Implications of first LHC results

1) Large extra dimensions (http://arxiv.org/abs/1101.4919)
2) SuperSymmetry (http://arxiv.org/abs/1101.2195)

Alessandro Strumia

Talk at Moriond EW 2011

The main goal of LHC

is understanding why the weak scale is small.

Maybe the hierarchy problem was a good guideline. Maybe we lost 30 years.

A new symmetry

Scalar	Vector	Fermion
$H \to H + \theta$	$A_\mu \to A_\mu + \partial_\mu \theta$	$\Psi \to e^{i\theta\gamma_5}\Psi$
Keeps H massless.	Keeps A_μ massless	Keeps Ψ massless.
Goldstone boson.	In 5 dims: $H = A_5$	$H \overset{\text{SUSY}}{\leftrightarrow} \Psi$.

Higgs has weak-scale size

Technicolour	Large extra dims	Warped extra dims
H bound state like π	H is a string or...	Dual to technicolor

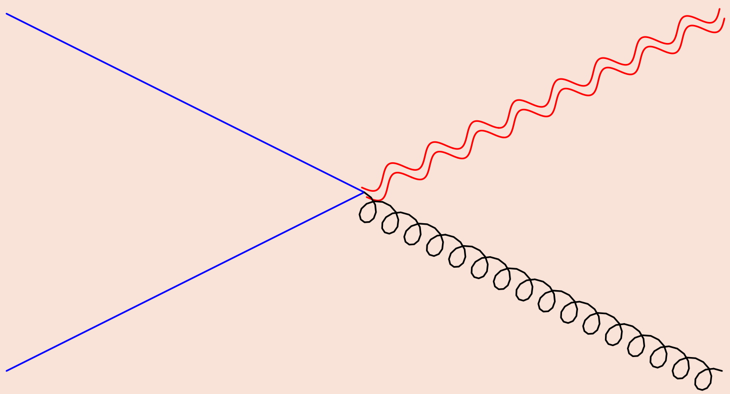
Large extra dimensions

with R. Franceschini, G. Giudice, P. Paolo Giardino, P. Lodone

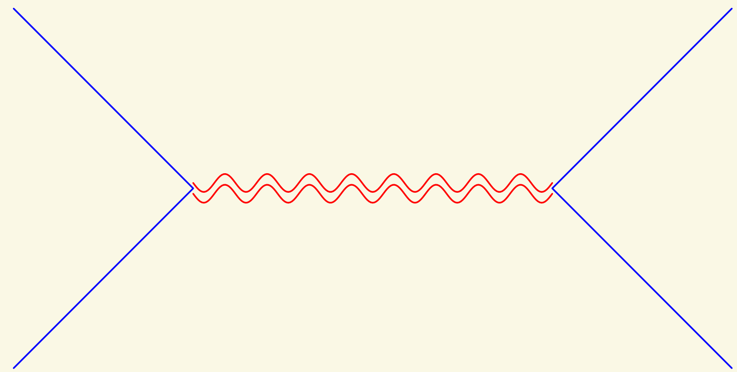
Collider signals

Quantum gravity is unknown; signals computable at $E \ll M_D$ and $E \gg M_D$:

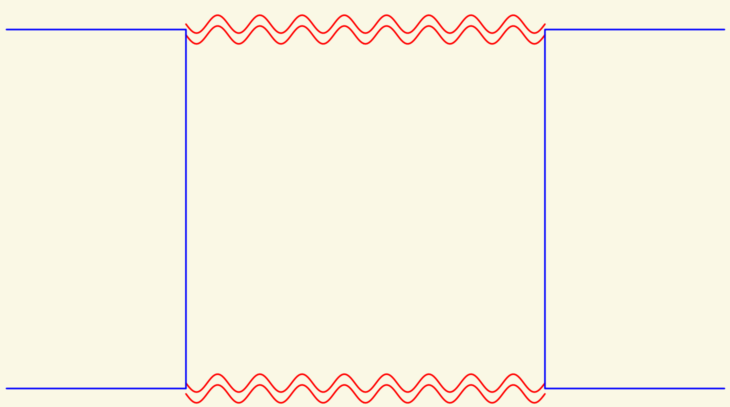
(1) Graviton emission



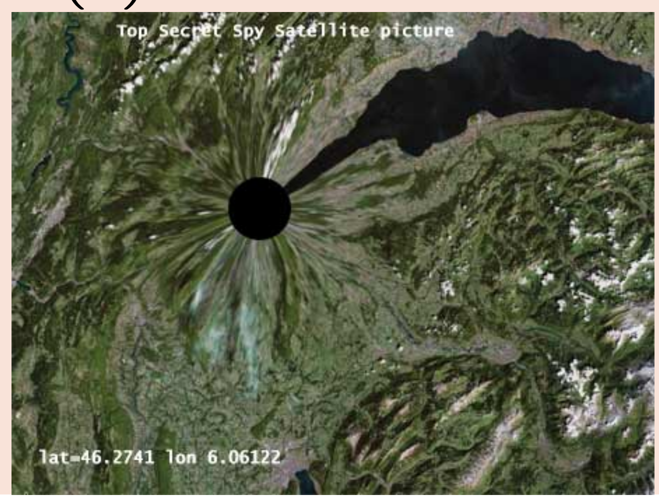
(2) Tree-level graviton exchange



(3) Graviton loop

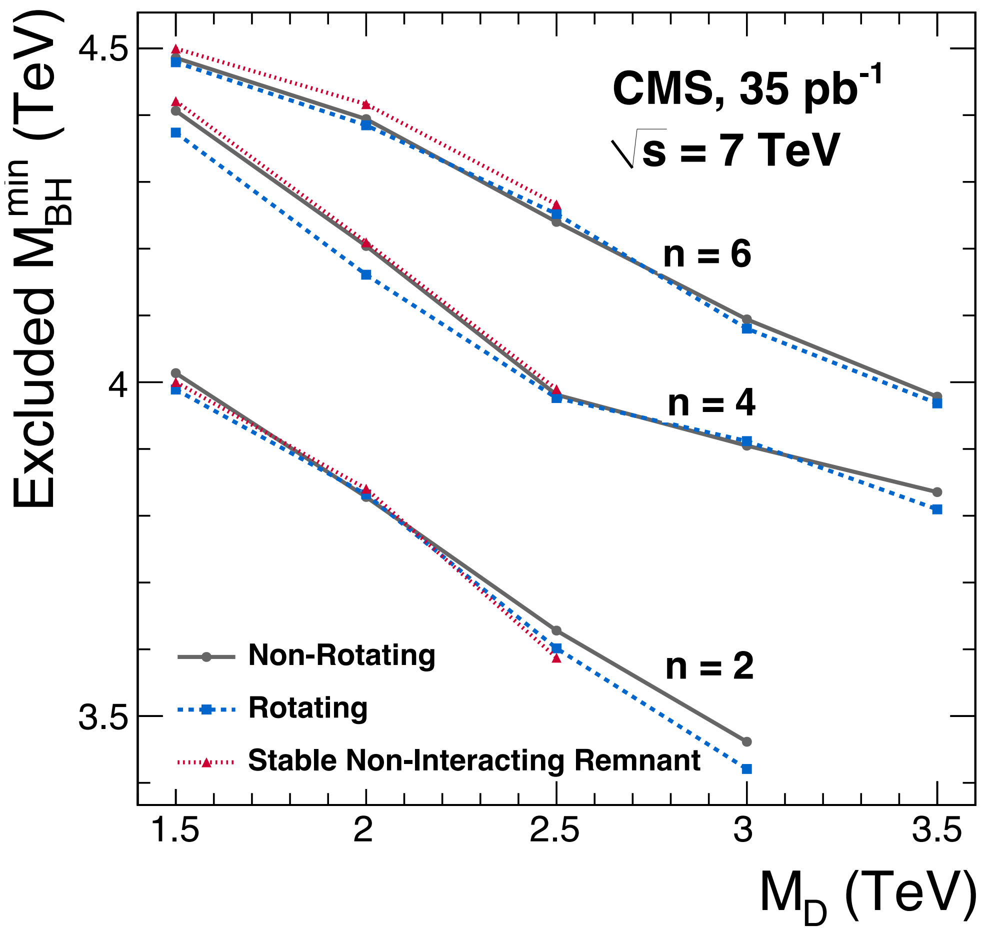


(4) Trans-Planckian



No black holes in first LHC data

$$\sigma \sim (M_{\text{BH}}/M_D)^{2/(\delta+1)}/M_D^2 \text{ depends on } M_{\text{BH}} > M_{\text{BH}}^{\min} \overset{?}{\gtrsim} M_D$$



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"È LA FINE DEL MONDO"

La conferma del Cern

Il buco nero creato dal Large Hadron Collider è destinato a inghiottire il nostro pianeta nelle prossime settimane. Secondo Walter Wagner anche l'universo è in pericolo. Scene di panico durante la conferenza stampa del Cern a Parigi.

