Low energy leptons in High energy physics

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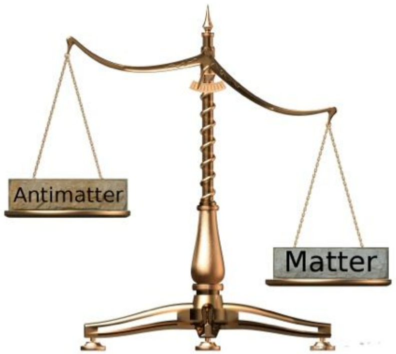
Zurich PhD Seminar

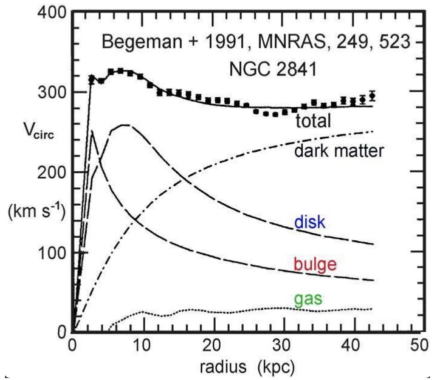
The Standard Model is <u>incomplete</u>

Despite its extraordinary success, we have some problems!

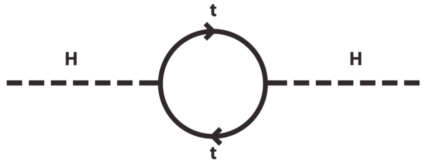
Baryon asymmetry problem



Dark matter problem



Hierarchy problem



m_H → m_{planck}

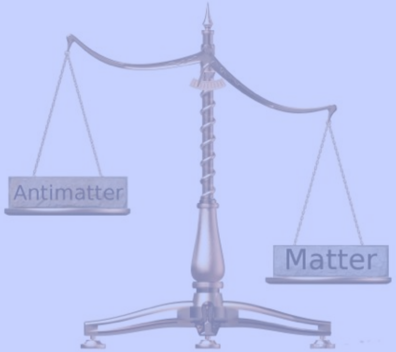
$\sim 10^2$ GeV $\sim 10^{19}$ GeV

And many more questions left unanswered…

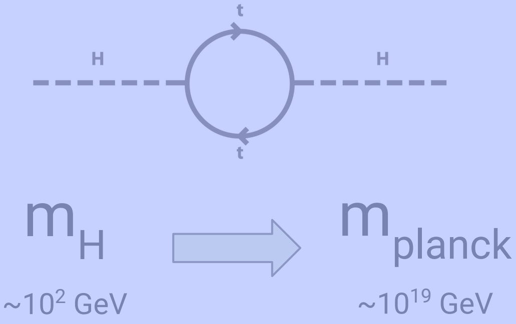
The Standard M

Despite its extraordina

Baryon asymmetry problem



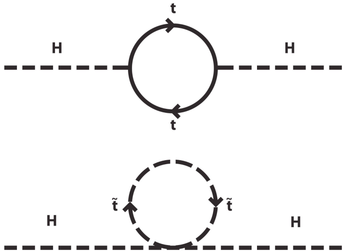
Hierarchy problem

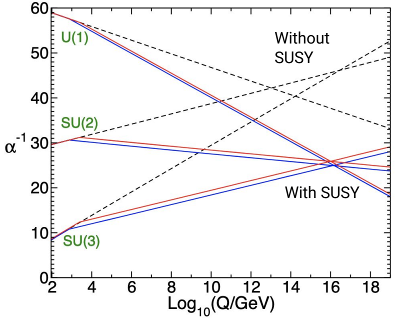


And many more questi

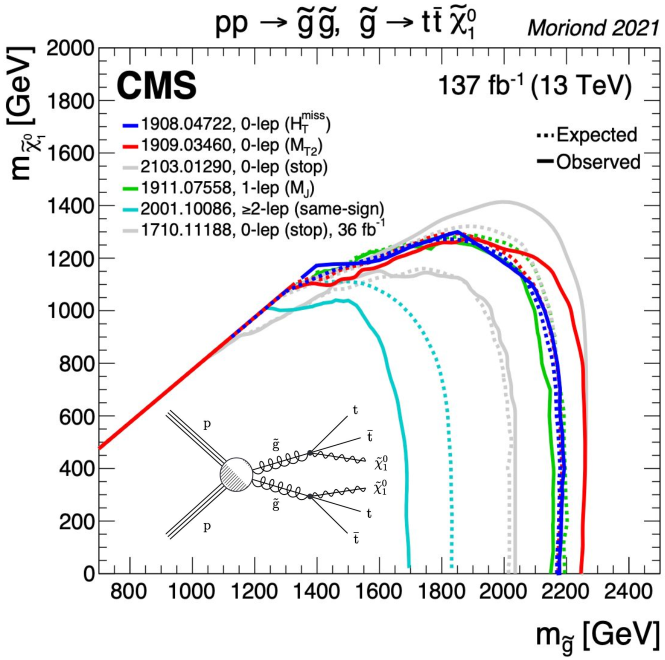
Supersymmetry still a main contender!

- SUSY still a key contender for New Physics
  - **Can solve Hierarchy problem**
    by canceling loop-corrections to the Higgs mass
  - **Can provide Dark Matter candidates**
    via a stable Lightest Supersymmetric Particle (LSP)
  - **Can predict Grand Unification**
    via new gauge interactions that are spontaneously broken at high energies
- Boosted interest by recent theory/experimental results (W-mass [1], muon g-2 [2])



