Top Physics (Experiment)

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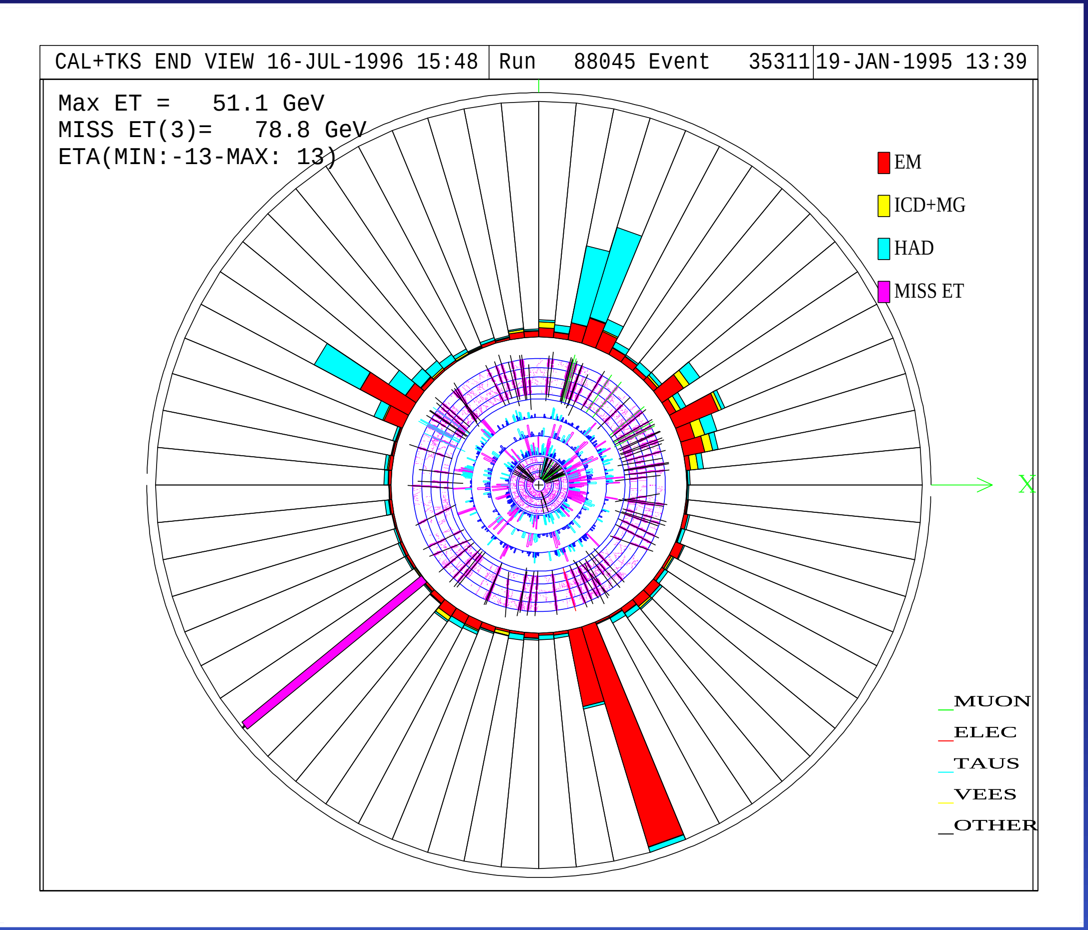
- t-production at hadron colliders (Tevatron and LHC)
  - $\mathrm{t\bar{t}}$-production
  - electroweak single t-production
  - t-decays
- Experimental techniques
  - jet reconstruction
  - b-tagging
  - lepton identification
  - missing $E_\perp$
- Analyses
  - $\sigma_{\mathrm{t\bar{t}}}$
  - t-mass
  - spin reconstruction (W helicity, t spin)
  - t-charge
- Outlook



D0 $\mathrm{e} + 4\ \mathrm{jet}$-event from Run I

t production at hadron colliders

- with a mass of $(172.7 \pm 1.7_{\text{stat}} \pm 2.4_{\text{syst}})$ GeV [hep-ex/0507091] the t-quark is the heaviest known elementary particle.
- its weight is between Tantalum (168.6 GeV) and Osmium (177.2 GeV) – not quite Gold, but . . .

	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	1 II
Sc um 910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zi 65
Y um 585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybd. 95.94	43 Tc Technet. (97.907216)	44 Ru Ruthen. 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cadı 112
1 a- s	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	Re enium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Mer 20(
03 des	104 Rf Rutherford. (261.10877)	105 Db Dubnium (262.1141)	106 Sg Seaborg. (263.1221)	107 Bh Bohrium (262.1246)	108 Hs Hassium (277.1498)	109 Mt Meitner. (268.1387)	110 Ds Darmstadt. [269,271]	111 [272]	

- can be produced currently only at the Tevatron
  $p\bar{p}$: $\sqrt{s} = 1.8\,\text{TeV}_{\text{RunI}}, 1.96\,\text{TeV}_{\text{RunII}}$
- and in the future at the LHC
  pp: $\sqrt{s} = 14\,\text{TeV}$

- most processes at hadron colliders are described by a factorization ansatz:

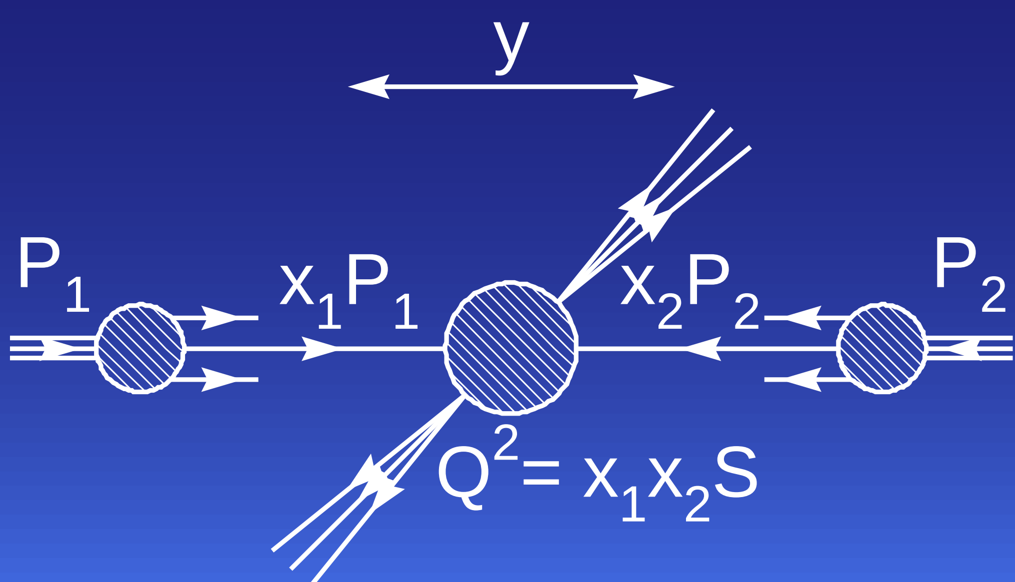
$$\sigma_{\mathrm{pp}(\bar{\mathrm{p}})\to X} = \sum_{i,j} \int \mathrm{d}x_i \mathrm{d}x_j f_i(x_i) f_j(x_j) \sigma_{ij\to X}$$

  - the total cross section σ to produce X in hadron collisions is given by the convolution of the parton distribution functions (PDF) $f_i(x_i)$ with the parton cross section σ_{ij}
  - the PDF $f_i(x_i)$ describe the probability to find parton i with a fraction x_i of the proton momentum
  - to produce the final state X the center of mass frame of the two partons is relevant:

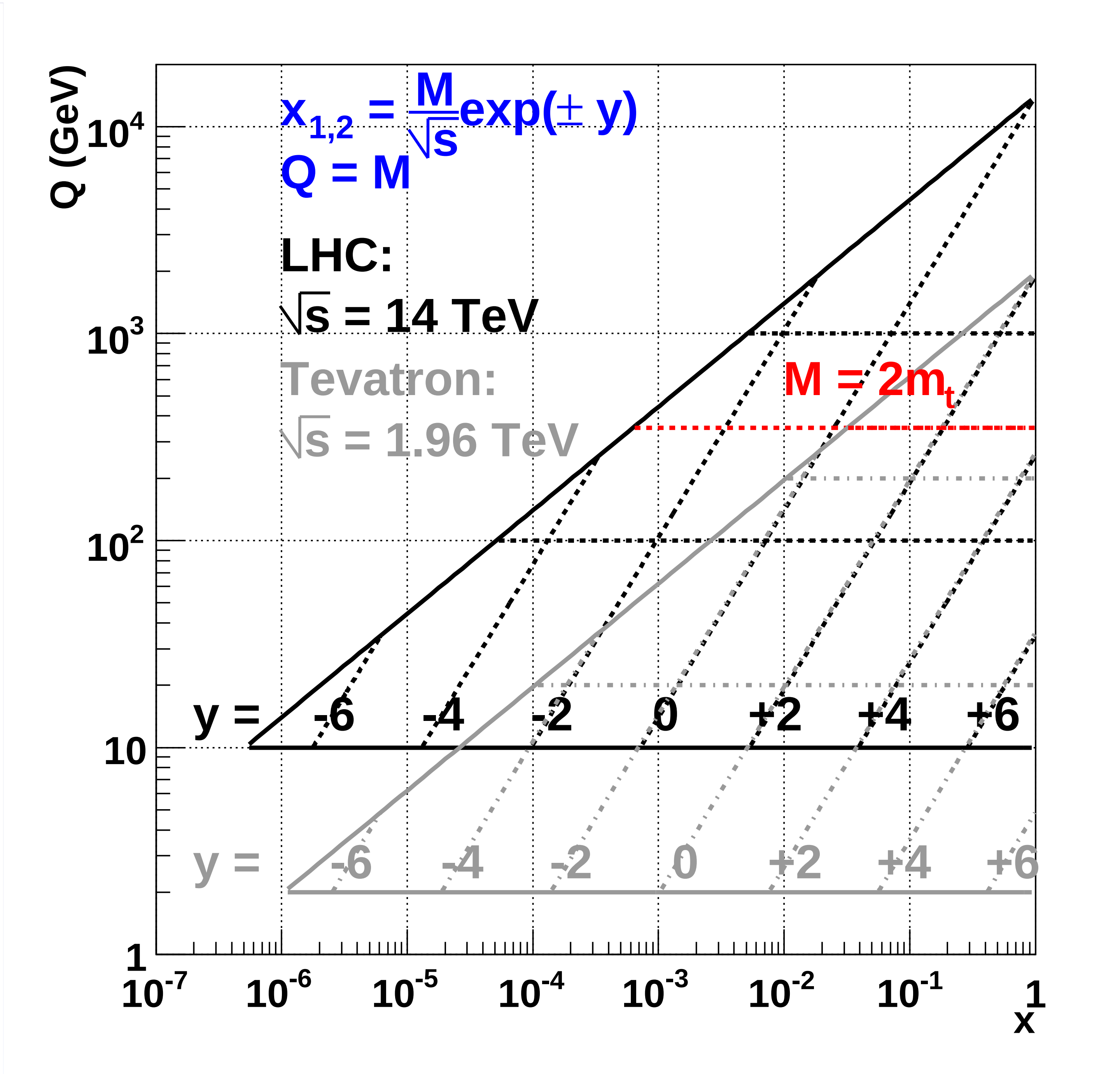
$$Q^2 = x_1 x_2 S$$

  - the final state X moves with the rapidity y:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$



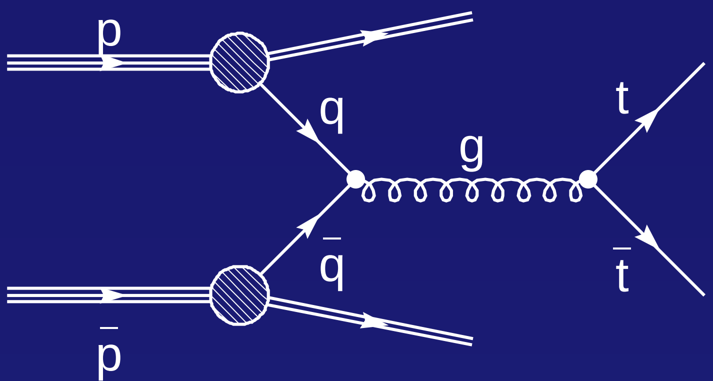
- Q vs. $x_{1,2}$ for Tevatron and LHC
- red curve shows top-pair production



- The LO processes for $t\bar{t}$ production in $p\bar{p}$ collisions (for pp just exchange the $\bar{p}$ with a p)

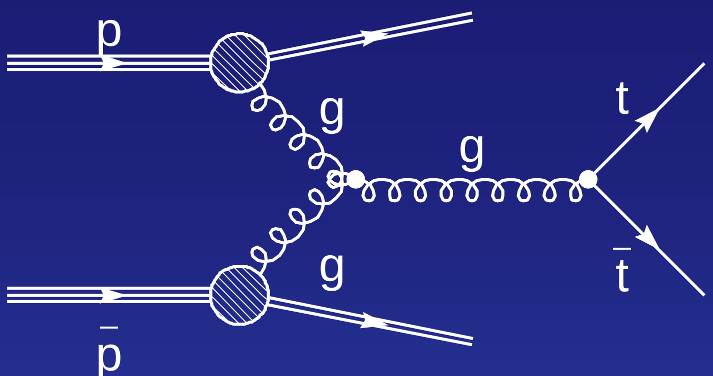
- $q\bar{q}$ annihilation

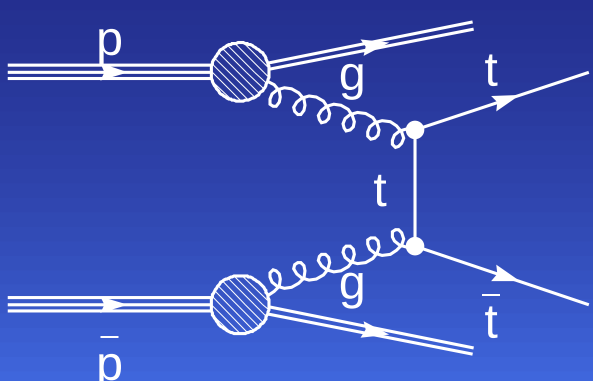
$\sqrt{s}$	$\sigma_{q\bar{q}\to t\bar{t}}/\sigma_{t\bar{t}}$
1.8 TeV	90 %
1.96 TeV	85 %
14 TeV	5 %

