What ever happened to SUSY? Spelunking in the vast MSSM with FastSim

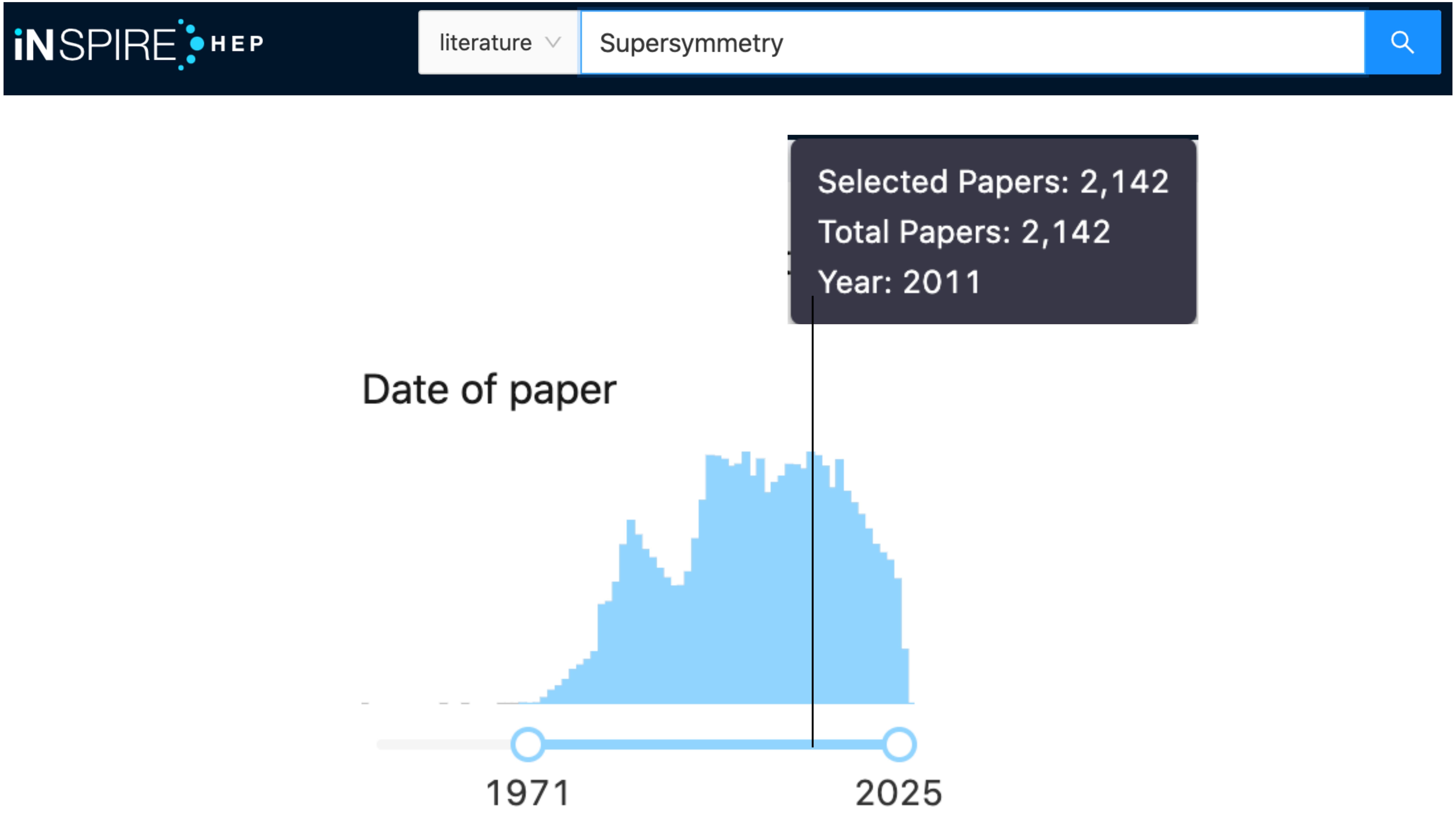
by Sam Bein

CMS
Compact Muon Solenoid

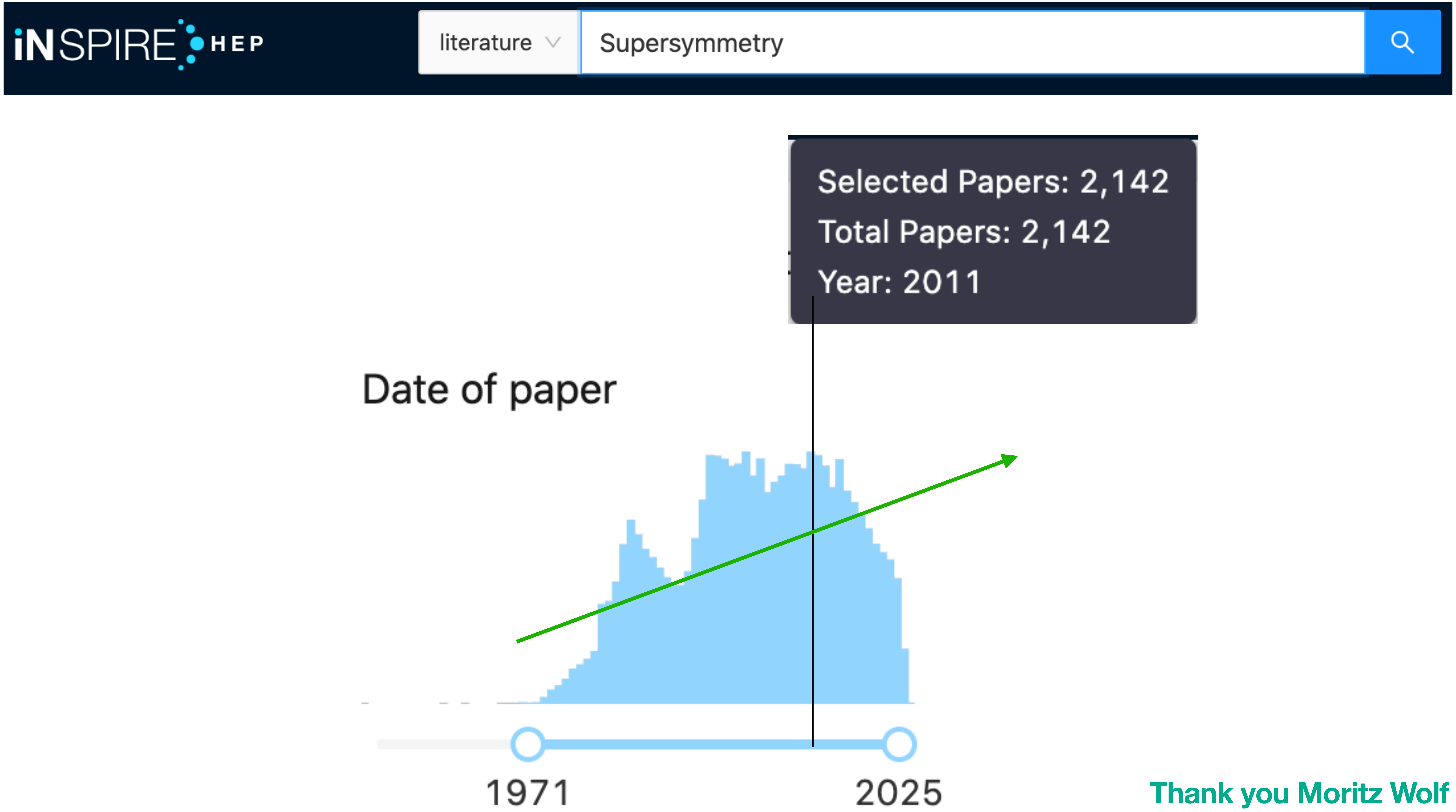
CP3 Seminar
29 October, 2024

UCLouvain

Supersymmetry



Supersymmetry

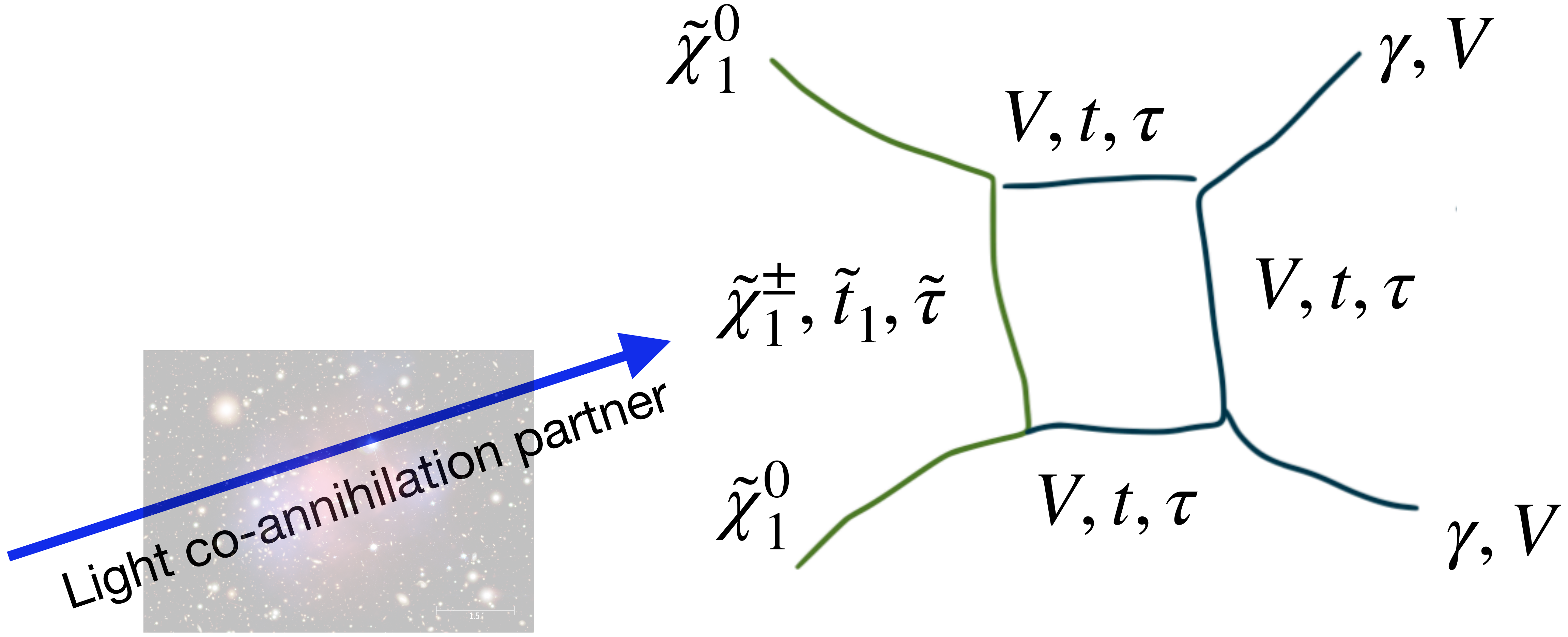


Thank you Moritz Wolf for this joke

Supersymmetry can

A. account for dark matter (DM) if

- neutralino $\tilde{\chi}_1^0$ is the "LSP" (Lightest SUSY particle)
- R-parity is conserved
- If enough LSPs can annihilate before freeze-out
  -requires small Δm or funnel mechanism



B. Solve the large hierarchy problem if

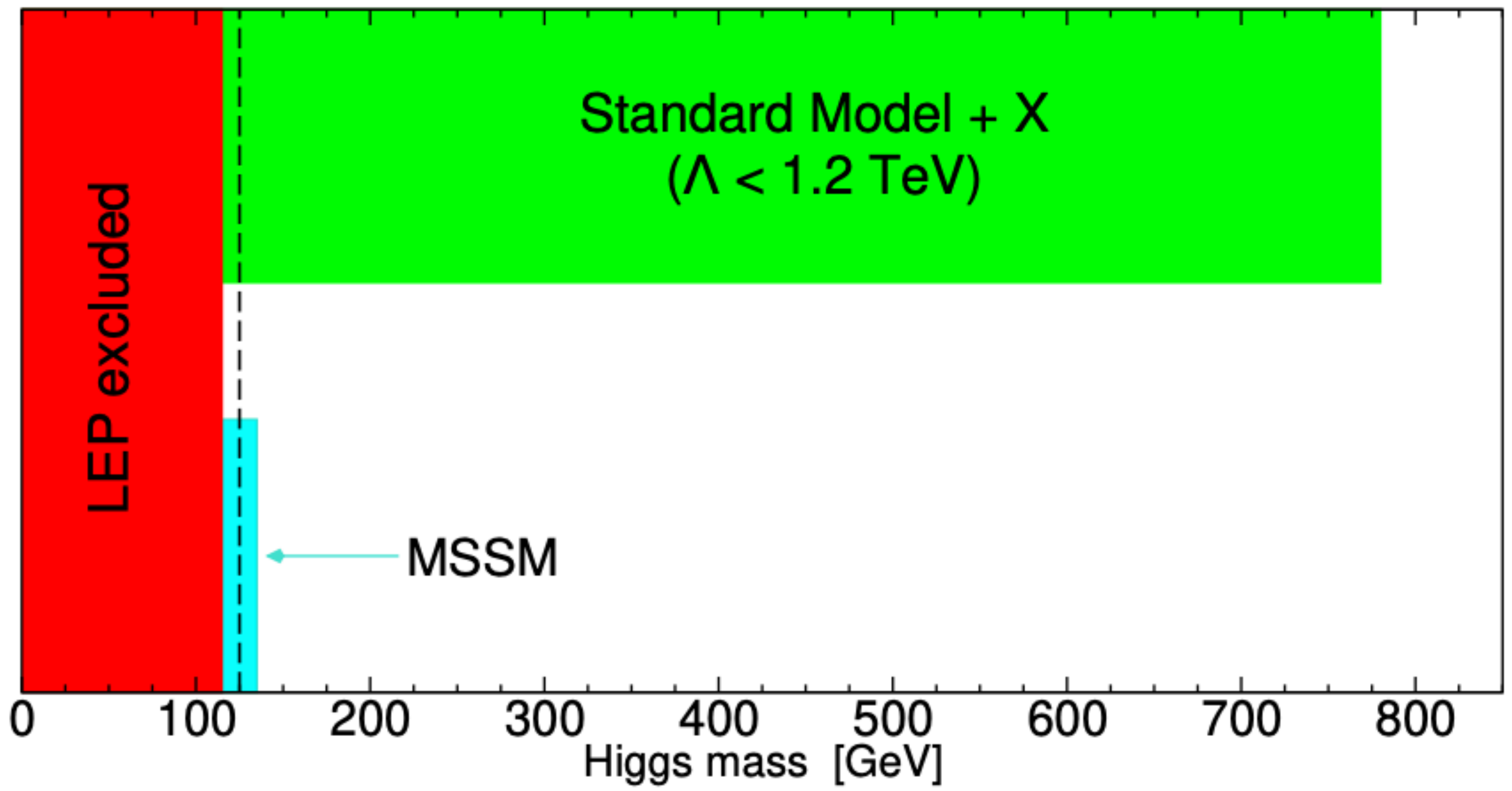
- SUSY is "softly" broken
- If little hierarchy problem doesn't arise
  (Large terms involving many parameters needing to cancel)

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_\mu^\mu)\tan\beta}{\tan^2\beta - 1} - \mu^2$$

Z mass; Down-type Higgs mass; sfermion loops; VEV ratio; sfermion loops; Higgsino mass

Supersymmetry can

3. Make successful predictions, like the Higgs mass

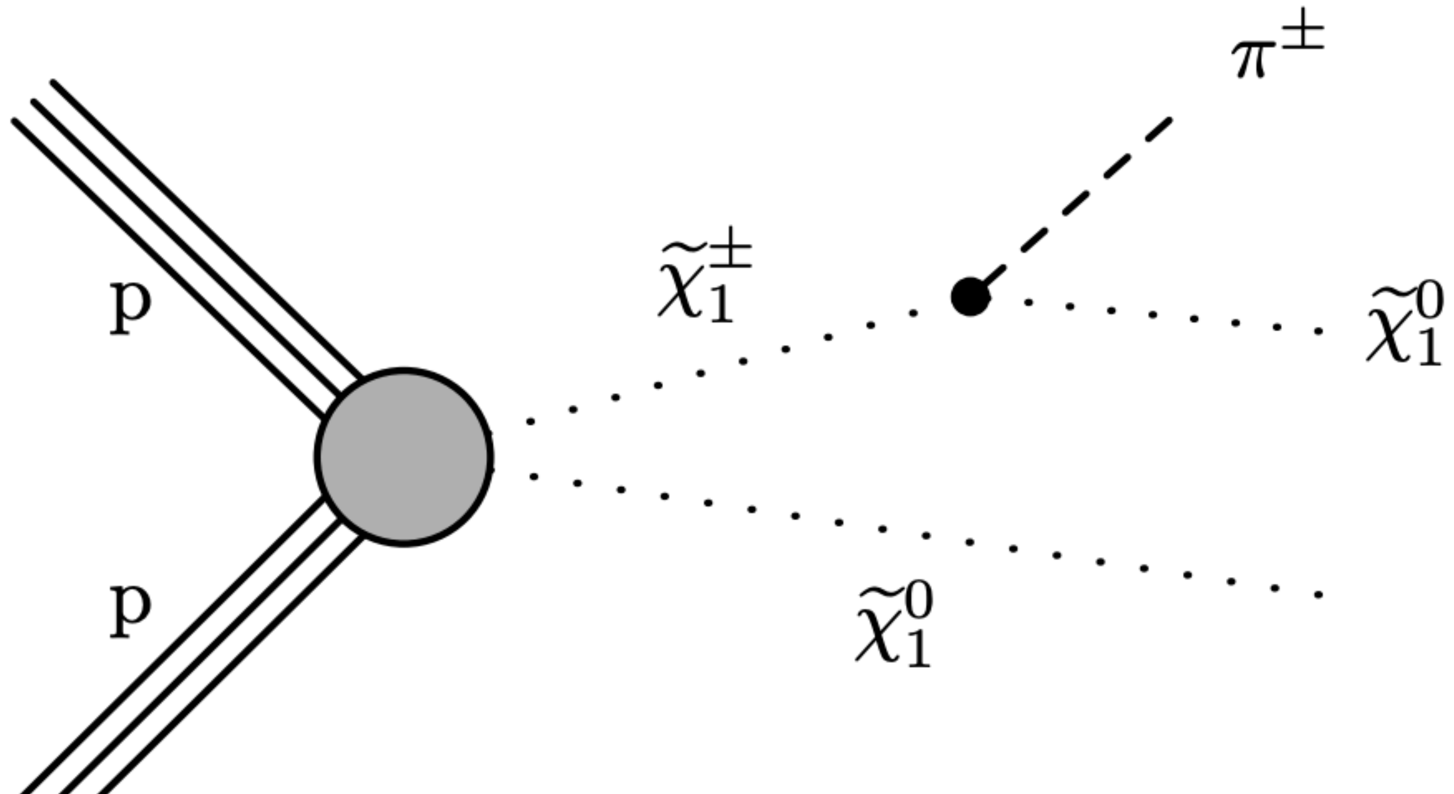


Future of supersymmetry, Stephen Martin@SUSY2023

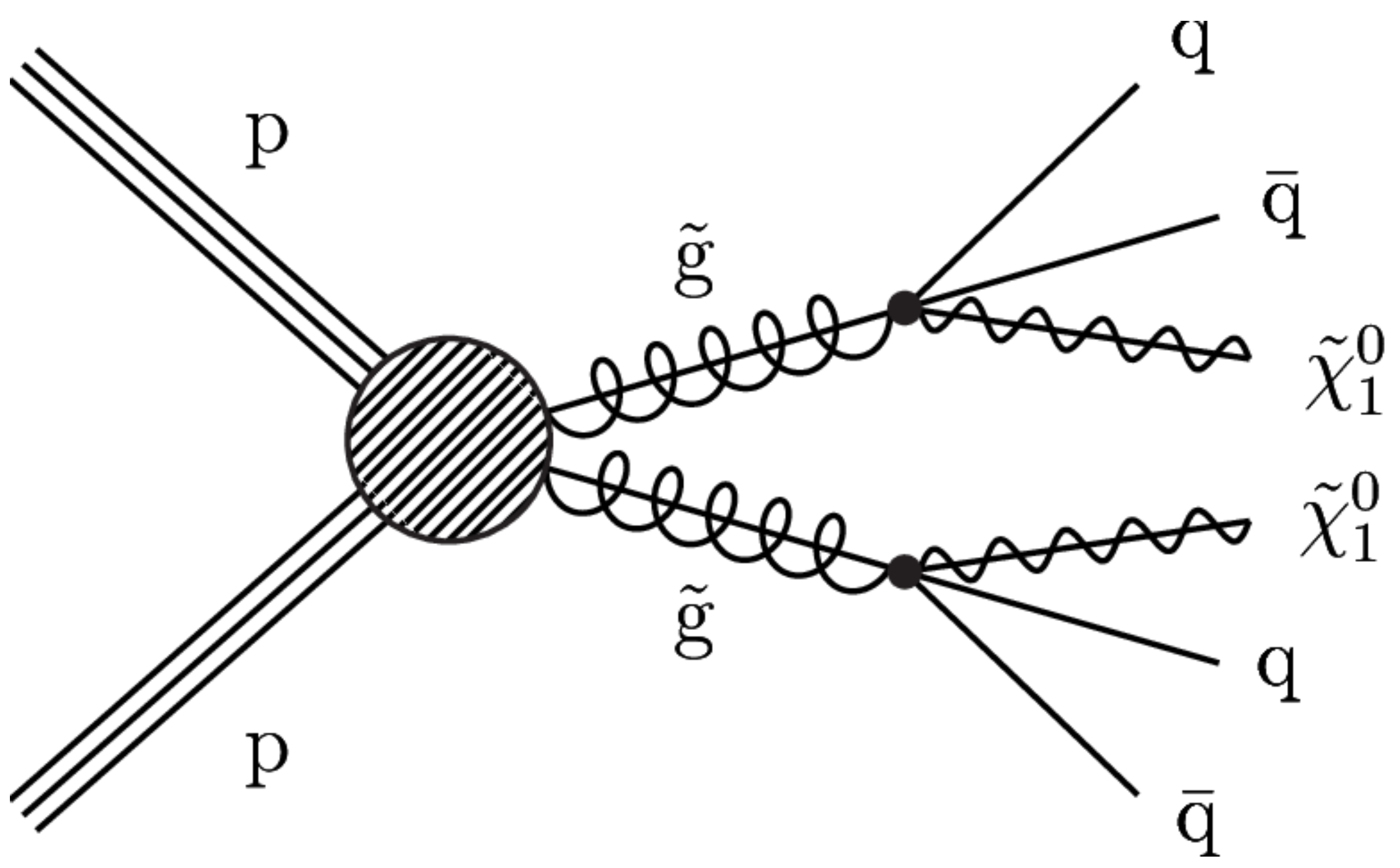
4. …

Looking for SUSY

Step 1) Come up with some specific models



TChiW



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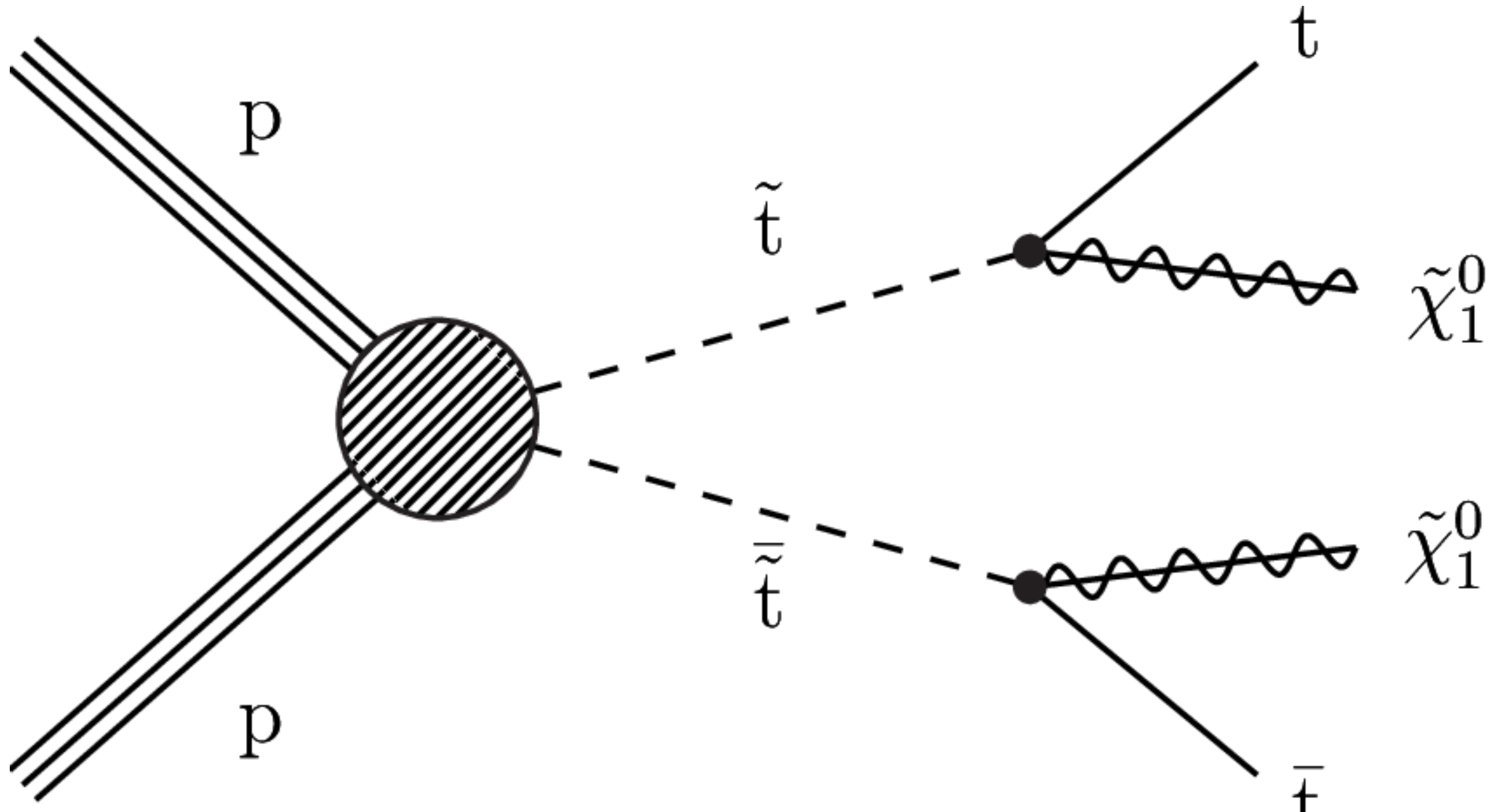
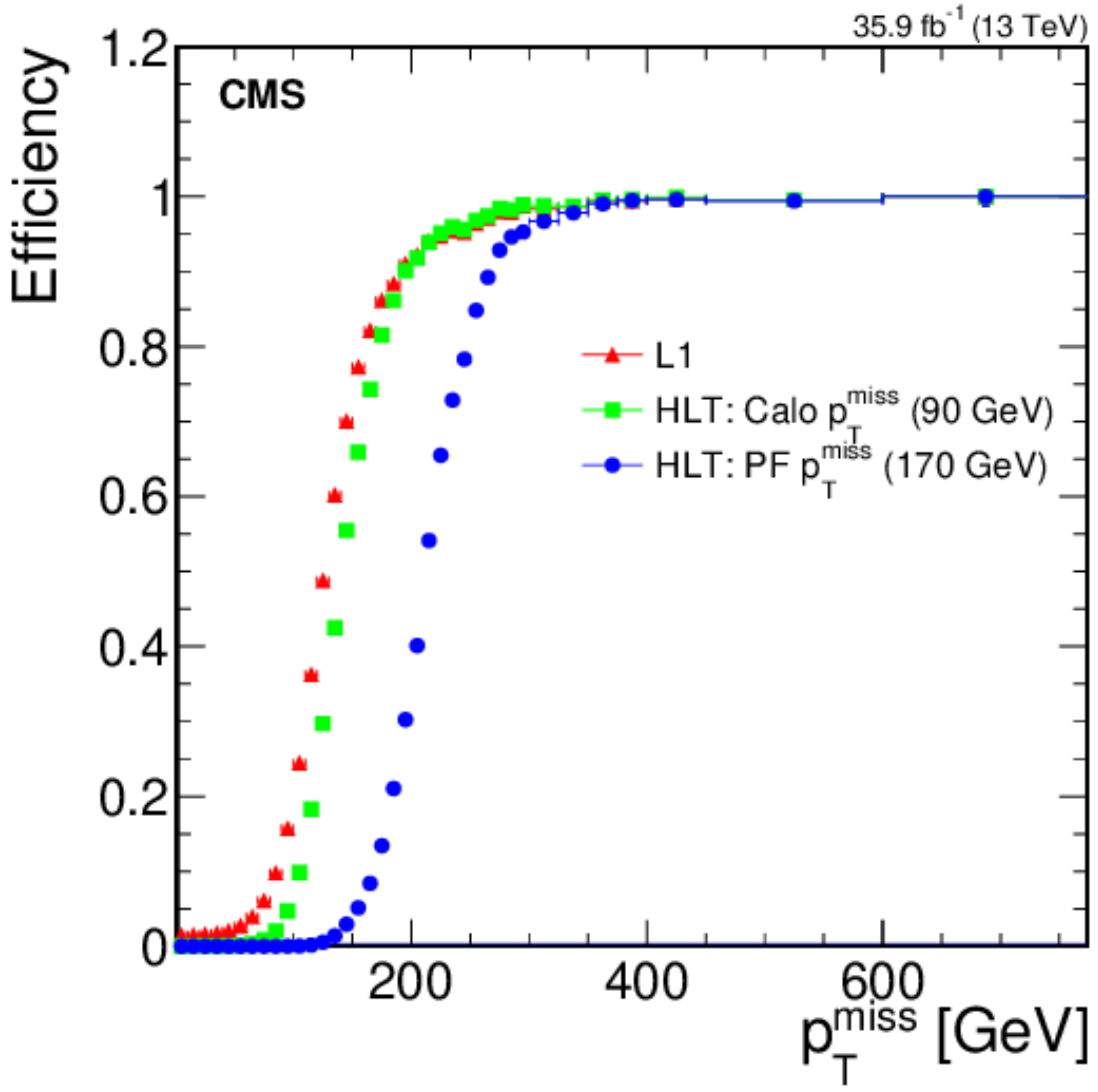


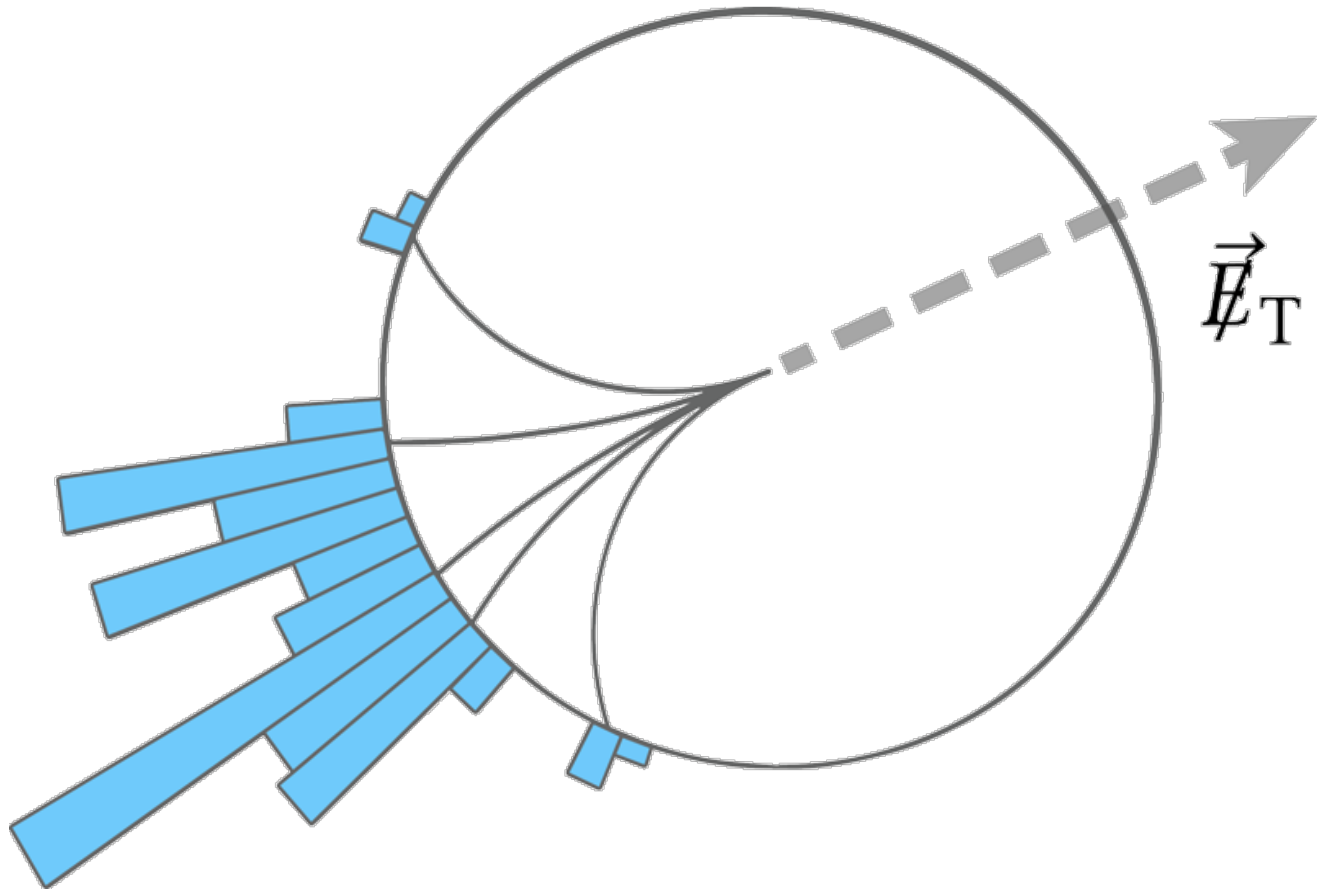
T2tt

Looking for SUSY

Step 1) Come up with some specific models

Step 2) trigger events





p_T^{miss}=missing transverse momentum

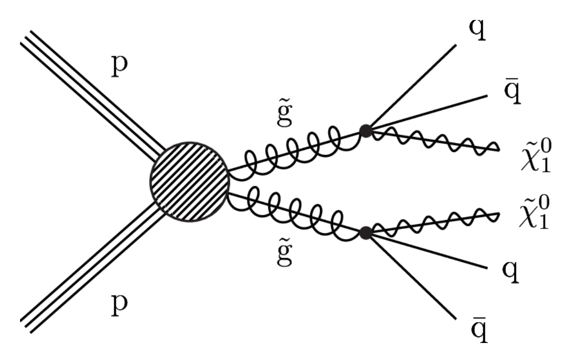
Looking for SUSY

Step 1) Come up with some specific models

Step 2) trigger events

Step 3) select events and objects, analyse data, construct signal regions, estimate background yields, **simulate signal events**, compute systematic uncertainties, unblind the data, interpret with a likelihood

[JHEP 10 (2019) 244](https://doi.org/10.1007/JHEP10(2019)244)



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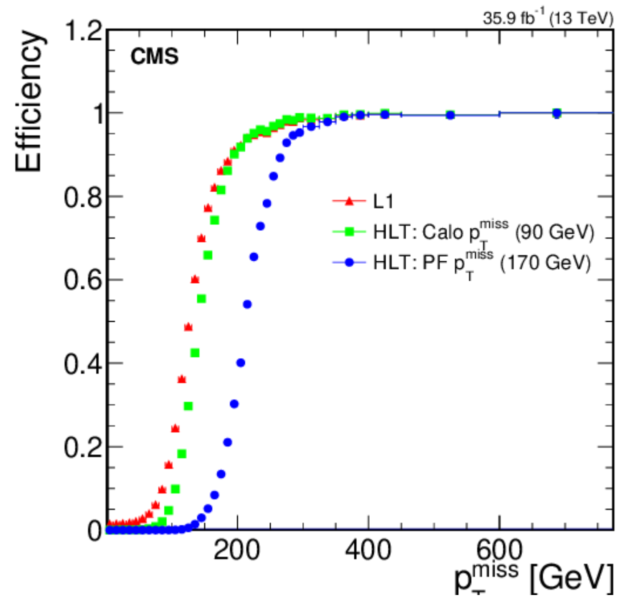

