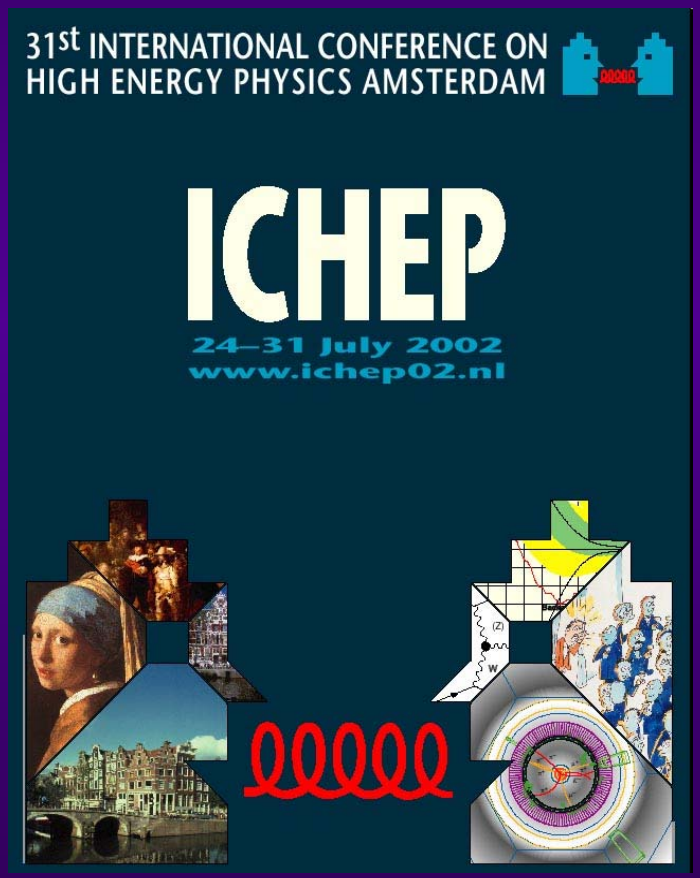
Beyond the Standard Model: experimental results



31st International Conference on High Energy Physics

Rob McPherson
University of Victoria and
Canadian Institute of
Particle Physics

Amsterdam

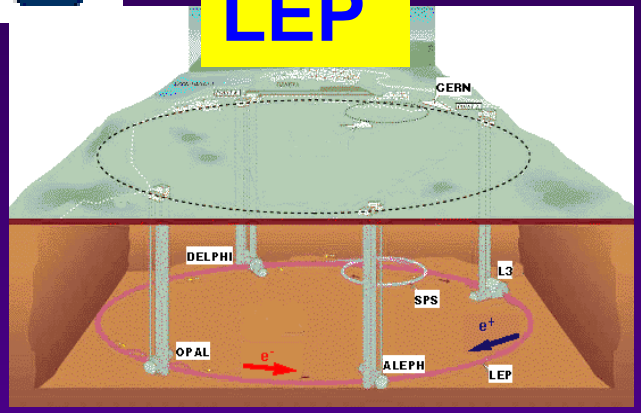
24-31 July 2002

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



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

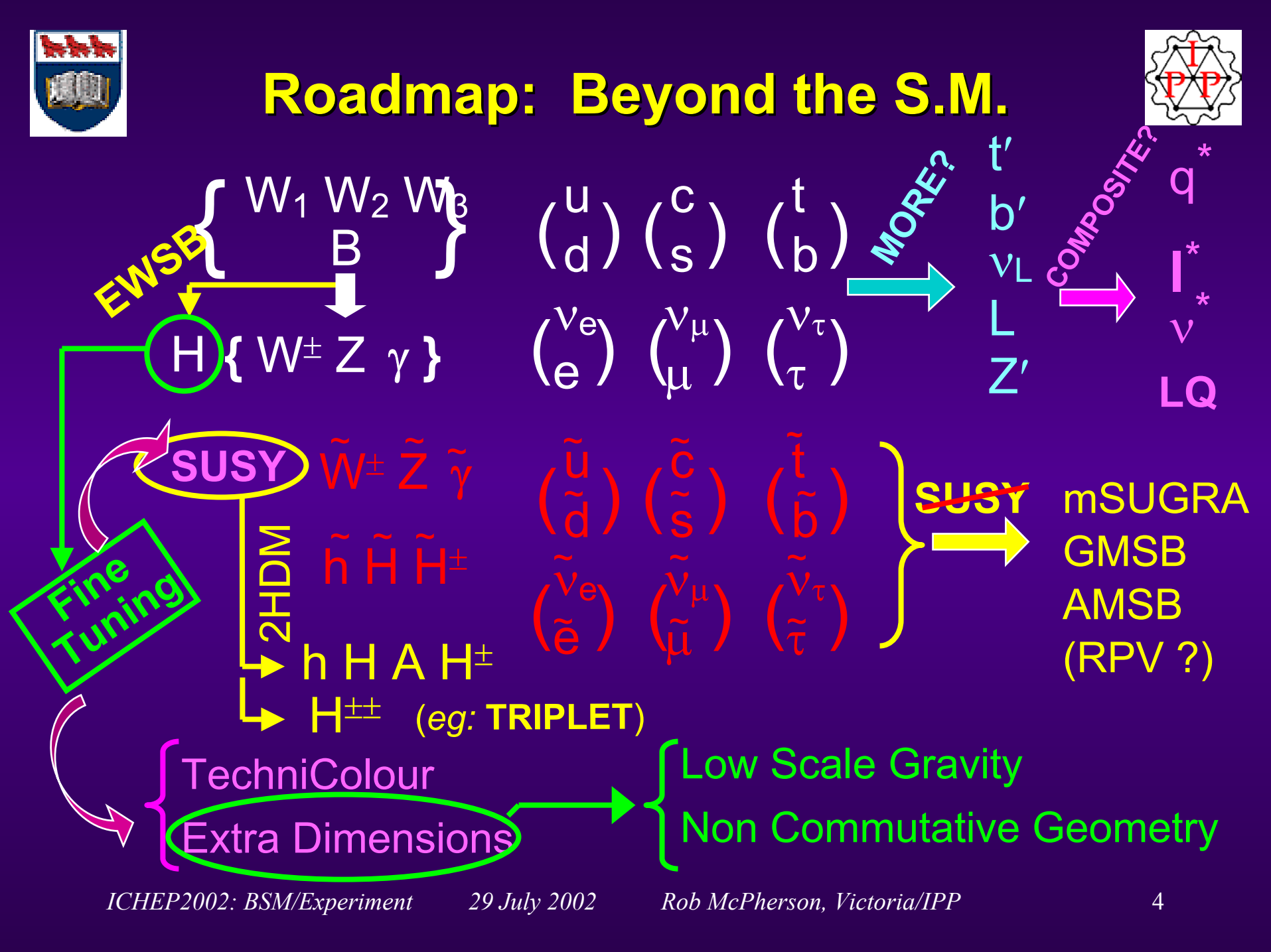
Tevatron

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

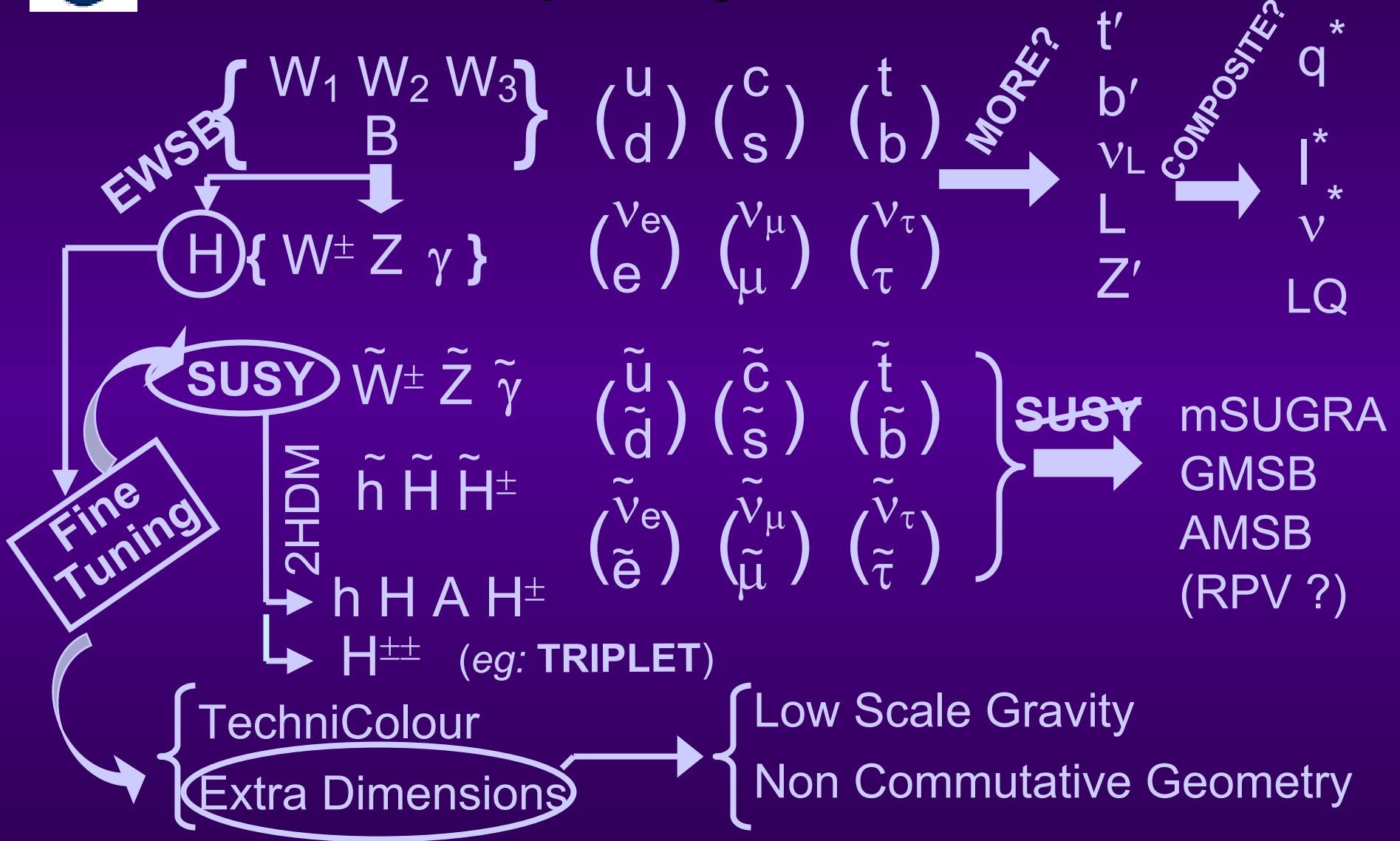
HERA

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

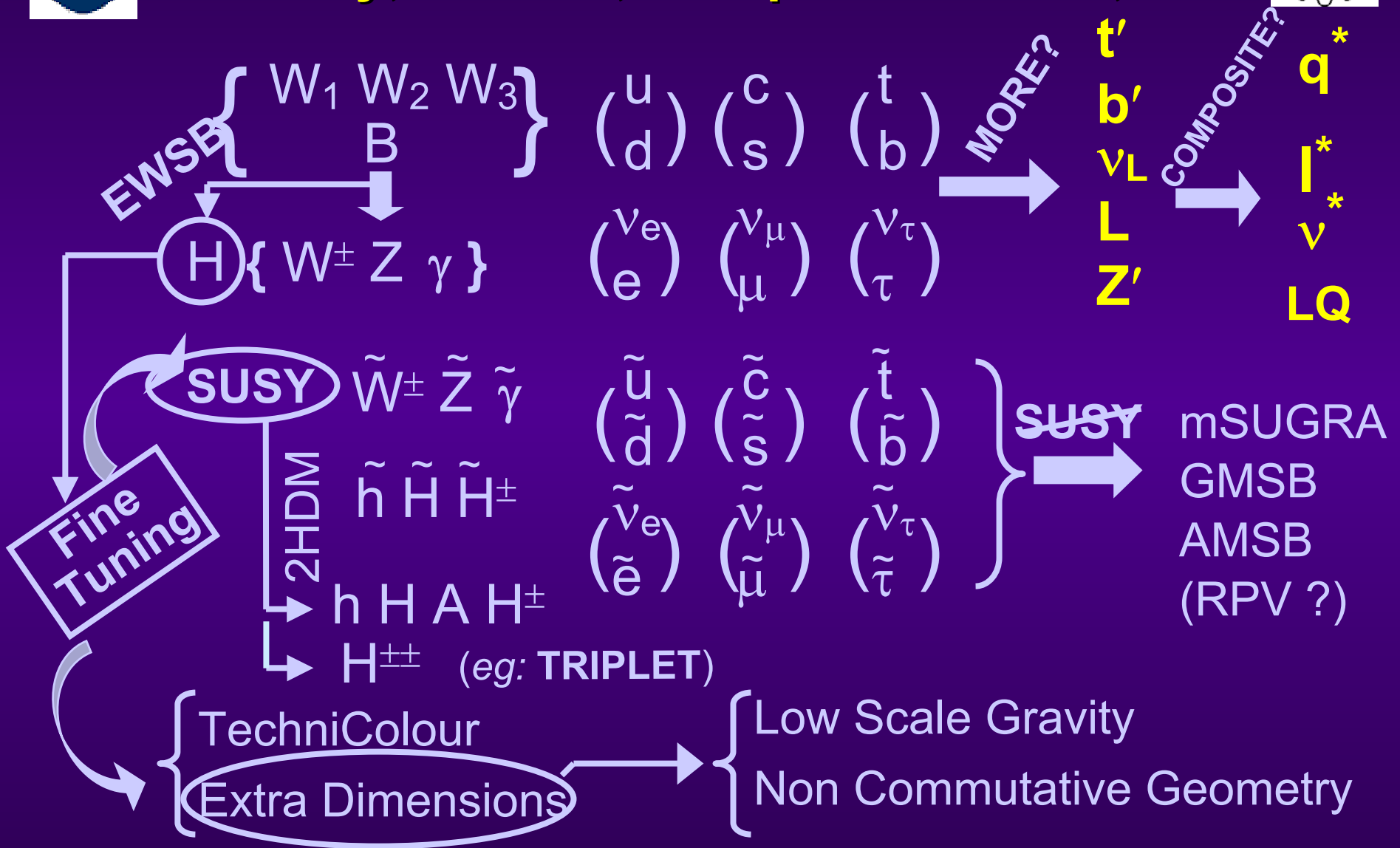
Roadmap: Beyond the S.M.



Roadmap: Beyond the S.M.

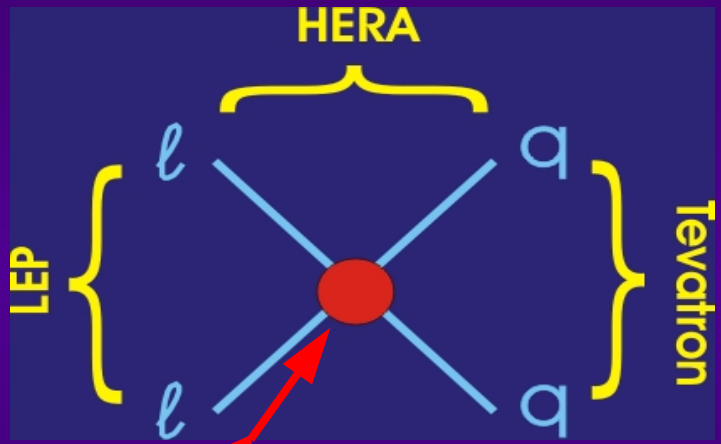


Heavy, Excited, Composite States, …



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



Λ > ≈1-20 TeV

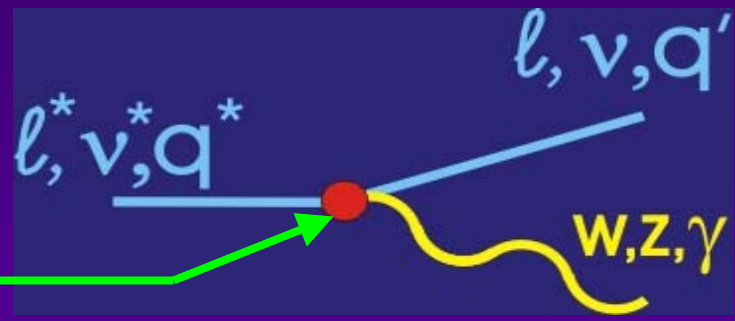
(For large couplings ~ E.M. Strength)

Both indirect constraints and direct searches

Quantitative comparison ⇒ Need model of new physics

eg: excited fermions

- Assume a coupling
  - $f^* \rightarrow f V, \quad V = \gamma, Z, W$
- Typically pick:
  - Arb. Coupling: g, κ
  - Yukawa: λ
  - Coupling/Scale: f_V/Λ
  - Sometimes: $\Lambda = M_*$
  - Or even: $f_V=1$



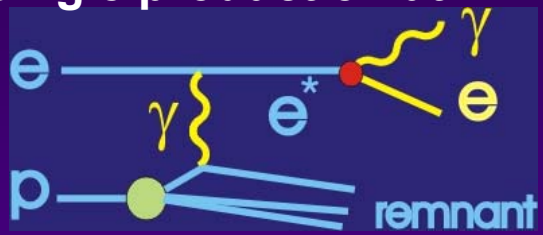
(eg, Boudjema,Djouadi,Kneur Z.Phys.C57(1993)425
Hagiwara,Zeppenfeld,Komamiya Z.PhysC29(1985)115)

Many f^* Searches:

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

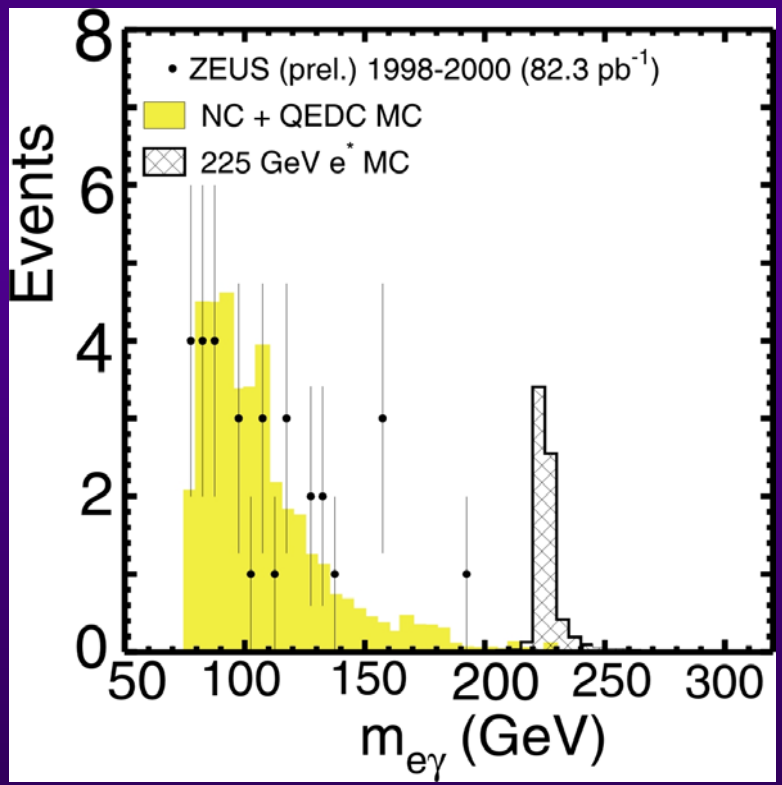
Example of $f^* : e^* \rightarrow e\,\gamma$