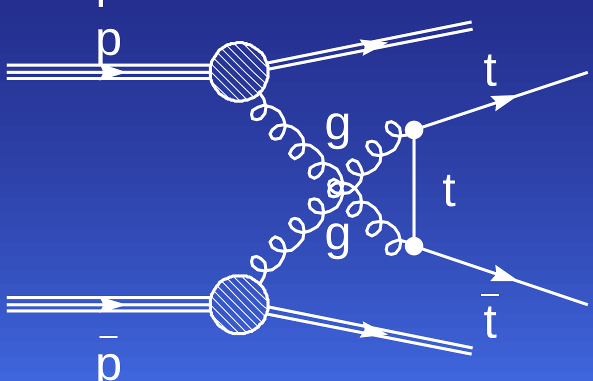


- gluon fusion

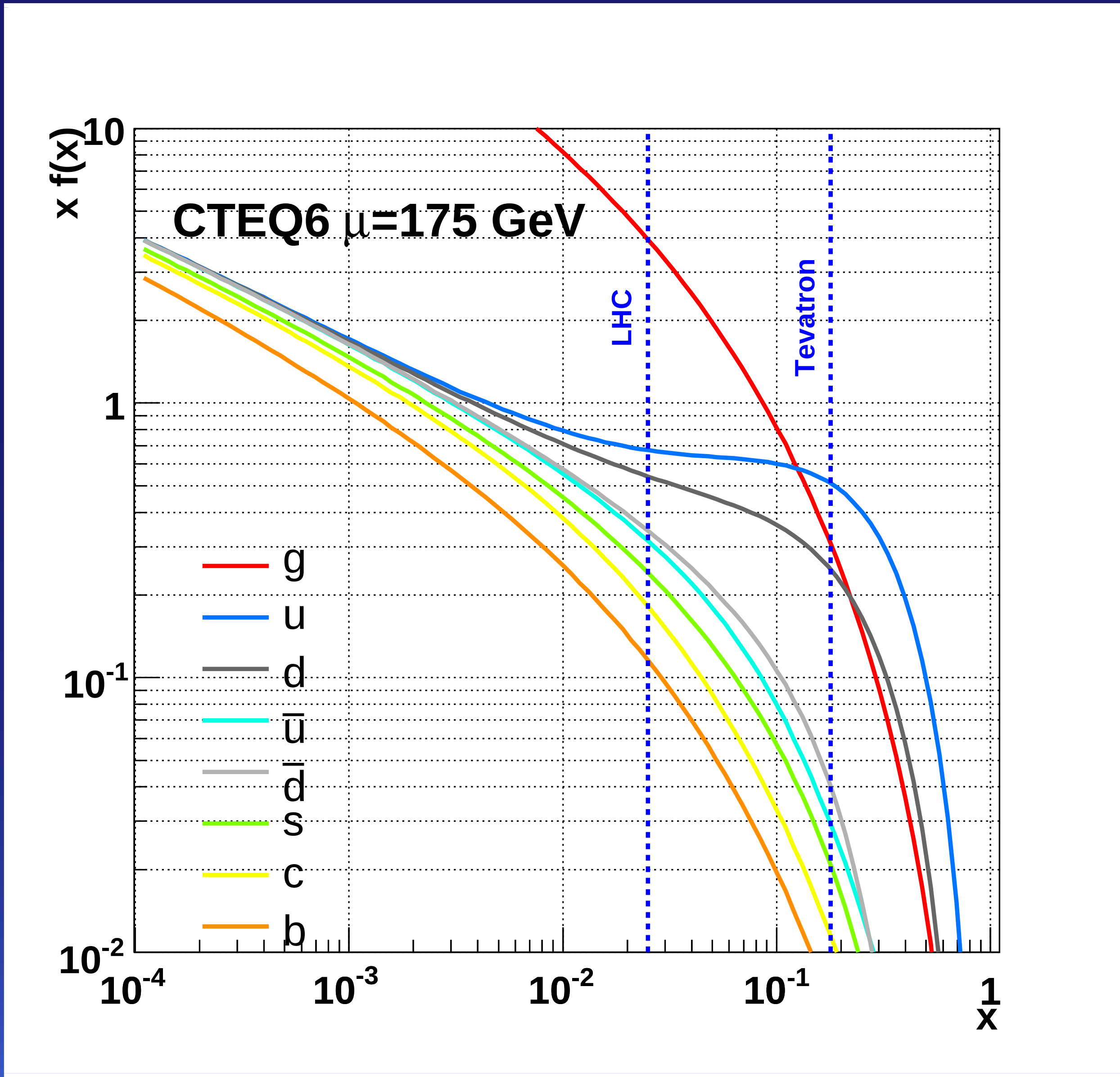
$\sqrt{s}$	$\sigma_{gg\to t\bar{t}}/\sigma_{t\bar{t}}$
1.8 TeV	10 %
1.96 TeV	15 %
14 TeV	95 %



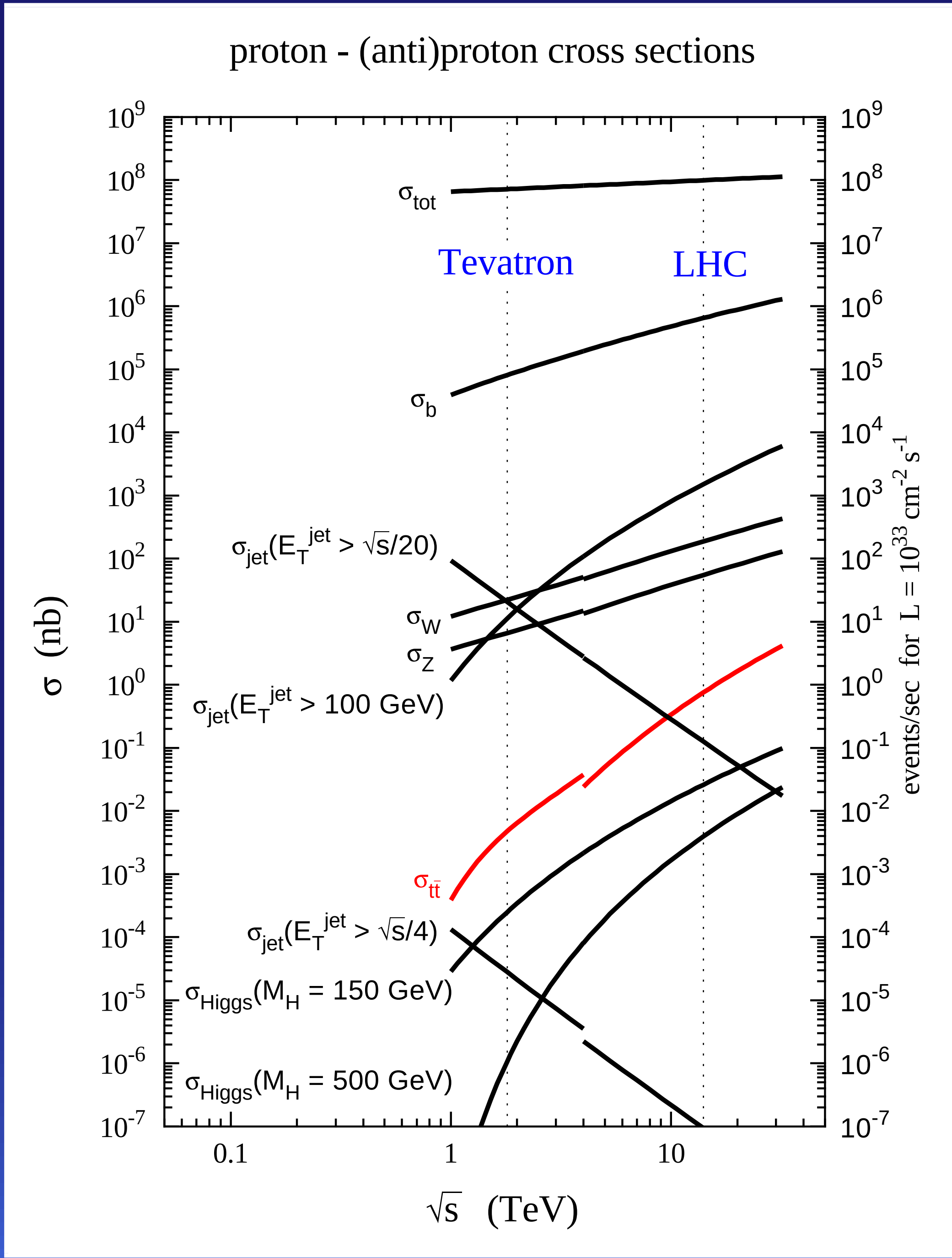




- $\sqrt{x_1 x_2 S} = 2m_t$
- assume
  $$x_1 \simeq x_2 = x = \frac{2m_t}{\sqrt{S}}$$
- $x_{\text{Tevatron}} = 0.18$
- $x_{\text{LHC}} = 0.025$
- you need antiprotons for antiquarks at large x at Tevatron (dominant production through $q\bar{q}$)
- protons are just fine for plenty of gluons at small x at LHC (dominant production through gg)



- parton level cross sections have similar magnitude for Tevatron and LHC
- $x\,f(x)$ is about a factor of 10 larger for $t\bar{t}$-production at the LHC
- total cross section for $t\bar{t}$-production is about a factor of 100 larger at LHC
- $\sigma_{t\bar{t}}(1.80\,\mathrm{TeV}) = 5\,\mathrm{pb}$
- $\sigma_{t\bar{t}}(1.96\,\mathrm{TeV}) = 7\,\mathrm{pb}$
- $\sigma_{t\bar{t}}(14.0\,\mathrm{TeV}) = 800\,\mathrm{pb}$

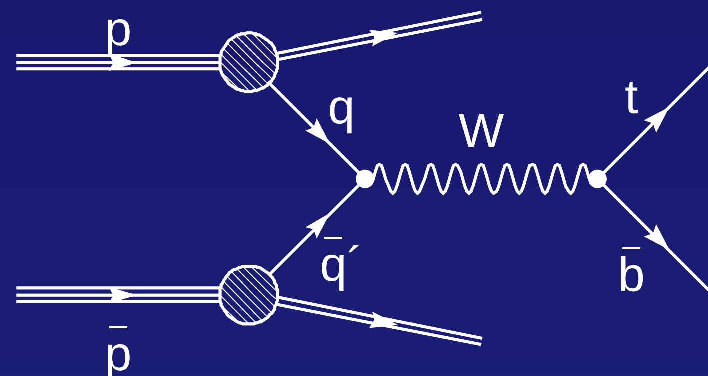


W.J. Stirling, 1998

- The LO processes for e.w. single t production in $p\bar{p}$ and pp collisions (2 upper graphs)
- Total cross section for single top production surprisingly large ($\simeq 40\,\%$ of $\sigma_{t\bar{t}}$)

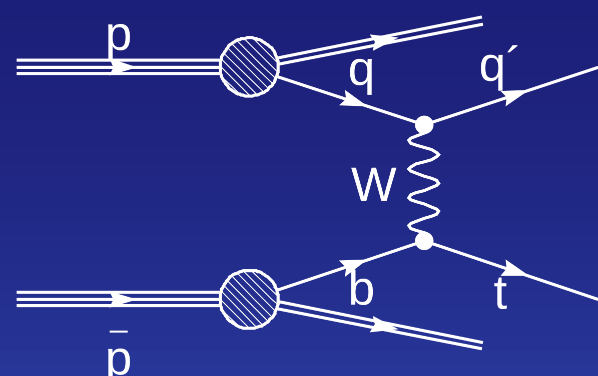
- s-channel

$\sqrt{s}$	$\sigma_{\mathrm{EWs}}/\sigma_{\mathrm{single\ t}}$
1.8 TeV	35 %
1.96 TeV	30 %
14 TeV	3 %



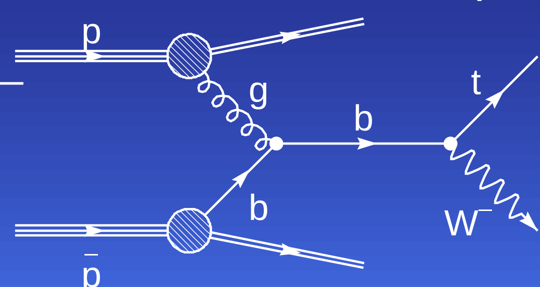
- t-channel

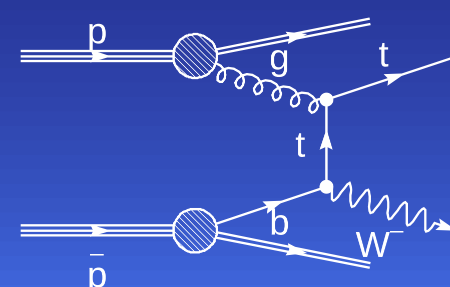
$\sqrt{s}$	$\sigma_{\mathrm{EWt}}/\sigma_{\mathrm{single\ t}}$
1.8 TeV	60 %
1.96 TeV	65 %
14 TeV	77 %



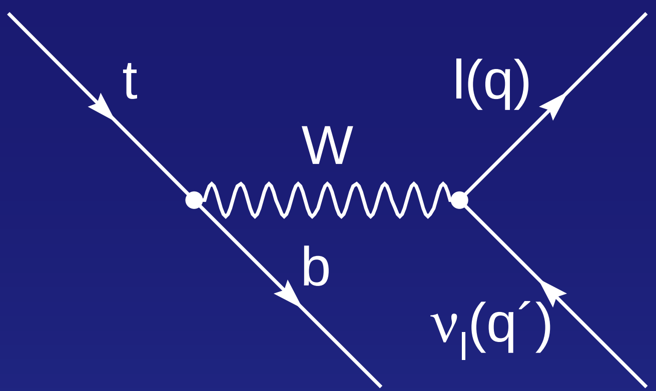
- Wt prod.

$\sqrt{s}$	$\sigma_{\mathrm{Wt}}/\sigma_{\mathrm{single\ t}}$
1.8 TeV	5 %
1.96 TeV	5 %
14 TeV	20 %



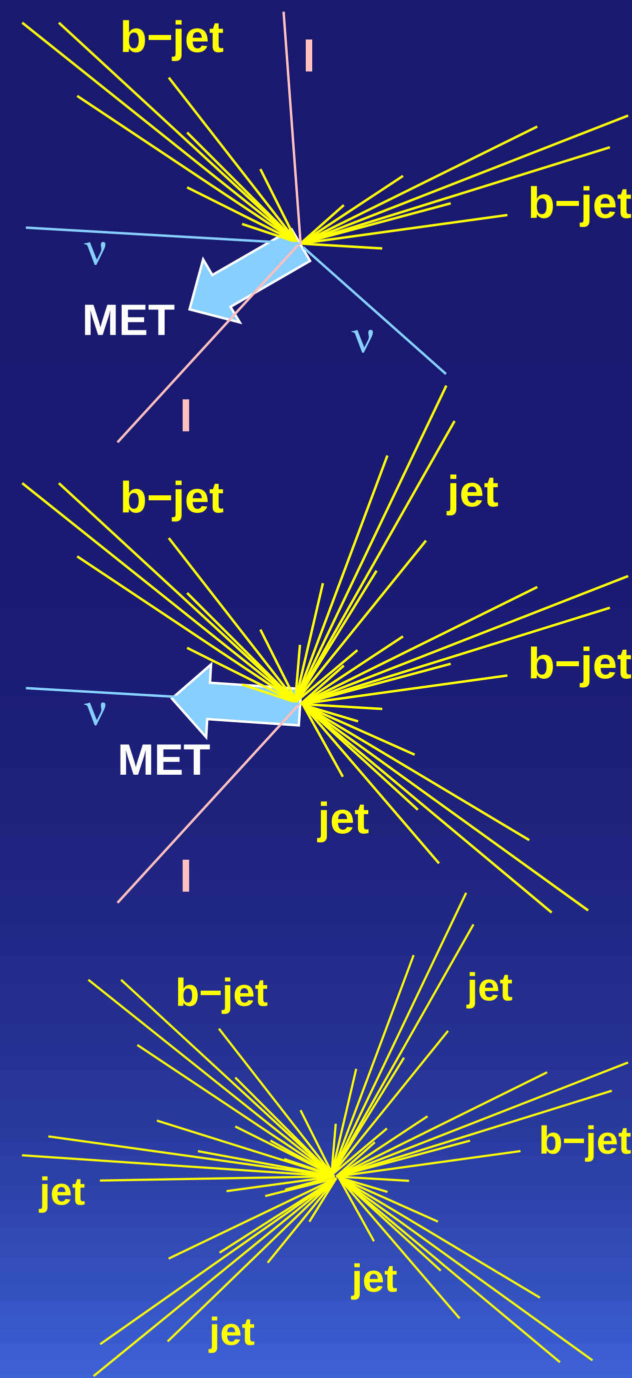


- $\Gamma_{\mathrm{t}} \simeq 1.4\,\mathrm{GeV} > \Lambda_{\mathrm{QCD}}$
  - $\tau_{\mathrm{t}} \simeq 0.46\,10^{-24}\,\mathrm{s}$
  - the top decays before it can interact via QCD
  - no top-mesons
- $m_{\mathrm{t}} > m_{\mathrm{W}} + m_{\mathrm{b}}$
  - only 2-body decays into real W and quark



