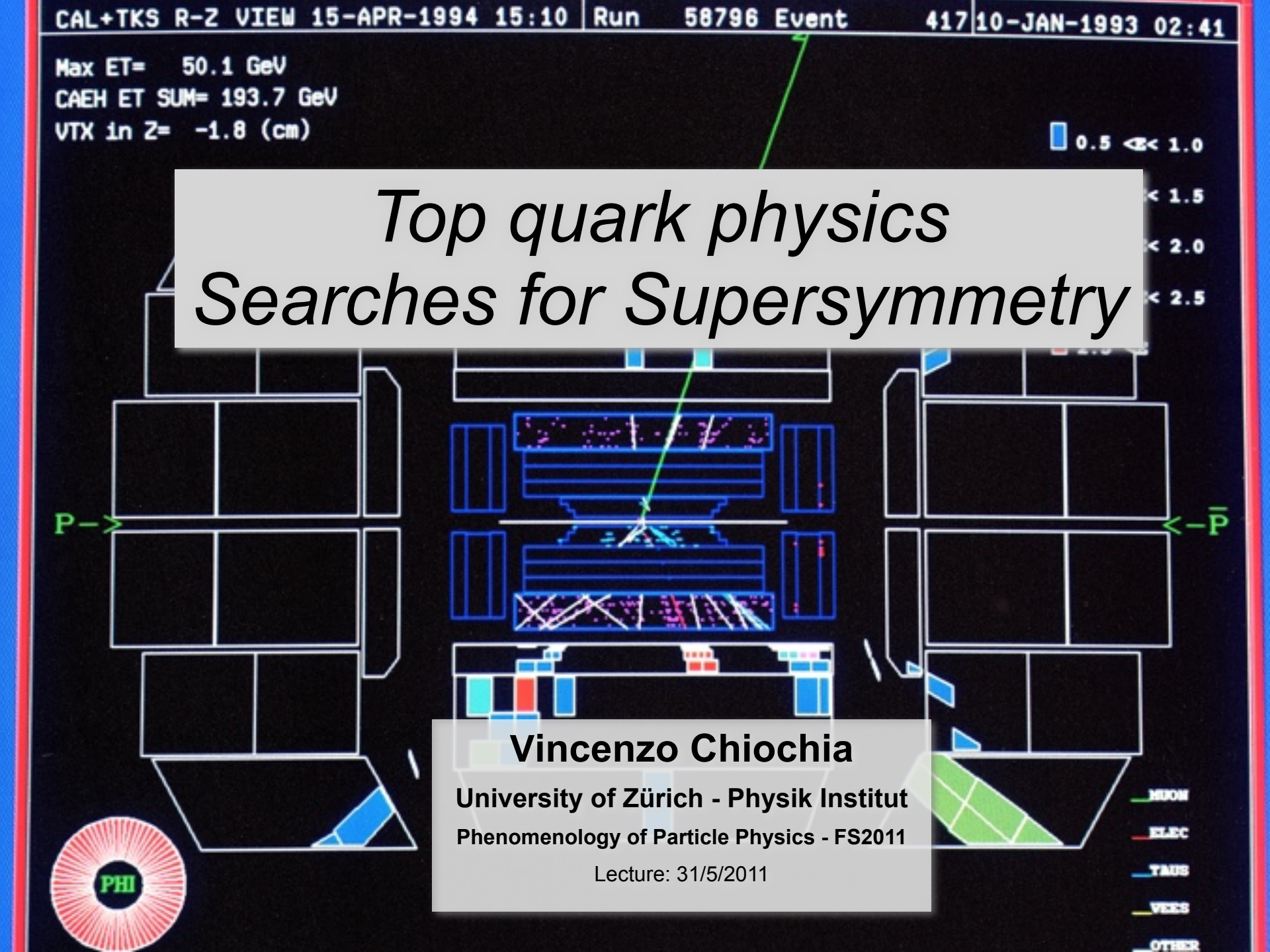


Top quark physics
Searches for Supersymmetry

Vincenzo Chiochia

University of Zürich - Physik Institut

Phenomenology of Particle Physics - FS2011

Lecture: 31/5/2011

Topics in this lecture

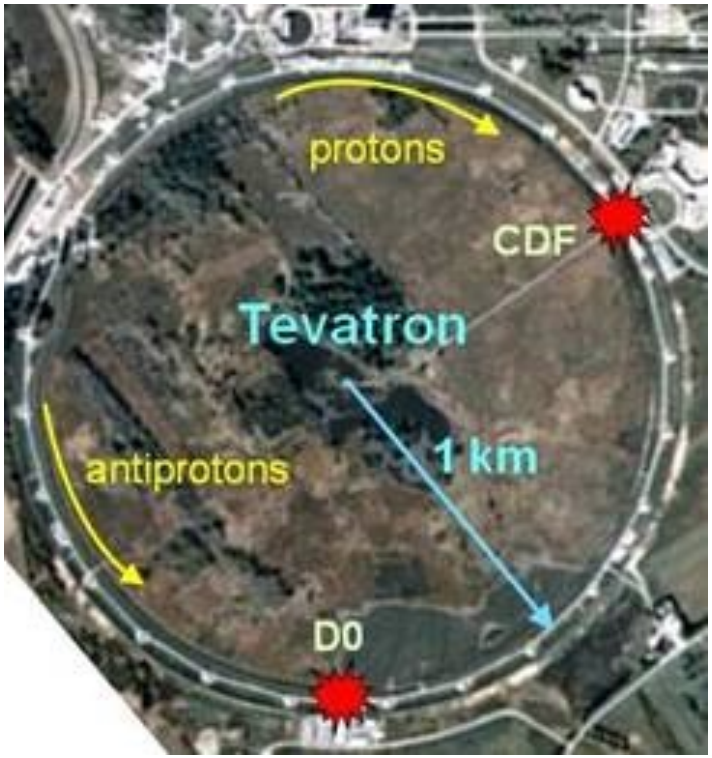
- Part 1:
  - Evidence of top quark production
  - Measurement of top mass
- Part 2:
  - Searches for Supersymmetry
    - Full hadronic searches
    - Multi-leptonic searches

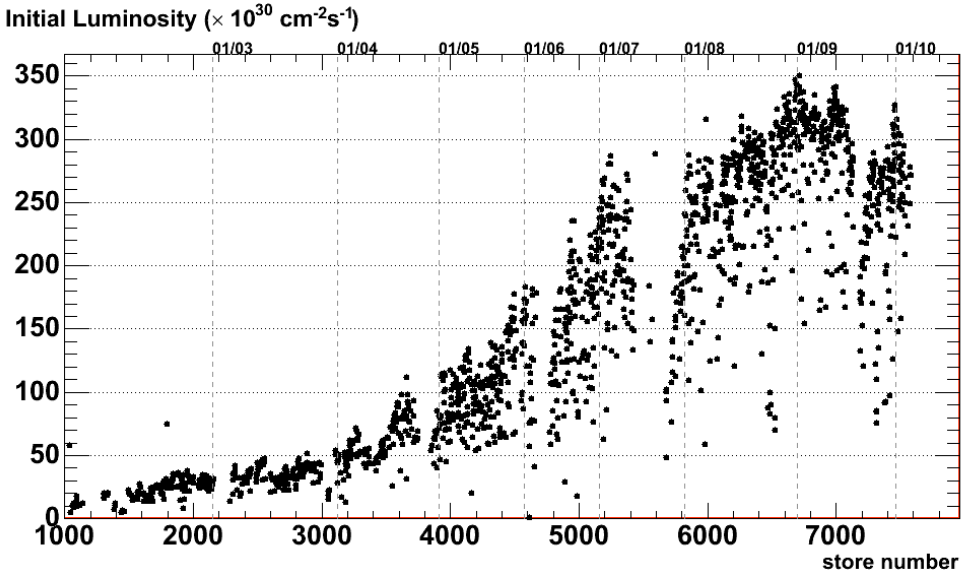
Historical outline

- **1977: Discovery of the Upsilon family at Fermilab**
  - Existence of the bottom (*b*) quark
  - Is there a heavier weak isospin partner of the *b* quark (third quark family)?
- **After 1990:**
  - Limits to top mass imposed from global EW fits: m_{top}=177±20 GeV
  - Direct searches at Tevatron: m_{top}>135 GeV
- **1994-5: Discovery of the top quark at Tevatron**
  - Observed both by CDF and D0 collaborations
  - First observation:
    - **174±10 GeV** with about 19 pb^{-1} of p-anti(p) data at $\sqrt{s}$=1.78 GeV
    - Production cross section of about **7 pb**

