SUSY and Dark Matter at the Muon Collider

Patrick Fox

Fermilab

Supersymmetry

the model to which all other
models should be compared

- Most general spacetime symmetry allowed by nature
- Ubiquitous in string theory
- Solves the hierarchy problem, grand unification
- (more than) Doubles the particle content of SM - lots of things to measure

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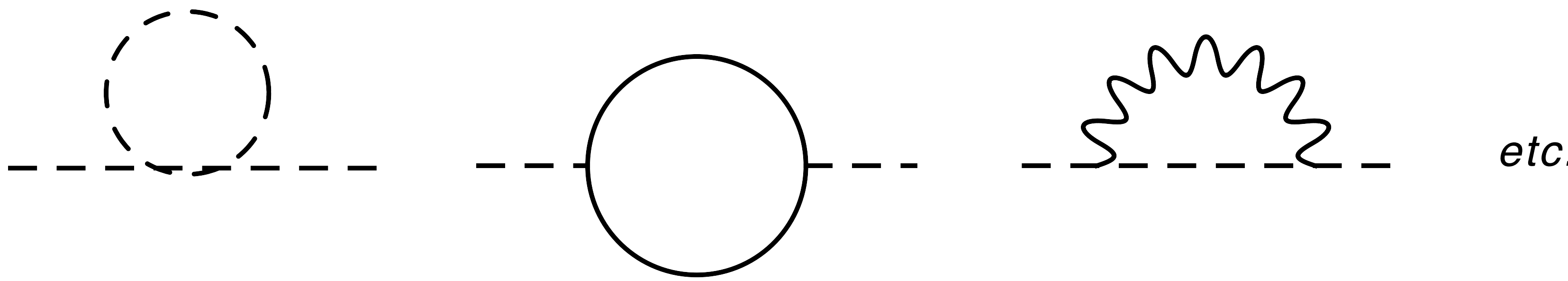
(Weak scale) Supersymmetry

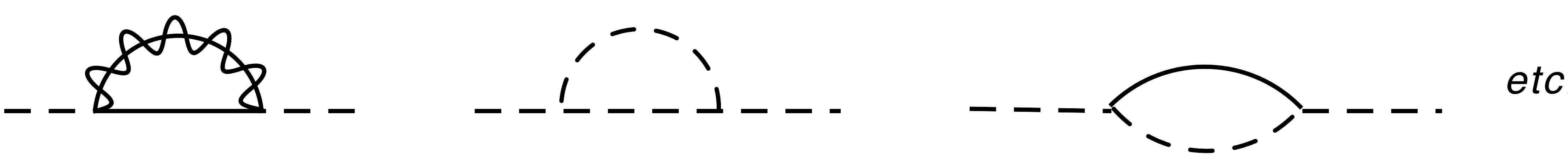
Pre-LEP:



$$\Delta m_\phi^2 \sim \frac{\lambda^2}{16\pi^2}\Lambda^2$$

Fundamental scalars not good news for QFT

Naturalness implies new physics at the weak scale



Superpartners

(Weak scale) Supersymmetry

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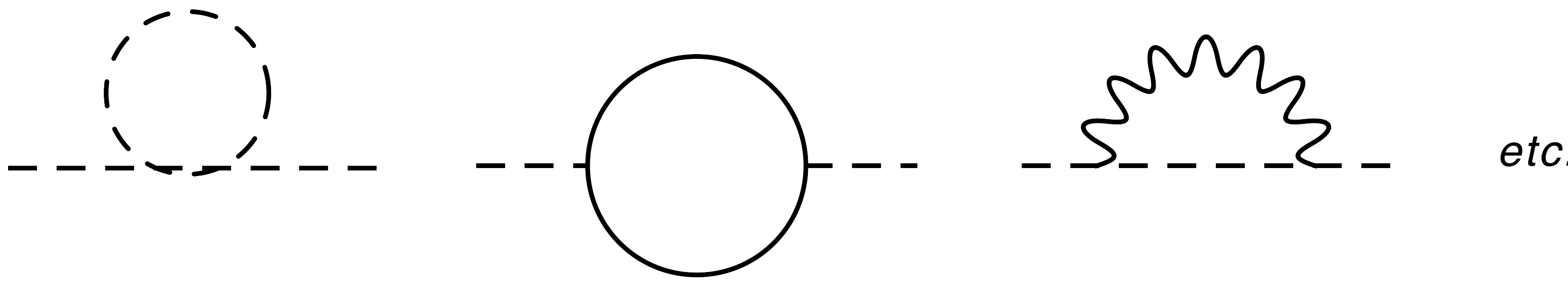

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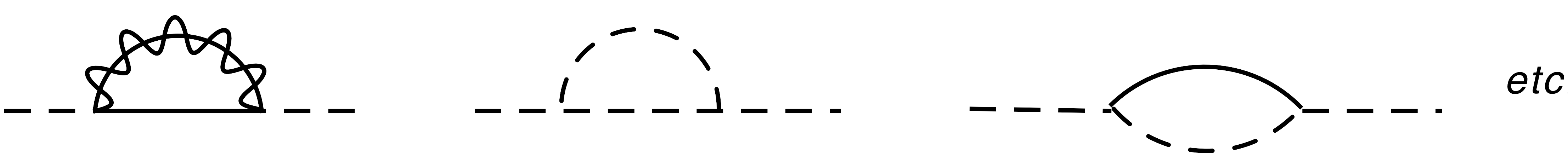
see also Adam Martin, Yang Bai, George Fleming



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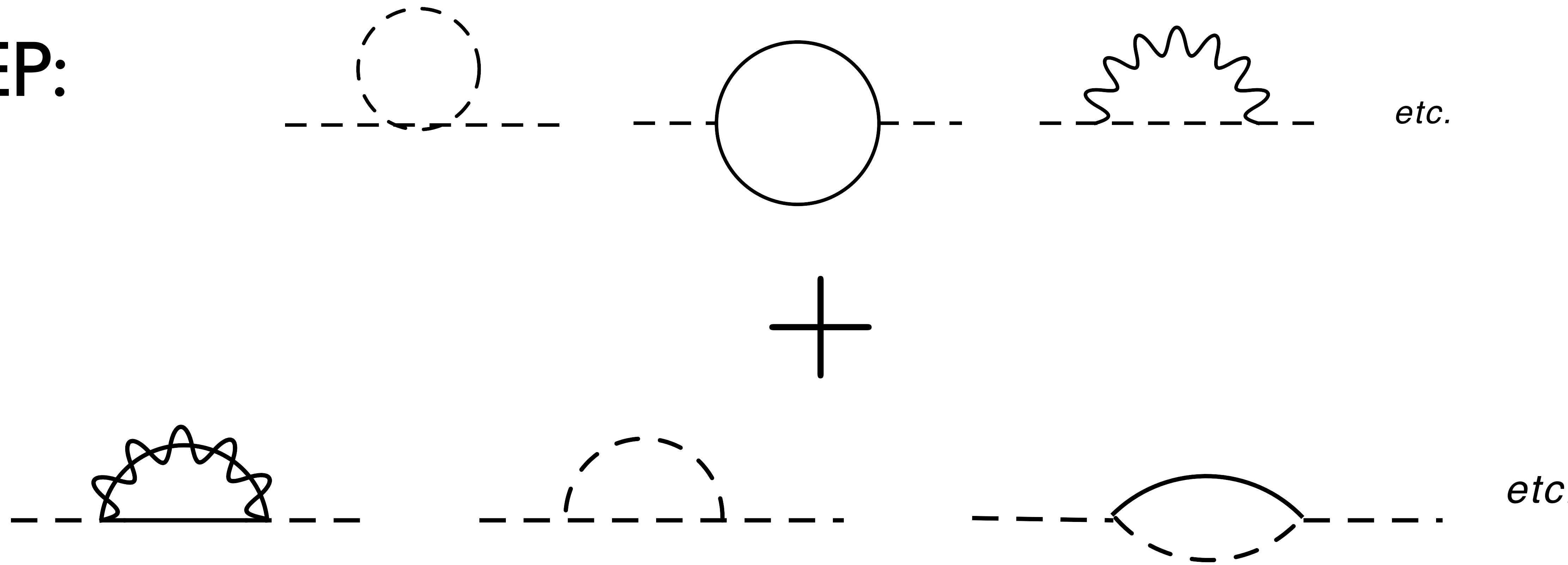


$$\frac{\lambda^2}{16\pi^2}\Lambda^2 \rightarrow \frac{y^2}{16\pi^2} m_{\tilde{t}}^2 \log \frac{\Lambda}{m_{\tilde{t}}}$$

$$m_h^2 \leq m_z^2 \cos^2 2\beta$$

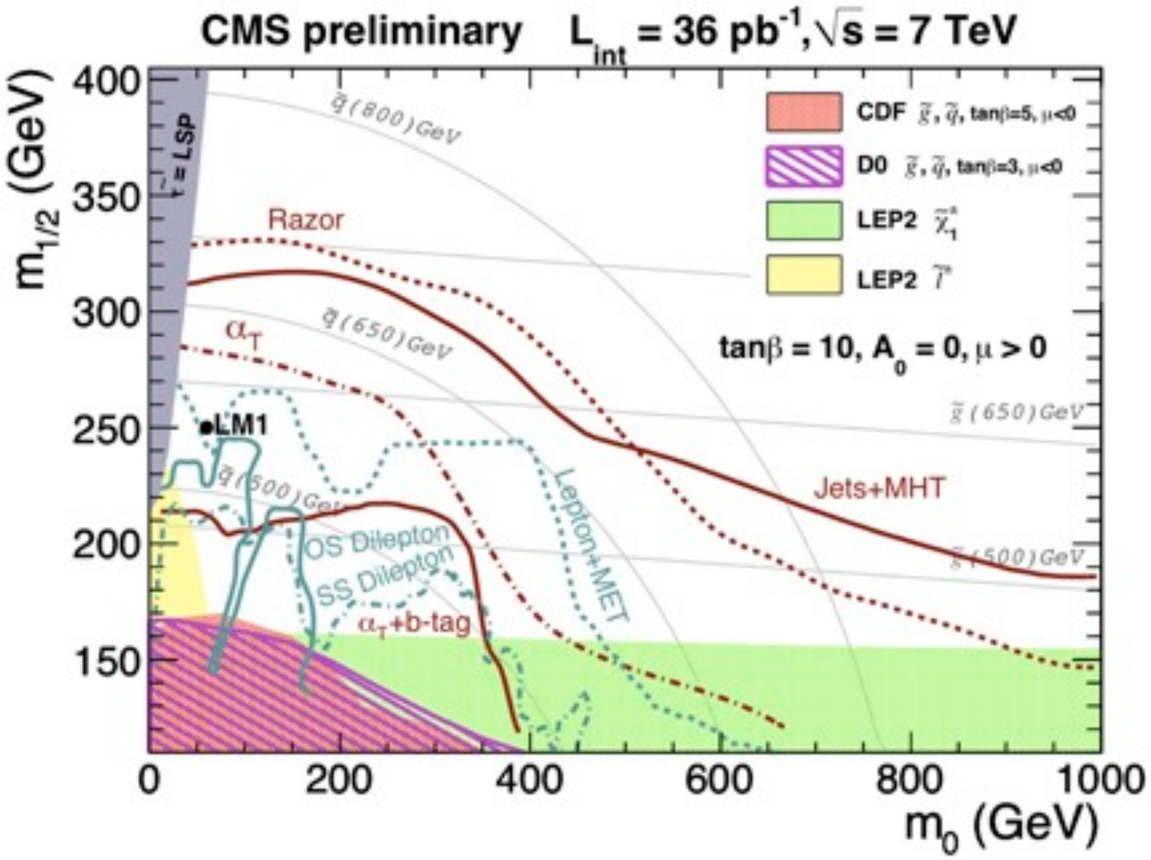
(Weak scale) Supersymmetry

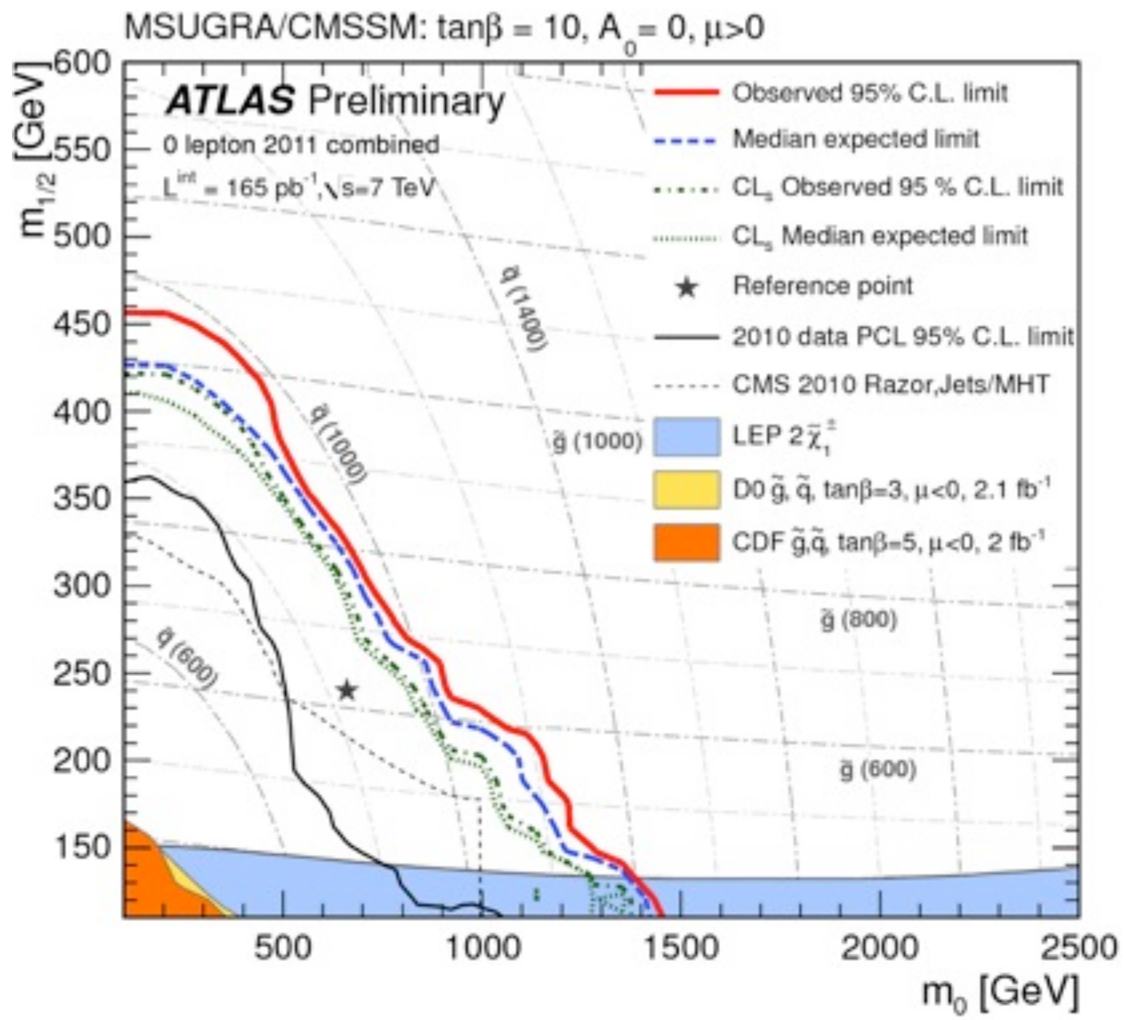
Post-LEP: $$m_h \gtrsim 115 \text{ GeV}$$

1% fine tuning, superpartners ~1 TeV

Less minimal variants of SUSY (NMSSM etc)

LHC:





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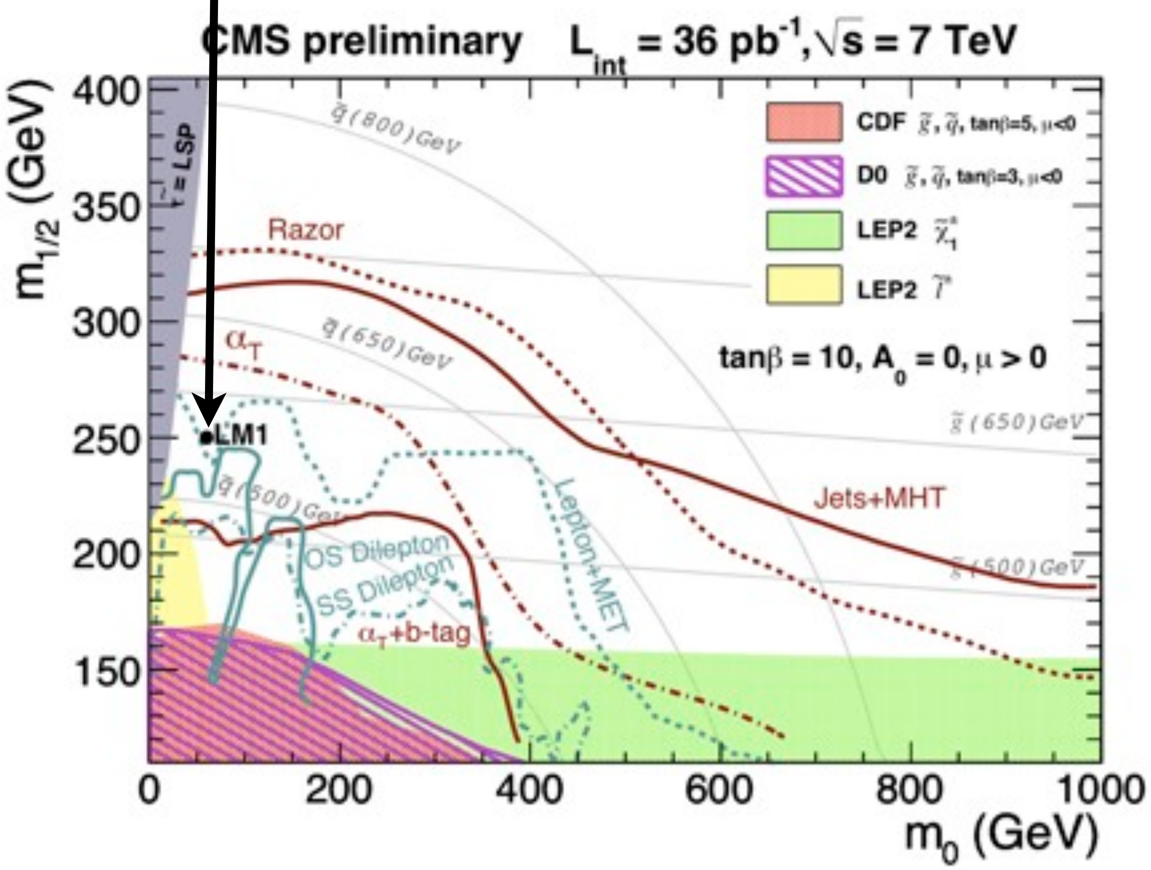

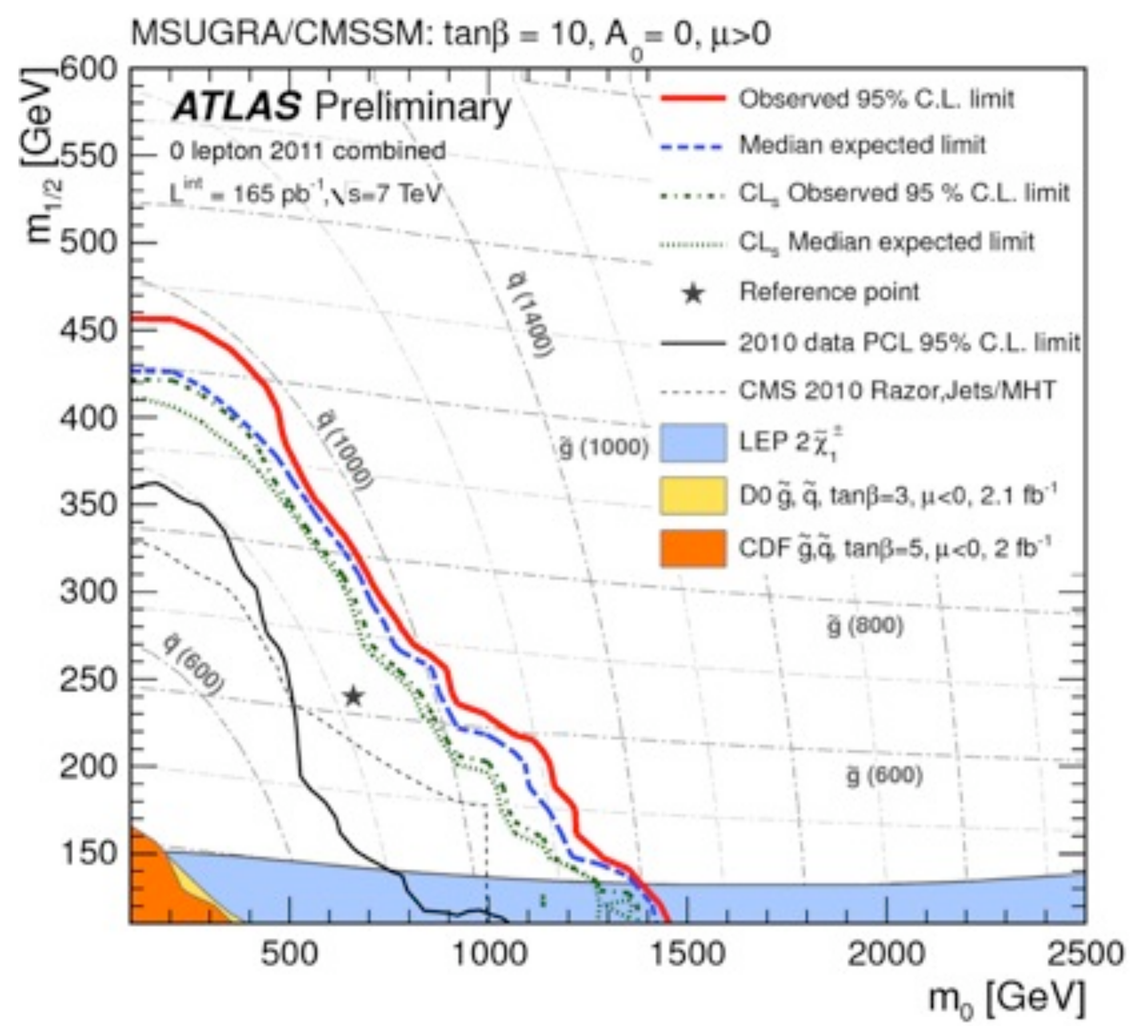

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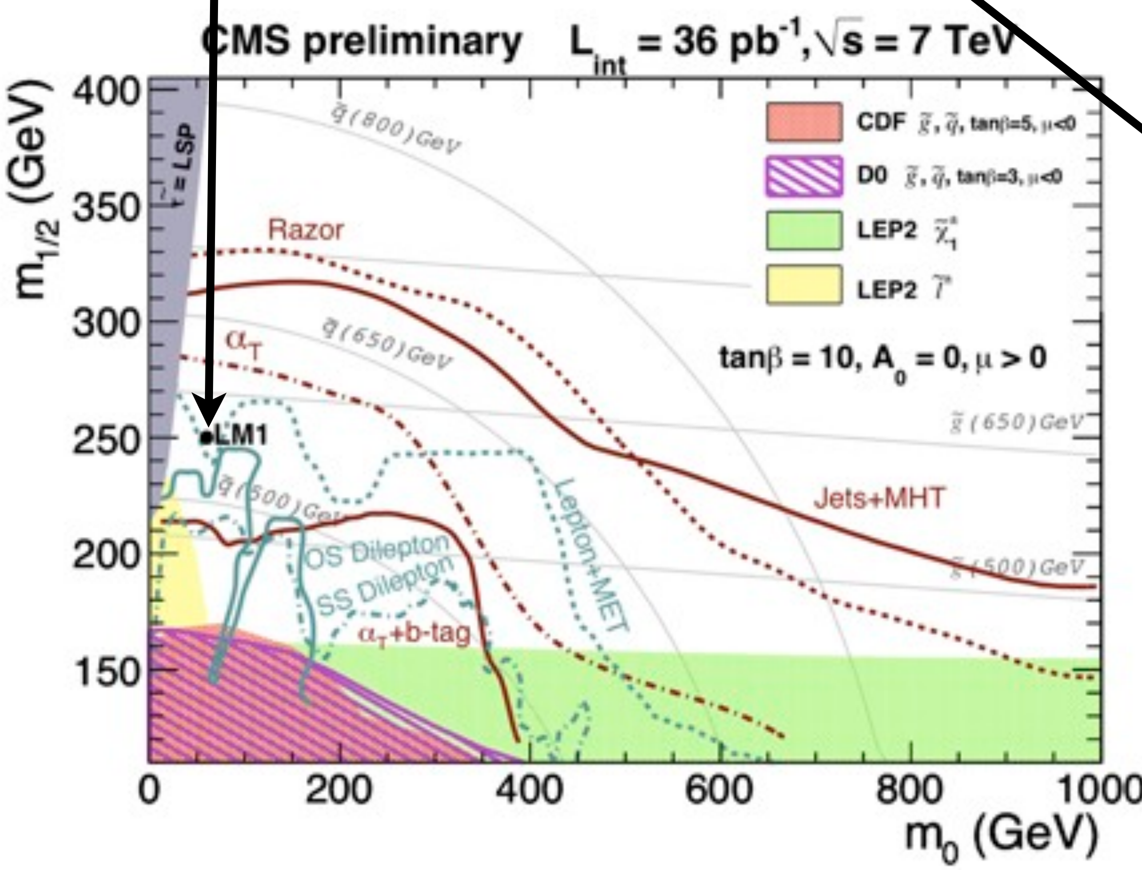
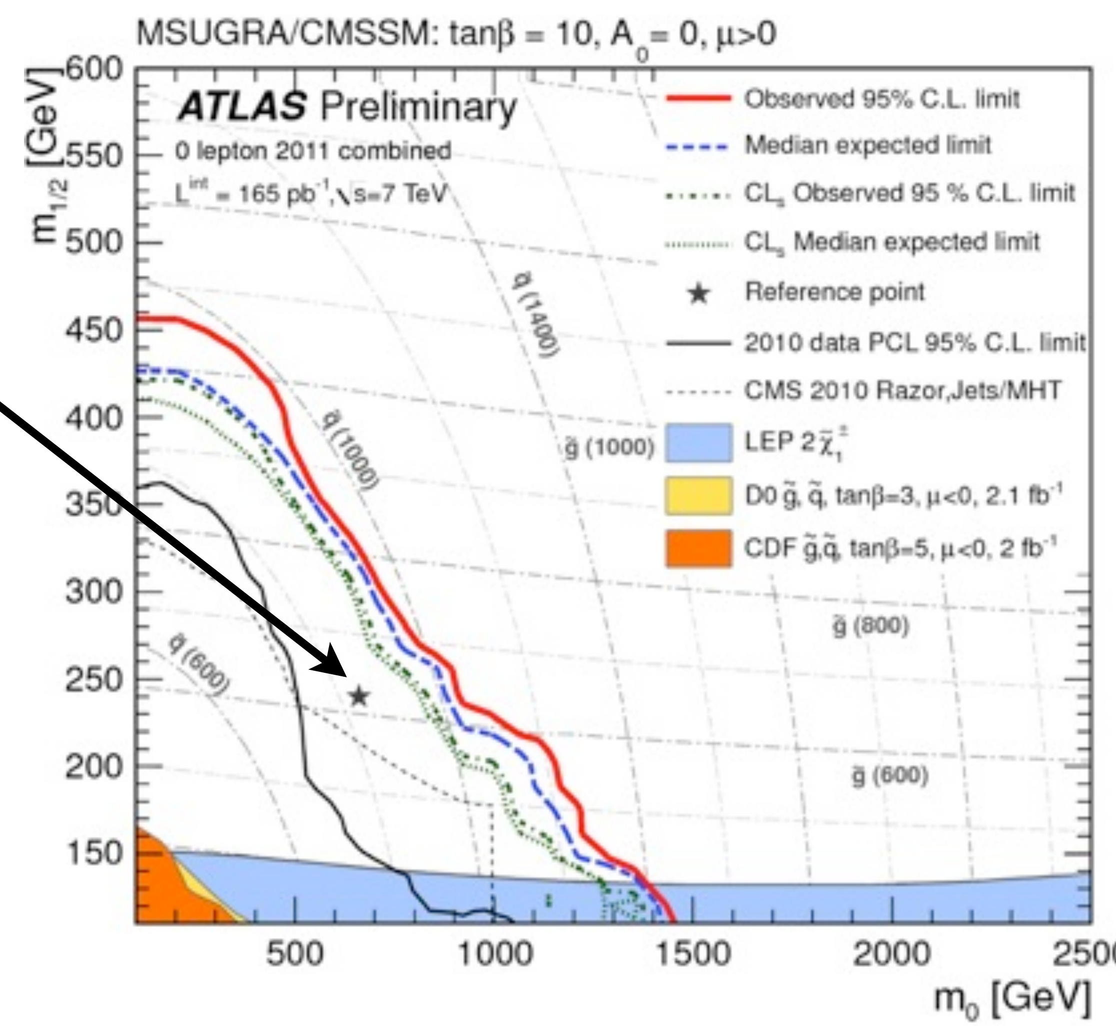
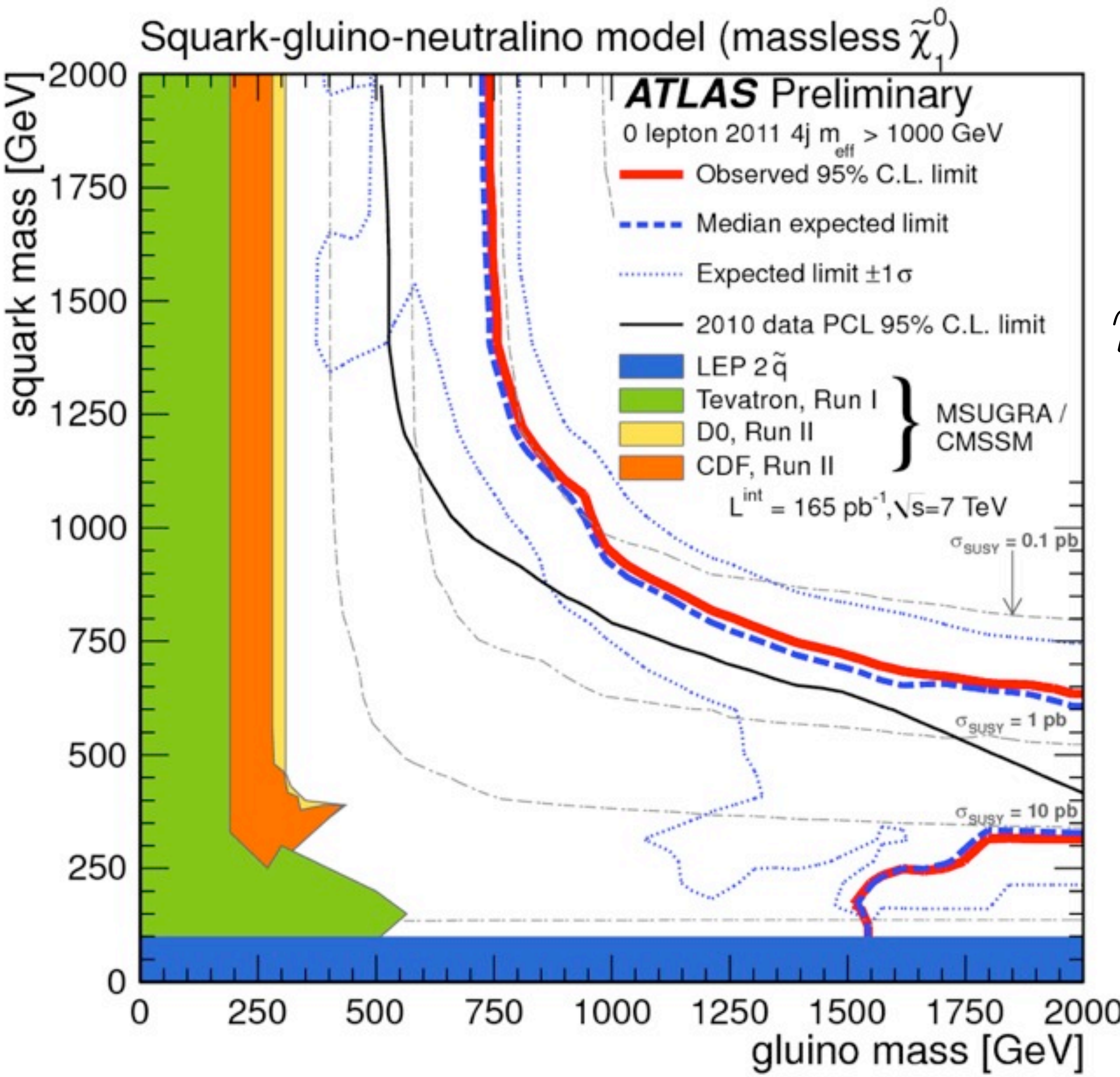




SUSY at LHC?