IL VIDEO / LE PRIME IMMAGINI

La Svizzera inghiottita dal buco nero Sarkozy contrario all'evacuazione

"*A quoi bon?* Tra qualche ora saremo comunque tutti morti". Berlusconi caustico: "risolta la questione Alitalia".

"Pregate, ma non garantisco niente" Lo scetticismo di Papa Benedetto

"Il buco nero è il risultato ultimo di ricerca scientifica dissennata che ha voluto porre l'uomo davanti a Dio. Non resta che la preghiera, forse". Dal suo ritiro in Alto Adige, il Papa gela i pellegrini venuti ad ascoltare un messaggio di speranza.

IL VIDEO / LE IMMAGINI / "SANTITA', IL BUCO NERO E' L'INFERNO?"

Net Monitor: "Proprio adesso che andavo in ferie" *di* V. ZAMBARDINO

Hawking deluso: "mi sono sbagliato"

"La mia radiazione avrebbe dovuto eliminare il buco nero, ma evidentemente ho sbagliato qualcosa". Lo scienziato non esclude la possibilità che un nuovo universo possa riformarsi dal caos. "Ci vorranno milioni di anni, ma la prossima volta saremo più prudenti".

Software | Società | Curiosità

Troppa pancia per Babbo Natale è tempo di dieta

Si sono incontrati in 150 per l'annuale congresso in Danimarca. E hanno deciso di perdere qualche chilo. Messa da parte la slitta, per qualche tempo andranno in bici e faranno ginnastica

LE IMMAGINI
La dea del metrò colpisce ancora lap dance sui pali della strada
LA FOTOSEQUENZA NEL METRO'

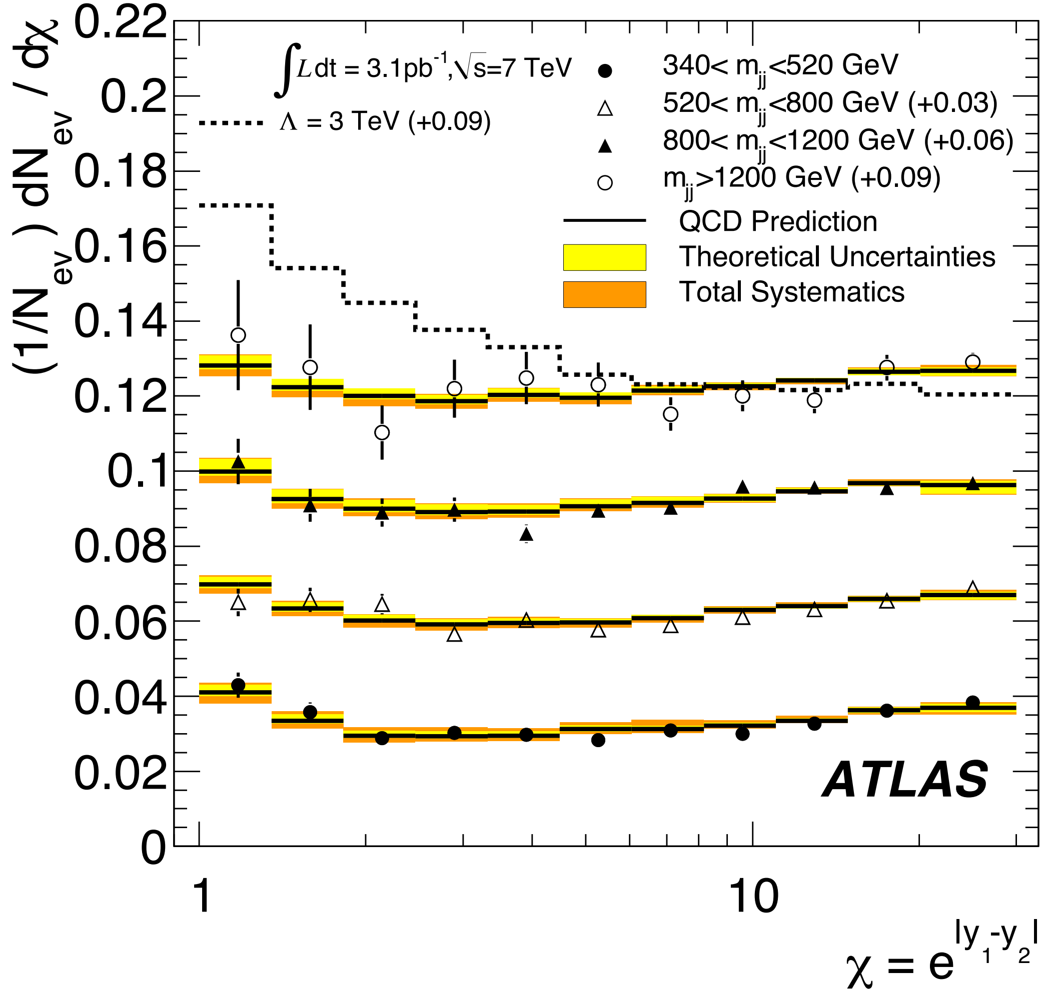
LE IMMAGINI
Pechino indossa la sottoveste sono le olimpiadi della lingerie

LE IMMAGINI
Miracolo a Saint Tropez in acqua c'è Bar Rafaeli

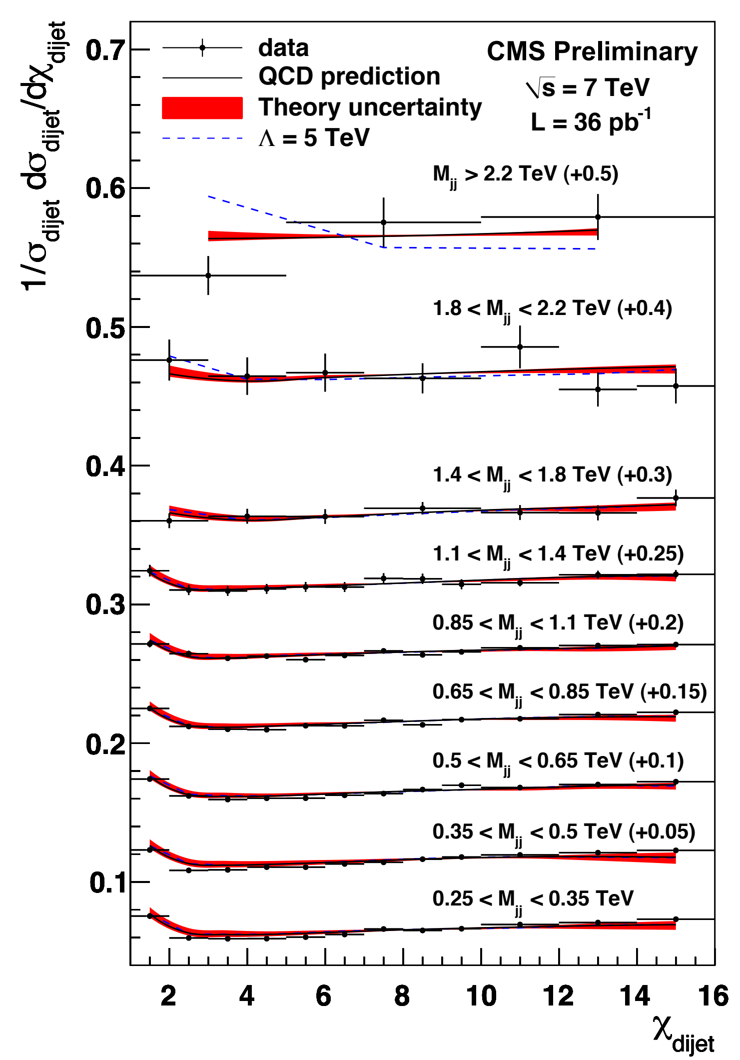
LE IMMAGINI
Pamela a Central Park spunta l'amico misterioso

First LHC data: $pp \to jj$

ATLAS at 3.1/pb



CMS at 36/pb



χ = angular jj distance. Coulomb-like QCD gives a quasi-flat distribution. New massive particles or effective $\mathcal{O}$ give effects at large M_{jj} and small angle χ

Loop level graviton exchange

At low energy is described by the dimension 6 effective operator

$$\mathscr{L} = c_\Upsilon \times \Upsilon, \qquad \Upsilon = \frac{1}{2}\Big(\sum_f \bar{f}\gamma_\mu\gamma_5 f\Big)^2$$

95% CL limits on $\lvert c_\Upsilon/4\pi\rvert^{-1/2}$ in TeV			
Experiment	Process	$+$	$-$
LEP combined	$e^+e^- \to \ell^+\ell^-$	17.2	15.1
LEP combined	$e^+e^- \to b\bar{b}$	15.3	11.5
ZEUS, H1	e^+p and e^-p	4.6	5.3
DØ	$p\bar{p} \to e^+e^-$	4.7	5.5
CDF	$p\bar{p} \to \ell^+\ell^-$	4.5	5.6
CCFR	νN scattering	3.7	5.9
DØ	$p\bar{p} \to jj$	3.2	3.1
ATLAS at 7 TeV with 3.1/pb	$pp \to jj$	5.3	4.2
CMS at 7 TeV with 36/pb	$pp \to jj$	11	8.1
combined		22.4	15.7

LHC improves on TeVatron but not on LEP

Tree level graviton exchange

At low energy is described by the dimension 8 effective operator $\mathscr{L}_{\rm eff} = c_{\mathcal{T}}\ \mathcal{T}$

$$\mathcal{T} = \frac{1}{2}\Big(T_{\mu\nu}T^{\mu\nu} - \overbrace{\frac{T^\mu_\mu T^\nu_\nu}{\delta+2}}^{\text{irrelevant}}\Big)^2 \sim (\bar\Psi\partial\Psi + \bar\Psi A\Psi + F^2_{\mu\nu})^2$$

Independently produced by brane fluctuations at loop level.

