Top Quark Physics at the Tevatron

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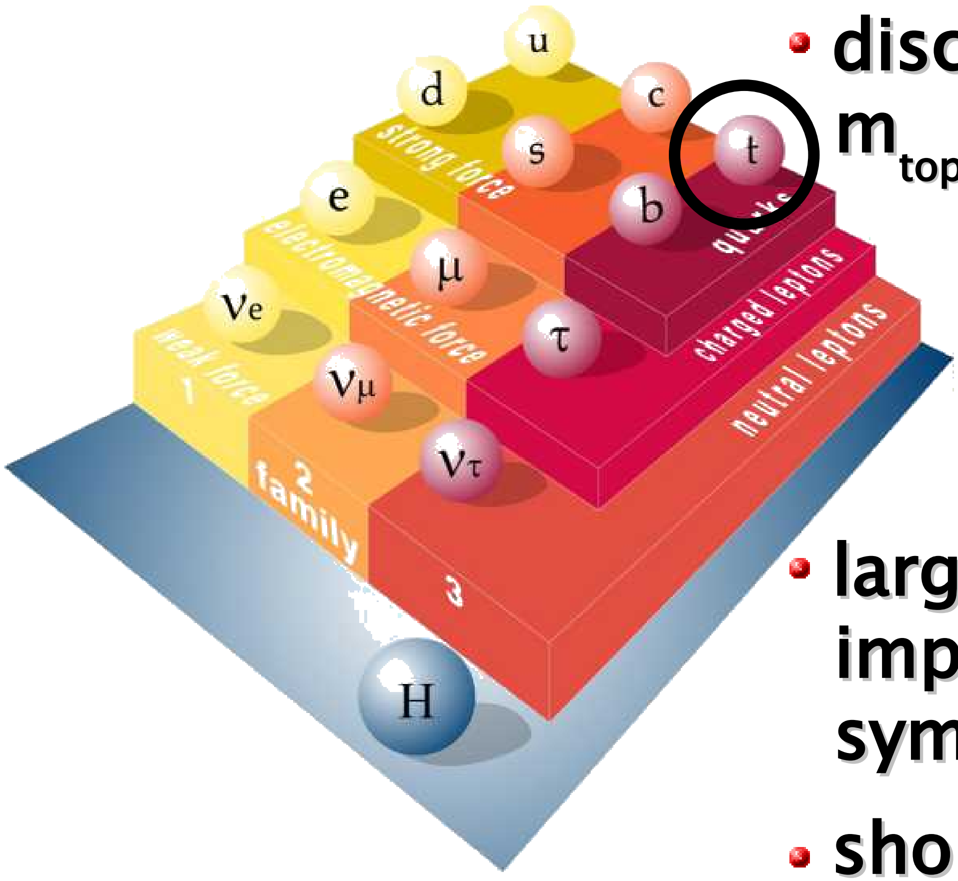
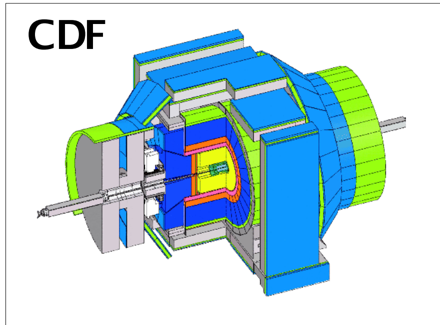
YETI 2008
Durham
07/01/2008

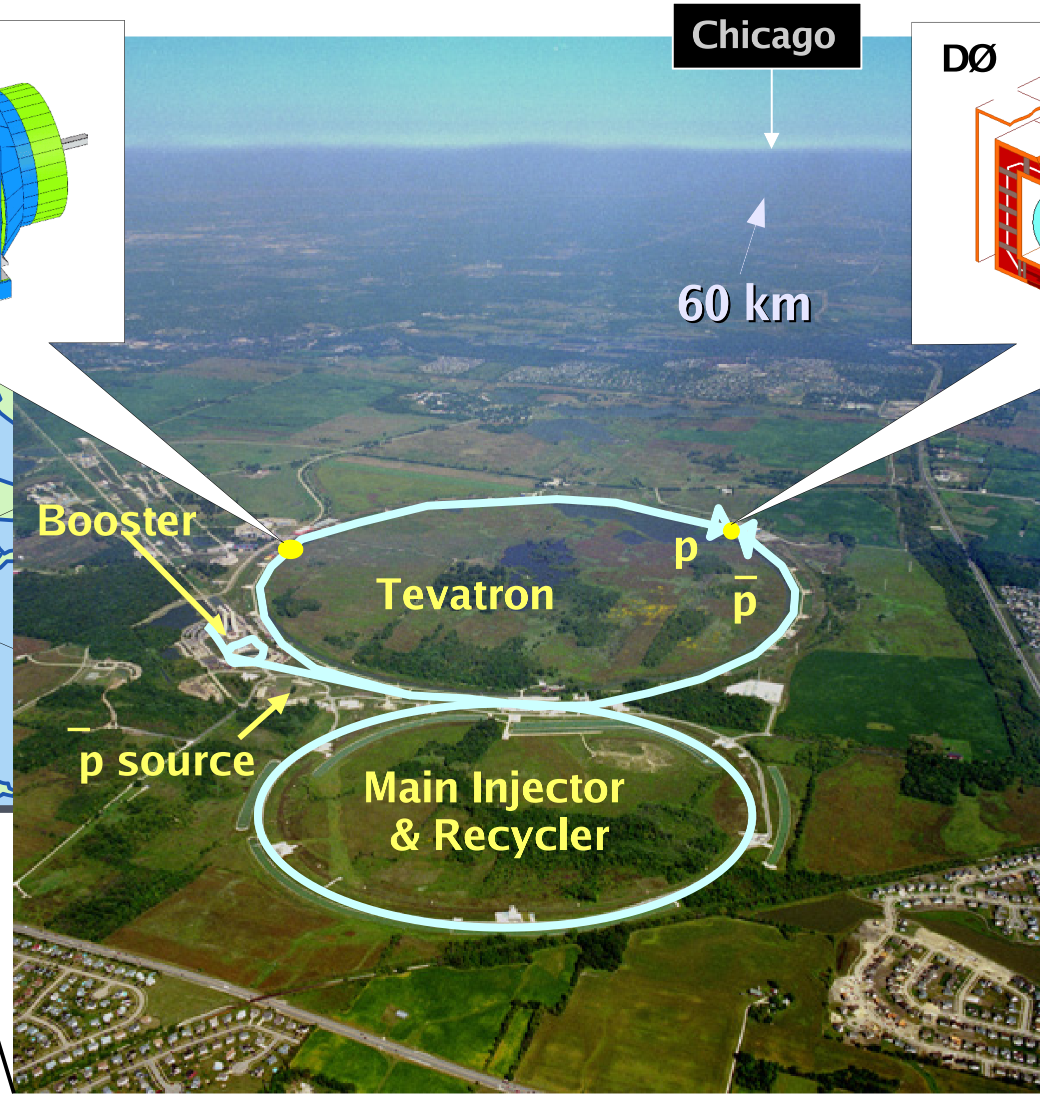
The Top Quark

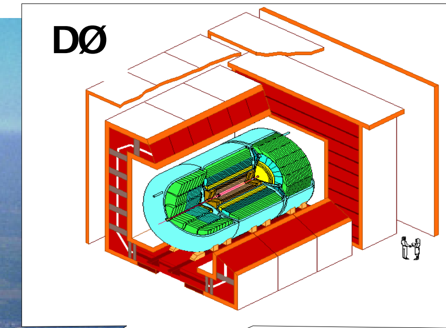


- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}$s $\ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe "naked"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

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







$\sqrt{s}$ =1.96 TeV
Δt = 396 ns

Run I 1987 (92)-95 ← **top quark discovery**
Run II 2001-09: 40x larger dataset at increased energy ← **measure properties with high precisions: is it really the particle expected in the SM?**

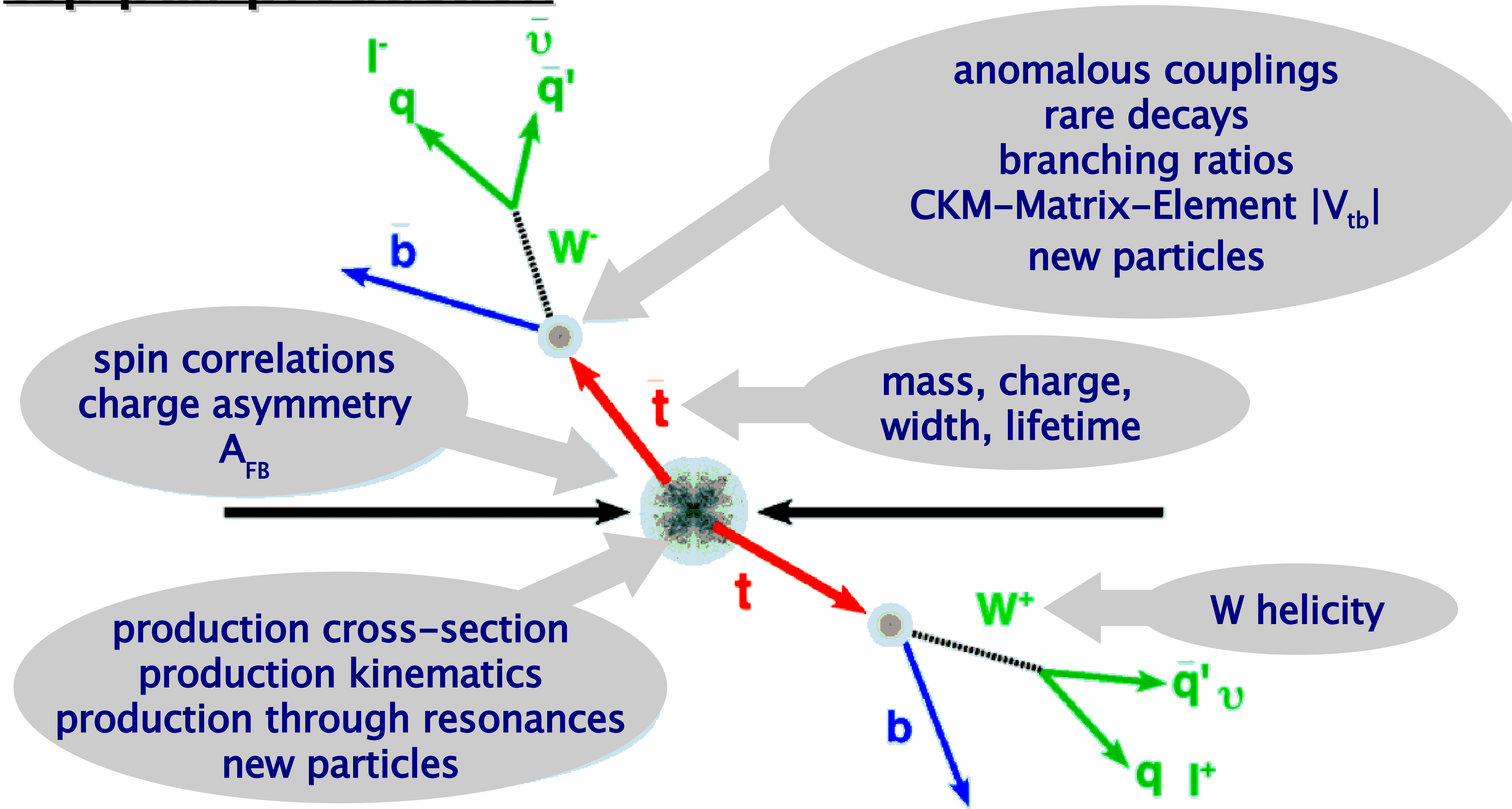
Top Quark Analyses at the Tevatron

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

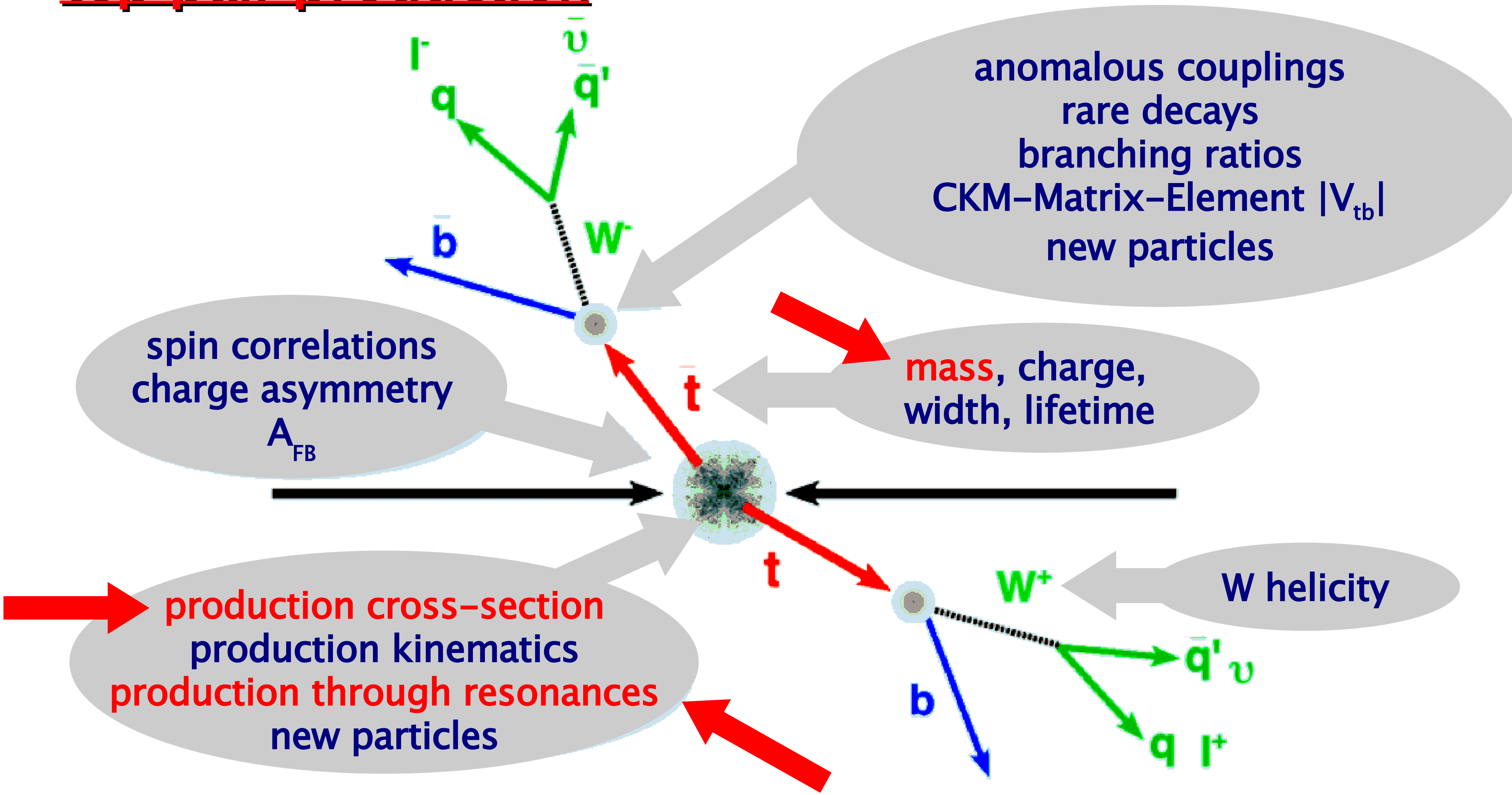
Top Quark Analyses at the Tevatron

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

- **top pair production**

Run II: with high precision answer...

- **is it really the particle expected in the SM?**



- **single top production**

Outline

Top Pair Production Cross Section

Searches in Top Pair Production

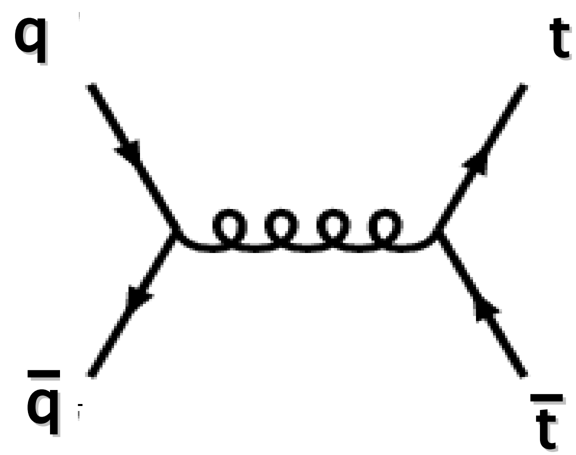
– New Resonances

Top Mass

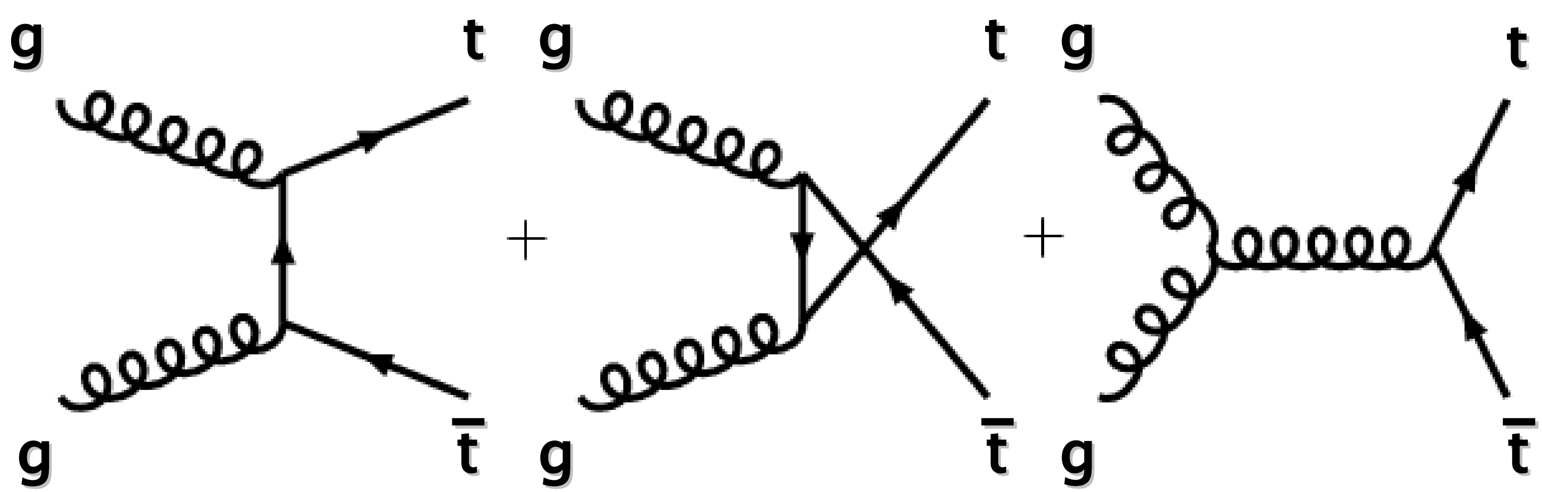
Single Top Production

Outlook: Top Physics at LHC

Top Quark Pair Production



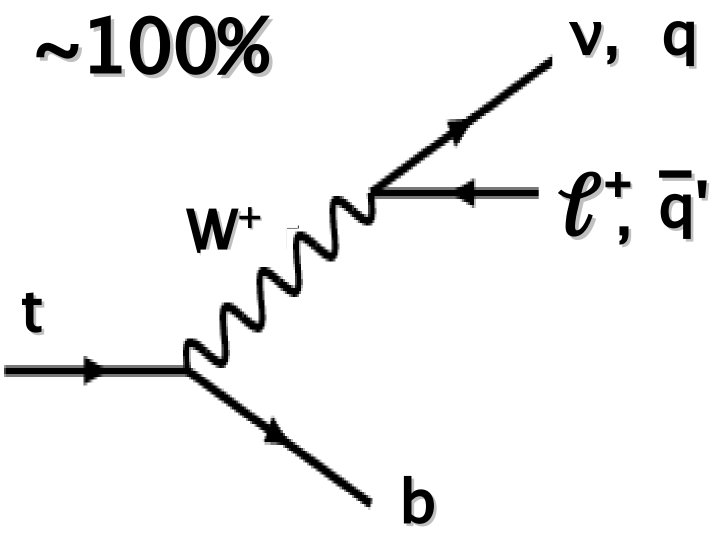
85%



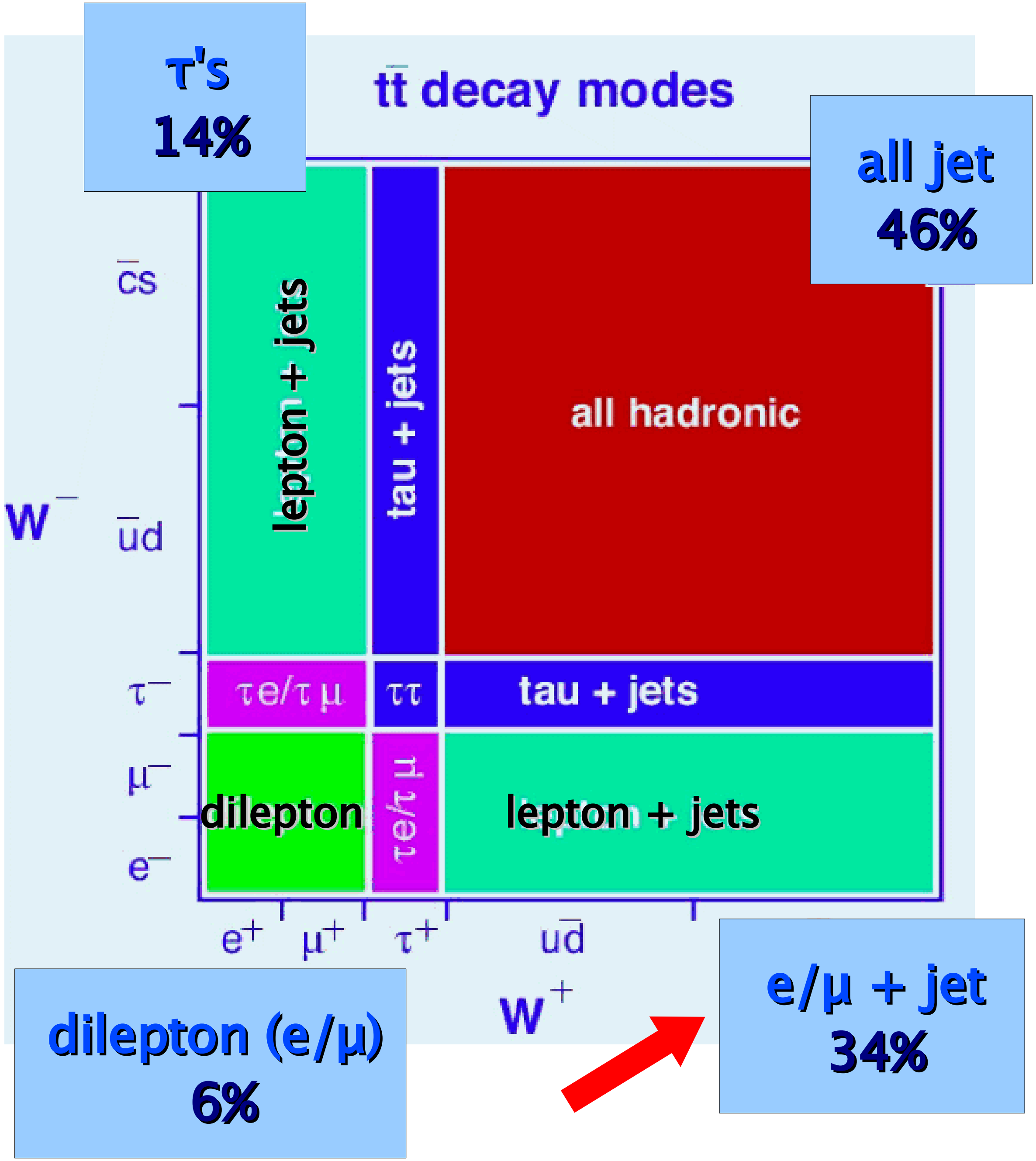
15%

Top Antitop Signatures

- top decay:



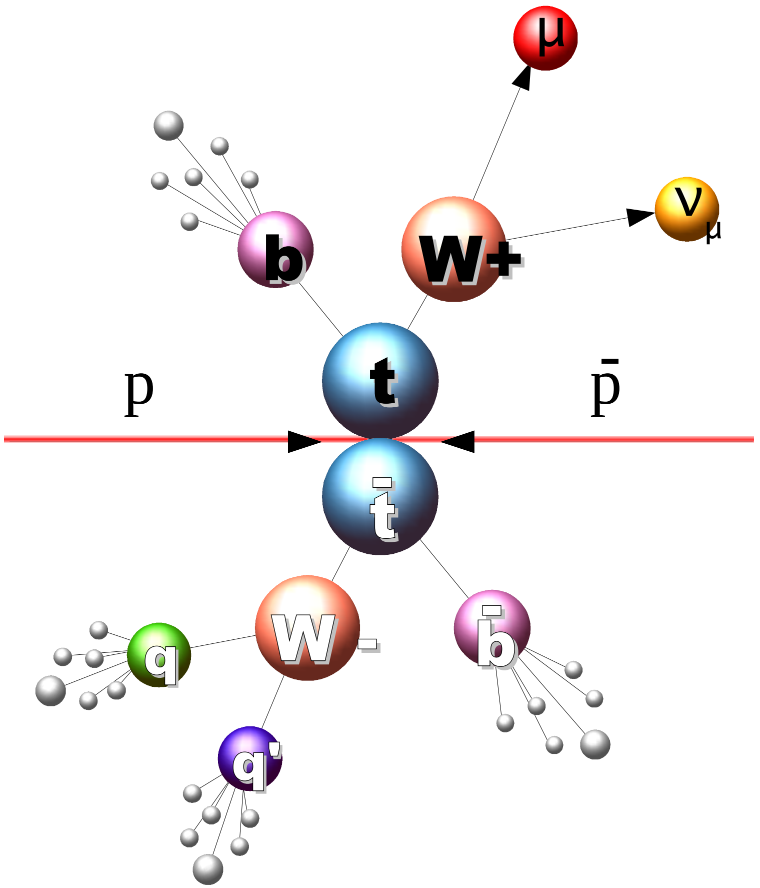
- reconstruct and identify: electrons, muons, jets, b-jets and missing transverse energy



Event Topology in Lepton+Jets

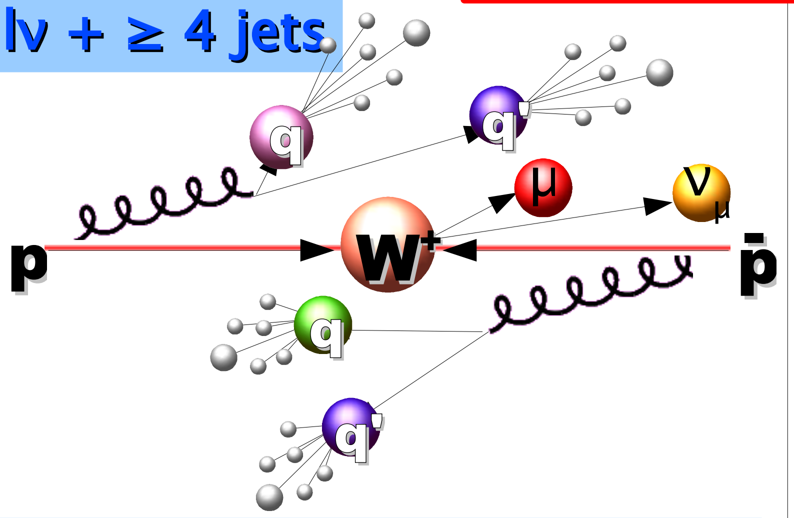
signal

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

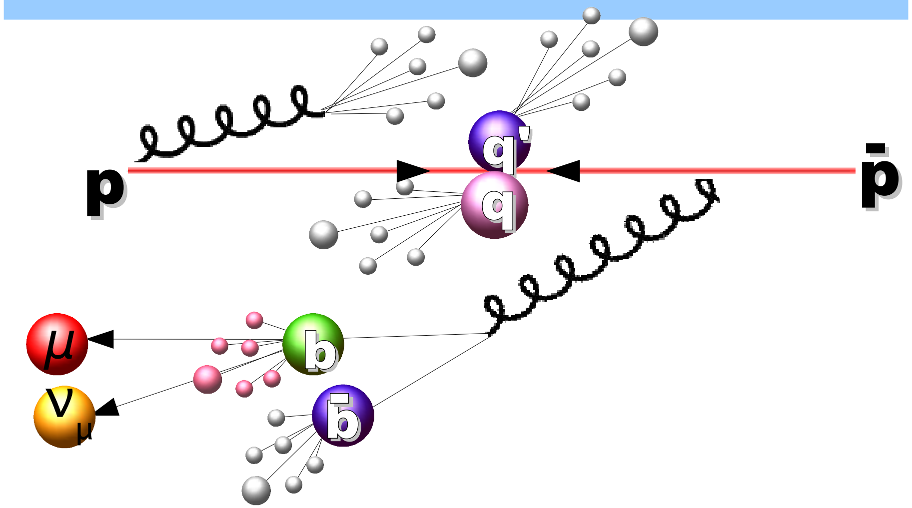


background

W → lν + ≥ 4 jets



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



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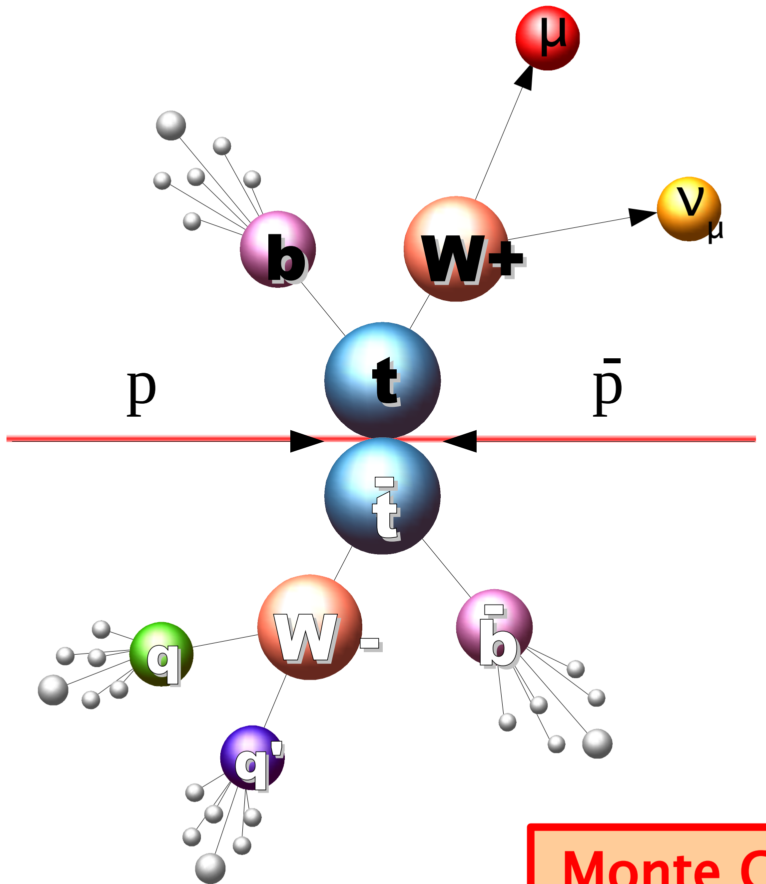
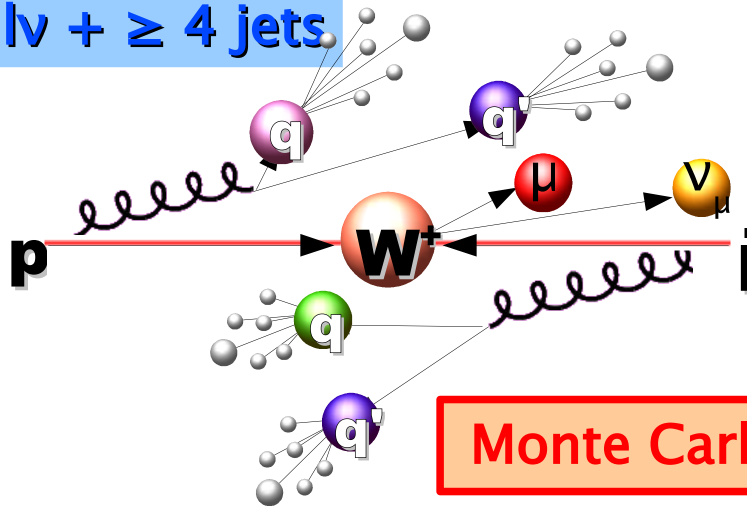


Monte Carlo

background

W → lν + ≥ 4 jets



Monte Carlo

multijet background (QCD)
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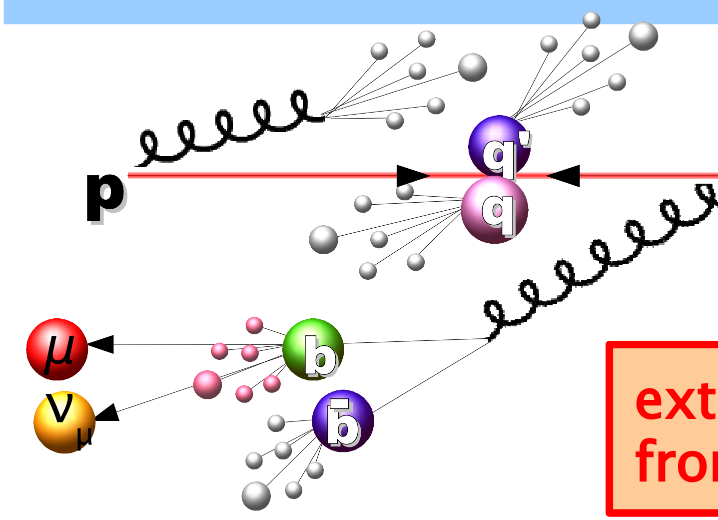
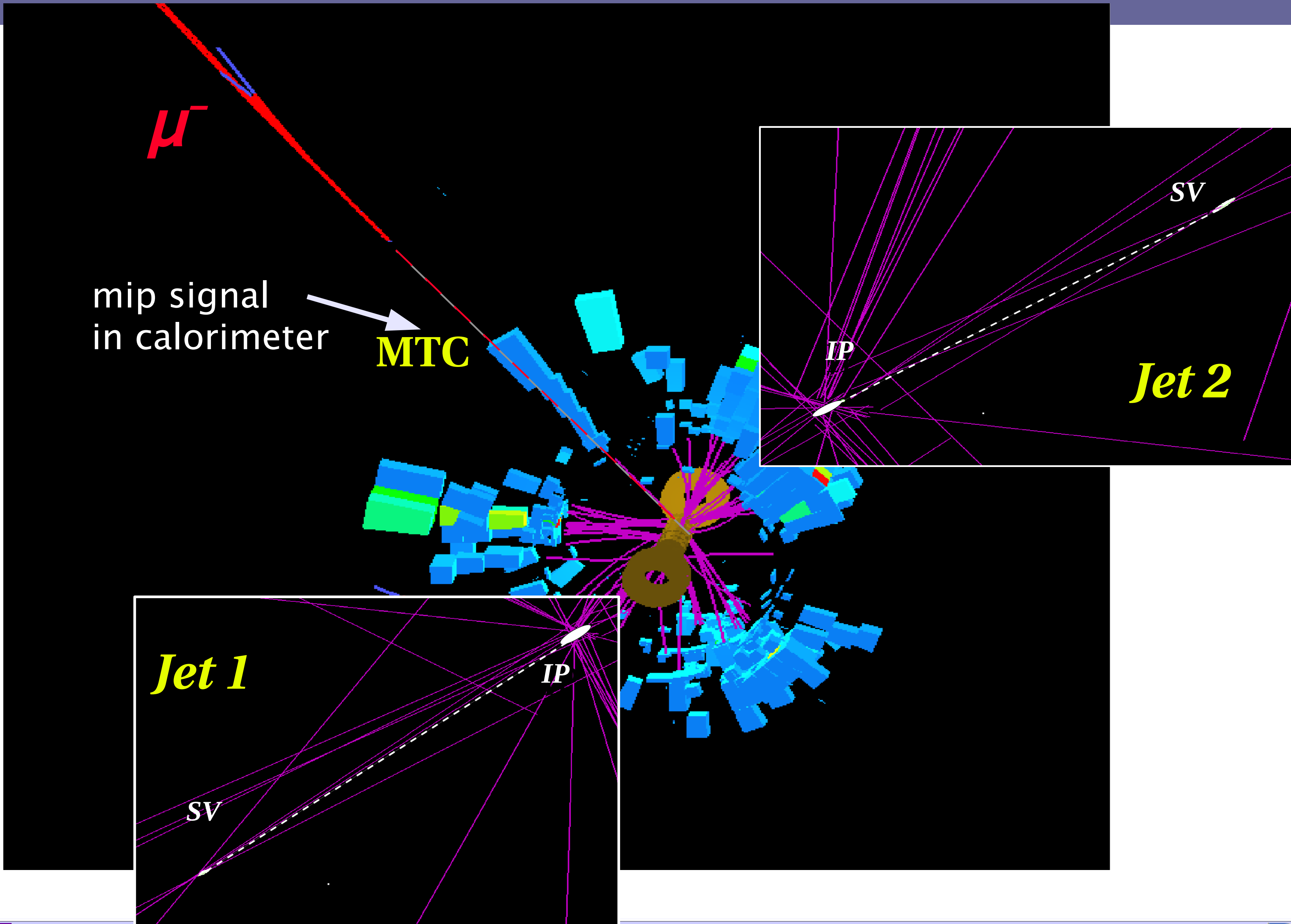


extract from data

Typical μ+jets Event



Lepton+Jets Topological Cross Section

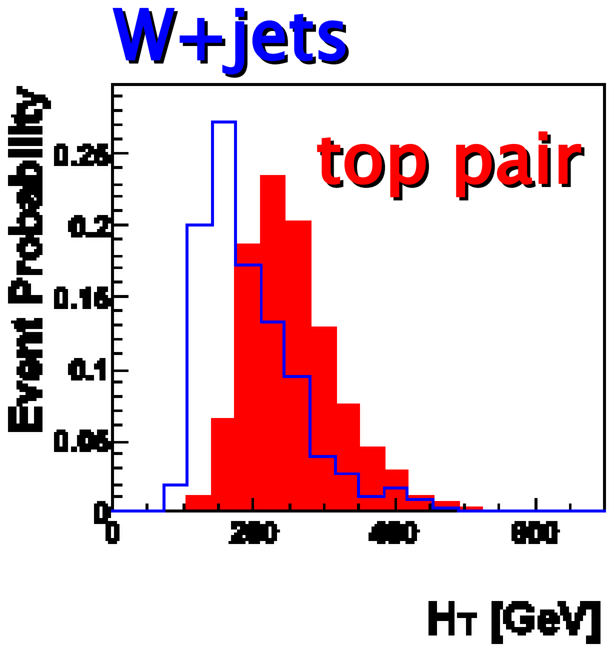
<u>no b-tag → less model dependent</u>

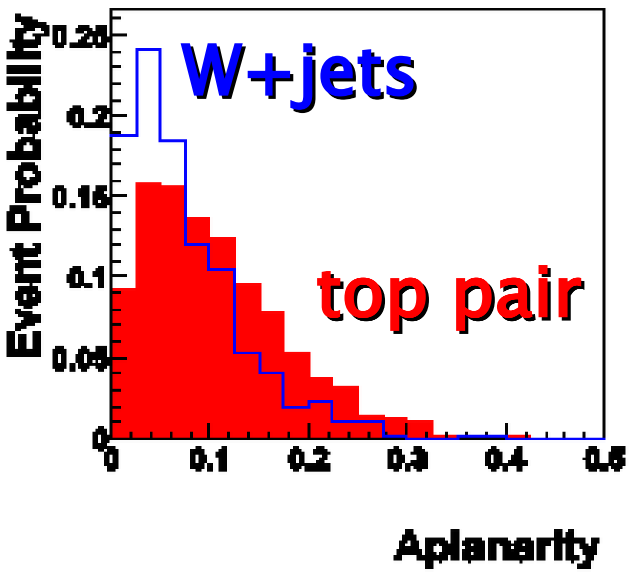
- kinematic properties allow separation between signal and background

use as variables:

energy-dependent quantities:
- e.g. H_T (scalar sum of p_T of 4 leading jets)

angular dependent:
- e.g. aplanarity



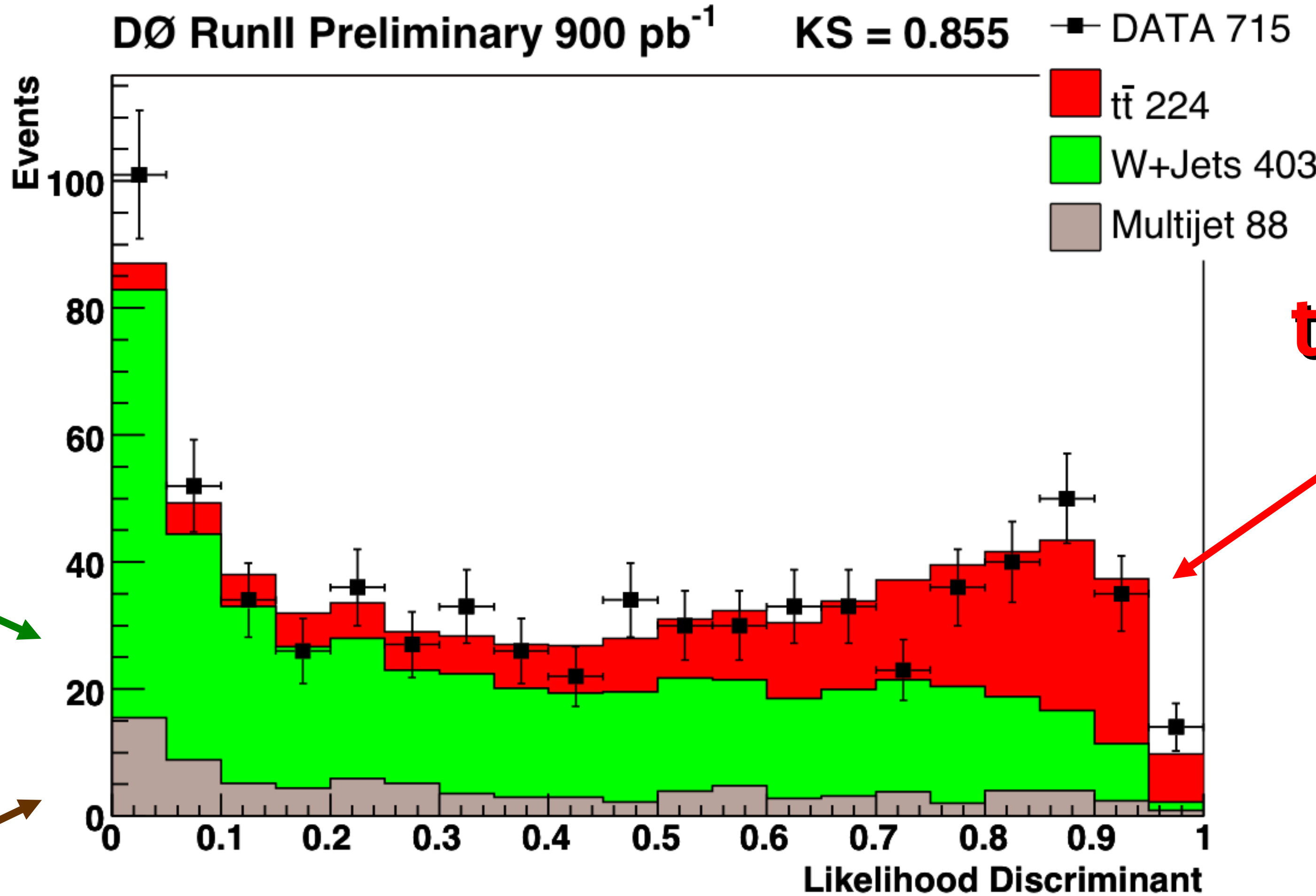


→ **Discriminant function:**

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

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

Lepton+Jets Topological Cross Section



W+jets

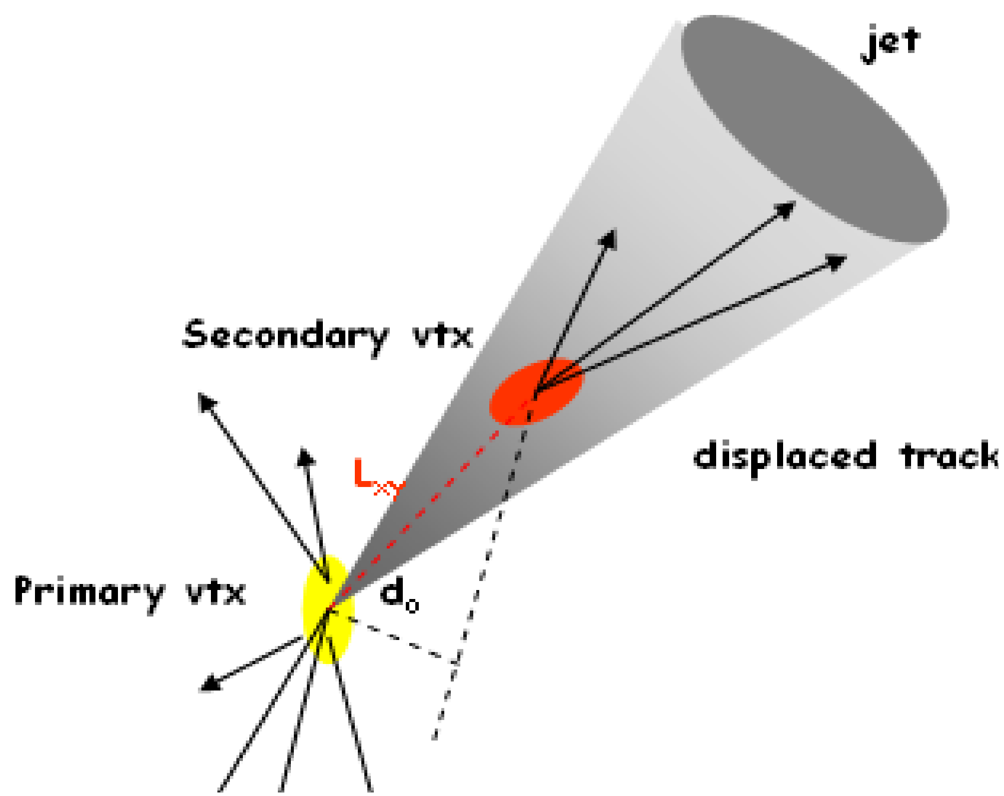
multijets

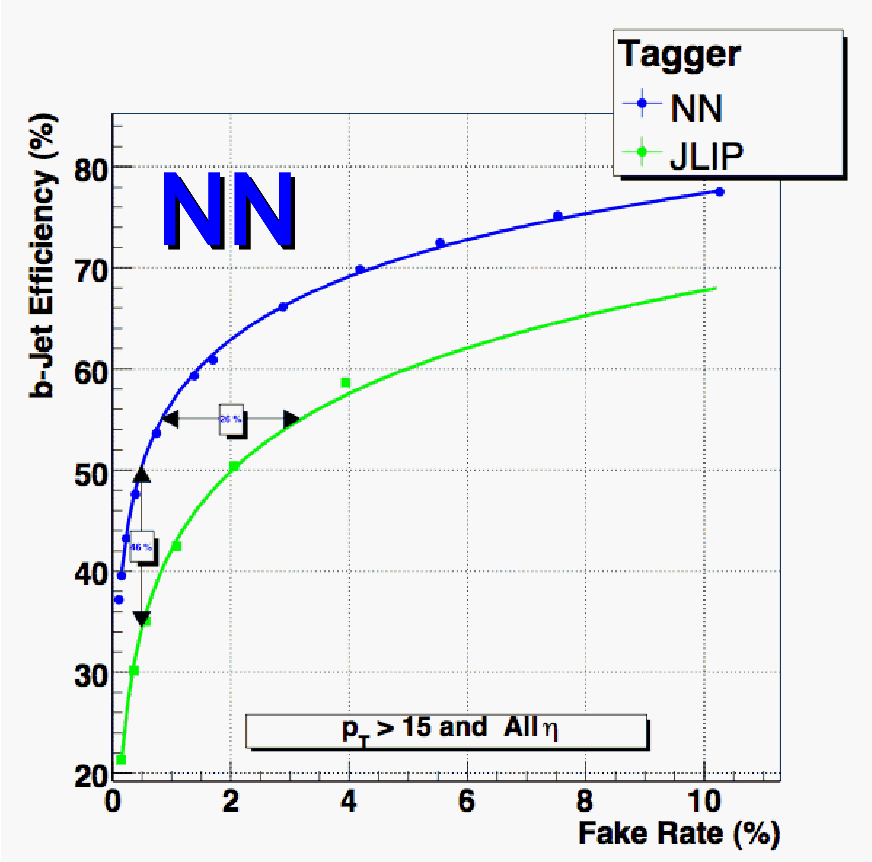
top pair

$$\sigma_{tt} = 6.3^{+0.9}_{-0.8}\ \text{(stat)} \pm 0.7\ \text{(syst)} \pm 0.4\ \text{(lumi) pb}$$

b–tagging

- B hadrons lifetime τ ~ 1 ps
- B hadrons travel L_{xy} ~ 1 mm before decay

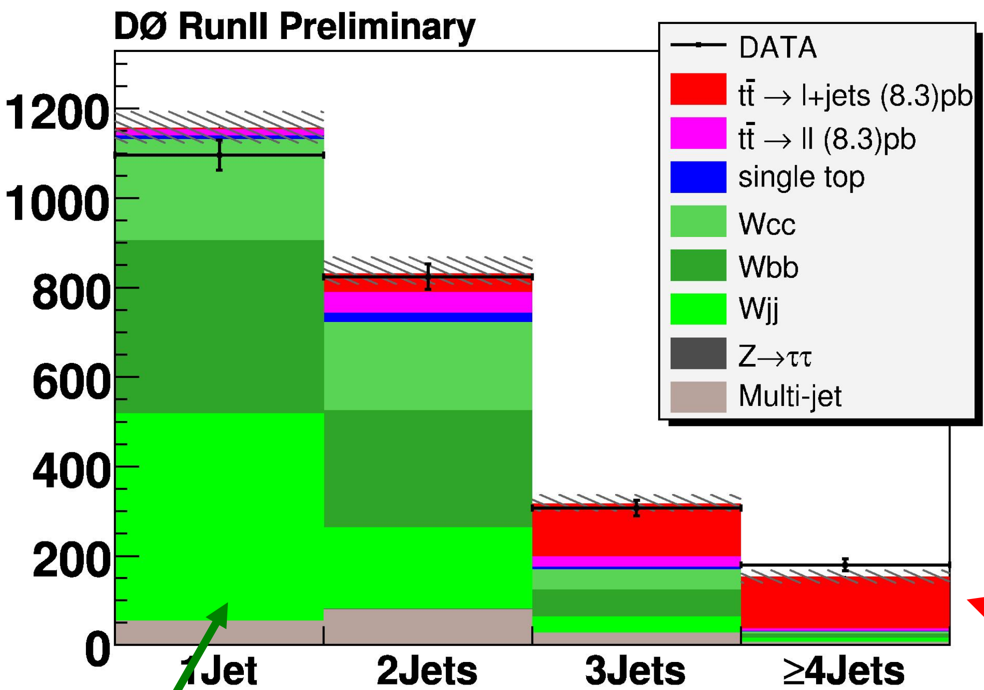




- explicitly reconstruct 3D vertices
- use properties from displaced tracks to form a 7-variable neural network
- improvements of up to 50%
- ttbar event tagging efficiency 54% (with fake rate of 1%)

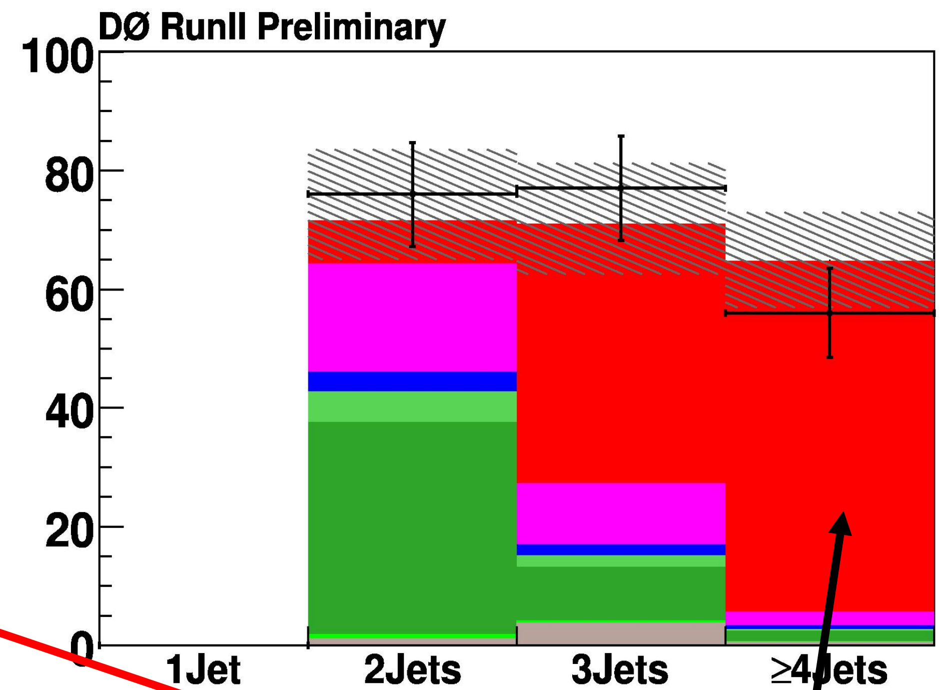
Lepton+jets cross section with b-tagging

1 b tag:



≥2 b tags:

L=900 pb^{-1}

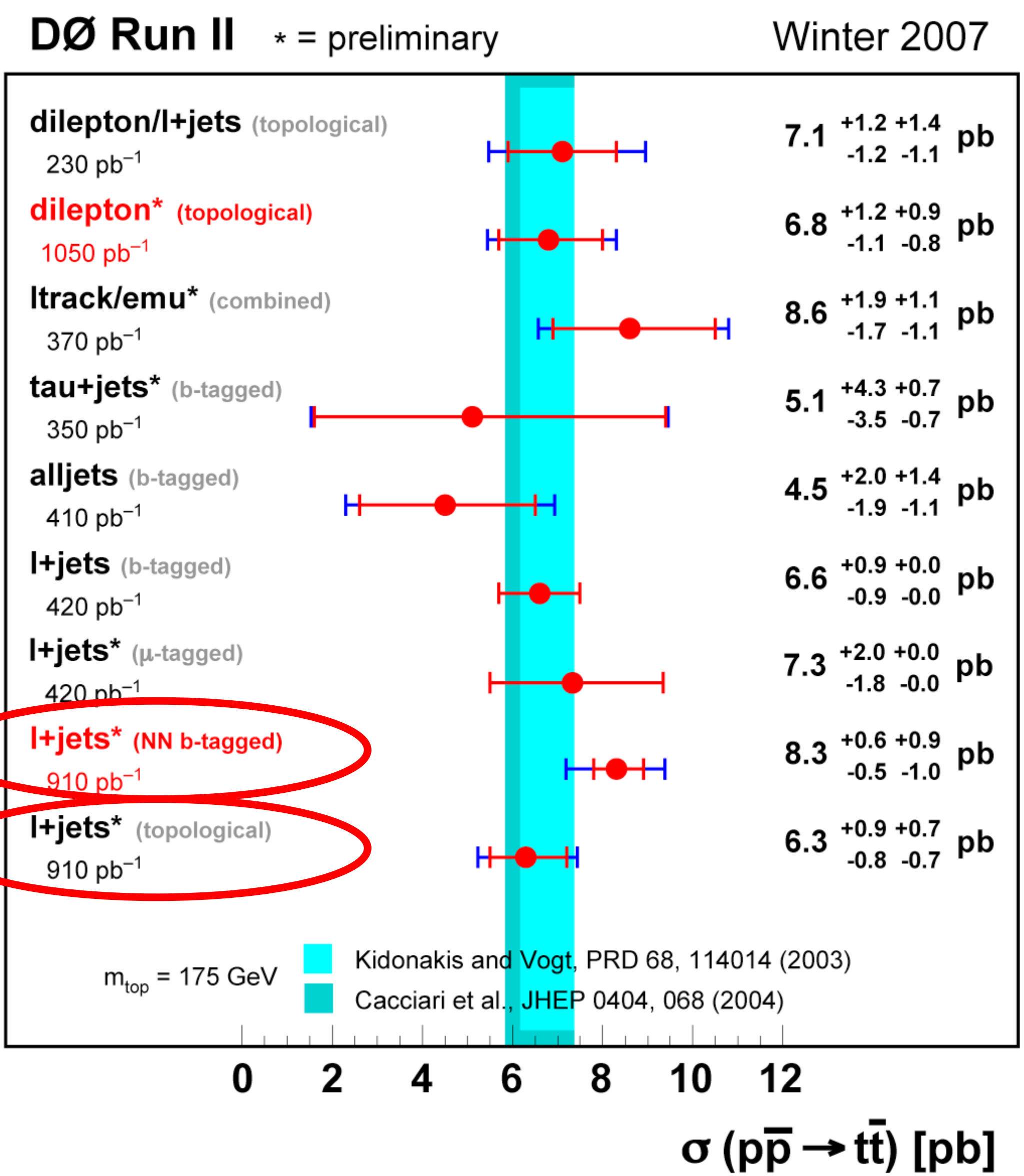


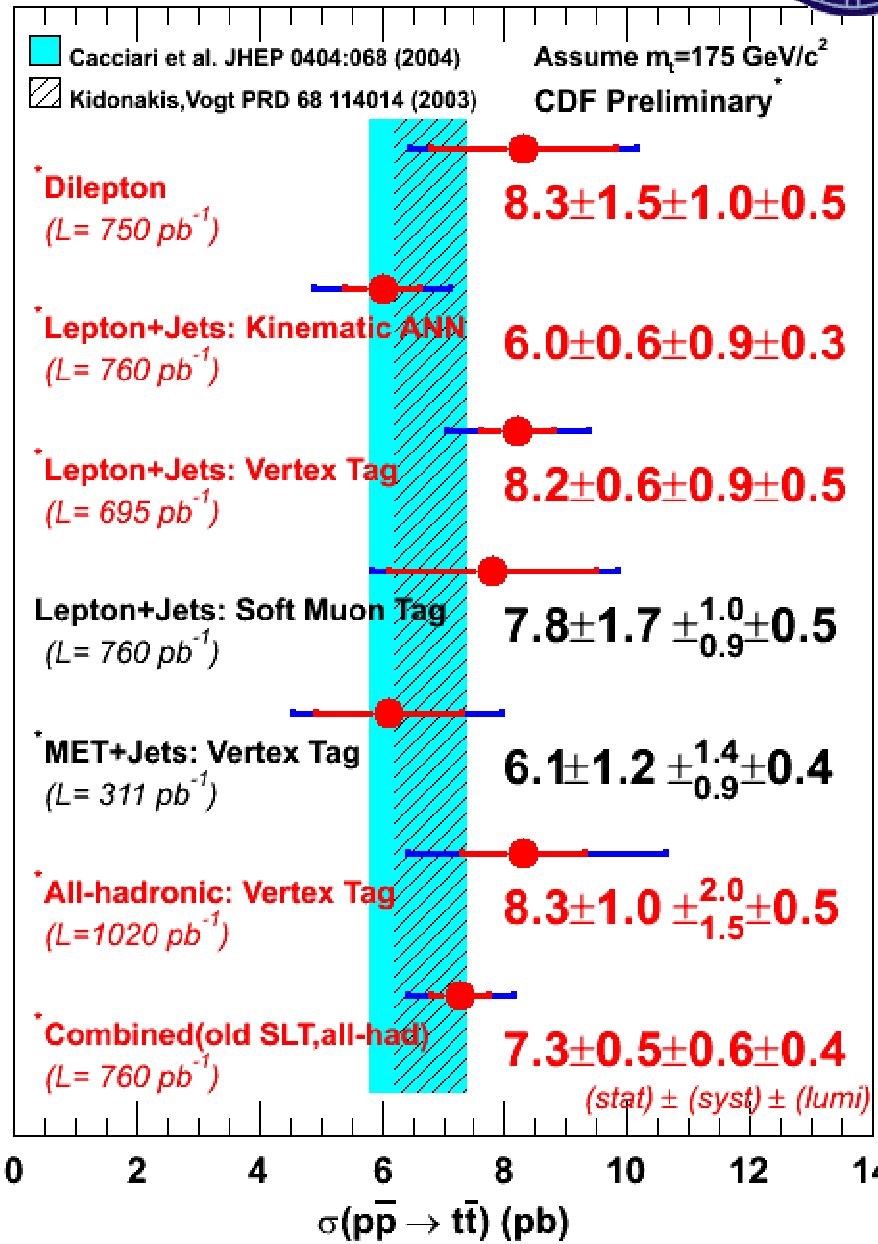
W+jets

top pair

$$\sigma_{tt} = 8.3 \,^{+0.6}_{-0.5}\,(\text{stat})\,^{+0.9}_{-1.0}\,(\text{syst}) \pm 0.5\,(\text{lumi})\text{ pb}$$

