Searches for Dark Mater at LHC in forward proton mode

Marek Taševský

Institute of Physics of the Czech Academy of Sciences, Prague

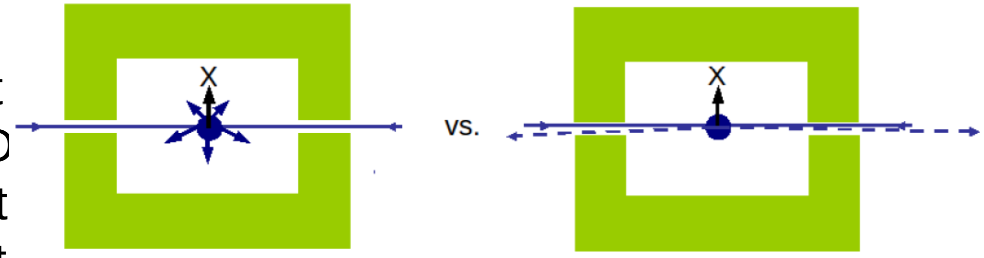
[based on JHEP 1904(2019)010, arXiv:1812.04886[hep-ph]]

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

Motivation

❑ **GOAL: detect DM in central exclusive production (CEP),**
e.g. $\gamma\gamma \rightarrow$ 2 sleptons $\rightarrow$ 2 invisible neutralinos (DM candidate) + dilepton

❑ **CEP: pp → p + X + p**
- Diffractive: color-singlet exchange between colliding protons, with large rapidity gaps ('+') in central detector
- Exclusive: protons lose energy but remain intact and are measured in Forward Proton Detector(FPD
- Central: system of mass M_X produced at interact point and its decay products detected in central det.



❑ **QED mechanism has 2 advantages:**
1) Experiment: pp → p(FPD) + ll + low missing E_T + p(FPD) (measure precisely mass in FPD)
2) Theory: Model independence in production stage

❑ **Focus on compressed mass scenario:** ΔM = $M_{\tilde{l}} - M_{\tilde{\chi}_1^0}$ small.
- $\langle m_{ll}\rangle$ ~ ΔM → aim is to keep $\langle m_{ll}\rangle$ low. Studied ranges: $M_{\tilde{l}}$ = 120-300 GeV, ΔM = 10,20 GeV
- Motivated by cosmology, naturalness and (g-2) considerations

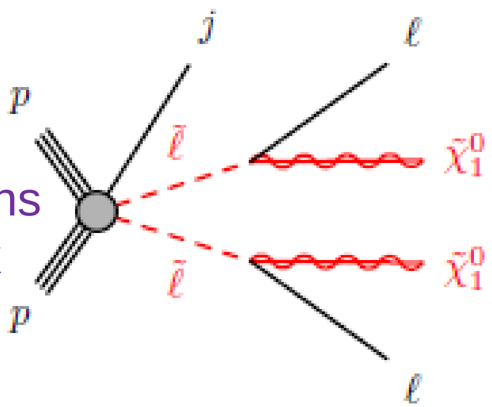
❑ **Profit from published analyses:**
1) Inclusive DM searches with soft leptons at high pile-up; 2) Exclusive leptons at high pile-up

Inclusive slepton searches

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

ISR jet (for trigger purposes)

