LHC/ILC

Hitoshi Murayama (Berkeley)

SLAC SSI, 7/27/2006

Technicolor

Lykken: *"It doesn't look good but is not going away"*

LHC/ILC

Hitoshi Murayama (Berkeley)

SLAC SSI, 7/27/2006

Outline

- e^+e^- Linear Collider
- Reconstruction of the Lagrangian
  - mass, spin, quantum numbers, mixing, couplings
  - use supersymmetry as an example
- Physics Significance

e^+e^- Linear Collider

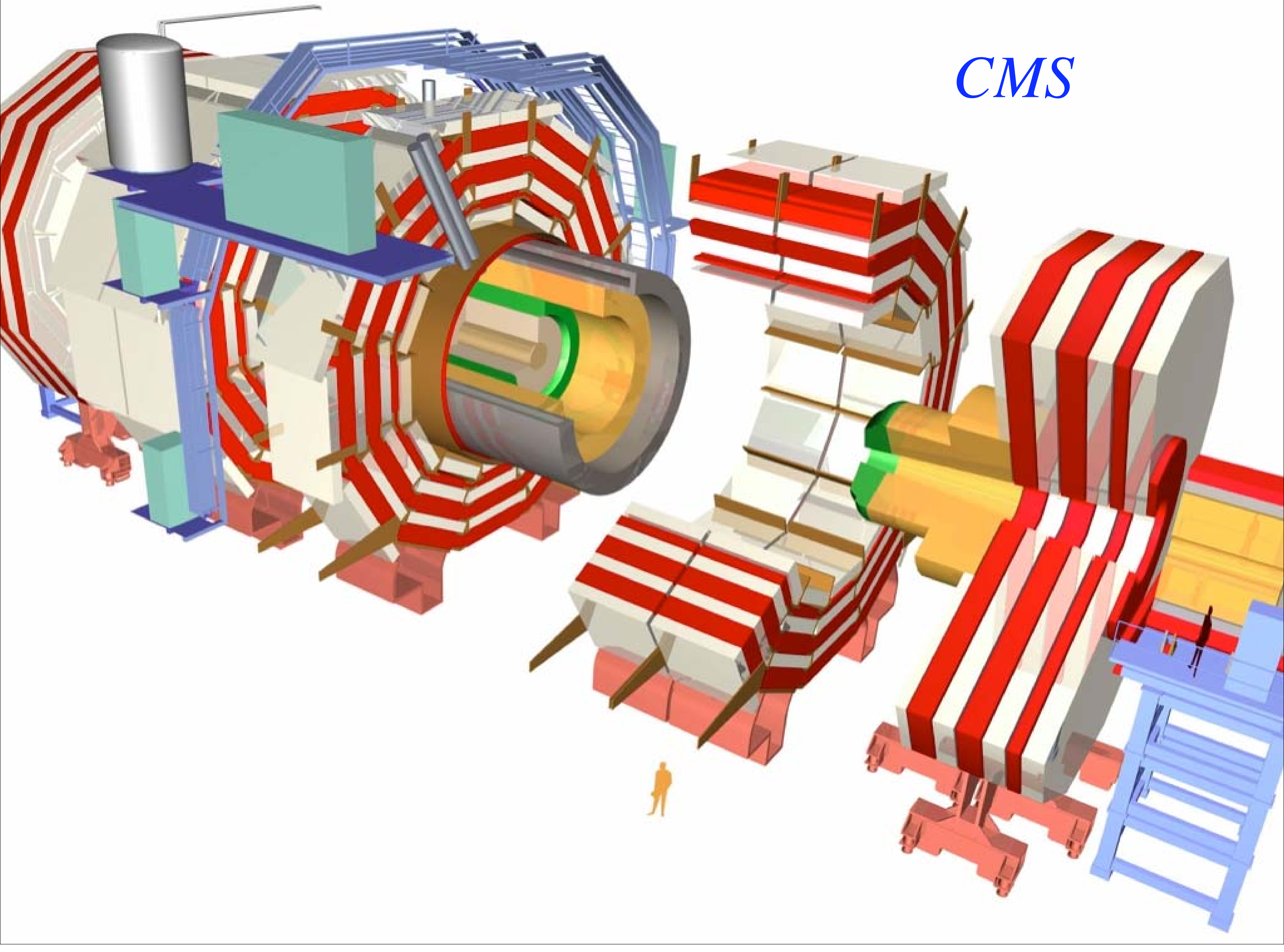
Large Hadron Collider (LHC)

- proton-proton collider
- 14TeV energy

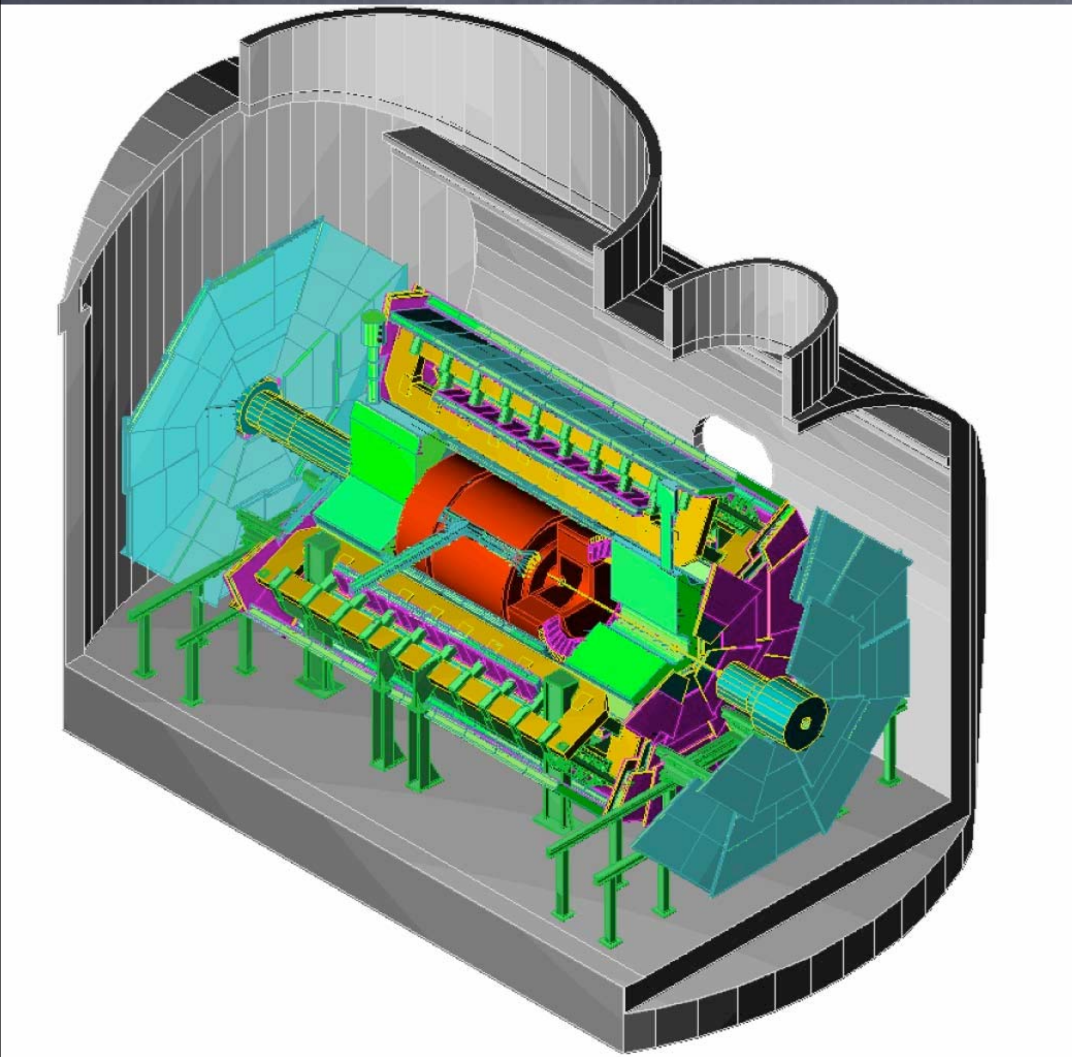
(cf. 2TeV @ Fermilab)

- Under construction at CERN, Geneva
- Turn on in 2007
- Finally reaching the energy Fermi told us about in 1933!

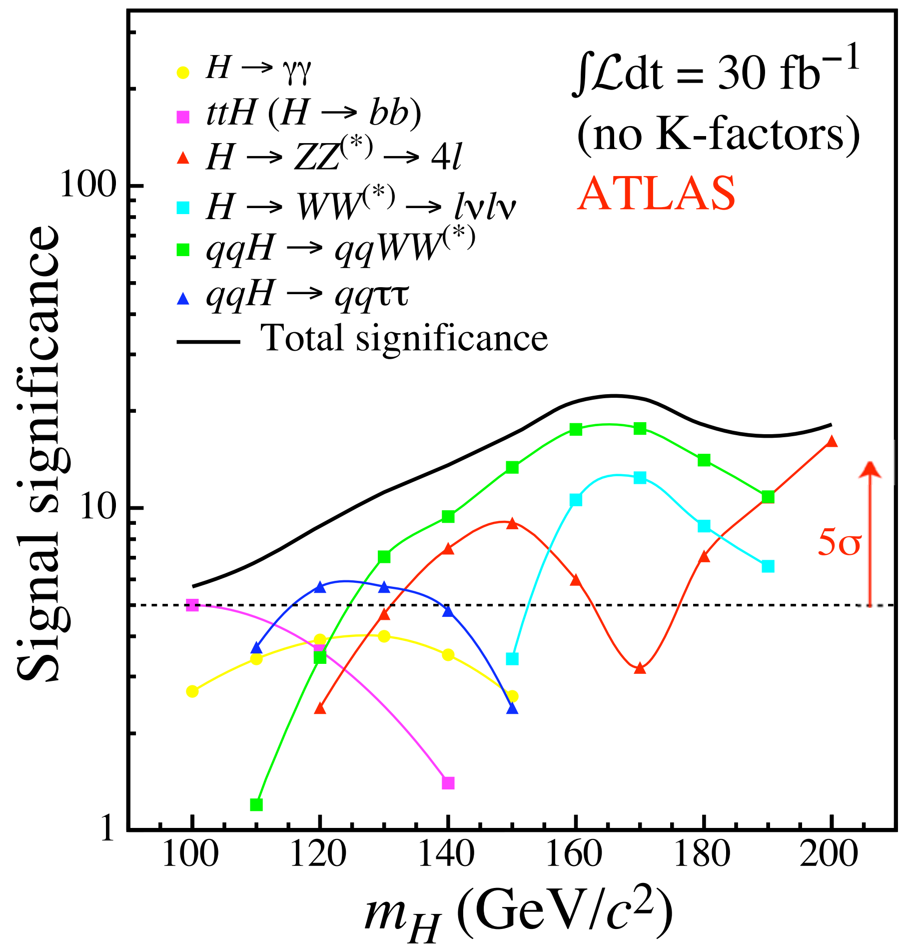
CMS



Higgs at ATLAS

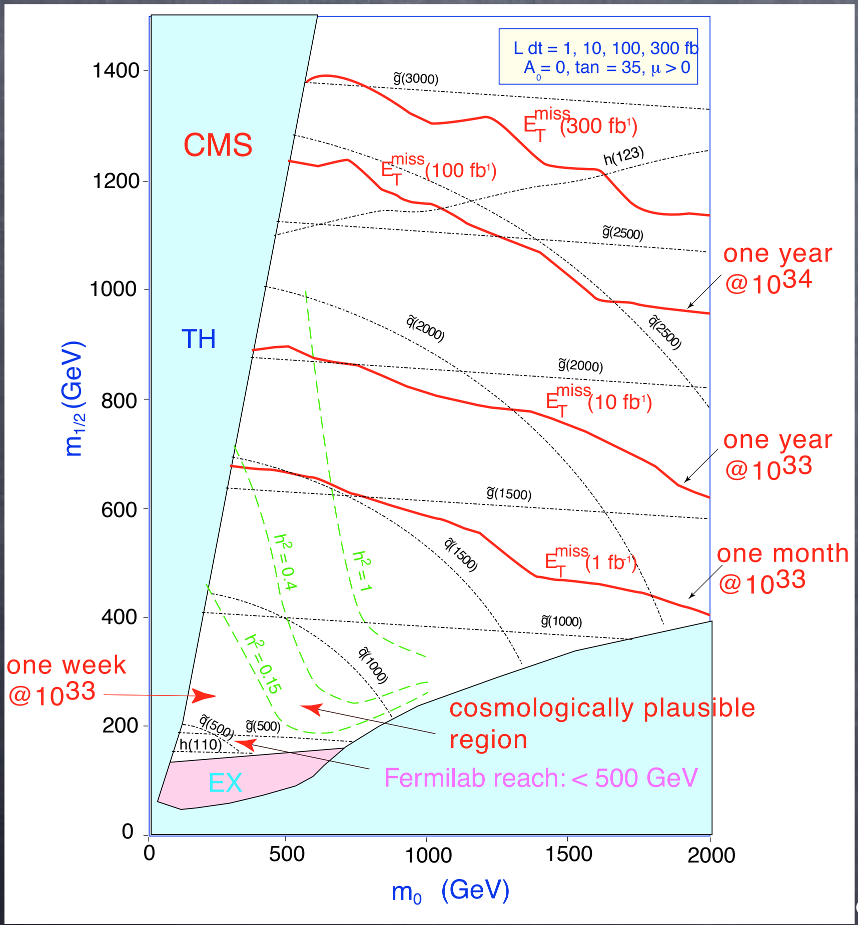


Robust discovery

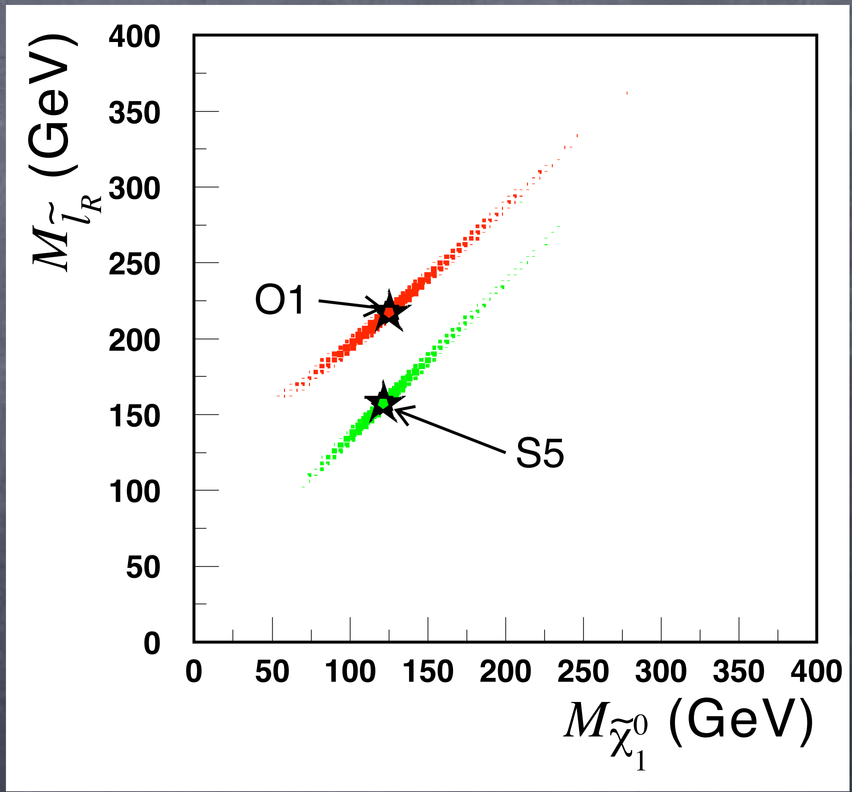


Supersymmetry

Tevatron/LHC will discover

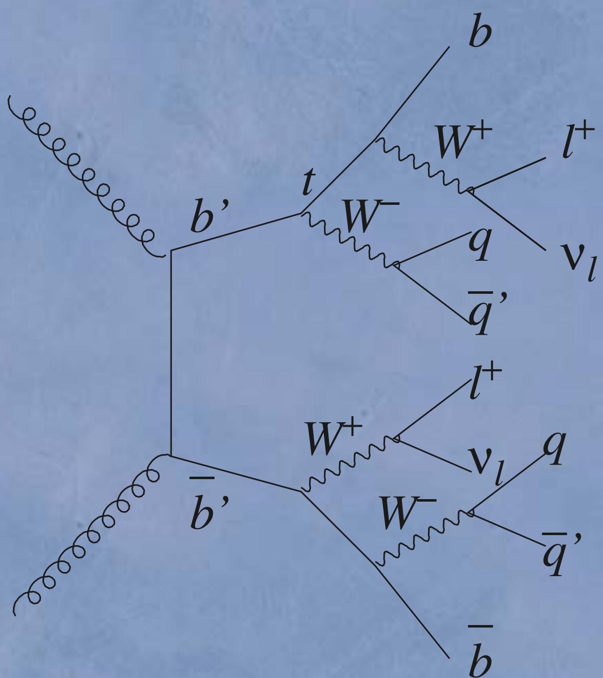


Can do many precision measurements at LHC

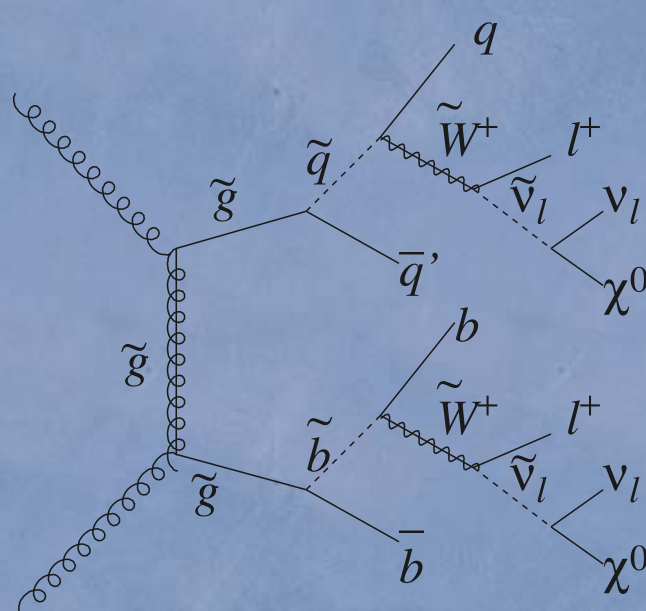


New physics looks alike

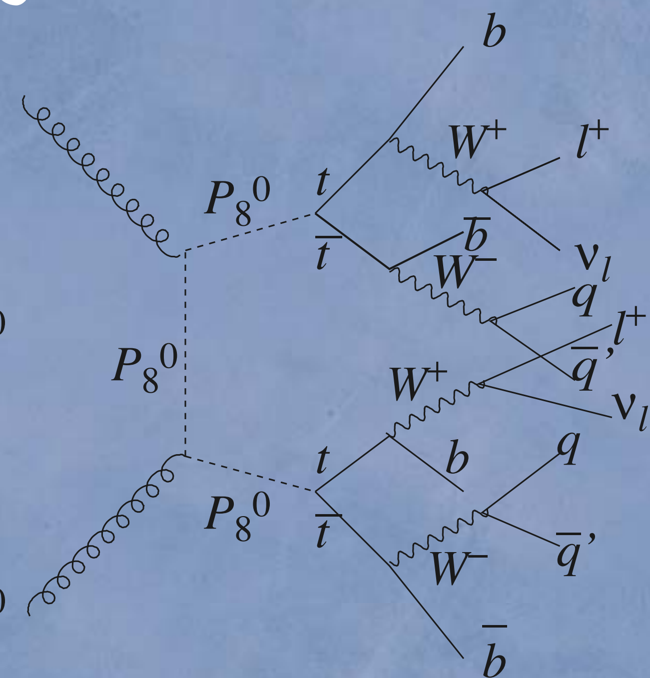
missing ET, multiple jets, b-jets, (like-sign) leptons



4th generation



SUSY



technicolor

+Universal extra dimension, little Higgs with T-parity

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

Task

Why do we live in a cosmic superconductor?

