

6th Workshop on QCD and Diffraction
joint with
**VARIOUS
FACES of**
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Fundamental Interactions of the Polish Physical Society

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Workshop on QCD and Diffraction – Various Faces of QCD

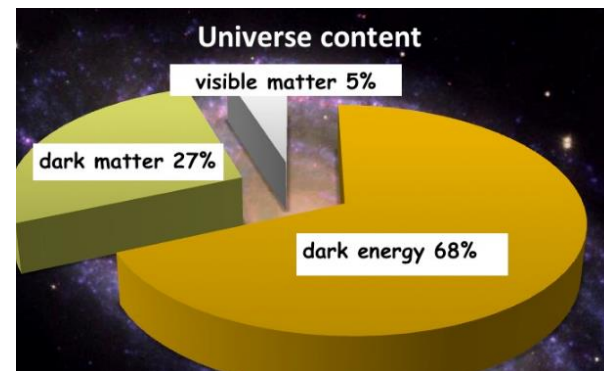
Challenges in searches for Dark Matter at the LHC in forward proton mode



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



Aims:

- to report current status of ongoing studies c :s of searches at the LHC for **ELECTROWEAKINO** pair production via photo with forward proton detectors (AFP, CT-PPS)



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

- an attempt to pick the expert brains for a guidance through uncharted waters



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

If (it looks like) squarks and gluinos are too heavy, sleptons, charginos, neutralinos- the main target.



(null search result so far)

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

$\tilde{\chi}_1^0$, natural candidate for cold Dark Matter –**LSP**

[arXiv:1710.02406](https://arxiv.org/abs/1710.02406)

(and quite a few other papers)

natural SUSY:

existence of light nearly

mass-degenerate Higgsinos/charged

Mass $\sim 100\text{--}200\text{ GeV}$

mass splitting $\sim 4\text{--}20\text{ GeV}$

Most challenging
scenario

between

Well motivated by naturalness and
cosmological observations

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

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What about the LHC during **MY** lifetime?

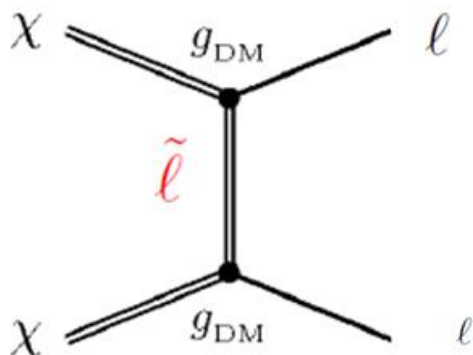
Supersymmetry, a theoretically and experimentally well-motivated extension of the Standard Model, predicts the existence of four light, nearly mass-degenerate Higgsinos with mass $\sim 100\text{--}200\text{ GeV}$ (not too far above m_Z). The small mass splittings amongst the higgsinos, typically $4\text{--}20\text{ GeV}$, 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 $\sqrt{s} > 2m_{\text{higgsino}}$ 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 $\sqrt{s} = 500\text{ GeV}$ of the proposed International Linear Collider currently under consideration for construction in Japan.

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

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

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

Boltzmann factor $\exp\left(-\frac{\Delta M}{T}\right)$

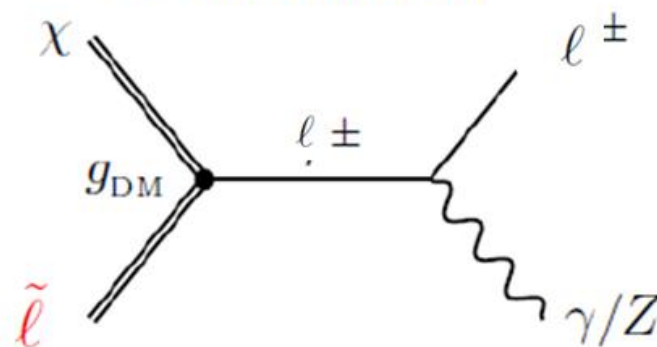


$$\Delta M \lesssim m_{DM}/25$$

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

(very conservatively <10%)

