Searches for Dark Mater at LHC in forward proton mode

Marek Taševský

Institute of Physics of the Czech Academy of Sciences, Prague

On behalf of Misha Ryskin, Valery Khoze and Lucian Harland-Lang

Basics

❑ $\gamma\gamma \to 2$ sleptons $\to 2$ invisible
  neutralinos (DM candidate) + dilepton

❑ QED mechanism has 2 advantages:

1) Experimental:
pp $\to$ p(FPD) + ll + low missing E_T + p(FPD)
(measure precisely mass in FPD)

2) Theoretical:
Model independence in production stage

❑ Focus on compressed mass scenario:
Keep ΔM = $M_{\tilde{l}} - M_{\tilde{\chi}_1^0}$ small.
$<m_{ll}> \sim \Delta M \to$ aim is to keep $<m_{ll}>$ low
- Motivated by cosmology, naturalness and
(g-2) considerations

Searches
for exclusive
soft dilepton and very
low missing E_T in high Pile-
up with forward proton detectors

Inclusive
DM searches
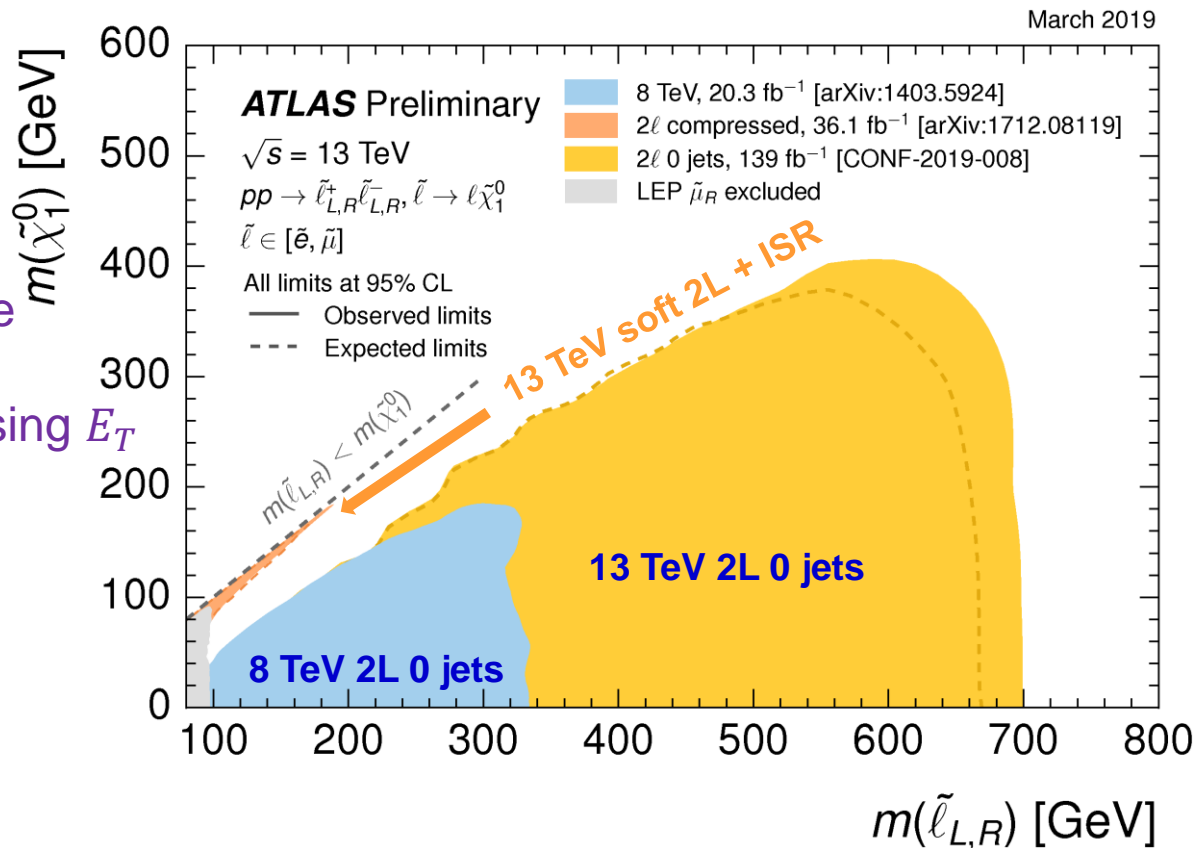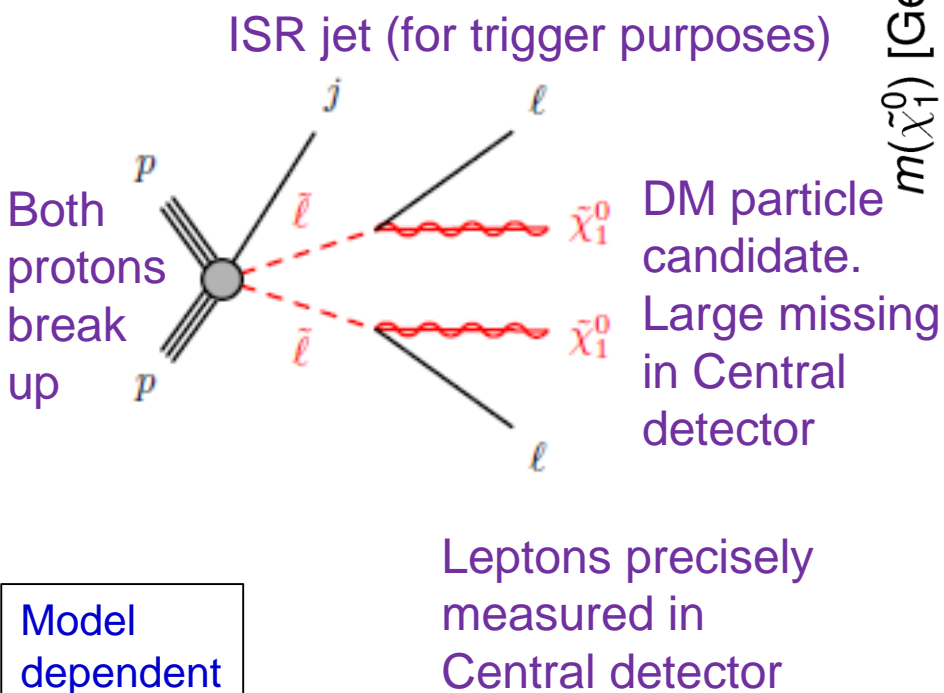with soft
dilepton &
missing E_T
in high
Pile-up
(ATLAS,CMS)

