Low-x 2019

26-31 August 2019
Nicosia, Cyprus

Searches for Dark Matter at the LHC in forward proton mode

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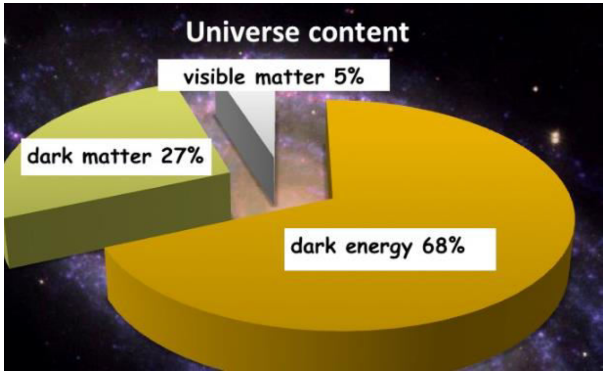
(in collaboration with Marek Tasevsky, Lucian Harland-Lang and Misha Ryskin)



Aim:

- to report current status of our ongoing long-term studies on prospects of searches at the LHC for ELECTROWEAKINO pair production via photon fusion with forward proton detectors (AFP, CT-PPS)

- exemplified within the framework of the compressed mass **MSSM**

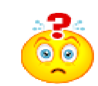
First discussed: KMR, J.Phys. G44 (2017) no.5, 055002 **HKRT JHEP 1904 (2019) 010**

Some recent studies: L.Beresford, Jesse Liu, ArXiv:1811.0645

S.I. Godunov et al, ArXiv: 1906.08568

SUSY – solution to various shortcomings of SM (as an example only)

If (it looks like) squarks and gluinos are too heavy, sleptons, charginos, neutralinos- the main target. **(null search result so far)**



MSSM : charginos $\tilde{\chi}^{\pm}_{1,2}$ four neutralinos $\tilde{\chi}^{0}_{1,2,3,4}$

$\tilde{\chi}^{0}_{1}$, natural candidate for cold Dark Matter –**LSP**

arXiv:1710.02406

(and quite a few other papers)

natural SUSY:
existence of light nearly
mass-degenerate Higgsinos/chargin
Mass~ 100-200GeV
mass splitting

Most challe
scenario
between

Motivated by naturalness, cosmological observations and (g-2) phenomenology.

What about the LHC during ou MY lifetime ?

Naturalness and light Higgsinos: why ILC is the right machine for SUSY discovery

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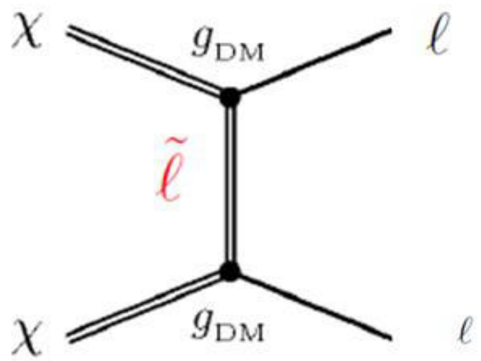
upersymmetry, a theoretically and experimentally well-motivated ... around the predicted existence of four light, nearly mass-degenerate Hig... with mass ~ 100 – 200 GeV (not too far above m_Z). The small mass splittings amongst the higgsinos, typically 4-20 GeV, results in very little visible energy arising from decays of the heavier higgsinos. Given that other SUSY particles are considerably heavy, this makes detection challenging at hadron colliders. On the other hand, the clean environment of an electron-positron collider with $\sqrt{s} > 2m_{higgsino}$ would enable a decisive search of these required higgsinos, and thus either the discovery or exclusion of natural SUSY. We present a detailed simulation study of precision measurements of higgsino masses and production cross sections at $\sqrt{s} = 500$ GeV of the proposed International Linear Collider currently under consideration for construction in Japan.

$$e^+e^- \to \widetilde{\chi}_1^+\widetilde{\chi}_1^- \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0 q\bar{q}' e\nu_e(\mu\nu_\mu).$$

Co-annihilation

(1702.00750, model-1a)

Dark matter annihilation

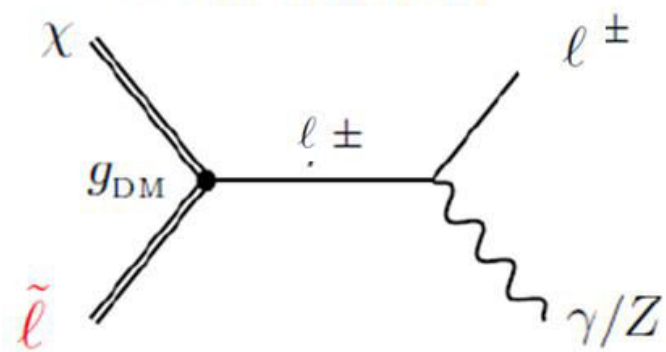


to bring DM abundance down to the observed value

Initially DM in thermal equilibrium with SM, later it freezes out

- Overproduces dark matter (Unless large couplings)
- We need a mechanism to reduce the DM relic density

Co-annihilation:



Freeze-out temperature $T_F \sim m_{DM}/25$

Boltzmann factor $\exp\left(-\frac{\Delta M}{T}\right)$ ⇒ $\Delta M \lesssim m_{DM}/25$

We need **mass splitting of 4% of m_{DM}**

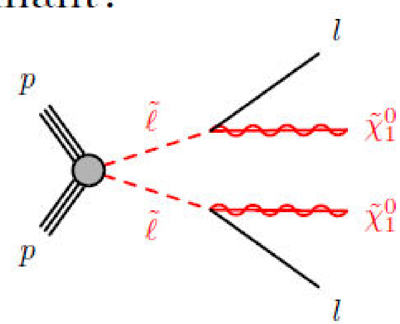
SUSY at the LHC

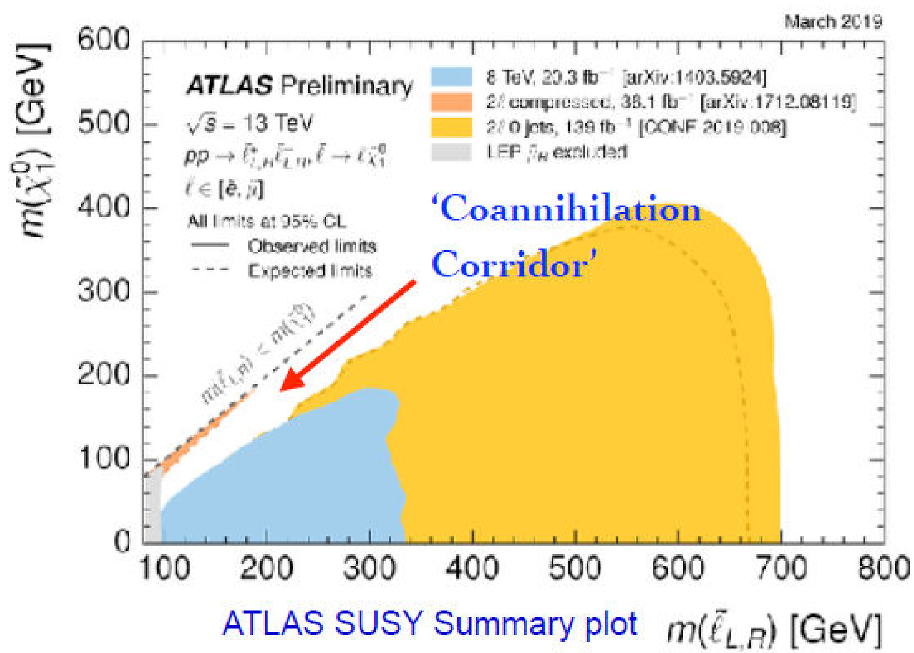
- **Pre-LHC**: EW-scale SUSY theoretically well motivated BSM scenario: hierarchy problem, coupling unification, natural DM candidate…
- **Post-LHC** folklore: no EW-scale SUSY to be seen!

