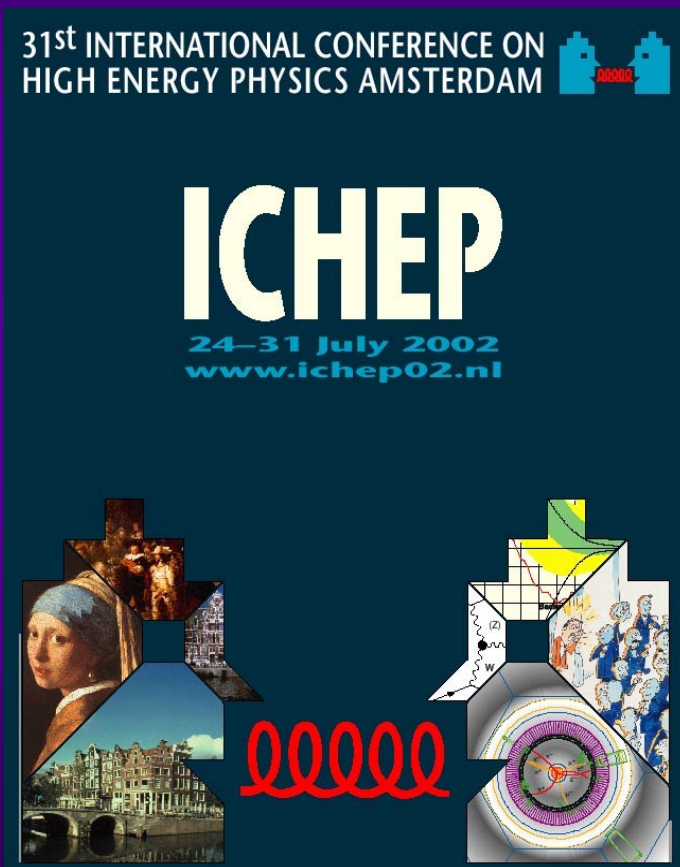


Beyond the Standard Model: experimental results



31st International
Conference on High
Energy Physics

Rob McPherson
University of Victoria and
Canadian Institute of



Particle Physics
Amsterdam



24-31 July 2002



This talk:

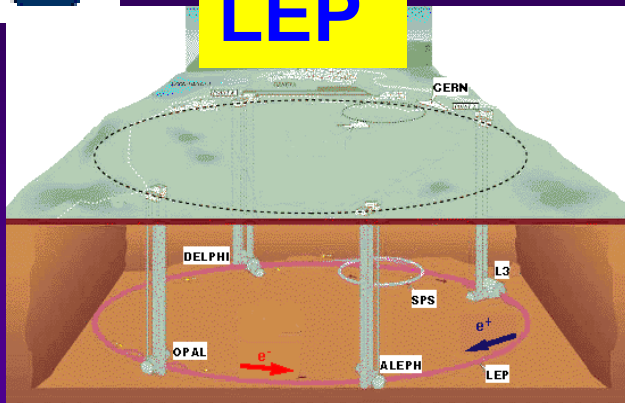
- ◆ Concentrate on results from current data
 - ◆ Direct searches for particles beyond the SM
 - ◆ Indirect constraints on physics beyond the SM
 - ◆ See Martin Grünewald's talk Tuesday for precision measurements and SM Higgs
- ◆ Will not devote (much) time to future prospects which are covered in other plenary talks
 - ◆ Tevatron: talks from Bedeschi and Narain
 - ◆ LHC: Sphicas (Tuesday)
 - ◆ Farther future: Wednesday ...
- ◆ Impossible (of course) to cover everything
 - ◆ 179 relevant abstracts submitted to ICHEP2002 alone!
 - ◆ ⇒ Selected topics and recent results



3 Colliders Dominate:



LEP



Tevatron



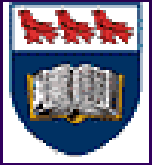
HERA



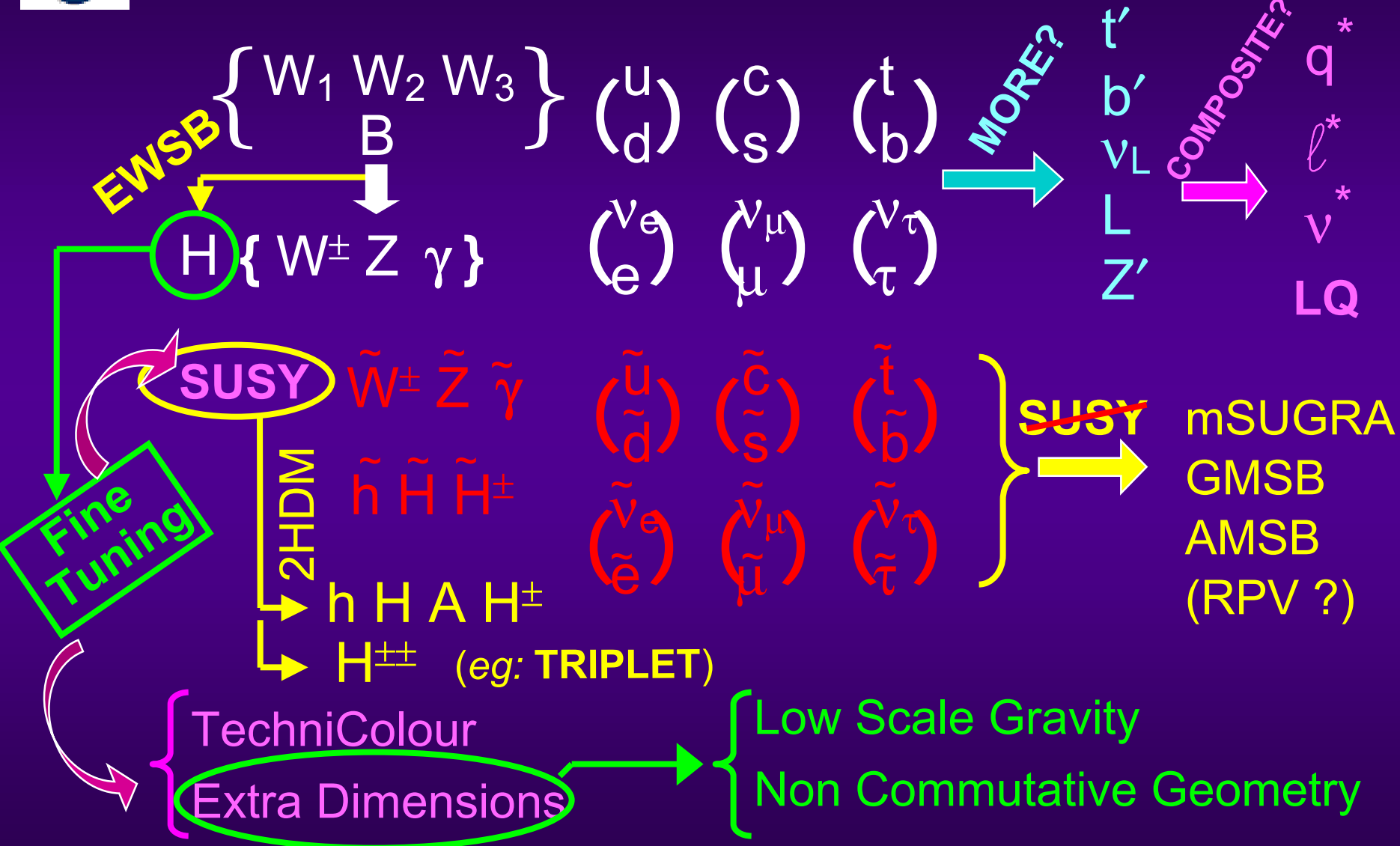
- ◆ $e^+ e^-$ collider
- ◆ $\sqrt{s} = 91\text{-}209$ GeV
- ◆ ≈ 900 pb⁻¹/expt
 - ◆ ALEPH
 - ◆ DELPHI
 - ◆ L3
 - ◆ OPAL
- ◆ Last data in 2000
- ◆ Analyses ongoing
- ◆ $\approx 71\%$ ICHEP02 BSM contributed papers

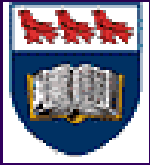
- ◆ $p\bar{p}$ collider
- ◆ $\sqrt{s} = 1.8\text{-}2$ TeV
- ◆ ≈ 100 pb⁻¹/expt
 - ◆ CDF
 - ◆ D0
- ◆ 2004: ≈ 2 fb⁻¹/expt
- ◆ 200x: 20 fb⁻¹/expt?

- ◆ $e^\pm p$ collider
- ◆ $\sqrt{s} = 300\text{-}320$ GeV
- ◆ ≈ 100 pb⁻¹/expt
 - ◆ H1
 - ◆ ZEUS
- ◆ 2006: ≈ 1 fb⁻¹/expt
- ◆ $\approx 12\%$ ICHEP02 BSM contributed papers

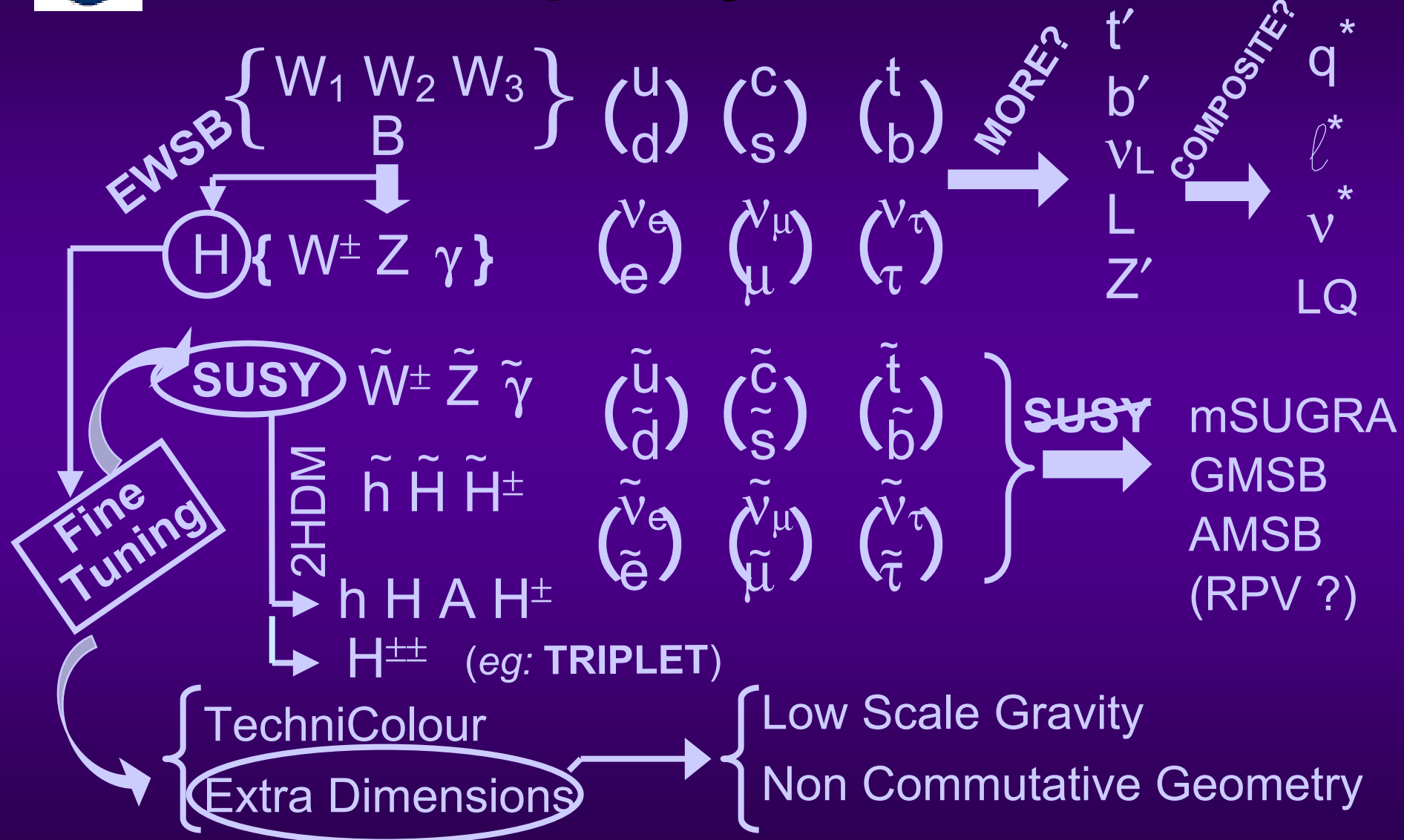


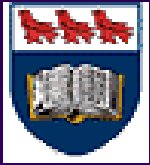
Roadmap: Beyond the S.M.



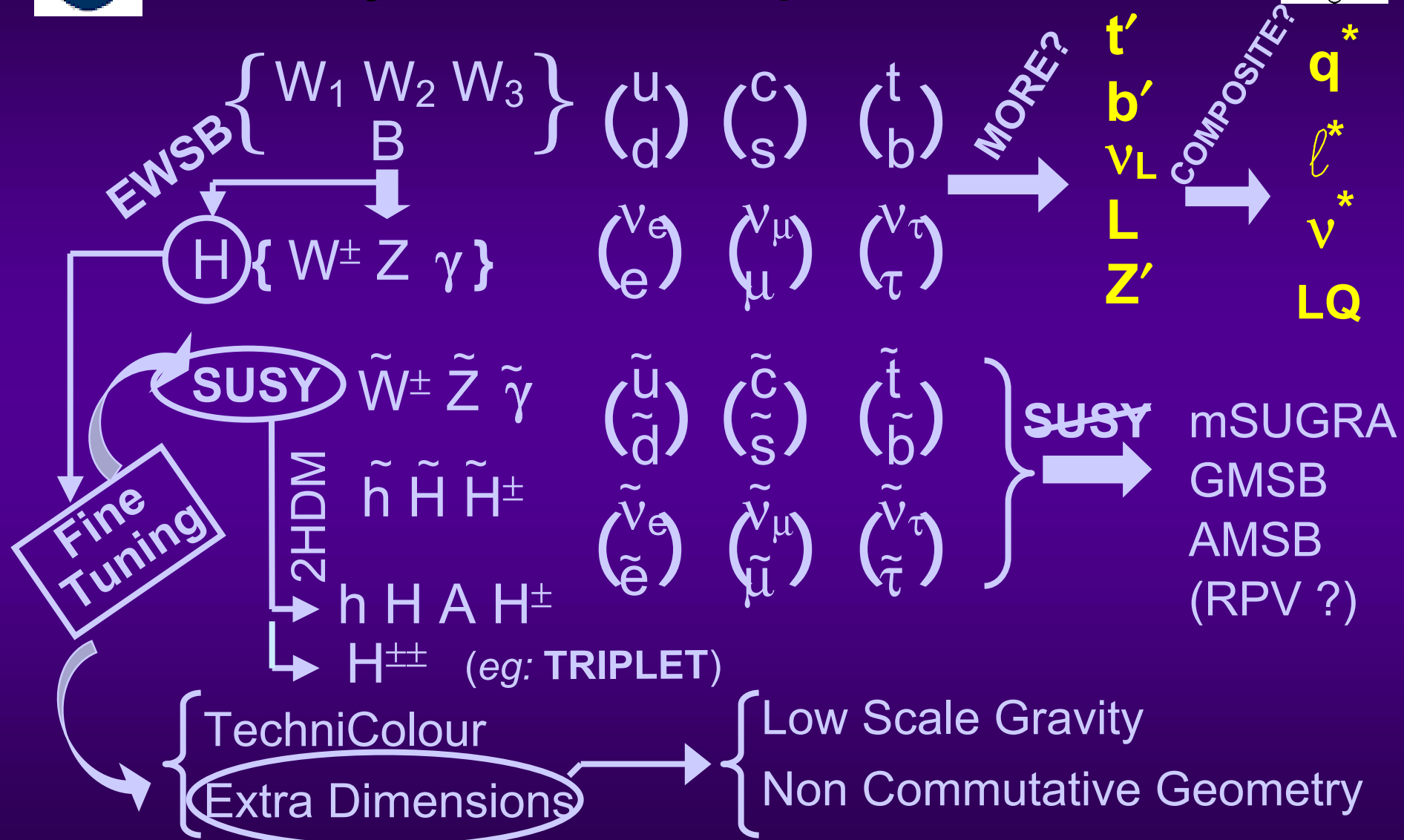


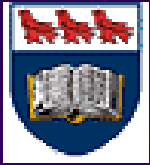
Roadmap: Beyond the S.M.





Heavy, Excited, Composite States, ...



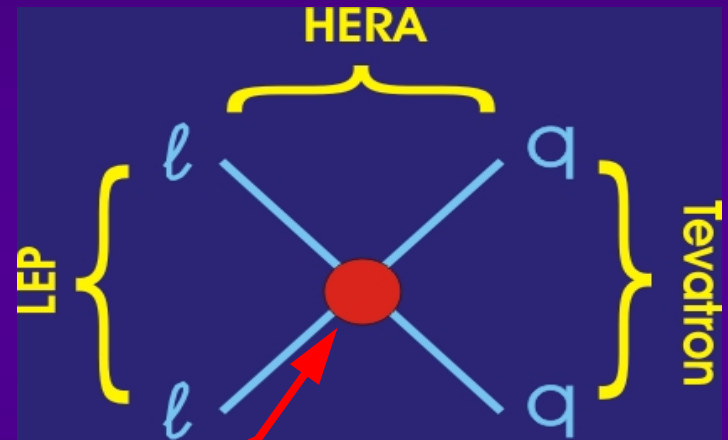


Prototypical example: Fermion Substructure?



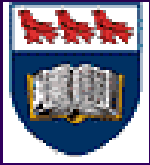
- ◆ Could have:
 - ◆ Excited states f^*
 - ◆ Leptoquarks LQ
- ◆ Severe existing constraints
 - ◆ $(g_e - 2)$, $(g_\mu - 2)$
 - ◆ FCNC, lepton number violation
 - ◆ Rare μ, K, B decays
- ◆ Direct Searches from Hera, LEP, Tevatron
 - ◆ Probe to few 100 GeV

- ◆ Many other constraints
 - ◆ 4-fermion contact interactions



$\Lambda > \approx 1-20 \text{ TeV}$
 (For large couplings \sim E.M. Strength)

Both indirect constraints and direct searches
Quantitative comparison \Rightarrow Need model of new physics



eg: excited fermions



◆ Assume a coupling

◆ $f^* \rightarrow f V, \quad V = \gamma, Z, W$

◆ Typically pick:

◆ Arb. Coupling:

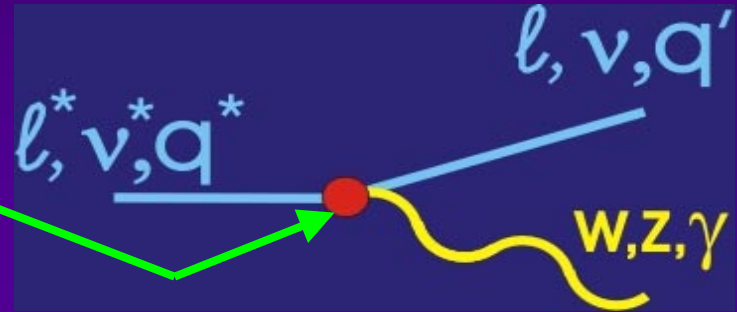
◆ Yukawa:

◆ Coupling/Scale:

◆ Sometimes:

◆ Or even:

g, κ
 λ
 f_V/Λ



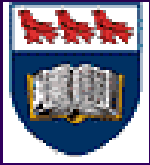
(eg, Boudjema,Djouadi,Kneur Z.Phys.C57(1993)425

$\Lambda = M_*$ Hagiwara,Zeppenfeld,Komamiya Z.PhysC29(1985)115)

$f = 1$

Many f^* Searches:

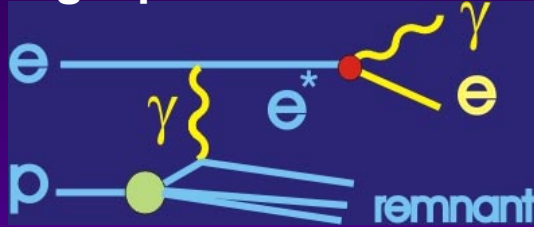
q^*	W, Z, γ, g	HERA, LEP, Tevatron
l^*, ν^*	W, Z, γ	HERA, LEP



Example of $f^* : e^* \rightarrow e \gamma$



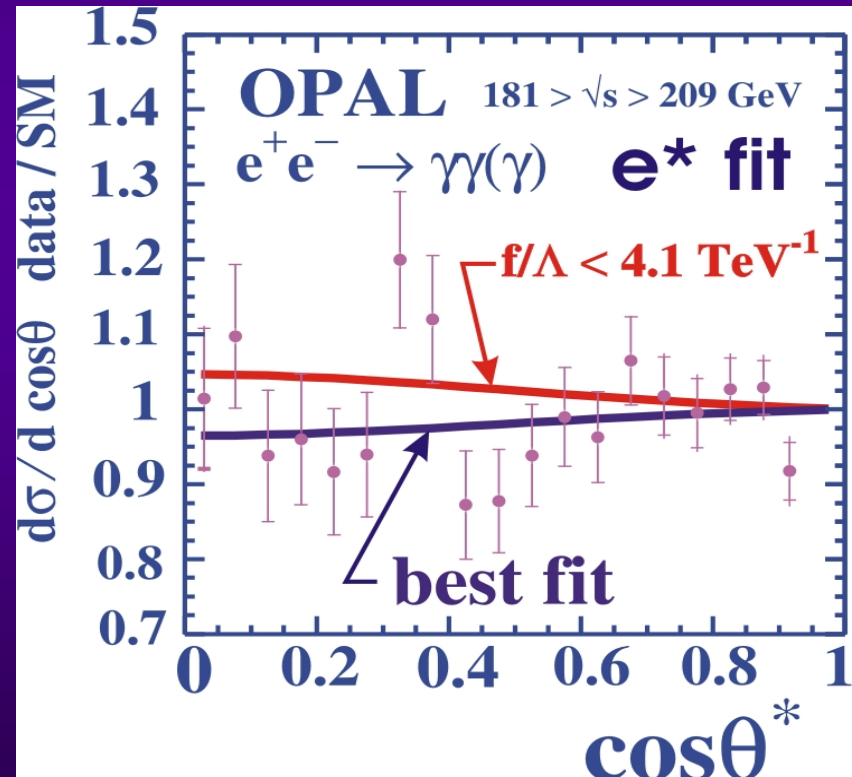
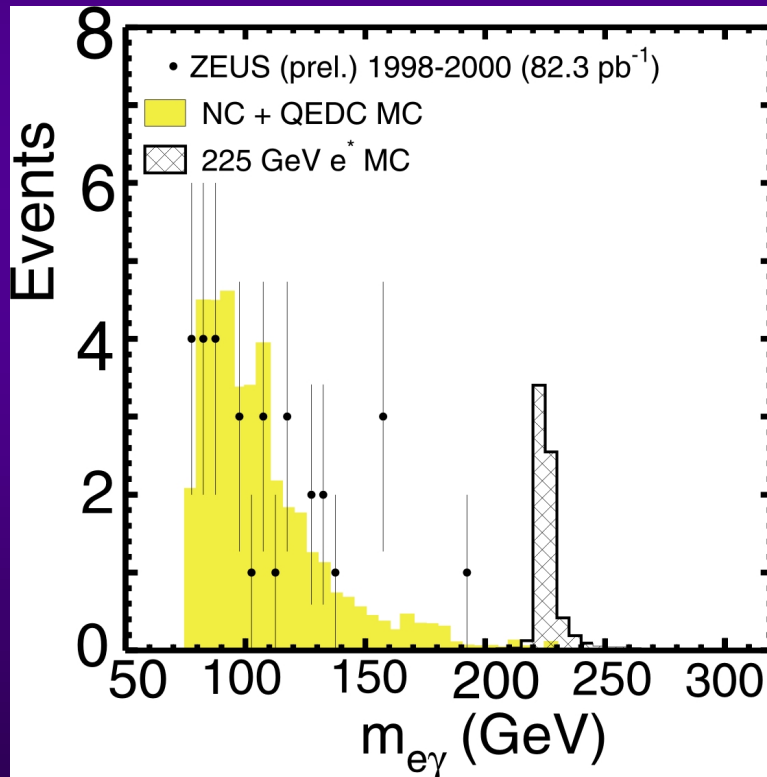
Single production at HERA