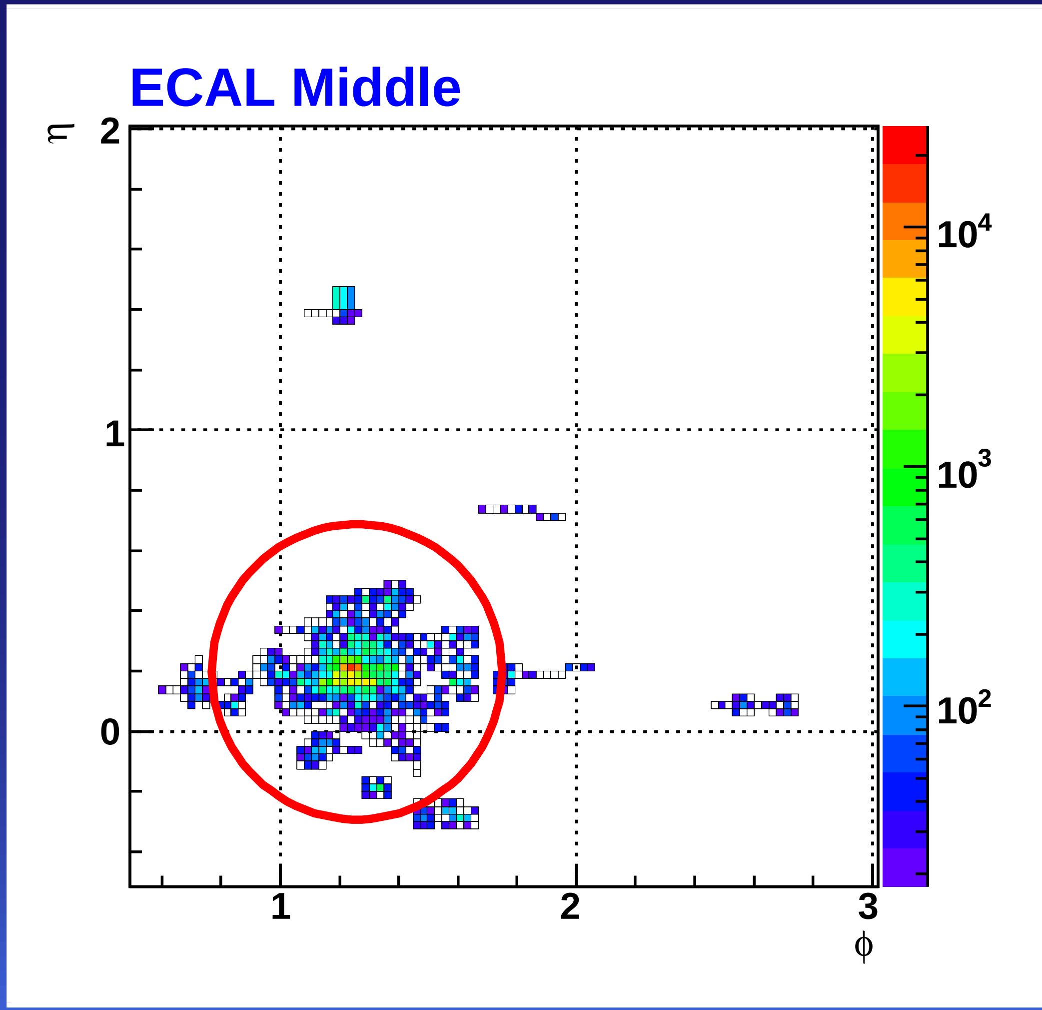
- $0.9990 < V_{\mathrm{tb}} < 0.9993$
  - $> 99.8\,\%$ of top decays are $\mathrm{t} \to \mathrm{Wb}$
- W decays characterize the experimental channel:
  - $\mathrm{t} \to \mathrm{bW} \to \mathrm{bqq}'$: ‘jets‘ ($2/3$ of all decays)
  - $\mathrm{t} \to \mathrm{bW} \to \mathrm{b}\ell\nu_\ell$: ‘lepton+jets‘ ($2/9$ of all decays for $\ell = \mathrm{e}, \mu$; $1/9$ decay to $\mathrm{b}\tau\nu_\tau$)

- $t\bar{t}$-channel is dominant mode for t-physics analyses
  - all properties of the top should be measured. In particular we will discuss:
  - cross section measurements
  - measurements of the mass of the t-quark
  - analyses of spins in the top decay products
  - charge of the top (is it realy $2/3\,e$?)
- EW single t-production not discovered yet
  - will be seen in Tevatron Run II
  - offers the opportunity to measure V_{tb} (room for a 4th generation?)
- characterize $t\bar{t}$-analyses by decay of the W
  - 'di-lepton': both W decay into leptons (5 % for $\ell = e, \mu$)
  - 'lepton+jets': one W decays leptonically, the other in a qq' pair (30 % for $\ell = e, \mu$)
  - 'all jets': both W decay into qq' pairs (40 %)
  - the rest involves at least one τ (25 %)



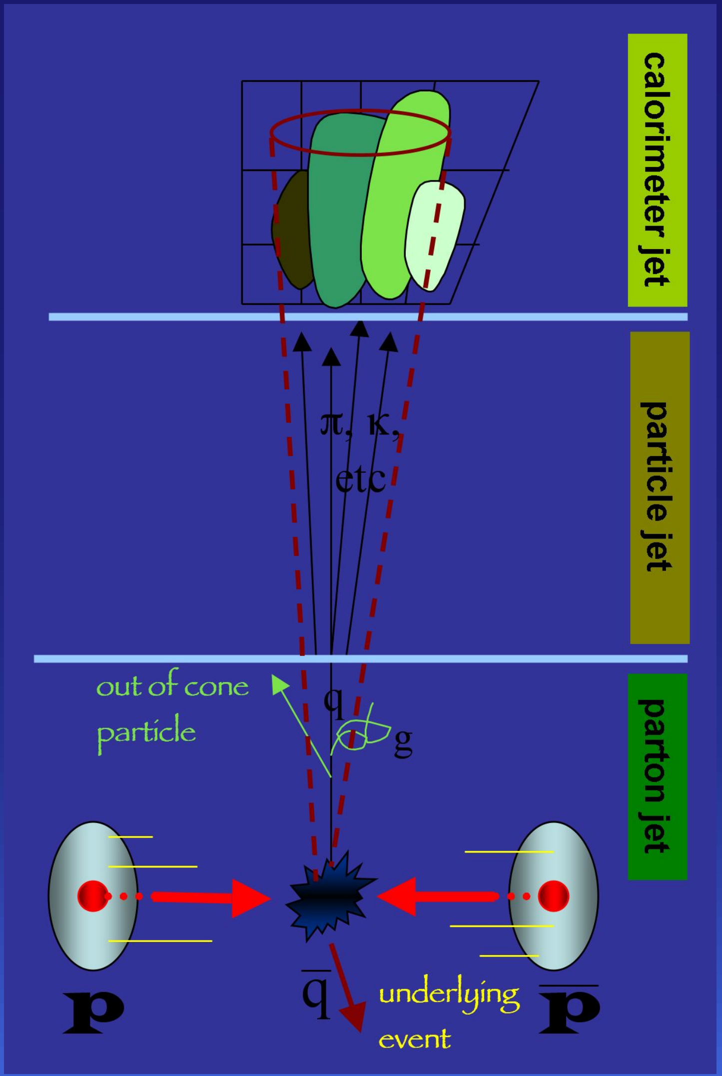
- all top analyses have to deal with 2 or more jets
- the jet energy scale is one of the biggest sources of systematic errors on m_t
- jet algorithms
  - fixed cone:
    - define an inital set of jets from high $p_\perp$ cells/towers/clusters
    - all cells/towers/clusters k within a fixed distance $\Delta R > R_{kl} = \sqrt{(\eta_k - \eta_l)^2 + (\phi_k - \phi_l)^2}$ to the jet l are included in jet l
    - close by jets are subject to a split/merge procedure based on the fraction of energy they share
    - the jet-positions are re-calculated
    - iterate until jet positions are stable
  - $k_\perp$:
    - make a (massless) protojet of each cell/tower/cluster
    - define for all protojets the distance to the beam: $d_{k\mathrm{B}} = \Delta R^2 p_{\perp k}$
    - define for all pairs of protojets the mutual distance: $d_{kl} = \min\left(p_{\perp k}^2, p_{\perp l}^2\right) R_{kl}^2$
    - find the minimum of the $d_{k\mathrm{B}}, d_{kl}$
    - exclusive mode: in case $d_{\mathrm{min}} > d_{\mathrm{cut}}$ all remaining protojets are converted to jets
    - in case the minimum is a $d_{k\mathrm{B}}$ make that protojet a jet and remove it from the algorithm
    - in case the minimum is a d_{kl} combine protojets k and l and iterate until all protojets have been converted to jets

- plot shows EM calorimeter cells from an Atlas QCD event simulation (dijet sample with $140\,\mathrm{GeV} < p_\perp < 280\,\mathrm{GeV}$) on a logarithmic energy scale (MeV)
- all cells shown belong to the same $k_\perp$ jet
- the corresponding cone jet would contain only the cells within the red circle
  - issues with $k_\perp$:
    - infrared safe
    - well defined algorithm (`KtJet`)
    - more difficult to calibrate
  - issues with cone jet:
    - not infrared safe
    - lots of different cone algorithms available
    - usually easier to calibrate

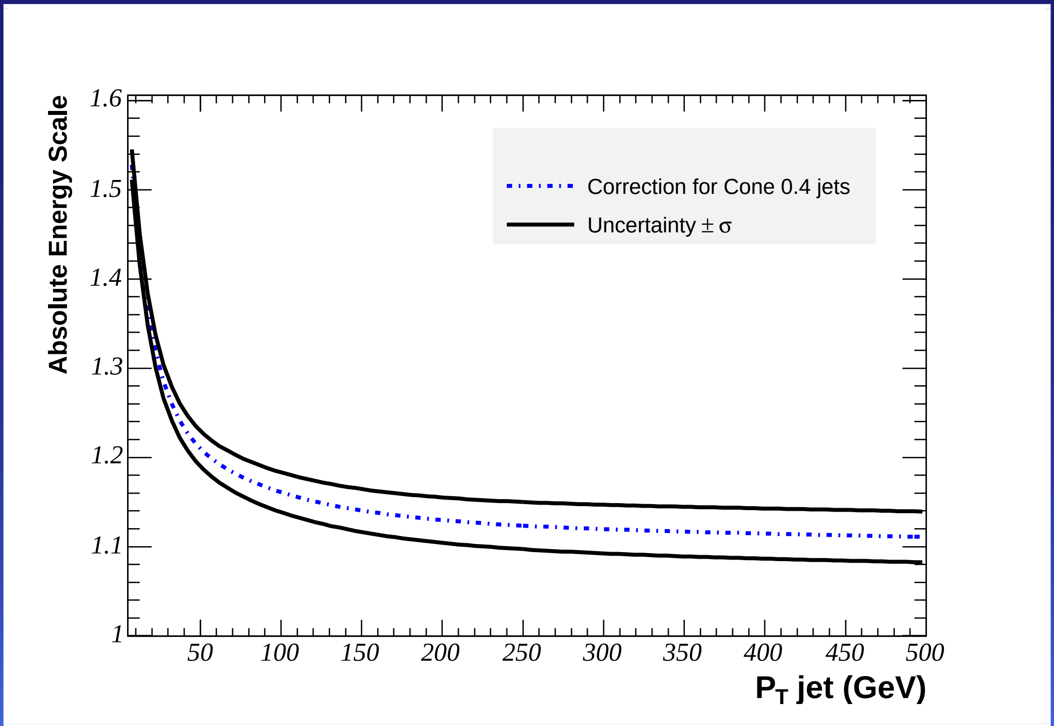


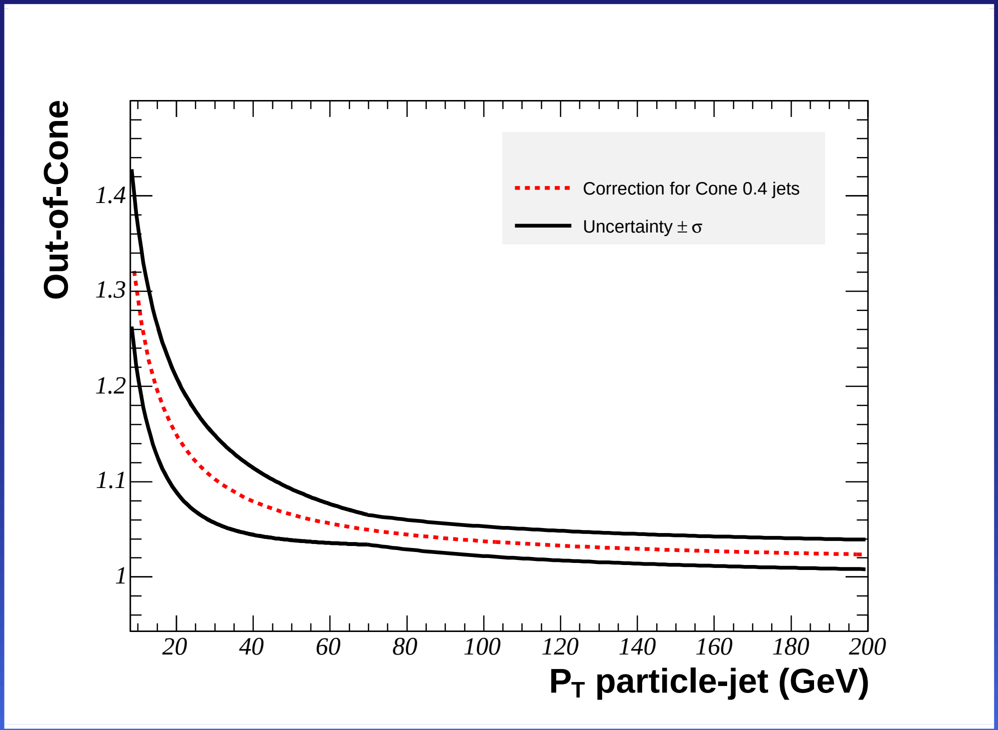
- aim of the jet energy calibration is to get from the measured energy in the calorimeter to the final state particles

