Top Quark Production and Final State Kinematics

Theoretical and experimental summary for Snowmass 2013

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Top Quark Production & Final State Kinematics

- Theory aspects of
  ttbar, single top, associated production
  beyond the leading order

- Review of experimental results

Top Quarks as Final States

- A complete description of top pair production requires the consideration of both the production of the top pair and the top quark decay.

- Inclusive observables such as the total pair production cross section and several distributions can be evaluated by considering top quarks to be on-shell stable particles.

Total Pair Production CS

- The precision with which the total CS is measured requires to go beyond NLO+NLL accuracy
- approximate NNLO/NNLL resummation available in several approaches; perturbative uncertainty ~ 5 % (Moch, Uwer ('08), Langenfeld et al ('09), Aliev et al ('10), Beneke et al. ('10), Ahrens et al. ('11), ...)
- Full NNLO corrections evaluated in the quark annihilation and qg channels; gg channel available soon (Baernreuther et al ('12), Czakon, Mitov ('12), Czakon et al. ('13))

Distributions

- NNLL resummation/approximate NNLO predictions are available for pair invariant mass , top-quark pT and rapidity, and pair pT distributions (Ahrens et al ('09,'10), Ahrens et al ('11), Aliev et al, Kidonakis ('10, '11), Zhu et al ('12)...):
  good agreement with available data
- Studies of the kinematic regions where $M_{tt} \gg m_t$ are in progress (Ferroglia et al ('12))
- Mixed EW/QCD and soft gluon emission corrections do not explain the FB asymmetry tension (Pagani, Hollik ('11) Kuhn, Rodrigo ('11), Ahrens et al ('11))

Future directions:

- Full calculation of the NNLO corrections to the total cross section. The missing gg channel should be soon available (Czakon et al. ('13)).
- A full evaluation of the NLO (α_s^2) corrections to the Tevatron FB asymmetry is possible: it requires the evaluation of two loop diagrams only in the quark-annihilation channel

Calculations including top quark decays

- Important for a proper simulation of selection cuts and for a precise description of kinematic variables of the top decay products.
  (Even measurements of the total cross section are sensitive to those effects through the acceptance function)

- In recent years significant progress has been made in advancing higher order corrections towards a more realistic modeling of top decays.

- NLO simulation tools mainly differ by their treatment of higher order corrections and spin correlations in the decay matrix elements

  positive weight MC's: MC@NLO, POWHEG (Frixione *et.al.*)
  weighted event MC's: MCFM, "private" codes (Bernreuther *et al.*, Melnikov *et al.*, Bevilacqua *et al.*, Denner *et al.*)

Calculations including top quark decays

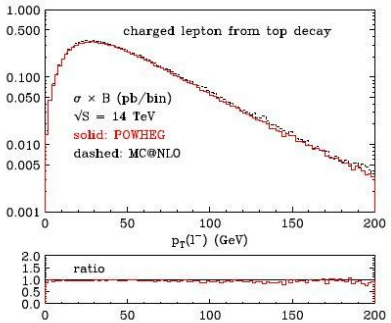
- A wide variety of important physics results have emerged from those calculations.

  A few examples include:

  - NLO (QCD+el.weak) predictions for pT(l), phi(ll), m(lb)
  - top quark spin correlations
  - leptonic AFB
  - mt determination from kinematic distributions
  - study of finite-width and bottom mass effects

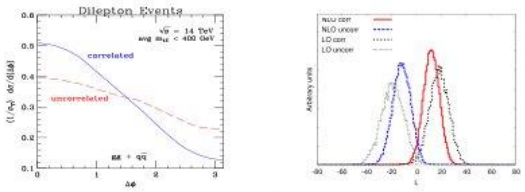
Calculations including top quark decays

Lepton, jet, missing energy observables



[Frixione,Nason,Ridolfi,Webber]

Spin Correlations



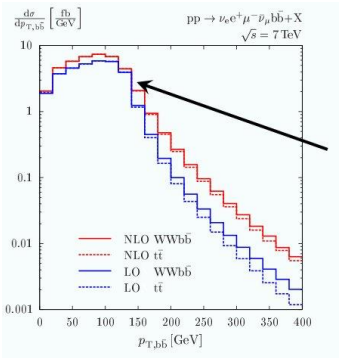
[Bernreuther,Brandenburg,Si,Uwer]
[Mahlon,Parke], [Melnikov, M.S.]

