INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Physics

Hitoshi Murayama (IPMU & Berkeley)

LCWS 2010, Beijing, March 26, 2010

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Physics case for ILC

- have been in the LC community since 1990
- NLC, JLC, TESLA, CLIC, ...
- many ups and downs in hopes and perceptions about ILC
- don’t think physics case has been really changed since then

(reassuring & disappointing)

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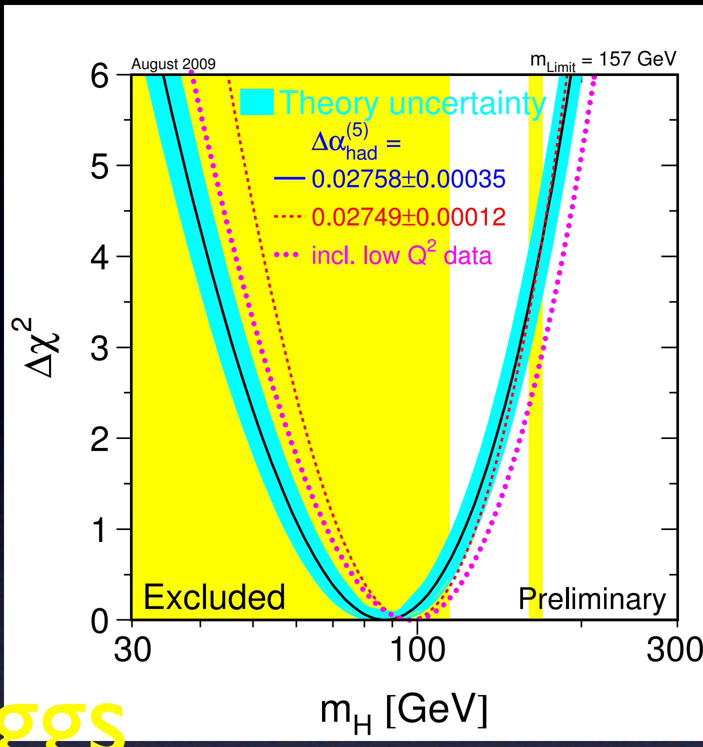
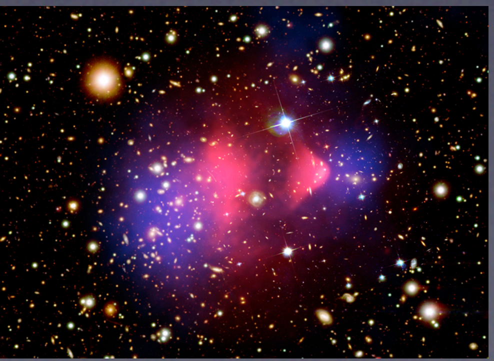
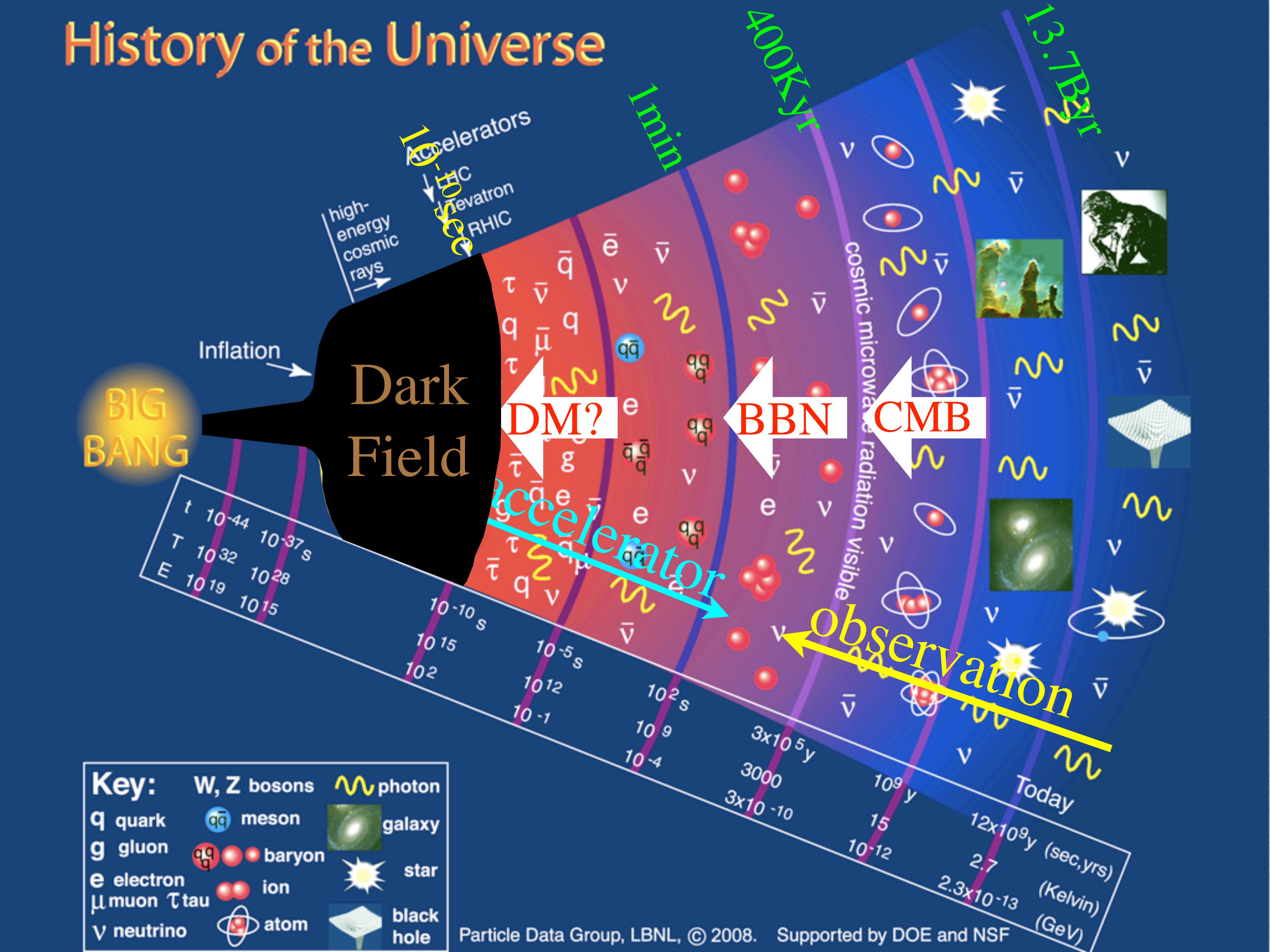
Physics case for ILC



- We know little about the origin of electroweak symmetry breaking
  - Higgs sector
  - hierarchy problem
- precision EW data suggest light Higgs
- dark matter may well be a TeV-scale WIMP
- Whatever we find at LHC, we need to reconstruct the Lagrangian from data@ILC
- What energy?




History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
Dark Field
10-10sec
1min
400Kyr
13.7Byr
DM?
BBN
CMB
cosmic microwave radiation visible
accelerator
observation
t 10-44 10-37 s 10-10 s 10-5 s 10 2 s 3x10 5 y 10 9 y 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10 -12 2.3x10 -13 (GeV)
Today
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
atom
black hole
ν neutrino
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF


bosonic TC
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
NOT YET THOUGHT OF
NOT YET THOUGHT OF
effective SUSY
SUSY
NMSSM
NMSSM
MSSM +νR
unnified SM
axigluon
sterile ν
6th gen
5th gen
4th gen
lepto quark
heavy Majorana
vector-like family
fractionally charged
S,T,U
Z'ψ
Z'LR
WR
Z'SM
Z'χ
X Y
Z'η
milli-charged
mono-pole
shadow matter
NOT YET THOUGHT OF
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
mirror symmetry
spontaneous CP
superweak
N=2
N=4
N=8
Majoron
saxion
axino
axion
Weinberg's 3HD
milli-weak
familon
NGB
worm-hole
Extra dim
quintessence
k-essence
composite W,Z
contact int.
string
heterotic
matrix
M
IIB
IIA
F
I

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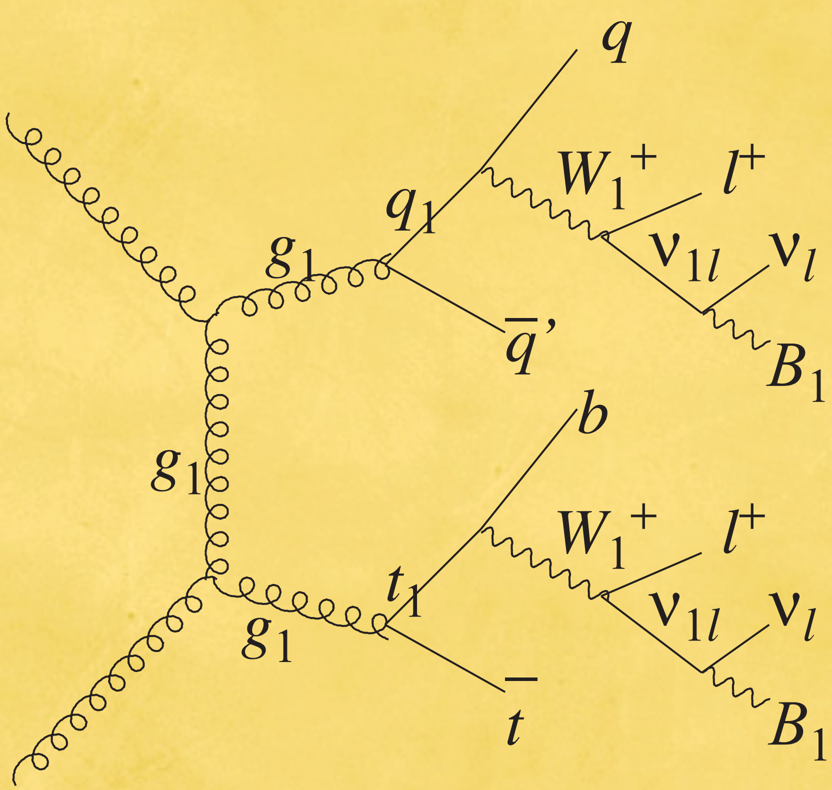
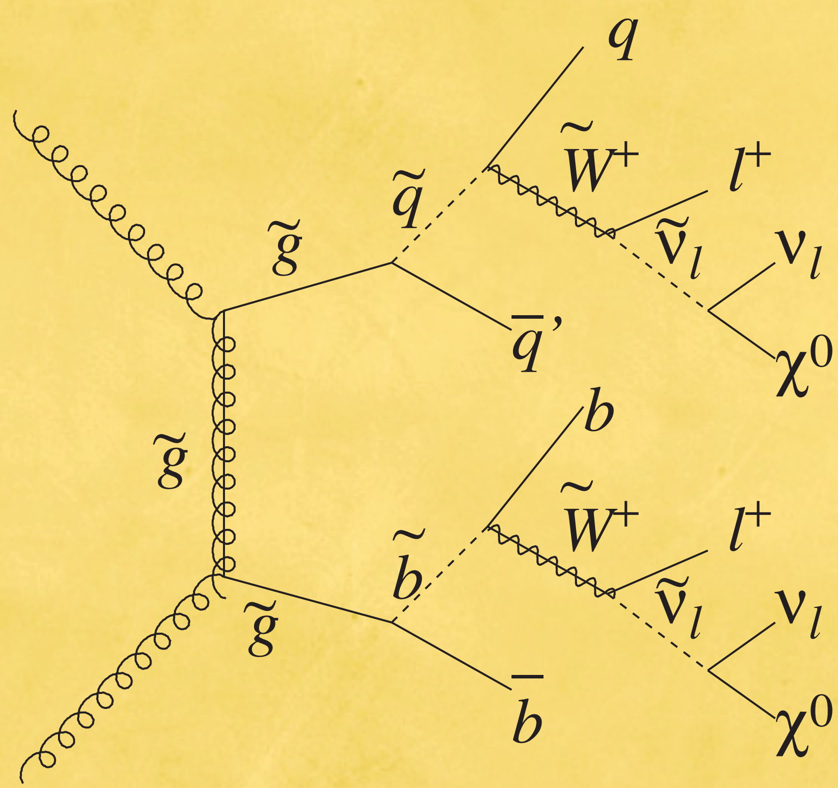
New physics looks alike

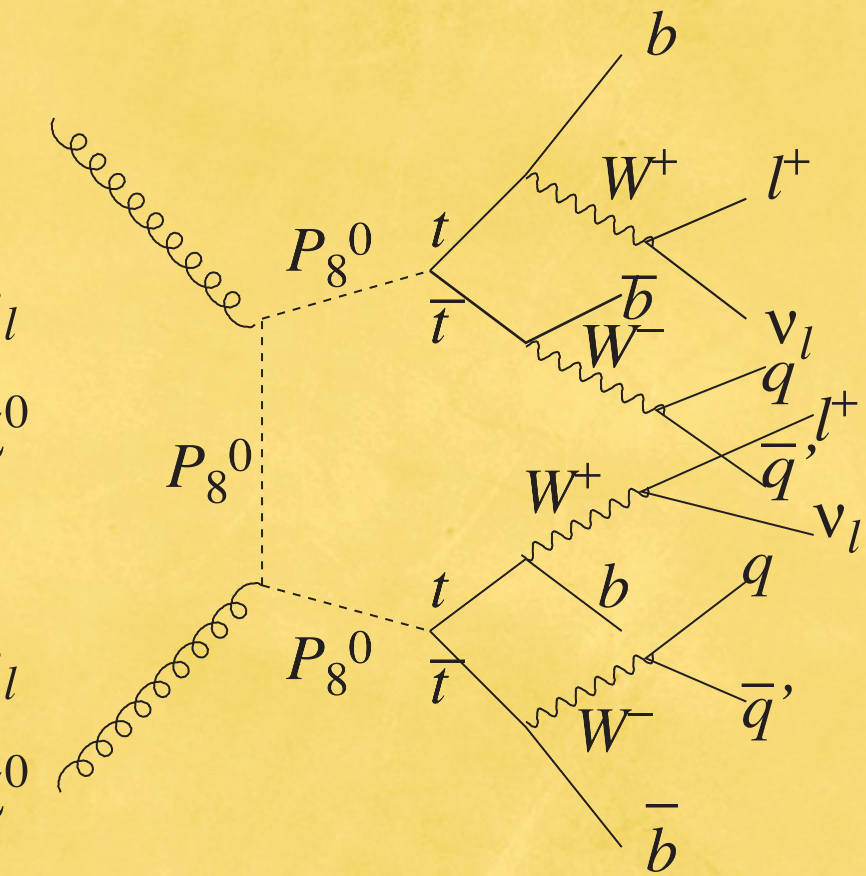
missing E_T, multiple jets, *b*-jets, (like-sign) di-leptons



UED
spin 1



SUSY
spin 1/2



technicolor
spin 0

+little Higgs with T-parity, warped ED with Z_3 baryon

The New York Times

July 23, 2015

The Other Half of the World Discovered

Geneva, Switzerland

As an example, supersymmetry

"New-York Times level" confidence

still a long way to

"freshman physics" level confidence

"We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances."

precision SUSY mea

- SUSY spectroscopy
- kinematic fits, partial wave analysis, Dalitz analysis, etc
- precision mass, BR measurements

$\boxed{\text{Squarks}}$ $J=0$? PDG 2016

The following data are averaged over all light flavors, presumably u, d, s, c with both chiralities. For flavor-tagged data, see listings for Stop and Sbottom. Most results assume minimal supergravity, an untested hypothesis with only five parameters. Alternative interpretation as extra dimensional particles is possible. See KK particle listing.