- jet energy calibration needs to correct for:
  - non-compensating calorimeters
    - hadronic showers have ‘invisible’ components due to nuclear reactions like break up of nuclei and excitation
  - cracks and gaps in the calorimeter
  - energy deposited in material in front and beyond the calorimeter (leakage)
  - energy deposited outside the jet/cluster (due to noise cuts, jet size cutoffs)
  - underlying event and pile up
    - energy deposits not belonging to the hard process under study need to be removed
- often these corrections are done on the full jet (D0, CDF) but smaller jet constituents (clusters) offer better factorizability of the corrections (ATLAS)
- in order to compare with theory a second correction to move from the final state particle level to the parton level is required
  - out-of-jet corrections e.g. gluons radiated from partons before the hadronization which might or might not be included in the jet

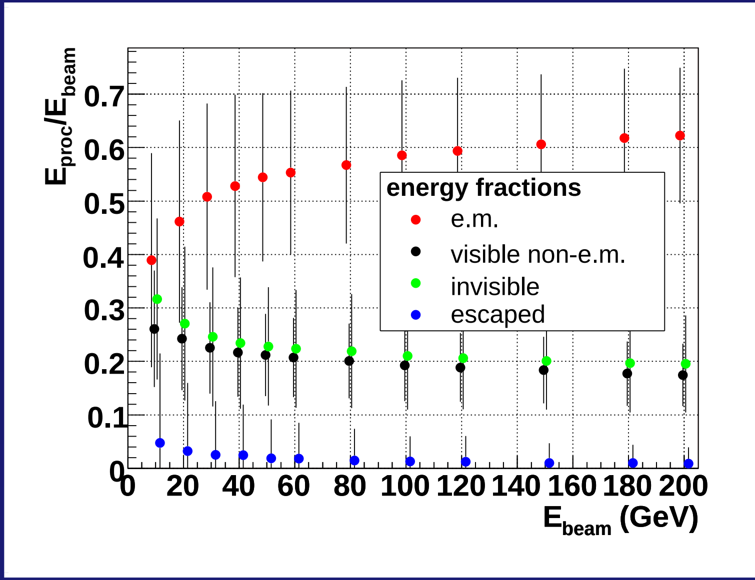


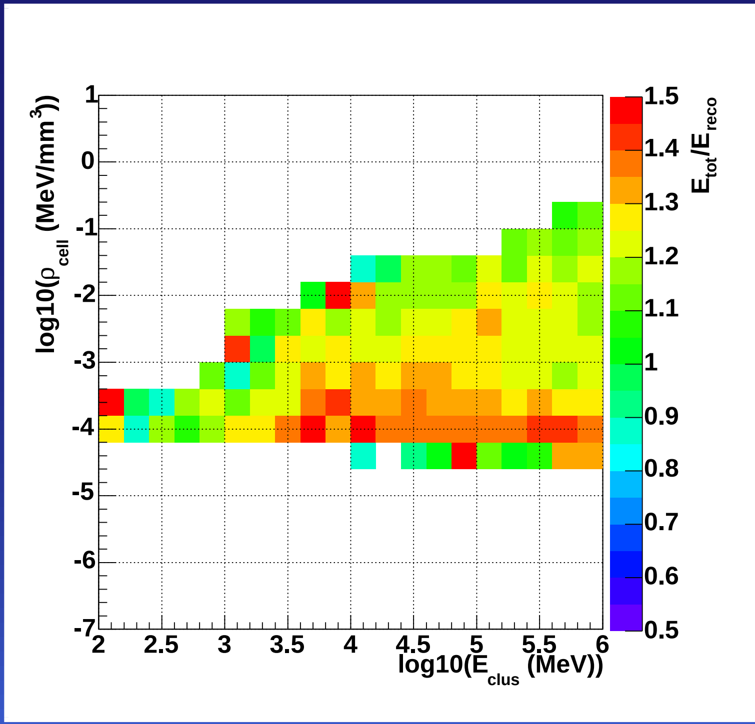
- corrections to get from calorimeter to particle level can be quite large
  - need to be determined mostly with simulations
  - should be factorized as much as possible
  - total correction depends on the jet algorithm and the jet size (ΔR or d_{cut})
  - typical resolution for jets: $\sigma_E/E \simeq (50 - 100)\,\%/\sqrt{E/\mathrm{GeV}}$
- left (right) plot shows absolute energy scale (out of cone) correction for CDF Run II as function of $p_\perp$



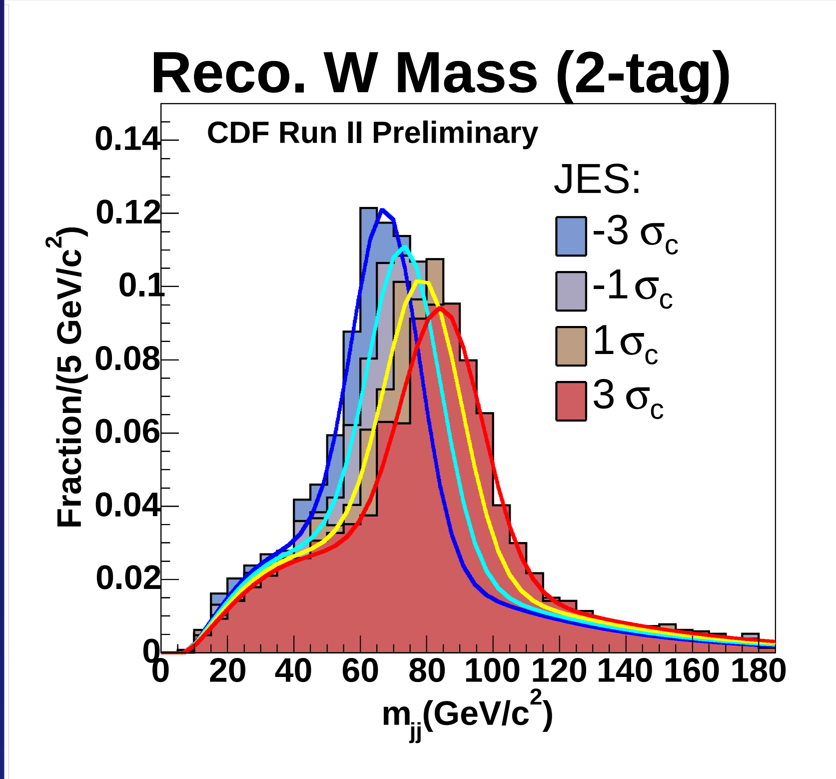


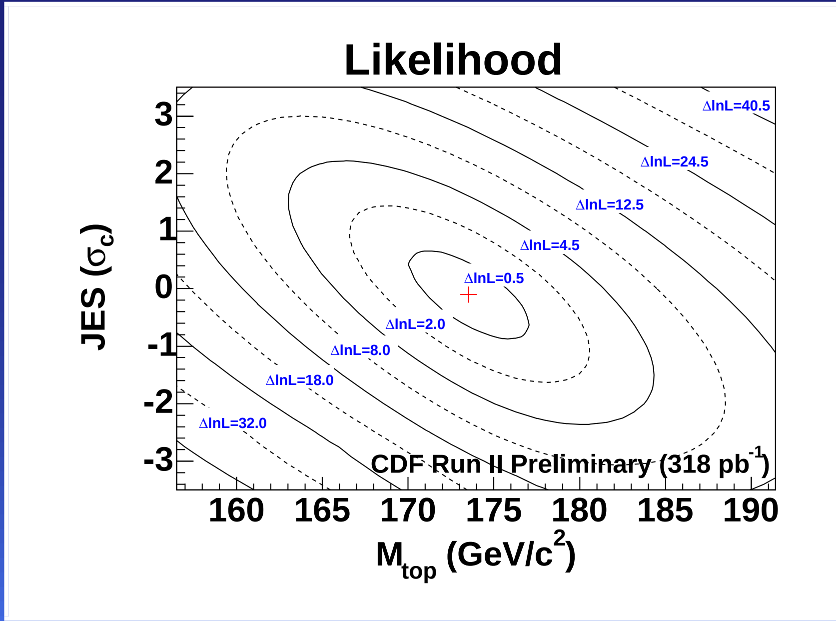
- use detailed information about the true energy components in every calorimeter cell and dead material from Geant4 simulations (calibration hits)
  - EM energy (e.g. $\pi^0 \to \gamma\gamma$) $O(50\,\%)$
  - visible non-EM energy (e.g. $\mathrm{d}E/\mathrm{d}x$ from $\pi^\pm$,$\mu^\pm$, etc.) $O(25\,\%)$
  - invisible energy (e.g. breakup of nuclei and nuclear excitation) $O(25\,\%)$
  - escaped energy (e.g. ν) $O(2\,\%)$
- derive cell weights as function of E/V to correct the observed cell energy to truely deposited energy
- correct for losses in gaps/dead material on cluster level
- use the so calibrated clusters as input for jet algorithms
- jets need to be corrected for the two out-of-jet effects
  - jet-size/noise cuts on clusters
  - parton radiation





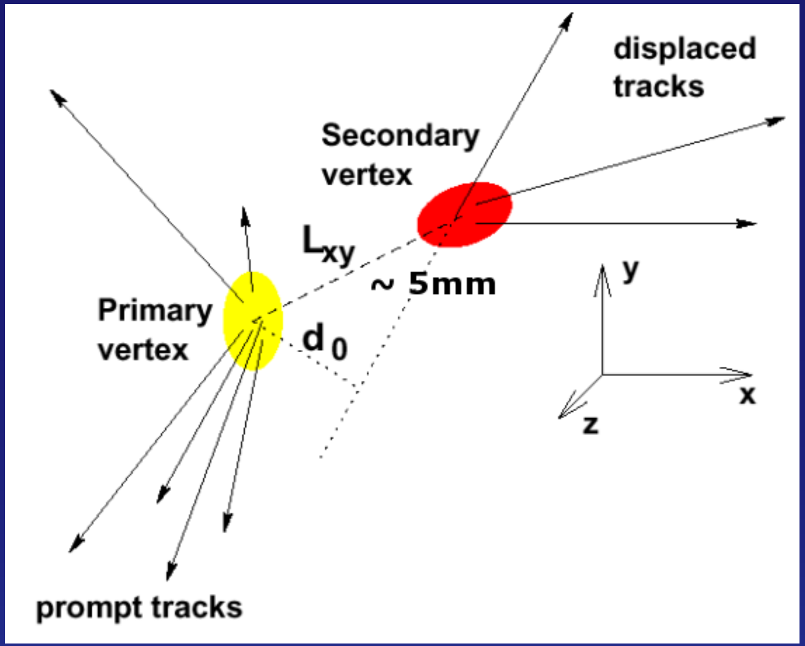
- in case two jets stem from the decay of a heavy particle of known mass this mass can be used to constrain the jet energy scale
- for the in-situ W calibration the decay W $\rightarrow jj$ is used with the constraint $m_{jj} = m_{\mathrm{W}}$
  - apply the jet calibration procedure as before
  - introduce a scale parameter (JES) that measures the deviation from the calibrated jet energy in units of the total uncertainty in the calibrated energy (σ_C)
  - use simulated events to study the dependency of the reconstructed dijet mass on JES ► W-mass templates
  - the deviation of JES from 0 can be fitted by comparing these templates with data
- in top-mass analyses JES can be determined simulataneously with m_t incorporating all correlations

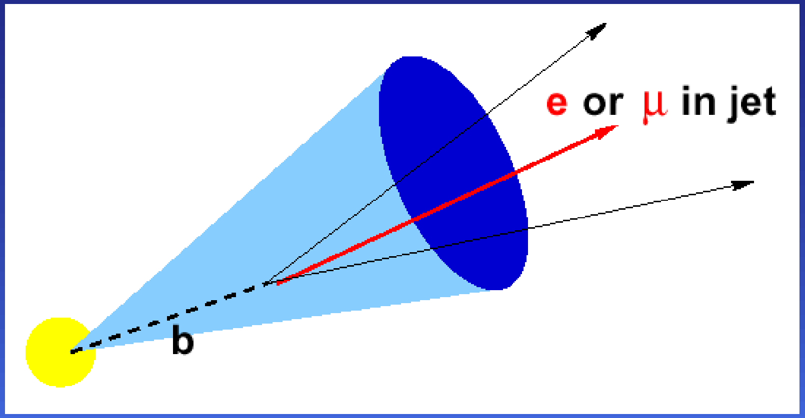




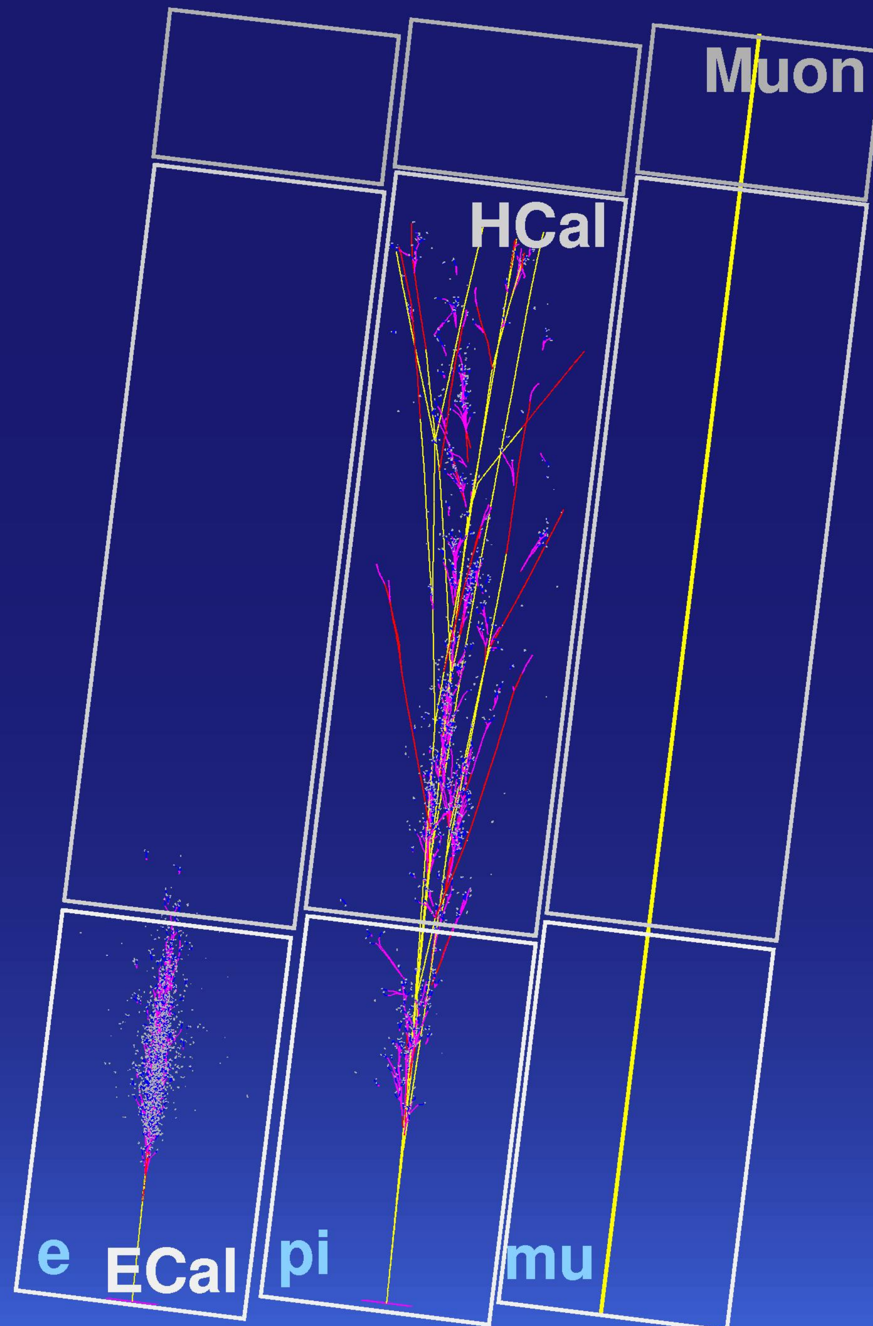
- virtually all top decay into a b-quark
- need efficient b-tag to identify top candidates

