Supersymmetry IV

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PiTP 05, IAS

Plan

Mon: Non-technical Overview

what SUSY is supposed to give us

Tue: From formalism to the MSSM

Global SUSY formalism, Feynman rules, soft SUSY breaking, MSSM

Wed: SUSY breaking

how to break SUSY, mediation mechanisms

Thu: SUSY at colliders

basic reactions, signatures, and how do we know it is SUSY?

Fri: SUSY as a telescope

supersymmetry breaking, GUT, string

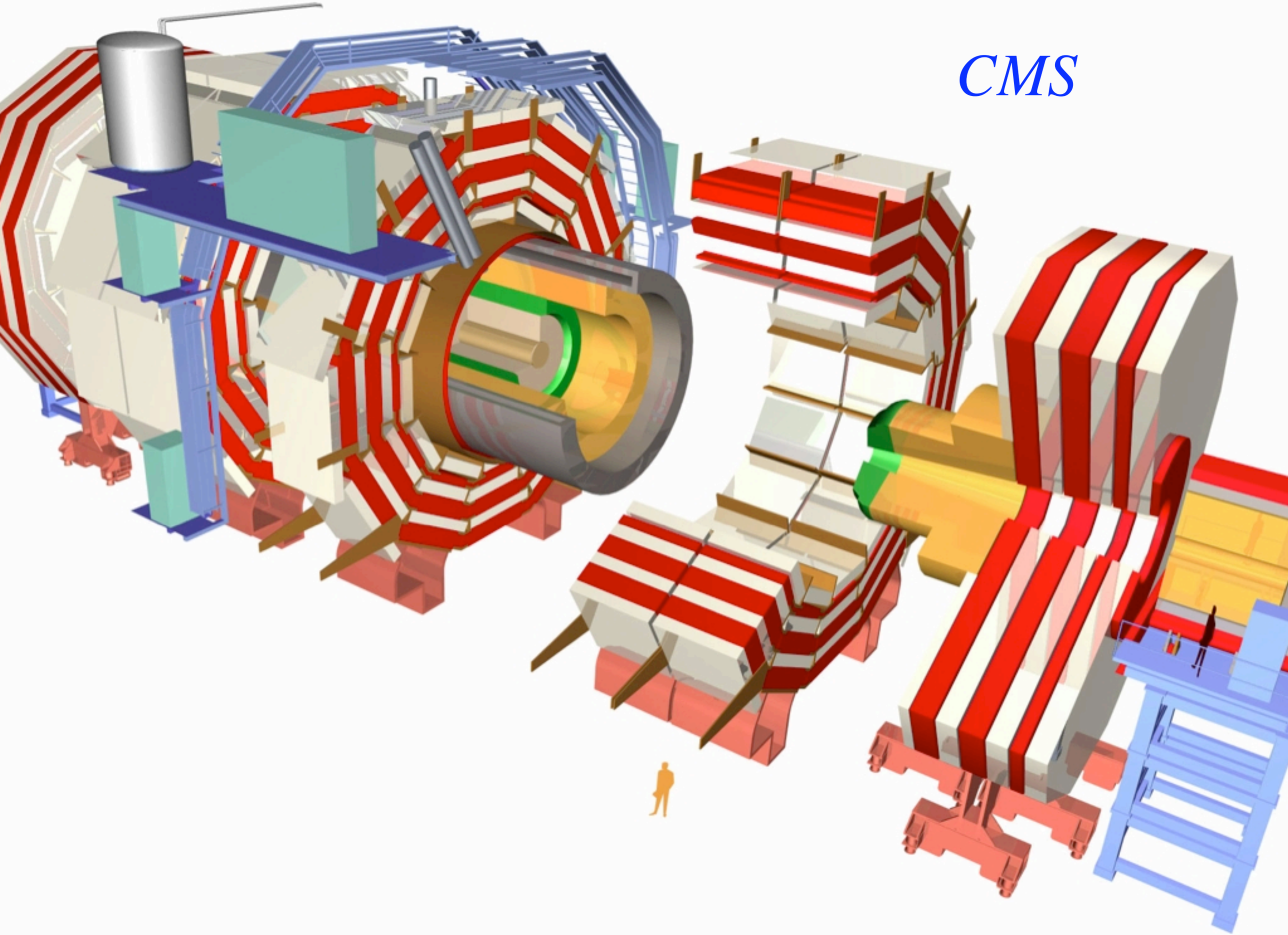
e+e- Linear Collider

Large Hadron Collider (LHC)

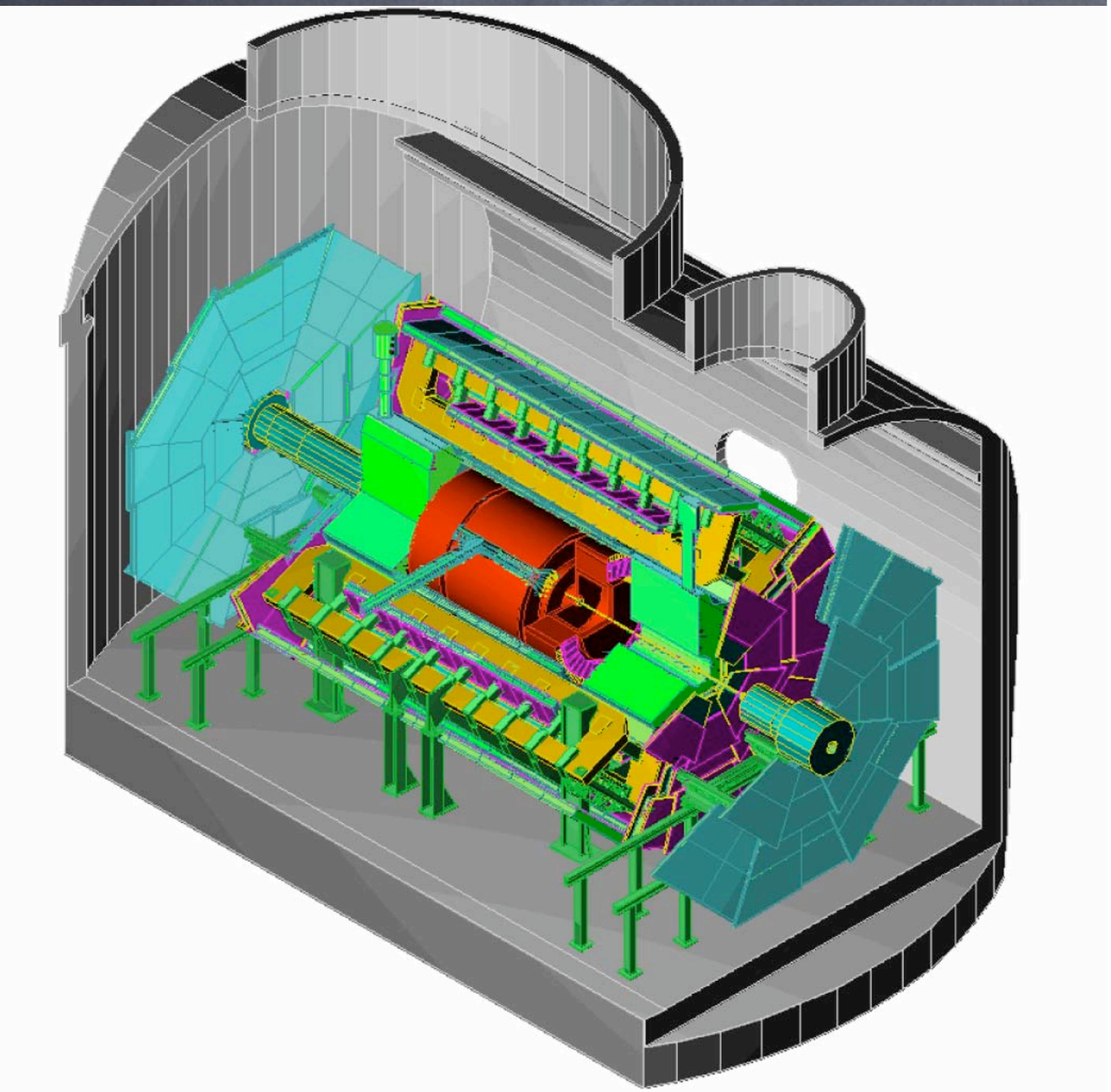
- proton-proton collider
- 14TeV energy

(cf. 2TeV @ Fermilab)

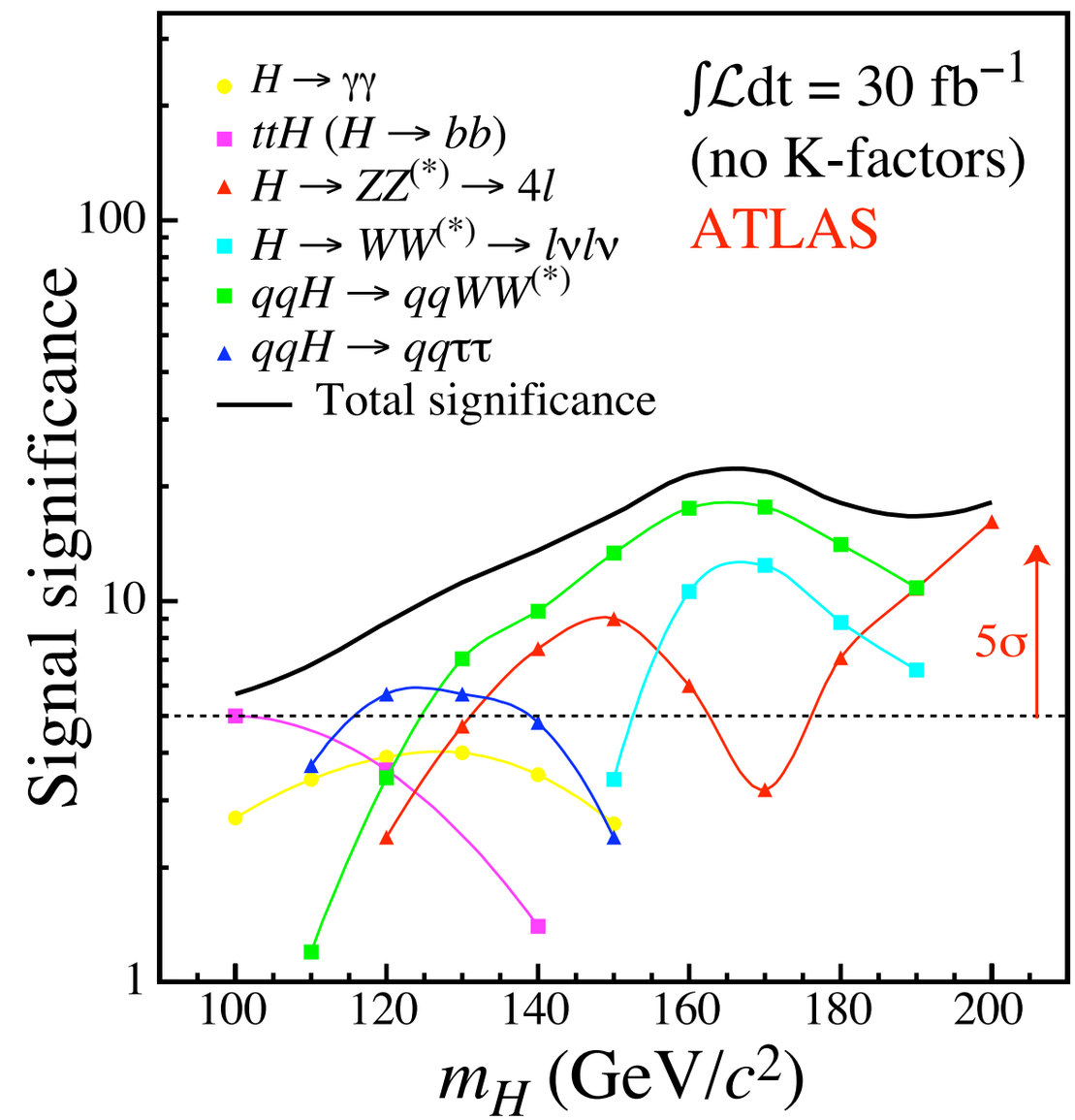
- Under construction at CERN, Geneva
- Turn on in 2007
- Finally reaching the energy Fermi told us about in 1933!