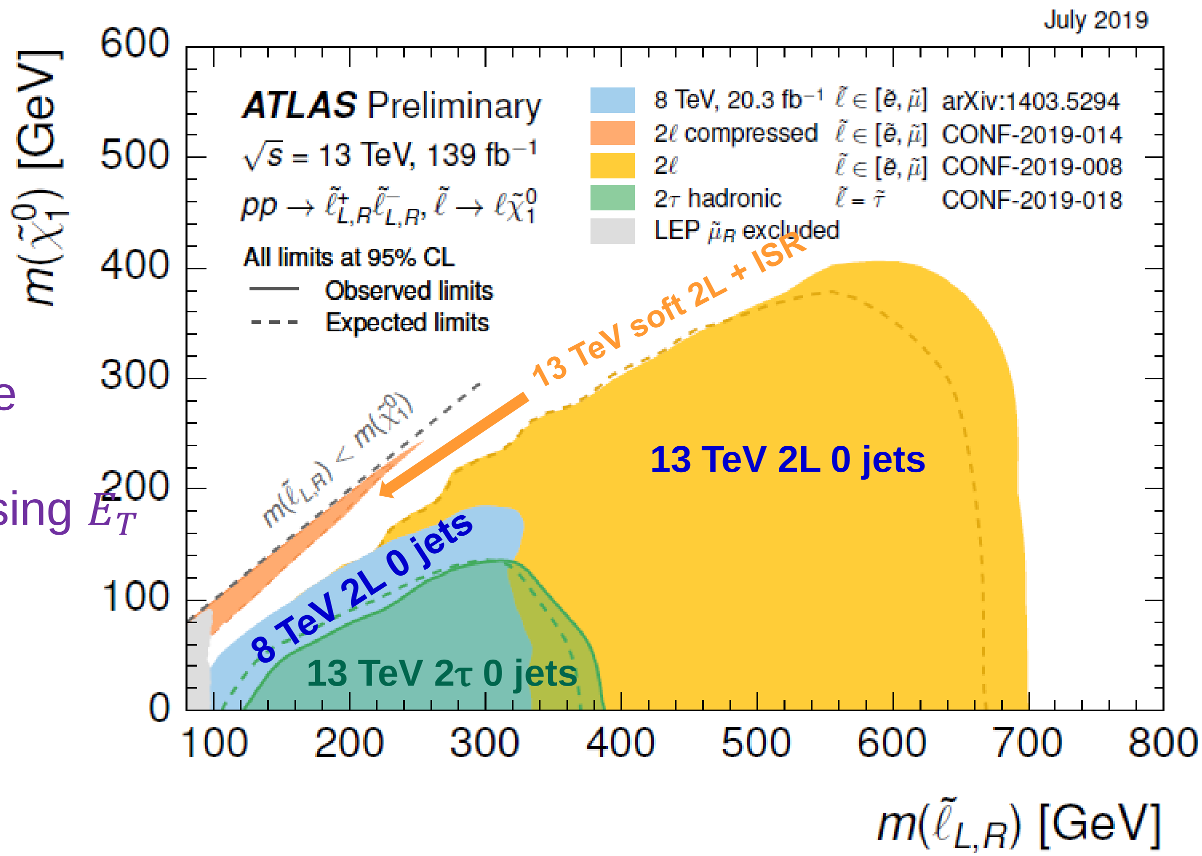
Both protons break up



DM particle candidate. Large missing $\not{E}_T$ in Central detector

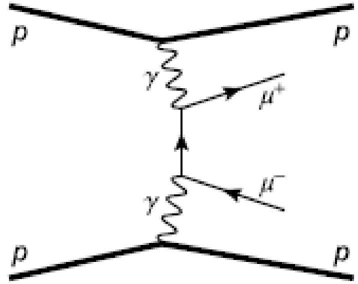
Leptons precisely measured in Central detector

