Interplay of the LHC and Dark Matter search experiments in unravelling Natural Supersymmetry

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Outline

- **Properties SUSY in the Focus Point region:**
  low fine-tuning, low Dark Matter (DM) relic density, potentially high direct DM detection rates, compressed spectrum and mono-jet signatures at the LHC

- **The "Far" Focus Point (FFP) region - compressed wino-higgsino scenario with heavy coloured sparticles - the worst case scenario (for LHC observation) to be prepared for!:**
  the status of the current LHC@8TeV mono-jet searches and their MSSM interpretations;
  LHC@13TeV projections and complementary of the DDM detection - LHC searches

SUSY principles

boson-fermion symmetry aimed to unify all forces in nature

$$Q|\text{BOSON}\rangle = |\text{FERMION}\rangle, \quad Q|\text{FERMION}\rangle = |\text{BOSON}\rangle$$

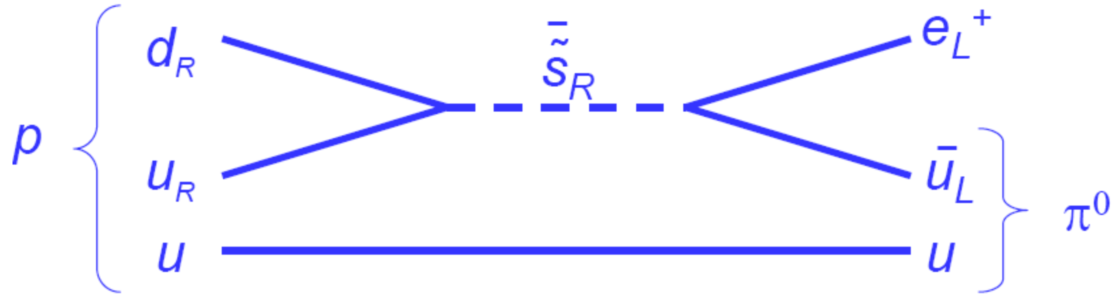
extends Poincare algebra to Super-Poincare Algebra:

the most general set of space-time symmetries! (1971-74)

$$\{f,f\}=0, \quad [B,B]=0, \quad \{Q_\alpha,\bar{Q}_\beta\}=2\gamma^\mu_{\alpha\beta}P_\mu$$

Golfand and Likhtman'71; Ramond'71; Neveu,Schwarz'71; Volkov and Akulov'73; Wess and Zumino'74

Particle	SUSY partner
e,ν,u,d *spin 1/2*	$\widetilde{e},\widetilde{\nu},\widetilde{u},\widetilde{d}$ *spin 0*
γ,W,Z h,H,A,H± *spin 1 and 0*	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^\pm$ $\tilde{\chi}_1^0\cdots\tilde{\chi}_4^0$ *spin 1/2*



could give rise the proton decay!

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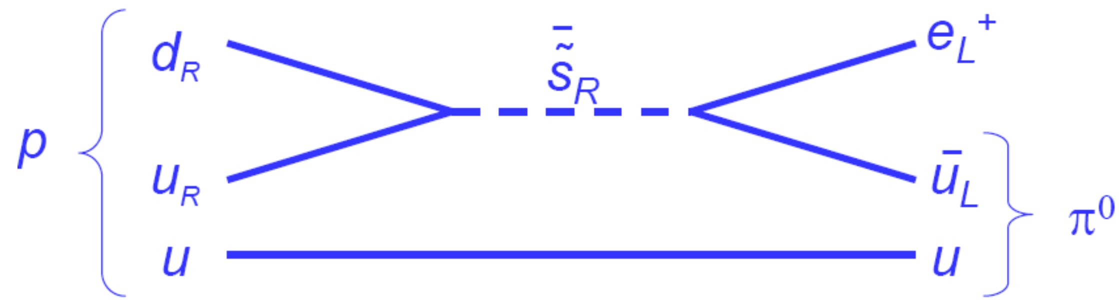
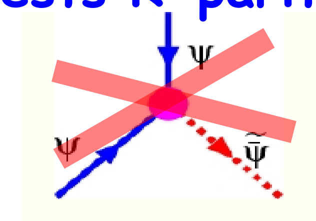


the absence of proton decay suggests R-parity

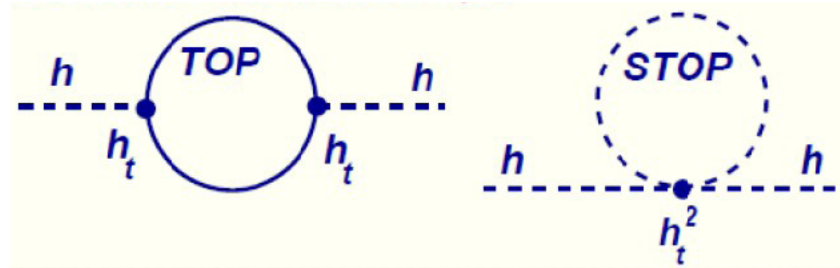
$$R = (-1)^{3(B-L)+2S}$$



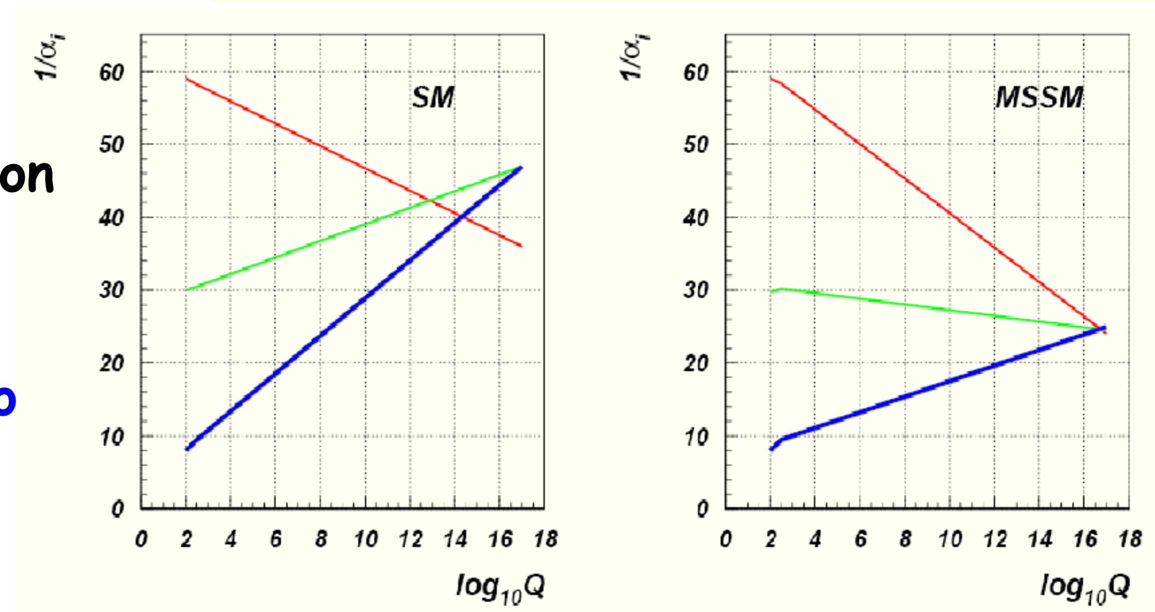
R-parity guarantees Lightest SUSY particle (LSP) is stable – DM candidate!

Beauty of SUSY

- Provides good DM candidate – LSP
- CP violation can be incorporated - baryogenesis via leptogenesis
- Radiative EWSB
- Solves fine-tuning problem
- Provides gauge coupling unification
- local supersymmetry requires spin 2 boson – graviton!
- allows to introduce fermions into string theories



$$\Delta M_H^2 \sim M_{SUSY}^2 \log(\Lambda/M_{SUSY})$$



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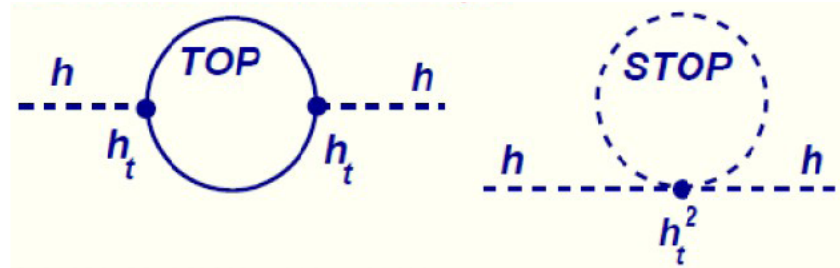

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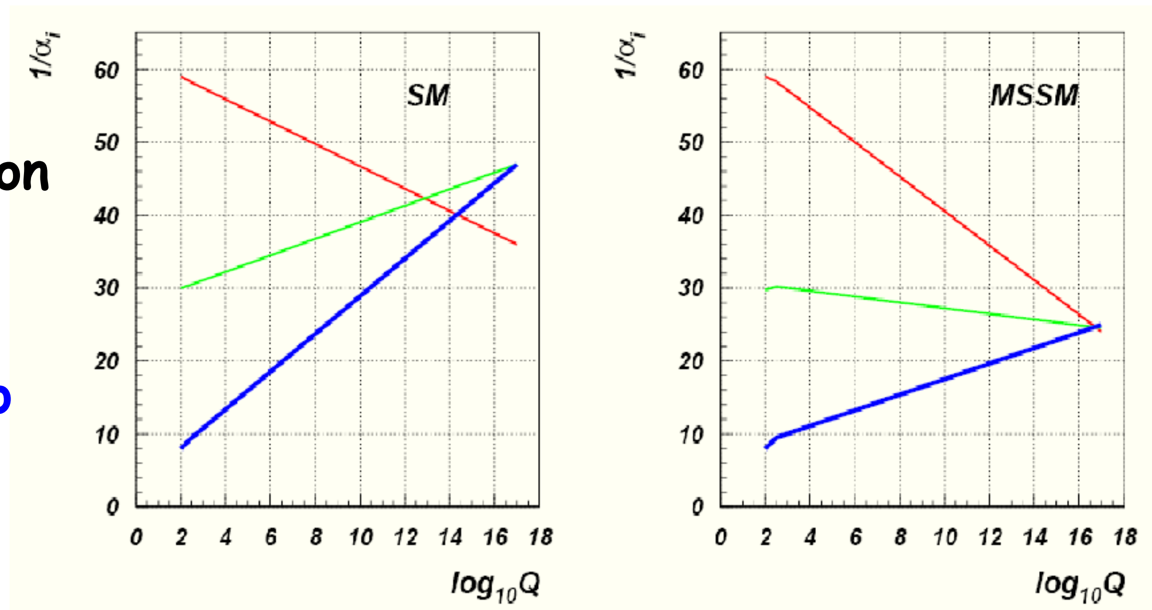
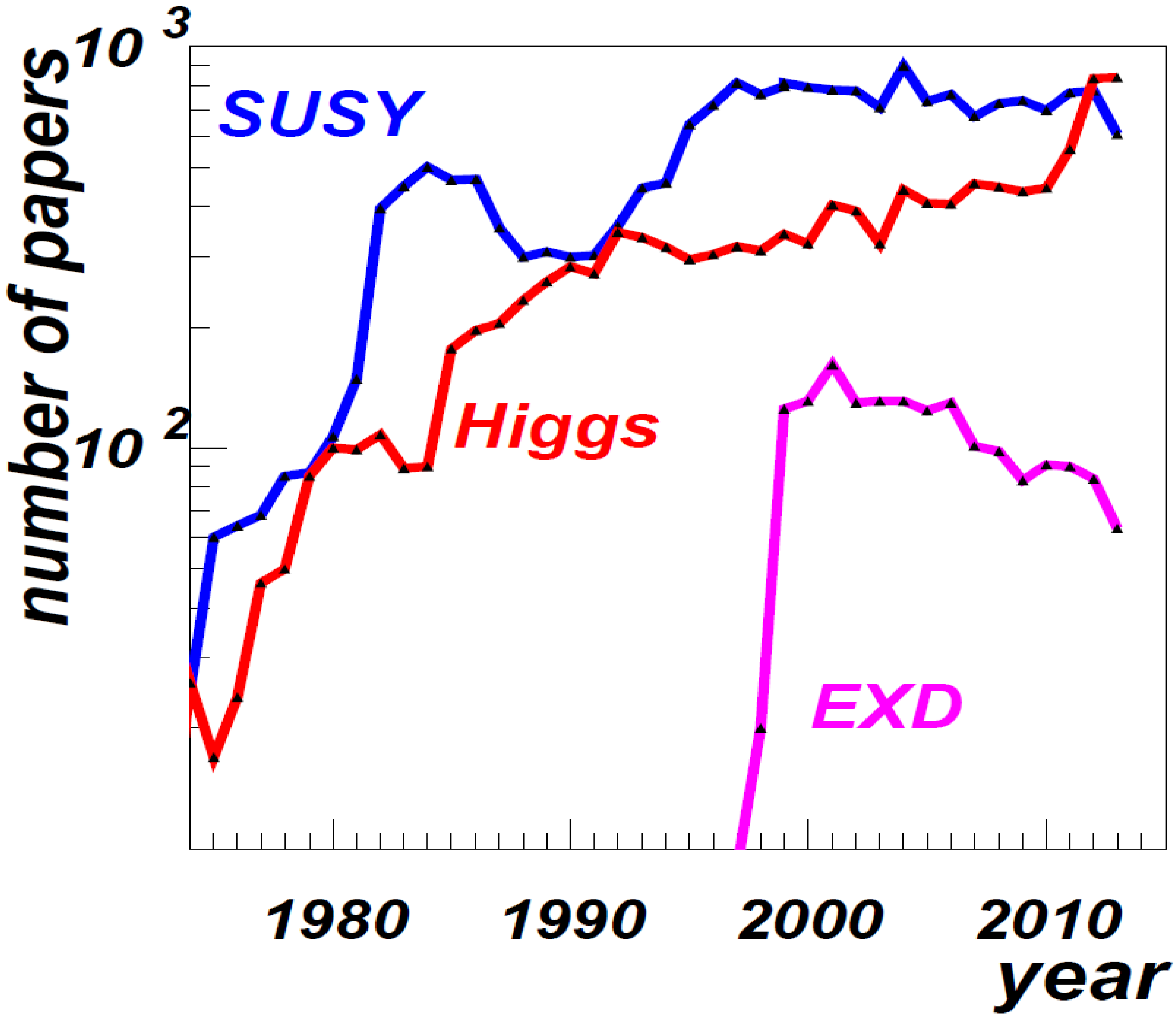