Discovery of the top quark

Tevatron accelerator

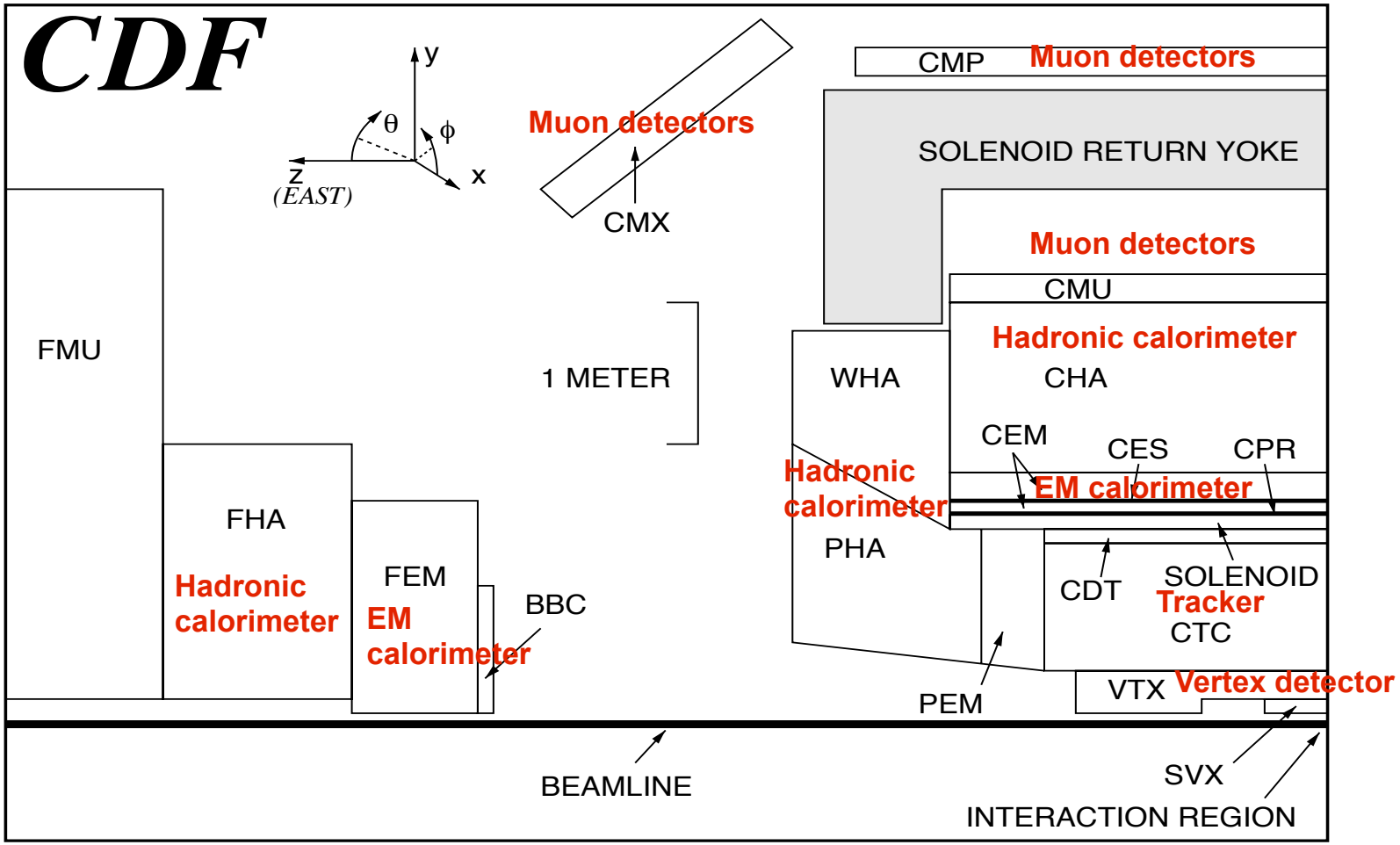




1992–1993 Tevatron Collider operating parameters

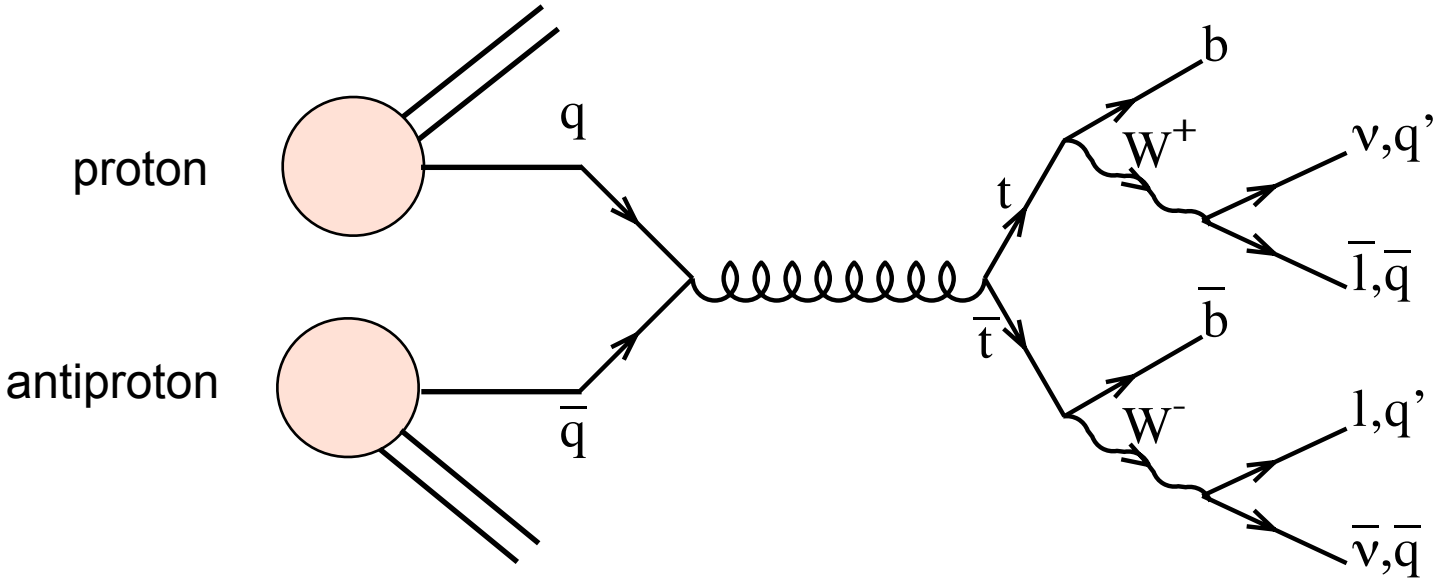
Beam:	proton–antiproton
Beam Energy:	900 GeV/beam
Luminosity:	10^{30}–10^{31} cm^{-2} s^{-1}
Bunches/Beam:	6
Bunch Spacing:	3.5 μs
Collision Region RMS:	30 cm
Beam Spot:	$\approx$ 40 μm
Beam Pipe:	1.5 in. diameter

Schema of the CDF experiment



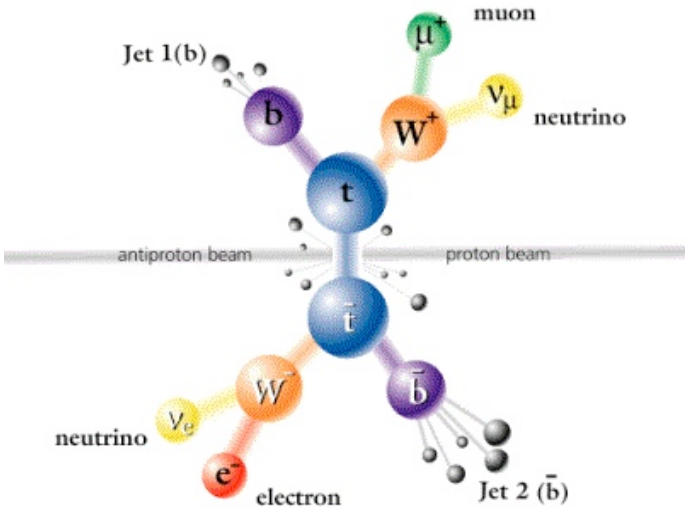
Production mechanism

- In proton-antiproton collisions pairs of quark anti-quark are produced in the gluon-gluon and quark-antiquark channels
- For heavy top (>130 GeV) the quark channel dominates
- Main production process and consequent decay:



Top quark decays

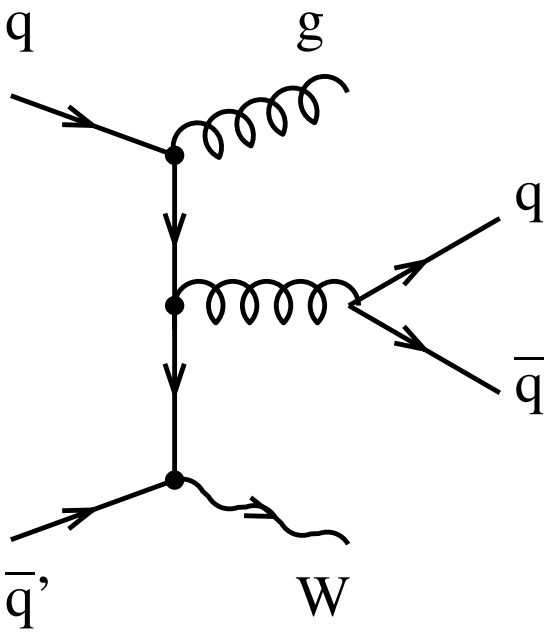
Decay mode	Branching ratio
$t\bar{t} \longrightarrow (q\bar{q}'b)(q\bar{q}'\bar{b})$	36/81
$t\bar{t} \longrightarrow (q\bar{q}'b)(e\nu\bar{b})$	12/81
$t\bar{t} \longrightarrow (q\bar{q}'b)(\mu\nu\bar{b})$	12/81
$t\bar{t} \longrightarrow (q\bar{q}'b)(\tau\nu\bar{b})$	12/81
$t\bar{t} \longrightarrow (e\nu b)(\mu\nu\bar{b})$	2/81
$t\bar{t} \longrightarrow (e\nu b)(\tau\nu\bar{b})$	2/81
$t\bar{t} \longrightarrow (\mu\nu b)(\tau\nu\bar{b})$	2/81
$t\bar{t} \longrightarrow (e\nu b)(e\nu\bar{b})$	1/81
$t\bar{t} \longrightarrow (\mu\nu b)(\mu\nu\bar{b})$	1/81
$t\bar{t} \longrightarrow (\tau\nu b)(\tau\nu\bar{b})$	1/81



- If m_{top}>85 GeV decays mainly in a real **W boson** and **b-quark jet**
- Consequent W decays to qq(bar): too much background from jet production
- **Solution**: require at least one leptonic W decay to **muons** and **electrons**
  - Identification of hadronic **tau** decay also has high background
- **Event selection:**
  - One lepton (μ or e) with E_T>20 GeV and |h|<2.1
  - **Neutrino**: missing transverse energy E_T(miss)>20 GeV
  - Require 1 to 4 jets

Background from W+jets

- By requiring W leptonic decays a considerable background channel remains
  W production recoiling against other jets
- **Example**:



- **Solution**: background processes do not necessarily include b quark jets.
  Identify at least one b or b(bar) quark among the jets