Lightest SUSY particle = 'LSP'

- Only half true: most significant limits based on 'classic' large missing $E_\perp$ signal, requiring **largish** SUSY particle **mass splittings**.

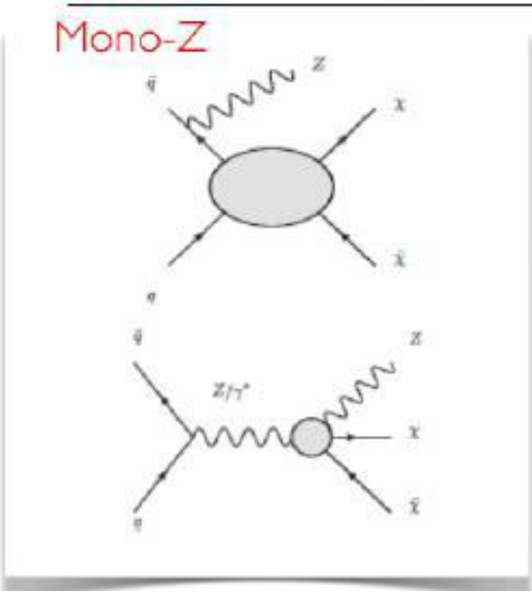
- For e.g. small slepton-neutralino mass differences, LEP constraints still dominant!

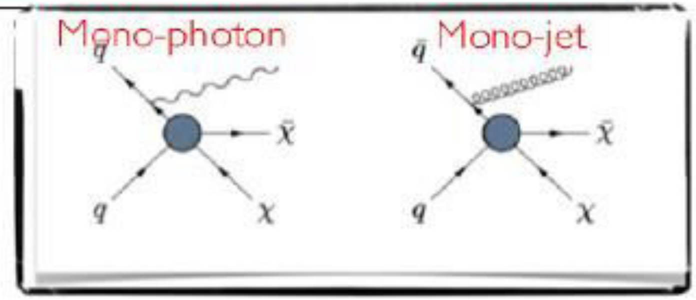


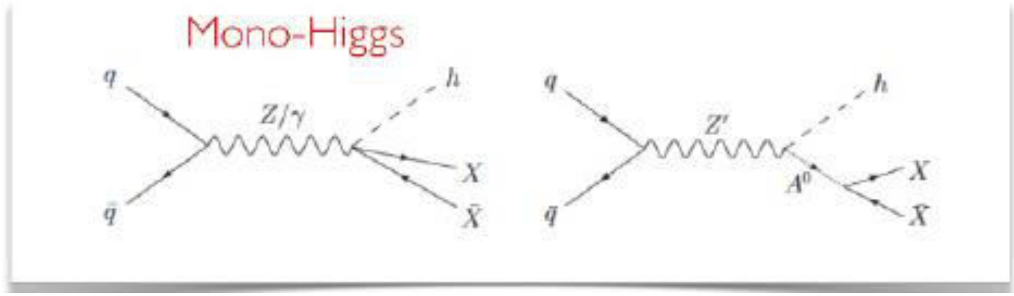


Mono-Mania (at the LHC)

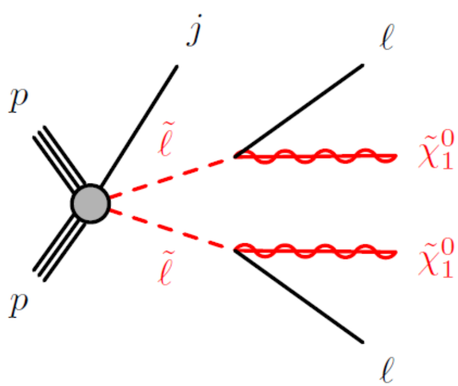
DM Searches @ LHC O. Buchmüller

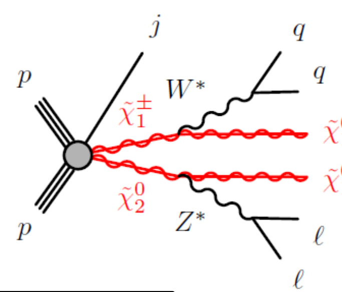






Searches for Electroweakinos at the LHC



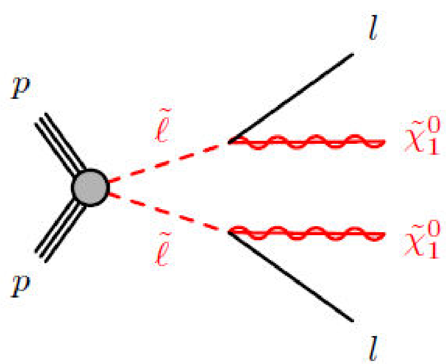


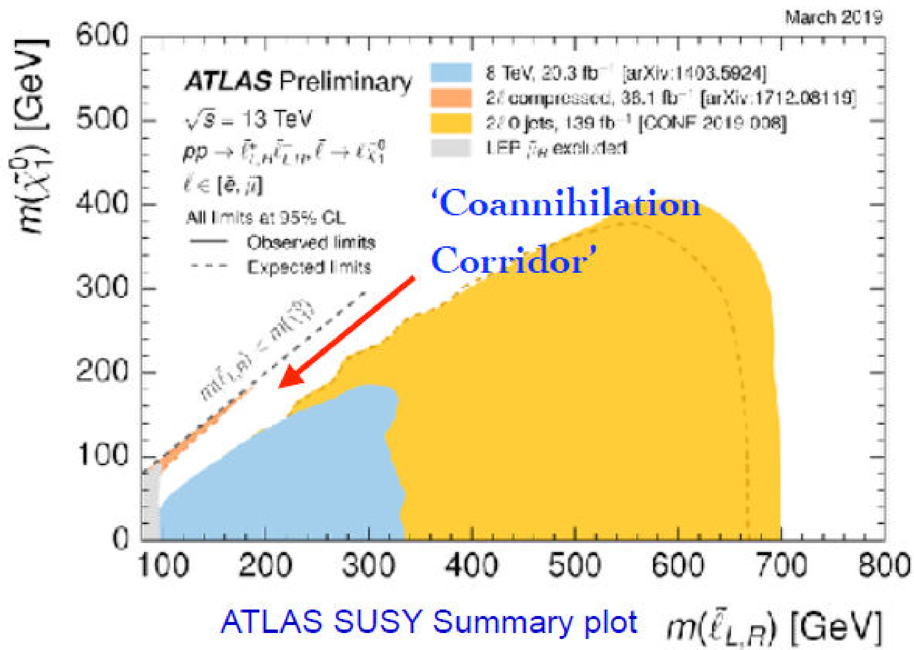
Model dependence

SUSY at the LHC

- Such '**compressed SUSY**' scenarios not just dreamt up to avoid limits.
- **Theoretically motivated** by naturalness, $(g-2)$ phenomenology, and cosmological considerations (coannihilation $\Rightarrow$ correct DM abundance).
- Inclusive cross sections not small (up to ~ 100s of fb) $\Rightarrow$ huge number of events may be produced at LHC, but **lost in BG**.