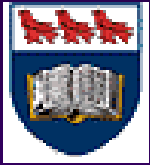


Constraints from LEP



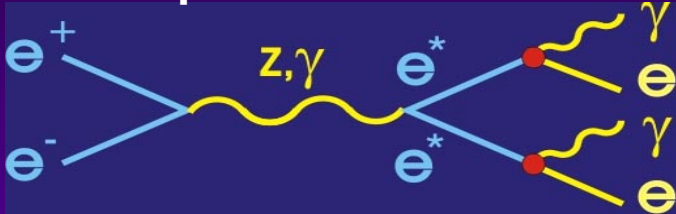
(cross-section from B. Vachon, hep-ph/0103132)



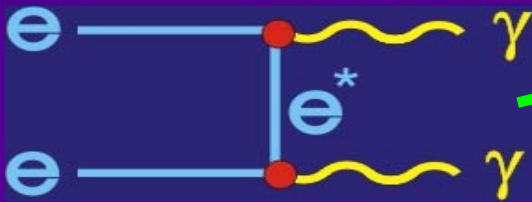


Results : $e^* \rightarrow e \gamma$

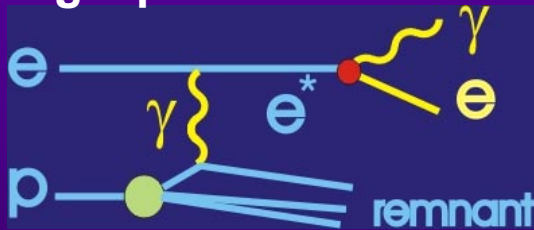
Pair production at LEP



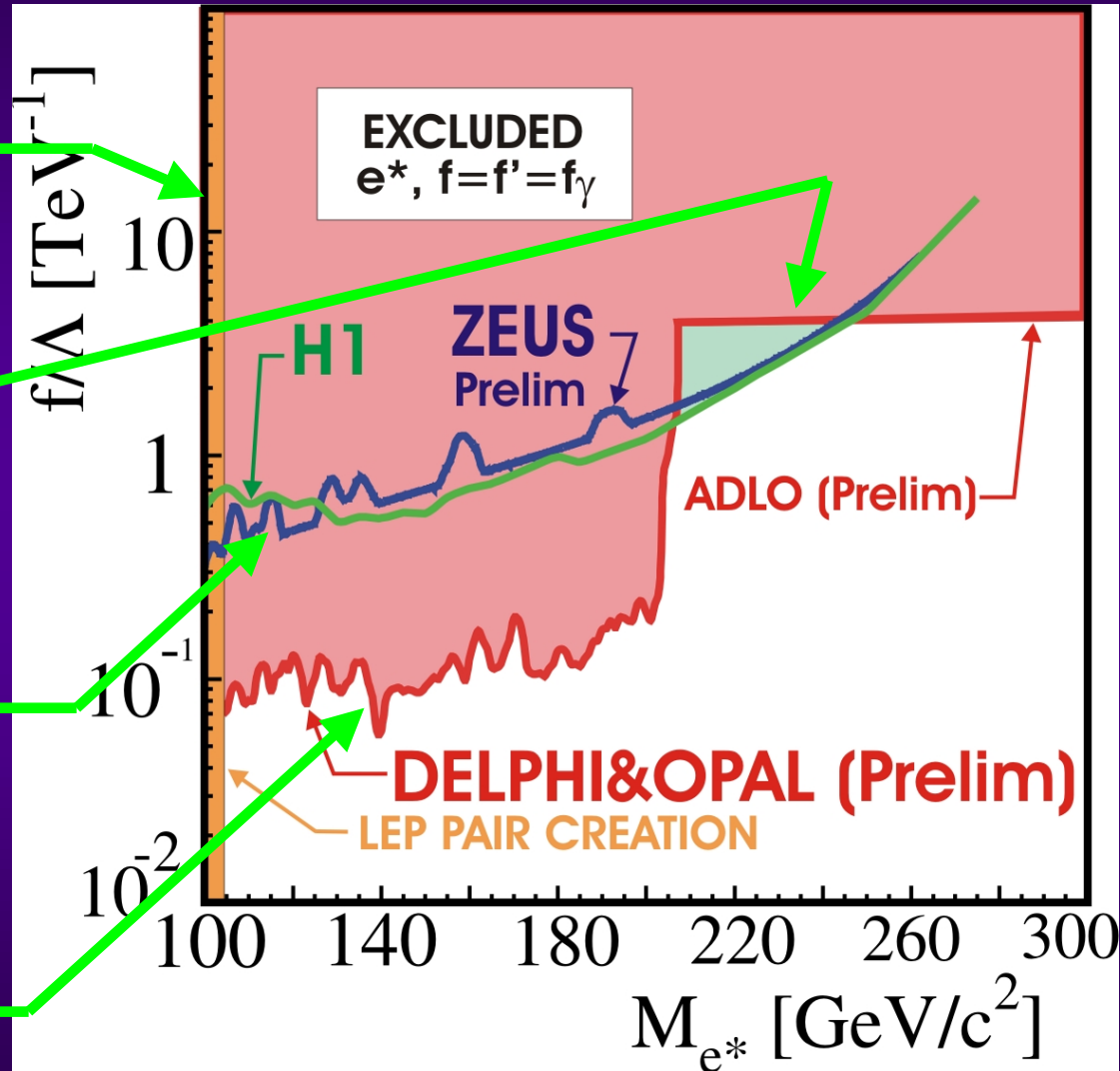
Indirect Constraints from LEP

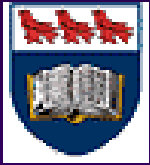


Single production at HERA



Single production at LEP



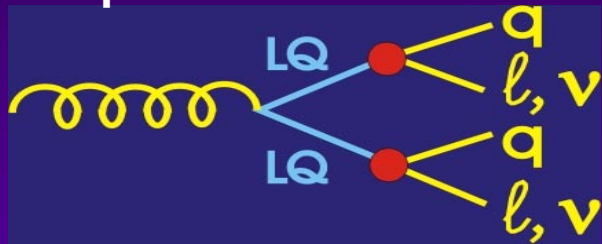


Another example: Leptoquarks



A bit like f^* but $f \leftrightarrow \lambda$ & LEP \leftrightarrow Tevatron

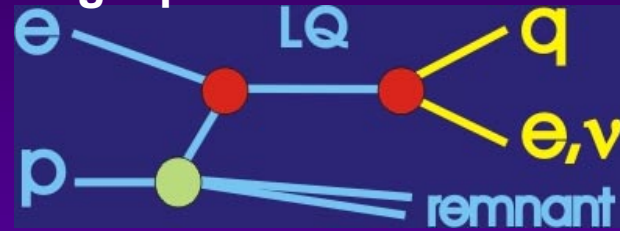
Pair production at Tevatron



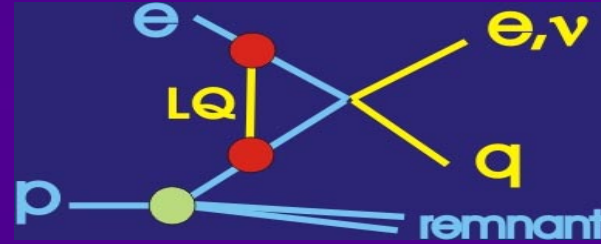
Indirect Constraints from LEP



Single production at HERA



Indirect Constraints from HERA

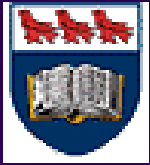


Many **LQ** to search for:

(Many searches assume family diagonal)

Spin	Q	F	β_l
Scalar	$\pm 1/3, 2/3,$	0, 2	0, 1/2, 1
Vector	$4/3, 5/3$		

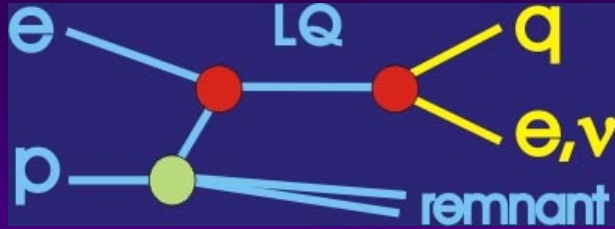
(Buchmuller-Ruckl-Wyler Phys.Lett. B191(1987)442)



LQ searches

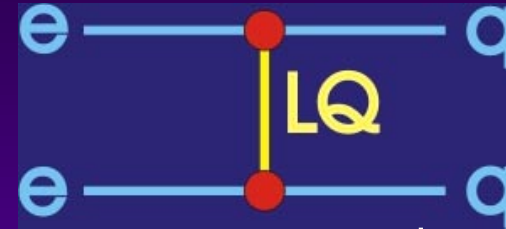


HERA

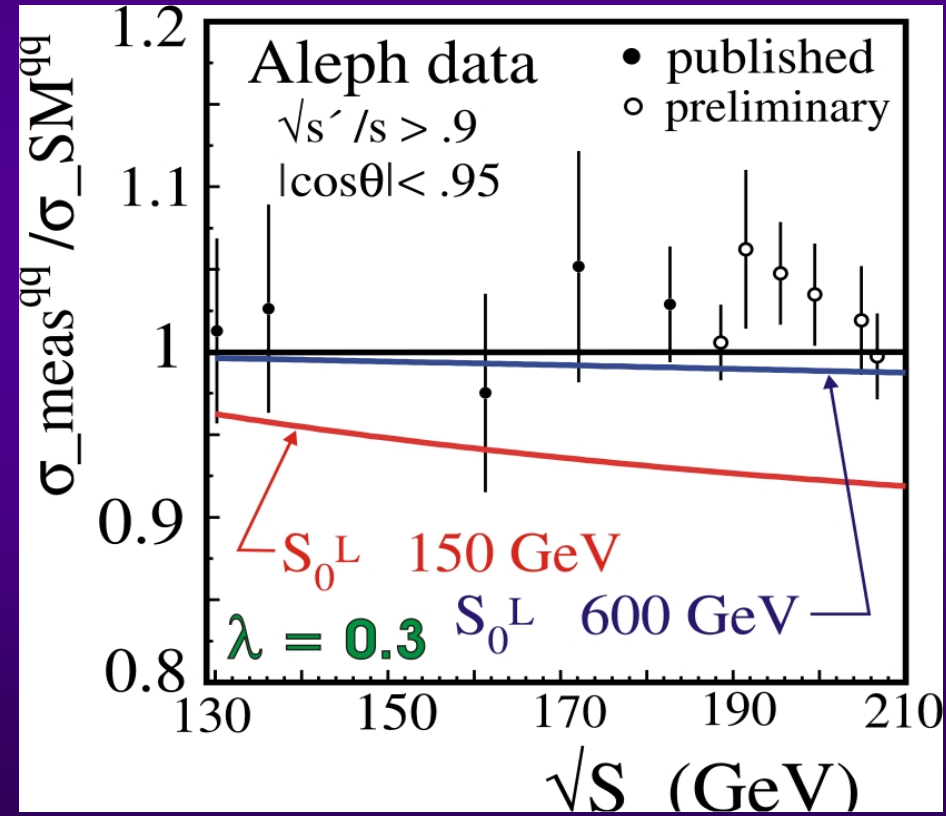
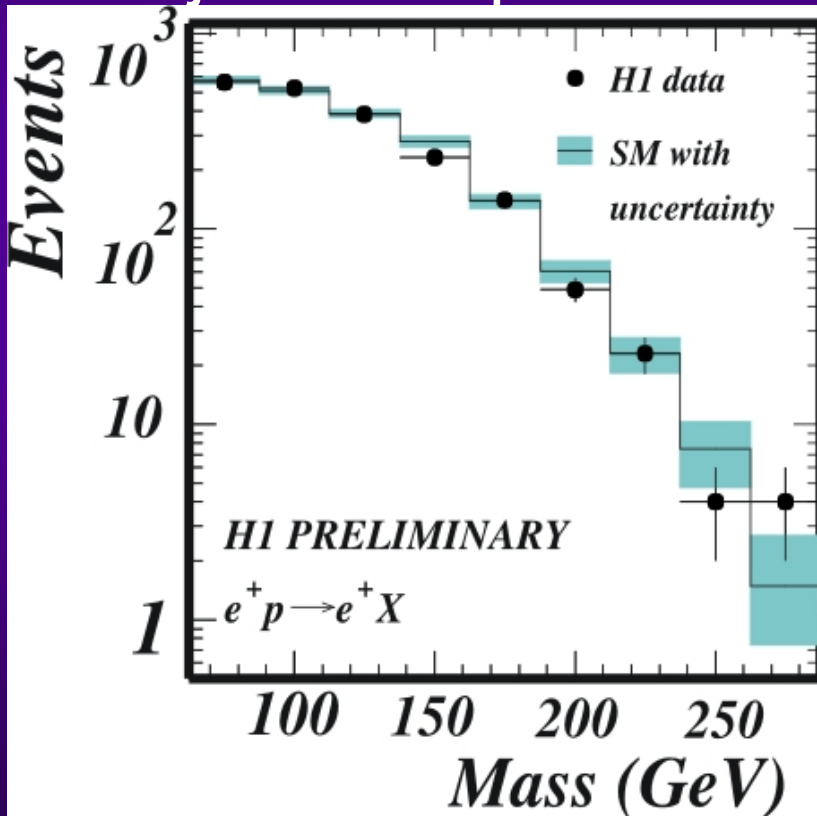


e-jet mass peaks

LEP



Deviations in $e^+e^- \rightarrow qq$





Leptoquark example limits

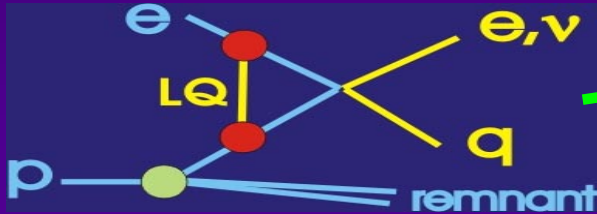


LEP Indirect

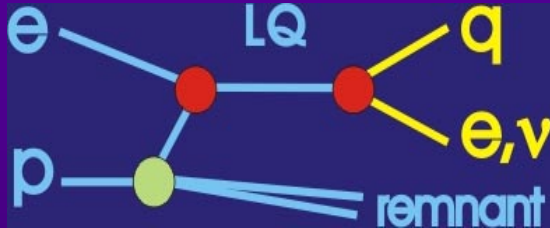
$Q=1/3, BR(LQ \rightarrow eq) = 1/2$



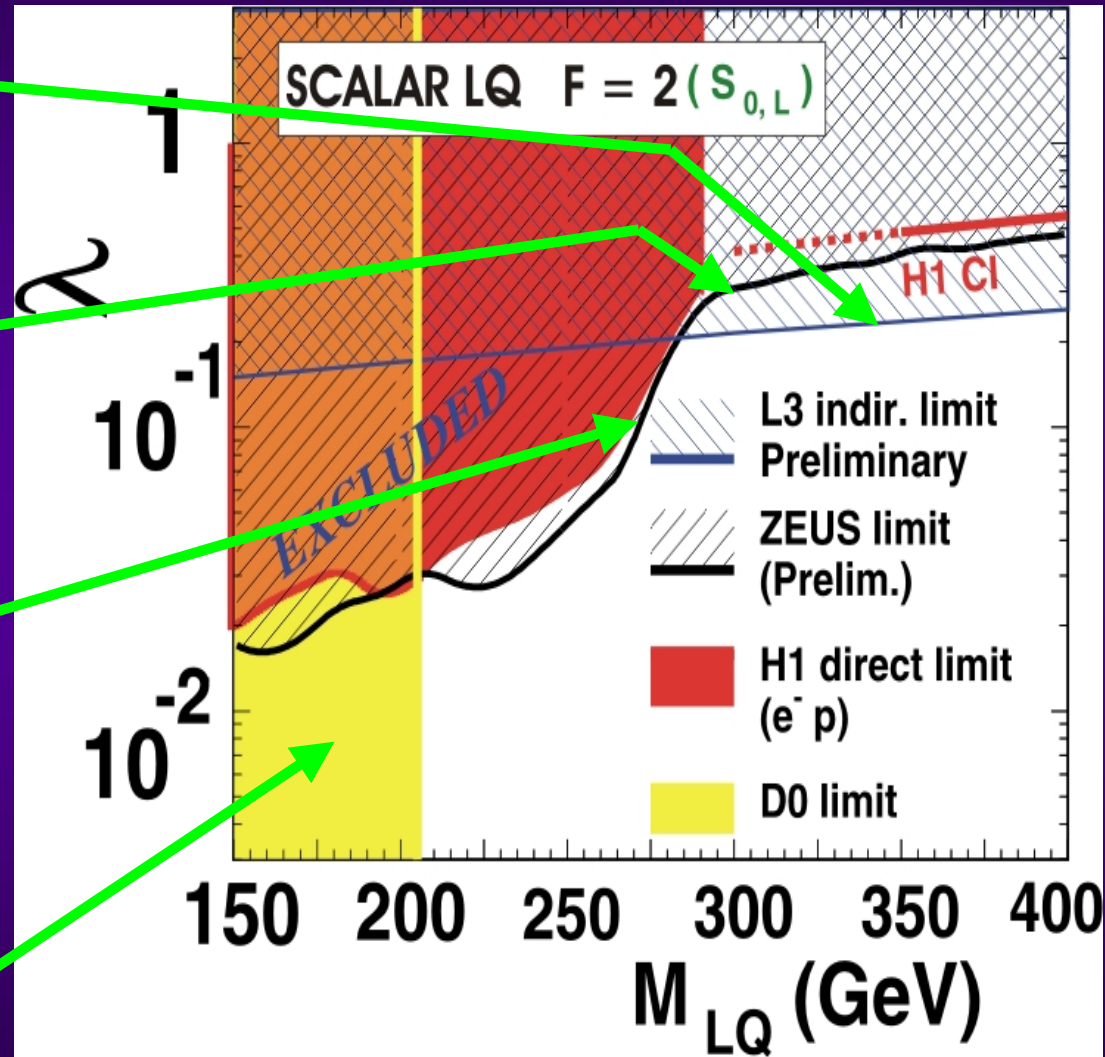
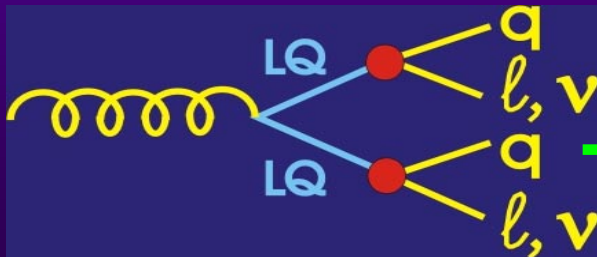
HERA Indirect

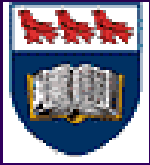


HERA Direct



Tevatron Pair Prod.

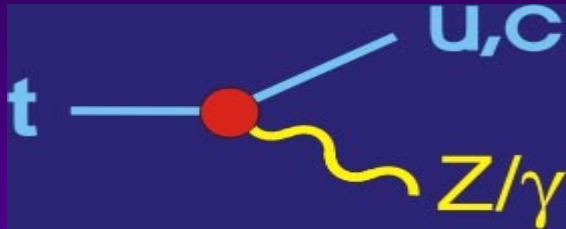




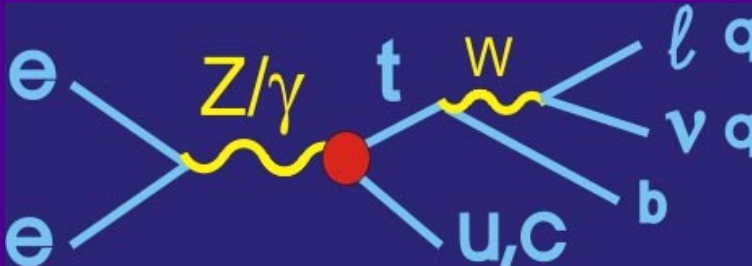
Anomalous Top Quark Couplings



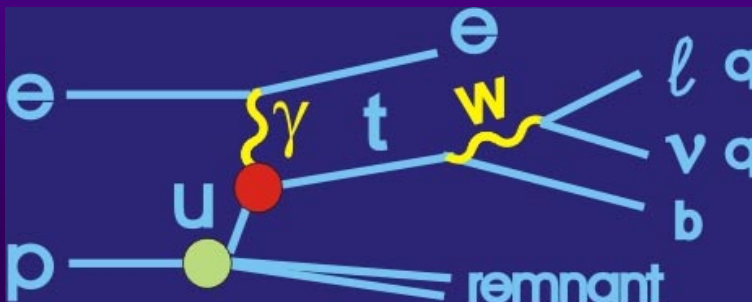
Top Decays at Tevatron



Single Top at LEP



Single Top at HERA



- ◆ Tevatron searches directly for anomalous FCNC top decays

- ◆ FCNC top couplings
⇒ Single top at LEP & HERA

- ◆ Use common model

- ◆ K_Z, K_γ different for U, C

- ◆ Signatures

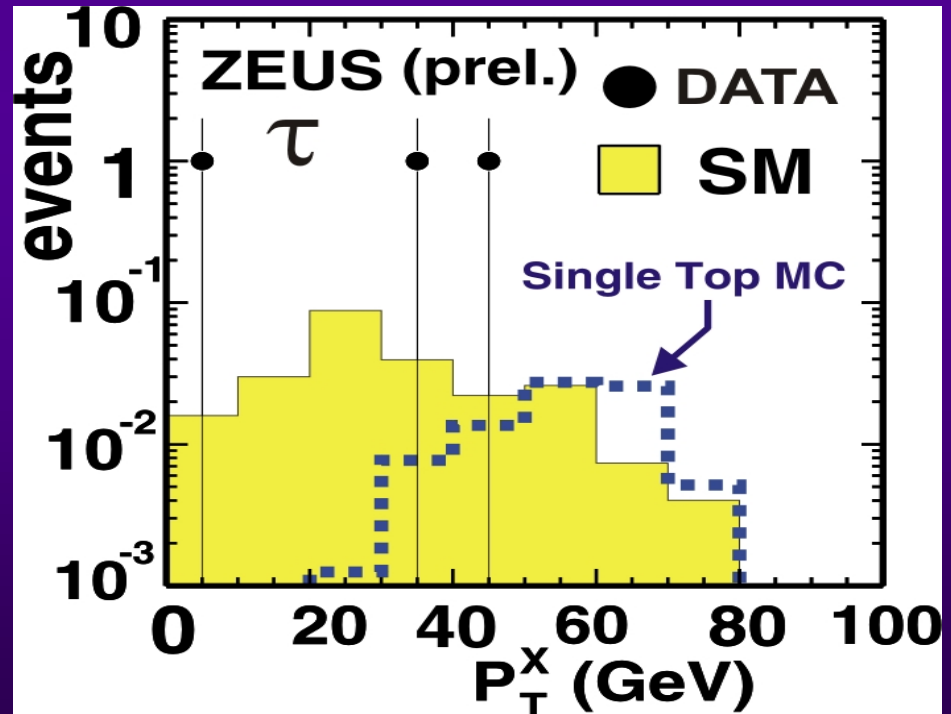
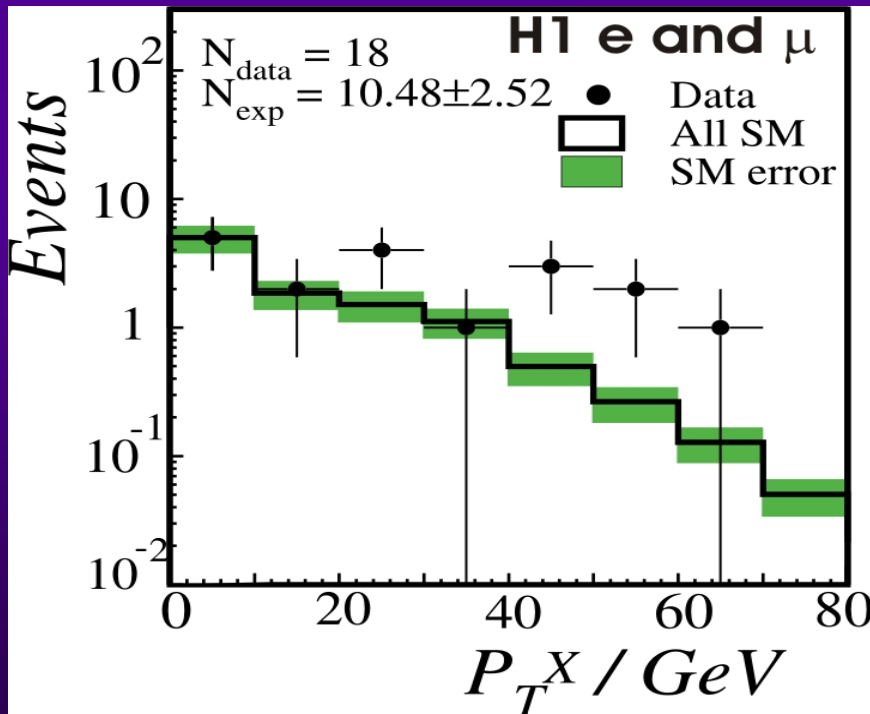
- ◆ Heavy Flavour events
- ◆ Isolated High P_t leptons at HERA →

