PART 3

Search for SUperSYmmetry (SUSY)

SUPERSYMMETRY

(see lectures of G. Giudice)

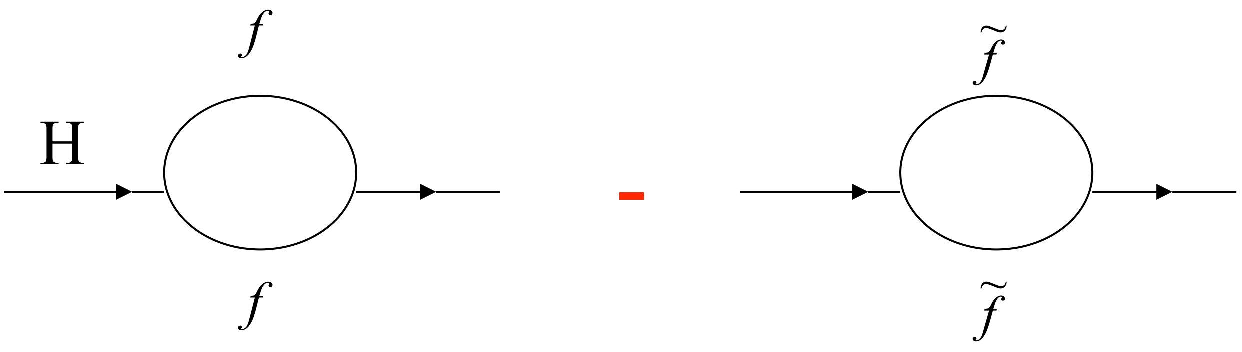
Relates fermions and bosons:

for each particle p with spin s,
there exists a SUSY partner $\tilde{p}$
with spin s-1/2.

Ex. :	q (s=1/2)	→	$\boxed{\tilde{q}}$	(s=0)	squarks
	Z (s=1)	→	$\boxed{\tilde{Z}}$	(s=1/2)	zino

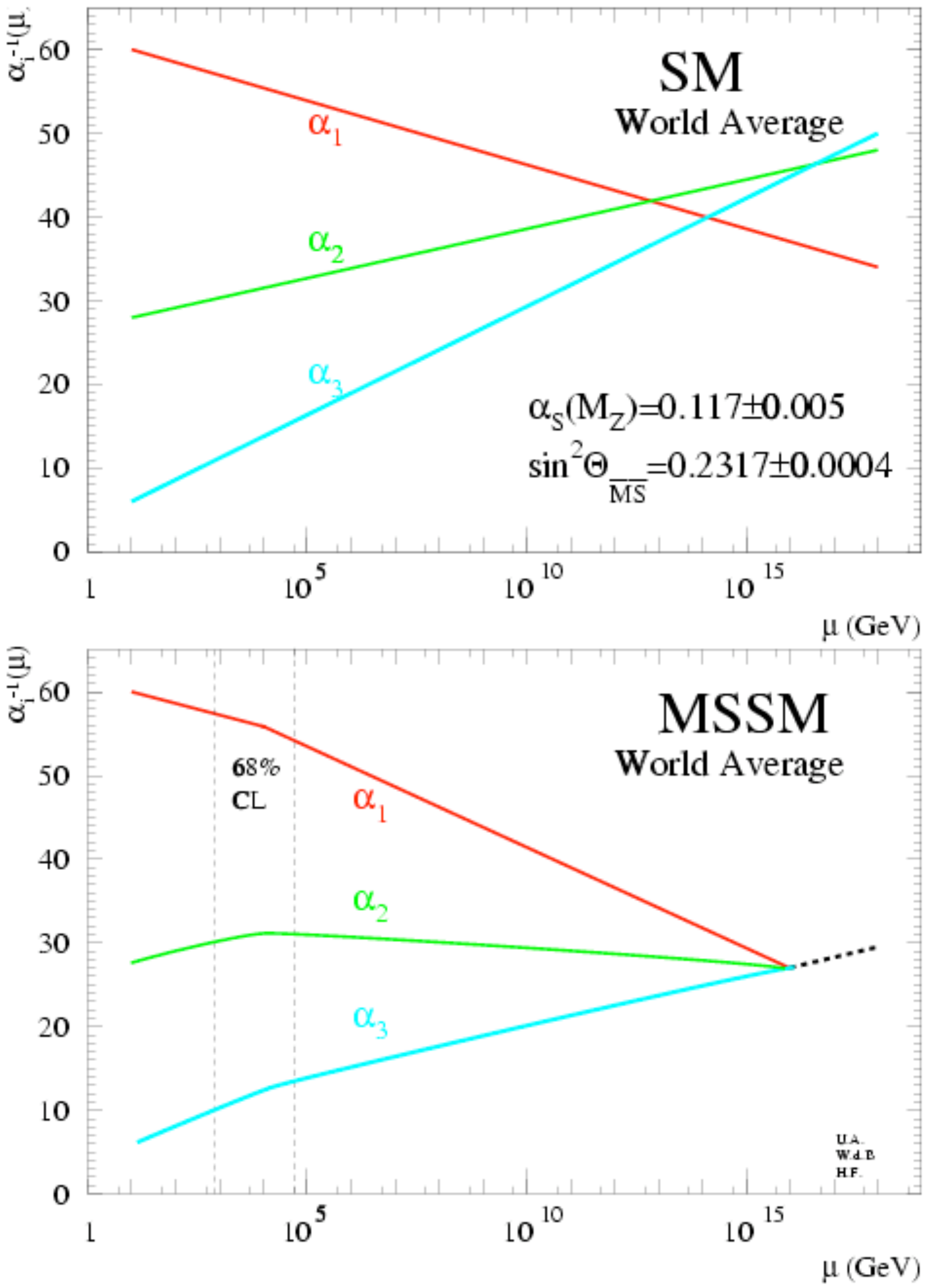
Motivations:

① unification of fermions and bosons is attractive
② solves problems of SM, e.g. divergence of Higgs mass :



Fermion and boson loops cancel, provided
$m_{\tilde{f}} \leq$ TeV.

③ Measured coupling constants unify at GUT scale in SUSY but not in SM.



④ Does not contradict predictions of SM at low energy → not ruled out by present experiments. Predicts a light Higgs

⑤ Ingredient of string theories that many consider best candidate for unified theory including gravity

However: no experimental evidence for SUSY as yet

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Either SUSY does not exist

OR

m_{SUSY} large (>> 100 GeV) → not accessible to present machines

⬇

LHC should say "final word" about SUSY if $m_{SUSY} \leq$ a few TeV

Drawback : many new particles predicted

Here : Minimal Supersymmetric extension of the Standard Model (MSSM) which has minimal particle content

⬇

MSSM particle spectrum :

5 Higgs bosons : h, H, A, H±

quarks	→	squarks	$\tilde{u}, \tilde{d}$, etc.
leptons	→	sleptons	$\tilde{e}, \tilde{\mu}, \tilde{\nu}$, etc.
$W^{\pm}$	→	winos	→ $\chi^{\pm}_{1}, \chi^{\pm}_{2}$ 2 charginos
$H^{\pm}$	→	charged higgsino	
γ	→	photino	→ $\chi^{0}_{1,2,3,4}$ 4 neutralinos
Z	→	zino	
h, H	→	neutral higgsino	
g	→	gluino	$\tilde{g}$

Masses not known. However charginos/neutralinos are usually lighter than squarks/sleptons/gluinos.

