Search for long-lived HNLs in leptonic final states with displaced vertices in *pp* collisions at CMS

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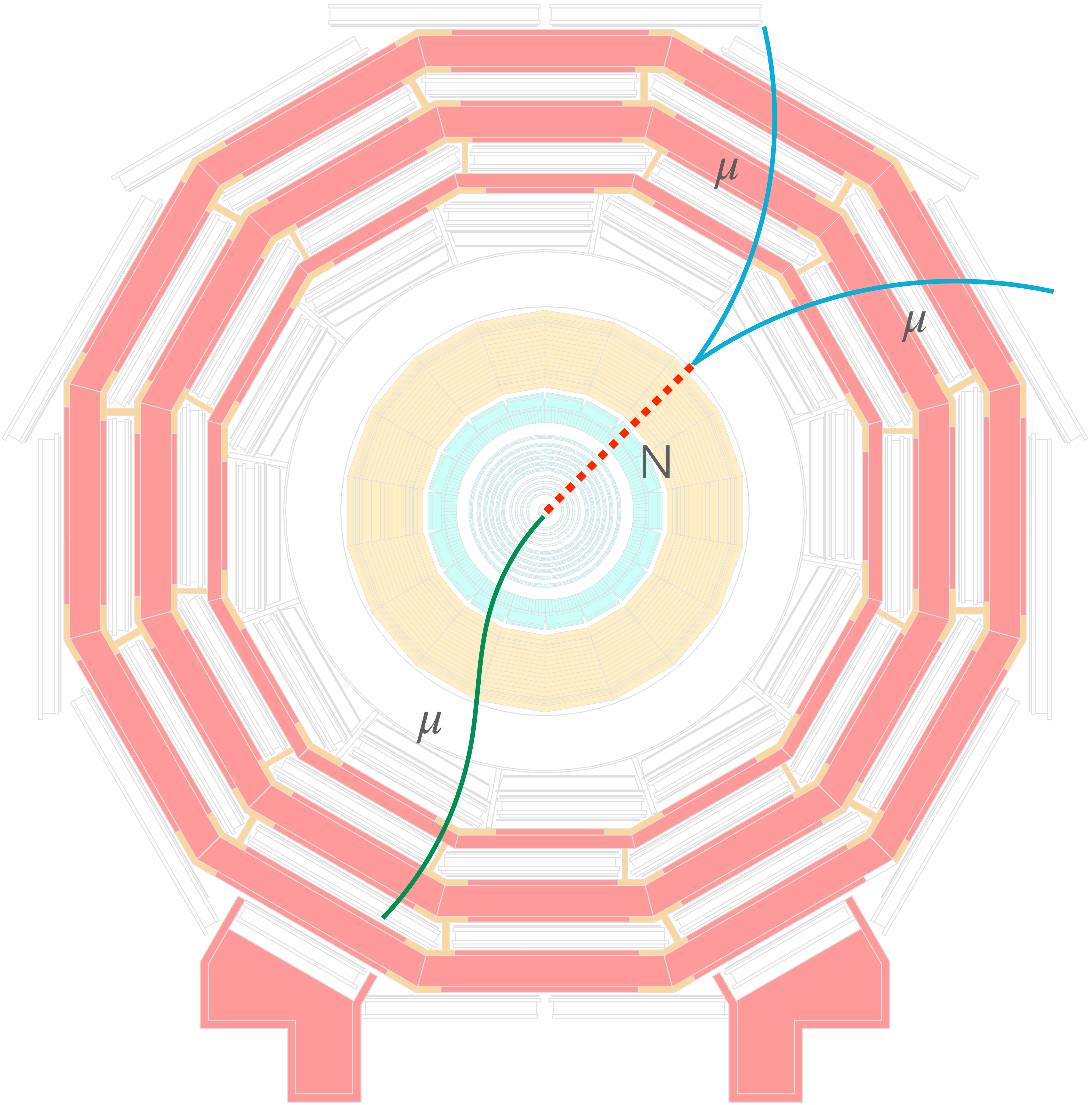
Introduction

Analysis Target

Heavy neutral leptons (HNLs) produced in the decay of a W boson, resulting in one prompt charged lepton and two displaced charged leptons, with common vertex beyond the tracker system, in the whole CMS Run 2 dataset



In this presentation

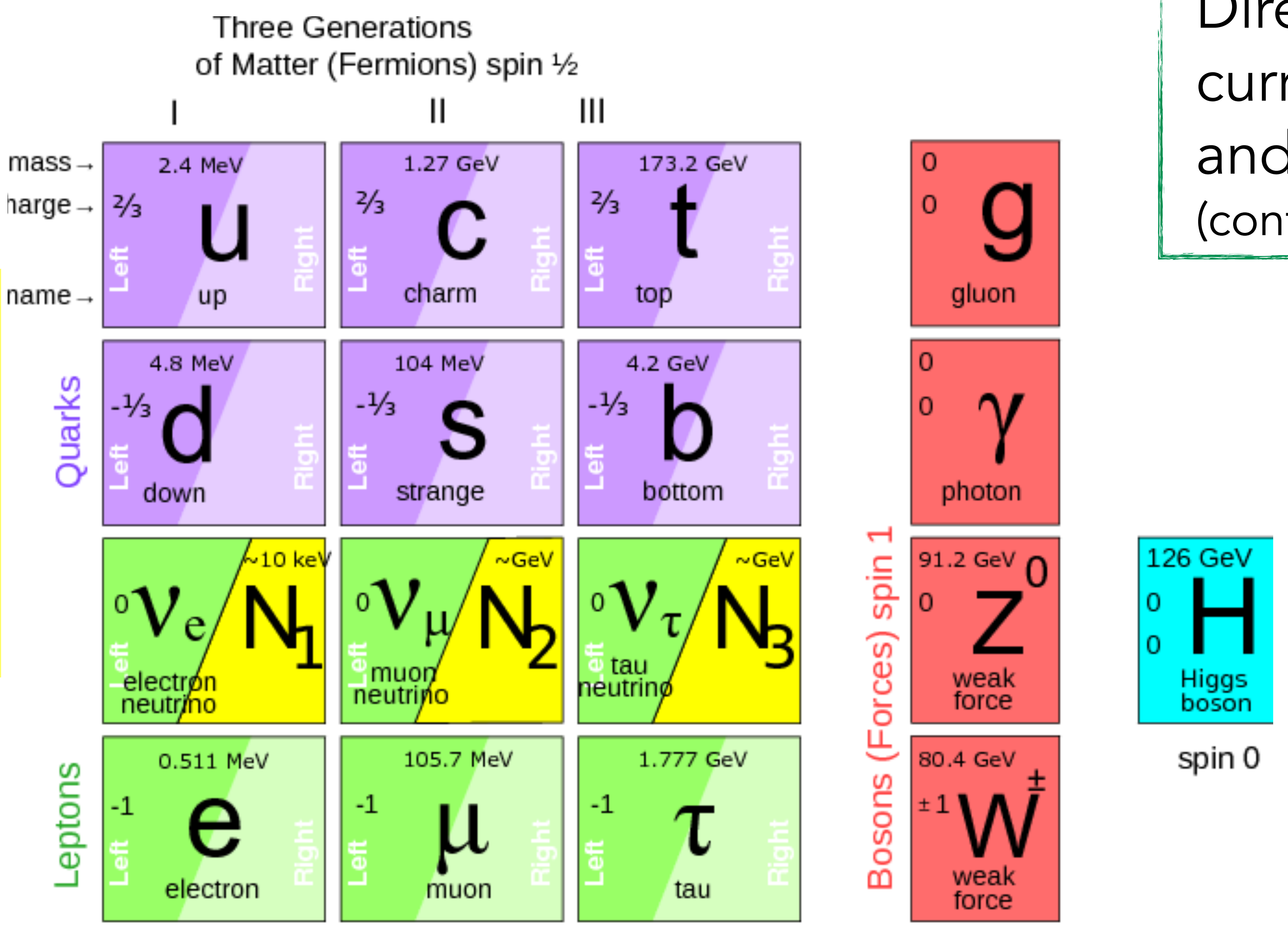
- Brief introduction to HNL theory and searches
- Probed signature and motivation
- Overview of the analysis strategy
- Study of the physics reach
- Outline of current status and future plans

The νMSM and the HNLs

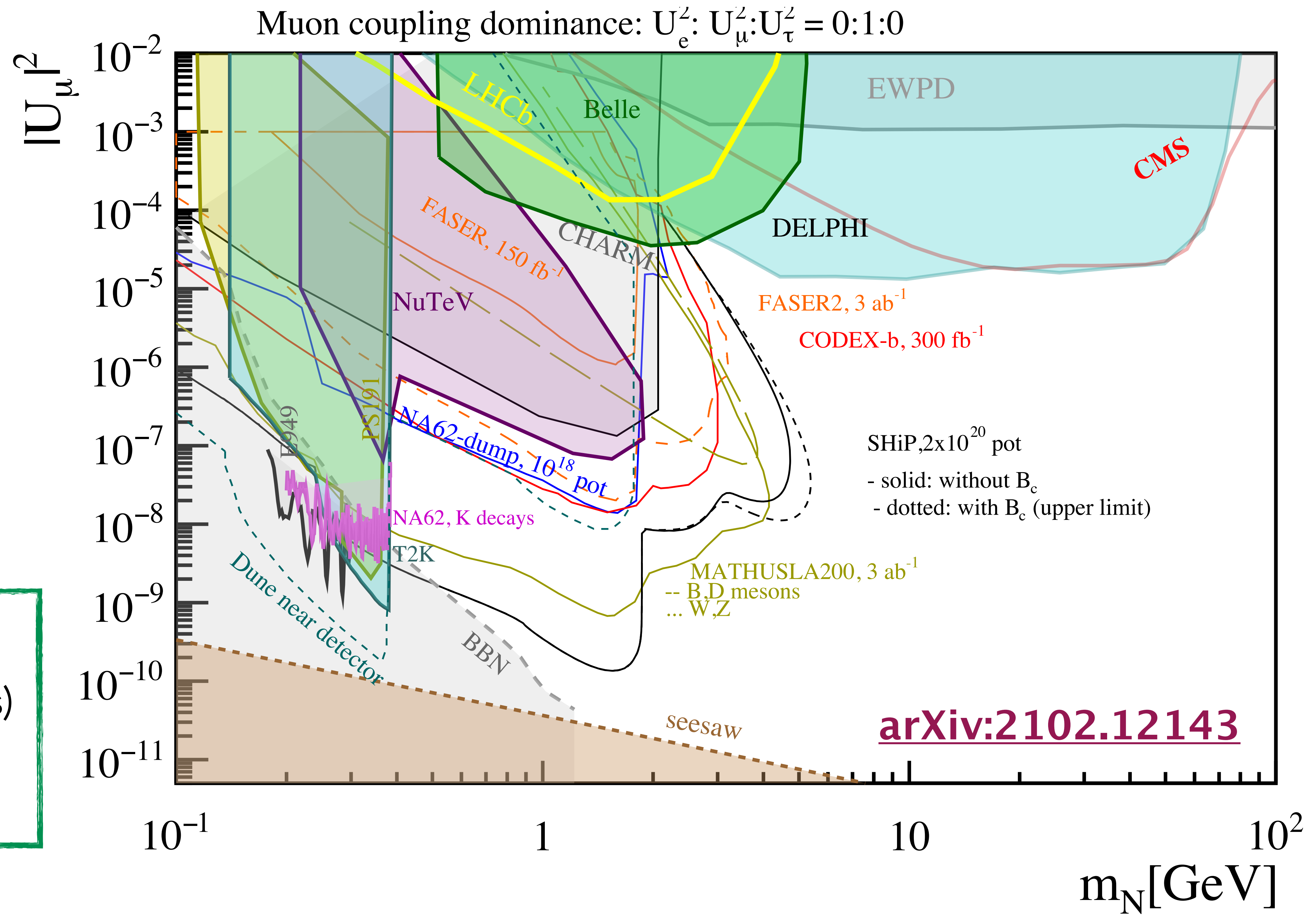
3 **right-handed** HNLs as potential solution for some of the outstanding problems of the SM:

- Origin of neutrino masses
- Anomalous mass scale for the neutrinos (allowing N to be Majorana → *Seesaw mechanism*)
- Lightest N (~ KeV range) as viable DM candidate
- Baryon asymmetry problem

Neutrino Minimal Standard Model (νMSM)



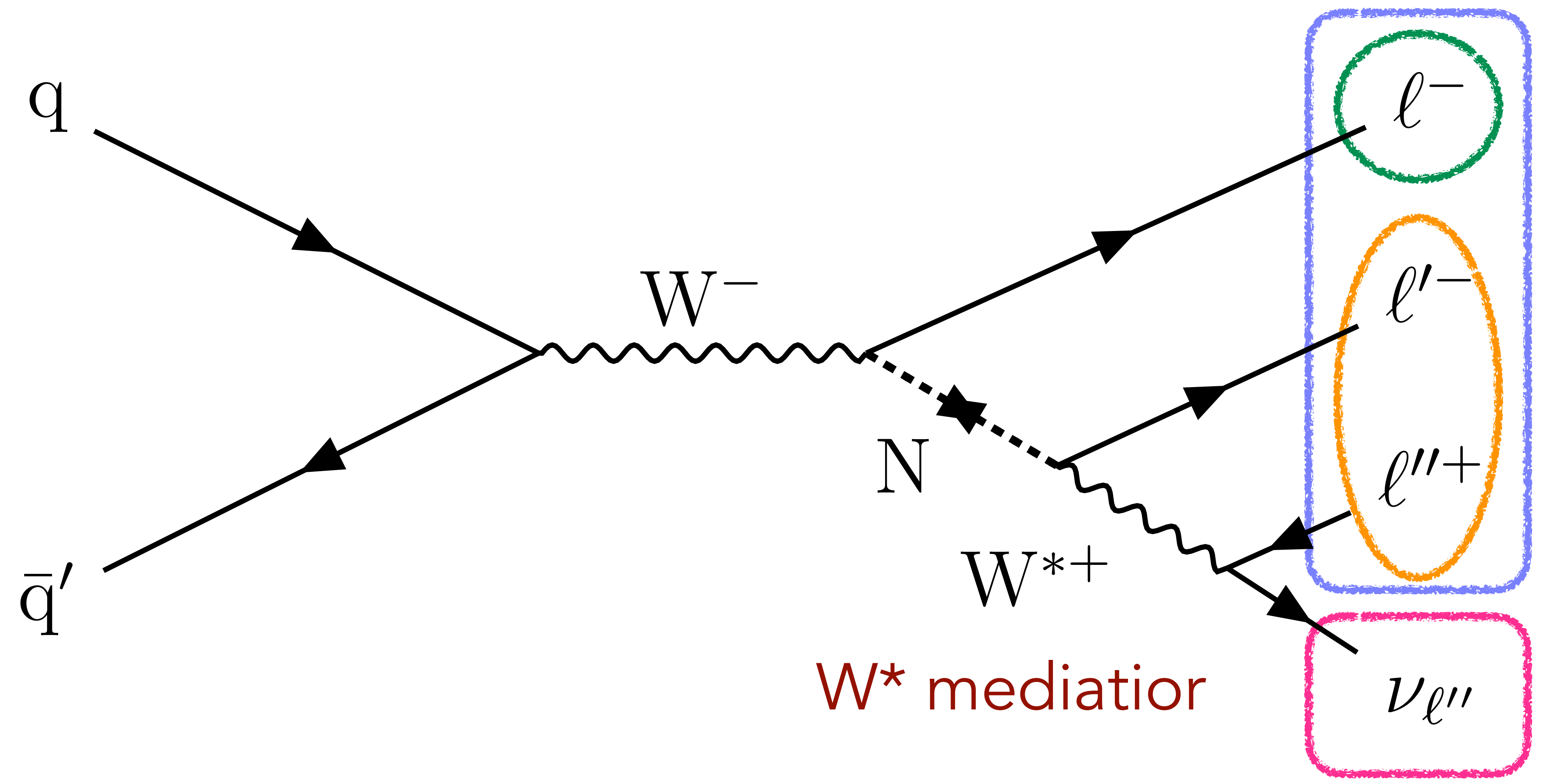
Direct searches set current limits (filled areas) and future projections (contours)

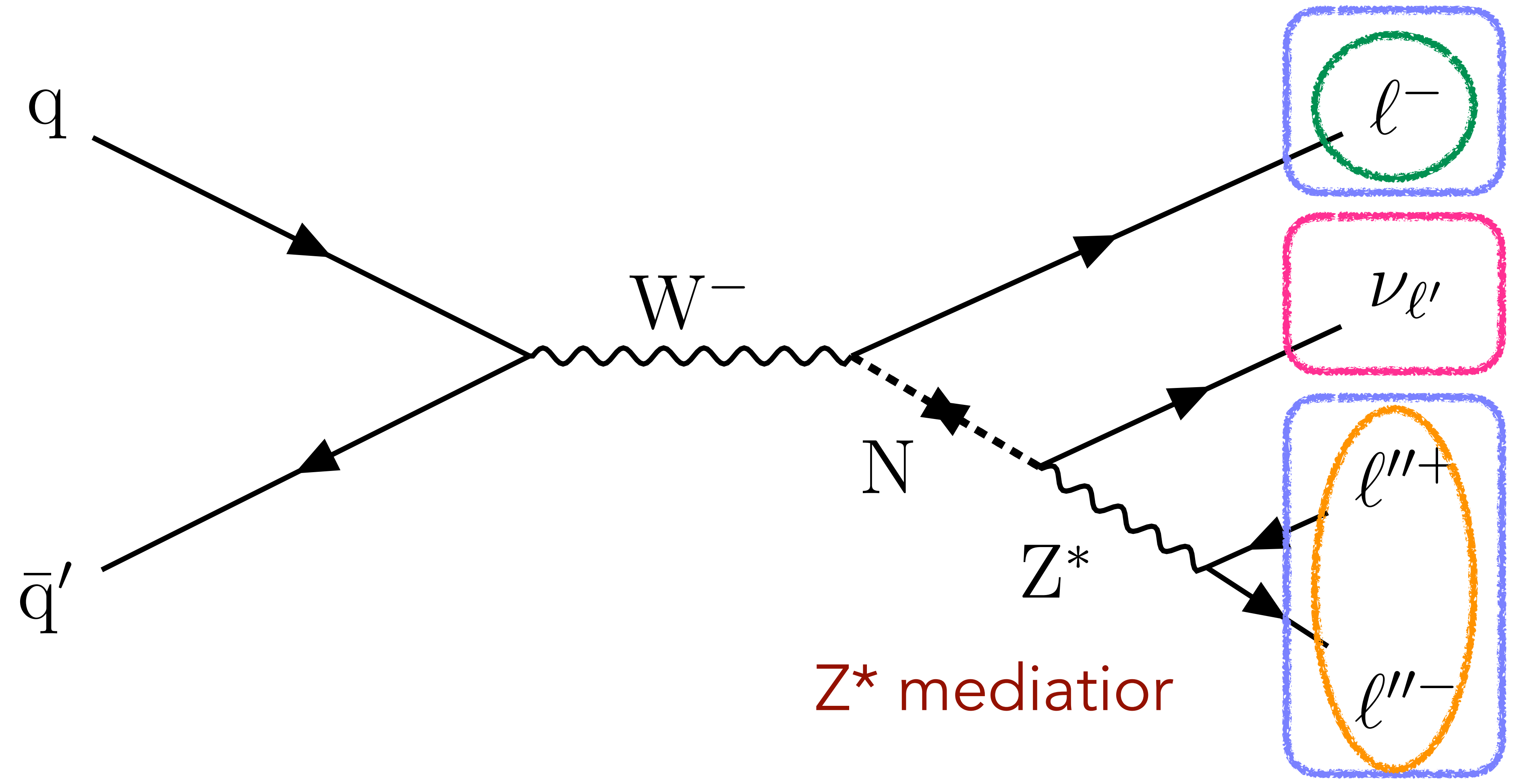


- Ns are **sterile:** only interaction through mixing with ν_{SM}
- Low production rates due to **low mixing parameters** $|V_{Nl}|^2$
- HNL production explored at colliders and beam-dump experiments

Probed Signature

HNL Production in **W Decays**





Final state:

- 3 charged leptons
- Low missing transverse momentum (no sensitivity)

For long-lived HNLs:

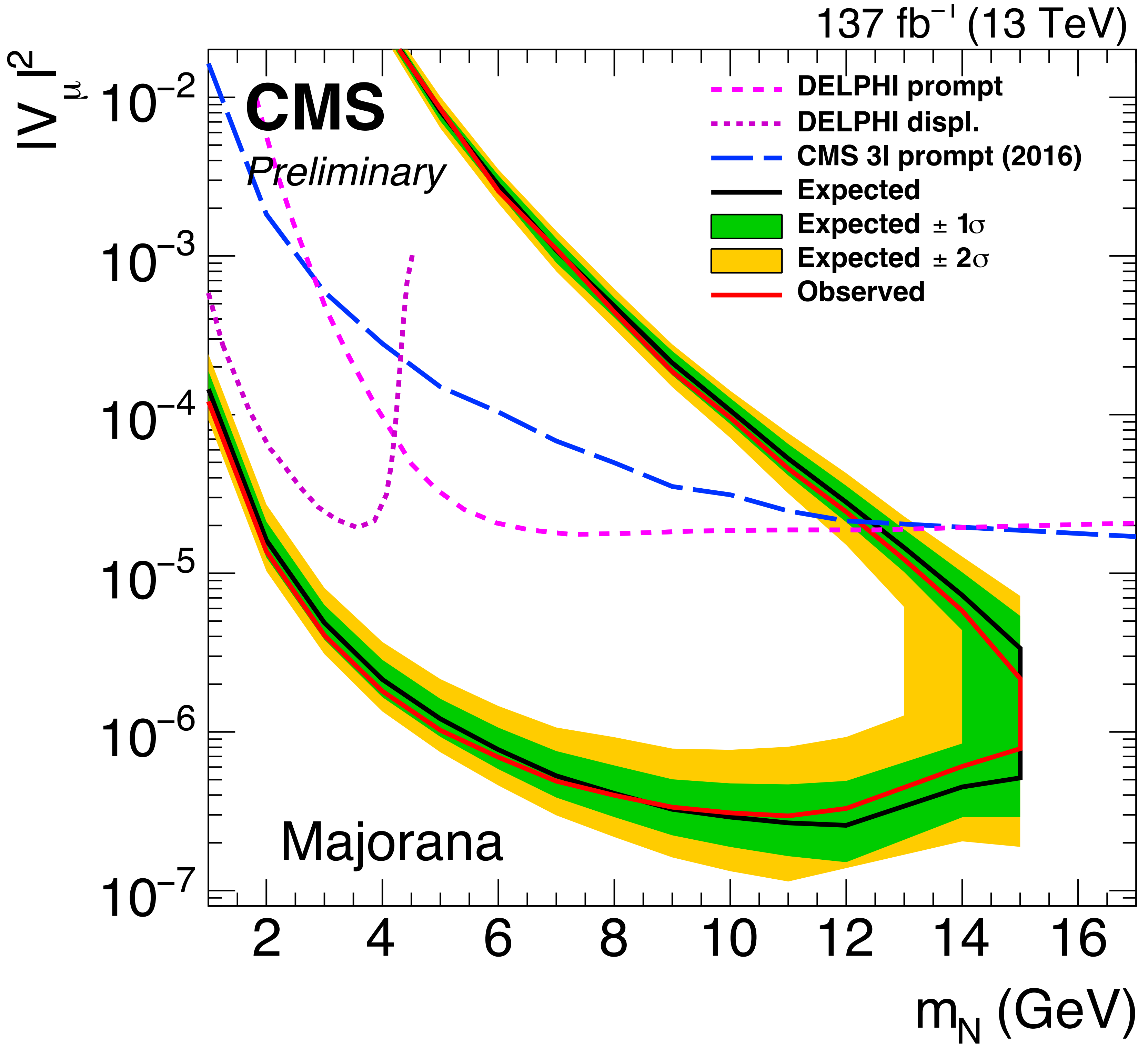
- 1 prompt-charge lepton
- 2 displaced charged leptons from same secondary vertex → Opposite electric charges

- Sensitivity to both Lepton-Number-Violating (LNV) and Lepton-Number-Conserving (LNC) signatures
- Flavour of final-state leptons depends on the mixing between HNLs and SM neutrinos
- Focus of this analysis: secondary vertices beyond the tracker system

Physics Reach

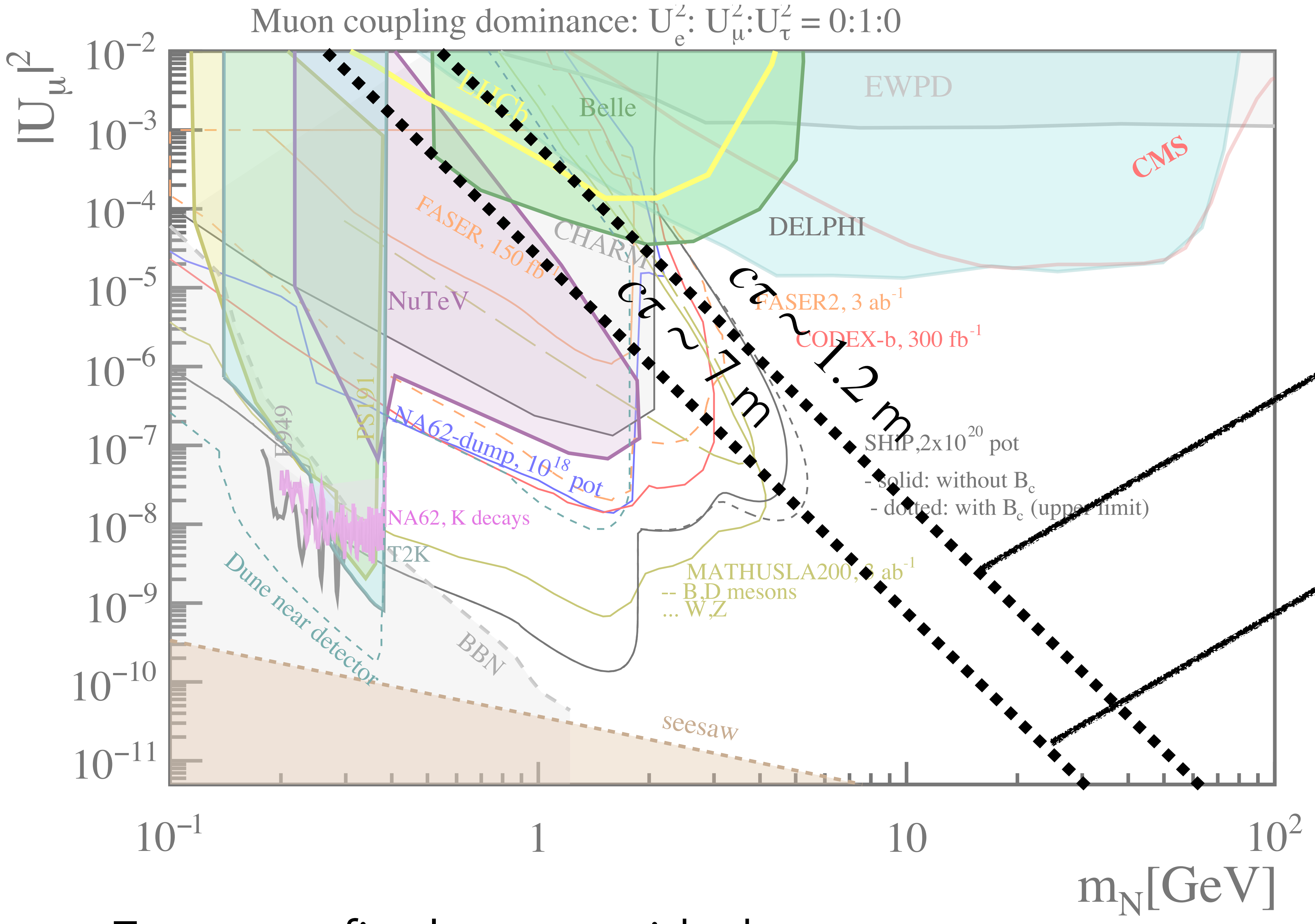
Previous CMS searches for both prompt and displaced HNL decays in final states with three charged leptons [6, 7]

CMS-PAS-EXO-20-009



Latest CMS limits for HNL searches with 3 charged leptons (electrons or muons) in the final state

Requiring secondary vertex displacement beyond the tracker system extends the sensitivity of previous CMS analyses to **lower HNL mass and coupling**



$$\tau_N \propto m_N^{-5} |V_{Nl}|^{-2}$$

End of CMS tracker system

End of CMS detector

- Focus on final states with three muons ⟶ $|V_{N\mu}|^2$
- Possible extension: prompt electron + 2 displaced muons ⟶ $|V_{Ne}|^2$