⬇

Knowledge
about
soft leptons
in high PU

Measurement
of **exclusive**
dilepton
in high
Pile-up
(ATLAS,
CMS+Totem)

⬇

Knowledge
about
exclusivity
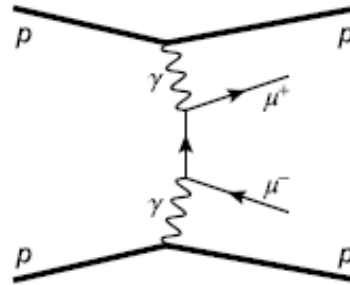in high PU

Inclusive slepton searches

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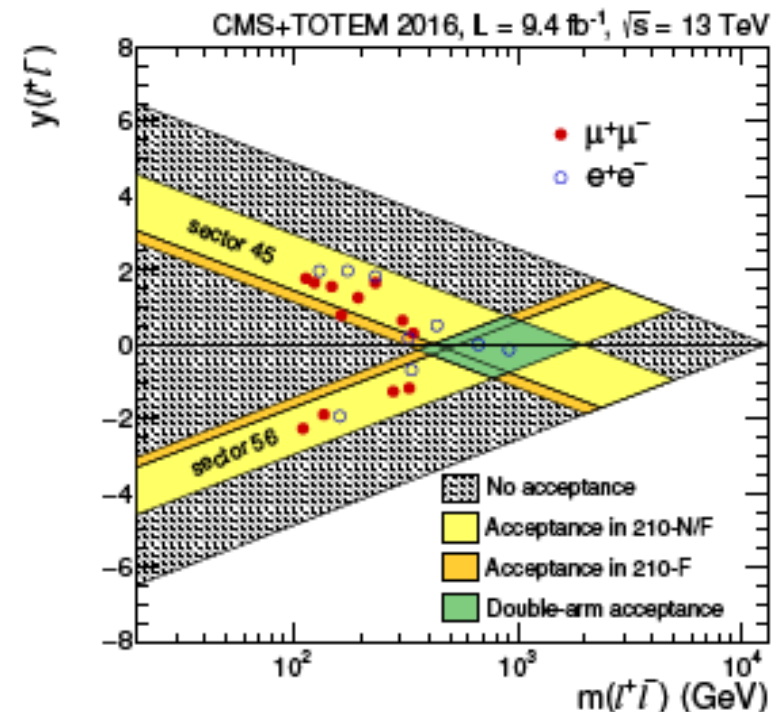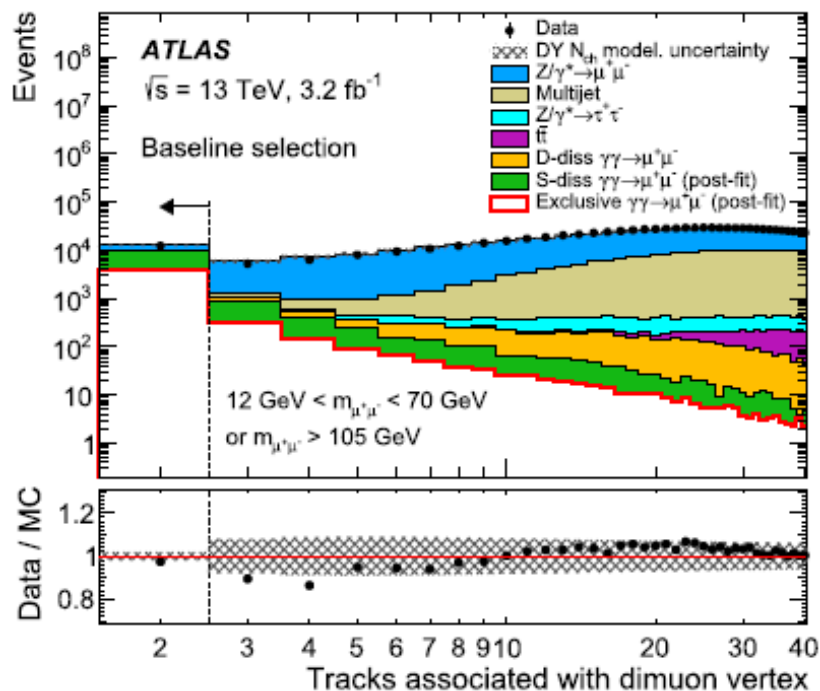- decays to fermionic DM + leptons with BR=100%