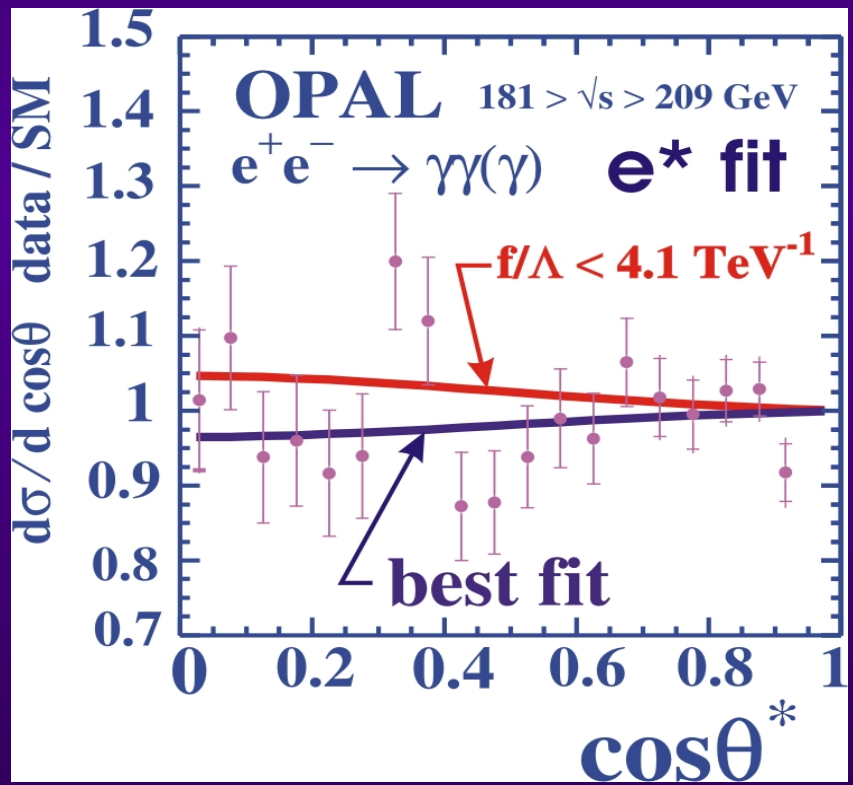
Single production at HERA



Constraints from LEP

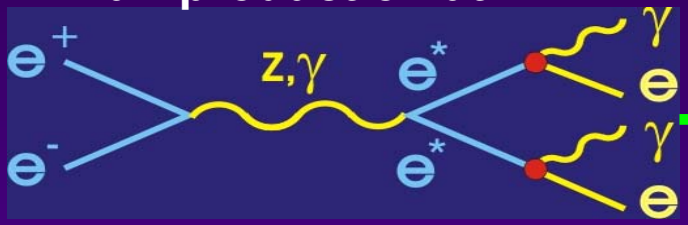
(cross-section from B. Vachon, hep-ph/0103132)





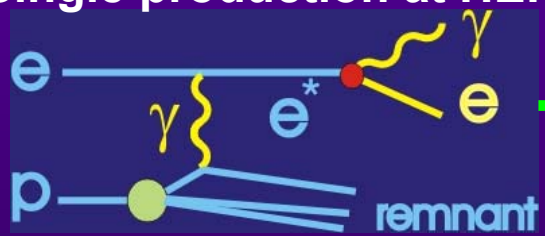
Results : $e^* \rightarrow e\,\gamma$

Pair production at LEP

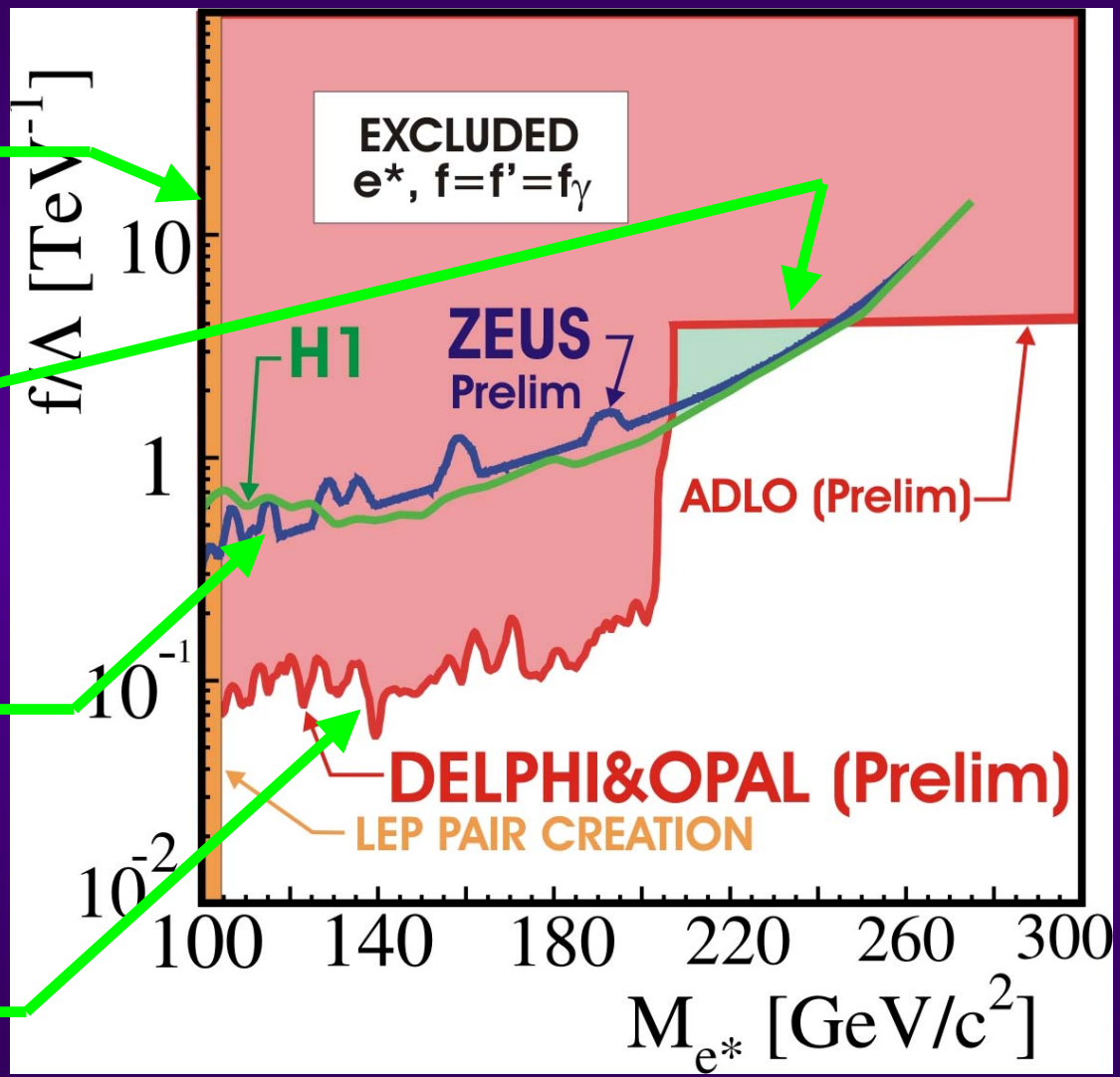


Indirect Constraints from LEP

Single production at HERA



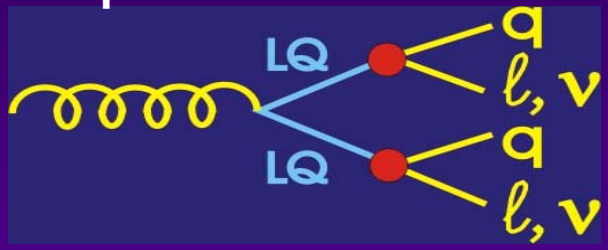
Single production at LEP



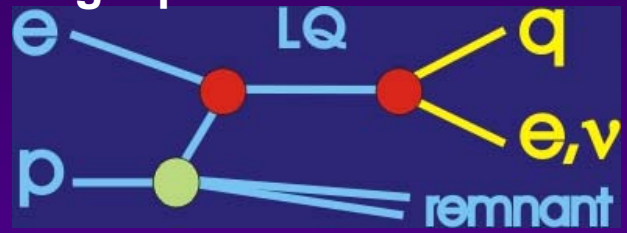
Another example: Leptoquarks

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

Pair production at Tevatron

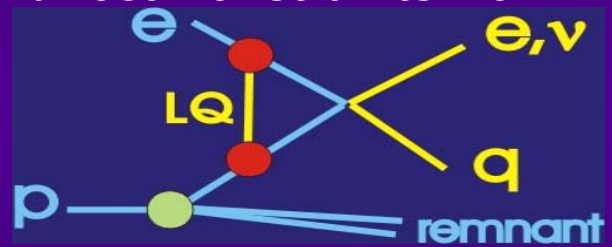


Single production at HERA



Indirect Constraints from LEP

Indirect Constraints from HERA



Many **LQ** to search for:

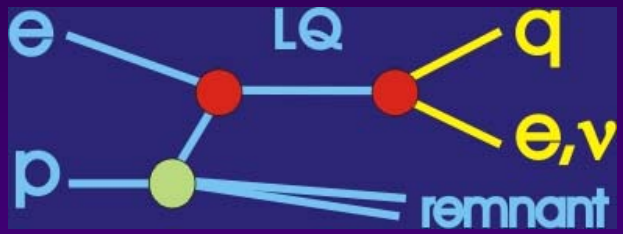
(Many searches assume family diagonal)

Spin	Q	F	β_l
Scalar **V**ector	±1/3, 2/3, 4/3, 5/3	0,2	0,½,1

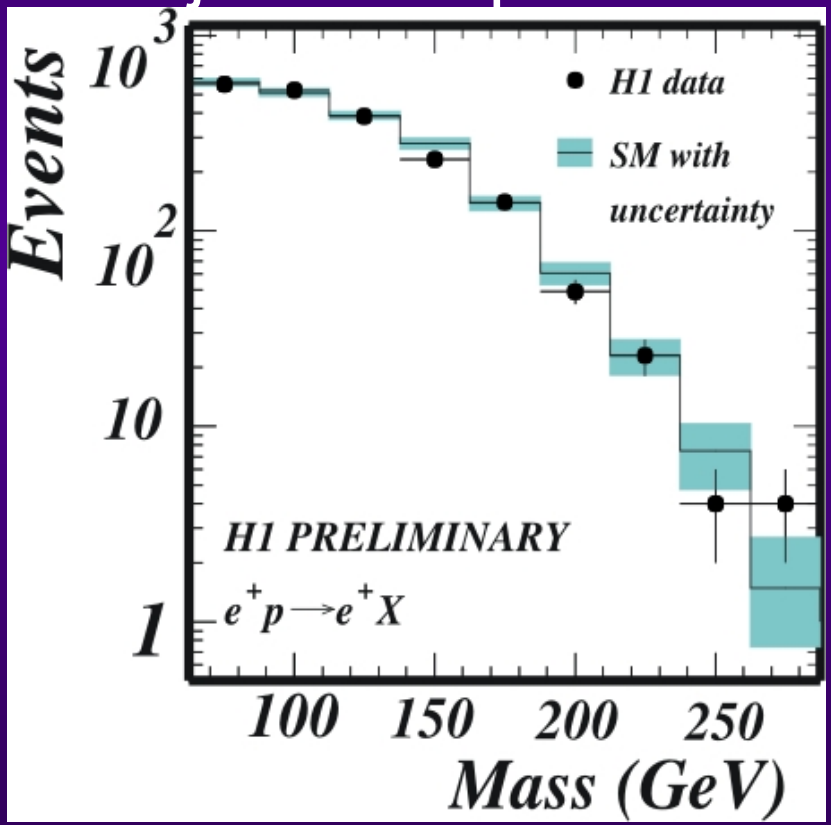
(Buchmuller-Ruckl-Wyler Phys.Lett. B191(1987)442)

LQ searches

HERA

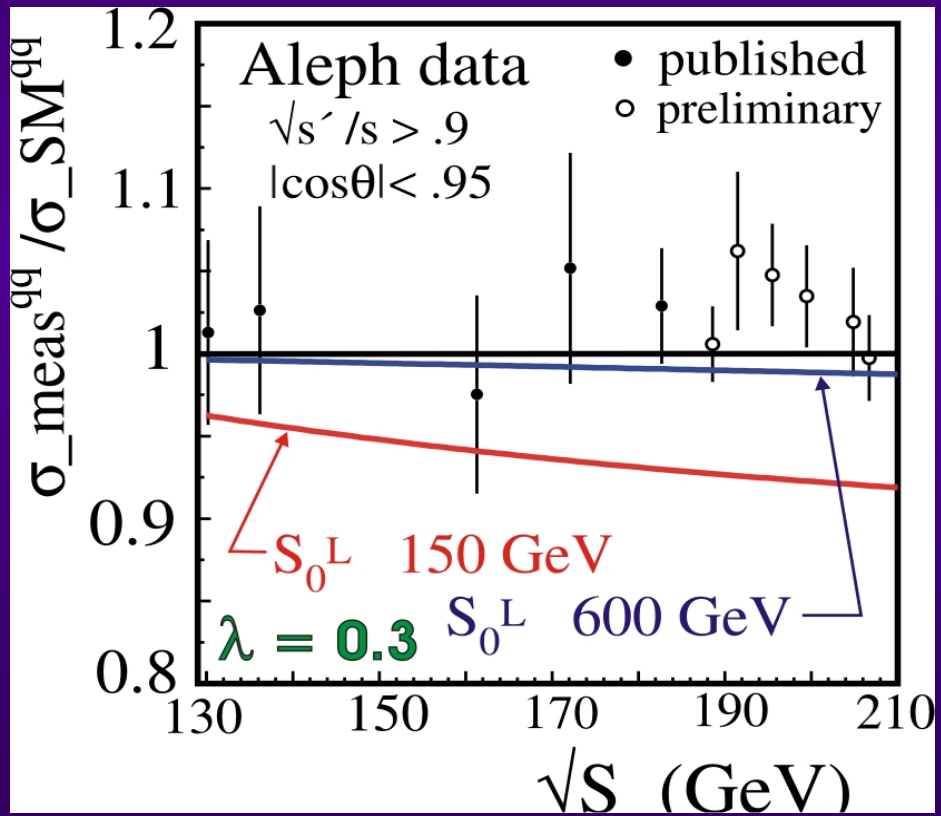


e-jet mass peaks



LEP

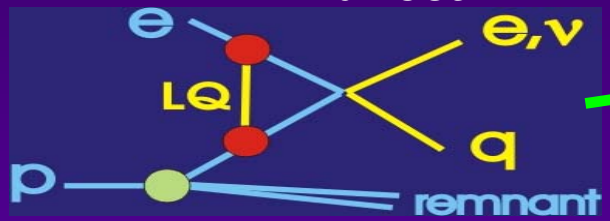
Deviations in $e^+e^- \to qq$



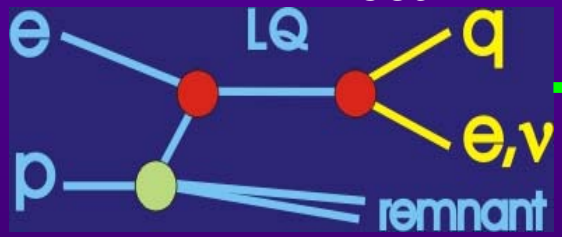
Leptoquark example limits

LEP Indirect

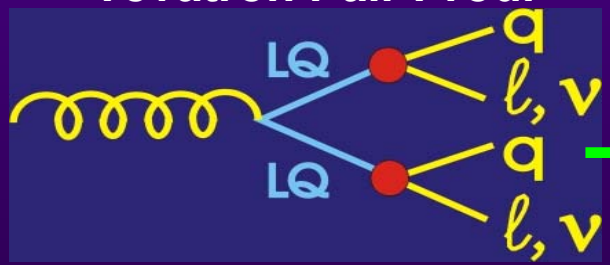
HERA Indirect



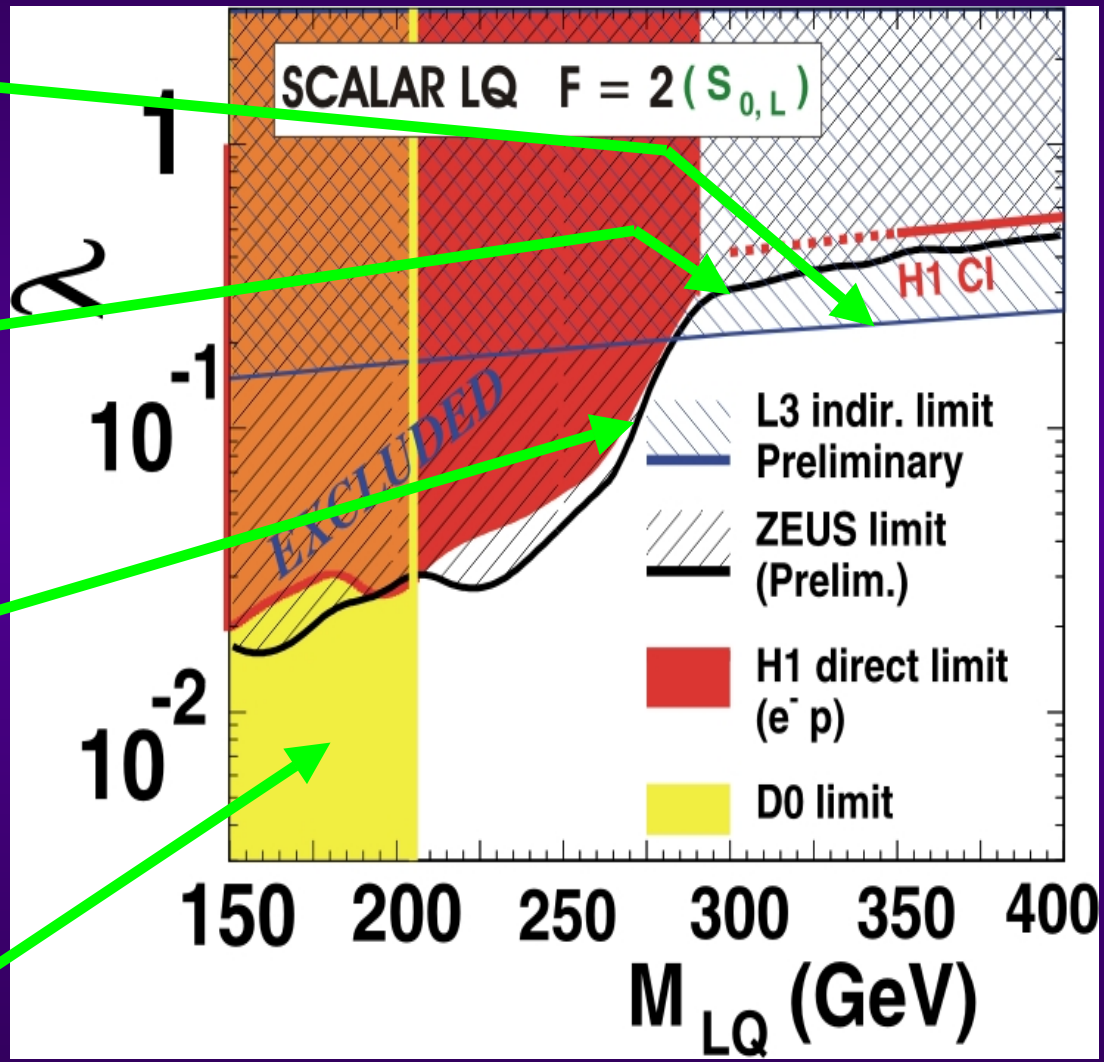
HERA Direct



Tevatron Pair Prod.

