Top mass measurement with BEST at 8 TeV

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2015.05.15

KNU-PKU Joint HEP Workshop at Beijing

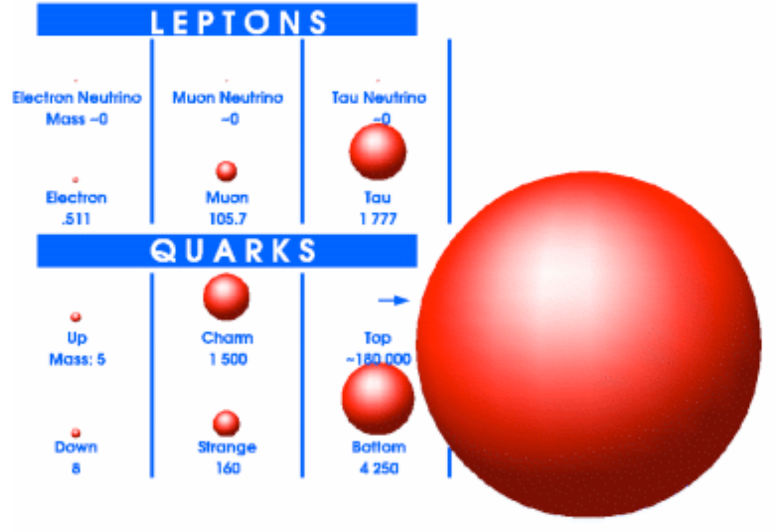
Outline

- Part I: Top mass at hadron collider
- Part II: Event mixing
- Part III: BEST analysis at CMS

Motivation

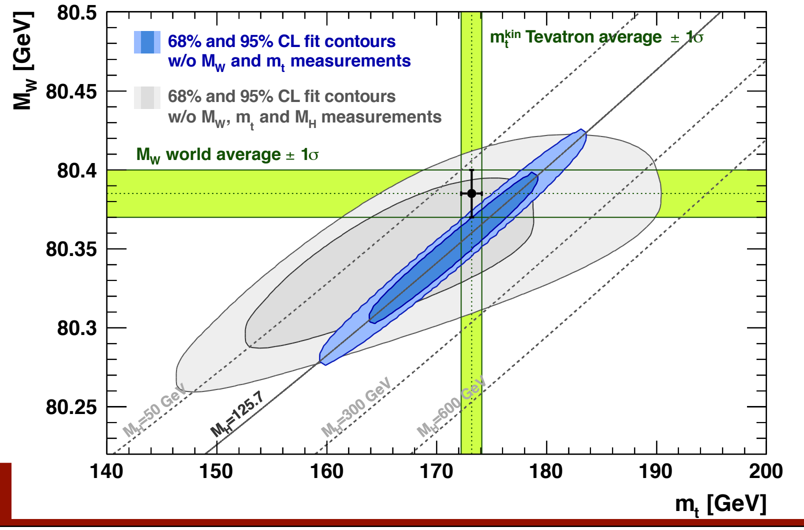
- Heaviest Elementary Particle in the Standard Model

			m_{top} (GeV)
	Tevatron	Run I	175 ± 6
Jul 2014	Tevatron	Run I + II	174.34 ± 0.64
Mar 2014	World	Tevatron LHC	173.34 ± 0.76



Top quark plays a special role in the SM and beyond

Precise top quark measurements
→ tighten constraints on SM parameters
→ sensitivity to New Physics



Measuring the Top Mass

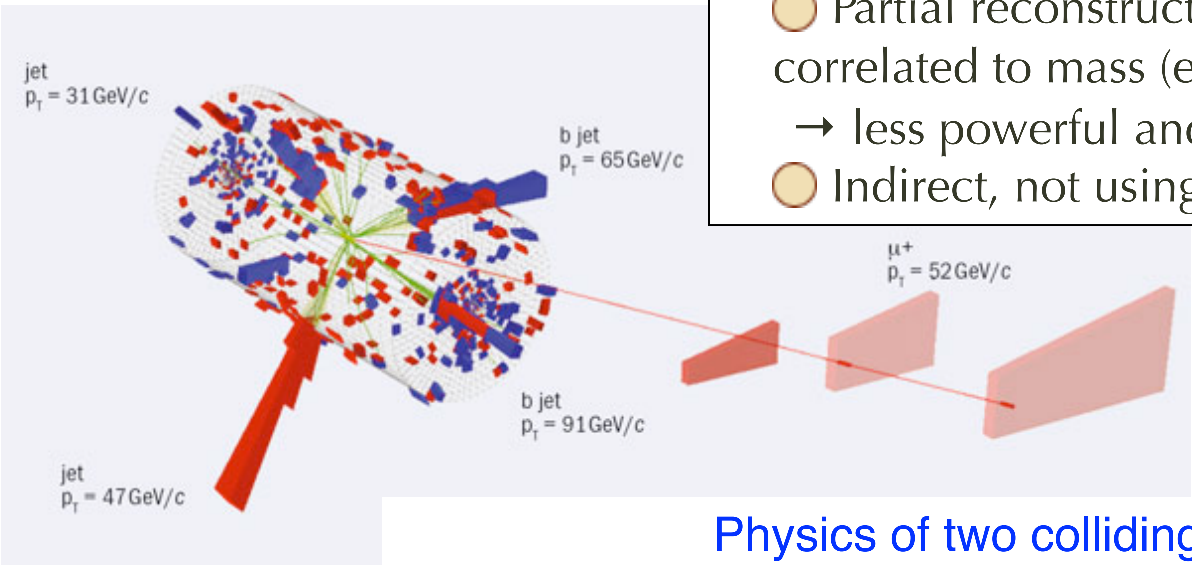
Experimental point of view:

- Top quark decays before hadronization (rapid decay)
- Processes can be calculated in QCD perturbation theory
- Measure invariant mass of decay products (narrow resonance)
- All processes can be simulated by MC and are corrected for

Basic methods:

- Full reconstruction of invariant mass
  → most powerful and conventional methods
- Partial reconstruction, fitting variable correlated to mass (endpoint, L_{xy}, J/ψ, ratio)
  → less powerful and different systematics
- Indirect, not using mass (cross-section)

Muon + jets channel

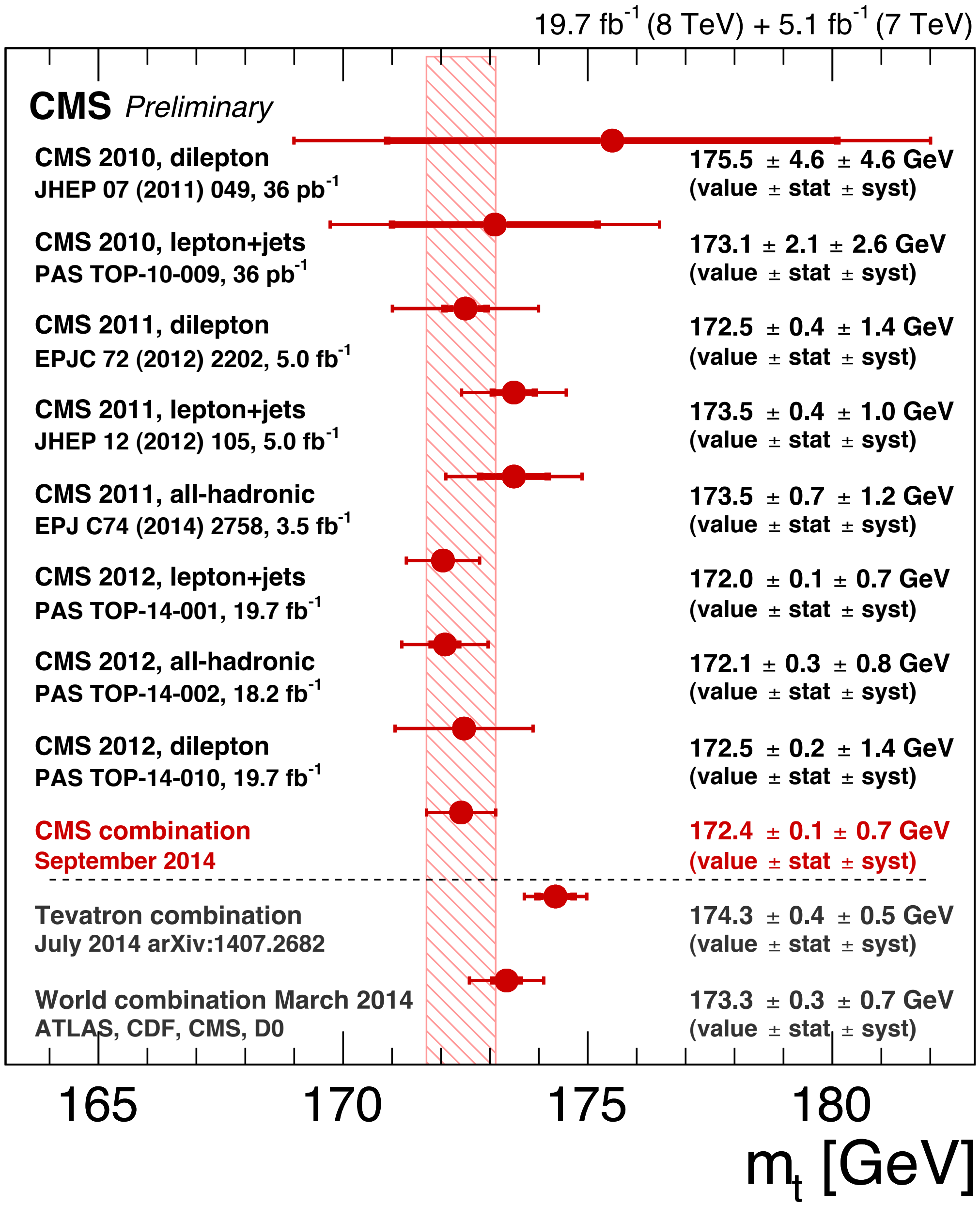


Physics of two colliding partons:
PDF → hard scattering → parton shower → hadronization

Top mass reconstruction

Principle: Calibrate with Monte Carlo → Fit data and extract m_{top}^{MC}

Template method	• simple and fast • compare an observable in data with MC generated with different masses
Matrix Element	• very precise but slow • build an event likelihood based on calculation of LO matrix element using the full kinematics of the event
Ideogram Method	• precise and fast • build analytical event likelihood based on kinematic fit, taking into account all jet combinations & background
A special case (dilepton channel)	• various methods to solve insufficiently constrained system • AMWT (Analytical Matrix Weighting Technique) and KINb (a full kinematic analysis), neutrino weighting, Dalitz-Goldstein...



CMS Preliminary Result
CMS-PAS-TOP-14-015
(September 2014)

Combined result

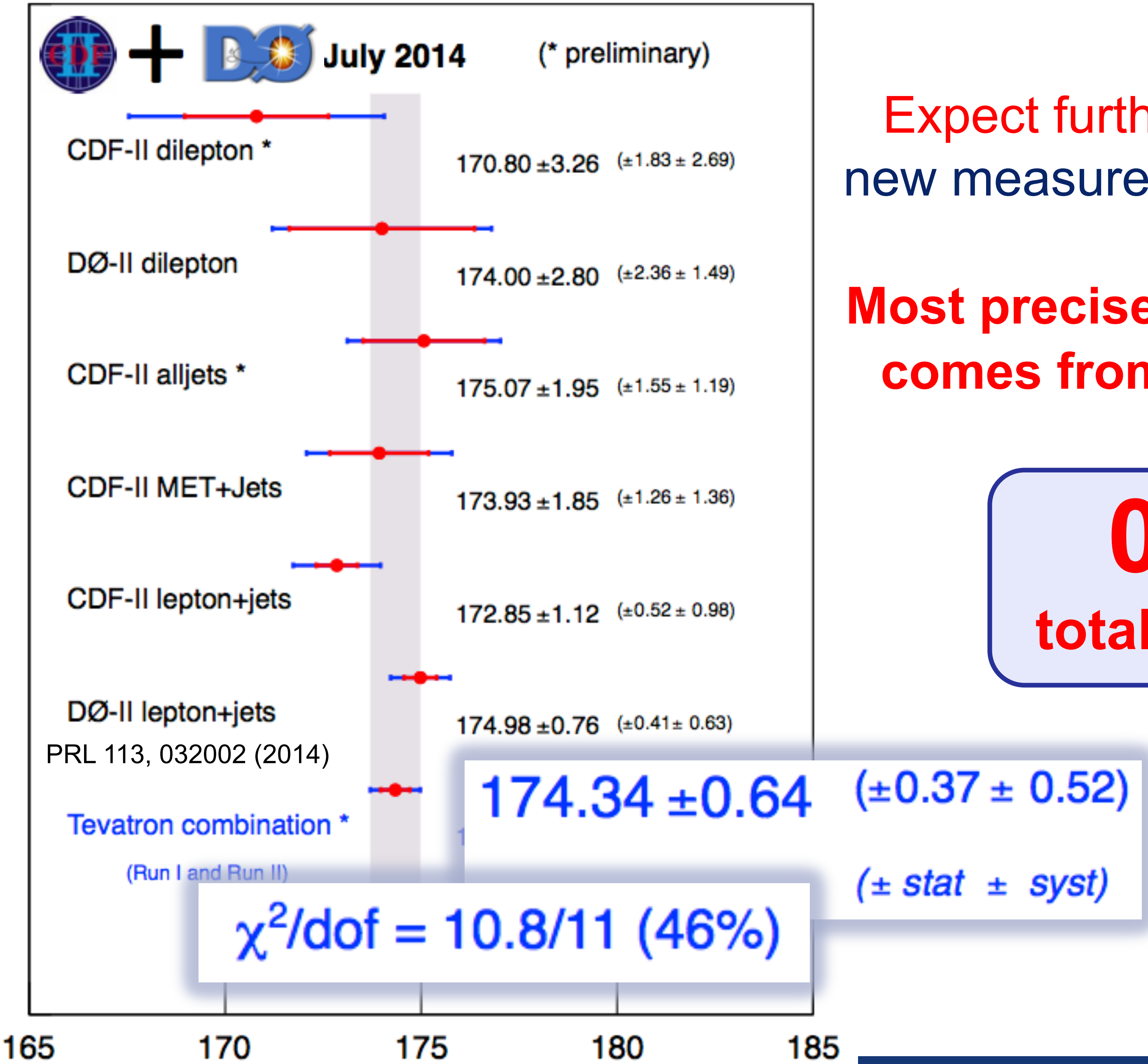
$m_t = 172.38 \pm 0.14$ (stat.+JSF)
$\pm\, 0.64$ (syst.) GeV

Uncertainty 660 MeV (0.4%)

total uncertainty 0.38%

BUT

Tevatron combination



Expect further improvements as new measurements enter the game

Most precise determination of m_t comes from the Tevatron (yet)