Model dependent



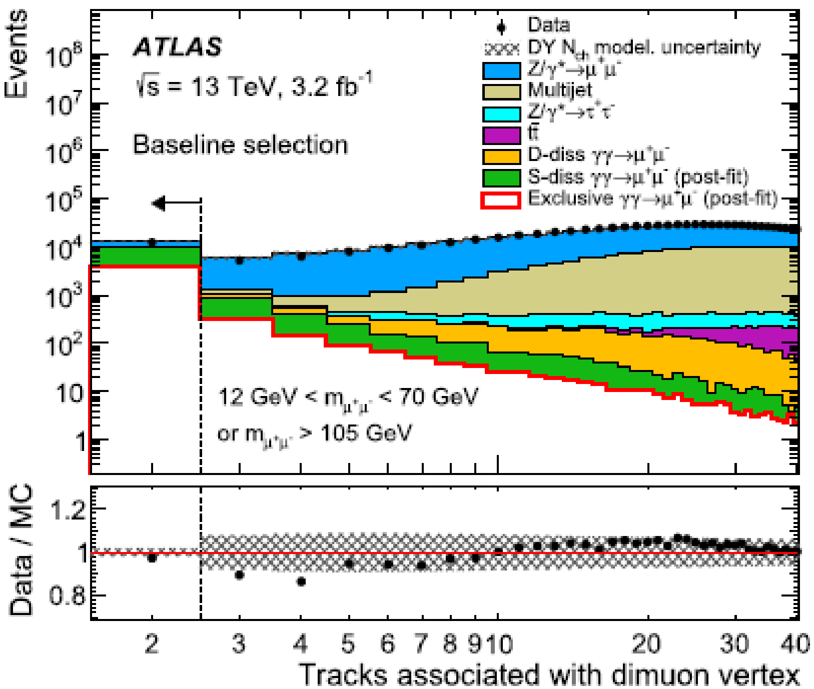
ATLAS SUSY Summary plot

Exclusive dileptons at high Pile-up

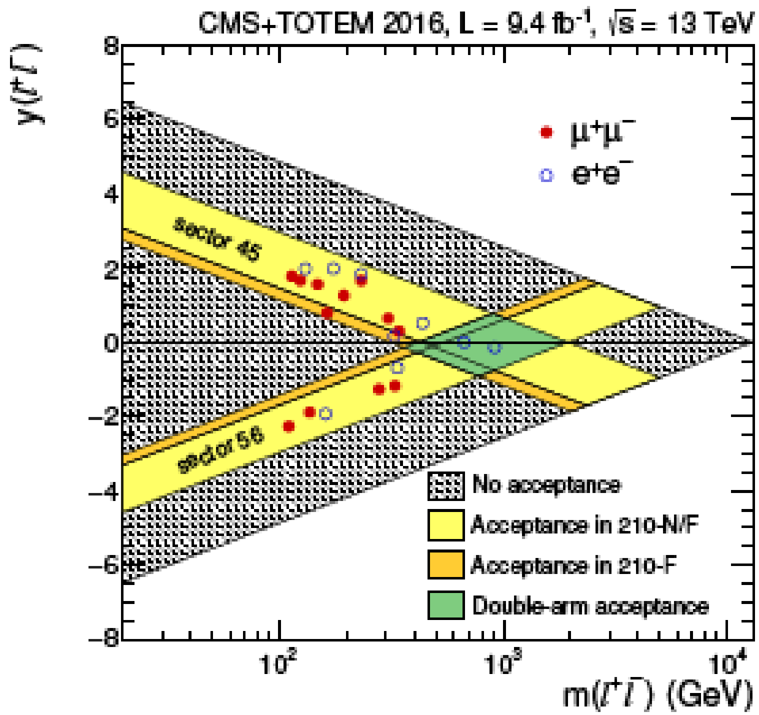


- Exclusive di-muons
- Without proton tagging

- Exclusive di-leptons
- With proton tagging



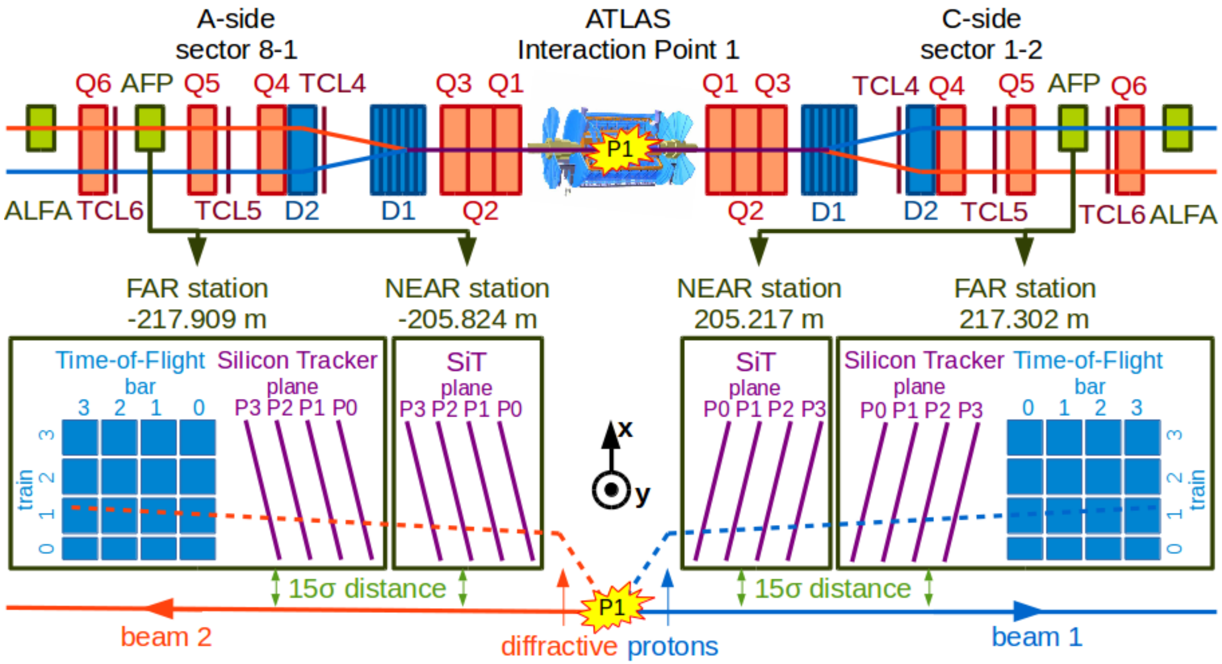
[Phys. Lett. B777 (2018) 303]

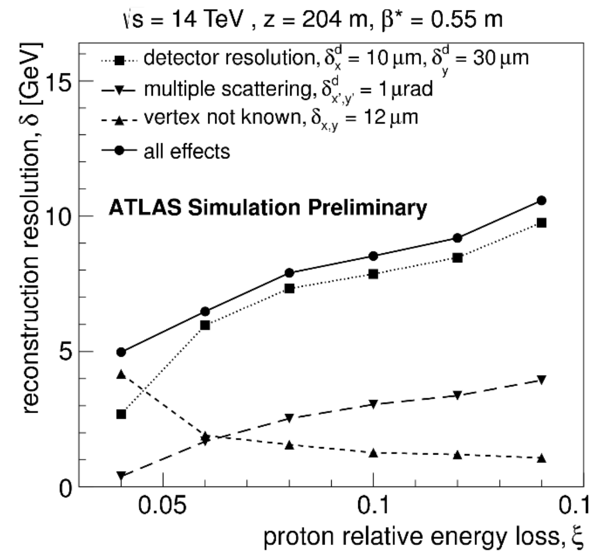


[JHEP1807 (2018) 153]