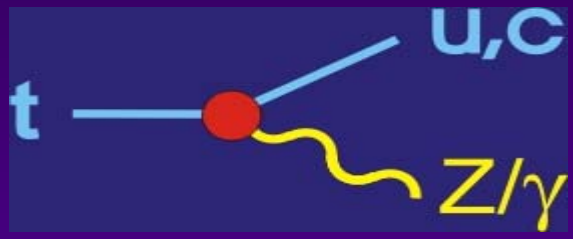


Q=1/3, BR(LQ→eq) = 1/2

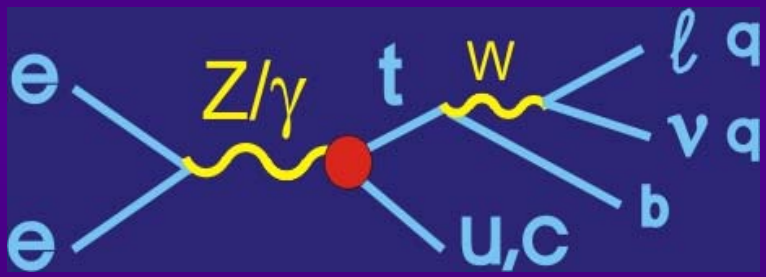


Anomalous Top Quark Couplings

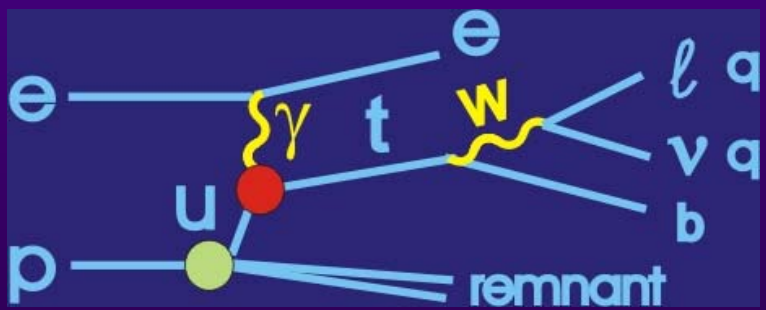
Top Decays at Tevatron



Single Top at LEP



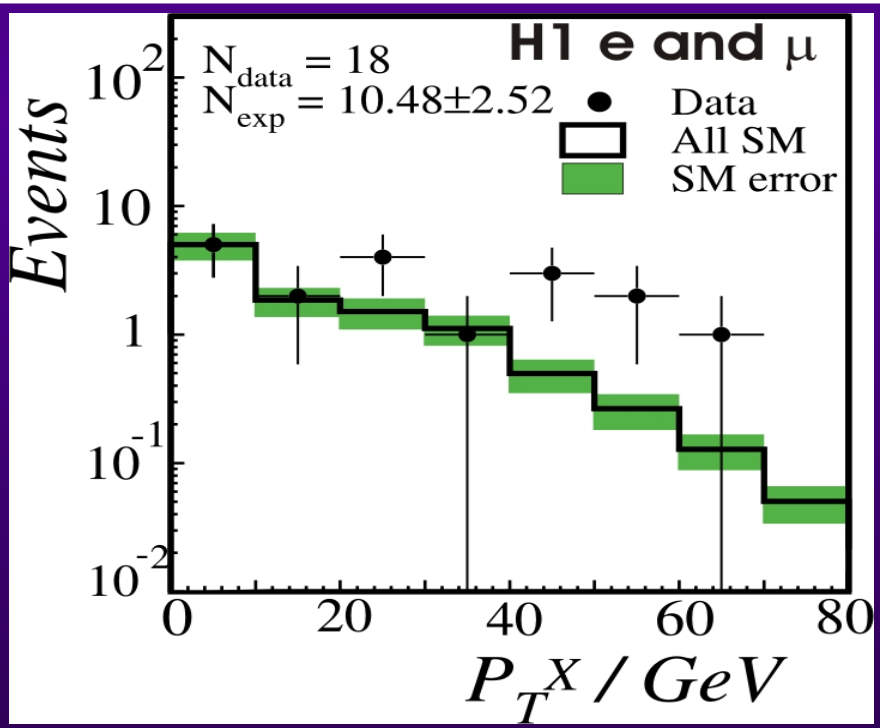
Single Top at HERA

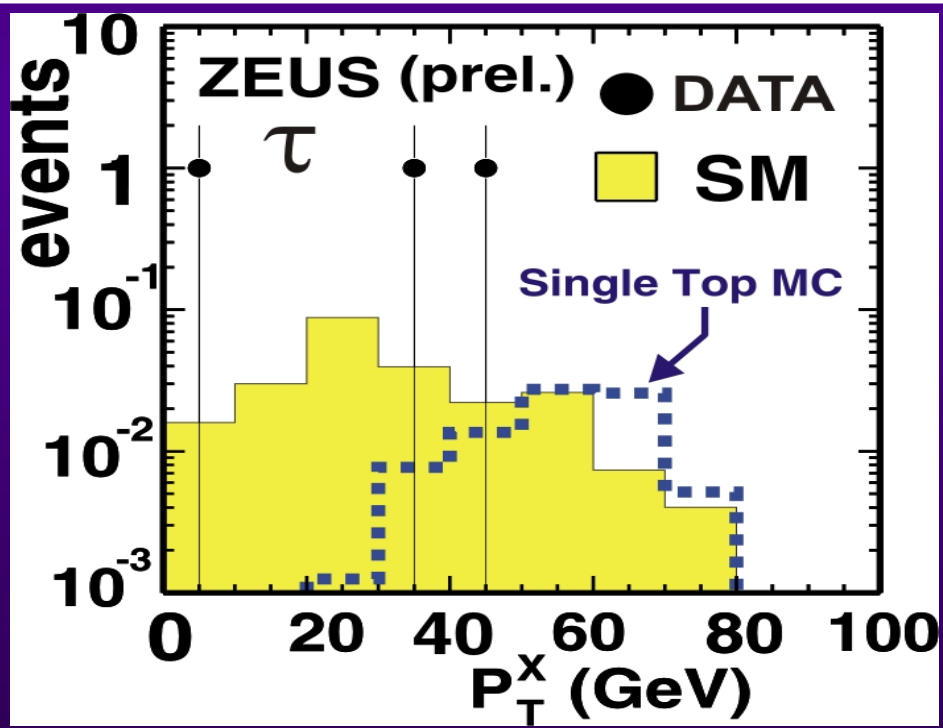


- Tevatron searches directly for anomalous FCNC top decays
- FCNC top couplings
  - ⇒ Single top at LEP & HERA
- Use common model
  - κ_Z , κ_γ different for u,c
- Signatures
  - Heavy Flavour events
  - Isolated High P_t leptons at HERA →

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

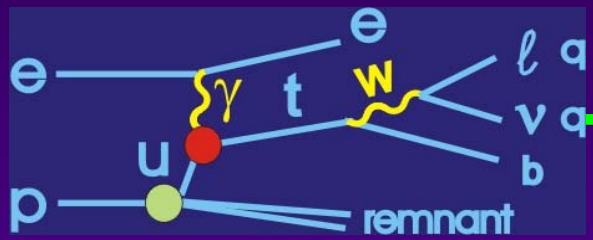
H1 (101.6 pb^{-1})	Electron obs/exp	Muon obs/exp	e and μ obs/exp
P_t^X > 25 GeV	4 / 1.29 ± 0.33	6 / 1.54 ± 0.41	10 / 2.8 ± 0.7
P_t^X > 40 GeV	2 / 0.41 ± 0.12	4 / 0.58 ± 0.16	6 / 1.0 ± 0.3
ZEUS (130.5 pb^{-1})	**Electron obs/exp**	**Muon obs/exp**	**Tau obs/exp**
P_t^X > 25 GeV	1 / 1.14 ± 0.06	1 / 1.29 ± 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



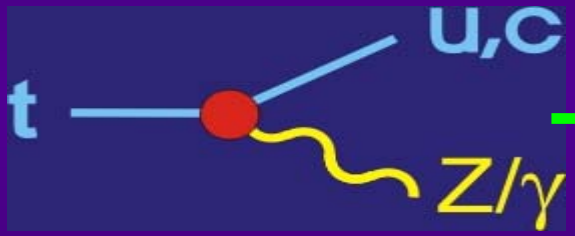


Anomalous top couplings: constraints

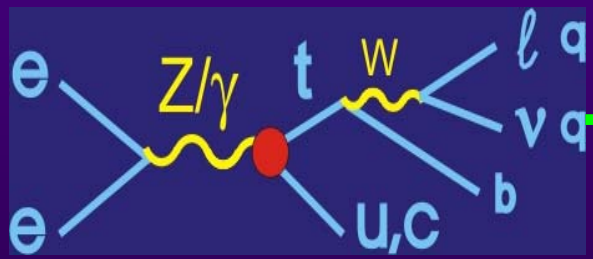
HERA

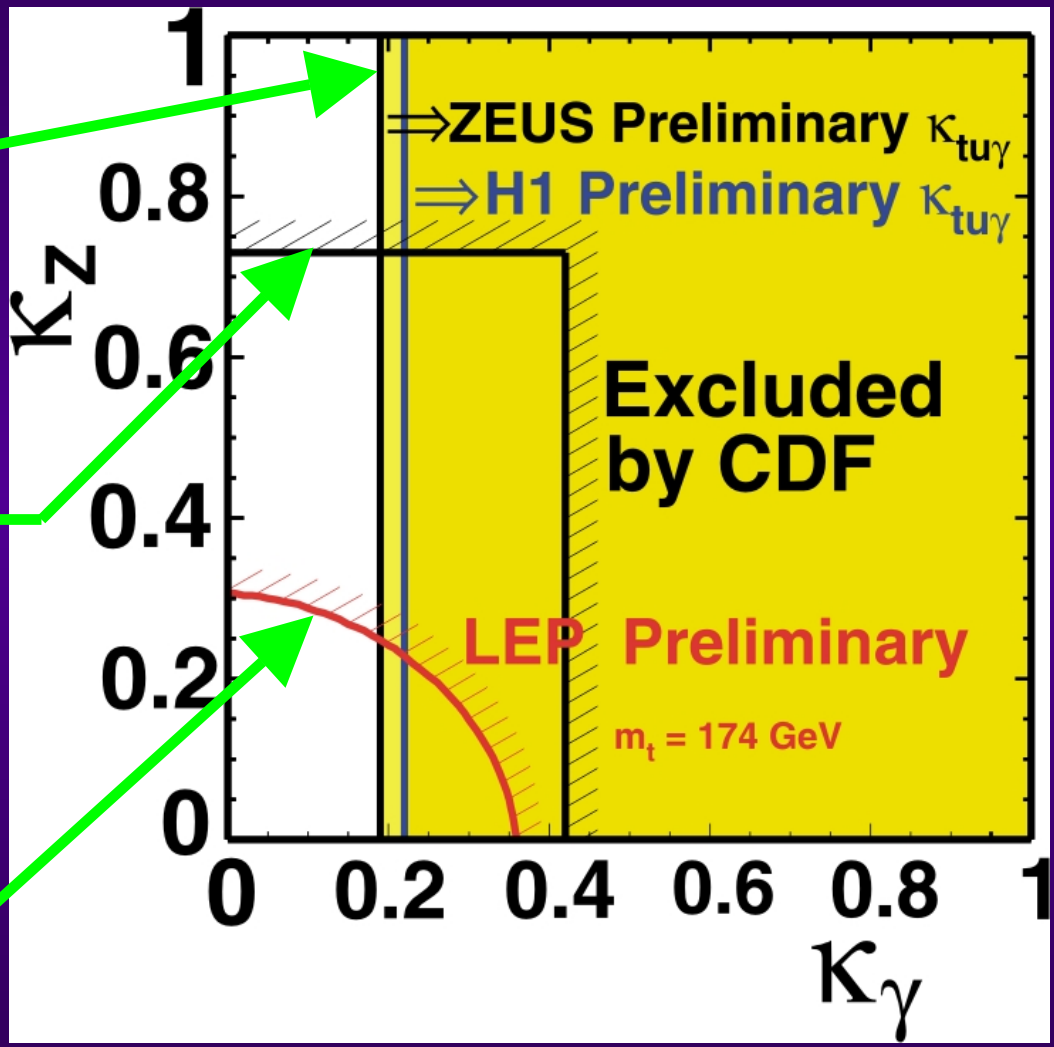


Tevatron

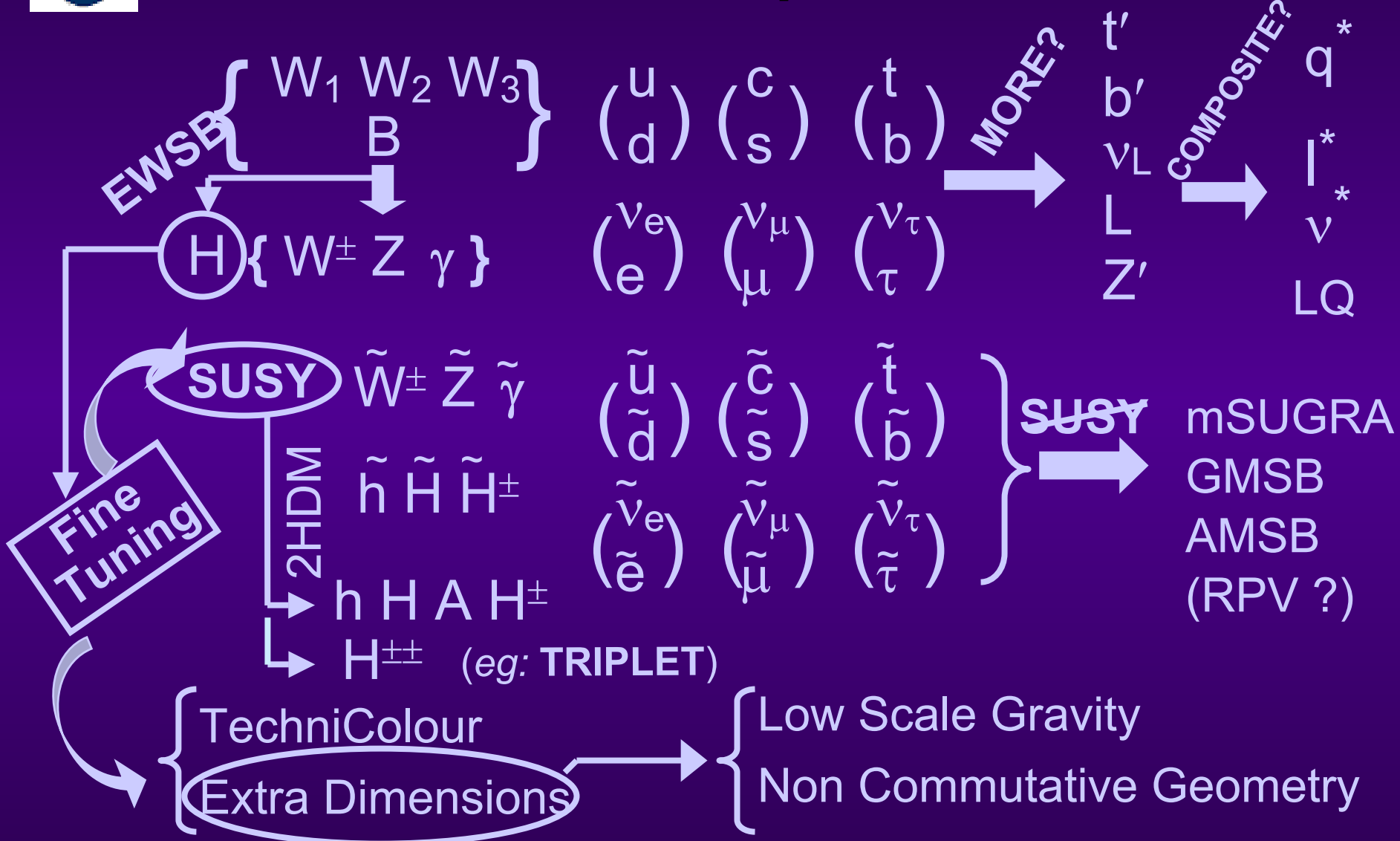


LEP

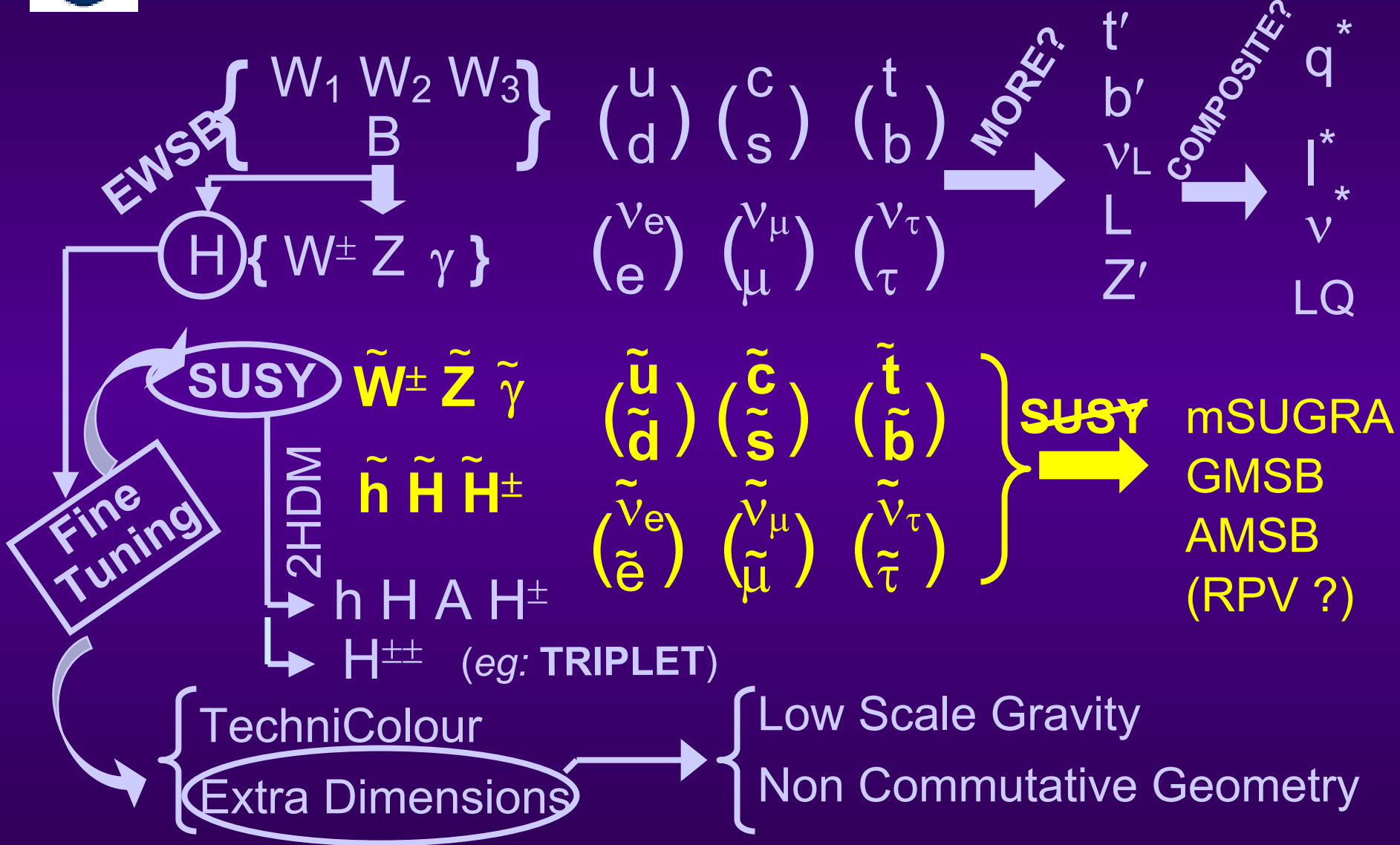




Roadmap …

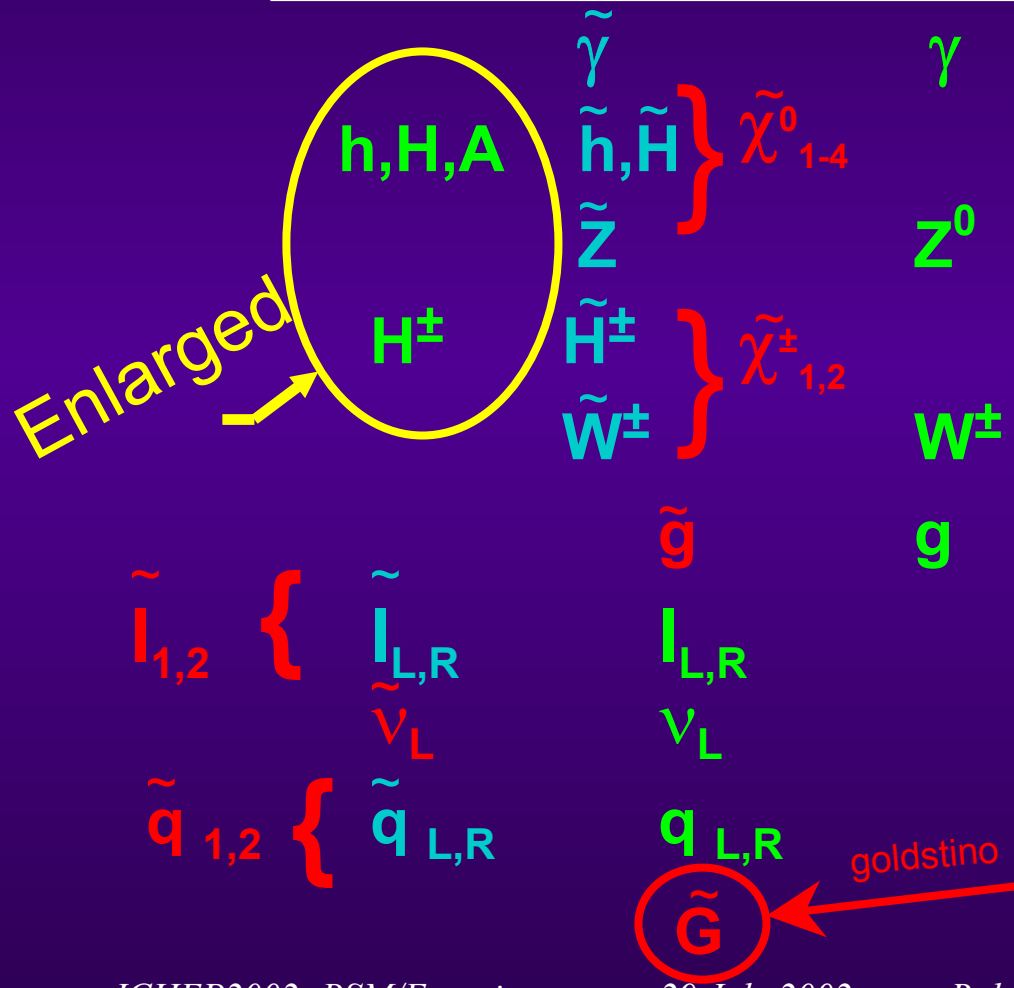

EWSB
W1 W2 W3
B
H
W± Z γ
(u d) (c s) (t b)
(νe e) (νμ μ) (ντ τ)
MORE?
t′
b′
νL
L
Z′
COMPOSITE?
q*
l*
ν*
LQ
SUSY
W̃± Z̃ γ̃
(ũ d̃) (c̃ s̃) (t̃ b̃)
(ν̃e ẽ) (ν̃μ μ̃) (ν̃τ τ̃)
SUSY
mSUGRA
GMSB
AMSB
(RPV ?)
Fine Tuning
2HDM
h̃ H̃ H̃±
h H A H±
H±±
(eg: TRIPLET)
TechniColour
Extra Dimensions
Low Scale Gravity
Non Commutative Geometry

