Relating matter unification to LHC event rates — the example of *SU(5)* unification in Supersymmetry

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"New physics at the junction of flavour and collider" — 20 april 2017 — Portorož, Slovenia

Motivation

Assumption (optimistic!): **A new state is observed at LHC**

Question: What can we learn from it…?

For this talk: **What can we learn about grand unification…?**

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potentially (almost) **insensitive to quantum corrections**

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In the following: Consider the example of *SU(5)*-like unification in Supersymmetry…

A simple example — *SU(5)*-type unification

Matter (super)fields fit into complete representations of the *SU(5)* gauge group

$$\mathbf{10} = (Q, U, E) \qquad \bar{\mathbf{5}} = (L, D)$$

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Hint towards Grand Unified Theory (GUT) containing *SU(5)* as a subgroup

$$SU(5) \to SU(3) \times SU(2) \times U(1)$$

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Is Nature *SU(5)*-symmetric at short distance…?

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Sfermions belonging to same representations share common soft mass matrices

$$M^2_{\mathbf{10}} \equiv M^2_{\tilde{Q}} = M^2_{\tilde{U}} = M^2_{\tilde{E}}$$
$$M^2_{\mathbf{5}} \equiv M^2_{\tilde{D}} = M^2_{\tilde{L}}$$

SU(5)-specific relations — GUT scale

Requiring the superpotential to be invariant implies:

$$\left(Y_d\right)_{ij} = \left(Y_\ell\right)_{ji} \iff \boxed{Y_d = Y_\ell^t}$$
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If SUSY-breaking mediated by *SU(5)* singlet, these relations propagate into soft sector:

$$\begin{aligned} (T_d)_{ij} &= (T_\ell)_{ji} \quad \Longleftrightarrow \quad \boxed{T_d = T_\ell^t} \\ (T_u)_{ij} &= (T_u)_{ji} \quad \Longleftrightarrow \quad \boxed{T_u = T_u^t} \end{aligned}$$

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Renormalization group evolution — **we expect at the TeV scale:**

$$\begin{aligned} Y_d &\neq Y_\ell^t \\ T_d &\neq T_\ell^t \end{aligned}$$

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not very useful…

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not very useful…

$$
\boxed{\begin{aligned} Y_u &\approx Y_u^t \\ T_u &\approx T_u^t \end{aligned}}
$$

↓

test *SU(5)* hypothesis…

SU(5)-specific relations — TeV scale

Renormalization group equations (one-loop) of up-type Yukawa and trilinear couplings

$$16\pi^2\ \beta_{Y_u} = Y_u\Big[3\,\mathrm{Tr}\{Y_u^\dagger Y_u\} + 3\,Y_u^\dagger Y_u + Y_d^\dagger Y_d - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\Big]$$

$$\begin{aligned}16\pi^2\ \beta_{T_u} &= T_u\Big[3\,\mathrm{Tr}\{Y_u^\dagger Y_u\} + 5\,Y_u^\dagger Y_u + Y_d^\dagger Y_d - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\Big] \\ &\quad + Y_u\Big[6\,\mathrm{Tr}\{T_u Y_u^\dagger\} + 4\,Y_u^\dagger T_u + 2Y_d^\dagger T_d + \frac{32}{3}M_3 g_3^2 + 6M_2 g_2^2 + \frac{26}{15}M_1 g_1^2\Big]\end{aligned}$$

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Beta-functions mostly dominated by symmetric contributions,
while non-symmetric terms are suppressed…

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$$\Big\{SU(5)\text{−type SUSY GUT}\Big\} \Longrightarrow \Big\{T_u \approx T_u^t \text{ at TeV scale}\Big\}$$

Related observables at LHC….?

SU(5)-specific relations — TeV scale

$$\mathcal{A}_{23} = \frac{\left|\left(T_u\right)_{23} - \left(T_u\right)_{32}\right|}{\mathrm{Tr}\left\{\mathcal{M}^2_{\tilde{u}}\right\}^{1/2}}$$

$(Q = 1\ \mathrm{TeV})$

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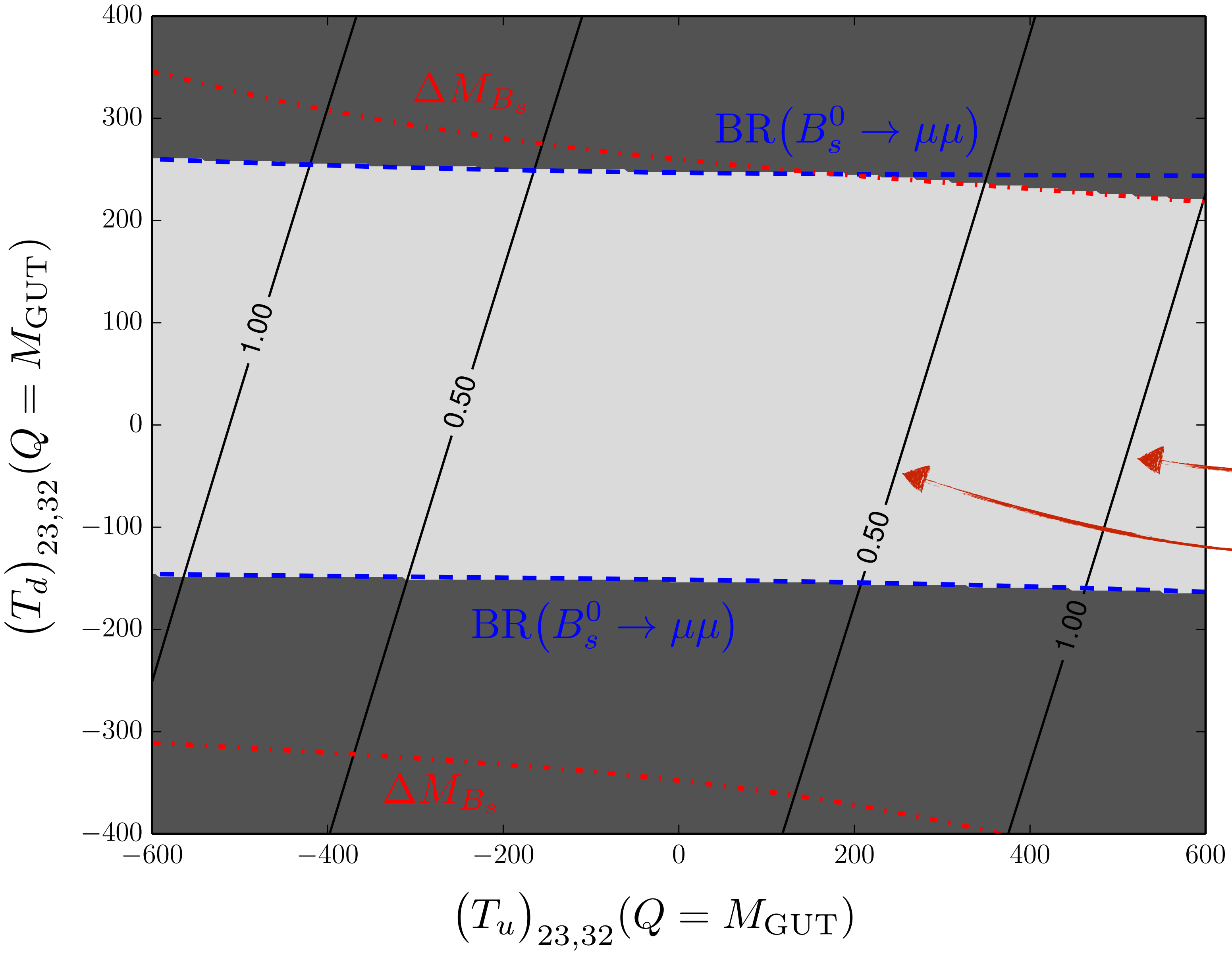