$$m_{\tilde{q}} \gtrsim 600 \text{ GeV}$$

$$m_{\tilde{g}} \gtrsim 750 \text{ GeV}$$

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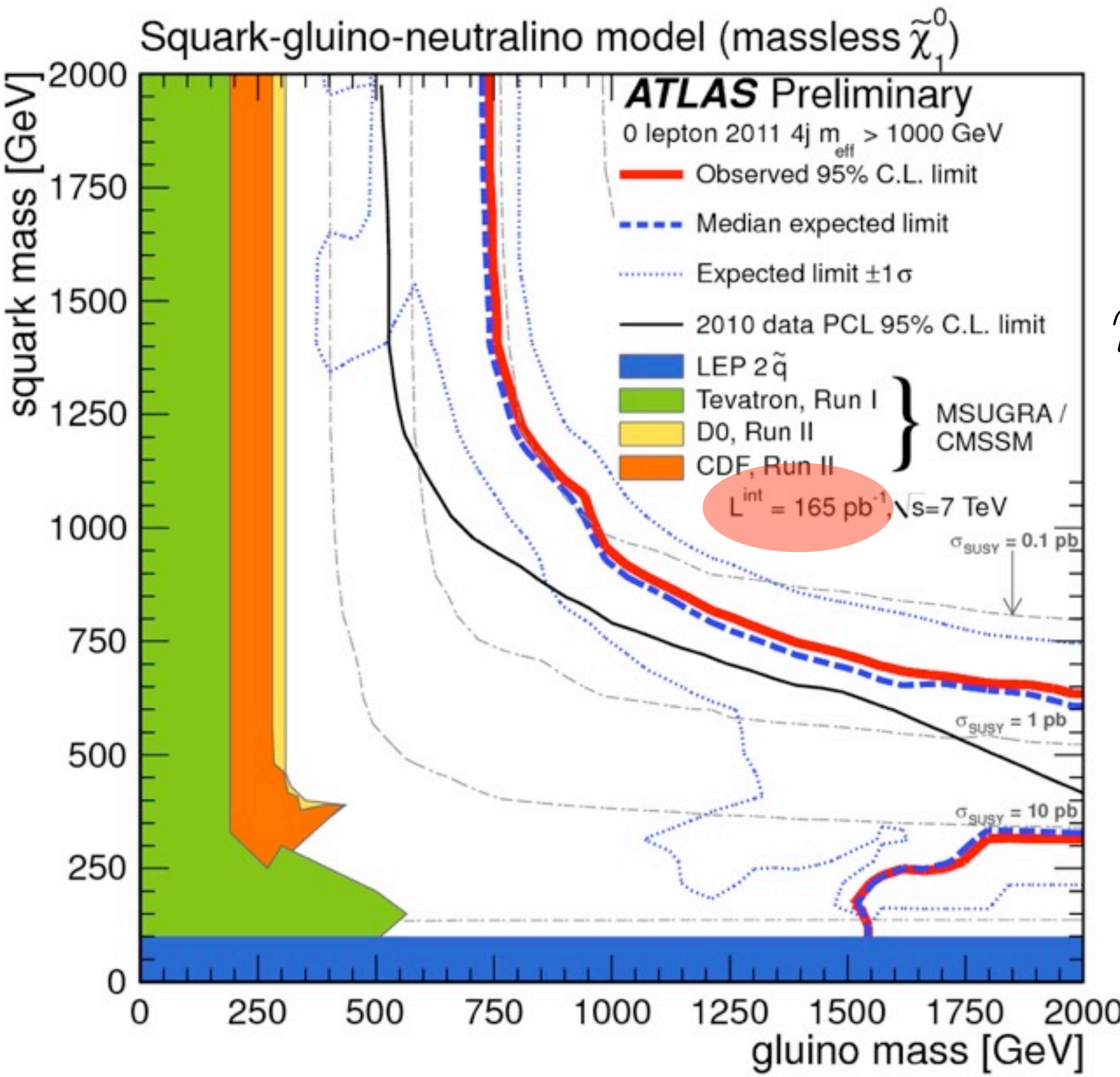

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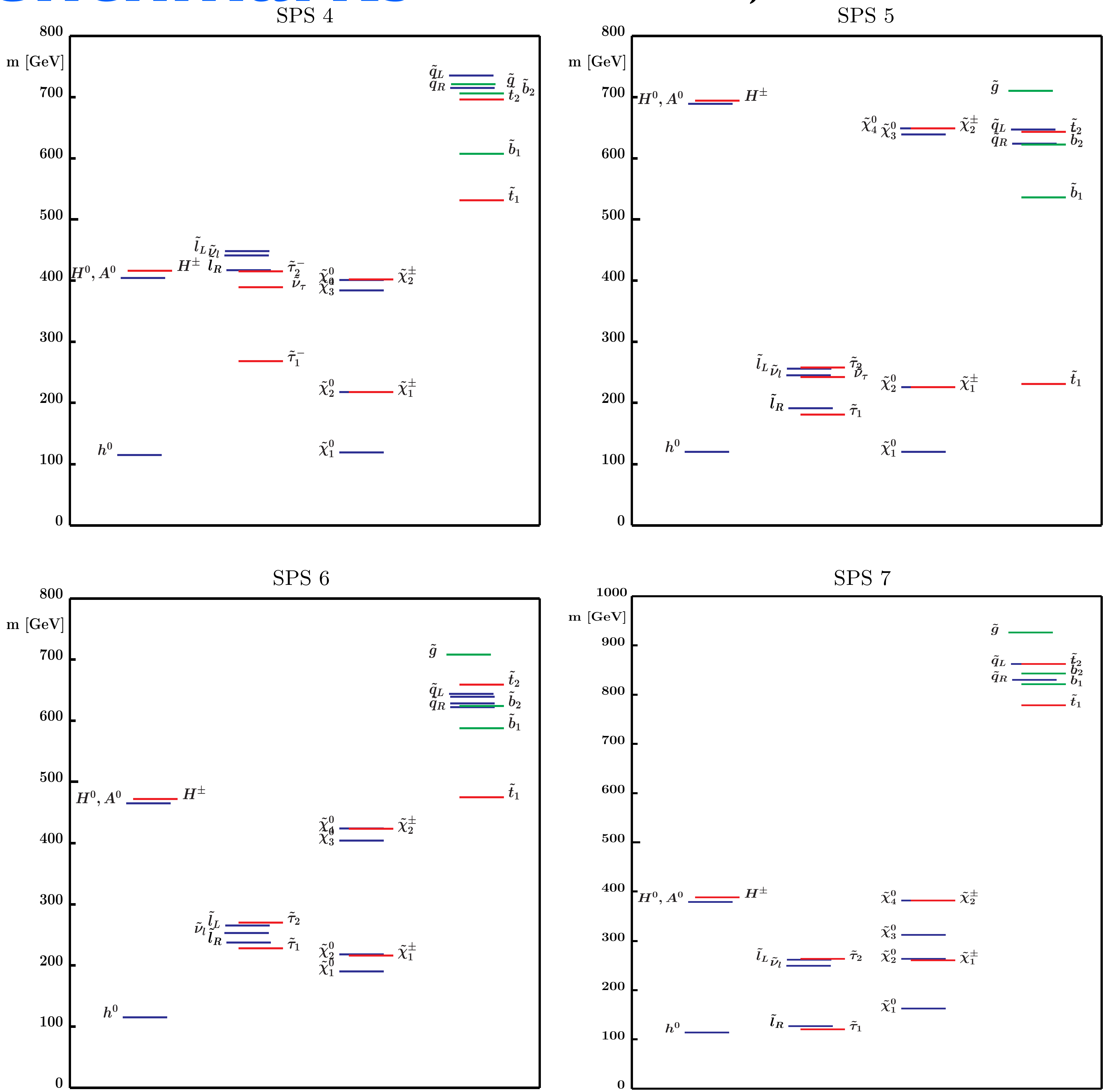
Benchmarks Snowmass, 2001



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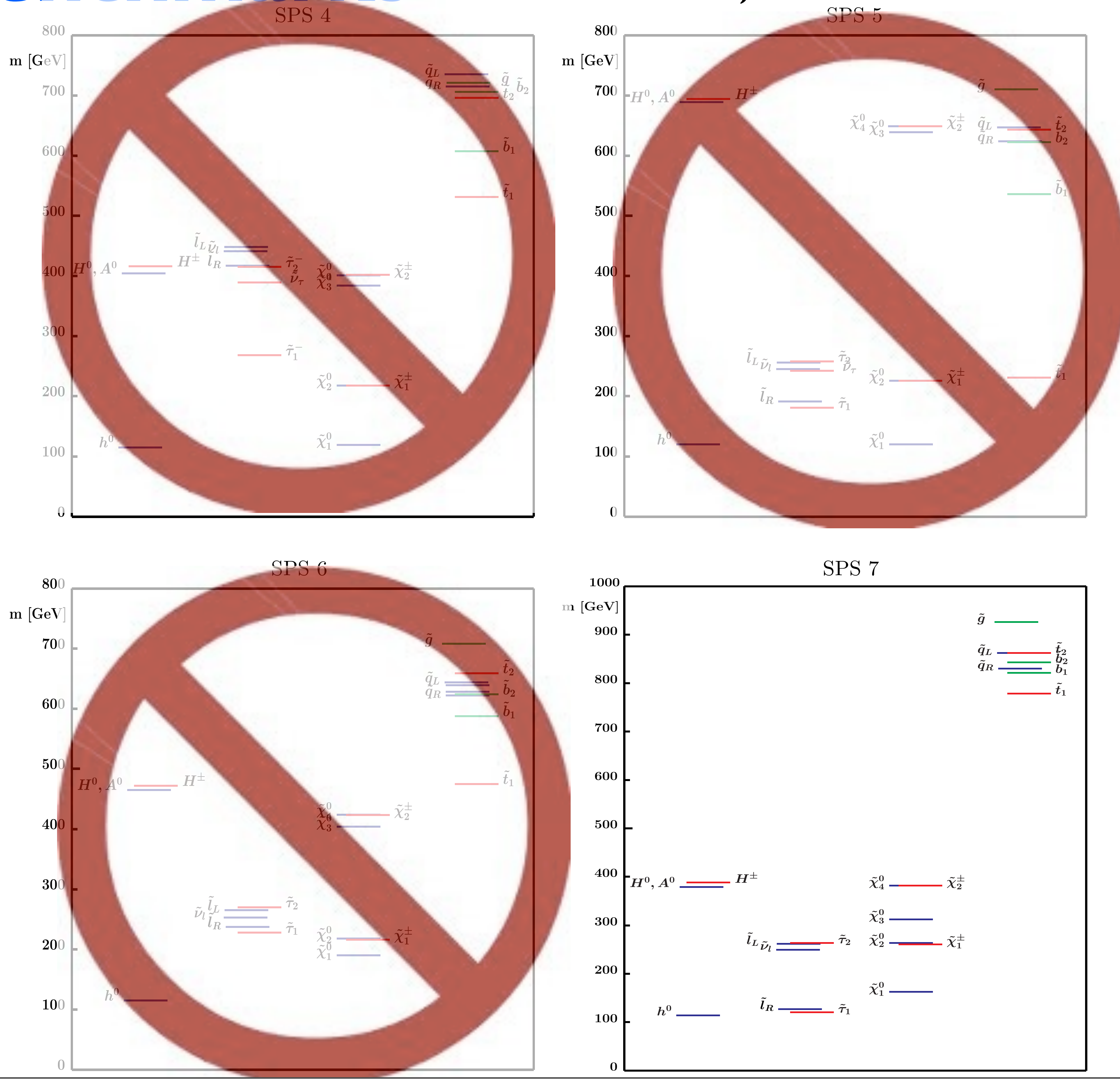


Joe Lykken, Muon Collider workshop 2009:

Short version of this talk

Question: Is it possible to identify the physics targets of the post-LHC energy frontier collider before we have any LHC results?

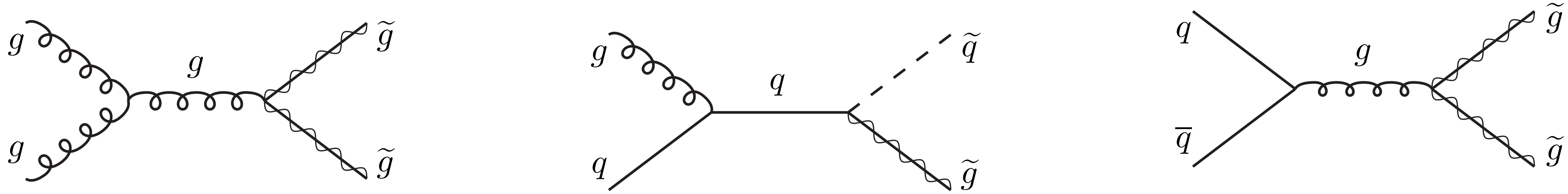
Answer: No

LHC -MC synergy

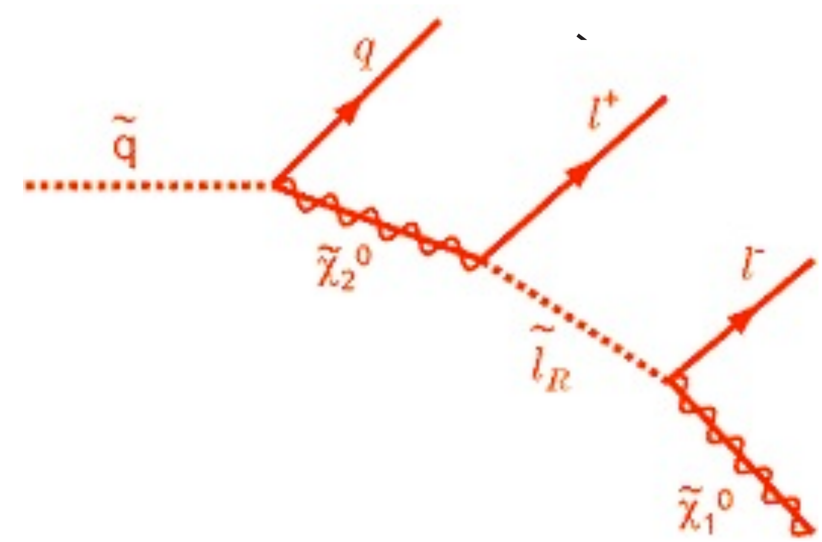
LHC will provide (part) of the benchmarks for us

(Or tell us to look elsewhere)

LHC produces squarks and gluinos



Observes cascade decays, MET

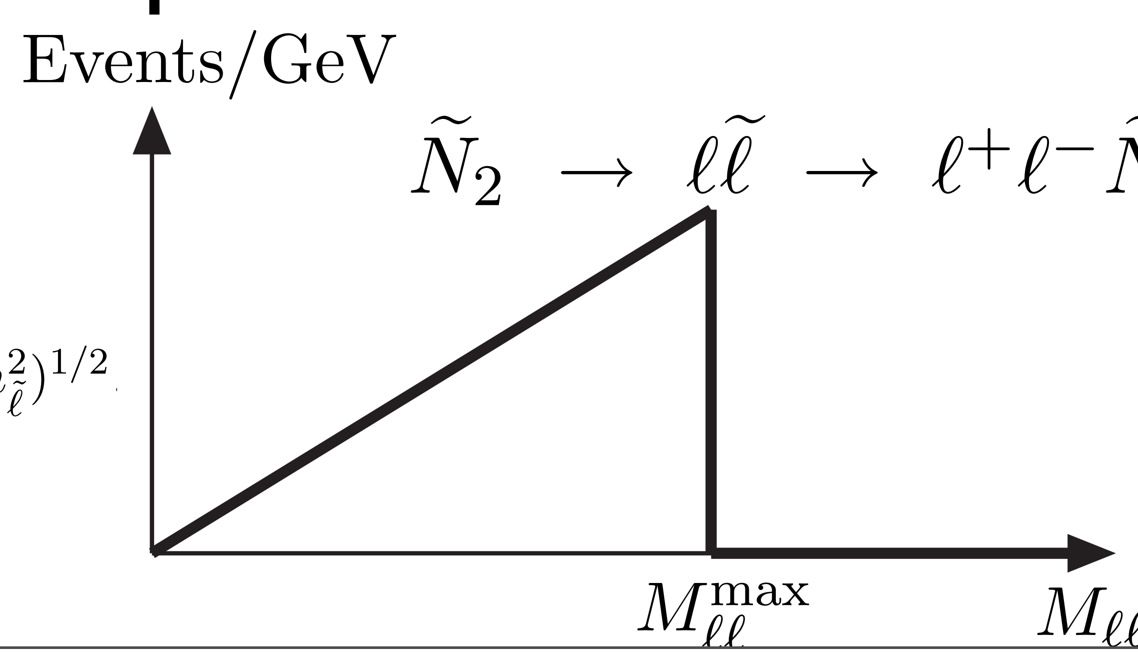


Measures edges and endpoints

- mass differences

$$\widetilde{N}_2 \rightarrow \ell\widetilde{\ell} \rightarrow \ell^+\ell^-\widetilde{N}_1.$$

$$M_{\ell\ell}^{\max} = m_{\tilde{N}_2}(1 - m_{\tilde{\ell}}^2/m_{\tilde{N}_2}^2)^{1/2}(1 - m_{\tilde{N}_1}^2/m_{\tilde{\ell}}^2)^{1/2}.$$



[hep-ph/9709356]

LHC -MC synergy

Electroweak production of -inos and sleptons harder

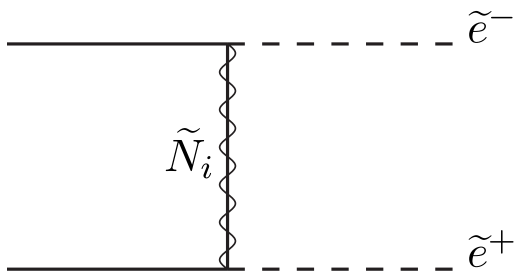
Overall mass scales, but accurate masses difficult

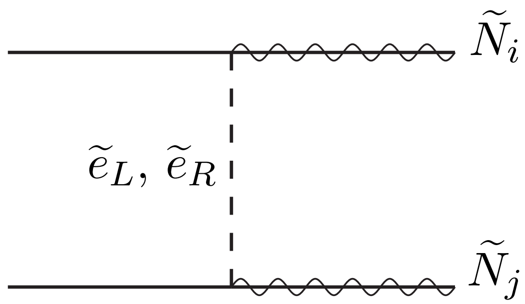
Couplings?

