Using Photon Collisions to Search for Dark Matter

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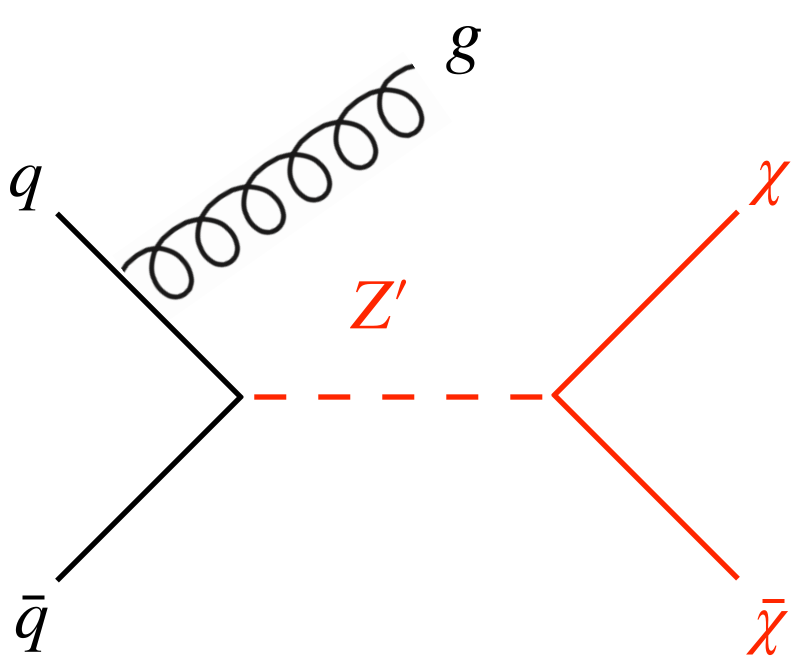
UNIVERSITY OF OXFORD

LHC Dark Matter Searches

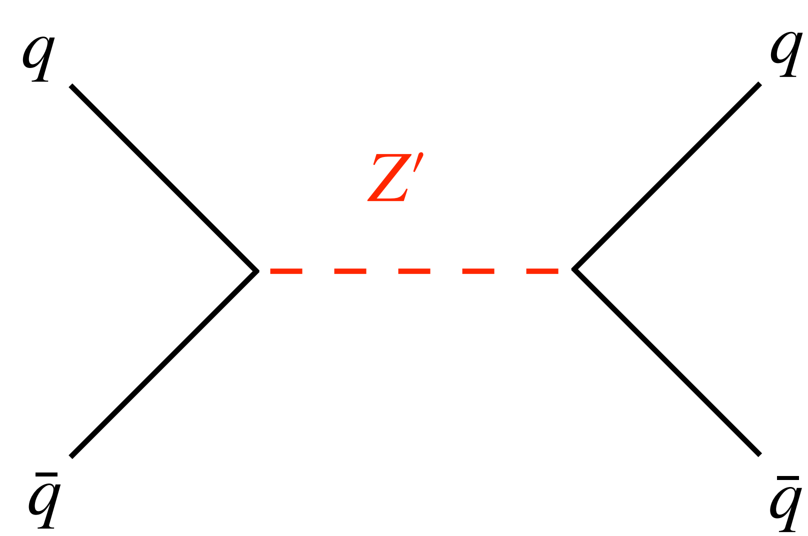
Nature of dark matter is a fundamental question in particle physics

Aim to create dark matter (or DM mediator) in LHC collisions

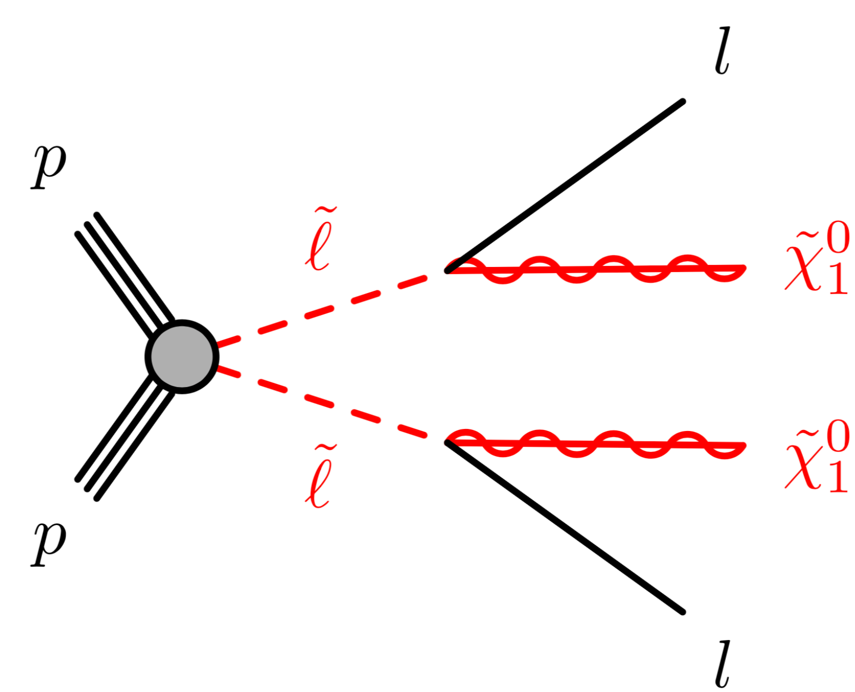
Mono-X



DM mediator search



SUSY



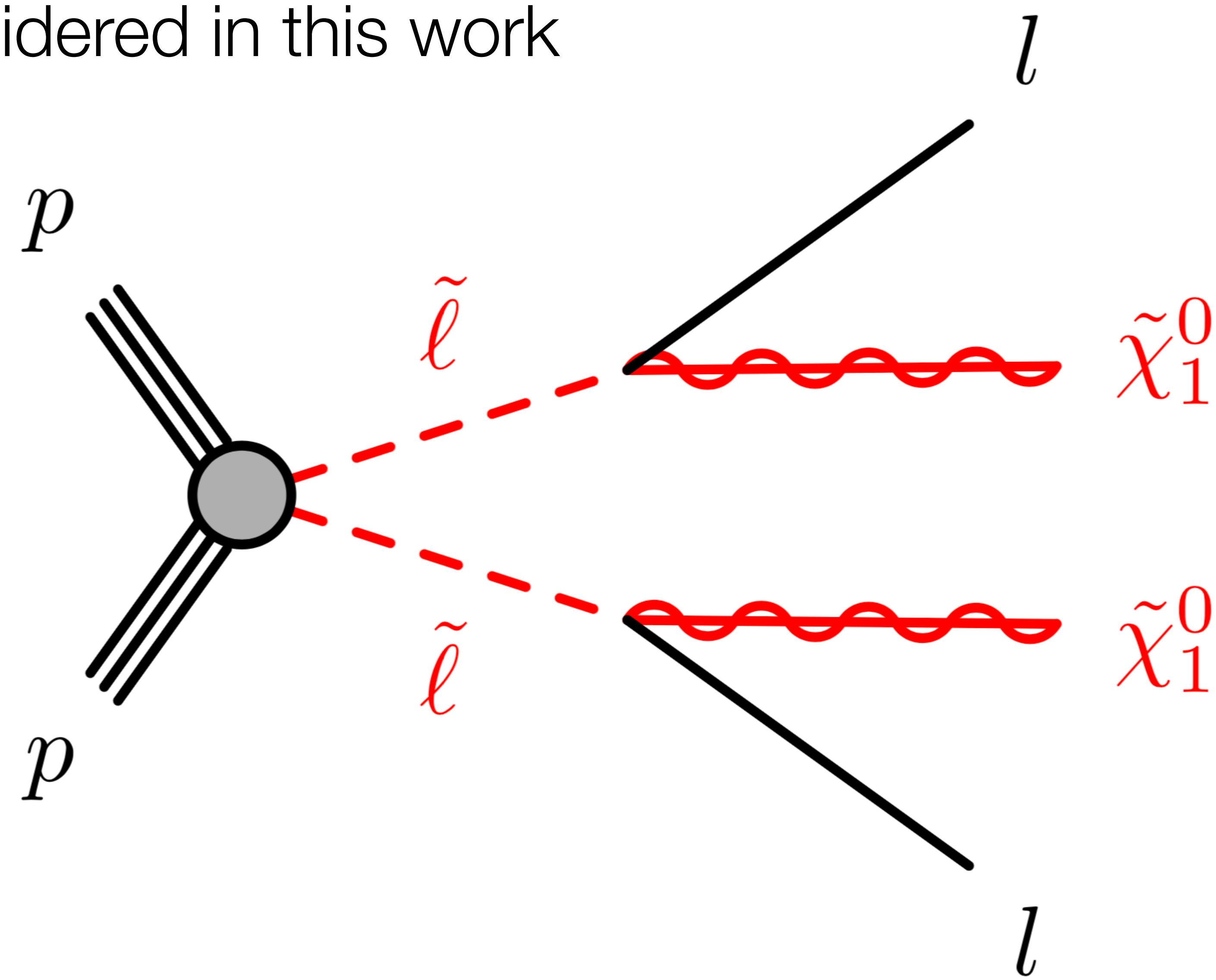
Examples

Benchmark Model

Charged scalar mediator (slepton)