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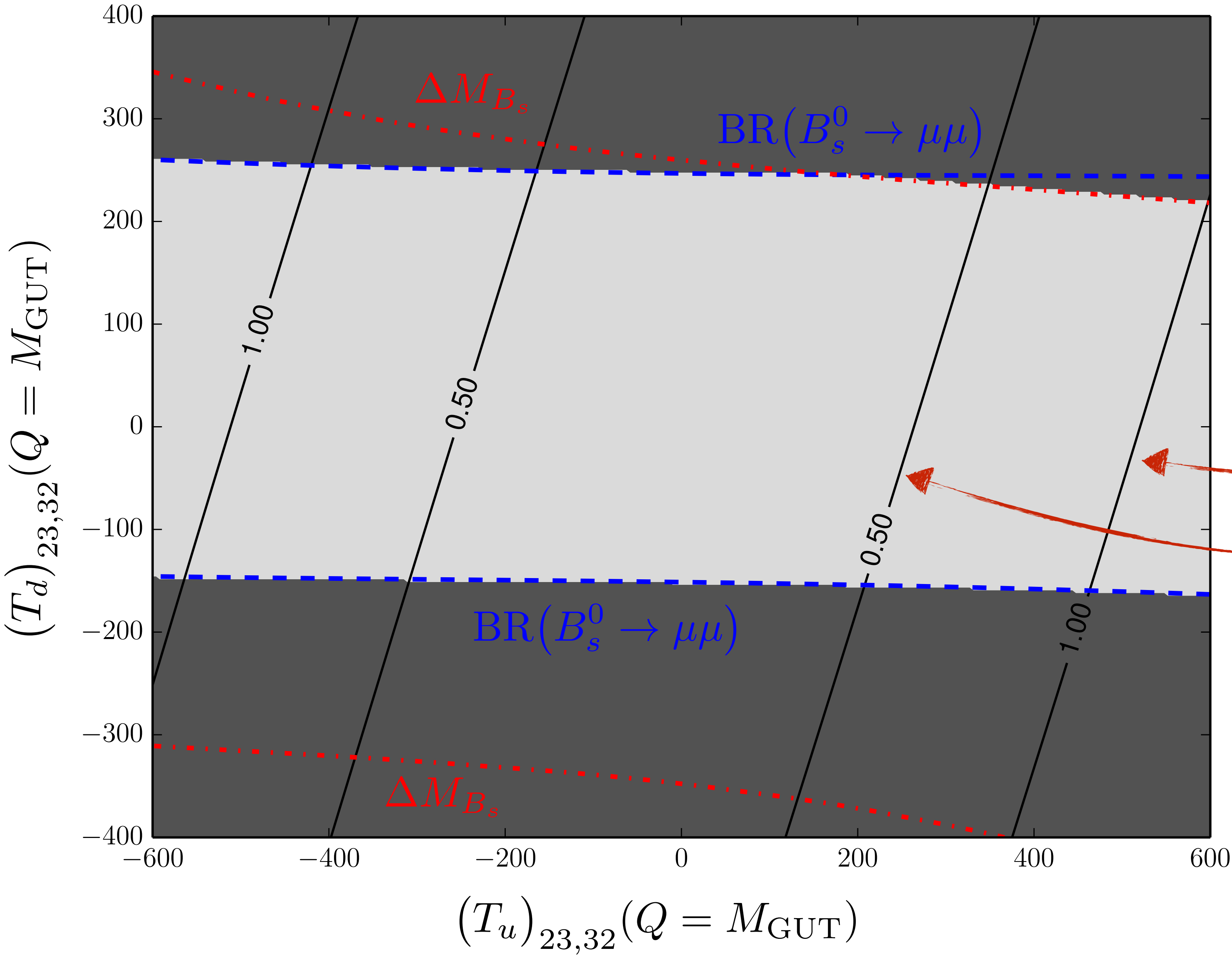

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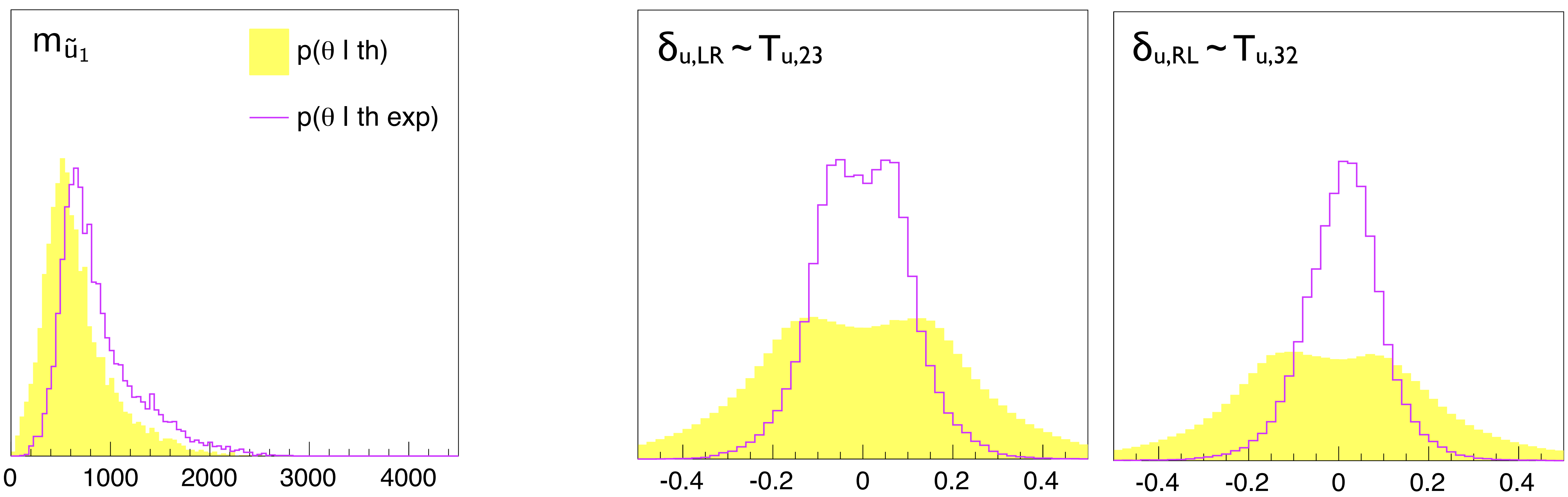
$\mathcal{A}_{23} \lesssim 2\%$	$\tan\beta = 10$
$\mathcal{A}_{23} \lesssim 5\%$	$\tan\beta = 40$

Asymmetry at the TeV scale **does not exceed a few percent** for typical scenarios — such a precision difficult to reach at LHC…

S. Fichet, B. Herrmann, Y. Stoll — JHEP 1505 (2015) 091 — arXiv:1501.05307 [hep-ph]

Squark flavour violation in the MSSM

Hypothesis of non-minimal flavour violation in the squark sector **not obviously disfavoured by experimental data** (B-physics, K-physics, Higgs mass…)



Lightest squark states (mixtures of stop and charm) **accessible at the LHC**

— and not completely ruled out (yet…?)

K. De Causmaecker, B. Fuks, B. Herrmann, F. Mahmoudi, B. O'Leary, W. Porod, N. Strobbe, S. Sekmen
JHEP 1511 (2015) 125 — arXiv:1510.01159 [hep-ph]

Testing the *SU(5)* hypothesis at the LHC…?

