Experimental aspects of the MEM using the example of m_{top}

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Today's Menu

- **First implementation** of the **MEM in particle physics**
- **Most recent** measurement of m_{top} with the MEM @ D0
  - Description of the **measurement technique**
  - **Experimental challenges:**
    - transfer functions, linearity of response, statistical sensitivity, sensitivity to systematic uncertainties, etc
  - **Numerical challenges:**
    - computing time
  - **Which m_{top}** do we measure?
  - Will we **gain** by going to **NLO**?
- **Other** measurements with the MEM:
  - At the Tevatron
  - At the LHC:
    - Where is the MEM used?
    - Why won't there be a measurement of m_{top} with the MEM?

A bit of history…

2/3/95, Ramsey Auditorium, FNAL

* FF: free food (doctorate student slang)

2/3/95, Ramsey Auditorium, FNAL

The birth of the top

- 24 Feb. 1995:
  - Simultaneous PRL submission by CDF and DØ

The birth size

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- CDF (67 pb^{-1}) :
  - $\sigma=6.8^{+3.6}_{-2.4}$ pb,
  - observed 19 events, expected 6.9 bkg
    - bkg-only hypothesis rejected at 4.8σ
  - m_{top}=176±13 GeV
- D0 (50 pb^{-1}):
  - σ=6.4±2.2 pb,
  - observed 17 events, expected 3.8 bkg
    - → bkg-only hypothesis rejected at 4.6σ
  - m_{top}=199±30 GeV

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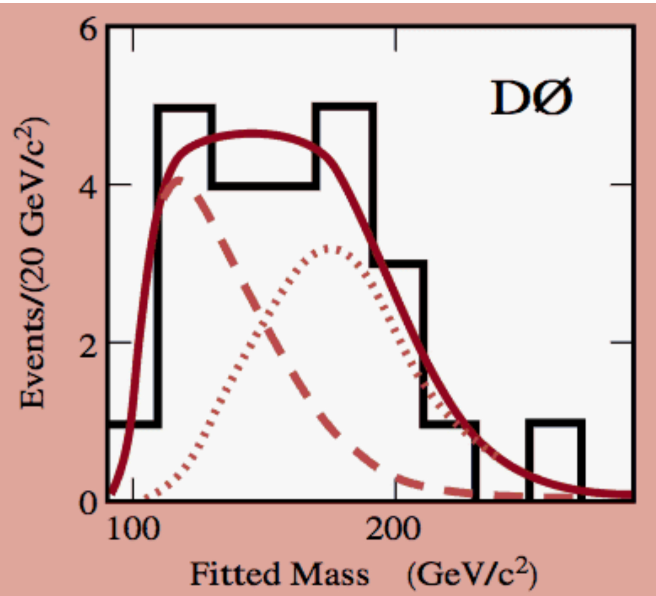

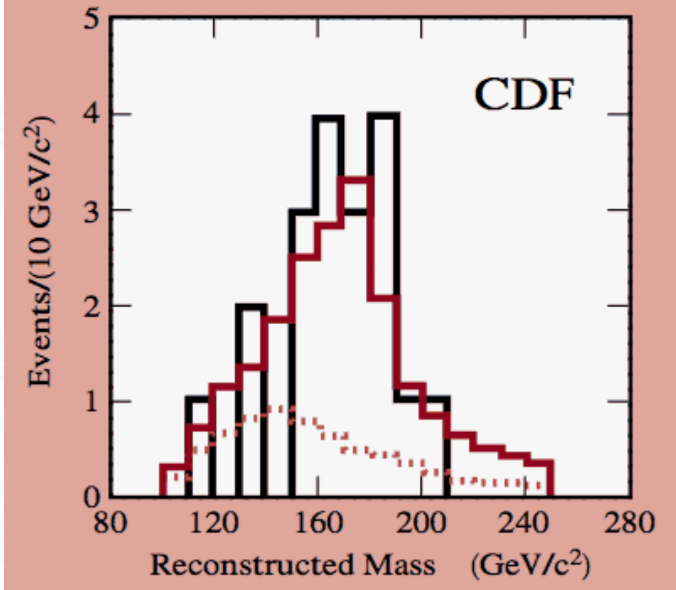

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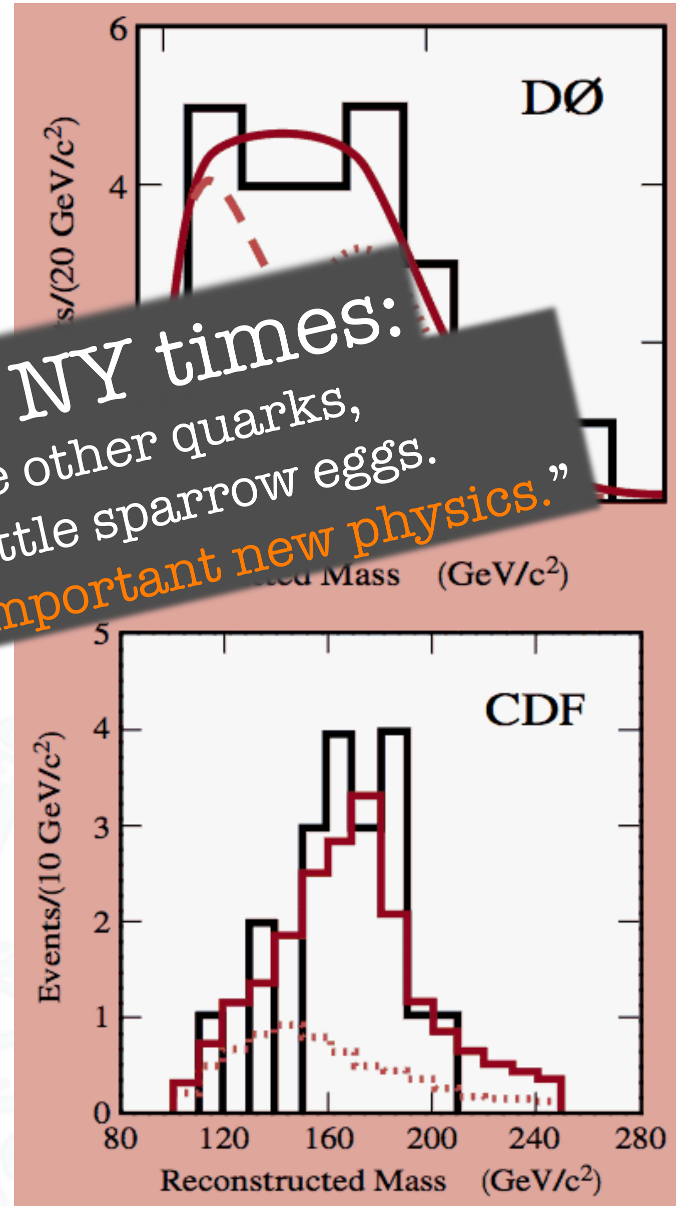
P. Grannis, DO spokes in NY times:

“This monster, compared with all the other quarks, is like a big cowbird's egg in a nest of little sparrow eggs. It's so peculiar it must hold clues to some important new physics.”



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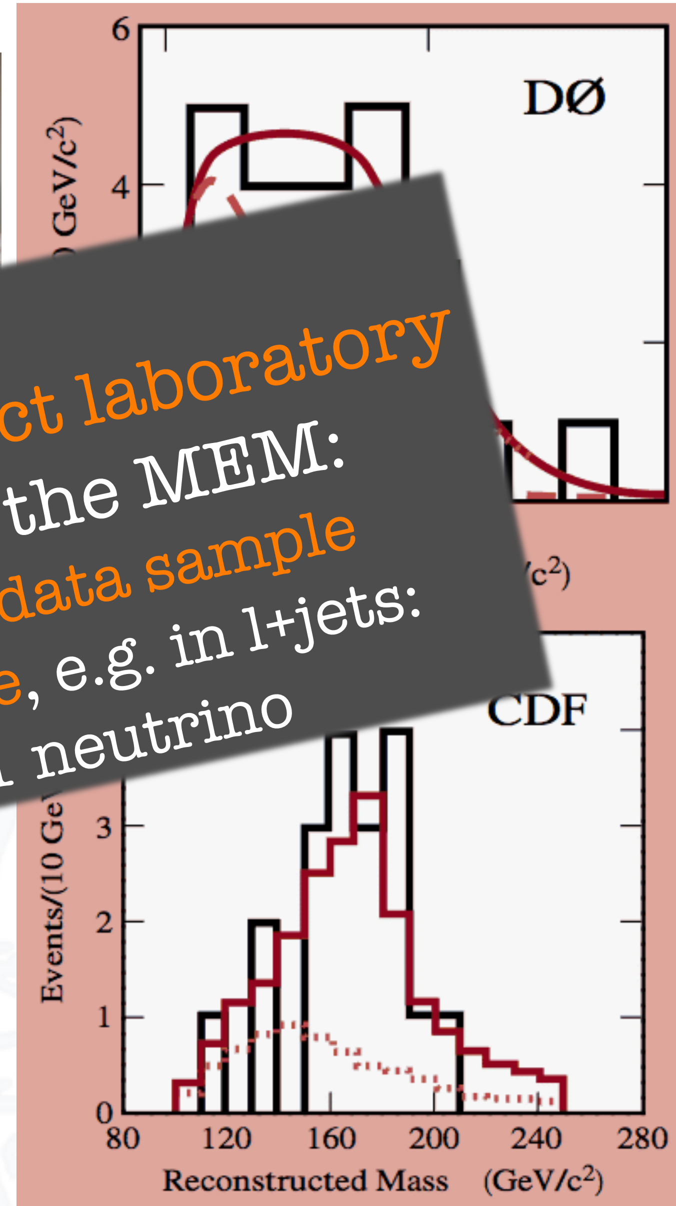
For our purposes,
the top quark provided a perfect laboratory
to test the performance of the MEM:
- It was a statistically limited data sample
- It has a challenging final state, e.g. in l+jets:
4 jets, 1 charged lepton, 1 neutrino



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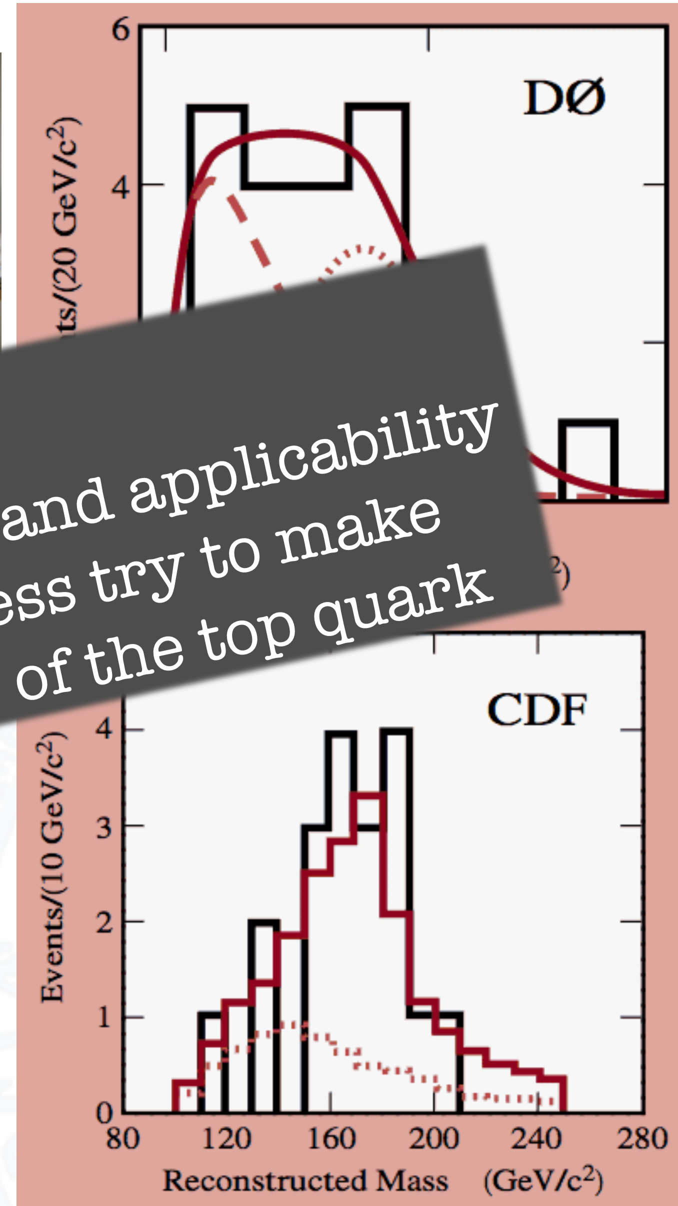
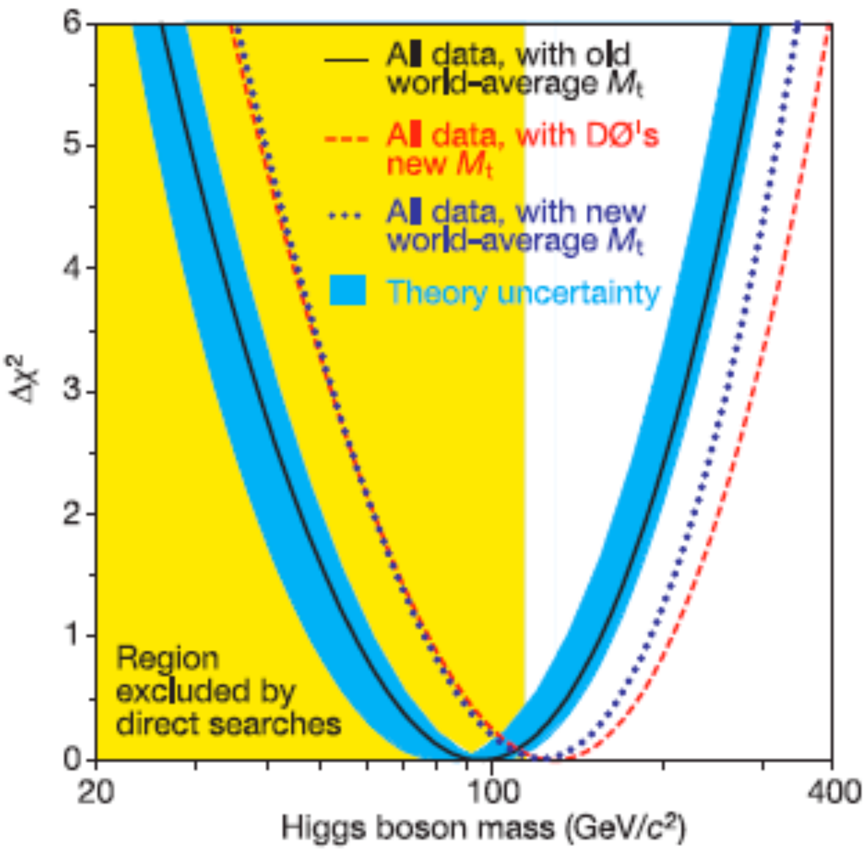


Disclaimer:
I do not claim absolute universality and applicability of my statements, but nevertheless try to make general points using the example of the top quark

First implementation of MEM in HEP

- The first (published) measurement in HEP using the MEM:



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Explorer satellite.

A precision measurement of the mass of the top quark

DØ Collaboration*

*A list of authors and their affiliations appear at the end of the paper

The standard model of particle physics contains parameters—such as particle masses—whose origins are still unknown and which cannot be predicted, but whose values are constrained through their interactions. In particular, the masses of the top quark (M_t) and W boson (M_W)[1] constrain the mass of the long-hypothesized, but thus far not observed, Higgs boson. A precise measurement of M_t can therefore indicate where to look for the Higgs, and indeed whether the hypothesis of a standard model Higgs is consistent with experimental data. As top quarks are produced in pairs and decay in only about 10^{-24} s into various final states, reconstructing their masses from their decay products is very challenging. Here we report a technique that extracts more information from each top-quark event and yields a greatly improved precision (of $\pm$ 5.3 GeV/c^2) when compared to previous measurements[2]. When our new result is combined with our published measurement in a complementary decay mode[3] and with the only other measurements available[2], the new world average for M_t becomes[4] 178.0 $\pm$ 4.3 GeV/c^2. As a

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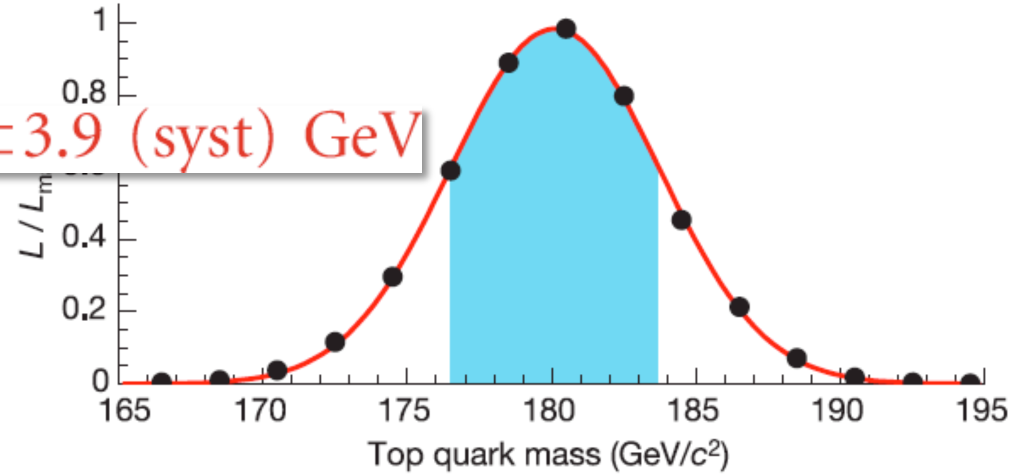
letters to nature

he experimen- top quark in our previous publication, and correspond to an

First implementation of MEM in HEP

- The final result:
  - $M_t = 180.1 \pm 3.6 \text{ (stat) } \pm 3.9 \text{ (syst) GeV}$
    - Using 125 pb^{-1} of p-pbar collisions @ 1.8 TeV, 71 events



- Previous result:
  - $M_t = 173.3 \pm 5.6 \text{ (stat) } \pm 5.5 \text{ (syst) GeV}$
    - same dataset, 91 candidates
- Much higher statistical sensitivity:
  - Corresponding to 2.4x more data with old method!
  - Systematic uncertainties are also smaller
- Already this analysis
  - Was using jet-parton transfer functions
  - Looked at 12 possible jet-parton assignments (4 jets)
  - Used numerical integration in 5 variables

The MEM today
(at the Tevatron, in top physics)

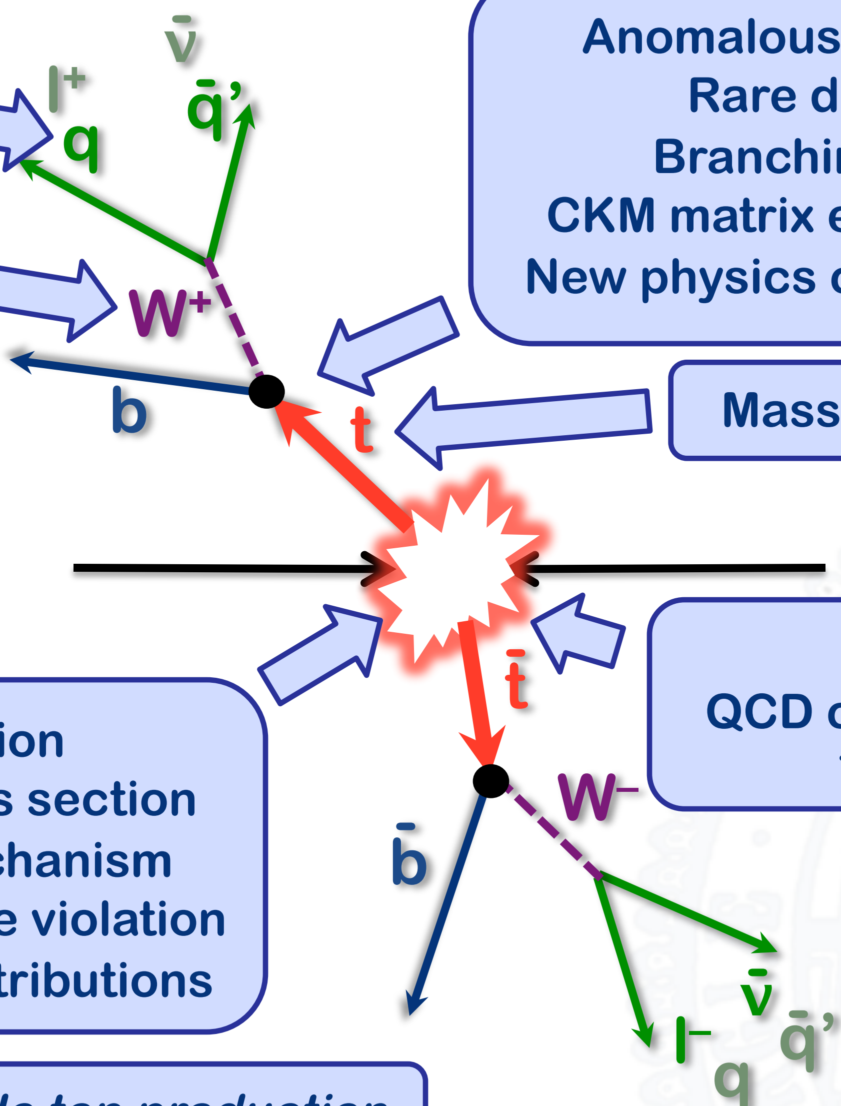
Today: top properties with the MEM

Color flow

W helicity

Anomalous couplings
Rare decays
Branching ratio
CKM matrix element $|V_{tb}|$
New physics contributions

Mass, charge, width



Spin correlation
QCD charge asymmetry A_{FB}
Top polarisation

Cross section
Differential cross section
Production mechanism
Lorentz invariance violation
New physics contributions

+ electroweak single top production

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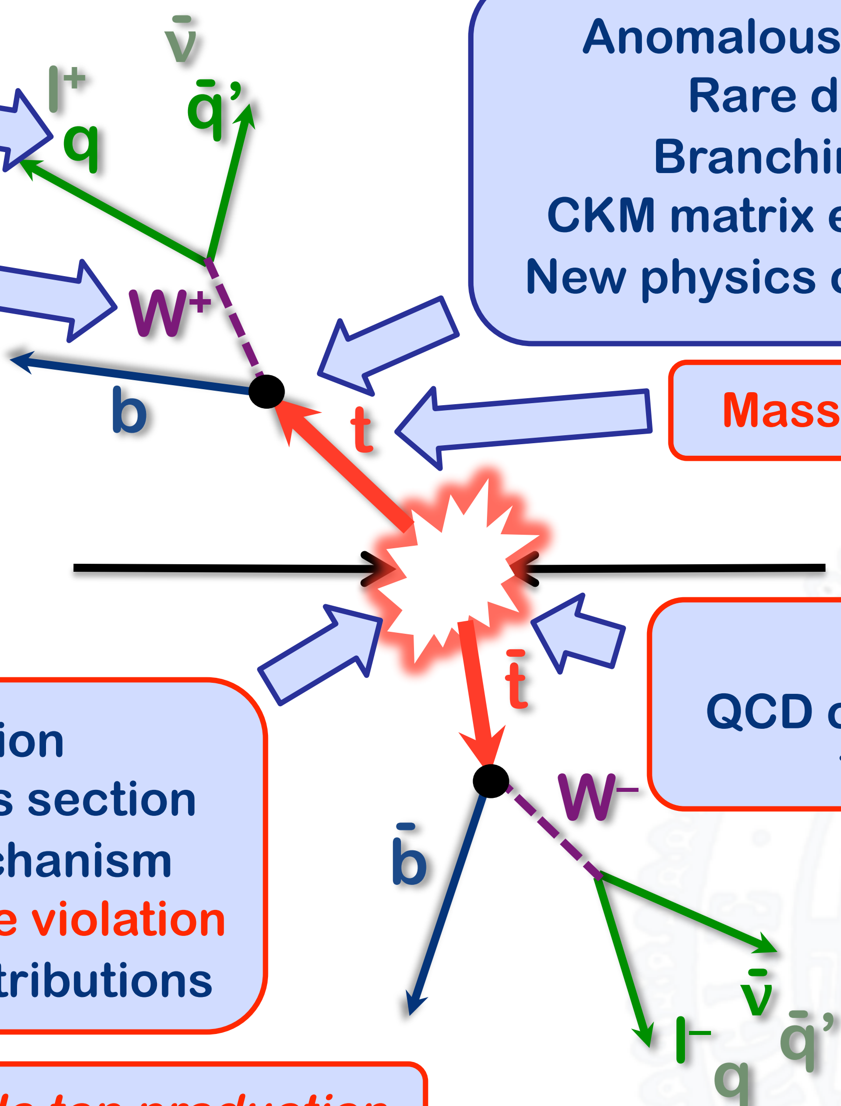


Spin correlation
QCD charge asymmetry A_{FB}
Top polarisation

Cross section
Differential cross section
Production mechanism
Lorentz invariance violation
New physics contributions

+ electroweak single top production

In red: measurements with the MEM

Top mass with the MEM @ D0

- The relatively small size of the datasets at Tevatron calls for the Matrix Element method:
  - Calculate signal P_{sig} and background probability P_{bkg} on an event-by-event basis:

$$P_{\mathrm{evt}} = A(x)[fP_{\mathrm{sig}}(x; m_{\mathrm{t}}, k_{\mathrm{JES}}) + (1 - f)P_{\mathrm{bkg}}(x; k_{\mathrm{JES}})]$$

  - The clue: calculate $d\sigma$ via

$$\mathrm{d}\sigma_{t\bar{t}} \propto |\mathcal{M}_{t\bar{t}}|^2(m_{\mathrm{top}})$$

  - Use Transfer Functions (TF) to map parton level quantities y to reco level quantities x
- Key advantage:
  - Use 4-vectors with maximal topological information + correlations
    - This is the maximally possible use of the event information

- P_{sig} in its full beauty:

b tagging-based weight to identify relevant jet-parton assignments

Integration over phase space (10 dim)

$$P_{\text{sig}} = \frac{1}{\sigma_{\text{obs}}^{t\bar{t}}} \sum_{i=1}^{24} w_i \int d\rho\, dm_1^2\, dM_1^2\, dm_2^2\, dM_2^2\, d\rho_\ell\, dq_1^x\, dq_1^y\, dq_2^x\, dq_2^y \sum_{\text{flavors},\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1) f'(q_2)}{\sqrt{(\eta_{\alpha\beta} q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\text{JES}})$$

LO matrix element
PRD 53, 4886 (1996)
PLB 411, 173 (1997)

Phase space factor

Transfer functions (TFs) to map
parton level quantities y to reco level quantities x

- P_{sig} in its full beauty:

Normalisation by observed cross section using the same LO ME

Sum over all 24 possible jet-parton assignments

$$P_{\rm sig} = \frac{1}{\sigma^{t\bar{t}}_{\rm obs}} \sum_{i=1}^{24} w_i \int d\rho\, dm_1^2 dM_1^2 dm_2^2 dM_2^2 d\rho_\ell dq_1^x dq_1^y dq_2^x dq_2^y$$

$$\sum_{\rm flavors,\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1) f'(q_2)}{\sqrt{(\eta_{\alpha\beta} q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\rm JES})$$

Sum over all flavours and all neutrino solutions

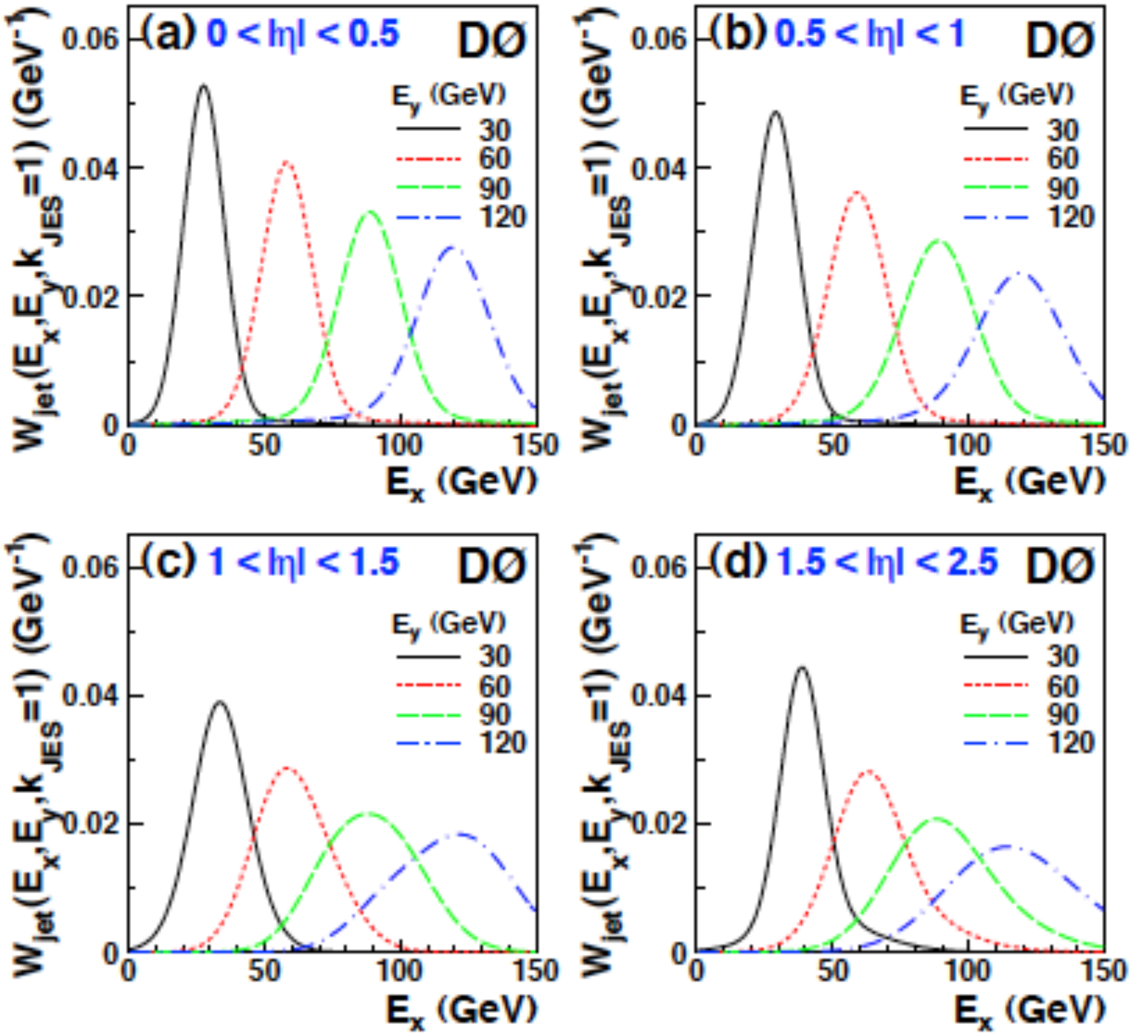
PDFs for Björken-x and transverse momenta of incoming partons