- How can **Photon-initiated** production help?





Motivation: photon-induced CEP

- Photon-initiated CEP of particular interest:

  ★ Very well understood initial state, via **equivalent photon approximation**:

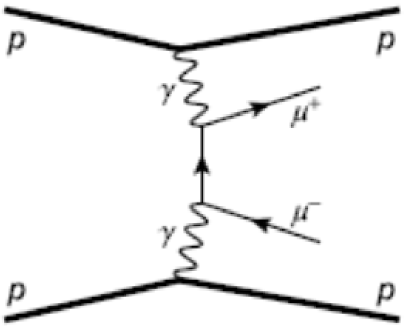
(Well known) EM Form Factors

$$n(x_i) = \frac{1}{x_i}\frac{\alpha}{\pi^2}\int \frac{\mathrm{d}^2 q_{i_\perp}}{q_{i_\perp}^2 + x_i^2 m_p^2}\left(\frac{q_{i_\perp}^2}{q_{i_\perp}^2 + x_i^2 m_p^2}(1 - x_i)F_E(Q_i^2) + \frac{x_i^2}{2}F_M(Q_i^2)\right)$$

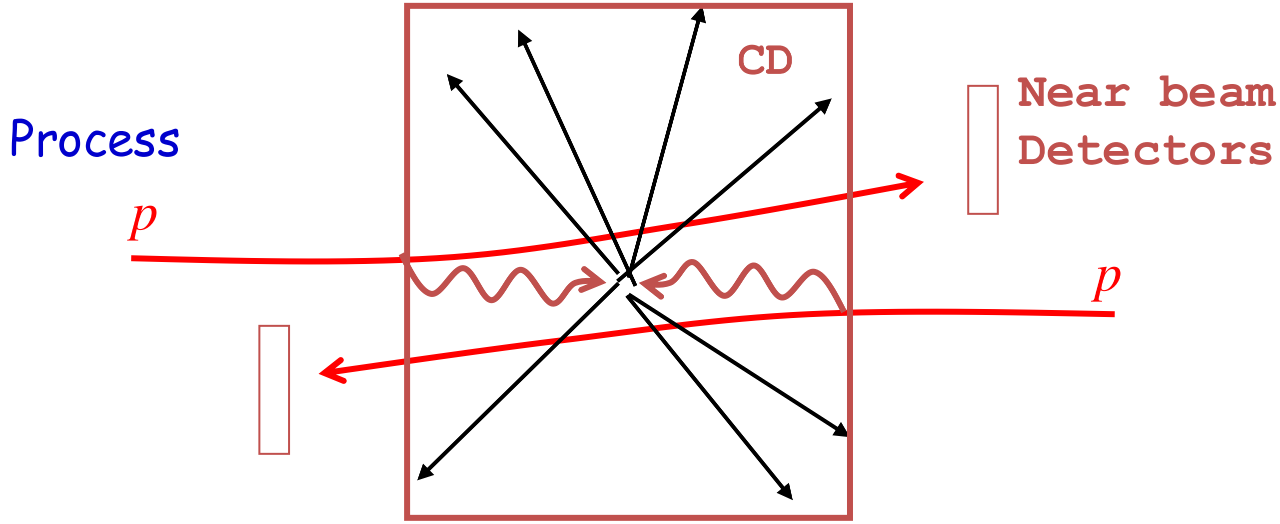
Photon flux

  ★ Low photon $Q^2 \Rightarrow$ large proton-proton impact parameter impact of QCD ('survival factor') small and under control.

$\longrightarrow$ LHC as a $\gamma\gamma$ collider! **Clean probe of BSM** with EW couplings.



$\gamma\gamma$ collisions at the LHC



AFP

CT-PPS

$$pp \to \tilde{\ell}^{+}_{L,R}\tilde{\ell}^{-}_{L,R} + pp$$

$$\tilde{\ell} \to \ell\tilde{\chi}^{0}_{1}, \ell \in [e, \mu]$$

Strong advantage-model independent production mechanism, accurate mass measurement

Extensive Program

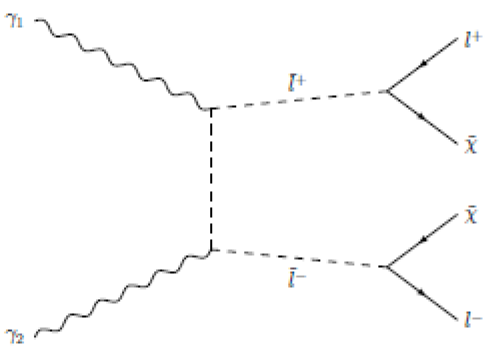
- $\gamma\gamma \to$ μμ, ee QED processes
- $\gamma\gamma \to$ QCD (jets..)
- $\gamma\gamma \to$ WW,...$\gamma\gamma$ anomalous couplings
- $\gamma\gamma \to$ squarks, top... pairs
- $\gamma\gamma \to$ Charginos, Sleptons, ALPS
- Other new BSM objects

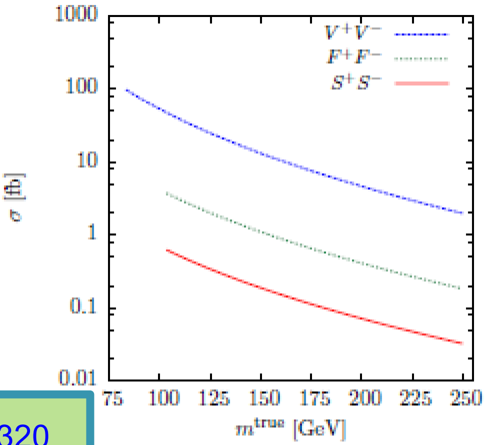
$$pp \to p + \gamma\gamma + p\,,$$
$$\gamma\gamma \to X^+X^-\,,$$

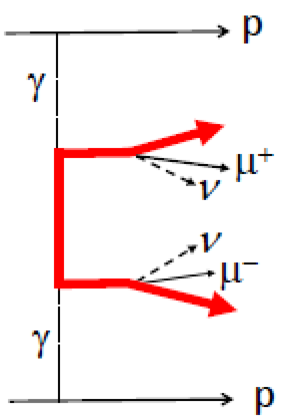
Diphoton X-Pair Production

where X = W–boson, lepton, slepton, chargino...

- If particle decays semi–invisibly, then additional information from tagged proton momenta can be used to measure masses and discriminate BG.







HKSS, arXiv:1110.4320

- Consider exclusive production of chargino pair $\tilde{\chi}_1^+\tilde{\chi}_1^-$, decaying via

$$\tilde{\chi}_1^+(\tilde{\chi}_1^-) \to l^+(l^-) + \nu(\overline{\nu}) + \tilde{\chi}_1^0\,,$$

electroweakinos

where the $\tilde{\chi}_1^0$ is an LSP neutralino.

