4th Annual Meeting of the Helmholtz Alliance
"Physics at the Terascale"
Dresden, December 1–3, 2010

First Top Quarks at the Large Hadron Collider

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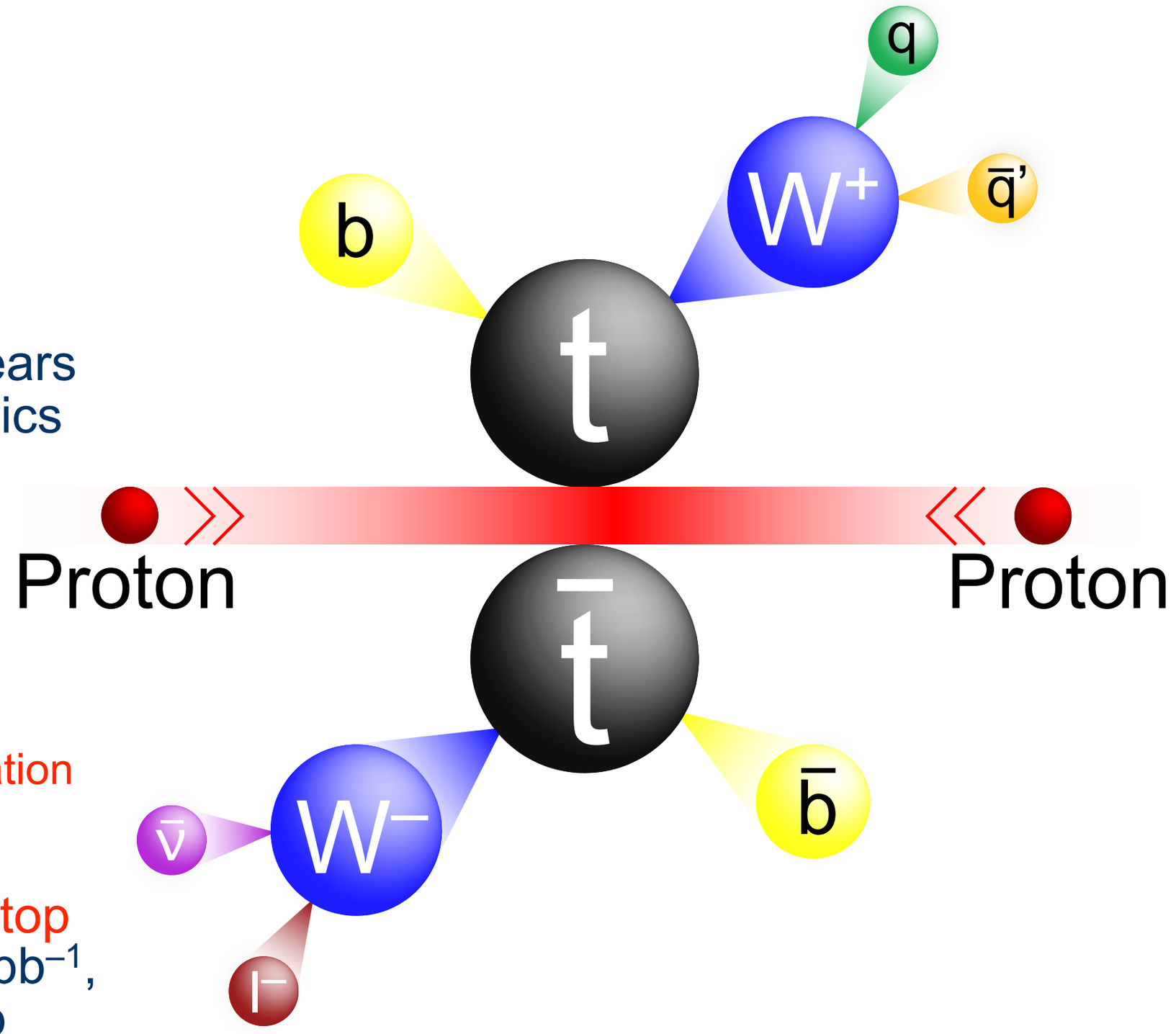
PHYSICS AT THE TERA SCALE
Helmholtz Alliance

DESY

Top Quarks Physics at the LHC

- Top – a heavy-weight among the quarks:
  - The only “bare” quark
  - Role in electroweak symmetry breaking?
- Tevatron: almost 20 years of impressive top physics program
- LHC = top factory
  - Today: top as a signal
  - Very soon: top as a background and calibration source
- Today’s talk: first LHC top results with approx. 3 pb^{-1}, outlook on full 2010 pp dataset



