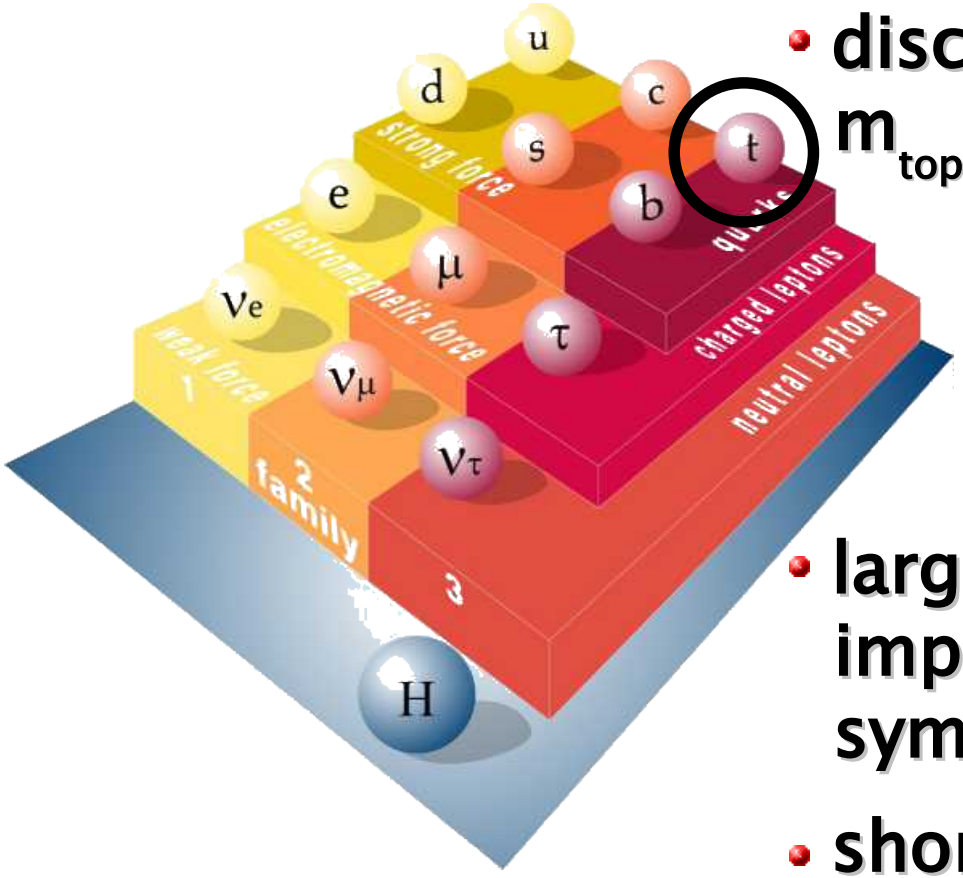
Top Quark Highlights from the DØ Experiment at the Tevatron

Christian Schwanenberger

University of Manchester

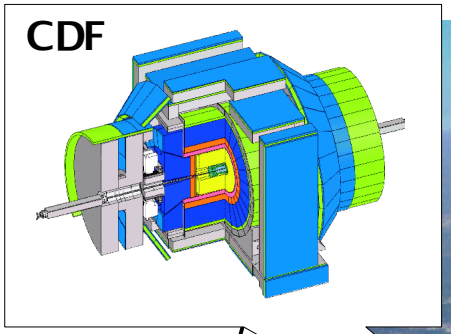
Research Progress Meeting,
Lawrence Berkeley National Laboratory,
04/01/2008

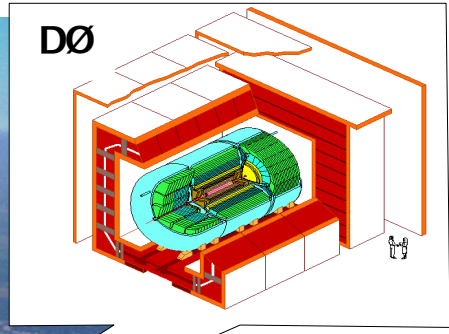
The Top Quark

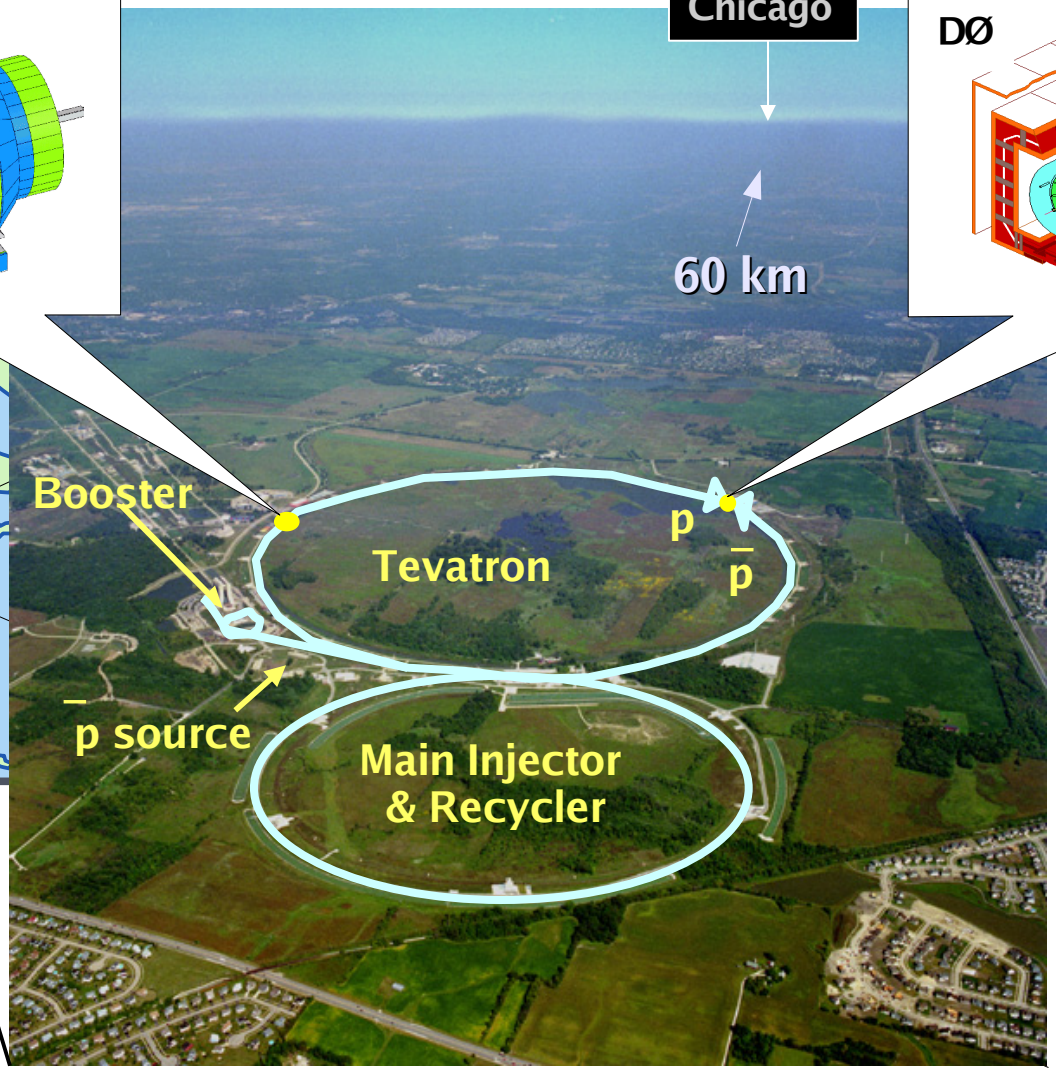


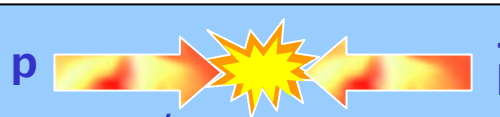
- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}$s $\ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe "naked" quark

The Tevatron at FERMILAB: $p\bar{p}$ Collisions









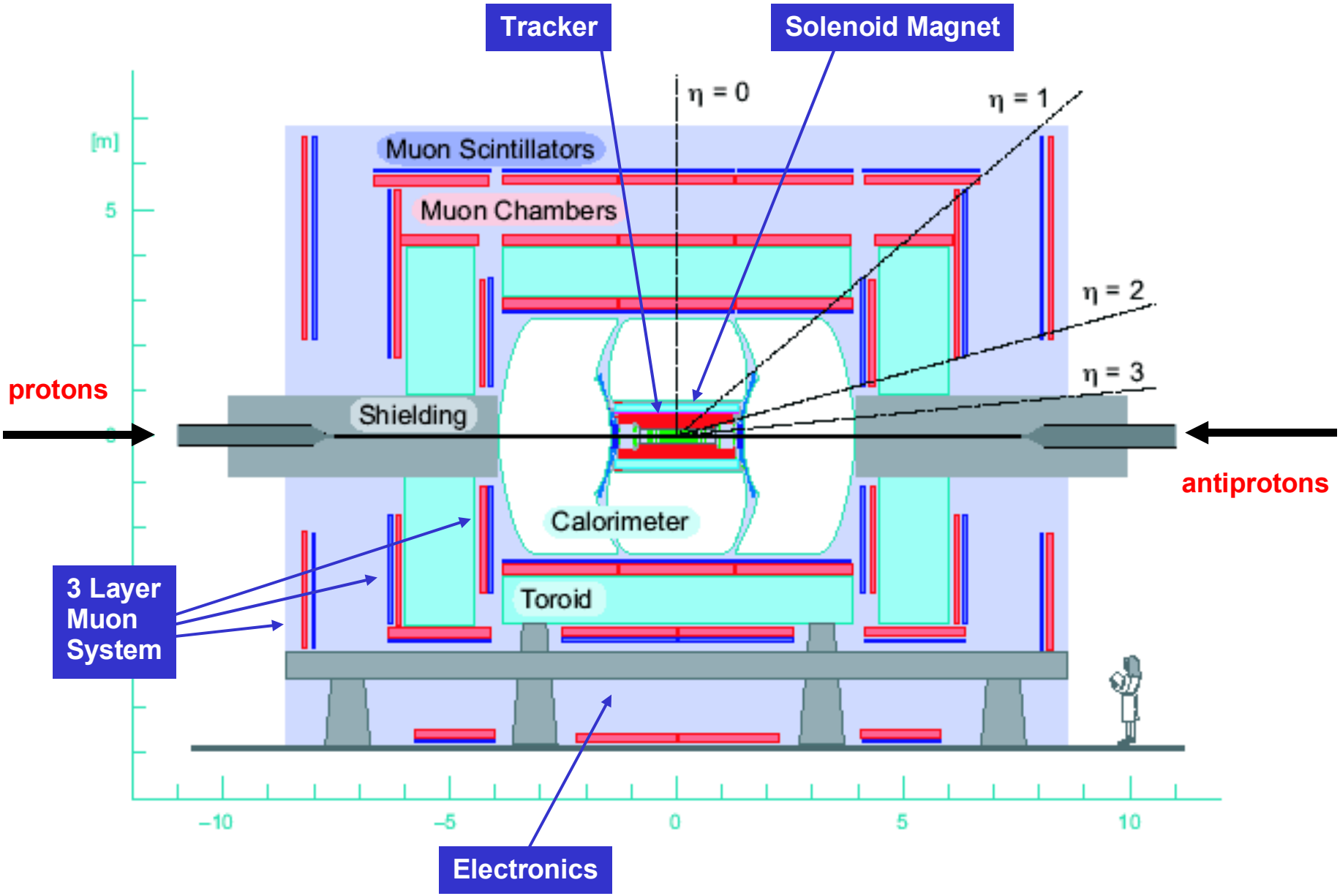
$\sqrt{s}$ =1.96 TeV
Δt = 396 ns

Run I 1987 (92)–95
Run II 2001–09: 40x larger dataset
at increased energy

top quark discovery

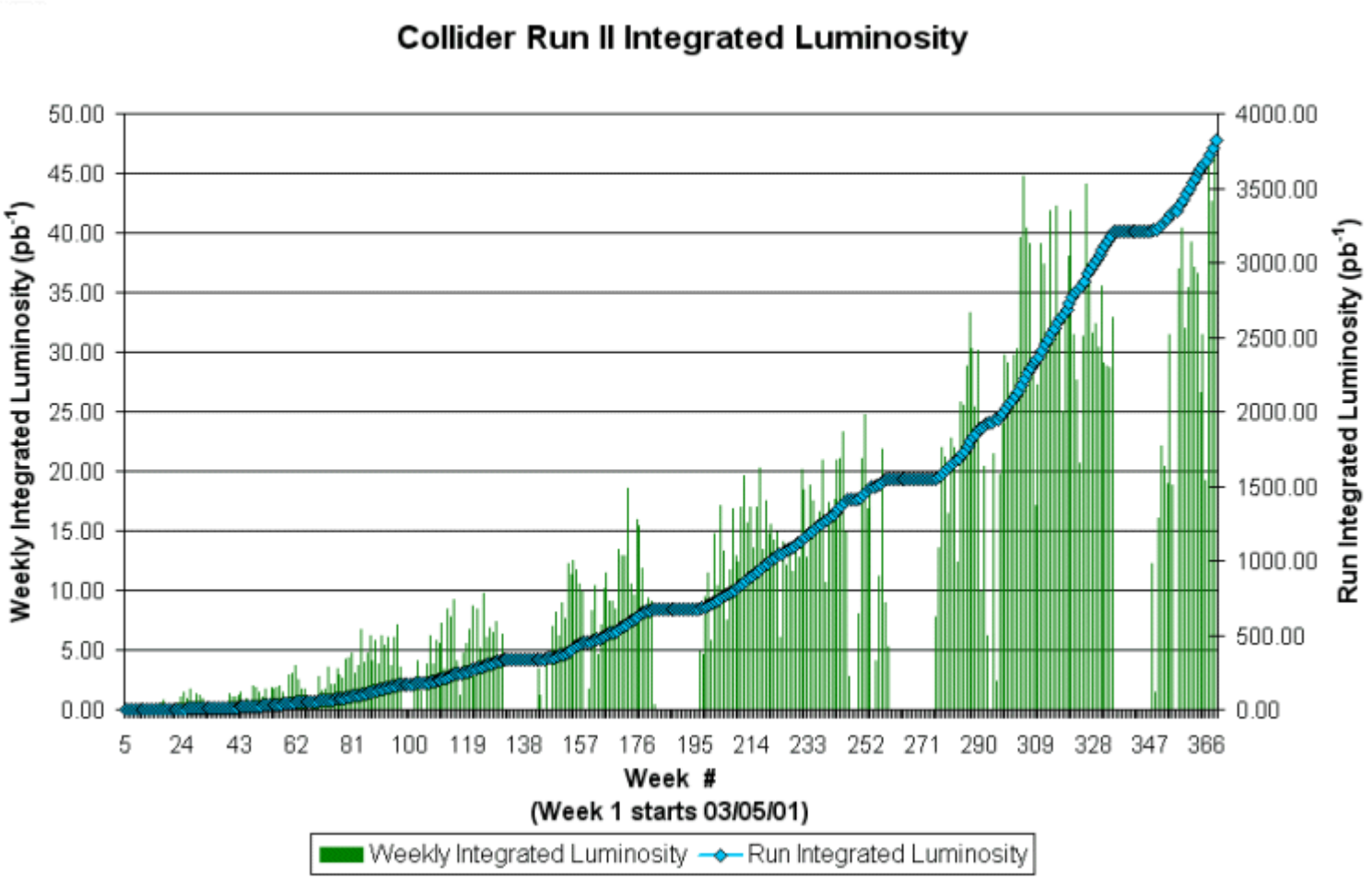
measure properties with high precisions:
is it really the particle expected in the SM?

The DØ Experiment



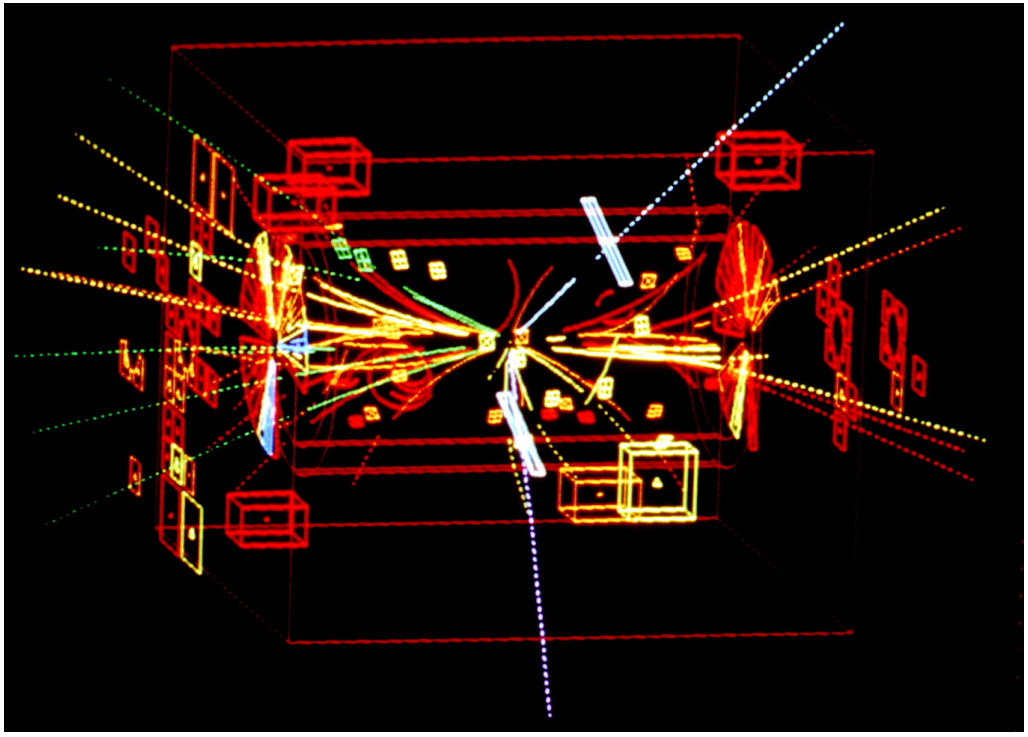
The Tevatron at Fermilab: Luminosity

- Tevatron has delivered ~3.5 fb^{-1} per experiment
- CDF and DØ ~3 fb^{-1} recorded each
- current data taking efficiency is approaching ~90%



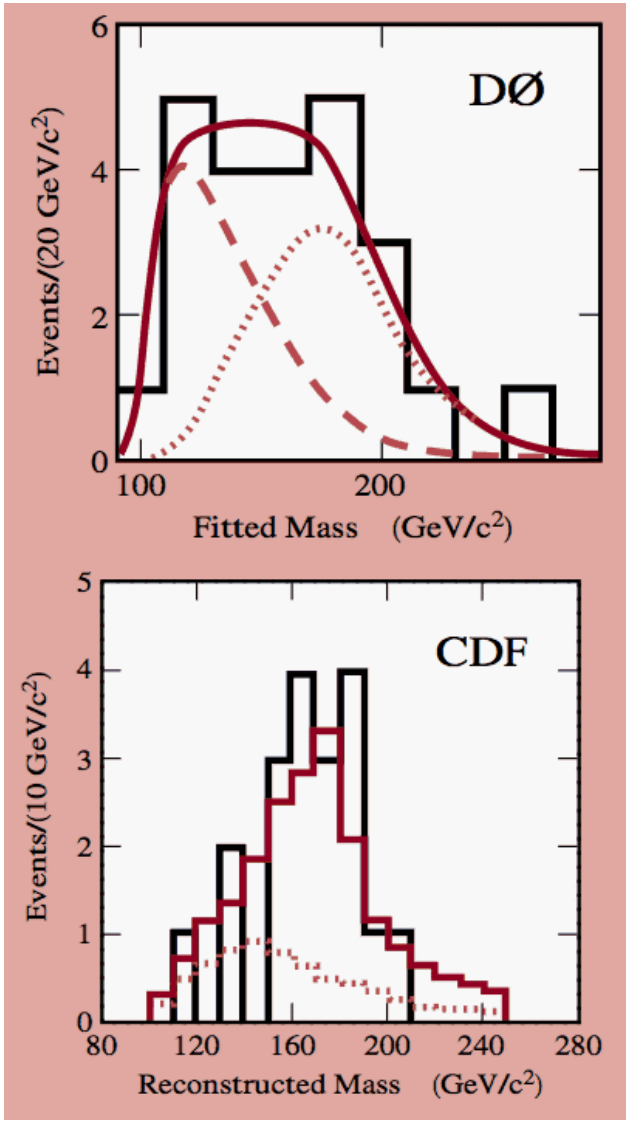
Phase I: Discovery

Z boson



1983, UA1 experiment, CERN

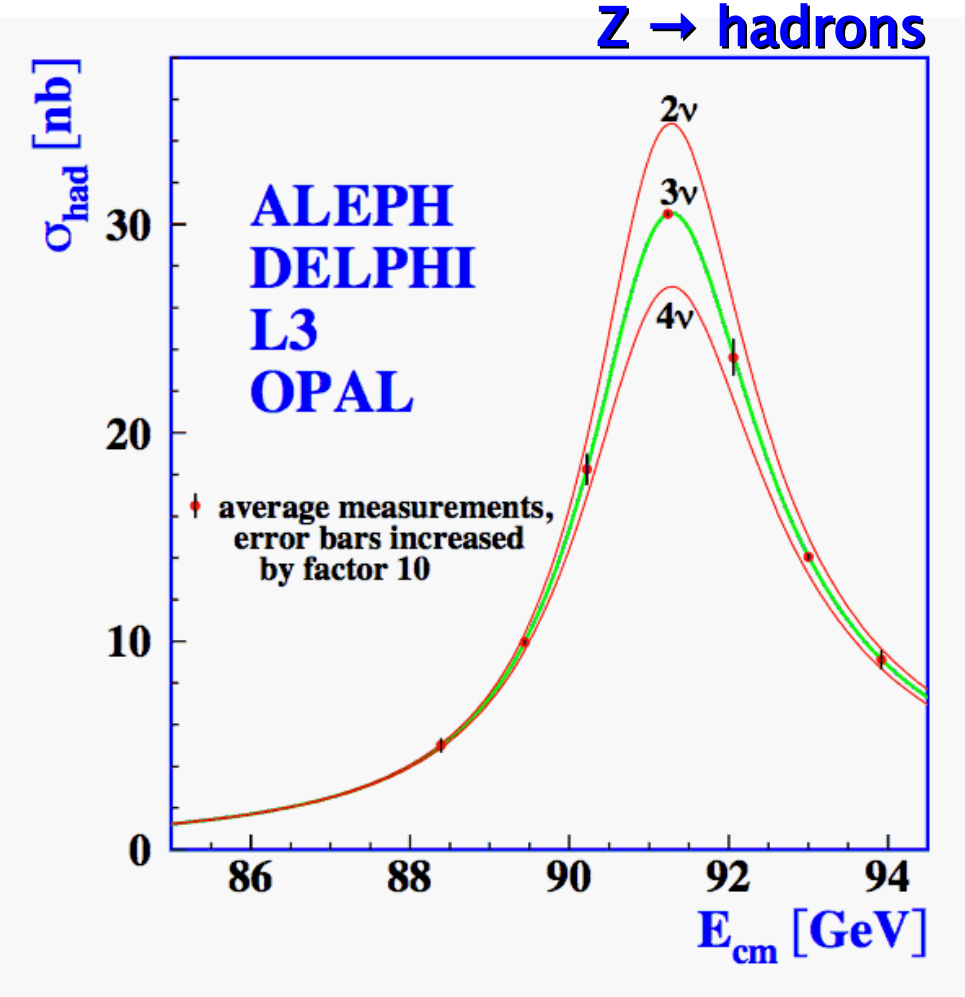
top quark



1995, CDF and DØ experiments, Fermilab

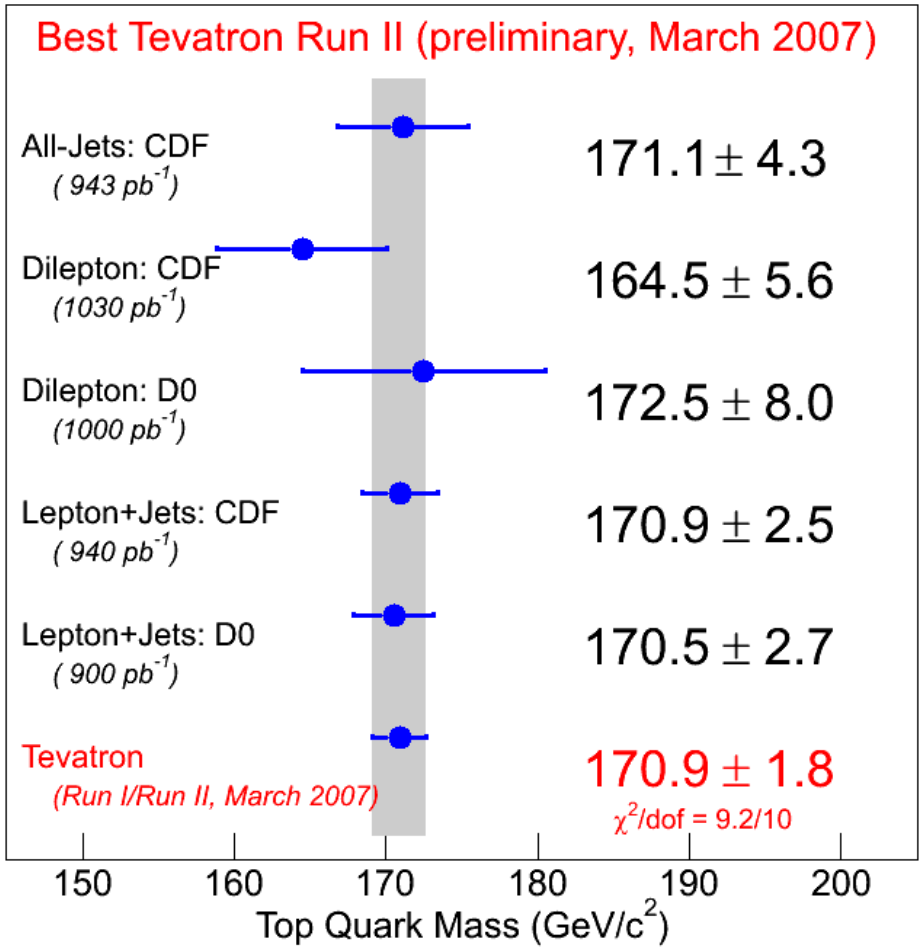
Phase II: Precision Measurements

Z boson



LEP experiments, CERN

top quark

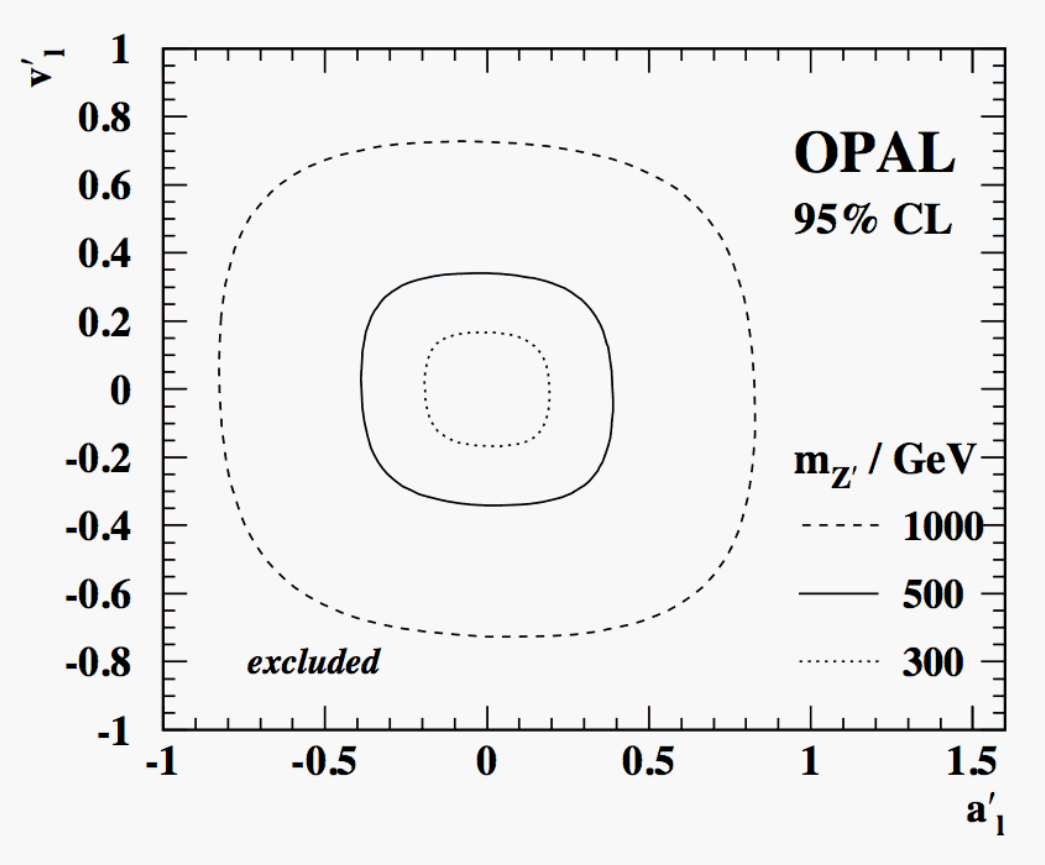


Tevatron experiments, Fermilab

Phase III: Searches for new physics

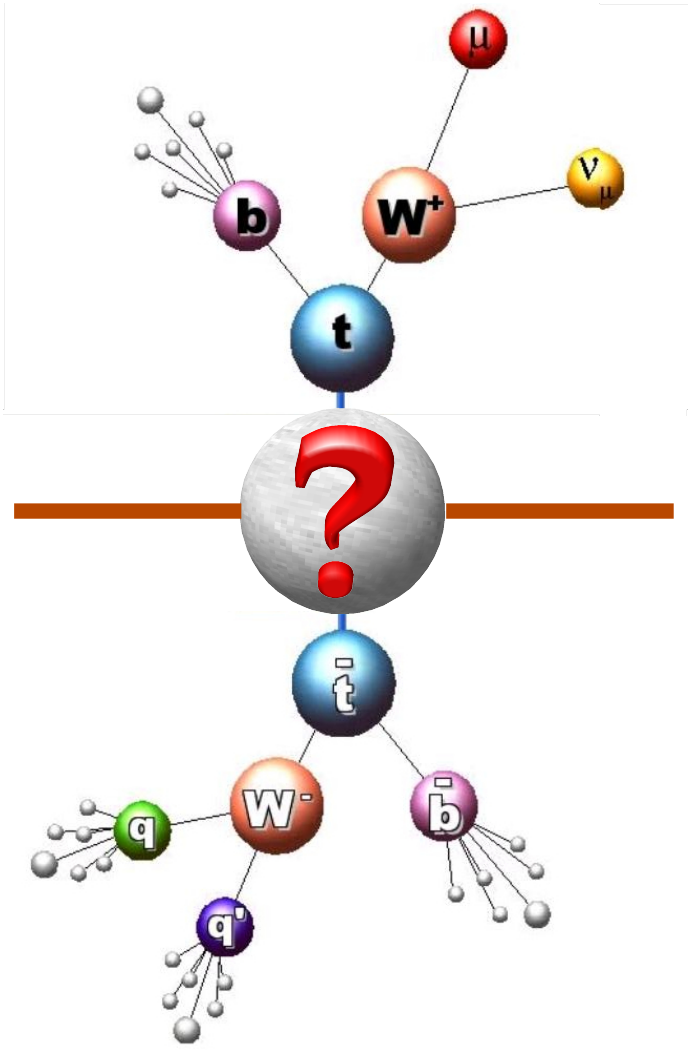
Z boson

vector and axial vector couplings of Z' boson to leptons



OPAL experiment, CERN

top quark



DØ experiment, Fermilab

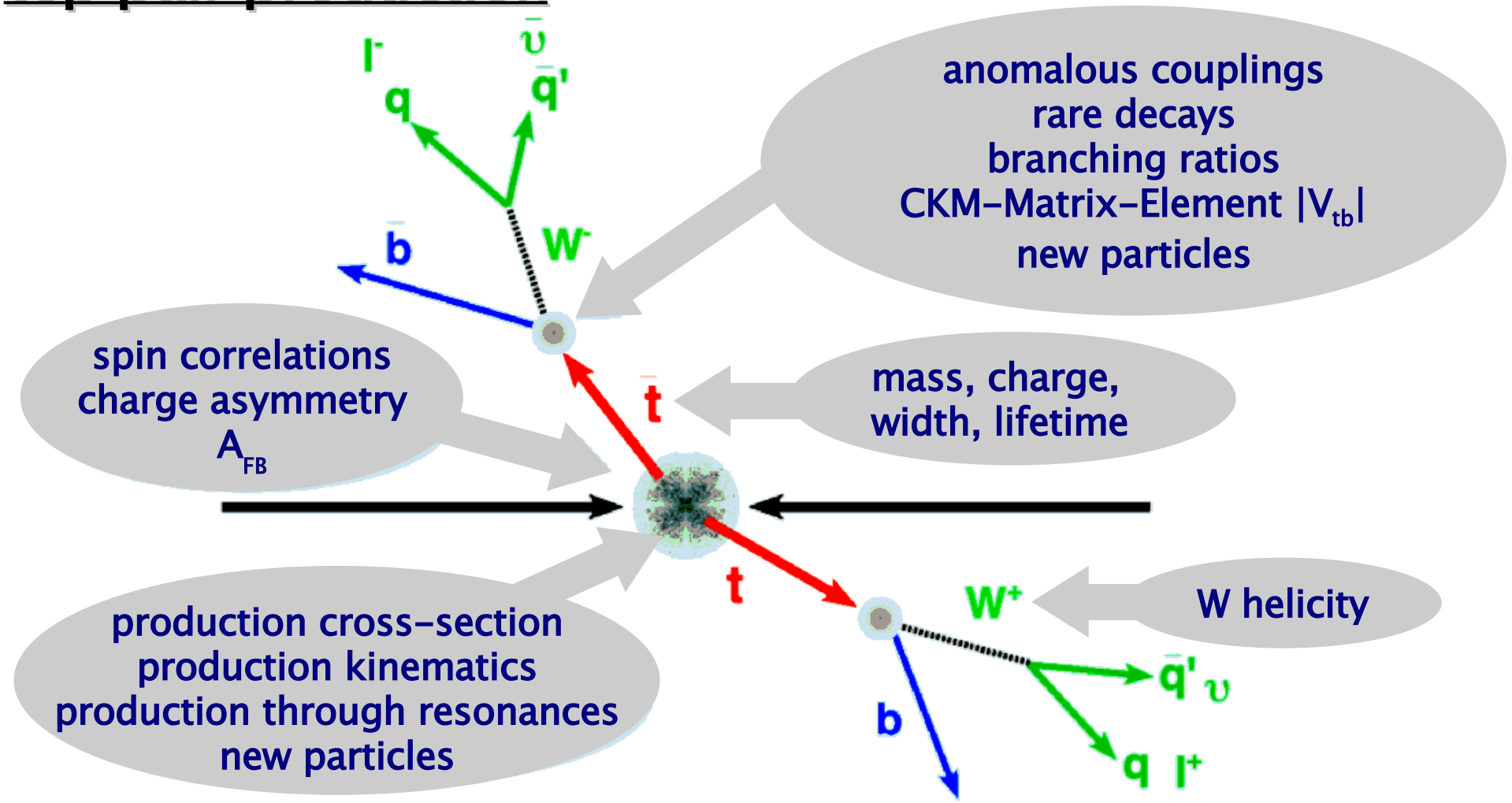
Top Quark Analyses at the Tevatron

Run I: top quark discovery (~125pb^{-1})

Run II: with high precision answer...