Present limits : $m_{\tilde{l},\chi^{\pm}}$ > 90-100 GeV LEP
$m_{\tilde{q},\tilde{g}}$ > 250 GeV Tevatron

SUSY phenomenology

There is a multiplicative quantum number:

R-parity $$R_p = \begin{cases} +1 & \text{SM particles} \\ -1 & \text{SUSY particles} \end{cases}$$

which is conserved in most popular models (considered here).

Consequences:

- SUSY particles are produced in pairs
- Lightest Supersymmetric Particle (LSP) is stable.

  LSP is also weakly interacting (for cosmological reasons, dark matter)

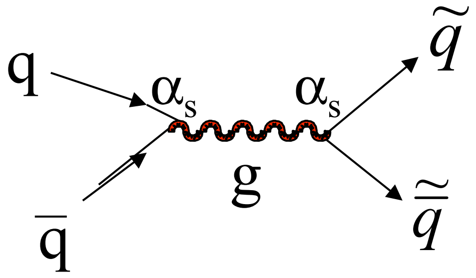
  → LSP behaves like a ν → escape detection
  → E_t^{miss} (typical SUSY signature)

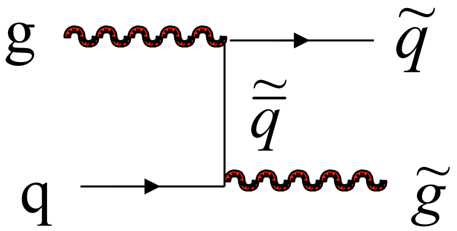
Most models : $\boxed{\mathrm{LSP} \equiv \chi^0{}_1}$

Production of SUSY particles at LHC

- Squarks and gluinos produced via strong processes → large cross-section

Ex.:

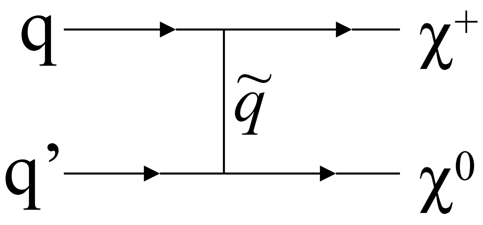




$m_{\tilde{q},\tilde{g}} \sim 1$ TeV $\quad \sigma \sim 1$ pb → 10^4 events per year produced at low L

- Charginos, neutralinos, sleptons produced via electroweak processes → much smaller rate

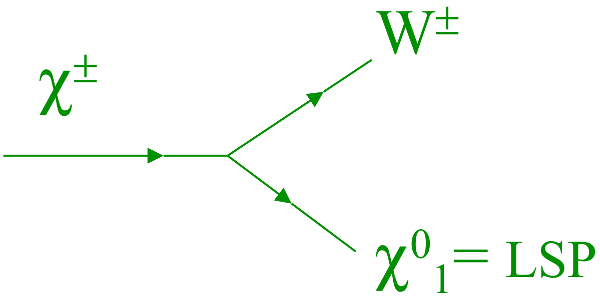
Ex.

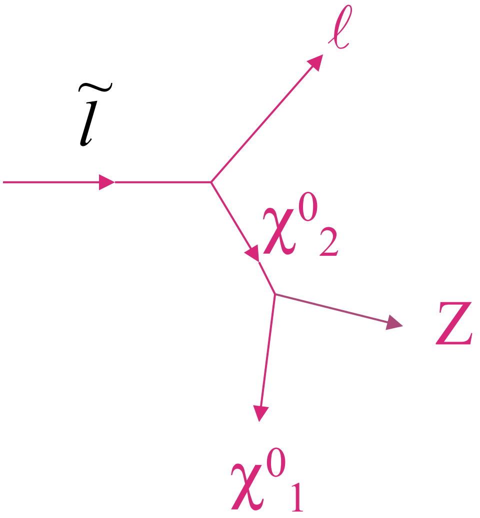


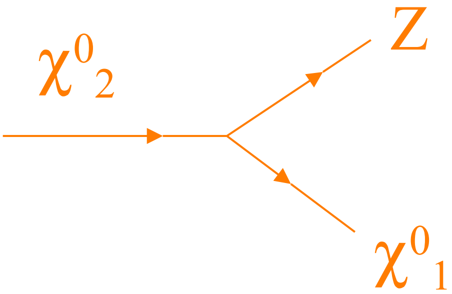
$\sigma \approx$ pb $\quad m_\chi \approx 150$ GeV

$\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ are dominant SUSY processes at LHC if kinematically accessible

Decays of SUSY particles : some examples

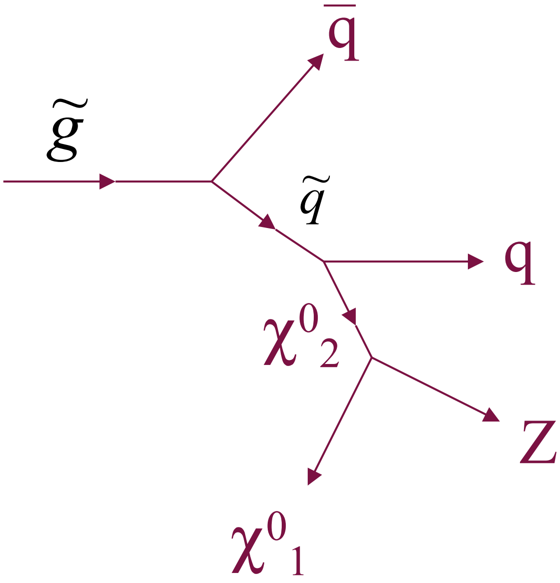






$\tilde{q}, \tilde{g}$ heavier → more complicated decay chains

Ex.



Cascade decays involving many leptons and /or jets + missing energy (from LSP)

Exact decay chains depend on model parameters (particle masses, etc.)