Lepton A_{FB} + el.weak corrections

		with cuts	without cuts
A^l (%)	QCD:	3.0 (3)	3.1 (3)
	QCD + EW:	3.6 (2)	3.8 (3)
A^l (%)	QCD:	5.2 (5)	5.8 (5)
($M_{t\bar{t}} \geq 450$ GeV)	QCD + EW:	6.4 (5)	7.0 (5)
A^l (%)	QCD:	1.6 (1)	1.5 (1)
($M_{t\bar{t}} < 450$ GeV)	QCD + EW:	1.9 (1)	1.8 (1)
A^{tt} (%)	QCD:	4.0 (4)	4.0 (4)
	QCD + EW:	4.8 (4)	4.8 (4)
A^{tt} (%)	QCD:	7.0 (6)	6.3 (6)
($\lvert\Delta y_t\rvert \geq 1$)	QCD + EW:	8.5 (6)	7.5 (6)
A^{tt} (%)	QCD:	1.9 (2)	1.6 (1)
($\lvert\Delta y_t\rvert < 1$)	QCD + EW:	2.3 (2)	1.9 (2)
A^{tt} (%)	QCD:	6.7 (5)	7.1 (6)
($M_{t\bar{t}} \geq 450$ GeV)	QCD + EW:	8.2 (5)	8.7 (6)
A^{tt} (%)	QCD:	2.3 (2)	2.0 (2)
($M_{t\bar{t}} < 450$ GeV)	QCD + EW:	2.7 (2)	2.3 (2)

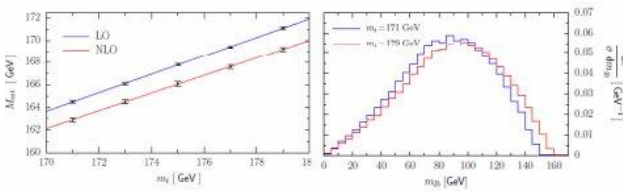
[Bernreuther,Si]
[Kühn,Scharf,Uwer]

Finite width effects



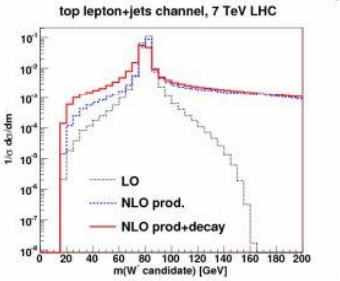
[Denner,Dittmaier,Kallweit,Pozzorini]
[Bevilacqua,Czakon,v.Hameren,Papadopolous,Worek]

Mass determination from kinematic distributions



[Biswas,Melnikov,M.S.]

Finite bottom quark mass effects



[Campbell,Ellis] (MCFM)

Top quark decay at NNLO QCD

Fully differential NNLO QCD correction based on SCET

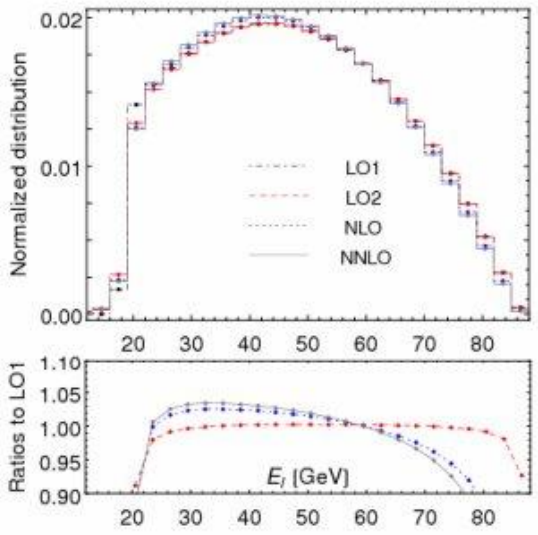
[Jun Gao,Chong Sheng Li,Hua Xing Zhu] (2012)