Top Pair Production Cross–Sections





Outline

Top Pair Production Cross Section

Searches in Top Pair Production
– New Resonances

Top Mass

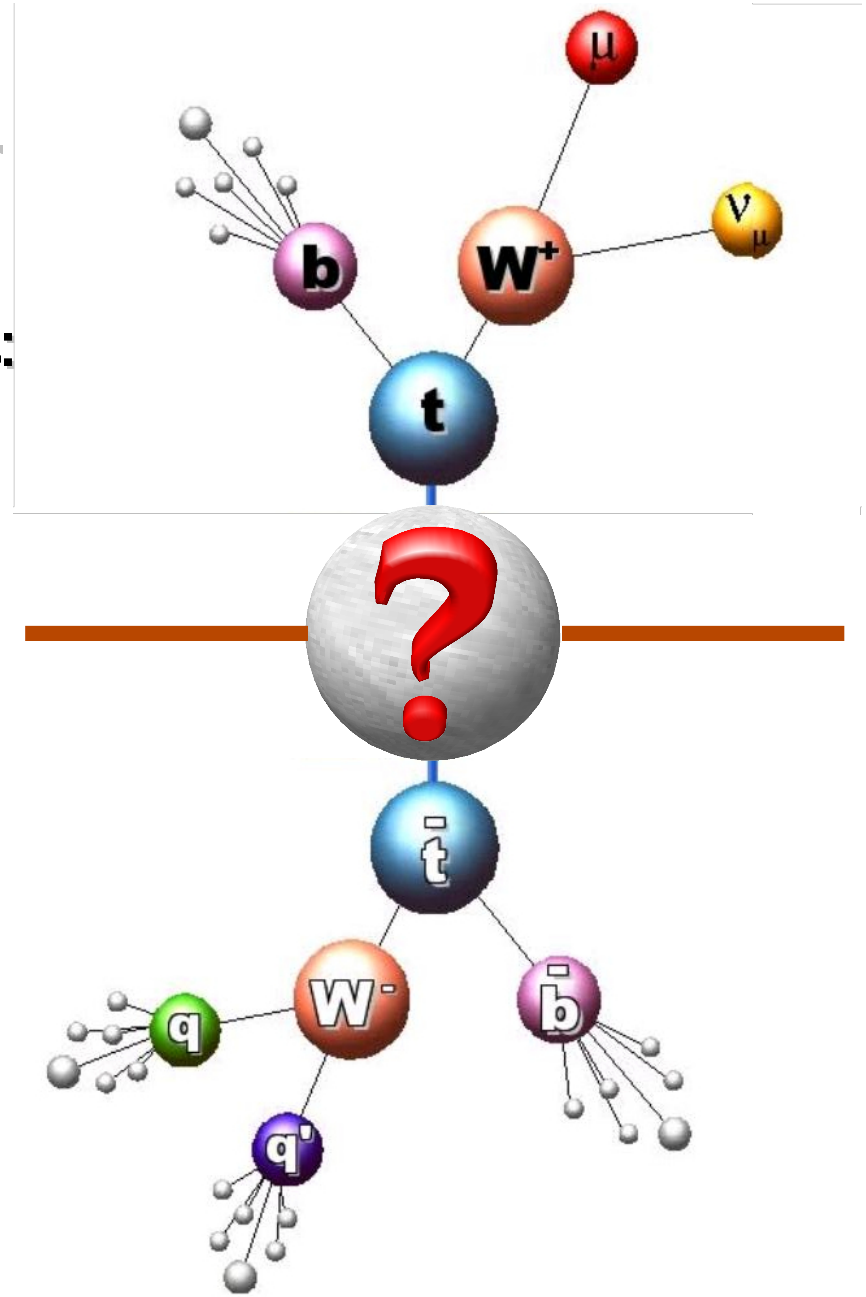
Single Top Production

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



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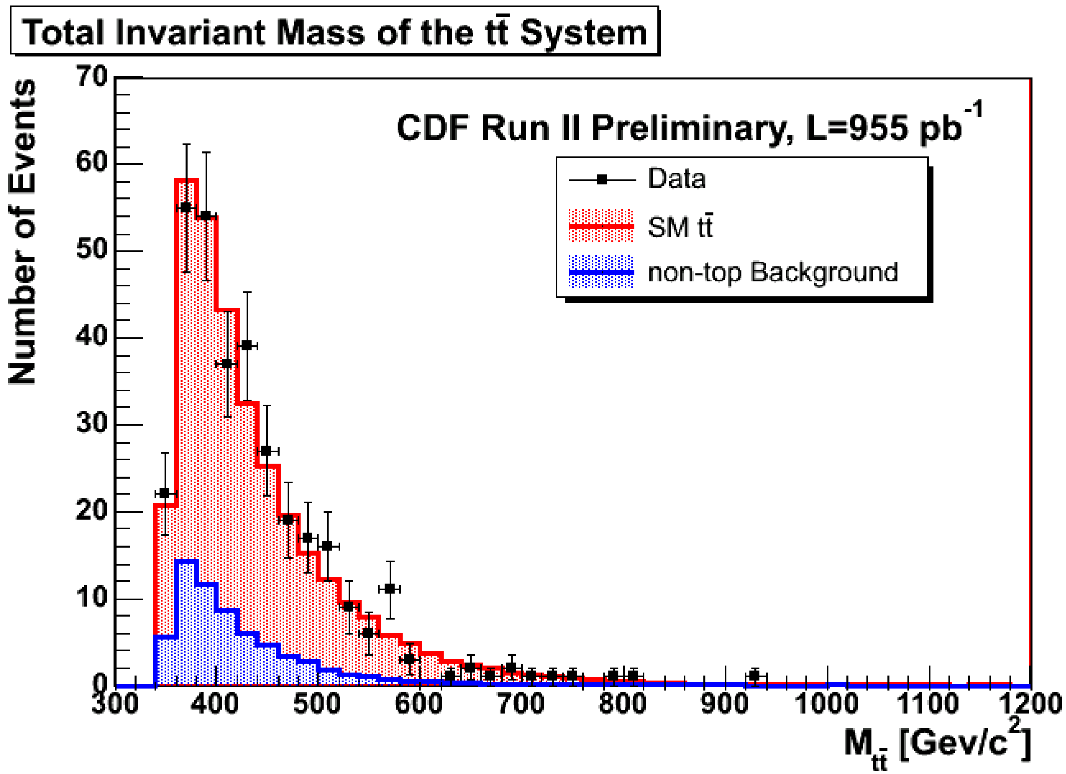

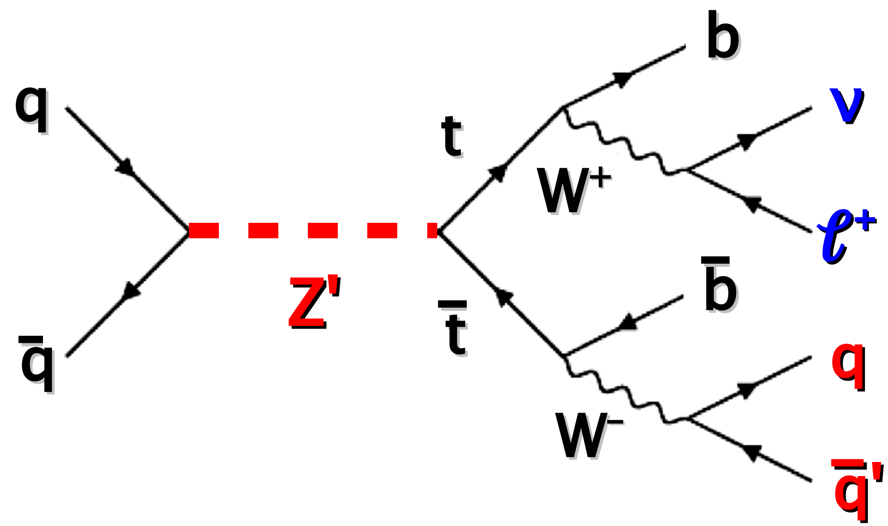

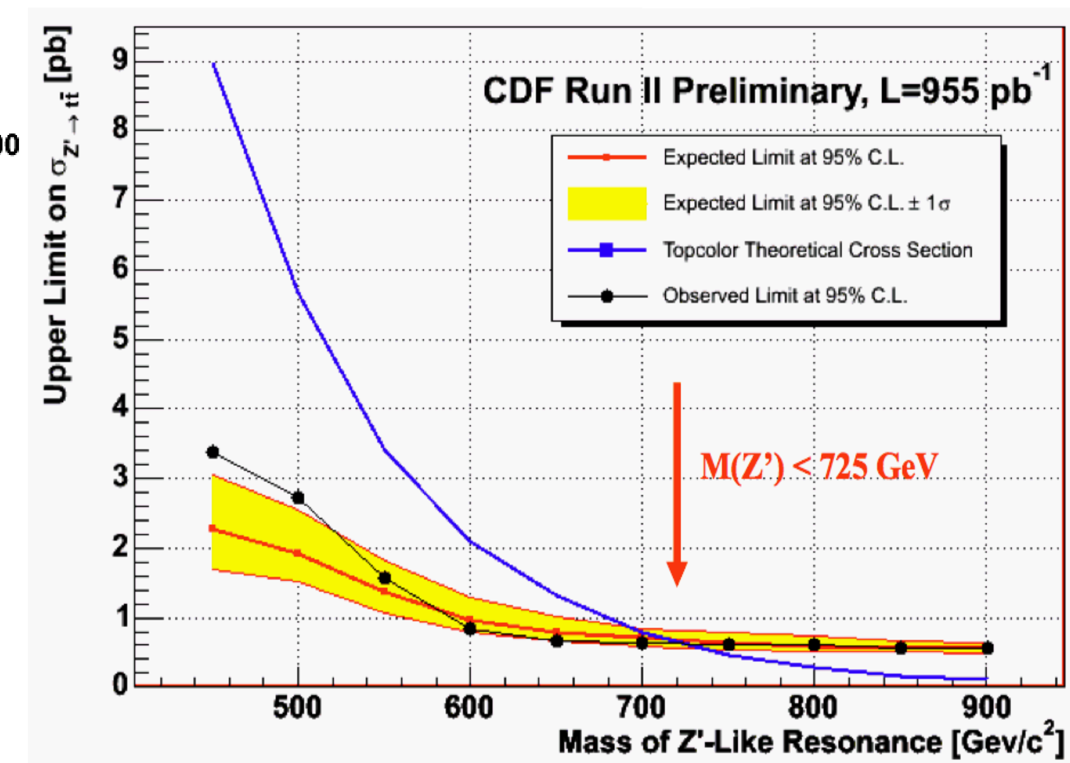

⇒ $M_{Z'} > 725$ GeV

Outline

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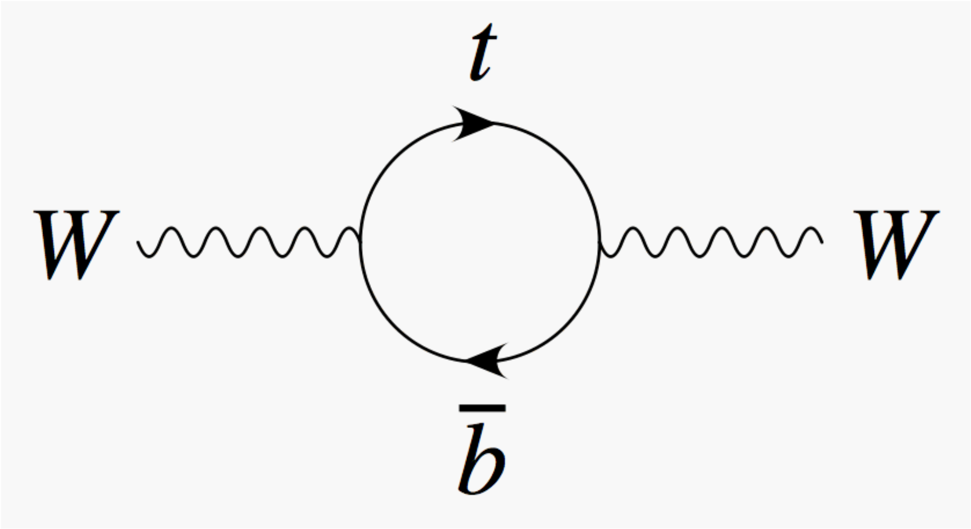
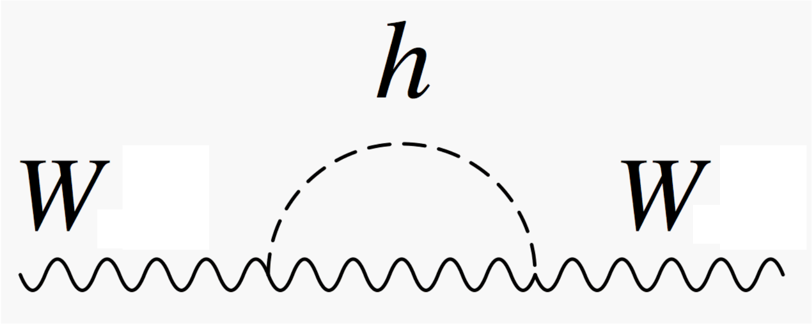
The Top Quark Mass

- free parameter in the Standard Model

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

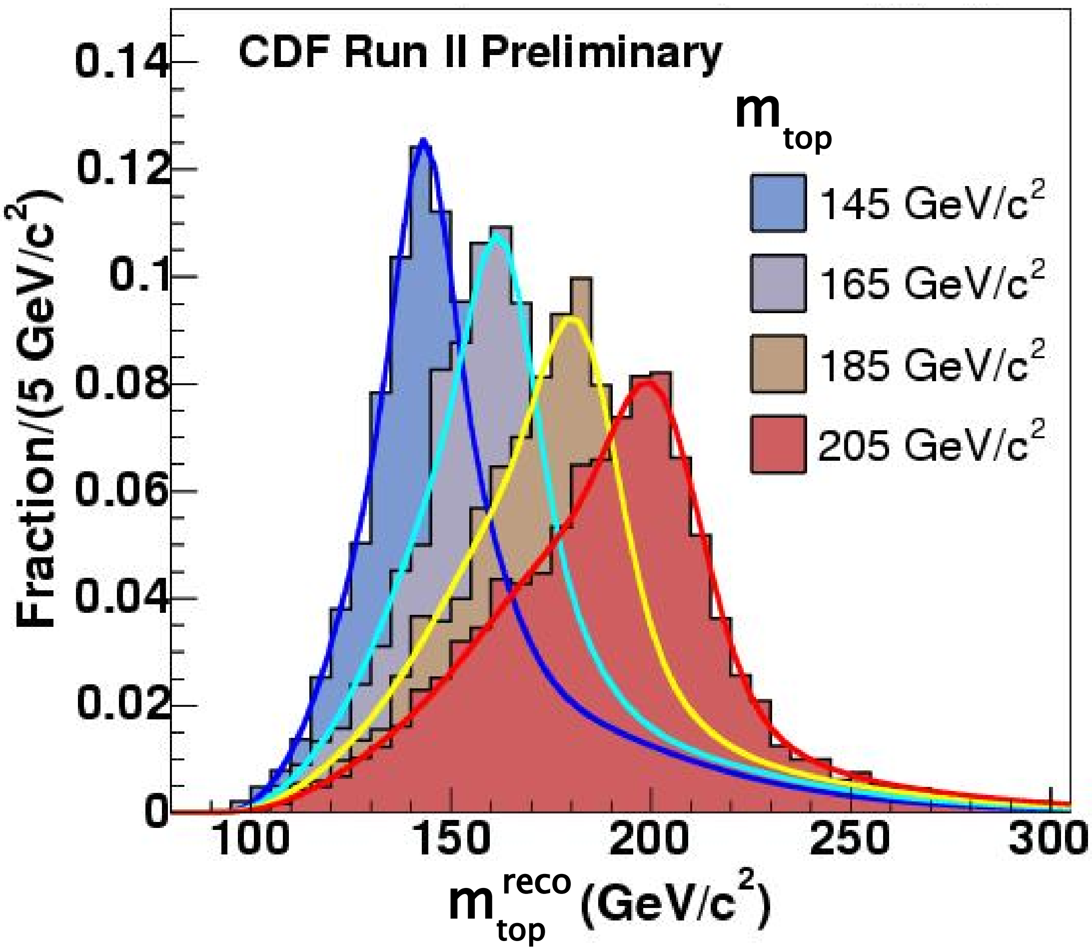




Extraction Techniques: Template Method

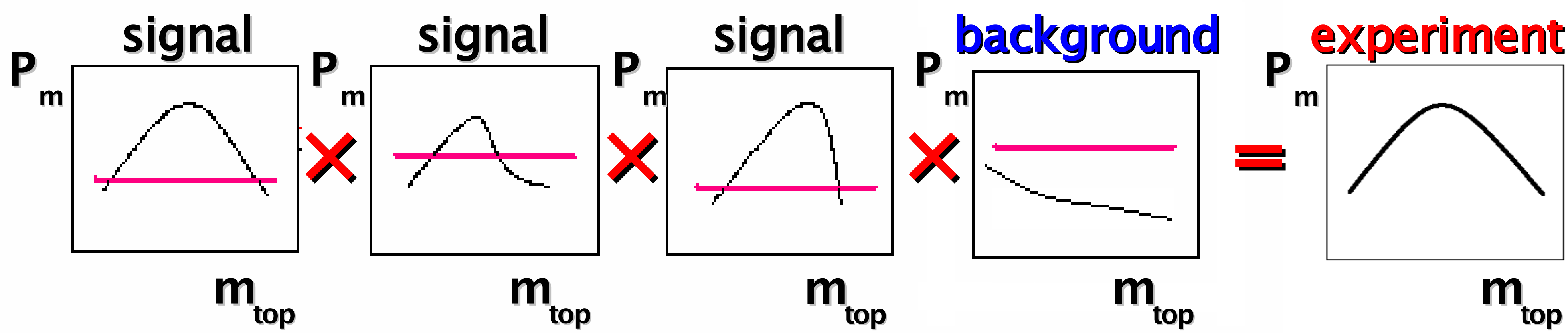
- use variables strongly correlated with m_{top}
- compare data to MC with different m_{top} hypotheses

l+jets



Extraction Techiques: Matrix Element

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



- Maximum Likelihood fit

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

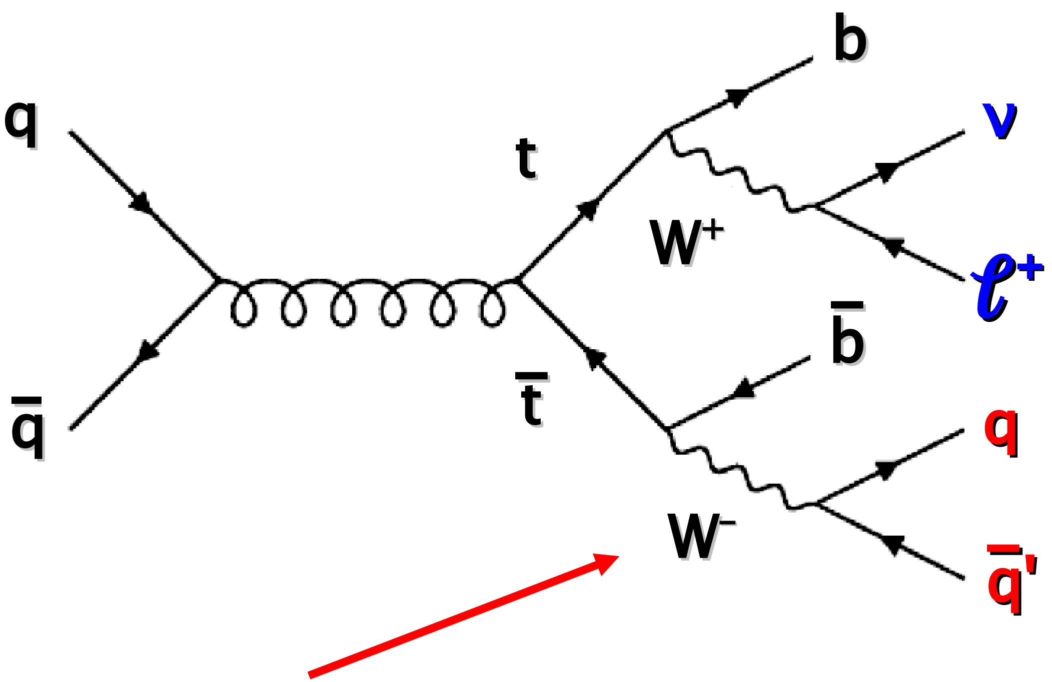
Acceptance (selection, trigger,...)

LO-Matrix element x phase space

PDF's

Transfer Functions (Probability to measure x when y was produced)

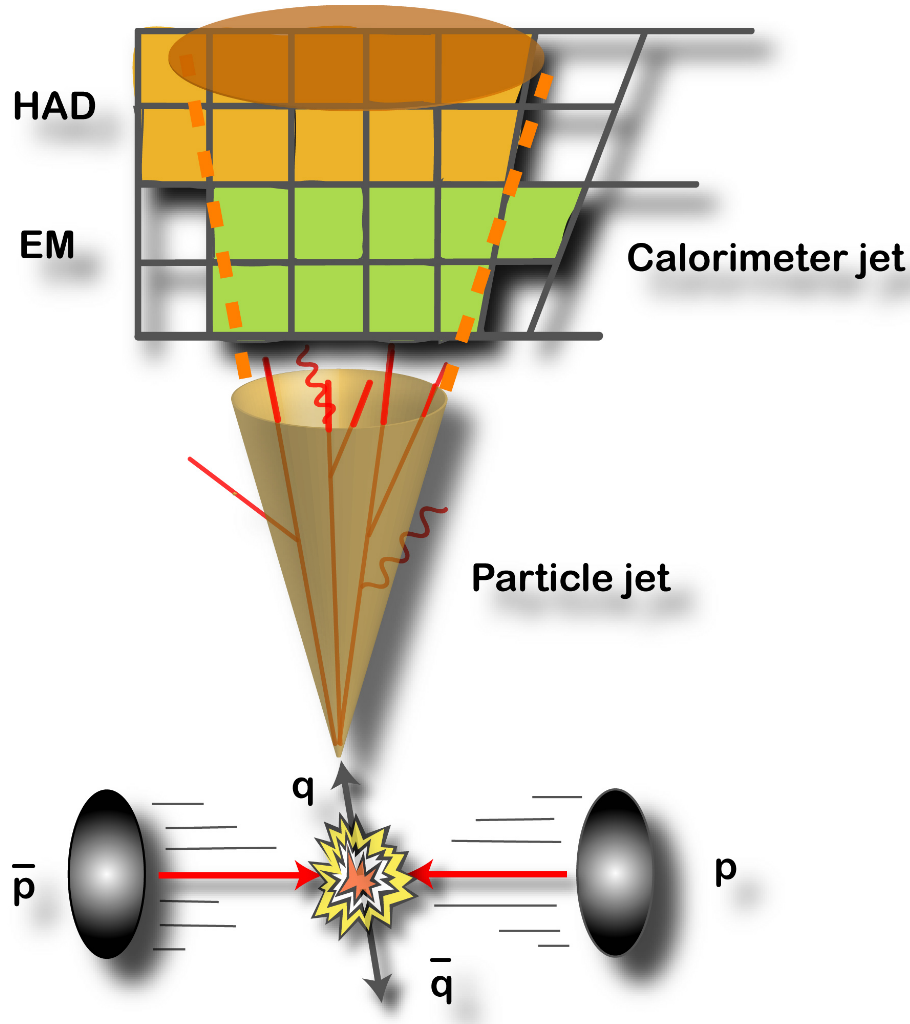
Lepton+Jets Channel



W mass constrains jet energy scale

jet energy scale:

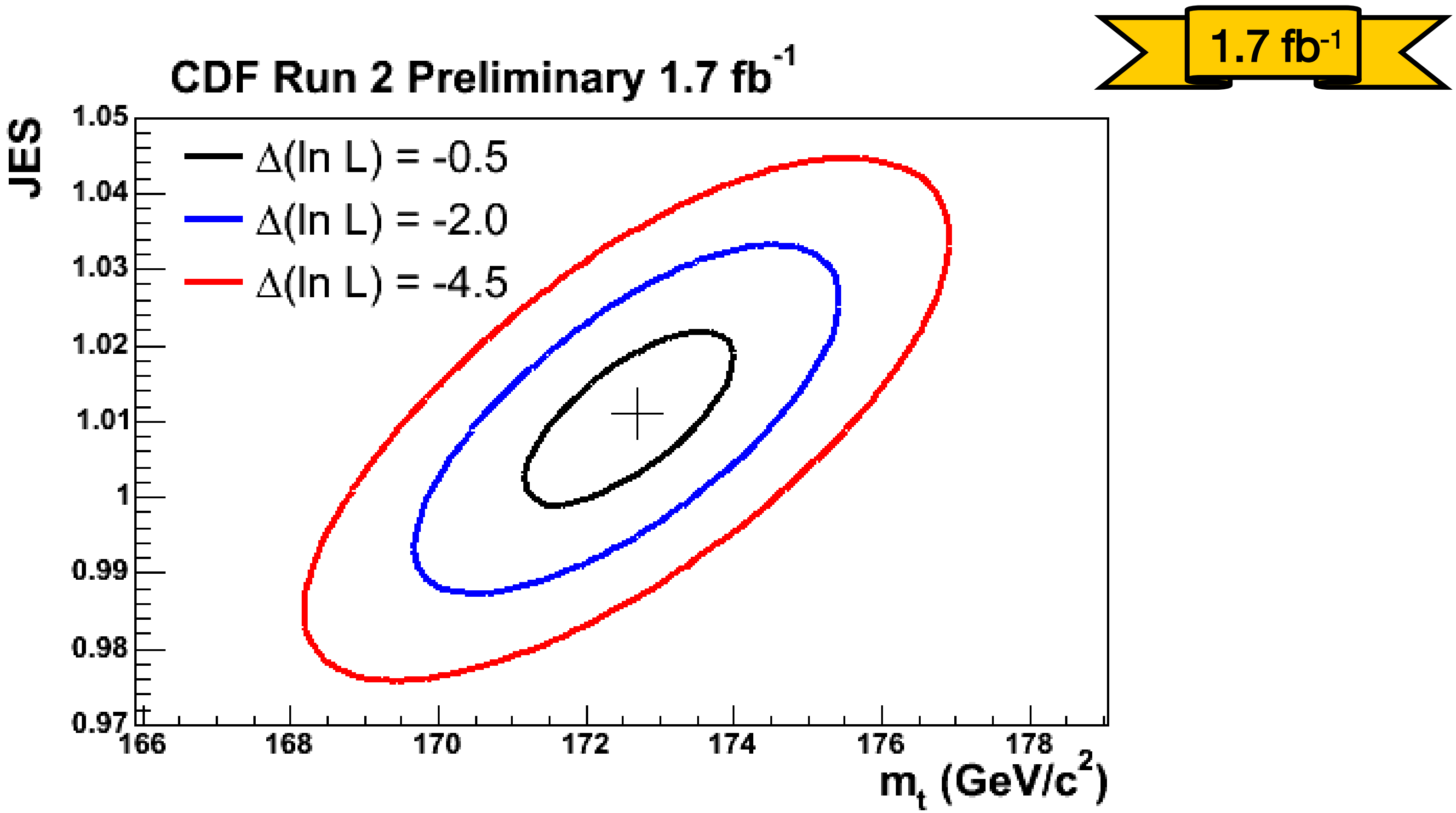
translate jet into parton energy



Results for Matrix Element Method

- maximum Likelihood fit using signal and background pdfs

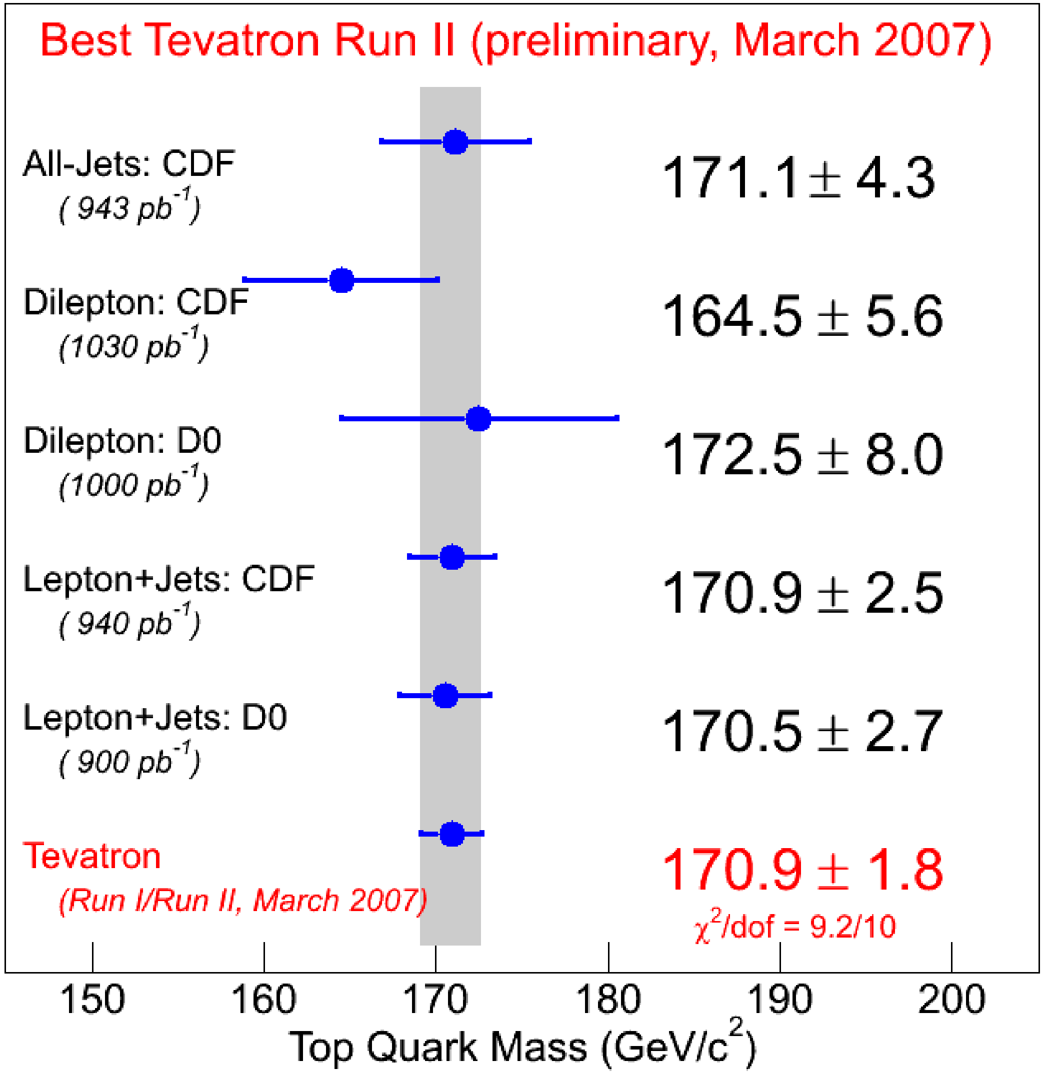
jet energy scale



- at least one jet has b-tag

$$m_{top} = 172.7 \pm 1.3\ (\text{stat}) \pm 1.2\ (\text{JES}) \pm 1.2\ (\text{syst})\ \text{GeV}$$

Tevatron Combination: March 2007



1 fb^{-1}

- **account for correlations**

$$m_{top} = 170.9 \pm 1.8 \text{ GeV}$$

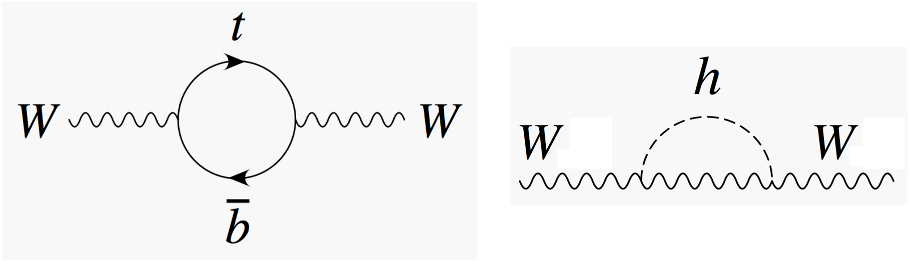
Summary: Top Mass Measurements

$m_{top} = 170.9 \pm 1.8$ GeV

world average (March 2007)

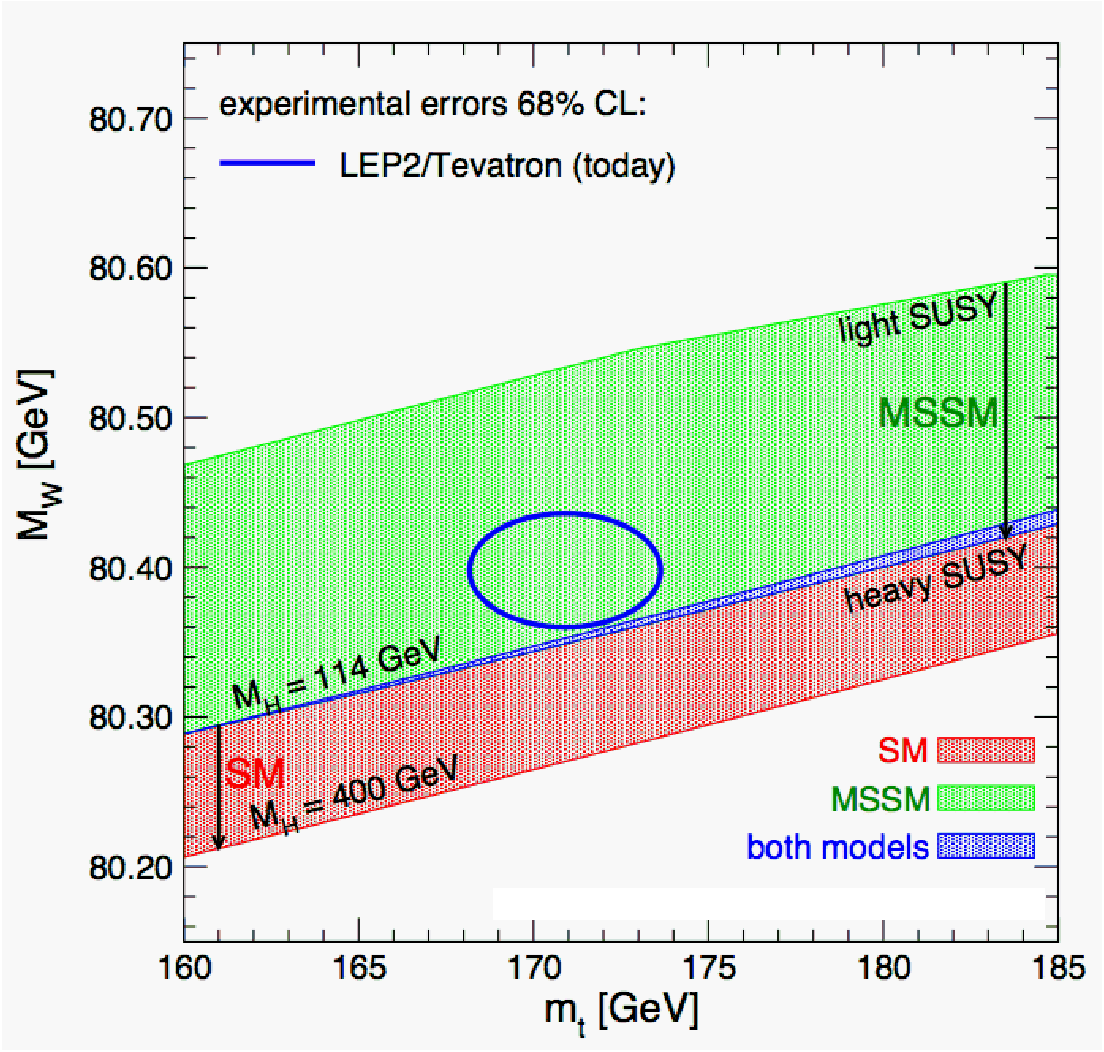
$m_W = 80398 \pm 25$ MeV

world average 2007



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

Heinemeyer, Hollik, Stockinger, Weber, Weiglein 2007



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

Outline

Top Pair Production Cross Section

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Top Mass

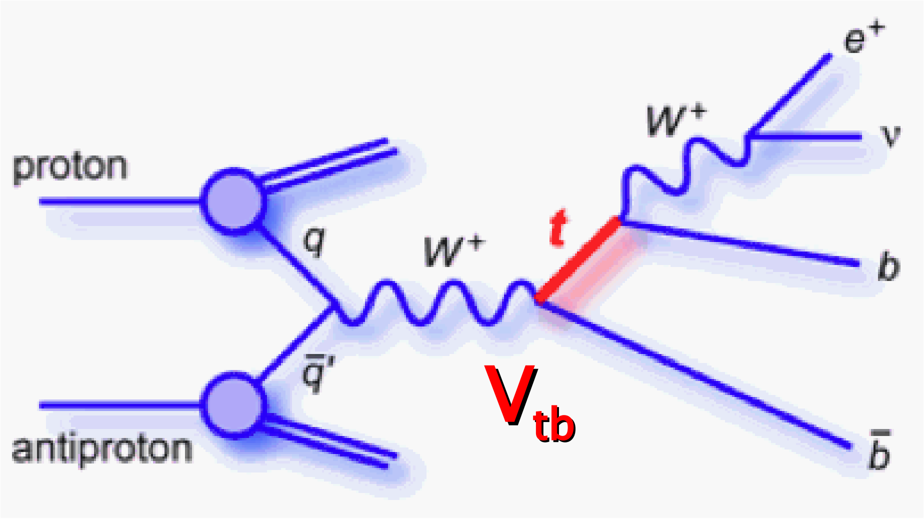
Single Top Production

Outlook: Top Physics at LHC

Single Top Quark Production

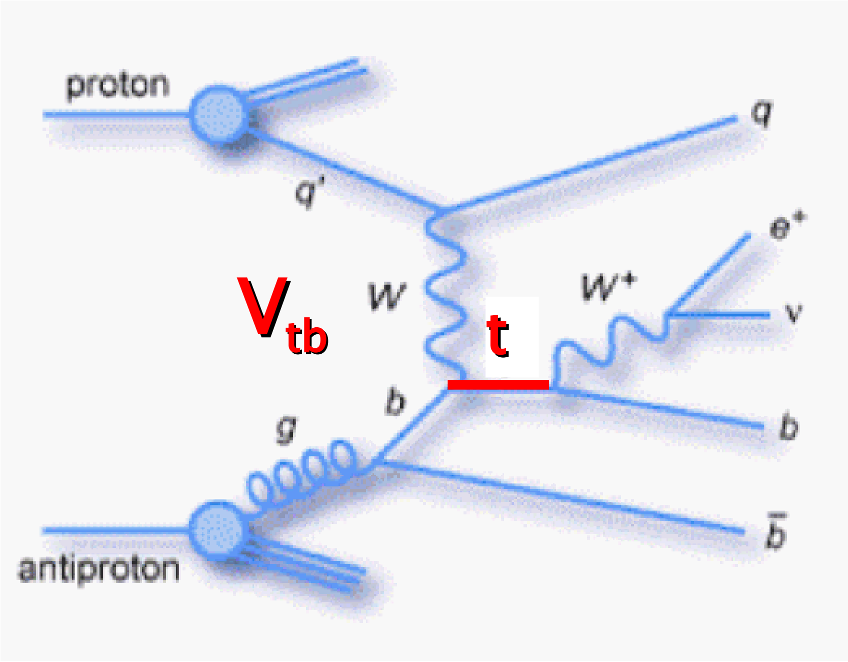
- first direct measurement of $|V_{tb}|$

Phys. Rev. D70 (2004) 114012



s-channel:

- NLO = 0.88 ± 0.11 pb
  (m_{top} = 175 GeV)

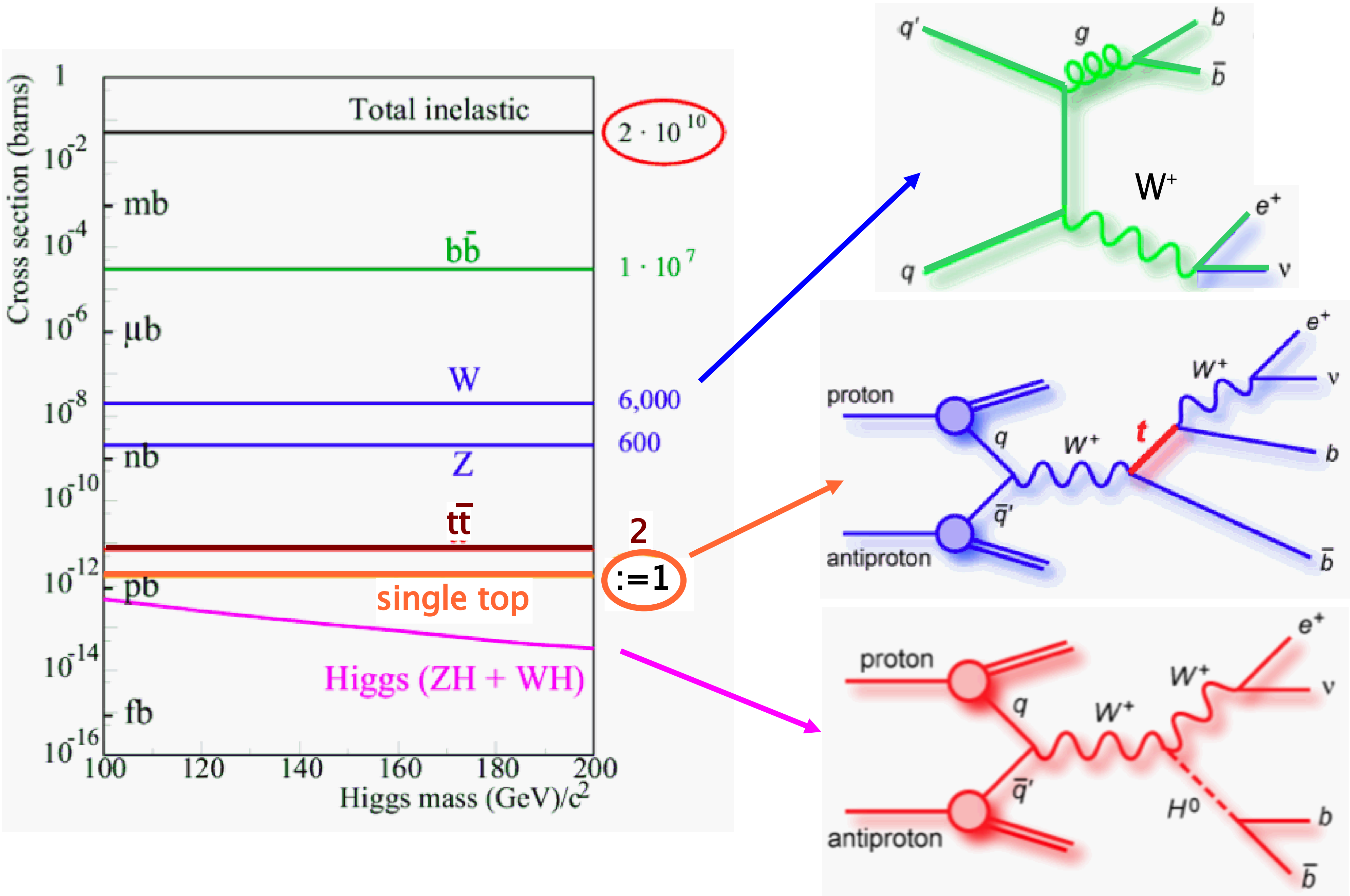


- jets
- isolated lepton
- missing E_T
- b-jets

t-channel:

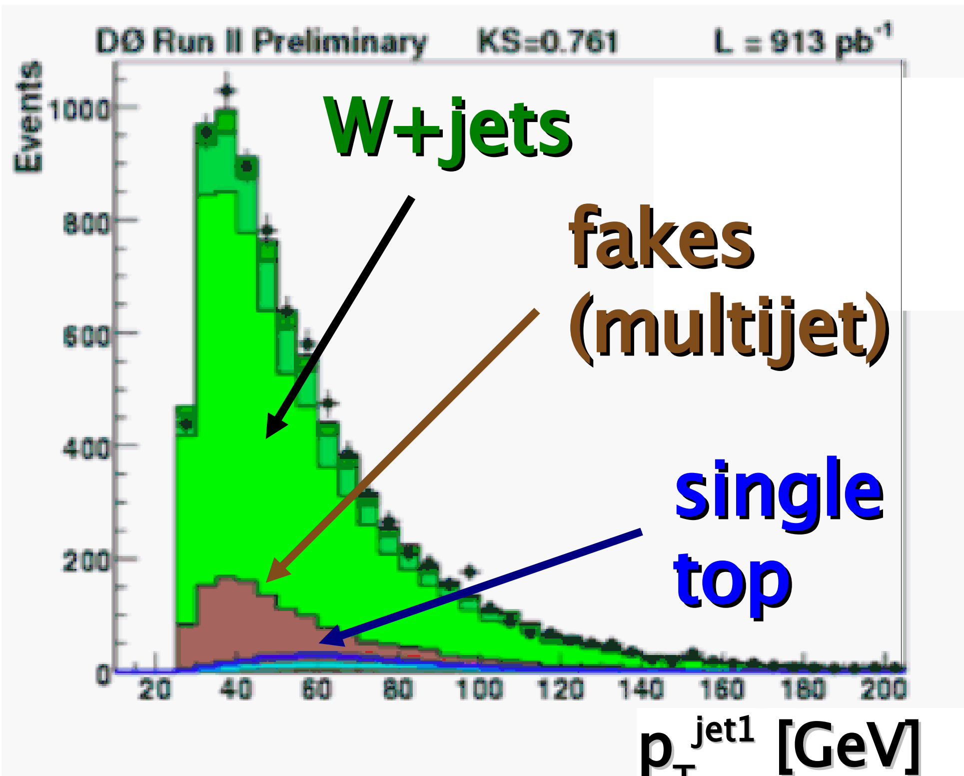
- NLO = 1.98 ± 0.25 pb
  (m_{top} = 175 GeV)

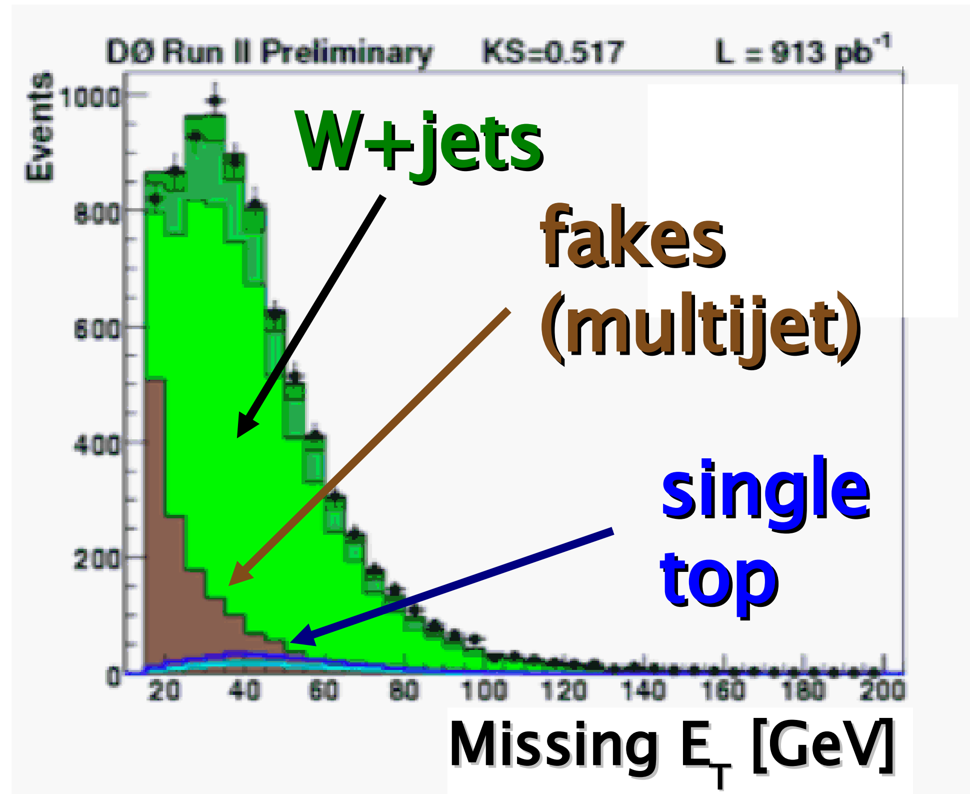
It has been challenging for years…



Single Top Quark Production

no b-tagging yet

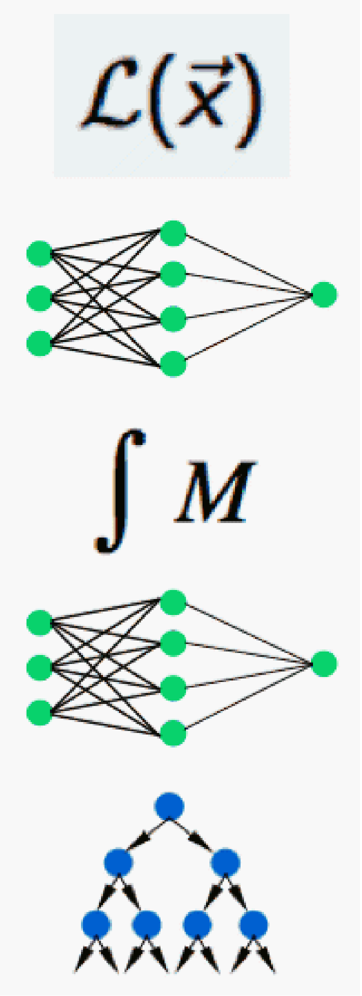




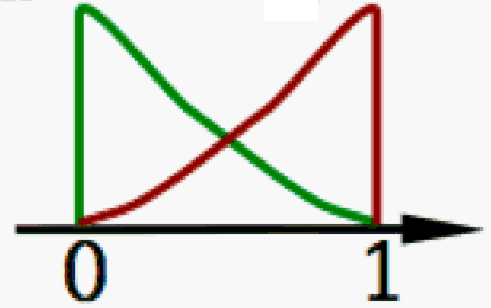
signal < background uncertainty!

Multivariate Analysis Techniques

- Likelihood discriminants (CDF)
- Artificial neural network (CDF)
- Matrix element (DØ, CDF)
- Bayesian neural network (DØ)
- Boosted decision trees (DØ)

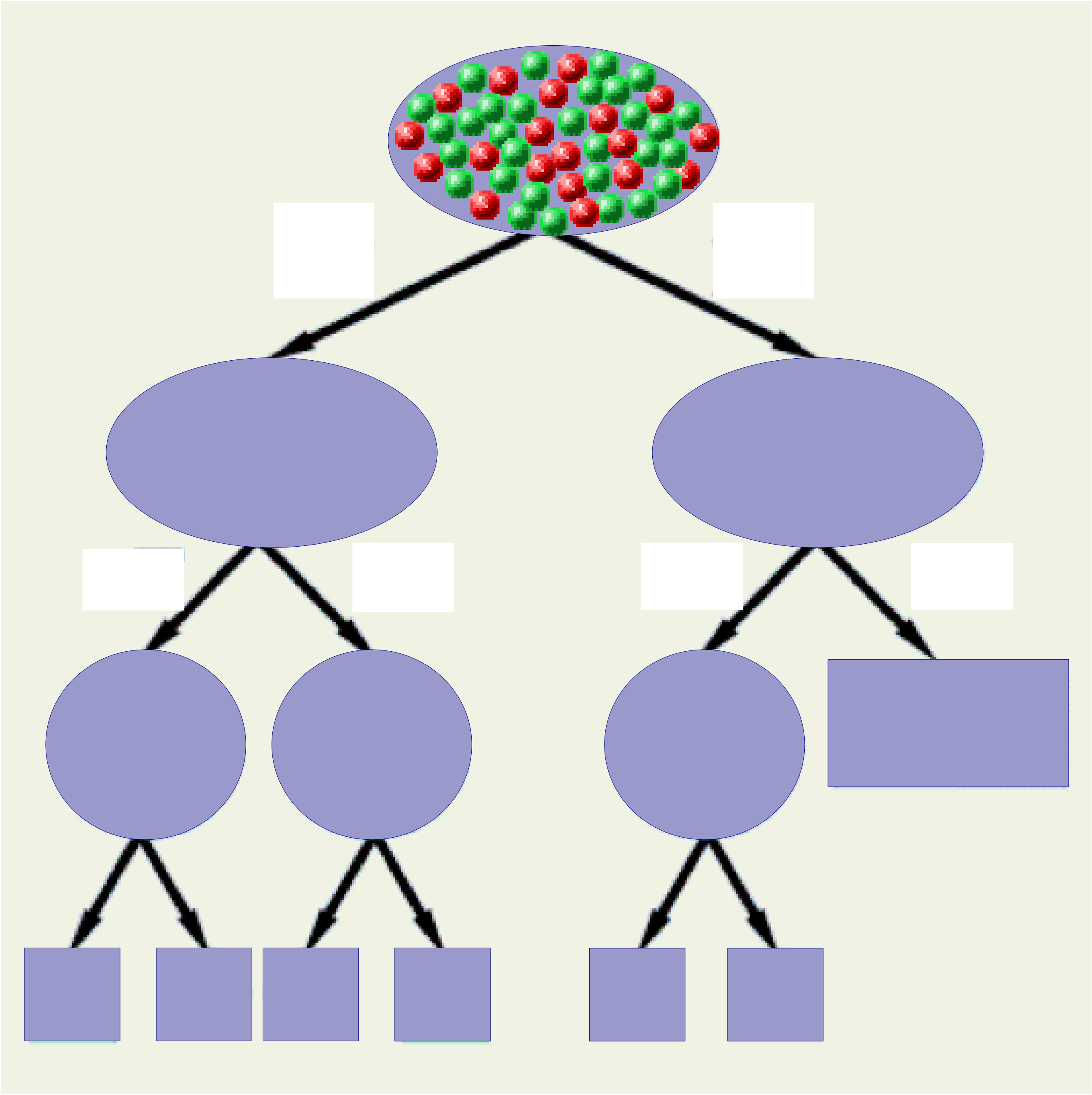


background



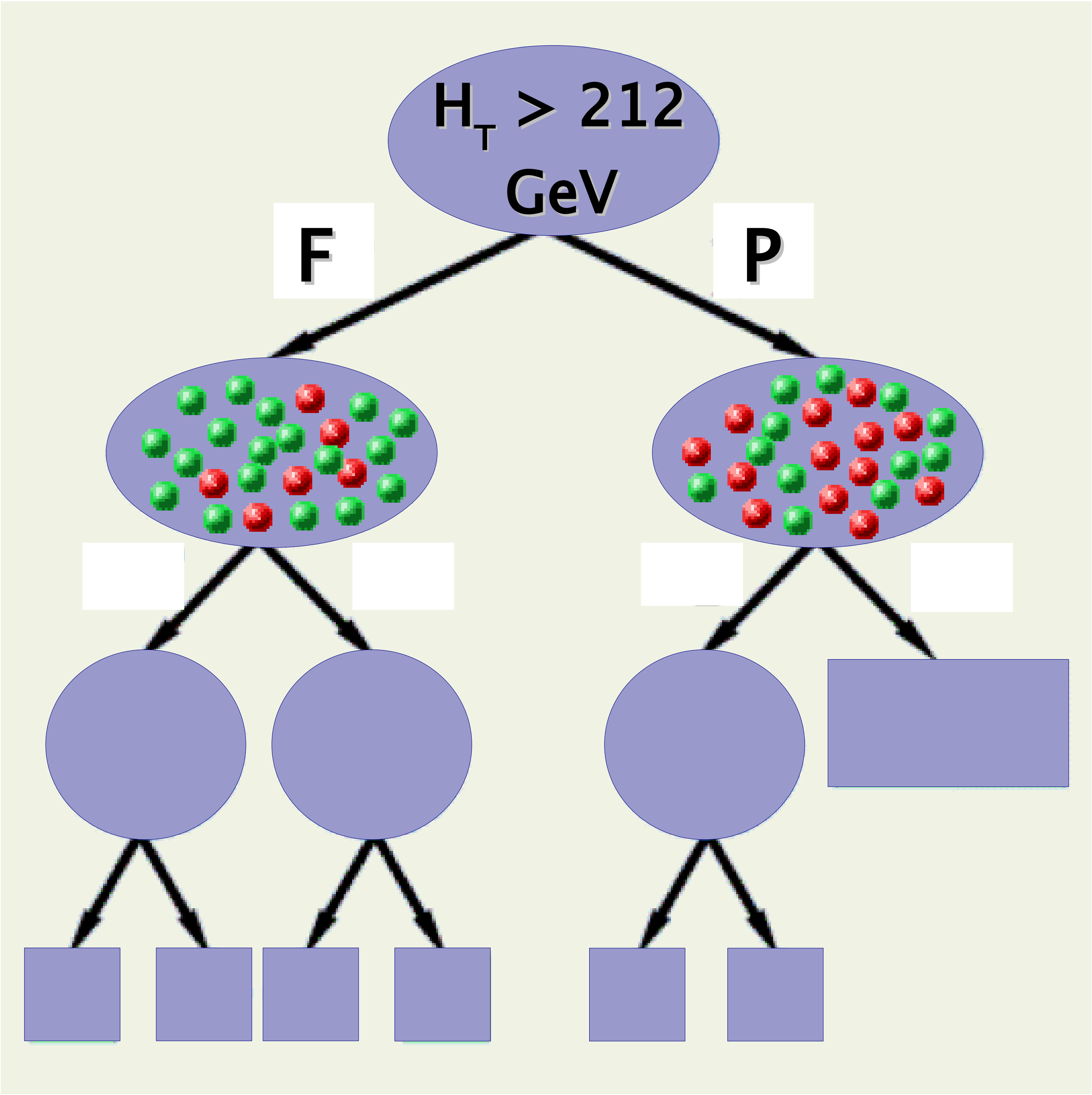
signal

Boosted Decision Trees



- **IDEA: recover events that fail criteria in cut-based analyses**

Boosted Decision Trees



- IDEA: recover events that fail criteria in cut-based analyses

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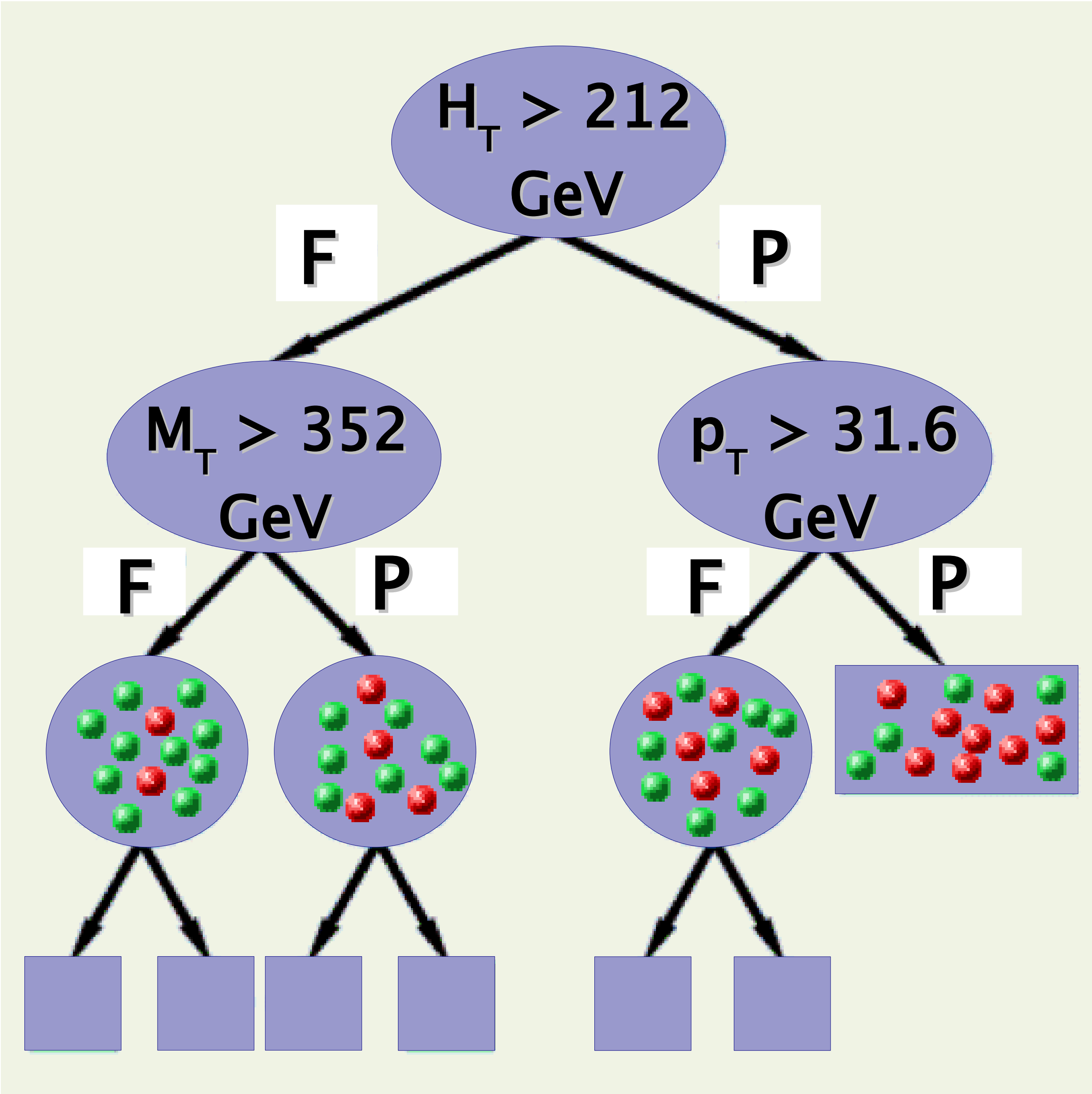