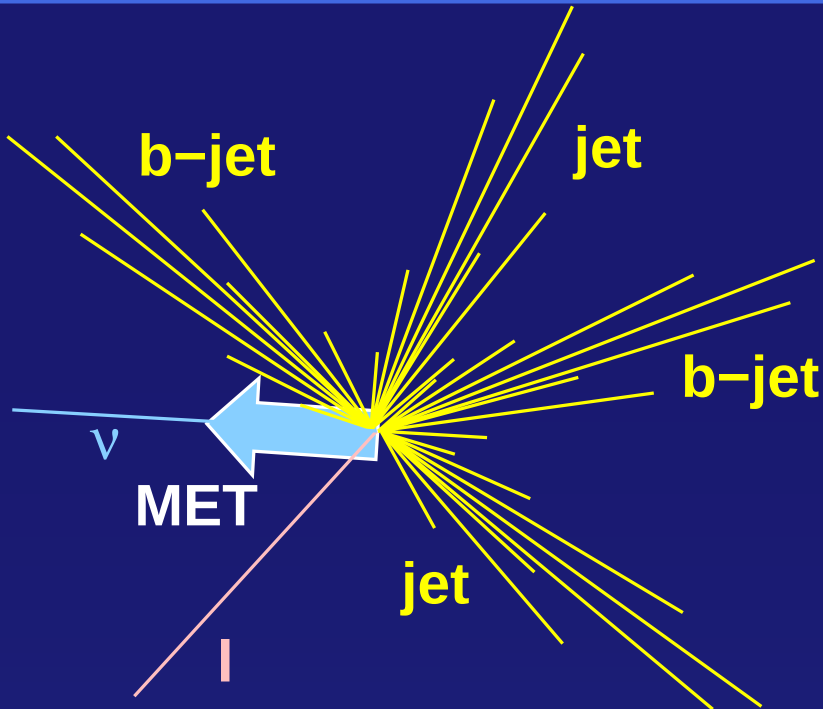
- basically two methods are used in top analyses
- secondary vertex finding
  - needs high resolution vertex detector (typically $\sigma = 10\,\mu$) ($L_{xy} \sim 5$mm for b from top decays at Tevatron)
  - many algorithmic variants (2D, 3D, etc.)
  - performance in $\geq$ 4jets events: $p_{t\bar{t}} \simeq 60\,\%$, $p_{W+\text{jets}} \simeq 4\,\%$
- slow lepton finding
  - the poor man's approach (does not need vertex detector)
  - $Br(b \longrightarrow c(u)\mu(e)\nu) \simeq 20\,\%$
  - $Br(c \longrightarrow s(d)\mu(e)\nu) \simeq 20\,\%$
  - performance (soft muon) in $\geq$ 4jets events: $p_{t\bar{t}} \simeq 16\,\%$, $p_{W+\text{jets}} \simeq 4\,\%$





- electrons
  - start with joint electron/photon reconstruction
  - isolated clusters in the electromagnetic calorimeter
  - consistent in transverse shape with an electromagnetic shower
  - in sampling calorimeters the longitudinal shape can be used
  - otherwise the energy fraction in the em calorimeter over the total energy in em and had calorimeters in a narrow cone around the electron/photon direction is used to discriminate against hadrons
  - track match separates electrons from photons
  - typical energy resolution: $\sigma_E/E \simeq 10\,\%/\sqrt{E/\mathrm{GeV}} \oplus (1-2)\,\%$
- muons
  - isolated tracks with hits in muon system
  - associated cluster (if any) is consistent with minimum ionizing particle
  - typical momentum resolution: $\sigma_{p_\perp}/p_\perp \simeq 0.15\,\% \times p_\perp/\mathrm{GeV}$



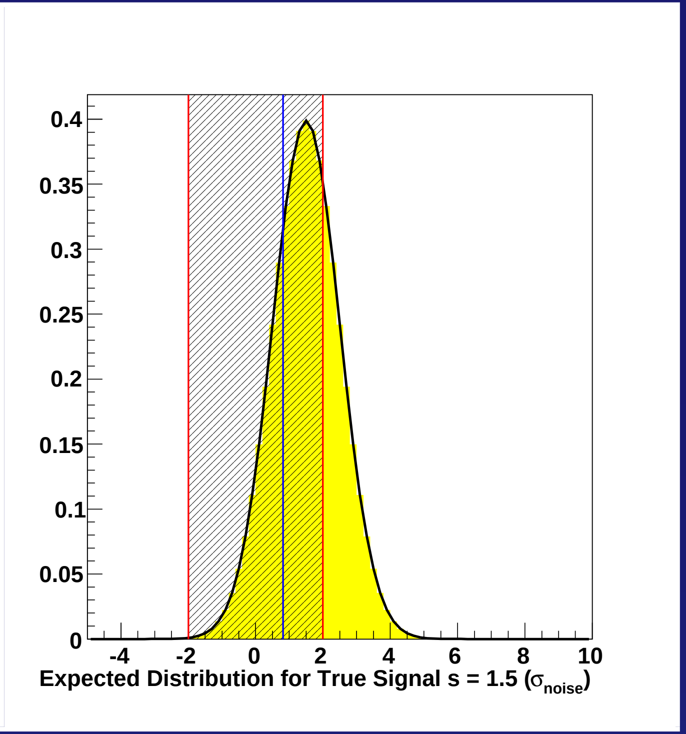


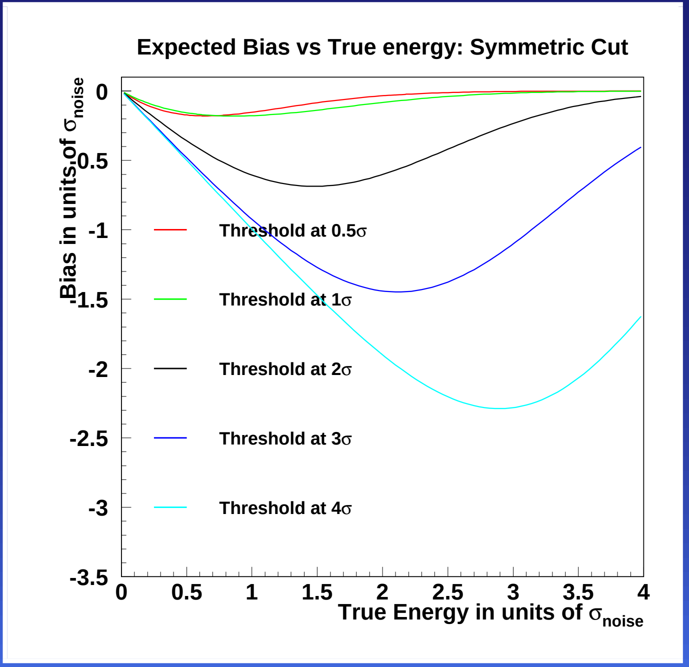
- all particles not observable in the detector (e.g. neutrinos) can only be indirectly and partially reconstructed by looking at missing transverse energy
- since the total $p_\perp$ of all particles vanishes the invisible particles must balance the sum of all visible particles

- $\not{E}_\perp = -\sum_{e/\gamma} E_\perp - \sum_{\mu} E_\perp - \sum_{\text{jets}} E_\perp - \sum_{\text{other}} E_\perp$
  - leptons and photons are usually measured with excellent accuracy
  - jets are subject to the jet calibration procedure outlined before and the resolution is still reasonable
  - biggest problem is all the rest – i.e. cells/towers/clusters not matched to the other
- Issues with $\sum_{\text{other}} E_\perp$
  - need to find best compromise between summing all calorimeter signals (lots of noise, no bias) and suppressing small signals (less noise, negative bias)

- assume calorimeter with N cells and average noise per cell σ_c
- energy resolution for sum of all cells for an empty event (no signal, just noise):
  $\sigma_{\sum_N} = \sqrt{N}\,\sigma_c$
- sum only cells with $|E| > 2\,\sigma_c$:
  $\sigma_{\sum_{|E|>2\,\sigma_c}} = \sqrt{0.046\,N}\,\sigma_c = 1/5\,\sigma_{\sum_N}$
- BUT: in case some small positive signals $E = O(\sigma_c)$ are present in the event those are replaced by 0 ► negative bias!

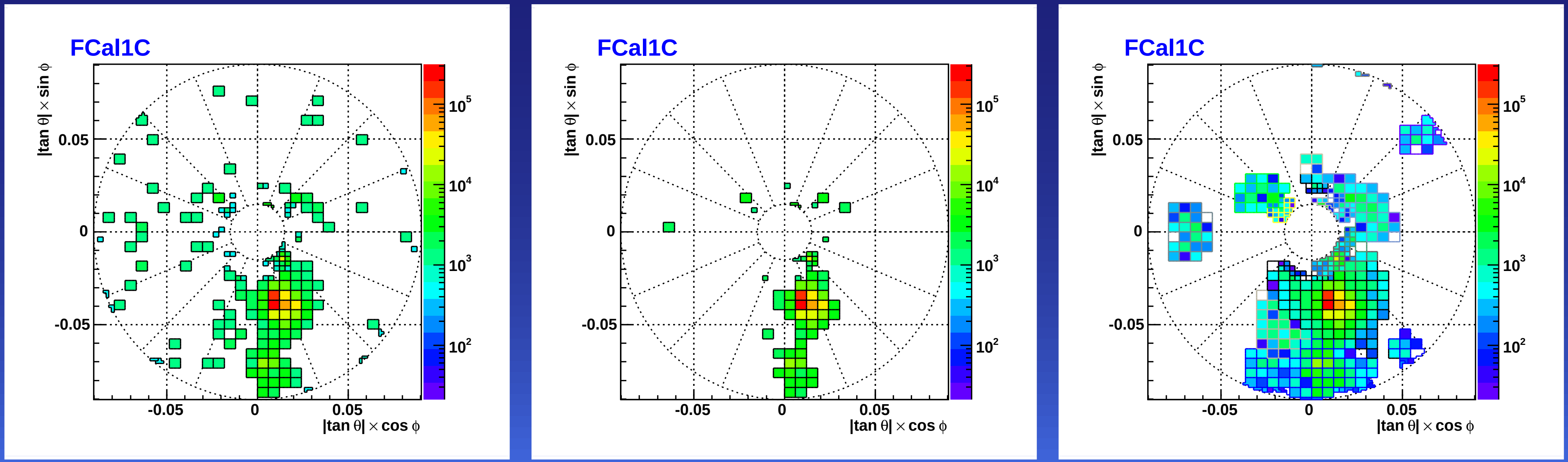
True Cell Signal (σ_c)	Bias per Cell (σ_c)
0.0	0.00
1.0	−0.60
1.5	−0.69
2.0	−0.60
3.0	−0.23
4.0	−0.04





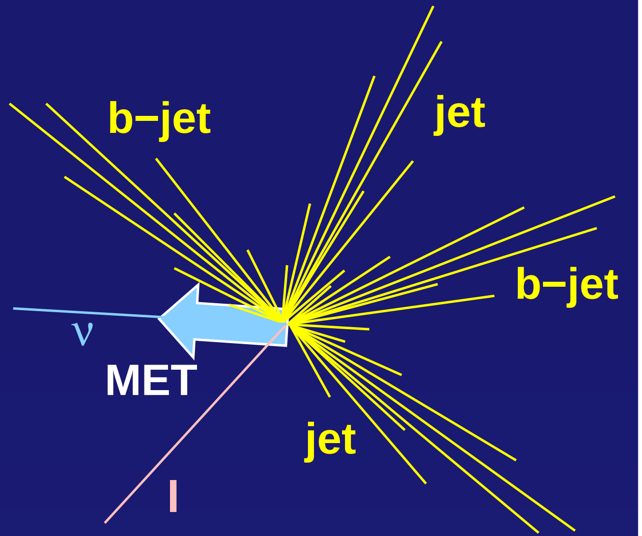
- the compromise bewteen high noise, low bias and low noise, high bias can be found by using the fact that true signal produces correlations between neighbouring cells
- the idea is to keep cells which are either well above the noise threshold (e.g. $E > 4\,\sigma_c$) or
- smaller (e.g. $E > 2\,\sigma_c$) and neighbour to a cell above the higher threshold
  - modifications to this algorithm can involve 3 thresholds for seeds, neighbours and normal cells (e.g. ATLAS uses $4/2/0\,\sigma_c$)

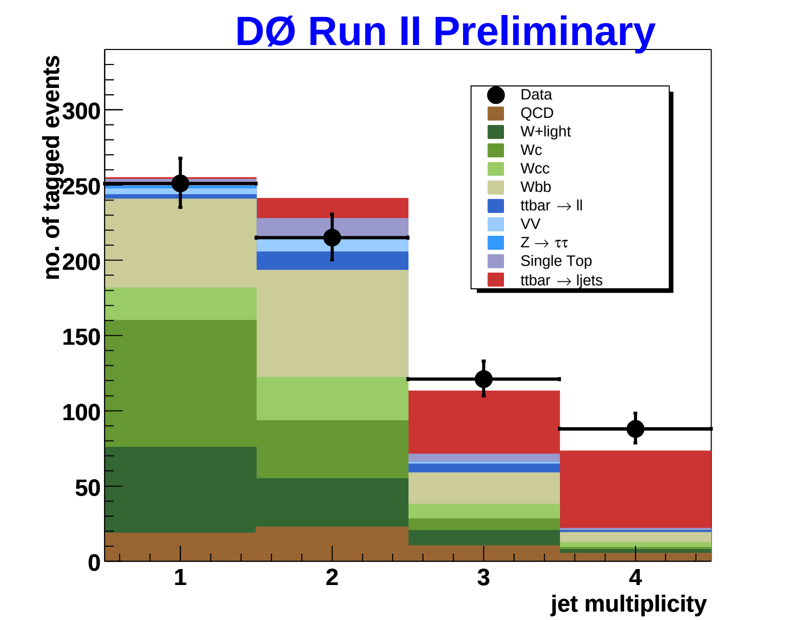
$|E| > 2\,\sigma_c$ $\quad$ $|E| > 4\,\sigma_c$ $\quad$ $4/2/0\,\sigma_c$

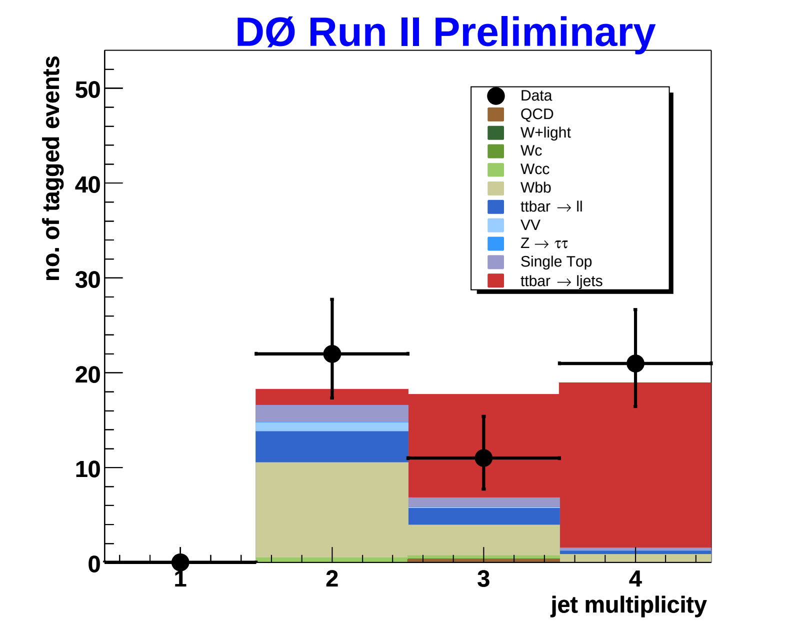


- $t\bar{t}$ cross section measurements at Tevatron Run II
  - identify $t\bar{t}$ pairs with different topologies and different methods
    - di-lepton
    - lepton+jets
    - all-jets
    - with and and without b-tagging
  - count them
  - correct for acceptance, efficiency and cuts
  - divide by integrated luminosity
- $\sigma_{t\bar{t}} = \dfrac{N}{\epsilon\mathcal{L}}$ (actually a maximum likelihood method is used in most analyses to extract $\sigma_{t\bar{t}}$)
- basis for all other top analyses to understand efficieny and background
- cross section is important for theorists (sensitivity to m_t, new phsyics, etc.)

