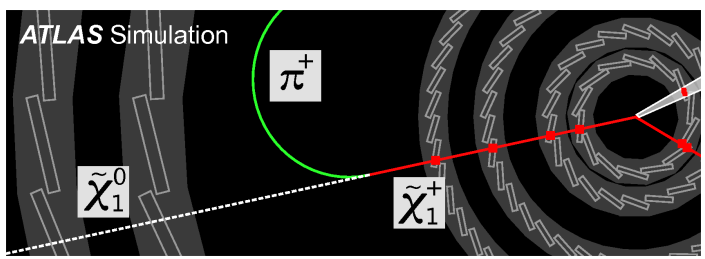


Disappearing track

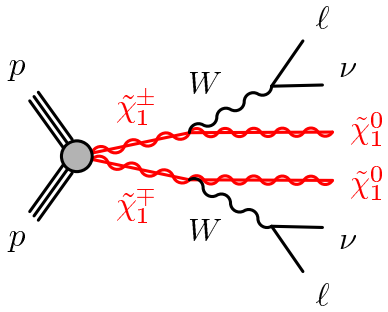
Pixel tracklets

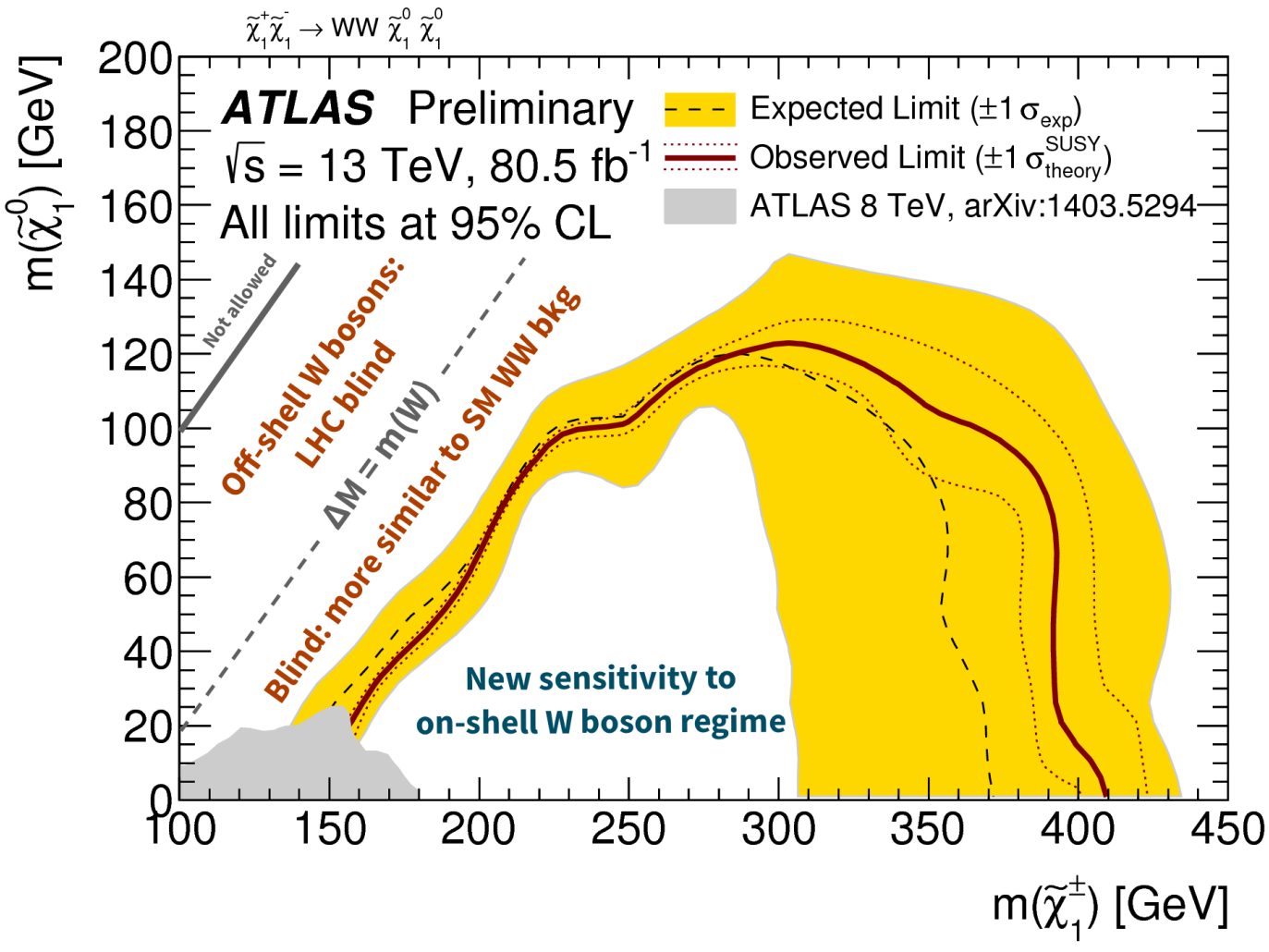
[1712.02118, PUB-2017-019]





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