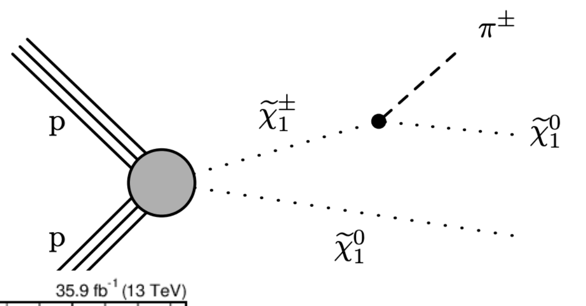

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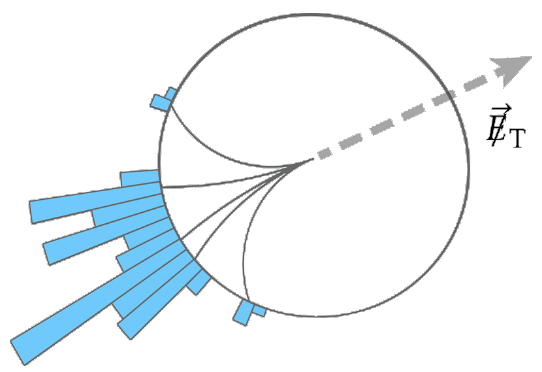
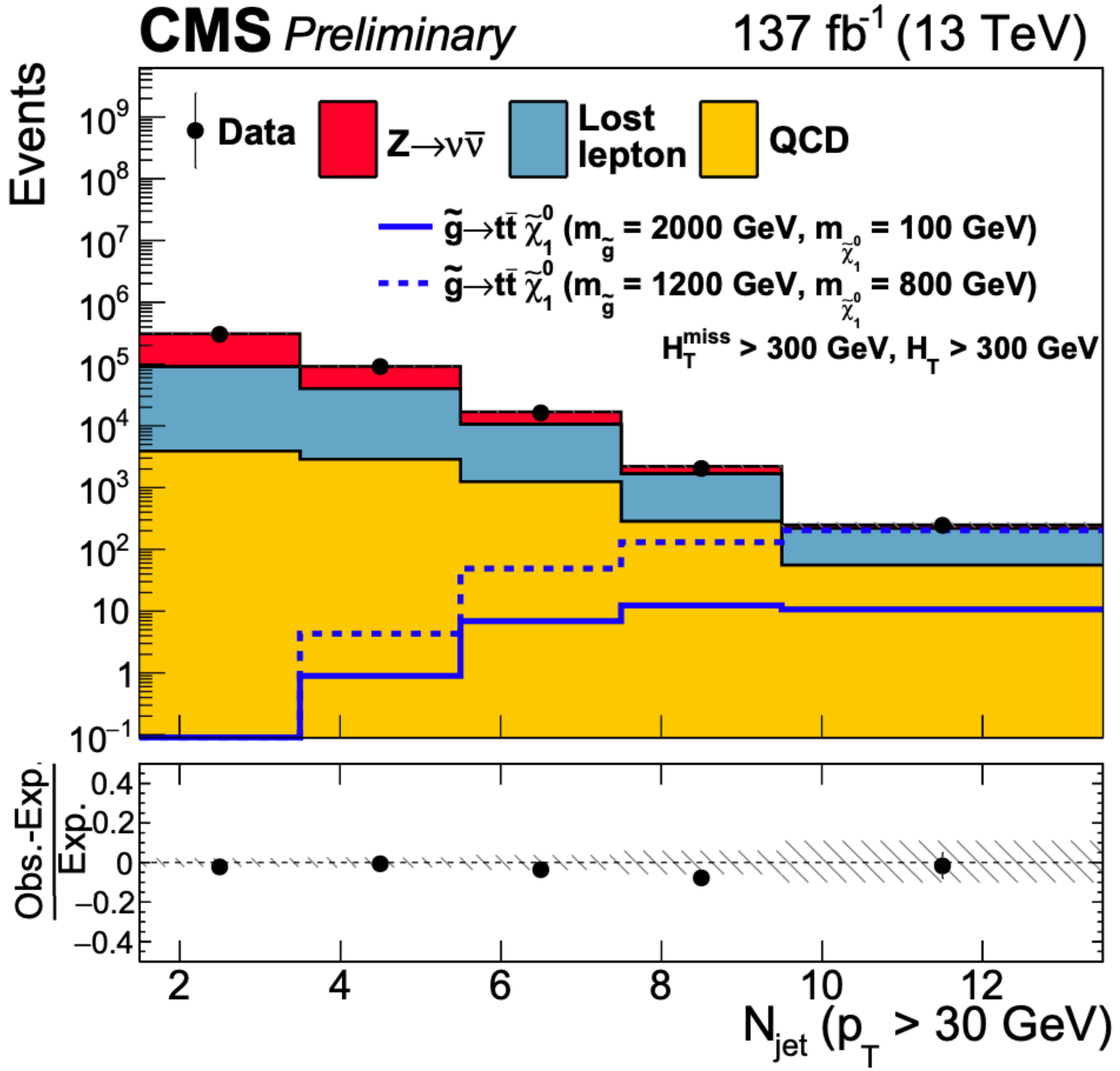
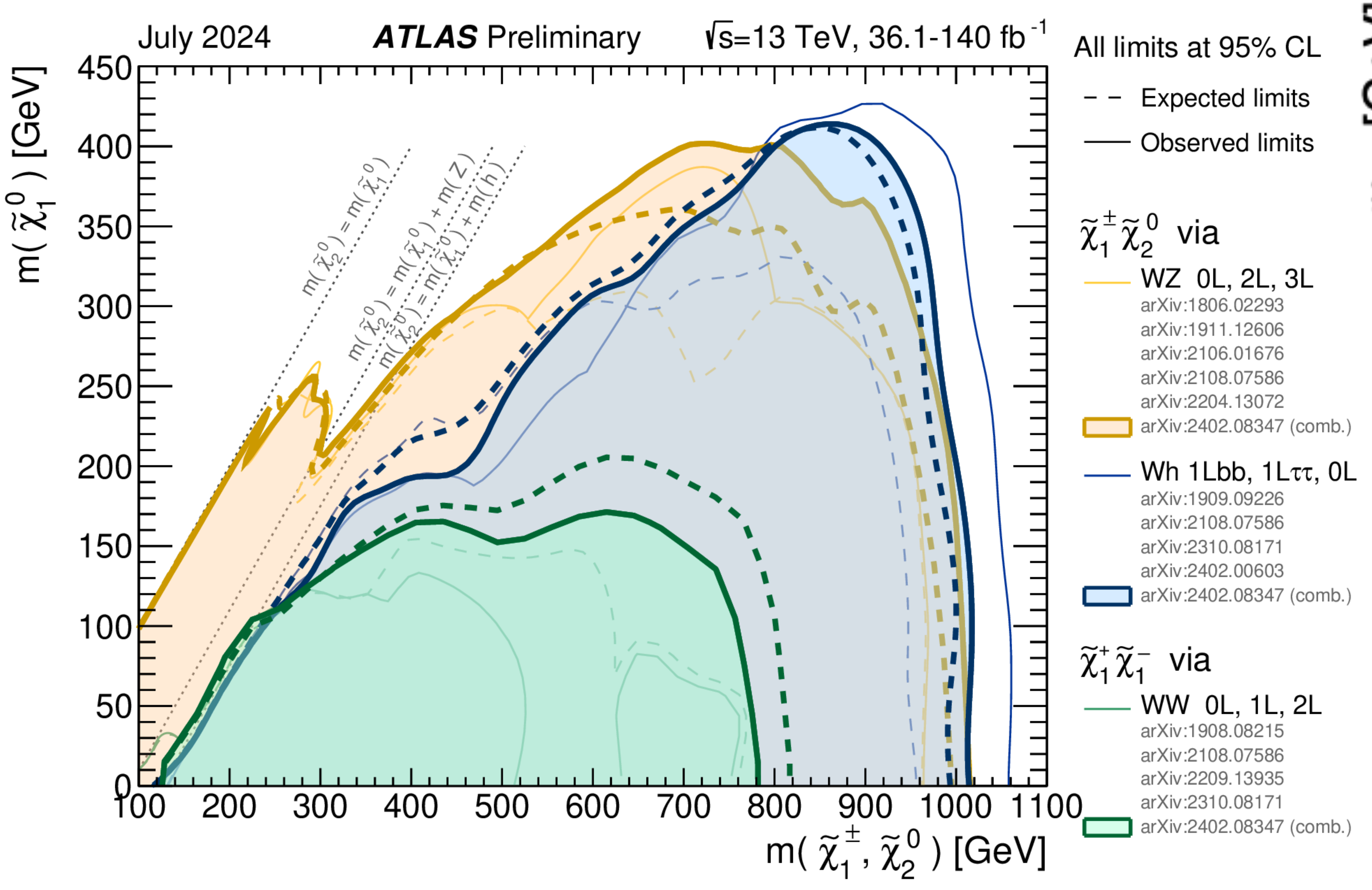
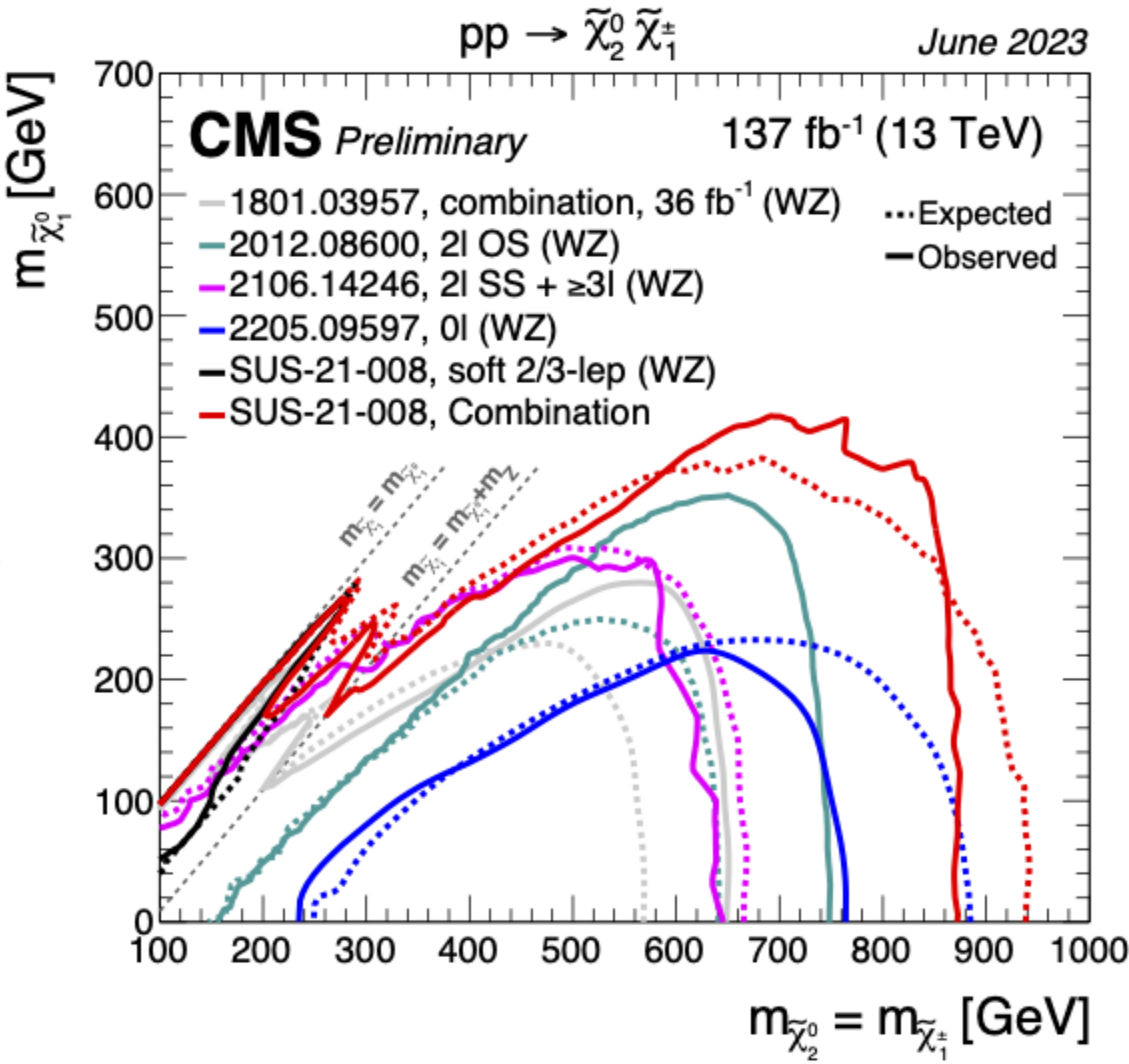




Dozens of Searches (simplified models)



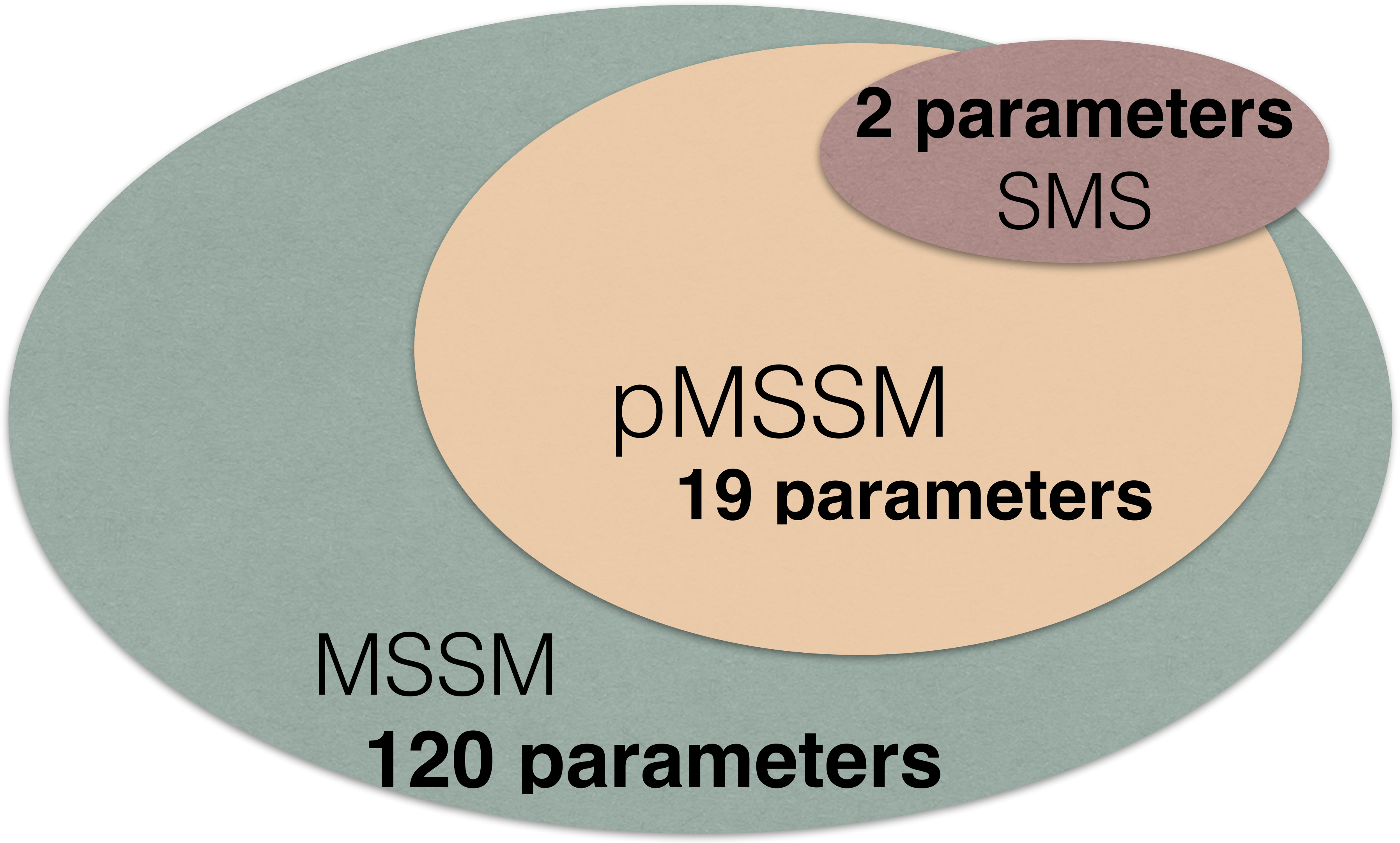


No SUSY, can I go home yet?

Beyond simplified models (pMSSM-19)

<u>*Supersymmetry without prejudice*</u>, Berger, Gainer, Hewett, Rizzo

- phenomenological minimal supersymmetric. Standard Model (pMSSM)
    - 19-parameter sub-model of MSSM
    - captures most phenomenology
    - LHC, dark matter, naturalness insights
    - Need to exhaustively scan in 19D parameter space!



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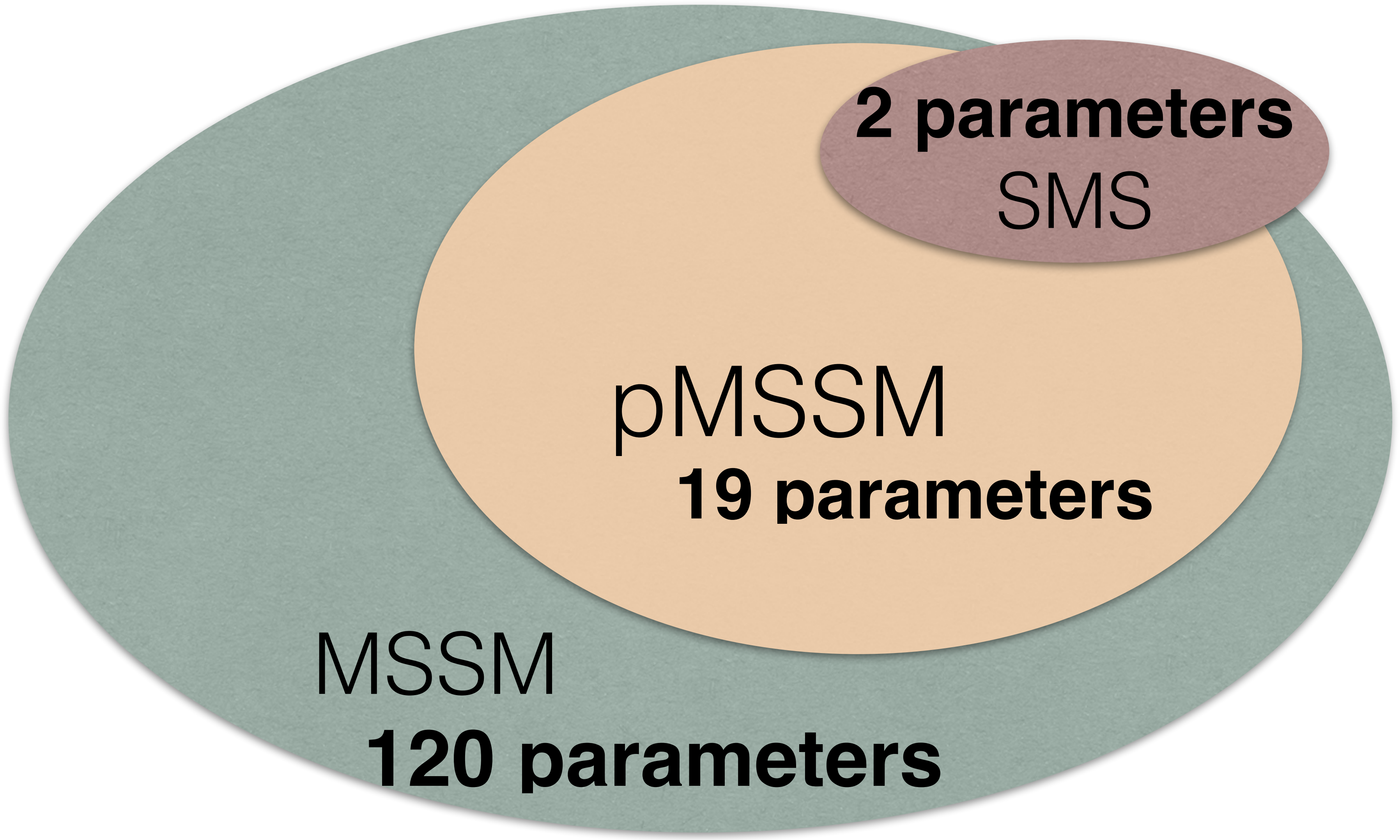
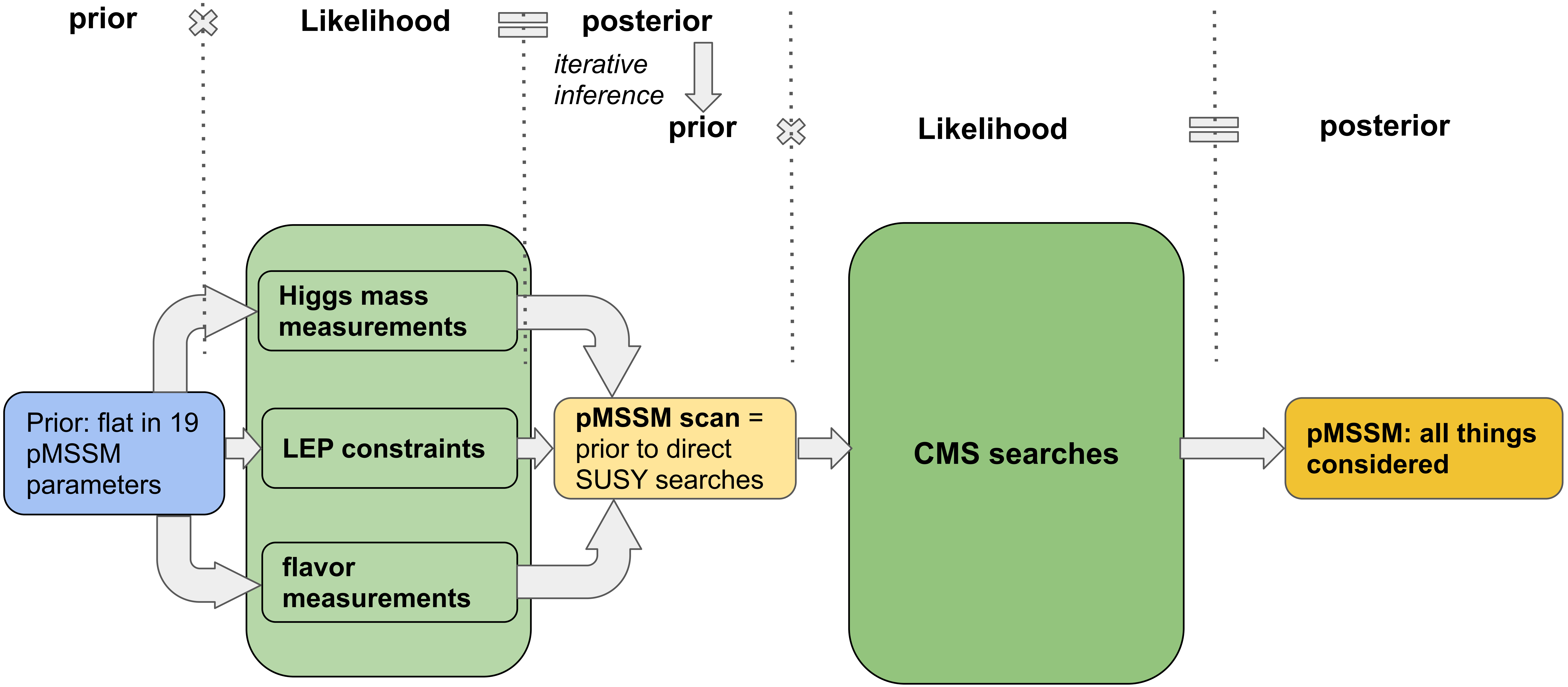


Scan ~2^{19} points in th. space, need **lots of simulation**!

Bayesian pMSSM analysis



Prior

Flat prior in pMSSM-19

squarks up to 10 TeV

gluino up to 10 TeV

sleptons up to 4 TeV

heavy Higgs up to 4 TeV

electroweakinos up to 4 TeV

trilinear couplings up to 7 TeV

tan β from 2 to 60

Markov chain Monte Carlo (McMC)

Higgs mass m(h^0)

LEP constraints

flavor measurements:

BR($b\to s\,\gamma$)*

BR($b\to s\,\mu\mu$)*

BR($b\to s\,ee$)*

BR($B_s \to \mu\mu$)*

BR($B_d \to \mu\mu$)*

BR($B_u \to \tau\nu$)*

BR($D_s \to \tau\nu$)**

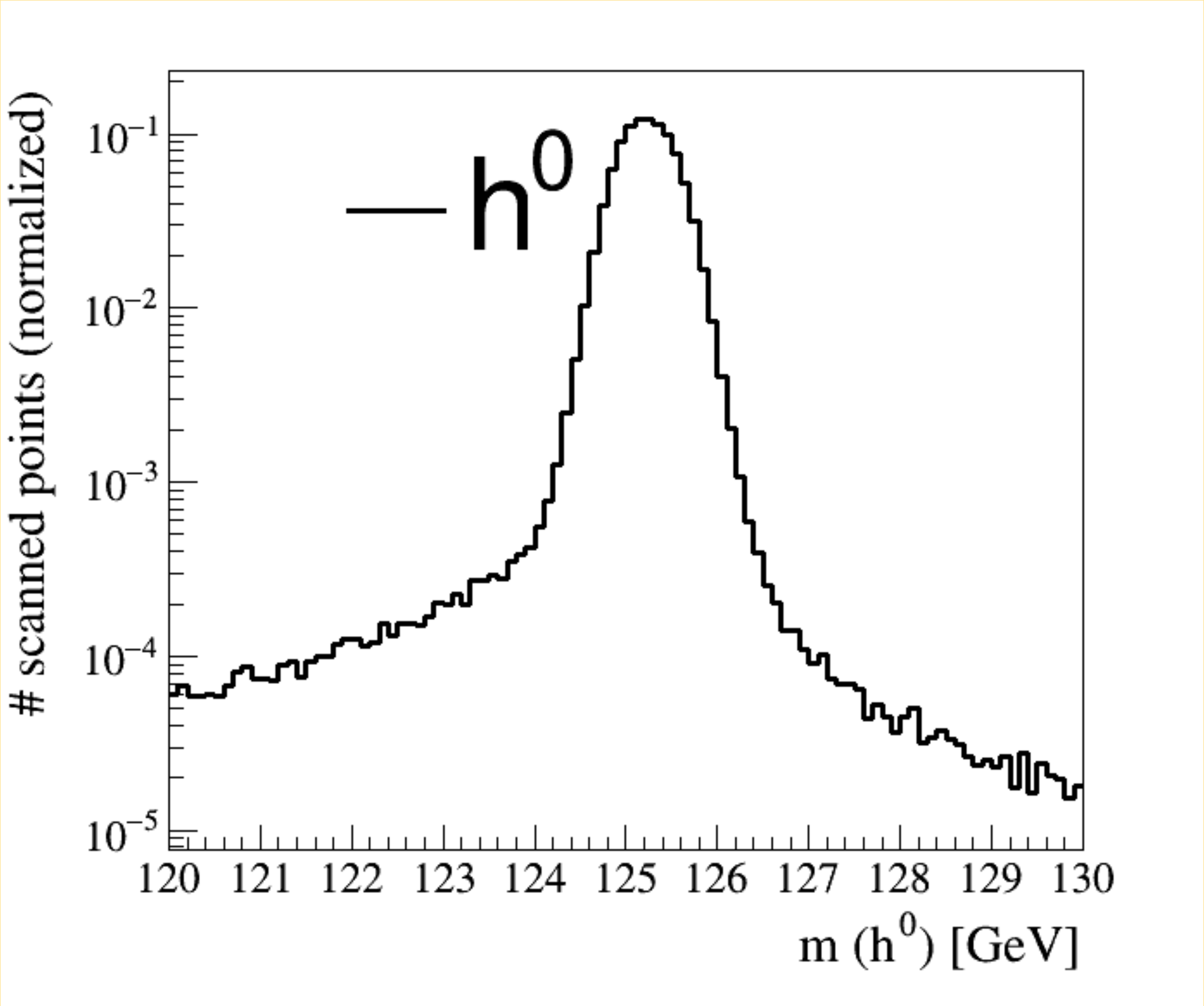
BR($D_s \to \mu\nu$)**

BR($B^0\to K^{*0}\,\gamma$)*

Δ_0 ($B\to K^*\,\gamma$) **

$\Delta\rho$

- 1 grand scan, 2^{19} points sampled



- Bounds->~50% EWK, 50% strong production

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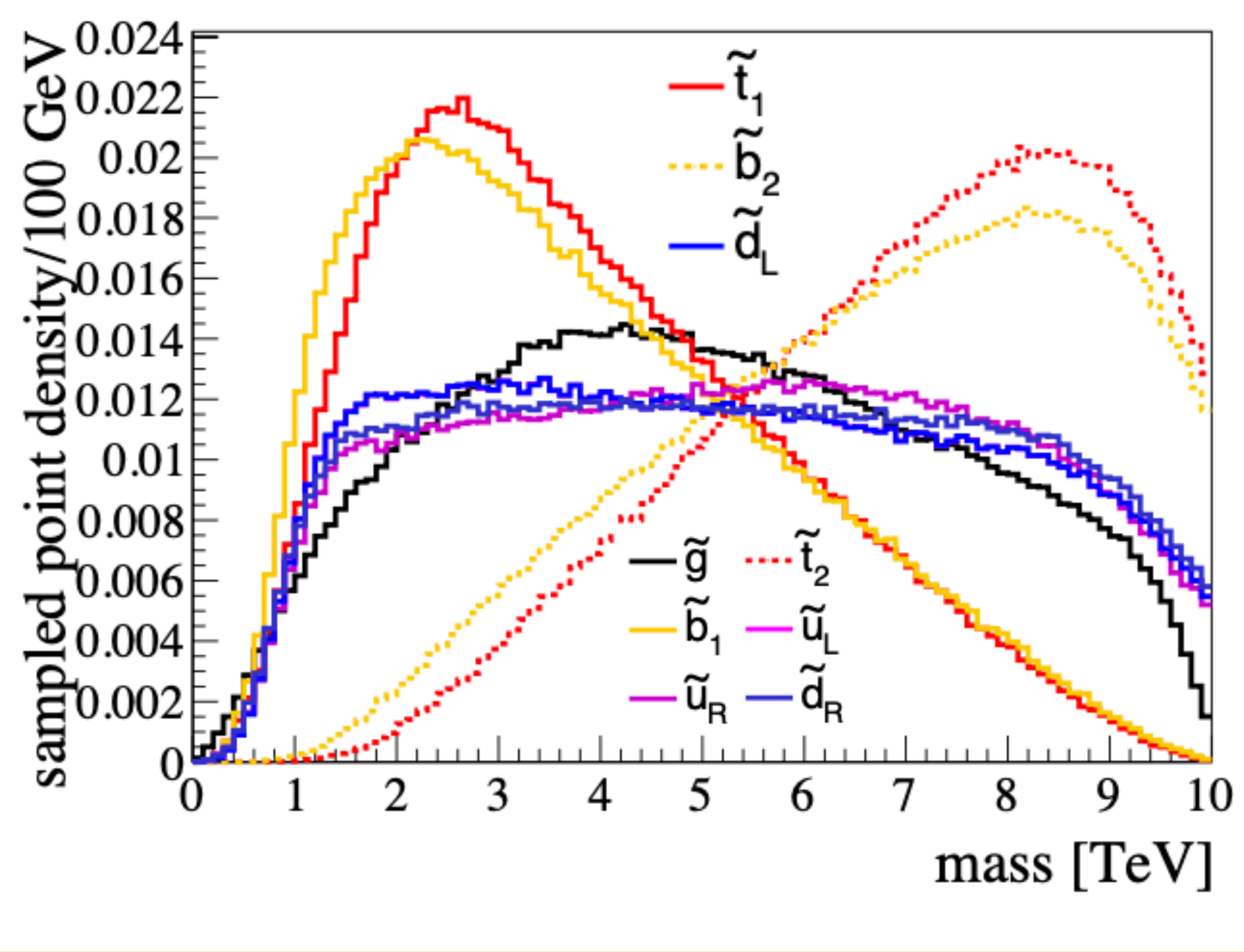


- Bounds->~50% EWK, 50% strong production

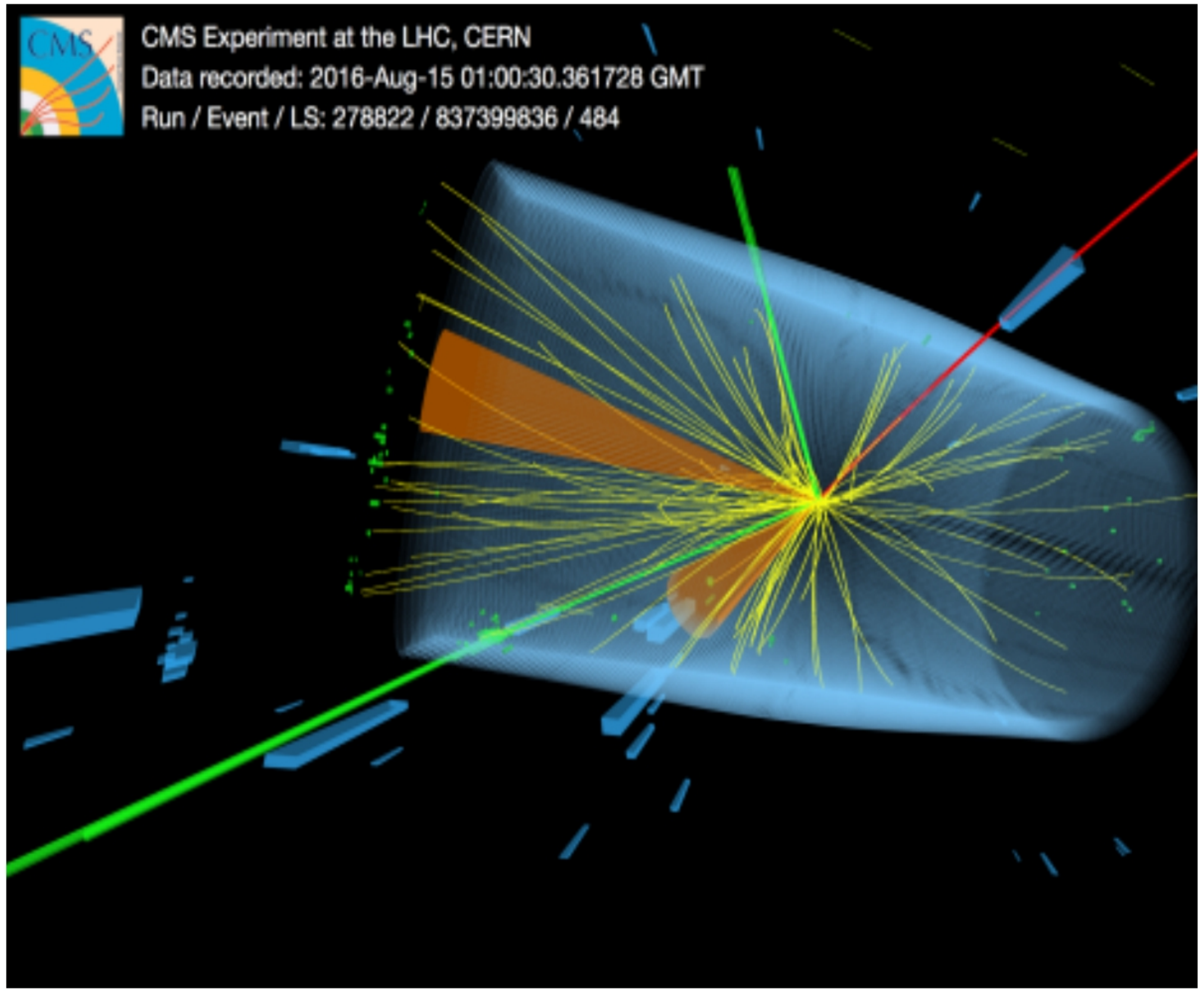
Two simulation engines

FullSim chain (1 event per minute)

- Detailed **Geant4**-based detector simulation customised for CMS, digitisation
- Full reconstruction as applied to data

FastSim chain (1 event per few seconds)

- Fast **alternative** to FullSim
- Fast particle propagation, analytical interaction models, tracking



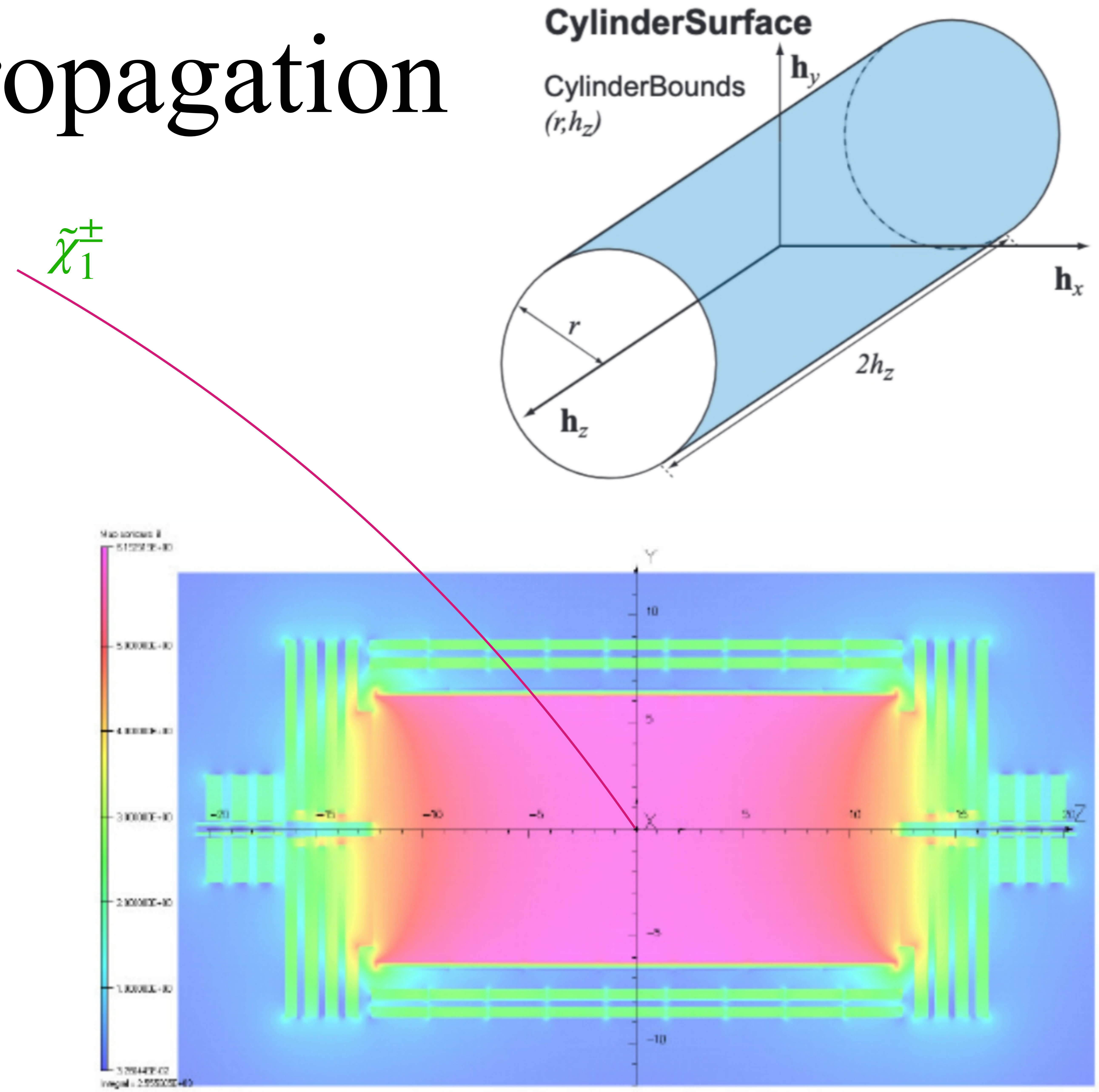
FastSim simplified propagation

Geometry

- Infinitesimally thin layers
- Particles interact on the boundaries but not in the volume

Transport

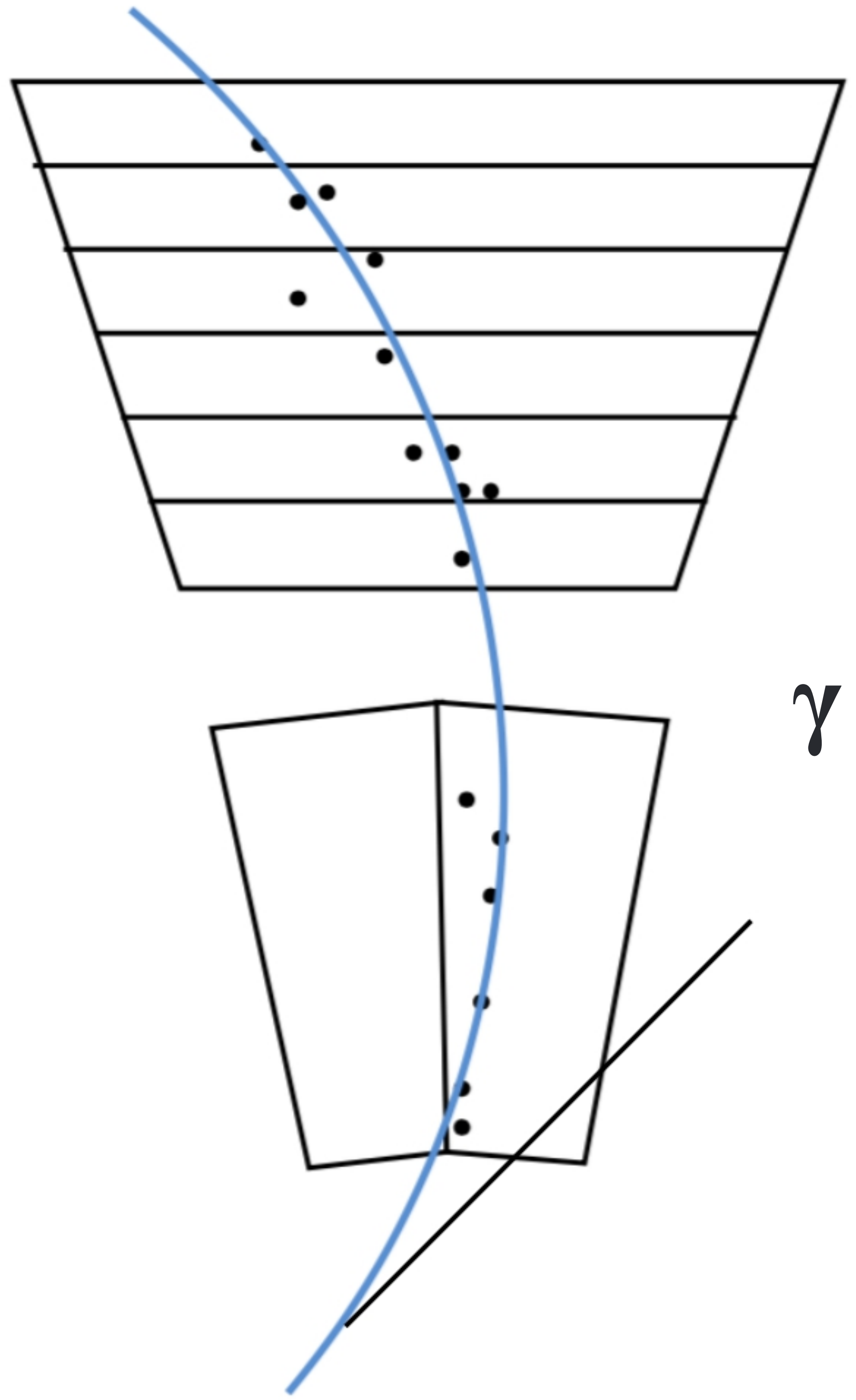
- Particles modeled after passing beam-pipe radius
- Detailed magnetic field map

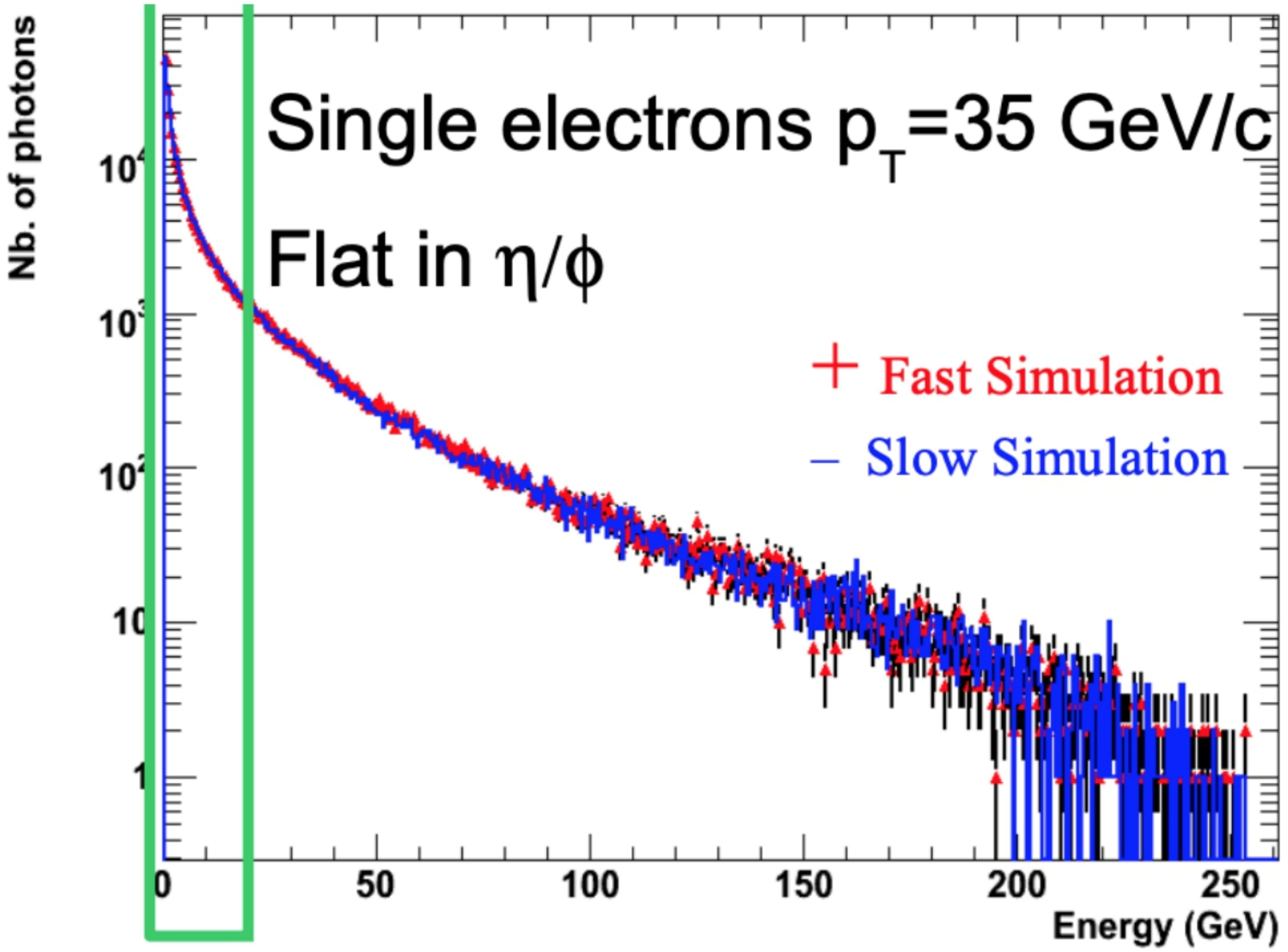


Analytical interaction models

Material interactions

- Energy loss by ionization
- Multiple coulomb scattering
- Bremsstrahlung
- $e^{\pm}$ conversion
- Elastic, inelastic nuclear interactions



