Top quark physics at and around the LHC

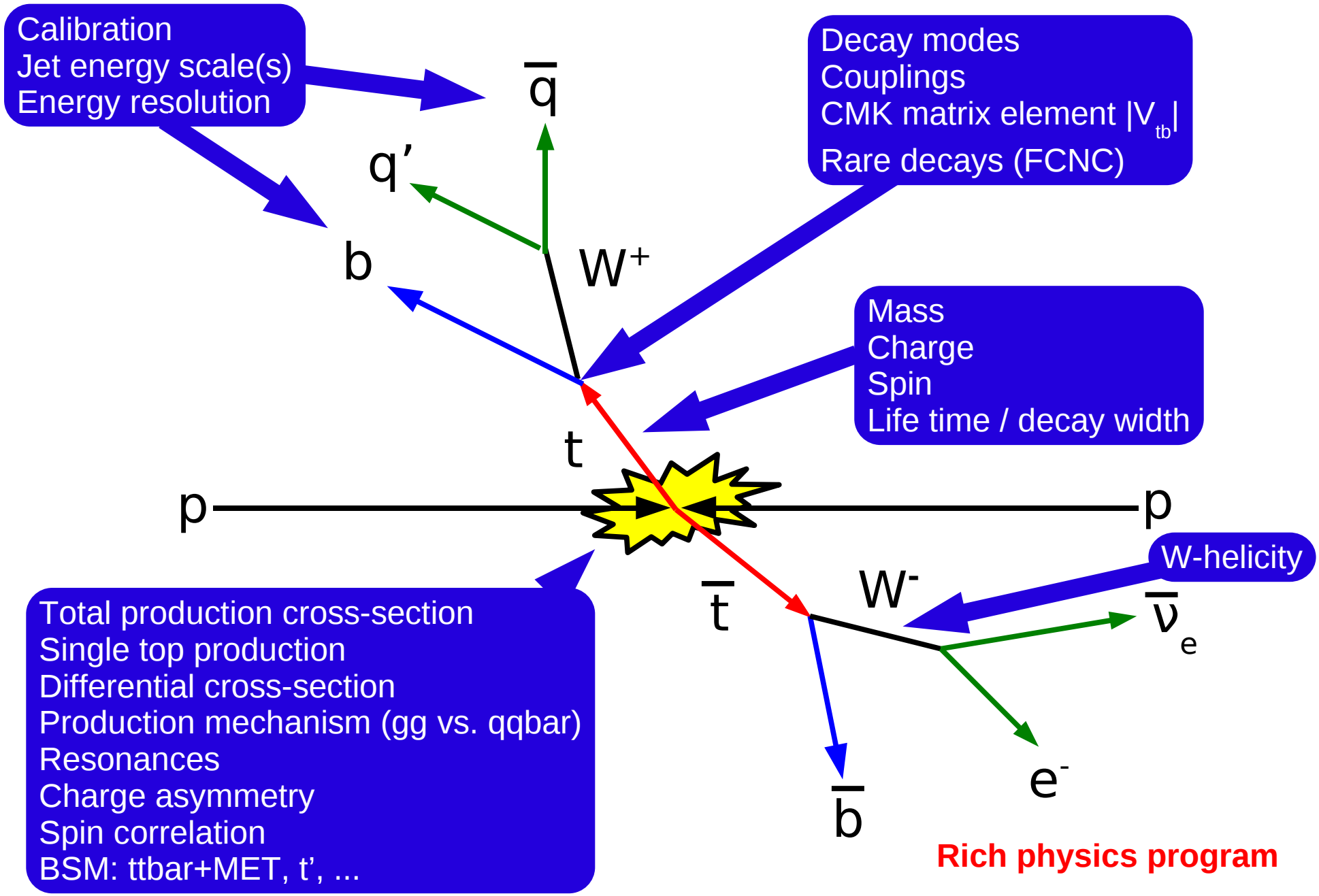
Helmholtz Alliance Annual Meeting, Bonn

December 7th - 9th 2011

Kevin Kröninger

University of Göttingen

Introduction ∘ Overview ∘ Comparison LHC/Tevatron ∘ Two examples ∘ Summary


Calibration
Jet energy scale(s)
Energy resolution
Decay modes
Couplings
CMK matrix element |V_tb|
Rare decays (FCNC)
Mass
Charge
Spin
Life time / decay width
W-helicity
Total production cross-section
Single top production
Differential cross-section
Production mechanism (gg vs. qqbar)
Resonances
Charge asymmetry
Spin correlation
BSM: ttbar+MET, t', ...
q̄
q'
b
W+
t
p
p
t̄
W-
ν̄e
b̄
e-
Rich physics program

Summary & Outlook

- First LHC top physics results on limited dataset: 3 pb^{-1}
  - ATLAS and CMS can extract involved top signature after only 1/2 year
  - Cross section for top pair production compatible with QCD predictions
- Prospects with full 2010 dataset (around 35 pb^{-1})
  - Refined $t\bar{t}$ cross section analyses
  - First top mass from the LHC, further top properties, single top, first searches for new physics with top
  - Interesting perspectives for collaboration between experimentalists and theorists, e.g. MSbar mass from cross section, top anomalous couplings, …

Much more to come in 2011 – Stay tuned!

4th Annual Terascale Alliance Meeting, Dresden, Dec 1–3, 2010, U. Husemann: First Top Quarks at the LHC 21

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- > 50 preliminary results
- > 5 publications
- Significant contributions from german institutes (analysis, performance and organization)

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Cross-section:

- Total cross-section prediction
  several recent theory updates: NLO QCD+resum.
- Single lepton channels (e/μ+jets)
  ATLAS-CONF-2011-023, ATLAS-CONF-2011-035
  ATLAS-CONF-2011-121, PAS TOP-10-002,
  PAS TOP-10-003, **Eur. Phys. J. C71 (2011) 1721**,
  arXiv:1108.3773, CMS PAS TOP-11-003.
- Dilepton channels (ee, μμ, eμ)
  ATLAS-CONF-2011-034, arXiv:1108.3699,
  ATLAS-CONF-2011-100, CMS PAS TOP-10-005,
  JHEP 07 (2011) 049, CMS PAS TOP-11-005
- Dilepton channels (μ+τ)
  ATLAS-CONF-2011-119, CMS PAS TOP-11-006
- All hadronic channel
  ATLAS-CONF-2011-066, **ATLAS-CONF-2011-140,**
  CMS PAS TOP-11-007
- Combinations
  ATLAS-CONF-2011-040, ATLAS-CONF-2011-108,
  CMS PAS TOP-11-001, CMS PAS TOP-11-024
- Jet multiplicity
  ATLAS-CONF-2011-142

Top parallel session

- *Kirika Uchida* on ttbar cross-section in the dilepton channel (ATLAS)
- *Eike Schlieckau* on ttbar cross-section in the all-hadronic channel (CMS)
- *Clemens Lange* on ttbar cross-section in the l+jets channel (ATLAS)
- *Christian Schwinn* on NNLL threshold resummation for ttbar cross-section (theory)
- *Jan Kieseler* on ttbar/Z cross-section ratio in ee- and mumu-channels (CMS)

- Top pair + additional photons
  ATLAS-CONF-2011-153, [Melnikov, Scharf, Schulze]
- Top pair + X
  X=jet [Scharf], X=jet+parton shower [Alioli, Moch, Uwer], off-shell [Bevilaqua et al., Denner et al.], X=jj [Bevilacqua et al.], X=b bbar [Bredenstein et al.]

blue/red/black: ATLAS/CMS/theory **bold face**: german contribution

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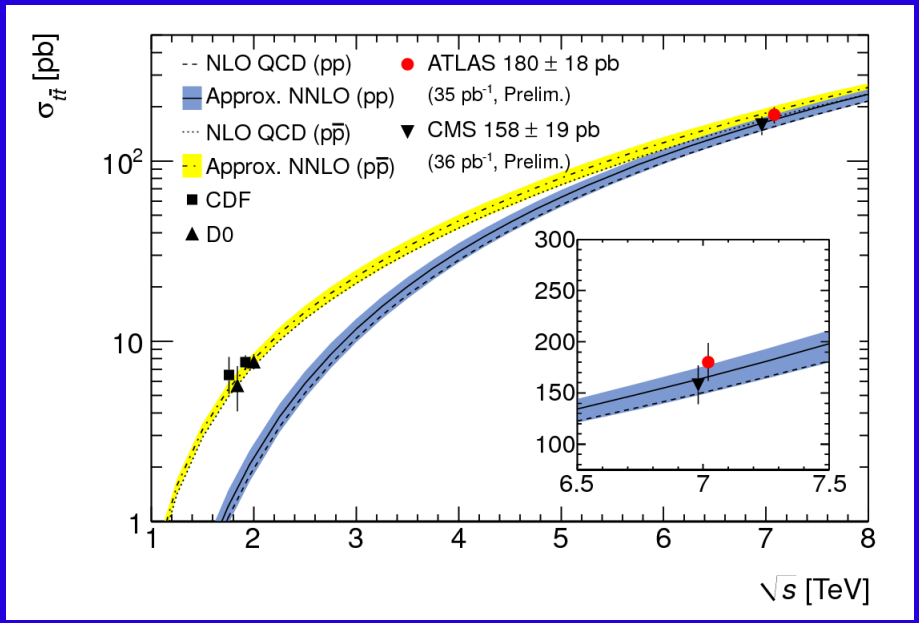
Highlights