ISR jet (for trigger purposes)

Both protons break up

Model dependent

DM particle candidate. Large missing E_T in Central detector

Leptons precisely measured in Central detector

March 2019

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
$pp \rightarrow \tilde{\ell}^+_{L,R}\tilde{\ell}^-_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}^0_1$
$\tilde{\ell} \in [\tilde{e}, \tilde{\mu}]$
All limits at 95% CL
—— Observed limits
---- Expected limits

8 TeV, 20.3 fb^{-1} [arXiv:1403.5924]
2ℓ compressed, 36.1 fb^{-1} [arXiv:1712.08119]
2ℓ 0 jets, 139 fb^{-1} [CONF-2019-008]
LEP $\tilde{\mu}_R$ excluded

$m(\tilde{\chi}^0_1)$ [GeV]

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

$m(\tilde{\ell}_{L,R}) < m(\tilde{\chi}^0_1)$

13 TeV soft 2L + ISR

13 TeV 2L 0 jets

8 TeV 2L 0 jets

ATLAS SUSY Summary plot

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Exclusive dileptons

- Exclusive di-muons, untagged protons
- High Pile-up

- Exclusive di-leptons, tagged protons
- High Pile-up

ATLAS
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}

Baseline selection

Data
DY N$_{ch}$ model. uncertainty
Z/$\gamma^* \to \mu^+\mu^-$
Multijet
Z/$\gamma^* \to \tau^+\tau^-$
t$\bar{t}$
D-diss $\gamma\gamma \to \mu^+\mu^-$
S-diss $\gamma\gamma \to \mu^+\mu^-$ (post-fit)
Exclusive $\gamma\gamma \to \mu^+\mu^-$ (post-fit)

12 GeV < $m_{\mu^+\mu^-}$ < 70 GeV
or $m_{\mu^+\mu^-}$ > 105 GeV

Events

Data / MC

Tracks associated with dimuon vertex

CMS+TOTEM 2016, L = 9.4 fb^{-1}, $\sqrt{s}$ = 13 TeV

$y(l^+l^-)$

$\mu^+\mu^-$
e^+e^-

sector 45
sector 56

No acceptance
Acceptance in 210-N/F
Acceptance in 210-F
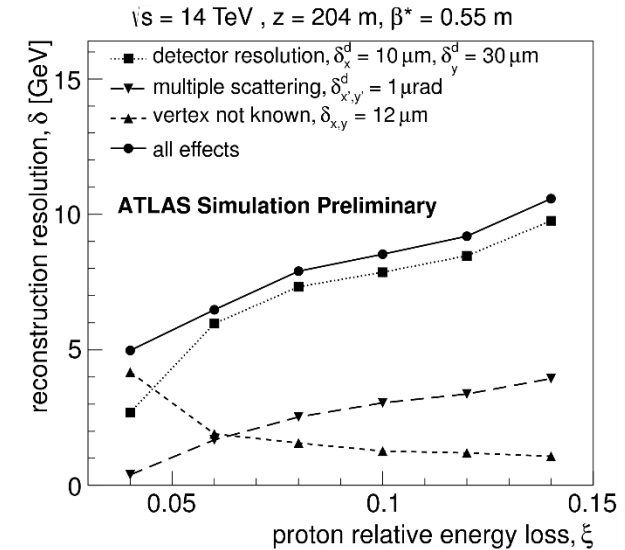Double-arm acceptance

$m(l^+\bar{l})$ (GeV)

[Phys. Lett. B777 (2018) 303]

[JHEP1807 (2018) 153]