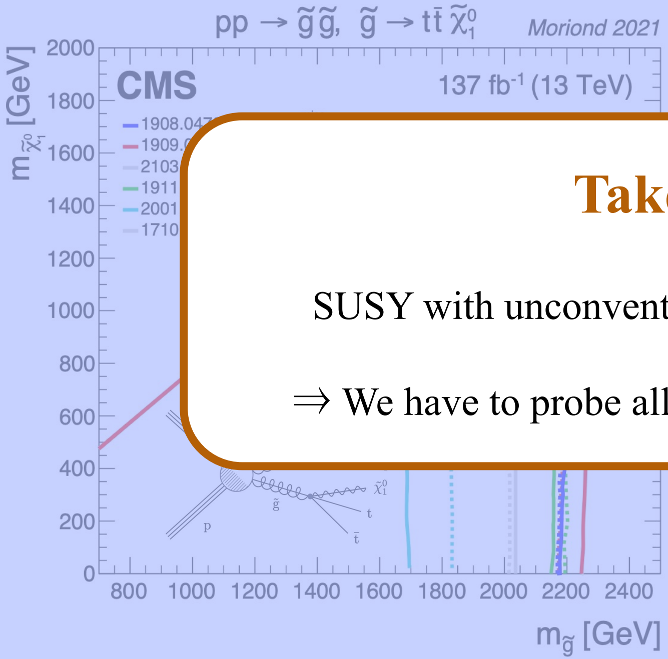


But no hint of Supersymmetry… **YET!**



- LHC most powerful tool to search for Supersymmetry
- Traditional search strategy:
  - Final states with **high p_T^{miss}** and **high p_T^{vis}**
  - "*Didn't find it? Then it must be at even higher energy!*"
- But **Supersymmetry with unconventional signatures** could have been missed!
  - Compressed mass-spectra, Long-lived particles, etc.

But no hint of Supersymmetry… **YET!**



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…h p_T^{vis}

…ven higher energy!"

…**al signatures** could have been missed!

  - Compressed mass-spectra, Long-lived particles, etc.

Take-home message:

SUSY with unconventional signatures could have been missed!

⇒ We have to probe all phase-space where SUSY may still reside

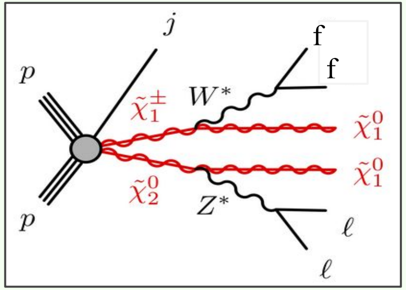
My PhD project(s): **Low energy (=soft) leptons**

Typically $3<p_T<30$ GeV

Data-analysis

Mass-Compressed, long-lived SUSY

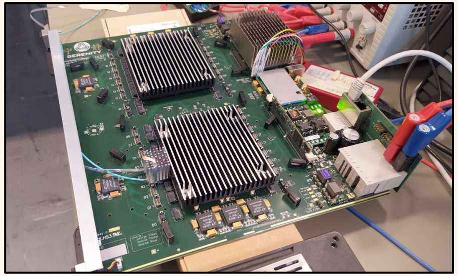
Search for Supersymmetry in final states with (displaced) **soft leptons**



Detector development

CMS Level 1 Trigger for Phase 2

Development and implementation of trigger algorithms targeting **soft electrons**

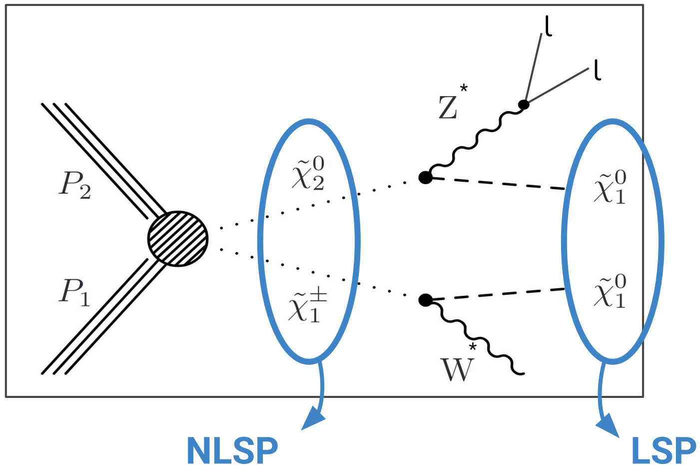


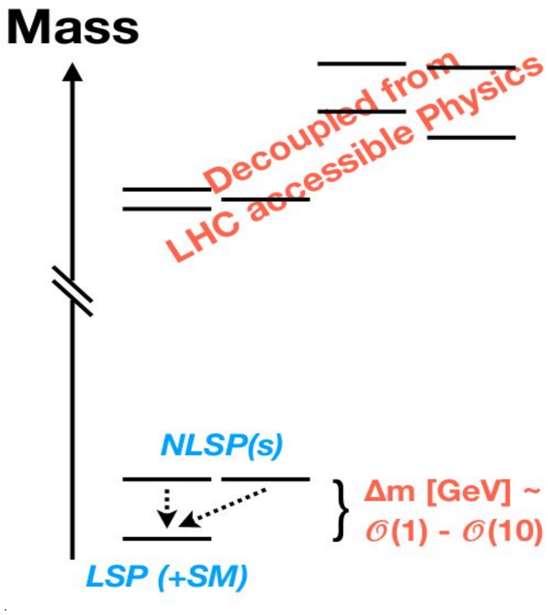
Search for mass-compressed electro-weakinos

Mass-compressed Electro-weakinos

- Challenging SUSY phase-space, that is barely probed
  $\Rightarrow$ Small signal acceptance, statistically limited searches

- Theoretically appealing (Bino-Wino cohanniliation, naturalness)





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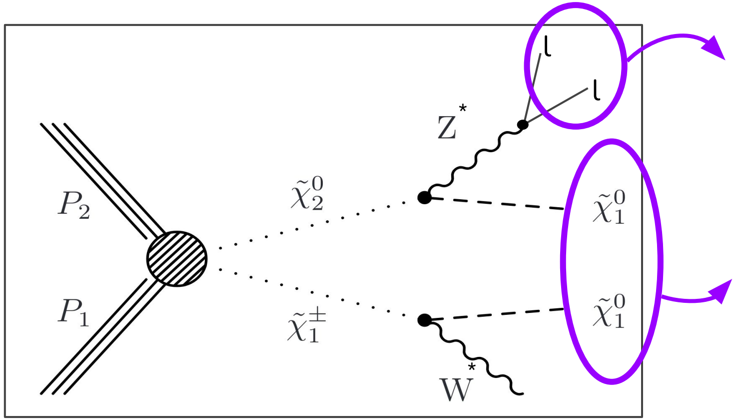

Soft (>3.5 GeV) leptons from off-shell vector bosons

Low p_T^{miss} from stable, undetected LSP

Unconventional signature, without handle to select these event online!

