Measurement of the top quark mass in $t\bar{t}$ events with a J/ψ

top-LHC-France 2016

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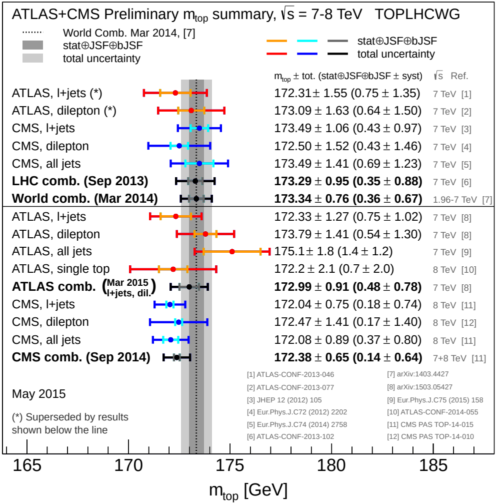
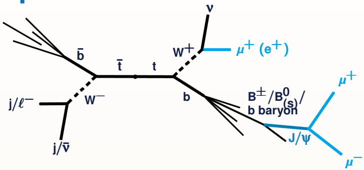
Top quark mass measurements at Run I



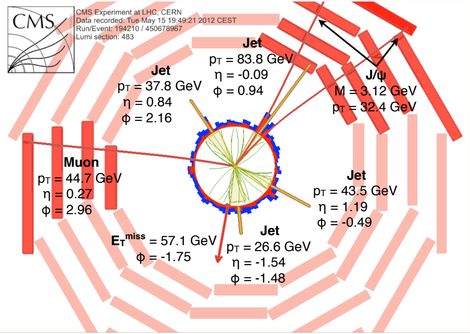
Reconstructing all the top quark decay products:

- total uncertainty dominated by **systematic uncertainties**
  - strongly **correlated** between decay channels, methods, and experiments
  - mostly due to **b-jet energy scale**, **color reconnection**, and ISR
- need of **"alternative" measurement** methods

Leptonic final states with $b \rightarrow J/\psi + X \rightarrow \mu^+\mu^- + X$



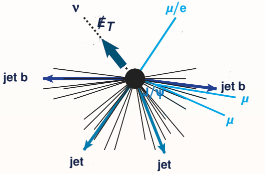
- Based on the correlation between M_t and the invariant mass of the $J/\psi + \ell$ combination
  CERN/LHCC92-3 (1992) 90, PLB476(2000)73, ATL-PHYS-2001-016, CMS-NOTE-2006-058
- Systematic uncertainty expected to be **weakly affected by jet energy scale, not affected by b-tagging**, but **sensitive to soft QCD modeling**



- Branching ratio: $BR(t\bar{t} \rightarrow (W^+b)(W^-\bar{b}) \rightarrow (\bar{\ell}\,\nu_\ell\, J/\psi\, X)(qq'\bar{b})) \sim 0.55\%$
  only $J/\psi \rightarrow \mu^+\mu^-$ and $\ell \in \{e, \mu\}$: $\boldsymbol{BR \sim 2.1 \cdot 10^{-4}}$
  ↪ **1st time** that this method is used: 8 TeV data
  - 19.7 fb^{-1} with CMS: CMS-PAS-TOP-13-007, arXiv:1603.06536[hep-ex], CMS-PAS-TOP-15-014
  - 20.3 fb^{-1} with ATLAS: ATLAS-CONF-2015-040

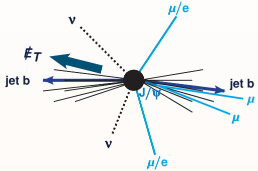
Selection criteria

Semileptonic $t\bar{t}$ events with a J/ψ



- exactly 1 isolated $\ell^\pm$
- ≥ 4 **jets** with $p_T > 25$ **GeV** *(ATLAS)*
  or ≥ 2 **jets** with $p_T > 40$ **GeV** *(CMS)*

Dileptonic $t\bar{t}$ events with a J/ψ



- exactly 2 isolated $\ell^\pm$ of opposite sign
- ≥ 1 **jets** with $p_T > 25$ **GeV** *(ATLAS)*
  or ≥ 2 **jets** with $p_T > 40$ **GeV** *(CMS)*

- exactly 1 $J/\psi \to \mu^+\mu^-$ candidate

for ATLAS

- $p_T(\mu^\pm) > 3$ GeV, $|\eta| < 2.5$
- $IP_\perp$, $IP_\parallel < 3$ mm
- $M(J/\psi) \in [2.9; 3.3]$ GeV

for CMS

- $p_T(\mu^\pm) > 4$ GeV, $|\eta| < 2.4$, in the **same jet**
- vertex fit with a Kalman filter: $\chi^2 < 5$
- $c\tau/\Delta c\tau > 20$
- $M(J/\psi) \in [3.0; 3.2]$ GeV

