Search for the direct production of slepton pairs in $\sqrt{s}$=13 TeV pp collision with the ATLAS detector

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ATLAS EXPERIMENT

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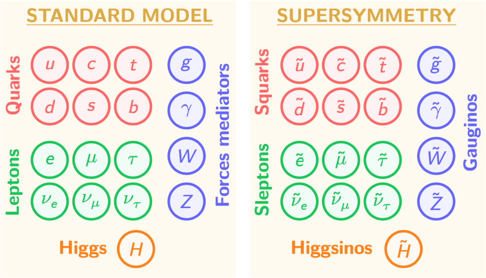
Supersymmetry (SUSY)

Supersymmetry is an extension of the Standard Model (SM), which introduces a new symmetry between bosons and fermions:

- To each SM particle it associates a supersymmetric partner, which differs of 1/2 in spin:
  - ✓ quarks → **squarks** $\tilde{q}$
  - ✓ leptons → **sleptons** $\tilde{\ell}$
  - ✓ gauge → **gauginos** $\widetilde{Z}, \widetilde{W}, \tilde{\gamma}, \tilde{g}$
  - ✓ higgs → **higgsinos** $\widetilde{H}$



- It'd solve the "hierarchy problem" and the unification of electroweak and strong interactions
- A new quantum number, R-parity, is introduced: $\boldsymbol{R = (-1)^{3(B-L)+2S}}$

$$R = \begin{cases} +1 & \text{for SM particles} \\ -1 & \text{for SUSY particles} \end{cases}$$

The simplest formulation is the **Minimal Supersymmetric Standard Model (MSSM)**:

- Charged higgsinos and gauginos mix to form **charginos** $\tilde{\chi}_i^{\pm}$, with $i = 1, 2$
- Neutral higgsinos and gauginos mix to form **neutralinos** $\tilde{\chi}_j^{0}$, with $j = 1, 2, 3, 4$
- If R-parity is conserved → $\tilde{\chi}_1^0$ = **Lightest Supersymmetric Particle (LSP)** stable and a good dark matter candidate

Slepton electroweak production

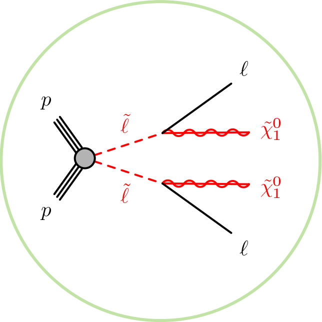
- Direct production of sleptons

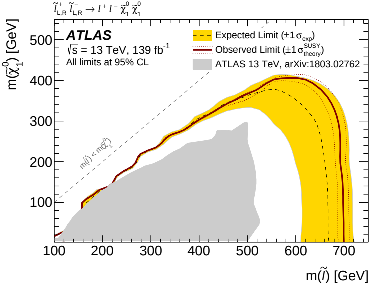
$$pp \to \tilde{\ell}\tilde{\ell} \to \ell\tilde{\chi}_1^0\ell\tilde{\chi}_1^0$$

- Bino-like decay $\tilde{\ell} \to \ell\tilde{\chi}_1^0$
- Only $\tilde{e}$ and $\tilde{\mu}$ considered $\to$ $\tilde{\tau}$ production is targeted in a different search:

ATLAS Collaboration, *Search for direct stau production in events with two hadronic τ-leptons in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector*, Phys. Rev. D 101, 032009

- The final state is: 2 oppositely charged sign (**OS**) same flavor (**SF**) leptons (only e and μ) + missing transverse energy E_T^{miss}





Published results with LHC full Run 2 data:

- Improvement in respect with the previous result (gray shaded region) which uses 36 fb^{-1} data (2015-2016) of LHC Run 2
- For massless $\tilde{\chi}_1^0$, masses up to 700 GeV are excluded for $\tilde{\ell}$

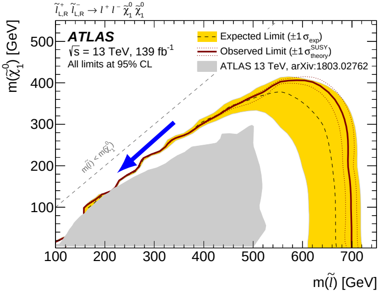
ATLAS Collaboration, *Search for electroweak production of charginos and sleptons decaying into final states with two leptons and missing transverse momentum in $\sqrt{s}$ = 13 TeV pp collisions using the ATLAS detector*, Eur. Phys. J. C 80 123, 2020, arXiv:1908.08215