Partners of leptons: selectron, smuon

stau not considered in this work

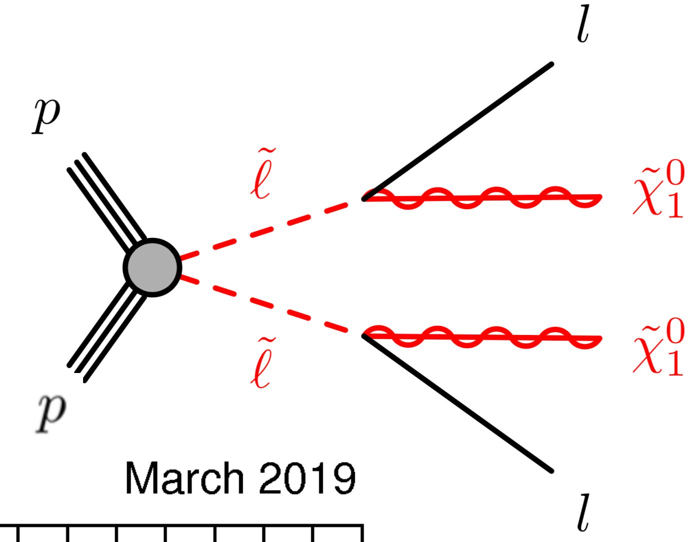


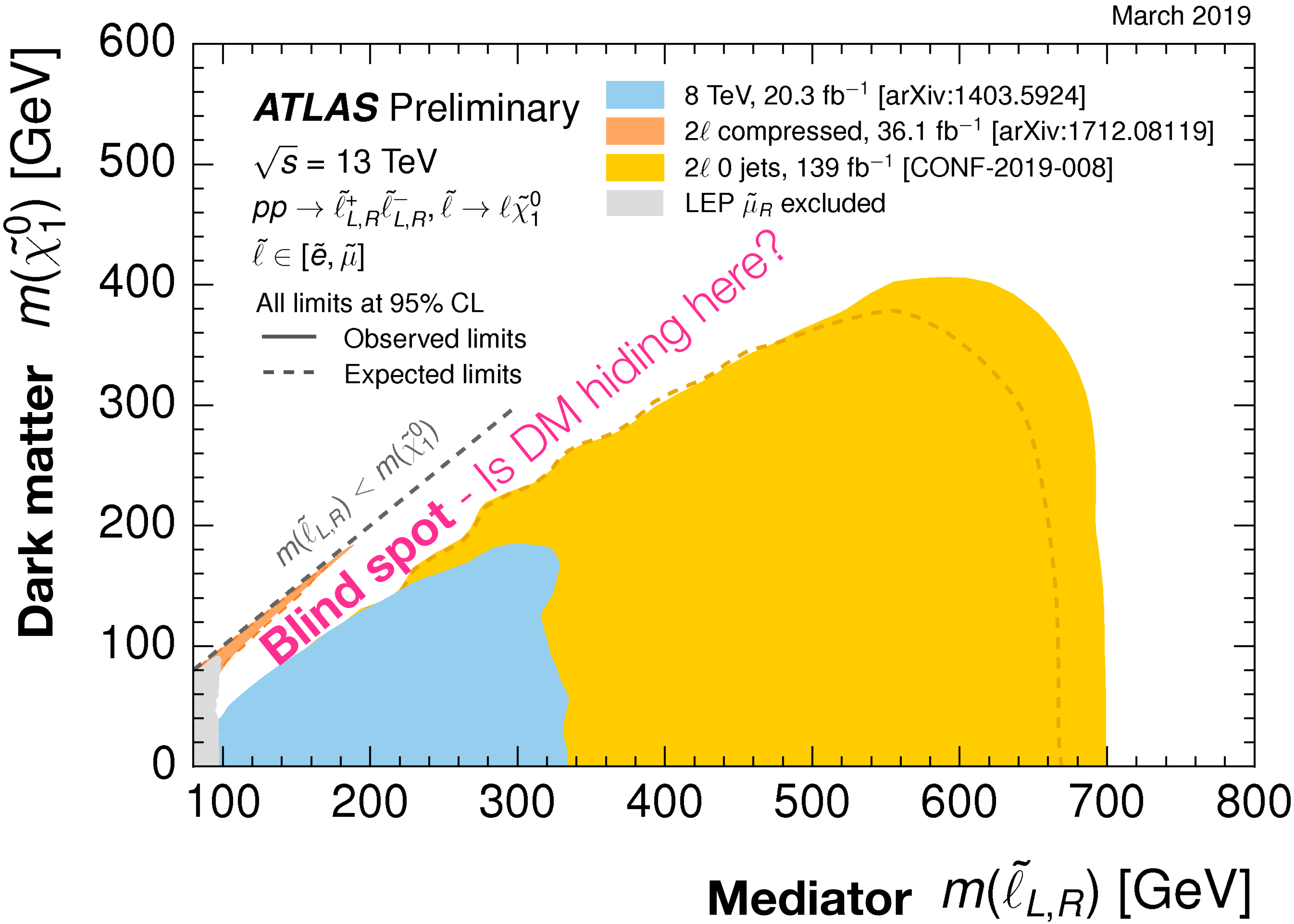
Fermion dark matter (neutralino)

Assume mass degeneracy $m(\tilde{e}_L) = m(\tilde{e}_R) = m(\tilde{\mu}_L) = m(\tilde{\mu}_R)$

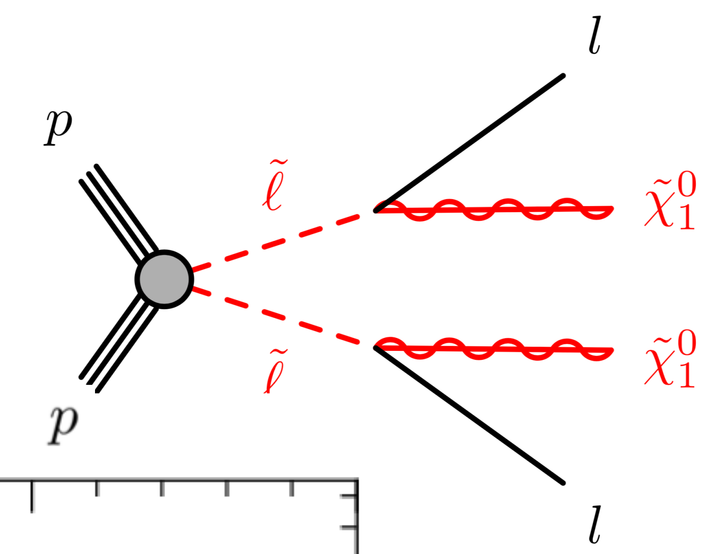
Motivation

Gap in sensitivity for electroweak scale sleptons

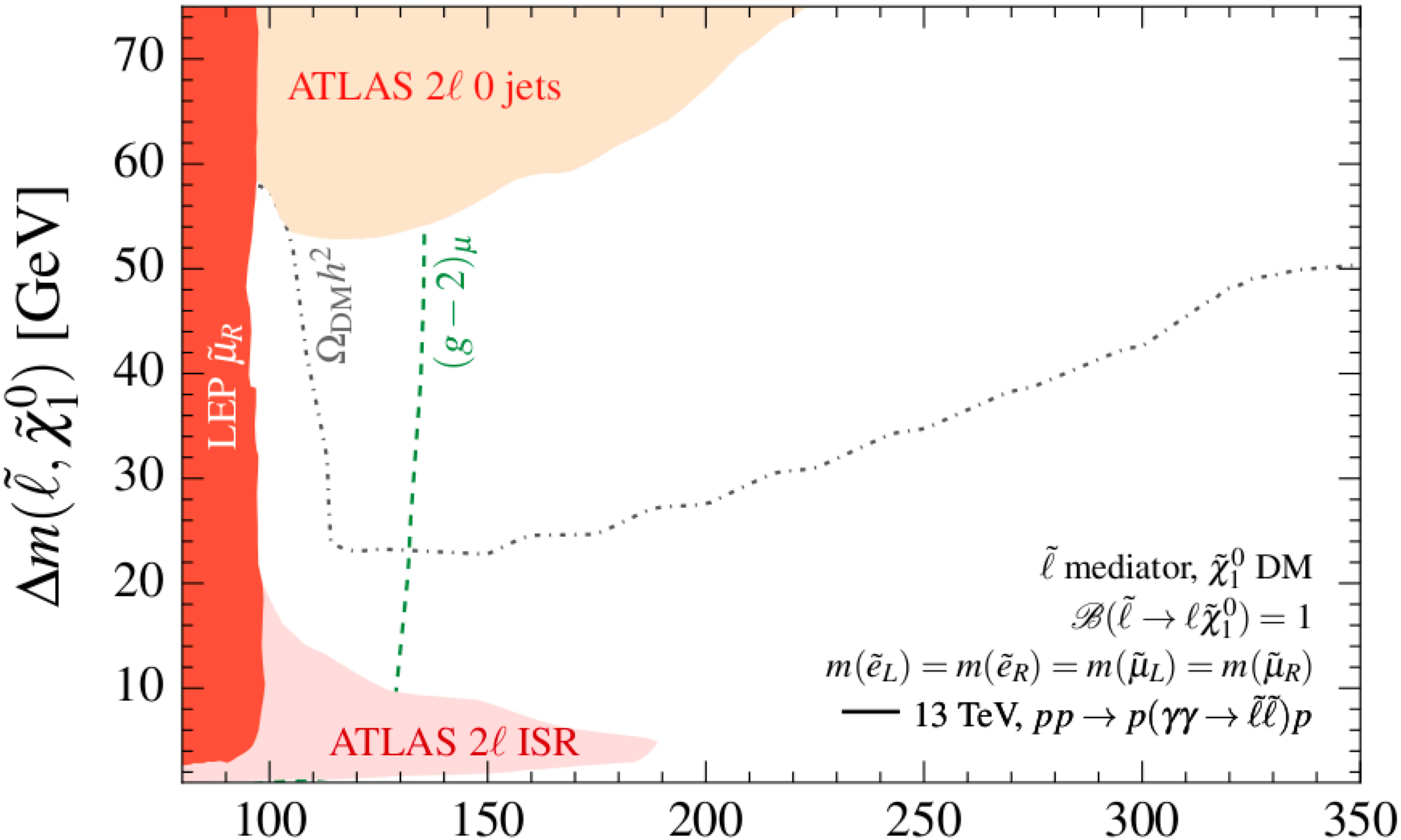




Motivation



Blind in dark matter & g-2 favoured regions



Mass difference (mediator,DM)