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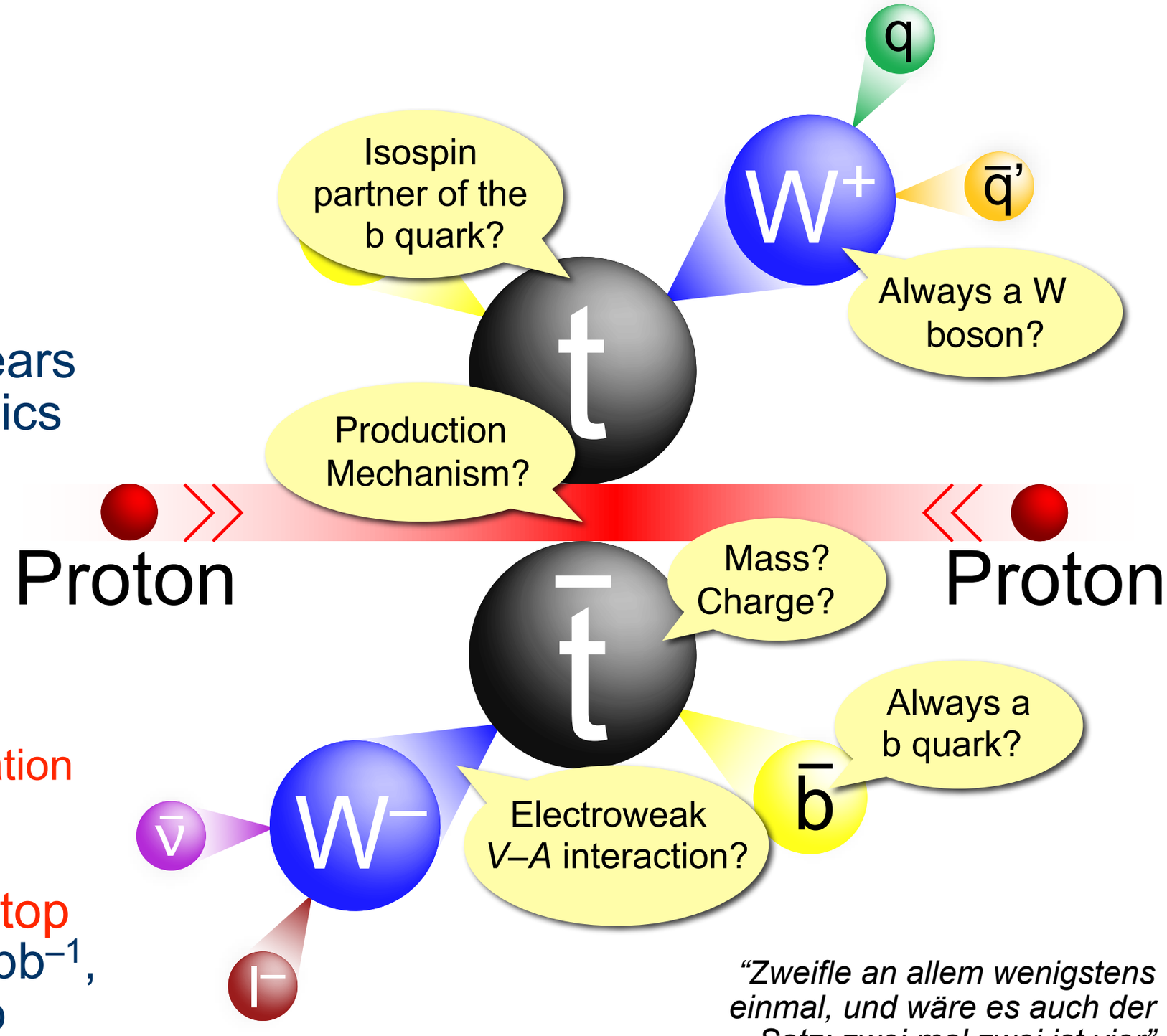
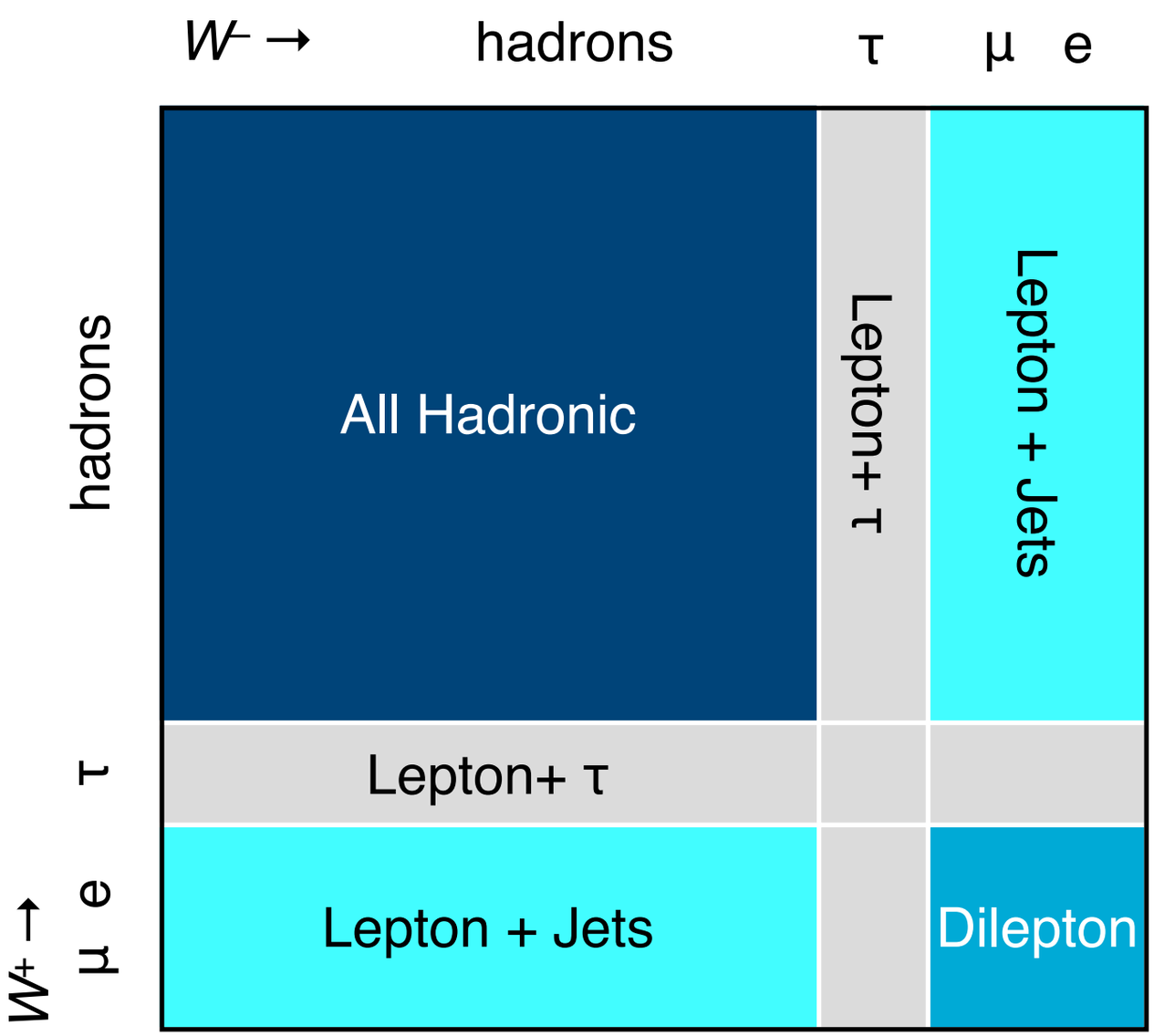


