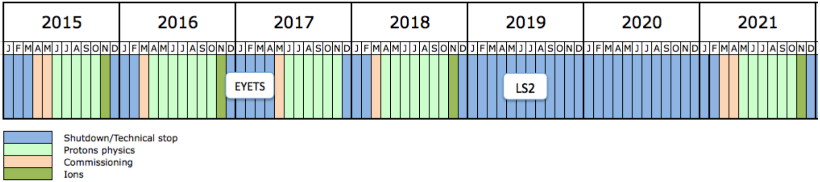
Measurement of $t\bar{t}$ quark pair cross-section with tau lepton in final state and lepton universality test

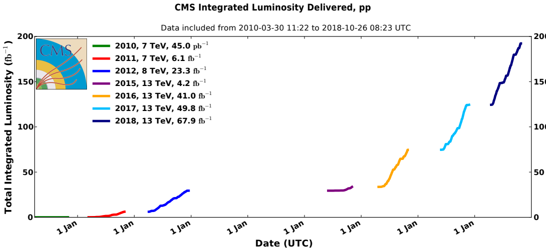
Oleksii Toldaiev
supervised by Michele Galinaro and Joao Varela

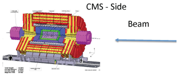
LIP, CMS

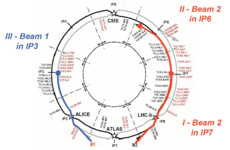
1 July 2019

CMS detector, available data



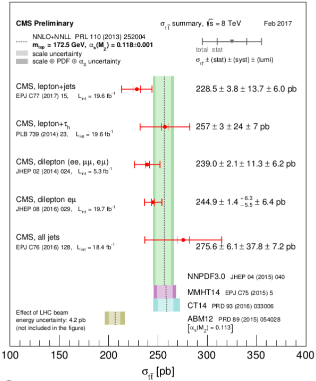






The LHC schedule and the data collected by CMS in Run1 (30 fb^{-1}) and Run2 (162 fb^{-1}).

Motivation



Cross-section measurements in $t\bar{t}$ channels at 8 TeV CMS data from 2012.

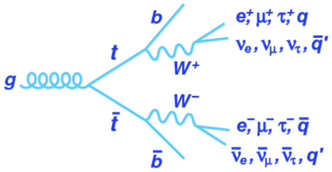
- Measurement in $t\bar{t} \to b\bar{b}l\tau$ channel
- Improved systematic uncertainties
- A spin-off measurement with the ratio to dilepton channel

$\Gamma(\tau^+\nu)/\Gamma(e^+\nu)$ Γ_4/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.046±0.023 OUR FIT					
0.961±0.061	980	[42] ABBOTT	00D	D0	$E^{p\bar{p}}_{cm}$ = 1.8 TeV
0.94 ±0.14	179	[43] ABE	92E	CDF	$E^{p\bar{p}}_{cm}$ = 1.8 TeV
1.04 ±0.08 ±0.08	754	[44] ALITTI	92F	UA2	$E^{p\bar{p}}_{cm}$ = 630 GeV
1.02 ±0.20 ±0.12	32	ALBAJAR	89	UA1	$E^{p\bar{p}}_{cm}$ = 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.995±0.112±0.083	198	ALITTI	91C	UA2	Repl. by ALITTI 92F
1.02 ±0.20 ±0.10	32	ALBAJAR	87	UA1	Repl. by ALBAJAR 89

from Particle Data Group (2012)

Features of $t\bar{t} \to b\bar{b}\ell\tau$ channel, measurement method



Many particular final products:

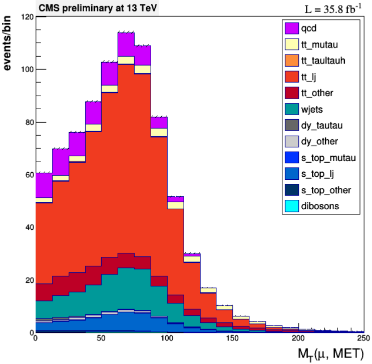
- 2 b-jets (displaced vertex of jet)
- 1 lepton (muon or electron)
- 2 neutrinos
- 1 hadronicaly decaying tau lepton

- Sample of $t\bar{t}$ events is selected with simple cuts and identification requirements.
- Main background from fake taus in $t\bar{t} \to \ell\nu_\ell q\bar{q}$ channel.
- The events are separated into background-rich and signal-rich categories according to kinematics of jets.
- The shape fit of $M_T(\ell, E_T^{miss})$ distributions is performed.
- Both methods constrain background of misidentified taus and cross-check each other.

