Diffraction and Low-x 2018

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


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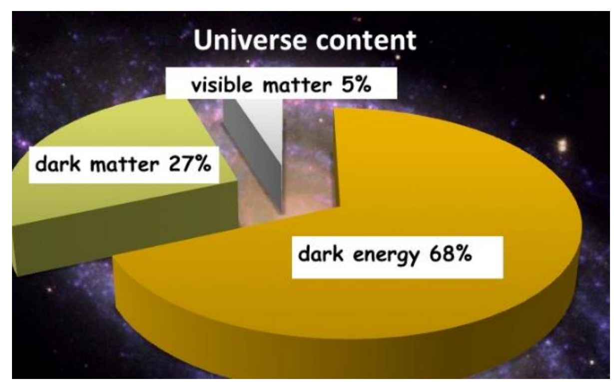
(in collaboration with Marek Tasevsky, Lucian Harland-Lang and Misha Ryskin)





# Aims:

- to report current status of ongoing studies on p  searches at the LHC for ELECTROWEAKINO pair production via photon fu forward proton detectors (AFP, CT-PPS)



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

- to attempt to pick the expert brains for a guidan  charted 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 $\tilde{\chi}^{\pm}_{1,2}$ 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

Well motivated by naturalness and cosmological observations

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

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

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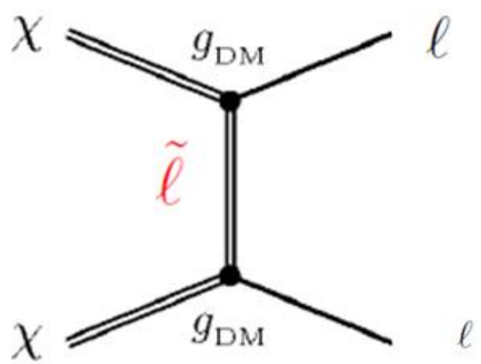
upersymmetry, a theoretically and experimentally well-motivated ers around the predicted existence of four light, nearly mass-degenerate Hig- gsinos with mass ~ 100 – 200 GeV (not too far above $m_Z$). The small mass splittings amongst the higgsinos, typically 4-20 GeV, results in very little visible 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.

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

# Co-annihilation

(1702.00750, model-1a)

Dark matter annihilation

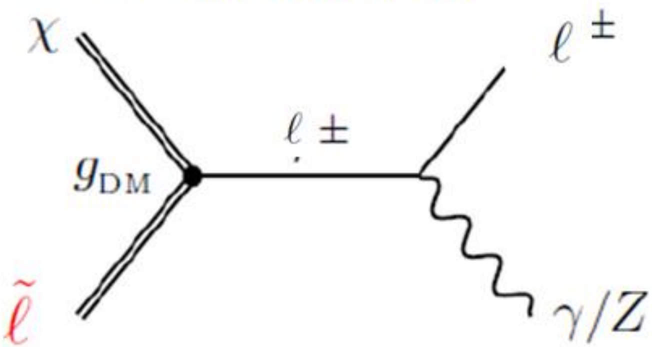



to bring DM abundance down to the observed value

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

Co-annihilation:



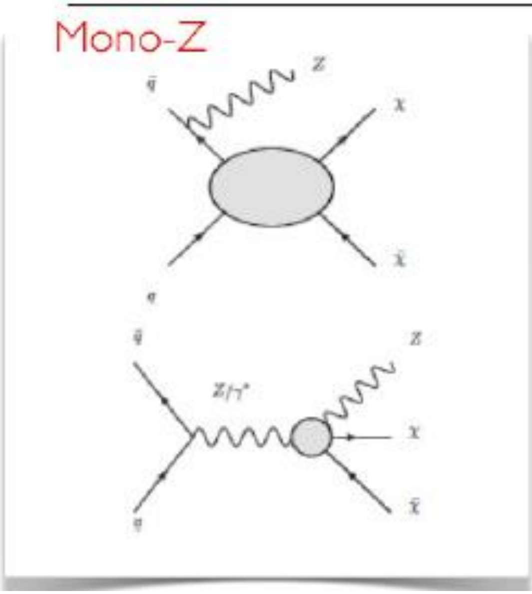

Freeze-out temperature $T_F \sim m_{DM}/25$

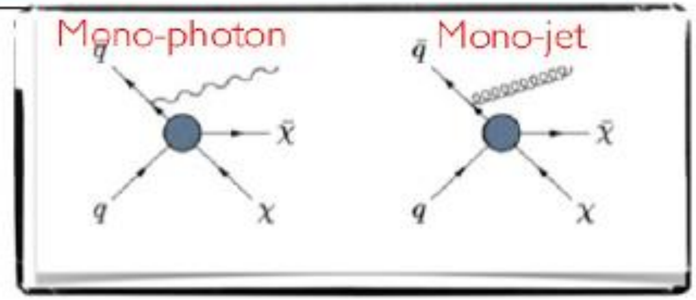
Boltzmann factor $\exp\left(-\frac{\Delta M}{T}\right)$ ⟹ $\Delta M \lesssim m_{DM}/25$

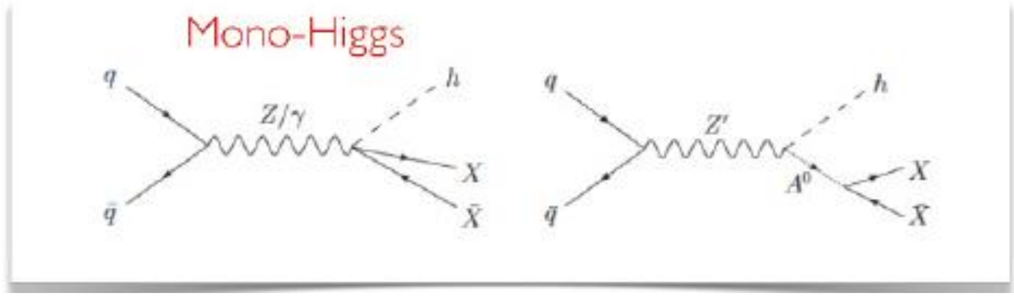
We need **mass splitting of 4% of $m_{DM}$** (conservatively, 10%)