0.37%
total uncertainty

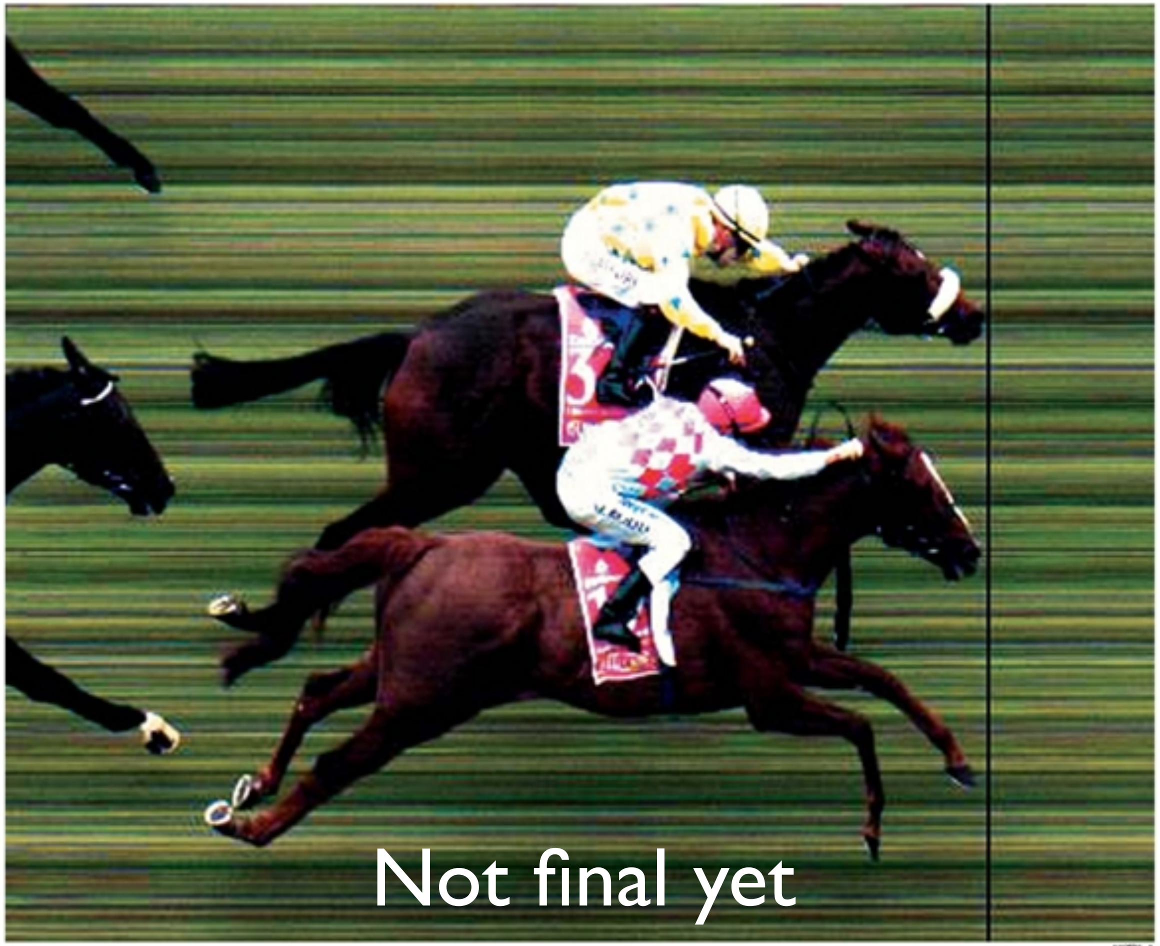
arXiv:1407.2682 [hep-ex]

for details, see https://indico.cern.ch/event/333696 (Sep 2nd)

That was close!

손톱 하나 차이로… 32억원이 갈렸다

Melbourne Cup in 2011, Australia

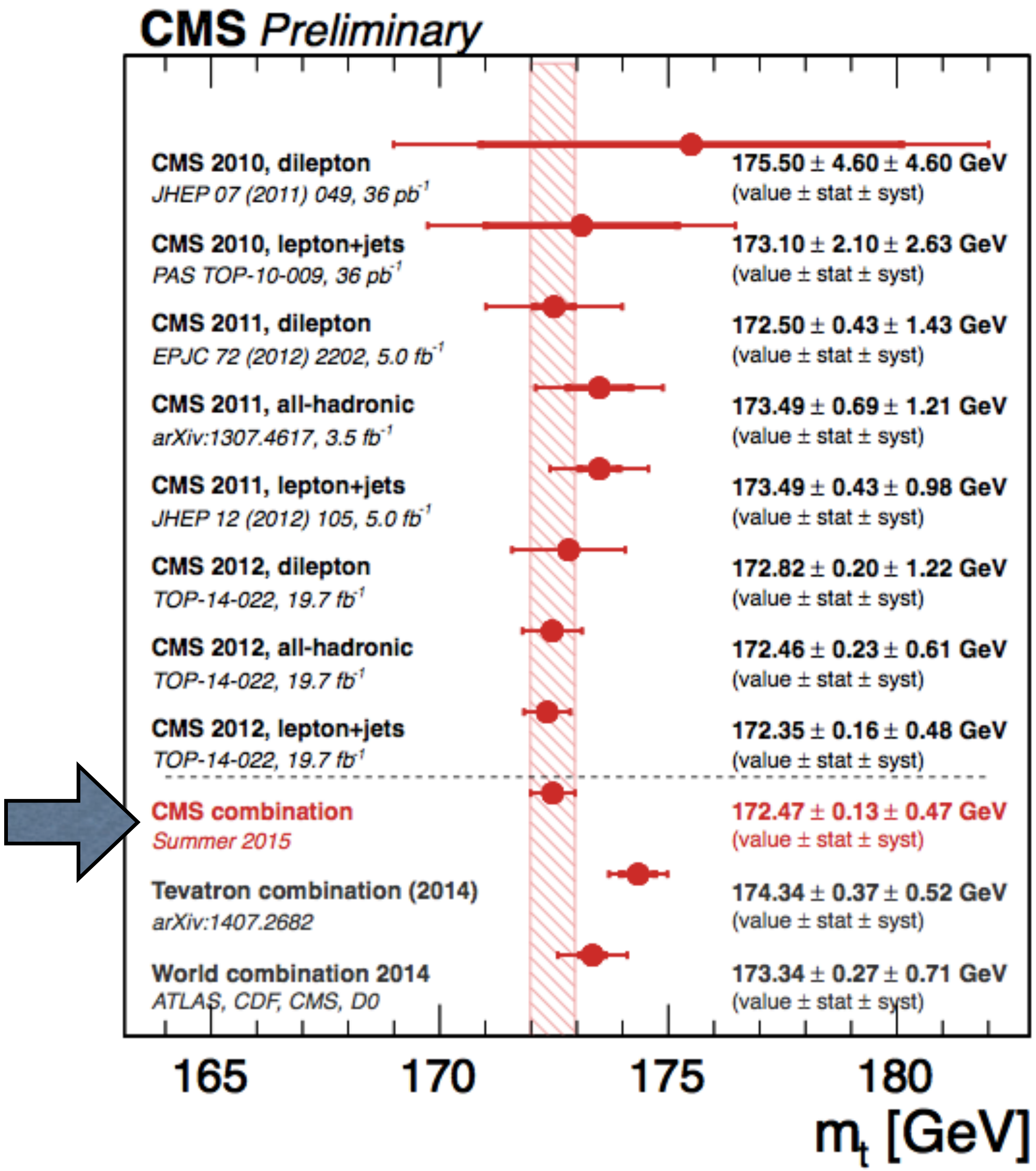


AP연합뉴스

올해로 151년의 역사를 자랑하는 호주 멜버른컵 경마대회의 승자가 사진 판독 끝에 가려졌다. 1일 멜버른 플레밍턴 레이스코스에서 열린 이번 대회에선 '두나든(위·기수 크리스토프 르메르)'이 '레드 카도'를 간발의 차로 제치고 우승상금 360만호주달러(약 42억원)의 주인공이 됐다. 2위 레드 카도는 90만 호주달러(약 10억원)를 가져갔다.

Dunaden

Red **C**adeaux



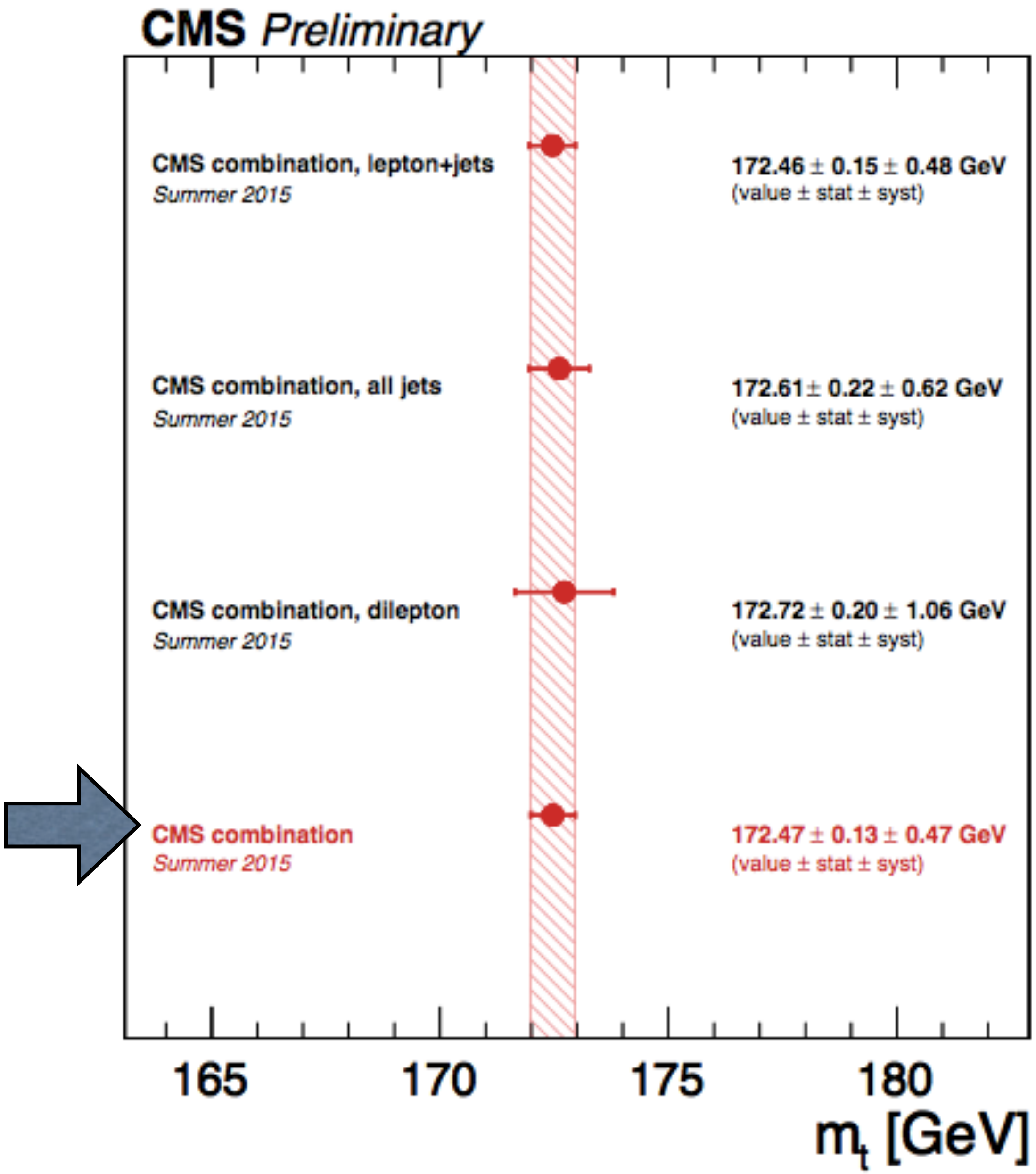
Comparison with CMS Inputs current World Average and Tevatron combinations

Combination uncertainty:

490 MeV (0.3%)

Result is more precise than any of its predecessors

Paper reading for TOP-14-022 (April 2015)
Run 1 top mass legacy paper

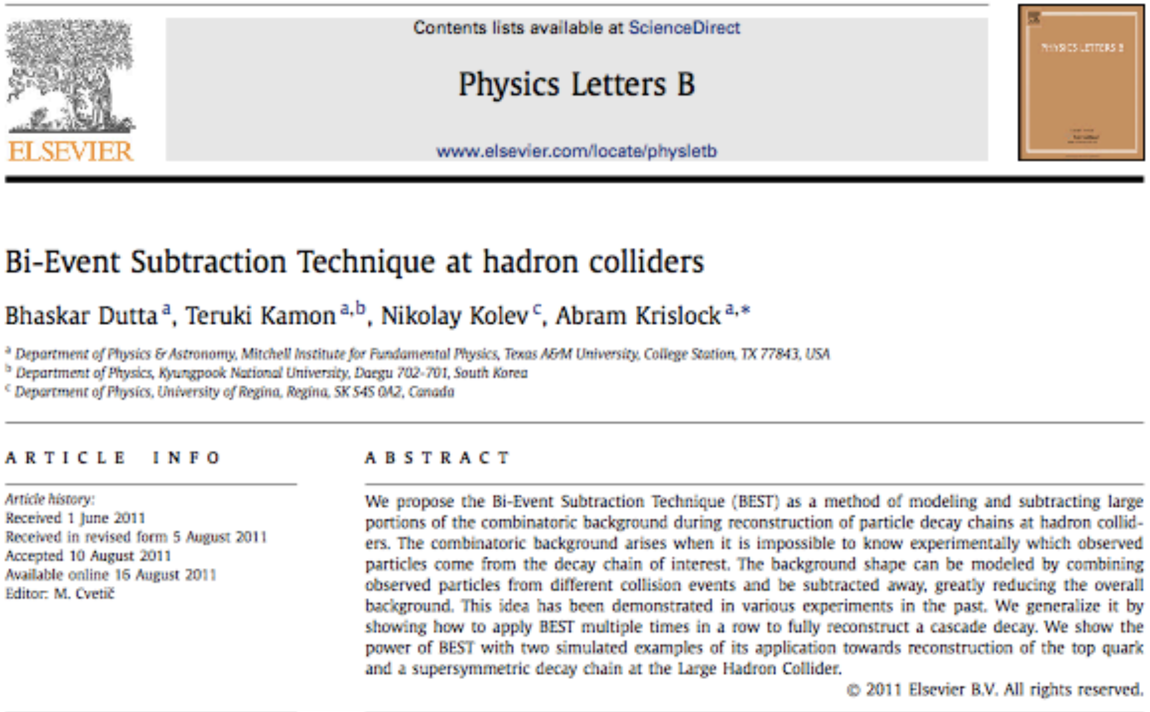


Results by ttbar decay mode

The results for each decay mode are fully consistent with the combined result

Paper reading for TOP-14-022 (April 2015)
Run 1 top mass legacy paper

Bi-Event Subtraction Technique



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Bi-Event Subtraction Technique at hadron colliders

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ABSTRACT

We propose the Bi-Event Subtraction Technique (BEST) as a method of modeling and subtracting large portions of the combinatoric background during reconstruction of particle decay chains at hadron colliders. The combinatoric background arises when it is impossible to know experimentally which observed particles come from the decay chain of interest. The background shape can be modeled by combining observed particles from different collision events and be subtracted away, greatly reducing the overall background. This idea has been demonstrated in various experiments in the past. We generalize it by showing how to apply BEST multiple times in a row to fully reconstruct a cascade decay. We show the power of BEST with two simulated examples of its application towards reconstruction of the top quark and a supersymmetric decay chain at the Large Hadron Collider.