Particle jets from b-quarks

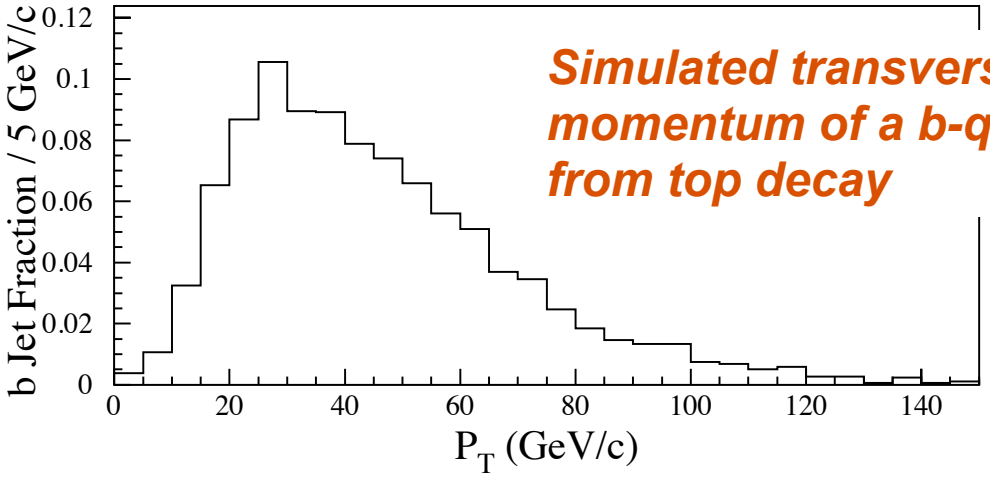
- A b-quark hadronizes in B-hadrons (mainly B+, B0, Bs, Lb)
  - Mass ~ **5 GeV**, typical lifetime ~ **1.4-1.6 ps**

Dominant fractions

b hadron	Fraction at Z [%]	Fraction at $\overline{p}p$[%]	Combined [%]
B^+, B^0	40.2 ± 0.9	33.2 ± 3.0	40.0 ± 1.2
B_s^0	10.5 ± 0.9	12.2 ± 1.4	11.5 ± 1.3
b baryons	9.1 ± 1.5	21.4 ± 6.8	8.5 ± 2.1

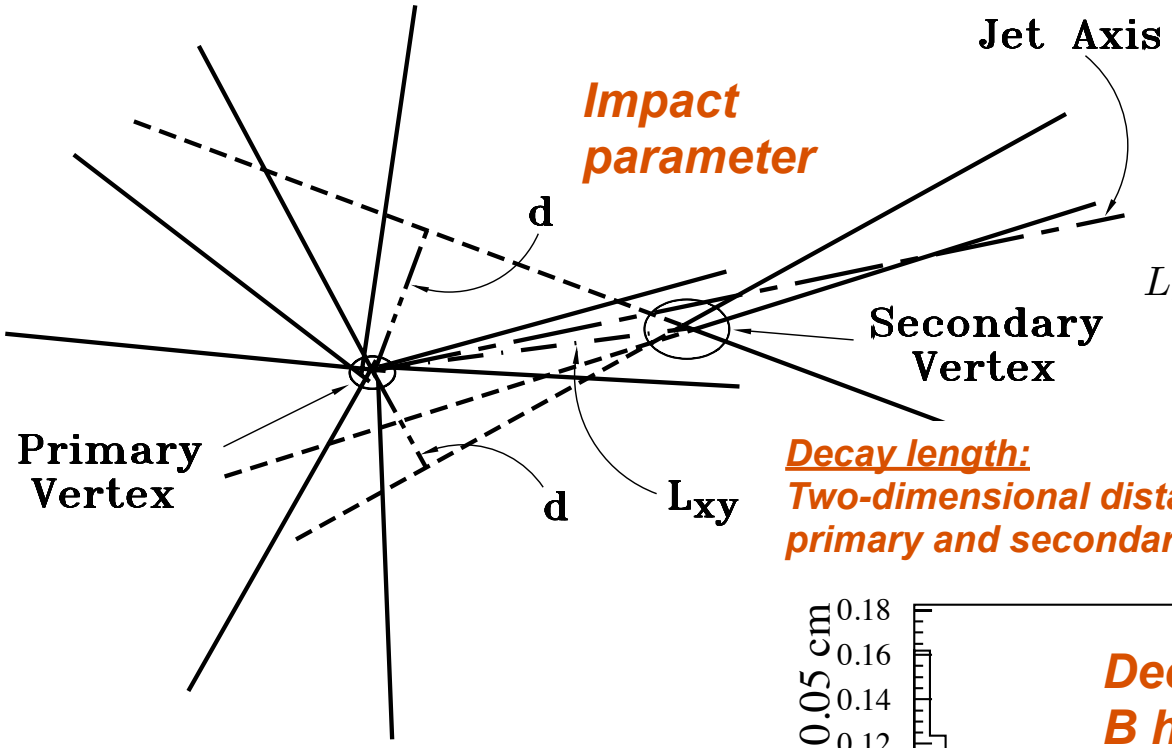
Particle	Lifetime [ps]
B^+	1.638 ± 0.011
B^0	1.525 ± 0.009
B_s^0 (flavor-specific)	1.417 ± 0.042
B_s^0 $(1/\Gamma_s)$	$1.472^{+0.024}_{-0.026}$
B_c^+	0.453 ± 0.041
Λ_b^0	$1.391^{+0.038}_{-0.037}$
Ξ_b^-	$1.56^{+0.27}_{-0.25}$
Ω_b^-	$1.13^{+0.53}_{-0.40}$

- The transverse momentum of a b-jet from a top decay (~50 GeV) is larger than the b-quark mass (~5 GeV)



Simulated transverse momentum of a b-quark jet from top decay

Secondary vertices



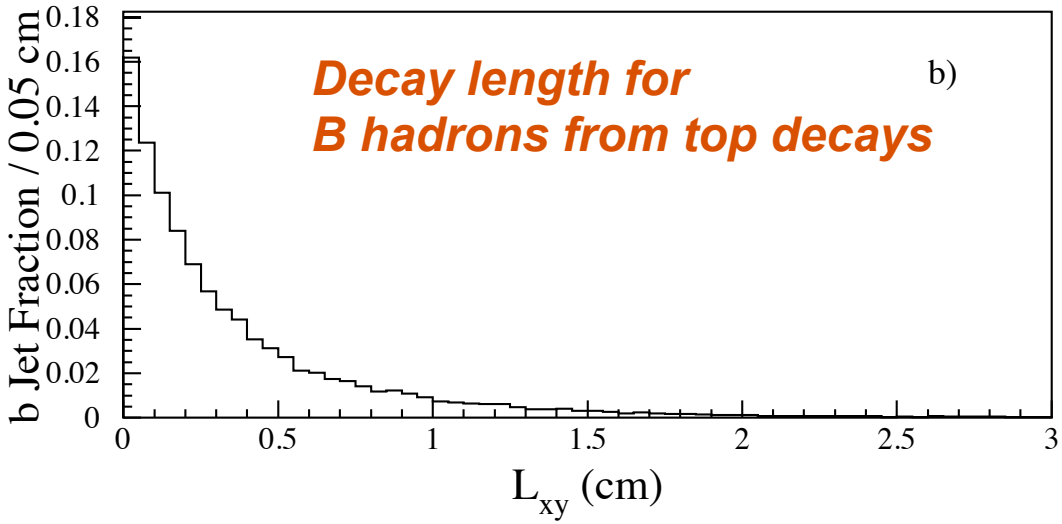
$$L_{xy} = \sqrt{(x_{PV} - x_{SV})^2 + (y_{PV} - y_{SV})^2}$$

$$ct = L_{xy} \frac{m_B}{p_T}$$

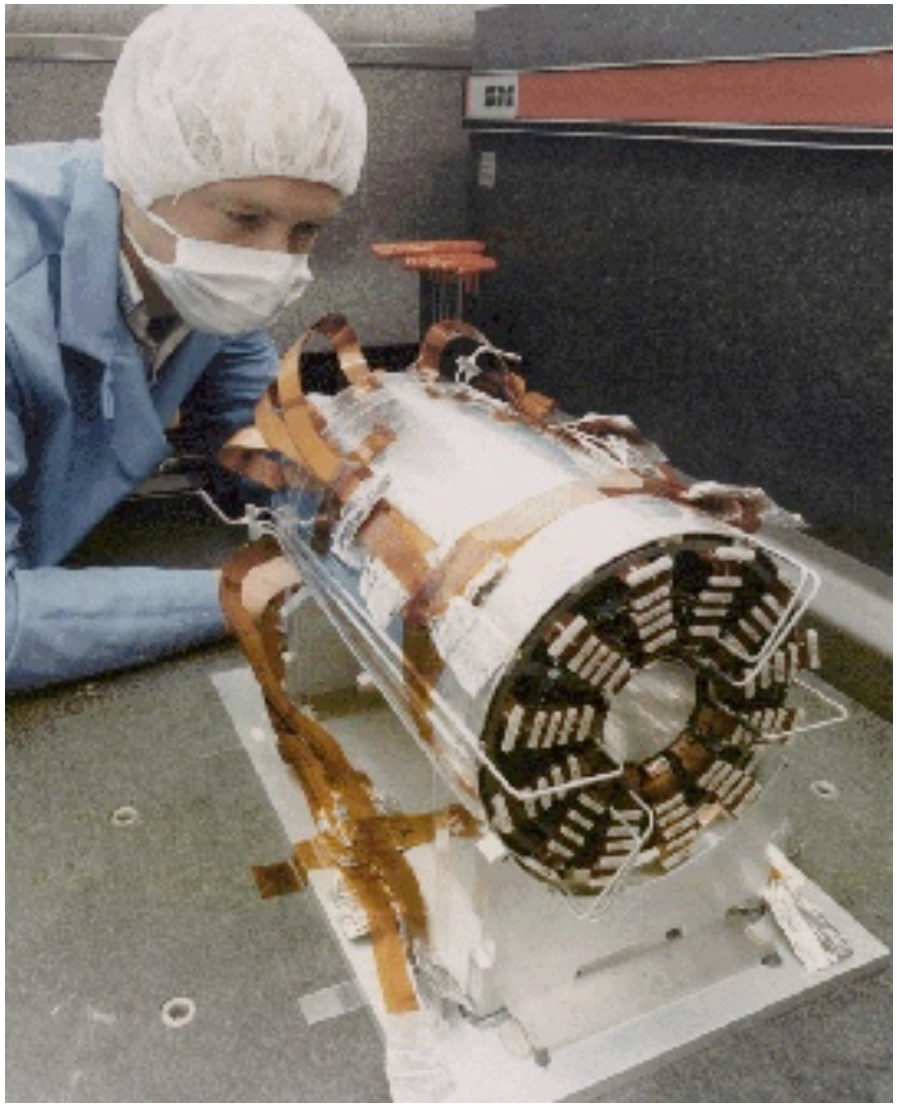
Decay length:
Two-dimensional distance between primary and secondary vertex

Tagging algorithm:
1) Vertex with 3 tracks (loose track requirements)
2) Vertex with 2 tracks (tight track requirements)