High dimensionality: energy is the key factor and early LHC wins

Coefficient: parameterize as $c_{\mathcal{T}} = 8/M^4_{\mathcal{T}}$ (Hewett normalization).

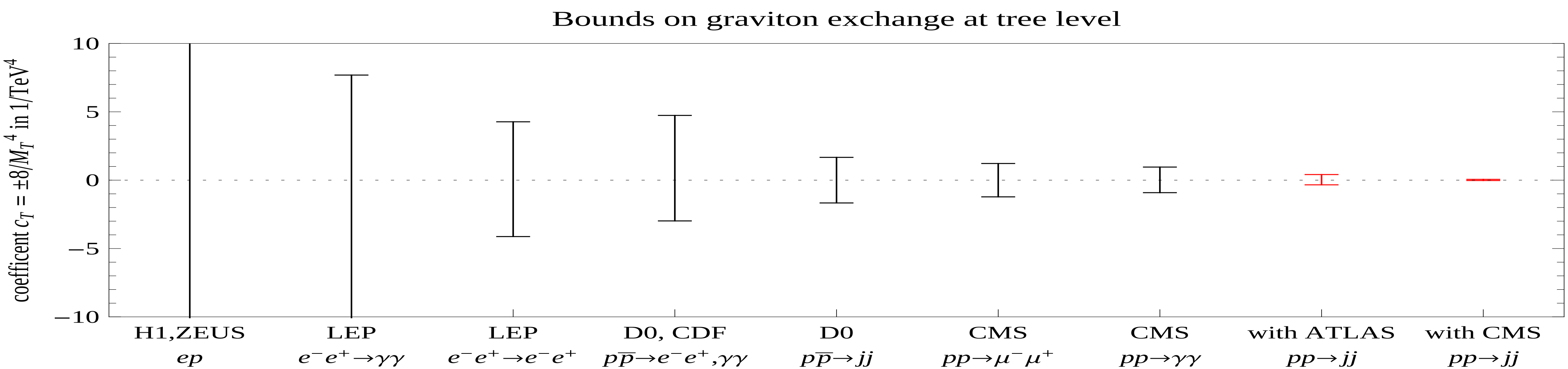
Signals: $pp \to jj$ is considered dirty by actually is much better at low statistics:

$$\sigma = \left(\frac{2\,\text{TeV}}{M_{\mathcal{T}}}\right)^8 \times \begin{cases} 12.5\,\text{pb} & \text{for } pp \to jj \\ 10.4\,\text{fb} & \text{for } pp \to \mu^+\mu^- \\ 21.3\,\text{fb} & \text{for } pp \to \gamma\gamma \end{cases}$$

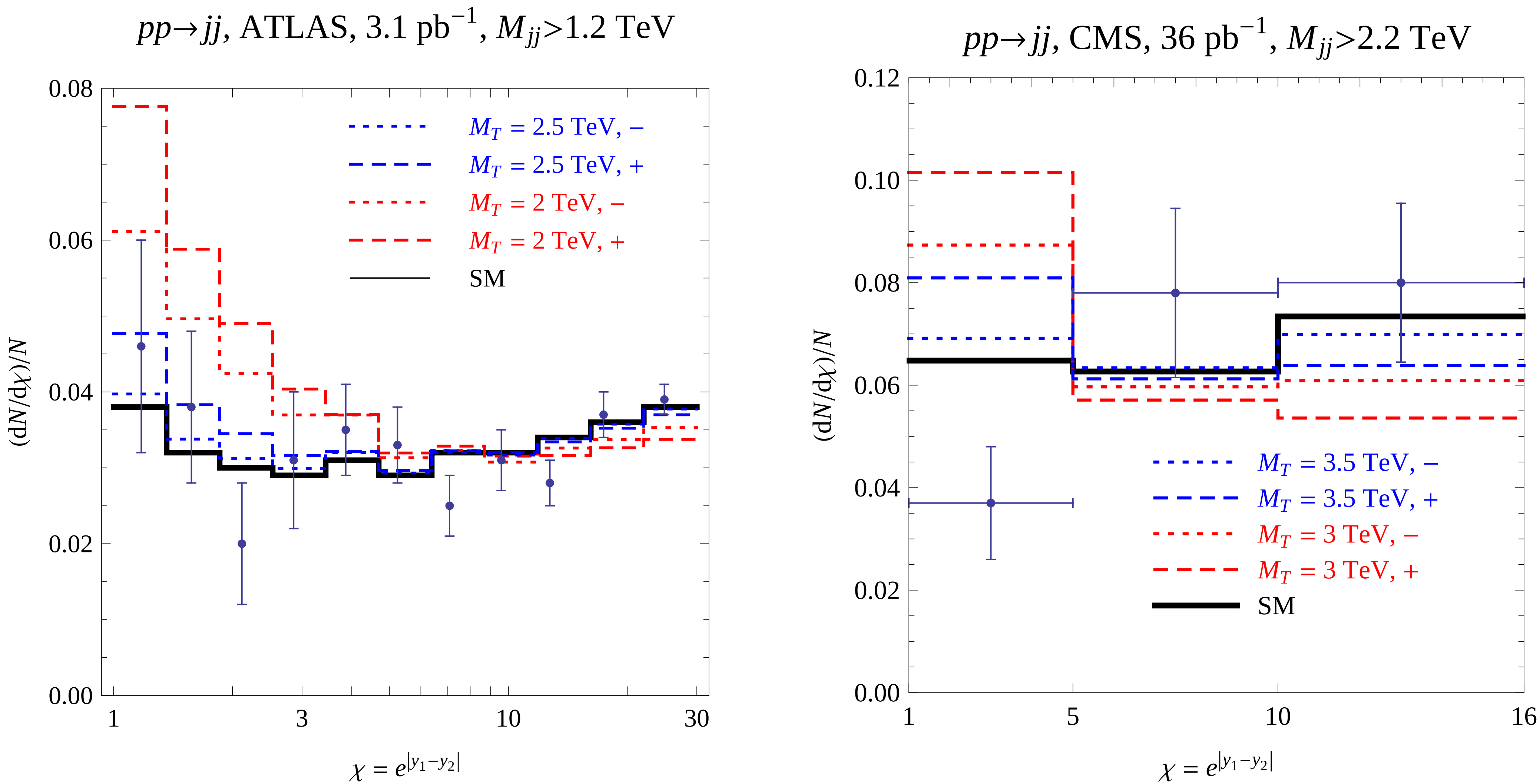
thanks to the energetic $uu \to uu$. (cuts: $\sqrt{s} = 7\,\text{TeV}$, $M_{\rm eff} > 1\,\text{TeV}$, $\eta < 2.5$)

Bounds on M_T

Experiment	Process	+	−
LEP	$e^+e^- \to \gamma\gamma$	0.93 TeV	1.01 TeV
LEP	$e^+e^- \to e^+e^-$	1.18 TeV	1.17 TeV
CDF	$p\bar{p} \to e^+e^-, \gamma\gamma$	0.99 TeV	0.96 TeV
DØ	$p\bar{p} \to e^+e^-, \gamma\gamma$	1.28 TeV	1.14 TeV
DØ	$p\bar{p} \to jj$	1.48 TeV	1.48 TeV
CMS at 7 TeV with 34/pb	$pp \to \gamma\gamma$	1.72 TeV	1.70 TeV
CMS at 7 TeV with 40/pb	$pp \to \mu^-\mu^+$	1.6 TeV	1.6 TeV
ATLAS at 7 TeV with 3.1/pb	$pp \to jj$	2.2 TeV	2.1 TeV
CMS at 7 TeV with 36/pb	$pp \to jj$	4.2 TeV	3.4 TeV