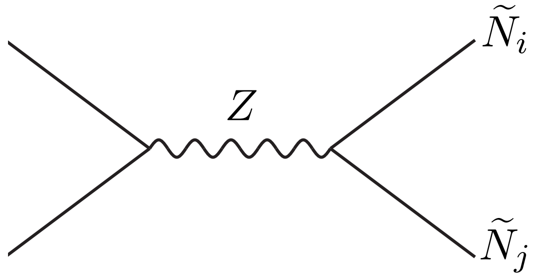
Determining LSP mass is difficult

Spin: SUSY vs UED

LHC -MC synergy







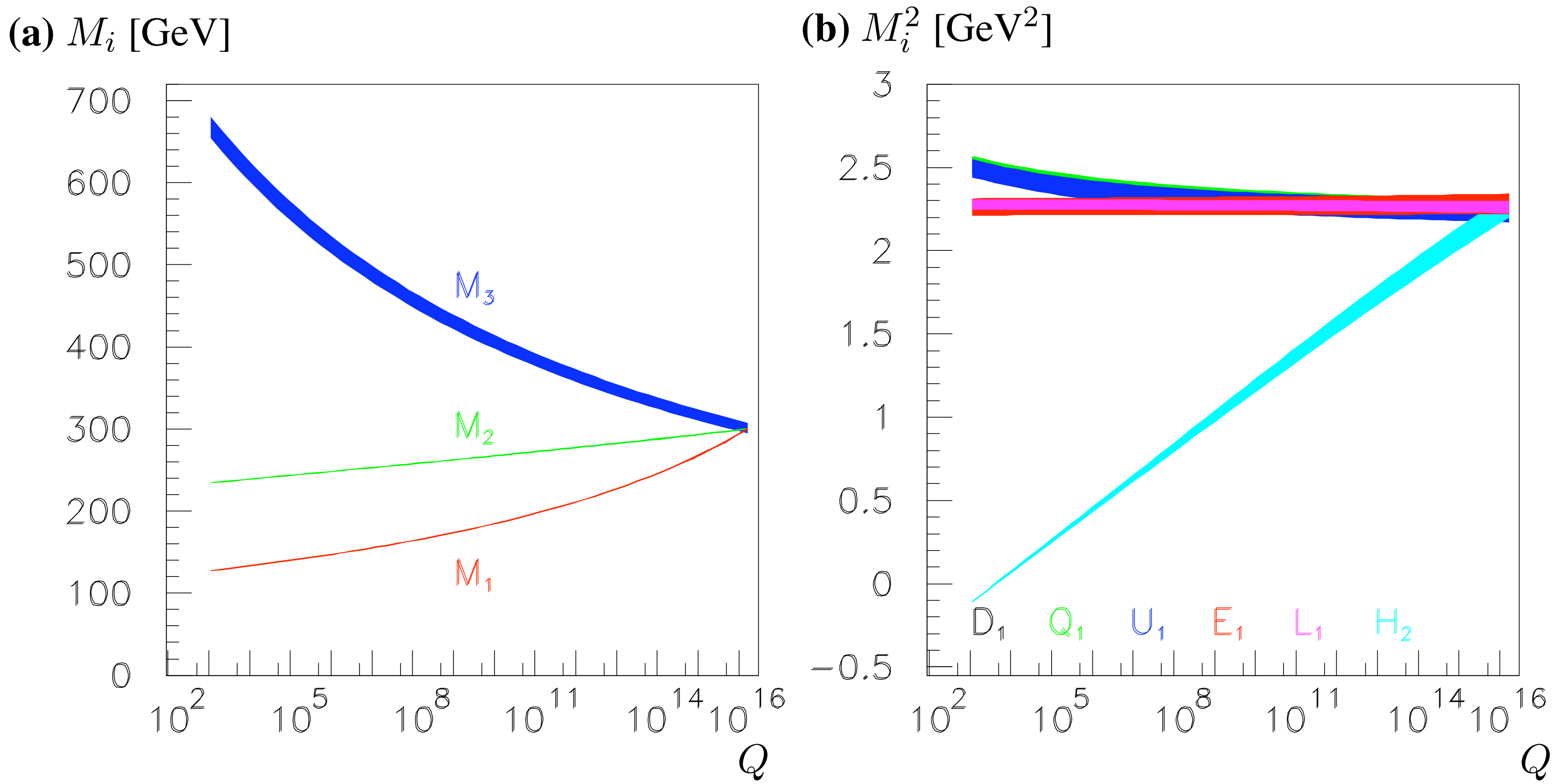
"Typically" lighter than coloured states, but .....

Measuring couplings and mixing parameters requires some amount of polarization

Tests models of SUSY breaking, high scale predictions

LHC -MC synergy

Unified gaugino masses: $M_1 : M_2 : M_3 \approx 1 : 2 : 7$



[hep-ph/0412251]

Fig. 5.14: Running of (a) gaugino mass parameters and (b) first-generation sfermion mass parameters and $M^2_{H,2}$ assuming 1% errors on sfermion masses and heavy Higgs boson masses. The width corresponds to 1σ errors.

LHC -MC synergy

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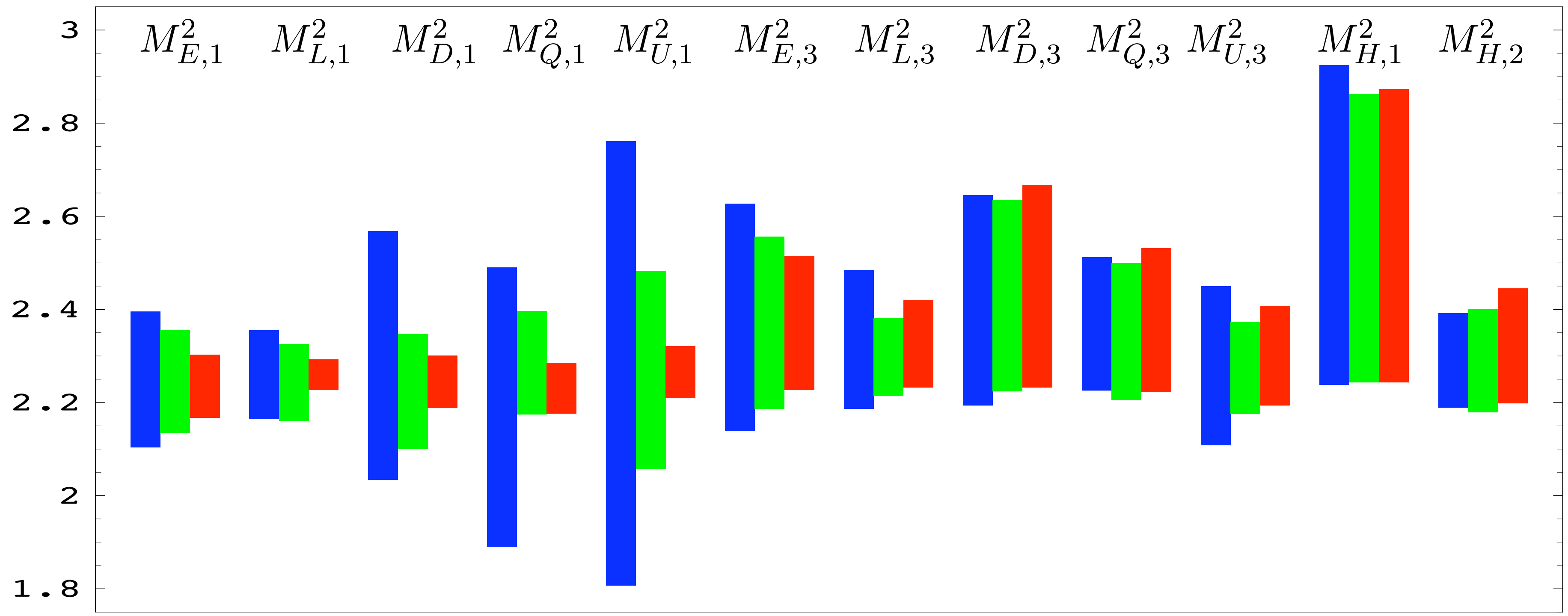


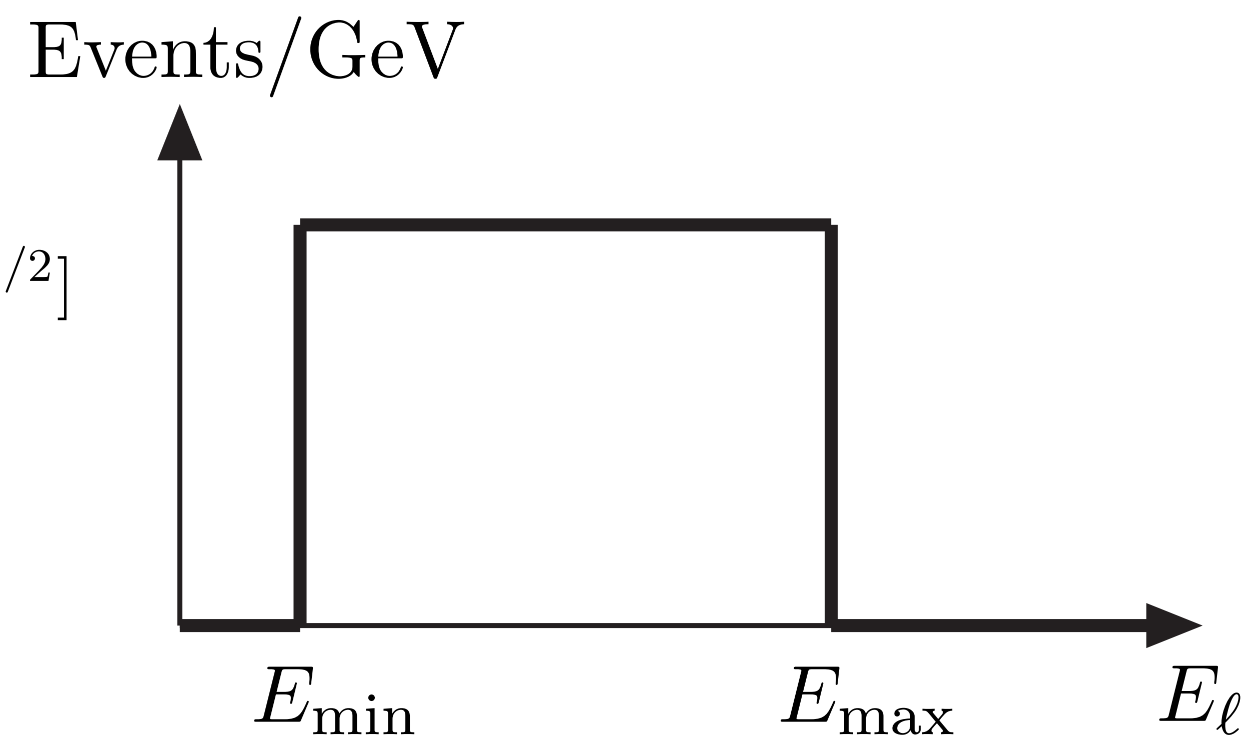
Fig. 5.15: The 1σ bands for the sfermion and Higgs mass parameters in TeV^2 at M_{GUT}. The following cases are considered: (dark boxes) slepton masses can be measured with an accuracy of 2% and the remaining particle masses within 7%; (light gray boxes) slepton masses can be measured with an accuracy of 2% and the remaining particle masses within 3%; (dark gray boxes) sfermion and heavy Higgs boson masses can be measured with an accuracy of 1%.

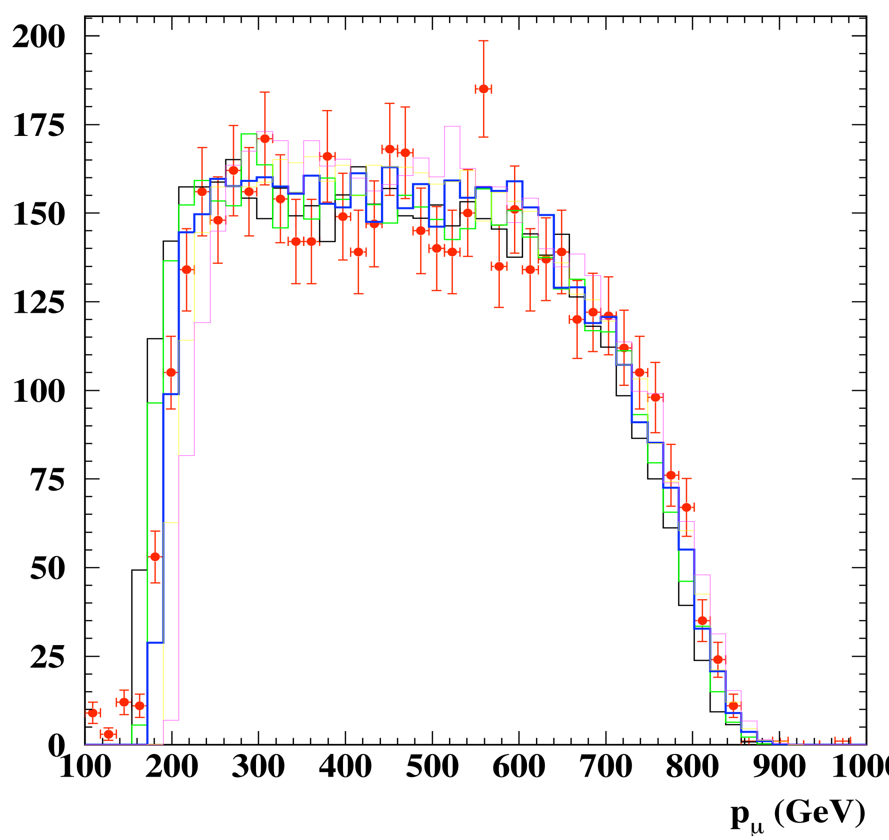
LHC -MC synergy

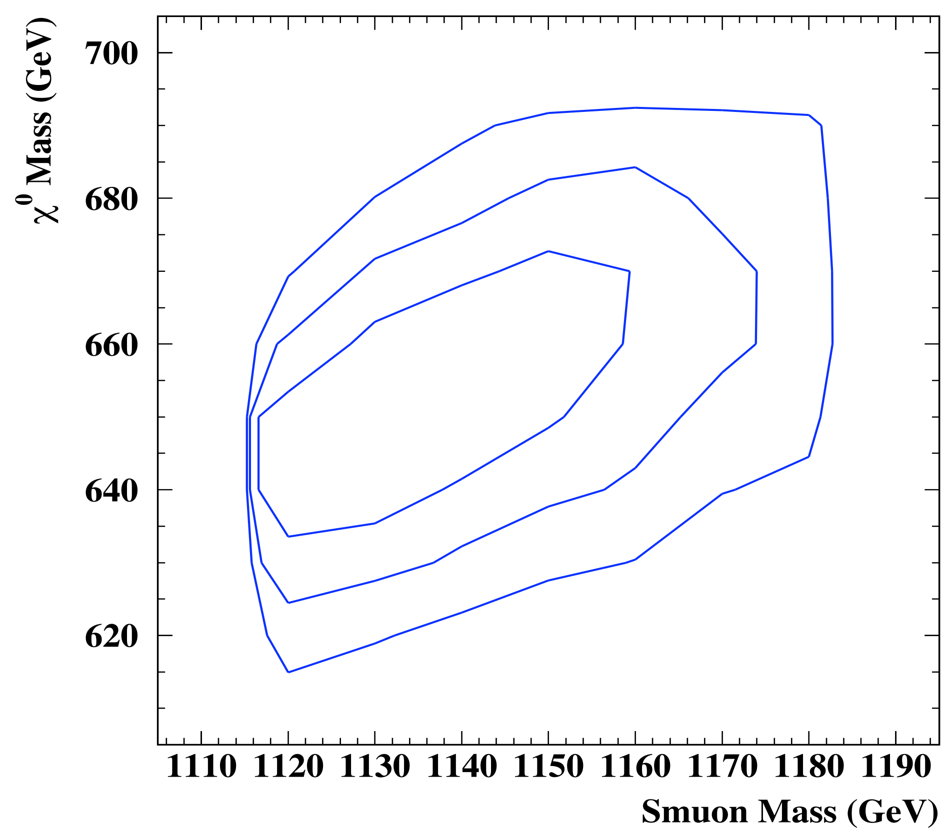
MC gives access to particle masses, couplings, widths, mixing angles

$$E_{\max,\min} = \frac{\sqrt{s}}{4}(1 - m^2_{\tilde{N}_1}/m^2_{\tilde{\ell}})[1 \pm (1 - 4m^2_{\tilde{\ell}}/s)^{1/2}]$$

$$\mu^+\mu^- \to \tilde{\ell}^+\tilde{\ell}^- \to \ell^+\ell^-\tilde{N}_1\tilde{N}_1$$