# Mono-Mania (at the LHC)

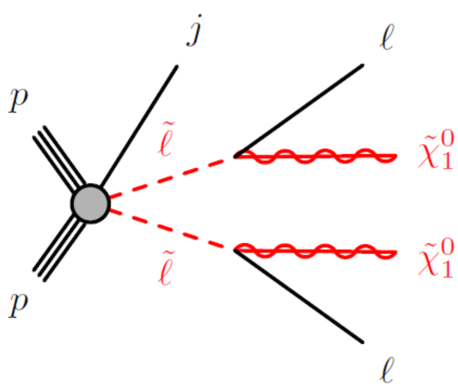
DM Searches @ LHC O. Buchmüller

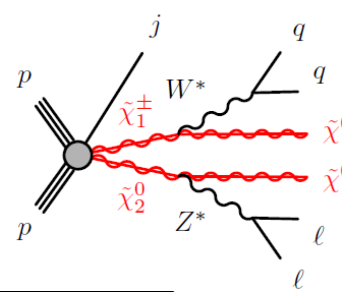



## Searches for Electroweakinos at the LHC



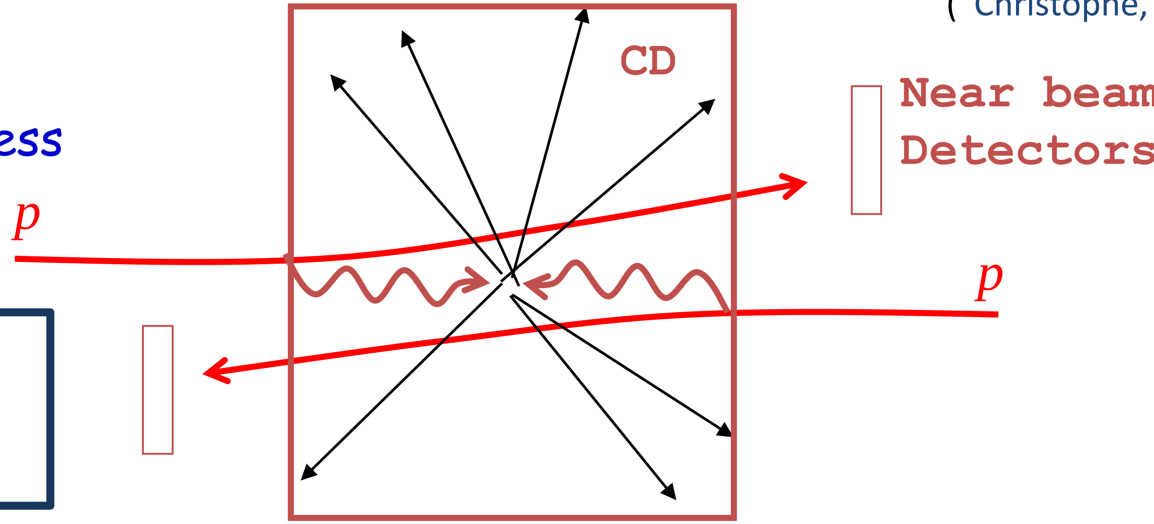




**Model dependence**

# $\gamma\gamma$ collisions at the LHC

( Christophe, Cristian, Lucian)

Process




Installed (AFP)
Installed (CT-PPS)
(Ksenia,Ada)

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

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

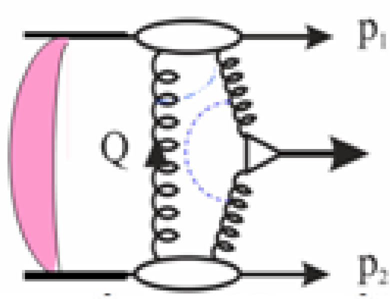
**Extensive Program**

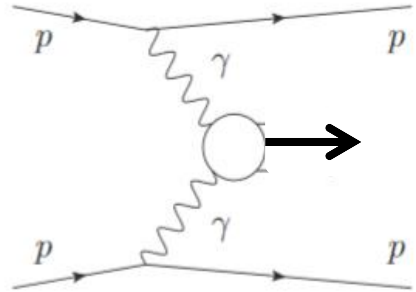
- $\gamma\gamma \to$ μμ, ee QED processes
- $\gamma\gamma \to$ QCD (jets..)
- $\gamma\gamma \to$ WW,… γ γ anomalous couplings
- $\gamma\gamma \to$ squarks, top… pairs
- $\gamma\gamma \to$ Charginos, Sleptons, ALPS
- Other new BSM objects

**Strong advantage-**model independent production mechanism, accurate mass measurement

# AFP , CT-PPS

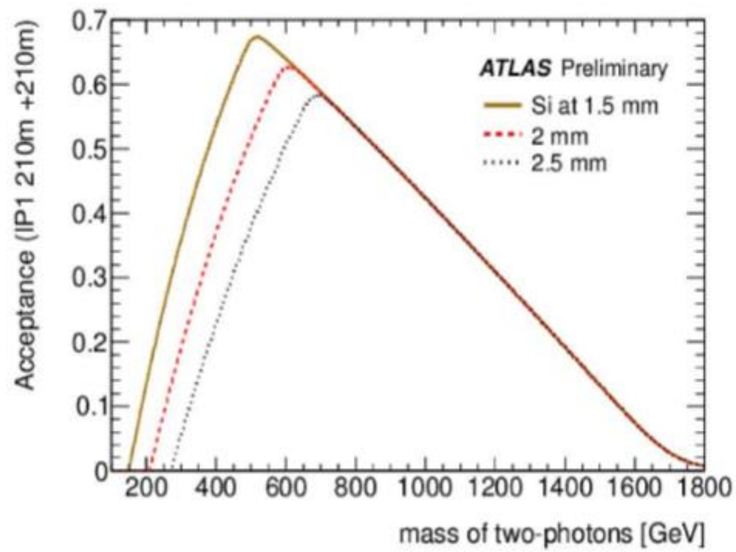
At large masses $\gamma\gamma$ takes over , KMR-02 (Lucian)




$$0.03 < \xi < 0.15$$

M ~200- 2000 GeV




(CT-PPS:Ksenia,Ada)