CMS

Higgs at ATLAS

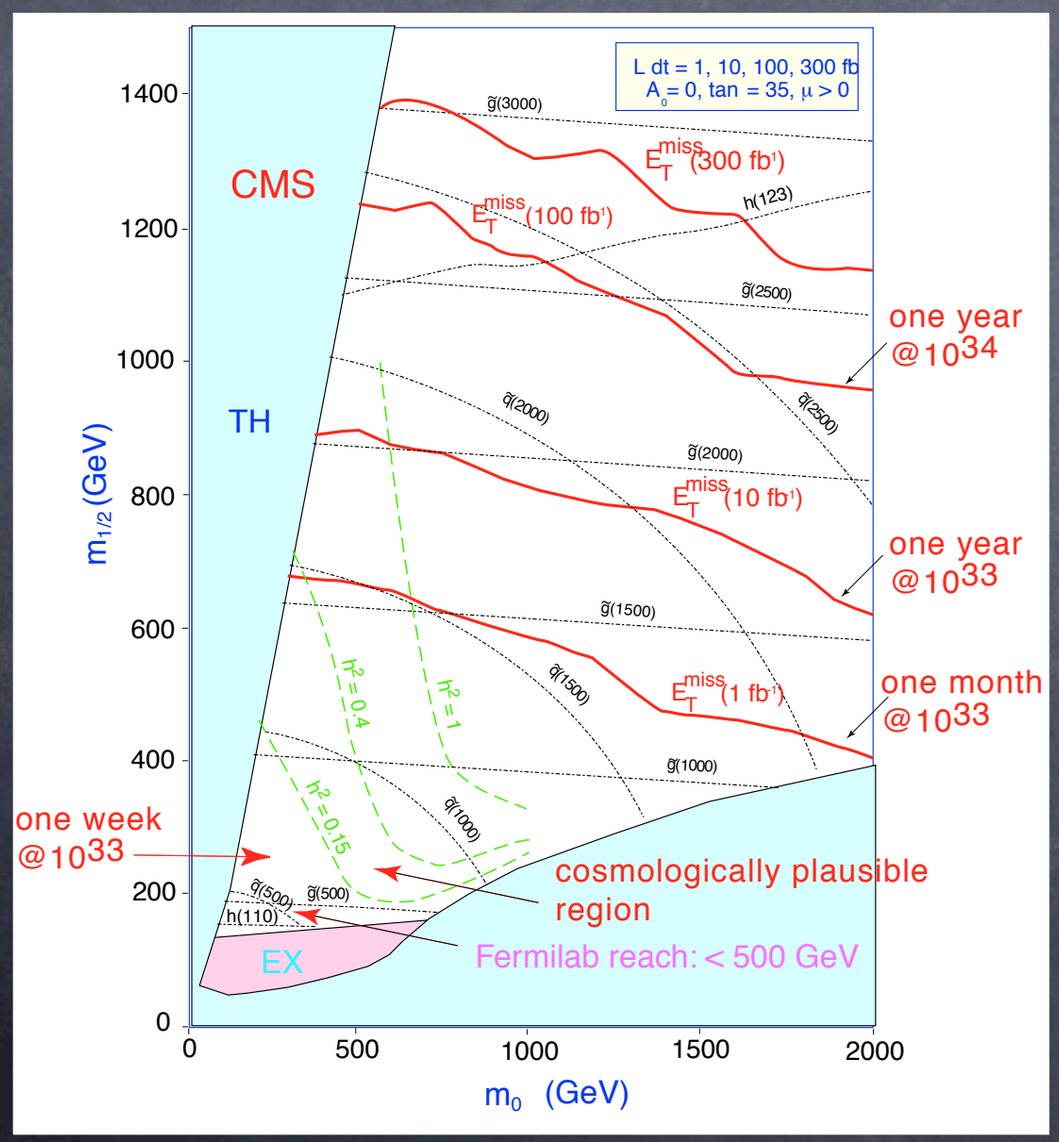


Robust discovery

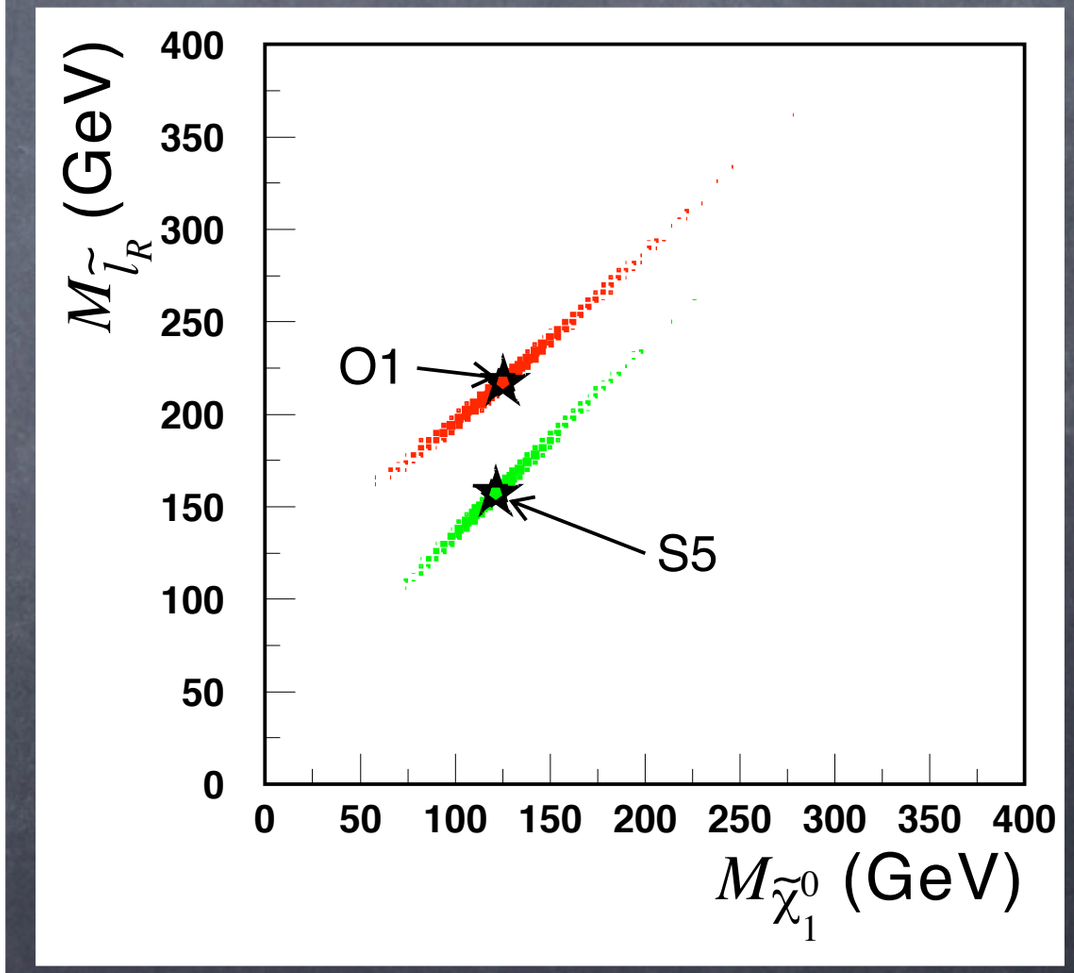


Supersymmetry

Tevatron/LHC will discover

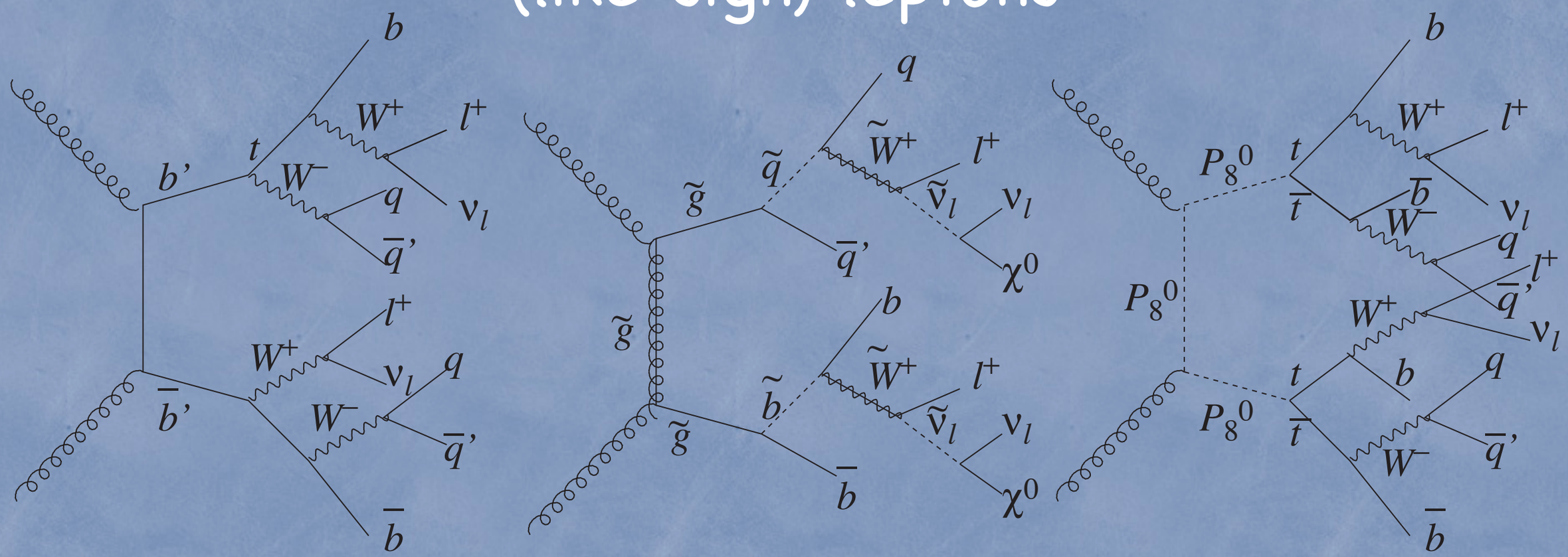


Can do many precision measurements at LHC



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


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

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

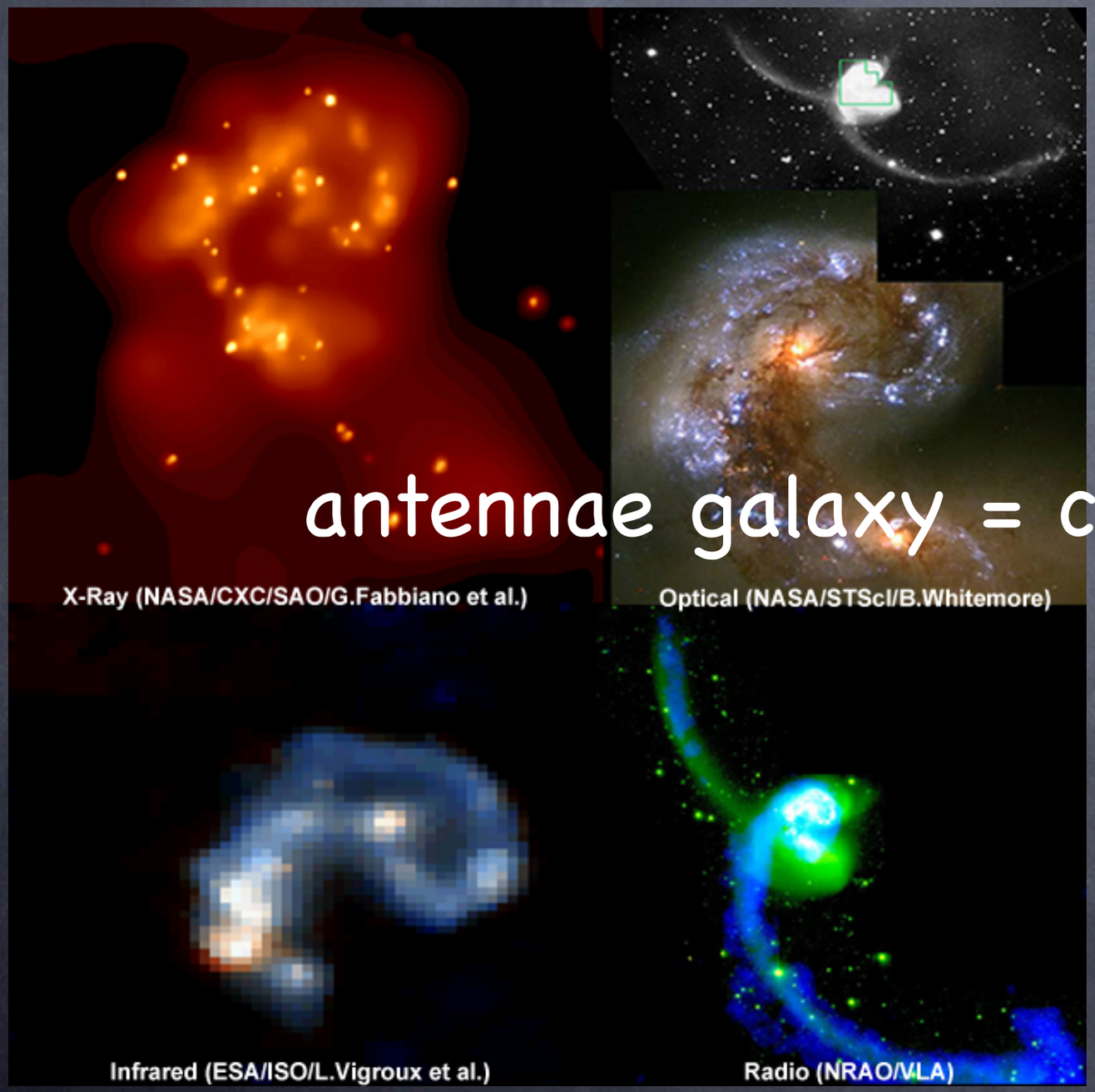
"New-York Times level" confidence

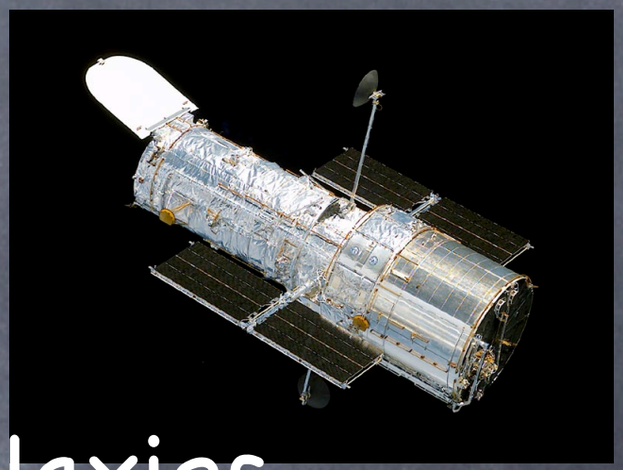
still a long way to

"Halliday-Resnick" level confidence

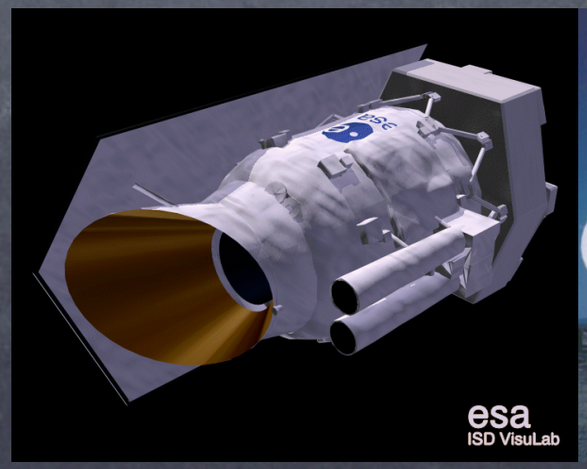
"We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances."

Multiple Wavebands in Astronomy





antennae galaxy = collision of galaxies

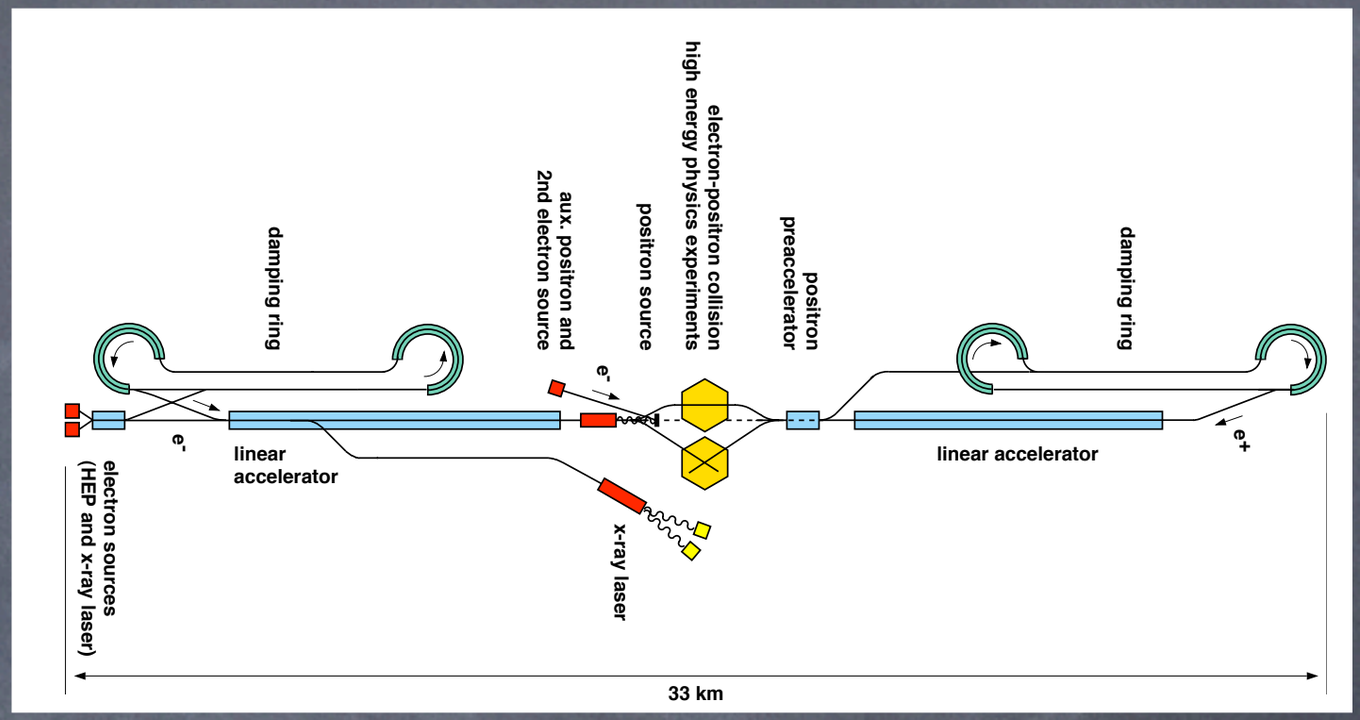


Telescopes vs Accelerators

aim	need	telescopes	accelerators
probe deeper	better resolution	better mirrors, CCD	higher energy
better image	better exposure	larger telescopes, more time	more powerful beams (luminosity)
full understanding	multiple probes	visible, radio, X-ray, infrared, UV, gamma	protons, electrons, neutrinos