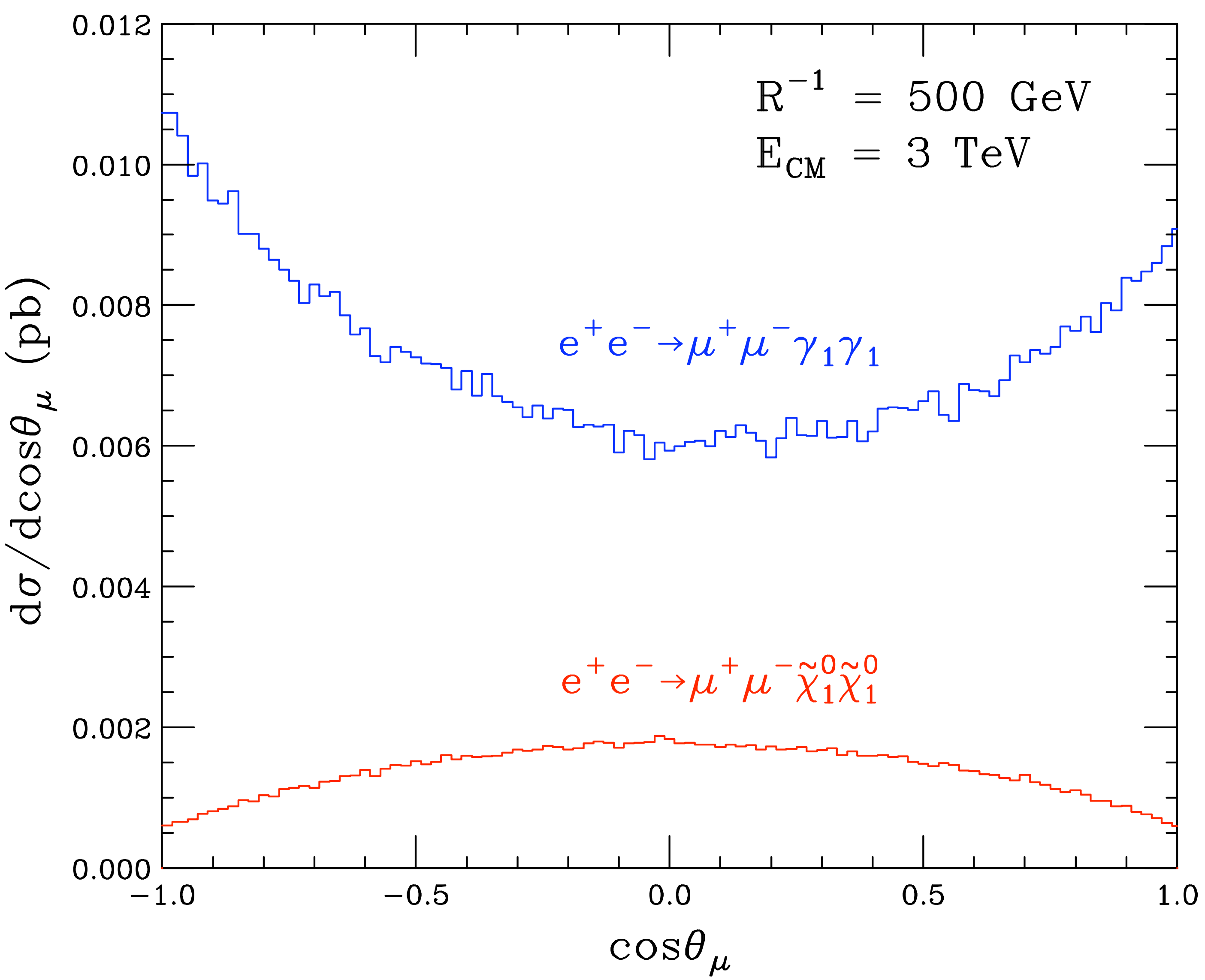




LHC -MC synergy

Q: See new states, how do we know it's SUSY?

A: Spin



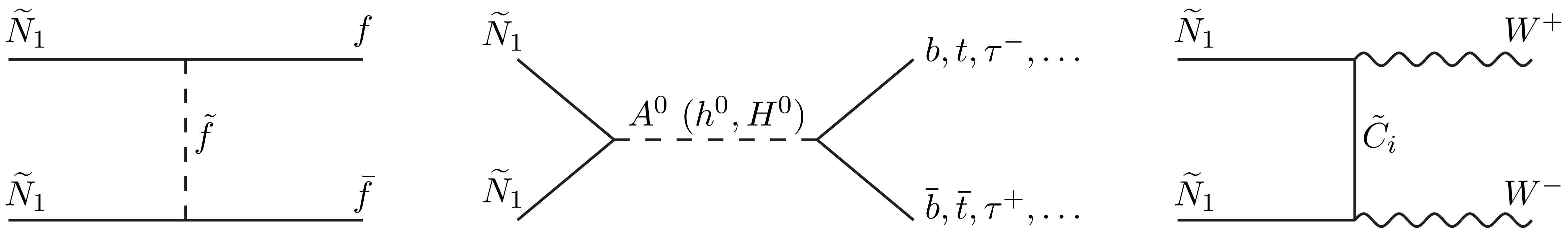
$$\frac{d\sigma}{d\cos\theta} \propto 1 \pm \cos^2\theta$$

[hep-ph/0502041]

Dark Matter

In SUSY and many complete "top-down" models precise measurements of masses and couplings allows us to test cosmology in the collider

LSP (neutralino) as a WIMP



Dark Matter

see also Graham Kribs

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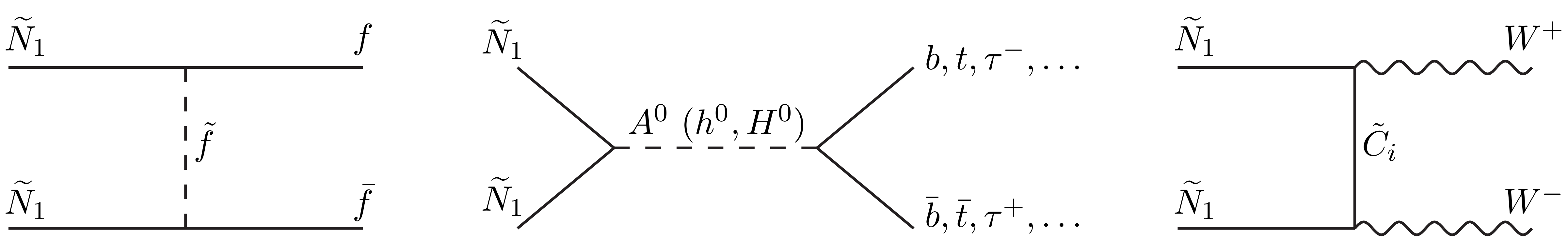
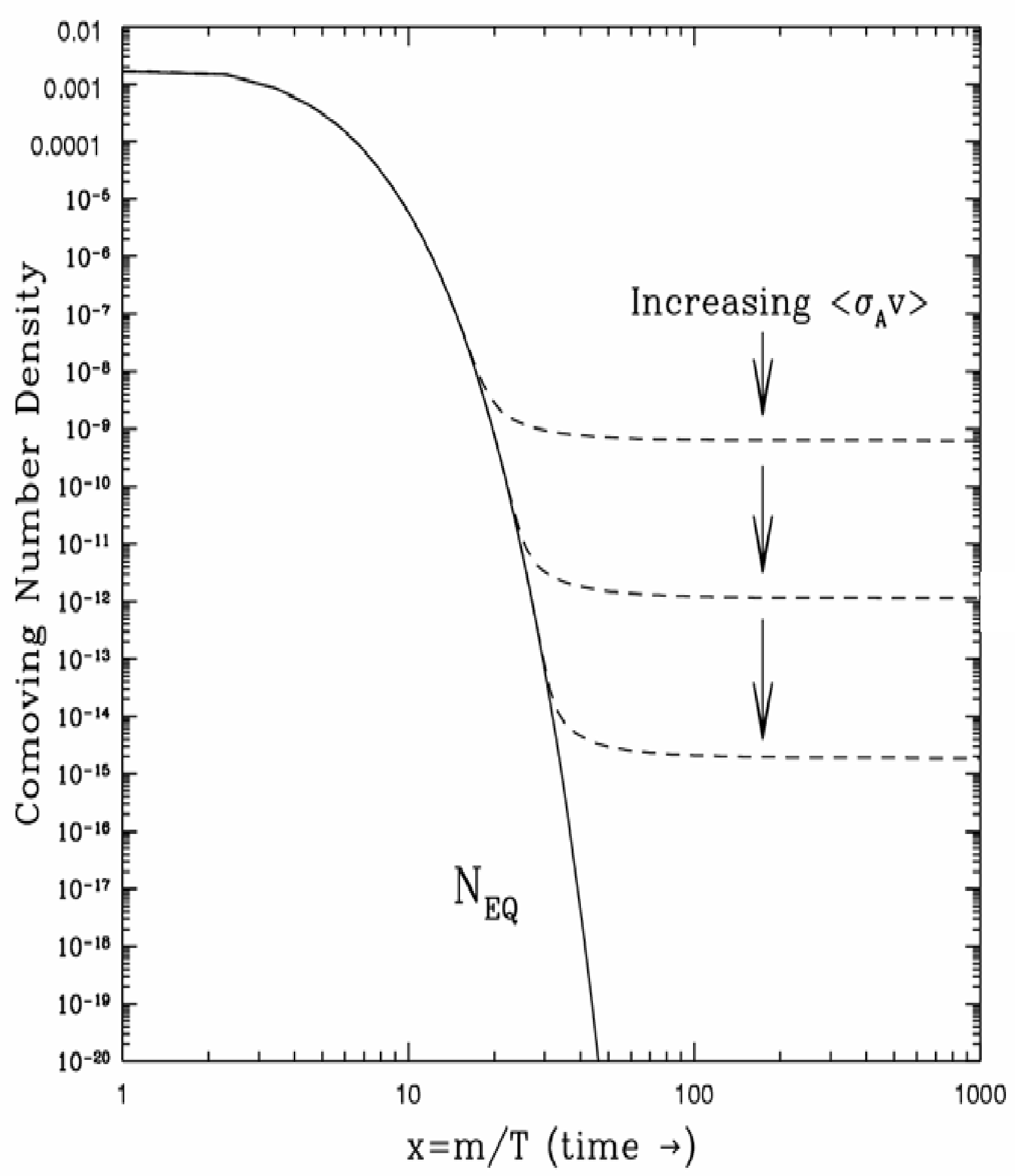


DM as a thermal relic

"The weak shall inherit the Universe"

A weak scale particle (WIMP) freezes out to leave the correct relic abundance - the WIMP "miracle"



$$\chi\chi \leftrightarrow \bar{f}f$$

$$\Omega h^2 \approx 0.1 \left(\frac{m/T}{20}\right)\left(\frac{g_*}{80}\right)^{-1}\left(\frac{3\times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}}{\sigma v}\right)$$

Amazing (misleading?) fact:

[Feng and Kumar]

$$\langle\sigma v\rangle \sim \frac{\alpha_W^2}{M_W^2} \sim 1\,\mathrm{pb} \sim 3\times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}$$

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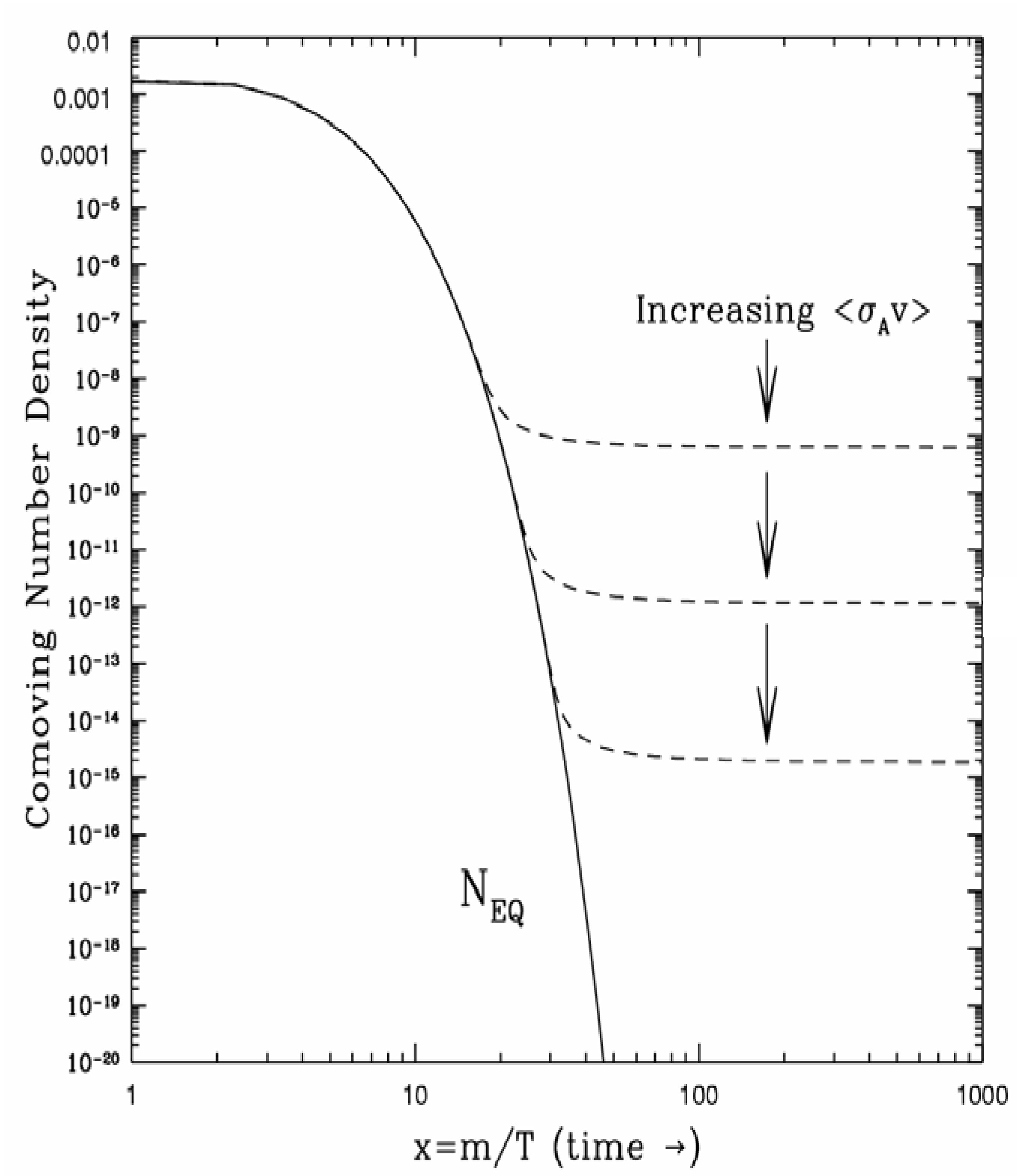

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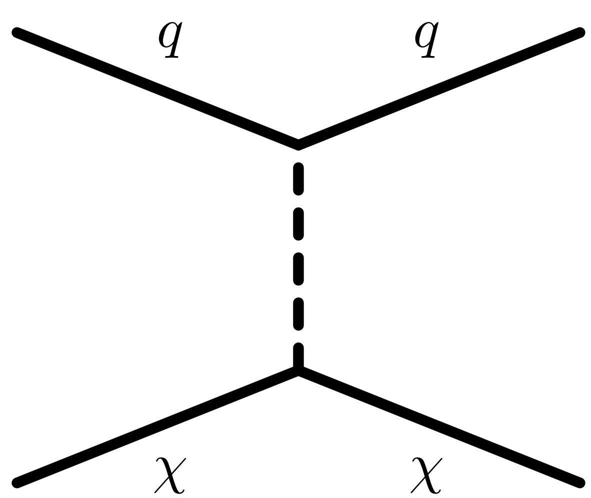
SUSY neutralino in ball park