Good agreement between the observation and predictions

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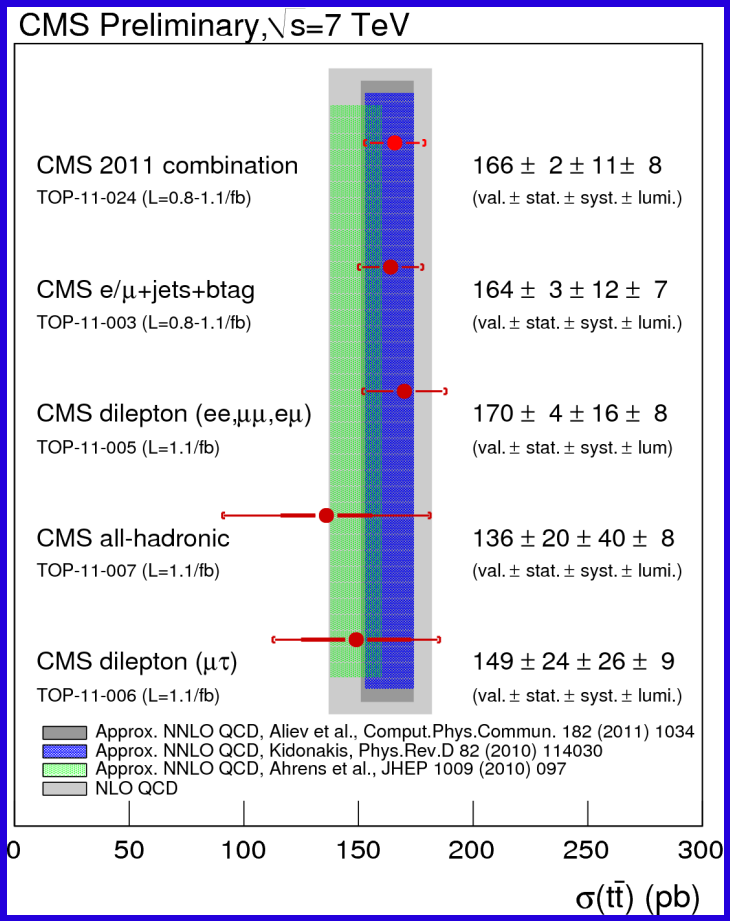

Precision measurement of cross-section. Combination ongoing.

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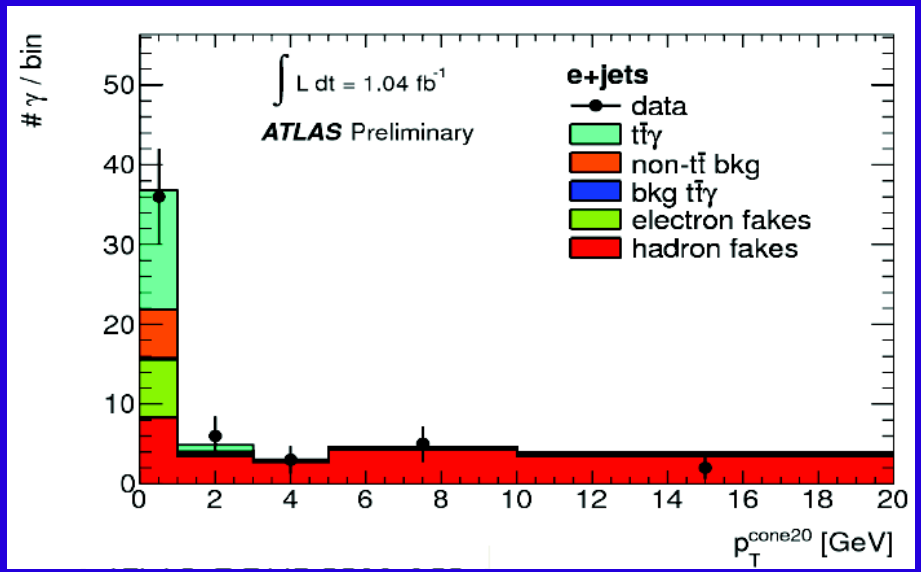

Test EM coupling of top quarks.

blue/red/black: ATLAS/CMS/theory **bold face**: german contribution

Top properties:

- Top charge
  ATLAS-CONF-2011-141
- W boson polarisation
  ATLAS-CONF-2011-037, ATLAS-CONF-2011-122
- Spin correlation
  ATLAS-CONF-2011-117
- Charge asymmetry
  ATLAS-CONF-2011-106, CMS PAS TOP-10-010, CMS PAS TOP-11-014, many theory papers
- Top mass in l+jets
  ATLAS-CONF-2011-033, ATLAS-CONF-2011-120
  CMS PAS TOP-10-009
- Top mass in dilepton
  CMS PAS TOP-10-006, JHEP 07 (2011) 049
- Top mass from cross-section
  ATLAS-CONF-2011-054, CMS PAS TOP-11-008
- Top/Antitop mass difference
  CMS PAS TOP-11-019

Top parallel session

- *Giorgio Cortiana* on top mass in the l+jets channel (ATLAS)
- *Markus Seidel* on top mass in the l+jets channel (CMS)
- *Kaven You* on top mass in the dilepton channel (ATLAS)
- *Stefan Berge* on NLO MSSM corrections to the charge asymmetry (theory)
- *Christian Boeser* on charge asymmetry (CMS)
- *Andreas Scharf* on top production and decay with a hard jet (theory)
- *Wolf Behrenhoff* on differential cross-sections (CMS)
- *Johannes Erdmann* on top production with additional photons (ATLAS)

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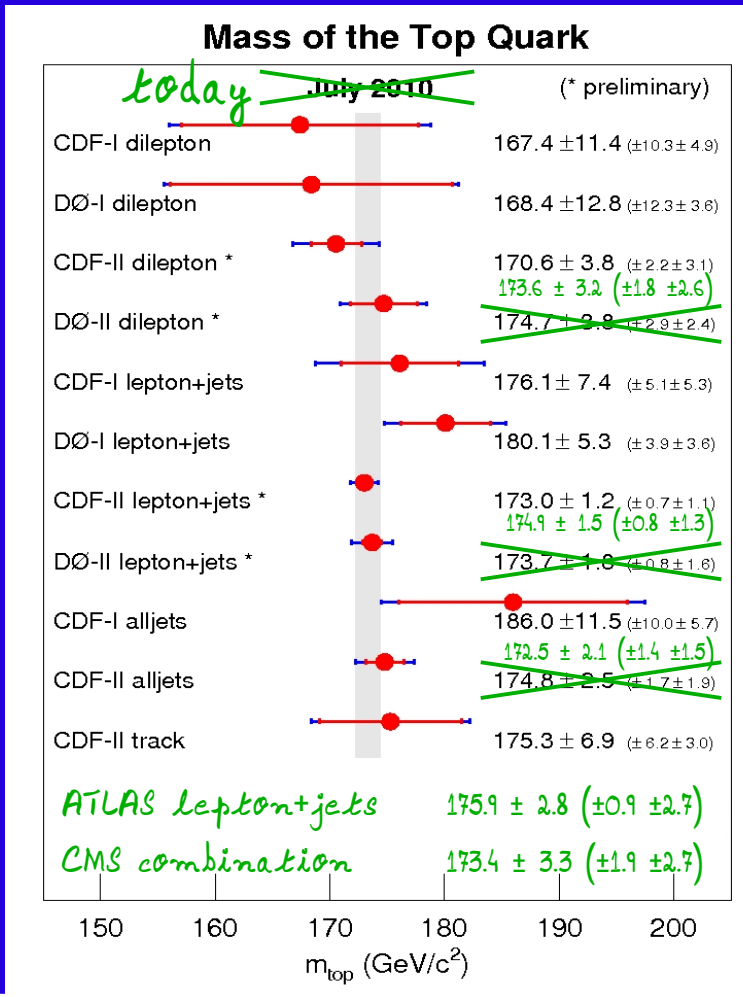

LHC is starting to play a role.
Combination ongoing

blue/red/black: ATLAS/CMS/theory **bold face**: german contribution

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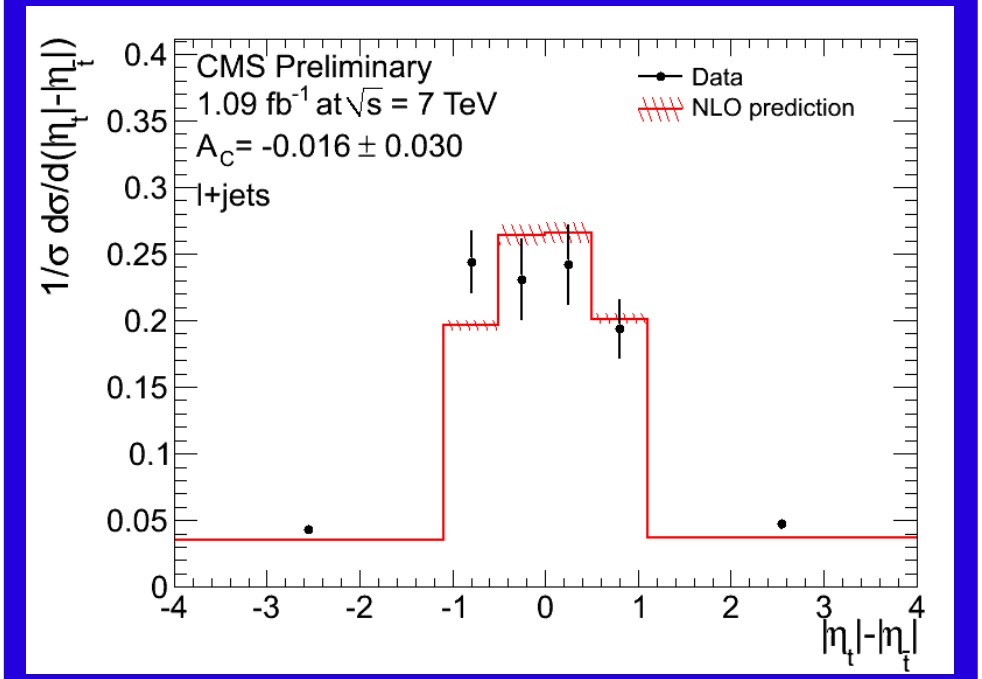

No deviation from the SM in the ttbar charge asymmetry observed.

blue/red/black: ATLAS/CMS/theory **bold face**: german contribution

Searches:

- ttbar+anomalous MET
  ATLAS-CONF-2011-036, arXiv:1109.4725
- FCNC
  ATLAS-CONF-2011-061, ATLAS-CONF-2011-154
- Like-sign top quark pairs
  ATLAS-CONF-2011-139, arXiv:1106.2142
- Resonances (l+jets)
  ATLAS-CONF-2011-070, ATLAS-CONF-2011-087, CMS PAS TOP-10-007, CMS PAS EXO-11-055
- Resonances (dilepton)
  ATLAS-CONF-2011-123
- Resonances (boosted)
  CMS PAS EXO-11-006
- Fourth generation
  CMS PAS EXO-11-050, CMS PAS EXO-11-051, CMS PAS EXO-11-054

Top parallel session

- *Marcello Barisonzi* on ttbar resonances (ATLAS)
- *Thomas Peiffer* on Z' searches (CMS)
- *Philipp Kant* on increased theoretical precision in single top quark production (theory)

Single top:

- s-channel cross-section
  ATLAS-CONF-2011-027, ATLAS-CONF-2011-118
- t-channel cross-section
  ATLAS-CONF-2011-088, ATLAS-CONF-2011-101, CMS PAS TOP-10-008, Phys. Rev. Lett. 107 (2011) 091802
- tW-channel cross-section
  ATLAS-CONF-2011-104, **CMS PAS TOP-11-022**

blue/red/black: ATLAS/CMS/theory **bold face**: german contribution

Moving target: comparison with Tevatron (12/2011)

Measurement	CDF	D0	ATLAS	CMS
Top pair cross-section	(7.50±0.48) pb (all channels) CONF note 9913	($7.56^{+0.63}_{-0.56}$) pb (dil and l+jets) PLB 704 (2011) 403	(179.0 ± 11.8) pb (l+jets) ATLAS-CONF-2011-121	(165.8±13.3) pb (all channels) CMS-PAS-TOP-11-024
Single top cross-section (s-channel)	($1.8^{+0.7}_{-0.5}$) pb PRD 82 (2010) 112005	(0.98±0.63) pb PLB 705, 313 (2011)	< 26.5 pb (95% CL) ATLAS-CONF-2011-118	-
Single top cross-section (t-channel)	(0.8± 0.4) pb PRD 82 (2010) 112005	(2.90±0.59) pb PLB 705, 313 (2011)	(90^{+32}_{-22}) pb ATLAS-CONF-2011-101	(83.6±30.0) pb PRL 107 (2011) 091802
Single top cross-section (tW-channel)	-	-	< 39 pb (95% CL) ATLAS-CONF-2011-104	(22^{+9}_{-7}) pb CMS-PAS-TOP-11-022
Top mass	(172.7±1.09) GeV (all channels) CONF note 10444	(175.1±1.5) GeV (dil and l+jets) D0 Note 6189	(175.9±2.8) GeV (l+jets) ATLAS-CONF-2011-120	(173.4±3.3) GeV (dil and l+jets) CMS-PAS-TOP-10-009

LHC more precise comparable precision Tevatron more precise

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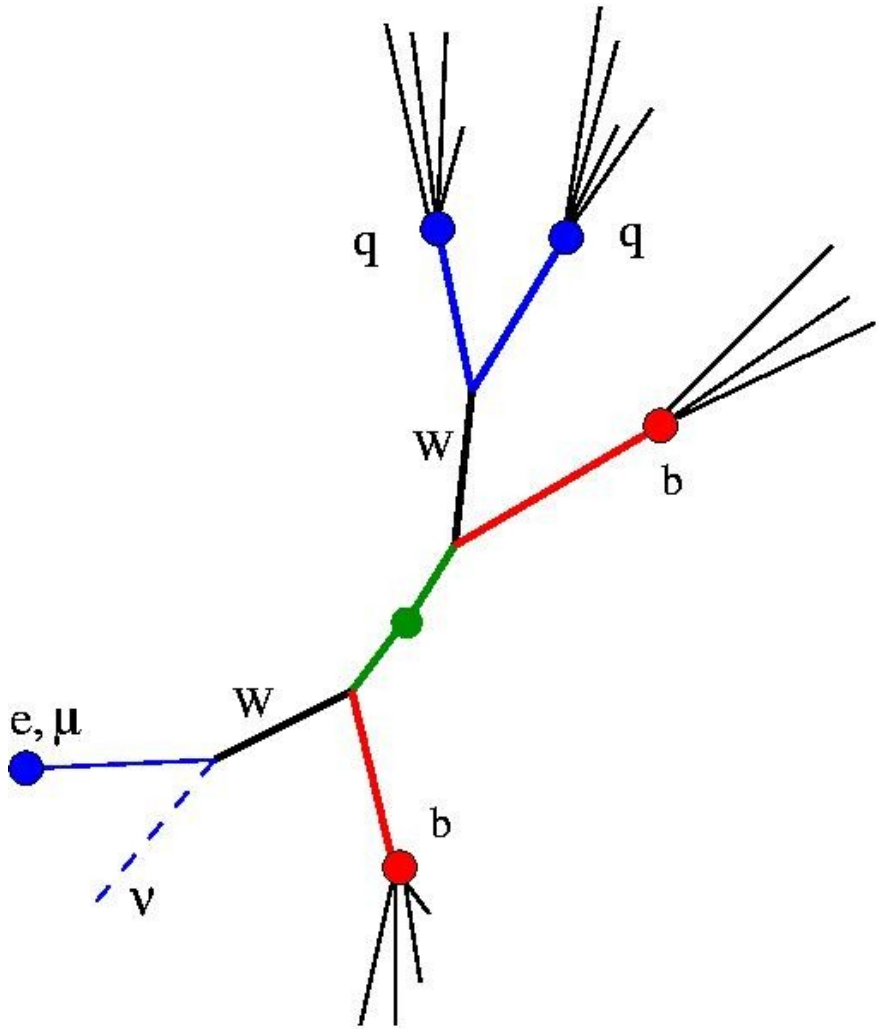
LHC more precise | comparable precision | Tevatron more precise

ATLAS-CONF-2011-121

Event selection:

- Single lepton trigger
- 1 isolated high-pT lepton:
  - E_T>25 GeV for e,
  - p_T>20 GeV for μ
- (4) anti-k_T (R=0.4) jets with p_T>25 GeV and |η|<2.5
- Large MET:
  - e: MET>35 GeV and M_T(W)>25 GeV
  - μ: MET>20 GeV and MET+M_T(W)>60 GeV
- Event cleaning



ATLAS-CONF-2011-121

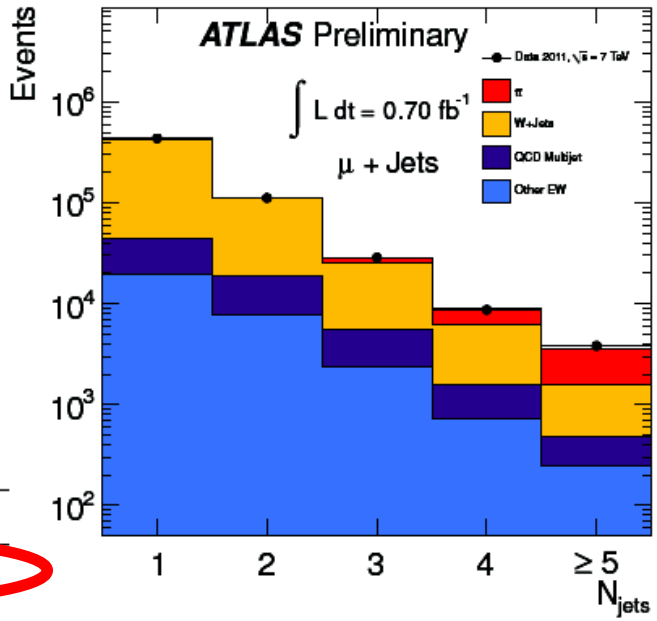
Sample composition:

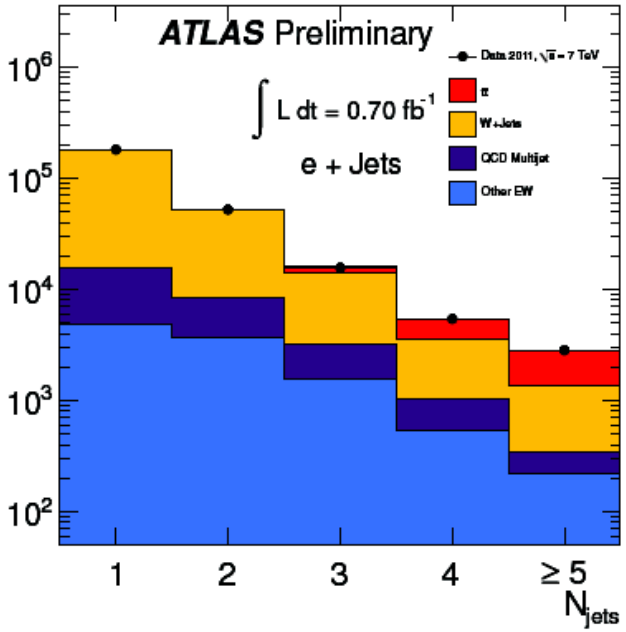
- QCD estimated from data (MM)
- W+jets shapes from MC, normalization from data (W^+/W^- asymmetry)
- Single-top, diboson, Z+jets from MC

	1 Jet	2 Jet	3 Jet	4 Jet	≥ 5 jet
$t\bar{t}$	225±15	1005±32	1934±44	1835±43	1463±38
W+jets (DD)	161600±400	43170±210	10840±100	2486±50	1032±32
QCD multijet (DD)	11000±5000	4800±2400	1600±800	510±250	177±89
Single Top	571±24	711±27	391±20	156±13	65±8
Z+jets	3732±61	2444±49	996±32	333±18	146±12
Diboson (WW,WZ,ZZ)	599±25	538±23	178±13	45±7	10±3
Total Predicted	177000±5000	52600±2400	15900±800	5360±260	2892±100
Data Observed	179469	51820	15614	5398	2812