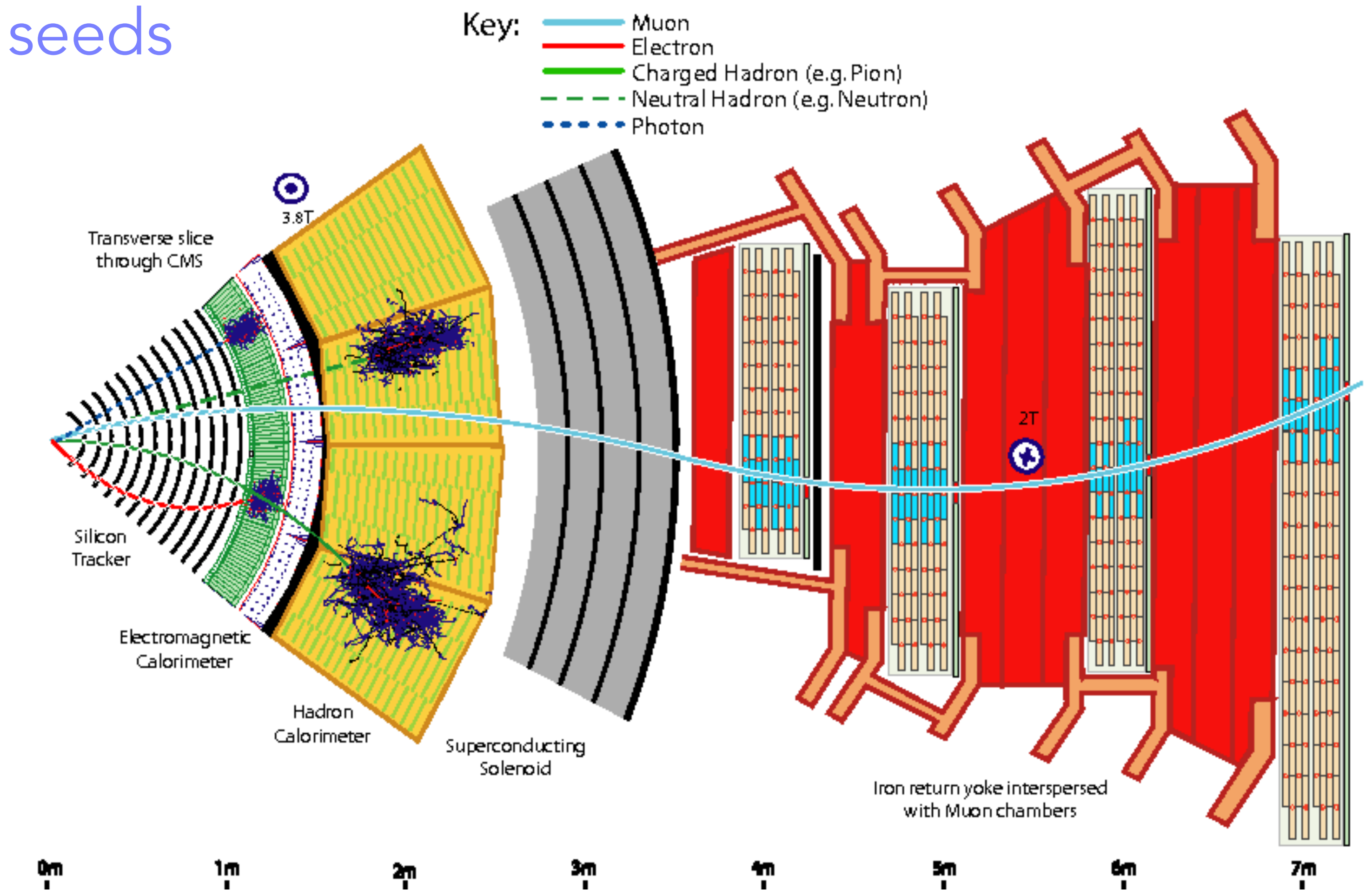
Analysis Strategy

Signal Selection

- *Event objects*:
  - 1 prompt muon ($p_T > 24$ GeV)
  - **2 Displaced STandAlone (DSA) muons** with common vertex fit

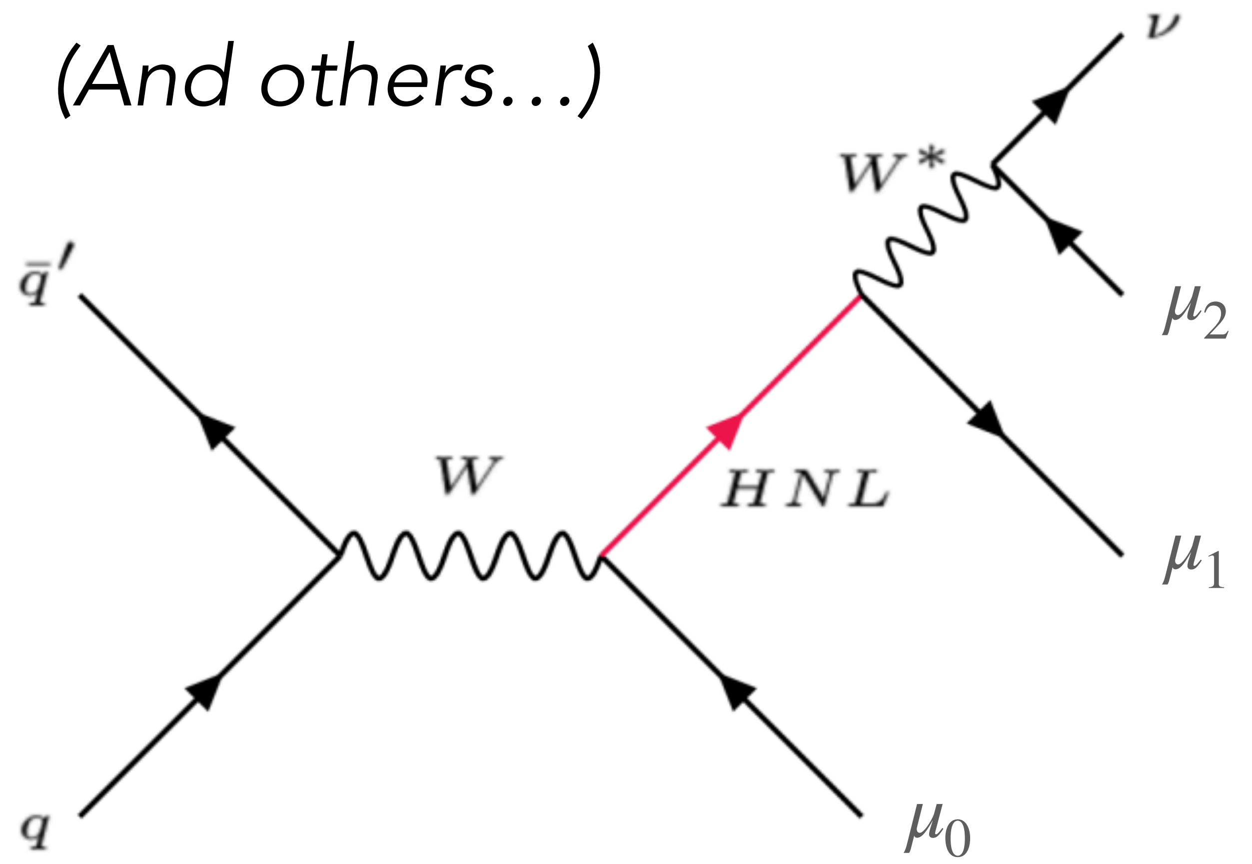
DSA muon track:

- Only hits in the muon system
- Reconstruction from cosmic seeds



- *Signal topology cuts*
  - Highly boosted HNLs:
    $\cos\theta > 0.9$
    $p_T(\mu_1 + \mu_2) > 10$ GeV
    $\Delta R(\mu_1, \mu_2) < 1$
  - Background suppression:
    Nbr(b jets) $== 0$
    Z veto: $m(\mu_1 + \mu_2) \leq 80$ GeV

(And others…)



Main challenge

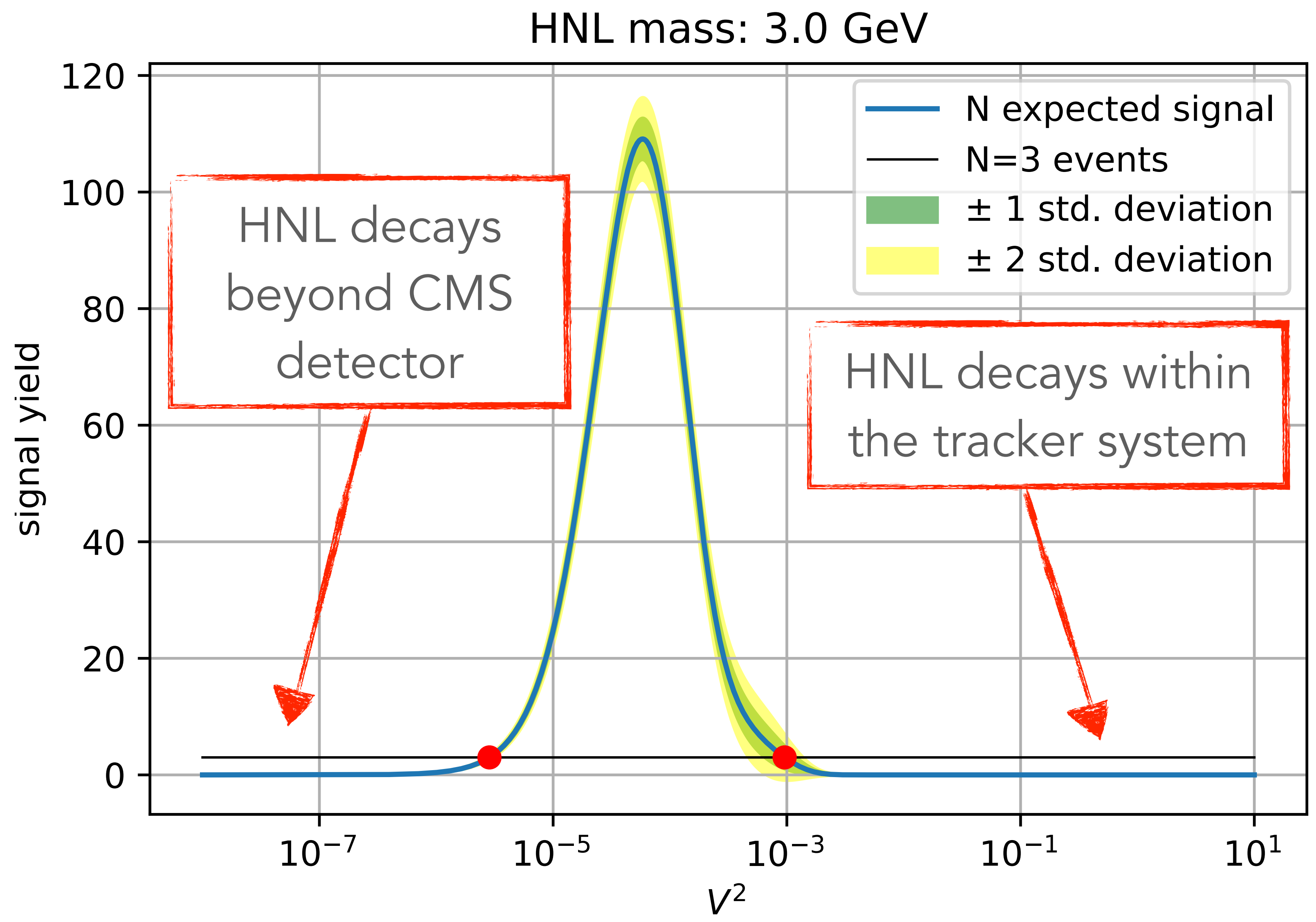
Background estimation

- **Main SM background sources**: 1 or 2 prompt muons in final state: $t\bar{t}$, Drell-Yan, W+jets
- Need for **data-driven methods** for background estimation (unreliable simulation samples)
- **Current hypothesis:** main background source = real muons produced near the primary interaction vertex, but for which no track is reconstructed in the tracking system (work in progress…)