However : whatever the model is, we know that

$\tilde{q}, \tilde{g}$ are heavy (m > 250 GeV)

decays through cascades favoured

⇒ many high-p_T jets/leptons/W/Z in the final state + E_T^{miss}

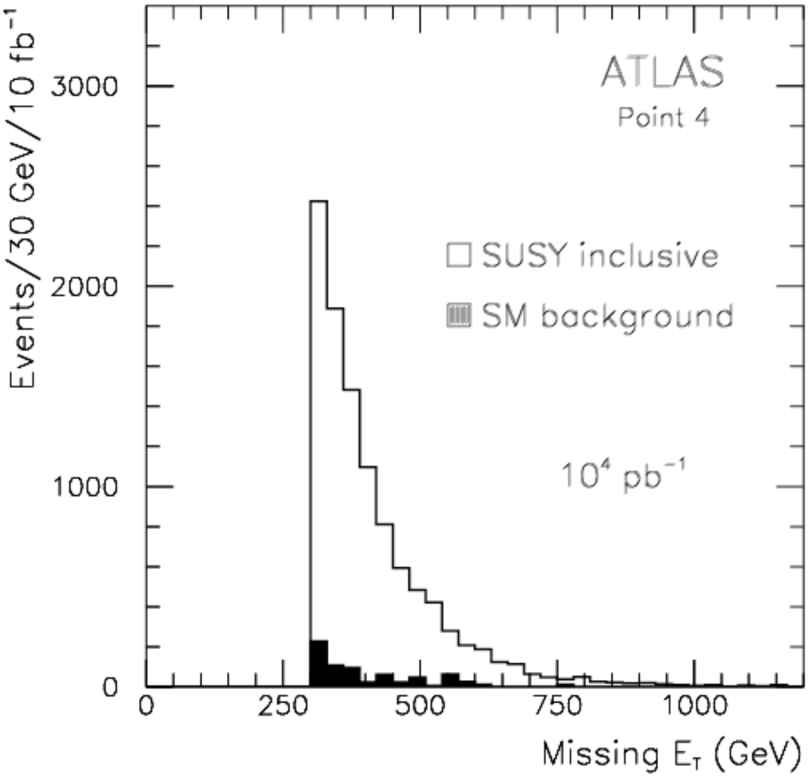
at LHC is easy to extract SUSY signal from SM background

Example: if Nature had chosen the following point in the parameter space:

$m_{\tilde{q}} \approx 900$ GeV $m_{\chi^\pm} \approx 150$ GeV

$m_{\tilde{g}} \approx 600$ GeV $m_{\chi^0} \approx 80$ GeV

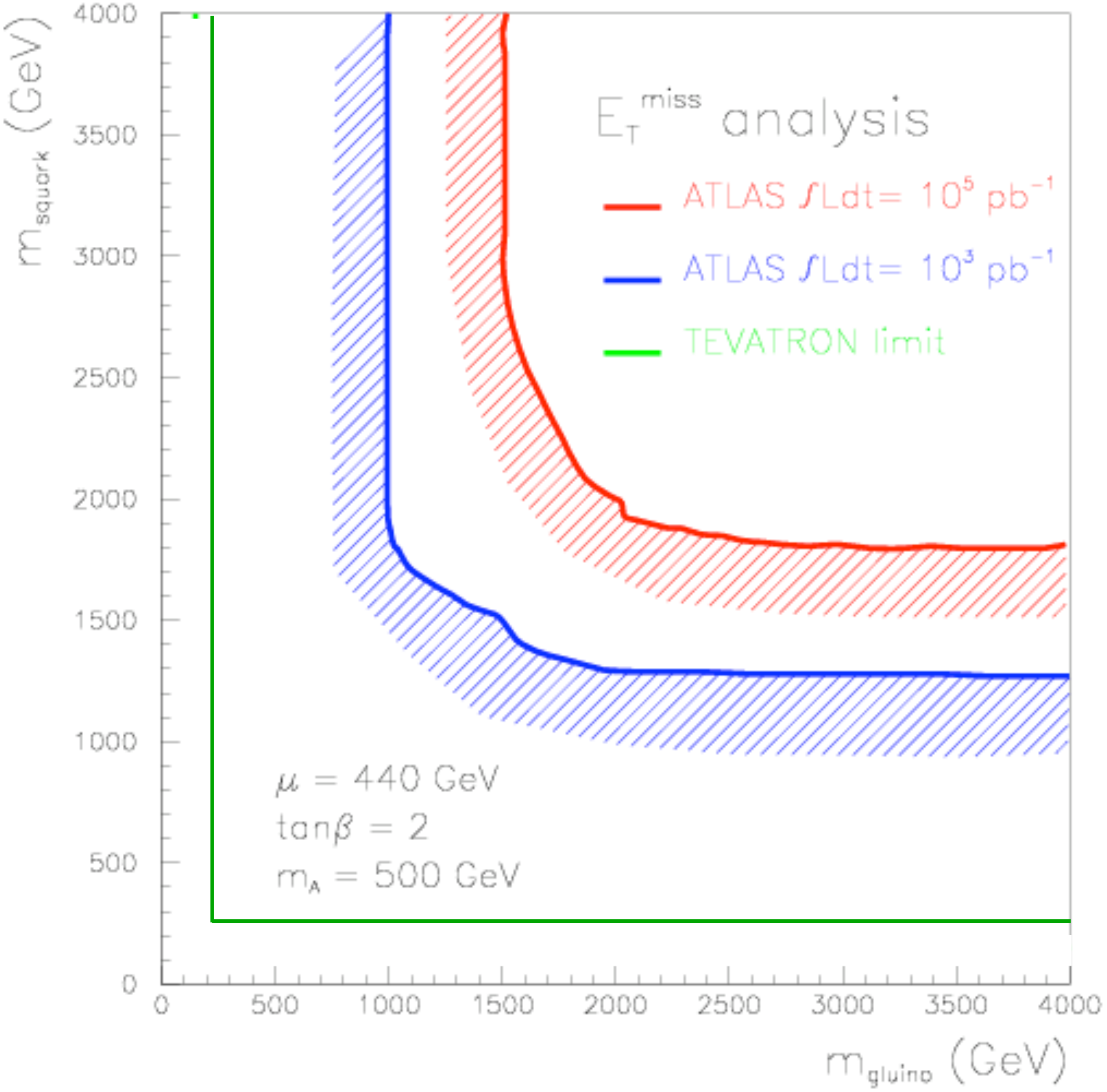
Requiring : $E_T^{miss} > 300$ GeV
5 jets $p_T > 150, 150, 100, 100, 90$ GeV



In one year at low L:
$N_S = 11600$ events
$N_B = 560$ events

S ~ 500 !!

With similar analysis, discover or exclude $\tilde{q}, \tilde{g}$ with masses up to 1.5-2 TeV in one year at high luminosity (L = 10^{34} cm^{-2} s^{-1})



Thanks to:

-- large cross-section

-- very clear signature

Conclusion on SUSY

If SUSY exists, it will be easy and fast to discover at LHC up to m ≈ 2-3 TeV.

Several measurements of SUSY particle masses can be performed.

Thanks to large cross-section, small backgrounds and variety of signatures.