- is it really the particle expected in the SM?

- **top pair production**



- **single top production**

- evidence found by CDF and DØ!

searches for new particles

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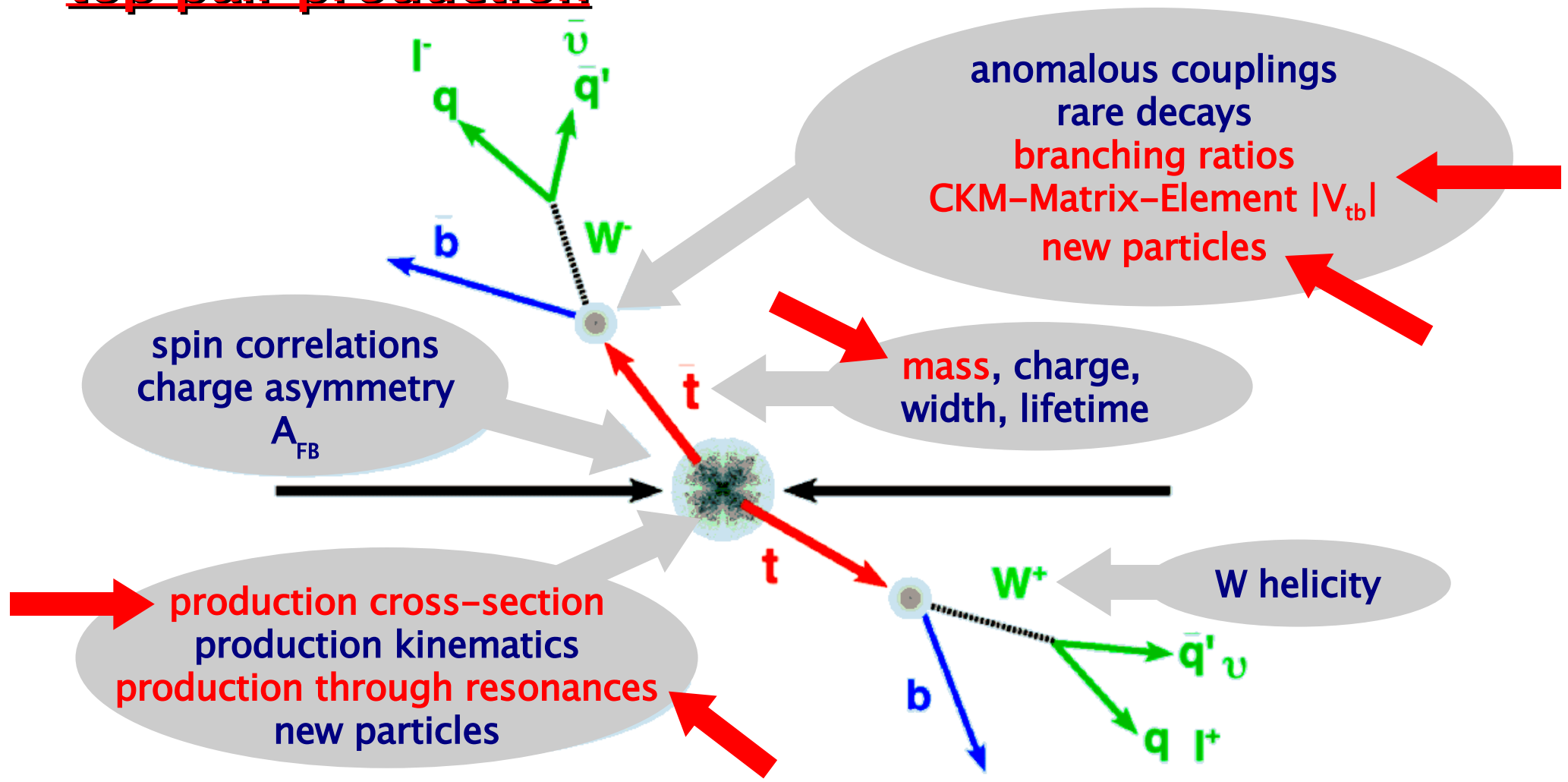

- **single top production**
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searches for new particles

Outline

Top Pair Production Cross Section

Searches in Top Production

- new resonances

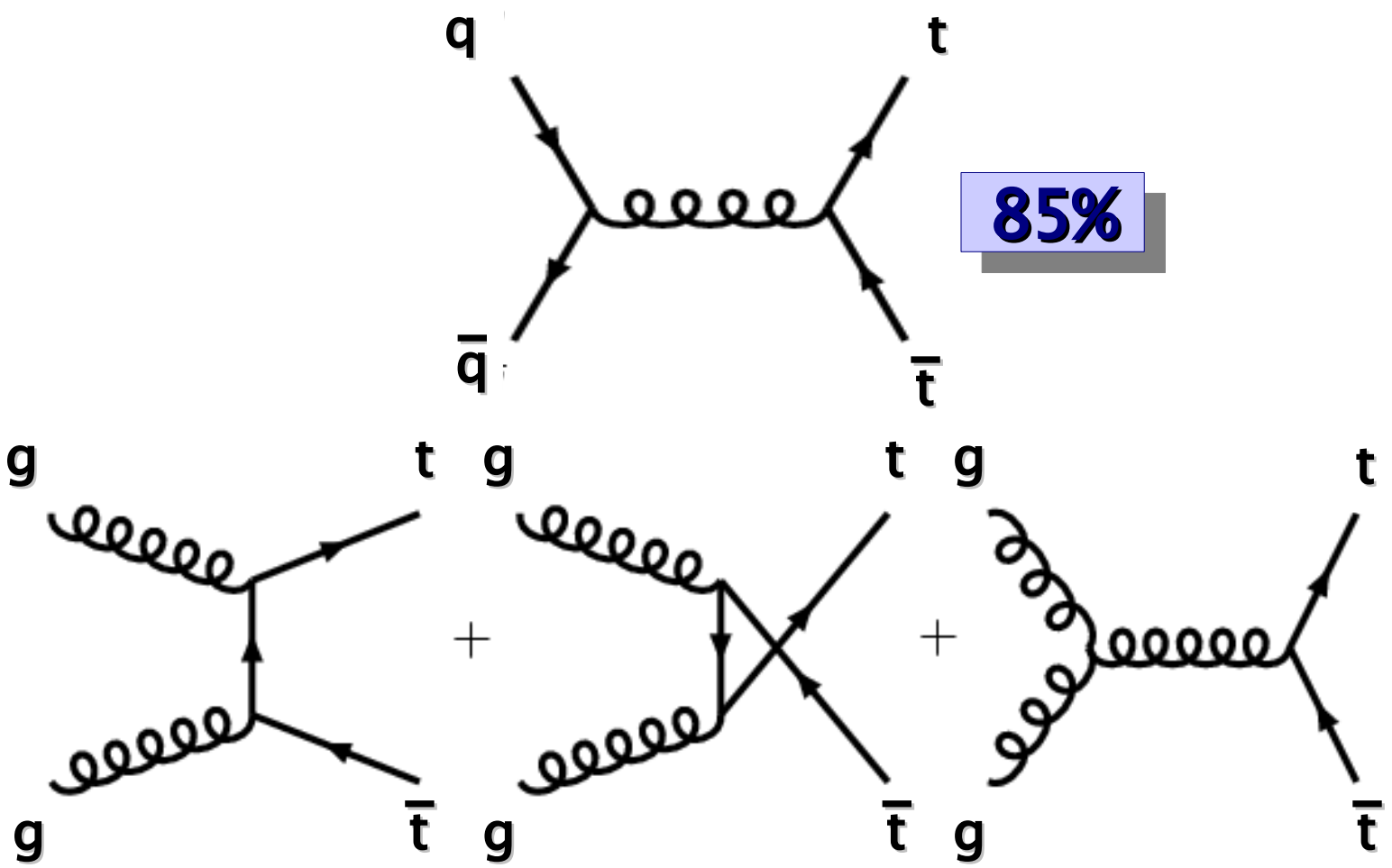
Searches in Top Decays

- branching fractions
- charged Higgs boson

Top Mass

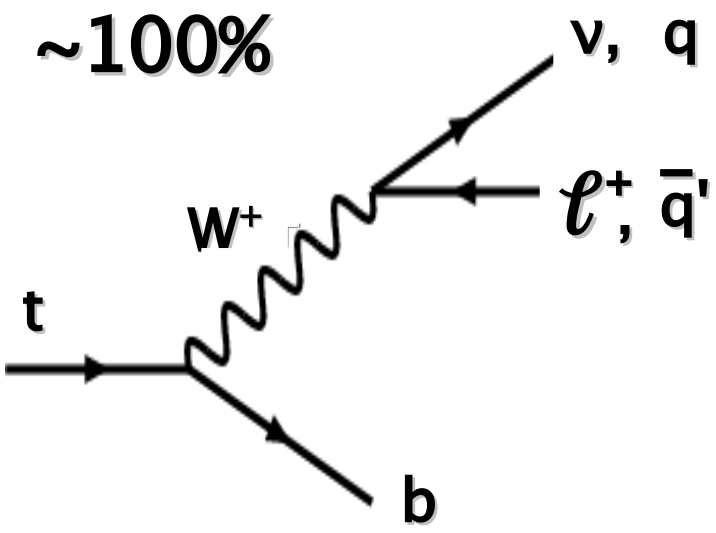
Outlook: Top Physics at LHC

Top Quark Pair Production

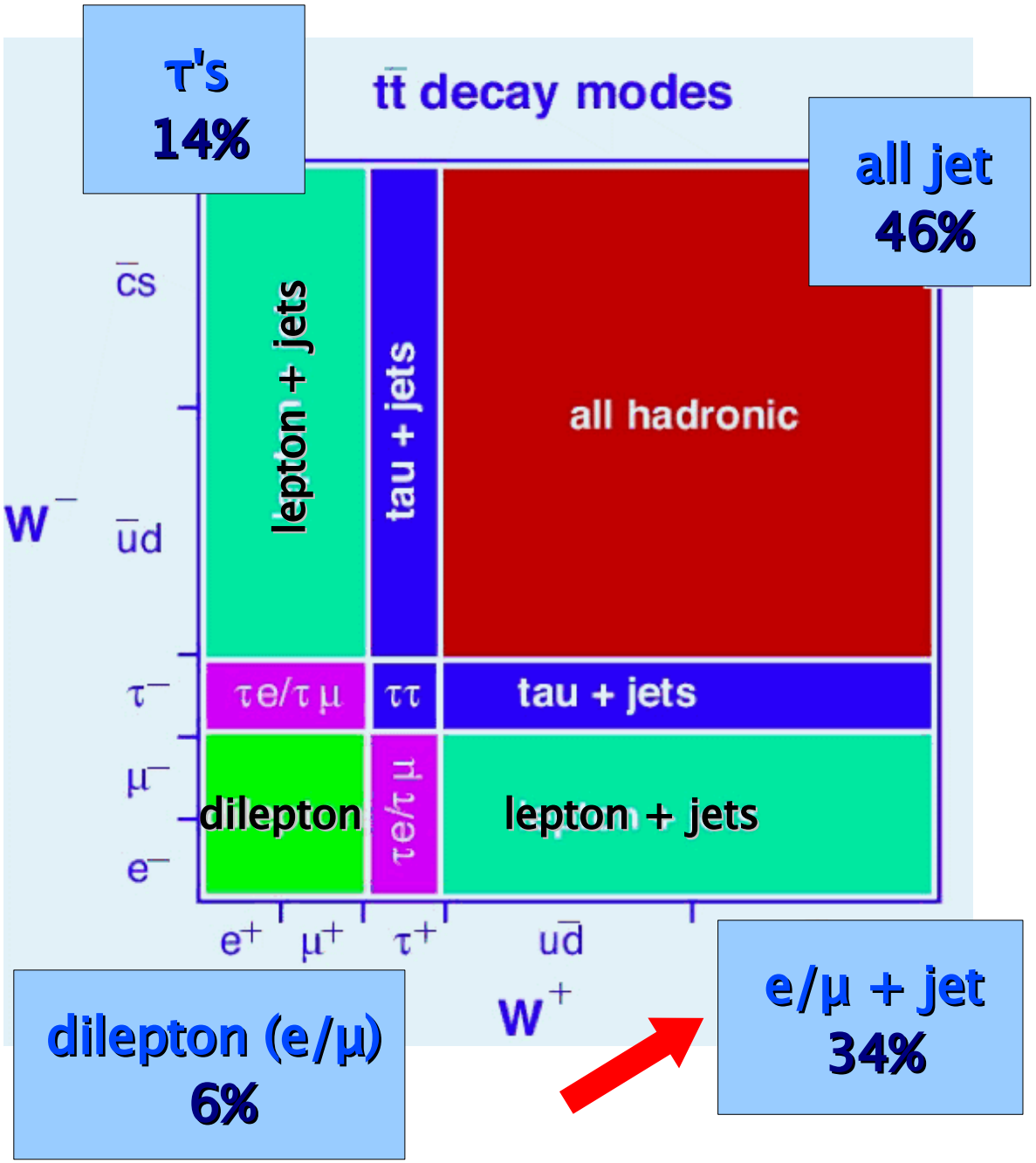


Top Antitop Signatures

- **top decay:**



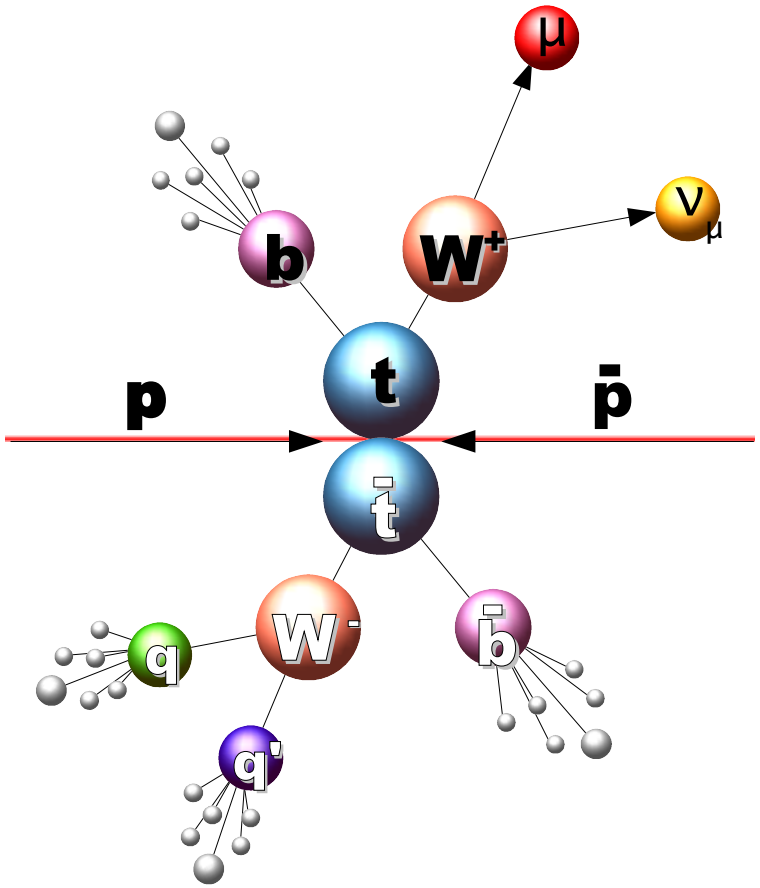
- reconstruct and identify: electrons, muons, jets, b-jets and missing transverse energy



Event Topology in Lepton+Jets

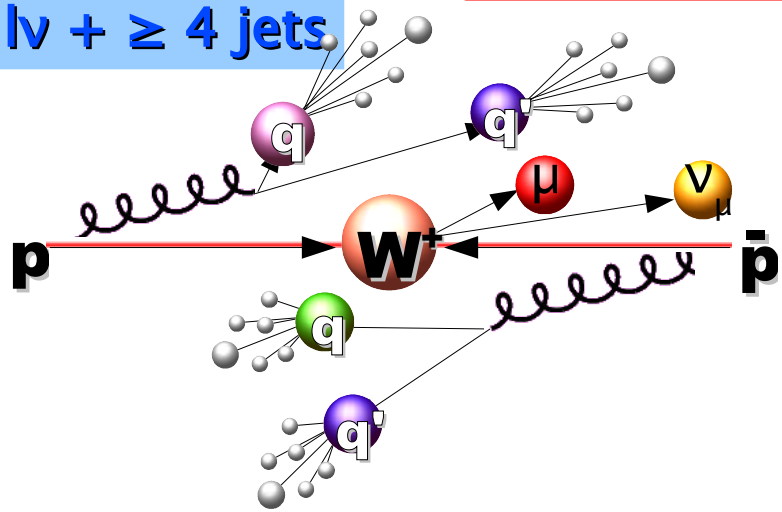
signal

- 1 lepton with high p_T
- 1ν: high missing transverse energy
- ≥ 4 jets

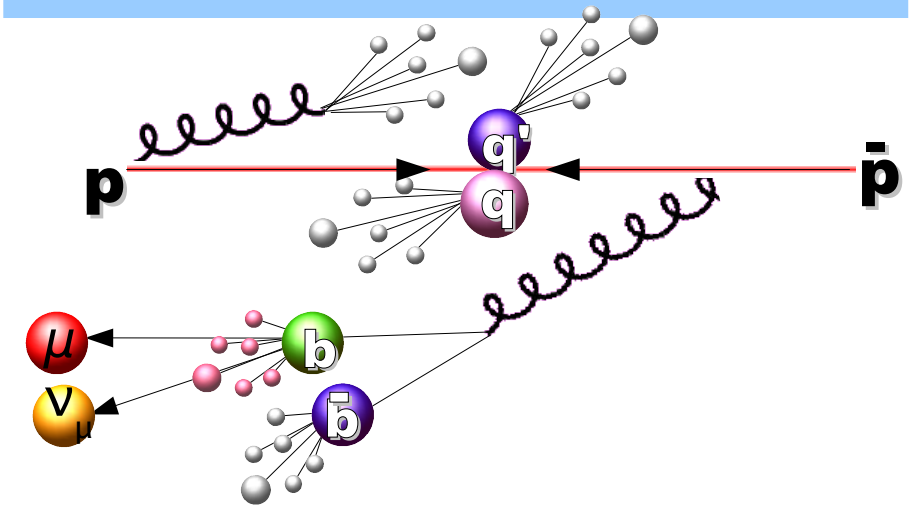


background

W → lν + ≥ 4 jets



multijet background (QCD)
+ misreconstructed met
+ fake isolated μ or e



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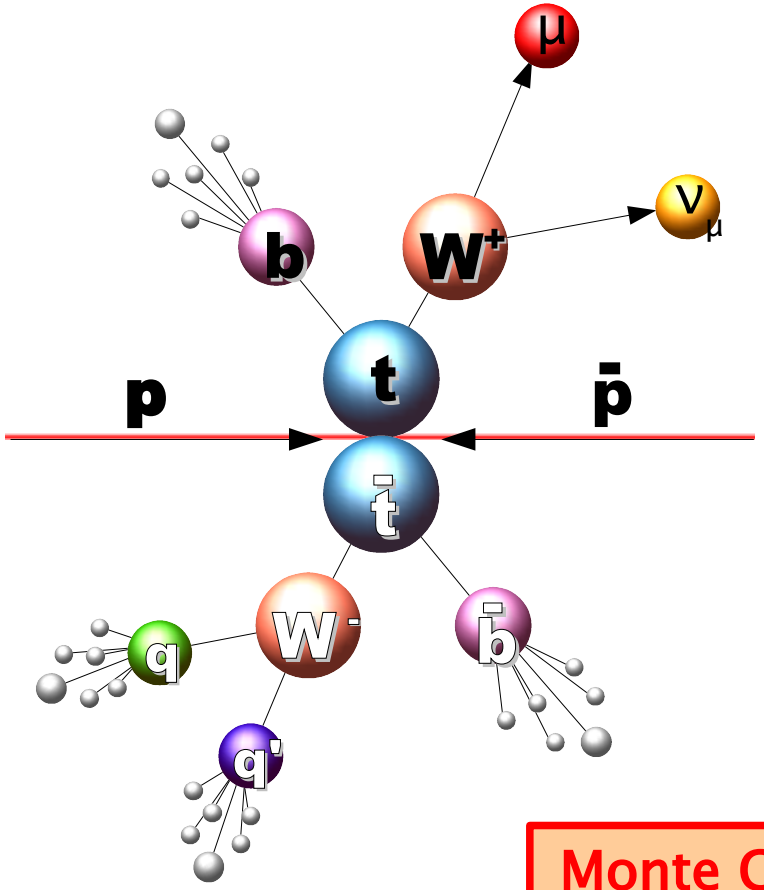
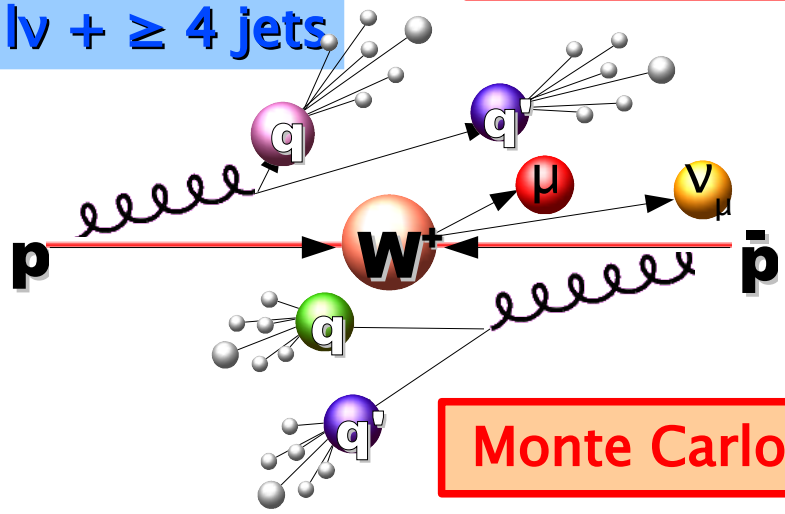


Monte Carlo

background

W → lν + ≥ 4 jets



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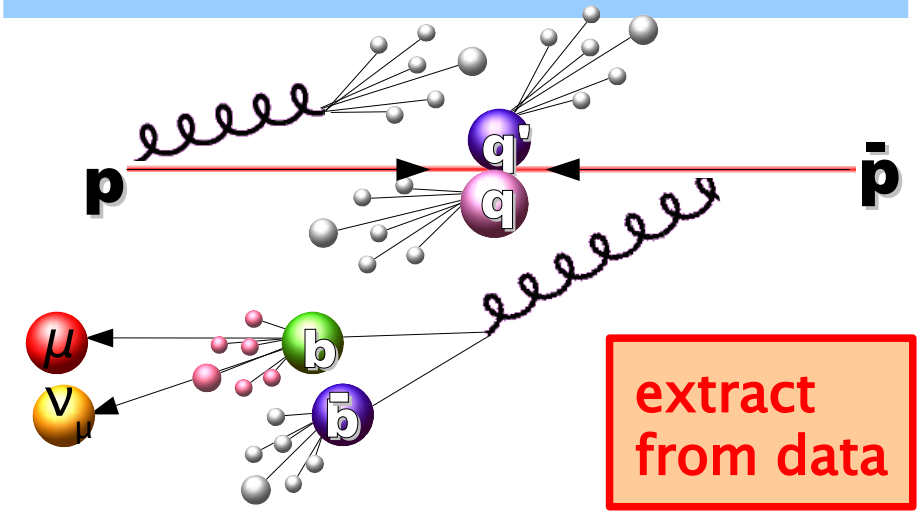
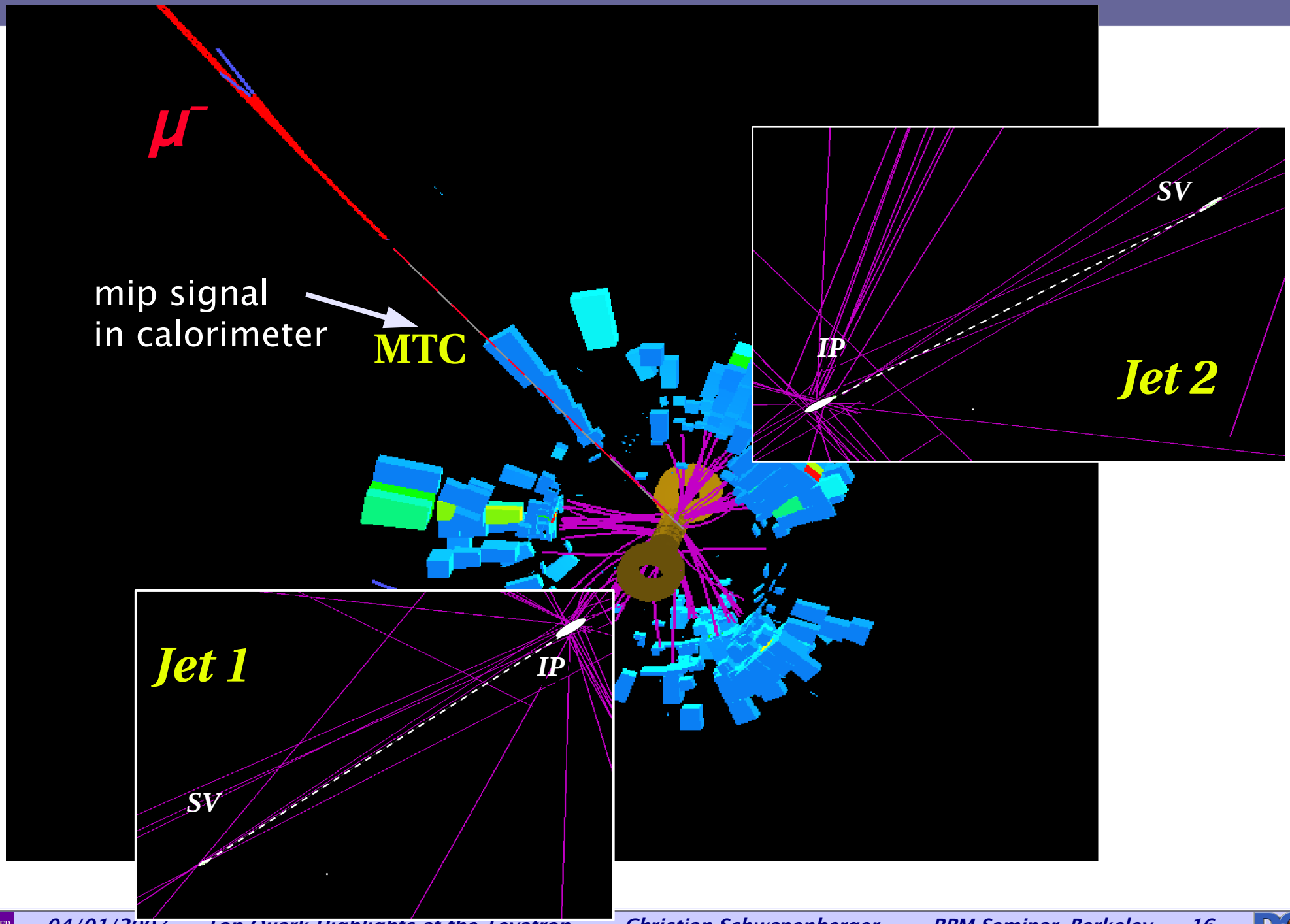


extract from data

Typical μ+jets Event



Lepton+Jets Topological Cross Section

no b-tag → less model dependent

- **kinematic properties allow separation between signal and background**

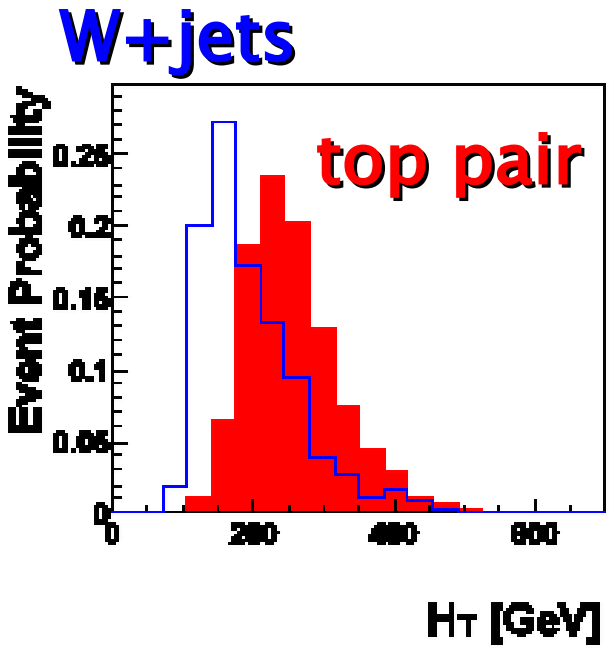
use as variables:

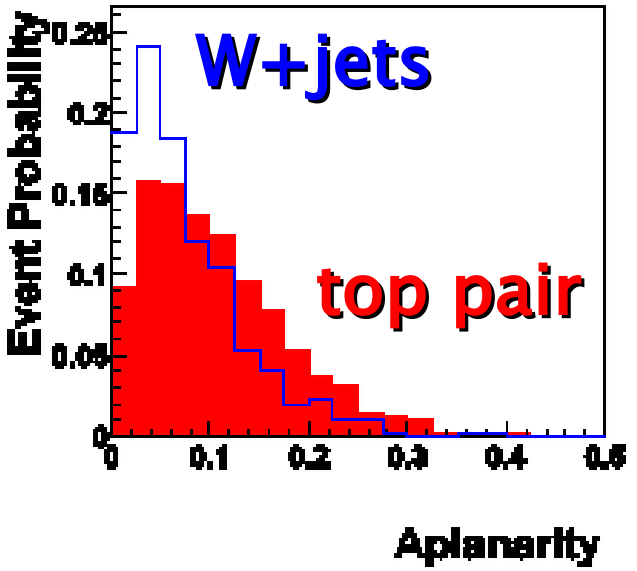
energy-dependent quantities:

- **e.g. H_T (scalar sum of p_T of 4 leading jets)**

angular dependent:

- **e.g. aplanarity**



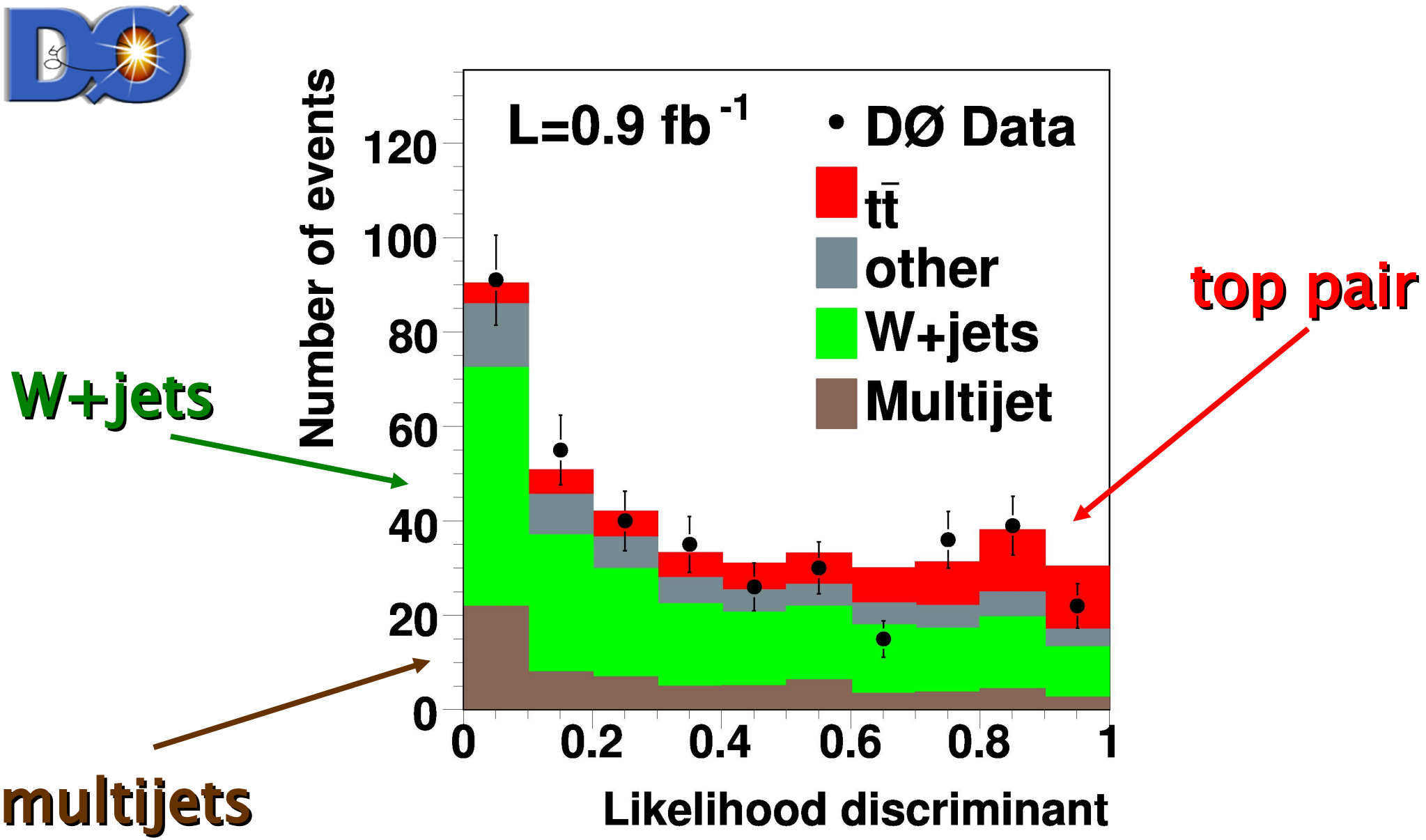


Discriminant function:

$$D = \frac{\prod_i S_i}{\prod_i S_i + \prod_i B_i}$$

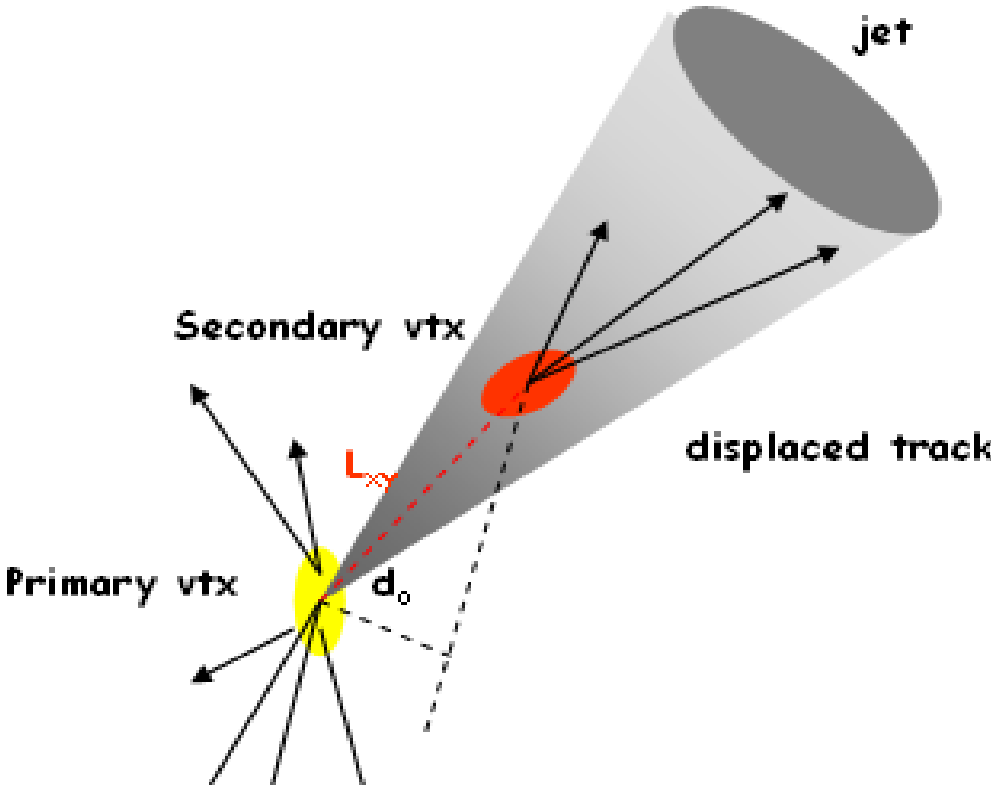
i=1,..,5 (6) e (μ)+jets
S = $\bar{t}t$-distribution,
B = Wjjjj-distribution

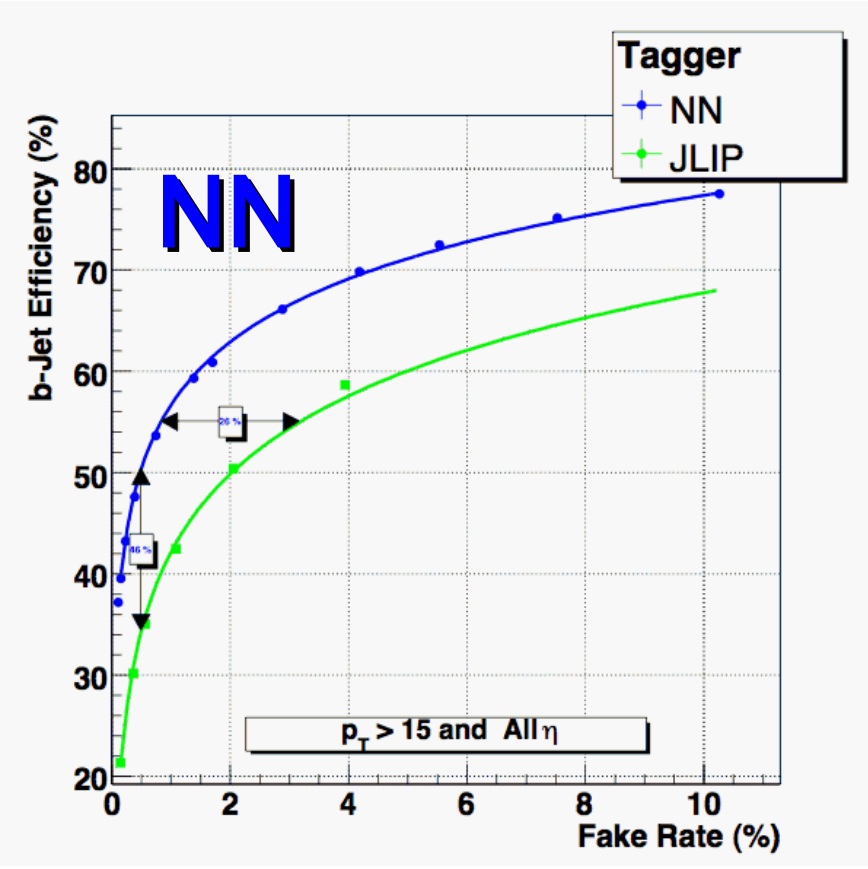
Lepton+Jets Topological Cross Section



b-tagging

- B hadrons lifetime $\tau \sim 1$ ps
- B hadrons travel $L_{xy} \sim 1$ mm before decay

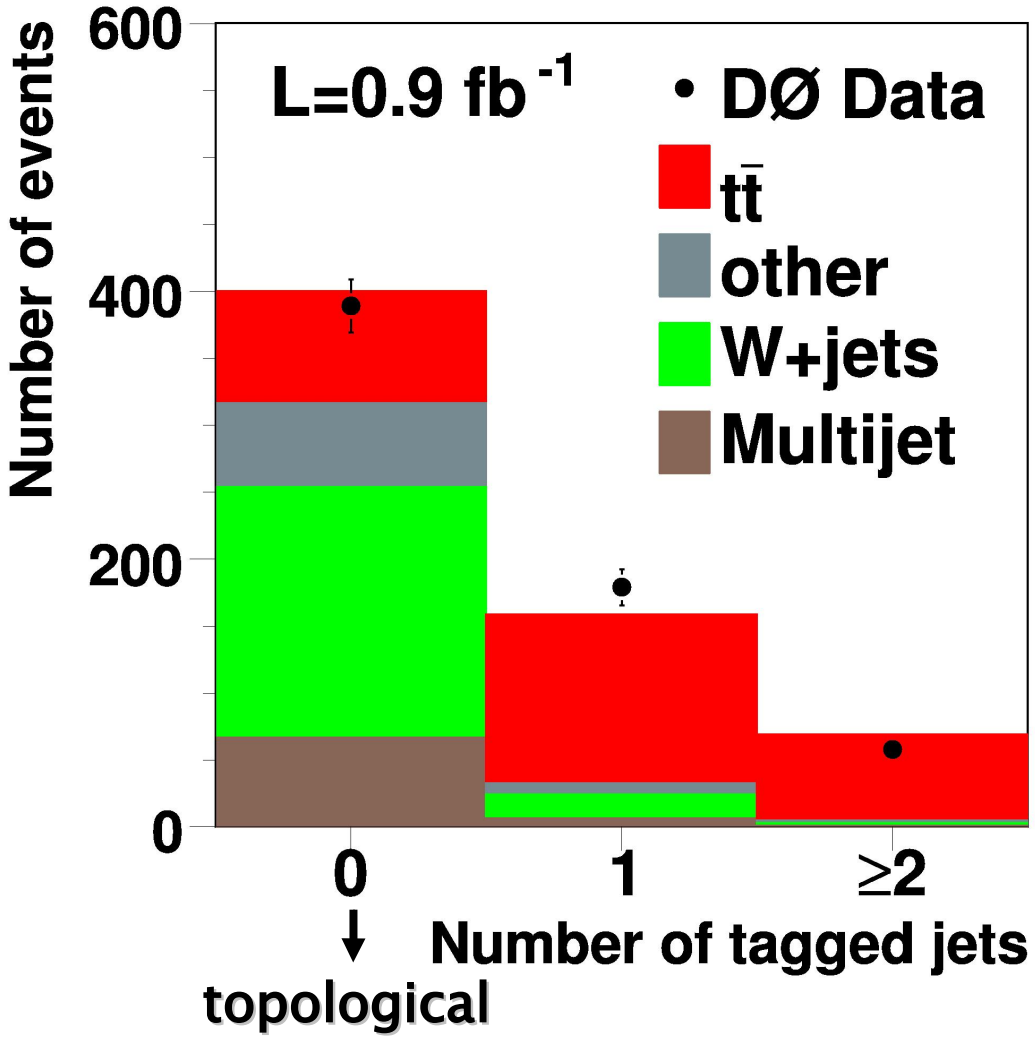




- explicitly reconstruct 3D vertices
- use properties from displaced tracks to form a 7-variable neural network
- improvements of up to 50%
- ttbar event tagging efficiency 54% (with fake rate of 1%)

Lepton+jets cross section with b-tagging

≥ 4 jets:



L=900 pb^{-1}

top pair

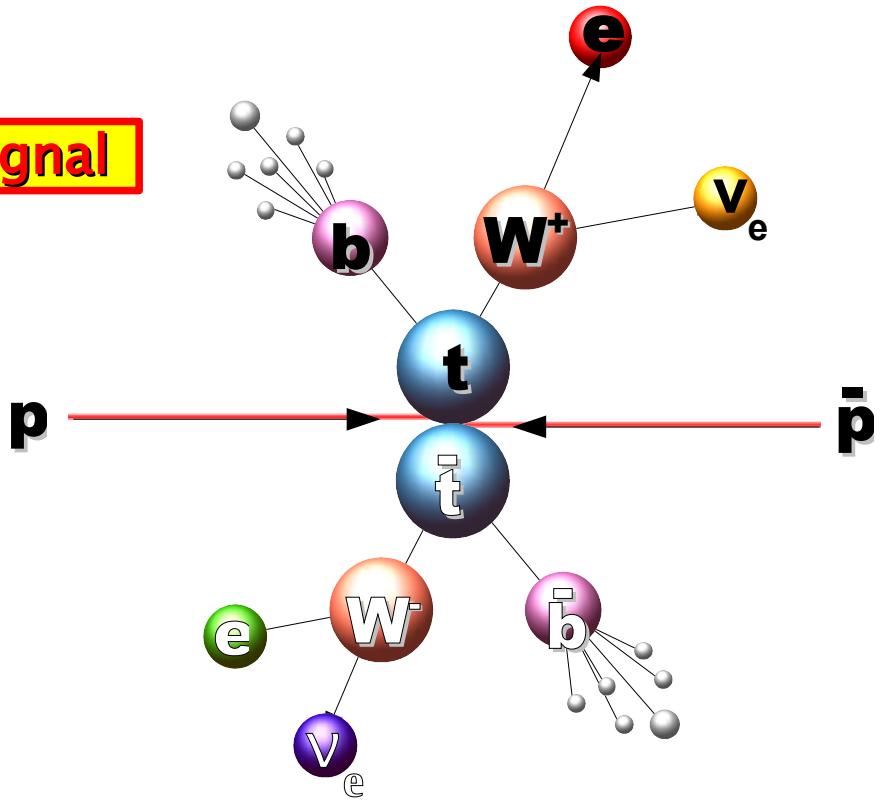
$$\sigma_{tt} = 8.08\,^{+0.53}_{-0.52}\,(\text{stat})\,^{+0.74}_{-0.74}\,(\text{syst}) \pm 0.49\,(\text{lumi})\ \text{pb}$$

±13%

m_{top} = 175 GeV

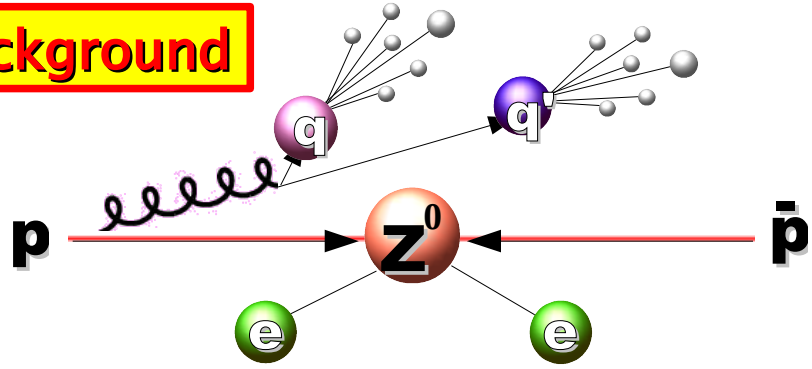
Event Topology in Dilepton Channel

signal



- 2 opposite charge leptons with high p_T (ee,eμ,μμ)
- 2 ν's: high missing transverse energy
- ≥ 2 jets (1 jet for eμ)
- cuts on topological variables

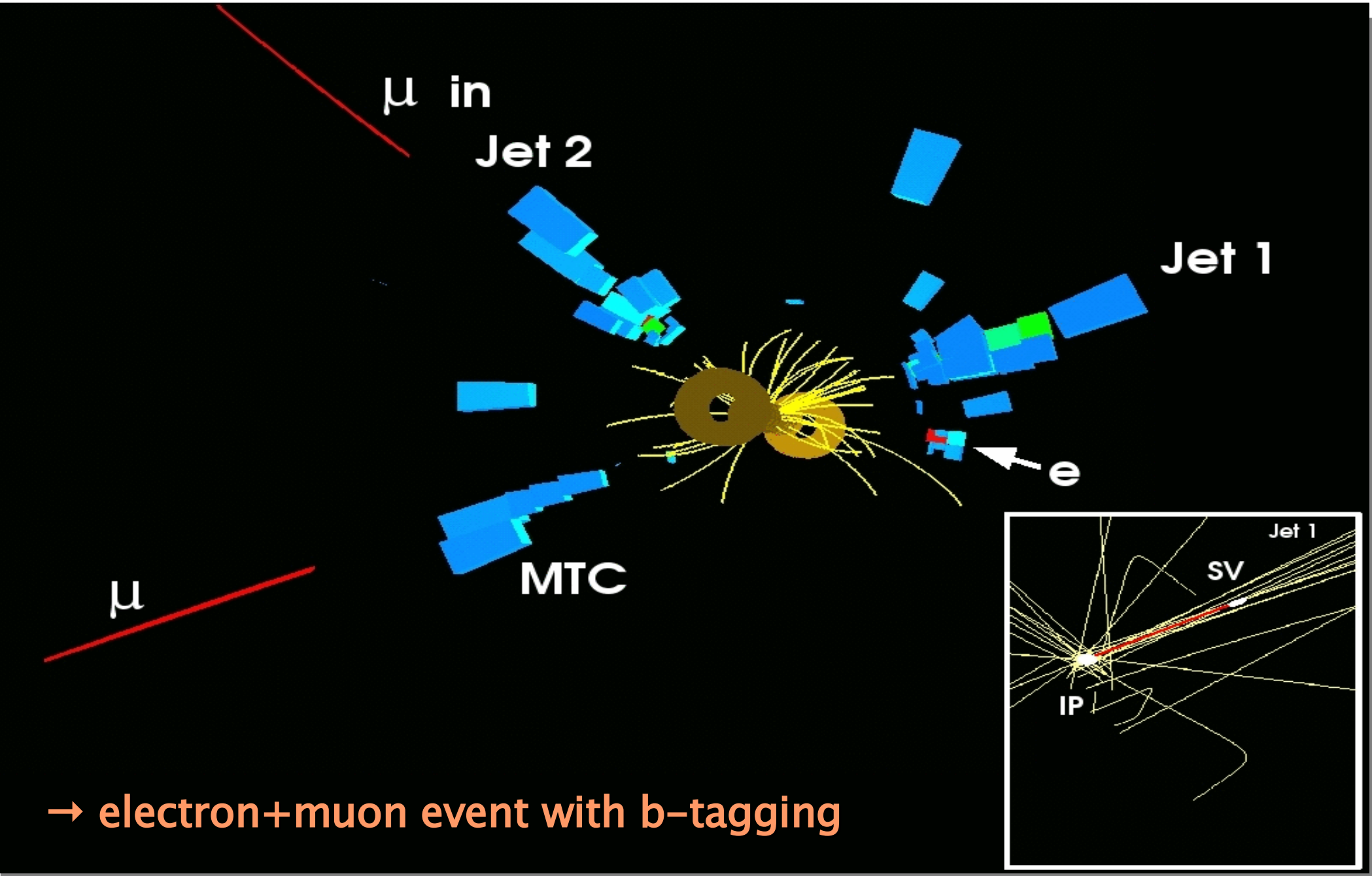
background



Z+jets production:
+ misreconstructed missing energy

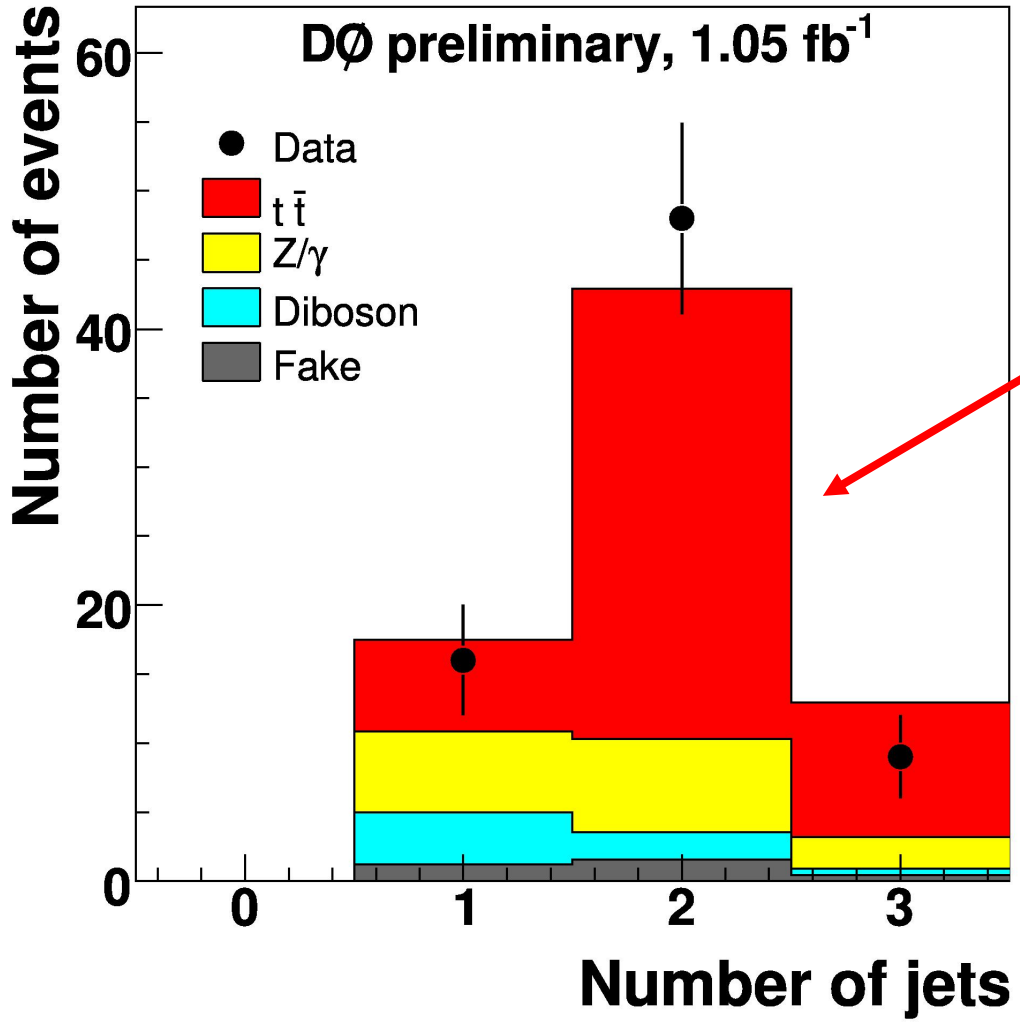
small background → precise measurement in future

Dilepton: Typical eμ Event



→ electron+muon event with b-tagging

Dilepton Topological Cross Section



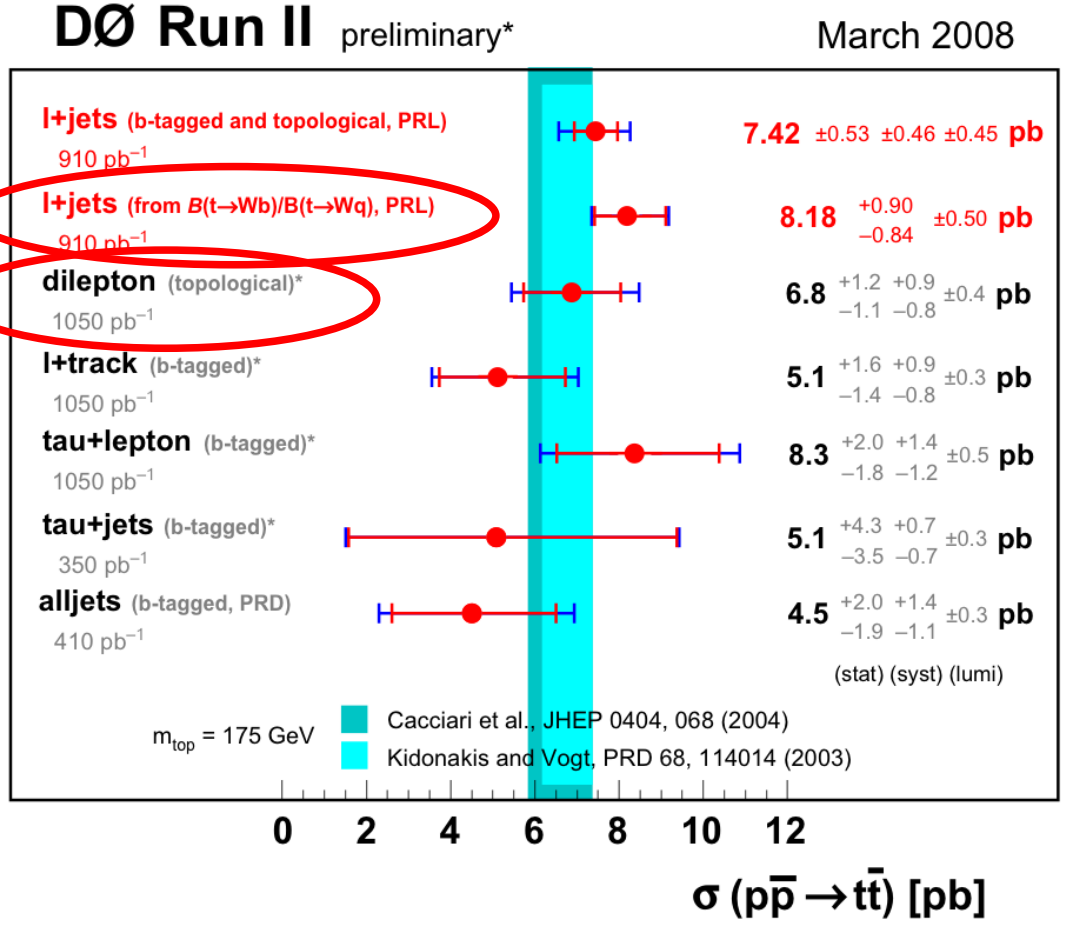
top pair

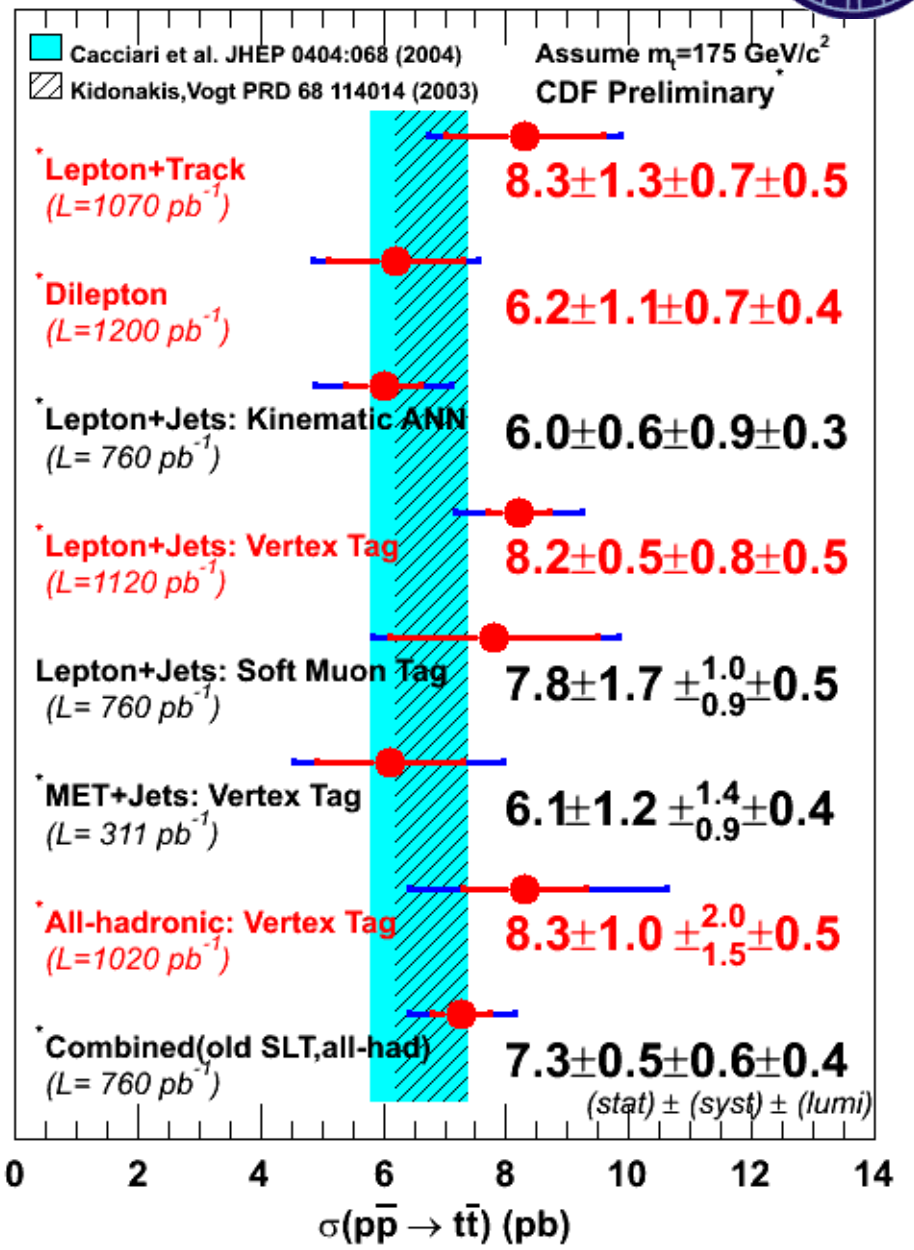
±23%

$$\sigma_{tt} = 6.8\ ^{+1.2}_{-1.1}\ (\text{stat})\ ^{+0.9}_{-0.8}\ (\text{syst}) \pm 0.4\ (\text{lumi})\ \text{pb}$$

m_{top} = 175 GeV

Top Pair Production Cross-Sections





Outline

Top Pair Production Cross Section

Searches in Top Production

- new resonances

Searches in Top Decays

- branching fractions
- charged Higgs boson

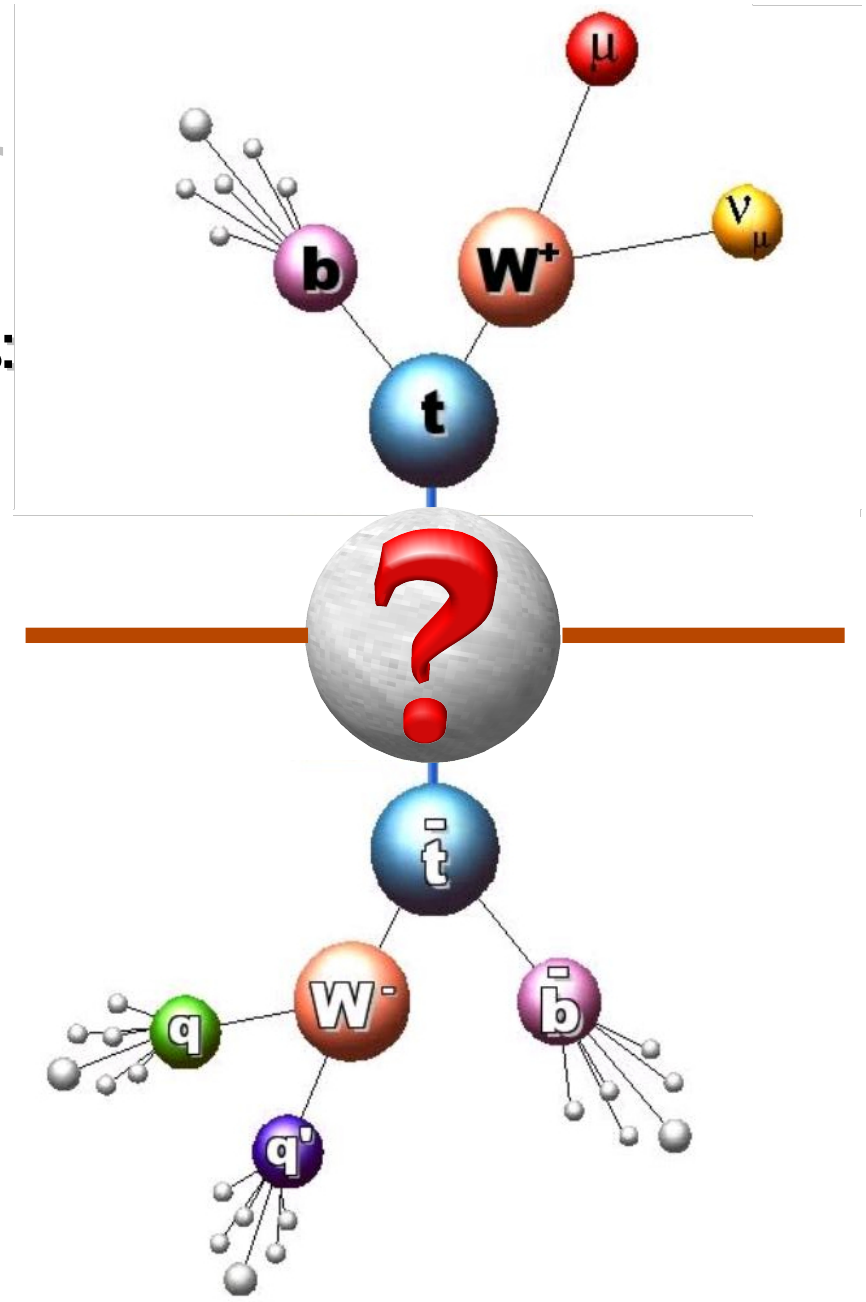
Top Mass

Outlook: Top Physics at LHC

Search for $t\bar{t}$ Production via New Resonances

Harris, Hill, Parke, hep-ph/9911288

- no resonance production in ttbar system is expected in SM
- some models predict ttbar bound states: large top mass can be generated through dynamical ttbar condensate X formed by new strong gauge force coupling to 3rd generation
- e.g. topcolor assisted technicolor predicts leptophobic Z' with strong 3rd generation coupling
- experimental check: search for bumps in ttbar reconstructed mass spectrum
- sufficiently narrow so that width is dominated by detector effects