SQUARK MASS

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
538±10	**OUR FIT**		**mSUGRA assumptions**
532±11	[1]ABBIENDI 11D	CMS	Missing ET with mSUGRA assumptions
541±14	[2]ADLER 11O	ATLAS	Missing ET with mSUGRA assumptions
• • • We do not use the following data for averages, fits, limits, etc • • •			
652±105	[3]ABBIENDI 11K	CMS	extended mSUGRA with 5 more parameters

[1]ABBIENDI 11D assumes minimal supergravity in the fits to the data of jets and missing energies and set $A_0=0$ and $\tan\beta = 3$. See Fig. 5 of the paper for other choices of A_0 and $\tan\beta$. The result is correlated with the gluino mass M_3. See listing for gluino.
[2]ADLER 11O uses the same set of assumptions as ABBIENDI 11D, but with $\tan\beta = 5$.
[3]ABBIENDI 11K extends minimal supergravity by allowing for different scalar masses-squared for Hu, Hd, 5* and 10 scalars at the GUT scale.

SQUARK DECAY MODES

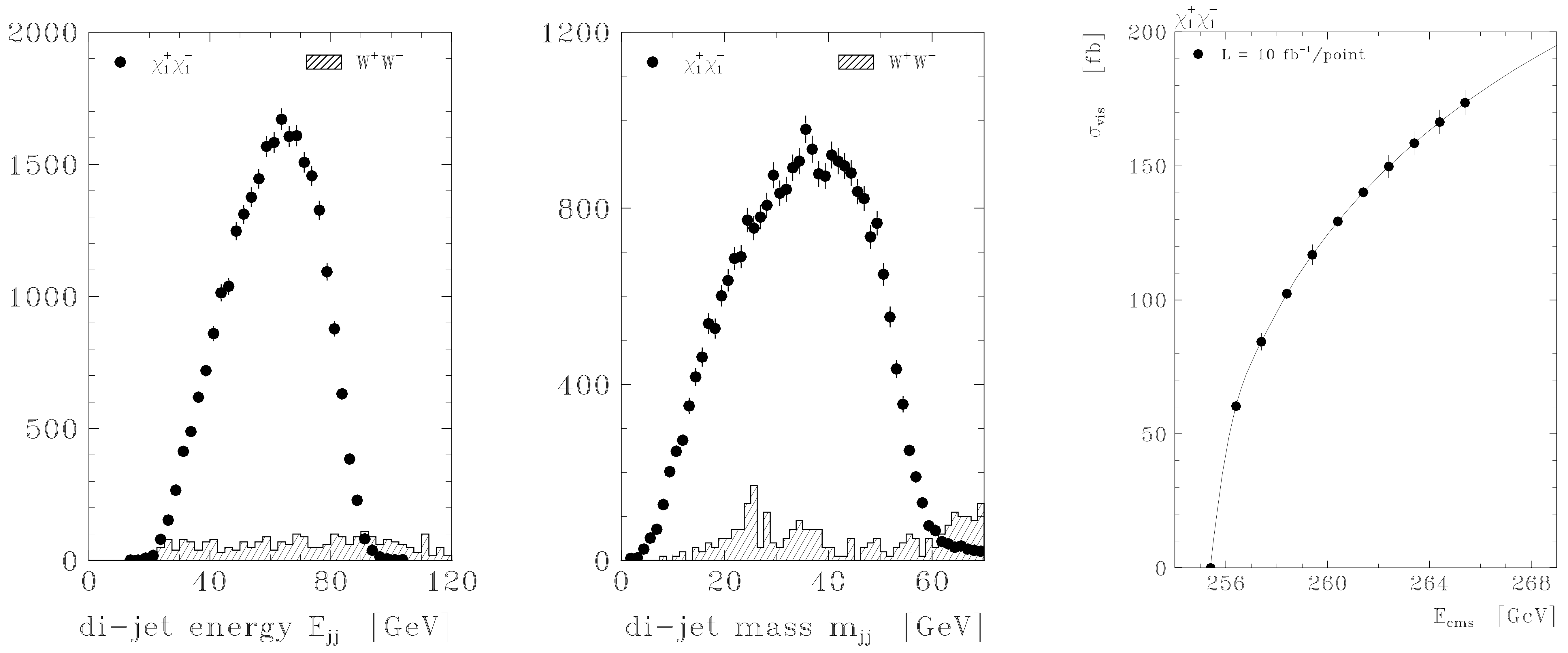
MODE	BR(%)	DOCUMENT ID	TECN	COMMENT
j+miss	32±5	ABE 10U	ATLAS	
j l+miss	73±10	ABE 10U	ATLAS	lepton universality
j e+miss	22±8	ABE 10U	ATLAS	
j μ +miss	25±7	ABE 10U	ATLAS	
q χ^+	seen	ABE 10U	ATLAS	

Reconstruct Lagrangian from data

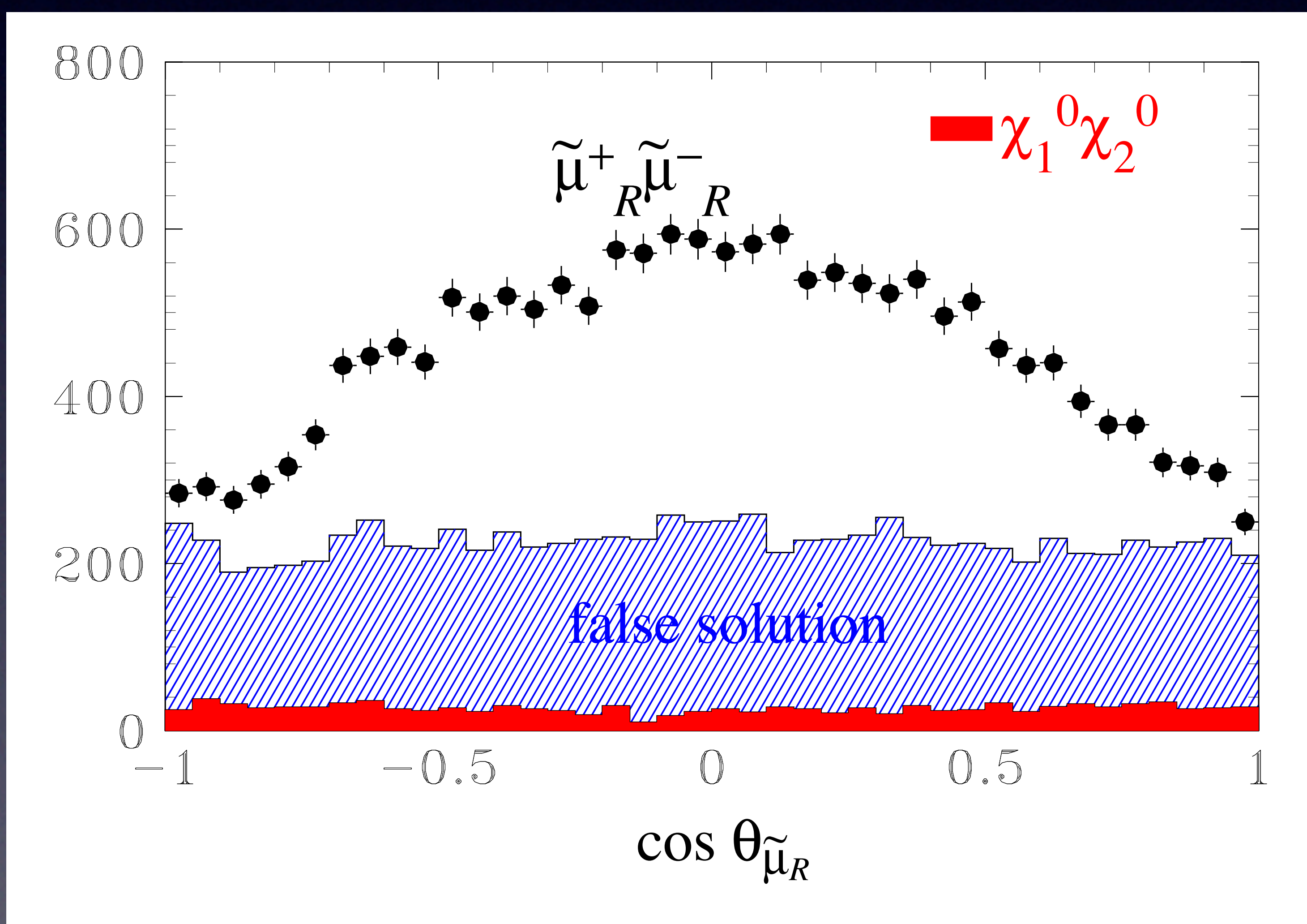
- Specify the fields
  - mass
  - spin:Klein-Gordon, Dirac, Majorana, gauge
  - SU(3)xSU(2)xU(1) quantum numbers
  - mixing of states
- Specify their interactions
  - gauge interactions
  - Yukawa couplings
  - trilinear and quartic scalar couplings

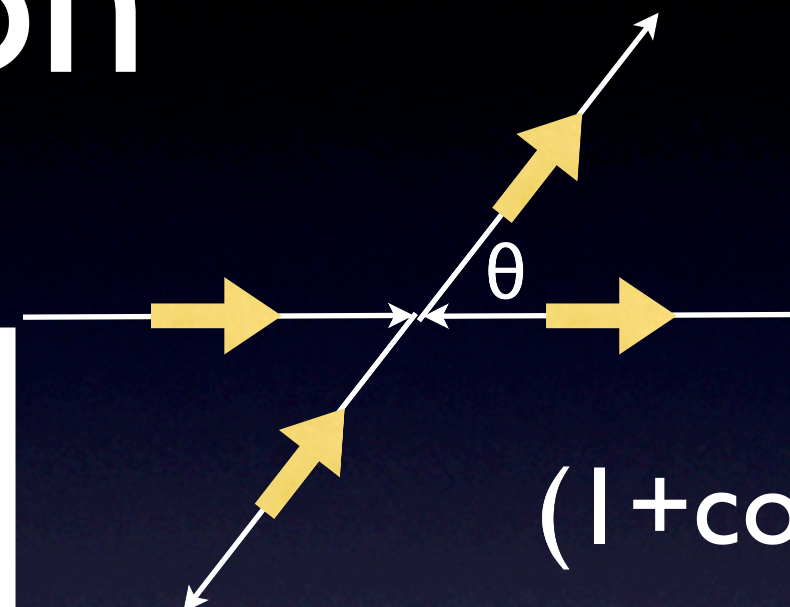
mass

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to (\tilde{\chi}_1^0 l^\pm \nu_l)(\tilde{\chi}_1^0 q\bar{q}')$$