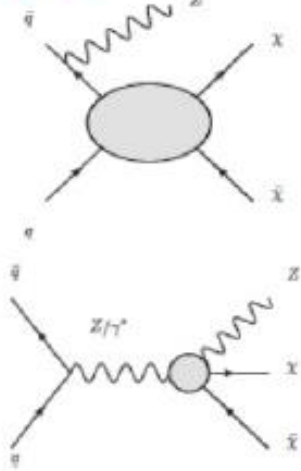
Co-annihilation:



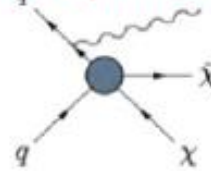
Mono-Mania (at the LHC)

DM Searches @ LHC O. Buchmüller

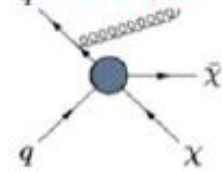
Mono-Z



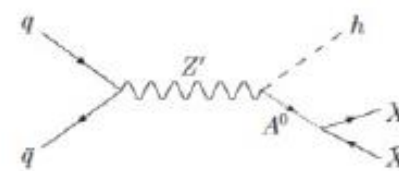
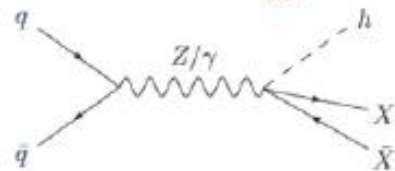
Mono-photon



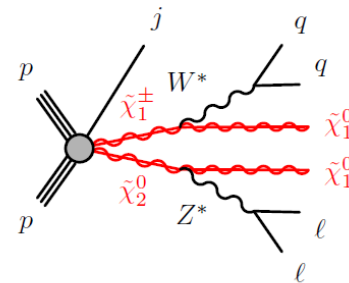
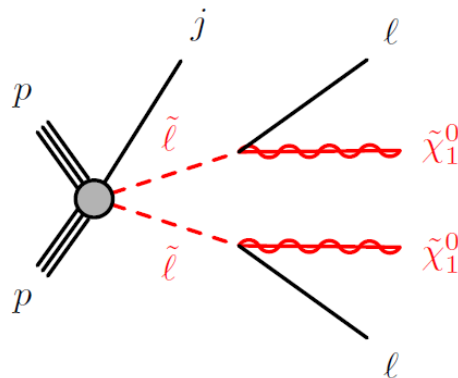
Mono-jet