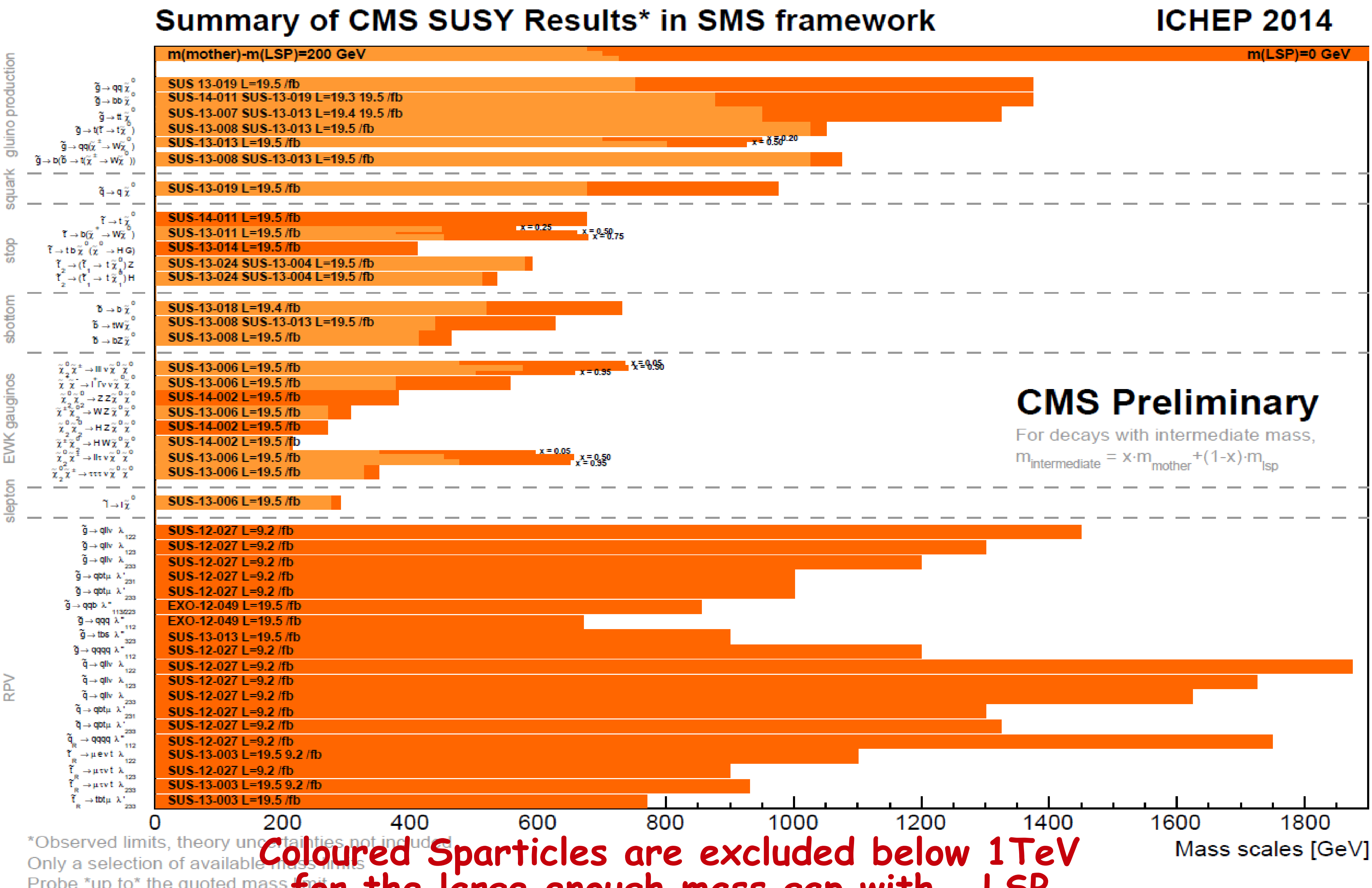
But the real beauty of SUSY from my point of view is that

It was not deliberately designed to solve the SM problems!

We are still inspired by this beauty ...



... but SUSY, where are you?!



Coloured Sparticles are excluded below 1TeV for the large enough mass gap with LSP

The EW measure of Fine Tuning

$$\mathcal{L}_{\rm MSSM} = \mu \tilde{H}_u \tilde{H}_d + \text{h.c.} + (m^2_{H_u} + |\mu|^2)\ |H_u|^2 + (m^2_{H_d} + |\mu|^2)\ |H_d|^2 + \ldots$$

The EW measure requires that there be no large/unnatural cancellations in deriving m_Z from the weak scale scalar potential:

$$\frac{m_Z^2}{2} = \frac{(m^2_{H_d} + \Sigma^d_d) - (m^2_{H_u} + \Sigma^u_u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2 \simeq -m^2_{H_u} - \mu^2$$

using fine-tuning definition which became standard

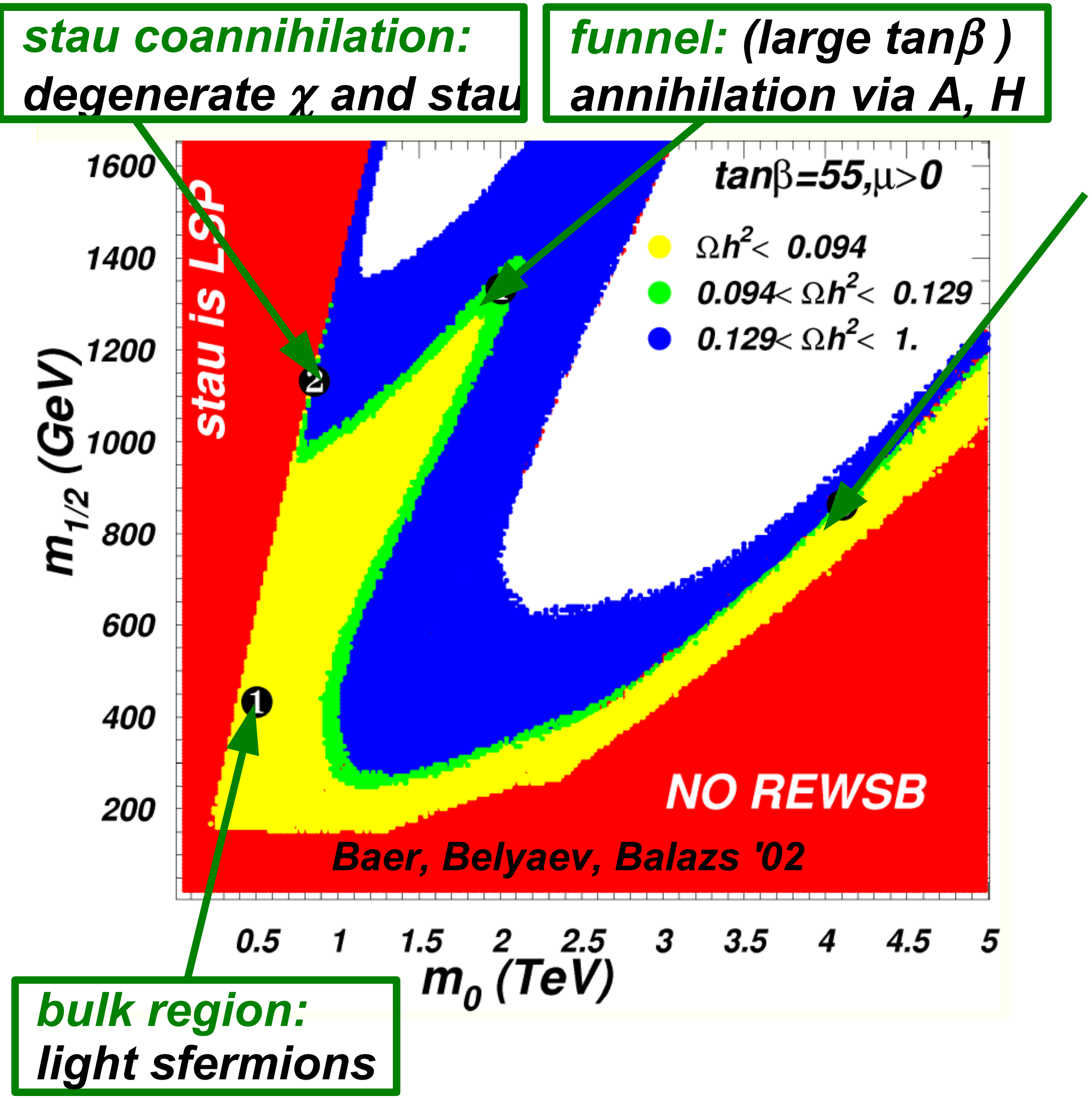
Ellis, Enqvist, Nanopoulos, Zwirner '86; Barbieri, Giudice '88

$$\Delta_{FT} = max[c_i], \qquad c_i = \left|\frac{\partial \ln m_Z^2}{\partial \ln p_i}\right| = \left|\frac{p_i}{m_Z^2}\frac{\partial m_Z^2}{\partial p_i}\right|$$

one finds $\Delta_{FT} \simeq \Delta_{EW}$ **which requires** $|\mu^2| \simeq M_Z^2$ **as well as** $|m^2_{H_u}| \simeq M_Z^2$

The last one is GUT model-dependent, so we consider the value $|\mu^2|$ as a measure of the minimal fine-tuning

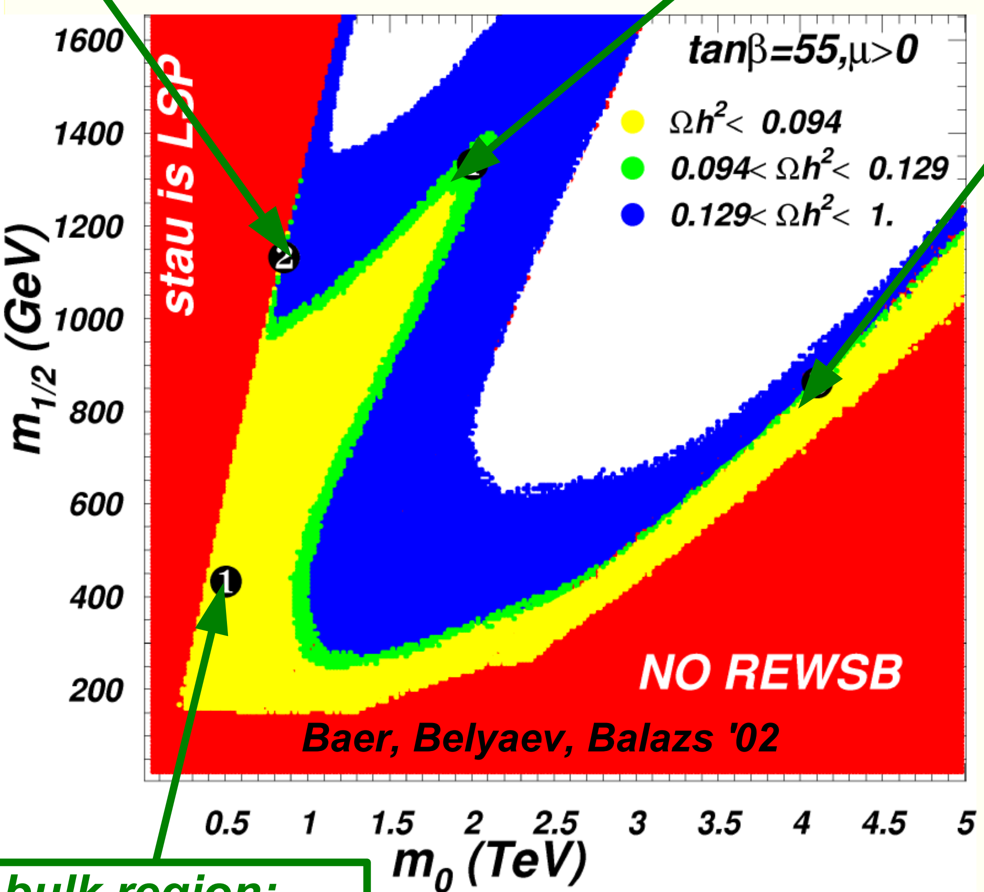
Natural SUSY in the Focus Point



Natural SUSY in the Focus Point

stau coannihilation: degenerate χ and stau

funnel: (large $\tan\beta$) annihilation via A, H

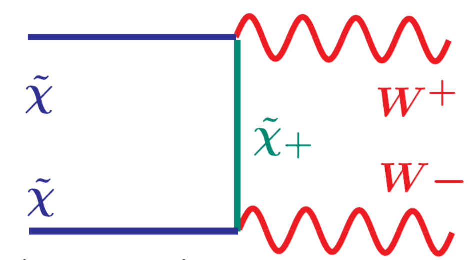


bulk region: light sfermions

Focus Point region

- mixed (Higgsino-Bino-Wino) χ
- low μ – potentially low fine-tuning

  initially pointed in
  Chan, Chattopadhyay, Nath '97
  Feng, Matchev, Moroi '99
  Baer, Chen, Paige, Tata '95 papers as
  Hyperbolic Branch/Focus Point region
  which being re-analised again in recent papers
- low DM relic density, because of in large annihilation CS