- For cases that $\Delta M = M(\tilde{\chi}_1^0) - M(\tilde{\chi}_1^\pm)$ is relatively small, can be difficult to observe inclusively. (compressed mass BSM scenarios)

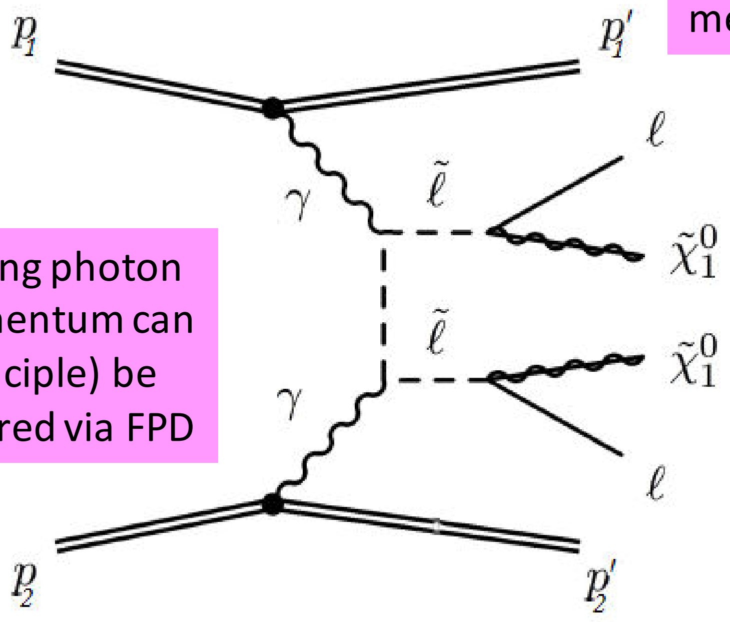
Advantage of exclusivity & compressed mass

Outgoing proton 4-momentum measured in FPD

$\xi_i = 1 - \frac{E_{p'_i}}{E_{p_i}}$, $i=1,2$

measured precisely in FPD

Lepton 4-momentum measured in Central detector



Incoming photon 4-momentum can (in principle) be measured via FPD

4-momentum of system of 2 DM particles could be constrained from photon & lepton 4-momenta

FPD measures precisely mass system. If mass splitting $M_{\tilde{l}} - M_{\tilde{\chi}_1^0}$ low → FPD can give quite a precise hint about $2m_{DM}$

CEP and SUSY

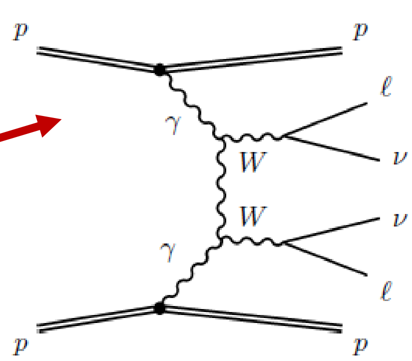
- Possibility of ~ 100 GeV mass slepton/chargino production at LHC begin swamped by huge inclusive BGs.
- **Exclusive photon-initiated** production a natural mechanism:

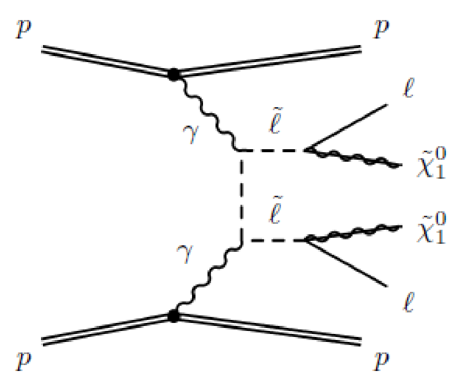
  ★ **Well understood**, model-independent signal cross section.

  ★ Irreducible WW BG can be controlled. No need for large missing $E_\perp$.

  ★ **Proton tagging**: can reconstruct mass of central system from protons alone ('missing mass'). Crucial handle for BGs.

- But, how feasible is this in **high pile-up** environment?





Classes of Background

$(M_{\tilde{l}}, M_{\tilde{\chi}_1^0}) = (120, 110)$ GeV

↓

$(M_{\tilde{l}}, M_{\tilde{\chi}_1^0}) = (300, 280)$ GeV

- Take **slepton pairs** for concreteness. Signal selection:

★ Low $\Delta M_{\tilde{l}\tilde{\chi}_0} \Rightarrow$ two relatively low $p_\perp$ leptons, with low m_{ll} , in central detector.

★ Two proton hits in AFP/PPS (~ 220m) acceptance.

$5 < p_{T,l_1,l_2} < 40$ GeV

$2 < m_{l_1 l_2} < 40$ GeV

$|\eta_{l_1,l_2}| < 2.5\ (4.0)$

$0.02 < \xi_{1,2} < 0.15$

- What are **backgrounds**?

★ Irreducible CEP of **W pairs**.

★ Reducible **semi-exclusive** production $(l^+l^-\ldots)$ with proton from dissociation system giving hit in forward proton detector (FPD).

★ Reducible **pile-up** background: conicidence of non-diffractive event with hits from independent diffractive events.

- Realistic analysis must consider all three.

$M_{\tilde{l}}$ =120-300GeV, $\Delta M = M_{\tilde{l}} - M_{\tilde{\chi}^0_1} = 10-20$ GeV

Major backgrounds

- $\gamma\gamma \to W^+W^- \to l^+\nu + l^-\bar{\nu}$
- Low mass $\gamma\gamma \to l^+l^-$ production
  Semi-exclusive process with proton from (SD,DD) dissociation detected in the FPD.
- Semi-exclusive QCD-initiated BGs due to low-pt (mainly c-quark) jets, with SD and DD followed by proton hits in the FPD.
- Coincidence of inelastic lepton pair production with two independent SD/DD events from the PU interactions that mimics the signal.
  (danger for other New Physics searches with $\sigma \leq 1$ fb)
- $\tau\tau$, dimeson, vector resonances etc...

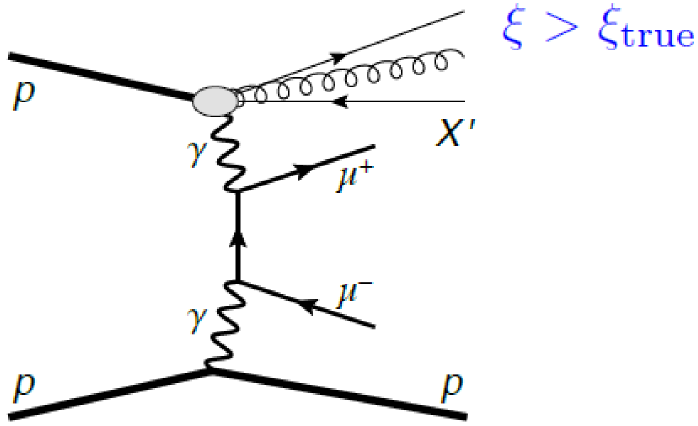
Semi-exclusive production

- **Exclusive** lepton pair production: FPDs require $M_{ll} \gtrsim 280\,\mathrm{GeV}$ through acceptance in proton momentum loss ξ , while centrally we require $M_{ll} < 40\,\mathrm{GeV} \Rightarrow$ **not a BG**.