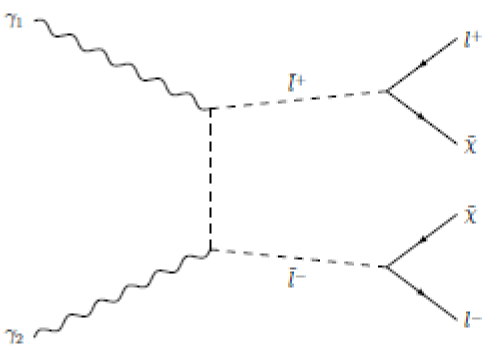
- Tag and measure protons at ±210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- Sensitivity to high mass central system, X, as determined using AFP/CT-PPS: Very powerful for exclusive states: kinematical constraints coming from AFP and CT-PPS proton measurements

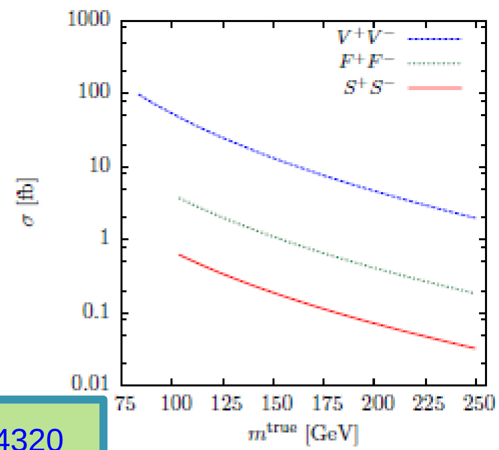
$$pp \to p + \gamma\gamma + p \,, \quad \gamma\gamma \to X^+X^- \,,$$

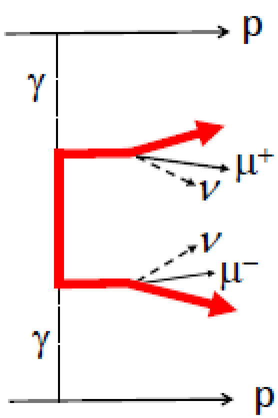
# Diphoton X-Pair Production

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](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)**

# Event Selection

$m(\tilde{l})$ = 120-300 GeV , $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0)$ =10-25 GeV

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

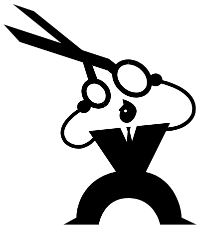
- $|\eta(l)| < 2{,}5$, cuts on $\eta(l_1) - \eta(l_2)$ (to supress BG)
- $p_T(l)$ >5 GeV (trigger conditions)

  $p_T(l)$ <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)

- **z-vertex veto :** no vertices/tracks within $\pm 1$ 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 |
|---|
| $0.02 < \xi_{1,2} < 0.15$ |
| $l_1, l_2 = e^+e^-$ or $\mu^+\mu^-$ |
| $p_{T,l_1,l_2} > 5$ GeV |
| $\lvert\eta_{l_1,l_2}\rvert < 2.5$ |
| $\Delta R(l_1, l_2) > 0.3$ |
| Acoplanarity $> 0.06$ |
| $2 < m_{l_1 l_2} < 40$ GeV |
| $W_{miss} > 200$ GeV |
| gap / z-vertex veto |

Forward proton detector acceptance

Di-lepton system

No-charged
(No activity around primary vertex)

Courtesy of Marek Tasevsky

# 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: μ = 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 ($\sim 10^{14}$) → sufficient statistics cannot be generated in reasonable time -> cuts are factorized into cut classes for the inclusive background

**AFP acceptance** .AND. **Di-lepton system** .AND. **No-charged**

**AFP 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

Courtesy of Marek Tasevsky

# Processes and MC event generators

- All exclusive processes: Superchic 2.07

QED: Exclusive sleptons (slepton masses 120-300 GeV, mass splittings 10 and 20 GeV, σ: 0.01-0.3 fb)
Exclusive $l^+l^-$ ($M_X$>20 GeV, σ ~ 1.2pb)
Exclusive $W^+W^-$ ($M_X$>160 GeV, semi-leptonic decays, σ ~ 1.3 fb)