Any test of the *SU(5)* relation relies on a comparison involving at least two (up-type) squarks

The mass spectrum may exhibit different features:

Natural supersymmetry → **Effective theory approach…**

Heavy supersymmetry → **Effective theory approach…**

Top-charm supersymmetry → **Mass insertion approximation…**

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Need for a more general analysis not relying on specific mass hierarchies:

Arbitrary mass spectra → **Bayesian analysis…**

Y. Stoll — PhD Thesis — Université Grenoble-Alpes — sept. 2015
B. Herrmann, S. Fichet — *ongoing work…*

A Bayesian approach

Probability = "measurement of the **degree of belief** about a proposition"

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Important application: Comparison of two models with respect to a given set of data

$$B_{01} = \frac{p(d|\mathcal{M}_0)}{p(d|\mathcal{M}_1)}$$

Bayes factor

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$|\log B_{01}|$	Odds	Probability	Strength of evidence
< 1.0	$\lesssim 3:1$	< 0.750	Inconclusive
1.0	$\sim 3:1$	≈ 0.750	Weak evidence
2.5	$\sim 12:1$	≈ 0.923	Moderate evidence
5.0	$\sim 150:1$	≈ 0.993	Strong evidence

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Here: **nested models**

$$\mathrm{SDDR} = \left.\frac{p(\mathcal{A}_{23}|d)}{p(\mathcal{A}_{23})}\right|_{\mathcal{A}_{23}=0}$$

Savage Dickey density ratio

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In practice, the probability densities (and thus the SDDR) can be evaluated by using **Markov Chain Monte Carlo** methods…

Test scenario — derived from *SU(5)* boundary conditions

$(M^2_{\mathbf{10}})_{ij}$	$j=1$	$j=2$	$j=3$
$i=1$	$(10000)^2$	0	0
$i=2$	0	$(609)^2$	$(841)^2$
$i=3$	0	$(841)^2$	$(1564)^2$

$(M^2_{\bar{\mathbf{5}}})_{ij}$	$j=1$	$j=2$	$j=3$
$i=1$	$(8600)^2$	0	0
$i=2$	0	$(1180)^2$	0
$i=3$	0	0	$(1317)^2$

$(T_u)_{ij}$	$j=1$	$j=2$	$j=3$
$i=1$	0	0	0
$i=2$	0	0	-575
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Renormalisation group evolution
and spectrum calculation: **SPHENO** [W. Porod 2003-2017]

	$m_{\tilde{u}_1}$	$m_{\tilde{u}_2}$	$m_{\tilde{u}_3}$	$m_{\tilde{u}_4}$	m_{h^0}	$m_{\tilde{\chi}^0_1}$	$(T_u)_{33}$	$(T_u)_{23}$	$(T_u)_{32}$
R	1144.6	1405.4	1468.8	1786.5	122.6	419.3	-2017.0	-810.6	-884.3
C	1153.9	1381.1	1471.3	1792.5	121.4	419.2	-1965.2	1199.1	-1252.7

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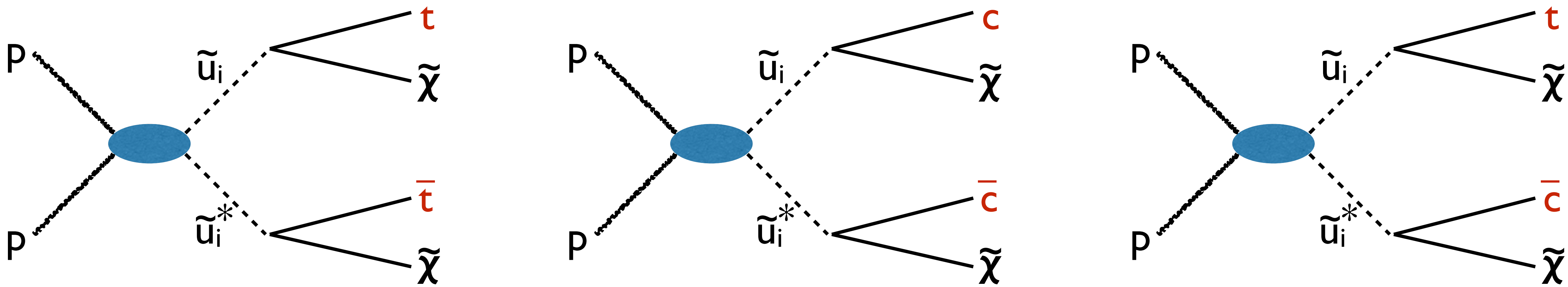
Counter example at TeV scale

$$(T_u)_{23} \approx -(T_u)_{32}$$

Both scenarios are viable with respect to most stringent flavour constraints

Test observables — Large Hadron Collider

Consider production of up-type squarks and subsequent decay into top and charm jets



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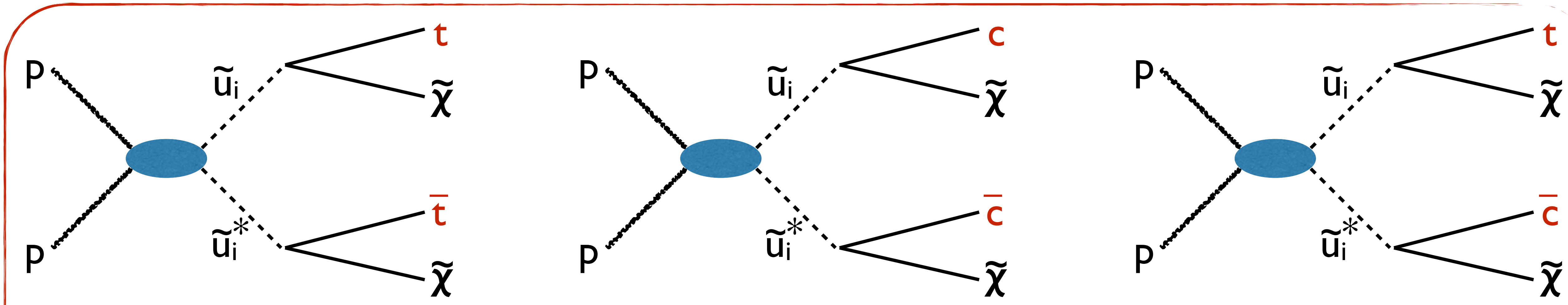

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Cross-sections and branching ratios numerical evaluated using **XSUSY** [Fuks, Herrmann 2007]

Test scenario: $N_{tt} = 328, \quad N_{cc} = 51, \quad N_{ct} = 26$

Statistical errors evaluated assuming Gaussian distributions for these observables

Minimal scenario — *SU(5)* case

$\mathcal{O}_1 = N_{cc}/N_{tt}$	$\sigma_1 = 3\%$
$\mathcal{O}_2 = N_{ct}/N_{tt}$	$\sigma_2 = 6\%$
$\mathcal{O}_3 = m_{\tilde{u}_1}/m_{\tilde{u}_2}$	$\sigma_3 = 5\%$
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$$\sqrt{s} = 14 \text{ TeV}$$