- High direct detection DM rate

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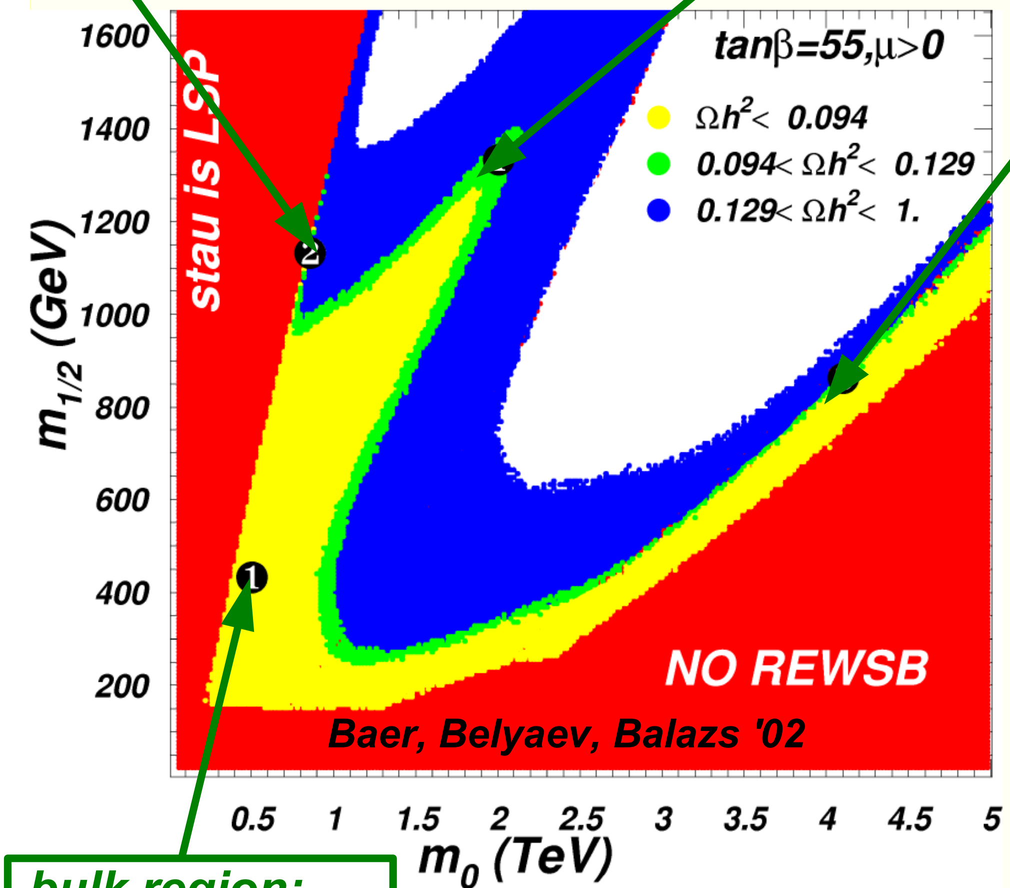

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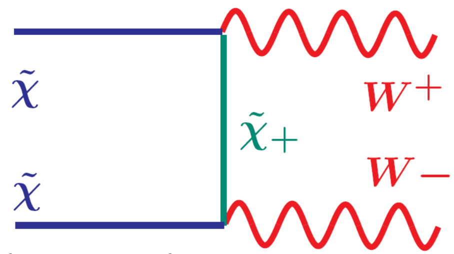


- High direct detection DM rate

It was recently argued [Baer, Barger, Mickelson '13] that EW fine-tuning in SUSY can be grossly overestimated by neglecting additional non-independent terms which lead to large cancellations favouring HB/FP for NSUSY

Far Focus Point Scenario

chargino-neutralino mass matrices

in $(\tilde{W}^-, \tilde{H}^-)$ basis

$$\begin{pmatrix} M_2 & \sqrt{2} m_W c_\beta \\ \sqrt{2} m_W s_\beta & \mu \end{pmatrix}$$

charginos

in $(\tilde{B}^0, \tilde{W}^0, \tilde{H}^0_1, \tilde{H}^0_2)$ basis

$$\begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w \\ 0 & M_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w \\ -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu \\ m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0 \end{pmatrix}$$

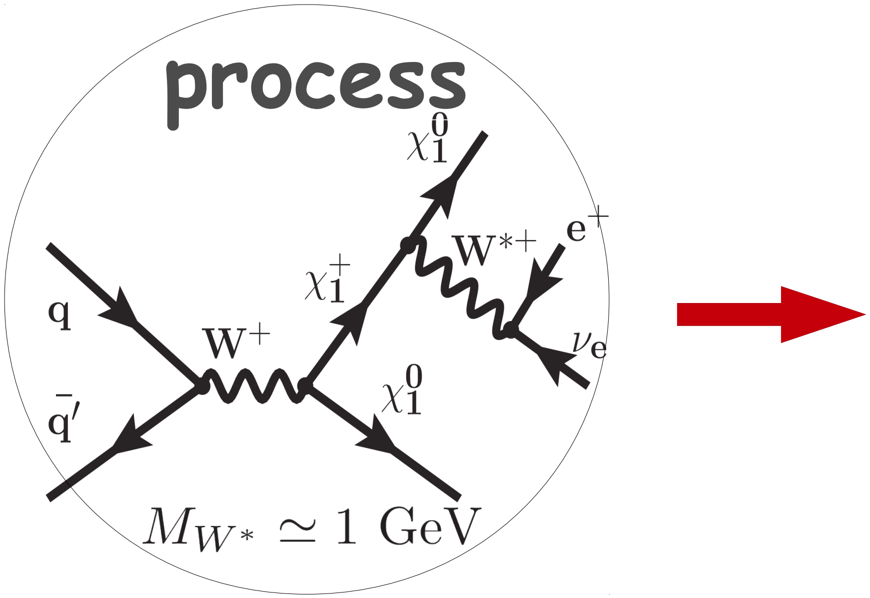
neutralinos

M_2 real, $\quad M_1 = |M_1| e^{-\Phi_1}, \quad \mu = |\mu| e^{i\Phi_\mu}$

- **Case of μ << M1, M2: $\chi^0_{1,2}$ and $\chi^\pm$ become quasi-degenerate and acquire large higgsino component. This provides a naturally low DM relic density via gaugino annihilation and co-annihilation processes into SM V's and H**
- **This is the case of relatively light higgsinos-electroweakinos compared to the other SUSY particles.**
- **This scenario is not just motivated by its simplicity, but also by the lack of evidence for SUSY to date, indicating that a weak scale SUSY spectrum is likely non-universal**

FFP Mass Spectrum and Challenge for the LHC

- HB/FP parameter space is challenging to probe at the LHC even if the mass gap between gauginos is large enough to for leptonic signatures
  [Baer, AB, Krupovnickas, O'Farrill '04].
- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for any leptonic signature as happen in FFP scenario.
- The only way to probe FFP is a mono-jet signature
  [Where the Sidewalk Ends? ... Alves, Izaguirre,Wacker '11] ,
  which has been used in studies on compressed SUSY spectra, *e.g.*
  Dreiner,Kramer,Tattersall '12; Han,Kobakhidze,Liu,Saavedra,Wu'13; Han,Kribs,Martin,Menon '14



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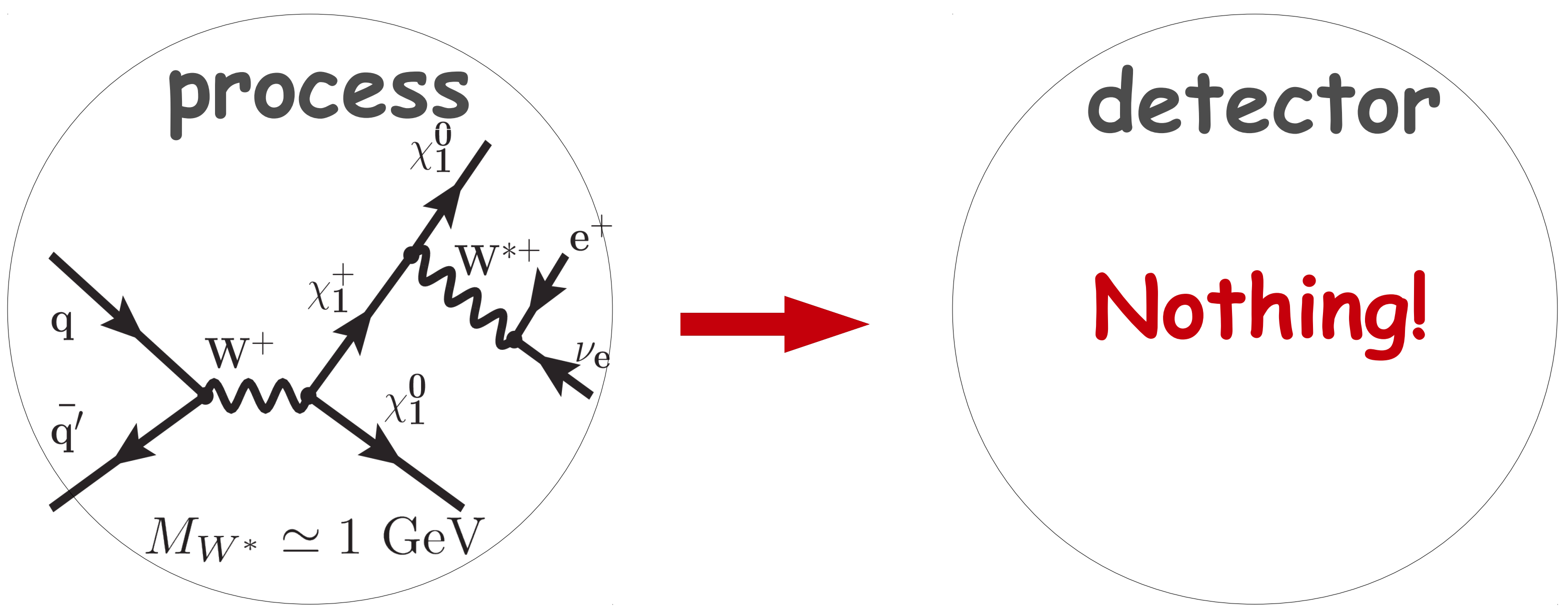

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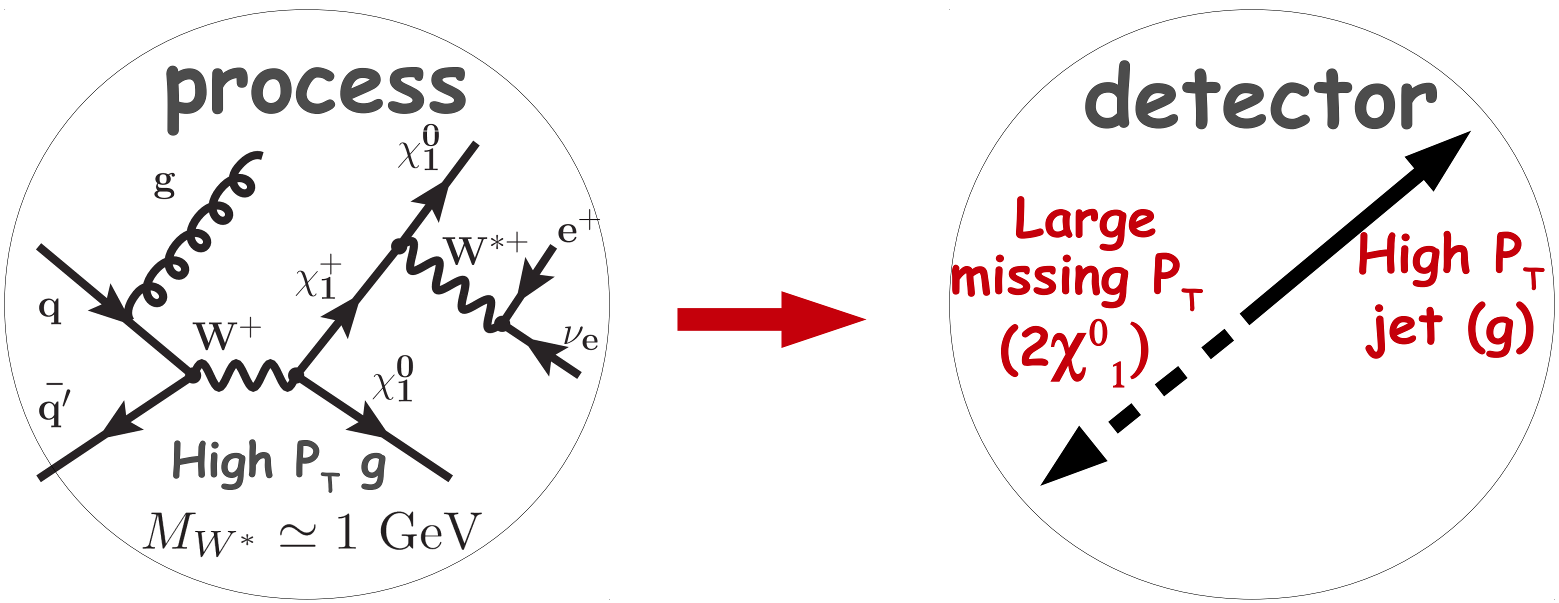

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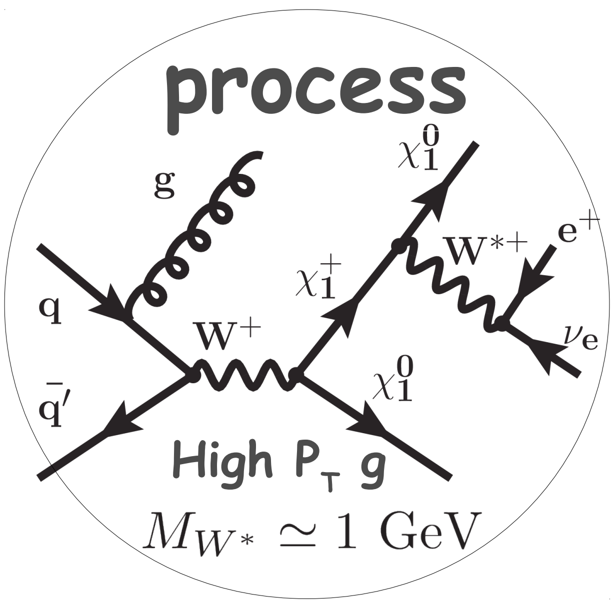
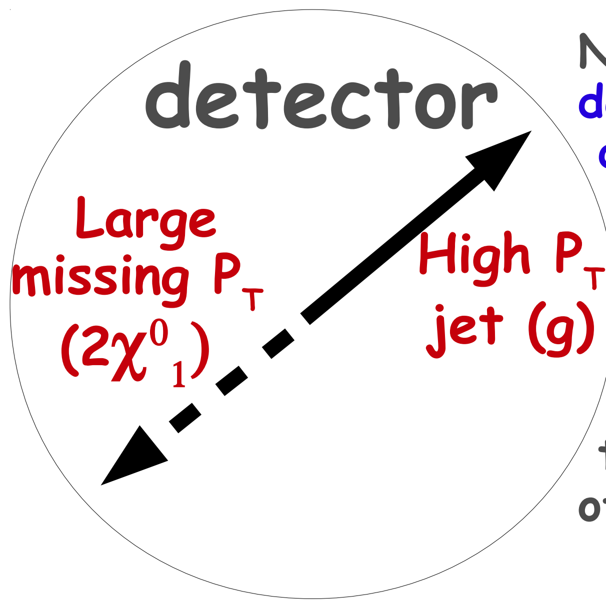