Forward Proton detectors (FPDs) at LHC

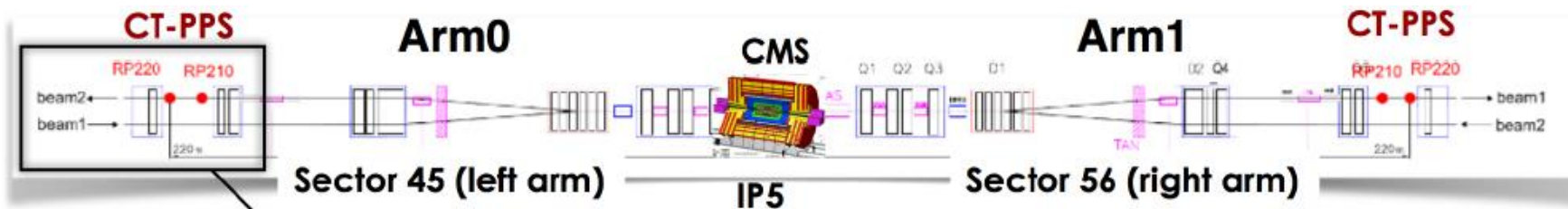**AFP**
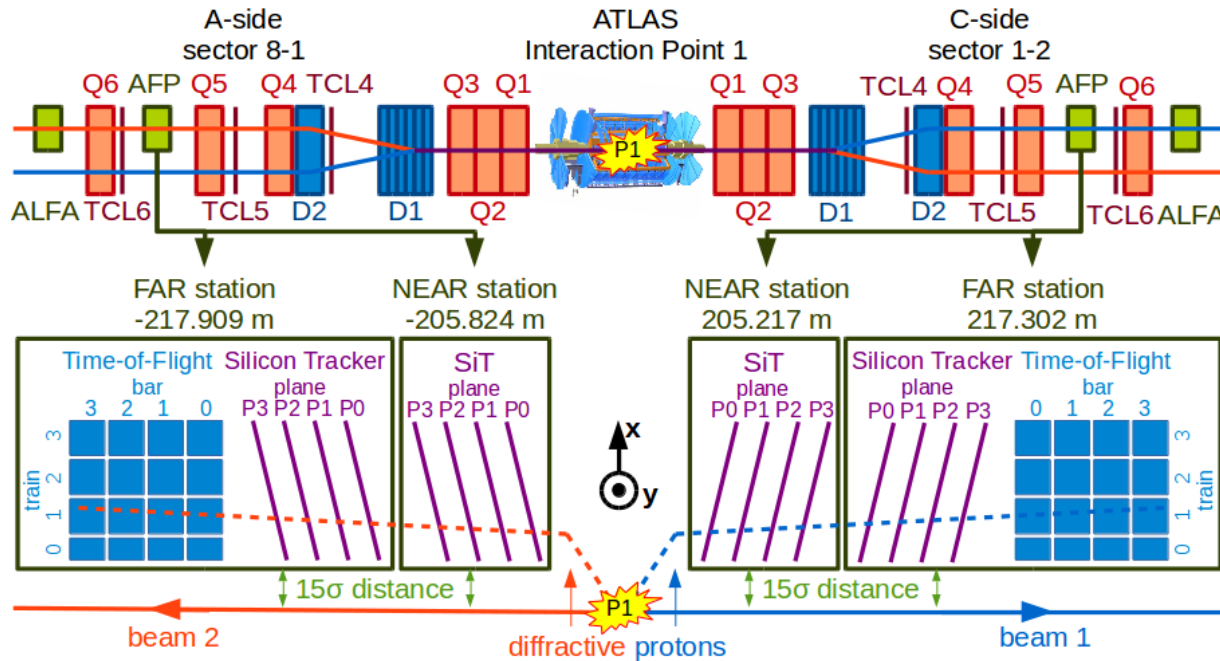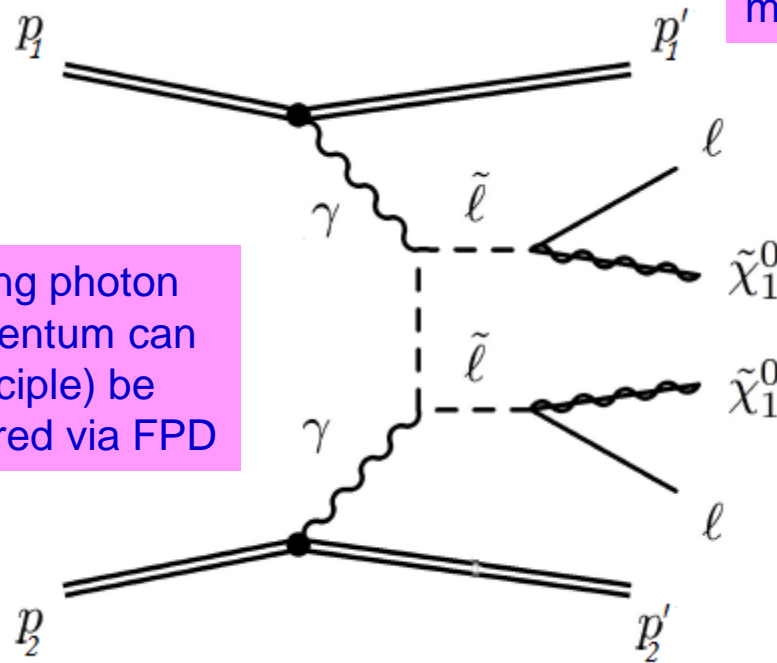

Excellent ξ (mass) resolution
[AFP TDR, CERN-LHCC-2015-009]

CT-PPS

Advantage of exclusivity & compressed mass

Outgoing proton 4-momentum measured in FPD

Lepton 4-momentum measured in Central detector

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

measured precisely in FPD

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

Incoming photon 4-momentum can (in principle) be measured via FPD
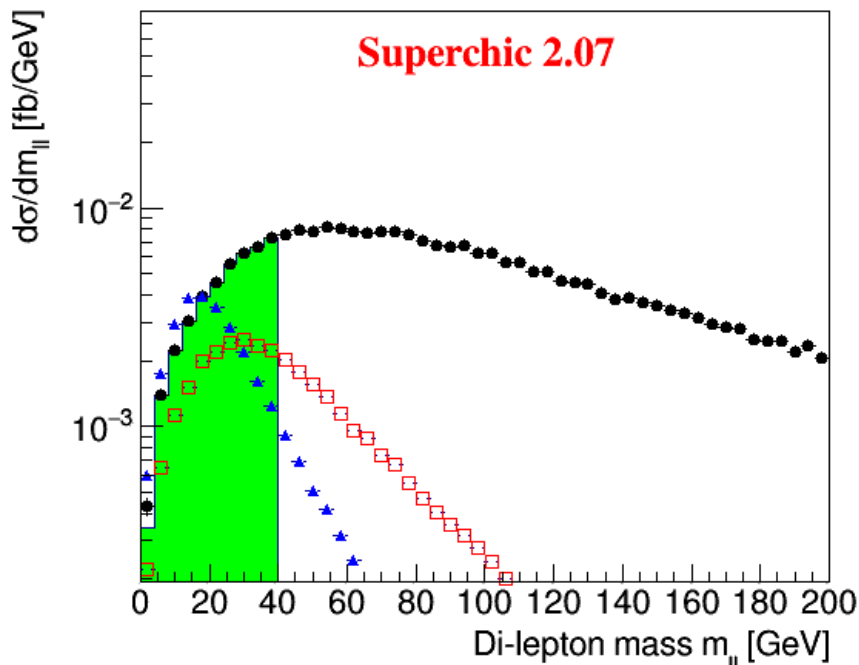
FPD measures precisely mass of central system. If mass splitting $M_{\tilde{l}} - M_{\tilde{\chi}_1^0}$ low → FPD can give quite a precise hint about $2m_{DM}$