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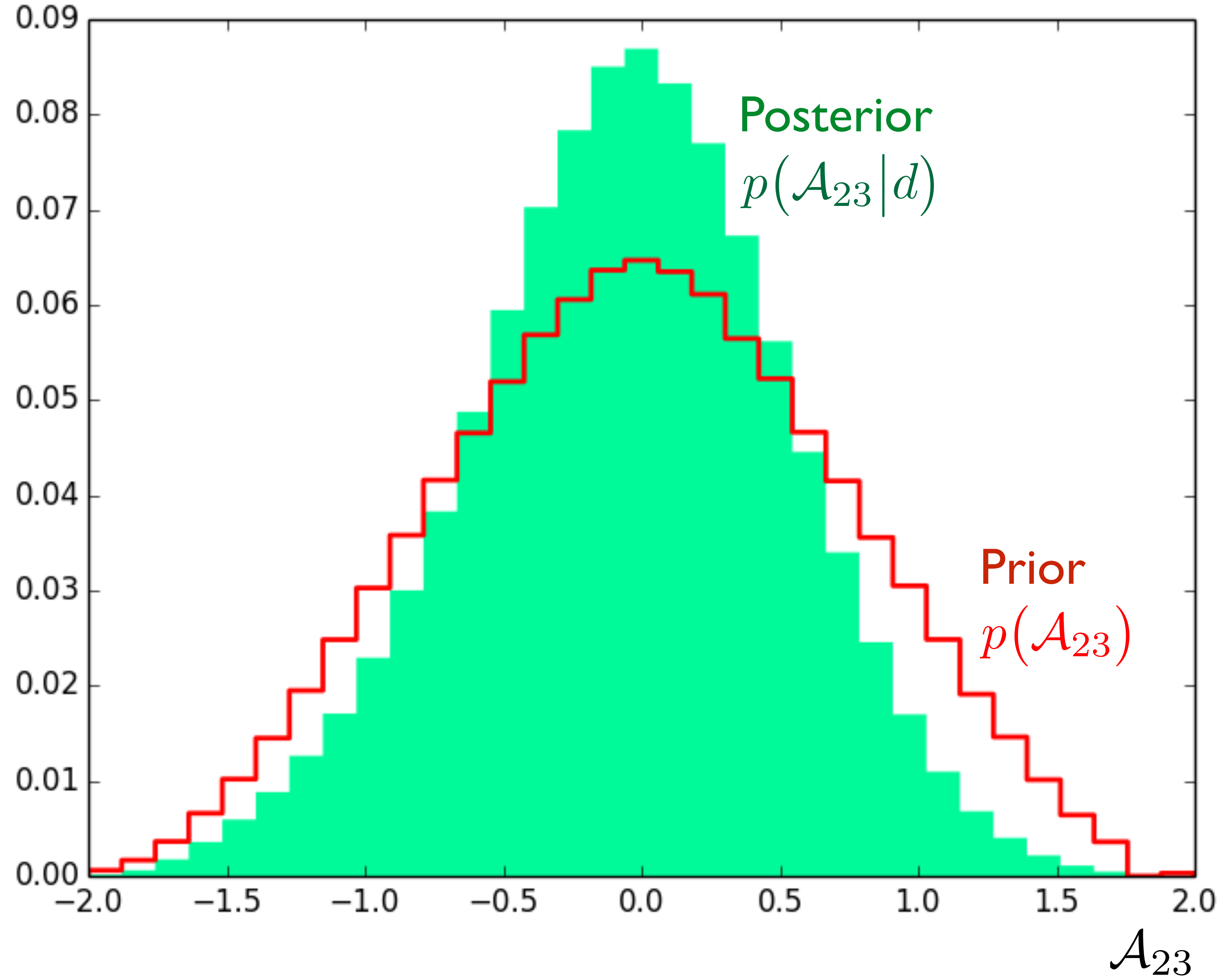

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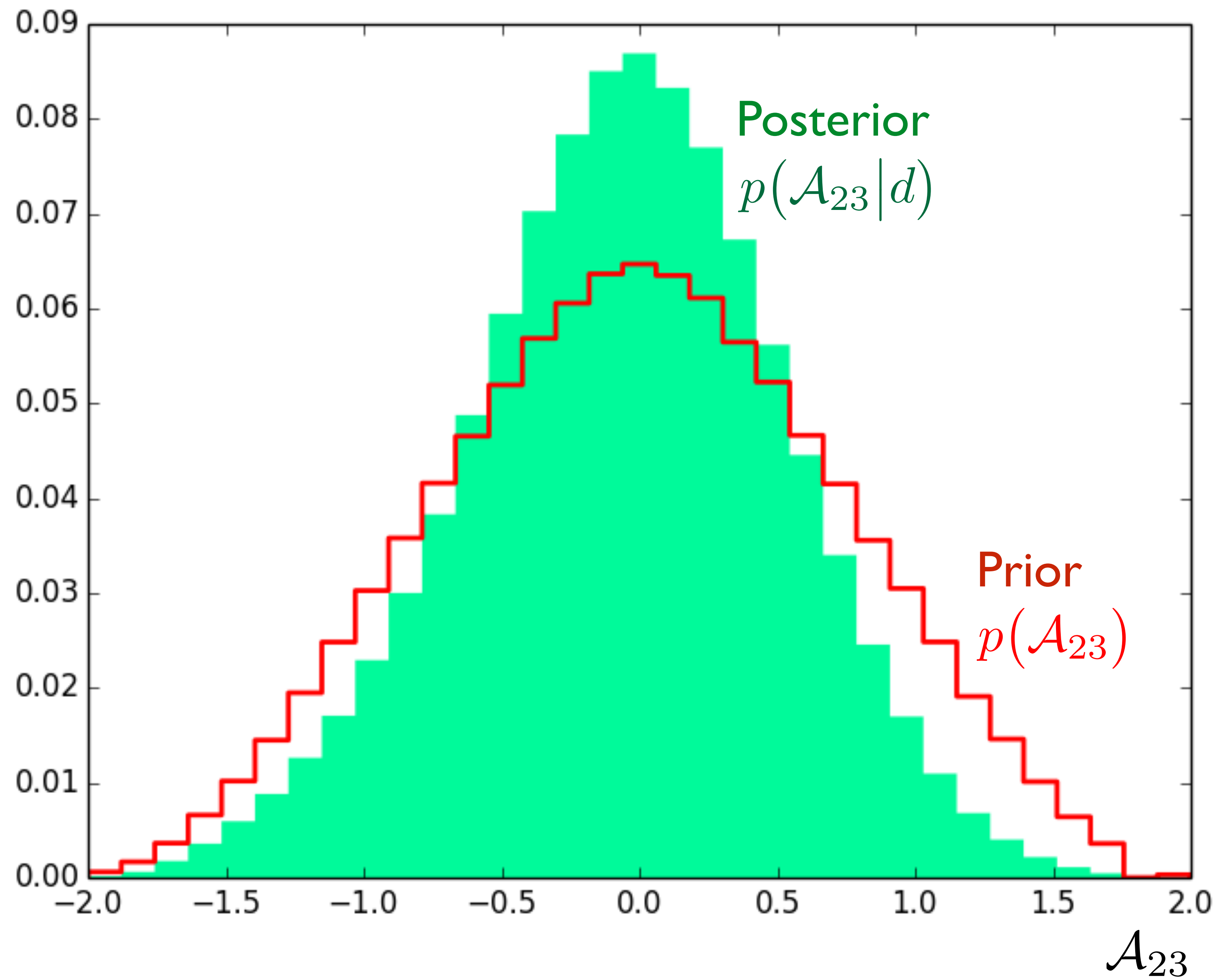

$$\text{SDDR} = \left.\frac{p(\mathcal{A}_{23}|d)}{p(\mathcal{A}_{23})}\right|_{\mathcal{A}_{23}=0} = 1.35 < 3.0$$

Test inconclusive…
(idem for counter-example)