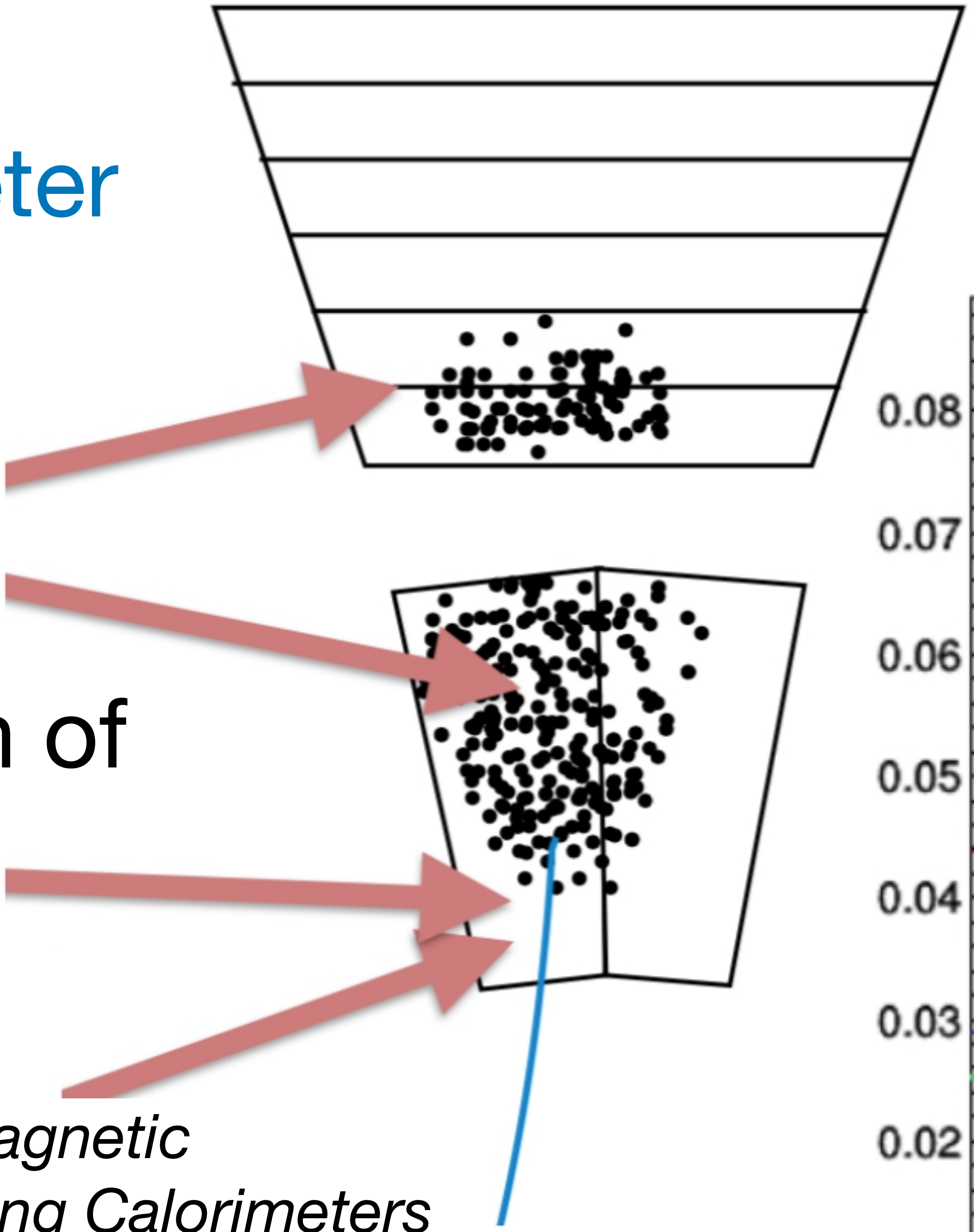


FastSim-CERN workshop

Calorimetry with GFLash

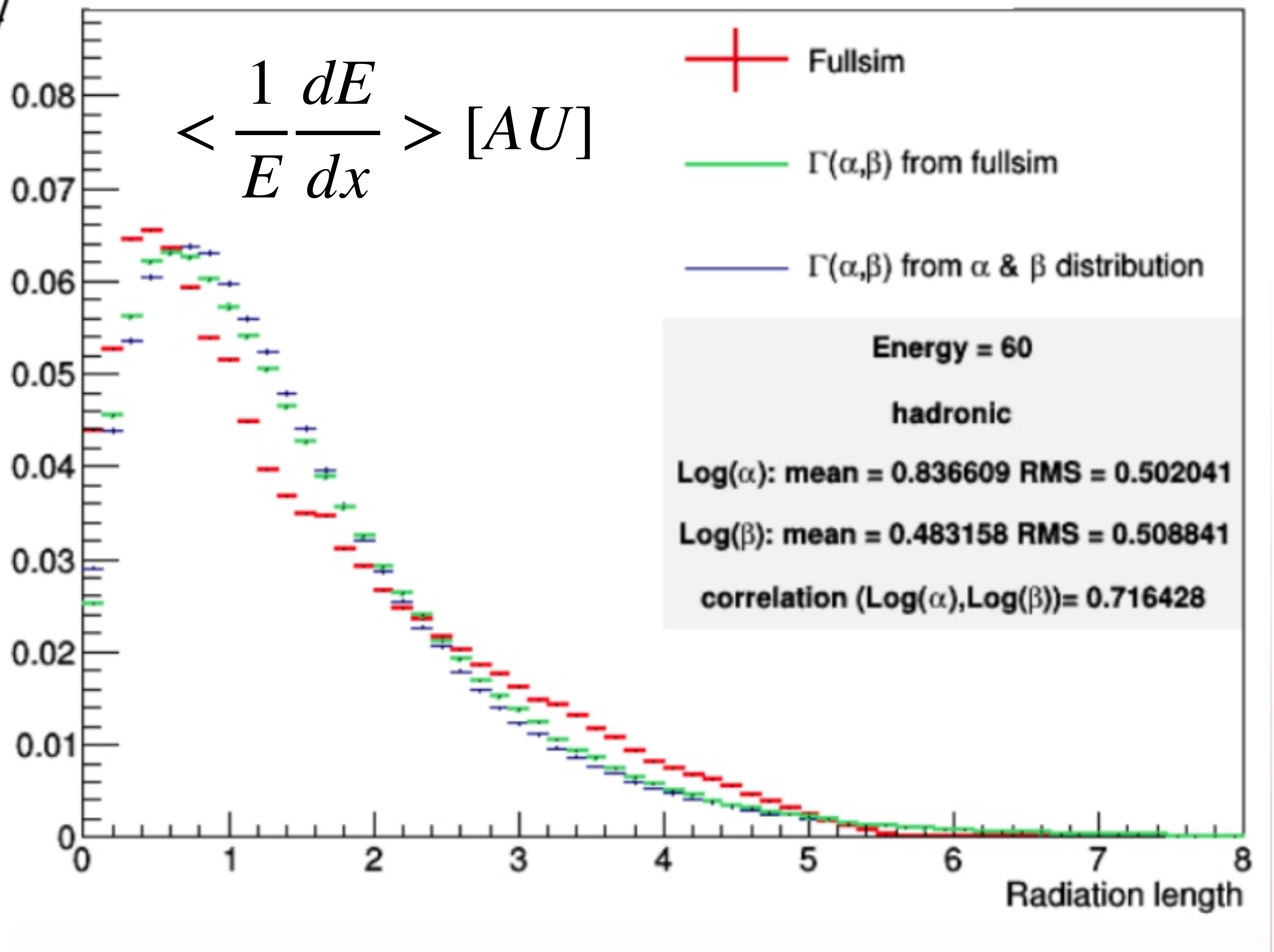
Particles reaching calorimeter

- Shower depositions modeled with probability distributions
- Start position as function of radiation lengths
- GFlash - G. Grindhammer

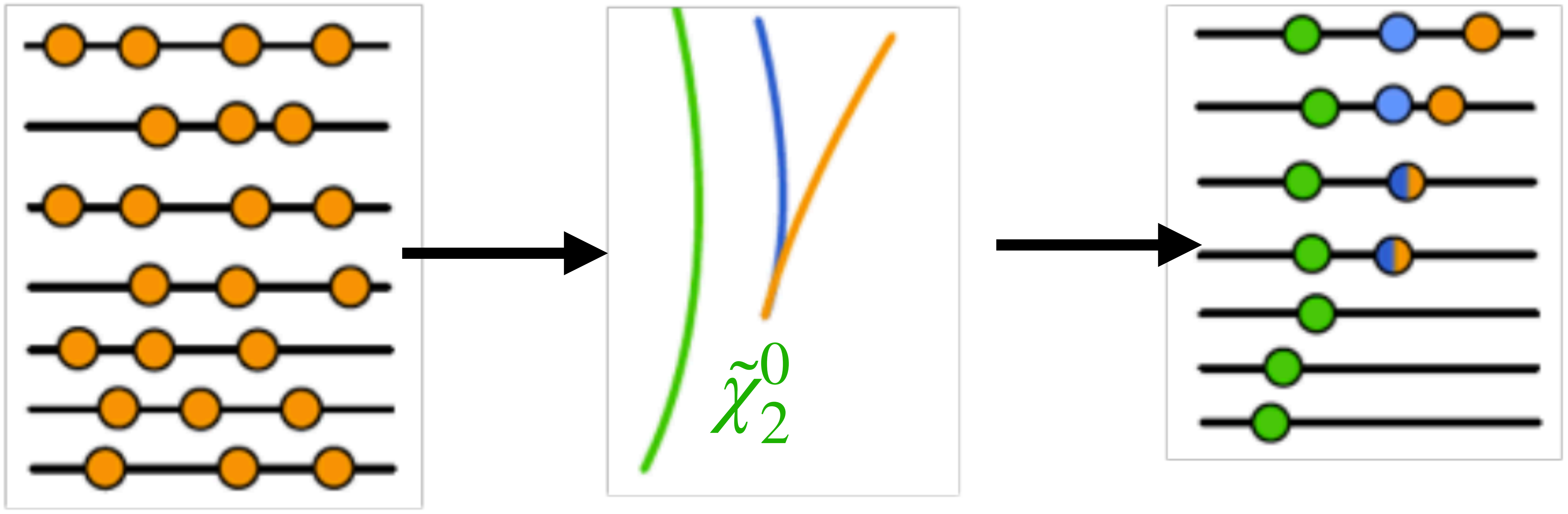


Parameterized Simulation of Electromagnetic Showers in Homogeneous and Sampling Calorimeters

  - Gamma for longitudinal shower, 2-component for radial
  - Geometry-specific profiles



Fast Reconstruction

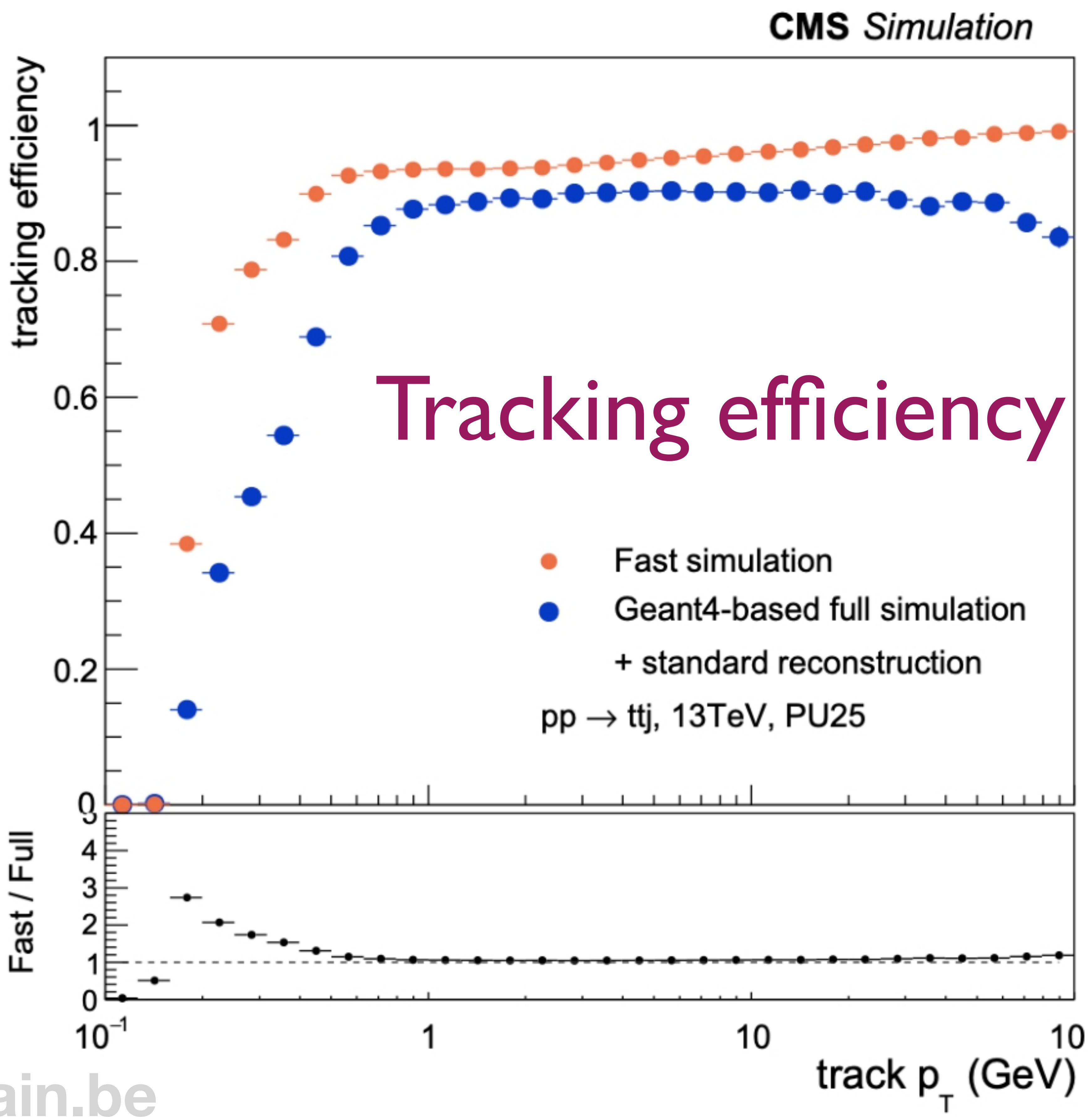


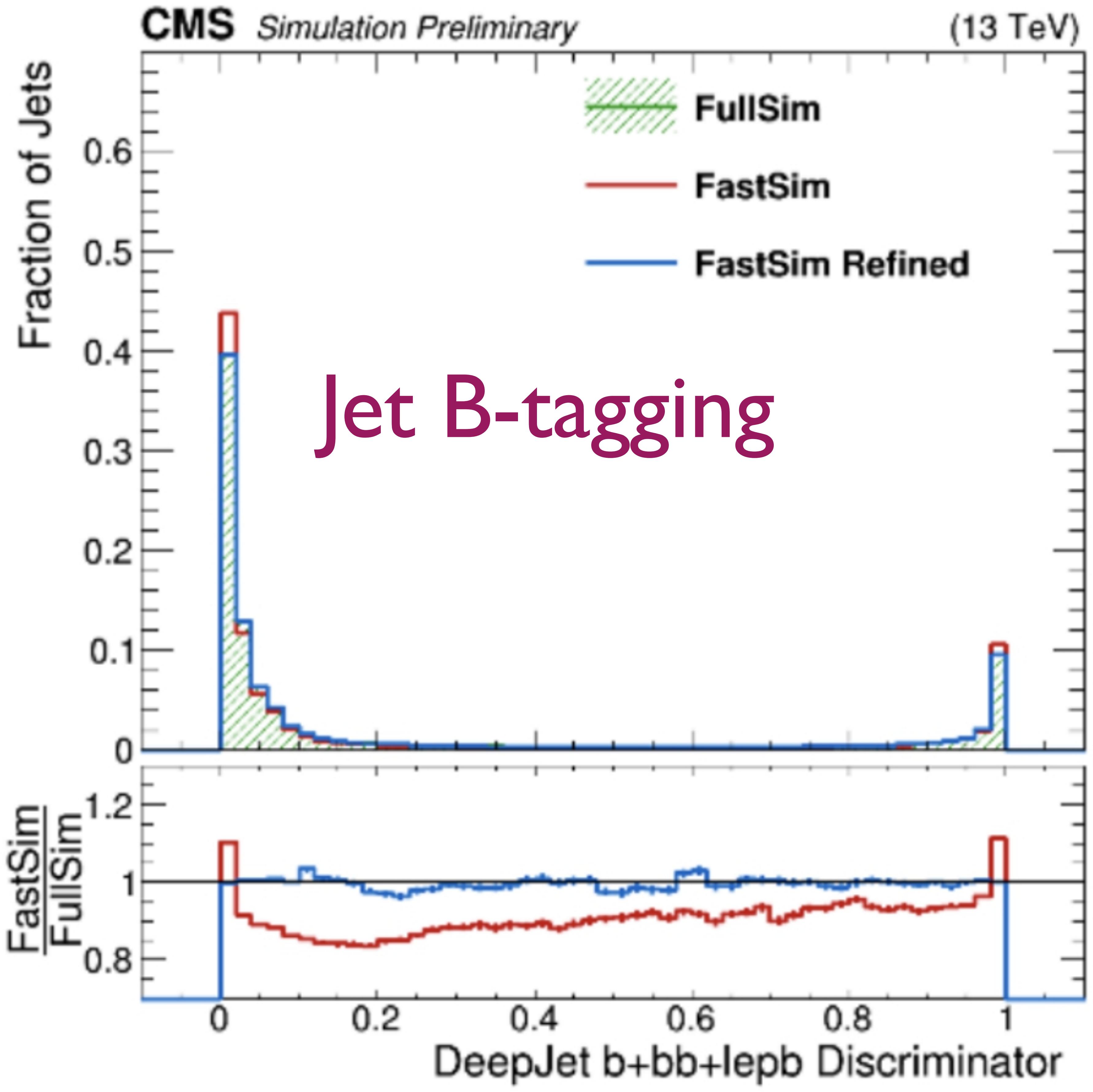
Fast tracking

- GEN-assisted hit/track association
- Iterative tracking run over hit subsets

Impact on performance

- x5 speed-up in reconstruction
- Underestimates fake-rate, biases b-tagging

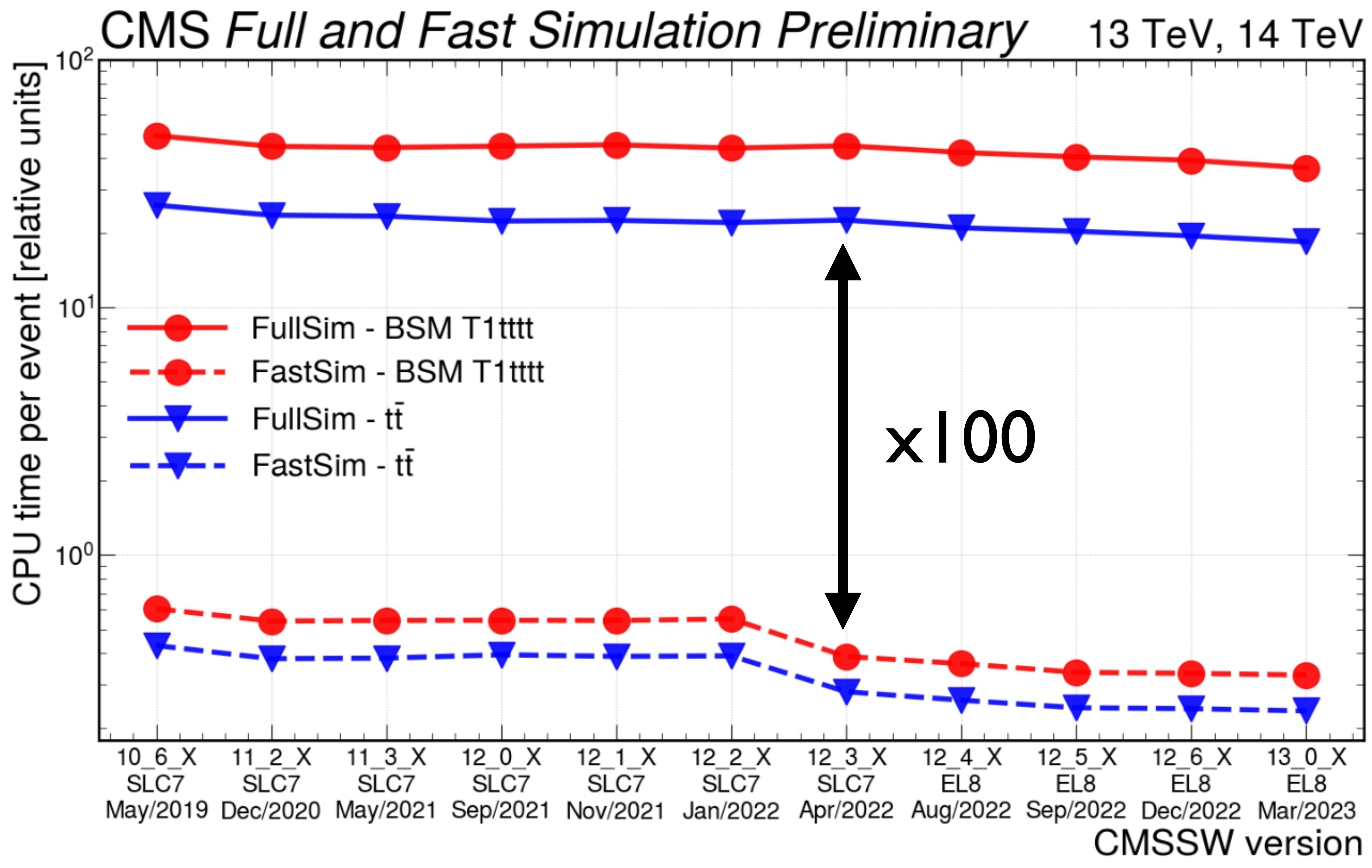




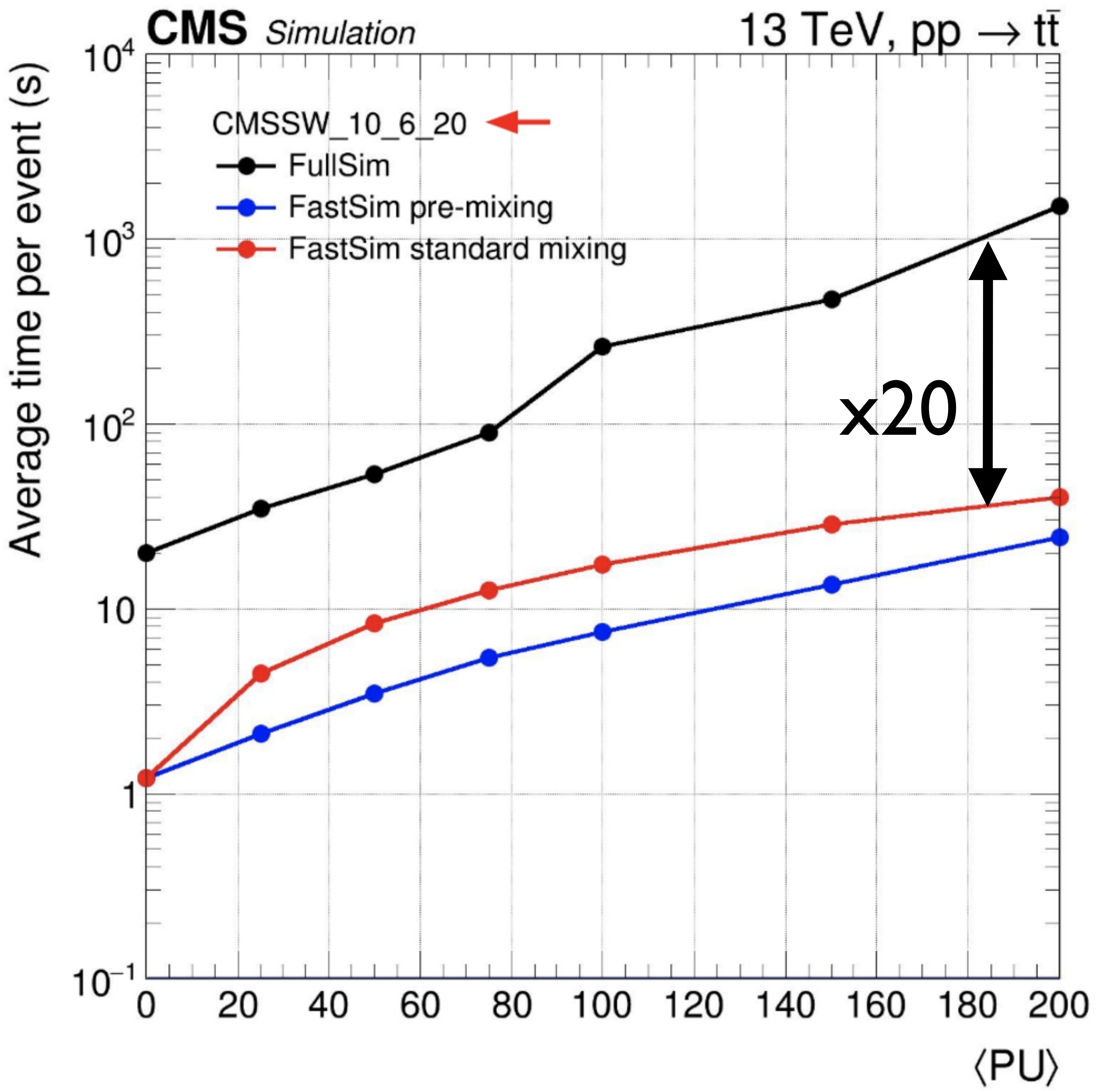
Sam Bein - samuel.bein@uclouvain.be

Events/second FastSim and FullSim

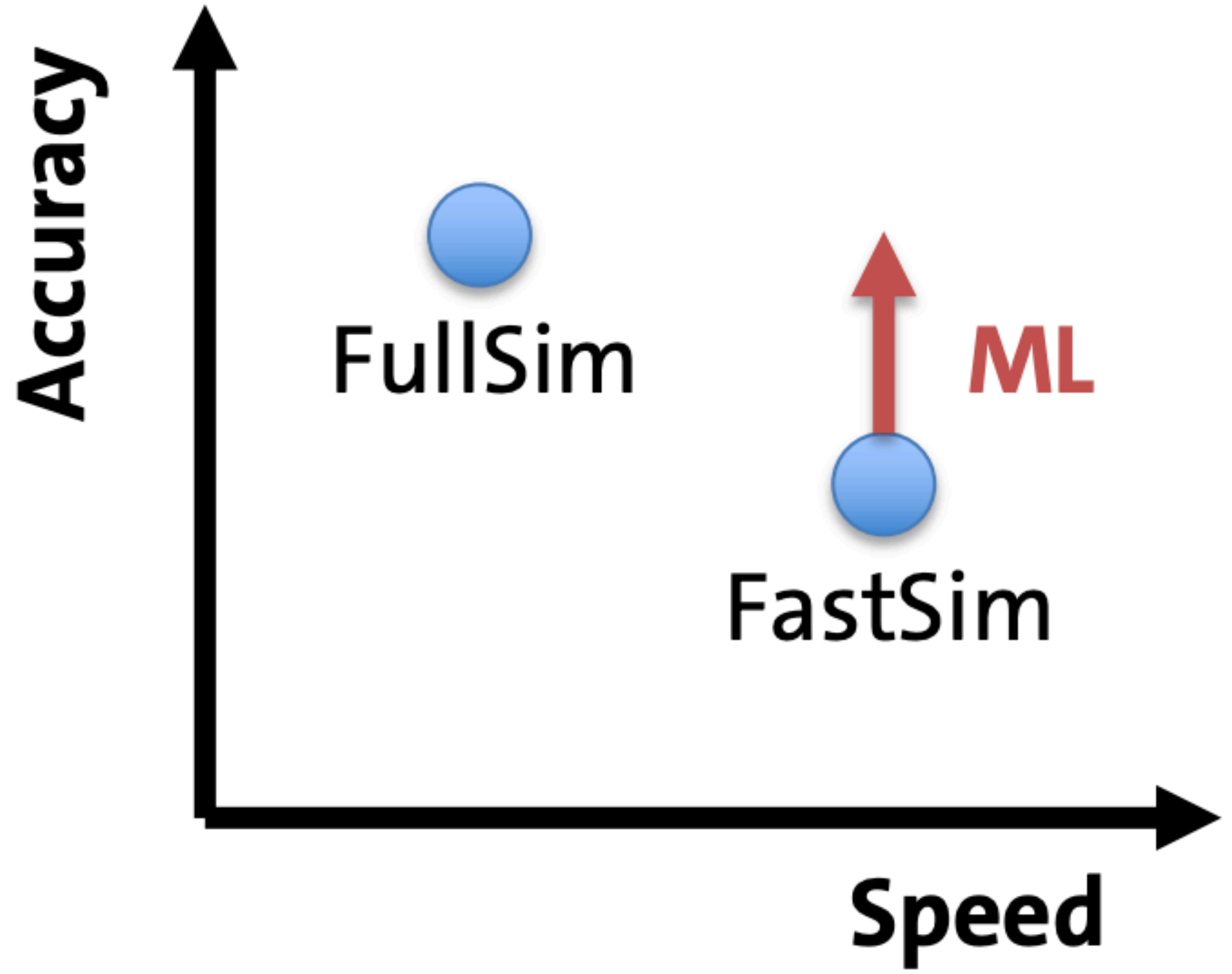
Detector step



Complete chain

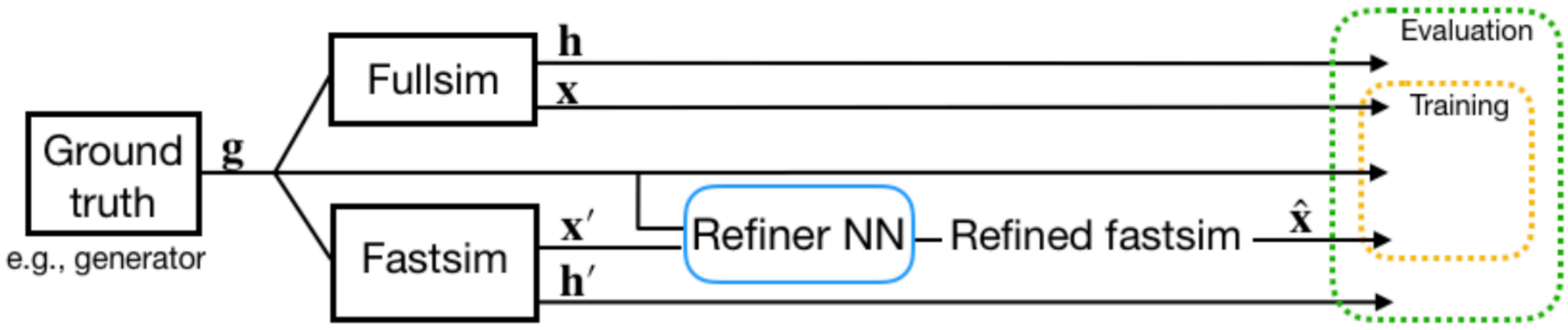


Regression based refinement



Ansatz

- Apply ML with ample domain knowledge to yield accurate, detailed fast simulation
- Tweak the final output of the FastSim so that it better matches FullSim
  - *Fast Perfekt: regression-based refinement of FastSim* - arXiv:2410.15992



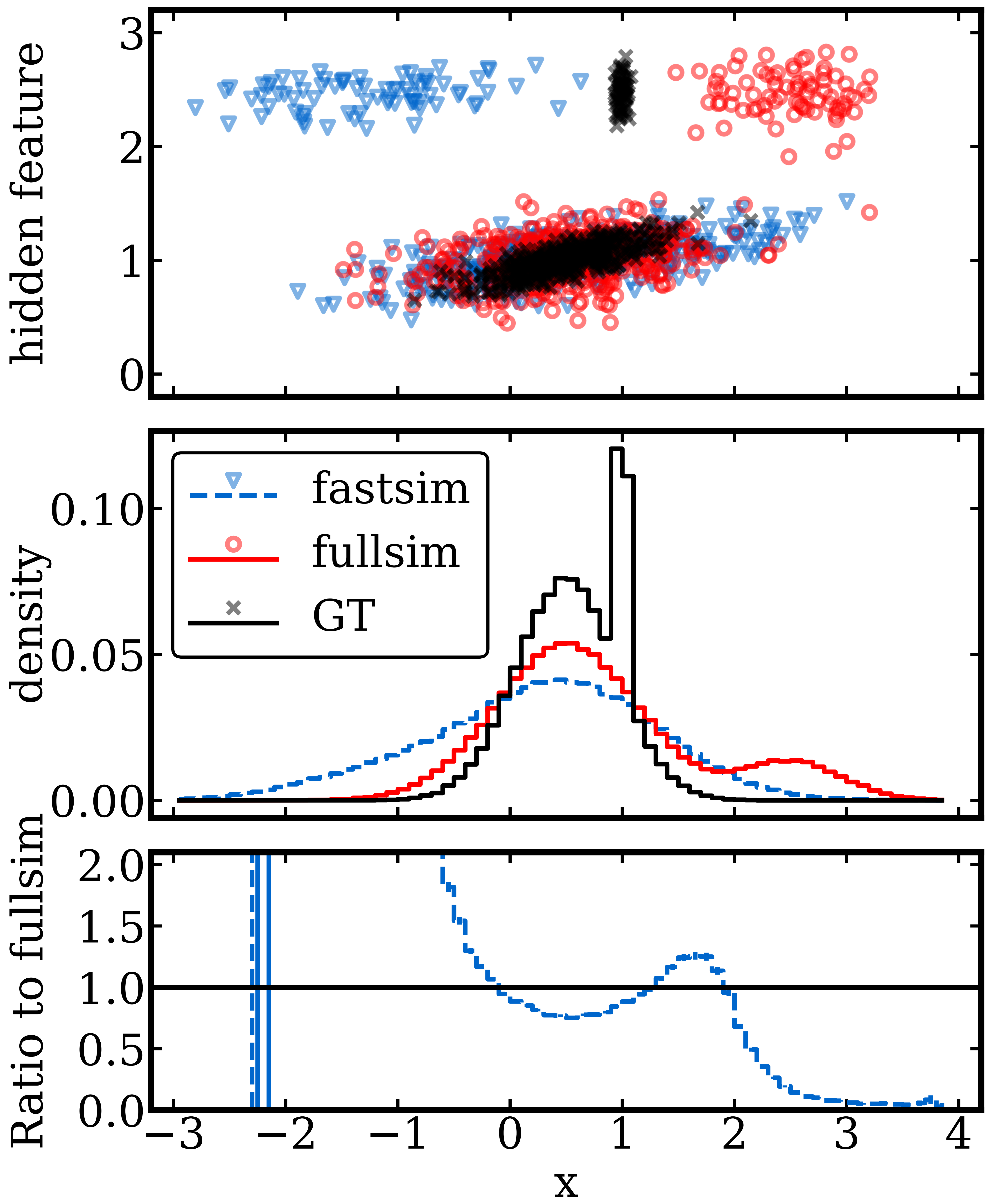
Fast Perfekt

2-dimensional analytical example

- x: Feature to be refined
- h: Hidden feature to be examined
- GT: ground truth (generator truth)
  - there is GT for x and h
- Two populations: big and small
- Unique smearing and bias for “fullsim” and “fastsim” for each population

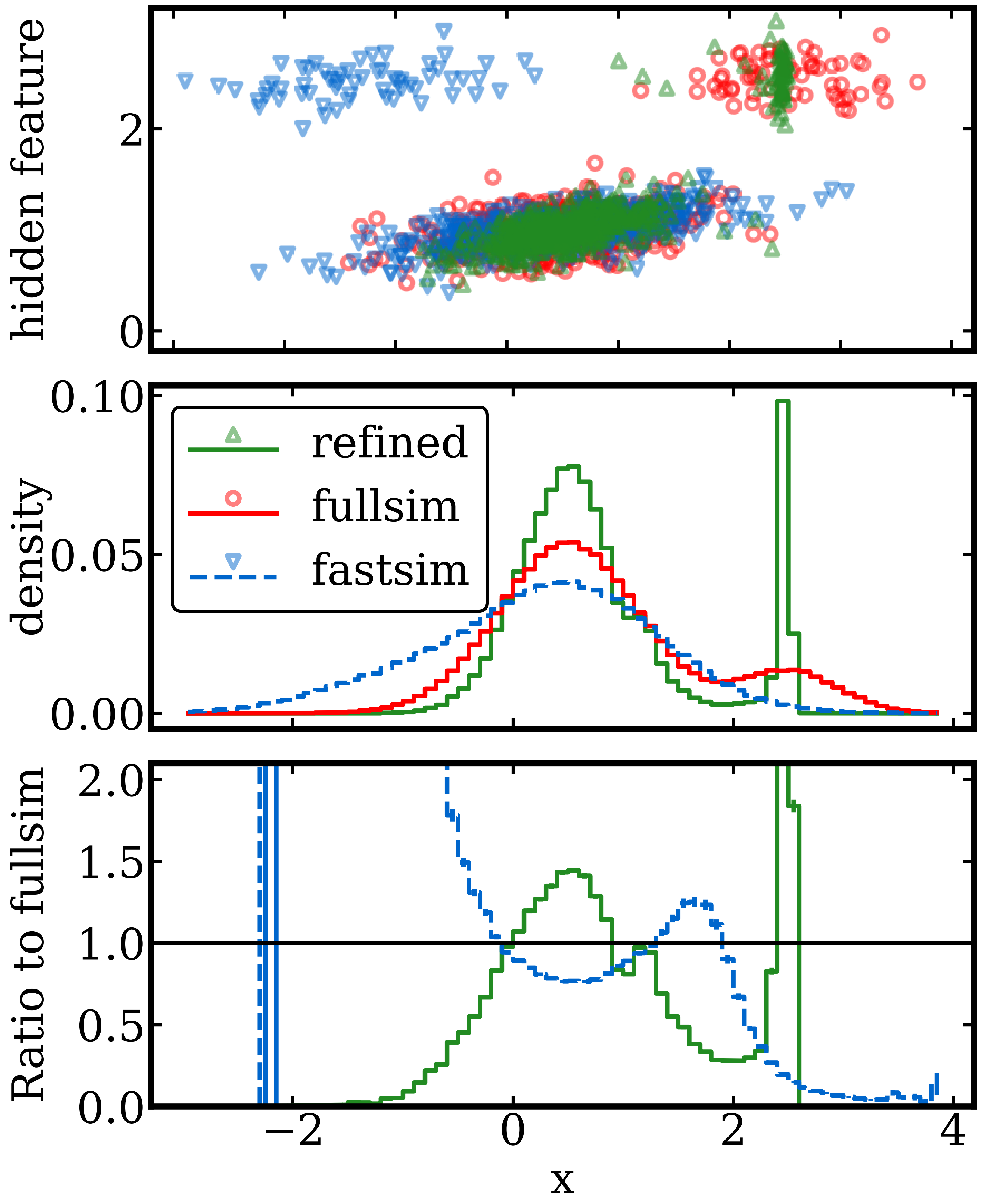
$$G_L \sim \mathcal{N}(\mu_L, \Sigma_L), \quad G_s \sim \mathcal{N}(\mu_s, \Sigma_s)$$

$$s_{\text{fast}} \sim \mathcal{N}(0, \Sigma_{\text{fast}}),\ s_{\text{full}} \sim \mathcal{N}(0, \Sigma_{\text{full}})$$



Fast Perfekt loss

MSE-only training



Mean squared error (MSE)

- Compare each fastsim data point with its fullsim

$$\mathrm{MSE}(\theta) = \frac{1}{m}\sum_{i=1}^{m} ||\hat{\mathbf{x}}_{\mathbf{i}}(\theta) - \mathbf{x}_{\mathbf{i}}||_2^2$$

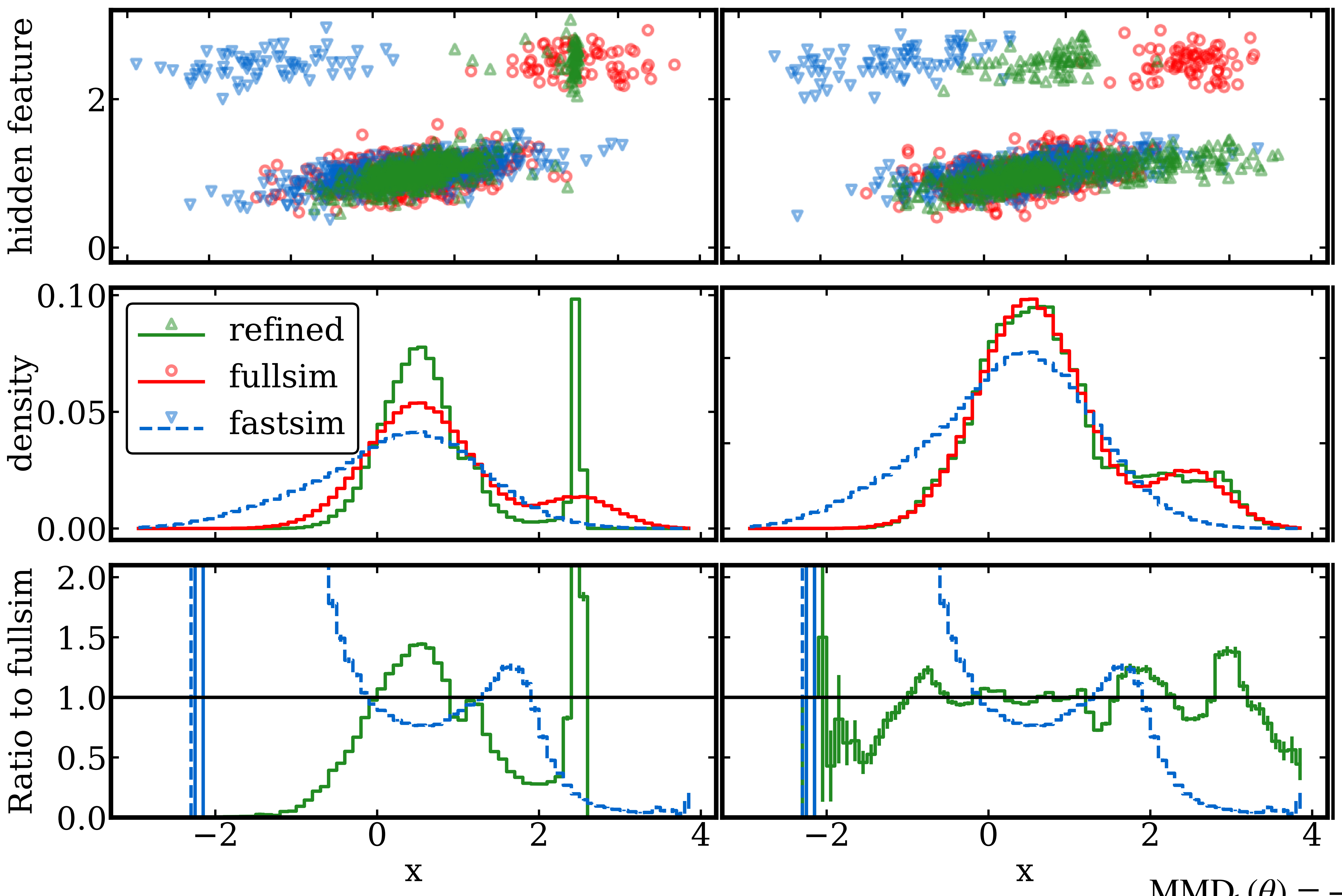
  - Good for bias correction, bad for tails

arXiv:2410.15992

Fast Perfekt loss

MSE-only training

MMD-only training



Mean squared error (MSE)