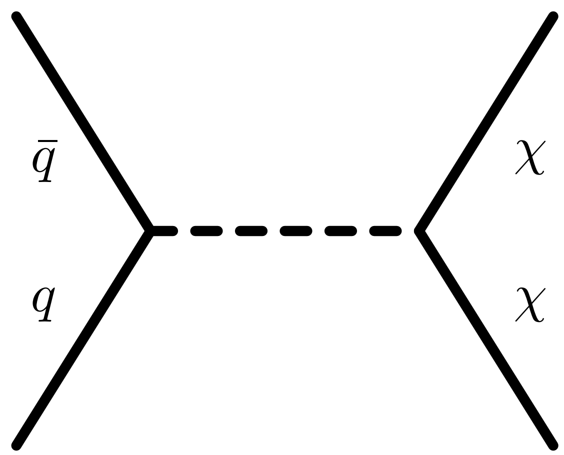
MDI - Muon DM Interface



Direct detection

<u>Look down</u>

Low rate, low energy recoil events in underground labs

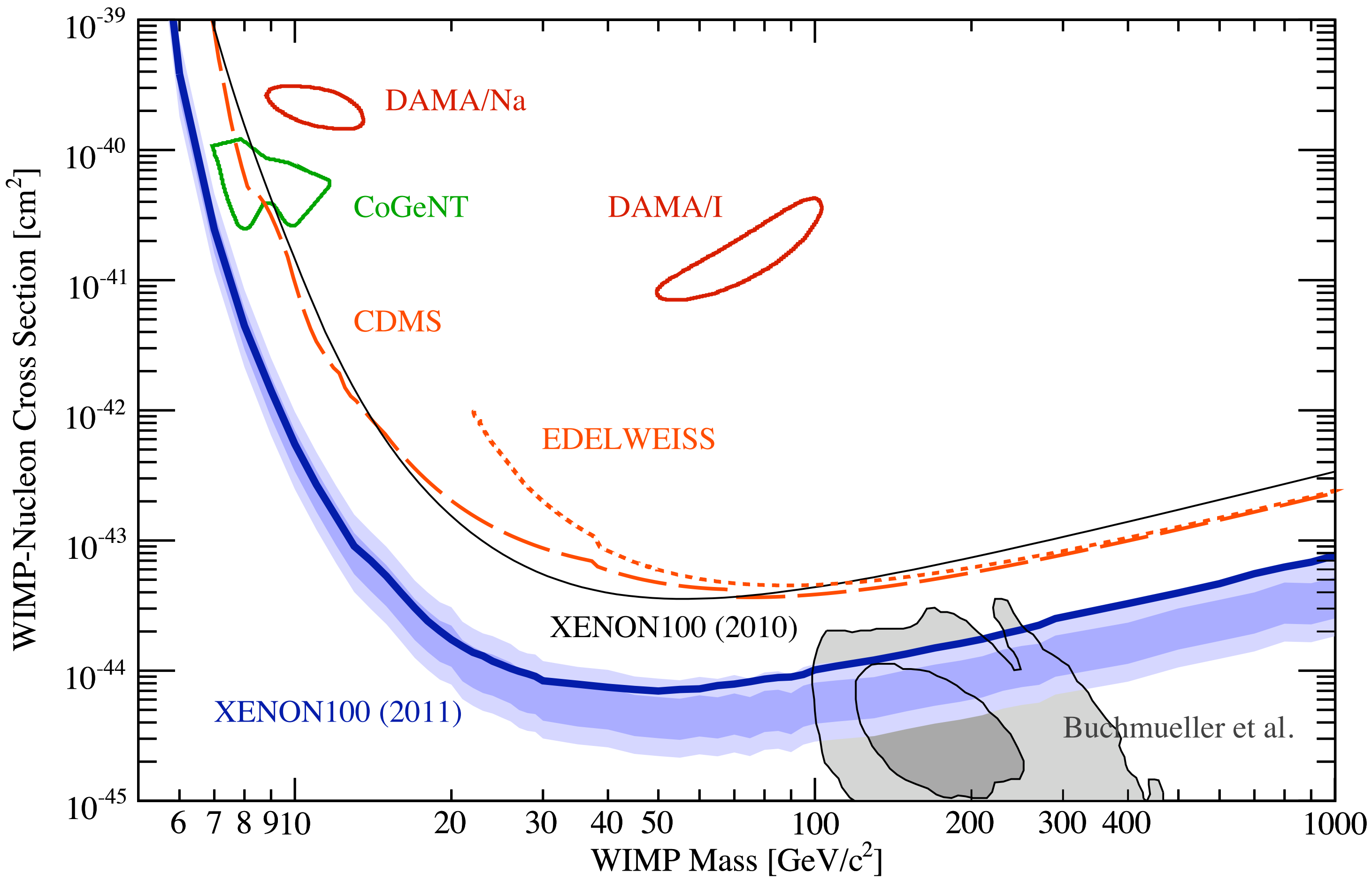


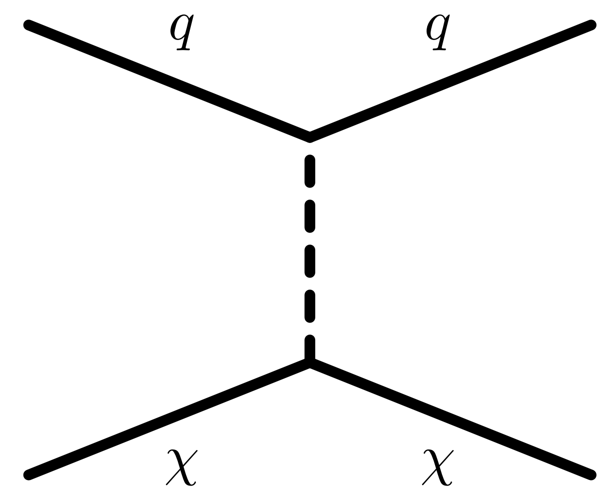
Collider searches

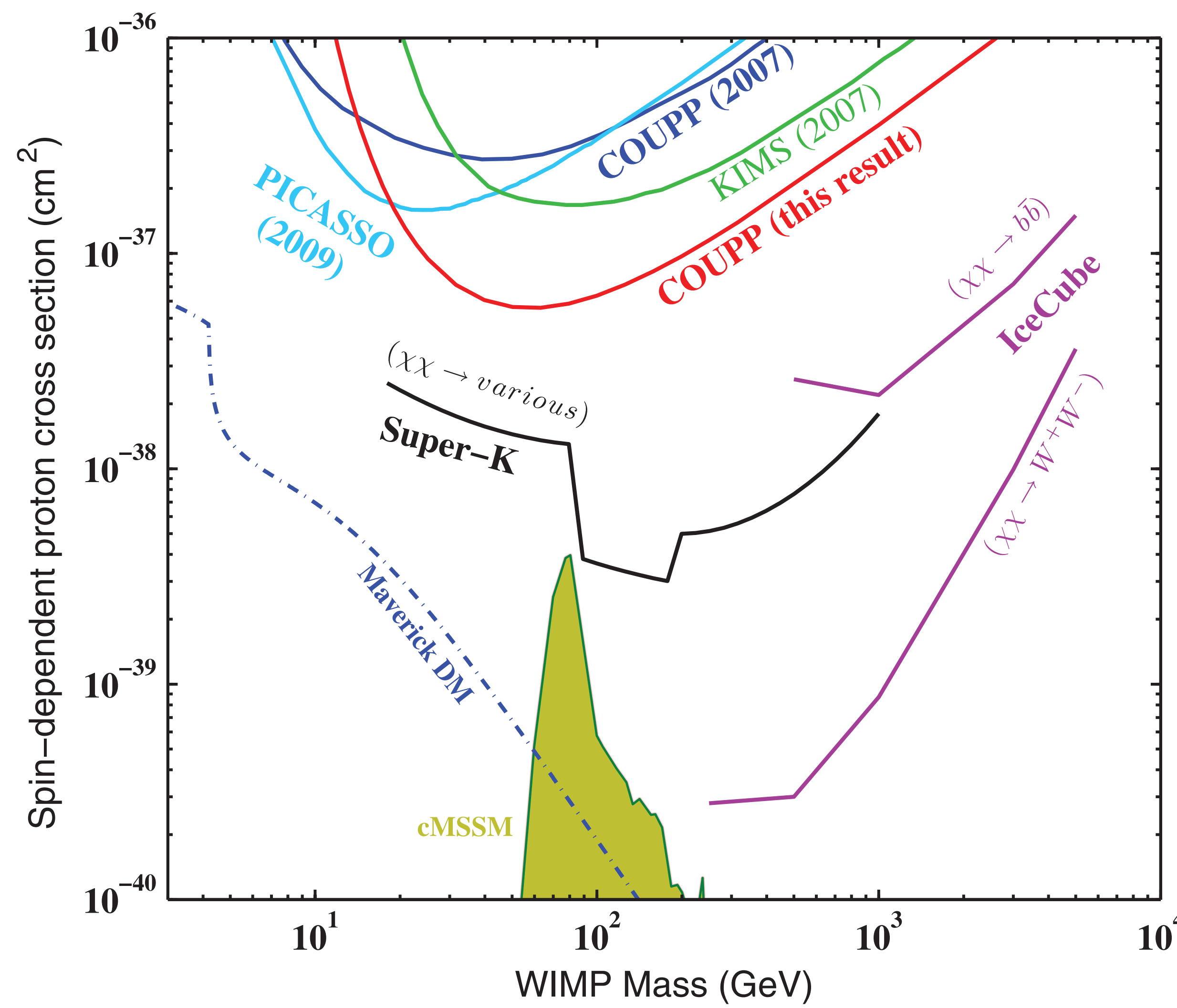
<u>Look small</u>

Missing energy events at colliders

Dark Matter Direct Detection

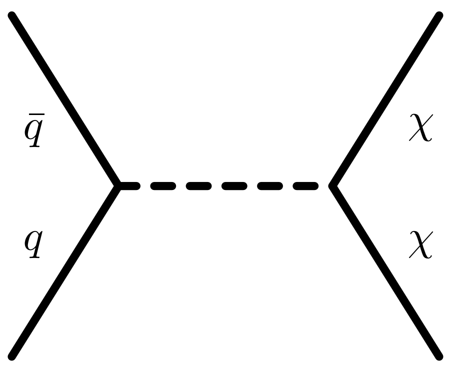






Dark Matter at the Tevatron

[arXiv:1005.3797]



Mono-jet + $\not{E}_T$

$$\not{E}_T > 80\,\text{GeV}$$
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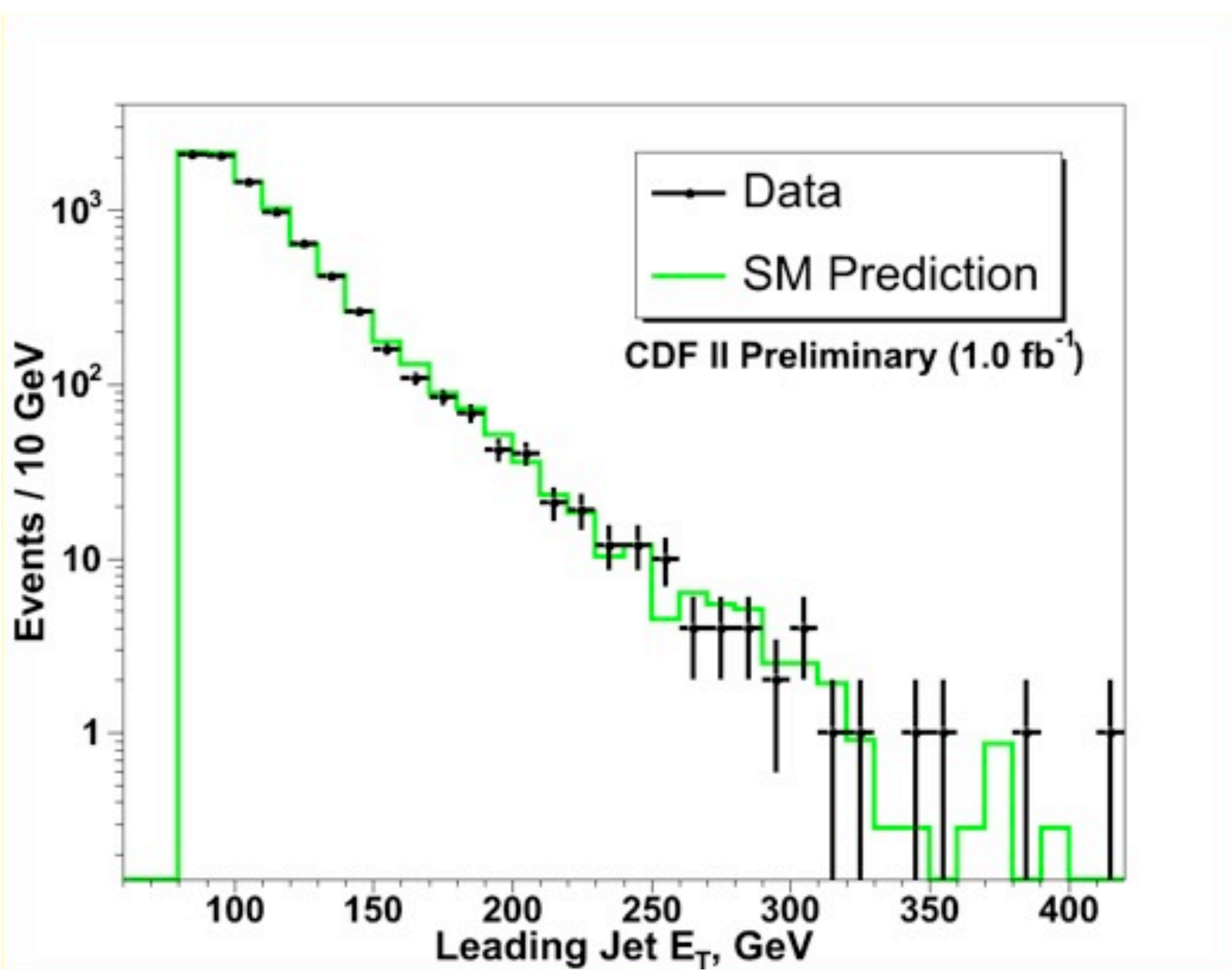

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W -> tau nu	2010 +/- 69
W -> mu nu	1570 +/- 54
W -> e nu	824 +/- 28
Z -> l l	87 +/- 3
QCD	708 +/- 146
Gamma plus Jet	209 +/- 41
Non-Collision	52 +/- 52
Total Predicted	8663 +/- 332
Data Observed	8449

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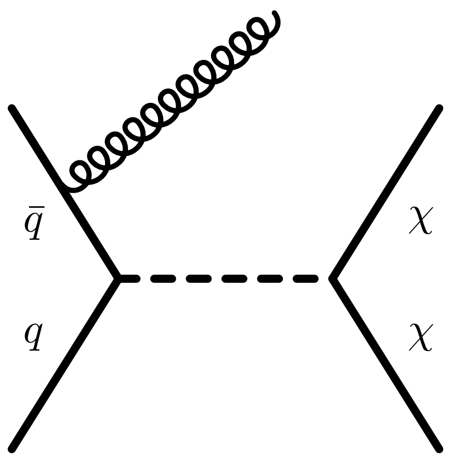

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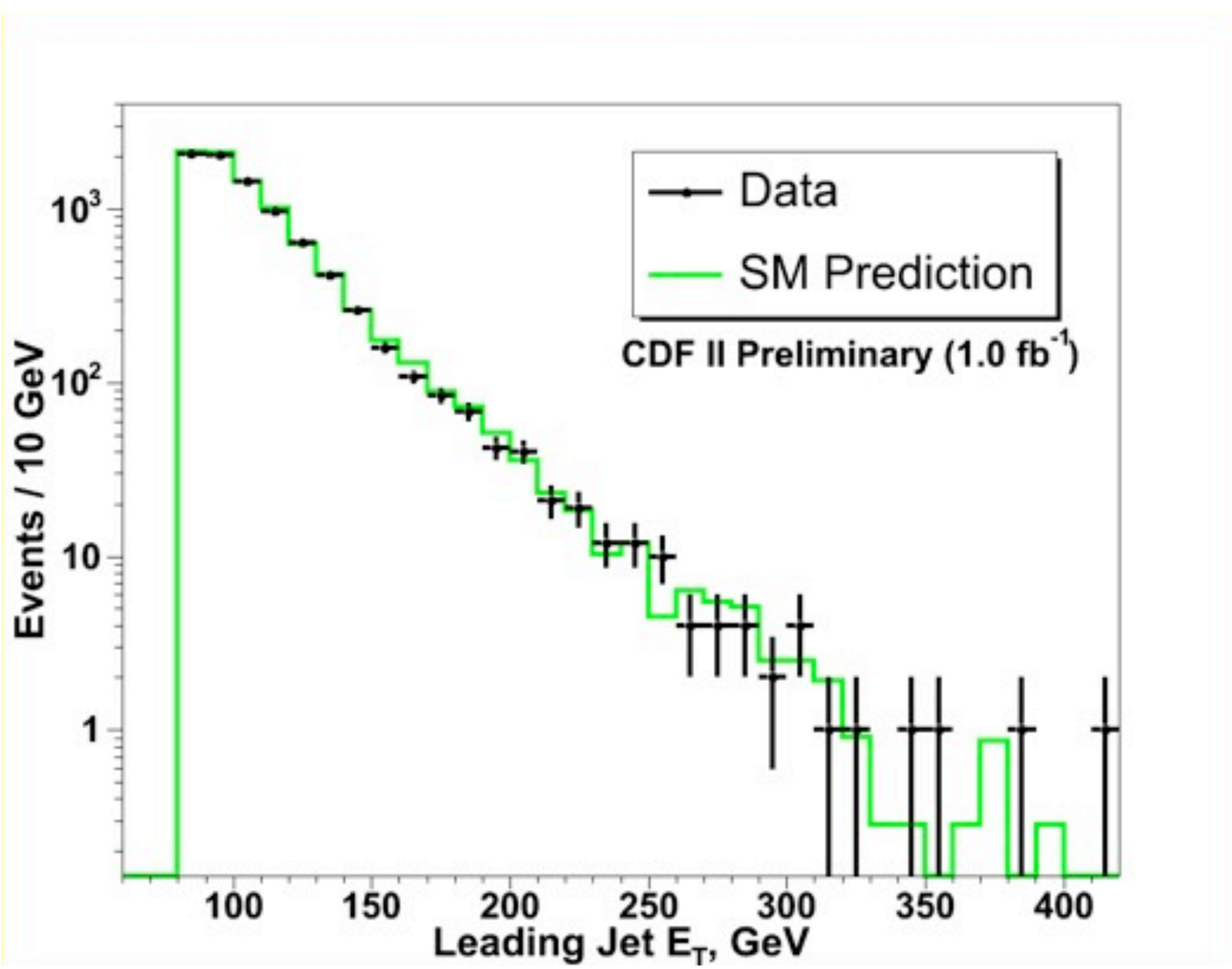