Precise measurements of: m_W , m_{top}

Motivation:

W mass and top mass are fundamental parameters of the Standard Model:

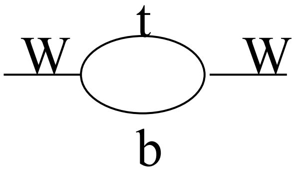
Electromagnetic constant
measured in atomic transitions,
e+e- machines, etc.

$$m_W = \left(\frac{\pi\,\alpha_{EM}}{\sqrt{2}\,G_F}\right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

Fermi constant
measured in muon
decay

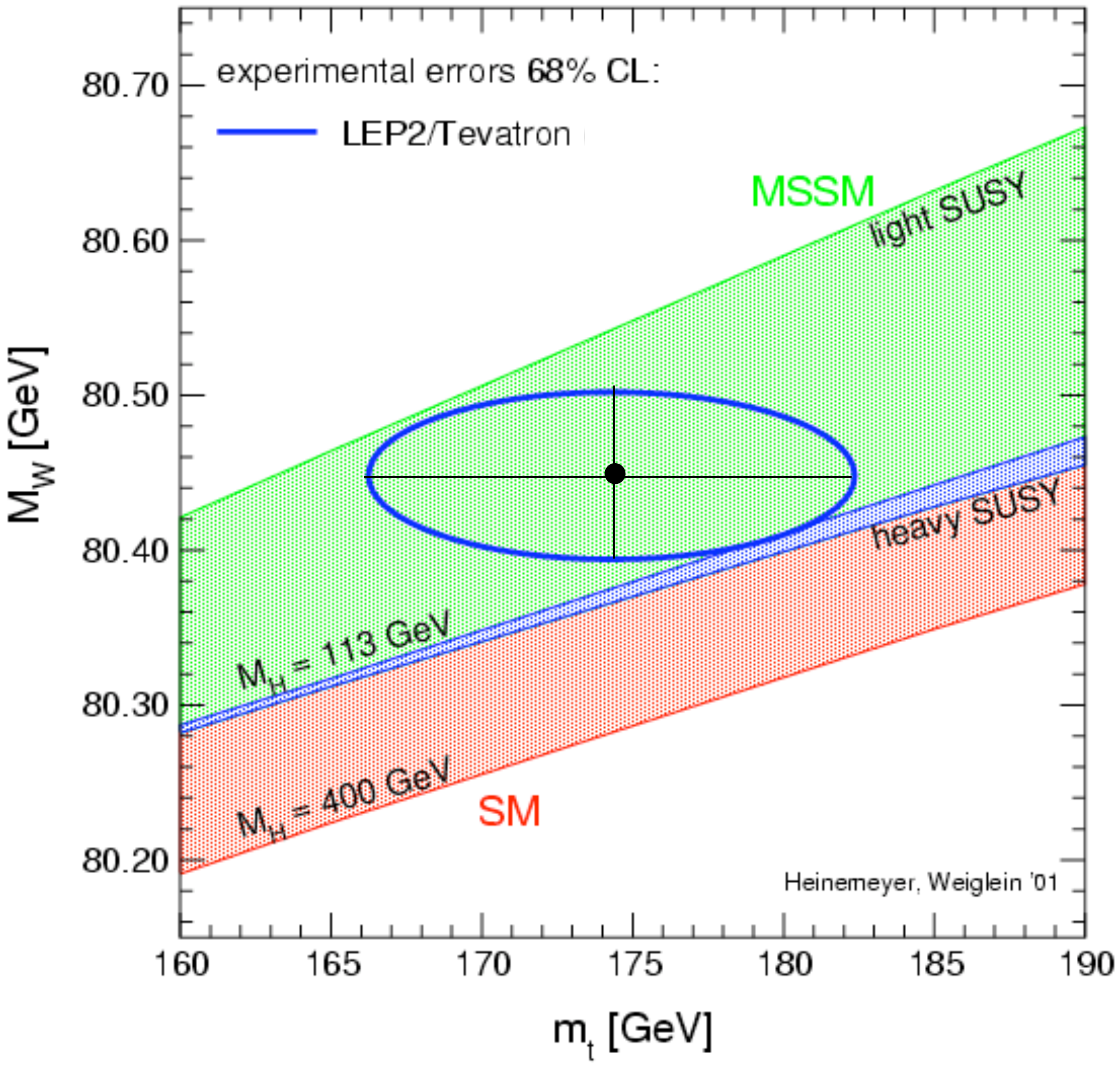
Weinberg angle
measured at
LEP/SLC

$f\,(m_{top}^2, \log m_H)$
radiative corrections



→ since G_F, α_{EM}, $\sin\theta_W$ are known with high precision, precise measurements of m_{top} and m_W allow constraining Higgs mass (weakly because of logarithmic dependence)

$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$



m_W (LEP2 + Tevatron) = 80.451 ± 0.033 GeV

m_{top} (Tevatron) = 174.3 ± 5.1 GeV

Year 2006:

$\Delta m_W < 30$ MeV (0.4 ‰) from LEP/Tevatron

$\Delta m_{top} \approx 3$ GeV (2 %) from Tevatron

Can LHC do better ?

YES : thanks to large statistics

Measurement of W mass

Method used at hadron colliders different from e^+e^- colliders

- $W \rightarrow$ jet jet : cannot be extracted from QCD jet-jet production ⇒ cannot be used
- $W \rightarrow \tau\nu$: since $\tau \rightarrow \nu + X$, too many undetected neutrinos ⇒ cannot be used

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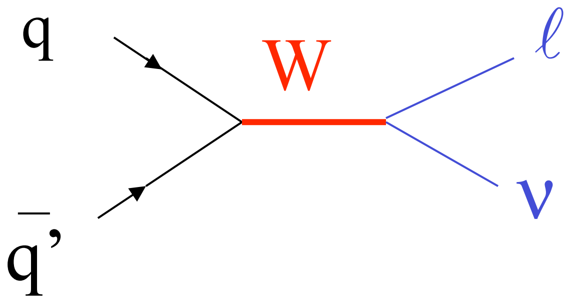
① only $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays are used to measure m_W at hadron colliders

W production at LHC :

Ex.



$$\sigma\,(pp \to W + X) \approx 30\ \text{nb}$$

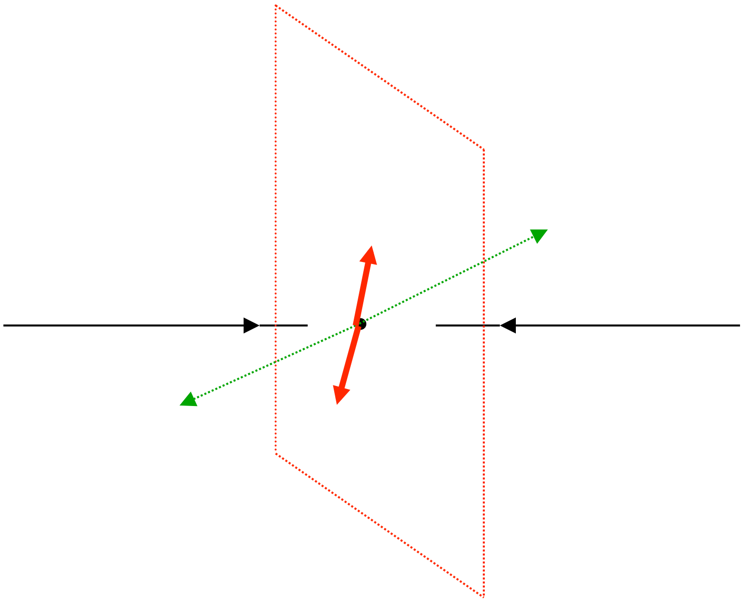
$$\hookrightarrow e\nu,\ \mu\nu$$

$\sim 300 \times 10^6$ events produced
$\sim 60 \times 10^6$ events selected after analysis cuts