The LHC data



Computed implementing in MadGraph and Pythia

Fitting the full amplitude $\mathcal{A} = \mathcal{S}(s) T^2_{\mu\nu}$

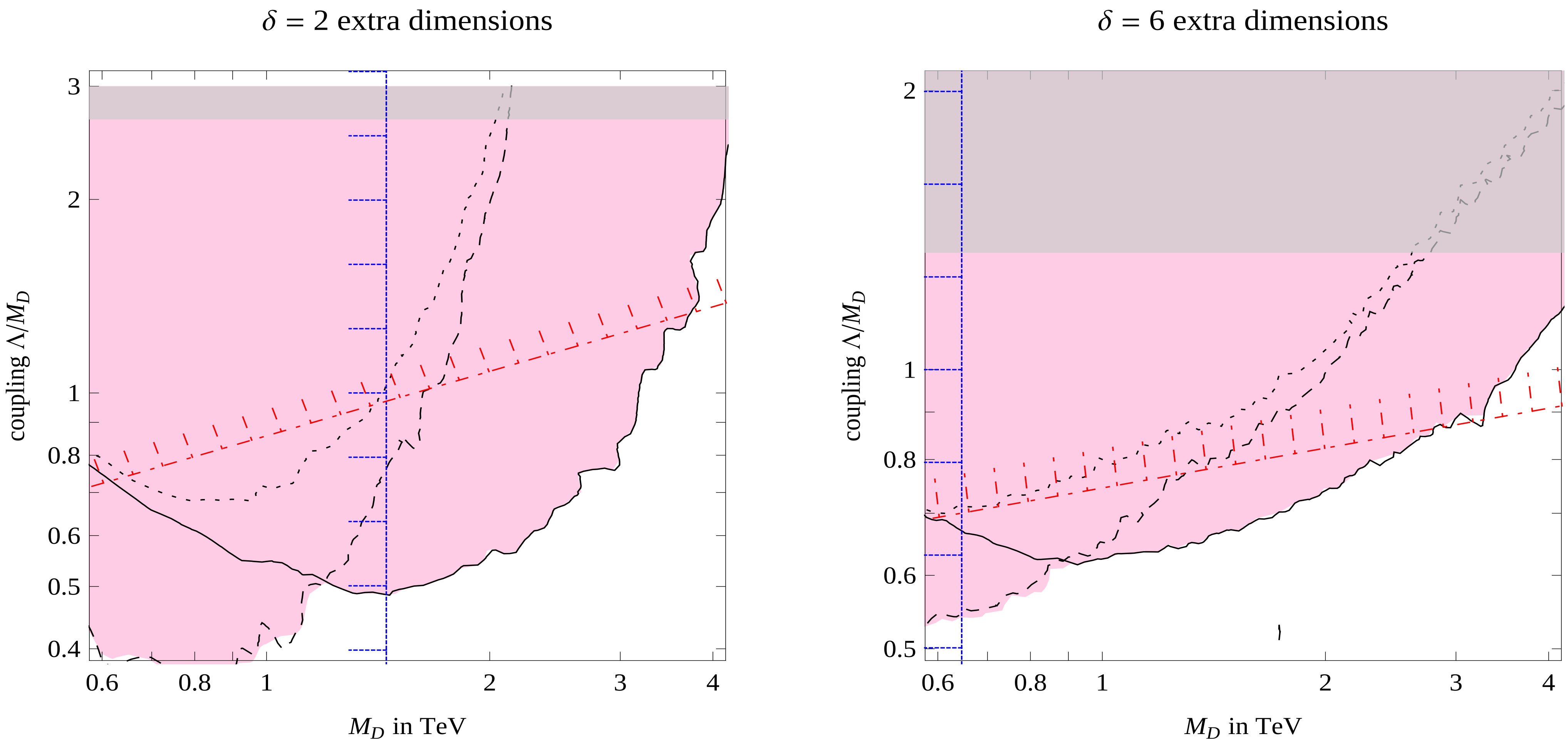
Truncate KK tower at $m < \Lambda$ to avoid UV divergence:

$$\mathcal{S}(s) = \frac{1}{M^2_{\mathrm{Pl}}} \sum_i \frac{1}{s - m_i^2 + i m_i \Gamma_G(m_i)} = \frac{1}{M_D^{2+\delta}} \int_{|q|<\Lambda} \frac{d^\delta q}{s - q^2 + i\varepsilon}$$

$$c_{\mathcal{T}} = \mathcal{S}(s \ll \Lambda^2) = \begin{cases} \dfrac{\pi^{\delta/2}}{(1-\delta/2)\Gamma(\delta/2)} \dfrac{\Lambda^{\delta-2}}{M_D^{\delta+2}} \equiv \dfrac{8}{M_{\mathcal{T}}^4} & \text{for } \delta > 2 \\ \dfrac{\pi}{M_D^4} \ln \dfrac{s}{\Lambda^2} & \text{for } \delta = 2 \\ \dfrac{-i\pi}{M_D^3 \sqrt{s}} & \text{for } \delta = 1 \end{cases}$$

Subtelty: $\mathcal{S}_\int = \langle \mathcal{S}_\sum \rangle$ i.e. it is ok to $\sum_{\mathrm{KK}} \approx \int_q$ and ignore the graviton width

Bound on the full amplitude (M_D, Λ)

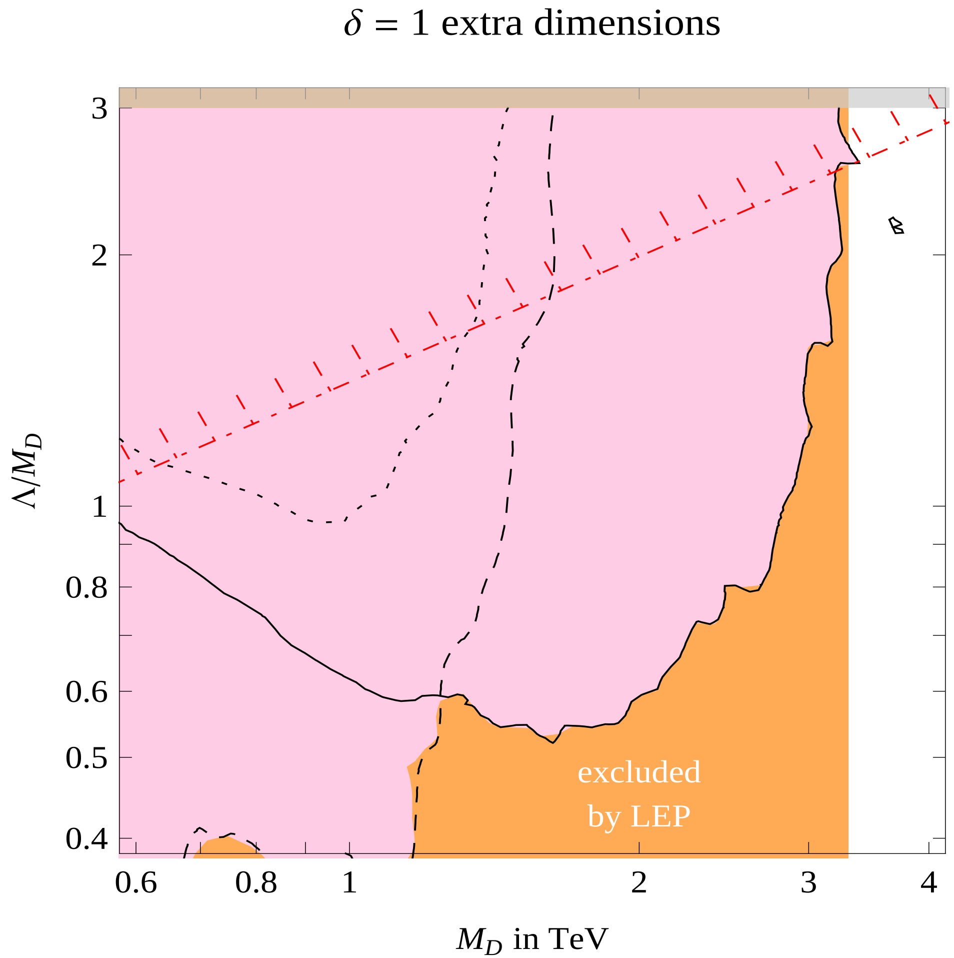


- Shaded: LHC (continuous = CMS; dashed = ALTAS; dotted ATLAS F_χ)
- Blue: gravition emission, ignoring the dependence on Λ
- Red: NDA estimate of graviton loop
- Gray: non-perturbative quantum gravity

Bound on the full amplitude (M_D, Λ)

A bit of warping makes less KK gravitons with larger couplings: $\delta = 1$ is allowed.
But special: gravitons decay promptly in the detector:

- graviton production gives no $\not{E}_T$ signals.
- tree level exchange of *virtual and real* gravitons give $e^+e^- \to \ell^+\ell^-$ and $pp \to jj$.