KNU

2011

For top in new particle decay

arXiv:1104.2508 [hep-ph]

2012

For top mass

- BEST analysis at CMS
  - Measurement of m_{top} by fitting signal+background
  - Signal modeled from the templates
  - Background modeled by the BEST method

Data-driven
No kinematic fit

BEST analysis at CMS

2014

Template method
Blind analysis
(pre-approved)

- Performed using 19.7 fb^{-1} of 8 TeV
  - CMS AN-2014/091 and TOP-14-011
  - Using Jan22 rereco, from golden JSON file
  - Primary datasets: SingleMu (passed HLT_IsoMu24_eta2p1)
  - Using Top PAT-tuples (processed with CMSSW 5.3.11)
  - Measuring the invariant mass of the decay products of the top quark candidates (jet triplets) without a kinematic fit for selection
  - Using a likelihood fit to the distribution (mass or R) to obtain the value for m_{top} that best describes the pseudo-data
  - Estimating the systematic uncertainties using MC

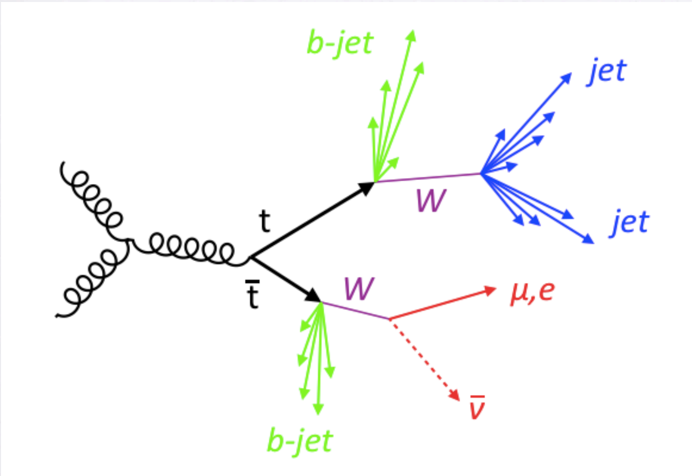
Part 2: Event mixing

- Introduction
  - Background estimation and subtraction
- Event-Mixing Method
  - Concept and history
  - Pros and cons
  - Correlated distribution
  - Modeling of combinatorial background

Background estimation

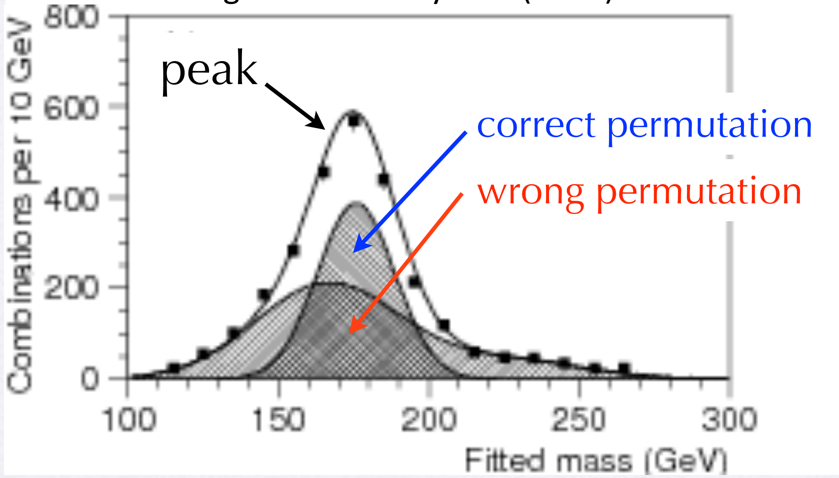
- A standard way to observe resonance production
  - ✦ make an invariant mass distribution of particles which may be decay products of resonances

ttbar production in l + jets channel



simulated data and prediction

Prog.Part.Nucl.Phys. 63 (2009) 239



- An estimation of the background is essential
  - ✦ if the background has a simple falling or rising form, it will not be difficult to approximate the background shape with an analytical function

Background estimation (2)

- A potential problem with an analytical function
  - ✦ kinematic restrictions induced by the experimental setup and the event selection can lead to wrong estimation
  - ✦ it requires further study to understand the effects of detector acceptance and event selection cuts in the analysis
- Event mixing to overcome these problems
  - ✦ artificial mass distribution obtained from taking one particle from one event and the other particle from another event
  - ✦ cross-event particle combinations are called mixed events

Background subtraction

- In hadron colliders, lots of particles produced in a single event
  - ✦ reconstruct particles by (mis)identifying their decay product
- Reconstruction of Z^0 in di-lepton mass: $Z^0 \rightarrow e^+e^-$ / $\mu^+\mu^-$
  - ✦ collect a sample of opposite-sign same-flavor (OSSF) pairs
  - ✦ combinatorial: opposite-sign opposite-flavor (OSOF) pairs

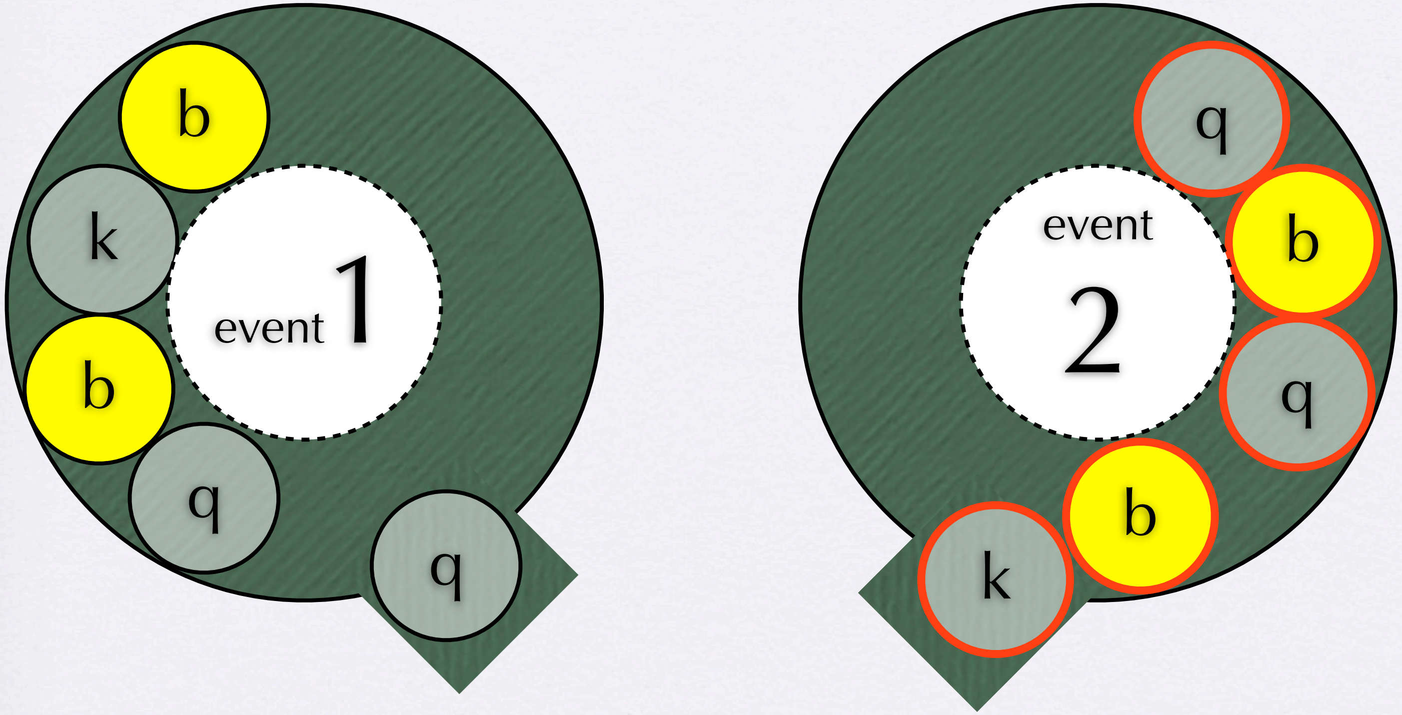
h(OSSF) - C·h(OSOF) in m_{ll} distribution

- However, such a subtraction technique not available for jets
  - ✦ introduce and develop a background subtraction technique

Phys. Lett. B 703 (2011) 475, arXiv:1404.1013, and **CMS PAS TOP-14-011**

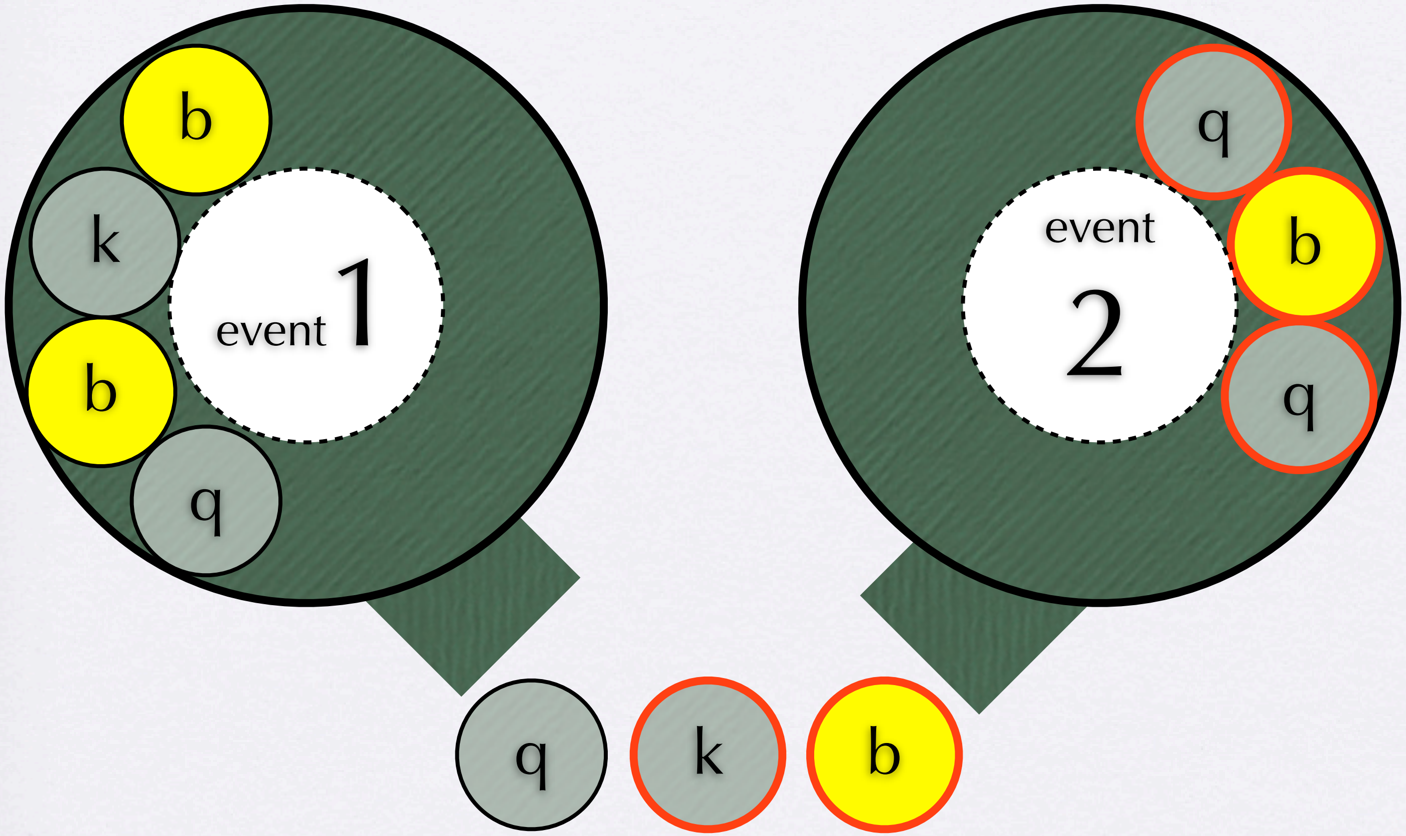
Event mixing

- To estimate the background
  - ✦ mass distribution with combinations of particles from different events (e.g., three jets in top quark reconstruction)



Mixed events

- To estimate the background
  - ✦ mass distribution with combinations of particles from different events (e.g., three jets in top quark reconstruction)



History of event mixing

- Idea came up in the 1970s in the meson physics
  - ✦ interference analyses with di-pion sources: distribution calculated from two pions from different events is used for the modeling of the non-interfering contribution

- Modeling of the combinatorial background in invariant two-particle mass spectra
  - ✦ used to extract ρ and ω resonances from the di-pion spectrum at the ISR storage ring at CERN
  - ✦ provided background predictions in other di-particle mass spectra (kaons, protons, and pions) searching for further resonances and setting limits
  - ✦ but, another experiment found that it is not a suitable method