- ► b-tagged 'lepton+jets' analysis
  - based on 365 pb^{-1} of integrated luminosity in Run II @$\sqrt{s} = 1.96$ TeV





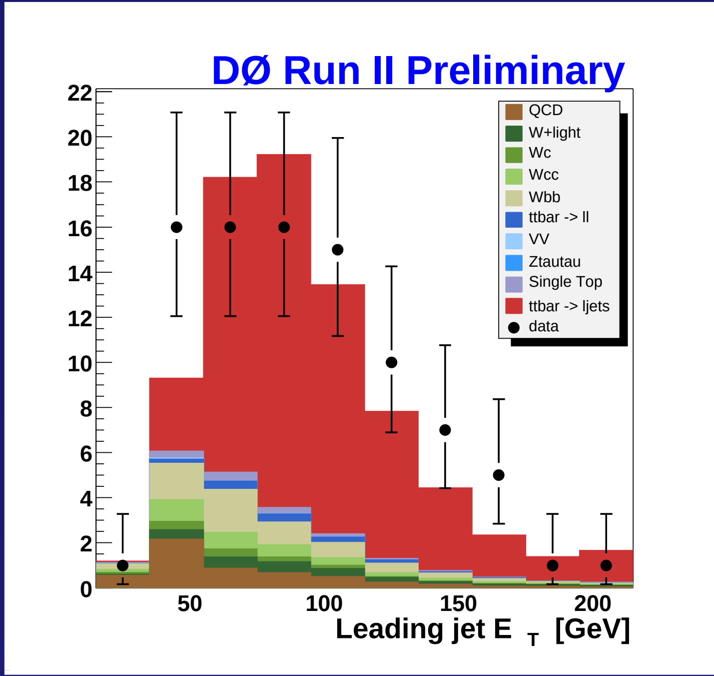


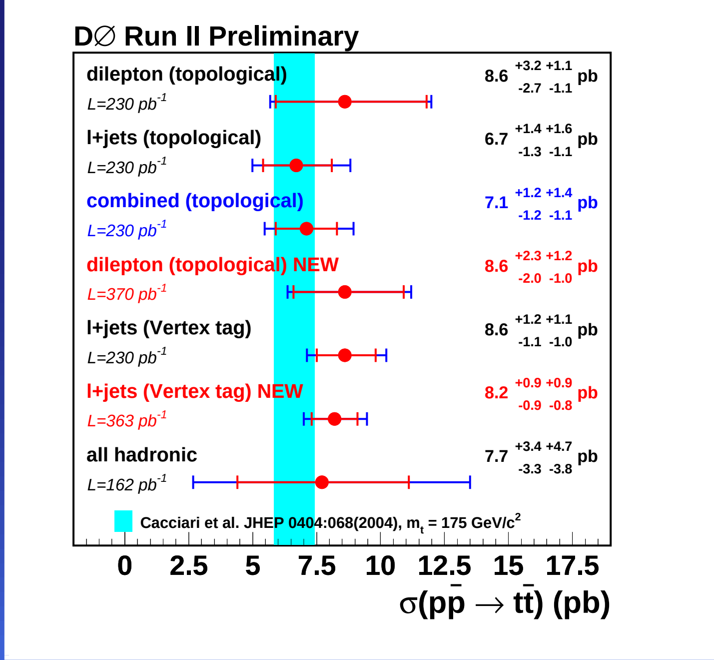
- ► Event selection criteria
  - exactly 1 isolated high $p_\perp$ lepton (e or μ, $p_\perp > 20$ GeV)
  - missing transverse energy from the undetected neutrino ($\not{E}_\perp > 20$ GeV)
  - jets are reconstructed with a cone algorithm ($\Delta R = 0.5$)
  - at least one high $p_\perp$ jet in the central region ($p_\perp > 15$ GeV, $|y| < 2.5$)
  - at least one jet is b-tagged (has a secondary vertex with $L_{xy} > 7\sigma_{L_{xy}}$)
- ► upper (lower) plot shows single (double) b-tagged events as function of jet multiplicity

- $\sigma_{t\bar{t}} = \left(8.14\,^{+0.94}_{-0.88}\,\text{stat}\;^{+0.85}_{-0.77}\,\text{syst} \pm 0.53_{\text{lumi}}\right)$ pb
- main systematic errors arrise from

effect	relative error (%)
Luminosity	± 6.5
W background fractions	± 5.4
b-tagging efficiency	$^{+4.9}_{-4.3}$
Muon trigger	$^{+4.2}_{-3.4}$
Jet Energy Scale	$^{+3.0}_{-2.6}$
Various Other	$^{+5.4}_{-4.9}$
Total	$^{+12.3}_{-11.5}$

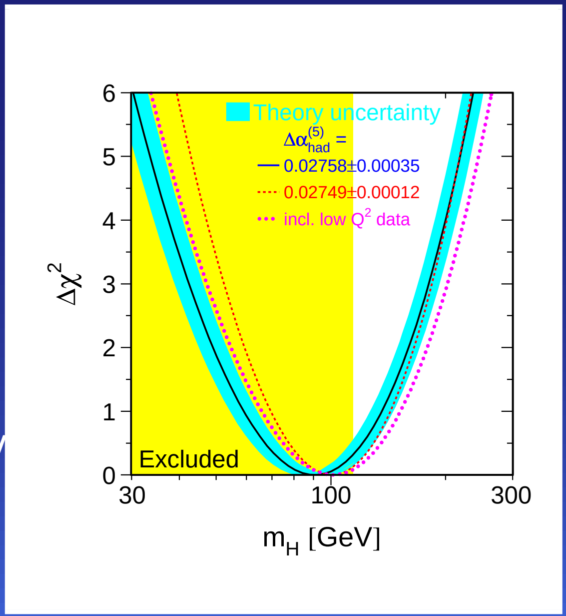
- cross check backround composition in jet multiplicity bins 1 and 2
  - see plots on previous slide
- check consistency in lots of kinematic variables in signal region (jet multiplicity bin ≥ 4 and ≥ 1 b-tag)
  - $E_\perp$ of leading jet shown here (upper plot)
- comparison to other D0 results and SM prediction (lower plot)

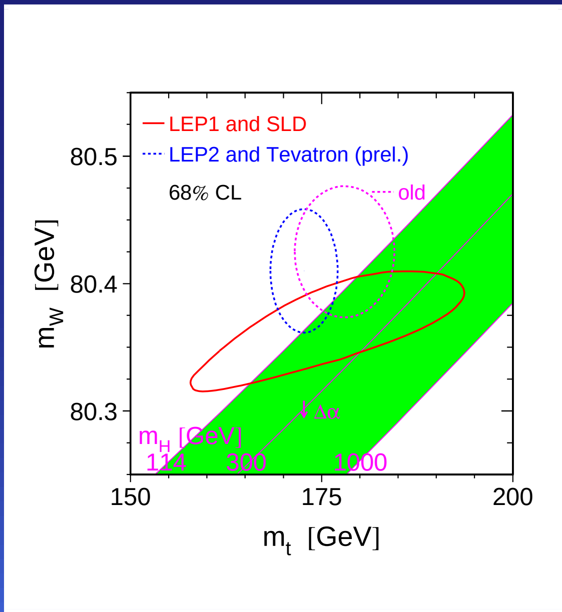




- top mass measurements at Tevatron Run II
  - identify (again) $t\bar{t}$ pairs with different topologies as in cross-section measurement
  - use different methods to extract the t-mass
    - kinematic fit
    - matrix element method
    - template method
    - with in-situ calibration of $W \to jj$
  - be careful about the actual definition of m_t
    - parameter in matrix elements/MC generator
    - peak value from a fit to a mass spectrum from combination of jets

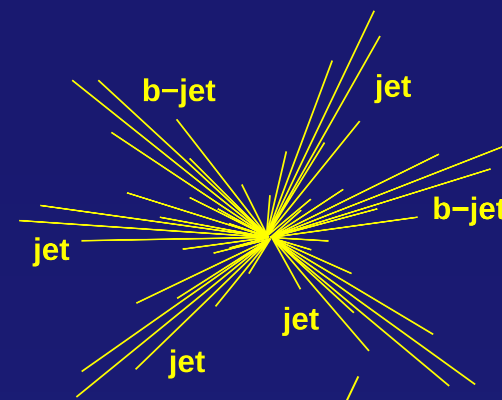
- top mass is one of the key measurements for EW fits ► Higgs mass determination
  - remember that the top-mass itself was predicted from EW fits and found exactly at that predicted value . . .

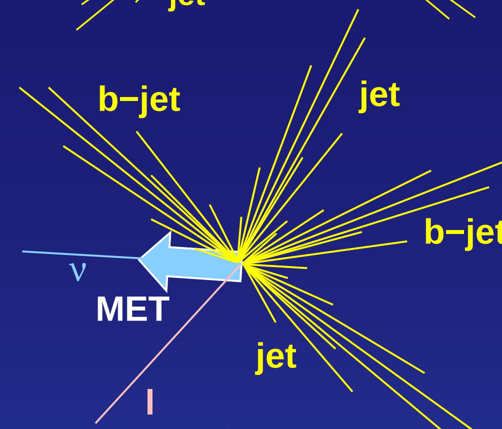


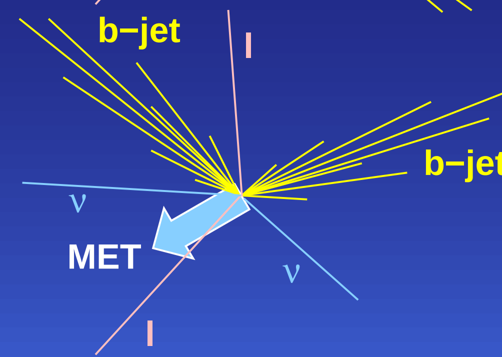


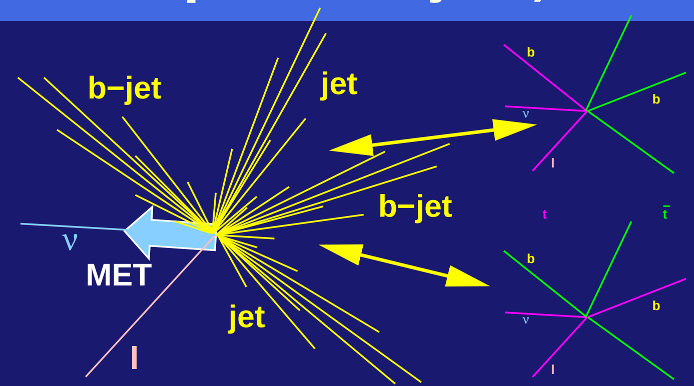
Analyses ► m_{t} ► Strategies

- in general we are concerned about the reconstruction of the 4-vectors of up to 6 final state partons to define the $\mathrm{t\bar{t}}$ system ► 24 unknowns
- usually only a subset of those 24 unknowns can be measured and most of the time with multifold ambiguities for making the correct lepton/jet/ $\not\!\!E_\perp$ – parton assignments
- given a certain topology (e.g. 'lepton + 4 jets + 2 b-tags + $\not\!\!E_\perp$') the number of measured quantities is usually the same (e.g. 5 complete 4-vectors and $\not\!\!E_{\perp\,x}$, $\not\!\!E_{\perp\,y}$ ► 22 measurements)
- the quality of the individual measurements is not the same (e.g. charged lepton momenta are much more precise than jet energies)
- the system can be further constrained by using one or more of the following assumptions (if applicable to the topology in question):
  - $m_{\mathrm{W^+b}} = m_{\mathrm{W^-\bar{b}}}$ – both produced top should have the same mass
  - $m_\nu = 0$ – neutrinos are massless
  - $m_{\ell\nu(jj')} = m_{\mathrm{W}}$ – the lepton or light quark pair add up to the W
- this leaves us with (assuming 2 b-tags):
  - 24 measurements, 3 constraints and a 9-fold ambiguity for 6 jets ► over-constrained by 3
  - 22 measurements, 4 constraints and a 2-fold ambiguity for a lepton + 4 jets ► over-constrained by 2
  - 18 measurements, 5 constraints and a 2-fold ambiguity for di-lepton + 2 jets ► under-constrained by 1