Optimistic scenario — *SU(5)* case

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$\mathcal{O}_2 = N_{ct}/N_{tt}$	$\sigma_2 = 6\%$
$\mathcal{O}_3 = m_{\tilde{u}_1}/m_{\tilde{u}_2}$	$\sigma_3 = 5\%$
$\mathcal{O}_4 = \mathcal{R}_{\tilde{u}_1\tilde{t}_L}$	$\sigma_4 = 10\%$
$\vdots$	$\vdots$
$\mathcal{O}_{11} = \mathcal{R}_{\tilde{u}_2\tilde{c}_R}$	$\sigma_{11} = 10\%$

$$\mathcal{L} = 300 \text{ fb}^{-1}$$

$$\sqrt{s} = 14 \text{ TeV}$$

Optimistic scenario — *SU(5)* case

$\mathcal{O}_1 = N_{cc}/N_{tt}$ $\quad\sigma_1 = 3\%$

$\mathcal{O}_2 = N_{ct}/N_{tt}$ $\quad\sigma_2 = 6\%$

$\mathcal{O}_3 = m_{\tilde{u}_1}/m_{\tilde{u}_2}$ $\quad\sigma_3 = 5\%$

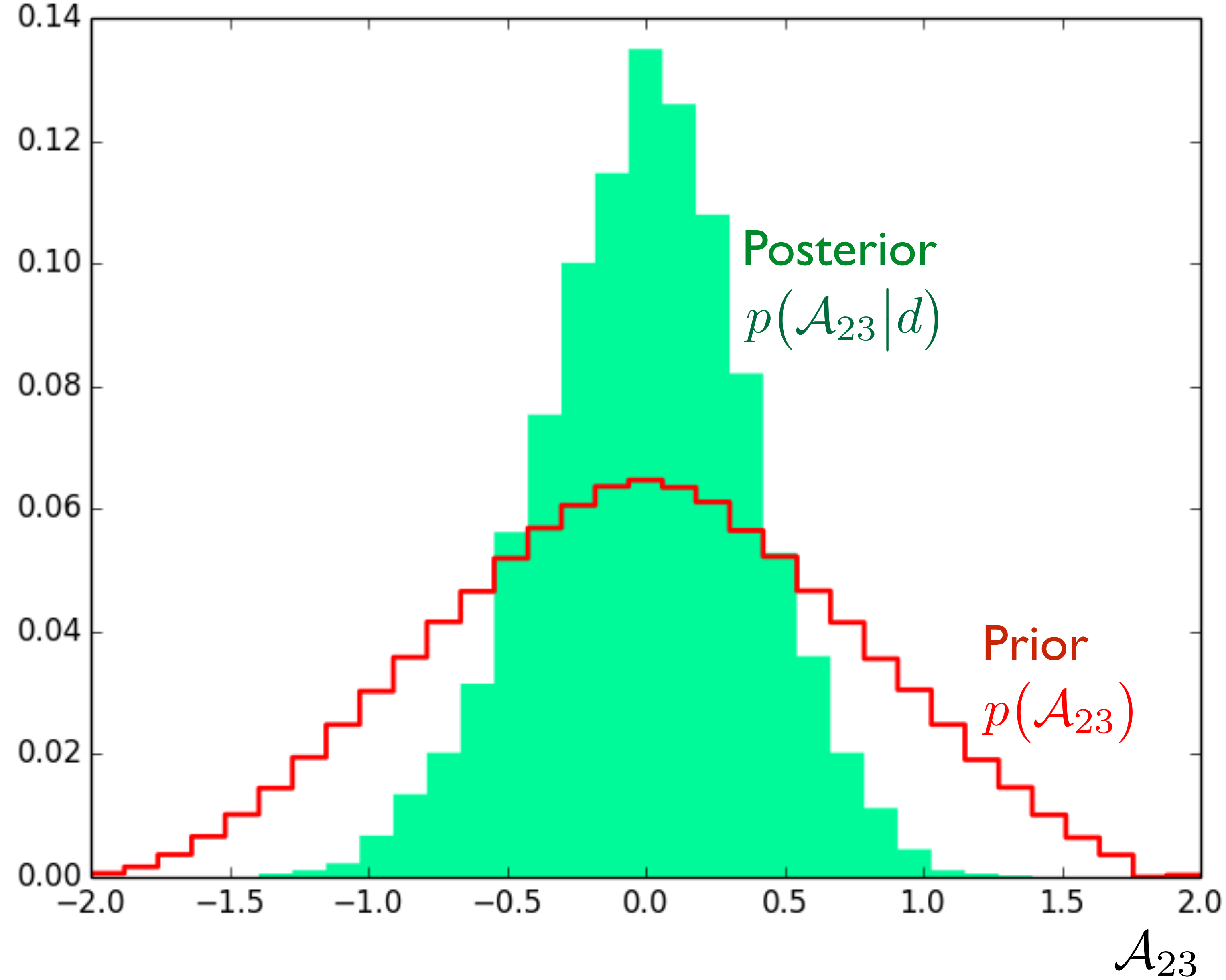
$\mathcal{O}_4 = \mathcal{R}_{\tilde{u}_1\tilde{t}_L}$ $\quad\sigma_4 = 10\%$

$\vdots$ $\quad\vdots$

$\mathcal{O}_{11} = \mathcal{R}_{\tilde{u}_2\tilde{c}_R}$ $\quad\sigma_{11} = 10\%$