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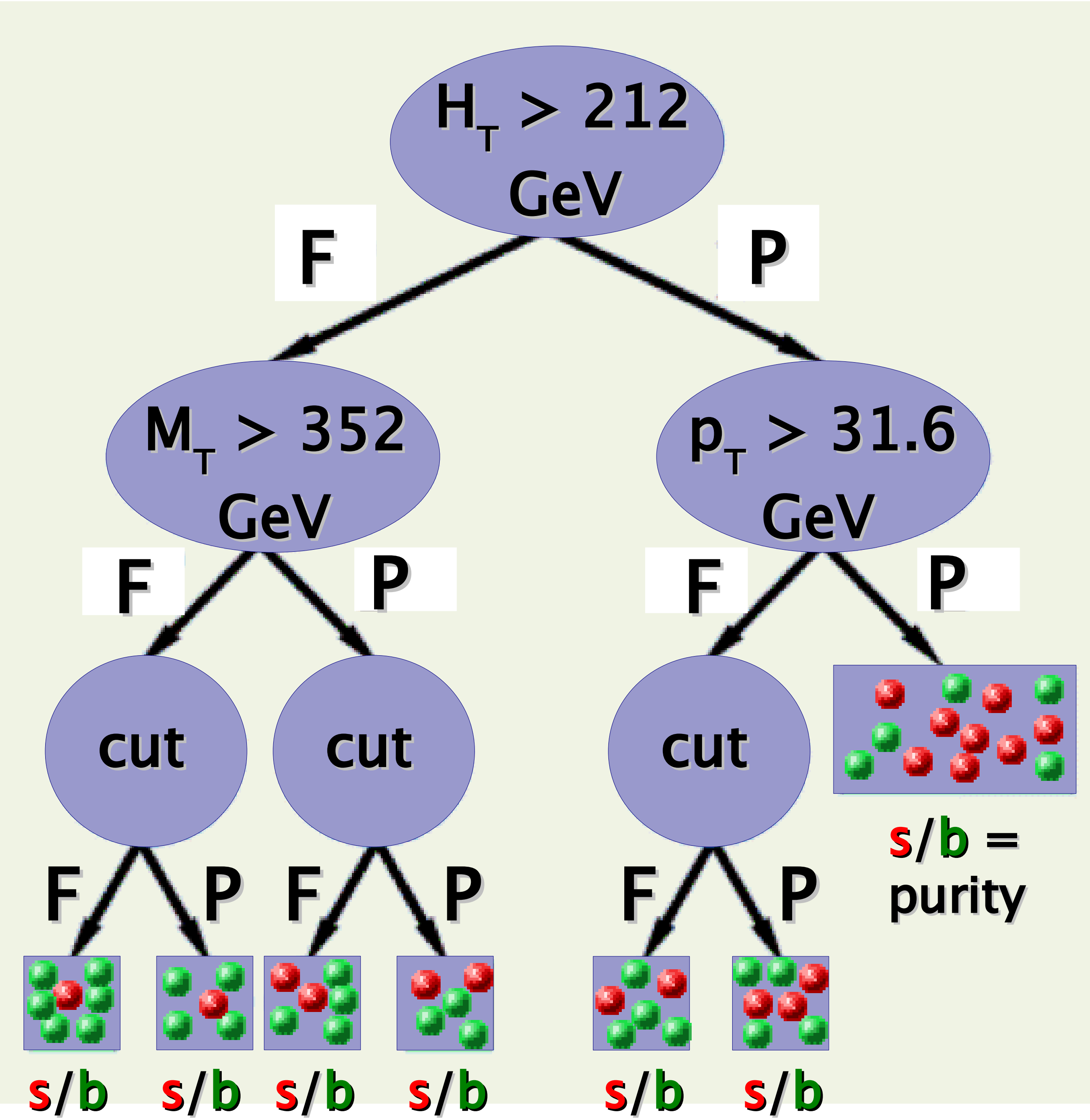
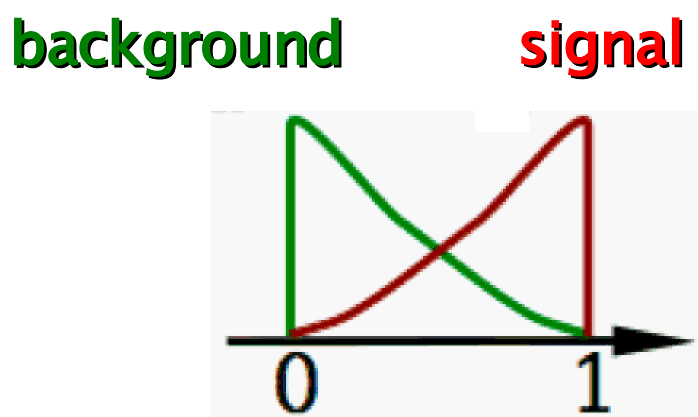
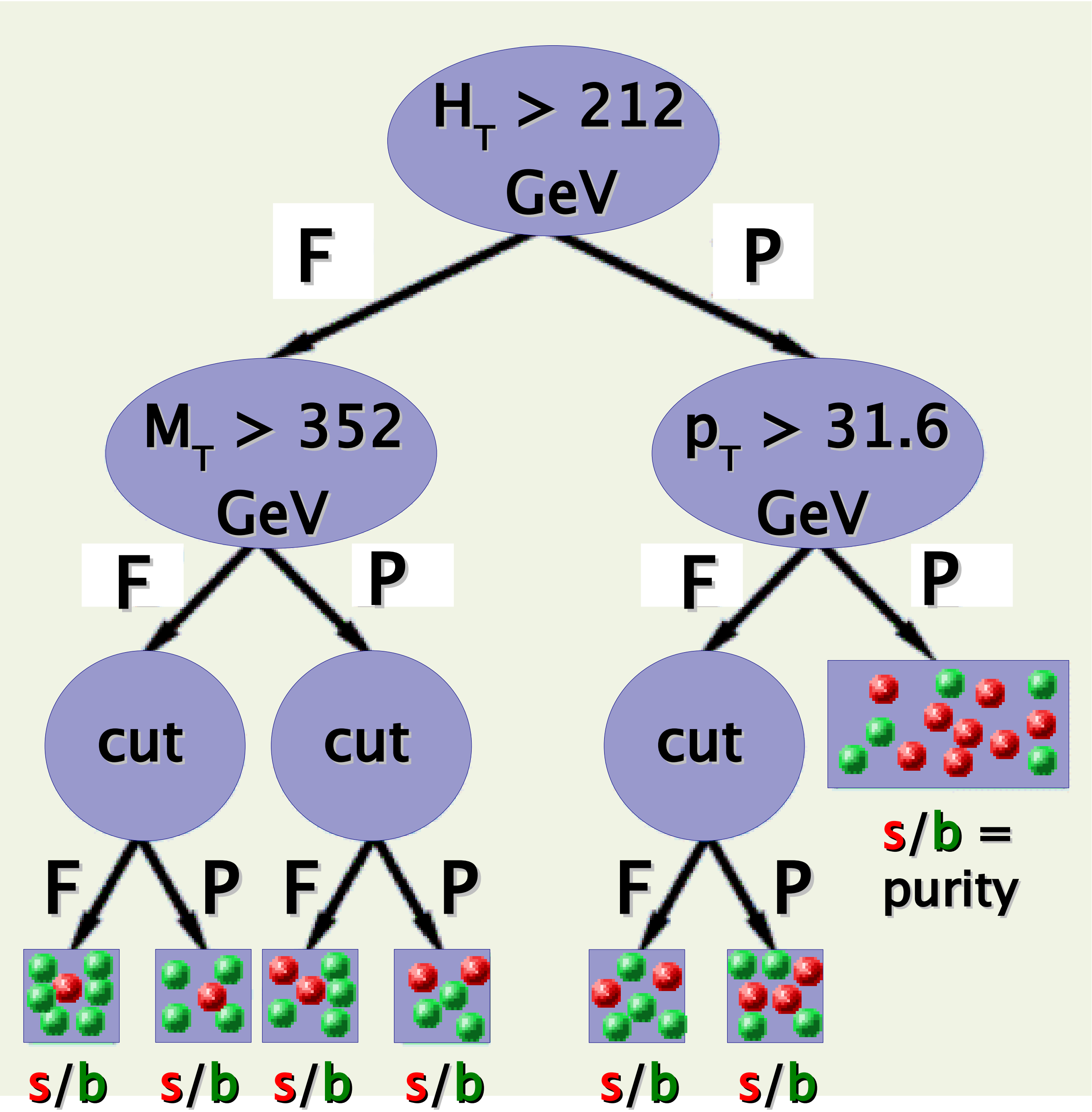
Boosted Decision Trees



- **IDEA: recover events that fail criteria in cut-based analyses**
- **result: weight for every event**



Boosted Decision Trees

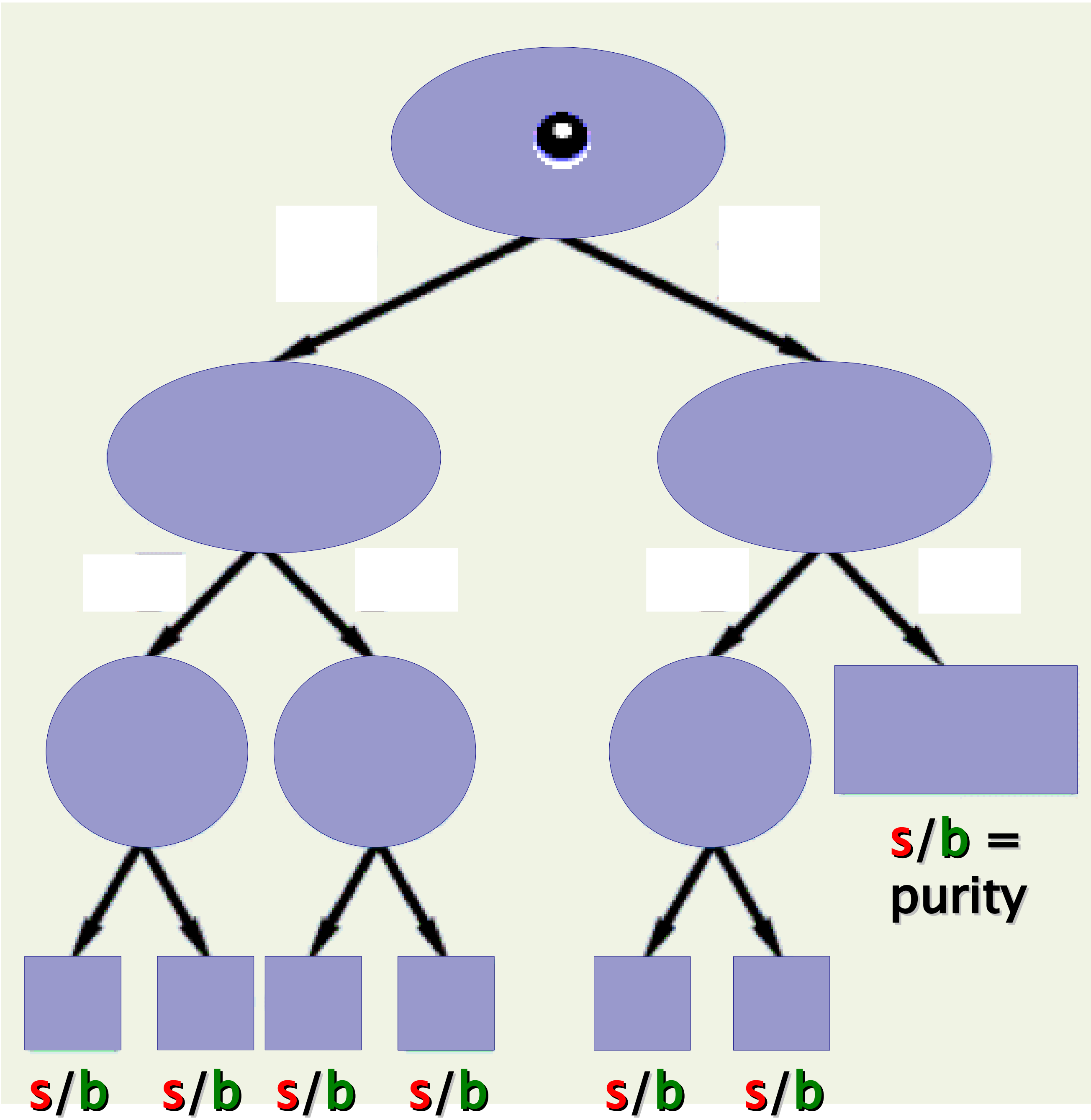


- **IDEA: recover events that fail criteria in cut-based analyses**

boosting:

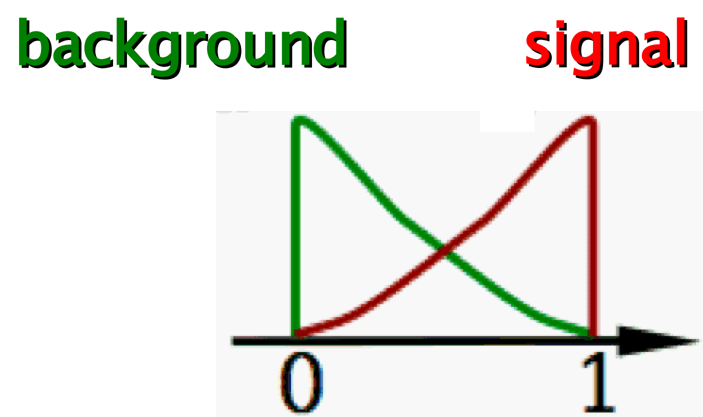
- train tree: T_k
- derive weight: α_k
- retrain tree: T_{k+1} to minimize error
- average: $T = \Sigma\, \alpha_i\, T_i$

Boosted Decision Trees

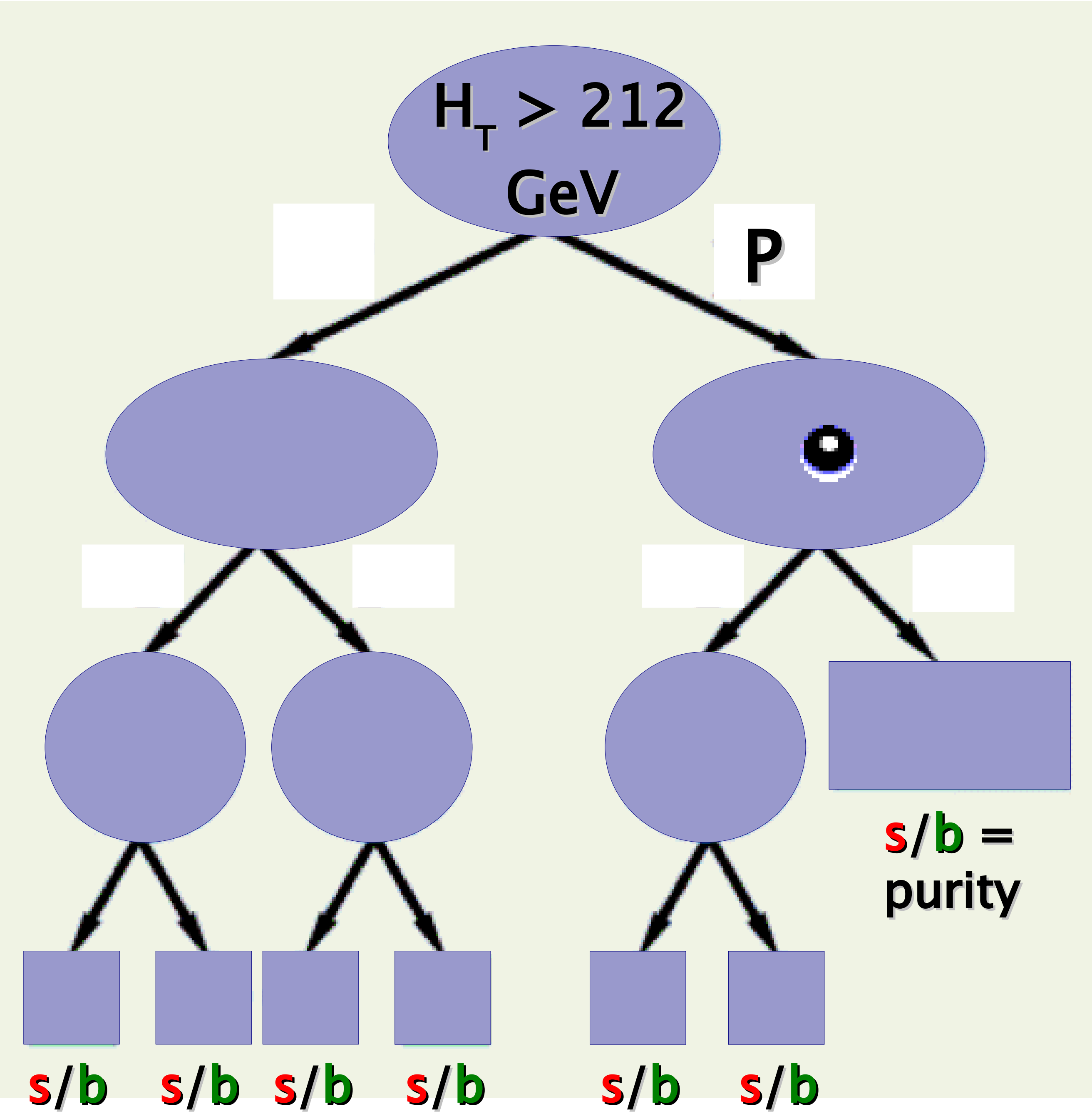


- **IDEA**: recover events that fail criteria in cut-based analyses

- result:
  weight for every event



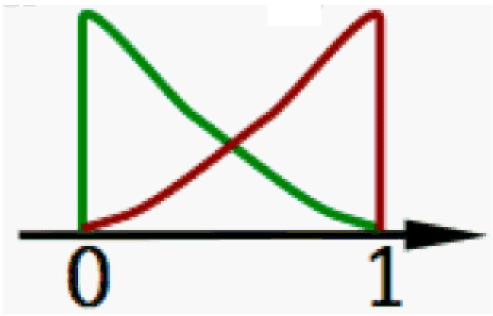
Boosted Decision Trees



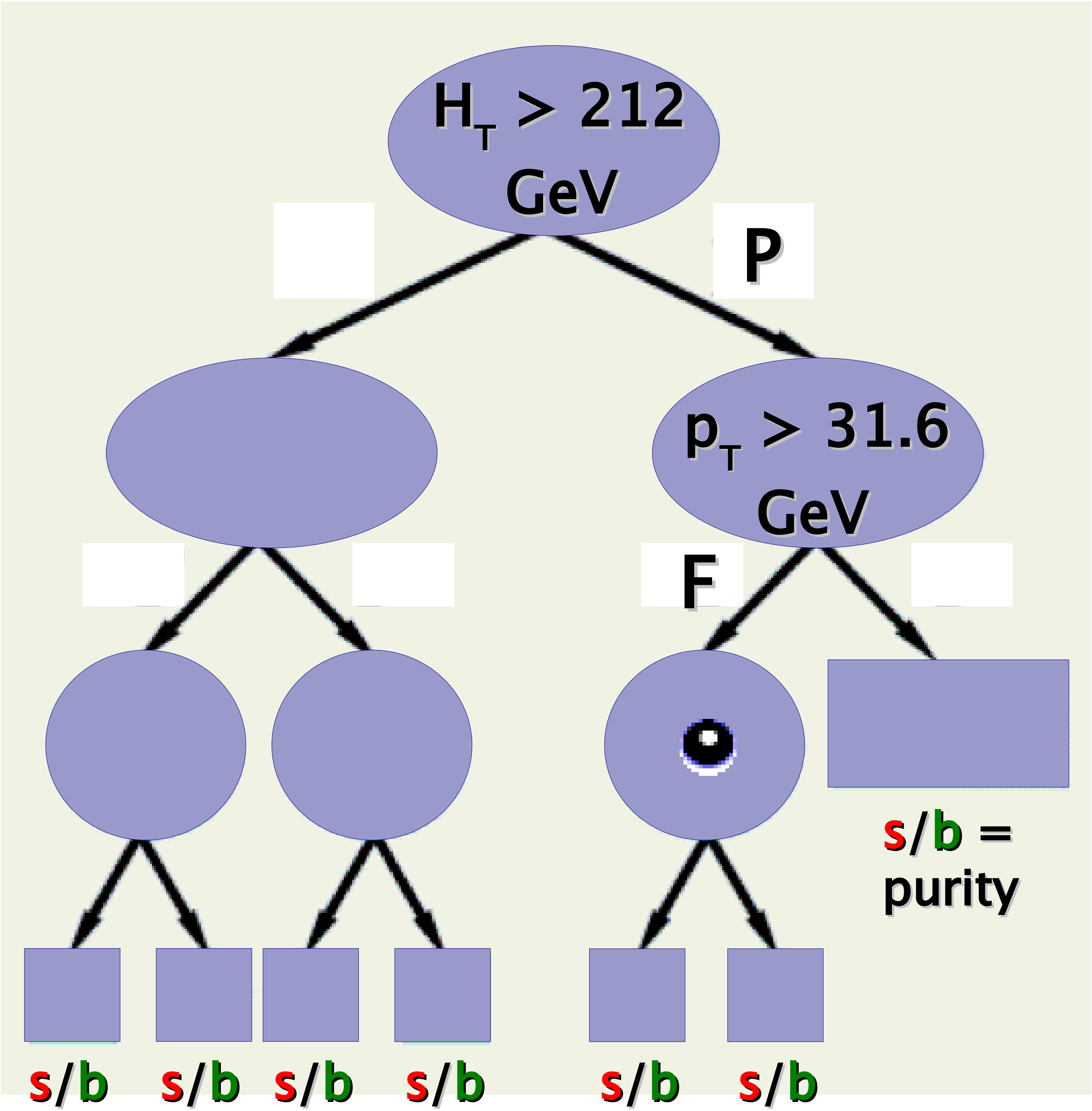
- IDEA: recover events that fail criteria in cut-based analyses

- result:
  weight for every event

background signal



Boosted Decision Trees



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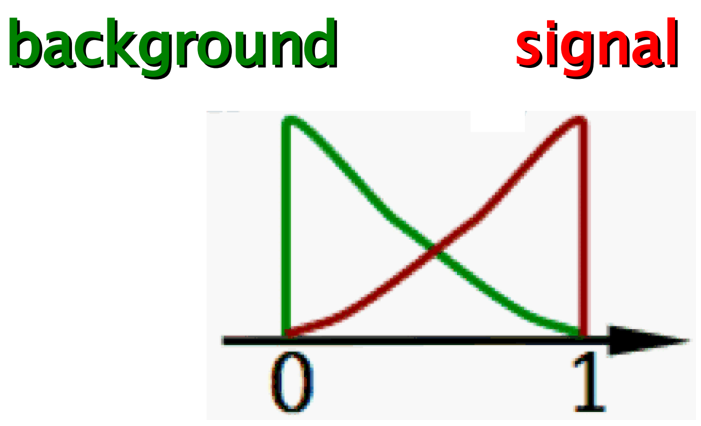
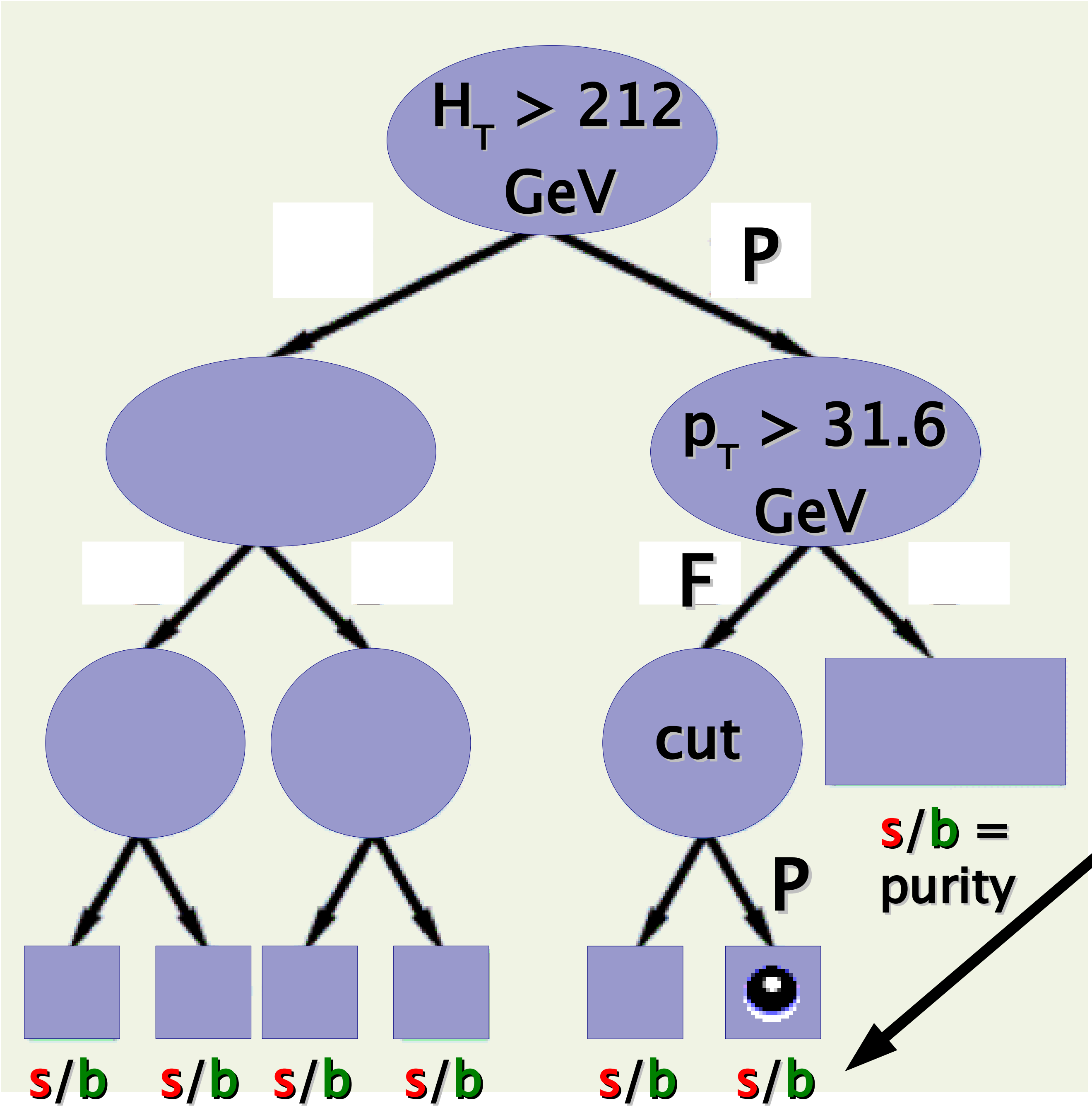


Boosted Decision Trees



- IDEA: recover events that fail criteria in cut-based analyses

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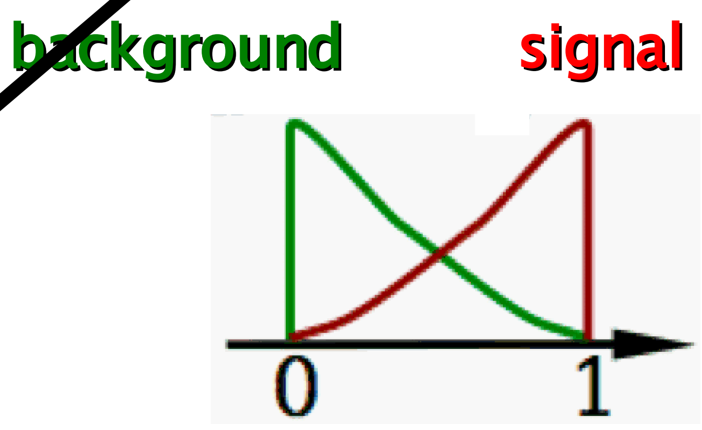
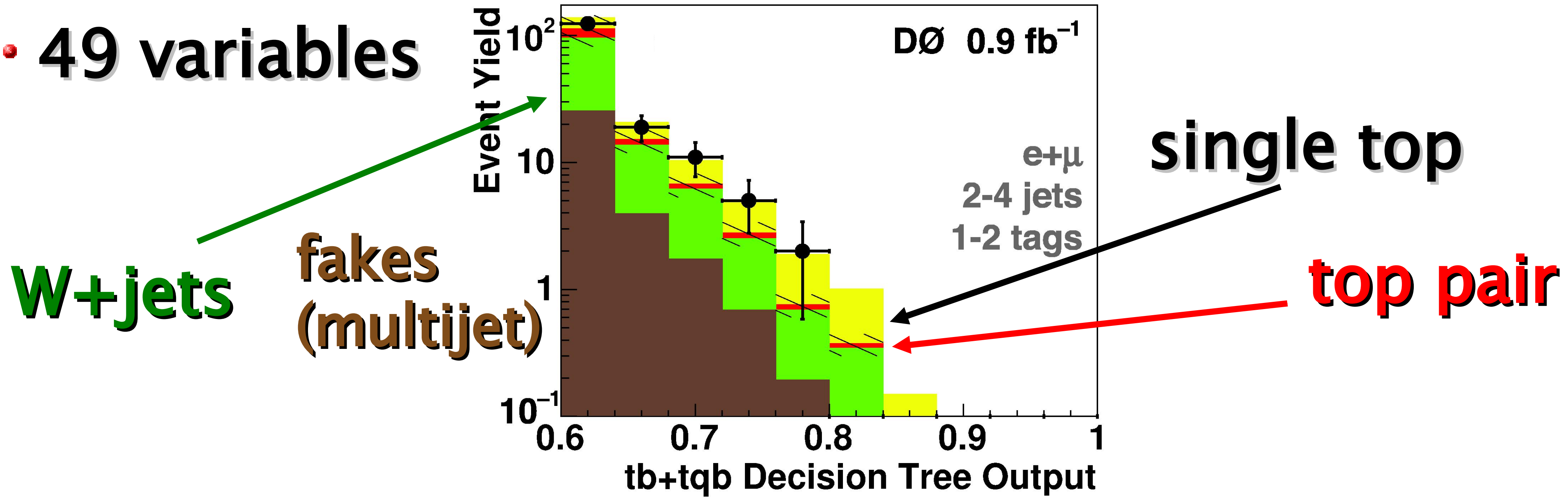


Boosted Decision Tree Output

- 49 variables



Boosted Decision Tree Output

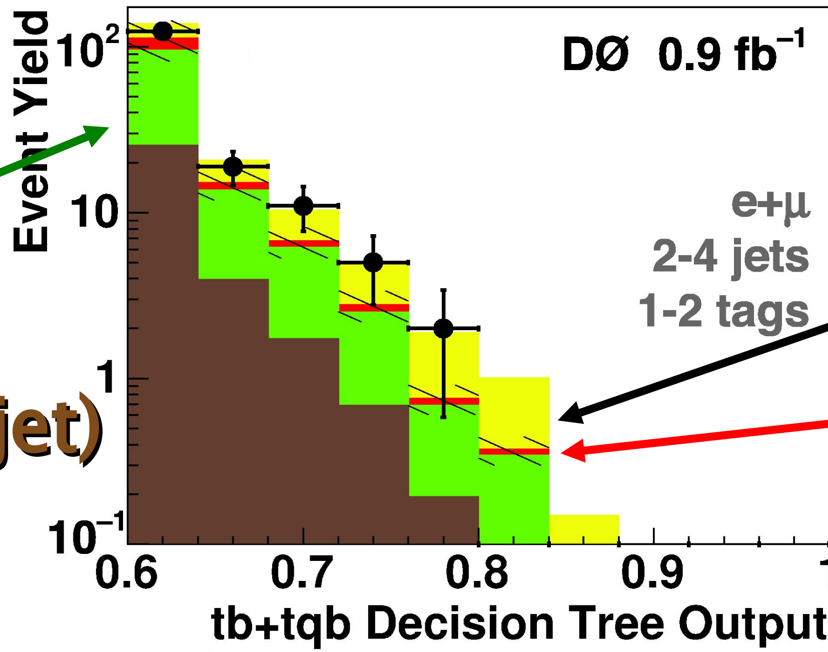
- 49 variables

W+jets

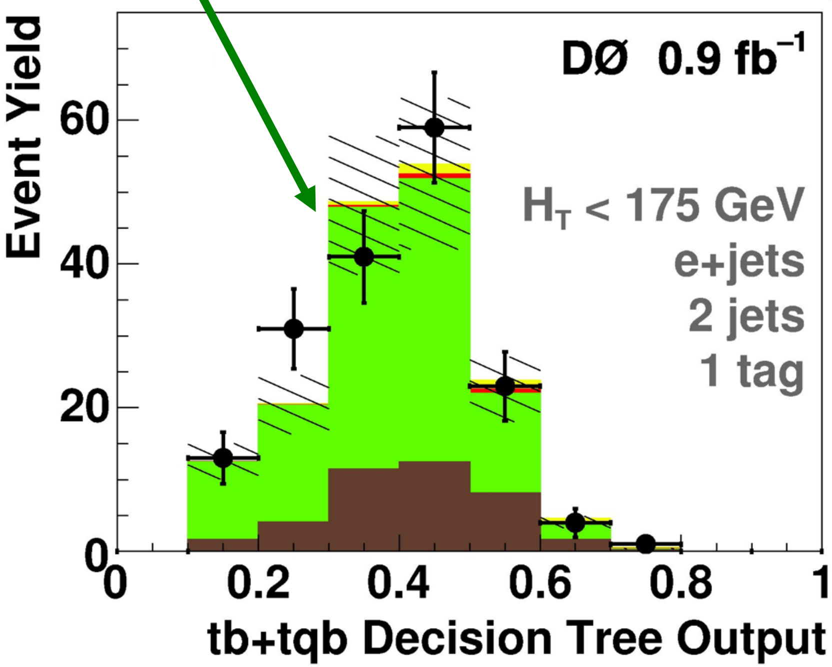
fakes (multijet)

single top

top pair



H_T < 175 GeV



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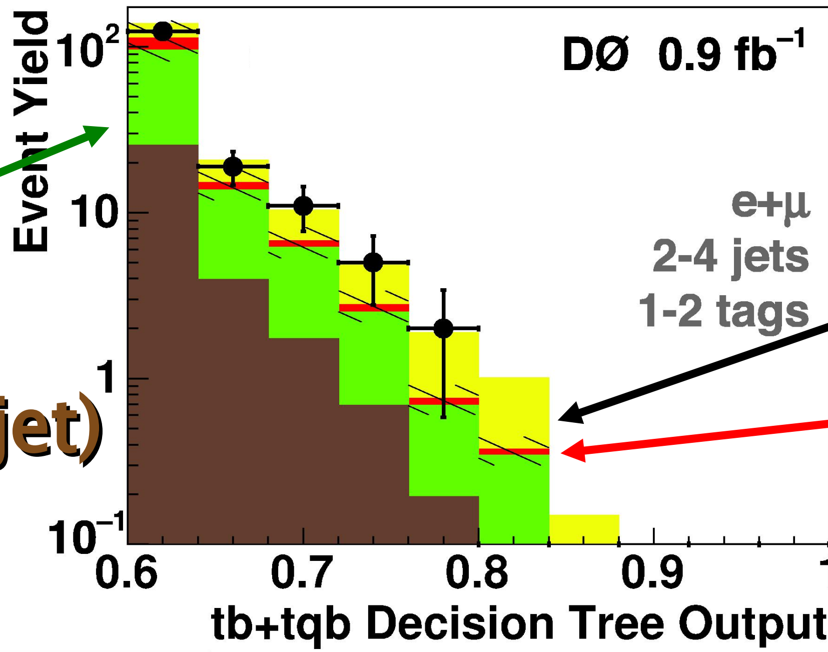
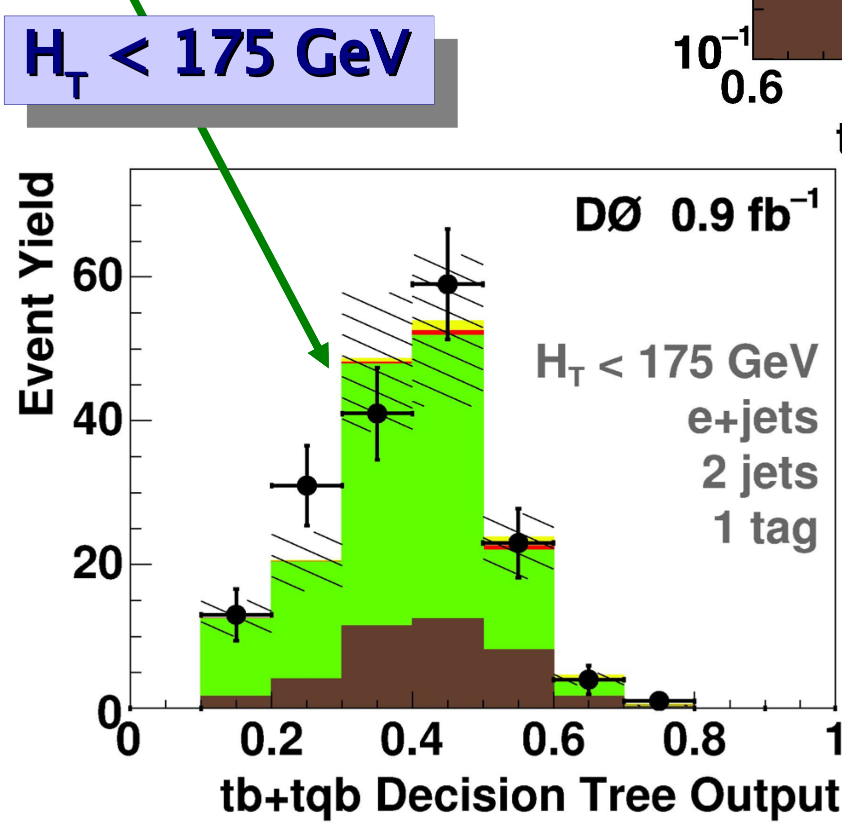
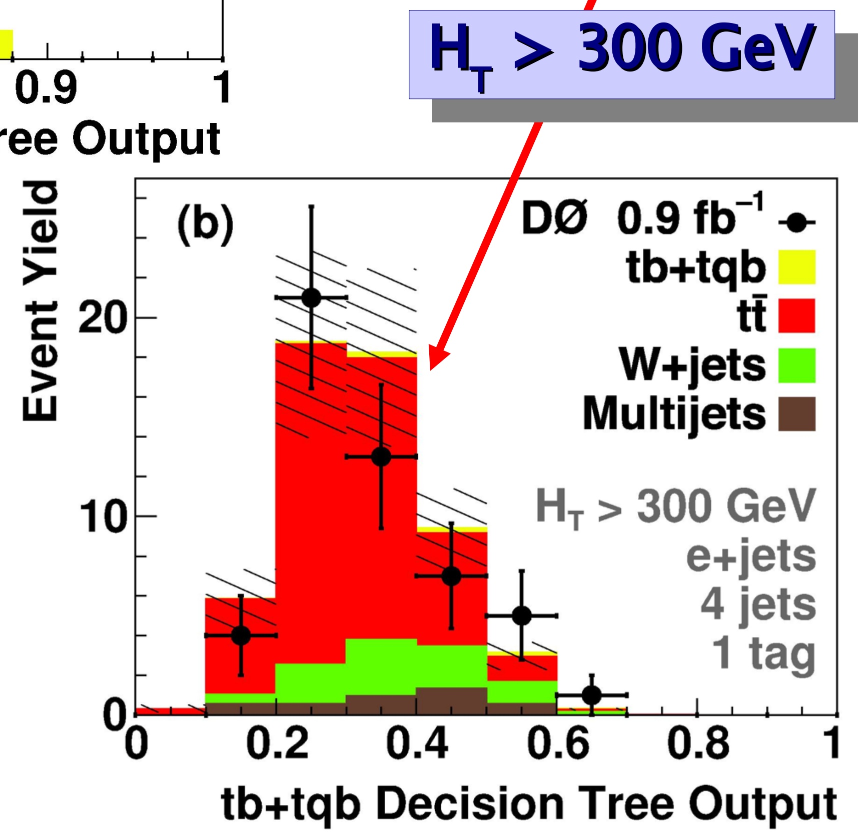
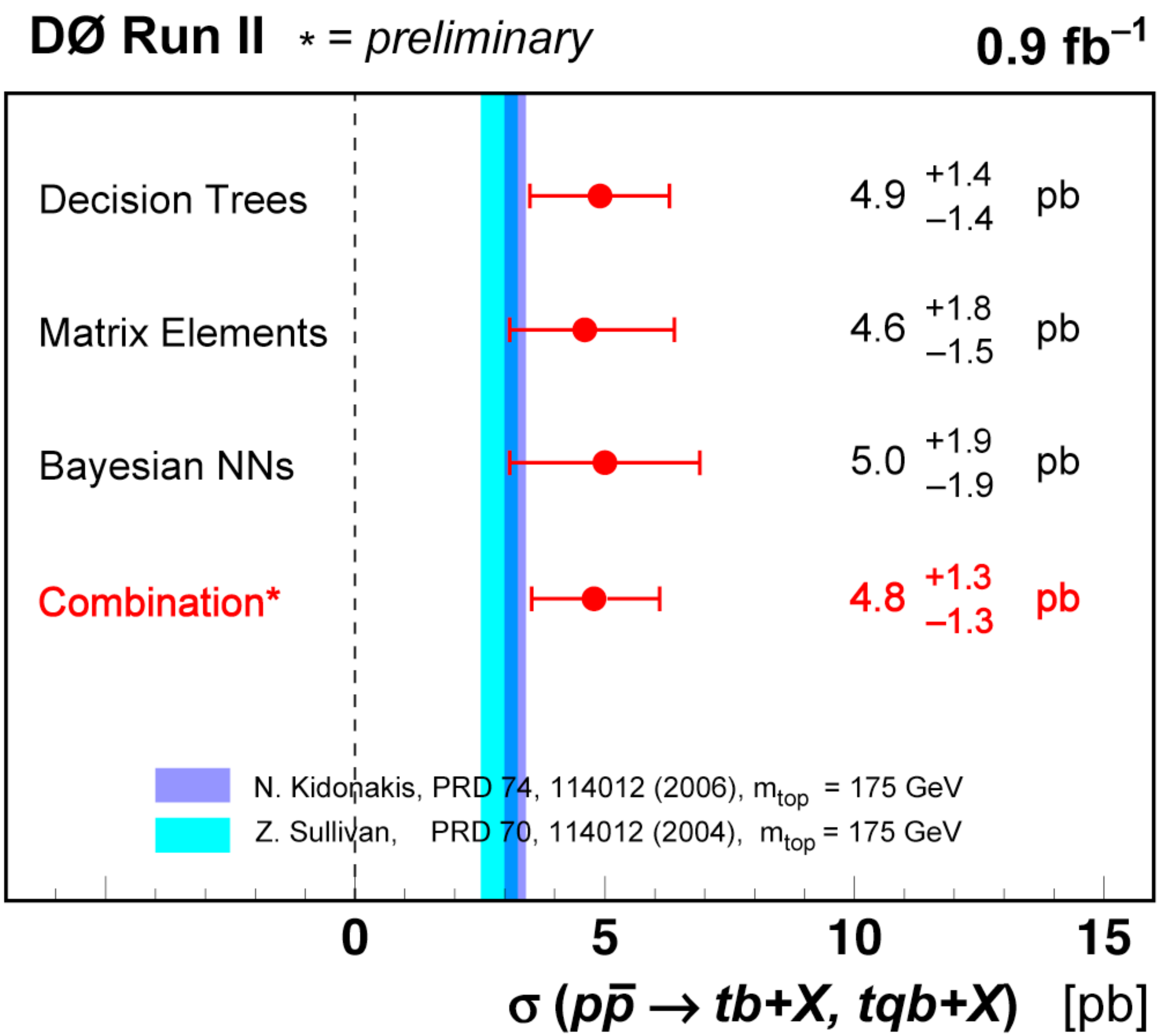






1 fb^{-1}

Results of other Methods

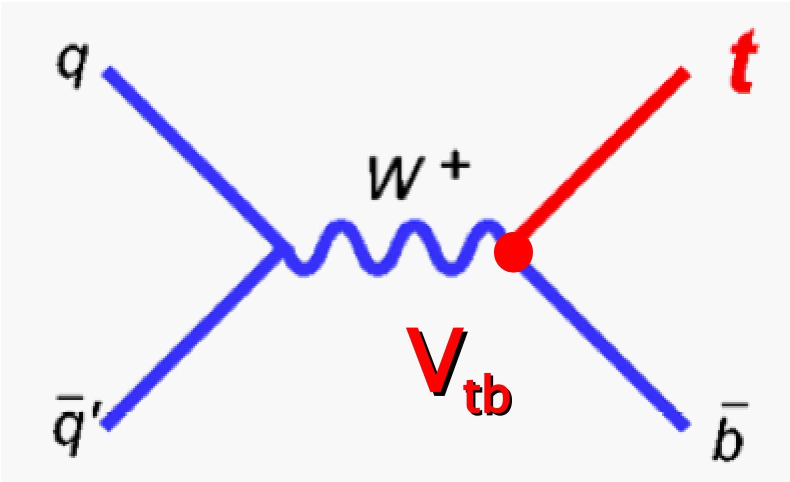


3.4σ

3.5σ evidence

- **CDF has found evidence as well for matrix element (3.1σ) but not yet for likelihood (2.7σ) and NN...**

First direct measurement of $|V_{tb}|$



1 fb^{-1}

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

- before only indirect limits: $|V_{tb}| = 0.999127 \pm 0.00026$ (1σ CL)

  CKM Fitter Group for Beauty 2006

- assume: $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$
- assume: pure V–A and CP–conserving Wtb interaction
- no assumption on quark families or CKM matrix unitarity

$|V_{tb}| = 1.3 \pm 0.2$

$0.68 < |V_{tb}| \leq 1$ (95% CL)

Summary

new era of top physics at the Tevatron:

precision measurements & searches in the top sector

- cross section measurement top pair production
- search for new resonances
- top mass
- evidence for single top production

$\Rightarrow$ **all measurements are in agreement with SM**

$\Rightarrow$ **more interesting results will follow with more data**

$\Rightarrow$ **will continue to explore top sector in detail**

$\Rightarrow$ **important experiences as preparation for LHC:**

analysis techniques, trigger efficiencies, background estimation, systematics as e.g. jet energy scale, statistical methods

Outline

Top Pair Production Cross Section

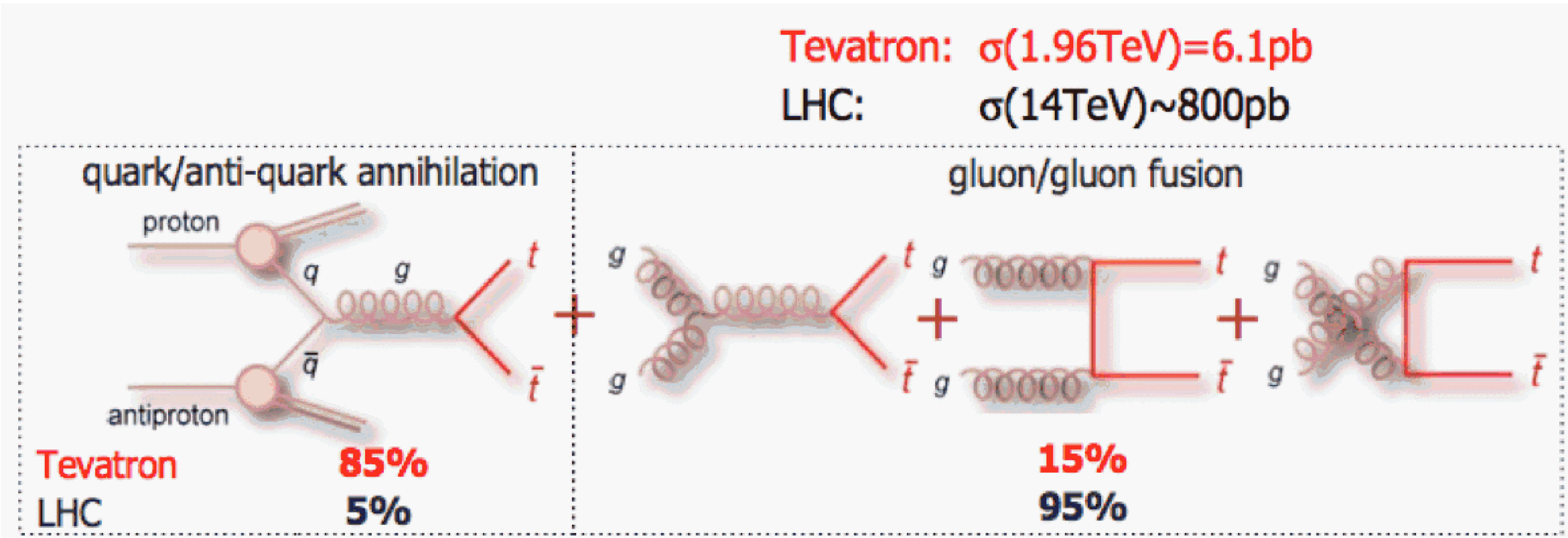
Searches in Top Pair Production
– New Resonances

Top Mass

Single Top Production

Outlook: Top Physics at LHC

Top Pair Production at the LHC

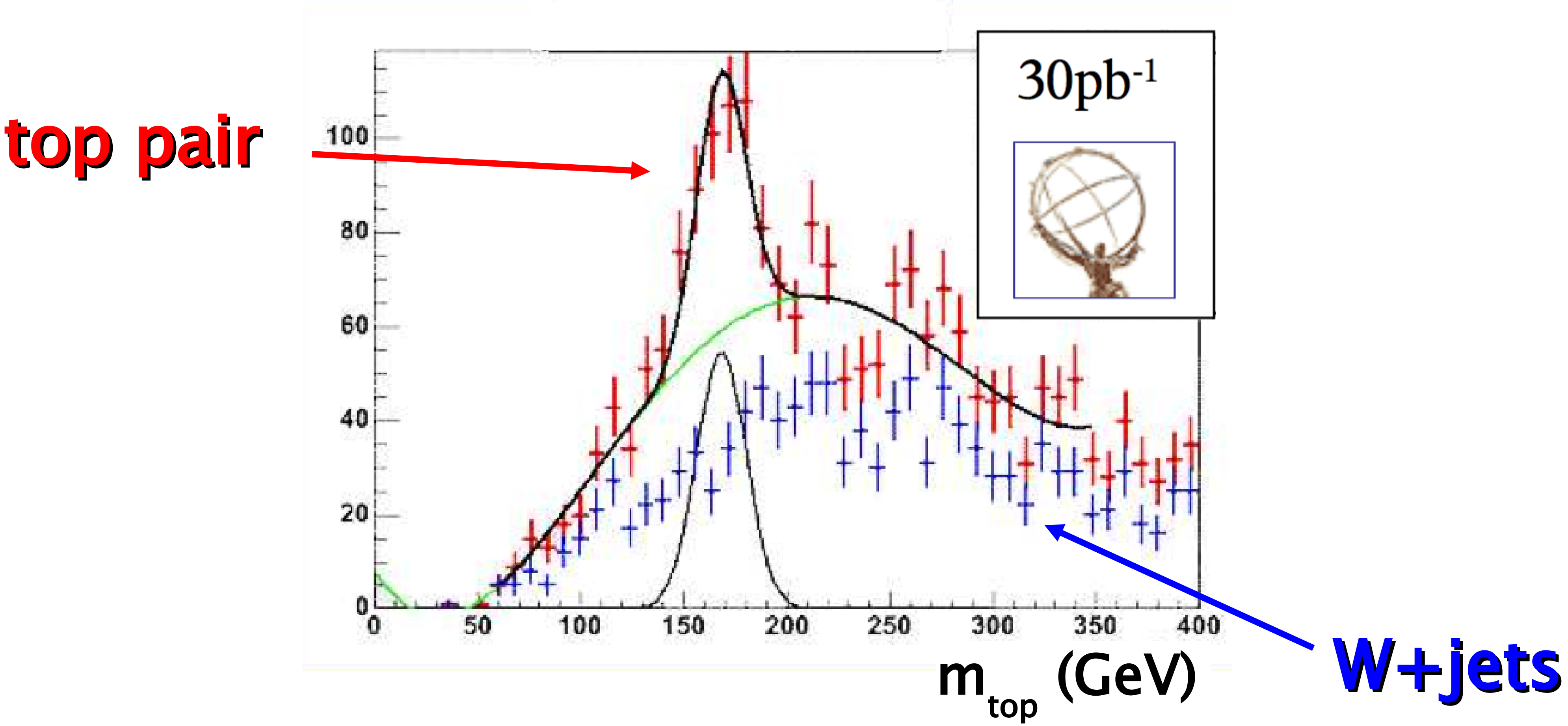


10 top pairs per day @ Tevatron ↔ 1 top pair per second @ LHC

Top Quarks as "Standard Candles"

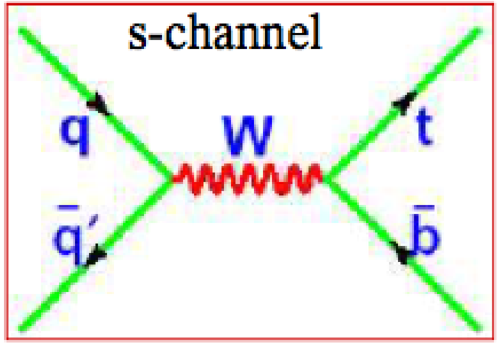
few hours of data taking

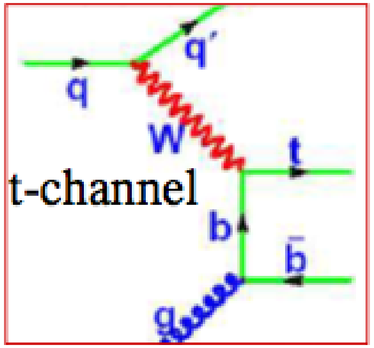
ATLAS ATL-PHYS-PUB-2005-024

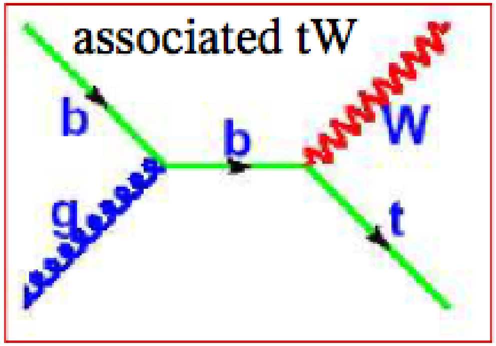


- top mass peak one of the first signals to detect
- use for detector commissioning:
  e.g. trigger, b-tagging, jet energy scale

Single Top Production at the LHC







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

LHC

$\sigma^{NLO} = 6.6$ pb
$\sigma^{NLO} = 4.1$ pb

$\sigma^{NLO} = 153$ pb
$\sigma^{NLO} = 90$ pb

$\sigma^{NLO} = 60$ pb
$\sigma^{NLO} = 60$ pb

→ top production
→ 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

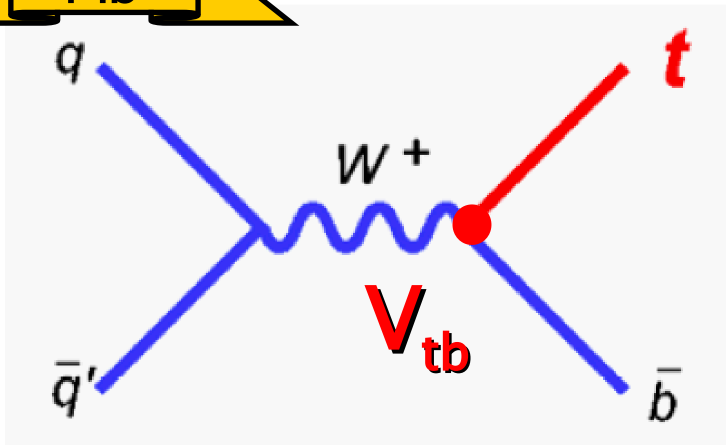
⇒ much wider range of topics

⇒ explore top quark physics in great detail

Backup

First direct measurement of $|V_{tb}|$

1 fb^{-1}



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CKM Fitter Group for Beauty 2006

- before only indirect limits: $|V_{tb}| = 0.999127 \pm 0.00026$ (1σ CL)
- assume: $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$
- assume: pure V–A and CP–conserving Wtb interaction

$$|V_{tb} f_1^L| = 1.3 \pm 0.2$$

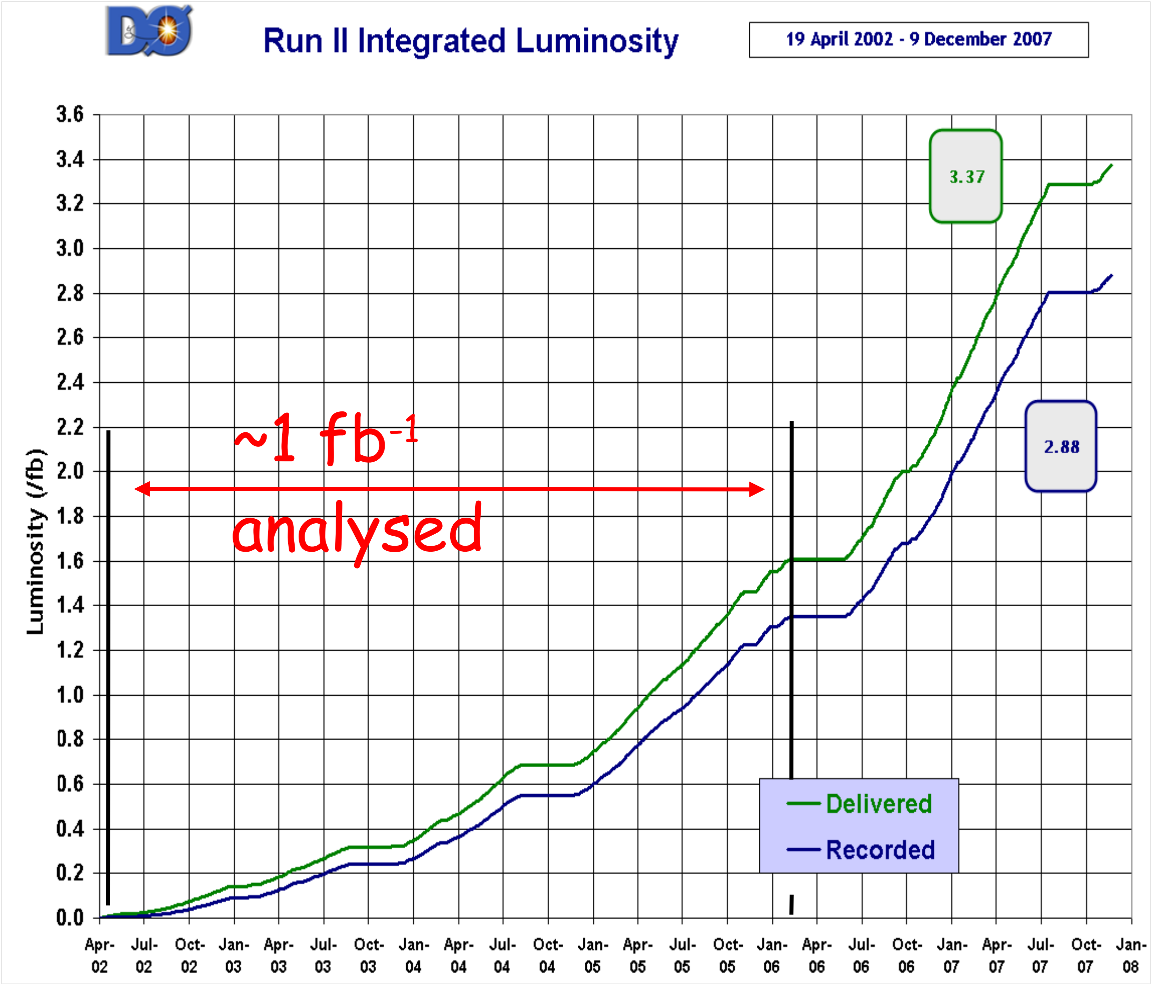
- assume: $f_1^L = 1$

$$0.68 < |V_{tb}| \leq 1 \quad (95\%\ \text{CL})$$

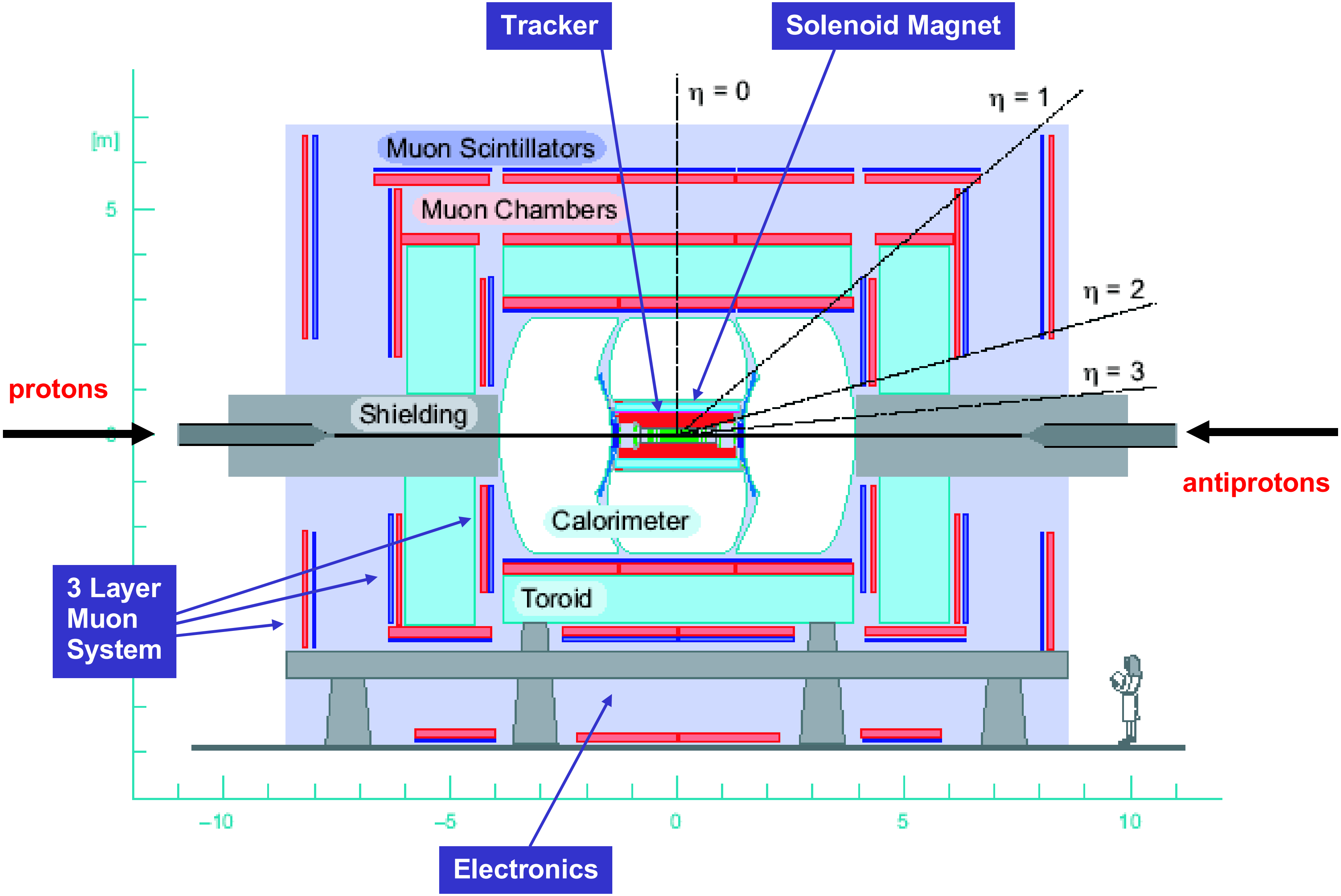
- no assumption on quark families or CKM matrix unitarity

The Tevatron at Fermilab: Luminosity

- Tevatron has delivered ~3.4 fb^{-1} per experiment
- CDF and DØ ~2.9 fb^{-1} recorded each
- current data taking efficiency is approaching ~90%