} one year at low L, per experiment

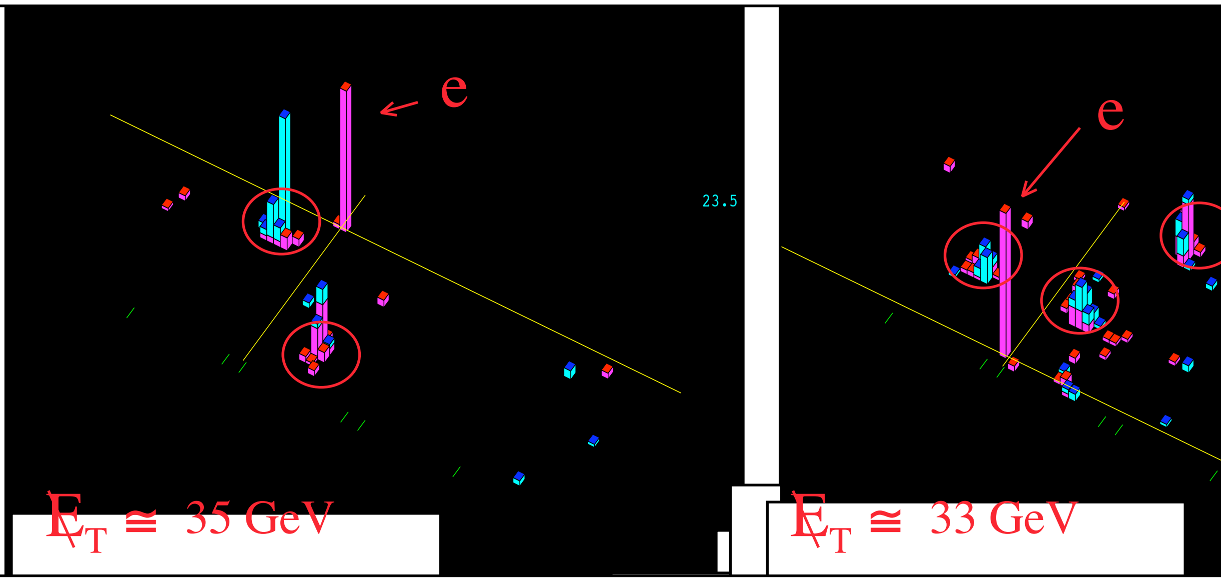
$\sim$ 50 times larger statistics than at Tevatron
$\sim$ 6000 times larger statistics than at LEP

② Since $\vec{p}_L{}^{\nu}$ not known (only $\vec{p}_T{}^{\nu}$ can be measured through E_T^{miss}), measure transverse mass, i.e. invariant of ℓν perpendicular to the beam :



$$m_T{}^{W} = \sqrt{p_T{}^{1}\, \underset{\uparrow\ \equiv E_T^{\text{miss}}}{p_T{}^{\nu}}\,(1-\cos\Delta\varphi_{l\nu})}$$

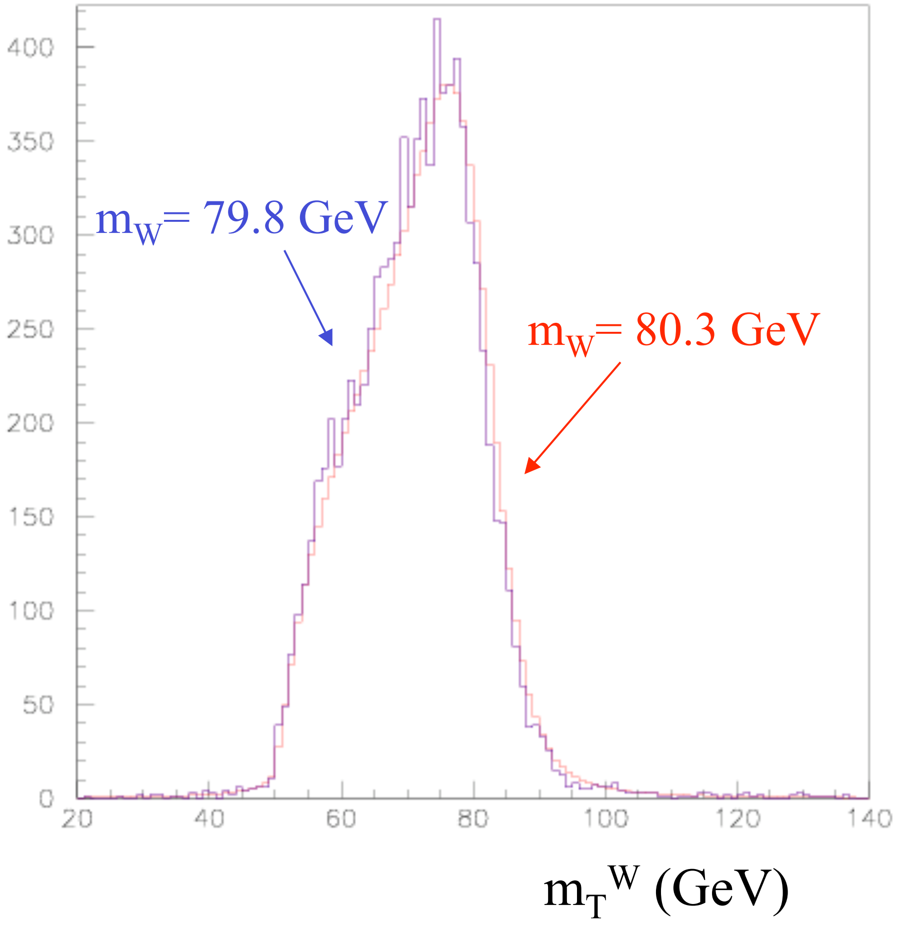
W$\rightarrow$ eν event (data) from CDF experiment at the Tevatron