Linear Collider

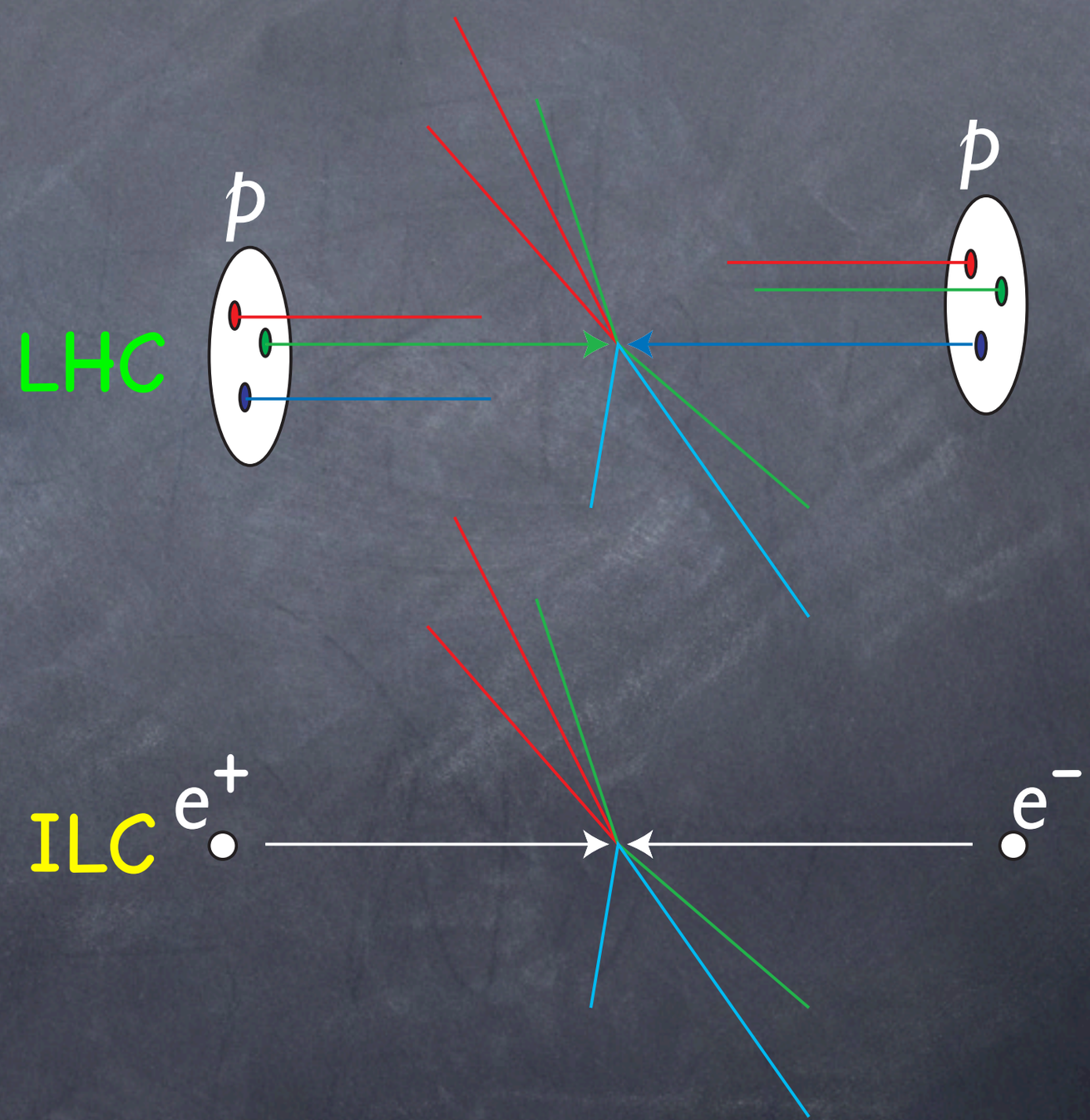
- Electron-positron collider
- e^-, e^+ point-like with no structure
- Well-understood environment
- Linear instead of ring to avoid synchrotron loss
- Super-high-tech machine
- Accelerate the beam over >15km
- Focus beam down to a few nanometers and make them collide



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	under construction	needs to finish design

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
  - trilinear and quartic scalar couplings

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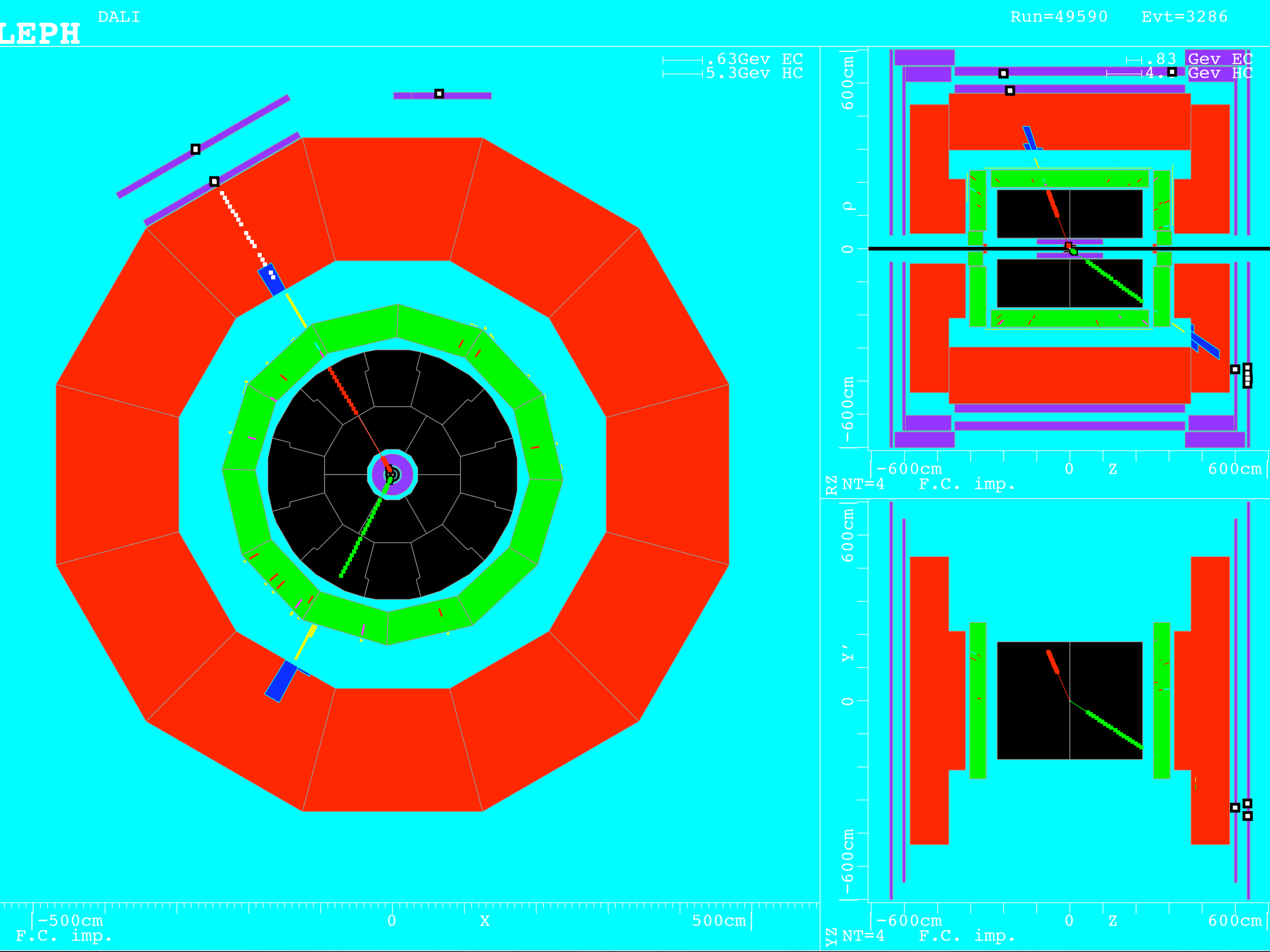
mass


LEPH
DALI
Run=49590 Evt=3286
.63Gev EC
5.3Gev HC
-500cm
0
X
500cm
F.C. imp.
.83 Gev EC
4. Gev HC
600cm
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.

Two-body kinematics

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

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

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

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

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

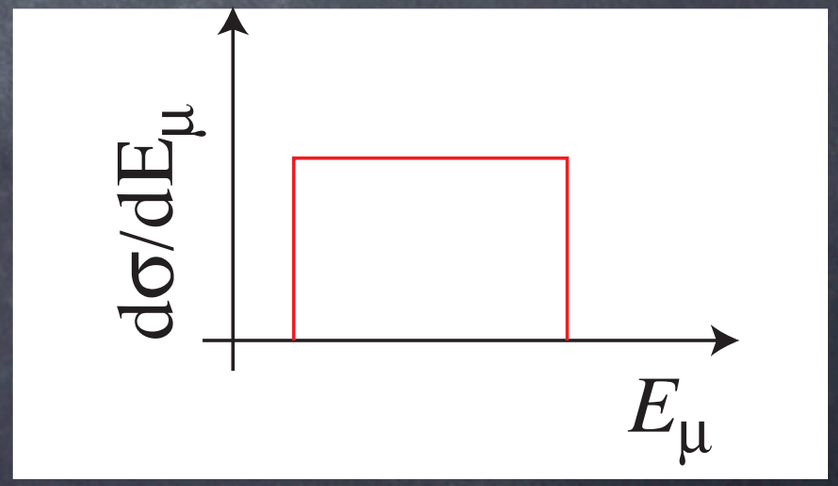
- In the smuon rest frame $\hat{p}_\mu = \frac{m_{\tilde{\mu}}}{2}\left(1 - \frac{m^2_{\tilde{\chi}^0}}{m^2_{\tilde{\mu}}}\right)(1, \sin\hat{\theta}, 0, \cos\hat{\theta})$
- In the lab frame $\gamma_{\tilde{\mu}} = \frac{E_{\tilde{\mu}}}{m_{\tilde{\mu}}} = \frac{\sqrt{s}}{2m_{\tilde{\mu}}}$ $\quad \beta_{\tilde{\mu}}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

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

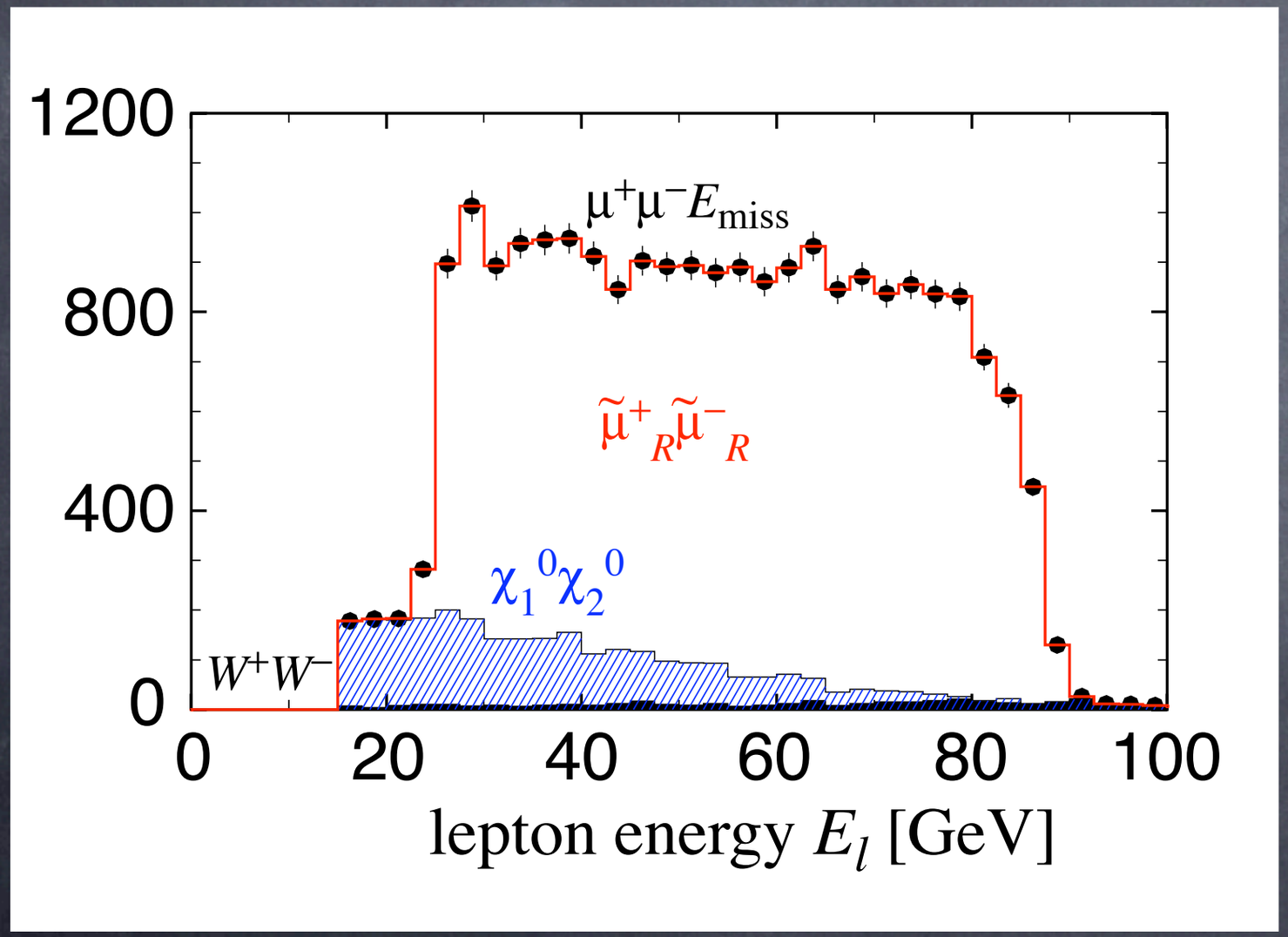
- Therefore, the muon energy is

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

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



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

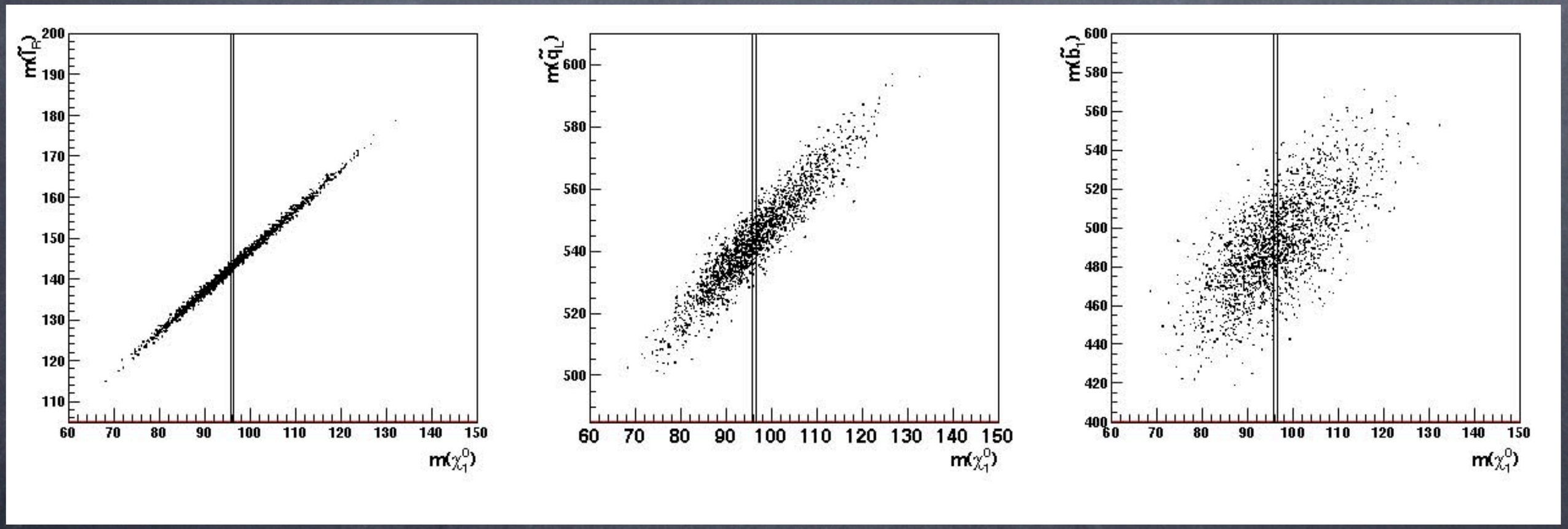


- fit to the kinetic distribution

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

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

LHC/LC synergy



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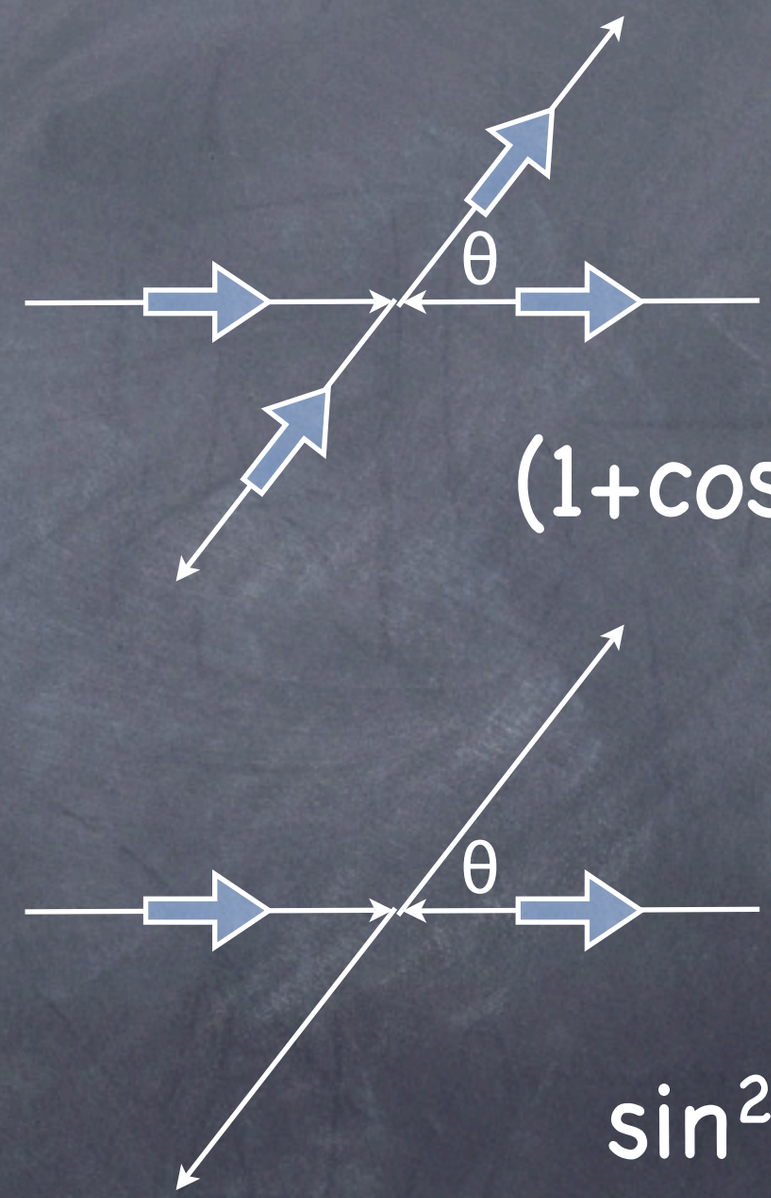
Spin