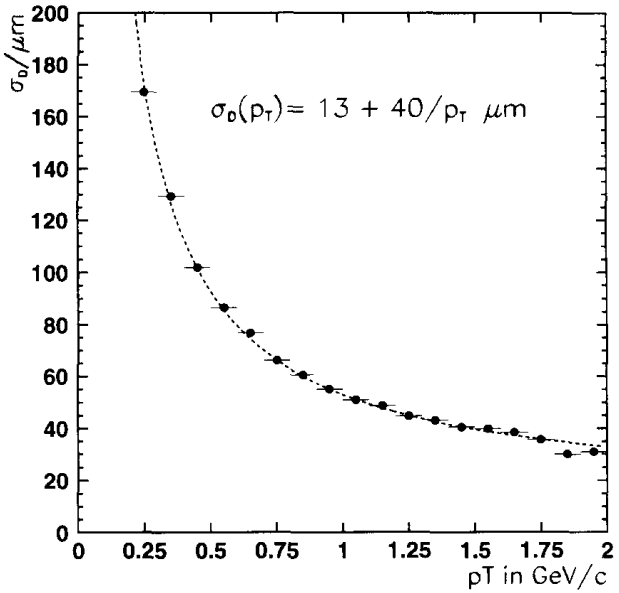
Tagging efficiency ~ 42%



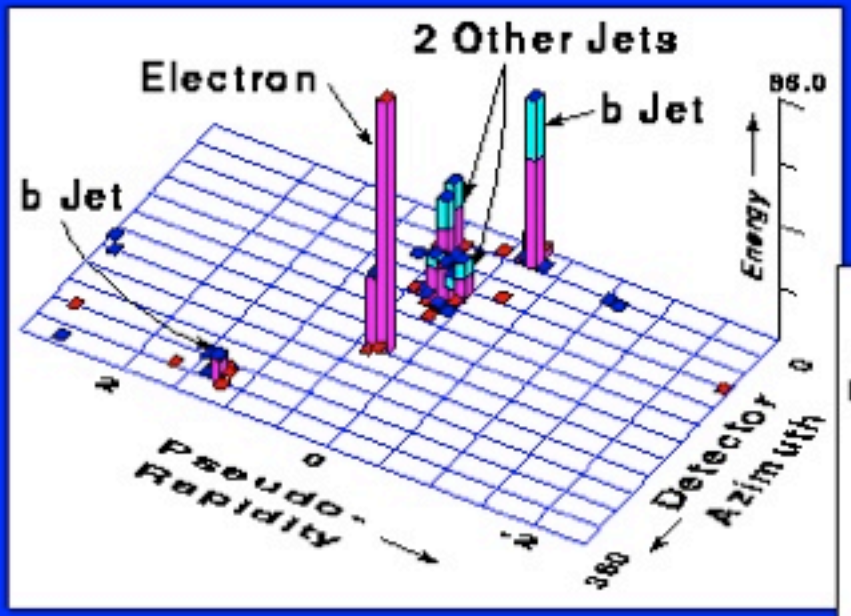
SVX detector

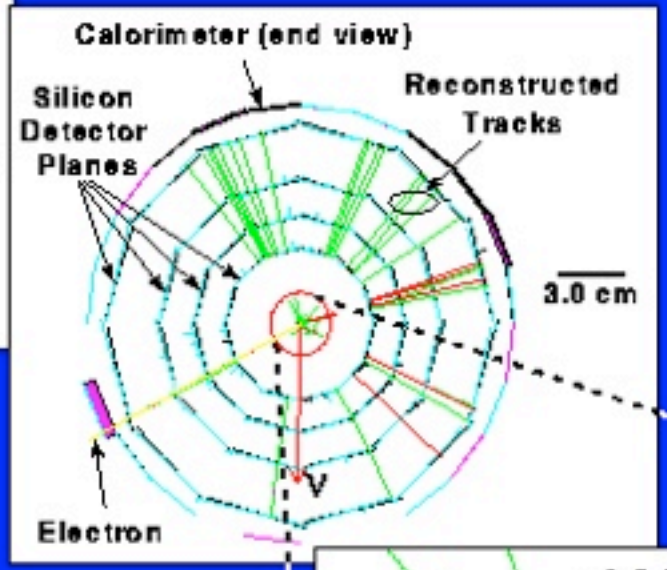


- Micro-strip vertex detector
  - Four layers of micro-strip sensors
  - 51 cm long with innermost layer at 3 cm from beam line, outermost at 8 cm
  - Strip pitch 60 μm
  - Hit resolution = 13 μm
  - Impact parameter resolution = 17 μm (at high momentum)