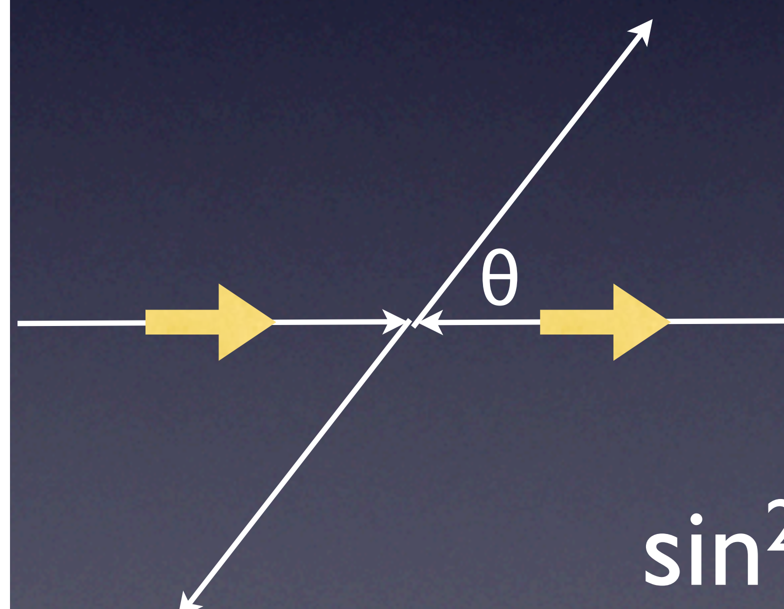


spin
smuon





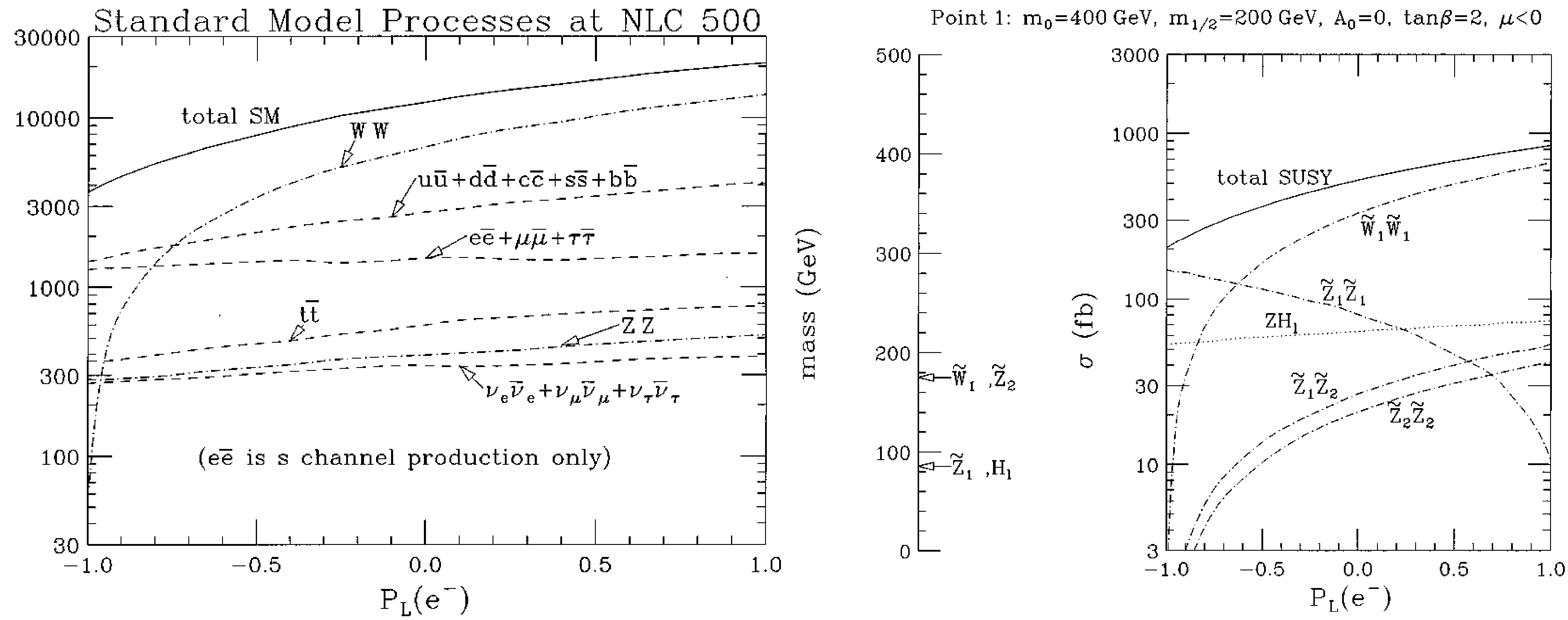
$(1+\cos\theta)^2$



$\sin^2\theta$

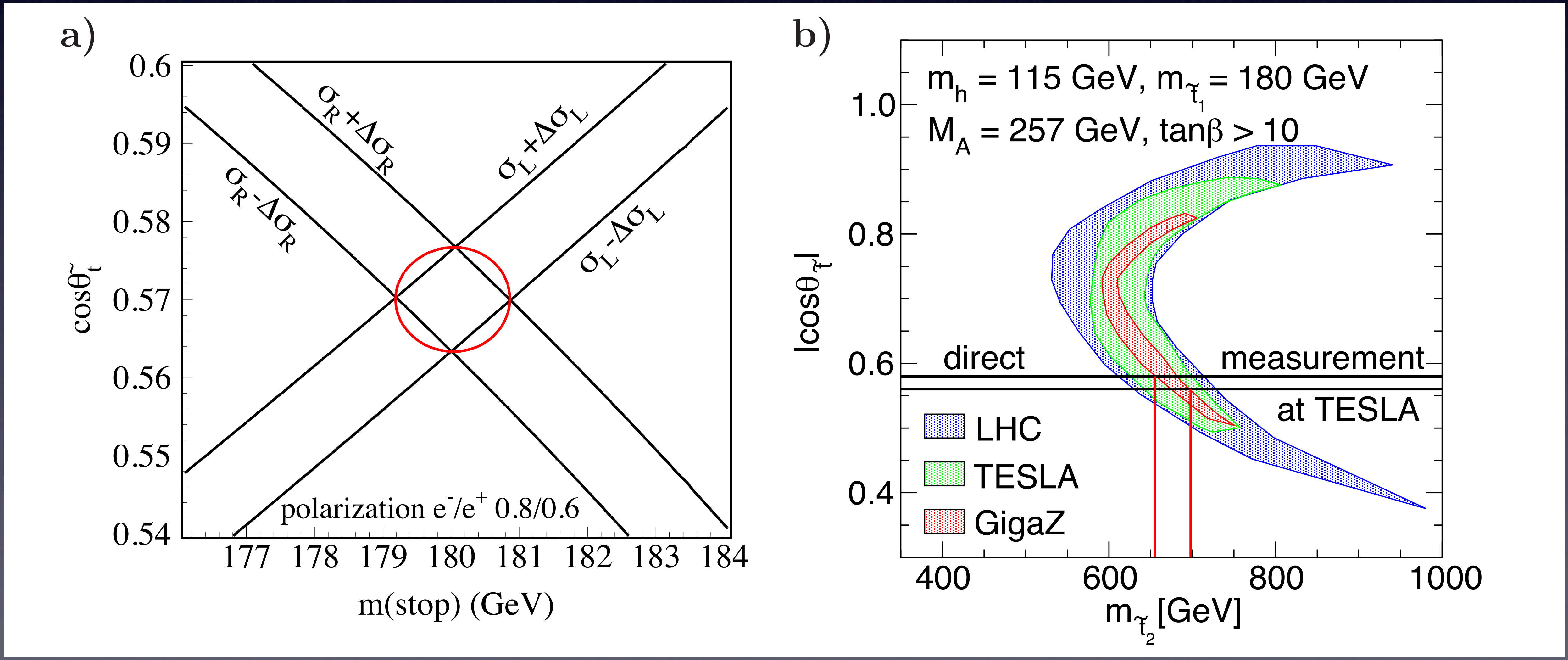
SU(2)$_L$xU(1)$_Y$ quantum numbers

- e_L and e_R are really different particles at $E \gg m_Z$, measure I_3 and Y

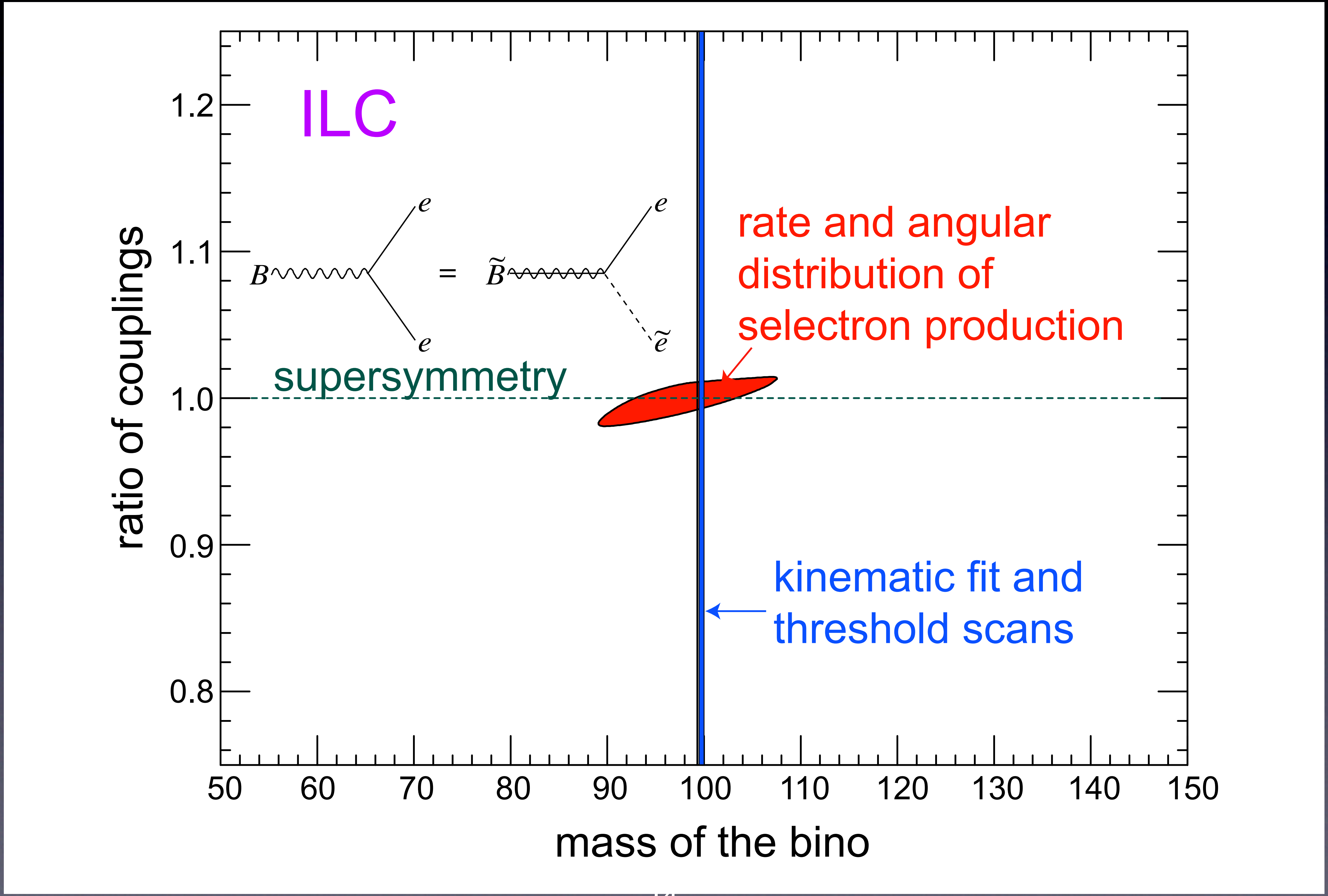


Disentangle mixing Stop

$$(\tilde{t}_L^* \; \tilde{t}_R^*) \begin{pmatrix} m_{\tilde{Q}_3}^2 + m_t^2 & (A_t - \mu^* \cot\beta) m_t \\ (A_t^* - \mu \cot\beta) m_t & m_{\tilde{t}}^2 + m_t^2 \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$



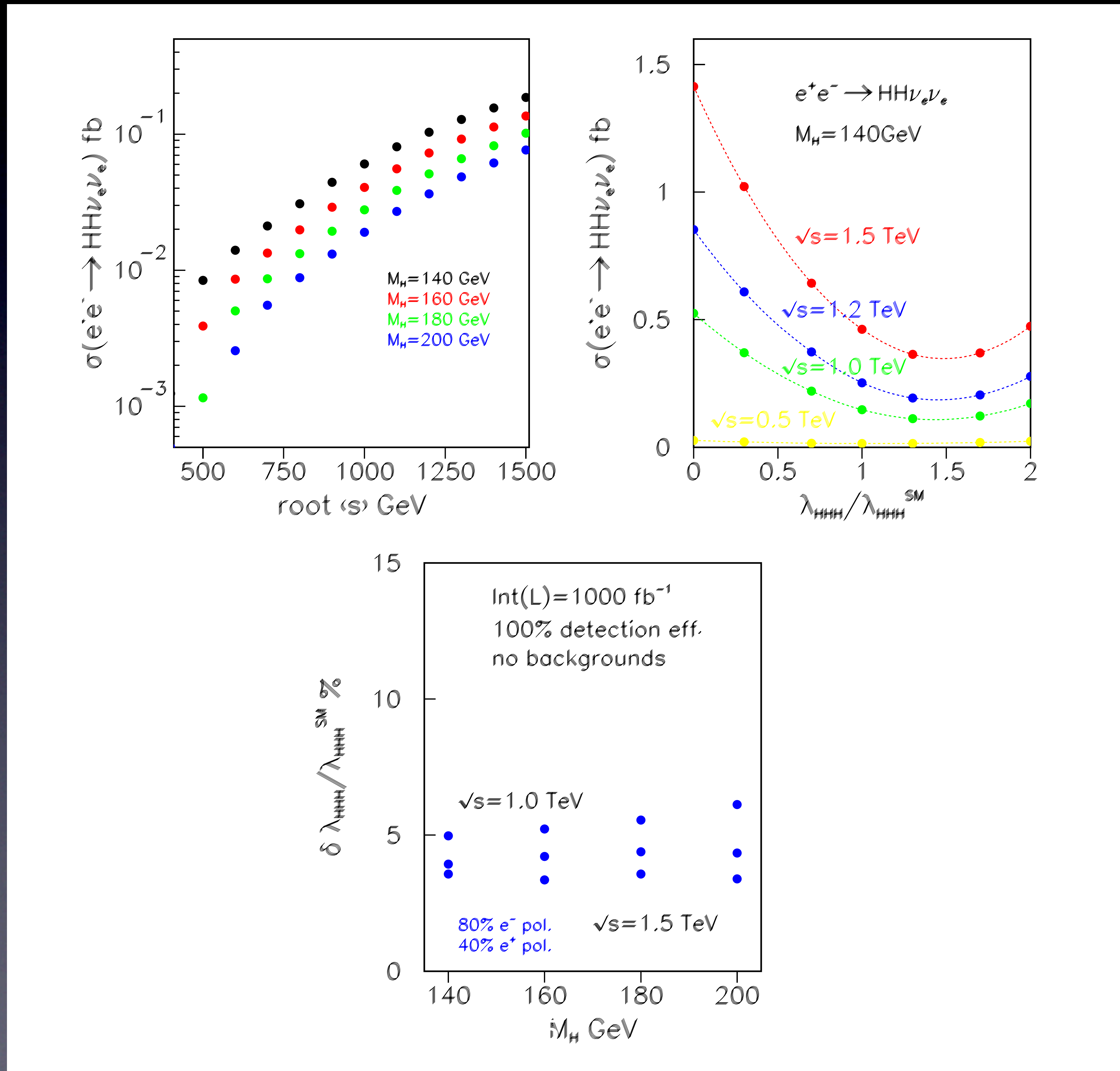
Yukawa coupling



triple scalar coupling

$e^+e^- \to \nu_e\bar{\nu}_e H^*$

$H^* \to HH$



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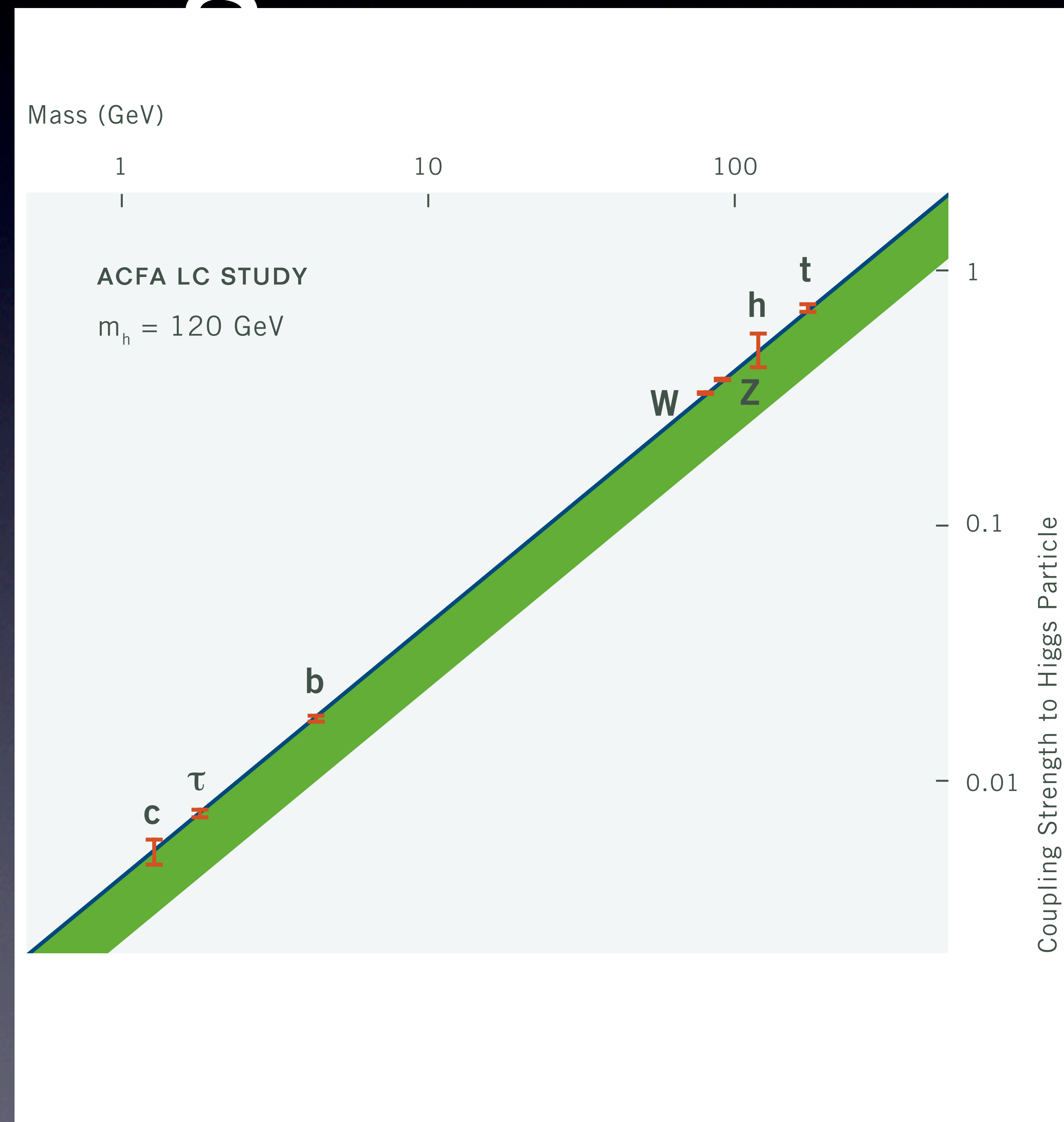
Physics Significance