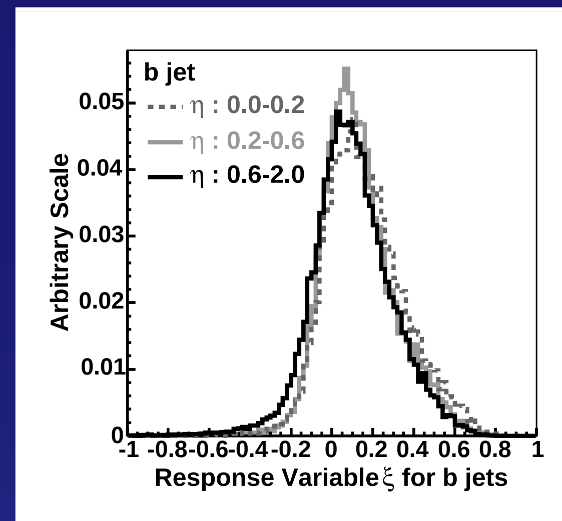


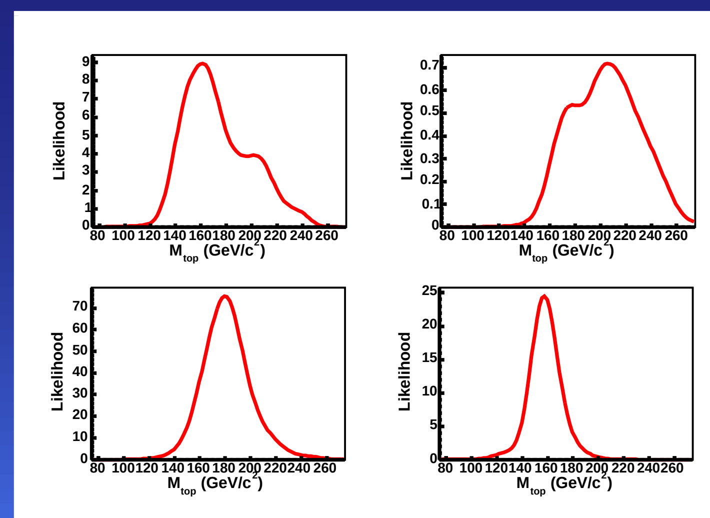






- generate for each event i a likelihood as function of m_t based on $d\sigma/d\Phi_6$
  1. assign reconstructed objects to partons ► 2 or 6 possible topologies (t) for 2 or 1 b-tag(s)
  2. the direction of the parton is taken from the measured jet directions
  3. generate random parton kinematics (r) according to transfer functions derived from the measured $E_\perp$ of the jets: $E_\perp(\text{parton}) = E_\perp(\text{jet})/(1-\xi)$
  4. identify the transverse energy of the neutrino with the measured (corrected) missing energy $\not{E}_\perp$:
  $$E_\perp(\nu) = -E_\perp(\text{lep}) - \sum_{j=1}^{4} E_\perp(\text{corr}) - X_\perp$$
  5. the z-component of the neutrino is taken from the constraint $m_{\ell\nu} = m_W$ ► 2 solutions (n)
  6. calculate likelihood $L(t,r,n,m_t)^i \sim d\sigma/d\Phi_6(t,r,n,m_t)$ and scan m_t from $155-195$ GeV
  7. the event likelihood is the average over all possible topologies (t), many random draws for the parton kinematics (r) (~ 50000) and the 2 neutrino solutions (n)





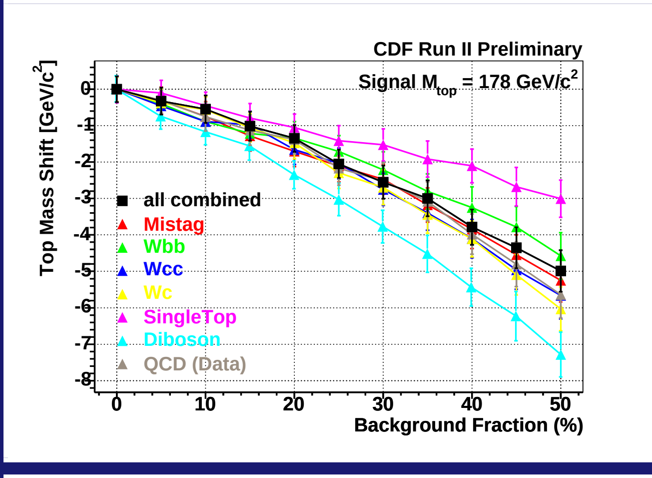
- the product of these event likelihoods is the combined likelihood:
$$L(m_t) = \prod_{i=1}^{N_{ev}} L(m_t)^i$$
- the value of m_t maximizing the combined likelihood is the result of this method

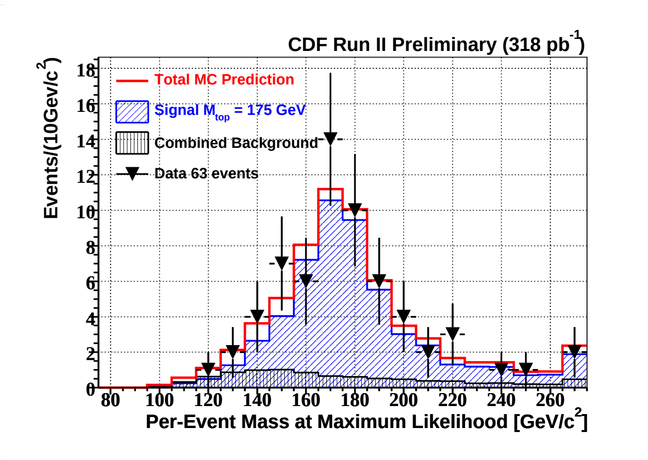
Analyses ► m_t ► matrix element method (CDF RunII lepton + 4 jets)

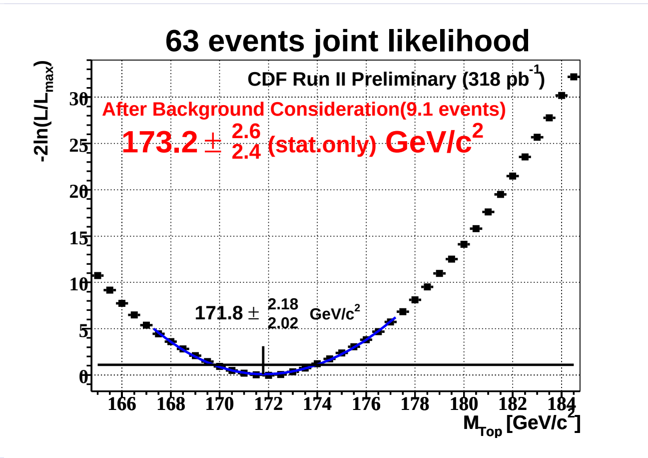
- the presence of background shifts the mass obtained from the likelihood
  - correct with mapping function
- systematic effects on the top-mass measurement are

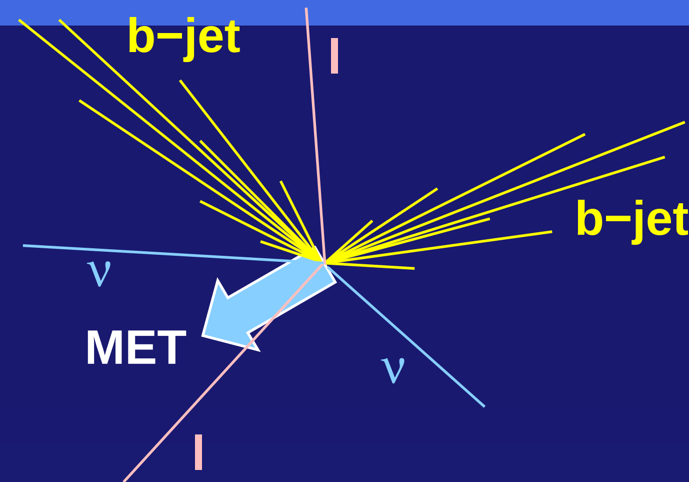
effect	error (GeV)
Jet Energy Correction	± 3.2
b-jet Energy Modeling	± 0.6
FSR	± 0.5
PDFs	± 0.5
Background Modeling	± 0.4
ISR	± 0.4
Generator	± 0.3
Transfer Function	± 0.2
Generator	± 0.2
b-tagging	± 0.2
Total	± 3.2

- dominant remaining systematic is the jet energy scale
  - next iteration will be done with m_W constraint
- $m_t = (173.2\,^{+2.6}_{-2.4}\,{}_{\text{stat}} \pm 3.2_{\text{syst}})$ GeV



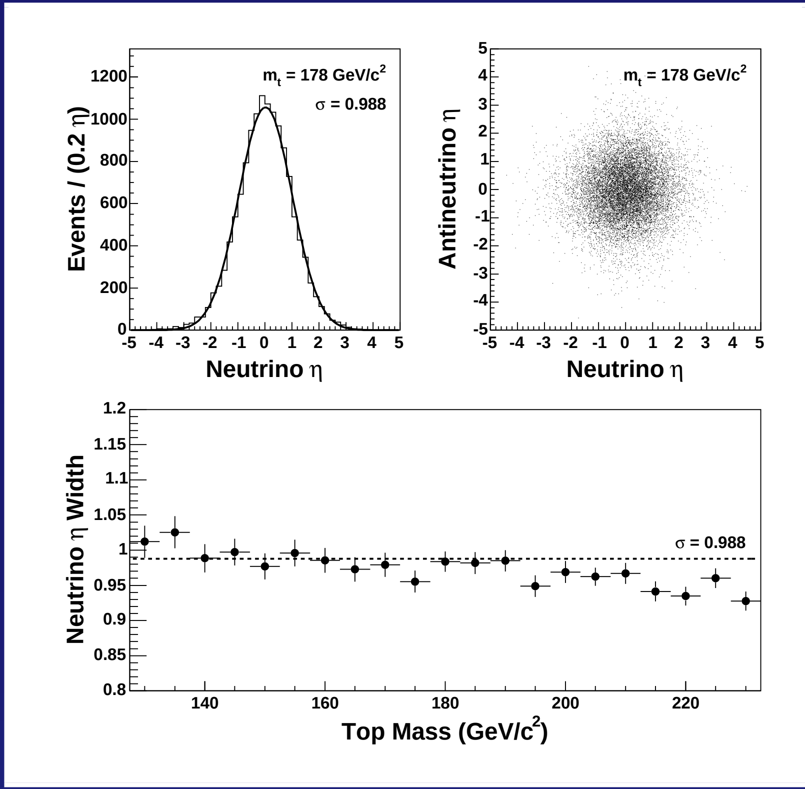


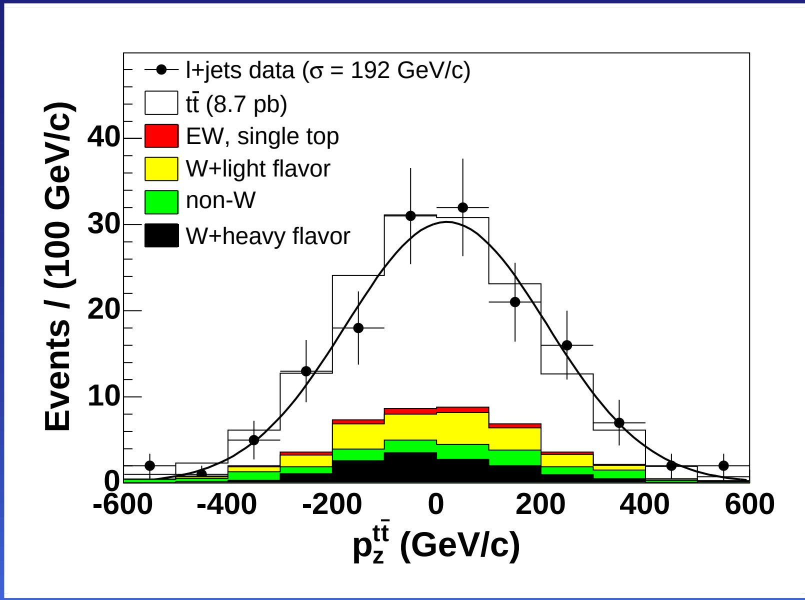




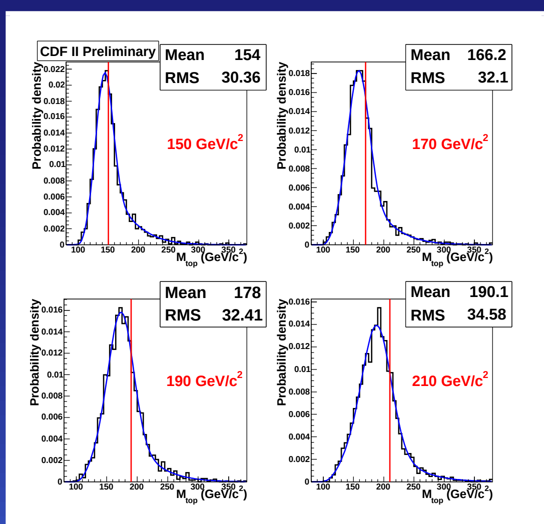
- di-leptons form the most under-constrained sample
- this gives lots of room for creative physicists to find additional contstraints
- the general idea of a template analysis is as follows:
  - jets/leptons are assigned to a top or anti-top decay and values for m_t and m_W are assumed
  - an additional kinematic constraint is selected (e.g. the neutrino direction) and drawn from simulated distributions
  - energy-momentum conservation leads to a small number of possible solutions (e.g. up to 4 different $\nu, \overline{\nu}$ pairs).
  - weights w as function of the top mass and the additional kinematic variables (e.g. comparing $p_\perp^{\nu+\overline{\nu}}$ with $\not{E}_\perp$) are averaged over all possible topological combinations and many random draws
  - from the distribution of $w(m_t)$ an indicative top mass is derived for each event
  - the 'measured' mass values are compared with probability density functions (templates) derived from fully simulated events with different input top-masses and the same reconstruction method
  - a mximum likelihood fit yields the final result for the mass
- instead of going back from detector to parton level (matrix element method) here we go from parton to detector level
- in both cases MC simulations are needed to model the transfer

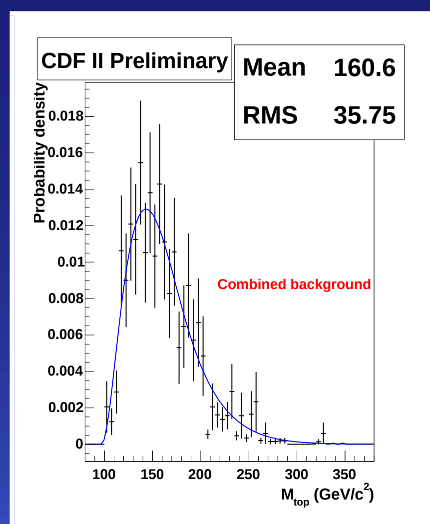
- CDF uses 3 different template methods
- NWA: Neutrino Weighting Algorithm
  - the η directions of the neutrino and anti-neutrino are random drawn form their simulated distribution (upper plots)
- KIN: Full Kinematic Analysis
  - the z component of the momentum of the $t\bar{t}$ system is random drawn from its simulated distribution (bottom plot)
- PHI: Neutrino Phi Weighting Method
  - the ϕ directions of the neutrino and anti-neutrino are random drawn form a flat distribution

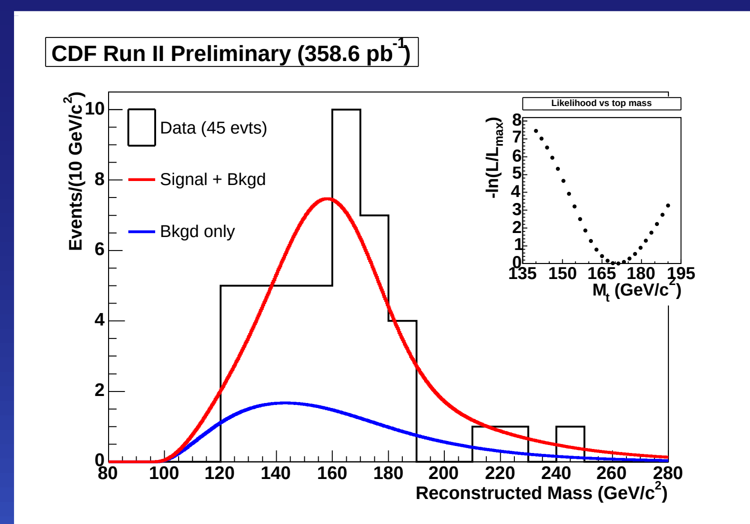




- any bias introduced by the reconstruction algorithm needs to be simulated
- the simulation is done for a wide range of top masses
- applying the analysis to a given sample generated with a fixed top mass (or background) gives a distribution of reconstructed top masses
- the distribution is parameterized and gives the probability density function (template) to ‘measure’ m_t^{rec} for a certain true value m_t used as input to the simulation
- plots show signal templates, background template, and final results for NWA