The MEM today:
Experimental challenges

Transfer functions

- The Transfer Functions $W(x, y; JES)$ relate parton-level quantities to reconstruction-level ones
- Ideally, would use full detector simulation to do this, however:
  - we typically need o(100k) samplings of the integral when performing numerical integration (per m_{top},k_{JES} hypothesis and per permutation)
  - Technically, it is simply not feasible, as the full simulation of a jet takes o(minutes)
- Parametrise the detector response using:
  - Well-behaved function
    - (e.g. a Gaussian or a sum of Gaussians)
  - A sufficiently finely binned look-up table

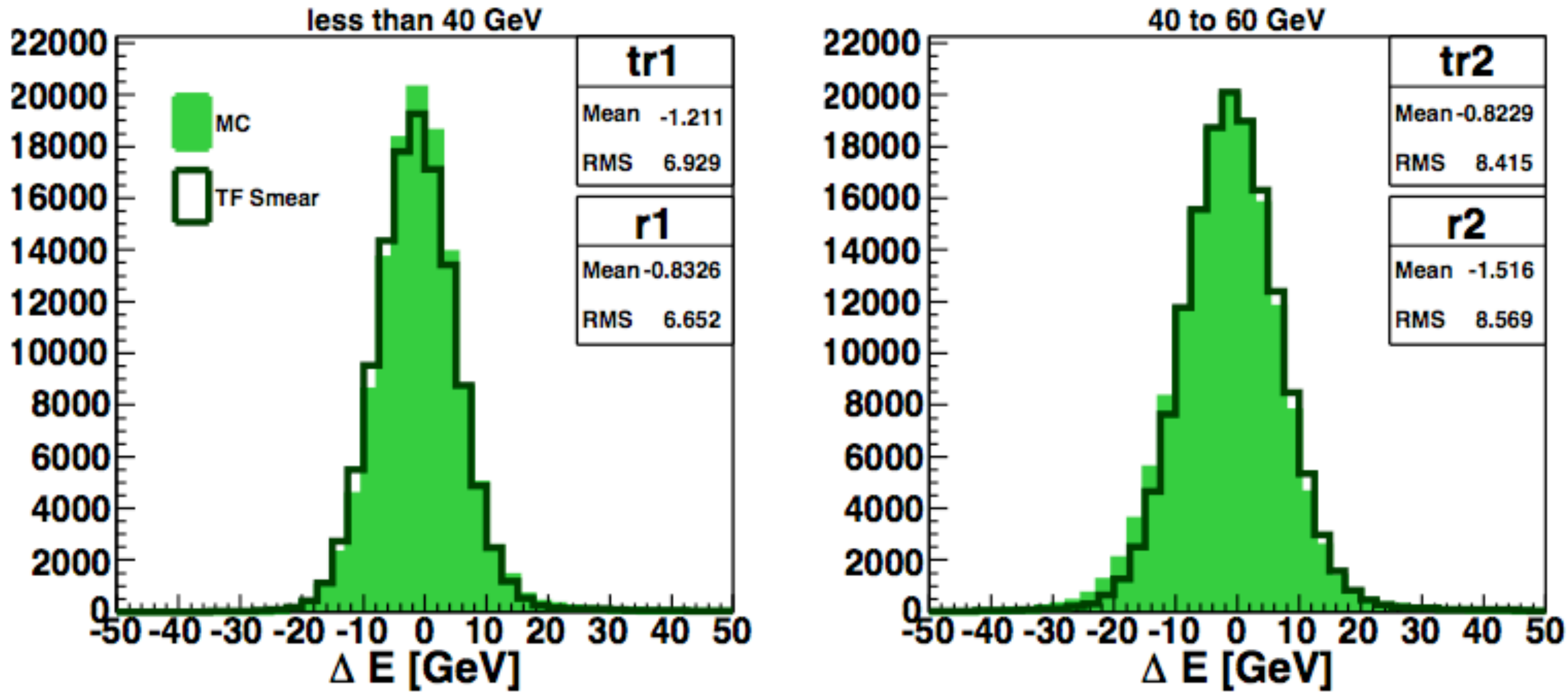
- The **Transfer Functions** $W(x, y; JES)$ relate parton-level quantities to reconstruction-level ones
- **Jet energies:**
  - Treat **separately**:
    - Light quark jets
    - b-tagged jets with soft muon tag
    - All other b-jets
  - x 4 | η | regions for each
- The **directions** of jets and leptons in η x ϕ are **well-measured**
  - → use δ-function as transfer function!



- **Jet energy transfer function:**

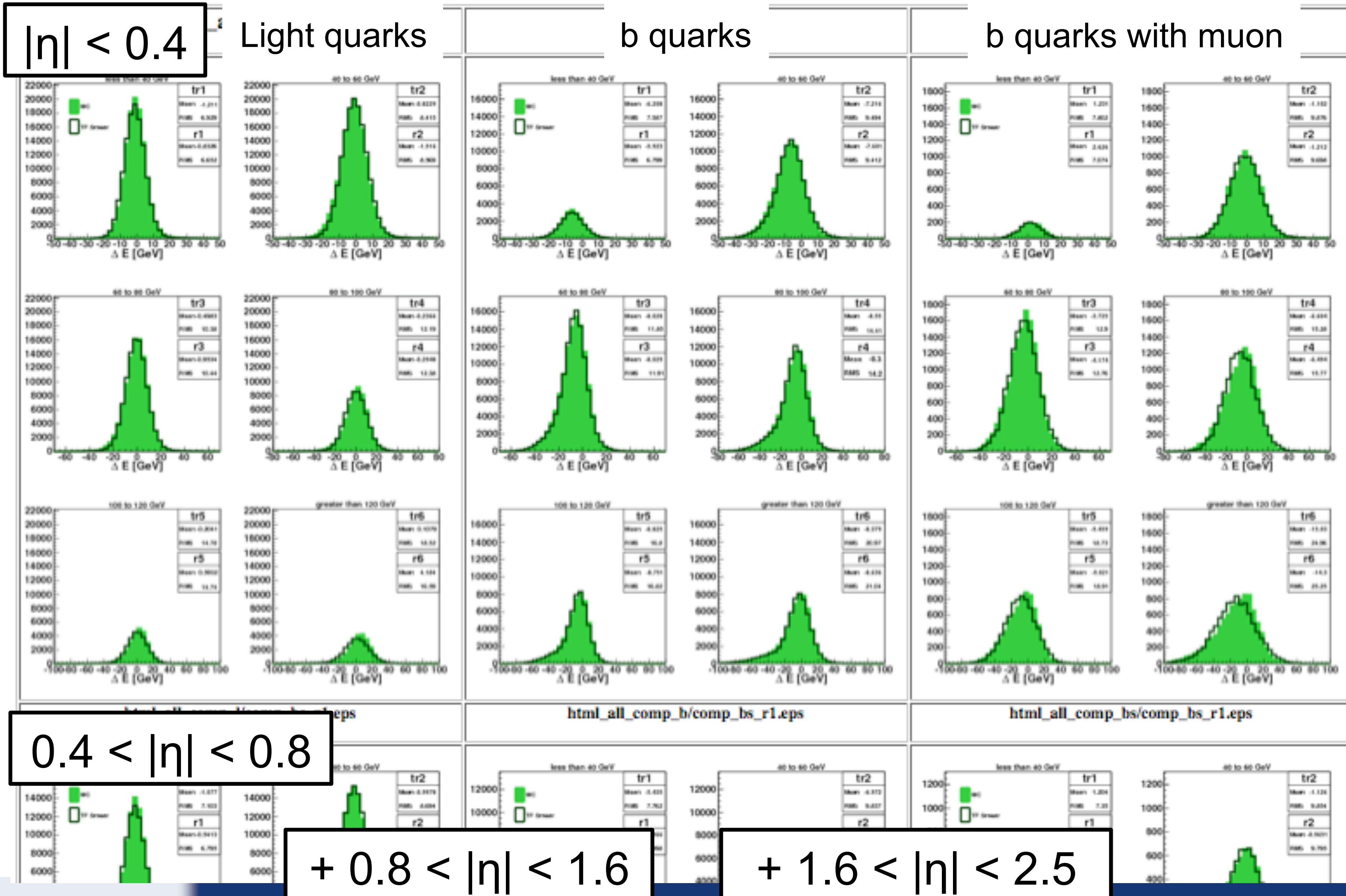
$$W_{\text{jet}}(E_x, E_y; k_{\text{JES}} = 1) = \frac{1}{\sqrt{2\pi}(p_2 + p_3 p_5)}[e^{-([(E_x-E_y)-p_1]^2)/2p_2^2} + p_3 e^{-([(E_x-E_y)-p_4]^2)/2p_5^2}]$$

  - derived by performing (unbinned) maximum LH fit:



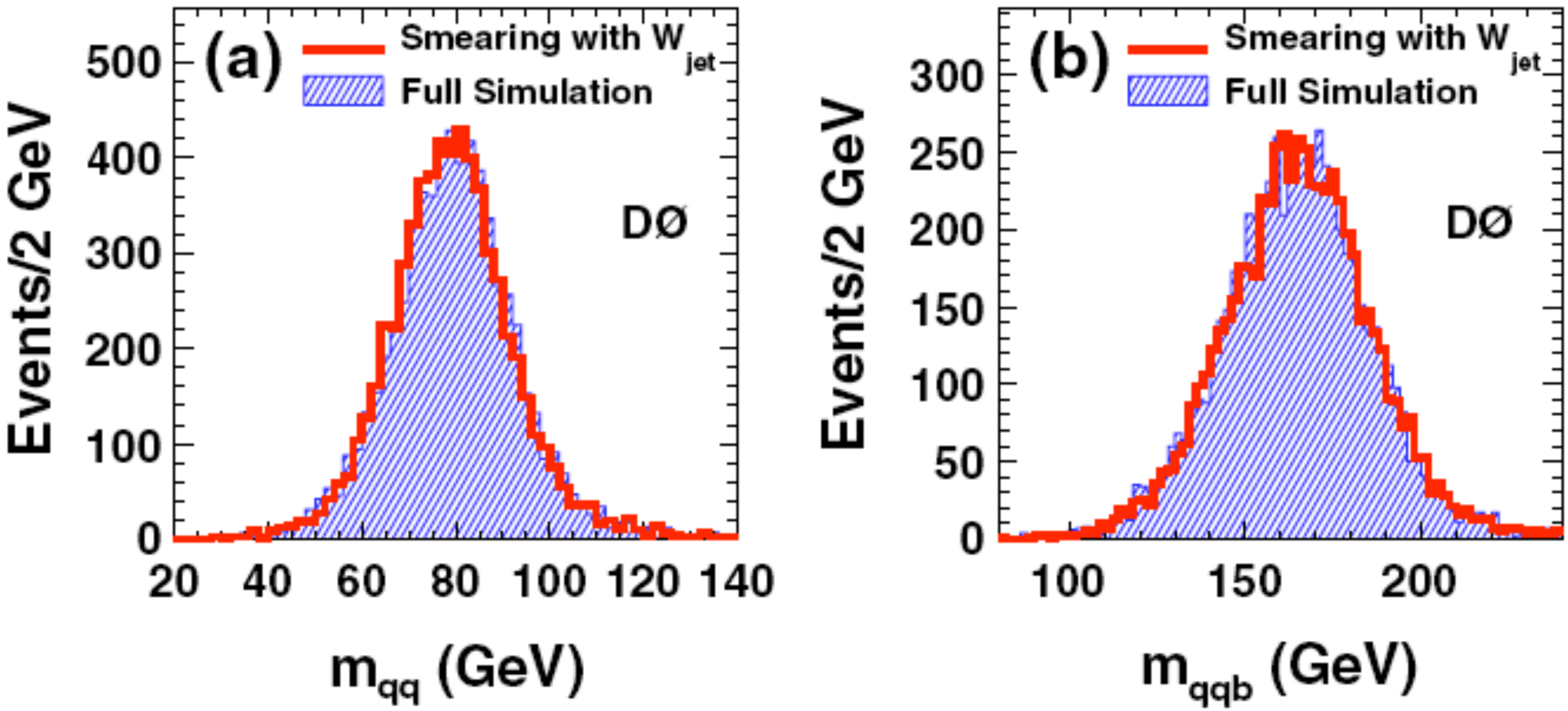
Full-simulation MC Partons smeared with transfer functions

Transfer functions



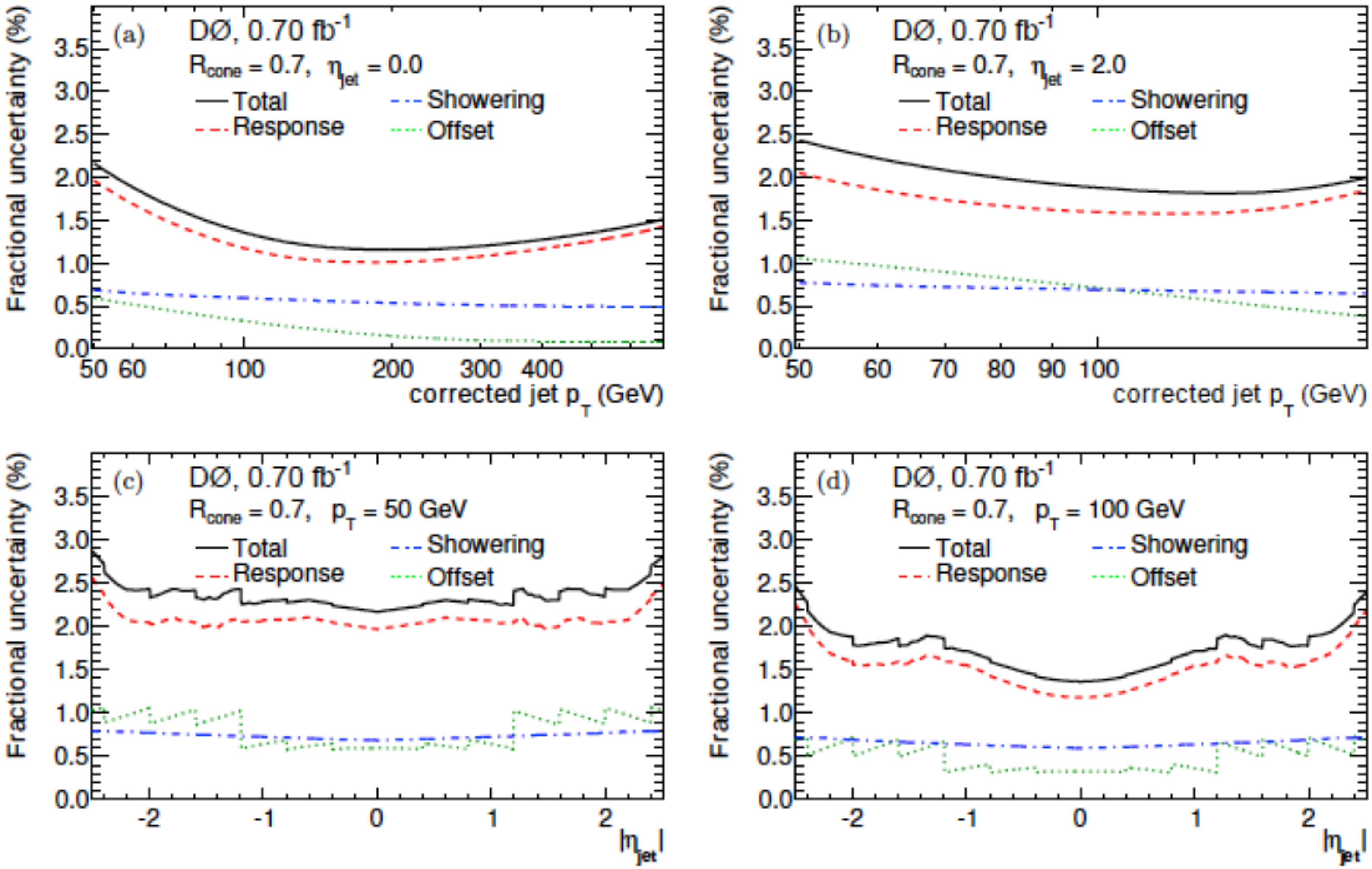
Transfer functions

- Highly non-trivial to find a set of parameters to fit a double-Gaussian to data in all 6 bins of the jet energy while accounting for resolution tails
  - → lots of "playing around" with Minuit…
- Ultimate validation:



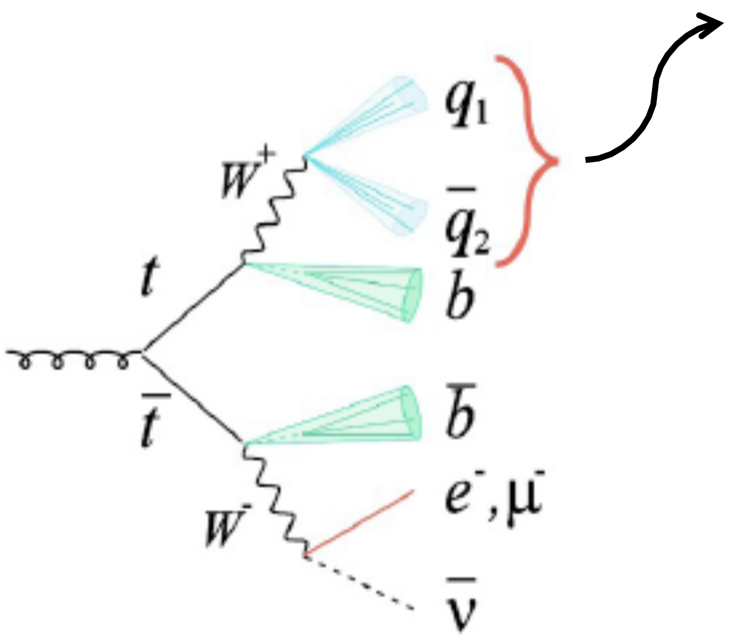
Jet energy scale (JES)

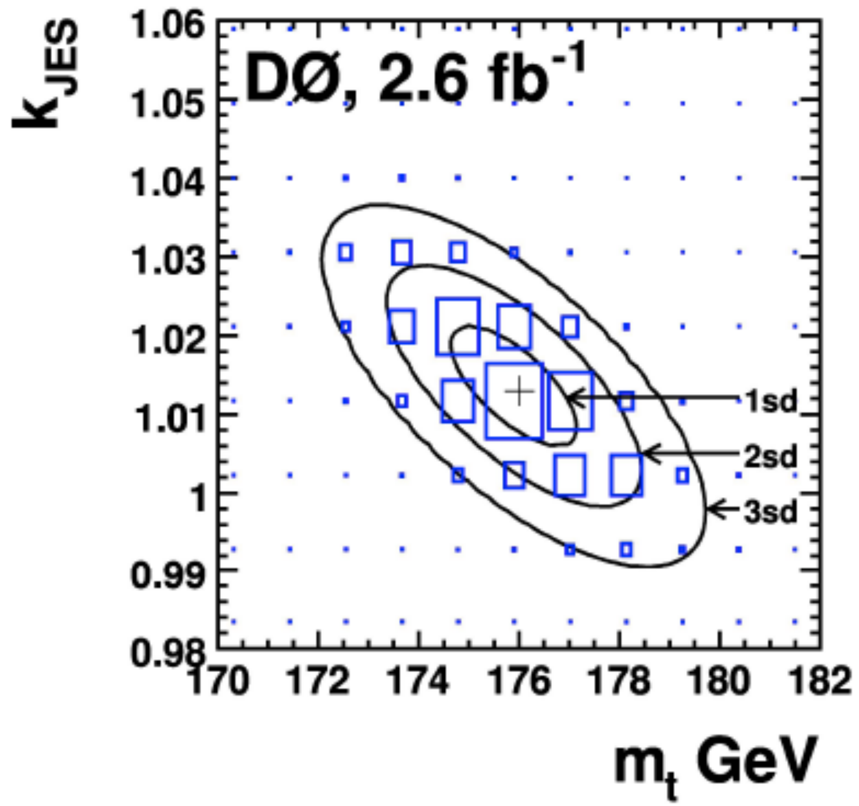
- Typical **JES uncertainty 2-3 %**
  - → can lead to an uncertainty on m_{top} as large as **2 GeV**!



Jet energy scale (JES)

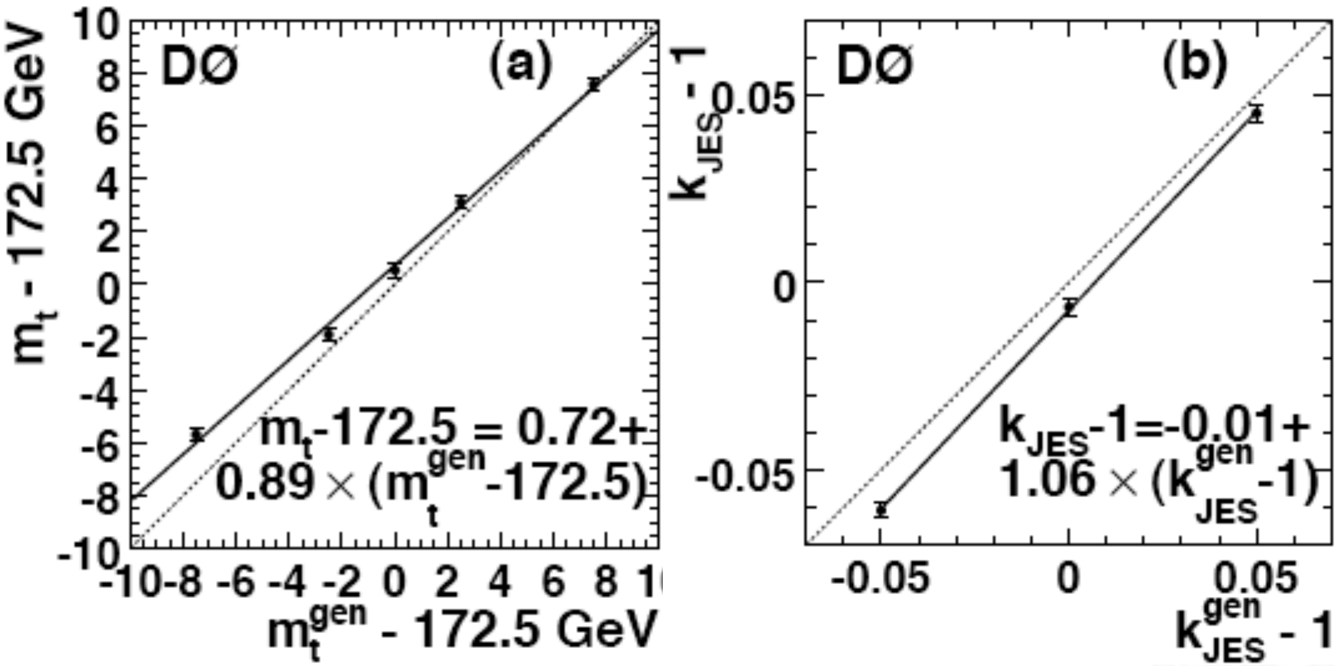
- perform an **in-situ calibration of the JES:**
  - Constrain the two jets from W decay to m_W
  - This allows a simultaneous extraction of m_{top} and k_{JES}!
    - Can in principle extend to more dimensions





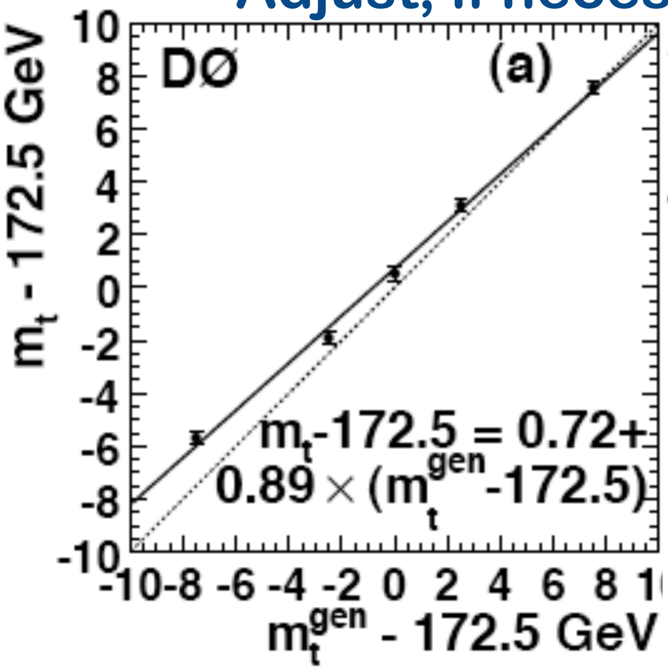
Method calibration

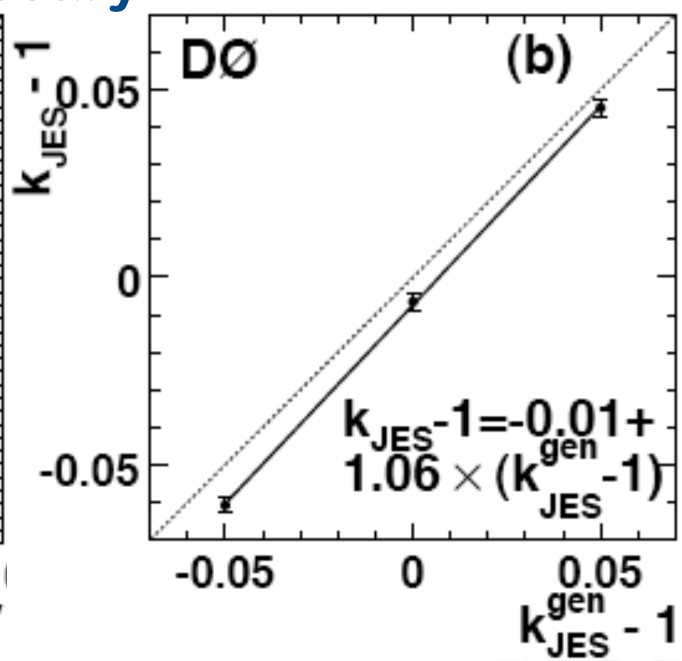
- **Verify the linearity of response**
  - **For perfect transfer functions and other approximations expect calibration curve of f(x)=0+x**

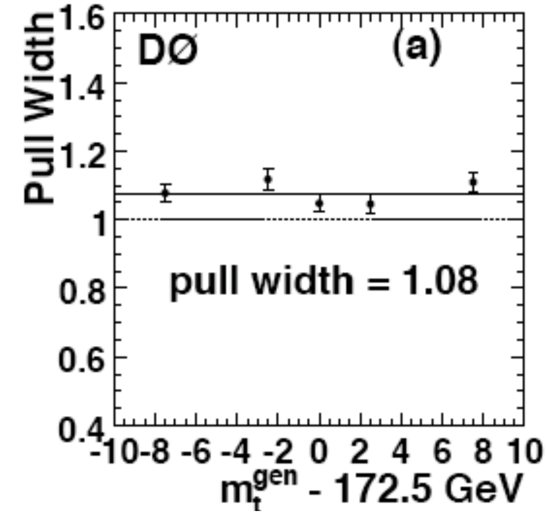


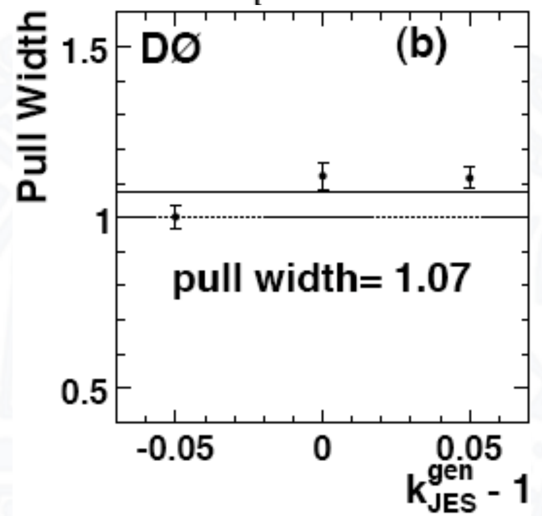
Method calibration

- Verify the **linearity of response:**
  - For perfect transfer functions and other approximations expect calibration curve of f(x)=0+x
- Check if the **statistical sensitivity is estimated correctly**
  - Adjust, if necessary