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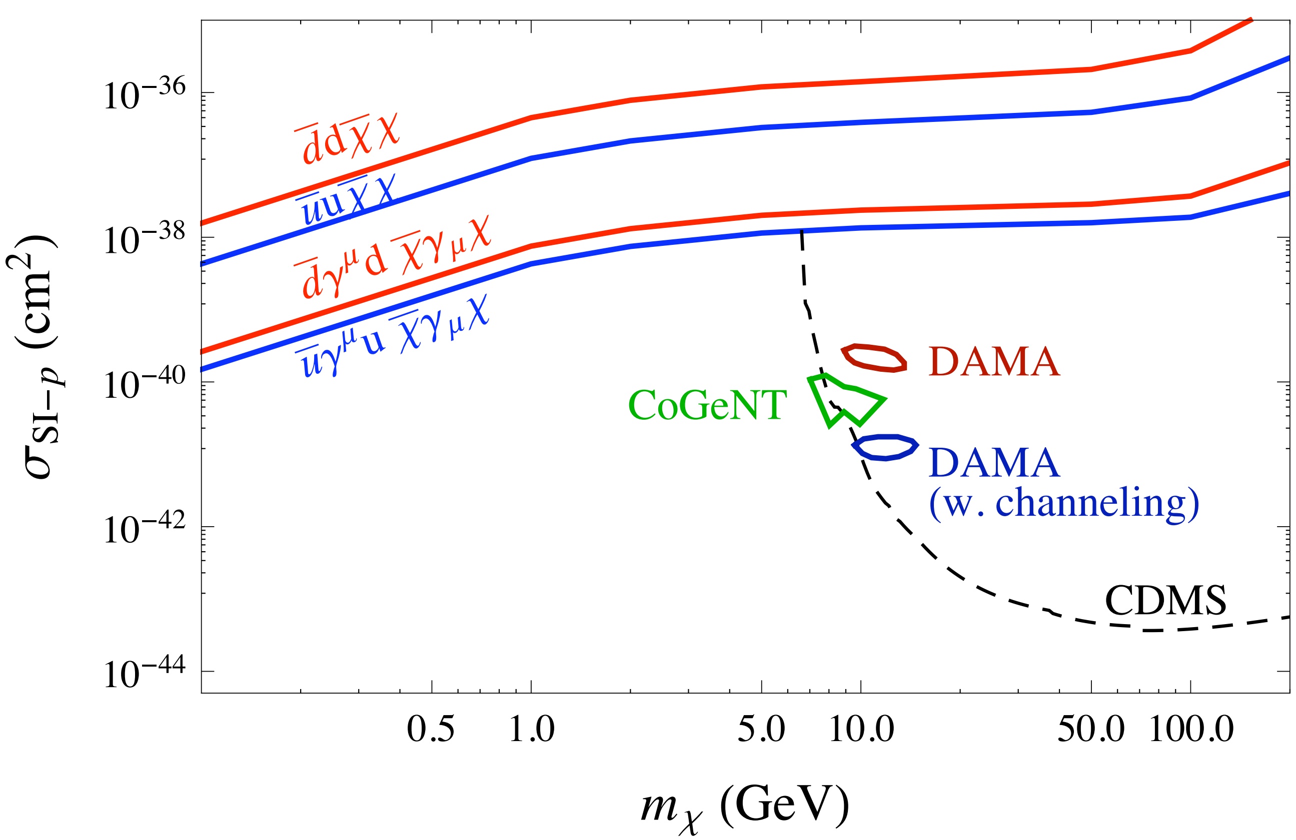
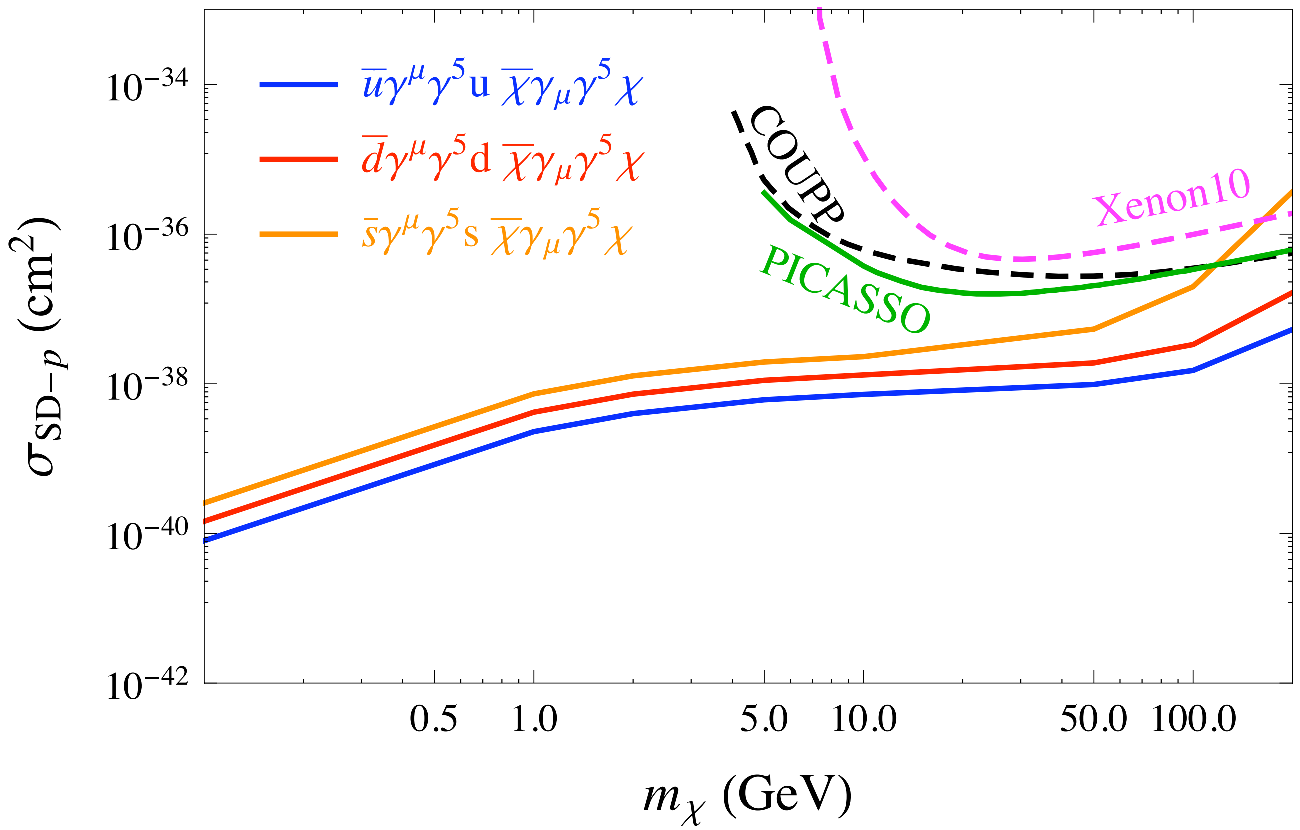
DM at Tevatron