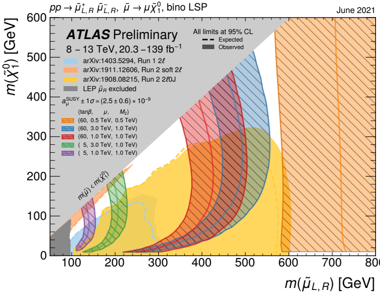
Slepton electroweak production in "compressed" regions

- Analysis of the **moderately compressed region**:

$$\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) = m(\tilde{\ell}) - m(\tilde{\chi}_1^0) \sim m_W$$

- Data collected by ATLAS experiment during Run 2 of LHC at $\sqrt{s} = 13$ TeV, corresponding to 139 fb^{-1} of integrated luminosity





- Light smuons $\tilde{\mu}$ and light LSP can explain the $(g-2)_\mu$ **anomaly**
- The $(g-2)_\mu$ anomaly, at small $\tan\beta$, favours the mass region in the $(m(\tilde{\mu}), m(\tilde{\chi}_1^0))$ plane that is moderately compressed or compressed:

$$\Delta m(\tilde{\mu}, \tilde{\chi}_1^0) = m(\tilde{\mu}) - m(\tilde{\chi}_1^0) \lesssim m_W$$

- Results from LEP and previous LHC searches excluded portions of this mass region, but an important part of it is still not ruled out

Slepton search strategy

1. **SUSY simplified models**
   - Mass of $\widetilde{\ell}$ and $\widetilde{\chi}_1^0$ are the only free parameters
   - All the other particles are assumed to be heavy and decoupled
   - $\text{BR}(\widetilde{\ell} \to \ell\widetilde{\chi}_1^0) = 100\%$
   - Lepton flavour is conserved

2. **Event selection**
   - Selective criteria are applied on the relevant kinematic variables
   - *Signal Regions* (SRs) are defined, where the SUSY signal is maximized and the SM background rejected

3. **Background estimation**
   - SM Background estimated with Monte Carlo (MC) simulations
   - Dedicated data-driven technique to estimate some of the dominant backgrounds

4. **Results**
   - Multi-bin fit using a variable with high discrimination power
   - SR "unblinding" and data-expected bkg comparison, after having optimized the background estimation strategy

5. **Interpretation**
   - If a significant excess of data over the expected background is observed $\to$ signal **evidence/discovery**
   - Otherwise an **upper limit** on the SUSY production cross section is set and limits on some other parameters of the considered model are derived

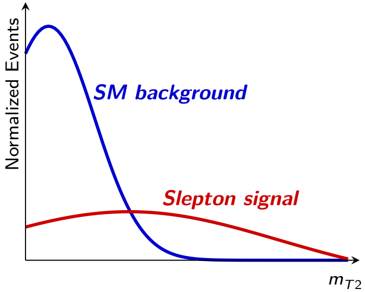
Event preselection and kinematic variables

- Events are required to:
  1. have exactly two opposite charge sign (OS) signal leptons ℓ_1 and ℓ_2
     - ✓ Same Flavour (SF): $e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$
     - ✓ Different Flavour (DF): $e^{\pm}\mu^{\mp}$
  2. ℓ_1 (leading lepton*) having:
     $p_{T,\ell_1} > 27$ GeV
  3. ℓ_2 (sub-leading lepton) having:
     $p_{T,\ell_2} > 9$ GeV
  4. to remove low-mass resonances the dilepton invariant mass:
     $m_{\ell\ell} > 11$ GeV
  5. have no more than one jet and b-jet veto:
     $n_{jet} < 2$ and $n_{b-jet} = 0$
  6. E_T^{miss} significance > 3
  7. SF are required to have a dilepton invariant mass far from the Z peak, to reduce VZ and Z+jets:
     $|m_{\ell\ell} - 91 \text{ GeV}| > 15$ GeV

* Single-lepton triggers have been adopted, which require the $p_T > 27$ GeV threshold for the leading lepton