Forward Proton detectors (FPDs) at LHC

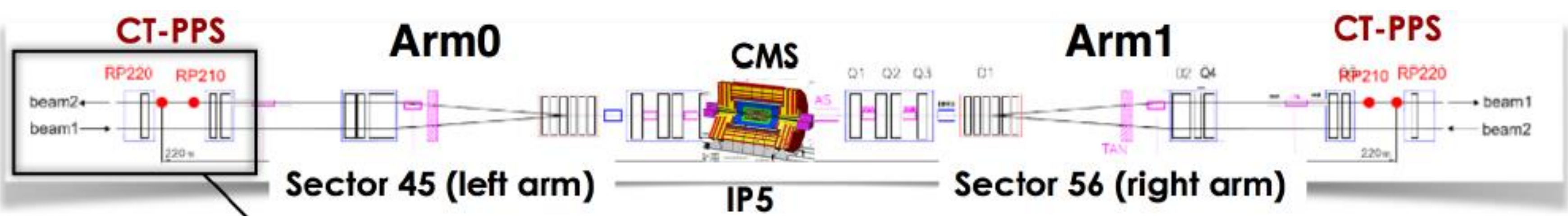
AFP



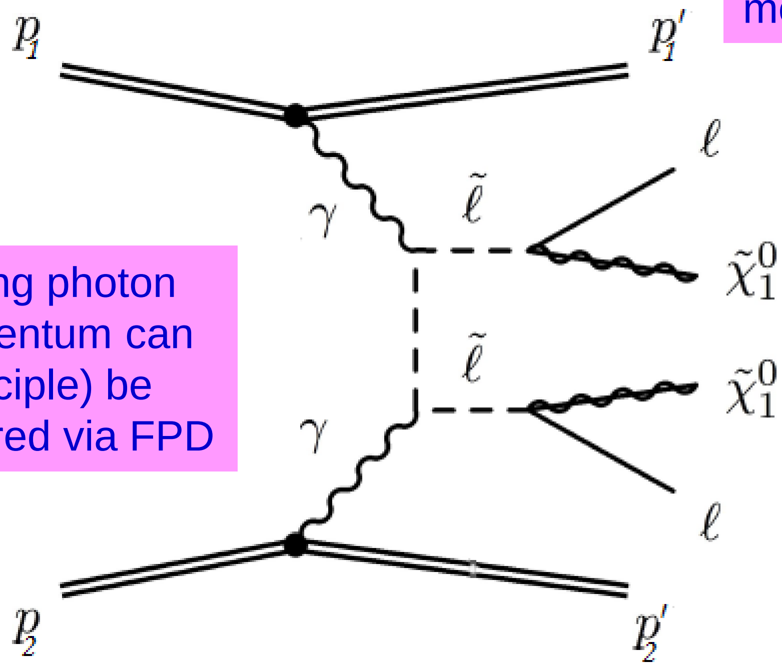


Excellent ξ (mass) resolution
[AFP TDR, CERN-LHCC-2015-009]

CT-PPS



Advantage of exclusivity & compressed mass



Outgoing proton 4-momentum measured in FPD

$\xi_i = 1 - \frac{E_{p_i'}}{E_{p_i}}$, *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 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

Procedure

- Effective signal cross-section very low → high luminosities needed
- **Backgrounds:**

1) Exclusive WW
2) Semi-exclusive dilepton production with proton from dissociation giving hit in FPD
3) Pile-up background: overlay of inclusive non-diffractive event in central detector with unrelated soft diffractive protons in FPD acceptance

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

Inclusive processes (ND dijets, p_T>7 GeV)

FPD * DI-LEPTON * NO-CHARGED

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

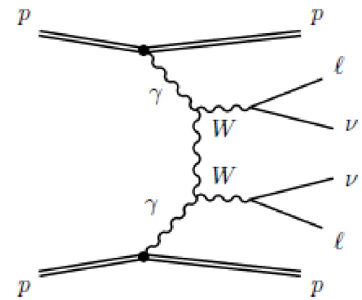
$5 < p_{T,l_1,l_2} < 40$ GeV	$\lvert\eta_{l_1,l_2}\rvert < 2.5$ (4.0)
$\mathrm{Aco} \equiv 1 - \lvert\Delta\phi_{l_1 l_2}\rvert/\pi > 0.13$ (0.095)	$2 < m_{l_l l_2} < 40$ GeV
$\Delta R(l_1, l_2) > 0.3$	$\lvert\eta_{l_1} - \eta_{l_2}\rvert < 2.3$
$\bar{\eta} \equiv \lvert\eta_{l_1} + \eta_{l_2}\rvert/2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