Model independent

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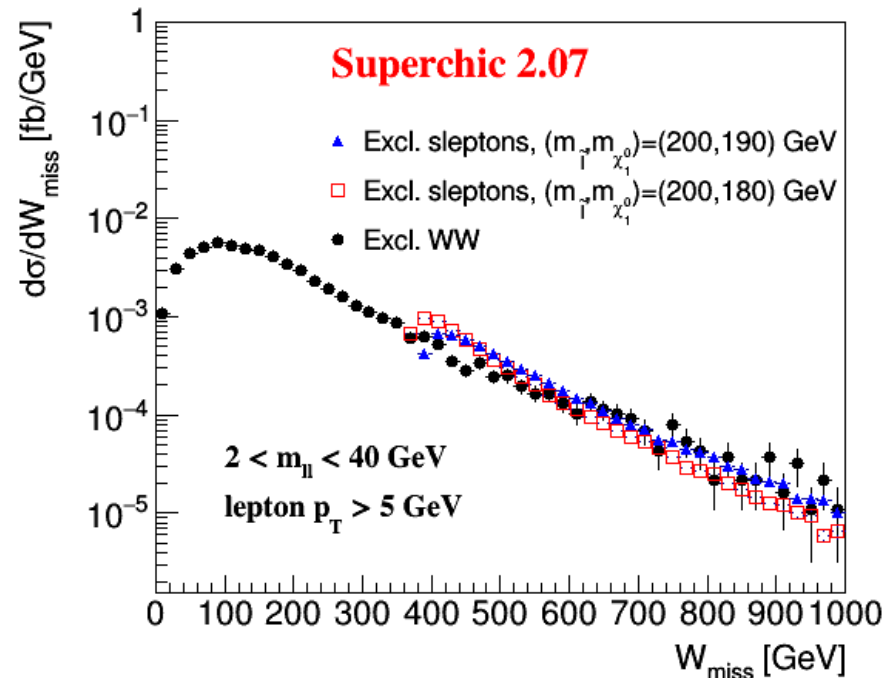
Signal & Exclusive WW

Exclusive WW background significantly suppressed by:
- $5 < p_{T,lepton} < 40$ GeV
- $2 < m_{l1l2} < 40$ GeV
- $W_{miss} > X$

$W_{miss} > X$[GeV]	200	300	400	500
N_{ev}/300fb-1	0.6	0.3	0.2	0.1

Another approach based on max. kinematically allowed values of $M_{\tilde{l}}$ and $M_{\tilde{\chi}}$ [Eur.phys. J. C72(2012)1969] (see also arXiv: 1811.06465[hep-ph])

- Only mild improvement in stat. significance

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What about other backgrounds?

➢ Not only exclusive WW is dangerous

➢ Semi-exclusive low-mass QED dilepton production ?

➢ Dileptons from B-decays in hadronization of large-σ processes?

➢ PILE-UP???

Processes and MC event generators

❑ All exclusive processes: **Superchic 2.07**

QED: **Exclusive sleptons** (slepton masses 120-300 GeV, mass splitting 10 and 20 GeV, σ: max 2 fb)
   Exclusive $\mu^+\mu^-, e^+e^-, \tau^+\tau^-$ (M_X>10 GeV, p_T > 3 GeV, σ ~ 8.4 pb)
   Exclusive W^+W^- (M_X>160 GeV, fully-leptonic decays, σ ~ 1.0 fb)

QCD (CEP): **Exclusive K^+K^-** (M_X>10 GeV, p_T > 4 GeV, σ ~ 1.3 fb)
   Exclusive $c\bar{c}$ (M_X>10 GeV, p_T > 5 GeV, $|y_X|$ < 3.0: σ ~ 3 nb)
   Exclusive gg (M_X>10 GeV, p_T > 7 GeV, $|y_X|$ < 3.0: σ ~ 2 μb)

For exclusive processes with too low generated masses to produce protons in
FPD acceptance (**$\mu^+\mu^-, e^+e^-, \tau^+\tau^-$, $c\bar{c}$, gg**) → consider:
   - Single-proton dissociation
   - Double-proton dissociation

❑ **Inclusive ND dijets**: p_T > 7 GeV, ISR on, FSR on, MPI on
Pythia 8.2 : σ ~ 27 mb
Herwig 7.1: σ ~ 16 mb

❑ PU (=MinBias) events generated by Pythia 8.2 and mixed with signal by Delphes

Procedure

❑ Signal cross-section very low → high luminosities needed

❑ Three points studied: μ = 0, 10, 50 (average number of PU events per bunch crossing)

❑ Huge suppression factors needed for inclusive backgrounds (~10^{14}) → sufficient statistics cannot be generated in reasonable time → cuts factorized into cut classes

| Exclusive processes (QED, QCD) | ALL – NO-CHARGED | * | NO-CHARGED |

| Inclusive processes (ND dijets, pt>7 GeV) | FPD | * | DI-LEPTON | * | NO-CHARGED |