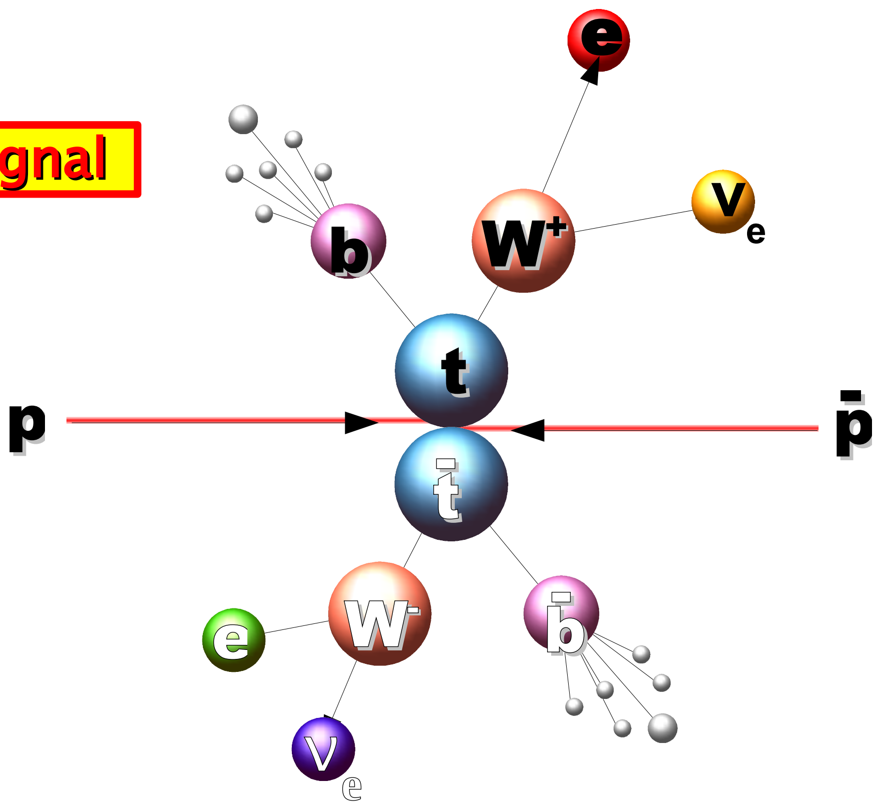
The DØ Experiment



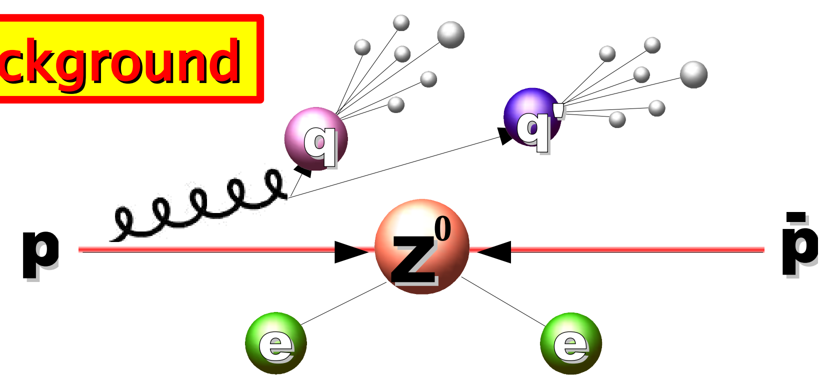
Event Topology in Dilepton Channel

- 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

signal



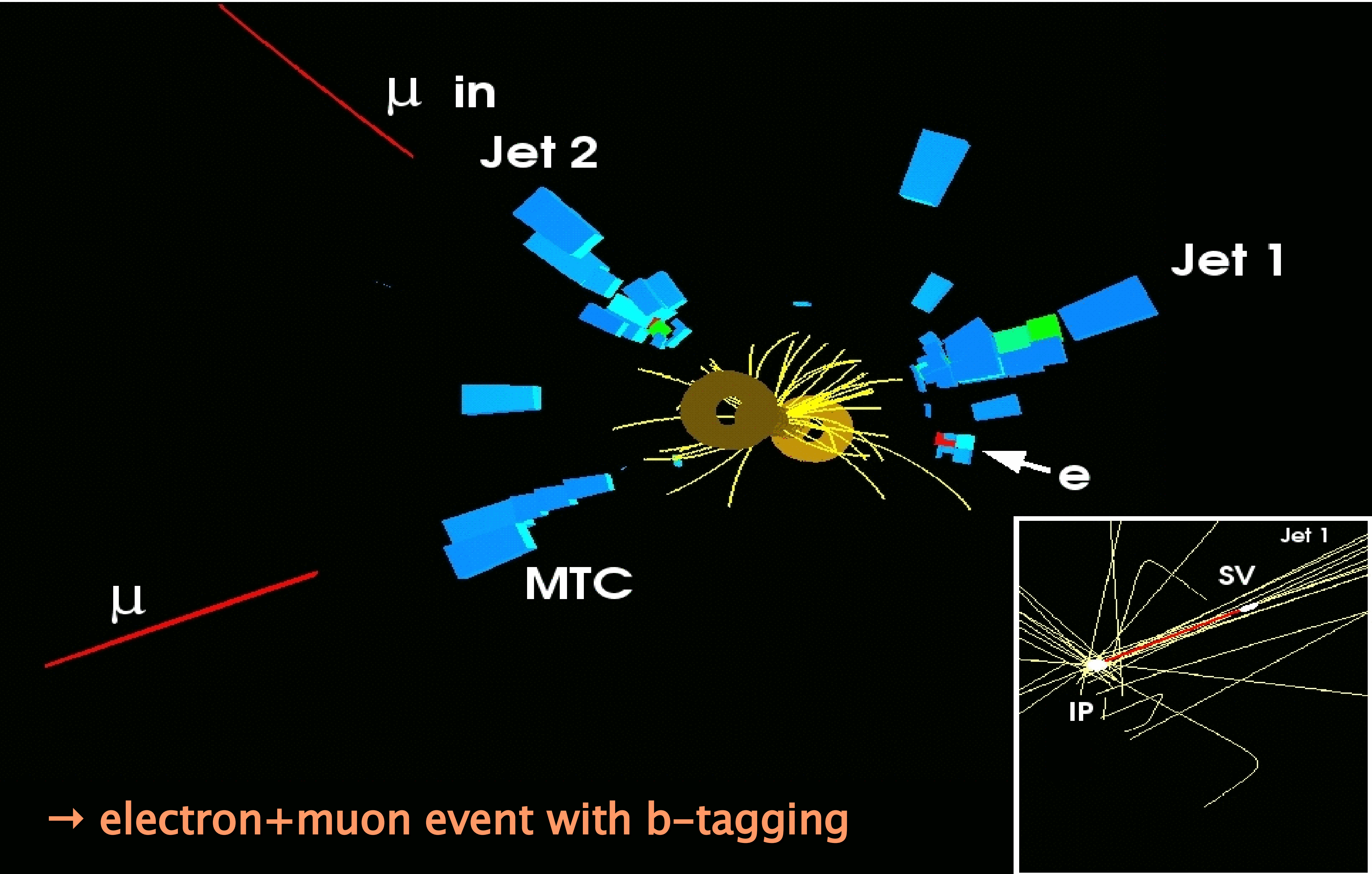
background



Z+jets production:
+ misreconstructed missing energy

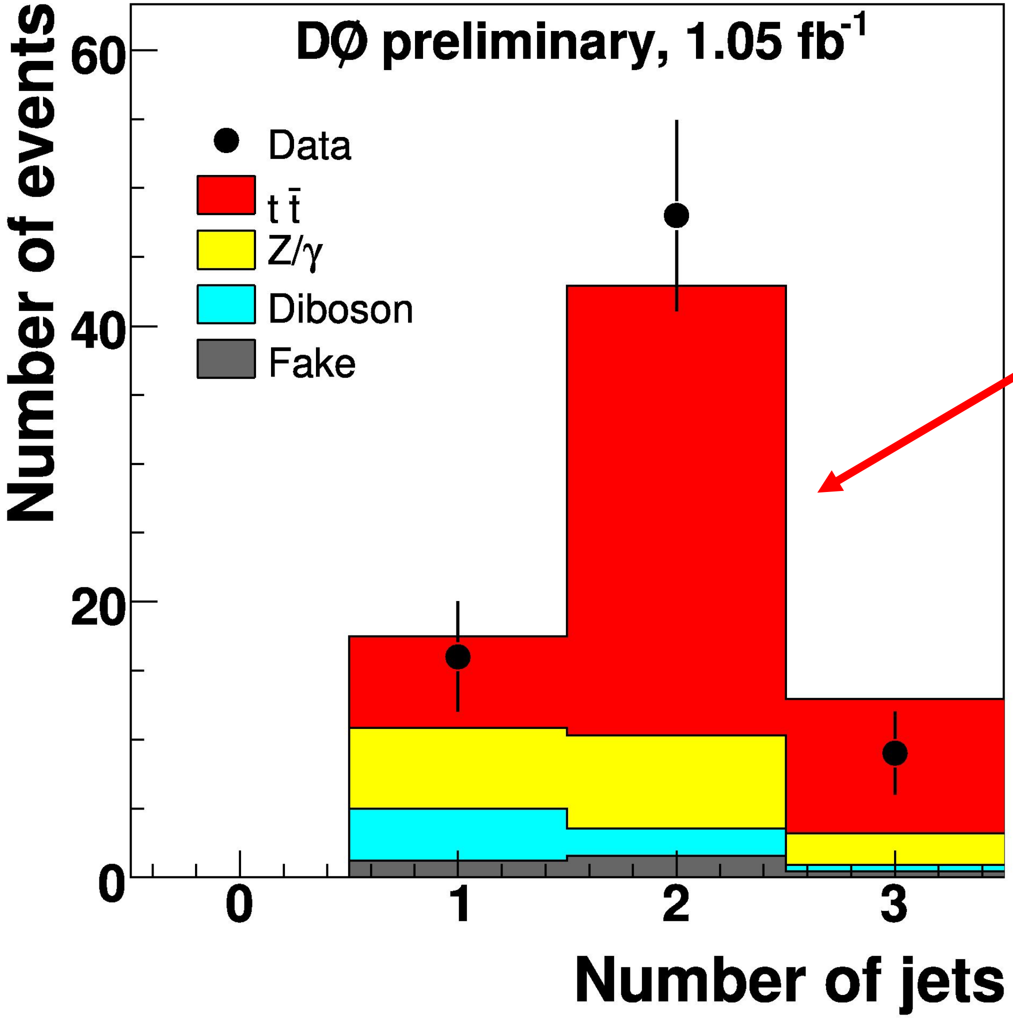
small background → precise measurement in future

Dilepton: Typical eμ Event



→ electron+muon event with b-tagging

Dilepton Topological Cross Section

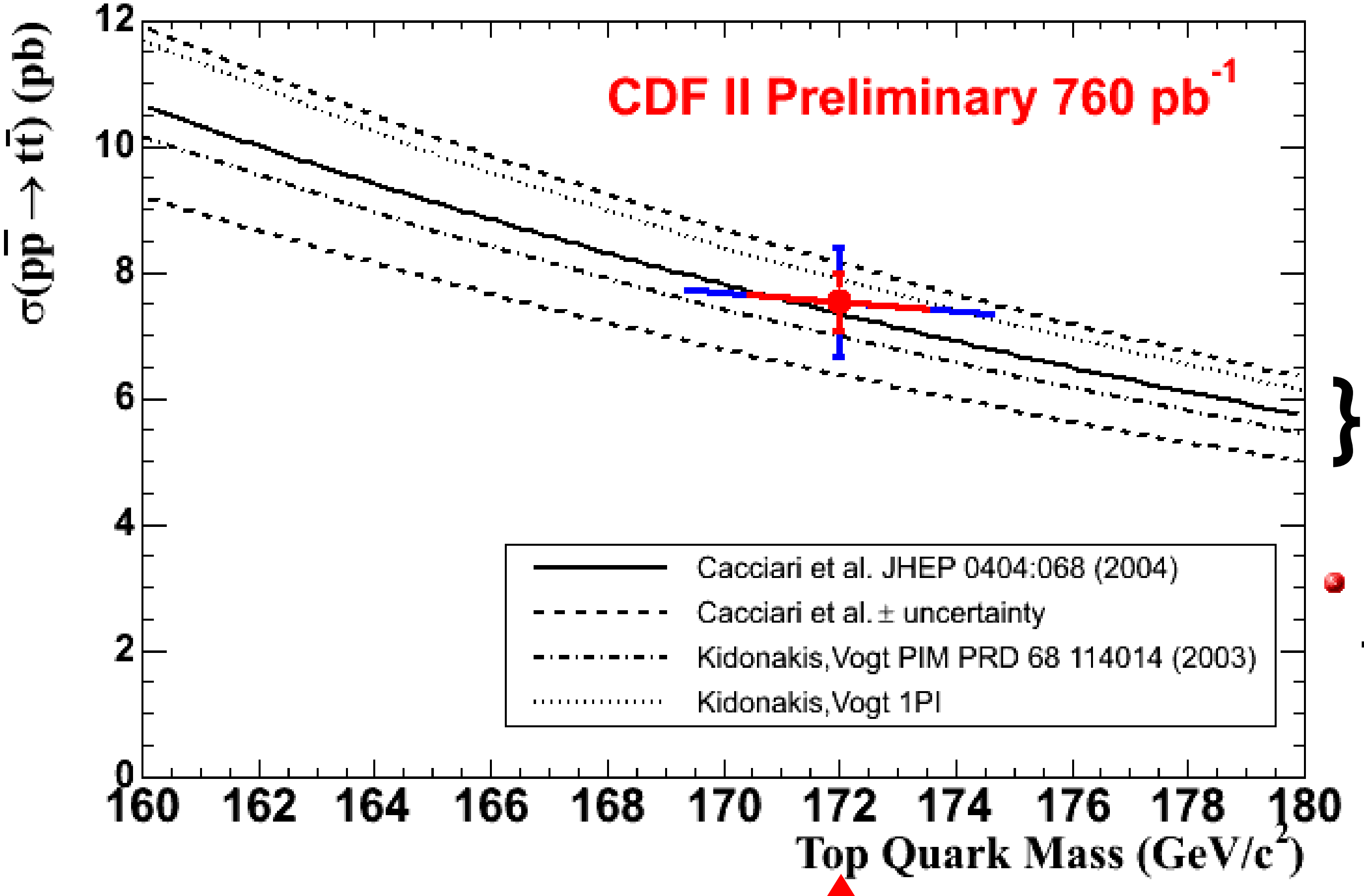


top pair

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

Top Pair Production Cross-Section

combined:



} SM

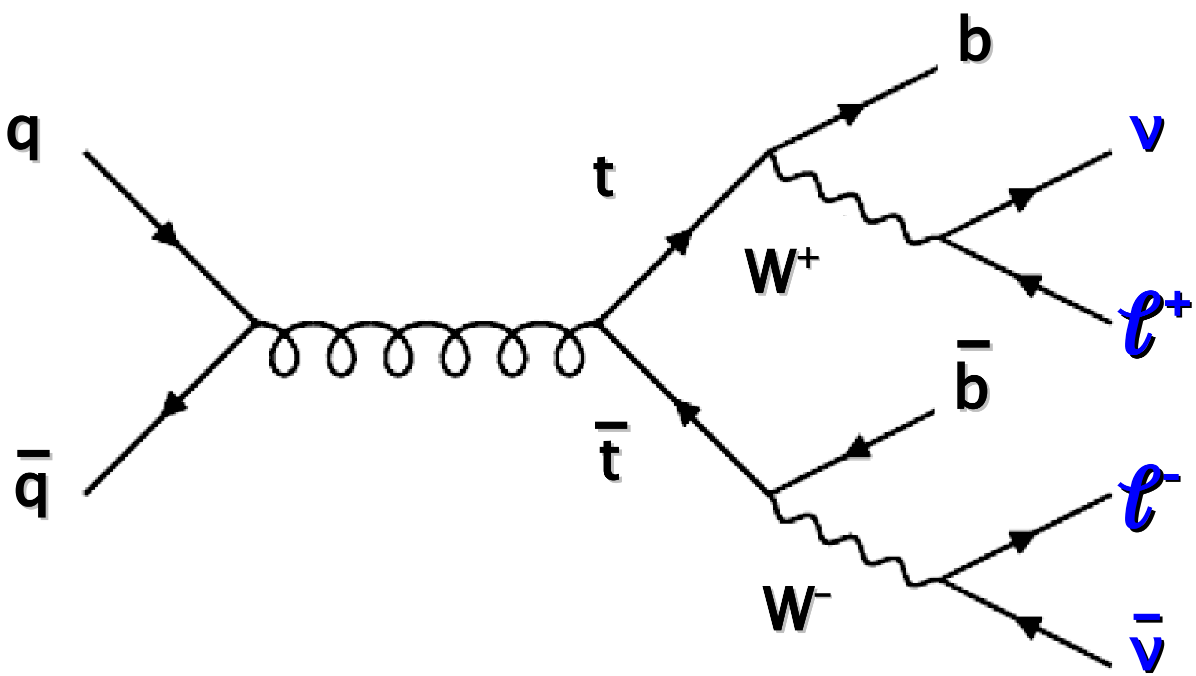
- need NNLO in the future...

σ_{tt} = 7.53 ± 0.87 pb for m_{top} = 172.0 ± 2.7 GeV

Measurement of cross section ratios

$$\frac{\sigma(t\bar{t})_{L+J}}{\sigma(t\bar{t})_{DIL}} = 1 \text{ in SM}$$

- 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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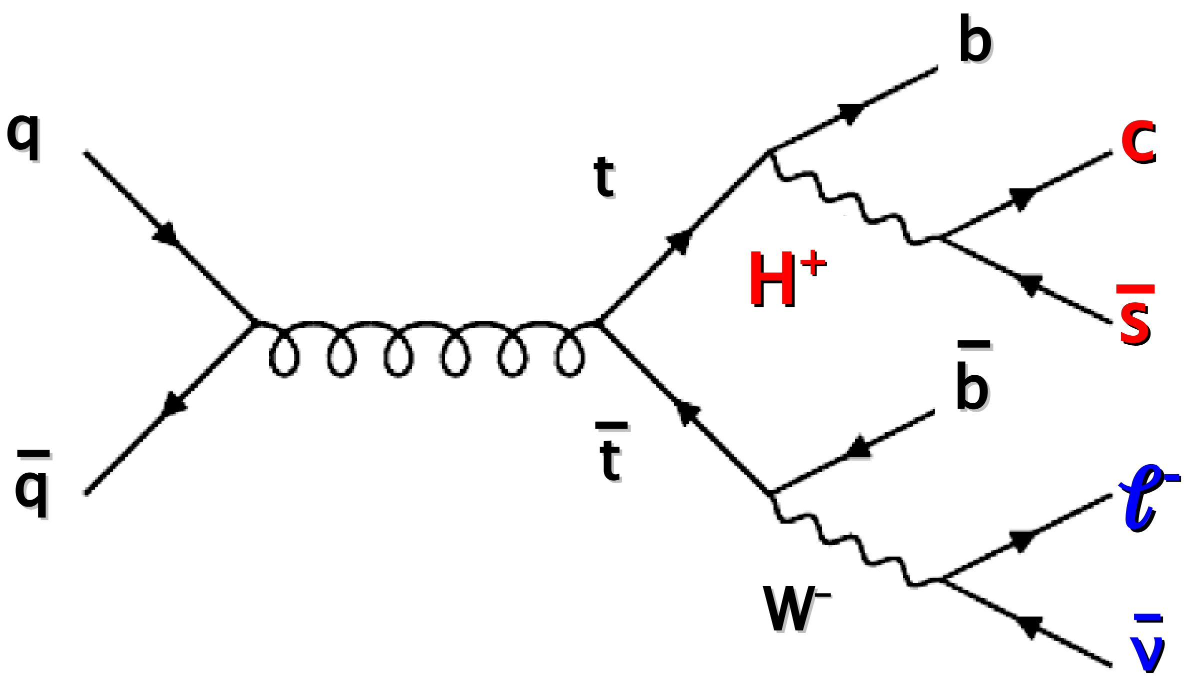


- radiative corrections in MSSM hep-ph/9907422
- in multi Higgs dublet models hep-ph/9509203 hep-ph/9401311

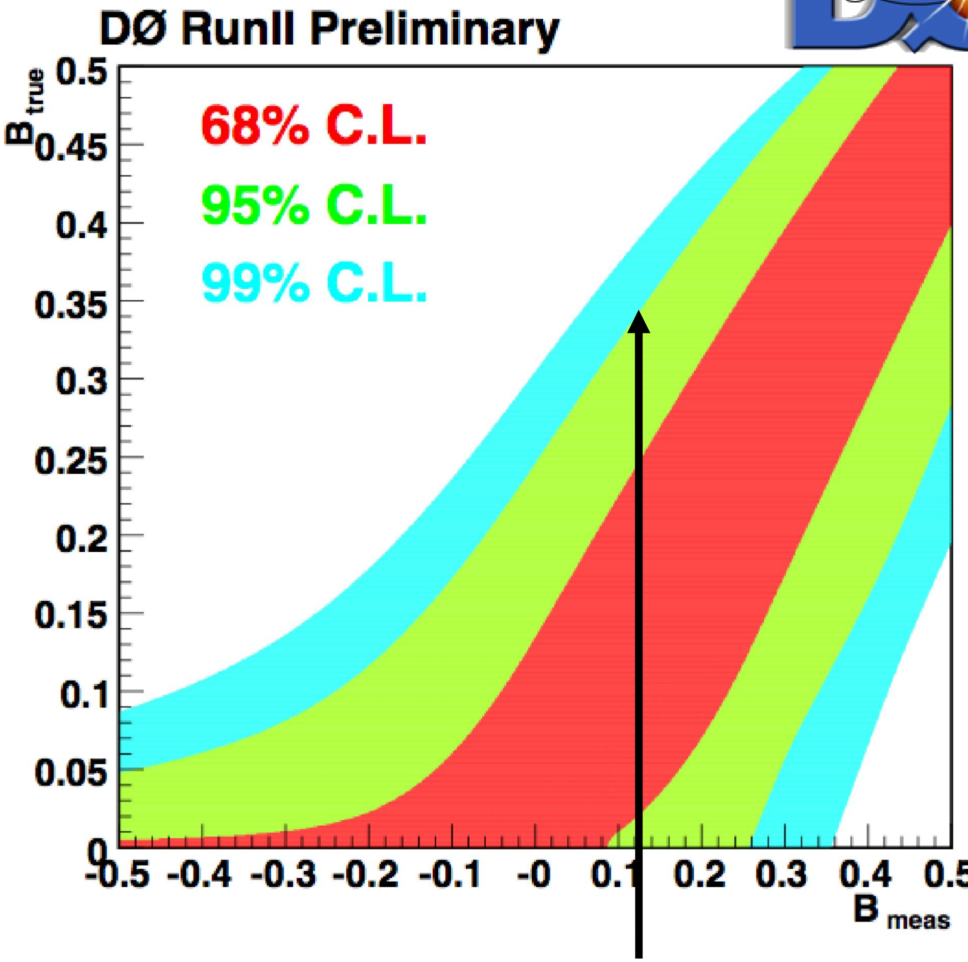
⇒ W disappearance

Cross section ratio and limit on $B(t \to b H^+)$

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

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

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

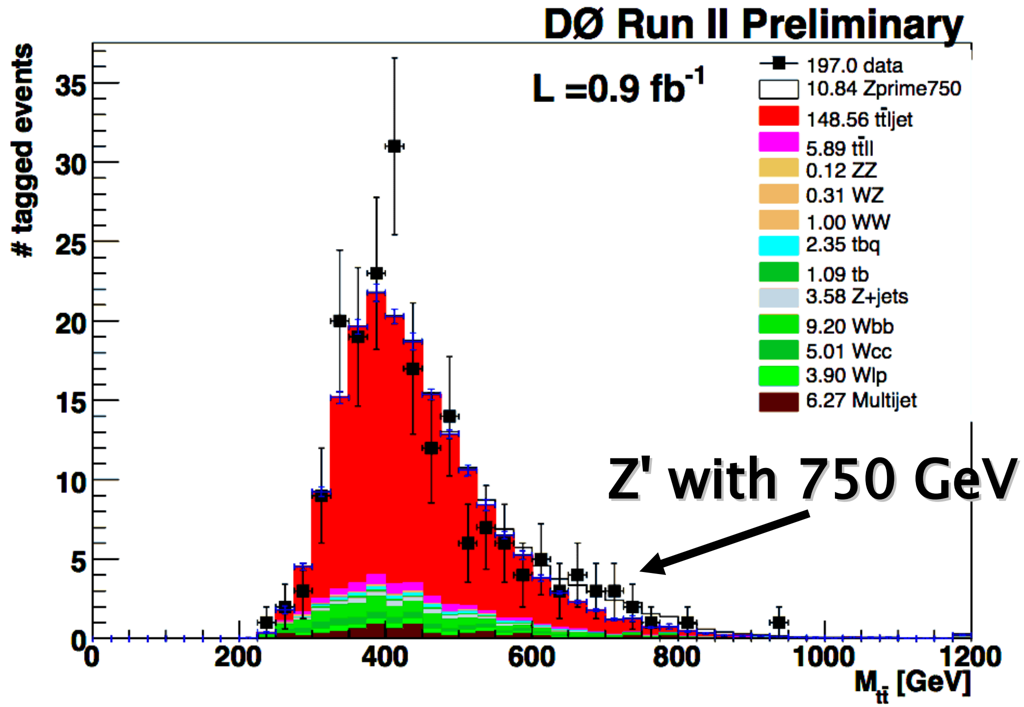


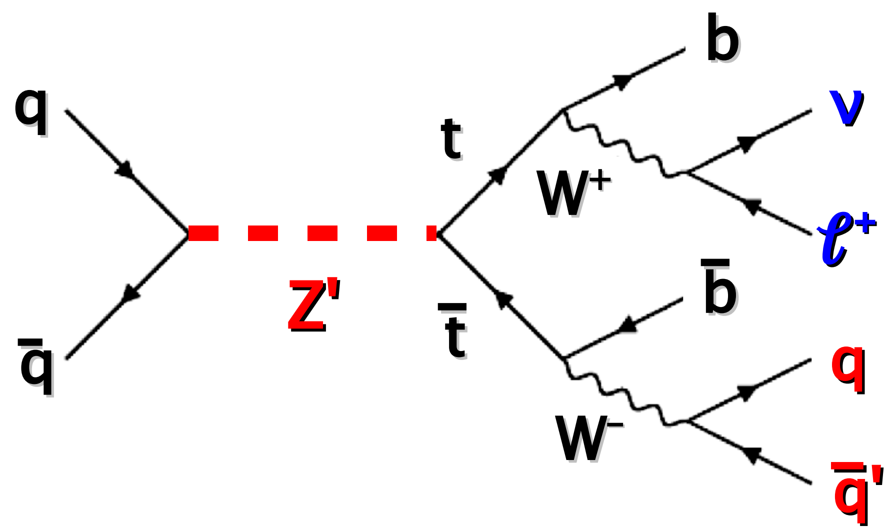
B < 0.35 @ 95% C.L.

Results for e, μ + jets combined

data and SM:

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

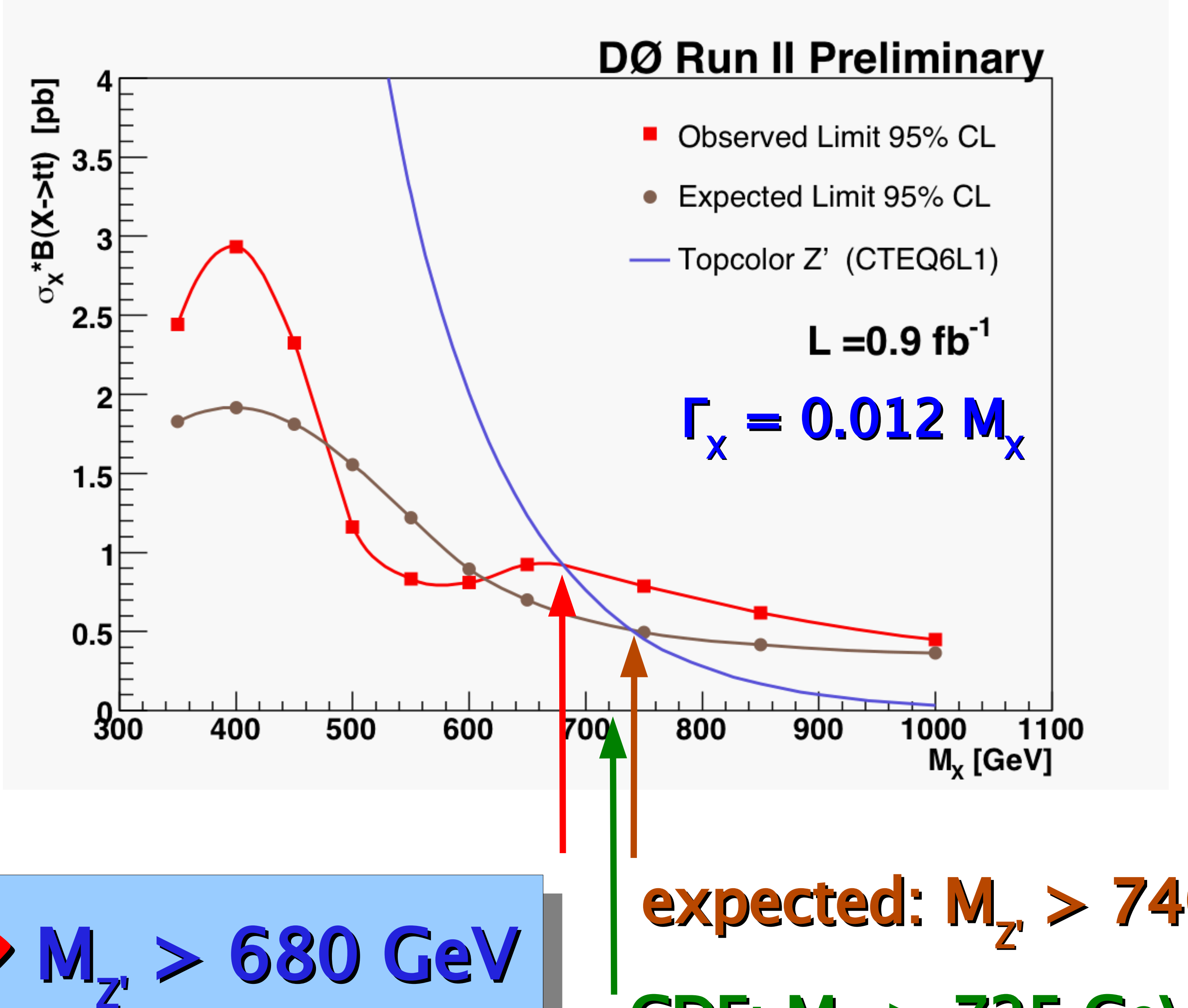




⇒ e, μ + jets combined: 197 events, 187 expected

⇒ binned Likelihood fit to get upper limit

Limits for e, μ + jets combined



⇒ $M_{Z'} > 680$ GeV

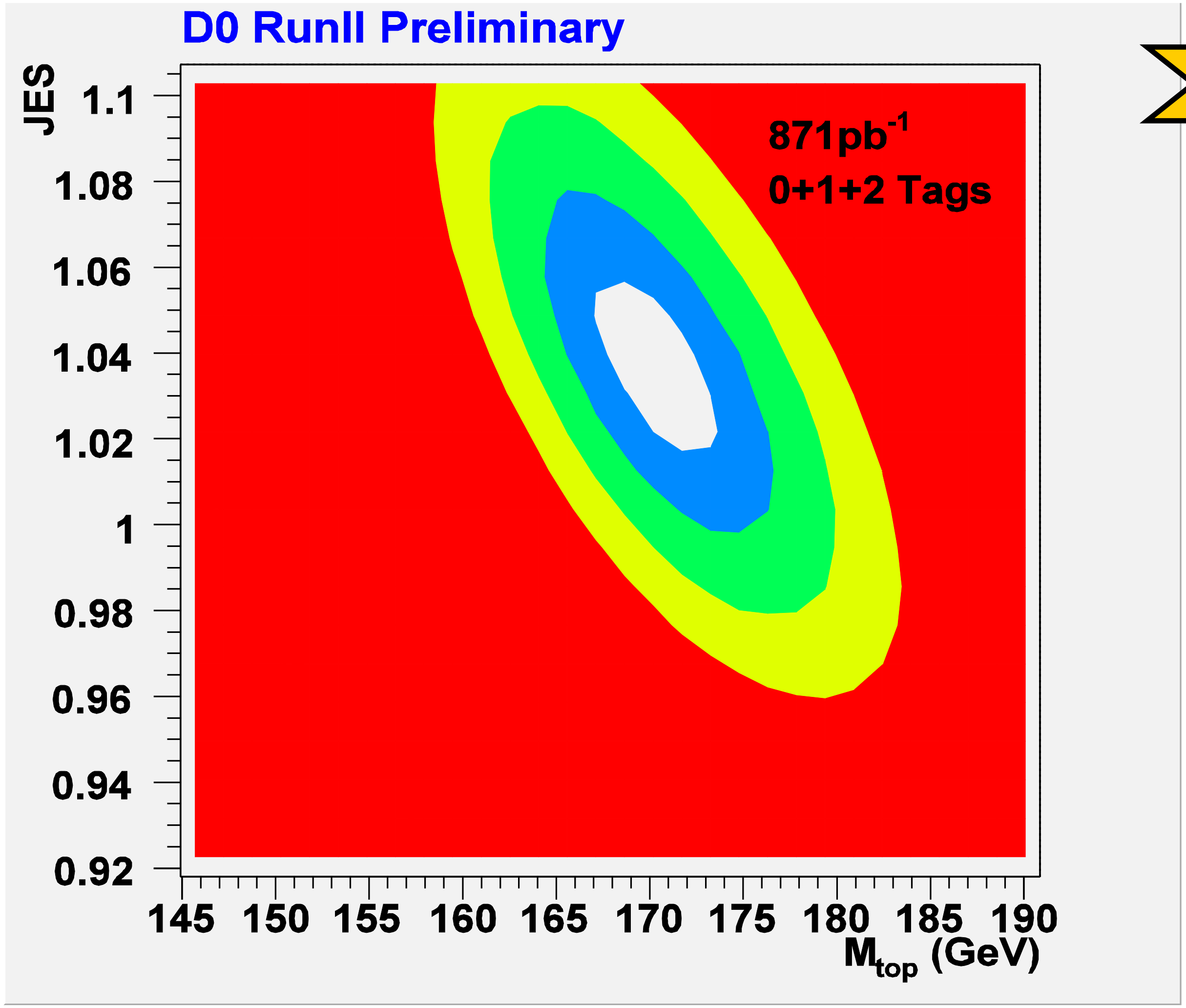
expected: $M_{Z'} > 740$ GeV

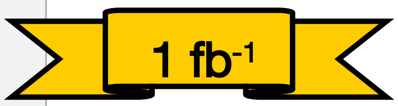
CDF: $M_{Z'} > 725$ GeV

Results for Matrix Element Method

- maximum Likelihood fit using signal and background pdfs

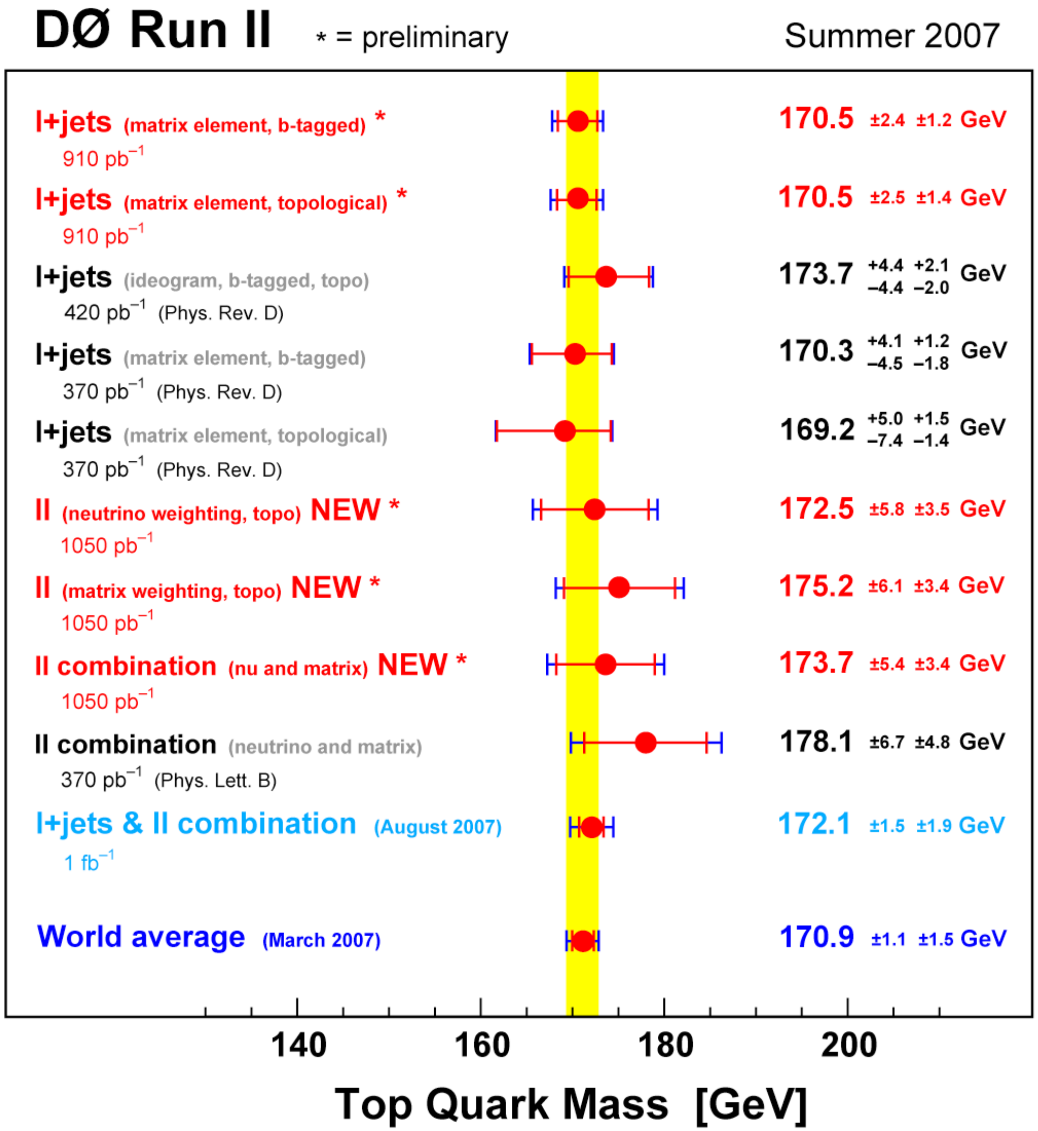
jet energy scale





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

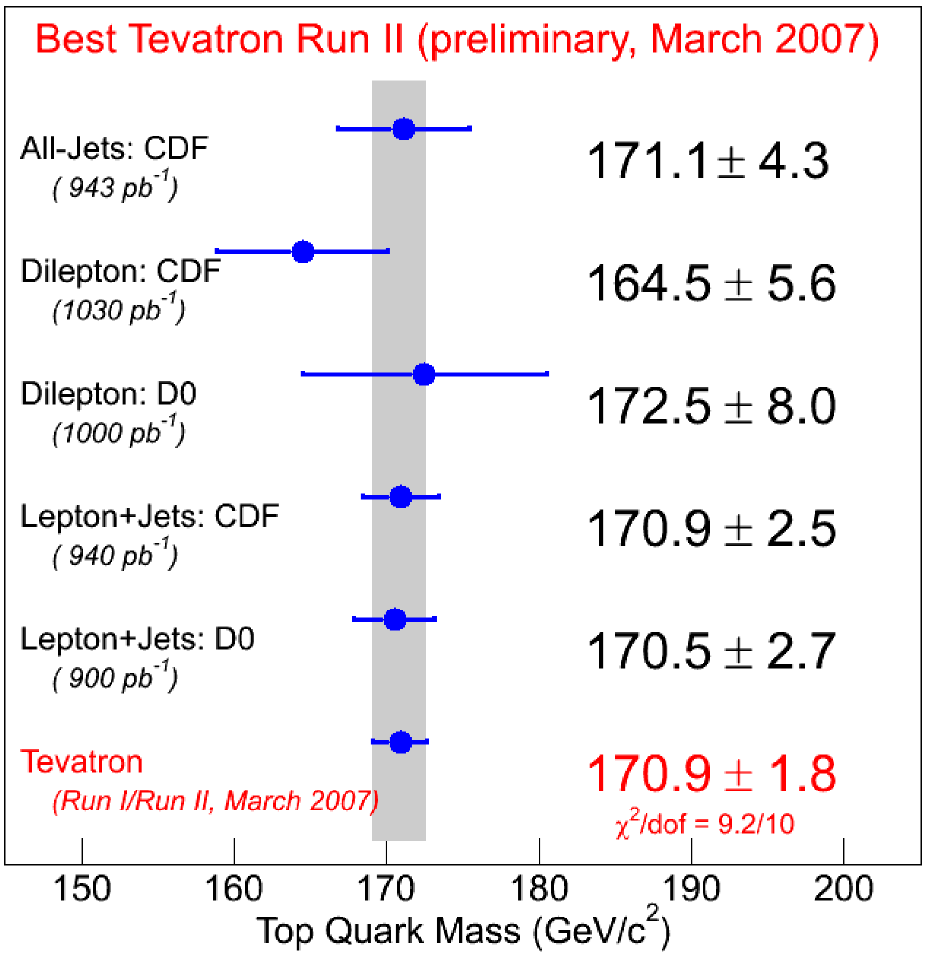
Tevatron Combination: March 2007



$$m_{top} = 170.9 \pm 1.8 \text{ GeV}$$

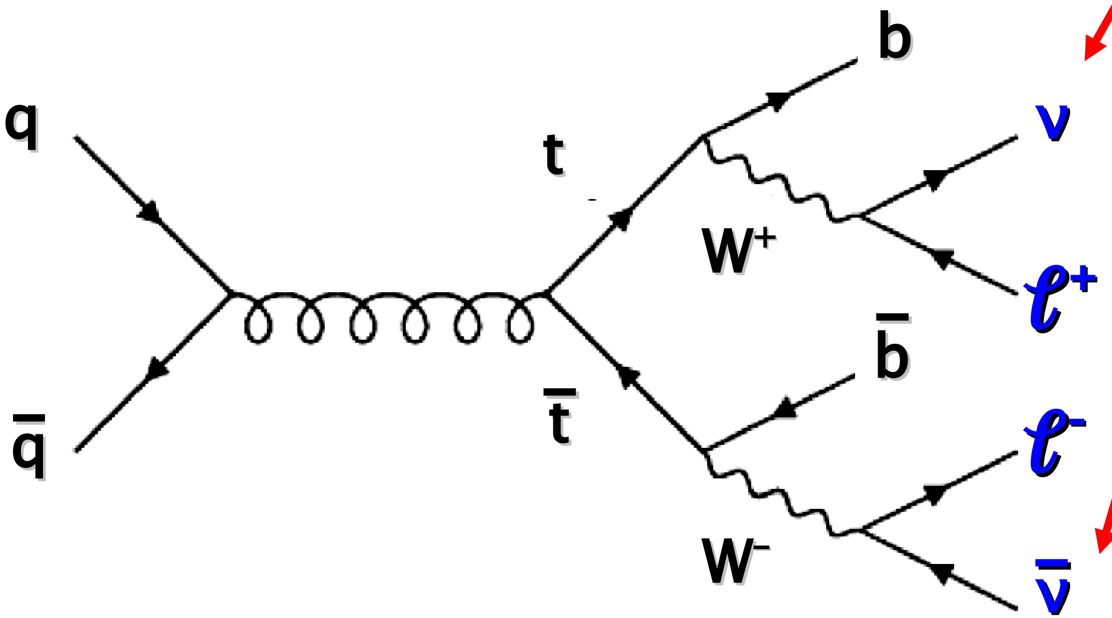
1 fb^{-1}

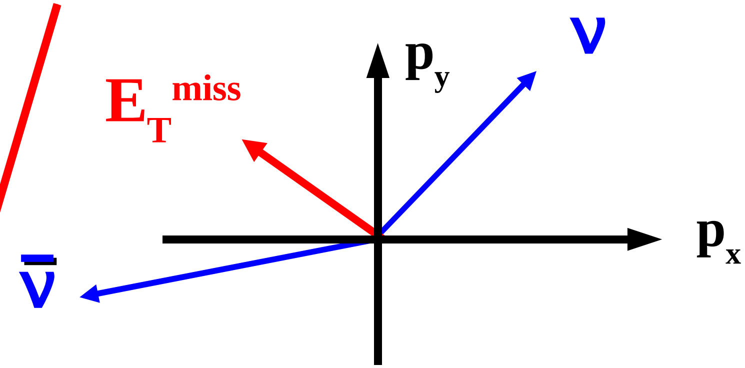
- account for correlations



Dilepton-Channel: Neutrino Weighting

2 neutrinos: kinematics underconstrained



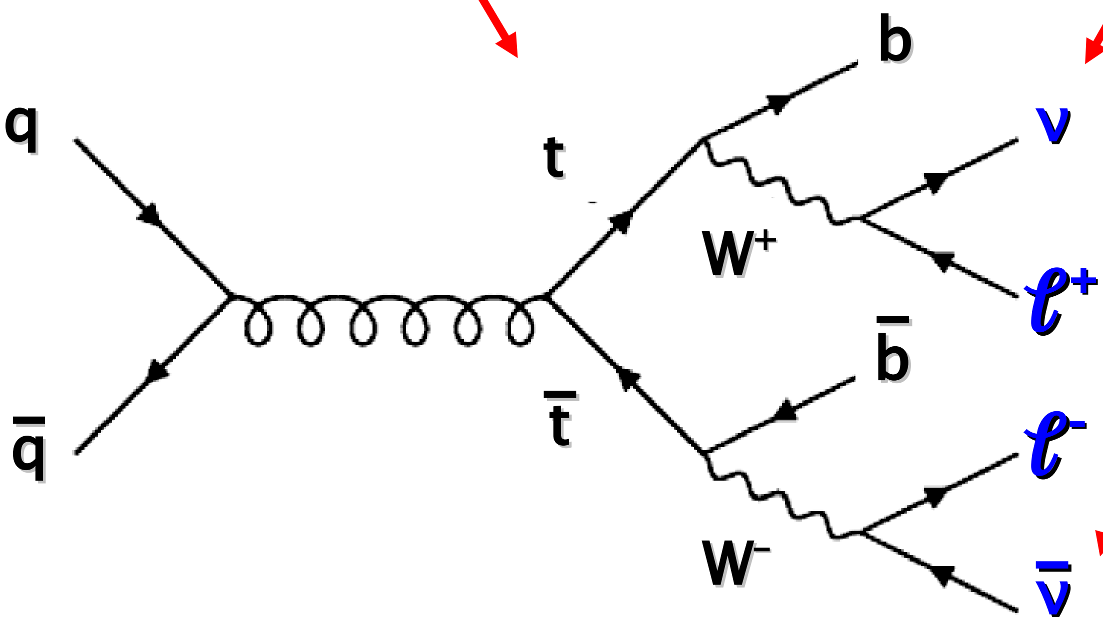


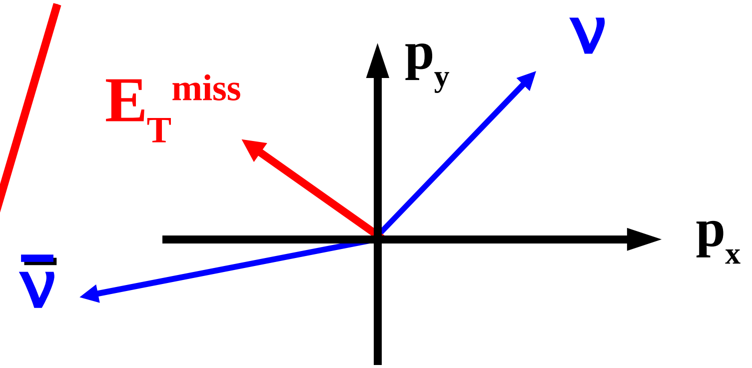
no ν p_z information

Dilepton–Channel: Neutrino Weighting

- assume top mass

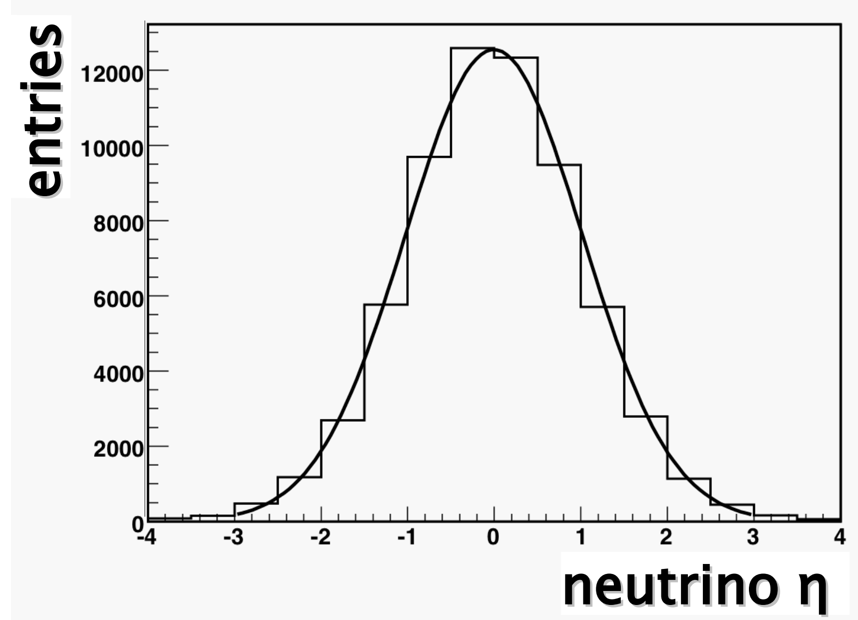
2 neutrinos:
kinematics underconstrained





no ν p_z information

- take (anti–) neutrino η from MC



Dilepton–Channel: Neutrino Weighting

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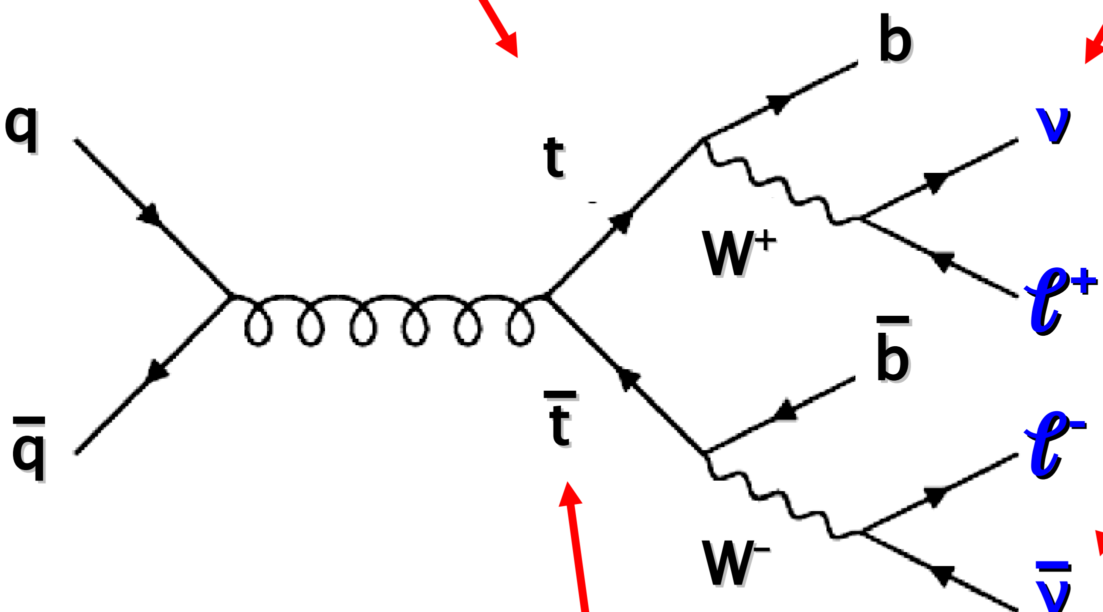

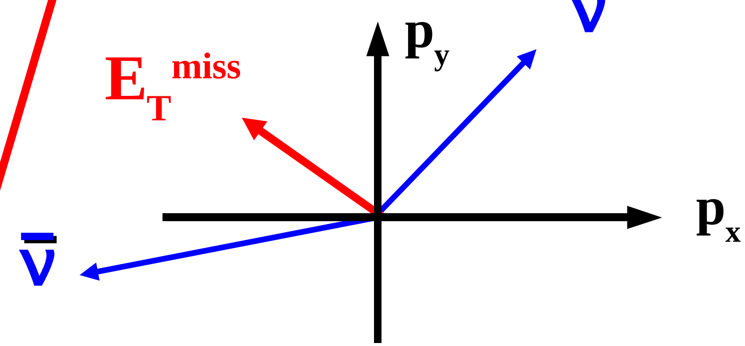

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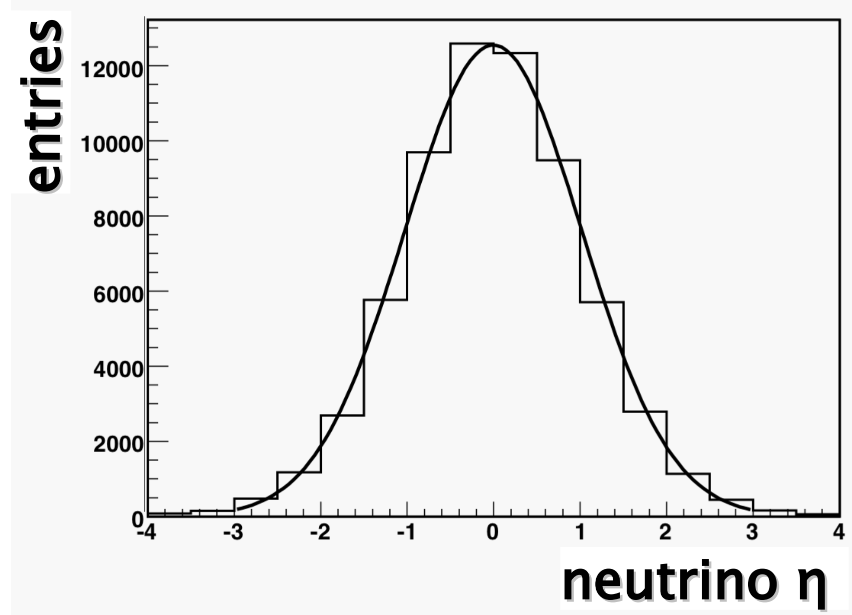
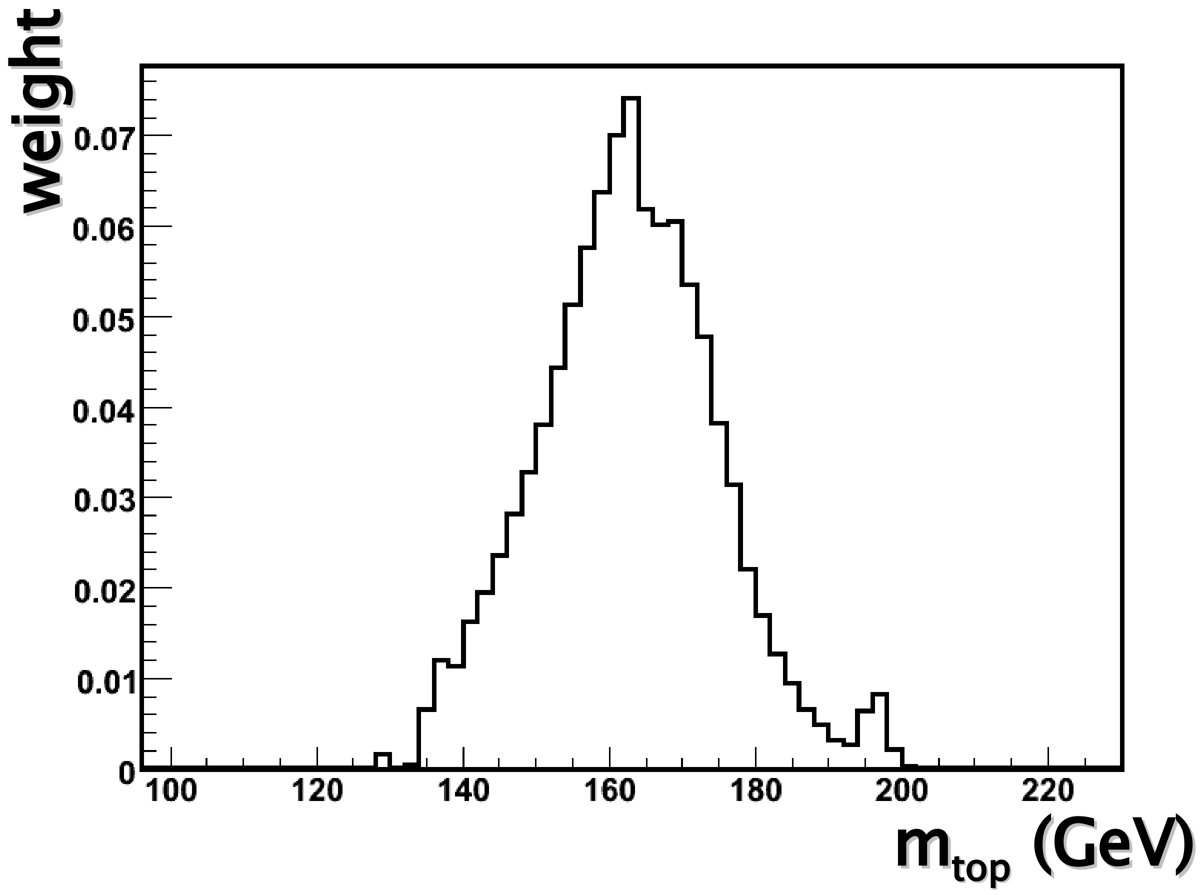


- sum over all solutions

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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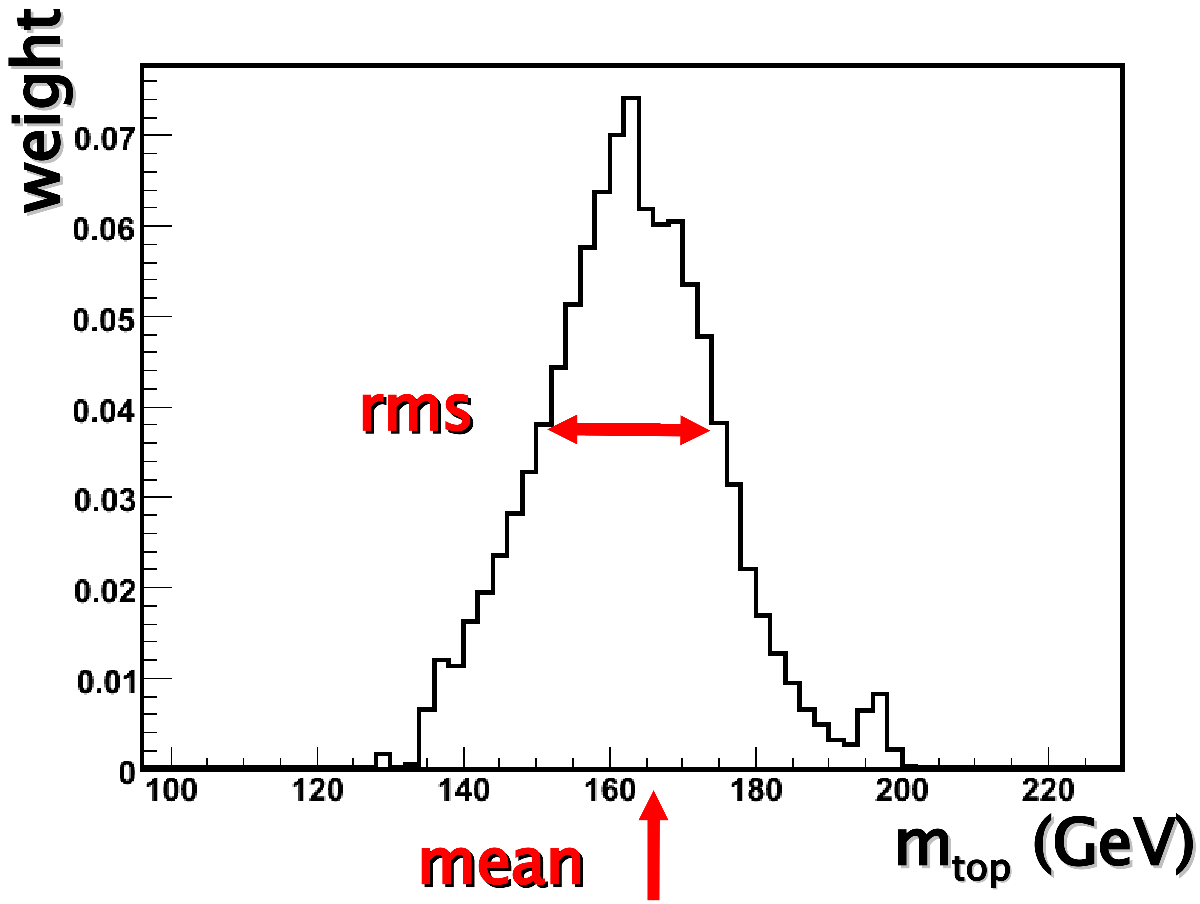


- extract templates

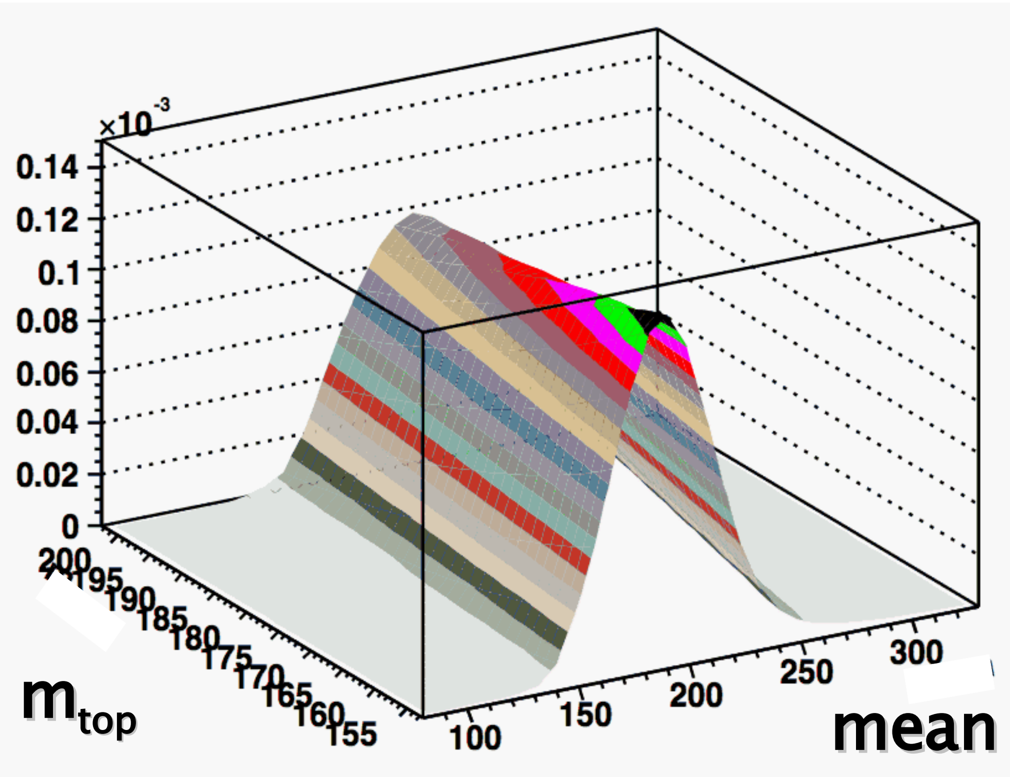
Neutrino Weighting Method: Result

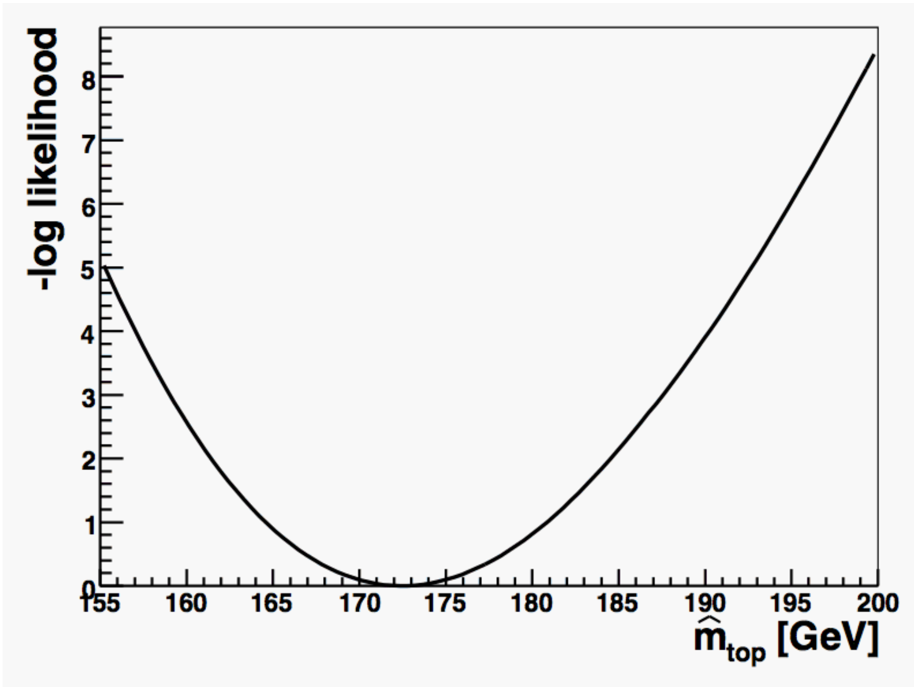
NEW: simultaneous 3 (2)-dimensional fit to signal (background) templates

rms=45 GeV

1 fb^{-1}

- 57 events



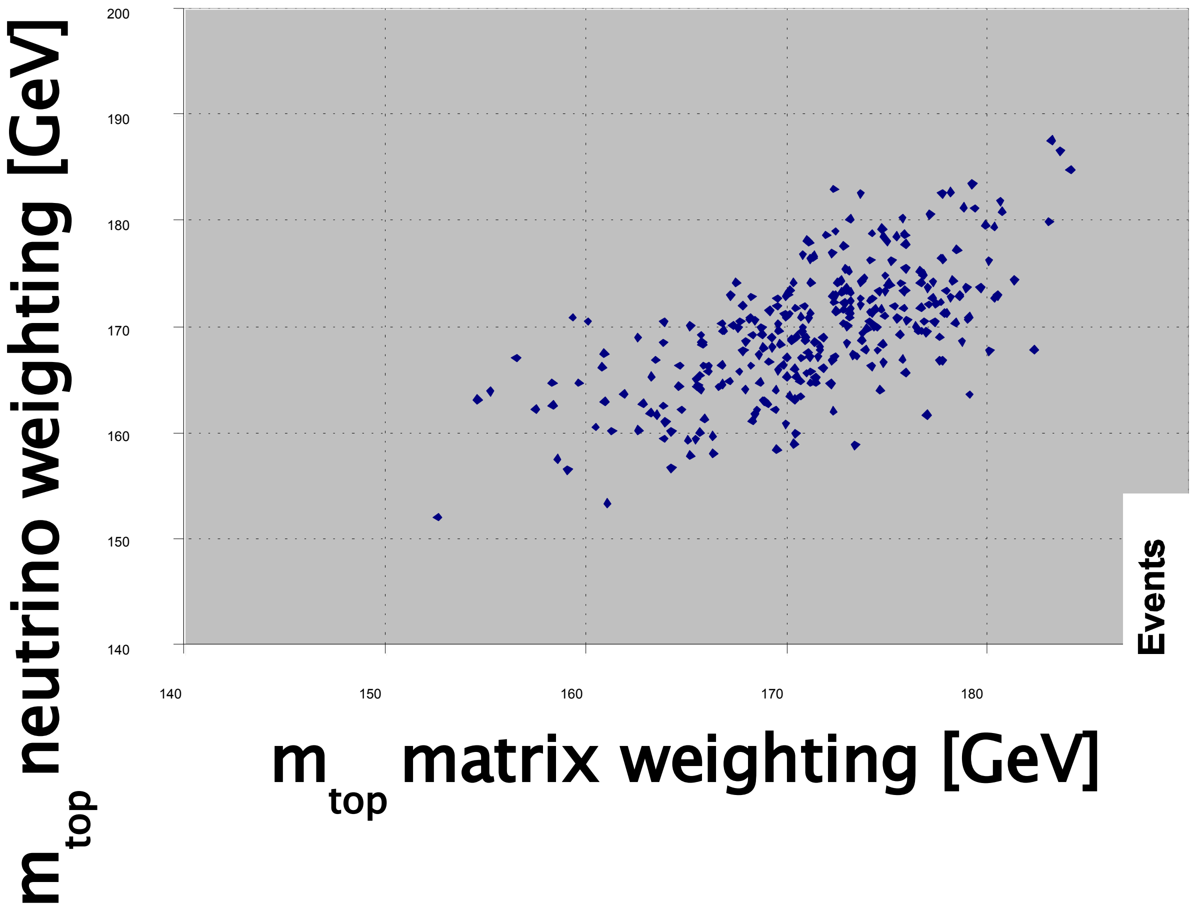


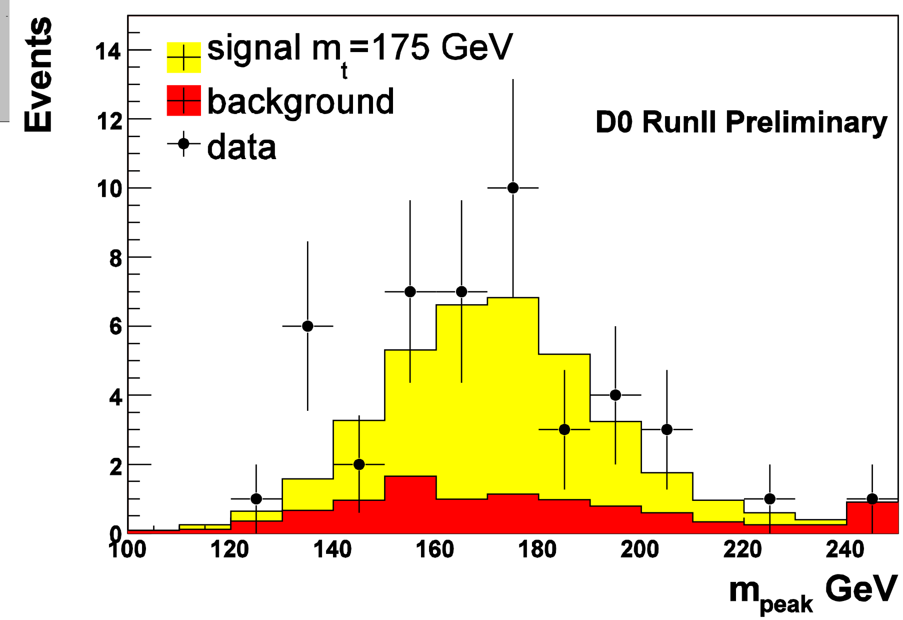
- maximum Likelihood function $L(m_{top}, mean, rms)$:

PRELIMINARY

$$m_{top} = 172.5 \pm 5.8(stat.) \pm 3.5\ (syst.)\ \ GeV$$

Combination for matrix/neutrino weighting





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

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

"Bare" parameters of QCD:

$$g_s,\ m_u,\ m_d,\ m_s,\ m_c,\ m_b,\ m_t$$

Renormalised parameters of QCD:

$$g_s(M),\ m_u(M),\ m_d(M),\ m_s(M),\ m_c(M),\ m_b(M),\ m_t(M)$$

the concept of quark mass is convention-dependent!