- The **stransverse mass m_{T2}** is the most sensitive variable for the signal/bkg discrimination:

> ***SM background*** *and* ***slepton signal*** *have different endpoints in the mass*



- Since the mass of the invisible particle enters as a free parameter in the m_{T2} definition, imposing its values to 100 GeV gives the best sensitivity $\rightarrow$ $\boldsymbol{m_{T2}^{100}}$
- $\cos\theta^*_{\ell\ell}$ is sensitive to the slepton production angle
- $\Delta\phi_{\ell,\ell}$, $\Delta\phi_{p_T^{\text{miss}},\ell_1}$, $\Delta\phi_{p_T^{\text{miss}},\ell_2}$, $p_{T,\text{boost}}^{\ell\ell}$, $\Delta\phi_{\text{boost}}$

Signal Region definition

- **Signal Regions (SRs)** are defined and optimized for benchmark signal models by maximizing the discovery significance

- **Slepton model requires**:
  - ✓ Same-flavour opposite-charge-sign (SFOS) lepton pair in the event
  - ✓ E_T^{miss} from $\tilde{\chi}_1^0$
  - ✓ Low hadronic activity

- Only events with 0 b-jets are considered, $n_{b-jet} = 0 \rightarrow$ to reduce top bkg

- Then, further classification in non-b-tagged jet multiplicity:
  - ✓ SR with $n_{jet} = 0$: **SR-0J**
  - ✓ SR with $n_{jet} = 1$: **SR-1J**

- SR binned in m_{T2}^{100} bins, chosen to maximize the search sensitivity:

$$m_{T2}^{100} = [100, 105, 110, 115, 120, 125, 130, 140, \infty)$$

Search of excess of SF events over the SF SM background

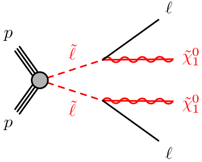
Variable	SR-0J
n_{jet-20}	$= 0$
$n_{bjet-20}$	$= 0$
$N_{\text{OS SF leptons}}$	$= 2$
$p_T^{\ell_1}$	> 140 GeV
$p_T^{\ell_2}$	> 20 GeV
E_T^{miss} significance	> 7
$m_{\ell\ell}$	> 11 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	> 15 GeV
$p_{T,\,boost}^{\ell\ell}$	< 5 GeV
$\cos\theta^*_{\ell\ell}$	< 0.2
$\Delta\phi_{\ell\ell}$	> 2.2
$\Delta\phi_{E_T^{miss},\ell_1}$	> 2.2

Variable	SR-1J
n_{jet-20}	$= 1$
$n_{bjet-20}$	$= 0$
$N_{\text{OS SF leptons}}$	$= 2$
$p_T^{\ell_1}$	> 100 GeV
$p_T^{\ell_2}$	> 50 GeV
E_T^{miss} significance	> 7
$m_{\ell\ell}$	> 60 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	> 15 GeV
$\cos\theta^*_{\ell\ell}$	<0.1
$\Delta\phi_{\ell\ell}$	> 2.8

Background estimation

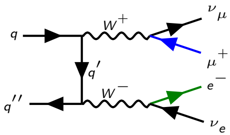
- SM background can be classified into:
  - ✓ **IRREDUCIBLE** → Main backgrounds are **dibosons (VV)** and **top ($t\bar{t} + Wt$)**
  - ✓ **REDUCIBLE** → **Fake Non-Prompt (FNP) leptons**

- **Slepton signal** is always two SF leptons → **flavour asymmetric**



100% SF: ee, $\mu\mu$

- **Backgrounds** can have SF and DF leptons → **flavour symmetric (FSB)**



50% SF: ee, $\mu\mu$
50% DF: $e\mu$, μe

FS backgrounds:
WW, $t\bar{t}$, Wt,
$Z \to \tau\tau$

- Estimate the SF FS background events inside SRs → using the number of DF data in SR, N_{DF}

Efficiency correction method: e and μ have different acceptances and trigger, reconstruction, isolation and identification efficiencies → these differences must be taken into account through the factors:

$$\kappa = \sqrt{\frac{N_{\mu^+\mu^-}}{N_{e^+e^-}}} \quad \text{and} \quad \alpha = \frac{\sqrt{\varepsilon^{trig}_{\mu\mu}\varepsilon^{trig}_{ee}}}{\varepsilon^{trig}_{e\mu}}$$