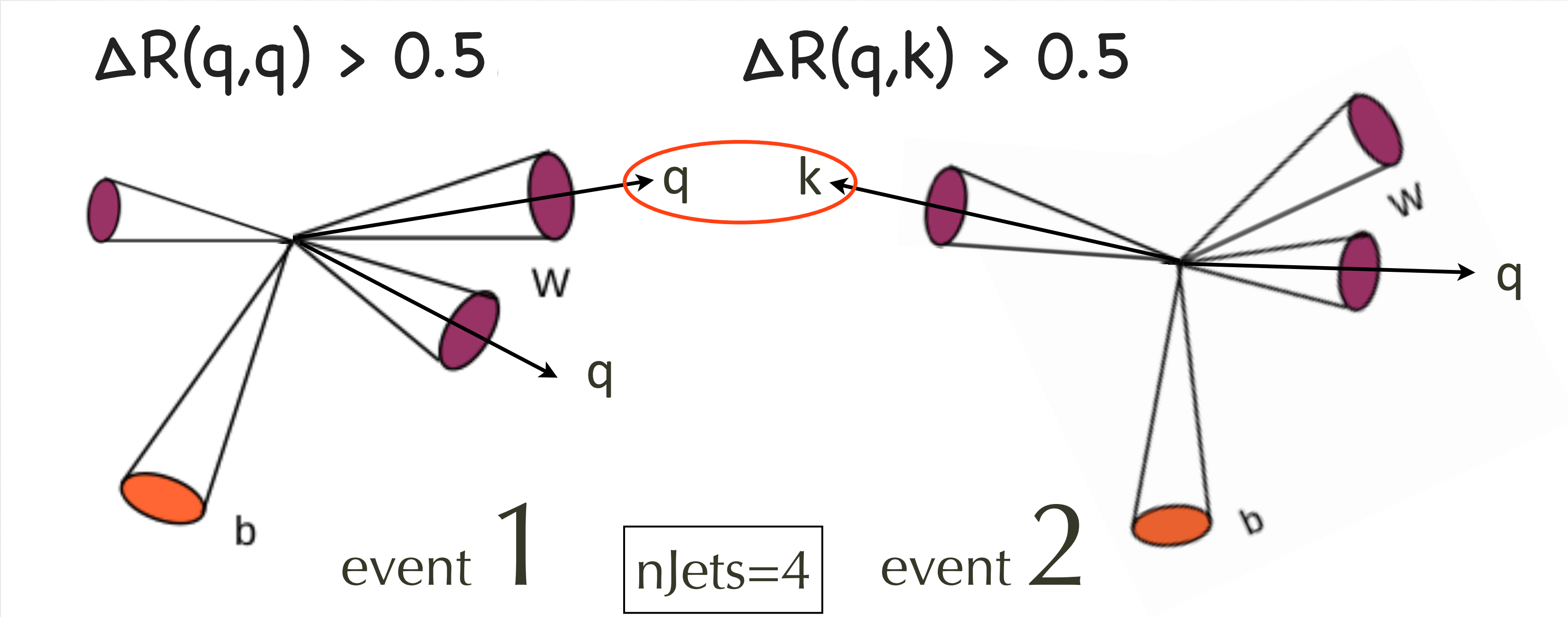
Pros and cons

- Pros
  - ✦ no application of kinematical fitting to reconstruction of decay products of resonances
- Cons
  - ✦ a correlation if
    - ◉ same kinematical restrictions are applied to event mixing
    - ◉ combining two particles from different events whose mass distribution is narrower than that of the combinatorial background

Selection of bi-event

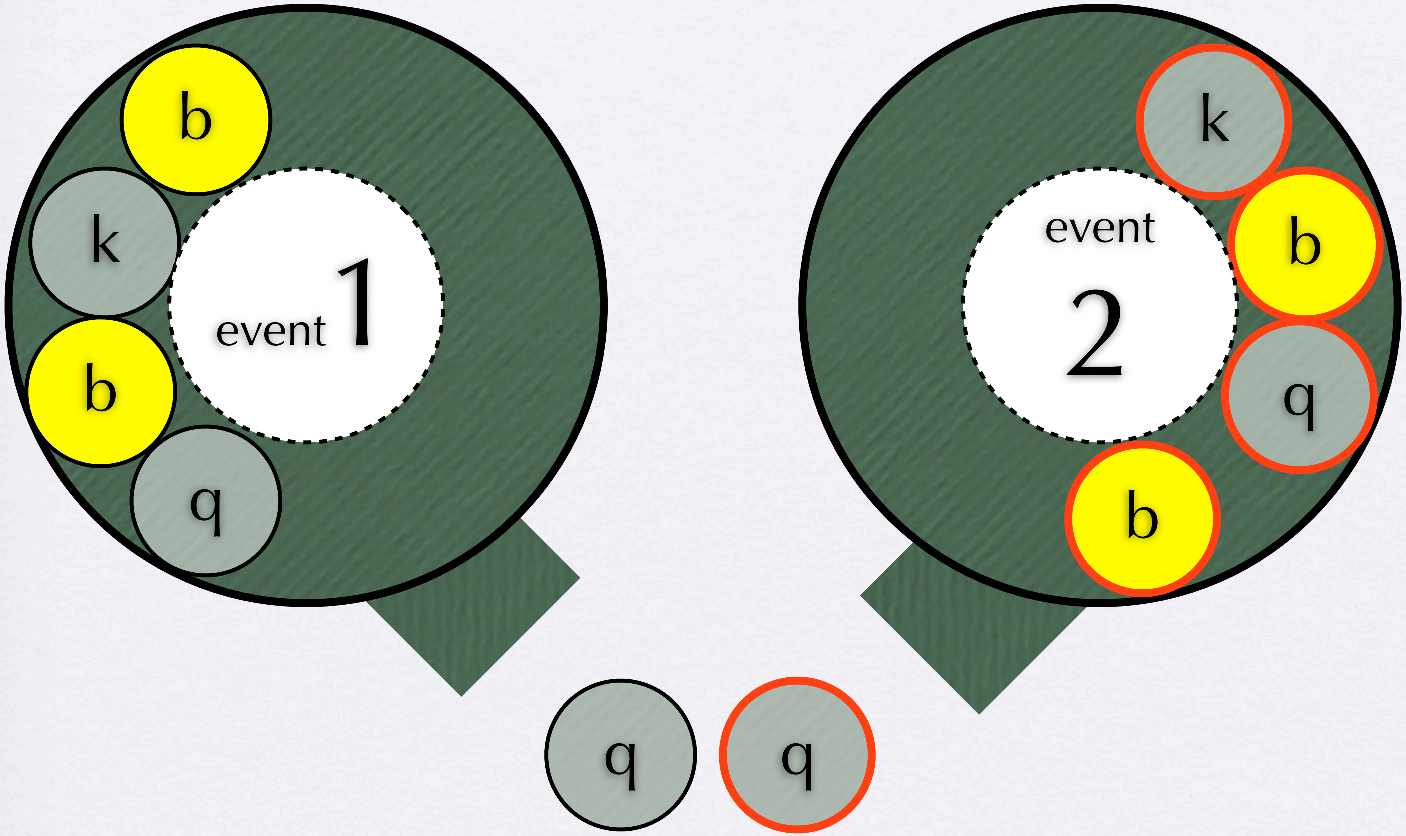
- Most important requirements
  - ✦ mixing events with the same number of jets
  - ✦ mixing jets with the angular separation of $\Delta R > 0.5$

(here, $\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$)



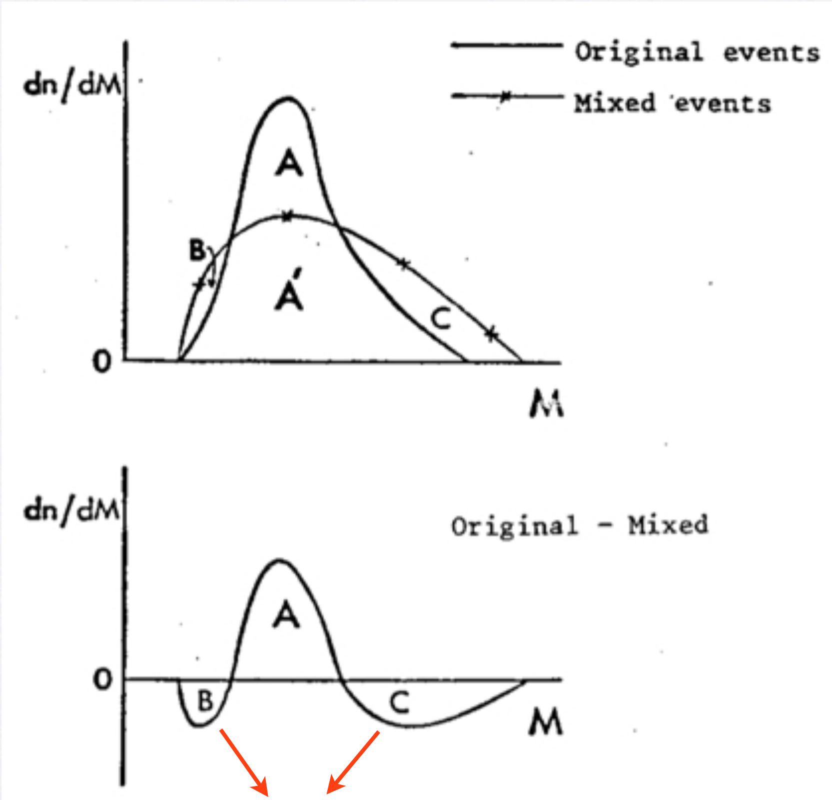
Correlated distribution

- Combining two particles from different events
  - ✦ each jet contributes a resonance (W→qq) in corresponding event



Correction

- Negative in background subtraction due to a correlation induced by event mixing



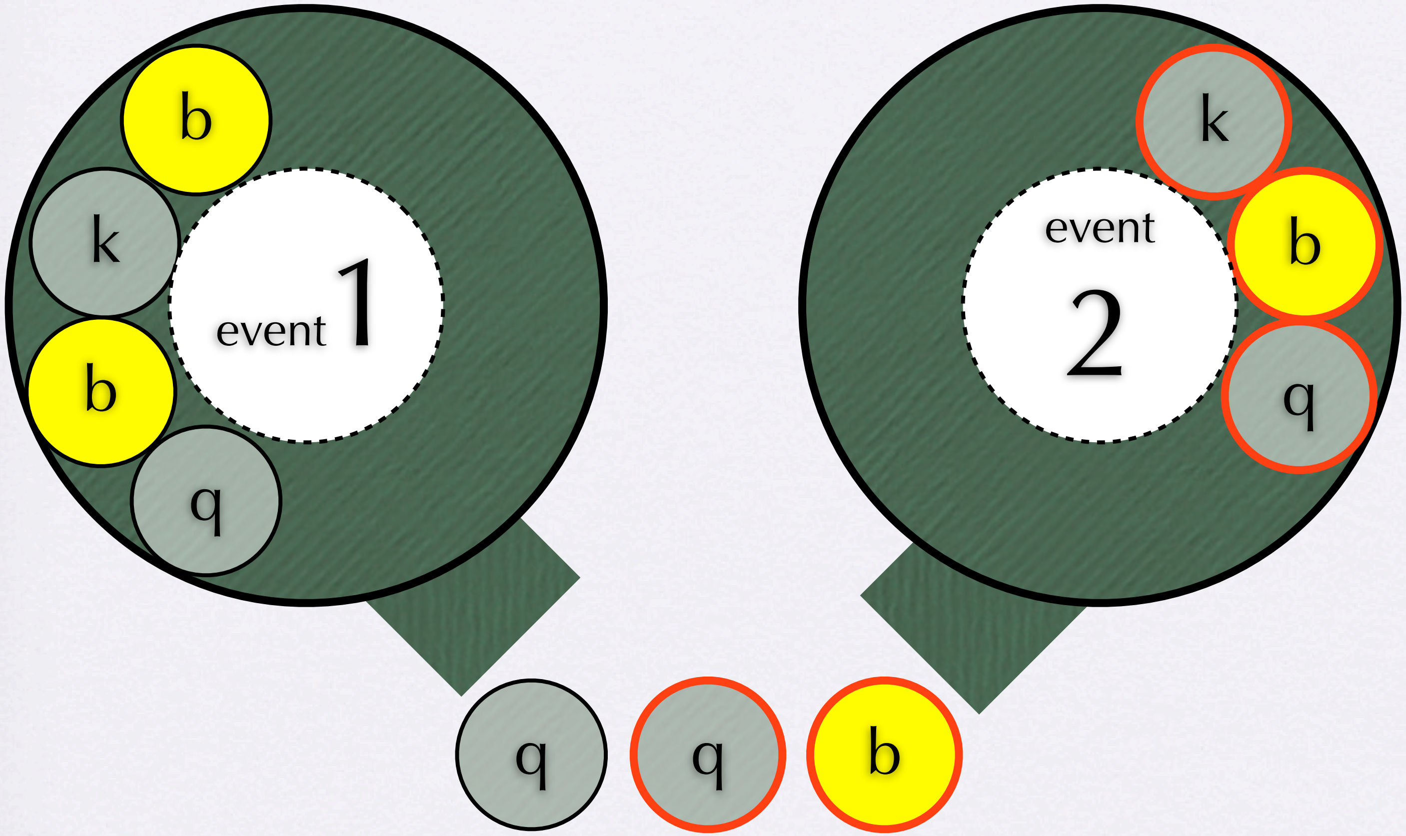
D. Drijard, H. Fischer, and T. Nakada
"Study of Event Mixing and its Application to the Extraction of Resonance Signals"
Nucl. Instrum. Meth. A225 (1984) 367
doi:10.1016/0167-5087(84)90275-8

➔ negative resulted by subtraction

- We should make a correction for this

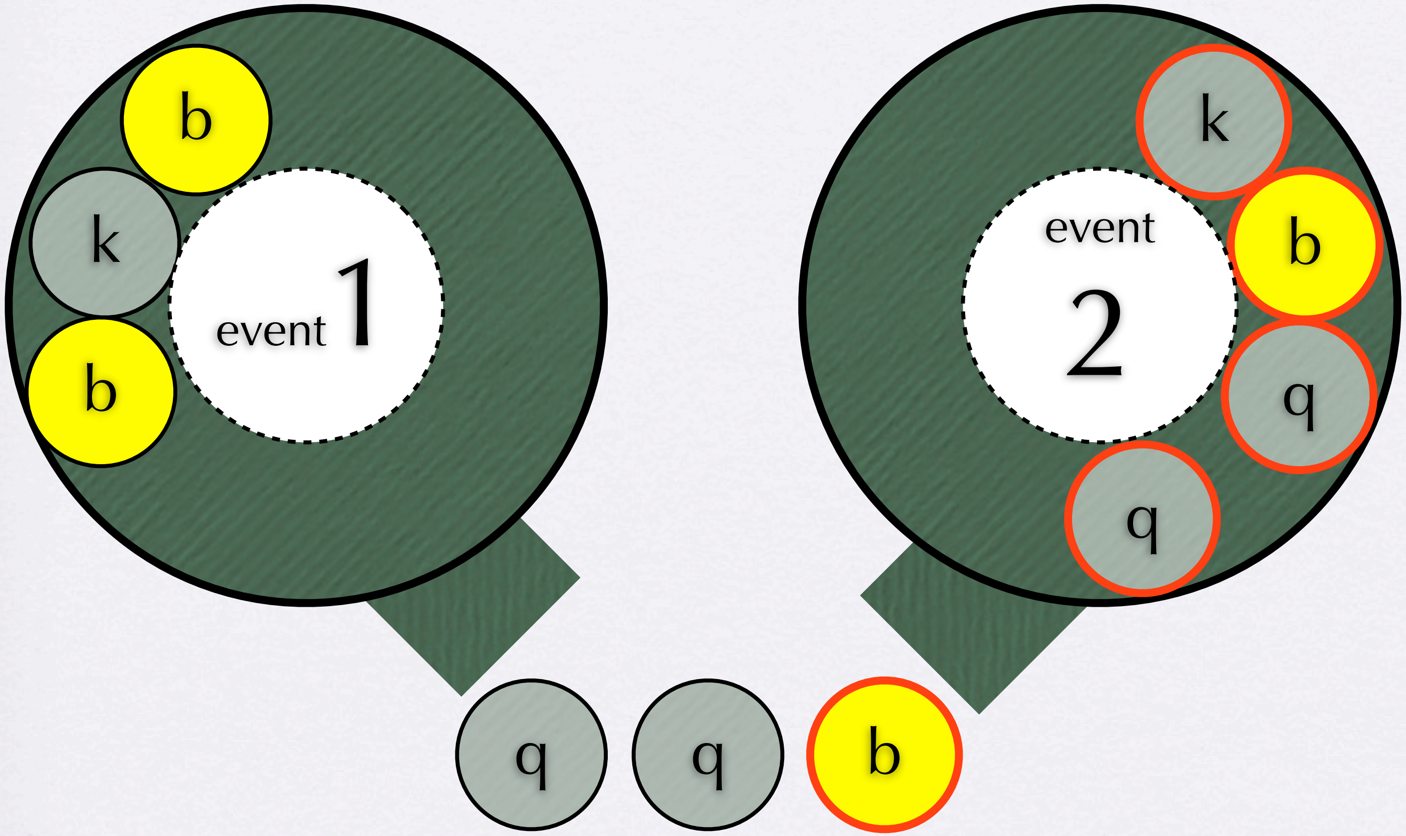
However

- Combining three particles from different events
  - ✦ no such a correlation, thus no correction