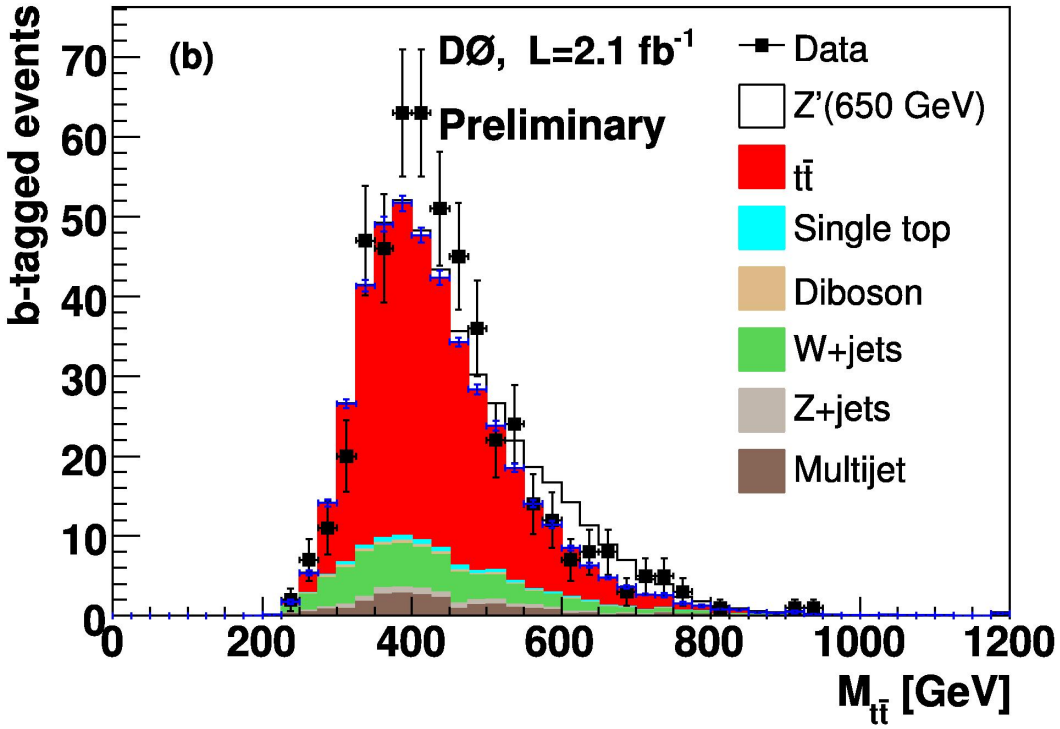


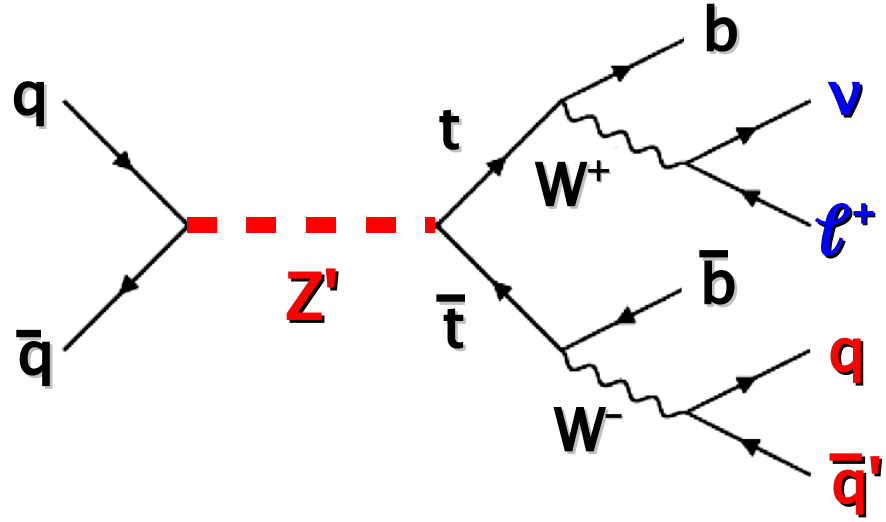
Results for e, μ + jets combined

data and SM:

2.1 fb^{-1}

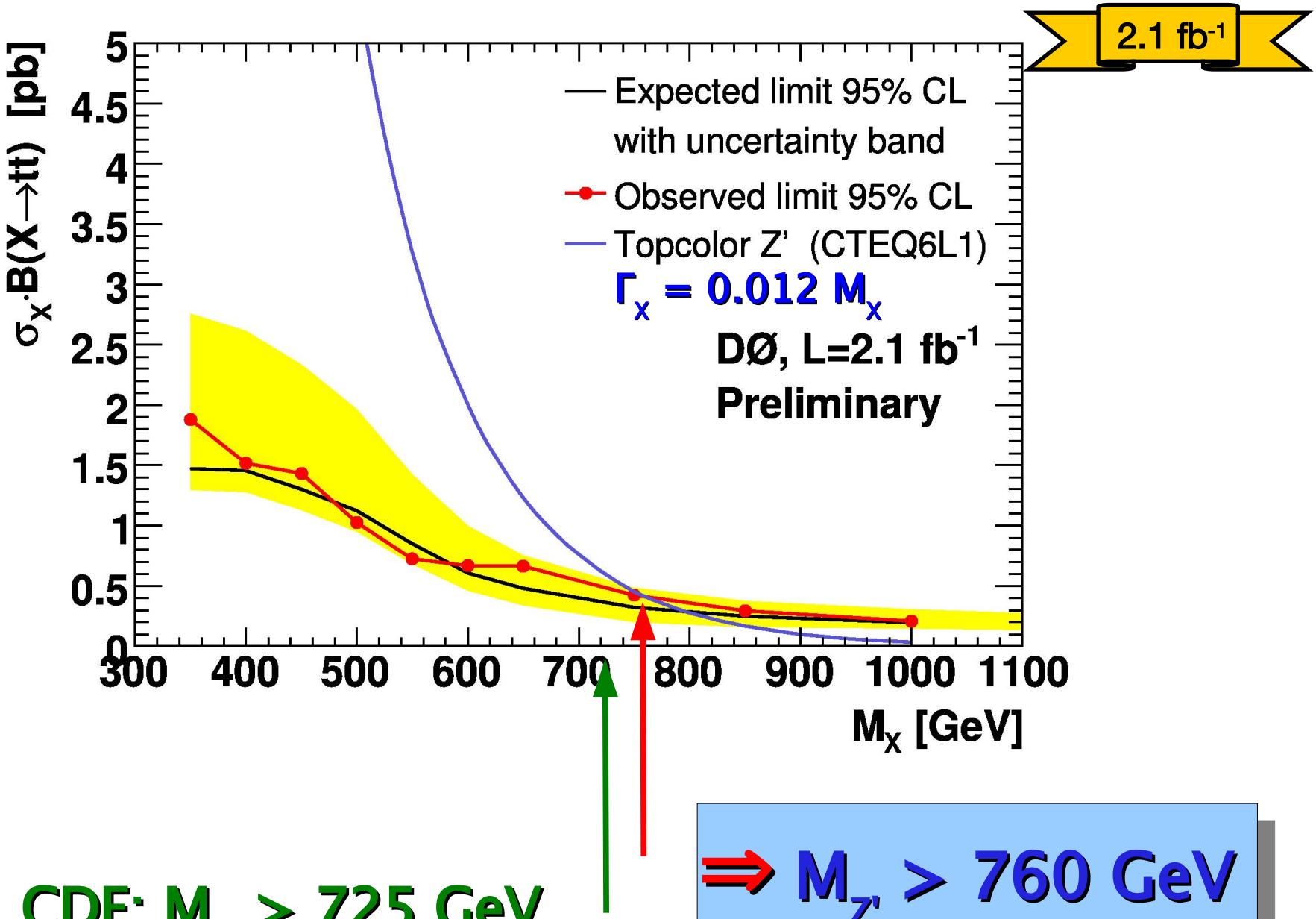
SM: use ttbar cross section
6.77 ± 0.60 pb (NLO+resummations)





⇒ binned Likelihood fit to get upper limit

Limits for e, μ + jets combined



CDF: $M_{Z'} > 725$ GeV

⇒ $M_{Z'} > 760$ GeV

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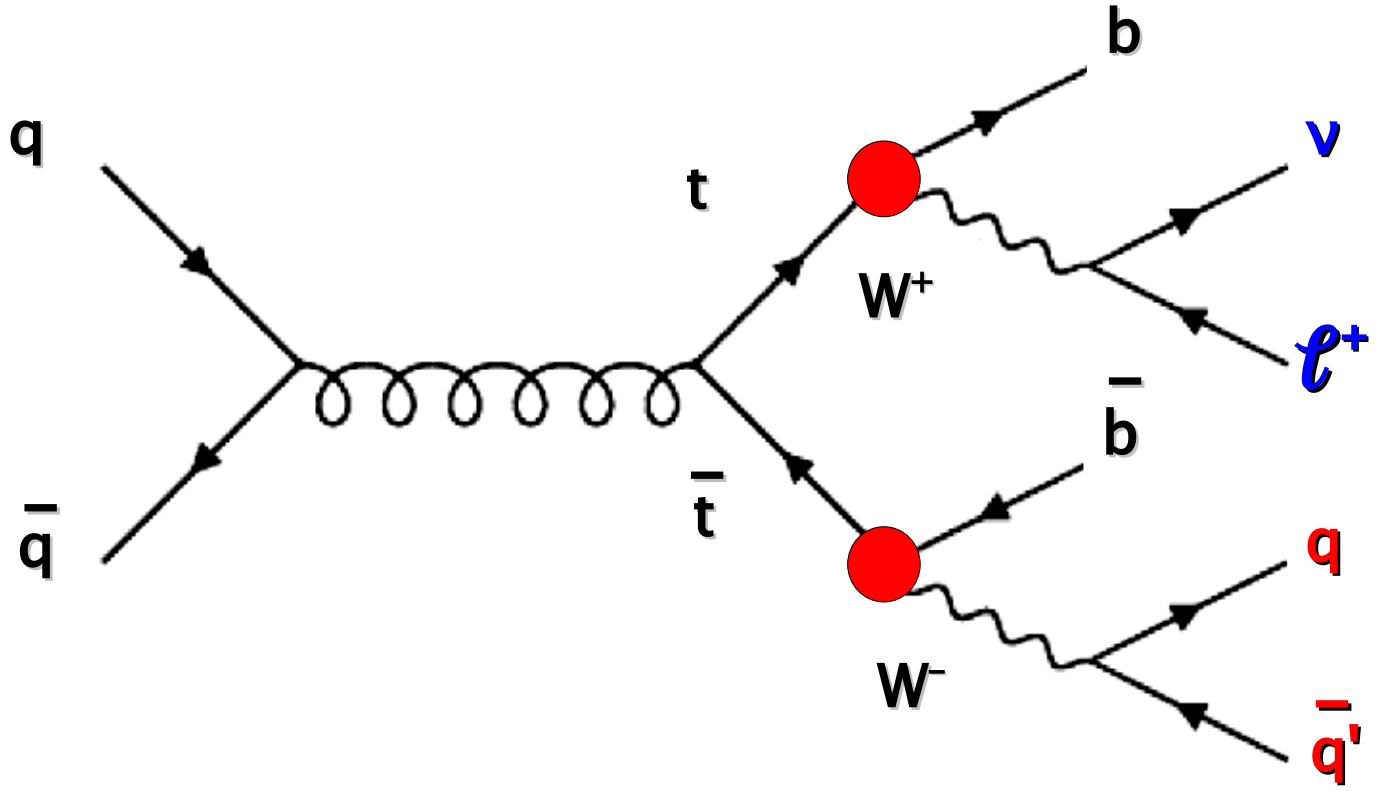
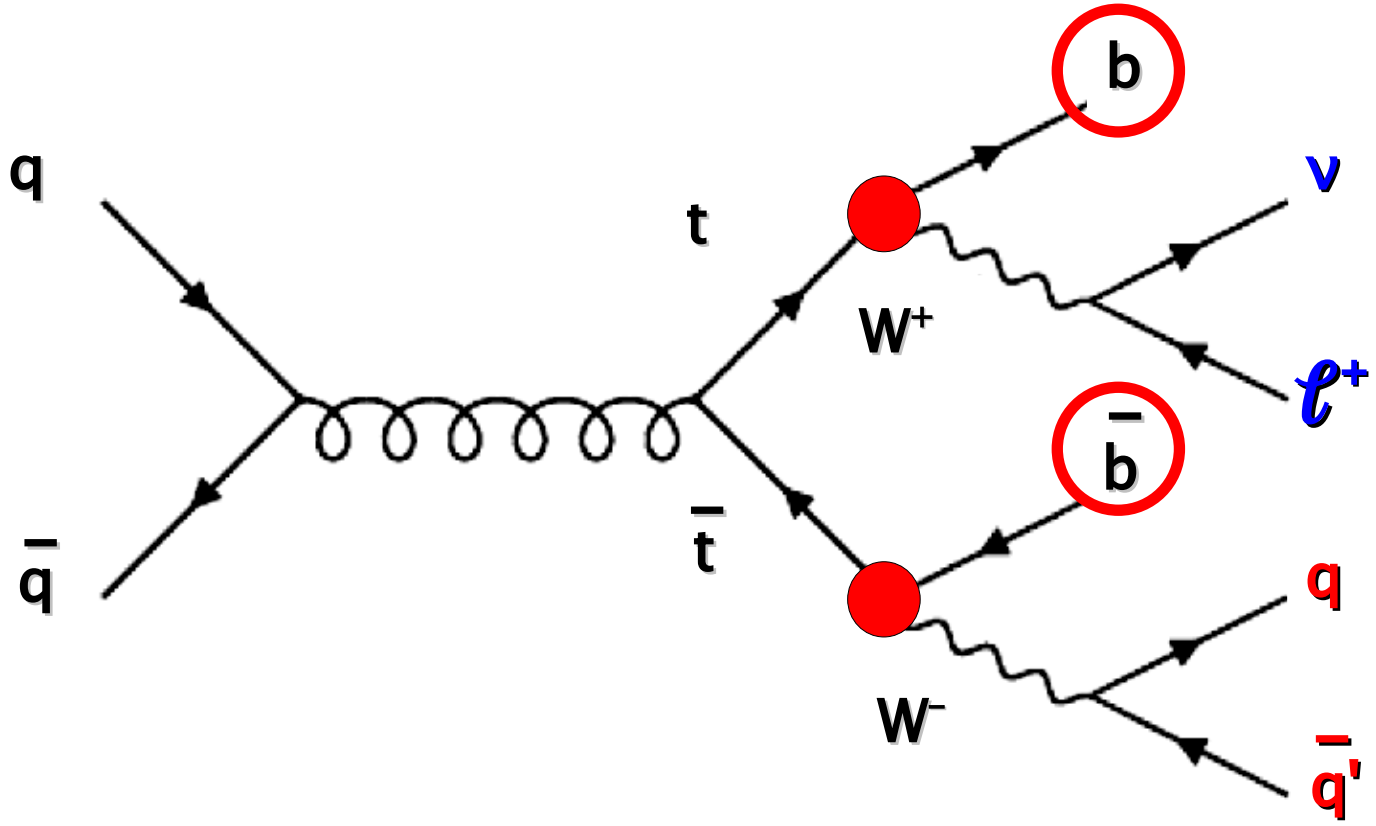
Outlook: Top Physics at LHC

Searches in Top Decays



Searches in Top Decays: b disappearance



Measurement of Branching Fractions

$$R = \frac{B(t \to Wb)}{B(t \to Wq)}$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Standard Model:

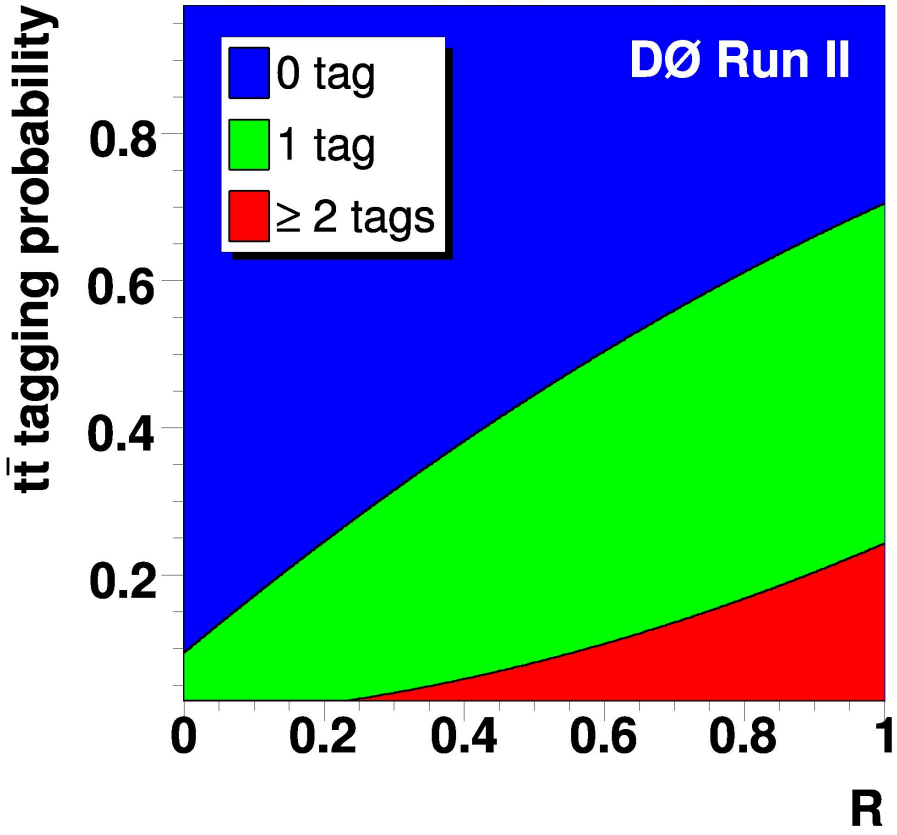
$$R_{SM} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = |V_{tb}|^2 = 1$$

unitarity of CKM matrix

beyond SM:

R ≠ 1

R changes fractions of b-tagged jets:



e.g. decay into 4th generation quark:
R<1
sensitive to b disappearance

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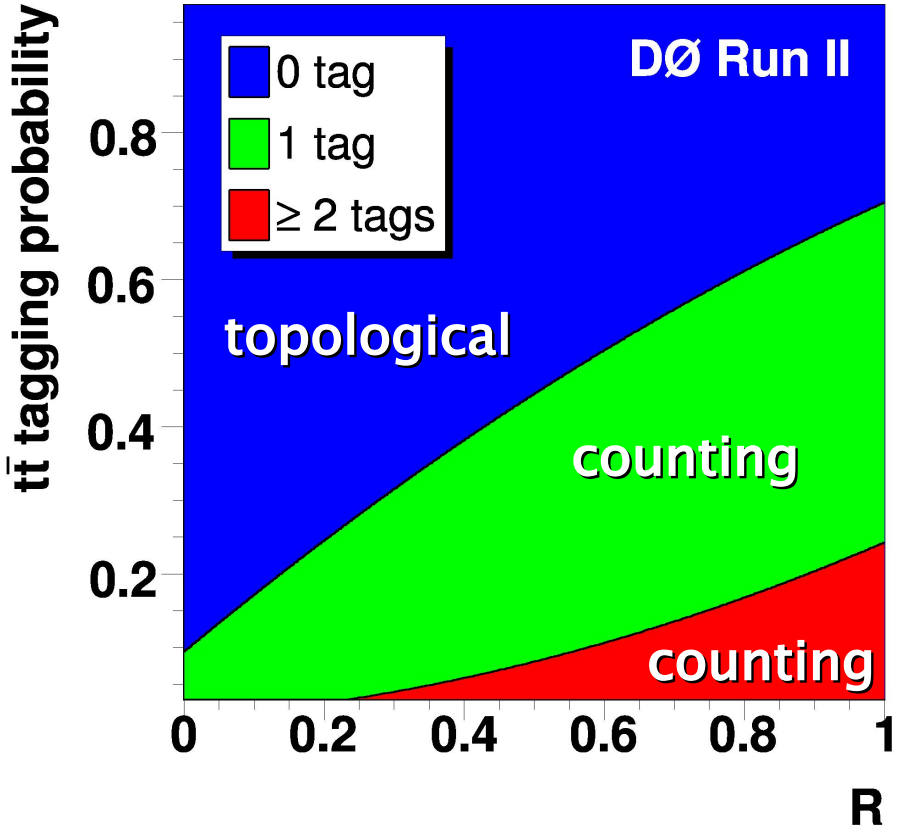
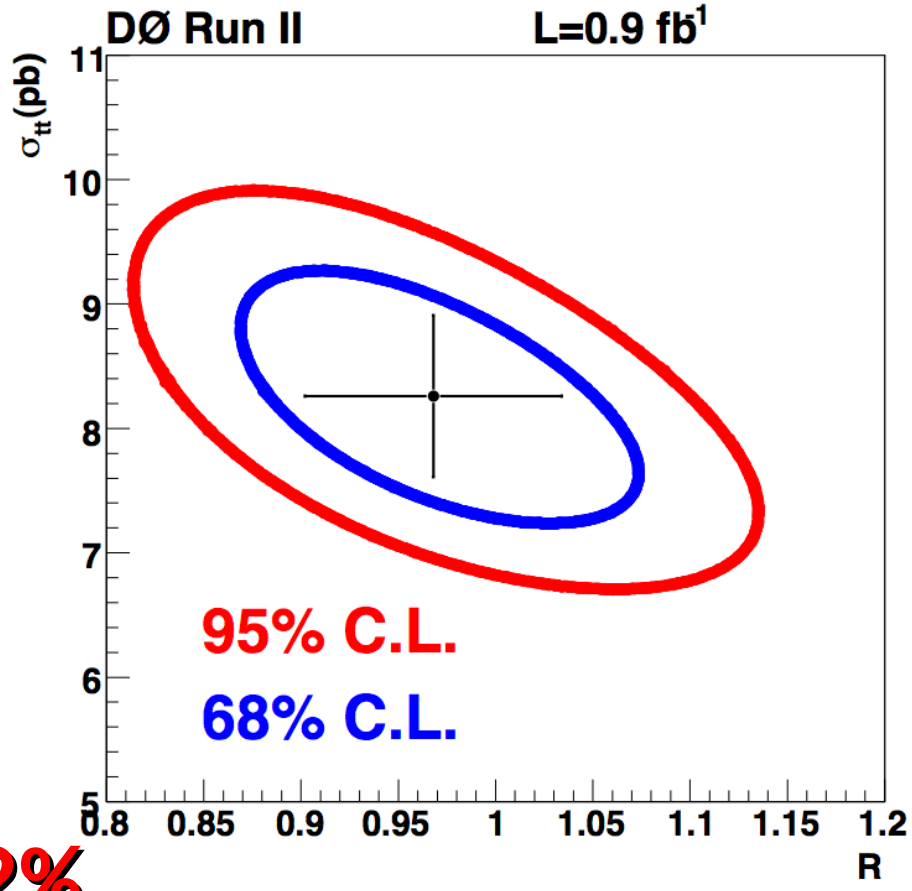


Simultaneous Measurement of σ and R

Maximize total Likelihood function simultaneously for branching ratio R and top pair production cross section



$$R = 0.97^{+0.09}_{-0.08}\ \text{(stat+syst)}$$

using unitary of CKM matrix:

$$|V_{tb}| > 0.89 \text{ @ } 95\%\ \text{C.L.}$$

12%

$$\sigma_{tt} = 8.18^{+0.90}_{-0.84}\ \text{(stat+syst)} \pm 0.50\ \text{(lumi)}\ \text{pb}$$

⇒ agrees with SM

Outline

Top Pair Production Cross Section

Searches in Top Production

- new resonances

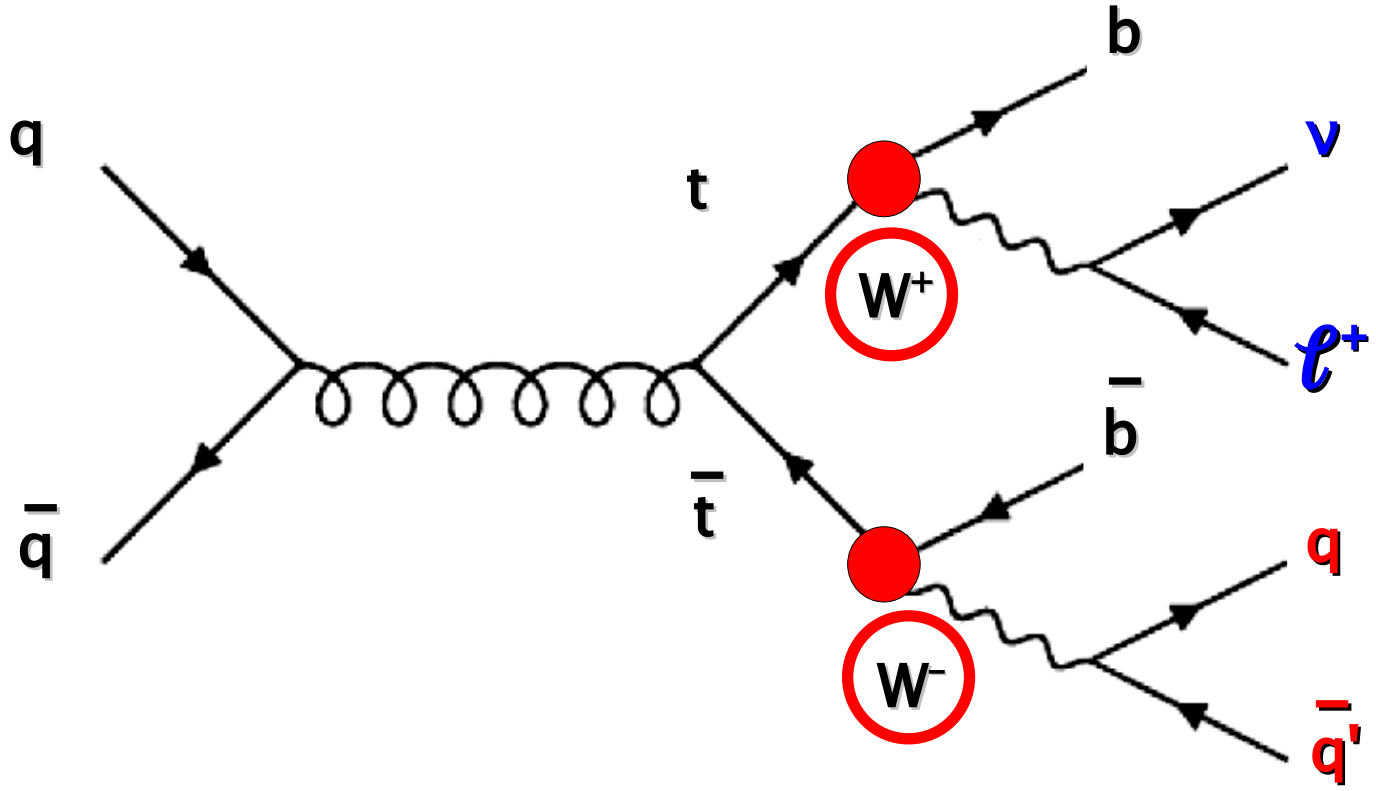
Searches in Top Decays

- branching fractions
- charged Higgs boson

Top Mass

Outlook: Top Physics at LHC

Searches in Top Decays: W disappearance

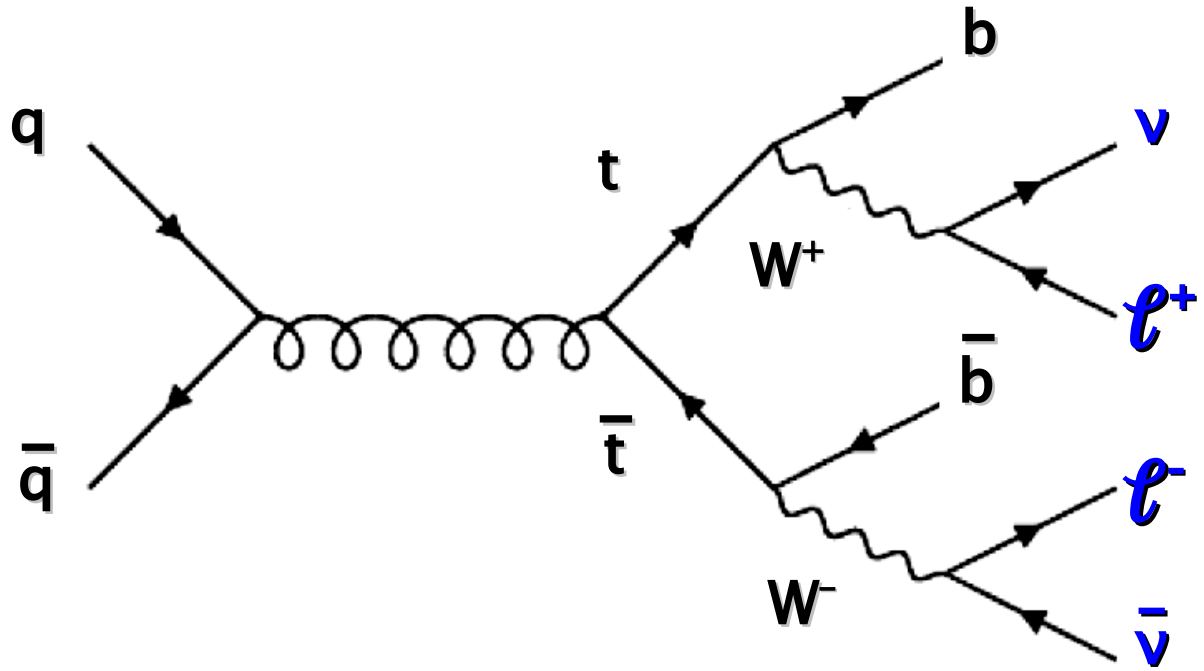


Measurement of cross section ratios

$$\frac{\sigma(t\bar{t})_{L+J}}{\sigma(t\bar{t})_{DIL}}$$

= 1 in SM

- **many uncertainties cancel!**



< 1 due to e.g.

$t \rightarrow b\, H^+$

$\hookrightarrow c\, \bar{s}$

- **radiative corrections in MSSM** hep-ph/9907422
- **in multi Higgs dublet models** hep-ph/9509203 hep-ph/9401311

⇒ **W disappearance**

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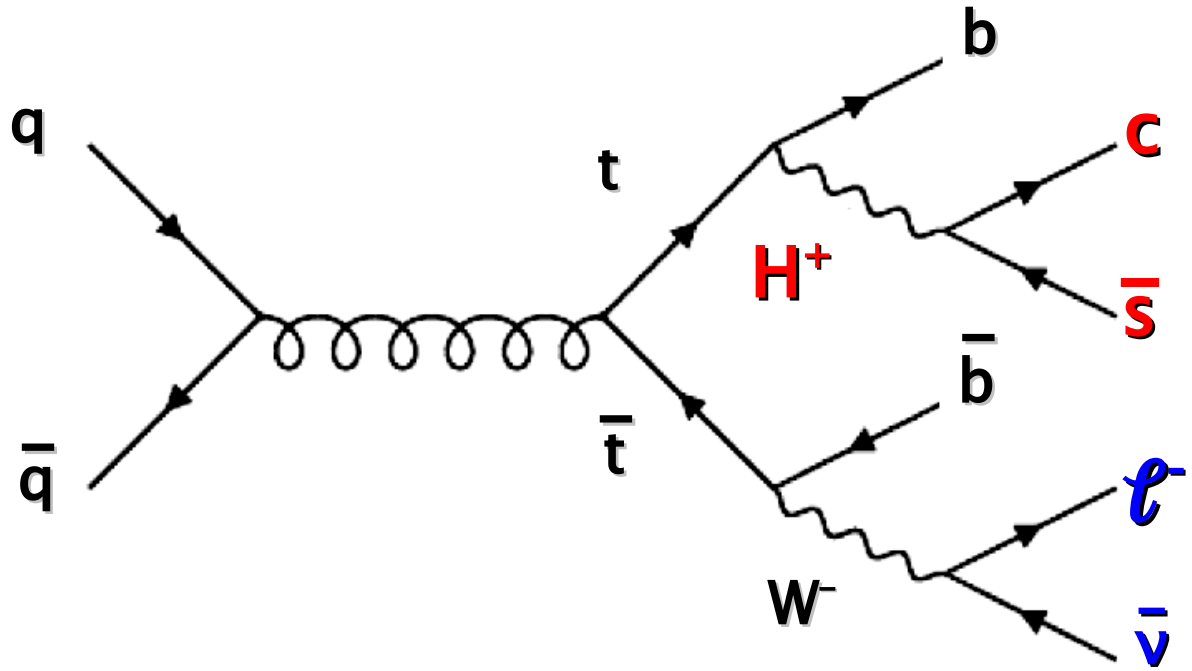

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- radiative corrections in MSSM hep-ph/9907422
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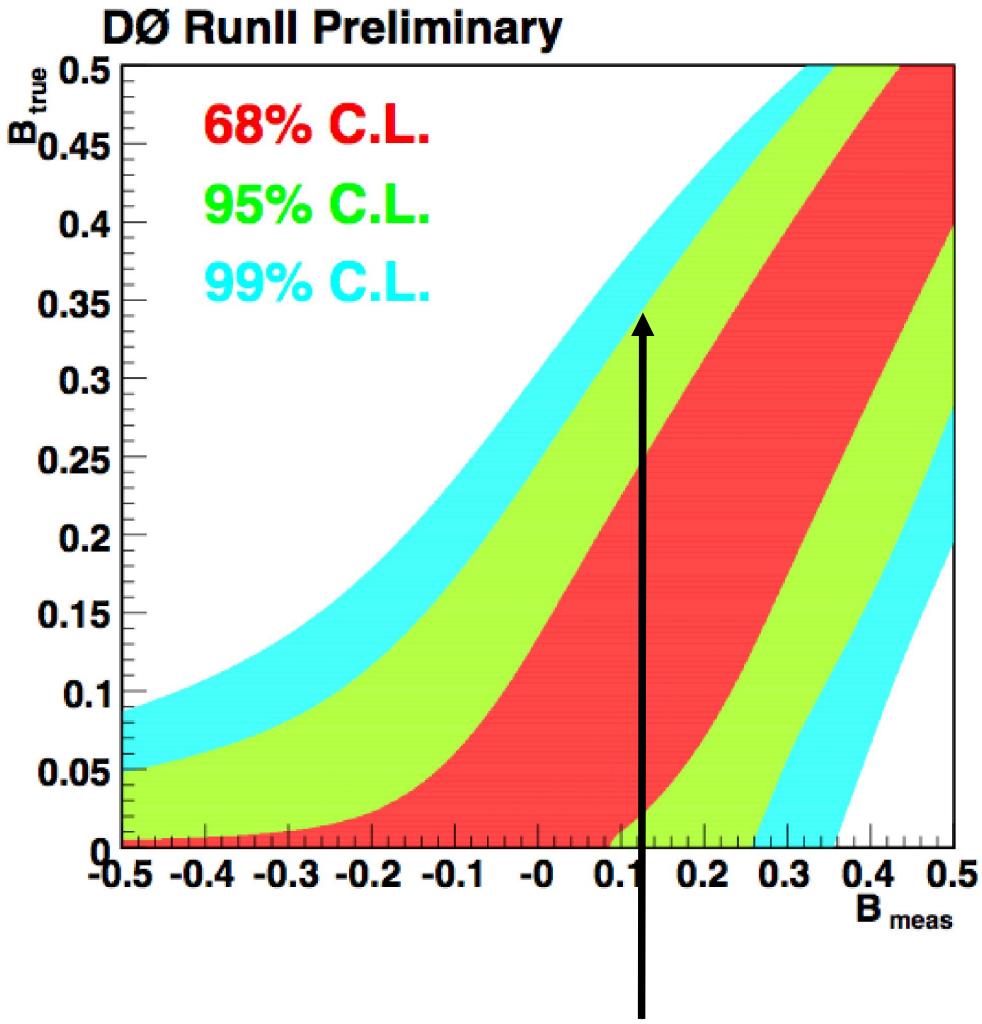
⇒ W disappearance

Cross section ratio and limit on B(t → b H^+)

$$R_\sigma = 1.21\ ^{+0.27}_{-0.26}\ \text{(stat+syst)}$$



- **leptophobic charged Higgs with mass close to W boson**

$$B = 0.13\ ^{+0.12}_{-0.11}\ \text{(stat+syst)}$$

B < 0.35 @ 95% C.L.