Note that **W* decay products do not get large boost** – it is proportional to the mass of W* which is much smaller than the mass of the LSP

Spectrum and Decays in FFP

in the limit |μ| ≪ |M1|, |M2| we find

$$m_{\tilde\chi^0_{1,2}} \simeq \mp\left[|\mu| \mp \frac{m_Z^2}{2}(1\pm s_{2\beta})\left(\frac{s_W^2}{M_1}+\frac{c_W^2}{M_2}\right)\right]$$

$$m_{\tilde\chi_1^\pm} \simeq |\mu|\left(1+\frac{\alpha(m_Z)}{\pi}\left(2+\ln\frac{m_Z^2}{\mu^2}\right)\right) - s_{2\beta}\frac{m_W^2}{M_2}$$

$$\Delta m_o = m_{\tilde\chi^0_2} - m_{\tilde\chi^0_1} \simeq m_Z^2\left(\frac{s_W^2}{M_1}+\frac{c_W^2}{M_2}\right)$$

$$\Delta m_\pm = m_{\tilde\chi_1^\pm} - m_{\tilde\chi^0_1} \simeq \frac{\Delta m}{2} + \mu\frac{\alpha(m_Z)}{\pi}\left(2+\ln\frac{m_Z^2}{\mu^2}\right)$$

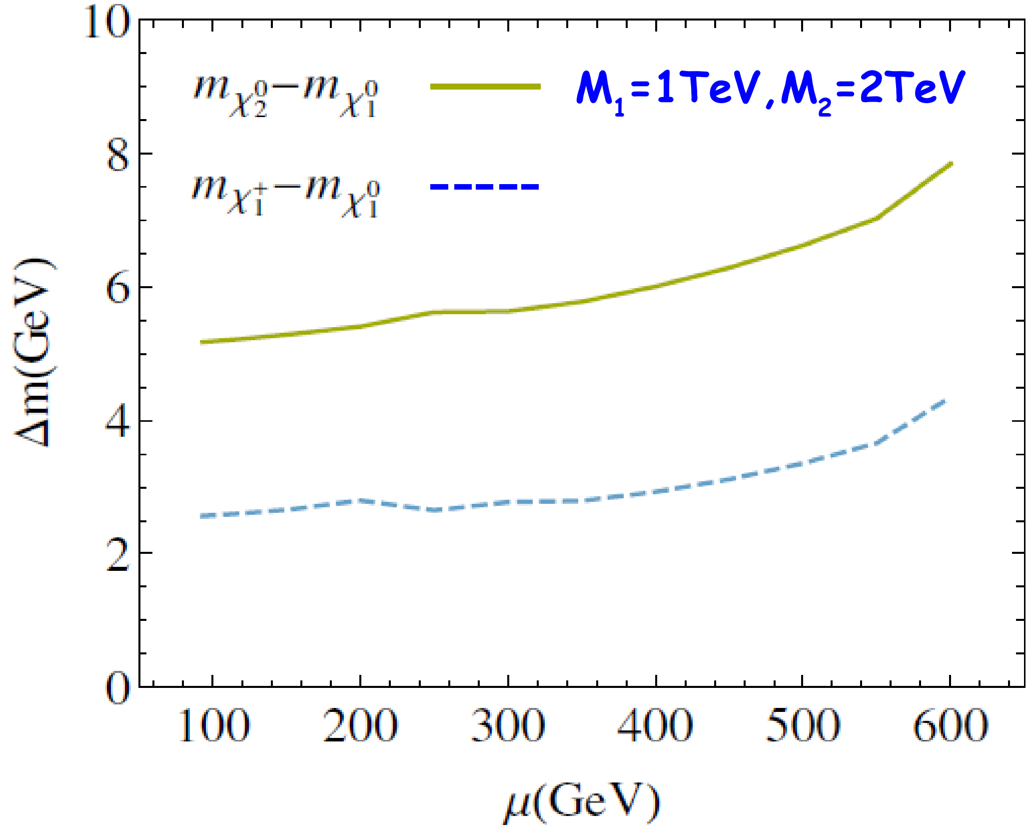
$$\Gamma(\tilde\chi_1^\pm, \tilde\chi_2^0 \to f\, f'\, \tilde\chi_1^0) = \frac{C^4}{120\pi^3}\frac{\Delta m^5}{\Lambda^4}$$

$$C^4 \simeq \frac{1}{4}\frac{g^4}{c_W^4}(s_w^2 - 1/2)^2$$

$$L = c\tau \simeq 0.01\ \text{cm}\left(\frac{\Delta m}{1\ \text{GeV}}\right)^{-5} \quad \tilde\chi_2^0 \to f\,\bar f\,\tilde\chi_1^0 \ \text{(Z-exchange)}$$

$$L = c\tau \simeq 0.006\ \text{cm}\left(\frac{\Delta m}{1\ \text{GeV}}\right)^{-5} \quad \tilde\chi_1^\pm \to f\,f'\,\tilde\chi_1^0 \ \text{(W-exchange)}$$

for Δm < 1 GeV one expect to start seeing displaced vertices ~ 0.1mm

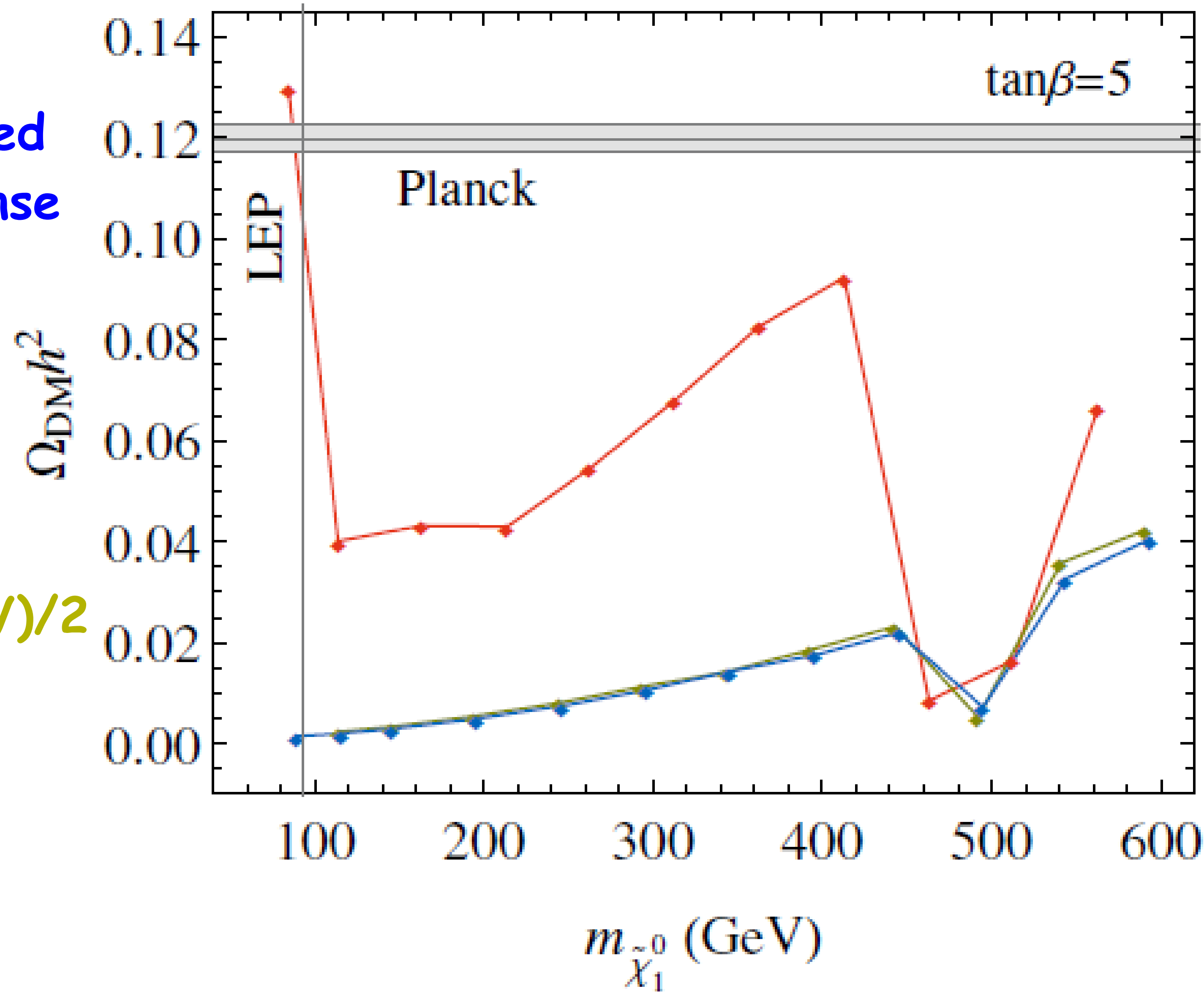


Dark Matter: Relic Density

in the FFP region DM relic density is below the measured one because of intense LSP annihilation and co-annihilation processes

- Red: M1=m
- Yellow: M1=(m+1TeV)/2
- Blue: M1=1TeV

$$\Omega_{DM}^{Planck} h^2 = 0.1198 \pm 0.0026$$



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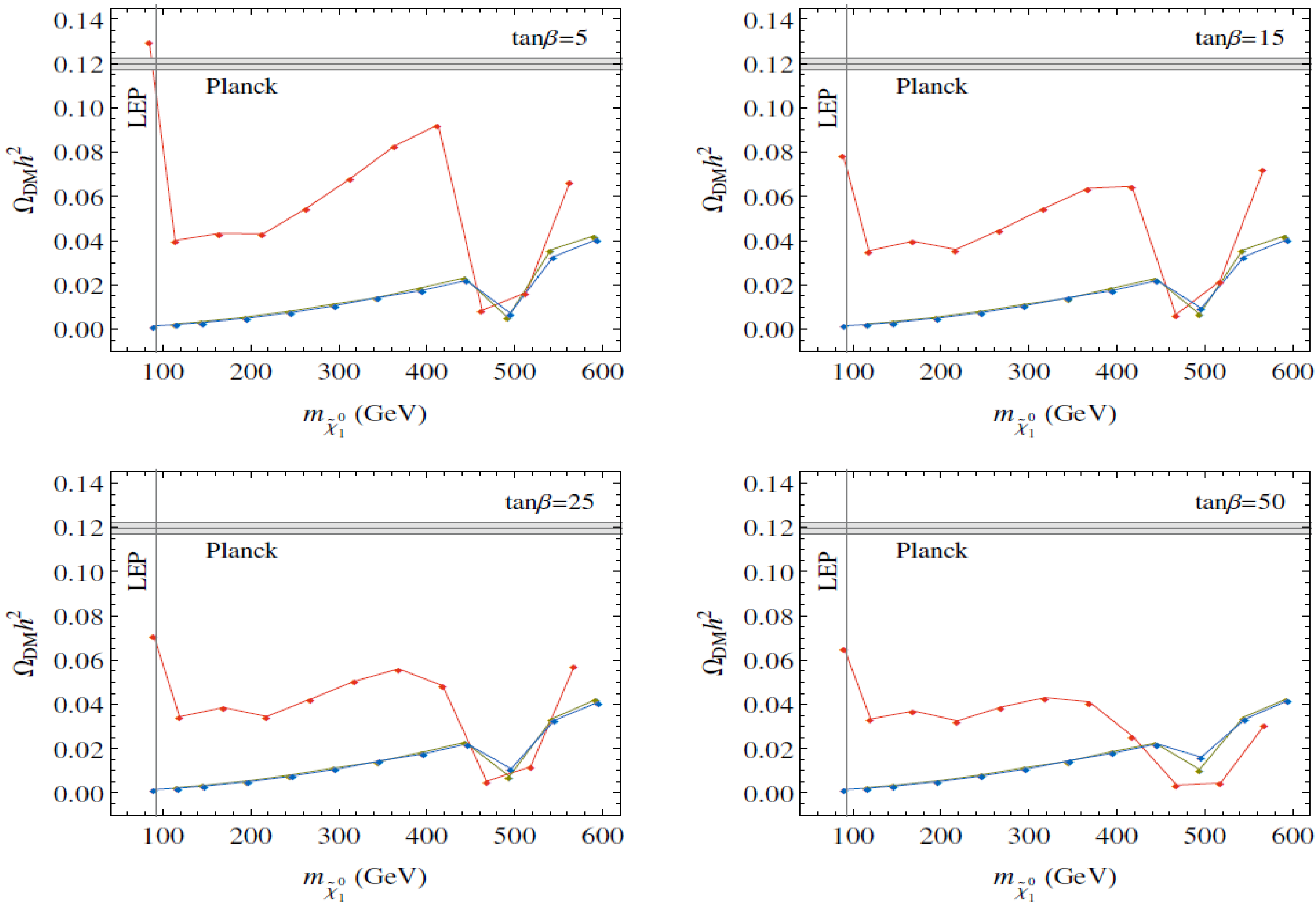
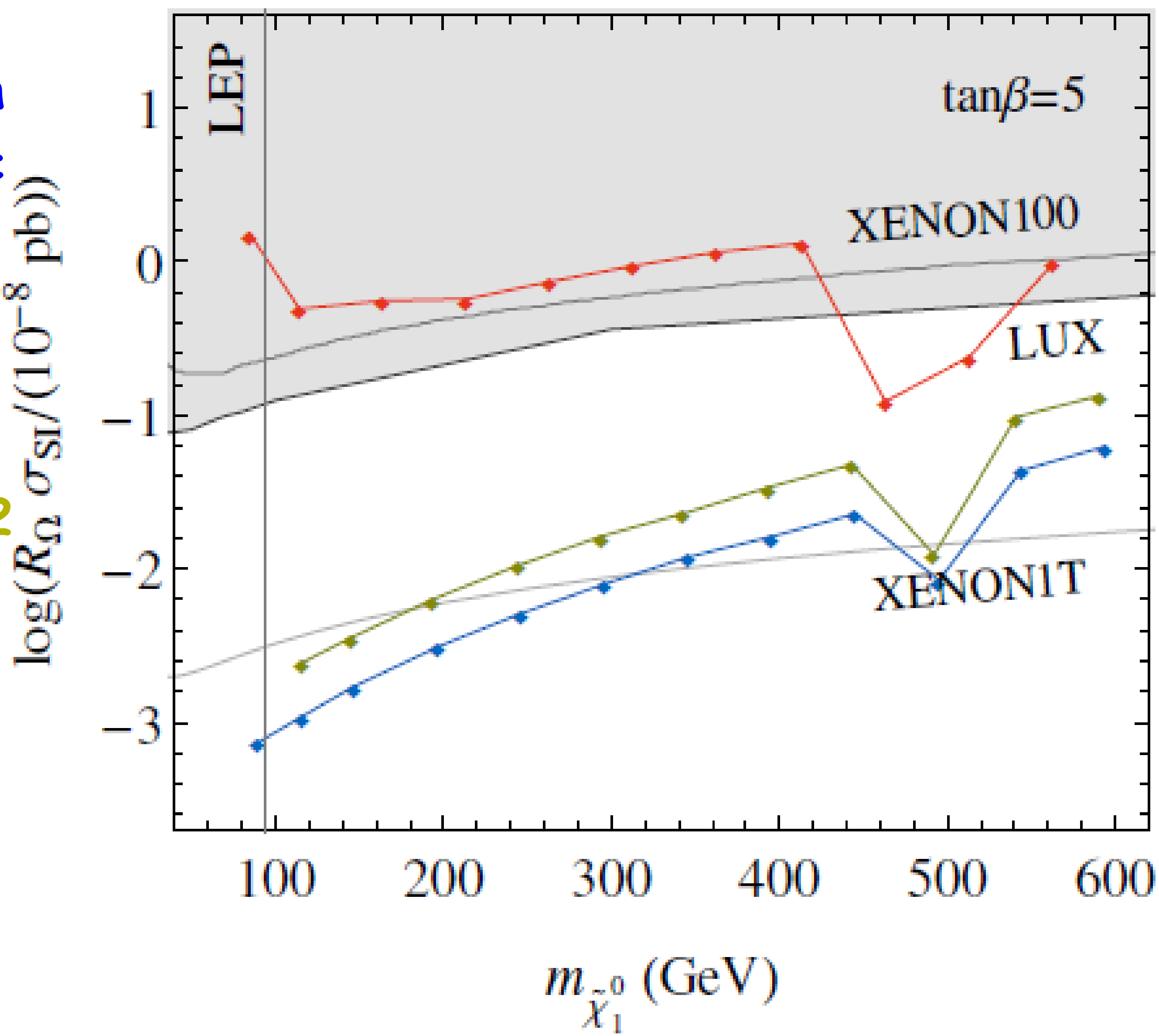