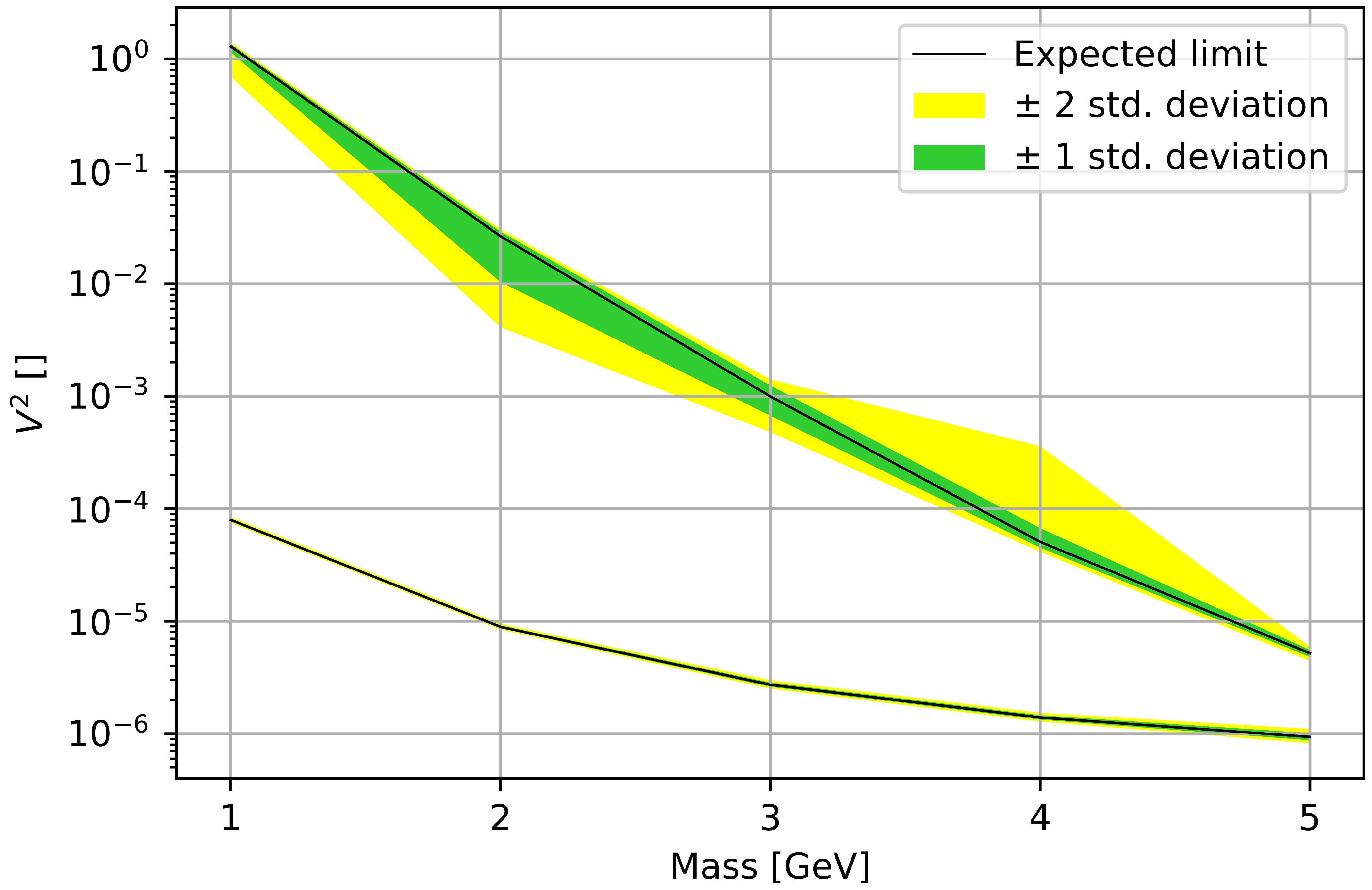
Final goal: setting exclusion limits at 95% confidence level for HNL production in the m_N - $|V_{N\mu}|^2$ plane

Sensitivity Study

- Preliminary studies showed very low background levels after current selection ($\mathcal{O}(1)$ - $\mathcal{O}(10)$ events)
- First study of exclusion sensitivity conducted under the hypothesis of 0 background
- Signal estimation performed on HNL simulation samples at different mass values and scanning over $|V^2_{N\mu}|$



Expected signal yield for the whole Run 2 from HNL MC sample as a function of squared coupling for an HNL mass of 3 GeV



Estimated exclusion limits for the coupling of one single HNL with the muon neutrino

- Sensitivity for low HNL masses: $m_N < 6$ GeV
- Improved limits in the lower coupling region

Summary and Future Plans

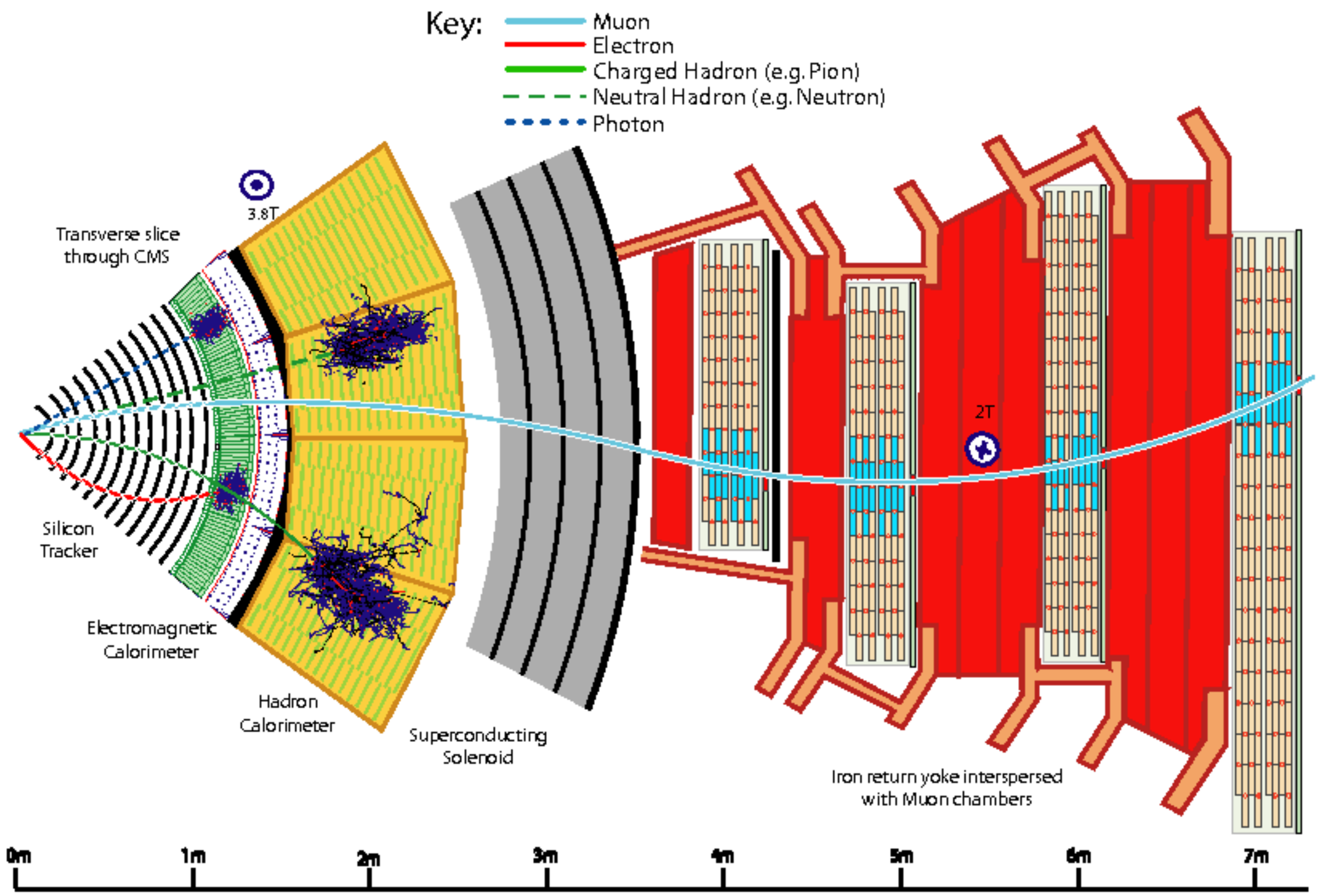
- **Main goal**: extend the sensitivity of HNL searches at CMS towards low masses and coupling values by considering higher HNL flight-lengths
- **Probed signature**: final states with three charged muons, one prompt and two super-displaced from the same secondary vertex
- **First results**: low background levels with sensitivity to HNL production up to HNL mass of 5 GeV
- **Current effort**: background estimation (dominant source: true non-displaced muons misidentified as super-displaced due to tracking inefficiency)
- **Future plans**:
  - Finalisation of background estimation strategy
  - Optimisation of selection process
  - Statistical interpretation to set exclusion limits in the m_N - $|V_{N\mu}|^2$ plane
  - Evaluation of systematic uncertainty on expected signal and background yields