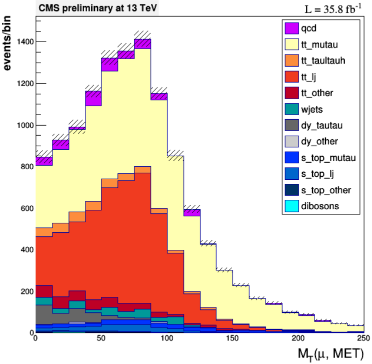
Reconstruction algorithms and event selection

Standard algorithms are employed: Particle Flow for basic objects, anti-Kt jet clustering, MVA-based b-tagging, quality requirements for muons and electrons, MVA-based tau ID etc.

Require: 1 lepton, ≥ 3 jets, ≥ 1 b-tagged and 1 tau lepton.



no tau requirement



tau of Opposite Sign to muon

Background of mis-identified taus

Jets mis-identified as taus cause a lot of trouble:

- the mis-identification probability varies significantly with different properties of jets
- it cannot be simply measured in any convenient region
- and the simulation is not perfectly trustworthy

Means to handle it:

- target the processes which produces mis-identified taus instead of taus
- use kinematic information which distinguishes the signal from these processes
- for example the transverse mass between the lepton and E_T^{miss} and the kinematics of jets
- if this kinematic information does not correlate with the mis-identified taus, the fit of the kinematic shapes constrains the background significantly

Profile Likelihood Ratio (PLR) shape fit in two categories

- Background- or signal-rich categories are defined by jet kinematics. Profile likelihood ratio fit is performed in bins of M_T distribution.
- Likelihood function includes per-bin yields and systematic uncertainties as constraint nuisance parameters:

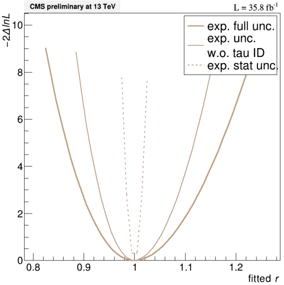
$$\mathcal{L}(\boldsymbol{\mu}, \theta_i) = \prod_k \mathcal{P}_{oisson} \left[N_k | \hat{N}_k(\boldsymbol{\mu}, \theta_i) \right] \cdot \prod_i pdf(\theta_i, 0, 1) \quad (1)$$

- Based on the likelihood function the PLR test statistic is defined:

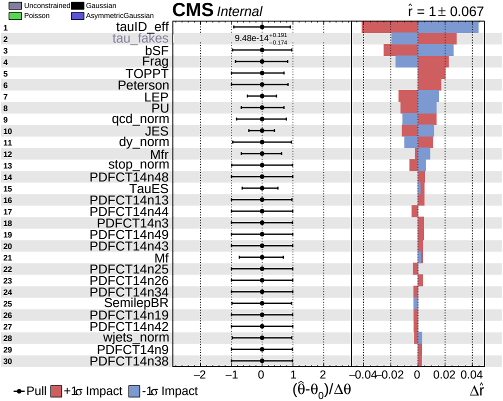
$$\lambda(\boldsymbol{\mu}) = \frac{\mathcal{L}(\boldsymbol{\mu}, \hat{\hat{\theta}}_i(\mu))}{\mathcal{L}(\hat{\boldsymbol{\mu}}, \hat{\theta}_i)} \quad (2)$$

— scans over $\lambda(\mu)$ provide estimation of uncertainties.

Example of fit in both $e\tau_h$ and $\mu\tau_h$ in simulation



Scan of signal strength.



Impacts of uncertainties on signal strength.

Results show agreement with SM and uncertainty of about 6-7% in both channels. Plots show simultaneous fit over both channels. The largest uncertainty is 5% from Tau ID.

Lepton universality in W decays

$\Gamma(\tau^+\nu)/\Gamma(e^+\nu)$ Γ_4/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.046±0.023 OUR FIT					
0.961±0.061	980	[42] ABBOTT	00D	D0	$E^{p\overline{p}}_{cm}$= 1.8 TeV
0.94 ±0.14	179	[43] ABE	92E	CDF	$E^{p\overline{p}}_{cm}$= 1.8 TeV
1.04 ±0.08 ±0.08	754	[44] ALITTI	92F	UA2	$E^{p\overline{p}}_{cm}$= 630 GeV
1.02 ±0.20 ±0.12	32	ALBAJAR	89	UA1	$E^{p\overline{p}}_{cm}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.995±0.112±0.083	198	ALITTI	91C	UA2	Repl. by ALITTI 92F
1.02 ±0.20 ±0.10	32	ALBAJAR	87	UA1	Repl. by ALBAJAR 89