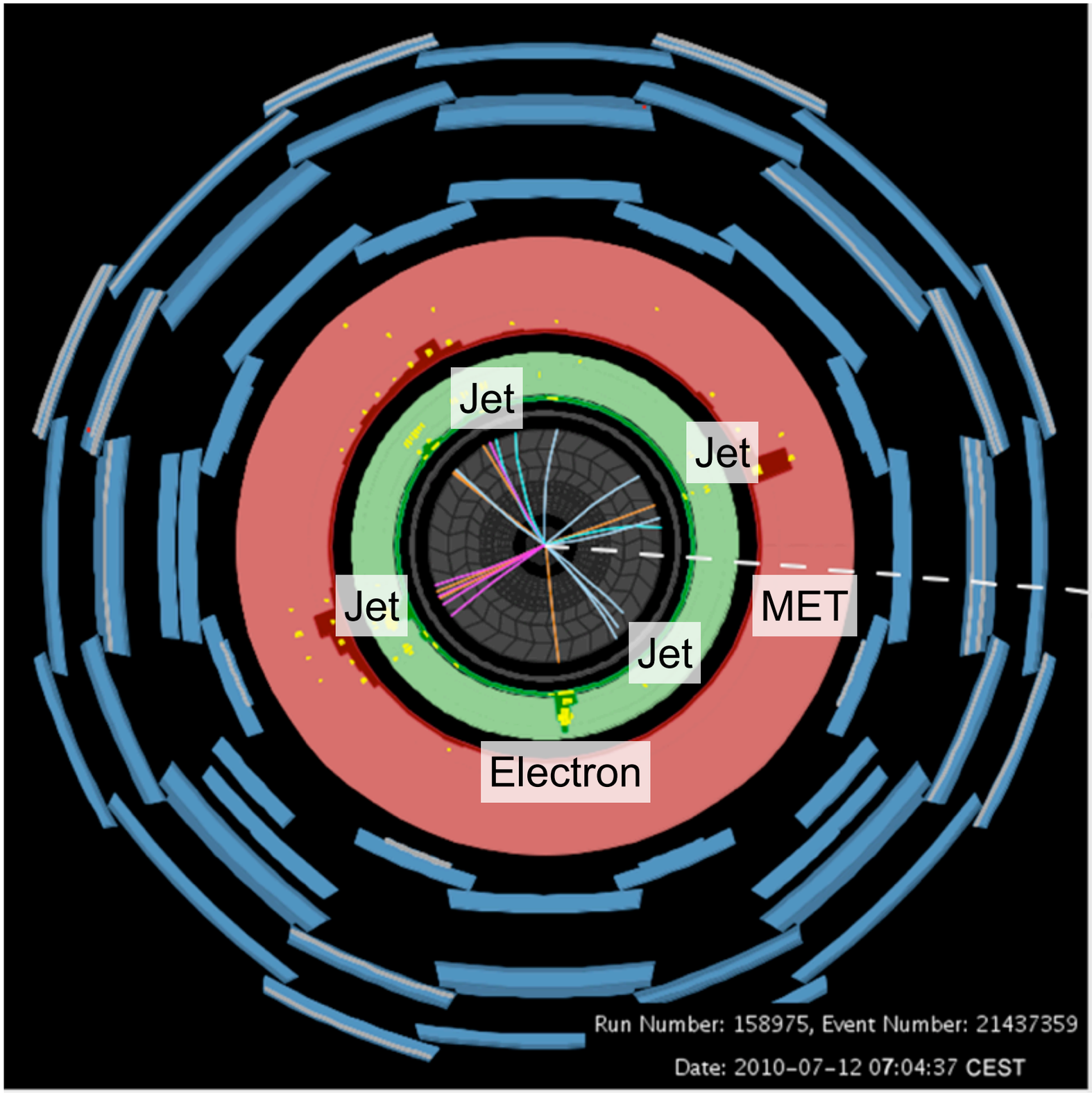
“Zweifle an allem wenigstens einmal, und wäre es auch der Satz: zwei mal zwei ist vier” (G. F. Lichtenberg)