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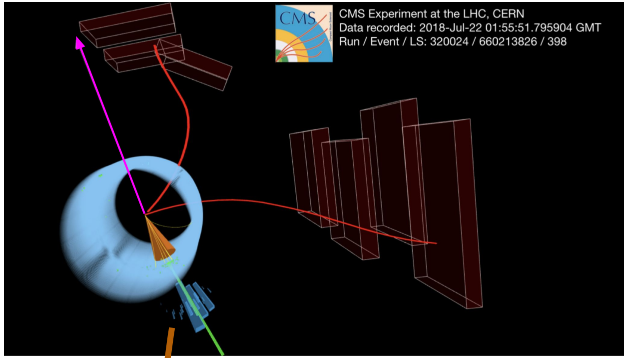

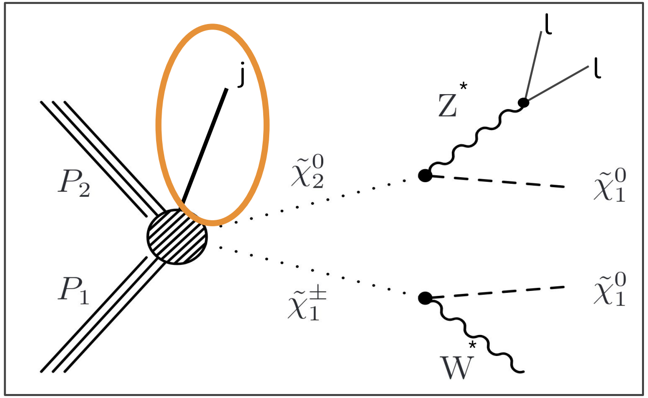

Require a **jet from initial-state radiation** to boost the sparticle pair. Allows usage of triggers based on p_T^{miss}:

p_T^{miss} > 200 GeV

Also designed our own trigger*:

p_T^{miss} > 120 GeV & μμ (p_T > 3 GeV)

*And also a p_T^{miss} + ee trigger is being developed for Phase-2, based on my low work on p_T electron triggers (see backup)

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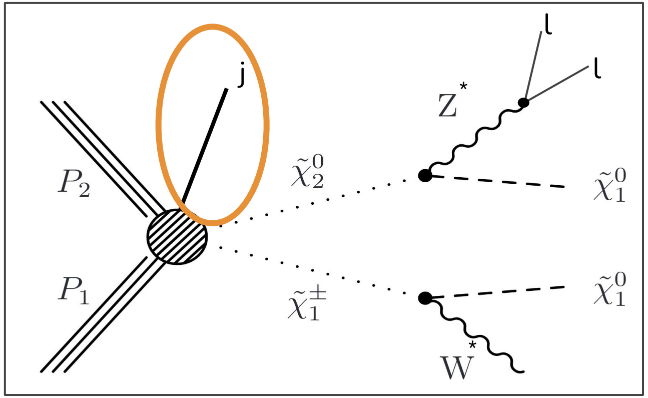

But this drastically **reduces signal cross-section**…

We are chasing very rare events!

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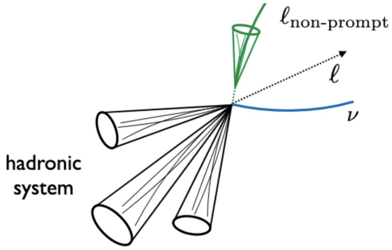
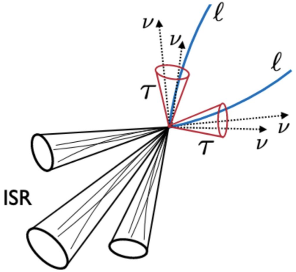
Main backgrounds



W+jets (b-jets) bkg



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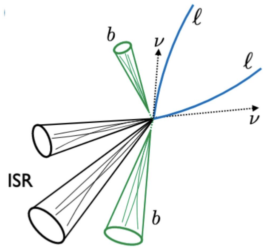
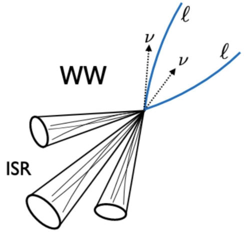
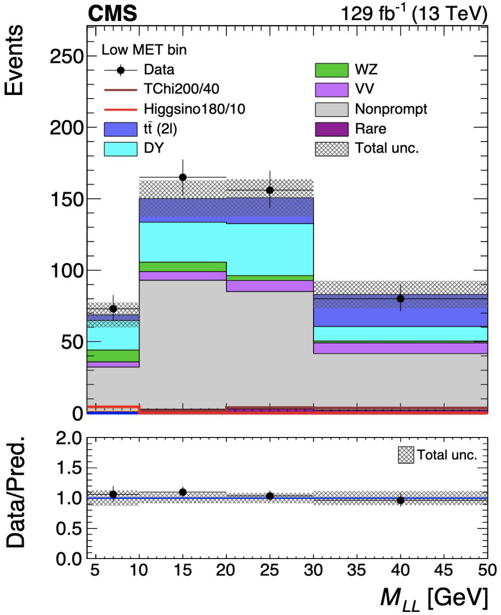


Top background: tt

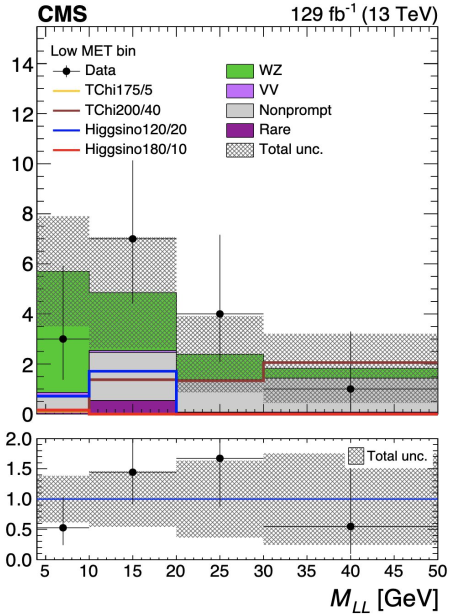


Diboson: VV, WZ

2L signal region
(Low p_T^{miss} bin)