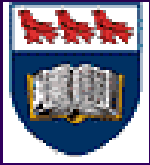


HERA Prelim. 91-00: isolated Leptons (I)



H1 (101.6 pb ⁻¹)	Electron obs/exp	Muon obs/exp	e and μ obs/exp
$P_T^X > 25$ GeV	4 / 1.29 ± 0.33	6 / 1.54 ± 0.41	10 / 2.8 ± 0.7
$P_T^X > 40$ GeV	2 / 0.41 ± 0.12	4 / 0.58 ± 0.16	6 / 1.0 ± 0.3
ZEUS (130.5 pb ⁻¹)	Electron obs/exp	Muon obs/exp	Tau obs/exp
$P_T^X > 25$ GeV	1 / 1.14 ± 0.06	1 / 1.29 ± 0.16	2 / 0.12 ± 0.02
$P_T^X > 40$ GeV	0 / 0.46 ± 0.03	0 / 0.50 ± 0.08	1 / 0.06 ± 0.01

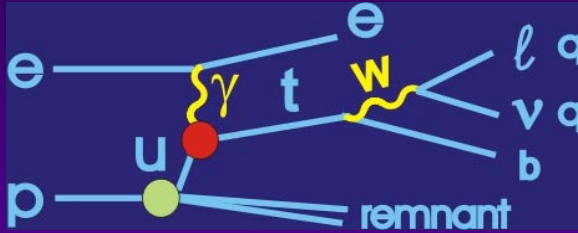




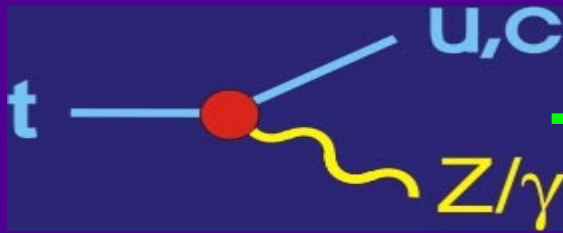
Anomalous top couplings: constraints



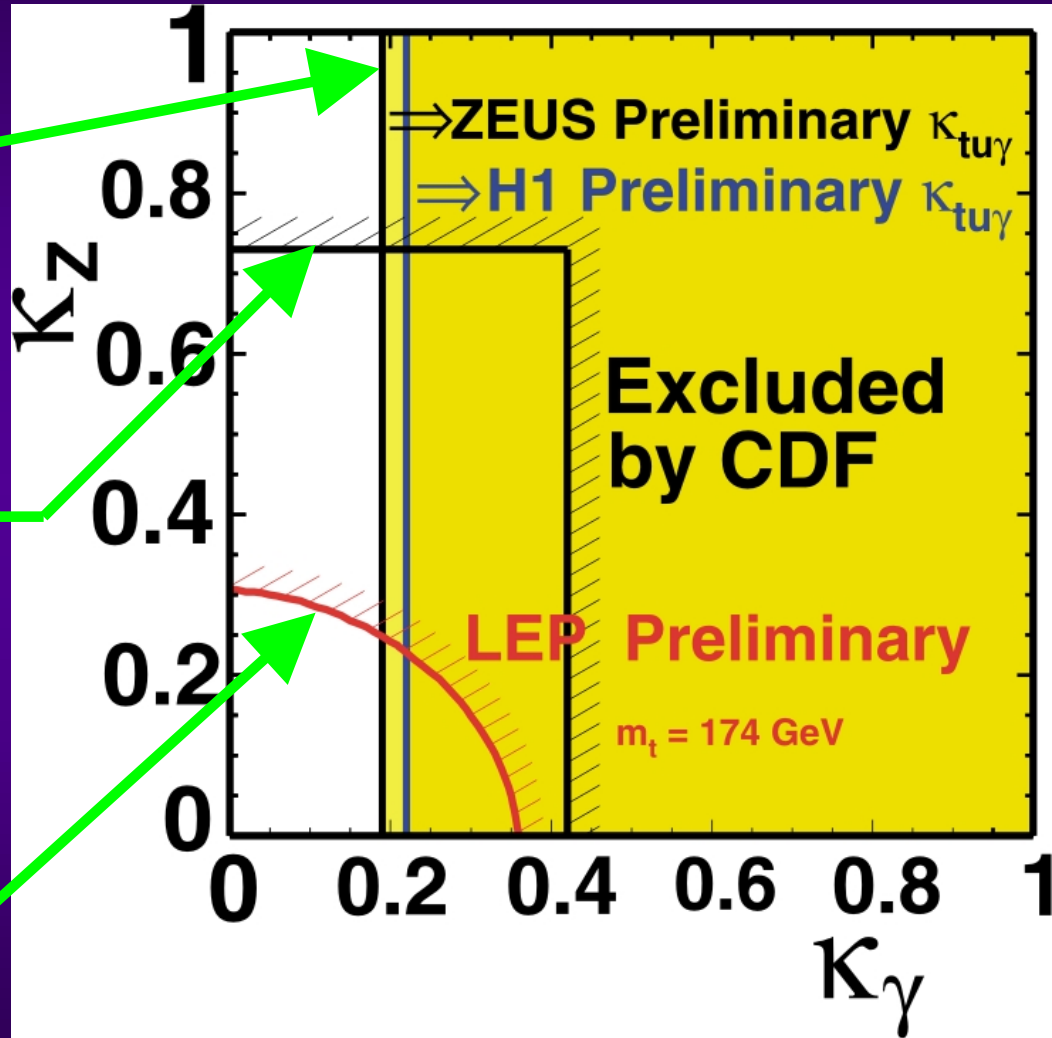
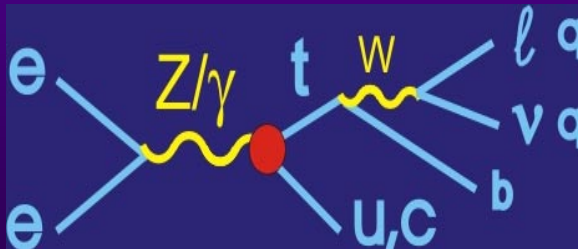
HERA



Tevatron

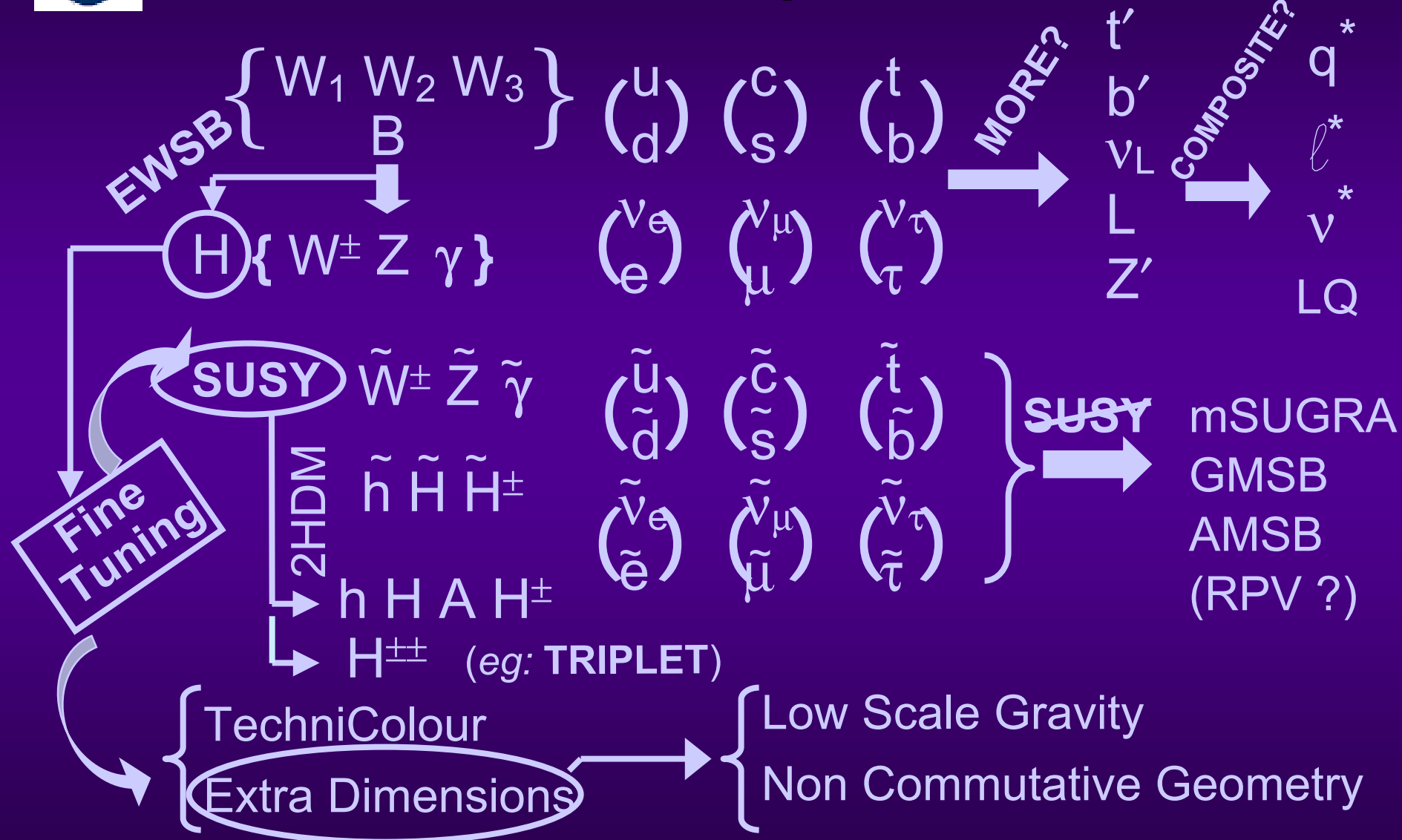


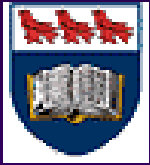
LEP



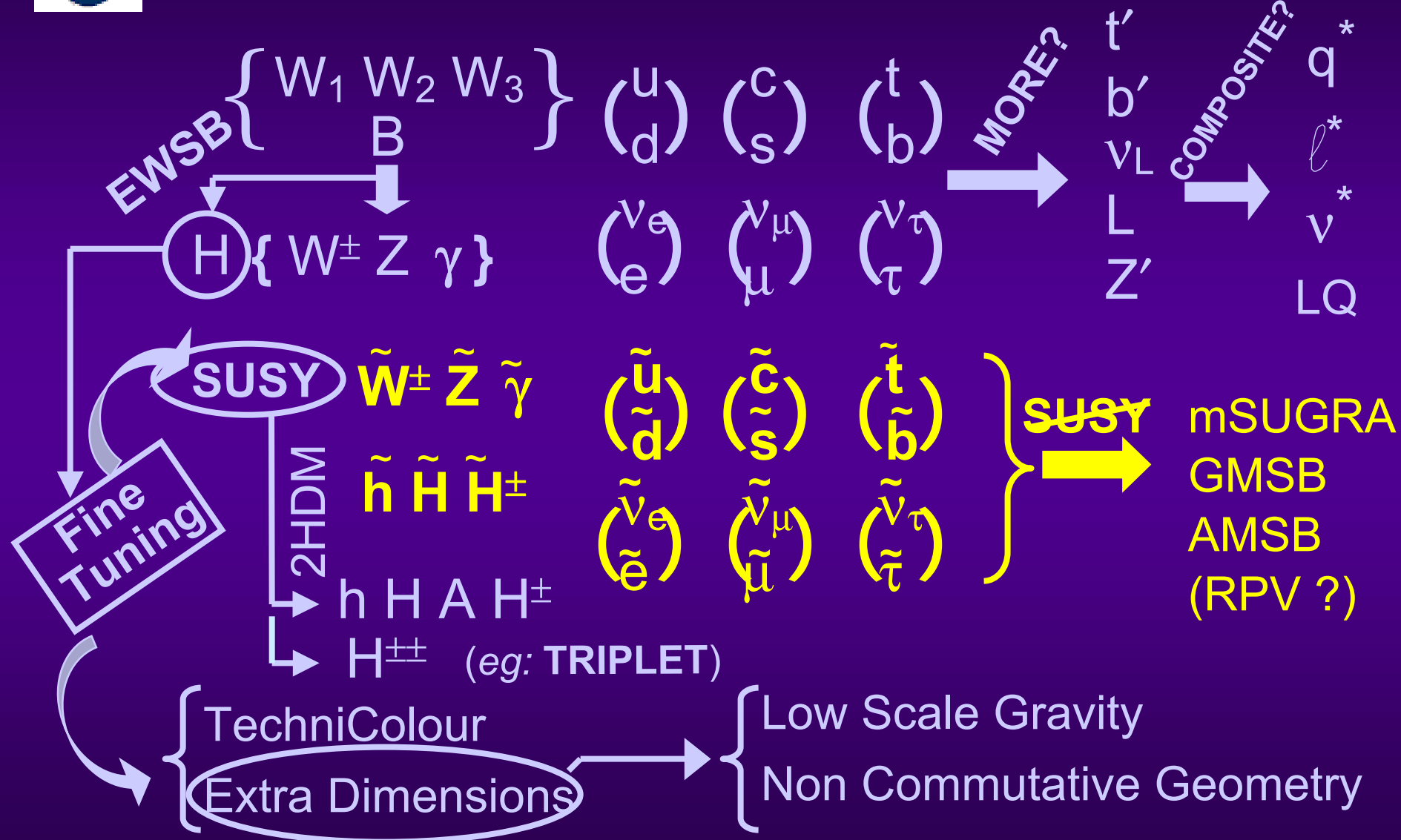


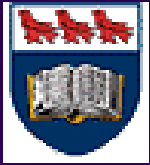
Roadmap ...





SUSY: Overview

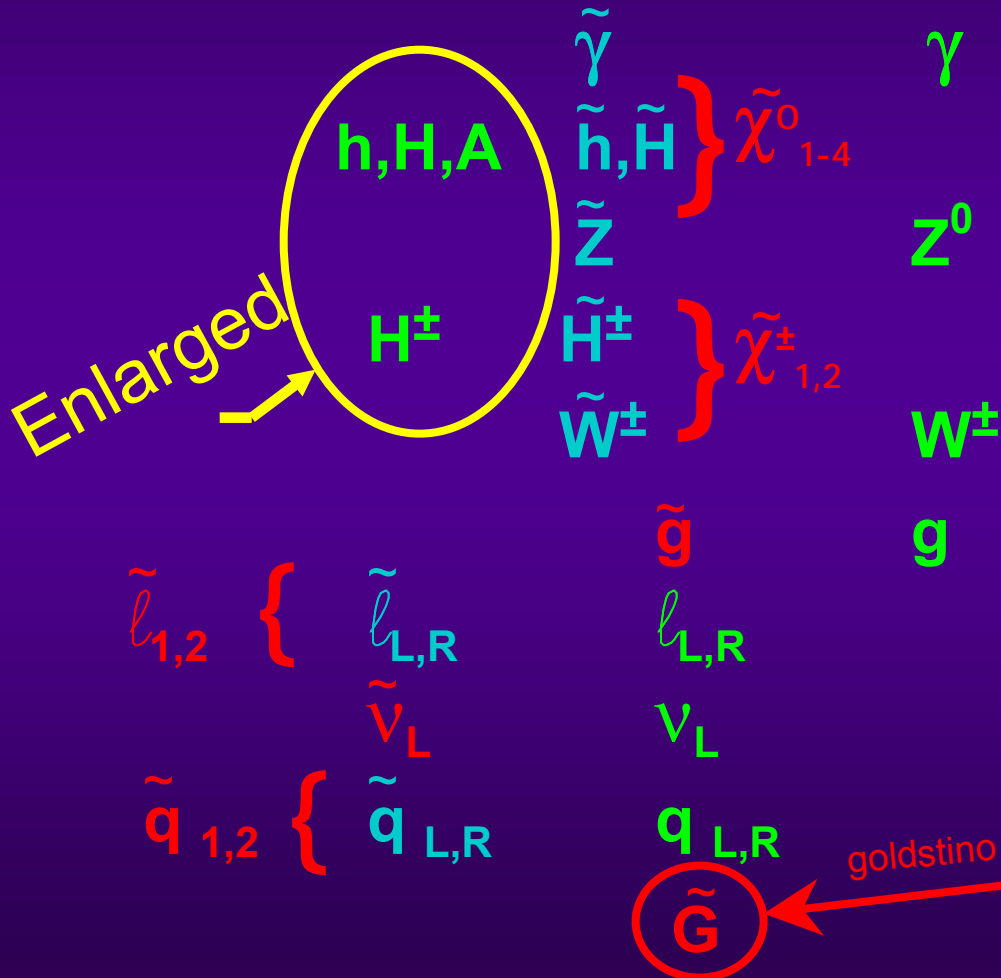




(s)particles List



0 1/2 1 3/2 2

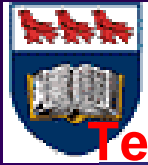


“General” MSSM

M_1, M_2, M_3	Gaugino masses
m_f	Sfermion masses
$v, \tan\beta, m_A, \mu$	Higgs(ino)
A_U, A_D, A_L	Trilinear couplings
+105 Params	→ FCNC, ...
RPV: +45	$\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}$



~~SUSY~~



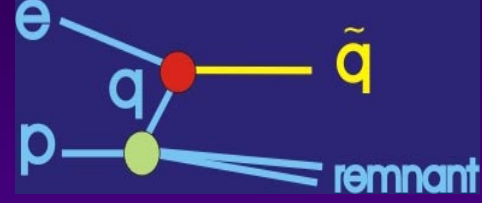
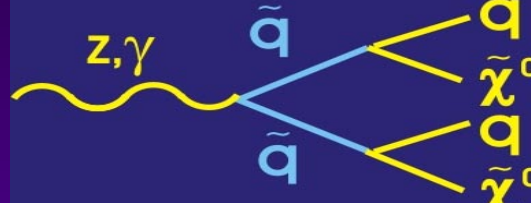
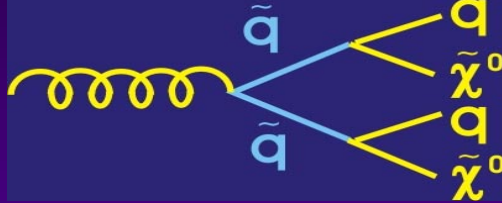
General SUSY eg: $\tilde{\chi}^0$ LSP squarks/gluinos



Tevatron: Dominates

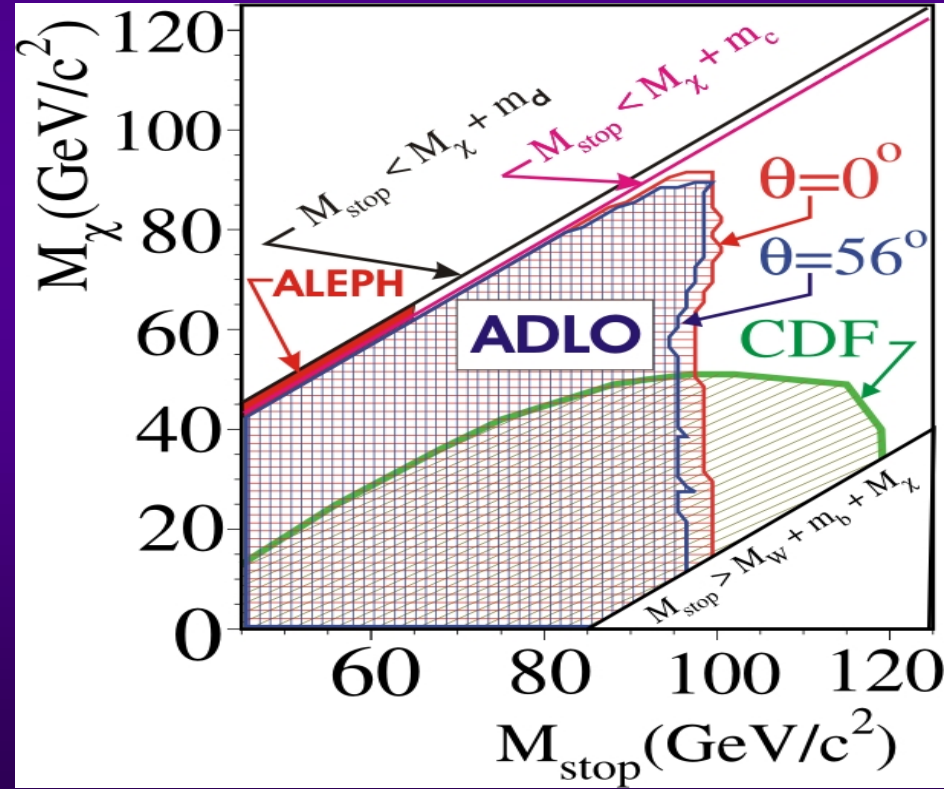
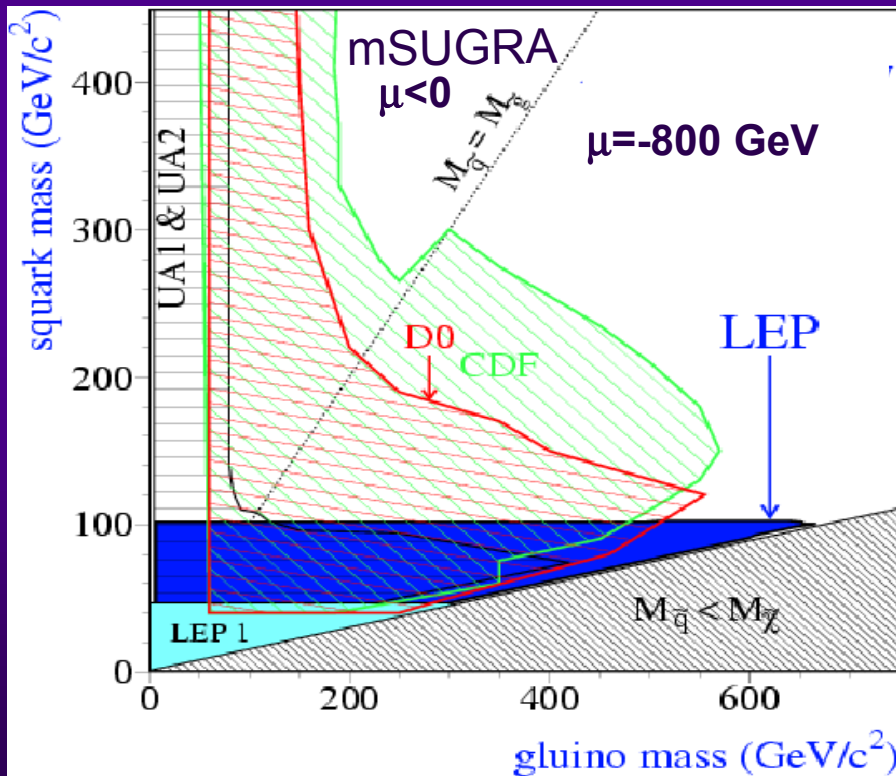
LEP: Small ΔM