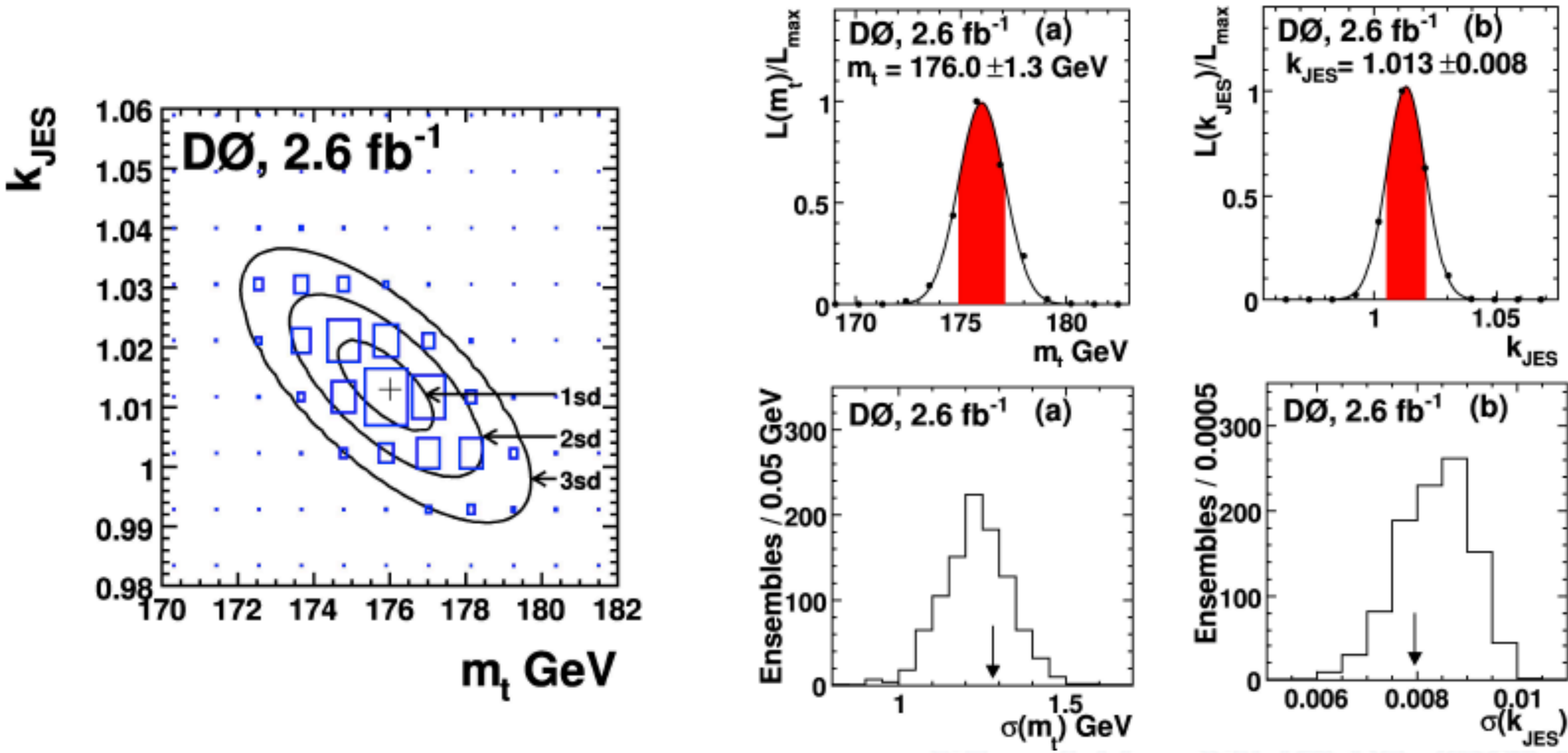








Final result, after all calibrations



$$m_t(3.6\ \text{fb}^{-1}) = 174.9 \pm 0.8(\text{stat}) \pm 0.8(\text{JES}) \pm 1.0(\text{syst})\ \text{GeV}$$

$$= 174.9 \pm 1.5\ (\text{GeV})$$

relative uncertainty 0.9%

Note that uncertainty on in-situ JES calibration is statistical in nature!

A word on the sensitivity

- Now, the size of the data sample is given by hundreds of candidate events (at the Tevatron)
  - the advantage of the ME method in terms of a higher statistical uncertainty is swindling:
    - One can gain few 10%
      - (cf. 240% for first MEM implementation and 71 candidates!)

- With the MEM method, we are sensitive to the specific model described by the MEM:
  - For ttbar production via qQ annihilation @ Tevatron:
    - ☑ via a gluon propagator in s-channel
    - ☐ via a Higgs propagator in s-channel
  - This restriction is not in place for template-like methods which "just" calculate the invariant mass
  - This restriction is also present for kinematic fitters…

Systematic uncertainties

Source	Uncertainty (GeV)
Modeling of production:	
Modeling of signal:	
Higher-order effects	±0.25
ISR/FSR	±0.26
Hadronization and UE	±0.58
Color reconnection	±0.28
Multiple $p\bar{p}$ interactions	±0.07
Modeling of background	±0.16
W+jets heavy-flavor scale factor	±0.07
Modeling of b jets	±0.09
Choice of PDF	±0.24
Modeling of detector:	
Residual jet energy scale	±0.21
Data-MC jet response difference	±0.28
b-tagging efficiency	±0.08
Trigger efficiency	±0.01
Lepton momentum scale	±0.17
Jet energy resolution	±0.32
Jet ID efficiency	±0.26
Method:	
Multijet contamination	±0.14
Signal fraction	±0.10
MC calibration	±0.20
Total	±1.02

The interesting thing is the small print

Note that some systematic uncertainties are expected to be smaller for the MEM, e.g. ISR/FSR for ME @ LO and 4 jets in the final state

Note that we quote the stat. uncert. on a syst. uncert. if it is larger than the syst. uncert. at face value → due to higher stat. sensitivity MEM has an advantage

The MEM today:
Numerical challenges

Numerical integration

- **Make a smart choice of integration variables to enhance convergence of the numerical integration:**

$d\rho$	energy of jet 1	
$dm_1^2 dm_2^2$	top masses	chosen for computational efficiency due to 4 B.W.'s
$dM_1^2 dM_2^2$	W masses	
$d\rho_l$	lepton energy	
$dq_1^x dq_1^y dq_2^x dq_2^y$	transverse momenta of initial state partons	

  - E.g. integrating in E_{jet} is not a smart choice…
  - Rather, multiply result with transfer functions in the end

- The probability drops rapidly away from the Breit-Wigner bulk in m_{top} and m_W
  - Use importance sampling with SM predictions for Γ_{top}, Γ_W
- Use importance sampling for dq_1, dq_2
- Use adaptive importance sampling (a la VEGAS) for $d\rho$

Numerical integration

- There are 24 possible jet-parton assignments:
  - Save computation time and accept limited precision for numerically non-relevant assignments early:
    - Perform pre-integration (whichever occurs first):
      - Until 10k of integral samplings have been made
      - Until a numerical precision of 10% has been reached
    - Stop integration for assignments with $P_{sig} < 0.005\ P_{sig}^{max}$

- Use integration in 5 steps with increasing number of integral samplings
  - Use the results from the previous step to further refine the importance sampling for integration in $d\rho$

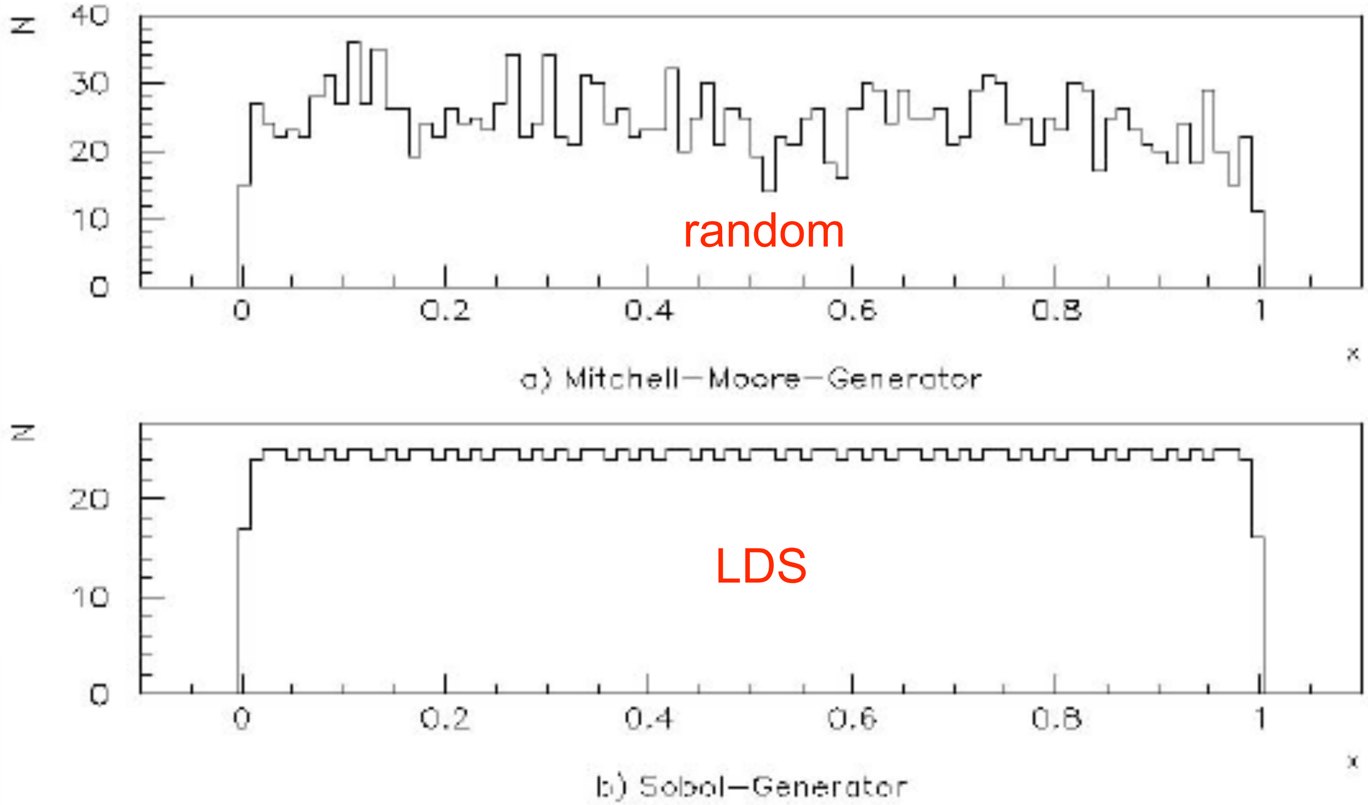
Numerical integration

- Despite all the above, the average time to calculate P_{sig} is about 1.5 hours!
  - For the previous iteration of the analysis (with 3.6 fb^{-1}):
    - Used about 1 M CPUh to calculate P_{sig}, P_{bkg}
      - Largest fraction of this (99%) went into method calibration and evaluation of systematic uncertainties
    - Even with this enormous computing time, the systematic uncertainty was statistically limited to o(1/4 GeV)
- Clearly, this was not acceptable for the final, most precise m_{top} measurement:
  - We have to produce 4 sets of calibrations with dedicated MC for 4 parts of the full dataset
  - Increase the size of systematic uncertainty samples (per each part of the full dataset) by a factor of ~ 4


Be wise in choosing your next step,
let the light guide you,
may the Force be with you

Numerical integration

- Introduce **low-discrepancy sequences (LDS)**, aka quasi-random numbers, for integration
  - Sample the unit hypercube $[0,1]^d$ maximally uniform, in contrast to “normal” pseudo-random numbers
    - → faster convergence!



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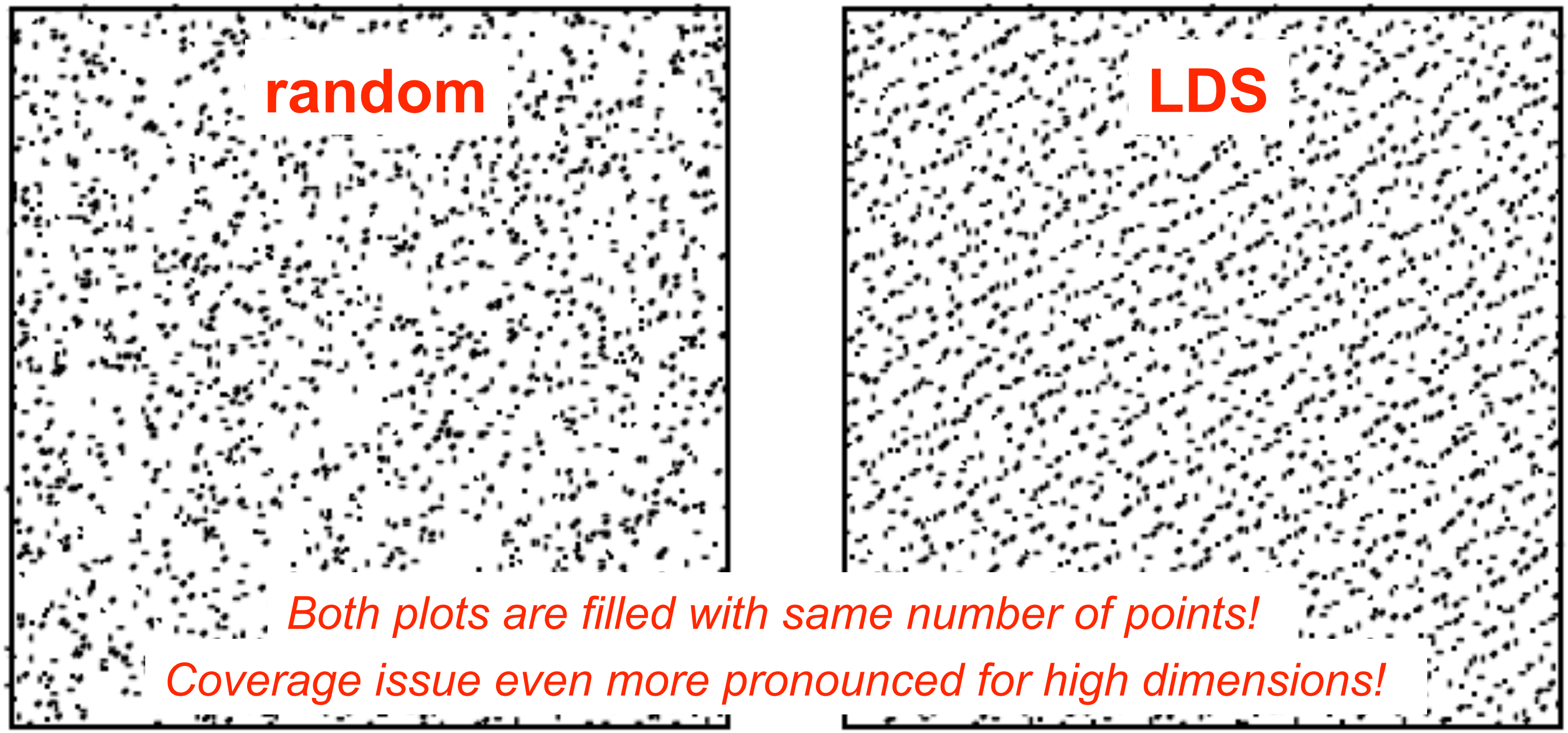


Both plots are filled with same number of points!

Coverage issue even more pronounced for high dimensions!

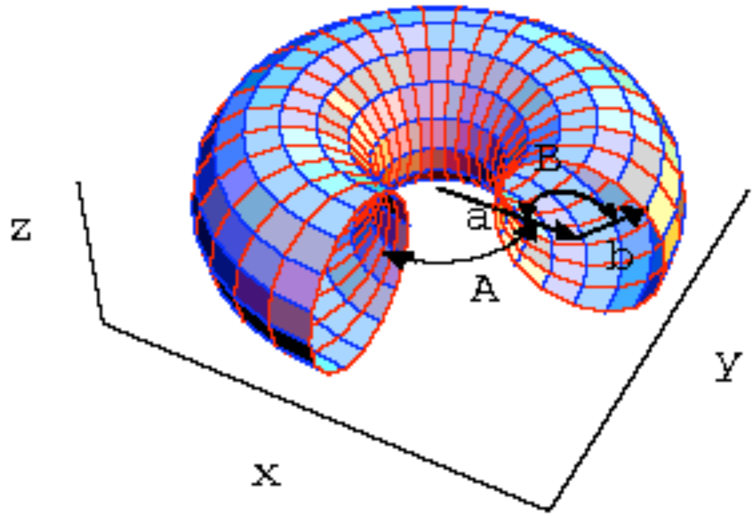
Numerical integration

- Convergence rate for pseudo-random numbers:
  - $\mathcal{O}(1/\sqrt{N})$ for $N \to \infty$
- Convergence rate for LDS:
  - $\mathcal{O}(1/N)$ for $N \to \infty$
    - where N is the number of points in $[0,1]^d$
- In other words, numerically evaluated integrals converge much faster with LDS:
  - Advantage grows with increasing required precision, i.e. with *N*

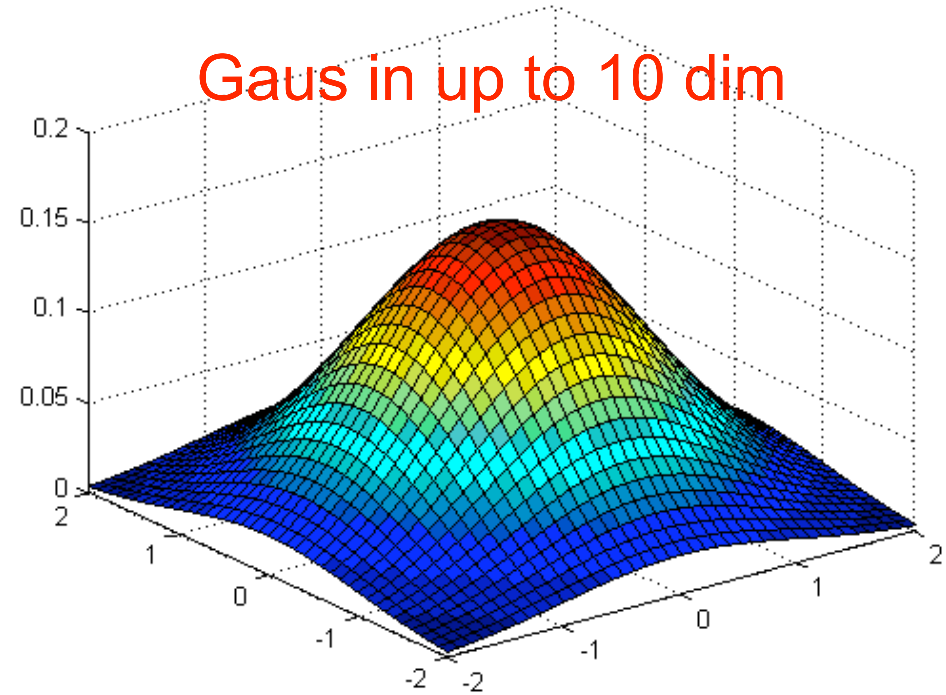
- Some remarks:
  - Don't confuse with integration on a lattice
    - On a lattice, need n^d samplings for a pitch $1/n$
  - Don't confuse with pseudo-random numbers
    - The low-descrepancy ***sequence*** is fully deterministic

- Applied both Sobol' and Niederreiter LDS
  - Evaluated performance using toy models:

Torus in 3 dim



Gaus in up to 10 dim



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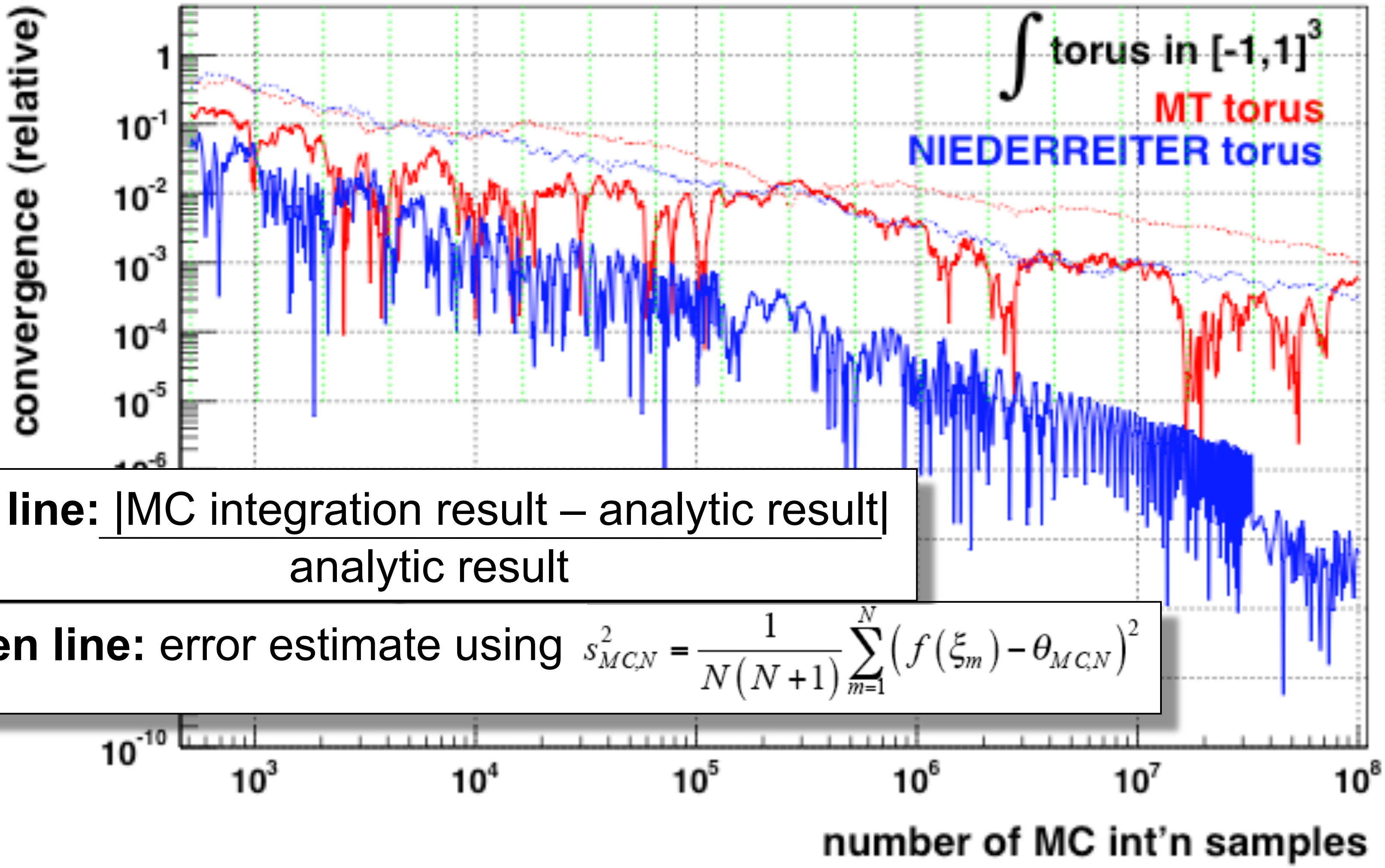
  - Evaluated performance using toy models:

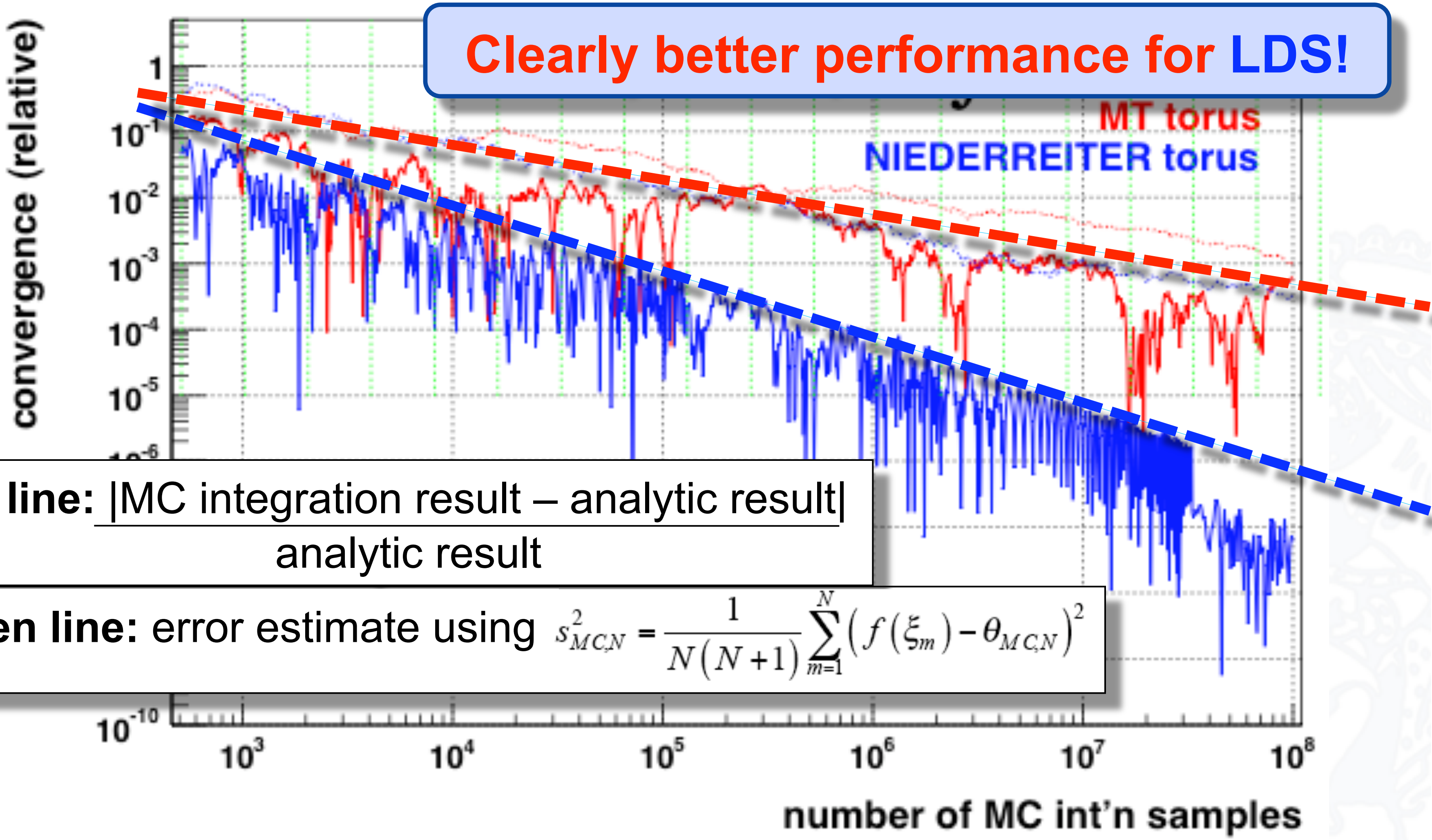


Solid line: $\frac{|\text{MC integration result} - \text{analytic result}|}{\text{analytic result}}$

Broken line: error estimate using $s^2_{MC,N} = \frac{1}{N(N+1)} \sum_{m=1}^{N} \left(f(\xi_m) - \theta_{MC,N} \right)^2$

- Applied both Sobol' and Niederreiter LDS
  - Evaluated performance using toy models:

Clearly better performance for LDS!