QCD (CEP): Exclusive $K^+K^-$ ($M_X$>10 GeV, σ ~ 14fb)
Exclusive $c\bar{c}$ ($M_X$>20 GeV, σ ~ 73 pb)
Exclusive gg ($M_X$>50 GeV: σ ~ 1.6 nb, $M_X$>100 GeV: σ ~ 30 pb)

For exclusive processes with generated masses too low to produce protons in AFP acceptance ($l^+l^-$, $c\bar{c}$, 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 events generated by Pythia 8.2 and mixed with signal (or background) 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 even
Time-of-flight detectors necessary to suppress the PU background.

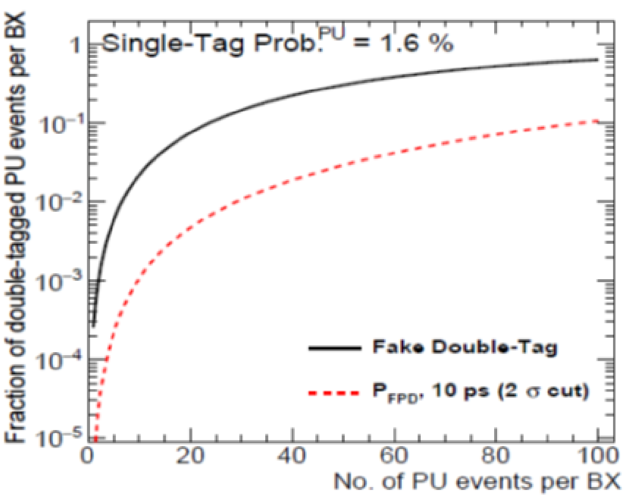
1) estimate probability to find a proton from PU in the FPD acceptance: 1.6%(PY 8.2) / 2.2% (HW7.1)

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: $2\sigma_t$

$$\sigma(PU + jet) = \sigma(jet) * P_{lep} * P_{no-ch} * P_{FPD}$$
$$P_{FPD} = [\mu P_{AFP}]^2 * P\{z_{jet} = z_{tim}\}$$

matching z-coordinates within $2\sigma$ t




| | PYTHIA 8.2 | | | HERWIG 7.1 | | |
|---|---|---|---|---|---|---|
| | $\langle\mu\rangle_{PU}$ | | | $\langle\mu\rangle_{PU}$ | | |
| | 0 | 10 | 50 | 0 | 10 | 50 |
| Fake DT | 24E-8 | 0.0182 | 0.295 | 7.3E-8 | 0.0325 | 0.435 |
| ToF rejection | | 17.0 | 10.1 | - | 16.1 | 8.2 |
| $P_{FPD}$ | 24E-8 | 1.1E-3 | 2.9E-2 | 7.3E-8 | 2.0E-3 | 5.3E-2 |

PRELIMINARY

These factors only applied for inclusive jet background

**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 |η| < 2.5 (coming e.g. from heavy-particle decays $D^0 \to K^- e^+ \nu$ or $D^+ \to \rho^0 \mu^+ \nu$).

- Calculate the probability to see such events out of all generated events

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

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

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

**Courtesy of Marek Tasevsky**

# 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 +- 1mm from the primary vertex
- Using Delphes: overlay PU events and use fast simulation of ATLAS tracker
- Find the efficiency of the z-vertex veto $\boldsymbol{P_{z-veto}(\mu = 10) = 0.84}$ and $\boldsymbol{P_{z-veto}(\mu = 50) = 0.48}$.