$\mathcal{L} = 300\ \text{fb}^{-1}$

$\sqrt{s} = 14\ \text{TeV}$

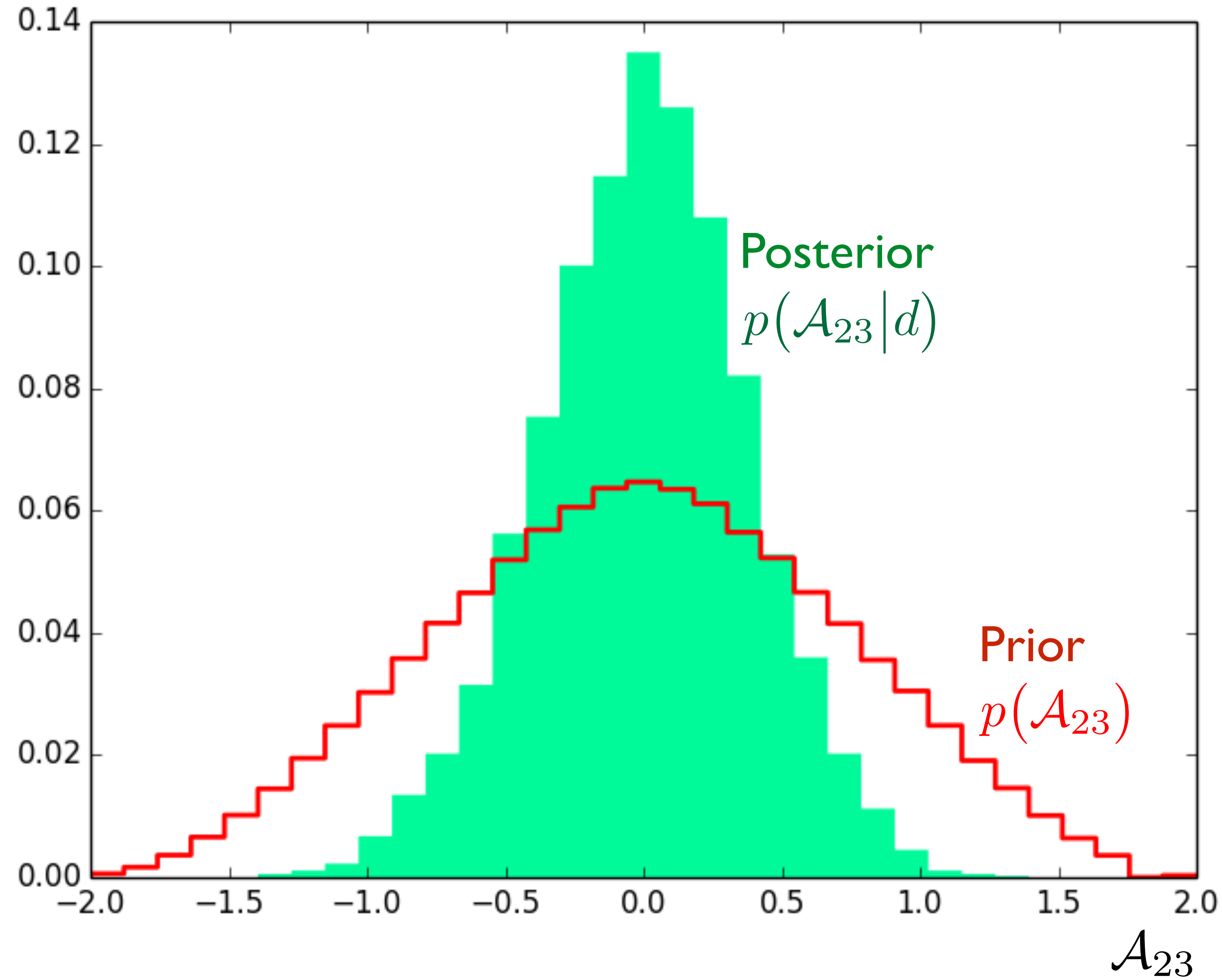


Optimistic scenario — *SU(5)* case

$$\begin{array}{ll} \mathcal{O}_1 = N_{cc}/N_{tt} & \sigma_1 = 3\% \\ \mathcal{O}_2 = N_{ct}/N_{tt} & \sigma_2 = 6\% \\ \mathcal{O}_3 = m_{\tilde{u}_1}/m_{\tilde{u}_2} & \sigma_3 = 5\% \\ \mathcal{O}_4 = \mathcal{R}_{\tilde{u}_1\tilde{t}_L} & \sigma_4 = 10\% \\ \vdots & \vdots \\ \mathcal{O}_{11} = \mathcal{R}_{\tilde{u}_2\tilde{c}_R} & \sigma_{11} = 10\% \end{array}$$

$$\mathcal{L} = 300 \text{ fb}^{-1}$$

$$\sqrt{s} = 14 \text{ TeV}$$



$$\text{SDDR} = \left.\frac{p(\mathcal{A}_{23}|d)}{p(\mathcal{A}_{23})}\right|_{\mathcal{A}_{23}=0} = 2.08 < 3.0$$

Test inconclusive…

— but **weak evidence against** *SU(5)* for counter-exemple!

High-luminosity scenario — *SU(5)* case

$\mathcal{O}_1 = N_{cc}/N_{tt}$	$\sigma_1 = 0.3\%$
$\mathcal{O}_2 = N_{ct}/N_{tt}$	$\sigma_2 = 0.6\%$
$\mathcal{O}_3 = m_{\tilde{u}_1}/m_{\tilde{u}_2}$	$\sigma_3 = 1\%$
$\mathcal{O}_4 = \mathcal{R}_{\tilde{u}_1 \tilde{t}_L}$	$\sigma_4 = 1\%$
$\vdots$	$\vdots$
$\mathcal{O}_{11} = \mathcal{R}_{\tilde{u}_2 \tilde{c}_R}$	$\sigma_{11} = 1\%$

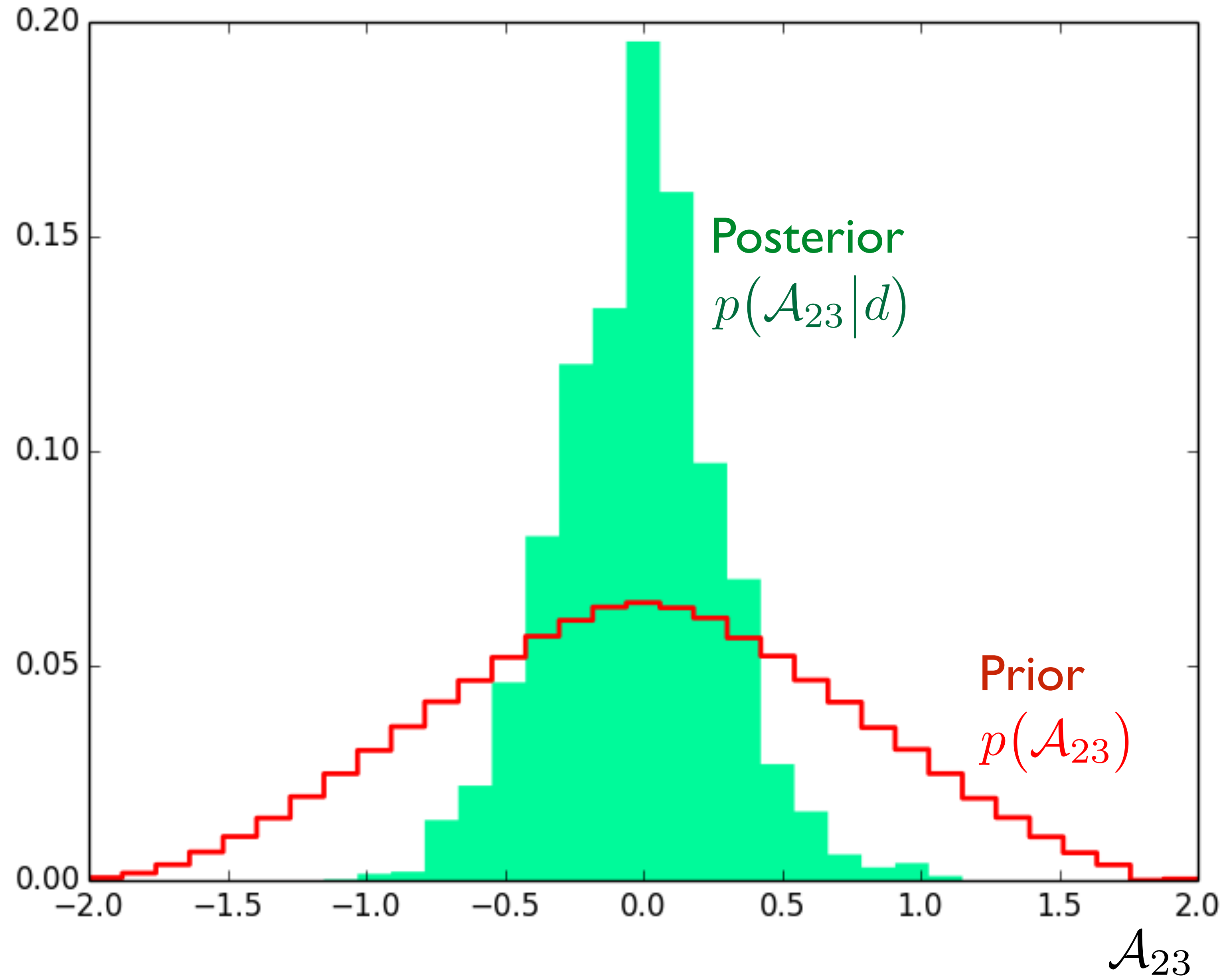
$$\mathcal{L} = 3000 \text{ fb}^{-1}$$

$$\sqrt{s} = 14 \text{ TeV}$$

High-luminosity scenario — *SU(5)* case

$$\mathcal{O}_1 = N_{cc}/N_{tt} \qquad \sigma_1 = 0.3\%$$
$$\mathcal{O}_2 = N_{ct}/N_{tt} \qquad \sigma_2 = 0.6\%$$
$$\mathcal{O}_3 = m_{\tilde{u}_1}/m_{\tilde{u}_2} \qquad \sigma_3 = 1\%$$
$$\mathcal{O}_4 = \mathcal{R}_{\tilde{u}_1\tilde{t}_L} \qquad \sigma_4 = 1\%$$
$$\vdots \qquad \vdots$$
$$\mathcal{O}_{11} = \mathcal{R}_{\tilde{u}_2\tilde{c}_R} \qquad \sigma_{11} = 1\%$$