- Compare each fastsim data point with its fullsim

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  - Good for bias correction, bad for tails

Maximum mean discrepancy

- Compare each fastsim data point with its fullsim
- Good for PDFs of input x
- Unconstrained

$$\mathrm{MMD_b}(\theta) = \frac{1}{m^2}\sum_{i,j=1}^{m} k(\mathbf{a_i}, \mathbf{a_j}) + \frac{1}{m^2}\sum_{i,j=1}^{m} k(\hat{\mathbf{a}}_{\mathbf{i}}(\theta), \hat{\mathbf{a}}_{\mathbf{j}}(\theta)) - \frac{2}{m^2}\sum_{i,j=1}^{m} k(\mathbf{a_i}, \hat{\mathbf{a}}_{\mathbf{j}}(\theta))$$

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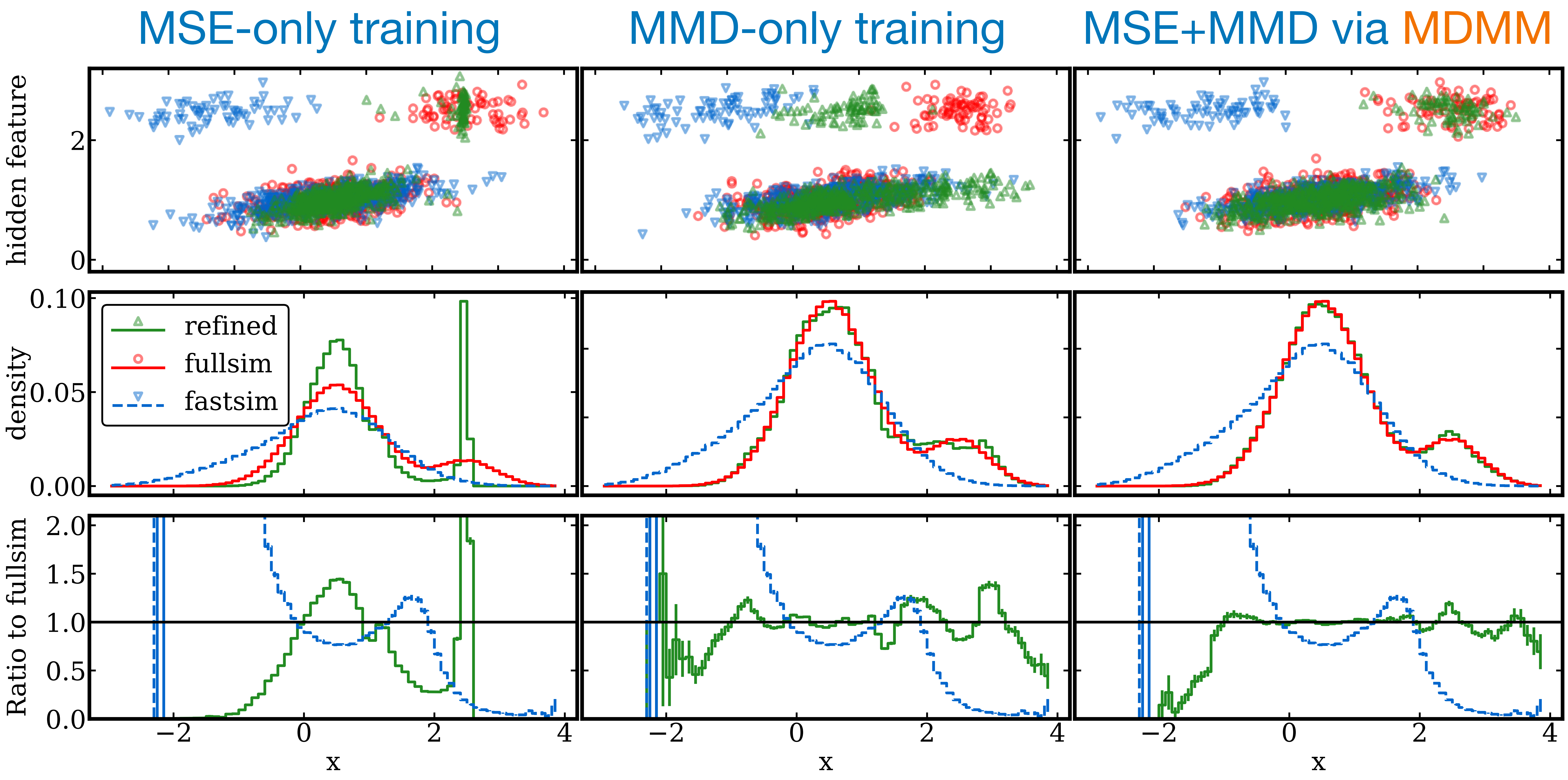
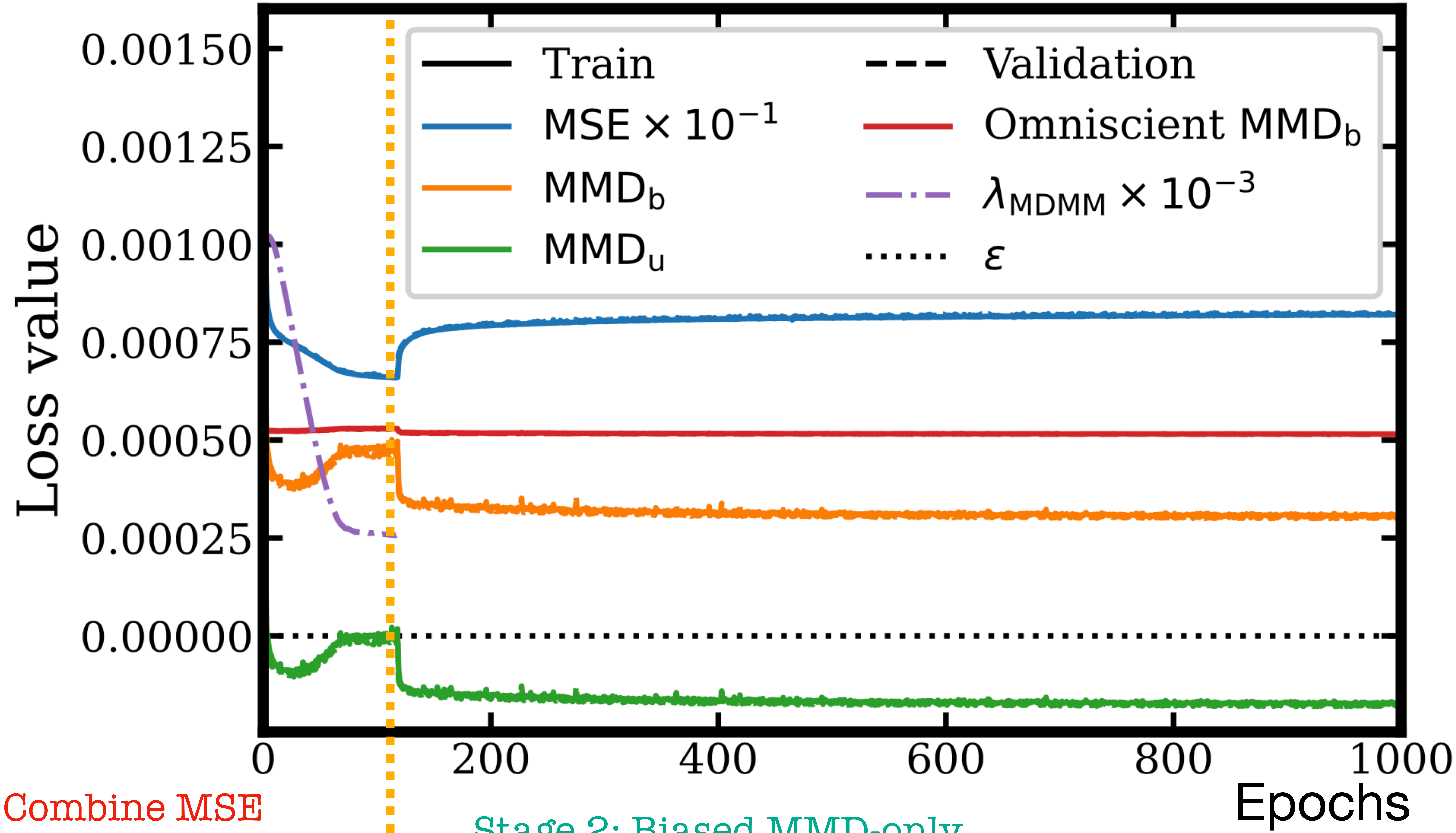
arXiv:2410.15992

Fast Perfekt loss

Modified differential method of multipliers
blog - place constraints on constraints!



Fast Perfekt 2-stage training



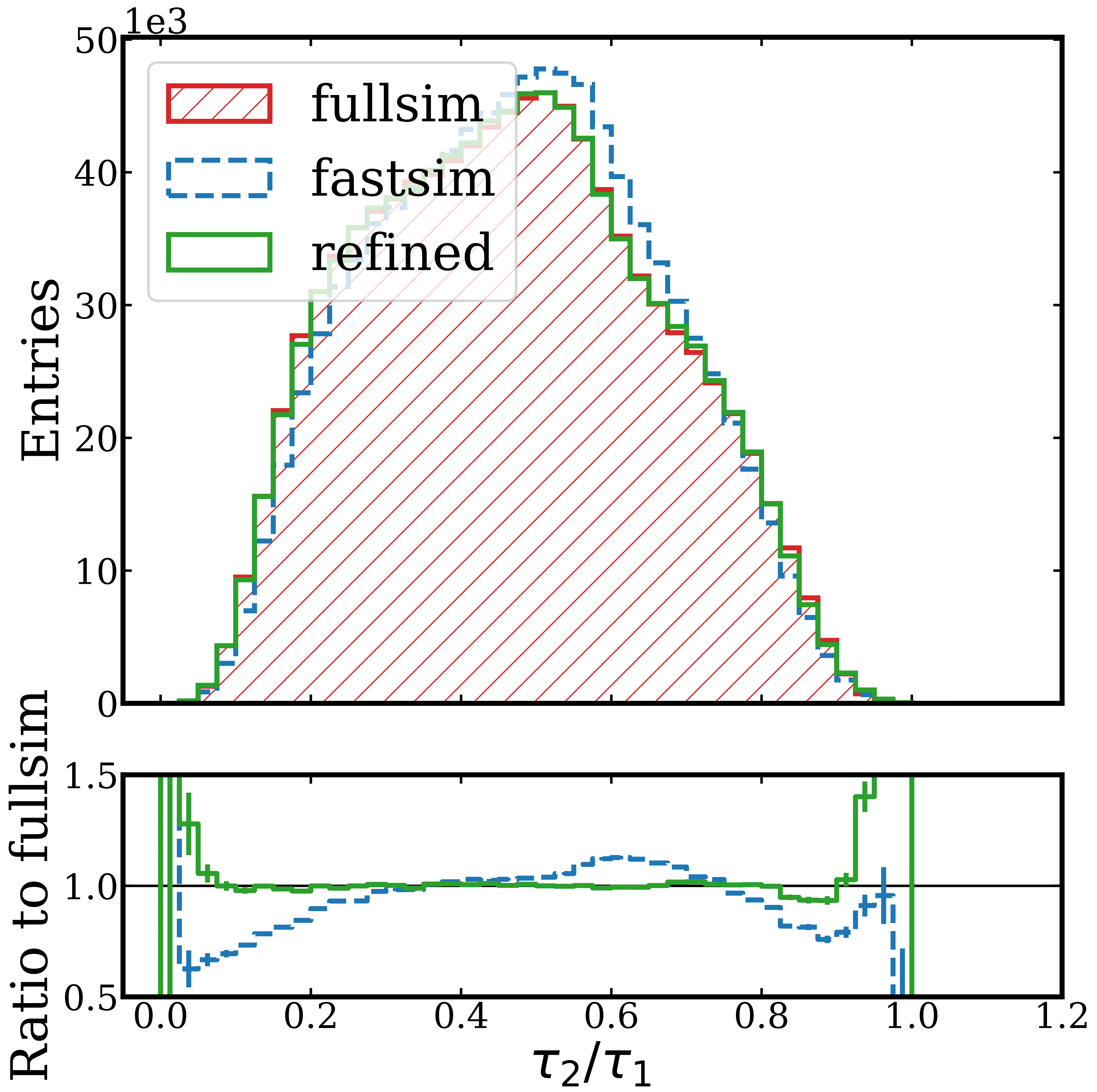
Stage 1: Combine MSE and unbiased MMD via MDMM with MMD=0

Stage 2: Biased MMD-only training until converged

Fast Perfekt loss

Delphes-based model

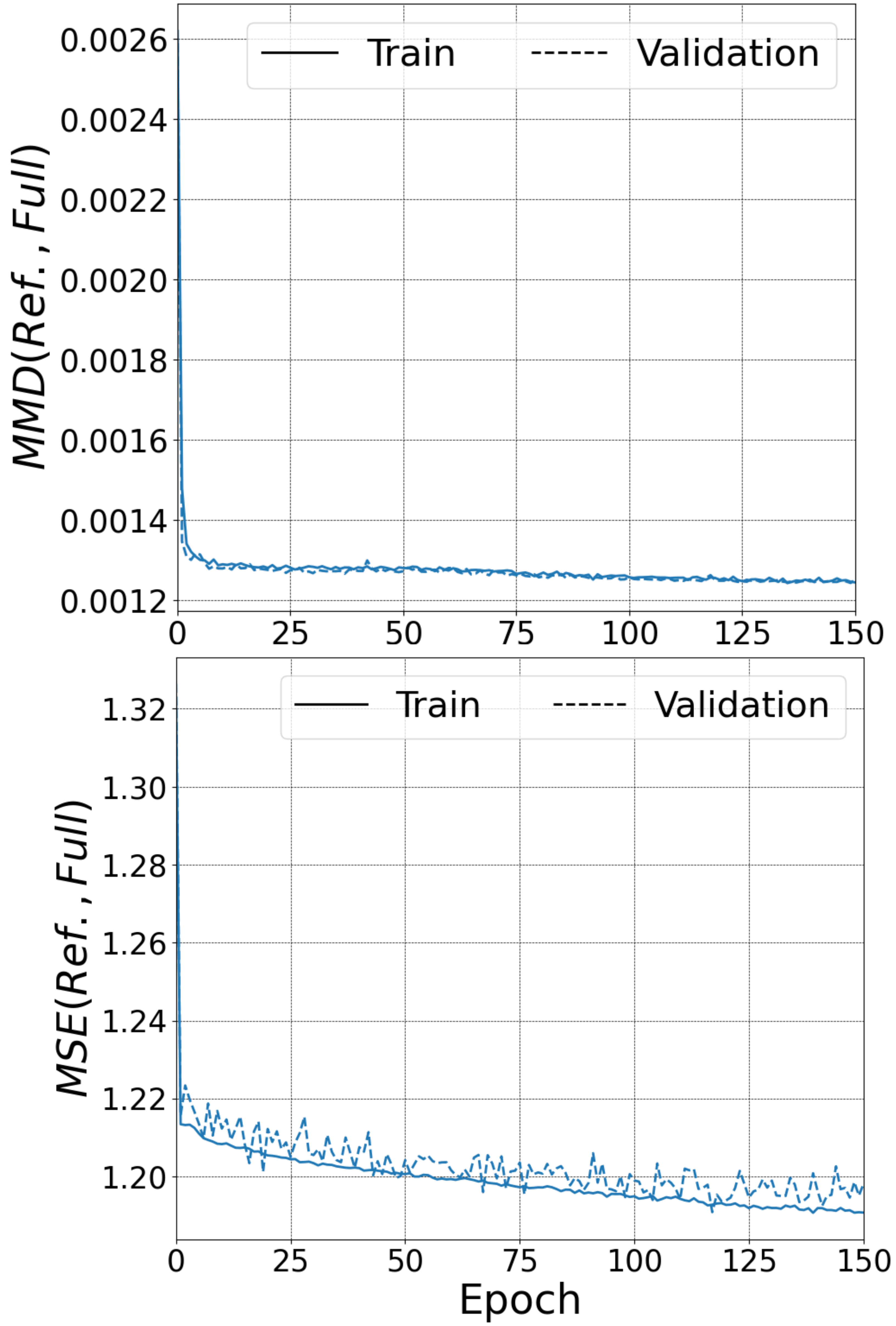
- Generate $t\bar{t}$ inclusively
- Process with
  - Delphes 3 (FullSim) arXiv:1307.6346
  - Modified Delphes 3 (remove E-dependent jet response - flat smear)
  - Refine n-Subjettiness
    - τ_1, τ_2, τ_3 ratios



Refine CMS FastSim jets

Apply Fast Perfekt to CMS jets

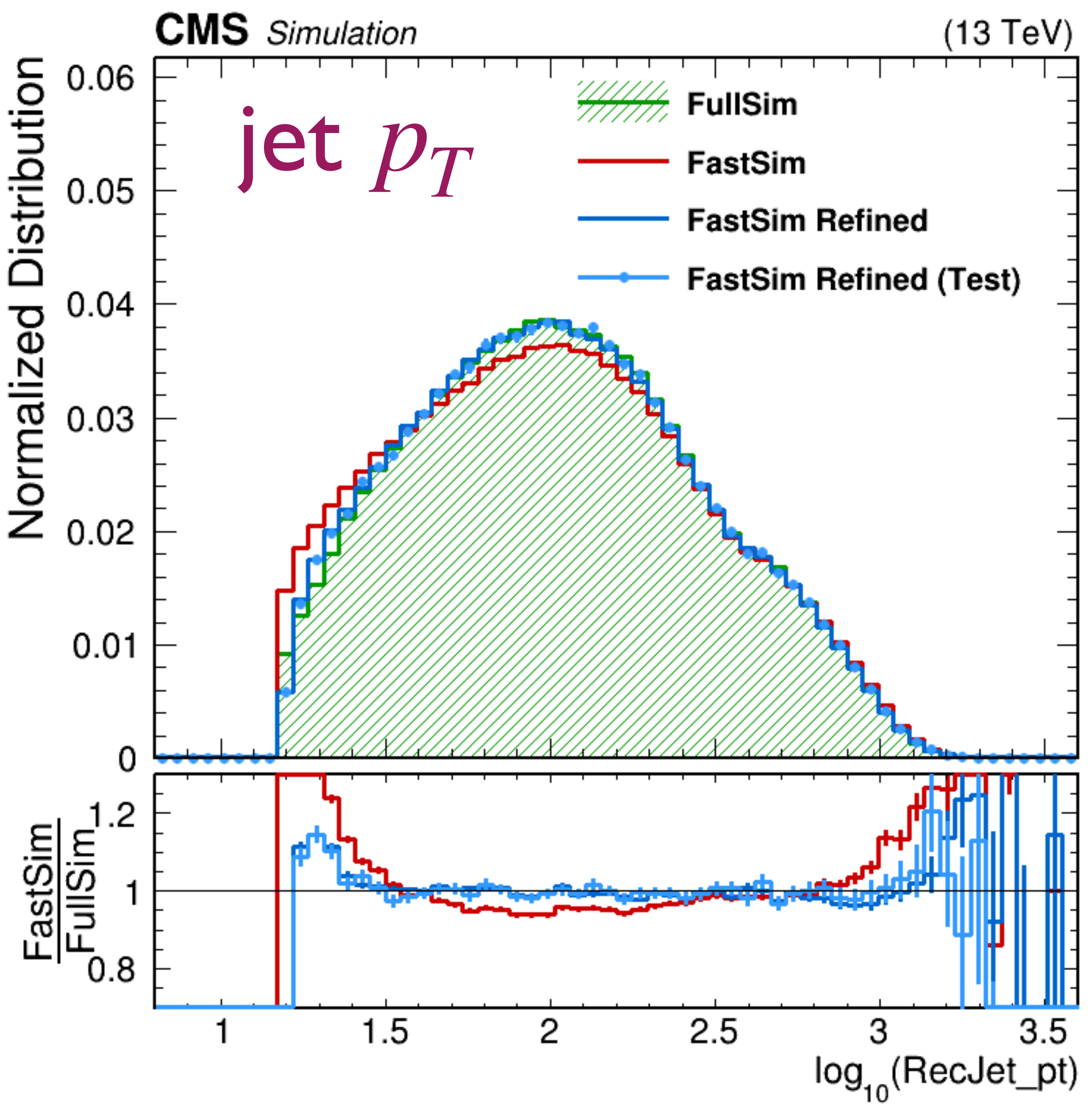
- Refine jets with regression NN
  - Kinematics, Flavour tagging variables
  - DeepJet, ParT Jet discriminators:
    - B, CvB, CvL, QG
  - Jet triplets: FastSim, FullSim, GEN
  - **Input**: FastSim jet+GEN jet p_T, η
  - **Output**: refined FastSim jet
- Single-stage MMD-based training

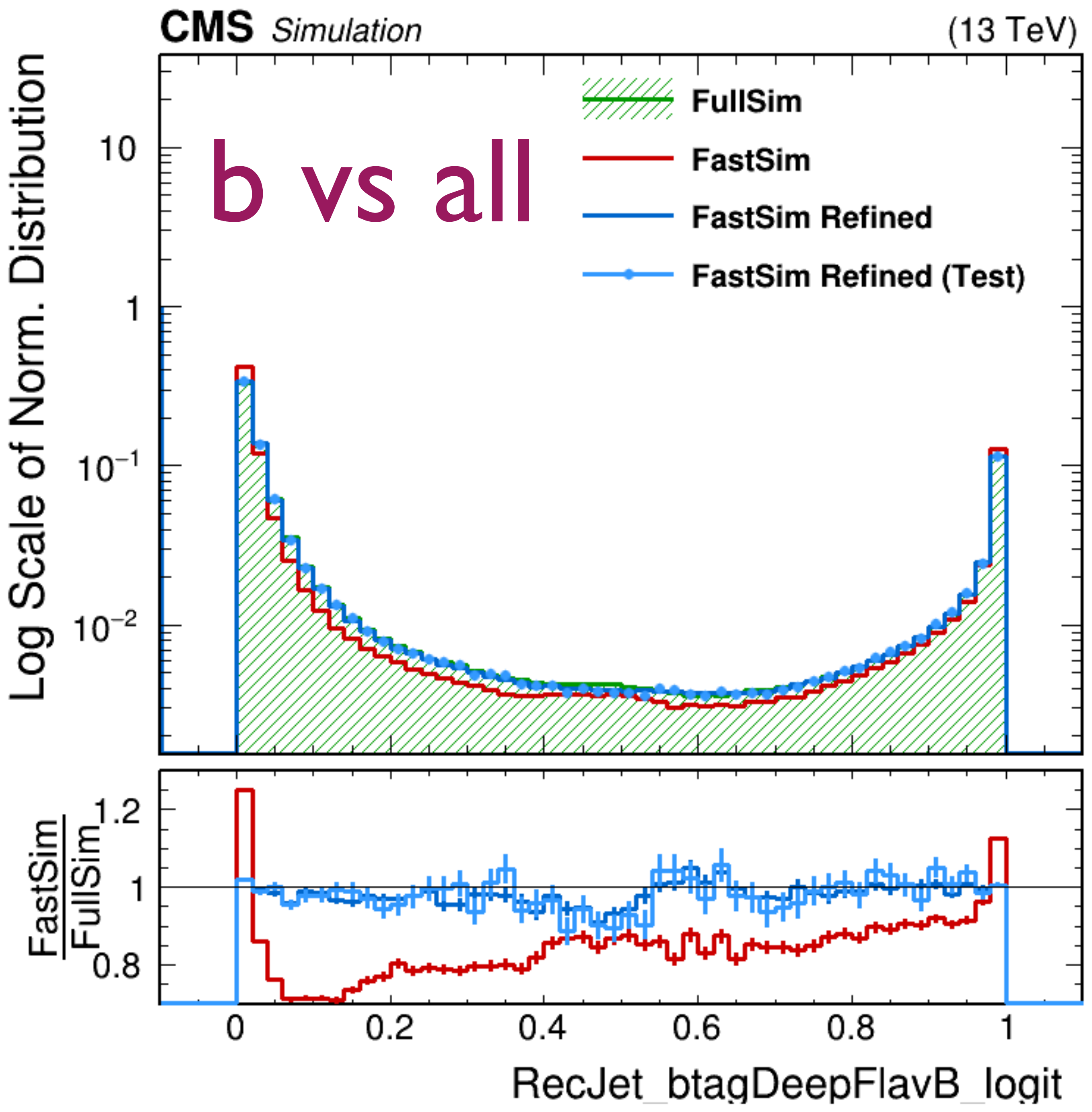


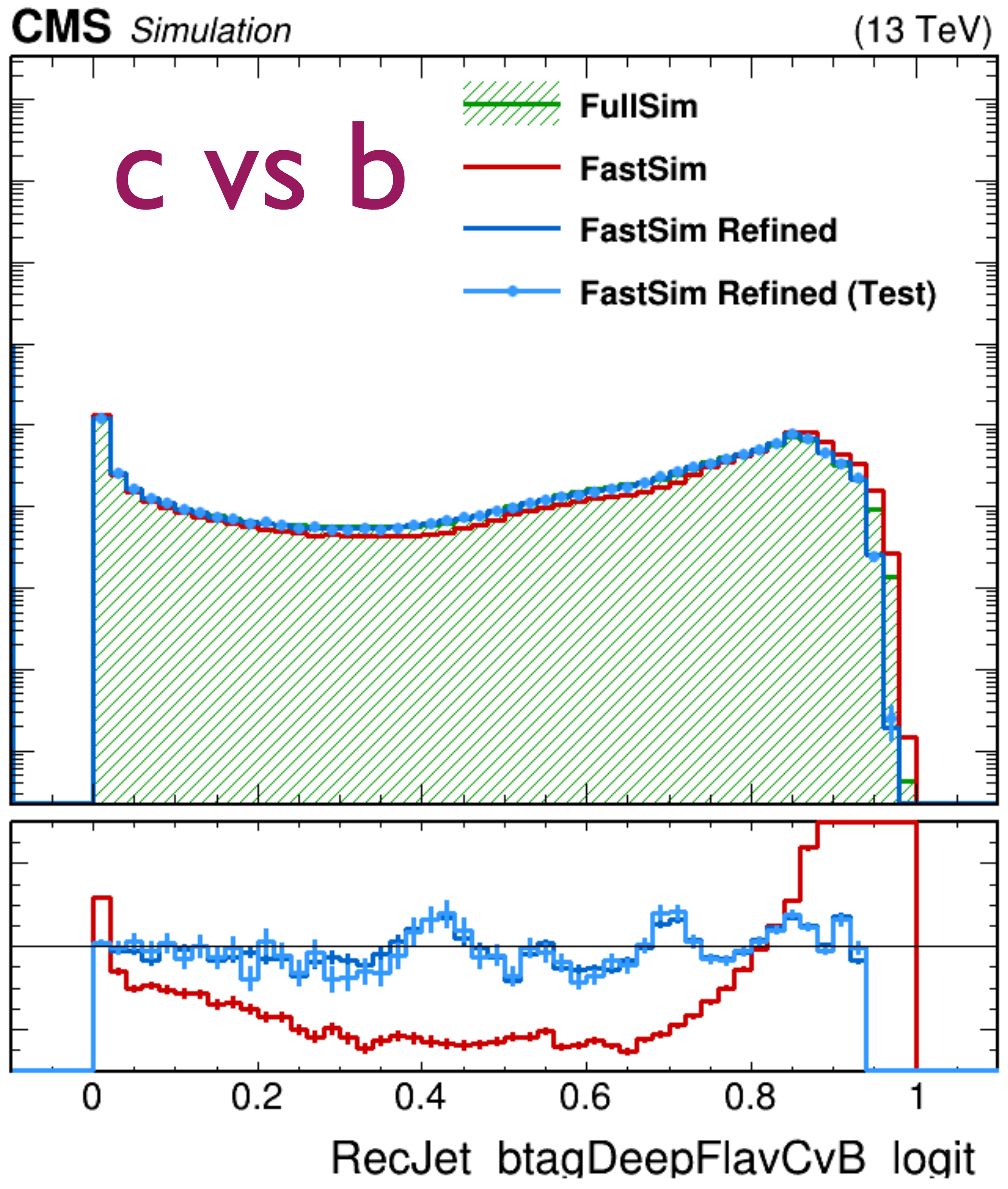
Refine CMS FastSim jets

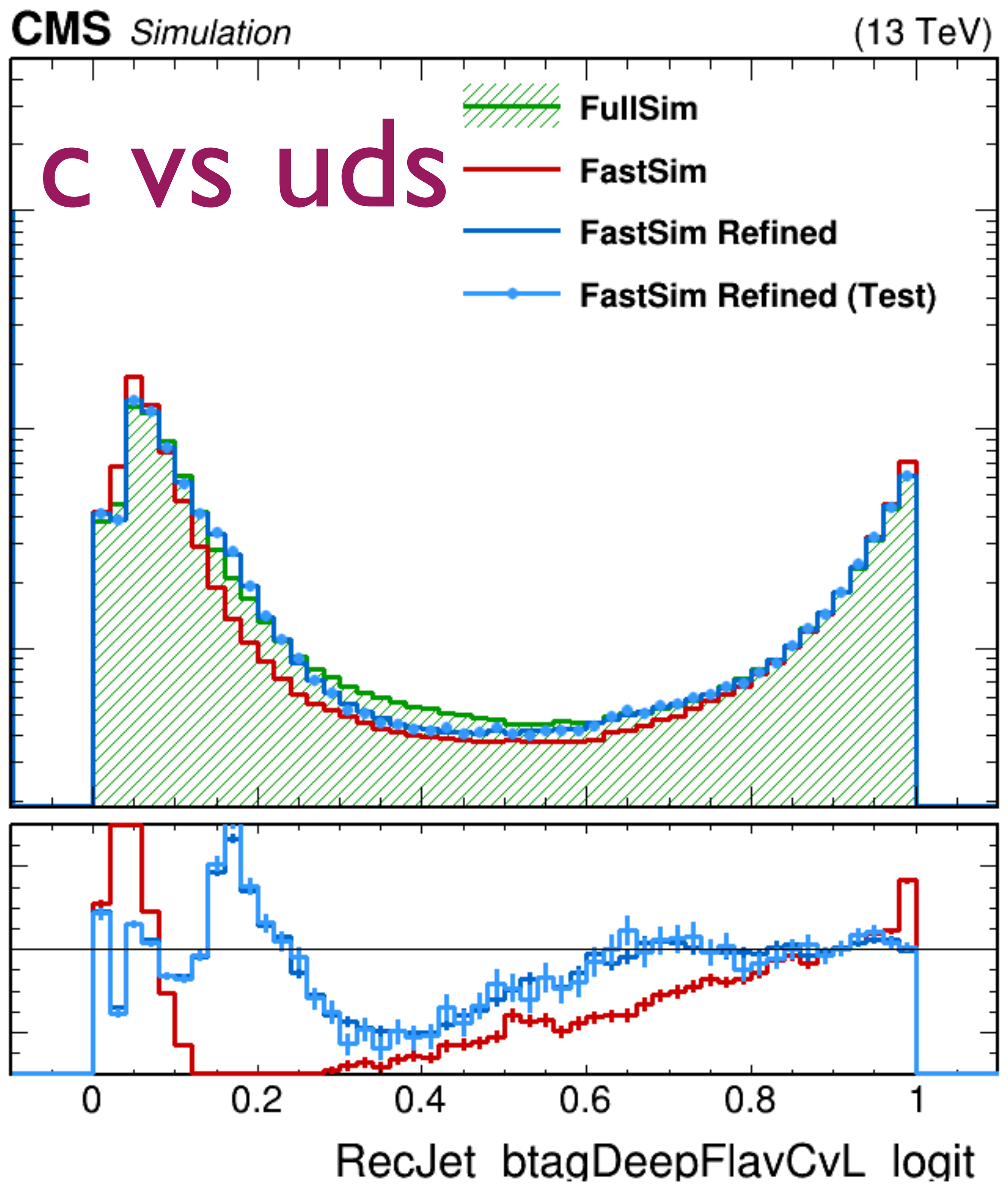
Comparing distributions

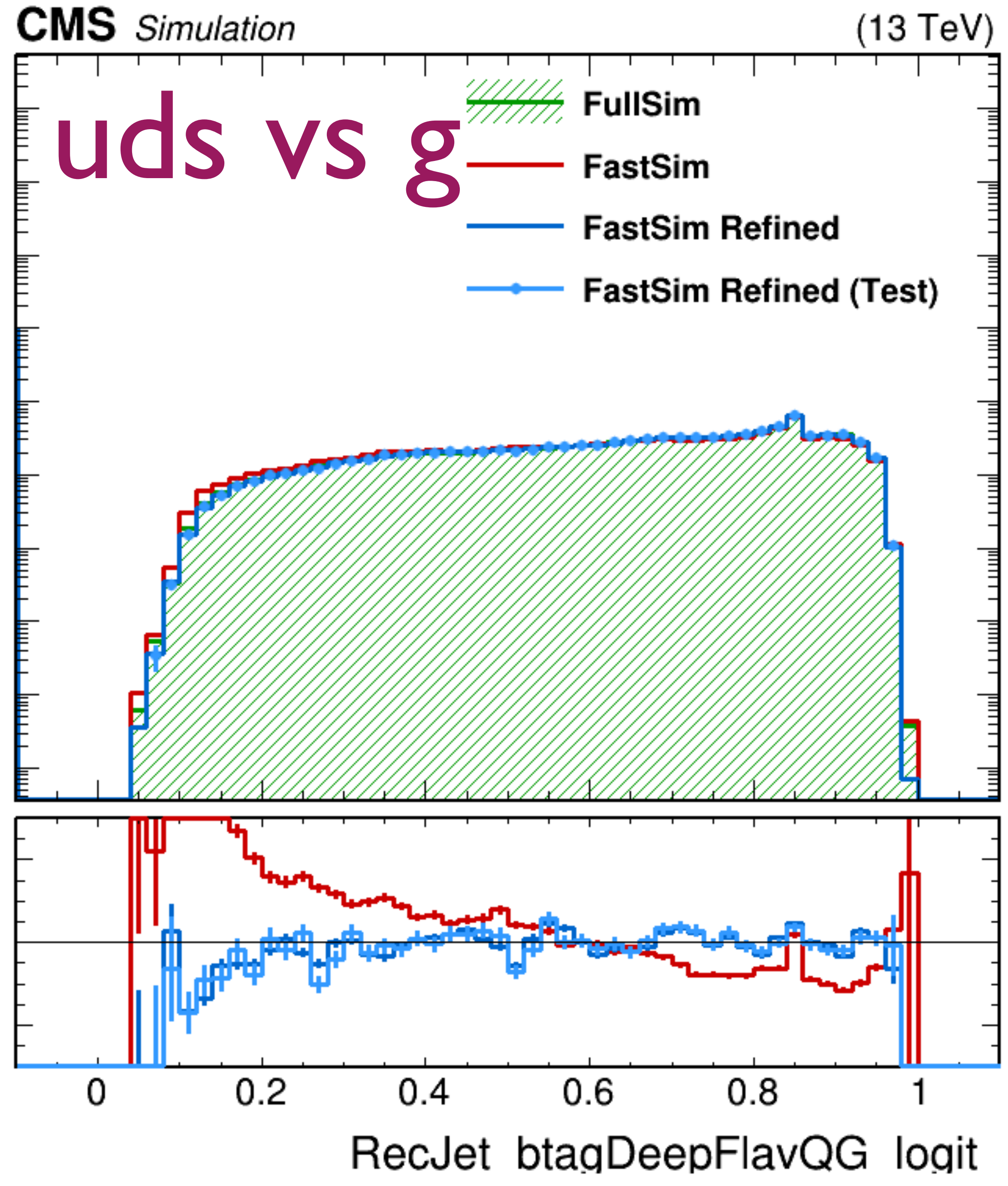
- Kinematics - p_T
- Jet flavour taggers (DeepJet)