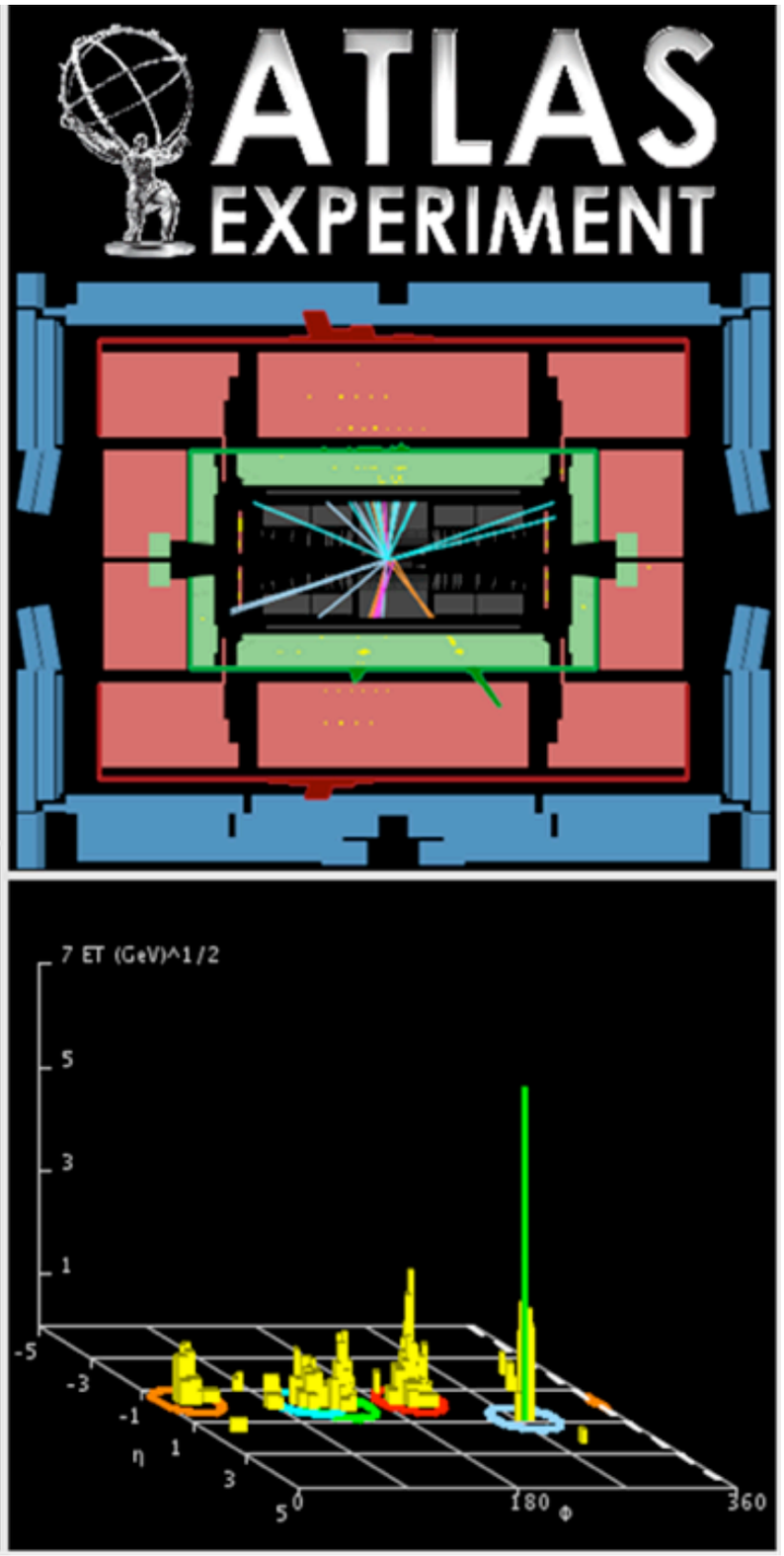
Analyzing Top Quark Events



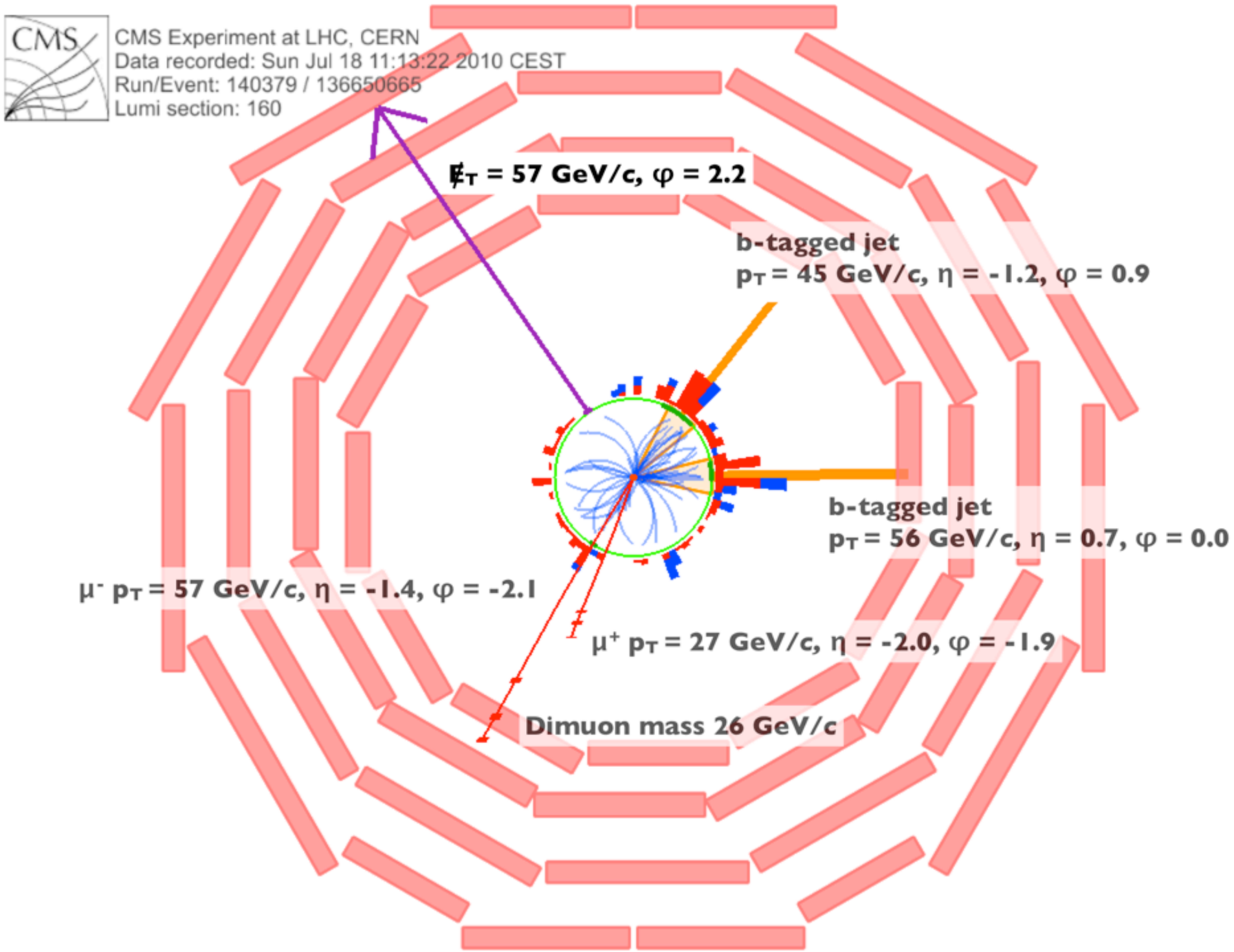
- Top decay in the standard model: $t \rightarrow Wb$ (BR ≈ 100%)
- Challenging signature: multiple leptons & jets, MET
- $t\bar{t}$ decay signatures characterized by W decays:
  - All-Hadronic: 45% of all decays, large QCD background
  - Lepton+Jets: 30% of all decays, moderate backgrounds
  - Dilepton: 5% of all decays, very clean, but small branching fraction
- Dominant backgrounds for leptonic channels
  - W/Z bosons + jets (similar signature)
  - QCD jets (misidentified as leptons)