Differences in top mass definitions

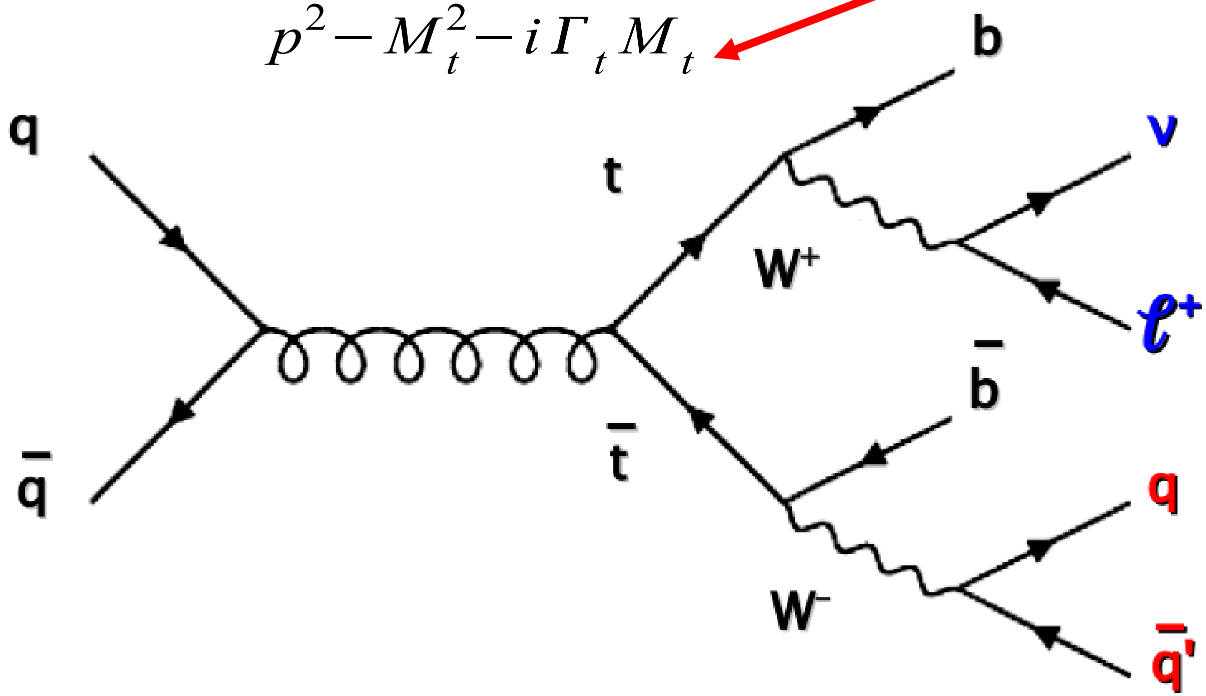
hep-ph/0001002

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

pole mass

$\overline{\mathrm{MS}}$ scheme

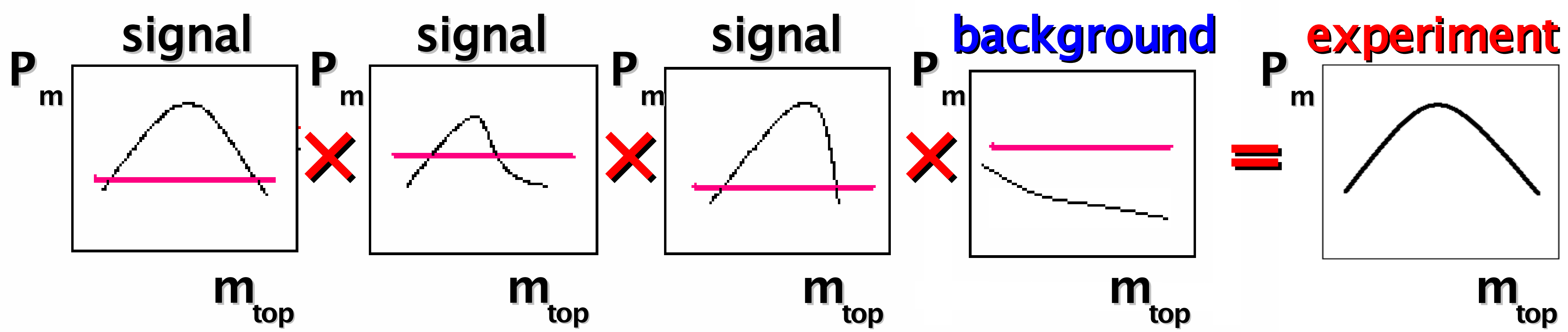
$$\frac{1}{p^2 - M_t^2 - i\Gamma_t M_t}$$



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

Extraction techniques: Matrix Element

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



- Maximum Likelihood fit

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

Acceptance (selection, trigger,...)

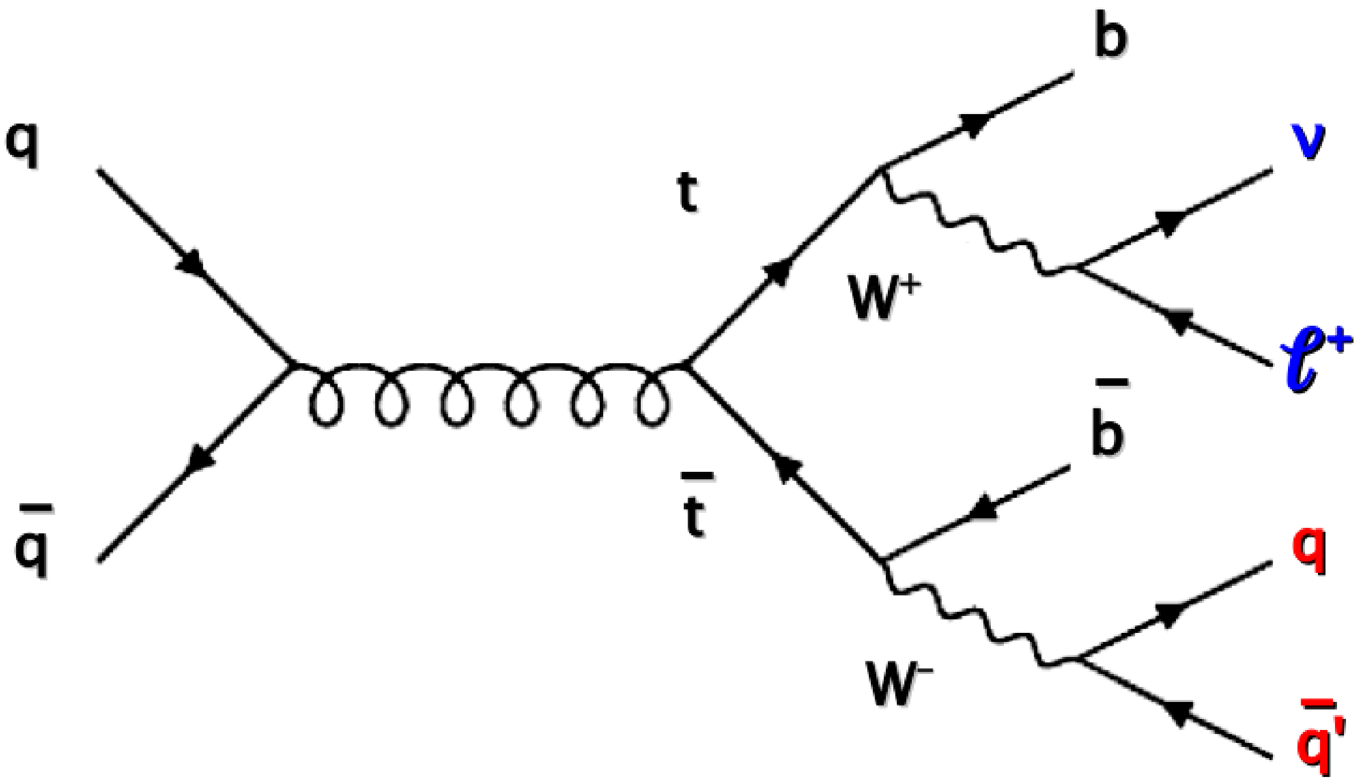
LO-Matrix element x phase space

PDF's

Transfer Functions (Probability to measure x when y was produced)

What top mass is in a LO Monte Carlo?

- **matrix element in LO QCD**



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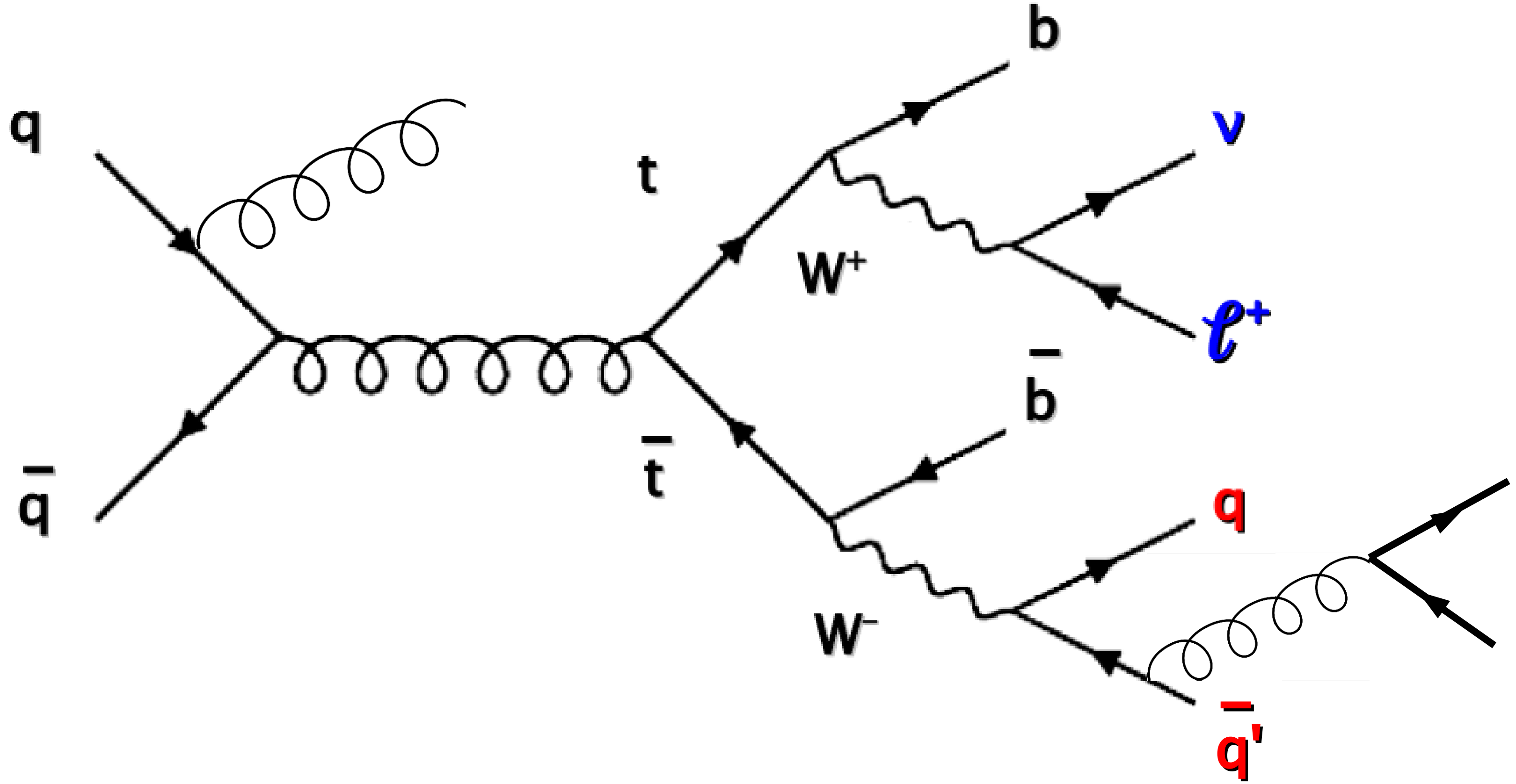
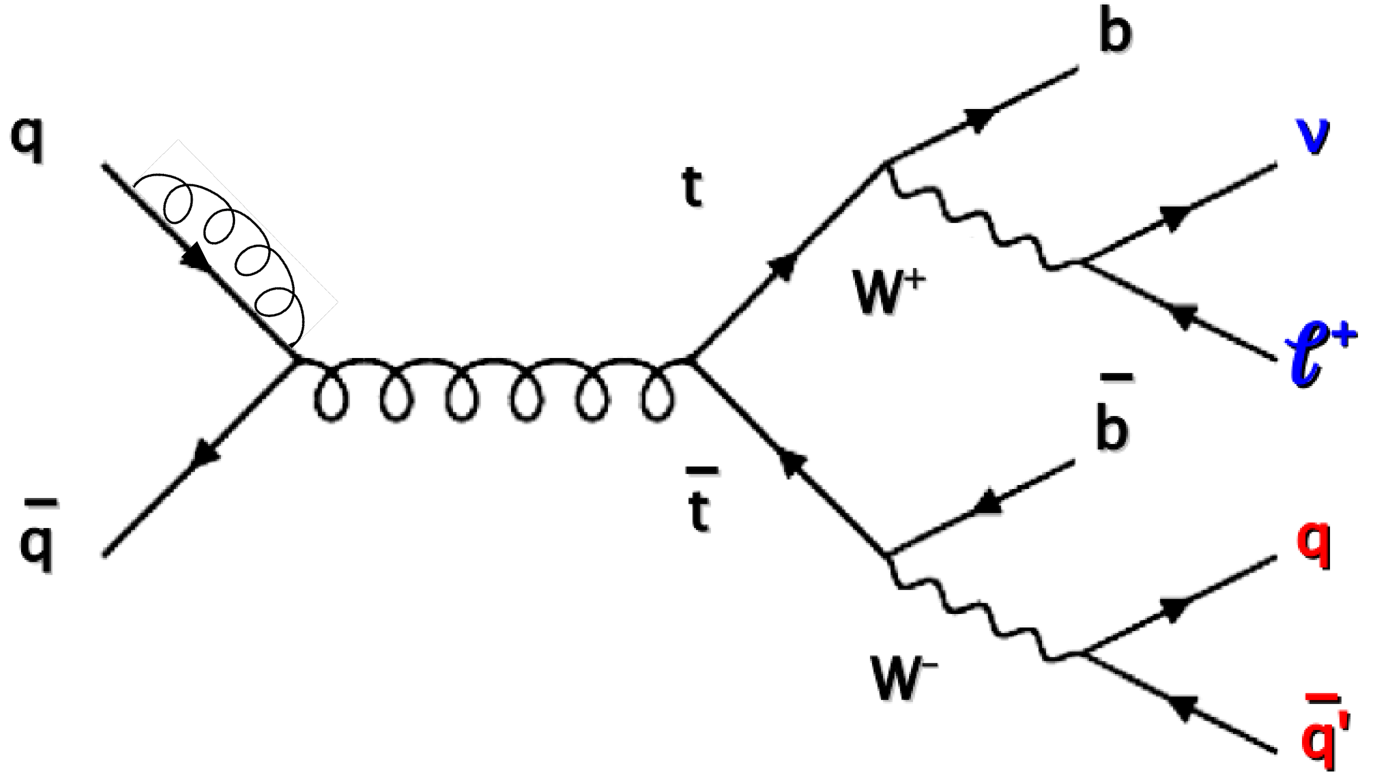


- parton showers simulate higher orders,

What top mass is in a LO Monte Carlo?

- matrix element in LO QCD



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

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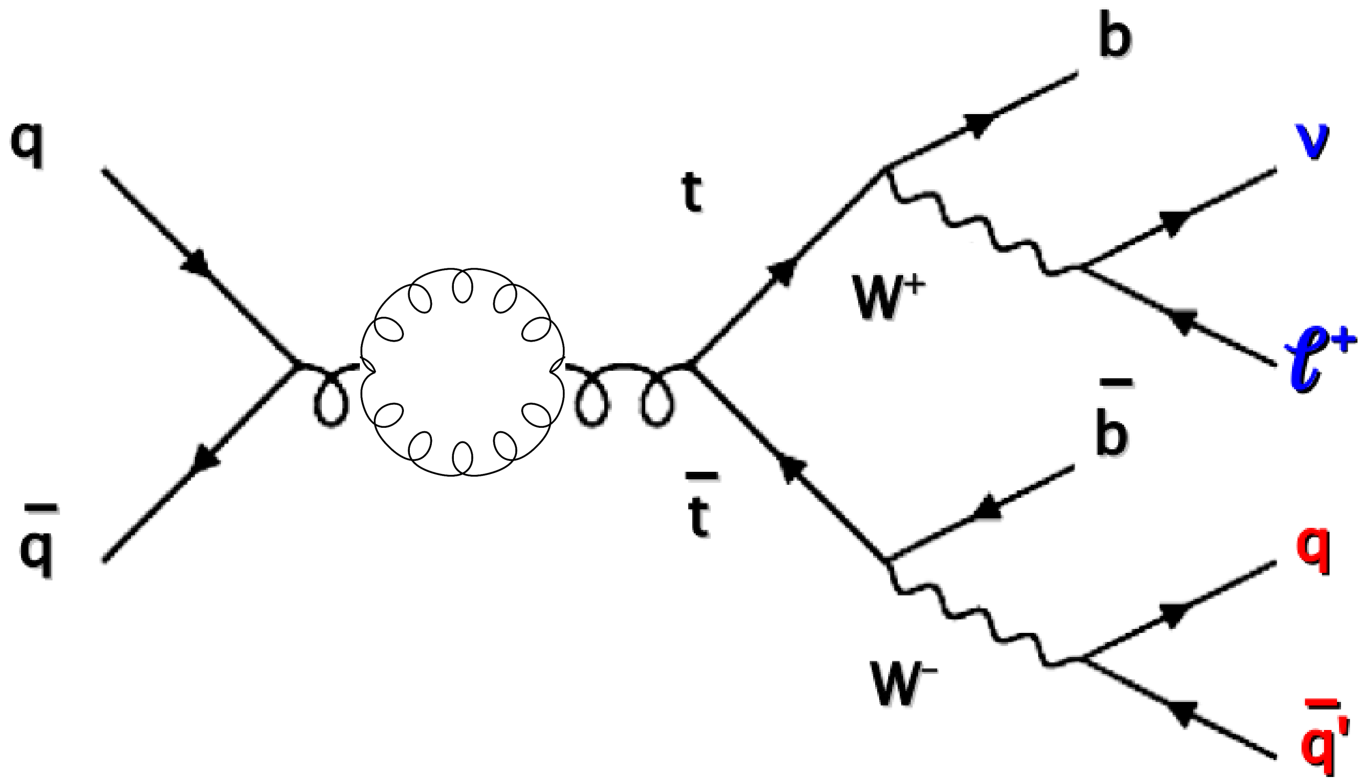

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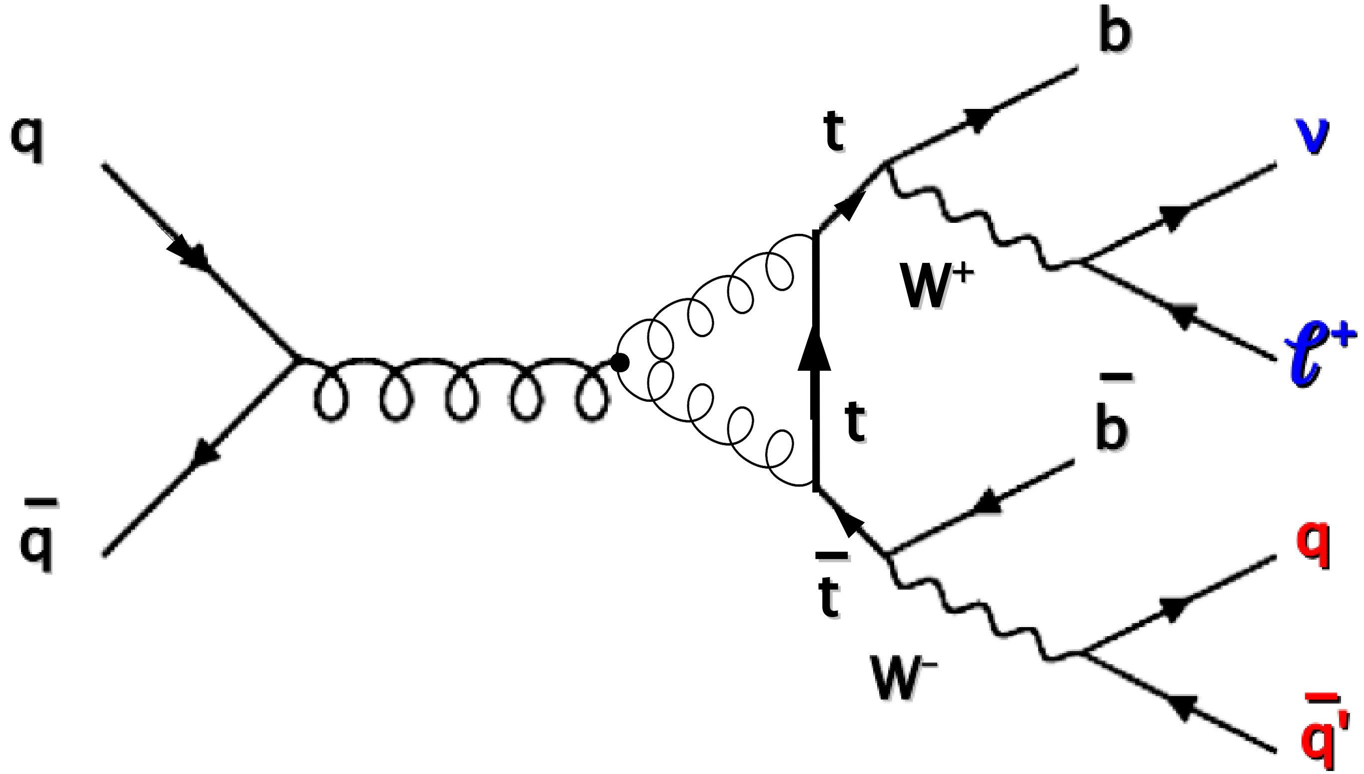

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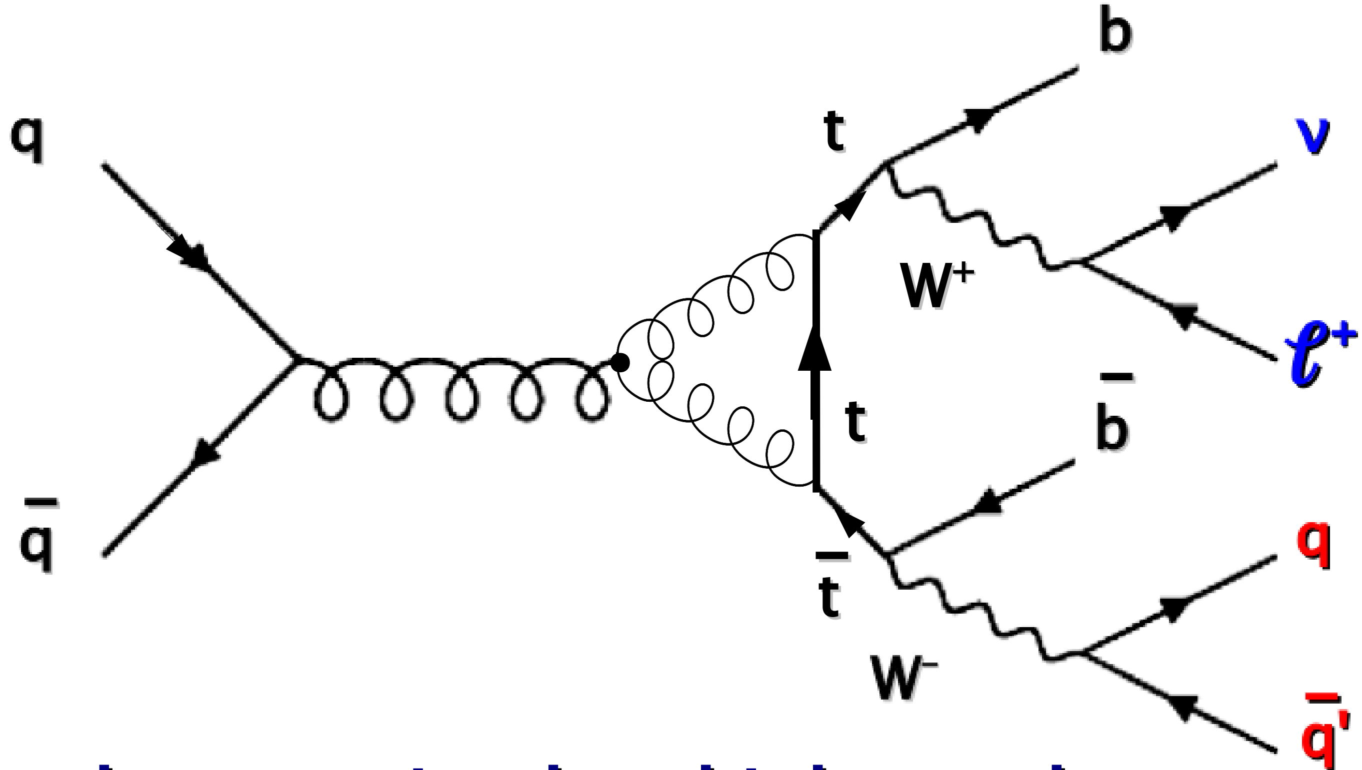


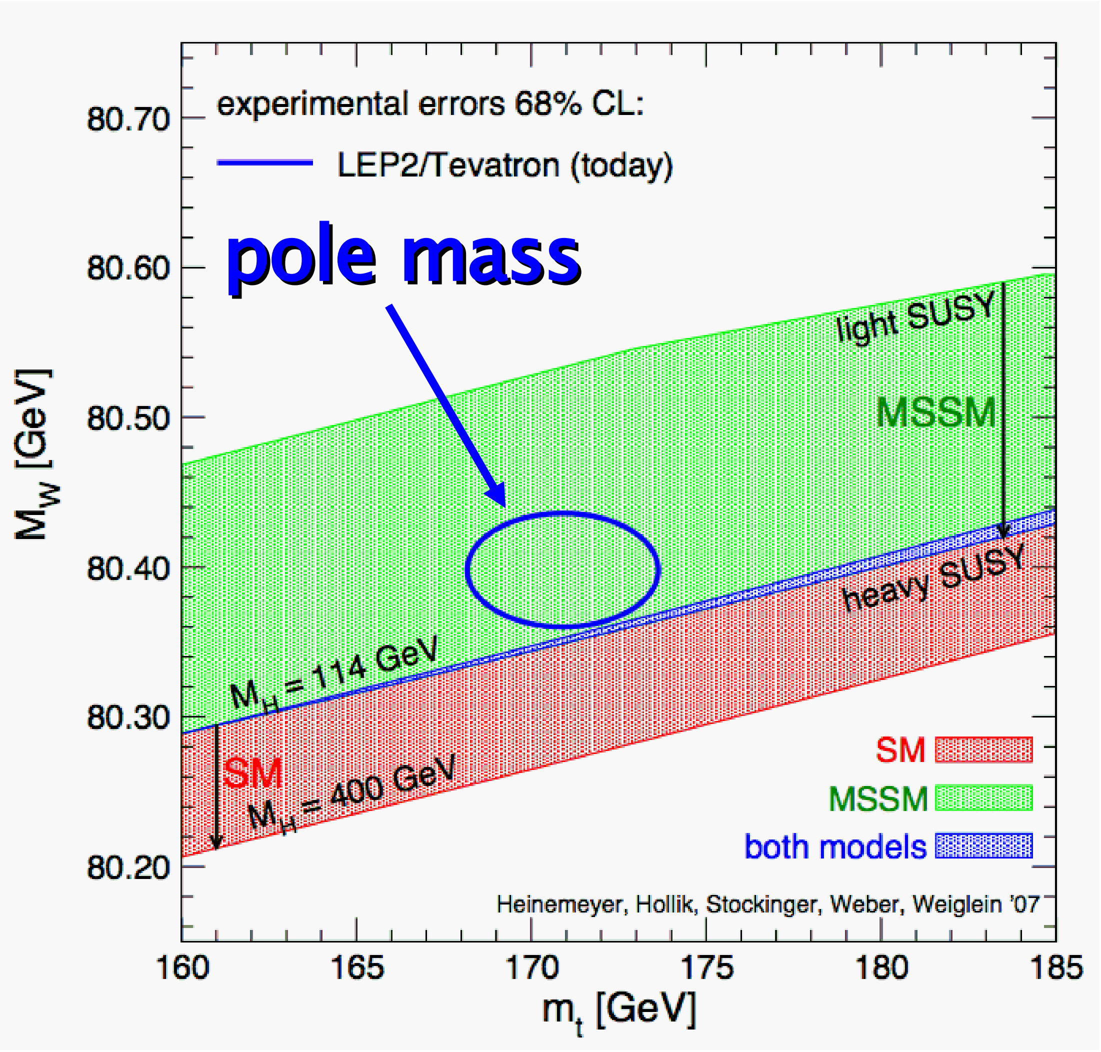
- parton showers simulate higher orders, i.e. not only radiating additional gluons!

⇒ 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} = 170.9 ± 1.8 GeV

m_W = 80398 ± 25 MeV

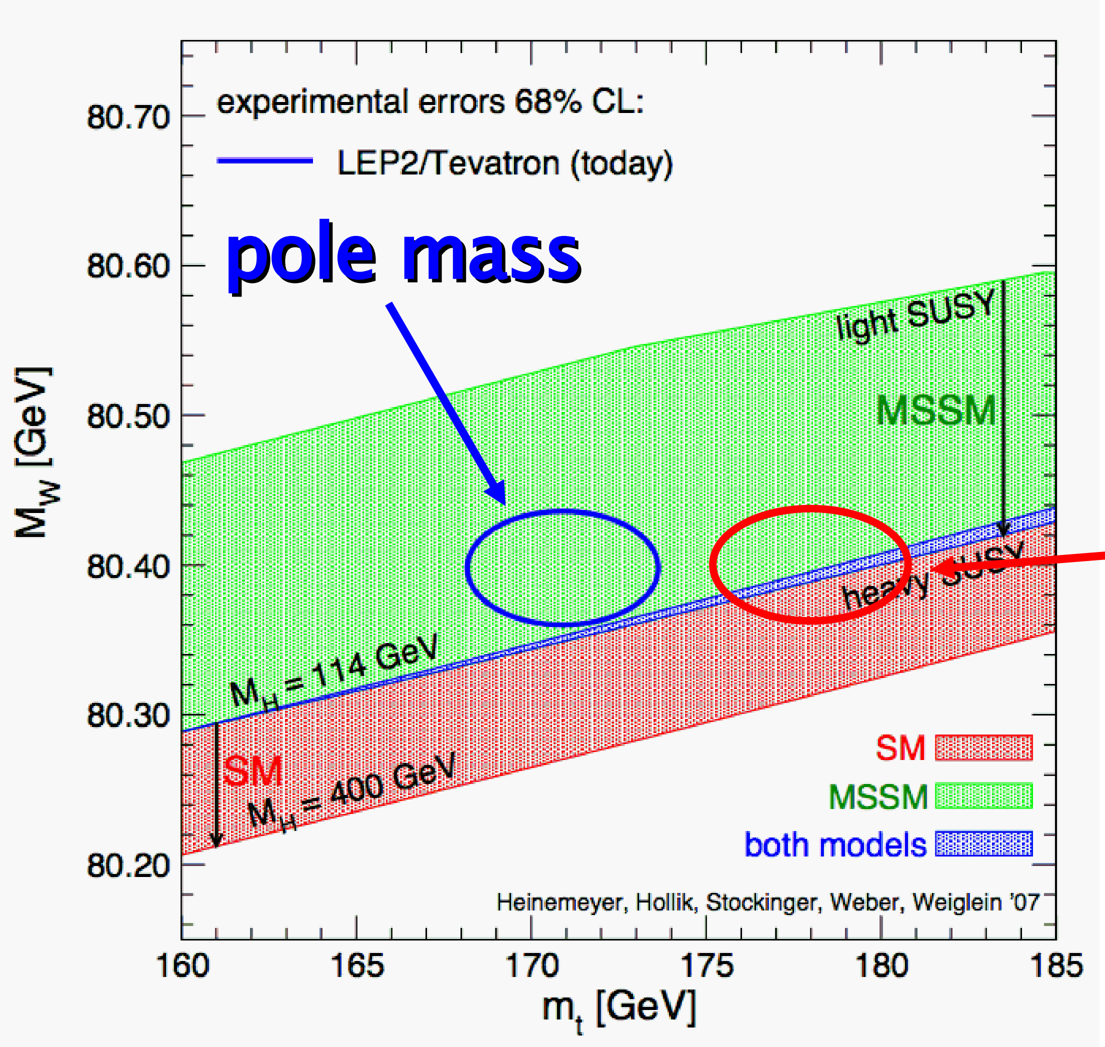
world average (March 2007)

- **will continue at the LHC!**

Heinemeyer, Hollik, Stockinger, Weber, Weiglein 2007

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} = 170.9 ± 1.8 GeV

m_W = 80398 ± 25 MeV

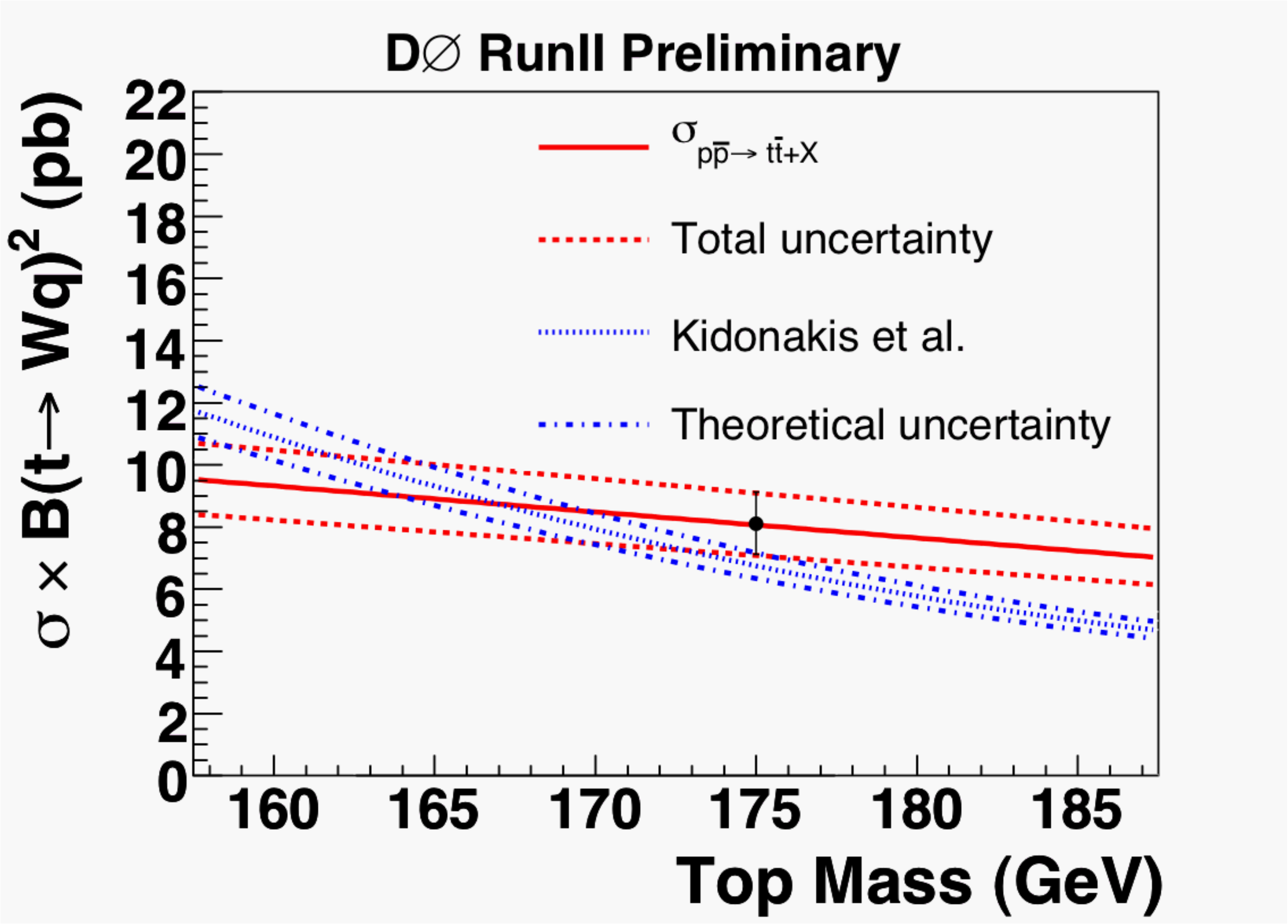
world average (March 2007)

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

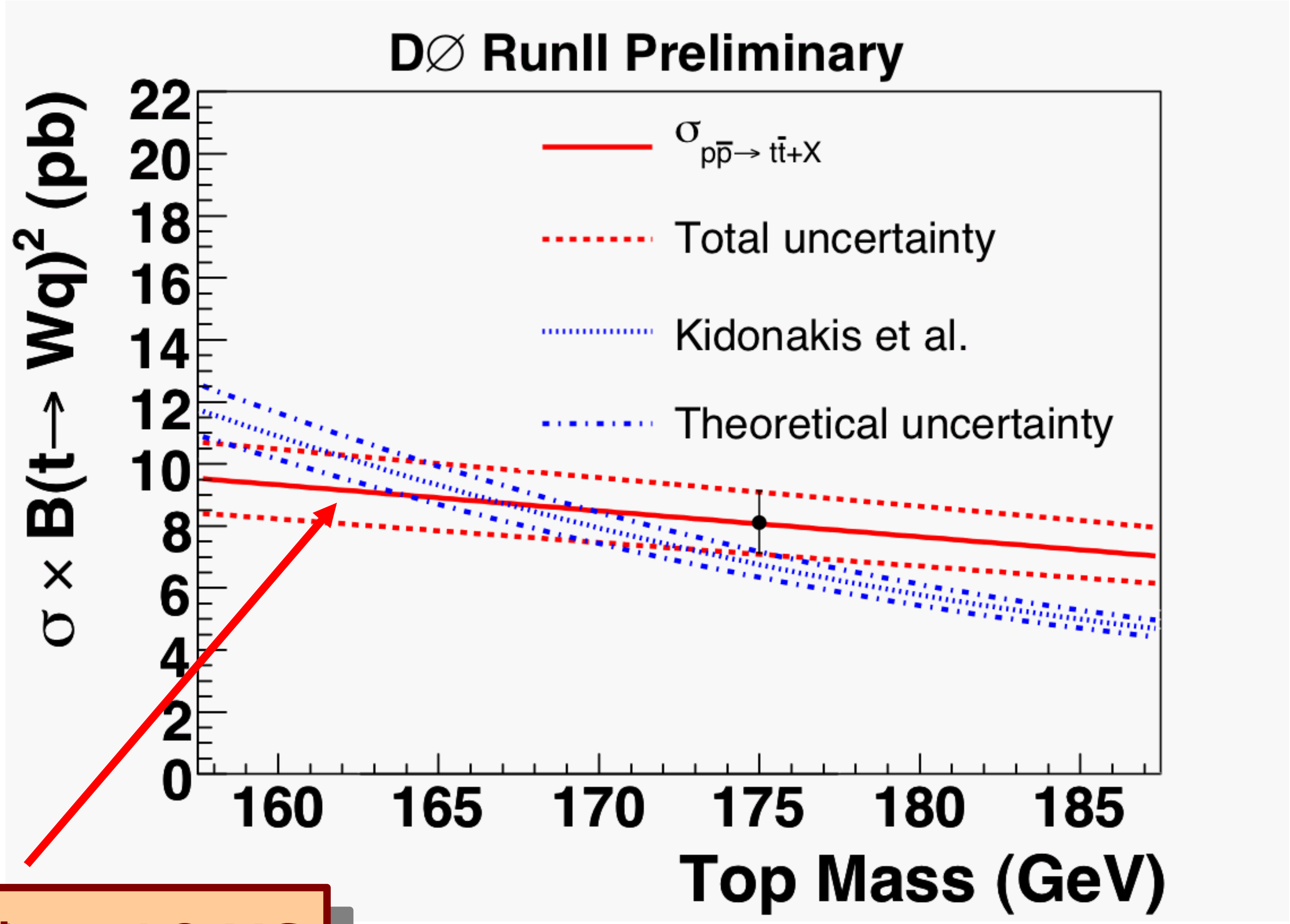
- will continue at the LHC!

Heinemeyer, Hollik, Stockinger, Weber, Weiglein 2007

Top mass from cross section measurement



Top mass from cross section measurement

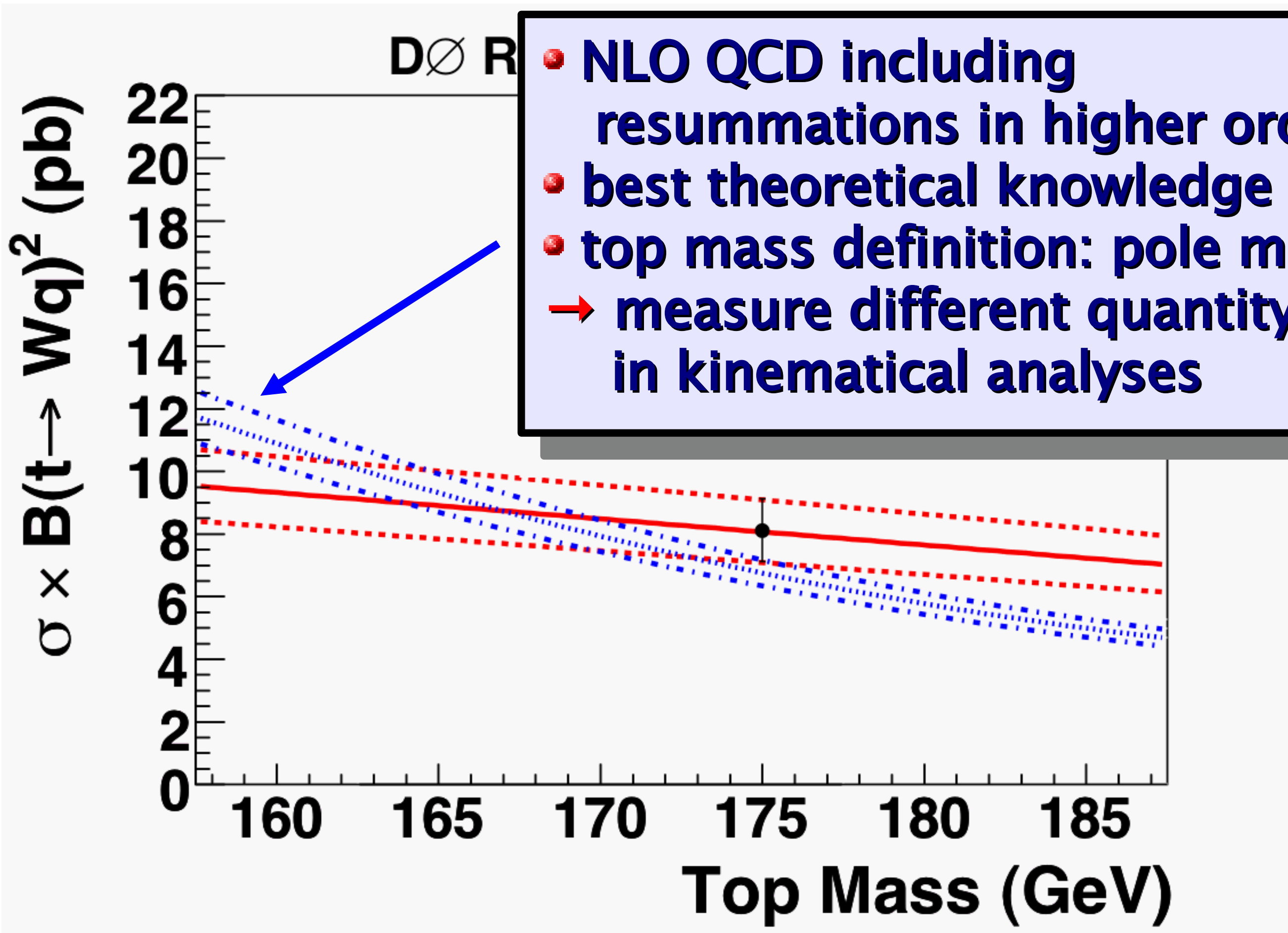


- signal efficiency: rely on LO MC
- kinematical distributions very similar between LO and NLO

→ 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

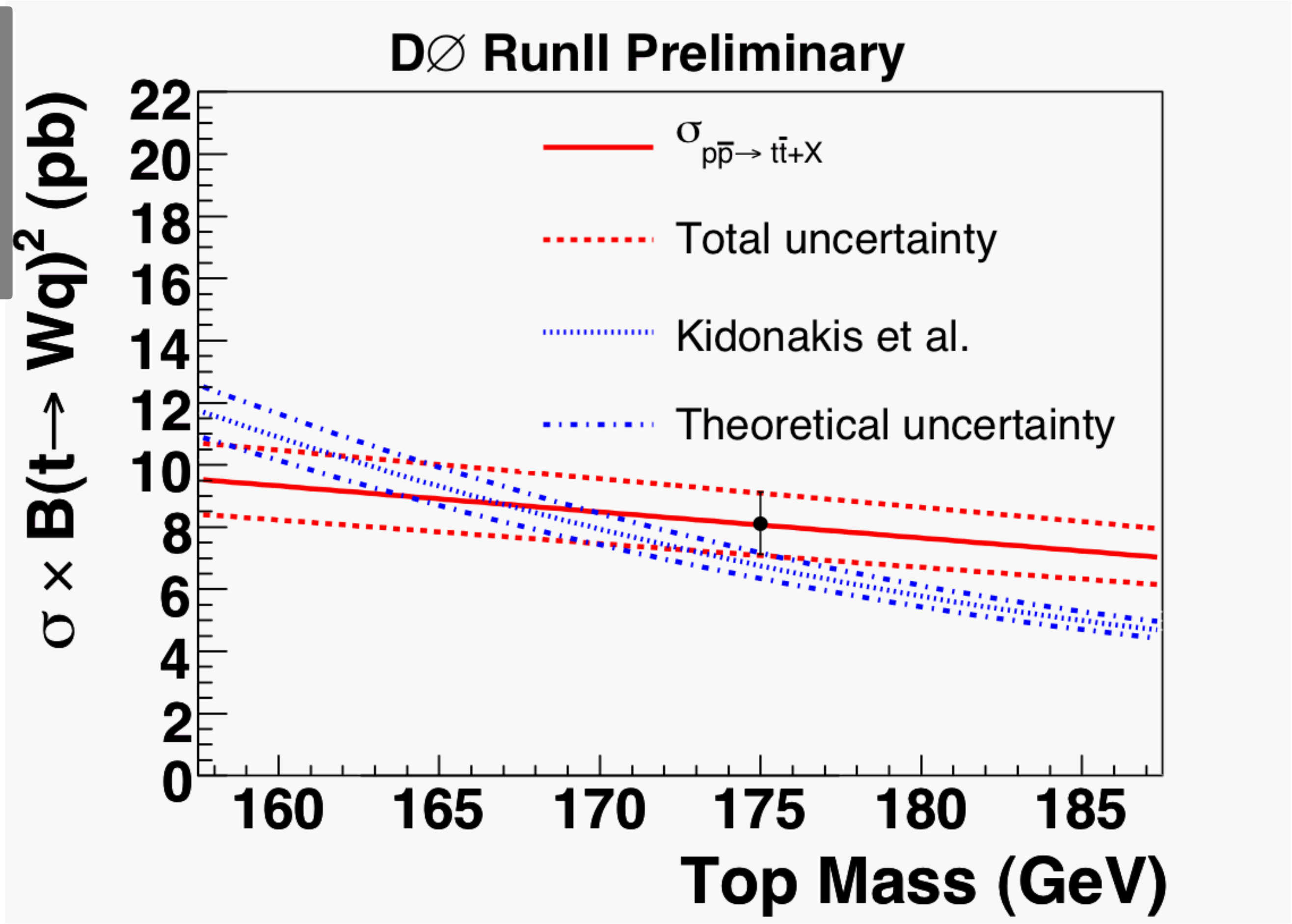
→ measure different quantity than in kinematical analyses

M. Cacciari: "... at least in principle the mass you measure from the kinematical fits is not the same as the one you might extract from the cross section (LO pythia mass versus NLO pole mass)"

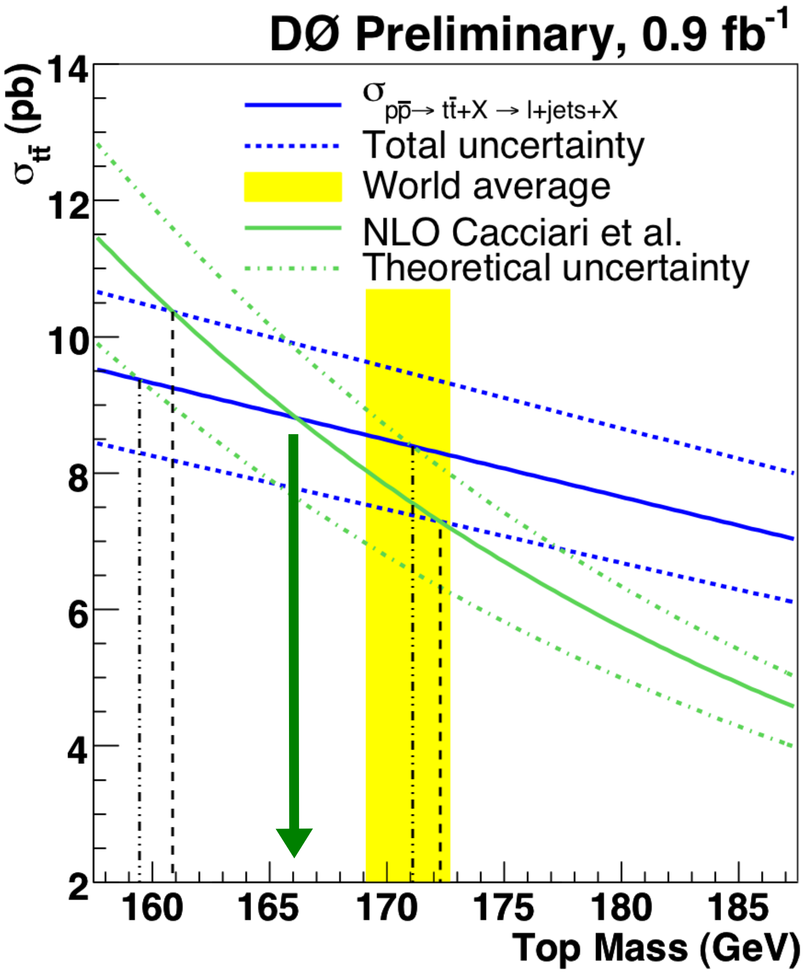
Top mass from cross section measurement

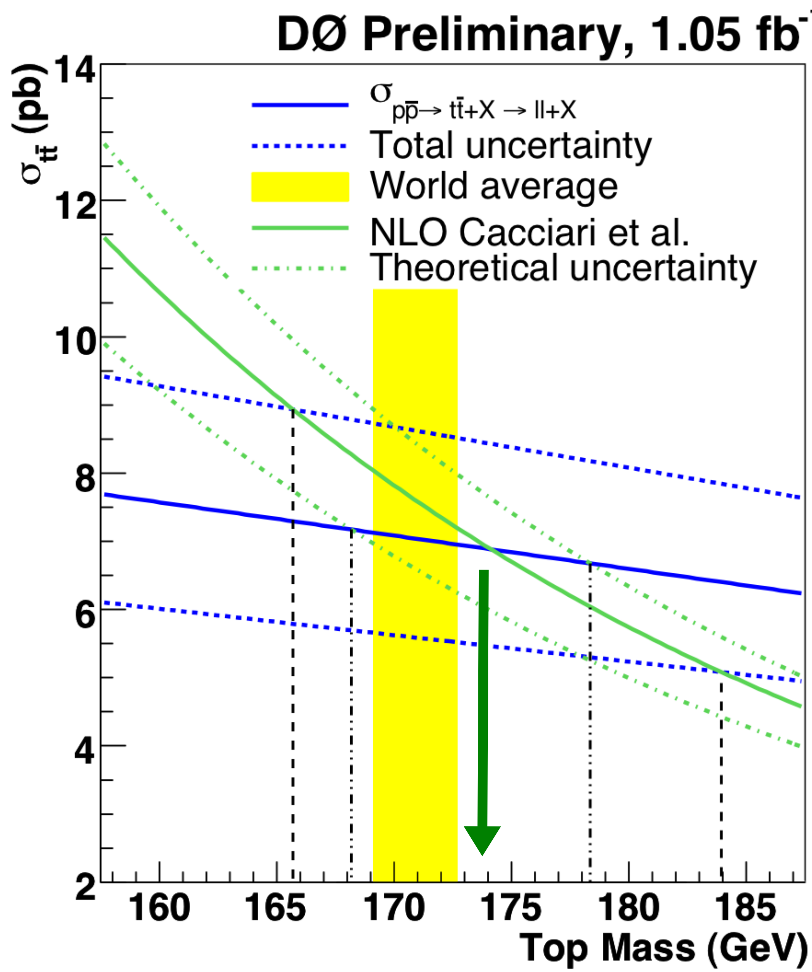
- "simpler" analyses
- good cross check

→ complementary information



Cross section in lepton+jets/dilepton channel





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

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

kinematical analyses:

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

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

CDF Results of all Methods

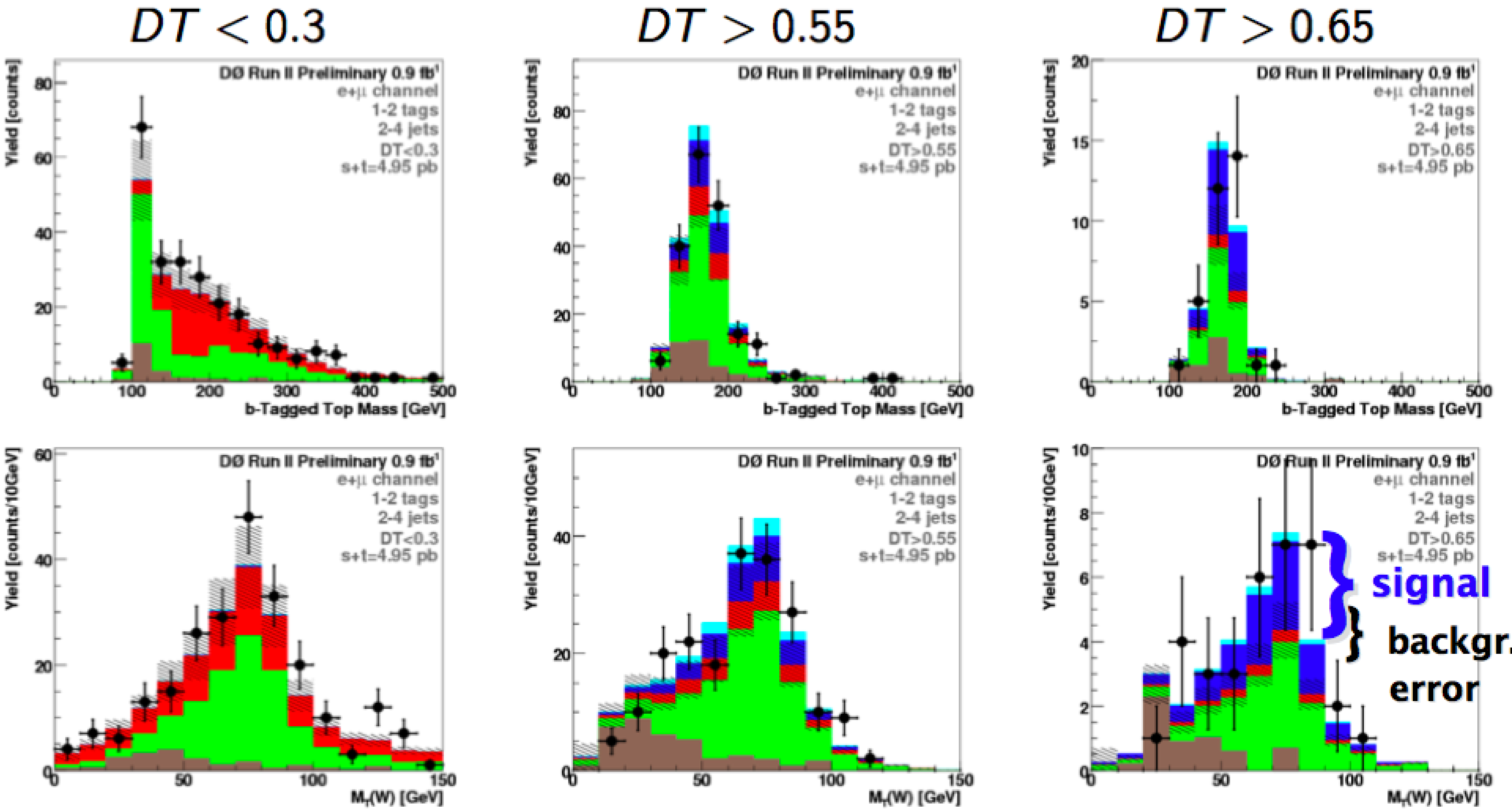
1 fb^{-1}

- Likelihood discriminants: $\sigma < 2.7$ pb @ 95% CL
- 2 artificial neural networks: $\sigma < 2.6$ pb @ 95% CL
- matrix element: $\sigma = 2.7^{+1.5}_{-1.3}$ pb (2.3σ)