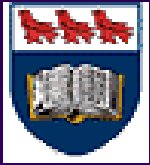
HERA: RPV



- 5 degenerate quarks
- GUT relations

$$t \rightarrow c \tilde{\chi}^0 \text{RPC}$$



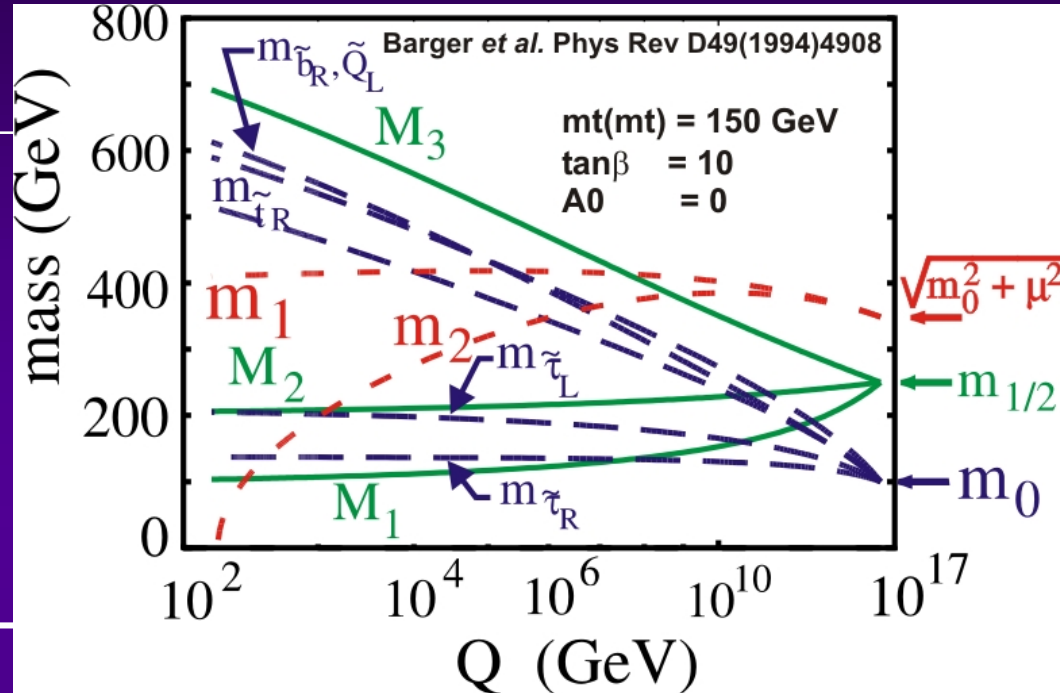


Favorite (?) model: mSUGRA



High scale Params.

$m_{1/2}$	Gaugino mass at GUT scale
m_0	Scalar mass at GUT scale
$\tan\beta$	v_u/v_d , ratio of higgs vevs
A_0	Common trilinear coupling (drives \tilde{t} , \tilde{b} , $\tilde{\tau}$ mixing)
$\text{sign}(\mu)$	Sign(Higgs mixing param) ($ \mu $ from EWSB)

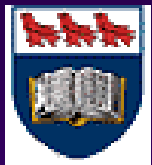


◆ Calculate masses, cross-section, BRs

- ◆ Phenomenology
- ◆ ⇒ Guides the search

◆ Dominant sensitivity

- ◆ Higgs search at LEP
- ◆ Chargino search at LEP
 - ◆ (needs slepton search too)
- ◆ (Also $b \rightarrow s\gamma$ at large $\tan\beta$)



SUSY Breaking (Mediation)



Gravity

$\sqrt{F} \sim 10^{11} \text{ GeV}$
(heavy \tilde{G})

$M \sim M_P \sim 10^{18} \text{ GeV}$

Hidden ~~SUSY~~

M

Visible
 $e, \mu, \tau, \dots, W, Z$
 $\tilde{e}, \tilde{\mu}, \tilde{\tau}, \dots, \tilde{W}, \tilde{Z}$

Gauge

$10^3 < \sqrt{F} < 10^{10} \text{ GeV}$
(light \tilde{G})

$10^3 < M < 10^{15} \text{ GeV}$

◆ FCNC problems

◆ Fix in mSUGRA

◆ 4(+1) Params

◆ SUSY/GUT: $\sin^2 \theta_w$

◆ CDM Candidate $\tilde{\chi}^0$

◆ Decay chains to $\tilde{\chi}^0$

◆ SUSY "Missing Energy" signature

◆ No severe FCNC

◆ Lose CDM candidate

◆ NLSP $\tilde{\chi}^0$ or $\tilde{\ell}$

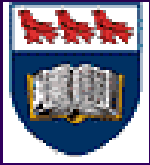
◆ Decay chains to NLSP then to \tilde{G}

◆ Extra γ or ℓ

◆ Arbitrary suppression

◆ Lifetime Signatures

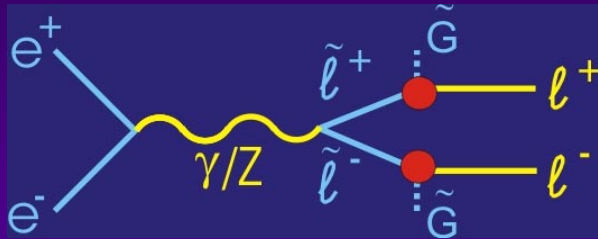
◆ Minimal model 5(+1) Par.



SUSY eg 1: GMSB sleptons @ LEP

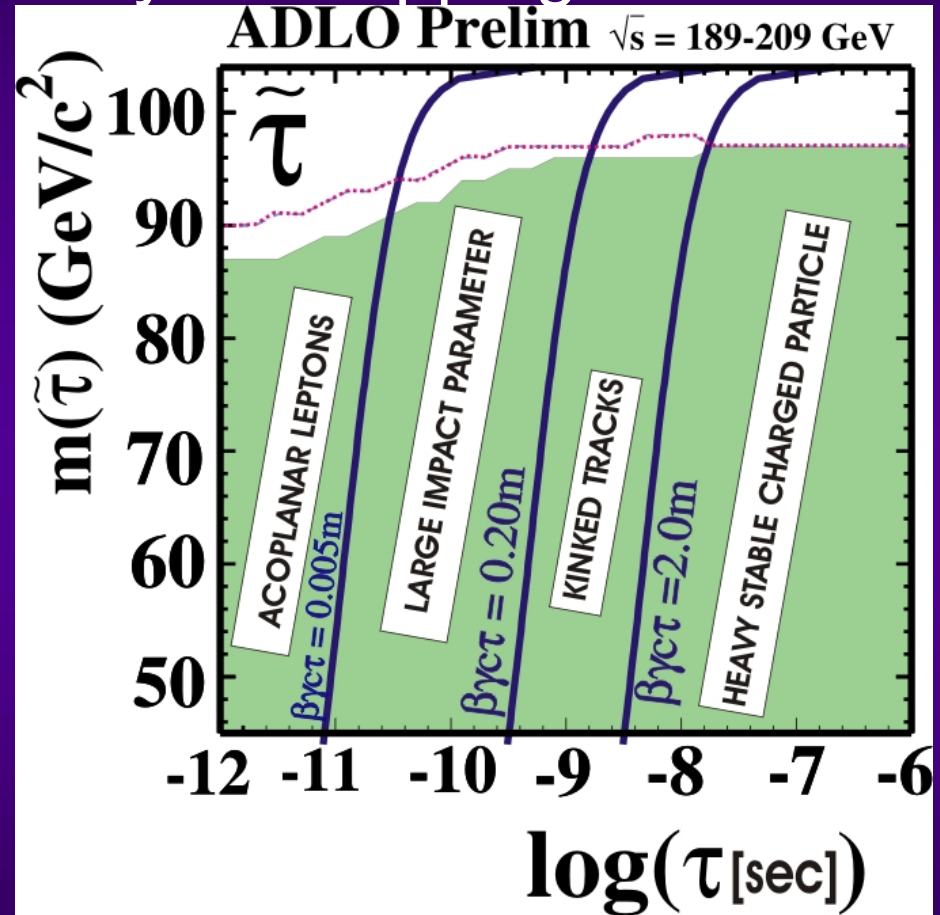
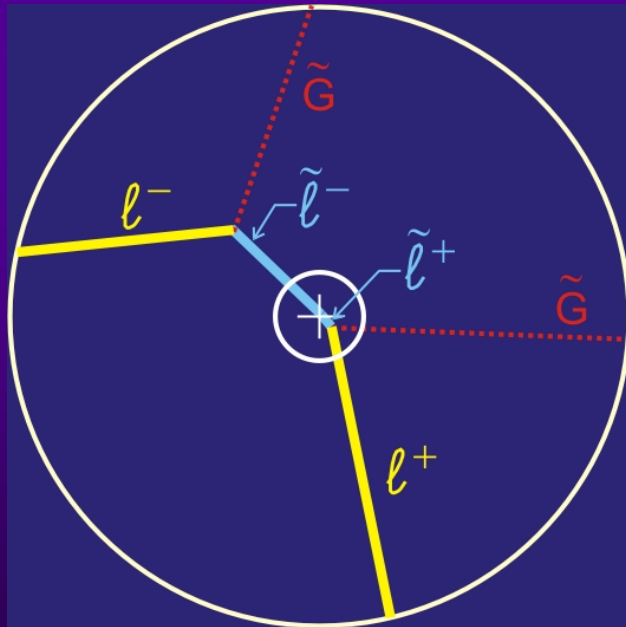


Leptons + Emiss:



Many overlapping channels

+ Lifetime:



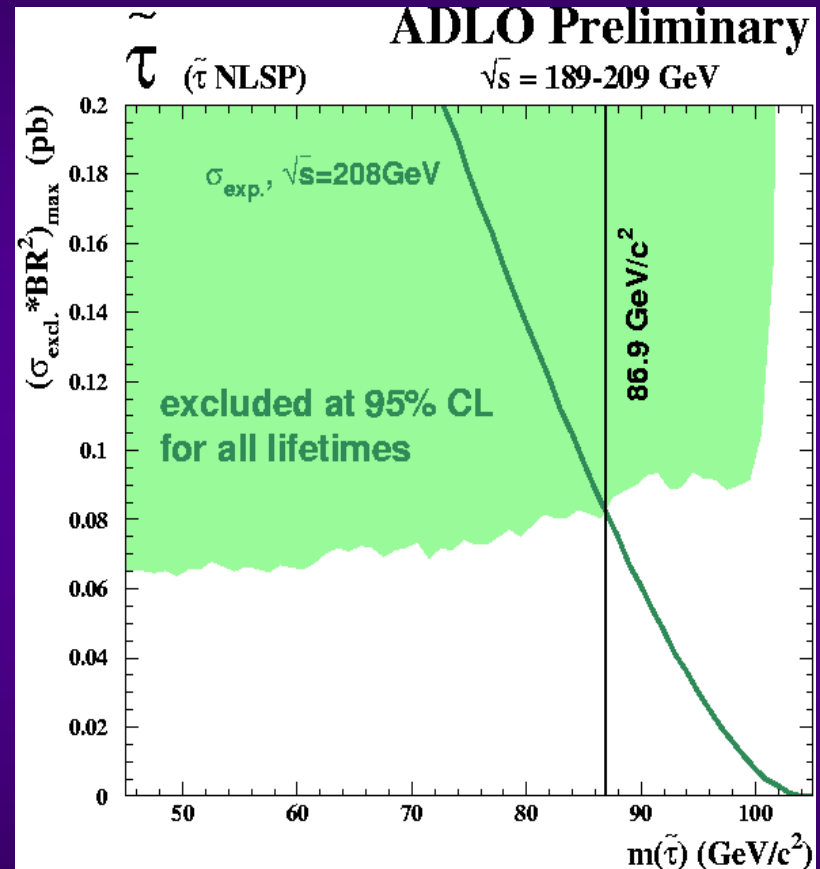
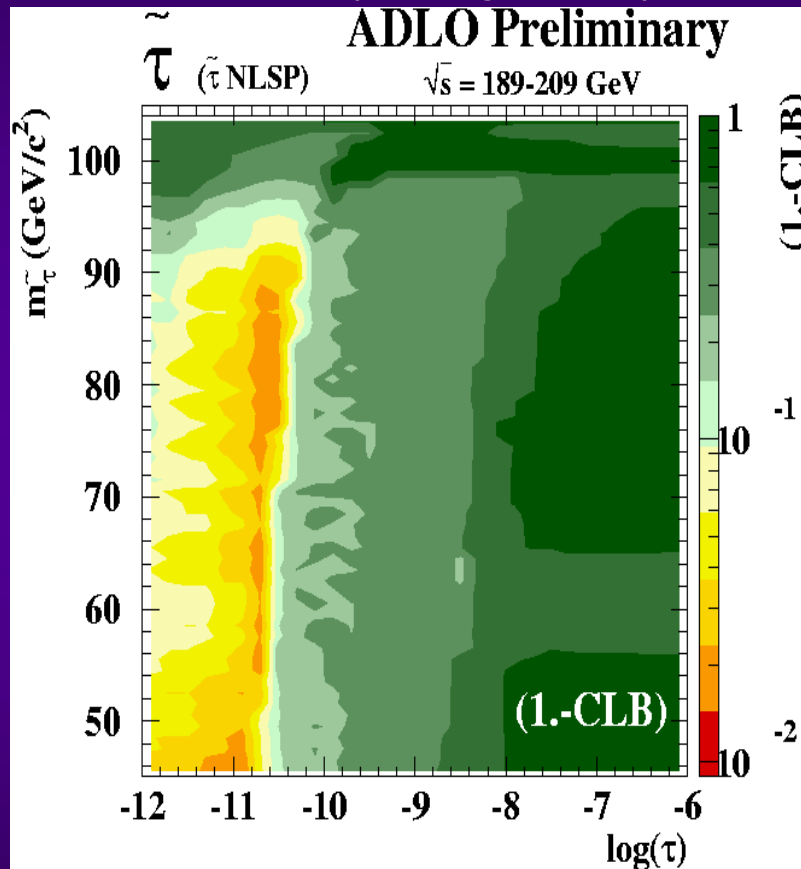
New LEP results →



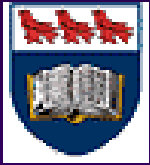
GMSB $\tilde{\tau}^+ \tilde{\tau}^-$: : results



1 – Prob(background)



Cross-sections from model scans using Dimopoulos, Thomas, Wells
Nucl.Phys.B488:39-91,1997



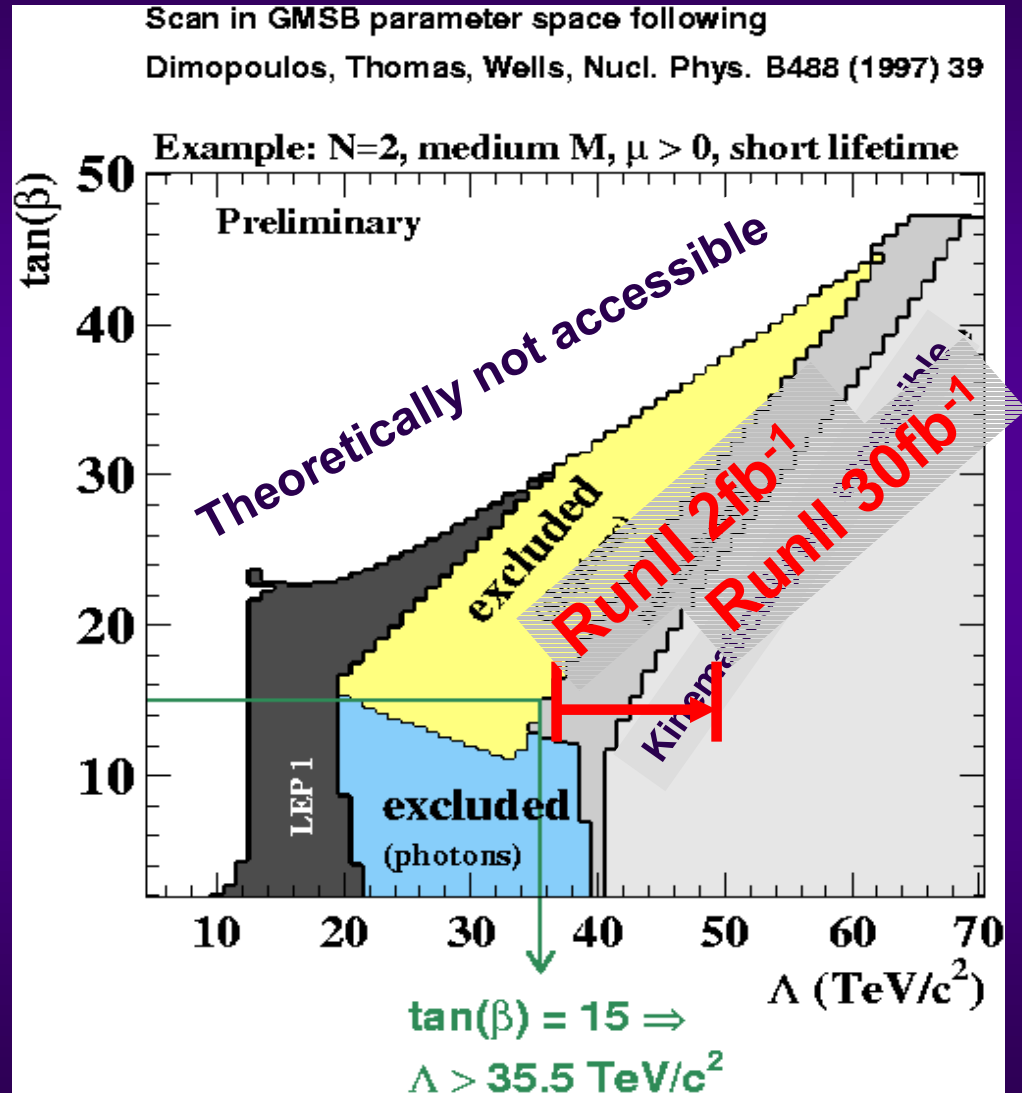
GMSB: parameter constraints

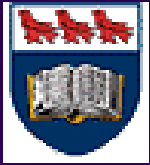


Important parameters:

Λ	Sparticle mass scale
$\tan\beta$	v_u/v_d , ratio of higgs vevs

⇒ Plot limits in this plane, scanning over rest



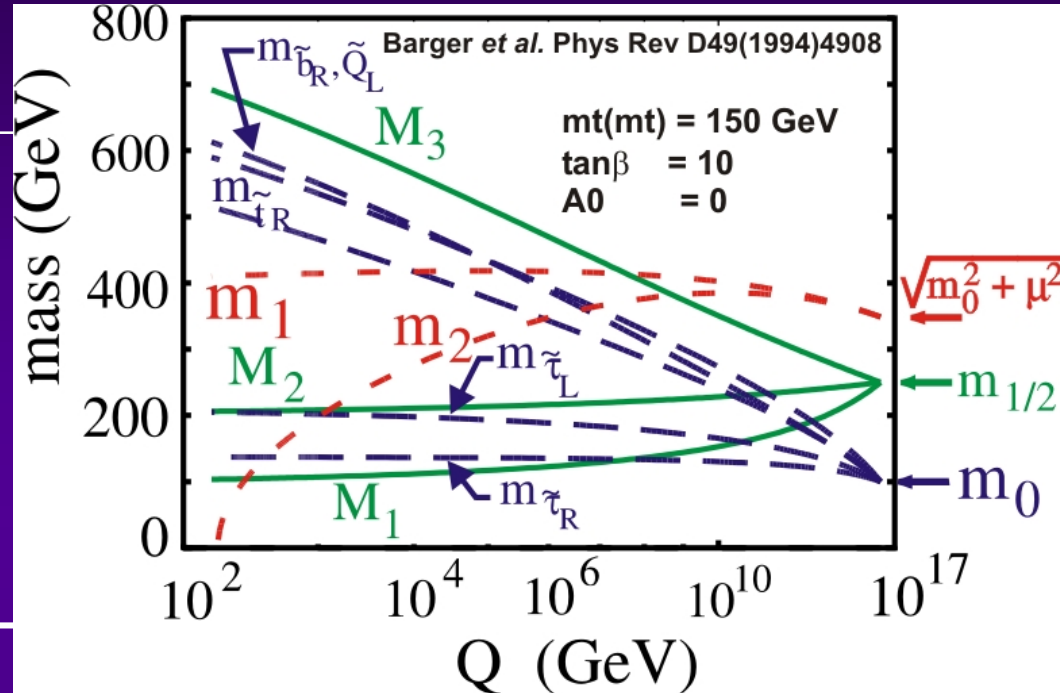


Favorite (?) model: mSUGRA



High scale Params.