Prove
Higgs coupling ∝ mass

- Branching Fractions test the relation

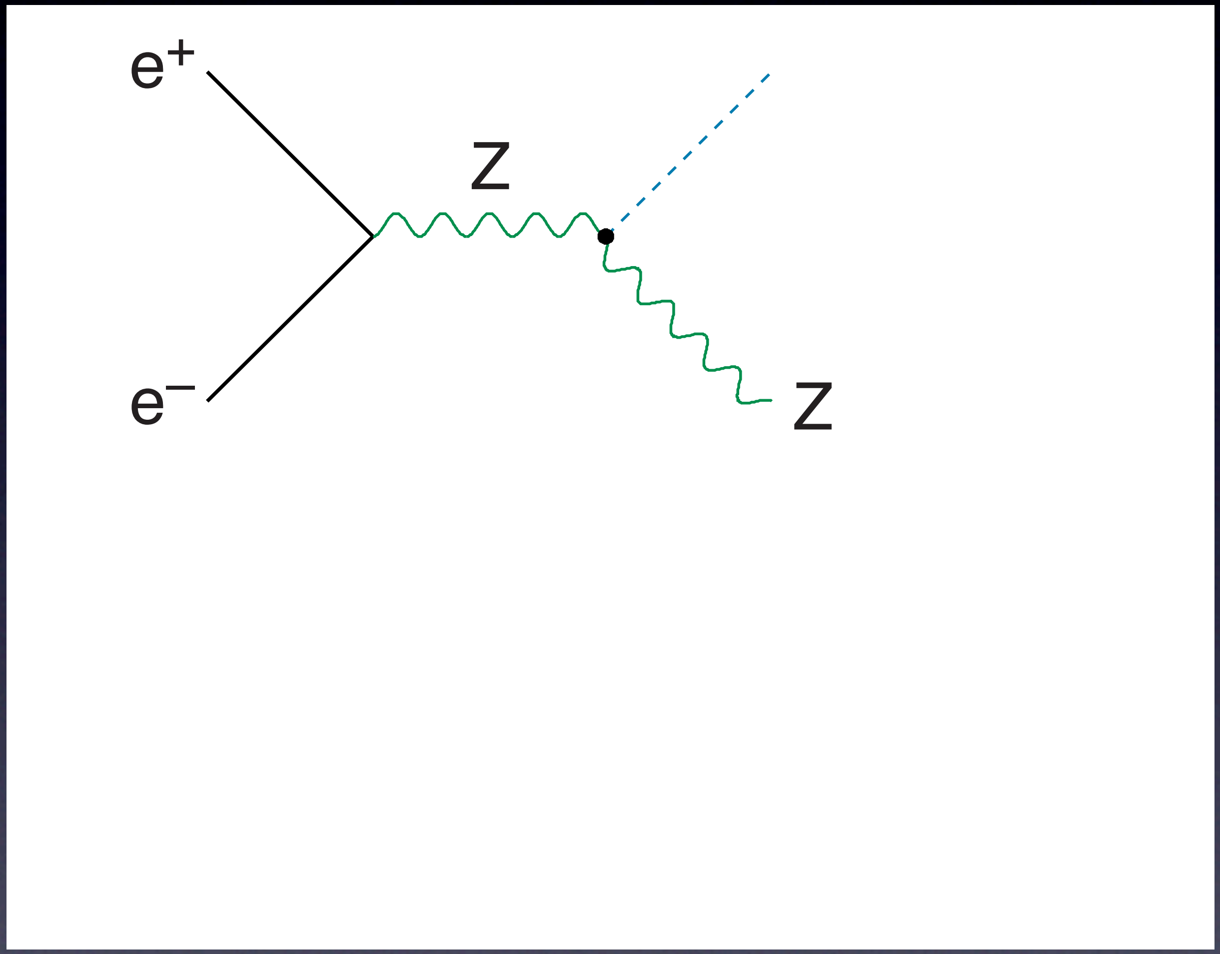
coupling ∝ mass

⇒ proves that Higgs Boson is the Mother of Mass



Prove it is condensed

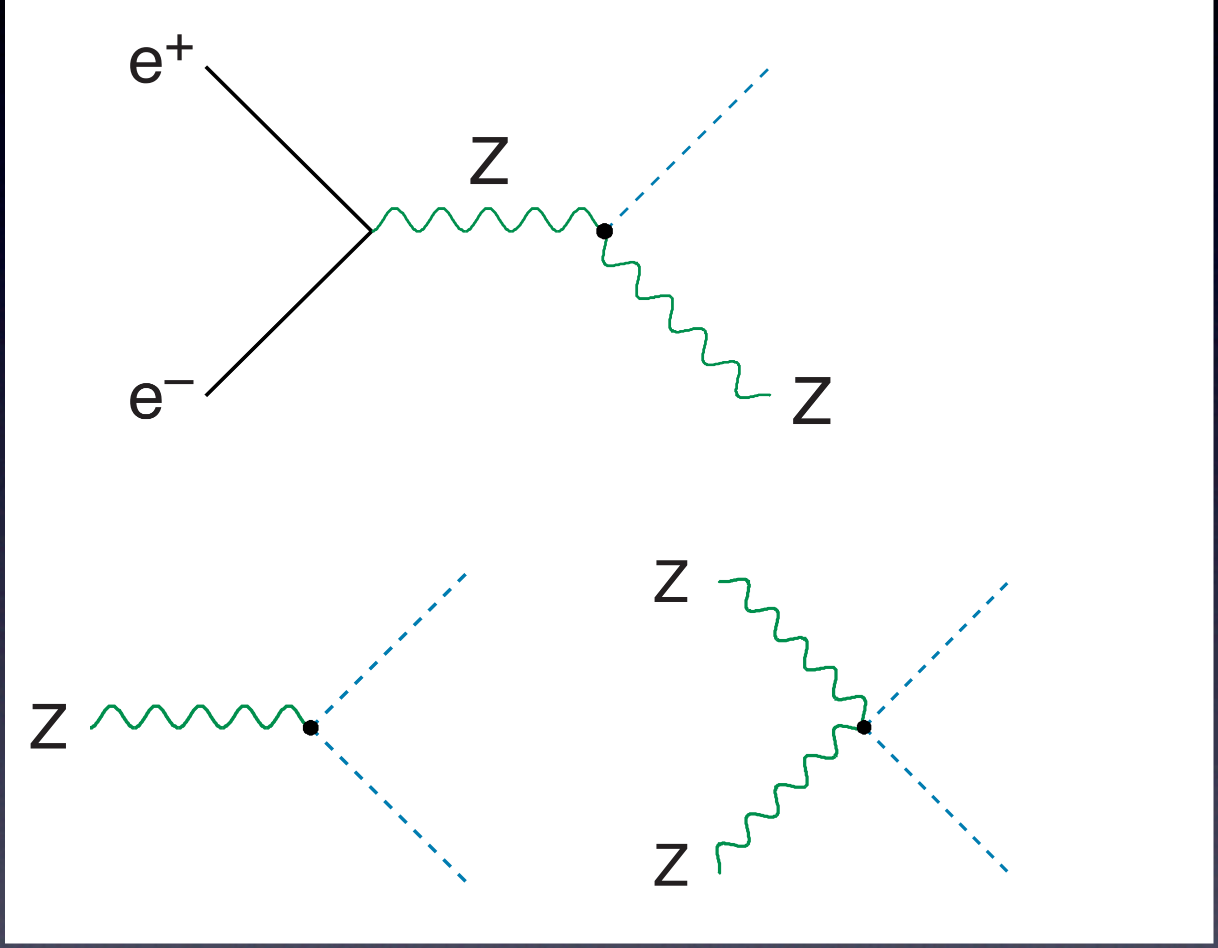
- ZH final state
- Prove the ZZH vertex



Prove it is condensed

- ZH final state
- Prove the ZZH vertex
- We know Z:gauge boson, H: scalar boson

⇒ *only two types of vertices*



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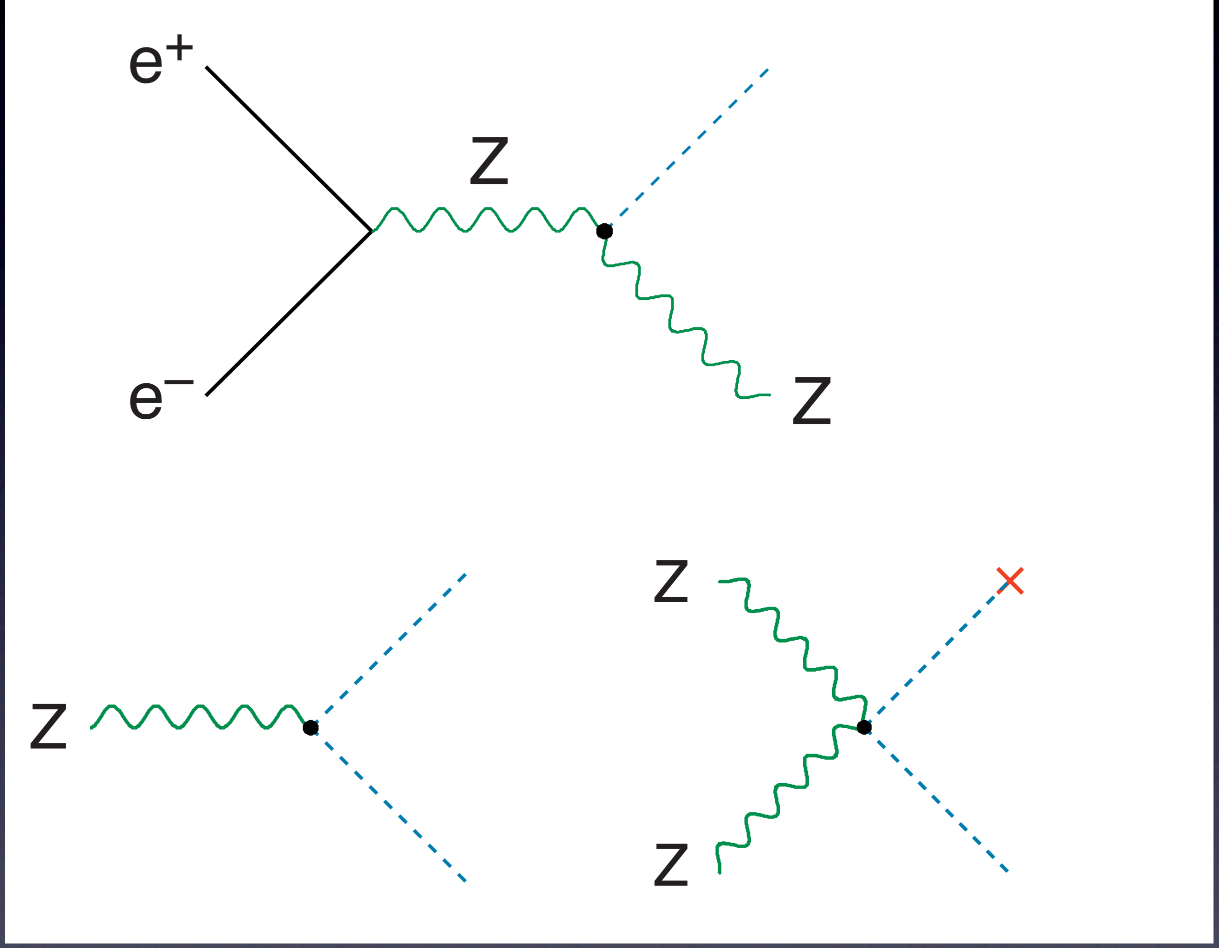
$\Rightarrow$ *only two types of vertices*

- Need a condensate to get ZZH vertex

$\Rightarrow$ *proves it is condensed in Universe*

HM, hep-ex/9606001



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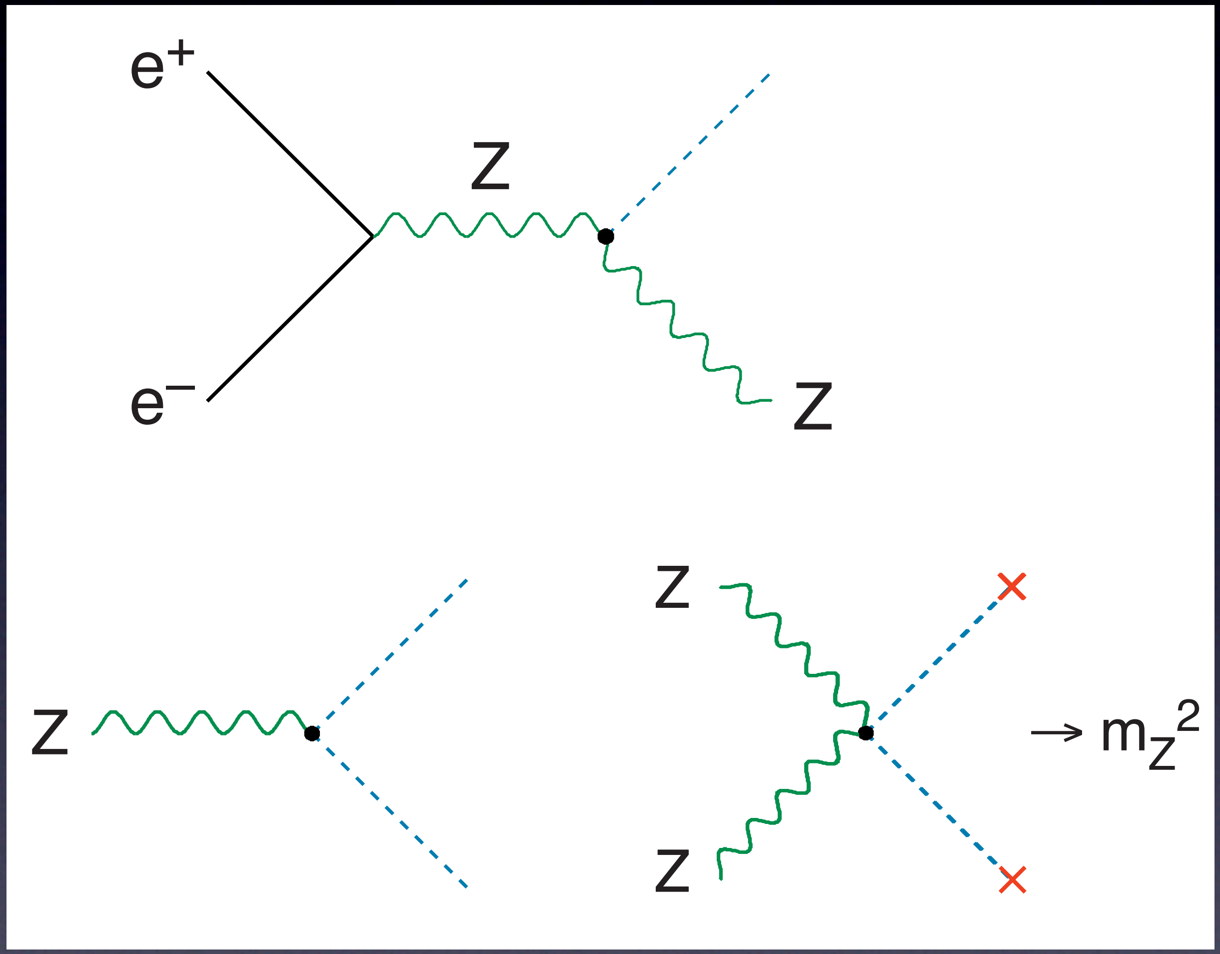