Mediator $m(\tilde{\ell}_{L,R})$ [GeV]

We focus on moderate mass splittings: $15 \lesssim \Delta m(\tilde{l}, \tilde{\chi}^0) \lesssim 60$ GeV

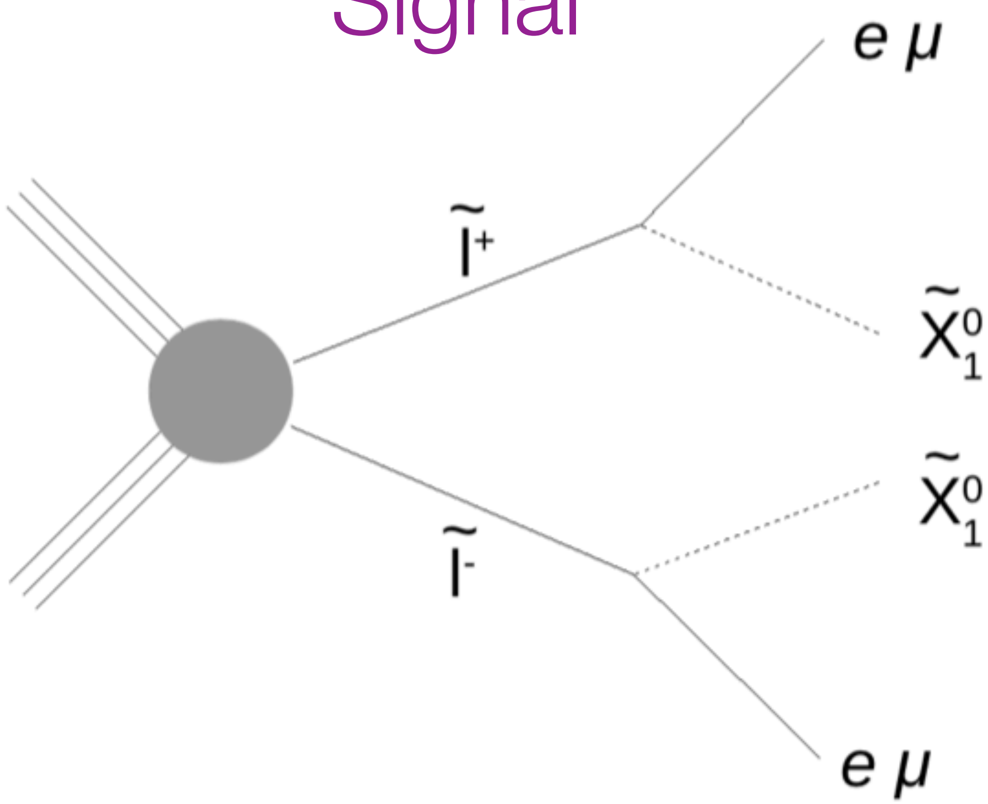
Why is it so challenging to probe?

Substantial production cross-section: 730 fb (100 GeV slepton)

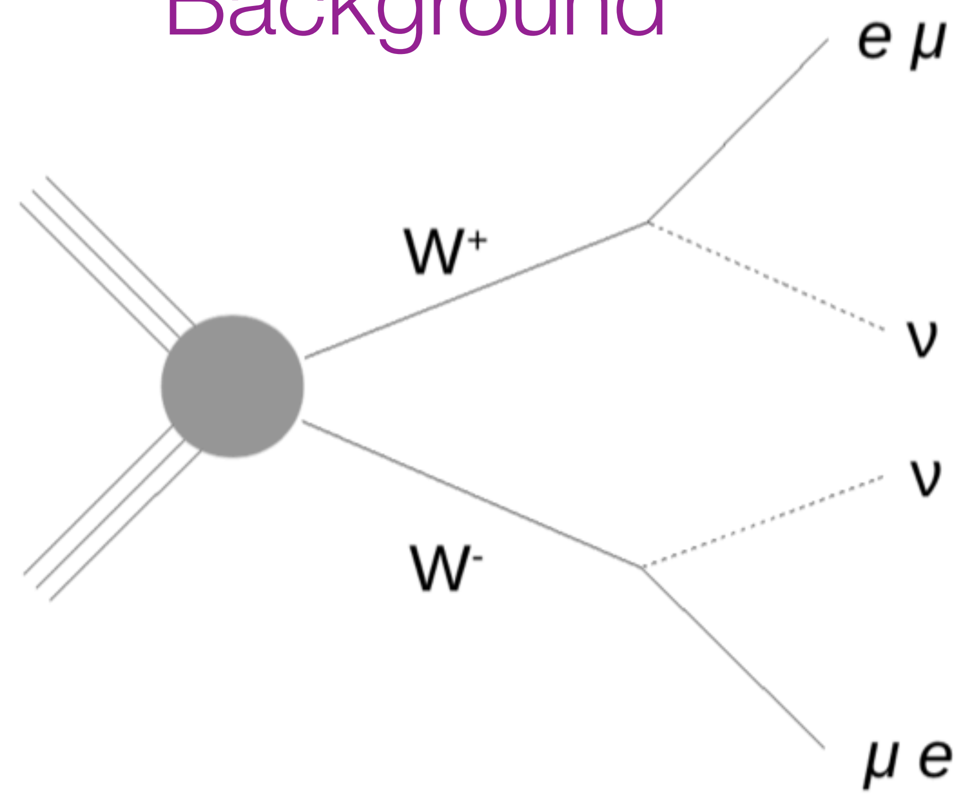
-> 100,000 events with 140 ifb dataset

But …

Signal



Background



Key differences: mediator spin, decay channels, DM mass, mediator mass

Why is it so challenging to probe?

Key differences:

Mediator spin: new charged mediator is a **scalar** & W boson is a **vector**
-> Use spin sensitive variable (scalar decays more central)

Decay channels: pair of sleptons -> $ee, \mu\mu$; WW -> $ee,\ \mu\mu, e\mu$
-> Require same flavour leptons

DM mass: **Dark matter mass** may not be equal to neutrino mass
Mediator mass: **Charged mediator mass** may not be equal to W mass

↓

Fundamental Hadron Collider problem

Why is it so challenging to probe?

Fundamental Hadron Collider problem

- Don't have access to initial state kinematics -> Can only use MET!
- Combine it with lepton kinematics & approx mediator mass using mT2 relies on DM mass assumption

- In blind spot $15 \lesssim \Delta m \lesssim 60$ GeV mT2 similar shape for sleptons & WW!
- No signal or background end point to exploit!
- Discrimination very challenging

-> Need more information!