ALL-NO-CHARGED: generator level + lepton reconstruction efficiencies
FPD: generator level
Di-lepton: generator level + lepton reconstruction efficiencies
No-charged: $P_{no-charged} = P_{gap}$(gen. level) * P_{z-veto}(fast sim. Delphes)

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Selection cuts

Can be divided into three cut classes

Forward proton detector acceptance

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

Di-lepton system

$5 < p_{T,l_1,l_2} < 40\,\text{GeV}$	$|\eta_{l_1,l_2}| < 2.5\ (4.0)$
$\text{Aco} \equiv 1 - |\Delta\phi_{l_1l_2}|/\pi > 0.13\ (0.095)$	$2 < m_{l_l l_2} < 40\,\text{GeV}$
$\Delta R(l_1, l_2) > 0.3$	$|\eta_{l_1} - \eta_{l_2}| < 2.3$
$\bar{\eta} \equiv |\eta_{l_1} + \eta_{l_2}|/2 < 1.0$	$\left| |\vec{p_T}_{l_1}| - |\vec{p_T}_{l_2}| \right| > 1.5\,\text{GeV}$
$W_{\text{miss}} > 200\,\text{GeV}$	

No-charged
(No activity around primary vertex)

No hadronic activity	z-veto

Fake Double-Tag events in FPD

❑ What is the rate of fake double-tagged events with protons coming from PU in the acceptance $0.02 < \xi < 0.15$ and $p_{T,proton} < 0.35$ GeV?
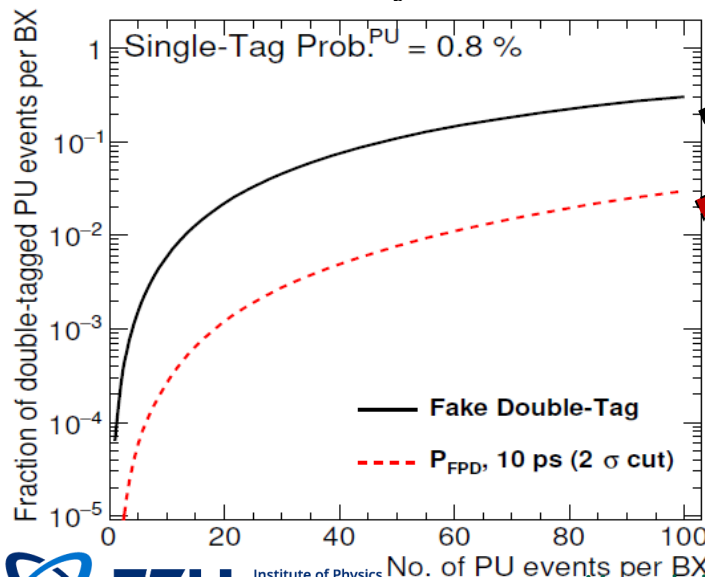
Most dangerous combination: 2x soft SD events + hard-scale di-lepton event.
Time-of-flight detectors necessary to suppress the PU background.

1) Single-Tag probability to find a PU proton in FPD acceptance: 0.8%(PY8.2) / 1.3% (HW7.1)

Minimum Bias events, MPI on

2) Rate of fake Double-Tagged events, assuming
- bunch longitudinal size: 7.5 cm
- time resolution: σ_t = 10 ps
- time window: $2\sigma_t$

	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}

These factors only applied for inclusive jet background

(<μ>=0: calculate directly from inclusive dijet events)

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Fake dileptons

❑ Take inclusive ND dijets with $p_T > 7$ GeV and ISR, FSR, MPI on

❑ Select events with $\mu^+\mu^-$ or e^+e^- pairs with $p_{T,l} > 5$ GeV & $|\eta| < 2.5$, dR>0.3

❑ Isolation: remove events where the selected lepton is accompanied by at least one charged particle from the same heavy-particle decay and having $p_T > 0.4$ GeV & $|\eta| < 2.5$ (effectively rejecting decays with extra charged particle, e.g. $D^0 \rightarrow K^- e^+ \nu$ or $D^+ \rightarrow \rho^0 \mu^+ \nu$)

▪ Examples of surviving events: leptons from W-decays, pi-decays, parton showers…

❑ Calculate probability to see such events in the control sample

❑ Apply lepton reconstruction efficiencies (from ATLAS inclusive slepton searches)

PYTHIA 8.2: $P_{lep} = 0.8$x10^{-7} (W-bosons not included in inclusive jets)
HERWIG 7.1: $\boldsymbol{P_{lep} = 2.5}$**x$10^{-7}$** (45% of surviving events contain a W-boson)

Correct PYTHIA number by 1.45: $\boldsymbol{P_{lep} = 1.2}$**x$10^{-7}$**

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Fake No-charged

☐ **Signal** : get the 'z-vertex veto' efficiency : P_{z-veto}
- z-vertex veto: no other vertices and tracks in the region 1mm from the primary vertex
- Using Delphes (overlay PU events and fast simulation of ATLAS tracker), we get

$$P_{z-veto}(\mu = 10) = 0.84 \; ; \; P_{z-veto}(\mu = 50) = 0.48.$$

   ↳ Agrees with exclusive dileptons w/o FPDs [ATLAS Phys.Lett.B777(2018)303]

☐ **Inclusive ND jets and exclusive $c\bar{c}$ and gg**

o zero PU:

1) Select events with 2-4 charged particles with p_T > 5 GeV & |η| < 2.5(4.0) and at least two of them separated by dR>0.3.
2) Fraction of those not having additional particles with p_T > 0.4 GeV & |η| < 2.5(4.0): $P_{gap}(\mu = 0)$

o non-zero PU: assume that di-lepton cuts select events resembling the signal, i.e. exactly two leptons. Then $P_{no-charged}(\mu = 10, 50) = P_{gap}(\mu = 0) * P_{z-veto}(\mu = 10, 50)$

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

PYTHIA8.2/HERWIG7.1

ATLAS and CMS tracker upgrades: |η| < 4.0.