$m_{1/2}$	Gaugino mass at GUT scale
m_0	Scalar mass at GUT scale
$\tan\beta$	v_u/v_d , ratio of higgs vevs
A_0	Common trilinear coupling (drives \tilde{t} , \tilde{b} , $\tilde{\tau}$ mixing)
$\text{sign}(\mu)$	Sign(Higgs mixing param) ($ \mu $ from EWSB)

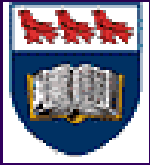


◆ Calculate masses, cross-section, BRs

- ◆ Phenomenology
- ◆ ⇒ Guides the search

◆ Dominant sensitivity

- ◆ Higgs search at LEP
- ◆ Chargino search at LEP
 - ◆ (needs slepton search too)
- ◆ (Also $b \rightarrow s\gamma$ at large $\tan\beta$)



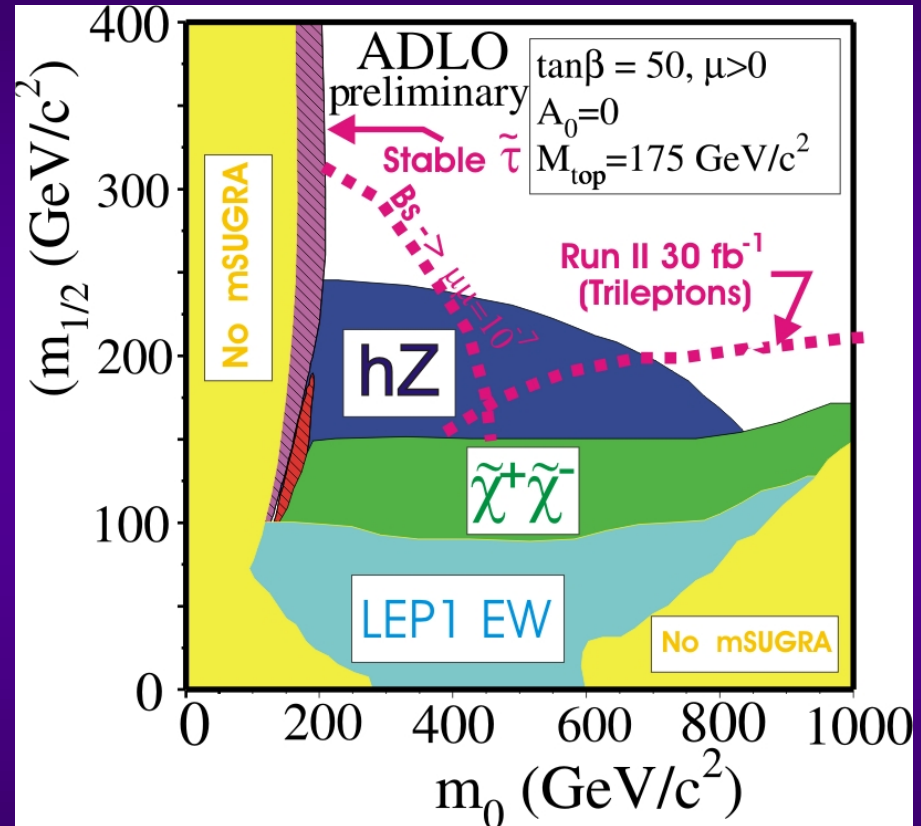
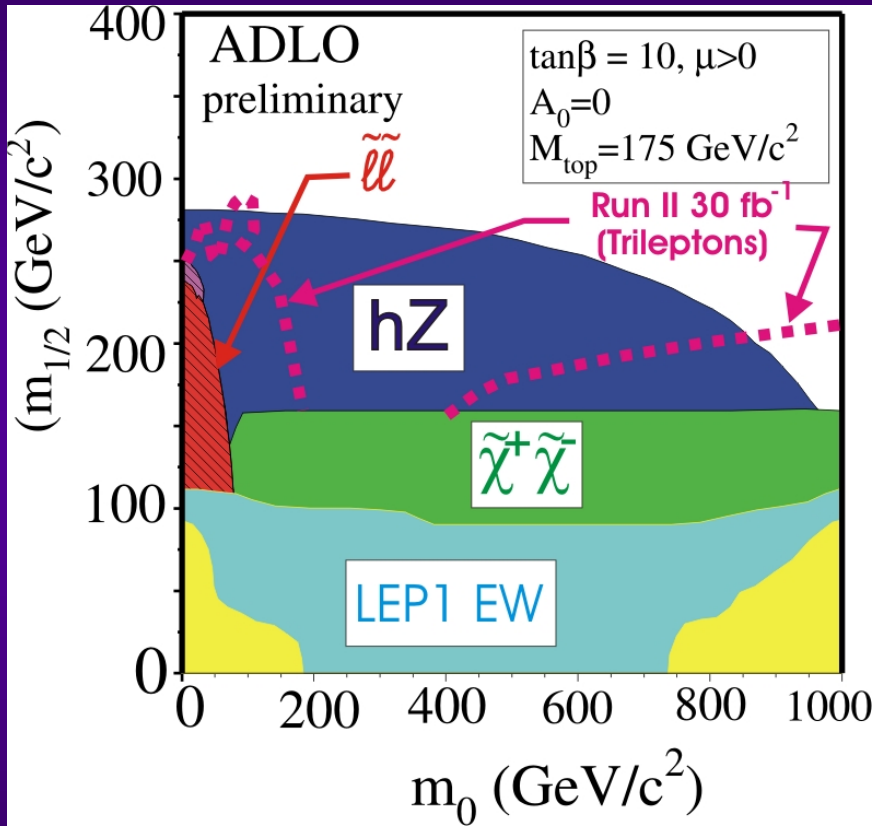
mSUGRA constraints (from LEP)



$\tan\beta=10$

$A_0 = 0$

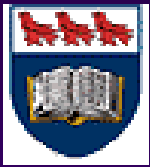
$\tan\beta=50$



Run II sensitivity estimates from:

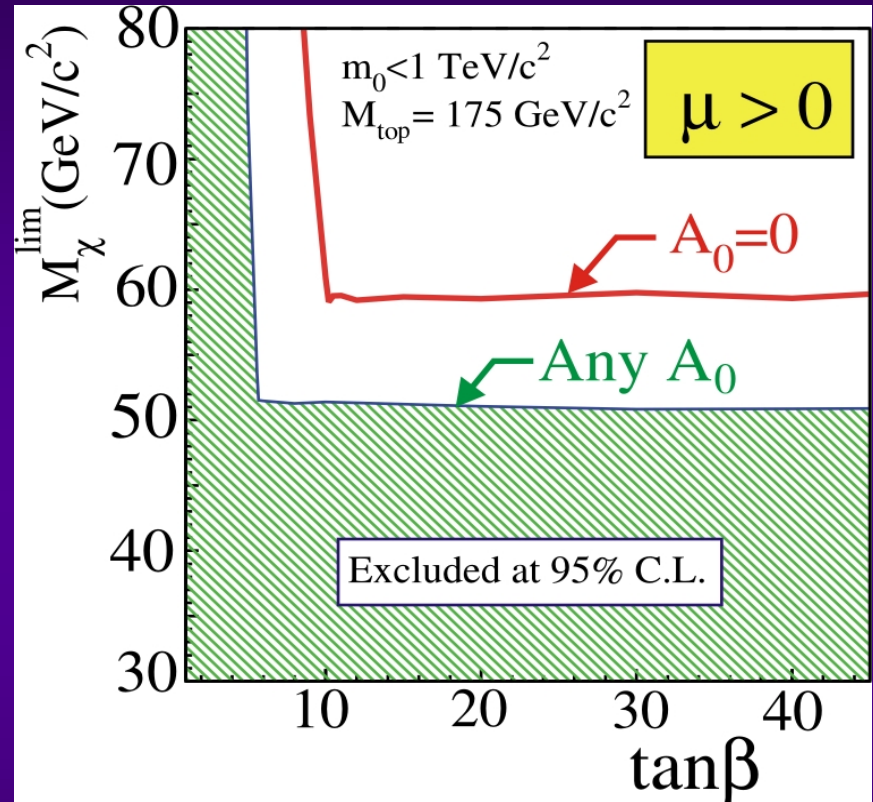
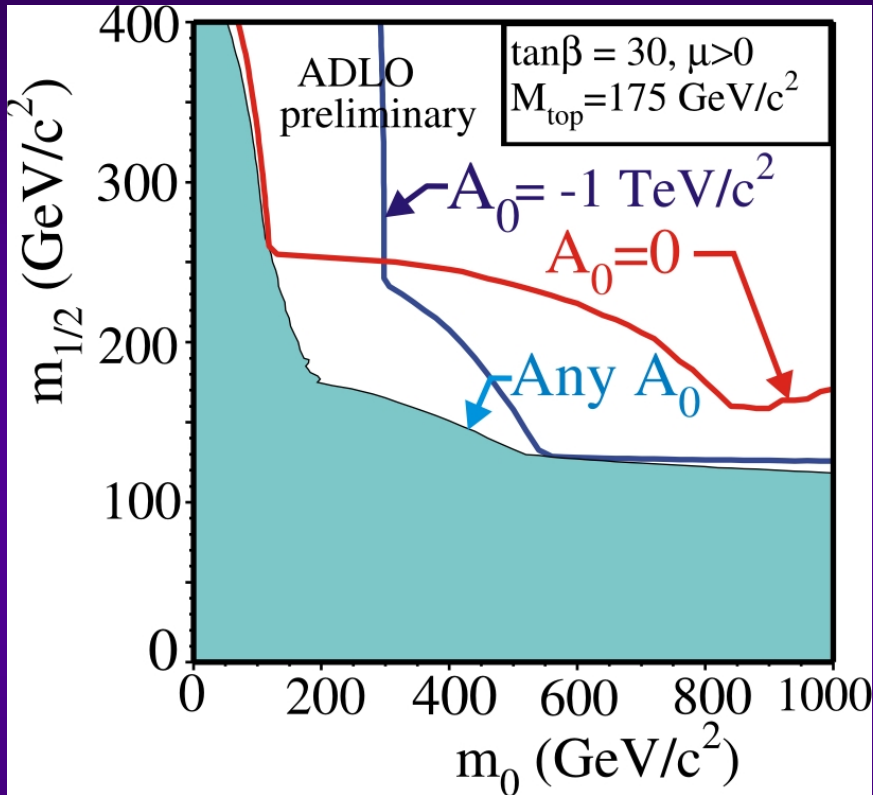
Dedes, Dreiner, Nierste, Phys.Rev.Lett. **87** (2001) 251804 & also hep-ph/0207026 and Arnowitz et al. hep-ph/0203069

($b \rightarrow s\gamma$ excludes \sim whole visible plane)



First time: mSUGRA $A_0 \neq 0$

(LEP SUSY WG, G.Ganis *et al.*)



◆ A_0 Drives \tilde{f} mixing

- ◆ Especially $\tilde{t}, \tilde{b}, \tilde{\tau}$
- ◆ Large effect on higgs
- ◆ Also affects charginos

$M(\tilde{\chi}^0)$

$A_0=0$

Any A_0

$\mu > 0$

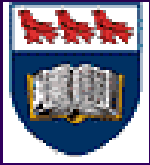
59.0

50.9

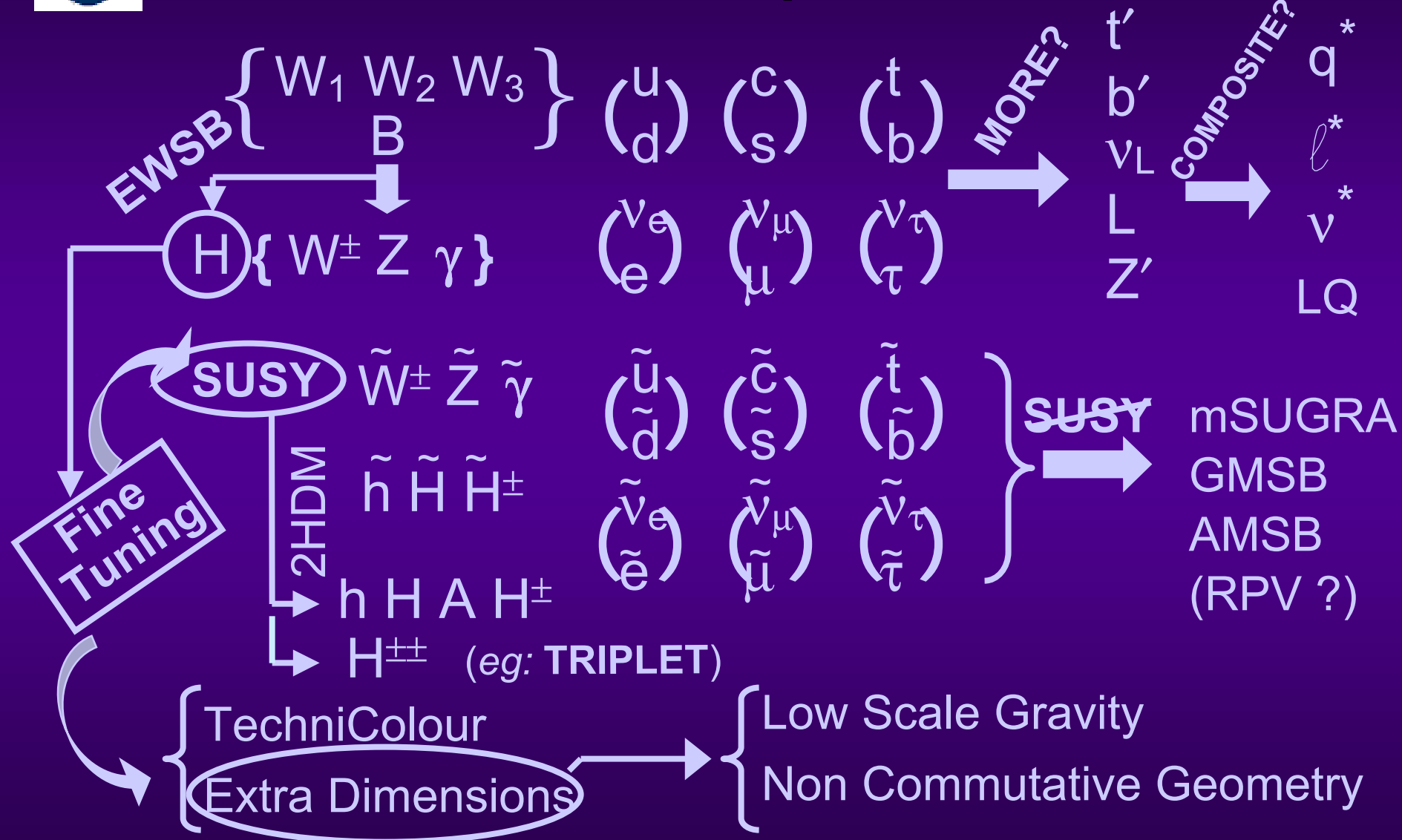
$\mu < 0$

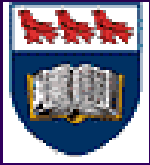
58.6

50.3

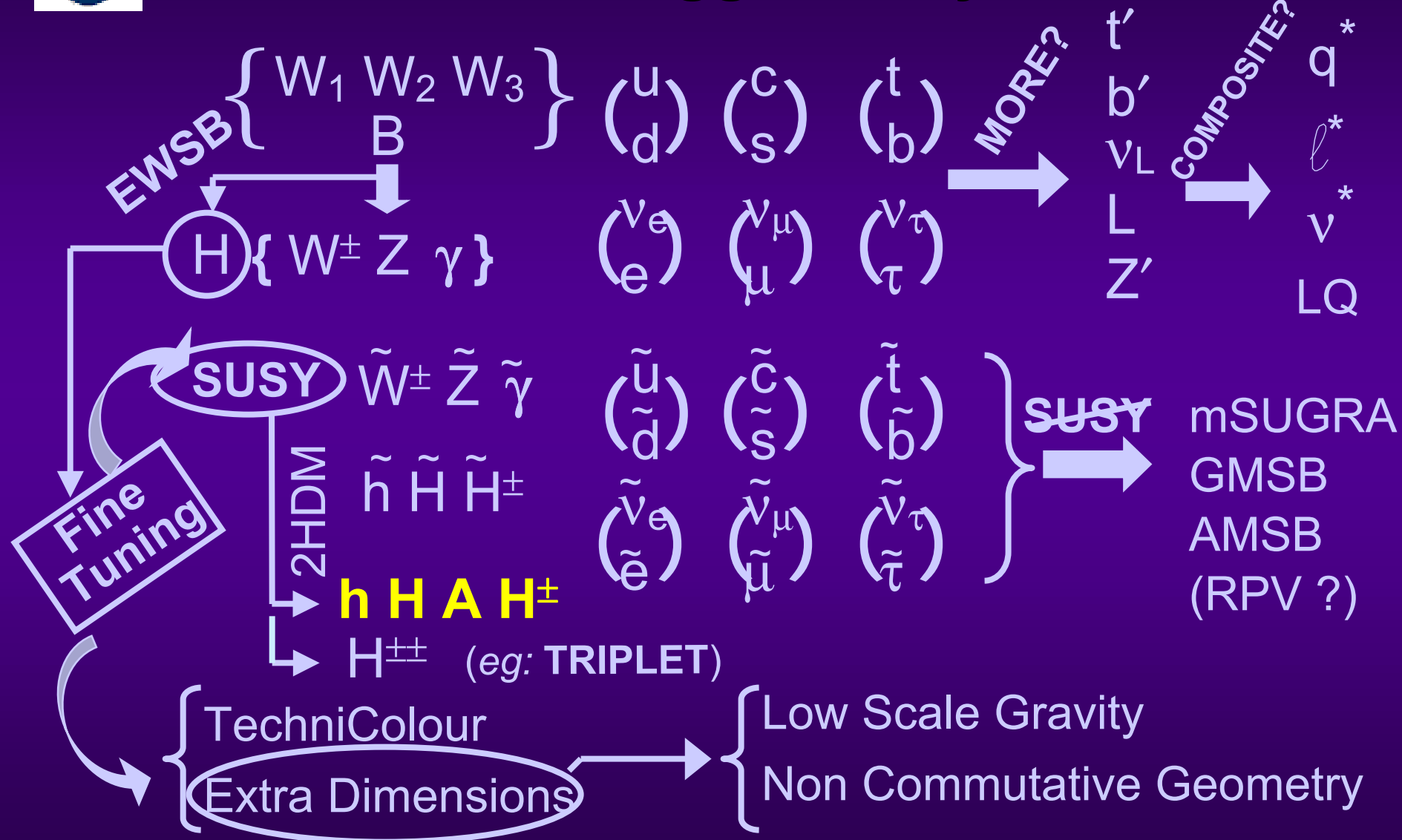


Roadmap ...





Exotic Higgs Decays





Exotic Higgs?



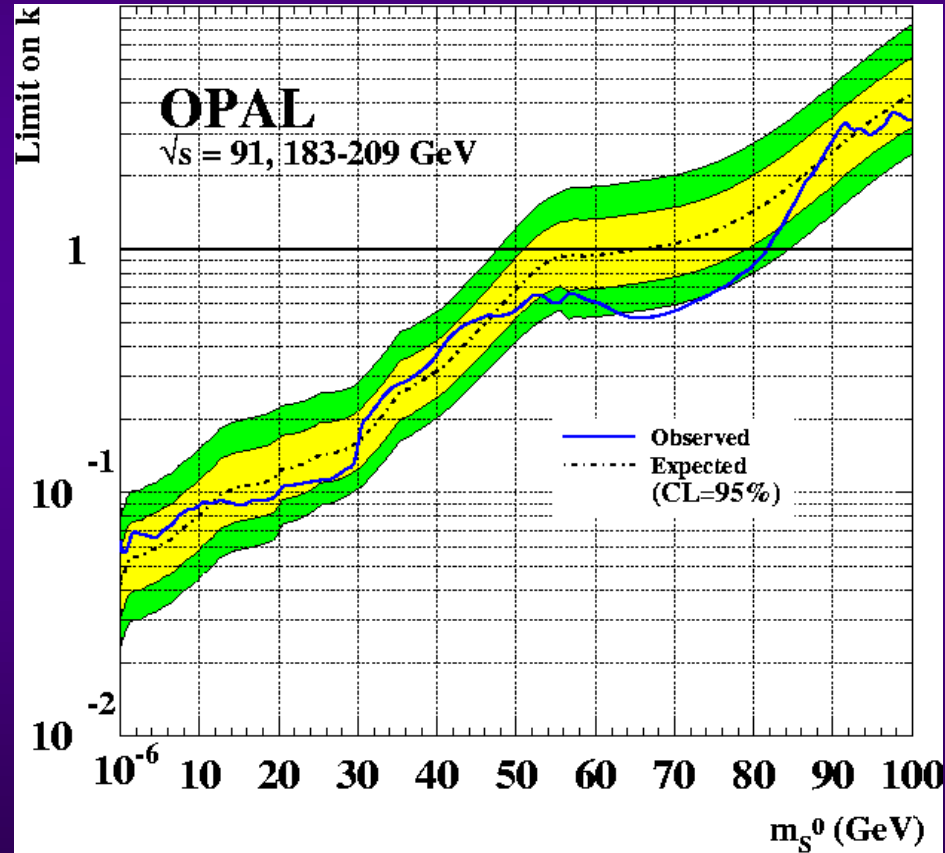
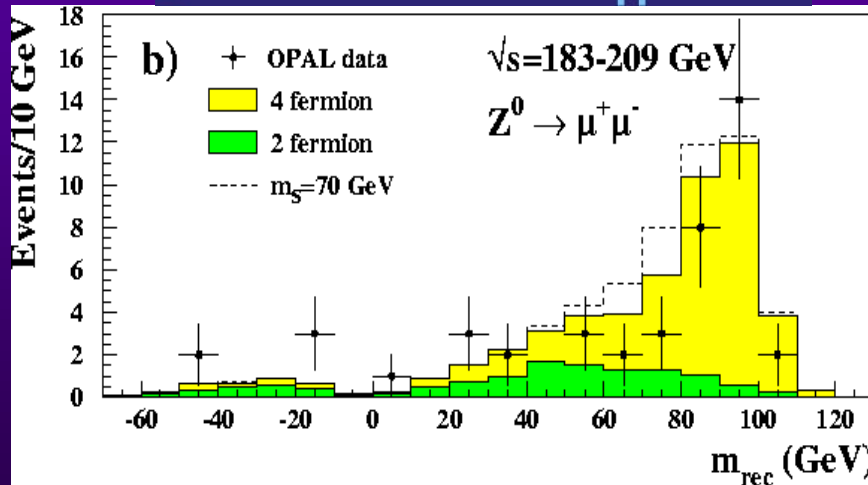
What if Higgs has different couplings?