Dark Matter: Direct Detection

Direct detection rates are re-scaled with with the respective DM relic density



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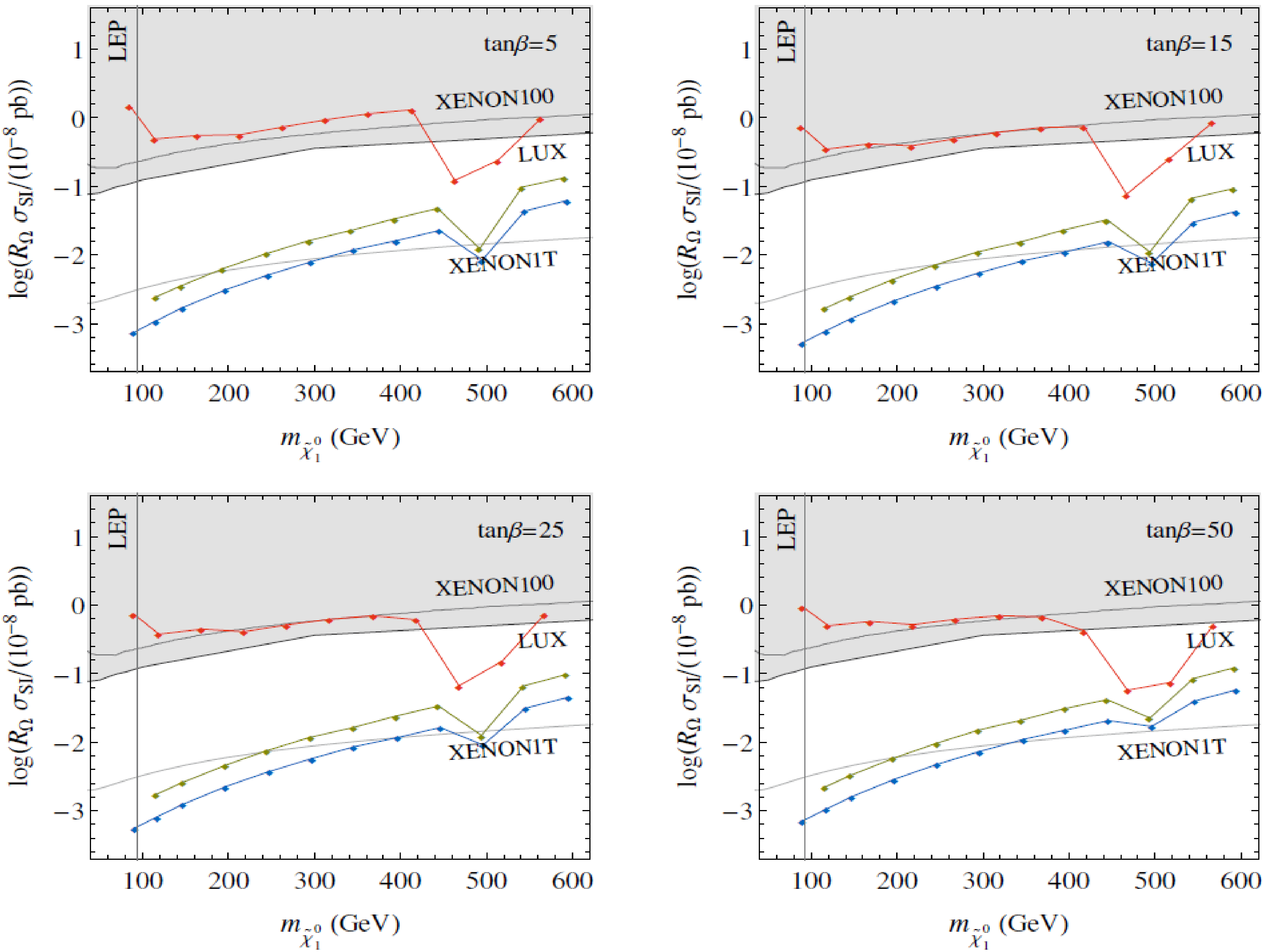
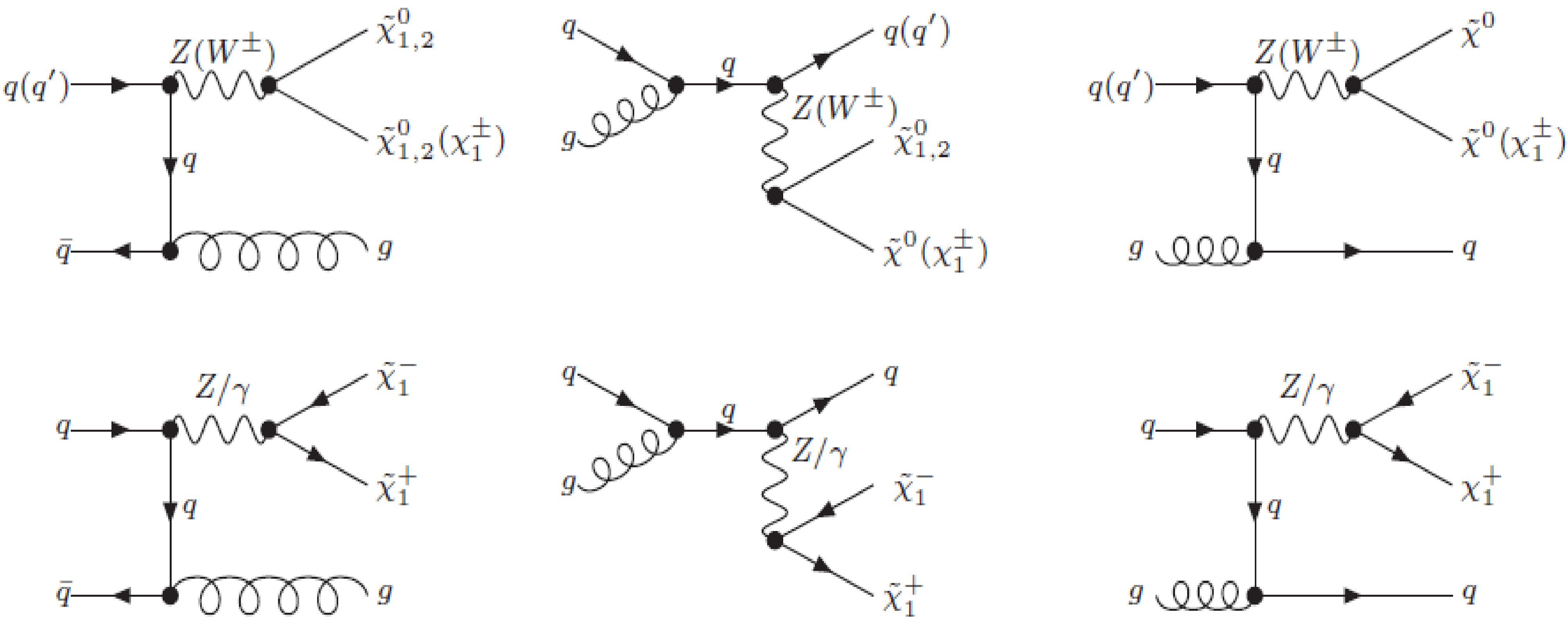


LHC sensitivity to FFP

through the pp → $\chi\chi j$: $\chi = \chi^0_{1,2}$, $\chi^\pm_1$ process



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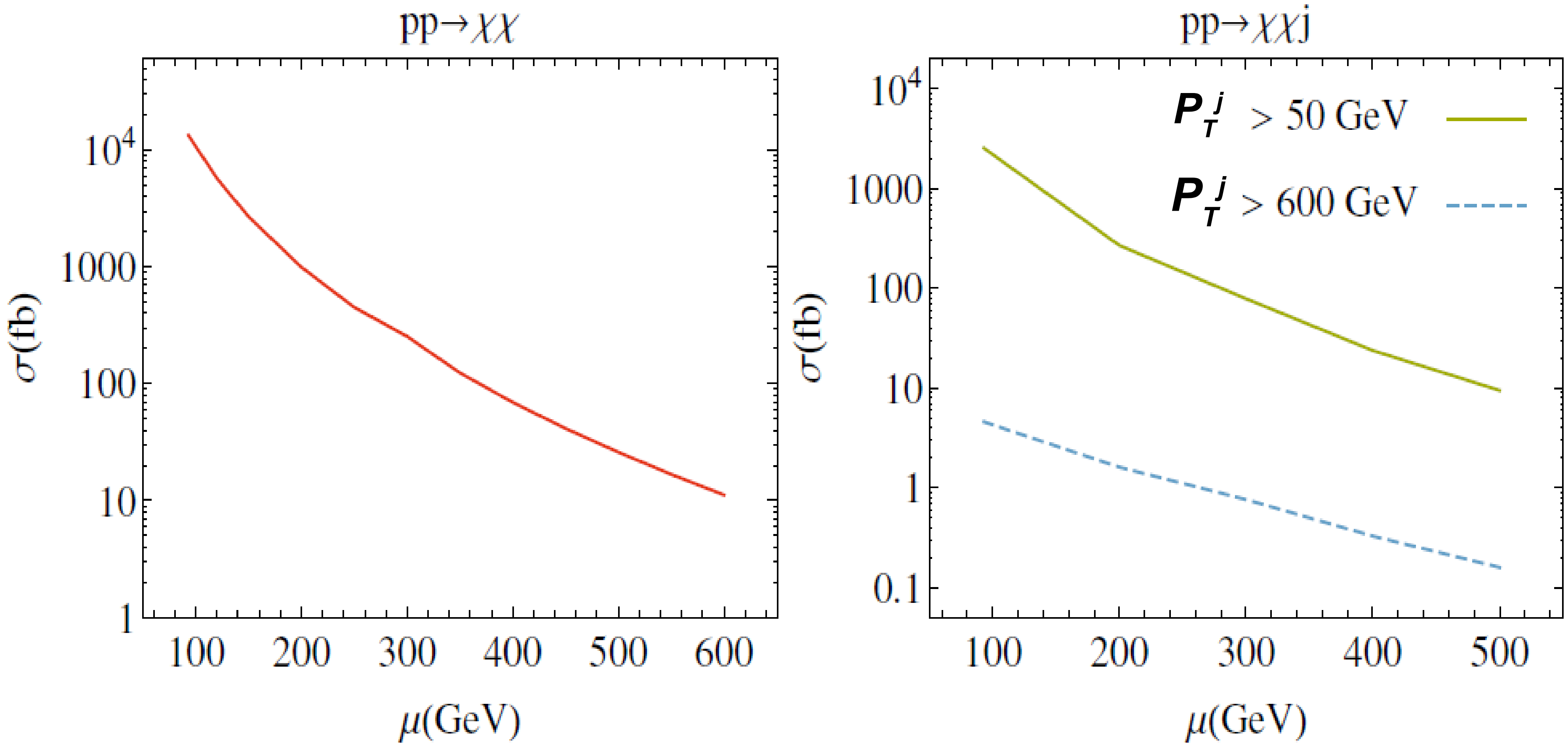