Background estimation: flavour symmetric

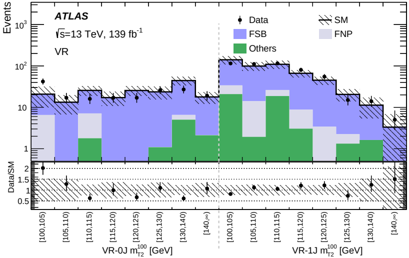
- SF events can then be computed as:

$$N_{SF}^{expected} = N_{ee}^{expected} + N_{\mu\mu}^{expected} = 0.5 \times \left(\kappa + \frac{1}{\kappa}\right) \times \alpha \times N_{DF}$$

- κ and α factors have been obtained in dedicated **Control Regions (CRs)**

- In order to validate the efficiency correction method

  two **Validation Regions (VRs)**, VR-0J and VR-1J, are defined, similar to SR but inverting the $|\cos\theta^*_{\ell\ell}|$ cut
- A good agreement is observed between the data and the total estimated SM background



$\kappa = \sqrt{\frac{N_{\mu^+\mu^-}}{N_{e^+e^-}}}$: where $N_{\mu^+\mu^-}$ and $N_{e^+e^-}$ are the numbers of dimuon and dielectron events respectively

$\alpha = \frac{\sqrt{\varepsilon_{\mu\mu}^{trig}\varepsilon_{ee}^{trig}}}{\varepsilon_{e\mu}^{trig}}$: where $\varepsilon_{\mu\mu}^{trig}$, ε_{ee}^{trig} and $\varepsilon_{e\mu}^{trig}$ are the efficiencies of triggering dimuon, dielectron and electron–muon events

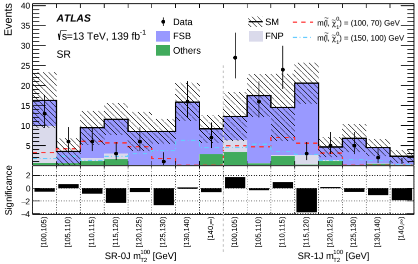
Statistical Interpretation

- A multi-bin likelihood fit as function of m_{T2}^{100} is performed

$$m_{T2}^{100} = [100, 105, 110, 115, 120, 125, 130, 140, \infty)$$

- Predicted number of FS background events, together with the observed data

No significant deviation from the SM expectations are observed in any of the SRs considered



SR-0J:

- 2 bins where the expected background exceeds the data with a local significance of about 2σ

same behavior observed when using pure MC for backgrounds

disagreement most likely arises from statistical fluctuations in data

SR-1J:

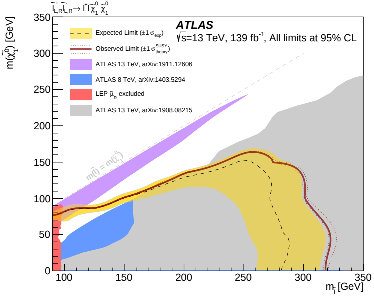
- 2 bins where data exceeds the expected background of about 1.5σ
- 1 bin where the data is below the expected background by about 3.5σ

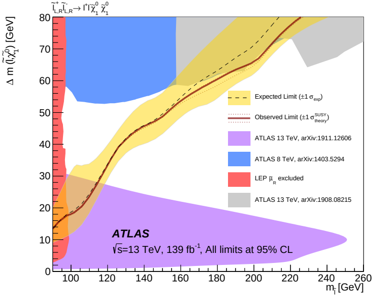
correlated with statistical fluctuations in the distribution of DF events in data which are used to estimate the FSB

Exclusion contours

- Exclusion limits at 95% CL on the masses of the sleptons and neutralino are shown for mass-degenerate $\tilde{e}_{L,R}/\tilde{\mu}_{L,R}$
- All the models with CLs values lower than 0.05 are excluded with 95% confidence level
- This contour bridges the gap between previous ATLAS searches and surpassing limits from LEP

Sleptons up to 150 GeV are excluded at 95% CL in the case of a 50 GeV mass-splitting between the slepton and the LSP