$\not{E}_T \cong$ 35 GeV

$\not{E}_T \cong$ 33 GeV

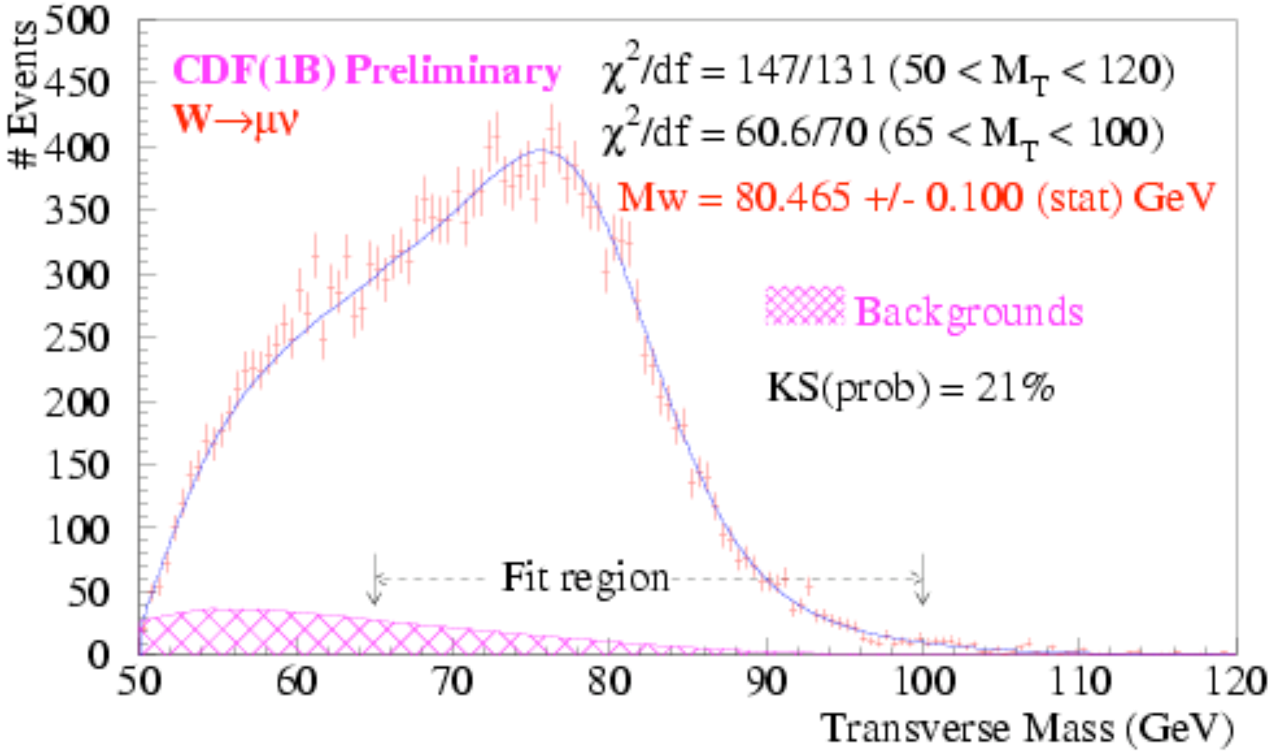
m_T^W distribution is sensitive to m_W



m_T^W distribution expected in ATLAS

⇒ fit experimental distributions with SM prediction (Monte Carlo simulation) for different values of m_W → find m_W which best fits data

CDF data :
W → μν transverse mass



From fit to transverse mass distribution:

$$m_W = 80.465 \pm 0.100 \text{ GeV}$$

Uncertainties on m_W

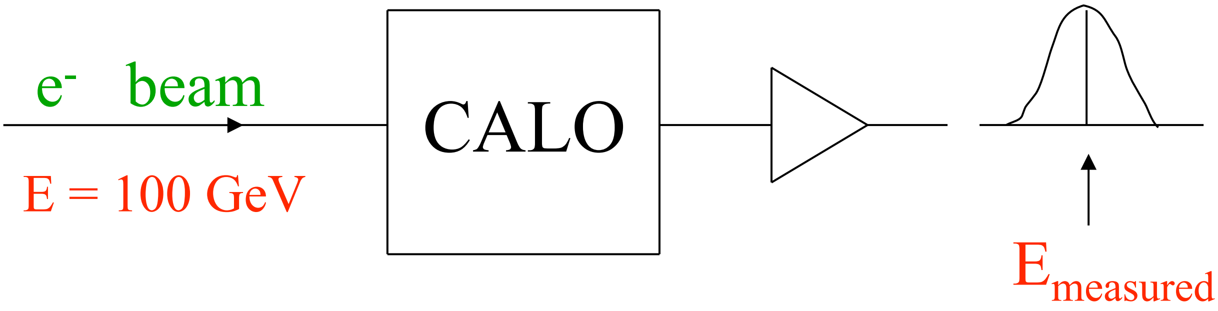
Come mainly from capability of Monte Carlo prediction to reproduce real life, that is:

- detector performance: energy resolution, energy scale, etc.
- physics: p_T^W, θ_W, Γ_W, backgrounds, etc.

Dominant error (today at Tevatron, most likely also at LHC):
knowledge of lepton energy scale of the detector:
if measurement of lepton energy wrong by 1%, then measured m_W wrong by 1%

Calibration of detector energy scale

Example : EM calorimeter



- if $E_{measured}$ = 100.000 GeV→ calorimeter is perfectly calibrated
- if $E_{measured}$ = 99, 101 GeV → energy scale known to 1%

- to measure m_W to better than 30 MeV need to to know energy scale to 0.2 ‰ , i.e.

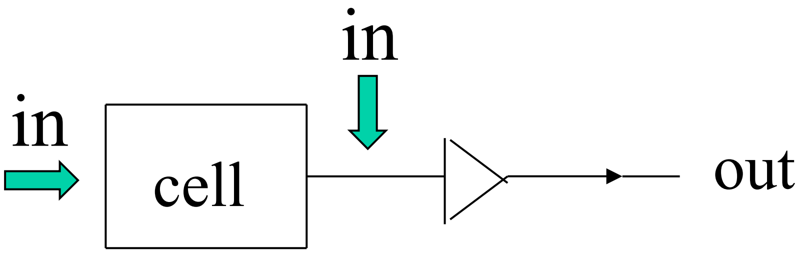
  if $E_{electron}$ = 100 GeV then

  $99.98 \text{ GeV} < E_{measured} < 100.02 \text{ GeV}$

⇒ one of most serious experimental challenges

Calibration strategy:

- detectors equipped with calibration systems which inject known pulses:



→ check that all cells give same response:
if not → correct

- calorimeter modules calibrated with test beams of known energy → set the energy scale

- inside LHC detectors: calorimeter sits behind inner detector → electrons lose energy in material of inner detector → need a final calibration " *in situ* " by using physics samples:

e.g. $Z \rightarrow e^+ e^-$ decays 1/sec at low L

constrain $m_{ee} = m_Z$

reconstructed ↑ m_{ee}

known to ≈ 10^{-5} from LEP ↖ m_Z

Expected precision on m_W at LHC

Source of uncertainty	Δm_W
Statistical error	<< 2 MeV
Physics uncertainties (p_T^W, θ_W, Γ_W, …)	~ 15 MeV
Detector performance (energy resolution, lepton identification, etc,)	< 10 MeV
Energy scale	15 MeV
Total (per experiment, per channel)	~ 25 MeV

Combining both channels ($e\nu$, $\mu\nu$) and both experiments (ATLAS, CMS), $\Delta m_W \approx 15$ MeV should be achieved.
However: very difficult measurement