- What about **semi-exclusive** production? Proton from **dissociation system** $\Rightarrow$ lower momentum fraction $\Rightarrow$ larger ξ , can be in FPD.

- What is probability, P_{SDnel} , of proton from SD giving FPD hit?

- Take two independent methods:
  - ★ Analytic Regge-based formula.
  - ★ From Pythia MC samples.



- Give similar small probability $P_{\mathrm{SDnel}} \approx 0.7\%$, but $\sigma_{ll}^{SD} \gg \sigma_{\tilde{l}\tilde{l}}^{CEP}$ in relevant mass regions $\Longrightarrow$ this is **not small enough**!

Semi-exclusive production

- How can we reduce this BG further? Range of cuts:

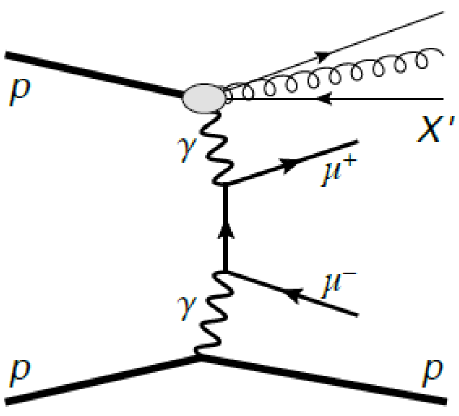
  ★ **Asymmetry** in SD topology: to give elastic proton in FPD, lepton system needs larger rapidity ⇒ require $\bar{\eta} = |\eta_{l_1} + \eta_{l_2}|/2 < 1$.

  ★ Events with dissociation will have larger proton $p_\perp$ (on SD side), and larger acoplanarity of lepton pair. Require:

Central: $\text{Aco} \equiv 1 - |\Delta\phi_{l_1 l_2}|/\pi > 0.13\ (0.095)$ for $|\eta_{l_1,l_2}| < 2.5\ (4.0)$

FPD: $p_{T,\text{proton}} < 0.35$ GeV

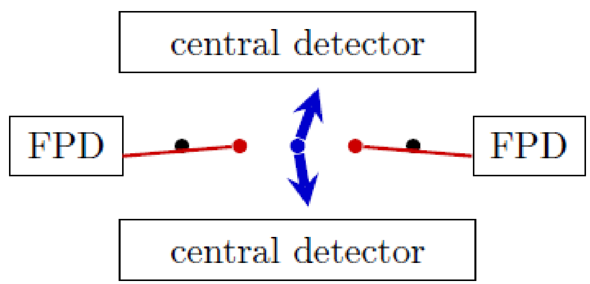
- Impact on Signal and BG evaluated using approx. modification to **SuperChic MC**, to include dissociation.
- Also consider BG from QCD-initiated CEP of K^+K^-, but find is **much smaller**.



Pile-up Background

- Relatively low $p_\perp$ leptons are produced **copiously** at the LHC: **inclusive** cross section for $p_\perp > 5\,\text{GeV}$ is about 10 nb!
- **Main sources**: decay of D mesons, W bosons, and pion/kaons.
- Such an inclusive event can coincide with hits from unrelated diffractive **pile-up** events in FPDs, mimicking signal.

(c) ND+SD+SD



R. Staszwksi, J. J. Chwastowski, arXiv:1903.03031

Background rejection using ToF

Pile-up Background

- Generate dominant source of background, inclusive jet production with **Herwig/Pythia**. Cross section ~ 10 mb, i.e. ~ 14 order of magnitude higher than signal!

- Impossible to generate event sample to evaluate effect of all cuts $\Rightarrow$ consider three **factorized** classes of cuts:

Forward proton detector acceptance

$0.02 < \xi_{1,2} < 0.15$	$p_{T,\text{proton}} < 0.35\,\text{GeV}$

Di-lepton system

$5 < p_{T,l_1,l_2} < 40\,\text{GeV}$	$\lvert\eta_{l_1,l_2}\rvert < 2.5\ (4.0)$
$\text{Aco} \equiv 1 - \lvert\Delta\phi_{l_1 l_2}\rvert/\pi > 0.13\ (0.095)$	$2 < m_{l_1 l_2} < 40\,\text{GeV}$
$\Delta R(l_1, l_2) > 0.3$	$\lvert\eta_{l_1} - \eta_{l_2}\rvert < 2.3$
$\bar{\eta} \equiv \lvert\eta_{l_1} + \eta_{l_2}\rvert/2 < 1.0$	$\lvert\lvert\vec{p_{T l_1}}\rvert - \lvert\vec{p_{T l_2}}\rvert\rvert > 1.5\,\text{GeV}$
$W_{\text{miss}} > 200\,\text{GeV}$	

No-charged
(No activity around primary vertex)

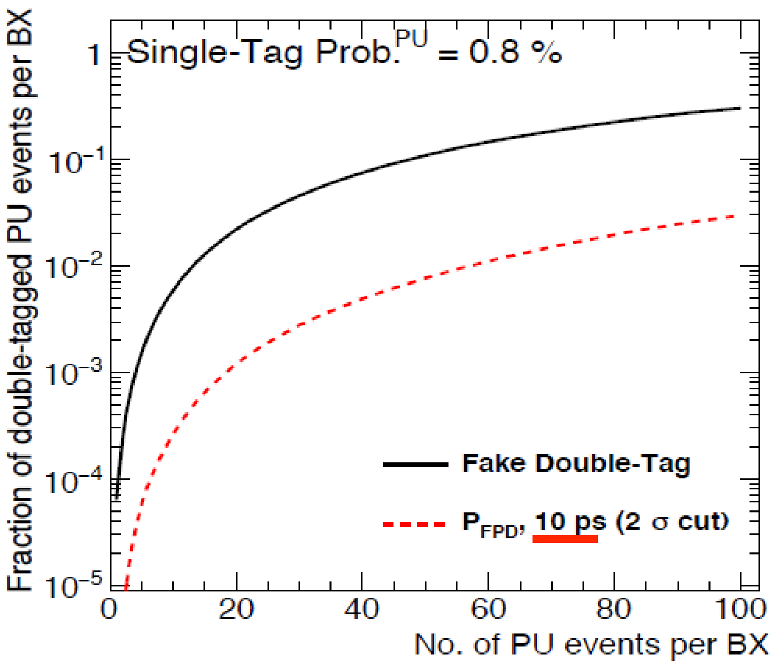
No hadronic activity	z-veto

Pile-up Background

- **First question:** rate of fake double-tag events coming from pile-up in FPD acceptance?

- Crucial element is use of **fast-timing** detectors: reject events where FPD arrival time does not match with central vertex.

- **Suppresses BG** significantly. Precise amount sensitive to pile-up, μ , and timing precision.



	Pythia 8.2		Herwig 7.1	
	$\langle\mu\rangle_{PU}$		$\langle\mu\rangle_{PU}$	
	10	50	10	50
Fake DT	0.0048	0.105	0.0123	0.222
ToF rejection	18.3	13.7	17.5	11.3
P_{FPD}	2.6×10^{-4}	7.6×10^{-3}	7.0×10^{-4}	2.0×10^{-2}

No Charged Cuts

- Inclusive dilepton production will typically have many **additional charged** particles associated with interaction vertex, while for CEP these are absent.

