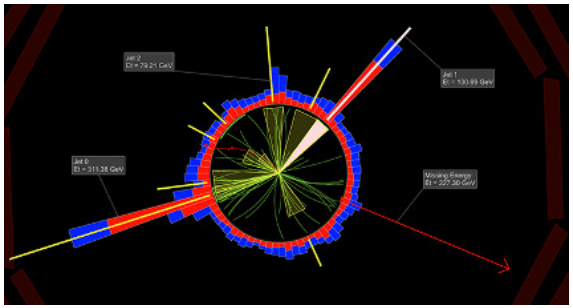
Phenomenological MSSM interpretation of CMS results

Jory Sonneveld
for the CMS collaboration



SUSY 2016, Melbourne

arXiv:1606.03577, CMS-SUS-15-010

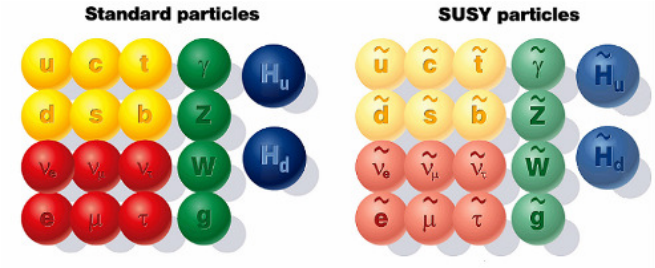


Figure courtesy of Jan Heisig

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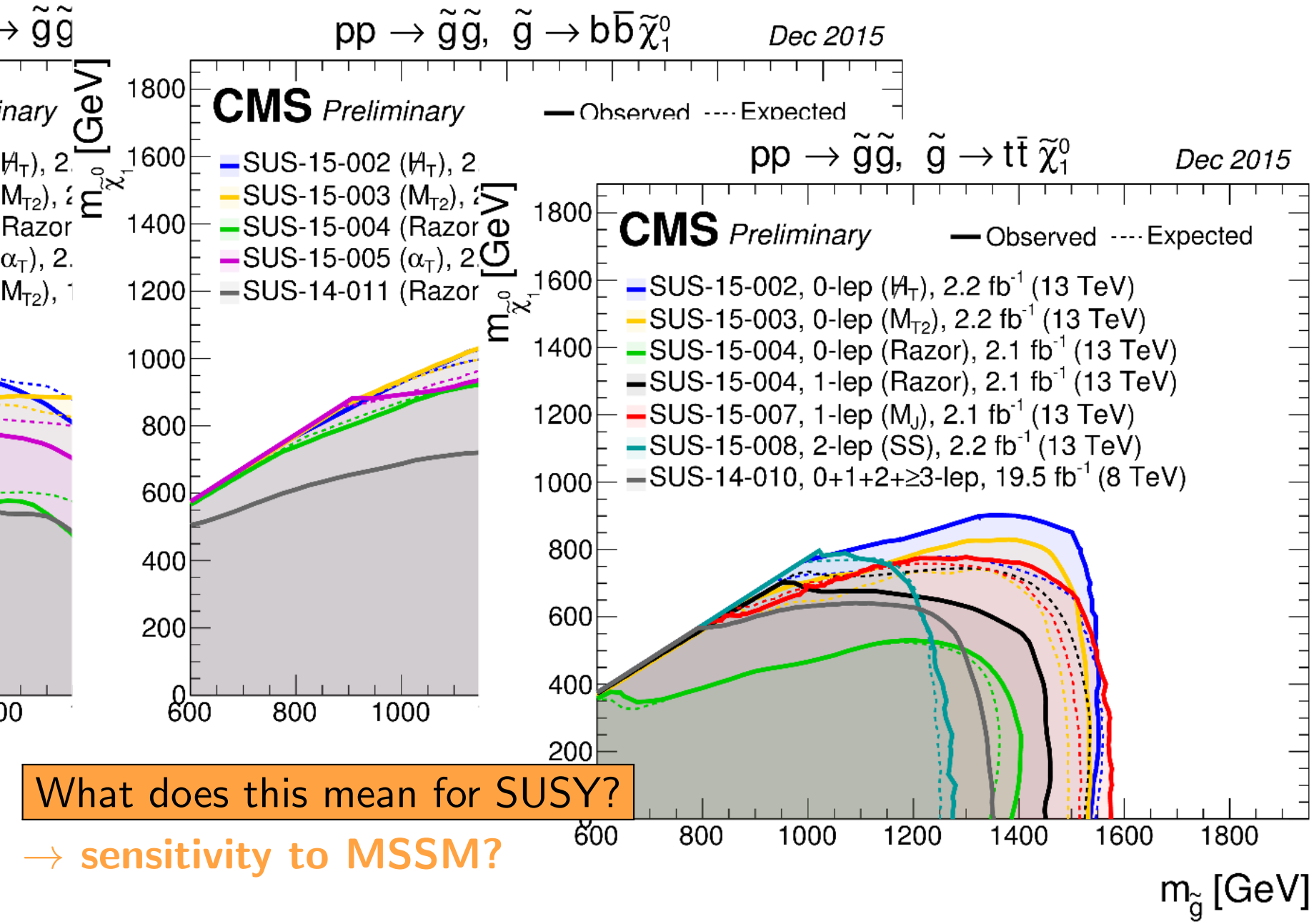
Bundesministerium für Bildung und Forschung

CMS

DFG Deutsche Forschungsgemeinschaft

CMS SUSY searches



What does this mean for SUSY?

→ **sensitivity to MSSM?**

Phenomenogical MSSM

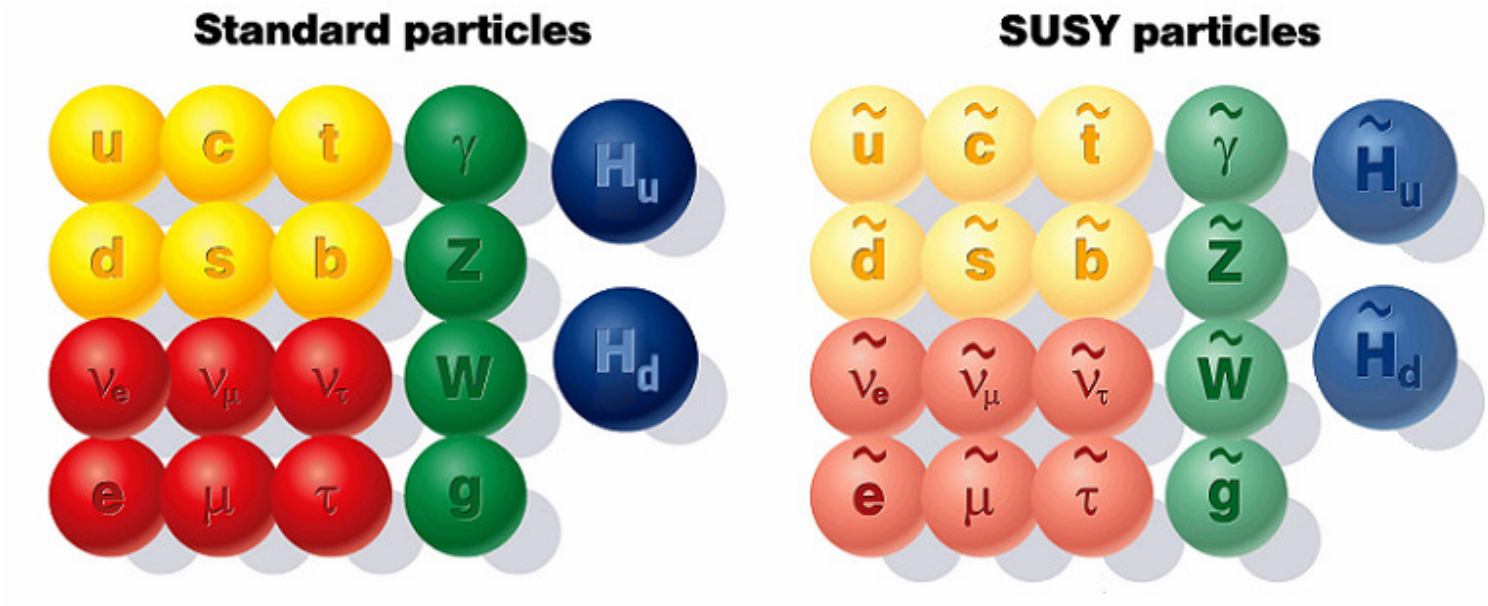


Figure courtesy of Jan Heisig

R-parity conserving Minimal Supersymmetric Standard Model

Reduce 119 free parameters to 19 by assuming:

1. *No new source of CP violation*
2. *No flavor-changing neutral currents*
3. *First and second generation universality*

[Djouadi et. al. 1998]

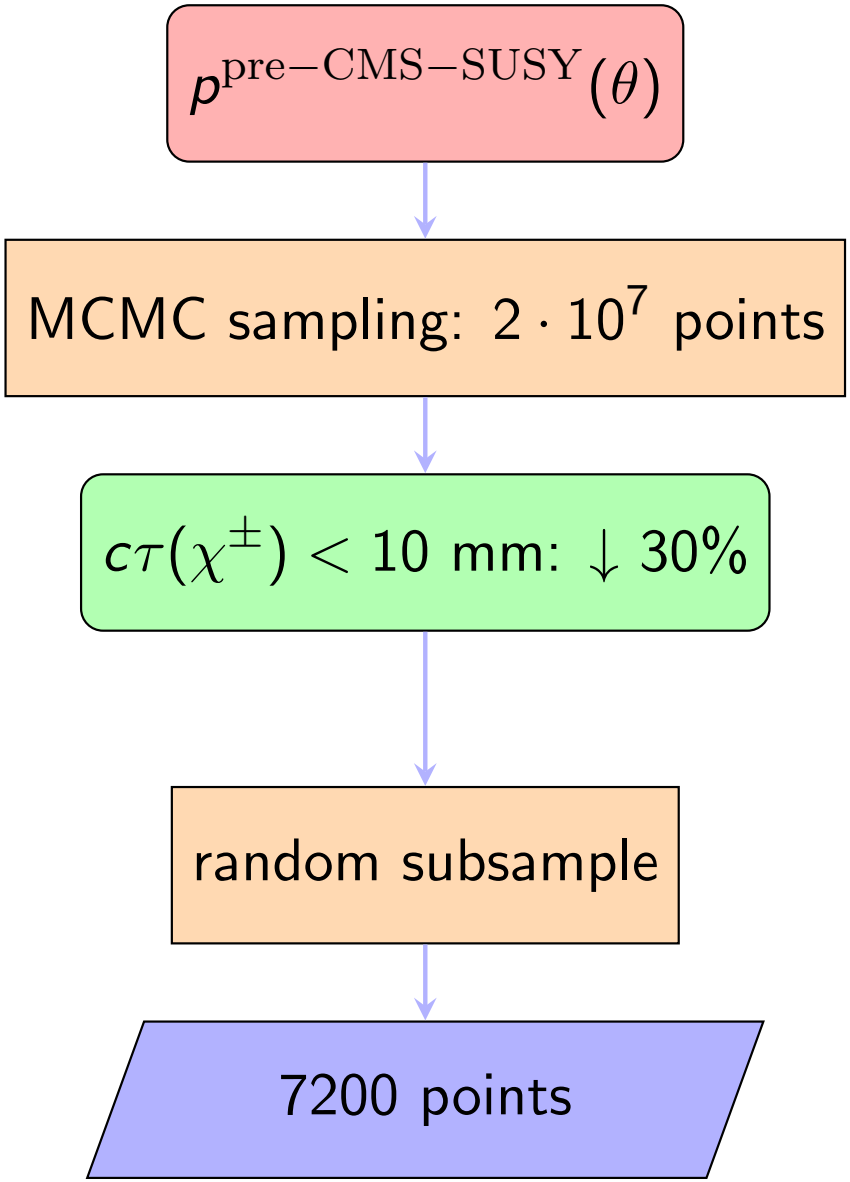
Parameter space considered in the pMSSM

$$
\begin{aligned}
-3 \leq\ & M_1, M_2 & \leq 3\,\text{TeV}, \\
0 \leq\ & M_3 & \leq 3\,\text{TeV}, \\
-3 \leq\ & \mu & \leq 3\,\text{TeV}, \\
0 \leq\ & m_\text{A} & \leq 3\,\text{TeV}, \\
2 \leq\ & \tan\beta & \leq 60, \\
0 \leq\ & m_{\tilde{\text{Q}}_{1,2}}, m_{\tilde{\text{U}}_{1,2}}, m_{\tilde{\text{D}}_{1,2}}, m_{\tilde{\text{L}}_{1,2}}, m_{\tilde{\text{E}}_{1,2}}, m_{\tilde{\text{Q}}_3}, m_{\tilde{\text{U}}_3}, m_{\tilde{\text{D}}_3}, m_{\tilde{\text{L}}_3}, m_{\tilde{\text{E}}_3} & \leq 3\,\text{TeV}, \\
-7 \leq\ & A_\text{t}, A_\text{b}, A_\tau & \leq 7\,\text{TeV},
\end{aligned}
$$

Additional theoretical assumptions:

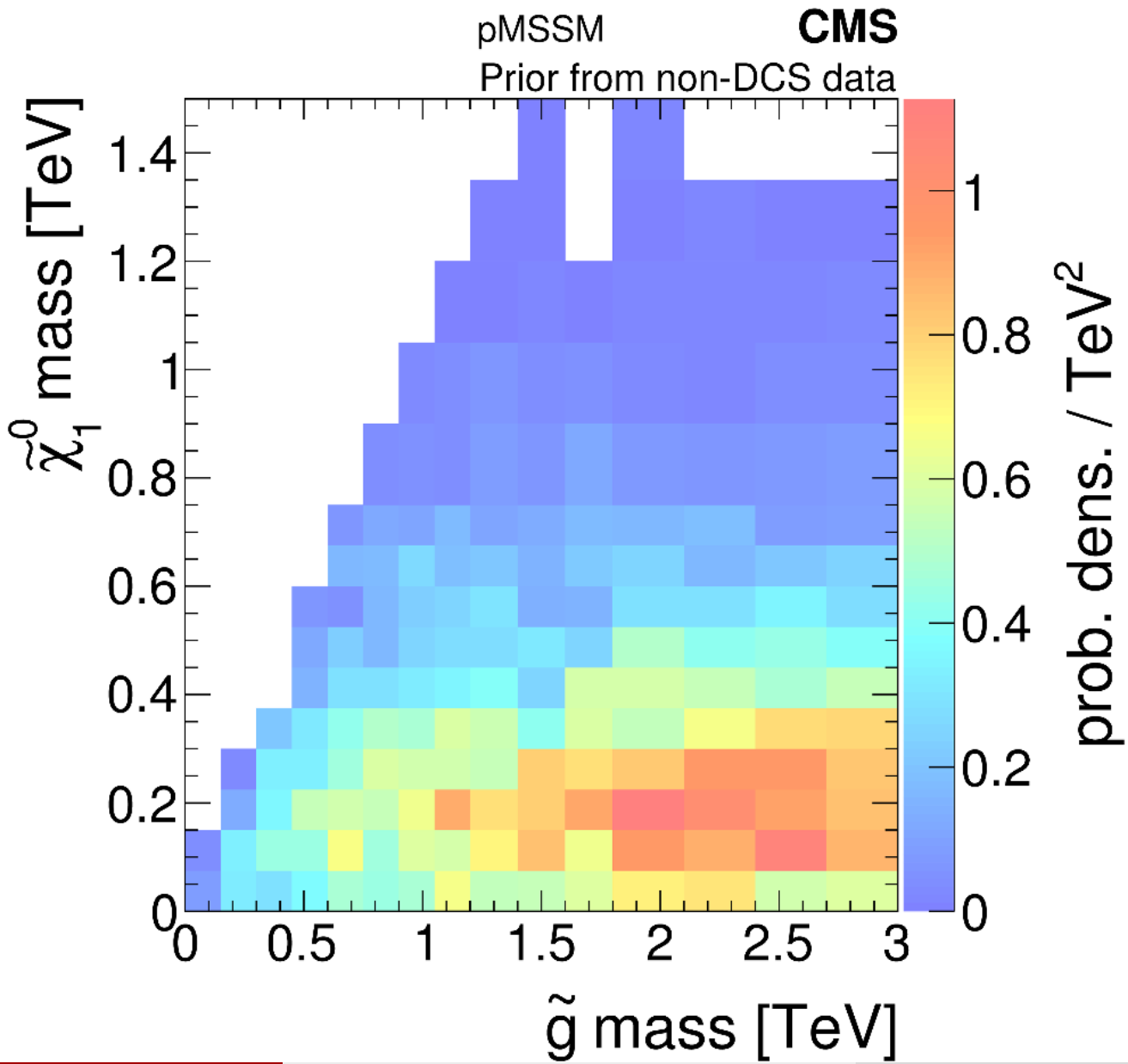
- χ_1^0 is the Lightest (stable) Supersymmetric Particle (LSP);
- parameters defined at EWSB scale $M_\text{SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$;
- no tachyons ($m < 0$);
- V_Higgs bounded from below, no ~~SU(3)~~ minima; EWSB-consistent.