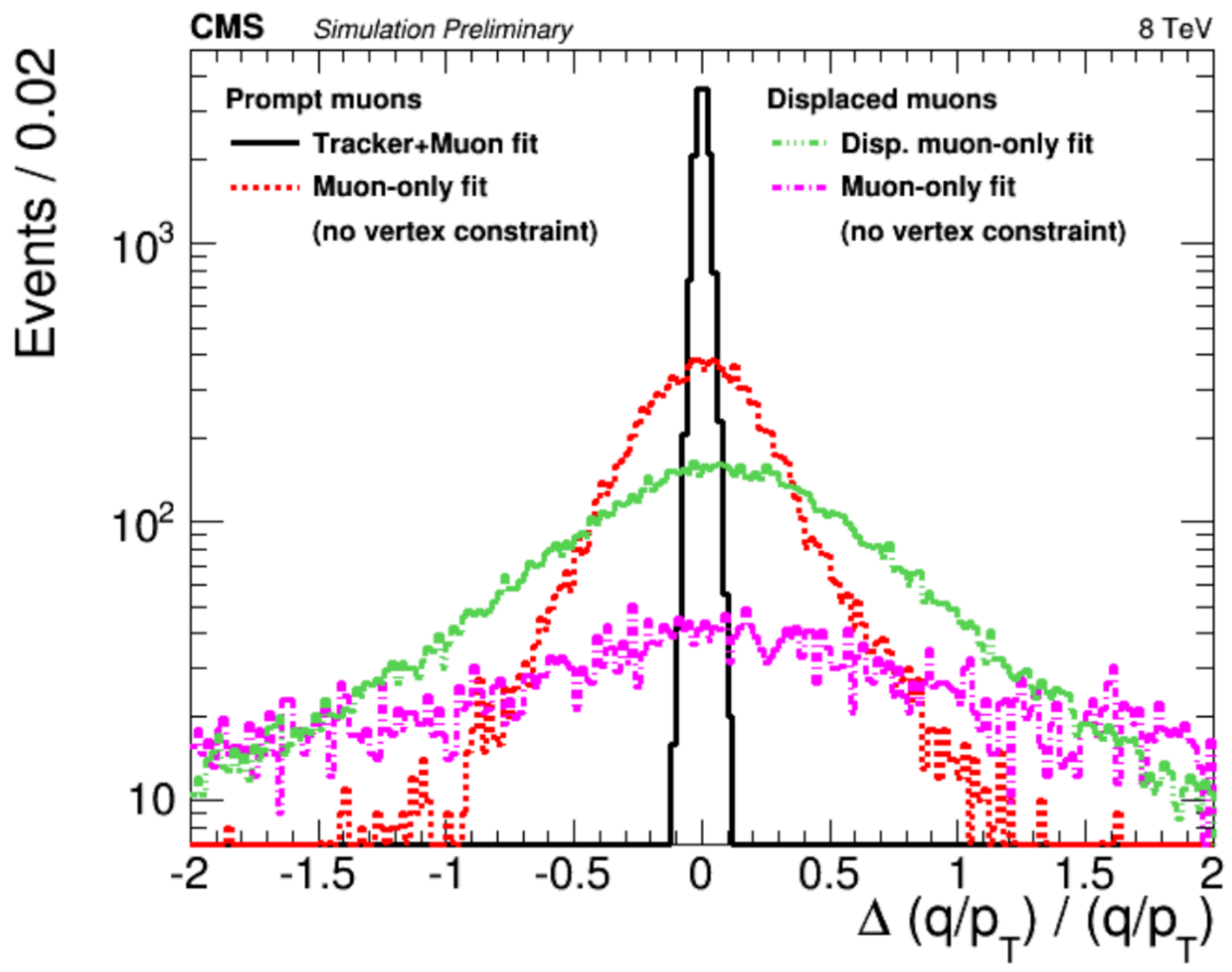
Backup Material

Muon Reconstruction at CMS

Tracks reconstructed independently in the inner tracker (tracker track) and in the muon system (standalone muon track) → inputs for muon track reconstruction:

- ❖ STandAlone muon (STA) track: reconstructed using muon-system information only
- ❖ Tracker muon track: tracker tracks matched with at least 1 muon segment (*inside-out*)
- ❖ Global muon track: STA track matched with tracker track (*outside-in*)





CMS DP-2015/015

Displaced StandAlone (DSA) muon track

Special STA reconstruction algorithm:

- Hits in the muon system only (same as standard STA algorithm)
- Seeds from cosmic muons

More suitable for muons from displaced vertices (no dependency on beam spot position)

Signal Selection - Details

Selection of DSA Muon Candidates

$\Delta R(\text{DSA}, \mu_0) > 1$
$p_T > 5$ GeV
$\sigma_{p_T}/p_T < 1$
Nbr(valid hits) > 12
$\chi^2/\text{ndof} < 2.5$

- **Global/tracker muon veto**: each DSA muon required not to match any mediumID global/tracker muon (matching given by $\Delta R < 0.7$)
→ Actually displaced muons
- **Matching with STA muons**: each DSA muon uniquely matched ($\Delta R < 0.4$) with an STA muon in the same event
→ Add time information to each muon object
- **Time selection**: reconstructed muon time (both the one reconstructed with the whole muon system and the one only reconstructed with the RPC) required to be lower than 10 ns
→ Reject out-of-time muons from other bunch crossings

Signal Topology Cuts

Z veto: $m(\mu, \mu') \leq 80$ GeV	
Charge selection: $q(\mu_1 + \mu_2) = 0$	
$\Delta\phi(\mu_0, \mu_1) > 1.5$ $\Delta\phi(\mu_0, \mu_2) > 1.5$	
$\Delta R(\mu_1, \mu_2) < 1$	HNL boost
$p_T(\mu_1 + \mu_2) > 10$ GeV	HNL boost
$\cos(\theta) > 0.9$	HNL boost
40 GeV $< m(\mu_0 + \mu_1 + \mu_2) <$ 90 GeV	
Nbr of b jets $= 0$ (• b jet $p_T > 25$ GeV • btagDeepFlavB > 0.2770)	Against $t\bar{t}$
prob$(SV) > 0.001$	

Notes on Background Estimation

- **Current hypothesis:** main background source given by real muons produced near the primary interaction vertex, but for which no track is reconstructed in the tracking system
  → Misidentified as super-displaced muons

- **Strategy** for data-driven background estimation:
  ABCD method by *inverting the global/tracker muon veto* (used to ensure real displacement) for the 2 DSA objects

		Dsa2 (subleading) veto	
		Passed	Failed
Dsa1 (leading) veto	Passed	A	B
	Failed	C	D

- Passed: dsa muon not matched with global/tracker muon
- Failed: dsa muon matched with global/tracker muon (inverted prompt veto)

- **Closure tests** on both 2016 UL W+jets MC sample and on opening-angle data sideband show that this method underestimates the background yield
  → Probable correlation between the two vetoes (More studies for strategy optimisation ongoing)

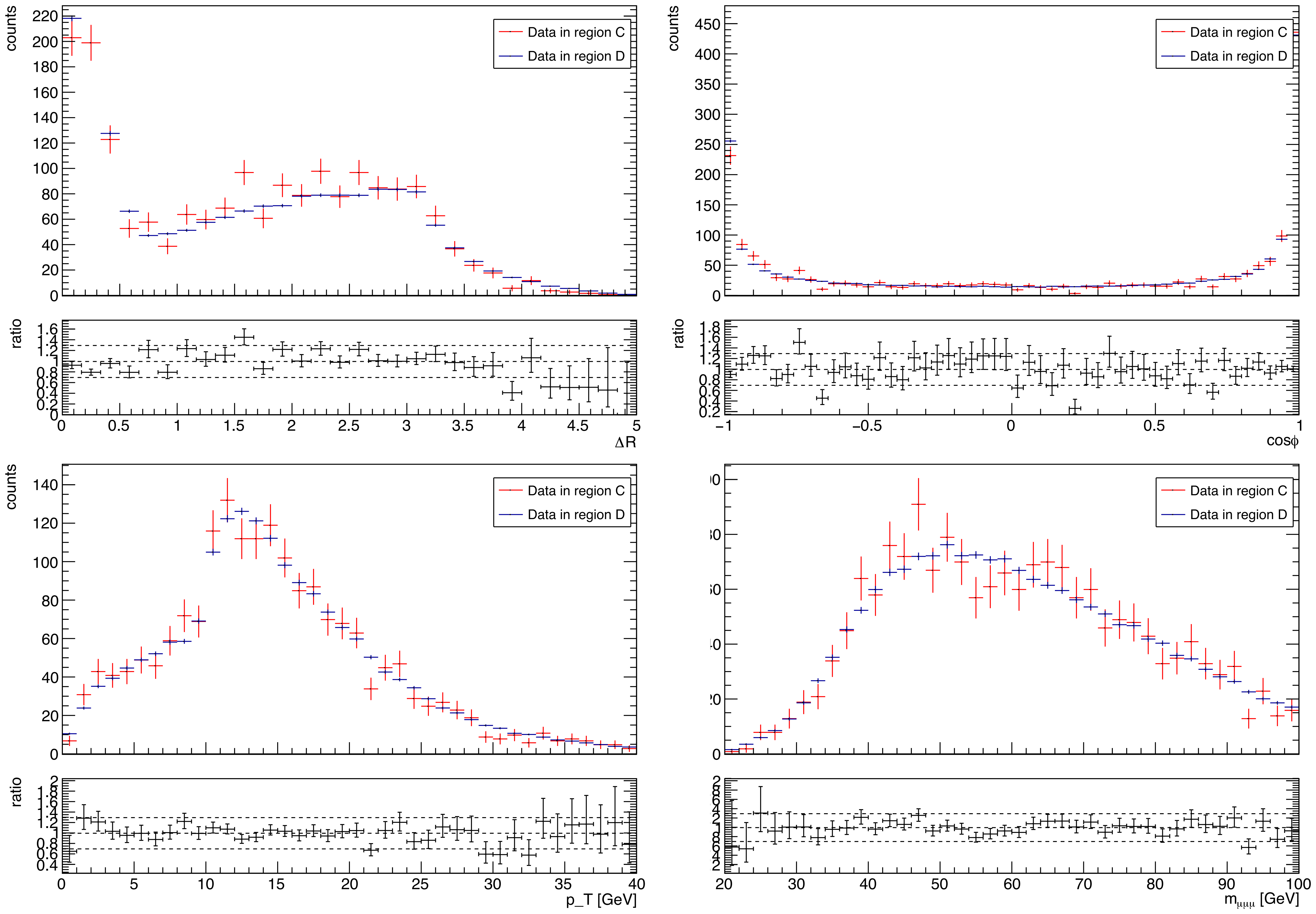
ABCD Method Details

$$\frac{n_A}{n_B} = \frac{n_C}{n_D}$$

- Apply weights in region D to match distribution of kinematic variables in region C:
  - $p_{T\mu_2}$ - dependent 1D weights $w_i = \dfrac{n_{i,C}}{n_{i,D}}$
  - 2D weights in $(p_{T\mu_2}, \eta_{\mu_2})$ and $(p_{T\mu_2}, \phi_{\mu_2})$
- Verify agreement between distributions in region C and D with respect to kinematic variables used in signal selection
- Apply derived weights to events in region B to estimate yields in region A

Why?