Spin

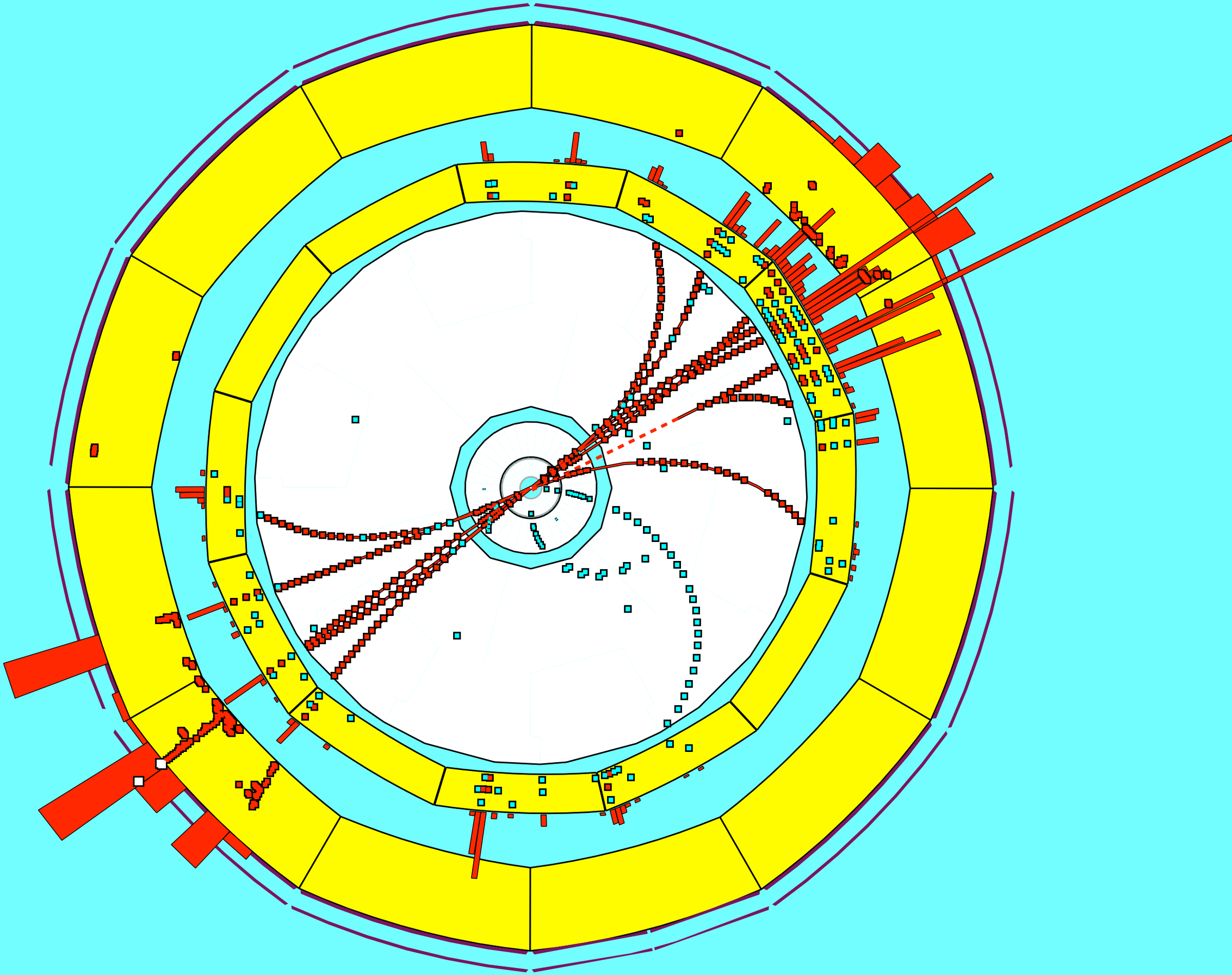
- production angle distribution well above the threshold:
- spin 1/2
- spin 0