Sampling



- θ are the pMSSM parameters;
- $p^{\mathrm{pre-CMS-SUSY}}(\theta)$ is the prior distribution including:
  - non-CMS-SUSY results;
  - theoretical assumptions.
- $c\tau(\chi^{\pm})$ is the chargino proper decay lifetime.

Prior distribution for the gluino vs LSP masses



Bayesian analysis

Quantification of performance

How well do CMS searches constrain the (p)MSSM?

Posterior densities

$$p(\theta|d) \propto L(d^{\mathrm{CMS-SUSY}}|\theta)L(d^{\mathrm{pre-CMS-SUSY}}|\theta)p(\theta)$$

- θ are the pMSSM parameters;
- $p(\theta) = p(\mathrm{prompt}\ \chi^{\pm}|\theta)p(\mathrm{theory}|\theta)p_0(\theta)$ is the prior (with $p_0(\theta)$ flat);
- $d^{\mathrm{pre-CMS-SUSY}}$ are measurements from experiments other than CMS SUSY searches;
- $d^{\mathrm{CMS-SUSY}}$ are results from 11 CMS SUSY searches.

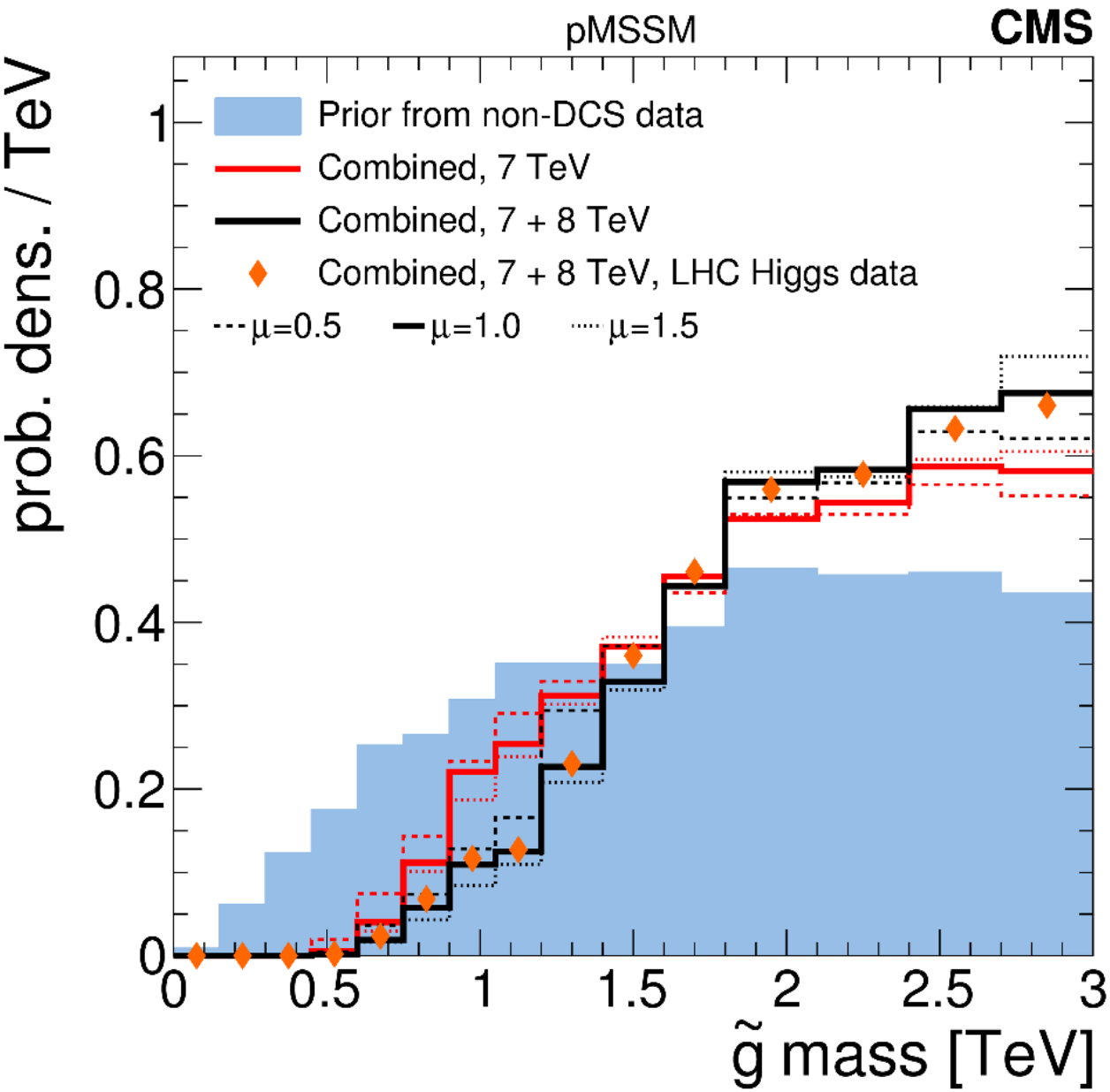
pre-CMS-SUSY results: $d^{\text{pre-CMS-SUSY}}$

i	Observable $\mu_i(\theta)$	Constraint $D_i^{\text{non-DCS}}$	Likelihood function $L[D_i^{\text{non-DCS}}\|\mu_i(\theta)]$
1	$\mathcal{B}(\mathrm{b} \to \mathrm{s}\gamma)$ [45]	$(3.43 \pm 0.21^{\text{stat}} \pm 0.24^{\text{th}} \pm 0.07^{\text{sys}}) \times 10^{-4}$	Gaussian
2	$\mathcal{B}(\mathrm{B_s} \to \mu\mu)$ [46]	$(2.9 \pm 0.7 \pm 0.29^{\text{th}}) \times 10^{-9}$	Gaussian
3	$R(\mathrm{B} \to \tau\nu)$[45]	1.04 ± 0.34	Gaussian
4	Δa_μ [47]	$(26.1 \pm 6.3^{\text{exp}} \pm 4.9^{\text{SM}} \pm 10.0^{\text{SUSY}}) \times 10^{-10}$	Gaussian
5	$\alpha_\mathrm{s}(m_\mathrm{Z})$ [48]	0.1184 ± 0.0007	Gaussian
6	m_t [49]	$173.20 \pm 0.87^{\text{stat}} \pm 1.3^{\text{sys}}\,\text{GeV}$	Gaussian
7	$m_\mathrm{b}(m_\mathrm{b})$ [48]	$4.19^{+0.18}_{-0.06}\,\text{GeV}$	Two-sided Gaussian
8	m_h	LHC: $m_\mathrm{h}^{\text{low}} = 120\,\text{GeV}$, $m_\mathrm{h}^{\text{high}} = 130\,\text{GeV}$	1 if $m_\mathrm{h}^{\text{low}} \leq m_\mathrm{h} \leq m_\mathrm{h}^{\text{high}}$ 0 if $m_\mathrm{h} < m_\mathrm{h}^{\text{low}}$ or $m_\mathrm{h} > m_\mathrm{h}^{\text{high}}$
9	μ_h	CMS and ATLAS in LHC Run 1, Tevatron	LILITH 1.01 [50, 51]
10	sparticle masses	LEP [52] (via MICROMEGAS [53–55])	1 if allowed 0 if excluded

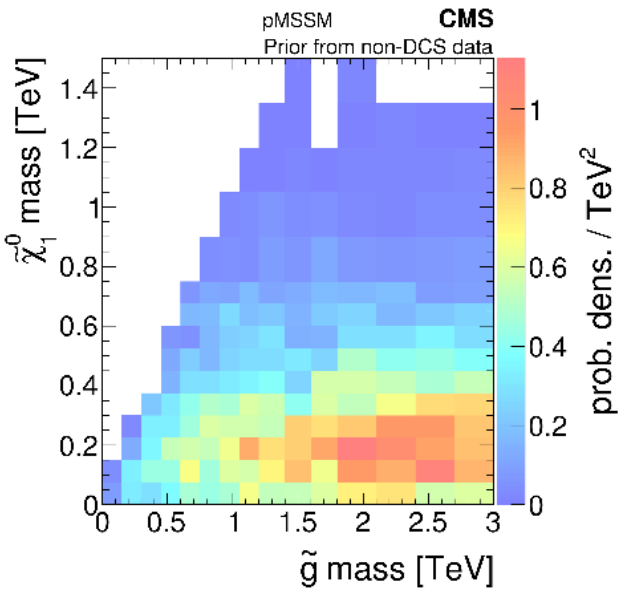
CMS results: $d^{\mathrm{CMS-SUSY}}$

Analysis/ Search	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb$^-$1]
Hadronic HT and MHT arXiv:1207.1898 (CMS-SUS-12-011)	7	4.98
Hadronic HT, MET and b-jet arXiv:1208.4859 (CMS-SUS-12-003)	7	4.98
Leptonic EW χ^0, $\chi^{\pm}$, $\tilde{l}$ production arXiv:1209.6620 (CMS-SUS-12-006)	7	4.98
Hadronic HT and MHT arXiv:1402.4770 (CMS-SUS-13-012)	8	19.5
Hadronic MT2 arXiv:1207.1798 (CMS-SUS-12-002)	8	19.5
Hadronic HT, MET and b-jet arXiv:1305:2390 (CMS-SUS-12-024)	8	19.4
Hadronic third generation squark arXiv:1503.08037 (CMS-SUS-14-001)	8	19.4
Monojet arXiv:1408.3583 (CMS-SUS-EXO-12-048)	8	19.7
OS dilepton arXiv:1502.06031 (CMS-SUS-14-014)	8	19.4
LS dilepton arXiv:1311.6736 (CMS-SUS-13-013)	8	19.5
Leptonic EW χ^0, $\chi^{\pm}$, $\tilde{l}$ production arXiv:1405.7570 (CMS-SUS-13-006)	8	19.5

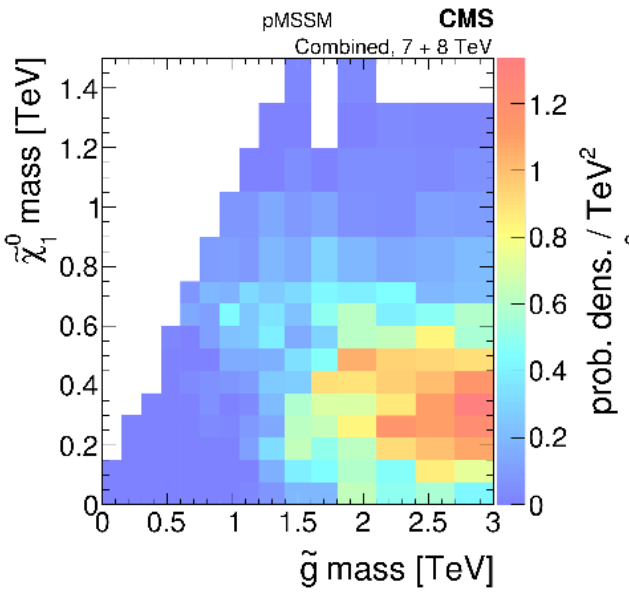
Posterior density for the gluino mass



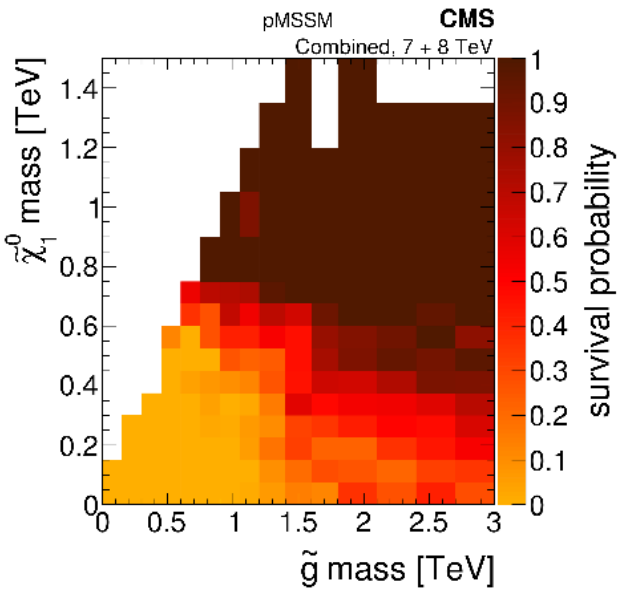
Prior and posterior distributions for the gluino and LSP mass