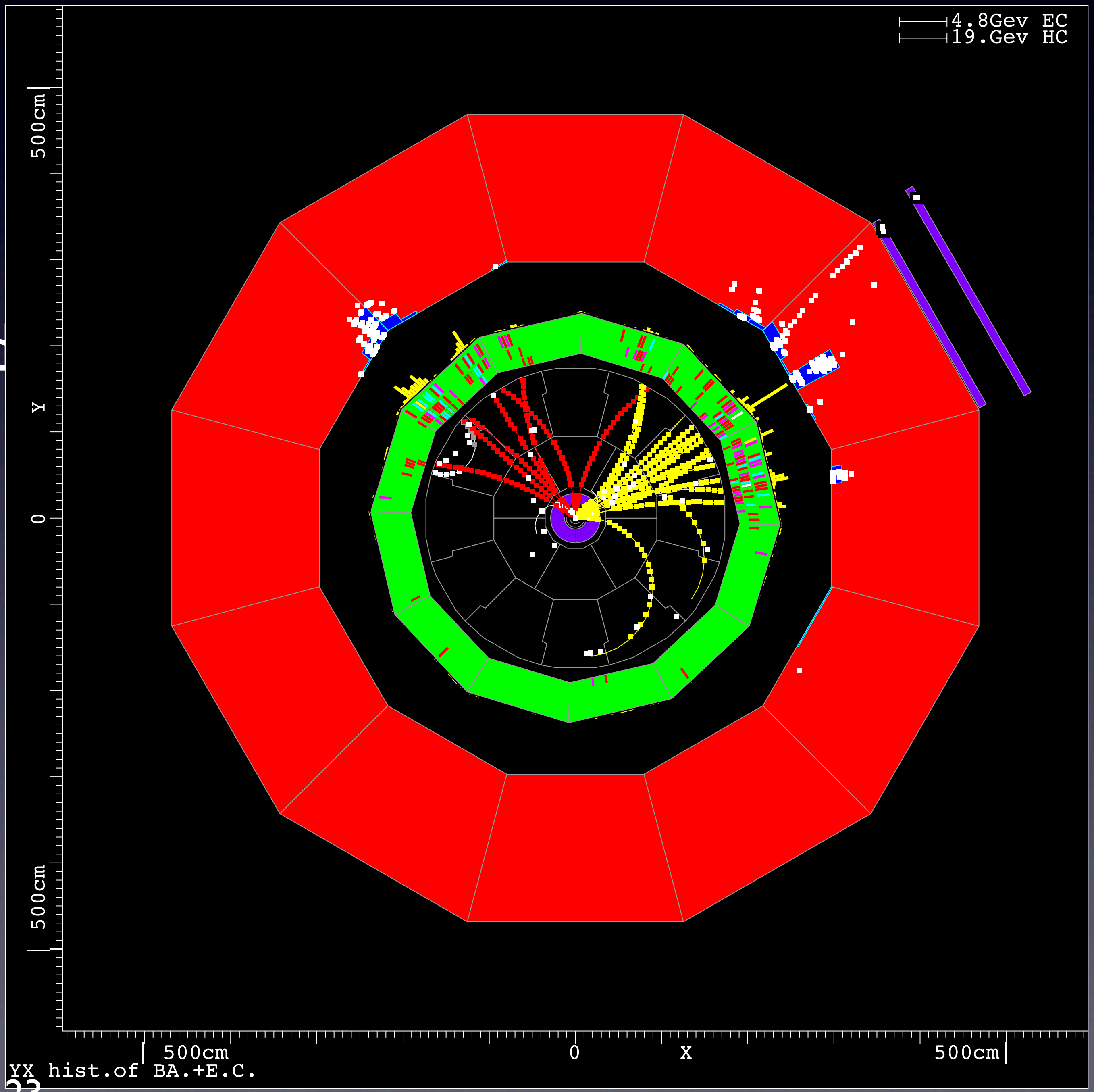
Producing Dark Matter in the laboratory

- Collision of high-energy particles mimic Big Bang
- We hope to create Dark Matter particles in the laboratory
- Look for events where energy and momenta are unbalanced

"missing energy" E_{miss}

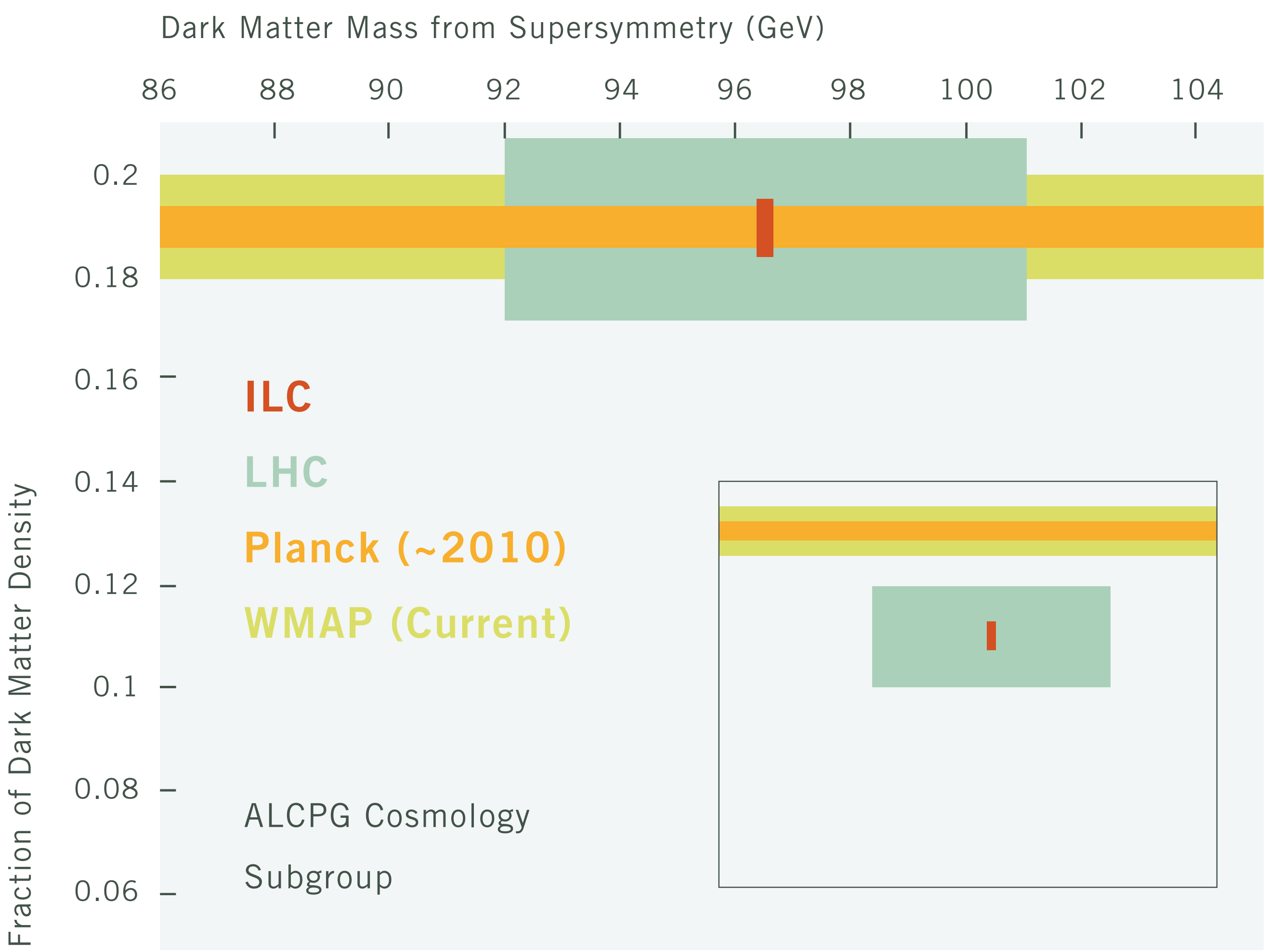
- Something is escaping the detector
- electrically neutral, weakly interacting

⇒Dark Matter!?