- We can eliminate many possibilities at LHC
- But new interpretations necessarily emerge
- Race will be on:

  theorists coming up with new interpretations

  experimentalists excluding new interpretations

  ⇒ A loooong process of elimination
- Crucial information is in details

  ⇒ Reconstruct the theory from measurements

The New York Times

July 23, 2008

The Other Half of the World Discovered

Geneva, Switzerland

As an example, supersymmetry

"New-York Times level" confidence

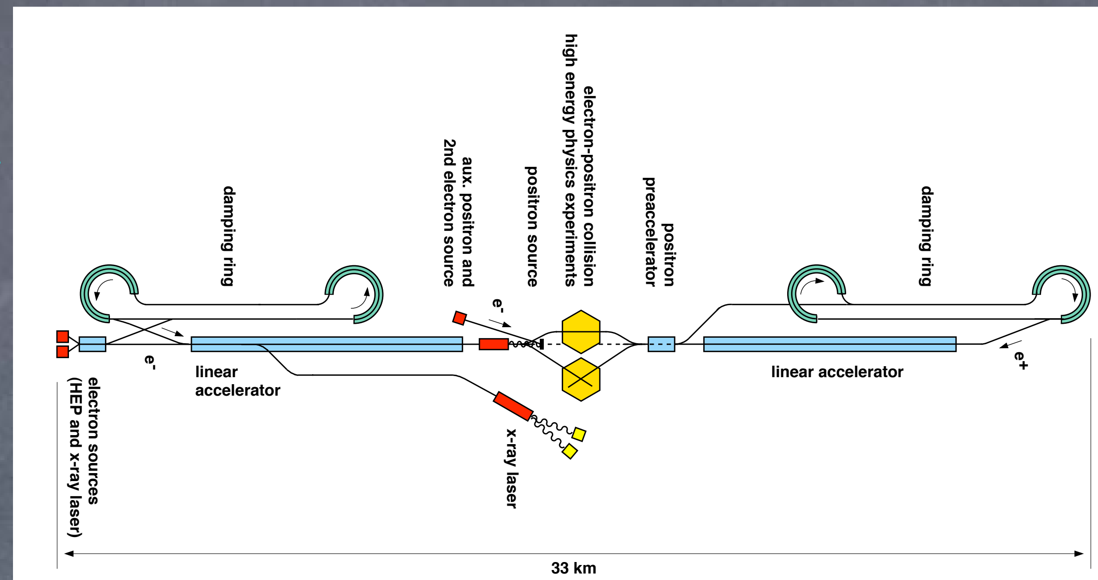
still a long way to

"Halliday-Resnick" 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."

Linear Collider

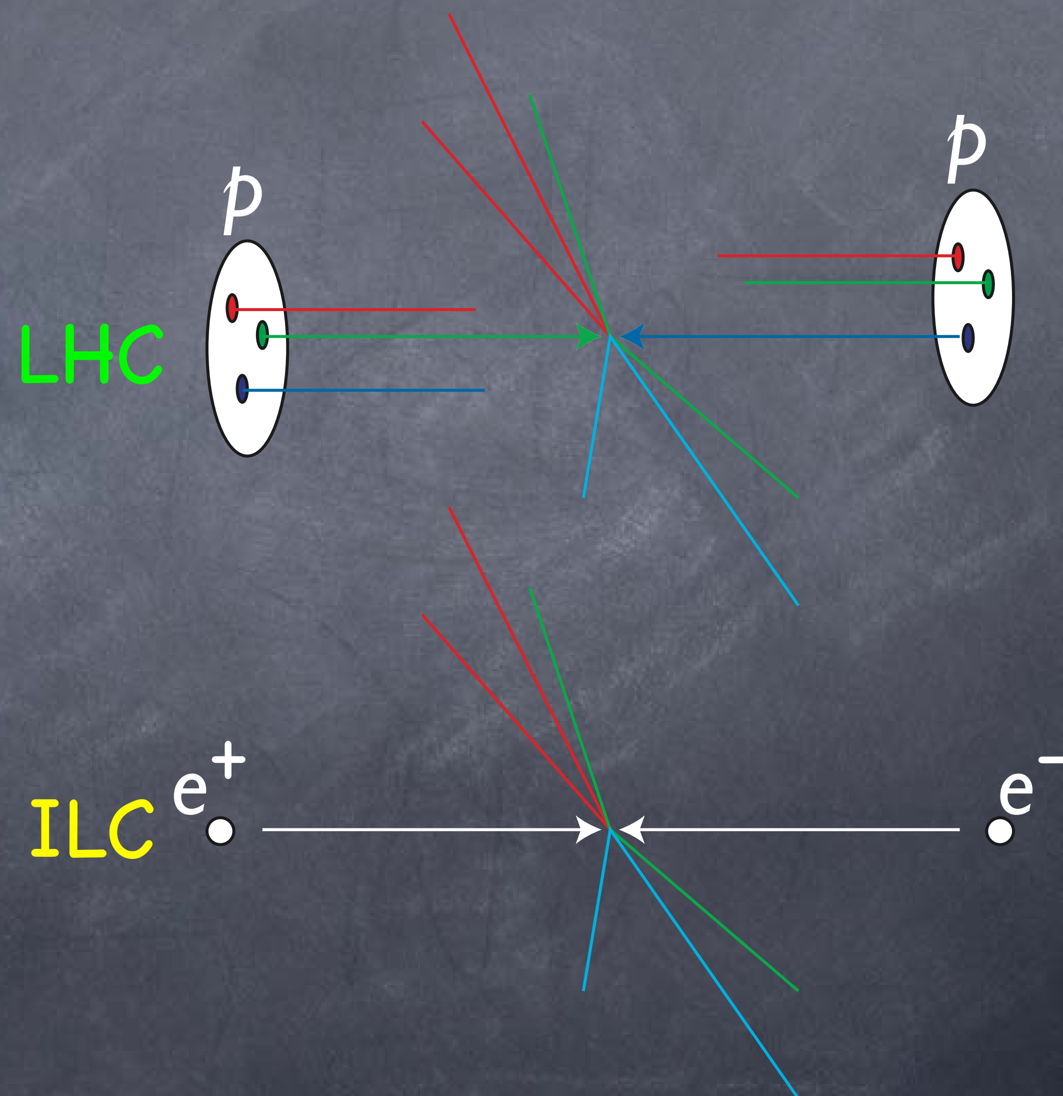
- Electron-positron collider
- e^-, e^+ point-like with no structure
- Well-understood environment
- Linear instead of ring to avoid synchrotron loss
- Super-high-tech machine
- Accelerate the beam over >15km
- Focus beam down to a few nanometers and make them collide



International Linear Collider (ILC)

ILC

- elementary particles
- well-defined energy, angular momentum
- uses its full energy
- can produce particles democratically
- can capture nearly full information

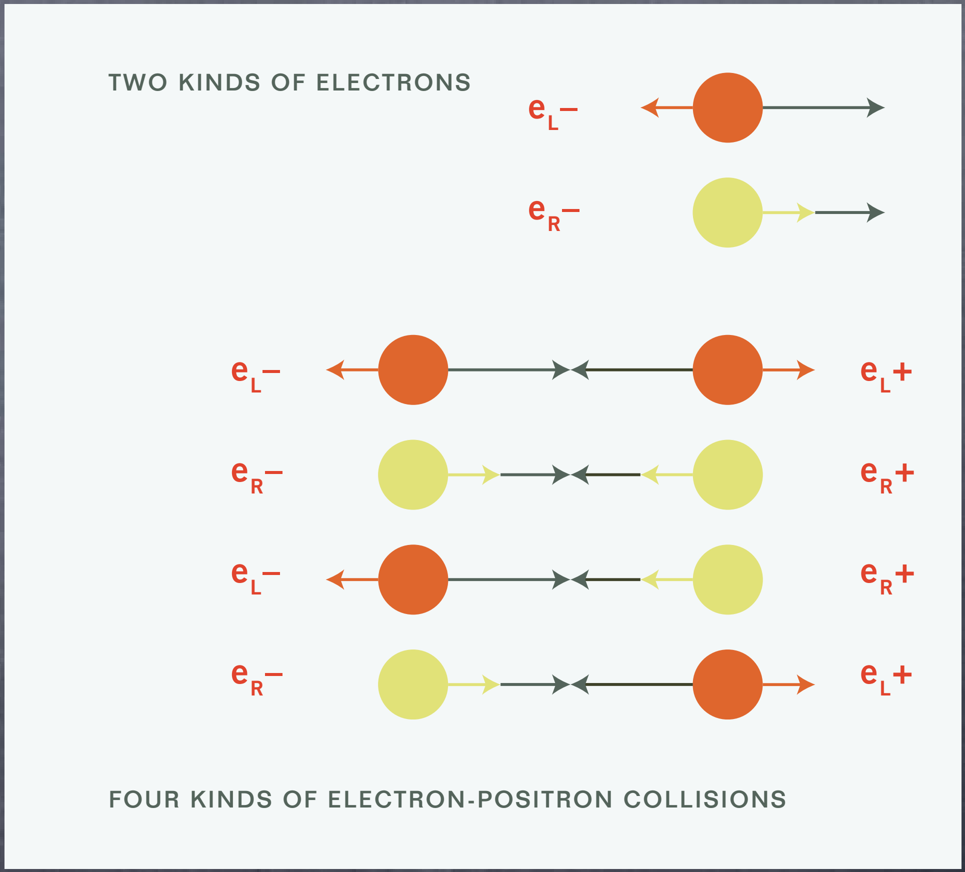


LHC vs ILC
(oversimplified)

total energy	14TeV	0.5-1 TeV
usable energy	a fraction	full
beam	proton (composite)	electron (point-like)
signal rate	high	low
noise rate	very high	low
analysis	specific modes	nearly all modes
events	lose info along the beams	capture the whole
status	NEARLY READY!	needs to finish design

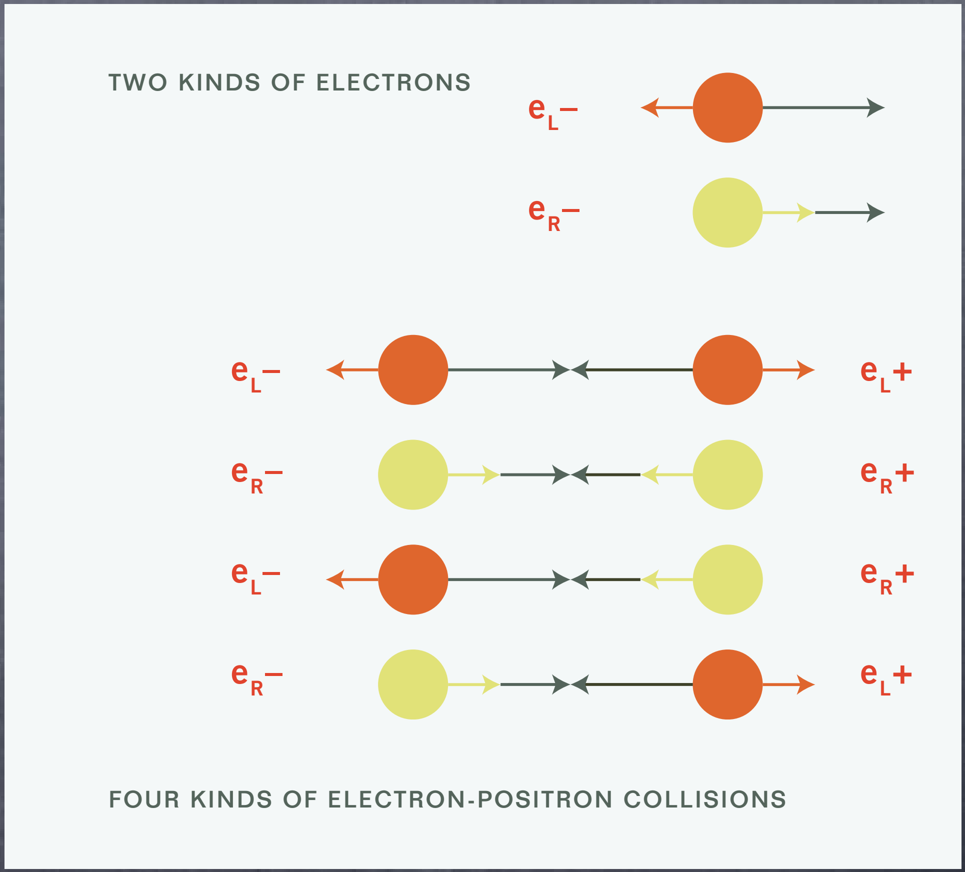
Polarized beams

- serves as two different machines
- $e^+ e_R^-$
- $e^+ e_L^-$



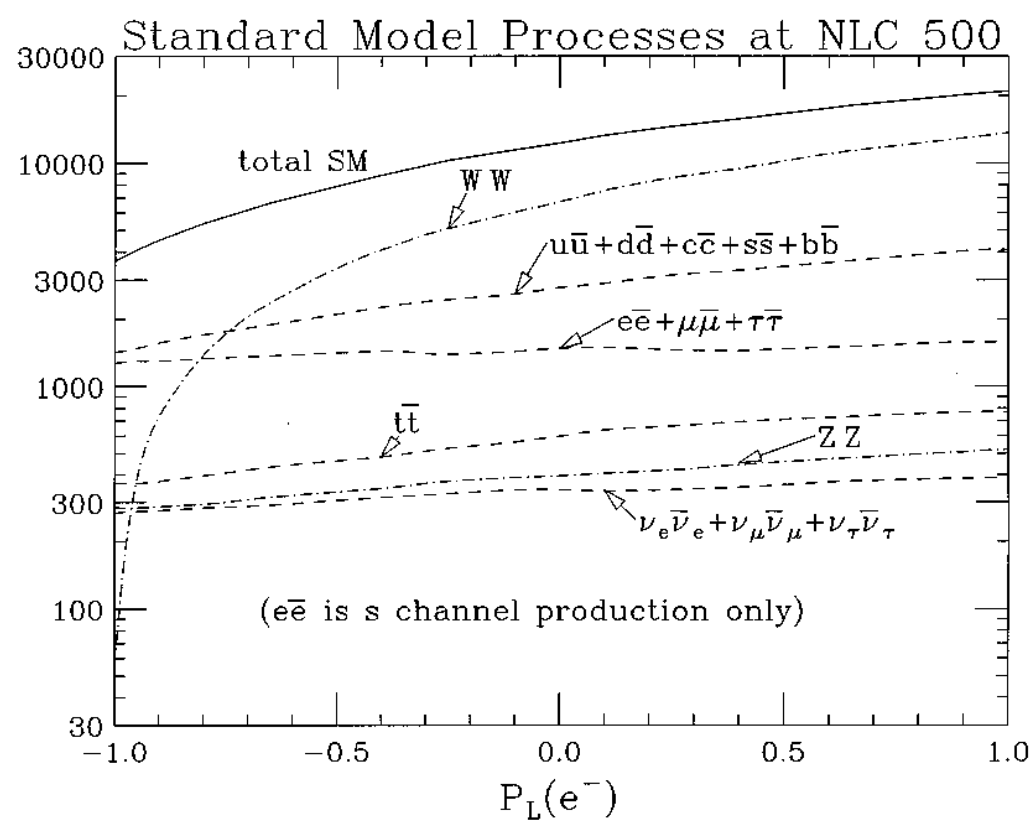
Polarized beams

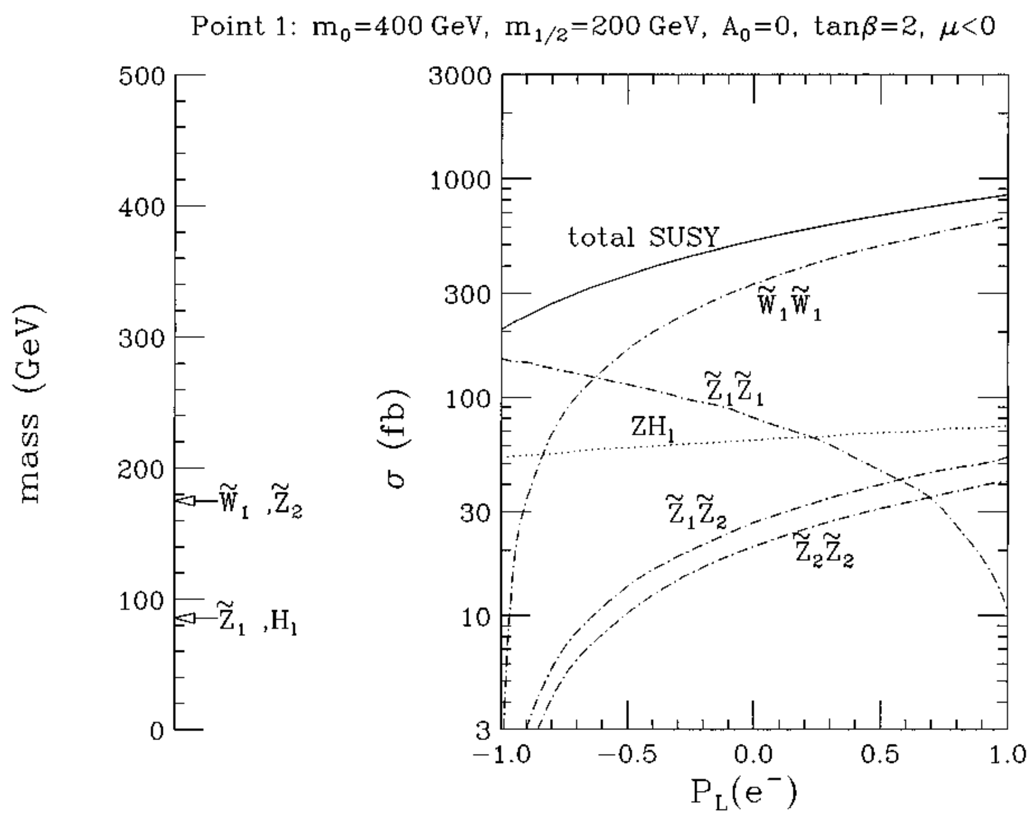
- serves as two (nine?) different machines
- $e_L^+ \ e_R^-$
- $e_R^+ \ e_L^-$
- $e_L^+ \ e_L^-$
- $e_R^+ \ e_R^-$
- $e^- \ \gamma$
- $\gamma \ \gamma$
- $e_L^- \ e_R^-$
- $e_L^- \ e_L^-$
- $e_R^- \ e_R^-$