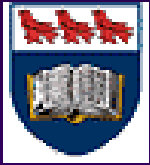
$H \leftrightarrow V V$ Searches



$$k = \frac{\sigma(HZ)}{SM}$$

General Higgs Search

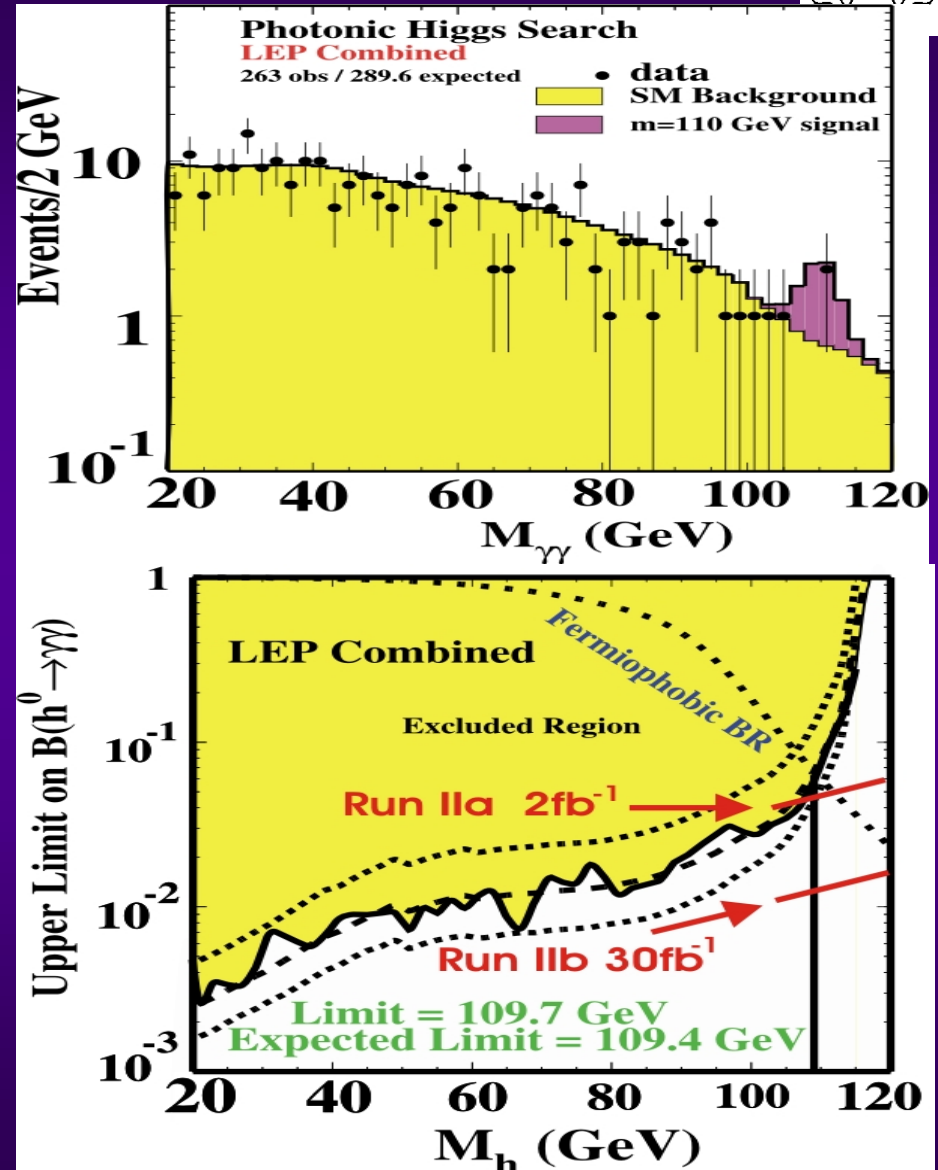
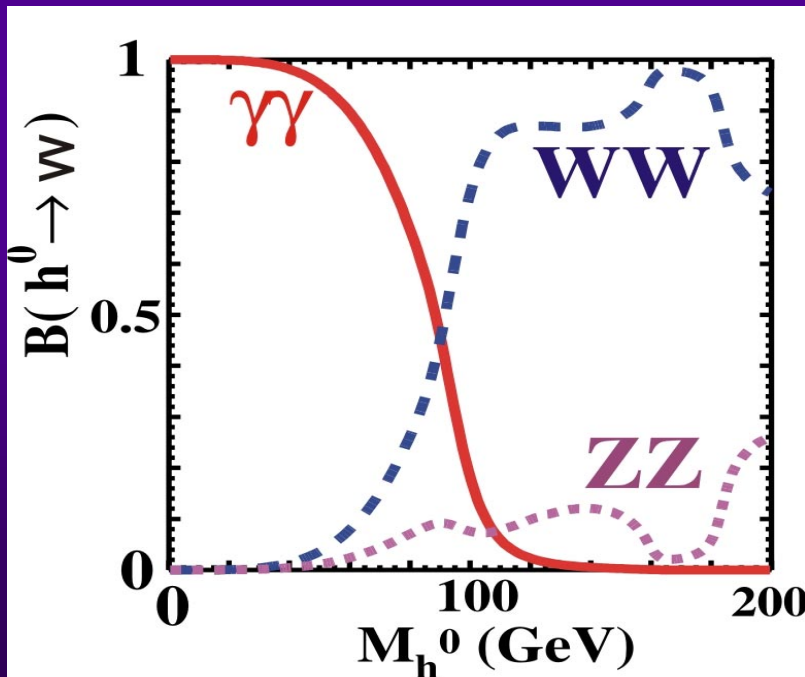


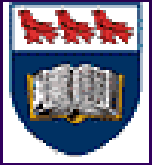


Exotic Higgs II: Fermiophobic

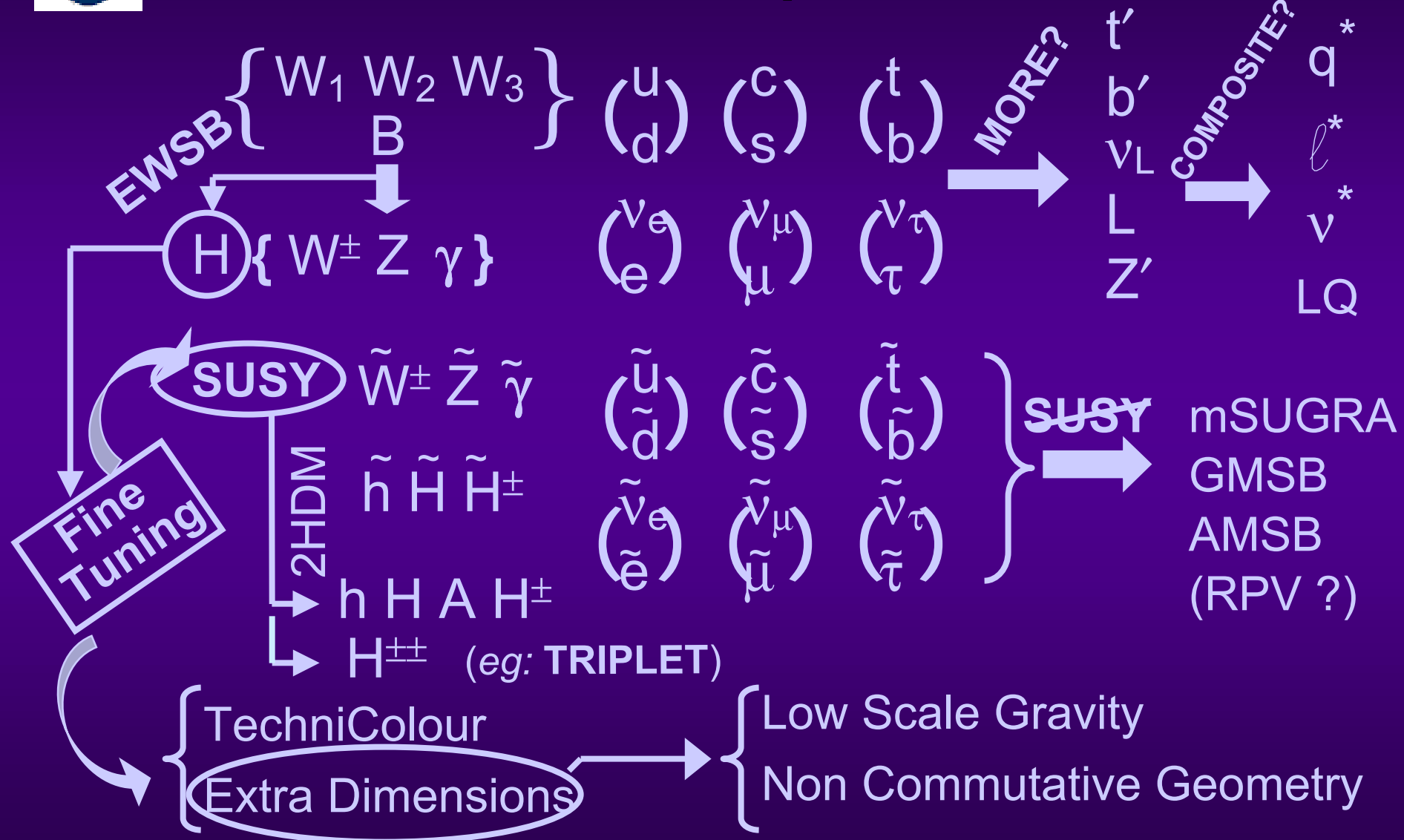


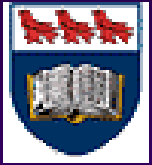
Turn off Fermion Couplings
 $H \rightarrow V V$ Decays



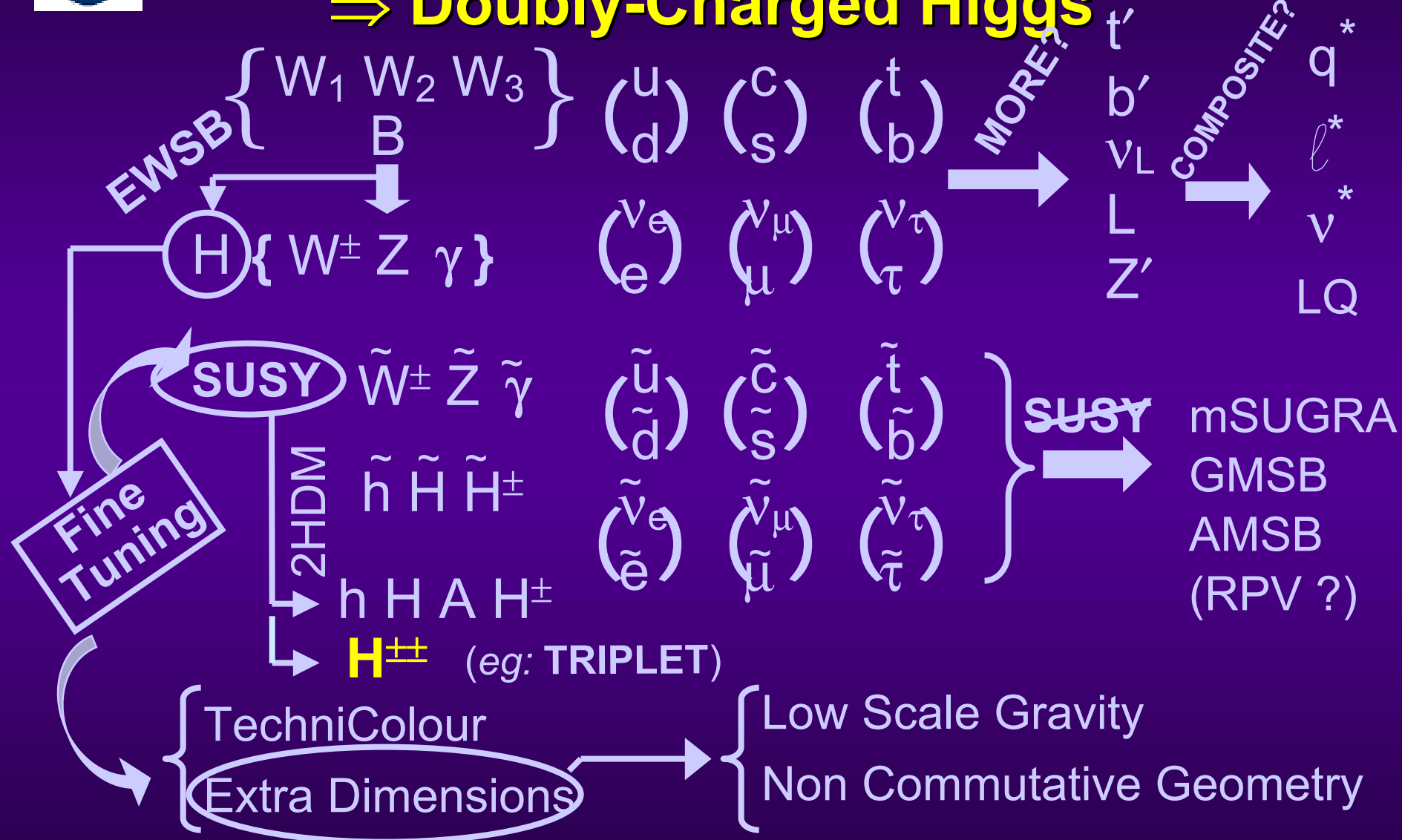


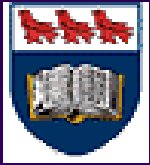
Roadmap ...





Higgs Triplets, L-R Symmetric ⇒ Doubly-Charged Higgs



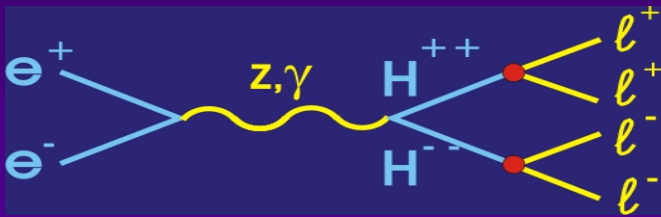


$H^{\pm\pm} (\Delta^{\pm\pm})$: Decays to $l^{\pm}l^{\pm}, W^{\pm}W^{\pm}, H^{\pm}W^{\pm}$

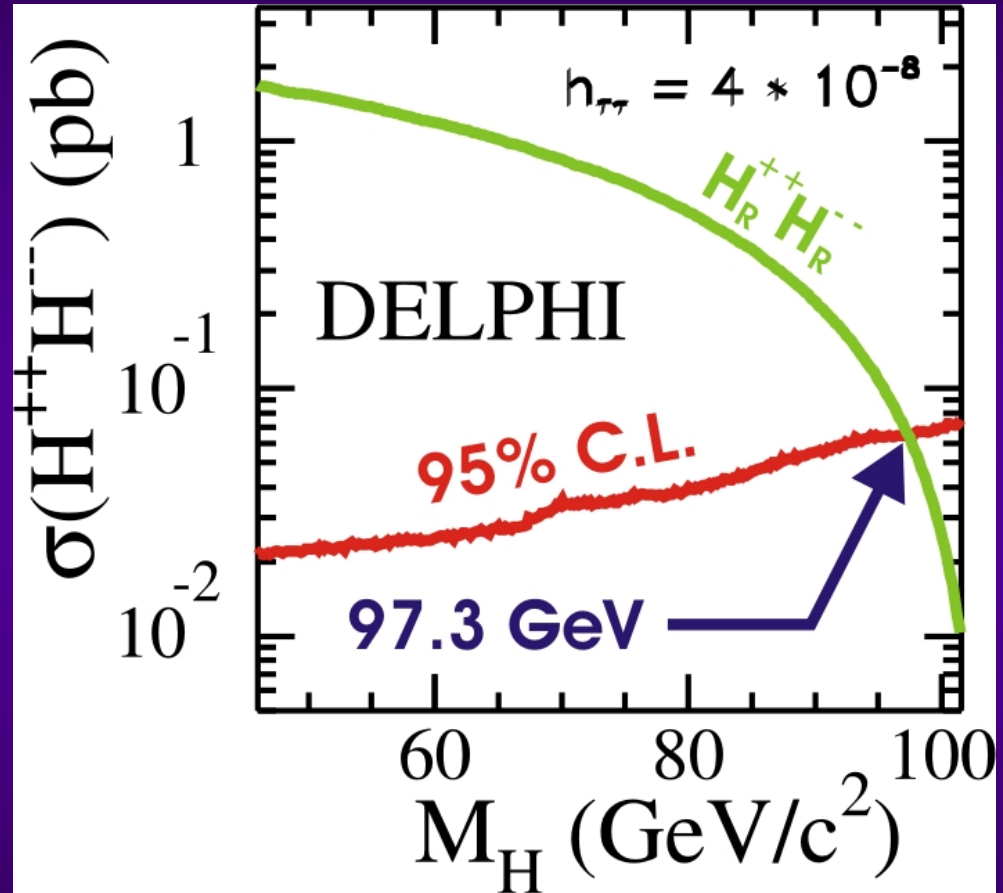


Dominant leptonic couplings via Yukawa $h_{ll'}$

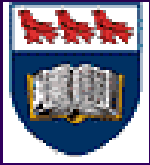
Pair production at LEP



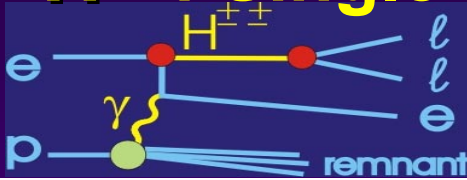
- ◆ Signature striking
 - ◆ Clean 4 lepton final states
 - ◆ DELPHI: 4 τ
 - ◆ OPAL: all leptons
- ◆ Arbitrary Yukawa $h_{ll'}$
 - ◆ $h_{ll'} < 10^{-7} \Rightarrow$ Lifetime
 - ◆ DELPHI: all lifetimes



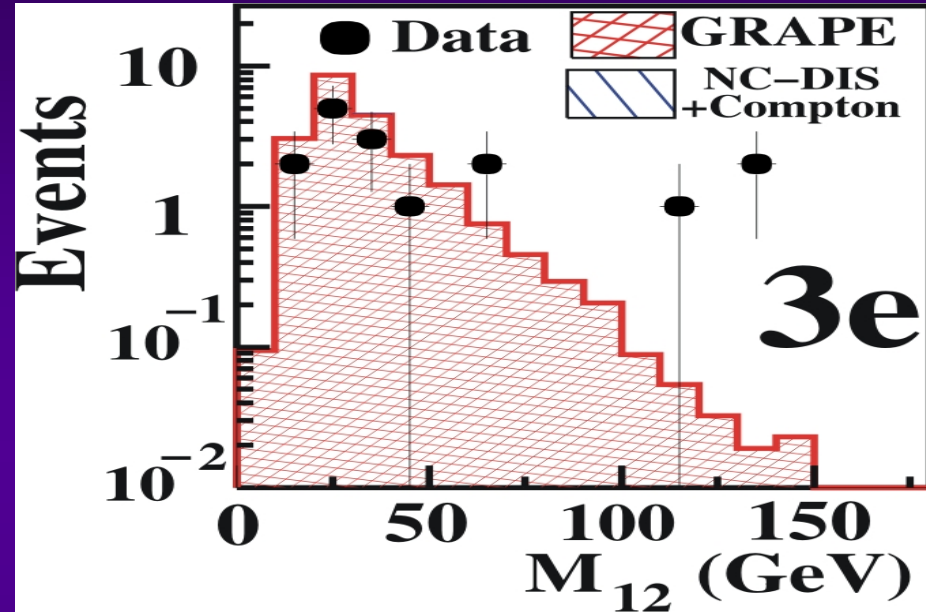
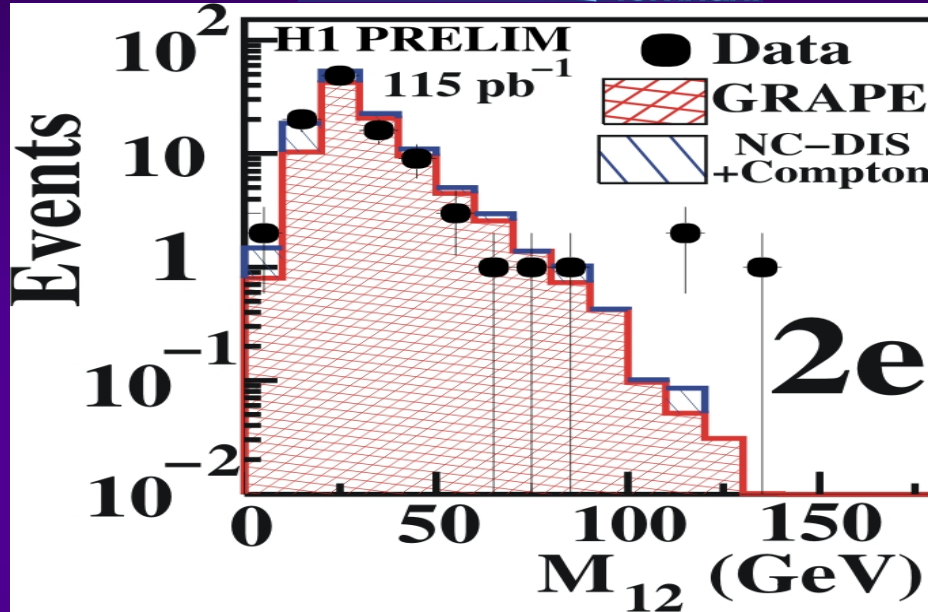
Exclusion to $\approx \sqrt{s}/2$



$H^{\pm\pm}$: Single production at HERA?



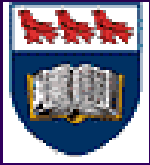
General H1 multi-lepton selection:



selection	Data	SM
2e $M > 100$	3	0.25 ± 0.05
3e $M > 100$	3	0.23 ± 0.04

H1 at ICHEP'02:

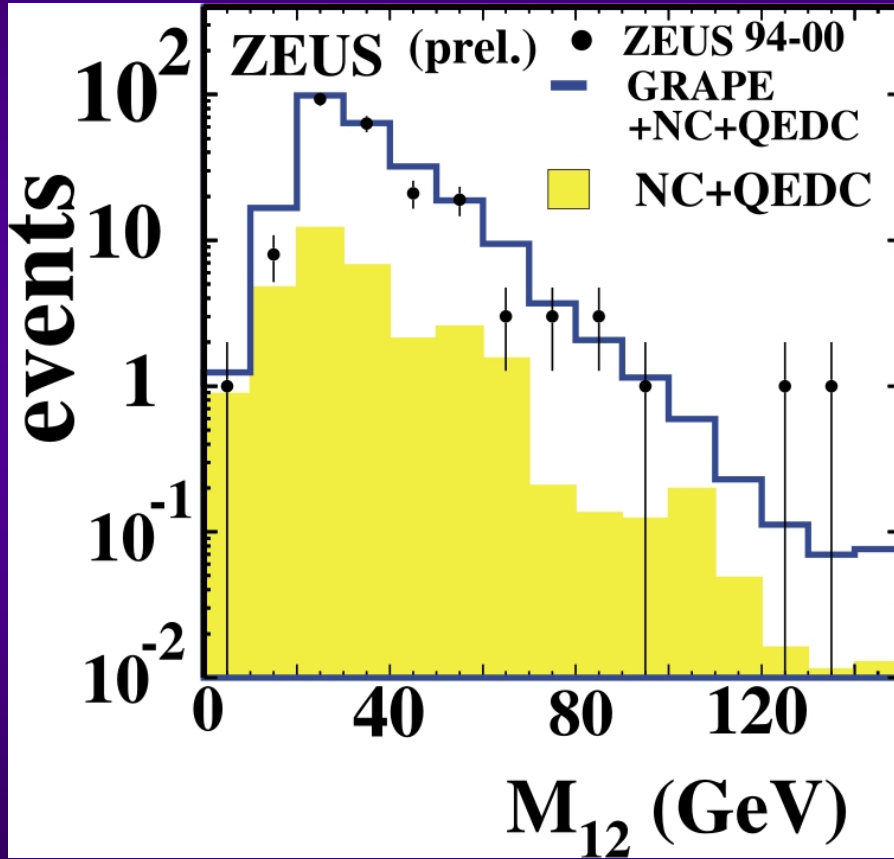
- ◆ Discussed recently (eg, SUSY'02) as a possible ~ 120 GeV $H^{\pm\pm}$ hint
- ◆ Dedicated $H^{\pm\pm}$ search
- ◆ 1 data / 0.34 background



ZEUS high mass ee?