Mono-Higgs



Searches for Electroweakinos at the LHC



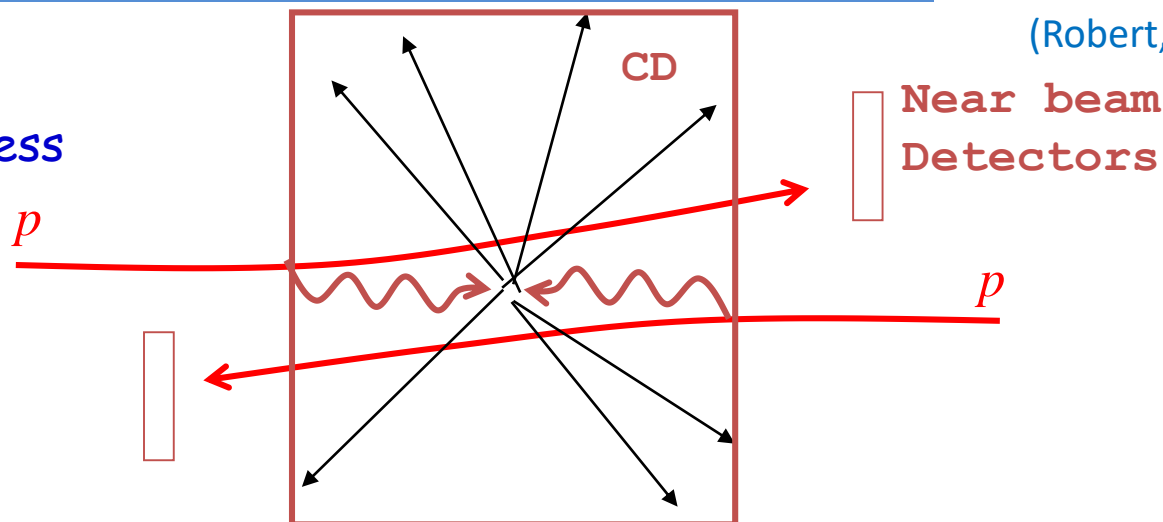
Model dependence



$\gamma\gamma$ collisions at the LHC

(Robert, Vlasios)

Process



Installed (AFP)
Installed (CT-PPS)

Extensive Program

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

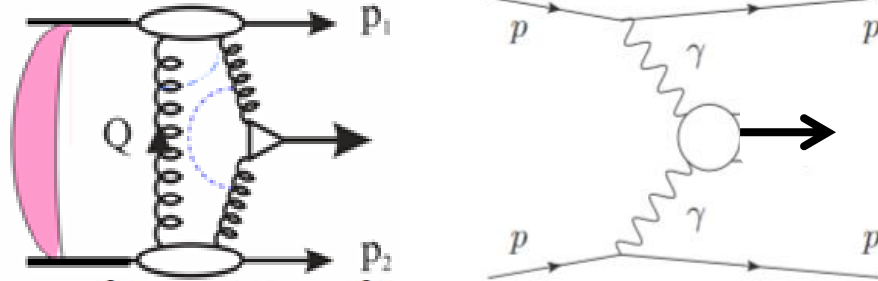
$$pp \rightarrow \bar{\ell}_{L,R}^+ \ell_{L,R}^- + pp$$

$$\bar{\ell} \rightarrow \ell \tilde{\chi}_1^0, \ell \in [e, \mu]$$

Strong advantage-model independent production mechanism, accurate mass measurement

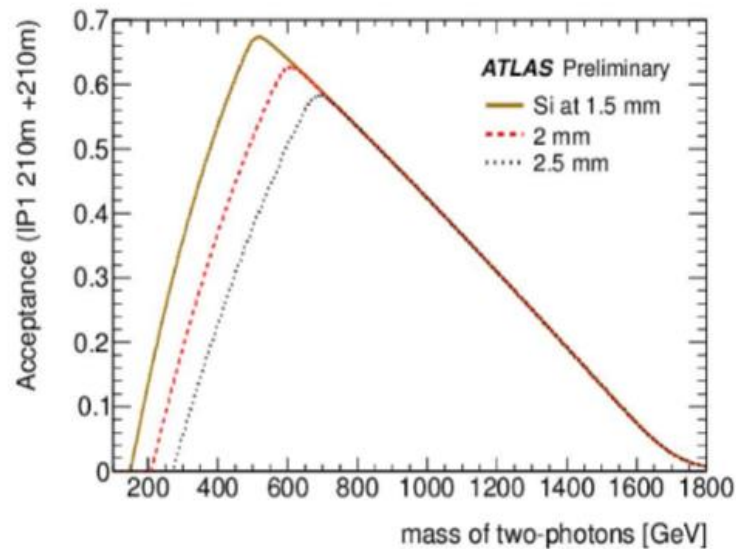
AFP , CT-PPS

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



$$0.03 < \xi < 0.15$$

M ~200- 2000 GeV



- Tag and measure protons at ± 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

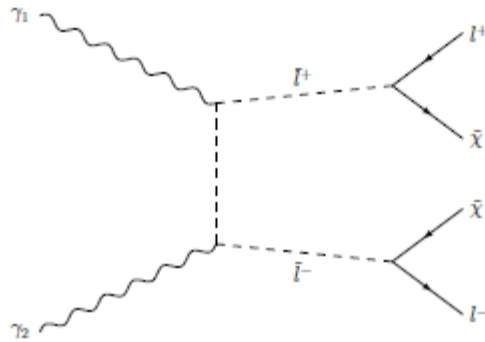
$$pp \rightarrow p + \gamma\gamma + p ,$$