Outline

Top Pair Production Cross Section

Searches in Top Production

- new resonances

Searches in Top Decays

- branching fractions
- charged Higgs boson

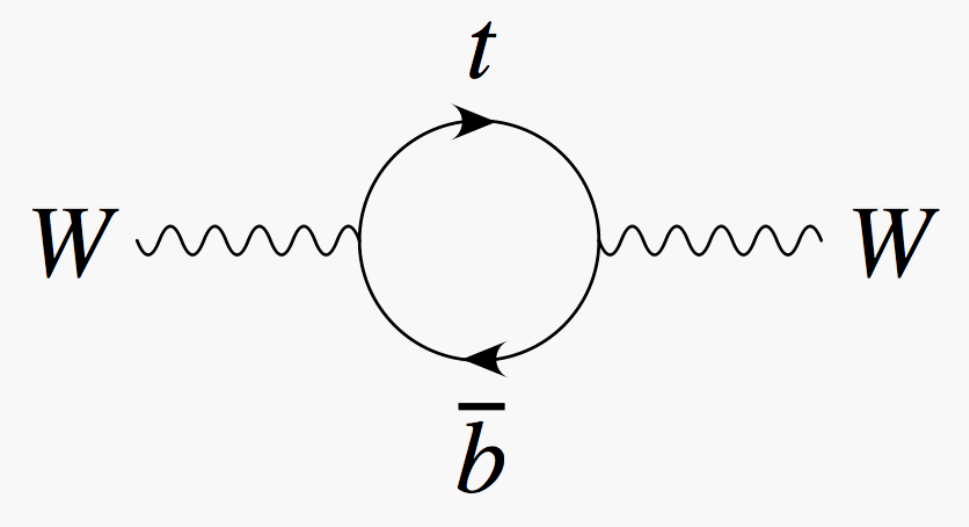
Top Mass

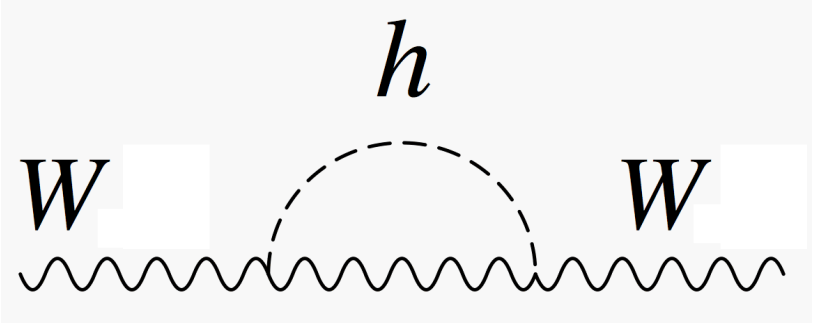
Outlook: Top Physics at LHC

The Top Quark Mass

- free parameter in the Standard Model

- check the self-consistency of the Standard Model in combination with W mass measurement

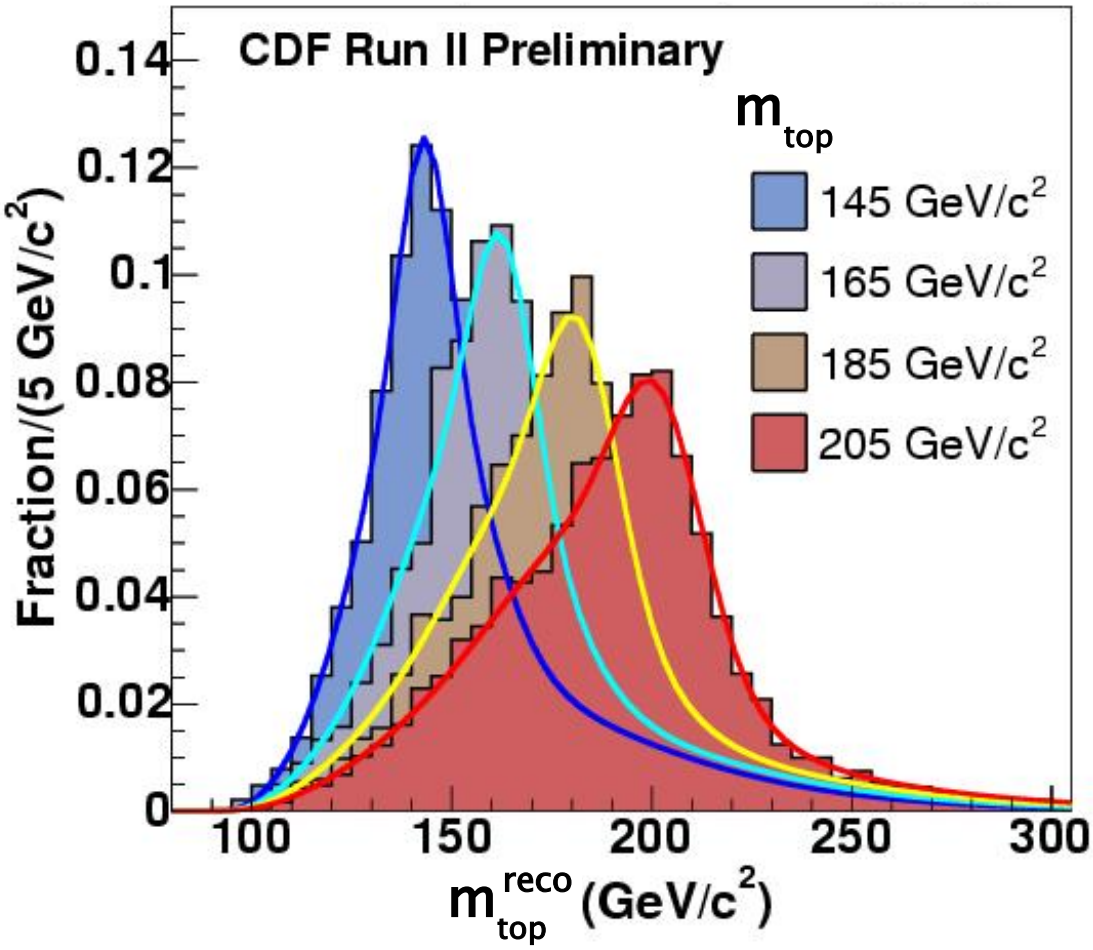




Extraction Techniques: Template Method

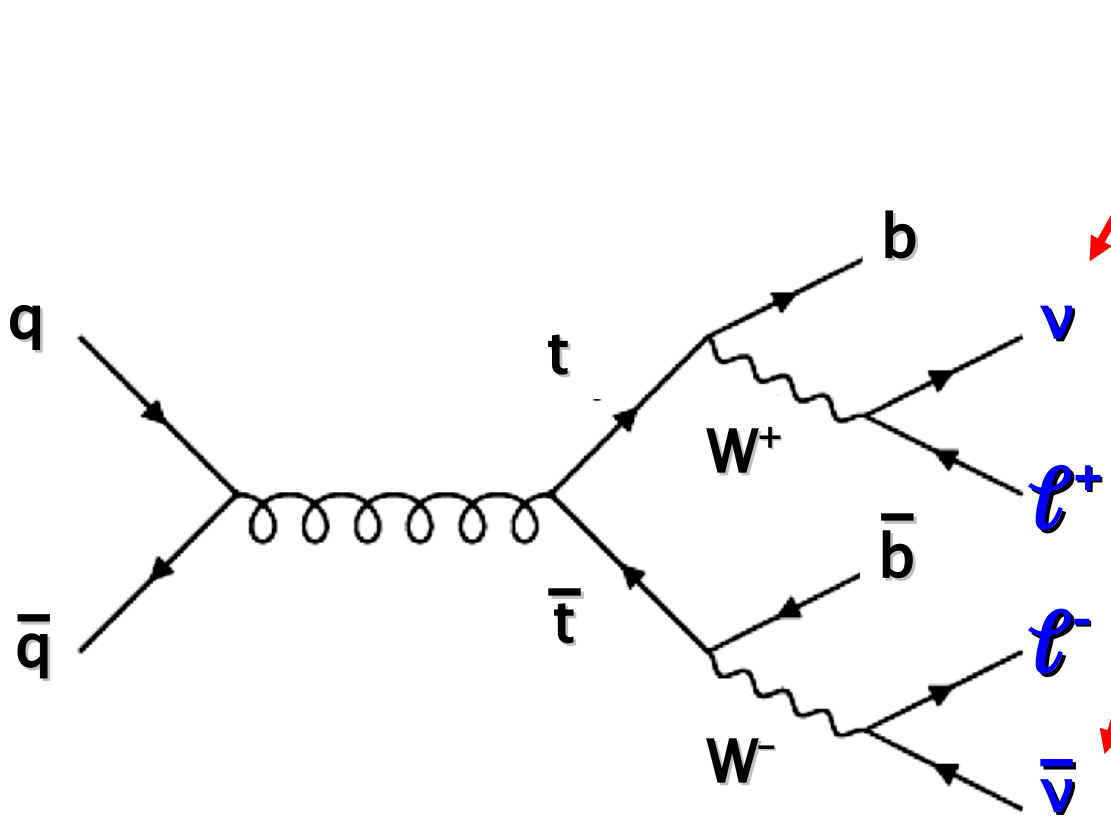
- use variables strongly correlated with m_{top}
- compare data to MC with different m_{top} hypotheses

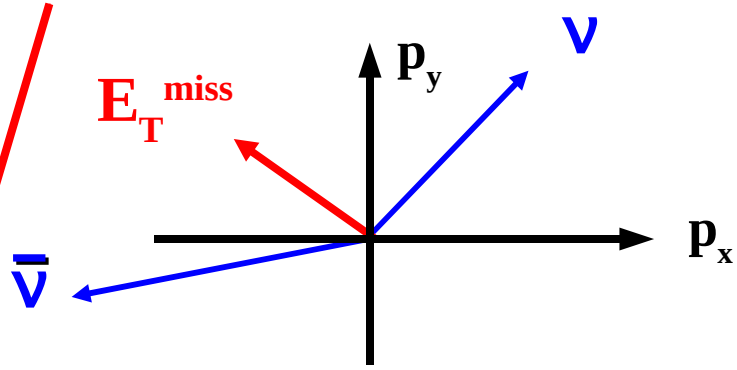
l+jets



Dilepton-Channel: Neutrino Weighting

2 neutrinos:
kinematics underconstrained

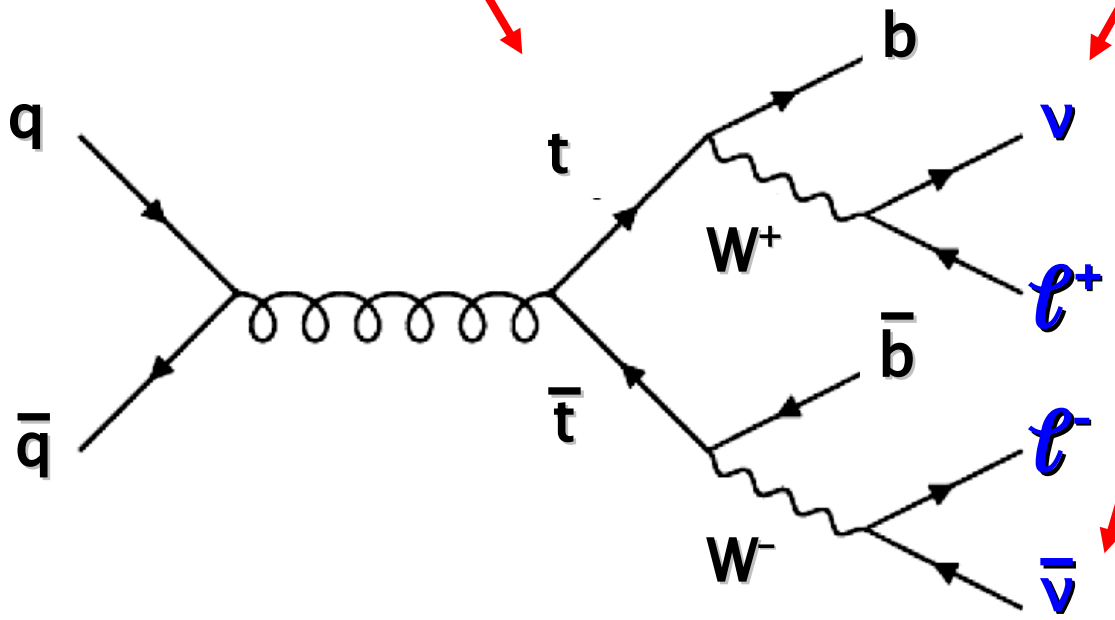




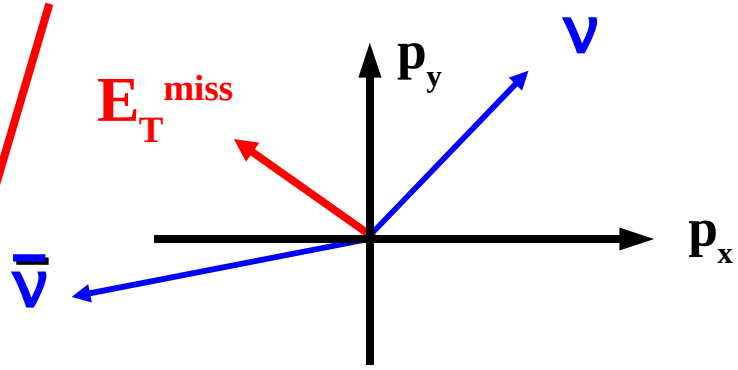
no ν p_z information

Dilepton–Channel: Neutrino Weighting

- assume top mass

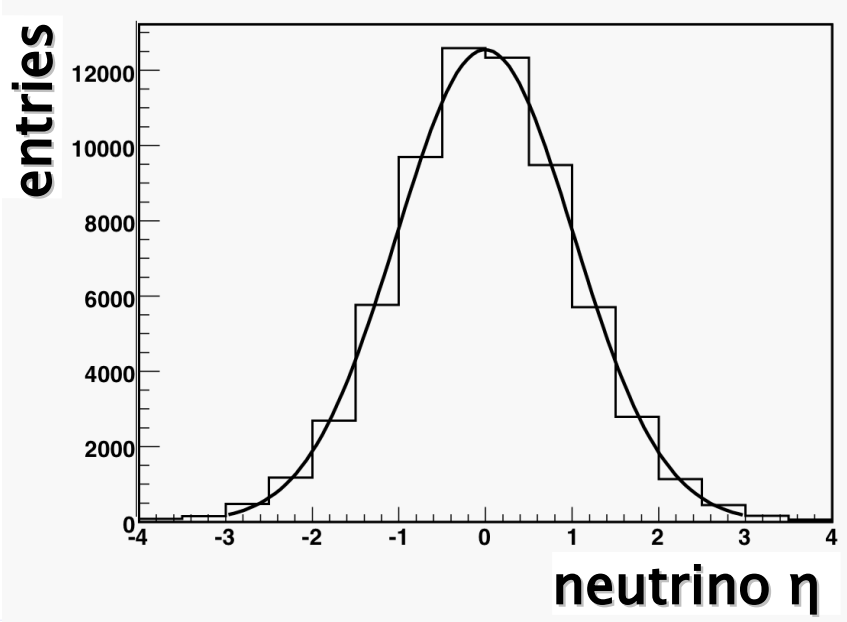


2 neutrinos: kinematics underconstrained



no ν p_z information

- take (anti–) neutrino η from MC



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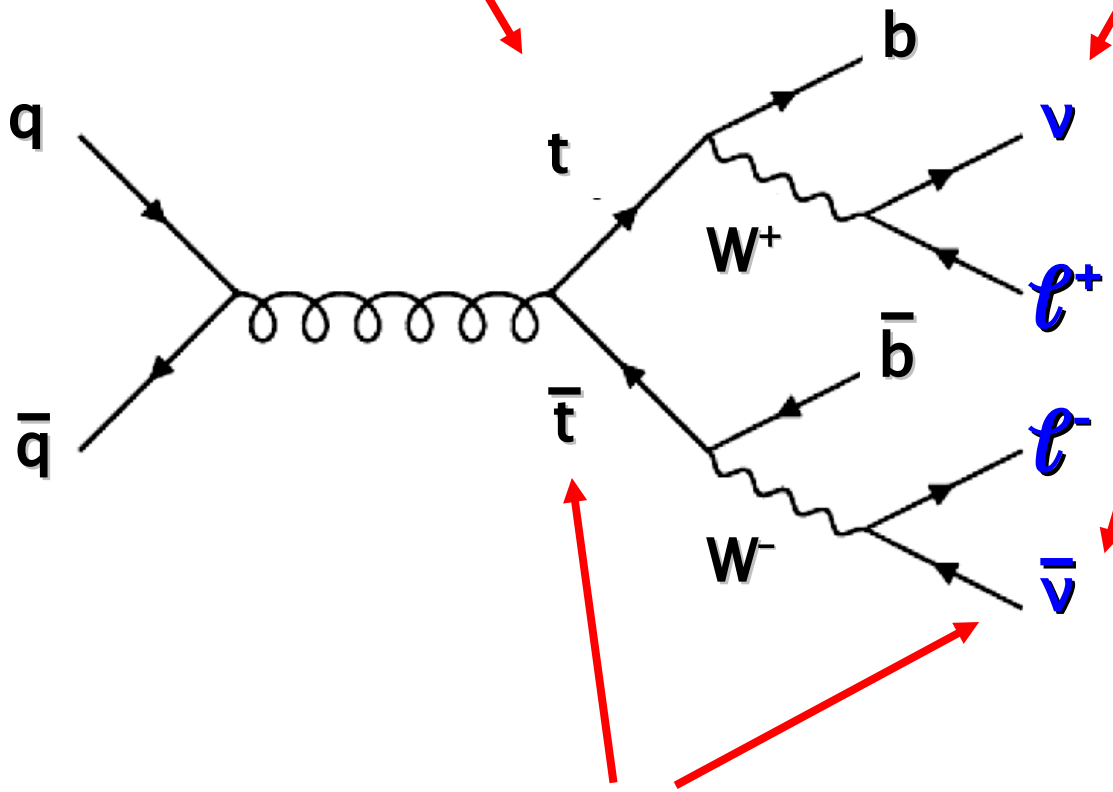
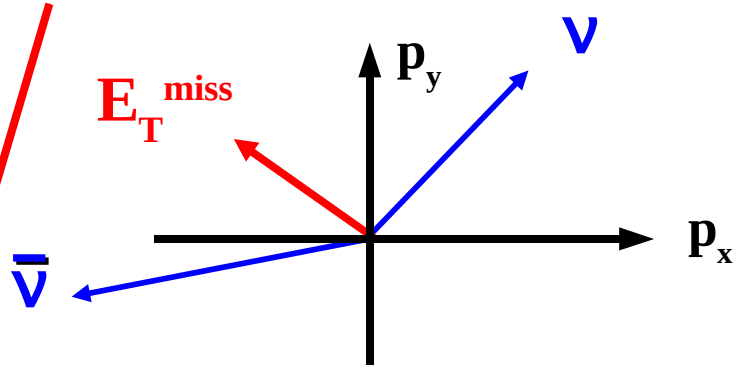


- sum over all solutions

2 neutrinos: kinematics underconstrained



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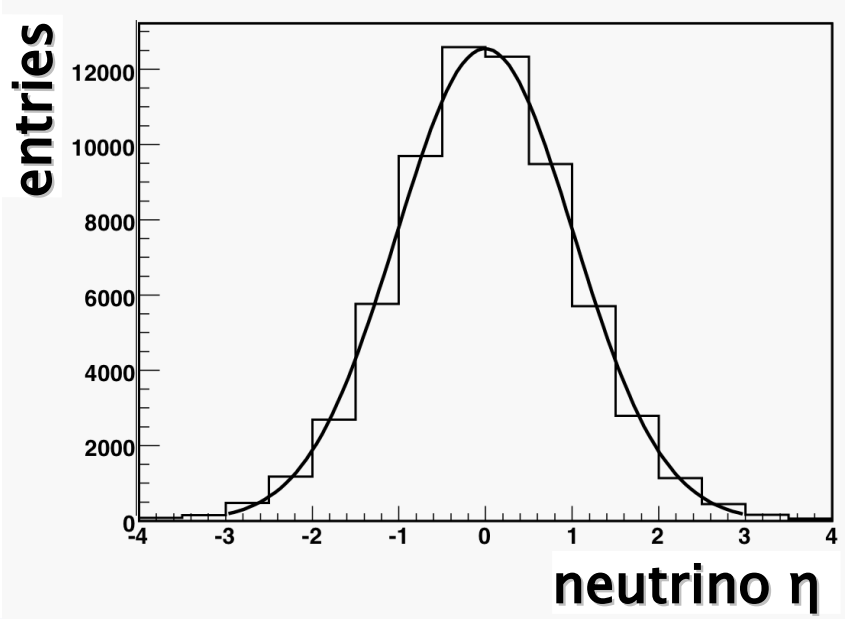
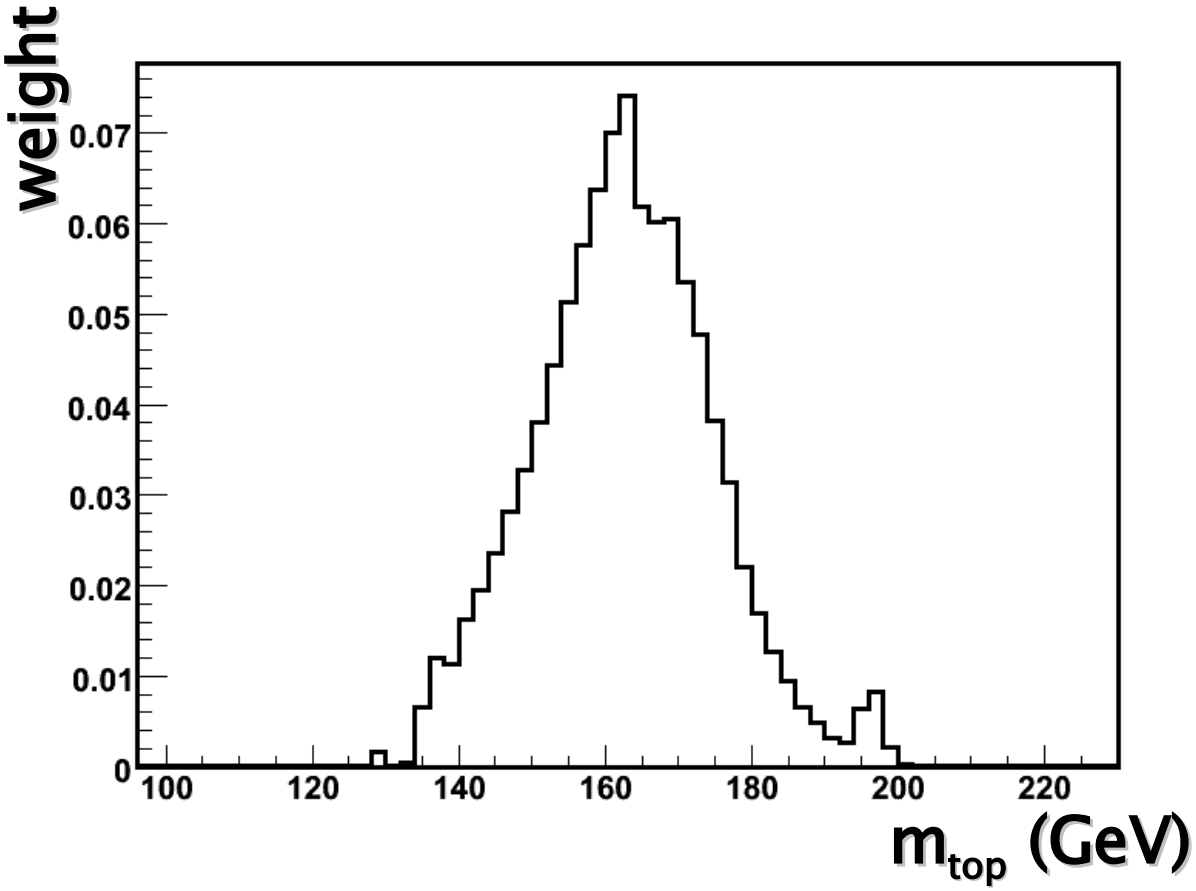


Neutrino Weighting Algorithm

- compare measured $\not\!\!E_t$ with expected (MC) for different m_{top} hypotheses

→ derive $w(m_{top})$ for every event



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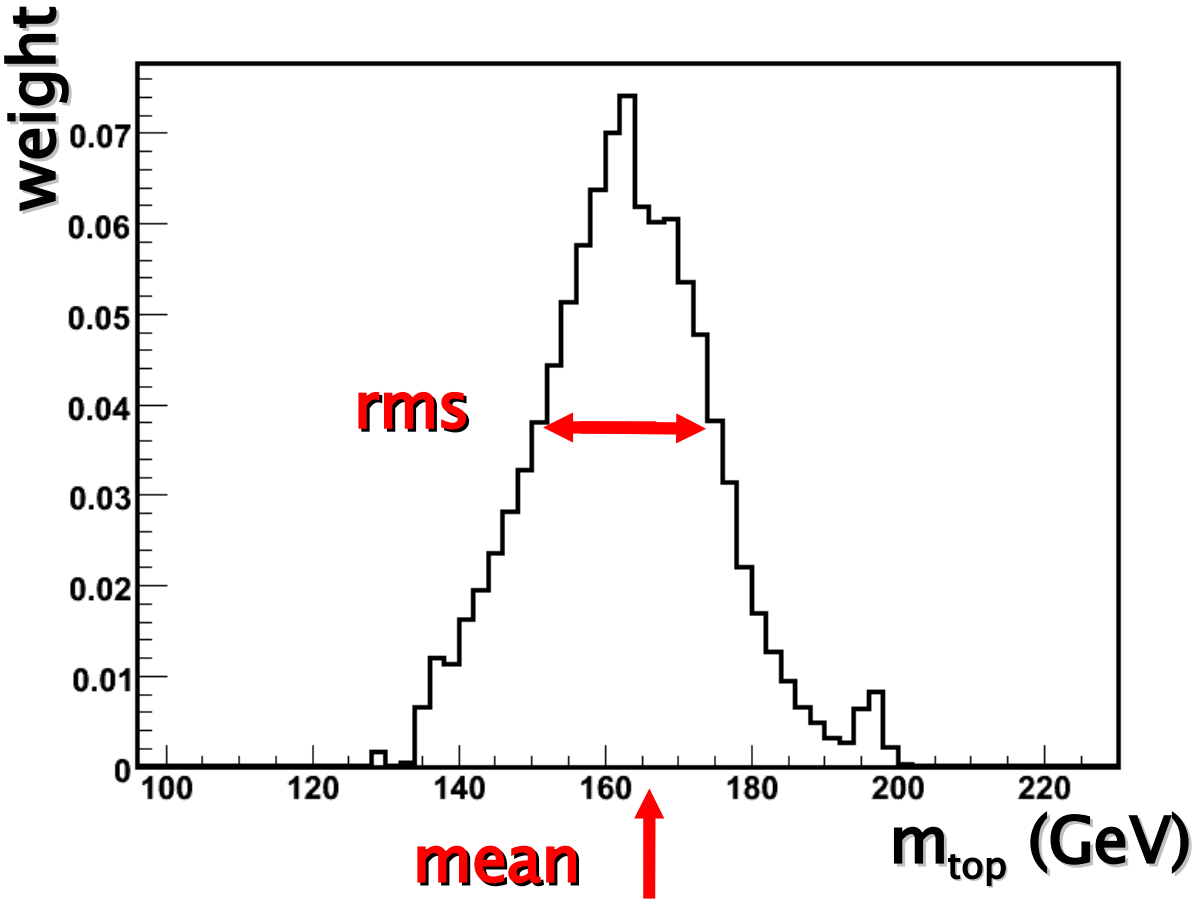


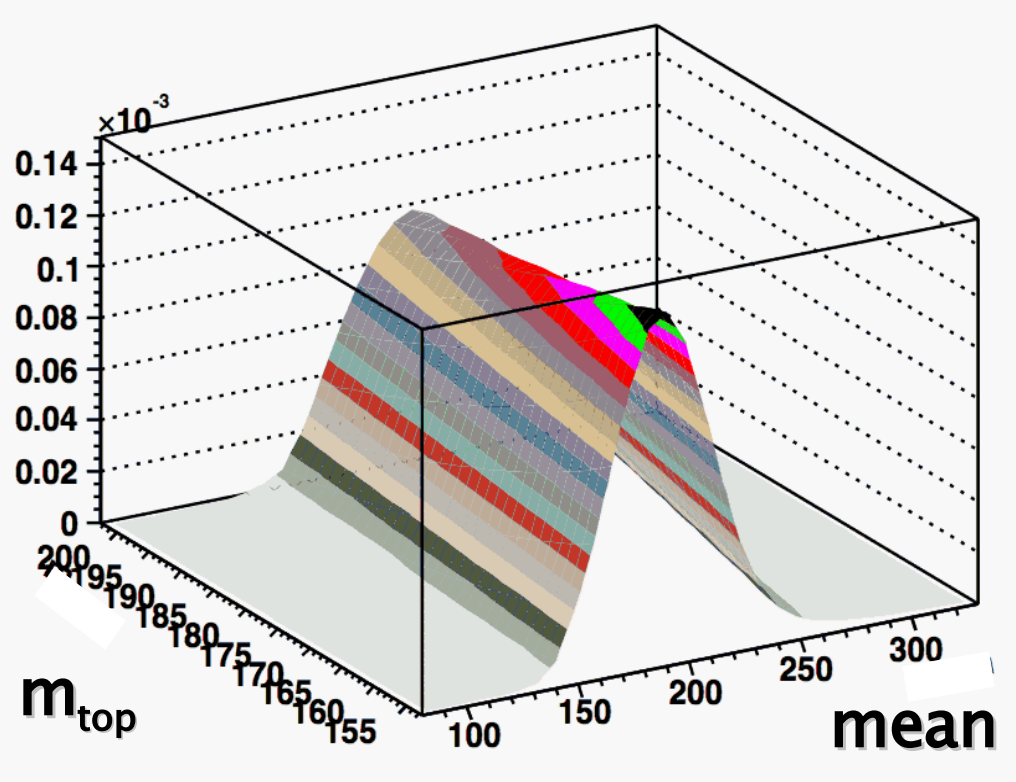
- extract templates

Neutrino Weighting Method: Result

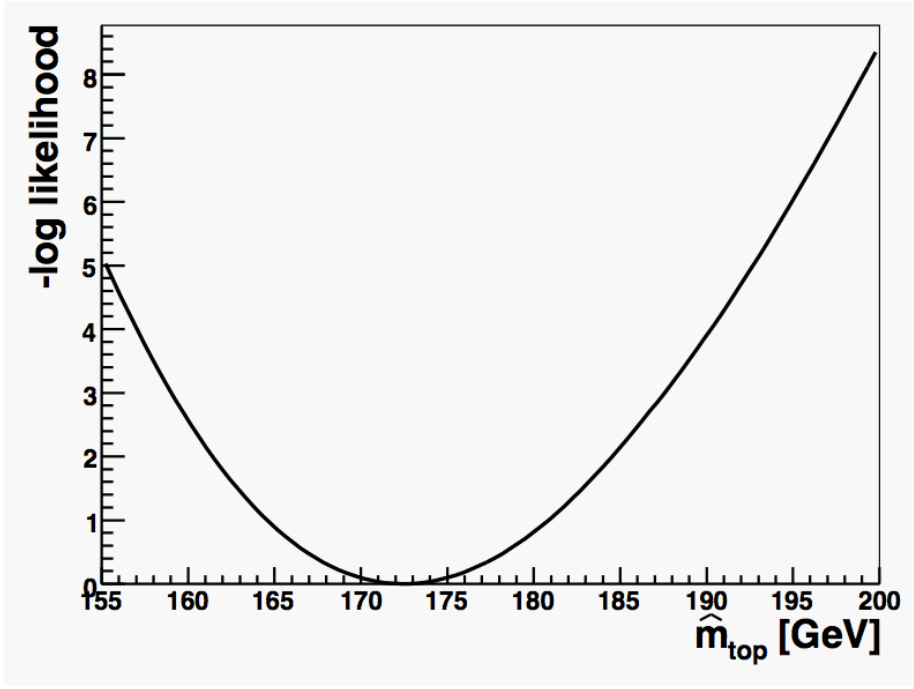
NEW: simultaneous 3 (2)-dimensional fit to signal (background) templates

rms=45 GeV

1 fb^{-1}



- 57 events



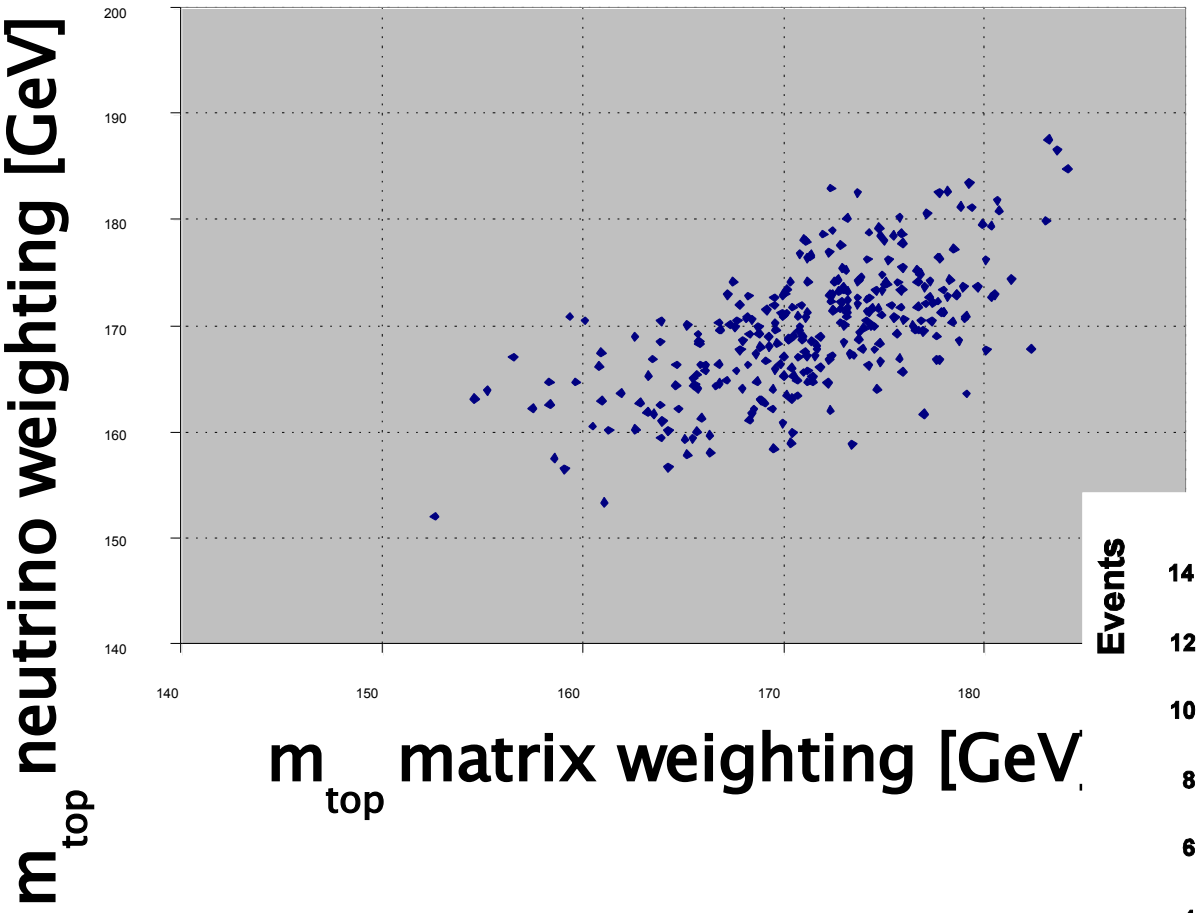
- maximum Likelihood function L(m_{top},mean,rms):