ZEUS: 94-00, 130 pb⁻¹:



selection	Data	SM
2e $M > 100$	2	0.77 ± 0.08
3e $M > 100$	0	0.37 ± 0.04
Both	2	1.14 ± 0.09

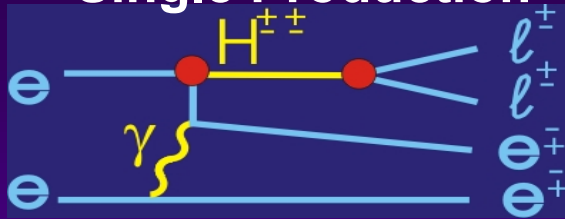
⇒ Good agreement with SM



$H^{\pm\pm}$: Higher Masses at LEP

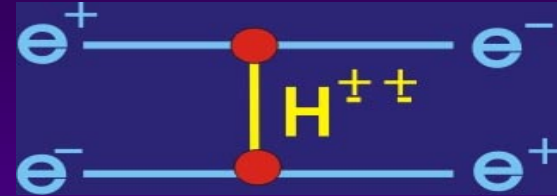


Single Production



(eg Barenboim *et al.*, Phys.Lett,B394(1997)132,
Godfrey,Kalyniak,Romanenko, hep-ph/0207240)

Also Constraints from Bhabhas

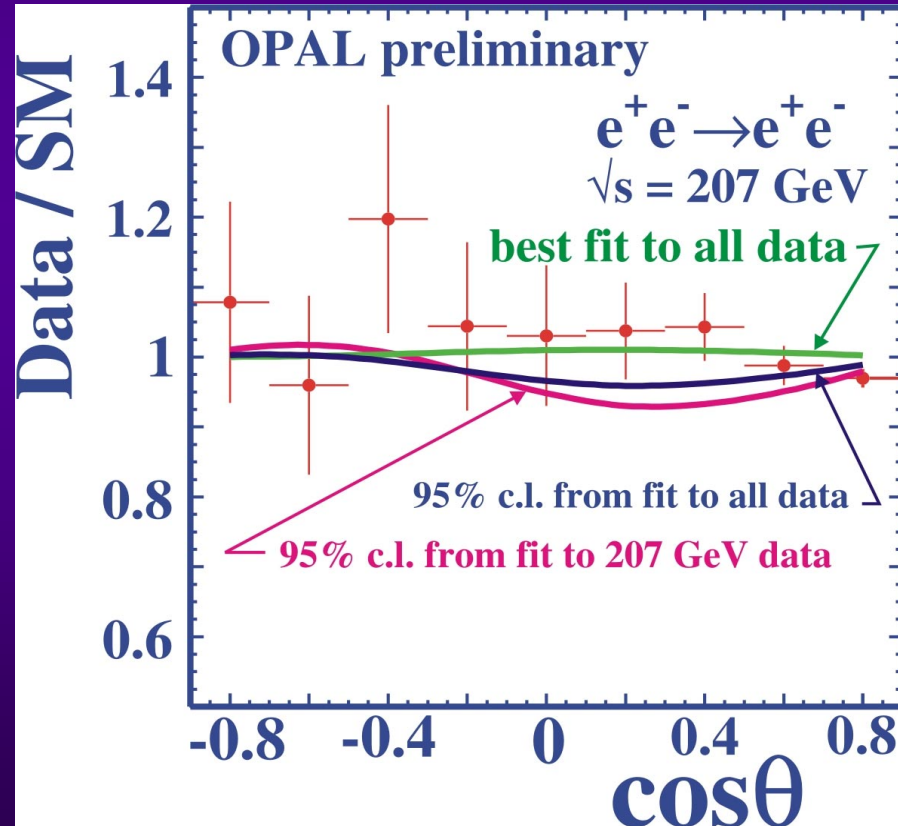
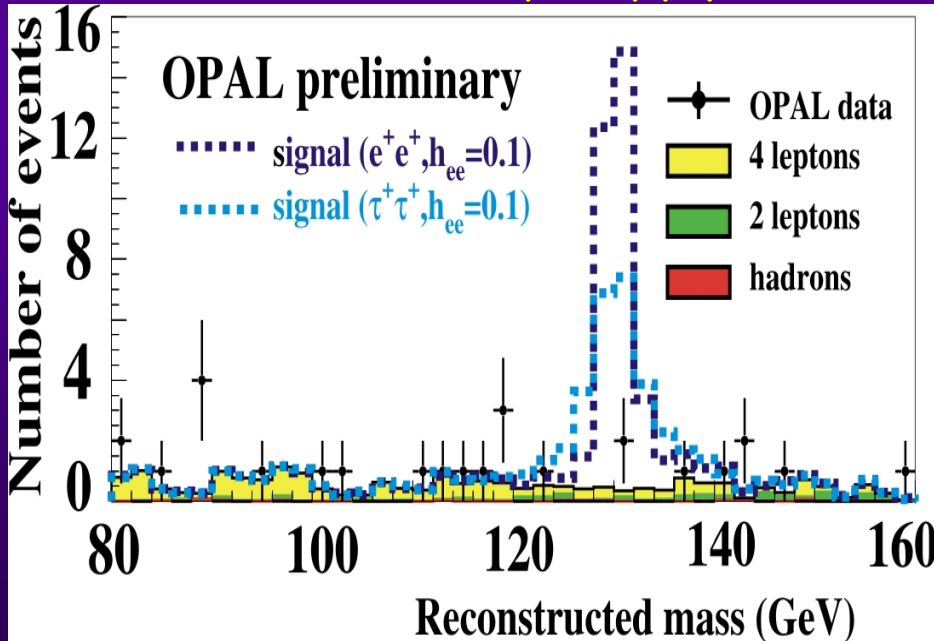


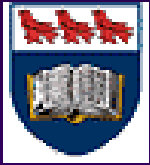
(eg M.L.Swartz, Phy.Rev.D40(1989)1521)

OPAL analysis:

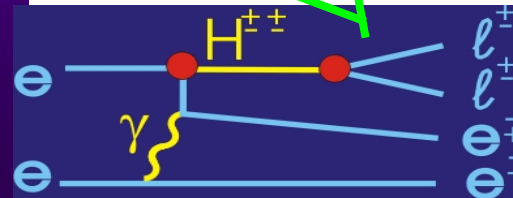
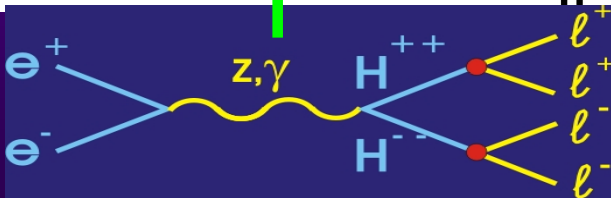
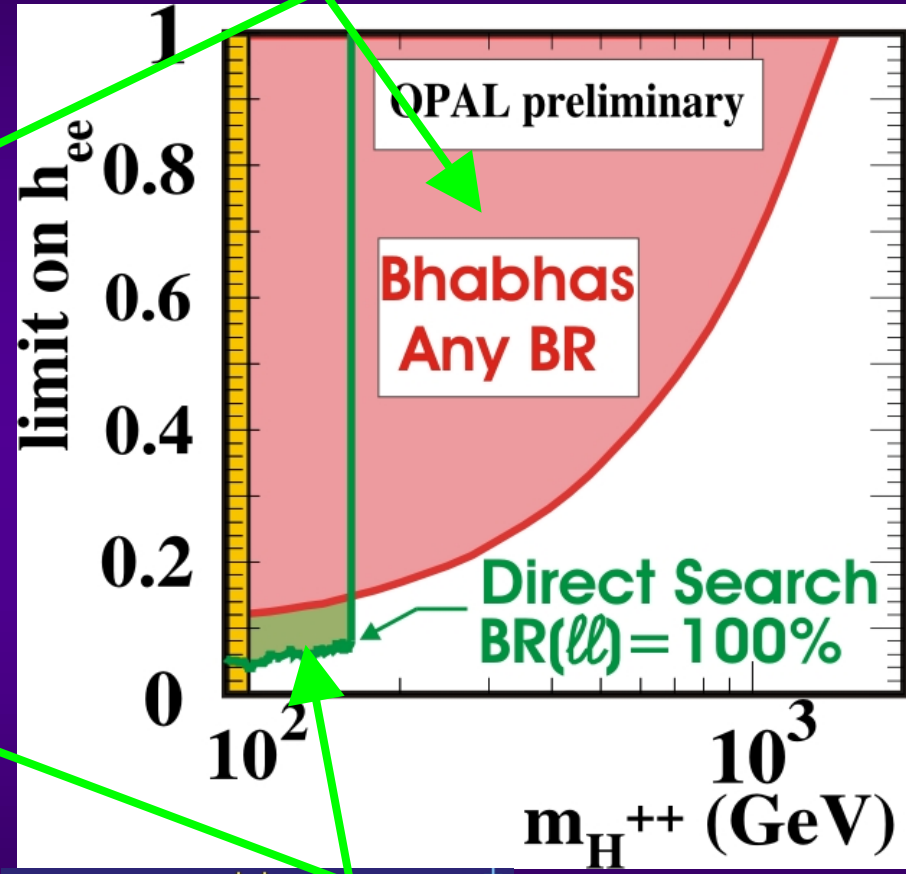
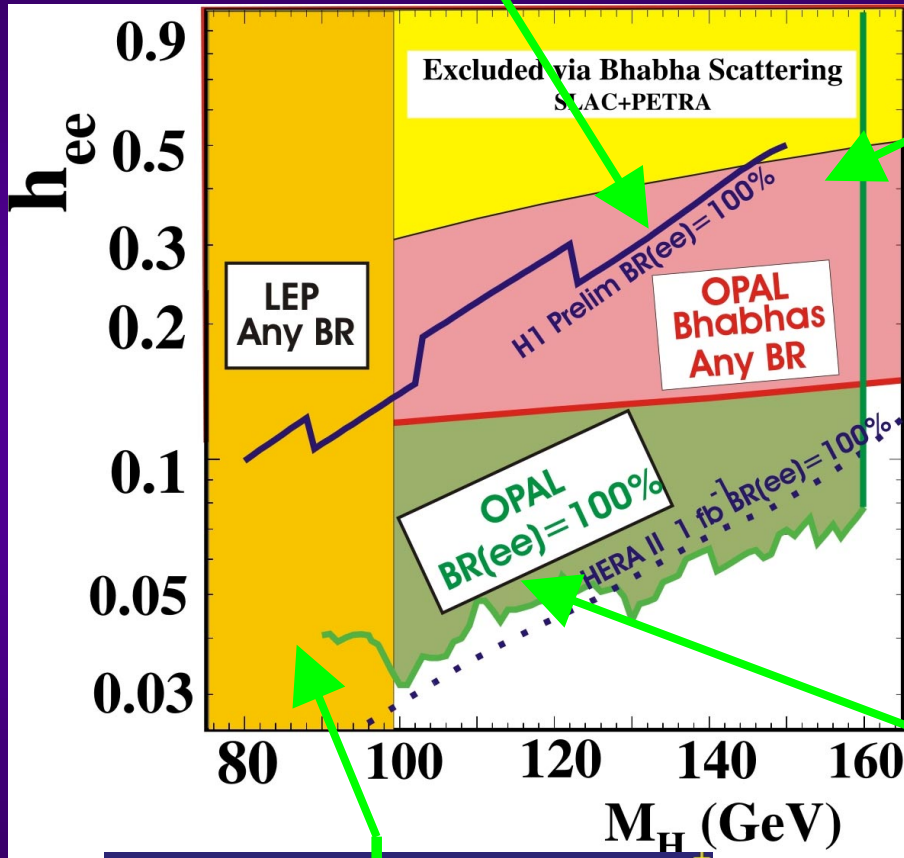
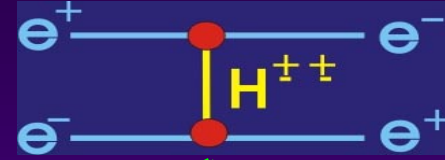
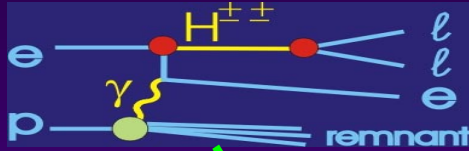
≥ 3 Lepton jets

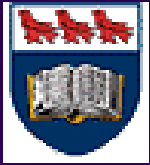
Full coverage $ee, e\mu, e\tau, \mu\mu, \mu\tau, \tau\tau$



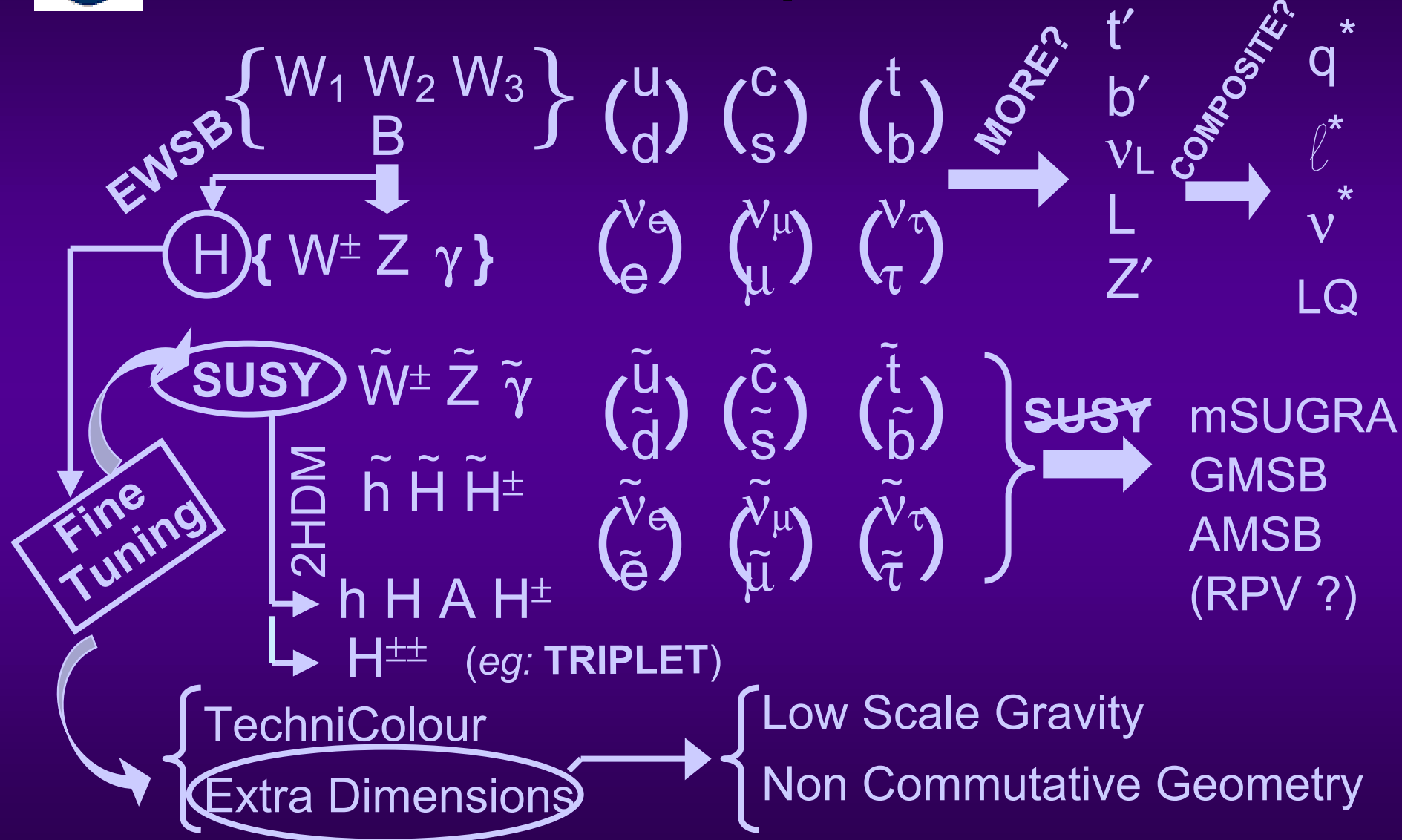


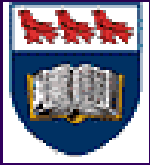
H^{++} : Constraints



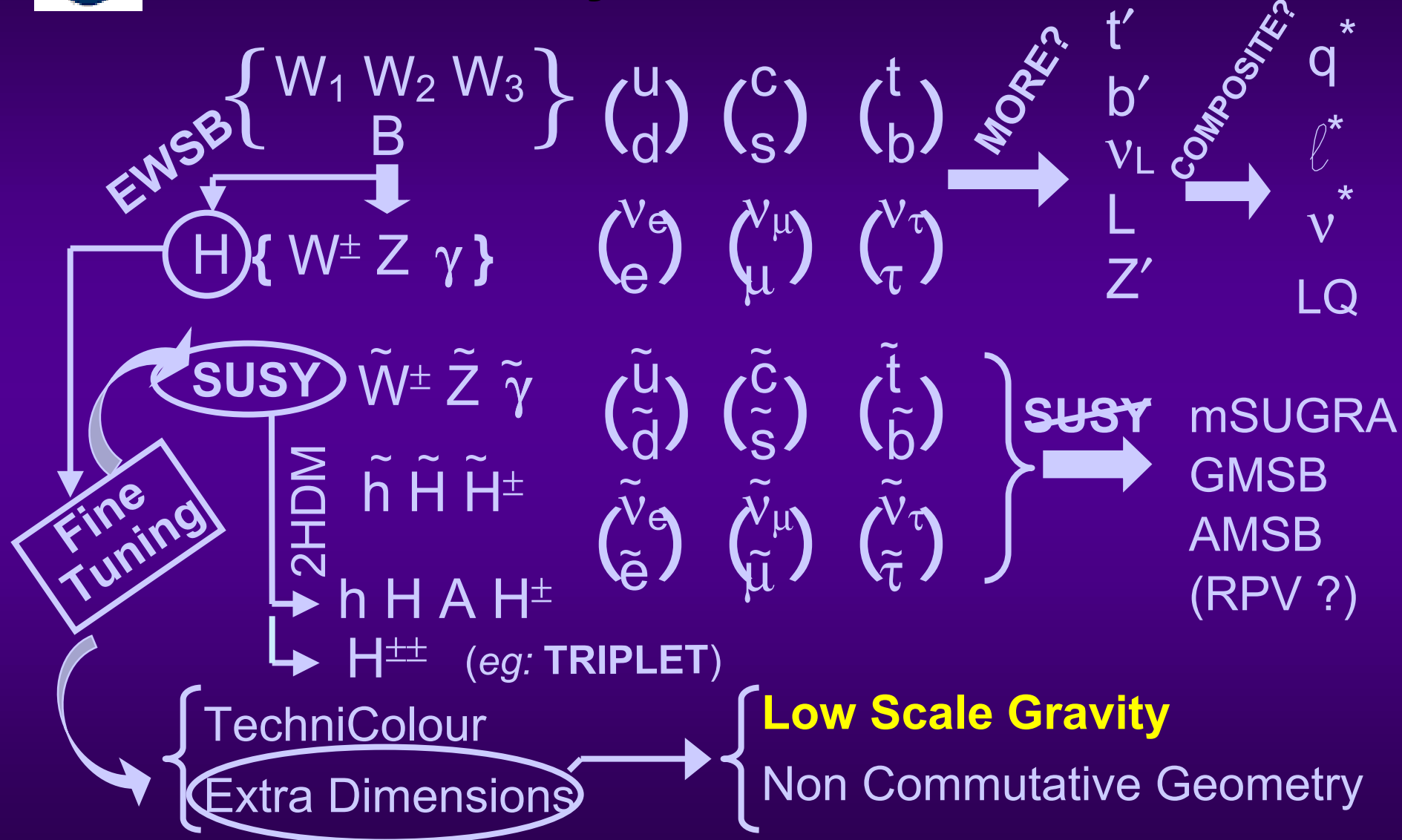


Roadmap ...





Gravity in Extra Dim.



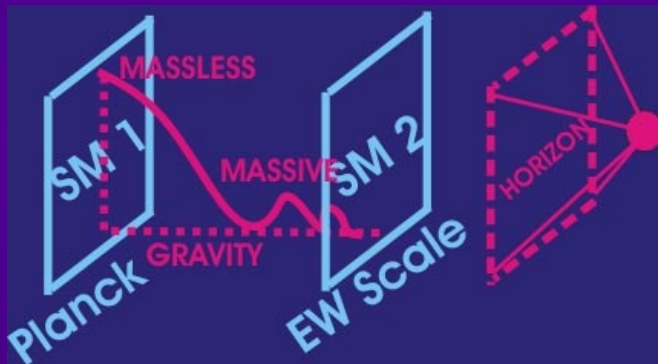


Extra Dimensions



- ◆ General idea:
 - ◆ Gravity actually strong
 - ◆ Xdim trick us into seeing $M_{Pl} \approx 10^{19} \text{ GeV}$
- ◆ Different Models on market

Randall-Sundrum



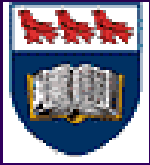
Arkani-Hamed, Dimopoulos, Dvali (ADD)



$$M_{Pl}^2 = R^n \times M_D^{n+2}$$

- ◆ Planck SM: gravity strong
- ◆ EW Scale SM: gravity weak
- ◆ Signature:
 - ◆ Production of 1st G_{KK} mode
 - ◆ Out of kinematic reach?

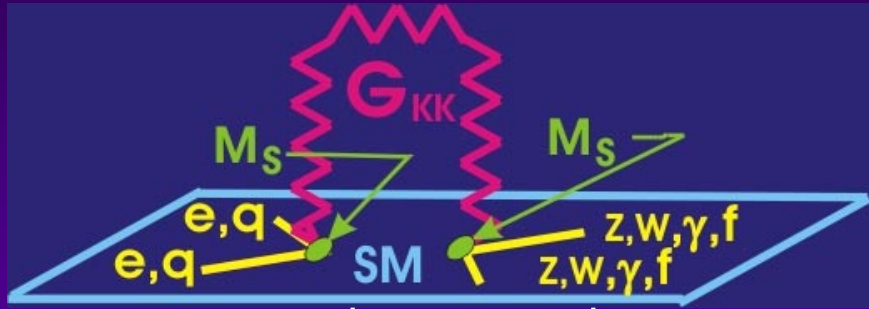
- ◆ “Planck” @ $M_D \approx \Lambda_{EW}$
- ◆ Still weak in “SM”, but see $\sum G_{KK}$ modes
 - ◆ Measurable effects



Large Xdim ...

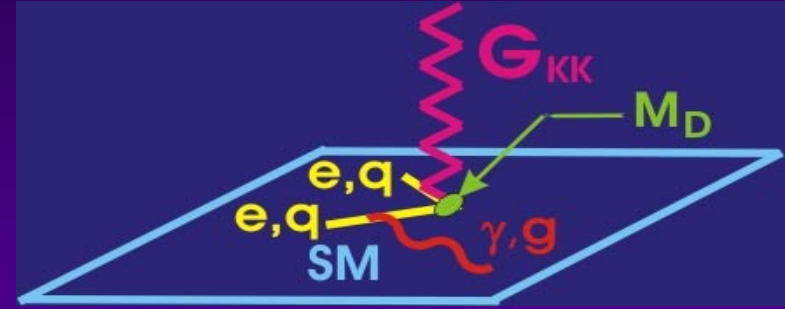


Indirect Effects

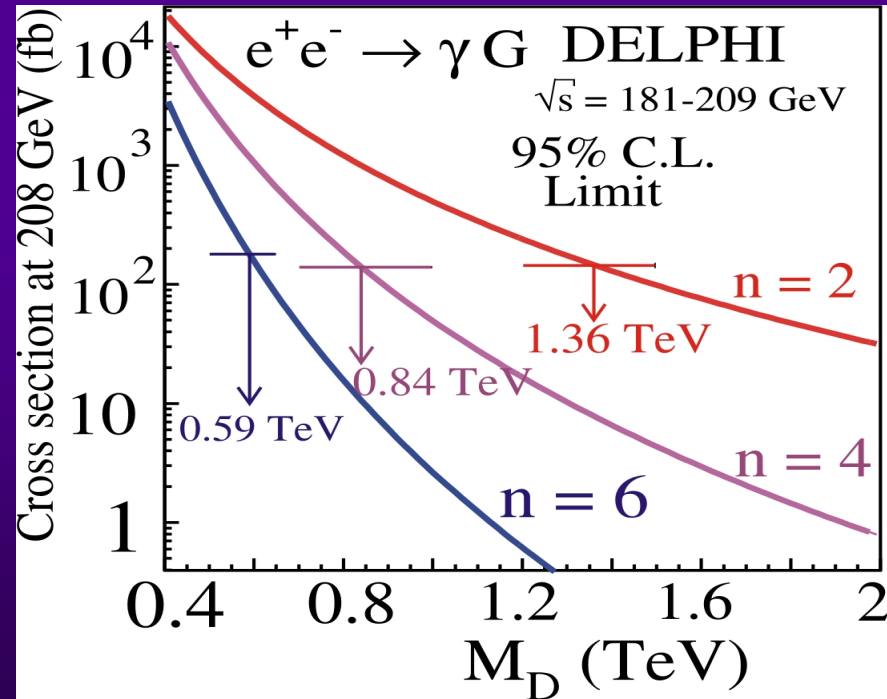
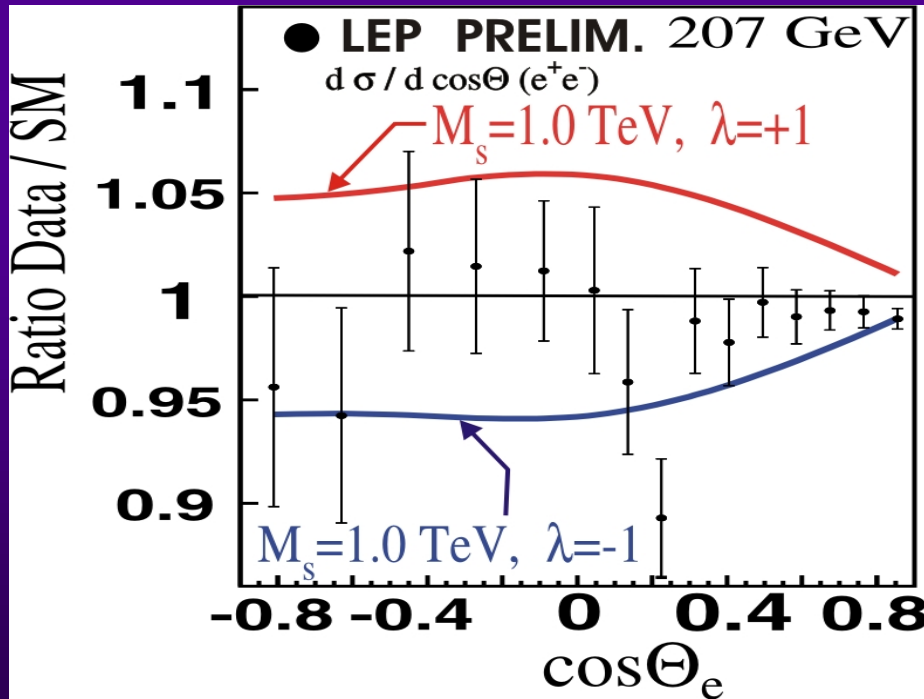


