Searches for Dark Matter at the LHC in the Forward Proton Mode

Lucian Harland-Lang, University of Oxford

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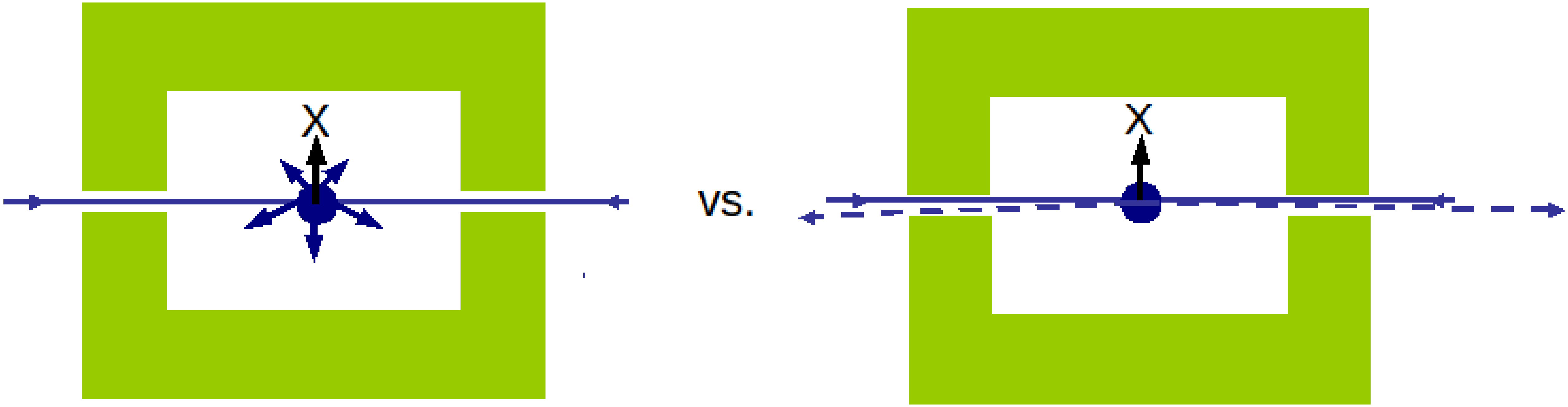
In collaboration with Valery Khoze, Marek Tasevsky and Misha Ryskin

Central Exclusive Production

Central Exclusive Production (CEP) is the interaction:

$$hh \to h + X + h$$

- Diffractive: colour singlet exchange between colliding protons, with large rapidity gaps ('+') in the final state.
- Exclusive: hadron lose energy, but remain intact after the collision.
- Central: a system of mass M_X is produced at the collision point and only its decay products are present in the central detector.



Motivation: photon-induced CEP

- **Photon-initiated** CEP of particular interest:

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

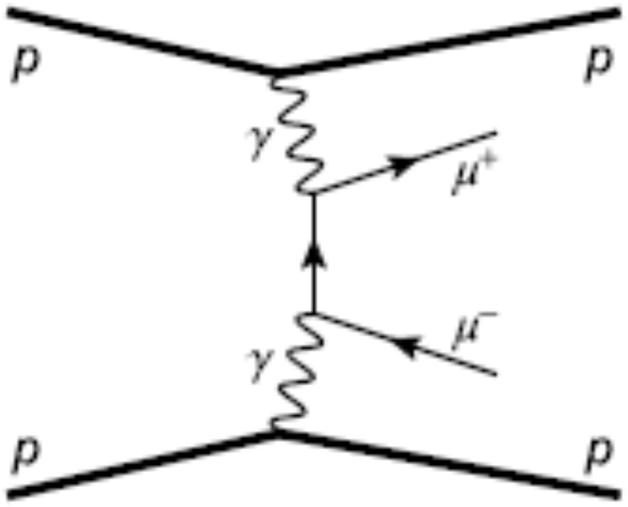
(Well known) EM Form Factors

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

Photon flux

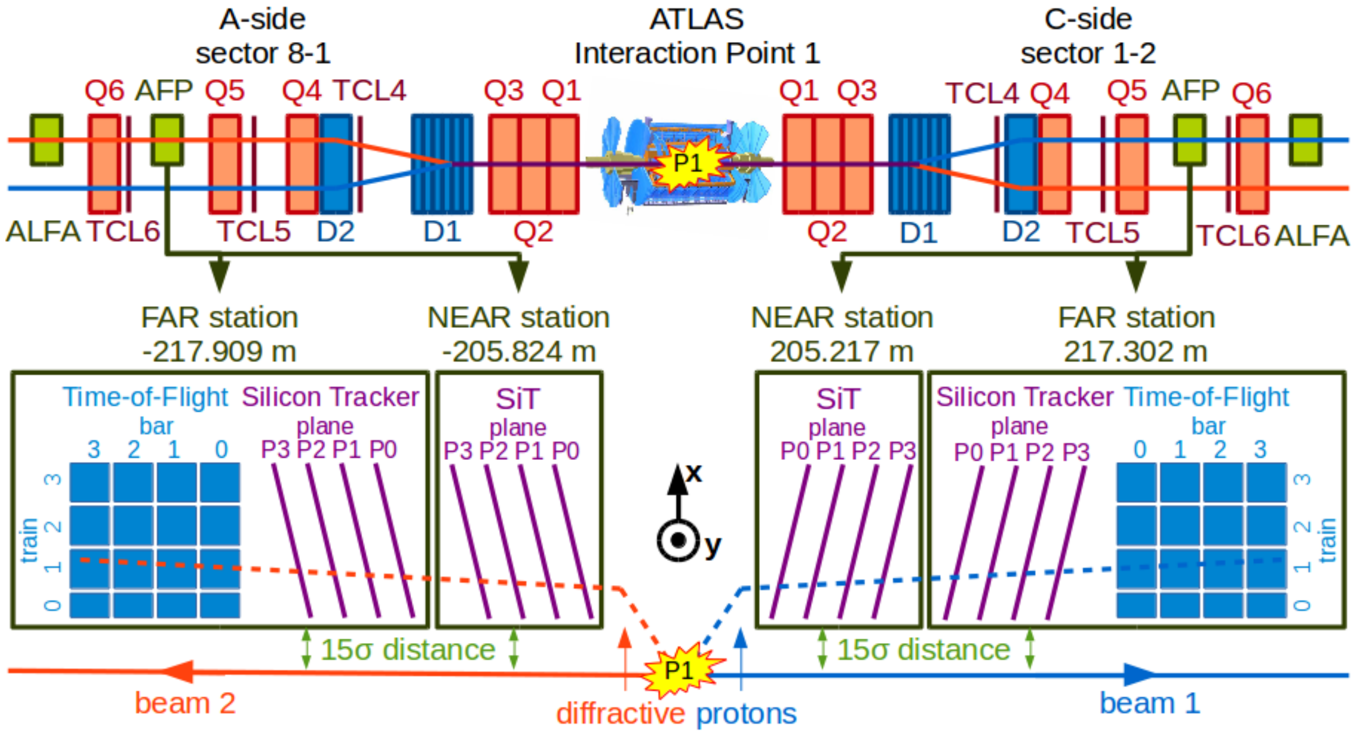
⋆ Low photon $Q^2 \Rightarrow$ large proton-proton impact parameter impact of QCD ('survival factor') small and under control.