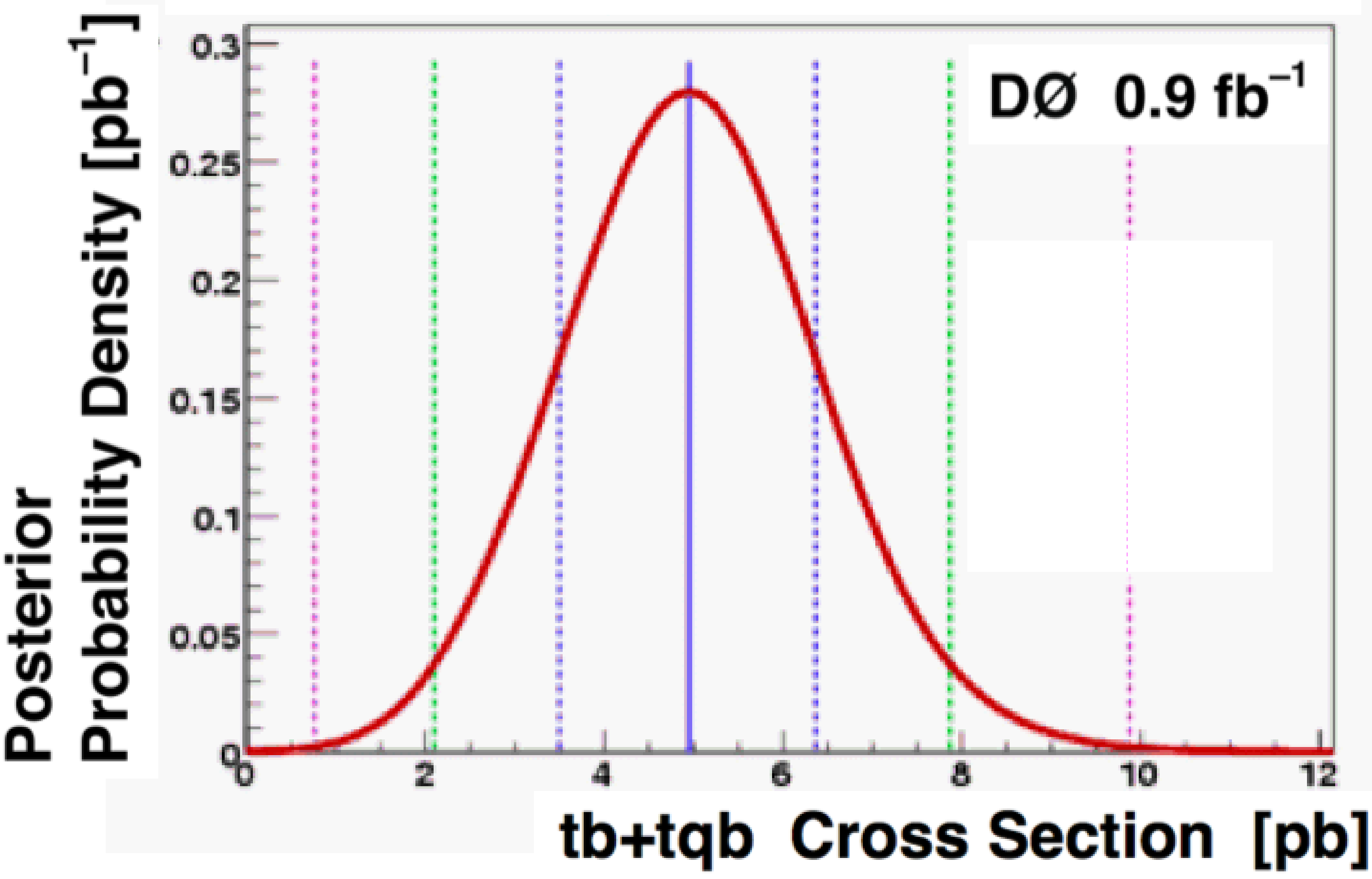
but: use same data selection correlation among analyses is 60–70%

→ 1.2% compatibility of all analyses (common pseudo experiments)

Boosted Decision Trees Event Charcteristics



Boosted Decision Tree s+t observed results



σ = 4.9 ± 1.4 pb

background compatibility: 0.035% (3.4σ)

SM compatibility: 11% (1.1σ)

Outline

Top Pair Production Cross Section

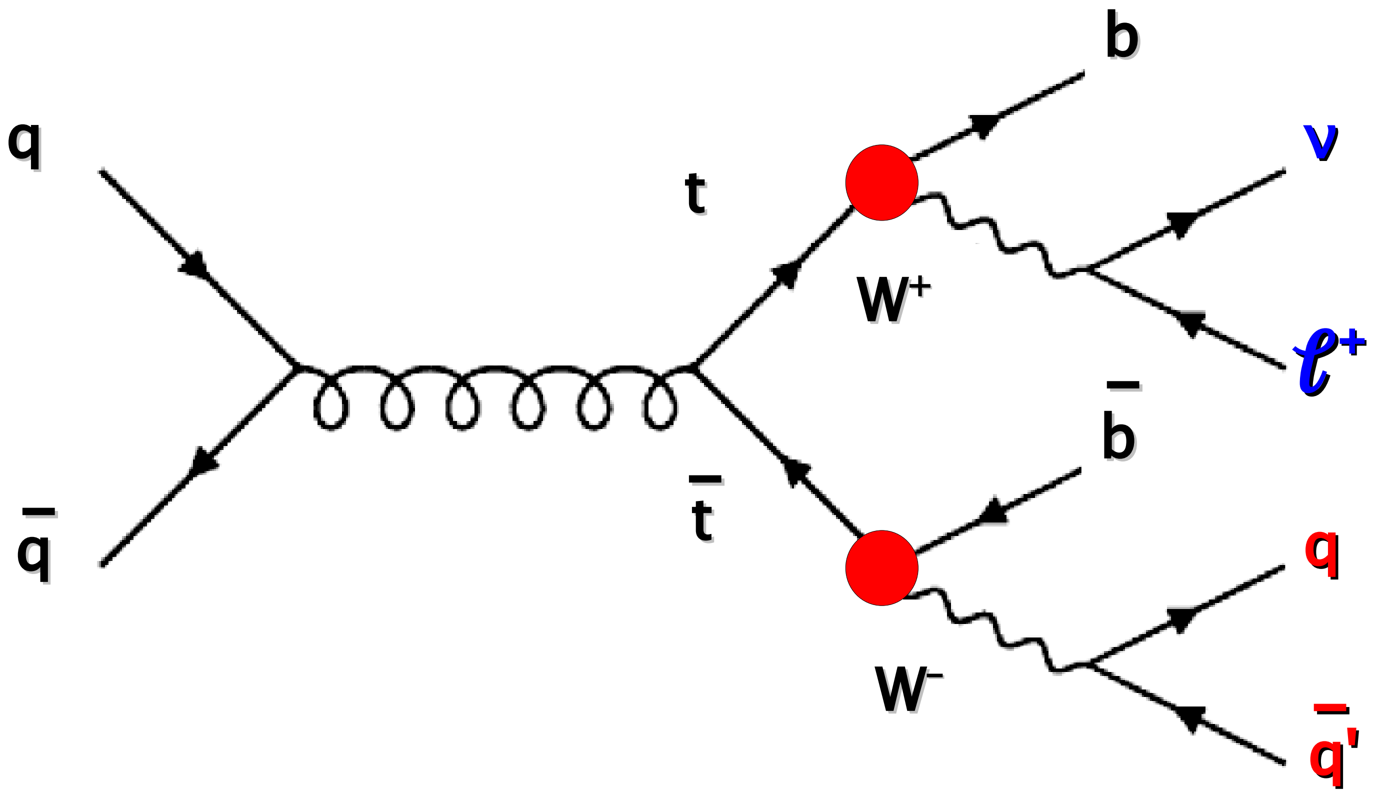
Top Mass

Searches in Top Decays

- cross section ratios
- **branching fractions**
- W helicity

Outlook: Top Physics at LHC

Search for new physics in top decays



Measurement of Branching Fractions

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

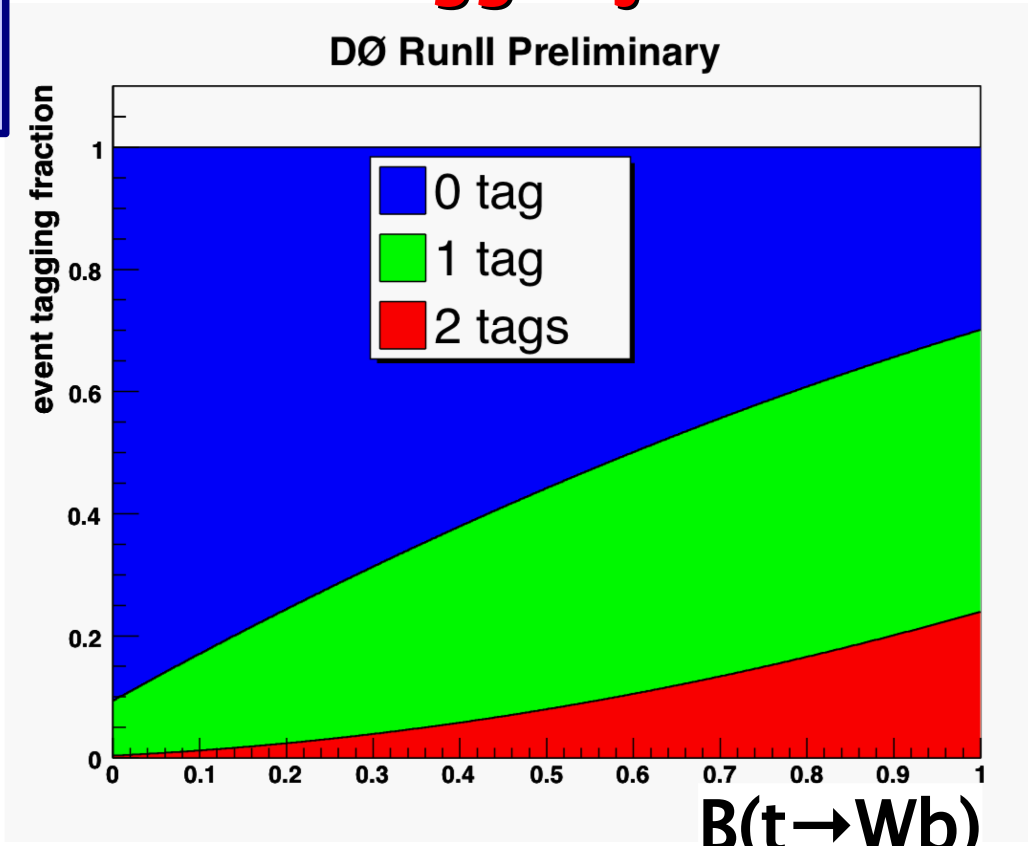
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

R changes fractions of b-tagged jets:



beyond SM:

$$R \neq 1$$

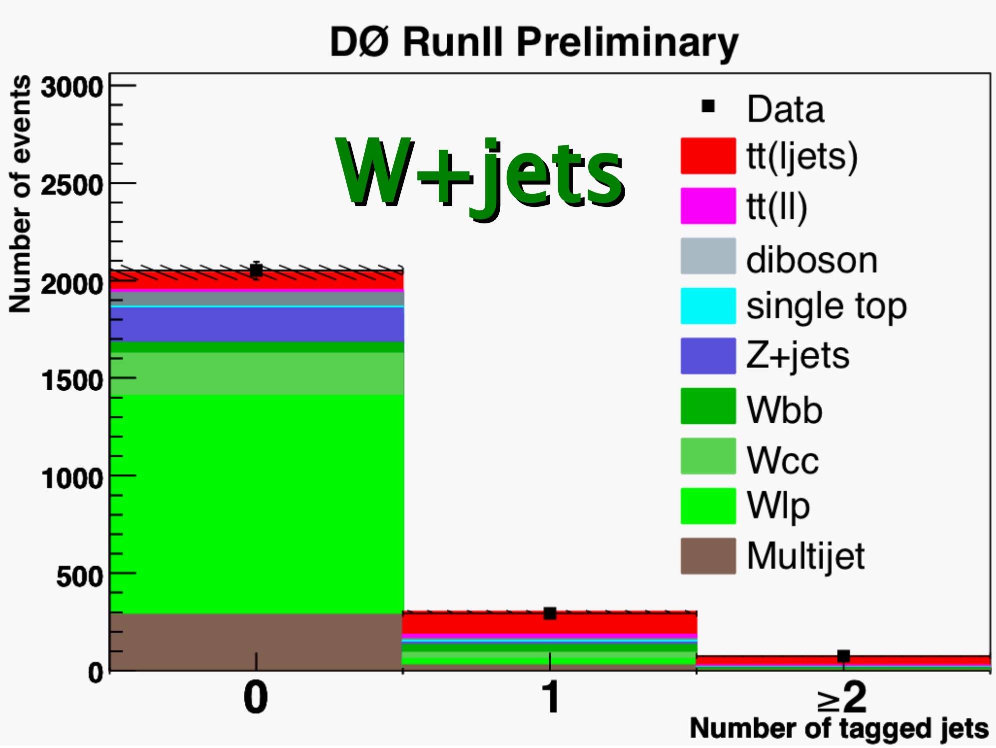
we assume: $B(t \to Wq) = 1$

e.g. decay into 4th generation quark: $R<1$

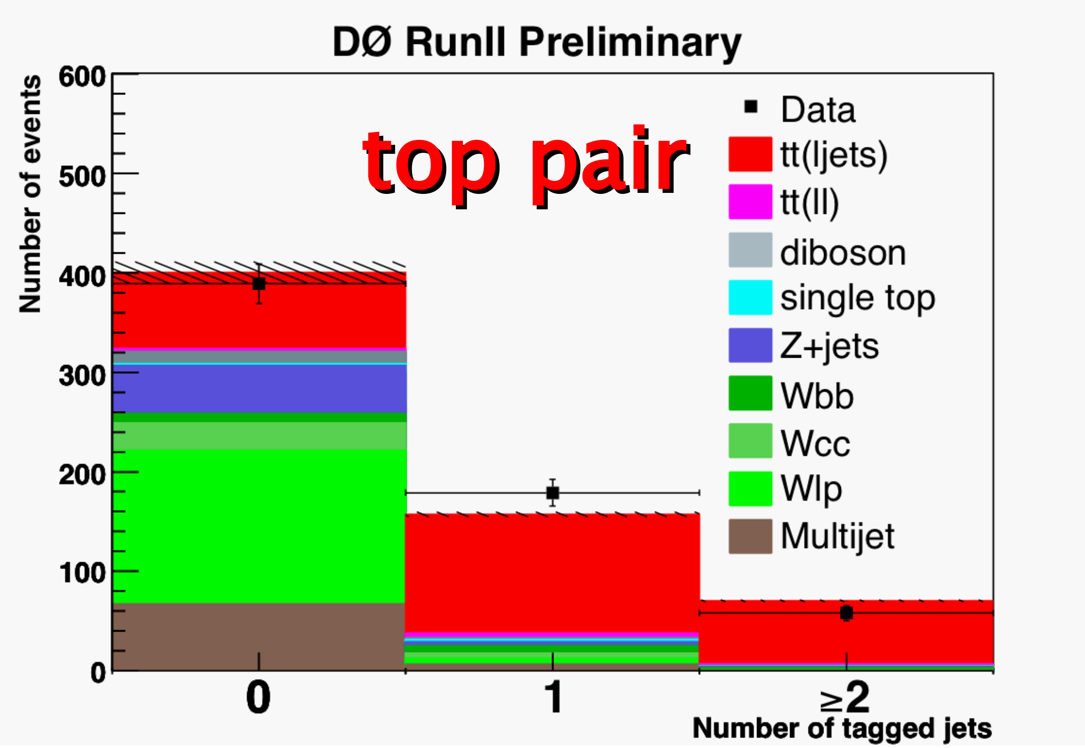
sensitive to b disappearance

Binned Likelihood fit in e,μ+jets channels

= 3 jets

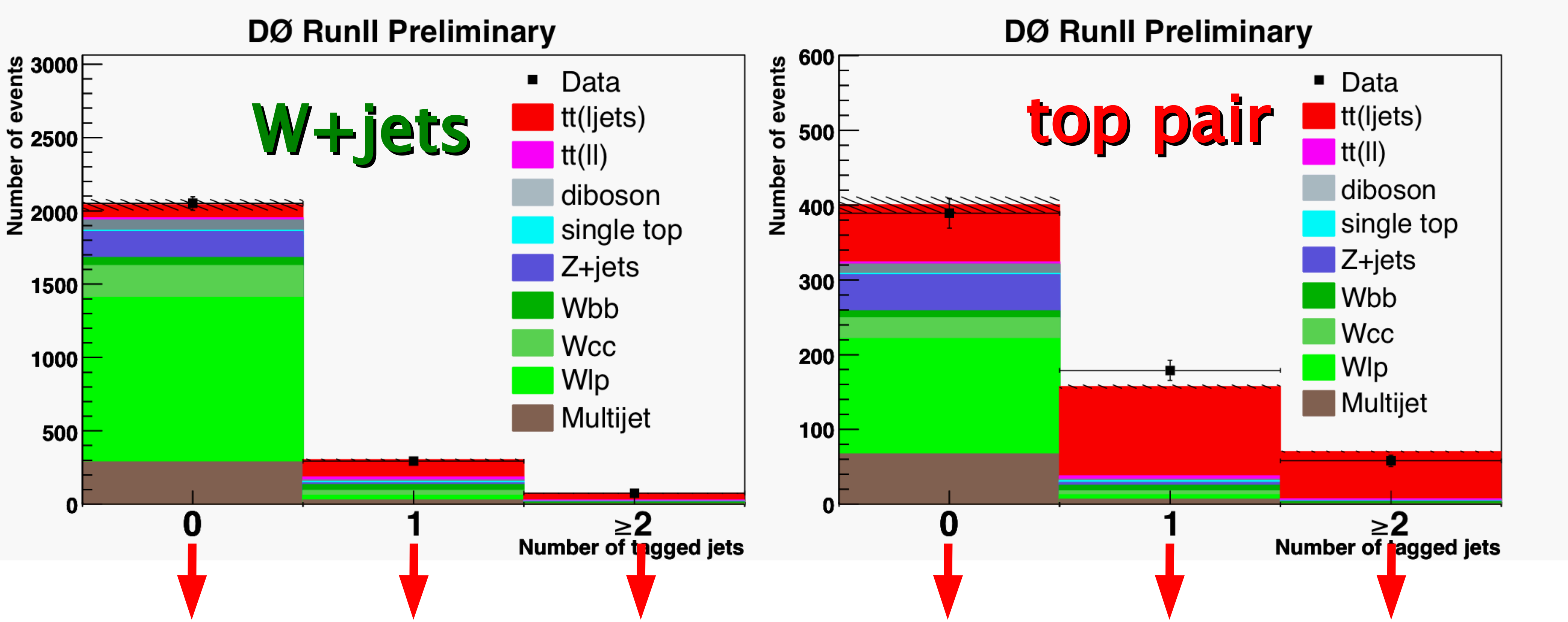


≥ 4 jets



Binned Likelihood fit in e,μ+jets channels

= 3 jets ≥ 4 jets



topological discriminant

topological discriminant

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

Lepton+jets cross section in SM

R = 1

M_{top} = 175 GeV

DØ: $\sigma_{tt} = 8.08^{+0.85}_{-0.82}$ (stat+syst) ± 0.49 (lumi) pb

12%

L=900 pb^{-1}

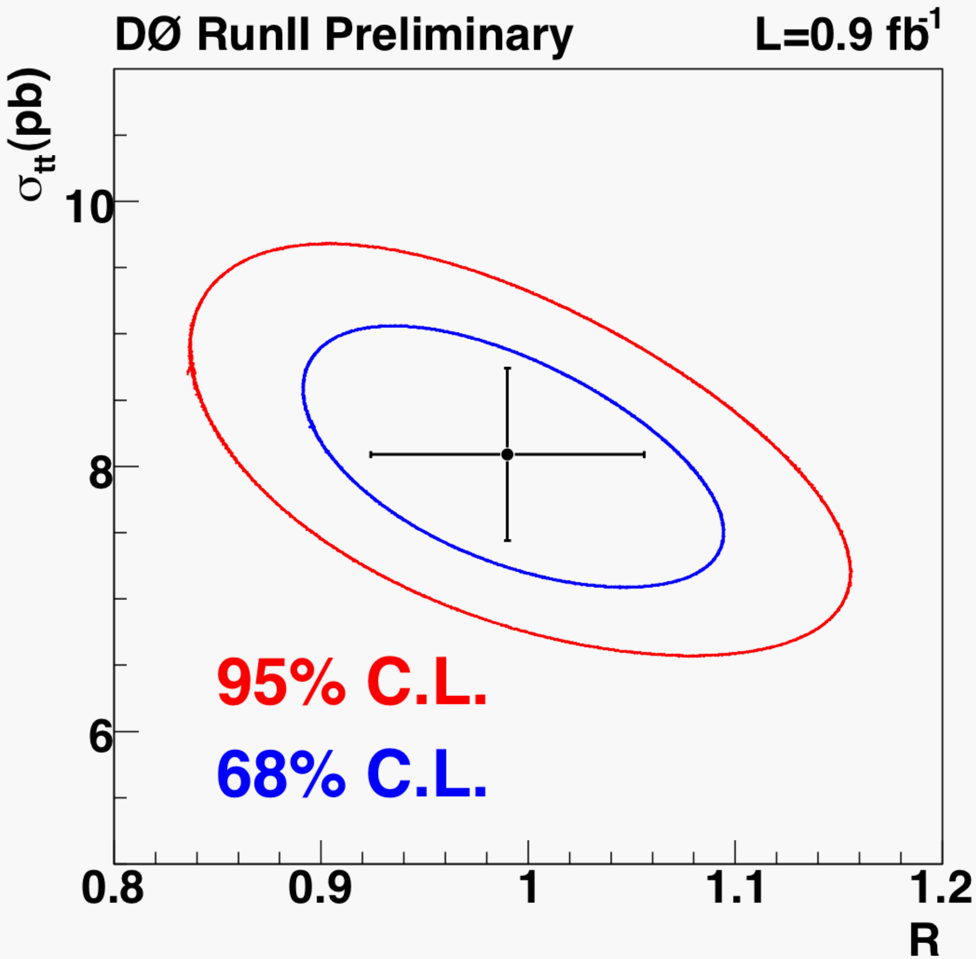
CDF: σ_{tt} = 8.2 ± 0.5 (stat) ± 0.8 (syst) ± 0.5 (lumi) pb

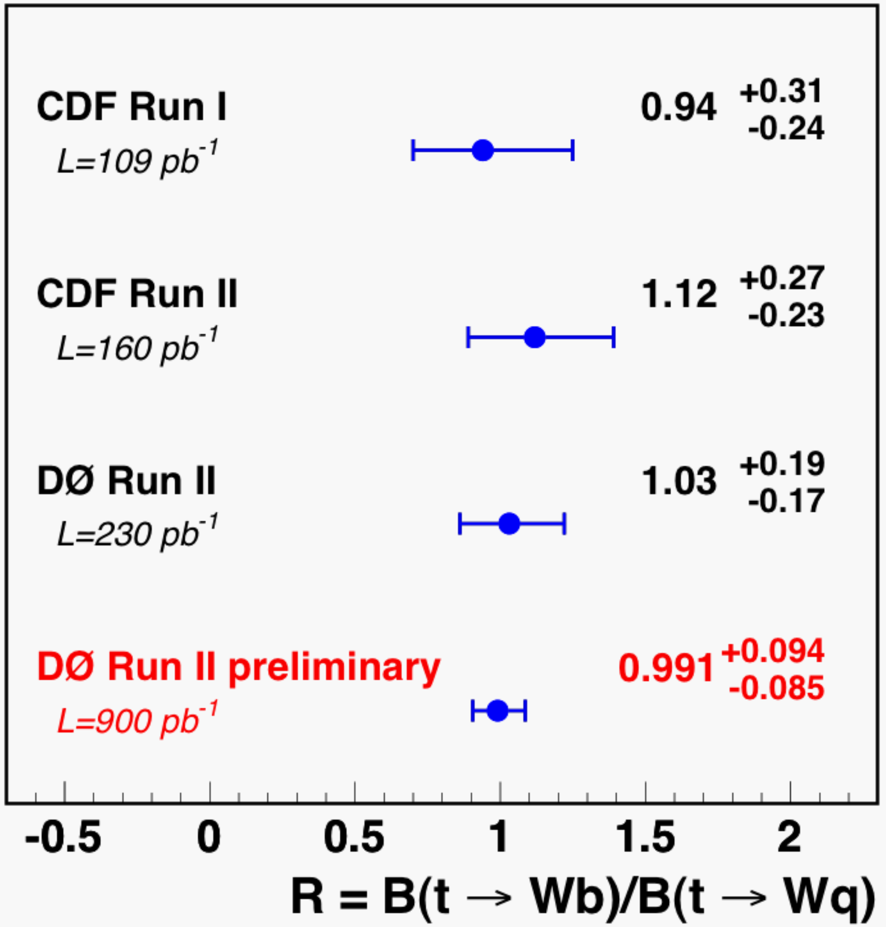
13%

L=1120 pb^{-1}

⇒ combine results

Simultaneous Measurement of σ and R



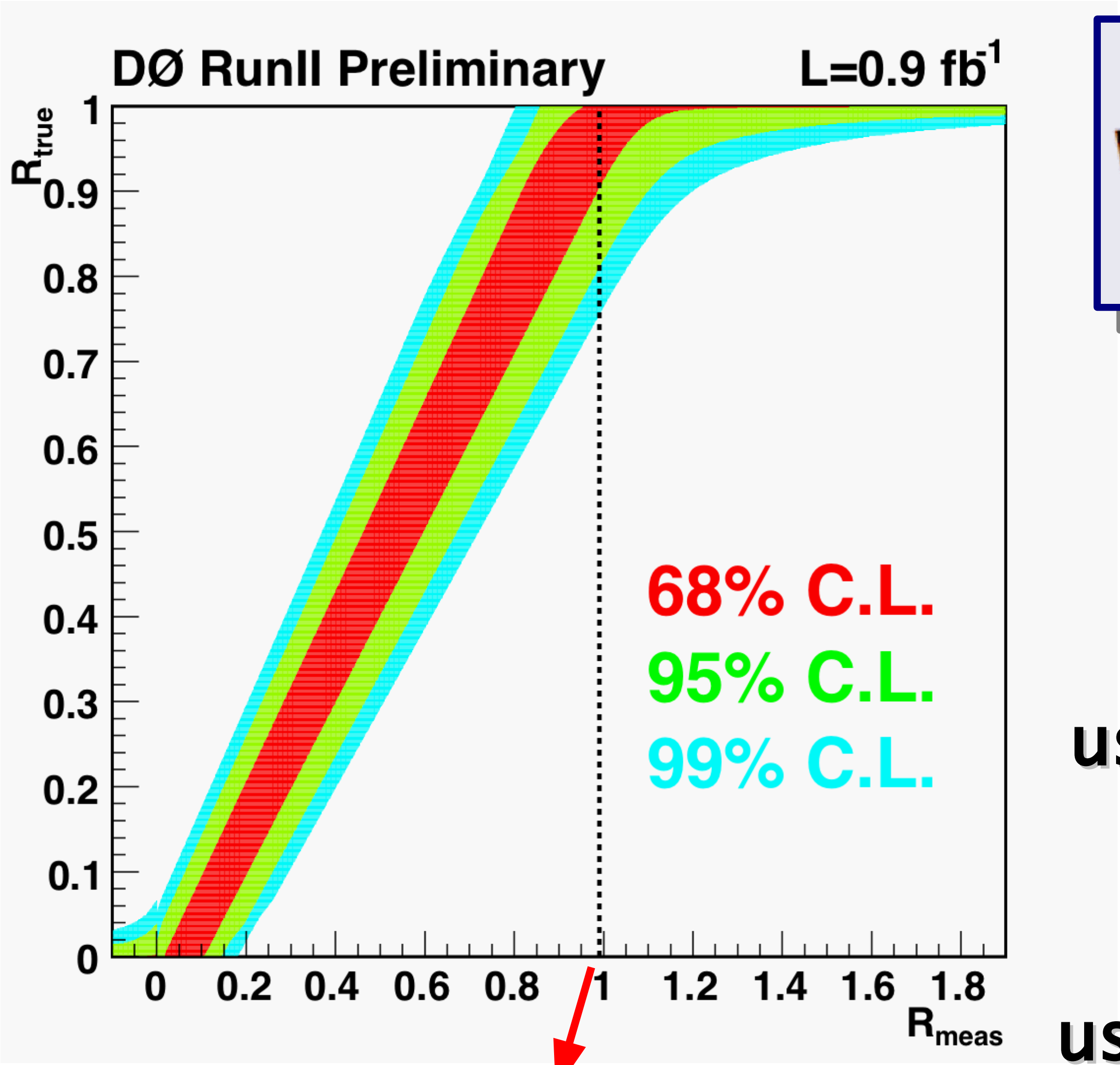


$\sigma_{tt} = 8.10^{+0.87}_{-0.82}$ (stat+syst) ± 0.49 (lumi) pb

$R = 0.991^{+0.094}_{-0.085}$ (stat+syst)

⇒ **agree with SM**

Lower limit to branching fraction R



R > 0.812 @ 95% C.L.

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

$$R = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

using measured $|V_{td}|$ and $|V_{ts}|$:

$|V_{tb}| > 0.096$ @ 95% C.L.

using unitary of CKM matrix:

$|V_{tb}| > 0.901$ @ 95% C.L.

Outline

Top Pair Production Cross Section

Top Mass

Searches in Top Decays

- cross section ratios
- branching fractions
- W helicity

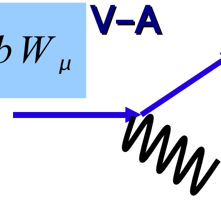
Outlook: Top Physics at LHC

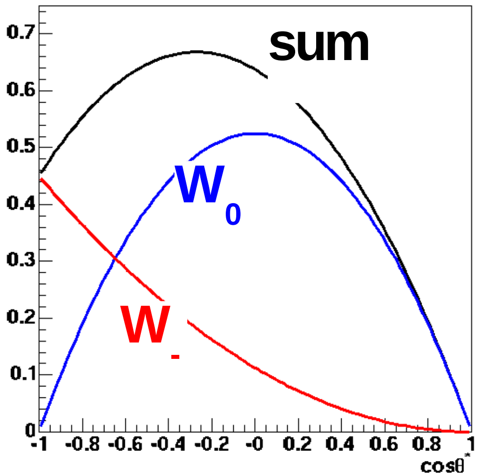
Helicity of the W in ttbar Events

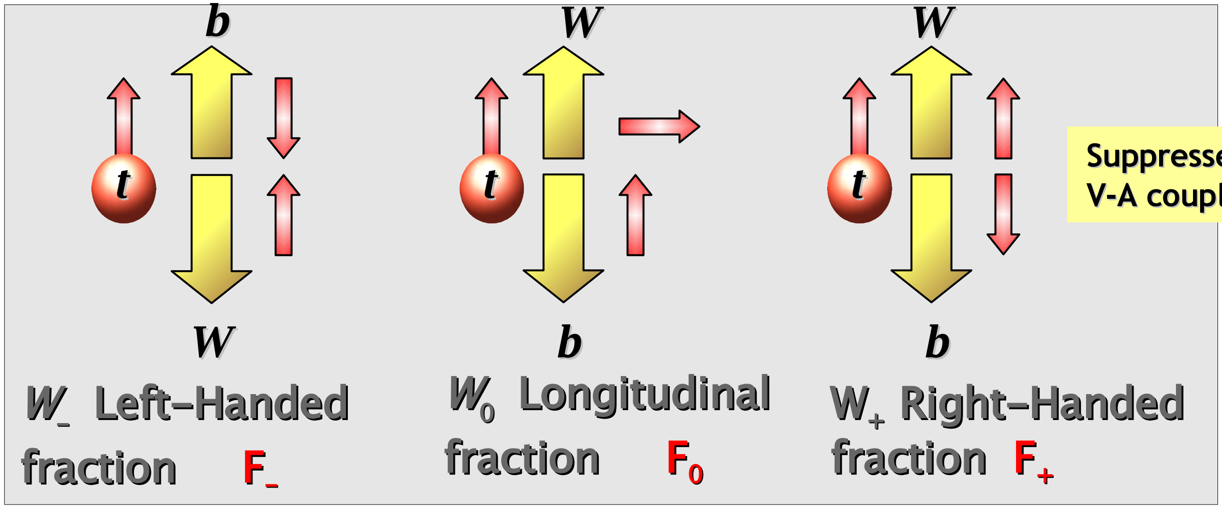
Top Standard Model weak decay →
V–A coupling as it is for all the other fermions

$$\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma^{5})V_{tb}\,b\,W_{\mu}$$

V–A

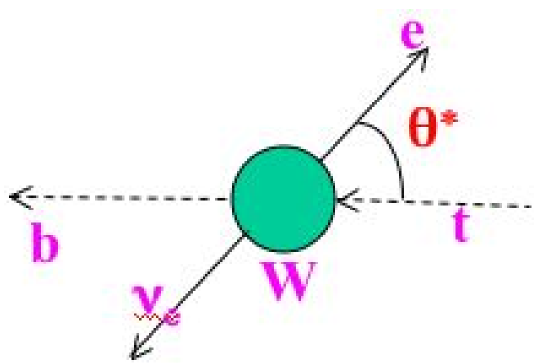






Suppressed by the V-A coupling

$$w(\cos\theta^*) = F_-\cdot\frac{3}{8}(1-\cos\theta^*)^2 + F_0\cdot\frac{3}{8}(1-\cos^2\theta^*) + F_+\cdot\frac{3}{8}(1+\cos\theta^*)^2$$



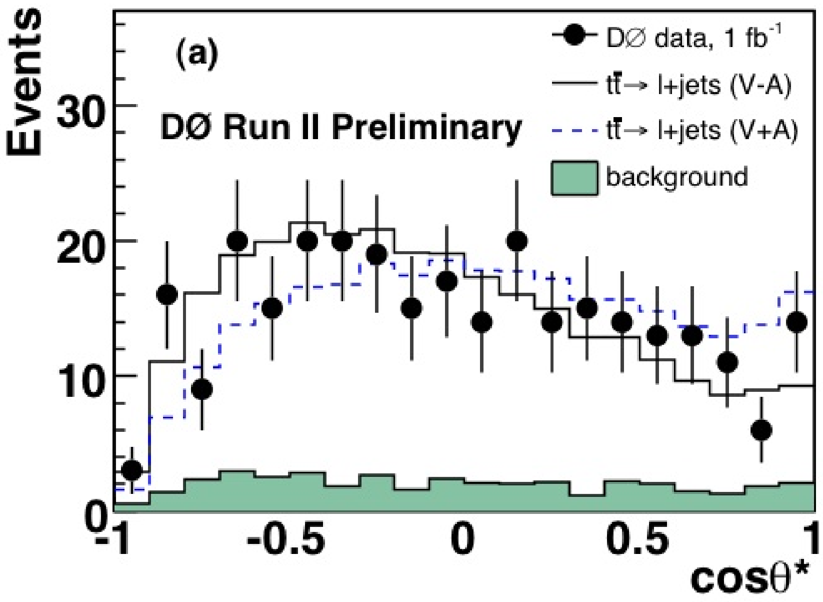
In SM (with $m_b=0$, M_{top} = 175 GeV and m_W = 80.4 GeV),

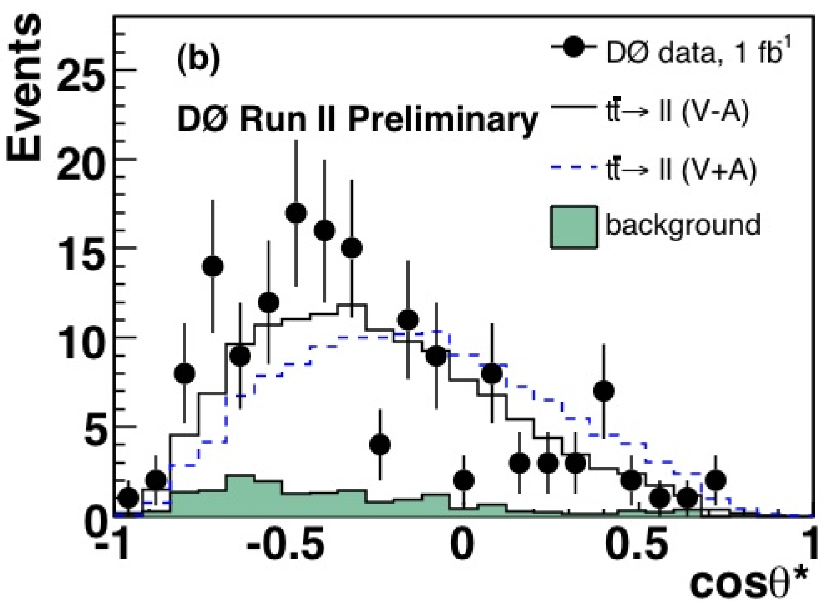
$$F_- = \frac{2\frac{m_W^2}{M_{top}^2}}{1+2\frac{m_W^2}{M_{top}^2}} \approx 0.30$$

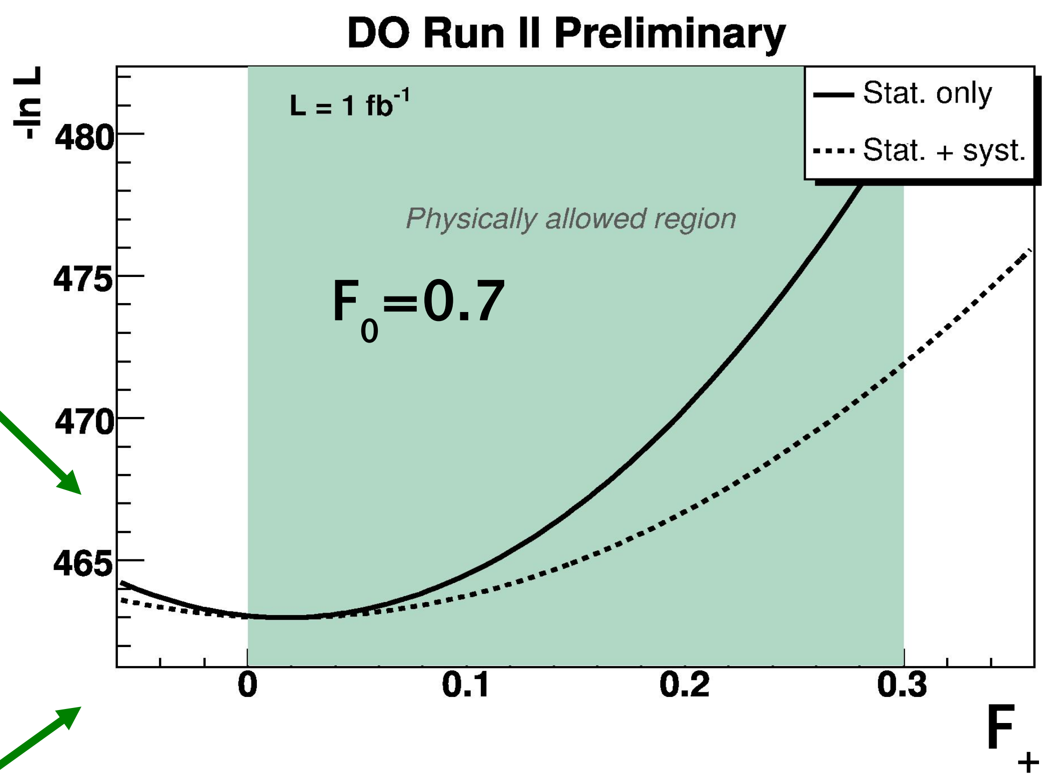
$$F_0 = \frac{1}{1+2\frac{m_W^2}{M_{top}^2}} \approx 0.70$$

$$F_+ = 0$$

Helicity of the W in ttbar Events







for F_0=0.7:

$F_+ = 0.017 \pm 0.048$ (stat) $\pm$ 0.047 (syst)

$F_+ < 0.14$ @ 95% CL

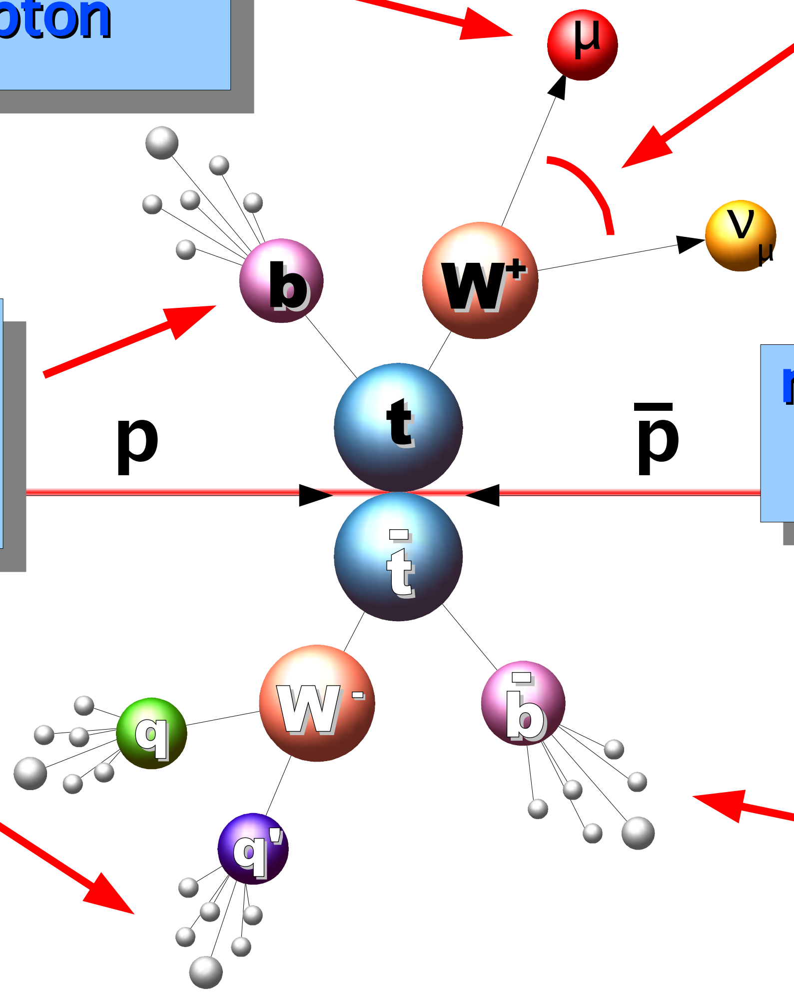
→ no deviations from SM predictions

Event Selection in Lepton+Jets

e (μ) isolated, p_T > 20 GeV,
$|\eta|$< 1.1 (2.0),
no other high p_T lepton

minimum $\Delta\phi$

at least 4 jets,
p_T > 20 GeV,
$|\eta|$< 2.5



missing E_T > 20 (25) GeV
for e (μ)+jets

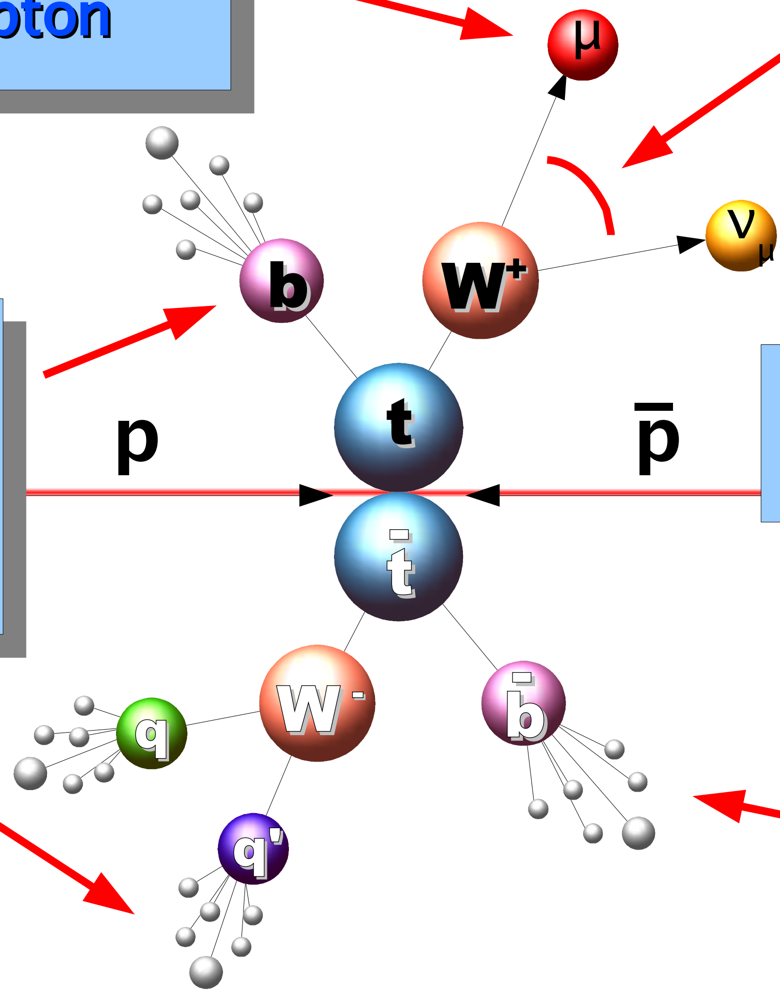
0, 1 or 2 jets
b-tagged
(Neural
Network)

Event Selection in Lepton+Jets

e (μ) isolated, $p_T > 20$ GeV,
$|\eta| < 1.1$ (2.0),
no other high p_T lepton

minimum $\Delta\phi$

at least 4 jets,
$p_T > 20$ GeV,
$|\eta| < 2.5$,
one jet $p_T > 40$ GeV



missing $E_T > 20$ (25) GeV
for e (μ)+jets

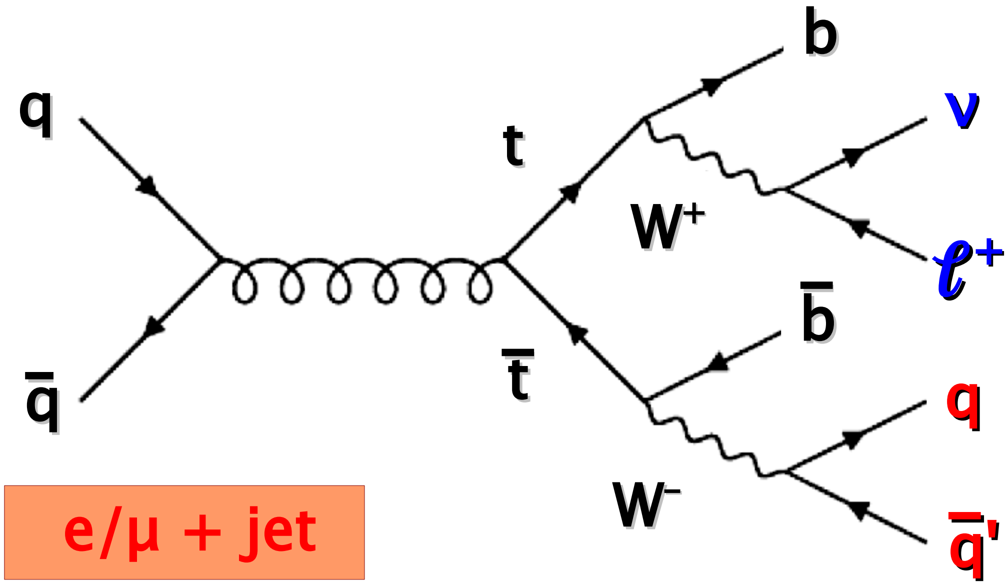
0, 1 or 2 jets
b–tagged
(Neural
Network)

Top anti-top signatures

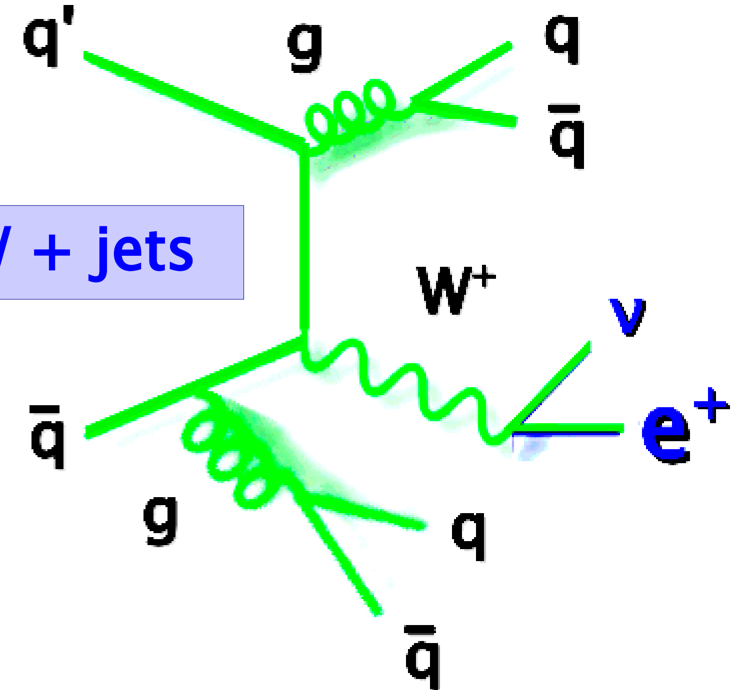
signal

background

3000 times more often

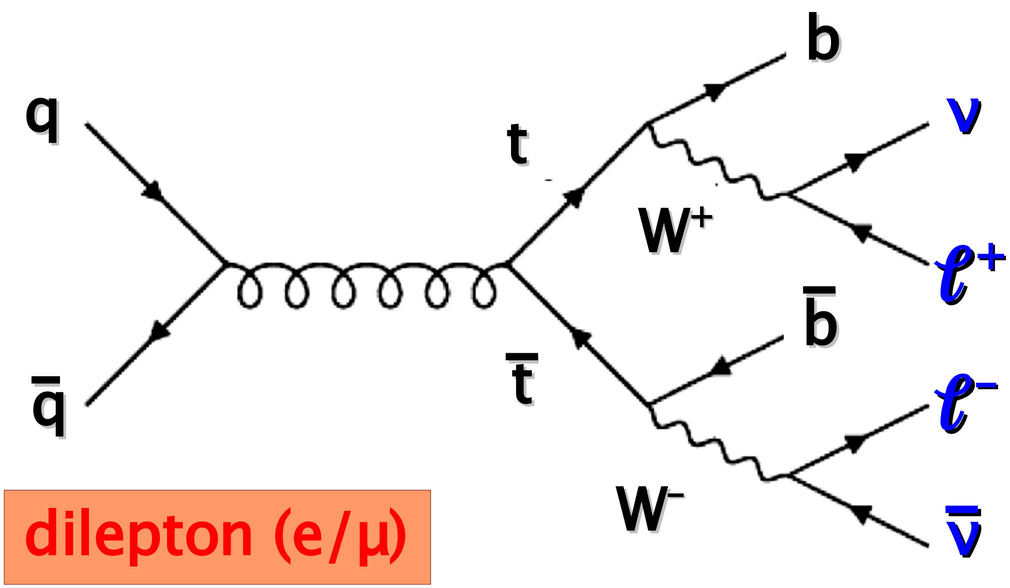


e/μ + jet

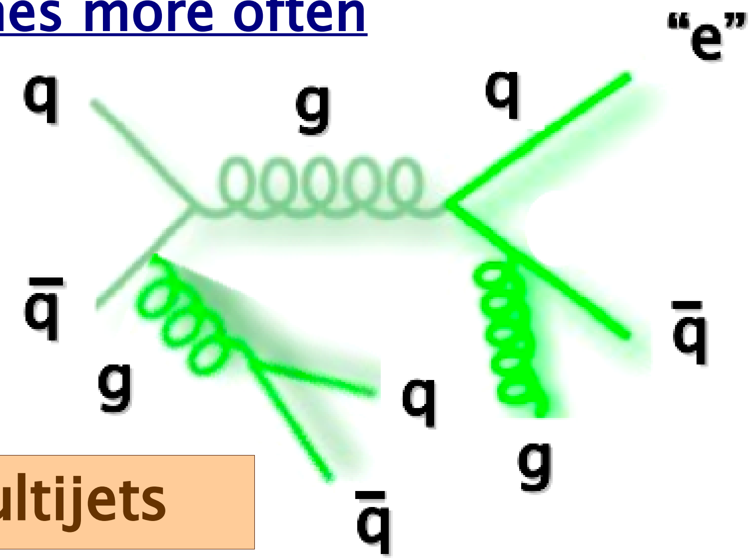


W + jets

10^{10} times more often



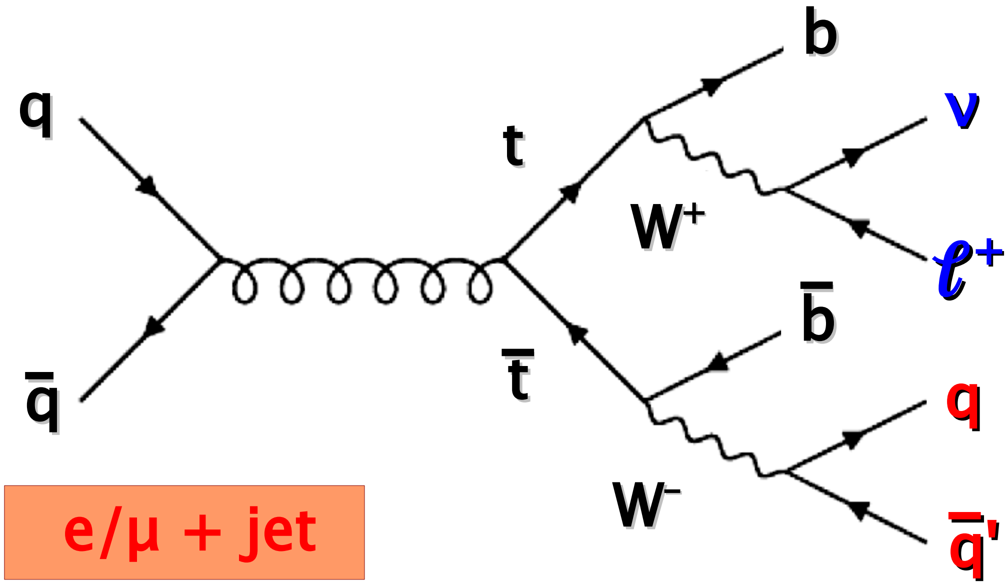
dilepton (e/μ)



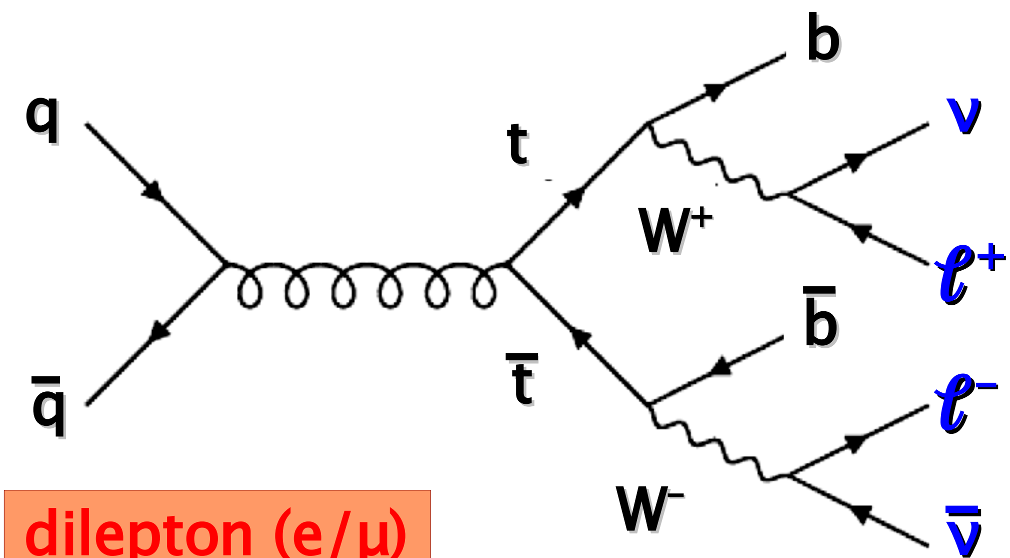
multijets

Top anti-top signatures

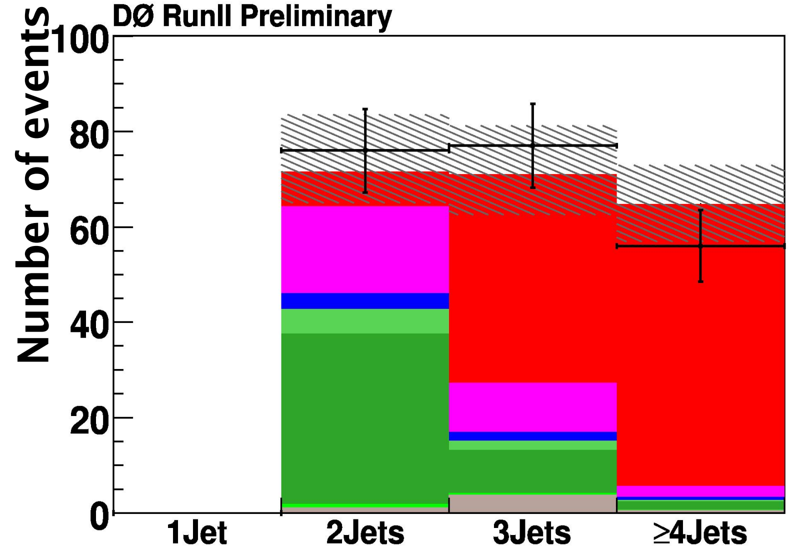
signal

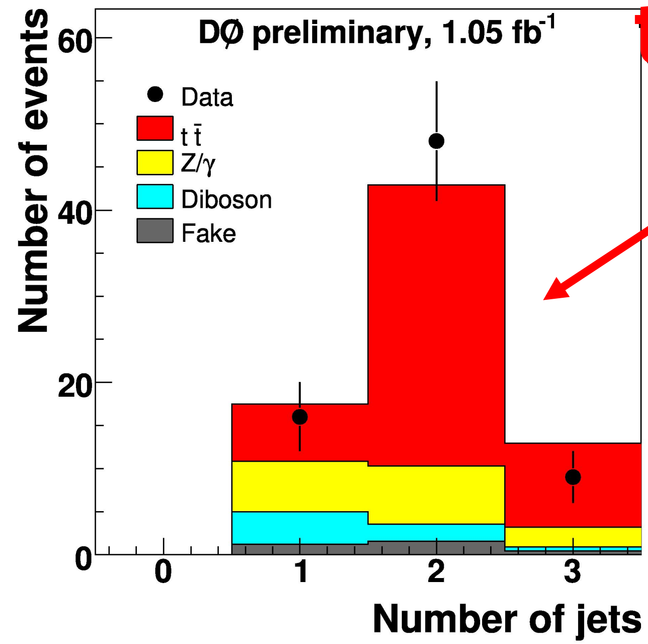


e/μ + jet



dilepton (e/μ)

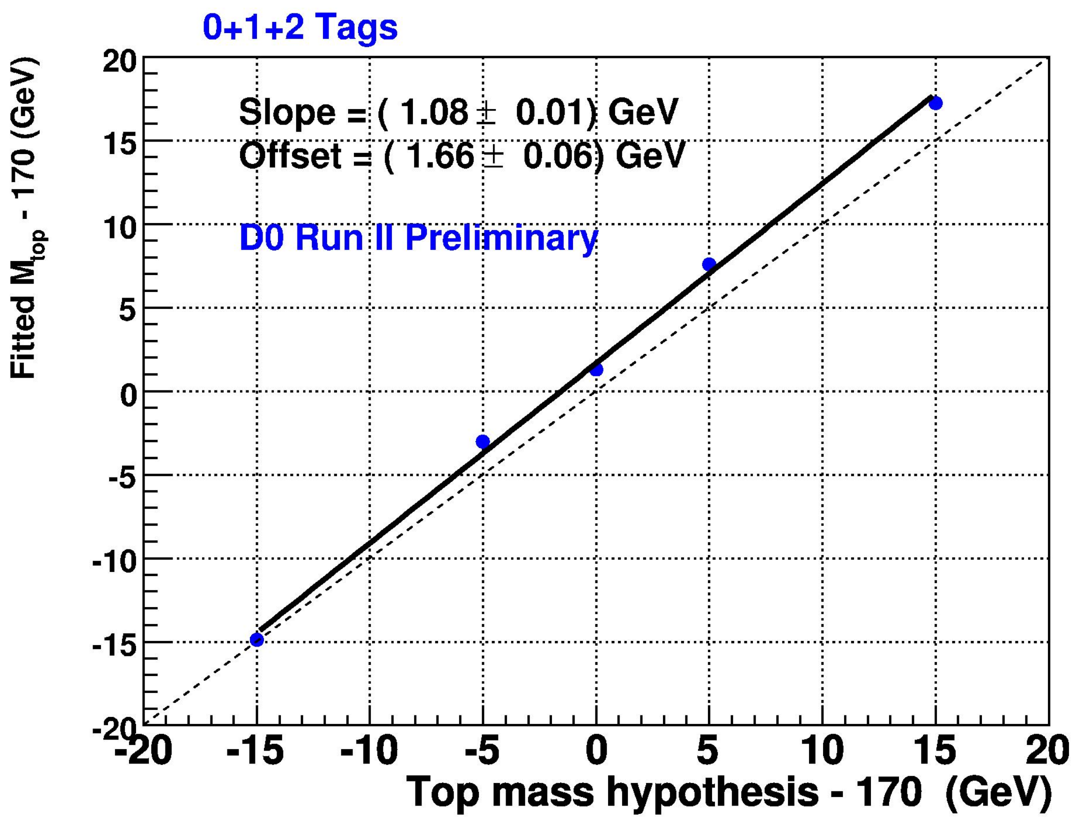




top pair

What are we measuring in mass analyses?