Spin independent



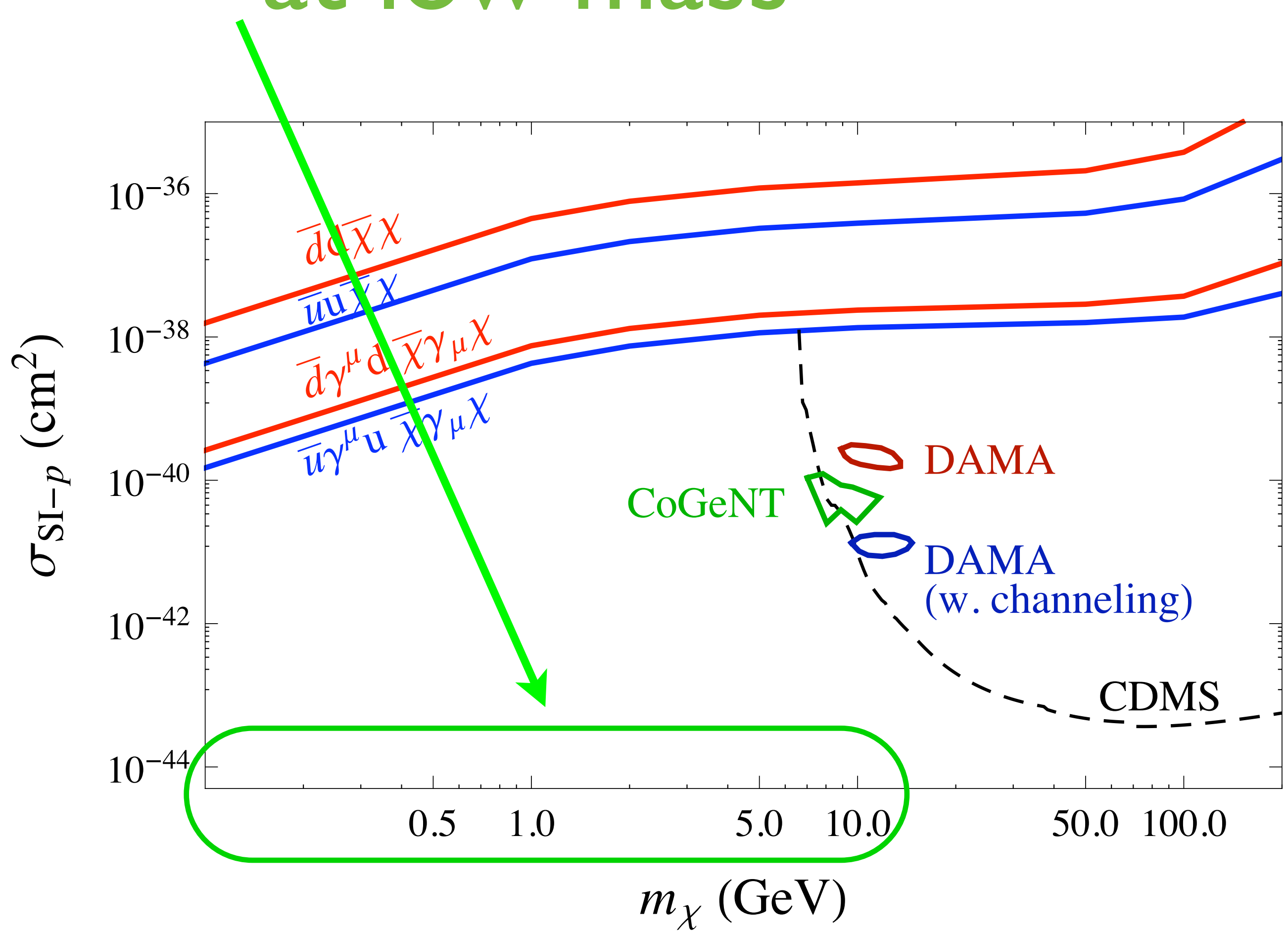


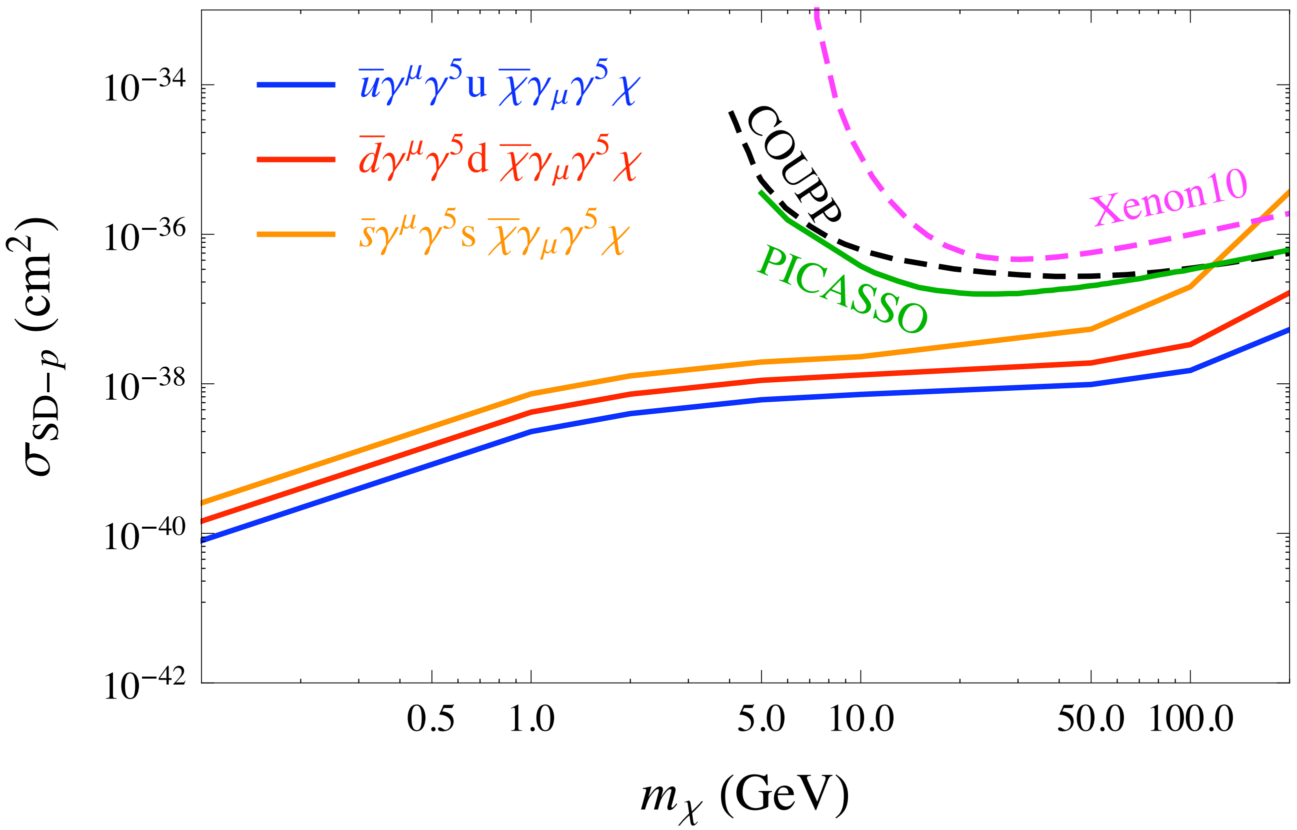
Spin dependent

DM at Tevatron

Spin independent

World's best limits at low mass

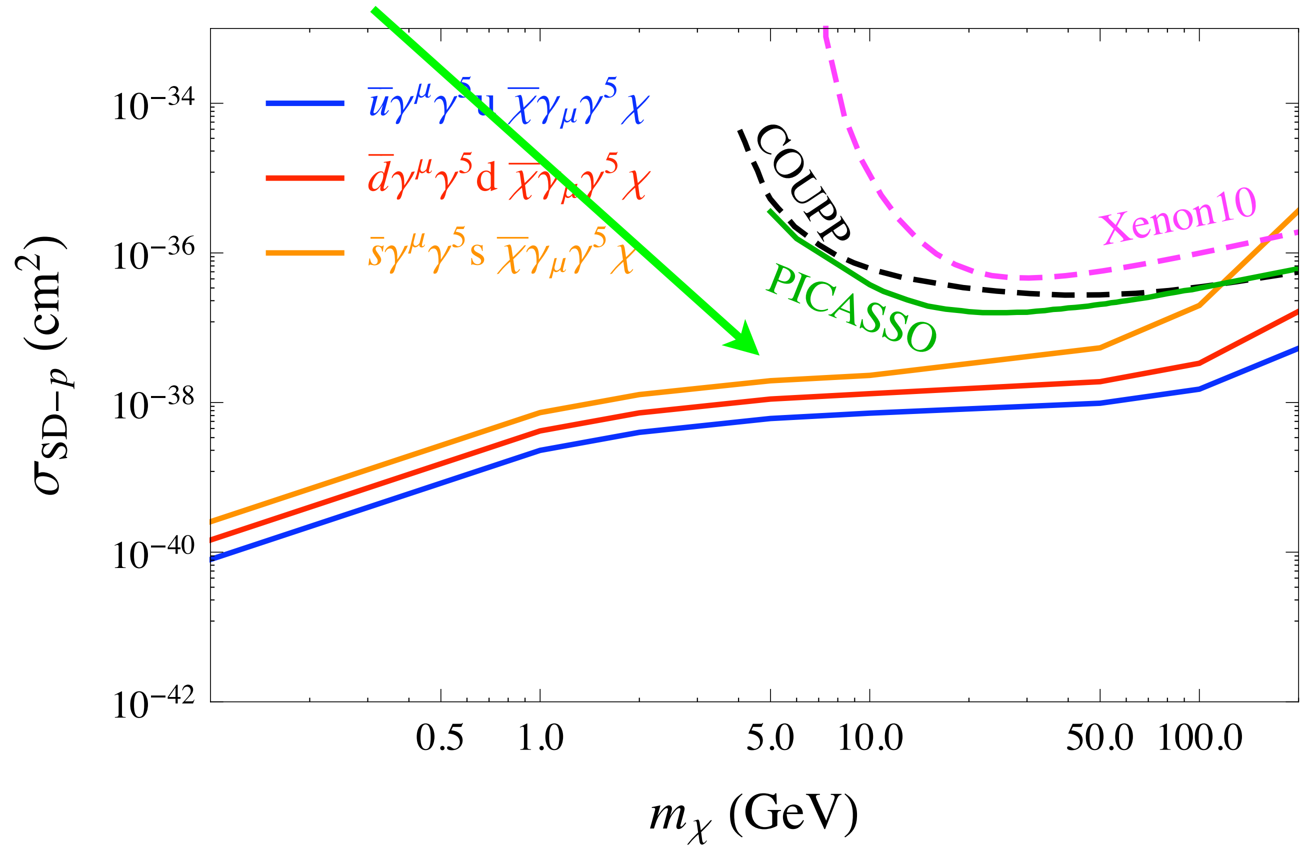




Spin dependent

DM at Tevatron

World's best limits, up to ~200 GeV



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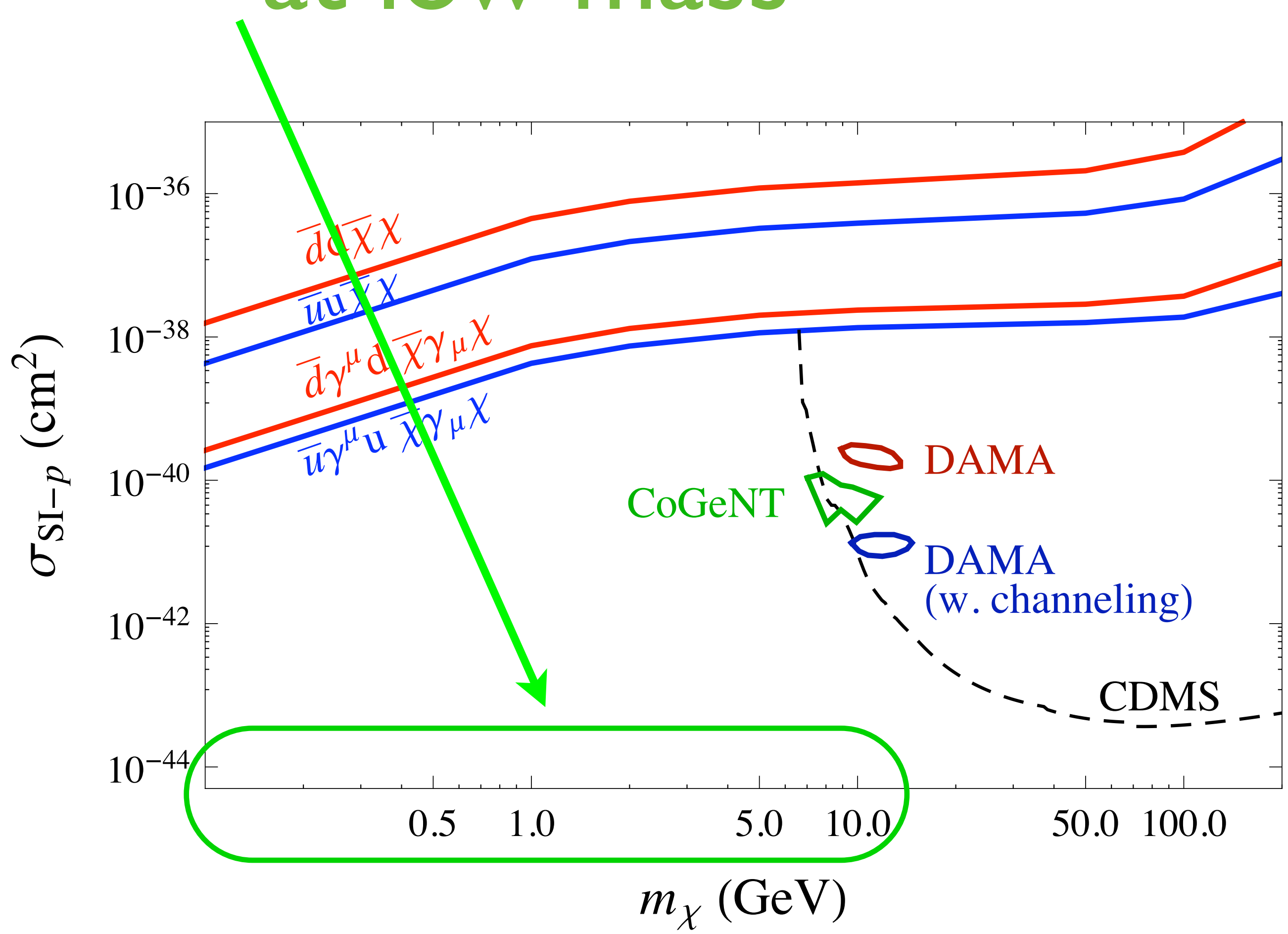


DM at LEP

[arXiv:1103.0240]

LEP can place bounds on DM-electron coupling

Alternative avenue of attack, "cleaner" environment

Hadrophobic DM proposed as explanation of DAMA

Equal couplings to quarks and leptons?

Mono-jets $\longleftrightarrow$ Mono-photons

$$q \leftrightarrow \ell$$

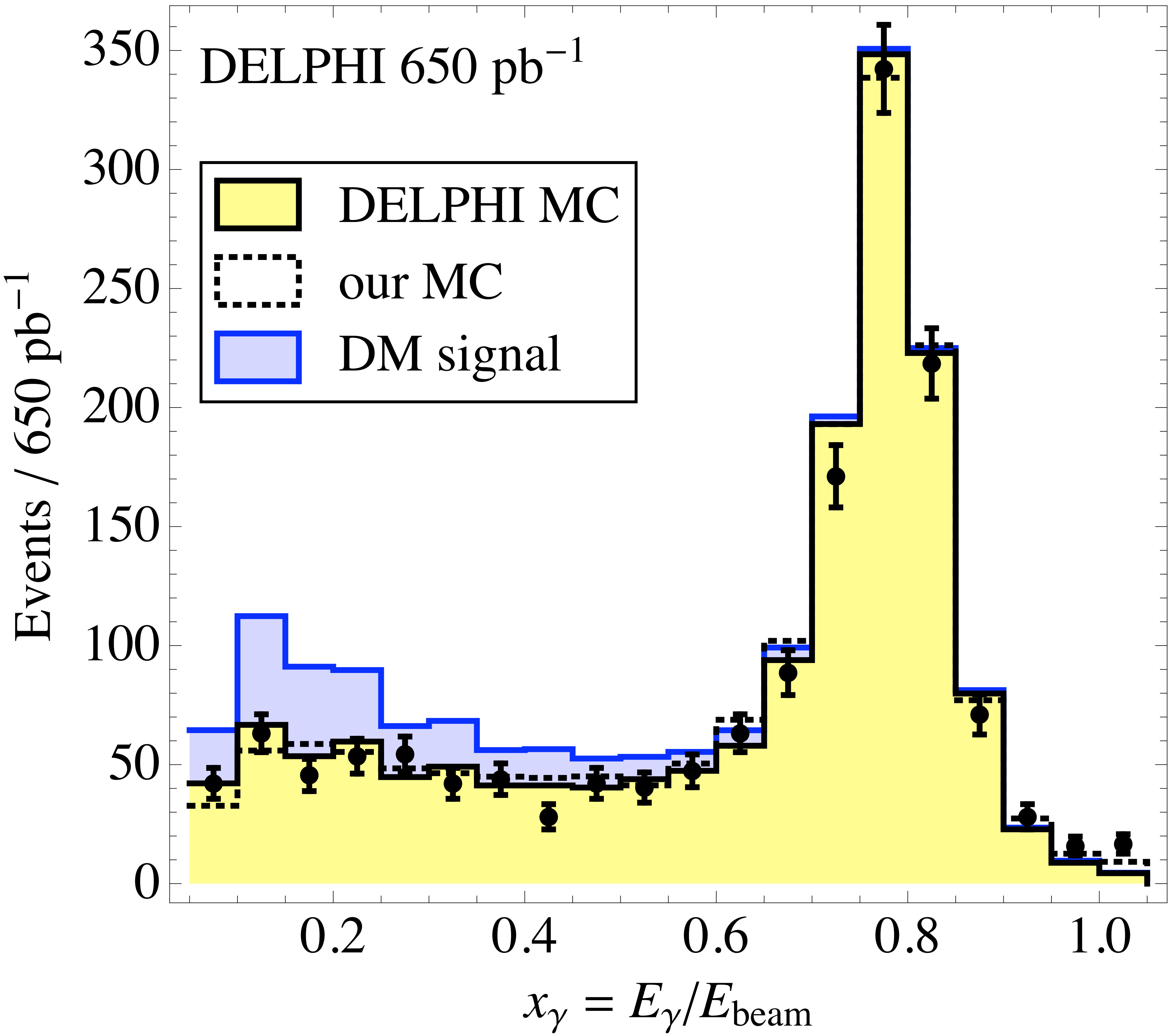
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell)}{\Lambda^2}\,, \qquad \text{(vector, } s\text{-channel)}$$

$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{\ell}\ell)}{\Lambda^2}\,, \qquad \text{(scalar, } s\text{-channel)}$$

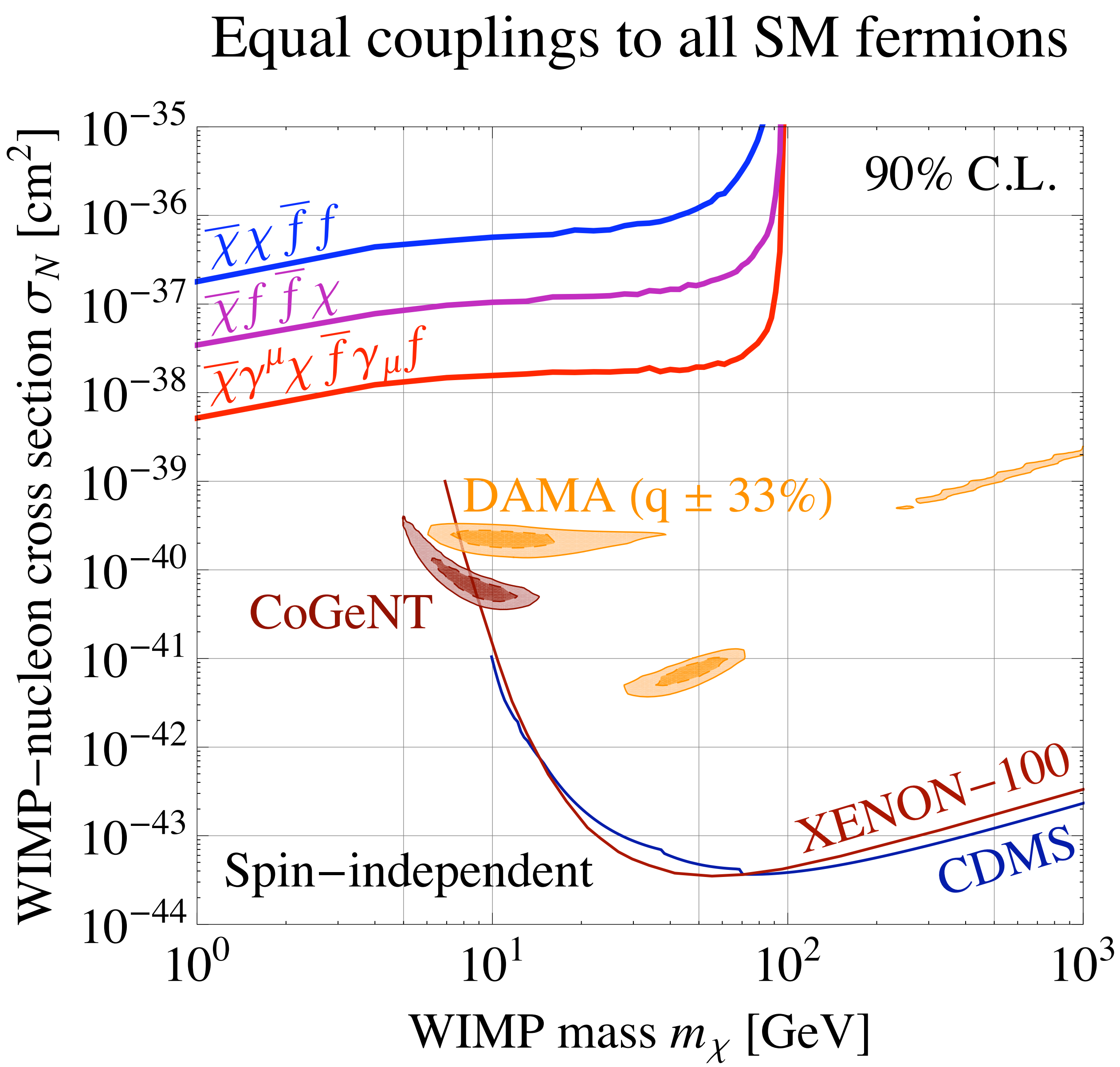
$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma_5\ell)}{\Lambda^2}\,, \qquad \text{(axial vector, } s\text{-channel)}$$

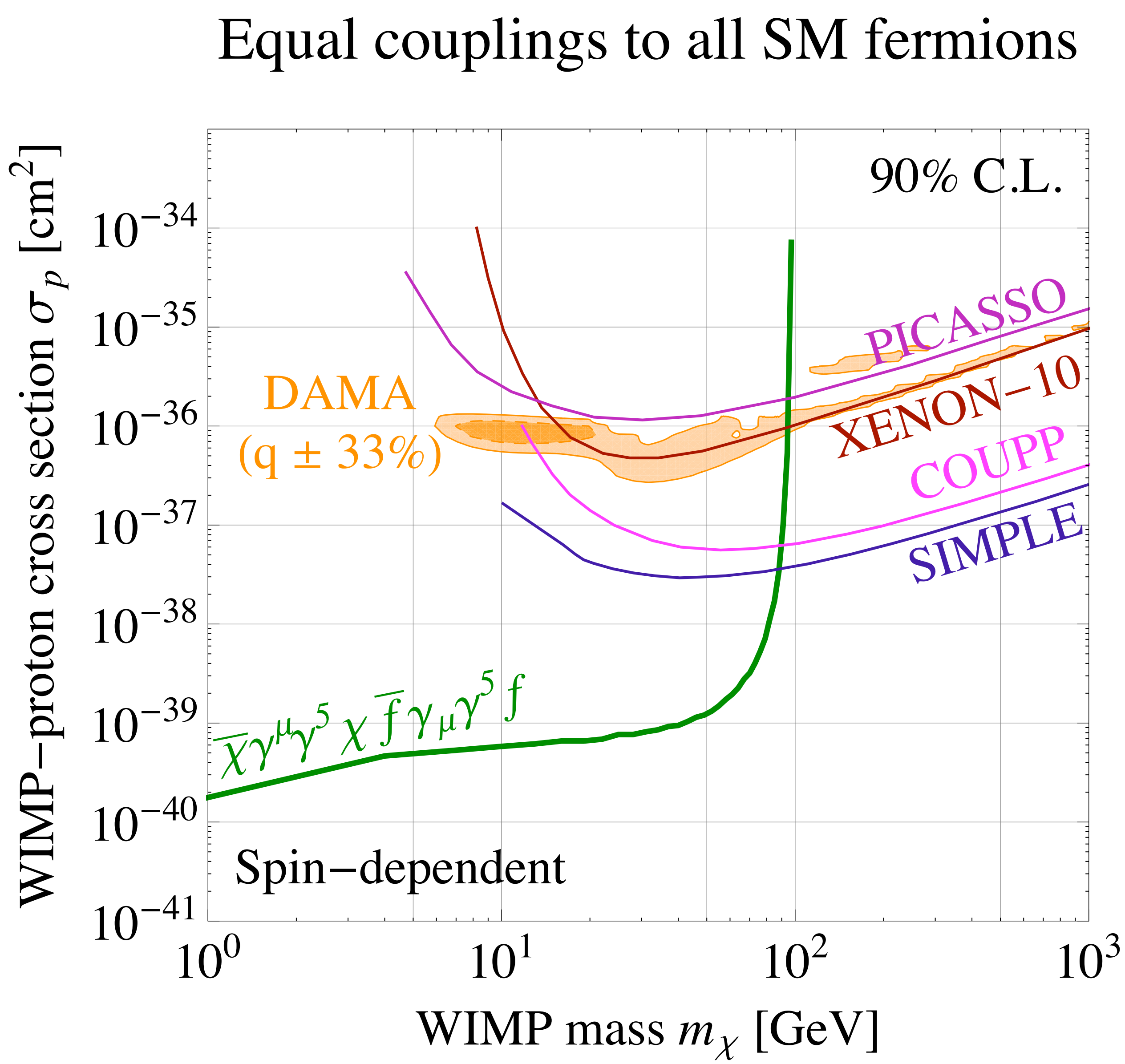
$$\mathcal{O}_t = \frac{(\bar{\chi}\ell)(\bar{\ell}\chi)}{\Lambda^2}\,, \qquad \text{(scalar, } t\text{-channel)}$$

LEP is cleaner, use spectral information



Equal couplings to all fermions





Conclusions

LHC will soon inform us about the Higgs and the solution to the hierarchy problem

Whether SUSY or another BSM model we must quickly determine what a MC can tell us

Ideal for precision determination of BSM parameters

Probe DM in the lab, free of astrophysics uncertainties

Nature may soon help us with the benchmarks