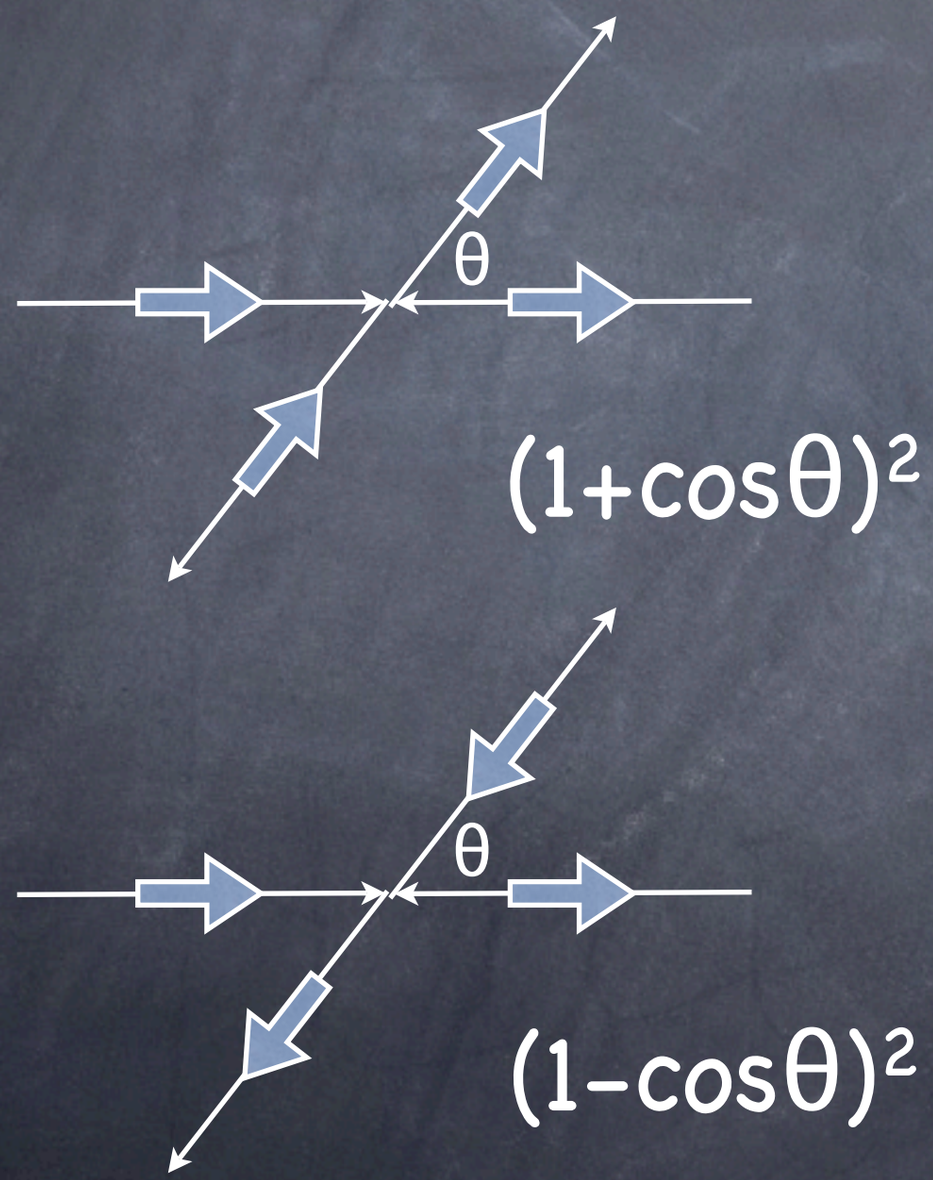
$(1+\cos\theta)^2$

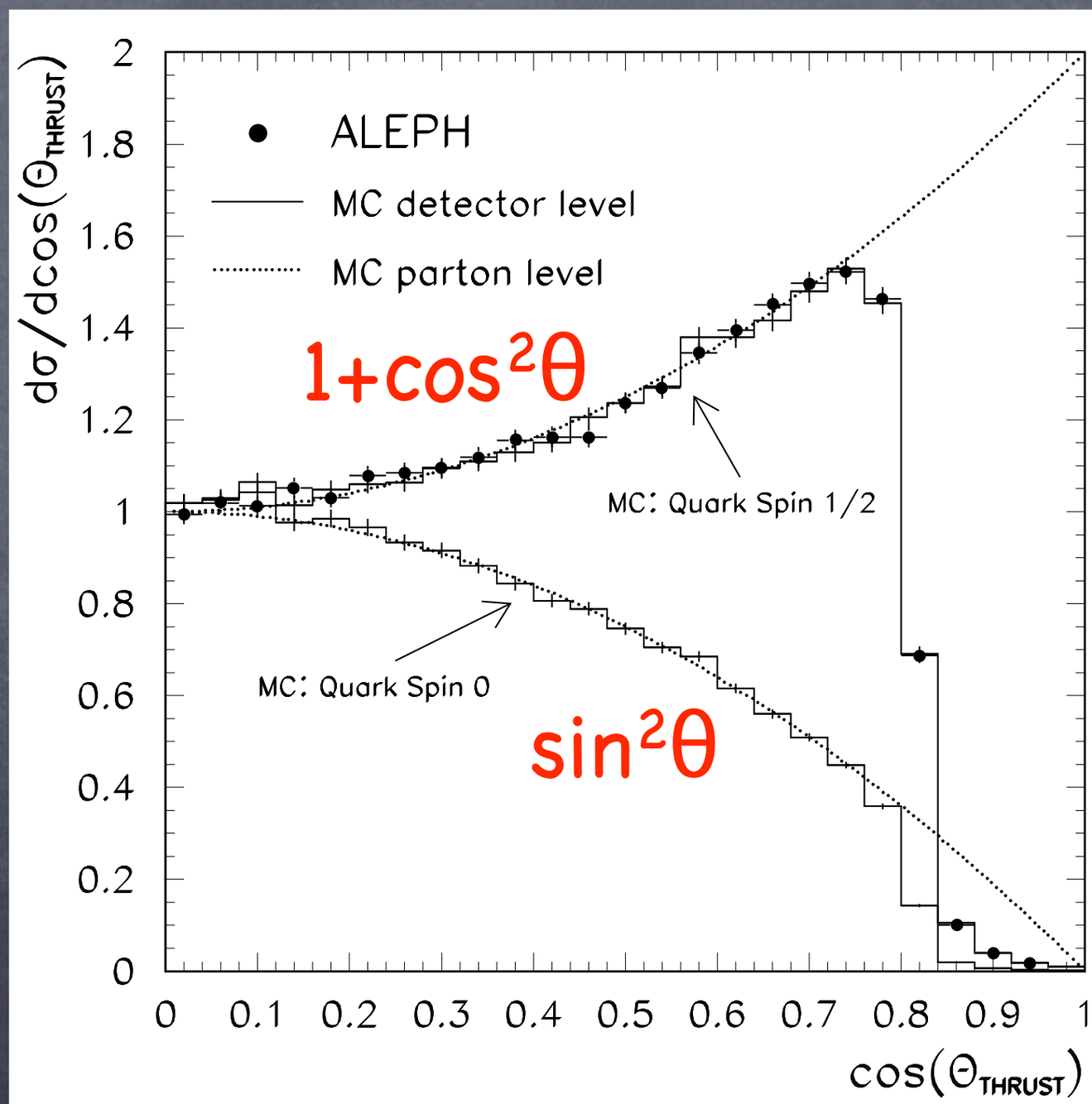
$\sin^2\theta$

ALEPH DALI Run=15768 Evt=5906

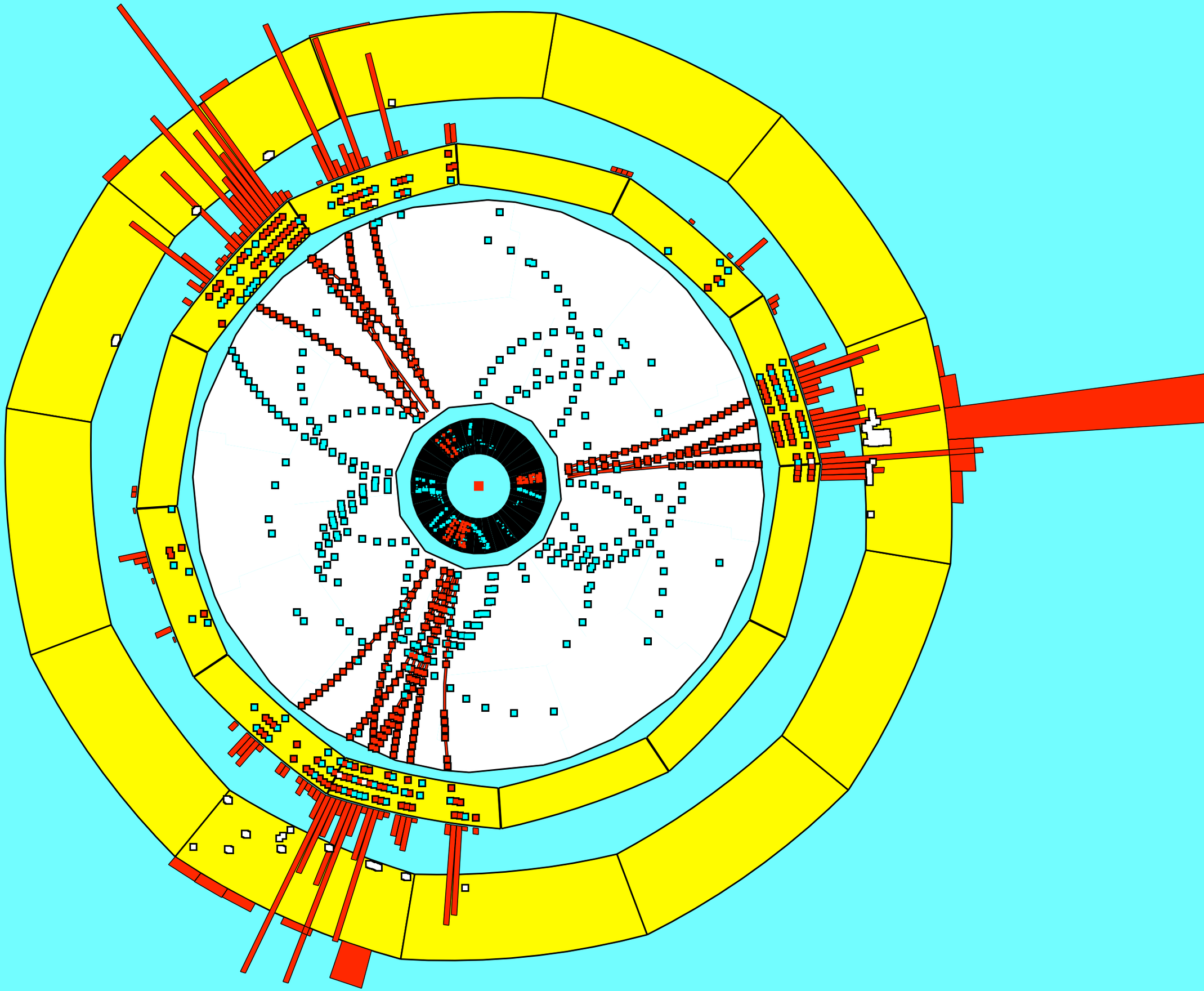


"New particle" has spin 1/2

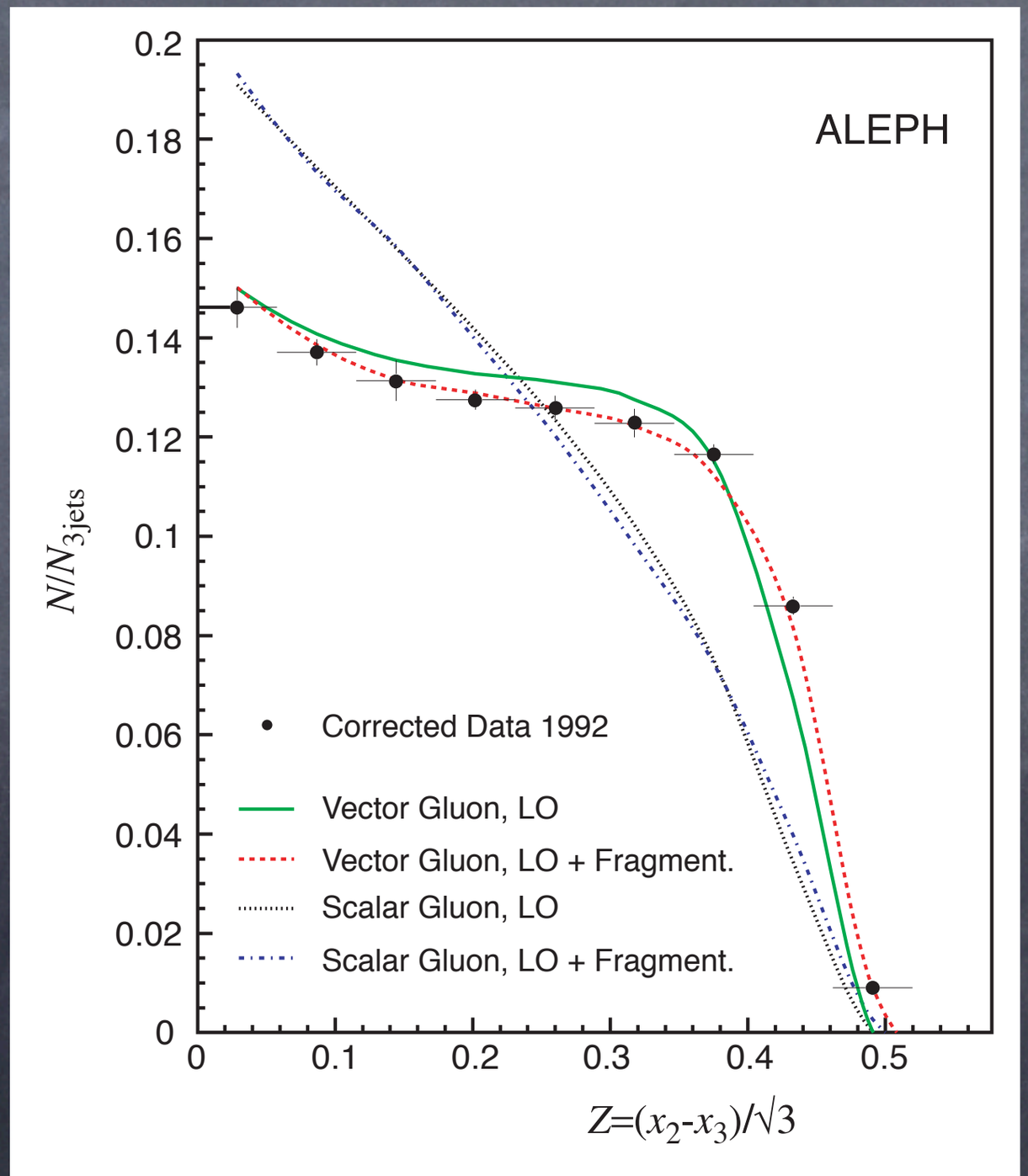


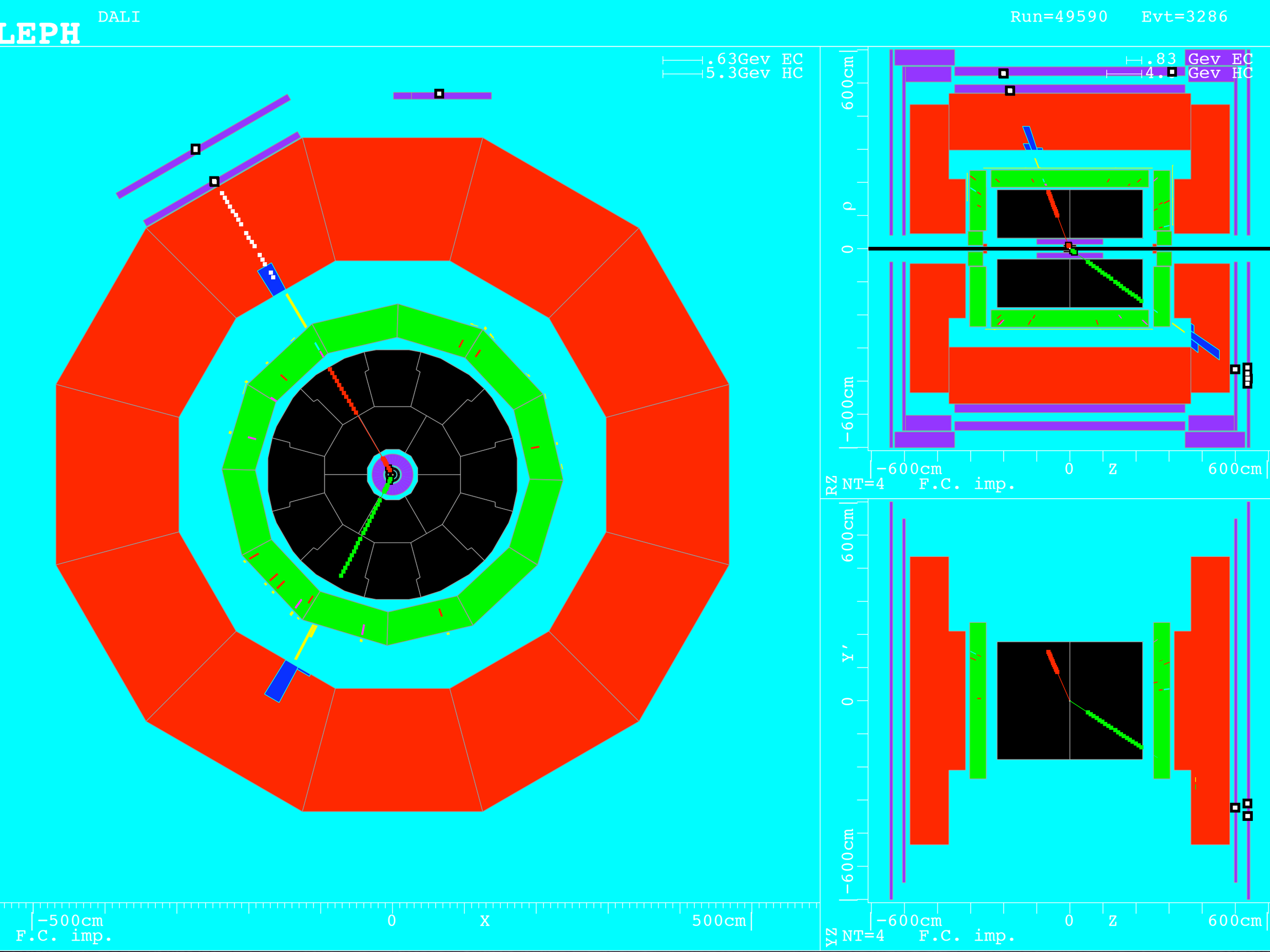


ALEPH DALI Run=9063 Evt=7848



"New particle" has spin 1




LEPH
DALI
Run=49590 Evt=3286
.63Gev EC
5.3Gev HC
-500cm
0
X
500cm
F.C. imp.
.83 Gev EC
4. Gev HC
600cm
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.

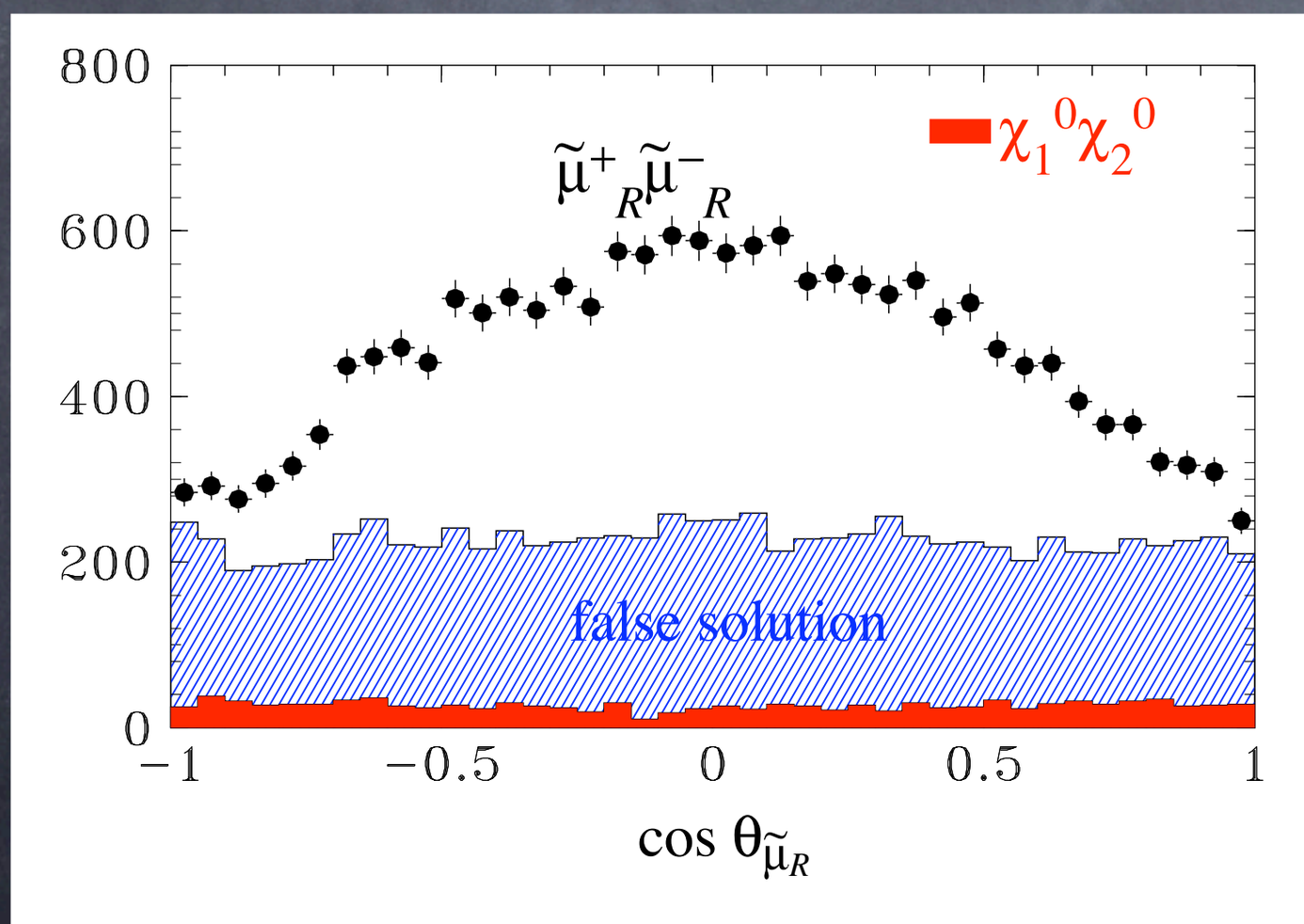
Smuon production

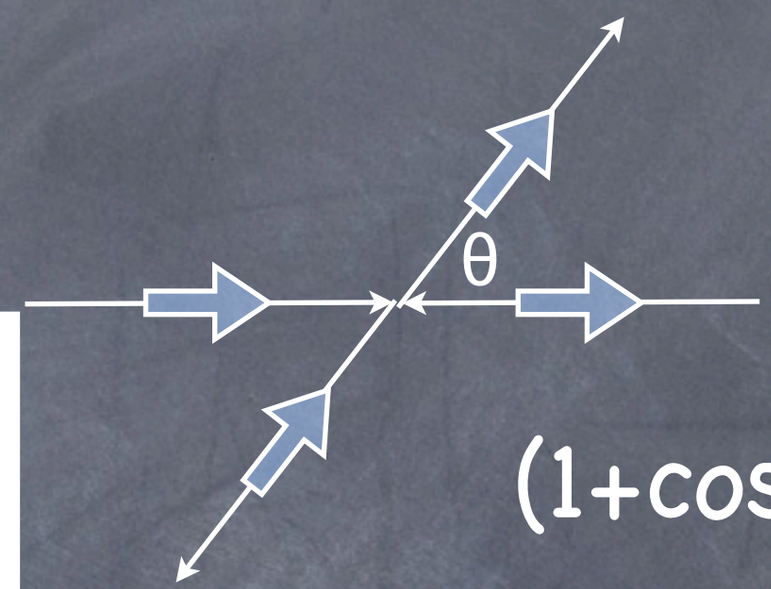
- $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \to (\mu^+\tilde{\chi}_1^0)(\mu^-\tilde{\chi}_1^0)$
- once masses known, you can solve kinematics up to a two-fold ambiguity
- muon momenta measured: $p^\mu_{1,2} = (E_{1,2}, \vec{p}_{1,2})$
- neutralino momenta: $q^\mu_{1,2} = \left(\frac{\sqrt{s}}{2} - E_{1,2},\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

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

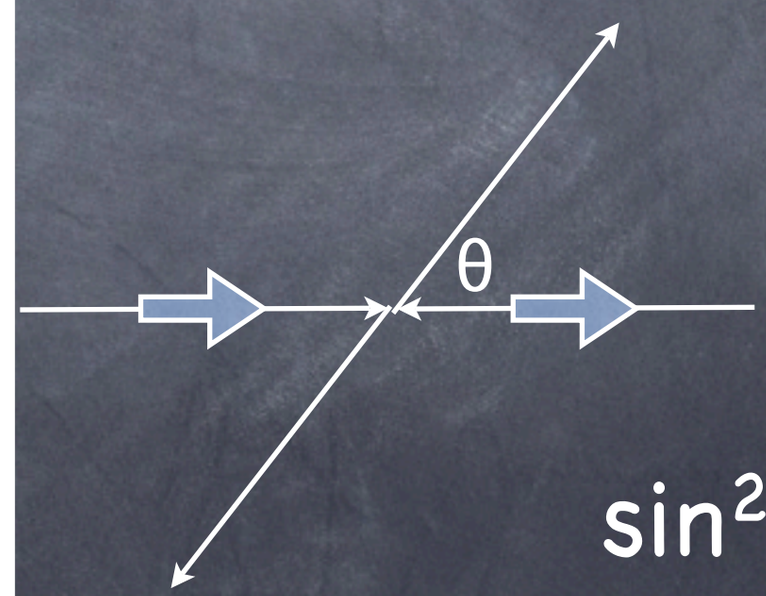
  - Now know $|\vec{q}_1|,\ \vec{p}_1 \cdot \vec{q}_1,\ \vec{p}_2 \cdot \vec{q}_1$
  - Know $\vec{q}_1$ up to a two-fold ambiguity