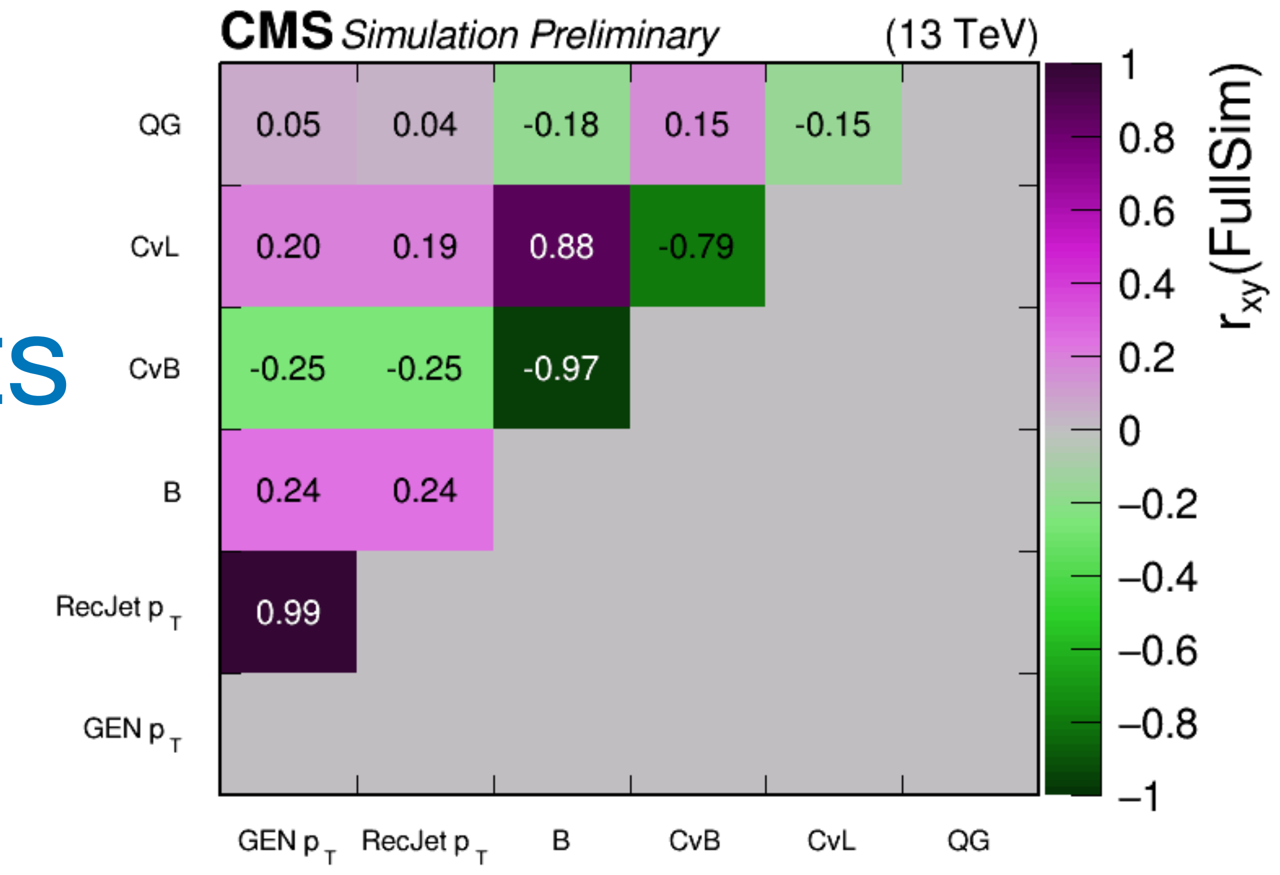


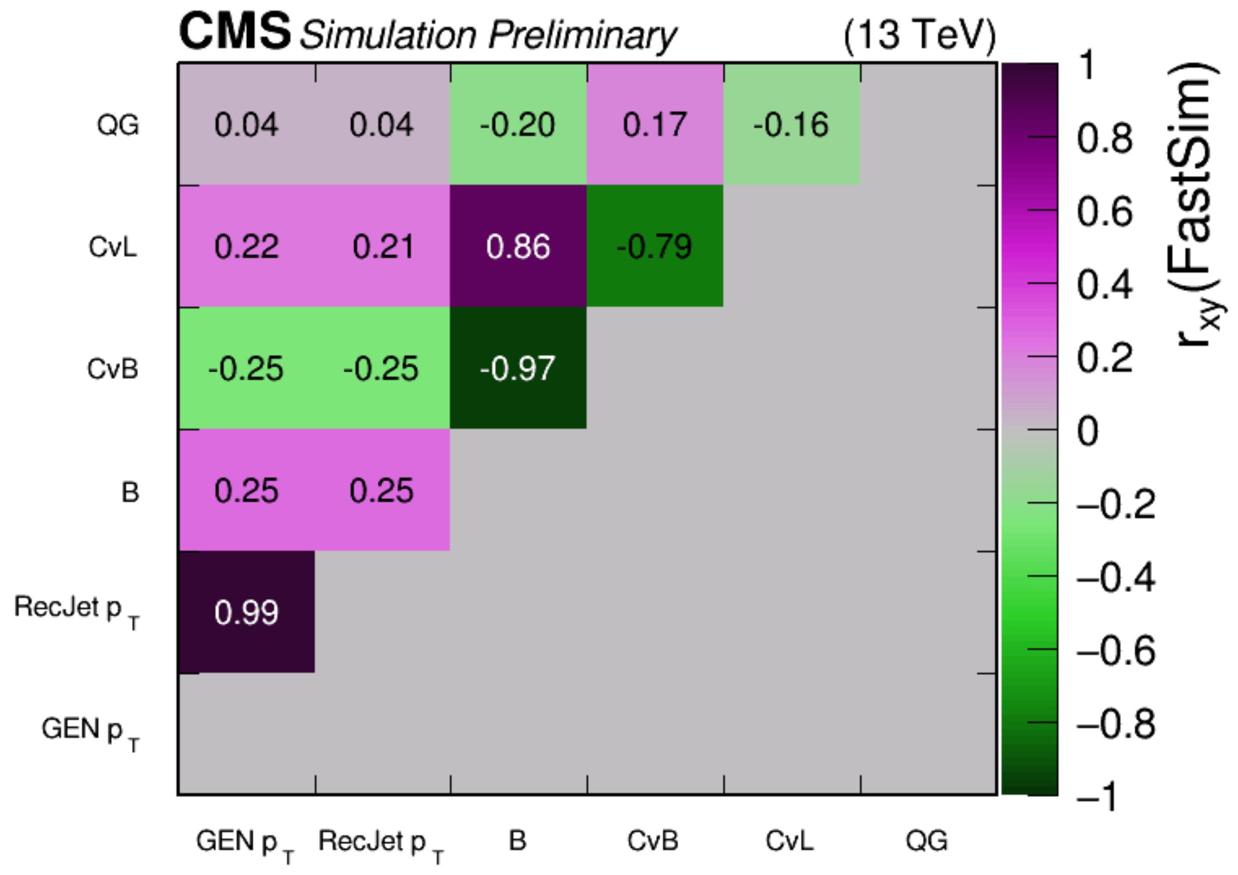


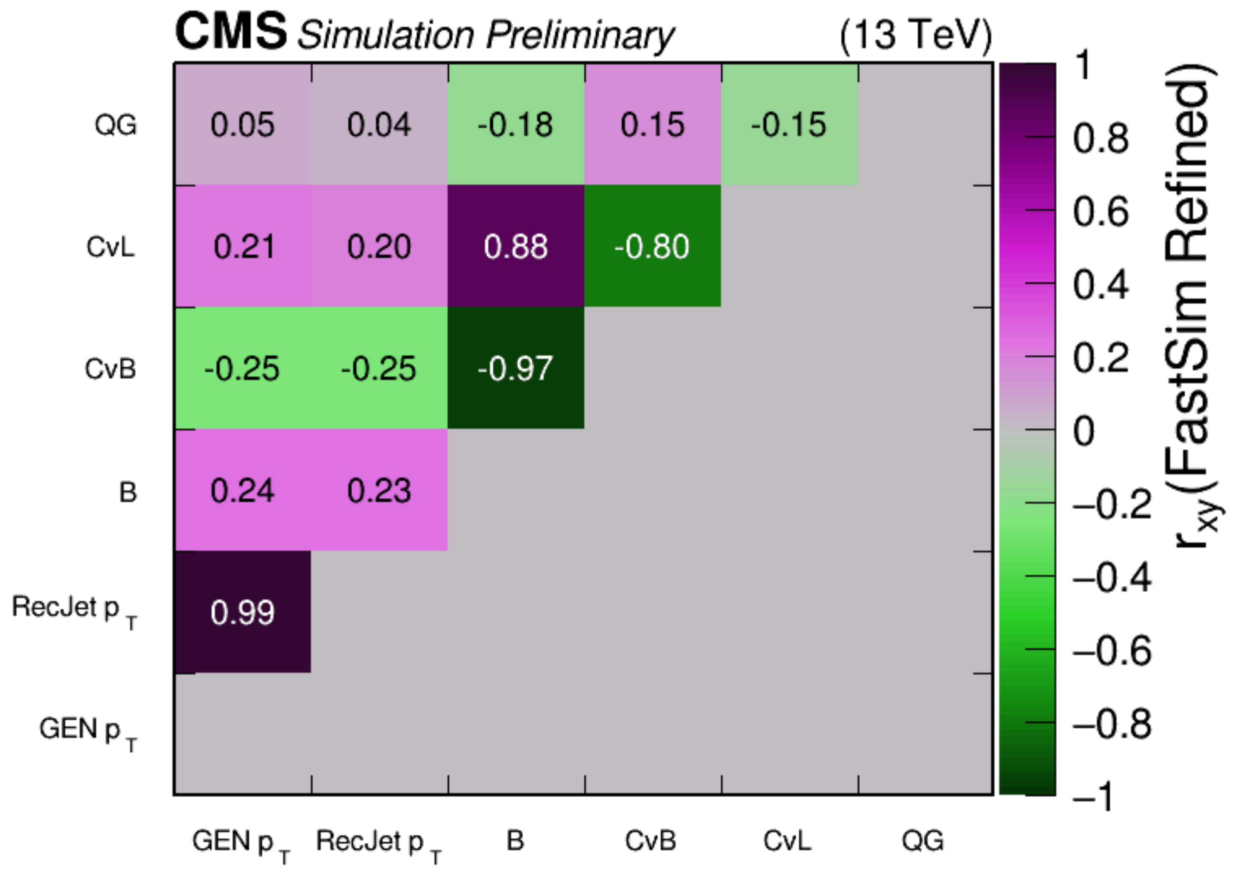
Refine CMS FastSim jets

FullSim | FastSim | Refined FastSim

Pearson coefficients

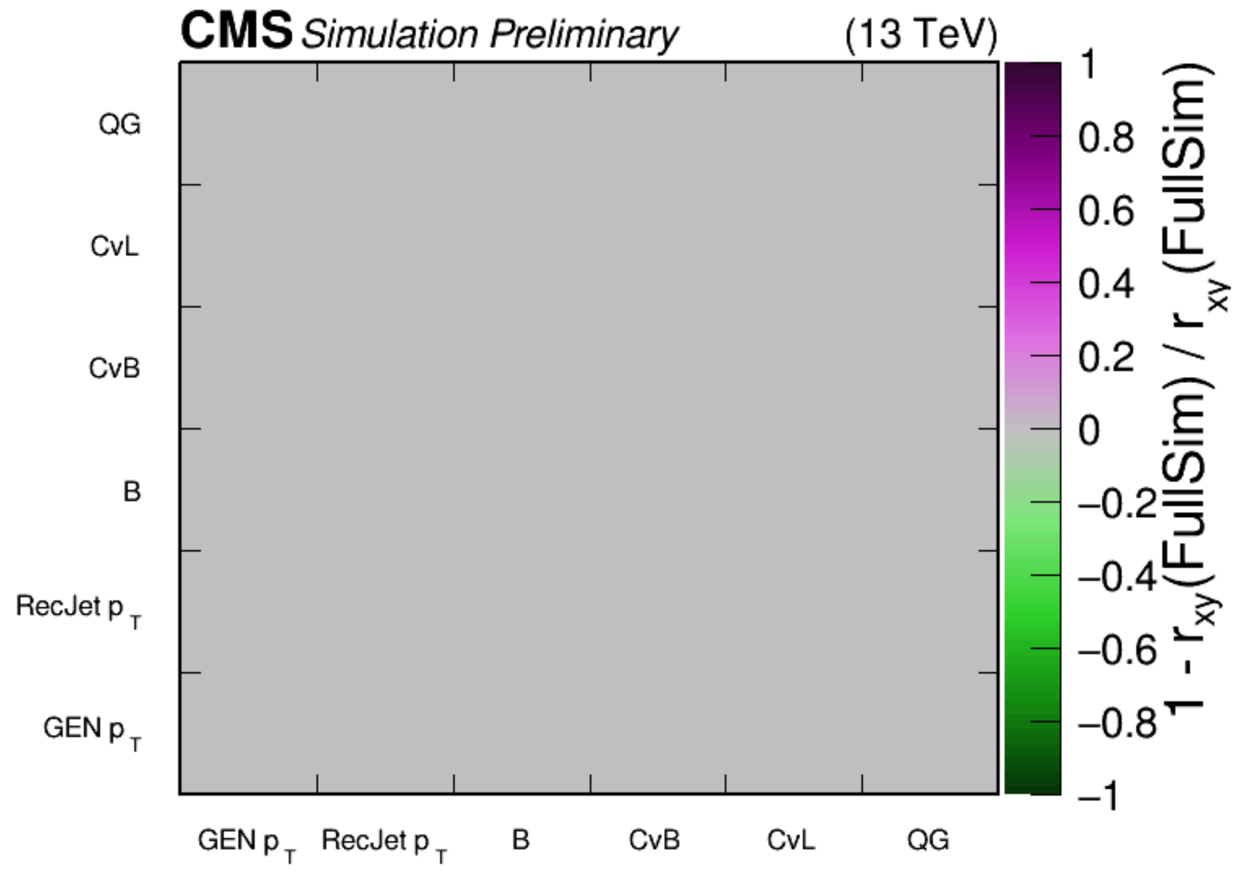


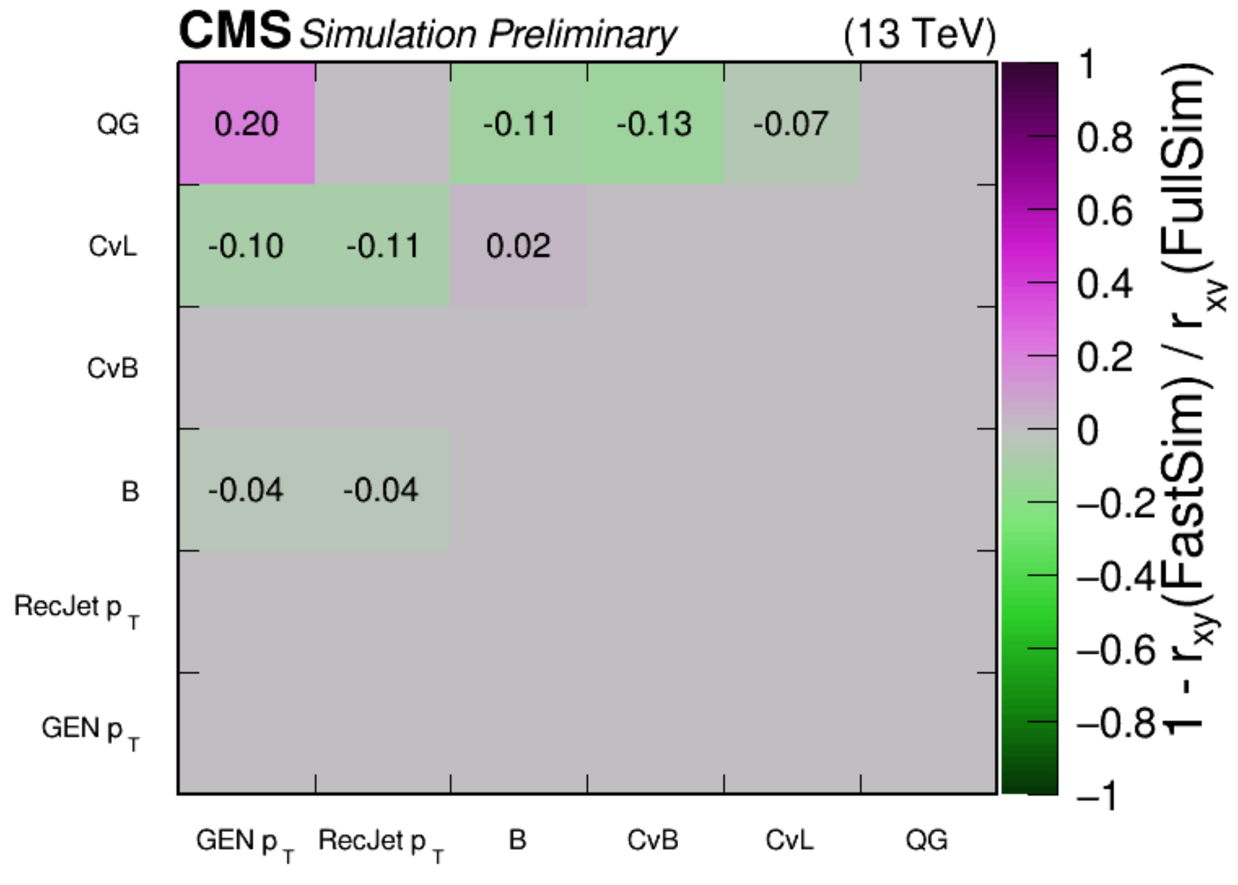


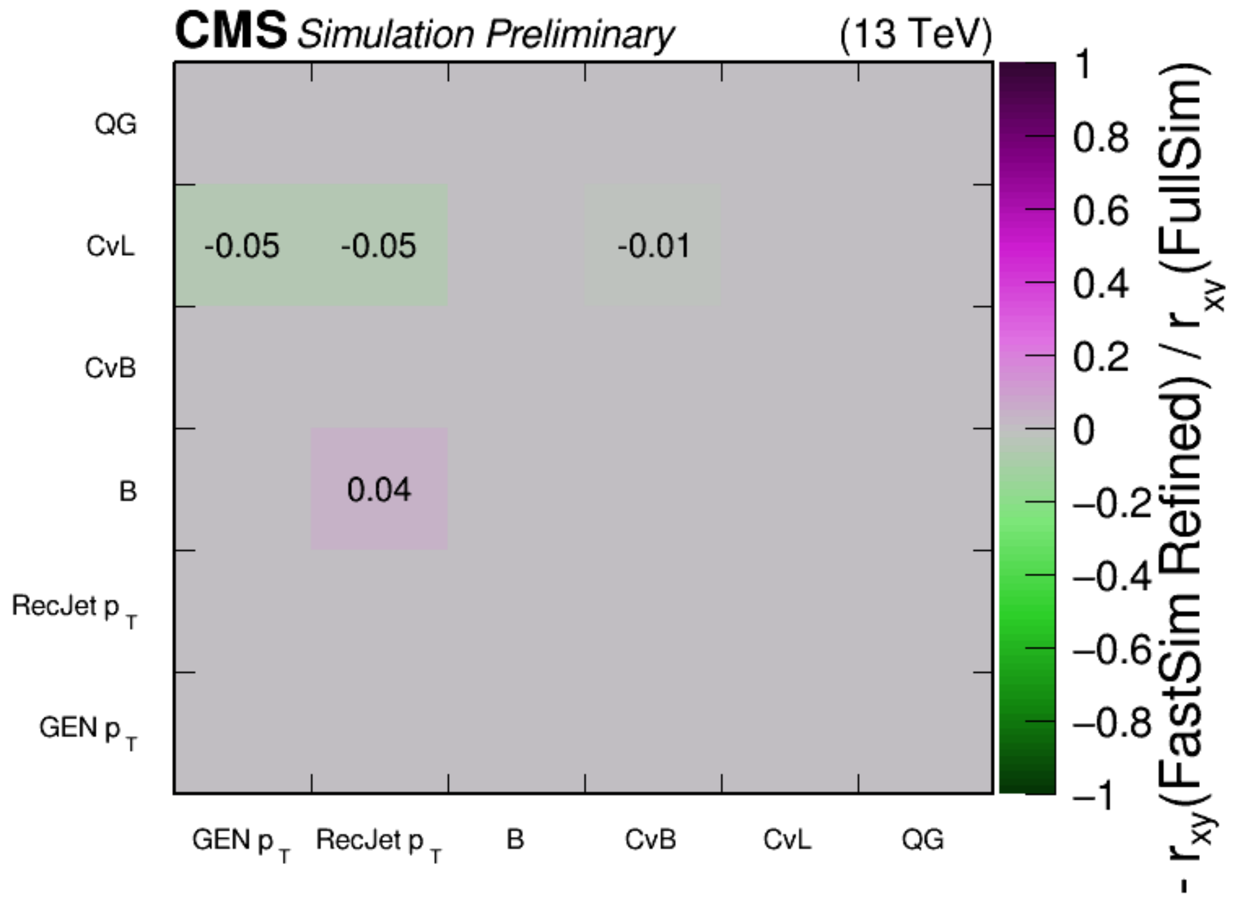


Residuals

x - FullSim



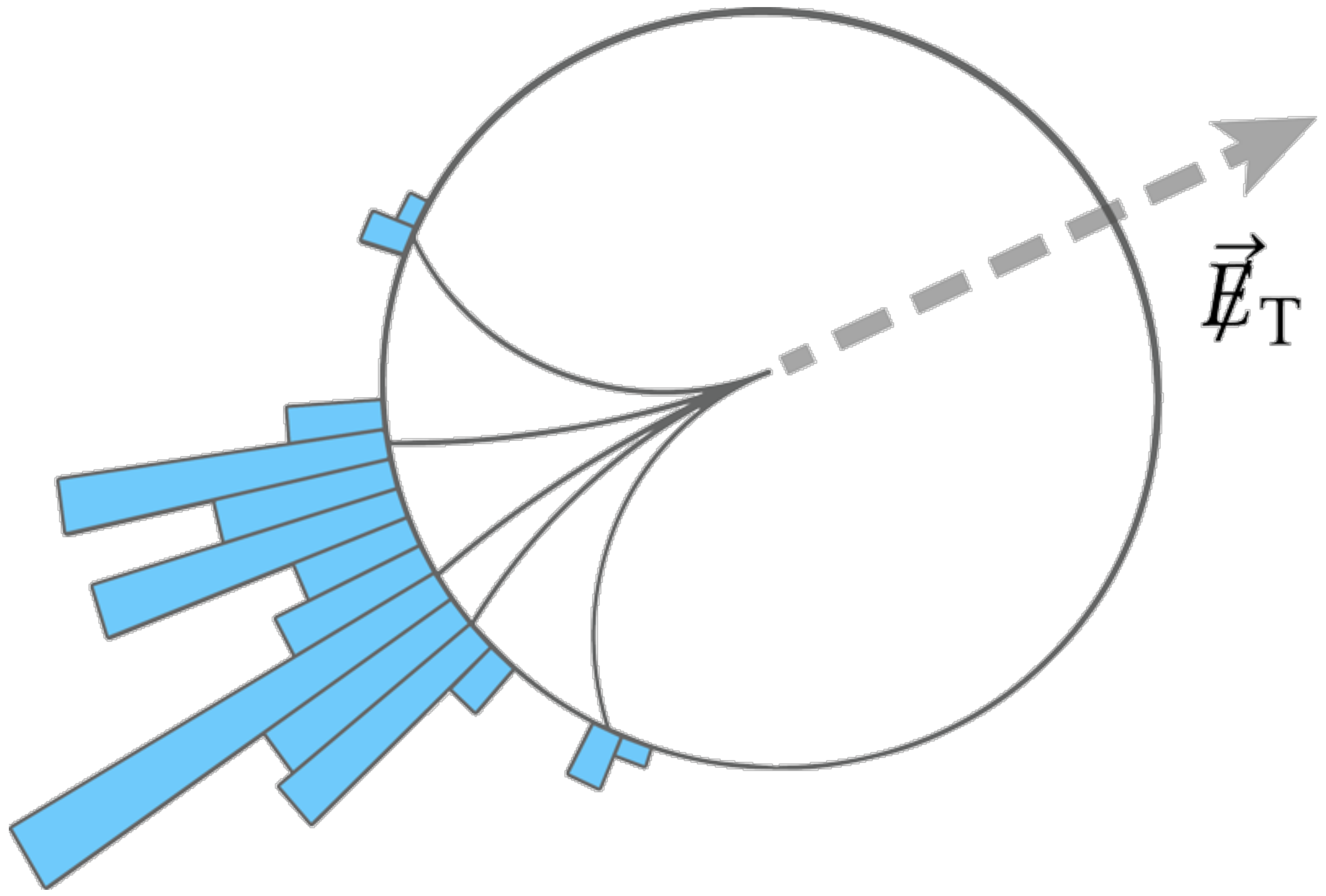


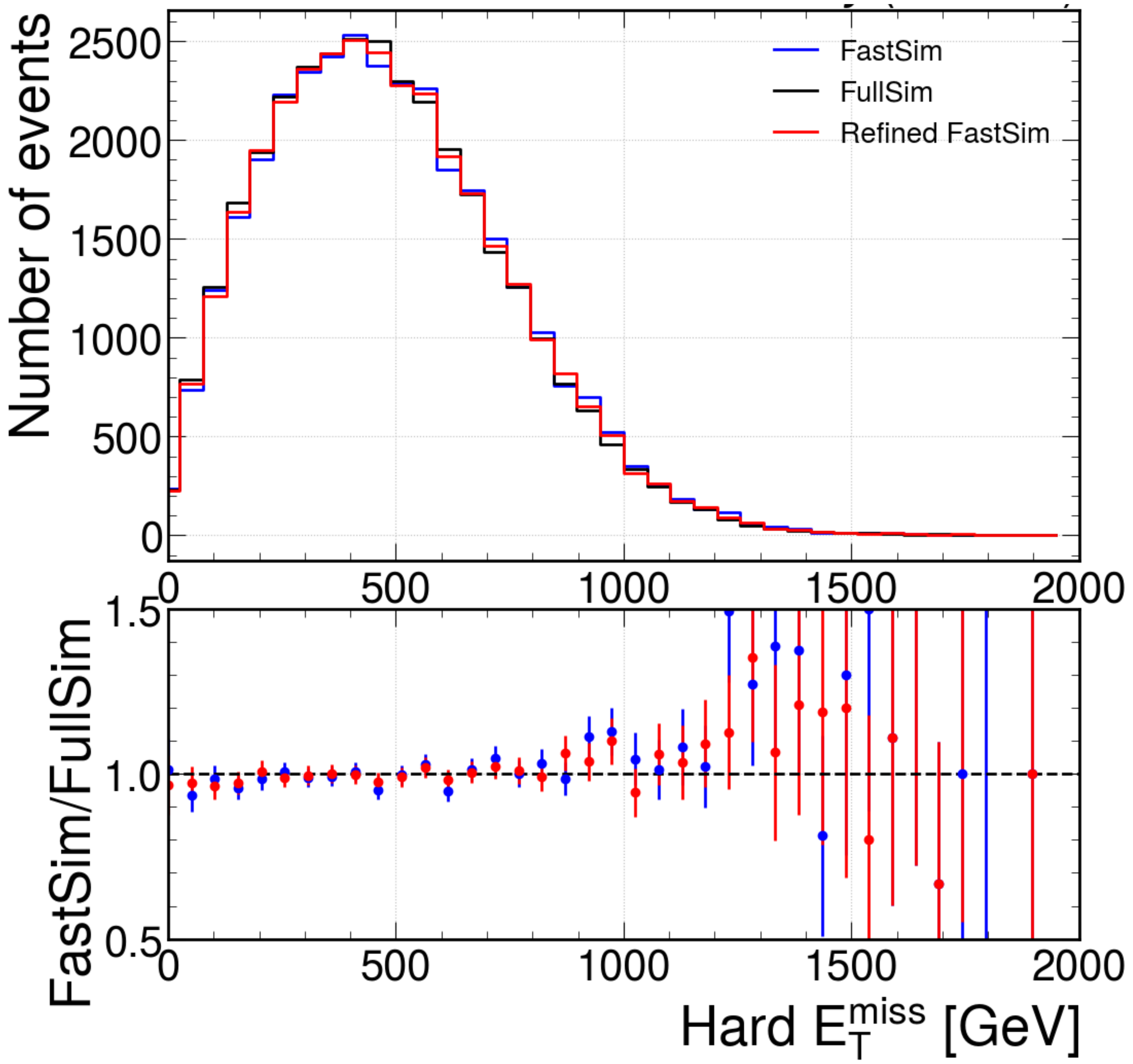


Propagation of refinement to MET

arXiv:2410.15992

Type-1 MET correction





- Propagate refined jet p_T to MET

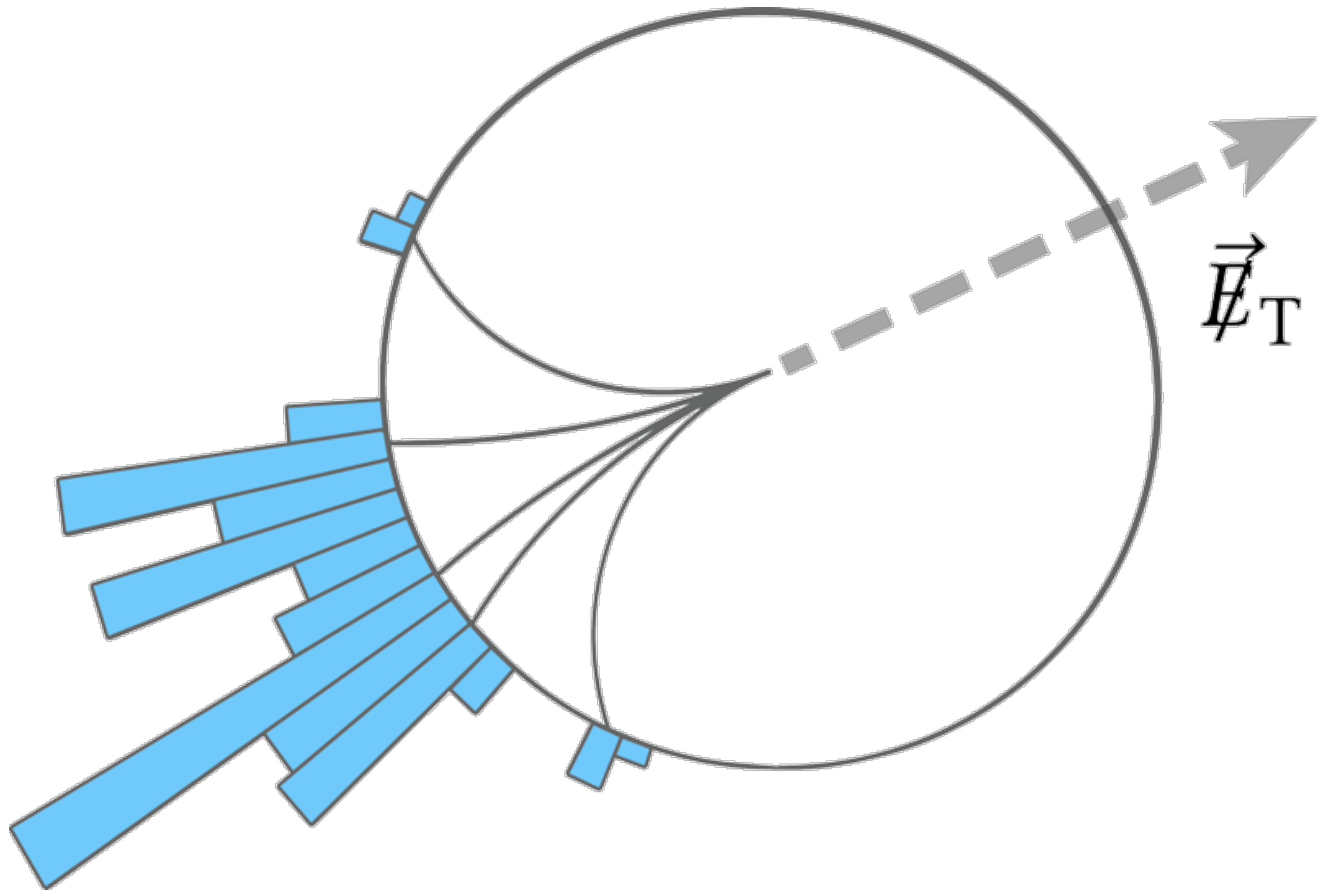
$$\text{refined } \vec{E}_T^{\text{miss}} = \text{Fast } \vec{E}_T^{\text{miss}} + \sum_{i \in \text{jets}} \vec{p}_{Ti}^{\,\text{Fast}} - \sum_{i \in \text{jets}} \vec{p}_{Ti}^{\,\text{refined}}$$

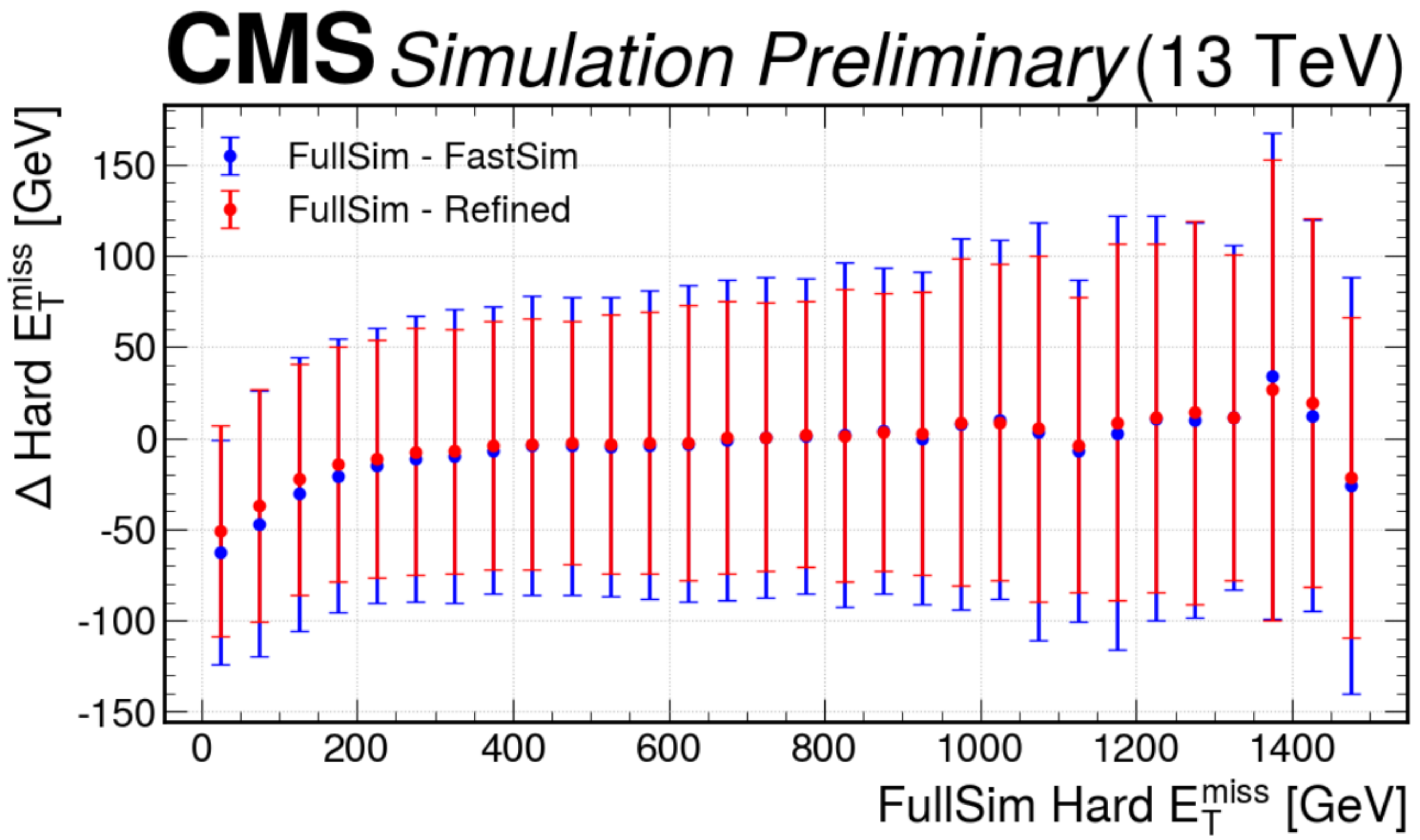
31

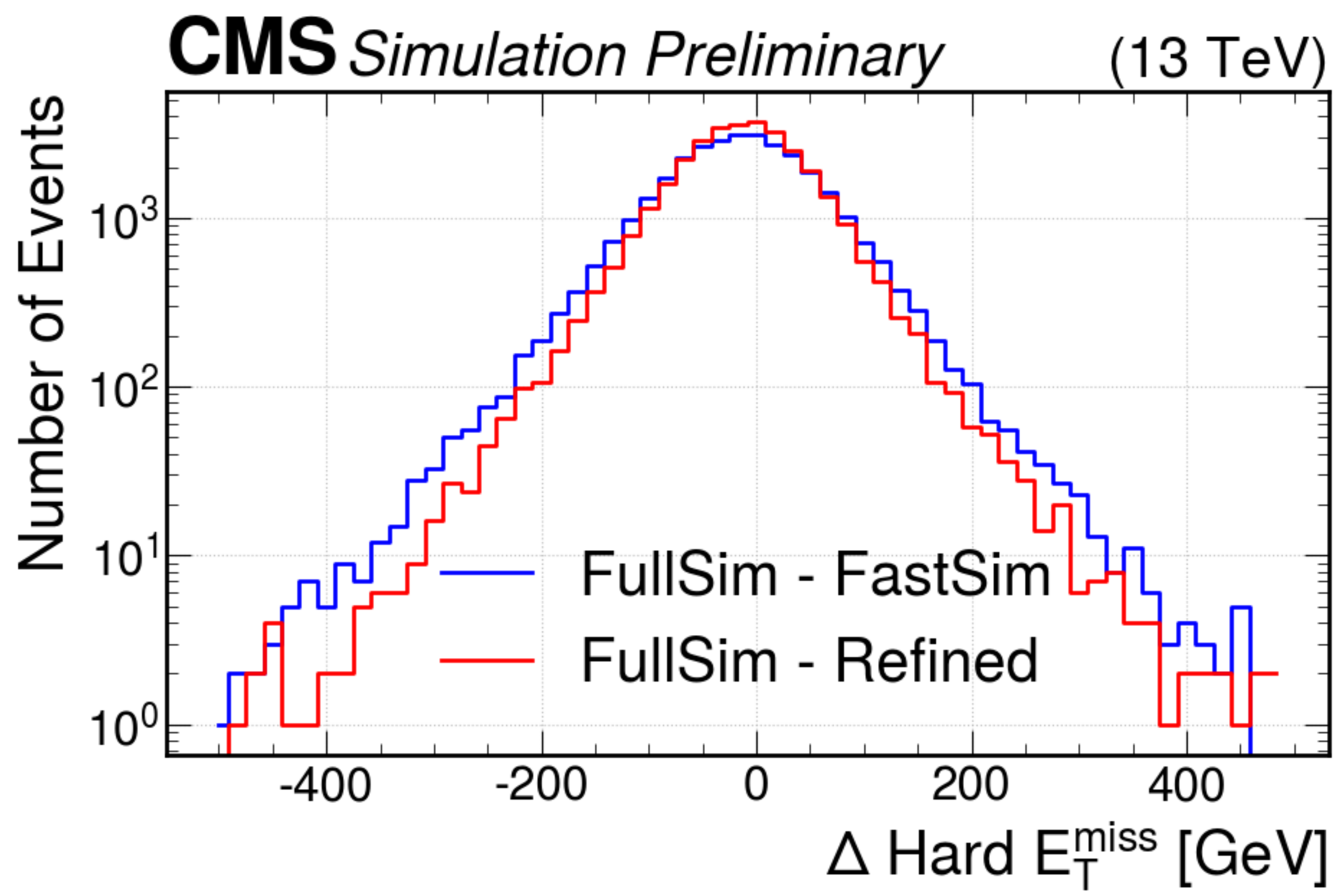
arXiv:2410.15992

Propagation of refinement to MET

Type-1 MET correction







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Bayesian pMSSM analysis

- CMS: **PAS-24-004** - *Phenomenological MSSM interpretation of CMS searches in pp collisions at 13 TeV*
  - *Electroweak* and *strong* SUSY production in a single scan
  - 500k model points scanned with MCMC likelihood
    - MCMC imposes constraint from dozens of pre-CMS results
  - Generator-level filter to loosely emulate trigger
    - 10 billion MC events!
  - Run over simulation with 5 analyses

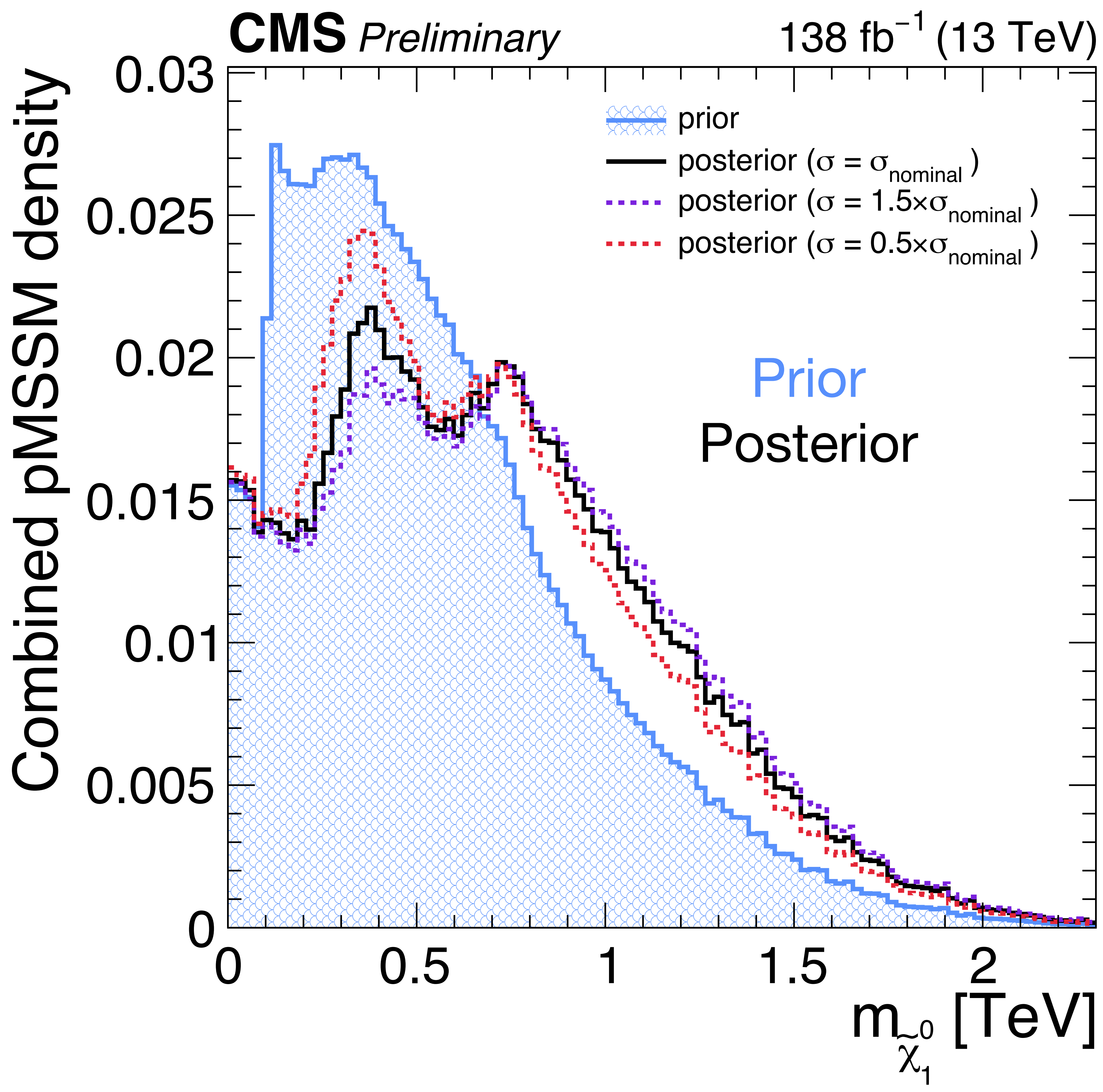
Included final states

Final State Category	Experiment	Analyses / Final State	Journal Reference
0 lepton (all-hadronic)	CMS	Jets+MHT, HT, n(b-tags)	JHEP 10 (2019) 244
1 lepton	CMS	Single-lepton $\Delta\phi$	JHEP 09 (2023) 149
2-lepton	CMS	Same-flavor opposite sign	JHEP 04 (2021) 123
Compressed/Soft	CMS	Soft opposite-sign leptons	JHEP 2204 (2022) 91
Disappearing track	CMS	short tracks with dE/dx	Phys. Rev. D 109 (2024) 072007