$$\gamma\gamma \rightarrow X^+ X^- ,$$

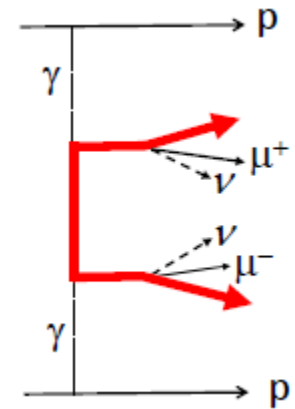
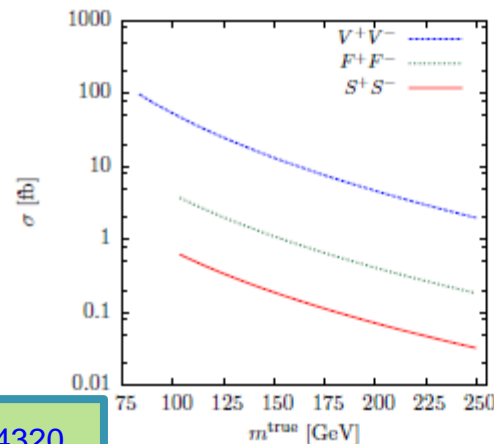
Diphoton X-Pair Production

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](https://arxiv.org/abs/1110.4320)



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

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

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)

Event Selection

≥ 100 GeV from
the LEP constraints

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

- $|\eta(l)| < 2,5$, cuts on $\eta(l_1) - \eta(l_2)$ (to suppress BG)

- $p_T(l) > 5$ GeV (trigger conditions)

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

$$\gamma\gamma \rightarrow W^+W^- \text{ with } W \rightarrow l\nu$$

- requirement of no additional tracks with $p_t > 0.4$ 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

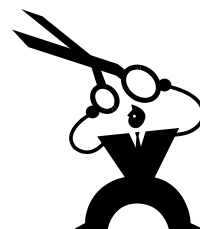


- chargino pair production- extra factor of ~ 25 suppression



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

- **z-vertex veto :** no vertices/tracks within ± 1 mm of the primary vertex
- processed by fast simulation **Delphes** software package with ATLAS detector input cards
- low $\mu = 0, 10$ benchmarks for disentangling PU-effects



Three cut classes:

Cut
$0.02 < \xi_{1,2} < 0.15$
$p_{T,proton} < 0.35$ GeV
$l_1, l_2 = e^+e^-$ or $\mu^+\mu^-$
$p_{T,l_1,l_2} > 5$ GeV
$ \eta_{l_1,l_2} < 2.5$ (4.0)
$\Delta R(l_1, l_2) > 0.3$
Acoplanarity > 0.4 (0.3)
$2 < m_{l_1 l_2} < 40$ GeV
$ \eta_{l_1} - \eta_{l_2} < 2.3$
$\bar{\eta} \equiv (\eta_{l_1} + \eta_{l_2})/2 < 1.0$
$W_{miss} > 200$ GeV
gap / z-vertex veto

← Forward proton detector acceptance

← Di-lepton system

← No-charged
(No activity around primary vertex)

Procedure

- Cross-section for signal very low -> signal has to be accumulated at high instantaneous luminosities
- Three reference points studied for the average number of PU events per bunch crossing: $\mu = 0, 10, 50$
- Signal as well background events overlaid with PU events (using Delphes)

Track resolutions and reconstruction efficiencies taken into account for the signal (using Delphes) and propagated to background samples

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

FPD ' acceptance .AND. **Di-lepton system** .AND. **No-charged**

FPD ' acceptance: generator level

Di-lepton system: generator level + lepton reconstruction efficiencies

No-charged: cannot be required at non-zero pile-up -> instead 'z-vertex isolation' required

Processes and MC event generators

❑ All exclusive processes: **Superchic 3**

QED: **Exclusive sleptons** (slepton masses 120-300 GeV, mass splittings 10 and 20 GeV, σ : 0.01-0.3 fb)