Photon collision search strategy

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

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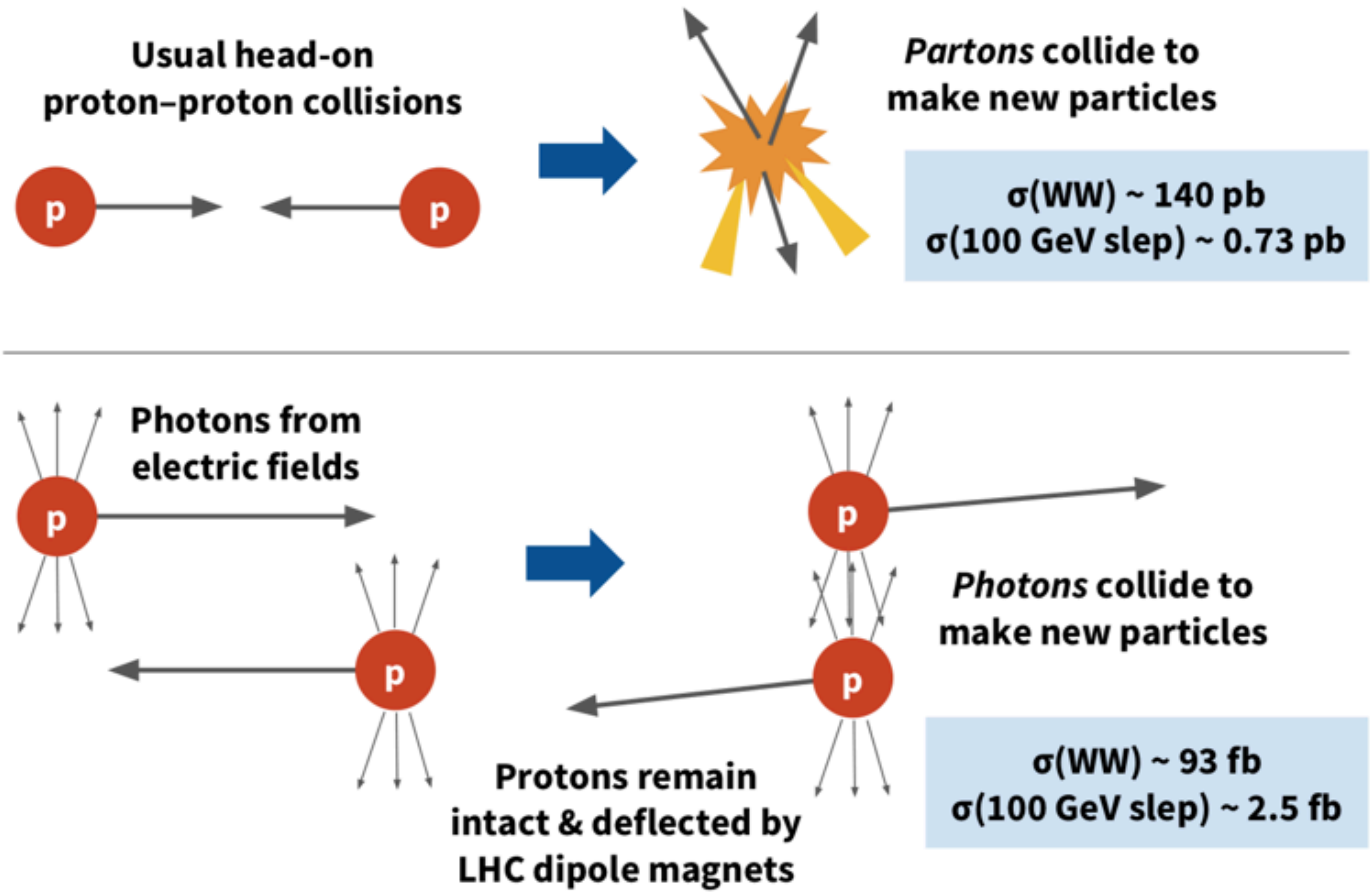
We propose a search strategy using the LHC as a photon collider to open sensitivity to scalar lepton (slepton $\tilde{\ell}$) production with masses around 15 to 60 GeV above that of neutralino dark matter $\tilde{\chi}_1^0$. This region is favored by relic abundance and muon $(g-2)_\mu$ arguments. However, 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.

1811.06465

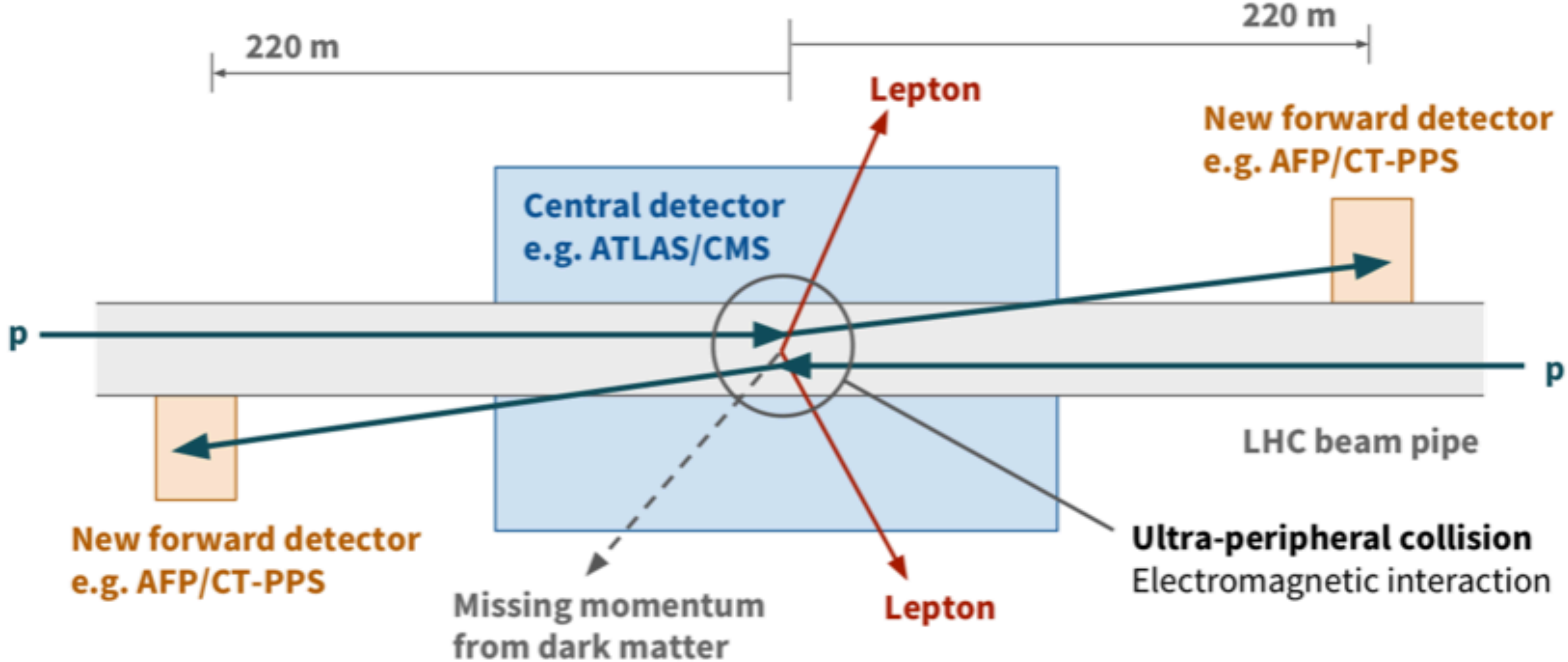
See also: Ohnemus et. al. hep-ph/9402302, de Favereau de Jeneret et. al. 0908.2020, Harland-Lang et. al. 1110.4320, Khoze et. al. 1702.05023 Harland-Lang et. al. 1812.04886

Overcoming Challenges: Photon Collider



Higher S/B for photon collisions (100 GeV slepton vs WW bkg)

Overcoming Challenges: Forward Detectors



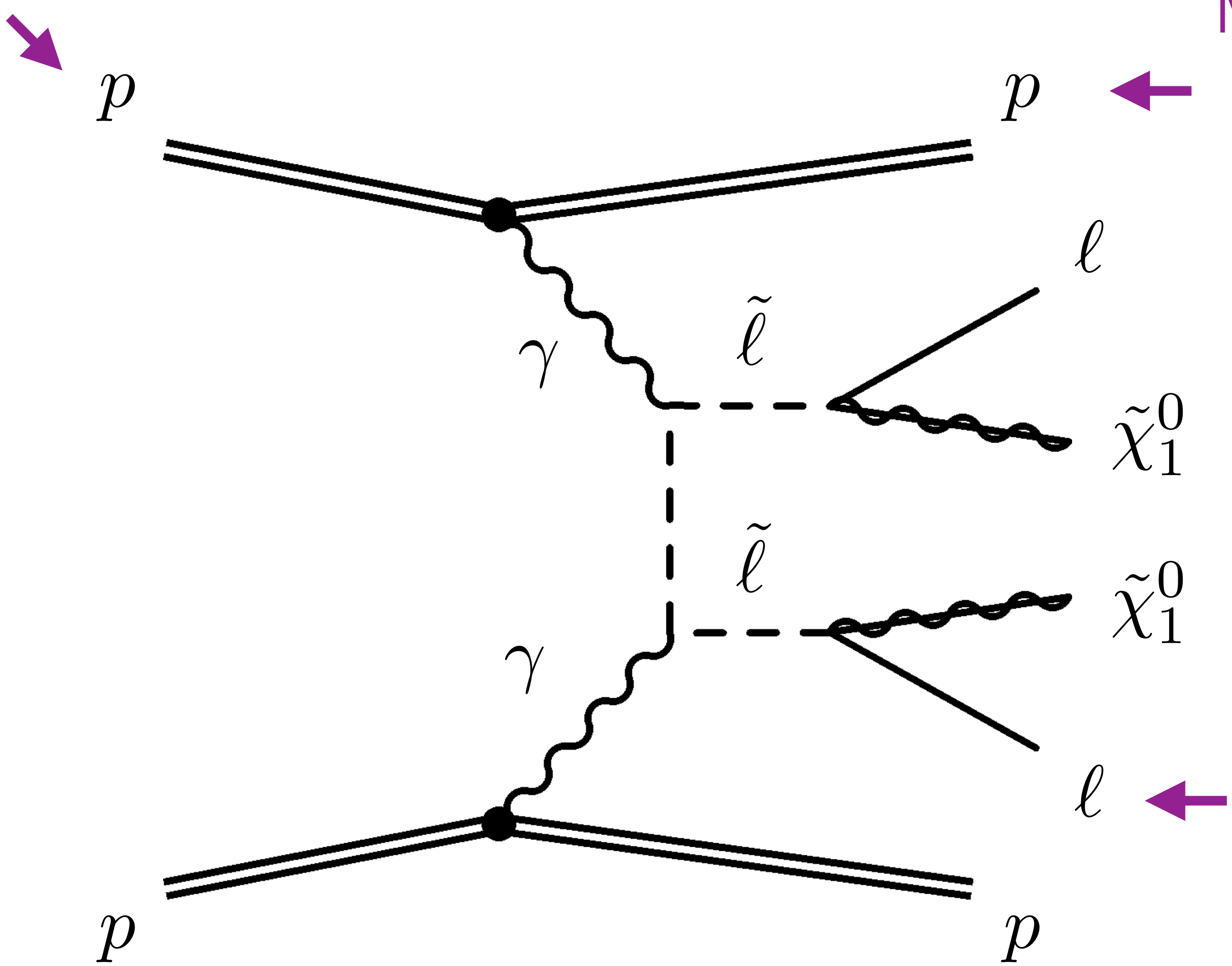
ATLAS Forward Proton (AFP) data taking from 2017