If considered particles are actual muons, the global/tracker muon veto only depends on the muon kinematics (p_T, η, ϕ)



ABCD Method Validation

Two possibilities for method validation:

- ☐ Background simulation samples
  → Low statistics ✗
- ☐ Data sideband regions ✓

Opening angle sideband

- Signal selection: $\cos\theta > 0.9$

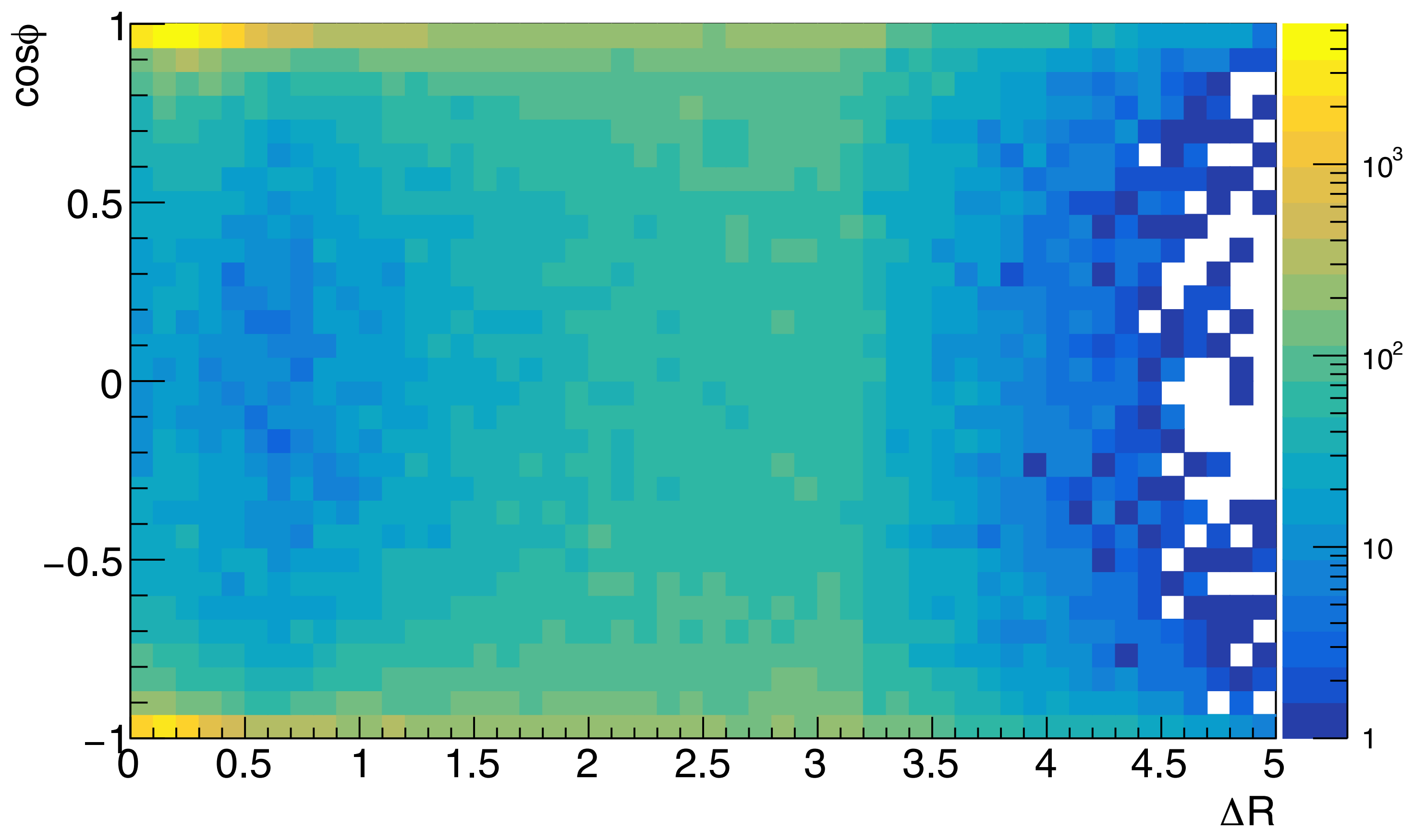
  $\Longrightarrow$ Sideband: $\cos\theta \leq 0.9$

- Good agreement in region C and D after kinematic re-weighting
- **Underestimation of background yield in region A** → Further studies ongoing

Validation in 2016 W+jets MC sample

- Good agreement in region C and D after kinematic re-weighting
- Comparison between estimated and expected yield in region A inconclusive

To catch eventual correlation of the misidentification fake rate with the detector geometry, sideband regions identified by cutting on **variables independent of** $\Delta R(\mu_1, \mu_2)$



Linear correlation factor:

$\rho = -0.1483$

ABCD Method Validation

- Main assumption in the ABCD method: leading muon veto independent of subleading muon veto

$$\Longrightarrow \frac{n_A}{n_B} = \frac{n_C}{n_D}$$

- Test of this assumption in opening angle sideband ($\cos\theta \leq 0.9$):
  - Prediction for n_A obtained by applying weights $\frac{n_{C,i}}{n_{D,i}}(p_{T\mu_2}, \eta_{\mu_2})$ to events in region B
  - Expected value for n_A given by count in region A in the data sideband

After Inclusive Selection

nA predicted	23.1
Error (nA predicted)	0.9
nA expected	54
Error (nA expected)	7
Pull	4.2

After Whole Selection
Opening Angle Sideband

nA predicted	1.51
Error (nA predicted)	0.24
nA expected	5.0
Error (nA expected)	2.2
Pull	1.55

Ongoing Work

- ABCD method tends to underestimate n_A
- If there is **correlation between the two vetos**, then the overall probability for μ_2 to pass the veto might be higher when μ_1 passes the veto

When does this happen?

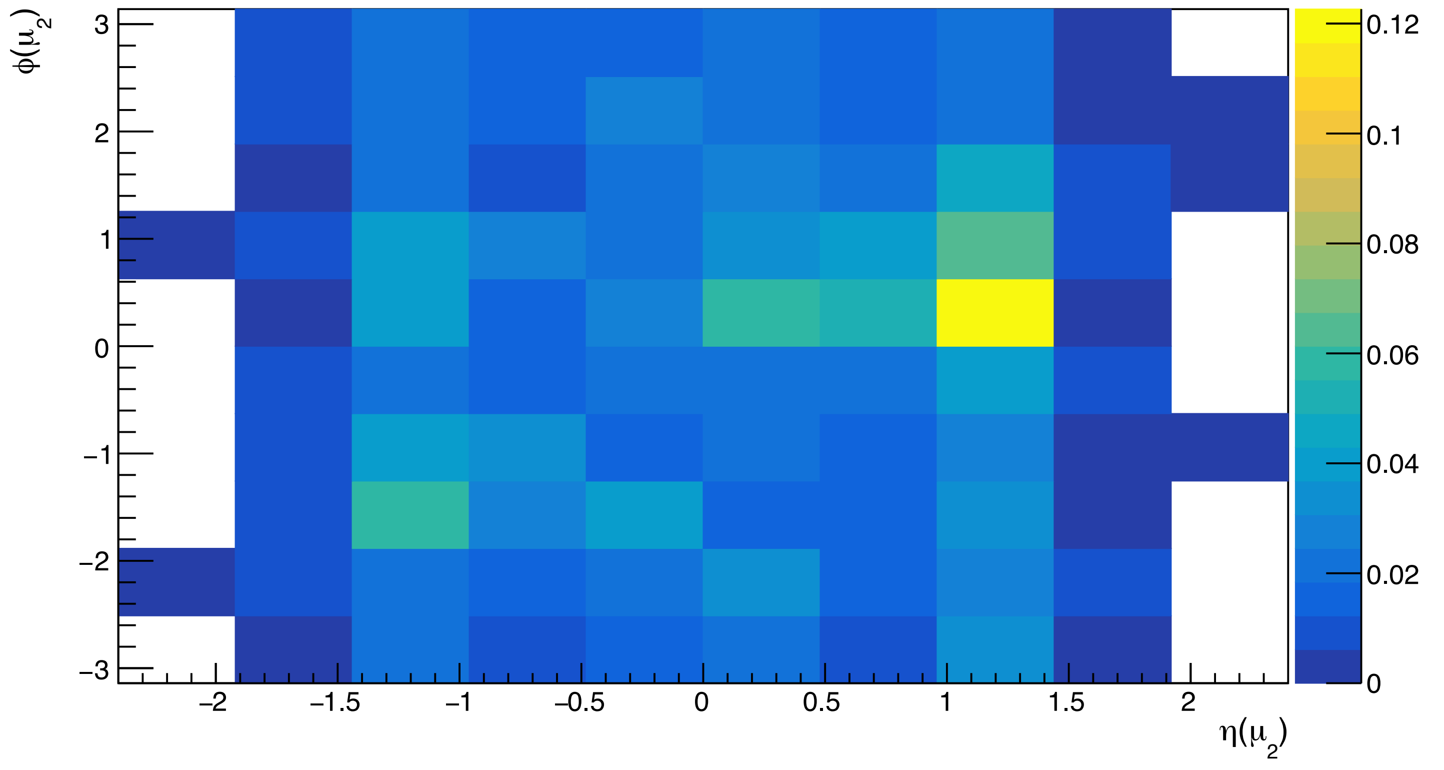
Presence of correlated (non-displaced) di-muon systems <u>and</u> fake rate correlation with specific detector regions

Presence of correlated (non-displaced) di-muon systems <u>and</u> fake rate correlation with charge isolation / presence of jets