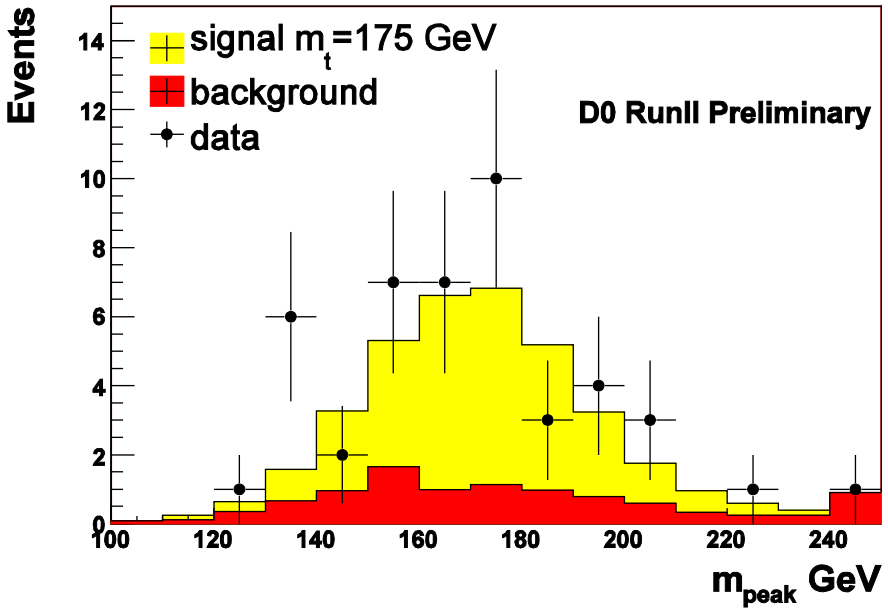
PRELIMINARY

m_{top} = 172.5 ± 5.8(stat.) ± 3.5 (syst.) GeV

±4.0%

Combination for matrix/neutrino weighting



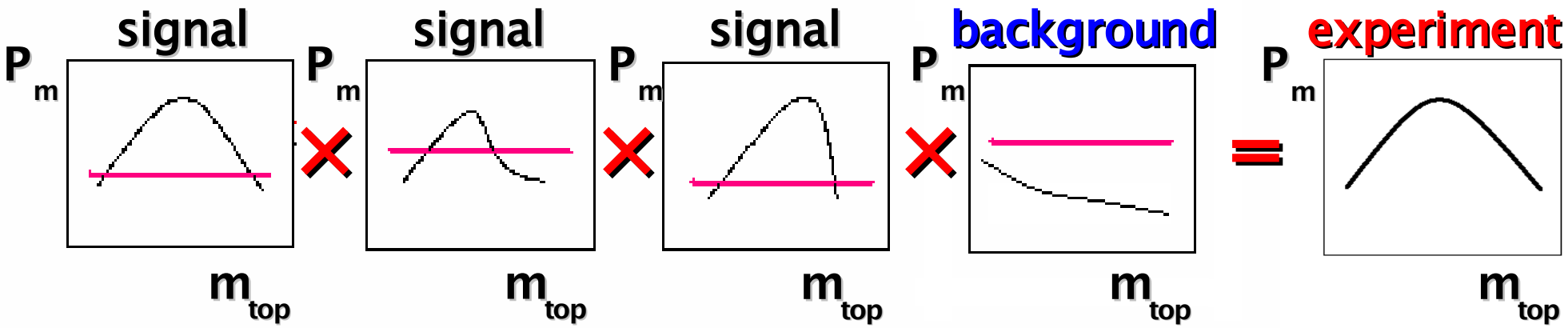


±3.7%

m_{top} = 173.7 ± 5.4(stat.) ± 3.4 (syst.) GeV

Extraction Techiques: Matrix Element

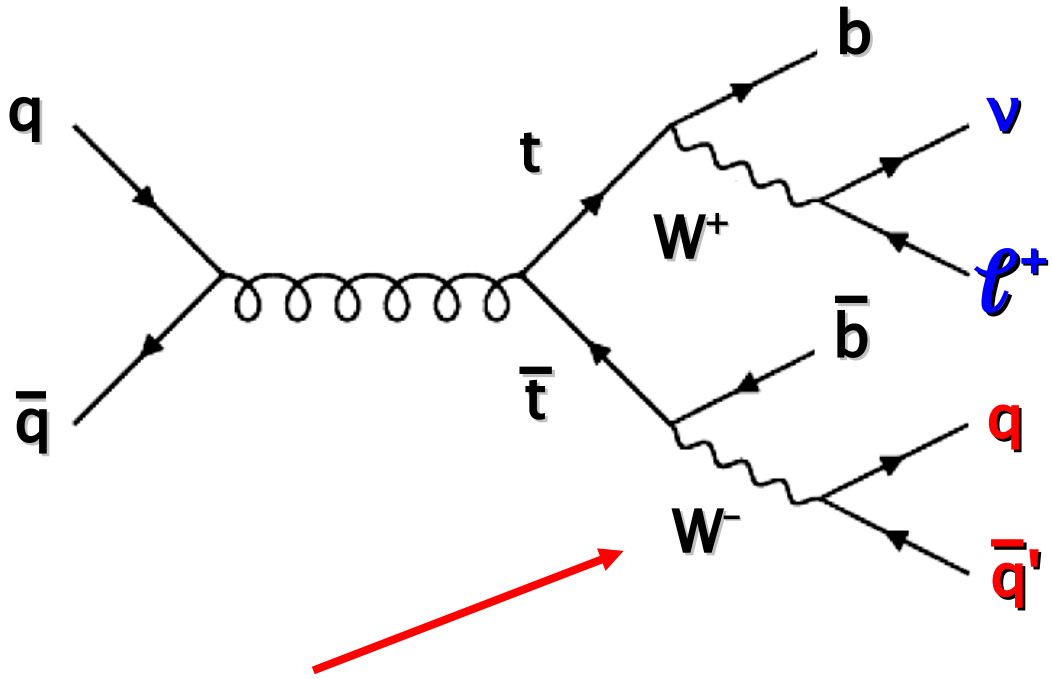
- probability densities for every event as function of m_{top}



- Maximum Likelihood fit

$$P_m(m_{top}, x) = \underbrace{Acc(x)}_{\text{Acceptance (selection, trigger,...)}} \times \frac{1}{\sigma} \int d^n \underbrace{\sigma(y; m_{top})}_{\text{LO-Matrix element x phase space}} dq_1 \underbrace{dq_2 \; f(q_1) \; f(q_2)}_{\text{PDF's}} \underbrace{W(x, y)}_{\text{Transfer Functions (Probability to measure x when y was produced)}}$$

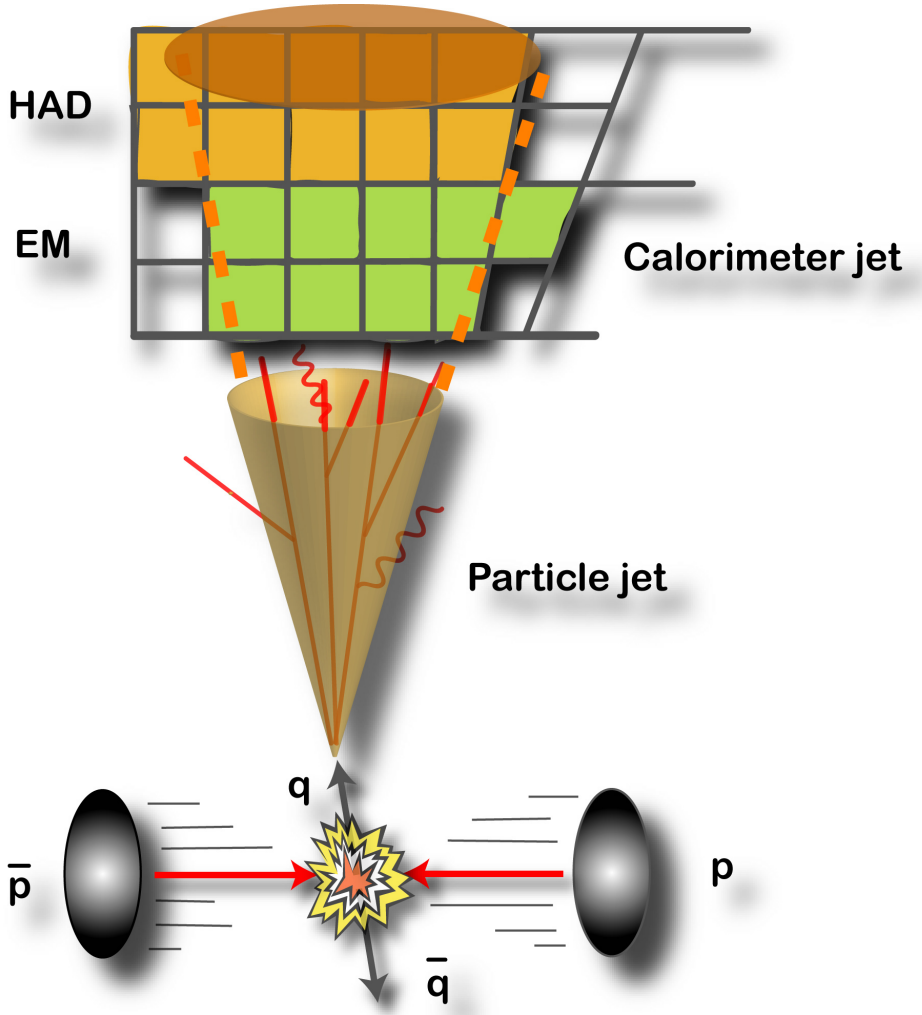
Lepton+Jets Channel



W mass constrains jet energy scale

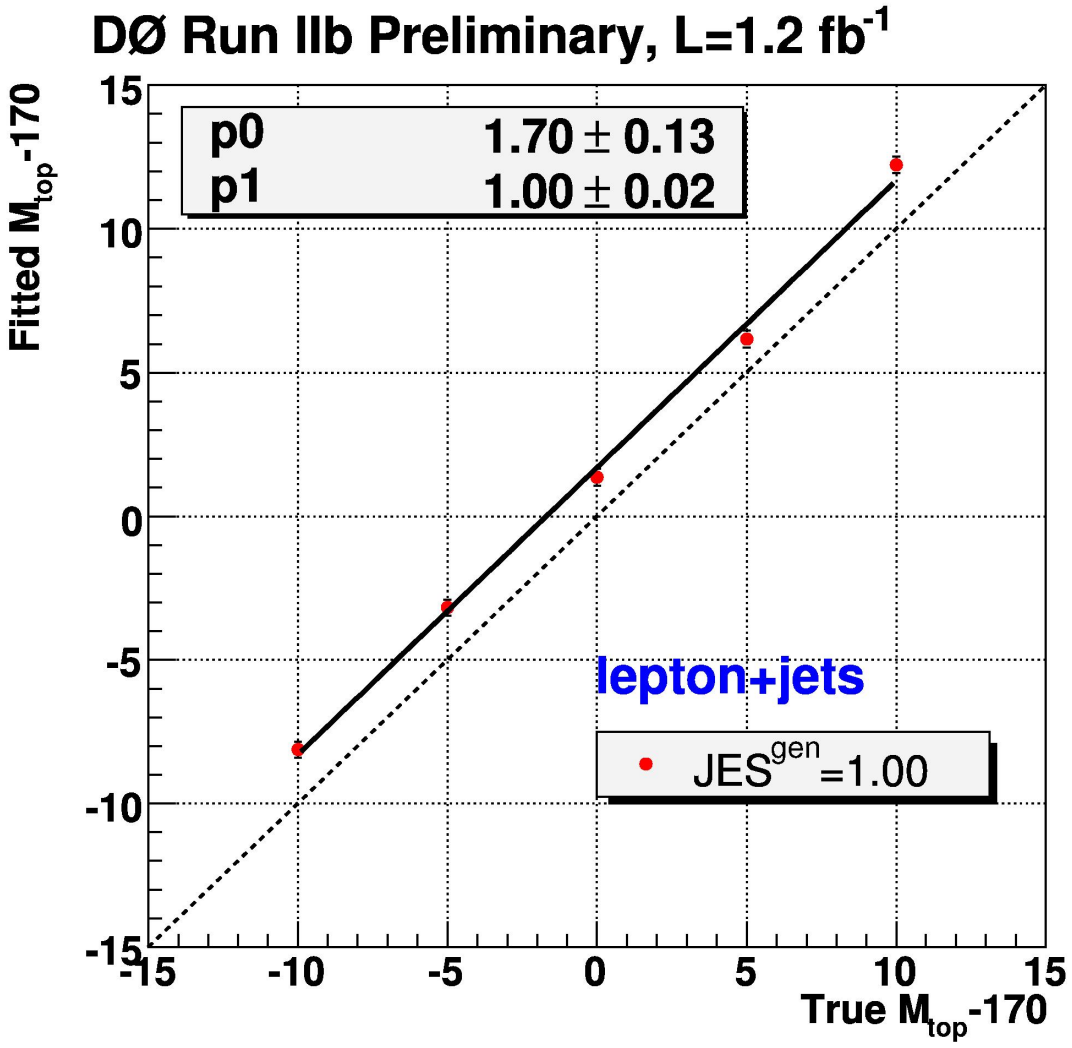
jet energy scale:

translate jet into parton energy



Calibration of the method

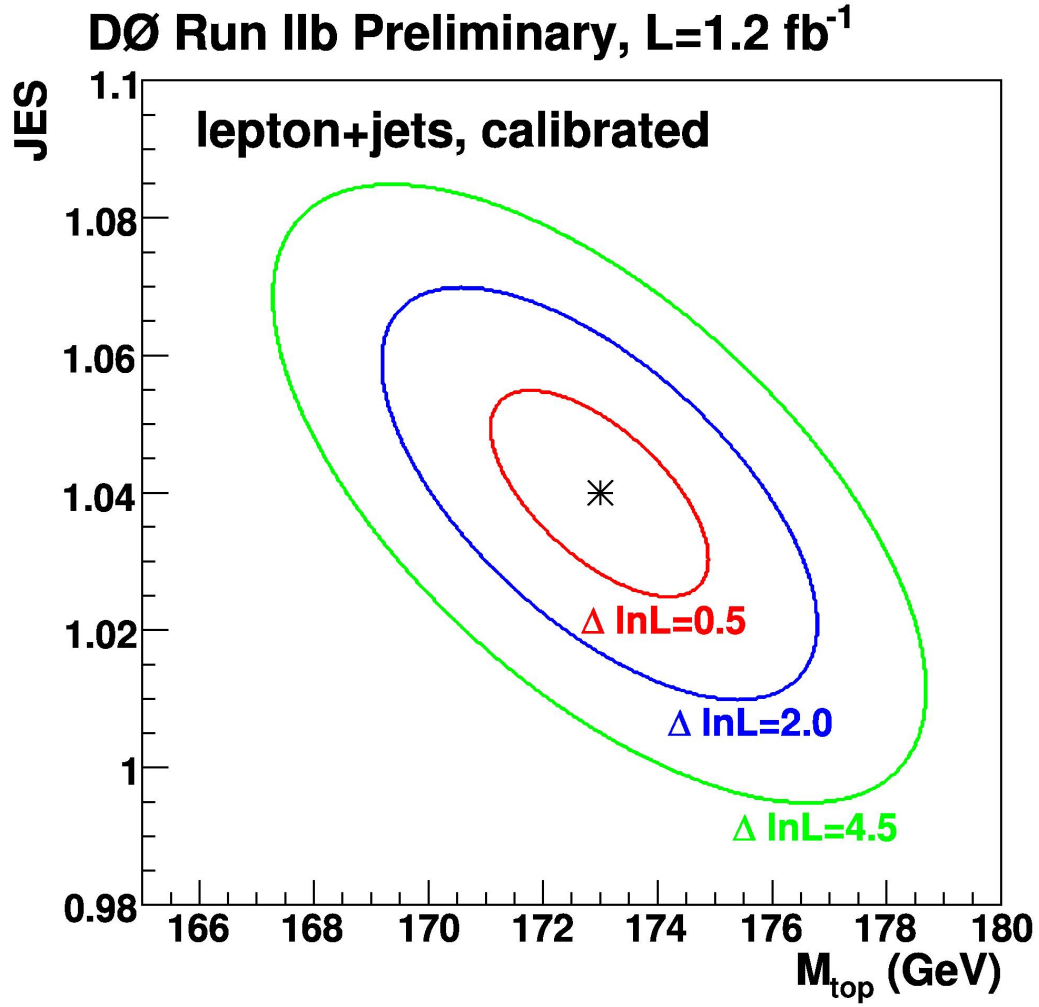
- pseudo experiments: compare measured mass with generated
- correct for differences: calibration curve



Results for Matrix Element Method

- maximum Likelihood fit using signal and background pdfs

jet energy scale



2.1 fb^{-1}

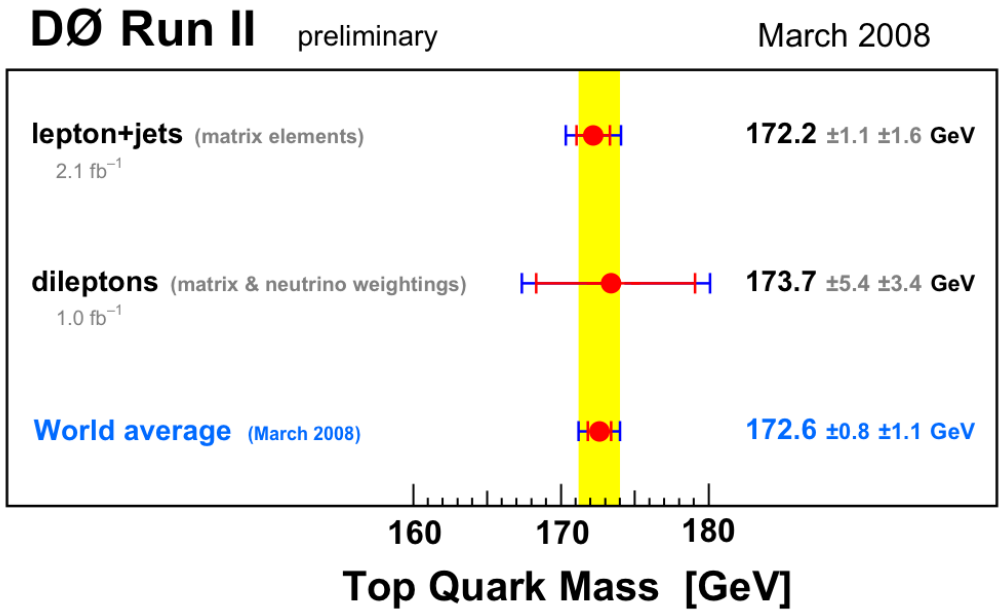
m_{top} = 172.2 ± 1.1 (stat) ± 1.6 (syst) GeV

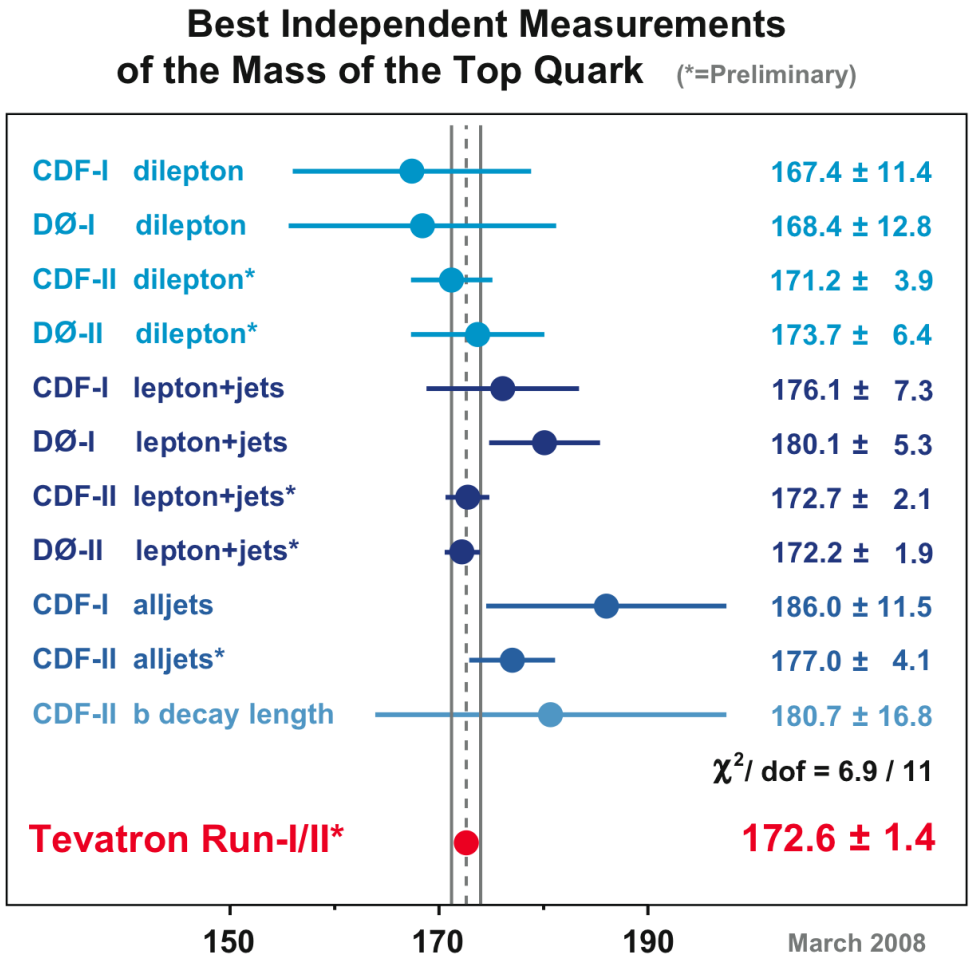
±1.1%

Tevatron Combination: March 2008

- account for correlations

2 fb^{-1}





$M_{top} = 172.6 \pm 1.4$ GeV

±0.8%

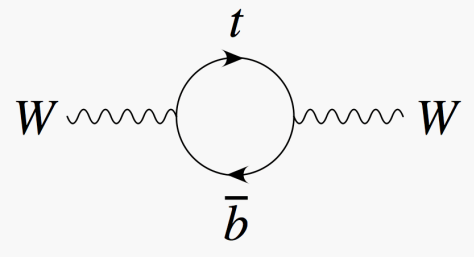
Summary: Top Mass Measurements

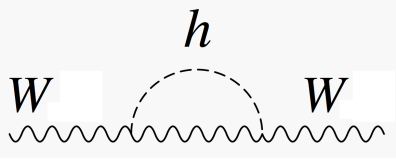
$m_{top} = 172.6 \pm 1.4$ GeV

world average (March 2008)

$m_W = 80398 \pm 25$ MeV

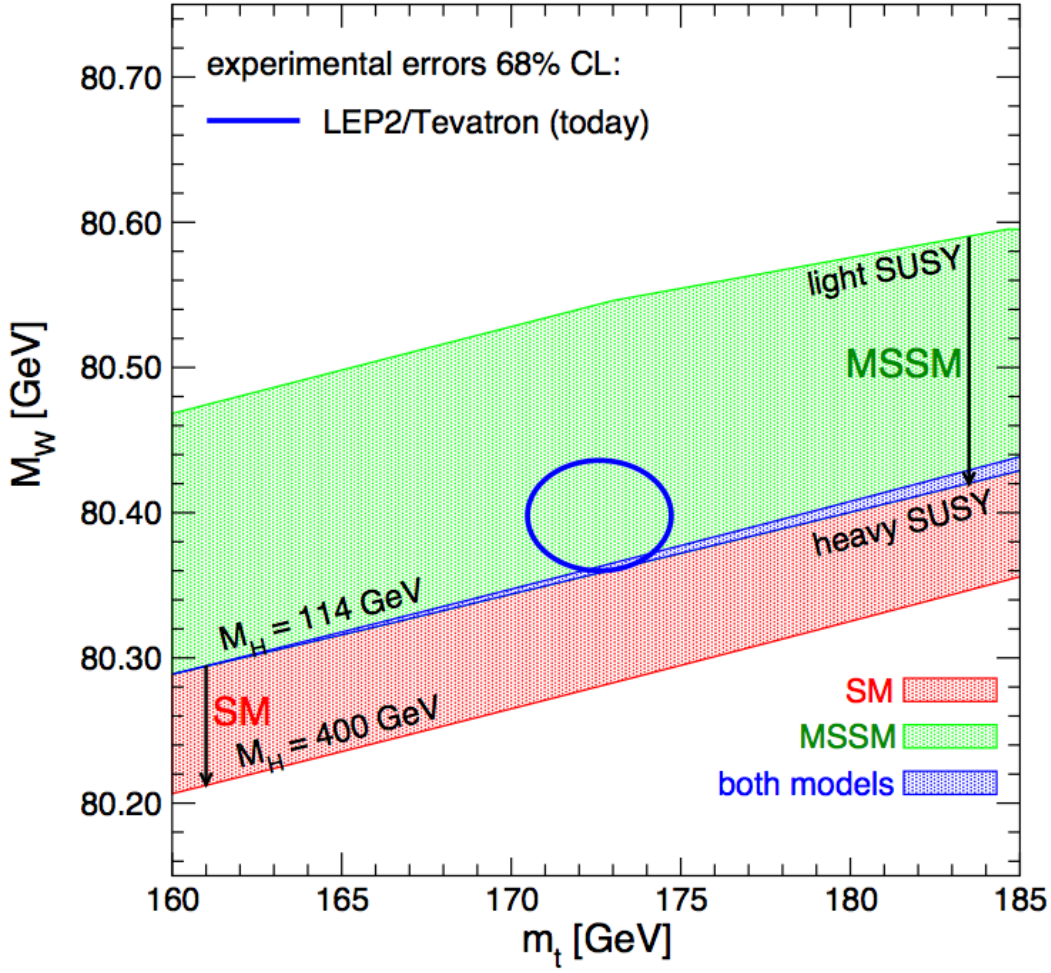
world average 2008





- Jan '05: $\Delta m_{top} = 4.3$ GeV
- Jan '06: $\Delta m_{top} = 2.9$ GeV
- Mar '07: $\Delta m_{top} = 1.8$ GeV

Heinemeyer, Hollik, Stockinger, Weber, Weiglein 2008



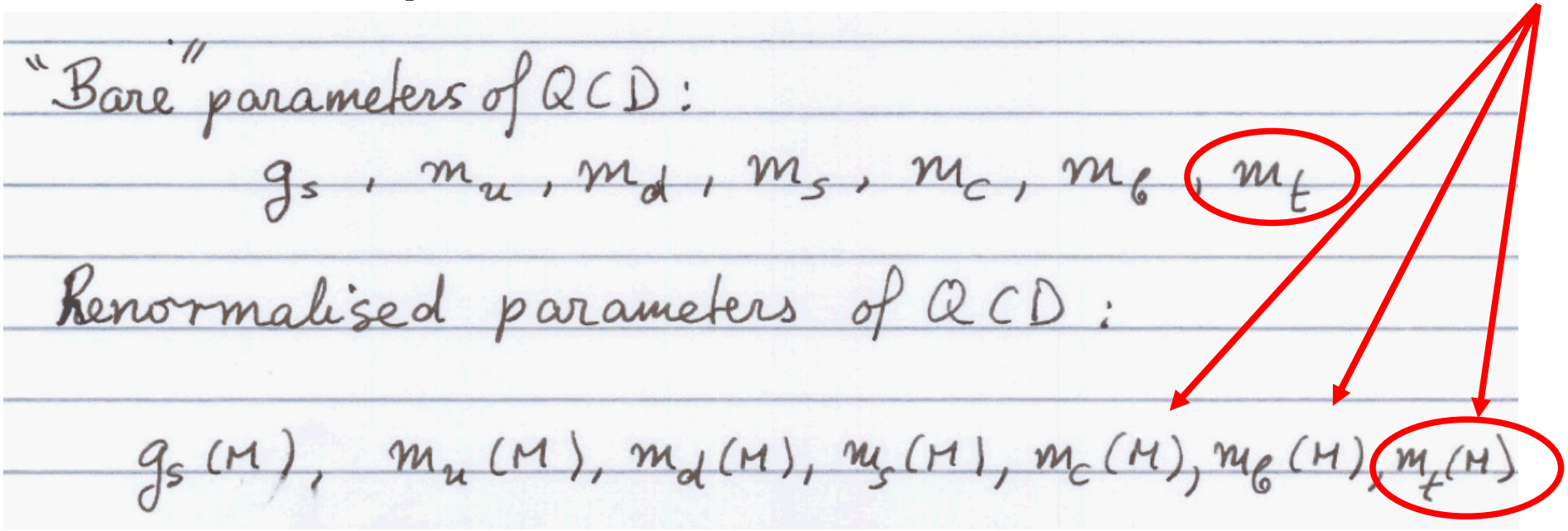
- **Tevatron should reach Δm_{top} ~1–1.5 GeV with full Run-II data set**

What mass do we measure?

$$\mathcal{L} = \ldots - \bar{\psi} M \psi \left(1 + \frac{H}{v}\right) \ldots$$

m_{top}

- **LO QCD: free parameter**
- **NLO QCD: dependent on the renormalisation scale M**



the concept of quark mass is convention-dependent!

Differences in top mass definitions

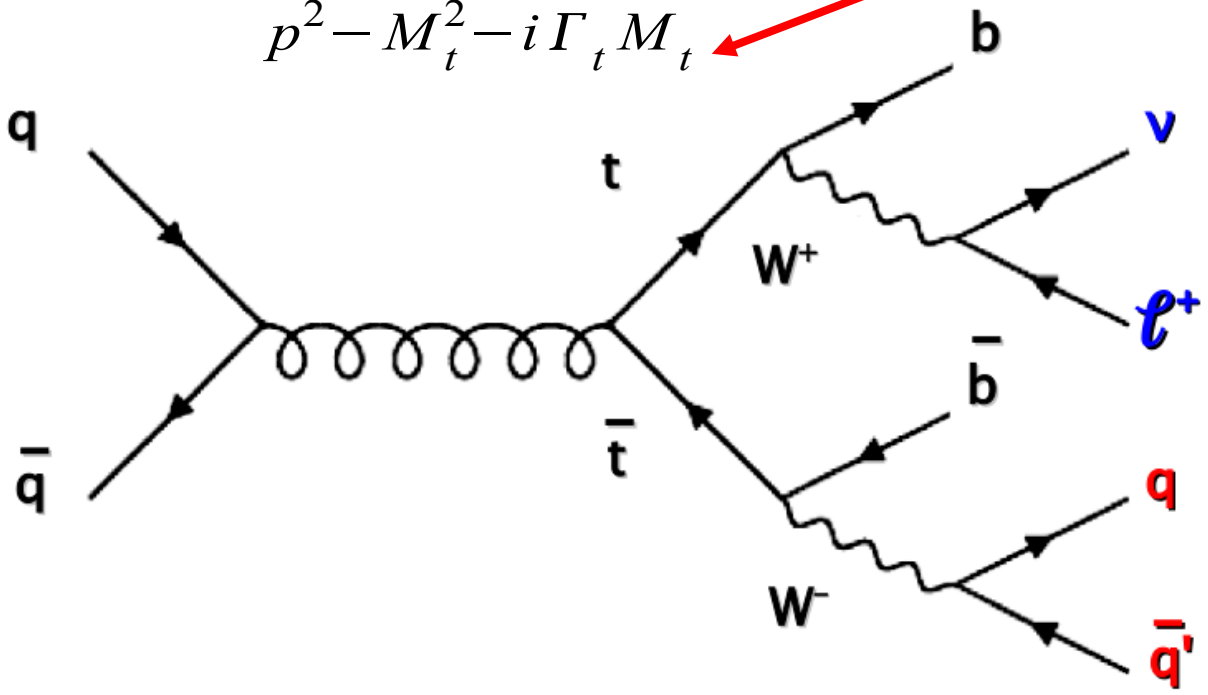
hep-ph/0001002

$$\overline{m}_t \equiv m_t^{\overline{\rm MS}}(m_t) = \frac{M_t}{1+\frac{4}{3\pi}\alpha_s(M_t)}$$

pole mass

$\overline{\rm MS}$ scheme

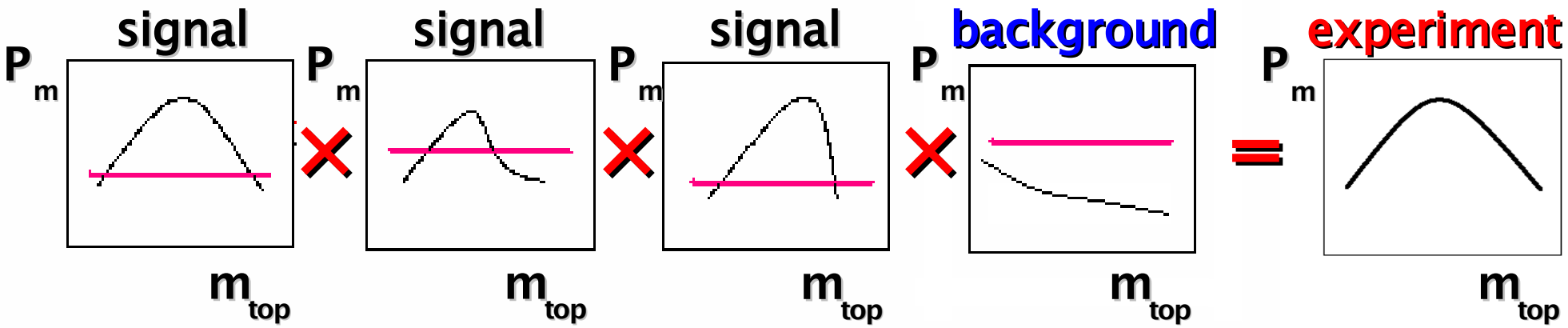
$$\frac{1}{p^2 - M_t^2 - i\Gamma_t M_t}$$



⇒ difference between $\overline{\rm MS}$ and pole mass is ≈7 GeV...