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

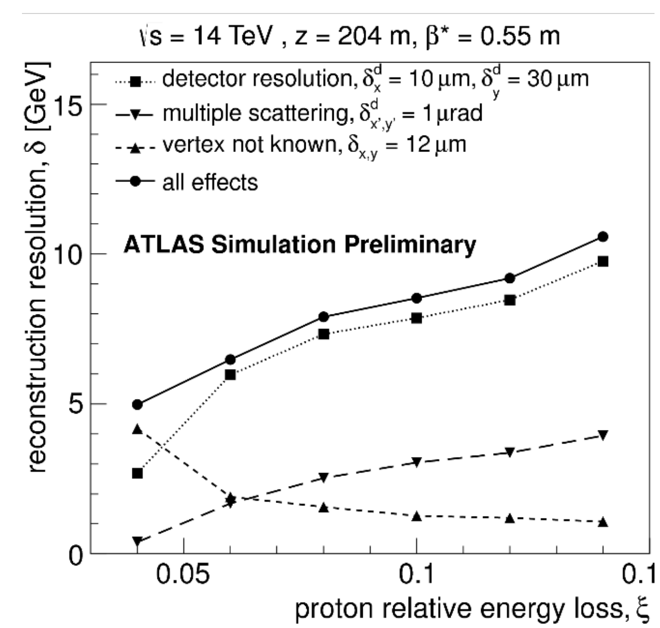


Motivation: Proton Tagging @ LHC

- Proton taggers installed in association with **ATLAS** and **CMS** detectors at LHC, allowing CEP processes to be selected directly.

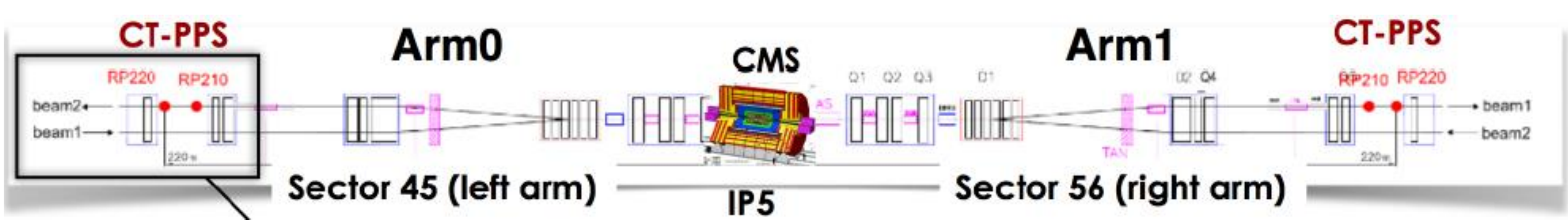


AFP



Excellent ξ (mass) resolution
[AFP TDR, CERN-LHCC-2015-009]