Smuon has spin 0





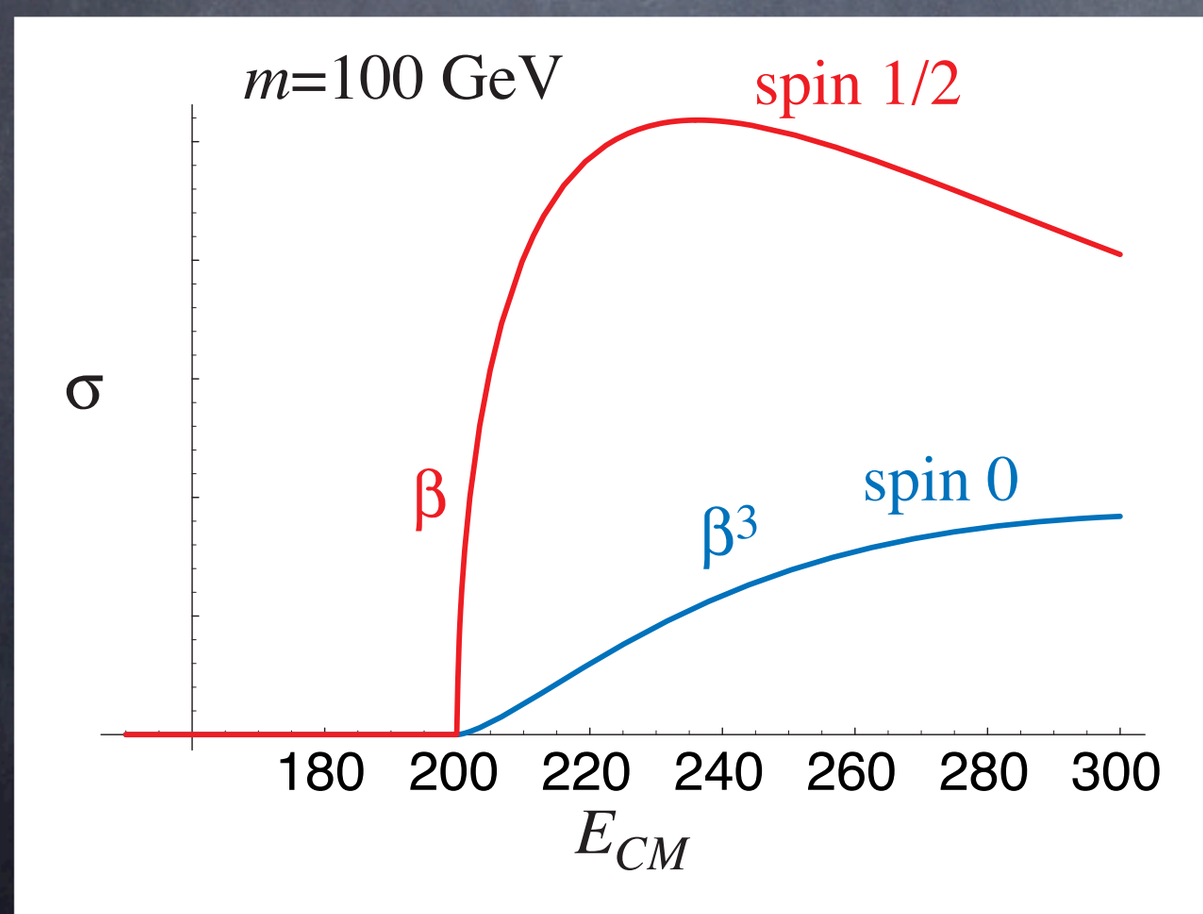
$(1+\cos\theta)^2$

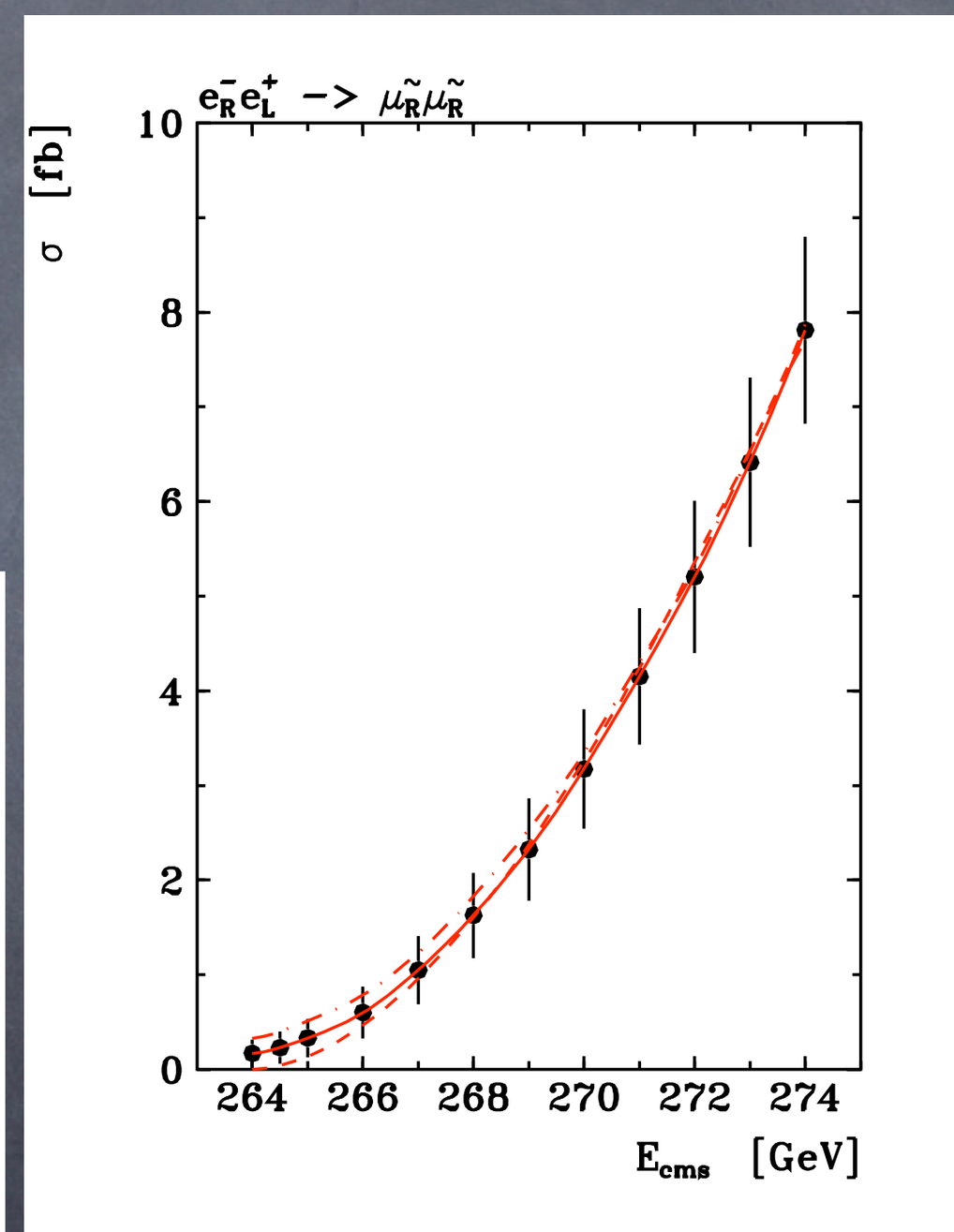


$\sin^2\theta$

Spin

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





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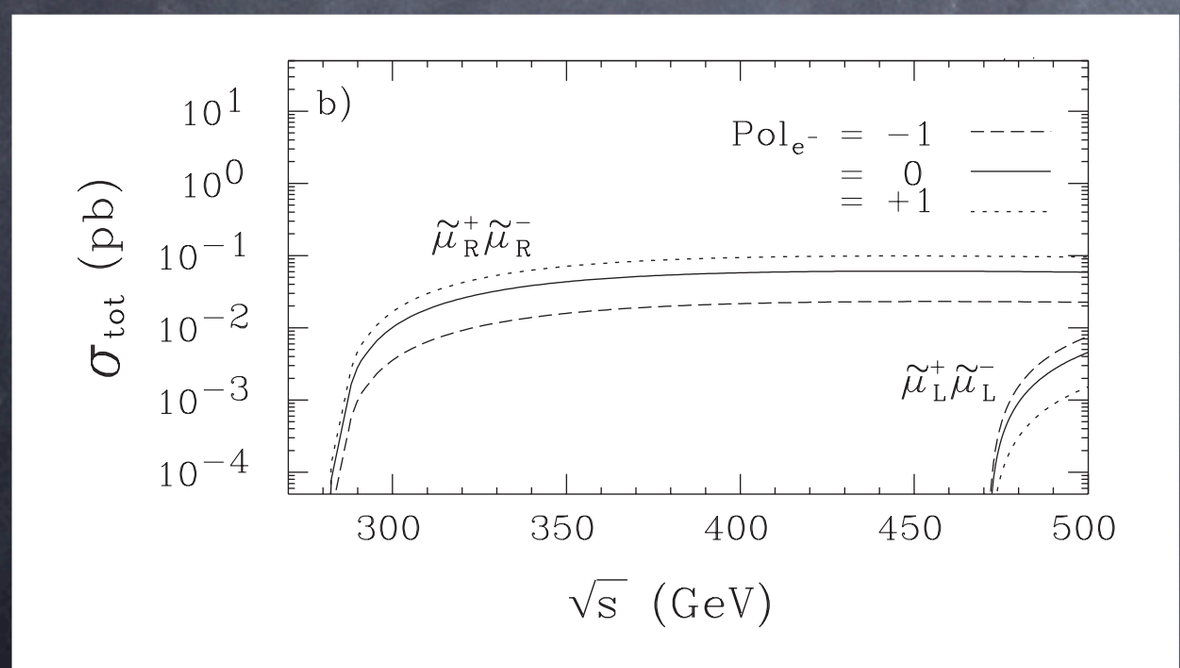
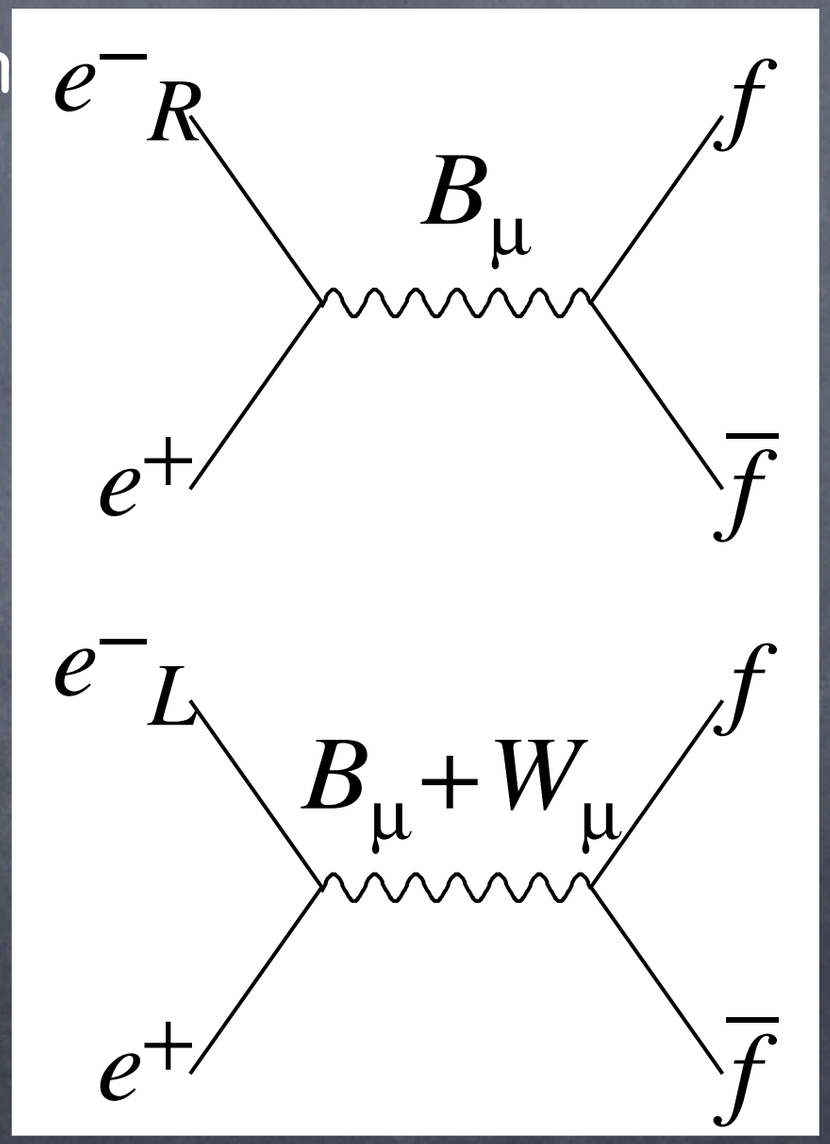
gauge quantum numbers

polarization

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





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

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

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Disentangle mixings

gauginos, higgsinos

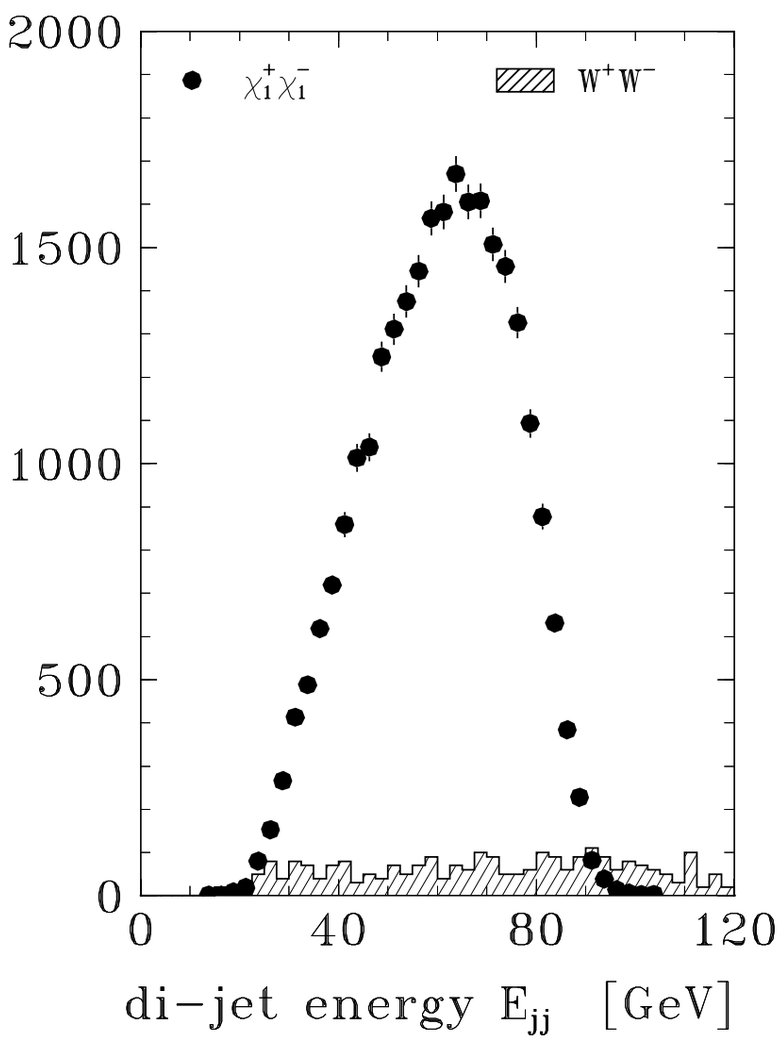
- charged ones "charginos"

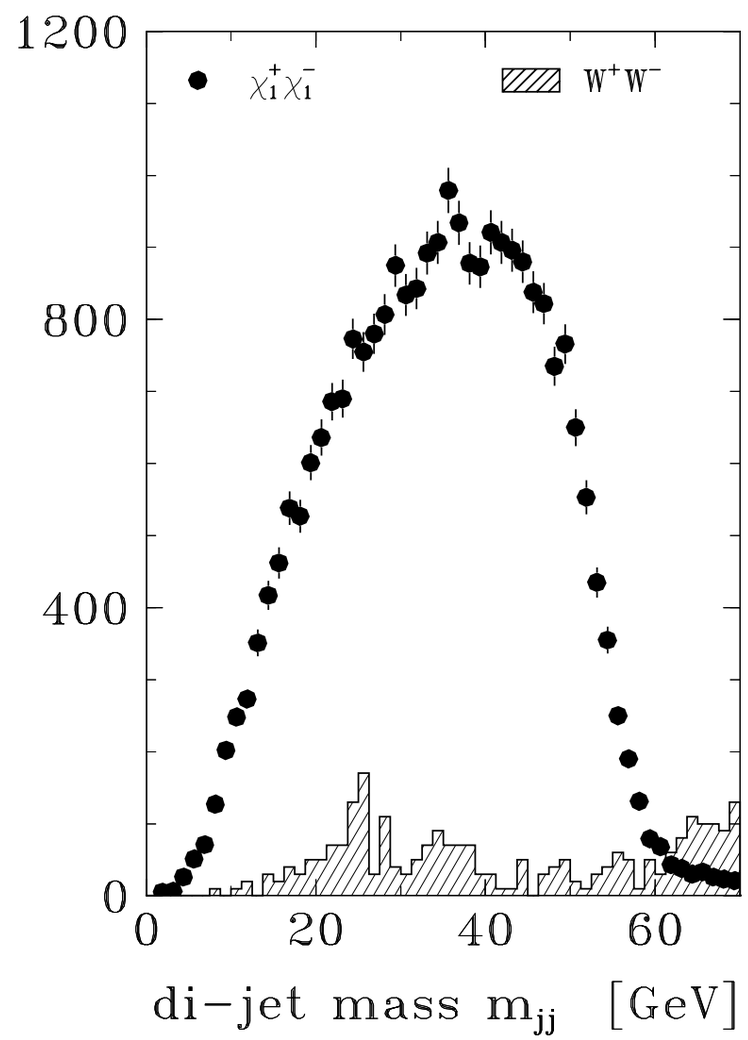
$$(\tilde{W}^- \ \tilde{H}_d^-)\begin{pmatrix} M_2 & \sqrt{2}m_W \sin\beta \\ \sqrt{2}m_W \cos\beta & \mu \end{pmatrix}\begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}$$