ATLAS Collaboration, *Search for direct pair production of sleptons and charginos decaying to two leptons and neutralinos with mass splittings near the W-boson mass in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, CERN-EP-2022-132, 2022, arXiv:2209.13935

Exclusion contours: selectrons and smuons

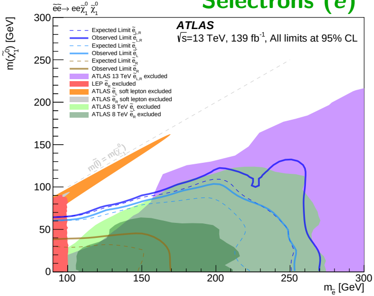
- Exclusion limits are also set for **selectrons** and **smuons** separately

⬇

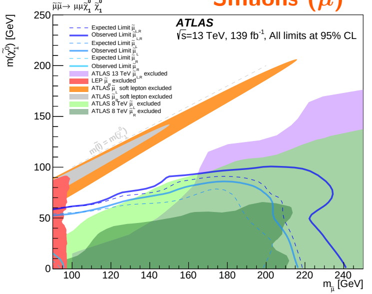
limits are set for single slepton species $\tilde{e}_L$, $\tilde{e}_R$, and $\tilde{\mu}_L$ along with combined limits for mass-degenerate $\tilde{e}_{L,R}$ and $\tilde{\mu}_{L,R}$

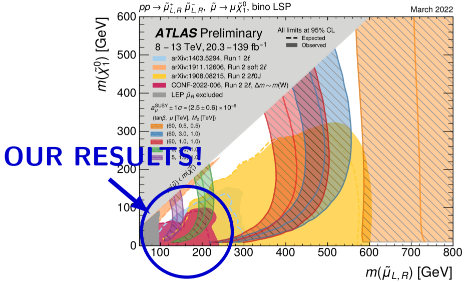
- For **smuons**: parts of the region excluded by this search in the $(m(\tilde{\mu}), m(\tilde{\chi}_1^0))$ plane are compatible with the $(g-2)_\mu$ anomaly for small $\tan\beta$ values.

Selectrons ($\tilde{e}$)



Smuons ($\tilde{\mu}$)





Conclusions

- The results of the **electroweak production of sleptons** decaying into final states containing two leptons with opposite electric charge and missing transverse momentum has been presented

> ATLAS Collaboration, *Search for direct pair production of sleptons and charginos decaying to two leptons and neutralinos with mass splittings near the W-boson mass in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, CERN-EP-2022-132, 2022, arXiv:2209.13935

- The search uses 139 fb^{-1} of $\sqrt{s} = 13$ TeV proton-proton collisions collected by the ATLAS Experiment at LHC during Run 2 (2015-2018)

- The regions with mass differences $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0)$ up to approximately 150 GeV between the sleptons and neutralino are explored

- Models with **smuon** production with mass differences in these regions of the $(m(\tilde{\mu}), m(\tilde{\chi}_1^0))$ plane are favoured to explain the **$(g-2)_\mu$ anomaly** for small $\tan\beta$ values

- The **data are found to be consistent with the Standard Model predictions**

- **Slepton** masses up to **150 GeV** are excluded at 95% CL in the case of a **50 GeV** mass-splitting between the slepton and the neutralino