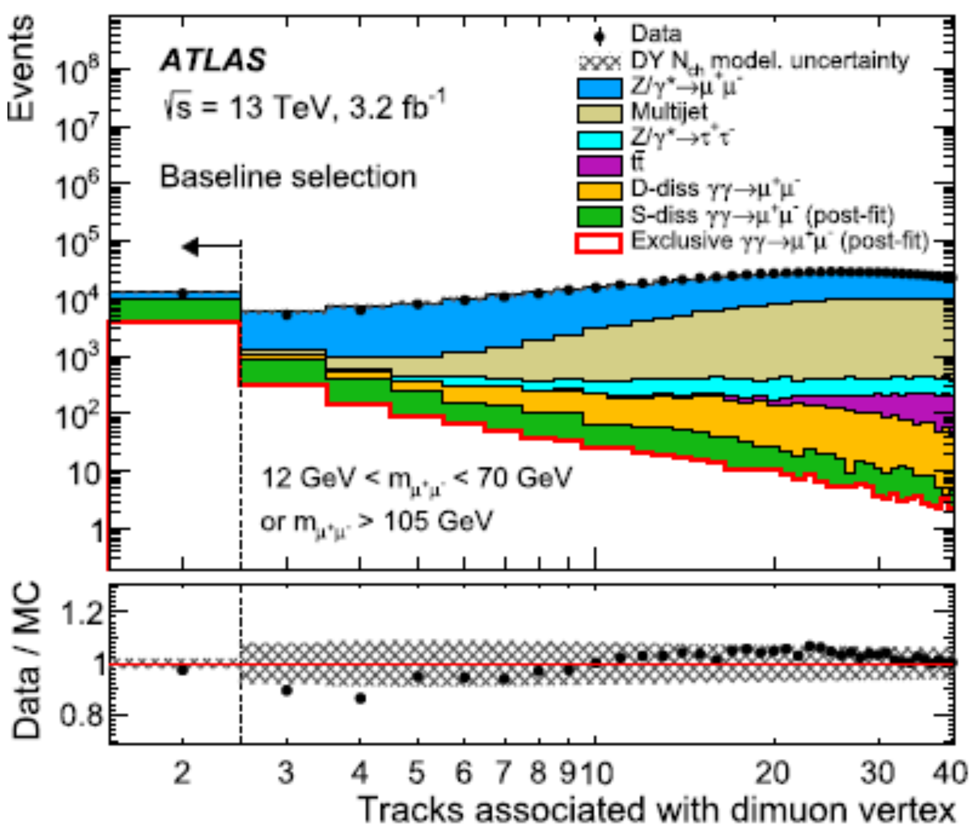
CT-PPS



Motivation: photon-induced CEP@LHC

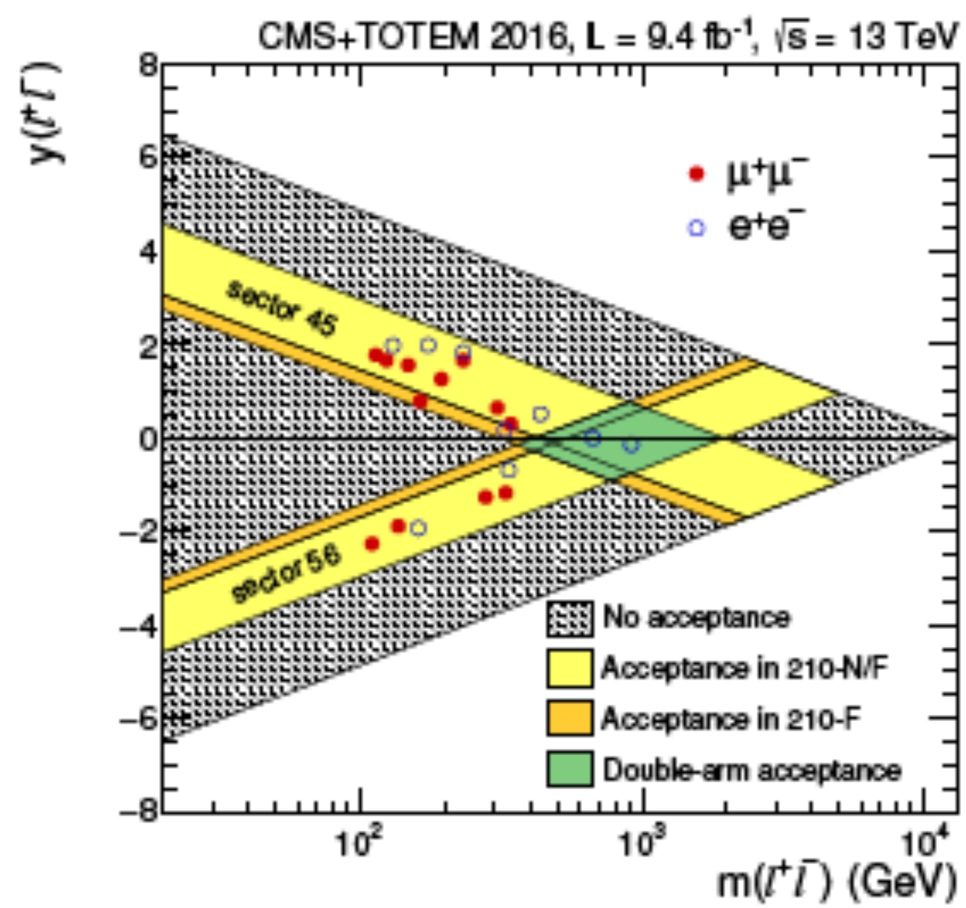
- Measurements of ‘exclusive-like’ lepton pair production made by both ATLAS and CMS in nominal **high pile-up** running.

w/o proton tagging



[Phys. Lett. B777 (2018) 303]

w/ proton tagging



[JHEP1807 (2018) 153]

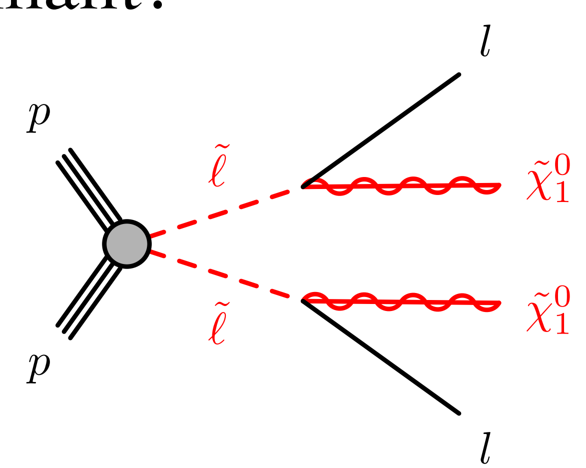
SUSY at the LHC

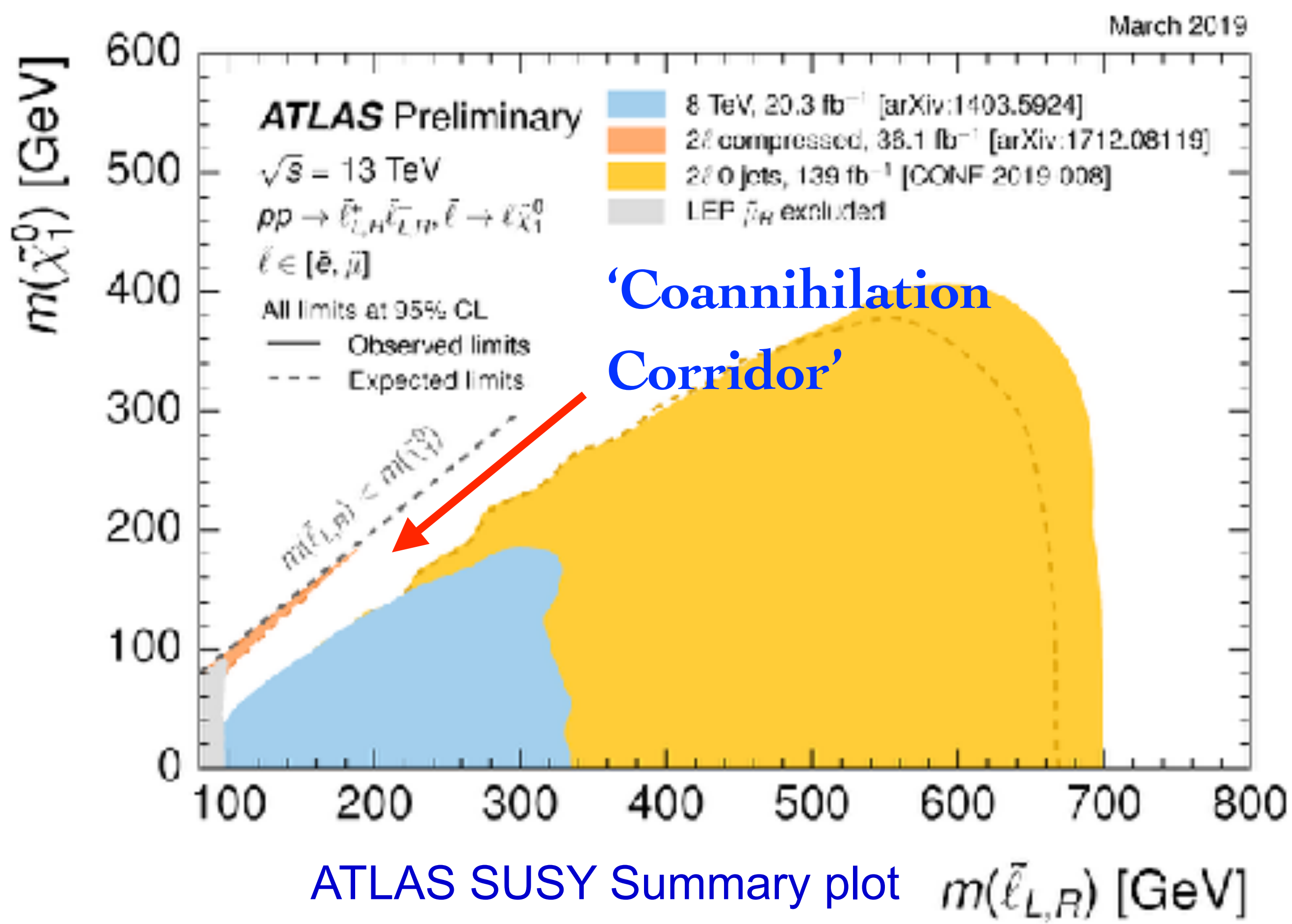
- **Pre-LHC**: EW-scale SUSY theoretically well motivated BSM scenario: hierarchy problem, coupling unification, natural DM candidate…
- **Post-LHC** folklore: no EW-scale SUSY to be seen!