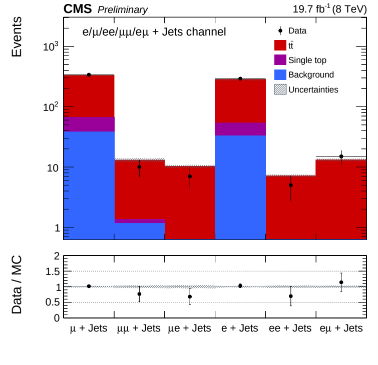
Event yields

- MC samples normalized at the integrated luminosity and their theoretical cross section
- $t\bar{t}$ samples produced for $M_t = 172.5$ GeV

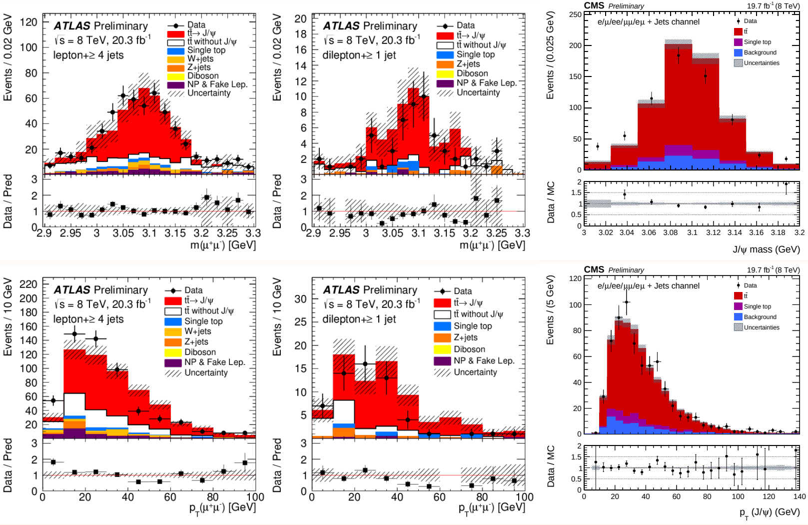
  for ATLAS: with POWHEG (CT10) + PYTHIA 6 (P2011C) + **EVTGEN** + TAUOLA

  for CMS: with MADGRAPH (CTEQ6L1) + PYTHIA 6 (Z2*) + TAUOLA

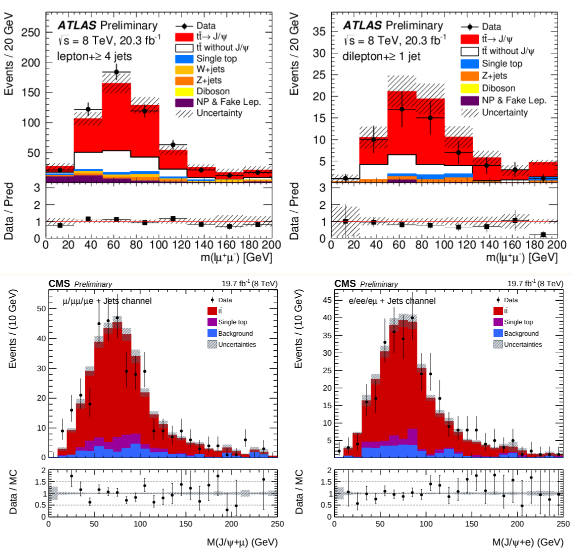
Process	Number of events ATLAS	CMS
$t\bar{t}$	520 ± 23	548 ± 6
single top	24 ± 5	70 ± 5
Z + jets	22.7 ± 4.8	10.8 ± 1.3
W + jets	22.6 ± 4.7	30.4 ± 4.2
Diboson	1.2 ± 1.0	2.3 ± 0.3
Total expected	609 ± 25	662 ± 9
Data	625	666