Analysis Setup

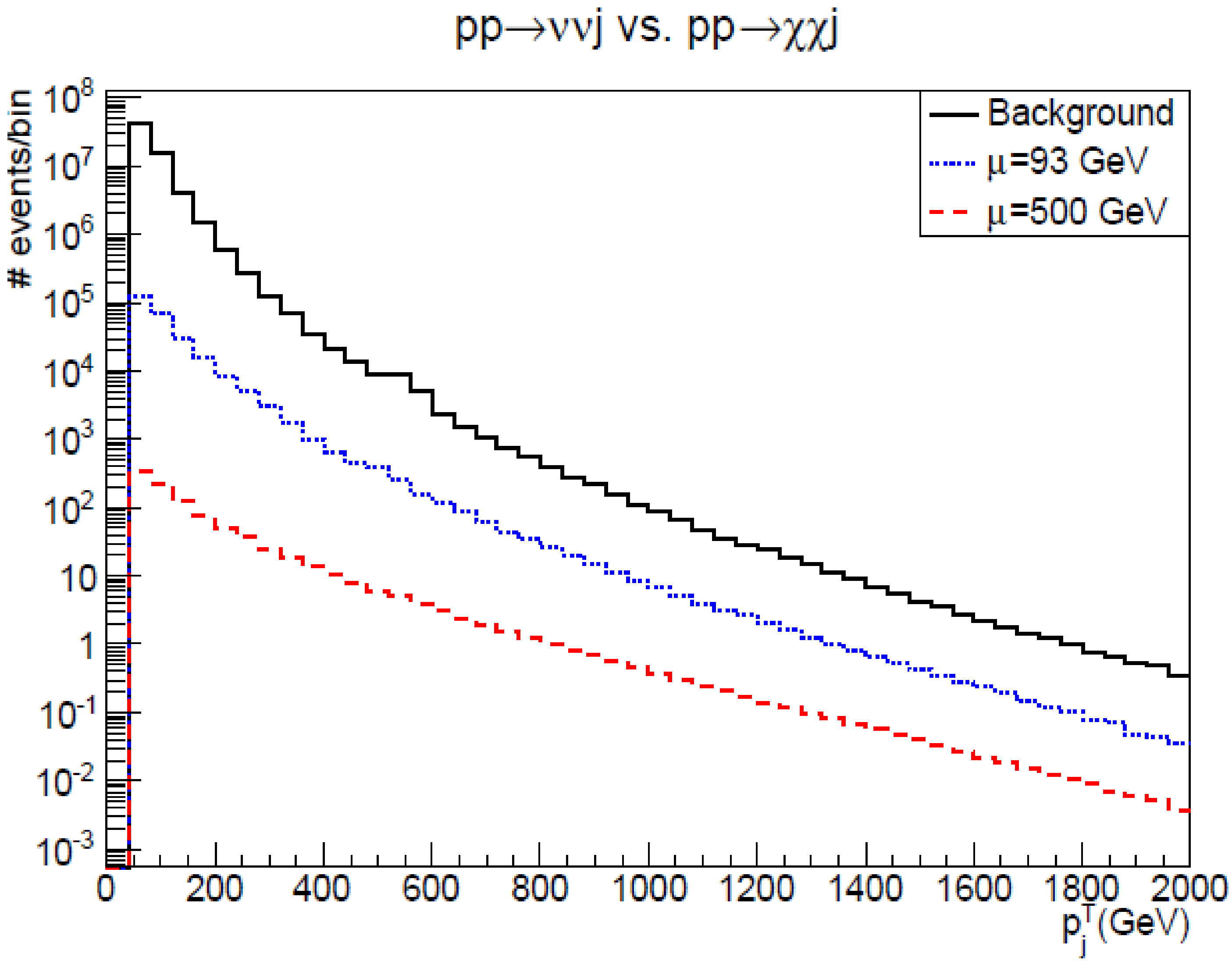
- MSSM
- SPHENO for mass spectrum, cross checked with
- ISAJET
- MadGraph for parton level simulations, cross checked with CalcHEP
- PYTHIA6 for hadronization and parton-showering
- Delphes3 for fast detector simulation
- CTEQ6L1 PDF

Main backgrounds for p_T jet + high MET signature

- Irreducible Z +jet → νν +jet (Zj)
- Reducible W +jet → ℓν + jet (Wj) when ℓ is missed

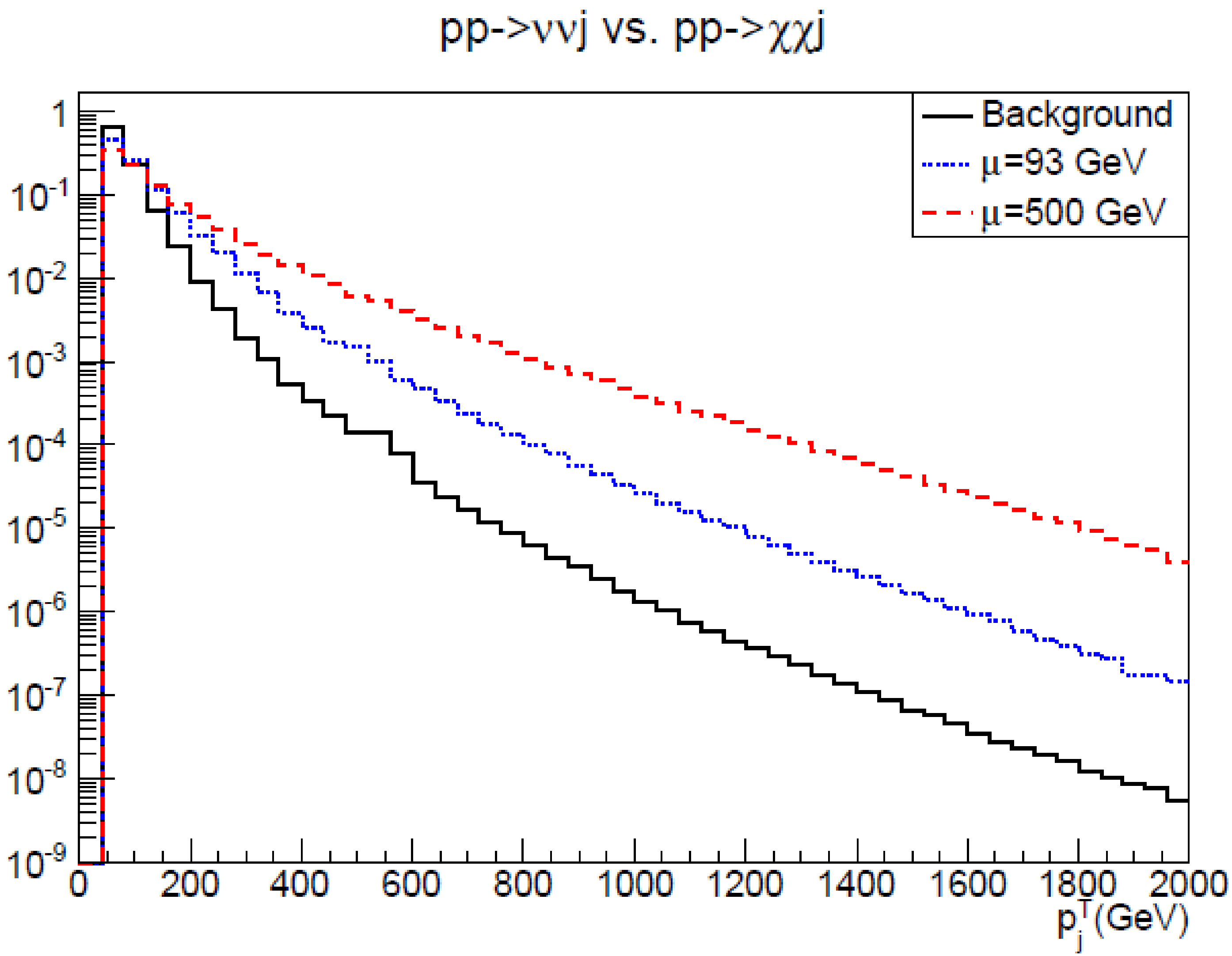
Signal vs Background analysis

difference in rates is quite pessimistic ...

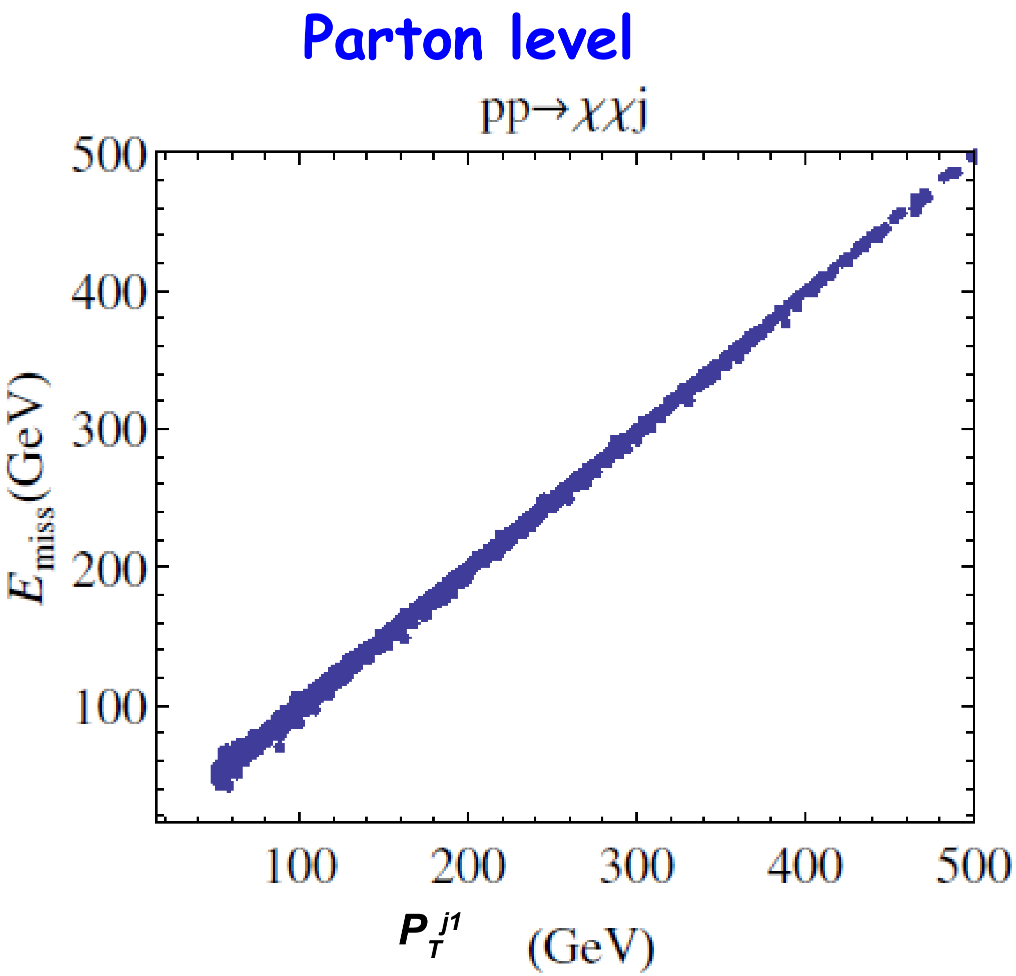


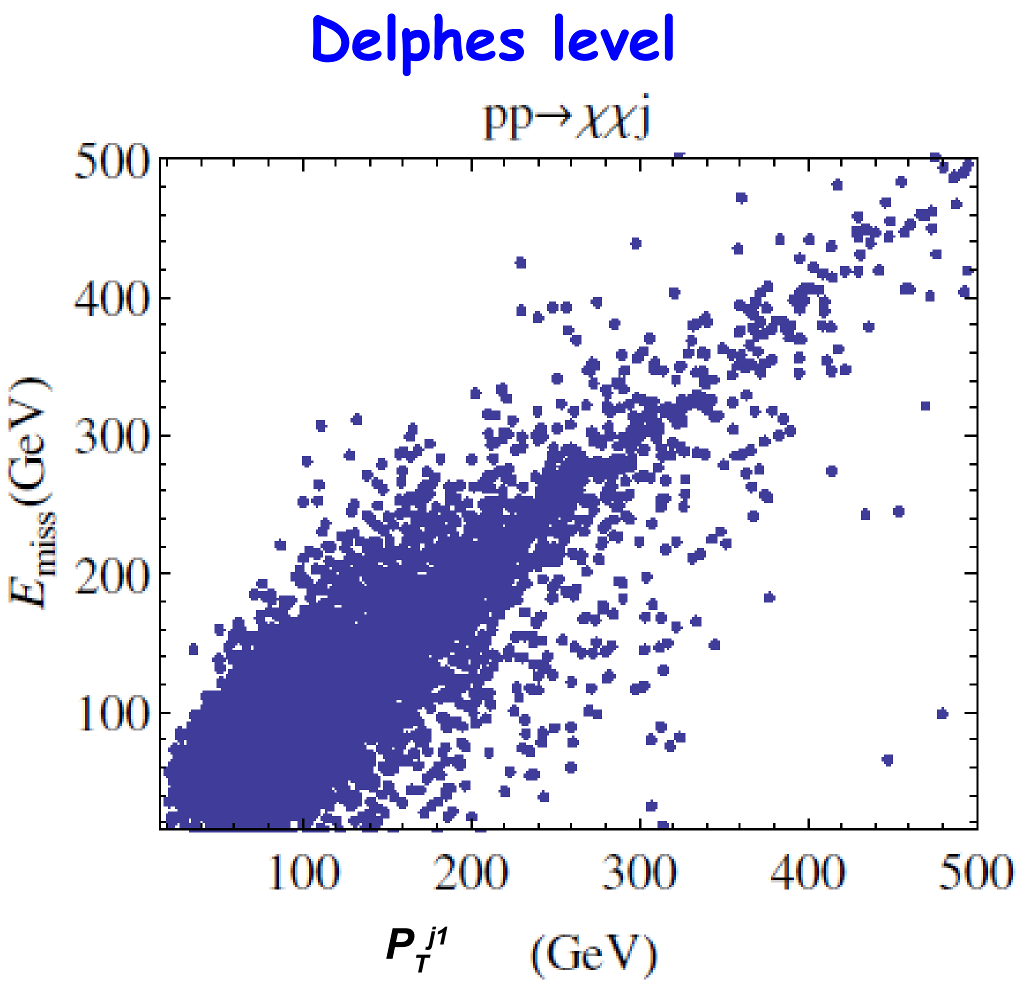
Signal vs Background analysis

but the difference in shapes is quite encouraging!