SUSY: Overview



(s)particles List

0	1/2	1	3/2	2

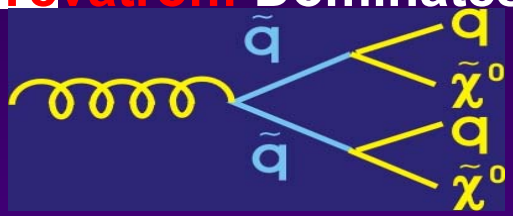


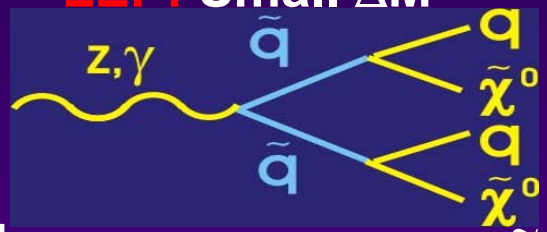
"General" MSSM

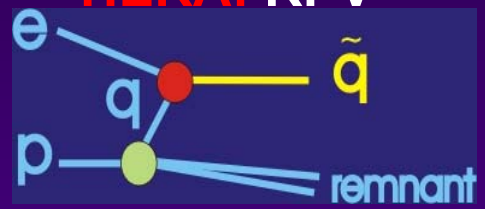
M_1, M_2, M_3	Gaugino masses
m_f	Sfermion masses
$v, \tan\beta, m_A, \mu$	Higgs(ino)
A_U, A_D, A_L	Trilinear couplings
+105 Params	$\rightarrow$ FCNC, …
RPV: +45	λ_{ijk}, λ'_{ijk}, λ''_{ijk}

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

Tevatron: Dominates **LEP:** Small ΔM **HERA:** RPV

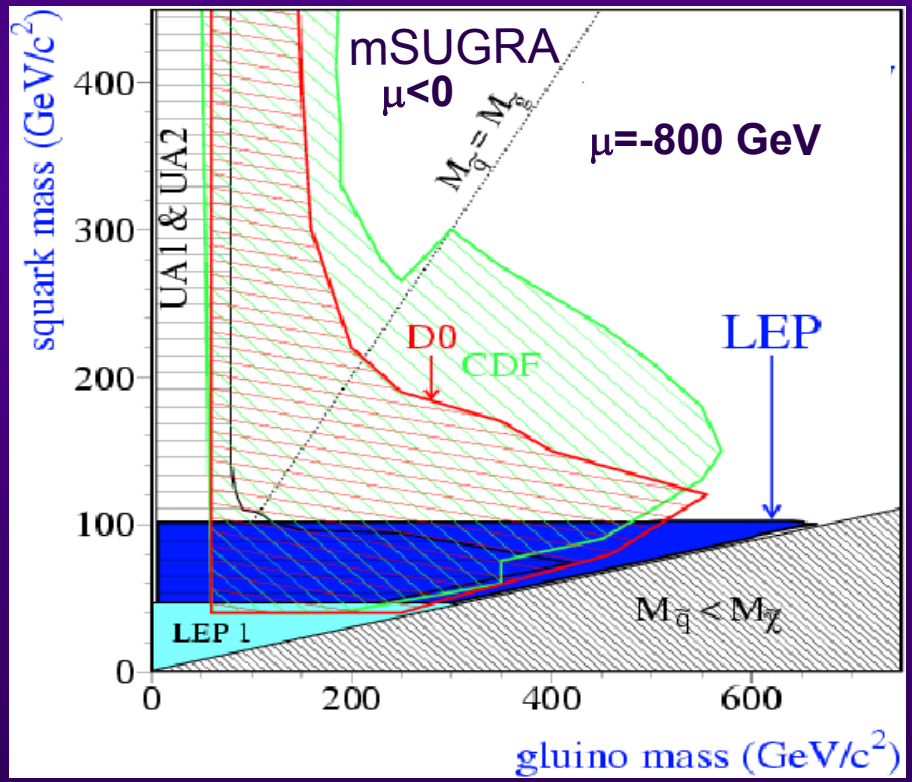


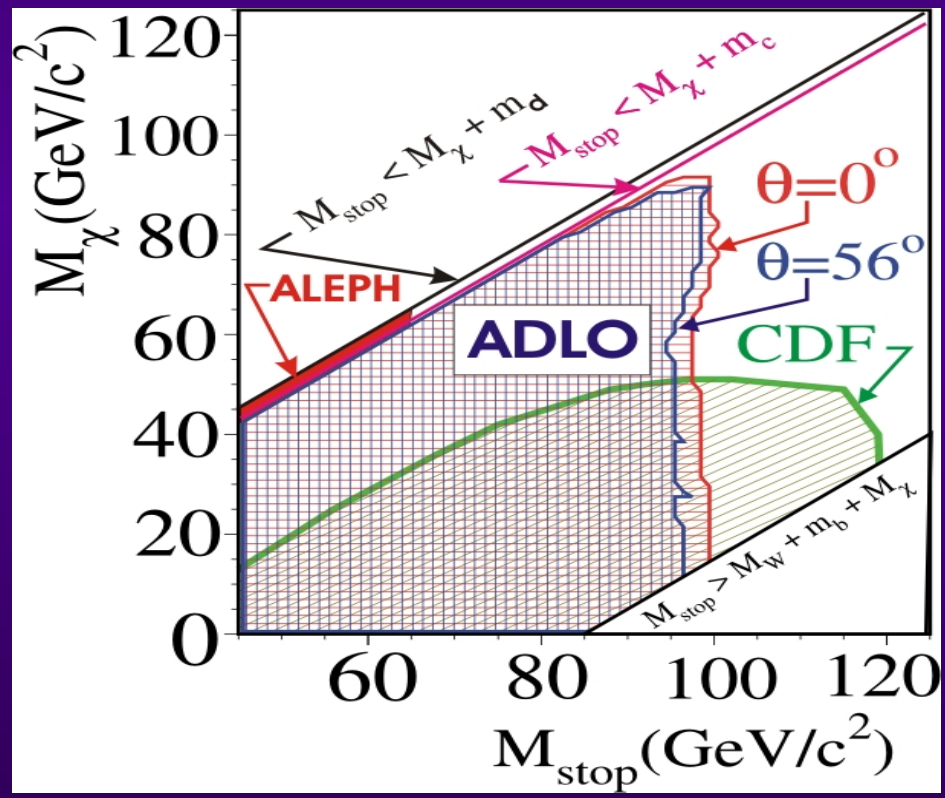




- 5 degenerate quarks
- GUT relations

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

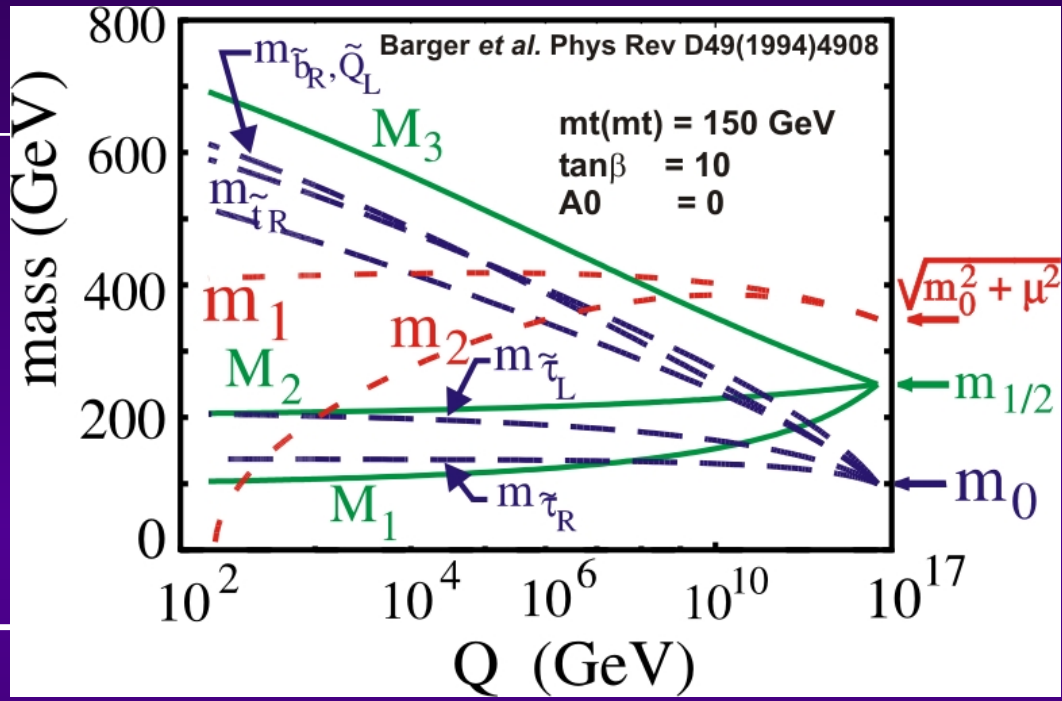




Favorite (?) model: mSUGRA

High scale Params.

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

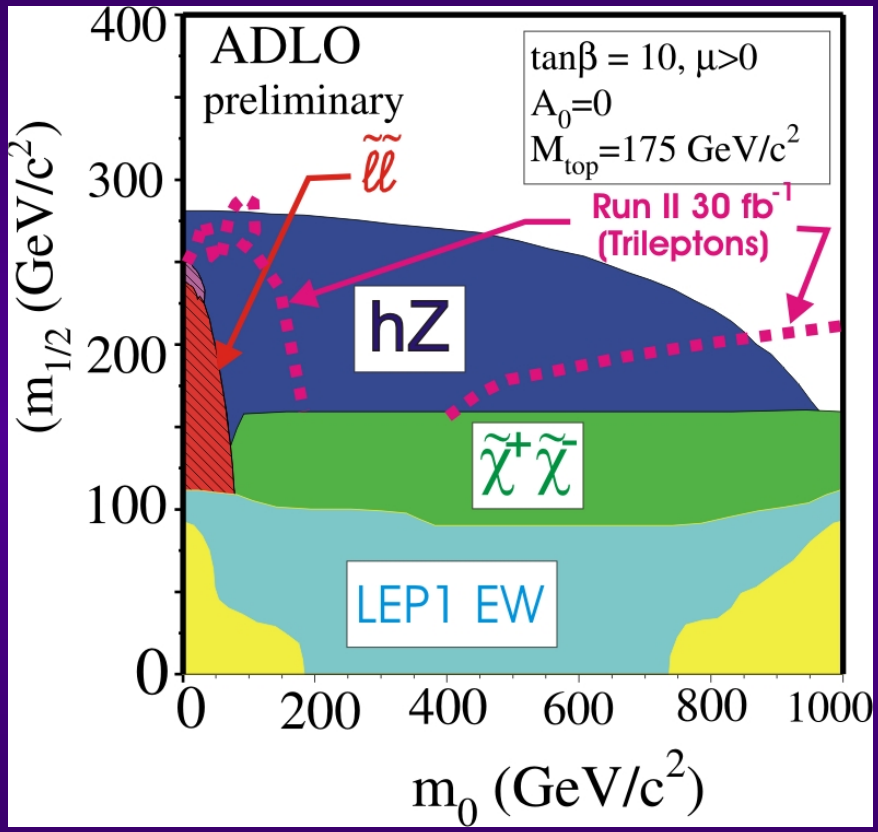


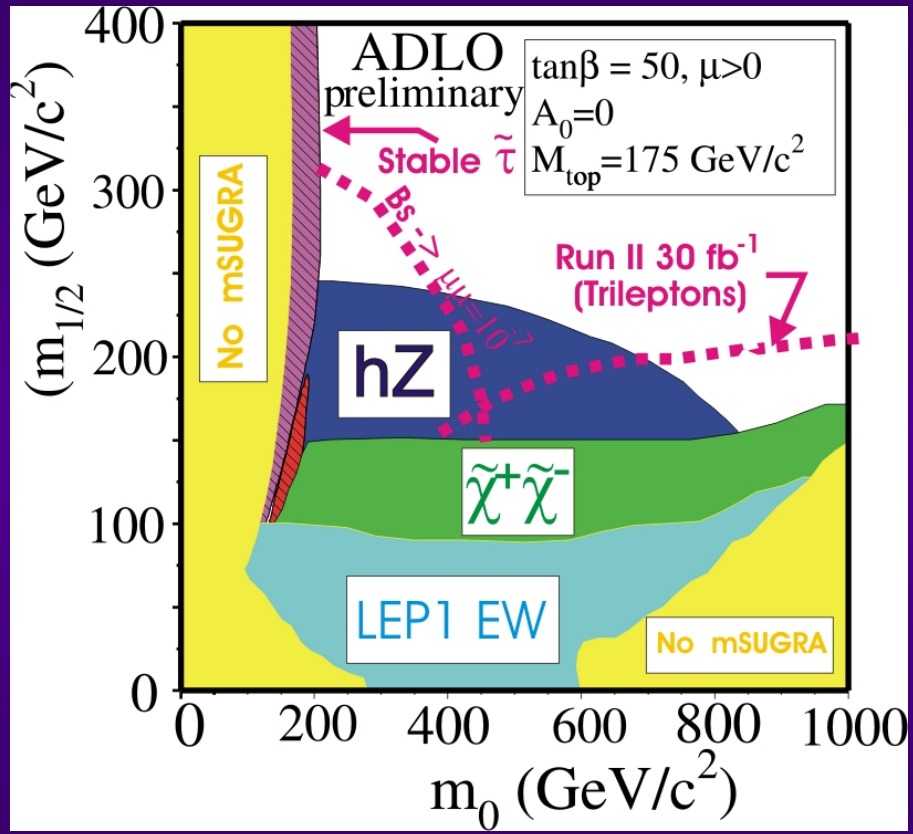
- Calculate masses, cross-section, BRs
  - Phenomenology
  - ⇒ Guides the search

- Dominant sensitivity
  - Higgs search at LEP
  - Chargino search at LEP
    - (needs slepton search too)
  - (Also b→sγ at large tanβ)

mSUGRA constraints (from LEP)

tanβ=10 $A_0 = 0$ tanβ=50





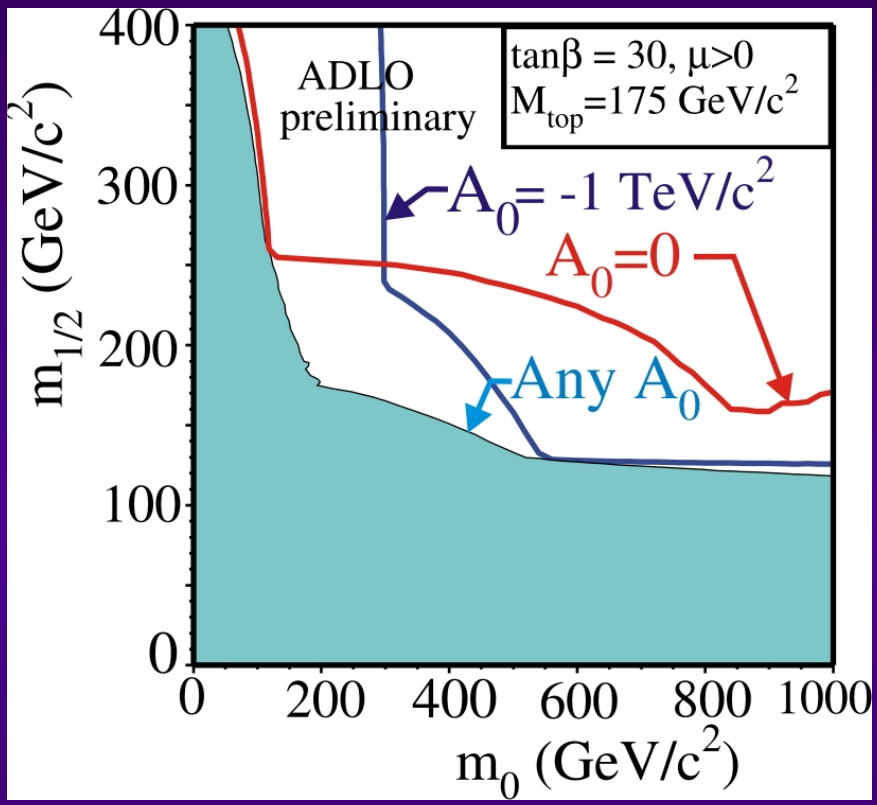
(b→sγ excludes ~ whole visible plane)

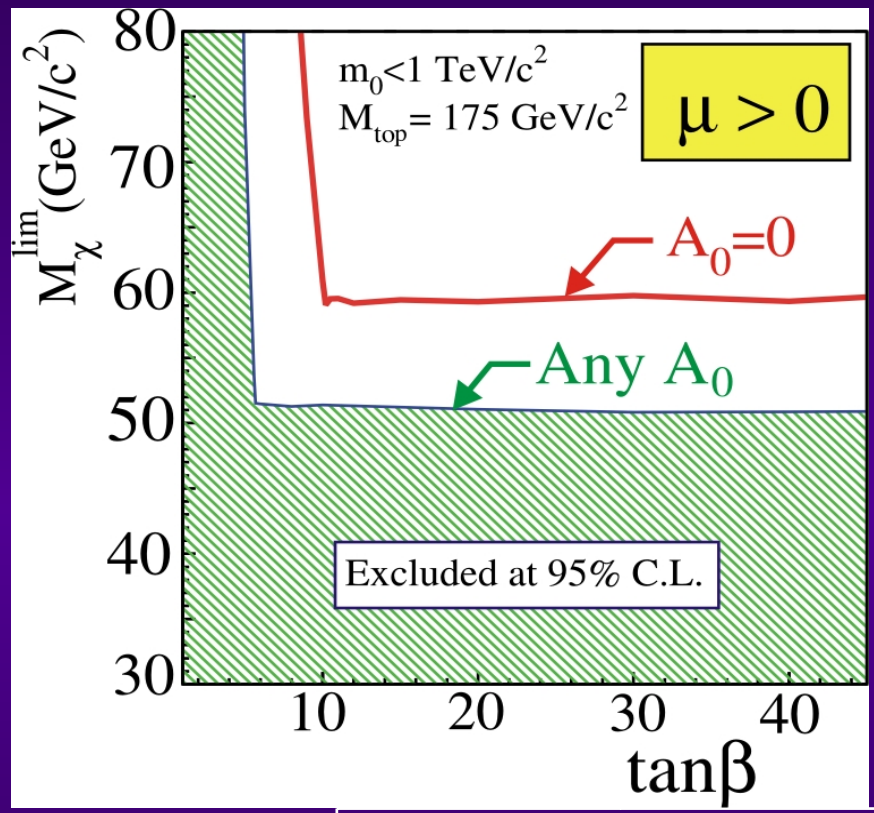
Run II sensitivity estimates from:

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

First time: mSUGRA $A_0 \neq 0$

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

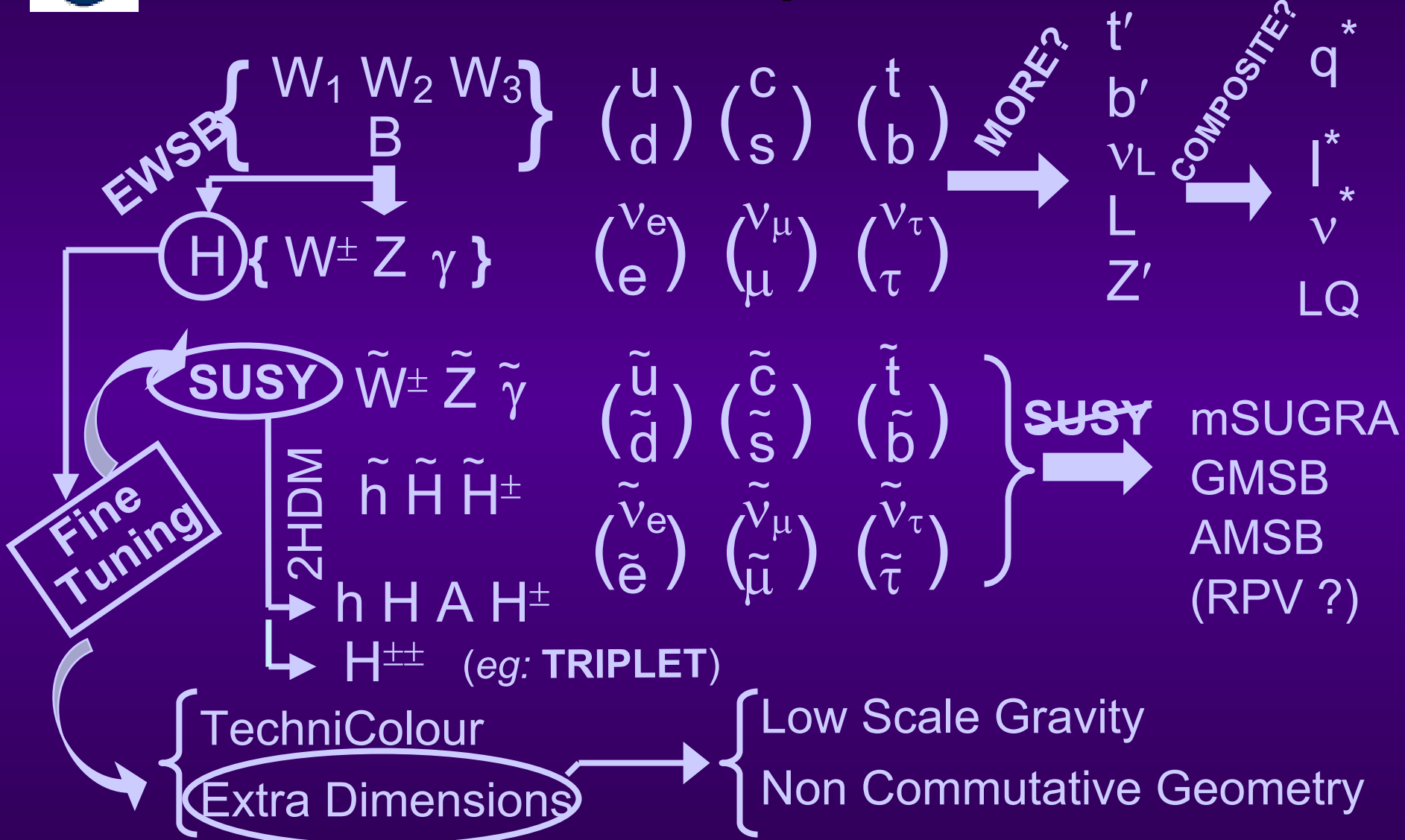




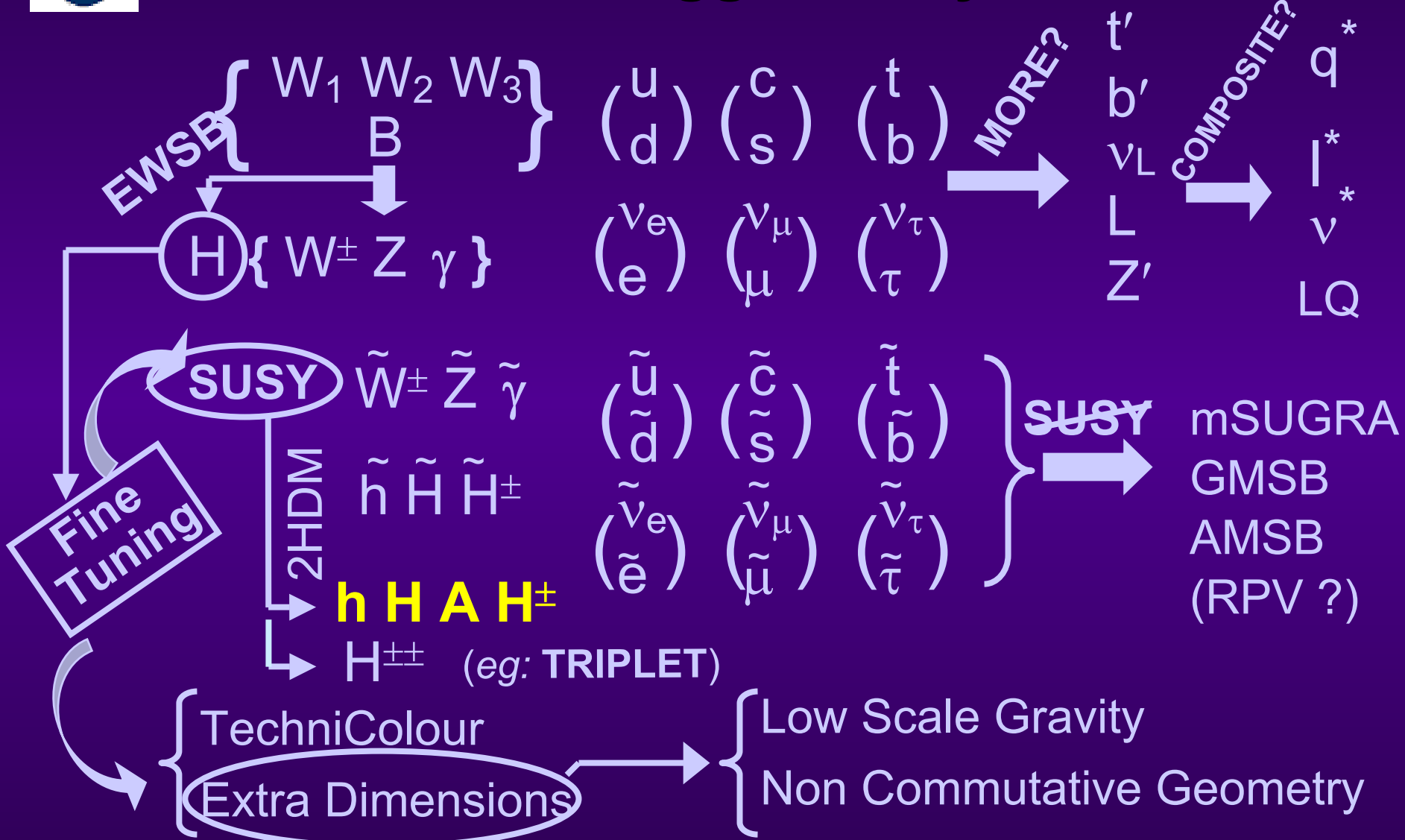
- A_0 Drives $\tilde{f}$ mixing
  - Especially $\tilde{t}$, $\tilde{b}$, $\tilde{\tau}$
  - Large effect on higgs
  - Also affects charginos

$M(\tilde{\chi}^0)$	A_0=0	Any A_0
μ > 0	59.0	50.9
μ < 0	58.6	50.3

Roadmap …


EWSB
W1 W2 W3
B
H
W± Z γ
(u d) (c s) (t b)
(νe e) (νμ μ) (ντ τ)
MORE?
t′
b′
νL
L
Z′
COMPOSITE?
q*
l*
ν*
LQ
SUSY
W̃± Z̃ γ̃
(ũ d̃) (c̃ s̃) (t̃ b̃)
(ν̃e ẽ) (ν̃μ μ̃) (ν̃τ τ̃)
SUSY
mSUGRA
GMSB
AMSB
(RPV ?)
Fine Tuning
2HDM
h̃ H̃ H̃±
h H A H±
H±±
(eg: TRIPLET)
TechniColour
Extra Dimensions
Low Scale Gravity
Non Commutative Geometry

Exotic Higgs Decays



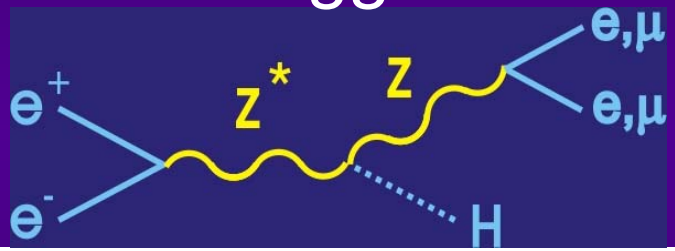
Exotic Higgs?

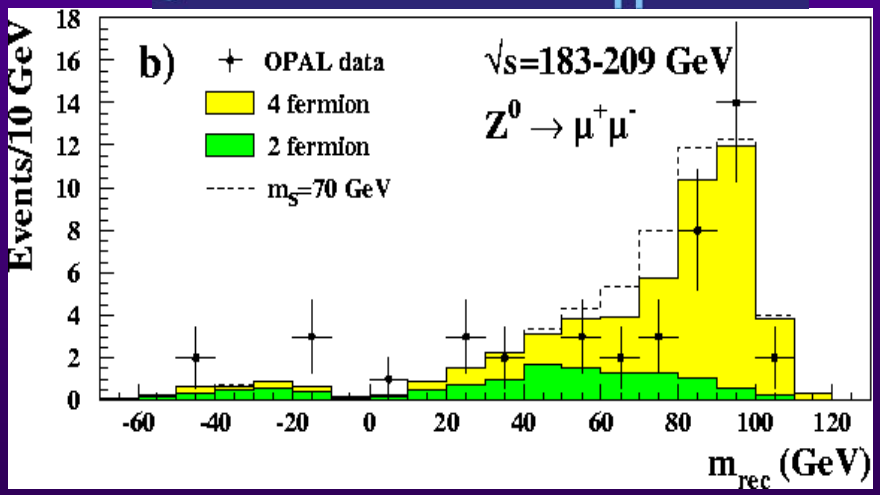
What if Higgs has different couplings?