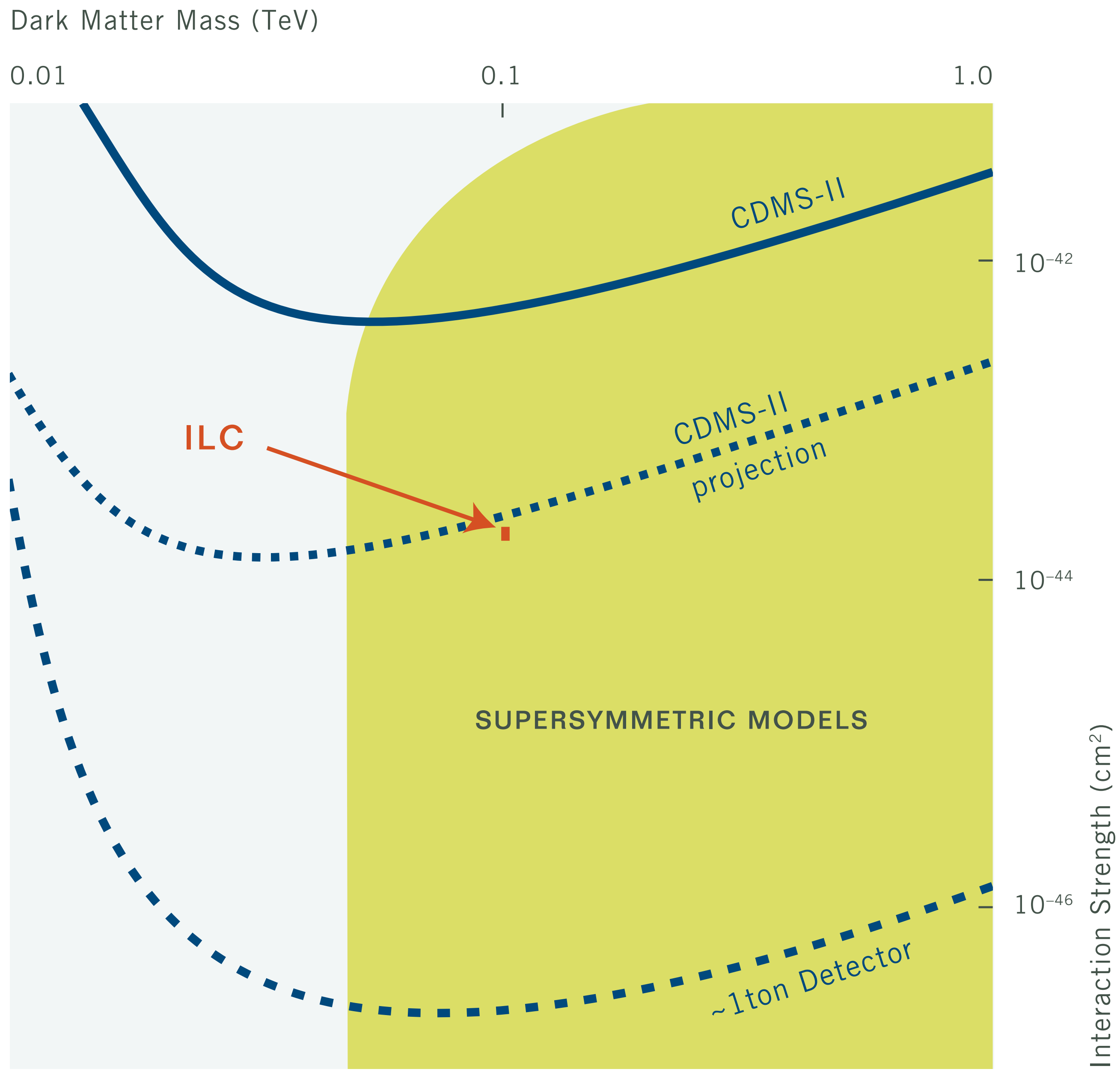


Dark Matter

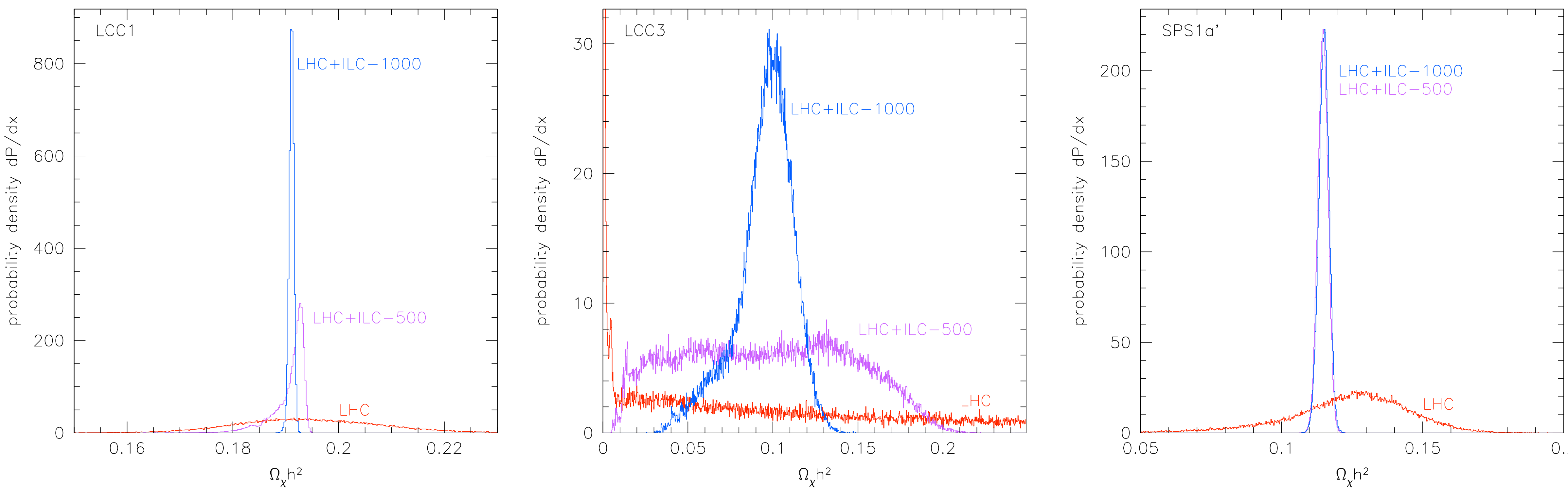
abundance

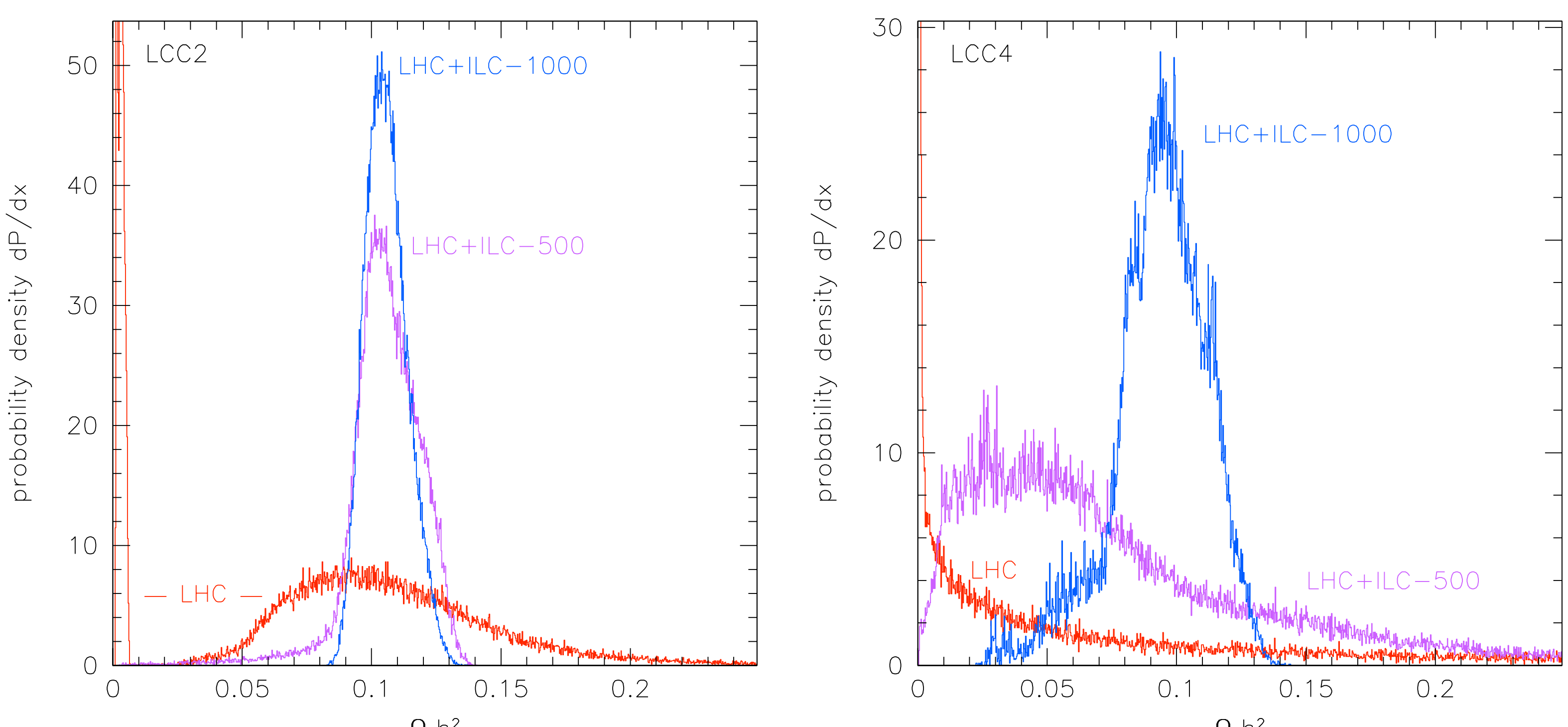


direct cross section

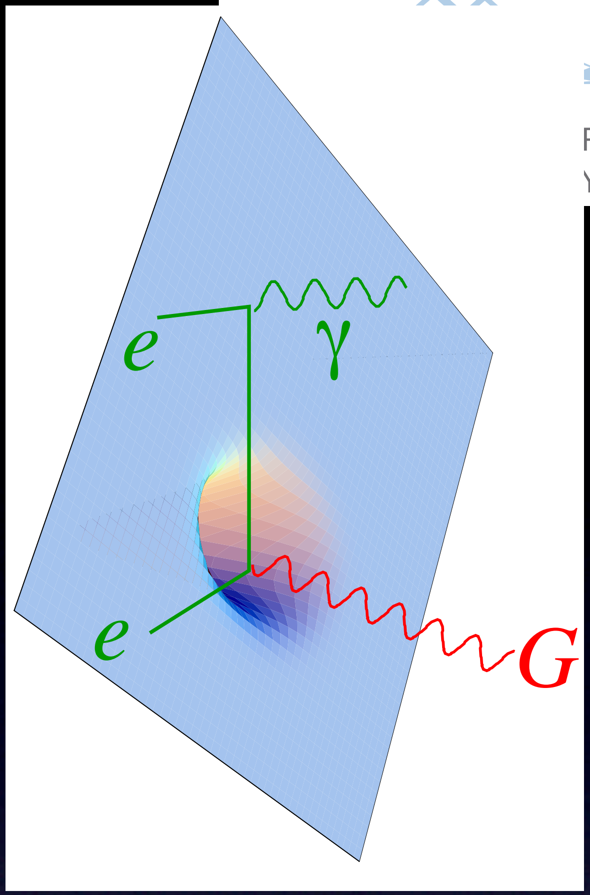


Omega from colliders



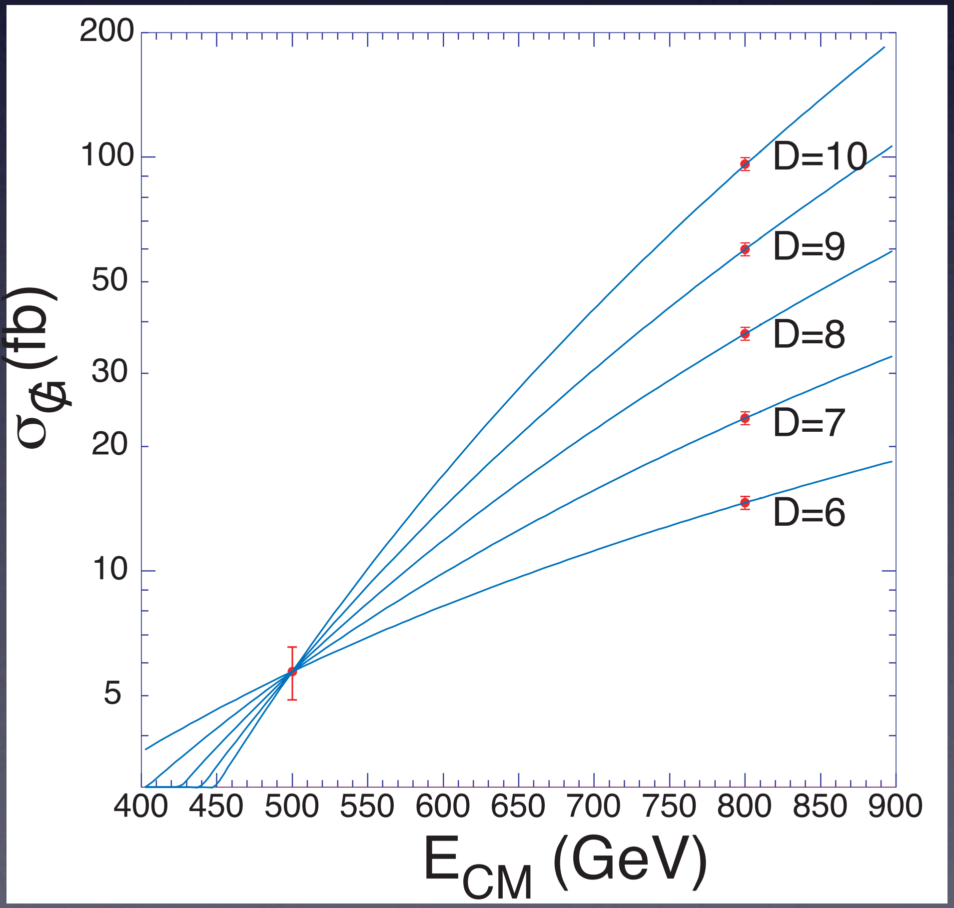


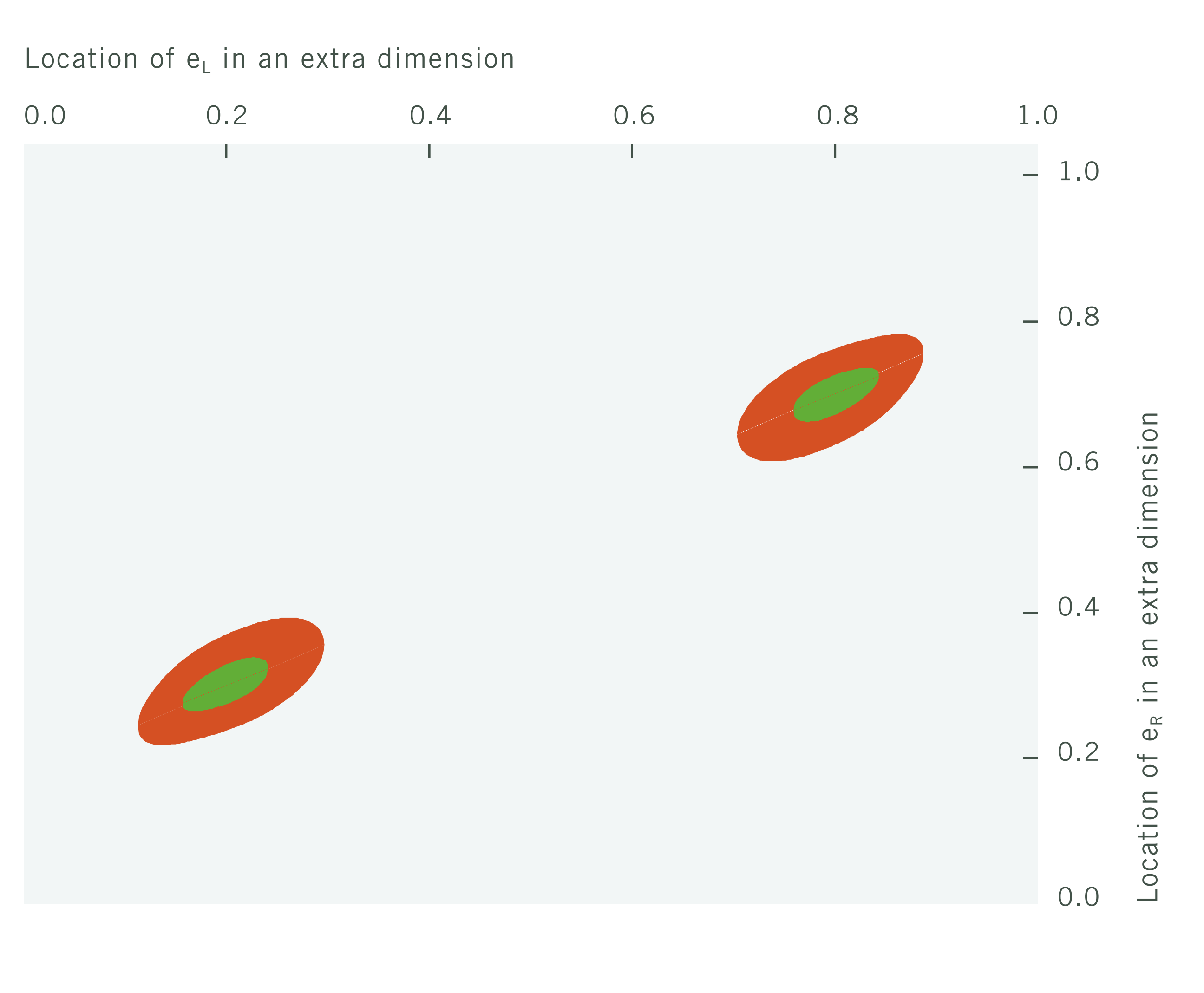
SUSY case study
Baltz, Battaglia, Peskin, Wizansky hep-ph/0602187