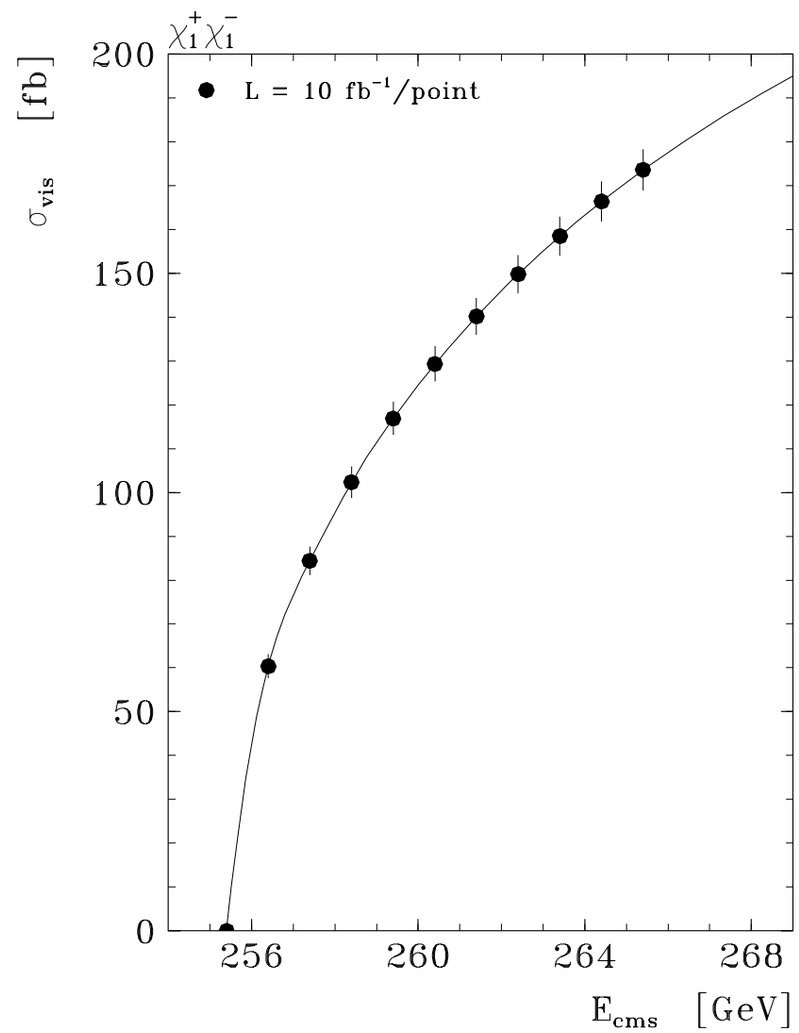
- neutral ones "neutralinos"

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

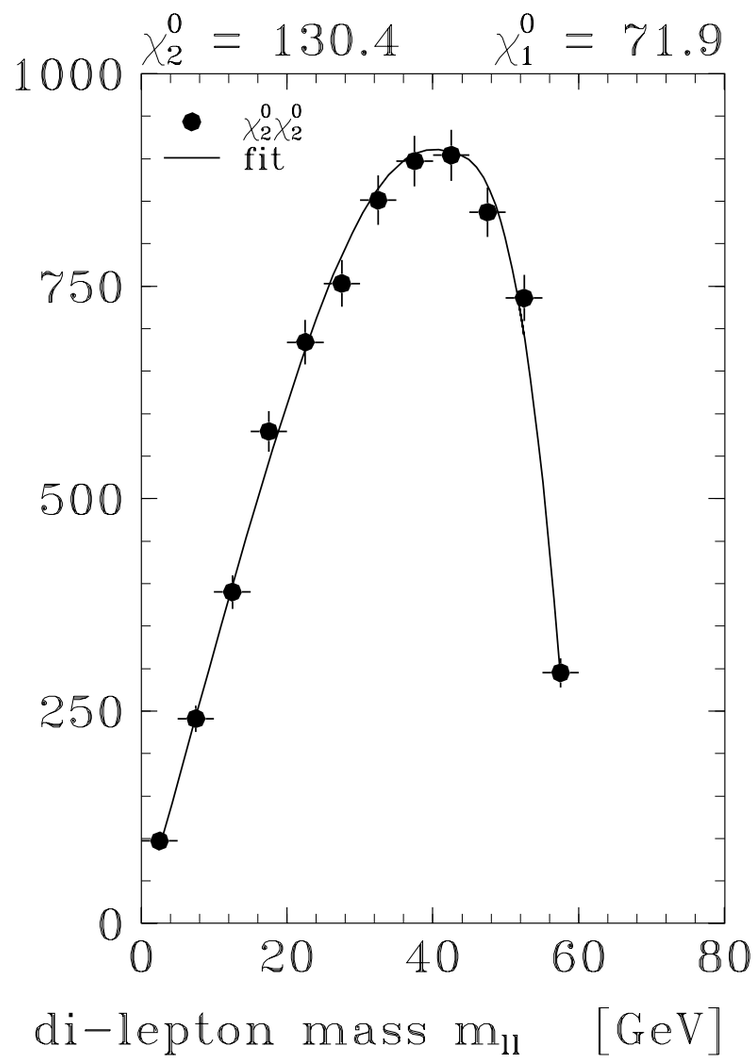
$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to (\tilde{\chi}_1^0 l^\pm \nu_l)(\tilde{\chi}_1^0 q\bar{q}')$$

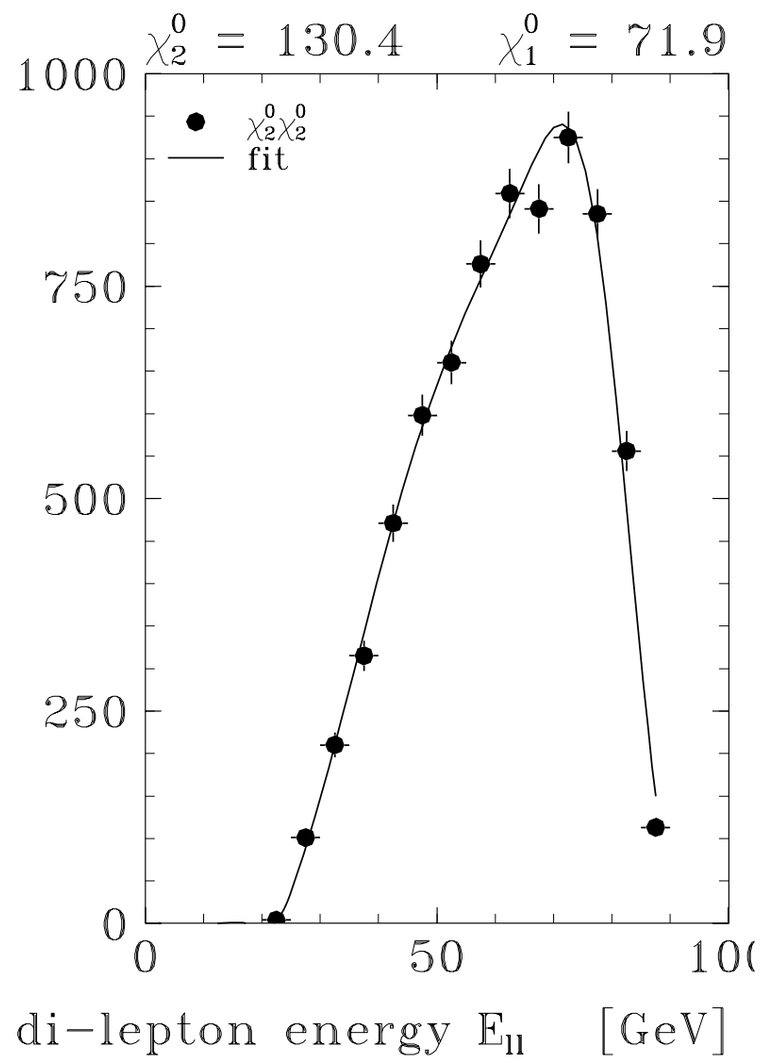


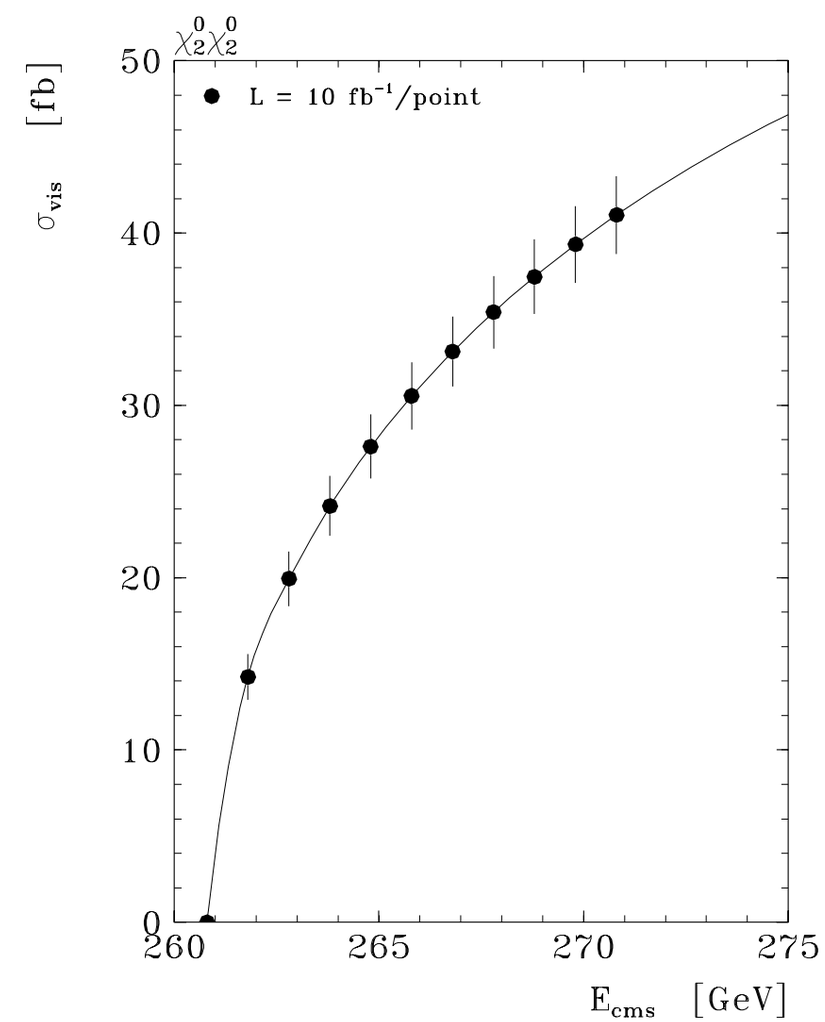




$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to (\tilde{\chi}_1^0 l^+ l^-)(\tilde{\chi}_1^0 l'^+ l'^-)$$





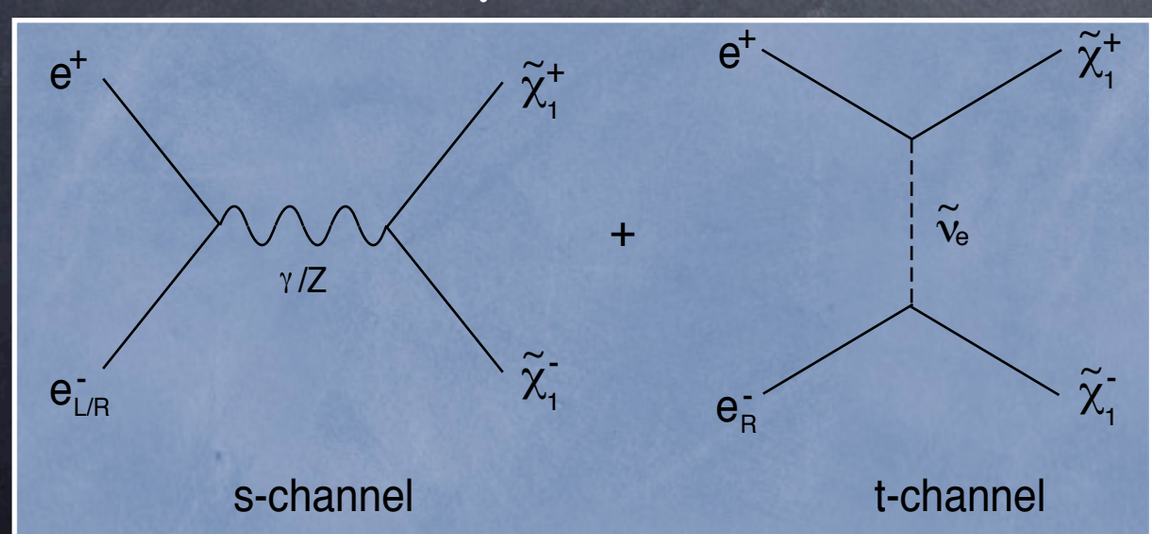


Model-independent parameter determination

- 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

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

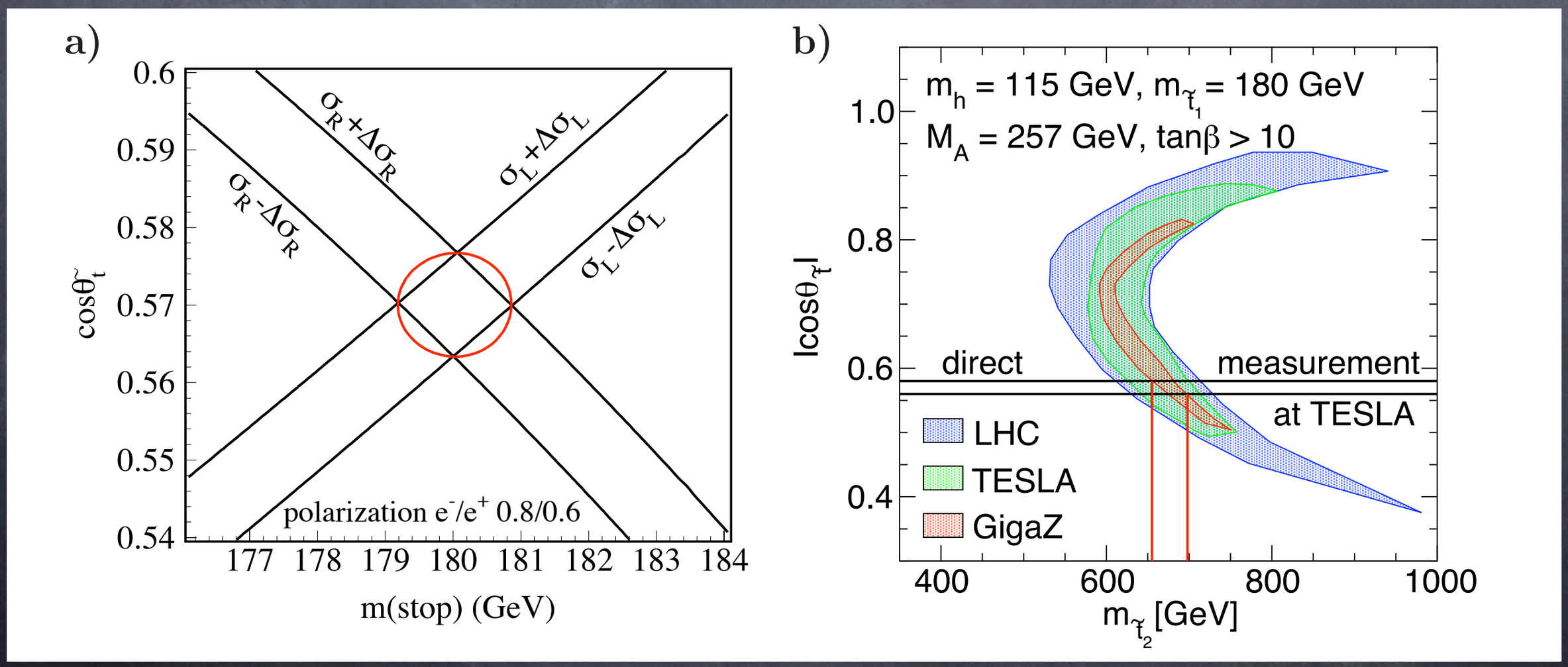
- can measure 3x2 chargino cross sections
- depend on masses of $\tilde{\nu}_e$, $\tilde{e}_L$, $\tilde{e}_R$