CMS-TOTEM Precision Proton Spectrometer (CT-PPS) data taking from 2016

Overcoming Challenges: Forward Detectors

Known proton beam E

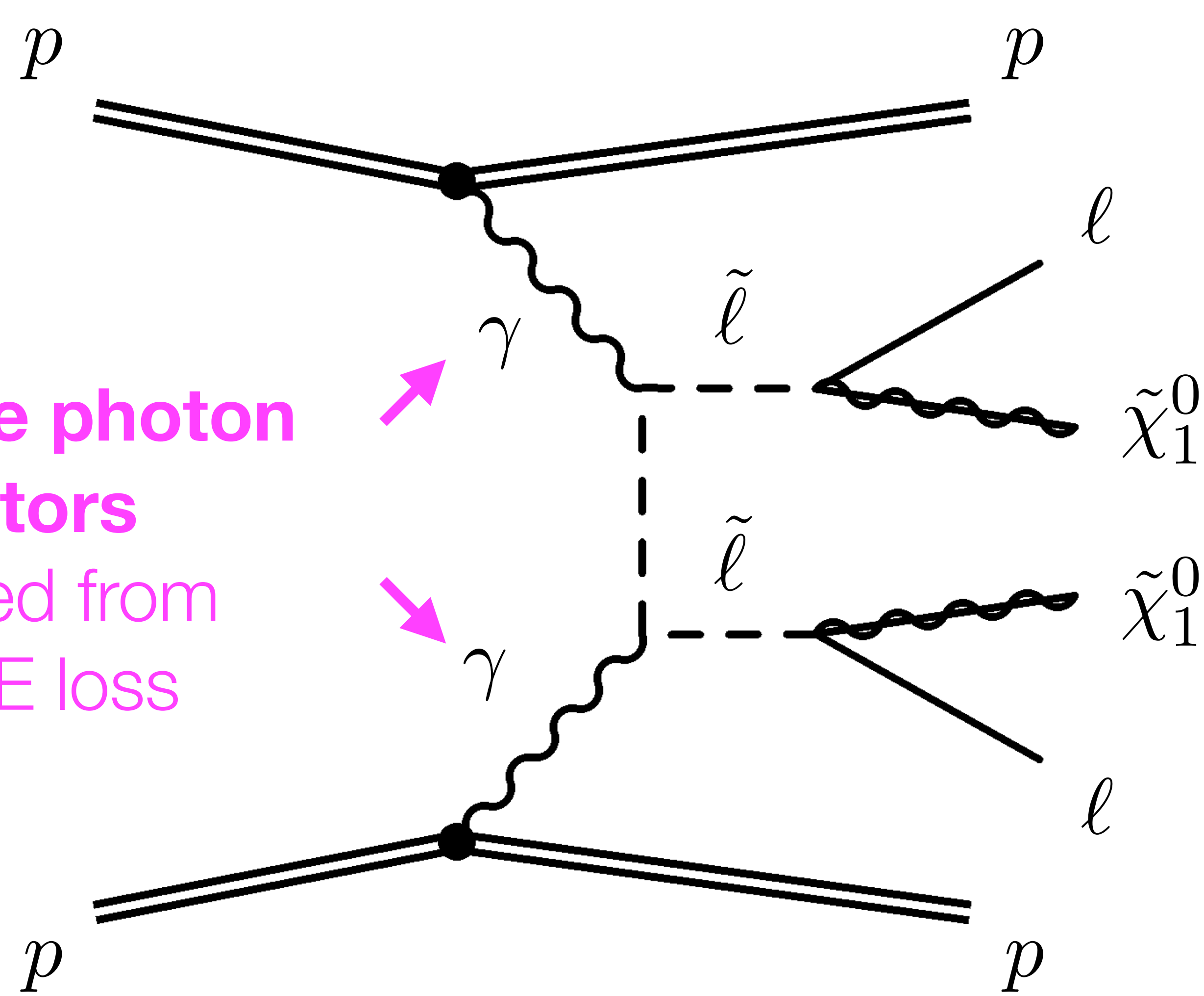
Measure outgoing proton E with forward detector



Measure lepton 4-vector with central detector

Overcoming Challenges: Forward Detectors

Initial state photon 4-vectors
Calculated from proton E loss

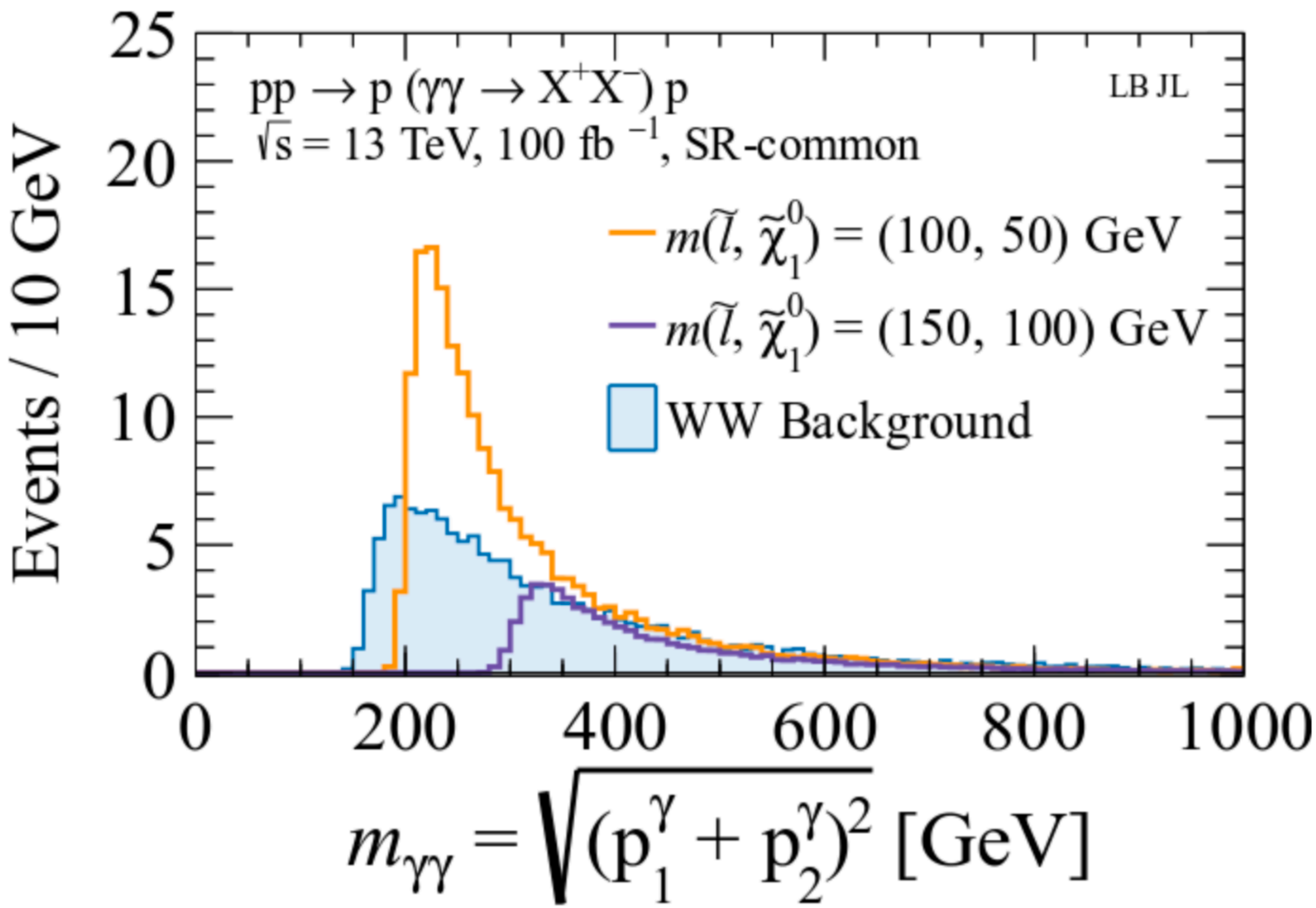


Missing momentum 4-vector
Calculated from photon & lepton 4-vectors

Living the dream: Probe initial state & full missing momentum 4-vector
Impossible in usual LHC searches!