~40% more in the μ+jets channel (pre-tag)

→ Successfully defines a baseline selection for all other ttbar measurements





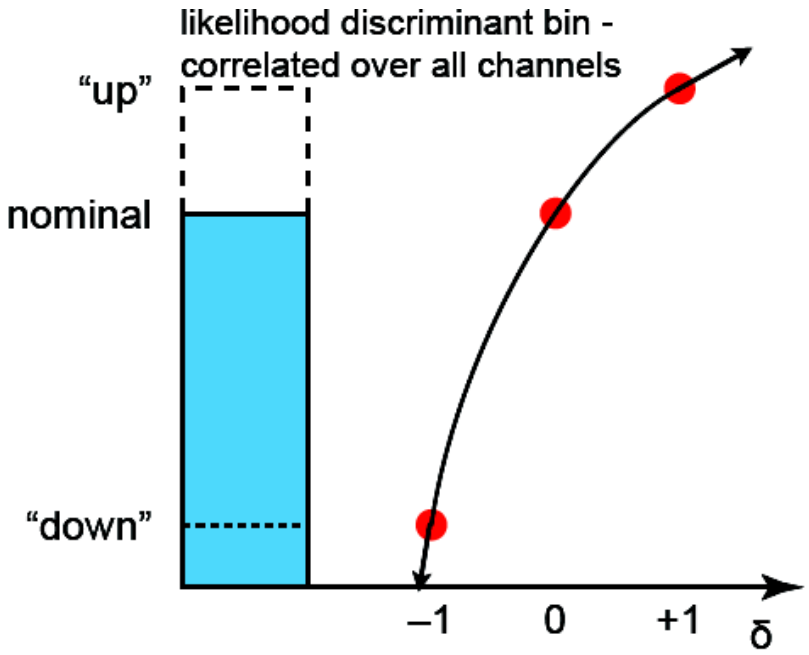
ATLAS-CONF-2011-121

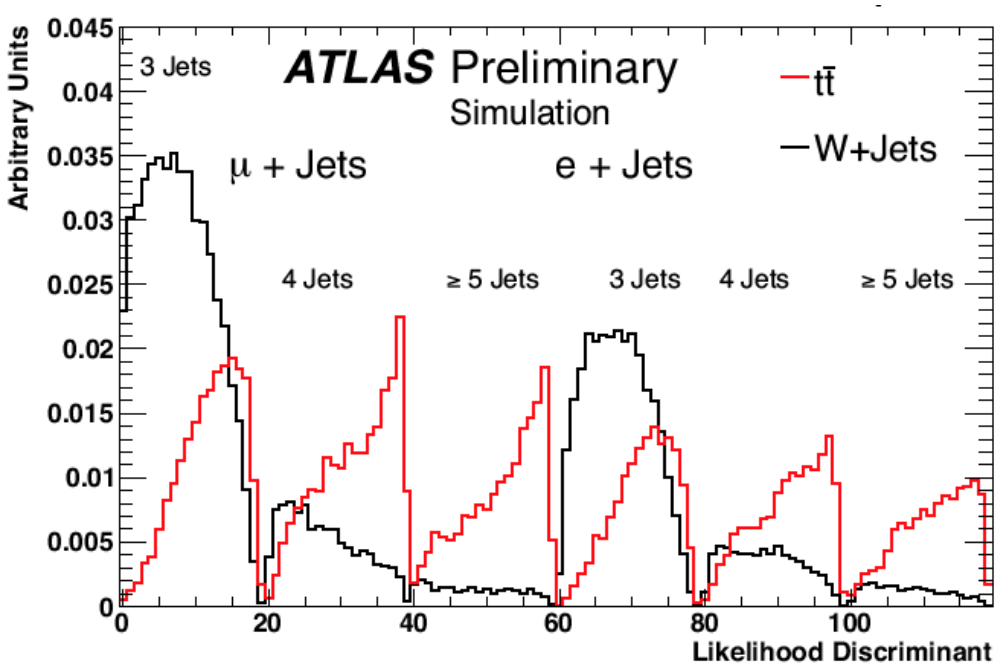
Strategy:

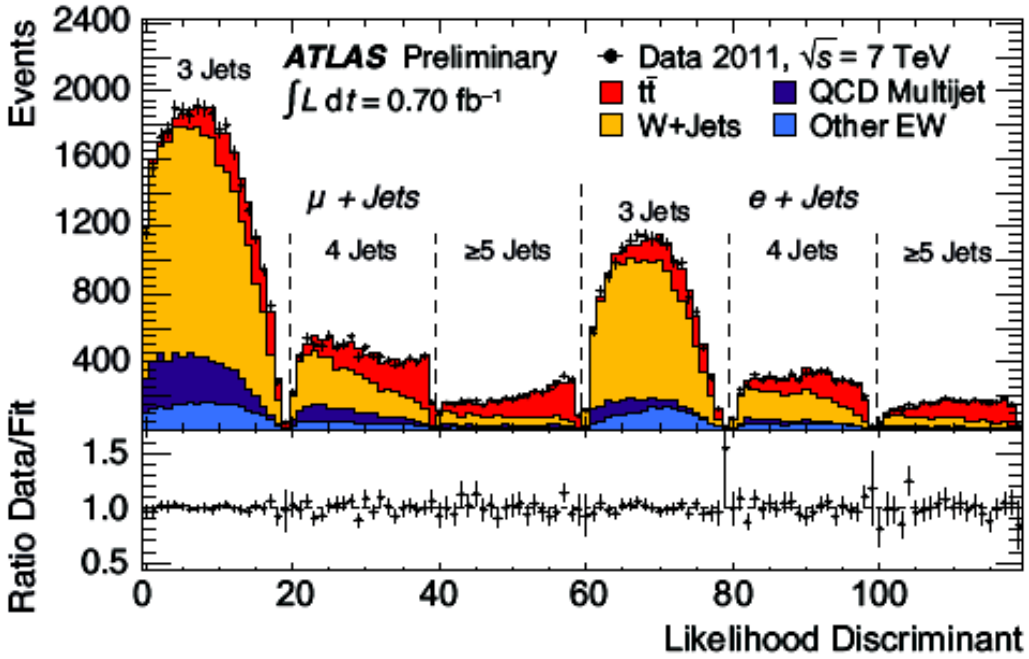
- Build a likelihood discriminant from topological variables
- Fit templates from all processes

$$\mathcal{L}(\vec{\beta},\vec{\delta}) = \prod_{k=1}^{120} \mathcal{P}(\mu_k, n_k) \times \prod_j \mathcal{G}(\beta_j, \Delta_j) \times \prod_i \mathcal{G}(\delta_i, 1)$$

- Use profiling







ATLAS-CONF-2011-121

Uncertainty	up (pb)	down (pb)	up (%)	down (%)
Statistical	3.9	−3.9	2.2	−2.2
Detector simulation				
Jets	3.2	−4.3	1.8	−2.4
Muon	4.1	−4.1	2.3	−2.3
Electron	2.7	−3.0	1.5	−1.7
MET	2.0	−1.6	1.1	−0.9
Signal model				
Generator*)	5.4	−5.4	3.0	−3.0
Hadronization*)	0.9	−0.9	0.5	−0.5
ISR/FSR	3.0	−2.3	1.7	−1.3
PDF*)	1.8	−1.8	1.0	−1.0
Background model				
QCD shape*)	0.7	−0.7	0.4	−0.4
W shape*)	0.9	−0.9	0.5	−0.5
Method*)	3.2	−3.2	1.8	−1.8
Systematic	9.0	−9.0	5.0	−5.0
Stat. & Syst.	9.8	−9.8	5.4	−5.4
Luminosity	6.6	−6.6	3.7	−3.7
Total	11.8	−11.8	6.6	−6.6

*) evaluated externally

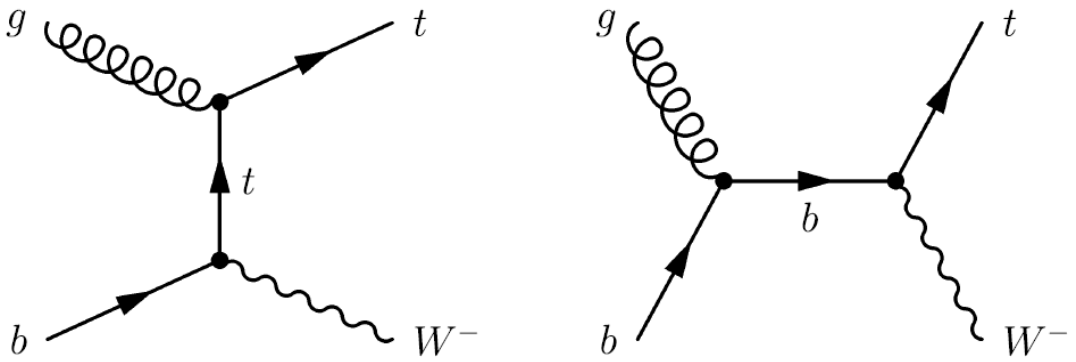
$$\sigma_{t\bar{t}} = 179.0 \pm 3.9\,(\text{stat}) \pm 9.0\,(\text{syst}) \pm 6.6\,(\text{lumi})\,\text{pb}$$

$\sigma_{t\bar{t}}(\text{theory}) = 164.57^{+4.30}_{-9.27}(\text{scale})^{+7.15}_{-6.15}\,(\text{PDF})\,\text{pb}$