Second mixing

- Combining three particles from different events
  - requires that we perform mixing twice taking into account wrong permutation issue

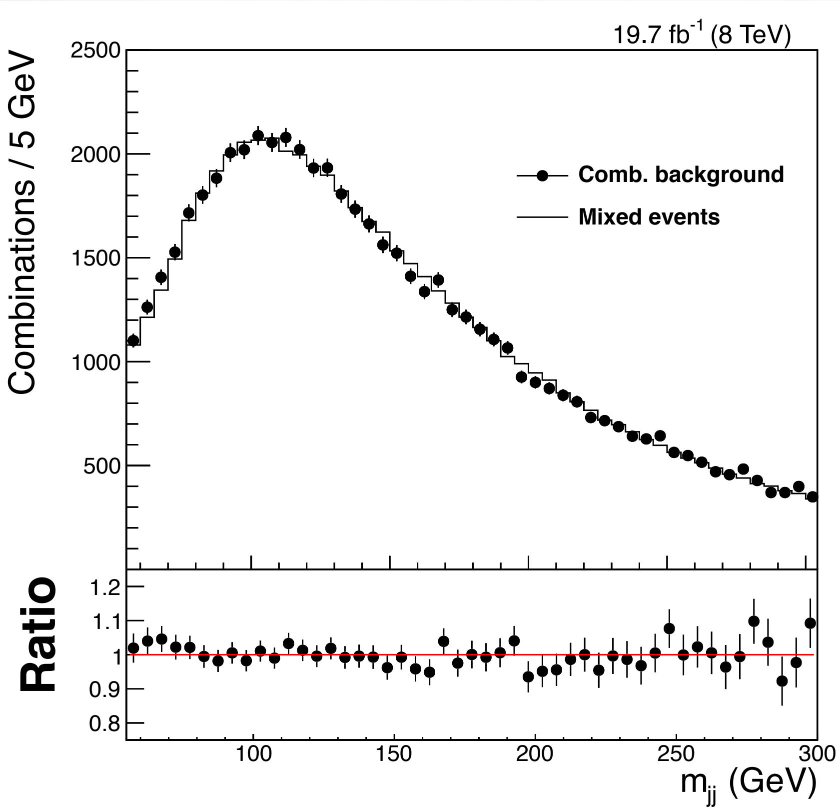


MC simulation

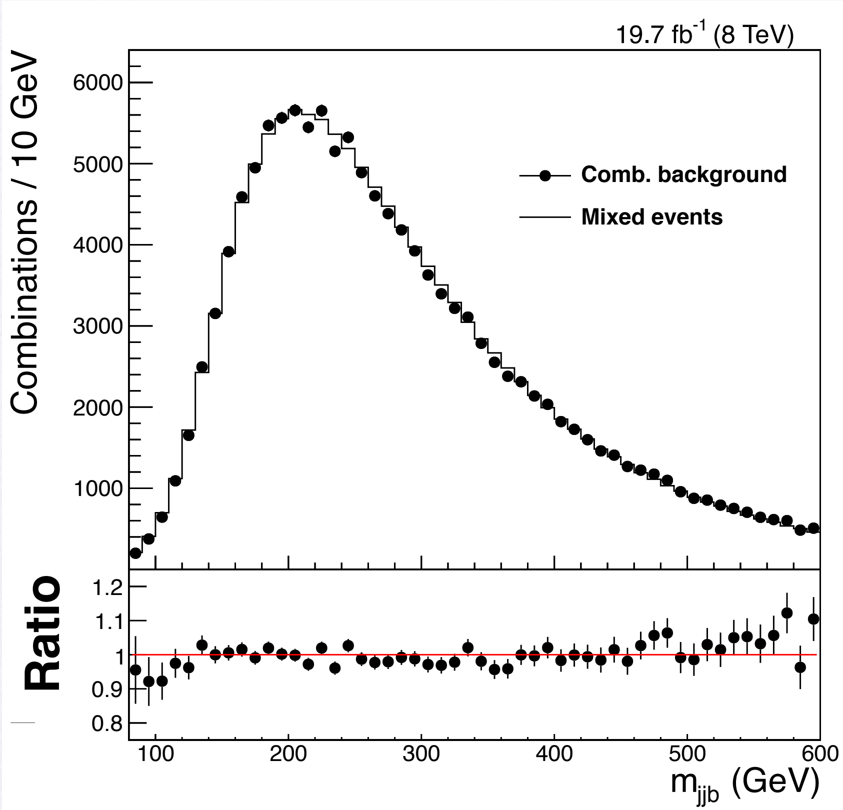
MadGraph+Pythia

- Input: combinatorial background of $t\bar{t}$ + jets events
  - ✦ modeled by event mixing

Di-jets invariant mass



Three-jets invariant mass

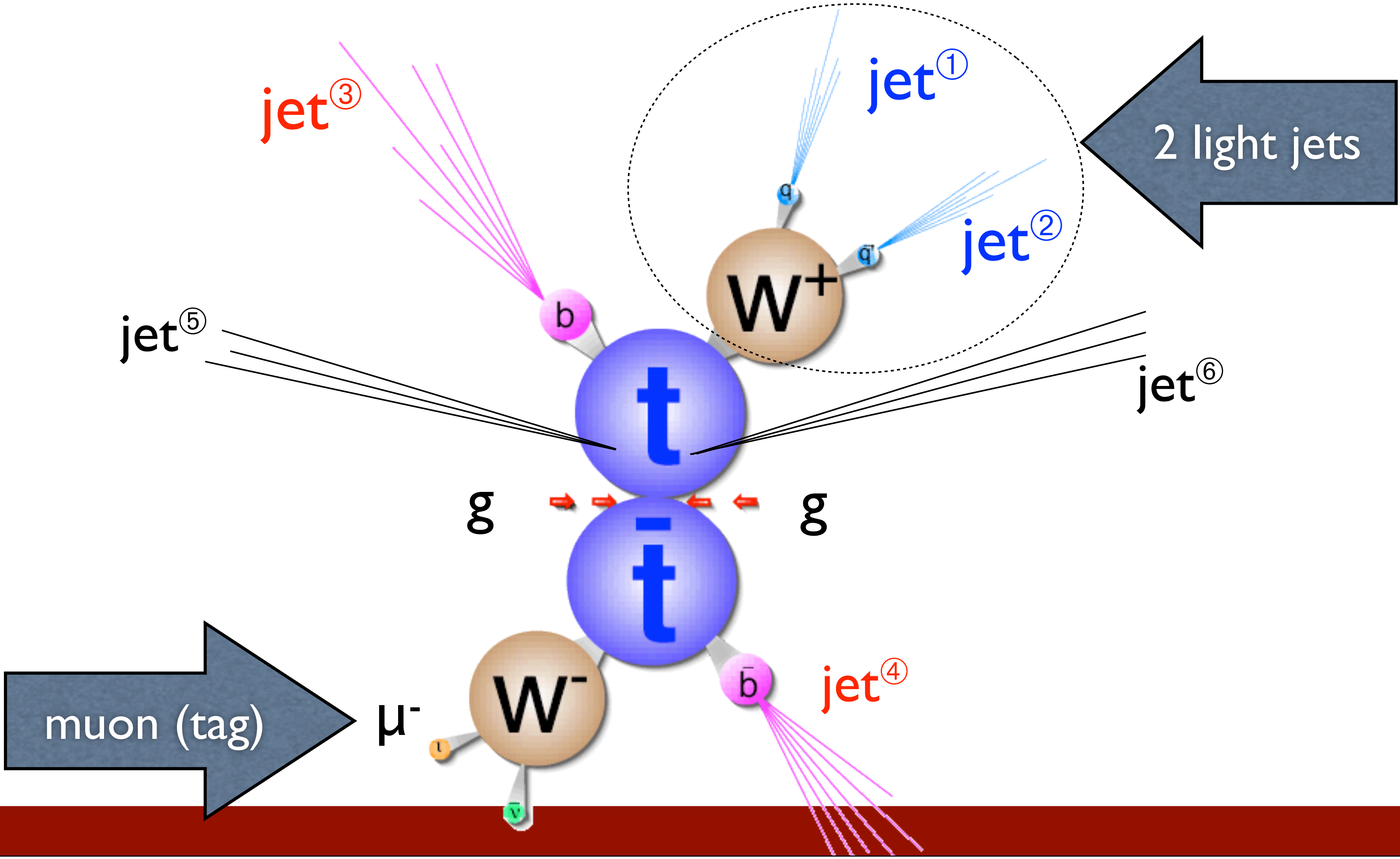


Part 3:
BEST analysis at CMS

- TTbar+jets event
- Basic idea and event mixing
- Analysis strategy
- Signal templates
- Fit to R and mass distributions of pseudo-data
- Fit calibration, validation, and results
- Systematic uncertainties
- Conclusions

TTbar+jets

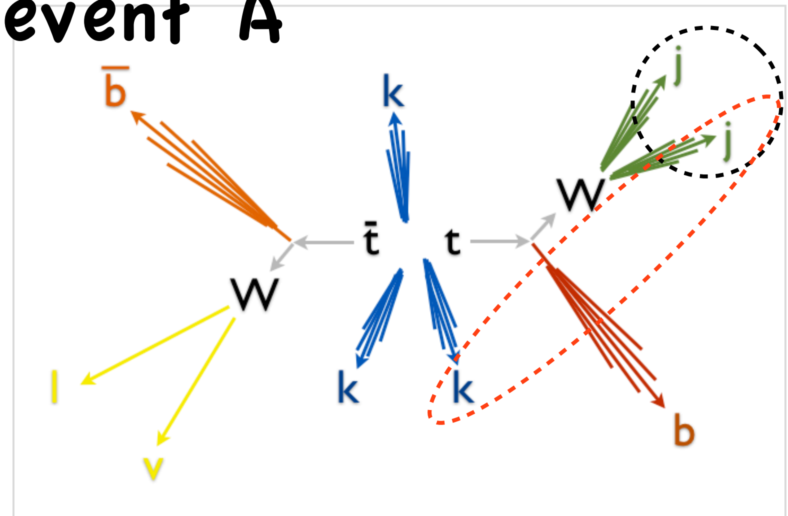
selection: μ + ≥4 jets (≥2 b-jets)



Basic idea of BEST:

Reconstruction of W decaying two jets

event A



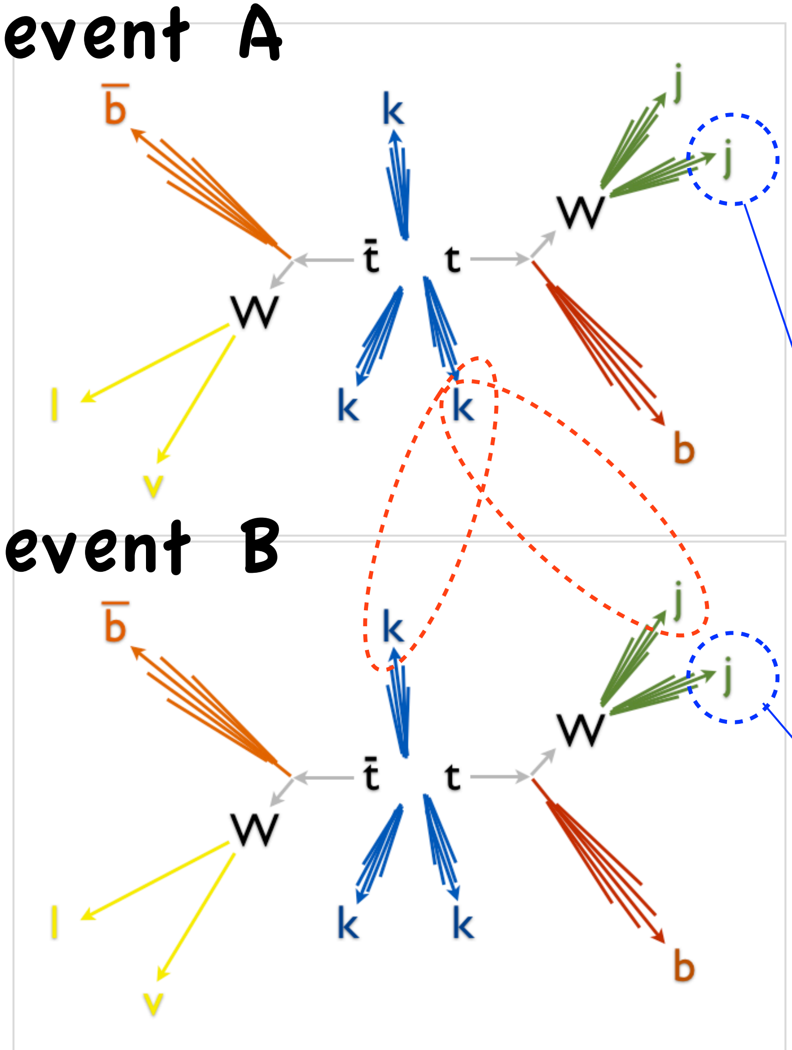
Jet pairs come from the same event

Signal (W→ qqbar)

or

combinatorial background

Event mixing



Jet pairs come from the same event

Signal (W→ qqbar)

or

combinatorial background

Another sample of jet pairs where each jet comes from a different event

Combinatorial background

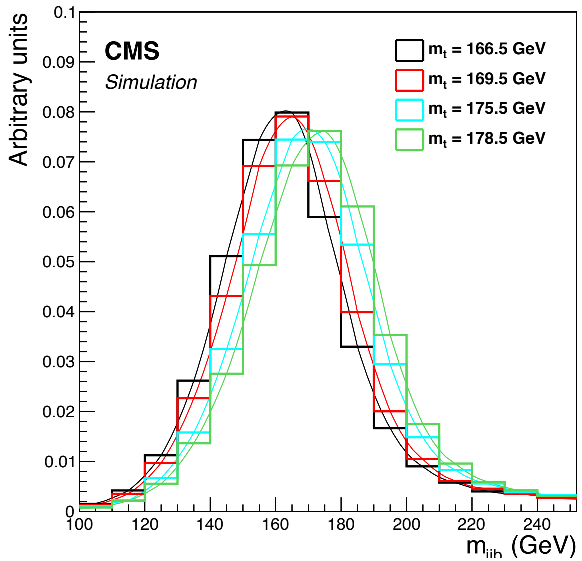
or

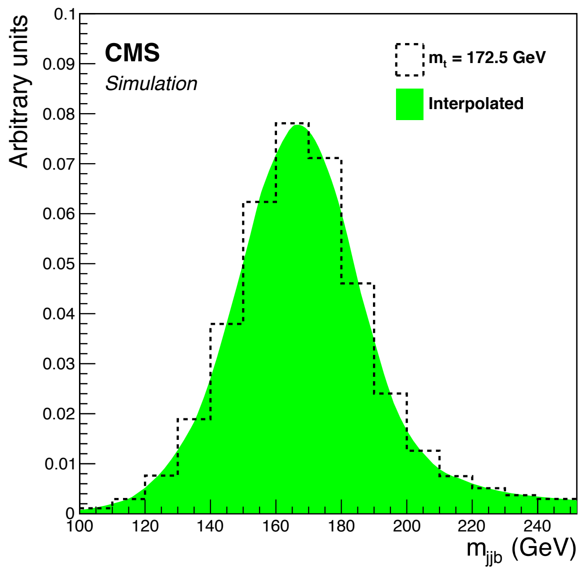
W' → qq' (call bi-W)