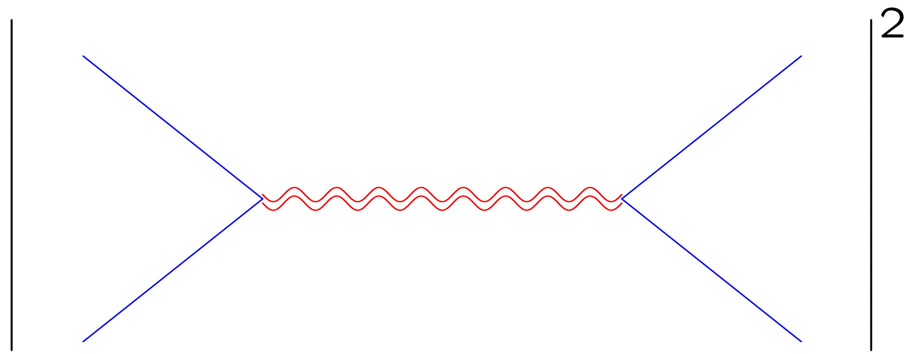
$\delta > 1$: how to subtract real gravitons?

$\Gamma_G = 283 m^3/960\pi M_{\text{Pl}}^2$ is small: gravitons decay far away. But the S-matrix keeps them: $\langle |\mathcal{S}|^2\rangle = (\text{Re}\,\mathcal{S})^2 + (\text{Im}\,\mathcal{S})^2/\epsilon$ with $\epsilon = \pi\Gamma_G/2\Delta m \sim (s/M_D^2)^{1+\delta/2}$.

Resonant graviton production must be subtracted

Consider just one particle with coupling g ($g \sim E/M_{\text{Pl}} \ll 1$ for KK gravitons):

$\sigma =$



One would guess $\sigma \sim g^4$ but actually $\sigma \sim g^2$, due to $pp \to$ graviton.
Next graviton decays with 100% probability and width $\Gamma \sim m g^2$.

We find $\sigma_{\text{subtracted}} \sim -g^4$, up to $\mathcal{O}(g^4)$ terms, such as NLO corrections to Γ.

We presume that $\langle |\mathcal{S}|^2\rangle_{\text{subtracted}} = |\langle \mathcal{S}\rangle|^2$ is the right result

Anyhow, even the unsubtracted $1/g^2$ enhancement (present for $\delta = 1$) is numerically irrelevant for $pp \to jj$.

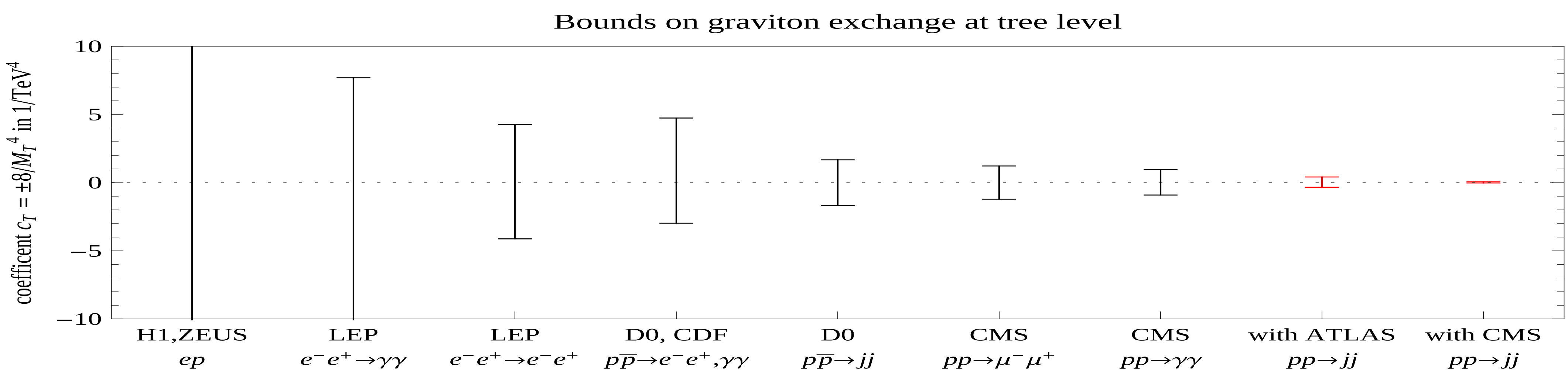
Take-home message

In models with large extra dimensions and quantum gravity at the weak scale, graviton exchange gives a dimension-8 operator: $8T_{\mu\nu}^2/M_T^4$.

- High dimensionality: energy is the key factor and early LHC is already more sensitive than all previous colliders.

- Initial low statistics: the dirty channel $pp \to$ jet jet (but with a 1000 $\times$ larger cross section) is more sensitive that the golden channels $pp \to \gamma\gamma, \ell^-\ell^+$.

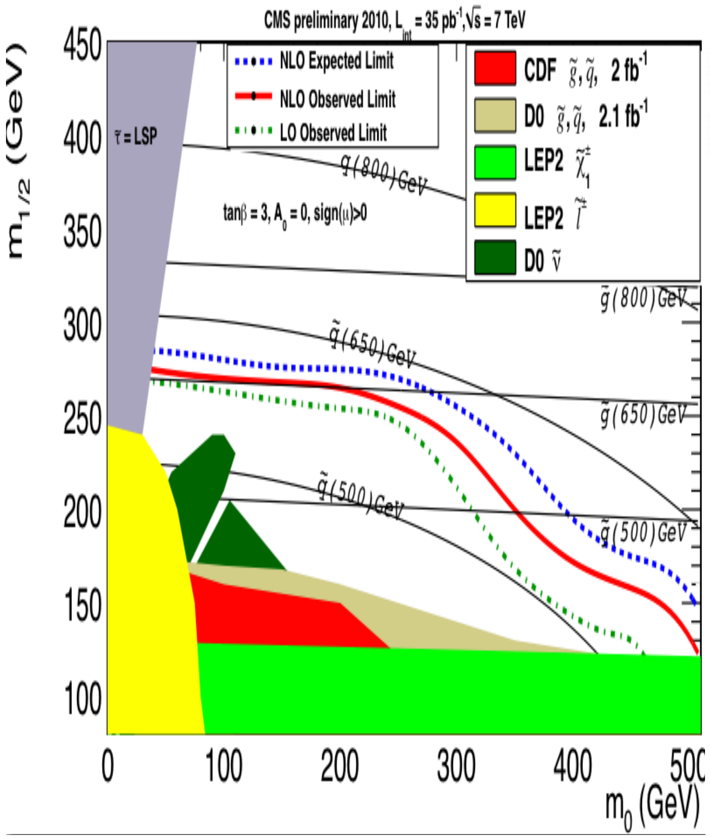
We derived the new dominant bound $M_T > 3.4$ TeV from first LHC data:

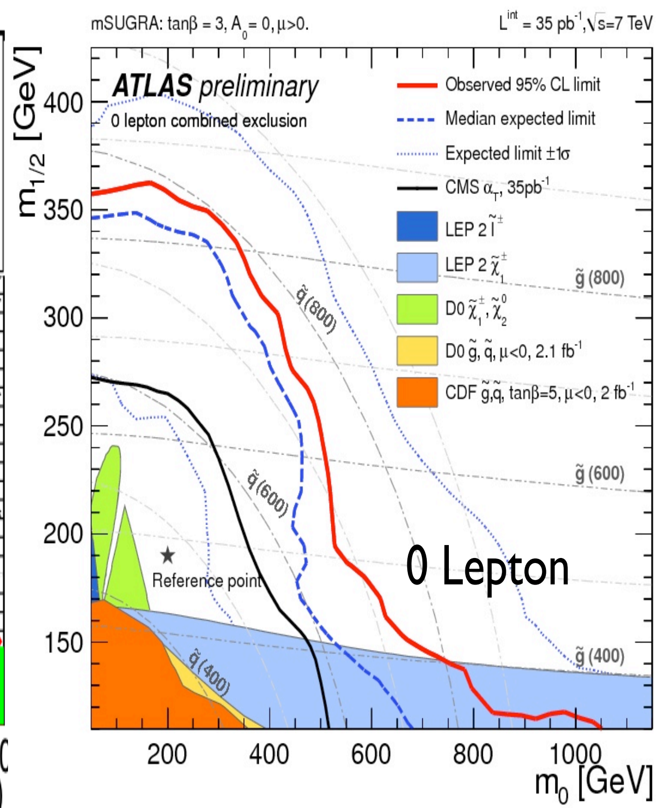


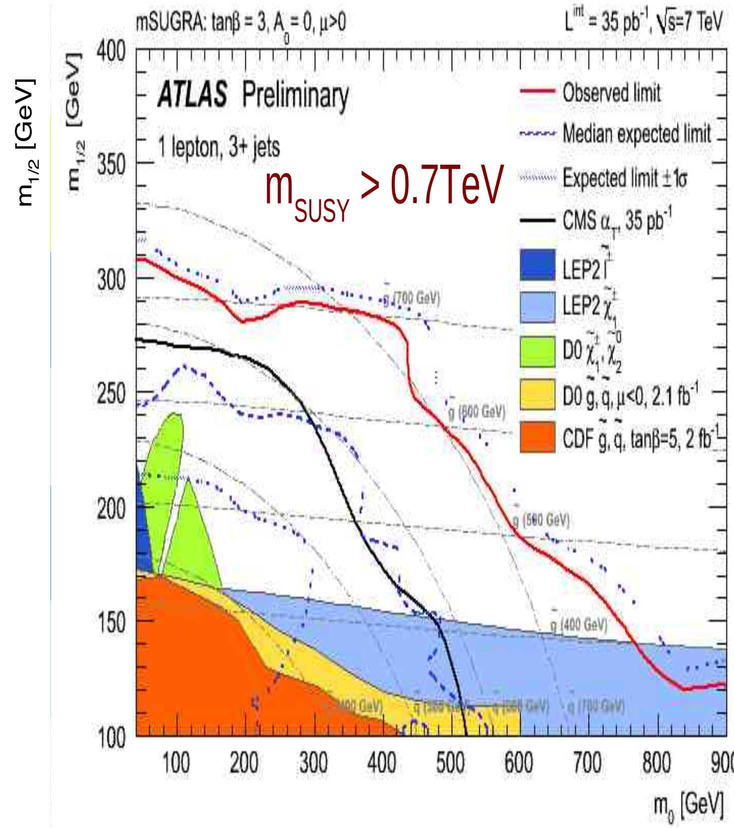
SUSY

First LHC data: CMSSM

CMS, $j \not\!\!E_T$ | ATLAS, $j \not\!\!E_T$ | ATLAS, $j\ell \not\!\!E_T$

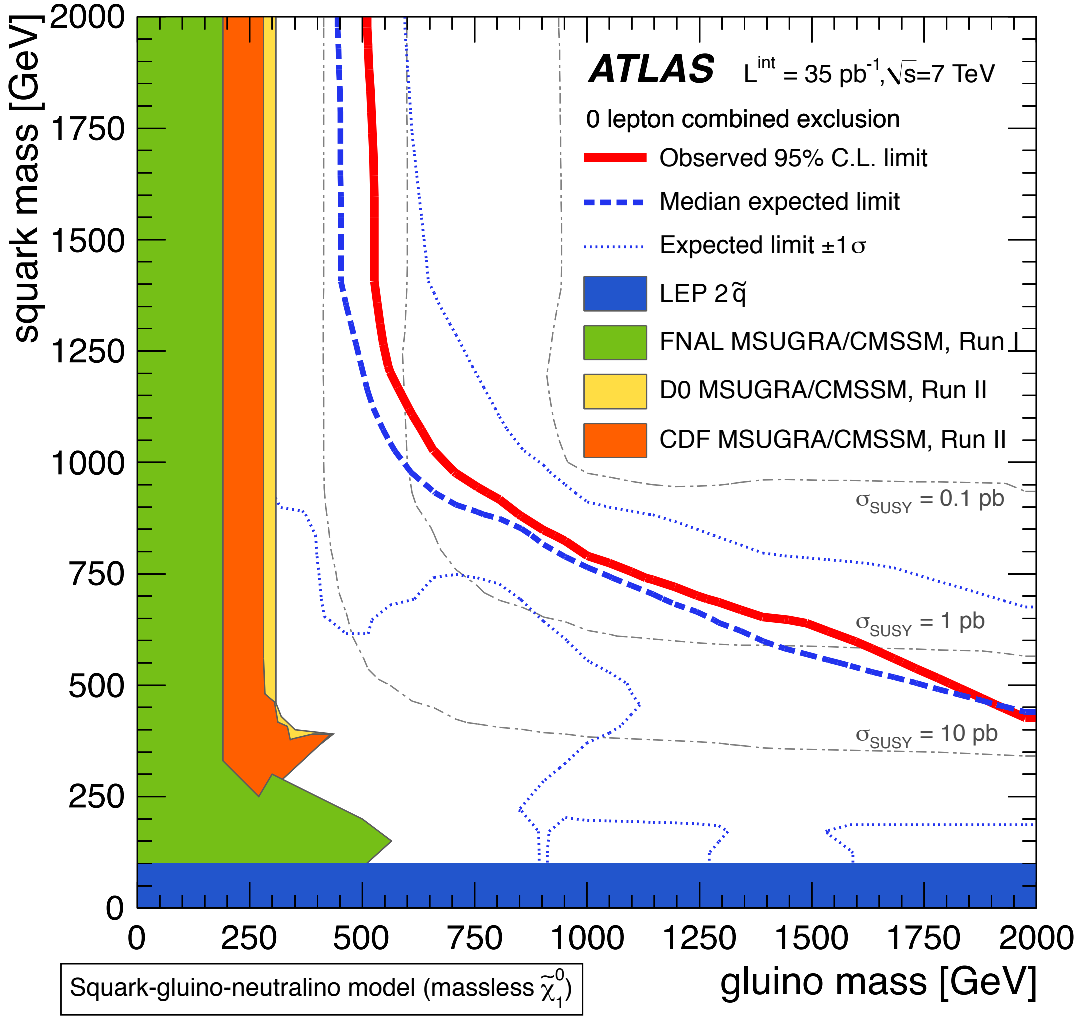






First LHC data

Are actually a bound on $m_{\tilde{q}}$ and M_3, up to 800 GeV



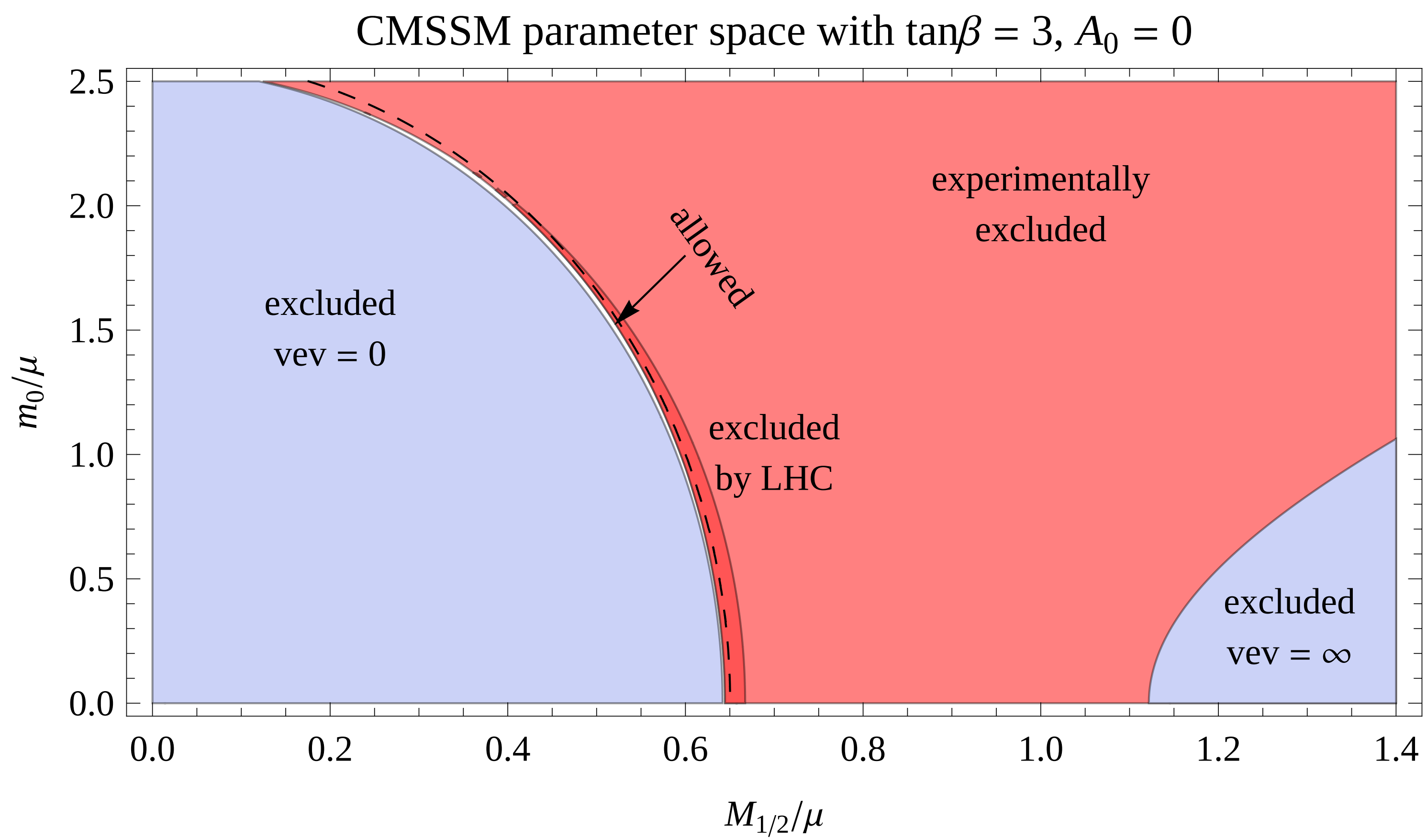
In the following we ignore $g_\mu - 2$ or $\Omega_{\rm DM}$; they point to heavier $m_{\rm SUSY}$.