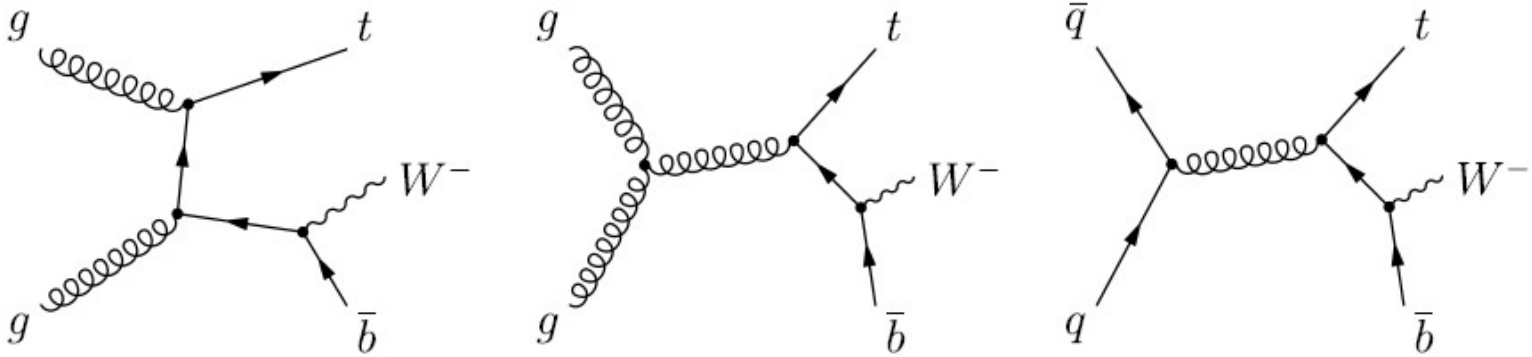
6.6%

CMS PAS TOP-11-022

LO:



NLO:



Cross-section

- NLO tW looks like LO ttbar (+decay)
- Invoke `diagram removal' or `diagram subtraction'
- Prediction in (approx. NNLO) at 7 TeV: σ = $15.6 \pm 0.4^{+1.0}_{-1.2}$ pb

CMS PAS TOP-11-022

Event selection:

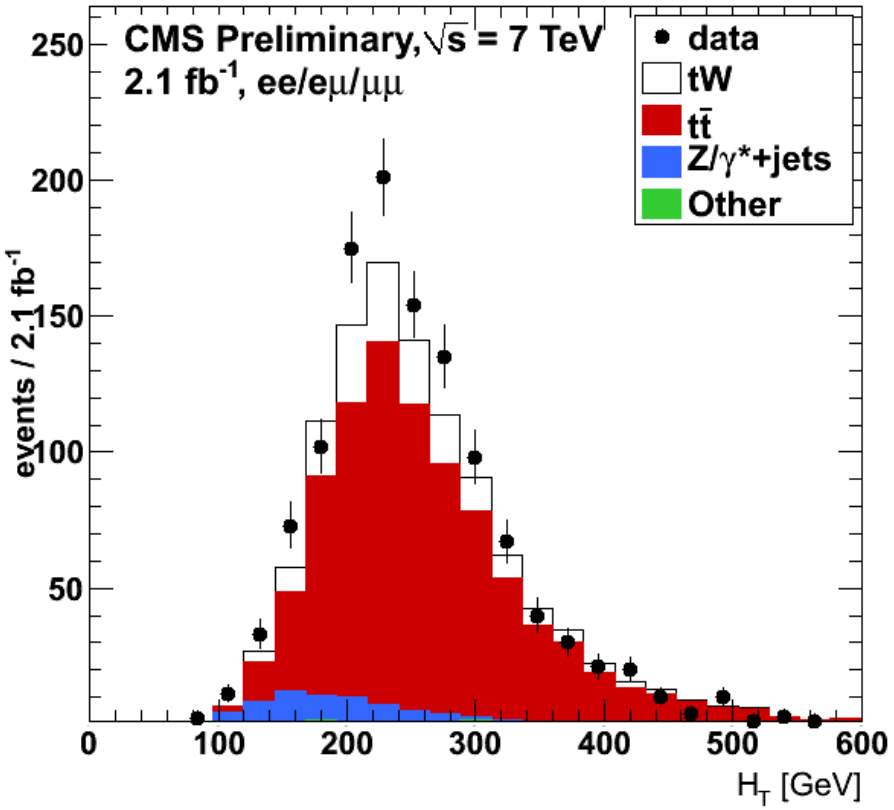
- Dilepton channel: both W's decay into e or μ
- Dilepton trigger
- Require two OS leptons (p_T>20 GeV for both)
- Require exactly one b-tagged jet with p_T>30 GeV
- ee/μμ: p_T^{system}<60 GeV, eμ: H_T>160 GeV

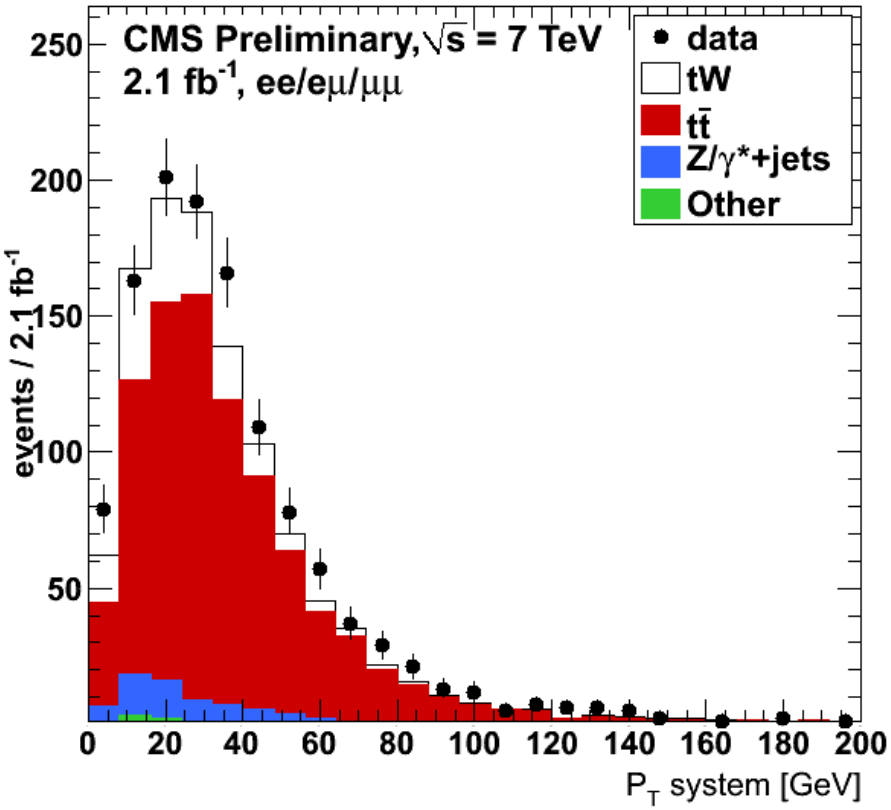
Sample composition:

- Main background l+jets top pairs (estimate from CR)
- Z+jets estimated from data
- W+jets, diboson, other single top estimated from MC

process	*ee* channel	*eμ* channel	*μμ* channel
Signal region (1jet, 1tag)			
tW	24.7±0.9	88 ±2	39±1
$t\bar{t}$	110±4	372±8	174±5
Z/γ^*(data-driven)	20.7 ± 3.9	10 ± 2	45.7 ± 6.1
other	1.0 ±0.2	5 ±1	2.1 ±0.2
all background	132 ± 4	387 ± 9	222 ± 8
data	149	539	276

CMS PAS TOP-11-022





Fit and results:

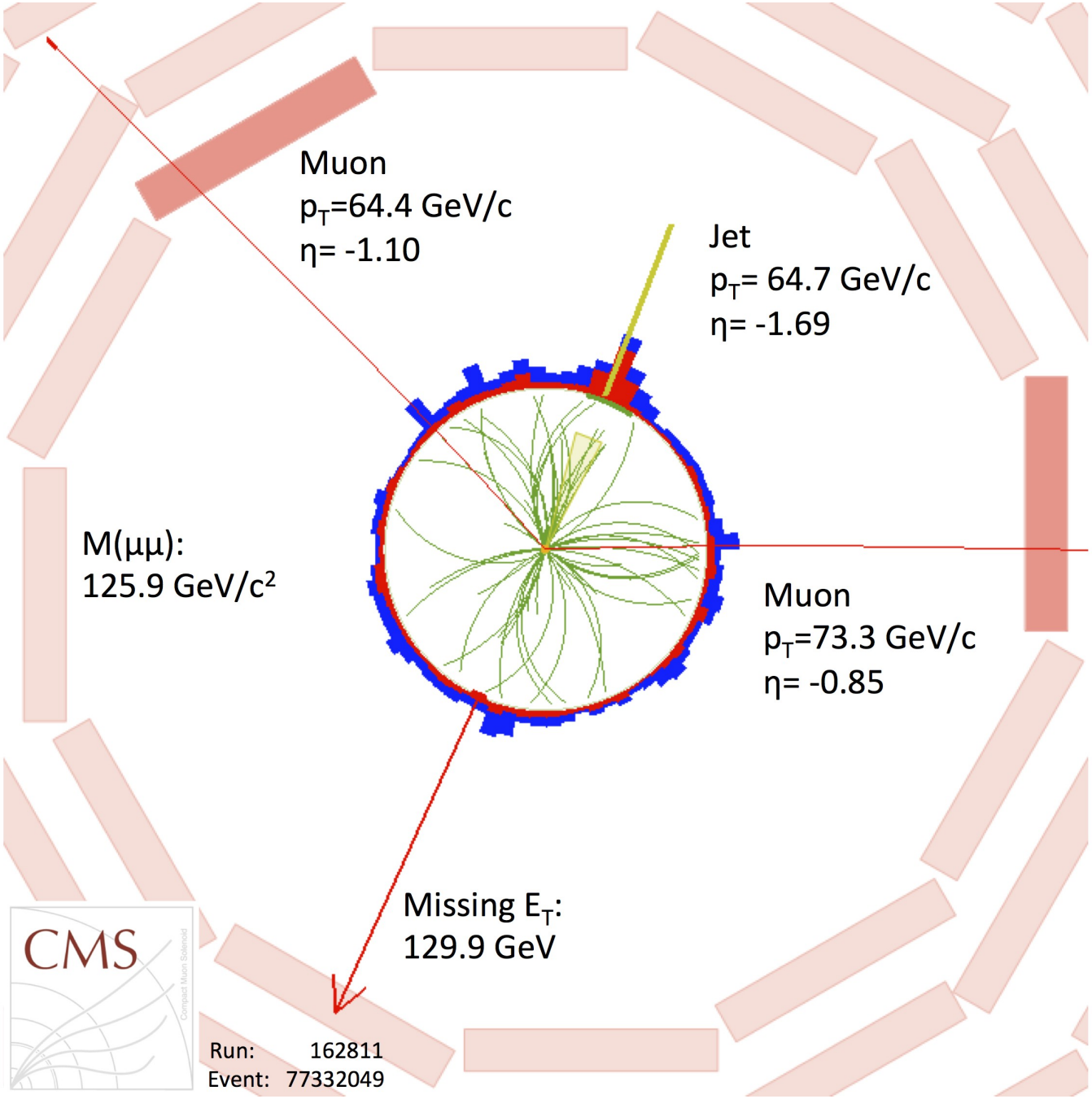
- Counting experiment using profiling
- Systematics:

CMS PAS TOP-11-022

Systematic uncertainty ($ee/e\mu/\mu\mu$) [%]	signal tW	$\bar{t}t$	$Z/\gamma^{\star}$	other
Luminosity	4.5	4.5	-	4.5
Pile-up multiplicity	0.48/0.55/0.73	$\star$	-	$\star$
Trigger Efficiency	1.5	1.5	-	1.5
Muon reconstruction and identification	- /1/1	- /1/1	-	- /1/1
Electron reconstruction and identification	2/2/ -	2/2/ -	-	2/2/ -
JES	$^{-2.5}_{+1.6}$ / $^{-2.4}_{+0.1}$ / $^{-0.6}_{+1.0}$	$^{-5.6}_{+4.4}$ / $^{-6.0}_{+4.7}$ / $^{-5.9}_{+2.3}$	-	$\star$
JER	1.1/0.5/0.4	3.1/3.9/4.4	-	$\star$
B-tagging	$^{-9.5}_{+10}$ / $^{-9.8}_{+9.8}$ / $^{-9.5}_{+10}$	$^{-8.5}_{+10}$ / $^{-11}_{+10}$ / $^{-9.1}_{+11}$	-	$\star$
Factorization/Normalization Scale (Q^2)	7.7/6/10	7.7/11/12	-	$\star$
ME/PS matching thresholds	-	5.7/0.7/2.3	-	$\star$
ISR/FSR	-	8.9/7.3/7.3	-	$\star$
DR/DS scheme	8.2/9.1/6.6	-	-	$\star$
$E_{\mathrm{T}}^{\mathrm{miss}}$ modeling	2.3/0.9/0.9	$\star$	-	$\star$
PDF uncertainties	4.5/4.5/4.5	$\star$	-	$\star$
Background Normalization	-	15/15/15	50/ 50/ 50	$\star$
Simulation statistics	3.5/1.9/2.7	-	-	17/21/11

- Significance: 2.7 σ (expected: (1.8±0.9) σ)
- Cross-section: $\sigma = 22^{+9}_{-7}$ pb

CMS PAS TOP-11-022



PROGRESS IN SM TOP PREDICTIONS

Top pair cross section and distributions:

- Updates of total top pair cross section (NLO QCD + threshold res. (NLL)) *Moch, Uwer; Cacciari et al; Kidonakis, Vogt*
- NNLL extensions *Czakon et al.; Beneke et al.; Ahrens et al., Cacciari et al.*
- Forward-Backward asymmetry from threshold resummation *Almeida et al; Ahrens et al.; Kidonakis;*
- Top pair invariant mass very close to production threshold (resonance peak) *Hagiwara et al; Kiyo et al.*
- Partial results towards top pair total rate at NNLO QCD *Czakon; Bonciani et al. ...*

Top pair + jets: top as a background to Higgs searches: $H \to W^+W^-$ and ttH

- $pp \to t\bar{t}$+jet *Dittmaier et al.; Melikov, Schulze*
- $pp \to t\bar{t}\,b\bar{b}$ *Bredenstein et al.; Bevilacqua et al.*
- $pp \to t\bar{t}\,jj$ *Bevilacqua et al.*
- $t\bar{t}$(+jet) production including decay at NLO QCD *Melnikov, Schulze, Melnikov et al.*; including weak interference corrections *Bernreuther, Si*
- $t\bar{t}$ spin correlations revisited *Mahlon, Parke; Bernreuther, Si*

Single-top:

- Single top t-channel production at NLO QCD in 5 and 4 flavor schemes *Campbell, Frederix, FM, Tramontano*
- Single top including decay at NLO QCD *Falgari et al.*

Monte Carlo at NLO:

- Wt production at NLO QCD in MC@NLO *Frixione et al.; White et al.*
- $t\bar{t}$+1jet in via the POWHEG-Box *Cardos et al..*
- 4F tj in aMC@NLO *Frederix,et al., Re...*

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PROGRESS IN SM

Top pair cross section and distributions:

- Updates of total top pair cross section (NLO QCD + thres
- NNLL extensions *Czakon et al.; Beneke et al.; Ahrens et al., C*
- Forward-Backward asymmetry from threshold resummation
- Top pair invariant mass very close to production threshold (
- Partial results towards top pair total rate at NNLO QCD *C*

Top pair + jets: top as a background to Higgs searches: H+

- pp → tt+jet *Dittmaier et al.; Melikov, Schulze*
- pp → tt bb *Bredenstein et al.; Bevilacqua et al.*
- pp→ tt jj *Bevilacqua et al.*
- tt(+jet) production including decay at NLO QCD *Melnikov,* corrections *Bernreuther, Si*
- tt spin correlations revisited *Mahlon, Parke; Bernreuther, Si*

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Highlights

		LHC (7 TeV)	LHC (14 TeV)
$\mathrm{NNLO}_{\mathrm{approx}}$	(Moch, Uwer et al.)	163^{+3}_{-9}	908^{+10}_{-40}
$\mathrm{NNLO}^{\mathrm{1PI}}_{\mathrm{approx}}$	(Kidonakis)	163^{+7}_{-5}	920^{+60}_{-39}
$\mathrm{NNLL}^{\mathrm{1PI}}_{SCET}$	(Ahrens et al.)	150^{+7}_{-7}	824^{+41}_{-44}
NNLL	(Beneke et al.)	163^{+7}_{-8}	896^{+40}_{-37}

Towards a total NNLO cross-section:

- **Only scale uncertainty**
- **Uncertainty dominated by PDFs**
- **Uncertainty of PDF+α_s > 2xPDF uncertainty**

PROGRESS IN SM

Top pair cross section and distributions:

- Updates of total top pair cross section (NLO QCD + thres
- NNLL extensions *Czakon et al.; Beneke et al.; Ahrens et al., C*
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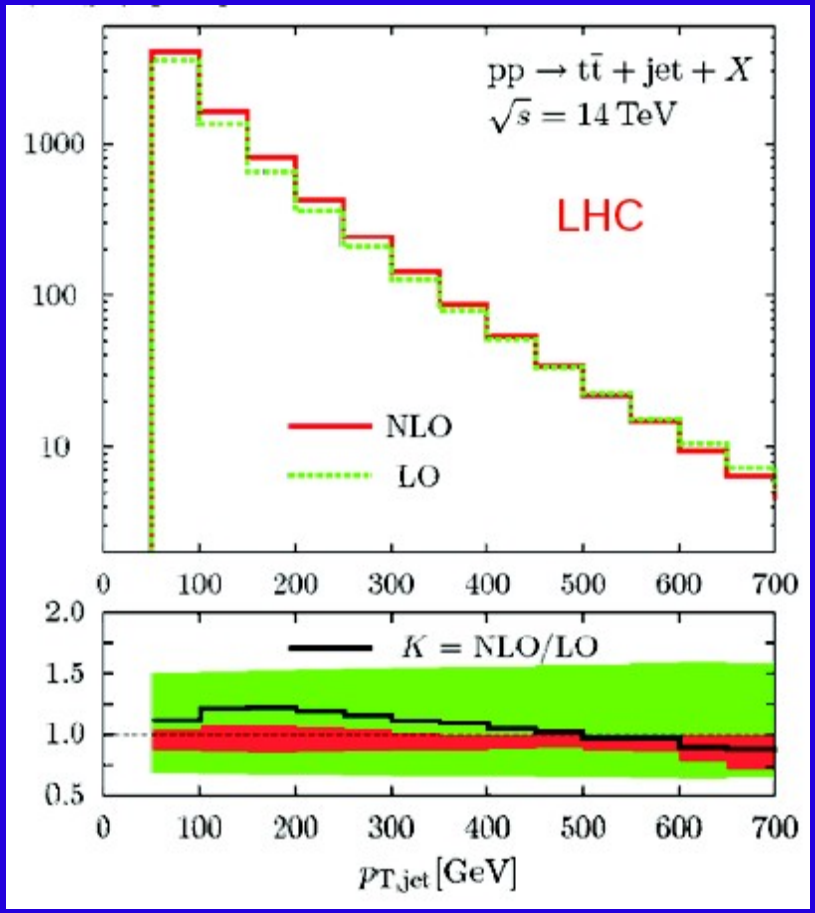
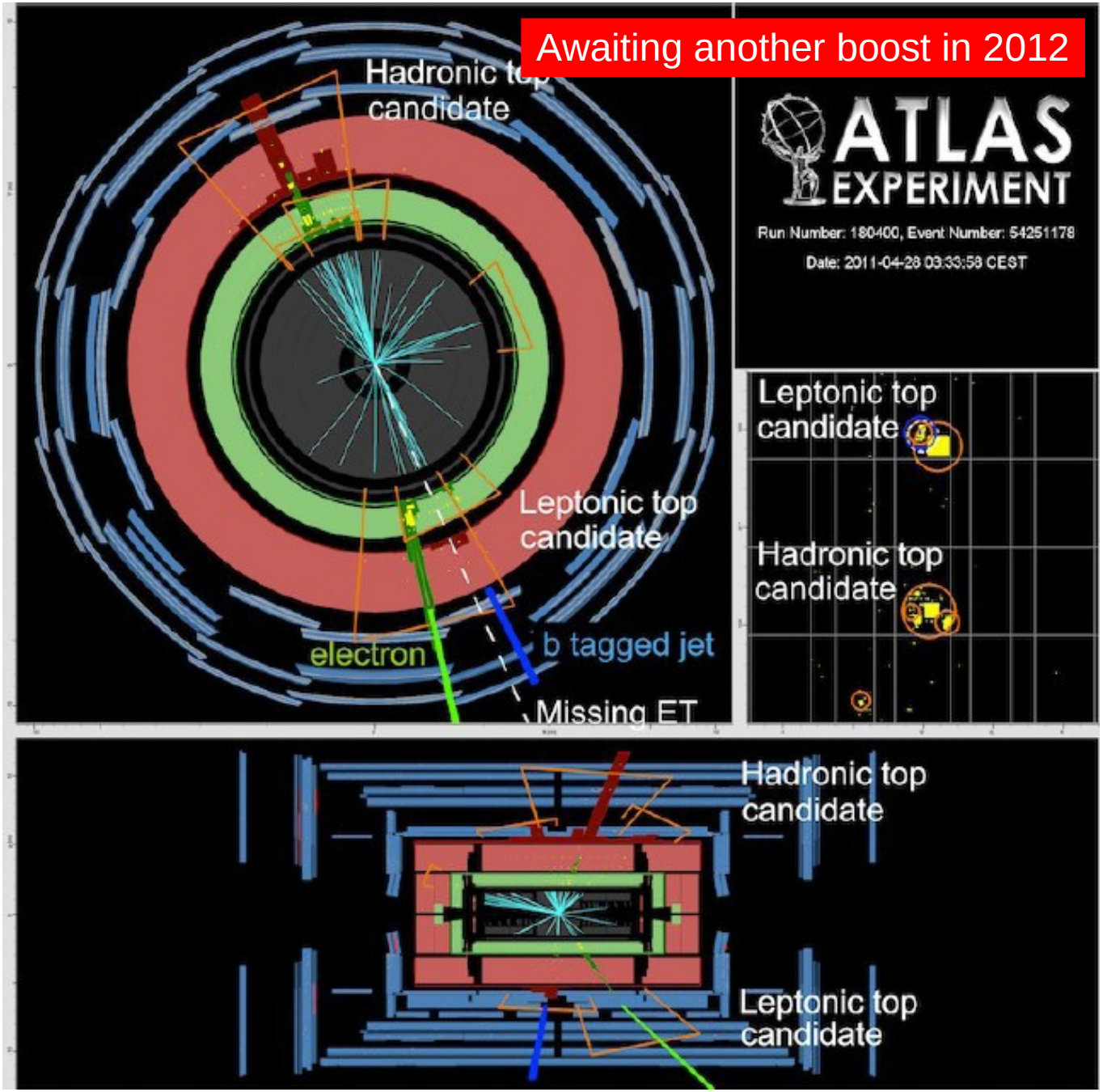
Highlights



Differential distributions also ttbar+jets in NLO

Summary:

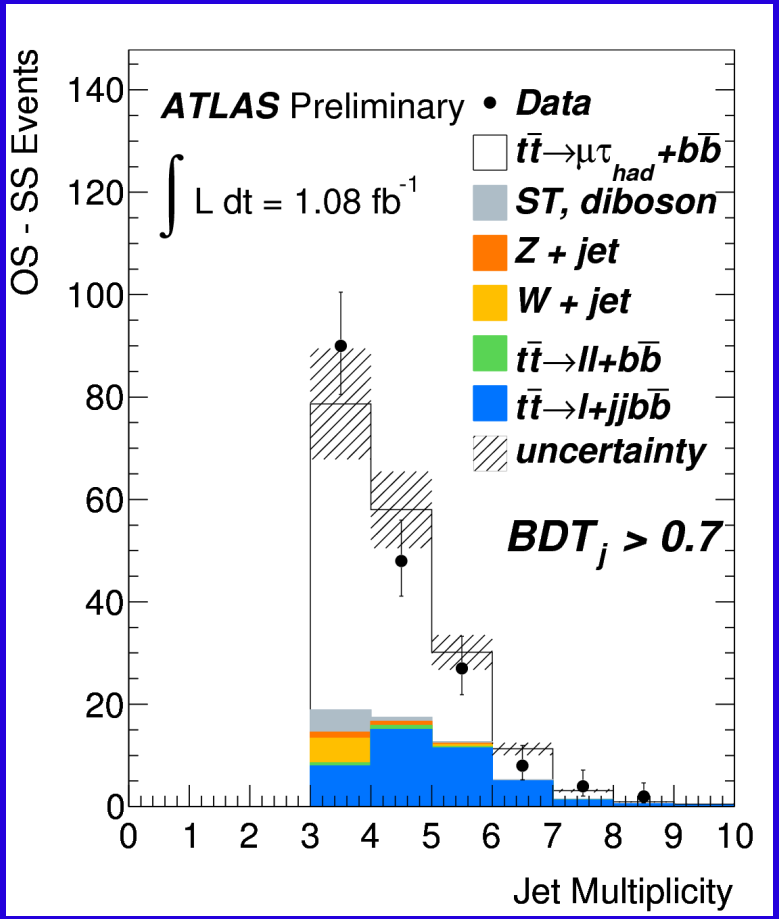
- The top quark offers a rich field of studies
- 2011 was a successful year for top quark physics at the LHC
  - >50 preliminary results, >5 publications
  - Strong participation of german institutes (experiments and theory)
  - Start to get comparable precision as Tevatron (not so easy!)
  - Most measurements are dominated by systematics
  - ATLAS and CMS start talking to each other (also not so easy!)
- Some highlights:
  - Cross-section measurements and predictions have similar precision, NNLO cross-section seems close
  - LHC starts to play a role in the top mass measurements
  - Start to test couplings and other properties
  - Start to reach (and improve) limits in searches from Tevatron, but no deviations found yet


Awaiting another boost in 2012
Hadronic top candidate
Leptonic top candidate
electron
b tagged jet
Missing ET
ATLAS EXPERIMENT
Run Number: 180400, Event Number: 54251178
Date: 2011-04-28 03:33:58 CEST
Leptonic top candidate
Hadronic top candidate
Hadronic top candidate
Leptonic top candidate

Cross-section:

- Total cross-section prediction
  several recent theory updates: NLO QCD+resum.
- Single lepton channels (e/μ+jets)
  ATLAS-CONF-2011-023, ATLAS-CONF-2011-035
  ATLAS-CONF-2011-121, PAS TOP-10-002,
  PAS TOP-10-003, **Eur. Phys. J. C71 (2011) 1721**,
  arXiv:1108.3773, CMS PAS TOP-11-003.
- Dilepton channels (ee, μμ, eμ)
  ATLAS-CONF-2011-034, arXiv:1108.3699,
  ATLAS-CONF-2011-100, CMS PAS TOP-10-005,
  JHEP 07 (2011) 049, CMS PAS TOP-11-005
- Dilepton channels (μ+τ)
  ATLAS-CONF-2011-119, CMS PAS TOP-11-006
- All hadronic channel
  ATLAS-CONF-2011-066, **ATLAS-CONF-2011-140,**
  CMS PAS TOP-11-007
- Combinations
  ATLAS-CONF-2011-040, ATLAS-CONF-2011-108,
  CMS PAS TOP-11-001, CMS PAS TOP-11-024.
- Jet multiplicity
  ATLAS-CONF-2011-142

Highlights



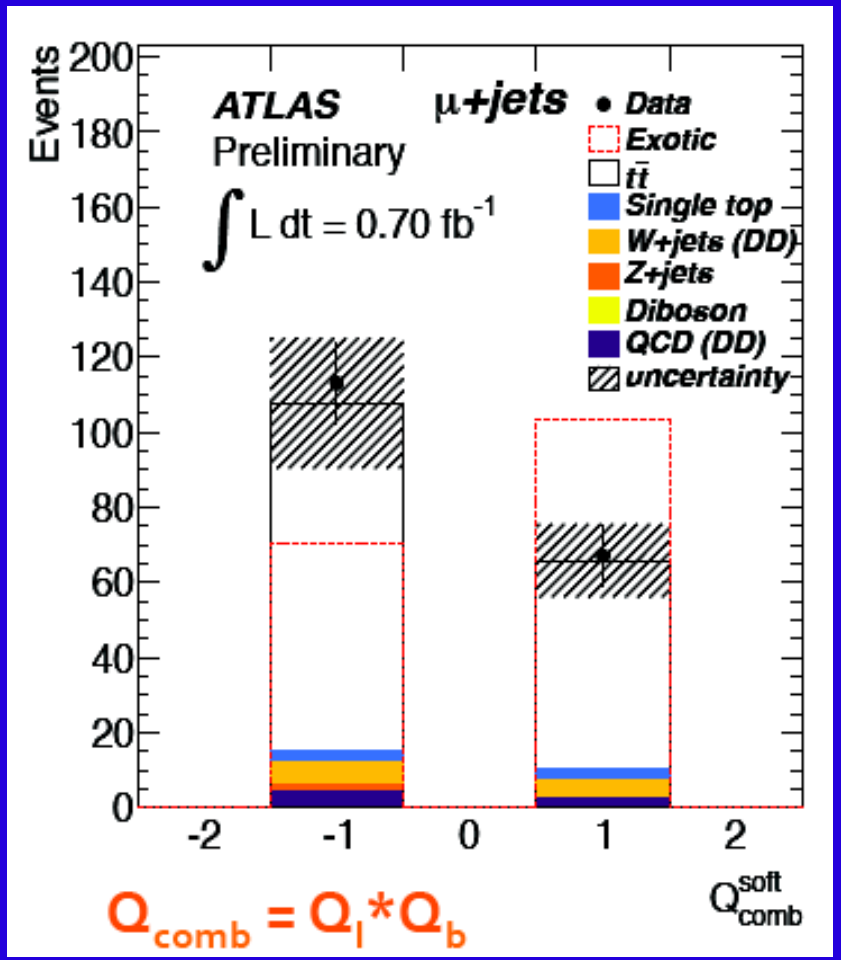
Can already now see taus in top events.