Extraction techniques: Matrix Element

- probability densities for every event as function of m_{top}



- Maximum Likelihood fit

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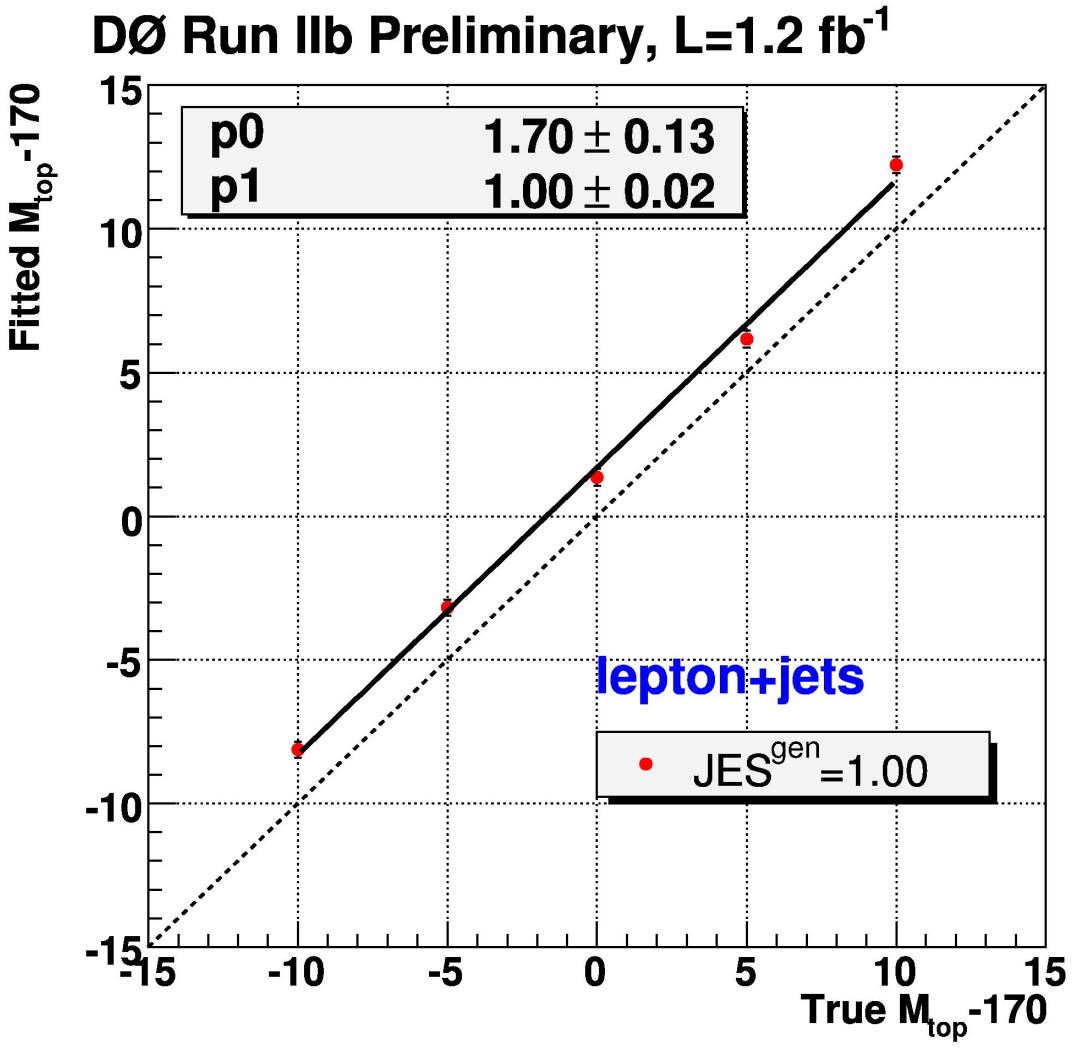
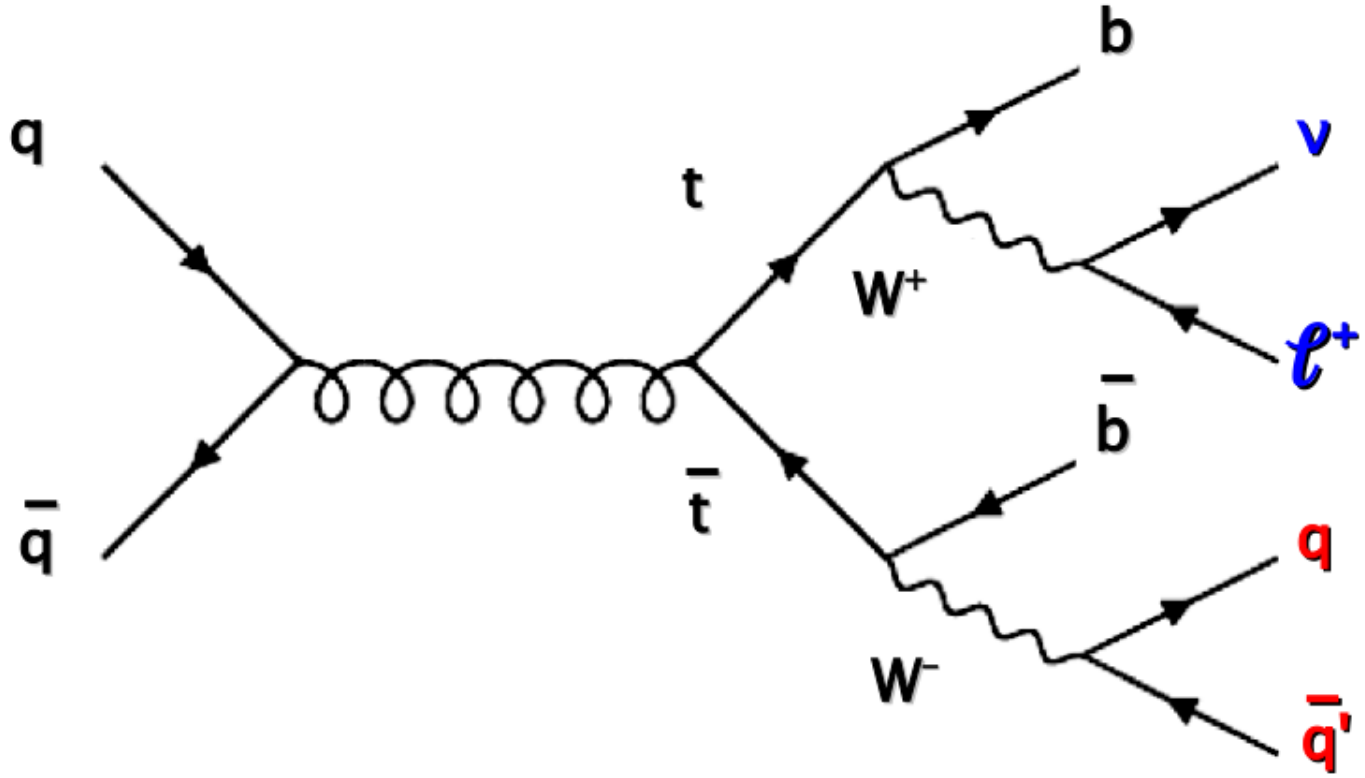


Which top mass does a LO MC contain?

- **matrix element in LO QCD**



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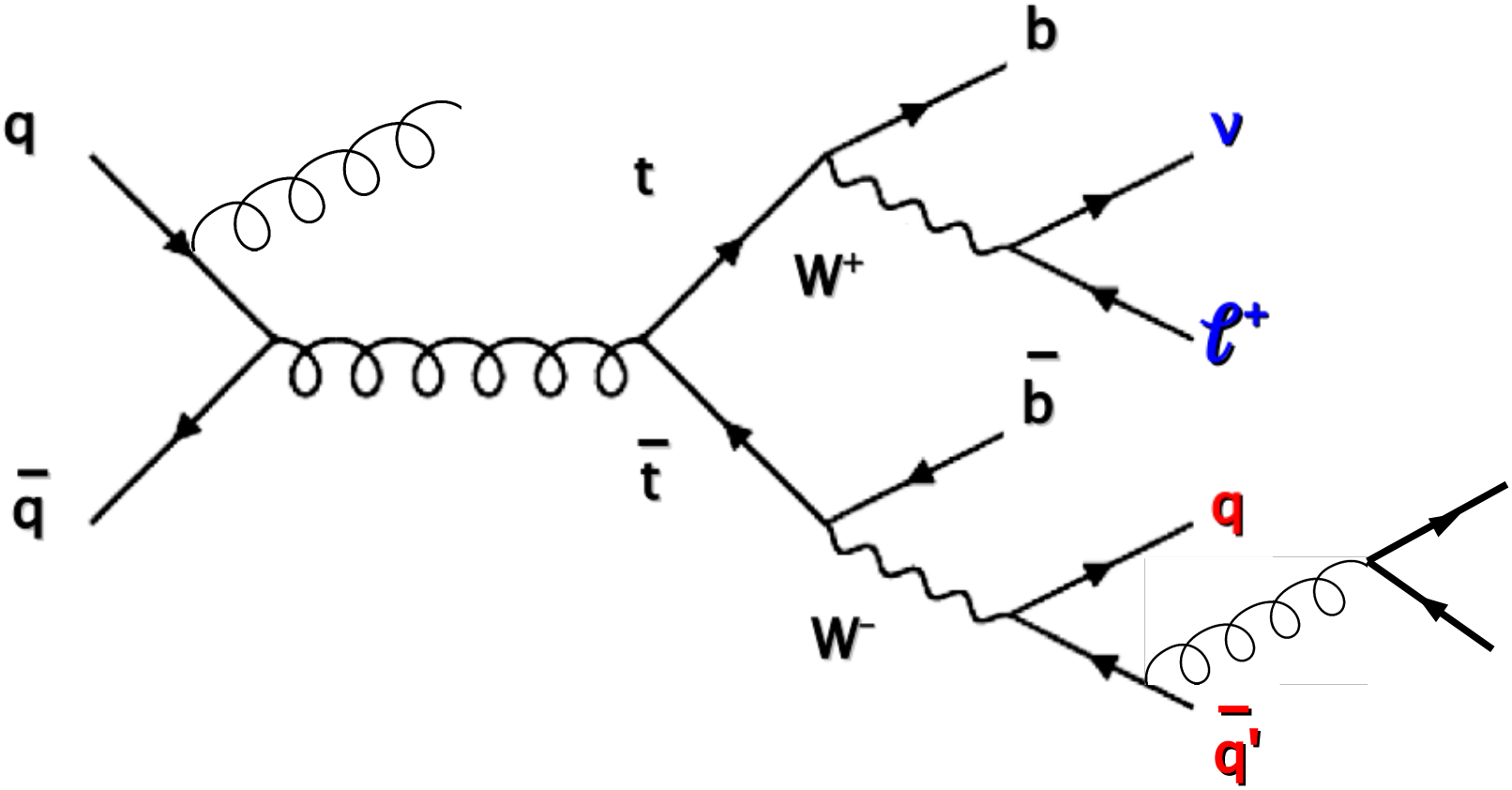
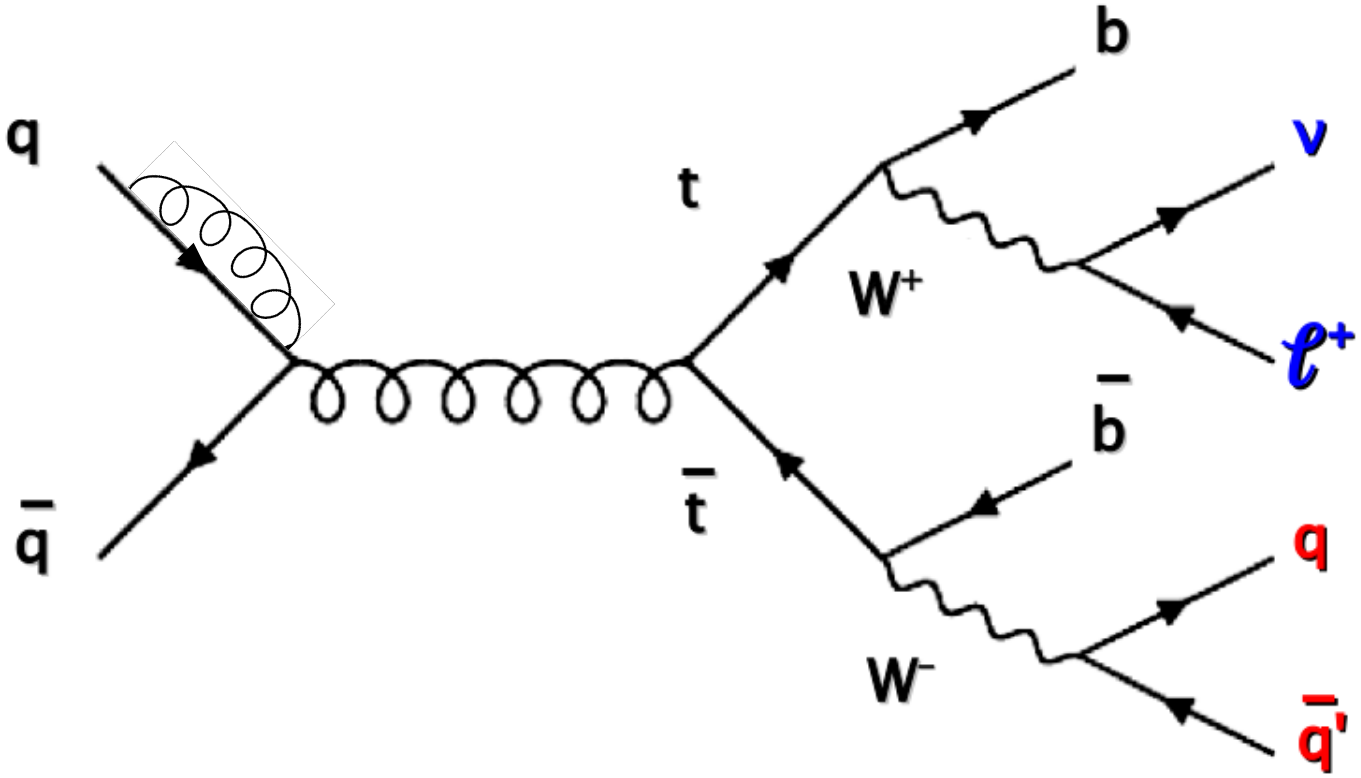


- **parton showers simulate higher orders,**

Which top mass does a LO MC contain?

- **matrix element in LO QCD**



- **parton showers simulate higher orders, i.e. not only radiating additional gluons!**

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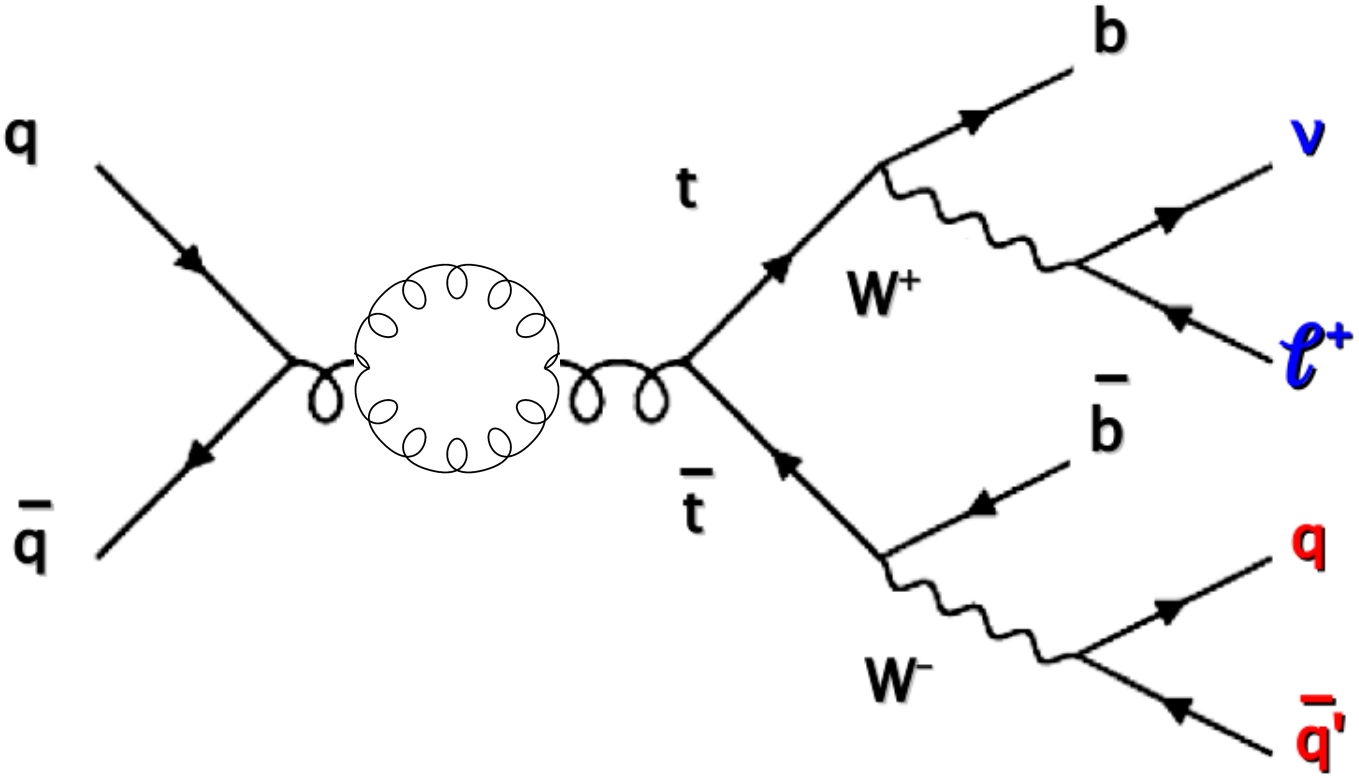
- **matrix element in LO QCD**



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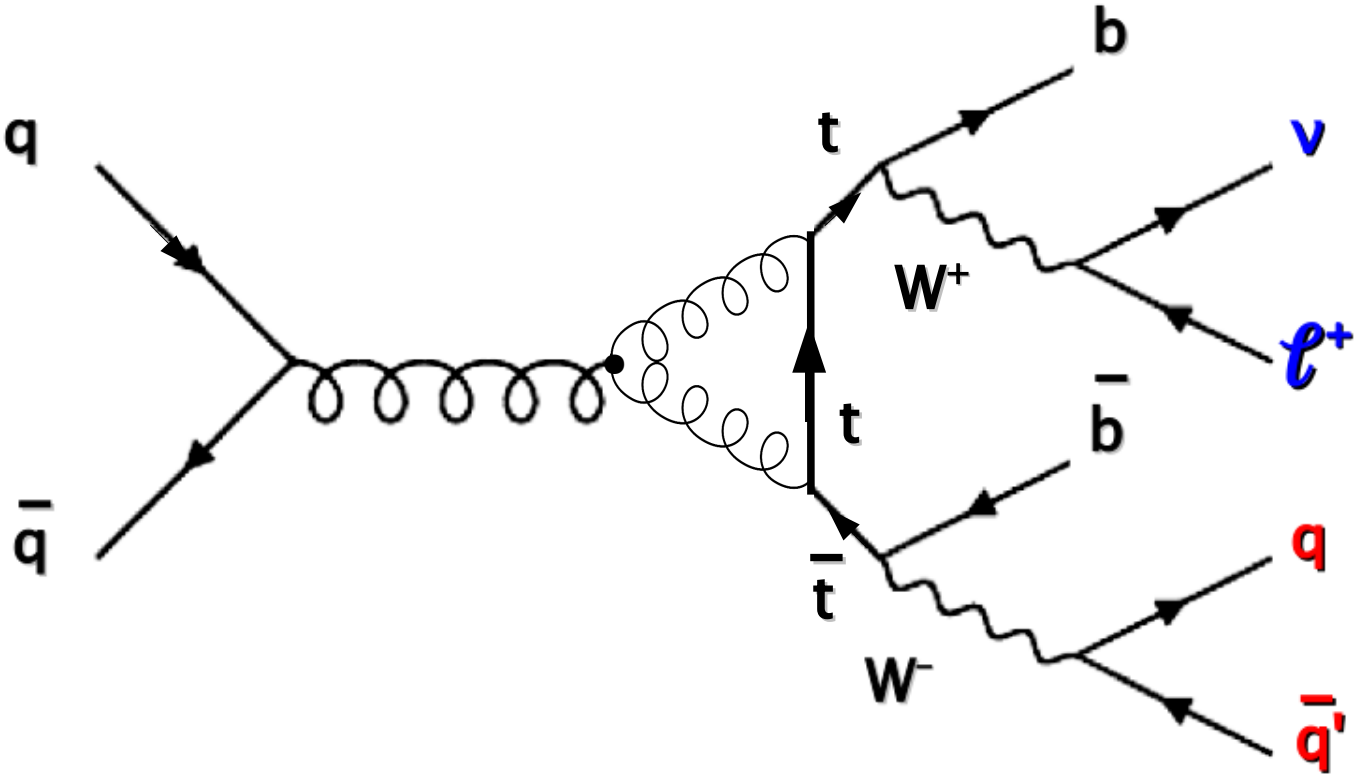

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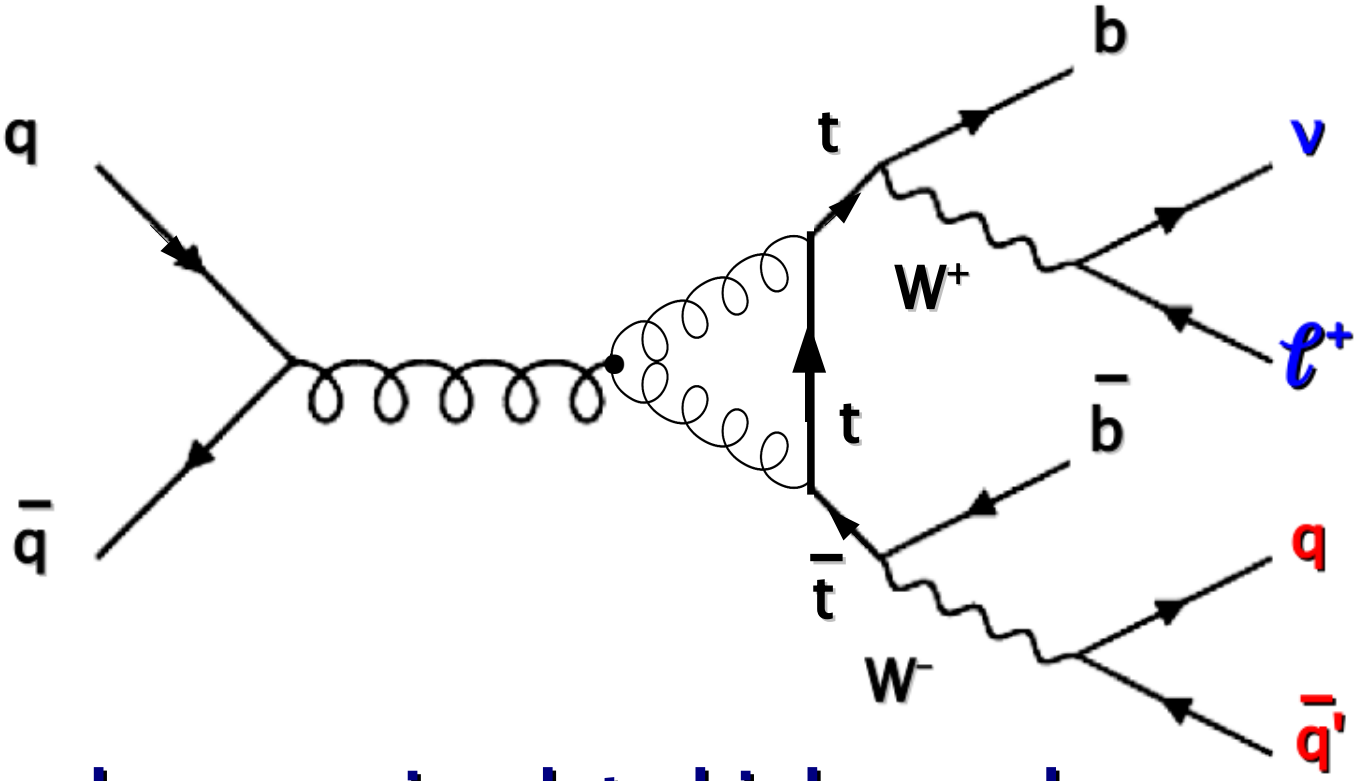


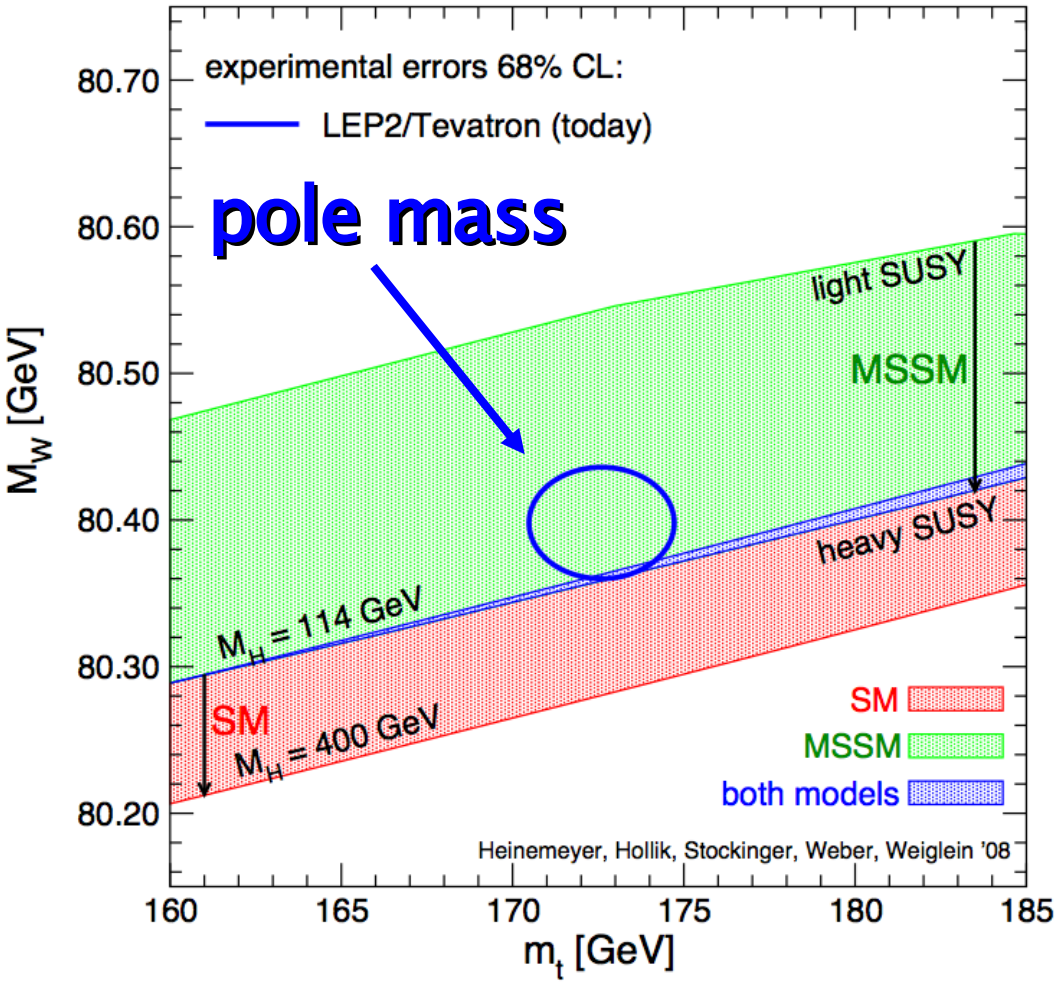
- parton showers simulate higher orders,
  i.e. not only radiating additional gluons!

⇒ NOBODY KNOWS...

- arguments that it should be close to pole mass

Important to know...

M. Seymour: "... as far as I know, noone understands in detail the relationship between the quantity you measure and any fundamental parameter of the theory."



$m_{top} = 172.6 \pm 1.4$ GeV

$m_W = 80398 \pm 25$ MeV

world average (March 2008)

- will continue at the LHC!

Heinemeyer, Hollik, Stockinger, Weber, Weiglein 2008

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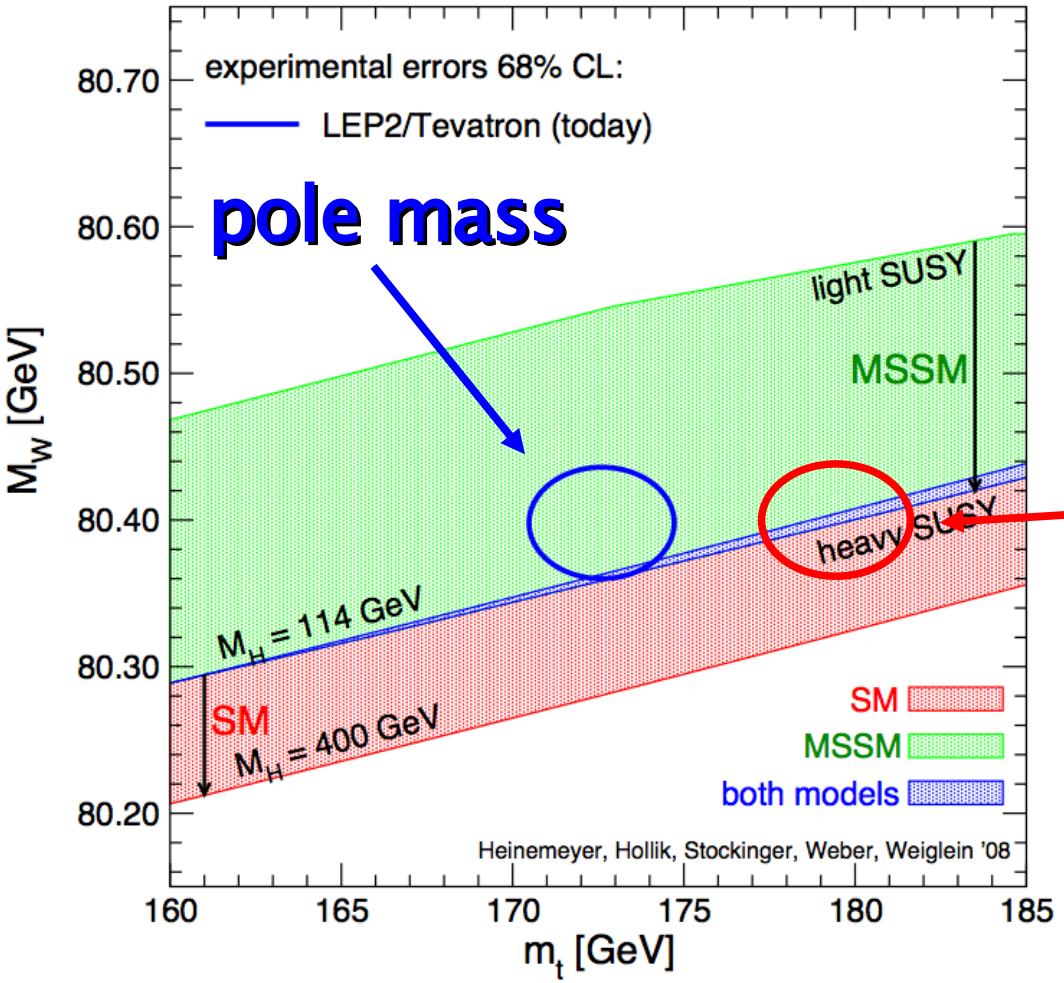

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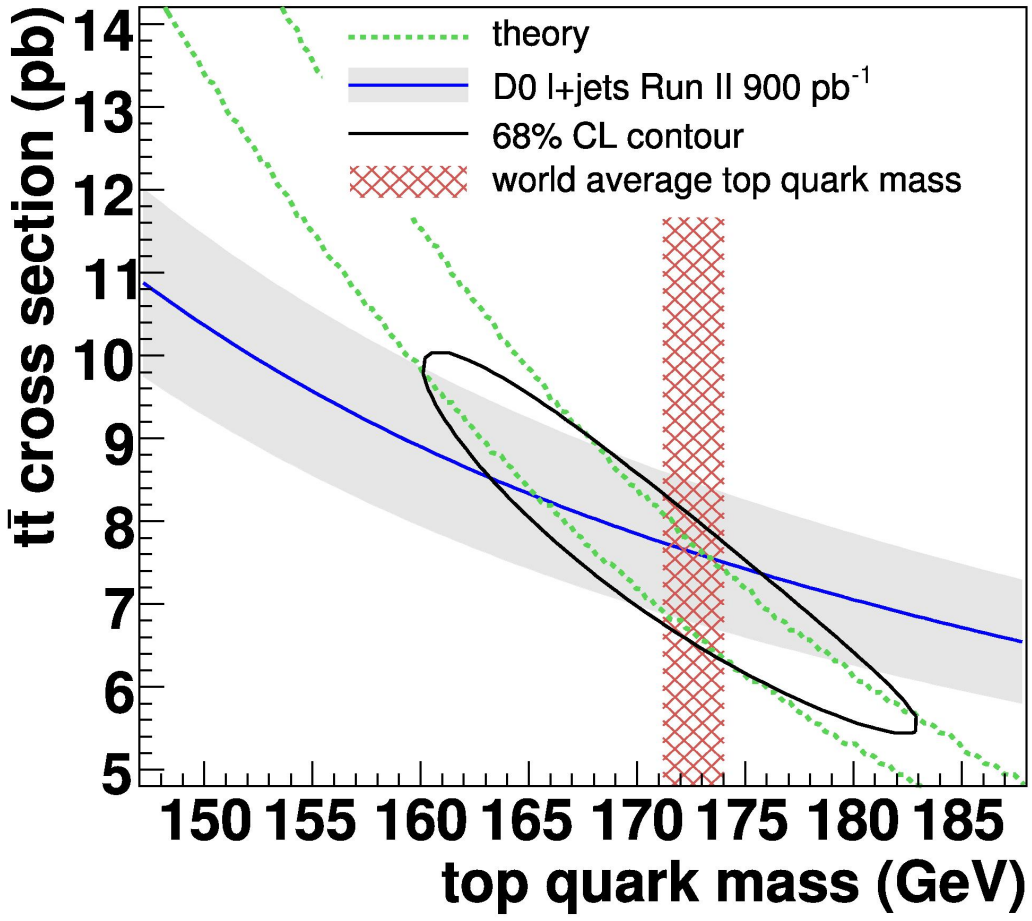
world average (March 2008)

world average interpreted as $\overline{\text{MS}}$ mass (too extreme...)