Analysis strategy

Event mixing	Background modeling
Histogram morphing	Signal template
Observable, R	Precision improvement

Signal templates





Template histograms morphing

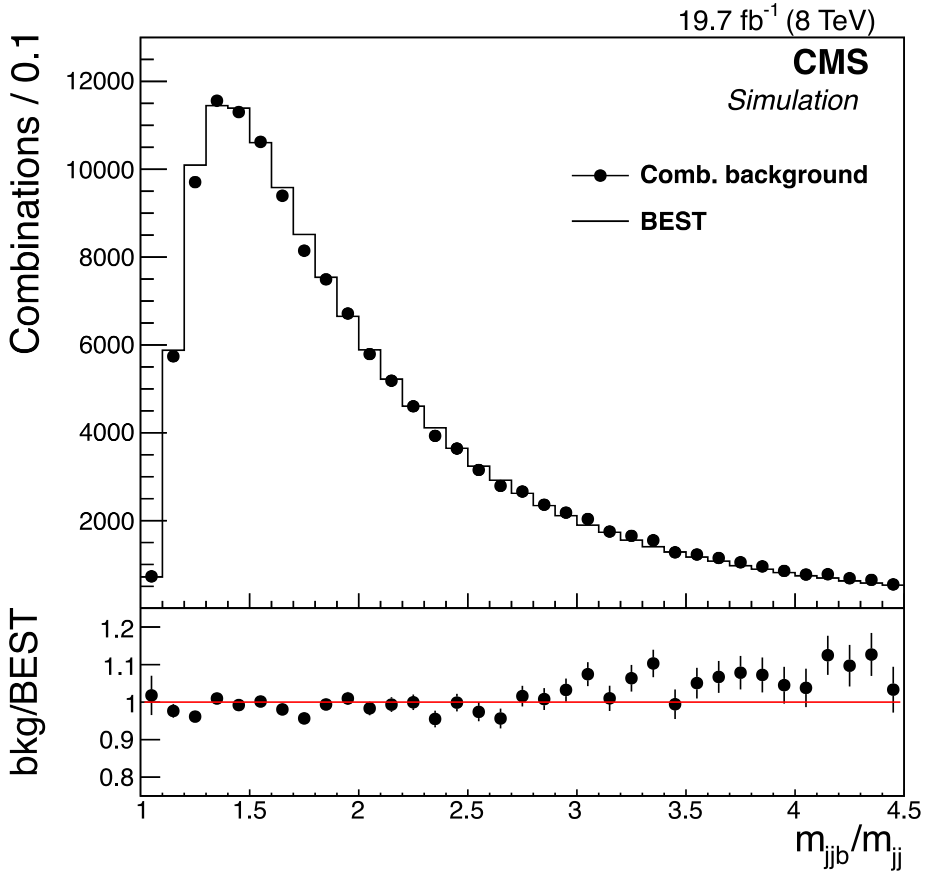
- Signal shape obtained by interpolating histograms between different input values of m_{top} assumed in the simulation
- Histogram interpolated by using RooMomentumMorph from RooFit package
- Performed linear interpolations of mean and sigma at the parameter of interest
- Applied histogram smoothing

➔ Result in good agreement with input

Improve precision

- Use R to reduce Jet energy scale uncertainty

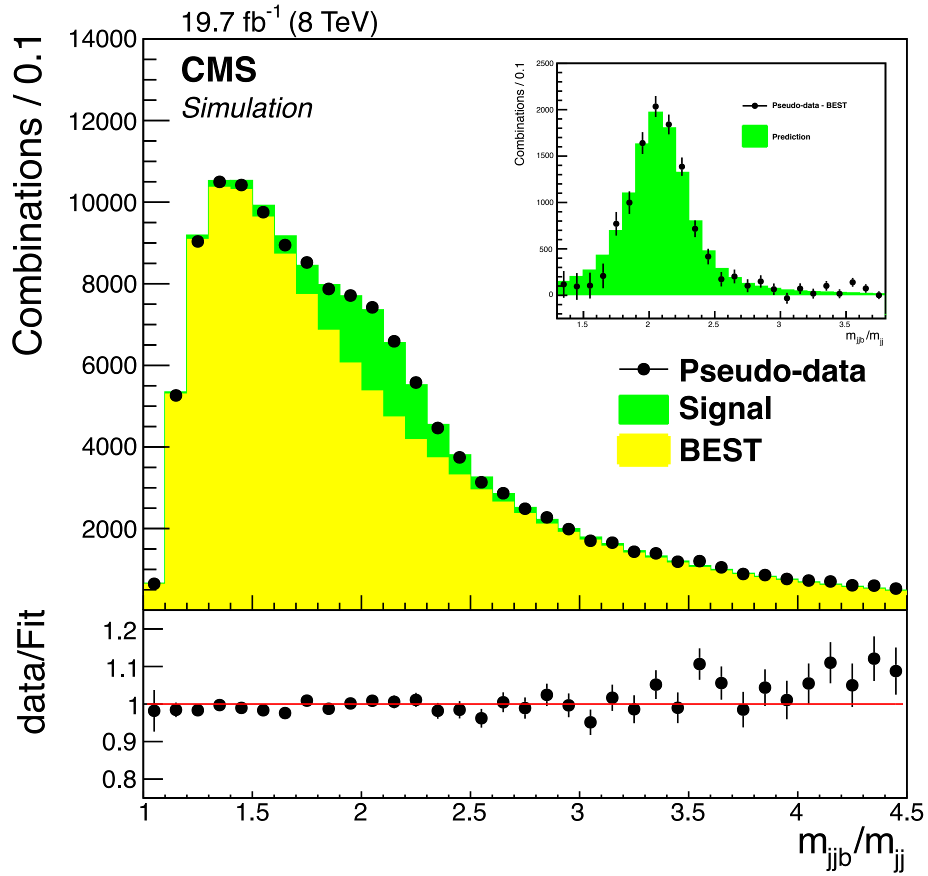
$$R = \frac{m_{jjb}}{m_{jj}}$$



MC top reconstruction

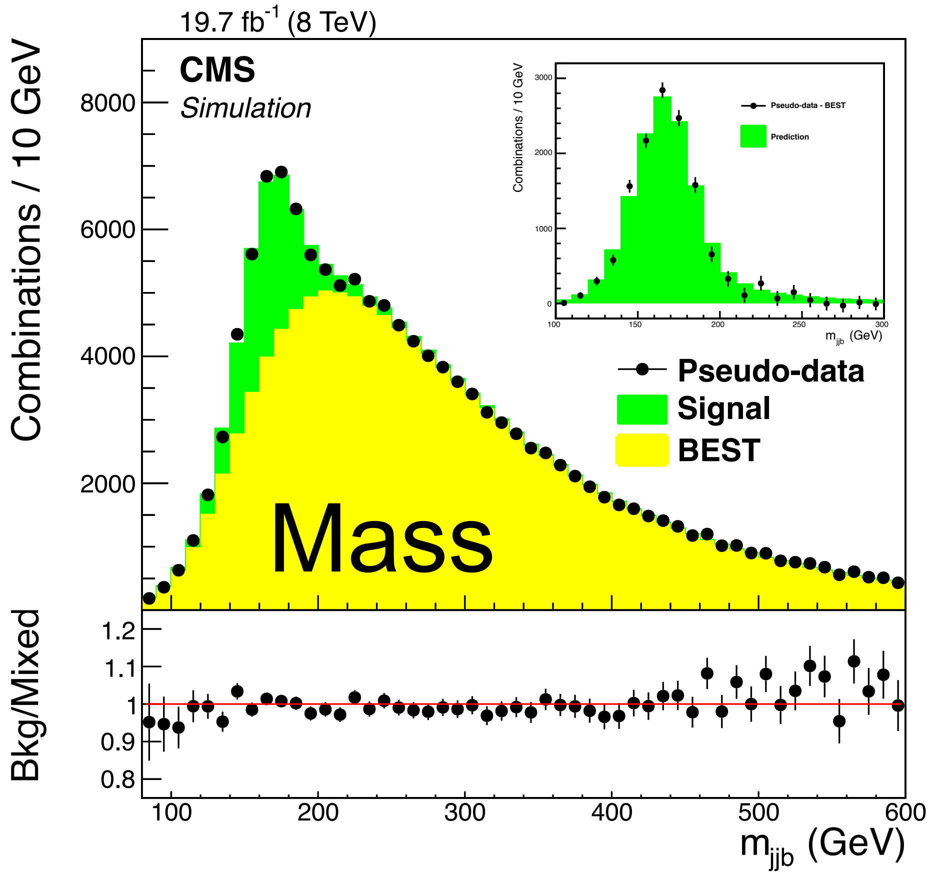
one of pseudo-experiments

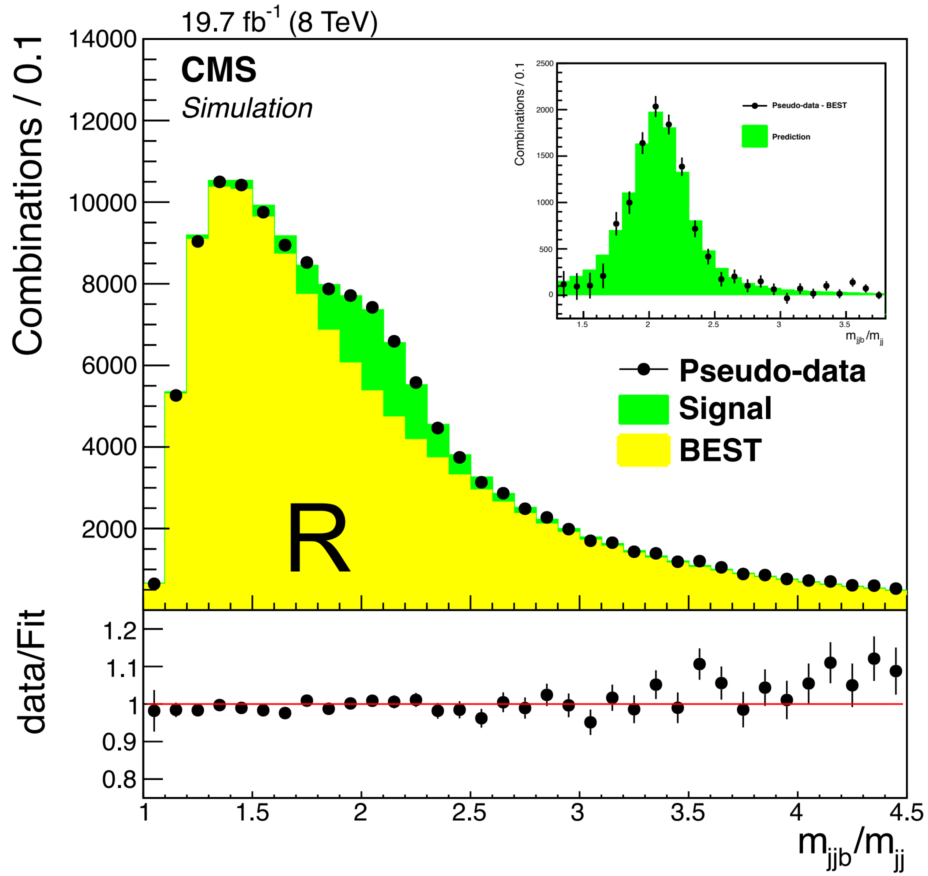
$$R = \frac{m_{jjb}}{m_{jj}}$$



Fit to mass and R

one of pseudo-experiments





Fit calibration

- fit to mass
- fit to R

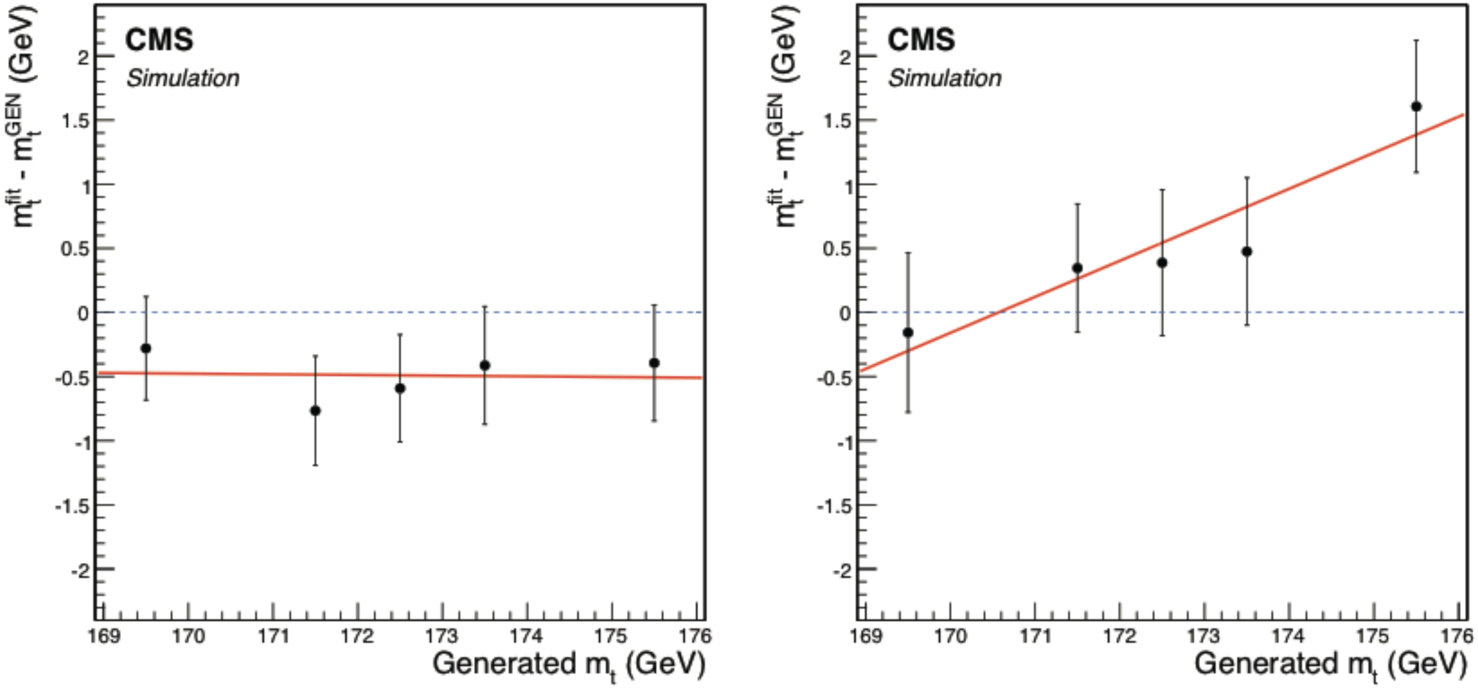


Figure 3: Fit results to the m_{jjb} (left) and R (right) distributions obtained from the pseudo-experiments. The error bars indicate the statistical uncertainty only. The solid line shows the residual biases (fit calibration), while the dashed line shows the expectation of zero. There is a bias as a function of the top quark mass and a correction to the final result was made for this.