Living the dream: Mediator mass

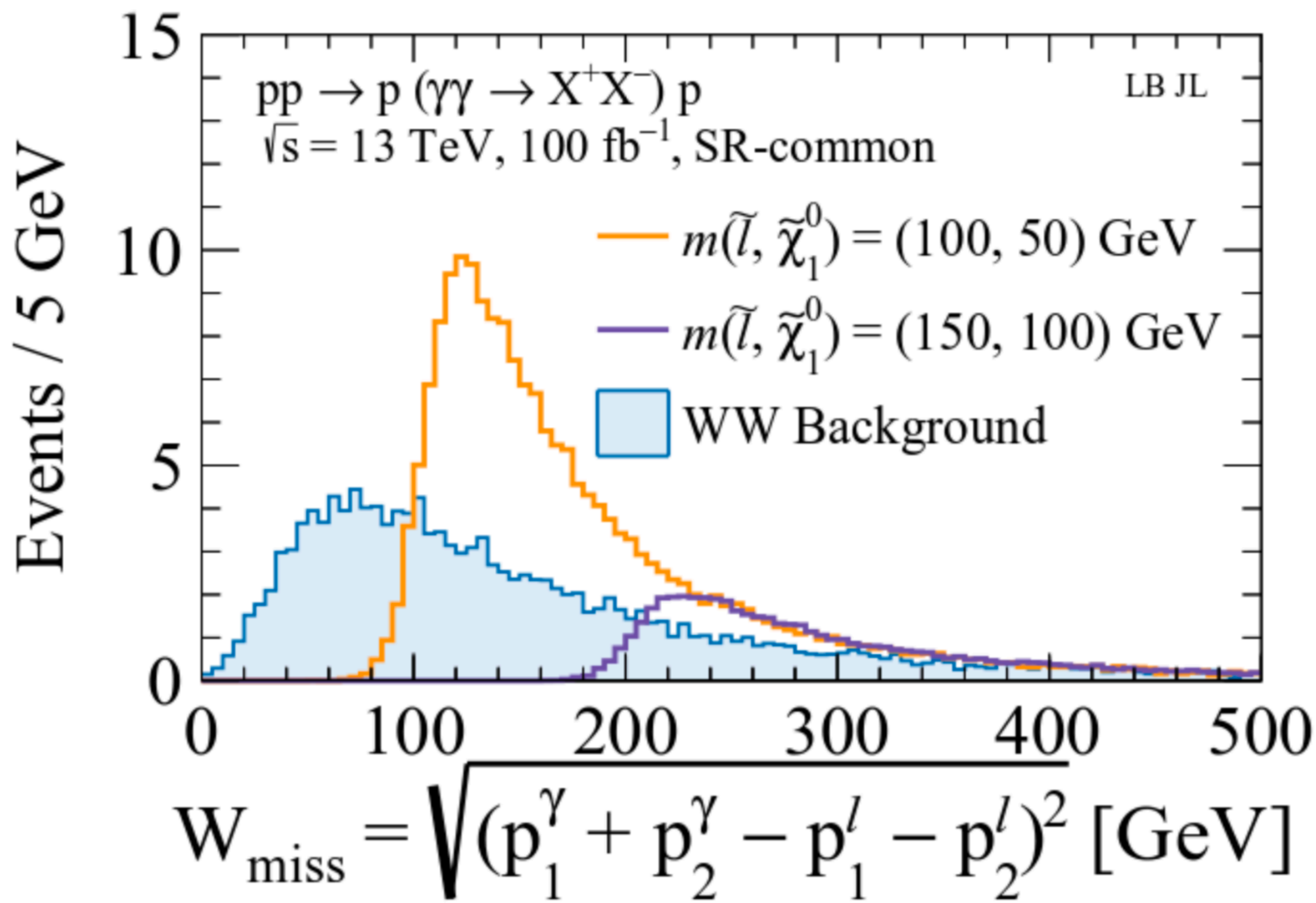
min($m_{\gamma\gamma}$) = 2 x $m_{mediator}$



Note: acceptance & efficiencies not applied, only resolution smearing

Living the dream: DM mass

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



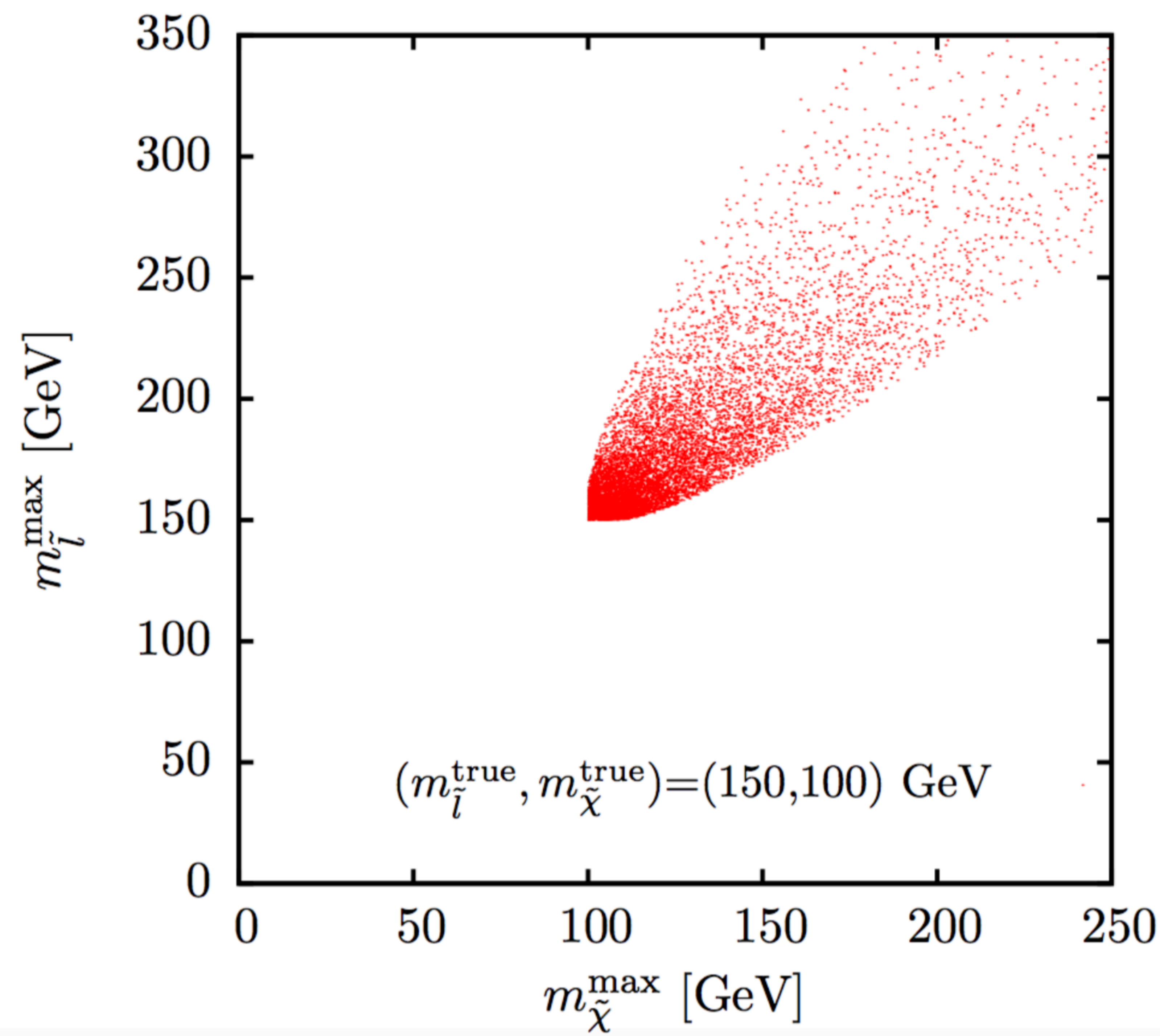
Note: acceptance & efficiencies not applied, only resolution smearing

Mass measurement

Harland-Lang et. al.
1110.4320 new variables
$m_{mediator}^{max}$ and m_{DM}^{max}

Uses photon & missing momentum 4-vectors & assume decay topology for additional kinematic constraints

-> Sharpens tails improving S vs B discrimination



Potential to classify DM & mediator mass in case of discovery!

Analysis - Putting it all together

Leptons

- 2 same flavour ($ee, \mu\mu$)
- p_T > 15 GeV (trigger emulation)
- $|\eta|$ < 2.5 (tracking acceptance)
- Smear 4-momentum by 5% (resolution)
- p_T dependent reco efficiency parametrised from ATLAS

Protons/photons

Acceptance: 100% $100 \leq E_\gamma \leq 1000$ GeV ($0.015 \lesssim \xi \lesssim 0.15,\ \xi = 1 - \frac{E_{forward}}{E_{beam}}$)

Smear photon 4-momentum by 5% (resolution)