blue/red/black: ATLAS/CMS/theory **bold face**: german contribution

Top properties:

- Top charge
  ATLAS-CONF-2011-141
- W boson polarisation
  ATLAS-CONF-2011-037, ATLAS-CONF-2011-122
- Spin correlation
  ATLAS-CONF-2011-117
- Charge asymmetry
  ATLAS-CONF-2011-106, CMS PAS TOP-10-010, CMS PAS TOP-11-014, many theory papers
- Top mass in l+jets
  ATLAS-CONF-2011-033, ATLAS-CONF-2011-120
  CMS PAS TOP-10-009
- Top mass in dilepton
  CMS PAS TOP-10-006, JHEP 07 (2011) 049
- Top mass from cross-section
  ATLAS-CONF-2011-054, CMS PAS TOP-11-008
- Top/Antitop mass difference
  CMS PAS TOP-11-019

Highlights



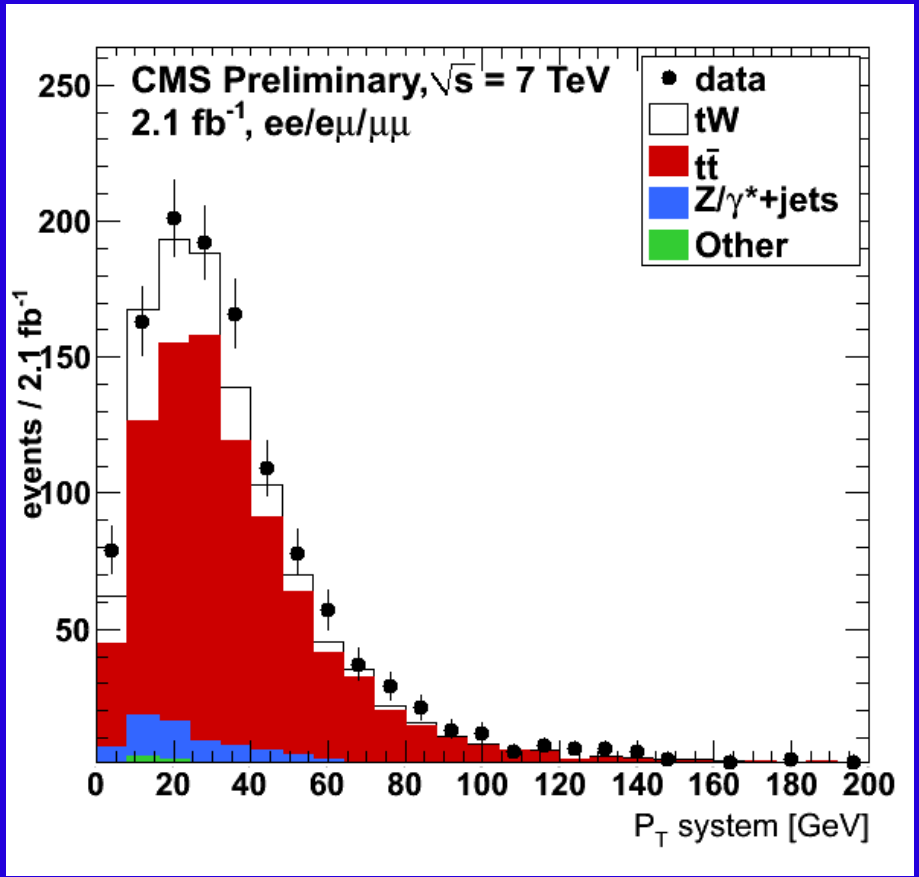
Chapter of exotic charge is closed.

blue/red/black: ATLAS/CMS/theory **bold face**: german contribution

Searches:

- ttbar+anomalous MET
  ATLAS-CONF-2011-036, arXiv:1109.4725
- FCNC
  ATLAS-CONF-2011-061, ATLAS-CONF-2011-154
- Like-sign top quark pairs
  ATLAS-CONF-2011-139, arXiv:1106.2142
- Resonances (l+jets)
  ATLAS-CONF-2011-070, ATLAS-CONF-2011-087,
  CMS PAS TOP-10-007, CMS PAS EXO-11-055
- Resonances (dilepton)
  ATLAS-CONF-2011-123
- Resonances (boosted)
  CMS PAS EXO-11-006
- Fourth generation
  CMS PAS EXO-11-050, CMS PAS EXO-11-051,
  CMS PAS EXO-11-054

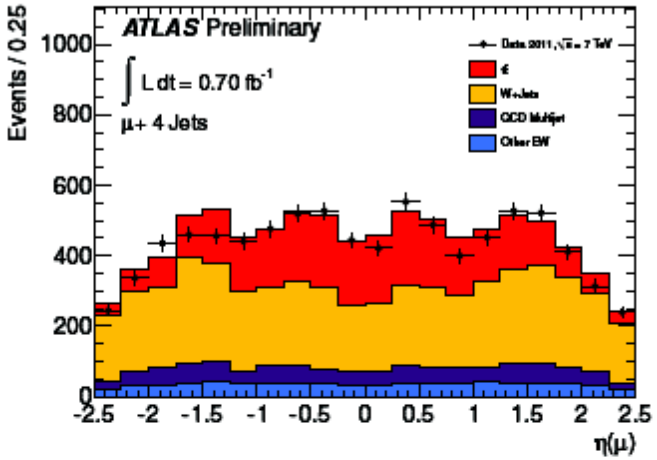
Highlights



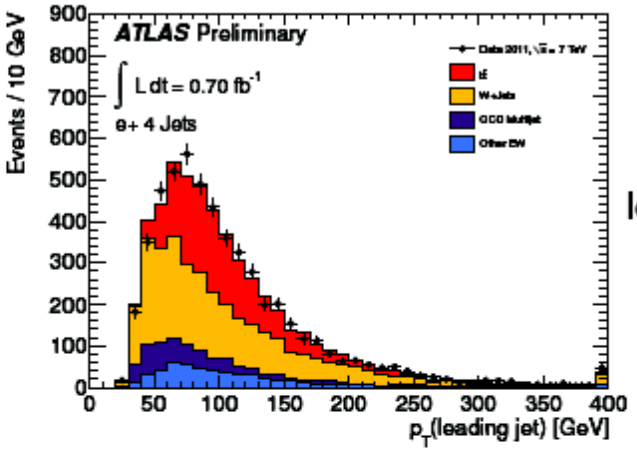
Two-sided limit on tW-channel

blue/red/black: ATLAS/CMS/theory **bold face**: german contribution

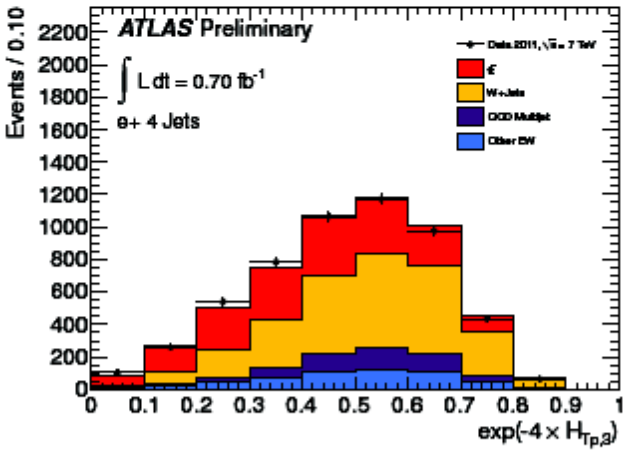
input variables

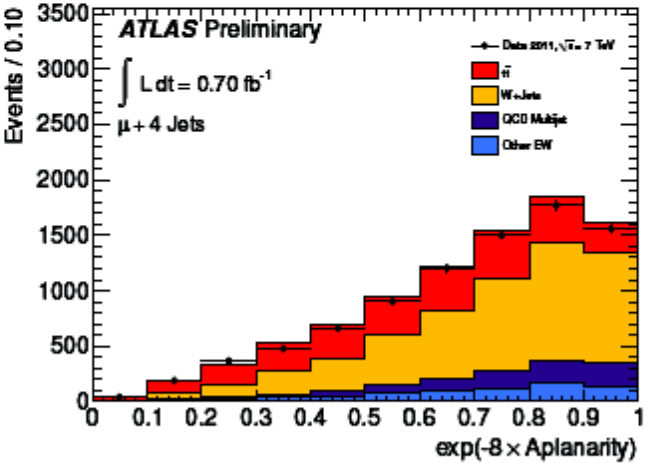


lepton η



leading jet p_T





p_T of 3rd (and 4th) leading jet normalised to absolute sum of all longitudinal momenta in the event:

$$H_{T,3p} = \frac{\sum_{i=3}^{N_{\text{jets}} \leq 4} |p_{T,i}|}{\sum_{j=1}^{N_{\text{objects}}} |p_{z,j}|}$$

aplanarity: 1.5 times smallest eigenvalue of the momentum tensor:

$$M_{ij} = \frac{\sum_{k=1}^{N'_{\text{objects}}} p_{ik} p_{jk}}{\sum_{k=1}^{N'_{\text{objects}}} p_k^2}$$