- **'No-Charged'** Cuts: veto on additional tracks and vertices within 1mm of central vertex. Leads to sizeable BG rejection.

$P_{\text{no-ch}}$	$\langle\mu\rangle_{PU}$		
	0	10	50
CEP $c\bar{c}$	3.5×10^{-3}	2.9×10^{-3}	1.7×10^{-3}
CEP gg	3.3×10^{-5}	2.8×10^{-5}	1.6×10^{-5}
Incl. jets ($\|\eta\| < 2.5$)	$5.2(2.0) \times 10^{-7}$	$4.4(1.7) \times 10^{-7}$	$2.5(1.0) \times 10^{-7}$
Incl. jets ($\|\eta\| < 4.0$)	$1.7(0.7) \times 10^{-7}$	$1.4(0.6) \times 10^{-7}$	$0.8(0.3) \times 10^{-7}$

Table 7: The no-charged rejection probabilities as a function of μ for $c\bar{c}$ and gg CEP, and inclusive ND jet production. The numbers in the first column were obtained at particle level and then used to calculate the numbers in the other columns using eq. 2 and P_{z-veto} probabilities from table 1. The inclusive jet events were generated with PYTHIA 8.2 (HERWIG 7.1).

- Additional cuts on dilepton system included, e.g. isolation requirements to remove decays from D mesons etc.

Event Selection

$\geq$ **100 GeV from the LEP constraints**

Compressed mass scenario → difference between slepton and DM candidate mass, ΔM, is small $\langle m_{ll} \rangle \sim \Delta M$ → aim is to keep $\langle m_{ll} \rangle$ low → $2 < m_{ll} < 40$ GeV

- $|\eta(l)| < 2{,}5$, cuts on $\eta(l_1) - \eta(l_2)$ (to supress BG)
- $p_T(l)$ >5 GeV (trigger conditions)

  $p_T(l)$ <30 GeV (in order to supress the WW BG)

  $\gamma\gamma \to W^+W^-$ with $W \to l\nu$
- requirement of no additional tracks with pt > 0.4 GeV at $|\eta| < 2{,}5$)
- both protons detected by the proton taggers (with FT)
- sleptons-quite small cross sections (0.01 -0.3 fb), +hostile PU environment 
- chargino pair production- extra factor of ~25 suppression 

Calculations: **SuperChic**, analytical, **PYTHIA 8.2, HERWIG 7.1** (quite reasonable agreement)

Results

$(M_{\tilde{l}}, M_{\tilde{\chi}_1^0}) = (120, 110)$ GeV → $(M_{\tilde{l}}, M_{\tilde{\chi}_1^0}) = (300, 280)$ GeV

|η| < 2.5

Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{PU}$ 0	10	50
Excl. sleptons	0.6—3.9	0.5—3.3	0.3—1.9
Excl. l^+l^-	1.4	1.2	0.7
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.7	0.6	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0(\sim 0)$	0.1(0.1)	1.8(2.4)

|η| < 4.0

Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{PU}$ 0	10	50
Excl. sleptons	0.7—4.3	0.6—3.6	0.3—2.1
Excl. l^+l^-	1.1	0.9	0.5
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.6	0.5	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0(\sim 0)$	0.03(0.05)	0.6(0.7)

- Final signal yield- **handful** of events.
- Irreducible WW BG under control. Most significant BG from **pile-up**, with dilepton production + **dissociation** a close runner-up.

Future Improvements

- What improvements might we expect in the future?

★ Cut on distance between **secondary** and **primary** vertex: reduce BG from decays of heavier particles (dominant part of inclusive BG).

★ Improved **ToF resolution** in **FPDs** (ToF rejection increases linearly with decreasing resolution).

★ Radiation hard **ZDCs** with timing to suppress proton dissociation BG.

★ Add **timing info** to **central detector** - considered for HL-LHC upgrades at forward rapidity, and envisaged by CMS centrally.

Journal of Physics G: Nuclear and Particle Physics

PAPER

Can invisible objects be 'seen' via forward proton detectors at the LHC?

V A Khoze[1,2], A D Martin[1,3] and M G Ryskin[1,2]

Published 7 April 2017 • © 2017 IOP Publishing Ltd
Journal of Physics G: Nuclear and Particle Physics, Volume 44, Number 5

$$pp \rightarrow p + \text{invisible} + p,$$

An attractive idea, but huge backgrounds caused by soft proton dissociation, photon bremsstrahlung and PU (at high lumi)

$p \rightarrow p + \gamma,\ N^* \rightarrow p + \gamma$ and $N^* \rightarrow p + \pi^o.$ $\quad p \rightarrow p\pi^+\pi^-$

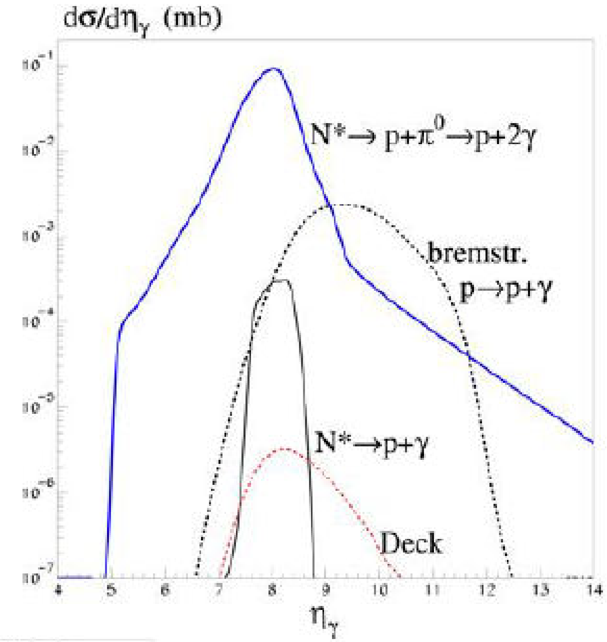
Measurements at low lumi ($\mu \sim 1$)with 'veto' detectors (like ZDC and FSC/ADA/ADC)

DM searches with AFP (exclusive $\gamma\gamma$)

KMR, J.Phys. G44 (2017) no.5, 055002

- Signal (WIMP itself): massive, neutral, weakly interacting particle
- **Signal with AFP: p(AFP) + invisible(Central Det.) + p(AFP)**

- x-section ~ fb



- **Backgrounds from neutral particles (escaping CD):**

1) Bremsstrahlung $p \to p + \gamma$
2) Dissociation $p \to N^* \to p + \pi^0 \to p + \gamma\gamma$
3) Resonance decay $p \to N^* \to p + \gamma$

Suppressed by vetoing using ZDC or using LHCf (see next slide).
But the fate of LHCf at HL-LHC unclear.
Suppression to ~nb level needs:

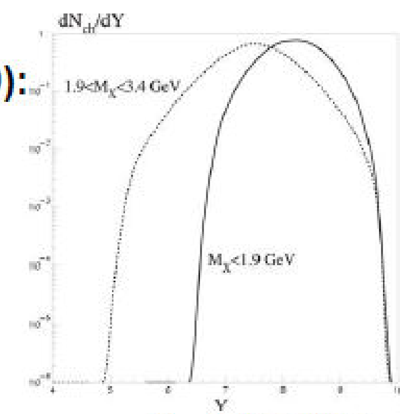
- ZDC coverage to be increased to $\pm$ 1.5mrad
- ZDC to have > 5 rad.lengths (photon detection efficiency > 99%)