- All exclusive BG: Superchic
- Inclusive BG: PYTHIA/HERWIG

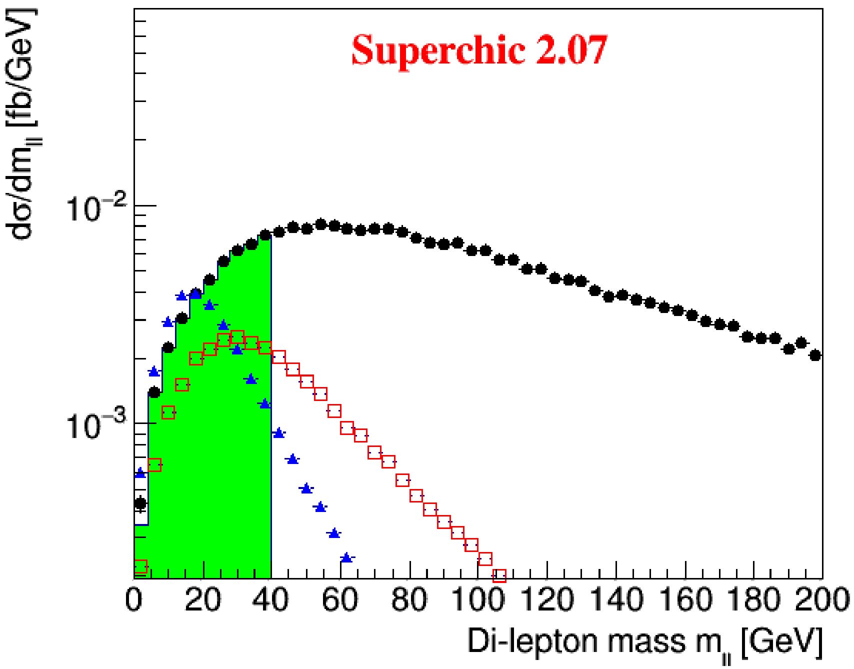
No hadronic activity	z-veto

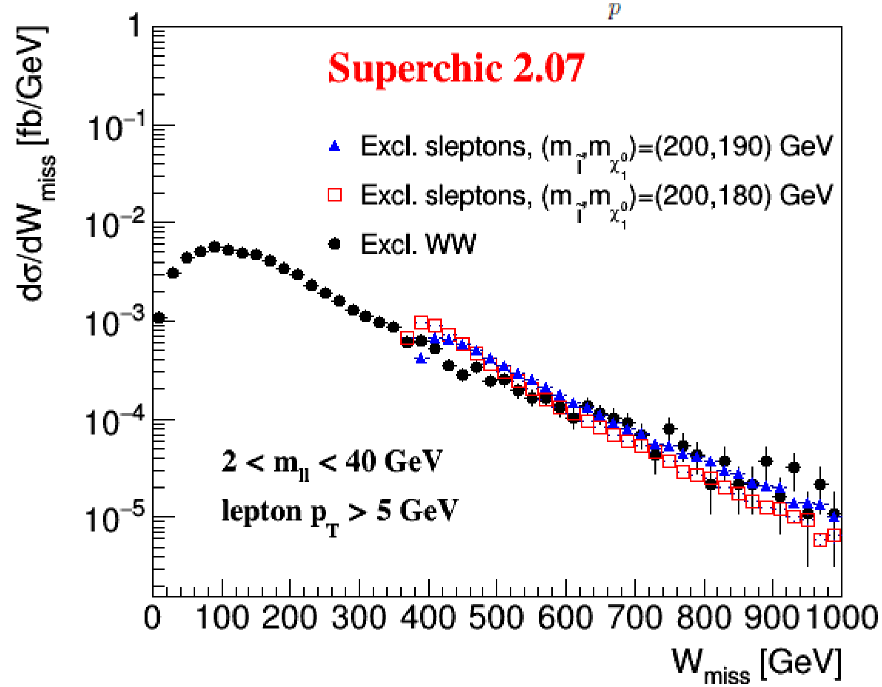
Exclusive WW

Exclusive WW gives the same dilepton final state as signal but much larger M_W - M_ν difference:



SIGNAL: $W_{miss} > 2M_{\chi^0}$ BG: $W_{miss} > 2M_\nu \sim 0$

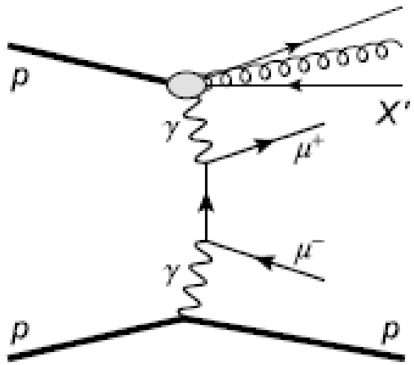




Exclusive WW background significantly suppressed by cuts on leptons and W_{miss}

Another approach: max. kinematically allowed $M_{\tilde{l}}$ and $M_{\tilde{\chi}}$ [Eur.phys. J. C72(2012)1969]: (also arXiv: 1811.06465[hep-ph])
only mild improvement seen

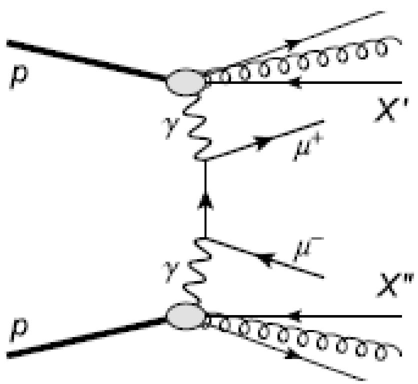
Single & Double-Dissociation background



Pure exclusive: m_{ll} > 10 GeV: σ = 8.4pb (Superchic).
Low m_{ll} → ξ outside FPD acceptance

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)

Not small enough since $\sigma_{ll}^{SD} \gg \sigma_{\tilde{l}\tilde{l}}^{CEP}$ in relevant mass regions.



How to reduce this BG?

Difference in signal and SD/DD topologies:
Events with SD/DD have larger proton p_T, dilepton system has larger η, smaller p_T and smaller acoplanarity.

- Impact of cuts evaluated using approximate modification to Superchic to include proton dissociation

PILE-UP Rejection using ToF

❑ What is the rate of fake double-tagged (DT) events with protons coming from PU in the acceptance 0.02 < ξ <0.15 and $p_{T,proton}$ < 0.35 GeV?

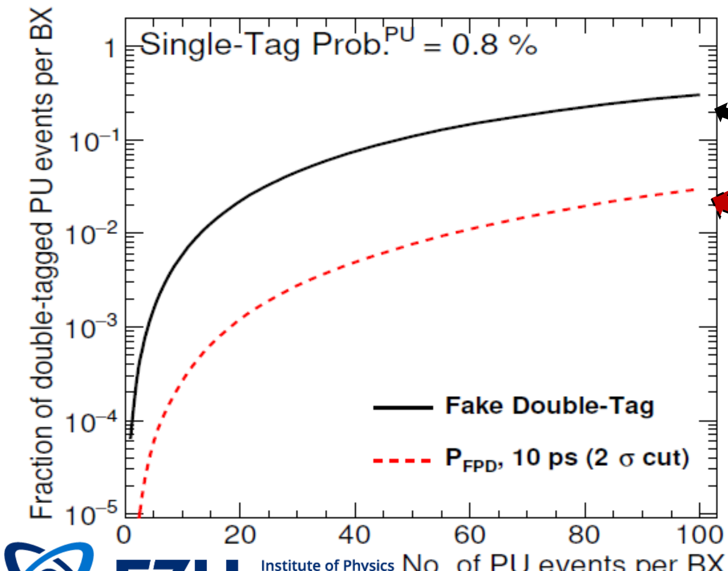
Most dangerous combination: 2x soft SD events + hard-scale di-lepton event.
Time-of-flight detectors (ToF) crucial: reject events where z_{vtx}(ToF) not matching z_{vtx}(central)

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}

ToF rejection depends on ToF resolution and size of PU

No-charged cuts

❑ Inclusive dilepton production has typically many additional charged particles associated with the primary vertex, while for CEP these are absent

❑ No charged cuts: based on

1) efficiency of vetoing additional vertices and tracks within 1mm of the primary vertex in pile-up for signal $\mathbf{P_{z-veto}(\mu = 10) = 0.84}$; $\mathbf{P_{z-veto}(\mu = 50) = 0.48}$ (Delphes fast simulation)
2) rejecting additional tracks in the central detector at zero pile-up for backgrounds $\mathbf{P_{gap}(\mu = 0)}$

$$\mathbf{P_{no-charged}(\mu = 10, 50) = P_{gap}(\mu = 0) * P_{z-veto}(\mu = 10, 50)}$$

Leads to sizable background 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 ($\|\eta\| < 4.0$)	$1.7(0.7) \times 10^{-7}$	$1.4(0.6) \times 10^{-7}$	$0.8(0.3) \times 10^{-7}$

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

PYTHIA8.2(HERWIG7.1)

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

|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)

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 < |η| < 4.0
- Timing detector also in |η|<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. Many potential avenues for improvement.