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!



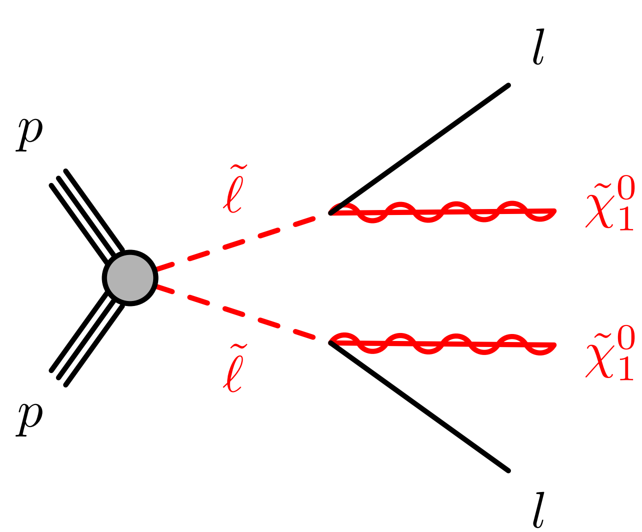


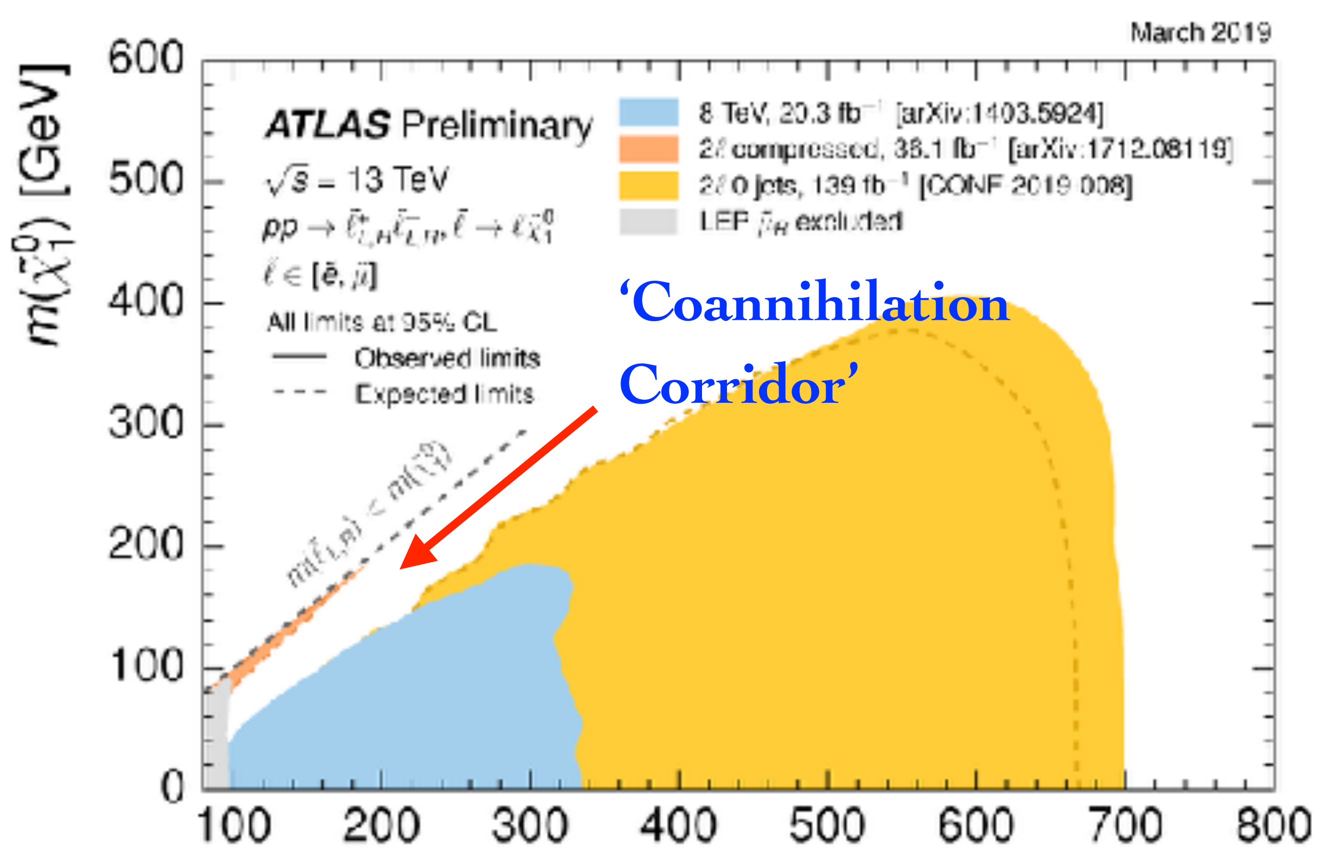
ATLAS SUSY Summary plot

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?