J/ψ properties

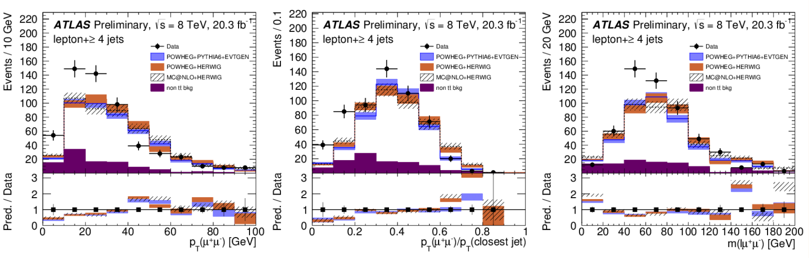


$J/\psi + \ell$ properties



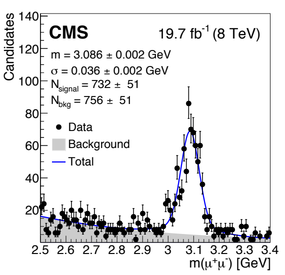
Hadronization modeling

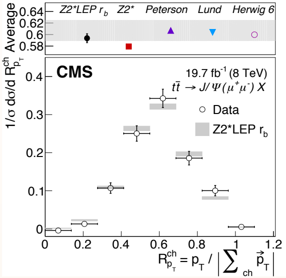
- **Charged leptons** better reconstructed and less affected by pileup
  $\hookrightarrow$ use of $J/\psi \to \mu^+\mu^-$ to probe b quark hadronization modeling
- Comparison between the **cluster model** (HERWIG) and the **Lund string model** (PYTHIA)



Fragmentation parameters

- arXiv:1603.06536[hep-ex] uses a different strategy for $J/\psi \to \mu^+\mu^-$ reconstruction in $t\bar{t}$ events
  $\hookrightarrow$ signal isolated from combinatorial background using $_s$Plot weights

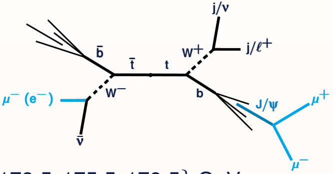




- **Bigger differences between fragmentation parameter sets** than between hadronization models
- **Not enough data** at $\sqrt{s} = 8$ TeV to rule out a set
  $\hookrightarrow$ other charmed mesons ($D^{\pm}$, D^{*}, D^{0},...) could also be used

Fit procedure

- **Summing all events**:
  - distributions for $J/\psi + e$ or $J/\psi + \mu$ final states reasonably well described by the MC, no significative differences between the channels
  - "wrong" pairings less sensitive to M_t, but still maintaining a correlation to M_t



- Six $M_{J/\psi+\ell}$ distributions, for $M_t \in \{166.5; 169.5; 171.5; 173.5; 175.5; 178.5\}$ GeV : **all processes are summed up** after normalization at their respective cross-section

  $\hookrightarrow$ background processes: same $M_{J/\psi+\ell}$ distribution $\forall M_t$

  $\hookrightarrow$ signal processes ($= t\bar{t} +$ single-top): different $M_{J/\psi+\ell}$ distribution for each M_t

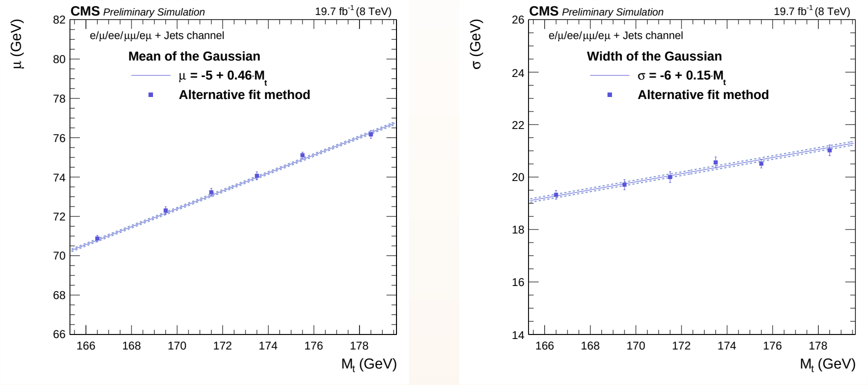
- **Simultaneous fit** of the six $M_{J/\psi+\ell}$ distributions between 0 and 250 GeV with the following PDF:

$$P_{\text{sig+bg}}(M_{J/\psi+\ell}) = \alpha \frac{1}{\sigma_g \sqrt{2\pi}} \exp\left(-\frac{(M_{J/\psi+\ell} - \mu_g)^2}{2\sigma_g^2}\right) + (1-\alpha)\frac{\beta_\gamma^{-\gamma_\gamma}}{\Gamma(\gamma_\gamma)} (M_{J/\psi+\ell} - \mu_\gamma)^{\gamma_\gamma - 1} \exp\left(-\frac{M_{J/\psi+\ell} - \mu_\gamma}{\beta_\gamma}\right)$$

  $\hookrightarrow$ each of the 6 parameters is a **1st order polynomial function** of M_t