Density before



Density after

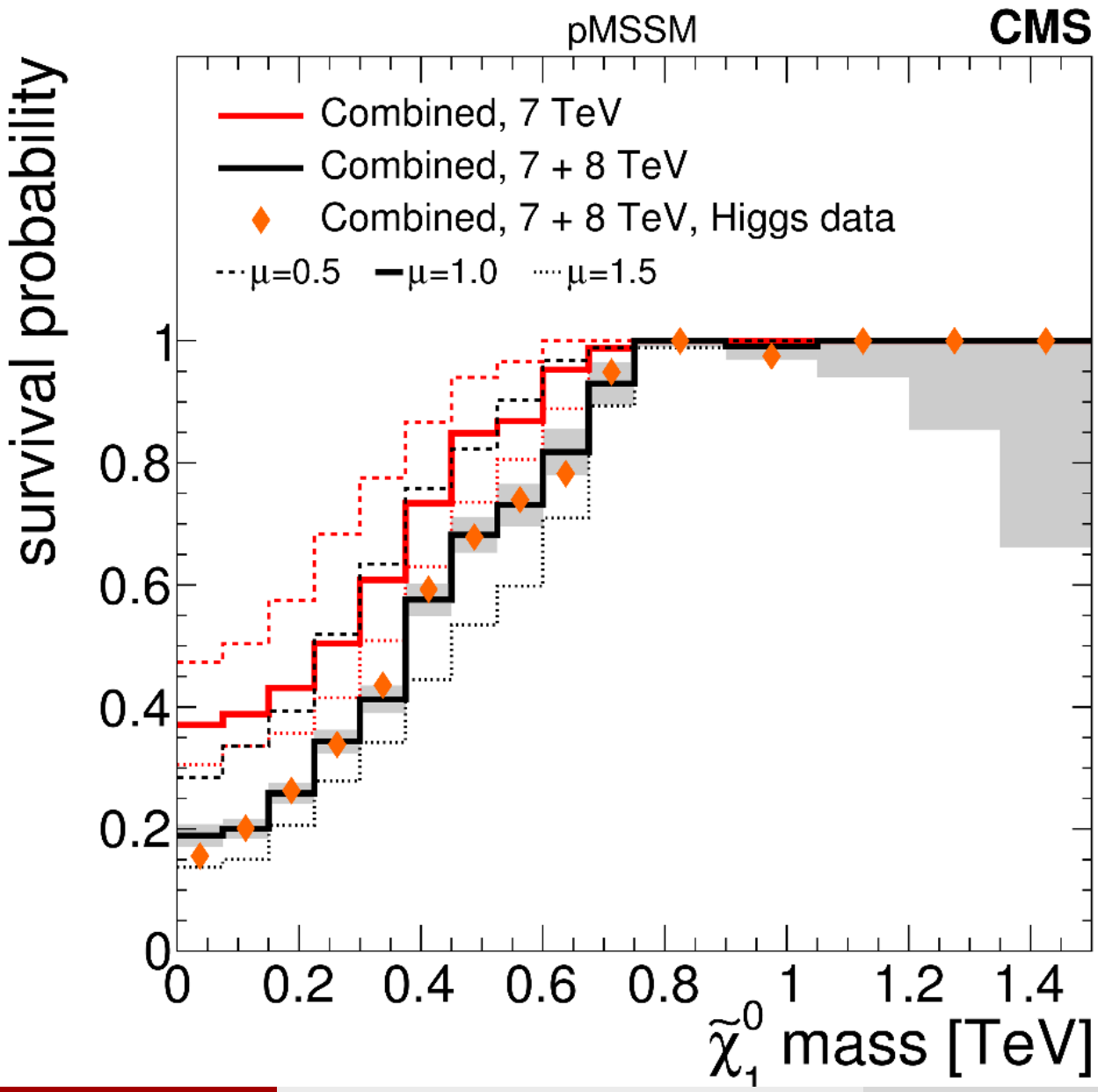


Fraction surviving

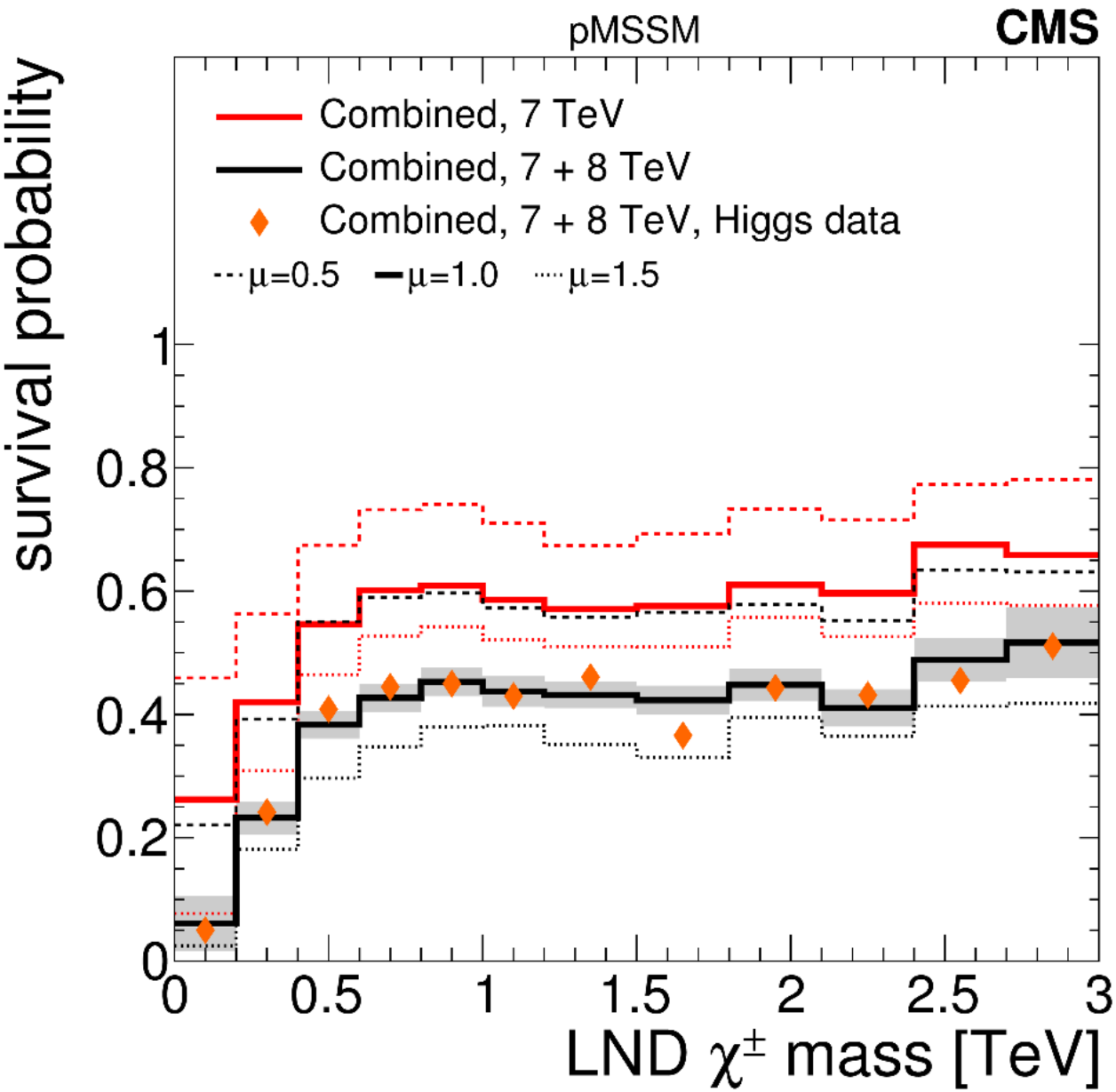
- pre-CMS-SUSY results
- theoretical assumptions

- pre-CMS-SUSY results
- theoretical assumptions
- 11 CMS SUSY results

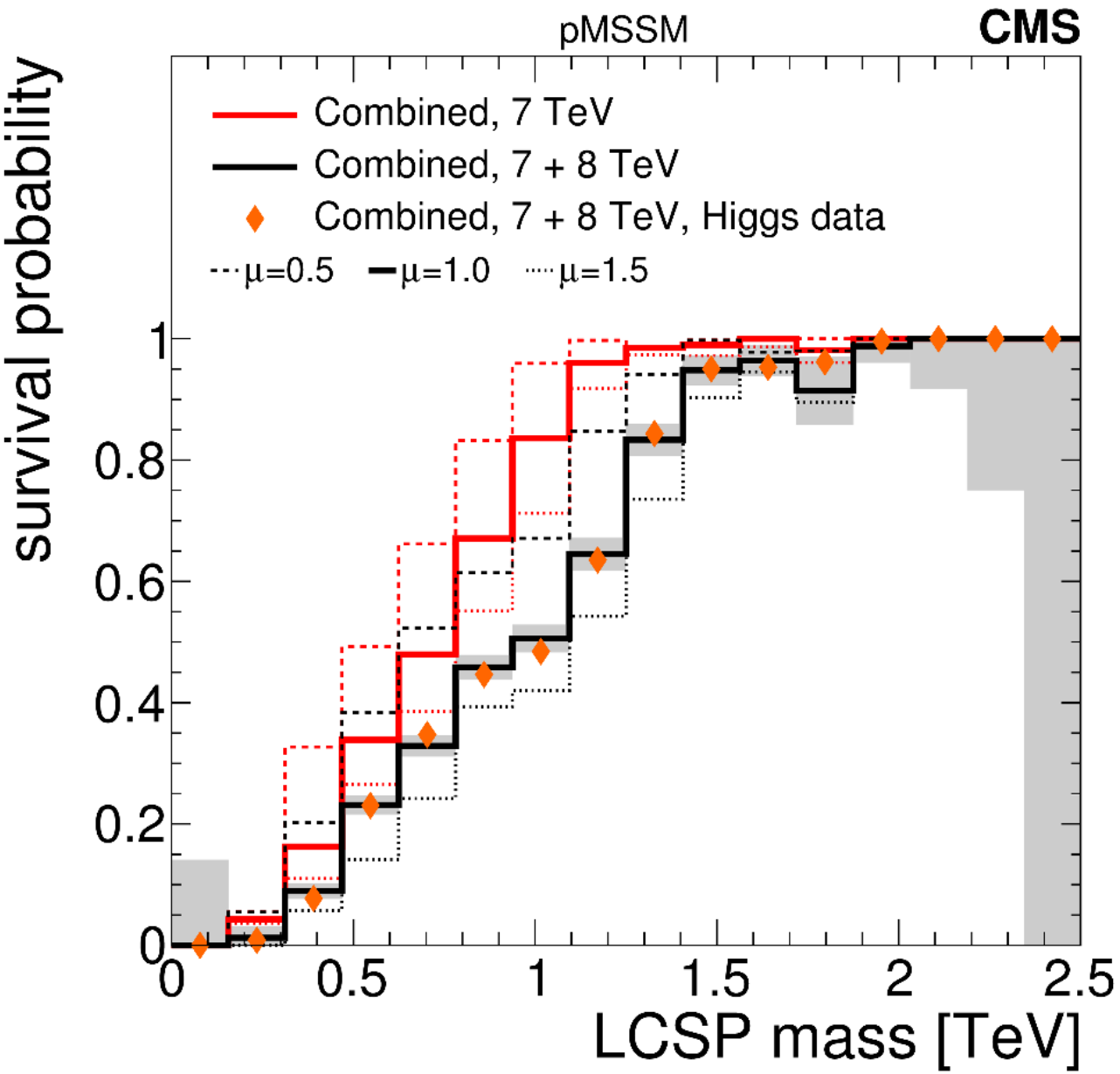
Survival fraction: LSP mass



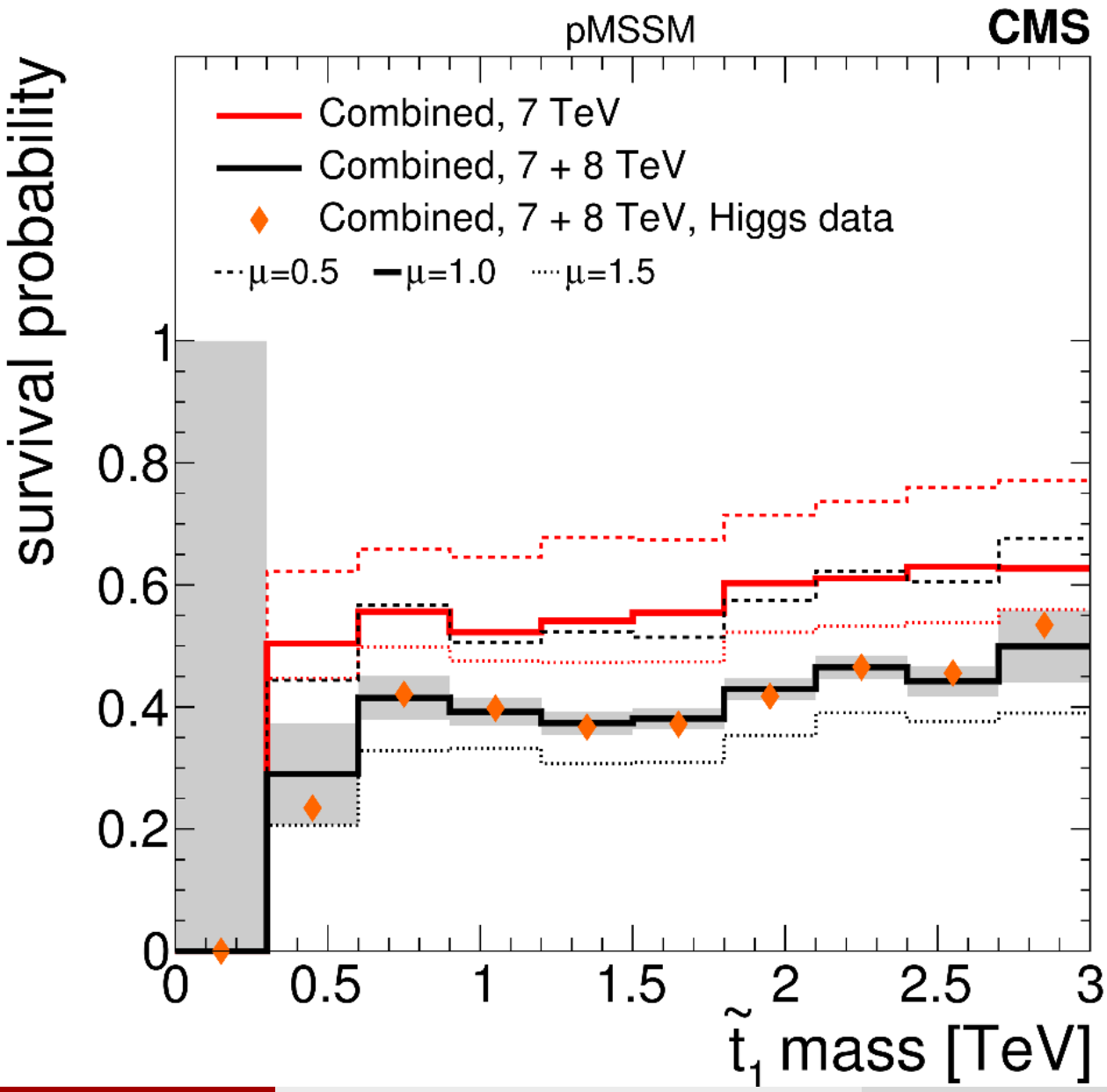
Survival fraction: LND $\chi^{\pm}$ mass



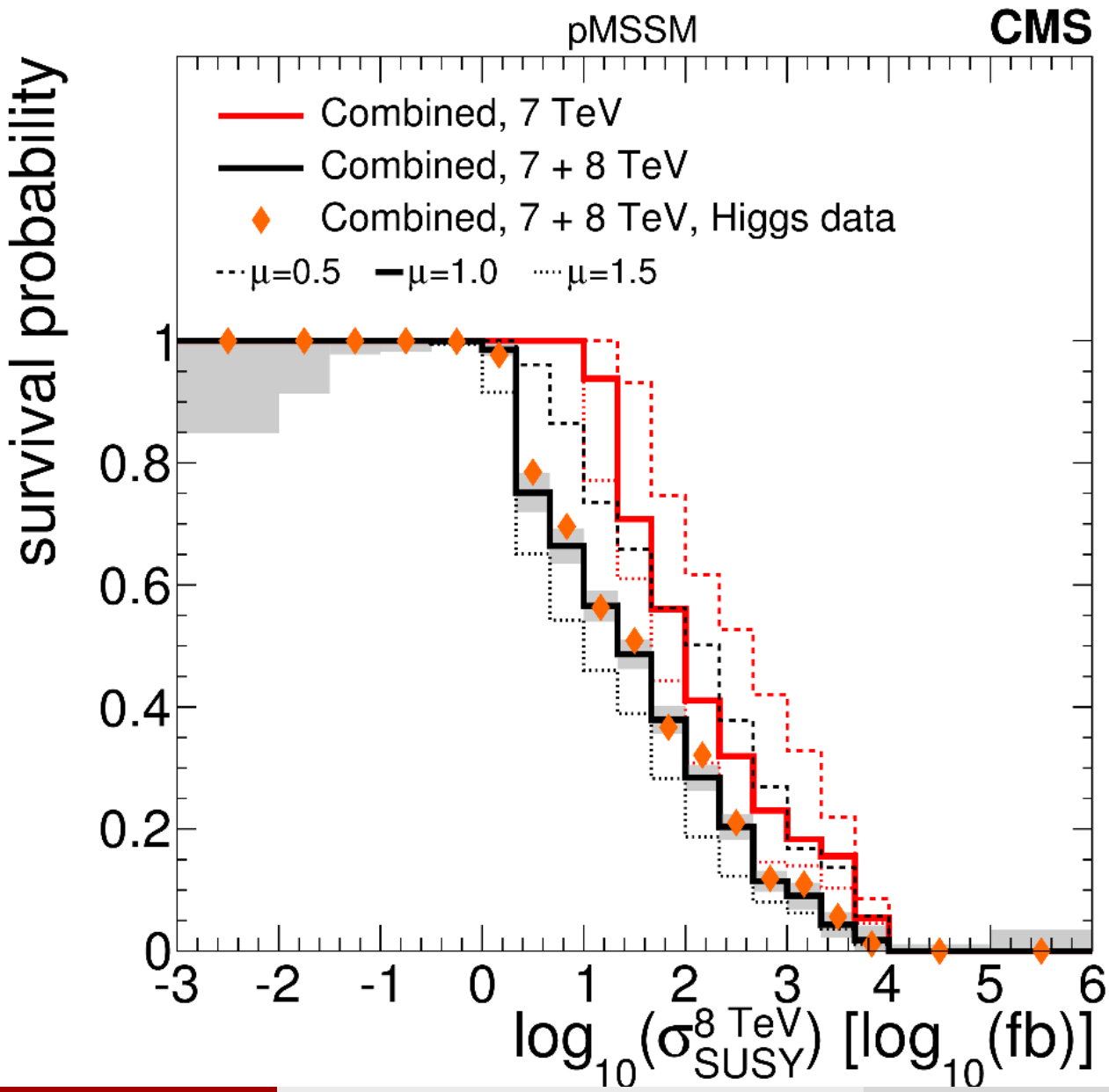
Survival fraction: LCSP mass



Survival fraction: stop mass



Survival fraction: inclusive sparticle cross section



Exclusion of pMSSM points

About 49% of the 7200 points studied were excluded:

Bayes factor

$$K_{\mathrm{Bayes}}\left(\mathrm{data},\theta\right) = \frac{L\left(\mathrm{data}|\mathrm{signal}+\mathrm{background}\right)}{L\left(\mathrm{data}|\mathrm{background}\right)}$$

Z-significance

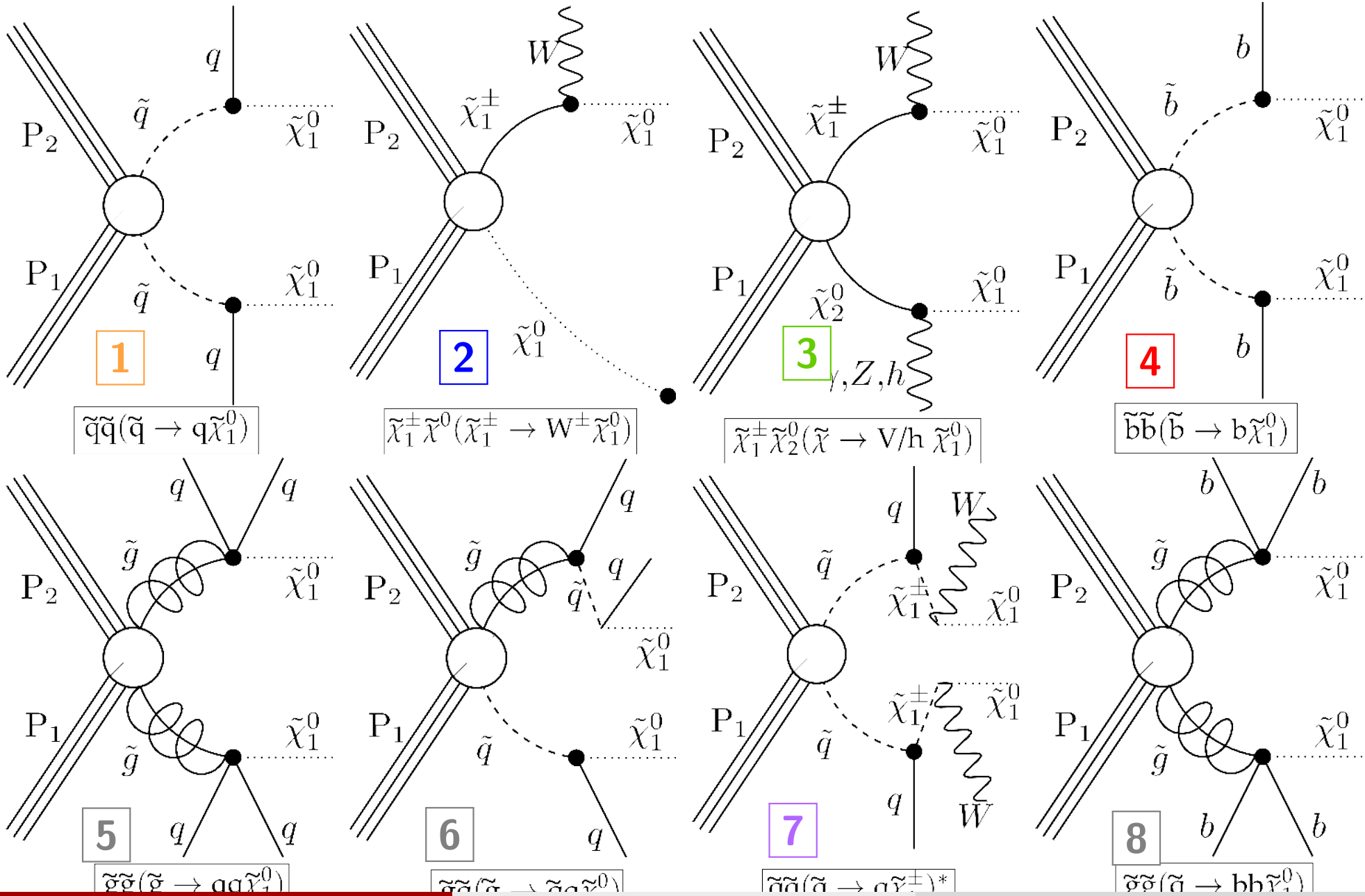
$$Z(\theta) = \mathrm{sign}\left[\log\left(K_{\mathrm{Bayes}}\left(\mathrm{data},\theta\right)\right)\right]\sqrt{2|\log\left(K_{\mathrm{Bayes}}\left(\mathrm{data},\theta\right)\right)|}$$

Exclusion

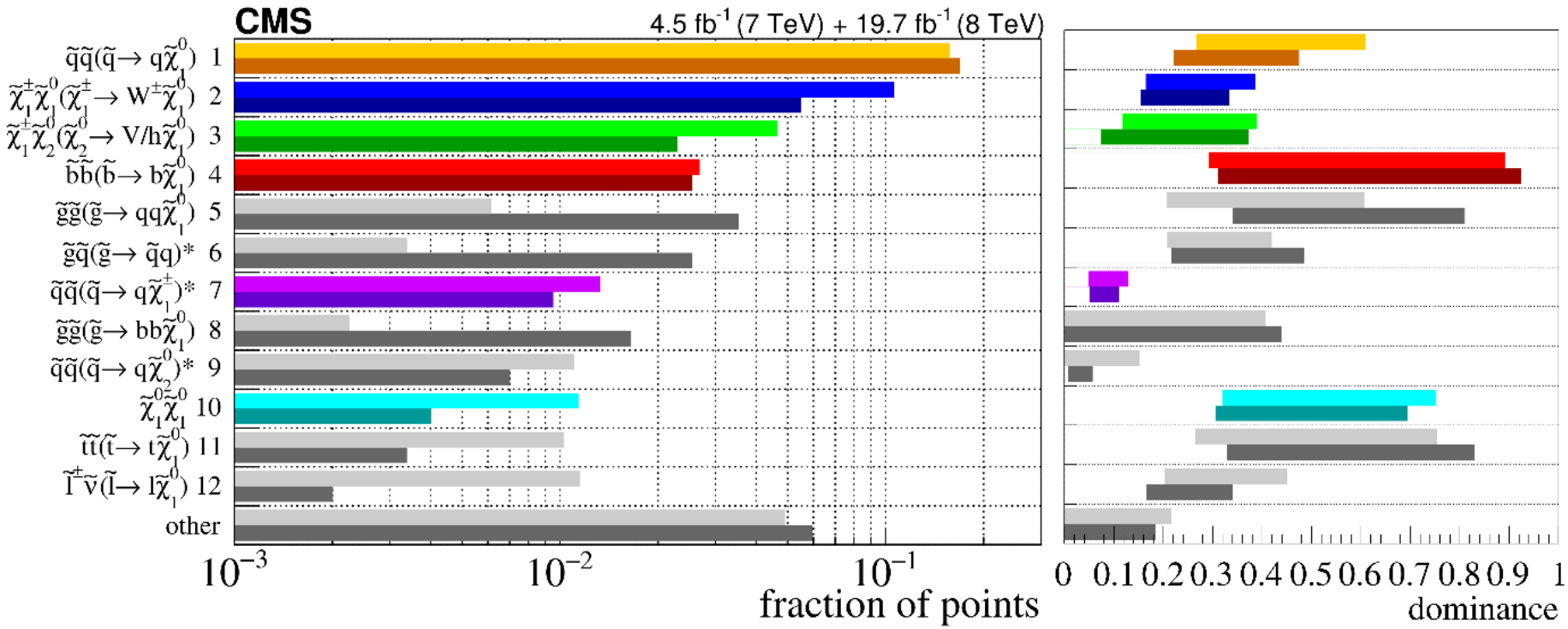
$$Z < -1.64 \quad \longleftrightarrow \quad 95\%\ \text{C.L. exclusion}$$

More than 50% of non-excluded points have a cross section $\geq$ 10 fb

Main processes



Most dominant excluded and non-excluded processes



non-excluded (light) fraction

excluded (dark) fraction

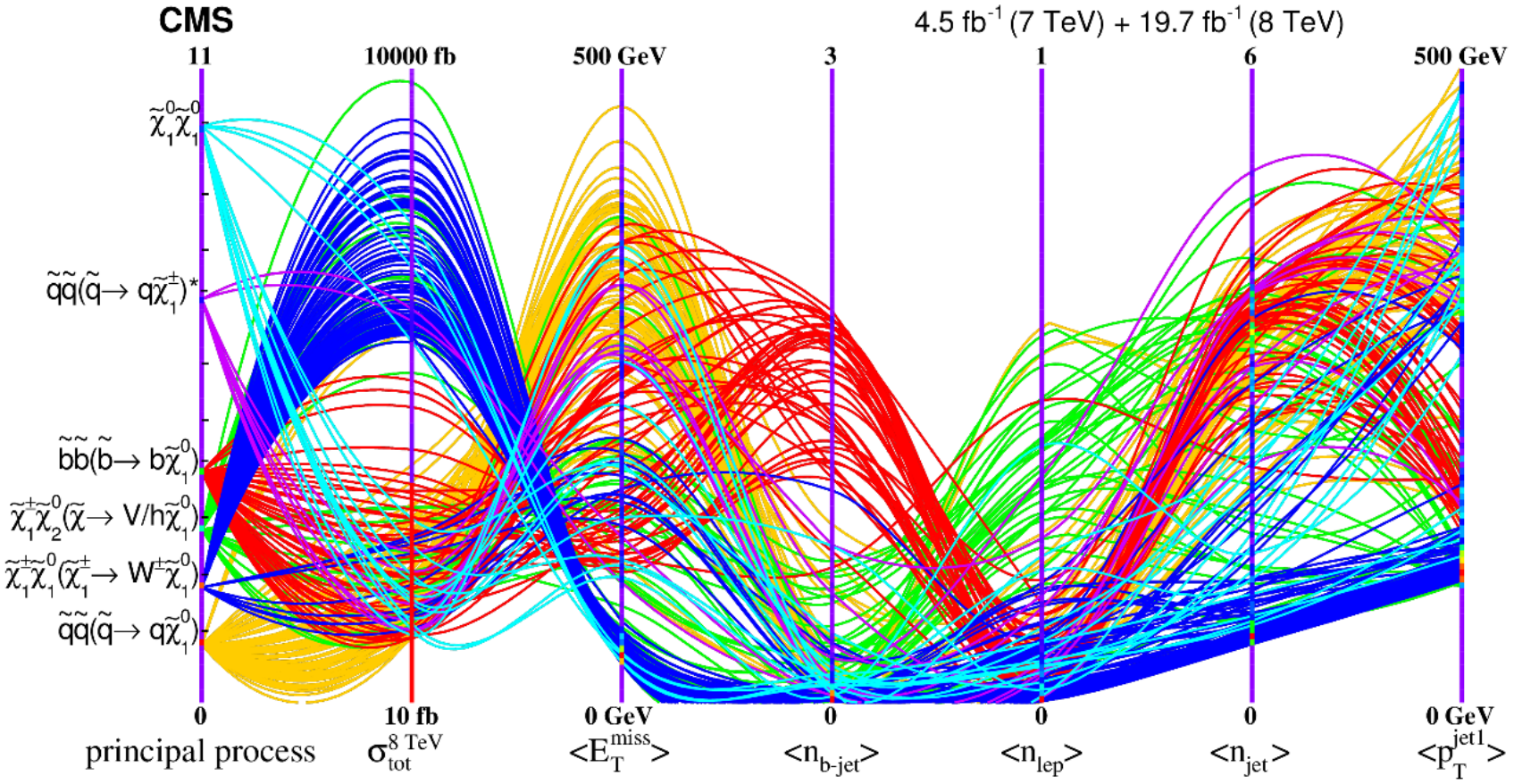
Fraction of all points considered by most occurring process

$$\frac{\sigma_i^{8\ \mathrm{TeV}}}{\sigma_{\mathrm{total\ SUSY}}^{8\ \mathrm{TeV}}}$$

Band: RMS range of dominance

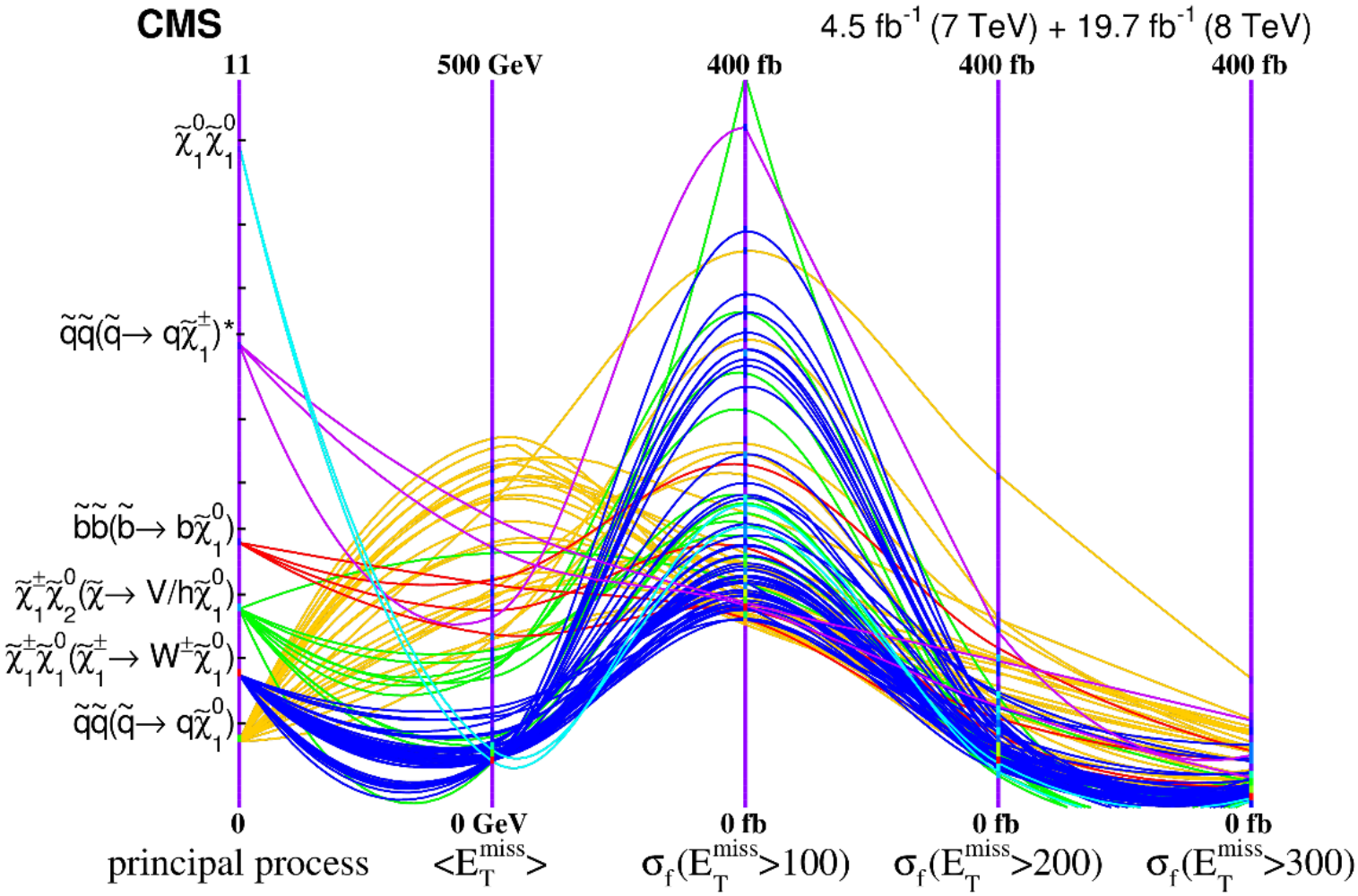
most dominant after CMS SUSY constraints