Polarized beams

- e_L and e_R are really different particles at $E >> m_Z$





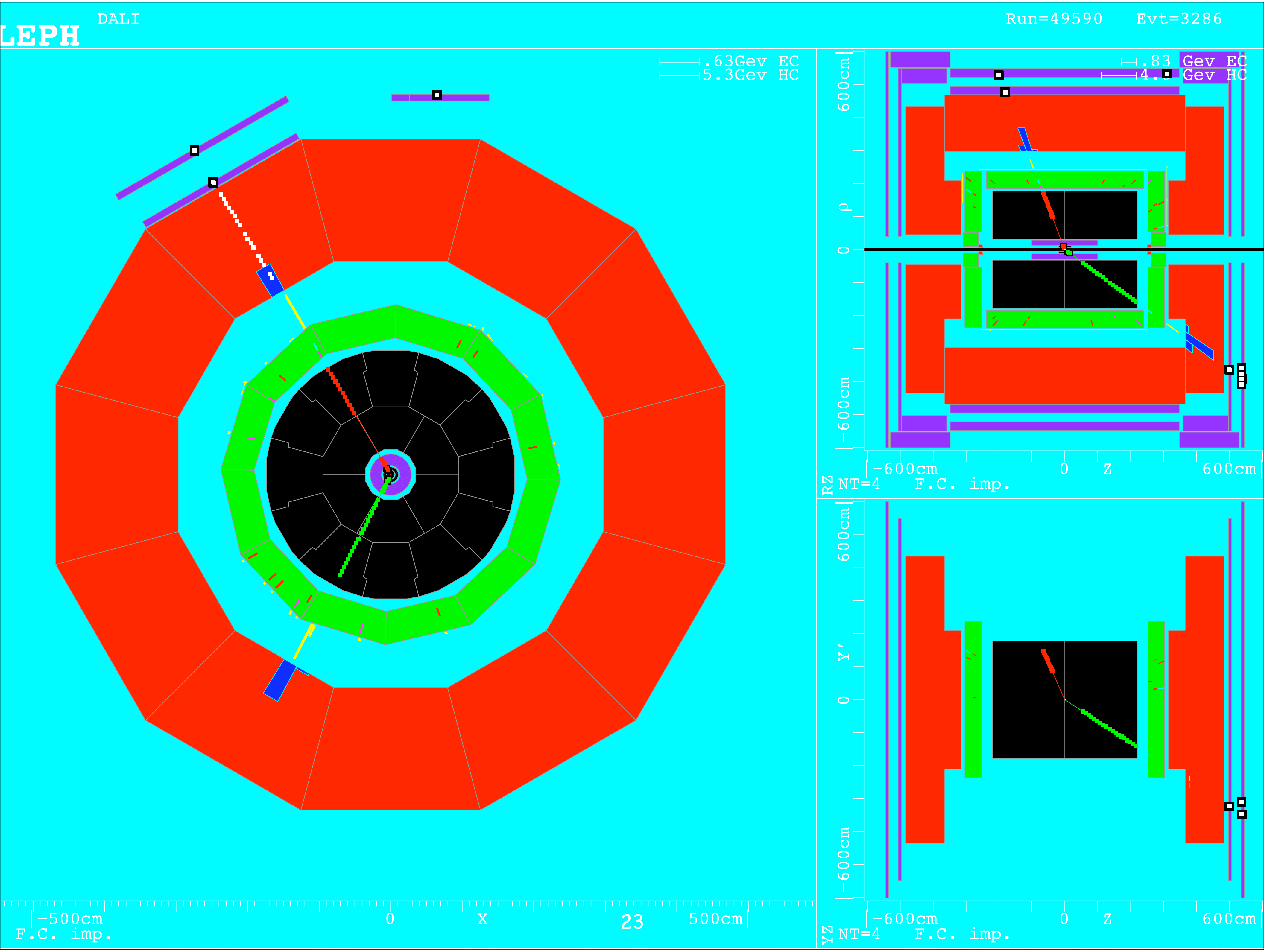
Reconstruct Lagrangian from data

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

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
  - SU(3)xSU(2)xU(1) quantum numbers determine gauge interactions
  - Yukawa couplings

mass



LEPH
DALI
Run=49590 Evt=3286
.63Gev EC
5.3Gev HC
.83 Gev EC
4. Gev HC
600cm
ρ
0
-600cm
-600cm
0
Z
600cm
RZ NT=4 F.C. imp.
600cm
Y'
0
-600cm
-600cm
0
Z
600cm
YZ NT=4 F.C. imp.
-500cm
0
X
500cm
F.C. imp.

Two-body kinematics

- In the CM frame of two particles of mass m_1 and m_2

$$E_1 = \frac{\sqrt{s}}{2}\left(1 + \frac{m_1^2}{s} - \frac{m_2^2}{s}\right)$$

$$E_2 = \frac{\sqrt{s}}{2}\left(1 + \frac{m_2^2}{s} - \frac{m_1^2}{s}\right)$$

$$p_1 = p_2 = \frac{\sqrt{s}}{2}\sqrt{1 - \frac{2(m_1^2 + m_2^2)}{s} + \frac{(m_1^2 - m_2^2)^2}{s^2}}$$

$\tilde{\mu} \rightarrow \mu\chi^0$

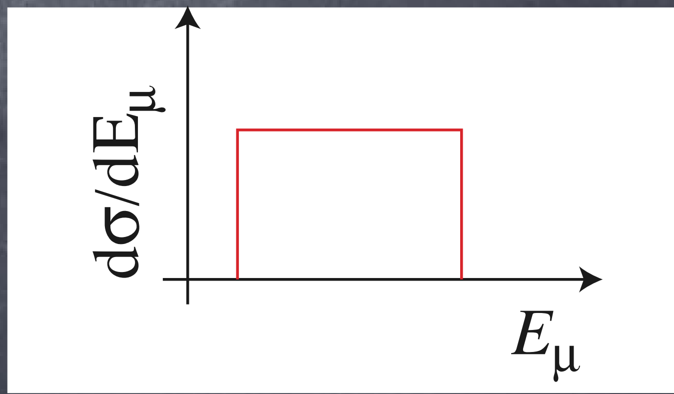
- In the smuon rest frame $\hat{p}_\mu = \frac{m_{\tilde{\mu}}}{2}\left(1 - \frac{m^2_{\tilde{\chi}^0}}{m^2_{\tilde{\mu}}}\right)(1, \sin\hat{\theta}, 0, \cos\hat{\theta})$
- In the lab frame $\gamma_{\tilde{\mu}} = \frac{E_{\tilde{\mu}}}{m_{\tilde{\mu}}} = \frac{\sqrt{s}}{2m_{\tilde{\mu}}}$ $\quad \beta_{\tilde{\mu}} = \sqrt{1 - \frac{4m^2_{\tilde{\mu}}}{s}}$
- muon momentum in the lab frame

$$p_\mu = \frac{m_{\tilde{\mu}}}{2}\left(1 - \frac{m^2_{\tilde{\chi}^0}}{m^0_{\tilde{\mu}}}\right)(\gamma_{\tilde{\mu}} + \gamma_{\tilde{\mu}}\beta_{\tilde{\mu}}\cos\hat{\theta}, \sin\hat{\theta}, 0, \gamma_{\tilde{\mu}}\cos\hat{\theta} + \gamma_{\tilde{\mu}}\beta_{\tilde{\mu}})$$

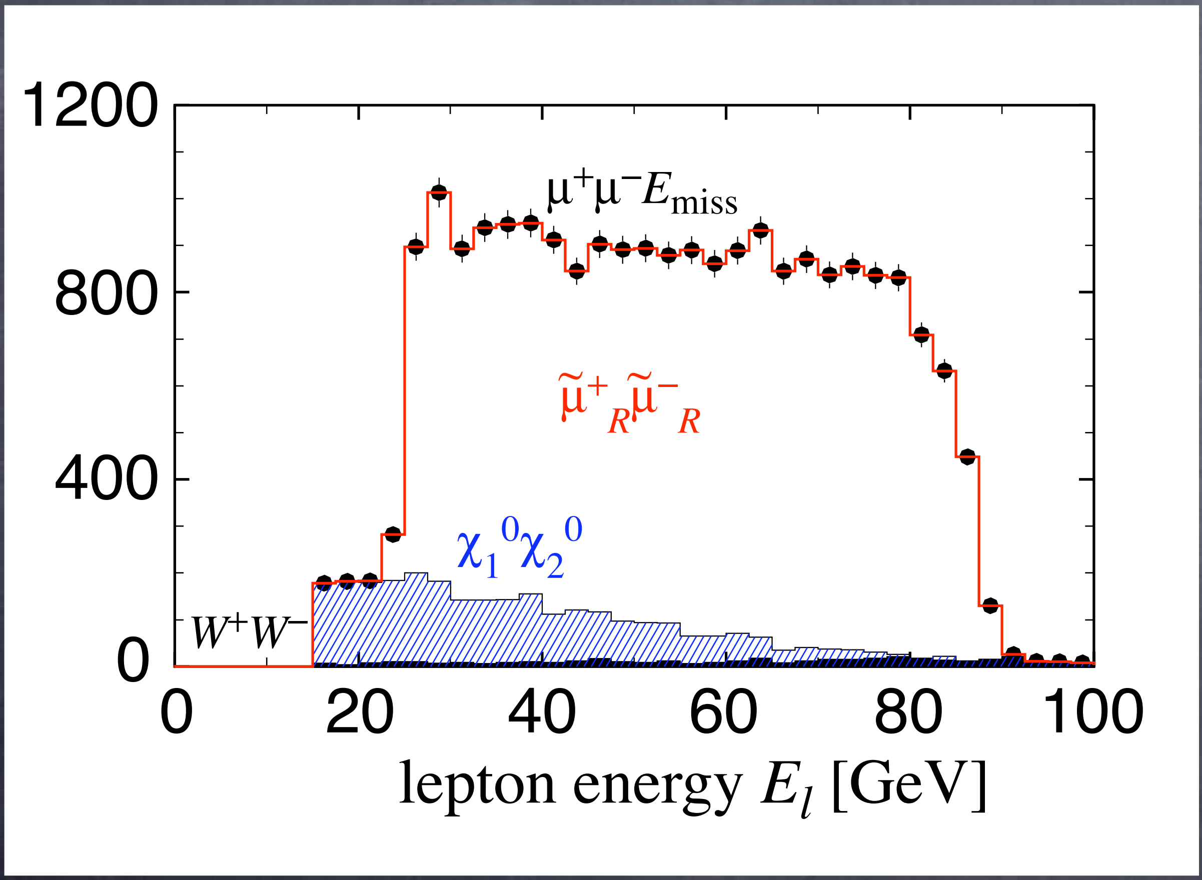
- Therefore, the muon energy is

$$\frac{\sqrt{s}}{4}\left(1 - \frac{m^2_{\tilde{\chi}^0}}{m^0_{\tilde{\mu}}}\right)(1 - \beta_{\tilde{\mu}}) < E_\mu < \frac{\sqrt{s}}{4}\left(1 - \frac{m^2_{\tilde{\chi}^0}}{m^0_{\tilde{\mu}}}\right)(1 + \beta_{\tilde{\mu}})$$

$$\frac{d\sigma}{dE_\mu} \propto \frac{d\sigma}{d\cos\hat{\theta}} = \text{constant}$$



$\tilde{\mu} \to \mu\chi^0$

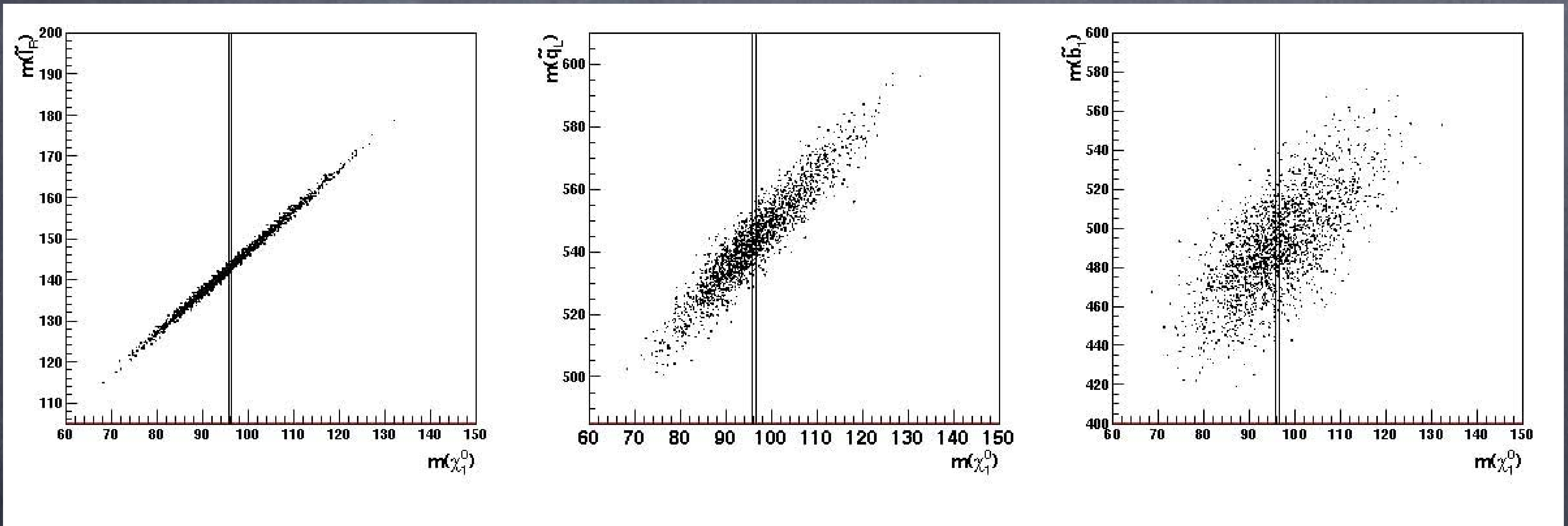


- fit to the kinetic distribution

$m_{\tilde{\mu}} = 132.0 \pm 0.3$ GeV

$m_{\tilde{\chi}^0} = 71.9 \pm 0.1$ GeV

LHC/LC synergy



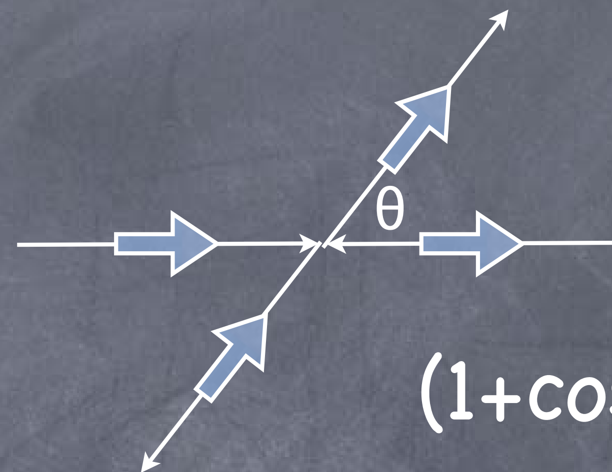
Reconstruct Lagrangian from data

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

Spin

Spin

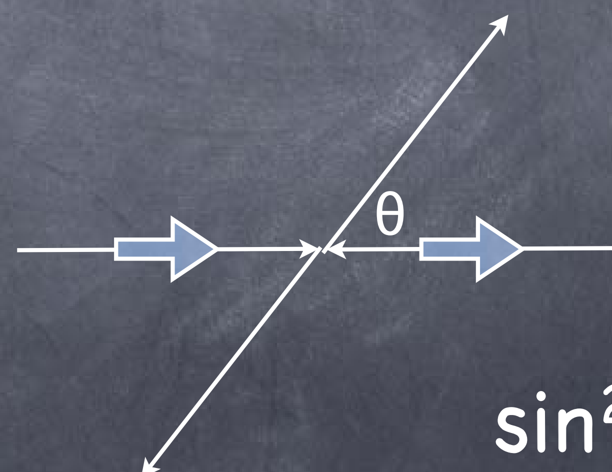
- production angle distribution well above the threshold:



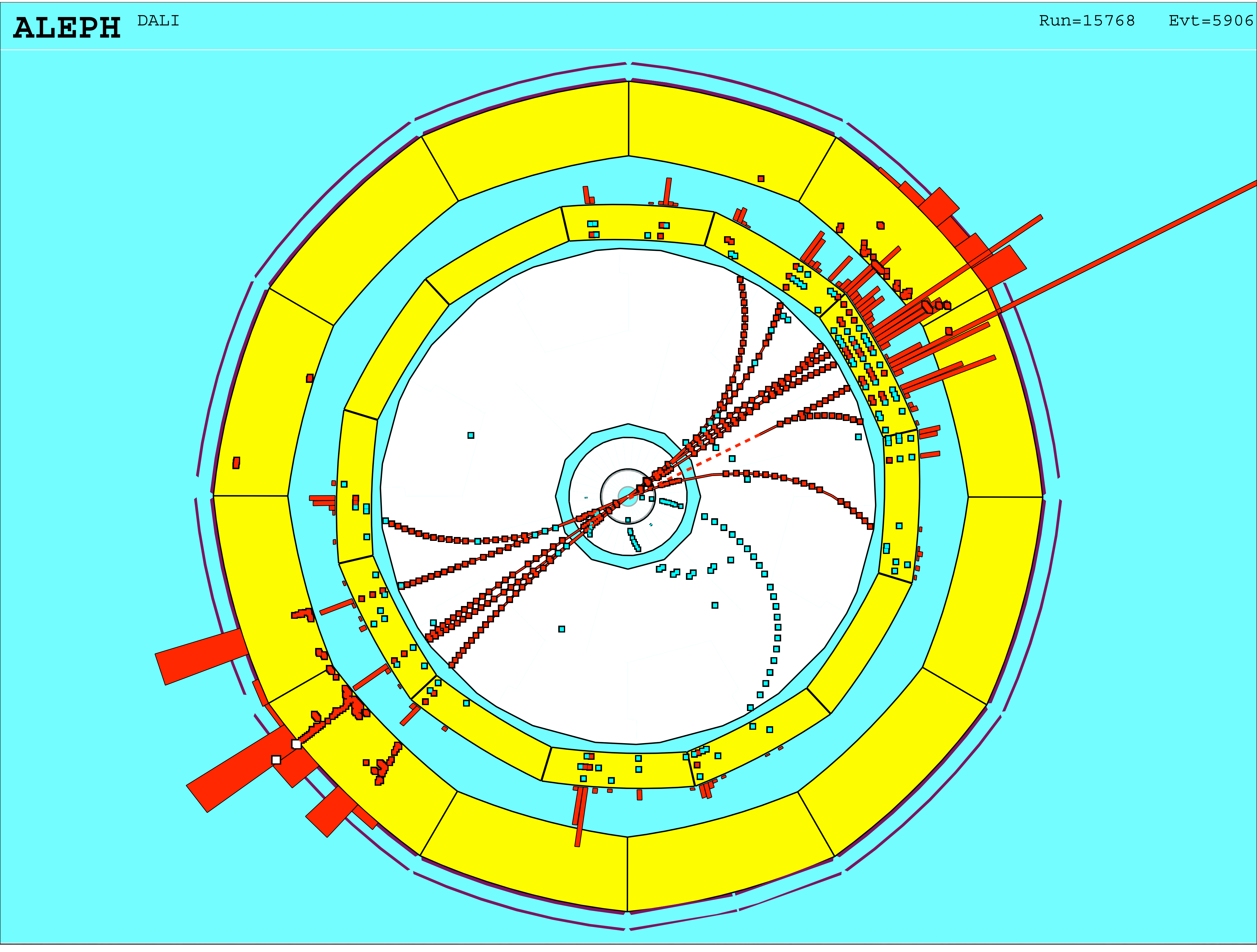
$(1+\cos\theta)^2$

- spin 1/2

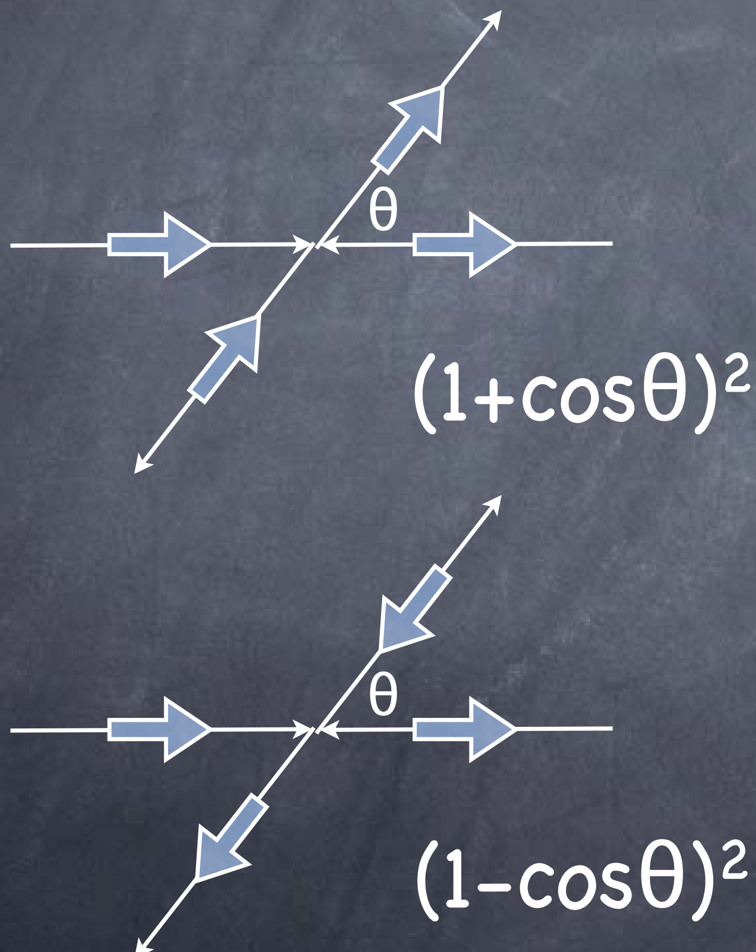
- spin 0

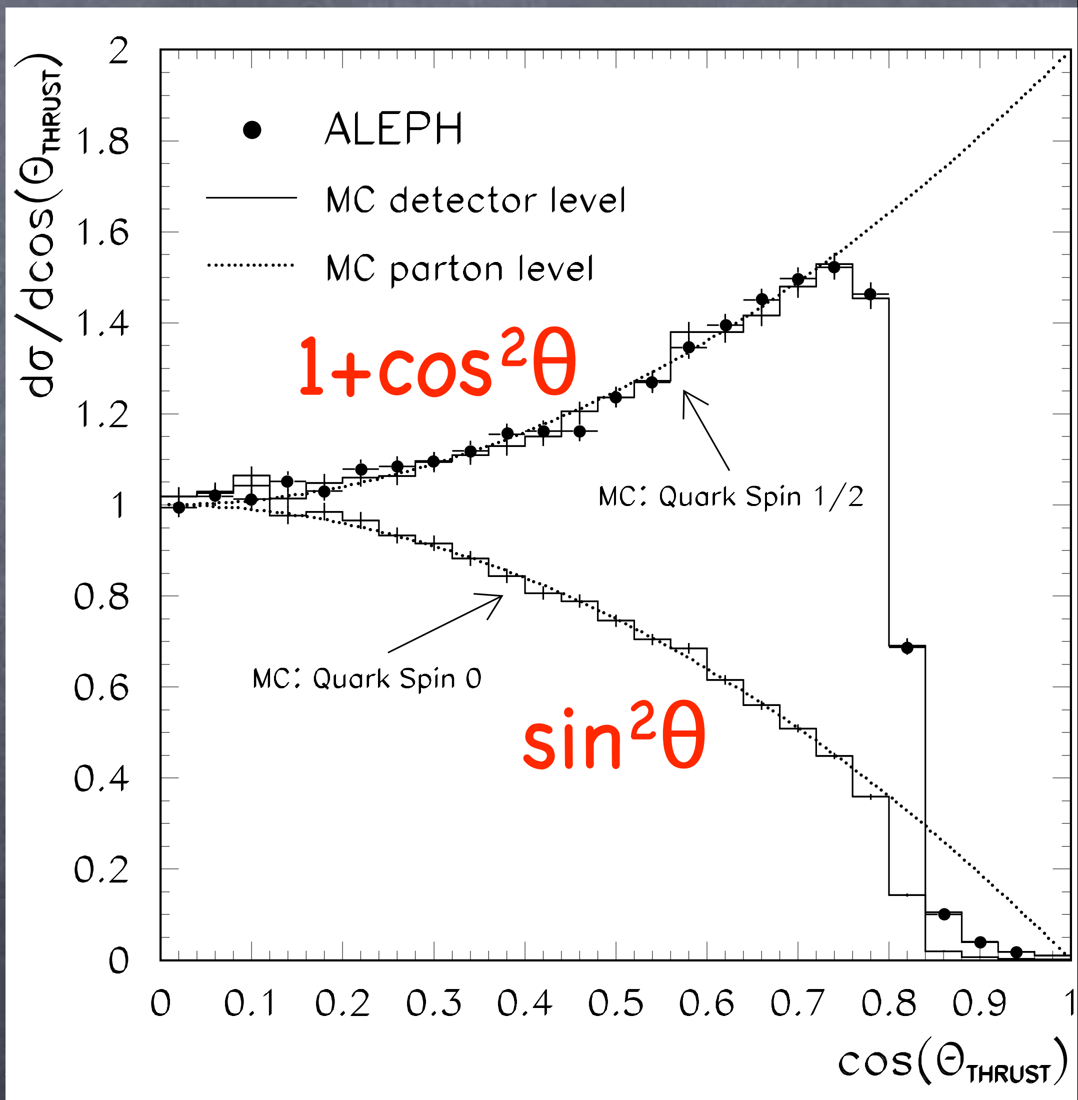


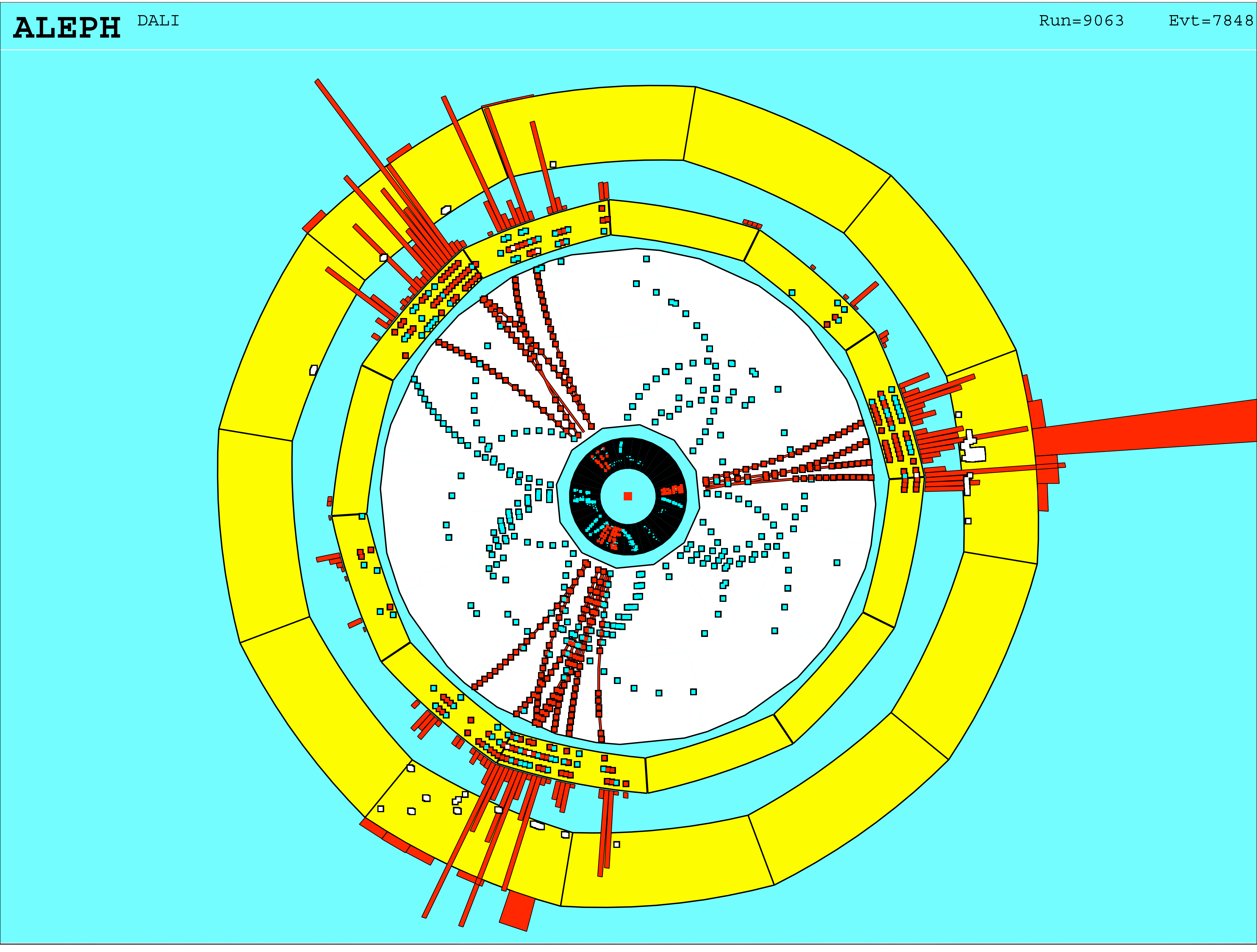
$\sin^2\theta$


ALEPH
DALI
Run=15768
Evt=5906

“New particle” has spin 1/2

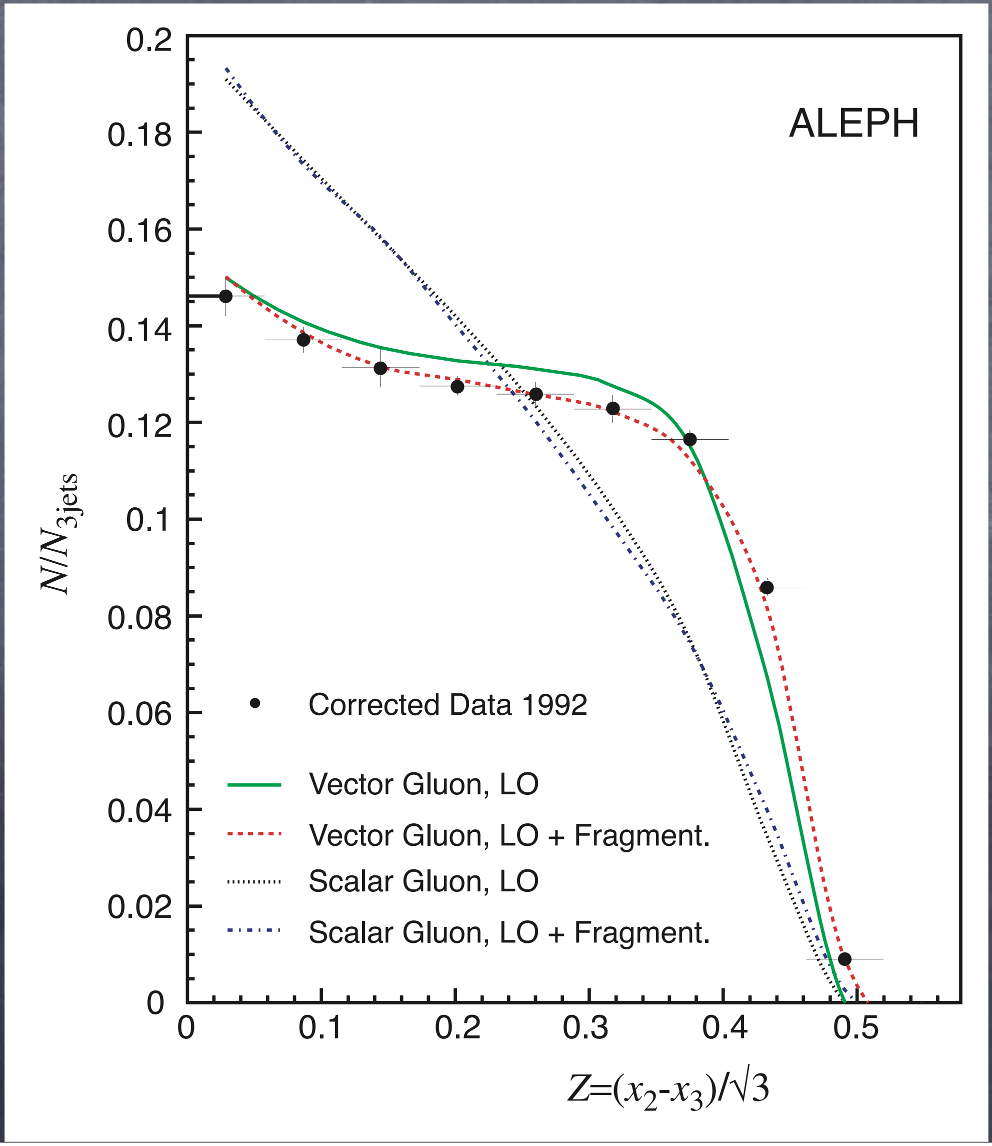


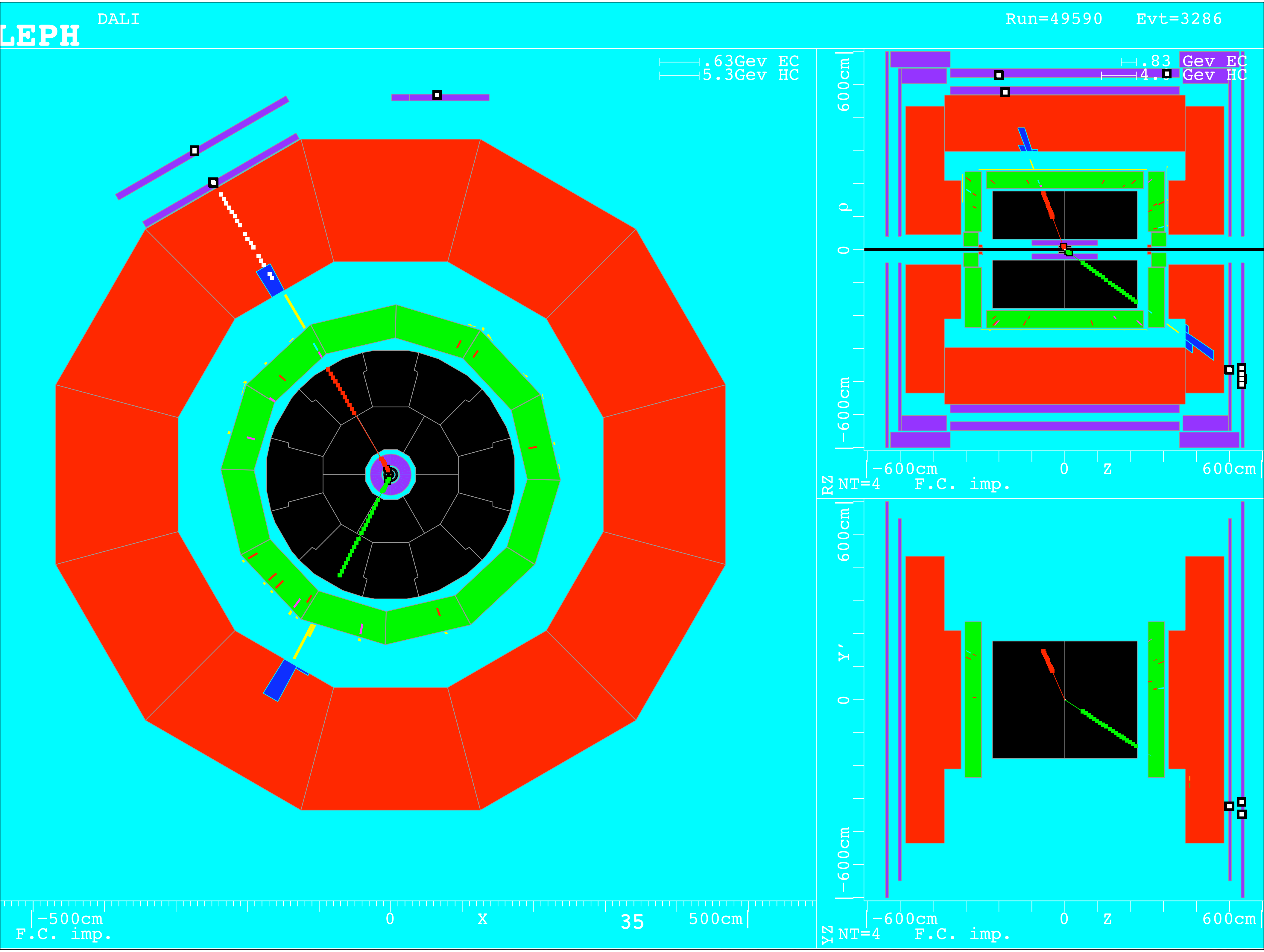




ALEPH
DALI
Run=9063
Evt=7848

"New particle" has spin 1





LEPH
DALI
Run=49590 Evt=3286
.63Gev EC
5.3Gev HC
.83 Gev EC
4. Gev HC
600cm
ρ
0
-600cm
-600cm
0
Z
600cm
RZ NT=4 F.C. imp.
600cm
Y'
0
-600cm
-600cm
0
Z
600cm
YZ NT=4 F.C. imp.
-500cm
0
X
500cm
F.C. imp.