$$\mathcal{L} = 3000 \text{ fb}^{-1}$$
$$\sqrt{s} = 14 \text{ TeV}$$



High-luminosity scenario — *SU(5)* case

$\mathcal{O}_1 = N_{cc}/N_{tt}$	$\sigma_1 = 0.3\%$
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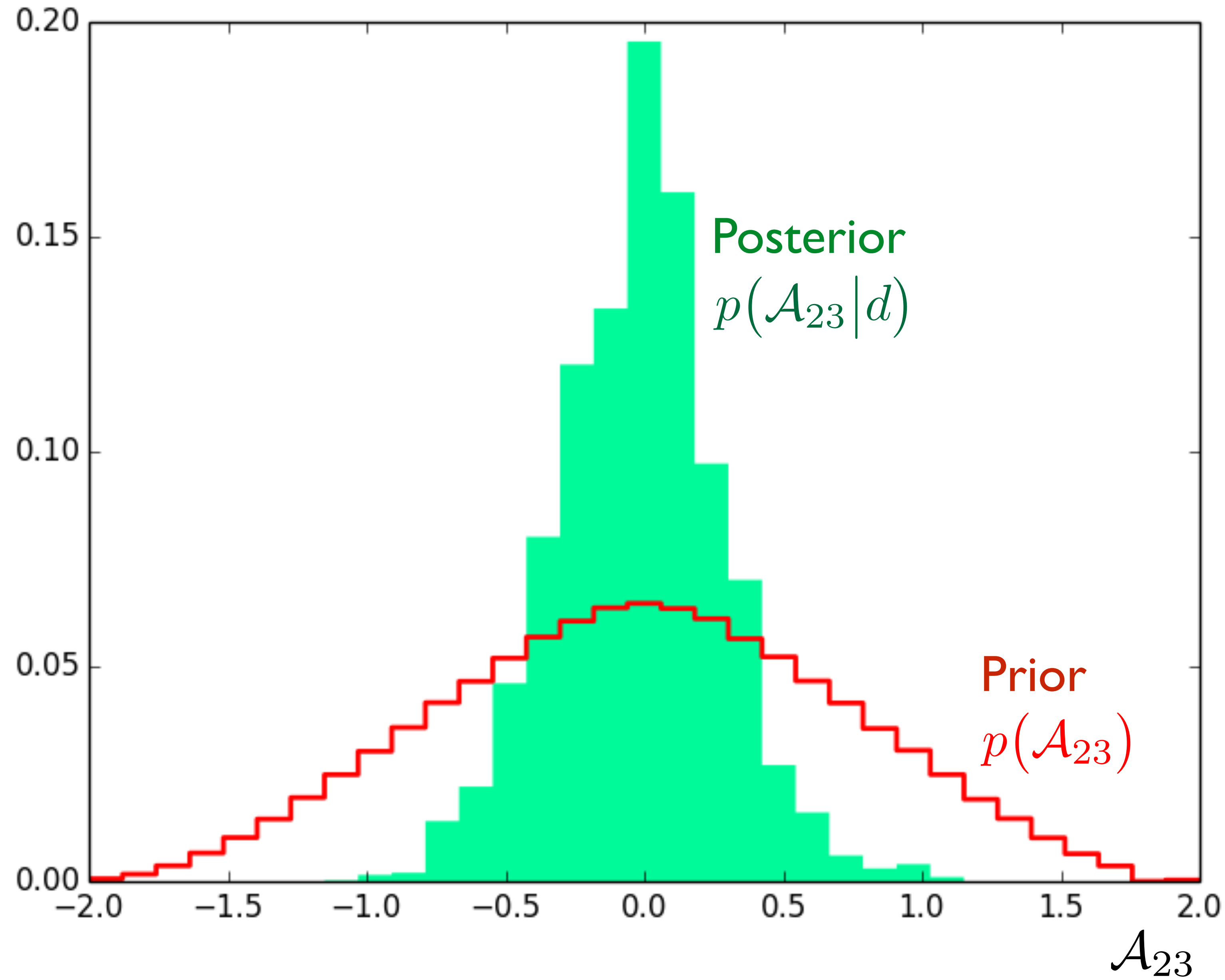
$$\mathcal{L} = 3000 \text{ fb}^{-1}$$

$$\sqrt{s} = 14 \text{ TeV}$$



$$\text{SDDR} = \left.\frac{p(\mathcal{A}_{23}|d)}{p(\mathcal{A}_{23})}\right|_{\mathcal{A}_{23}=0} = 3.02 \gtrsim 3.0$$

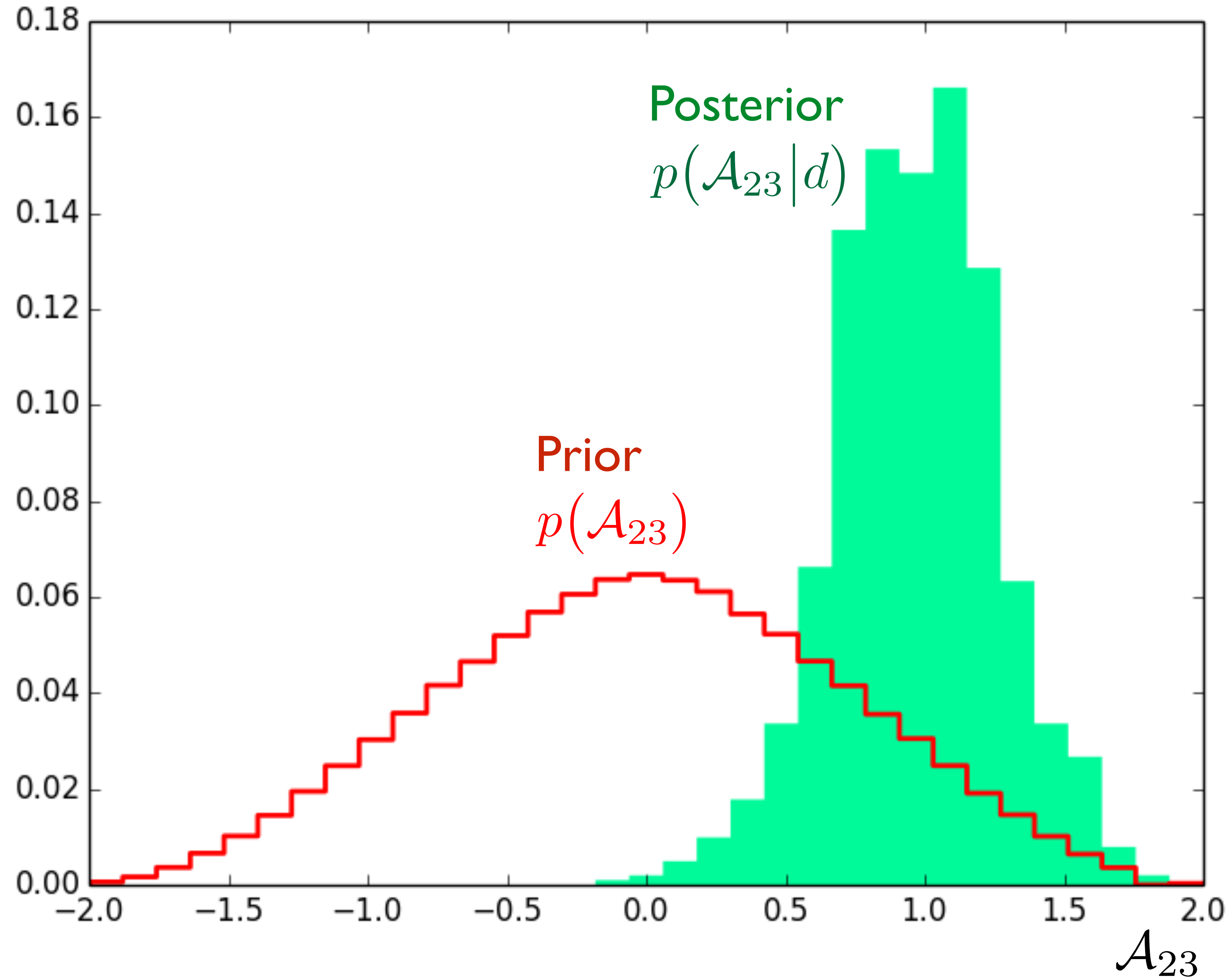
Weak evidence in favour of *SU(5)* hypothesis