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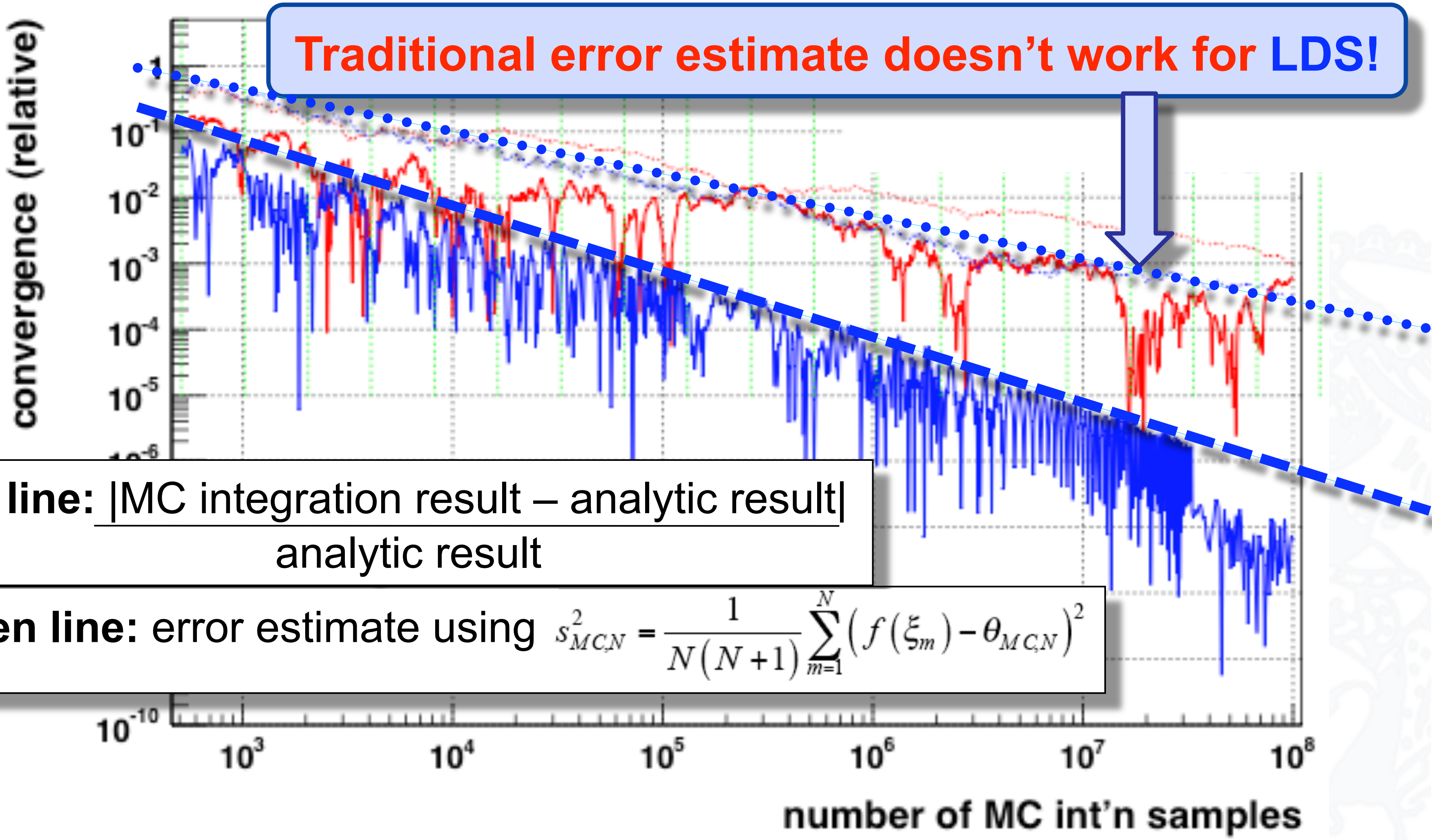
Broken line: error estimate using $s^2_{MC,N} = \frac{1}{N(N+1)} \sum_{m=1}^{N} \left(f(\xi_m) - \theta_{MC,N} \right)^2$

Numerical integration

- Applied both Sobol' and Niederreiter LDS
  - Evaluated performance using toy models:

Traditional error estimate doesn't work for LDS!

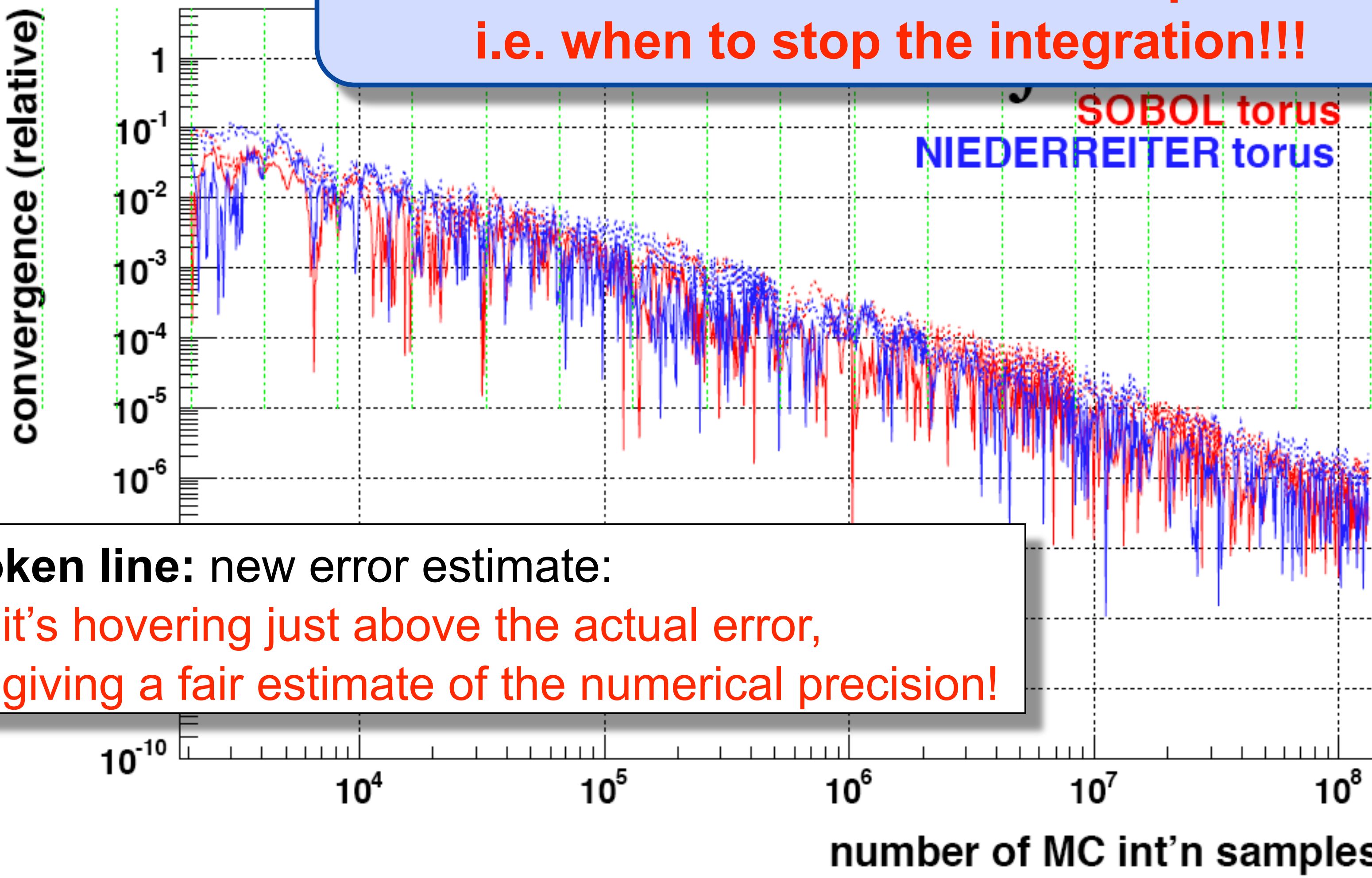


Solid line: $\frac{|\text{MC integration result} - \text{analytic result}|}{\text{analytic result}}$

Broken line: error estimate using $s^2_{MC,N} = \frac{1}{N(N+1)}\sum_{m=1}^{N}\left(f(\xi_m)-\theta_{MC,N}\right)^2$

Numerical integration

Now we have a good and precise tool to evaluate the achieved numerical precision, i.e. when to stop the integration!!!



Broken line: new error estimate:

it's hovering just above the actual error,
giving a fair estimate of the numerical precision!

Integration time reduced by one order of magnitude!

- The integration time per event for all permutations and all 25 x 21 (m_{top},k_{JES}) values is now 1.5 minutes
  - Used to be: 1.5 hours (on average)
- LDS universally usable for numerical integration
  - we use Sobol' LDS since its construction is computationally less intensive than Niederreiter)

Which m_{top} do we measure?

Which m_{top} do we measure?

- Generally, every method (MEM, templates, etc) has to be calibrated with MC simulations
  - This means that we are using the same m_{top} definition as in the MC used for calibration
  - Good news:
    - full NLO MC ~ available for tt decaying to dilepton final states (POWHEL, aMC@NLO)
      - Finite width of top quark is explicitly modelled in the propagators → can use m^{pole} (or m^{MSbar})
  - However, when using LO ME in the MEM estimator, we are sensitive to m as defined in our LO ME
    - If finite width effects are linearly correlated with our mass estimator, we can extract m^{pole} (or m^{MSbar}) as defined in the MC → needs to be checked
    - Otherwise need to go to higher orders also for ME in the MEM estimator → see next slides for technical issues

How much will we gain by going to NLO?

Gain from going to NLO?

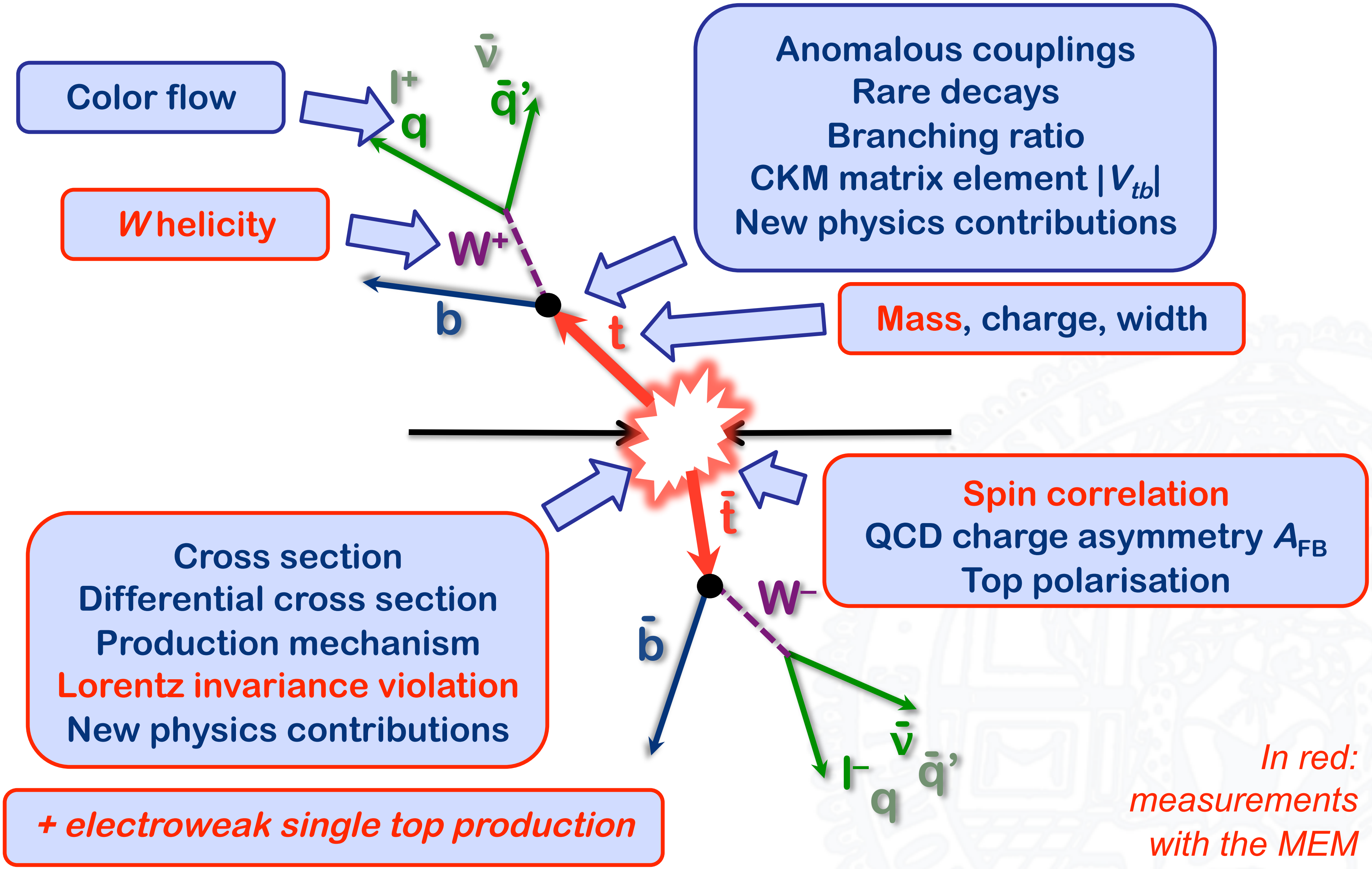
- Right now, we are using LO ME in the MEM, and thus only events with 4 jets
  - This introduces an inefficiency of about 10-20%
    - The inefficiency would be much larger at the LHC (~50%)
- With NLO ME, we could use events with 4 or 5 jets
  - This would recover the above inefficiency
    - For the TeVatron, marginal gain in statistical sensitivity
      - (unless this is necessary to extract well-defined mass)
  - The computational cost would be very high:
    - Consider “golden” l+jets final states:
      5 jets → 5! = 120 jet-parton assignments
      - Calculation time would increase up to a factor of 5x
      - This does not account for additional overhead due to longer calculation time of the NLO ME itself compared to LO (scaling linearly with the number of integral samplings)

Gain from going to NLO?

- My statement about the high numerical cost is highly process- and final state-dependent
  - E.g. for ttbar decaying into dilepton final states computation time would increase only by up to 3x
    - Probably even less if b-tagging information is considered
  - For processes decaying purely leptonically at tree level like WW → lnu lnu:
    - A jet from initial state radiation would be clearly identifiable as such
    - numerical cost would be only the additional time to calculate the NLO ME compared to LO ME

Other measurements using the MEM at the Tevatron

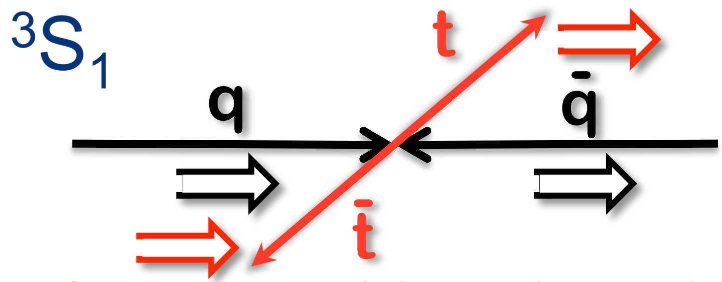
Top physics with MEM @ TeVatron



In red: measurements with the MEM

Spin correlations with the MEM

- $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s< hadronisation time
  - Decay products carry info about spin of tt system

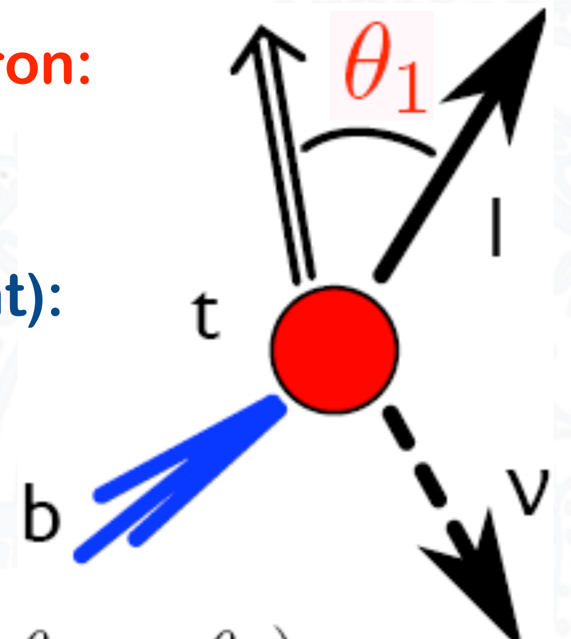


+ $^1S_0$ (15%)

  - In this form possible only at the Tevatron:
    - High qq fraction (LHC: ~10%)
    - production at threshold dominates
  - Correlation strength (frame dependent):

$$C = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\downarrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\downarrow\uparrow} + N_{\uparrow\downarrow}}$$

  - Analyse it using angular info:



$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

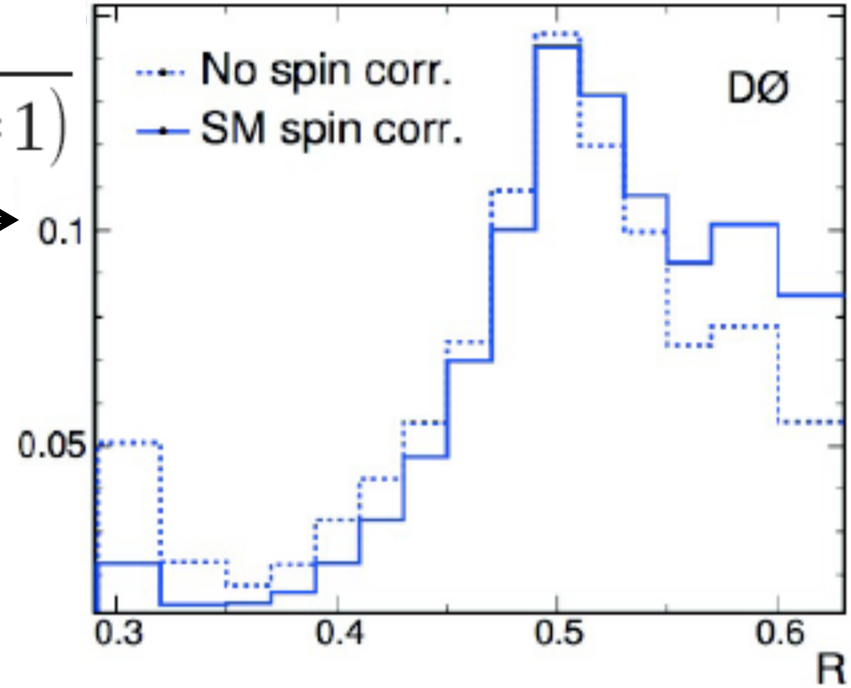
(for dilepton channel case)

Spin correlations with the MEM

- **How can we adapt the superior matrix element* (ME) technique for the spin correlation measurement?**
  - **Melnikov and Schulze (PLB 700, 17 (2011)):**

$$R(x)=\frac{P_{t\bar{t}}(x,H=1)}{P_{t\bar{t}}(x,H=0)+P_{t\bar{t}}(x,H=1)}$$

  - **Construct templates in R** →



  - **Observable:**
    - **Fraction of events with spin corr.:**

$$f=\frac{N_{t\bar{t}}(w./spin\,correlation)}{N_{t\bar{t}}(all)}$$

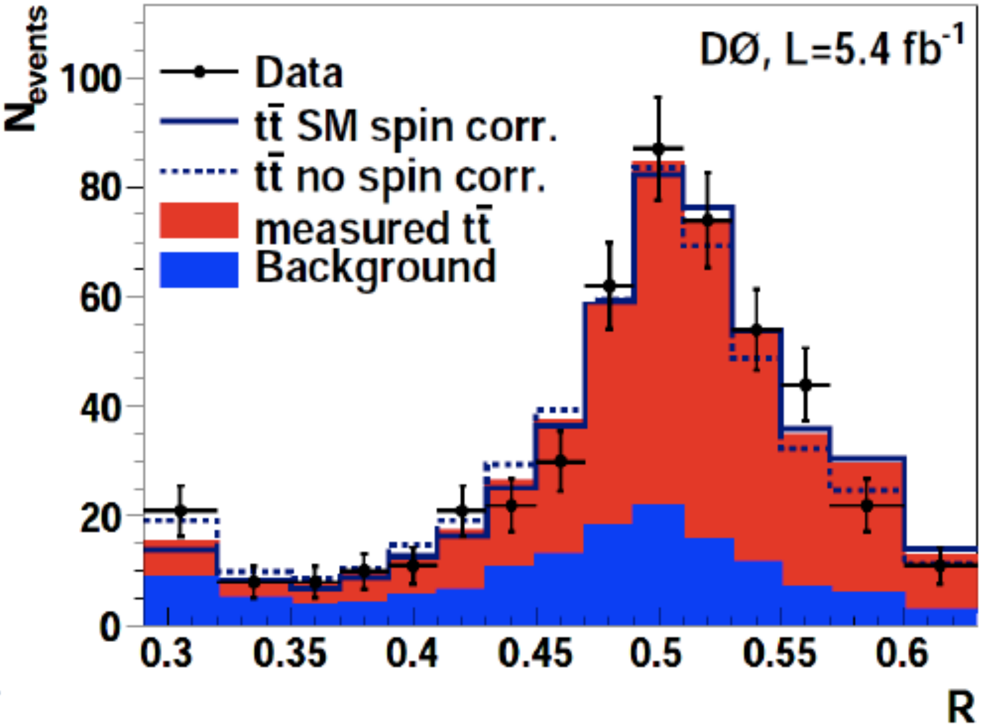
  - **Translates into C → $f * C_{SM}$**
    - **i.e. SM pred'n is f = 1**

Spin correlations with the MEM

- Take ME from Mahlon & Parke (PLB 411, 173 (1997)):

$$\sum |(M)|^2 = \frac{1+H}{2}\frac{g_s^4}{9} F\overline{F}(2-\beta^2 s_{qt}^2) - H\frac{g_s^4}{9} F\overline{F}\Delta$$

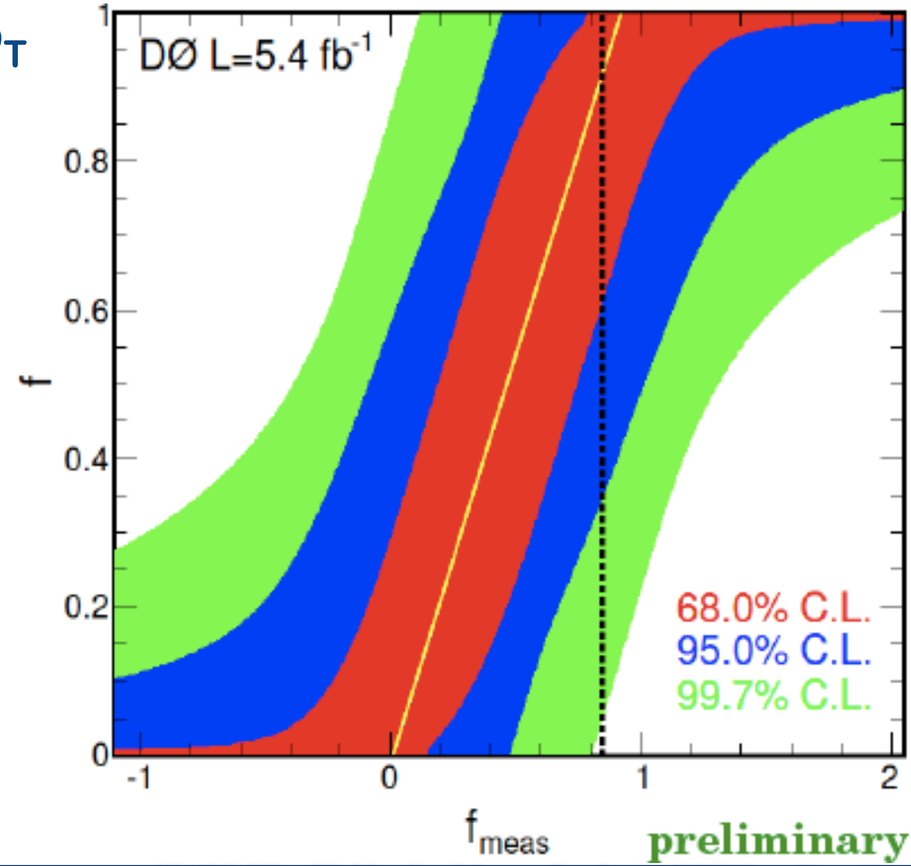
  - H=1: correlated spins
  - H=0: uncorrelated spins
- Perform measurement:
  - Dilepton channel
  - mc@nlo generator



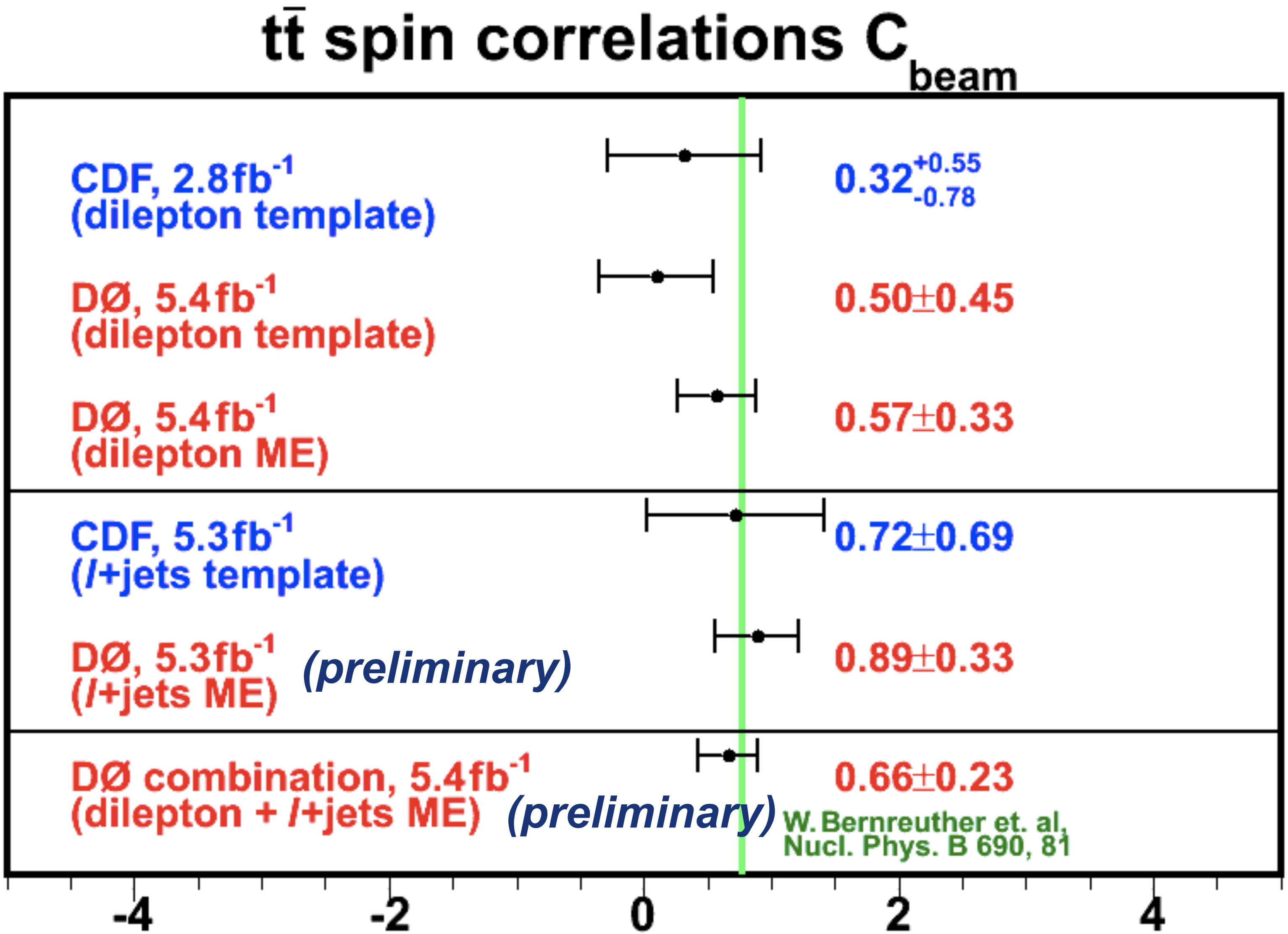
- We obtain:
  - f = 0.74 ± 0.41 (stat+syst)
  - f > 0.14 @ 95% CL
  - f=0 excluded at 97.7% CL (99.6% exp.)
    - 30% more sensitivity!
      - But still statistically dominated (0.27)

Spin correlations with the MEM

- Straight forward to extend the l+jets channel:
  - Same ME, mc@nlo as generator
  - Split in 4 and 4+ jet bins
  - Require two b-tags to reduce combinatorics (+ purity 90%)
  - Regard the other two hightest p_T jets as light jets
  - → four permutations
- Combine with dilepton result:
  - $f = 0.85 \pm 0.29$ (stat+syst)
  - $f < 0.34$ @ 95% CL
  - $f < 0.05$ @ 99.7% CL
  - f = 0 excluded @ 3.1 SD !!!
    - First evidence for non-vanishing spin correlations!