Measurement of m_{top}

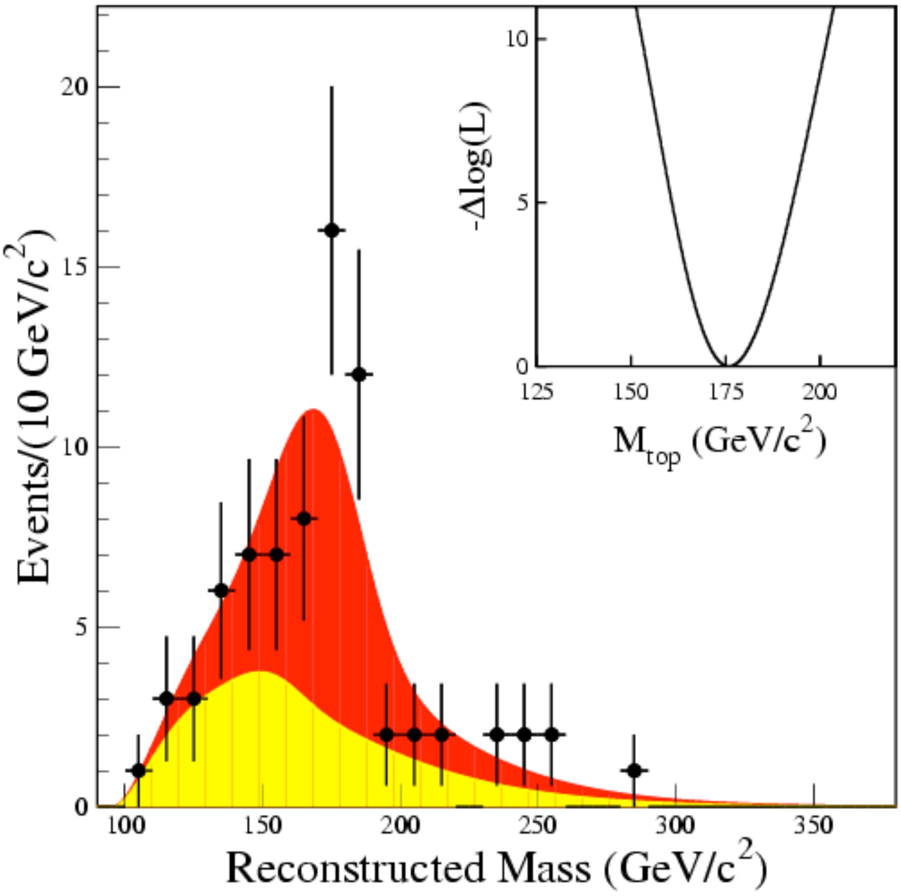
- Top is most intriguing fermion:

-- $m_{top} \approx$ 174 GeV → very heavy

-- $\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \longleftarrow$ Δm (t-b) ≈ 170 GeV

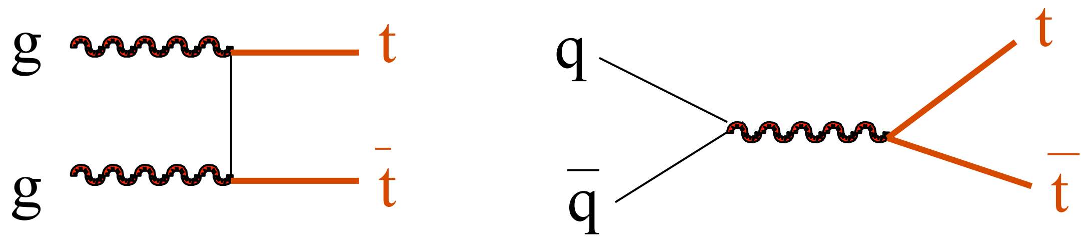
- Discovered in '94 at Tevatron → precise measurements of mass, couplings, etc. just started

Top mass spectrum from CDF



Top production at LHC:

e.g.



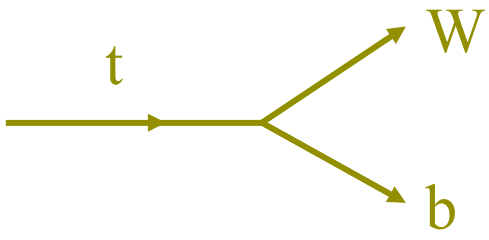
$$\sigma\,(pp \rightarrow t\bar{t} + X) \approx 800\ \text{pb}$$

$\Downarrow$

10^7 $t\bar{t}$ pairs produced in one year at low L

~ 10^3 times more than at Tevatron

Top decays:



BR ≈ 100% in SM

-- hadronic channel: both W → jj

⇒ 6 jet final states. BR ≈ 50 % but large QCD multijet background.

-- leptonic channel: both W → $\ell\nu$

⇒ 2 jets + 2ℓ + E_T^{miss} final states. BR ≈ 10 %. Little kinematic constraints to reconstruct mass.

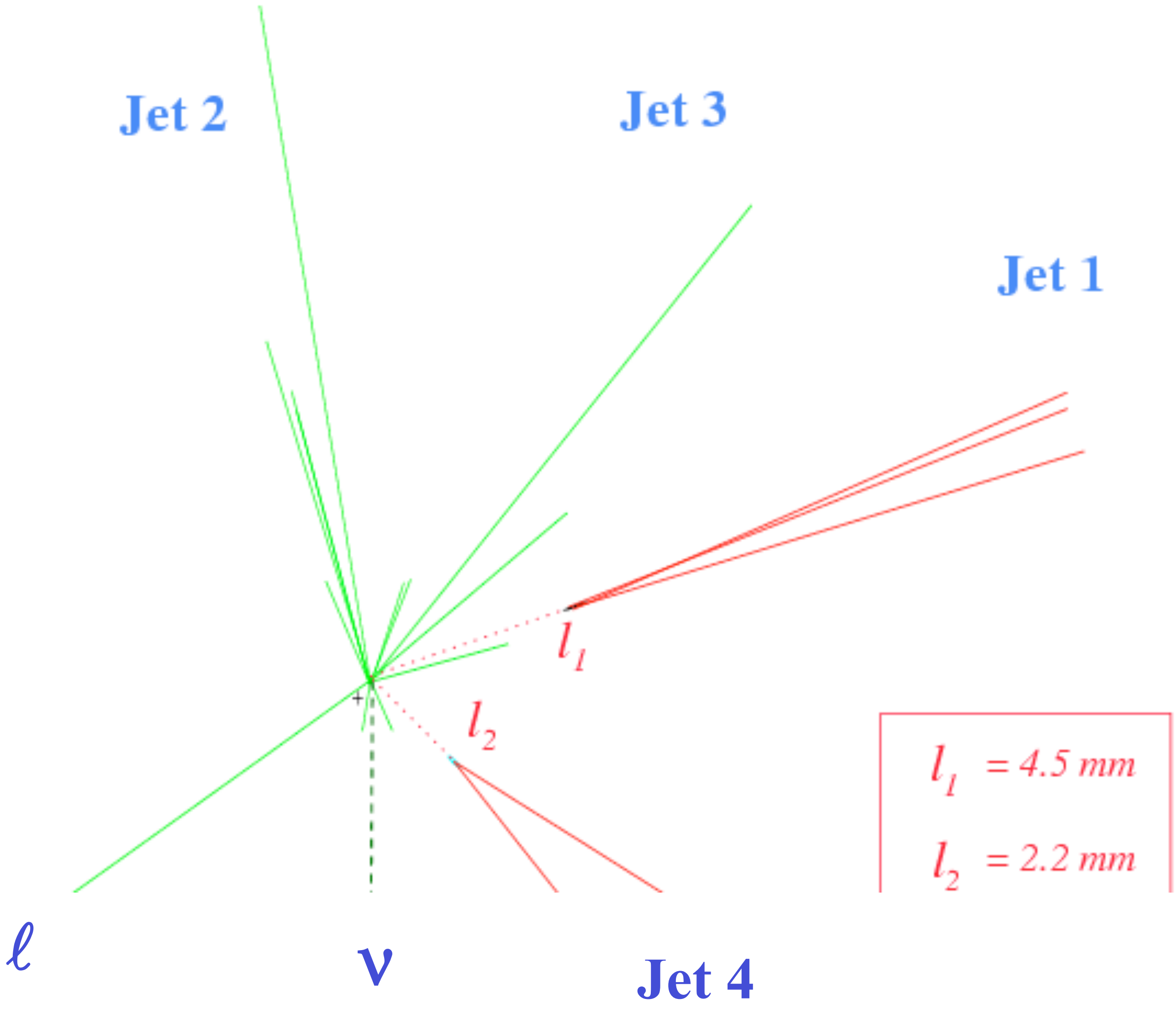
-- semileptonic channel: one W → jj , one W → $\ell\nu$