- will continue at the LHC!

Heinemeyer, Hollik, Stockinger, Weber, Weiglein 2008

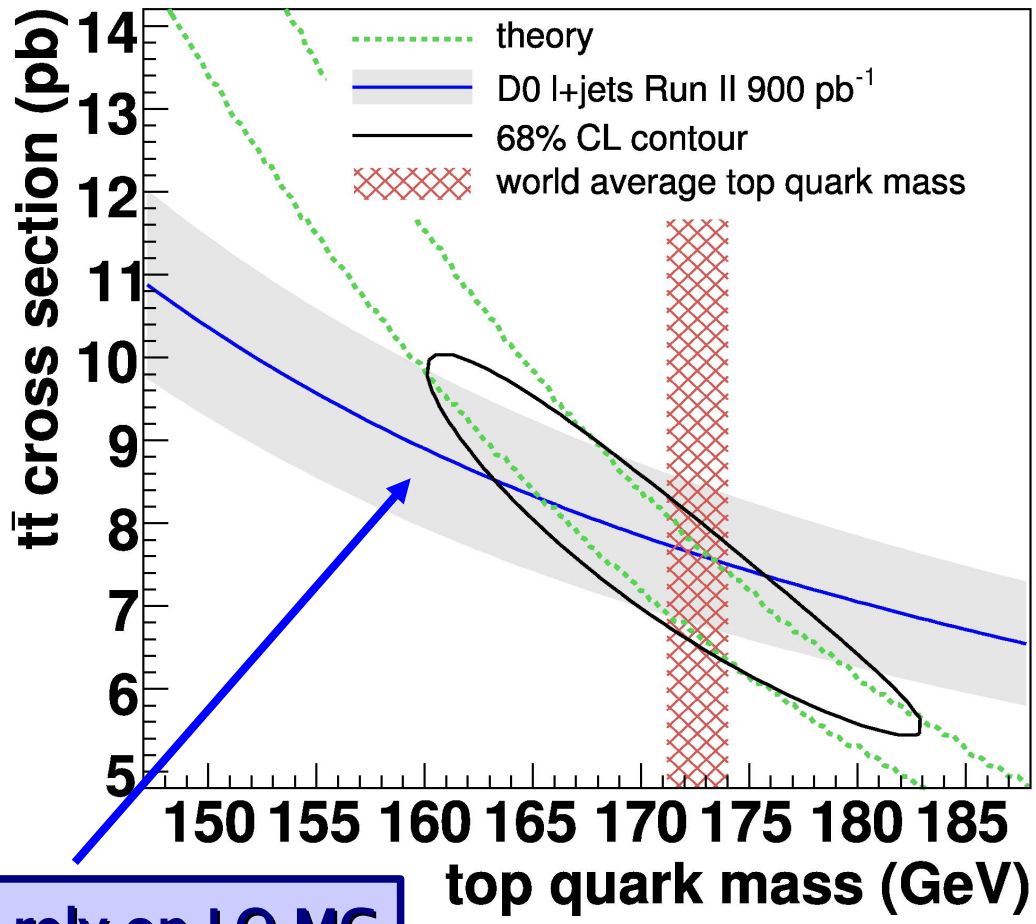
Top mass from cross section measurement



$\sigma_{tt} = 7.42 \pm 0.53\ (stat) \pm 0.46\ (syst) \pm 0.45\ (lumi)\ pb$

$m_{top} = 175\ GeV$

Top mass from cross section measurement

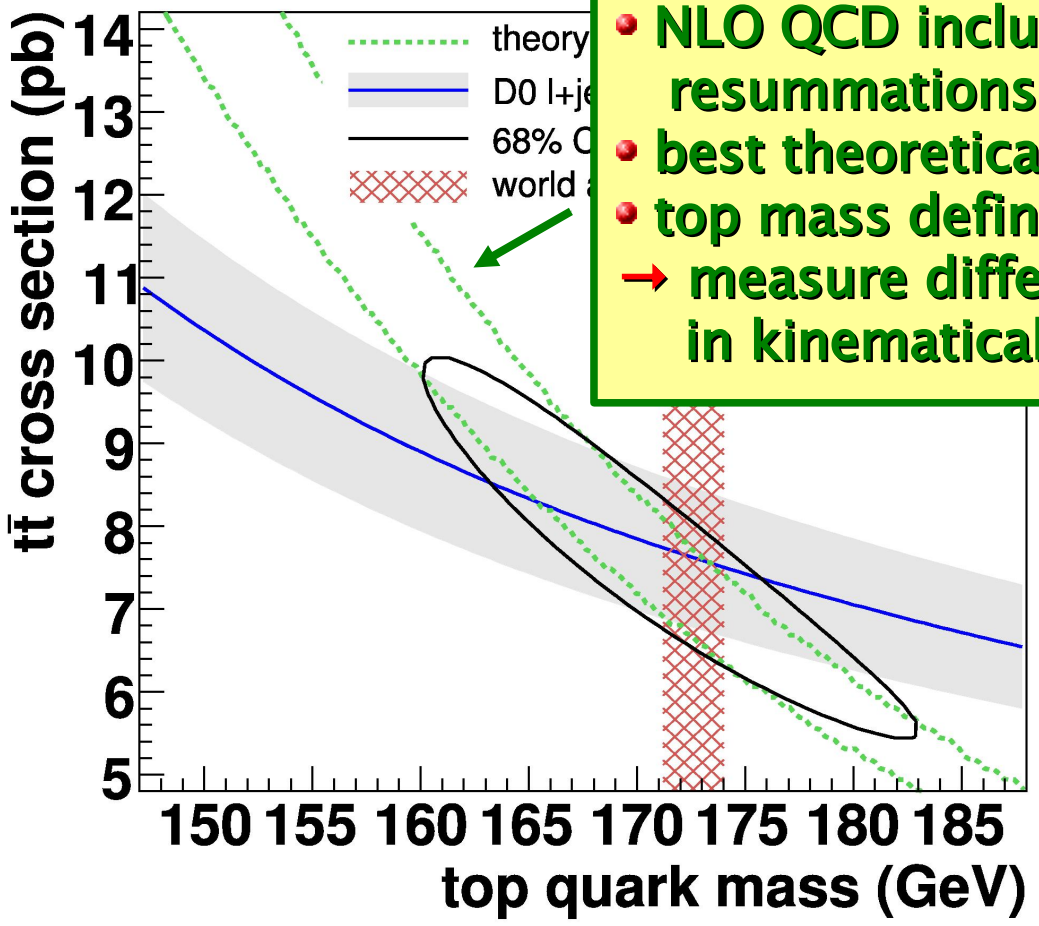


- signal efficiency: rely on LO MC
- kinematical distributions very similar between LO and NLO

→ assume no influence on top mass definition

Frixione, Mangano, Nason, Ridolfi, hep-ph/9503213

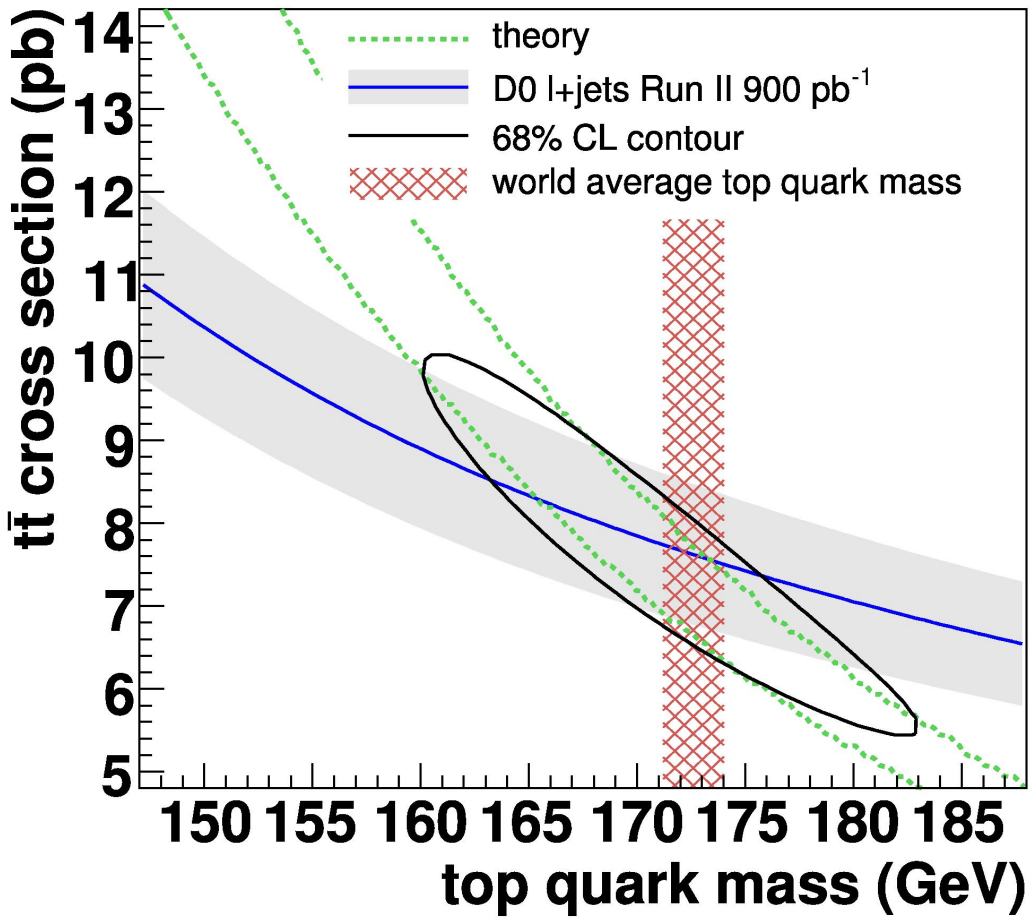
Top mass from cross section measurement



- NLO QCD including resummations in higher orders
- best theoretical knowledge
- top mass definition: pole mass

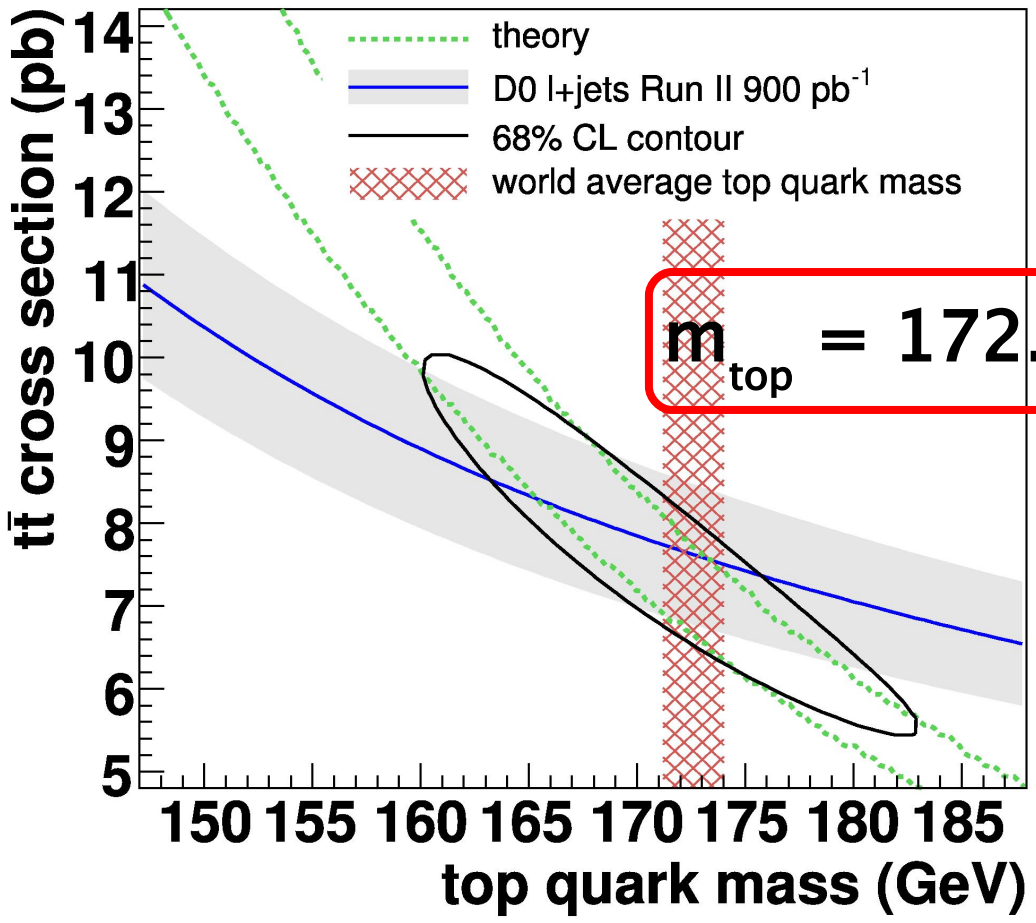
→ measure different quantity than in kinematical analyses

Top mass from cross section measurement



- "simpler" analyses
- good cross check
- → complementary information

Top mass from cross section measurement



$m_{top} = 172.6 \pm 1.4$ GeV

"LO Pythia mass"

$M_{top} = 170 \pm 7$ GeV

pole mass

Conclusions

new era of top physics at the Tevatron:

precision measurements & searches in the top sector

- cross section measurement top pair production
- search for ttbar resonances
- branching fractions
- search for charged Higgs bosons
- top mass

⇒ all measurements are in agreement with SM

⇒ more interesting results will follow with more data

⇒ will continue to explore top sector in detail

Outline

Top Pair Production Cross Section

Searches in Top Production

- new resonances

Searches in Top Decays

- branching fractions
- charged Higgs boson

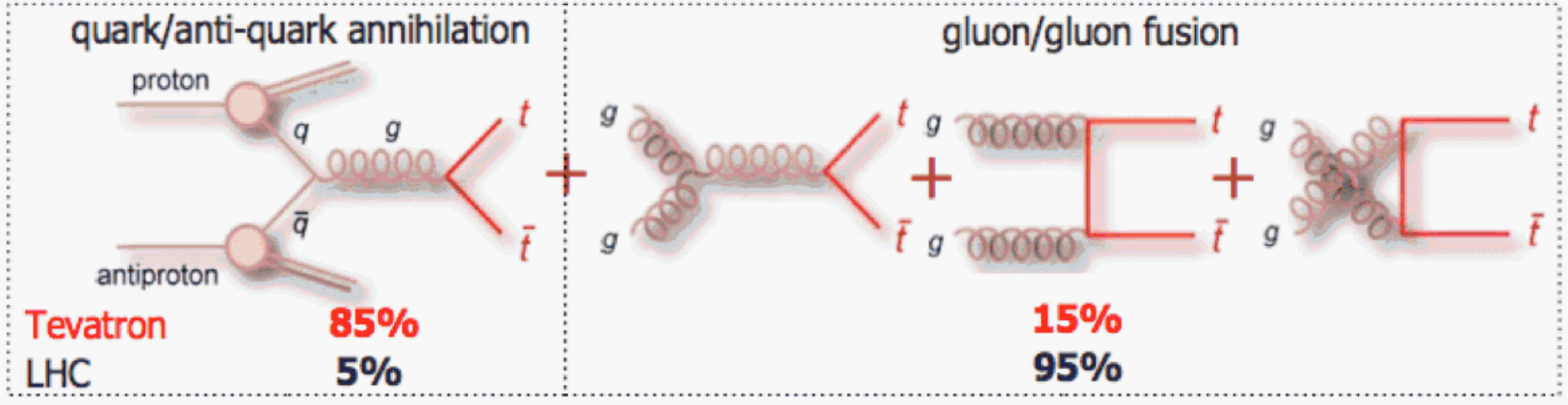
Top Mass

Outlook: Top Physics at LHC

Top Pair Production at the LHC

Tevatron: $\sigma(1.96\text{TeV})=6.1\text{pb}$

LHC: $\sigma(14\text{TeV})\sim 800\text{pb}$

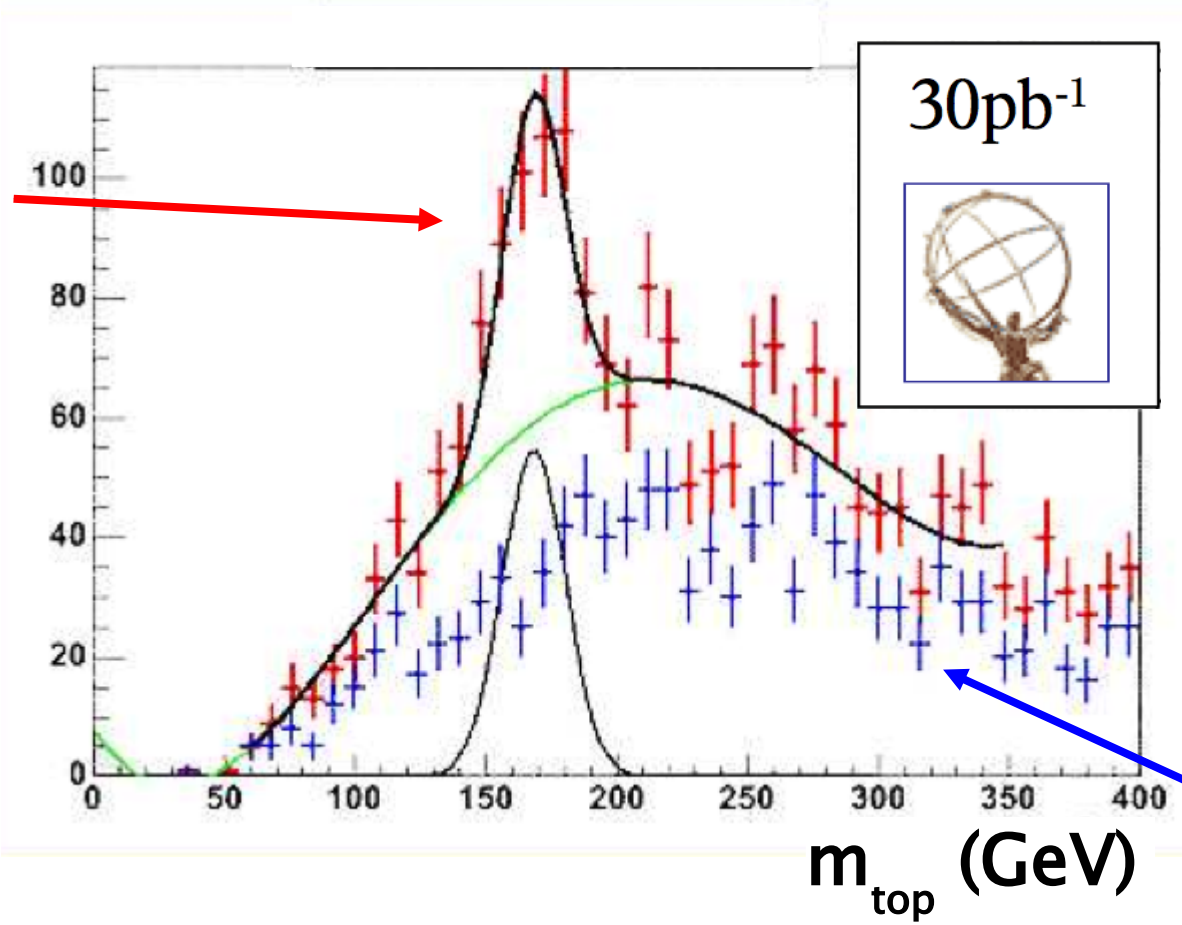


10 top pairs per day @ Tevatron ↔ 1 top pair per second @ LHC

Top Quarks as "Standard Candles"

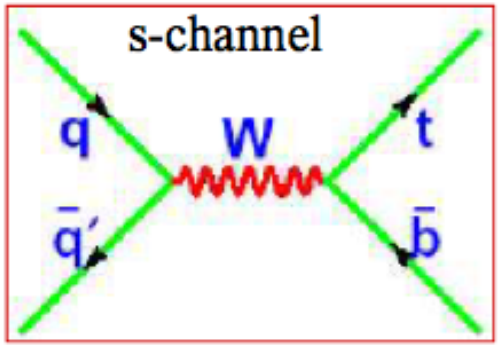
few hours of data taking

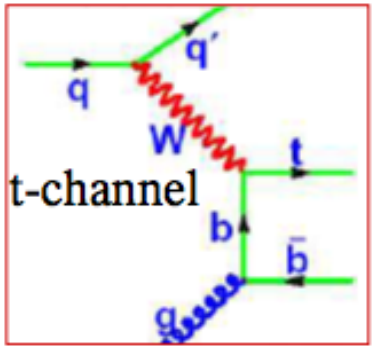
ATLAS ATL-PHYS-PUB-2005-024

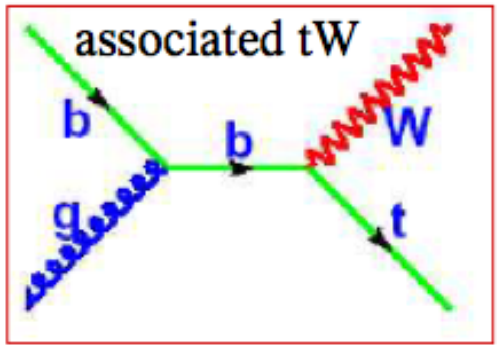


- top mass peak one of the first signals to detect
- use for detector commissioning:
  e.g. trigger, b-tagging, jet energy scale

Single Top Production at the LHC







σ_{top} & $\sigma_{anti\text{-}top}$ not equal

LHC	$\sigma^{NLO} = 6.6$ pb	$\sigma^{NLO} = 153$ pb	$\sigma^{NLO} = 60$ pb	→ top production
	$\sigma^{NLO} = 4.1$ pb	$\sigma^{NLO} = 90$ pb	$\sigma^{NLO} = 60$ pb	→ anti-top production
TeV	$\sigma^{NLO} = 0.75$ pb	$\sigma^{NLO} = 1.47$ pb	$\sigma^{NLO} = 0.15$ pb	

4 single tops per day @ Tevatron ↔ 30 single tops per minute @ LHC

Outlook: Top Quark Physics at the LHC

- LHC is a top factory: 1 top pair per second at nominal luminosity
  30 single top per minute at nominal luminosity
- systematically limited Tevatron analyses hard to beat:
  Δm_{top} ~1 GeV (instead of 1 – 1.5 GeV at the Tevatron)
- statistically limited Tevatron analyses important:
  2% statistical error expected for single top production in t-channel
- measure basic quantities as spin, charge and couplings!
- role of top quark in electroweak symmetry breaking:
  measure top-Yukawa coupling

⇒ high precision SM measurements

⇒ high sensitivity for new physics

⇒ much wider range of topics

⇒ role of top quark in electroweak symmetry breaking

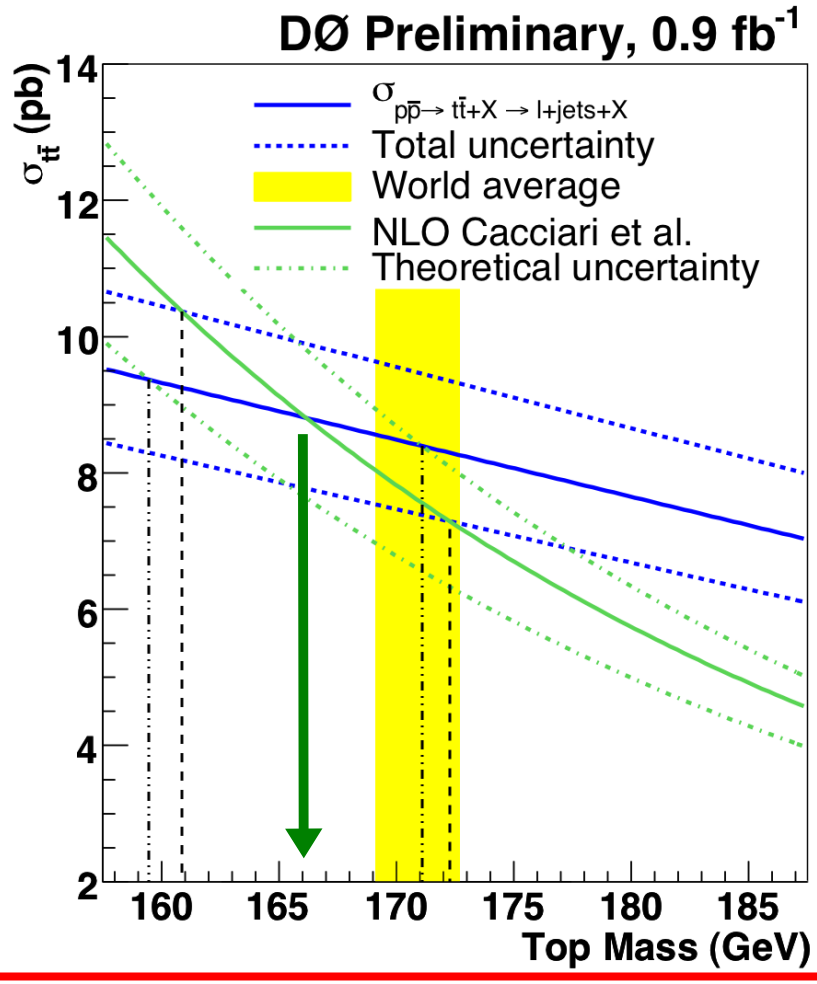
Backup

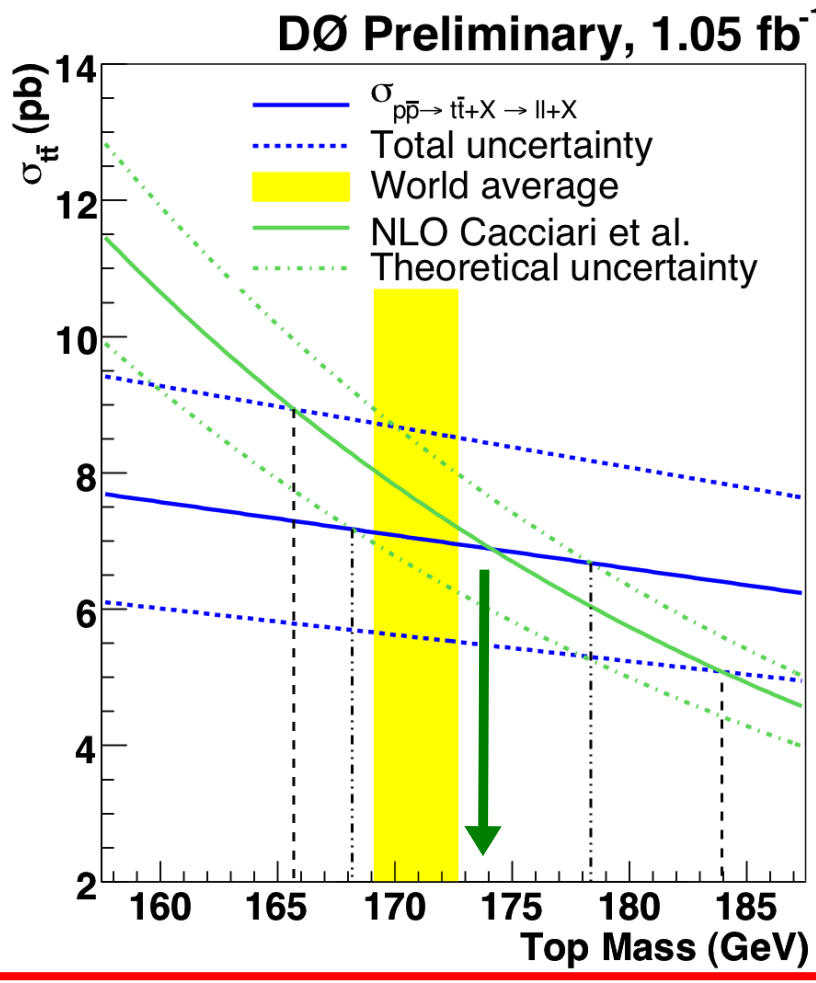
Outlook: Top Quark Physics at the LHC

quantity	CDF/DØ		ATLAS/CMS
$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$	11% with 1 fb^{-1}	[554]	5%–10% luminosity systematics dominated
$\Delta\sigma_{\text{single-top}}/\sigma_{\text{single-top}}$	26% with 1 fb^{-1}	[554]	10% ($<$ 2% stat. error with 10 fb^{-1}
$B(t \to Wb)$	3.3% with 1 fb^{-1}	[554]	
V_{tb} from $\sigma_{\text{single-top}}$	14% with 1 fb^{-1}	[554]	6.5%
V_{tb} from $B(t \to Wb)$	> 0.22 with 1 fb^{-1}	[554]	0.2% (stat. only)
single-top polarisation	–		1.6% with 10 fb^{-1}
$\Delta m_{\text{top}}/m_{\text{top}}$	≤ 2 GeV/c^2	Sect. 7	≈ 1 GeV/c^2
spin correlation θ	40% (2 fb^{-1})	[538]	7% ($\ell\ell \oplus \ell$+jets) for 10 fb^{-1}
spin correlation ϕ	–		4% ($\ell\ell \oplus \ell$+jets) for 10 fb^{-1}
W-helicity $\mathcal{F}_0$	6.5% with 1 fb^{-1}	[554]	2%–5% with 10 fb^{-1}
W-helicity $\mathcal{F}_+$	2.6% with 1 fb^{-1}	[554]	1% with 10 fb^{-1}
electric charge q_t	distinguish $\frac{2}{3}$ and $\frac{4}{3}$ cases with 1 fb^{-1}	Sect. 7.2	distinguish $\frac{2}{3}$ and $\frac{4}{3}$ cases with 10 fb^{-1}
Yukawa coupling y_t	–		4.8σ, 16% (12%) with 30(100) fb^{-1}
FCNC $B(t \to gq)$	$< 1.9 \times 10^{-2}$ with 2 fb^{-1}	[548, 555]	$< 1 \times 10^{-5}$ - $< 1.4 \times 10^{-3}$ (10 fb^{-1})
FCNC $B(t \to Zq)$	$< 1.5 \times 10^{-2}$ with 1 fb^{-1}	[554]	$< 6.5 \times 10^{-4}$ - 1.3×10^{-3} with 10 fb^{-1}
FCNC $B(t \to \gamma q)$	$< 3.0 \times 10^{-3}$ with 1 fb^{-1}	[554]	$< 8.6 \times 10^{-5}$ - 1.9×10^{-4} with 10 fb^{-1}
FCNC $B(t \to WbZ)$	–		$< 10^{-7}$ with 100 fb^{-1}
$\Delta\sigma^{M_{Z'}=1\text{ TeV/c}^2}$ $B(Z' \to t\bar{t})$	100 fb with 1 fb^{-1}	[554]	700 fb with 30 fb^{-1}
anom. coupling	$F_{2L}{}^{>+0.55}_{<-0.18}$	[553]	$F_{2L}{}^{>+0.097}_{<-0.052}$
	$F_{2R}{}^{>+0.25}_{<-0.24}$	[553]	$F_{2R}{}^{>+0.13}_{<-0.12}$
$\Delta F^Z_{1V,A}$	–	[542]	15%–85% (300 fb^{-1})
$\Delta F^\gamma_{1V,A}$	$^{<+1.03\ldots+2.60}_{>-1.17\ldots-1.88}$ (8 fb^{-1})	[542]	15%–50% (30 fb^{-1}), 4%–7% (300 fb^{-1})
ΔF^γ	–	[542]	35% (30 fb^{-1}), 20% (300 fb^{-1})

A. Quadt Eur. Phys. J. C48, 835 (2006)

Cross section in lepton+jets/dilepton channel





$$M_t = 166.1\ ^{+6.1}_{-5.3}\ (\text{stat+syst})\ ^{+4.9}_{-6.7}\ (\text{theory})\ \text{GeV}$$

$$M_t = 174.1\ ^{+9.8}_{-8.4}\ (\text{stat+syst})\ ^{+4.2}_{-6.0}\ (\text{theory})\ \text{GeV}$$

kinematical analyses:

$$m_{\text{top}} = 170.5\ \pm 2.4\ (\text{stat+JES})\ \pm 1.2\ (\text{syst})\ \text{GeV}$$

$$m_{\text{top}} = 173.7\ \pm 5.4\ (\text{stat})\ \pm 3.4\ (\text{syst})\ \text{GeV}$$