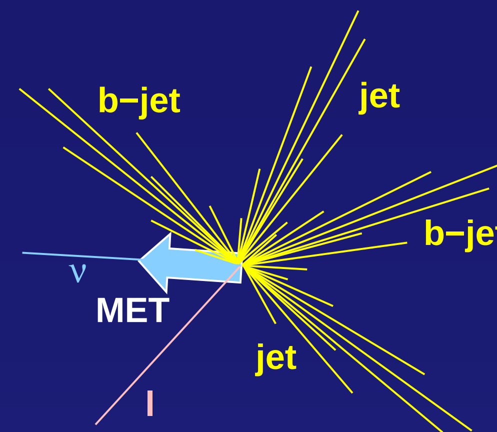


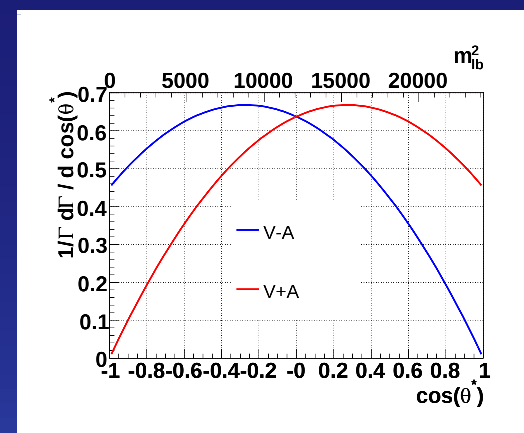




$$m_t = (170.7\,^{+6.9}_{-6.5}\,{}_{\text{stat}} \pm 4.6_{\text{syst}})\ \text{GeV}$$

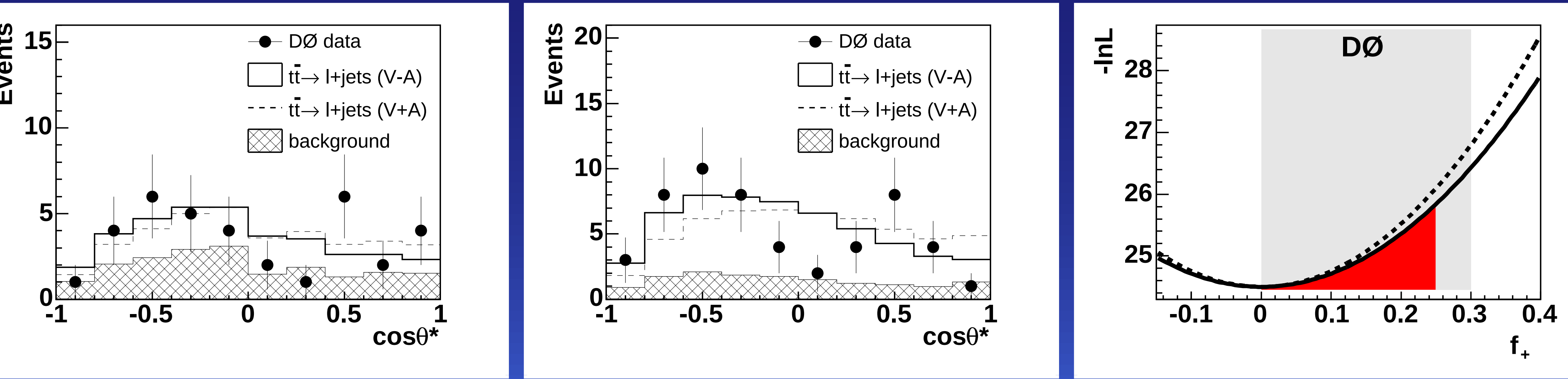
- the top decays before it can hadronize and passes its spin information to the decay products
  - in the SM the decay is almost always $\mathrm{t} \longrightarrow W^{+}\mathrm{b}$ via a $\mathrm{V} - \mathrm{A}$ current interaction
  - any deviation from the expected $\mathrm{V} - \mathrm{A}$ behavior would indicate new physics
  - in general for any combination of V and A:
    $\frac{1}{\Gamma}\mathrm{d}\Gamma/\mathrm{d}\cos(\theta^*) =$
    $\frac{3}{4}f_0(1 - \cos^2(\theta^*)) + \frac{3}{8}f_-(1 - \cos(\theta^*))^2 + \frac{3}{8}f_+(1 + \cos(\theta^*))^2$
    $f_0 + f_- + f_+ = 1$
    $f_0 \simeq \frac{m_\mathrm{t}^2}{2m_\mathrm{W}^2 + m_\mathrm{t}^2 + m_\mathrm{b}^2} \simeq 0.7$
    $f_+(SM) = 0$
  - θ^* is the polar angle in the W rest frame between the $W^{+(-)}$ momentum direction and the $\ell^{+(-)}$ or $\overline{q}(q)$
  - in general we can not distinguish between the quark-jet and the anti-quark jet ► use the lepton+jets channel



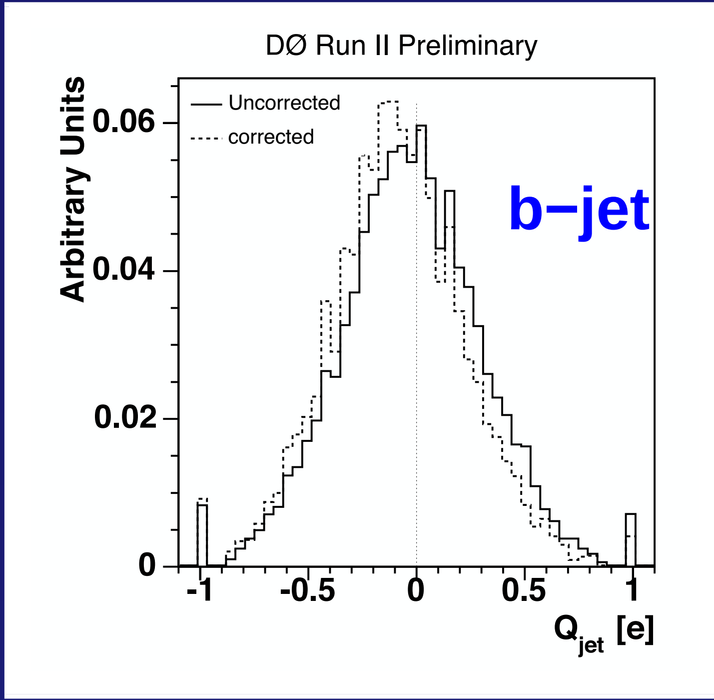


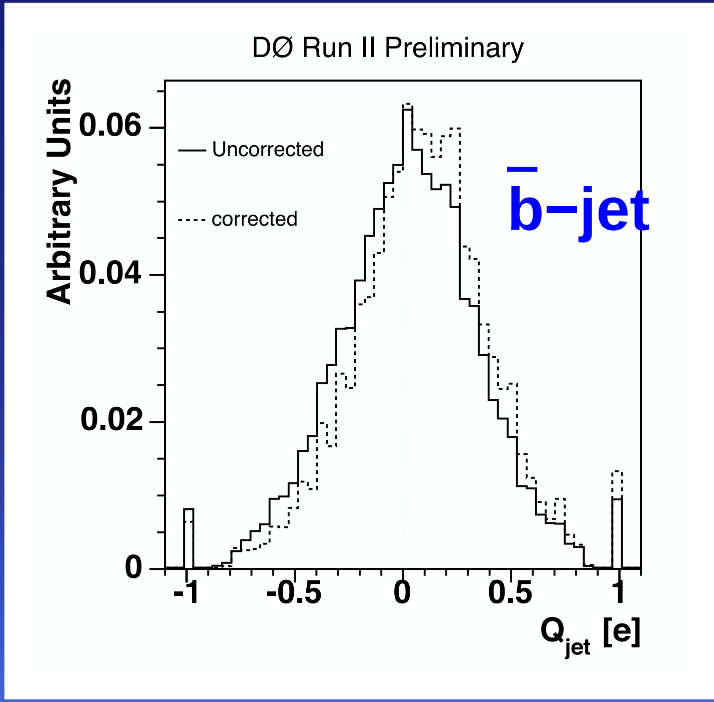
- reconstruction of $\cos(\theta^*)$
  - $m_{\ell b}^2 = \frac{1}{2}(m_\mathrm{t}^2 - m_\mathrm{W}^2)(1 + \cos(\theta^*))$
  - can be defined in the lepton+jets (dilepton) case with 4-fold ambiguity for 4 (2) jets without b-tag
  - with kinematic constraints from the entire event all 4-vectors can be reconstructed in the lepton+jets case (12-fold ambiguity for jet pairings ► keep the one with best χ^2)

- left (middle) plot shows the result from the kinematic (b-tagged) analysis from D0 in Run II
- dominant background is W+jets in both cases
- final right-handed fraction f_+ is obtained from maximum likelihood fits using templates for various f_+ values within the physical range $0 \leq f_+ \leq 0.3$
- right plot shows final likelihood with 95 % C.L. area in red
- measurement: $f_+ = 0.00 \pm 0.13_{\text{stat}} \pm 0.07_{\text{syst}}$
- limit: $f_+ < 0.25$ @ 95 % C.L.

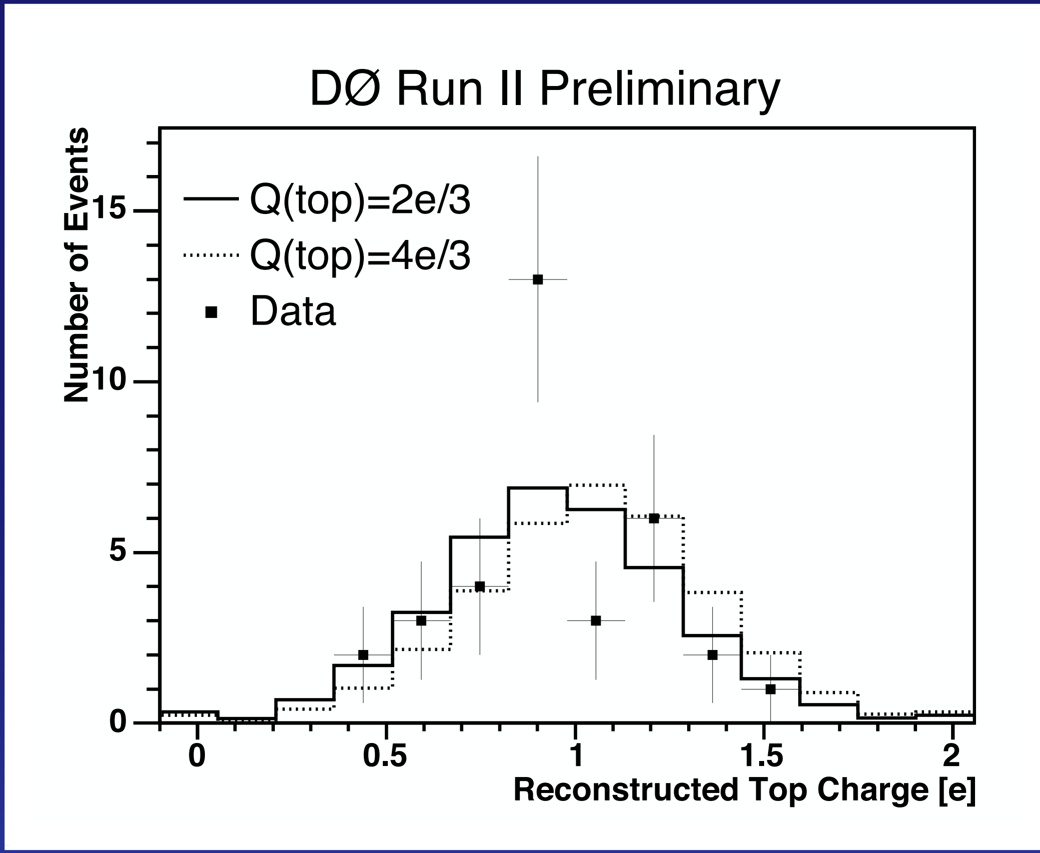


- has the top quark really charge $+2/3e$?
- D0 made a first measurement in the lepton+jets channel with 2 b-tags
- need to distinguish between b- and $\overline{\mathrm{b}}$-jet
  - measure the charge of the jet:
    - select all tracks ($|p_\perp| > 0.5\,\mathrm{GeV}$) within $\Delta R = 0.5$ of the b-tagged jet axis
    - define jet-charge: $q_{\mathrm{jet}} = \frac{\sum_i q_i p_{\perp i}^{0.6}}{\sum_i p_{\perp i}^{0.6}}$
    - distributions for the jet-charge are taken from $\mathrm{b}\overline{\mathrm{b}}$-data with
      - exactly two jets both with b-tag, $p_\perp > 15\,\mathrm{GeV}$ and back-to-back in ϕ ($\Delta\phi > 3.0$)
      - one of the jets (the tag jet) has to contain a muon with $p_\perp > 4\,\mathrm{GeV}$
      - from the other (the probe jet) the jet-charge is derived
      - the charge of the muon is correlated with the type of b (b or $\overline{\mathrm{b}}$) but not to 100 % due to cascade decays $\mathrm{B} \to \mathrm{D}X \to \mu \pm Y$, $\mathrm{B} - \overline{\mathrm{B}}$ mixing, and c-jets tagged as b-jets
      - in μ^+-events the jet charge in the probe jet corresponds to 66 % b-jets, 28 % $\overline{\mathrm{b}}$-jets and 6 % $\overline{\mathrm{c}}$-jets





- use kinematic fit to combine the jets and the lepton to reconstruct the t and $\bar{\mathrm{t}}$ ► correct assignment for $80\,\%$ of the events
- measure two top charges per event:
  - $Q_1 = |q_\ell + q_{\mathrm{b}_1}|$ with ℓ and b_1 from the same top
  - $Q_2 = |-q_\ell + q_{\mathrm{b}_2}|$ with b_2 from the other top
- test with two hypotheses from full simulation:
- $|Q_\mathrm{t}| = 2/3e$ with $Q_{1,2}$ like above
- $|Q_\mathrm{t}| = 4/3e$ with the oposite b-jet assignments
  - $Q_1 = |q_\ell + q_{\mathrm{b}_2}|$
  - $Q_2 = |-q_\ell + q_{\mathrm{b}_1}|$



- plot shows final distribution
- likelihood result: $|Q_\mathrm{t}| = 4/3e$ is excluded with $94\,\%$ C.L.

Outlook

- LHC will be a top factory
  - most top analyses will be limited by systematics
- top studies are important to
  - understand the detector (e.g. with in-situ W calibration)
  - estimate the backgrounds for Higgs analyses
  - enhance the precision for EW fits (cross-section, top-mass, etc.)
  - measure $|V_{\mathrm{tb}}|$ in single-top production
- Tevatron analyses are a good guideline for the top-studies at LHC