90% proton survival probability

Analysis - Putting it all together

Signal Regions

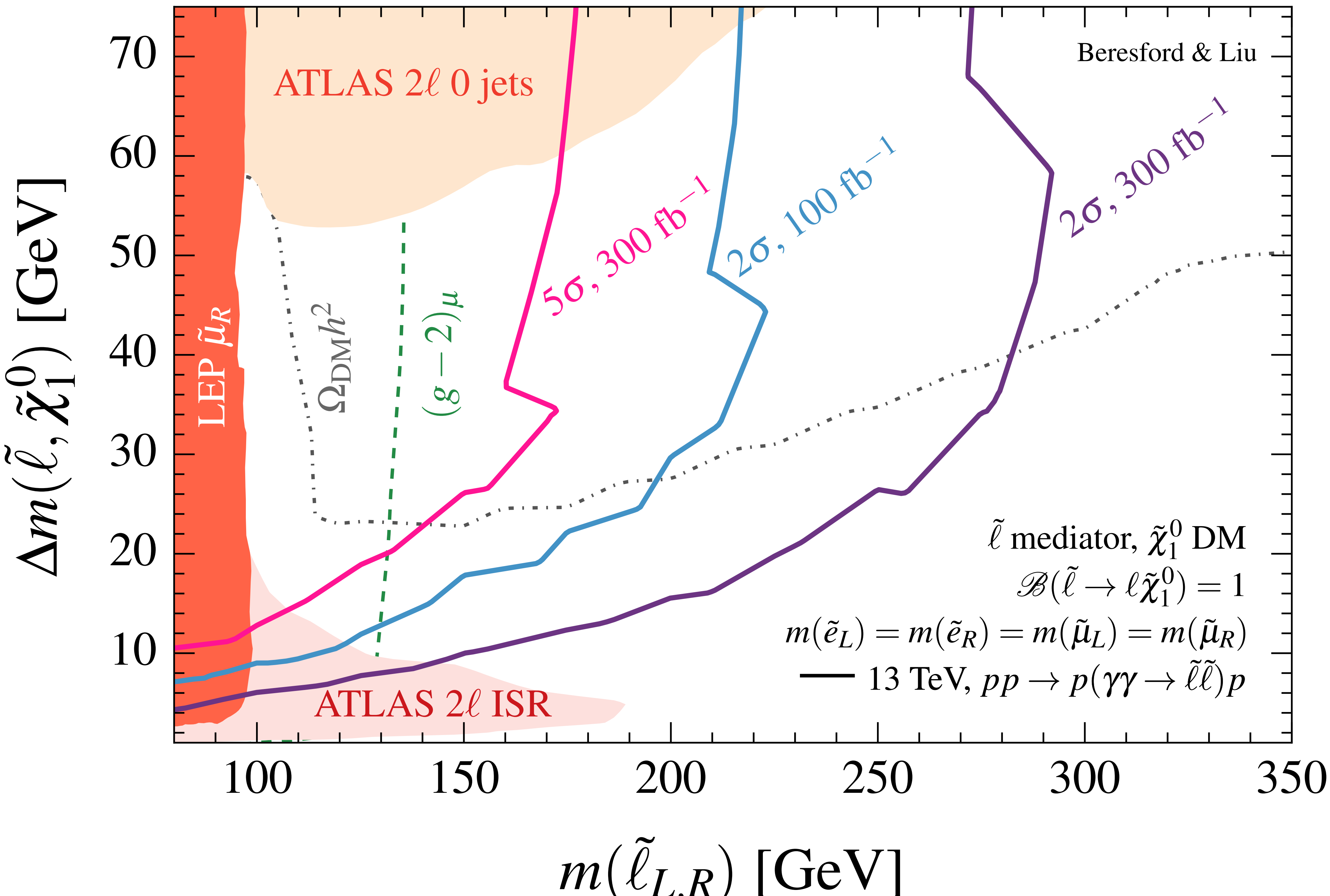
Designed signal regions targeting different mediator and DM mass splittings: small (compressed), medium (corridor) & large using $m_{mediator}^{max}$ and m_{DM}^{max}

In each SR exploit spin difference between S and B (S more central):

$\cos(\bar{\theta}_{ll}) < 0.65$ $\bar{\theta}_{ll}$ evaluated in di-lepton centre-of-mass frame

Exploring the unknown

Potential to probe well motivated ATLAS blind spot
& perform landmark measurements of new LHC observables!



Challenges

Quantified potential reach considering **irreducible WW bkg**

Reducible backgrounds e.g. Non-exclusive + pile-up protons

Potential to reduce via timing, N_{track} exclusivity cuts etc.

-> See Lucian's talk

-> Harland-Lang et al JHEP 1904 (2019) 010 complementary to our work:

- Details potential mitigation strategies for reducible bkgs
- Targets very compressed region $\Delta m(\tilde{l}, \tilde{\chi}^0) \lesssim 20$

Summary

Using LHC as a photon collider provides clean QED events
& enhances S/B for sleptons vs WW

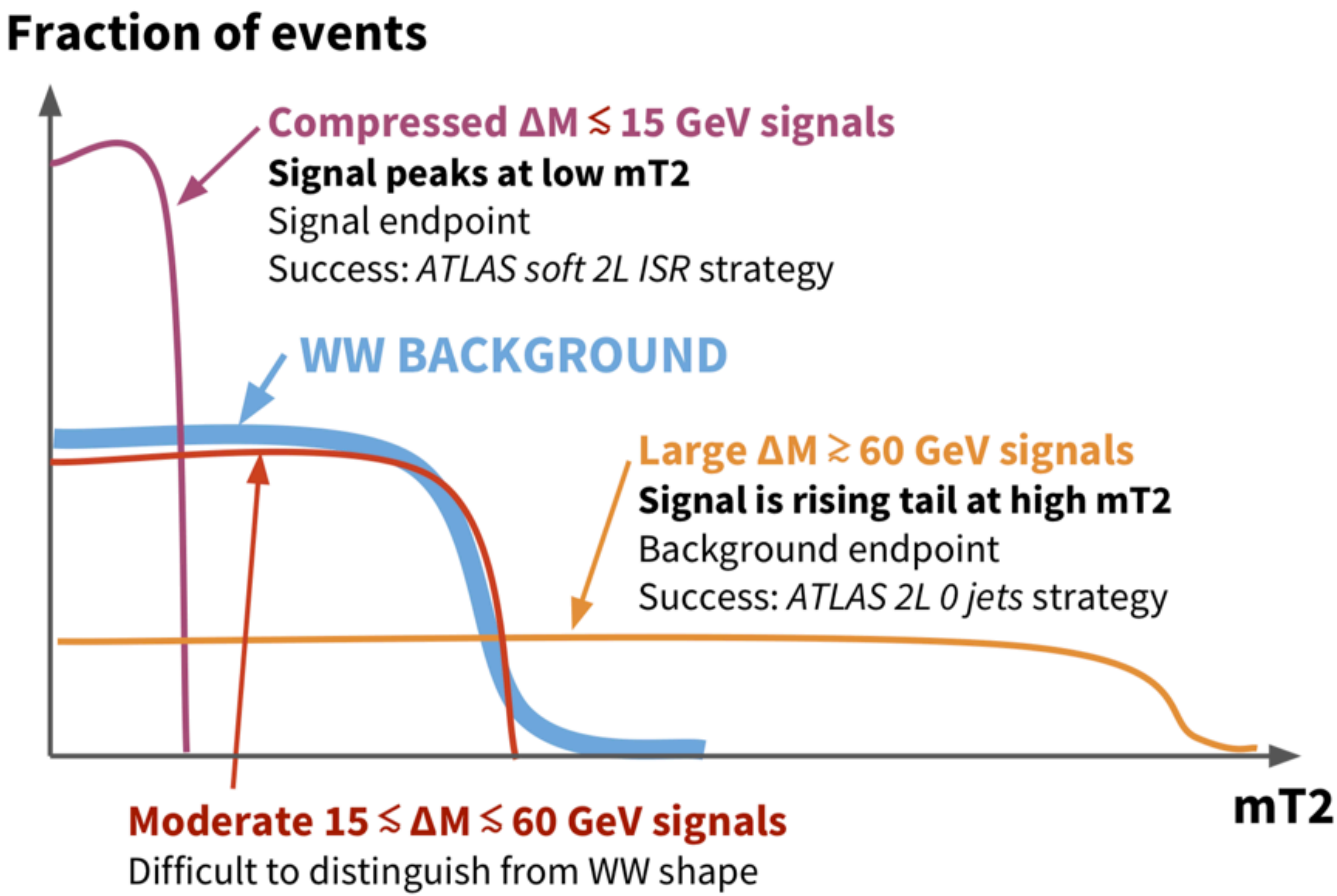
Forward proton detectors allow us to measure initial state & full missing momentum 4-vector **-> Truly new information to exploit!**

Demonstrated power of exploiting these features for slepton + DM case
-> Potential to probe promising unexplored phase space

ATLAS & CMS forward detectors recently recorded data
-> The forward frontier has arrived

BACKUP

What’s hindering sensitivity in the gap?



Cutflow

Requirement	$\tilde{\ell}:(100,80)$	$\tilde{\ell}:(125,80)$	$\tilde{\ell}:(125,40)$	$WW\to\ell\nu\ell\nu$
$\sigma\times\mathrm{BR}\times\mathcal{L}$	254	124	124	465
Same flavour leptons	254	124	124	232
$m_{\mathrm{T2}}^{0}>2$ GeV	240	120	121	227
$\lvert\cos\bar{\theta}_{\ell\ell}\rvert<0.65$	157	78.5	79	82.9
$\lvert\eta_{\ell_1}\rvert<2.5$	146	74.2	74.7	77
$\lvert\eta_{\ell_2}\rvert<2.5$	130	66.8	67.1	67
$p_{\mathrm{T}}^{\ell_1}>15$ GeV (trigger)	117	66.5	67.1	66.7
$p_{\mathrm{T}}^{\ell_2}>15$ GeV (trigger)	67.6	60.7	64.9	57.6
Lepton 1 efficiencies	51	47.6	51.2	45.3
Lepton 2 efficiencies	37.4	36.6	40.4	34.7
Forward proton tag 1	31.3	30.8	34	28.4
Forward proton tag 2	7.5	8.82	9.64	3.91
SR-compressed				
$m_{\mathrm{DM}}^{\mathrm{max}}>0$ GeV	7.5	8.8	9.6	3.9
$m_{\mathrm{parent}}^{\mathrm{max}}>80$ GeV	7.4	8.8	9.6	3.7
$m_{\gamma\gamma}/W_{\mathrm{miss}}<1.4$	6.7	2.8	0.94	0.55
SR-corridor				
$m_{\mathrm{DM}}^{\mathrm{max}}>80$ GeV	7.1	8.2	4.5	1.1
$m_{\mathrm{parent}}^{\mathrm{max}}>120$ GeV	6	8.1	4.5	1.1
SR-large				
$m_{\mathrm{DM}}^{\mathrm{max}}>20$ GeV	7.5	8.8	9.6	3.5
$m_{\mathrm{parent}}^{\mathrm{max}}>130$ GeV	5.4	7.8	8.5	1.6

TABLE I. Cutflow of background and signal yields after each requirement applied sequentially common to all signal regions (above bold line), then specific to each SR. Event yields are normalised to $\mathcal{L}=100.0\ \mathrm{fb}^{-1}$. The three benchmark signals are labeled by the slepton and dark matter (DM) masses $m(\tilde{\ell},\tilde{\chi}_1^0)$ in GeV. Event yields above (below) the bold line are rounded to 3 (2) significant figures.