- Suitable for HL-LHC: larger significances expected but additional timing information from Central detector needed

- Ongoing work: more complete treatment of proton dissociation in SC

BACKUP SLIDES

Motivation

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

- ❑ QED mechanism has 2 advantages:

1) Experimental:
pp $\rightarrow$ 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.
$<m_{ll}>$ ~ ΔM $\rightarrow$ aim is to keep $<m_{ll}>$ low
- Motivated by cosmology, naturalness and (g-2) considerations

Aim $\rightarrow$

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

Pillars = published analyses

Measurement of **exclusive** dilepton in high Pile-up (ATLAS, CMS+Totem)
↓
Knowledge about exclusivity in high PU

❑ γγ → 2 sleptons → 2 invisible neutralinos (DM candidate) + dilepton
❑ QED mechanism has 2 advantages:
1) Experimental:
pp → p(FPD) + ll + low missing E_T + p(FPD)
measure precisely mass in FPD)
2) Theoretical:

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 ($\sim 10^{14}$) → 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)

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

scenario $M_{\tilde{l}}/M_{\tilde{\chi}_1^0}$	lepton p_T interval [GeV]			
	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

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 & |η| < 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 & |η| < 2.5 (effectively rejecting decays with extra charged particle, e.g. $D^0 \to K^- e^+ \nu$ or $D^+ \to \rho^0 \mu^+ \nu$)

- Examples of surviving events: leptons from W-decays, π-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} = 0.8x10^{-7} (W-bosons not included in inclusive jets)
HERWIG 7.1: $\boldsymbol{P_{lep}}$ = **2.5x10^{-7}** (45% of surviving events contain a W-boson)

Correct PYTHIA number by 1.45: $\boldsymbol{P_{lep}}$ = **1.2x10^{-7}**

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

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

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

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

○ 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.

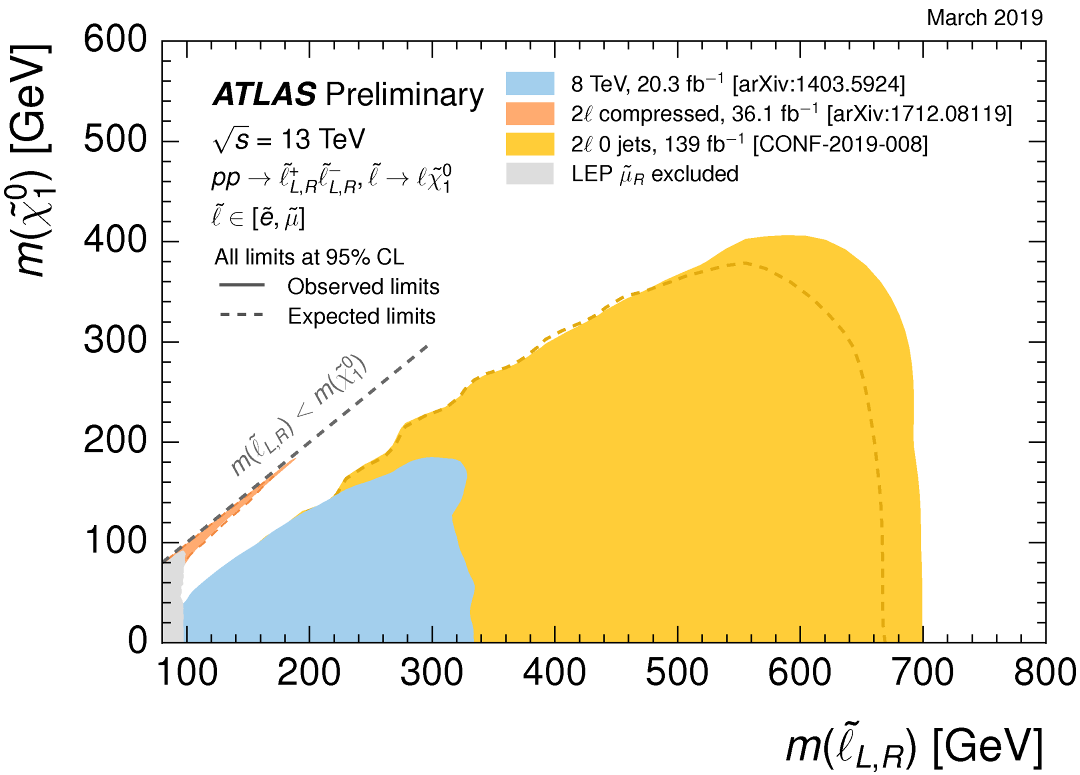
2) Fraction of those not having additional particles with p_T > 0.4 GeV & |η| < 2.5(4.0): $P_{gap}(\mu = 0)$