Spin correlations with the MEM



Other measurements with the MEM

- In the Higgs sector, there are few analyses which use the MEM:
  - ZH
  - WH
- No analyses using the MEM in:
  - New phenomena group
    - → MEM makes use of very precise predictions of new physics, which contradicts the idea of a general search
  - QCD group
    - → Most measurements are unfolded measurements, not clear how MEM can contribute
  - Electroweak group
    - → For W and Z physics we are not statistically limited
    - → For diboson production, the idea of MEM has never caught on

Measurements using the MEM at the LHC

Measurements with MEM @ LHC

- There are not many…
  - This is for several reasons:
    - Due to the typically large size of data samples the gain from using the MEM is not very big
    - Also due to the very successful start of the LHC is was simpler to wait for more data to gain sensitivity
    - It takes quite some time to set up a MEM analysis and validate it
- Now, during the technical shutdown, expect some MEM analyses to see the light…

Measurements with MEM @ LHC

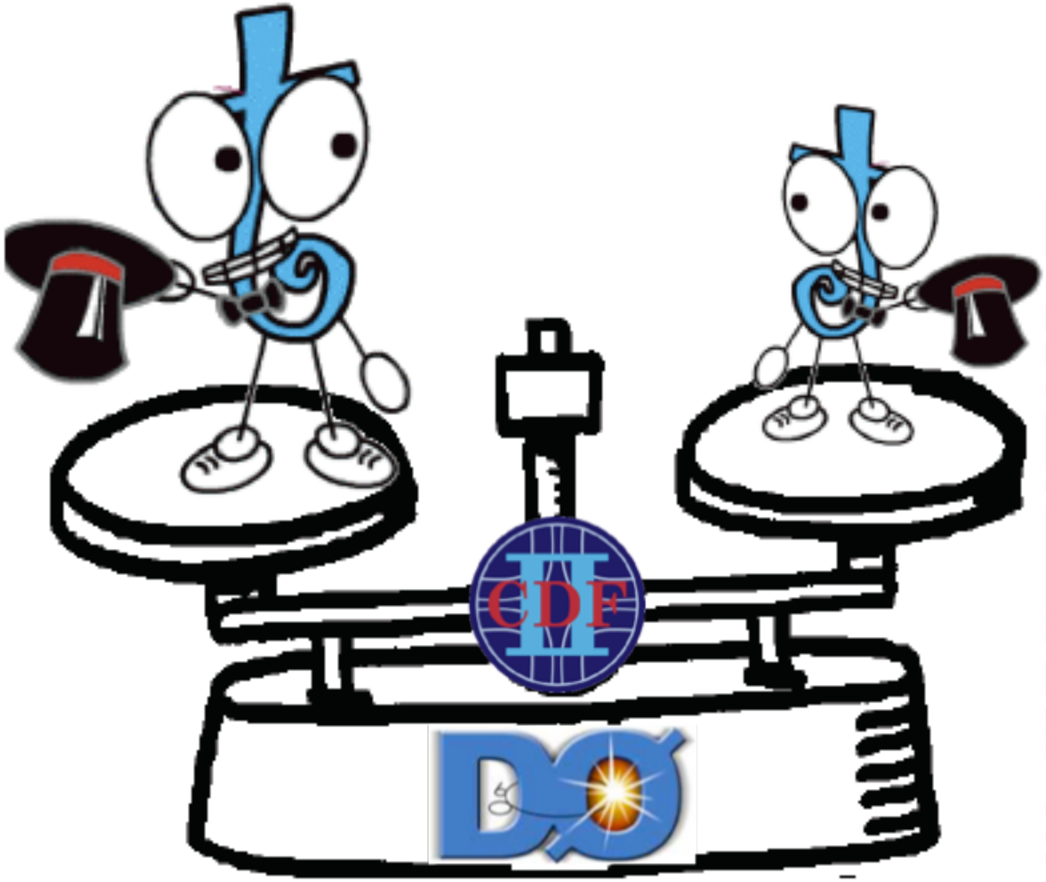
- In the top sector:
  - AFAIK, the only published analysis using MEM was the strong charge asymmetry measurement (ATLAS):
    - Use MEM to identify relevant jet-parton assignments
  - On CMS side: searches for stop with MEM (cf. talk Petra van Mulders)
- No MEM in SUSY/Exotics groups
- Several analyses in the Higgs group:
  - Both for ATLAS and CMS
  - The MEM could be used to further nail down the properties of the Higgs boson
    - Hope to enhance sensitivity to topological observables
      - Especially in not fully reconstructed final states
    - Several talks today/tomorrow
    - Sufficient manpower for quick analysis turn-around

Summary / Outlook

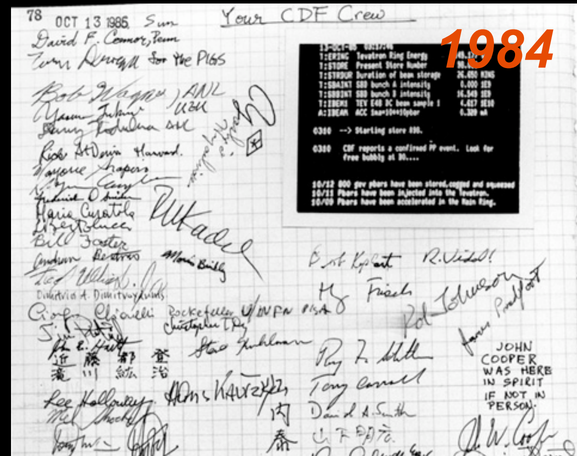
- MEM: particular advantage for low-statistics samples
  - it has been very successful in HEP since its first (published) implementation in 2004 to measure m_{top}:
    - Several analyses, mostly in the top sector, were using the MEM at the Tevatron, among others:
      - First observation of single top production
      - First evidence for non-vaninshing spin correlations between top and antitop quarks
    - Few analyses, mostly in the Higgs group, are using or planning to use the MEM at the LHC
- Main experimental challenge:
  - High computational demand
    - Need o(1M) of integral samplings per phase space point
    - Long turn-around, cannot publish if you are not first
    - Use of cutting-edge numerical techniques is imperative
    - Extensive and stable computing resources required


GAME OVER
... FOR THE TEVATRON (2011)

We are looking ahead to more exciting measurements from the Tevatron!




1983


OCT 13 1985 Sun
Your CDF Crew
1984
JOHN COOPER WAS HERE IN SPIRIT IF NOT IN PERSON

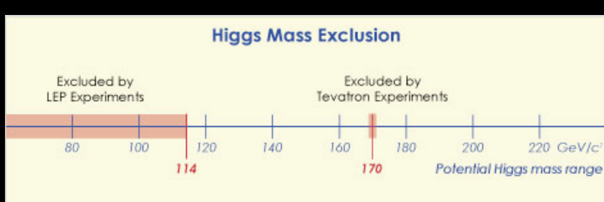

1985

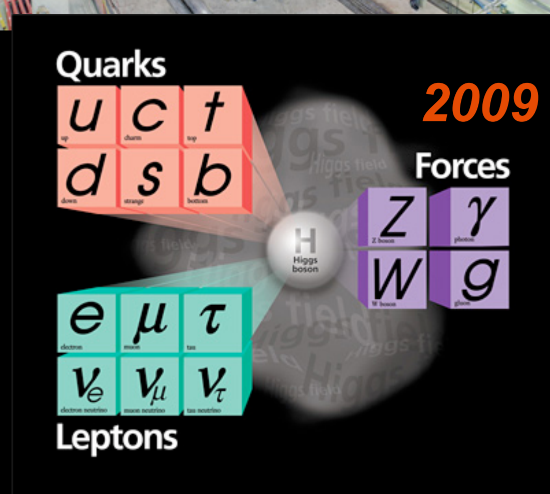

1991

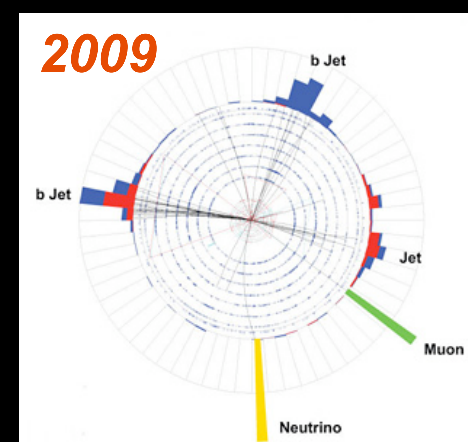

1992


1995
Cultura e Spettacoli
CORRIERE DELLA SERA
Dove vai, cacciatore di quark?
Laatste ontbrekende topquark lijkt ontdekt
Batavia is center of universe
Alles Quark, oder was?
I predatori del quark perduto
Nation
For physicists, last piece of a puzzle
RICERCA ITALIANA
Truth by Consensus

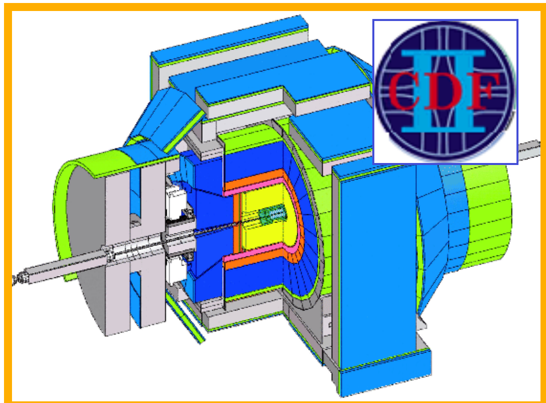
2008

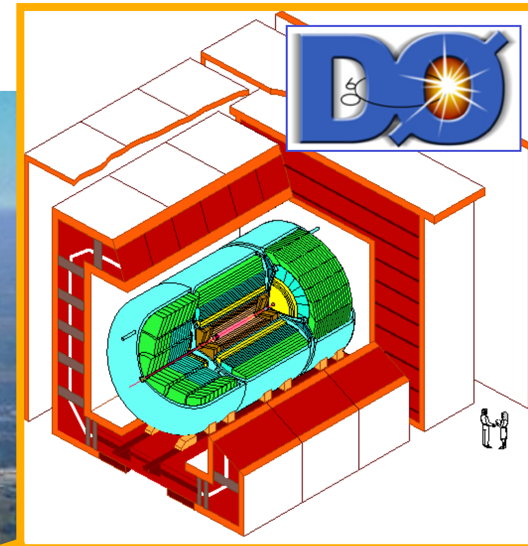

Higgs Mass Exclusion
Excluded by LEP Experiments
Excluded by Tevatron Experiments
80
100
120
140
160
180
200
220 GeV/c²
114
170
Potential Higgs mass range

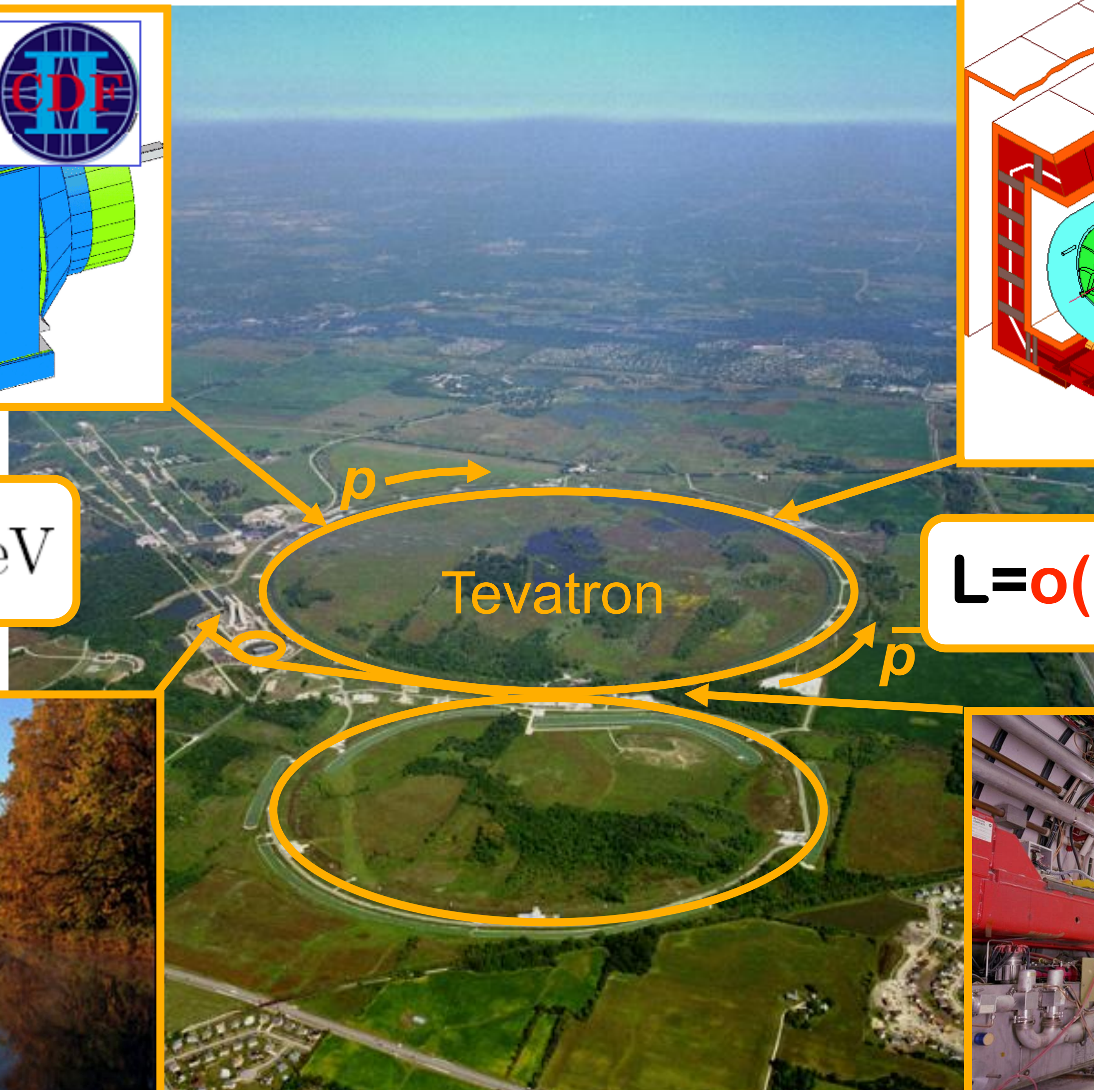

Quarks
u c t
d s b
2009
Forces
Z γ
W g
Higgs boson
e μ τ
νe νμ ντ
Leptons


2009
b Jet
b Jet
Jet
Muon
Neutrino

More about the top birth place…







$$\sqrt{s} = 1.96\,\mathrm{TeV}$$

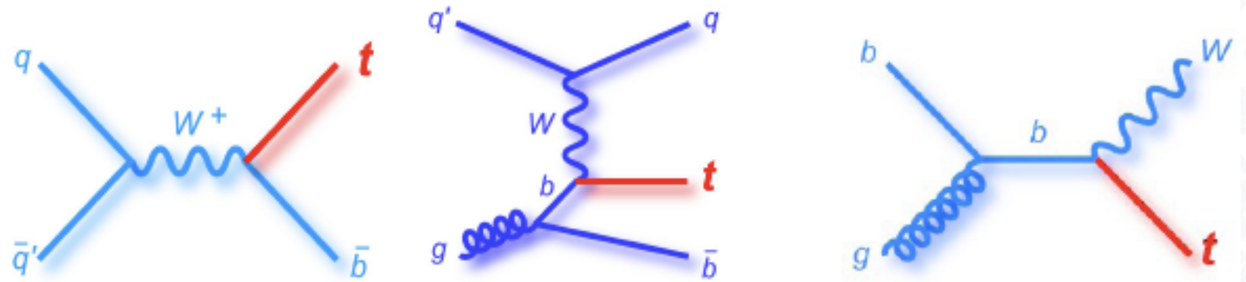
L=o(10 fb^{-1}) p.e.

Initial state @ Tevatron (and LHC)

- **Initial state for top-antitop pair-production rather different between Tevatron and LHC:**

Tevatron	LHC
$p\bar{p}$ initial state → *CP* eigenstate	pp initial state
centre-of-mass energy: 1.96 TeV	centre-of-mass energy: 7 (8) TeV
Initial state: qq (~85%), gg (~15%)	Initial state: qq (~25%), gg (~75%)

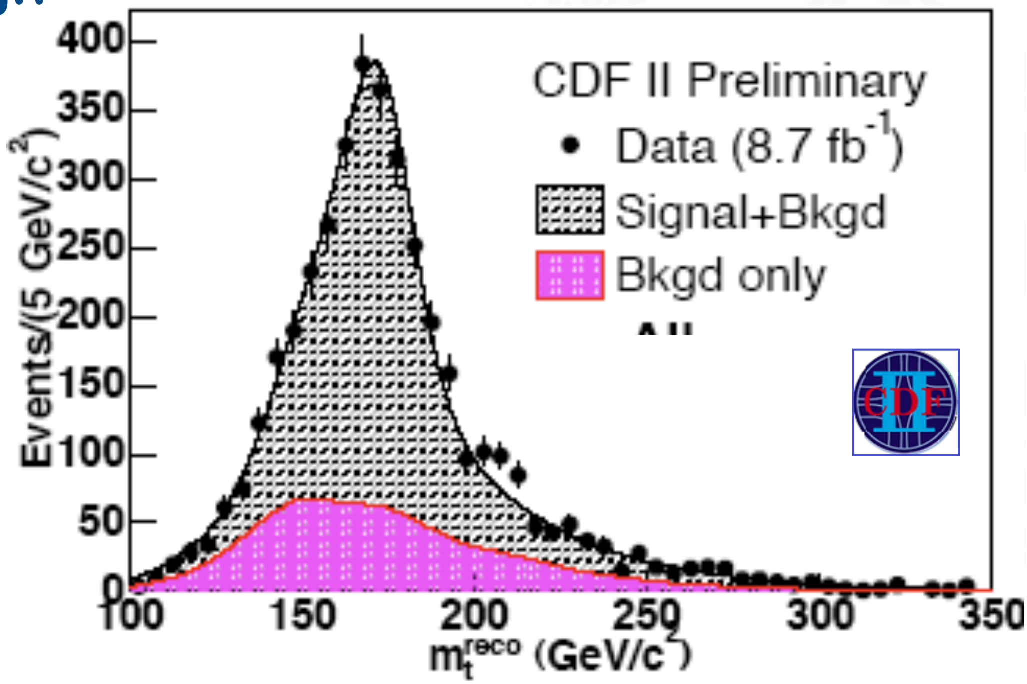
- **Dramatic differences for single top production:**



Collider	s-channel: σ_{tb}	t-channel: σ_{tqb}	Wt-channel: σ_{tW}
Tevatron: $p\bar{p}$ (1.96 TeV)	1.04 pb	2.26 pb	0.28 pb
LHC: pp (7 TeV)	4.6 pb	64.6 pb	15.7 pb

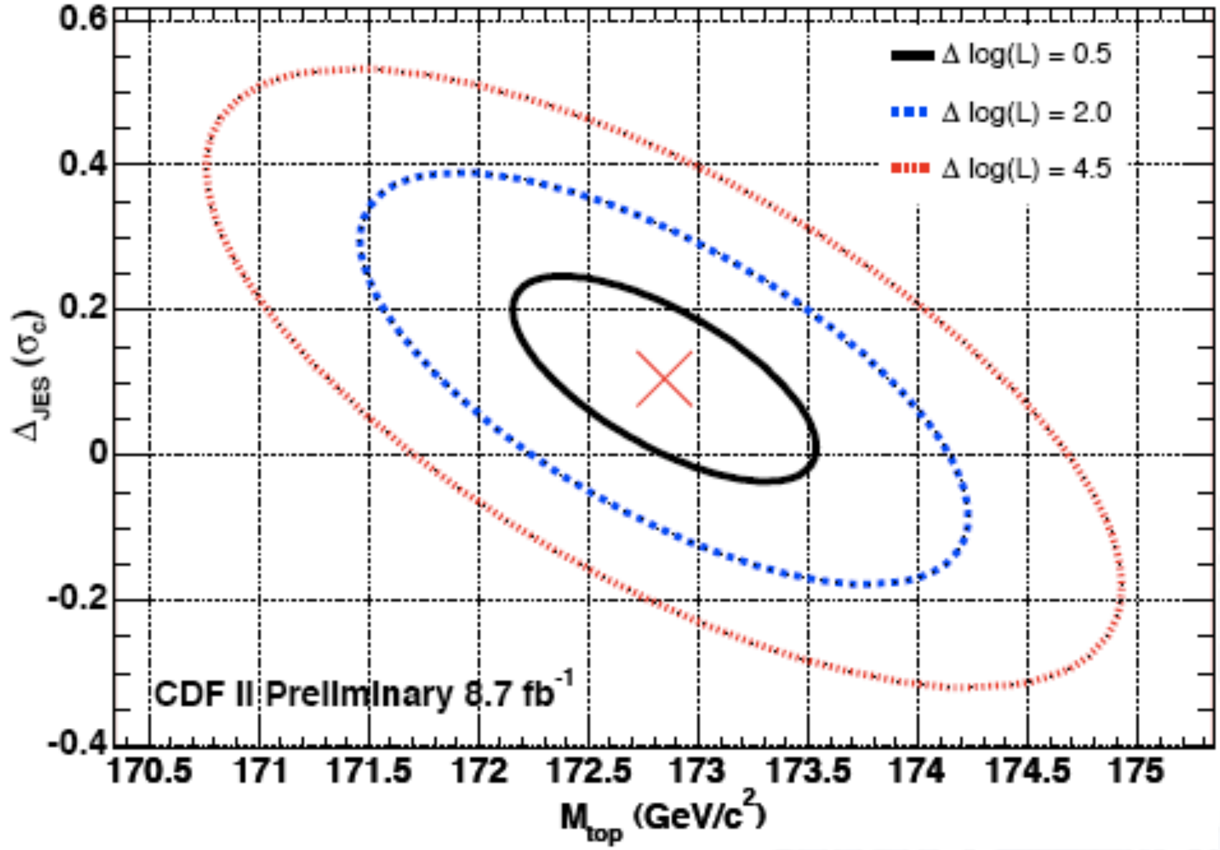
m_{top} with templates in l+jets

- Template method in lepton+jets final states, CDF (8.7 fb^{-1})
  - Reconstruct the event kinematics by minimising a χ^2-like quantity depending on e.g.:
    - matching between reconstructed and fitted momenta
    - *W* mass constraint for in-situ JES extraction
    - top quark mass constraint for m_{top} extraction
  - Consider jet-parton assignments consistent with b-tagging
  - Form templates from:
    - m_t^{reco} : best jet-parton assignment
    - $m_t^{reco(2)}$: second-best assignment
    - m_{jj}



Phys. Rev. Lett. **109**, 152003 (2012)

- **Final result:**



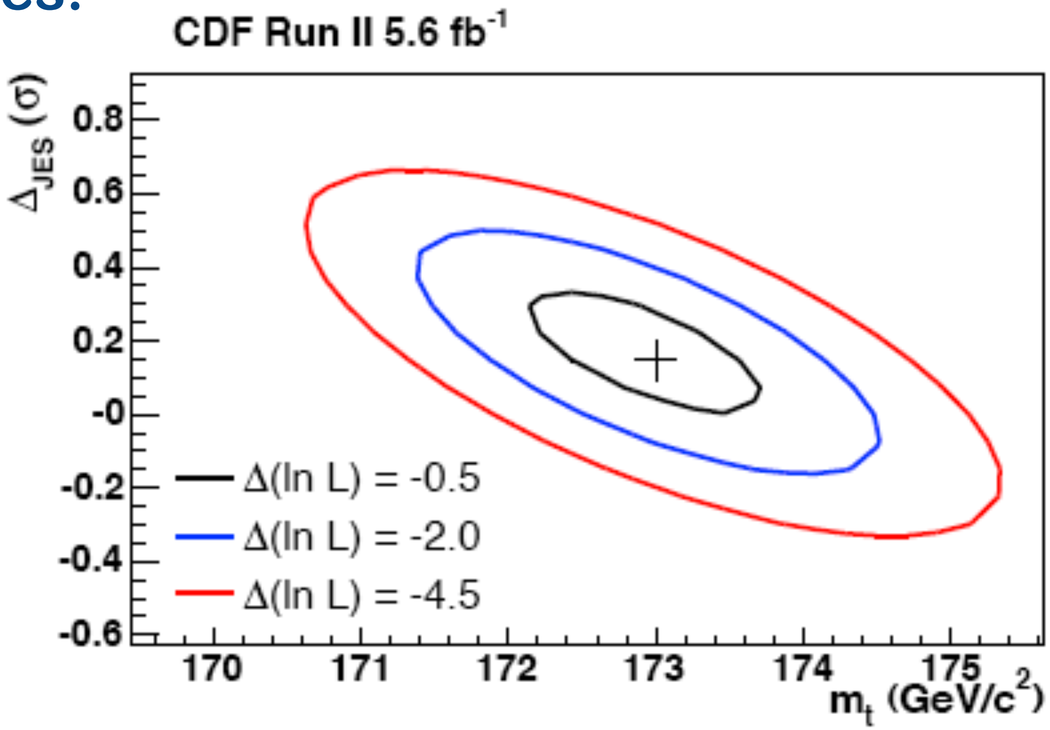
$$M_{top} = 172.85 \pm 0.71\ (\text{stat.}) \pm 0.84\ (\text{syst.})\ \text{GeV}$$

Most precise m_{top} measurement @ Tevatron

Phys. Rev. Lett. ***109****, 152003 (2012)*

m_{top} in lepton+jets channel at CDF

- **CDF's most precise measurement of m_{top} ($5.6\ fb^{-1}$):**
  - also done with the matrix element technique
  - no fundamental differences:
    - Angular resolution of calorimeter is included
    - A cut on the likelihood is introduced to further enhance the purity of the sample
    - No event-by-event background probability



$$m_t = 173.0 \pm 0.7\ (\text{stat.}) \pm 0.6\ (\text{JES}) \pm 0.9\ (\text{syst.})\ \text{GeV}$$

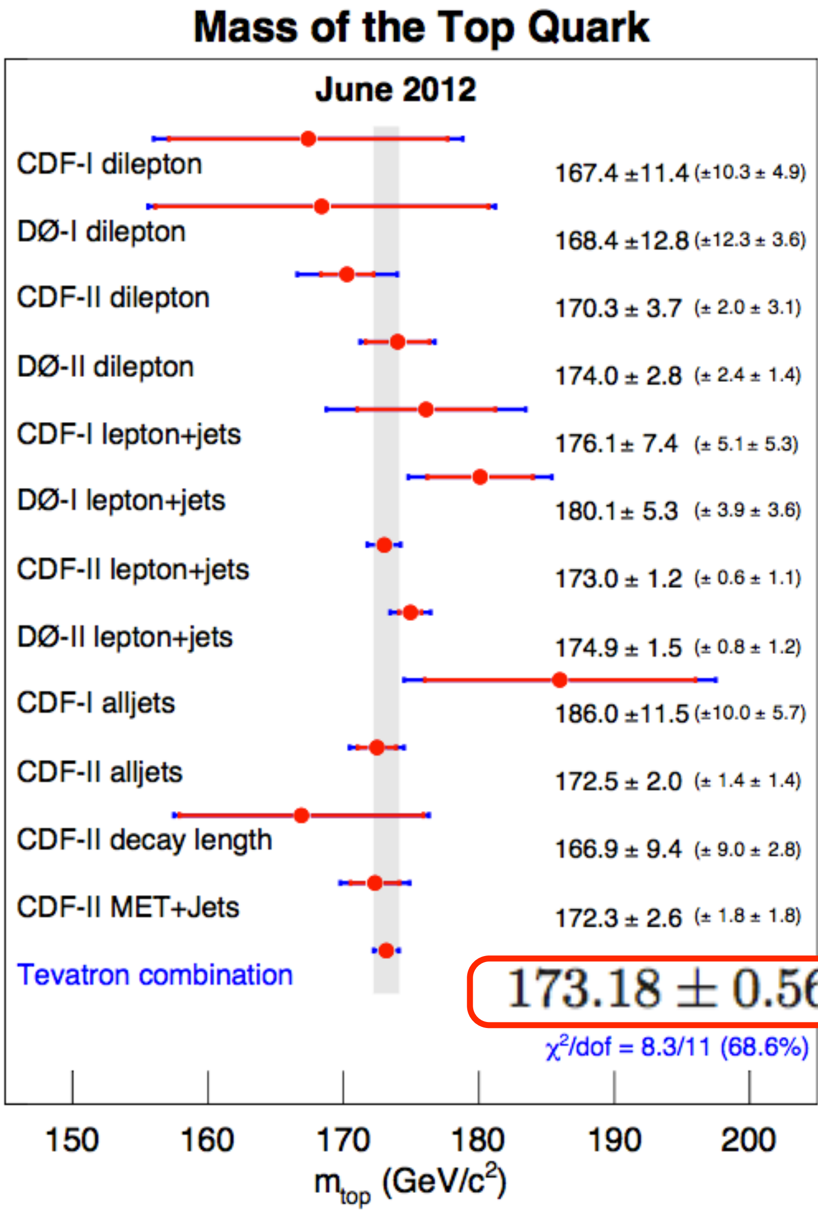
- Top mass in dilepton final states with, D0 (5.4 fb^{-1})
  - Dilepton final states provide a clean signature
    - Measure m_{top} in this clean experimental environment
    - Transfer the in-situ JES calibration from l+jets channel
      - Properly account for event topology, run period dependence, etc.
  - Extract m_{top} using:
    - Neutrino-weighting technique
    - Matrix Element technique
  - Properly combine the two methods (60% statistical correlation) to maximise statistical sensitivity!
  - Final result:

$$m_t = 173.9 \pm 1.9\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst})\ \mathrm{GeV}$$

Most precise m_{top} measurement in ll final states @ Tevatron!