THANKS FOR THE ATTENTION

BACKUP

Variable definitions

Variable	Definition
$p_T^{\ell_1}$	transverse momentum of the leading lepton, ℓ_1
$p_T^{\ell_2}$	transverse momentum of the sub-leading lepton, ℓ_2
$m_{\ell\ell}$	invariant mass of the two leptons, in particular, a $m_{\ell\ell}$ veto close to the Z mass window helps to reject Z + jets events
E_T^{miss} significance	It is define as, $$E_T^{\text{miss}} \text{ significance} = \frac{\lvert \mathbf{p}_T^{\text{miss}} \rvert}{\sqrt{\sigma_L^2(1-\rho_{LT}^2)}},$$ where σ_L is the (longitudinal) component parallel to $\mathbf{p}_T^{\text{miss}}$ of the total transverse momentum resolution for all objects in the event and the quantity ρ_{LT} is the correlation factor between the parallel and perpendicular components of the transverse momentum resolution for each object.
$\Delta\phi_{\ell\ell}$	The azimuthal angular separation between the two leptons. Since in absence of jets sleptons are produced back to back, the leptons coming from their decay are expected to be well separated in the azimuthal plane. This is not the case for backgrounds like $t\bar{t}$ or ZZ.
$\Delta\phi_{E_T^{\text{miss}},\ell\ell}$	The azimuthal angular separation between E_T^{miss} and the dilepton system. The leading lepton and the hardest $\tilde{\chi}_1^0$ will most likely back-to-back, E_T^{miss} (which will point towards the hardest $\tilde{\chi}_1^0$) is expected to be well separated from the leading lepton
$\Delta\phi_{E_T^{\text{miss}},\ell_1}$	The azimuthal angular separation between E_T^{miss} and the leading lepton. Momentum conservation implies that the hardest $\tilde{\chi}_1^0$ and the subleading lepton come from the same slepton, therefore the E_T^{miss} (pointing towards the hardest of $\tilde{\chi}_1^0$) is expected to be well separated from the $p_T^{\ell_1}$ direction

Variable definitions

<table>
<tr><th>Variable</th><th>Definition</th></tr>
<tr><td>$p_{T,\mathrm{boost}}^{\ell\ell}$</td><td>The module of the vectorial sum of the p_T of the two leptons and the E_T^{miss}. Since the final state consists fo two leptons and two $\widetilde{\chi}_1^0$, the vectorial sum of the system is expected to have low values due to the p_T balance of the system</td></tr>
<tr><td>$\cos\theta_{\ell\ell}^*$</td><td>It is defined as,
$$\cos\theta_{\ell\ell}^* = \cos(2\tan^{-1} e^{\Delta\eta_{\ell\ell}/2}) = \tanh(\Delta\eta_{\ell\ell}/2).$$
It is sensitive to the spin of the produced particles. Being sleptons scalar particles, their cross section is proportional to $\sin^2\theta^*$, where θ^* is the polar angle between the incoming quark in one of the protons and produced slepton. For spin 1 particles or spin half particles, the cross section behaves differently. Since θ^* is not directly accesible at the LHC, $\cos\theta_{\ell\ell}^*$ is built in such a way to capture the rapidity from the lepton parents.</td></tr>
<tr><td>m_{T2}</td><td>The stransverse mass m_{T2} which is a kinematic variable used to bound the masses of a pair of particles that are assumed to have each decayed into one visible and one invisible particle, it is defined,
$$m_{T2}^{m_\chi}(\mathbf{p}_{T,1}, \mathbf{p}_{T,2}, \mathbf{p}_T^{\mathrm{miss}}) = \min_{\mathbf{q}_{T,1}+\mathbf{q}_{T,2}=\mathbf{p}_T^{\mathrm{miss}}} \left\{ \max[\, m_T(\mathbf{p}_{T,1}, \mathbf{q}_{T,1}; m_\chi), m_T(\mathbf{p}_{T,2}, \mathbf{q}_{T,2}; m_\chi)\,] \right\},$$
where m_{T} indicates the *transverse mass*, defined as,
$$m_T(p_T, q_T, m_\chi) = \sqrt{m_\ell^2 + m_\chi^2 + 2\left(E_T^\ell E_T^q - \mathbf{p}_T \mathbf{q}_T\right)}.$$
$\mathbf{p}_{T,1}$ and $\mathbf{p}_{T,2}$ are the transverse-momentum vectors of the two leptons, and $\mathbf{q}_{T,1}$, $\mathbf{q}_{T,2}$ are vectors with $\mathbf{p}_T^{\mathrm{miss}} = \mathbf{q}_{T,1} + \mathbf{q}_{T,2}$ and m_χ is the mass of the invisible particle.</td></tr>
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The Stransverse mass

- The stransverse mass is defined as:

$$m_{T2}^{m_\chi}(\mathbf{p}_{T,1}, \mathbf{p}_{T,2}, \mathbf{p}_T^{\text{miss}}) = \min_{\mathbf{q}_{T,1}+\mathbf{q}_{T,2}=\mathbf{p}_T^{\text{miss}}} \left\{ \max[\, m_T(\mathbf{p}_{T,1}, \mathbf{q}_{T,1}; m_\chi), m_T(\mathbf{p}_{T,2}, \mathbf{q}_{T,2}; m_\chi)\,] \right\}$$