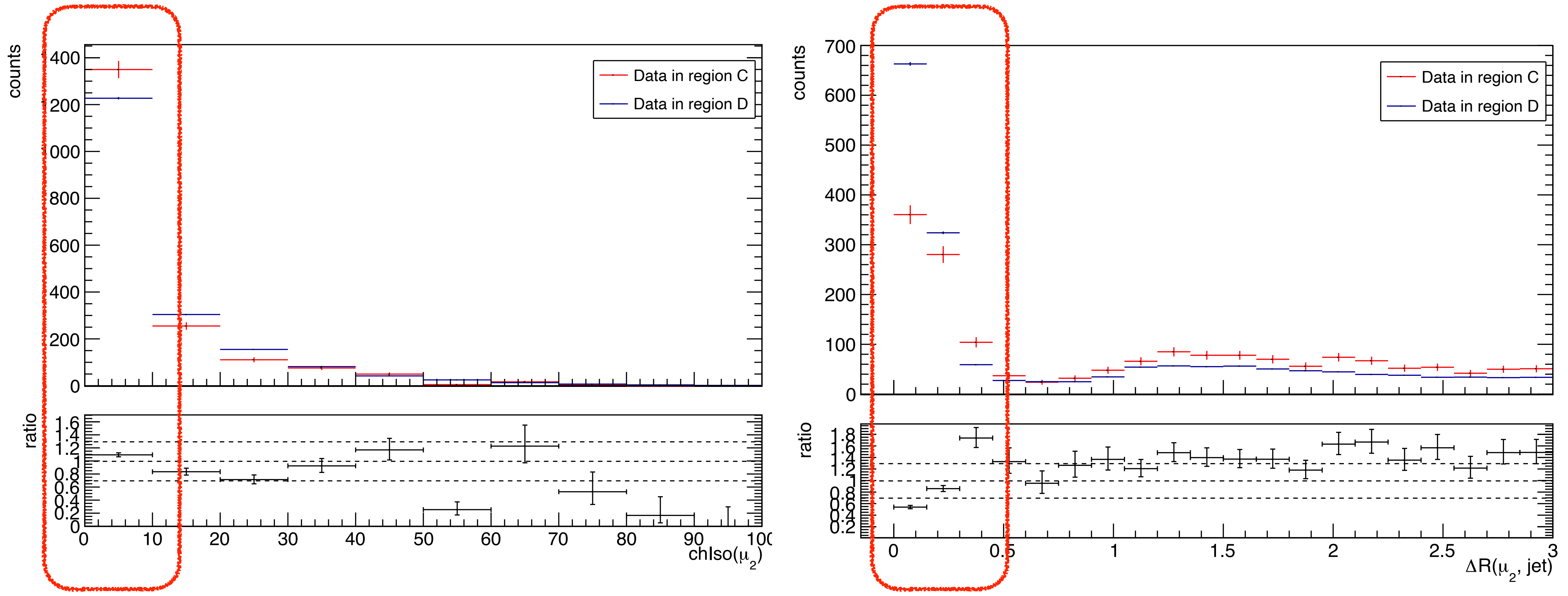
Presence of real super-displaced di-muon systems from physics background

Other effects to be analysed…

e.g. presence of correlated out-of-time di-muons

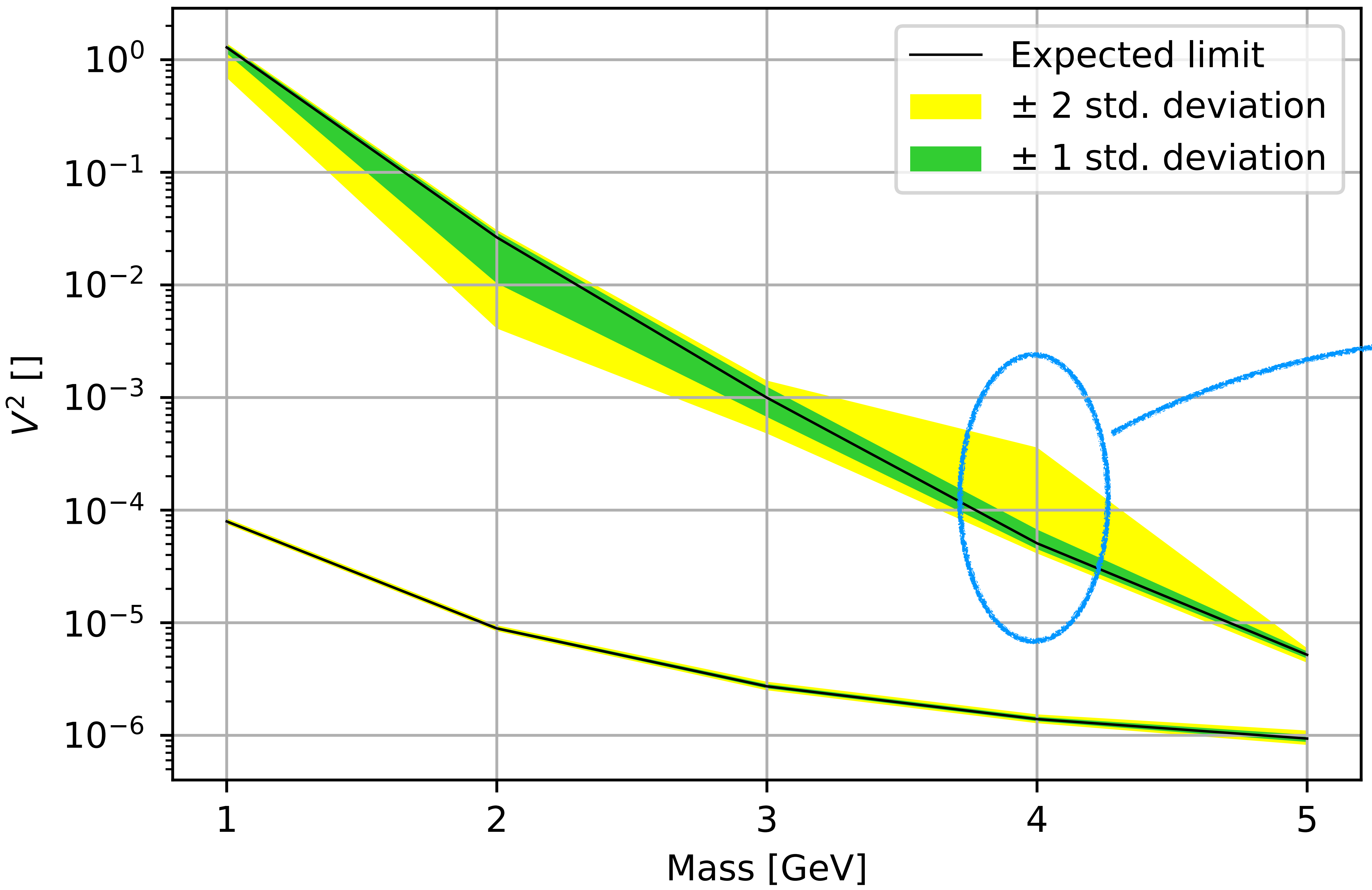


2D plot of fake-rate (ratio between yields in region C and D) as a function of η and ϕ of μ_2



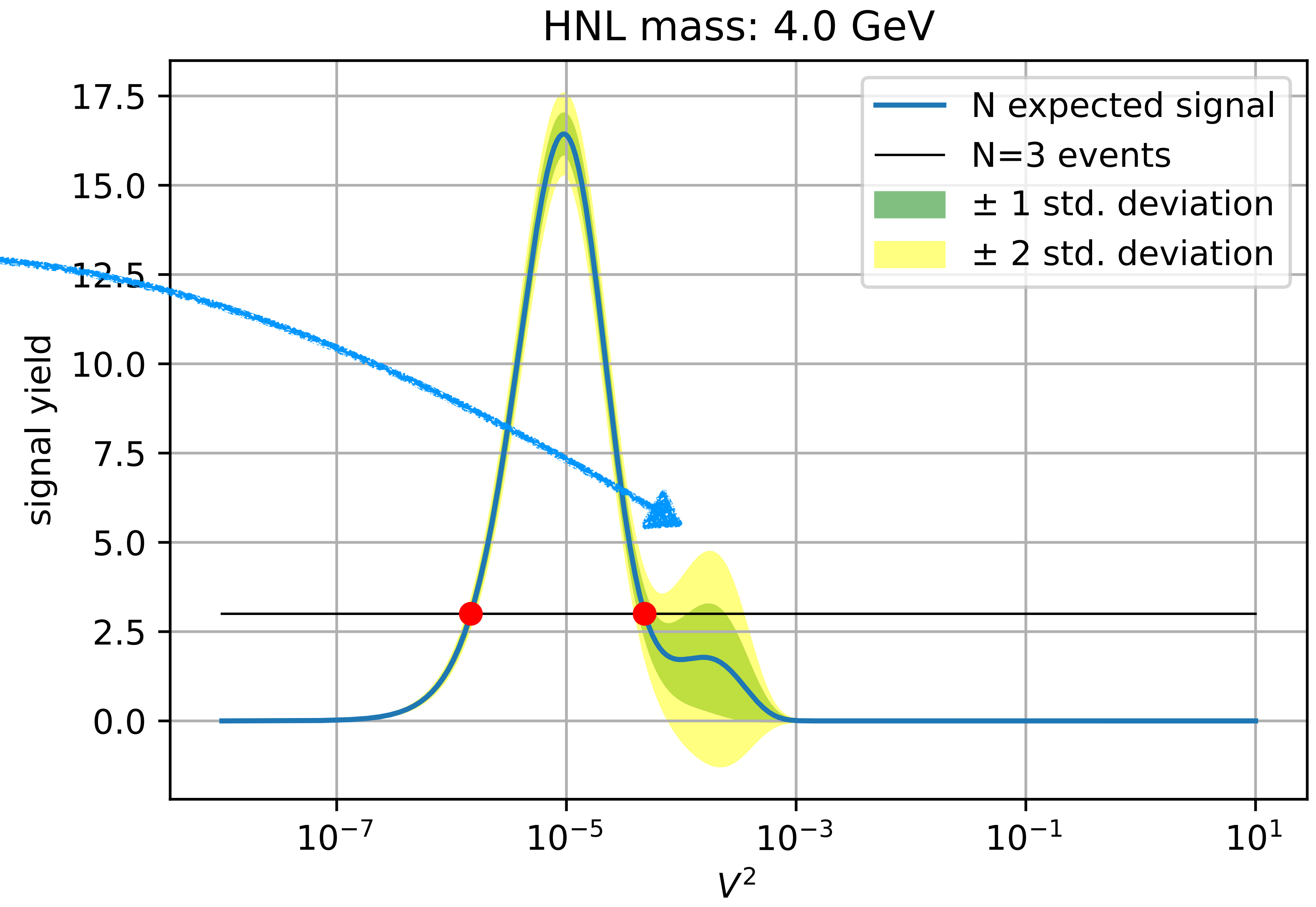
Fake rate as a function of μ_2 charge isolation and ΔR from the closest jet

Sensitivity Study



Exclusion limits in the m_N - $|V_{N\mu}|^2$ plane for HNL masses between 1 and 5 GeV.

Upper bound uncertainty larger than lower bound one due to "blobs" in signal yield uncertainty for some mass values



Origin of these blobs still unclear, but the sensitivity in the upper side of the plane is not higher than the previous CMS analysis, so the current focus is mainly on the lower part

References

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