Phys. Rev. D ***86****, 051103(R) (2012)*

Phys. Rev. D ***86***, *092003 (2012)*



$$173.18 \pm 0.56\,(\mathrm{stat}) \pm 0.75\,(\mathrm{syst})$$

Dominant uncertainties:

- In-situ JES calibration:
  - 0.39 GeV, ~ $1/\sqrt{N}$
- Residual JES calibration:
  - 0.19 GeV, ~ $1/\sqrt{N}$
- b quark jets energy scale:
  - 0.12 GeV, ~ √brain effort
- Signal modeling:
  - 0.51 GeV, ~ √brain effort

World's **most precise m_{top} measurement!**

Relative uncertainty: 0.54%

Top-antitop mass difference meas't

- CPT invariance is a necessary prerequisite for a locally Lorentz-invariant QFT
  - An established CPT invariance would be the end of not only the SM itself, but its theoretical footing!
- If $M_{particle}$!= $M_{antiparticle}$ → CPT violated!
  - We have never tested this on a bare quark (status 2yrs ago)
- The top quark is the only known quark where this test is possible:
  - Hadronisation time scale >> $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s
- First result (D0, 1 fb^{-1}):

PRL 103, 132001 (2009)

$$\Delta m_t = 3.8 \pm 3.4(\text{stat}) \pm 1.2(\text{syst})\ \text{GeV}$$

- First result from CDF (5.4 fb^{-1}):

PRL 106, 152001 (2011)

$$\Delta m_t = -3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})\ \text{GeV}$$

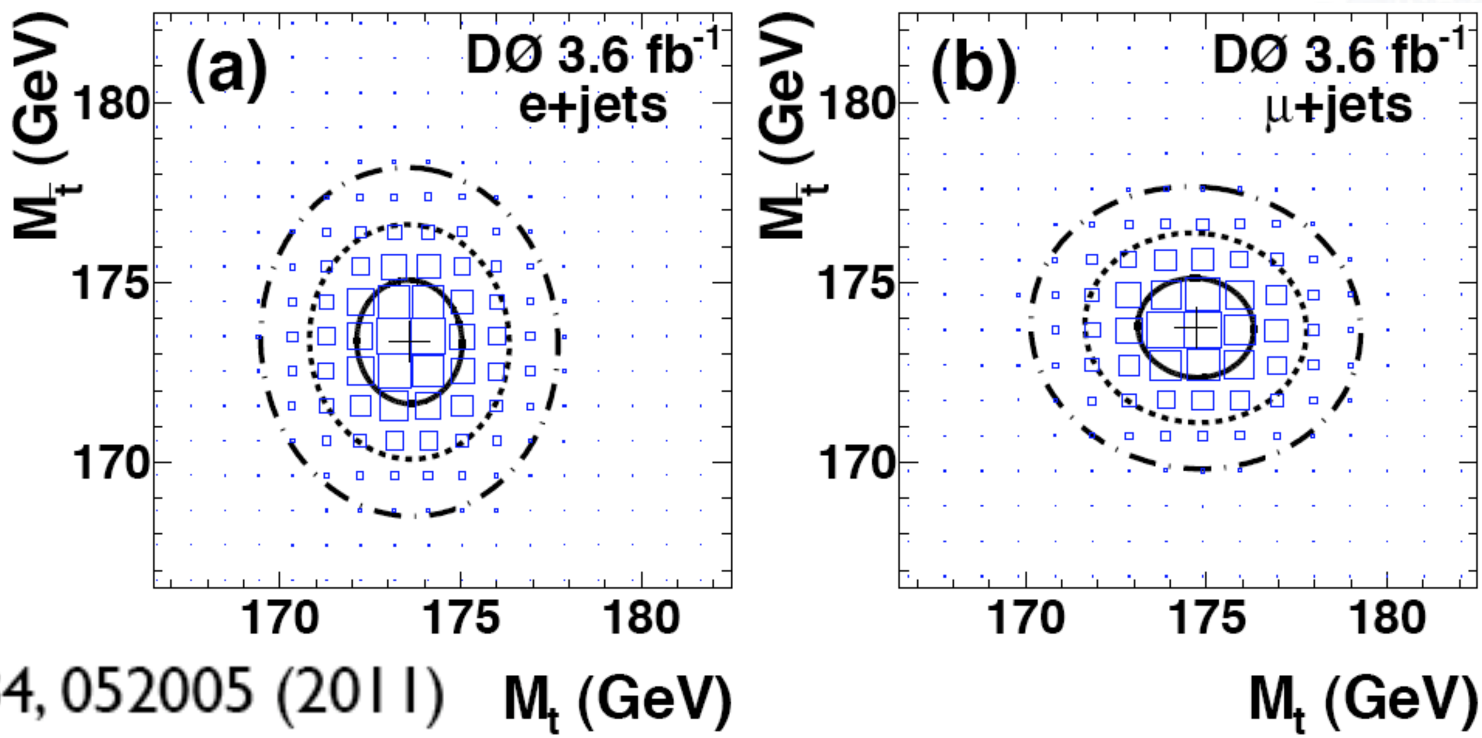
  - → 2 SD effect?

Top-antitop mass difference (D0)

- Use the most statistically sensitive technique – ME
  - $P(m_{top},k_{JES}) \rightarrow P(m_t,m_{tbar})$
    - Direct and indepentent measurement of m_t and m_{tbar}!
  - Use lepton charge to tag t and tbar:

$$\Delta m_t = 0.8 \pm 1.8(stat) \pm 0.5(syst)\ GeV$$

Relative precision: ***1%***



PRD 84, 052005 (2011)

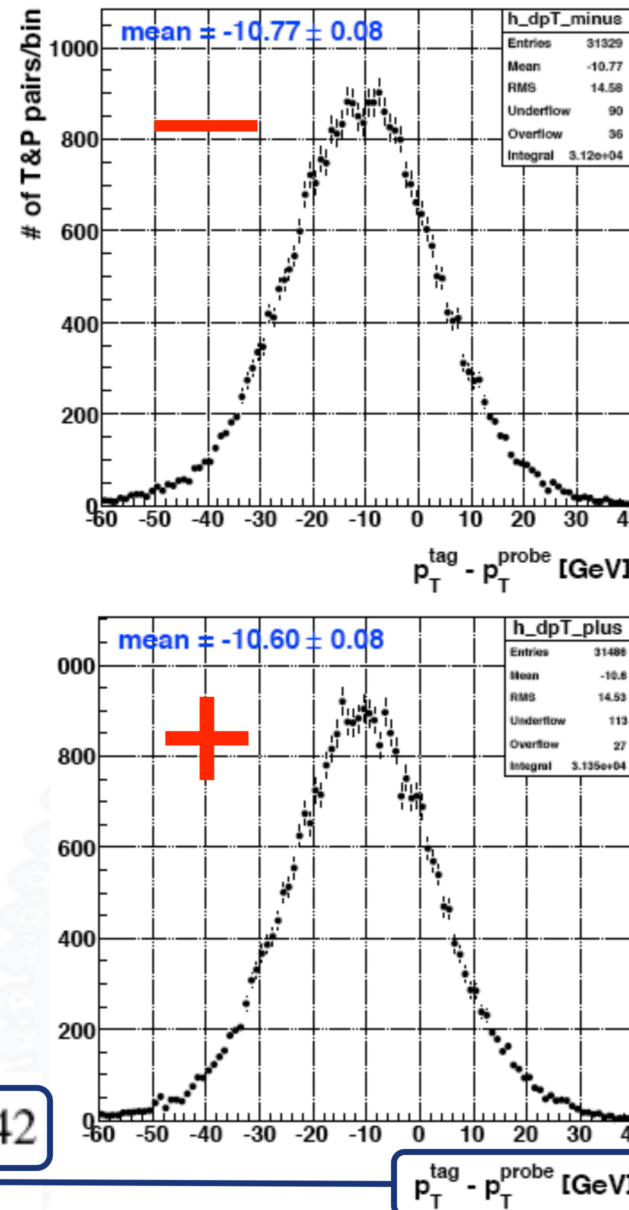
Top-antitop mass difference (D0)

- **Lots of work went into evaluating systematics this precision meas't**

Source	Uncertainty on Δm (GeV)
Modeling of detector:	
Jet energy scale	0.15
Remaining jet energy scale	0.05
Response to b and light quarks	0.09
Response to b and $\bar{b}$ quarks	0.23
Response to c and $\bar{c}$ quarks	0.11
Jet identification efficiency	0.03
Jet energy resolution	0.30
Determination of lepton charge	0.01
ME method:	
Signal fraction	0.04
Background from multijet events	0.04
Calibration of the ME method	0.18
Total	0.47

fractional response difference

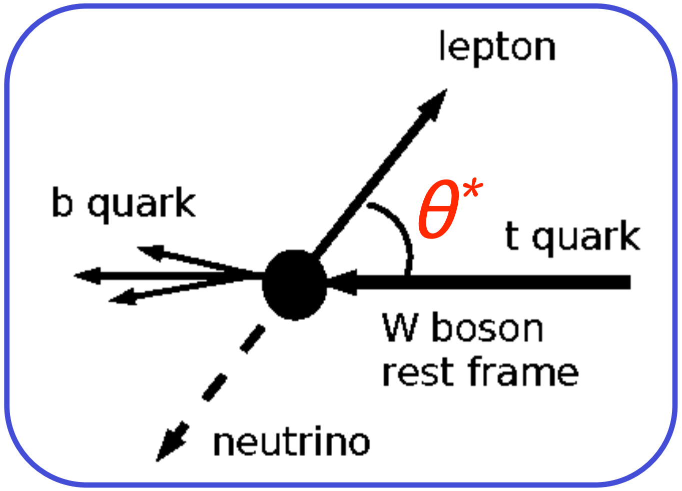
$$f_{\Delta\mathscr{R}} \equiv \frac{\Delta\mathscr{R}}{\langle 1/2 \cdot (p_T^{tag} + p_T^{probe}) \rangle} = 0.0042$$

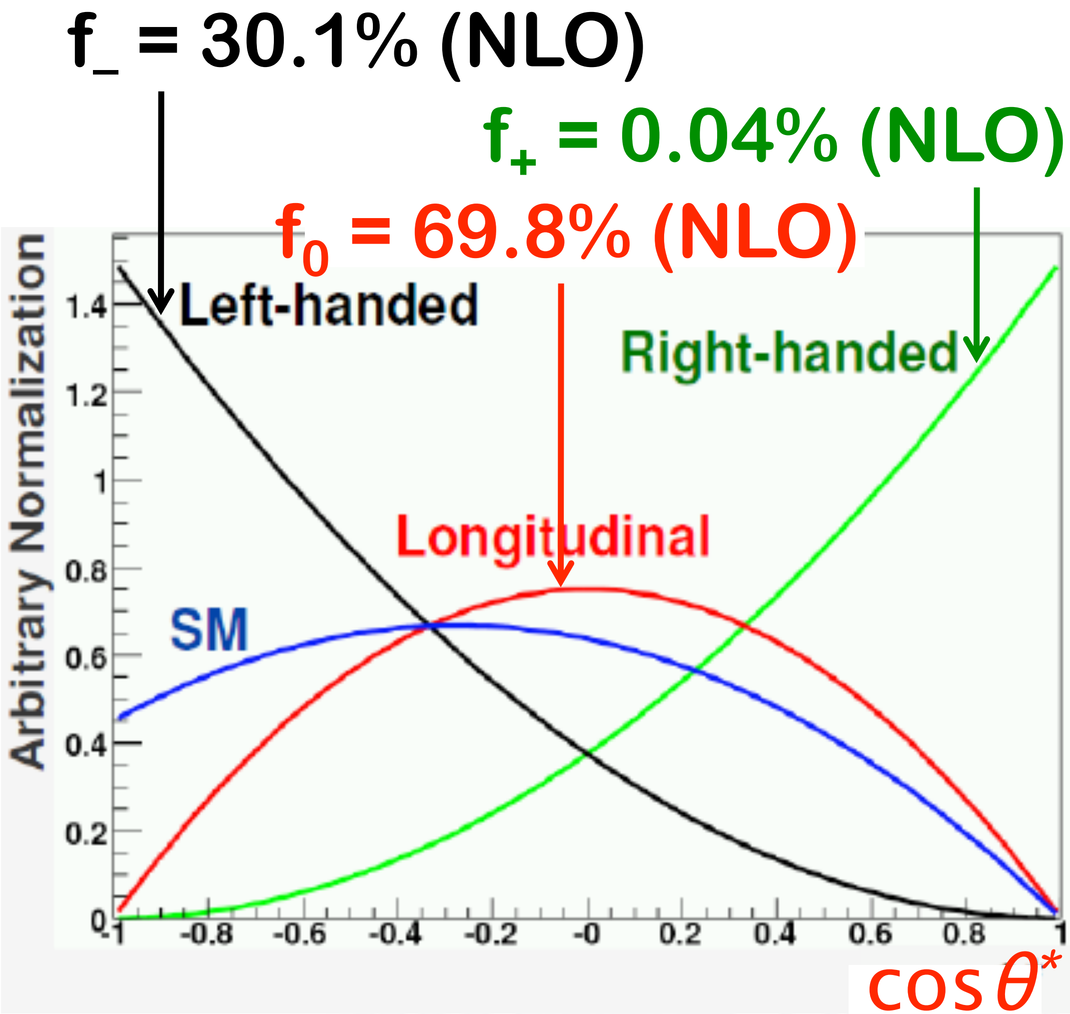


Use soft leptons to tag b and bbar jets

W boson helicity

- Study the *V-A* nature of the *Wtb* coupling
  - Deviations from SM would indicate new physics





- **W helicity measurement in l+jets, CDF (8.7 fb^{-1}):**
  - Use the **matrix element** technique
    - Include not only the cosθ^* of the leptonic *W* decays, but **also in the hadronic decays** despite the sign ambiguity!
  - Extract the polarisation fractions by maximising the LH:

$$L(f_0, f_+, C_s) = \prod_{i=1}^{N}[C_s \frac{P_s(x; f_0, f_+)}{\langle A_s(x; f_0, f_+)\rangle} + (1 - C_s)\frac{P_b(x)}{\langle A_b(x)\rangle}],$$

  - The clue:
    - Use the **LO matrix-element**

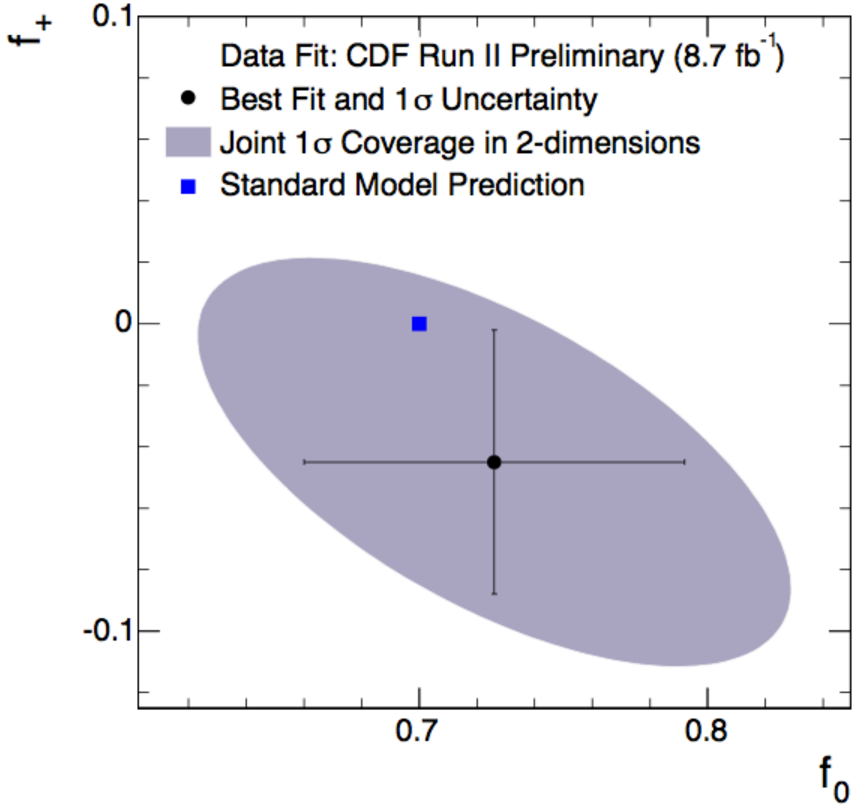
$$|M|^2 = \frac{g_s^4}{9} F_\ell \bar{F}_h (2 - \beta^2 \sin^2\theta_{qt})$$

      - to express P_{sig}
      - to introduce the dependence on the *W* boson polarisation!

$$F_\ell = \frac{2\pi g_W^4 m_{\bar{\ell}\nu}^2}{3 m_t \Gamma_t}(2E_b^{*2} + 3E_b^* m_{\bar{\ell}\nu} + m_b^2)(\frac{3}{8}(1 + \cos\theta^*)^2 f_+$$
$$+ \frac{3}{4}(1 - \cos^2\theta^*) f_0 + \frac{3}{8}(1 - \cos\theta^*)^2 (1 - f_0 - f_+)).$$

CDF Note 10855

- **Final result:**

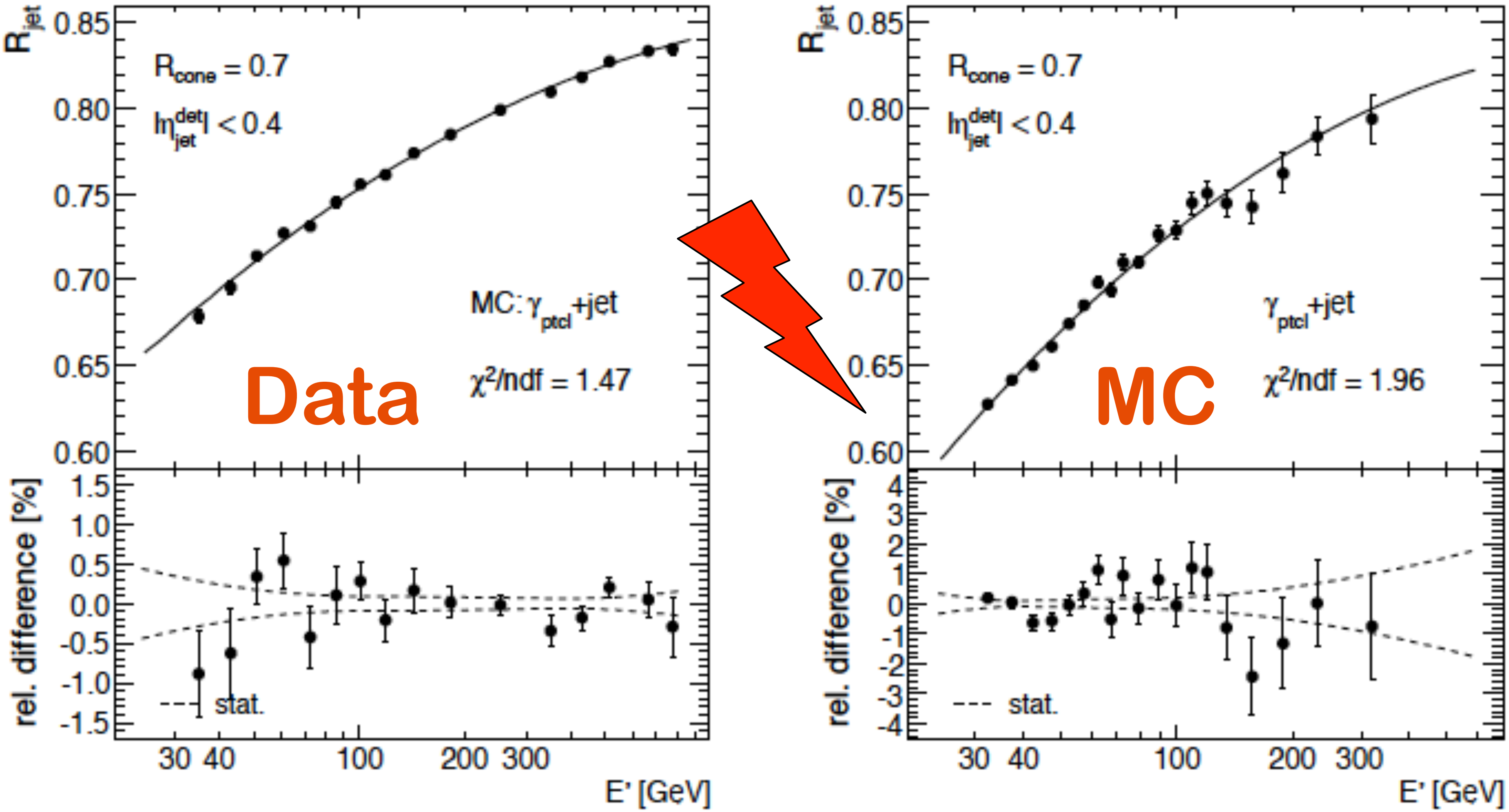


$$f_0 = 0.726 \pm 0.066(\text{stat}) \pm 0.067(\text{syst})$$
$$f_+ = -0.045 \pm 0.043(\text{stat}) \pm 0.058(\text{syst})$$

CDF Note 10855

Single particle response correction

- Compare calorimeter response after JES calibration and all default corrections:



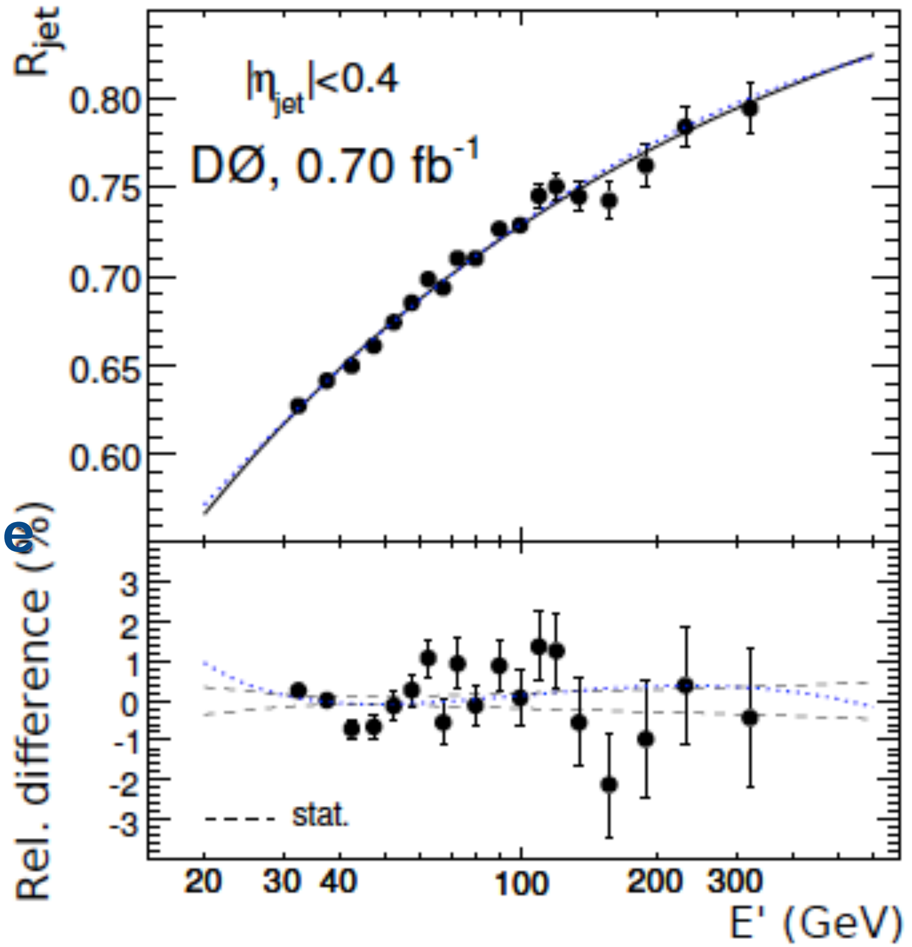
Single particle response correction

- Derive a correction for particle jets matched to reconstructed jets in MC:

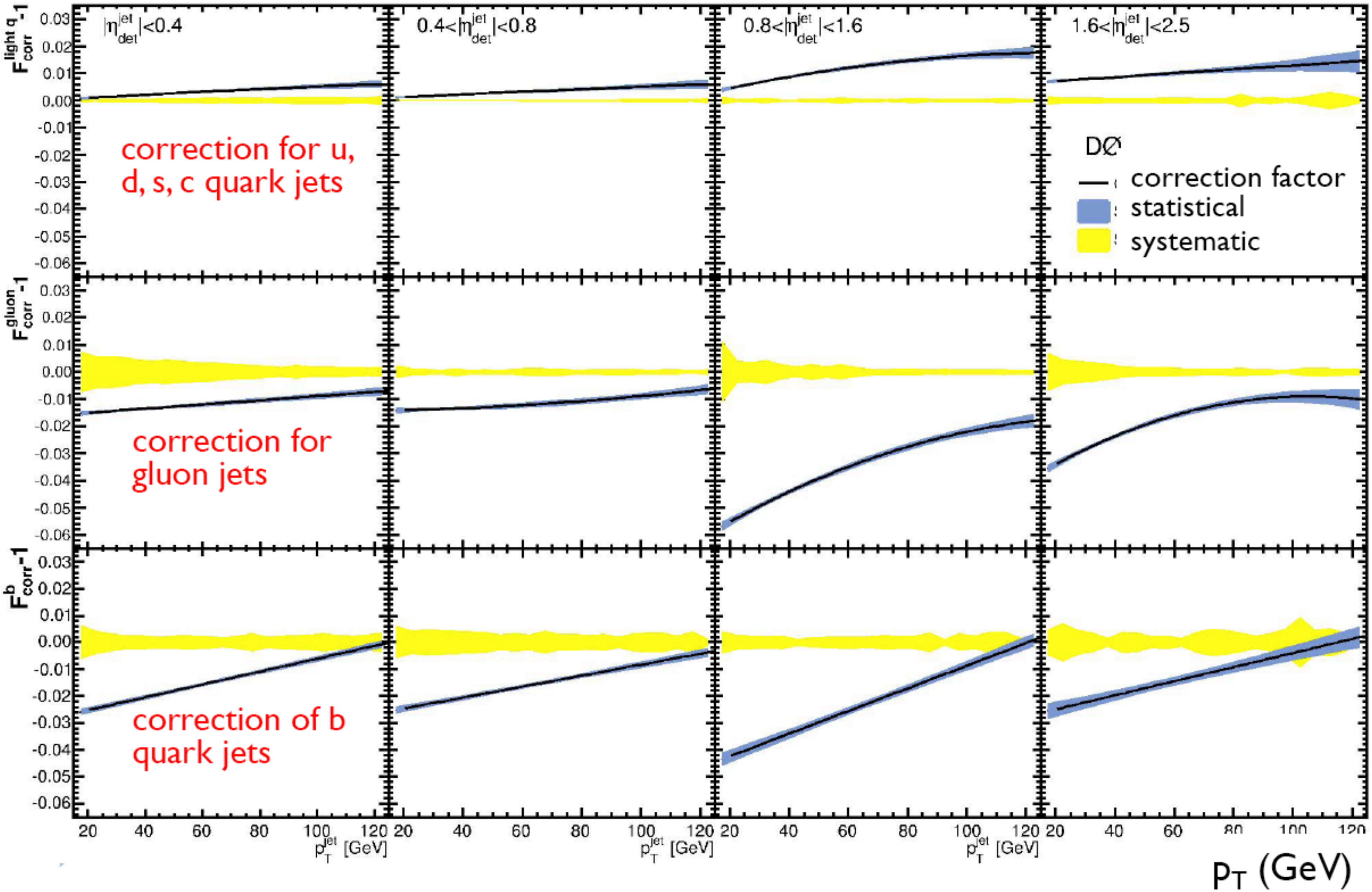
$$F^{corr} = \frac{\sum_i E_i^{true}(\text{particle}) \cdot R_i^{data}}{\sum_i E_i^{true}(\text{particle}) \cdot R_i^{MC}}$$