ATLAS Event Display: e + Jets + MET





CMS Event Display: μμ + 2 Jets + MET



Top at this Workshop

Parallel Session I

Threshold Resummation for Top-Pair Production (C. Schwinn)

HATHOR – a Program to Compute the Hadronic $t\bar{t}$ Cross Section to Approximate NNLO QCD (P. Uwer)

Cross Section Measurement for the Production of Isolated Muons and Jets with CMS (H. Enderle)

Top Lepton+Jets Cross Section with ATLAS – Part I (C. Lange)

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Towards a $t\bar{t}$ Cross Section Measurement in the Dilepton Channel with CMS (D. Dammann)

Towards a Cross Section Measurement for the Production of Top Quark Pairs in the Full Hadronic Decay Channel with CMS (E. Schlieckau)

Top Reconstruction with KLFitter at ATLAS (O. Nackenhorst)

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$t\bar{t}$ + Photon Signals at the LHC (M. Rammes)

Production-Decay Interferences in t-channel Single-Top Production at NLO in QCD (P. Falgari)

Prospects for a Measurement of the t-Channel Single Top Quark Cross Section and Search for Resonances decaying into Top Quark Pairs (D. Klingebiel)

$t\bar{t}$ Spin Correlations: NLO Standard Model Predictions (W. Bernreuther)

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Karlsruhe Top Activities (J. Ott)

Discussion on LHC Top Physics in Germany

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Discussion on LHC Top Physics in Germany

Very active field in Germany, both in theory and experiment

Top Cross Section: Towards NNLO

- QCD heavy flavor production at NLO: known for some 20 years
- NNLO calculation
  - Many active groups, many pieces of available today
  - Challenge: put all pieces together consistently → expected in the next few years

$$\sigma_{ij} = \int |\ \text{n-legs}\ |^2$$

Leading-order, Born approximation

$$+ \int 2\mathrm{Re}\ \text{n-legs} \times \text{n-legs}^* + \int |\ \text{(n+1)-legs, real corrections}\ |^2$$

Next-to-leading order (NLO)

$$+ \int |\ \text{n-legs, 1-loop}\ |^2 + \int 2\mathrm{Re}\ \text{n-legs, 2-loop} \times \text{n-legs}^*$$

$$+ \int 2\mathrm{Re}\ \text{n-legs, 1-loop} \times \text{n-legs, 1-loop}^* + \int |\ \text{(n+2)-legs, real corrections}\ |^2$$

Next-to-next-to-leading order (NNLO)

…

[P. Uwer]

Top Cross Section: Towards NNLO

- Current state of the art: "approximate NNLO" including threshold corrections + NNLL resummation