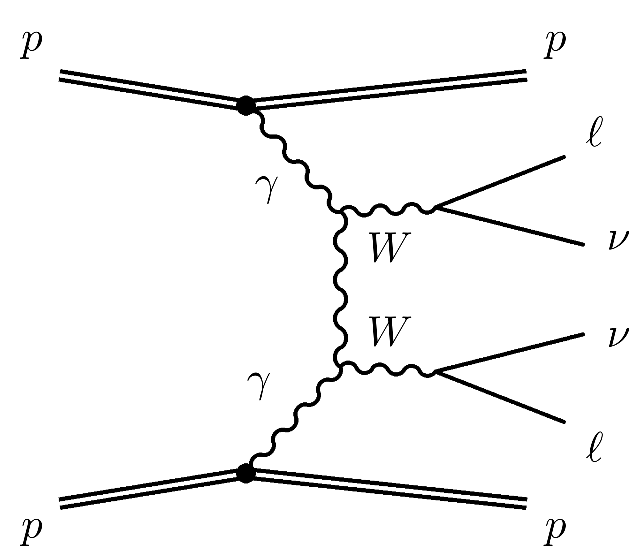


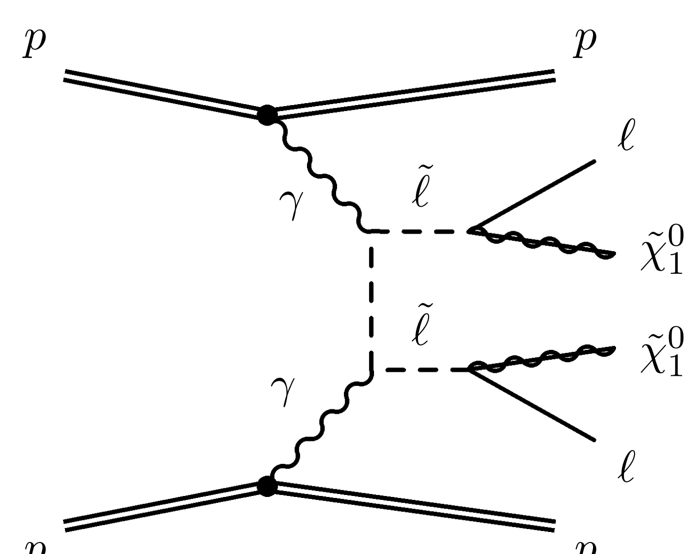


ATLAS SUSY Summary plot

CEP and SUSY

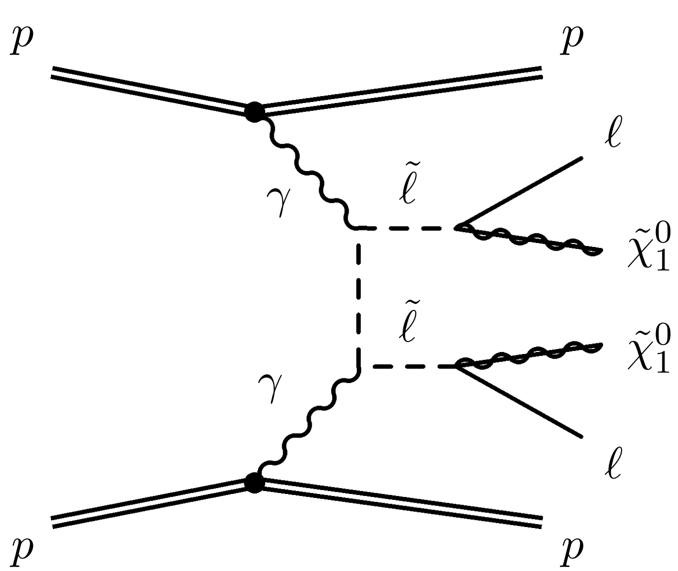
- Possibility of ~ 100 GeV mass slepton/chargino production at LHC begin swamped by huge inclusive BGs.
- **Exclusive photon-initiated** production a natural mechanism:
    - ⋆ **Well understood**, model-independent signal cross section.
    - ⋆ Irreducible WW BG can be controlled. No need for large 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?





Challenges in Forward Proton Mode

- Cross section for ~ 100 GeV slepton pair CEP ~ fb $\Rightarrow$ essential to take data during **nominal high-luminosity** LHC running.
- Question discussed in recent study: what are **challenges/backgrounds** in searching for such a signal via CEP?



IPPP/18/103

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§]

[1] *Rudolf Peierls Centre, Beecroft Building, Parks Road, Oxford, OX1 3PU, UK*

[2] *IPPP, Department of Physics, University of Durham, Durham, DH1 3LE, UK*

[3] *Petersburg Nuclear Physics Institute, NRC "Kurchatov Institute", Gatchina, St. Petersburg, 188300, Russia*

[4] *Institute of Physics, Czech Academy of Sciences, CS-18221 Prague 8, Czech Republic*

Abstract

We analyze in detail the LHC prospects at the center-of-mass enery of $\sqrt{s}$ = 14 TeV for charged electroweakino searches, decaying to leptons, in compressed supersymmetry scenarios, via exclusive photon-initiated pair production. This provides a potentially increased

LHL, V.A. Khoze, M.G. Ryskin, M. Tasevsky, JHEP 1904 (2019) 010

Classes of Background

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

$\downarrow$

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

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

$$2 < m_{l_l l_2} < 40 \text{ GeV}$$

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

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

- What are **backgrounds**?

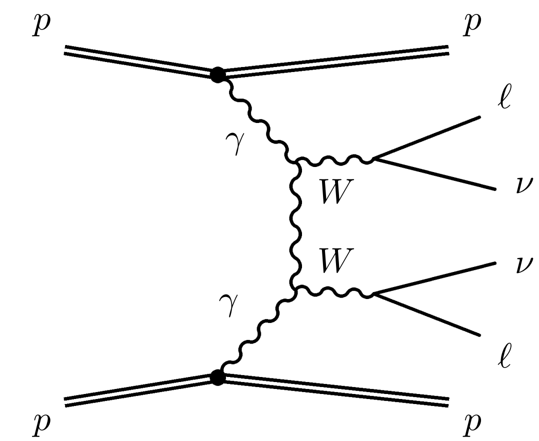
  ⋆ Irreducible CEP of **W pairs**.

  ⋆ 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.