$$\Gamma_t = \int_0^{\tau_0} \mathrm{d}\tau \frac{\mathrm{d}\Gamma_t}{\mathrm{d}\tau} + \int_{\tau_0}^{\infty} \mathrm{d}\tau \frac{\mathrm{d}\Gamma_t}{\mathrm{d}\tau} := \Gamma_A + \Gamma_B \qquad \tau = (p_b + p_X)^2/m_t^2$$

if τ_0 is chosen small enough:

$\Gamma_A \sim \mathcal{H}(x,\mu) \otimes J(m^2,\mu) \otimes S(k,\mu)$ can be calculated from SCET results

Γ_B can be calcuated from NLO QCD corrections to $t \to Wb$+jet



m_t	$\Gamma_t^{(0)}$	δ_f^b	δ_f^W	δ_{EW}	$\delta_{QCD}^{(1)}$	$\delta_{QCD}^{(2)}$
172.5	1.4806	-0.26	-1.49	1.68	-8.58	-2.09
173.5	1.5109	-0.26	-1.49	1.69	-8.58	-2.09
174.5	1.5415	-0.25	-1.48	1.69	-8.58	-2.09

GeV | percent

Calculations including top quark decays

Possible future directions:

- Combination of NNLO QCD calculation for ttbar production process with decay at the same order in perturbation theory

- Merging and matching different jet samples at NLO QCD

- Inclusion of New Physics effects for some of the most robust models, such as Z' / g' ->ttbar, T' Tbar' ,
  t->H+b, stop->Chi+ t, T'-> X + t

Associated production processes

ttb +H, Z, gamma,W, jets

- Some processes have never been observed at the Tevatron
- Study allows determination of top quark couplings

ttb+H: sensitive to yt and Higgs parity

ttb+Z, gamma: el.weak couplings of top quark

- NLO predictions exist for all those processes and extensive studies of sensitivity reach have been performed at LO
  --> should be repeated at NLO precision

Associated production processes

- Other processes such as

  ttbar+W, ttbar+bbbar, ttbar+jet(s)

  are mostly background to New Physics searches. Some need to be extended to include top quark decays to accommodate harsh experimental selection cuts.

Possible future directions:

- Electroweak corrections
- Precision studies, cross section ratios sigma(ttb+V) / sigma(ttb)
- ttb+(Z-->nu nu) as background to New Physics searches

Single Top Production

- NLO QCD corrections are available for all of the three production mechanisms (t-channel, s-channel, associated tW production)
- NLO/QCD corrections to the (dominant) t-channel are of moderate size (~5% at the Tevatron, ~ 10 % at the LHC)
- NNLL resummation and/or approximate NNLO corrections became recently available (Zhu et al ('10), Kidonakis ('10,'11,'12))

Possible future directions:

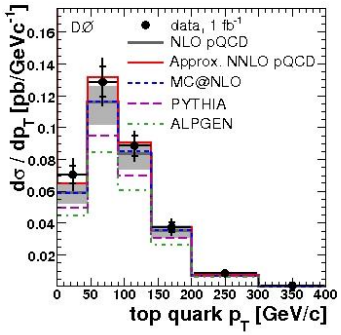
- rare processes: single top + Z, H

Top quark distributions at Tevatron & LHC

- Choice of unfolding data to parton or hadron level, important to define a kinematic range !
- Meanwhile a wealth of measurements exists:

Phys. Lett. B 693, 515 (2010)

CDF and D0 data unfolded to parton level & full phase space using regularized matrix unfolding



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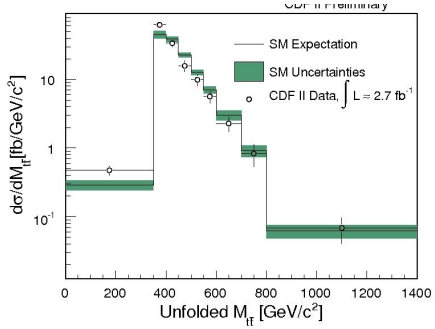
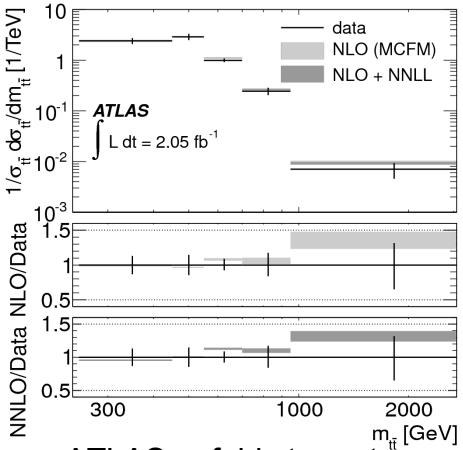
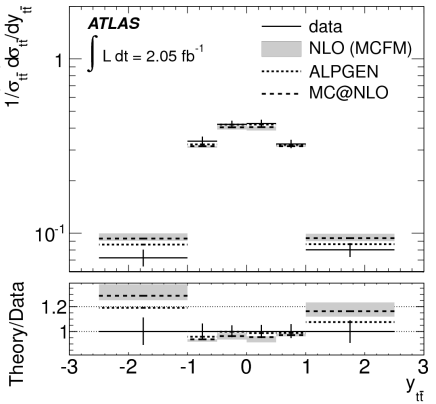
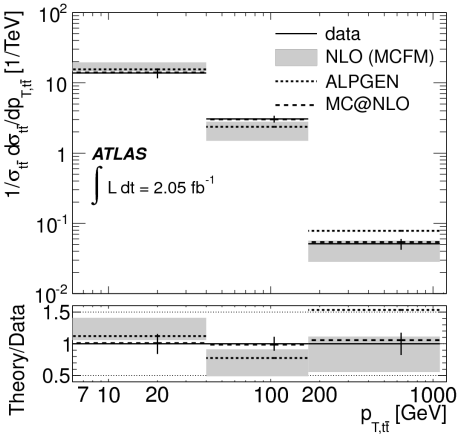


ATLAS Subm. to EPJ C



ATLAS unfolds to parton level & full phase space using matrix inversion



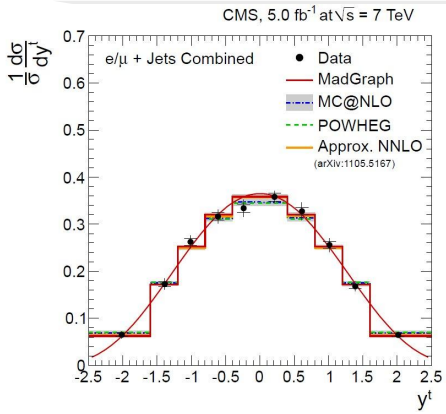


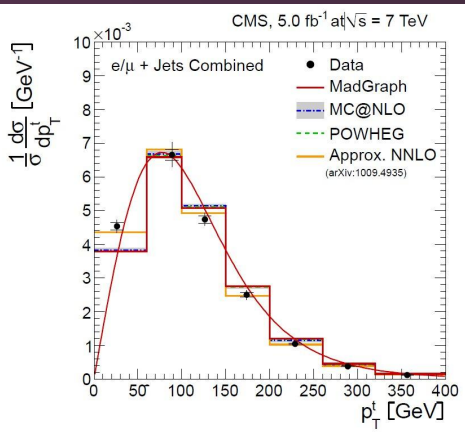
- Dominant systematic uncertainties:
  JES, hadronization, PDF @ high m(ttbar)