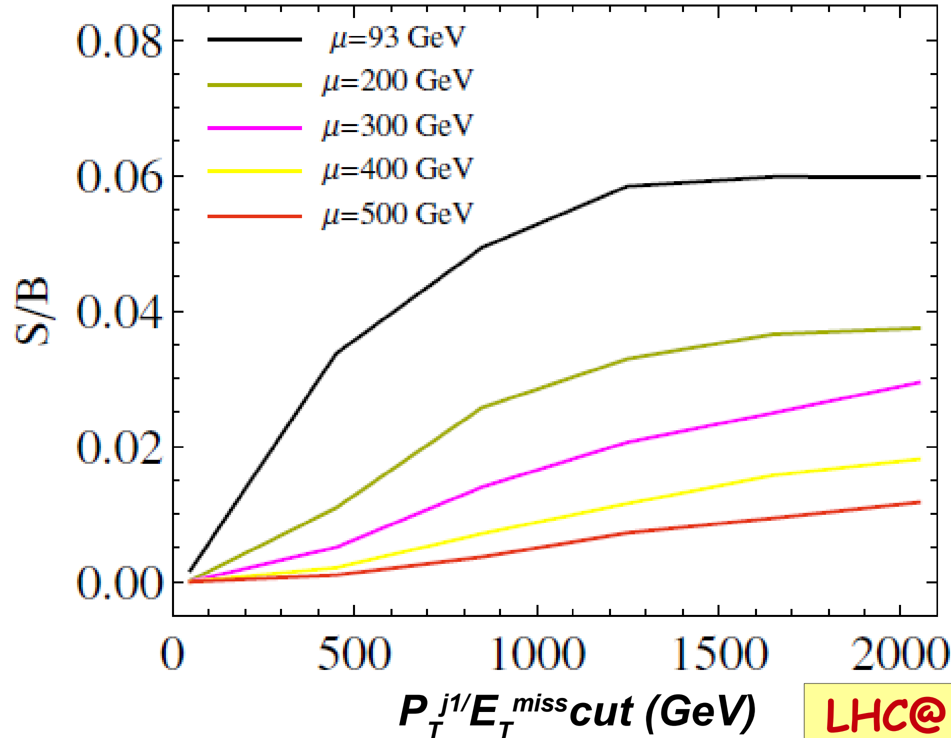
Parton vs Detector simulation level

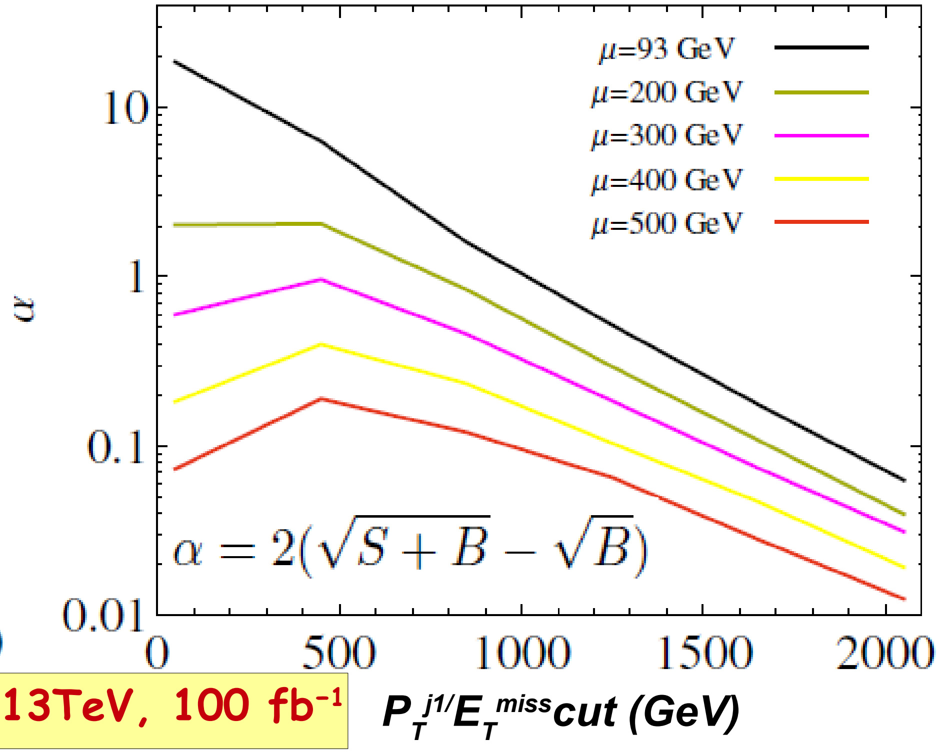




- the lack of the perfect p_T^{j1} vs MET correlations leads to a visible difference of the S/B ratio and significance, and should be taken into account.

S/B vs Signal significance





LHC@13TeV, 100 fb^{-1}

	$Z(\nu\bar{\nu})j$	$W(\ell\nu)j$	$\mu = 93$ GeV	$\mu = 500$ GeV
$p^T_{jet} > 50$ GeV, $\lvert\eta_{jet}\rvert < 5$	6.4 E+7	2.9 E+8	2.6 E+5	948
Veto $p^T_{e^\pm,\mu^\pm/\tau^\pm}$ >10/20 GeV	6.2 E+7	1.2 E+8	2.5 E+5	921
p^T_j >500 GeV	2.5 E+4	2.0 E+4	1051	32
$p^T_j = \not{E}_T$ >500 GeV	1.5 E+4	4.1 E+3	747	27
$p^T_j = \not{E}_T$ >1000 GeV	315 (375)	65 (32)	21 (31)	2 (2)
$p^T_j = \not{E}_T$ >1500 GeV	18 (20)	2 (1)	1 (2)	0 (0)
$p^T_j = \not{E}_T$ >2000 GeV	1 (1)	0 (0)	0 (1)	0 (0)

- There is an important tension between S/B and signal significance
- S/B pushes E_t^{miss} cut up towards an acceptable systematic
- significance requires comparatively low (below 500 GeV) E_t^{miss} cut

What is the minimal S/B is accessible?

- **ATLAS and CMS LHC@8 collaborations studied the related systematic error**

  sources of systematic uncertainty and their contributions (in %) to the total uncertainty on the Z(νν) background from CMS PAS EXO-12-048

E_T^{miss} (GeV)	> 250	> 300	> 350	> 400	> 450	> 500	> 550
Statistics (N^{obs})	1.7	2.6	3.9	5.6	7.6	10.9	14.6
Background (N^{bgd})	0.8	0.6	0.8	0.2	0.0	0.0	0.0
Acceptance (A)	2.0	2.0	2.0	2.1	2.1	2.2	2.4
Selection efficiency (ϵ)	2.0	2.0	2.1	2.2	2.4	2.7	3.1
Total	4.5	4.9	5.8	7.1	8.9	12.1	15.6

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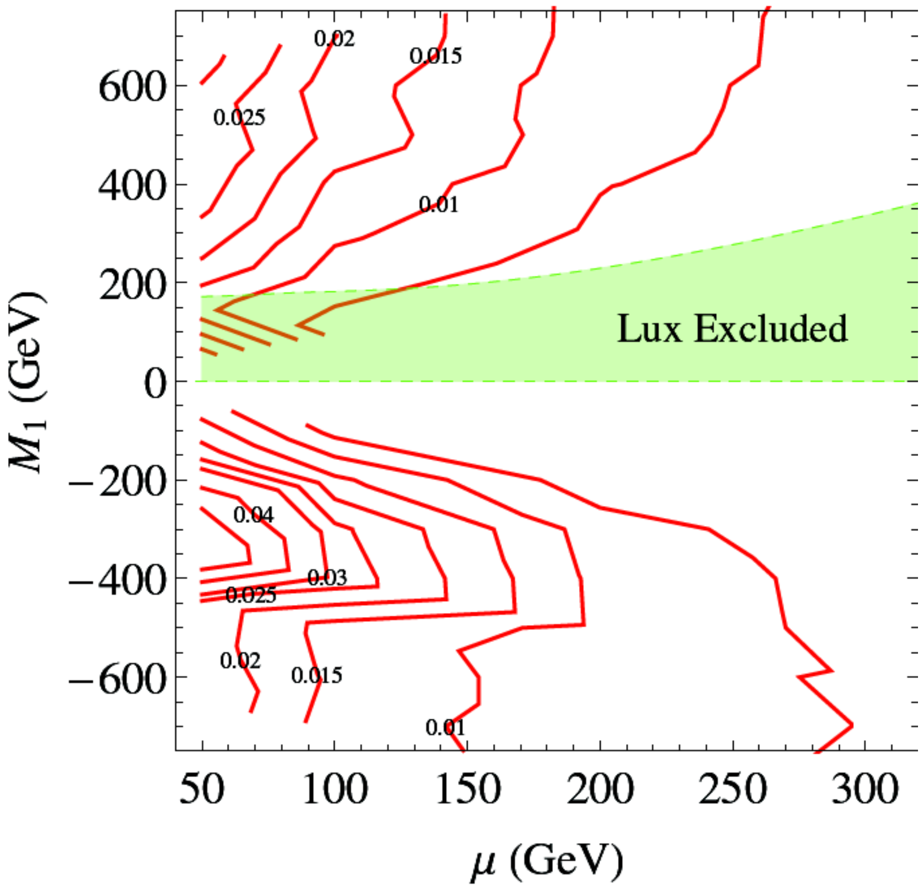
- So, the realistic (or even optimistic!) S/B one should be looking at is ~ 5% or more

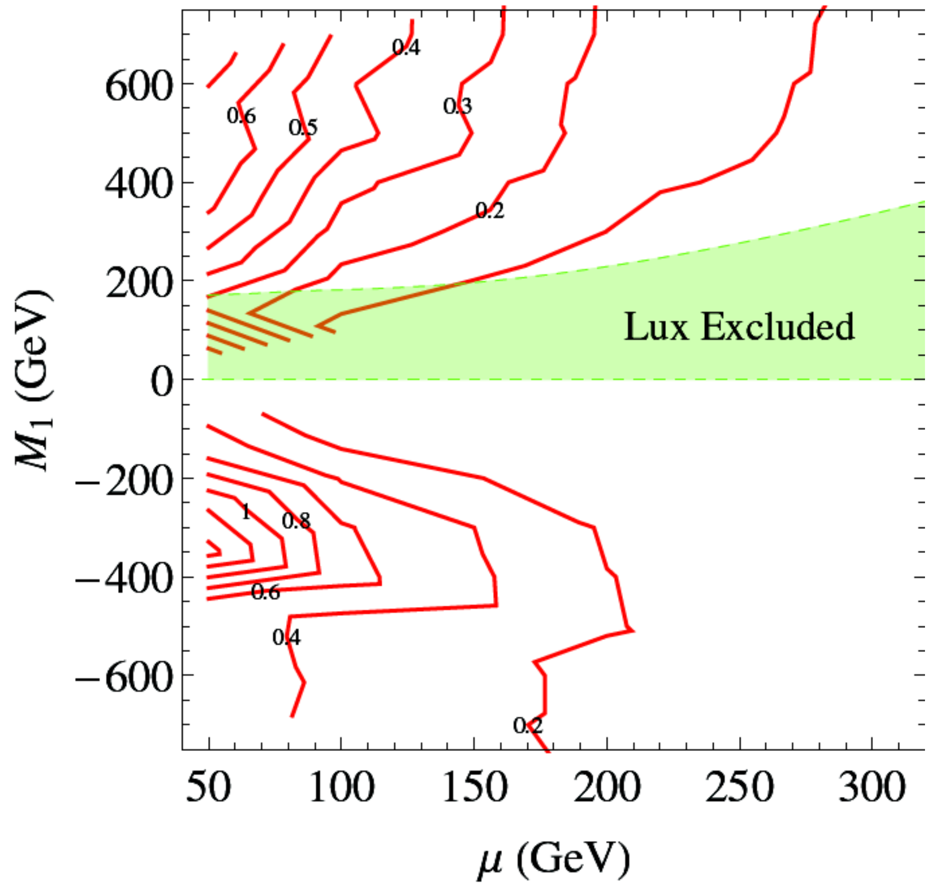
Interpreting LHC@8TeV results (CMS EXO-12-048)

Selection	W+jets	Z+j	Z($\nu\nu$)+j	$t\bar{t}$	QCD	Single top	Total
Cross section (pb)	229.0	34.1	588.3	225.2	1904.8	113.5	
$E_T^{miss} > 550$ GeV	136	1	429	3	0	0	569