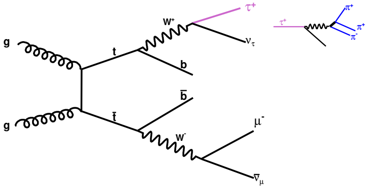
from Particle Data Group (2012)

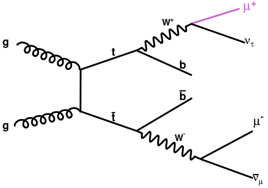
$W \to e\nu$	(10.75 ± 0.13) %
$W \to \mu\nu$	(10.57 ± 0.15) %
$W \to \tau\nu$	(11.25 ± 0.20) %

- excess of about 2.5σ in current measurements:
  - performed at LEP in WW channel (off mass shell)
  - Tevatron in W+jets (triggering on tau)
  - relative uncertainty $\approx 3.5\%$
- at LHC:
  - enough energy for on-shell dibosons and $t\bar{t}$
  - similar measurements (like searches for charged Higgs) lack precision (about 6-10%, when 2% needed)
  - with the amount of luminosity we can sacrifice efficiency for purity

Lepton universality test in $t\bar{t}$

The goal is to measure precisely the ratio $\frac{W \to \tau\nu}{W \to \ell\nu}$ within $t\bar{t}$ decay:





Roughly the ratio of the two channels looks like:

$$
\begin{aligned}
\sigma(\mu\tau_h) &= \sigma_{pp}(t\bar{t})B(W \to \mu)B(W \to \tau \to \tau_h) \\
\sigma(\mu\mu) &= \sigma_{pp}(t\bar{t})B(W \to \mu)(B(W \to \mu) + B(W \to \tau \to \mu))
\end{aligned} \tag{3}
$$

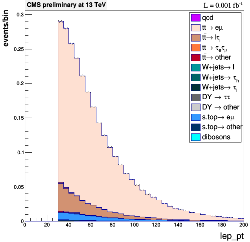
$$
\frac{\sigma(\mu\tau_h)}{\sigma(\mu\mu)} = \frac{B(W \to \tau \to \tau_h)}{B(W \to \mu) + B(W \to \tau \to \mu)} = \frac{\frac{B(W \to \tau)}{B(W \to \mu)} B(\tau \to \tau_h)}{1 + \frac{B(W \to \tau)}{B(W \to \mu)} B(\tau \to \mu)} \tag{4}
$$

The ratio cancels most of systematic uncertainties. But the remaining uncertainty due to tau ID is big (about 5%).

Approaches to the measurement

Fit many channels in one model:

- constraint from simultaneous fit with different number of taus (both hadronic and leptonic) in final state
- consider kinematic difference between ℓ and τ_ℓ

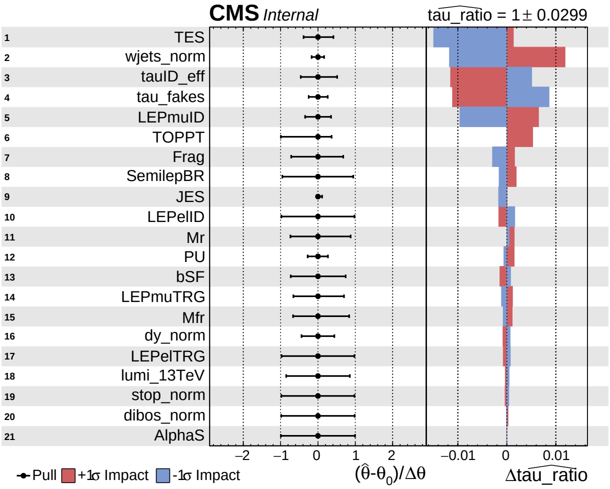


Get pure sample of hadronic taus and add DY in $\frac{\sigma(t\bar{t}\to\mu\tau_h)}{\sigma(t\bar{t}\to\mu\mu)} / \frac{\sigma(DY\to\mu\mu)}{\sigma(DY\to\tau_\mu\tau_h)}$:

- aggressively cut on tau ID
- consider tau fakes in Opposite Sign and Same Sign event selections
- use 3π tau decays and cut on high significance Secondary Vertex

Feasibility study of the measurement in full Run2 data

The construction of the double ratio with DY together with hard cuts on tau ID is expected to result in small enough uncertainty in full Run2 data:



Questions