- **Background from charged particles (escaping CD):**

4) $p \to p + \pi^+\pi^-$

Suppression to ~nb level needs:

- Calo coverage 5.5 < η < 9.5
- > 5 rad. lengths



Bgd taming difficult:

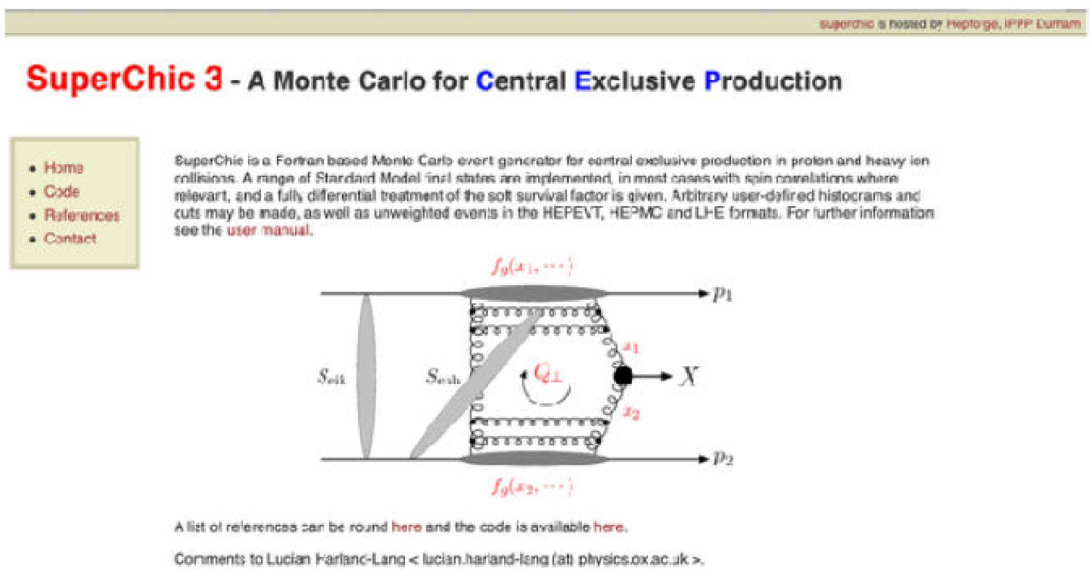
- ZDCs/Calo need to be upgraded
- Low pile-up needed

SuperChic 3 (Plug)

- Key element in this analysis - SuperChic MC.

- A MC event generator for CEP processes. **Common platform** for:
  - QCD-induced CEP.
  - Photoproduction.
  - Photon-photon induced CEP.

- For **pp**, **pA** and **AA** collisions. Weighted/unweighted events (LHE, HEPMC) available- can interface to Pythia/HERWIG etc as required.



CONCLUSIONS

- Have discussed possibility to search for compressed SUSY scenarios via exclusive photon-initiated production at LHC.
- Highly attractive proposal, as very hard to probe via inclusive channels.
- However, important to consider all sources of backgrounds in pile-up heavy nominal LHC environment.
- Possible to bring the backgrounds under control, at the price of a limited significance $S \sim 2$, $B \sim 2$ events for 300 fb^{-1}.
- But not the end of the story- only a first study, and many potential avenues for improvement to explore.
- Ongoing work: more complete treatment of proton dissociation in SuperChic. Stay tuned!


THANK YOU


QUESTIONS?

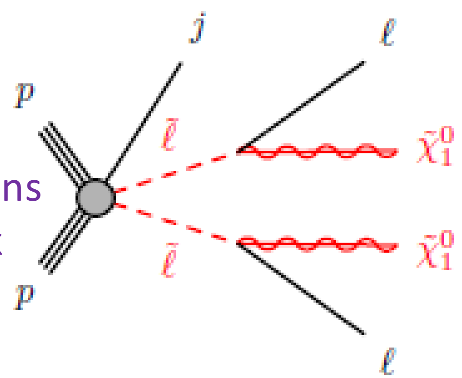
BACKUP

Inclusive slepton searches

Slepton: spin=0 partner of lepton
- decays to fermionic DM + leptons with BR=100%

ISR jet (for trigger purposes)

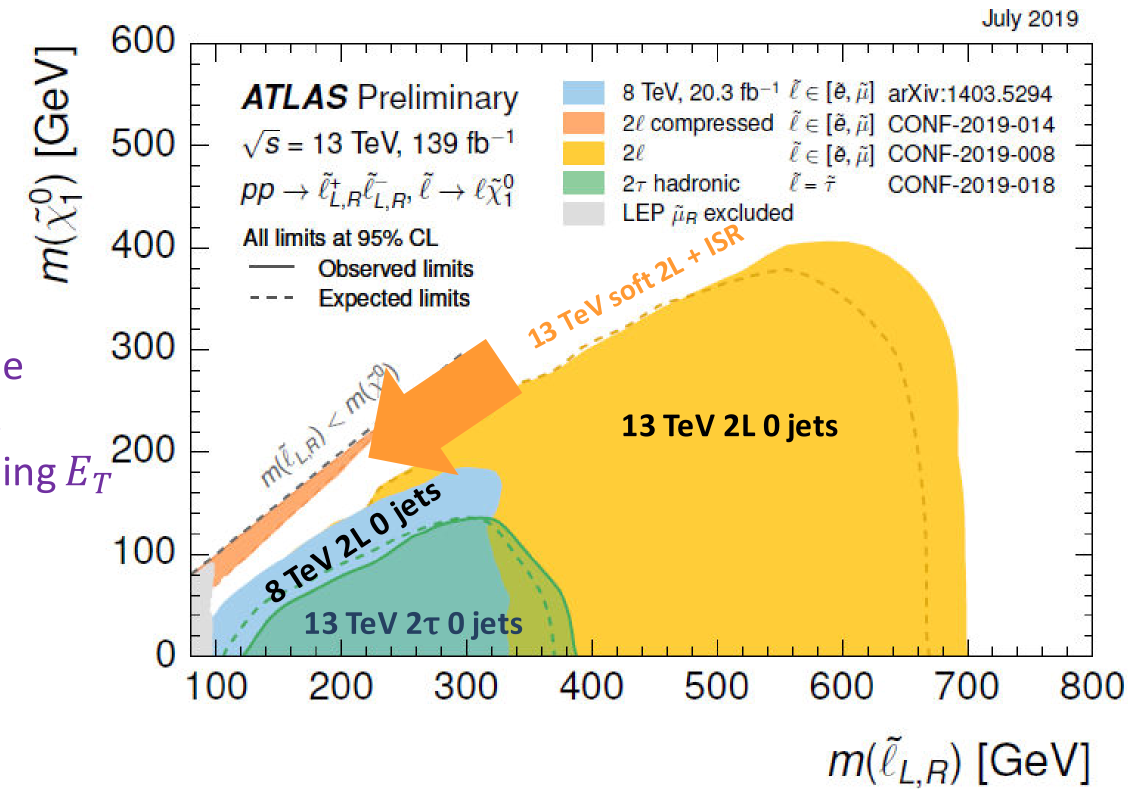
Both protons break up



DM particle candidate. Large missing E_T in Central detector

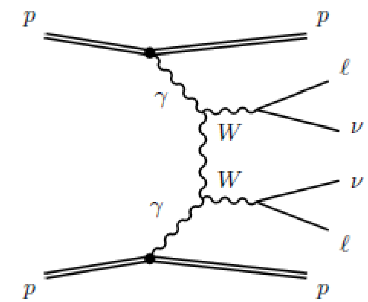
Leptons precisely measured in Central detector