Exclusive l^+l^- ($M_X > 10$ GeV, $p_T > 3$ GeV, $\sigma \sim 1.2$ pb)

Exclusive W^+W^- ($M_X > 160$ GeV, semi-leptonic decays, $\sigma \sim 1.0$ fb)

QCD (CEP): **Exclusive K^+K^-** ($M_X > 10$ GeV, $p_T > 4$ GeV, $\sigma \sim 1.5$ fb)

Exclusive $c\bar{c}$ ($M_X > 10$ GeV, $p_T > 5$ GeV, $0.0 < |y_X| < 3.0$: $\sigma \sim 2$ nb)

Exclusive gg ($M_X > 10$ GeV, $p_T > 7$ GeV, $0.0 < |y_X| < 3.0$: $\sigma \sim 3$ μ b)

For exclusive processes with generated masses too low to produce protons in
FPD acceptance (l^+l^- , $c\bar{c}$, gg) \rightarrow consider:

- Single-proton dissociation
- Double-Proton Dissociation

❑ **Inclusive ND dijets**: $p_T > 7$ GeV, ISR on, FSR on, MPI on

Pythia 8.2: $\sigma \sim 27$ mb

Herwig 7.1: $\sigma \sim 16$ mb

❑ PU events generated by Pythia 8.2 and mixed with signal by Delphes

Acceptance of Forward Proton Detector

- Calculate a rate of fake double-tagged events with protons coming from PU in the acceptance $0.02 < \xi < 0.15$

Courtesy of Marek Tasevsky

Zero PU: use directly the inclusive dijet events

Non-zero PU: most dangerous: overlay of three events: 2x soft Single Diffraction + hard di-lepton event
Time-of-flight detectors necessary to suppress the PU background.

1) estimate probability to find a proton from PU in the FPD acceptance: 1.6%(PY 8.2) / 2.2% (HW7.1)

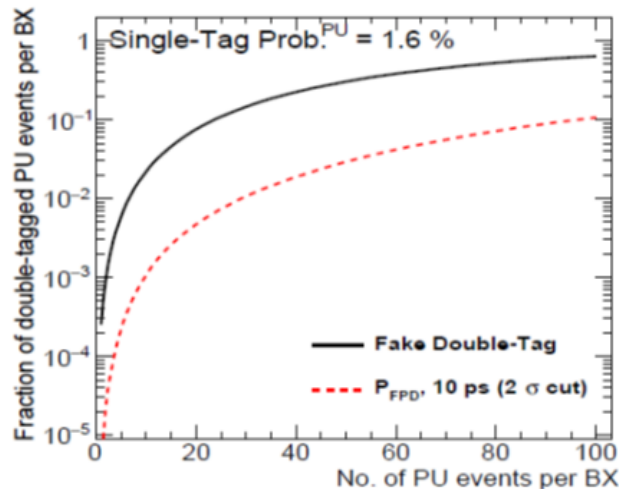
2) Calculate the rate of fake DT events as a function of μ , assuming

- bunch longitudinal size: 7.5 cm
- time resolution: $\sigma_t = 10$ ps
- time window: $2\sigma_t$

$$\sigma(PU + jet) = \sigma(jet) * P_{lep} * P_{no-ch} * P_{FPD}$$

$$P_{FPD} = [\mu P_{AFP}]^2 * P\{z_{jet} = z_{im}\}$$

matching z-coordinates within $2\sigma_t \sim 6$ mm



	PYTHIA 8.2			HERWIG 7.1		
	$\langle \mu \rangle_{jet}$			$\langle \mu \rangle_{PU}$		
	0	10	50	0	10	50
Fake DT	2.4E-8	0.0182	0.295	7.3E-8	0.0325	0.435
ToF rejection	-	17.0	10.1	-	16.1	8.2
P_{FPD}	2.4E-8	1.1E-3	2.9E-2	7.3E-8	2.0E-3	5.3E-2