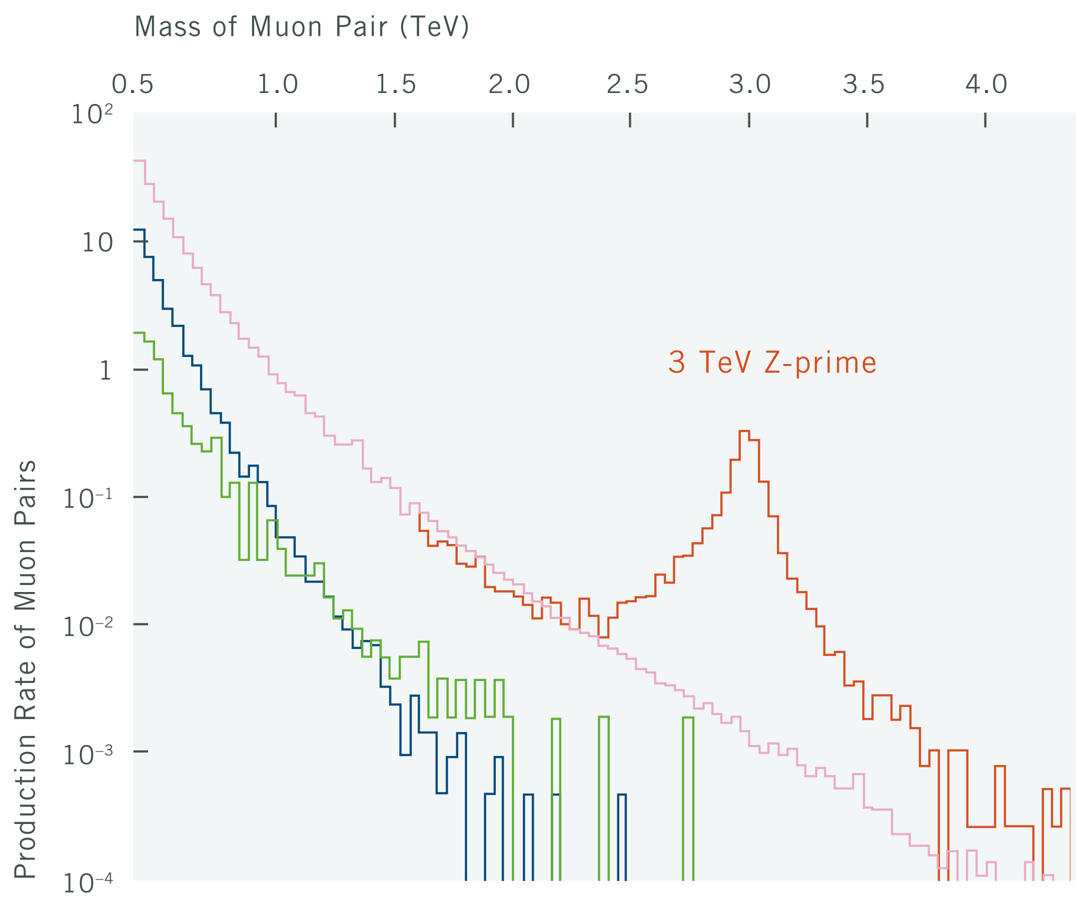
Extra D

- measure the number of dimensions
- location of the wave functions



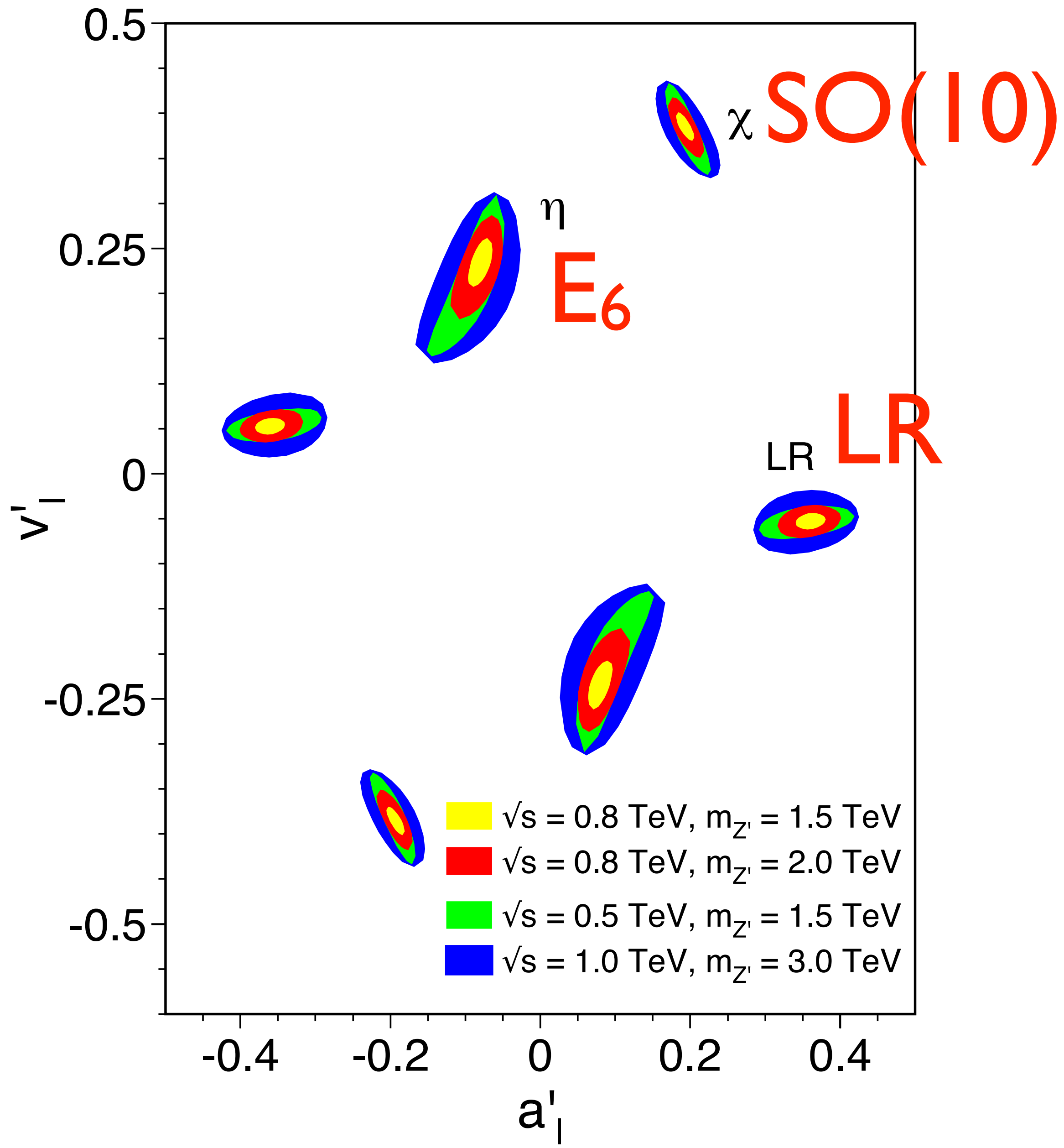


New force: Z′

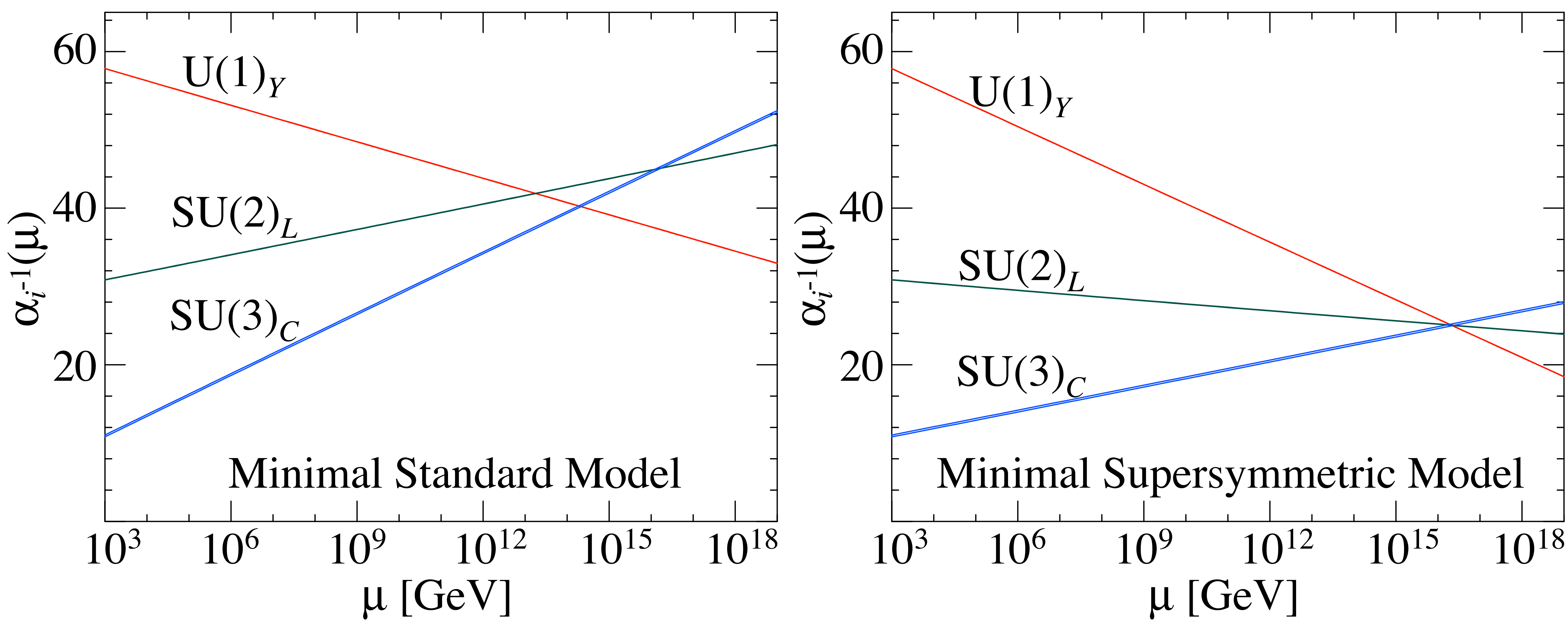


~1/2 event/bin/fb^{-1}

What kind of force?



cf. gauge coupling unification

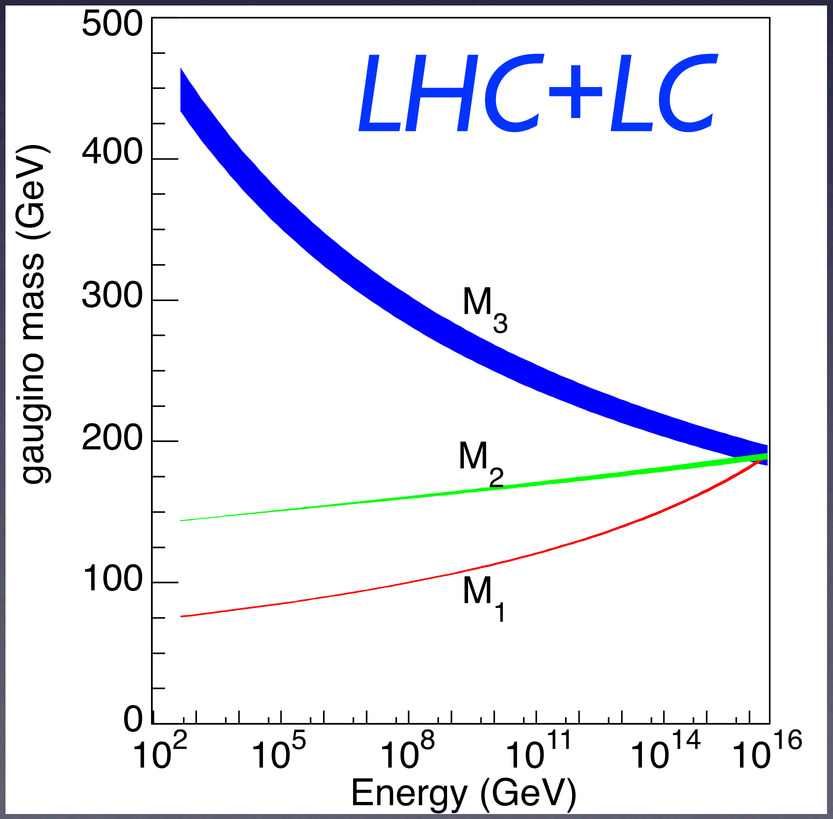


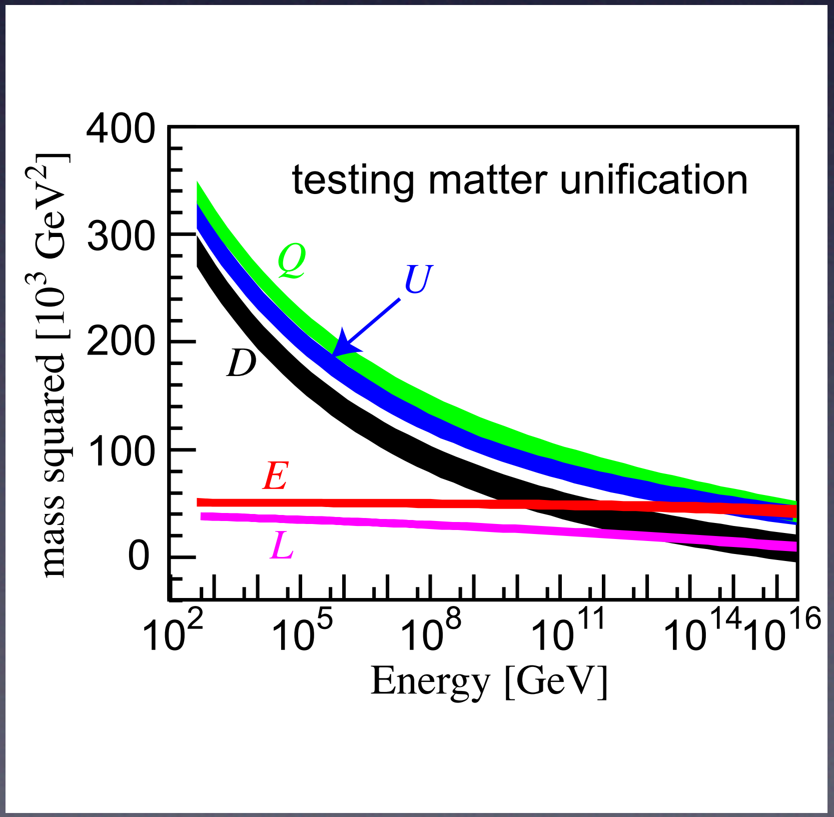
Gaugino and scalars

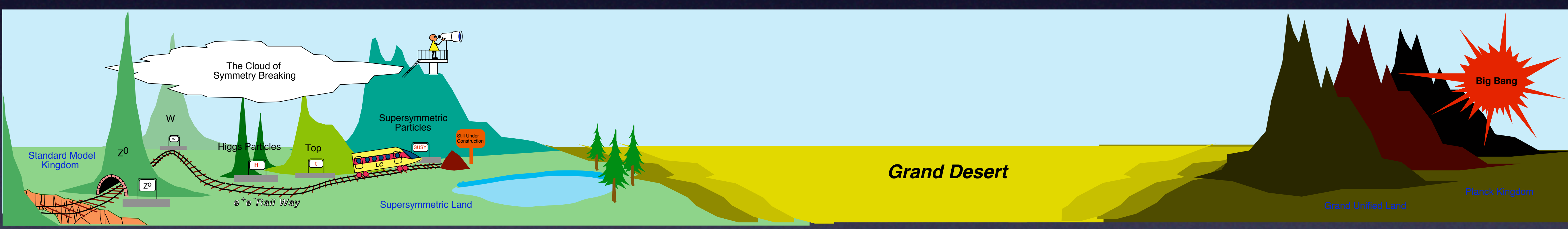
- Gaugino masses test unification itself independent of intermediate scales and extra complete SU(5) multiplets, also GMSB

- Scalar masses test beta functions at all scales, depend on the particle content

(Kawamura, HM, Yamaguchi)







Shoji Orito & Keisuke Fujii

Myths and Facts

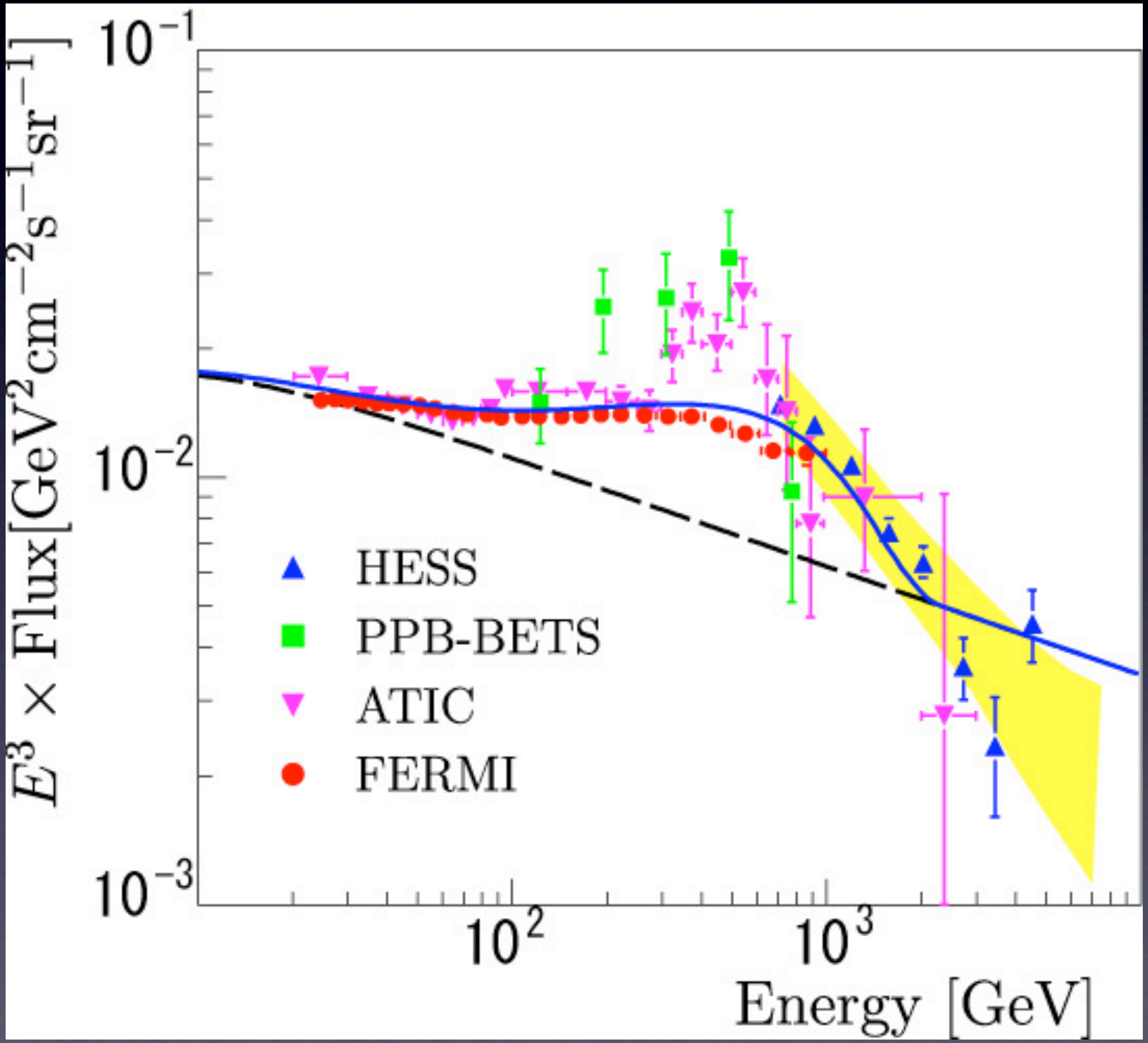
new physics is unlikely at LHC

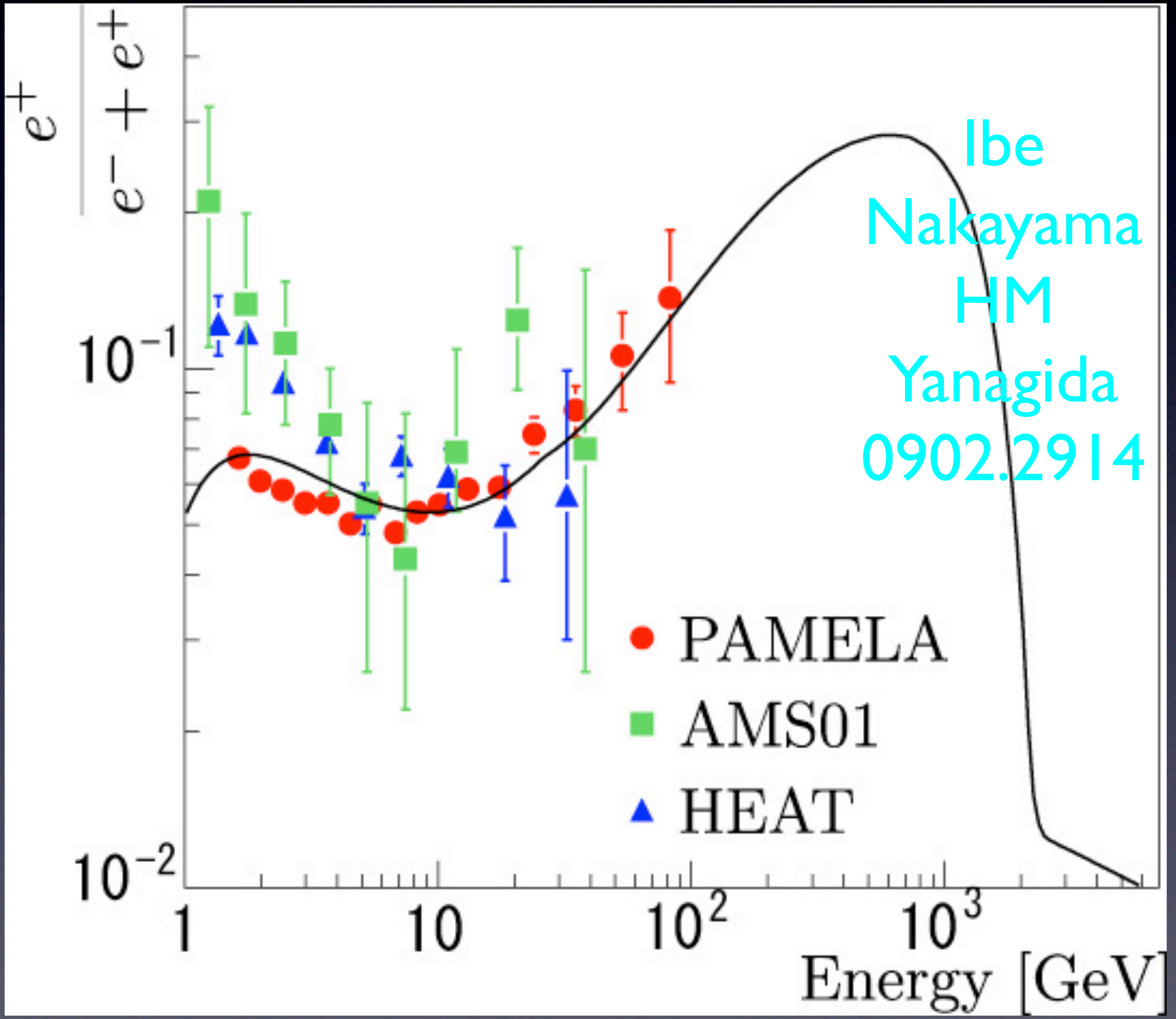
- Myth
- It is true that precision EW and flavor physics did not reveal new physics
- Very tight constraints on new physics below TeV (or even 100 TeV)
- Yet many exciting new physics candidates consistent with data
- e.g. SUSY with gauge mediation, little Higgs with T-parity, even some Higgsless

dark matter is out of reach for ILC

- Myth
- If you believe PAMELA & FERMI data to be dark matter signal, dark matter mass is 3–5 TeV
- they could well be due to nearby pulsars
- We really don't know