3L signal region
(Low p_T^{miss} bin)



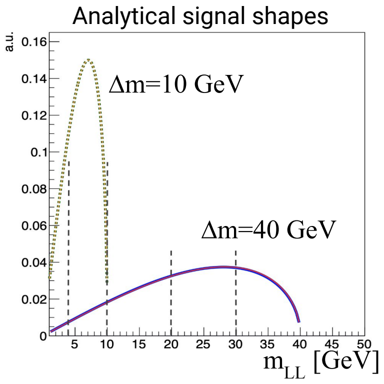
Estimation of background contributions in SR:
⇒ **Prompt bkg**: Dedicated CR or directly from MC
⇒ **Non-prompt bkg**: Tight-to-loose method (fake rate)

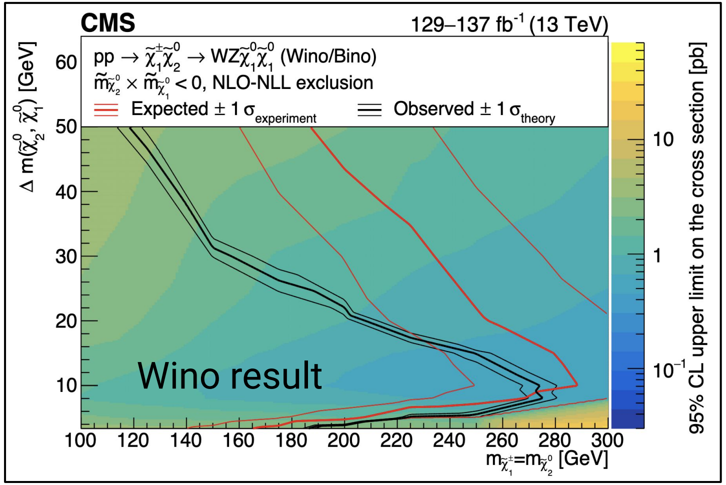
Limits on signal cross-sections

- Likelihood fit binned in $\mathbf{p_T^{miss}}$ **and** $\mathbf{m_{LL}}$
  - m_{LL} as proxy for Δm (NLSP, LSP) $\Rightarrow$ Good discriminator
  - Recently optimized binnings for each mass-hypothesis
    → Up to 30% increased sensitivity at low Δm

- Published in 2022:
  - Winos excluded up to 275 GeV at Δm=10 GeV
  - Higgsinos excluded up to 205 GeV at Δm=7.5 GeV

- Still statistically limited:
  → Expecting 70 GeV extension by adding Run 3 lumi (~300 fb^{-1})





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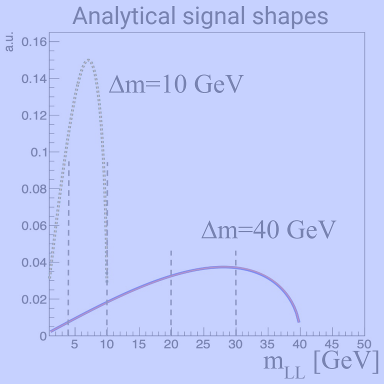
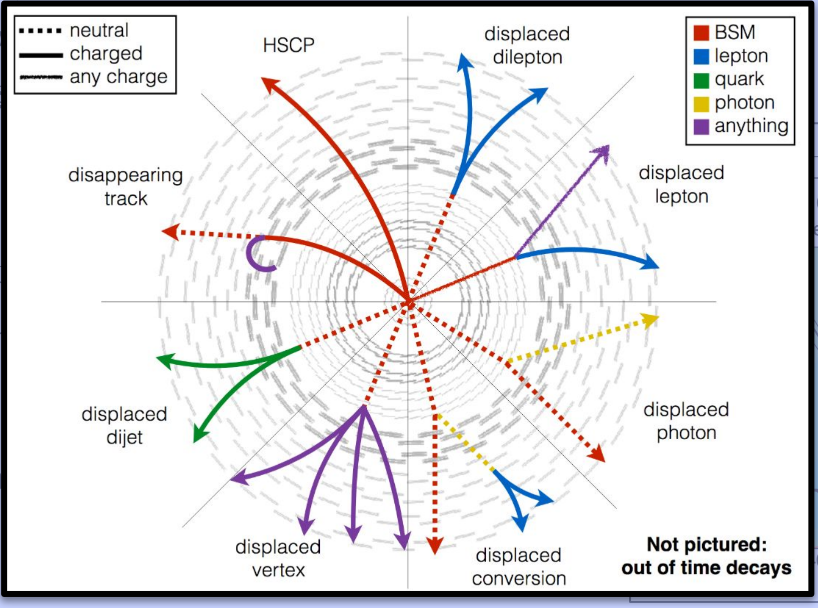
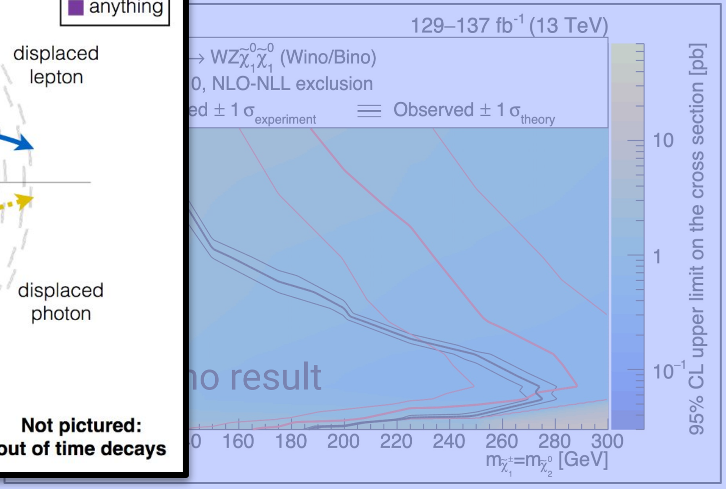


So is that it then?