The little hierarchy problem

Fix $\tan\beta = 3$ and $A_0 = 0$; the overall SUSY mass scale is fixed by

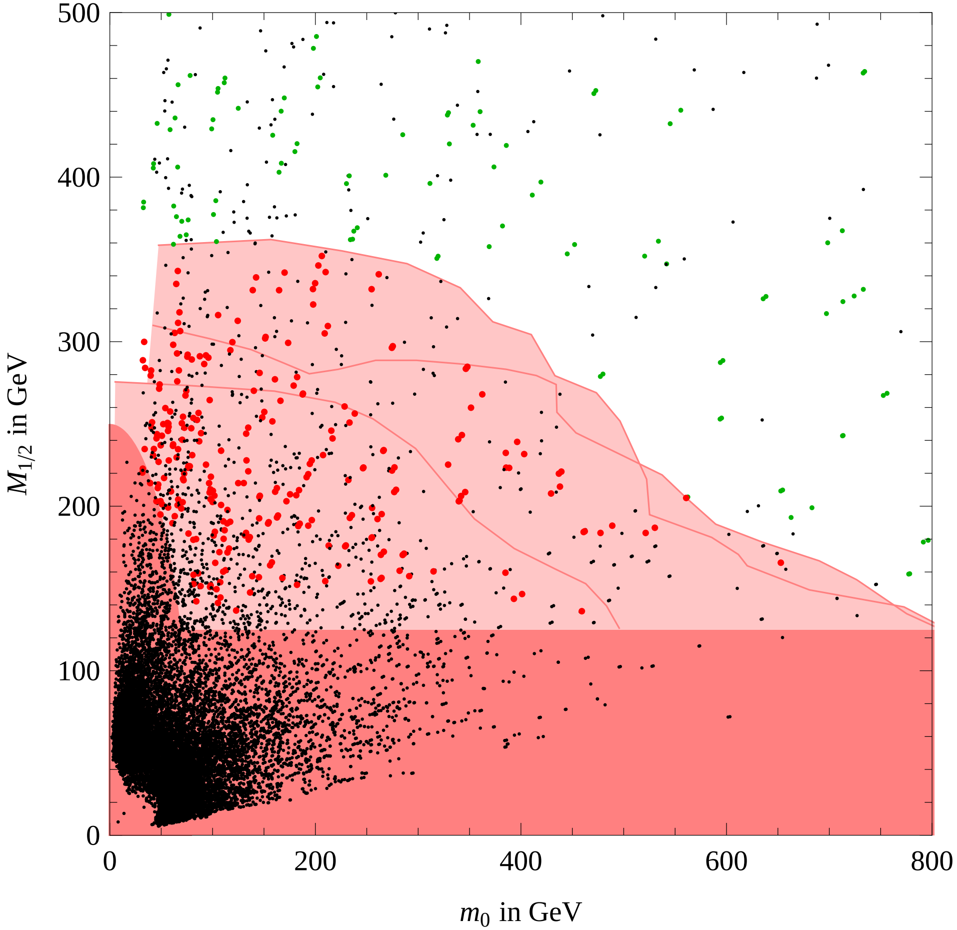
$$M_Z^2 \approx 0.2 m_0^2 + 0.7 M_3^2 - 2\mu^2 = (91\,\text{GeV})^2 \times 50\left(\frac{M_3}{780\,\text{GeV}}\right)^2 + \cdots$$

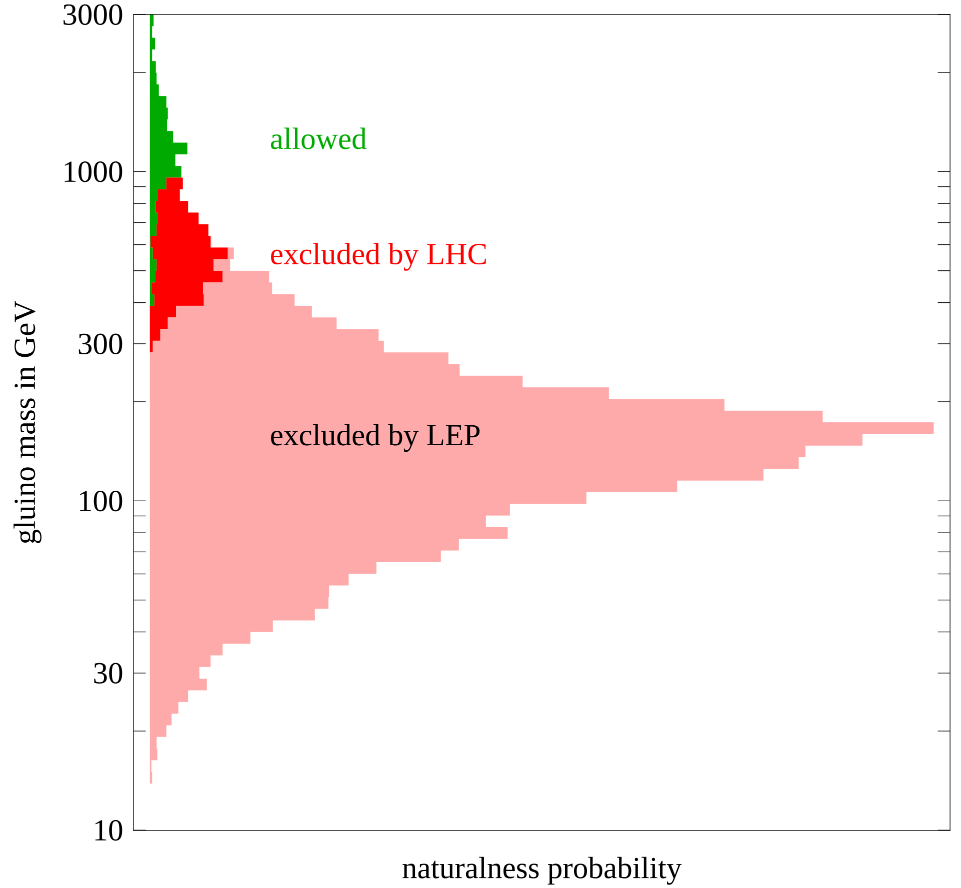
Plot this in the plane of the adimensional free parameters $(M_{1/2}, m_0)/\mu$:



Bayesian MonteCarlo technique

Scan over all adimensional parameters (m_0/μ, B_0/m_0,..., λ_t) compatible with measured m_t. Compute $\tan\beta$ and $m_{\rm SUSY}$ from $V_{\rm MSSM}$. Normally $m_{\rm SUSY} \sim M_Z$; rare accidents can make it bigger. All possible fine-tunings are included without using any explicit FT parameter Δ. E.g. focus point is fine-tuning of λ_t.