$\sigma_{t\bar{t}}$(pb)	Tevatron	LHC7	LHC10	LHC14
NLO	$6.50\,^{+0.32+0.33}_{-0.70-0.24}$	$150\,^{+18+8}_{-19-8}$	$380\,^{+44+17}_{-46-17}$	$842\,^{+97+30}_{-97-32}$
NLO+NLL	$6.57\,^{+0.52+0.33}_{-0.30-0.24}$	$151\,^{+23+8}_{-12-9}$	$382\,^{+60+17}_{-32-18}$	$848\,^{+136+30}_{-75-32}$
NLO+NNLL	$6.77\,^{+0.27+0.35}_{-0.48-0.25}$	$155\,^{+4+8}_{-9-9}$	$390\,^{+14+17}_{-26-18}$	$858\,^{+35+31}_{-64-33}$
$\text{NNLO}_{\text{app}}(\beta)$	$7.10\,^{+0.0+0.36}_{-0.26,-0.26}$	$162\,^{+2+9}_{-3-9}$	$407\,^{+9+17}_{-5-18}$	$895\,^{+24+31}_{-6-33}$
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($m_t = 173.1$ GeV, $\tilde{\mu}_f = mt$, MSTW08NNLO) (Beneke, Falgari, Klein, CS preliminary)

[C. Schwinn]

- Some recent discrepancies with alternative threshold expansions:

NLO + NNLL ($M_{t\bar{t}}$) (Ahrens et.al. 10)	$6.48\,^{+0.17+0.32}_{-0.21-0.25}$	$146\,^{+7+8}_{-7-8}$	$368\,^{+20+19}_{-14-15}$	$813\,^{+50+30}_{-36-35}$
$\text{NNLO}_{\text{app}}(s_4)$ (mt=173; Kidonakis 10)	$7.08\,^{+0.00+0.36}_{-0.24-0.27}$	$163\,^{+7+9}_{-5-9}$	$415\,^{+17+18}_{-21-19}$	$920\,^{+50+33}_{-39-35}$

[C. Schwinn]

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[C. Schwinn]

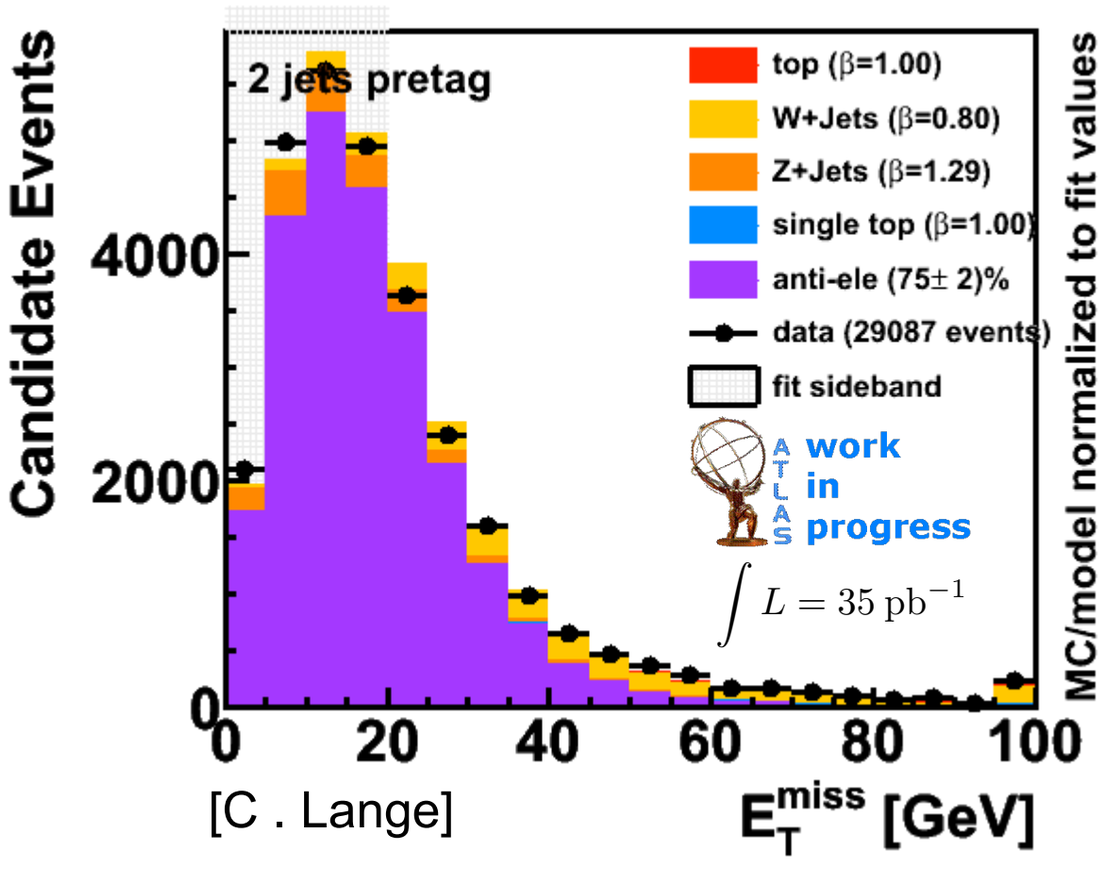
Top Cross Section at $\sqrt{s}$ = 7 TeV

- First public results from CMS (October) and ATLAS (November)
- Cut & count master formula