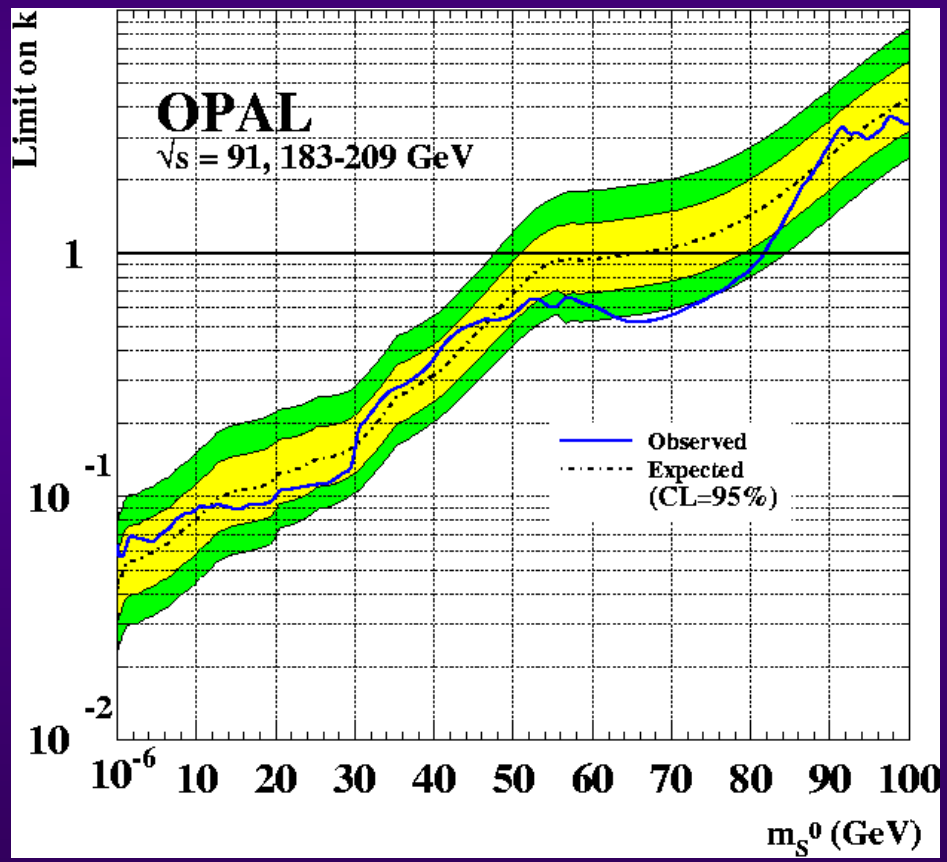
H↔V V Searches

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

General Higgs Search



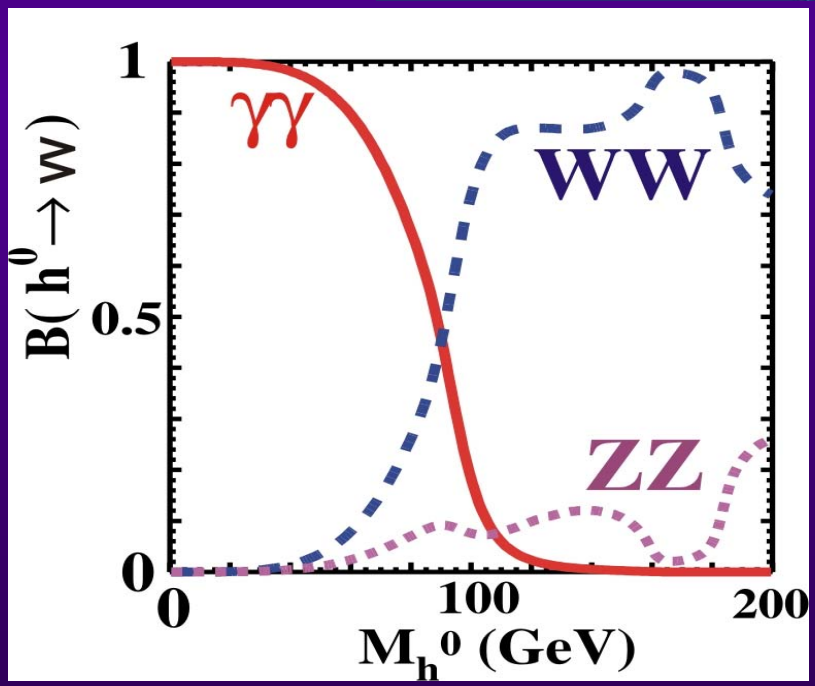


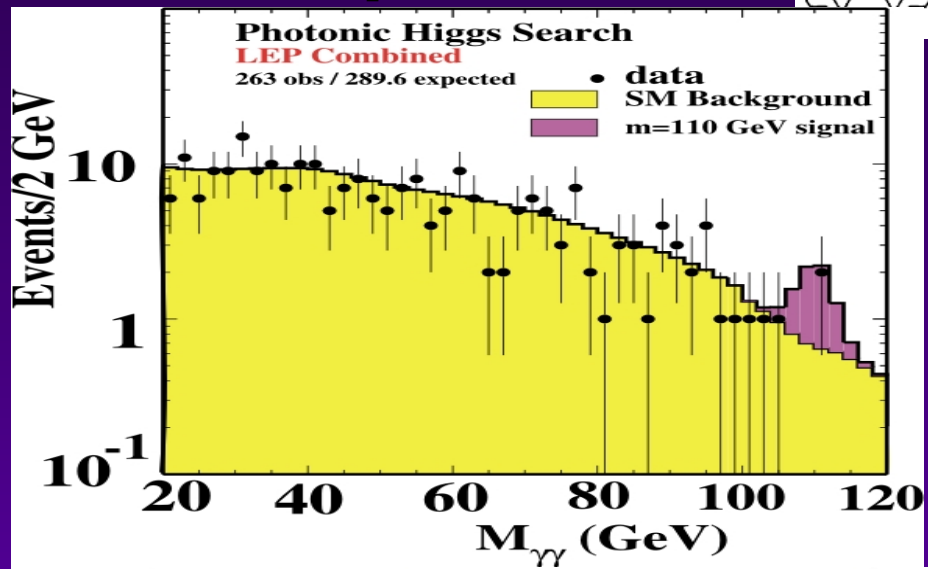


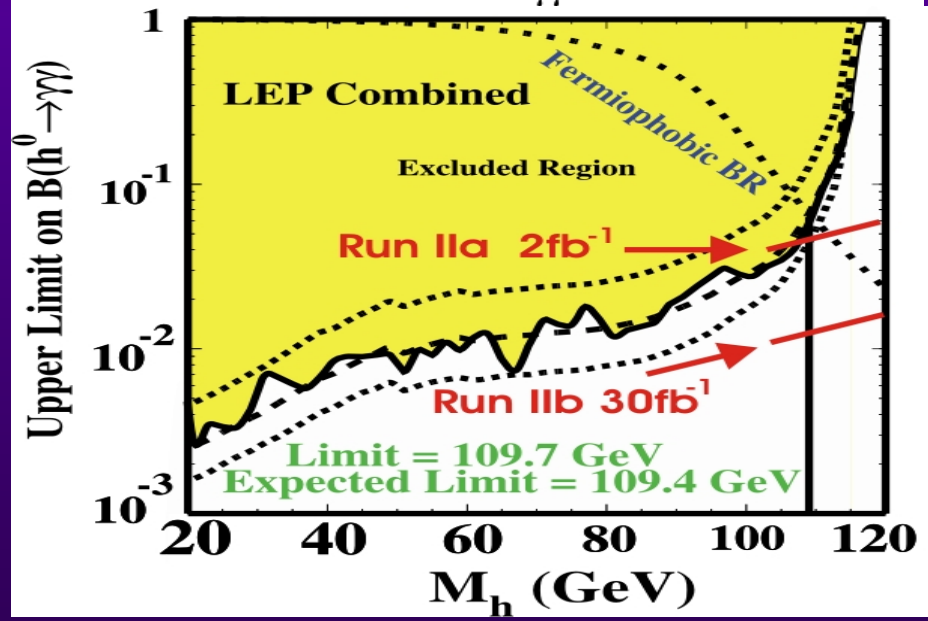
Exotic Higgs II: Fermiophobic

Turn off Fermion Couplings

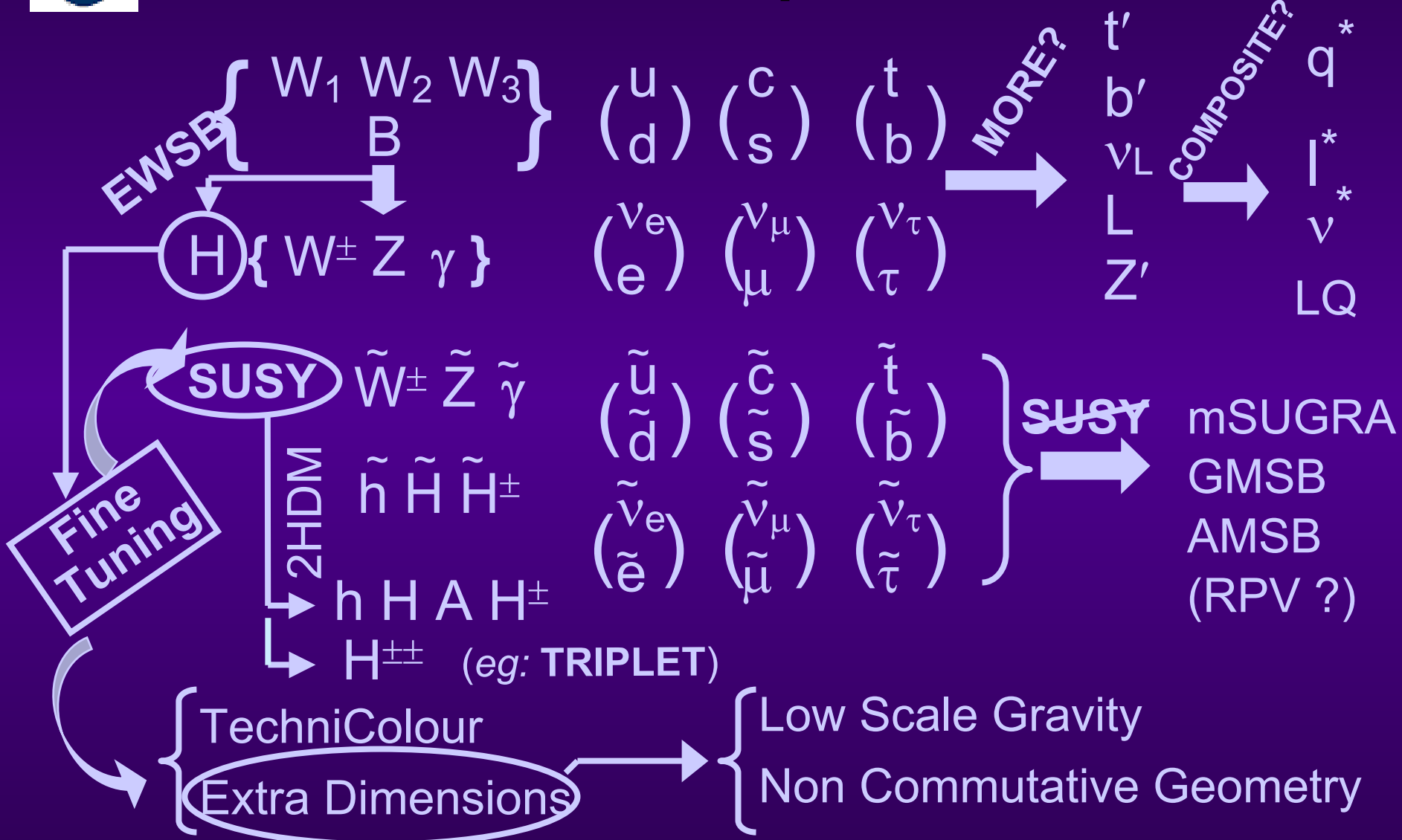
$H \rightarrow V\,V$ Decays







Roadmap …


EWSB
W1 W2 W3
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(u d) (c s) (t b)
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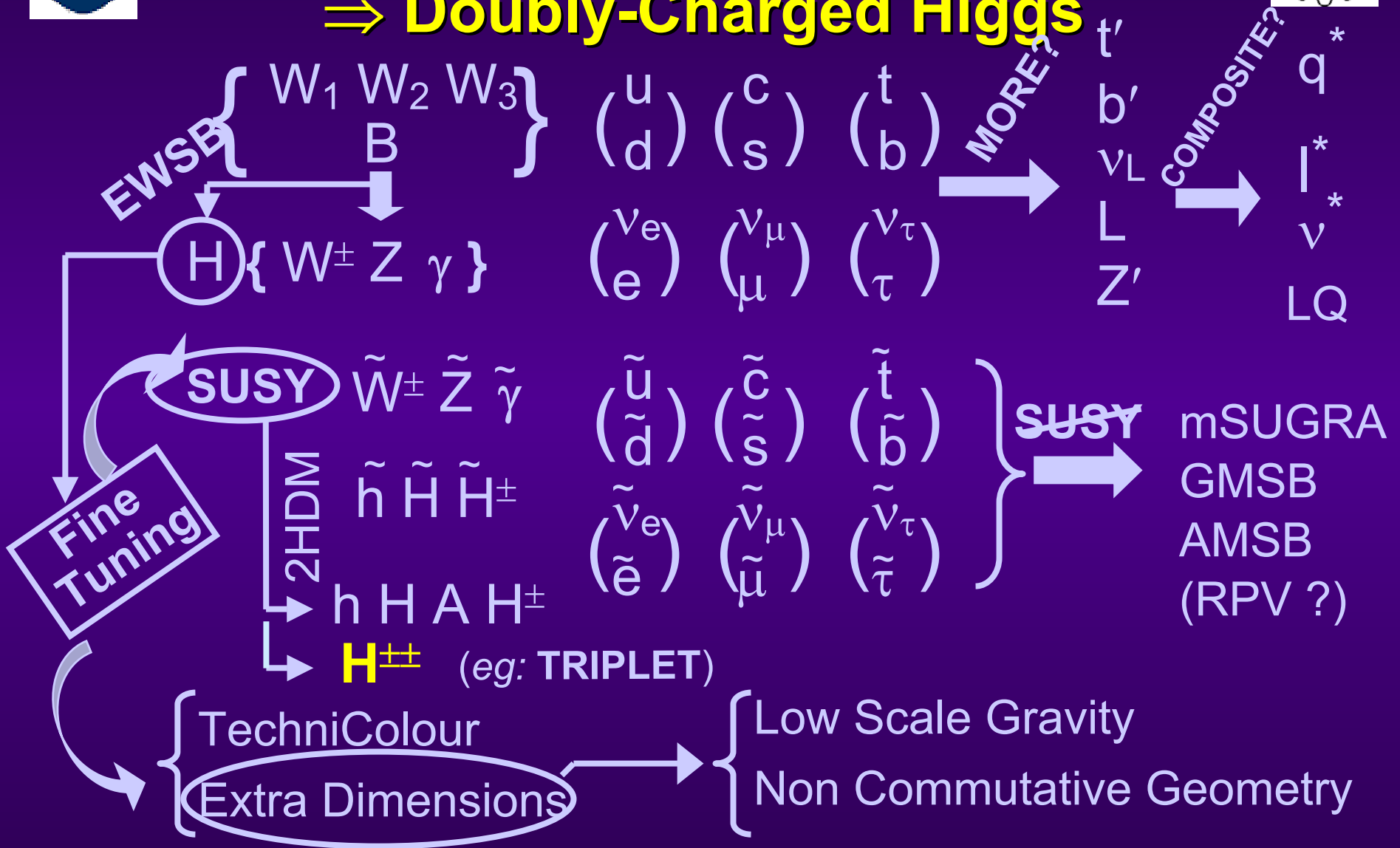
2HDM
h̃ H̃ H̃±
h H A H±
H±±
(eg: TRIPLET)
TechniColour
Extra Dimensions
Low Scale Gravity
Non Commutative Geometry

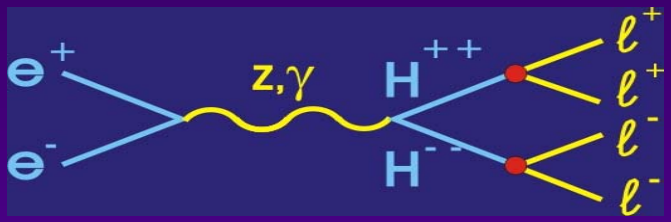
Higgs Triplets, L-R Symmetric ⇒ Doubly-Charged Higgs



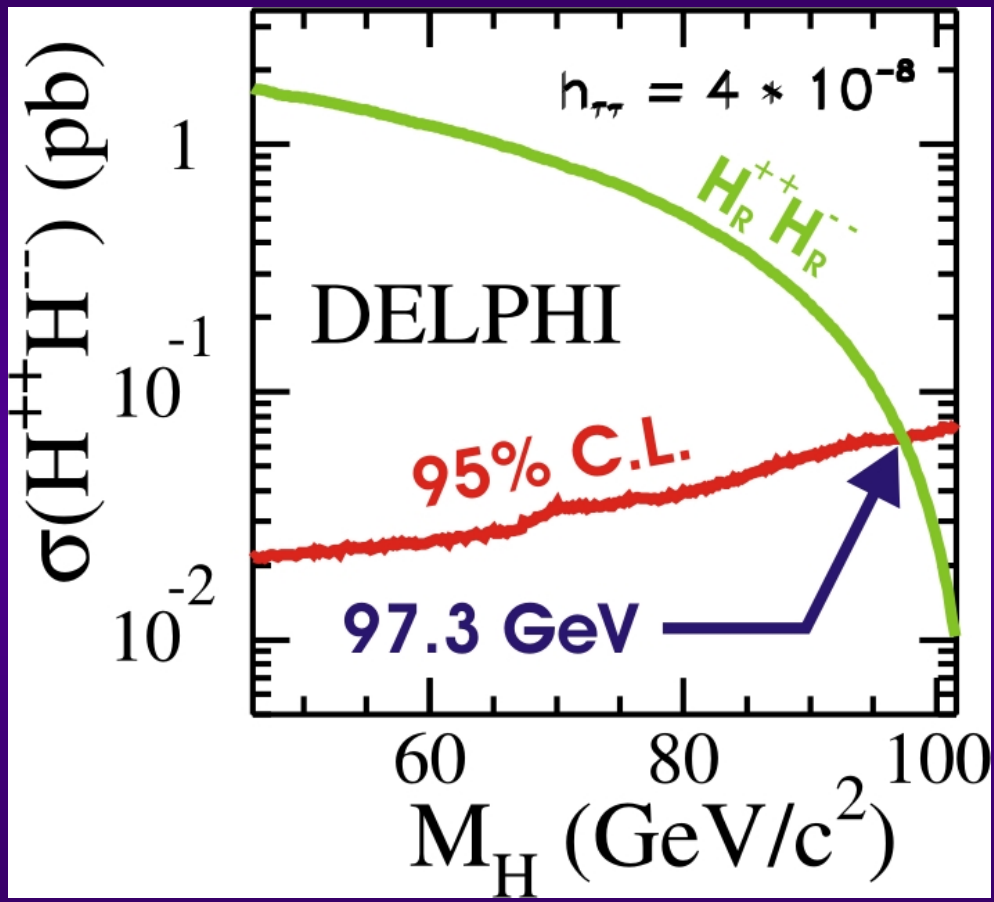
$H^{\pm\pm}$ ($\Delta^{\pm\pm}$): Decays to $l^{\pm}l^{\pm}$, $W^{\pm}W^{\pm}$, $H^{\pm}W^{\pm}$

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

Pair production at LEP

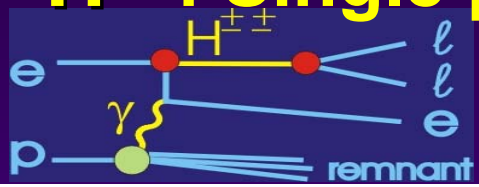


- **Signature striking**
  - Clean 4 lepton final states
  - DELPHI: 4 τ
  - OPAL: all leptons
- **Arbitrary Yukawa $h_{ll'}$**
  - $h_{ll'} < 10^{-7} \Rightarrow$ Lifetime
  - DELPHI: all lifetimes

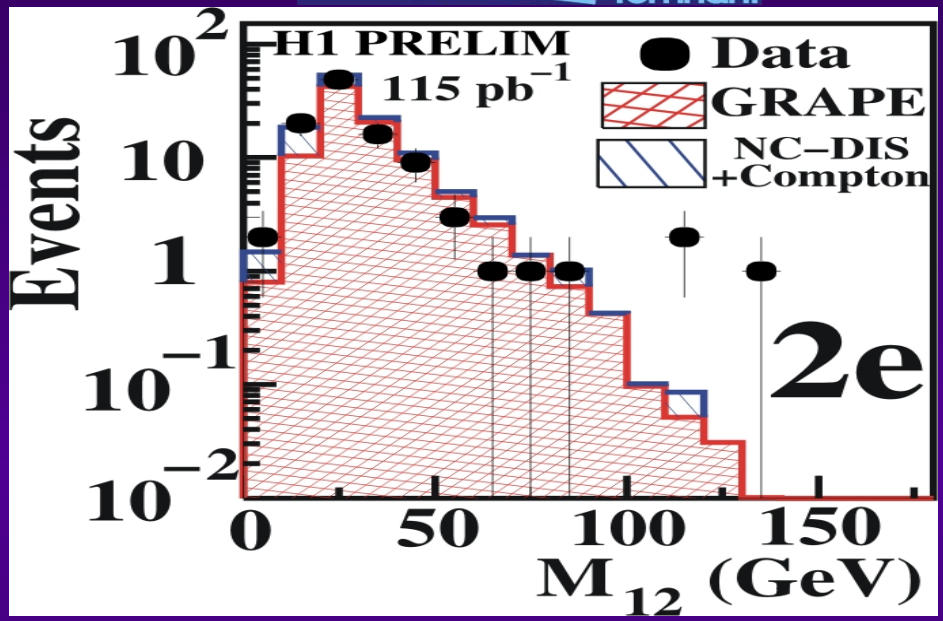


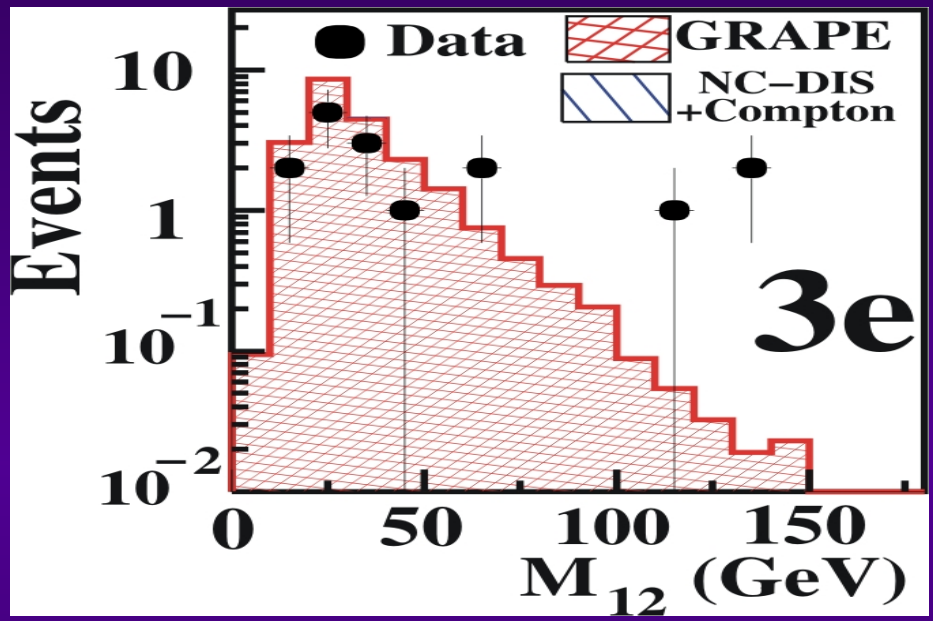
Exclusion to ≈ √s/2

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



General H1 multi-lepton selection:





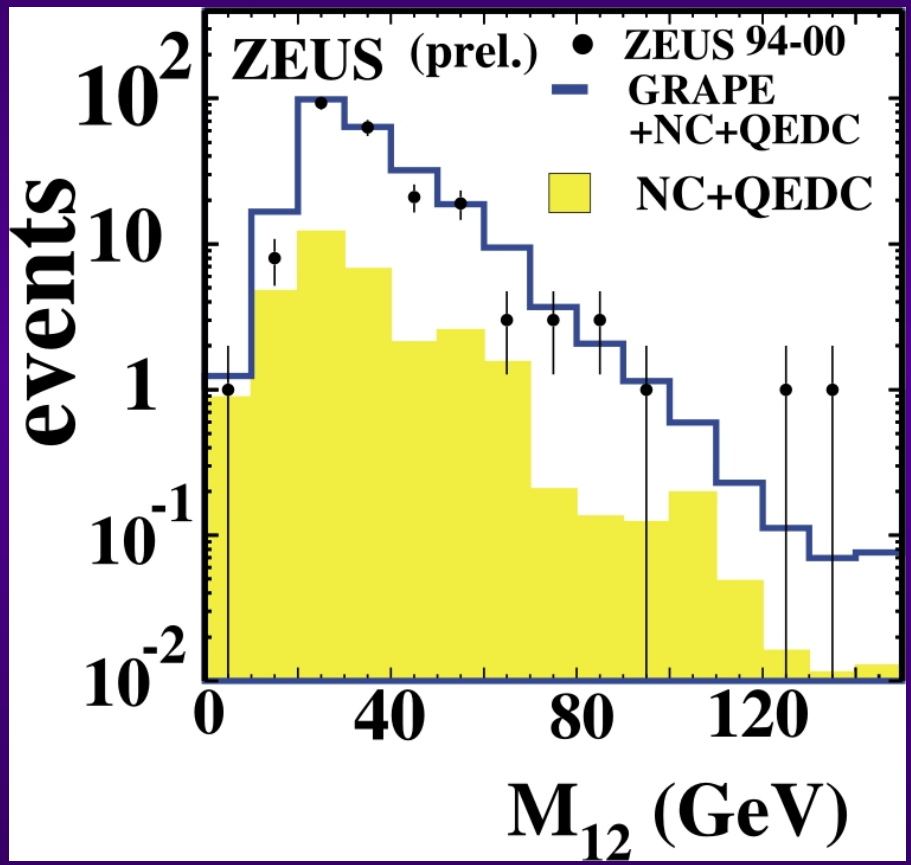
selection	Data	SM
2e M >100	3	0.25±0.05
3e M >100	3	0.23±0.04

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}:

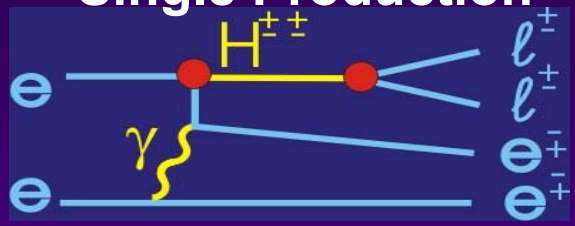


selection	Data	SM
2e M >100	2	0.77±0.08
3e M >100	0	0.37 ±0.04
Both	2	1.14±0.09

⇒ Good agreement with SM

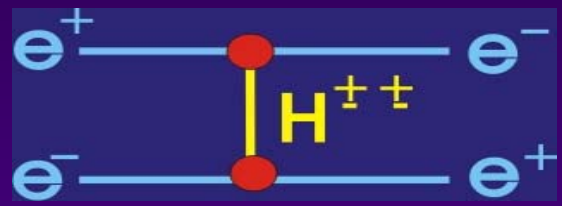
$H^{\pm\pm}$: Higher Masses at LEP

Single Production



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

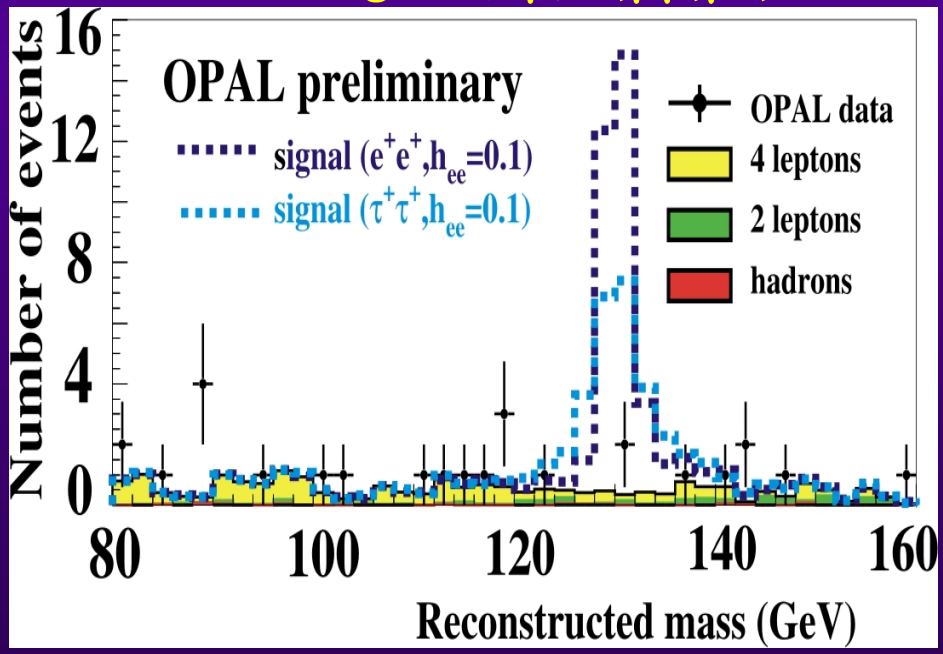
Also Constraints from Bhabhas

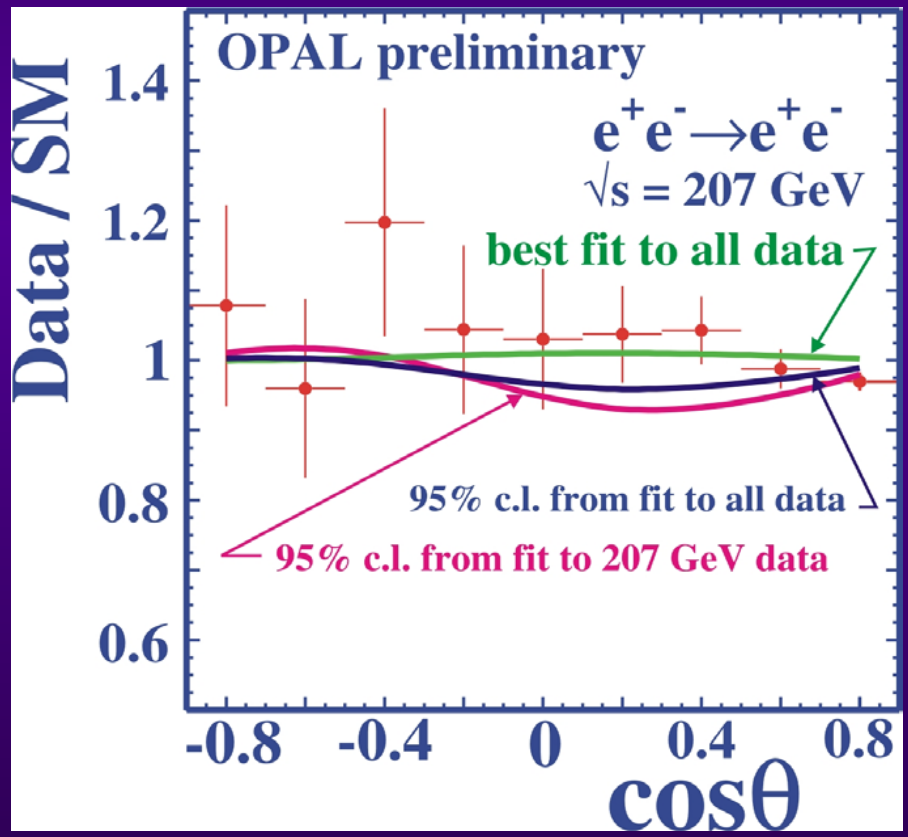


(*eg* M.L.Swartz, Phy.Rev.D40(1989)1521)