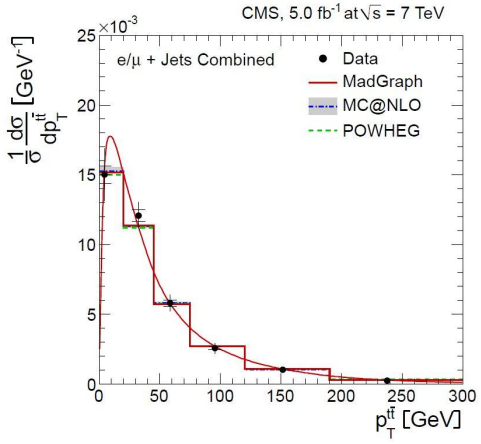
Top quark distributions at Tevatron & LHC

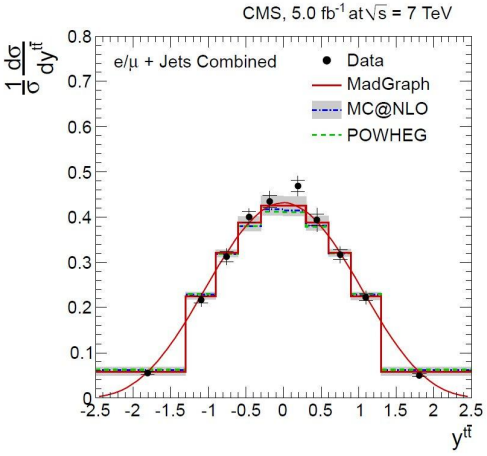
CMS TOP-11-013

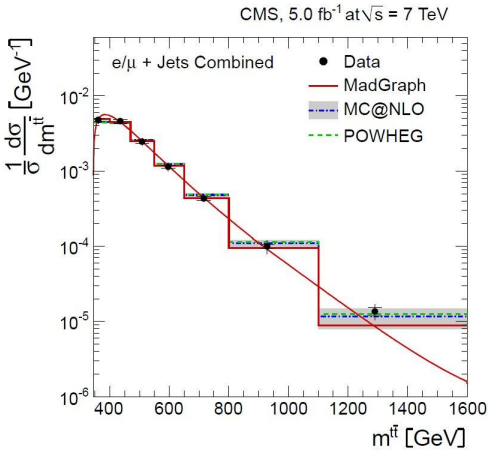
CMS unfolds to parton level and full phase space using regularized matrix unfolding while leptons, b quarks are corrected to visible phase space











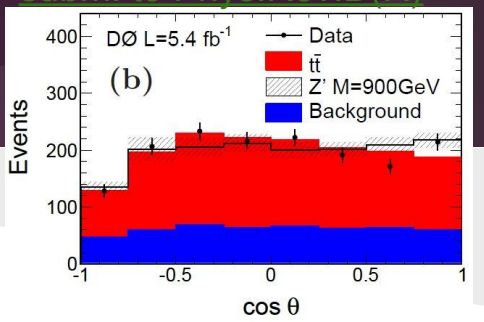
- Data are usually nicely described by various models at NLO or approx. NNLO

Top quark asymmetries at Tevatron & LHC

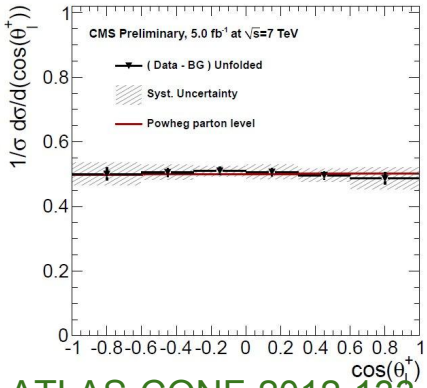
(-> see Talk by S.Westhoff)