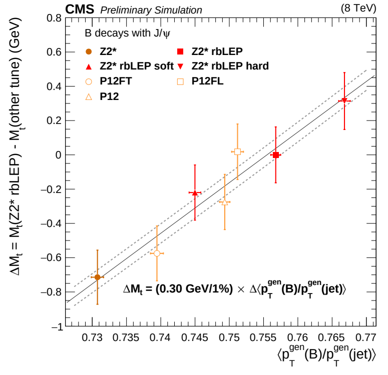
PDF parameterization

Parameters showing the strongest dependence on M_t



Change of fragmentation baseline

- Z2* not optimized for fragmentation modeling:
  - Z2* rbLEP family: a tune ($\pm 1\sigma$) of Z2* including the measurment of x_B at LEP by varying only the **b quark fragmentation description**
  - Perugia12 family: alternative tunes by varying the **fragmentation description for all flavors**
- Measuring M_t for each tune
- Difference between P12FT and P12FL $\sim$ difference between Z2* rbLEP soft and hard
  - **-0.71 GeV to the M_t value** obtained to use Z2* rbLEP as baseline
  - **± 0.30 GeV as systematic uncertainty** stemming from fragmentation modeling

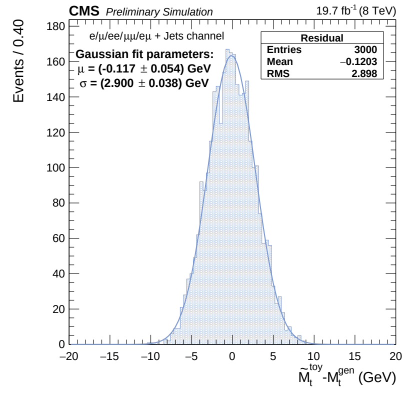


Statistical uncertainty and Monte Carlo statistics

- 3 000 pseudo-experiments of $N_{\text{evt}} = \text{Poisson}(\boldsymbol{N_{\text{data}}})$ **generated from** $\boldsymbol{P_{\text{sig+bg}}|_{M_t}}$ then **fitted with** $\boldsymbol{P_{\text{sig+bg}}}$ for several M_t^{gen} values
- **Width and mean** of the **residual distributions** represented as a function M_t^{gen}

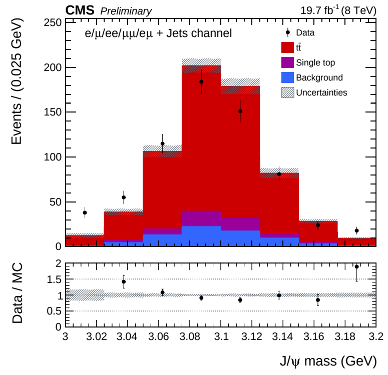
$$\Downarrow$$

- Expected statistical uncertainty: **2.9 GeV**
- Uncertainty stemming from MC statistics: **0.22 GeV**



Experimental uncertainties

- Monte Carlo statistics ✓
- Muon momentum scale
- Electron momentum scale
- Modeling of the J/ψ candidate mass distribution
- Jet energy scale
- Jet energy resolution
- Trigger efficiencies
- Background normalization
- Pileup



Theoretical uncertainties

Modeling of perturbative QCD

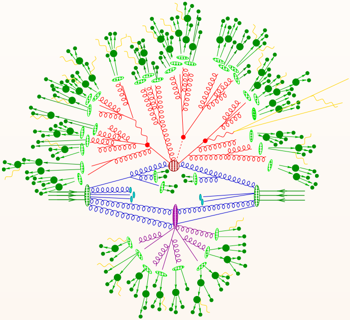
- Matrix-element generator
- top-quark p_T modeling
- Renormalization and factorization scale
- ME-PS matching threshold
- Parton density function

Modeling of non-perturbative QCD

- b fragmentation ✓
- Underlying event
- Color reconnection

Simulation of a proton-proton collision, including the modeling of:

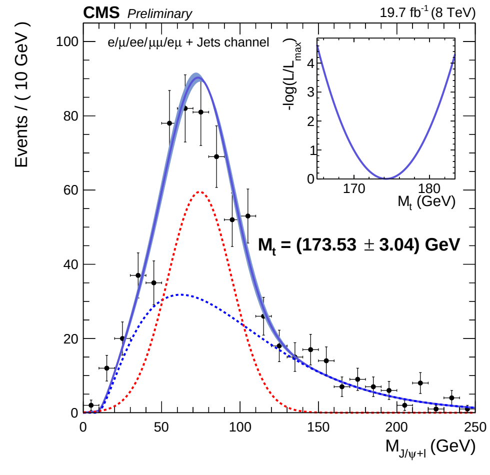
- the initial partons,
- the hard process,
- the underlying event,
- radiations,
- the hadronization.