⇒ 4 jets + 1ℓ + E_T^{miss} final states. BR ≈ 40 %.
If $\ell = e, \mu$: gold-plated channel for mass measurement.

In all cases two jets are b-jets
⇒ displaced vertices in the inner detector

Example from CDF (data) :

$t\bar{t} \rightarrow Wb\,Wb \rightarrow b\ell\nu\,bjj$ event



Selection of $t\bar{t} \to bW\,bW \to b\,\ell\nu\,bjj$

Require:

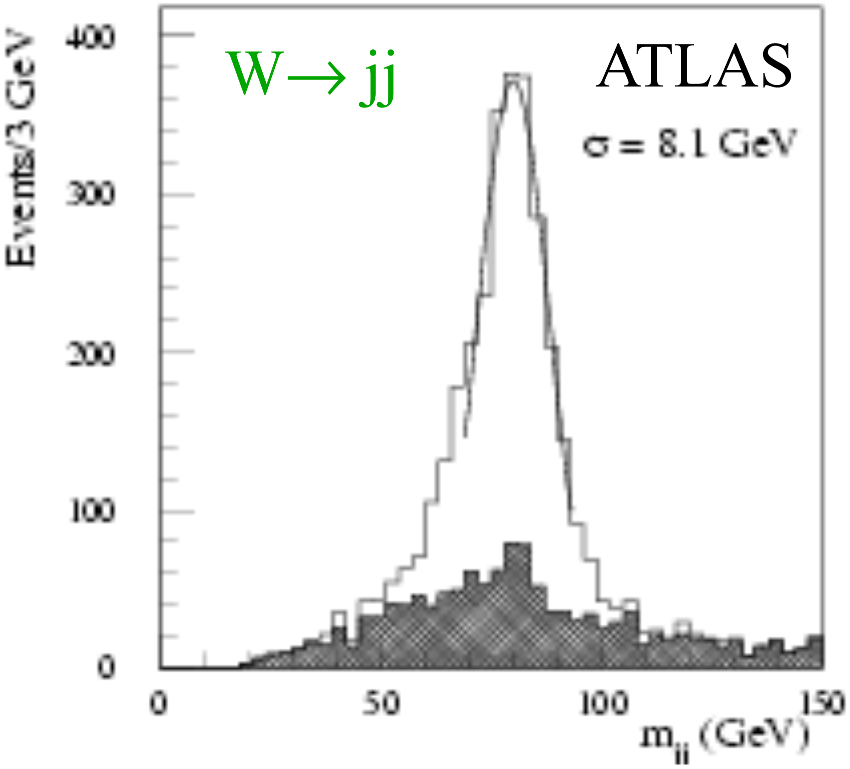
-- two b-tagged jets

-- one lepton

$p_T > 20$ GeV

-- $E_T^{miss} > 20$ GeV

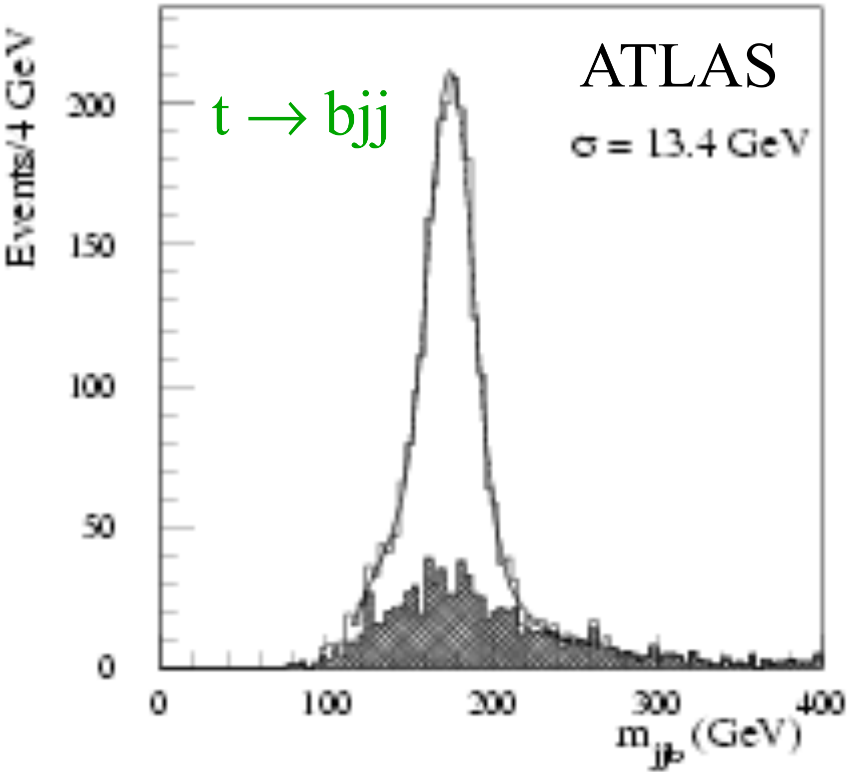
-- two more jets



Then require:

-- $|m_{jj}-m_W| < 20$ GeV

-- combine jj with b-jets. Choose combination which gives highest p_T top



Note : W → jj can be used to calibrate jet energy scale

Expected precision on m_{top} at LHC

Source of uncertainty	Δm_{top}
Statistical error	<< 100 MeV
Physics uncertainties (background, Final State Radiation, …)	~ 1.3 GeV
Jet scale	~ 0.8 GeV
Total (per experiment, per channel)	~ 2 GeV

-- Also hadronic and leptonic channels can be used to measure m_{top}.

-- $\Delta m_W \approx 15$ MeV, $\Delta m_{top} \approx 2$ GeV $\Rightarrow$ Higgs mass constrained to ≈ 30%.

-- Other measurements of top properties: branching ratios, rare decays, cross-section, resonances, etc.

CONCLUSIONS

LHC : most difficult and ambitious high-energy physics project ever realised (human and financial resources, technical challenges, complexity, ….)

Very broad and crucial physics goals:
understand the origin of masses,
look for physics beyond the SM,
precision measurements of known particles.

⇓

It will most likely modify our understanding of world

End of lectures