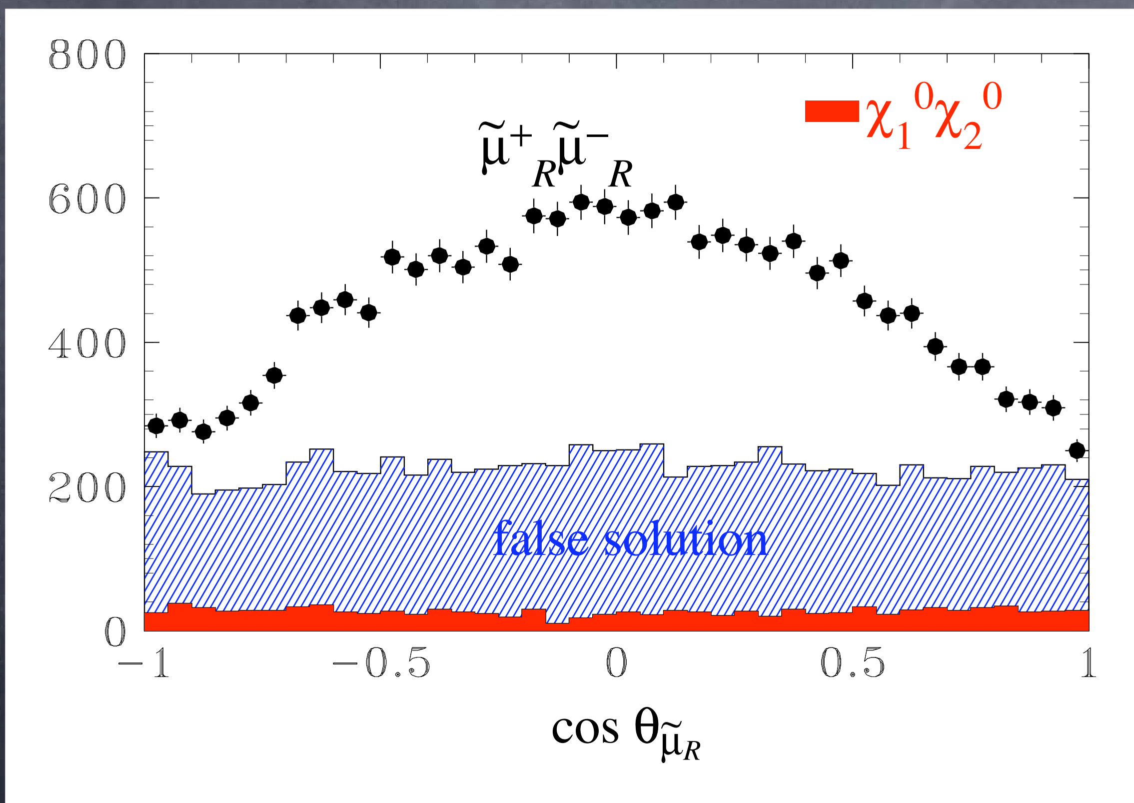
Smuon production

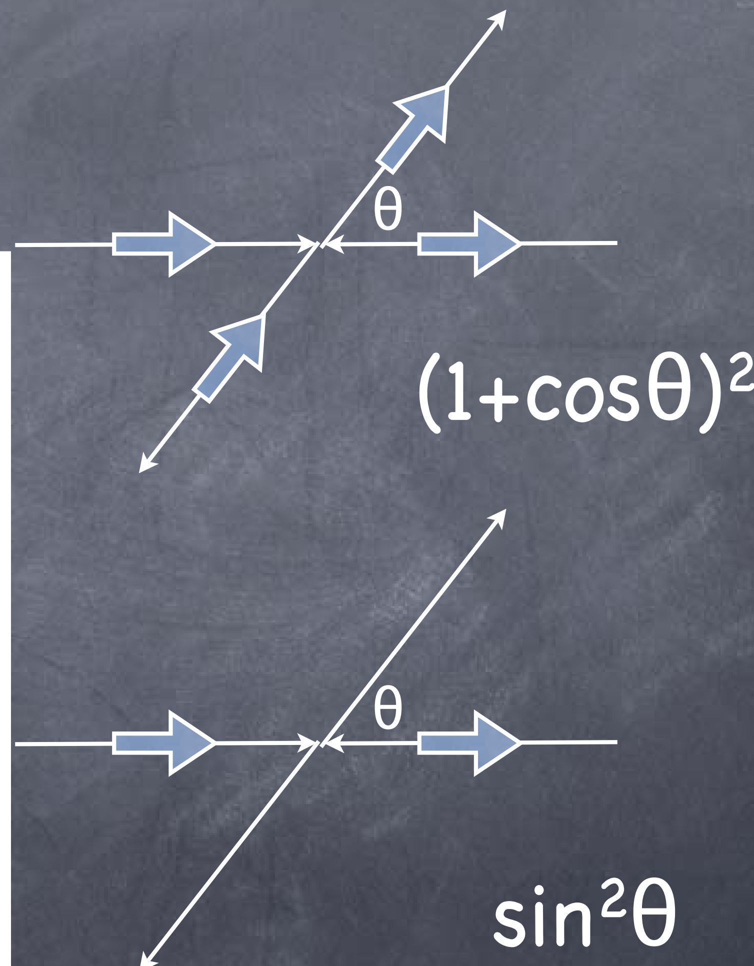
- $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \to (\mu^+\tilde{\chi}_1^0)(\mu^-\tilde{\chi}_1^0)$
- once masses known, you can solve kinematics up to a two-fold ambiguity
- muon momenta measured: $p^\mu_{1,2} = (E_{1,2}, \vec{p}_{1,2})$
- neutralino momenta: $q^\mu_{1,2} = \left(\frac{\sqrt{s}}{2} - E_{1,2},\ \vec{q}_{1,2}\right)$
- neutralino mass constraint: $\vec{q}^{\,2}_{1,2} = \left(\frac{\sqrt{s}}{2} - E_{1,2}\right)^2 - m^2_{\tilde{\chi}}$
- smuon mass constraint: $\left(\frac{\sqrt{s}}{2}\right)^2 - (\vec{p}_1 + \vec{q}_1)^2 = m^2_{\tilde{\mu}} \longrightarrow \vec{p}_1 \cdot \vec{q}_1$
- momentum conservation:

$$\vec{q}^{\,2}_2 = (\vec{p}_1 + \vec{p}_2 + \vec{q}_1)^2 = (\vec{p}_1 + \vec{p}_2)^2 + \vec{q}^{\,2}_1 + 2\vec{p}_1 \cdot \vec{q}_1 + 2\vec{p}_2 \cdot \vec{q}_1 \longrightarrow \vec{p}_2 \cdot \vec{q}_1$$

- Now know $|\vec{q}_1|,\ \vec{p}_1 \cdot \vec{q}_1,\ \vec{p}_2 \cdot \vec{q}_1$
- Know $\vec{q}_1$ up to a two-fold ambiguity

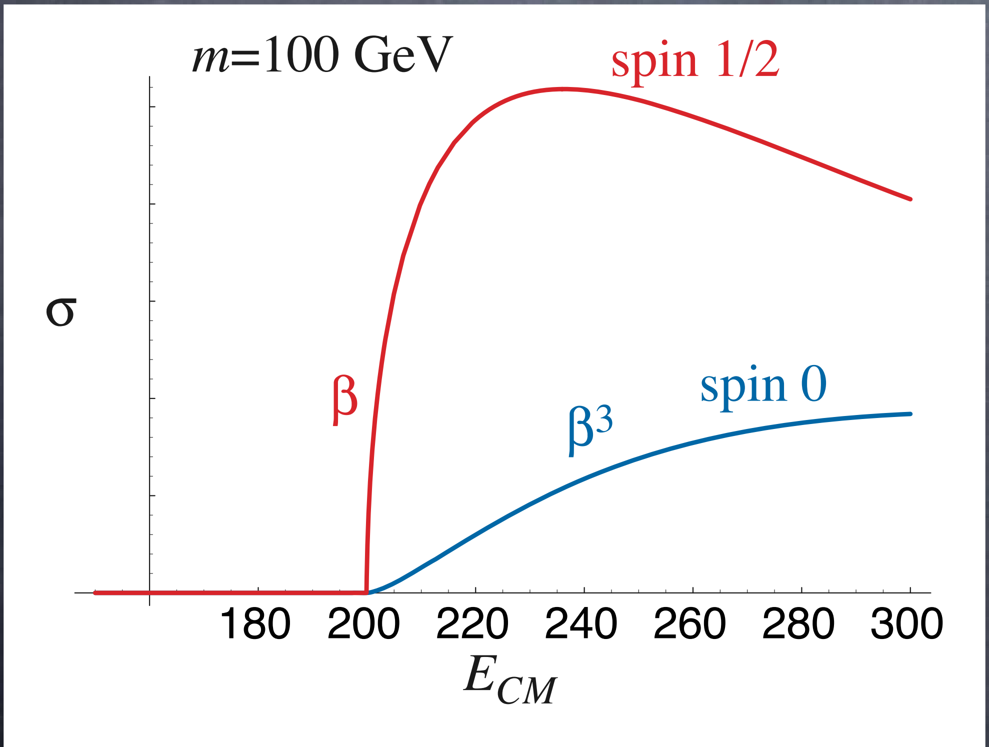
Smuon has spin 0

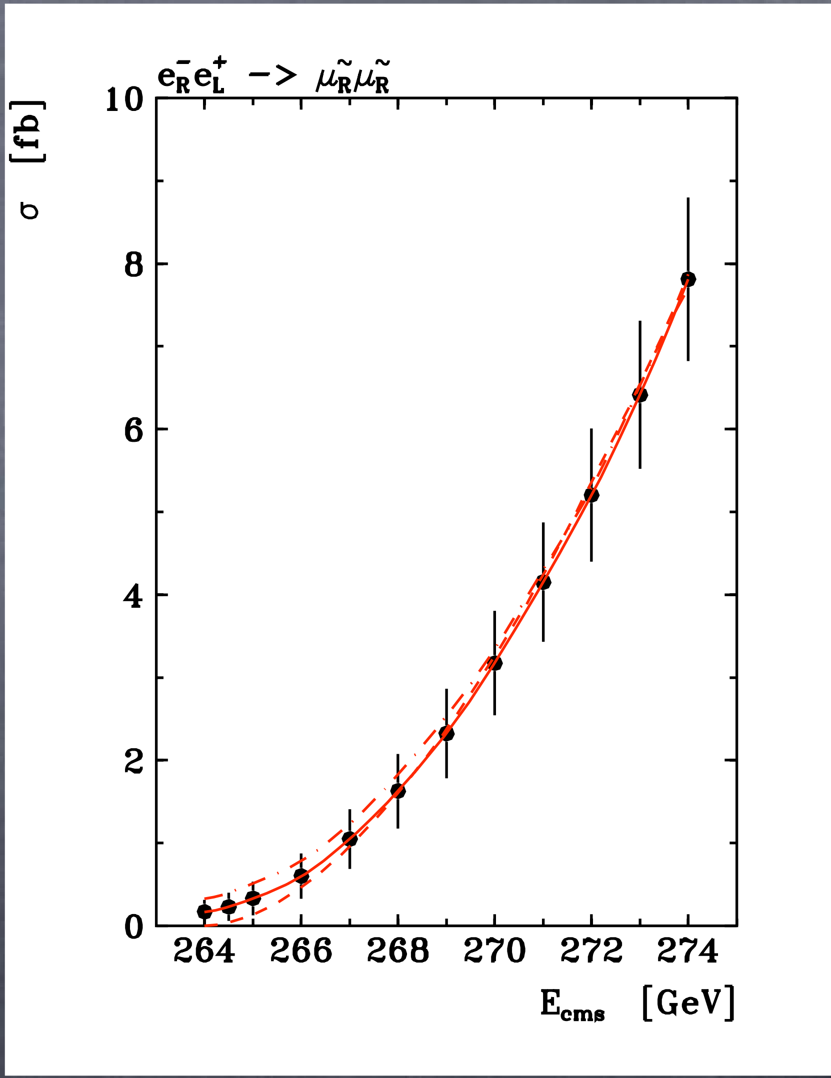




Spin

- threshold behavior
  non-relativistic limit:
  L, S separately
  conserved





$m_{\tilde{\mu}} = 132.0 \pm 0.09$ GeV
$m_{\tilde{\chi}^0} = 71.9 \pm 0.05$ GeV

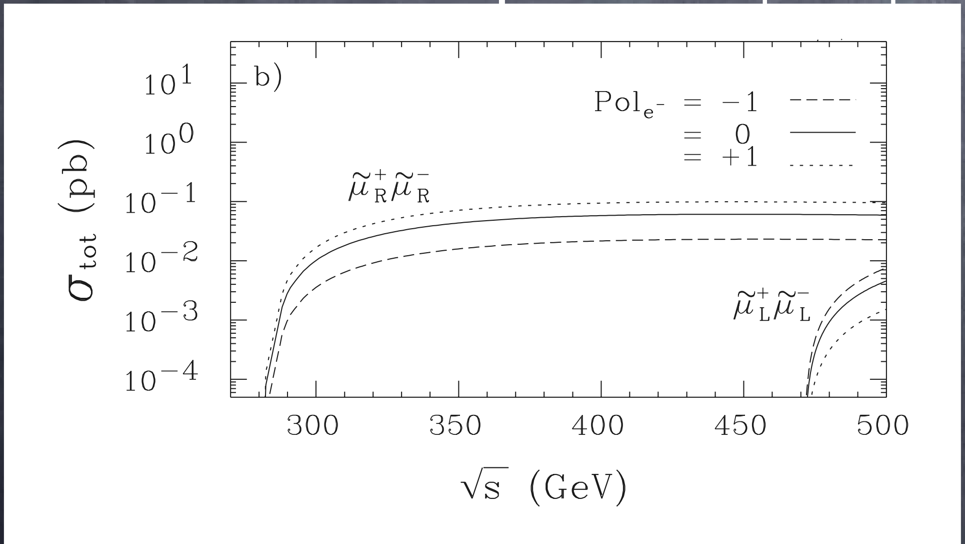
Reconstruct Lagrangian from data

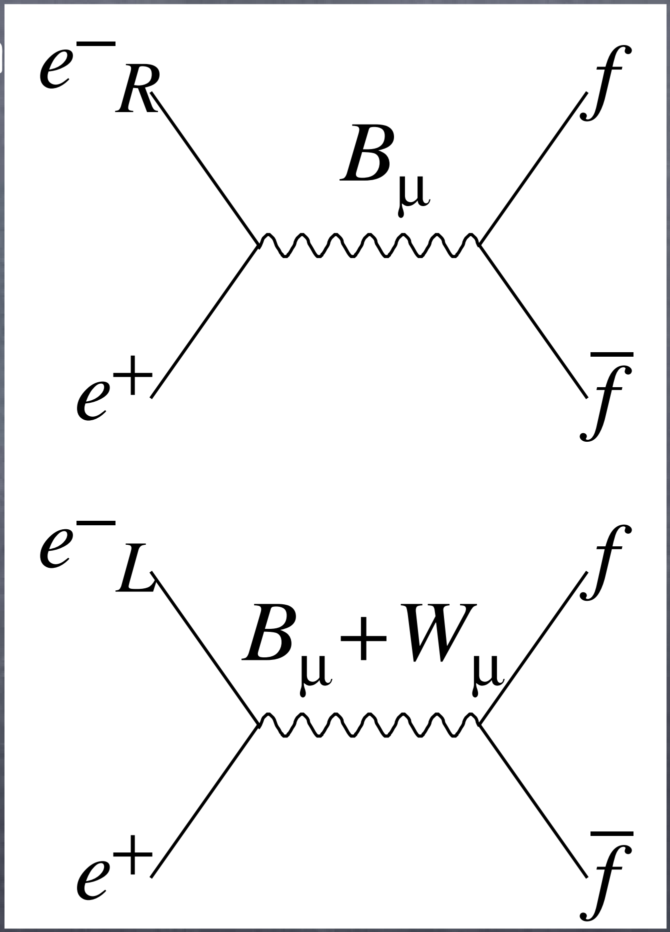
- Specify the fields
  - mass
  - spin⇒Klein-Gordon, Dirac, Majorana, gauge
  - SU(3)xSU(2)xU(1) quantum numbers
  - mixing of states
- Specify their interactions
  - SU(3)xSU(2)xU(1) quantum numbers determine gauge interactions
  - Yukawa couplings

gauge quantum numbers

polarization

- Use polarized electron beam
- can ignore $m_Z^2 \ll s$
- e_R couples only to B_μ
- e_L couples to $B_\mu + W_\mu^0$





$\propto (g'^2 Y_f)^2$

$\propto (g'^2 Y_f + g^2 I_{3f})^2 / 4$

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
  - SU(3)xSU(2)xU(1) quantum numbers determine gauge interactions
  - Yukawa couplings