High-luminosity scenario — Counter example

$\mathcal{O}_1 = N_{cc}/N_{tt}$	$\sigma_1 = 0.3\%$
$\mathcal{O}_2 = N_{ct}/N_{tt}$	$\sigma_2 = 0.6\%$
$\mathcal{O}_3 = m_{\tilde{u}_1}/m_{\tilde{u}_2}$	$\sigma_3 = 1\%$
$\mathcal{O}_4 = \mathcal{R}_{\tilde{u}_1 \tilde{t}_L}$	$\sigma_4 = 1\%$
$\vdots$	$\vdots$
$\mathcal{O}_{11} = \mathcal{R}_{\tilde{u}_2 \tilde{c}_R}$	$\sigma_{11} = 1\%$

$$\mathcal{L} = 3000 \text{ fb}^{-1}$$

$$\sqrt{s} = 14 \text{ TeV}$$



High-luminosity scenario — Counter example

$\mathcal{O}_1 = N_{cc}/N_{tt}$ $\sigma_1 = 0.3\%$

$\mathcal{O}_2 = N_{ct}/N_{tt}$ $\sigma_2 = 0.6\%$

$\mathcal{O}_3 = m_{\tilde{u}_1}/m_{\tilde{u}_2}$ $\sigma_3 = 1\%$

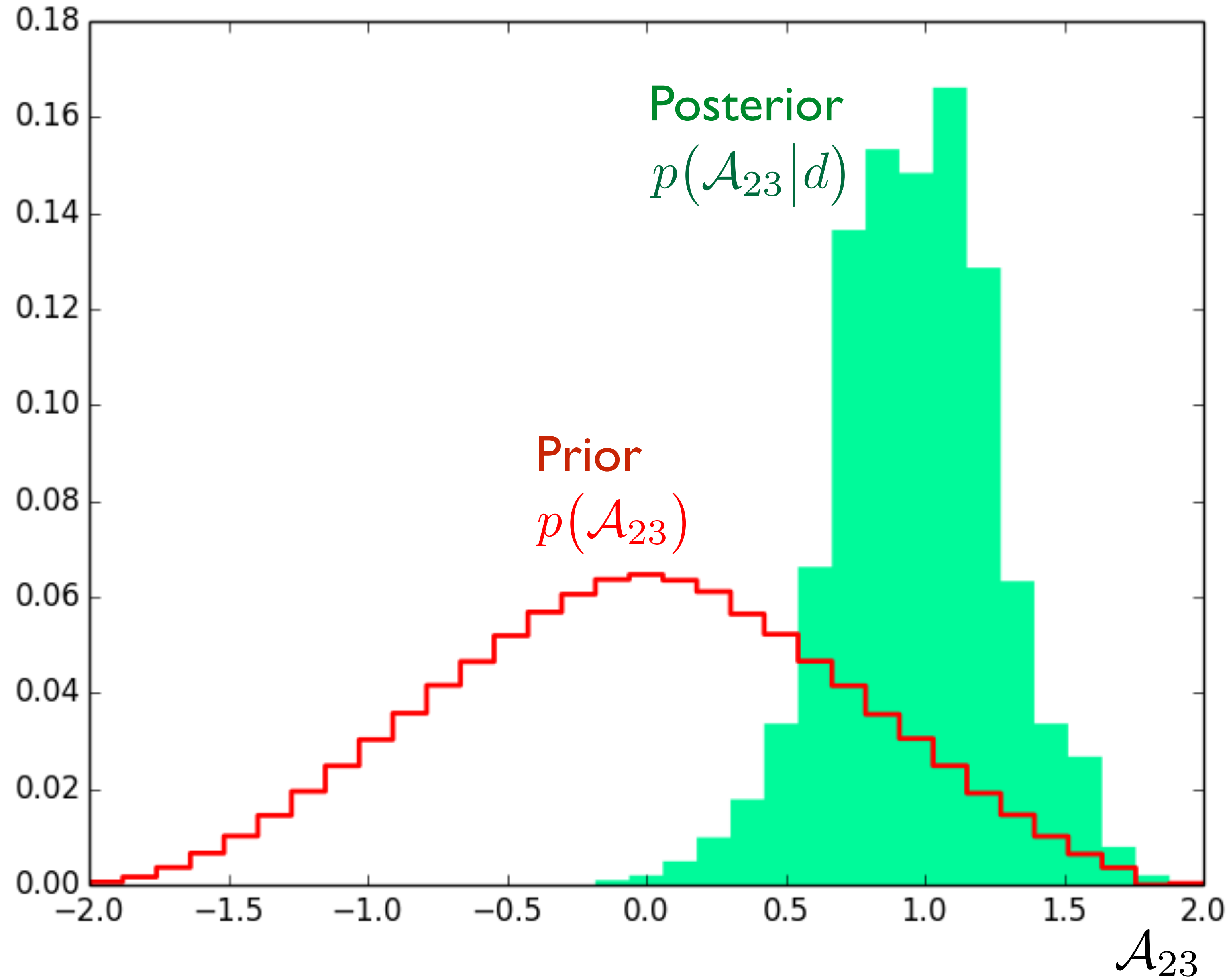
$\mathcal{O}_4 = \mathcal{R}_{\tilde{u}_1 \tilde{t}_L}$ $\sigma_4 = 1\%$

$\vdots$ $\vdots$

$\mathcal{O}_{11} = \mathcal{R}_{\tilde{u}_2 \tilde{c}_R}$ $\sigma_{11} = 1\%$

$\mathcal{L} = 3000 \text{ fb}^{-1}$

$\sqrt{s} = 14 \text{ TeV}$



$$\text{SDDR} = \left.\frac{p(\mathcal{A}_{23}|d)}{p(\mathcal{A}_{23})}\right|_{\mathcal{A}_{23}=0} = 0.03 < 1/12$$

Moderate evidence against *SU(5)* hypothesis

Conclusion and outlook

Non-minimally flavour-violating terms may be present in the Lagrangian of a supersymmetric theory at the TeV scale — **typical signatures at colliders**

Flavour-violating couplings may open **windows towards GUT physics** — effective theory and MCMC approaches in order to test *SU(5)* hypothesis

However, somewhat “extreme” conditions are needed to draw conclusions (high luminosity, good precision, charm tagging, top polarization, flavour decomposition…)

Conclusion and outlook

Non-minimally flavour-violating terms may be present in the Lagrangian of a supersymmetric theory at the TeV scale — **typical signatures at colliders**

Flavour-violating couplings may open **windows towards GUT physics**
— effective theory and MCMC approaches in order to test *SU(5)* hypothesis

However, somewhat "extreme" conditions are needed to draw conclusions
(high luminosity, good precision, charm tagging, top polarization, flavour decomposition…)

Possible improvements

— Include flavour constraints in analysis…
— Investigate additional collider signatures…

S. Fichet, B. Herrmann, Y. Stoll — Phys. Lett. B 742 (2015) 69-73 — arXiv:1403.3397 [hep-ph]
S. Fichet, B. Herrmann, Y. Stoll — JHEP 05 (2015) 091 — arXiv:1501.05307 [hep-ph]
S. Fichet, B. Herrmann — *work in progress…*


thank you
danke
謝謝
ngiyabonga
teşekkür ederim
спасибо
gracias
dank je
mochchakkeram
dziękuję
bedankt
go raibh maith agat
obrigado
sukriya
kop khun krap
arigato
dakujem
мерси
grazie
terima kasih
ありがとう
감사합니다
merci