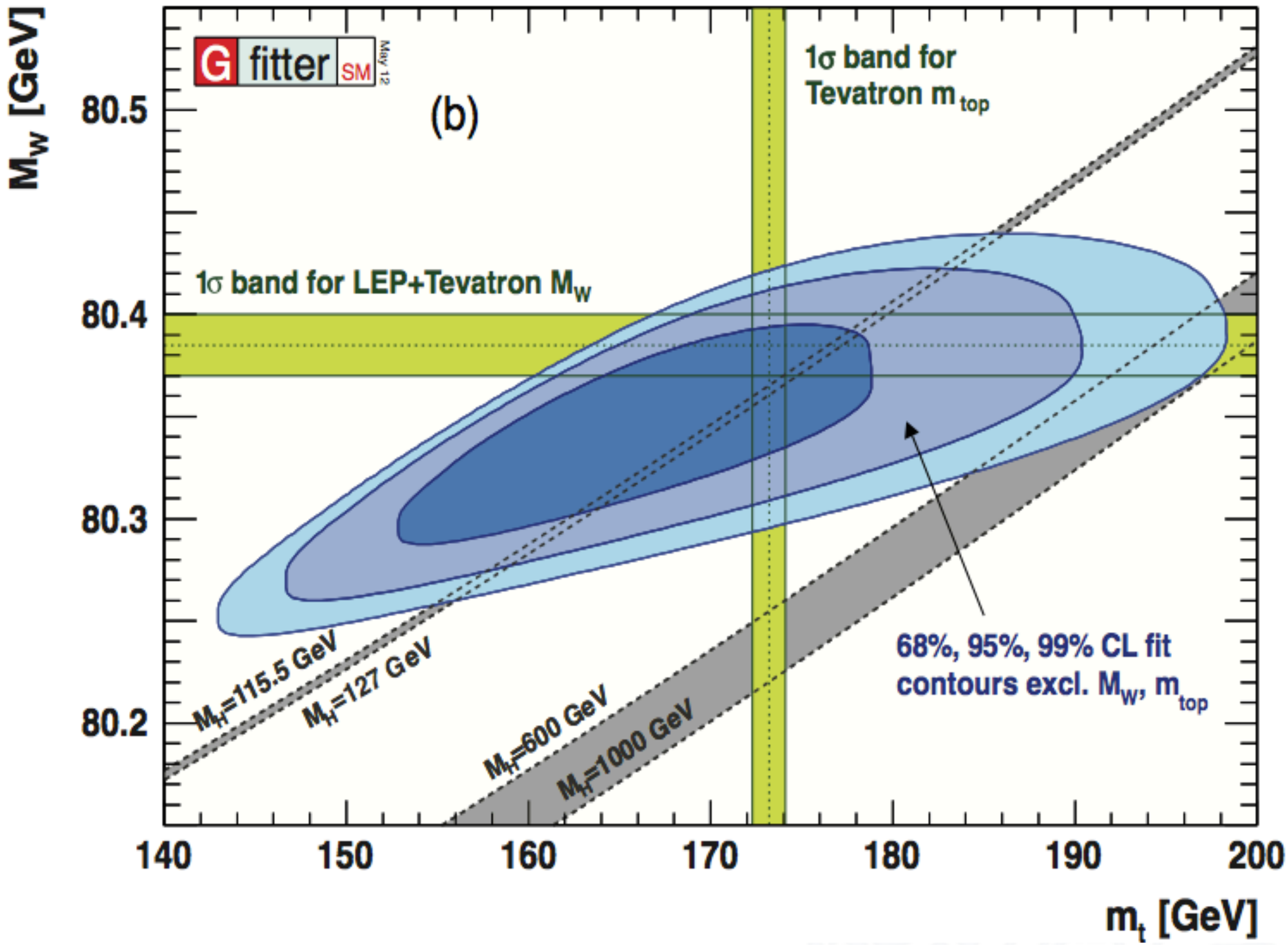
  - Sum runs over all particles
  - $R_i \rightarrow$ single particle response
  - R_i(particle type, E_{part}, eta_{part})
- Correct the MC:

$$E_{jet}^{corr} = F^{corr} \cdot (E_{jet}^{raw} - E_O)$$



Single particle response correction




G fitter SM
May 12
(b)
1σ band for
Tevatron m top
1σ band for LEP+Tevatron M W
80.5
80.4
80.3
80.2
M W [GeV]
140
150
160
170
180
190
200
m t [GeV]
M H=115.5 GeV
M H=127 GeV
M H=600 GeV
M H=1000 GeV
68%, 95%, 99% CL fit
contours excl. M W, m top

Challenges for ME in l+jets @ D0

2 initial state partons 6 final state particles	24 degrees of freedom
Assume perfectly measured angles: - for the four jets - and the lepton	10 constraints
Conservation of energy and momentum	4 constraints

24 – 14 = 10 integration variables

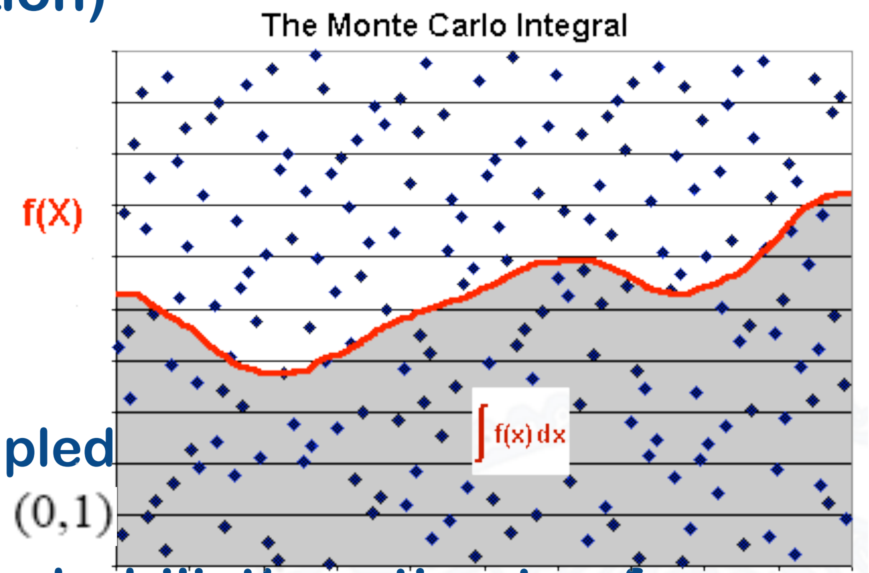
$d\rho$	energy of jet 1	
$dm_1^2 dm_2^2$	top masses	chosen for computational efficiency due to 4 B.W.'s
$dM_1^2 dM_2^2$	W masses	
$d\rho_l$	lepton energy	
$dq_1^x dq_1^y dq_2^x dq_2^y$	transverse momenta of initial state partons	

MC integration

- (don't confuse with MC simulation)
- Basic idea:
  - Approximate $\theta = \int_0^1 f(\alpha)\,\mathrm{d}\alpha$ as:

$$\theta_{MC,N} = \frac{1}{N}\sum_{m=1}^{N} f(\xi_m)$$

    - Here ξ_m are randomly sampled from uniform distribution in $(0,1)$



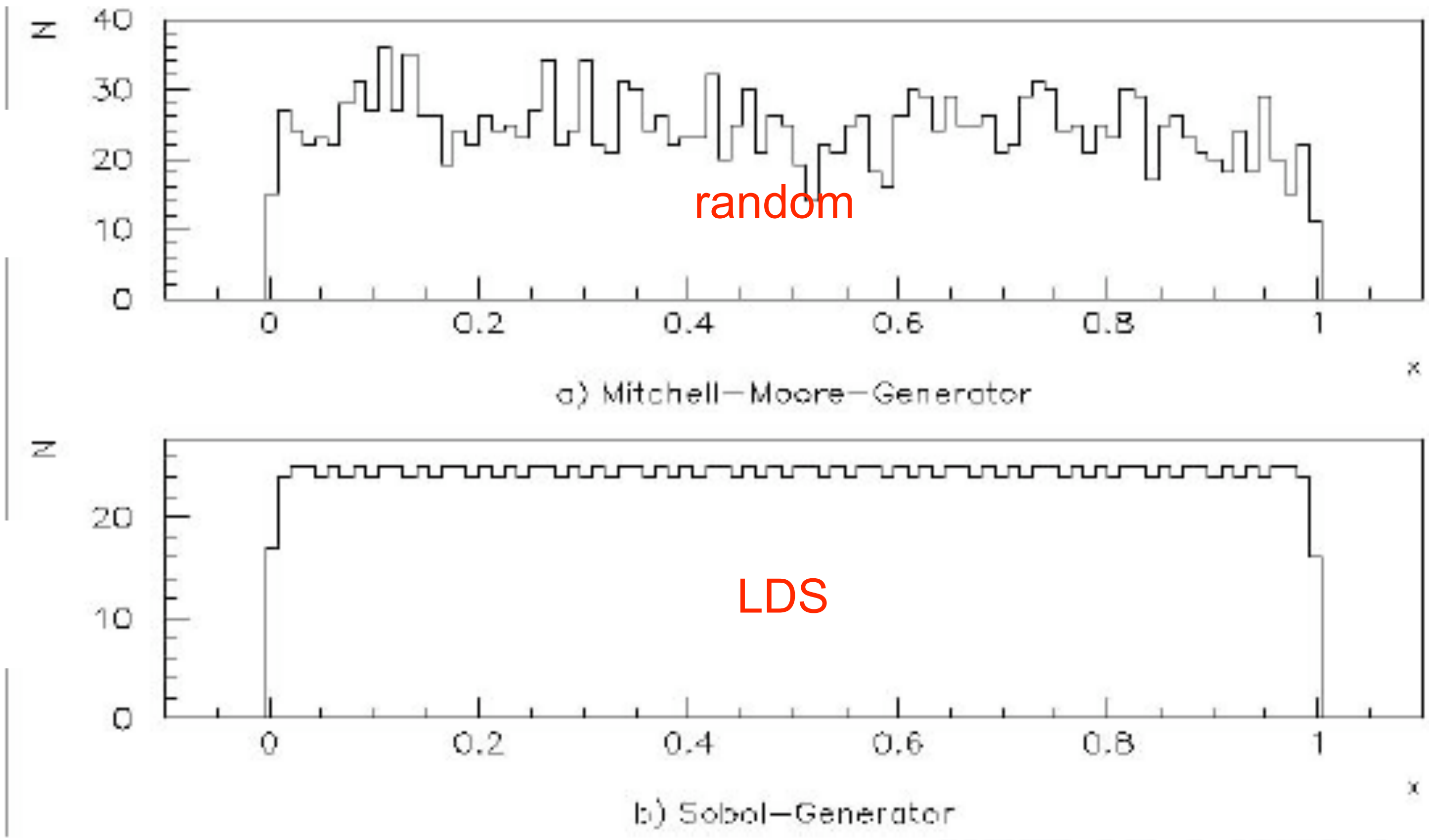
  - Use standard deviation as probabilistic estimate of integration uncertainty:

$$s^2_{MC,N} = \frac{1}{N(N+1)}\sum_{m=1}^{N}\left(f(\xi_m) - \theta_{MC,N}\right)^2$$

  - → Convergence rate is porportional to: $1/\sqrt{N}$
    - This means: to decrease error by a factor of 10, one needs 100x more MC sampling points ξ_m → CPU-expensive!

LDS for MC integration

- Random sampling of the unit hypercube $(0,1)^d$ is provides not maximally uniform coverage for $m < \infty$ sampling points
- Use low-discrepancy sequences (LDS) aka quasi-random numbers to cover $(0,1)^d$ maximally uniform:

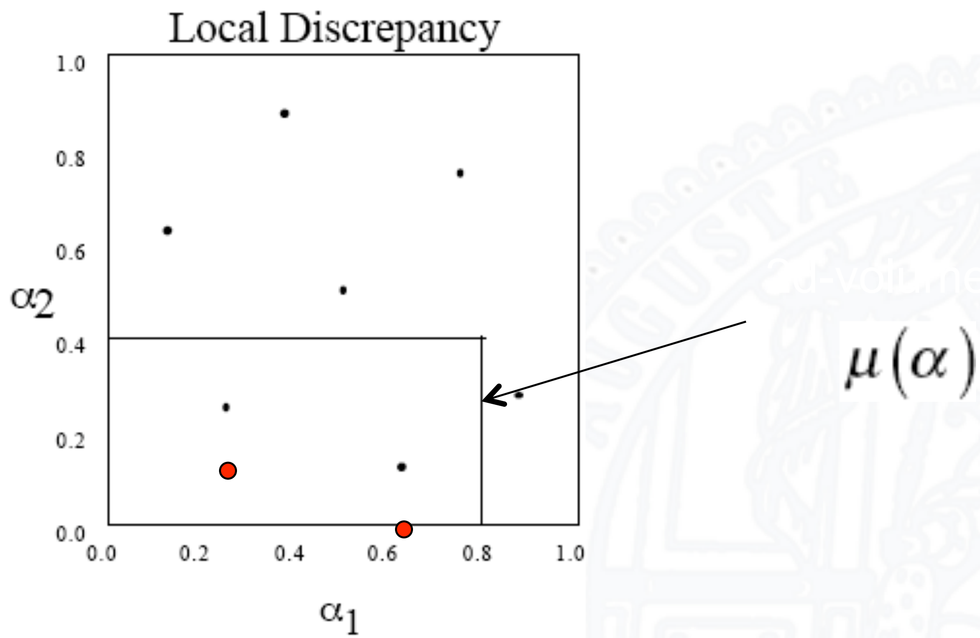


LDS for MC integration

- The concept of maximally uniform coverage for LDS can be formalised (and measured):
  - Introduce discrepancy $\Delta(\alpha)$ of a set of sampling points as:

$$\Delta(\alpha)=\frac{\nu(\alpha)}{N}-\mu(\alpha)$$

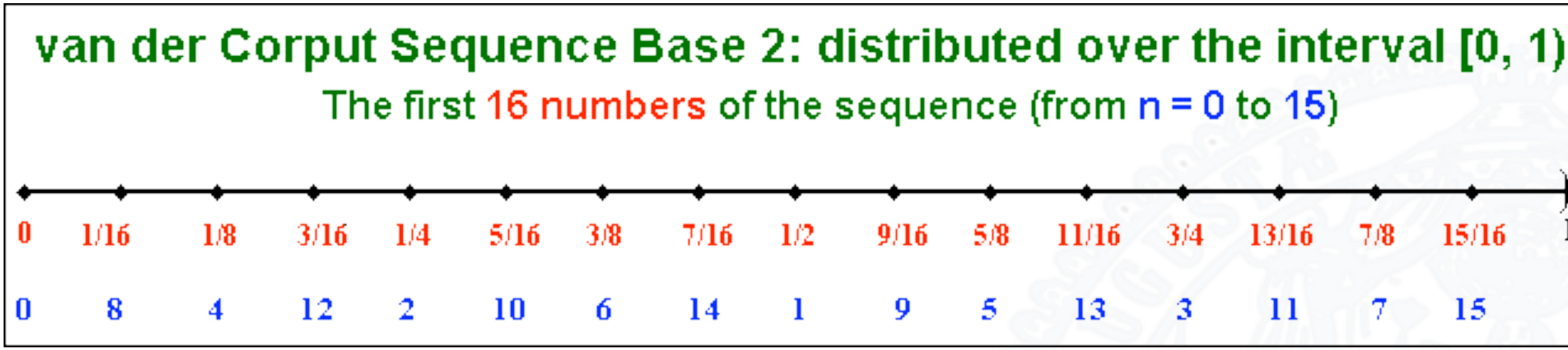
  - Example in 2d:



  - Where $\nu(\alpha)$ is the number of points with all coordinates less than the corresponding coordinates of α

LDS for MC integration

- A good sequence of sampling points ξ_m for MC integration has a **low discrepancy** value:
  - The MC sampling points “repel” each other
  - Sampling of the unit hypercube $(0,1)^d$ is more uniform
- Simplest example in 1 dimension: van-der-Corput sequence:



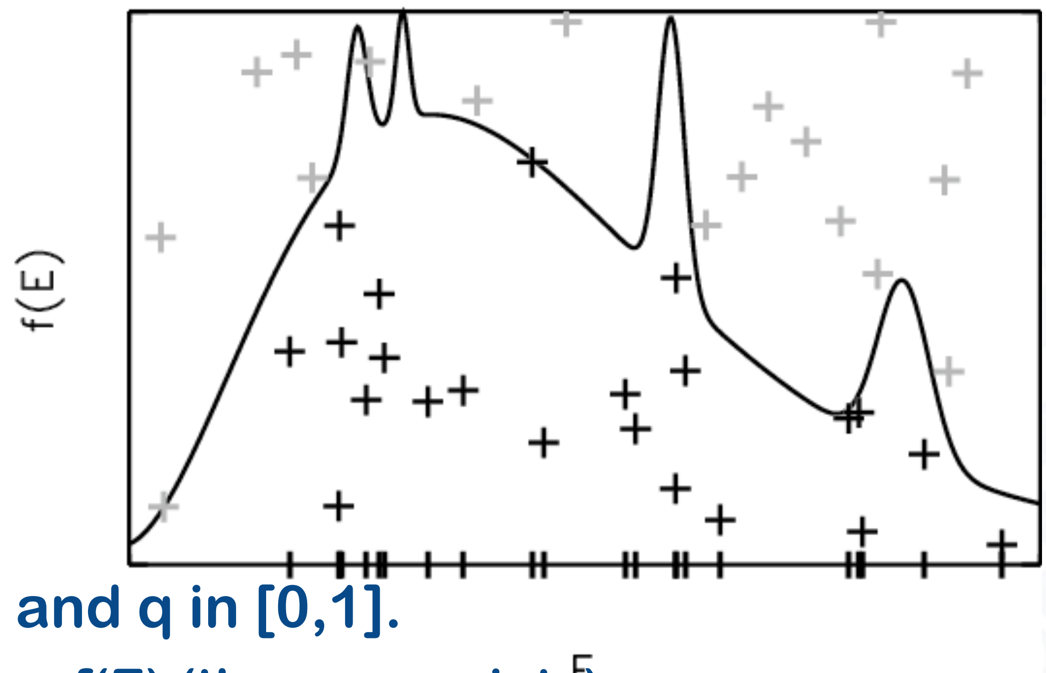
  - Blue numbers indicate the order in which the numbers appear in the sequence: 0, ½, ¼, ¾, etc.
- Sequences in multiple dimensions are based on the van-der-Corput sequence → the trick is “how”

Error estimation with LDS

- The real problem in numerical MC integration is to know when to stop, i.e. to know the error on the result
- Cannot use the traditional error estimate
  - → too pessimistic
- Randomly assigning sampling points into sub-sequences does not work either
  - → similarly too pessimistic (not shown)
- Need an error estimator with the same discrepancy as the sequence of sampling points used for MC integration!
  - Several rather complicated and CPU-expensive methods on the market

LD sequence implementation in ME code

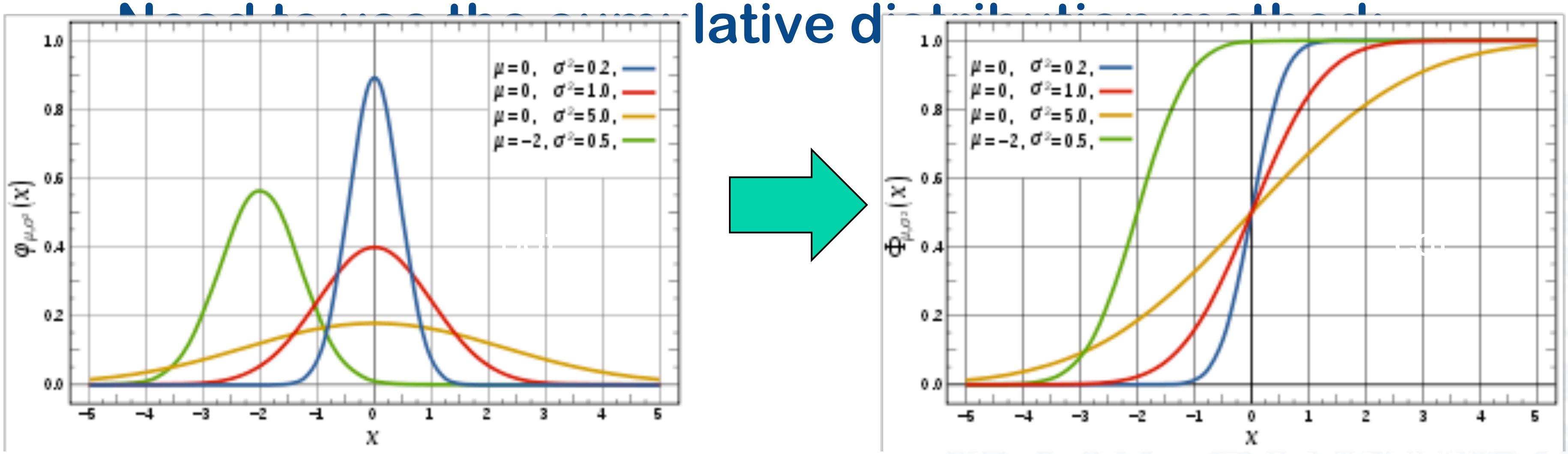
- In ME integration importance sampling (= generation of random numbers according to a pdf) is used
  - E.g. for BW distributions
- The accept-reject method was used for this:



  - Throw two RN for E and q in [0,1].
    - Reject the pair if q > f(E) (the gray points)
    - The accepted points will follow f(E)

LD sequence implementation in ME code

- Cannot use the accept-reject method for LD sequences
  - → If numbers from the sequence are rejected, the nice properties of LDS are lost!
- Need to use the cumulative distribution method:



  - Generate RN q in [0,1] and map it onto the x-axis using the inverse of the cdf function: $x = cdf^{-1}(q)$
    - → the resulting distribution in x will follow the pdf!
  - A substantial re-write of the code was needed! (>1

LD sequence implementation in ME code

- Use Sobol LD sequence for integration of ME method
  - Can switch back to pseudo random numbers using a flag
- Adjusted the precision to be achieved:
  - start from $\varepsilon = 3\%$ required relative precision
  - Linear increase to $\varepsilon = 9\%$ required relative precision for 10M of MC samplings
  - Adopted this procedure because:
    - Previous approach of using the full maximum 10M of MC samplings for "difficult" events and going away with the result is sub-optimal for LD sequences
    - However, there are "optimal" dips in achieved precision (this is specific for LD sequences)
    - → Can finish integration at the "right" point
      - For "most difficult" events the relative precision is about 7-8% after 10M of MC samplings

Additional tweaks

- Did more minor tweaks which cannot be listed here:
  - E.g. replace x2 by x*x for computing-intense applications
  - Moving from accept-reject method to cumulative distribution functions has given some performance increase (even for pseudo random numbers)
  - ...
- Ran with the head against the wall too:
  - Tried making TFs into look-up tables:
    - Did not work because:
      - CPU time per one MC sampling increased → OK
      - BUT: integrand was less smooth, more MC samplings were needed to reach required precision on final integral

Final cross-check: m_{sum}

- **Results from random number integration:**
  - **(used for 3.6 fb-1 dm analysis)**

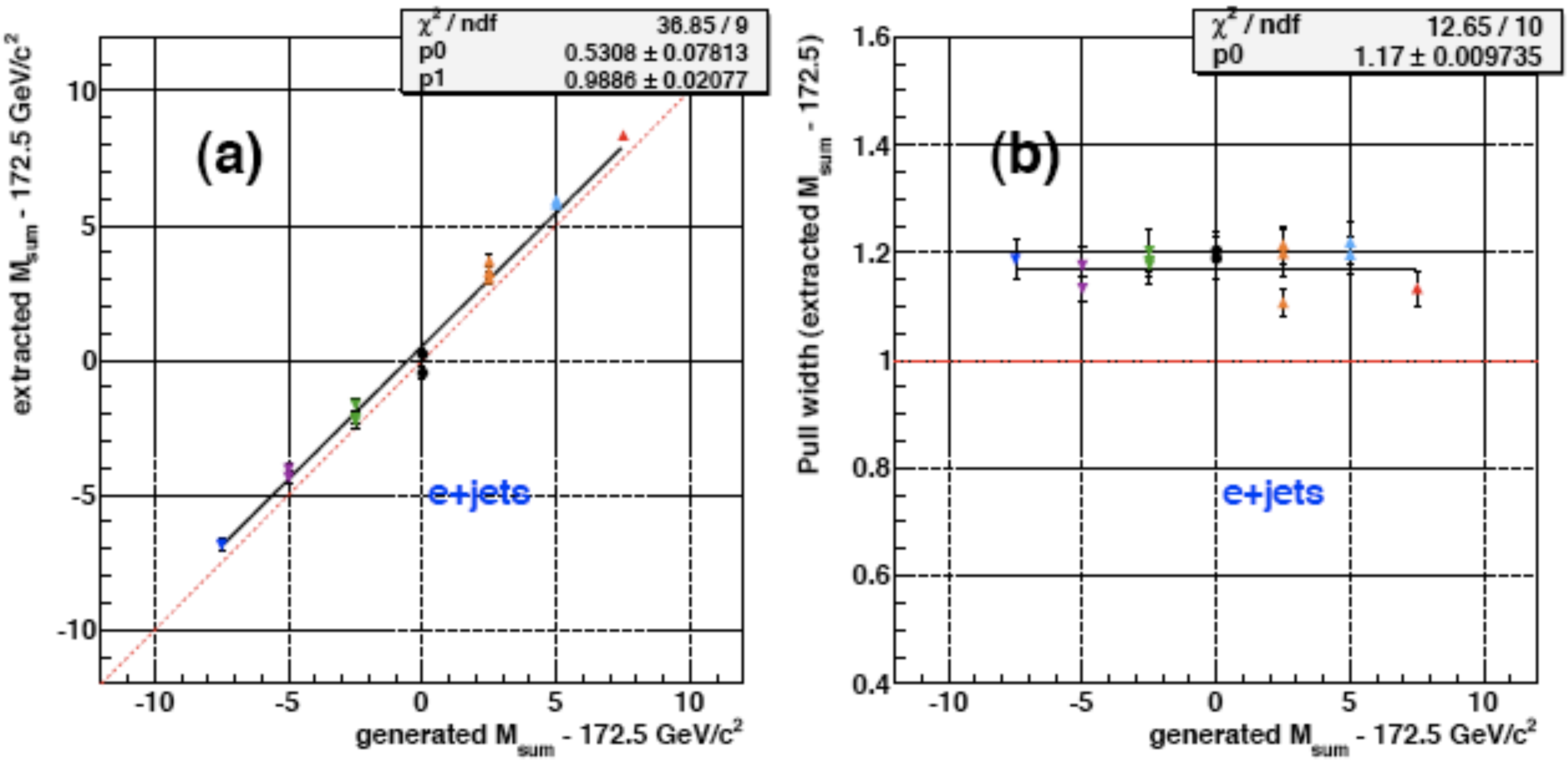


Figure 19: Calibration of the mean $t-\bar{t}$ mass M_{sum} for the $e+$jets channel.

Final cross-check: m_{sum}

- **Results using accelerated code**
  - **(using LDS, b-tagging information, etc.)**

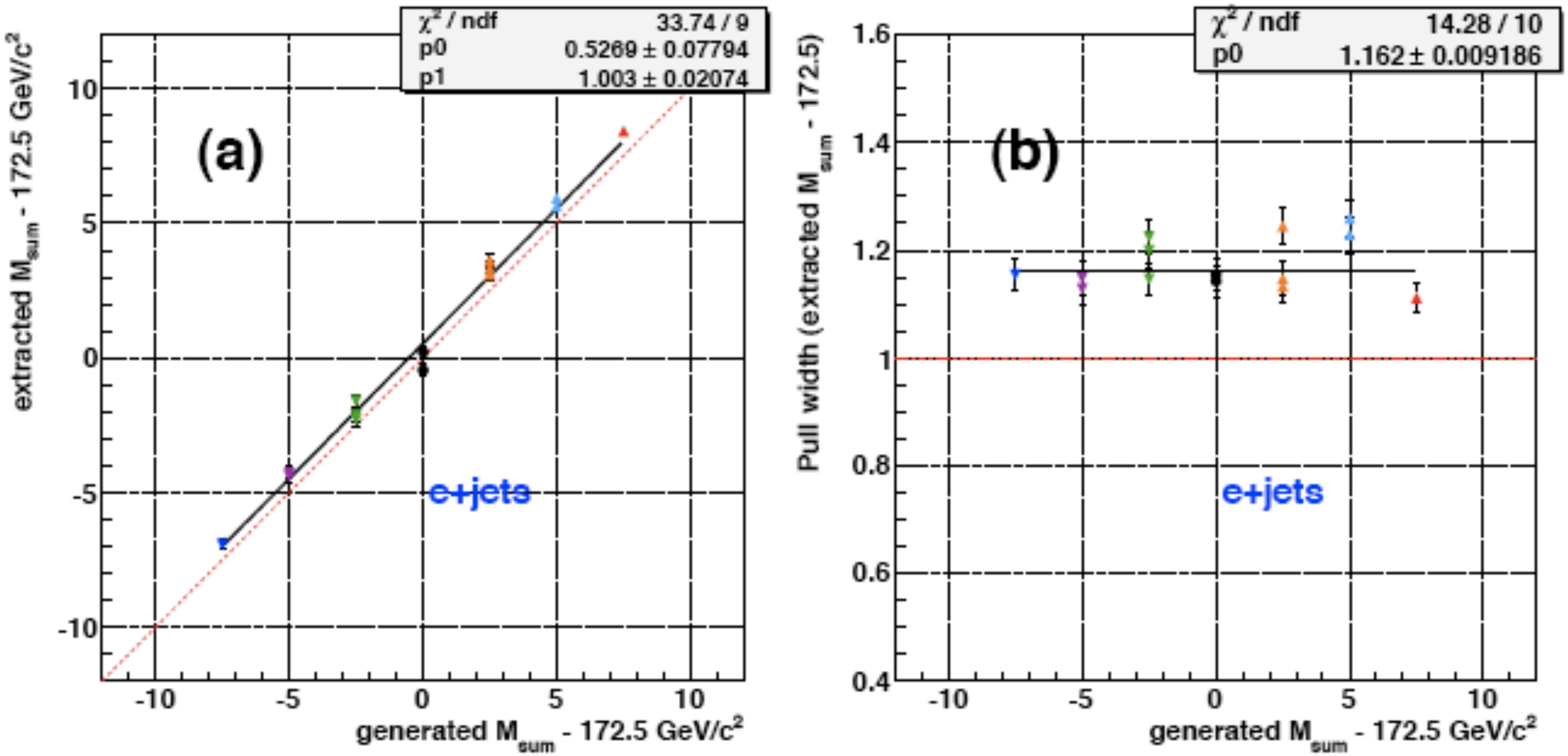


Figure 19: Calibration of the mean $t-\bar{t}$ mass $M_{\rm sum}$ for the $e+$jets channel.