Evidence for top: Critical SVX Role





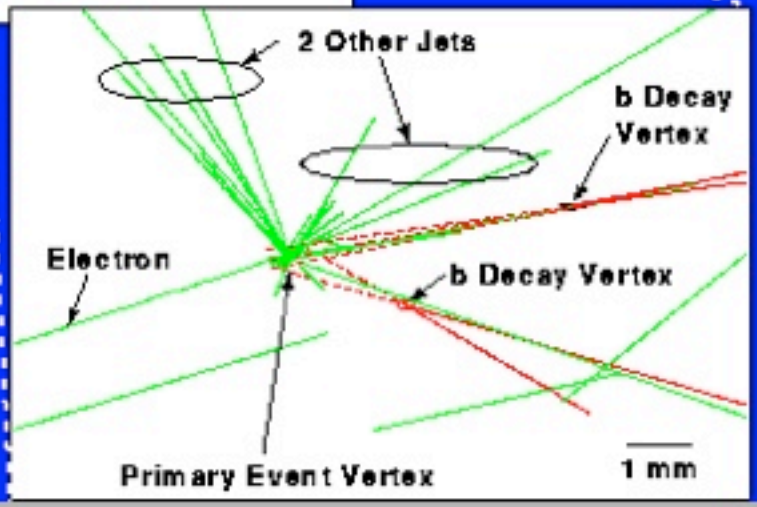
Run 40758 Event 44414

$t \rightarrow W^{+} + b$

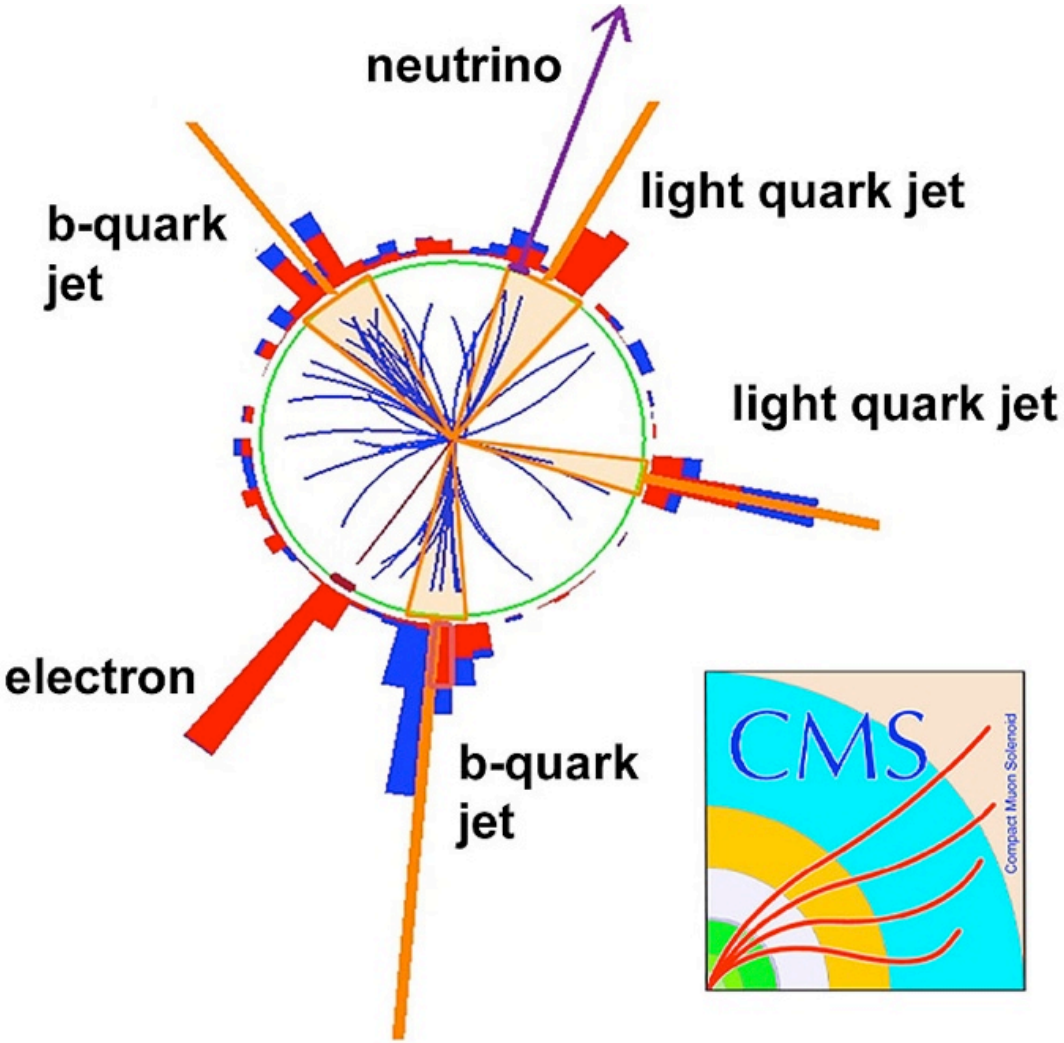
$\hookrightarrow e + \nu$

$\bar{t} \rightarrow W^{-} + \bar{b}$

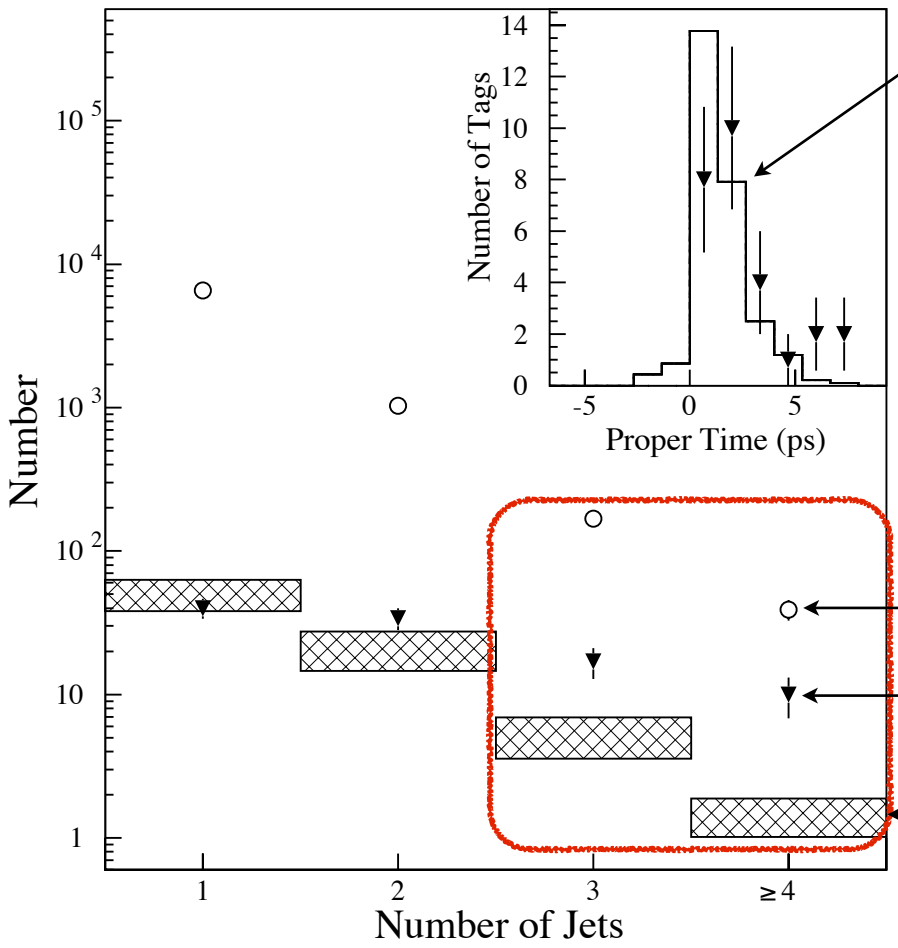
$\hookrightarrow$ 2 jets



Top event at the LHC

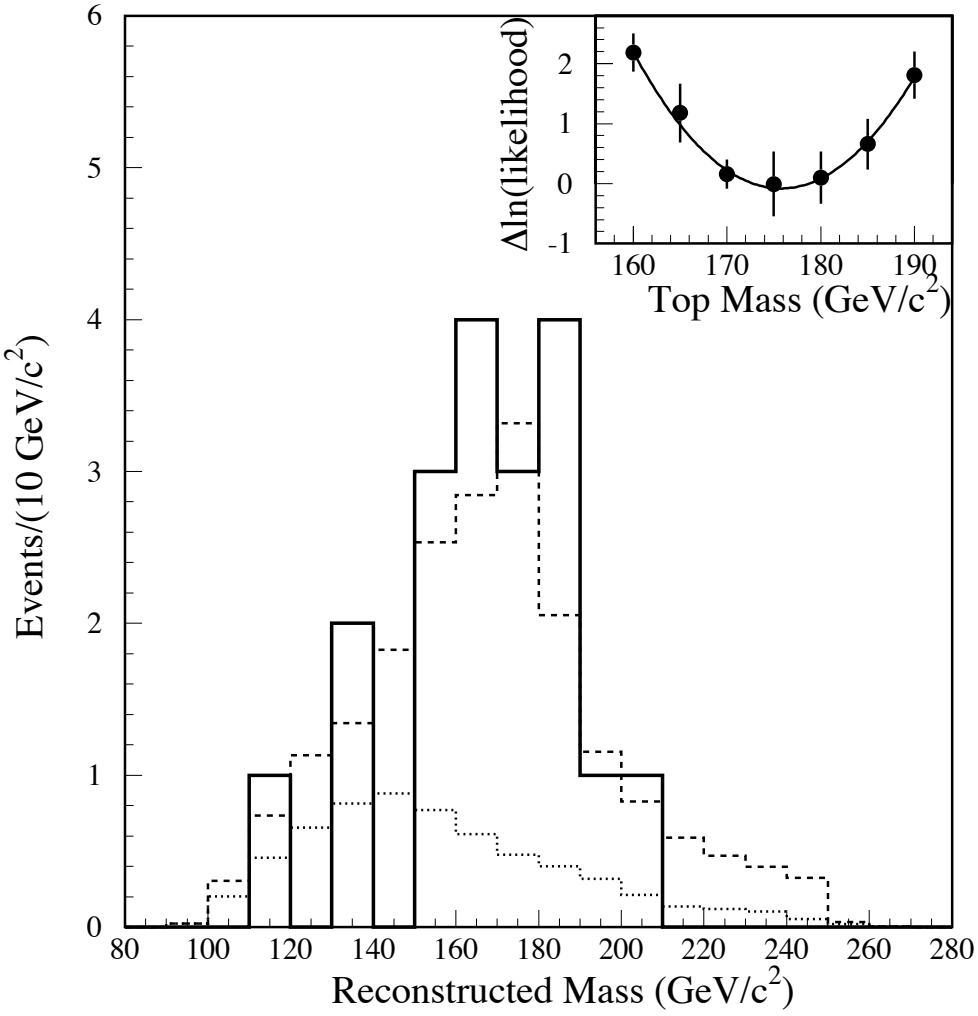


Signal extraction



N_{jet}	observed events	observed SVX tags	background tags expected
1	6578	40	50 ± 12
2	1026	34	21.2 ± 6.5
3	164	17	5.2 ± 1.7
≥ 4	39	10	1.5 ± 0.4

Mass measurement



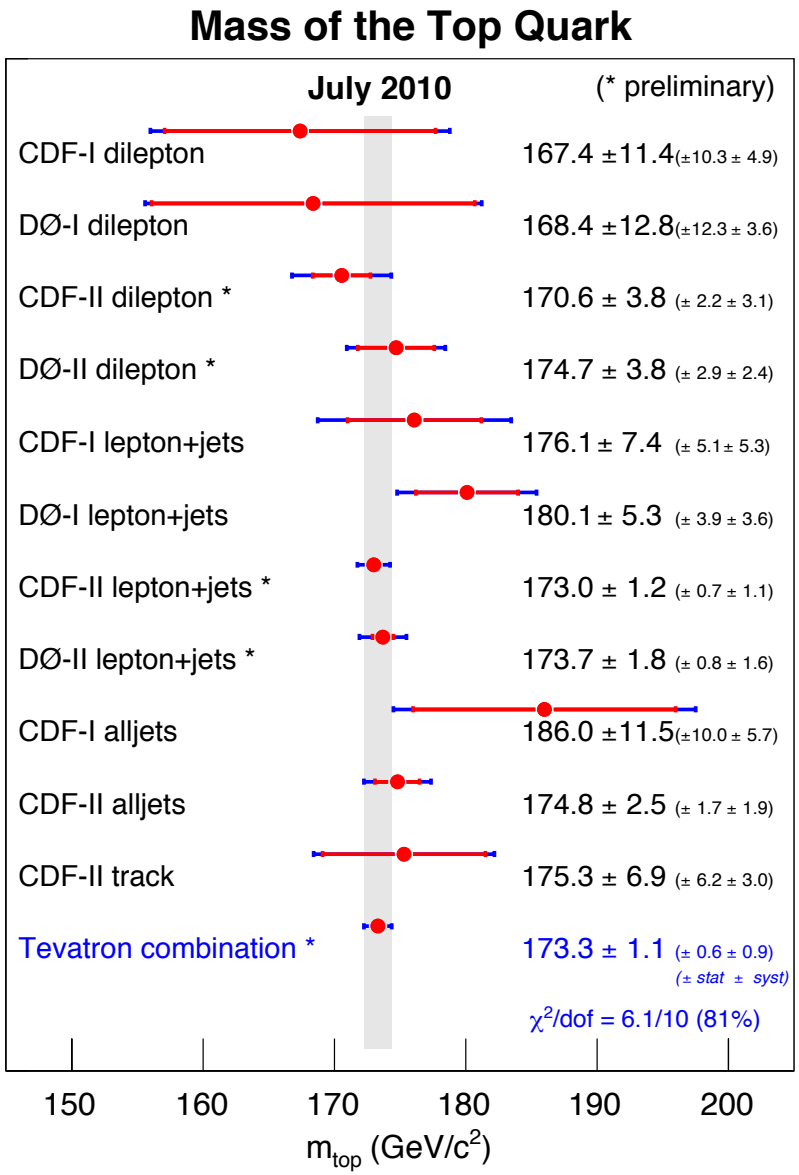
$$M_{top} = 176 \pm 8 \pm 10 \ \mathrm{GeV/c^2}$$

- Process

vertex	process
1	$\bar{p}p \to t_1 + t_2 + X$
2	$t_1 \to b_1 + W_1$
3	$t_2 \to b_2 + W_2$
4	$W_1 \to \ell + \nu$
5	$W_2 \to j_1 + j_2$

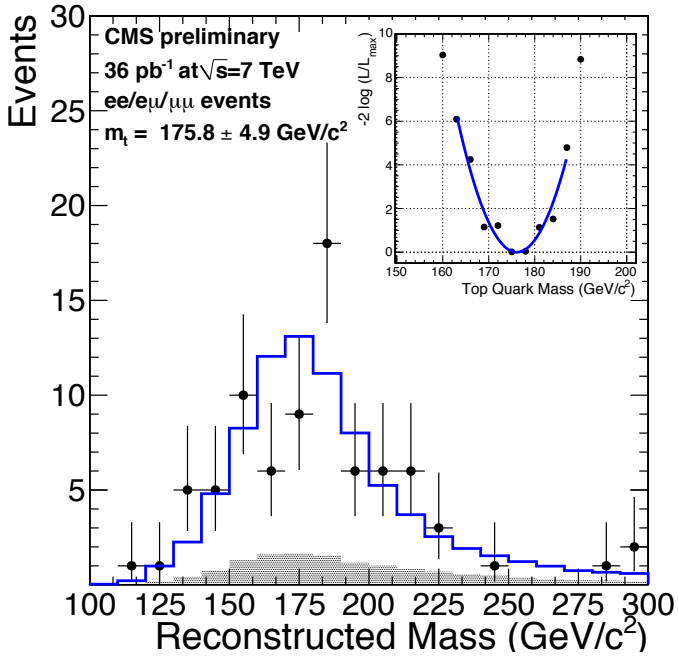
- Ingredients:
  - Lepton
  - Missing transverse energy
    - No longitudinal energy measurement → 2 solutions
  - 4 jets with highest E_T
- Fit data to sum of two distributions
  - W+jets background
  - Top quark for various masses M_{top}