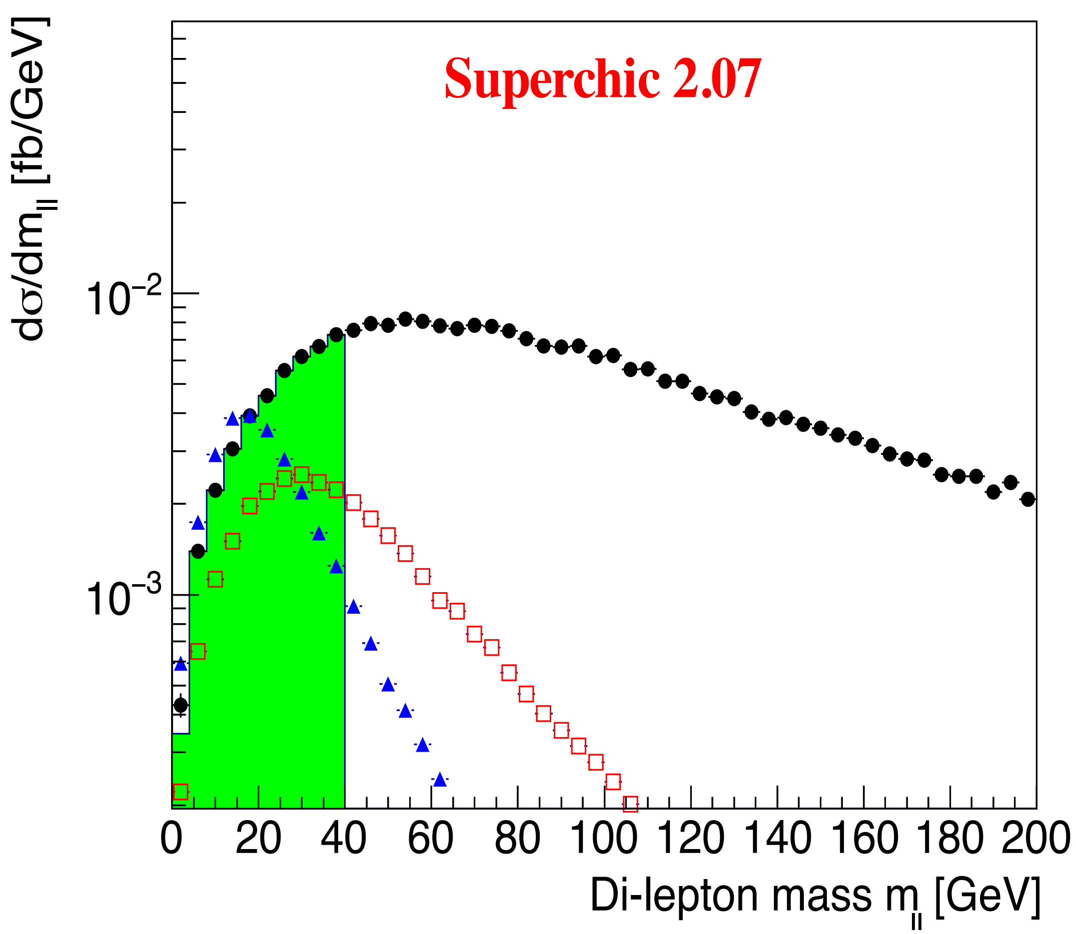
- Realistic analysis must consider all three. Will discuss in turn.

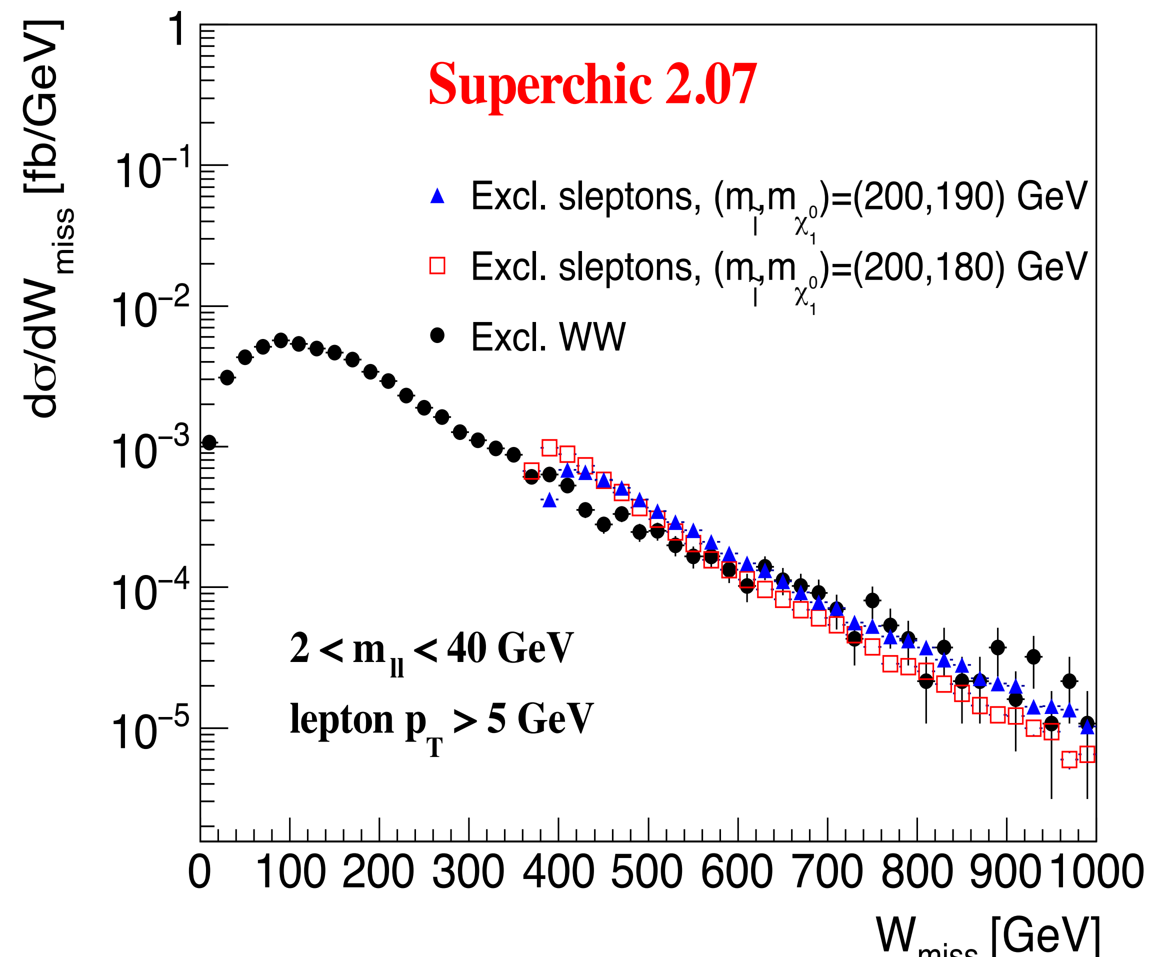
W pair production



- 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.

LHL et al., EPJC72 (2012) 1969

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**.