S/B contour, S region 7

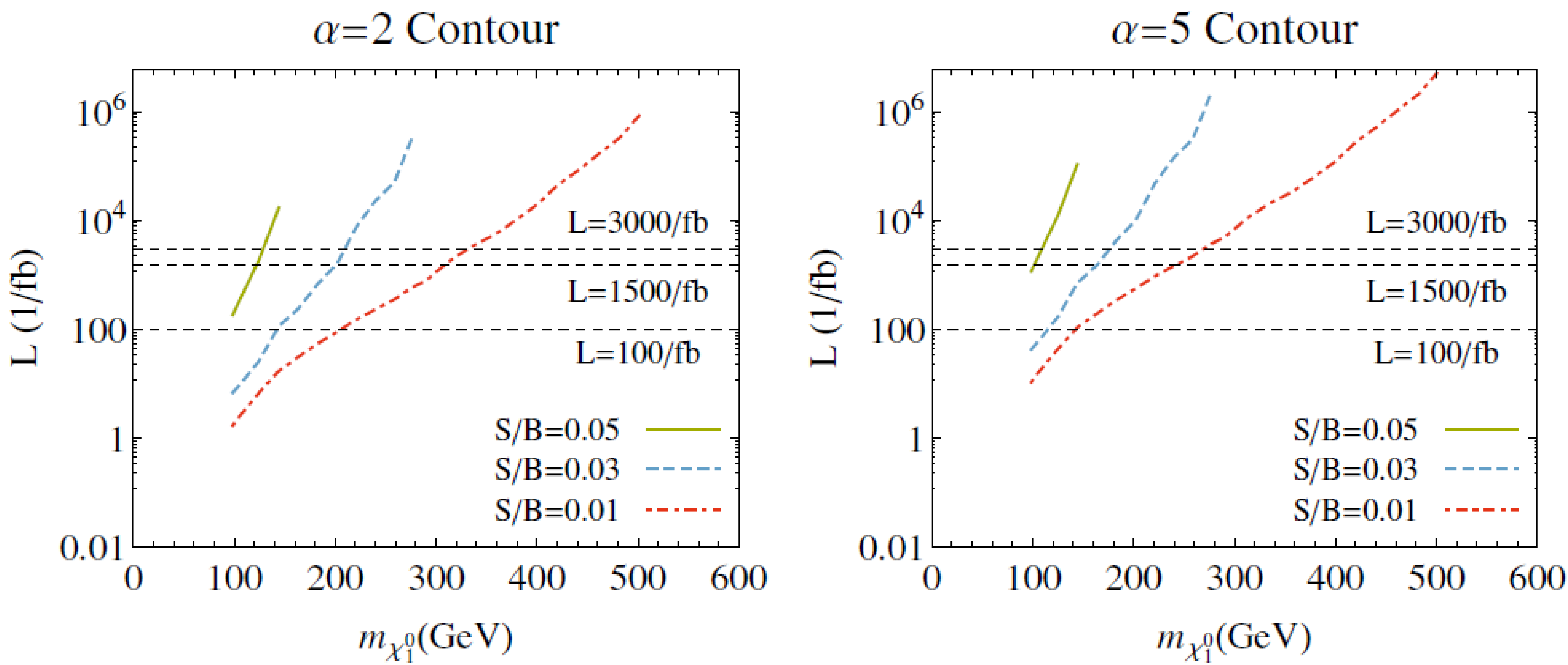


$2(\sqrt{S+B}-\sqrt{B})$ contour, S region 7



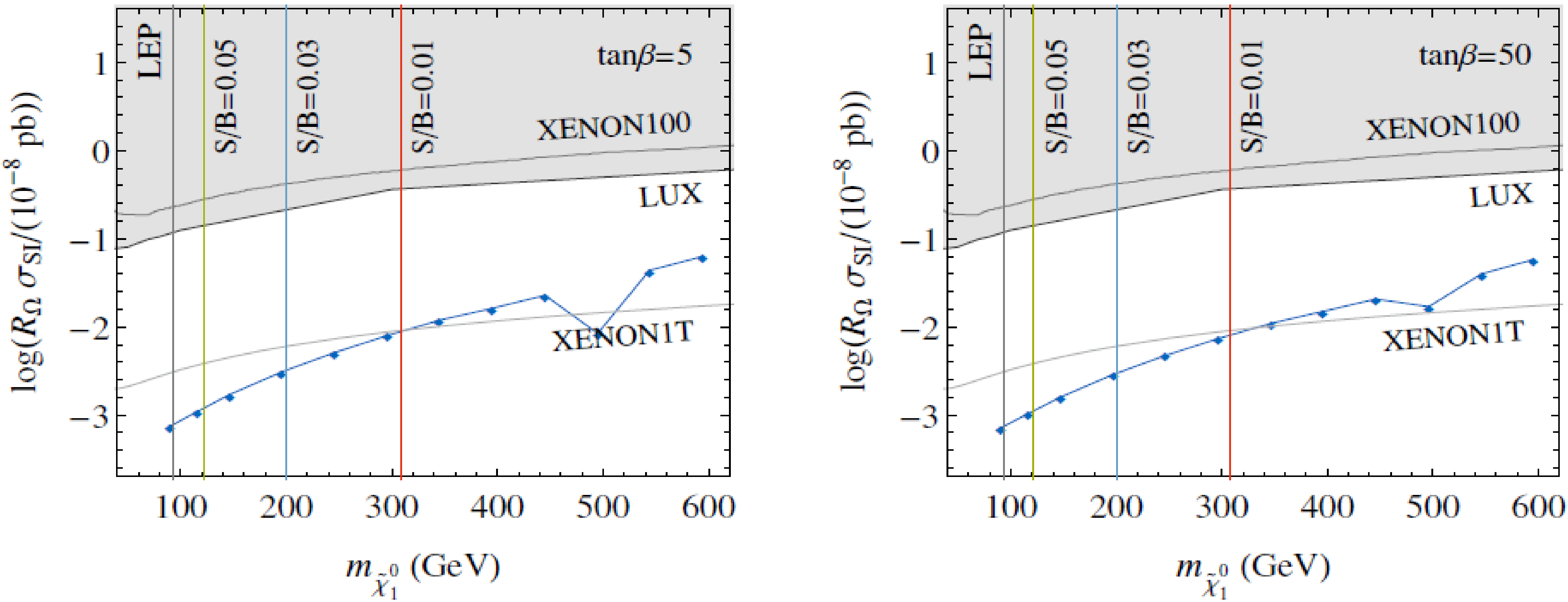
- **Both S/B and Significance are too low - so LHC@8 is unfortunately not sensitive to FFP region ...**

LHC@13 TeV potential to probe the FFP



- exclusion is limited to about 120 (130) GeV at 95%CL at 1.5 (3) ab^{-1}
- In case of S/B ratio at the 5% level, we could be able to claim a discovery up to 110 GeV LSP with 3 ab^{-1}

Dark Matter Direct detection complementary



- LUX and XENON1T are sensitive to the upper end of FFP of χ mass range starting from about 320 GeV
- making the very optimistic assumption that S/B ≃ 3%, the sensitivity of the LHC could extend up to 200 GeV LSP mass
- mass gap between 200 GeV and 320 GeV is problematic even for the combination of the LHC13TeV and XENON1T experiment and requires further attention

Discussion

- **Similar studies done in parallel:**
  - **Han,Kobakhidze,Liu,Saavedra,Wu,Yang '13 :**

    "FFP can be probed up to 200 GeV at 5 sigma level with 1.5 ab^{-1}"

    but S/B < 1% for 200 GeV LSP – not quite realistic to probe
  - **Baer, Mustafayev,Tata '14 :**

    "FFP can not be probed at the LHC, since S/B ~ 1%"

    may be bit too conservative, since S/B can be improved with high P_T cuts, this however requires high luminosity to keep statistics up
  - **Han,Kribs,Martin,Menon '14**

    interpreted LHC@8TeV results, found sensitivity up to 70-90 GeV

    study was done at the parton level, while at the detector level we have found that both S/B and significance are too low for LHC@8TeV to be sensitive to FFP

- **How important is the jet matching for this study?**
  - we have performed simulation starting from the hard P^j_T cut (500 GeV) to gain as much statistics as possible
  - we have checked that matching (up to the 3 jet) does not have visible effect (available in the backup slides)

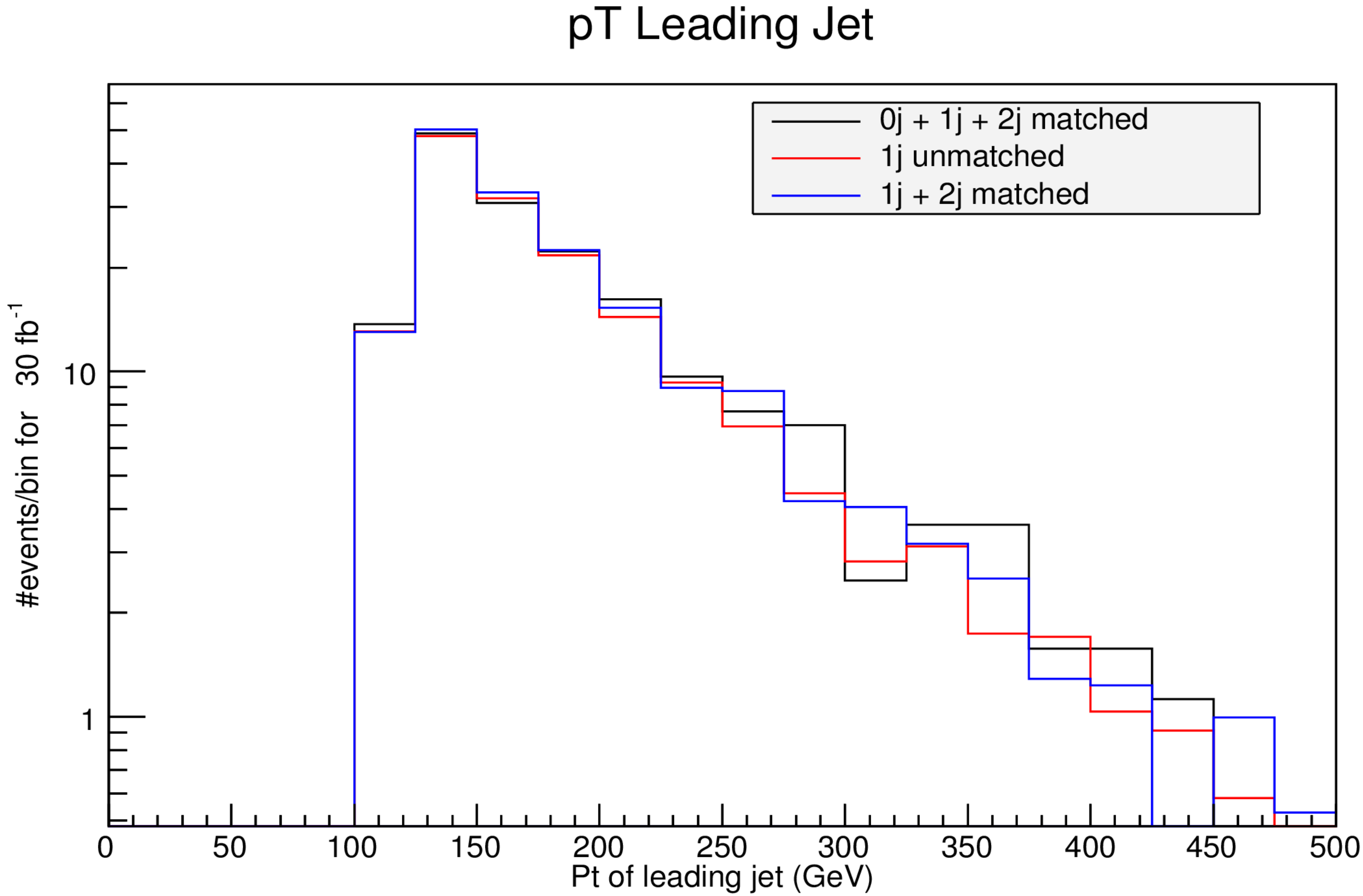
Conclusions

- FFP with light Higgsinos is not excluded (!) – so far we have ~ 100 GeV limit from LEP, so it is very important not to miss this scenario
- We have shown that in reality LHC@13 has potential to probe light Higgsinos up to about 130 GeV if S/B ~ 5% (or better) control is possible
- DDM search experiments – LUX and XENON1T are very complementary (from about 320 GeV)
- Mass gap 130-320 GeV requires a further attention

Thank You!

Matching vs non-Matching

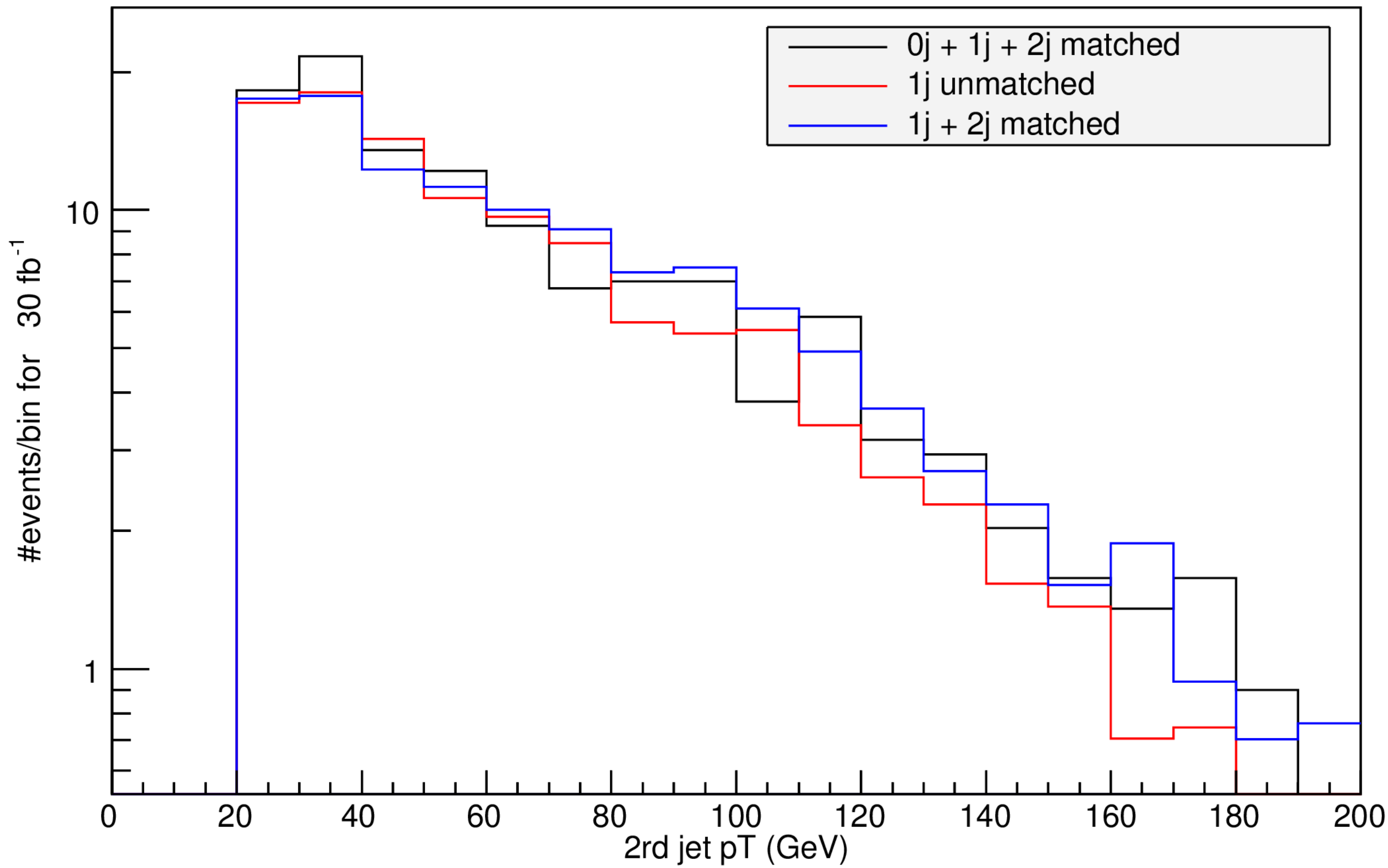
Marc Thomas



Matching vs non-Matching

Marc Thomas

2nd jet Pt



Matching vs non-Matching

Marc Thomas