Summary of Tevatron measurements



Very precisely known from Tevatron measurements

Relative error ~ 0.6%



First measurement at LHC

Searches for Supersymmetry

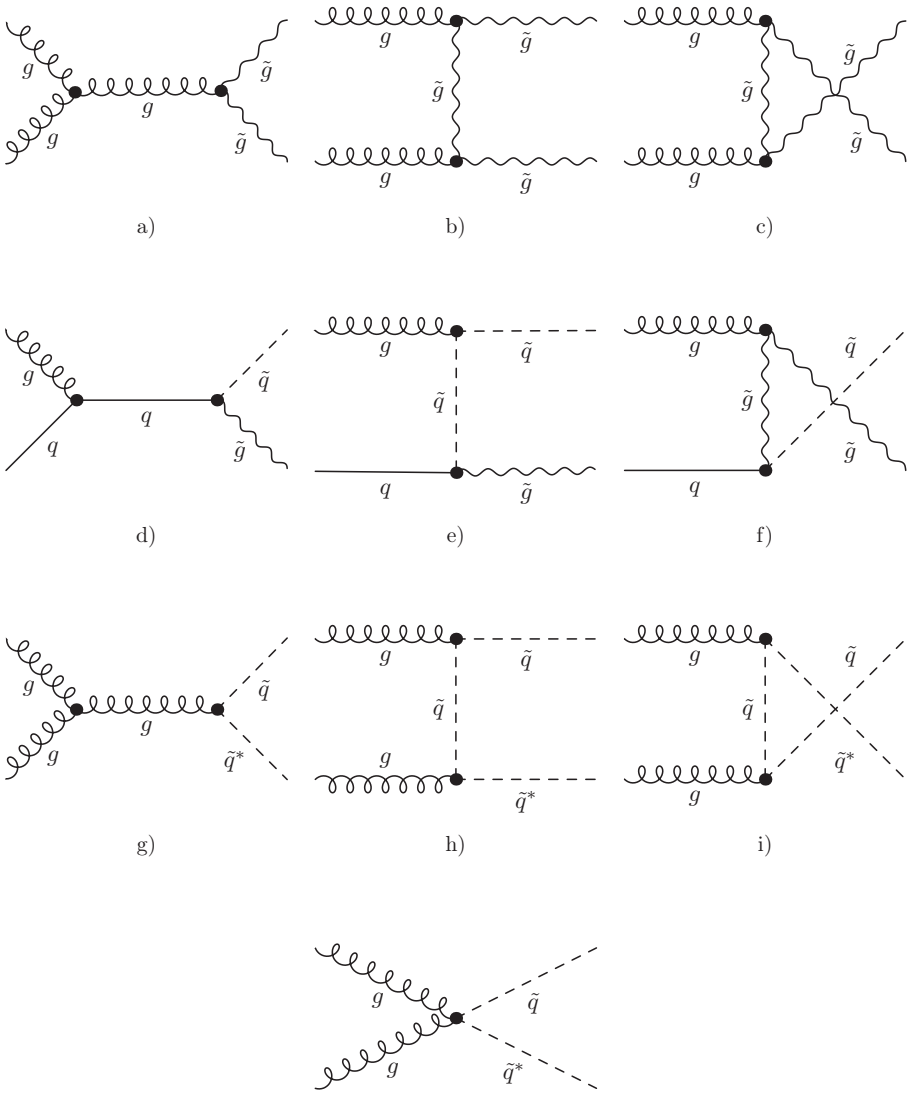
Extensions of the Standard Model

- Although very successful the standard provides no explanation for:
  - Dark matter
  - Origin of mass (Higgs?)
  - Dark energy
  - Excess of matter over antimatter
  - Quantum nature of gravity
- Possible extension of the Standard model given by **Su**per**Sy**mmetric theories
  - Postulate new symmetry between bosons and fermions
    - Quark and leptons have “bosonic” counterparts, called “squarks” and “sleptons”
  - Could fix SM divergency of Higgs boson mass
  - Could describe unification of coupling constants at very high energies
  - Could provide a dark matter candidate if lightest SuSy particle is stable

Ongoing searches at the LHC

- SuSy processes could be identified in a semi-infinite number of final states
  - First SuSY searches al the LHC focused on model meeting all the mentioned criteria
    - However, data analyses are model independent, interpretation of the results (limits) is.
  - Minimal model of SuSy with potential unification with gravity (mSUGRA)
    - At GUT scale all squarks, sleptons, Higgses have mass m_0
    - At GUT scale all gauginos have mass $m_{1/2}$
    - 5 parameters: m_0, $m_{1/2}$, sign(μ), A_0, tan(β)
  - R-parity conservation:
    - R-parity = $(-1)^{2S+3B+L}$. R=1 for SM particles, -1 for sparticles
    - SM particles produced in pairs with sparticles
    - Lightest supersymmetric particle (LSP) is stable
    - Neutralino escapes particle detectors → Large missing energy
- Experimental situation evolving very fast
  - ATLAS and CMS public results so far based on 36 pb^{-1} collected in 2010 at $\sqrt{s}$=7 TeV. More than 500 pb^{-1} have been collected since then!
    - **Atlas**: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
    - **CMS**: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Production process

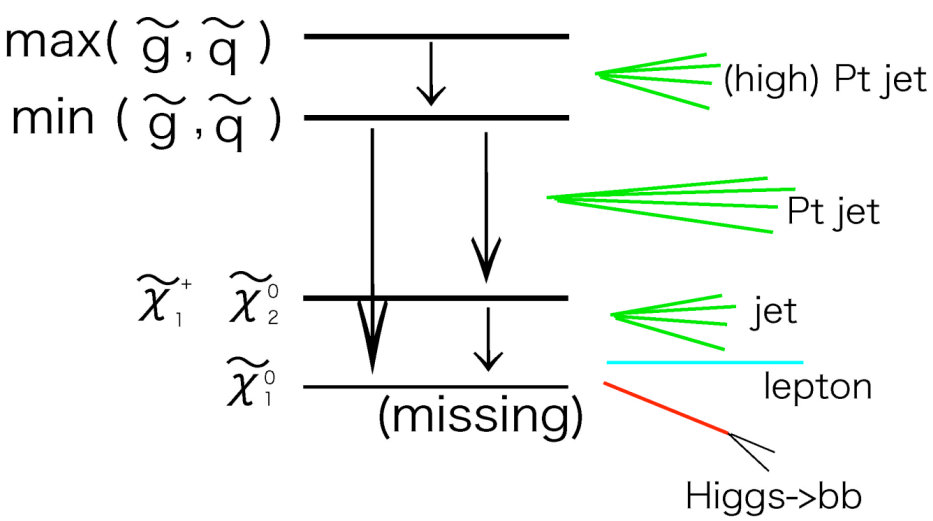


Dominant production processes are gluon-gluon and gluon-quark fusion

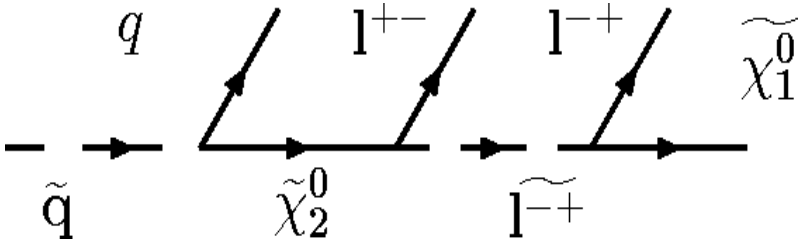
Mass spectrum depends on model parameters (e.g gluino can be lighter or heaview than squarks)

Experimental signatures

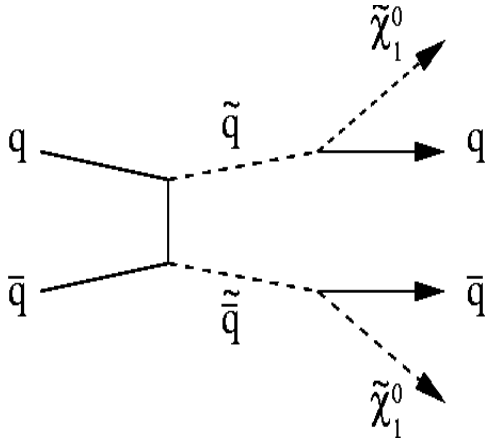
- **Decay of charginos/neutralinos**
  - Multi-leptonic events (opposite or same charge) with missing transverse energy
- **Decay of squarks**
  - Multi-jet events



Multi-leptonic topology



Hadronic topology



Search topologies

	Hadronic	Leptonic			
Number of leptons	0	1	2 same charge	2 opposite charge	3
Dominant SM background	QCD top pair W+jets	top pair QCD W+jets	fake top pair	top pair Z+jets	fake top pair

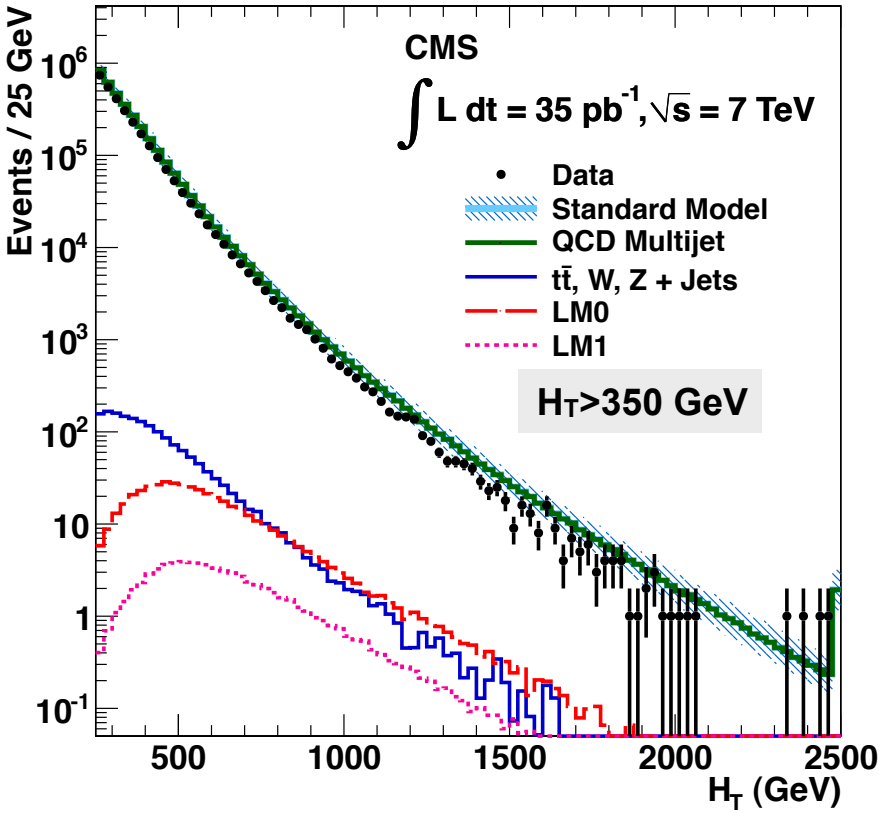
- Event selection is designed to suppress Standard Model background
- Data driven techniques to better constrain residual background
- Count events after all cuts
  - New process manifests as an 'excess' in the number of selected events