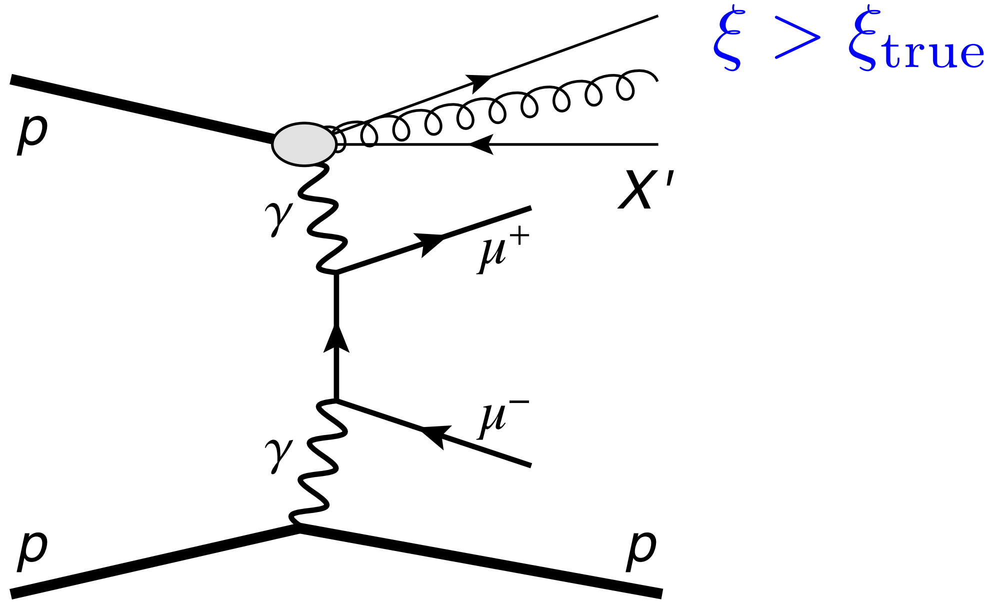
- What about **semi-exclusive** production? Proton from **dissociation system** $\Rightarrow$ lower momentum fraction $\Rightarrow$ larger ξ , can be in FPD.

- 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:

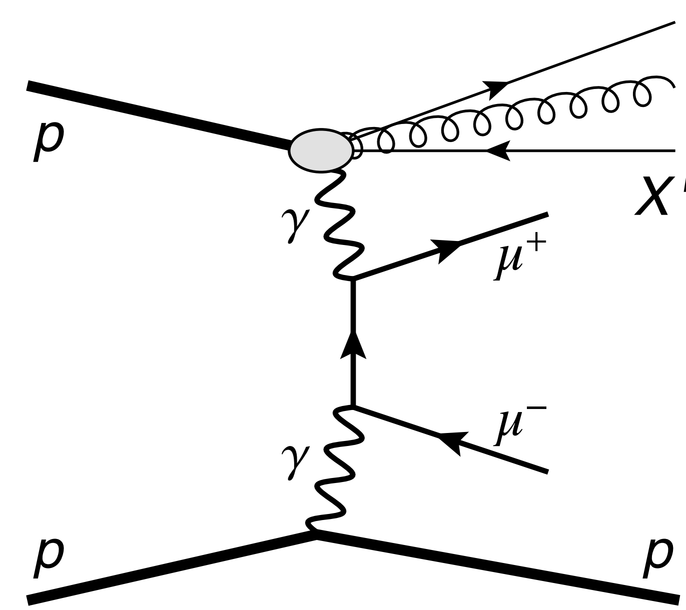
  ★ **Asymmetry** in SD topology: to give elastic proton in FPD, lepton system needs larger rapidity ⇒ require $\bar{\eta} = |\eta_{l_1} + \eta_{l_2}|/2 < 1$.

  ★ 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 $|\eta_{l_1,l_2}| < 2.5\ (4.0)$

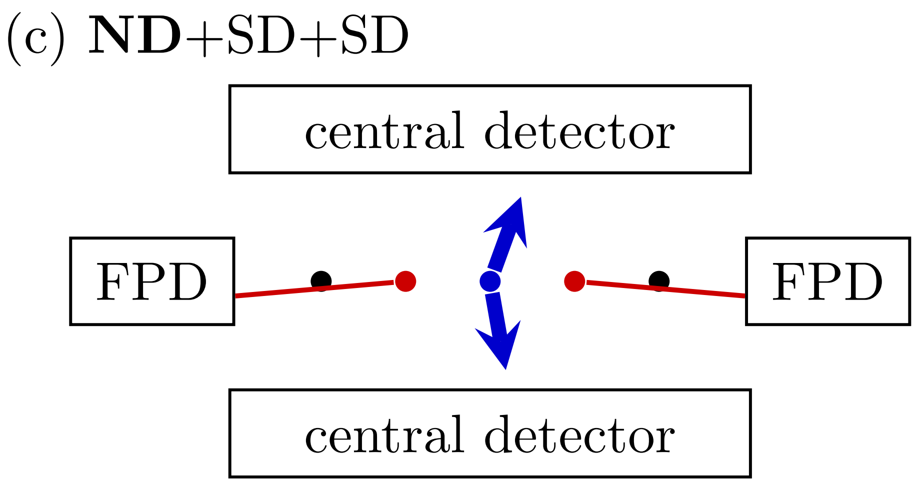
FPD: $p_{T,\text{proton}} < 0.35\ \text{GeV}$

- 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 $p_\perp > 5\,\mathrm{GeV}$ 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.



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

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)