Signal event yields for L=300fb^{-1} and μ=0

scenario	lepton p_T interval [GeV]			
$M_{\tilde{l}}/M_{\tilde{\chi}_1^0}$	5—15	5—20	5—30	5—40
120/100	0.4	0.9	2.2	2.8
120/110	1.2	2.4	3.7	3.9
200/180	0.2	0.8	1.9	2.2
200/190	1.4	1.9	2.3	2.3
250/230	0.1	0.4	1.1	1.2
250/240	0.8	1.1	1.2	1.2
300/280	0.1	0.2	0.6	0.7
300/290	0.4	0.6	0.6	0.6

Improvements?
- Improve lepton reconstruction efficiencies (they start at 70% at p_T=5 GeV)
- Extend lepton acceptance up to |η| = 4 → 10% increase of statistics
- Taking all dilepton masses doubles the signal yield. BUT:
a) backgrounds increase
b) $<m_{ll}>$ increases → loosing possibility to reconstruct precisely m_{DM} via FPD

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Integrated event yields for L=300fb^{-1}

$$|\eta| < 2.5$$

Event yields /	$\langle\mu\rangle_{PU}$		
$\mathcal{L} = 300$ fb^{-1}	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)

$$|\eta| < 4.0$$

Event yields /	$\langle\mu\rangle_{PU}$		
$\mathcal{L} = 300$ fb^{-1}	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)

Slepton range corresponds to slepton mass range studied: X(300 GeV) – Y(120 GeV)

Improvements?
- Cut on the distance between sec. and prim. vertex (or on the pseudo-proper lifetime)
- Improve ToF resolution (ToF rejection increases linearly with σ_t decreasing)
- Radiation-hard ZDC with timing information to suppress proton-dissociation background
- Add timing info in Central detector: included in HL-LHC A+C upgrades for 2.5 < $|\eta|$ < 4.0
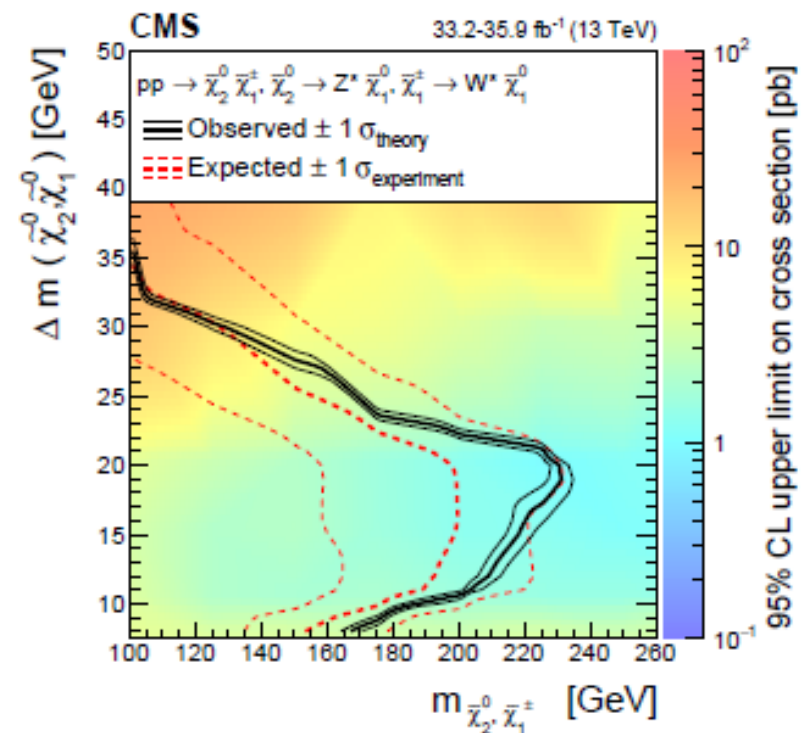- Timing detector also in $|\eta|$<2.5 envisaged in CMS (MTD = MIP Timing Detector)

SUMMARY

❑ DM search via exclusive production of sleptons:
pp → p(FPD) + 2 soft leptons + very low missing E_T + p(FPD)