Hadronic searches

- Jets are preselected (ordered in transverse energy):
  - $E_T(jet_1, jet_2) > 100$ GeV, $|\eta(jet_1)| < 2.5$
  - For all other jets: $E_T > 50$ GeV, $|\eta| < 3$
  - No leptons and photons allowed
- The scalar sum of the transverse energies of all jets is given by:

$$H_T = \sum_{i=1}^{\#jets} E_T(jet_i)$$

Standard model background from QCD jet production a few order of magnitudes above SuSy signals



SM background suppression

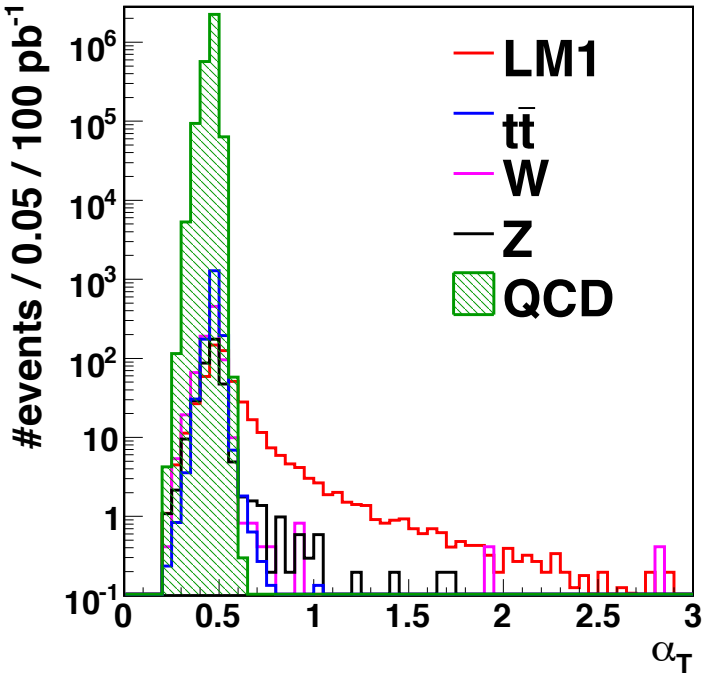
- Residual source of large missing momentum in multi jet events is given by jet energy mismeasurement
  - Detector inefficiencies
  - Miscalibration of calorimeters
- **Solution:**
  - Exploit different topology of QCD and SuSy events
  - Introducing variable α_T and **trasverse mass**.
  - For a two-jet event:

$$\alpha_T = \frac{E_T(jet_2)}{M_T}$$

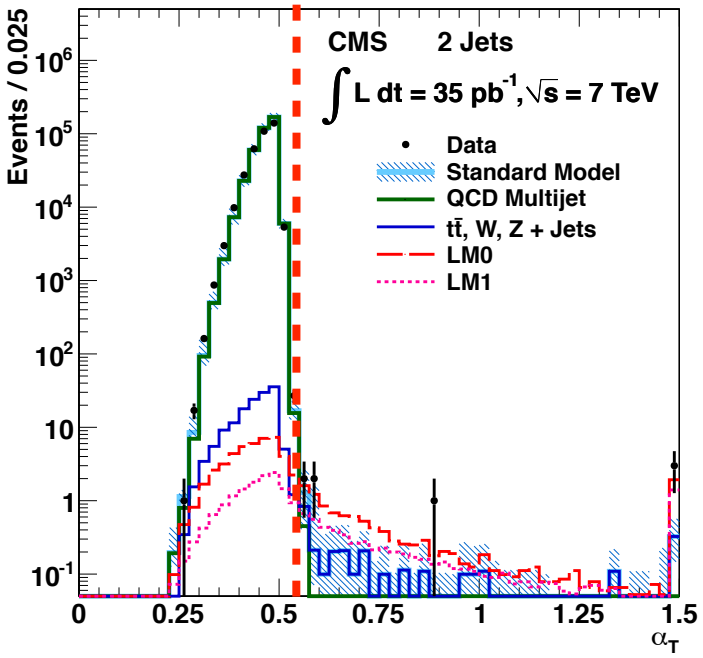
$$M_T = \sqrt{\left[\sum_{i=1}^{2} E_T(jet_i)\right]^2 - \left[\sum_{i=1}^{2} \vec{p}_T(jet_i)\right]^2}$$

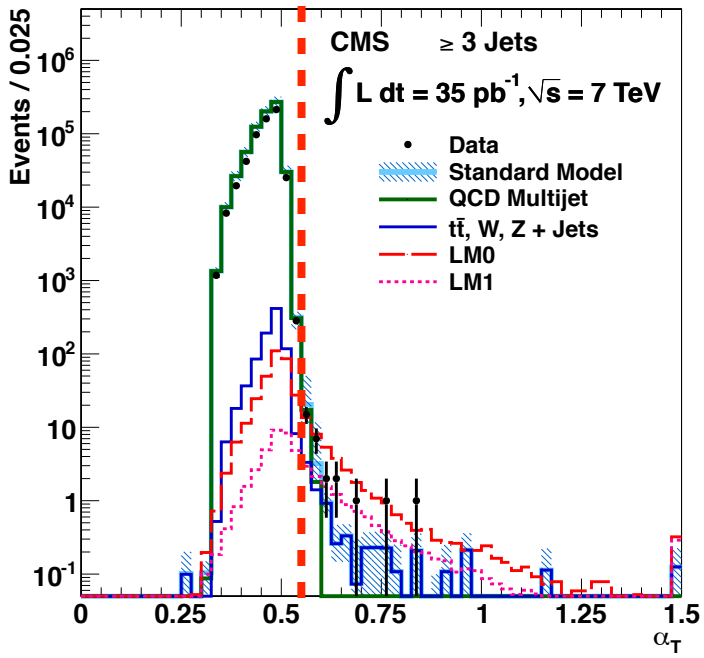
  - Multiple jets can be combined to form a di-jet event

QCD events give balanced jets and α_T~0.5
Large missing energy from SuSy gives α_T>0.5



Results



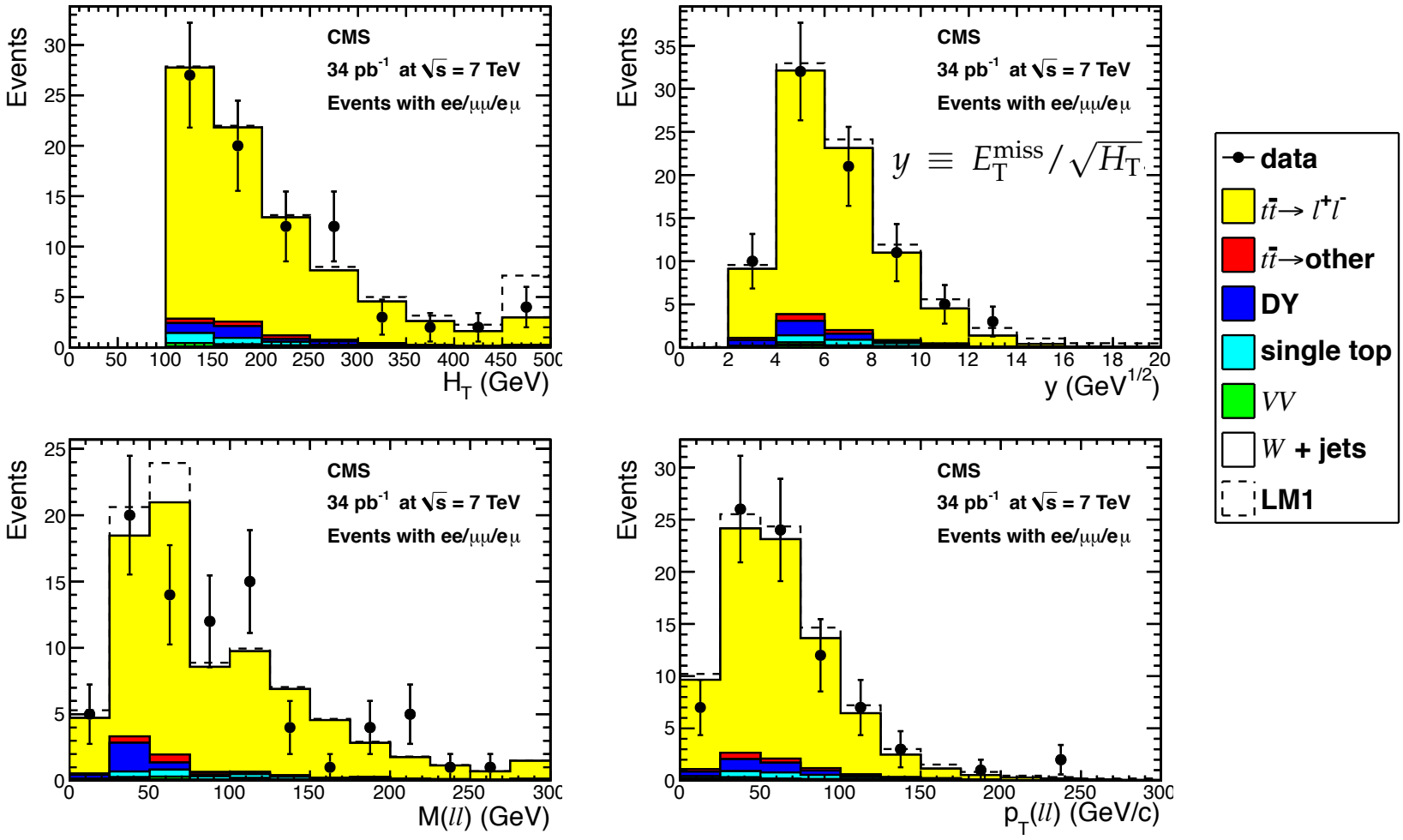


Selection	Data	SM	QCD multijet	$Z \to \nu\bar{\nu}$	W + jets	$t\bar{t}$
$H_T > 250\,\text{GeV}$	4.68M	5.81M	5.81M	290	2.0k	2.5k
$E_T^{j2} > 100\,\text{GeV}$	2.89M	3.40M	3.40M	160	610	830
$H_T > 350\,\text{GeV}$	908k	1.11M	1.11M	80	280	650
$\alpha_T > 0.55$	37	30.5±4.7	19.5±4.6	4.2±0.6	3.9±0.7	2.8±0.1
$\Delta R_{ECAL} > 0.3 \vee \Delta\phi^* > 0.5$	32	24.5±4.2	14.3±4.1	4.2±0.6	3.6±0.6	2.4±0.1
$R_{miss} < 1.25$	13	9.3±0.9	0.03±0.02	4.1±0.6	3.3±0.6	1.8±0.1