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

Stop

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



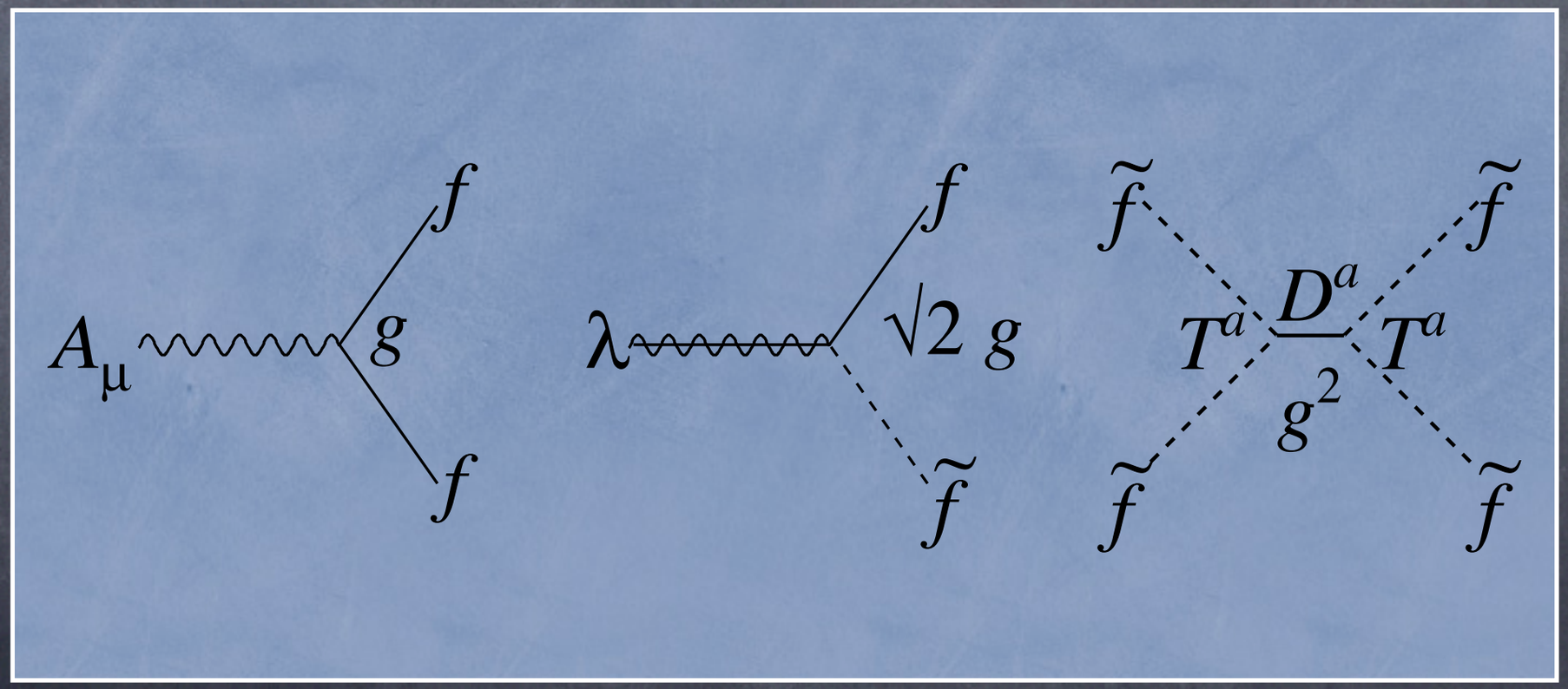
Reconstruct Lagrangian from data

- 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
  - trilinear and quartic scalar couplings

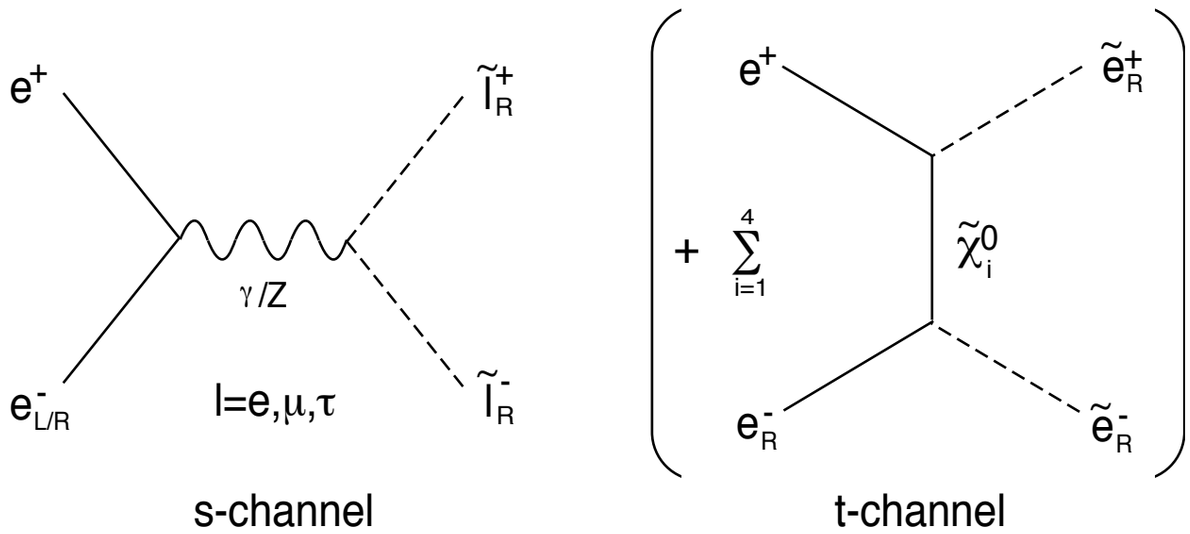
Interaction

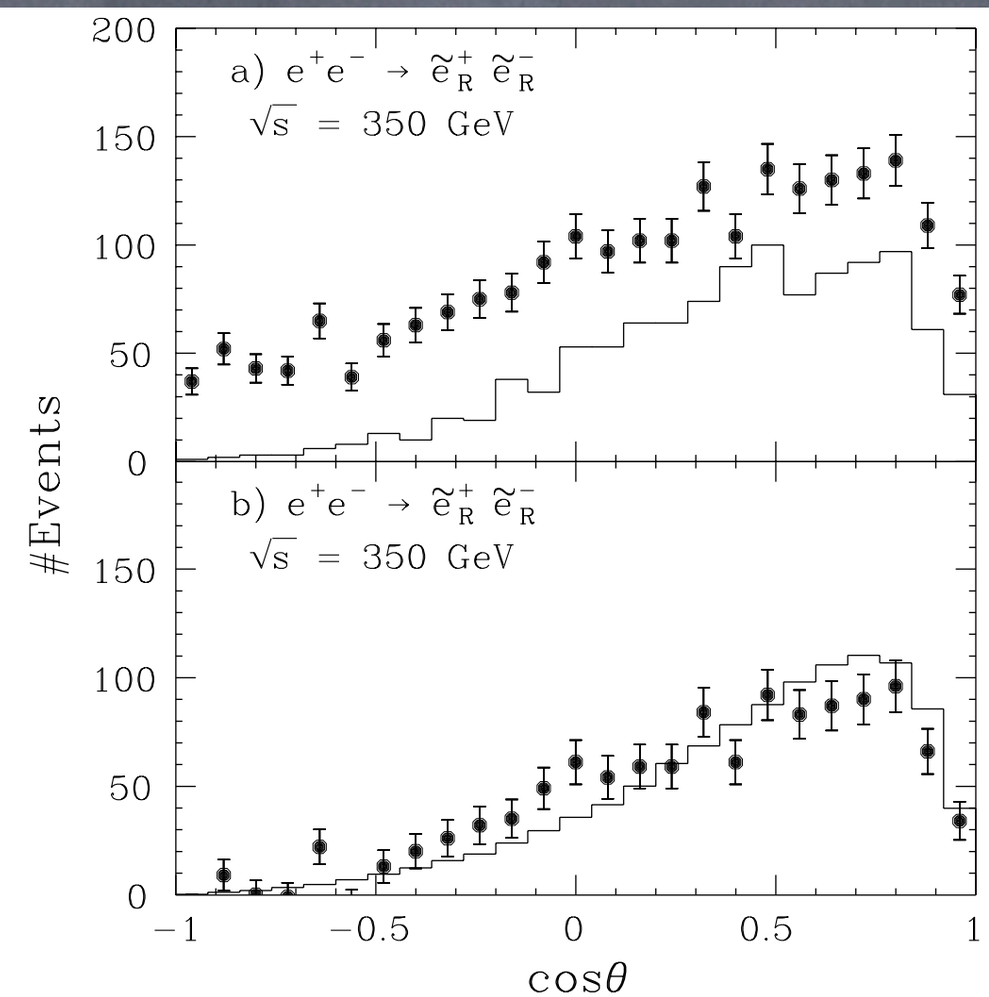
Feynman rules

- Single gauge coupling constant gives all of these Feynman vertices



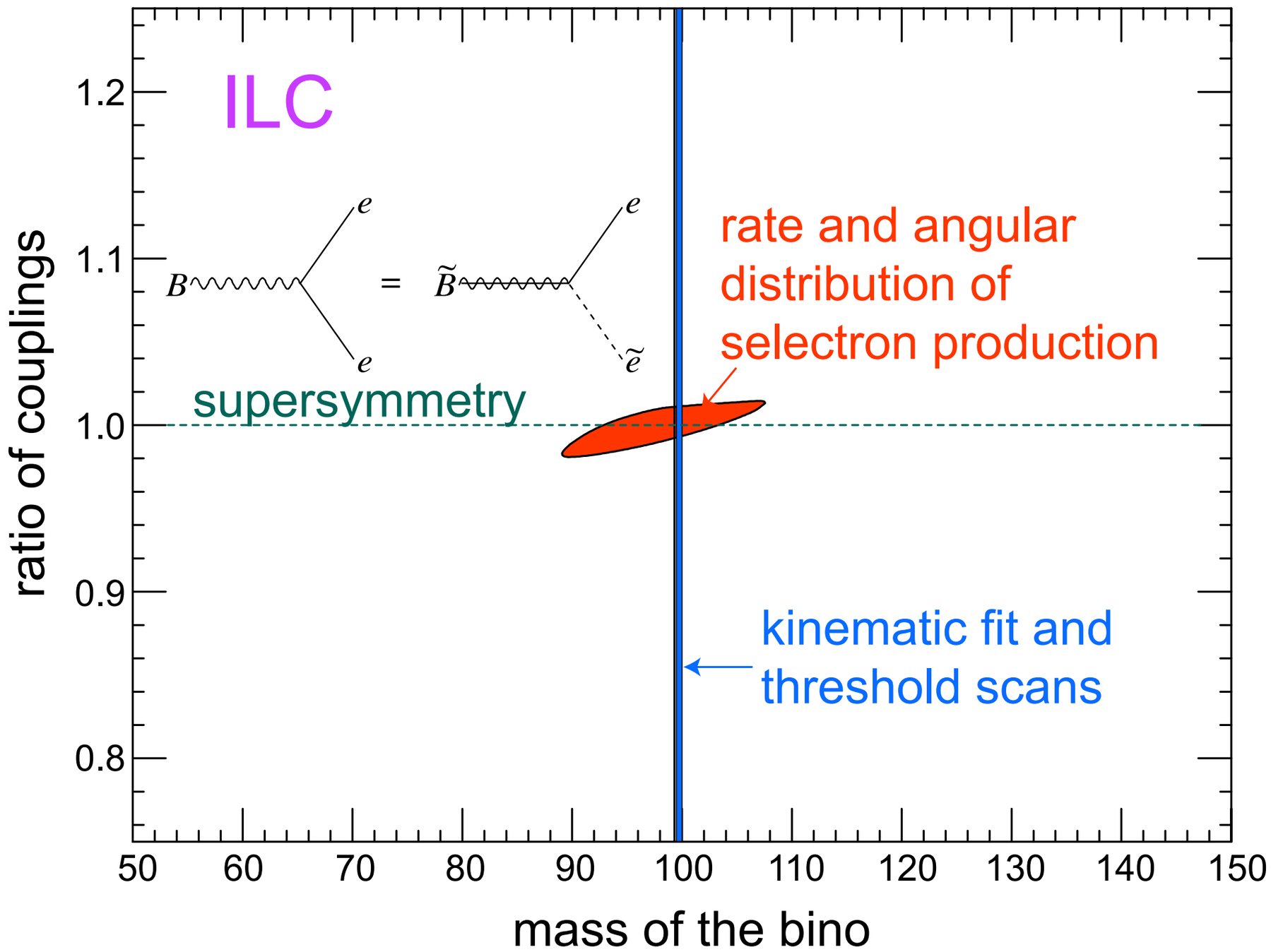
selectron production





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

gaugino coupling



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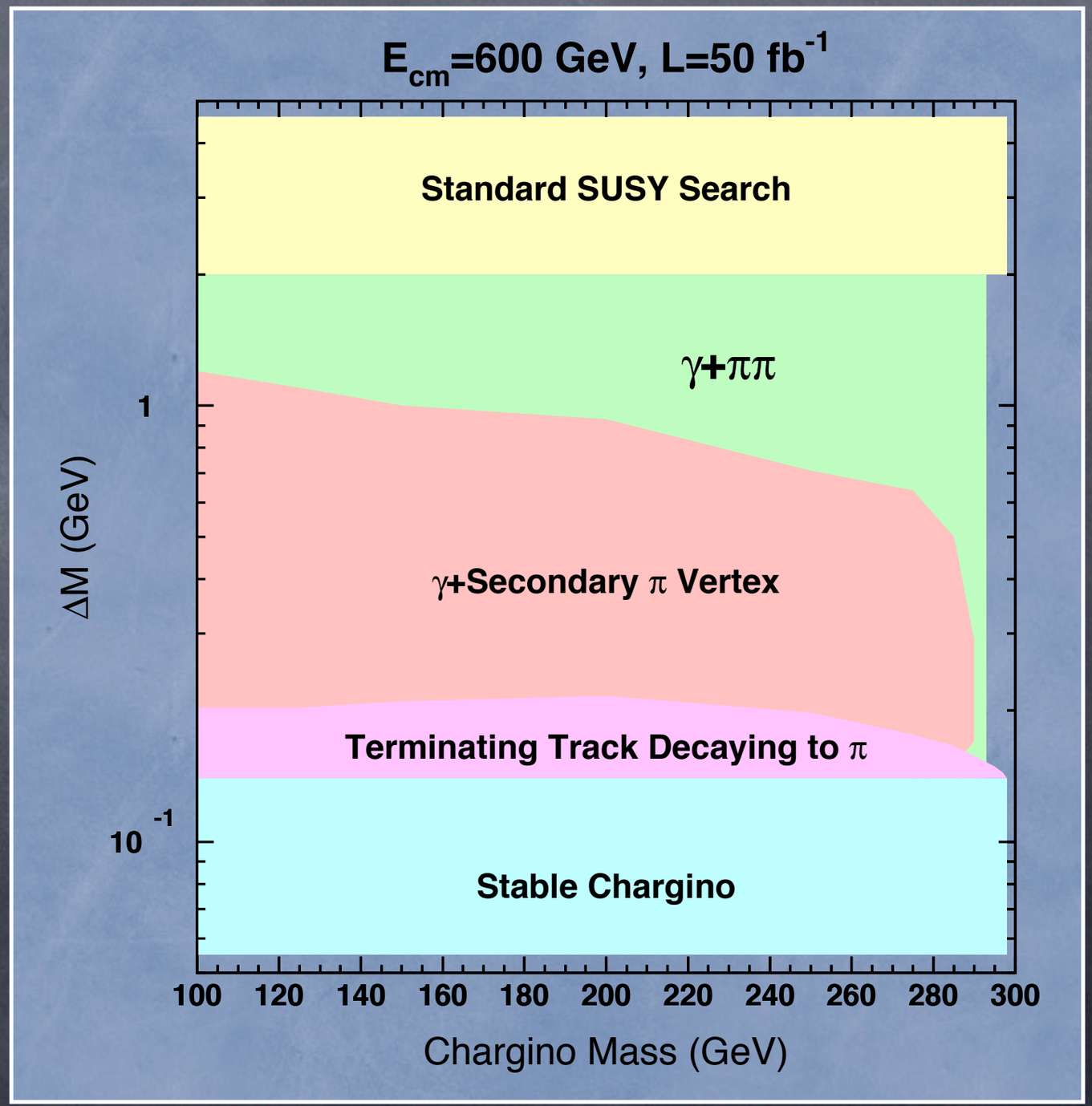
Proof of supersymmetry

- 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!

Robust search capability

Degenerate case (AMSB)

- In anomaly mediation, $M_2 < M_1$
- chargino (wino) nearly degenerate with neutralino (wino)
- decay products are soft and hard to see



Big Caveat

- e^+e^- LC great as long as the new particles are there for $m<\sqrt{s}/2$
- What energy is enough?
- LHC will tell us