Disentangle mixings

gauginos, higgsinos

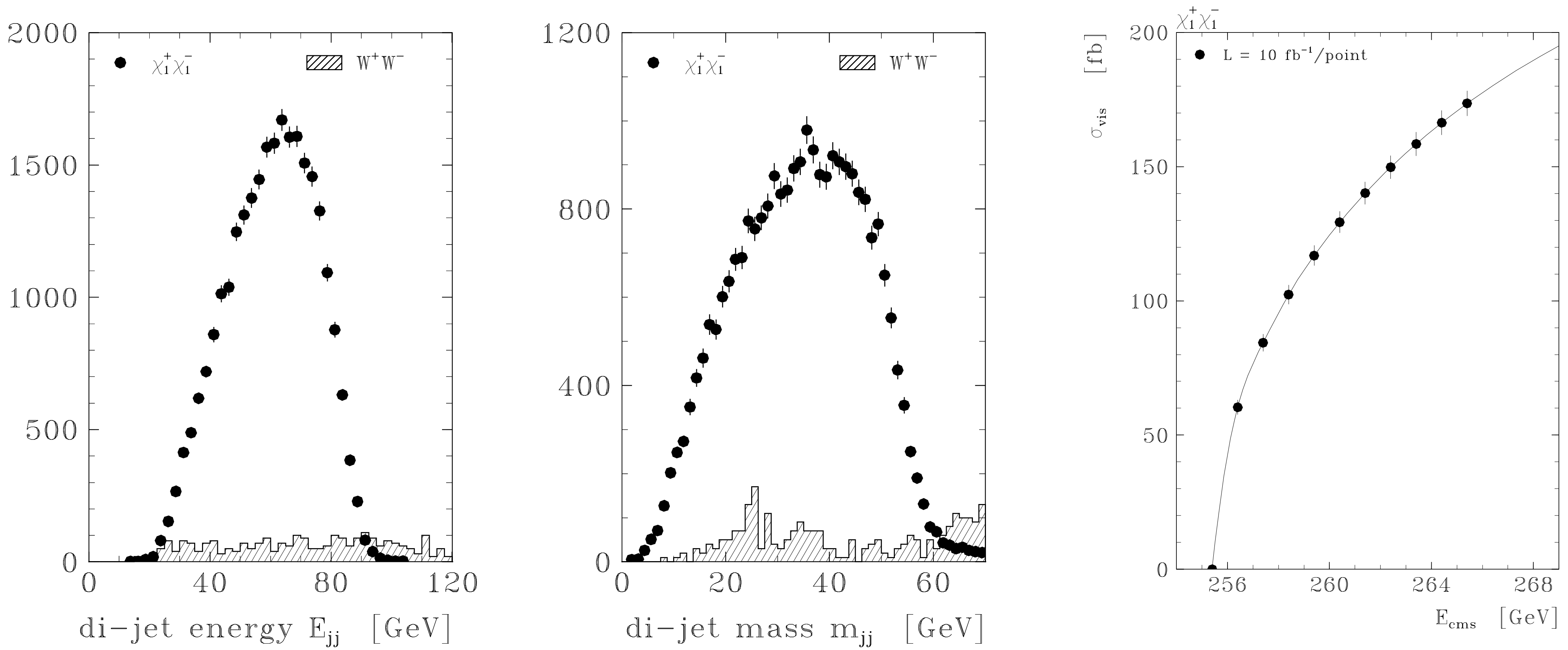
- charged ones "charginos"

$$(\tilde{W}^- \ \tilde{H}_d^-) \begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}$$

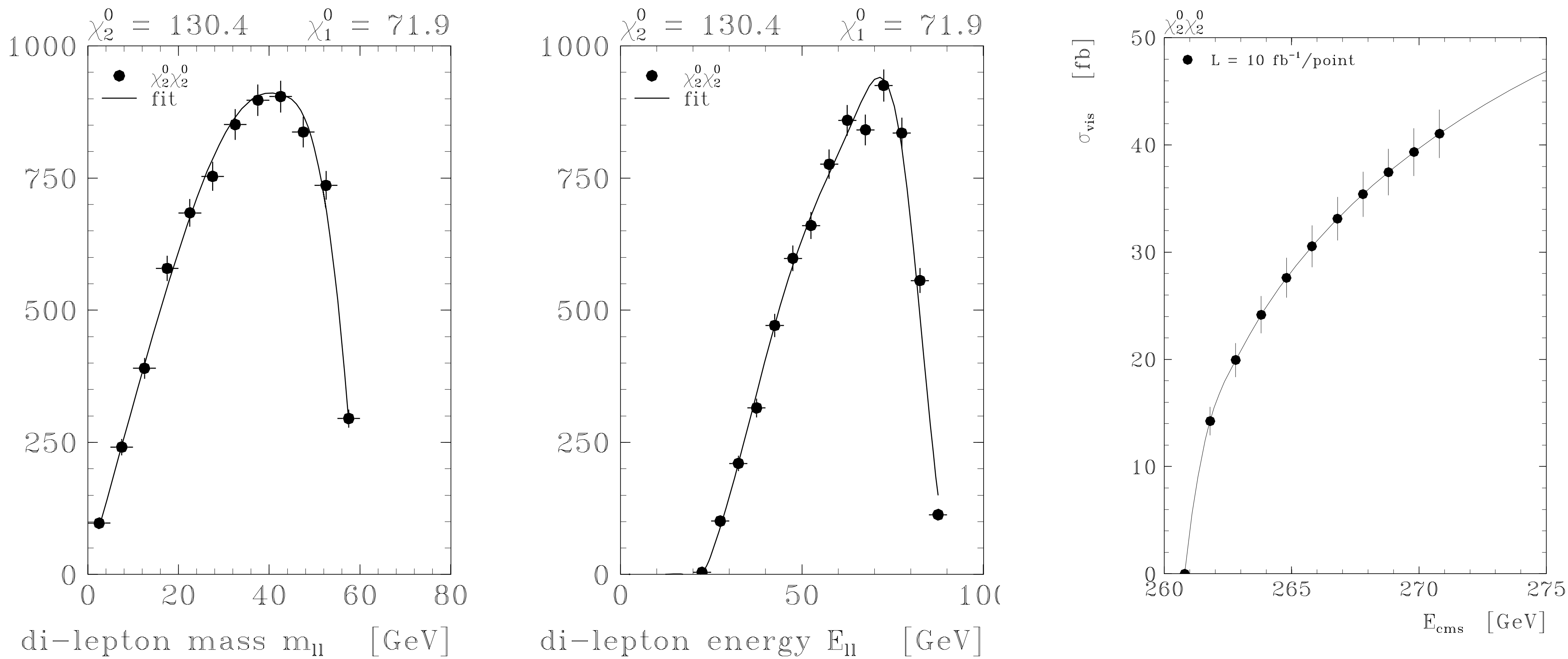
- neutral ones "neutralinos"

$$(\tilde{B},\, \tilde{W}^0,\, \tilde{H}_d^0,\, \tilde{H}_u^0) \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix}$$

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



$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to (\tilde{\chi}_1^0 l^+ l^-)(\tilde{\chi}_1^0 l'^+ l'^-)$$

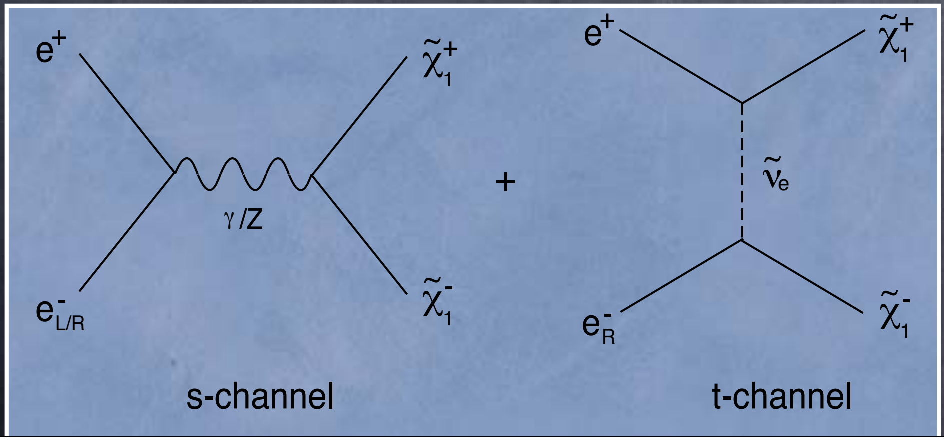


Model-independent parameter determination

- Chargino/neutralino mass matrices have four parameters M_1, M_2, μ, $\tan\beta$
- Can measure 2+4 masses
- can measure 10x2 neutralino cross sections

$$\sigma_{L,R}(e^+e^- \to \tilde{\chi}^0_i\tilde{\chi}^0_j) \qquad \sigma_{L,R}(e^+e^- \to \tilde{\chi}^+_i\tilde{\chi}^-_j)$$

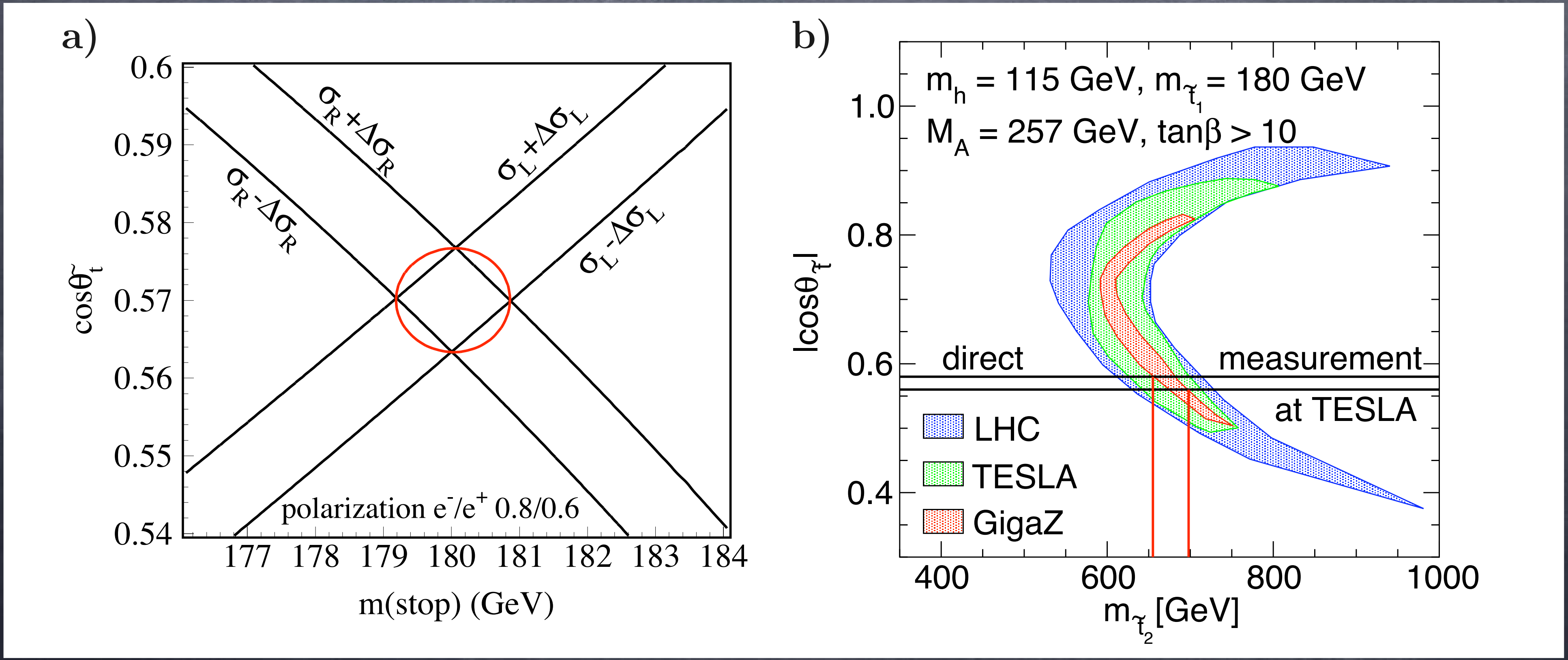
- can measure 3x2 chargino cross sections
- depend on masses of $\tilde{\nu}_e$, $\tilde{e}_L$, $\tilde{e}_R$



	input	fit
M_2	152 GeV	152 ±1.8 GeV
μ	316 GeV	316 ±0.9 GeV
$\tan\beta$	3	3 ±0.7
M_1	78.7 GeV	78.7 ±0.7 GeV

Stop

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



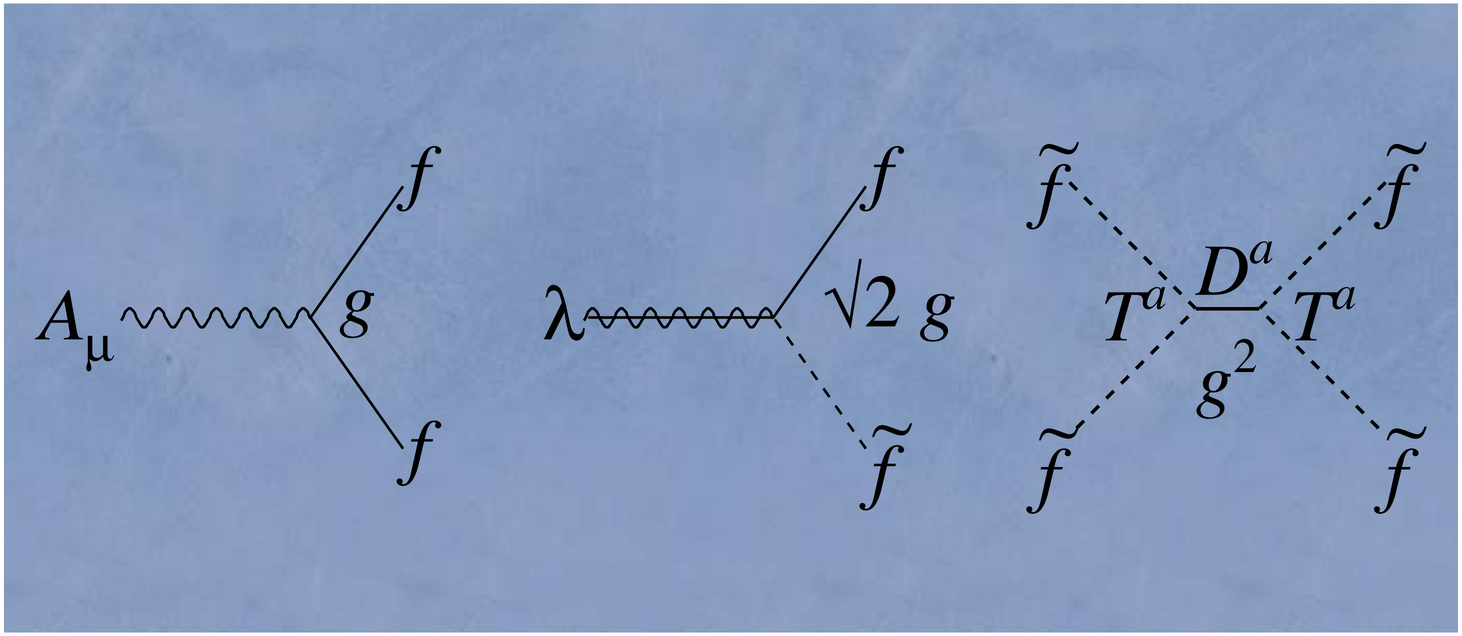
Reconstruct Lagrangian from data

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

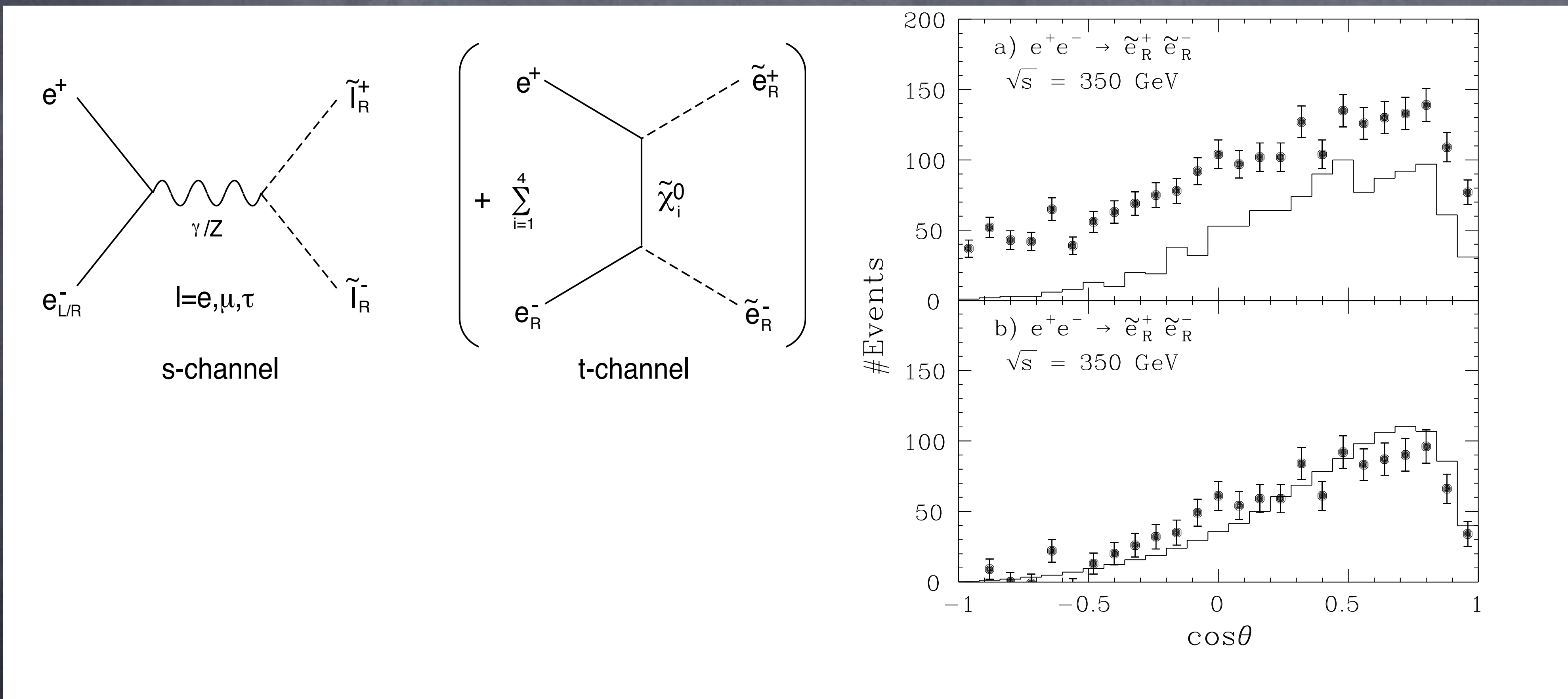
Interaction

Feynman rules

- Single gauge coupling constant gives all of these Feynman vertices

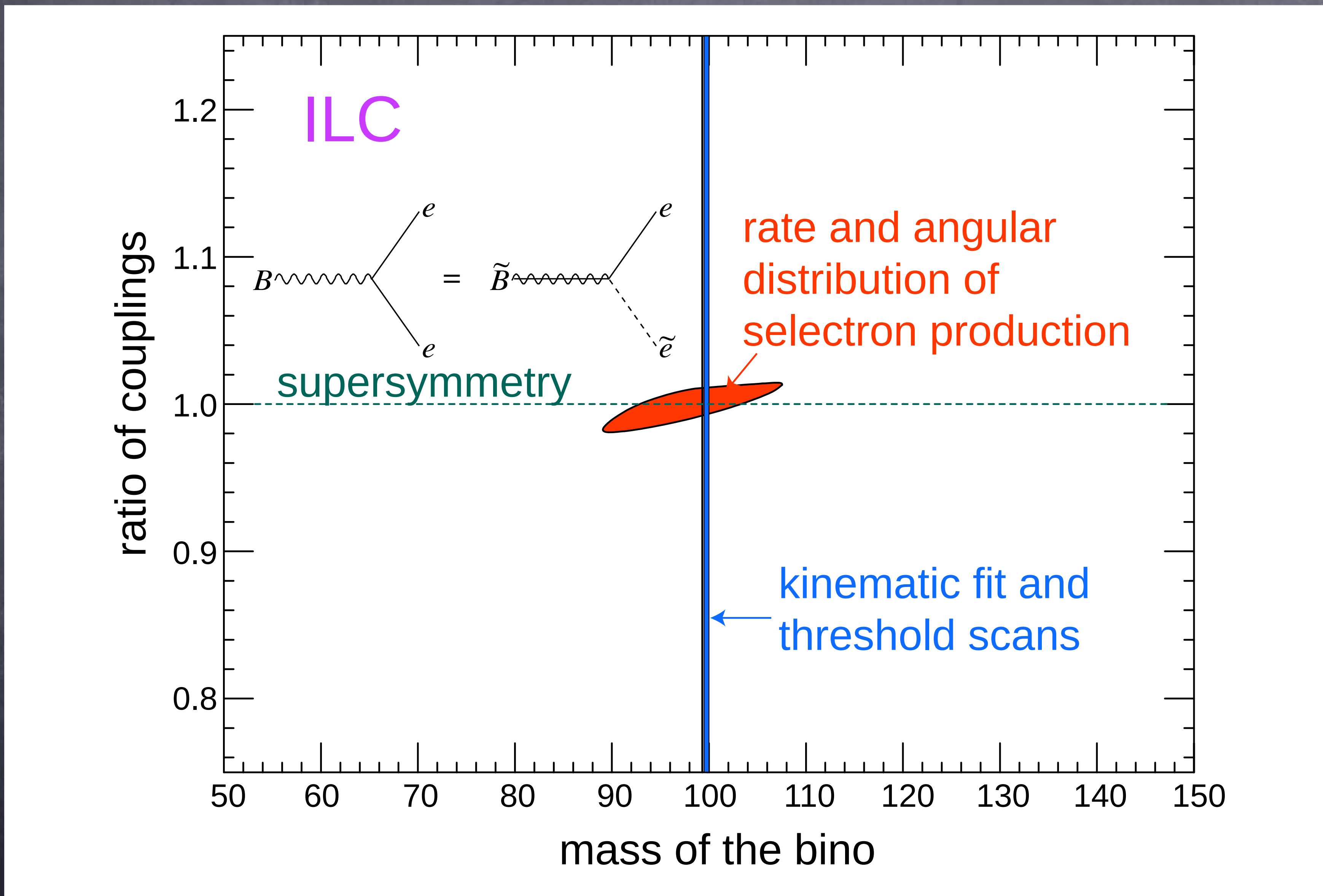


selectron production



$$\mathcal{M} \propto \sin\theta \left[1 - \frac{4Y_{\tilde{B}}^2}{1 - 2\cos\theta\beta_f + \beta_f^2 + 4M_1^2/s}\right] \qquad Y_{\tilde{B}} = \frac{g_{e_R\tilde{e}_R\tilde{B}}}{\sqrt{2}\, g'}$$

gaugino coupling



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
  - SU(3)xSU(2)xU(1) quantum numbers determine gauge interactions
  - Yukawa couplings