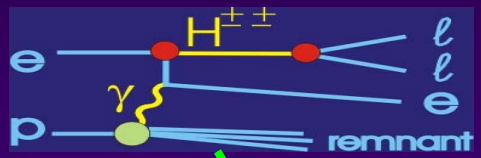
OPAL analysis:

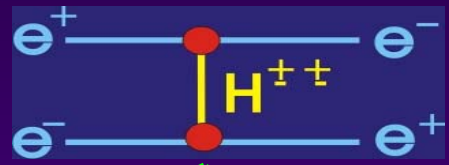
- ≥3 Lepton jets
- Full coverage ee,eμ,eτ,μμ,μτ,ττ

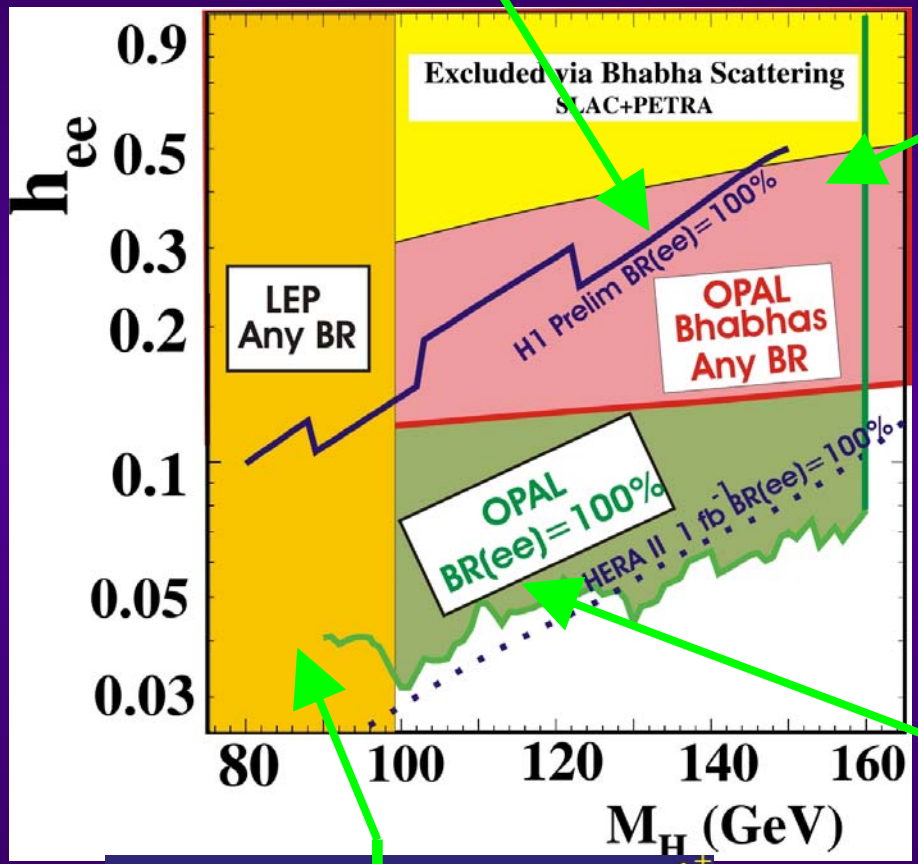


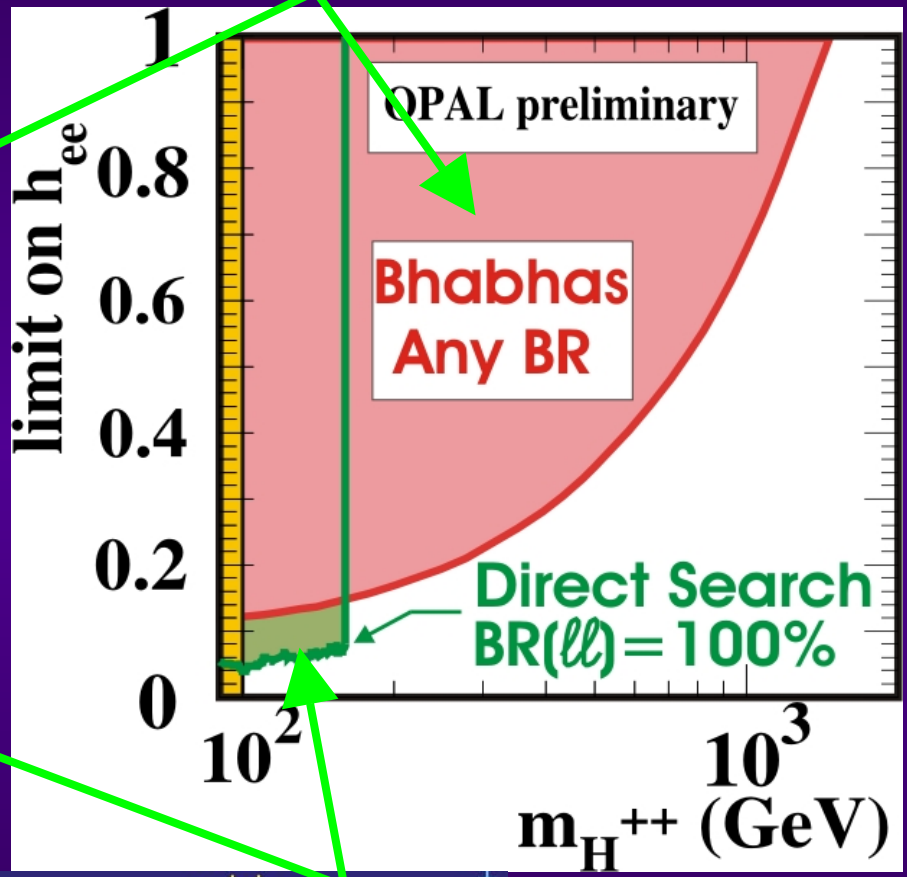


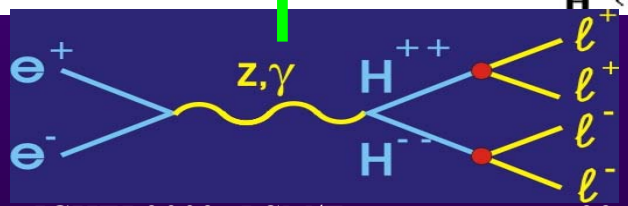
$H^{\pm\pm}$: Constraints

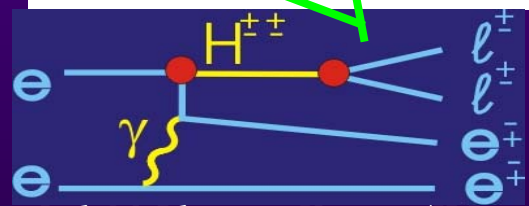




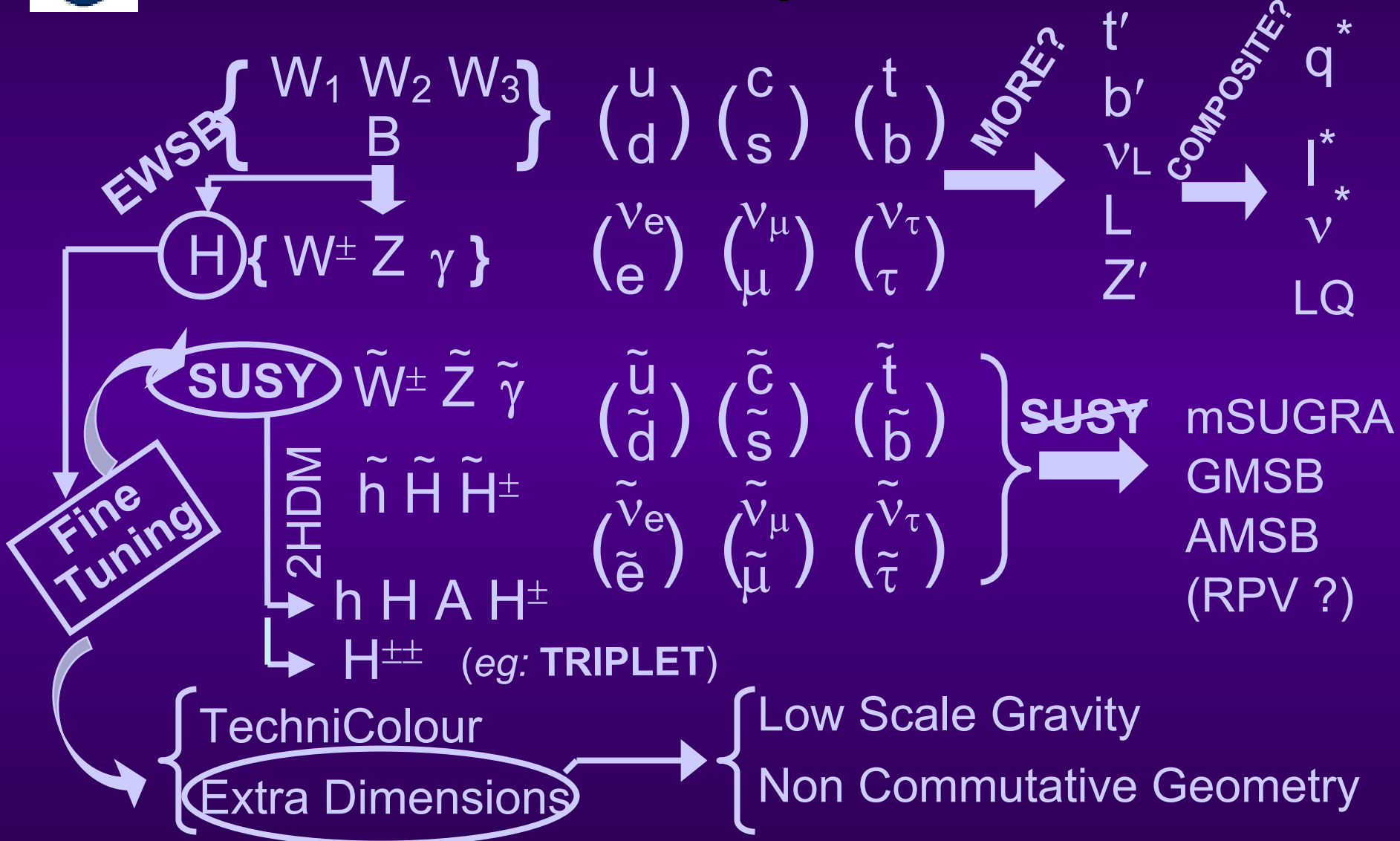








Roadmap …


EWSB
W1 W2 W3
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(u d) (c s) (t b)
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MORE?
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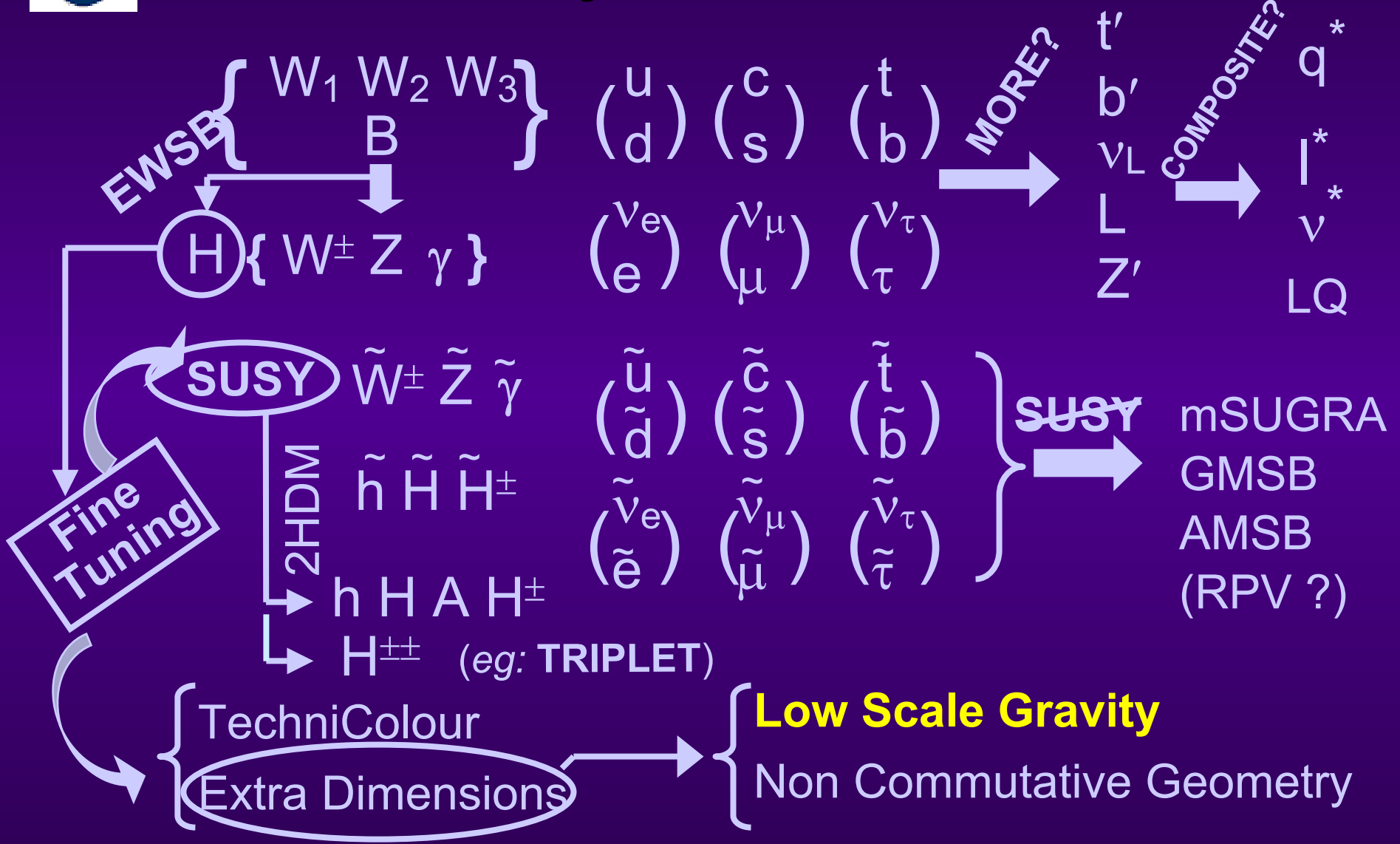
(eg: TRIPLET)
TechniColour
Extra Dimensions
Low Scale Gravity
Non Commutative Geometry

Gravity in Extra Dim.



Extra Dimensions

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

eg: Arkani-Hamed,Dimopoulos,Dvali (ADD)

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

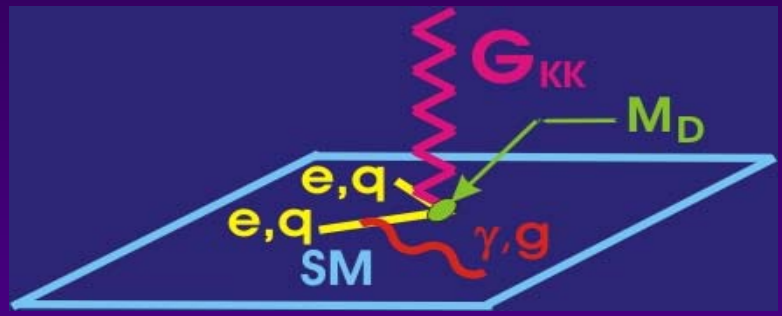
- "Planck" @ $M_D \approx \Lambda_{EW}$
- Still weak in "SM", but see Σ G_{KK} modes