These factors only applied for inclusive jet background

Di-leptons

Courtesy of Marek Tasevsky

- ❑ For inclusive ND jet events, apply only di-lepton cuts
- ❑ Remove events where the selected lepton is accompanied by charged particles with $p_T > 0.4$ GeV and $|\eta| < 2.5$ (coming e.g. from heavy-particle decays $D^0 \rightarrow K^- e^+ \nu$ or $D^+ \rightarrow \rho^0 \mu^+ \nu$).
- ❑ Calculate the probability to see such events out of all generated events
- ❑ Apply lepton reconstruction efficiencies (from ATLAS inclusive slepton searches)

PYTHIA 8.2: $P_{lep} = 0.8 \times 10^{-7}$ (W-bosons not included in inclusive jets)

HERWIG 7.1: $P_{lep} = 2.5 \times 10^{-7}$ (45% of surviving events contain a W-boson)

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



No-charged

□ **For signal** (just two leptons and missing ET in central detector): apply 'z-vertex veto':

- No other vertices and tracks in the region ± 1 mm from the primary vertex
- Using Delphes: overlay PU events and use fast simulation of ATLAS tracker
- Find the efficiency of the z-vertex veto $P_{z-veto}(\mu = 10) = 0.84$ and $P_{z-veto}(\mu = 50) = 0.48$.

These are in agreement with published results for exclusive dileptons without FPDs (ATLAS, CMS+Totem).

□ **For inclusive jets and exclusive $c\bar{c}$ and gg**

○ **zero PU:**

- 1) Select events with 2-4 charged particles with $p_T > 5$ GeV and $|\eta| < 2.5$ and require that at least two are separated by $dR > 0.3$.
- 2) Calculate the fraction of those that do not have any additional particles with $p_T > 0.4$ GeV and $|\eta| < 2.5$: get $P_{gap}(\mu = 0)$

○ **non-zero PU:** assume that the di-lepton cuts select events resembling the signal, i.e. exactly two leptons. Then

$$P_{no-charged}(\mu \neq 0) = P_{gap}(\mu = 0) * P_{z-veto}(\mu \neq 0)$$

No-charged probability	$\langle \mu \rangle_{PU}$		
	0	10	50
CF $c\bar{c}$	$3.5 \cdot 10^{-3}$	$2.9 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$
CF 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

Both ATLAS and CMS are going to upgrade their trackers to cover also $2.5 < |\eta| < 4.0$.

Signal event yields per $L=300fb^{-1}$

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	1.6	2.0
120/110	1.5	2.3	3.1	3.2
200/180	0.4	1.1	1.9	2.1
200/190	1.1	2.3	2.5	2.6
250/200	0.2	0.6	1.2	1.3
250/240	1.1	1.4	1.5	1.5
300/280	0.1	0.4	0.7	0.8
300/290	0.7	0.8	0.9	0.9

Possible ways to improve signal yields:

- Improve lepton reconstruction efficiencies (they start at 70% at $p_T=5$ GeV)
- Extend lepton acceptance up to $|\eta|=4$

Integrated event yields per $L=300\text{fb}^{-1}$

Event yields / $\mathcal{L} = 300 \text{ fb}^{-1}$	$\langle \mu \rangle_{PU}$		
	0	10	50
Excl. sleptons	0.8—3.5	0.7—2.9	0.4—1.7
Excl. l^+l^-	0.9	0.8	0.5
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	~ 0	0.6	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets ($ \eta < 2.5$)	~ 0	0.4/0.4	6.8/6.9
Incl. ND jets ($ \eta < 4.0$)	~ 0	0.1/0.1	2.2/2.3

PRELIMINARY

Work
in
progress

Extra factor of 1.5-2

Possible ways to suppress backgrounds:

- Cut on the distance of the secondary vertex from the primary vertex or on the pseudo-proper lifetime (many leptons from inclusive jets come from decays of heavy particles)
- Improve ToF resolution
- ATLAS and CMS tracker upgrade: extend coverage up to $|\eta|=4$ and provide timing for tracks in $2.5 < |\eta| < 4.0$.
- Timing in $|\eta| < 2.5$??? (envisaged for trackers at FCC)



BACKUP



***"Never, never,
never, give up."***

Winston Churchill