Fit validation

- fit to mass

(broad width → stat err underestimated)

- fit to R

(narrow width → stat err overestimated)

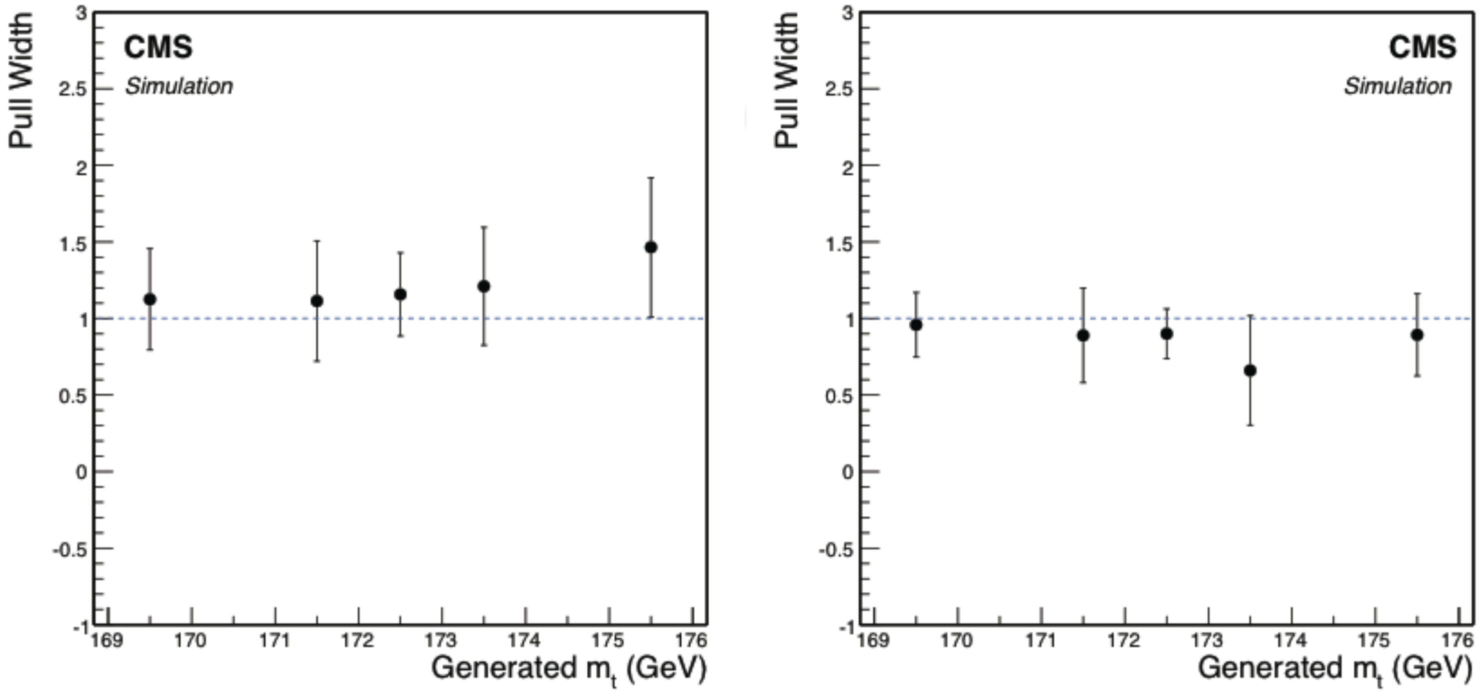
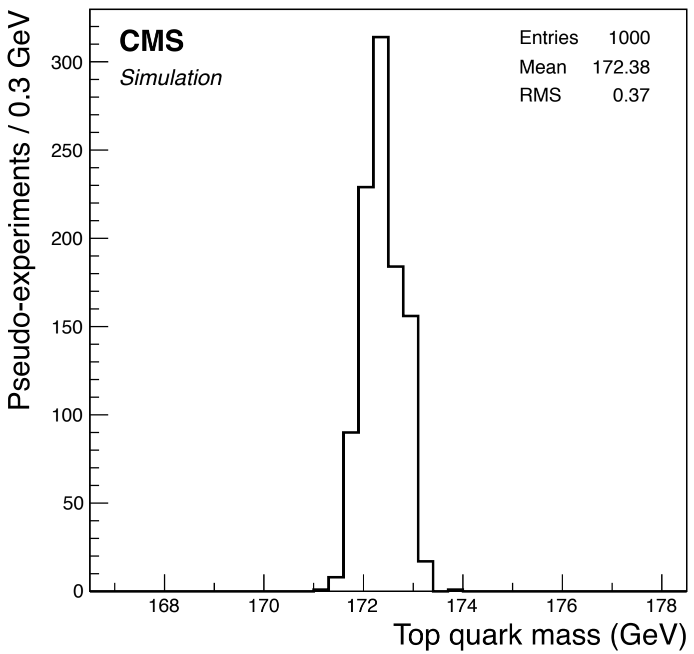


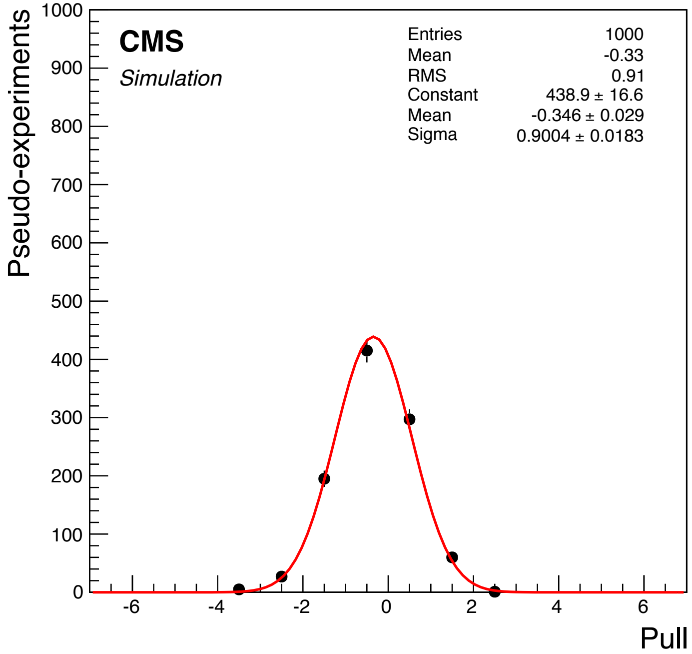
Figure 4: The widths of the pull distributions for the calibrated measurement of m_t as a function of the top quark mass, obtained from the fit m_{jjb} (left) and R (right). Within their statistical uncertainties, the widths are consistent with the expectation of one, shown in the dashed line.

Fit results

obtained from ttbar samples at m_{top}=172.5 GeV, performing pseudo experiments

Fit	Result (GeV)
m_{jjb}	172.40 ± 0.50 (stat.)
m_{jjb}/m_{jj}	172.38 ± 0.40 (stat.)





Systematic uncertainty

investigated with ttbar samples at m_{top}=172.5 GeV, performing pseudo experiments

Sources	fit to m_{jjb}	fit to R
Fit calibration	**0.19**	**0.25**
Bi-W shape	N/A	**0.32**
Non-$t\bar{t}$ background	**0.16**	**0.16**
p_T and η-dependent JES	**1.89**	**0.08**
Flavor-dependent hadronization	**0.50**	**0.36**
b fragmentation and B branching fractions	**0.19**	**0.19**
Jet energy resolution	**0.17**	**0.05**
b tagging efficiency	**0.04**	**0.03**
Pileup	**0.55**	**0.14**
Parton distribution function	**0.11**	**0.13**
Renormalization and factorization scales	**0.35** ± 0.22	**0.38** ± 0.14
ME-PS matching threshold	**0.57** ± 0.26	0.14 ± **0.20**
Signal MC generator	**0.37** ± 0.26	0.08 ± **0.19**
Top p_T reweighting	**0.28**	**0.30**
Underlying event	**0.45** ± 0.27	0.04 ± **0.22**
Color reconnection modeling	0.08 ± **0.23**	0.07 ± **0.16**
Total	**2.28**	**0.84**

fit to R: m_{top}=172.38 ± 0.40 (stat.) ± 0.84 (syst.) GeV

precision of 0.54%

Conclusions

- Latest top mass measurements have a precision level of 0.4%

  → Will be 0.3% in Summer 2015

- Since pre-approved, BEST has been upgraded
  - Combinatorial background only vs. signal + background

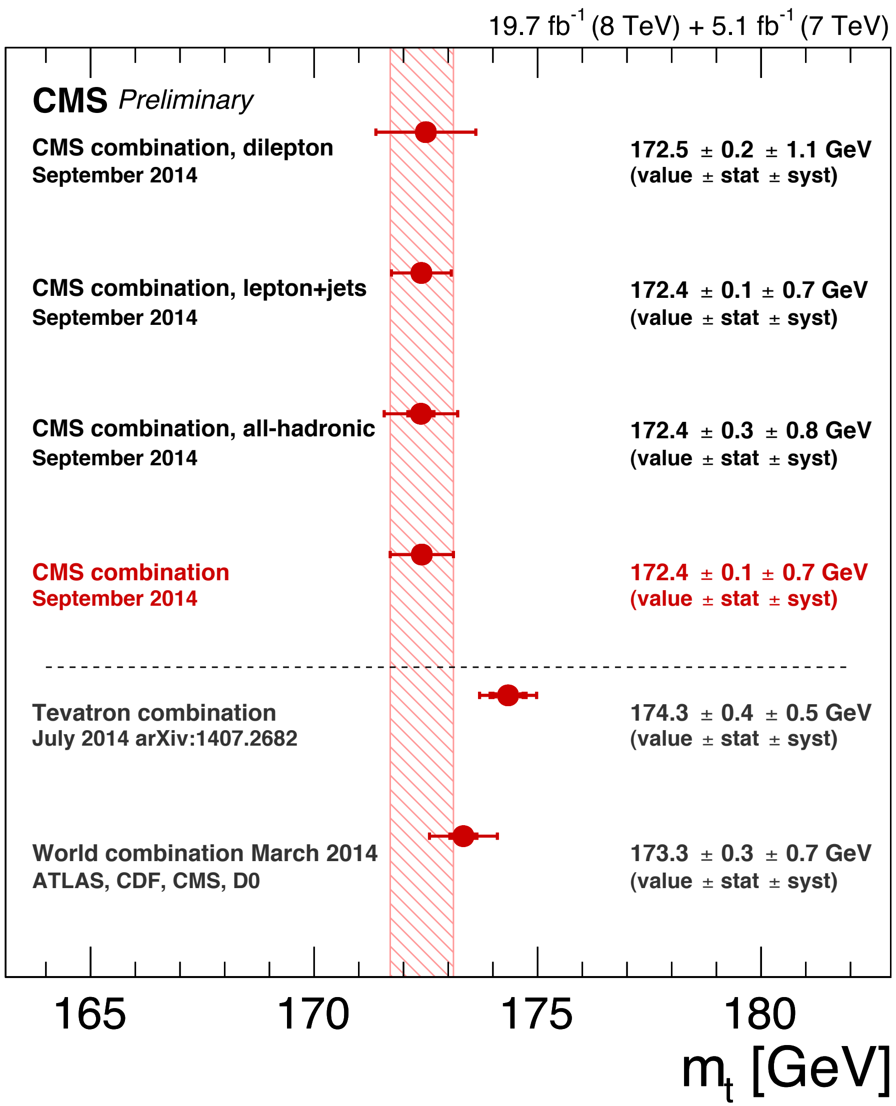
  → In very good agreement

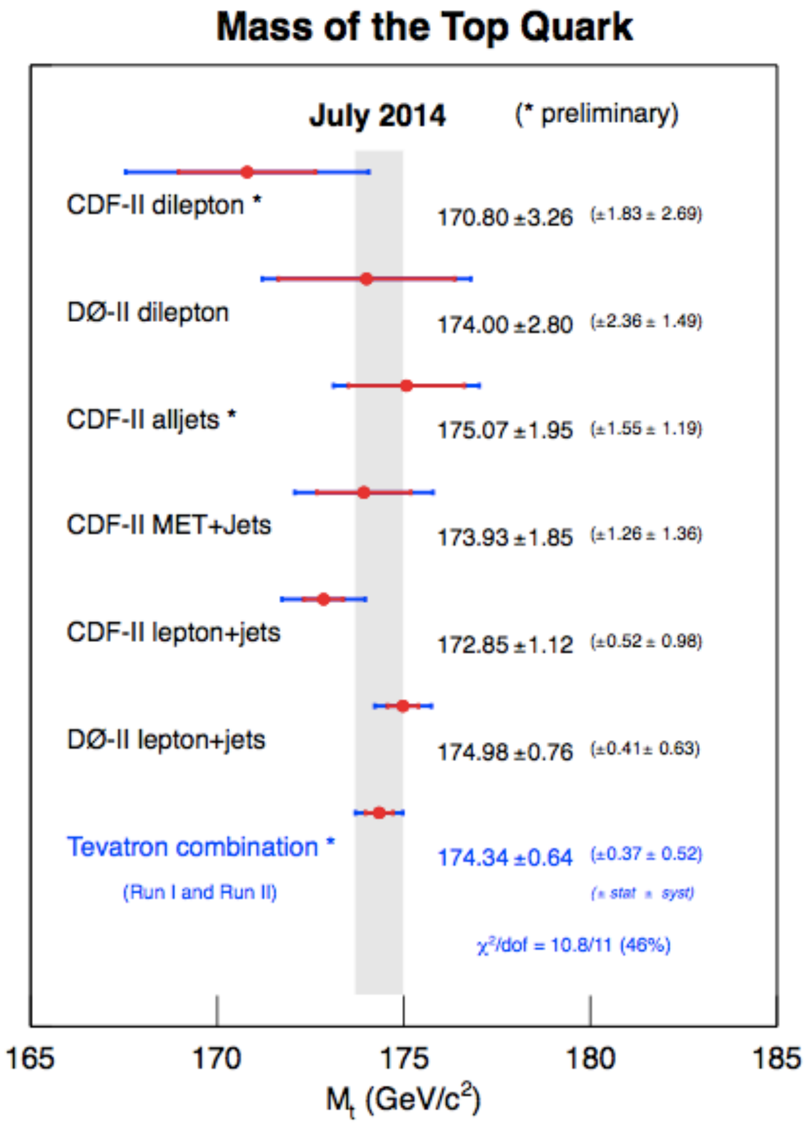
- BEST-assisted R analysis resulted in a precision of about 0.5%