eg: $e^+e^- \rightarrow e^+e^-$

Direct Effects

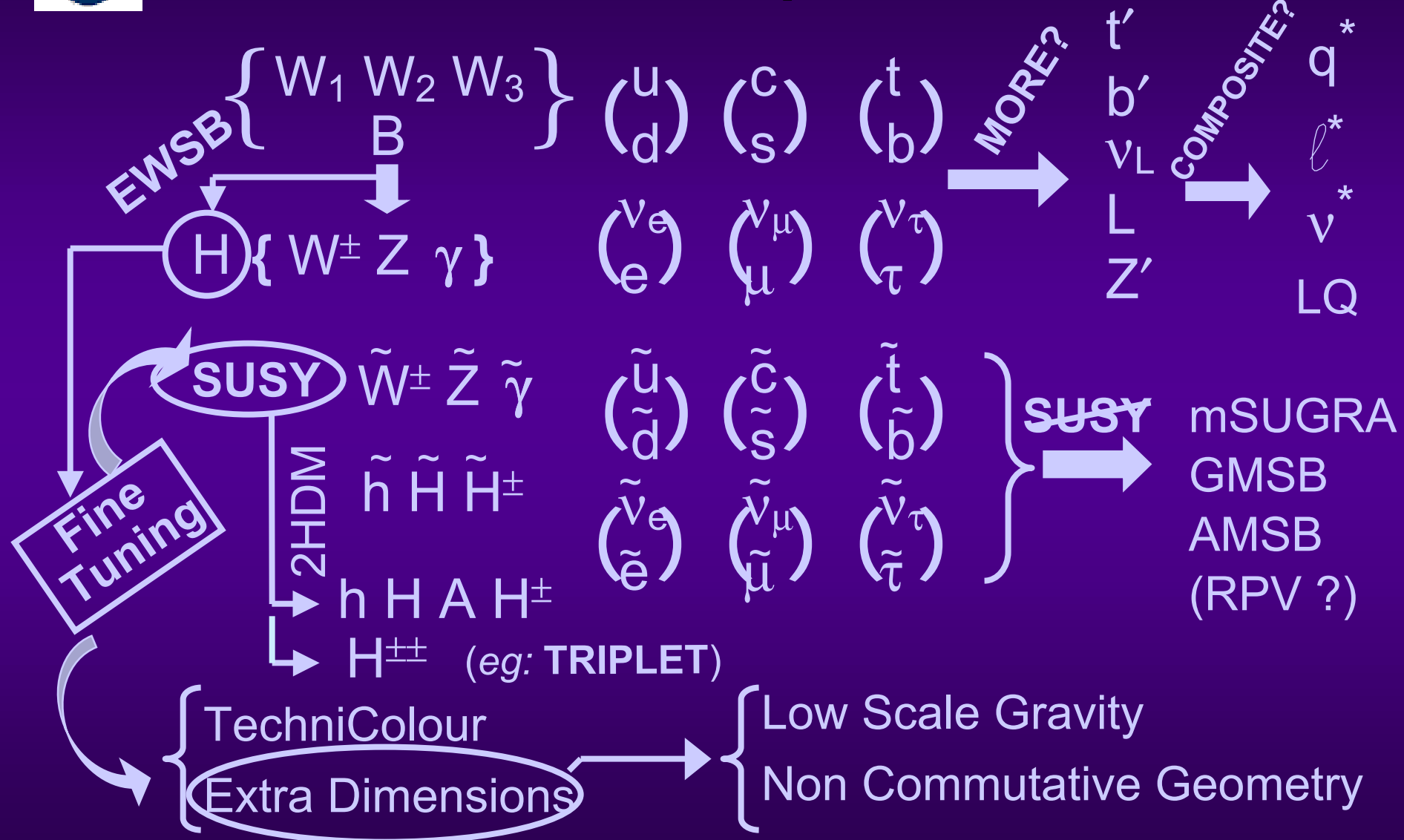


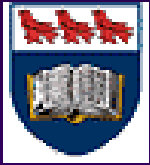
eg: $e^+e^- \rightarrow \gamma G$



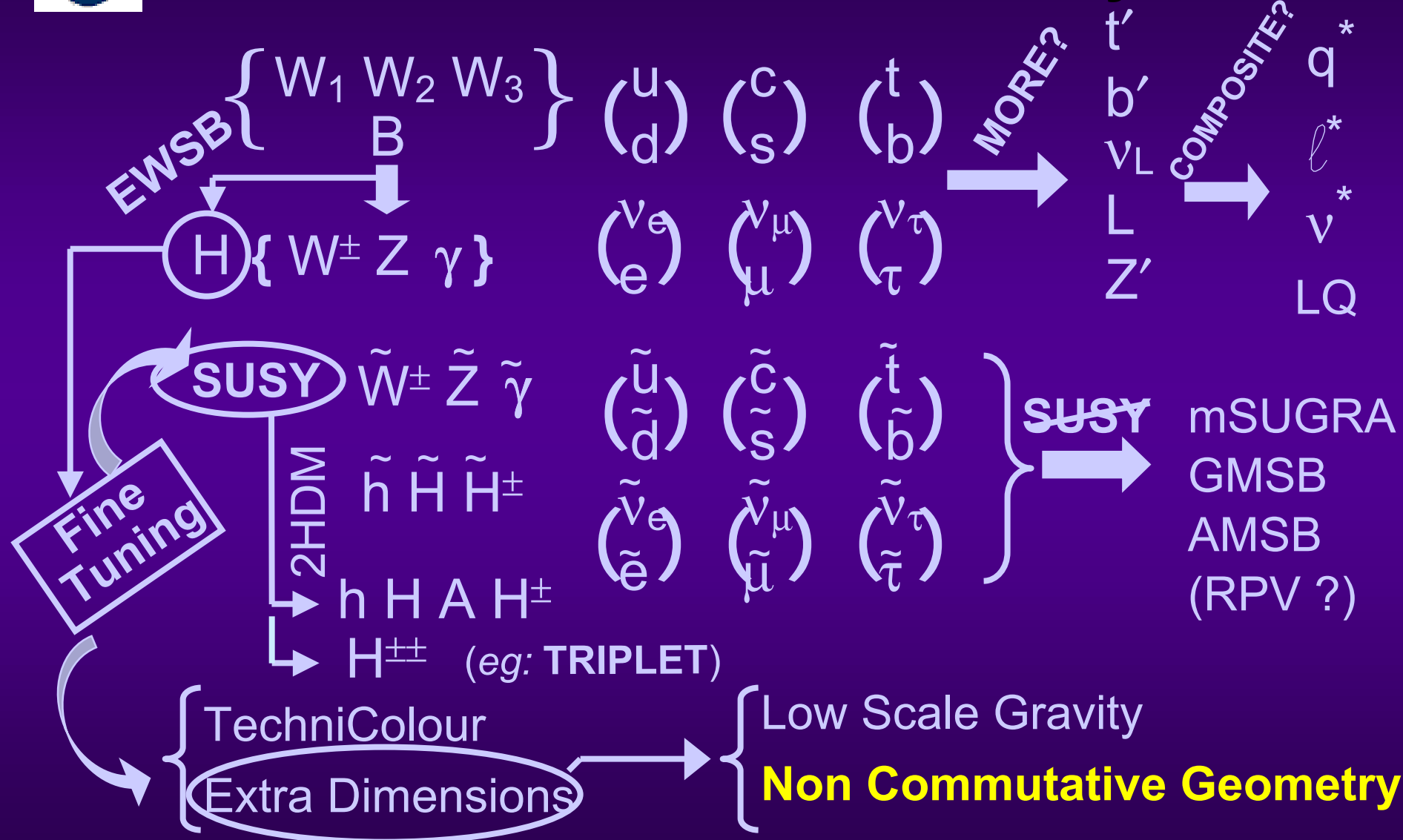


Roadmap ...





Non Commutative Geometry



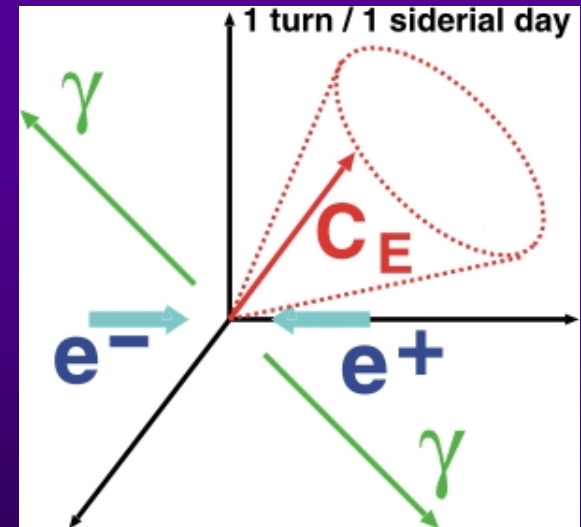
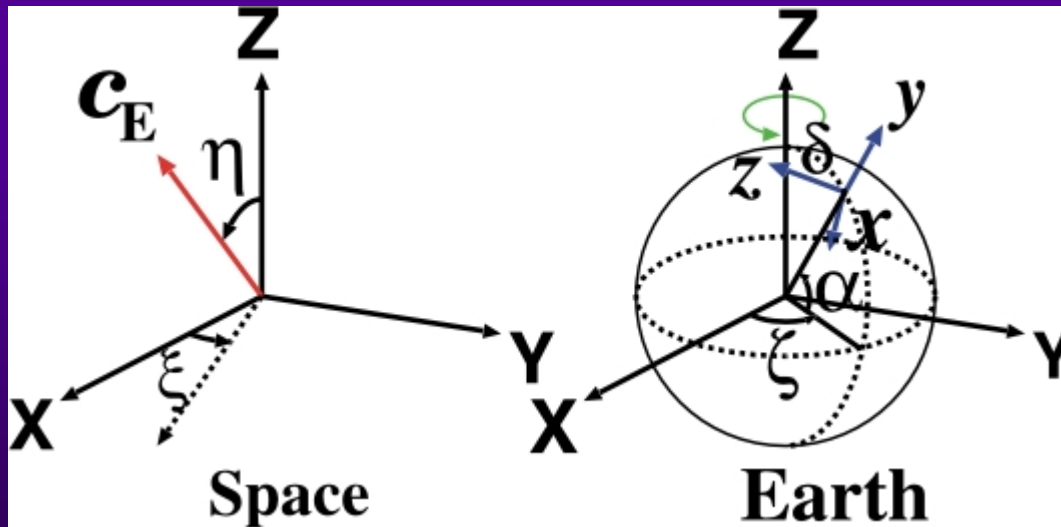


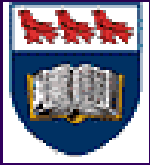
Non Commutative QED



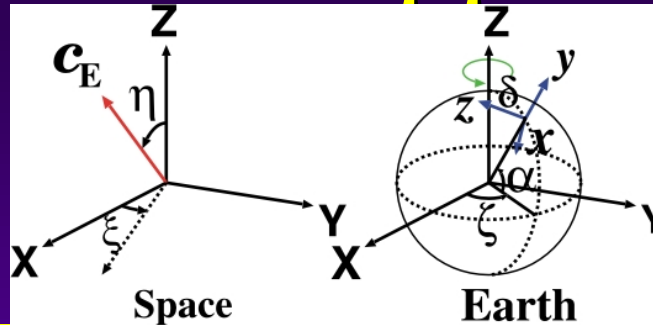
◆ Extra Dim. (eg: string theories) \Rightarrow Non Commutative Geometry

- ◆ $[X_\mu, X_\nu] = i \theta_{\mu\nu}$, $\theta_{\mu\nu} = \mathbf{c}_{\mu\nu} / \Lambda_{NC}^2$
 - ◆ $\mathbf{C}_{\mu\nu}$ = Unit vector pointing in preferred direction
 - ◆ Λ_{NC} = Energy scale of N.C. effects
 - ◆ $\Lambda_{NC} = M_{\text{planck}} = \text{TeV scale??}$ (low scale gravity ...)
- ◆ No full non-commutative Standard Model exists
 - ◆ But non-commutative QED does ... “NCQED”

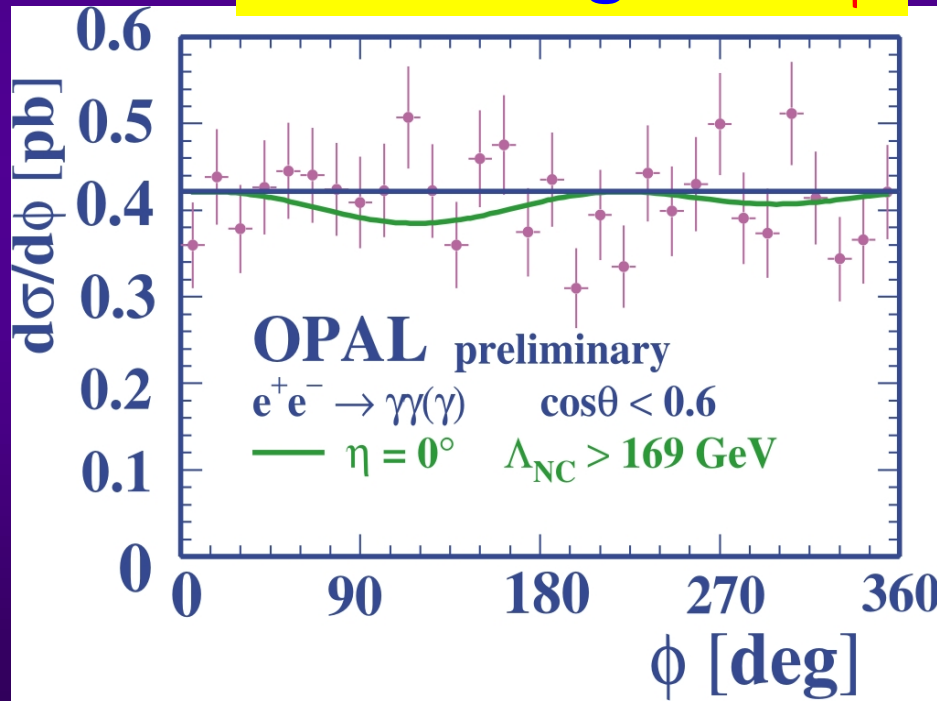




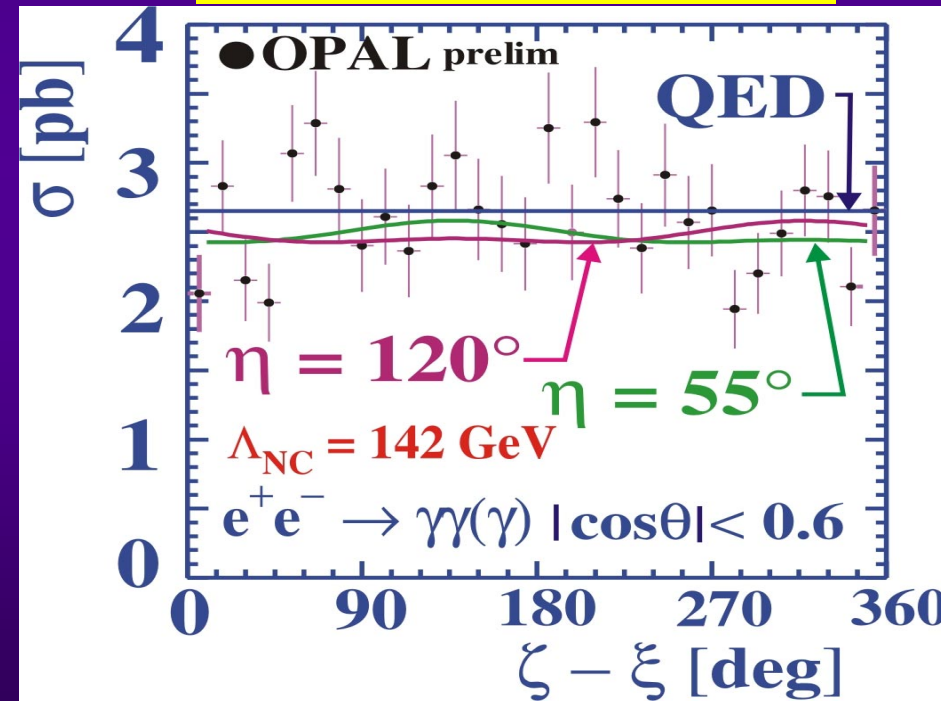
NCQED in $e^+e^- \rightarrow \gamma\gamma$ with OPAL



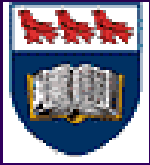
Time Integrated ϕ



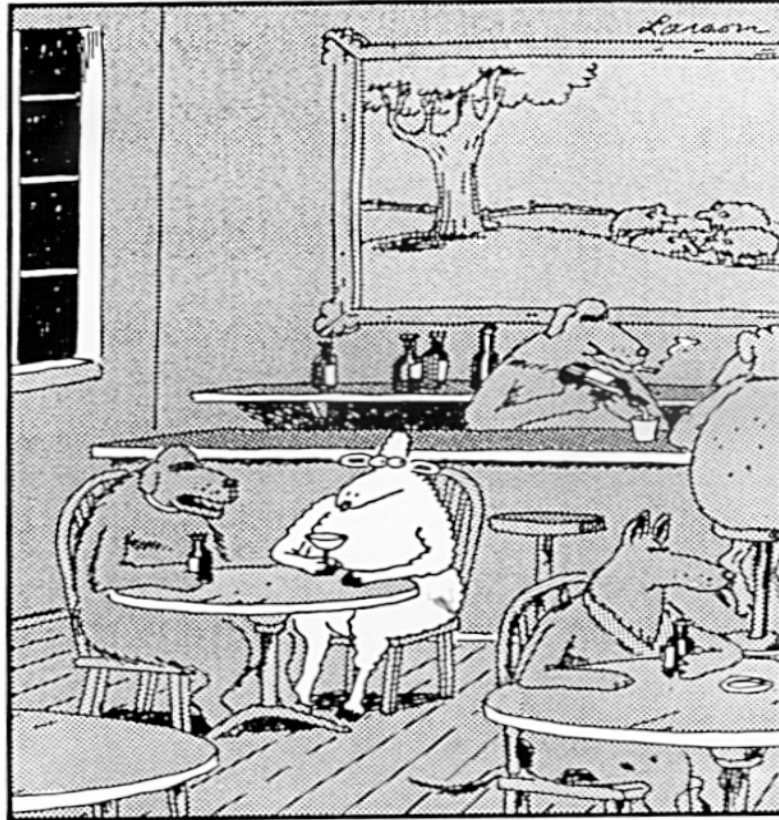
Time Dependent



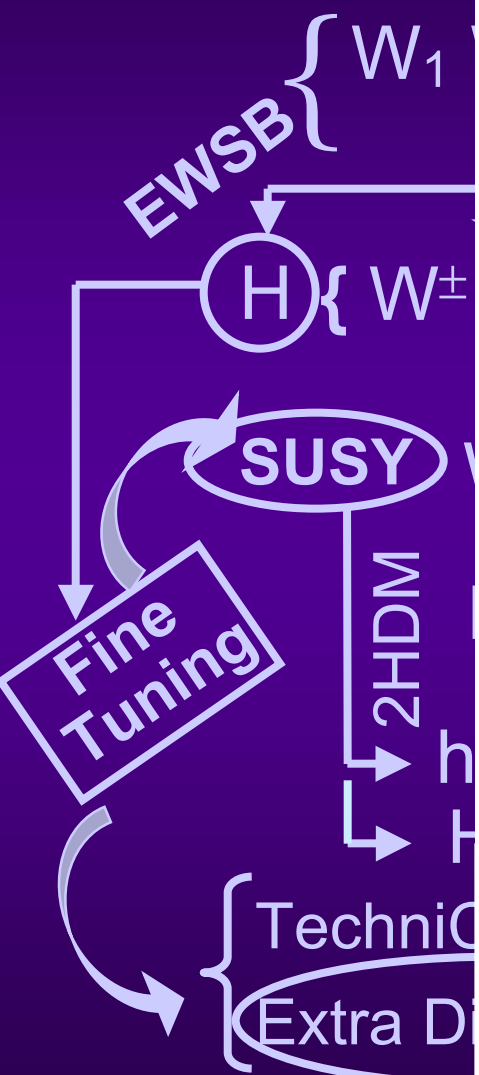
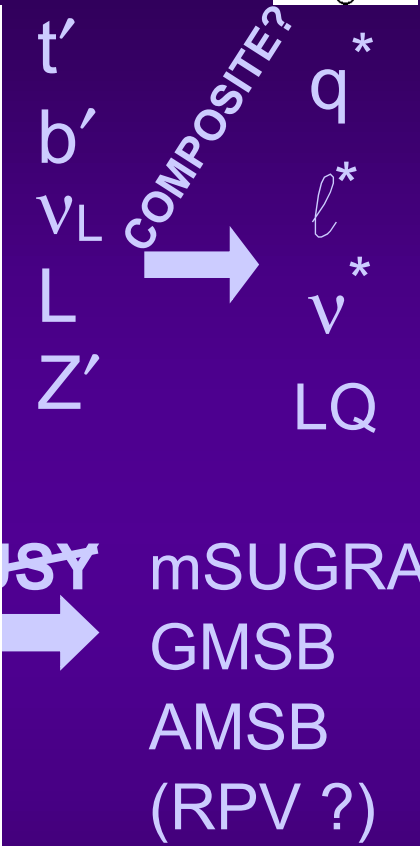
$\Lambda > 142 \text{ GeV, any } \eta \text{ (95\% C.L.)}$



Were we looking for the right things?



**“Confession time Mona:
I’ve led you astray.”**



vity
 ive Geometry

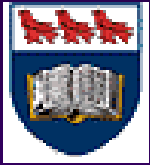


Conclusions

- ◆ Expect physics beyond the Standard Model
 - ◆ Higgs fine-tuning is problematic enough by itself
 - ◆ But unclear what form “new physics” will take
- ◆ Electroweak scale ??
 - ◆ Many models on the market
 - ◆ Searches both within model-frameworks and beyond
- ◆ Many constraints
 - ◆ Rare and S.M. forbidden processes
 - ◆ Precision measurements
 - ◆ Direct searches
- ◆ Evidence so far?
... **NO** ... (sigh)

But over next ~ 10 years:

Thoroughly probe the
TeV scale ...



Thanks ...



- ◆ Many contributors both directly and indirectly to this talk, including
 - ◆ **New results and plots**
 - ◆ **New combinations**
 - ◆ **Suggestions about what to show**
 - ◆ **Suggestions about what *NOT* to show**
- ◆ All mistakes and inconsistencies are mine!
- ◆ In particular, thanks to (not a complete list):
 - ◆ Wolfgang Adam, Herbert Dreiner, Elisabetta Gallo, Geraldo Ganis, Steve Godfrey, Corinne Goy, John Holt, Pat Kalyniak, Greg Landsberg, Paul Richard Newman, Mark Oreglia, David Plane, Christoph Rembser, Kirsten Sachs, André Schöning, Roberto Techini, Isabel Trigger, Brigitte Vachon