❑ $M_{\tilde{l}}$ = 120-300 GeV & ΔM =10, 20 GeV

❑ Detailed study of all relevant backgrounds + pile-up up to μ=50

❑ Forward proton detectors with good timing resolution (σ_t ~ 10ps) vital

❑ S=B~2 per 300fb-1 with current techniques and resolutions

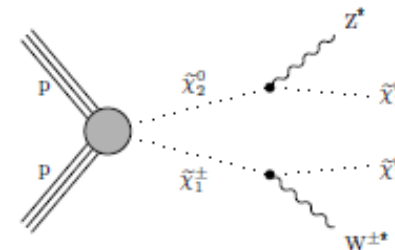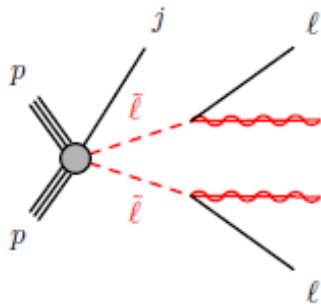❑ Suitable for HL-LHC: larger significances expected but additional timing information from Central detector needed
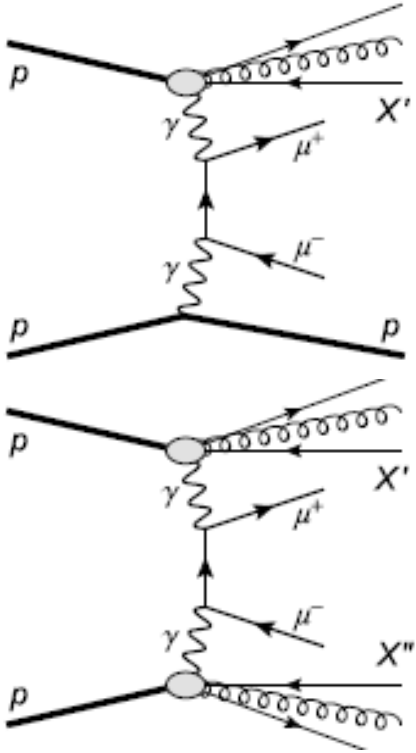
BACKUP SLIDES
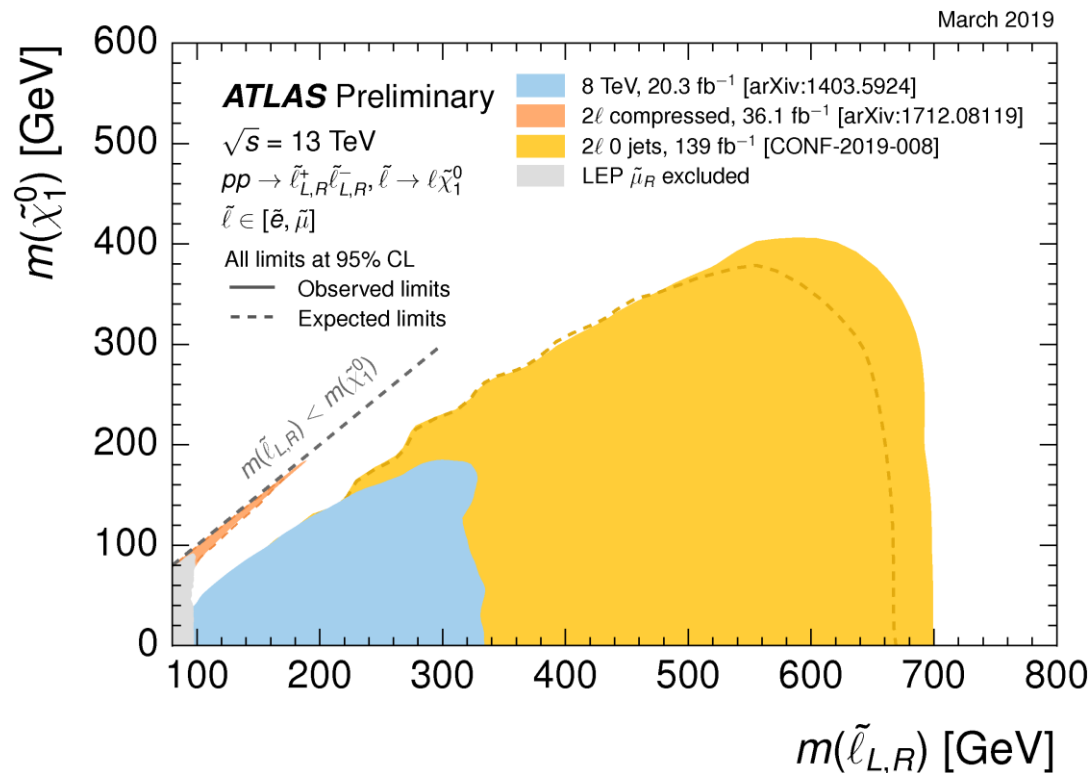
ATLAS SUSY Summary plot

Phys. Lett. B782 (2018) 440

Pure exclusive: m_{ll} > 10 GeV: σ = 8.4pb (Superchic [SC]).
Low $m_{ll} \to \xi$ outside FPD acc.

BUT: protons from dissoc. system may end up in FPD. What probability?
0.02 < ξ <0.15 & $p_{T,proton}$ < 0.35 GeV: 0.40% (PYTHIA 8.2 SD),
0.46% (triple Regge)

SD or DD not (yet) in Superchic.
Procedure:
- estimate using SC excl. processes $\gamma\gamma \to e^+e^-/\mu^+\mu^-/\tau^+\tau^-$
- consider all combinations of photon emissions: elastic, incoherent and DGLAP from quark
- evaluate effective flux which survives:

a) veto on central particle production (account for no-charged cuts)
b) acoplanarity cut – limit z,Q^2 integral which generates photon flux
- Photon q_T^2 distr. generated logarithmically between q_0=0.5 GeV and m_{ll}/2 (account for $|p_{T,l1}-p_{T,l2}|$>1.5 GeV cut)

See [EPJ C76 (2016) 255]

Nev/300fb-1 →
|η|<2.5/|η|<4.0

	SD	DD
$e^+e^- + \mu^+\mu^-$	0/0	1.4/1.1
$\tau^+\tau^-$	0.05/0.02	0/0

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