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 |η| < 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 |η| < 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

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

| No-charged probability | $\langle\mu\rangle_{PU}$ | | |
|---|---|---|---|
| | 0 | 10 | 50 |
| 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

PRELIMINARY

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

Courtesy of Marek Tasevsky

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

PRELIMINARY

| 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 | 2.4 | 3.1 | 3.2 |
| 200/180 | 0.4 | 1.1 | 1.9 | 2.1 |
| 200/190 | 1.[illegible] | 2.3 | 2.5 | 2.6 |
| 250/2[illegible]0 | 0.2 | 0.6 | 1.2 | 1.3 |
| 2[illegible]0/240 | 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 |η|=4

Courtesy of Marek Tasevsky

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

PRELIMINARY

| Event yields / $\mathcal{L} = 300$ fb$^{-1}$ | $\langle\mu\rangle_{PU}$ 0 | 10 | 50 |
|---|---|---|---|
| Excl. sleptons | 0.8—3.2 | 0.7—2.7 | 0.4—1.5 |
| Excl. $l^+l^-$ | 0.05 | 0.05 | 0.03 |
| Excl. $K^+K^-$ | $\sim 0$ | $\sim 0$ | $\sim 0$ |
| Excl. $W^+W^-$ | 1.4 | 1.2 | 0.7 |
| Excl. $c\bar{c}$ | $\sim 0$ | $\sim 0$ | $\sim 0$ |
| Excl. $gg$ | $\sim 0$ | $\sim 0$ | $\sim 0$ |
| Incl. ND jets ($\lvert\eta\rvert < 2.5$) | $\sim 0/\sim 0$ | 0.4/0.4 | 6.8/6.9 |
| Incl. ND jets ($\lvert\eta\rvert < 4.0$) | $\sim 0/\sim 0$ | 0.1/0.1 | 2.2/2.3 |

**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 |η|=4 and provide timing for tracks in 2.5<|η|<4.0.
- Timing in |η|<2.5??? (envisaged for trackers at FCC)

**(FP420- RIP)**


"Never, never,
never, give up."
Winston Churchill


THANK YOU


QUESTIONS?

# BACKUP

# DM searches with AFP (exclusive γγ)

- Signal (WIMP itself): massive, neutral, weakly interacting particle
- WIMP + visible SM particle (g, q, γ, Z, W, h): large missing $E_T$

KMR, J.Phys. G44 (2017) no.5, 05500:

BUT! In exclusive γγ collisions and Compressed mass spectra scenario: missing $E_T$ not large

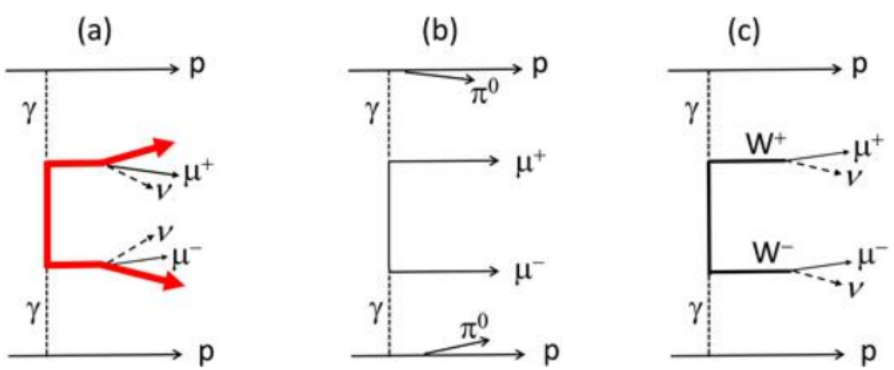
Lightest SUSY Particle close in mass to parent sparticle

- E.g. $\gamma\gamma \rightarrow$ 2 charginos $\rightarrow$ 2 heavy invisible neutralinos (LSP) + lνlν, $p_T$(l) ~ 3-10 GeV
- **Then signal with AFP: pp → p(AFP) + ll + missing $E_T$ + p(AFP)**

**Backgrounds:**

1) p dissociation in QED exclusive $\gamma\gamma \rightarrow ll$: tamed by
- vetoing using ZDC
- requiring $e^+\mu^-$ or $e^-\mu^+$
- separating mass peak at ~ 20 GeV from > 200 GeV

2) QED exclusive WW → lνlν: suppressed to ~fb level just by requiring $p_T$(l) < 10 GeV




Better outlooks than previous signal process: current devices suffice to tame the background.



Low energy release, but clear operating environment .