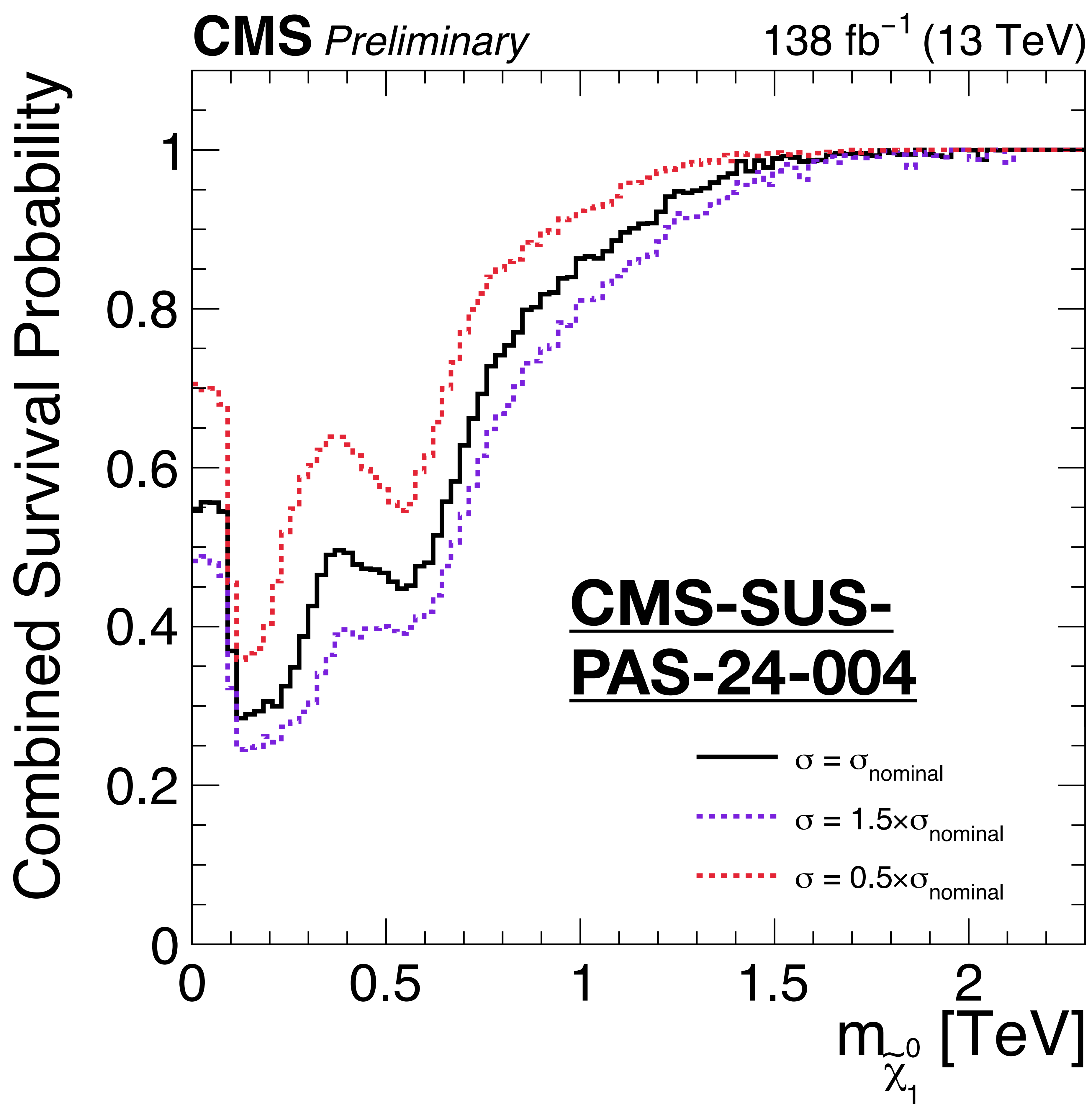
CMS-SUS-PAS-24-004

Dark matter candidate mass

Probability density

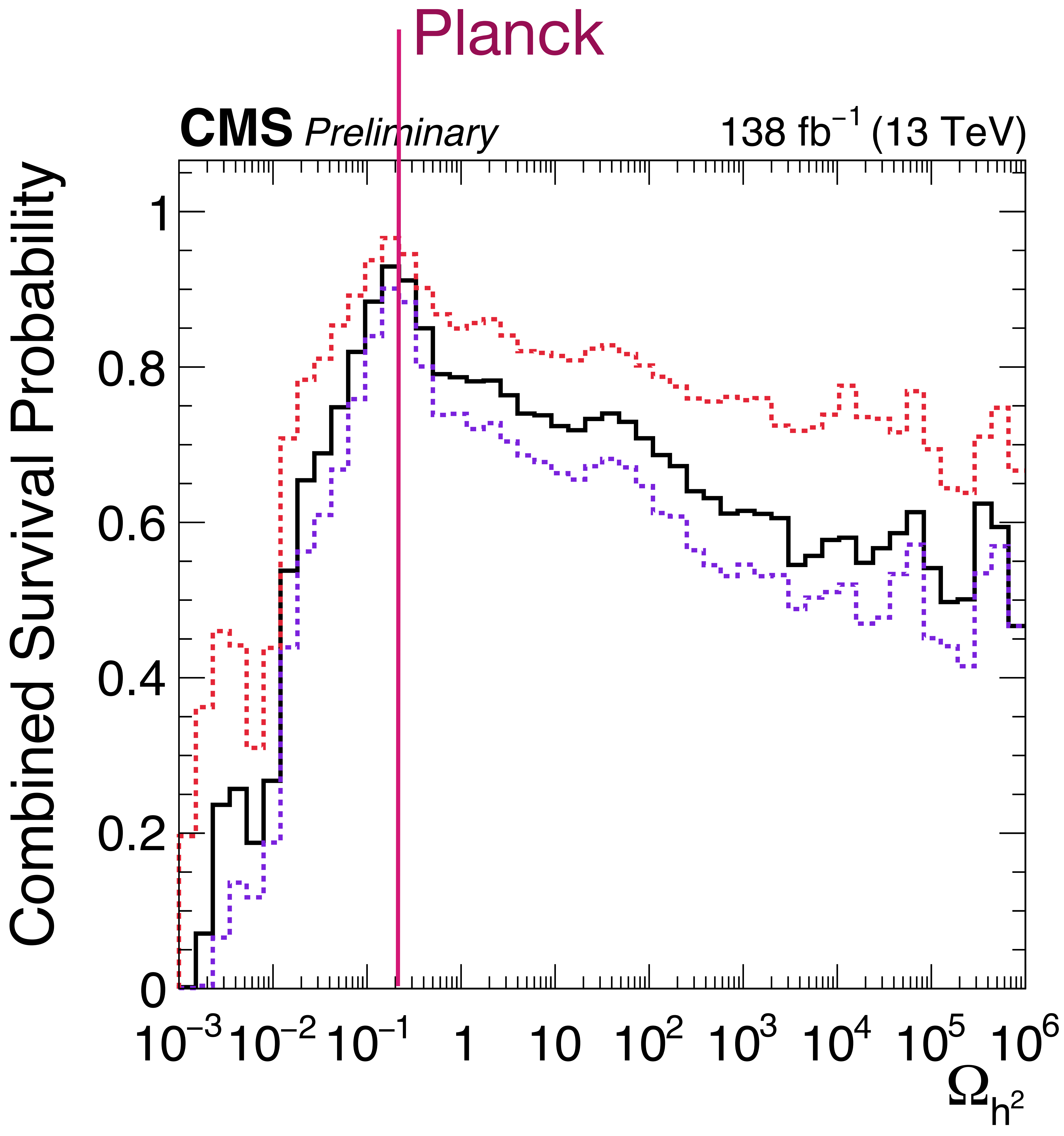


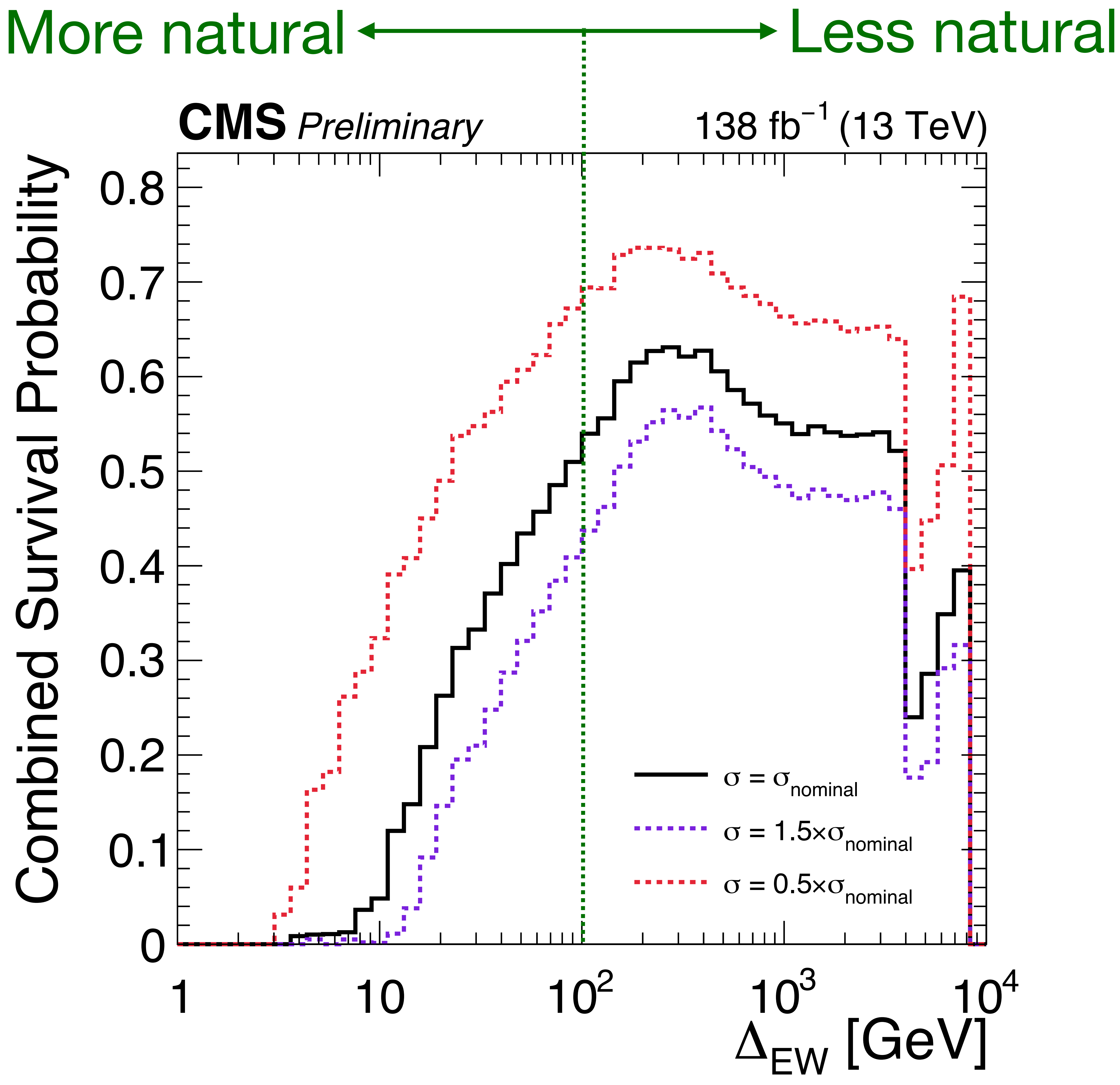
Survival probability



CMS-SUS-PAS-24-004

Relic density, naturalness





>90% of relic density models survive

<50% of natural models survive

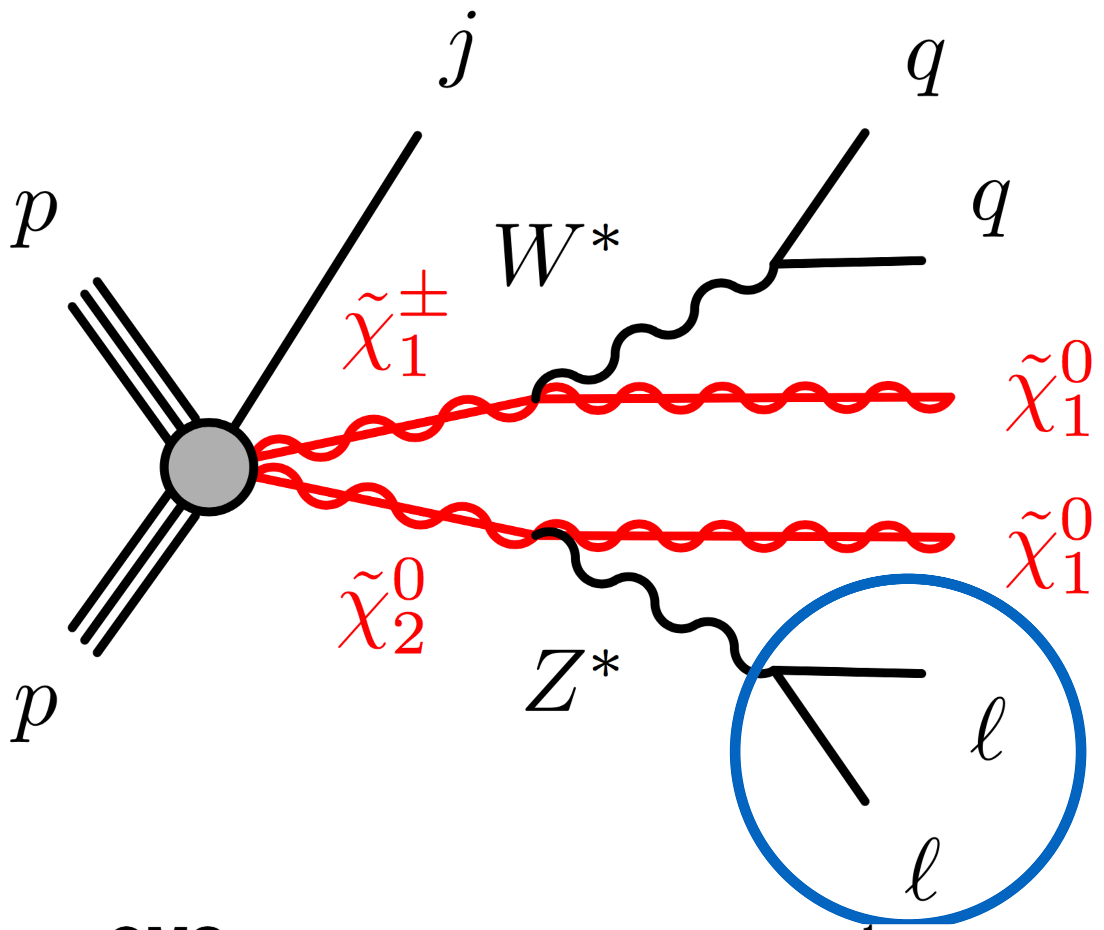
CMS impact by analysis

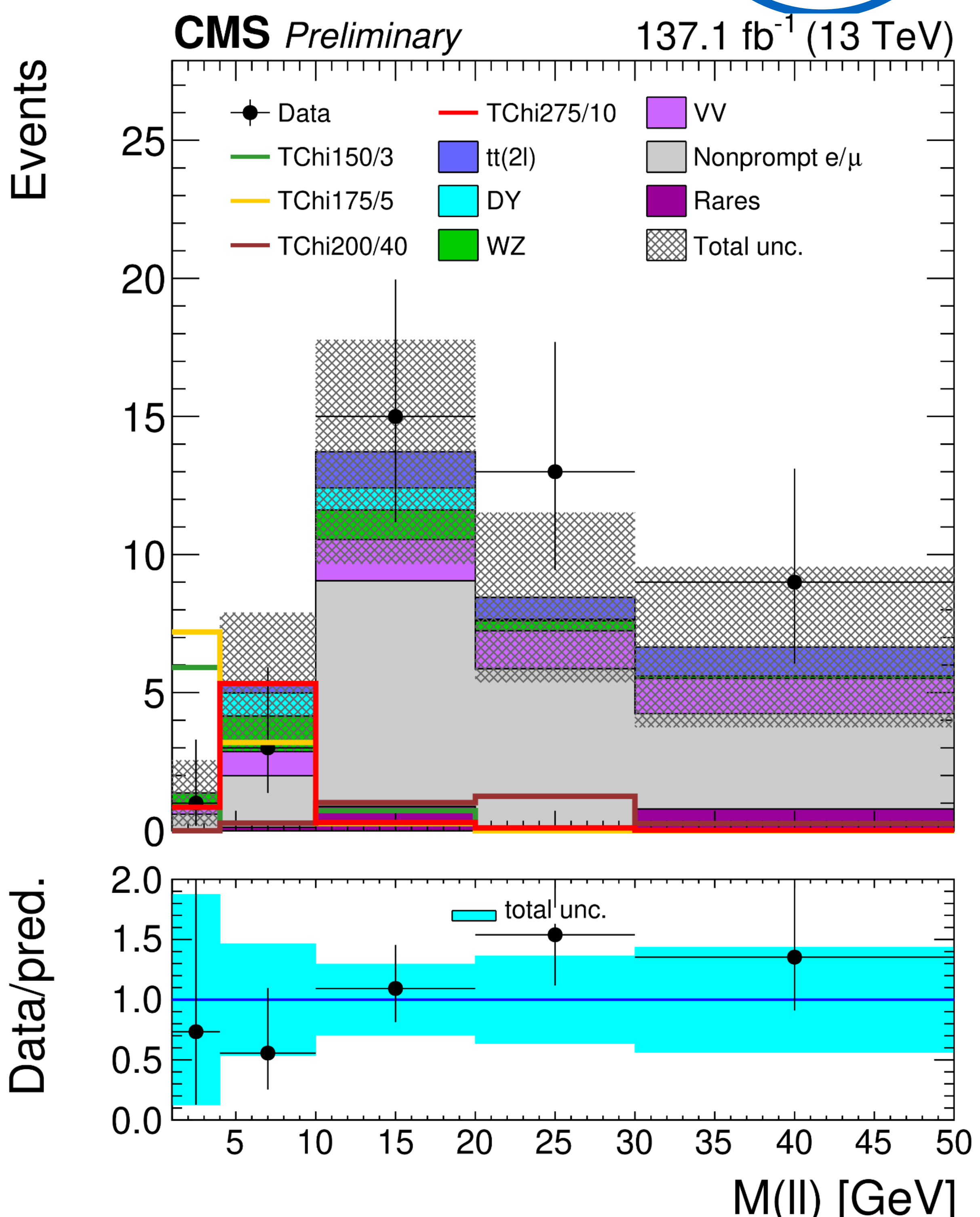
CMS-SUS-PAS-24-004

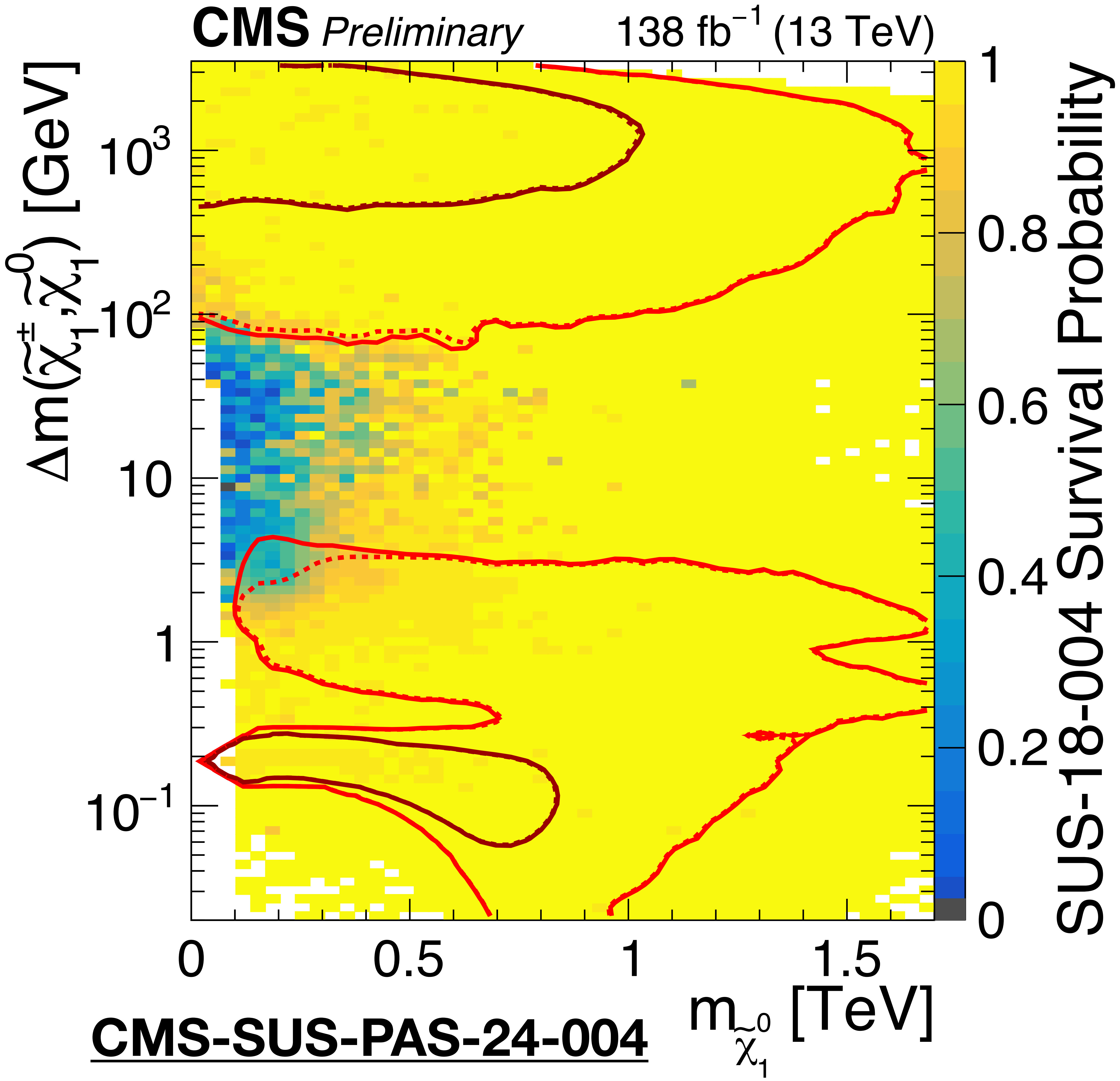
Soft opposite-sign lepton

JHEP 2204 (2022) pp.091

- 2- or 3 soft leptons
  - OSSF pair
  - $\geq 2\ell$ with $p_T > 3$ GeV
- ISR jet
- Binning in invariant mass M(ll)







CMS-SUS-PAS-24-004

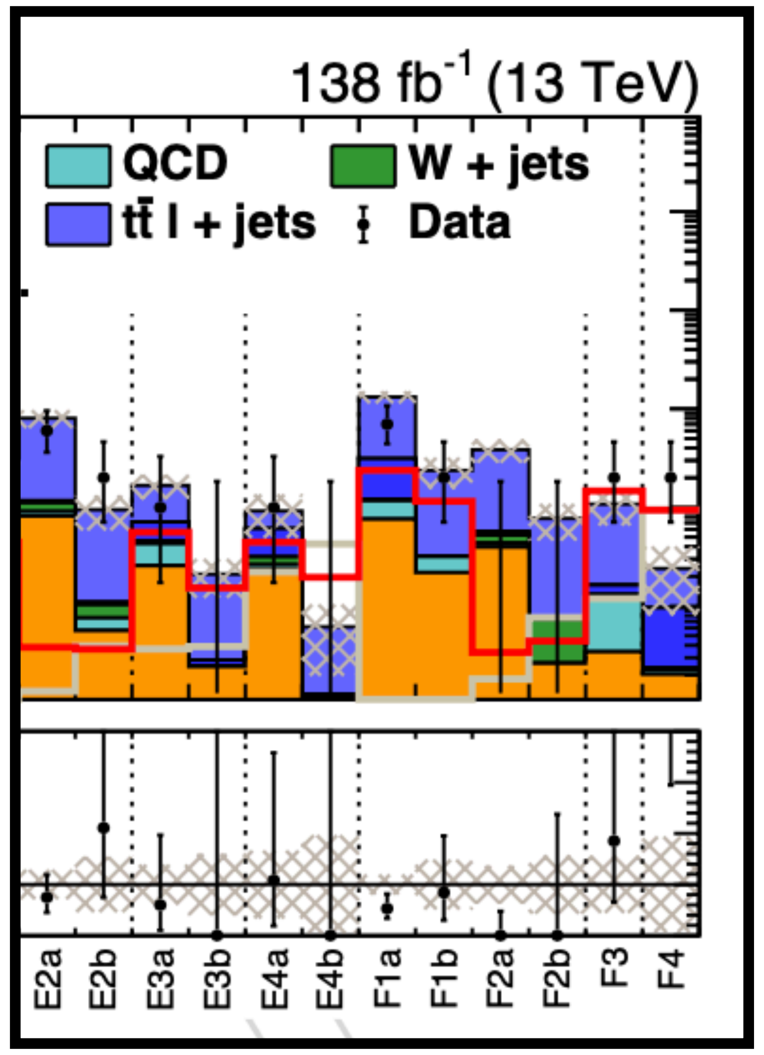
SUS-18-004

CMS impact by analysis

CMS-SUS-PAS-24-004

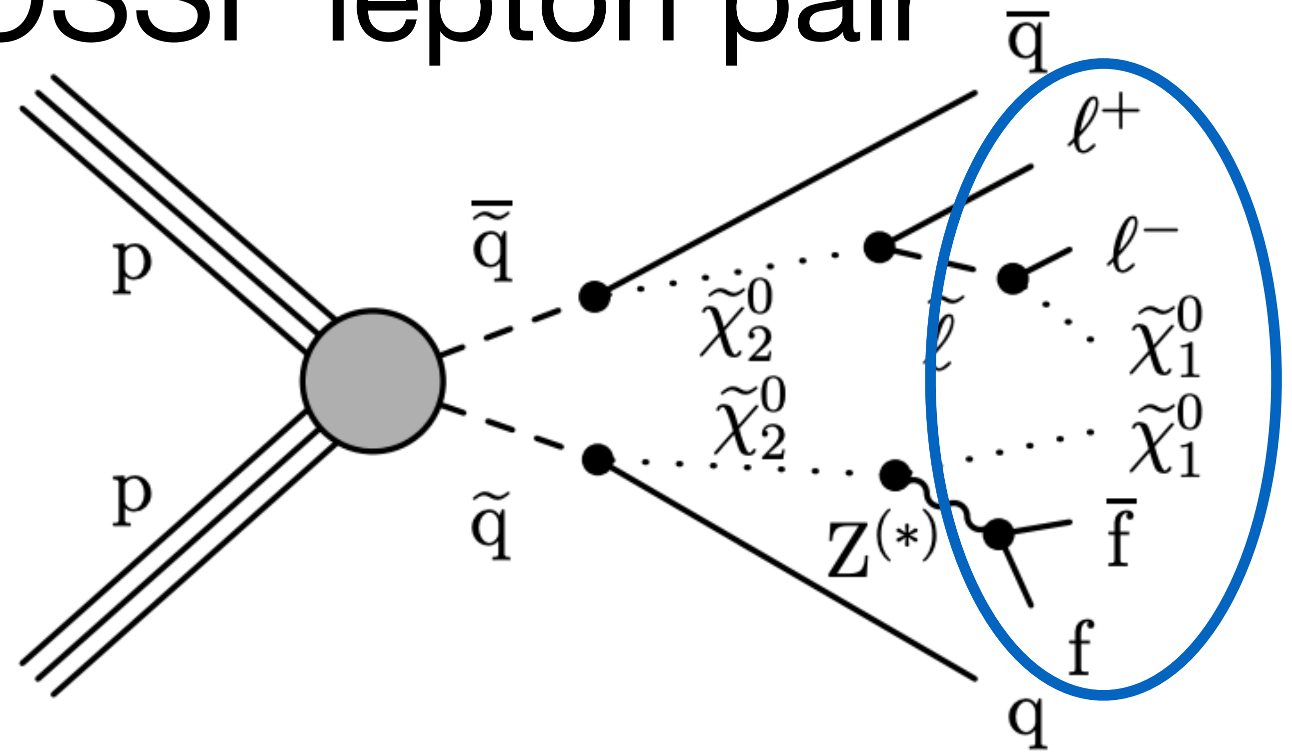
+Single-lepton, Delta-phi
JHEP 09 (2023) 149

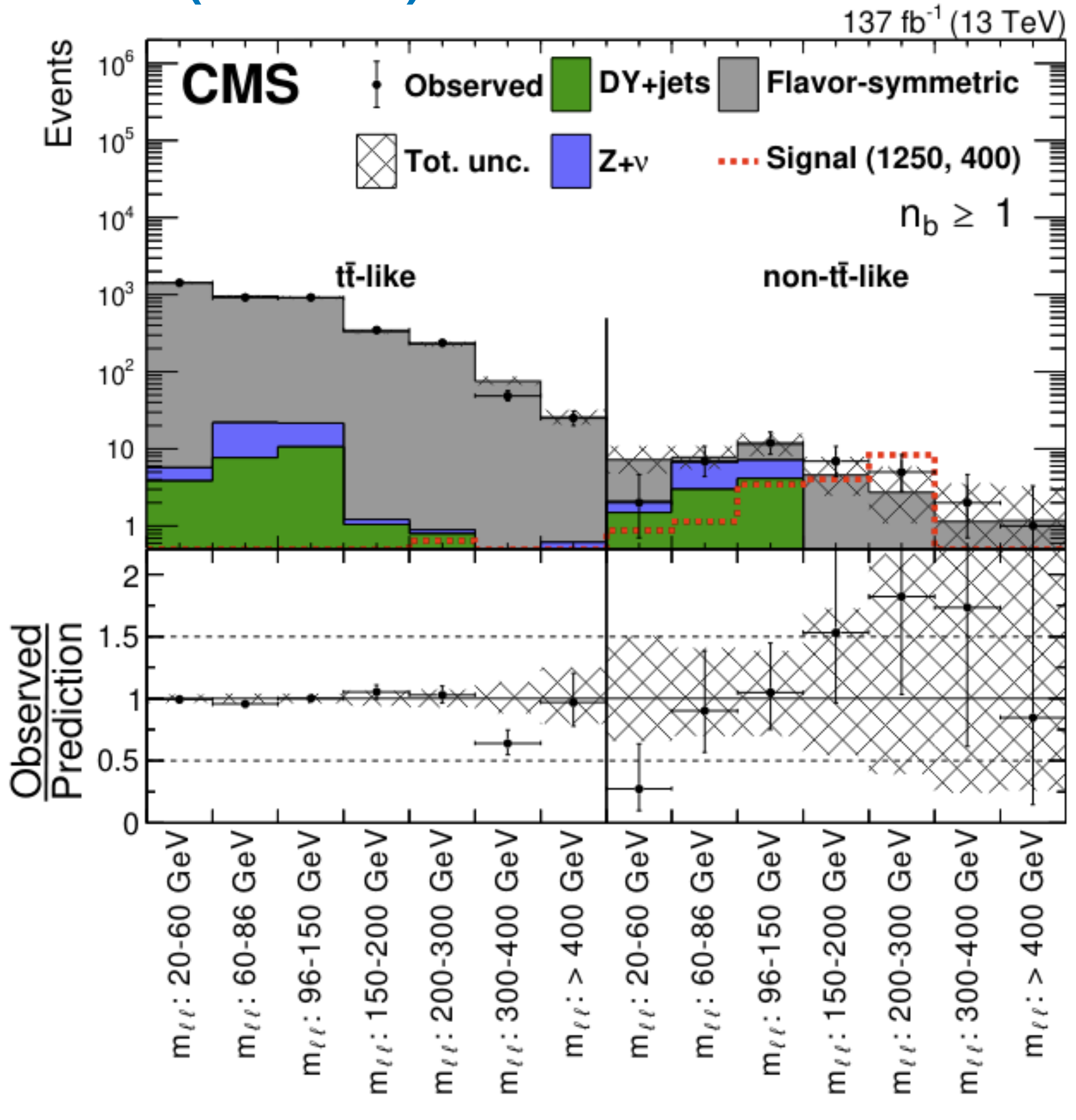
- Requires exactly 1 lepton
  - Ele or Mu with pT>25 GeV

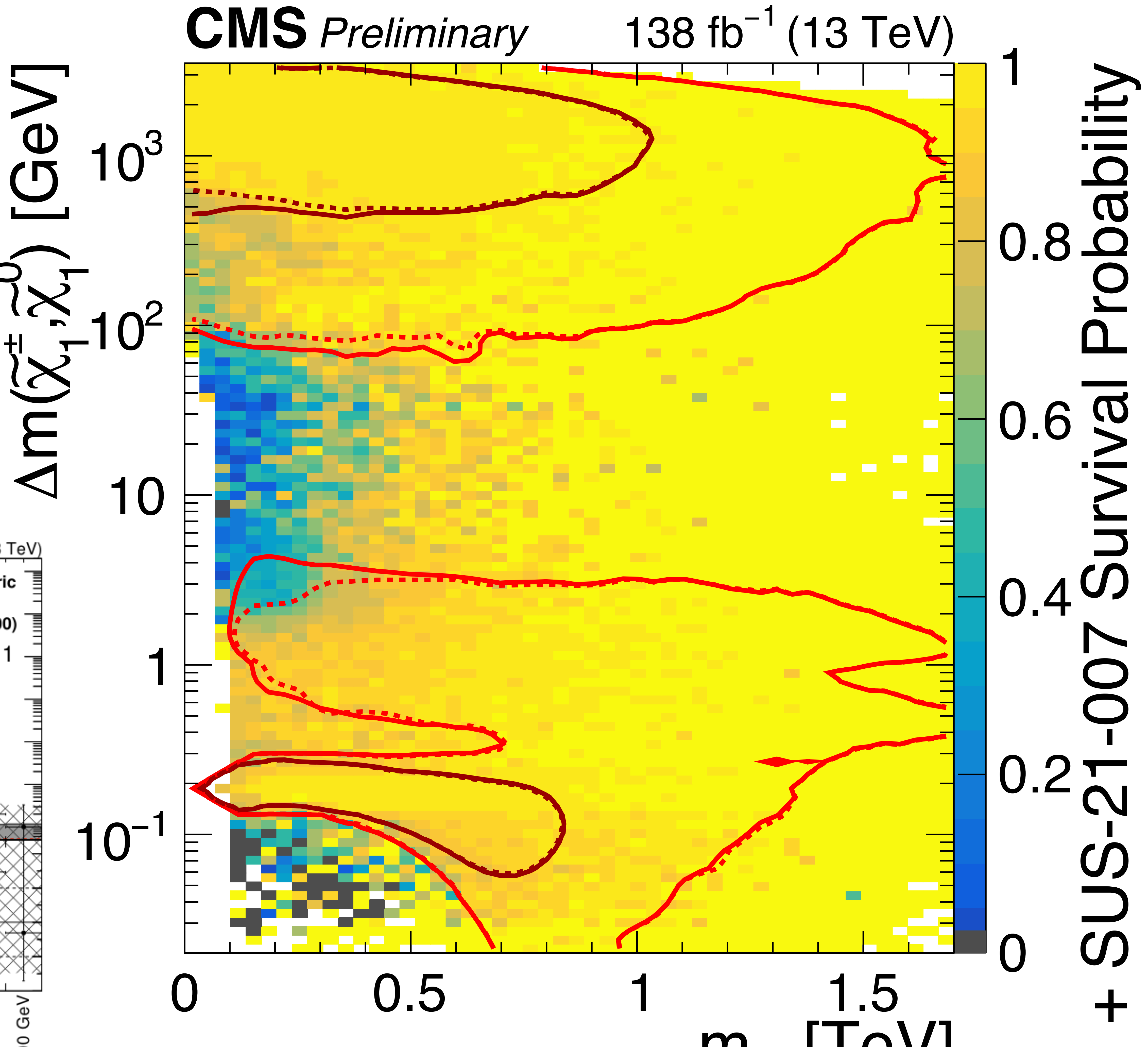


+Opposite-charge lepton JHEP 04 (2021) 123

- 2 high-pT leptons
- OSSF lepton pair







CMS-SUS-PAS-24-004

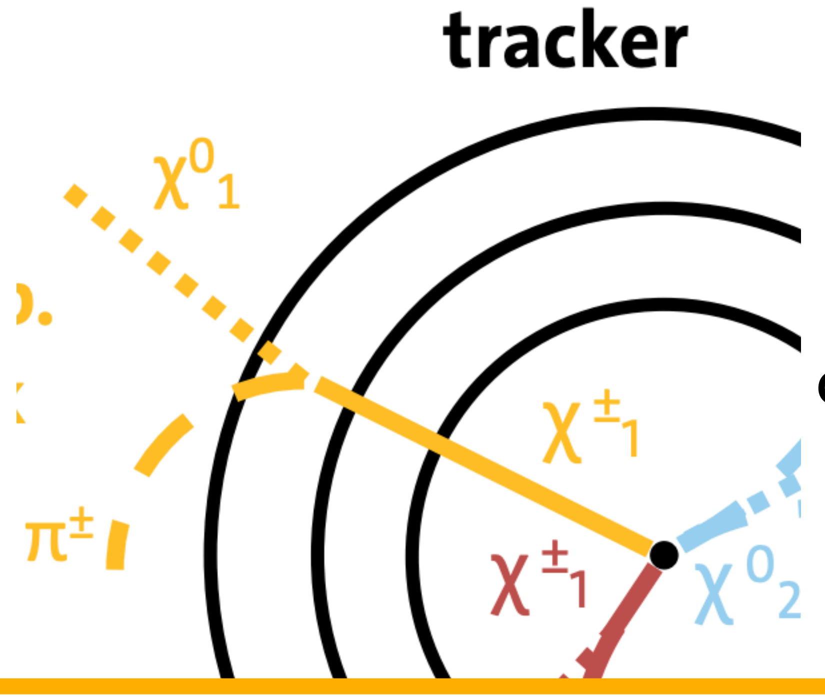
SUS-18-004+SUS-20-001+SUS-21-007

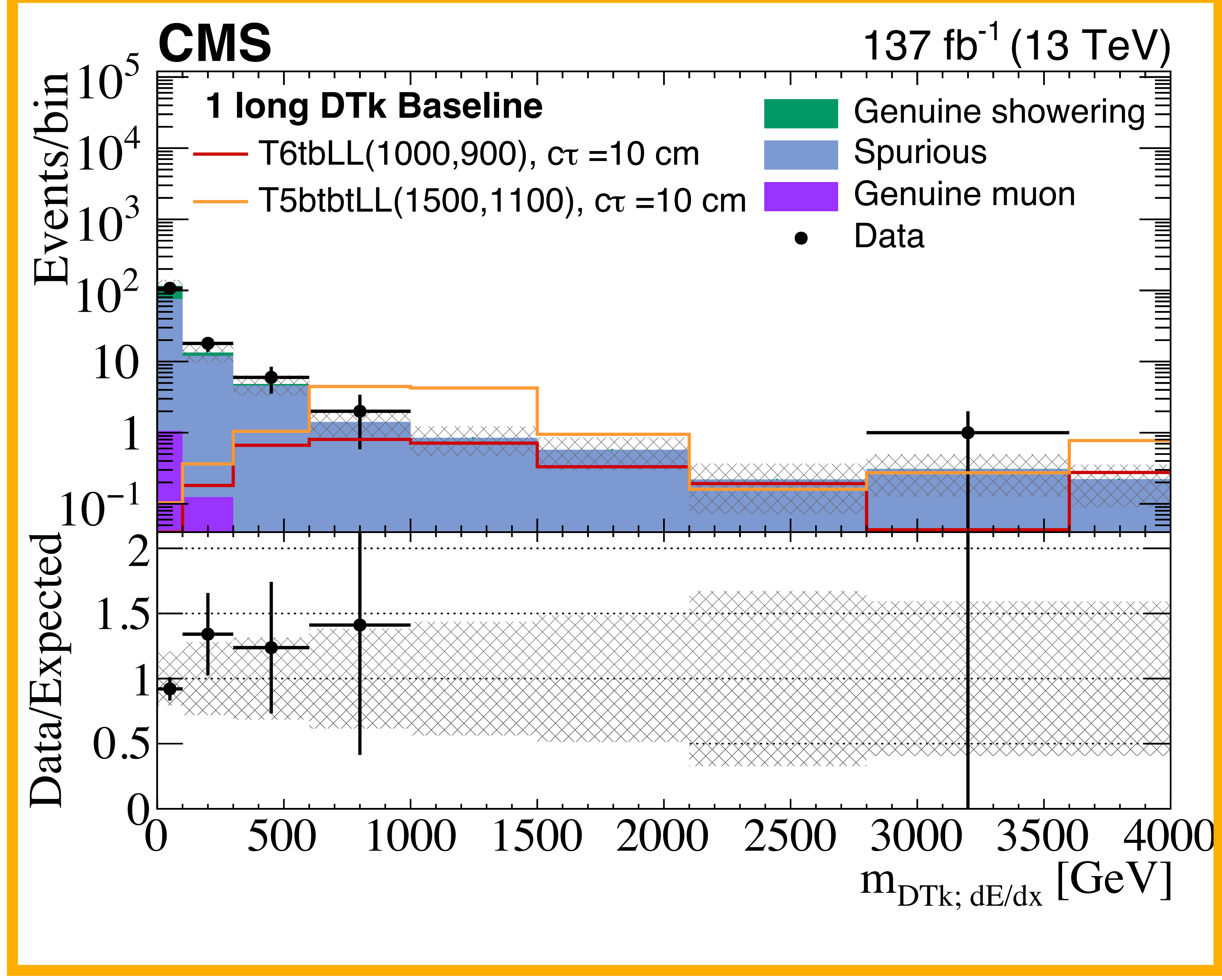
CMS impact by analysis

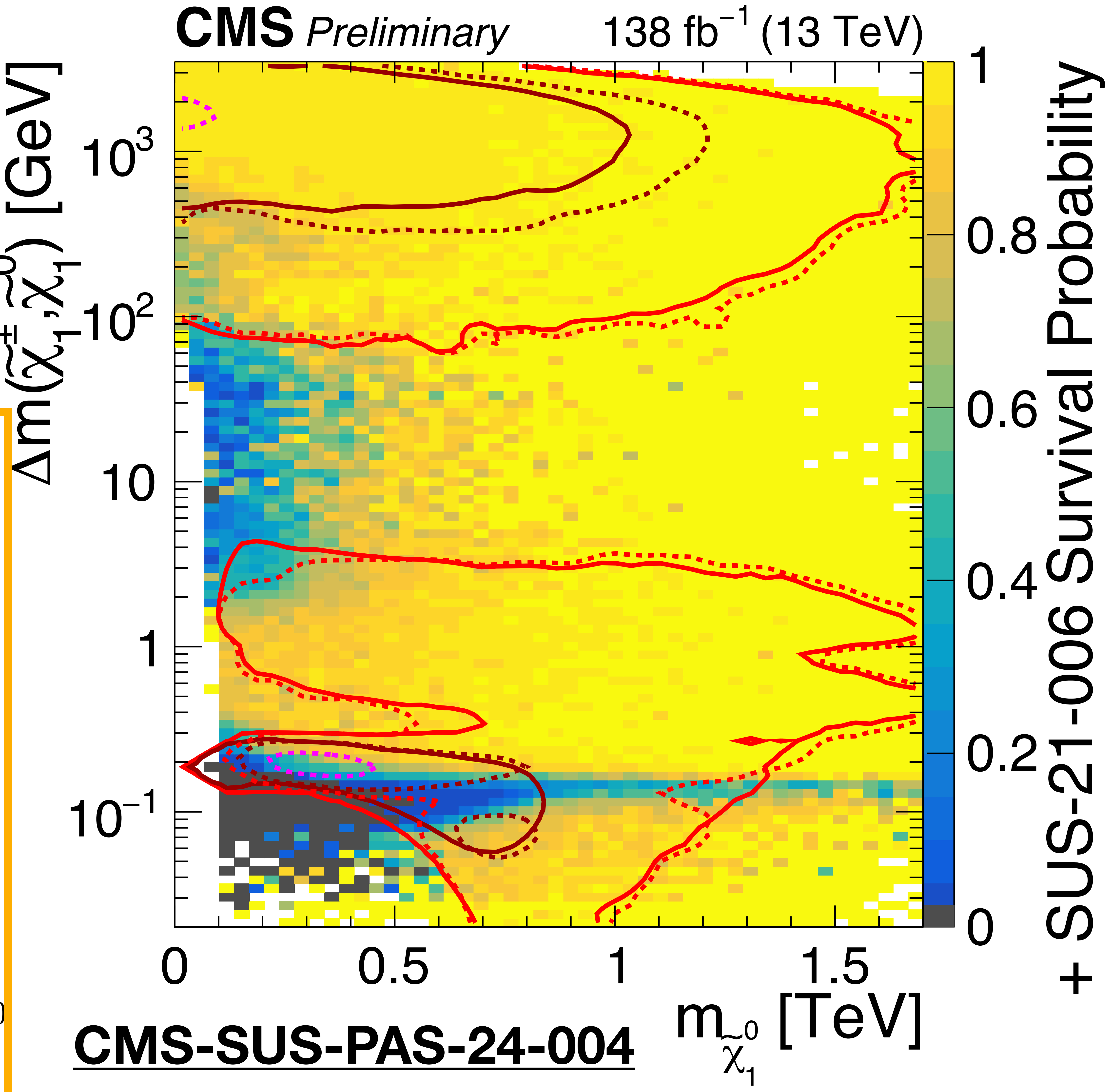
CMS-SUS-PAS-24-004

+SUSY disappearing track
Phys. Rev. D 109 (2024) 072007

- ≥1 disappearing tracks
- 0, 1 leptons; 0, >0 b-tags
- long/short
- dE/dx binning