Impact of search observables



high lines = more discoverable

Impact of search observables



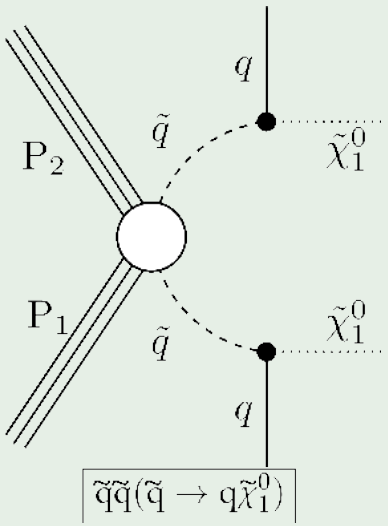
MET

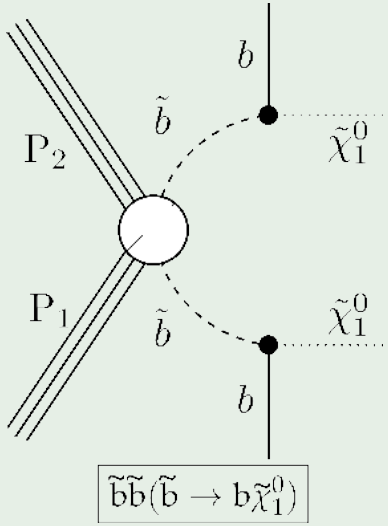
Conclusion of arXiv:1606.03577, CMS-SUS-15-010

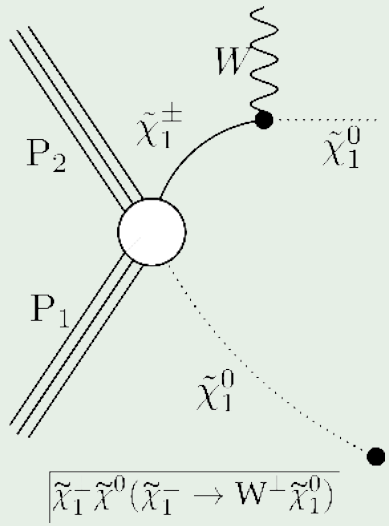
pMSSM after LHC-CMS-SUSY at 7 and 8 TeV

- about half of studied pMSSM points could be excluded;
- gluino masses below 500 GeV disfavored;
- light LSP masses disfavored;
- light stops of $m_{\tilde{t}} \sim \mathcal{O}(500)$ GeV could not be excluded.

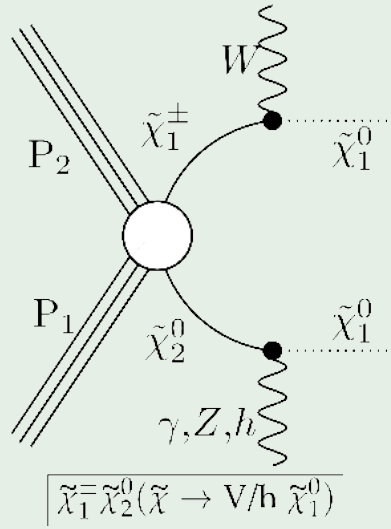
Sensitivity to the pMSSM could be enhanced by searching for:







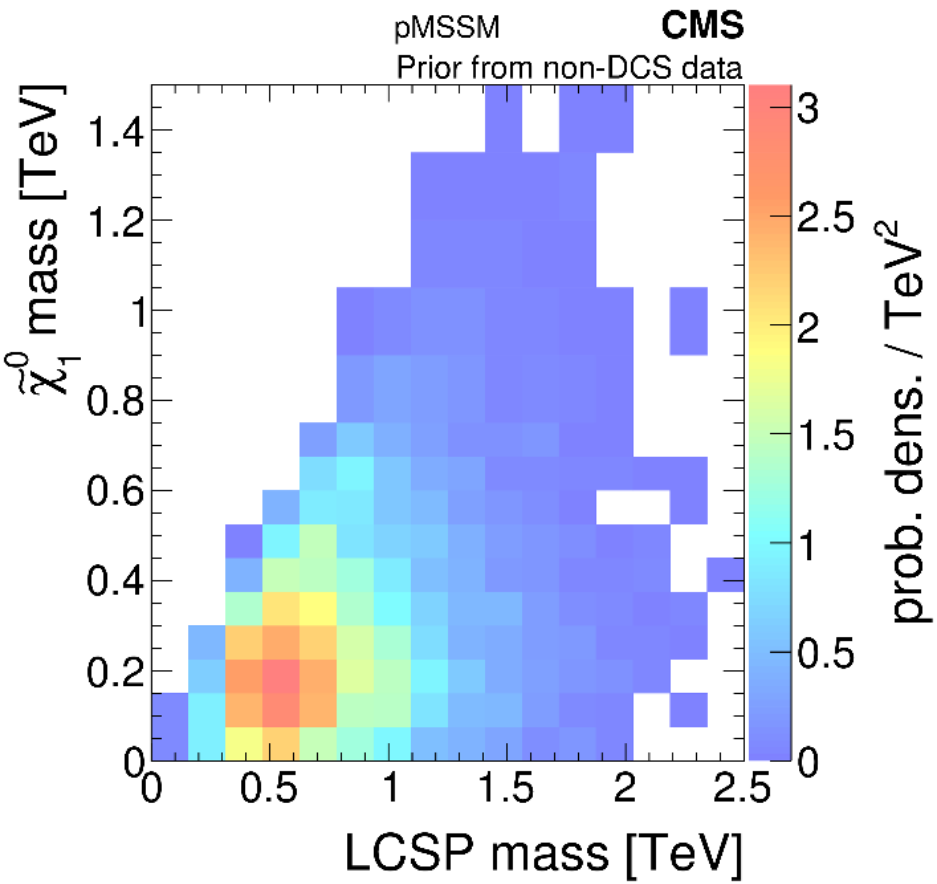
uncovered

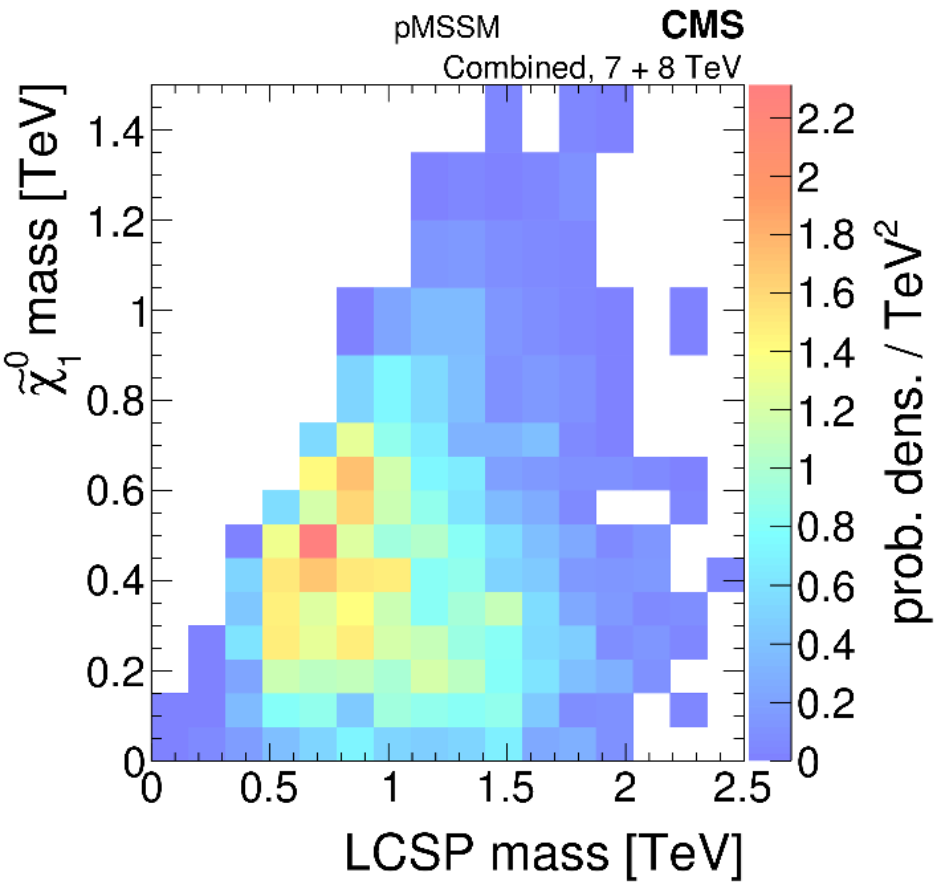


uncovered

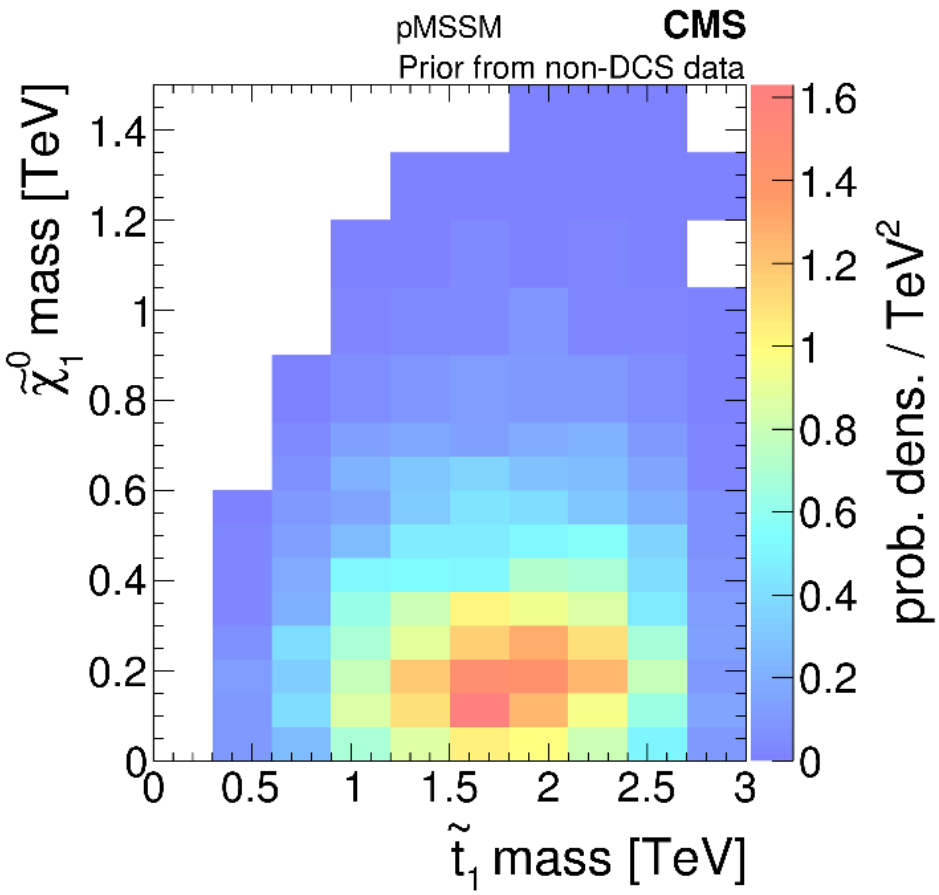
Backup

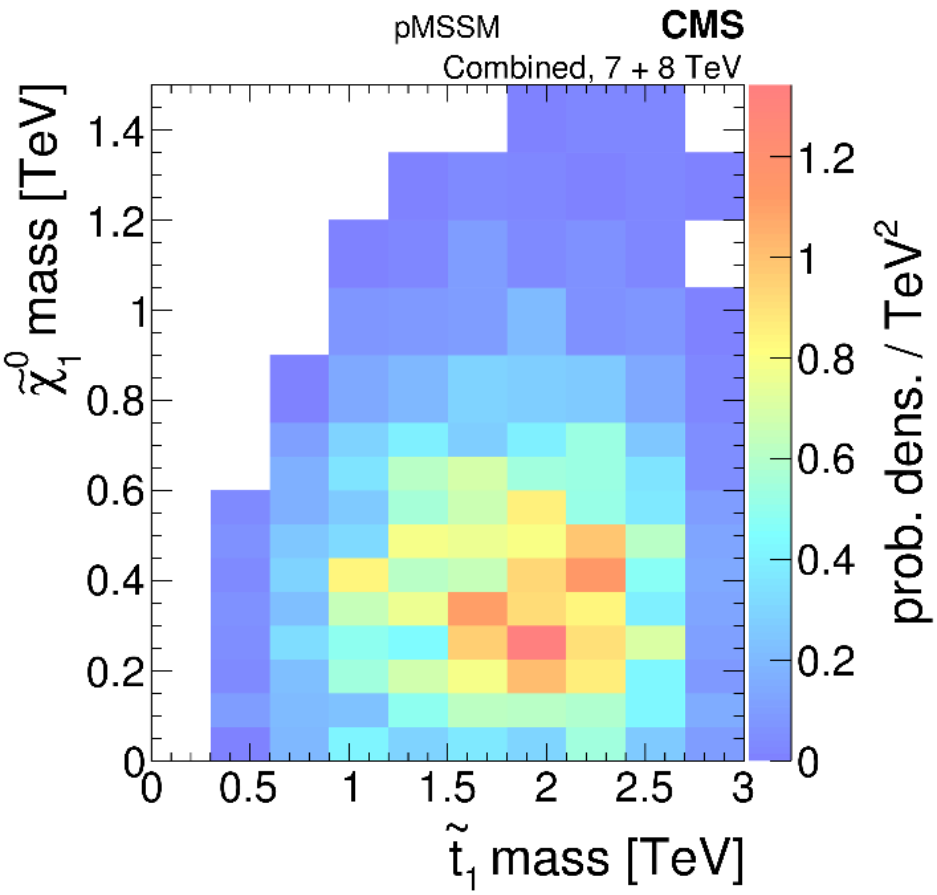
LCSP vs LSP mass



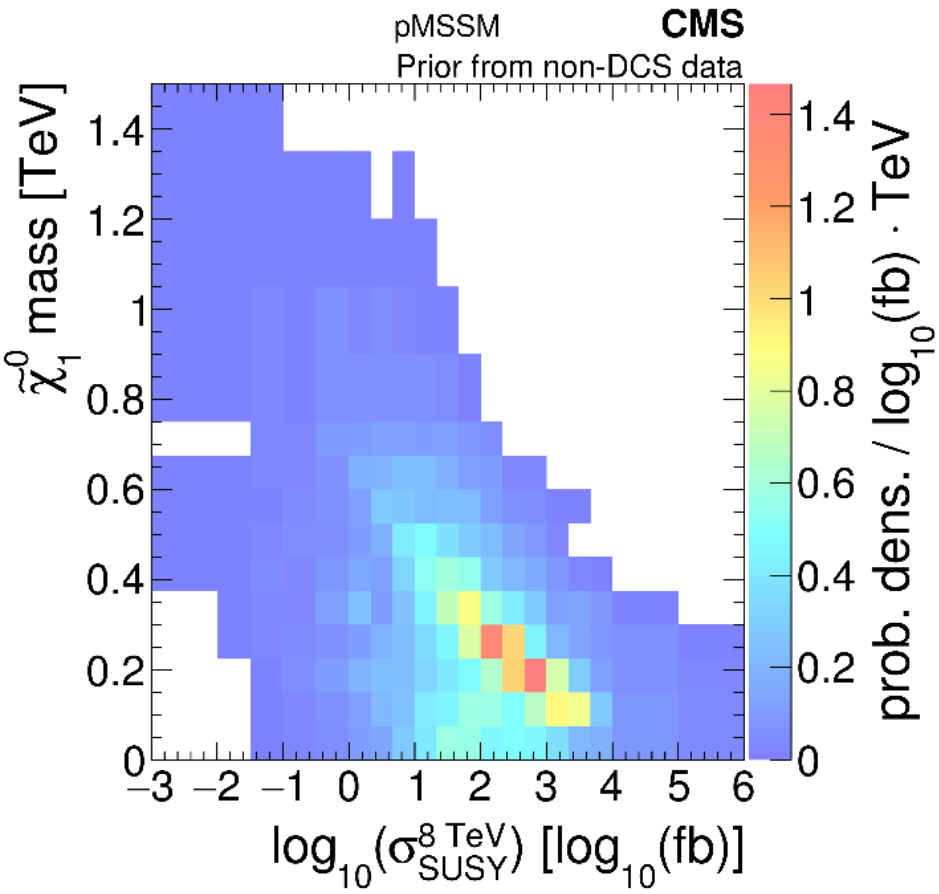


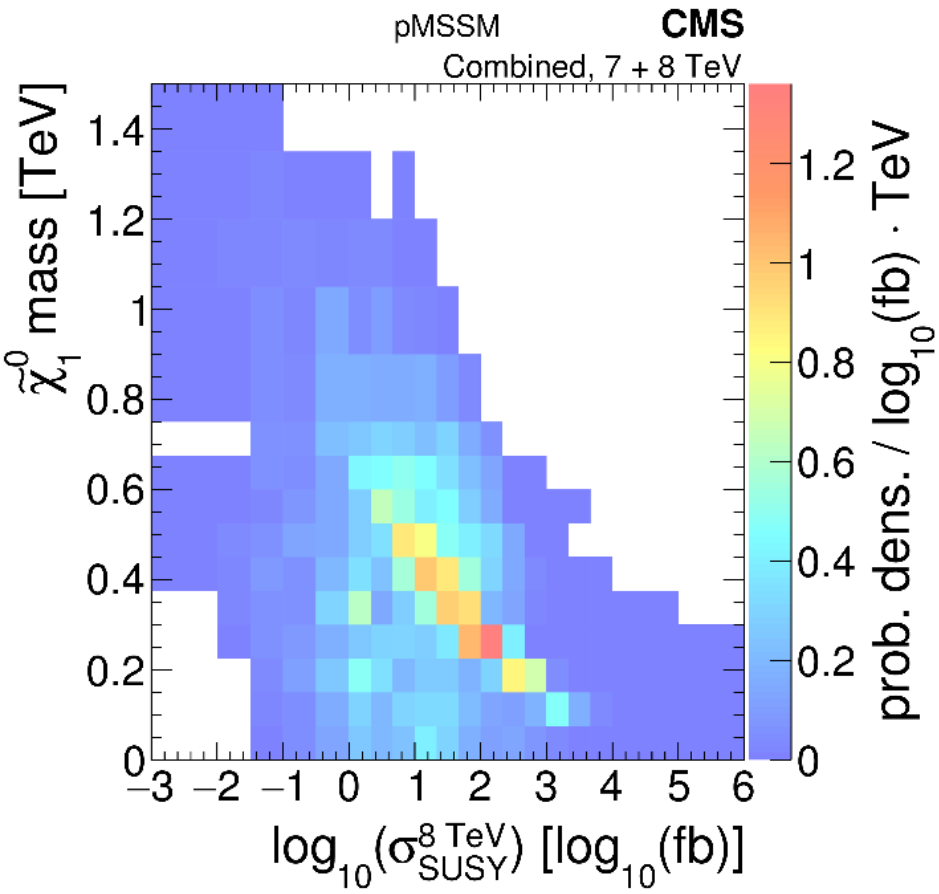
Stop vs LSP mass





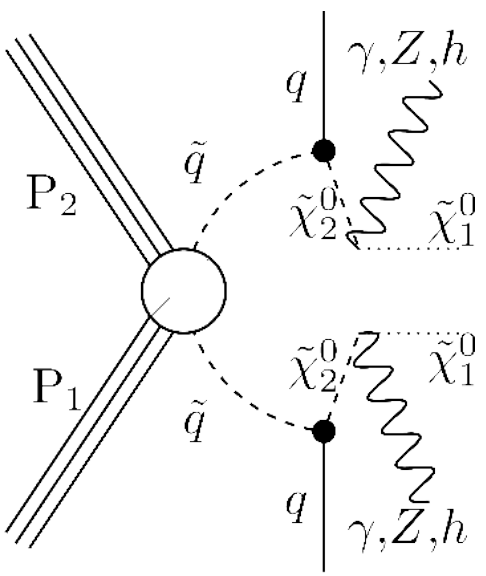
Inclusive SUSY cross section vs LSP mass



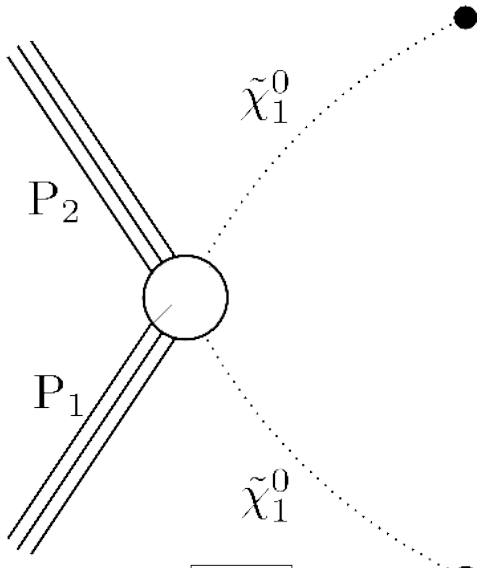


Other important processes

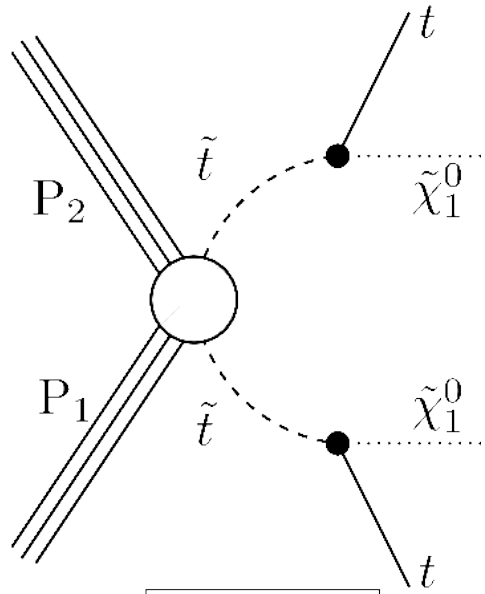
9 **10** 11 12



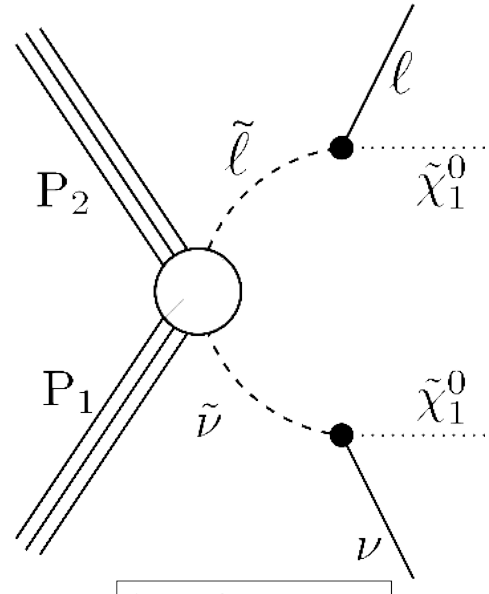
$\tilde{q}\tilde{q}(\tilde{q} \to q\tilde{\chi}_2^0)^*$



$\tilde{\chi}_1^0\tilde{\chi}_1^0$

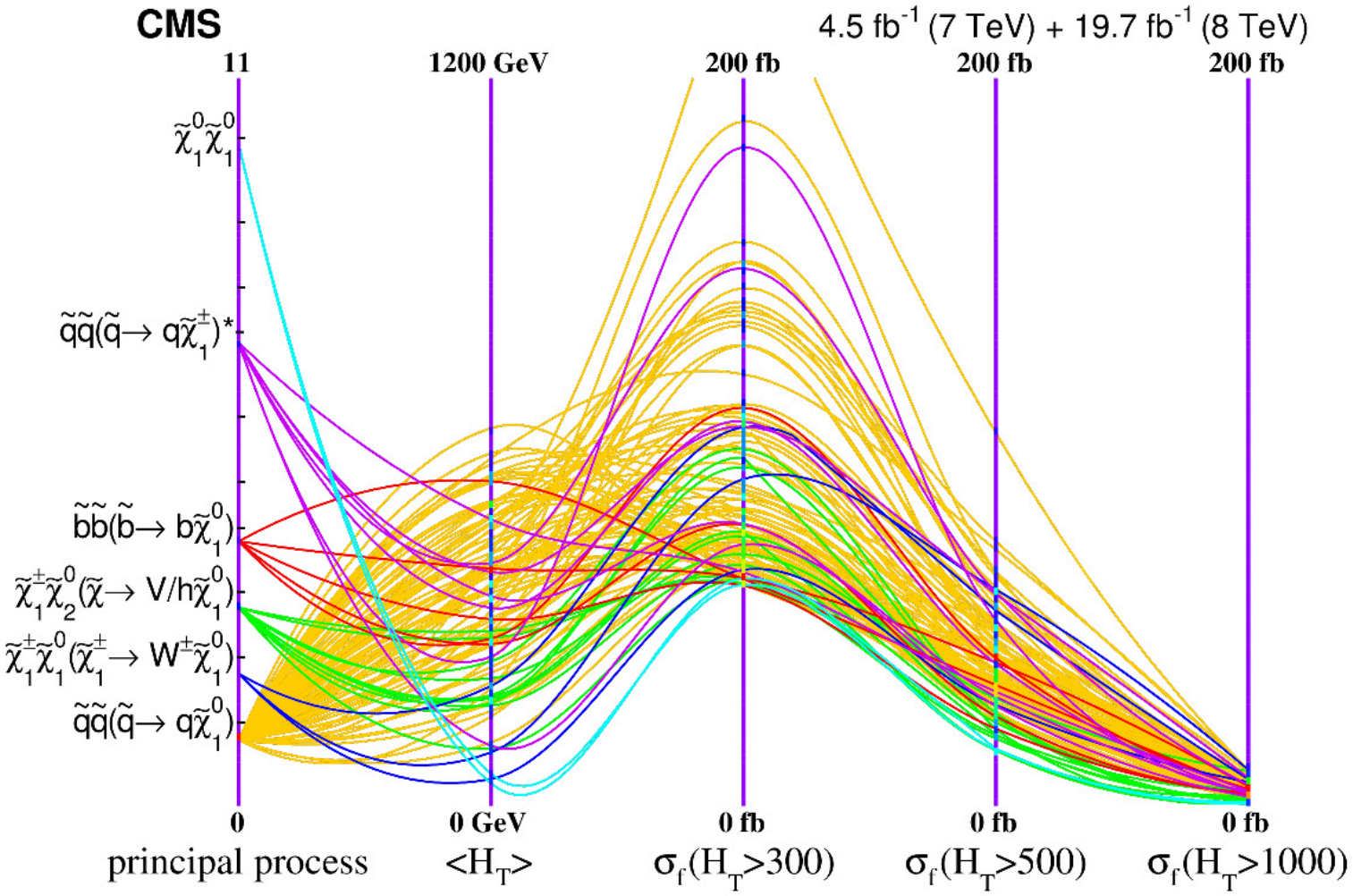


$\tilde{t}\tilde{t}(\tilde{t} \to t\tilde{\chi}_1^0)$



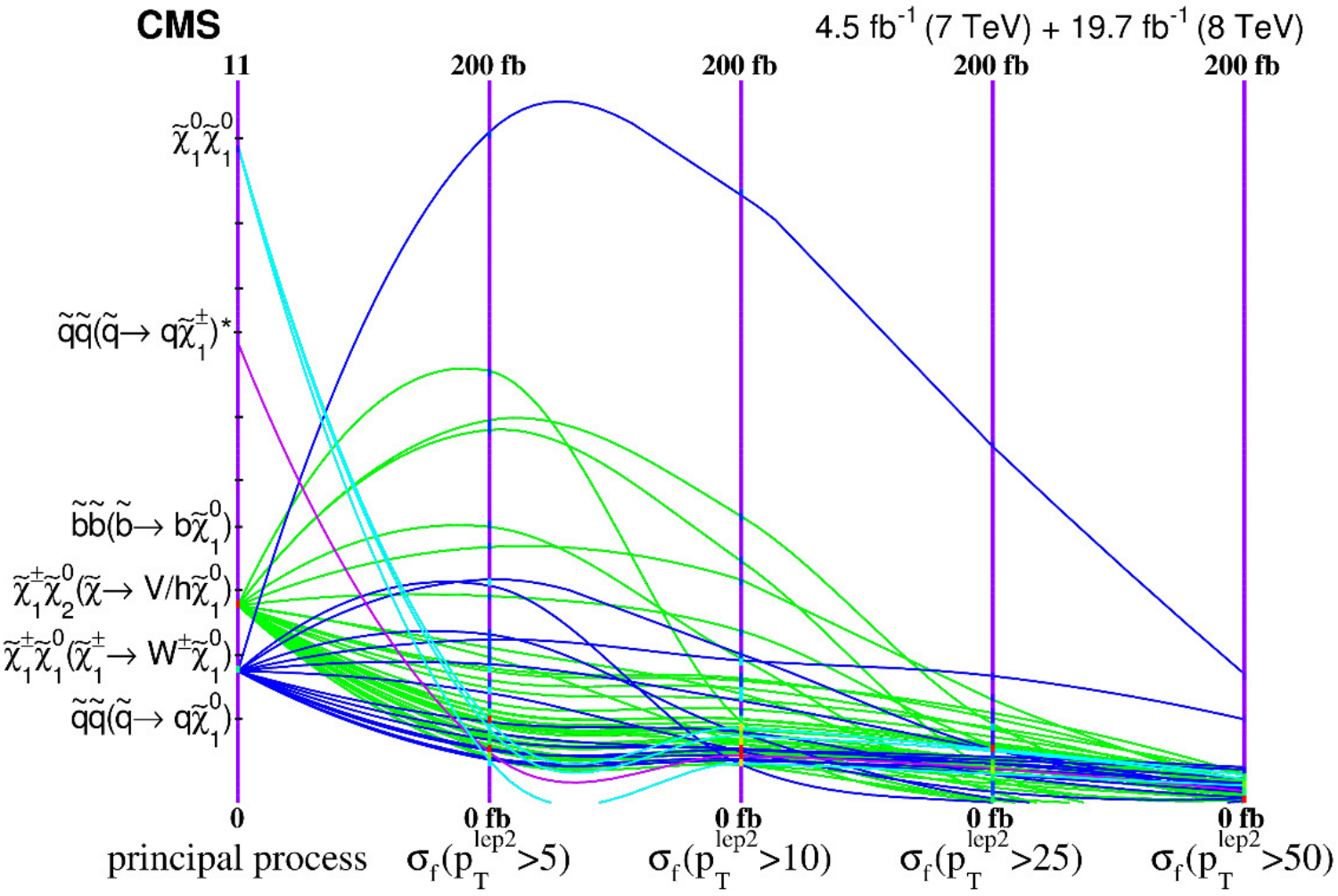
$\tilde{\ell}^{\pm}\tilde{\nu}(\tilde{\ell} \to \ell\tilde{\chi}_1^0)$