- If $m_\chi = m_{\text{inv}}$ the value of m_{T2} has a kinematic endpoint at the mass of the mother particle
- When the mass hypothesis is chosen, the distributions have an endpoint at $m_{\tilde{\ell}}$
- For the wrong mass assumption the endpoint is located at $\sim m_{inv} + \Delta m$
- By dividing the SR in bins of m_{T2}, sensitivity to a variety of slepton masses and mass splittings can be achieved

Control Region for κ factor

- κ factor extracted from a CR which has:
  - ✓ The E_T^{miss} significance cut is relaxed:

    E_T^{miss} significance > 6
  - ✓ p_{T,ℓ_1} is relaxed to capture dependencies for κ and α:

    $p_{T,\ell_1} > 30$ GeV
  - ✓ $\cos\theta^*_{\ell\ell}$ inverted, to make CR be orthogonal to SR:

    $\cos\theta^*_{\ell\ell} > 0.2$

Variable	Cut
$n_{jets-20}$	< 2
$N_{\text{OS leptons}}$	$= 2$
p_{T,ℓ_1}	> 30 GeV
p_{T,ℓ_2}	> 9 GeV
E_T^{miss} significance	> 6
$\cos\theta^*_{\ell\ell}$	> 0.2

- κ computed in different η regions $\rightarrow$ the reconstruction efficiencies can depend on the η region where the leptons reach the detector:
  - ✓ **Barrel**: κ tends to be lower $\rightarrow$ muons lack of coverage
  - ✓ **Endcaps**: κ increases $\rightarrow$ higher muon reconstruction efficiency
  - ✓ Dependency with p_{T,ℓ_1} observed for both data and MC:

$$\kappa(p_{T,\ell_1}) = b + \frac{a}{p_{T,\ell_1}}$$

	MC (FS)	Data
κ	1.1576 ± 0.0014	1.1942 ± 0.0043
$\kappa^{bar-bar}$	1.0352 ± 0.0029	1.0655 ± 0.0089
$\kappa^{end-end}$	1.38526 ± 0.0042	1.440 ± 0.010
$\kappa^{bar-end}$	1.1947 ± 0.0020	1.2198 ± 0.0061

Control Region for α factor

- Assess of the trigger efficiencies for the *ee*, $\mu\mu$ and $e\mu$ channels

$$\varepsilon^{trig} = \frac{N^{\text{METtrig and singlepTrig}}}{N^{\text{METtrig}}}$$

Variable	Cut
$n_{jets-20}$	< 2
$N_{\text{OS leptons}}$	$= 2$
p_{T,ℓ_1}	> 30 GeV
p_{T,ℓ_2}	> 20 GeV
E_T^{miss}	> 230 GeV
$m_{\ell\ell}$	> 11 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	> 15 GeV

- These efficiencies are computed in a CR:
  - ✓ The jet selection is relaxed and the b-jet veto removed
  - ✓ For ensuring to be in the METtrig efficiency plateau:

    $E_T^{miss} > 230$ GeV
  - ✓ For ensuring to be in the single lepton efficiency plateau:

    $p_{T,\ell_1} > 30$ GeV
- Trigger efficiencies: similar behavior observed for both data and MC $\rightarrow$ MC/data good agreement
- α factor $\rightarrow$ differences between data and MC stay around 1%

	MC	Data
ε_{ee}^{trig}	0.9915 ± 0.0019	0.9945 ± 0.0039
$\varepsilon_{\mu\mu}^{trig}$	0.9791 ± 0.0027	0.9803 ± 0.0080
$\varepsilon_{e\mu}^{trig}$	0.9879 ± 0.0012	0.9865 ± 0.0045
α	0.9973 ± 0.0021	$1.0008^{+0.0062}_{-0.0093}$
$\alpha^{bar-bar}$	0.9968 ± 0.0035	$1.006^{+0.007}_{-0.016}$
$\alpha^{end-end}$	0.9902 ± 0.0048	$1.010^{+0.018}_{-0.037}$
$\alpha^{bar-end}$	0.9996 ± 0.0031	$0.992^{+0.010}_{-0.018}$