Multi-lepton searches

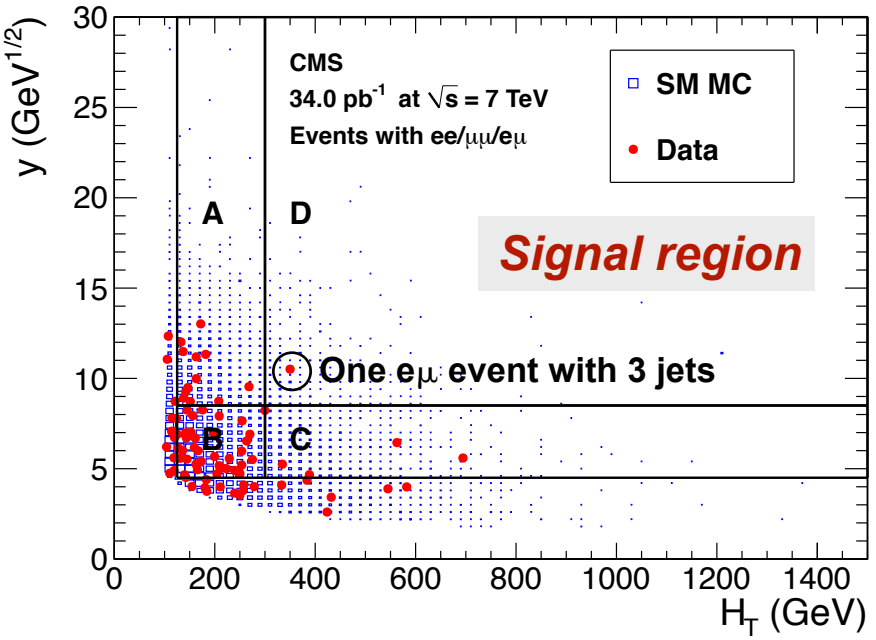
- Search for events with **opposite sign leptons** (e^+e^-, $e^\pm\mu^\pm$, $\mu^+\mu^-$), plus **jets** and **missing transverse energy**
- **Leptonic requirements:**
  - First lepton p_T>20 GeV, second lepton p_T>10 GeV
  - Resonance regions are removed (Z, Υ)
  - Isolation: no other particle in a cone DR=$\sqrt{(\Delta\phi^2+\Delta\eta^2)}$<0.3.
    - Removes leptons from semileptonic heavy-flavor decays
- **Hadronic requirements:**
  - Two jets with pT>20 GeV and |h|<2.5
  - Missing transverse energy > 50 GeV
  - H_T>100 GeV

Preselected events



Preselected events dominated by top pair production

"ABCD" method



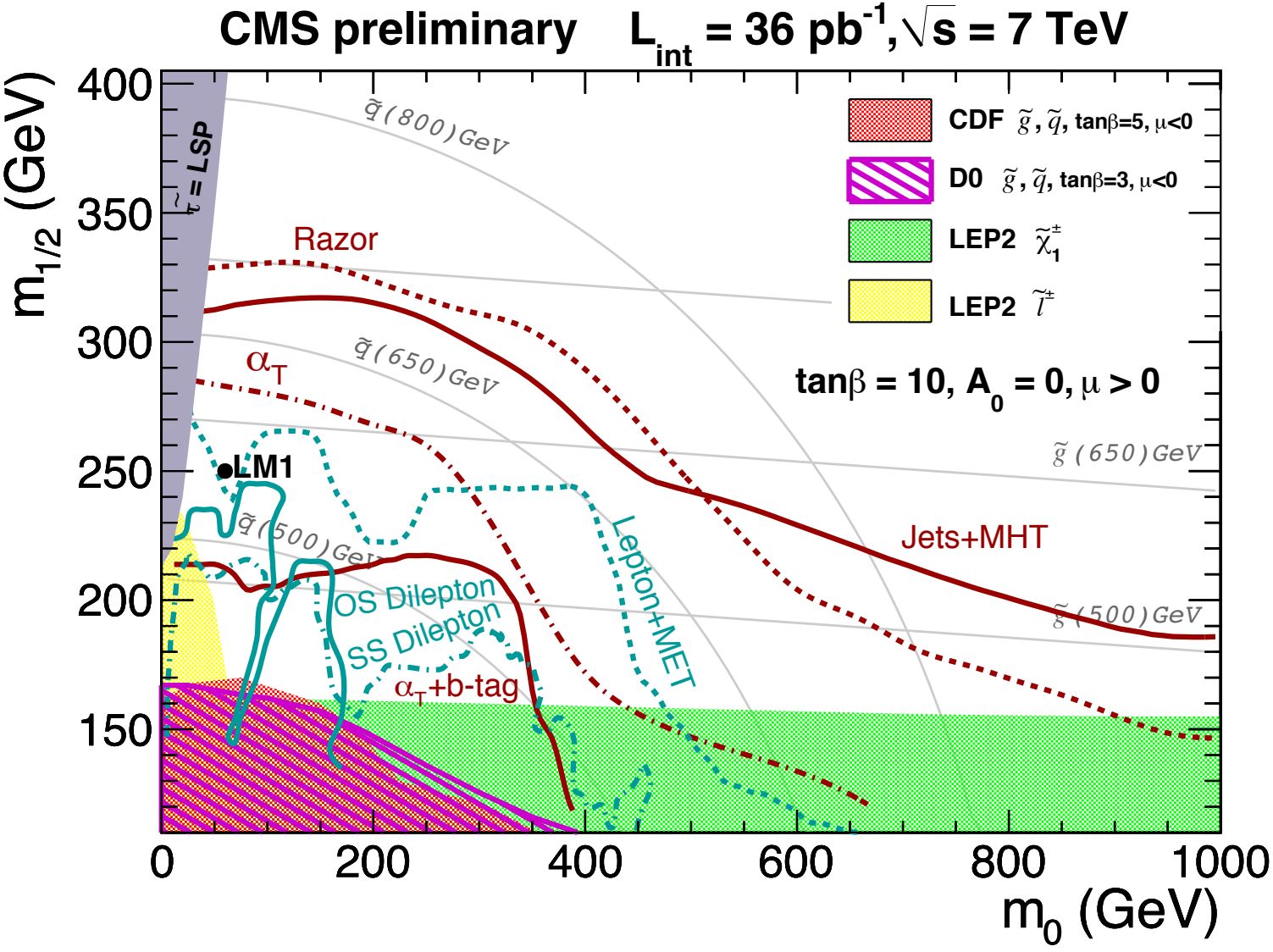
H_T and y nearly uncorrelated for top pair background.

Expected number of events in the signal region can be extracted from A,B,C

$$\frac{N_A}{N_B} = \frac{N_D}{N_C} \qquad \frac{N_A \times N_C}{N_B} = N_D$$

Sample	N_A	N_B	N_C	N_D	$N_A \times N_C / N_B$
$t\bar{t} \to \ell^+\ell^-$	8.44 ± 0.18	32.83 ± 0.35	4.78 ± 0.14	1.07 ± 0.06	1.23 ± 0.05
$t\bar{t} \to$ other	0.12 ± 0.02	0.78 ± 0.05	0.16 ± 0.02	0.02 ± 0.01	0.02 ± 0.01
Drell–Yan	0.17 ± 0.08	1.18 ± 0.22	0.04 ± 0.04	0.12 ± 0.07	0.01 ± 0.01
$W^{\pm}$ + jets	0.00 ± 0.00	0.09 ± 0.09	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
W^+W^-	0.11 ± 0.01	0.29 ± 0.02	0.02 ± 0.01	0.03 ± 0.01	0.01 ± 0.00
$W^{\pm}Z$	0.01 ± 0.00	0.04 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
ZZ	0.01 ± 0.00	0.02 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Single top	0.29 ± 0.01	1.04 ± 0.03	0.04 ± 0.01	0.01 ± 0.00	0.01 ± 0.00
Total SM MC	9.14 ± 0.20	36.26 ± 0.43	5.05 ± 0.14	1.27 ± 0.10	1.27 ± 0.05
Data	12	37	4	1	1.30 ± 0.78
LM0	4.04 ± 0.19	4.45 ± 0.20	13.92 ± 0.36	8.63 ± 0.27	12.63 ± 0.88
LM1	0.52 ± 0.02	0.26 ± 0.02	1.64 ± 0.04	3.56 ± 0.06	3.33 ± 0.27

mSUGRA exclusion limits



References

- CDF top quark discovery papers:
  - http://www-cdf.fnal.gov/top_status/first_ev.html
  - http://www-cdf.fnal.gov/top_status/top_prl_1994.ps
  - http://www-cdf.fnal.gov/top_status/prl_cdf.ps
- SuSy searches with CMS:
  - Hadronic search: http://arxiv.org/pdf/1101.1628v2
  - UZH PhD thesis: http://www.zora.uzh.ch/45730/1/thesis_Tanja.pdf
  - Leptonic search: http://arxiv.org/pdf/1103.1348