CMS-SUS-PAS-24-004

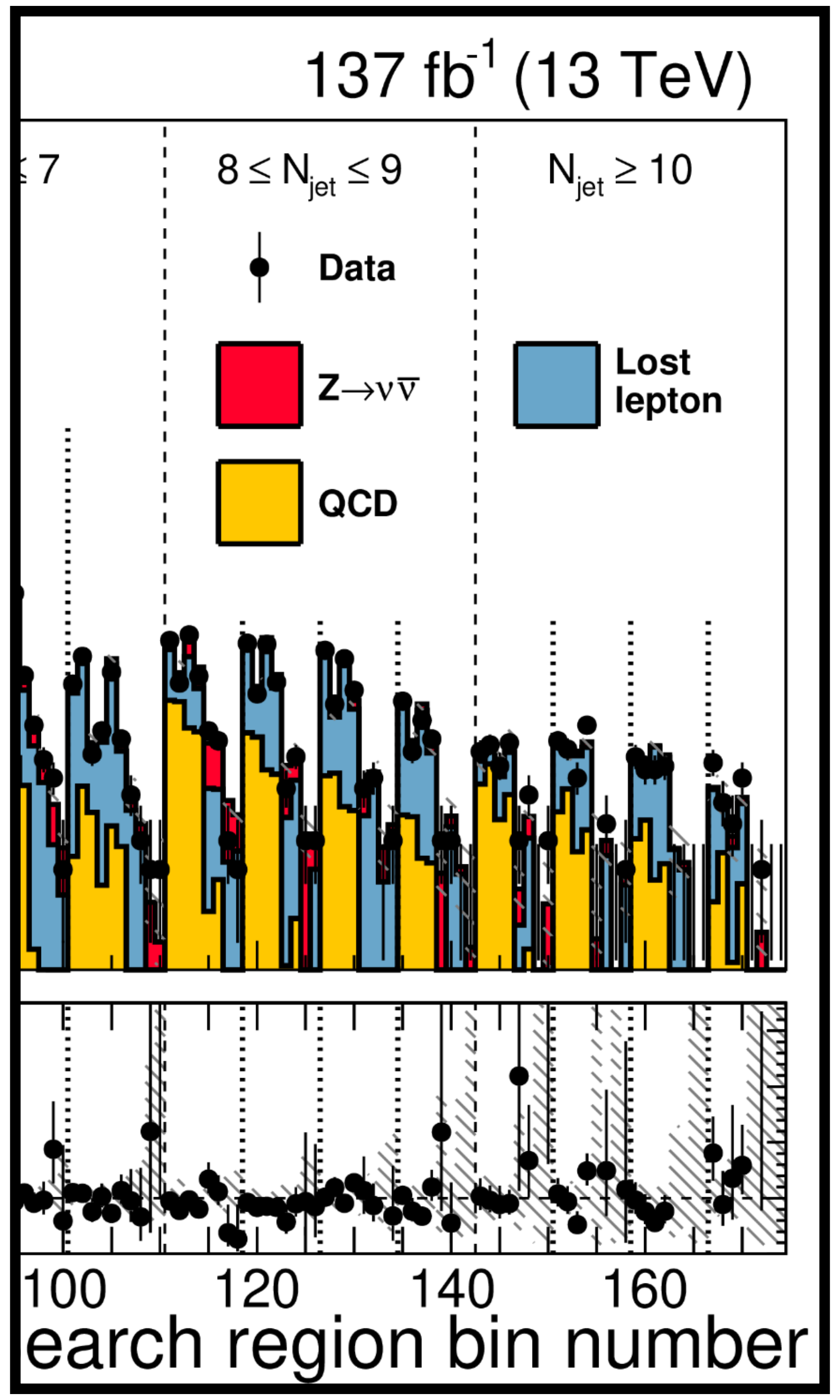
SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006

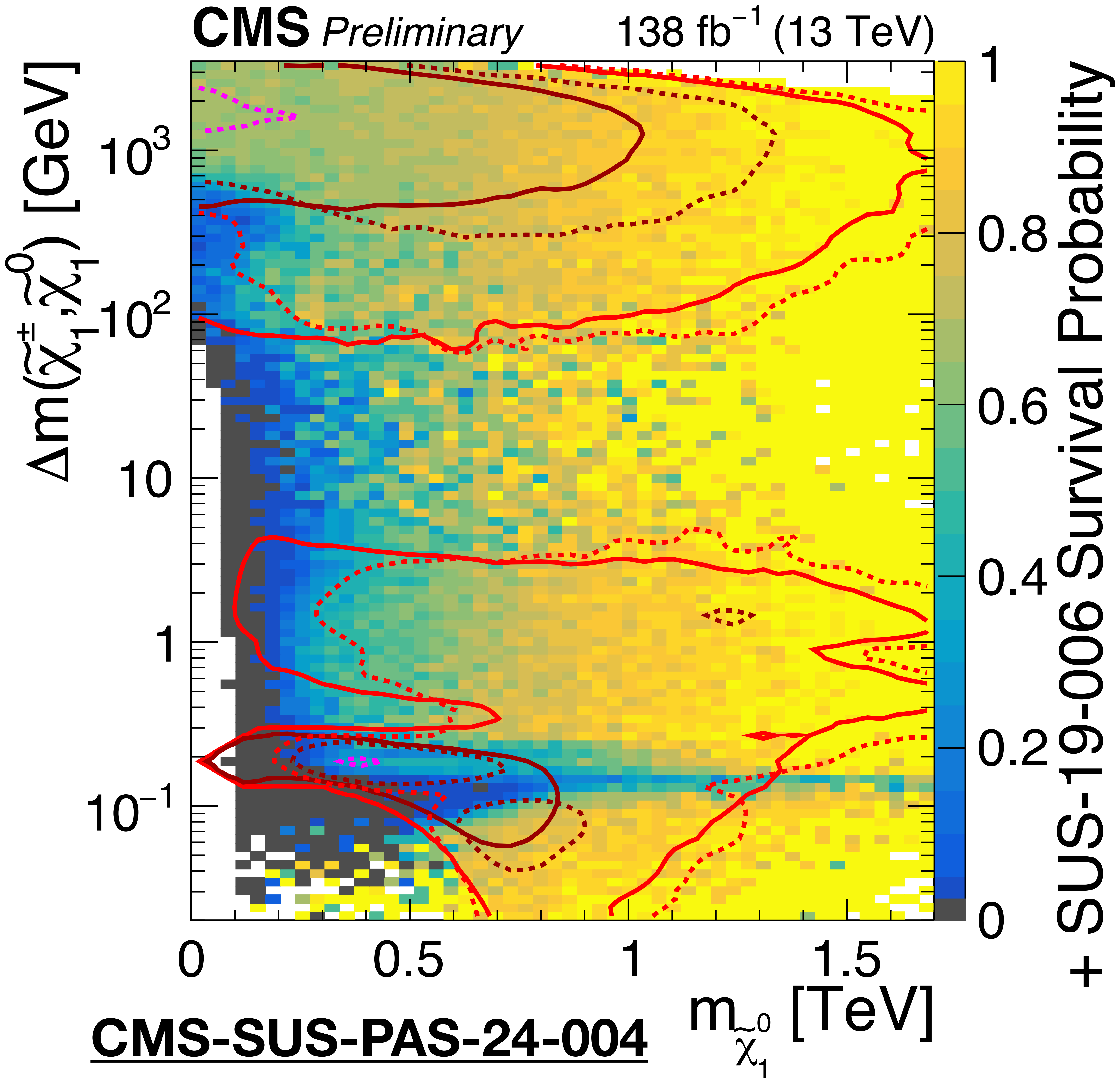
CMS impact by analysis

CMS-SUS-PAS-24-004

+Zero-lepton, jets, MHT
JHEP 10 (2019) 244

- Inclusive 0-lepton
  - Veto electron, muon candidates with pT>5 GeV
- >1 ak4 jets
- 0, >0 b-tagged jets
- Binning in MHT, HT, n(jets), nb





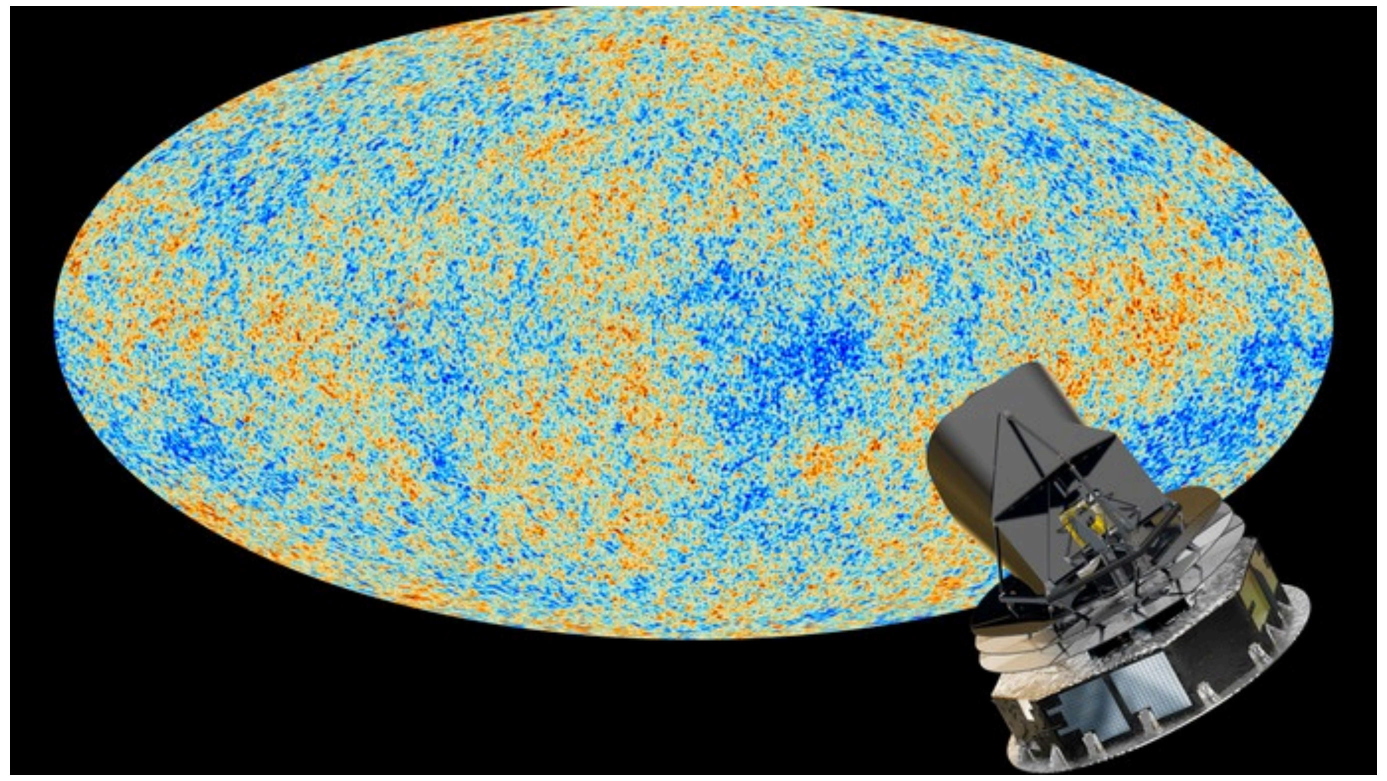
CMS-SUS-PAS-24-004

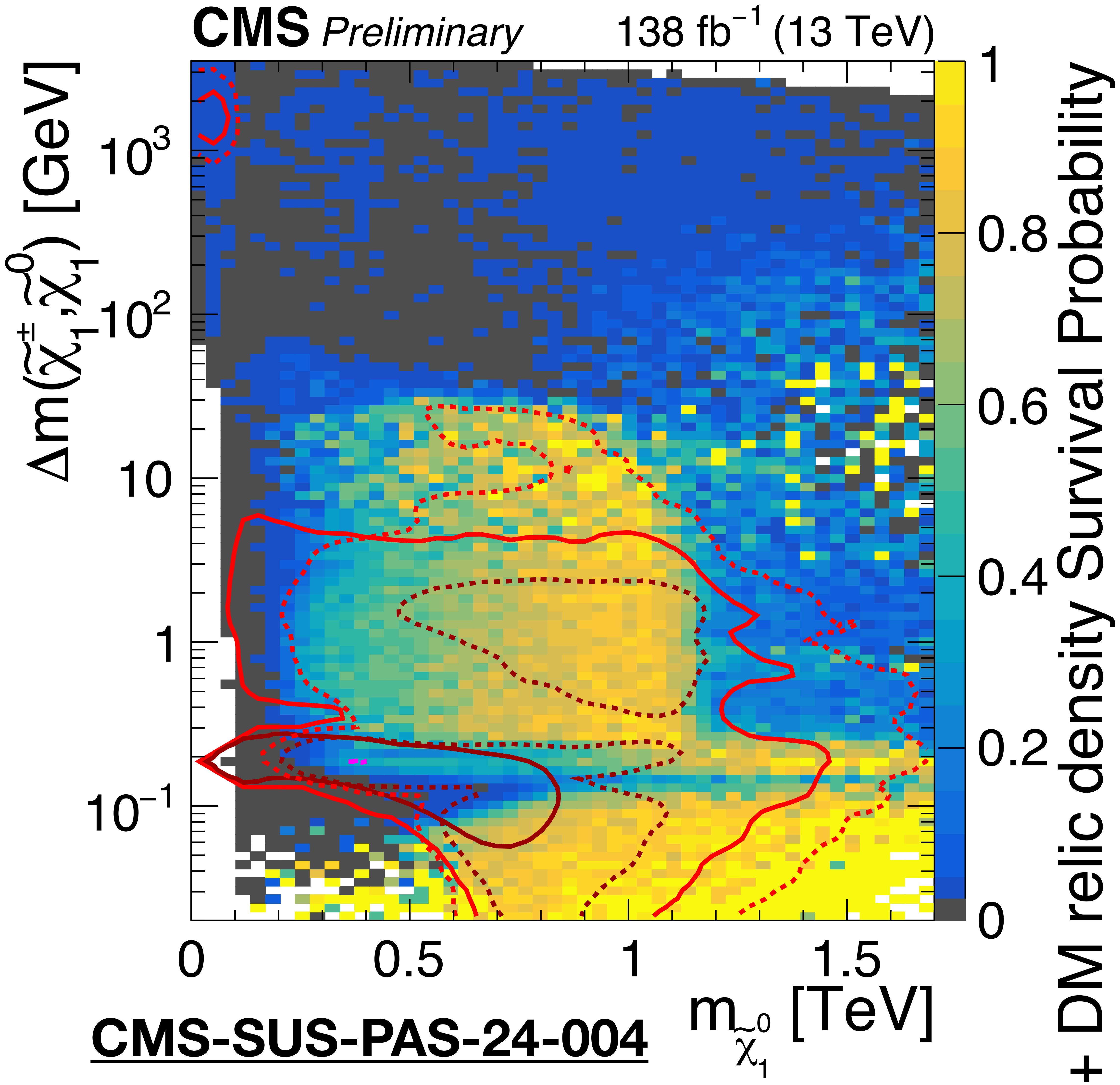
SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006

Supersymmetric DM

+Relic density (Planck) arXiv:1807.06209

$\Omega_h^2 < 0.12 * 1.1$





CMS-SUS-PAS-24-004

SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006+DM constraints

Supersymmetric DM

CMS-SUS-PAS-24-004

+Relic density (Planck) arXiv:1807.06209

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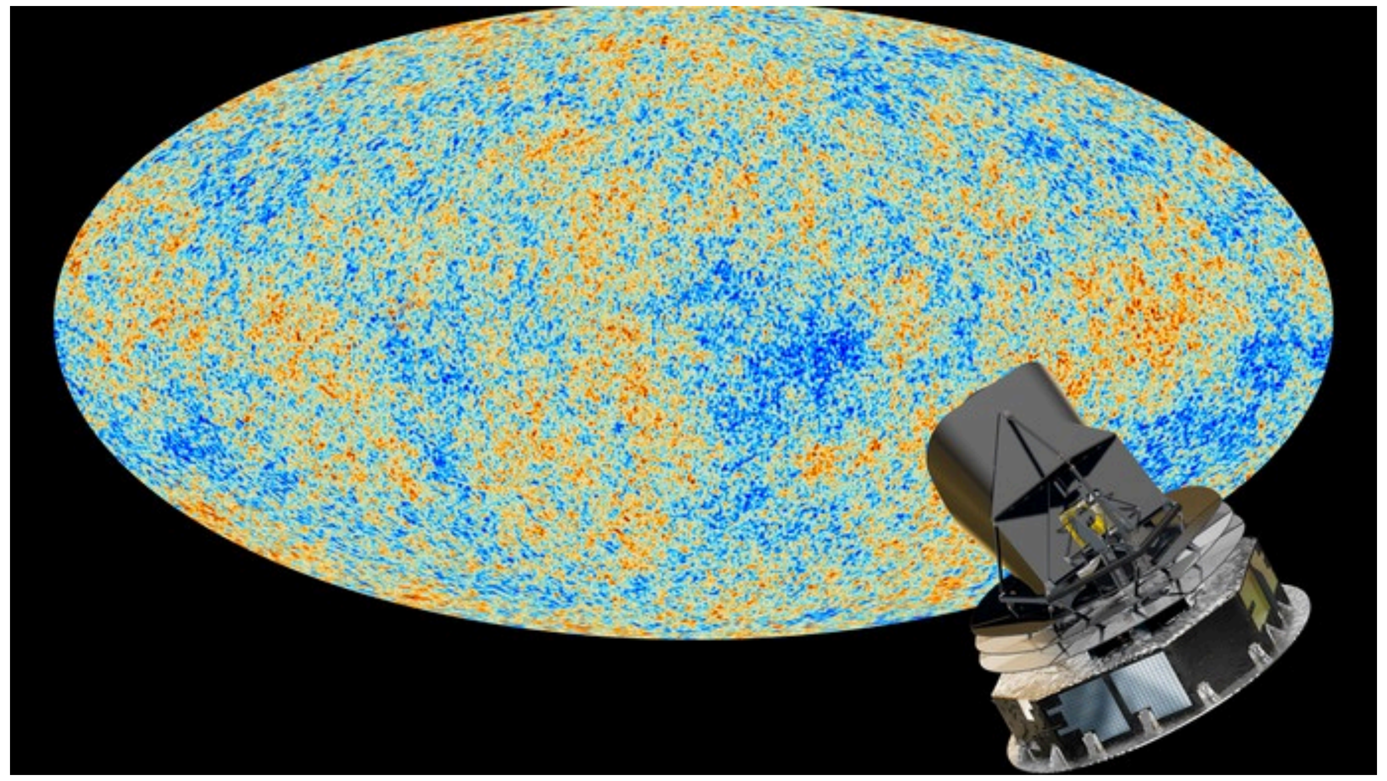
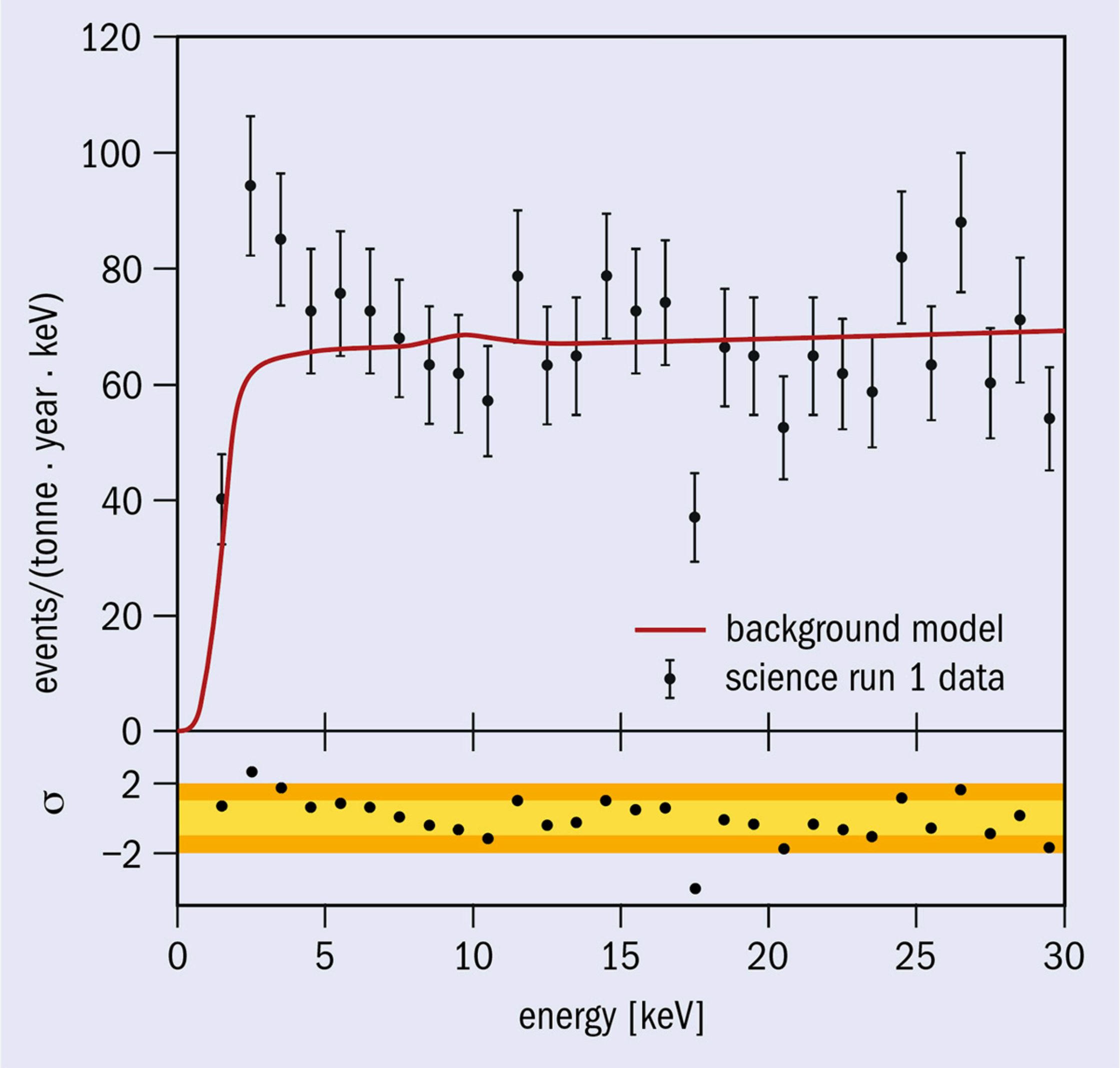
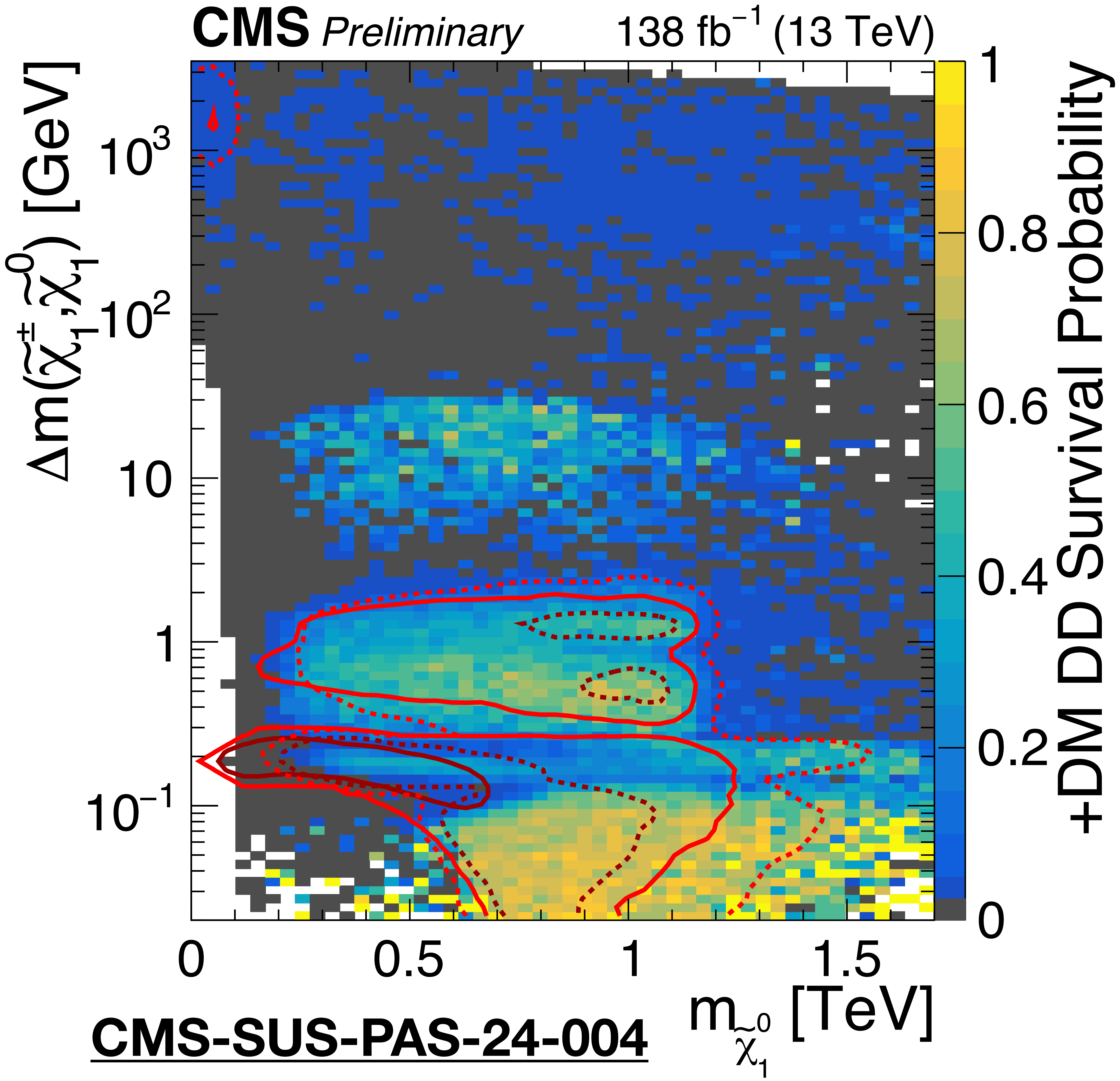


+Direct-detection LZ(22)



Update with LZ24 to this! "Recent results from (LZ)"



CMS-SUS-PAS-24-004

SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006+DM constraints

Supersymmetric DM

CMS-SUS-PAS-24-004

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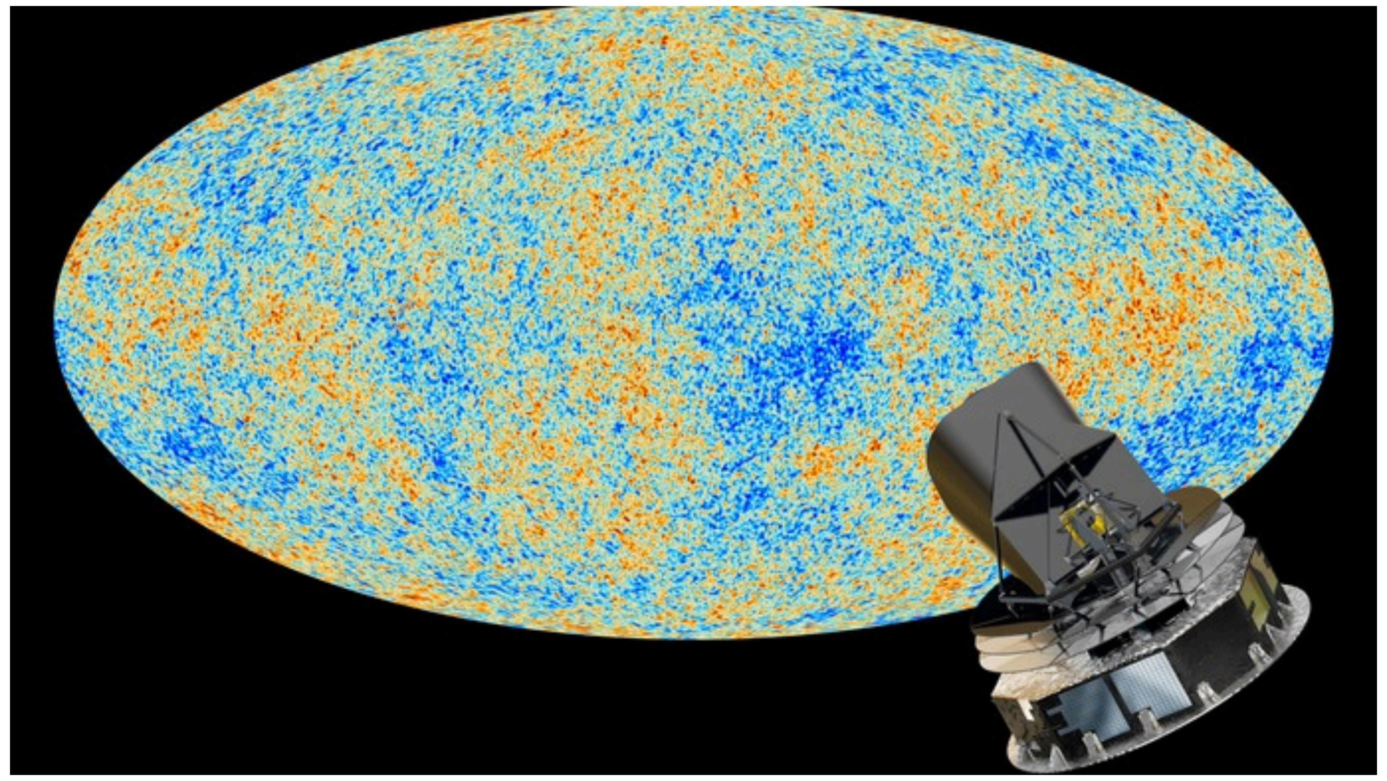

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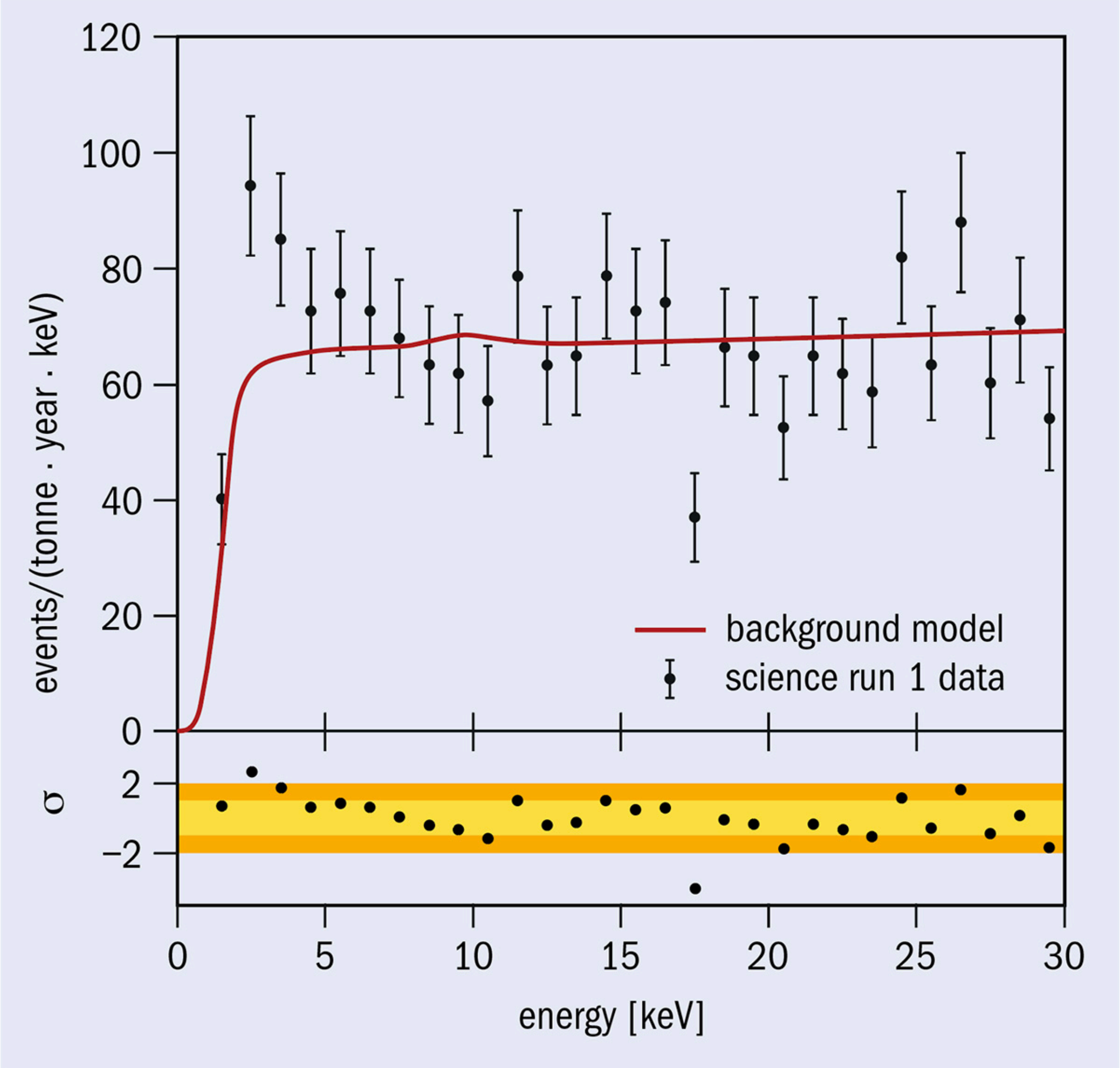
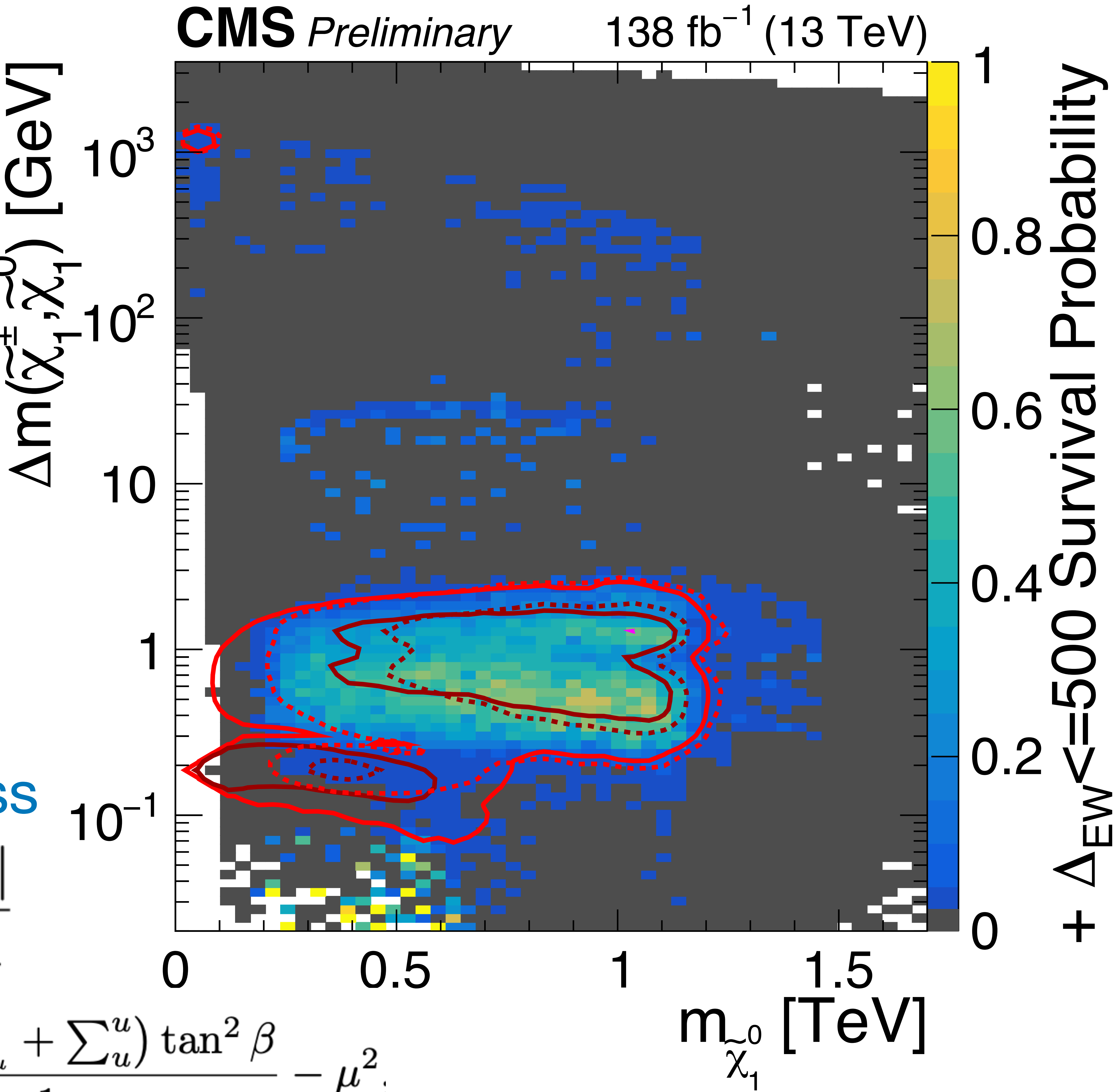


+Fine-tuning/naturalness

$$\Delta EW = max_i \frac{|C_i|}{\frac{m_Z^2}{2}}$$

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \sum_d^d - (m_{H_u}^2 + \sum_u^u) \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$



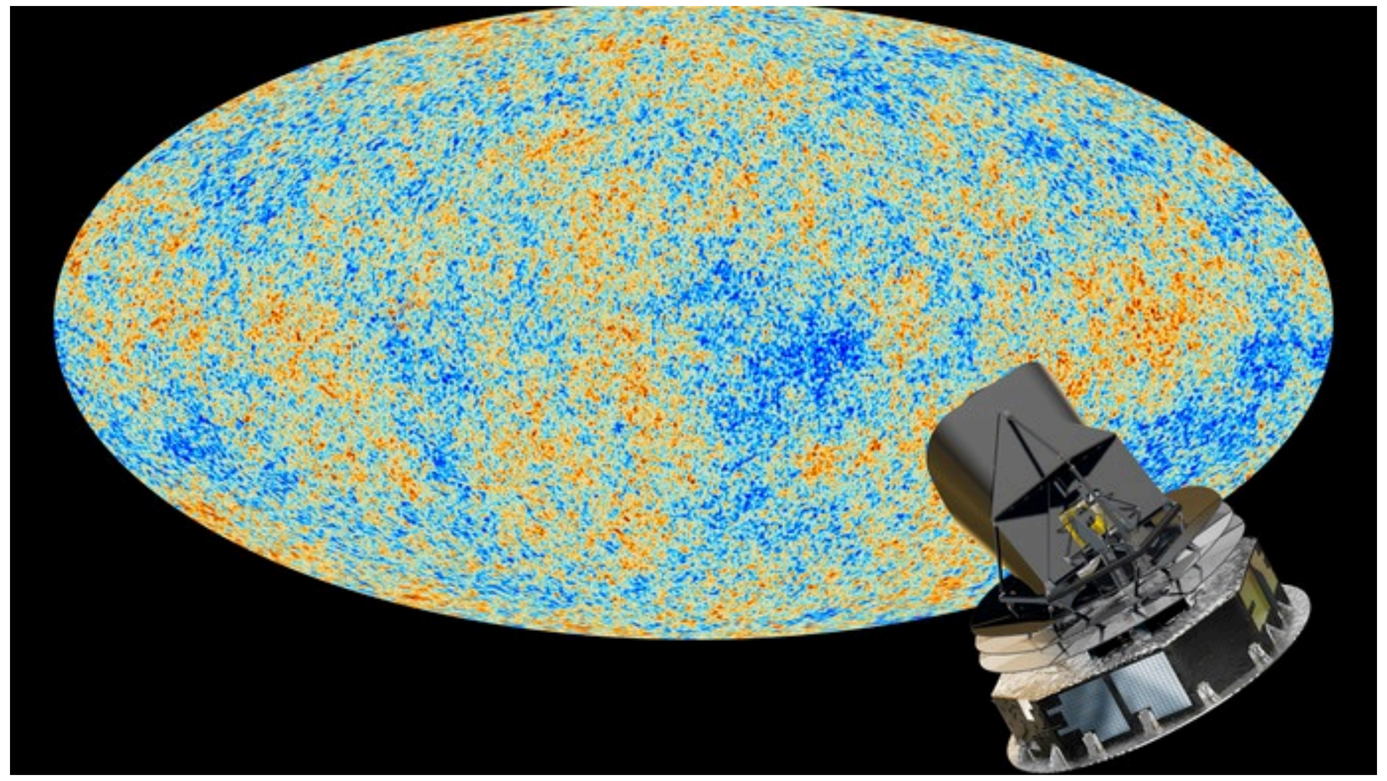
SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006+DM constraints+Δ_{EW}<200