- Puzzling situation, calls for measuring asymmetries of top (b's), leptons in various channels at both colliders

subm. to Phys.Rev.D(R)



CMS PAS TOP-12-016

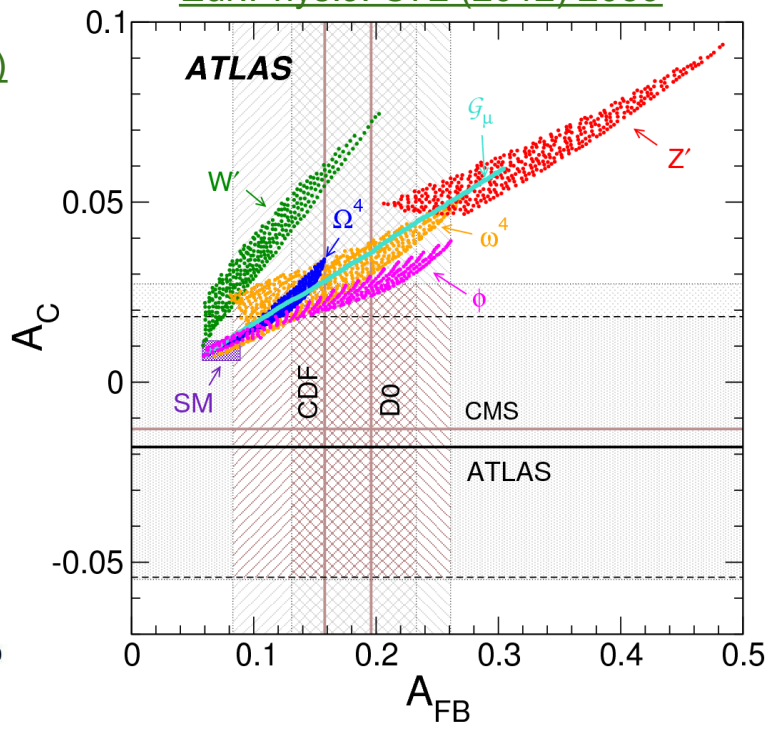


CMS-PAS-TOP-12-010

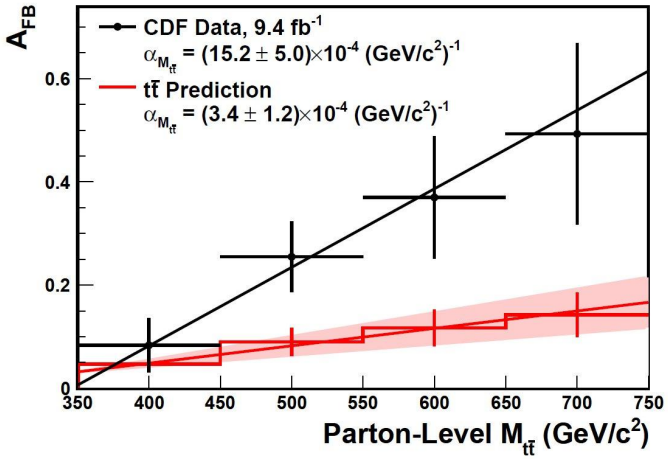
D0: Phys. Rev. D 84, 112005 (2011)

ATLAS-CONF-2012-057

Eur.Phys.J. C72 (2012) 2039



CDF: Subm. to PRD



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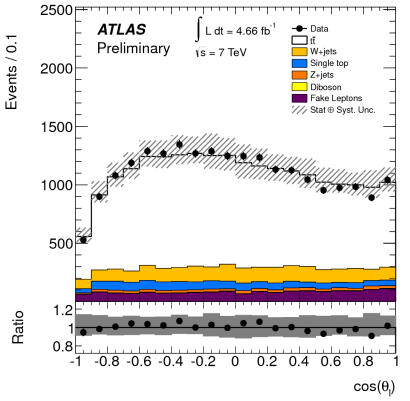

- Story continues...