- different methods: templates, matrix element, ideogram...
- calibration curve (e+jets with b-tagging)

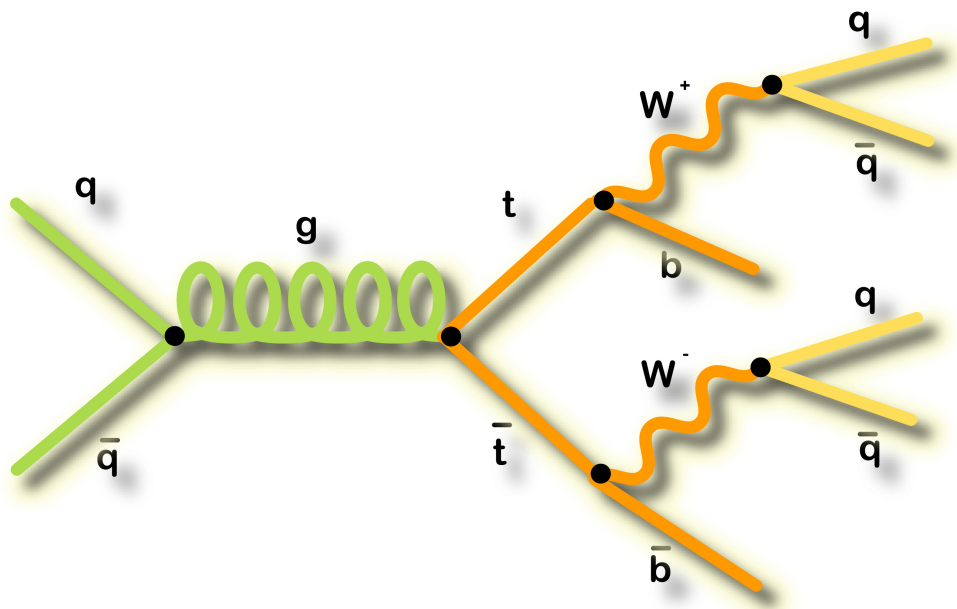


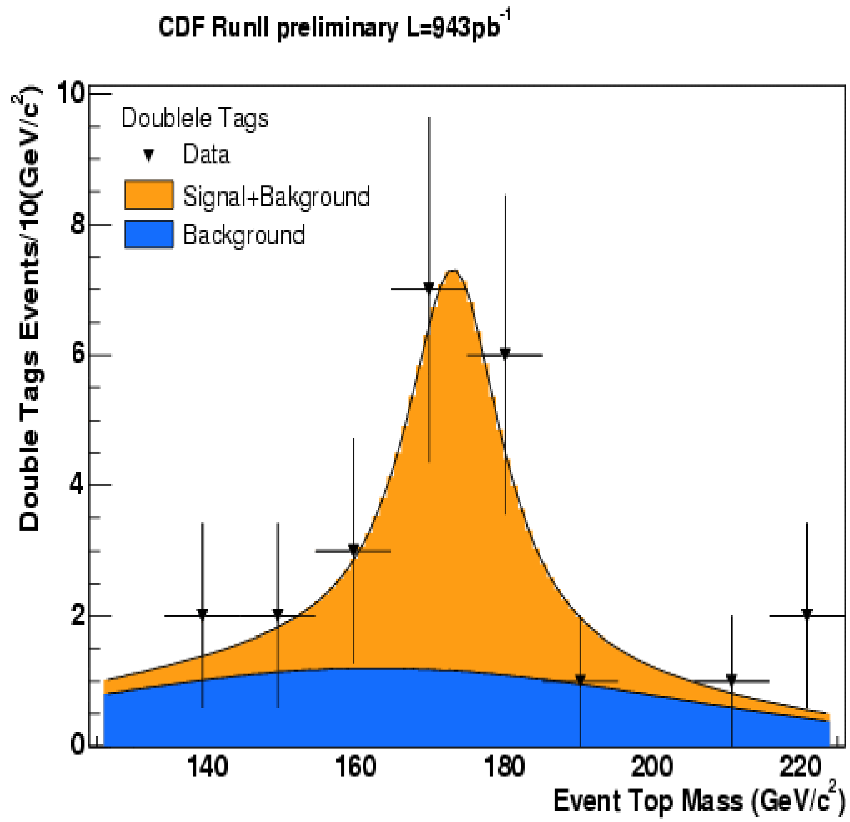
avoid:

Measurement of PMASS(6,1) using a data set of $4fb^{-1}$ at the Tevatron

All Hadronic Channel

1 fb^{-1}



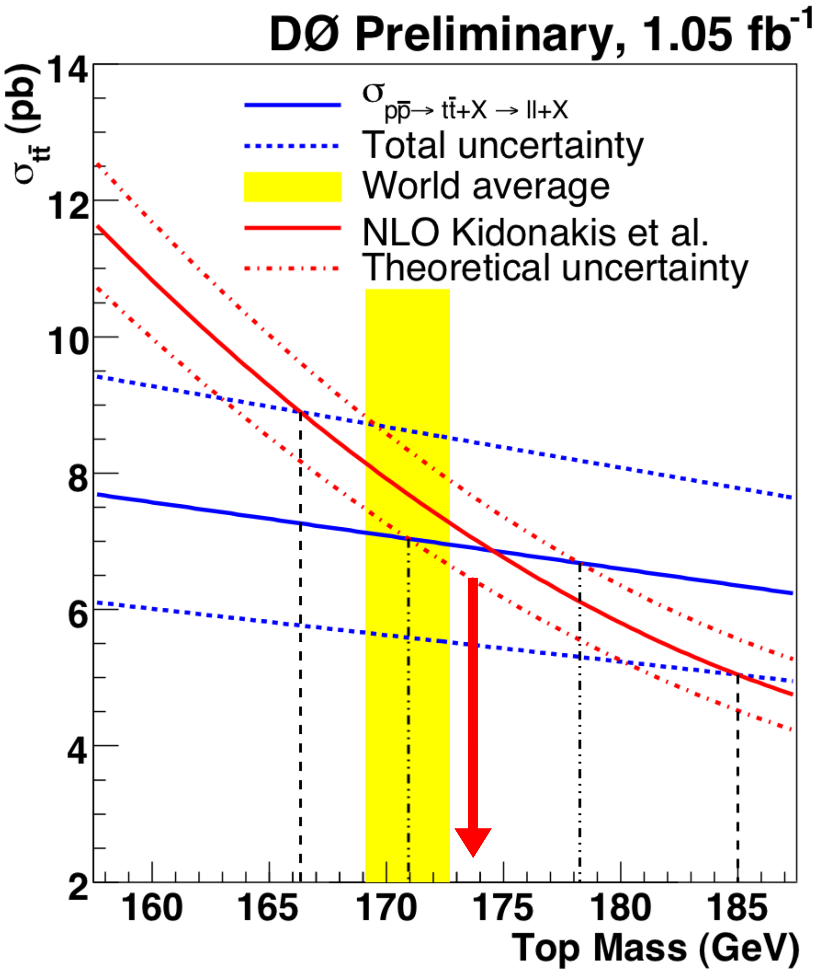


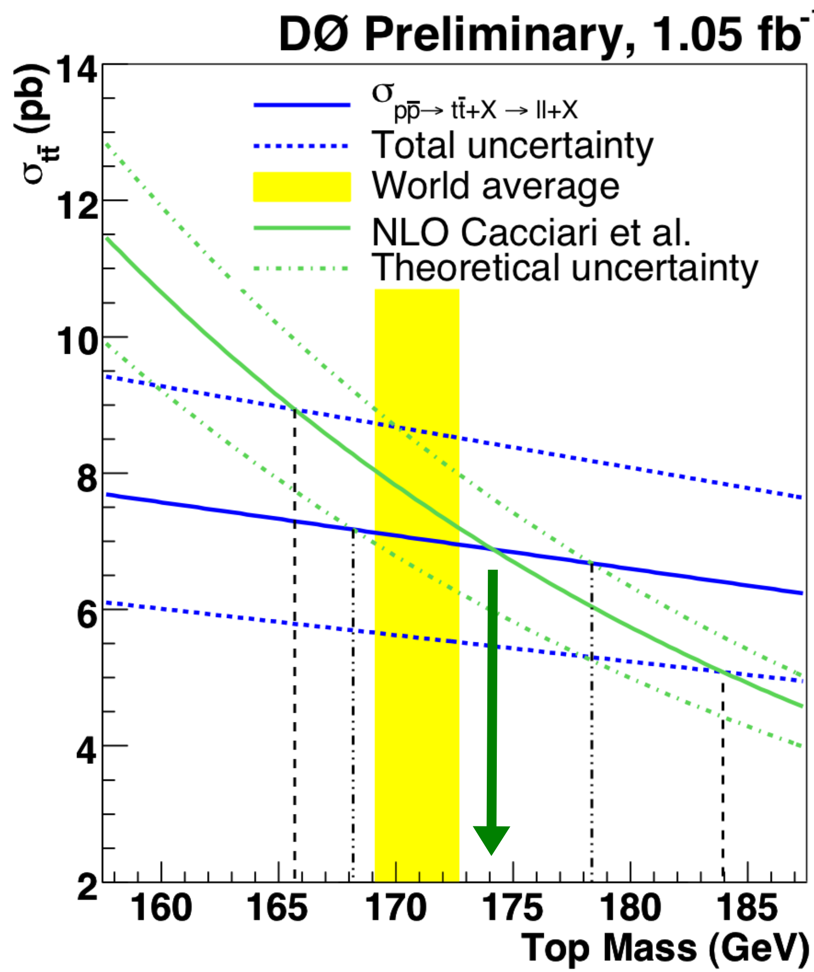
2D-template analysis (m_{top}, JES):

- signal template from matrix element calculations
- background templates inspired by data

m_{top}=171.1 ± 3.7(stat.+JES) ± 1.9(syst.) GeV

Cross section in dilepton channel





$$M_t = 174.5\ ^{+10.5}_{-8.2}\ \text{(stat+syst)}\ ^{+3.7}_{-3.6}\ \text{(theory) GeV}$$

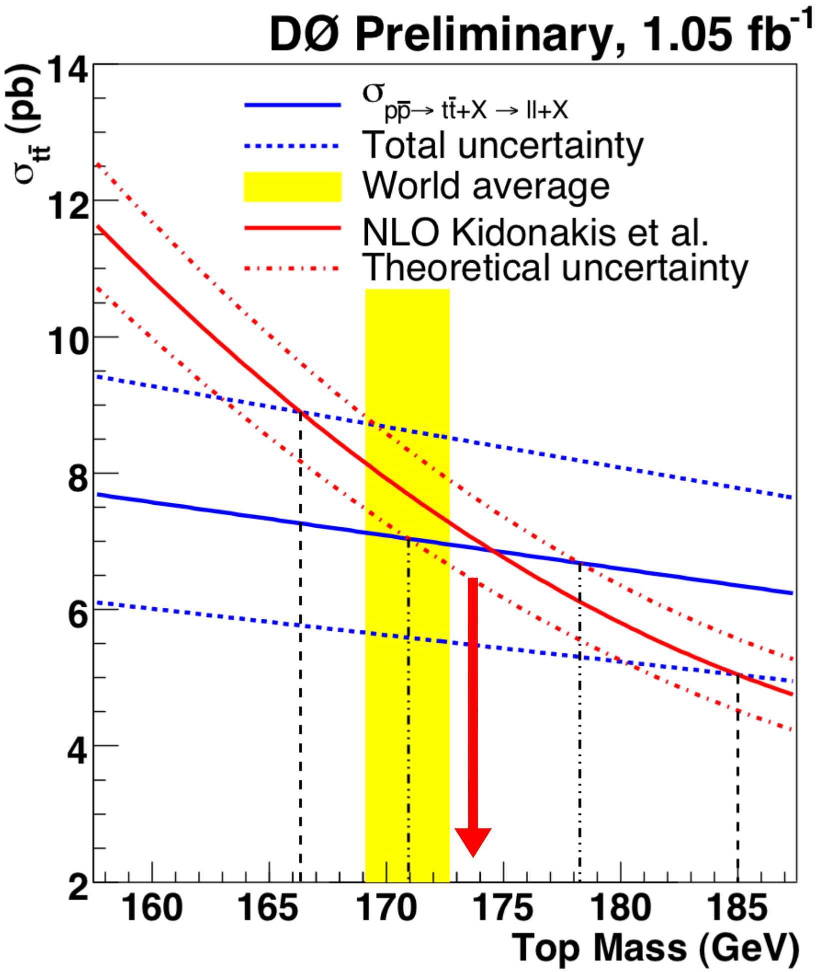
$$M_t = 174.1\ ^{+9.8}_{-8.4}\ \text{(stat+syst)}\ ^{+4.2}_{-6.0}\ \text{(theory) GeV}$$

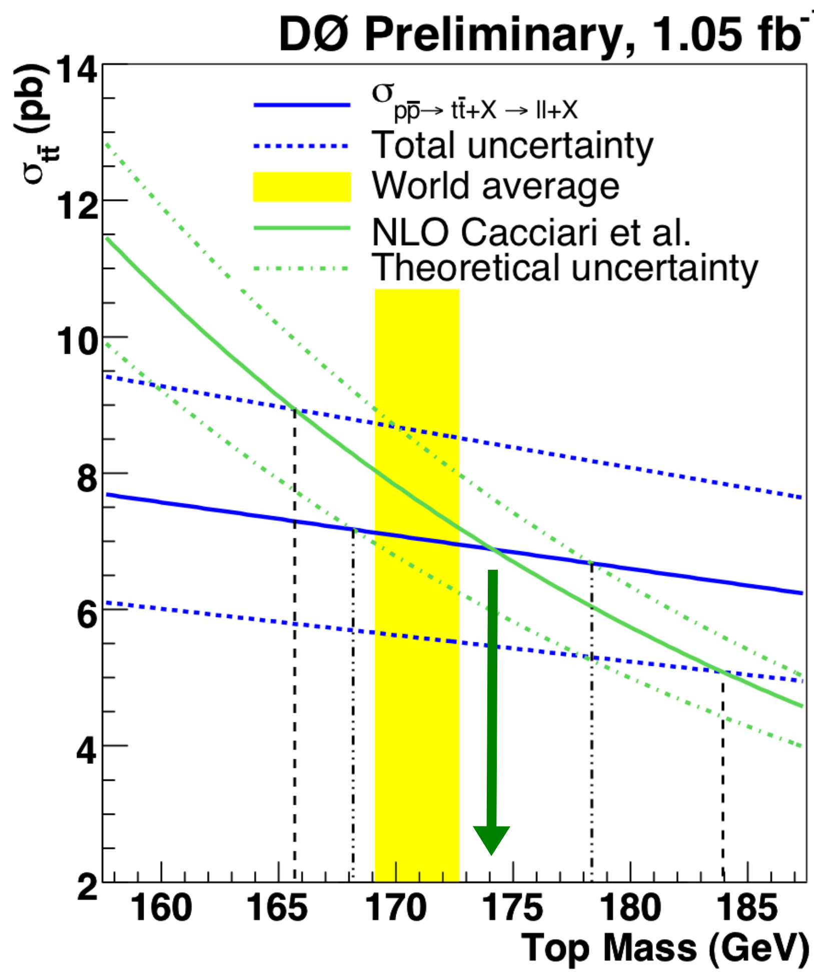
kinematical: MWT+νWT

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

DØ Note 5460-CONF

Cross section in dilepton channel





$$M_t = 174.5 \,^{+10.5}_{-8.2} \text{ (stat+syst) } ^{+3.7}_{-3.6} \text{ (theory) GeV}$$

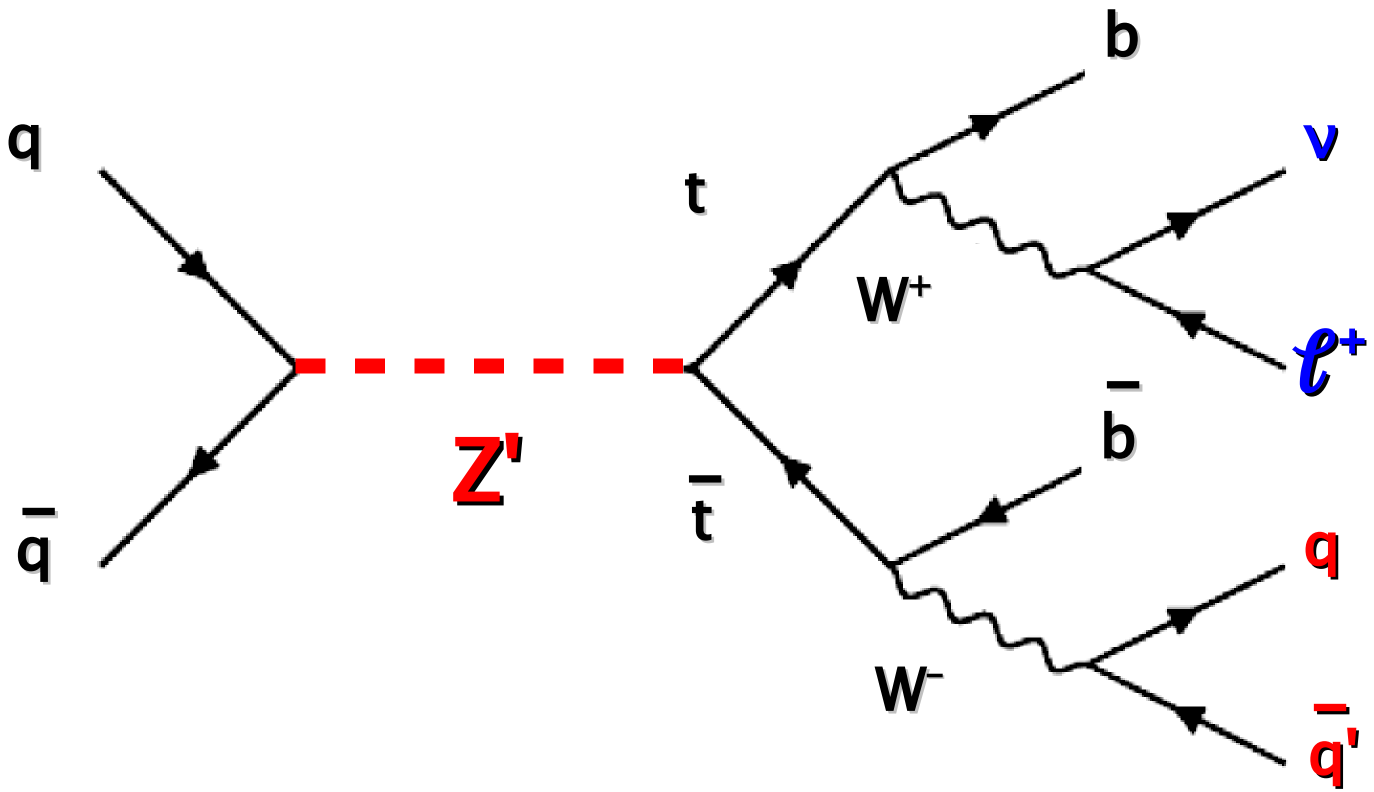
$$M_t = 174.1 \,^{+9.8}_{-8.4} \text{ (stat+syst) } ^{+4.2}_{-6.0} \text{ (theory) GeV}$$

kinematical:
MWT+νWT

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

DØ Note 5460-CONF

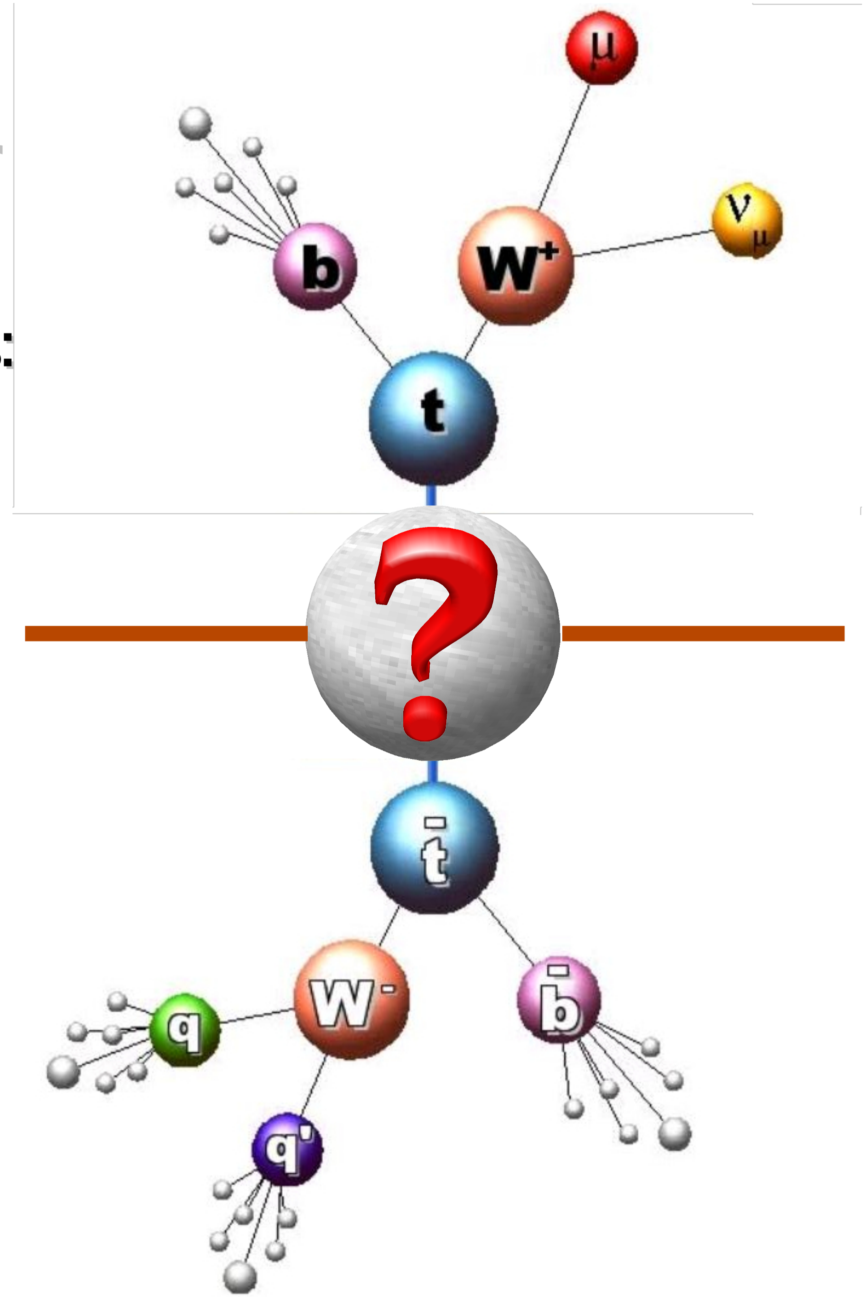
Search for resonances



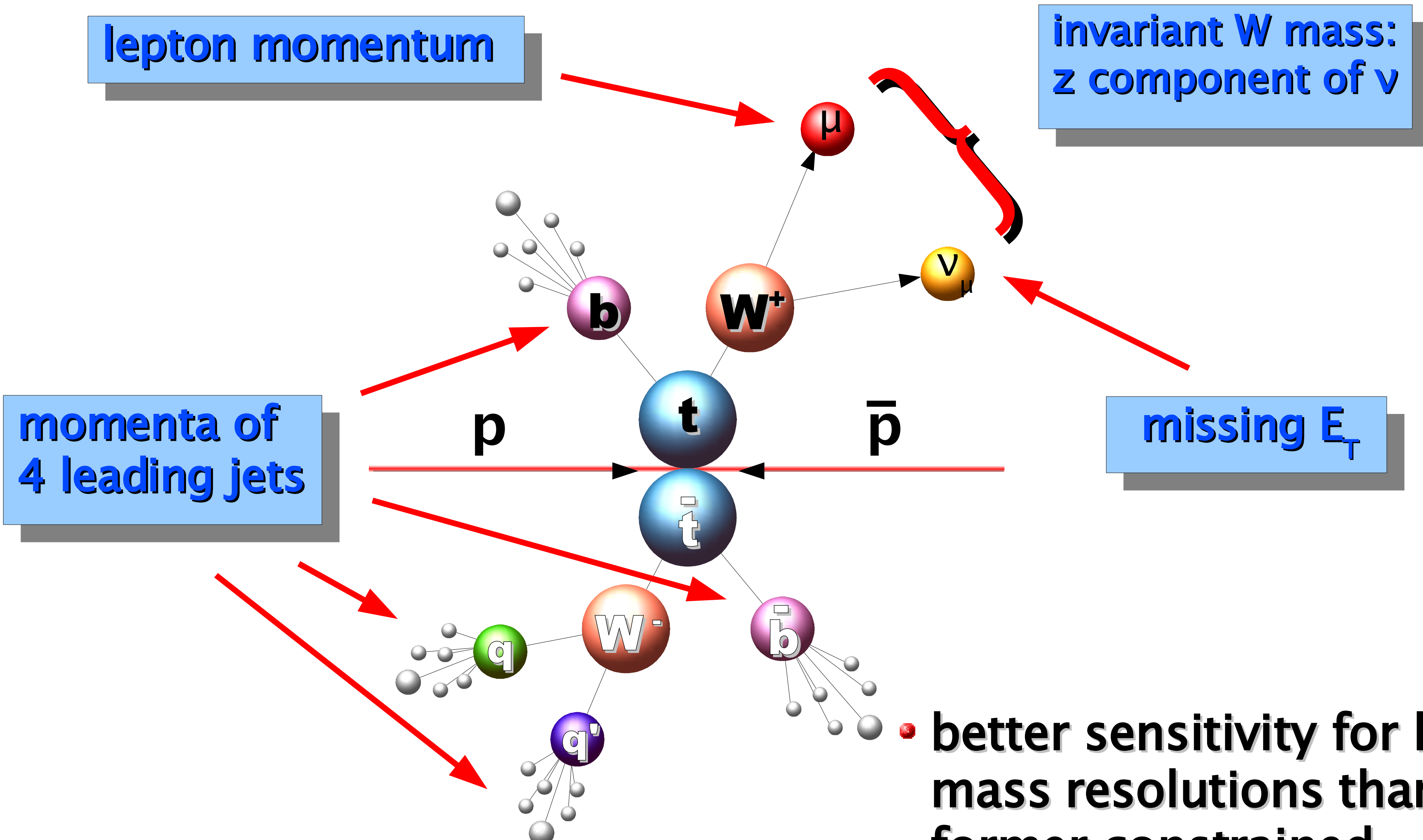
Search for $t\bar{t}$ Production via New Resonances

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



Reconstruction of $t\bar{t}$ invariant mass



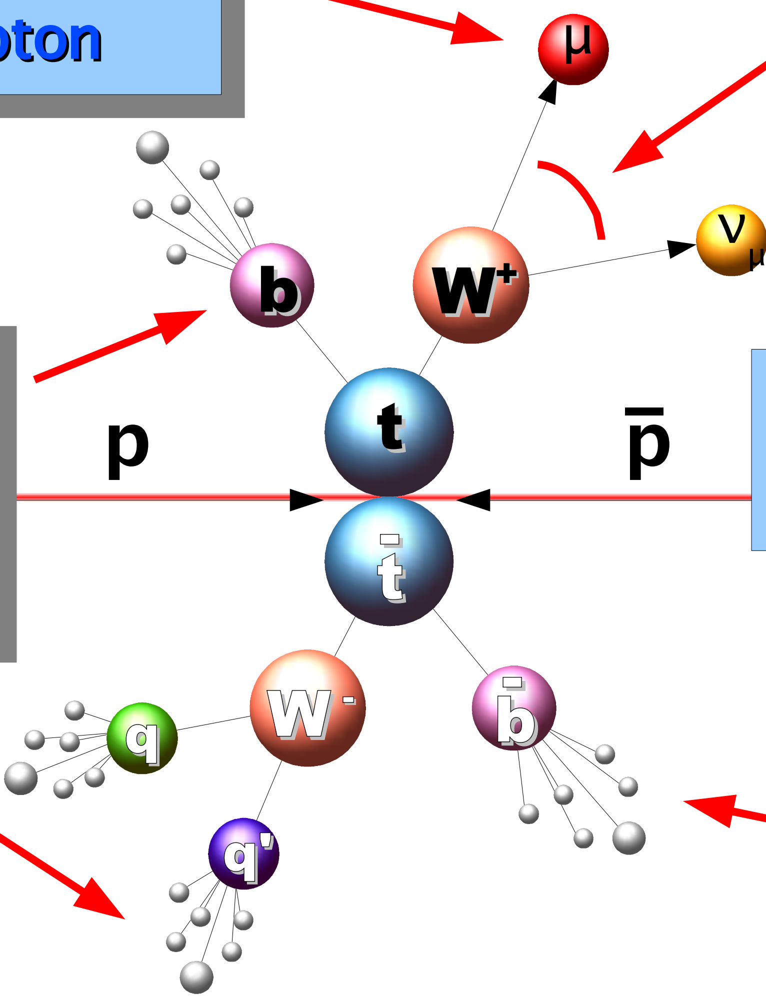
- better sensitivity for high mass resolutions than former constrained kinematic fit technique

Event Selection in Lepton+Jets

e (μ) isolated, p_T > 20 GeV,
|η|< 1.1 (2.0),
no other high p_T lepton

minimum Δφ

at least 4 jets,
p_T > 20 GeV,
|η|< 2.5,
one jet p_T > 40 GeV

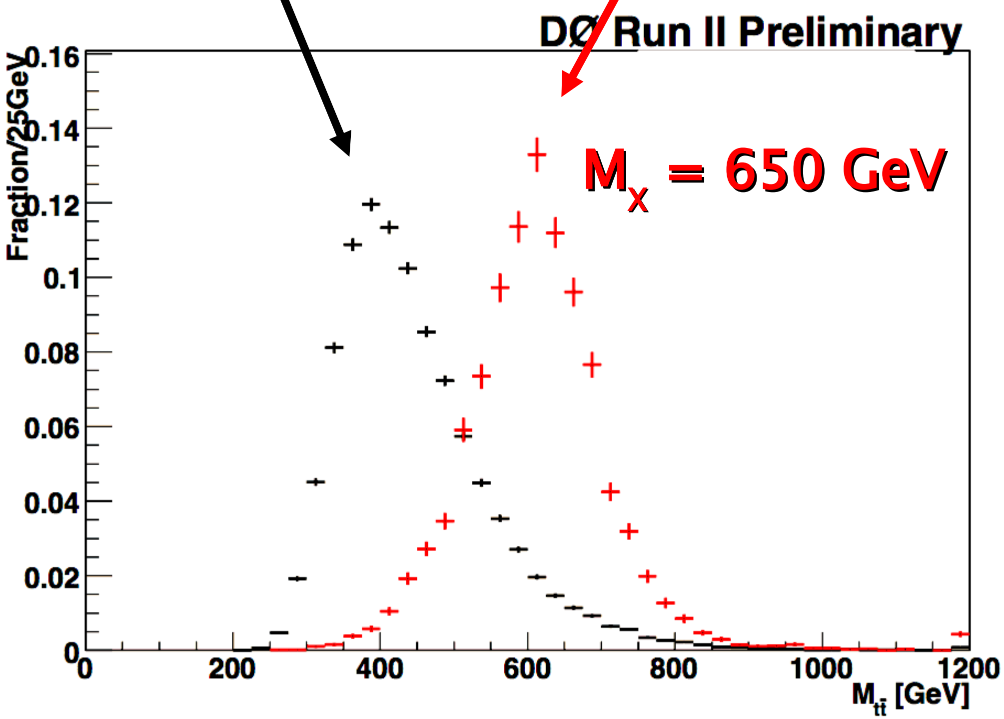


missing E_T > 20 (25) GeV
for e (μ)+jets

at least 1 jet
b–tagged
(Neural
Network)

Results for e, μ + jets combined

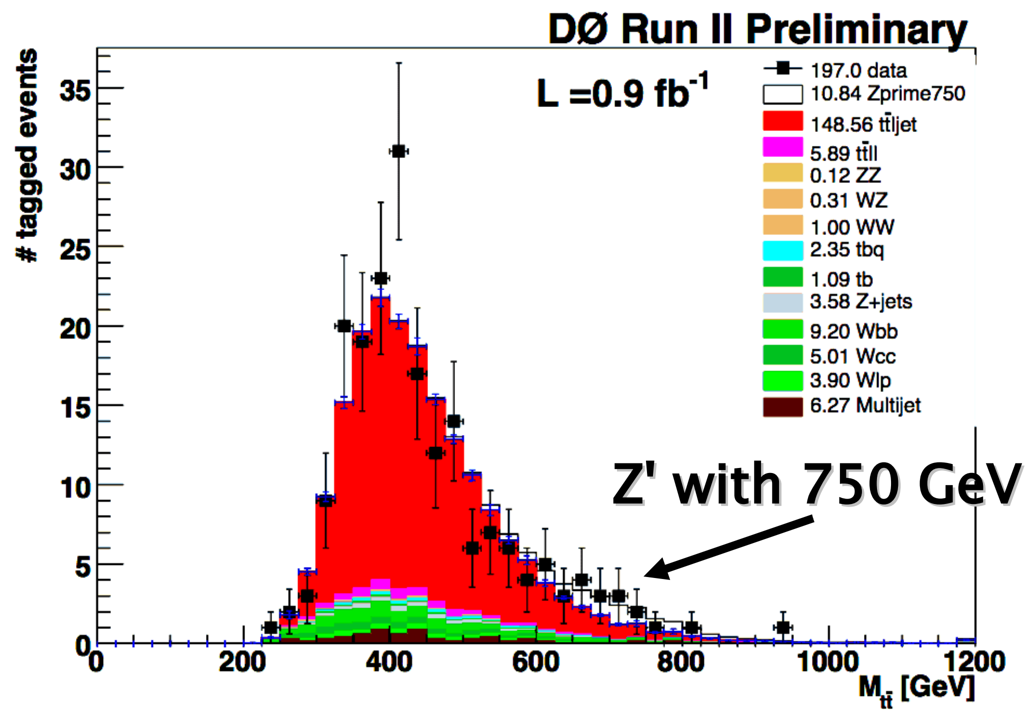
top pair and signal:



data and SM:

SM: use ttbar cross section

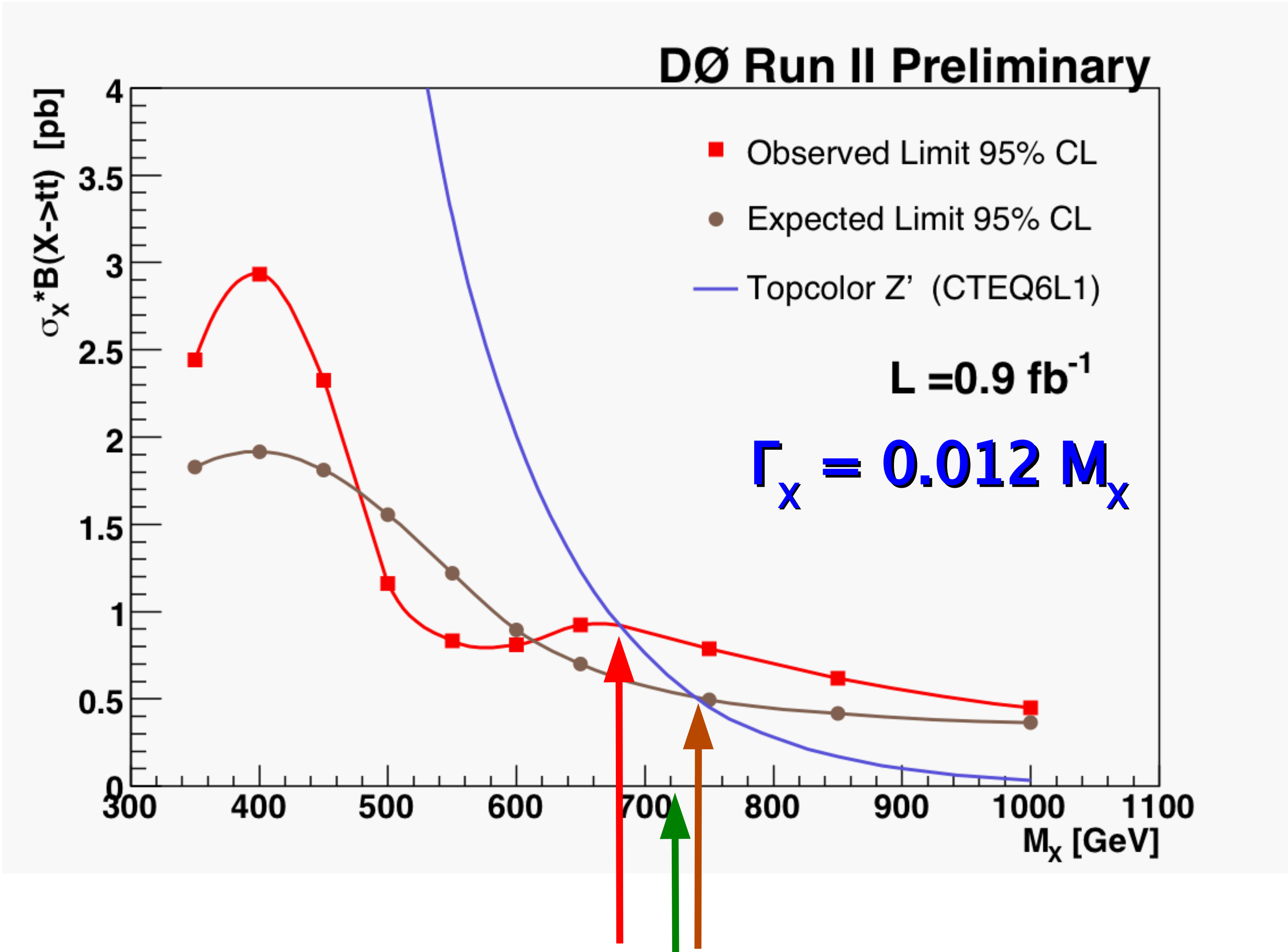
6.77 ± 0.60 pb (NLO+resummations)



⇒ e, μ + jets combined: 197 events, 187 expected

⇒ binned Likelihood fit to get upper limit

Limits for e, μ + jets combined

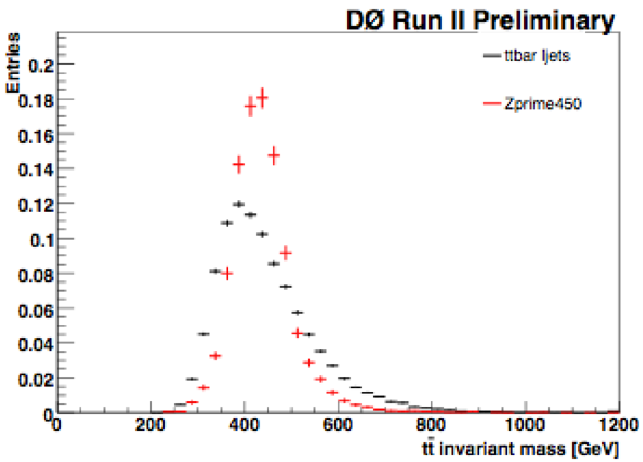


⇒ $M_{Z'} > 680$ GeV

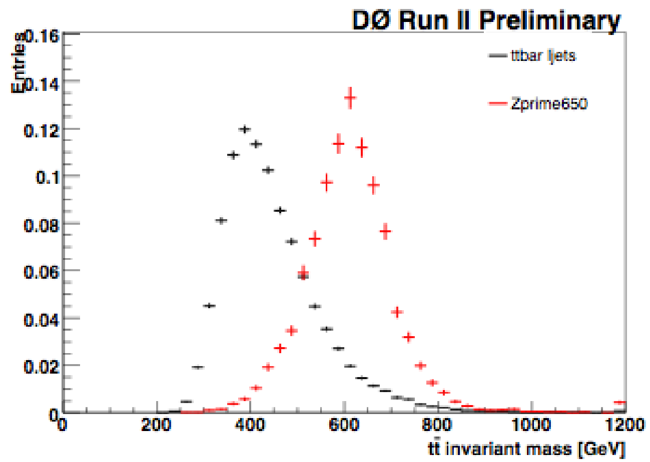
expected: $M_{Z'} > 740$ GeV

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

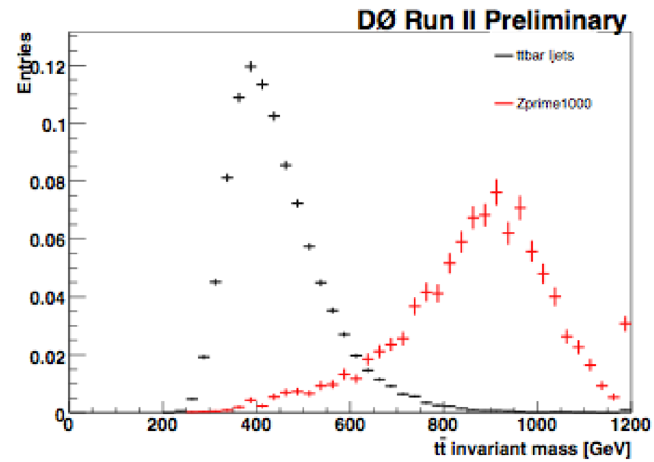
Mass dependence of resonance



$M_X = 450\,\mathrm{GeV}$

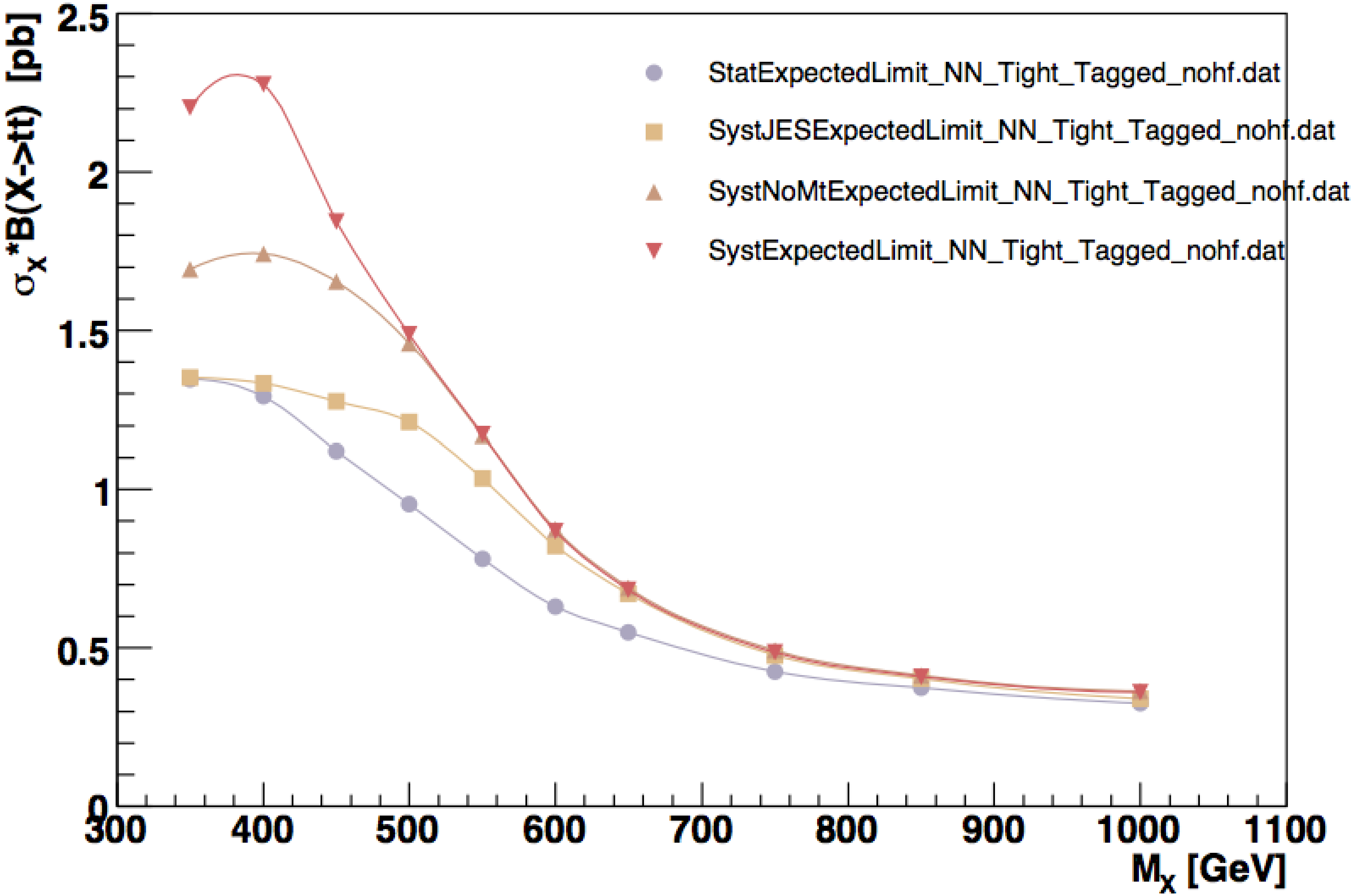


$M_X = 650\,\mathrm{GeV}$



$M_X = 1\,\mathrm{TeV}$

Error dependence on resonance limit

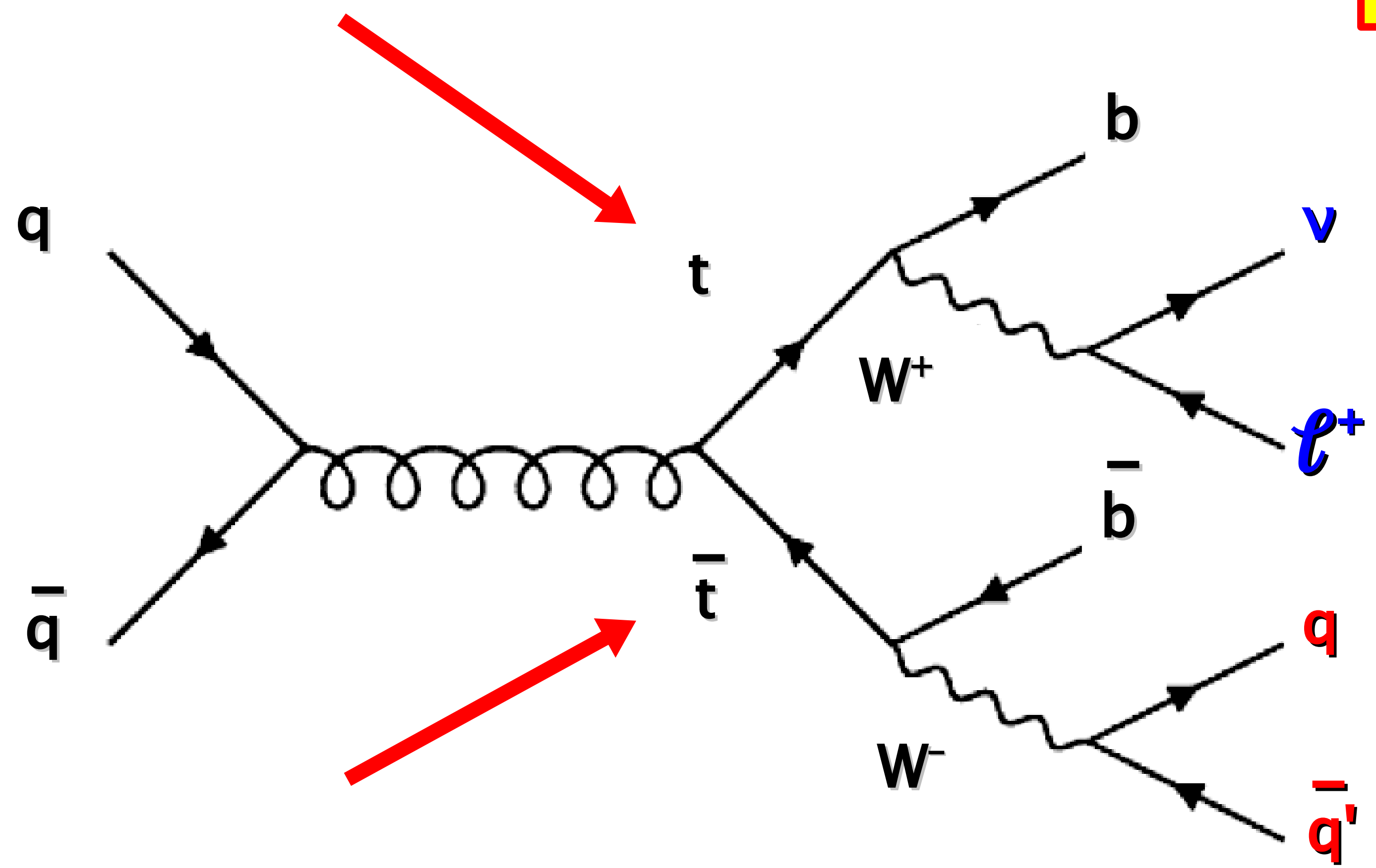


MSSM parameters

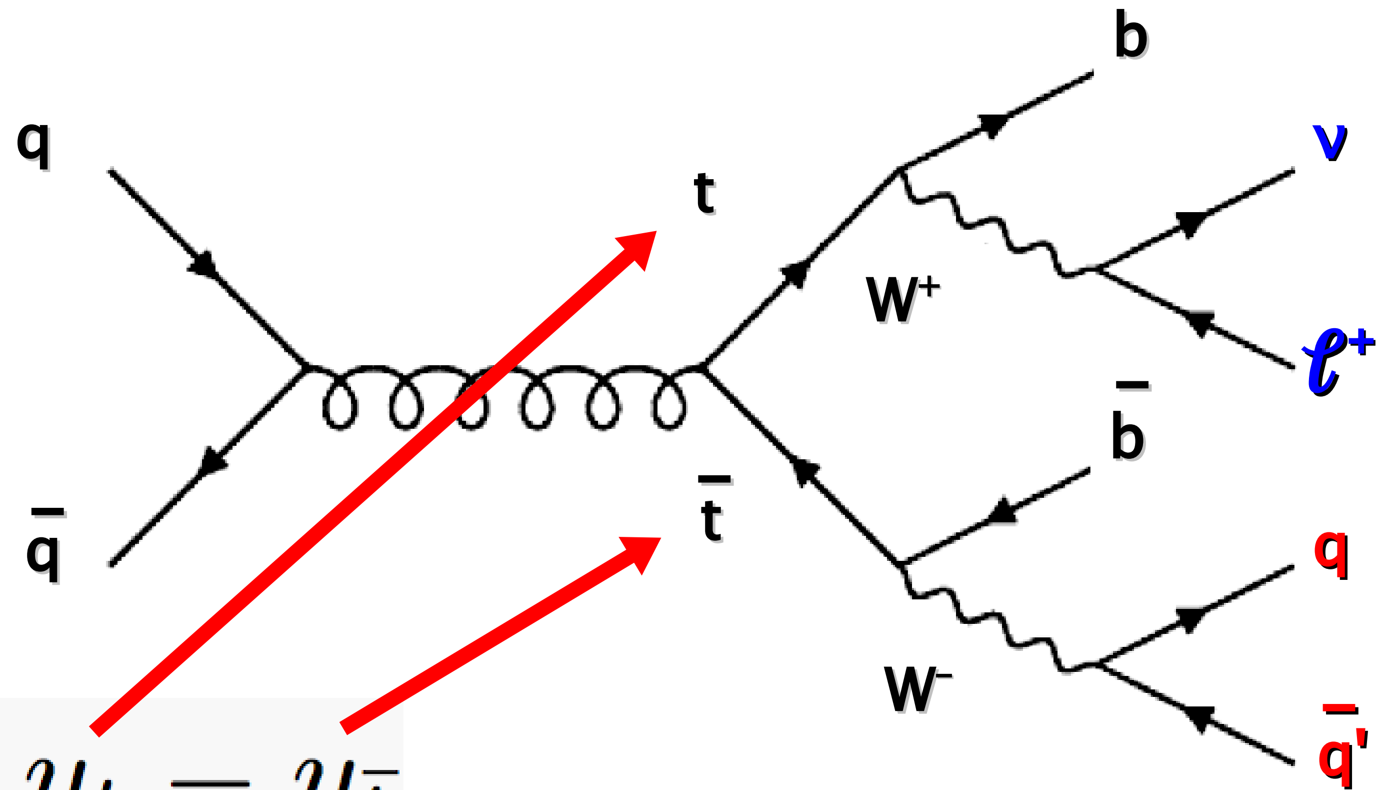
- $\tan\beta = 20$, $\mu = 225$ GeV, $M_A = 800$ GeV, $M_1 = 53$ GeV, $M_3 = 500$ GeV,
- Trilinear couplings $A_b = A_\tau = 200$ GeV,
- Scalar lepton masses $M_{\tilde{l}_L} = M_{\tilde{l}_R} = M_{\tilde{\tau}_L} = M_{\tilde{\tau}_R} = 200$ GeV,
- Scalar quark masses $M_{\tilde{q}_L} = M_{\tilde{q}_R} = M_{\tilde{b}_R} = M_{\tilde{t}_R} = 250$ GeV.

First measurement of charge asymmetry

NEW



Forward backward asymmetry



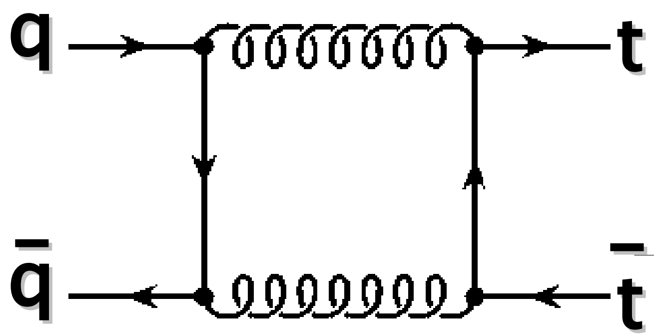
$$\Delta y \equiv y_t - y_{\bar{t}}$$

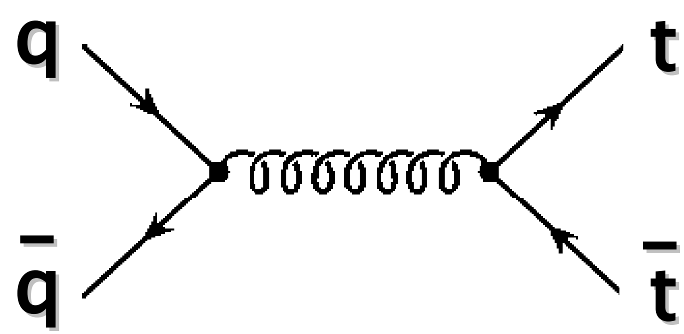
$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$

Charge asymmetry in SM

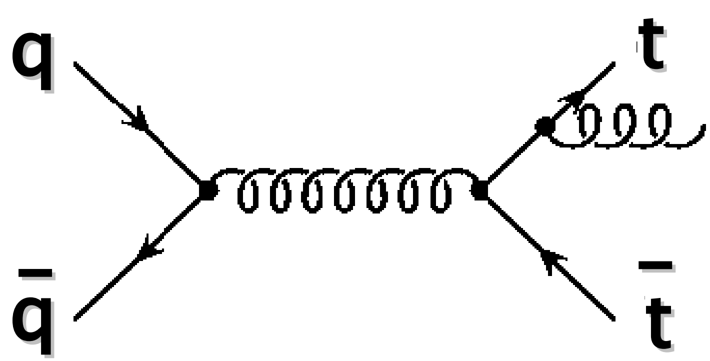
- no asymmetry in $O(\alpha_s^2)$
- asymmetry in $O(\alpha_s^3)$

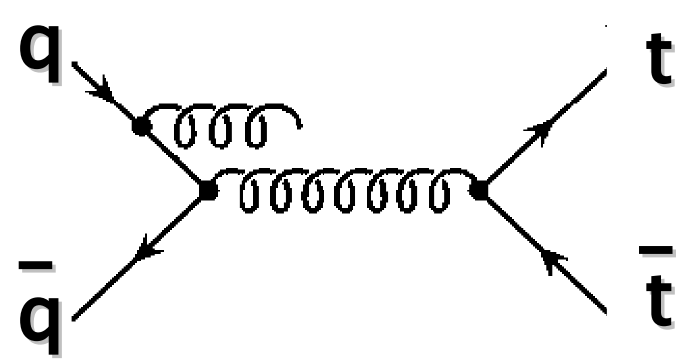
interference between:





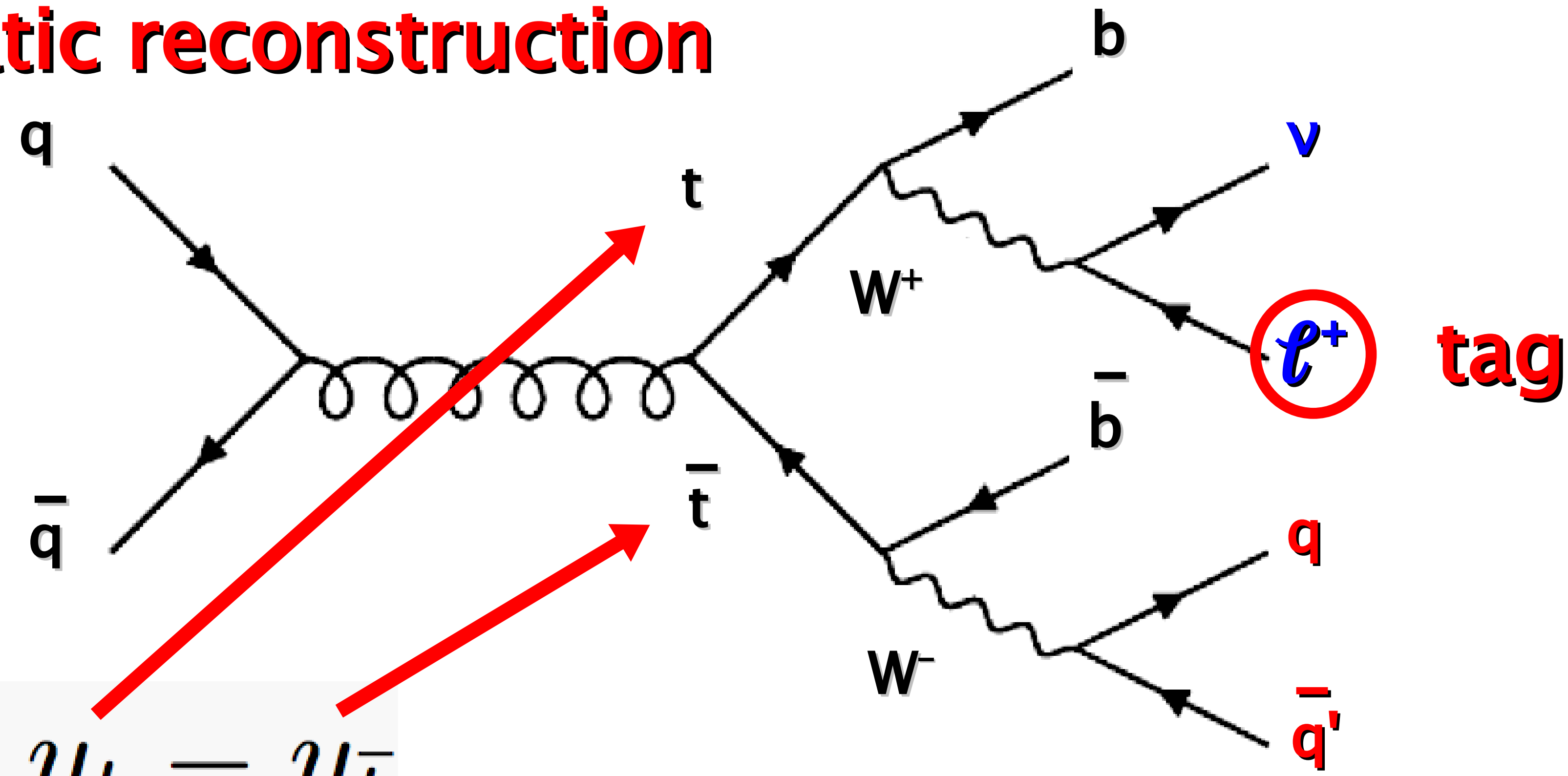
interference between:





Measurement of charge asymmetry

kinematic reconstruction



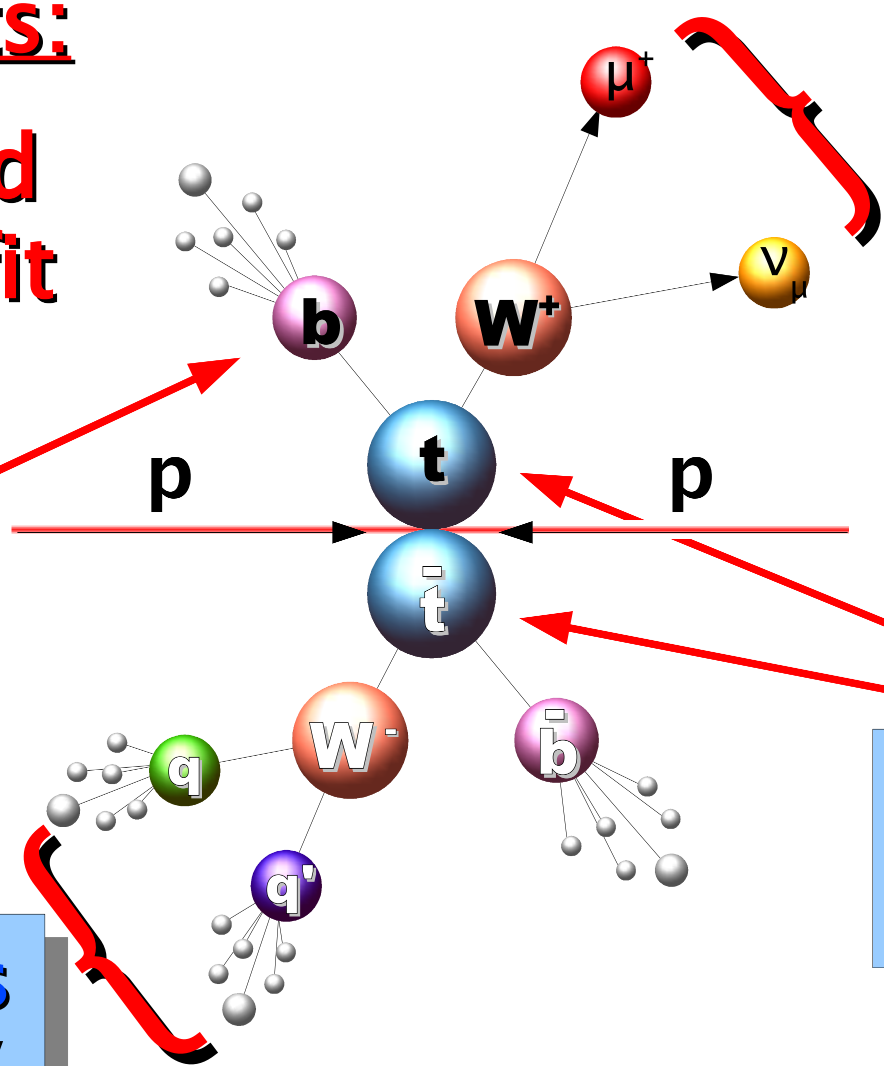
$$\Delta y \equiv y_t - y_{\bar{t}}$$

$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$

Top pair reconstruction

12 jet–parton assignments:

constrained kinematic fit
lowest χ^2



b–tag

invariant mass
m_W=80.4 GeV
(2 ν solutions)

m_{top} = 175 GeV
mass constraint

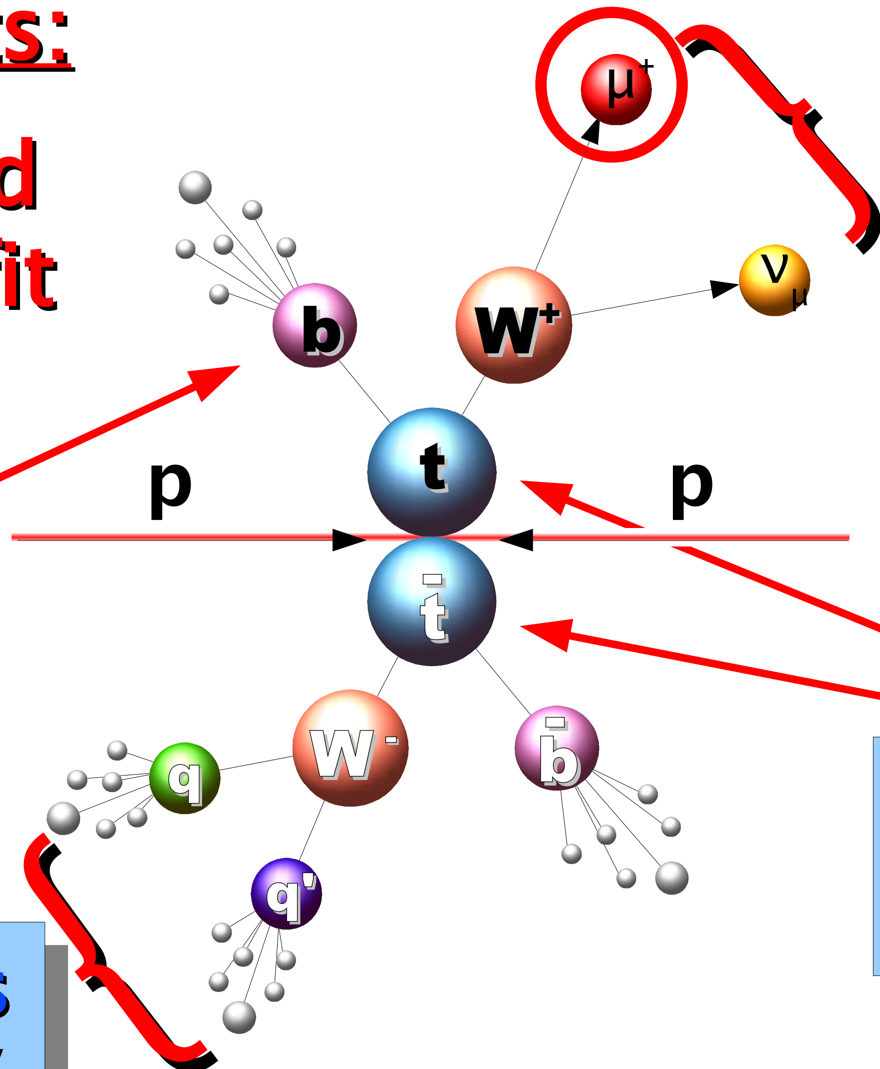
invariant mass
m_W=80.4 GeV

Top pair reconstruction

12 jet-parton assignments:

constrained kinematic fit lowest χ^2

b-tag

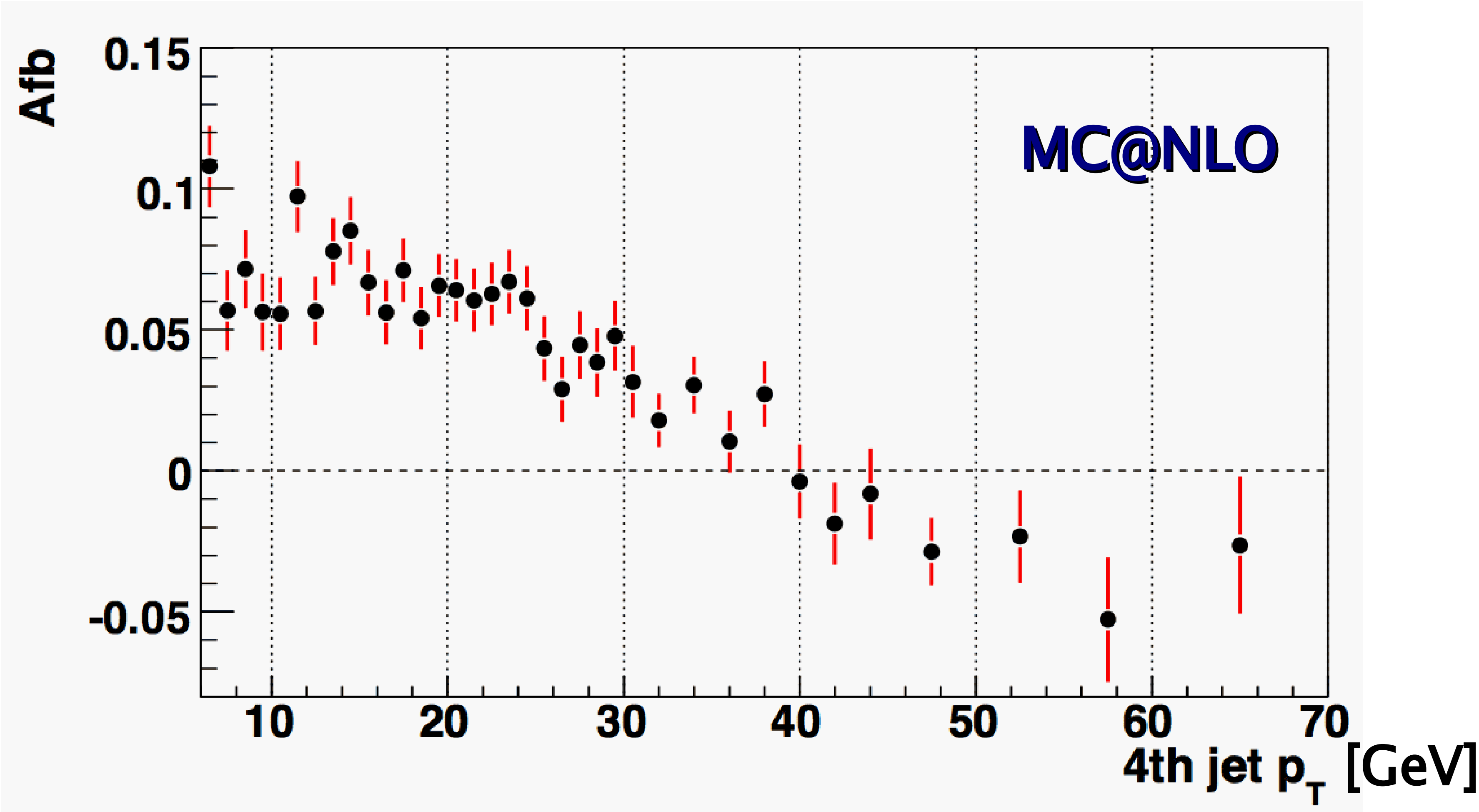


invariant mass m_W=80.4 GeV (2 ν solutions)

m_{top} = 175 GeV mass constraint

invariant mass m_W=80.4 GeV

Charge asymmetry in SM



- acceptance effects can be approximated by simple parton level cuts without changing asymmetry by more than 2%

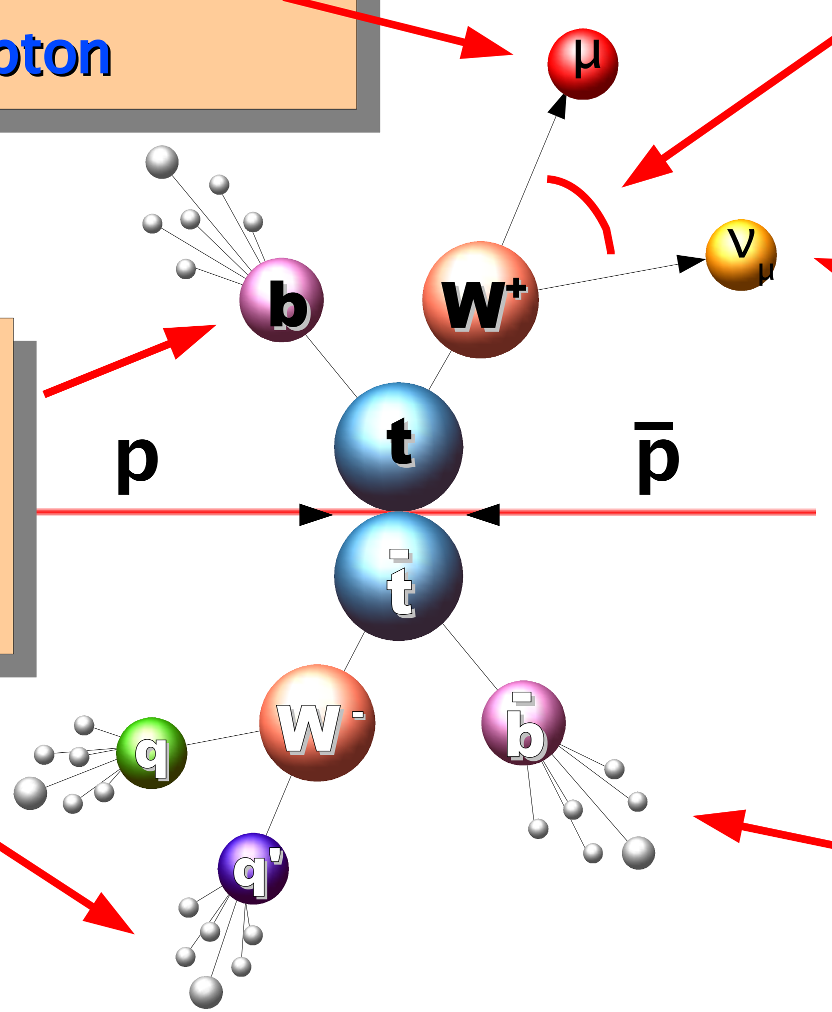
Event Selection in Lepton+Jets

e (μ) isolated, p_T > 15 (18) GeV,
|η|< 1.1 (2.0),
no other high p_T lepton

minimum Δφ

at least 4 jets,
p_T > 20 GeV,
|η|< 2.5,
one jet p_T > 35 GeV

missing E_T > 15 GeV
for e (μ)+jets



at least 1 jet
b–tagged
(Neural
Network)

Asymmetry Reconstruction

misreconstruction of Δy dilutes observed asymmetry:

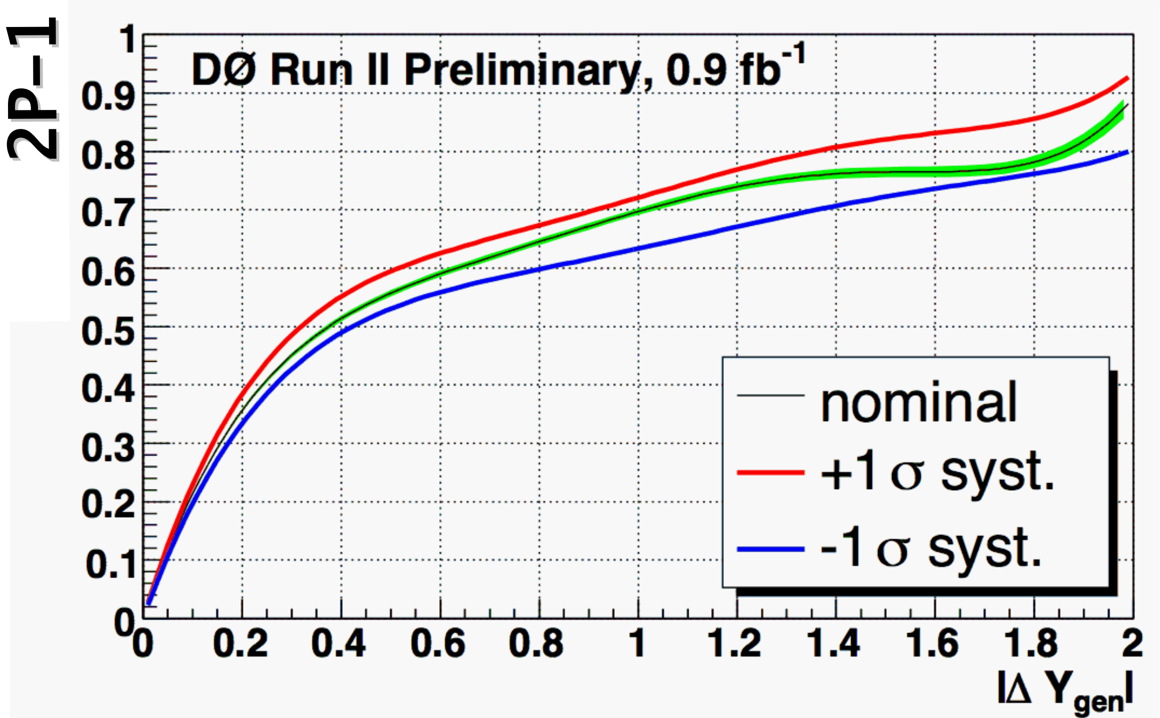
- misreconstruction of event geometry
- misidentification of lepton charge

$$\Delta y \equiv y_t - y_{\bar{t}}$$

$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$

How good are we?

P: is probability to reconstruct correct sign of Δy



- correction is very model dependent and may kill sensitivity to asymmetry due to new physics...

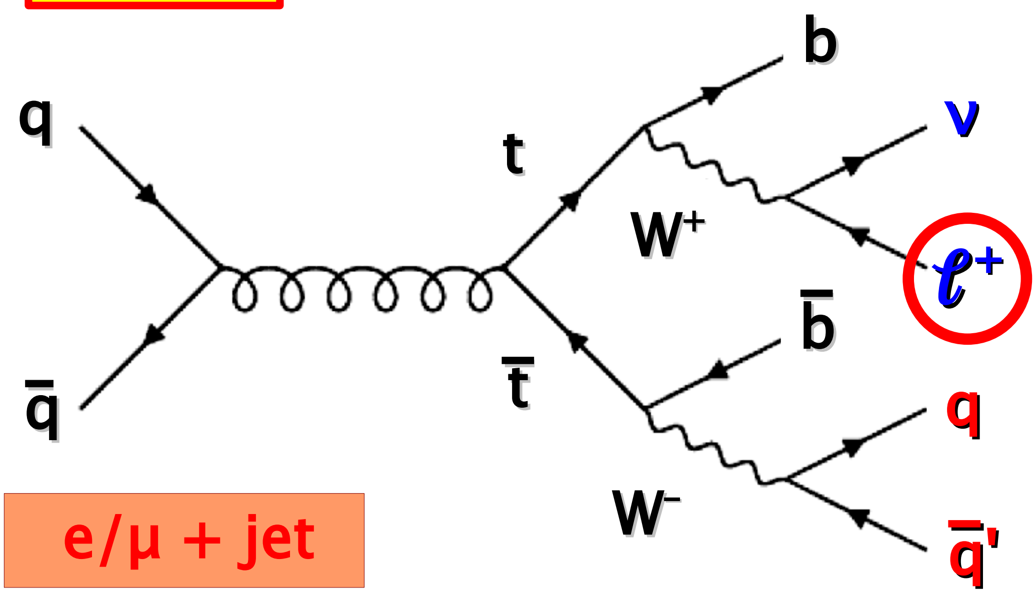
⇒ no correction, but we provide parameterization

Top anti-top signatures

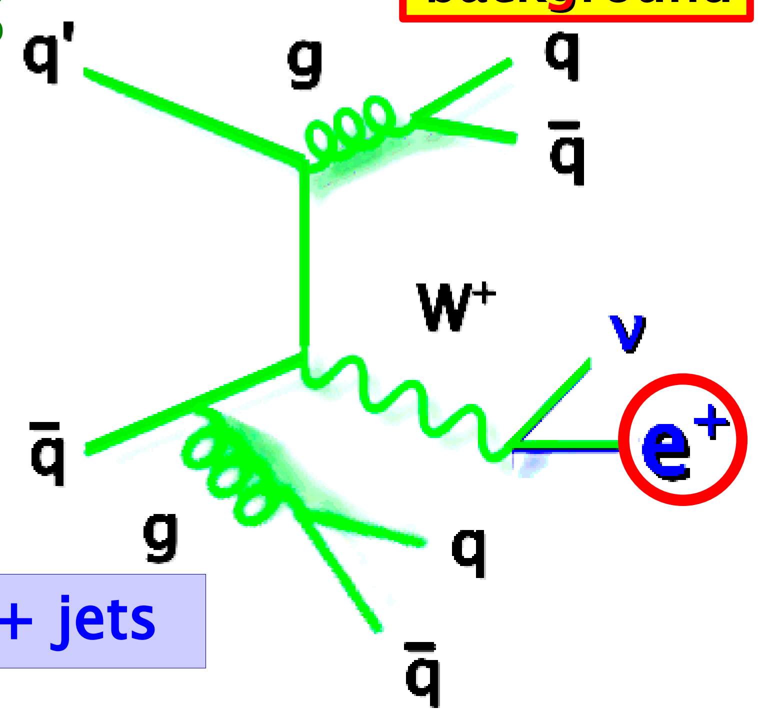
$A_{fb,W} = (\ 3.0 \pm 1.9\ )\ \%$
(due to top pair reconstruction) but smaller yield

background

signal



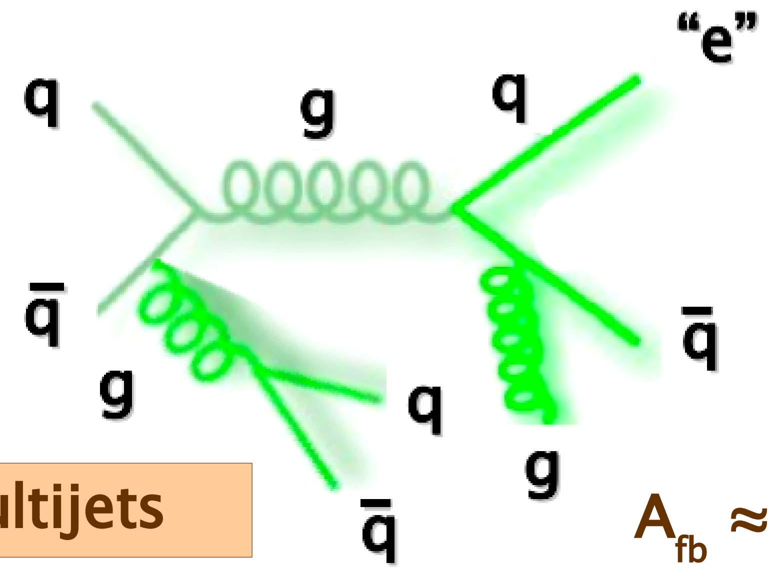
e/μ + jet



W + jets

MC@NLO:

$A_{fb} = (\ 0.8 \pm 0.2\ \text{(stat)} \pm 1.0\ \text{(accept)}\ )\ \%$



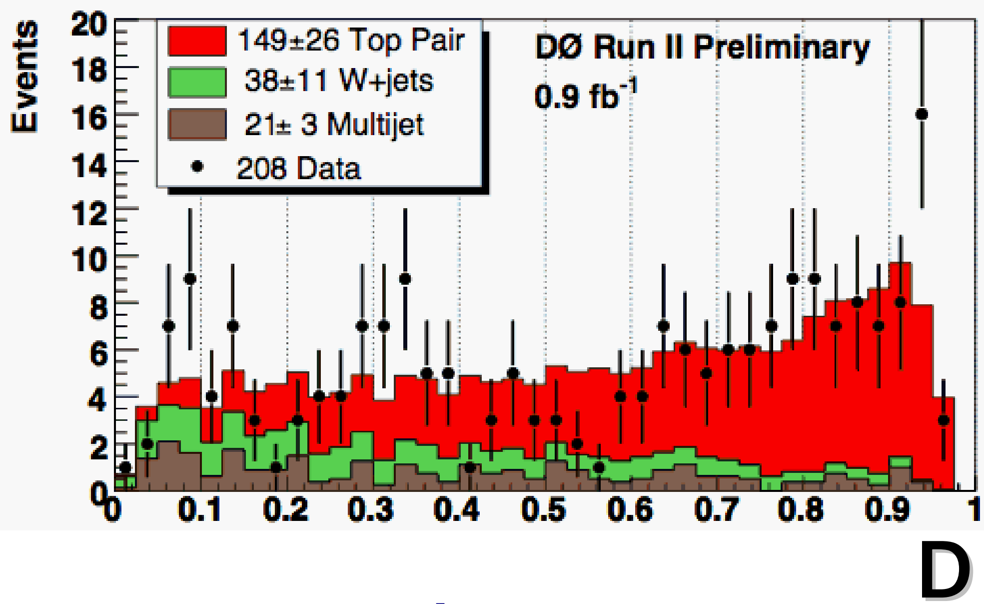
multijets

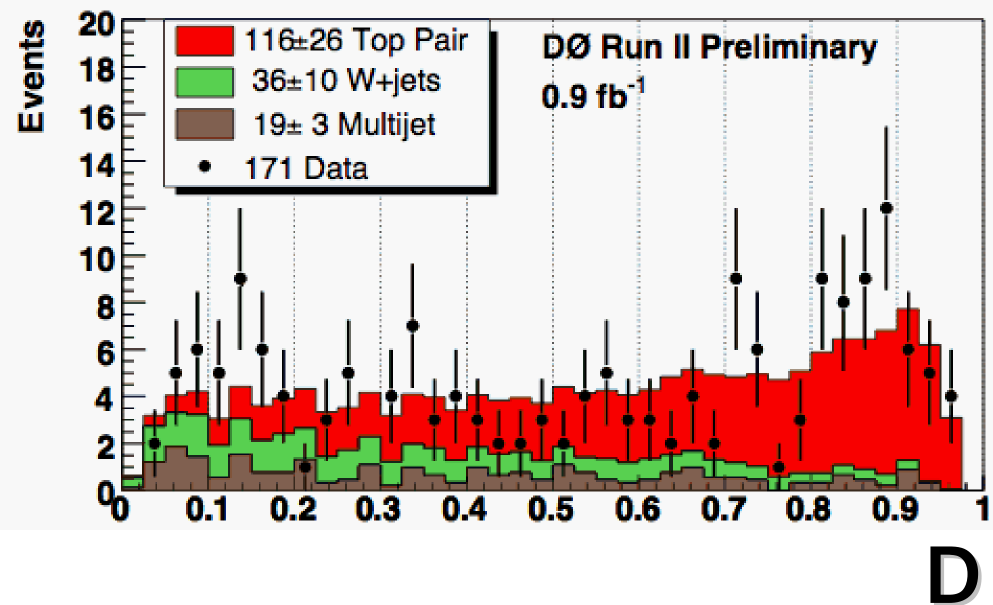
$A_{fb} \approx 0$

Asymmetry extraction

- maximum Likelihood fit:
  extract sample composition and asymmetry simultaneously

$\Delta y \equiv y_t - y_{\bar{t}} > 0$ $\Delta y \equiv y_t - y_{\bar{t}} < 0$





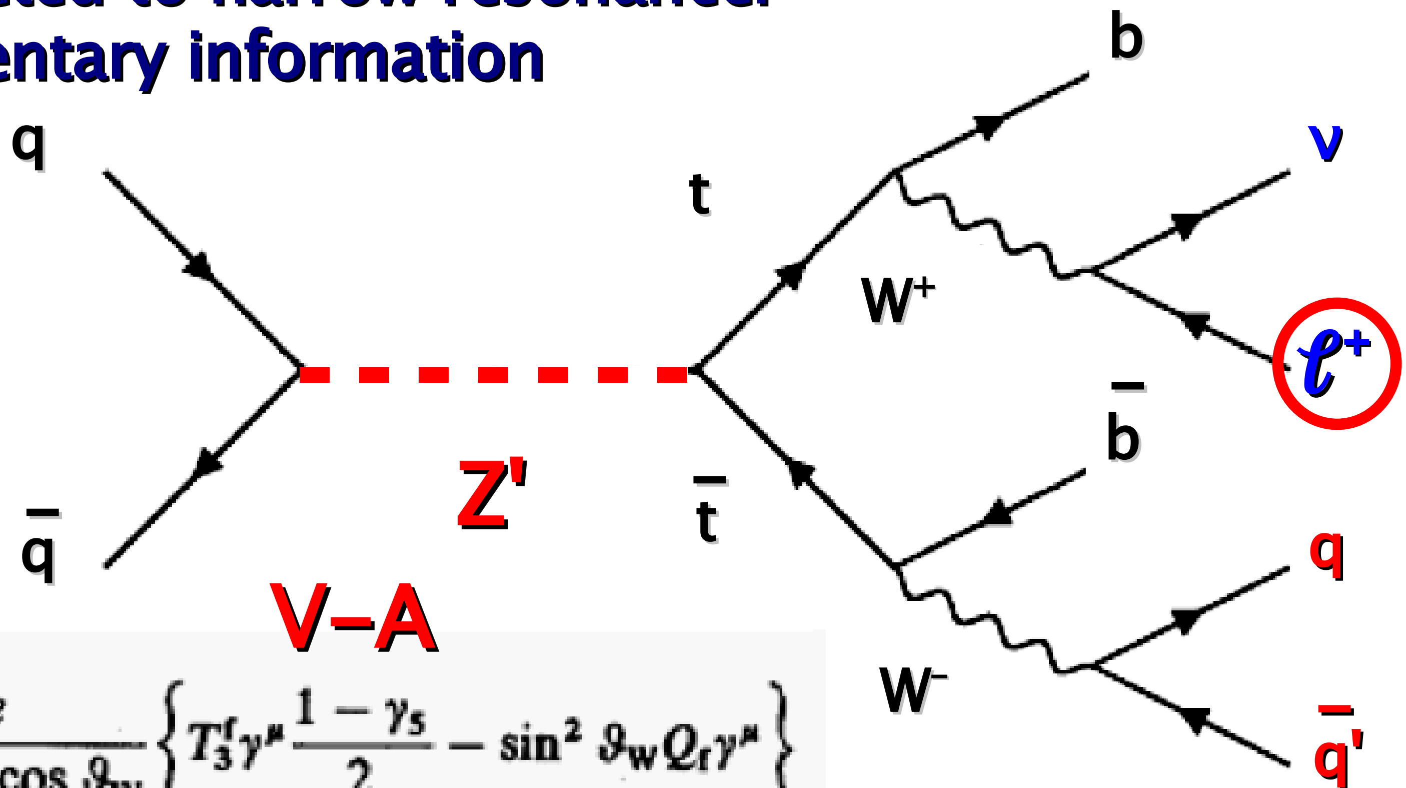
- top pair production cross sections consistent
- asymmetry in W+jets enriched sample consistent

$$A_{fb} = (\ 12 \pm 8\ (\text{stat}) \pm 1\ (\text{syst})\ )\ \%$$

consistent with prediction in NLO QCD

Asymmetry due to leptophobic Z'

not restricted to narrow resonance: complementary information



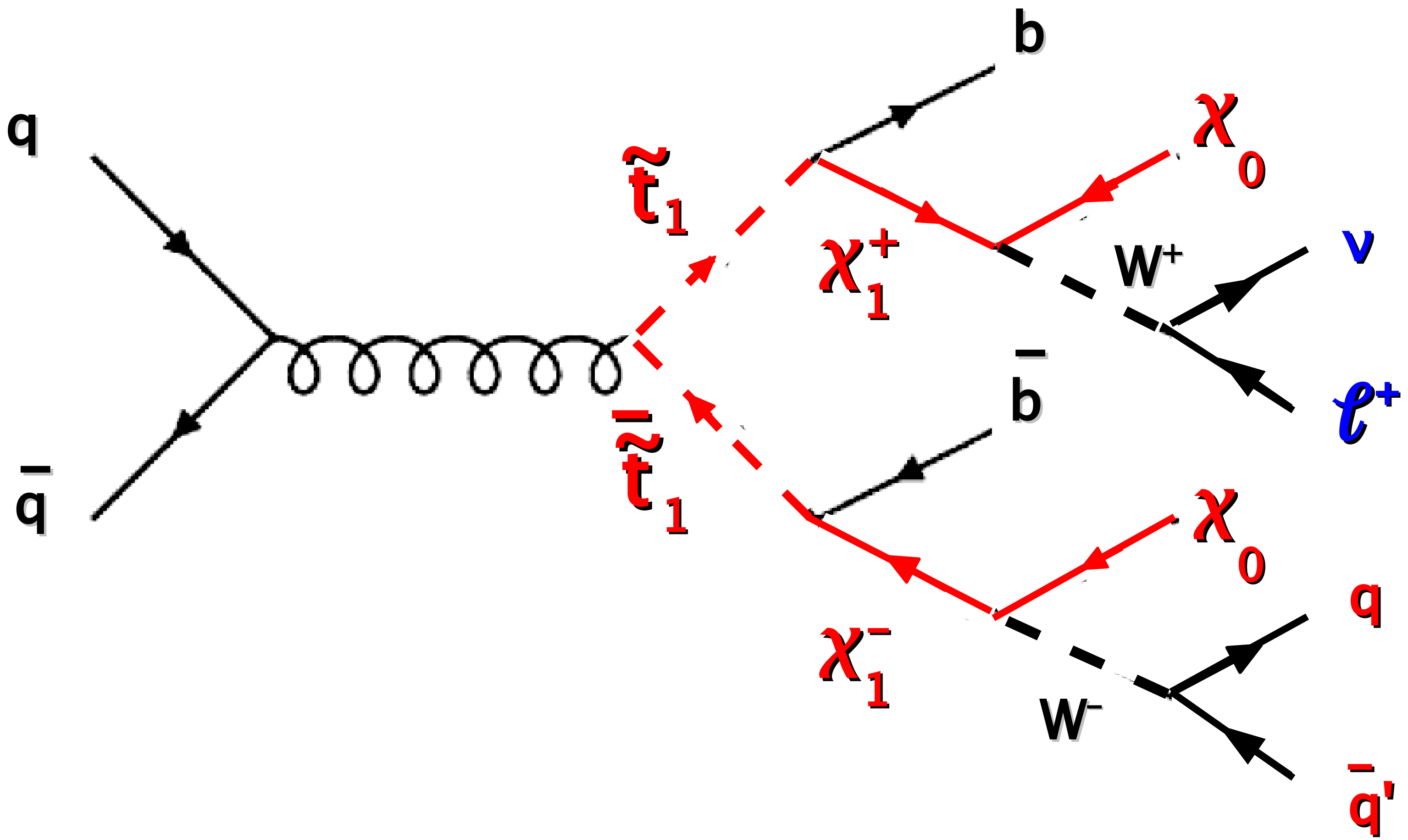
$$-i\frac{e}{\sin\vartheta_W\cos\vartheta_W}\left\{T_3^f\gamma^\mu\frac{1-\gamma_5}{2}-\sin^2\vartheta_W Q_f\gamma^\mu\right\}$$

F: fraction of top pair events produced via Z' resonance

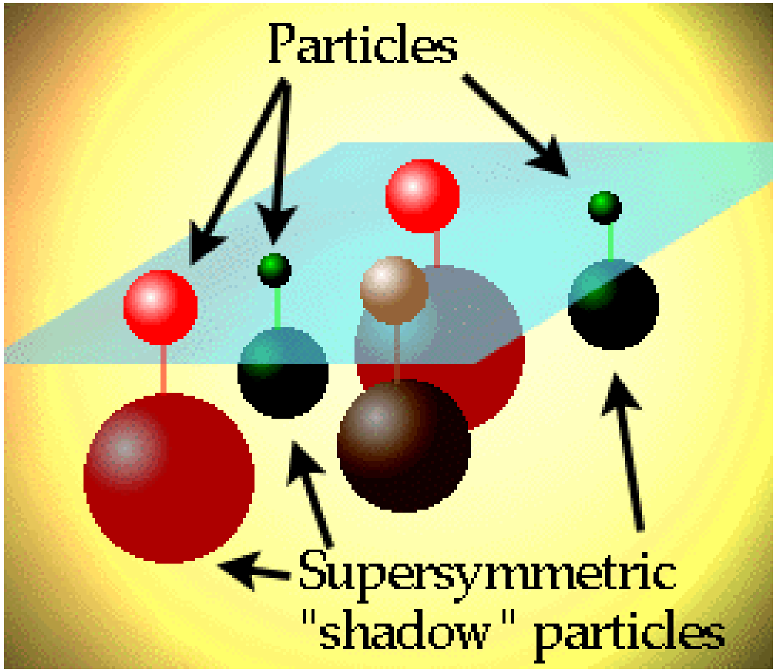
e.g. $M_{Z'} = 750$ GeV:

F < 0.44 (expected)
F < 0.81 (observed)

Search for stop pair production



Supersymmetry



Name	Spin	Superpartner	Spin
Electron	1/2	Selectron	0
Muon	1/2	Smuon	0
Tau	1/2	Stau	0
Neutrino	1/2	Sneutrino	0
Quark	1/2	Squark	0

Name	Spin	Superpartner	Spin
Graviton	2	Gravitino	3/2
Photon	1	Photino	1/2
Gluon	1	Gluino	1/2
$W^{+,-}$	1	$Wino^{+,-}$	1/2
Z^0	1	Zino	1/2
Higgs	0	Higgsino	1/2

Supersymmetry

- large top quark mass: large mixing between left- and right-handed superpartners
- $\tilde{t}_1$ can be lightest squark, lighter than top quark
- electroweak baryogenesis possible in such a scenario
- we haven't looked at it before...

Name	Spin	Superpartner	Spin
Electron	1/2	Selectron	0
Muon	1/2	Smuon	0
Tau	1/2	Stau	0
Neutrino	1/2	Sneutrino	0
Quark	1/2	Squark	0

stop quark

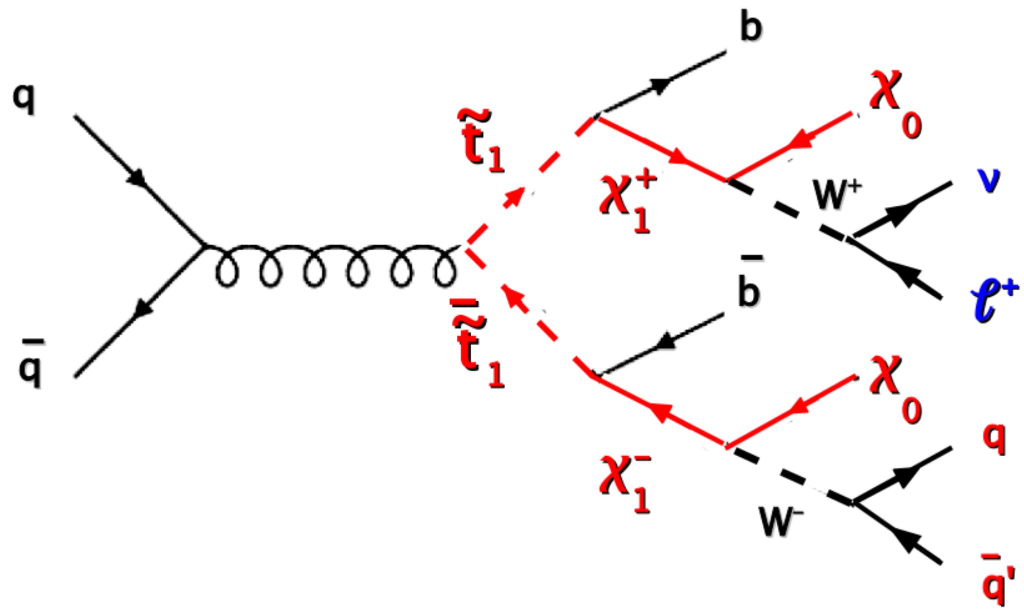
Name	Spin	Superpartner	Spin
Graviton	2	Gravitino	3/2
Photon	1	Photino	1/2
Gluon	1	Gluino	1/2
$W^{+,-}$	1	$Wino^{+,-}$	1/2
Z^0	1	Zino	1/2
Higgs	0	Higgsino	1/2

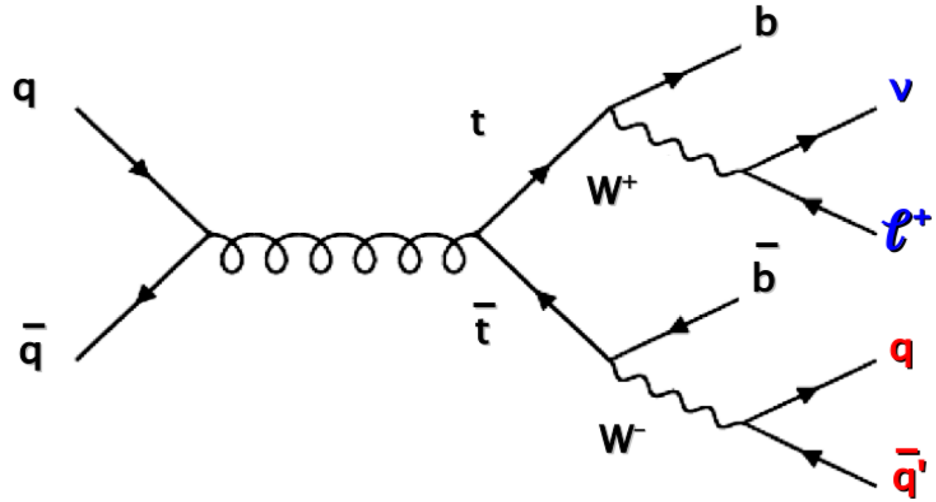
χ^+

χ^0 (LSP)

Stop pair production vs. top pair production

- 2 light jets
- 2 b jets
- one charged lepton
- missing transverse energy





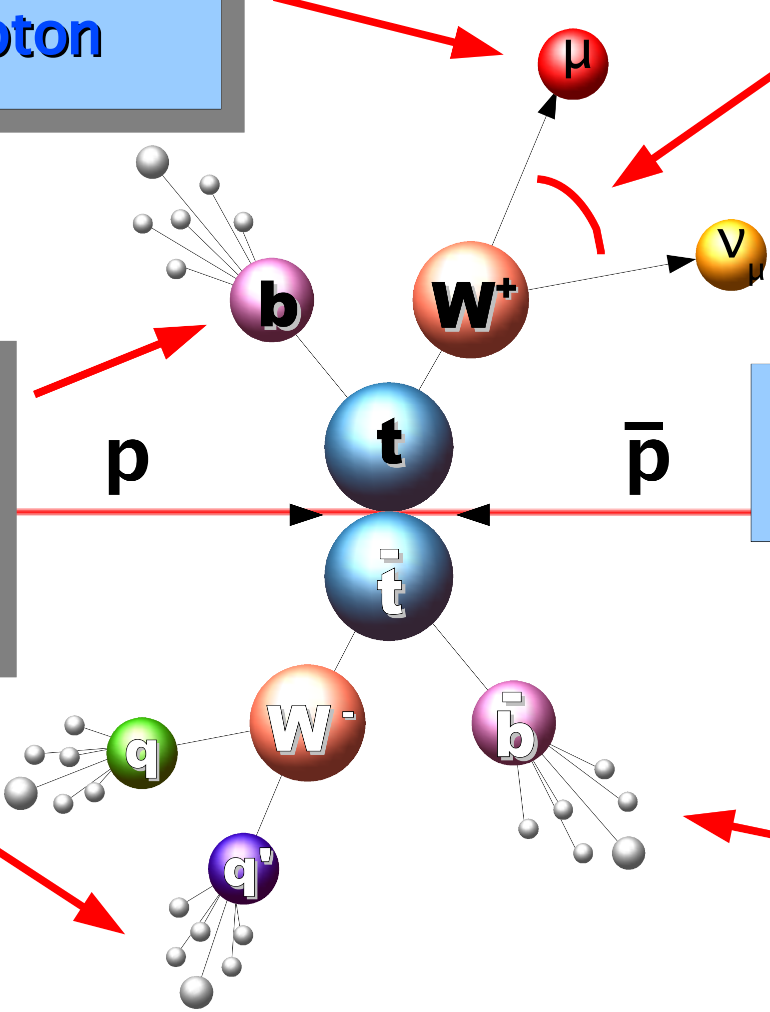
Event Selection in Lepton+Jets

e (μ) isolated, p_T > 20 GeV,
|η|< 1.1 (2.0),
no other high p_T lepton

minimum Δφ

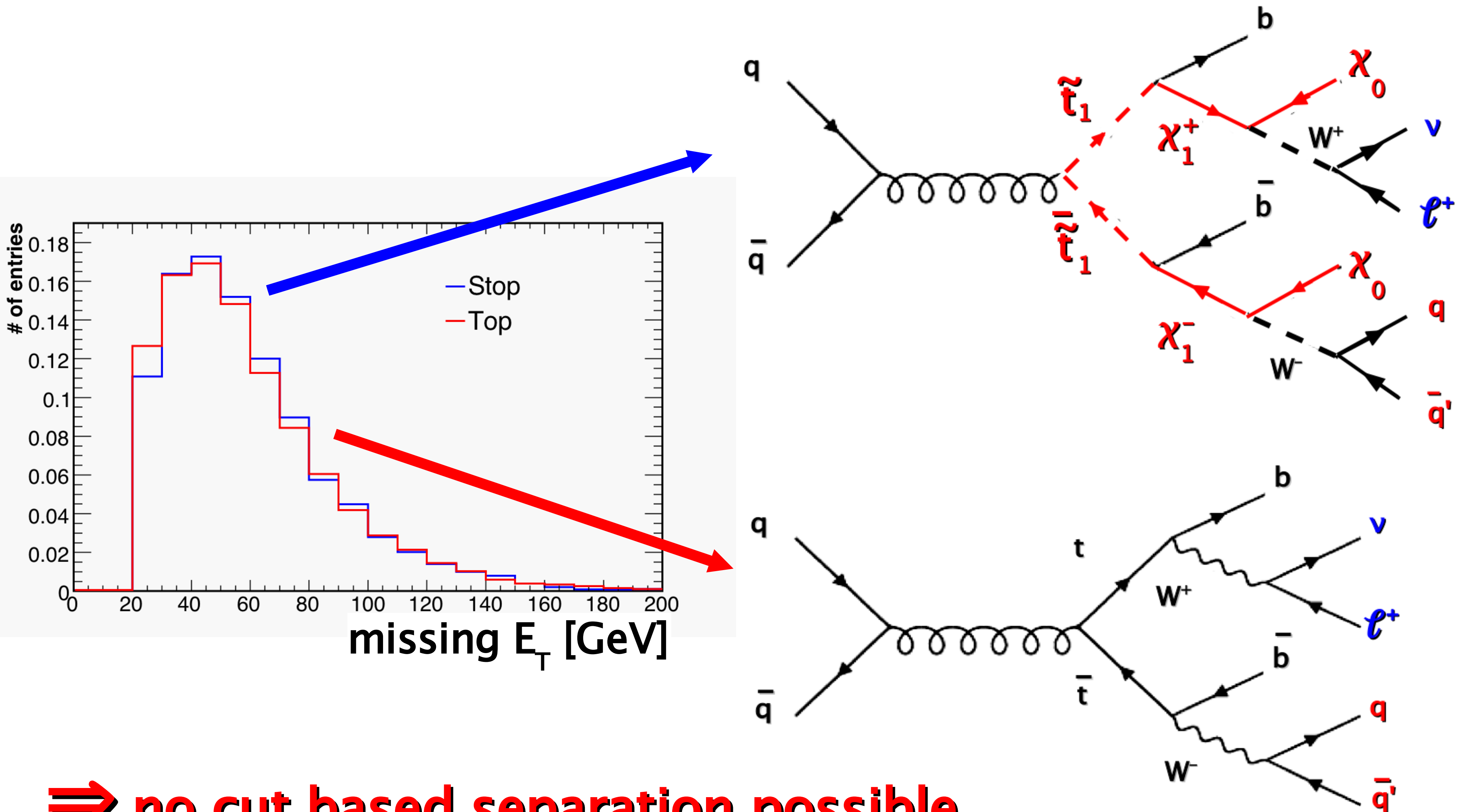
at least 4 jets,
p_T > 15 GeV,
|η|< 2.5,
one jet p_T > 40 GeV

missing E_T > 20 (25) GeV
for e (μ)+jets



at least 1 jet
b–tagged
(Neural
Network)

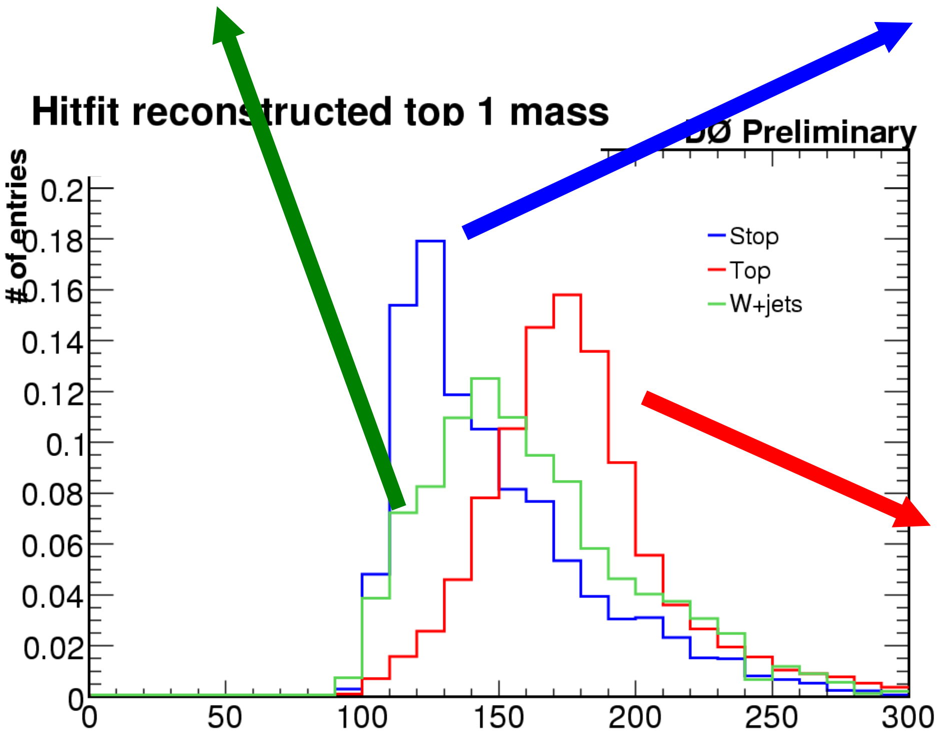
Stop pair production vs. top pair production



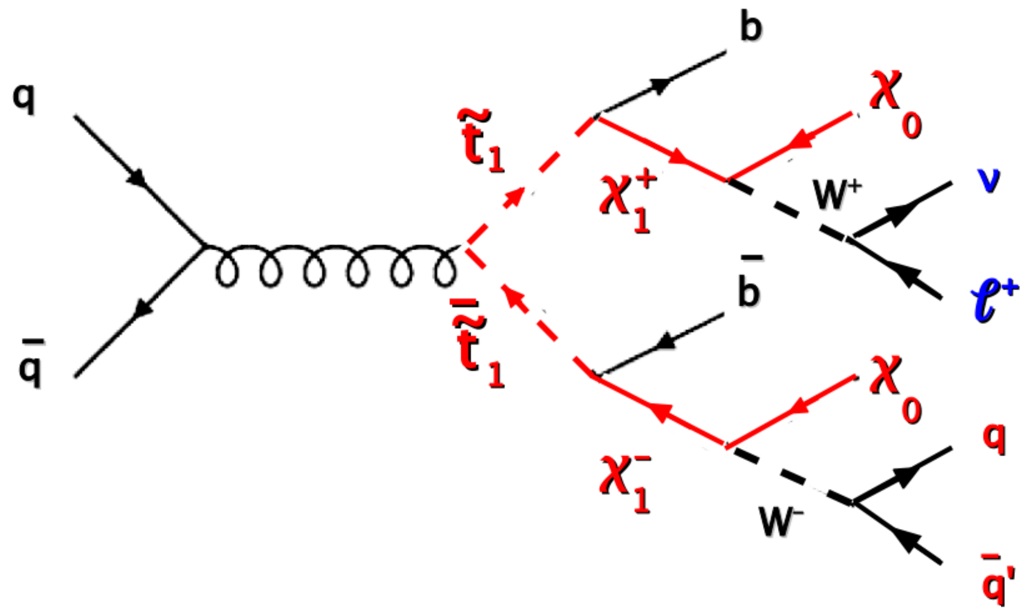
⇒ **no cut based separation possible**

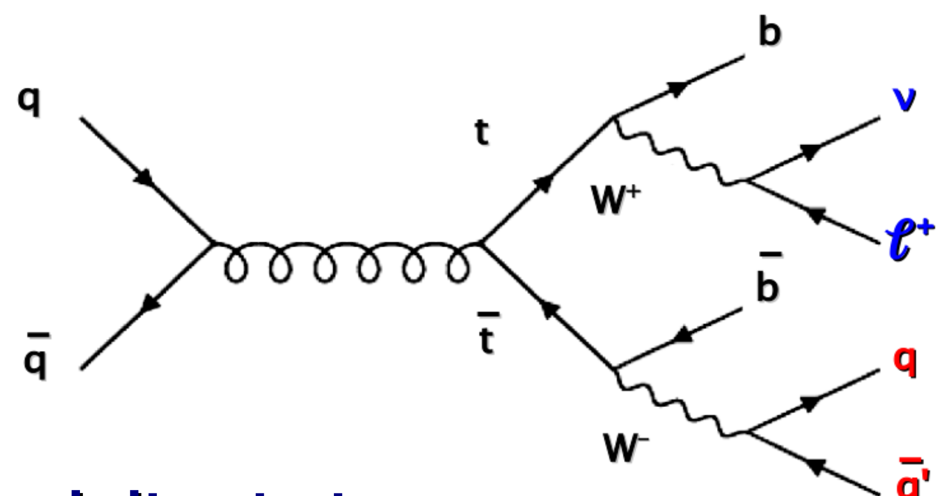
Stop pair production vs. top pair production

W+jets



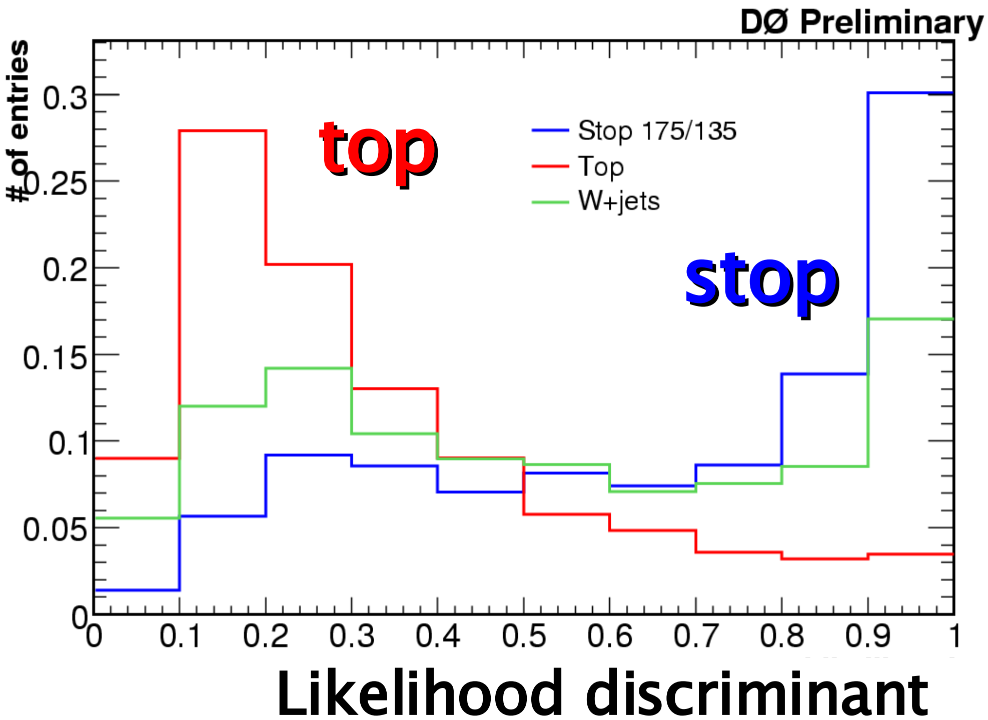
Reconstructed top mass

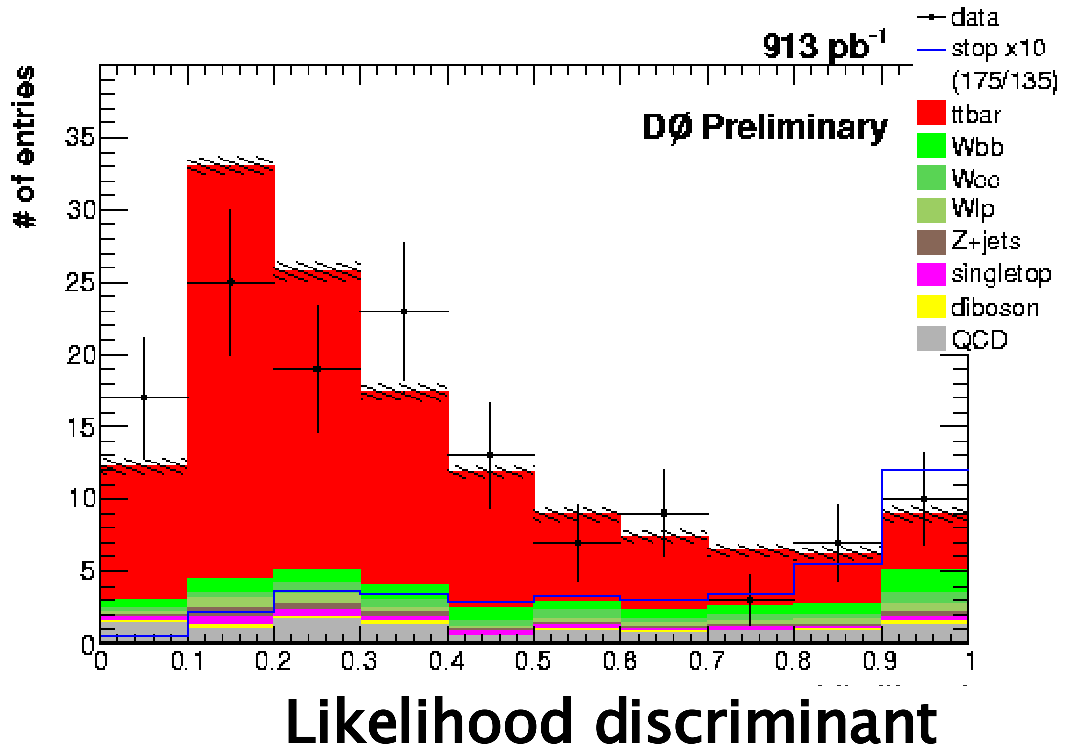




⇒ calculate topological Likelihood discriminant

Likelihood discriminant in e+jets channel

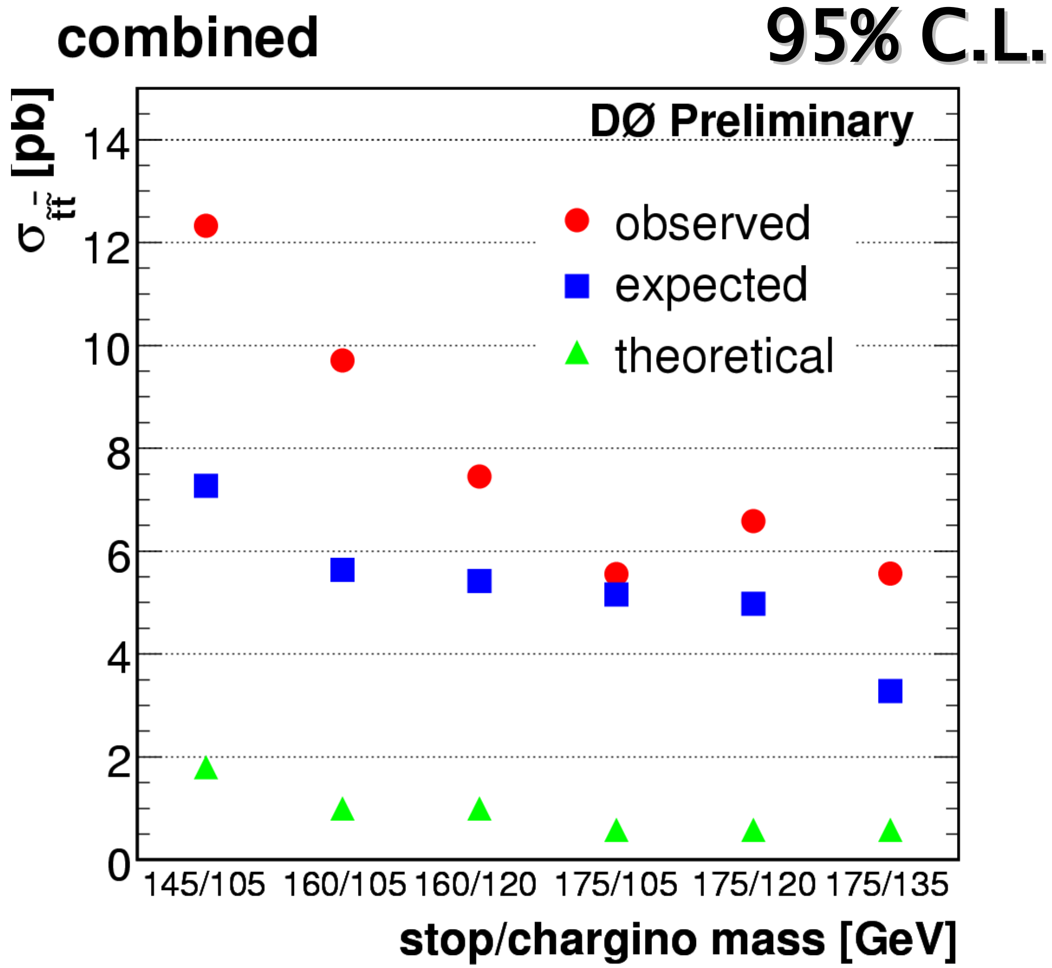




⇒ **no indication for stop pair production**

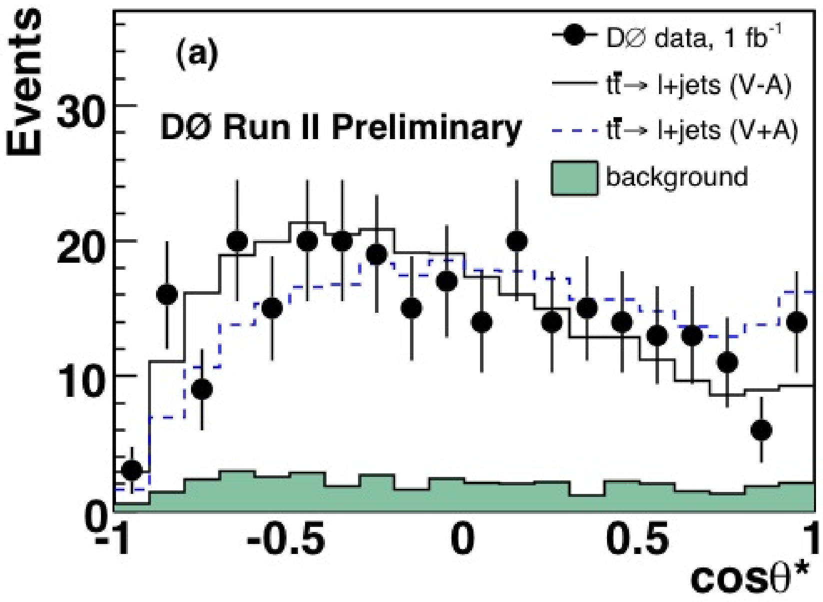
Cross section limits for e,μ+jets combined

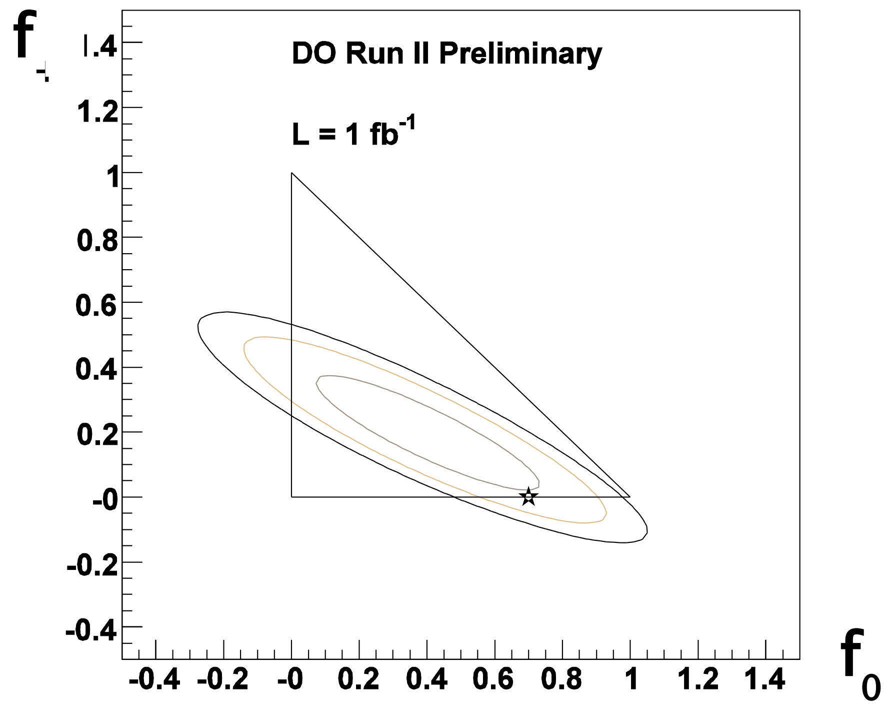
use Likelihood discriminant to calculate limits (Bayesian approach)

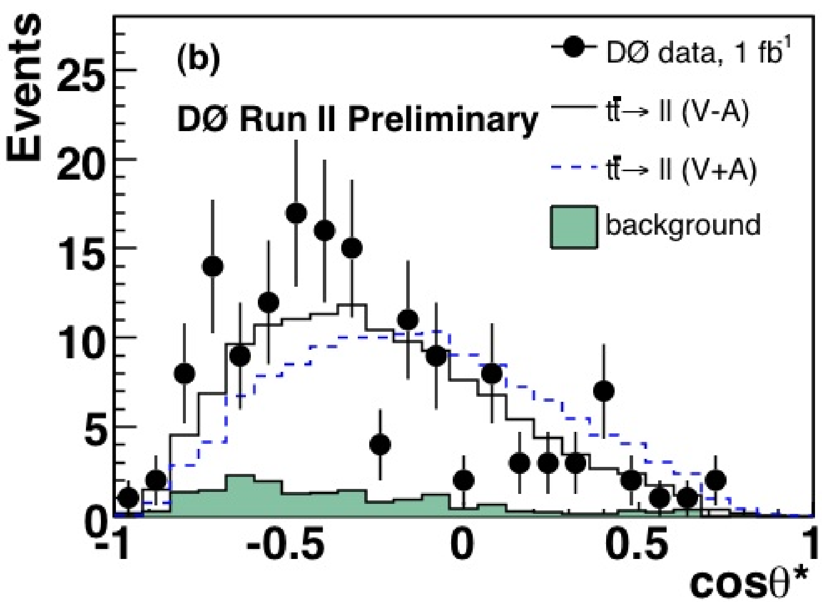


⇒ **limits are factor ≈7−12 above MSSM prediction**

Helicity of the W in ttbar Events







f_0 = 0.390 ± 0.177 (stat) ± 0.095 (syst)

f_+ = 0.171 ± 0.102 (stat) ± 0.059 (syst)

f_+=0: f_0 = 0.653 ± 0.086 (stat) ± 0.070 (syst)

f_0=0: f_+ = 0.018 ± 0.048 (stat) ± 0.047 (syst)

→ no deviations from SM predictions
(agreement at 27% level)