NO! Many more signatures to explore

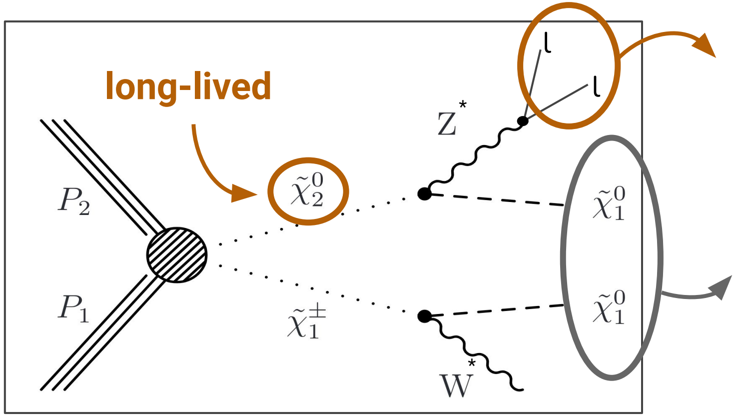




Analysis extension: **Long-lived states**

- Dominant background was from non-prompt leptons
  - Applied **tight cuts** on lepton **provenance from the primary vertex**
    → *We are blind to long-lived NP states*!

- **Aim for this year**: Target **long-lived NP scenarios** with **soft displaced muons** in the final state
  - Predicted by several BSM theories (e.g. Mini-split SUSY [1, 2])



Soft (>3.5 GeV) and displaced leptons from off-shell vector bosons

Low p_T^{miss} from stable, undetected LSP

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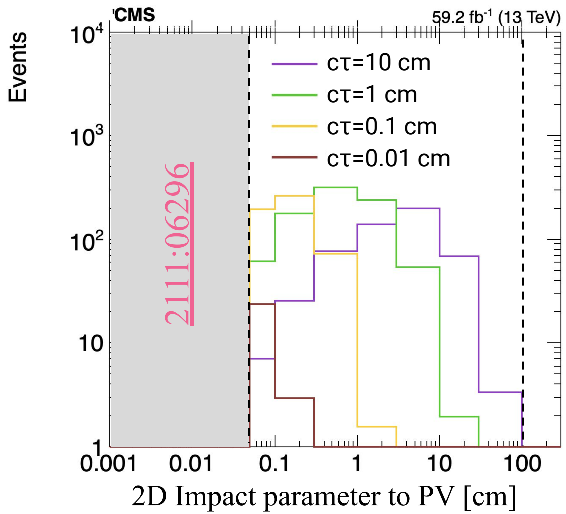
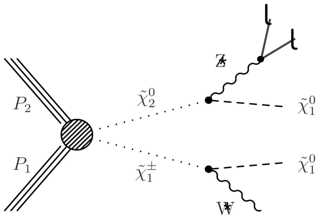
- Use muons identified by the inner Tracker and Muon Spectrometer
  - Allows for **higher reconstruction efficiency** at low p_T (3 GeV)
  - **Improves spatial resolution** of secondary vertex position

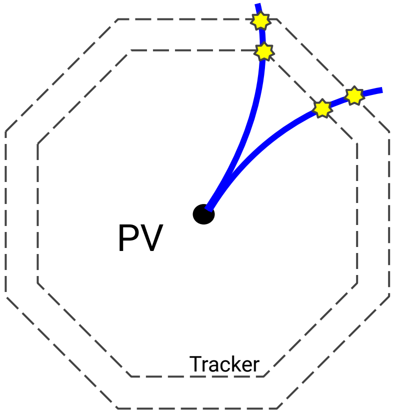
- Targeting **typical displacement** between 0.05 cm → 110 cm
  - <0.05 cm: already covered by previous "prompt" analysis
  - >110 cm : no acceptance for CMS Tracker



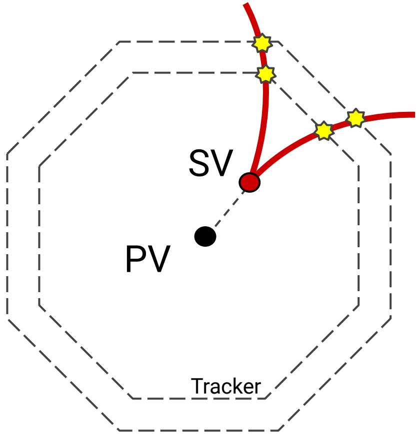
Di-muon object reconstruction



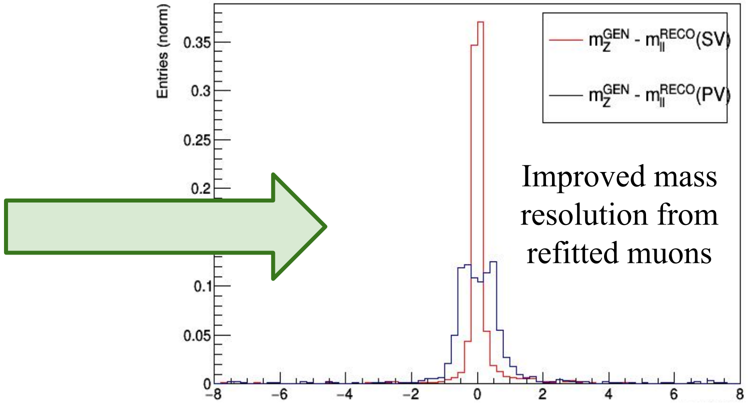
- Final state of signal includes **two displaced isolated muon tracks** from a common vertex
  - Implemented an alternative reconstruction for displaced di-muons



Standard muon tracks, fit to **primary vertex**



Two muon tracks, fit to a **common secondary vertex** (without PV as constraint)