Supersymmetric DM

CMS-SUS-PAS-24-004

+Relic density (Planck) arXiv:1807.06209

$$\Omega_h^2 < 0.12 * 1.1$$



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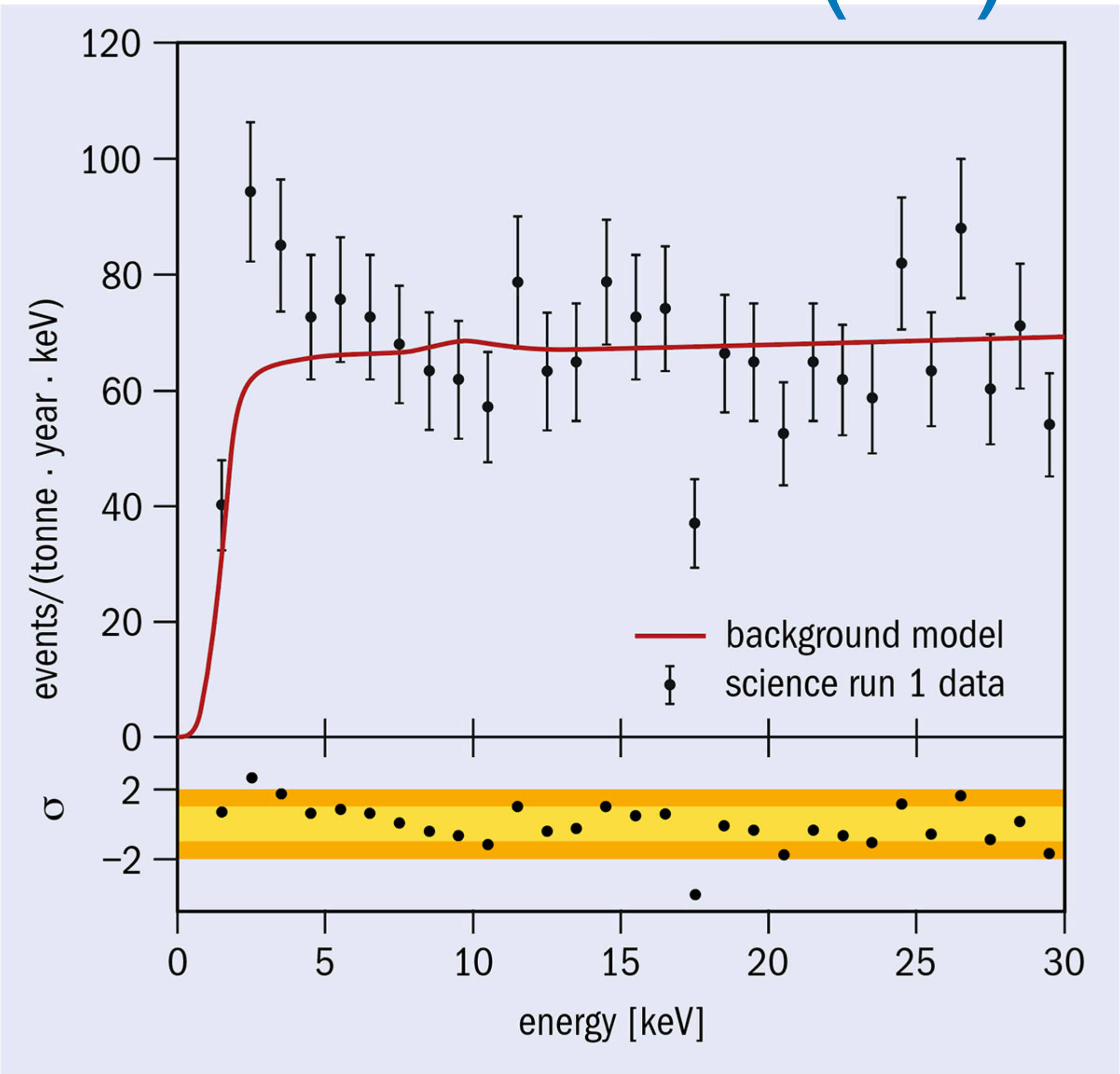

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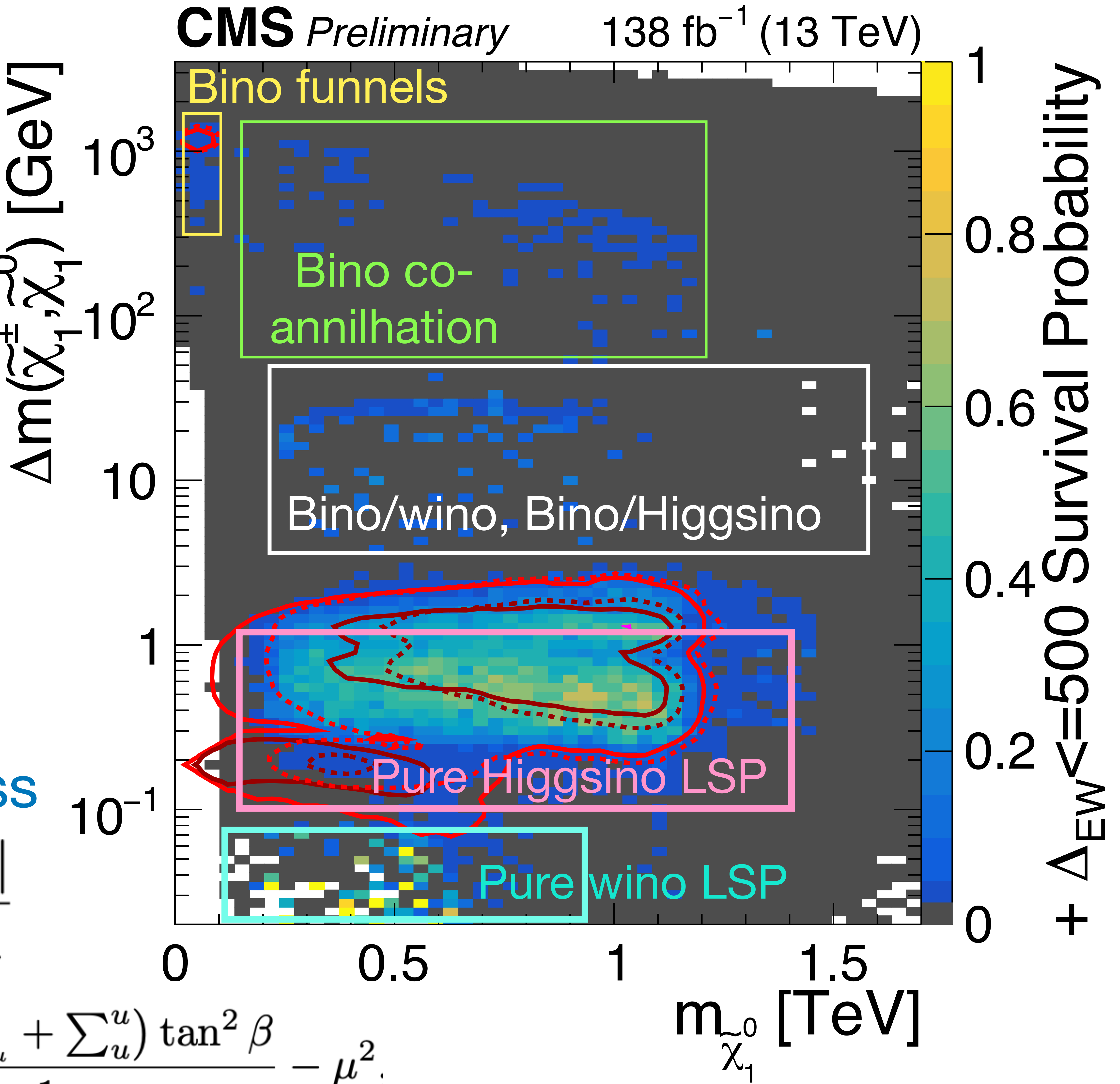
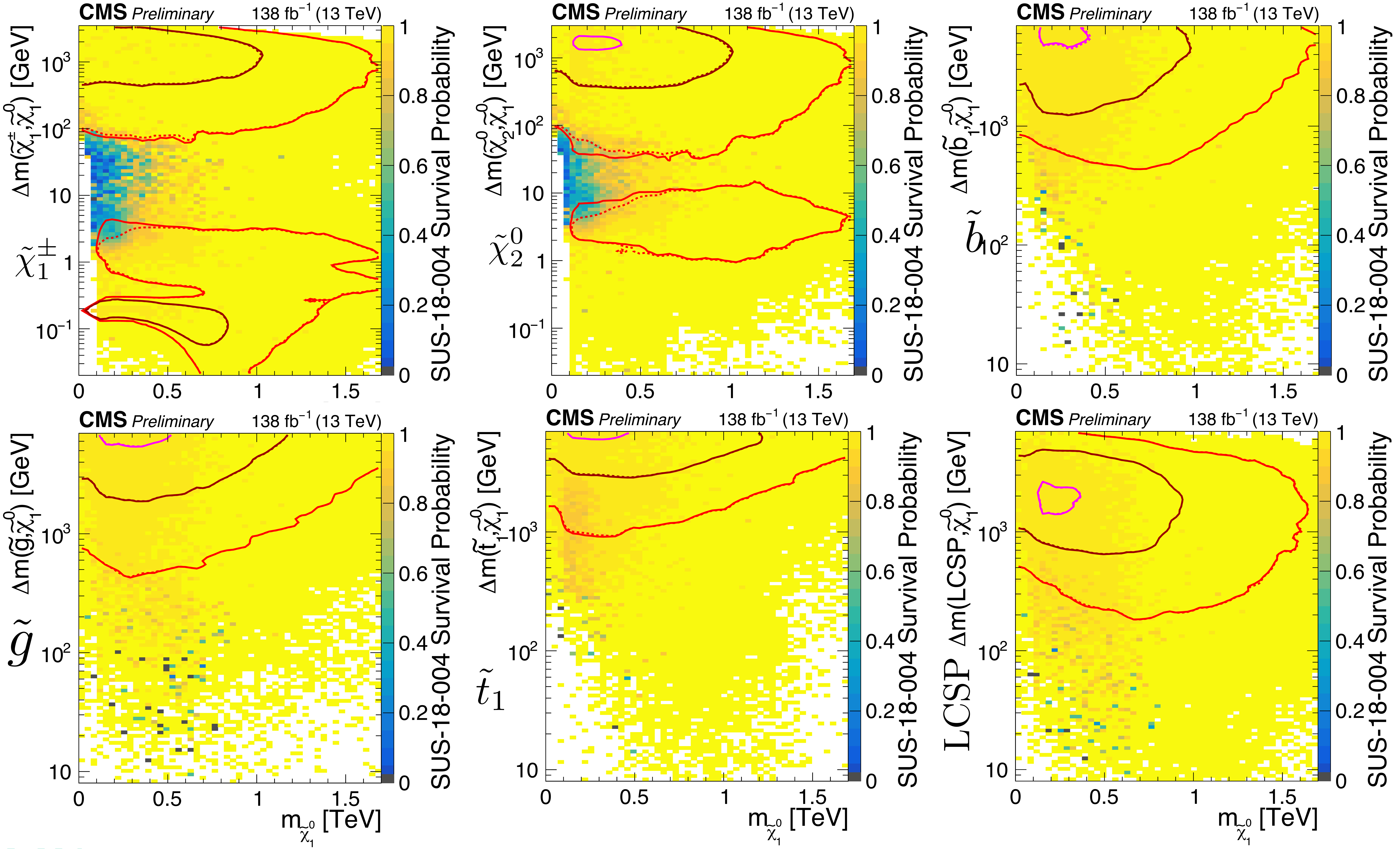


SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006+DM constraints+Δ_{EW}<200

pMSSM impact analysis sequence

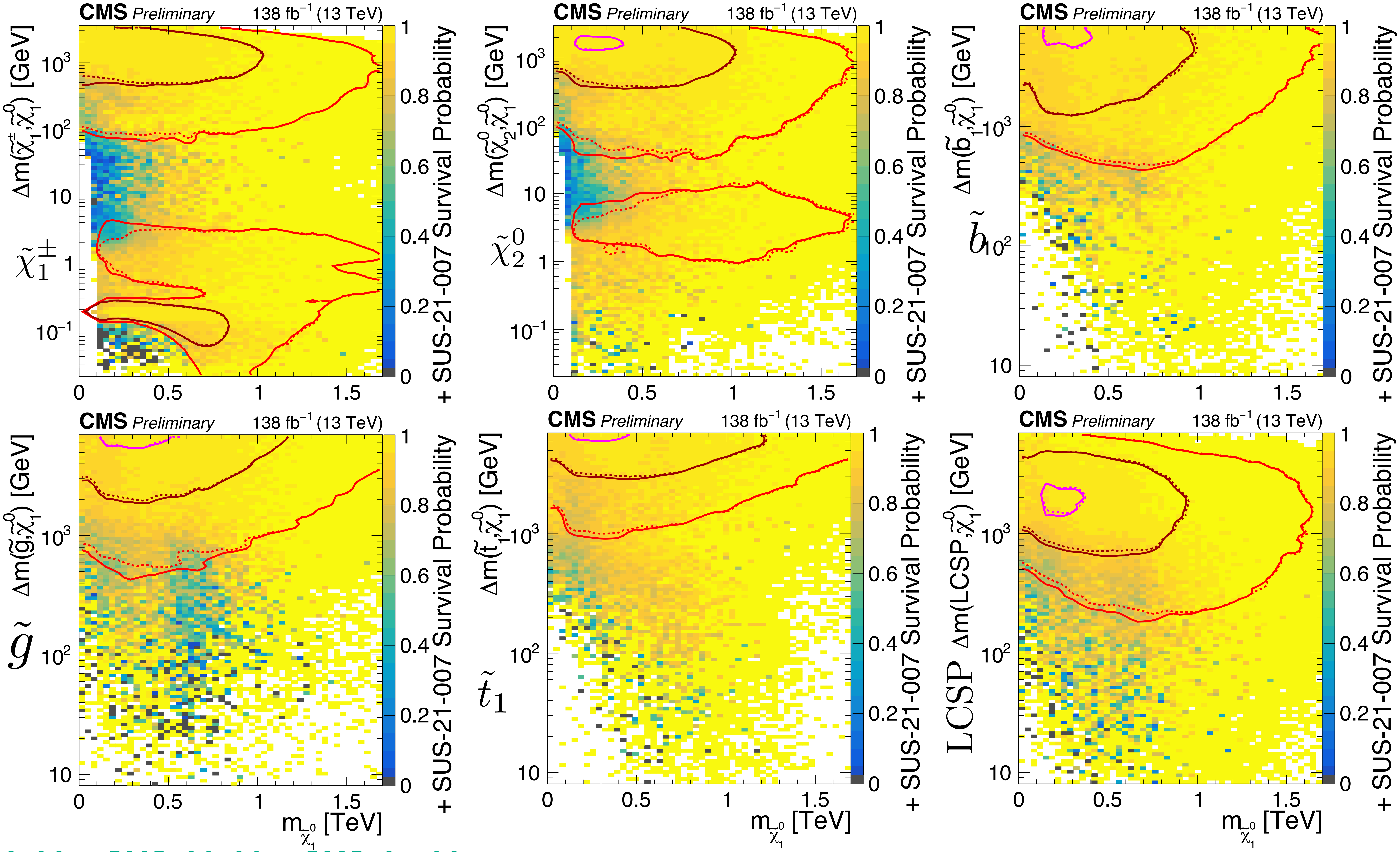
CMS-SUS-PAS-24-004



SUS-18-004

pMSSM impact analysis sequence

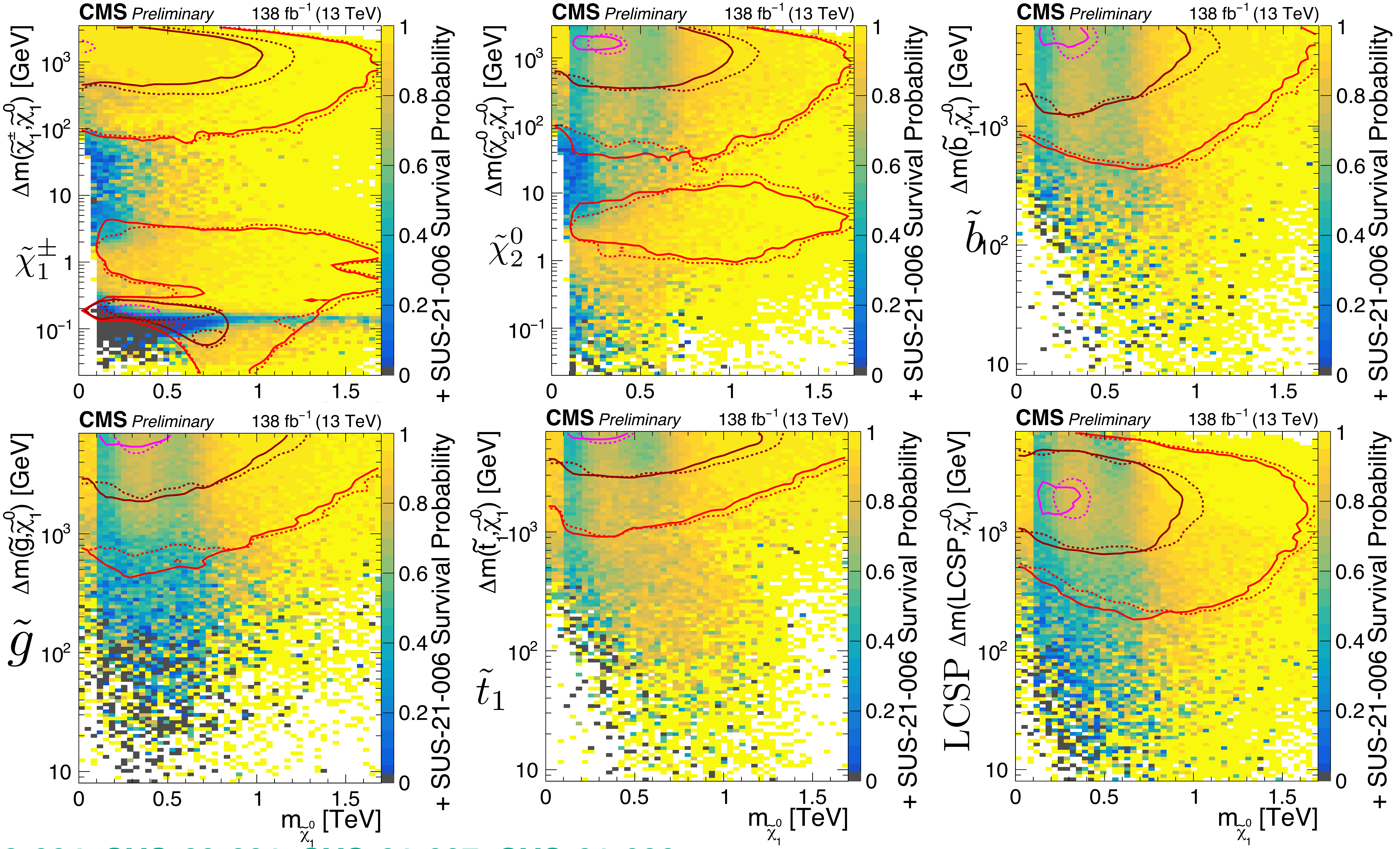
CMS-SUS-PAS-24-004



SUS-18-004+SUS-20-001+SUS-21-007

pMSSM impact analysis sequence

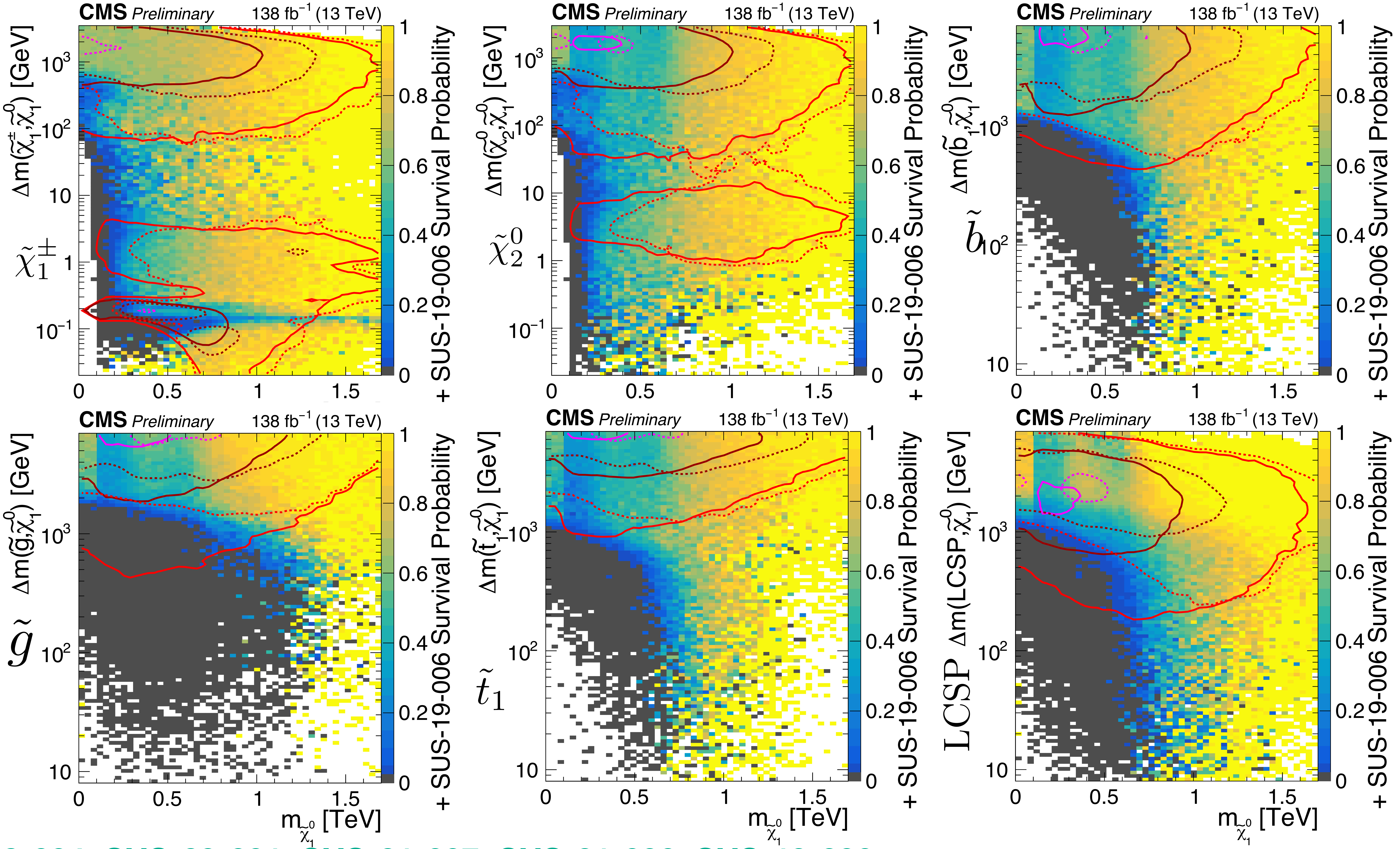
CMS-SUS-PAS-24-004



SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006

pMSSM impact analysis sequence

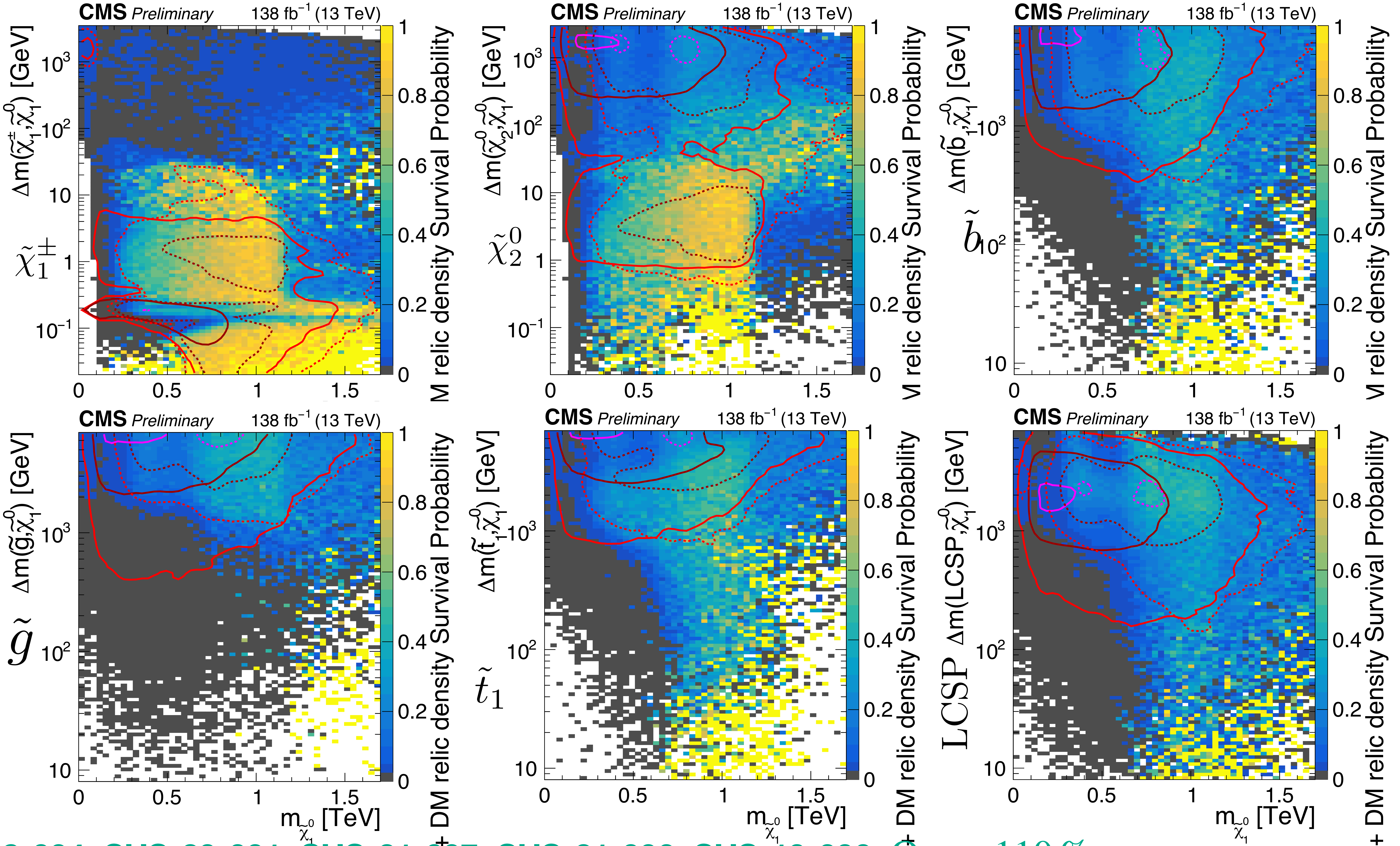
CMS-SUS-PAS-24-004



SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006

pMSSM impact analysis sequence

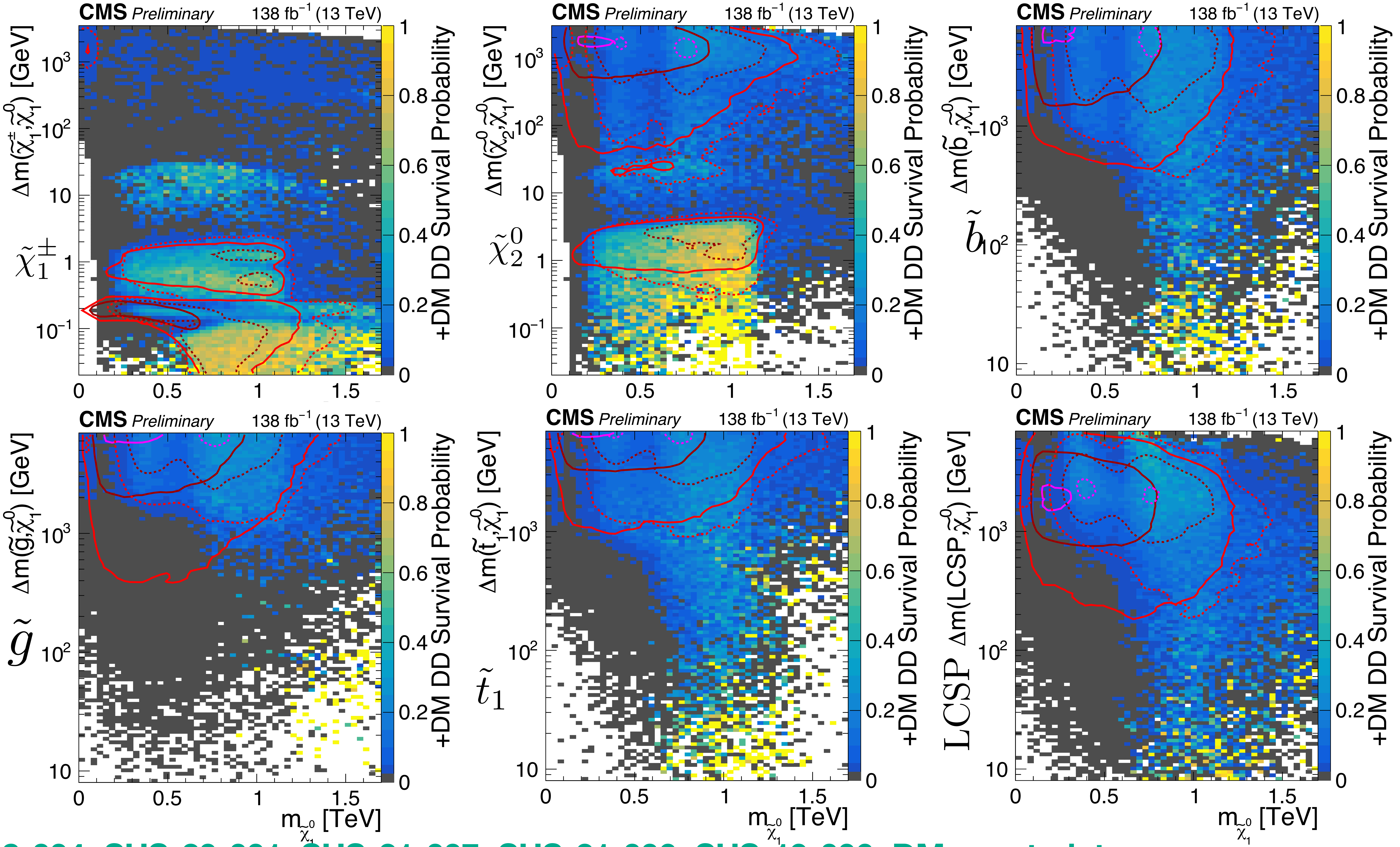
CMS-SUS-PAS-24-004



SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006+$\Omega_{h^2} < 110\,\%$

pMSSM impact analysis sequence

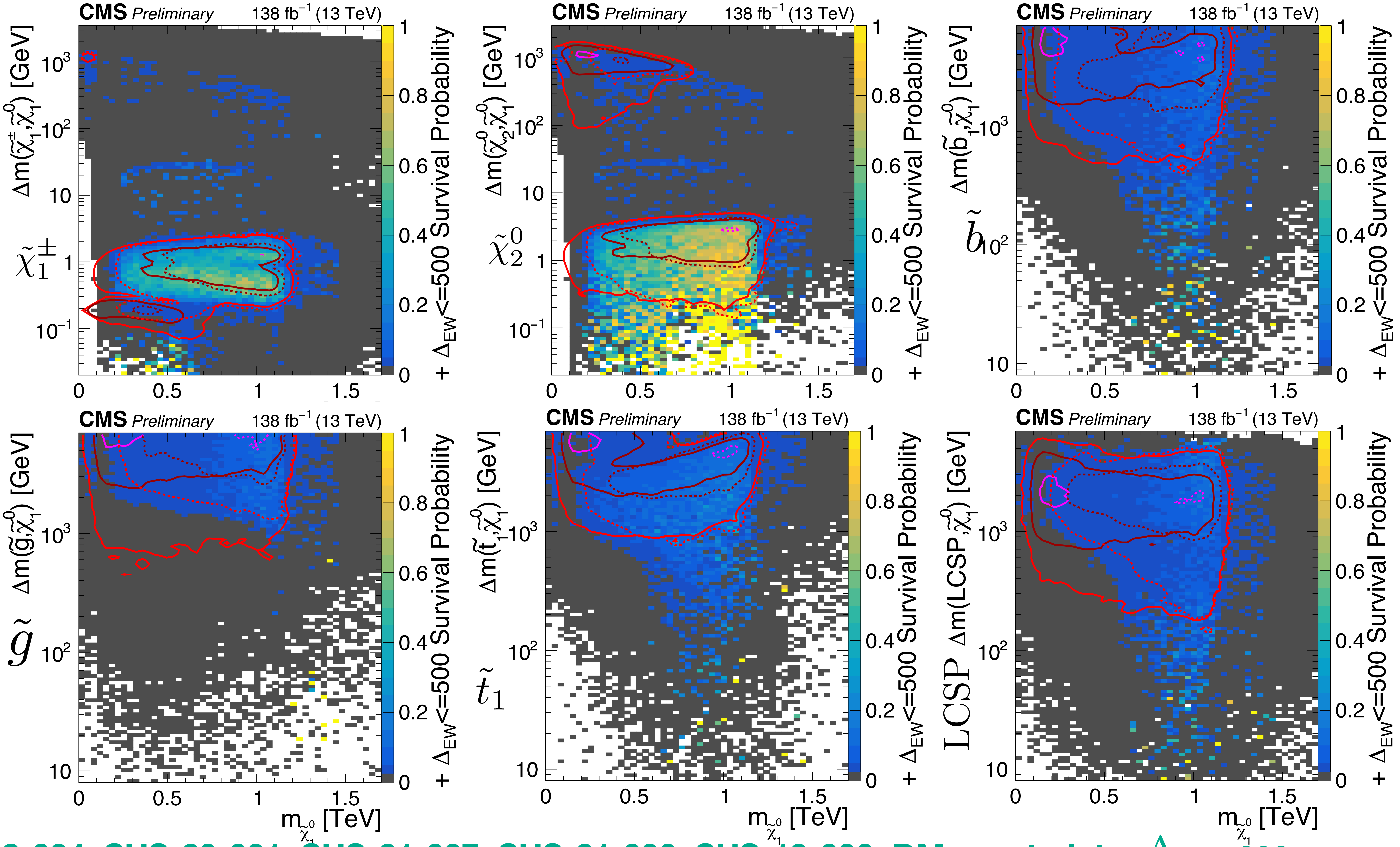
<u>CMS-SUS-PAS-24-004</u>



SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006+DM constraints

pMSSM impact analysis sequence

CMS-SUS-PAS-24-004

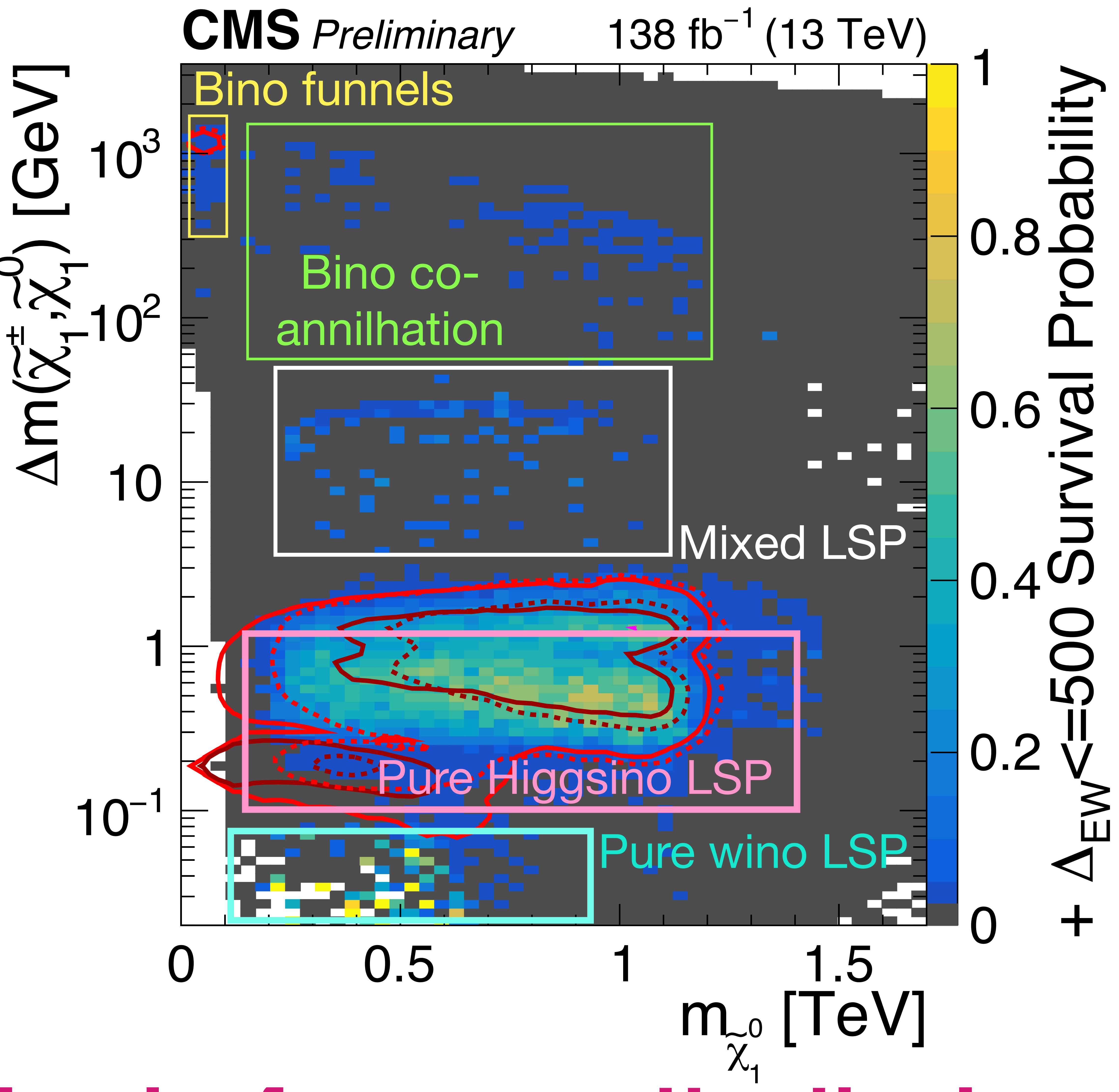


SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006+DM constraints+ Δ_{EW}<200

SUSY Summary

[CMS-SUS-PAS-24-004](CMS-SUS-PAS-24-004)

- CMS has evaluated viability of R-parity conserving SUSY
  - Natural SUSY under pressure, SUSY DM largely unconstrained
  - With DM and naturalness constraints, MSSM bounded from all sides
  - We've constructed a phase space map of the remaining phase space.



Thanks for your attention!

FastSim Summary

Fast Perfekt applied to CMS jets   arXiv:2410.15992   arxiv:2309.12919

- Single-stage training based on unbiased MMD
  - Refinement with realistic production conditions, e.g., pile-up,
  - Flavour tagging overvables, kinematics
  - Refinement propagated to event-level observables shows improvement
- Prototype in place for production, use with new data

Backup

Prior

Flat prior in pMSSM-19

squarks up to 10 TeV

gluino up to 10 TeV

sleptons up to 4 TeV

heavy Higgs up to 4 TeV

electroweakinos up to 4 TeV

trilinear couplings up to 7 TeV

tan β from 2 to 60

Markov chain Monte Carlo (McMC)

Higgs mass: m(h^0)***

LEP constraints

flavor measurements:

BR($b \to s\,\gamma$)*

BR($b \to s\,\mu\mu$)*

BR($b \to s\,ee$)*

BR($B_s \to \mu\mu$)*

BR($B_d \to \mu\mu$)*

BR($B_u \to \tau\nu$)*

BR($D_s \to \tau\nu$)**

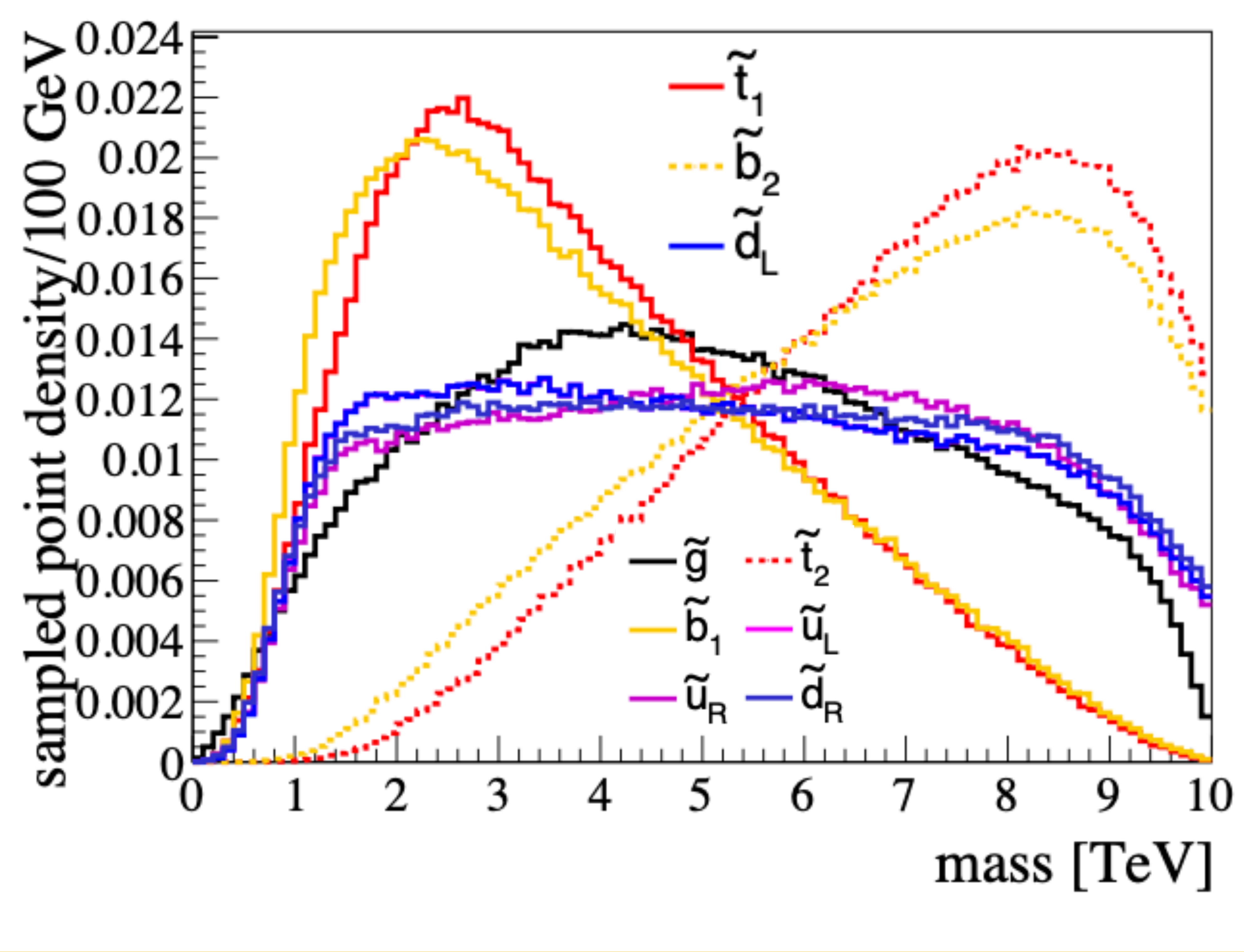
BR($D_s \to \mu\nu$)**

BR($B^0 \to K^{*0}\,\gamma$)*

Δ_0 ($B \to K^*\,\gamma$) **

Δρ

- 1 grand scan, 500k points sampled



- Bounds->~50% EWK, 50% strong production

pMSSM Bayes factor quantiles

CMS-SUS-PAS-24-004

5-analysis combination

- plotting upper quantiles of the Bayes Factor:

$$\mathrm{BF}(\theta) = \mathscr{L}(\theta, \mu = 1)/\mathscr{L}(\theta, \mu = 0)$$