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

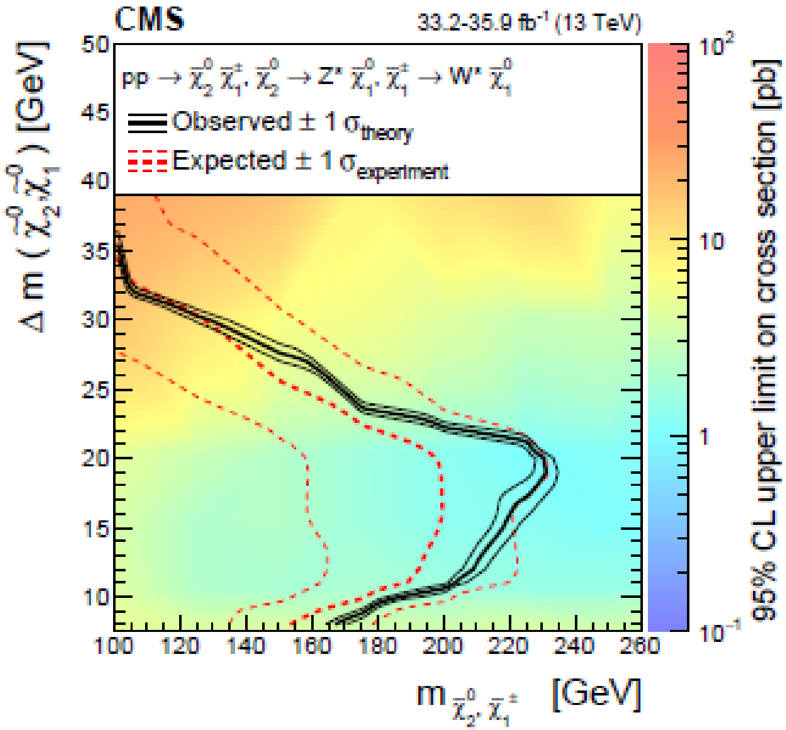
No-charged probability	$\langle\mu\rangle_{PU}$		
	0	10	50
CEP $c\bar{c}$	$3.5 \cdot 10^{-3}$	$2.9 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$
CEP gg	$3.3 \cdot 10^{-5}$	$2.8 \cdot 10^{-5}$	$1.6 \cdot 10^{-5}$
Incl. jets ($\lvert\eta\rvert < 2.5$)	$5.2/\mathit{2.0} \cdot 10^{-7}$	$4.4/\mathit{1.7} \cdot 10^{-7}$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

PYTHIA8.2/HERWIG7.1

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



ATLAS SUSY Summary plot



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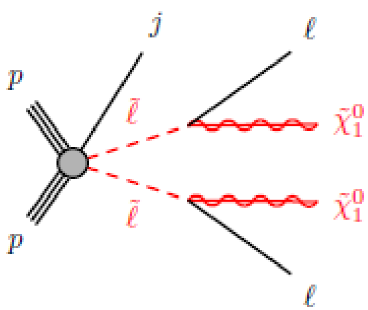
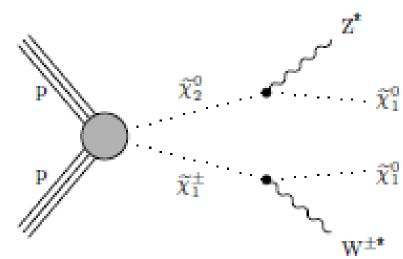
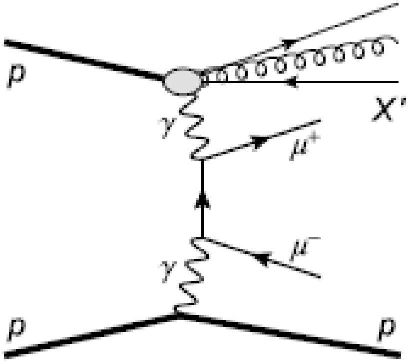


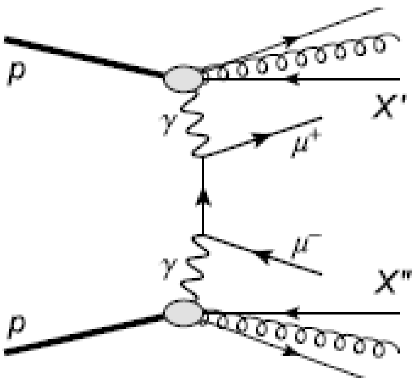


Single & Double-Dissociation background



Pure exclusive: m_{ll} > 10 GeV: σ = 8.4pb (Superchic [SC]).
Low m_{ll} → ξ 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 $\gamma\gamma \rightarrow e^+e^-/\mu^+\mu^-/\tau^+\tau^-$
- 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