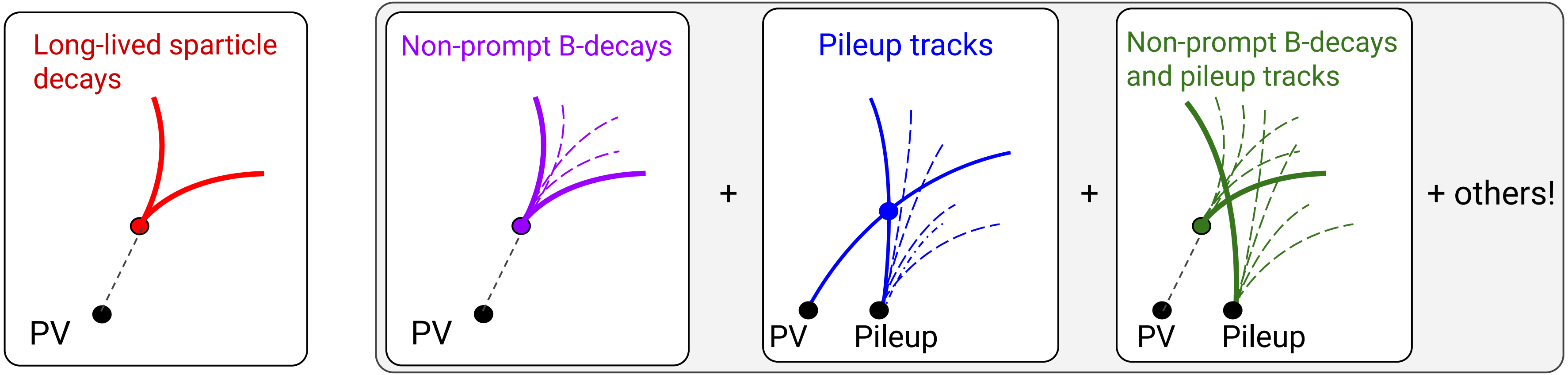


Mass resolution of long-lived signal [GeV]

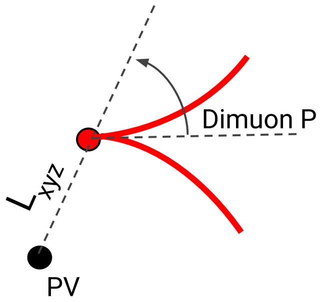
New backgrounds enter the game…

- Sources of **tricky backgrounds** processes can feature:
  - Refitted di-muons from non-prompt B-decays
  - Refitted di-muons from pileup tracks

- Tracks are less isolated. But standard Particle-Flow isolation is computed with objects originating from the PV!



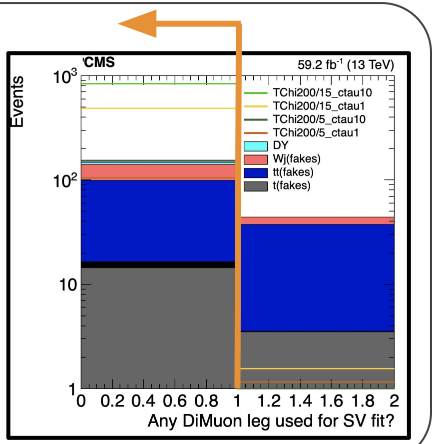
Designing the analysis



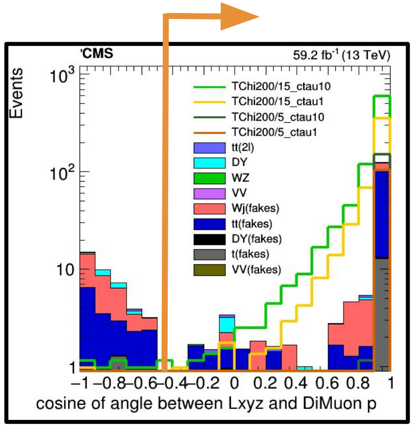
- Defining **new signal regions** based on presence of high-quality di-muon object
- Studying promising **cuts for background rejection** (still using MC for now):

Neither di-muon leg is used in a centrally reconstructed SV **compatible with B-decay**

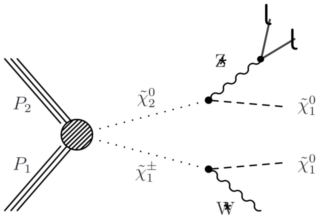
(m_{SV}<6.5 GeV, n_{Tracks}≥ 3)



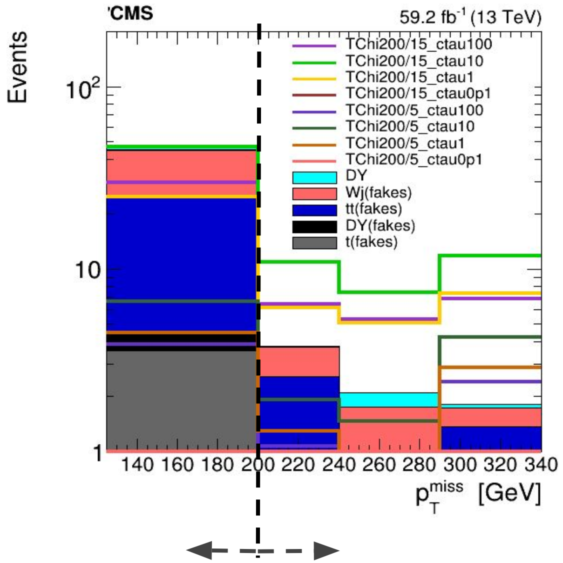
Di-muon momentum vector aligned with L_{xyz} (vector pointing from PV to di-muon vertex)