Impact of search observables



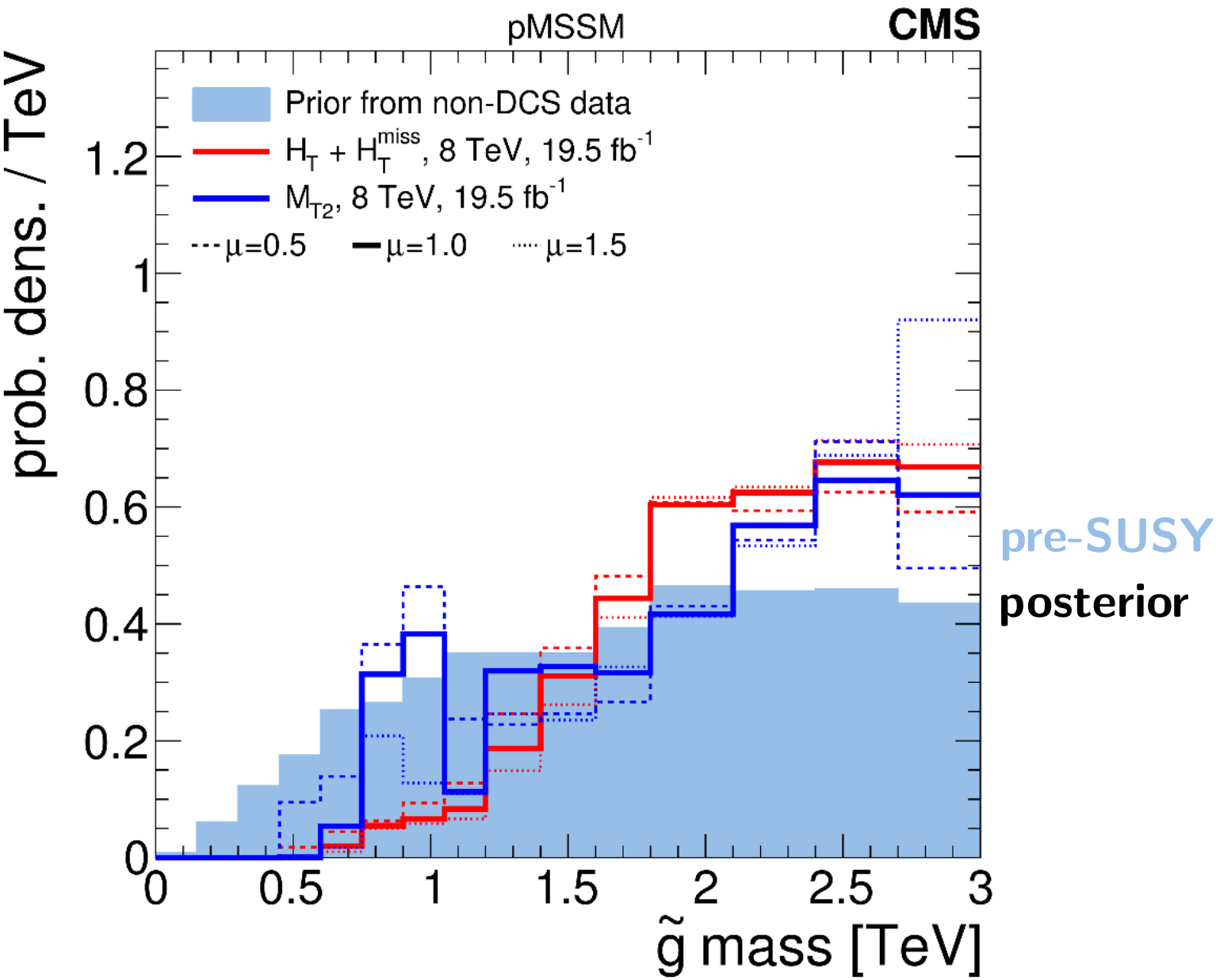
MHT

Impact of search observables

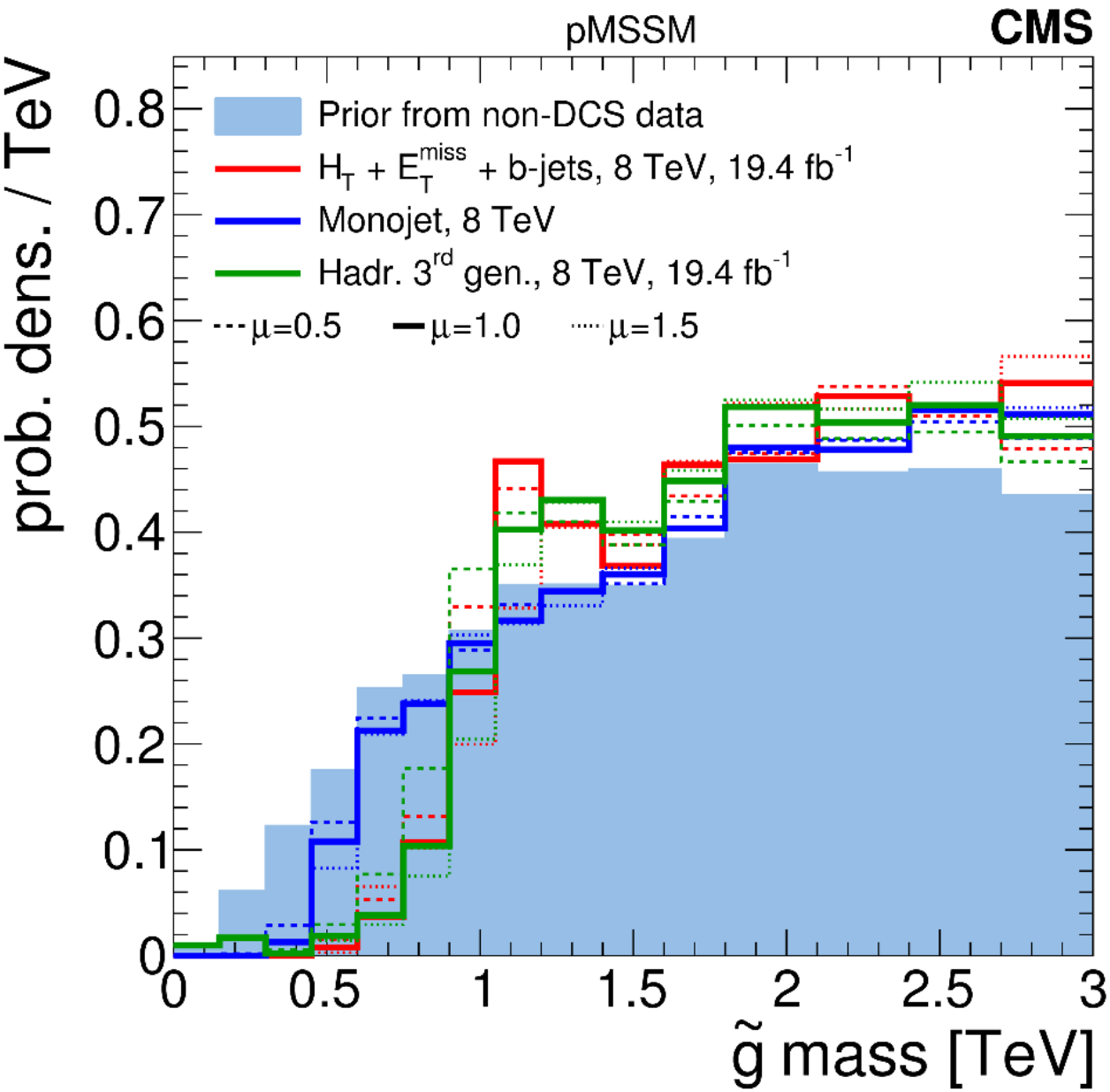


lepton p_T

Posterior density for the gluino mass



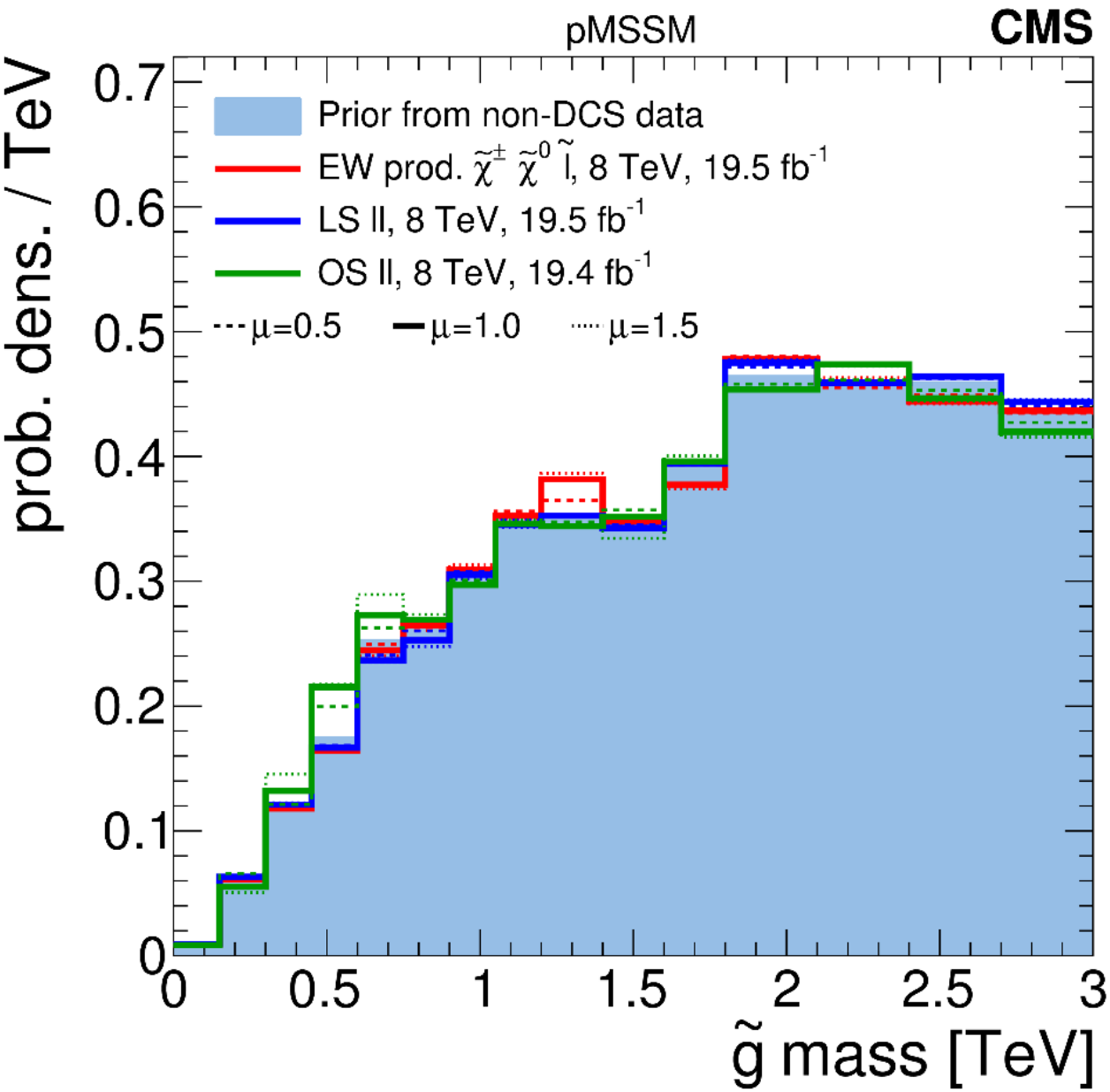
Posterior density for the gluino mass



pre-SUSY

posterior

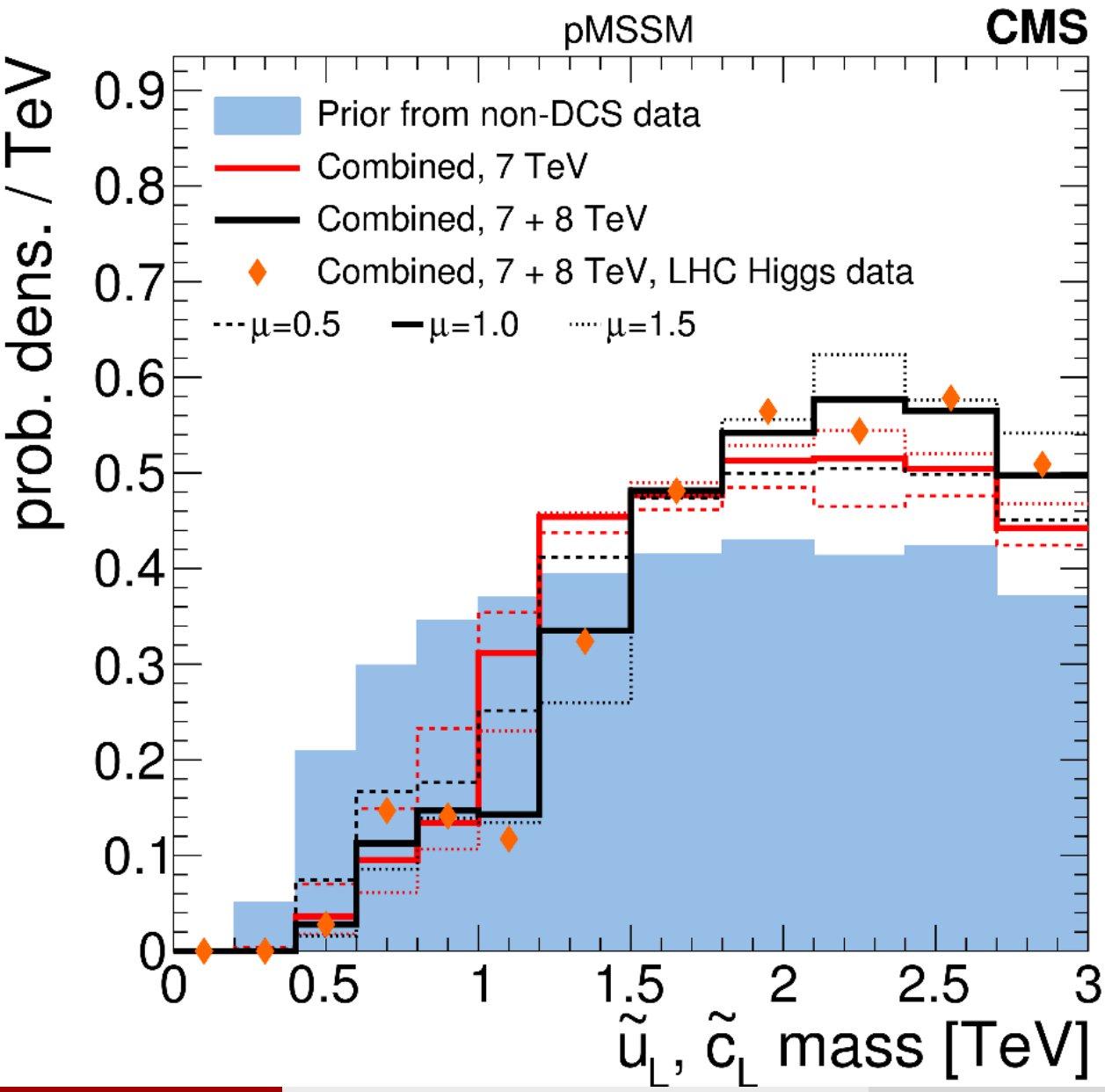
Posterior density for the gluino mass



pre-SUSY

posterior

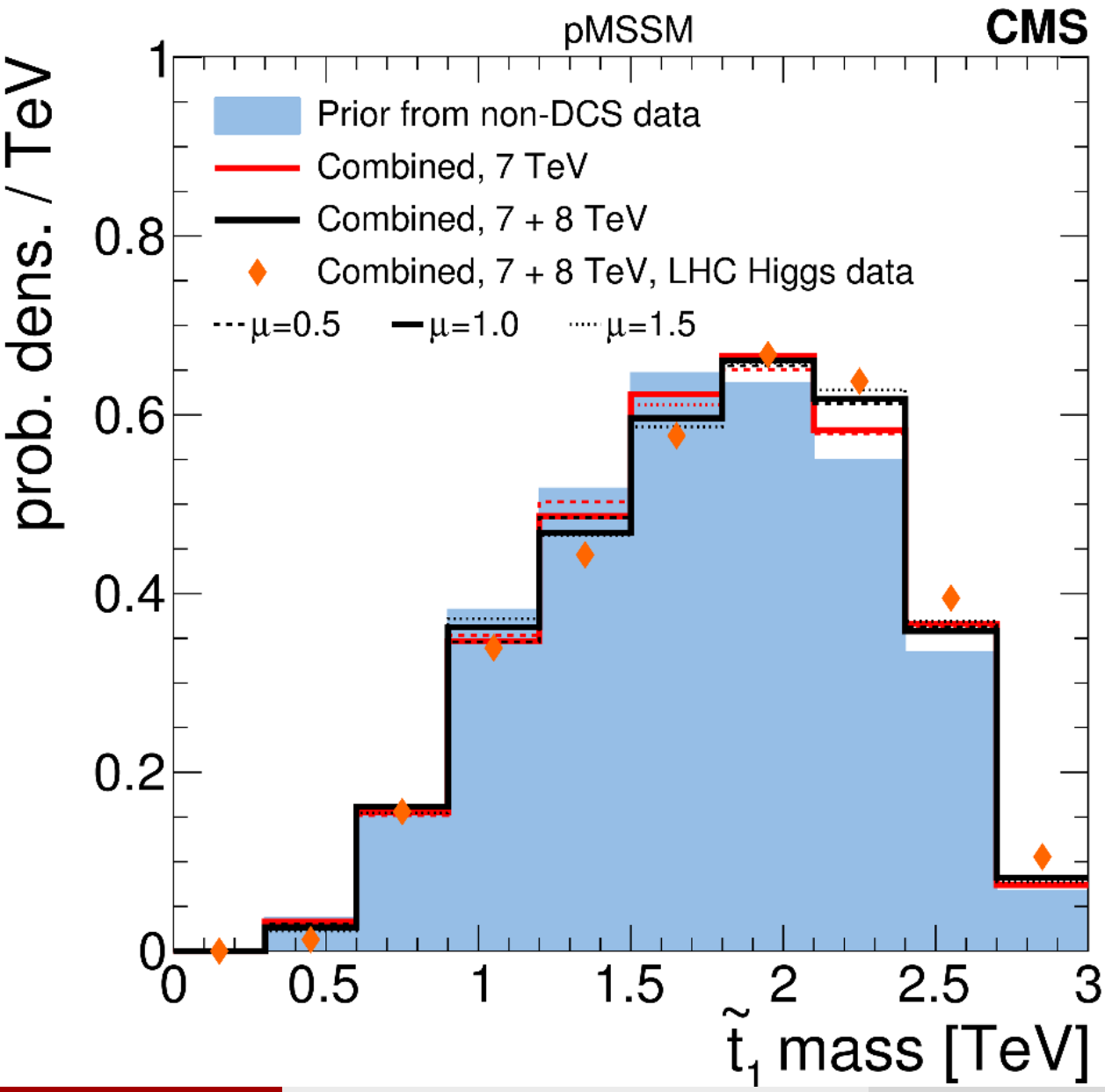
Posterior density for the doublet squark mass



pre-SUSY

posterior

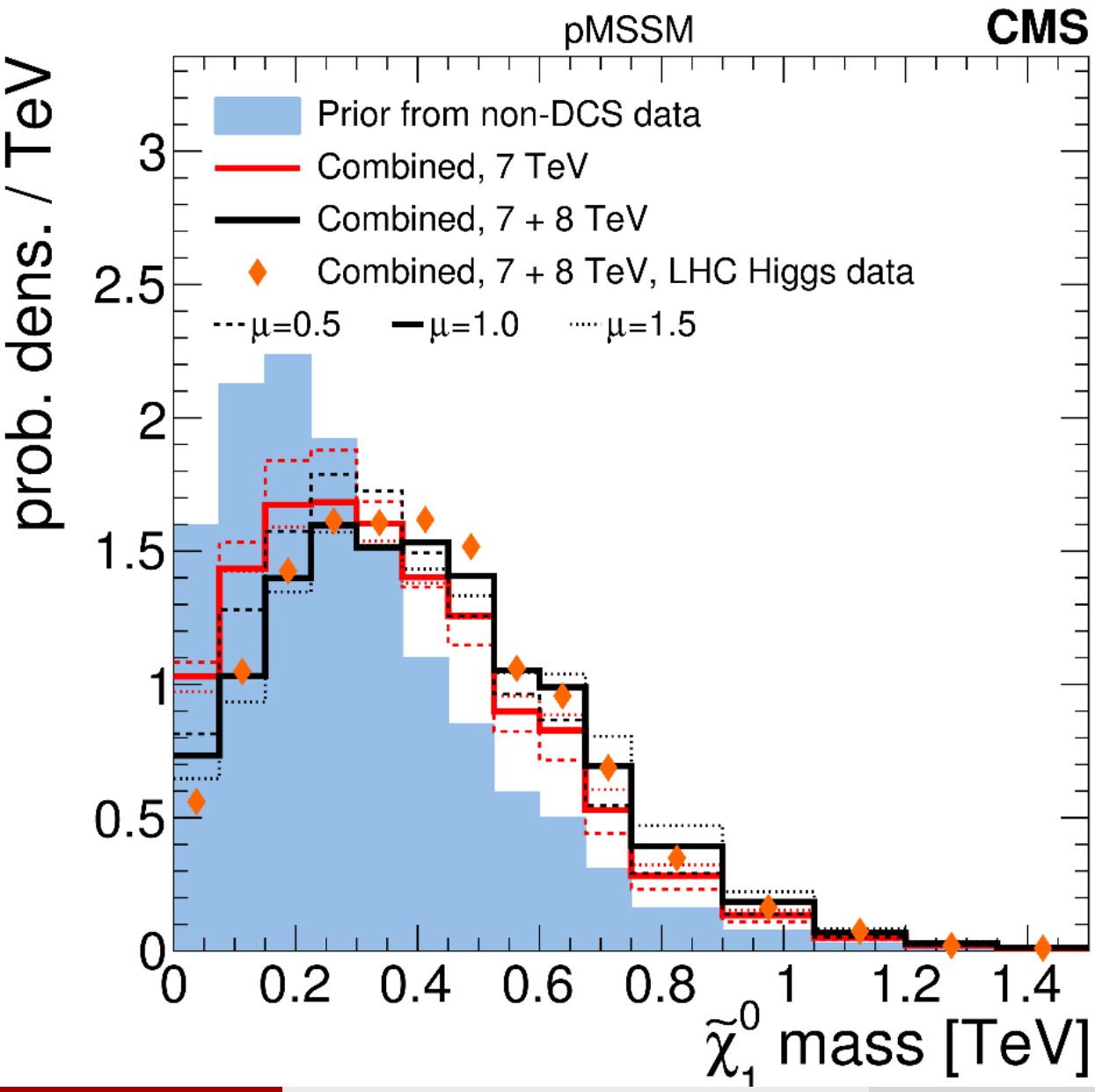
Posterior density for the stop mass



pre-SUSY

posterior

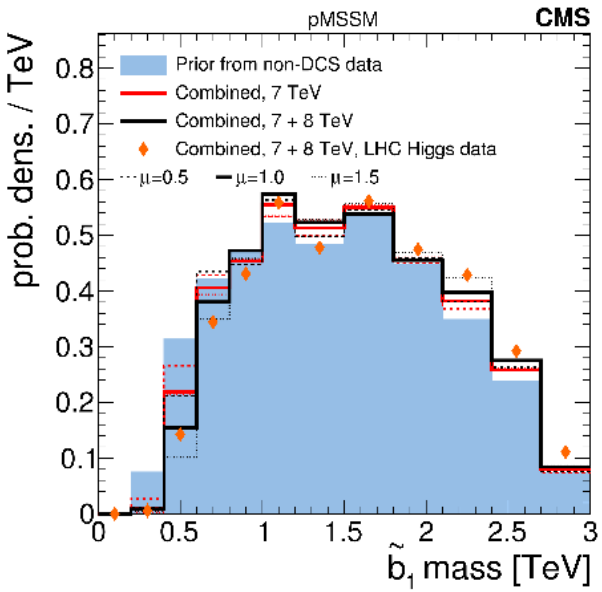
Posterior density for the LSP mass

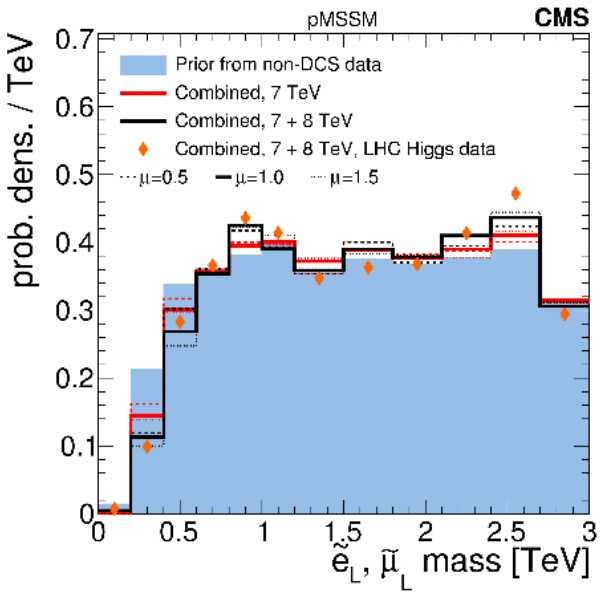


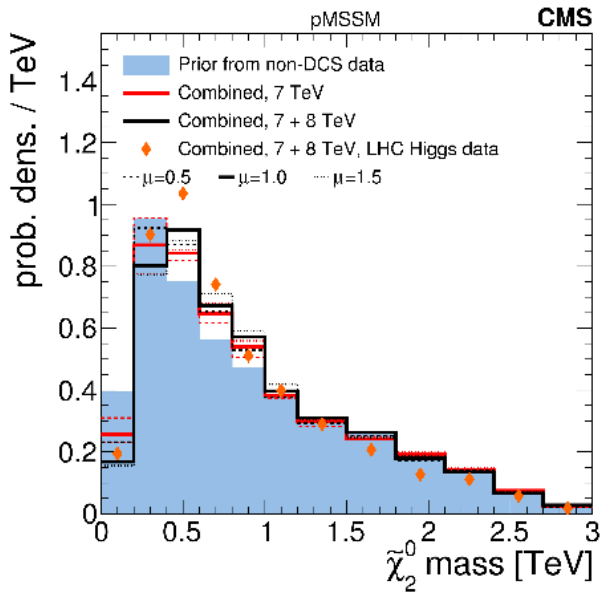
pre-SUSY

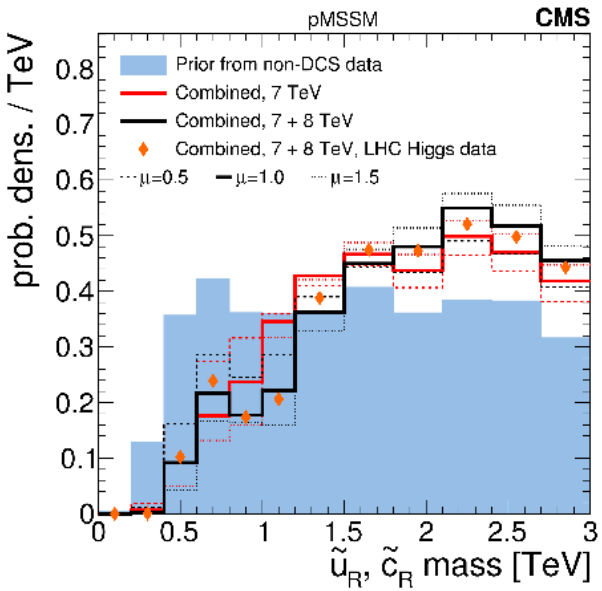
posterior

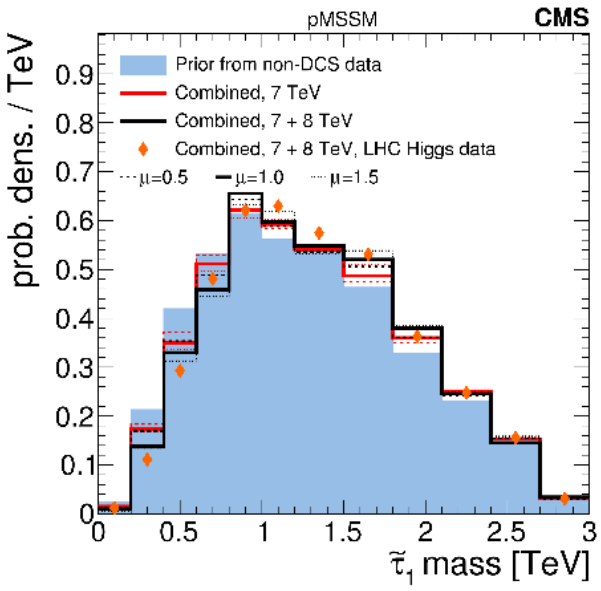
Posterior density for other sparticle masses

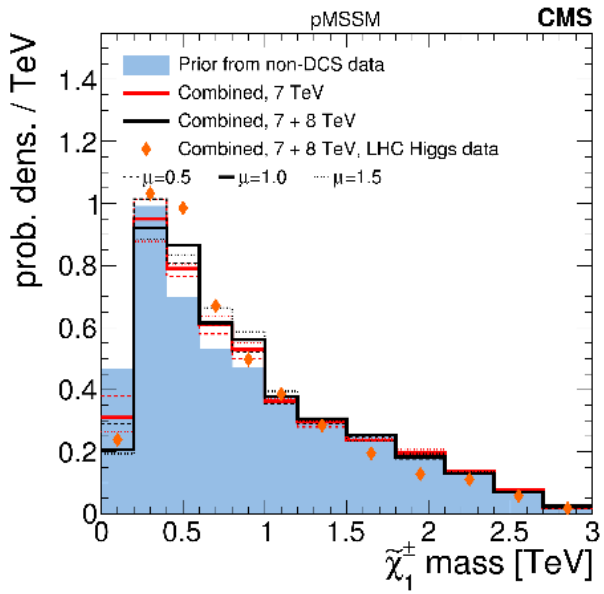












pre-CMS-SUSY searches – **posterior**

Light-flavor squark masses in the pMSSM

"degeneracy"