Summary

Source	Value (GeV)
Experimental uncertainties	
Monte Carlo statistics	**± 0.22**
Muon momentum scale	± 0.09
Electron momentum scale	± 0.11
Modeling of the J/ψ candidate mass distribution	$+0.09$
Jet energy scale	< 0.01
Jet energy resolution	< 0.01
Trigger efficiencies	± 0.02
Background normalization	± 0.01
Pileup	± 0.08
Theoretical uncertainties	
ME generator	-0.37
Renormalization scale	$\{^{+0.12}_{-0.46}$
ME-PS matching threshold	**$\{^{+0.12}_{-0.58}$**
top quark transverse momentum	**$+0.64$**
b fragmentation	± 0.30
Underlying event	± 0.13
Color reconnection modeling	$+0.12$
Parton density functions	$\{^{+0.39}_{-0.11}$
Total	$\{^{+0.89}_{-0.94}$

Results at $\sqrt{s} = 8$ TeV



1st measurement of M_t using top quark decays in the exclusive decay channel $t \to (W^+ \to \ell^+\nu)(b \to \mathbf{J/\psi} + X \to \mu^+\mu^- + X)$:

$$M_t = 173.5 \pm 3.0\,(\text{stat.}) \pm 0.9\,(\text{syst.})\ \text{GeV}$$

Prospects at $\sqrt{s} = 13$ TeV

- final state with 3 leptons: trigger and selection efficiencies expected to be **less affected by pileup increase**
- soft QCD modeling: contribution to **fragmentation tuning** ?
- top quark mass measurement:
  - weakly sensitive to JES and JER
    $\hookrightarrow$ JES and JER uncertainties hard to reduce with pileup increase
  - expecting a **decrease of some theoretical uncertainties**:
    - NLO Monte Carlo generators
    - fragmentation tuning ?
  - expected to be **competitive with other techniques** for a statistical uncertainty ~ 1 GeV
    - increase of the $t\bar{t}$ cross section by ~ 3.3
    - $\mathcal{L} \sim \mathbf{55\ fb^{-1}}$ expected in 2017

Backup

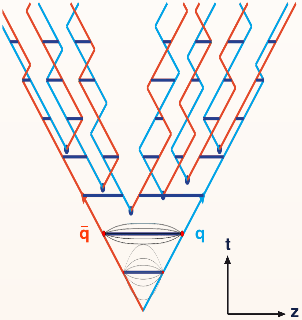
Lund string model

Between 2 colored objects, there is asymptotic freedom at short distances but a linear potential at long distances:

- color field lines compressed into a tube-like region
- linear confinement with a string tension $\sim 1\ \text{GeV}\cdot\text{fm}^{-1}$
- Lorentz invariance, causality, left-right symmetry

Lund fragmentation function:

$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{bm_\perp^2}{z}\right)$$



Bowler extension for heavy quarks:

$$f^{\text{heavy}}(z) \propto \frac{f(z)}{z^{r\cdot bm_\perp^2}}$$

$\hookrightarrow$ a, b, r tunable parameters

Cluster model

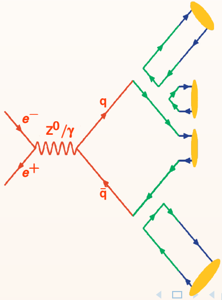
Following the color structure of the parton shower:

- color-singlet pairs (=clusters) end up close in phase space, with a mass of order of the parton shower cutt-off Q_0
- gluons can be non-perturbatively split into quark-antiquark pairs:

Color-singlet clusters are projected onto the continuum of high-mass mesonic resonances, which further decay to lighter well-known resonances and stable hadrons using a pure 2-body phase-space decay and phase space weight:

$$W \propto (2s_1+1)(2s_2+1)\frac{2p^*}{m}$$

- hadron-level properties fully determined by the parton shower
- suppression of heavier hadrons, including baryons and strange hadrons
- crucial role of Q_0

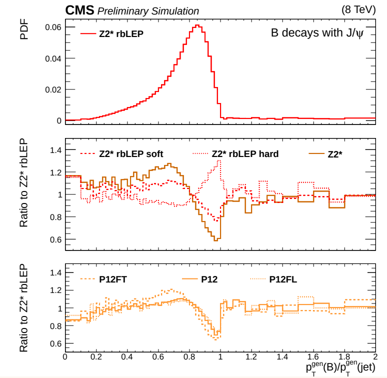


Tunes of the Lund-Bowler fragmentation function parameters

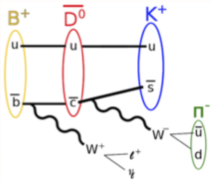
Comparing Z2* with two families of tunes:

- Z2* rbLEP and its hard and soft variations :
  a tune ($\pm 1\sigma$) of Z2* including the measurement of x_B at LEP
  ↪ *varying, for b quarks only, the r parameter in the Bowler extension of the fragmentation function*
- P12, P12FL, P12FT:
  variations of the fragmentation process so that it is harder in the longitudinal or transverse direction
  ↪ *varying, for all quarks, the a and b parameters of the Lund fragmentation function*

using the shape of the B hadron p_T at generator level relative to the jet one:

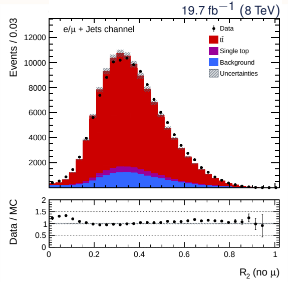


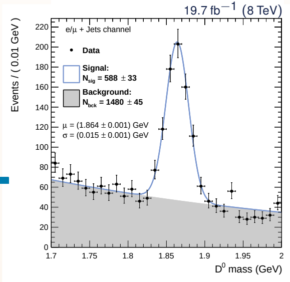
Reconstructing $D^0 \to \kappa^\pm\pi^\mp$ within $t\bar{t}$ events

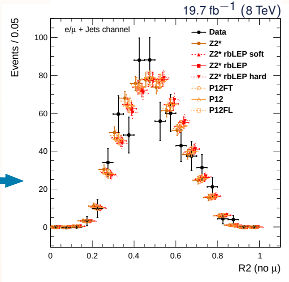


Studying jets with $\mu^\pm$ and $D^0 \to \kappa^\pm\pi^\mp$
$\hookrightarrow B^\pm$ proxy

- using the $_s$Plot technique to separate signal from backgrounds NIM A555(2005)
- $R2 \equiv \frac{\sum_1^2 p_{\text{track, no}\,\mu}}{\sum p_{\text{track}}}$ alike $p_T(D^0)/p_T(\text{jet})$



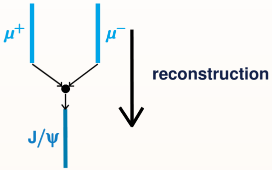


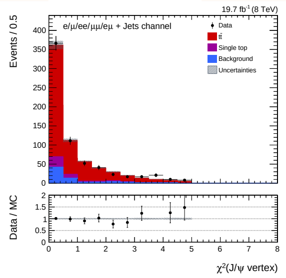


$\Rightarrow$ Would need to reconstruct J/ψ and D^0, using $\mathcal{L} \sim 150\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV

Fit of the $J/\psi \to \mu^+\mu^-$ vertex with a Kalman filter

CERN-2005-002.411





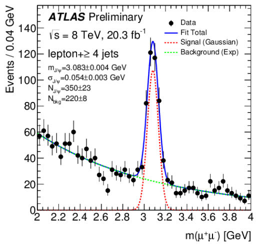
Particle: reconstructed trajectory, assigned mass ($\mu^\pm$) or reconstructed mass (J/ψ), charge, χ^2 and number of degrees of freedom in the vertex fit

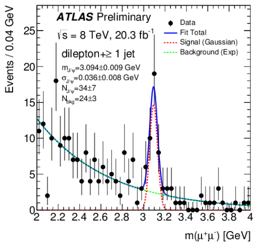
$\hookrightarrow$ 7 parameters $(x, y, z, p_x, p_y, p_z, M)$
+ covariance matrix

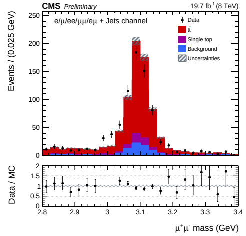
Vertex: position + covariance matrix, χ^2
(1 degree of freedom)

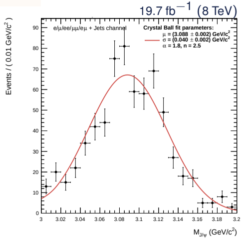
$$\chi^2 = (y^{\text{ref}} - y^{\text{mes}})\, V^{-1}_{y^{\text{mes}}}\, (y^{\text{ref}} - y^{\text{mes}})^T \text{ minimization}$$