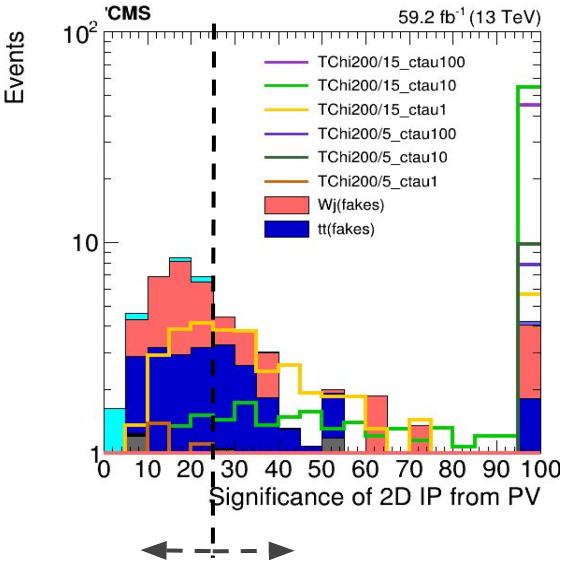
Signal regions in the making



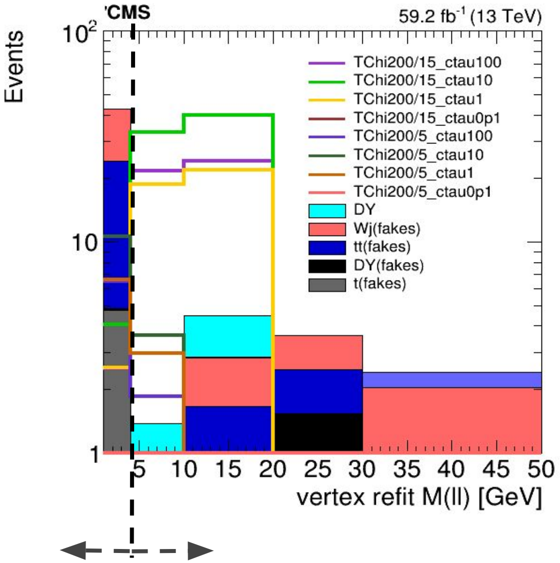
- Use same variables for SR binning as in prompt search (m_{LL}, p_T^{miss})
  - Adding displacement dimension (significance of $IP2D_{SV\text{-}PV}$)



2 p_T^{miss} bins (fixed by trigger)

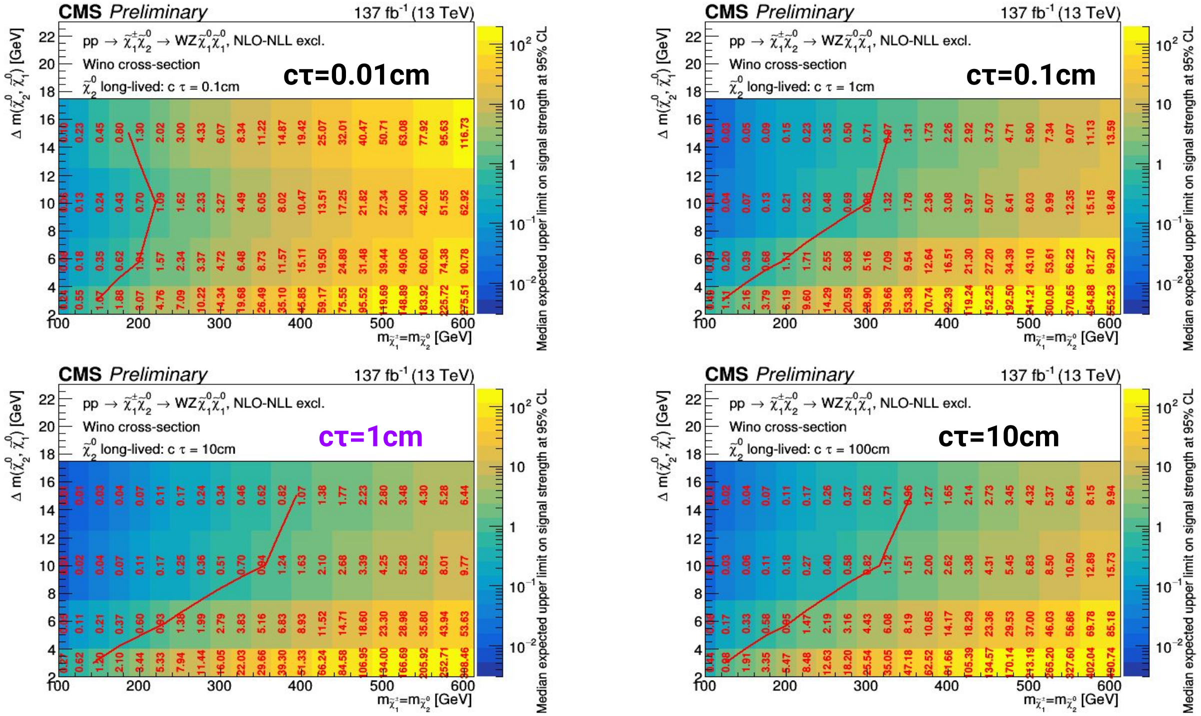


2 SIP bins (chosen by eye)



2 mll bins (low MC stat., will do more)

Preliminary upper limits*



New displaced SRs combined with prompt regions

Best sensitivity at cτ = 1cm
(+60 GeV w.r.t. prompt signal)

Note: still work in progress on many fronts!

*100% MC based, 2018 limits projected to Run 2 luminosity and m_{N2}!=200 GeV limits approximated via cross-section scaling

Summary and take-home message

- **SUSY with unconventional signatures** could have been missed!
  ⇒ We have to probe all phase-space where SUSY may still reside

- **LHC Run 3** will see many innovative searches targeting new, challenging signatures

- **My PhD project(s) aim to increase our New Physics reach by using soft leptons**
  - Search for SUSY with displaced **soft leptons**
  - CMS Phase-2 Level-1 Trigger algorithms targeting **soft electrons**

- Got you curious? Ask away!

Back-up

Electron L1T algorithms for Phase 2

- HL-LHC running conditions
- The Phase 2 Level-1 Trigger
- Current L1T algorithms for electrons
- Alternative electron trigger strategy

Phase 2 upgrade of the CMS Level-1 Trigger

- Many new physics searches are statistically limited
  - Future HL-LHC will provide ~4000 fb^{-1} due to the **much higher instantaneous luminosity**

- **Drawback:** Pile-up (PU) increased by a factor 5!