$$\begin{aligned} m_{\widetilde{Q}_1} &\equiv m_{\widetilde{Q}_2} \\ m_{\widetilde{U}_1} &\equiv m_{\widetilde{U}_2} \\ m_{\widetilde{D}_1} &\equiv m_{\widetilde{D}_2} \end{aligned} \longrightarrow \begin{aligned} m_{\widetilde{u}_\mathrm{L}} &\equiv m_{\widetilde{c}_\mathrm{L}} \\ m_{\widetilde{u}_\mathrm{R}} &\equiv m_{\widetilde{c}_\mathrm{R}} \\ m_{\widetilde{d}_\mathrm{L}} &\equiv m_{\widetilde{s}_\mathrm{L}} \\ m_{\widetilde{d}_\mathrm{R}} &\equiv m_{\widetilde{s}_\mathrm{R}} \end{aligned}$$

$$\begin{aligned} D\text{-term}(\widetilde{u}_\mathrm{L}) &= M_Z^2 \cos(2\beta)(1/2 - (2/3)\sin^2\theta_W) = 0.34 M_Z^2 \cos 2\beta \\ D\text{-term}(\widetilde{d}_\mathrm{L}) &= M_Z^2 \cos(2\beta)(-1/2 + (1/3)\sin^2\theta_W) = -0.42 M_Z^2 \cos 2\beta \end{aligned}$$

Heavier down-type quarks

Example: $\tan\beta = 10 \rightarrow \cos 2\beta = -0.98$:

$$\begin{aligned} m^2_{\widetilde{u}_\mathrm{L}} &\simeq m^1_{\widetilde{Q}_1} - 0.33 M_Z^2 \\ m^2_{\widetilde{d}_\mathrm{L}} &\simeq m^1_{\widetilde{Q}_1} + 0.42 M_Z^2 \end{aligned}$$

at tree level: $m_{\widetilde{d}_\mathrm{L}} - m_{\widetilde{u}_\mathrm{L}} \simeq 78$ GeV + radiative corrections.