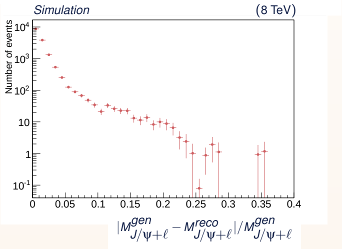
Experimental resolution





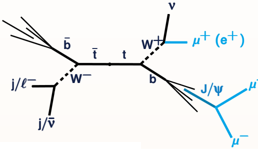


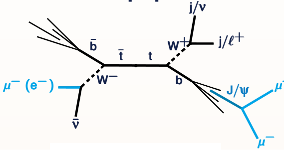


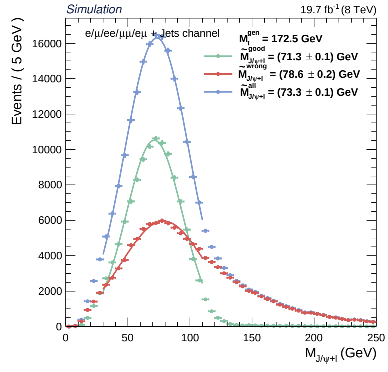


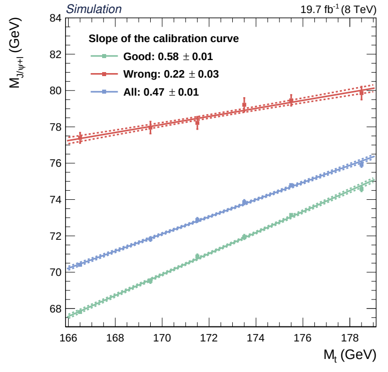
“Good” vs “wrong” pairings

- statistically, when combining an isolated lepton and a J/ψ in a semileptonic $t\bar{t}$ events, a **50% chance** that they come from the **same top quark**

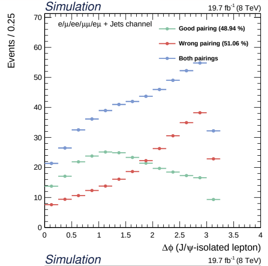


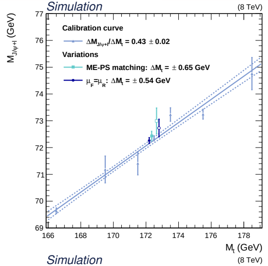


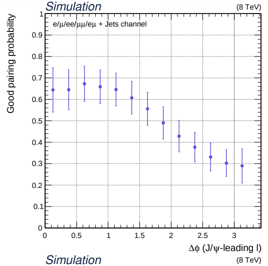


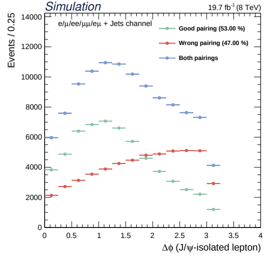


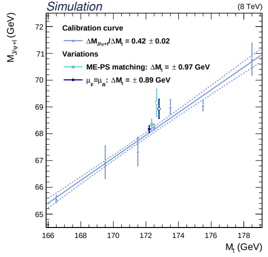
Weighting events using $\Delta\phi(J/\psi, \ell)$

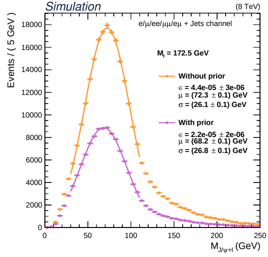








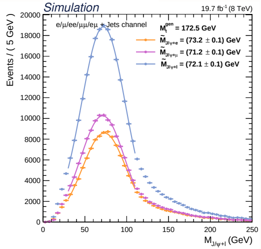


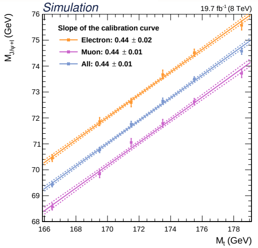


- still 47% of wrong pairings and not significant improvement of the sensitivity

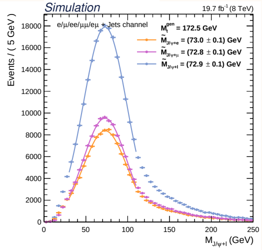
$J/\psi + e$ vs $J/\psi + \mu$

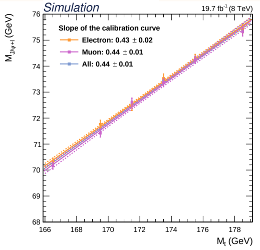
- peak position different but **as much correlated to M_t**





- peak position identical when requiring the same kinematic criteria





Use of dedicated $t\bar{t}$ samples

Problem peculiar to this measurement

- need of $\sim 2\,000\,000$ $t\bar{t}$ events with a $J/\psi \to \mu^+\mu^-$ per M_t value
- because of the very low $BR(b \to J/\psi + X \to \mu^+\mu^- + X)$, simulation of the detector response for the corresponding inclusive $t\bar{t}$ samples unreasonable