Large Xdim …

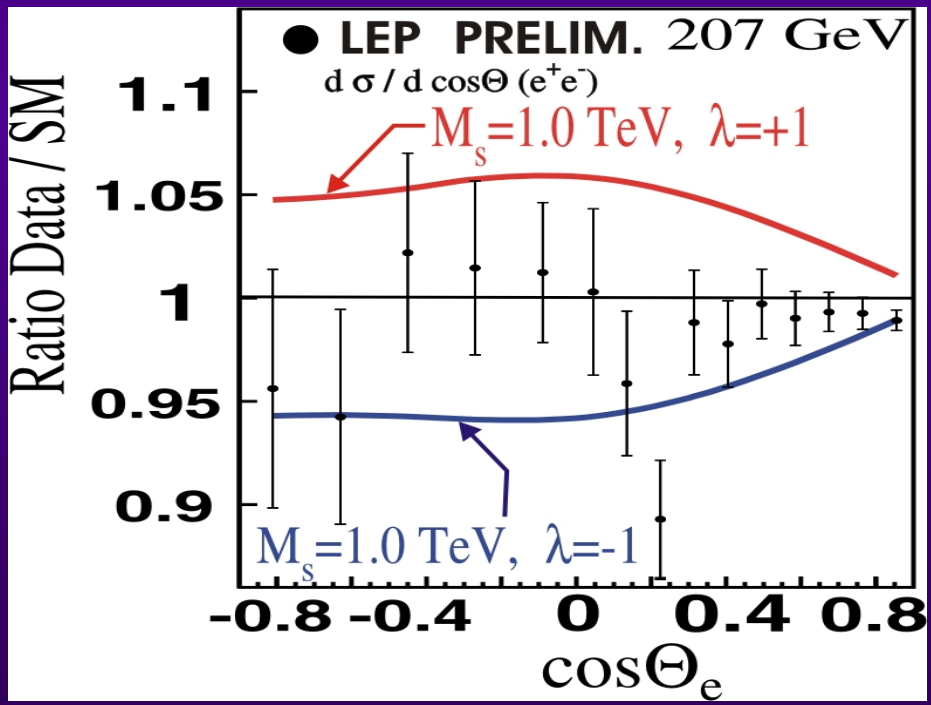
Indirect Effects

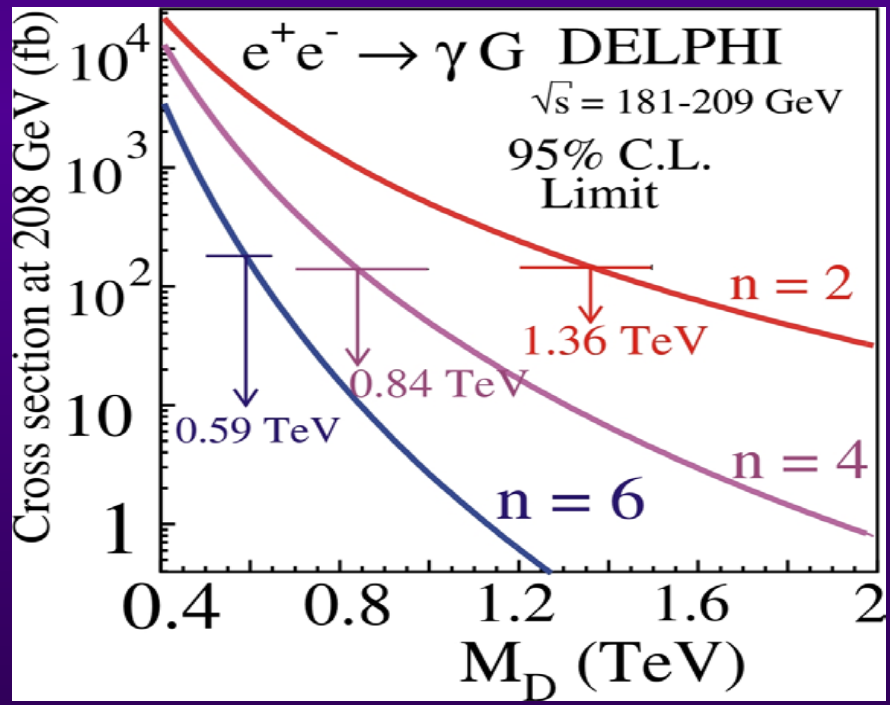
eg: $e^+e^- \rightarrow e^+e^-$

Direct Effects

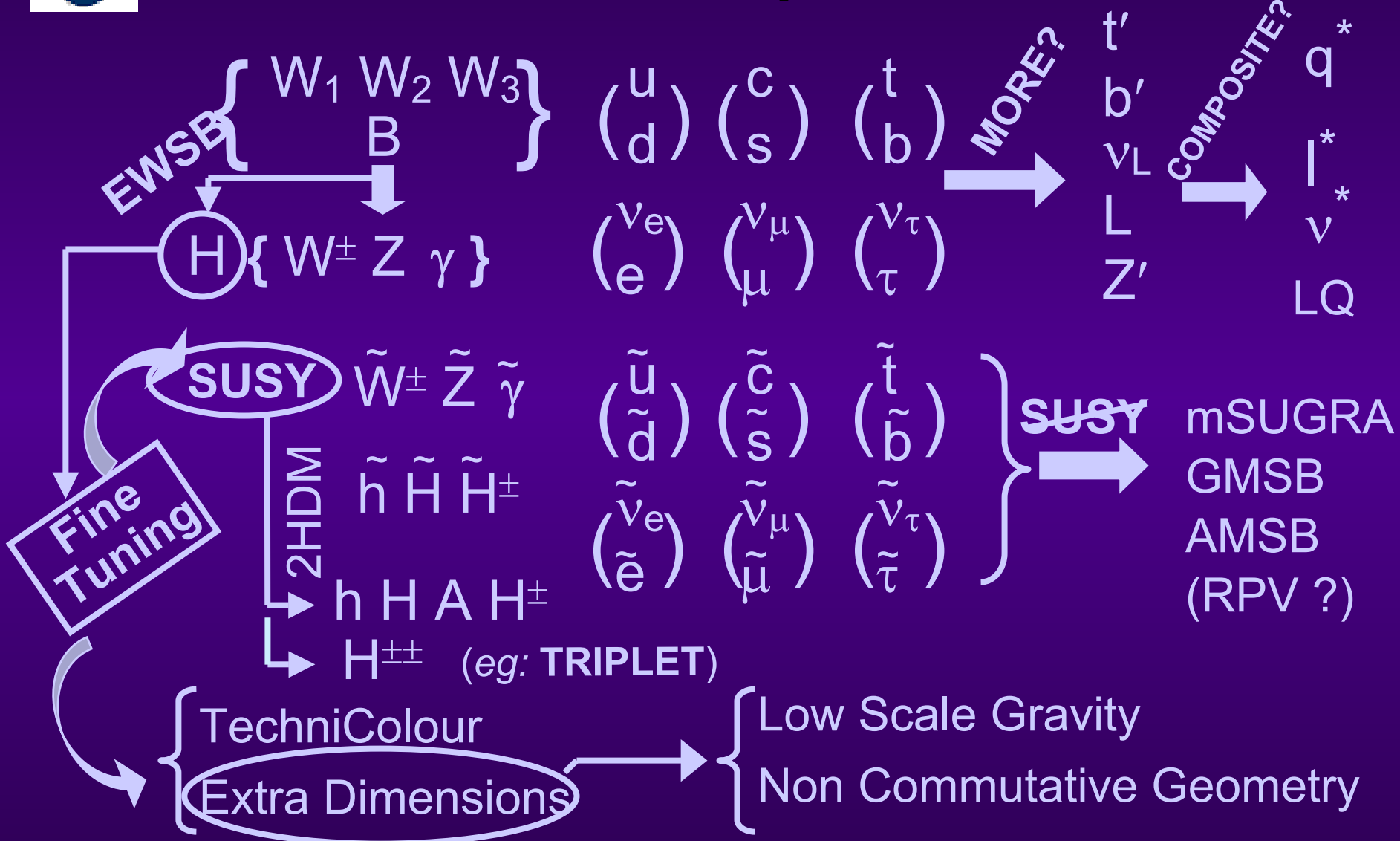


eg: $e^+e^- \rightarrow \gamma\, \mathbf{G}$





Roadmap …


EWSB
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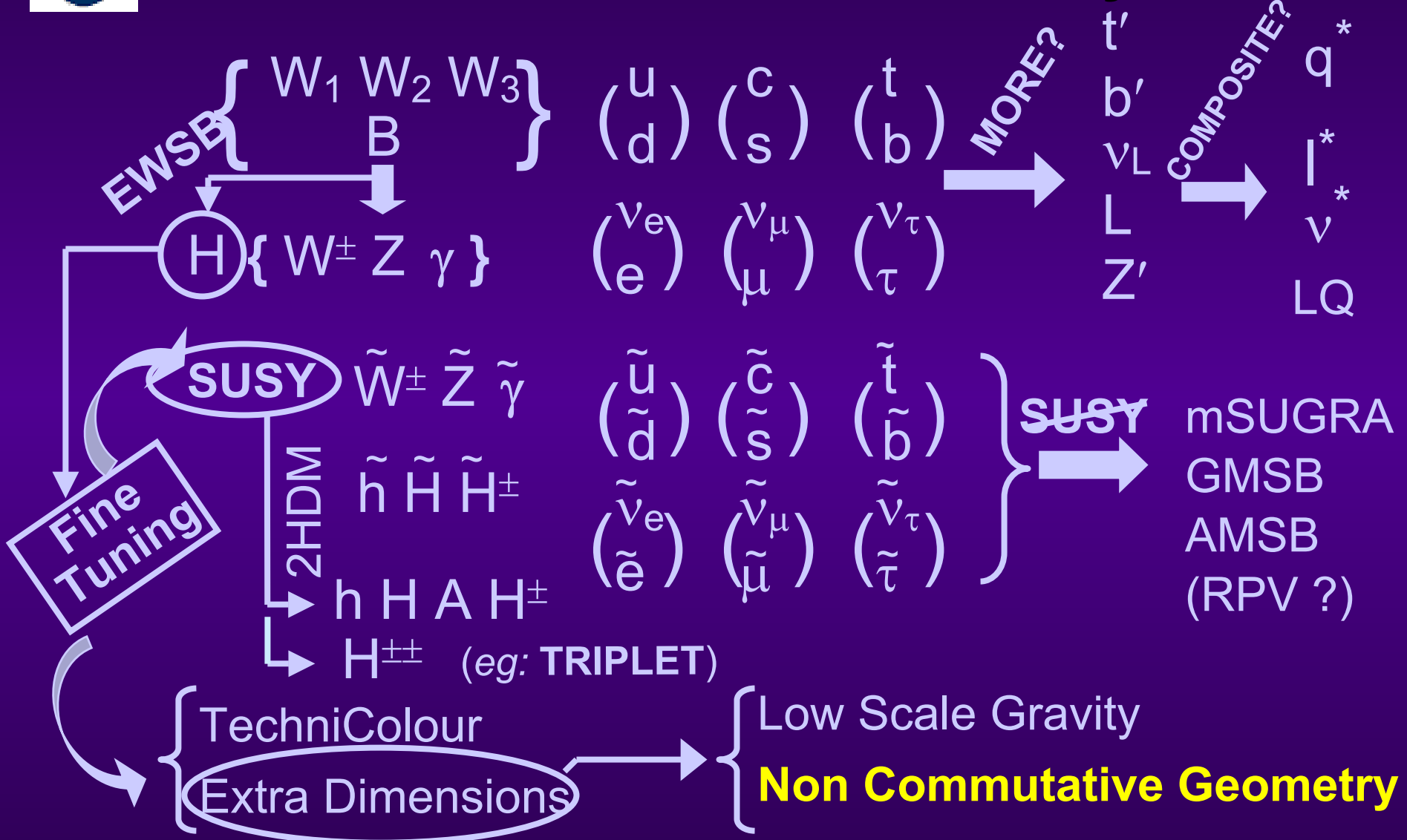
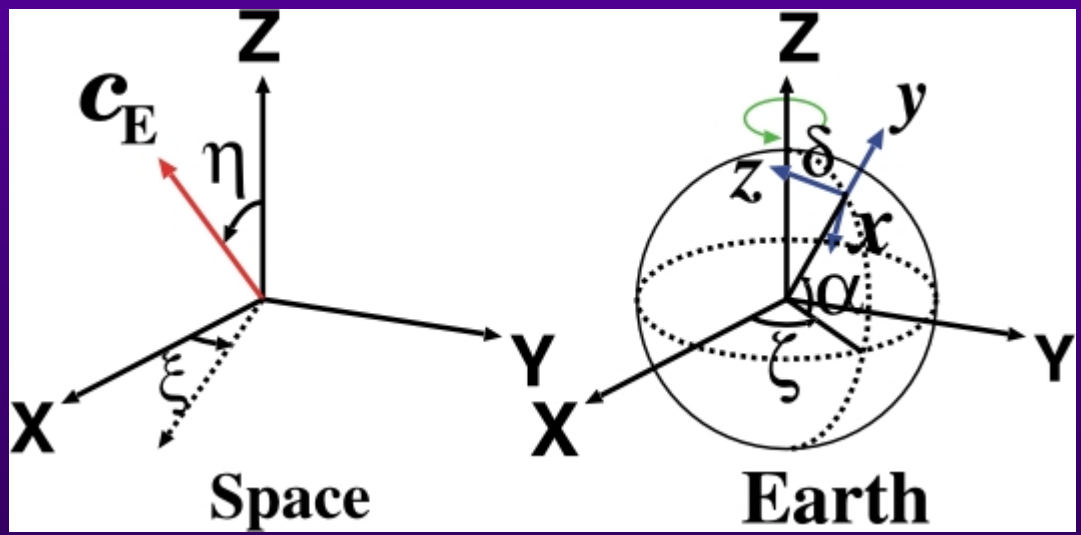
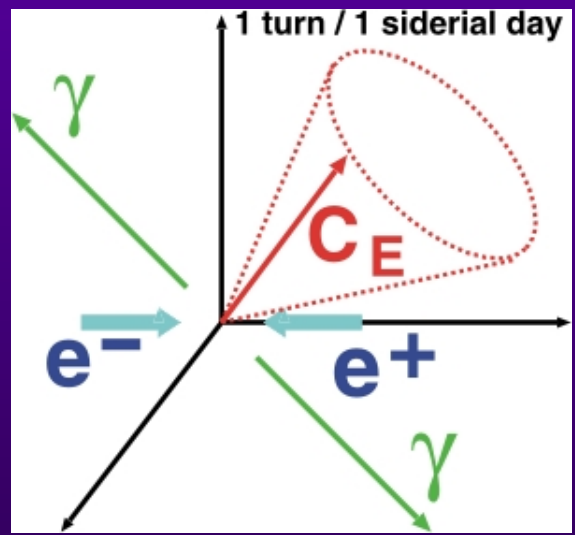
Non Commutative Geometry



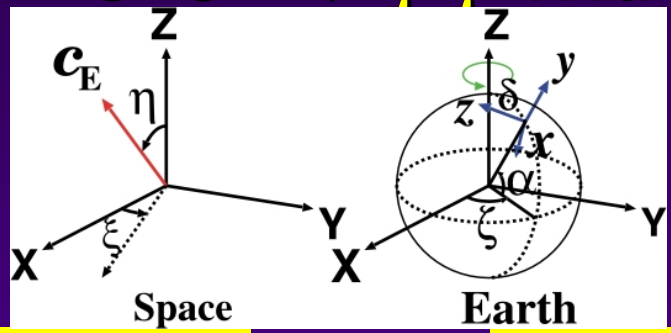
Non Commutative QED

- Extra Dim. (*eg*: string theories) ⇒ Non Commutative Geometry
  - $[X\mu, X\nu] = i\,\theta\mu\upsilon$, $\theta\mu\upsilon = c\mu\nu / \Lambda^2_{NC}$
    - $c\mu\nu$ = Unit vector pointing in preferred direction
    - Λ_{NC} = Energy scale of N.C. effects
      - $\Lambda_{NC} = M_{planck}$ = TeV scale?? (low scale gravity …)
  - No full non-commutative Standard Model exists
    - But non-commutative QED does … "NCQED"

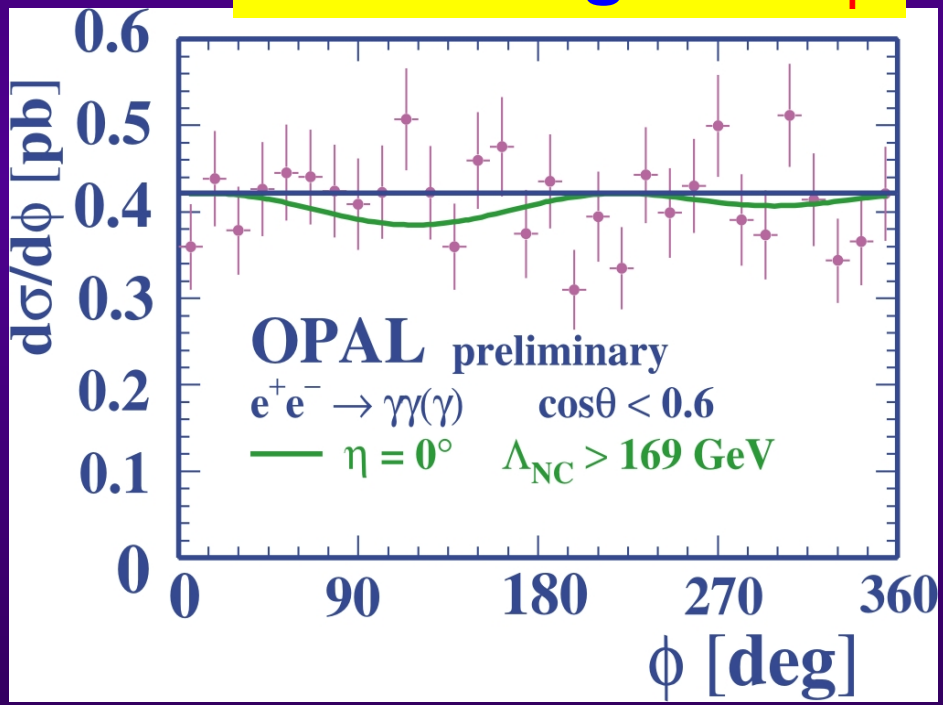




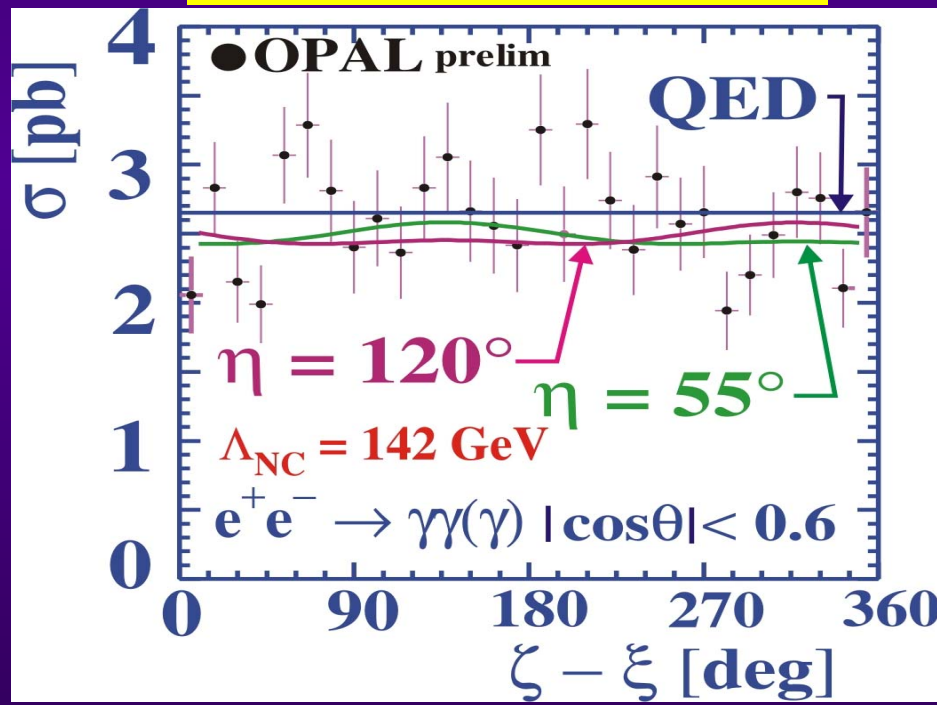
NCQED in $e^+e^- \to \gamma\gamma$ with OPAL



Time Integrated φ

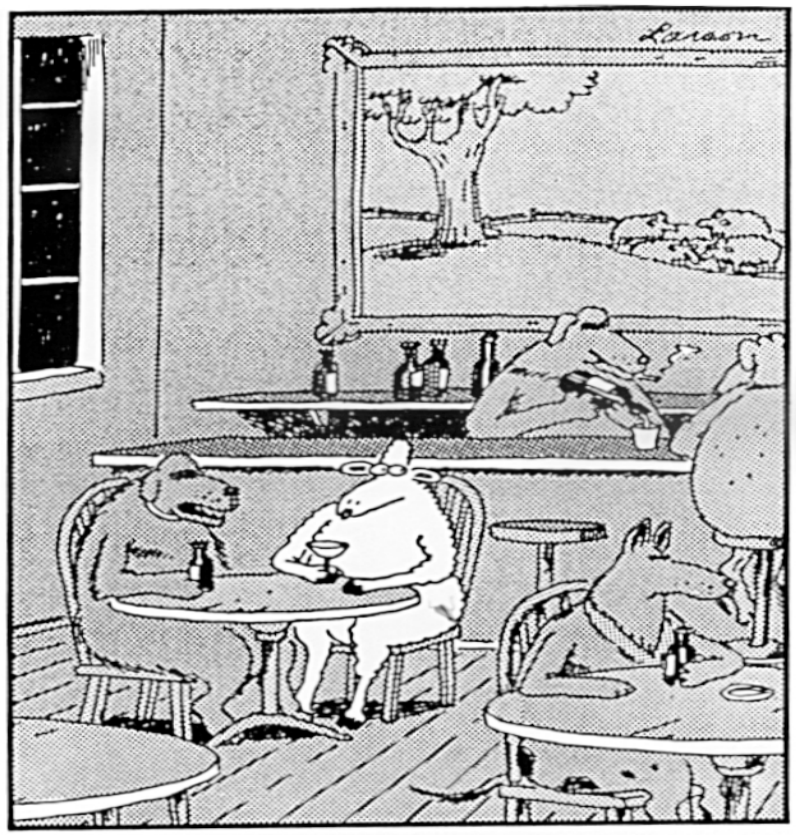


Time Dependent



Λ > 142 GeV, any η (95% C.L.)

Were we looking for the right things?



"Confession time Mona:

I've led you astray."

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