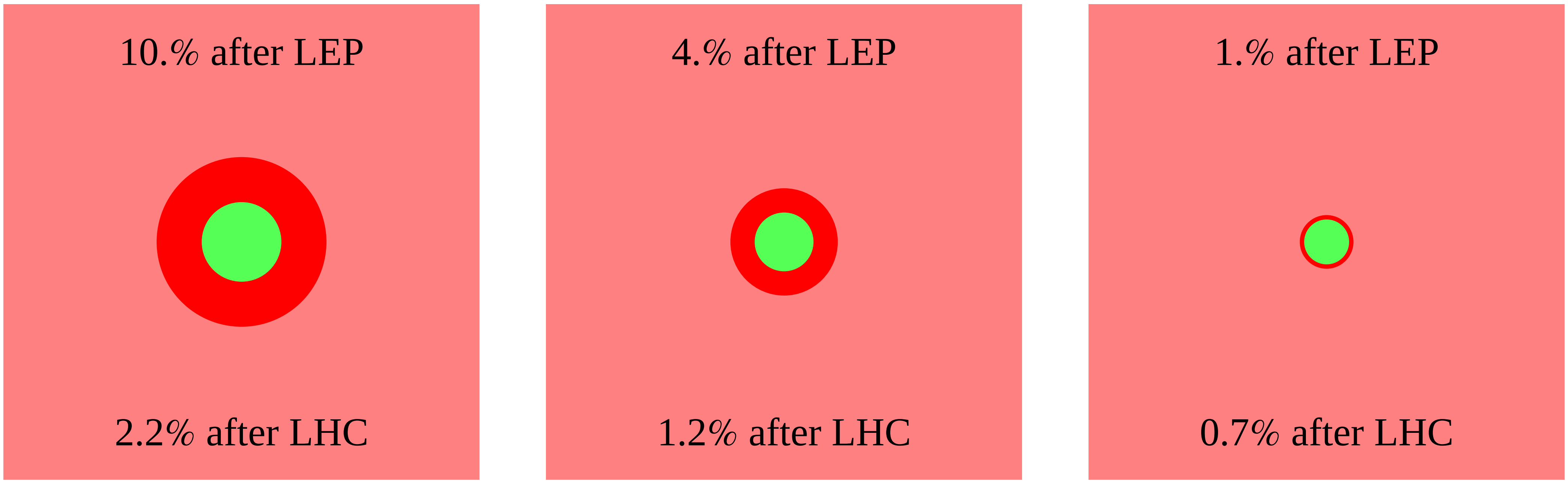


Black dot = excluded spectrum. Red = excluded by LHC. Green = allowed

Fraction of alive CMSSM $\approx 1/\Delta$

Fraction of surviving CMSSM parameter space

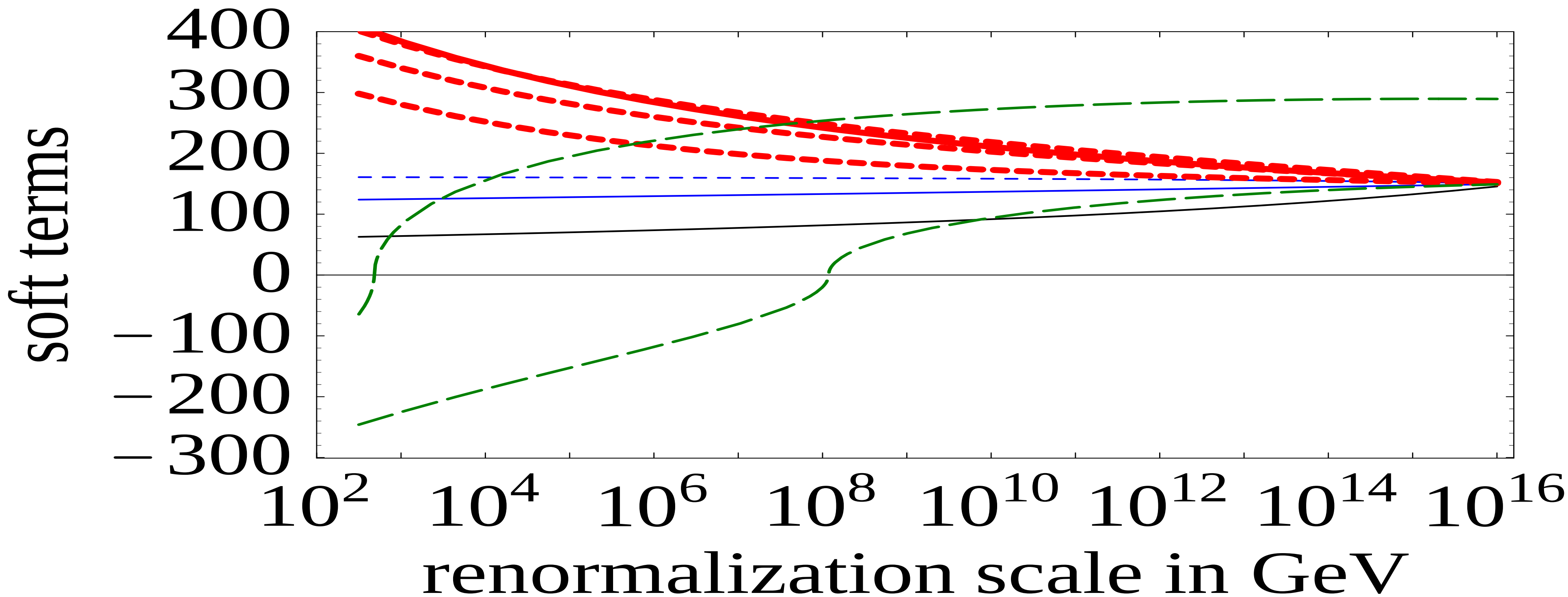
any m_h | $m_h > 100$ GeV | $m_h > 110$ GeV



(The CMSSM prediction for m_h can be circumvented;
the theoretical uncertainty in m_h is about 3 GeV)

$M_Z \ll m_{\text{SUSY}} \Rightarrow$ late SU(2) breaking

The scale Q_0 at which RGE running makes $m_h^2(Q) < 0$ must be close to m_{SUSY}



SUSY little Higgs as pseudo-Goldstone of some symmetry broken at Q_0?

The sliding m_{SUSY} model

Assume that m_{SUSY} is a free parameter determined by minimizing V_{MSSM} (!)

$$\min V_{\text{MSSM}} \sim \begin{cases} 0 & m_{\text{SUSY}} > Q_0 \\ -m_{\text{SUSY}}^4 & m_{\text{SUSY}} < Q_0 \end{cases}$$

Prediction [hep-ph/0005203, BS]: $m_{\text{SUSY}} \lesssim Q_0$ and a loop factor above M_Z:

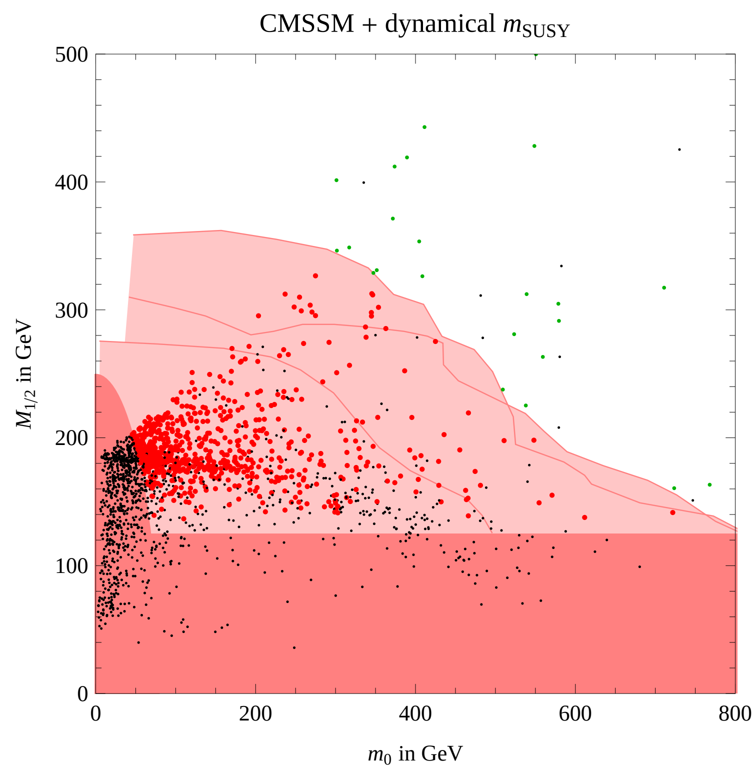
$$\frac{d\mu_{\text{u}}^2}{d\ln\mu}\sin^2\beta + \frac{d\mu_{\text{d}}^2}{d\ln\mu}\cos^2\beta - 2\frac{d\mu_{\text{ud}}^2}{d\ln\mu}\sin\beta\cos\beta = M_Z^2\cos^2 2\beta \overset{\text{one loop}}{\rightarrow} m_h^2$$

RGE loop factors are big: roughly this means

$$m_{\tilde{t}} \approx 4\pi M_Z/\sqrt{12} \approx 400\,\text{GeV}$$

Predicted: dashed line in the CMSSM plot.
Allowed: from 50% to 2% with LHC.

PS: BS hypothesis may be BS: $V \neq V_{\text{MSSM}}$.
Alternative interpretation in terms of anthropic pressure ($Q_0 \ll m_{\text{SUSY}}$): more rare than SM?



What does it mean?

We have significant hints for SUSY.
We have significant hints against SUSY.
At some point somebody will understand what is the logic.

Conclusions

"Now this is not the end.
It is not even the beginning of the end.
But it is, perhaps, the end of the beginning".