Analysis - Putting it all together

Signal Regions (SRs)

Design **3 SRs** targeting different mediator and DM mass splittings: small (compressed), medium (corridor) & large

	$m_{mediator}^{max}$	m_{DM}^{max}	$m_{\gamma\gamma}/W_{miss}$
- small:	> 80 GeV	> 0 GeV	< 1.4
- medium:	> 120 GeV	> 80 GeV	
- large:	> 130 GeV	> 20 GeV	

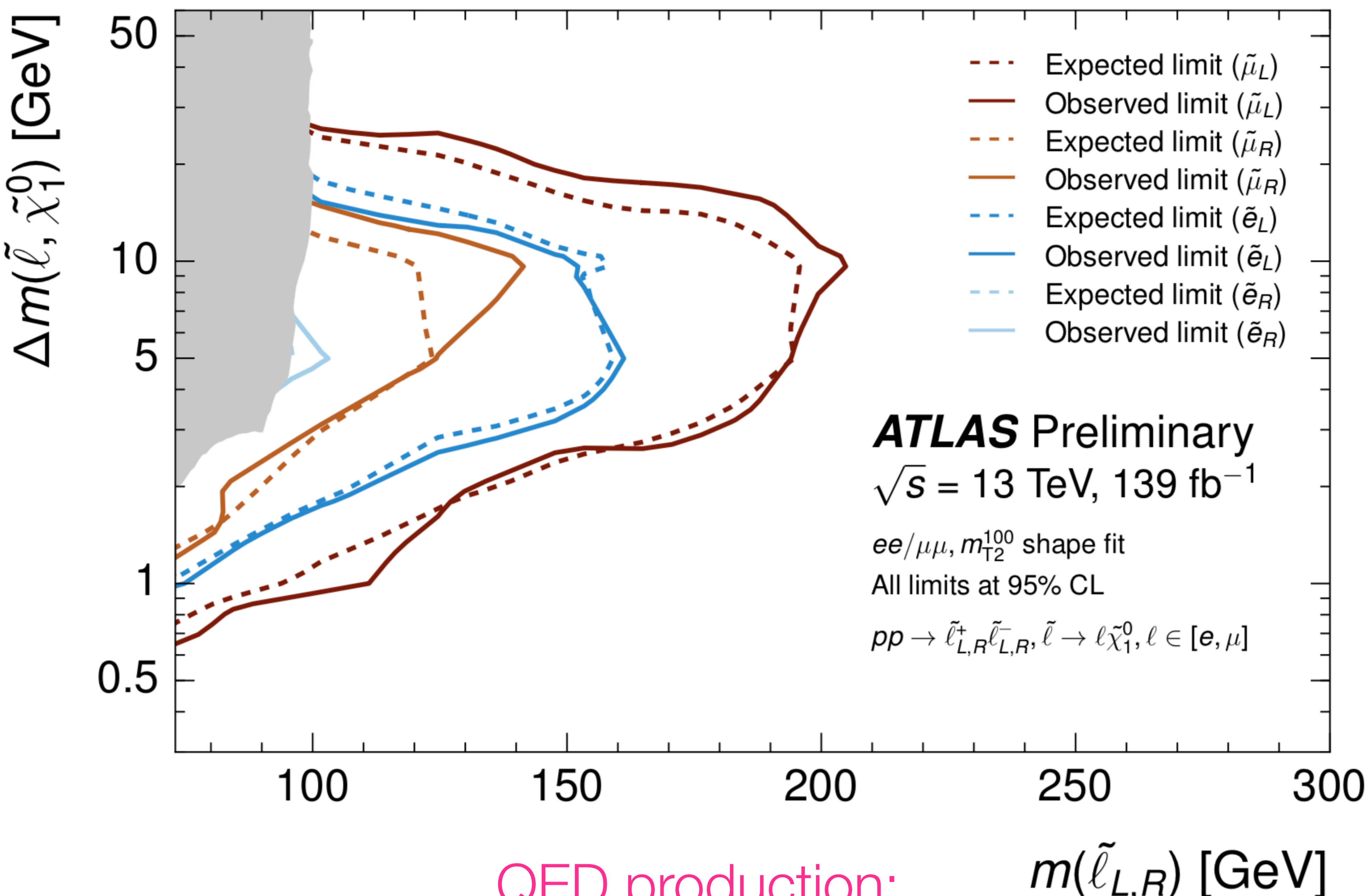
In each SR exploit spin difference between S and B (S more central):

$\cos(\bar{\theta}_{ll}) < 0.65$ $\bar{\theta}_{ll}$ evaluated in di-lepton centre-of-mass frame

Slepton handedness

Relax mass degeneracy & split into left and right handed sleptons

-> Weaker limits for right handed (lower cross-section)



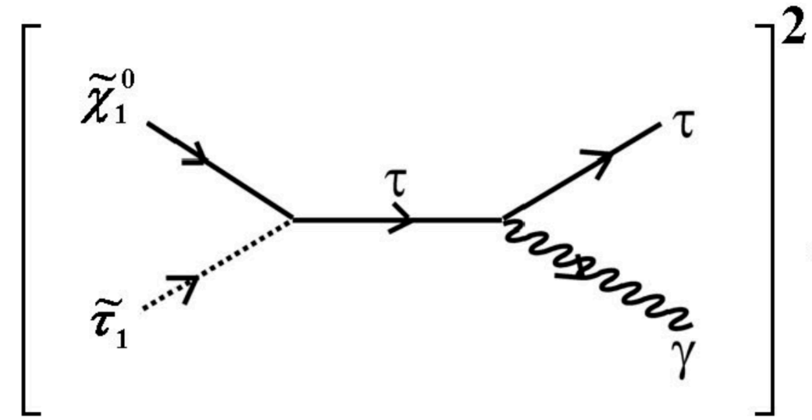
QED production:

Equal cross-sections for left and right handed!

Relic abundance and g-2

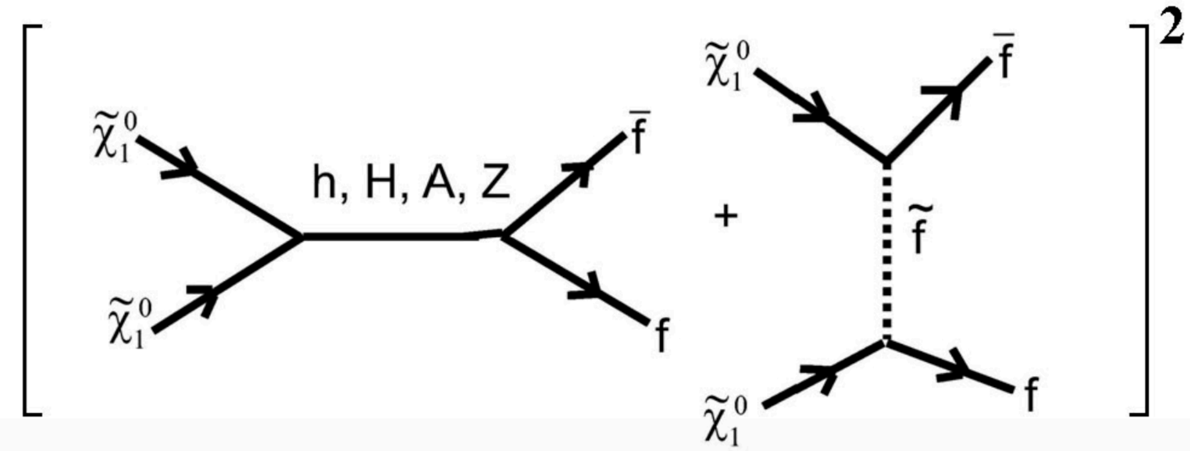
The gray dashed contour indicates where the $\tilde{\chi}_1^0$ relic abundance matches the Planck measurement $\Omega_{\tilde{\chi}_1^0} h^2 = \Omega_{\rm DM}^{\rm Planck} h^2 = 0.12$ [4]. Depletion of $\Omega_{\tilde{\chi}_1^0} h^2$ occurs via coannihilation processes such as $\tilde{\ell}\tilde{\chi}_1^0 \to \ell\gamma$, whose rate grows exponentially $\sim e^{-\Delta m(\tilde{\ell},\tilde{\chi}_1^0)/m(\tilde{\ell})}$ with smaller mass differences [5, 6]. At low $m(\tilde{\ell})$, the self-annihilation via the Z boson 'funnel' becomes competitive, allowing larger mass splittings to satisfy $\Omega_{\rm DM}^{\rm Planck} h^2$. Loop corrections from $\tilde{\ell}$ and $\tilde{\chi}_1^0$ states contribute to the muon anomalous magnetic moment $a_\mu = \frac{1}{2}(g-2)_\mu$. The green dashed line indicates modifications consistent with the measured discrepancy $\Delta a_\mu = a_\mu^{\rm measured} - a_\mu^{\rm predicted} \simeq 2.5 \times 10^{-9}$ [8].

Coannihilation



$e^{-\Delta M/20}$ +

Self-annihilation



g-2