Proof of supersymmetry

- This way, you can show:
  - new particle has the same gauge quantum numbers as one of the SM particle
  - their spins differ by 1/2
  - it has a Yukawa coupling whose size is $\sqrt{2}$ times the known gauge coupling
- You have reconstructed the supersymmetric Lagrangian from data!

The New York Times

July 23, 2008

The Other Half of the World Discovered

Geneva, Switzerland

As an example, supersymmetry

"New-York Times level" confidence

still a long way to

"Halliday-Resnick" 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."

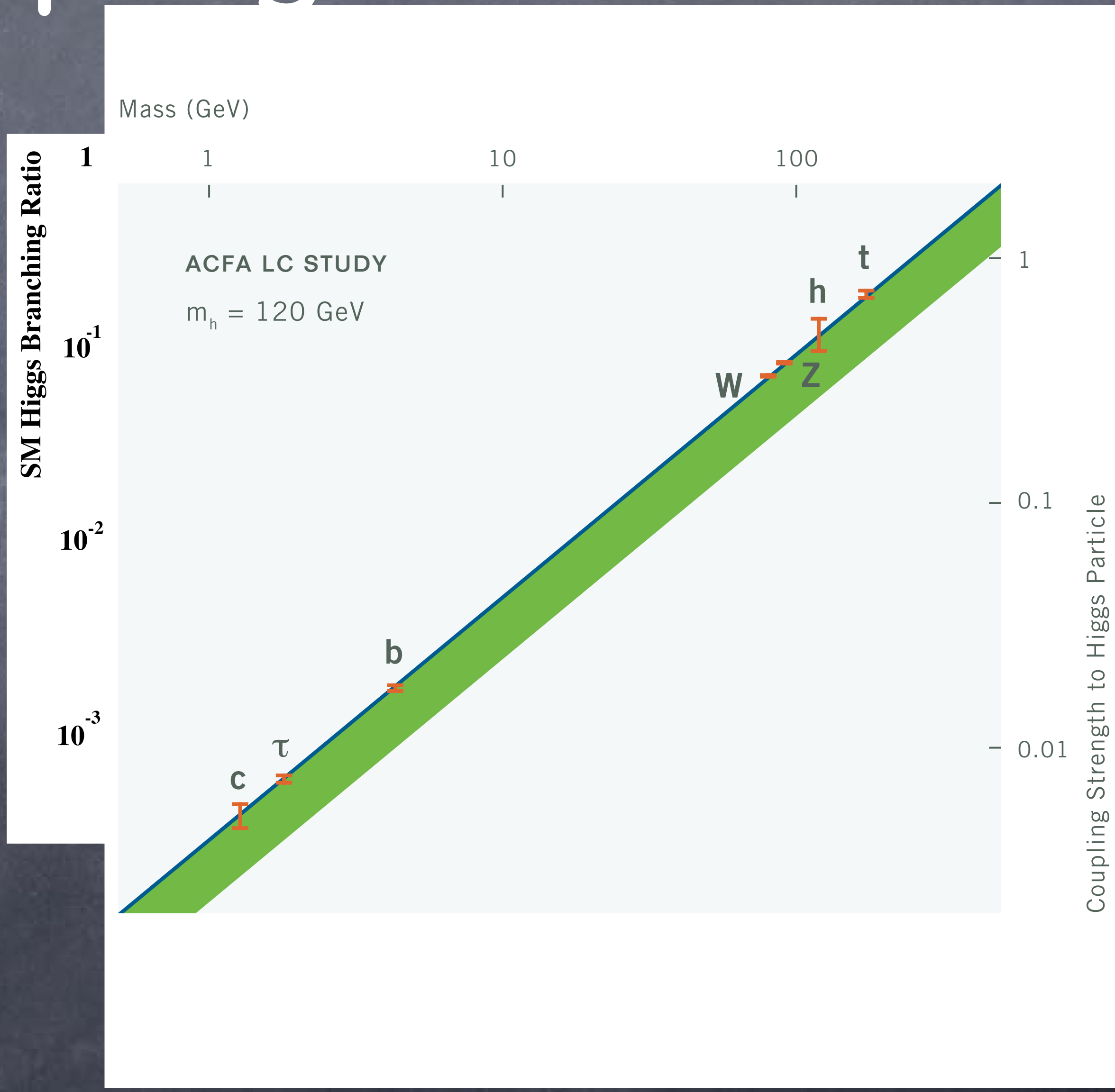
Physics Significance

Prove
Higgs coupling ∝ mass

- Branching Fractions test the relation

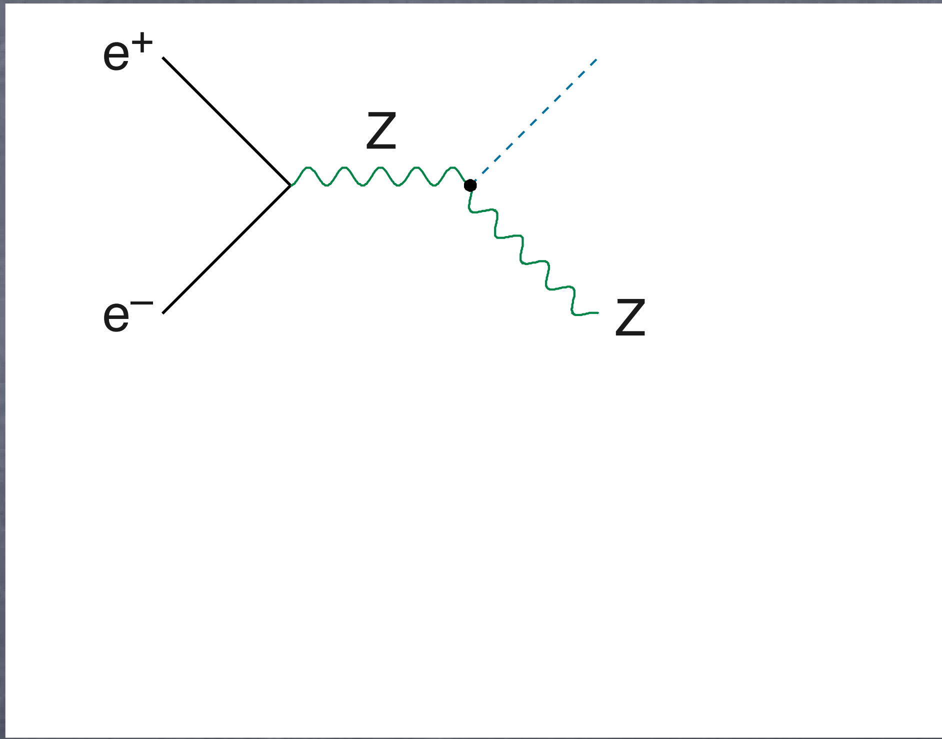
  coupling ∝ mass

⇒ proves that Higgs Boson is the Mother of Mass



Prove it is condensed

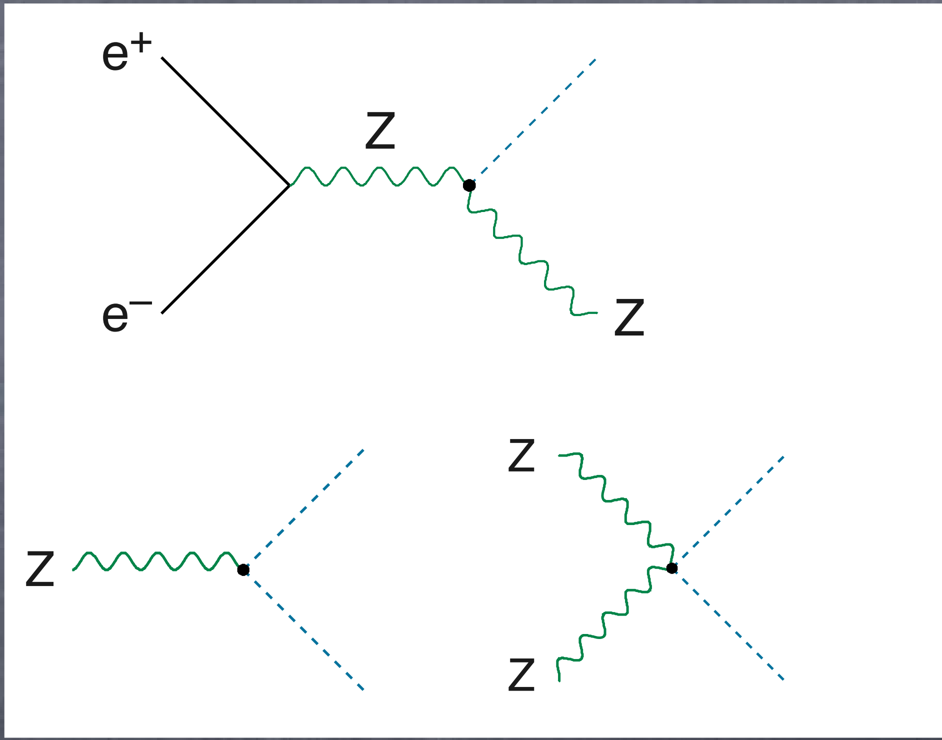
- ZH final state
- Prove the ZZH vertex



Prove it is condensed

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

$\Rightarrow$ *only two types of vertices*



Prove it is condensed

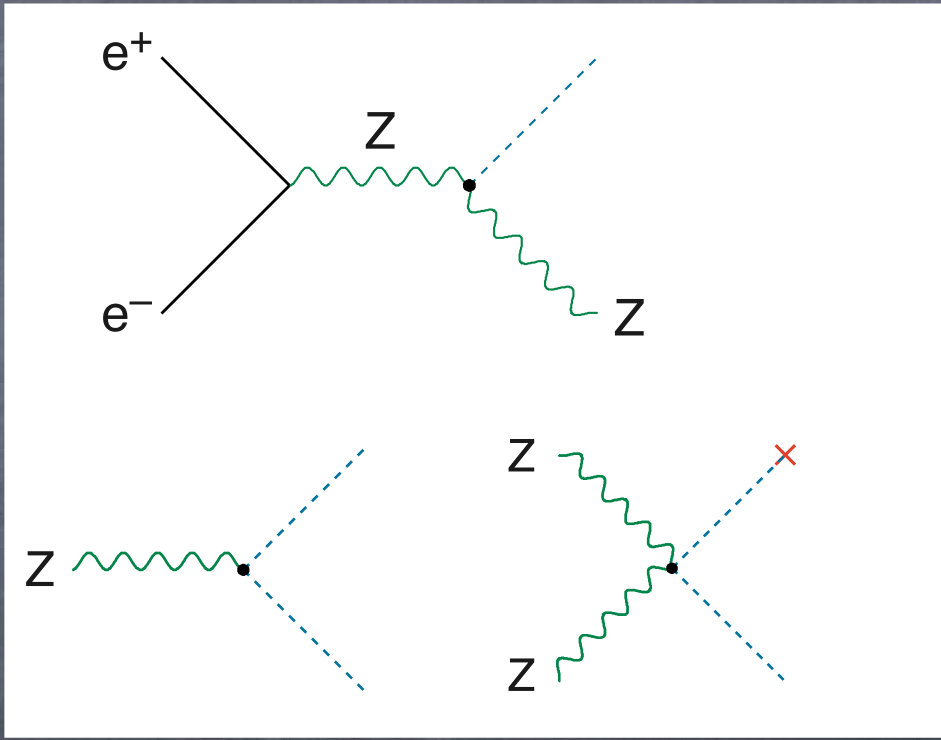
- ZH final state
- Prove the ZZH vertex
- We know Z:gauge boson, H: scalar boson

$\Rightarrow$ *only two types of vertices*

- Need a condensate to get ZZH vertex

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

HM, hep-ex/9606001



Prove it is condensed

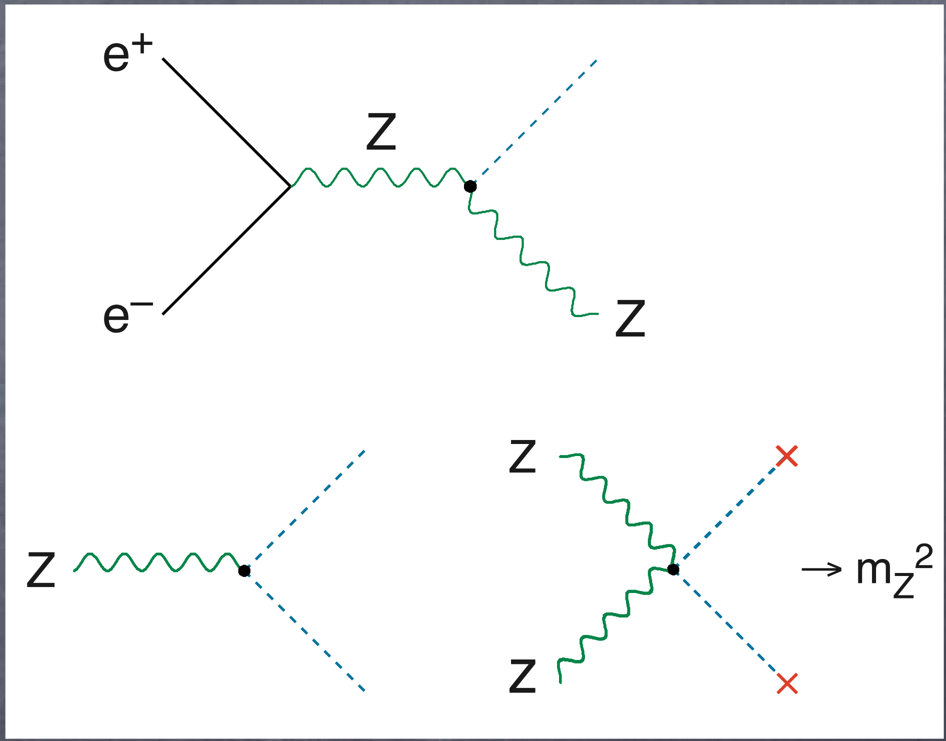
- ZH final state
- Prove the ZZH vertex
- We know Z:gauge boson, H: scalar boson