Model dependent



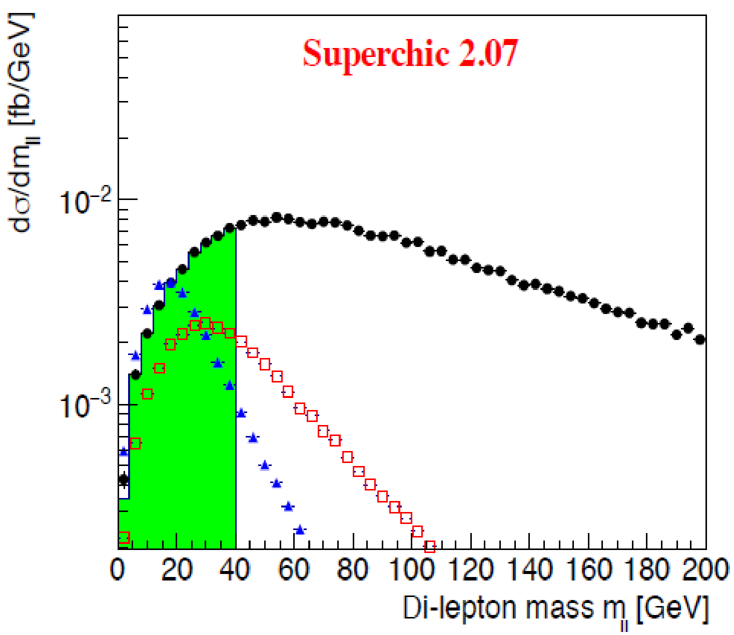
ATLAS SUSY Summary plot

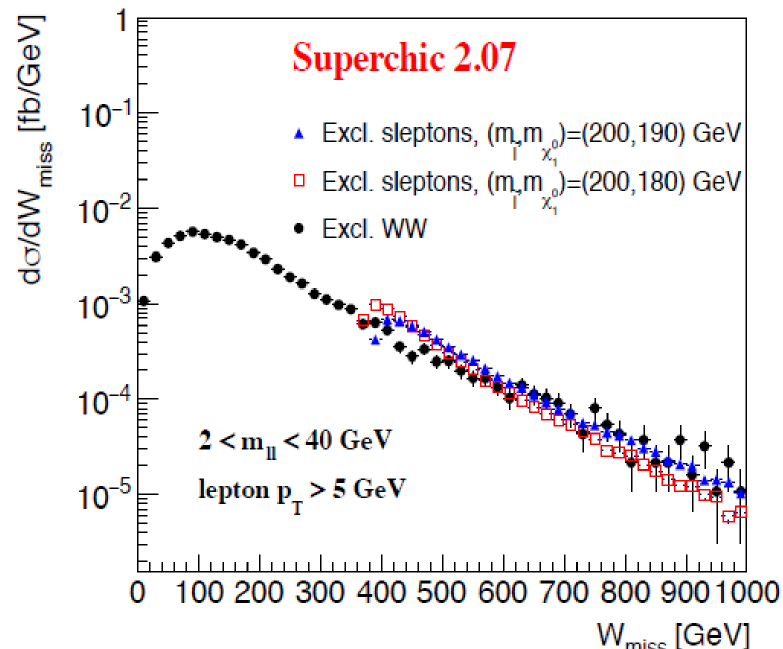
W pair production



- Exclusive WW gives same dilepton signal.
- But much larger $M_W - M_\nu$ mass difference: cuts on leptons and 'missing mass' effectively **suppress** this BG.

Signal: $W_{\rm miss} > 2M_{\tilde{\chi}_0}$ BG: $W_{\rm miss} > 2M_\nu \sim 0$

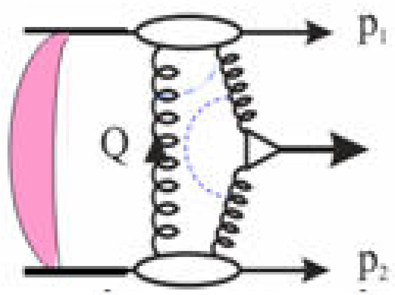


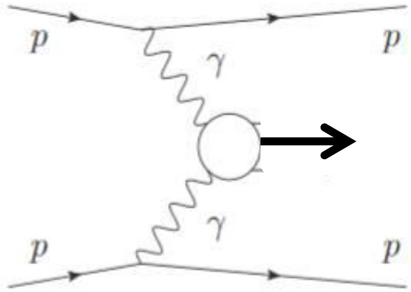


- Aside: considered more complete approach based on max. kinematically allowed $M_{\tilde{l}}, M_{\tilde{\chi}_0}$: only mild improvement seen.

AFP , CT-PPS

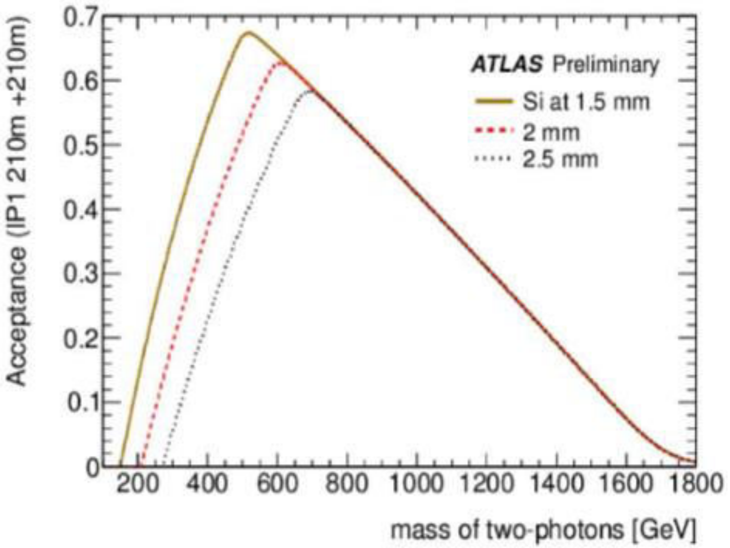
At large masses $\gamma\gamma$ takes over , KMR-02





$$0.03 < \xi < 0.15$$

M ~200- 2000 GeV



- Tag and measure protons at $\pm$210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- Sensitivity to high mass central system, X, as determined using AFP/CT-PPS: Very powerful for exclusive states: kinematical constraints coming from AFP and CT-PPS proton measurements

Courtesy of Marek Tasevsky

HL-LHC

Current analysis: μ≤50: only ToF with $\sigma_t = 10$ ps: S/B~1

μ>50: additional time information from the central detector necessary and/or $\sigma_t \sim 5$ ps from ToF

The effect of the time information from central/forward main det. needs to be studied in more detail:
- For special type of events with only two tracks (di-lepton system)
- For realistic assumptions about the primary vertex reconstruction (n_{trk} dependence, vertex merging in luminous region)