Top quarks in association with other particles

- Hottest topic clearly ttH - only limits exist so far
- ttV, V=gamma, Z, W and also tt+g (->bb) measurements exist

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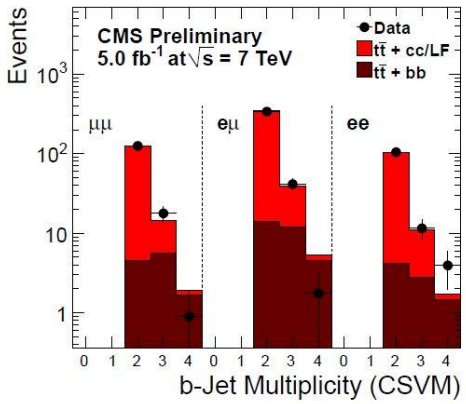

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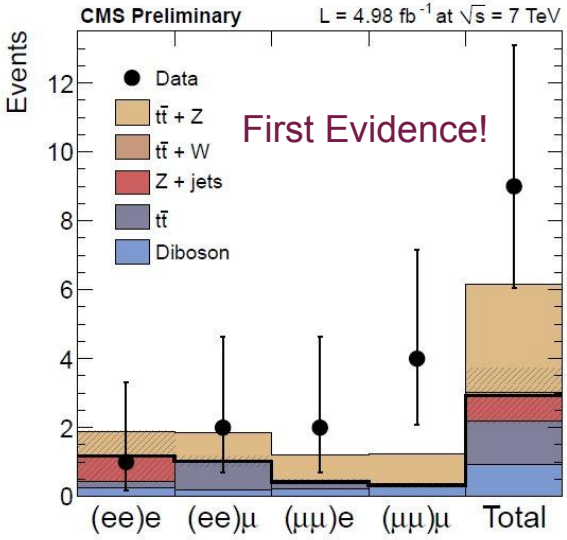
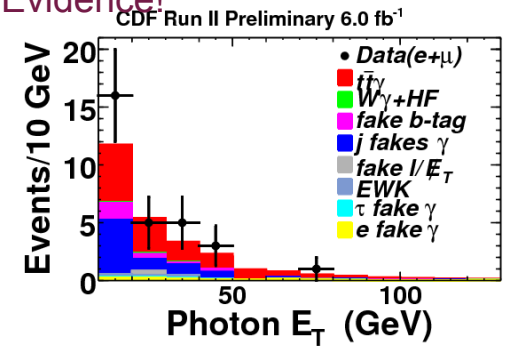


PRD 84 031104

First Evidence!



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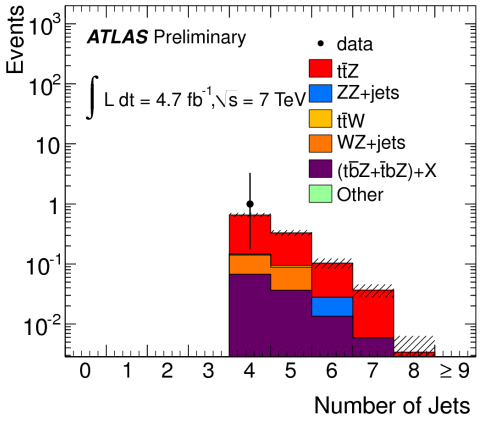

- Only 5.0 fb-1 measurements so far

(-> see Talk by A.Loginov)

Outlook / What can be done…

- More precise differential measurements in near future- make use of the top tagging !
- Consider and correct data for kinematic region of the measurement: Applies to all types of differential measurements: xsecs, asymmetries, polarization, etc.
- Possible studies: Look at / Cover 'extreme' phase space corners to understand different effects currently limiting precision in top measurements