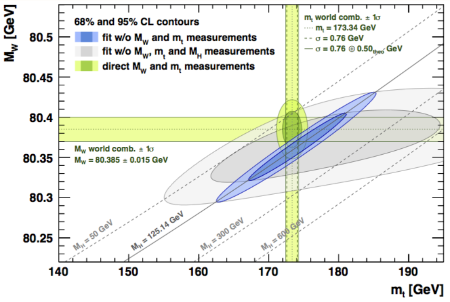
Solution brought by the collaboration

- hadronizing with PYTHIA 6 existing LHE events produced with MADGRAPH, using an iterative filter made of 2 steps:
  1. matrix element – parton shower matching
  2. identification of a $J/\psi \to \mu^+\mu^-$ among the particles produced during the hadronization
- same number of iterations for each event
  $\hookrightarrow$ optimized regarding CPU considerations
- assigning a weight per event reflecting the filter history
- simulating the detector response only for $t\bar{t}$ events with a $J/\psi \to \mu^+\mu^-$

A key variable

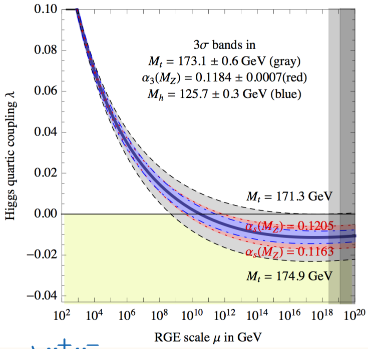
The electroweak fit and indirect measurement of M_W

EPJC 74(2014)3046

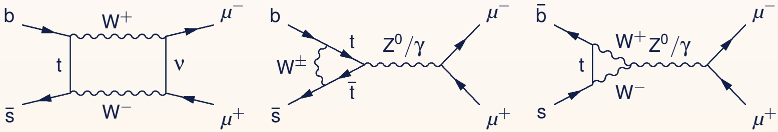


The electroweak vacuum stability

JHEP 1208(2012)098



Rare decays such as $B_s \to \mu^+\mu^-$

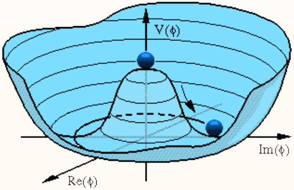


The Higgs mechanism

$$SU(2)_W \text{ doublet } : \phi(x) \equiv \begin{pmatrix} \phi^{(+)}(x) \\ \phi^{(0)}(x) \end{pmatrix}$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2,$$

$$\lambda > 0 \text{ et } \mu^2 < 0$$



$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \sqrt{\frac{-\mu^2}{\lambda}} + \mathrm{H}(x) \end{pmatrix}$$

$$\mathcal{L}_Y = -\sum_{j,k=1}^{N_g} \Bigg((\bar{\mathrm{u}}_j, \bar{\mathrm{d}}_j)_L \left[c_{jk}^{(\mathrm{d})} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} \mathrm{d}_{kR} + c_{jk}^{(\mathrm{u})} \begin{pmatrix} \phi^{(0)*} \\ -\phi^{(-)} \end{pmatrix} \mathrm{u}_{kR} \right]$$

$$+ (\bar{\nu}_j, \bar{\ell}_j)\, c_{jk}^{(\ell)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} \ell_{kR} \Bigg) + \text{c. h.}$$

symmetry breaking

$$\mathcal{L}_Y = \left(1 + \mathrm{H}\sqrt{\frac{\lambda}{-\mu^2}} \right) \left(\bar{\mathrm{d}}'_L \mathcal{M}_{\mathrm{d'}} \mathrm{d'}_R + \bar{\mathrm{u}}'_L \mathcal{M}_{\mathrm{u'}} \mathrm{u'}_R + \bar{\ell}'_L \mathcal{M}_{\ell'} \ell'_R + \text{c. h.} \right)$$

- mass eigenvectors $\propto v = \sqrt{-\mu^2/\lambda}$
- mixing of the flavor eigenstates: the Cabibbo-Kobayashi-Maskawa matrix

From the Lagrangien parameters to the observables

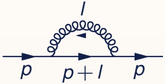
m_q mass:

Lagrangien parameter

1. Field quantification
2. Gauge fixing
   $\rightarrow$ Feynman rules

$$= \frac{i}{\not{p} - m_q}$$

3. Regularization
   $\rightarrow$ loop integrals



4. Renormalization
   $\rightarrow$ series of perturbative corrections

$\Rightarrow$ As many mass definitions as renormalization schemes

Pole mass:

real part of the propagator singularity for each order of the perturbative theory

- invariant mass of a free particle
- $\Delta \sim 200$ MeV/c^2

$\overline{\text{MS}}$, PS, MSR. . . masses:

- short-distance masses
- convenient to parameterize the Yukawa coupling to the Higgs boson

Monte Carlo generator definition:

- interpretation depends on how much MC simulations are based on QCD
- $M_t^{MC} - M_t^{pole} = 0.05^{+0.31}_{-0.62} \pm 0.50$ GeV
  PoS LL2014:054 (2014)