Nambu-Goldstone Dark Matter

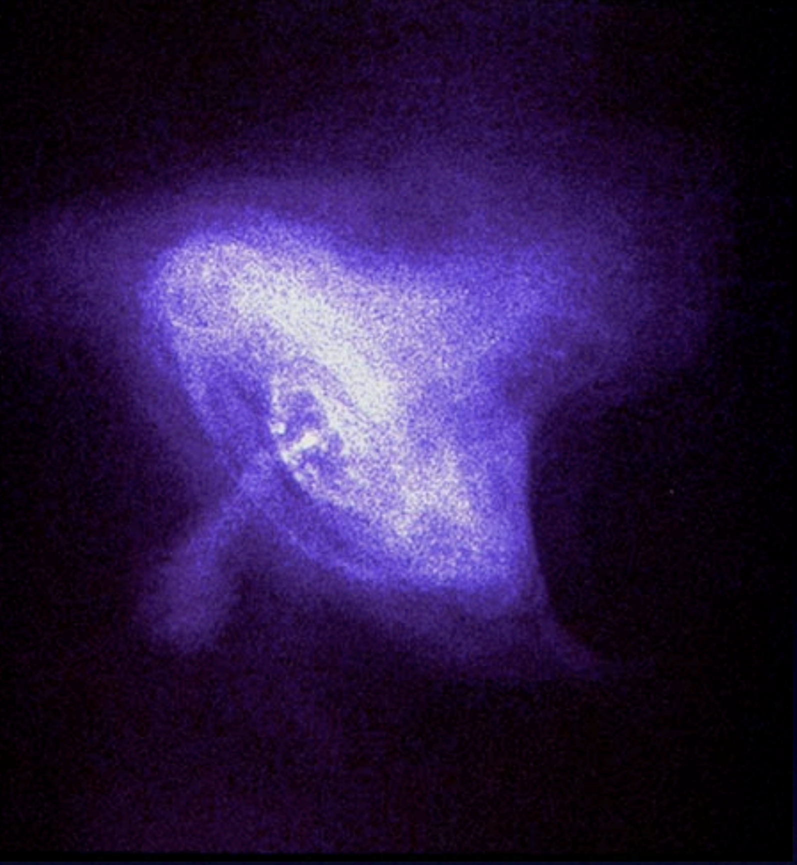




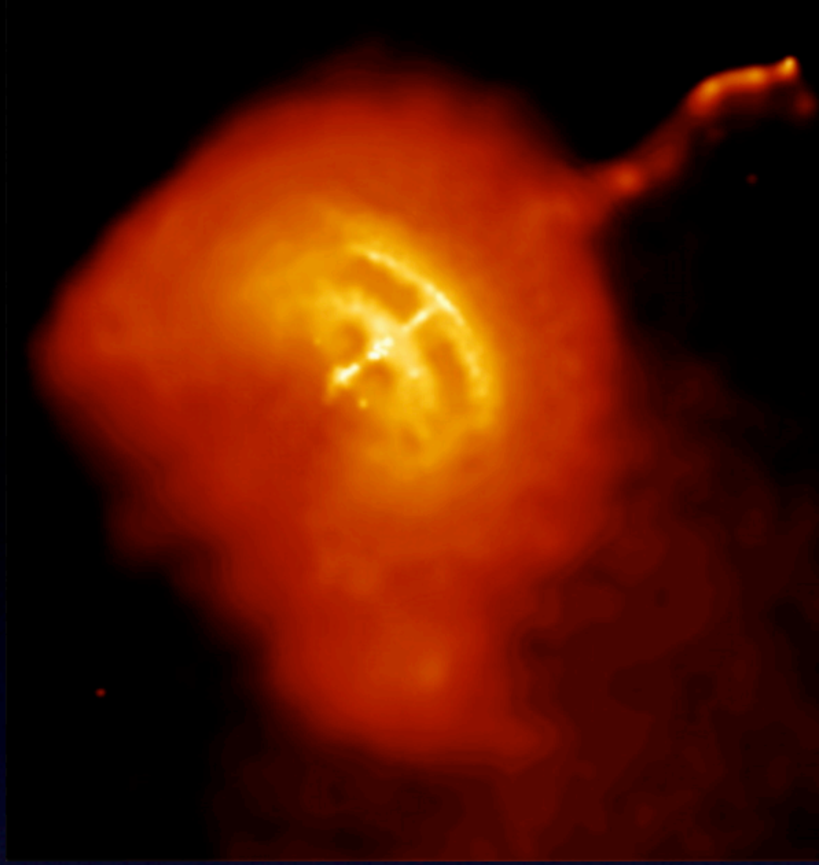
Ibe
Nakayama
HM
Yanagida
0902.2914

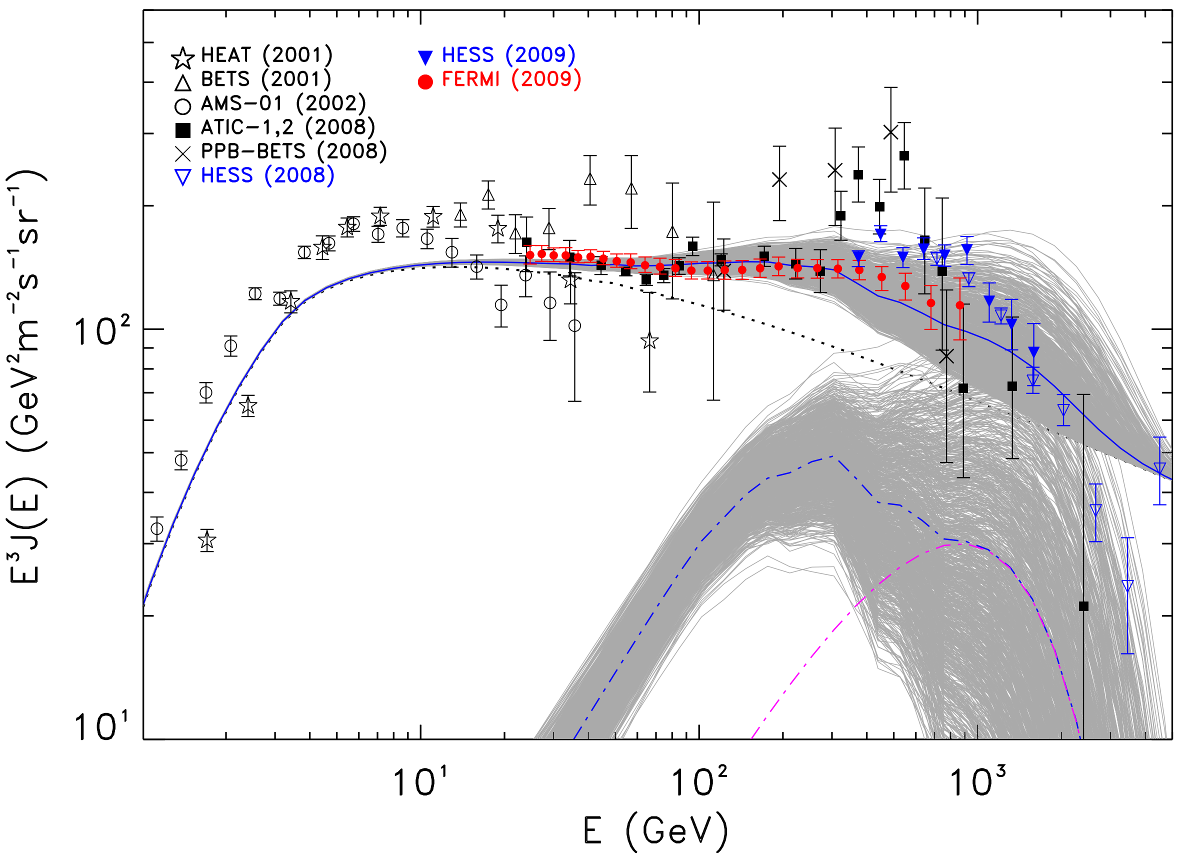
5TeV $\tau = 1.3 \times 10^{26}$ sec

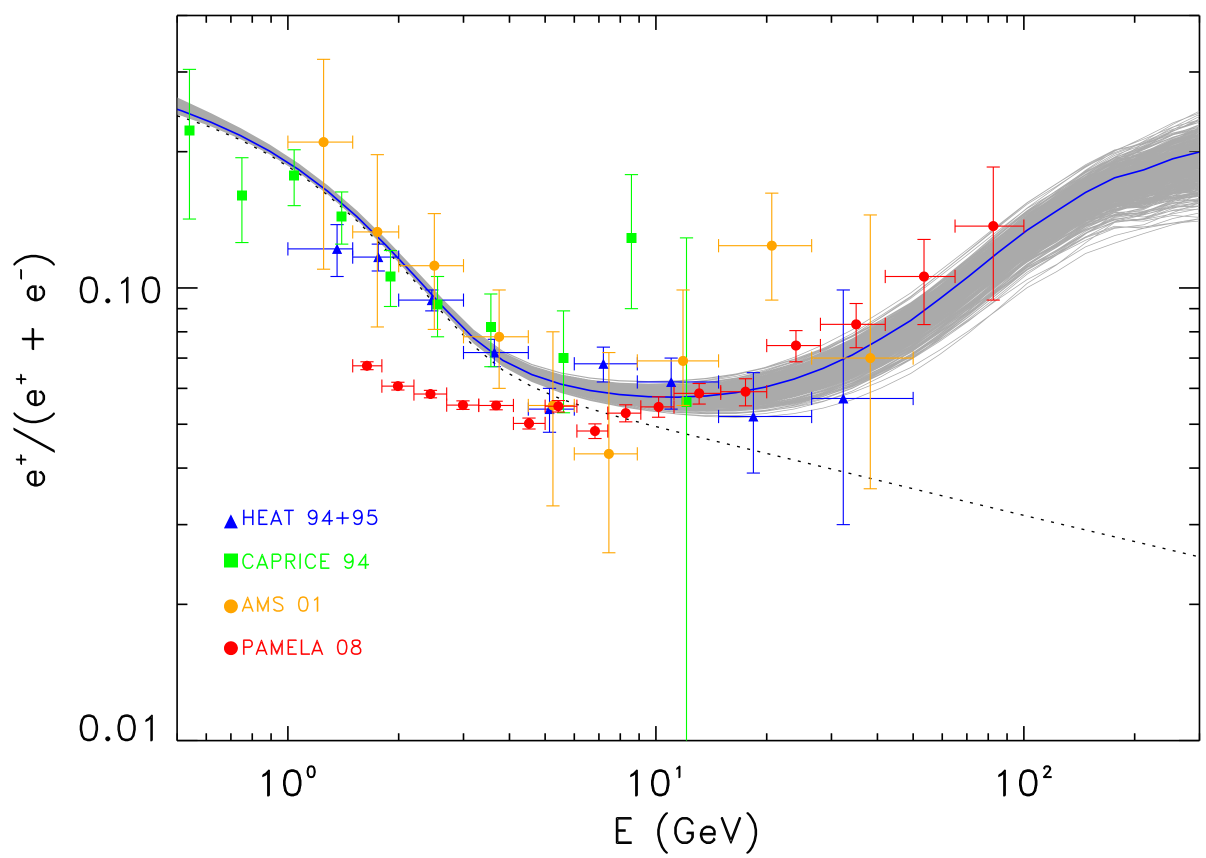
Ibe, HM, Shirai, Yanagida, JHEP 0911, 120 (2009)



pulsars




HEAT (2001)
BETS (2001)
AMS−01 (2002)
ATIC−1,2 (2008)
PPB−BETS (2008)
HESS (2008)
HESS (2009)
FERMI (2009)
E³J(E) (GeV²m⁻²s⁻¹sr⁻¹)
E (GeV)


HEAT 94+95
CAPRICE 94
AMS 01
PAMELA 08
e⁺/(e⁺ + e⁻)
E (GeV)

ILC is pushed farther into the future

- Fact
- At this point, I can't imagine politicians approving ILC without seeing LHC data
- With LHC slipping, ILC slips together

HEP community is not behind ILC anymore

- Myth
- This is largely a sociological issue coupled with political reality
- We see a core community right here
- Once people see prospect, they start jumping on it

There are many other options than ILC

- Fact & Myth
  - Numerous great ideas, R&D
  - muon collider ⇒ MICE
  - plasma ⇒ Bella & FACET
  - LHC energy upgrade ⇒ magnet R&D
  - Keep our mind open!
- HM understands that they won't be mature enough to be proposed as a TeV-scale collider right after promising LHC data

hierarchy problem is overblown

- neither fact nor myth
- some argue that EW scale ≪ M_{Pl} because Universe doesn't support life otherwise
- *there is nothing beyond SM Higgs@LHC*
- We simply don't know
- will see at LHC
- no point arguing about it now

ILC cost is growing out of control

- Myth
- US accounting requires *escalation* in cost estimates
- assume a slip by N years, multiply by assumed inflation $\sim(1 + 4\%)^N$
    - $N=10$ $\sim(1 + 4\%)^N \sim 1.5$
    - $N=20$ $\sim(1 + 4\%)^N \sim 2.2$

ILC is dead

Absolutely not!

Conclusion

- We expect rich physics at "TeV" because of dark matter and cosmic superconductor, but not rigorously proven
- e^+e^- LC great *as long as* the new particles are there within reach, allowing us to reconstruct theory based on data
- May even see physics well above TeV, connect to dark matter, cosmology
- *What energy is enough?*
- LHC will tell us. Look forward!
- We need to be ready once new physics