⇒ only two types of vertices

- Need a condensate to get ZZH vertex

⇒ proves it is condensed in Universe

HM, hep-ex/9606001



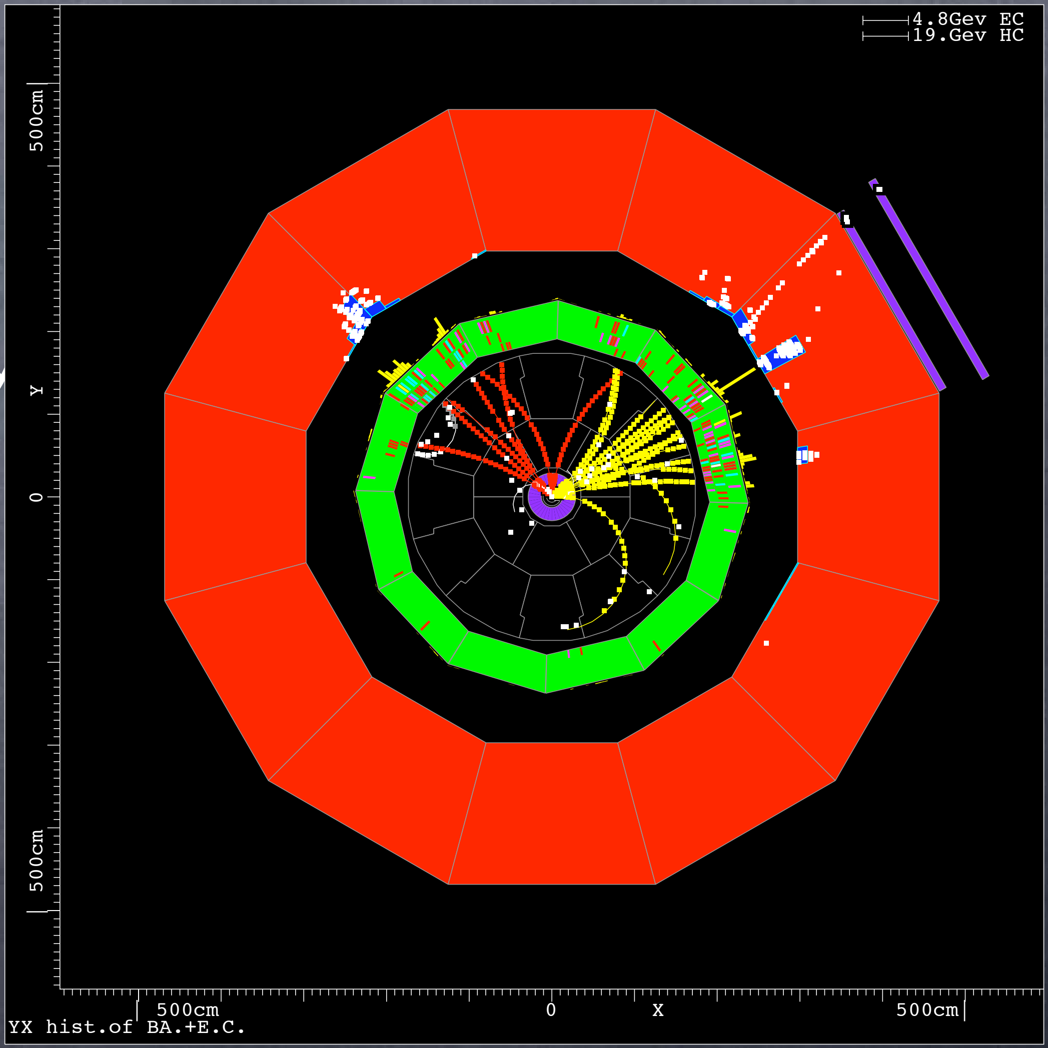
Producing Dark Matter in the laboratory

- 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

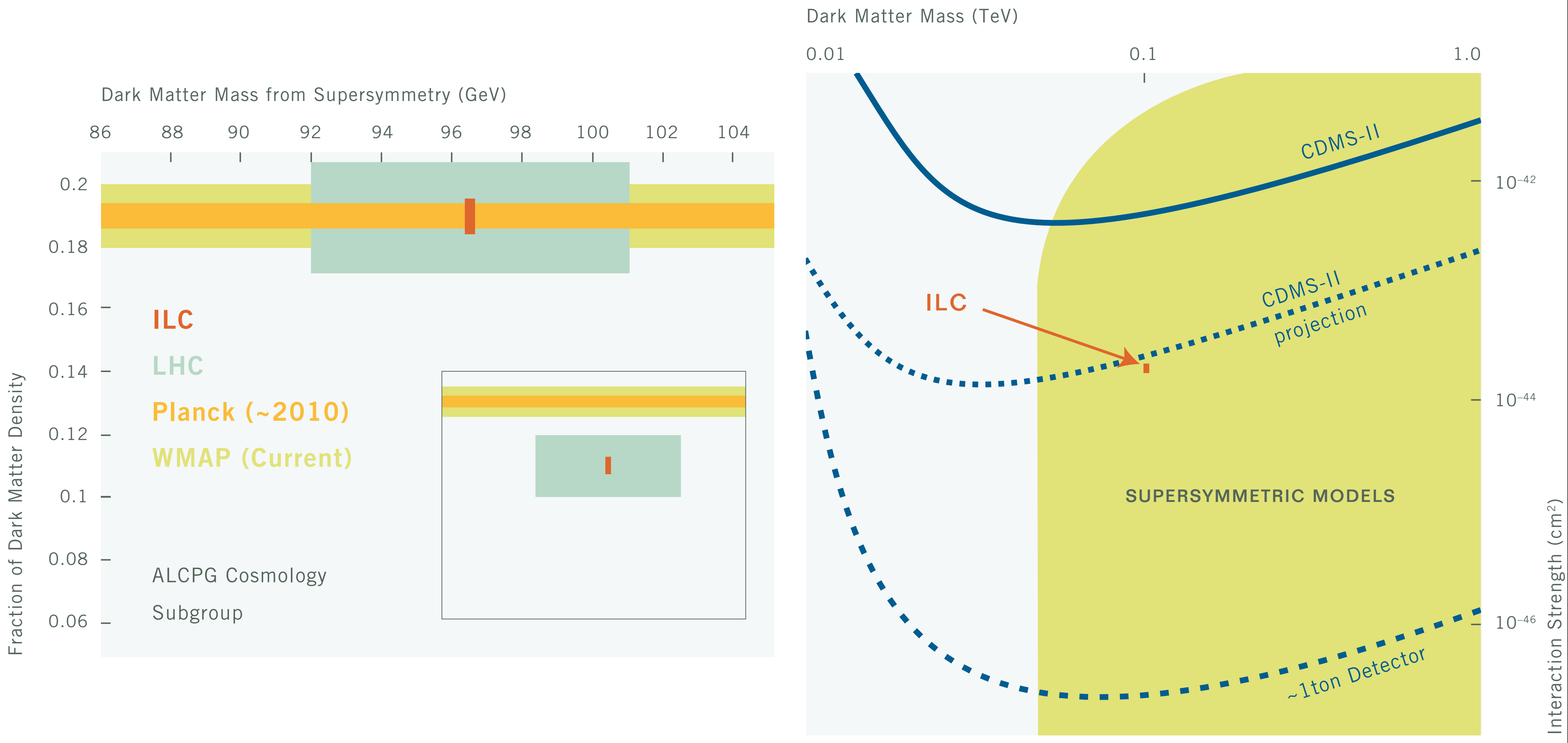
"missing energy" E_{miss}

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

⇒Dark Matter!?

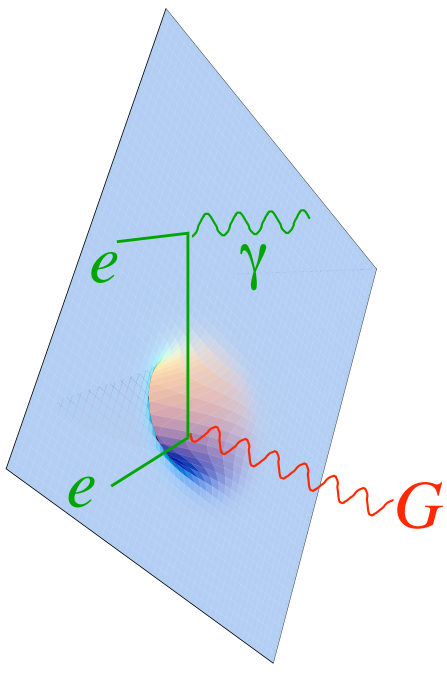


Dark Matter

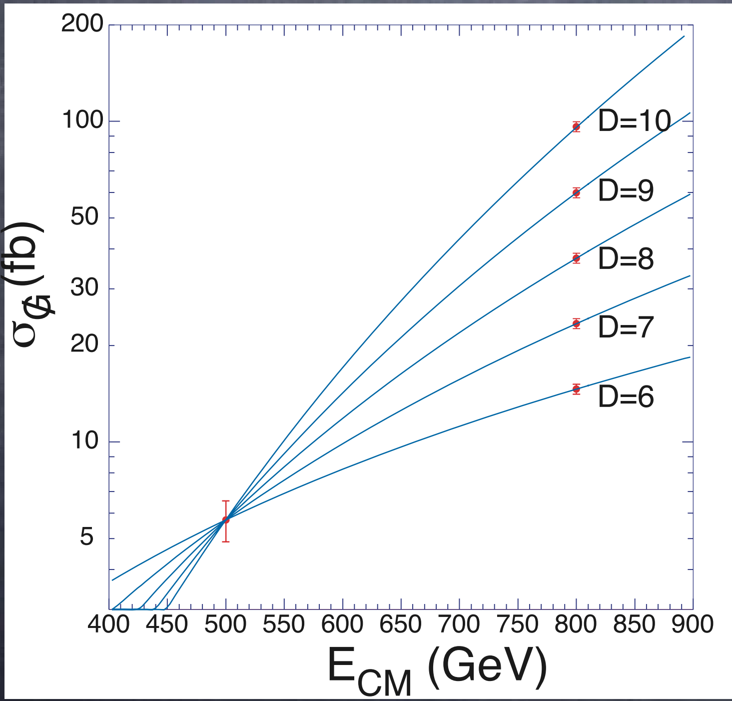


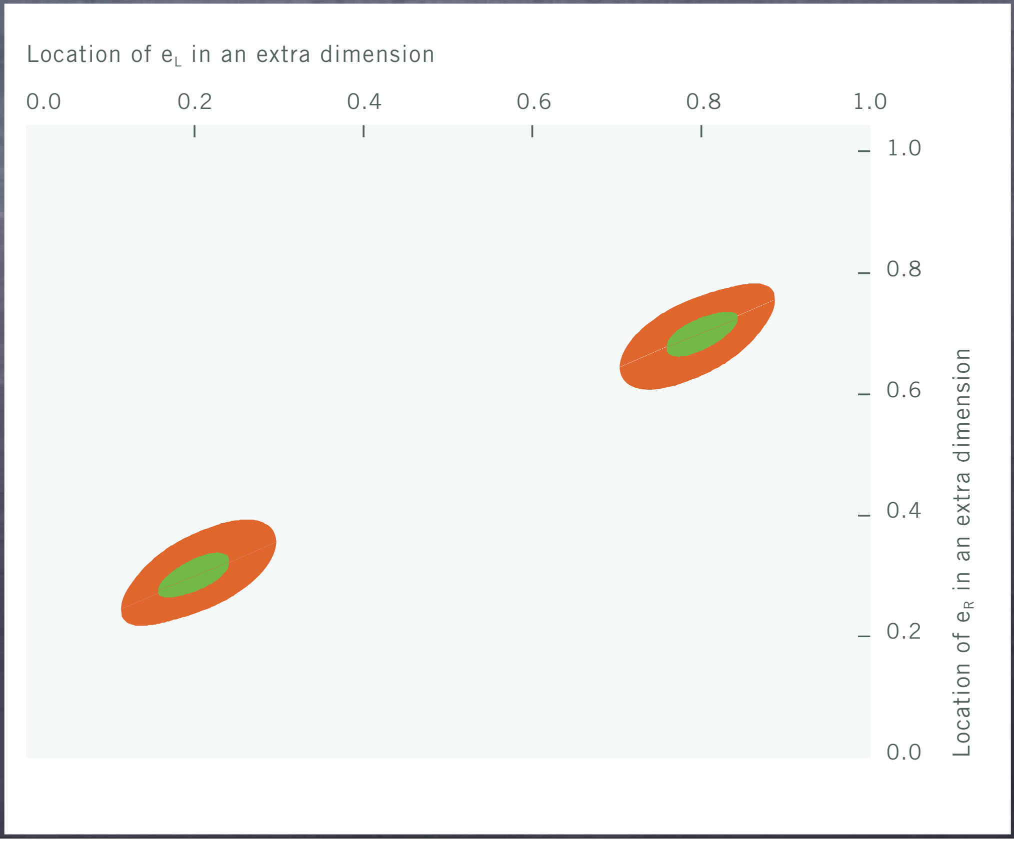
Dark Matter Mass from Supersymmetry (GeV)
86
88
90
92
94
96
98
100
102
104
Fraction of Dark Matter Density
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
ILC
LHC
Planck (~2010)
WMAP (Current)
ALCPG Cosmology Subgroup
Dark Matter Mass (TeV)
0.01
0.1
1.0
CDMS-II
ILC
CDMS-II projection
SUPERSYMMETRIC MODELS
~1ton Detector
10^{-42}
10^{-44}
10^{-46}
Interaction Strength (cm^2)

Extra D



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

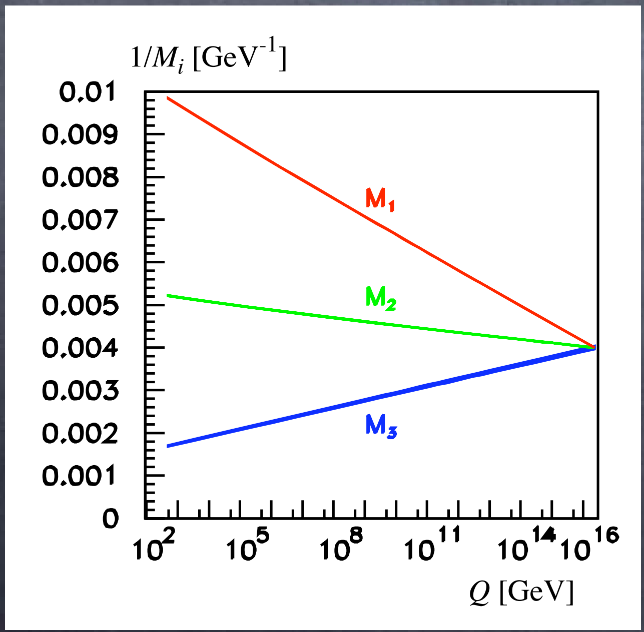




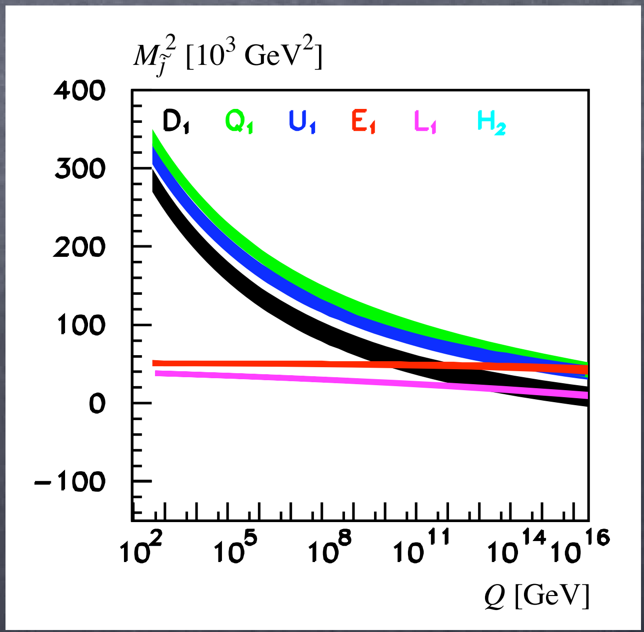
Unification

Do the forces and matter unify?
We know coupling constants appear to unify with supersymmetry

gaugino masses



scalar masses

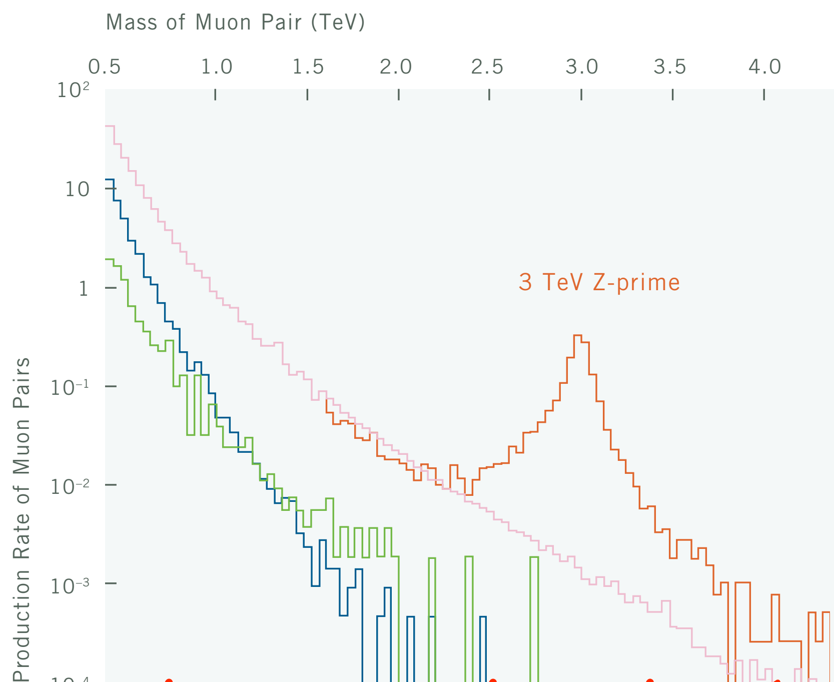


Implications

- There is indeed unification!
- No gauge non-singlet particles below 10^{14}GeV
- Neutrino mass must come from gauge singlet exchange (i.e. seesaw!)
- Constraints on baryogenesis models (strong preference to leptogenesis by ν_R), axion models

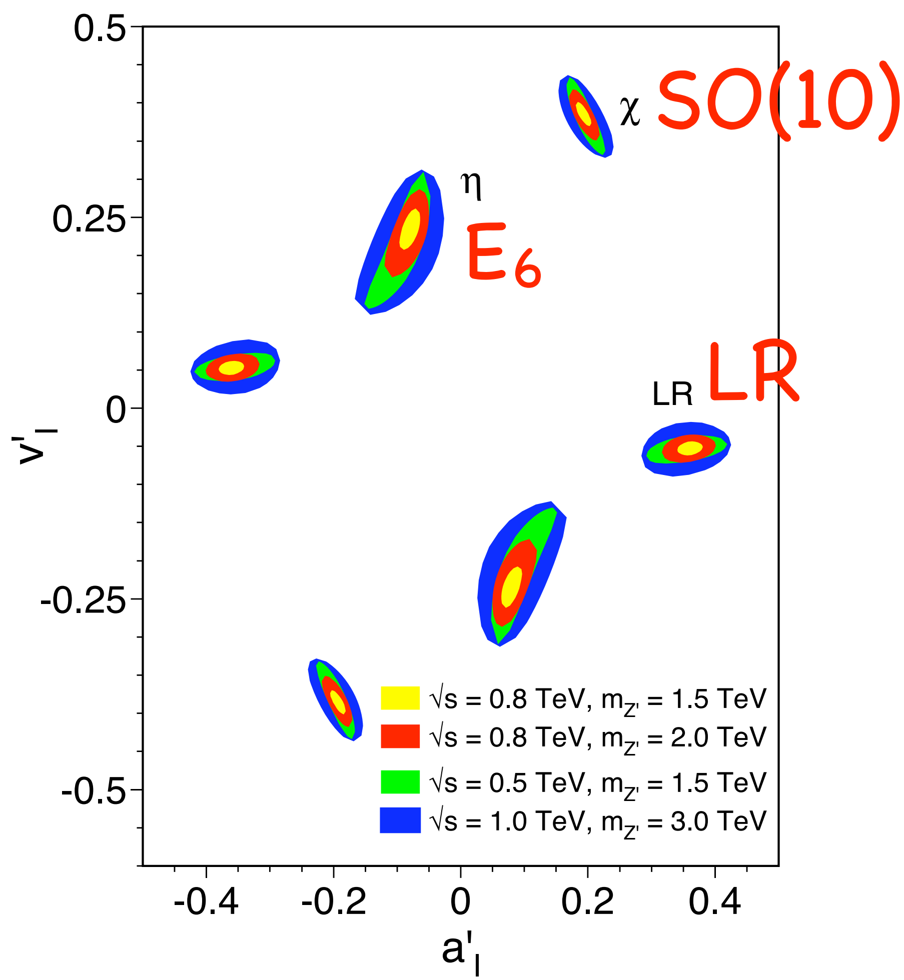
Buckley, HM

New force: Z′



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

What kind of force?



Einstein's Telescope

- With both LHC and ILC, we hope to see way beyond the energy scale we can probe directly, i.e. GUT and string scales