  → Work in progress to green light

Backup

m_{top} per channel





Event mixing upgraded

after pre-approved

- Phase matching: mix if ONLY two events have same jet multiplicity
- Bi-W: jj' is biW while jj'b is NOT
- We need both W mixing and b-jet mixing

	signal	combinatorial	mixing (biW to be removed)
dijet	jj	jk, kk.....	jj', jk', kj', kk'...
jet triplet	jjb_{had}	jjb_{lep}, jkb, kkb...	jj'b, jk'b, kj'b, kk'b..., and jjb'

Mixing components	
W	b
↓	↓

$$\mathcal{P}_{combinatorial}(j,k,b;m_{top},R) \sim \mathcal{P}_{best}(j',k',b';m_{top},R) = \mathcal{P}_{best}^{W} \oplus \mathcal{P}_{best}^{b}$$

Fitting parameters

- Three parameters for m_{jj} and R: m_{top}, f_{sig}, and f_{biW}
  - f_{biW} : a fraction of the biW background to the background modeled by BEST
    - Note: m_{jjb} doesn't need, thus two parameters: m_{top} & f_{sig}
  - f_{sig} : signal fraction
- Distribution fitting with probability density function
  - $N_{bkg} \cdot [\, f_{biW} \cdot P_{biW} + (1 - f_{biW}) \cdot P_{best} \,] + N_{sig} \cdot P_{sig} = N_{obs}$
  - $(1 - f_{sig}) \cdot [......] + f_{sig} \cdot P_{sig} = 1$
    - Here, $f_{biW} \cdot P_{biW} + (1 - f_{biW}) \cdot P_{best}$ for BEST correction

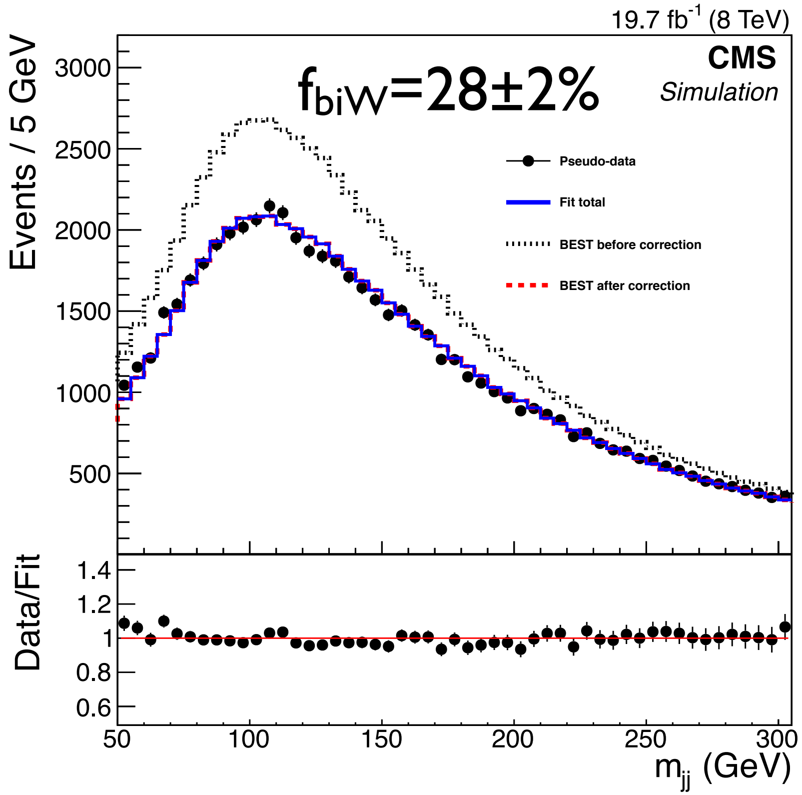
MC closure test

- Run 1000 pseudo-experiments
  - obtain f_{biW} from $\mathcal{P}_{best}{}^{W}$ and $\mathcal{P}_{best}{}^{W} \oplus \mathcal{P}_{best}{}^{b}$
  - plots from one pseudo-experiment as an example
- Results from two cases
  - [Left] combinatorial background only (i.e, $f_{sig} = 0$)
  - [Right] signal + combinatorial background
- Results from fit to m_{jj} and R are shown in order

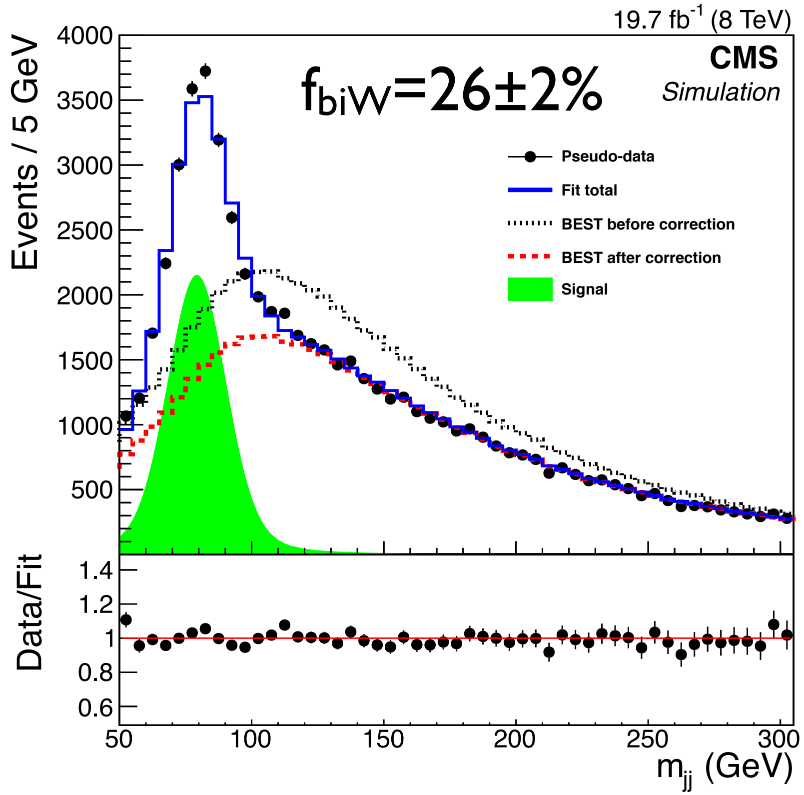
For W reconstruction (m_{jj})

$\mathcal{P}_{best}^{W}$

case: combinatorial background only (i.e, f_{sig}=0)



signal + background



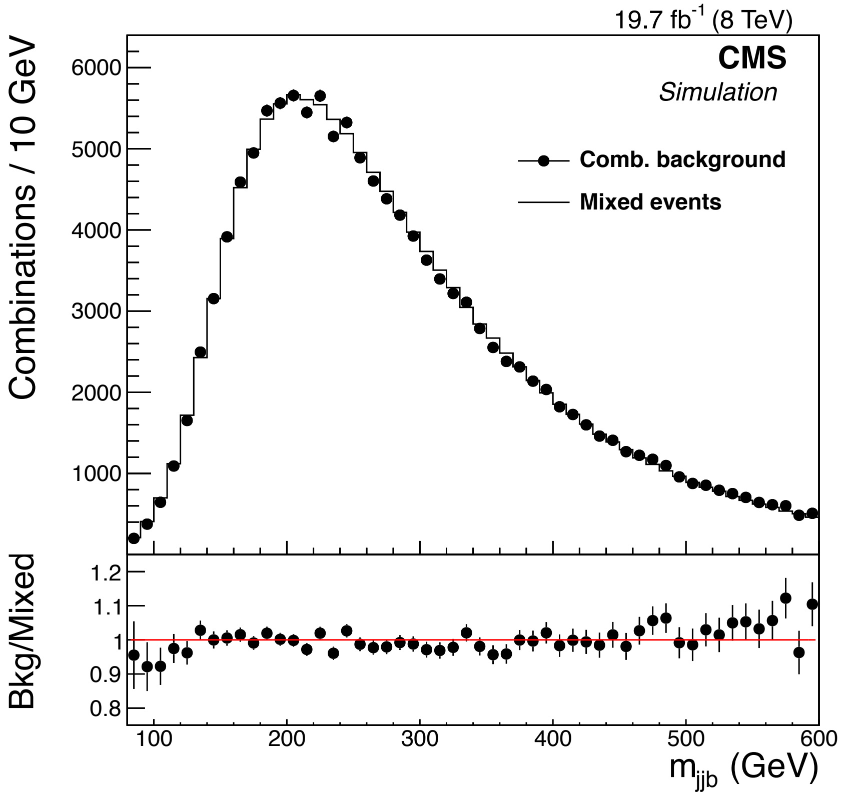
On the left, red dashed lines (BEST after correction) = blue (Fit total)

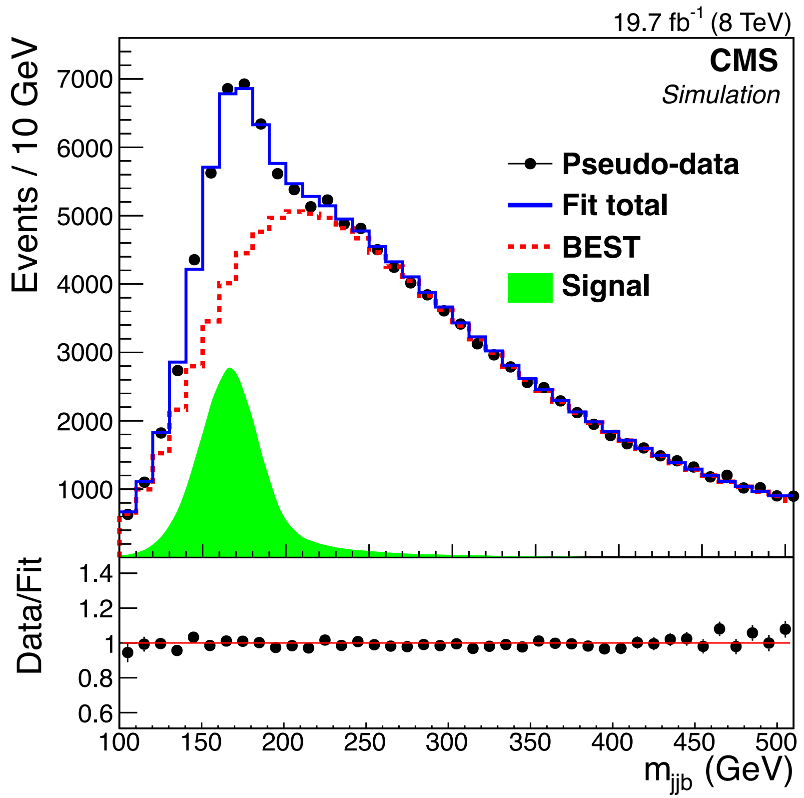
For Top reconstruction (m_{jjb})

$\mathcal{P}_{best}{}^{W} \oplus \mathcal{P}_{best}{}^{b}$

case: combinatorial background only
(i.e, f_{sig}=0)

signal + background





Dataset and event selection

CM energy : 8 TeV

MC : TTJets (MadGraph+Pythia) - PU reweighting & SFb

DATA : 2012 full (19.7 fb^{-1})

JEC levels			
L1FastJet	L2Relative	L3Absolute	
	same to MC		+ L2L3Residual

Event selection:

- Single mu triggered dataset (HLT_IsoMu24_eta2p1)
- One isolated muon with $|\eta| < 2.1$ (Veto muons from dilepton and lepton+jets channels)
- ≥ 4 jets with $p_T > 35$GeV
- ≥ 2 b tagged jets

High purity after event selection

Jet reconstruction and selection:

- Particle Flow, Anti-kT (R=0.5) with JES and JER
- $p_T > 35$GeV, $|\eta| < 2.4$
- b-tagging algorithm based on CSVM

W and top quark reconstruction:

- No overlap between jets ($\Delta R > 0.5$)
- 2 untagged jet for W and W+b for top quark
- No lepton/MET required for mass reconstruction

Template, Matrix-Element methods

- Methods inherited from Tevatron and used at LHC
  - aims at best exploitation of small data statistics

Principle Calibrate with Monte Carlo → Fit data and extract m_{top}^{MC}

- Compare m_{top}-dependent observables with MC predictions
- Fit best mtop value and likelihood of the event to be consistent with ttbar + background → greater weight for higher likelihood
- Constraint on W-mass (lepton+jets)

Observable with highest impact

- Reconstructed top invariant mass distribution

Problems addressed:

- Mismatch $E_{measured}$ vs. E_{true} (jet energy scale, b-jet energy) → detector issues
- MC description of radiation (jet cone), underlying event → MC uncertainties

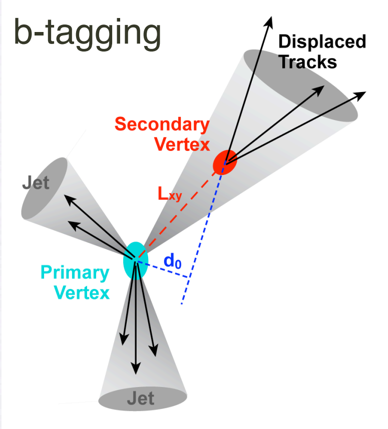
Problems not addressed what is m_{top} in PYTHIA?

- Additional conceptual uncertainty in m_{top} in PYTHIA: O (1 GeV)

Experimental ingredients

Standard methods in lepton + Jets channel as example

- Isolated leptons (electron, muon or tau)
  - isolation cuts against QCD backgrounds
- Jet (and Missing E_T)
  - particle flow (combining tracking & calorimetry at particle level, before jet clustering)
  - optimal resolution and scale uncertainties
  - minimal flavor-dependent energy response differences
- Pileup subtraction
  - based on charged component
- b-tagging
  - combination of several techniques



Alternative approaches

aiming for improved understanding

- Alternative methods to m_{top} are considered
  - probe m_{top} invariant mass observable in different corners of phase space
  - provide consistency checks
  - factorize specific systematic uncertainties
  - impact final combination or backup if the standard methods do not evolve as initially projected

→ *having different systematics from the standard methods*