  → More particles traveling through the detector → Problem for the CMS Trigger system*

Collisions @ 40MHz → **Level 1 Trigger (L1T)** *Hardware-based* → 100 kHz → **High Level Trigger** *Software-based* → 1 kHz to data-storage

- Using the L1T algorithms of Phase 1 in the running conditions of Phase 2 would increase the rate to ~4000kHz, which is **beyond technical feasibility**

  → **Complete redesign needed to maintain Phase-1 physics acceptance in Phase-2**

*Rates correspond to the Phase 1 CMS Trigger system

Phase 2 upgrade of the CMS Level-1 Trigger

- Preliminary design of L1T for Phase 2 documented in CMS L1-Technical Design Report [1]

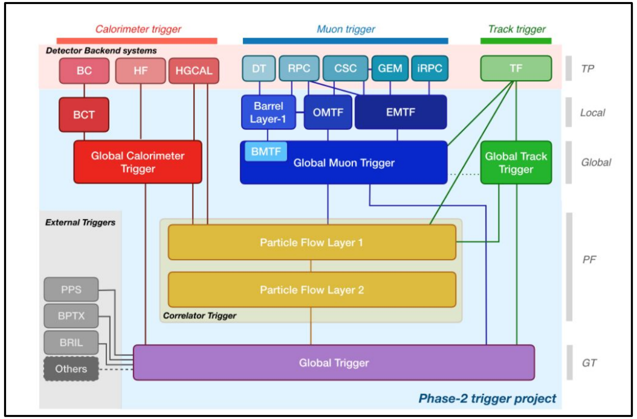
- For the first time **Tracker information** available in the L1T!
  - Precise momentum measurements
  - Reconstruction of pp collision vertices

  → Important handle for PU mitigation (rate reduction)

- **Correlator Trigger** central role in L1T design
  - Inputs from **Calorimeter**, **Muon** and **Track** trigger

    → data from multiple subsystems available on single board!

L1T design architecture



- Other upgrades:
  - Increased bandwidth (100→750kHz) and higher latency (3.8us→12.5us)
  - More FPGA processing power (Xilinx Ultrascale+ 7.5x more resources than Virtex 7 used in Phase 1)
  - Tools now available to synthesize BDTs and NNs to modern FPGAs

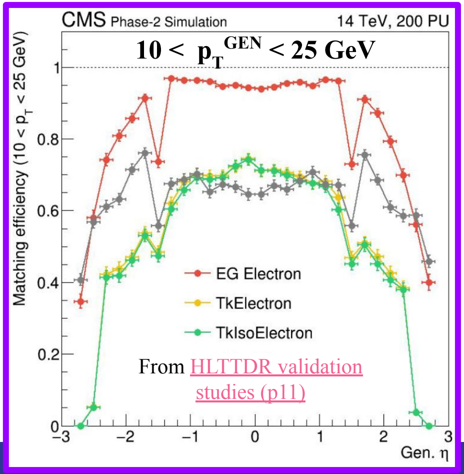
- All these upgrades allow implementation of complex "offline-like" algorithms for object identification, and the usage of ML to build more powerful discriminators

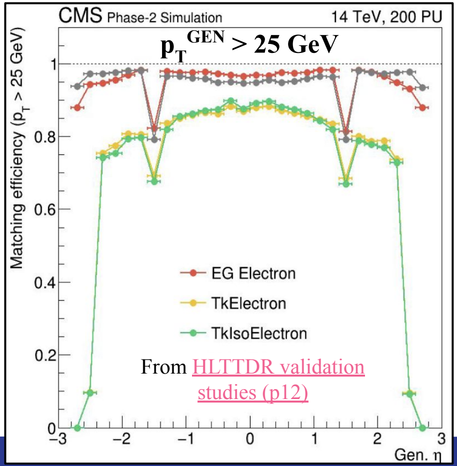
Track-matched electrons

- Crucial objects for the Phase-2 L1 Trigger
  - Only way to construct single-electron triggers for Phase 2 with Phase 1 thresholds and sustainable rates

Current flagship electron object

TkElectron = Calorimeter cluster that passes standalone EG ID (tight WP) + Track with $p_T > 10$ GeV





Cut on p_T^{track} comes with cost of decreased efficiency, especially for **soft electrons**

But loosening costs rate!

Track-matched electrons

- Crucial objects for the Phase-2 L1 Trigger
  - Only way to construct single-electron triggers for Phase 2 with Phase 1 thresholds and sustainable rates

- Developing a new "**Composite ID**" as alternative to the TkElectron
  - Aiming to recover efficiency of electrons in HGCAL, over the full p_T spectrum
  - Still using clusters matched to tracks, but with several key differences:

Standard TkElectron

- Only use tracks with **p_T > 10 GeV**
- **Tight elliptical match** of track & cluster
- MVA ID applied on **cluster only**

New Composite ID

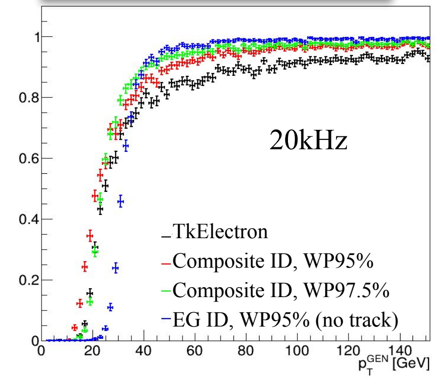
- Use tracks down to **p_T > 2 GeV**
- **Loosely match** track & cluster with dR<0.2
- MVA ID applied on **composite (track+cluster)** object
  → Tracks used as input to the ID, not for a-posteriori matching

Construct loose composite object and rely (more) on ML algorithm to control background

Preliminary results

- Composite ID being developed as alternative to the TkElectron ID
  - **Simulation studies** demonstrated high potential of Composite ID
- Trained a realistic version of the Composite ID and implemented in firmware
  - Less input features, reduced model complexity, single bit precision
  - Showed that BDT inference in firmware and in simulation are identical
  - Requires 5 clock-cycles with 3% resources (SLR) of U250 to infer BDT
- Integrated the Composite ID in the **L1T emulator**
  - **Composite ID outperforms flagship TkElectron at high p_T**
  - Still room for improvement, considering new features, NN models, etc.
- Developing also dedicated low p_T electron ID (e.g. for p_T^{miss}+ee triggers), based on the same concept!

Simulated
Composite ID (high p_T)



Simplified, emulated
Composite ID (high p_T)