Final cross-check: dm

- Results from random number integration:
  - (used for 3.6 fb-1 dm analysis)

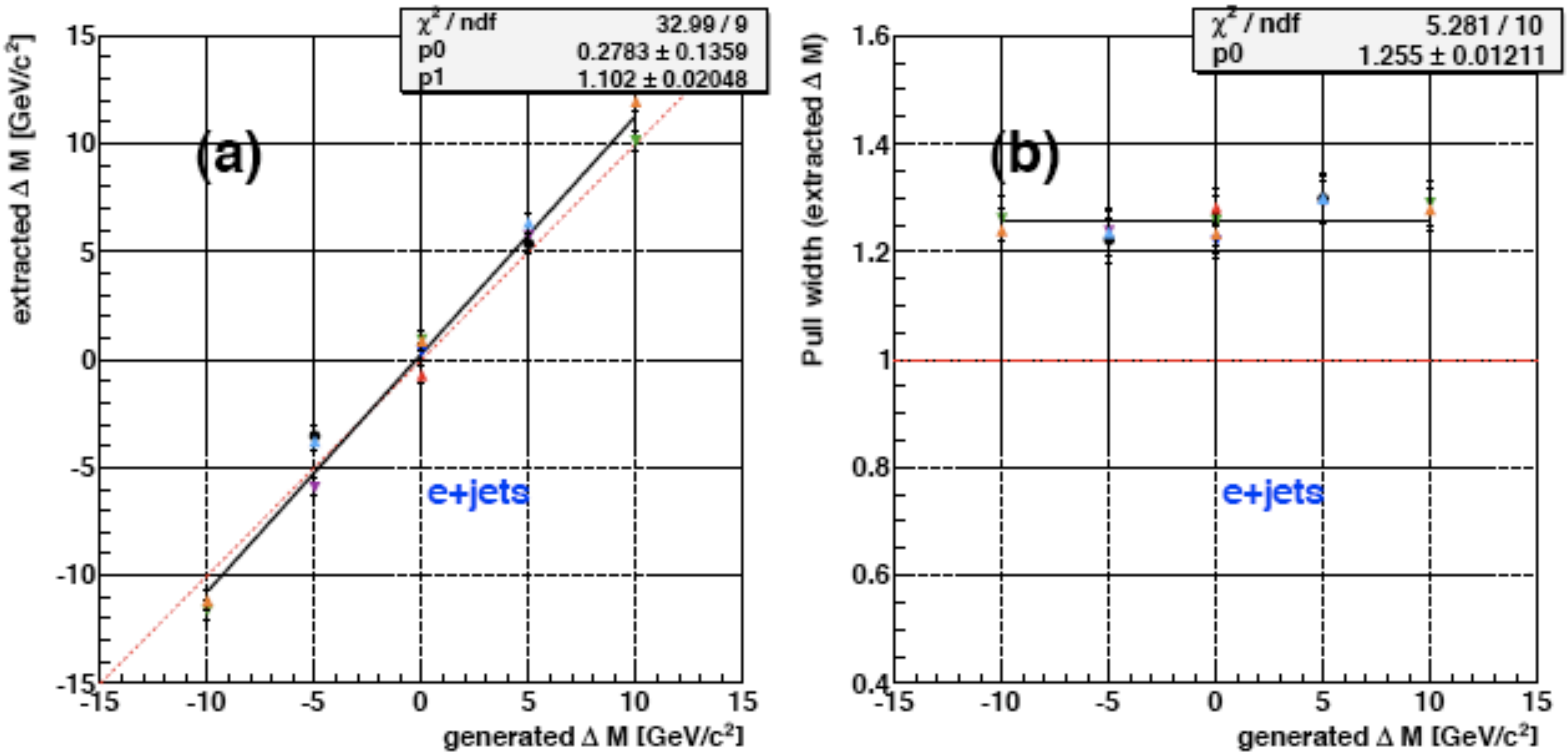


Figure 17: Calibration of the $t - \bar{t}$ mass difference ΔM for the $e +$jets channel.

Final cross-check: dm

- **Results using accelerated code**
  - (using LDS, b-tagging information, etc.)

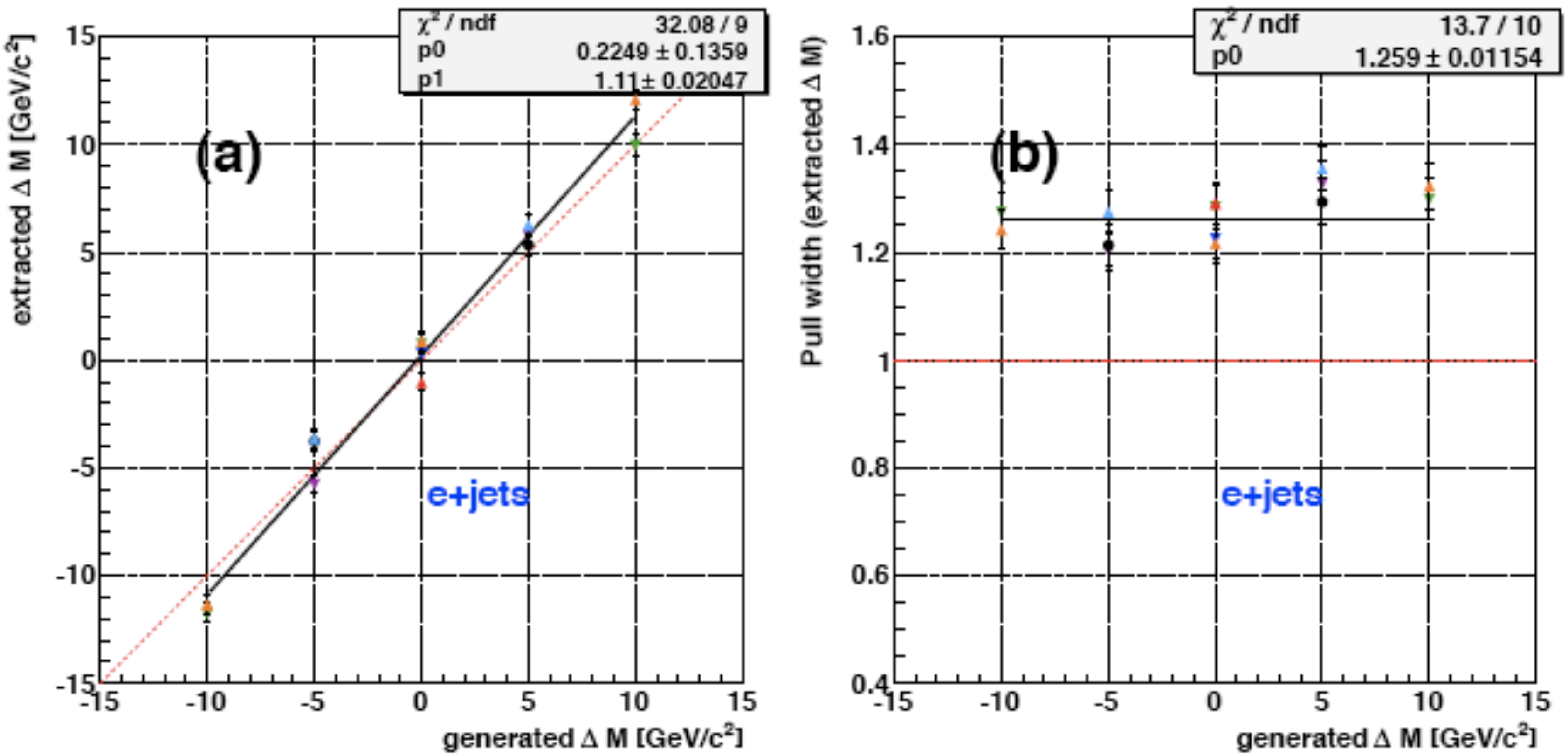


Figure 17: Calibration of the $t-\bar{t}$ mass difference ΔM for the $e+$jets channel.

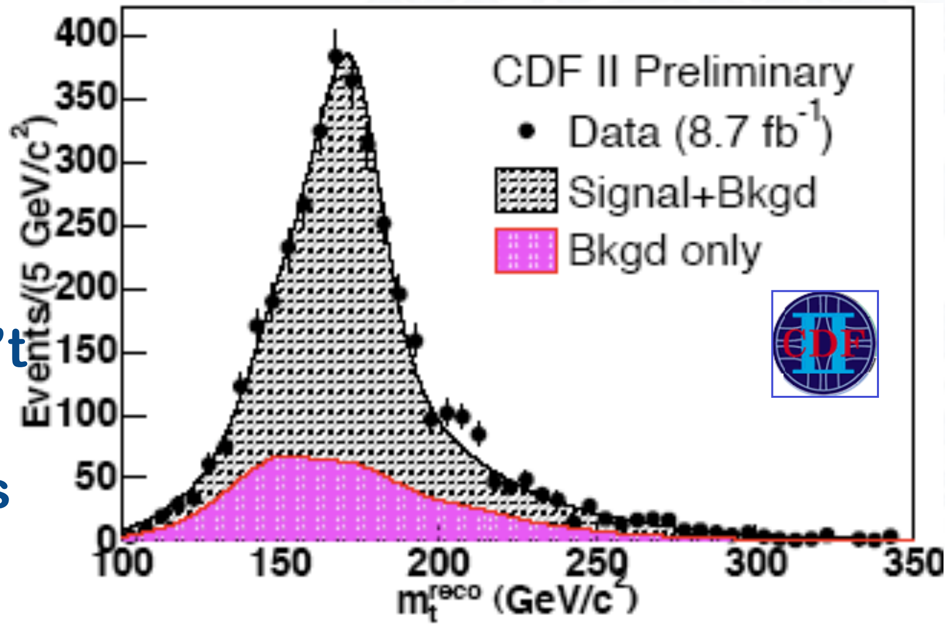
m_{top} with templates in ll and l+jets

- **Template method in lepton+jets final states, CDF (8.7 fb^{-1})**
  - **Reconstruct the event kinematics by minimising:**

$$\chi^2 = \Sigma_{i=\ell,4jets}\frac{(p_T^{i,fit}-p_T^{i,meas})^2}{\sigma_i^2} + \Sigma_{j=x,y}\frac{(U_j^{fit}-U_j^{meas})^2}{\sigma_j^2}$$

$$+\underbrace{\frac{(M_{jj}-M_W)^2}{\Gamma_W^2}}_{\text{JES constraint}}+\underbrace{\frac{(M_{\ell\nu}-M_W)^2}{\Gamma_W^2}}_{\text{MET constraint}}+\underbrace{\frac{(M_{bjj}-m_t^{\text{reco}})^2}{\Gamma_t^2}+\frac{(M_{b\ell\nu}-m_t^{\text{reco}})^2}{\Gamma_t^2}}_{m_{top}\text{ extraction}}$$

  - **Consider jet-parton assignments consistent with b-tagging**
  - **Form templates from:**
    - $\mathrm{m}_t^{\mathrm{reco}}$: best jet-parton ass't
    - $m_t^{\mathrm{reco}(2)}$: second-best ass't
    - m_{jj} : dijet invariant mass



Phys. Rev. Lett. ***109****, 152003 (2012)*

Lorentz invariance violation

- **Invariance under Lorentz transformation is a fundamental property of the SM**
  - **Thoroughly tested in the leptonic sector and for first generation, some tests for second generation, b-system**
  - **Quantify Lorentz invariance violation (LIV) in the top sector using in the SM Extension formalism:**

$$|\mathcal{M}|^2_{\mathrm{SME}} = PF\bar{F} + (\delta P)F\bar{F} + P(\delta F)\bar{F} + PF(\delta\bar{F})$$

P @ prod'n vertex *F @ decay vertex* *δ Dependence on SM extension coefficiencts*

[D. Colladay and V.A. Kostelecky, Phys. Rev. D 58, 116002 (1998)]
[V.A. Kostelecky, Phys. Rev. D 69, 105009 (2004)]

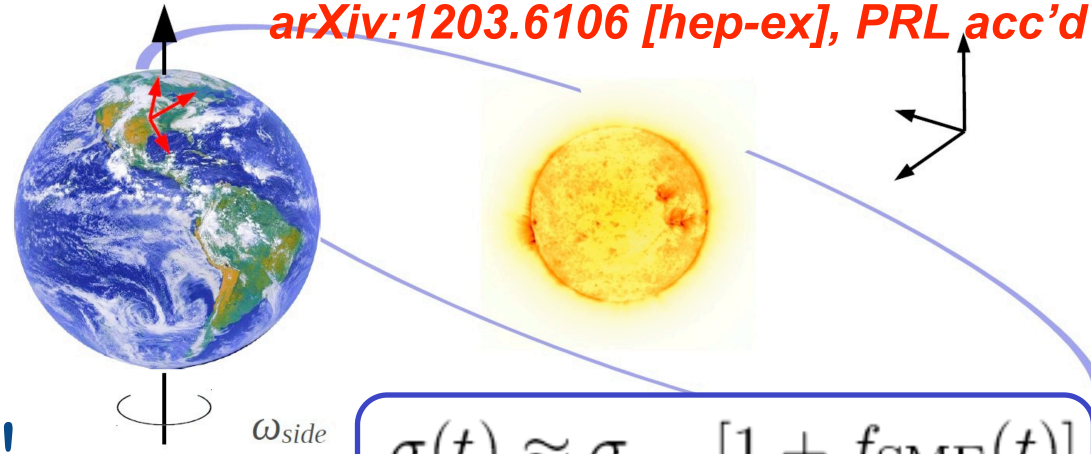
- **Parametrise LIV $f_{\mathrm{SME}}(t)$ in terms of coefficients $C_{\mu\nu}$:**
  - $f_{\mathrm{SME}}(t) = C_{\mu\nu} R^{\mu}_{\alpha}(t) R^{\nu}_{\beta}(t) A^{\alpha\beta}$
- **Non-zero $C_{\mu\nu}$ will result in time dependent *tt* production due to the rotation of the Earth!**

arXiv:1203.6106 [hep-ex], PRL acc'd

Lorentz invariance violation

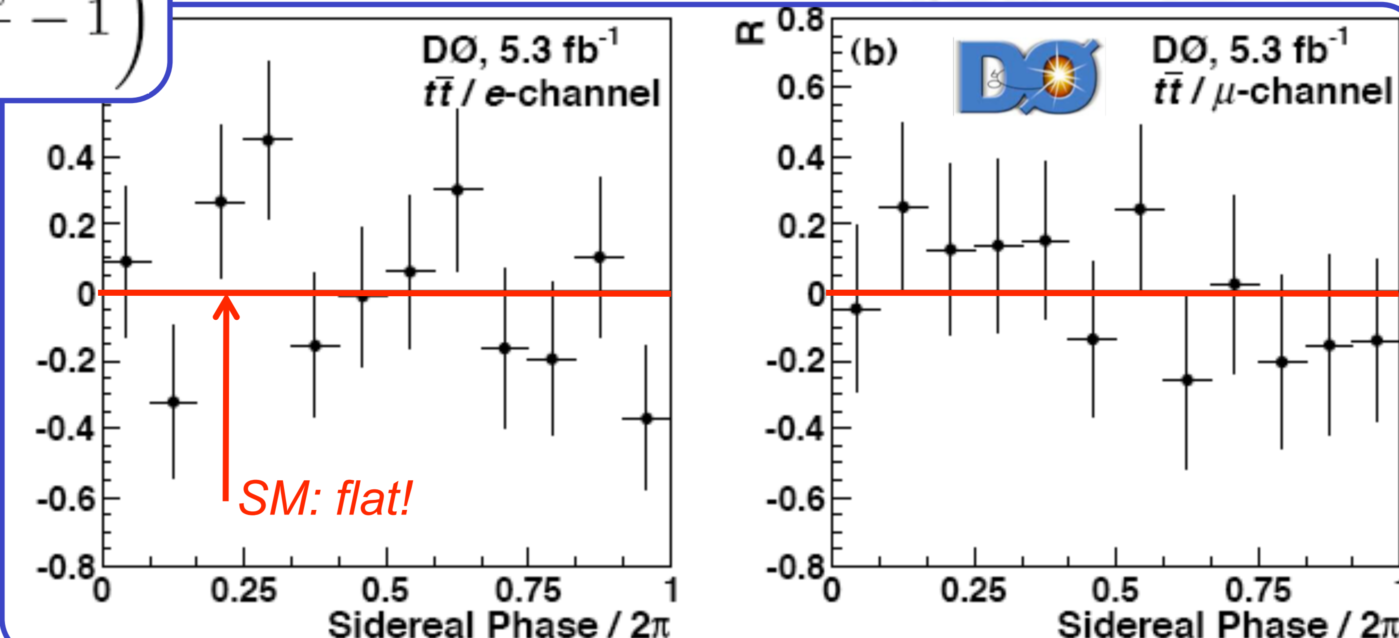
- **The period is 1 or ½ siderial day**
  - 1 Solar day ≈ 0.997 siderial day
  - Use time stamp to check perodicity!

arXiv:1203.6106 [hep-ex], PRL acc'd



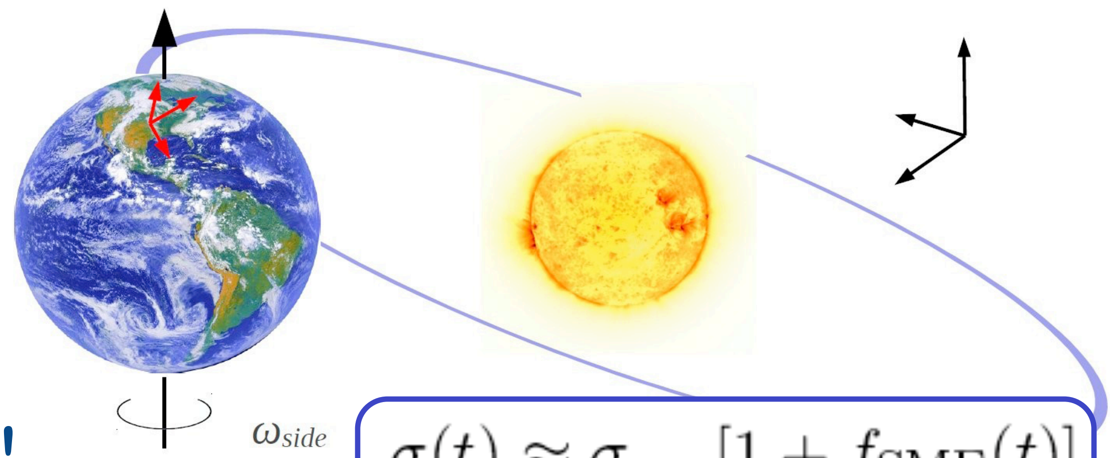
$$\sigma(t) \approx \sigma_{\rm ave}\left[1 + f_{\rm SME}(t)\right]$$

$$R_i \equiv \frac{1}{f_S}\left(\frac{N_i/N_{\rm tot}}{\mathcal{L}_i/\mathcal{L}_{\rm int}} - 1\right)$$



Lorentz invariance violation

- **The period is 1 or ½ siderial day**
  - 1 Solar day
    ≈ 0.997 siderial day
  - Use time stamp
    to check perodicity!



$$\sigma(t) \approx \sigma_{\rm ave}\left[1 + f_{\rm SME}(t)\right]$$

TABLE III: Limits on SME coefficients at the 95% C.L., assuming $(c_U)_{\mu\nu} \equiv 0$.

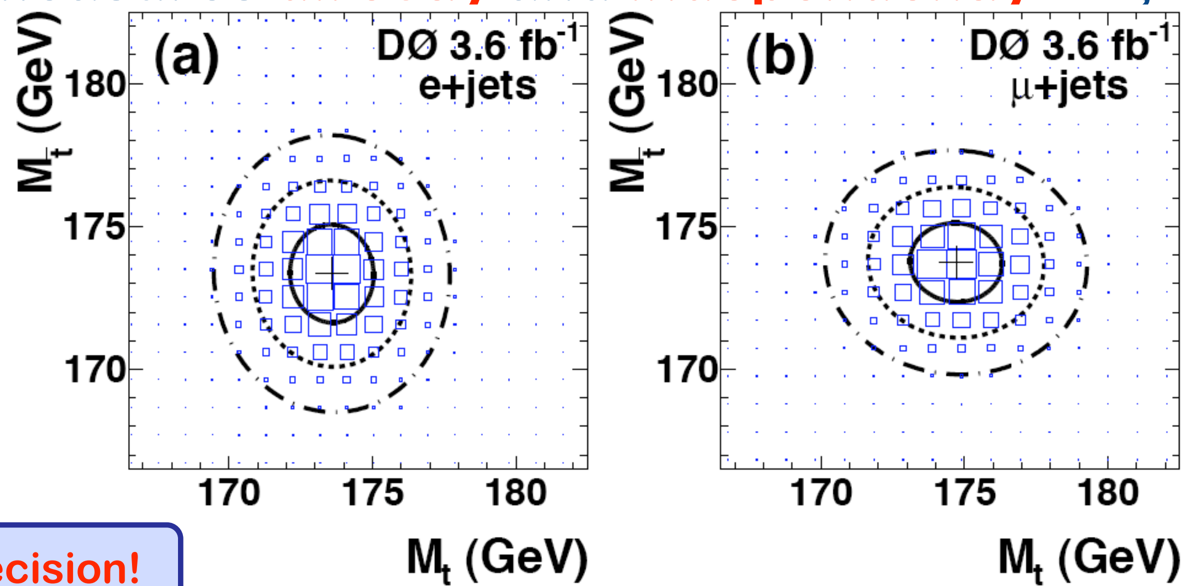
Coefficient	Value ± Stat. ± Sys.	95% C.L. Interval
$(c_Q)_{XX33}$	$-0.12 \pm 0.11 \pm 0.02$	$[-0.34, +0.11]$
$(c_Q)_{YY33}$	$0.12 \pm 0.11 \pm 0.02$	$[-0.11, +0.34]$
$(c_Q)_{XY33}$	$-0.04 \pm 0.11 \pm 0.01$	$[-0.26, +0.18]$
$(c_Q)_{XZ33}$	$0.15 \pm 0.08 \pm 0.02$	$[-0.01, +0.31]$
$(c_Q)_{YZ33}$	$-0.03 \pm 0.08 \pm 0.01$	$[-0.19, +0.12]$

TABLE IV: Limits on SME coefficients at the 95% C.L., assuming $(c_Q)_{\mu\nu} \equiv 0$.

Coefficient	Value ± Stat. ± Sys.	95% C.L. Interval
$(c_U)_{XX33}$	$0.10 \pm 0.09 \pm 0.02$	$[-0.08, +0.27]$
$(c_U)_{YY33}$	$-0.10 \pm 0.09 \pm 0.02$	$[-0.27, +0.08]$
$(c_U)_{XY33}$	$0.04 \pm 0.09 \pm 0.01$	$[-0.14, +0.22]$
$(c_U)_{XZ33}$	$-0.14 \pm 0.07 \pm 0.02$	$[-0.28, +0.01]$
$(c_U)_{YZ33}$	$0.01 \pm 0.07 \pm < 0.01$	$[-0.13, +0.14]$

[arXiv:1203.6106]

- CPT is essential for a locally Lorentz-invariant QFT
  - $m_{particle}$!= $m_{antiparticle}$ → CPT violated!
    - Top is the only quark where this test is po… $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s
  - DØ measures directly and independe… m_t, $m_{\bar{t}}$, (ME):



<1% relative precision!

$$\Delta m \equiv m_t - m_{\bar{t}} = 0.8 \pm 1.8\ (\text{stat}) \pm 0.5\ (\text{syst})\ \text{GeV}$$

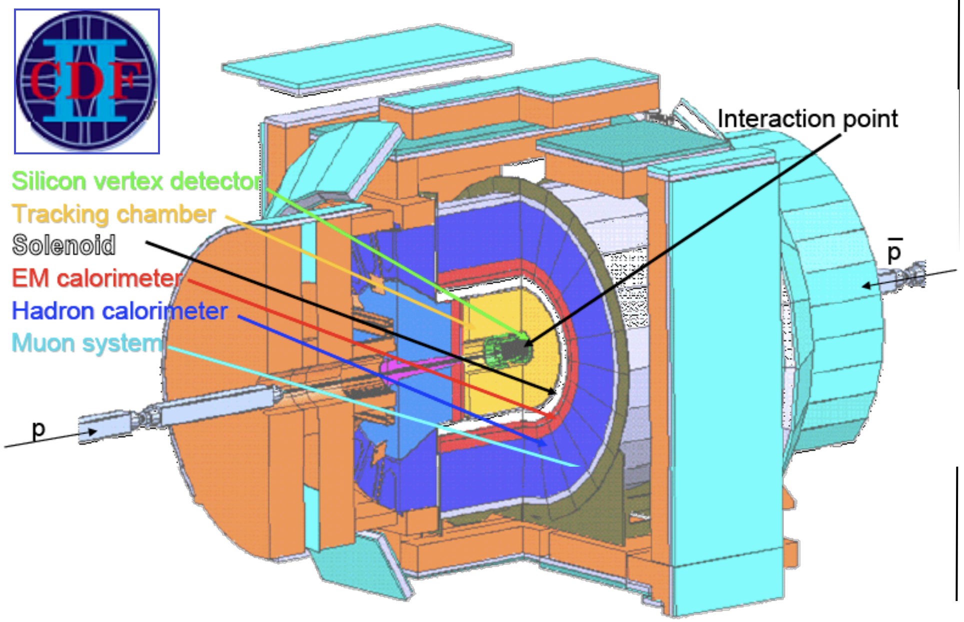
$$\Delta m \qquad \frac{m_t + m_{\bar{t}}}{2} \equiv 172.5\ \text{GeV}$$

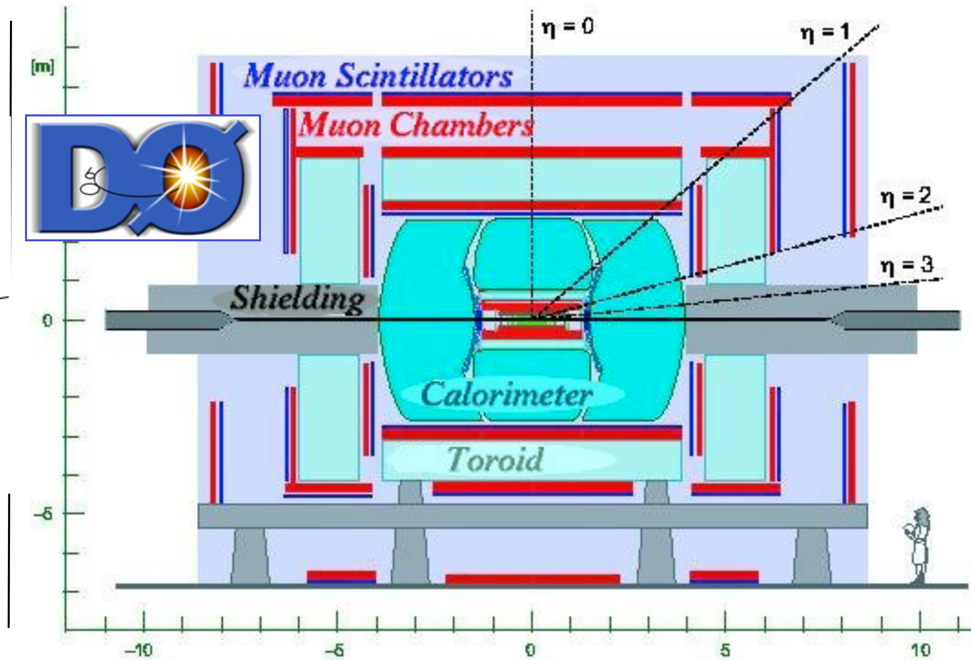
$$\Delta m = -1.95 \pm 1.11\ (\text{stat}) \pm 0.59\ (\text{syst})\ \text{GeV}$$ (8.7 fb^{-1})

  - CDF measures directly … with …

D0: Phys. Rev. D **84**, 052005 (2011)
CDF: Conf-Note 10777 (2012)

The CDF and D0 detectors





	CDF	DØ
EM calorimeter	14%/√E + 1%	22%/√E + 4%
Hadronic calorimeter	70%/√E + 5%	68%/√E + 5%

Experimental Challenges

- We are interested in parton-level quantities for our top measurements
  - Map the energies of reco-level jets particle jets (D0) / partons (CDF)
  - This is referred to as a Energy Scale (JES) corr'n
  - With the current size of samples:
    - s(JES)/JES ~ 1.5% (D0)
    - s(JES)/JES ~ 3% (CDF)
- And many more:
  - Lepton ID, p_T scale