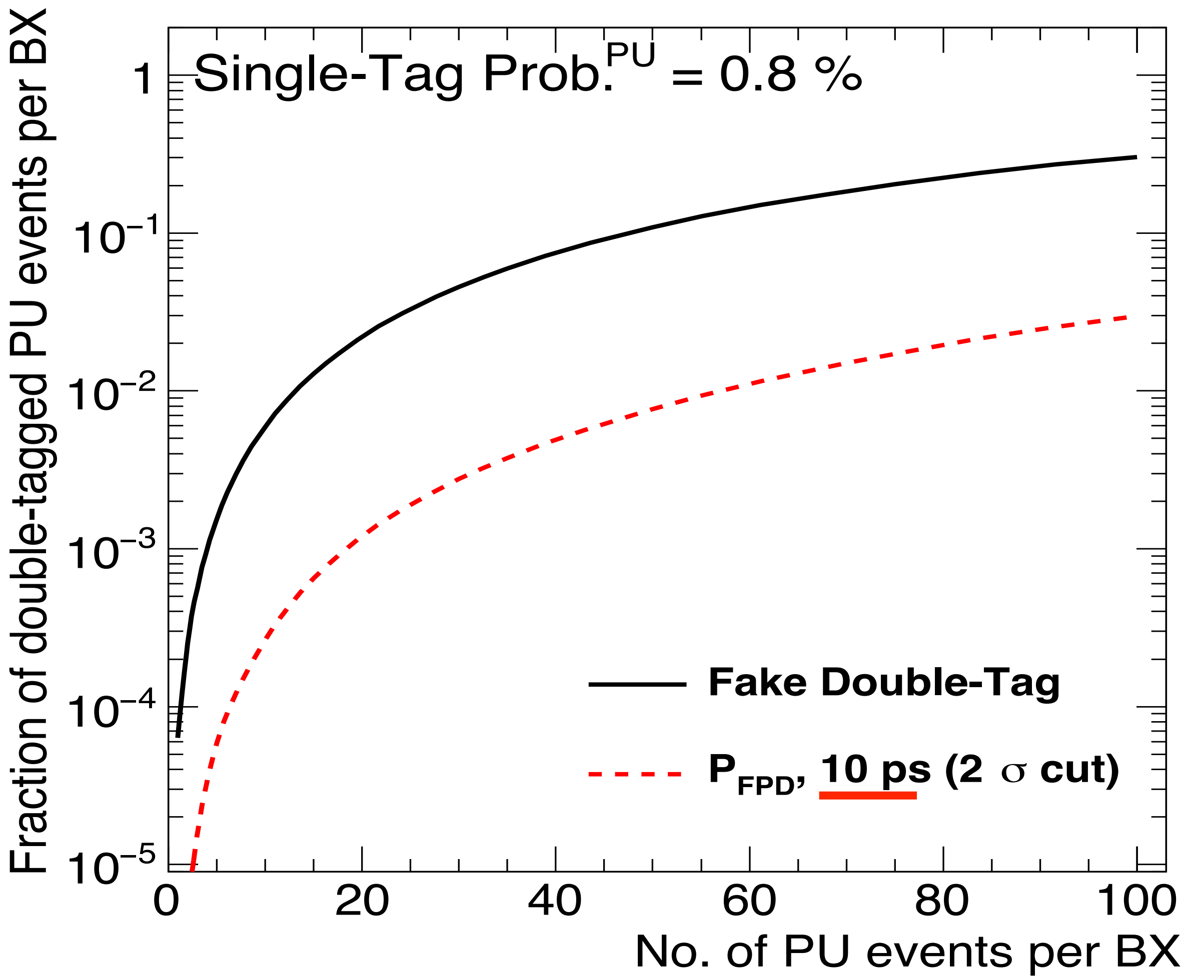
No hadronic activity	z-veto

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.

$P_{\rm no-ch}$	$\langle\mu\rangle_{PU}$		
	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.

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.

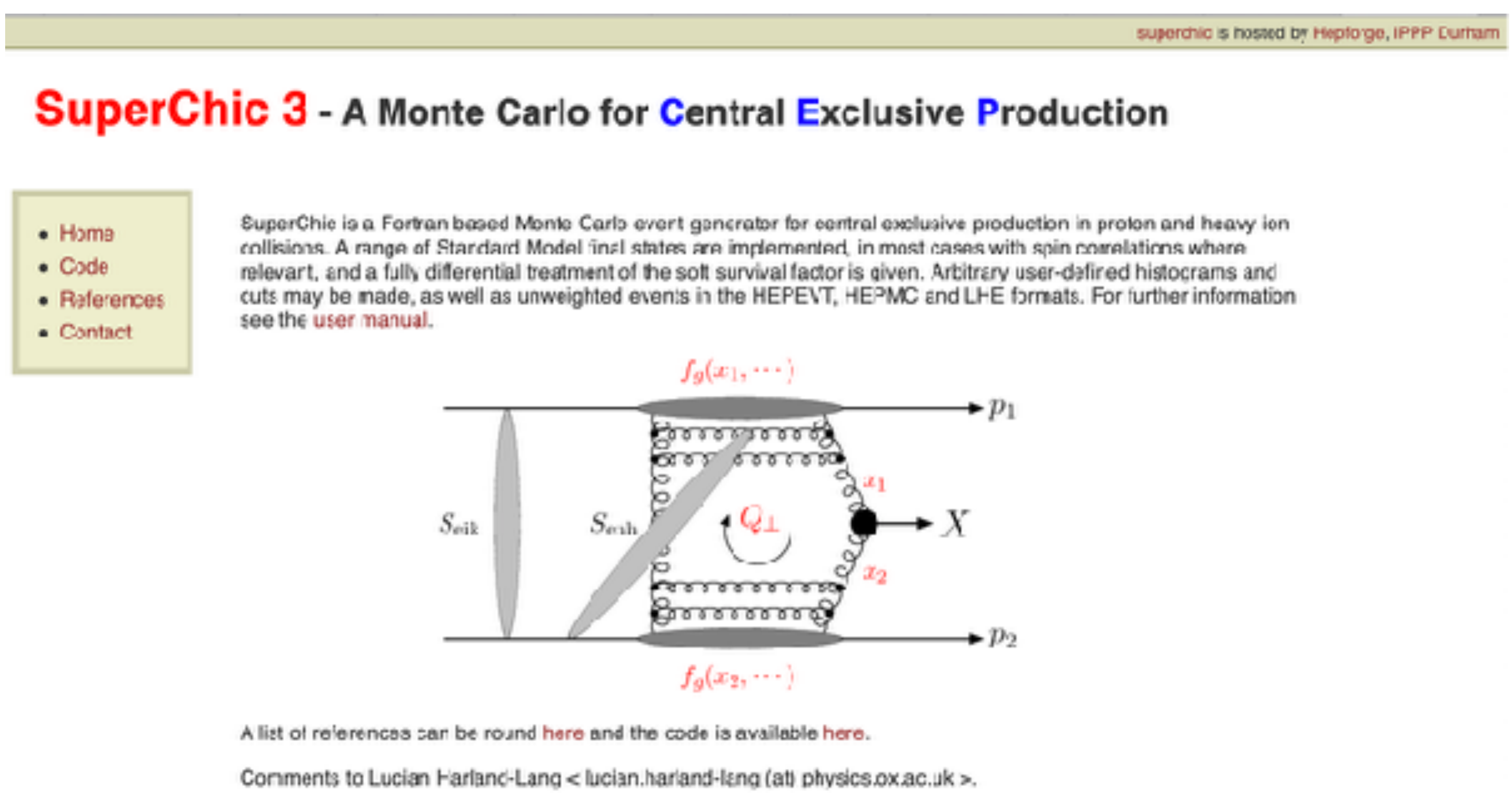
    ⋆ Add **timing info** to **central detector** - considered for HL-LHC upgrades at forward rapidity, and envisaged by CMS centrally.

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.



https://superchic.hepforge.org

Summary

- 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 ~ 2, B ~ 2 events for $300\,\text{fb}^{-1}$.
- 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 for listening!