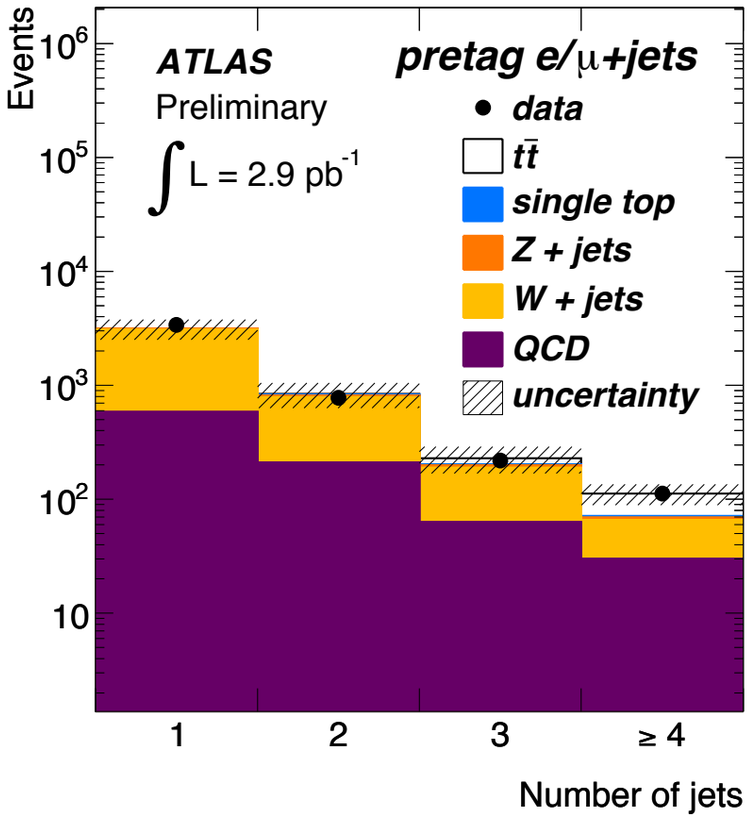
$$\sigma_{t\bar{t}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{L}\varepsilon}$$

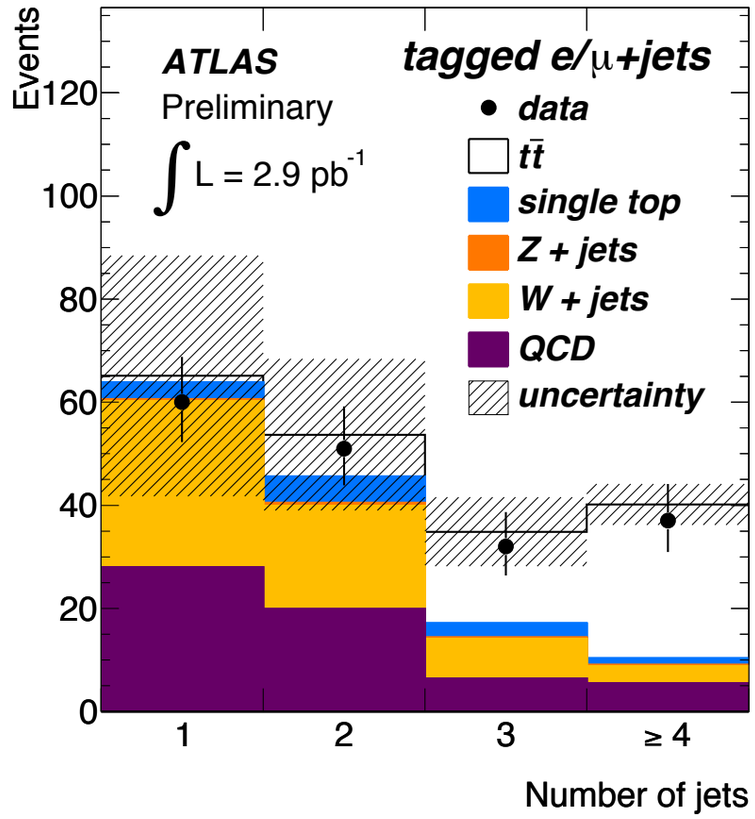
- Challenge: absolute background predictions → data-driven methods preferred
- Example: "fake" electrons from misidentified QCD jets → background model from inverting electron ID cuts

ATLAS	CMS
"Cut & Count" Analysis	"Cut & Count" Analysis
2.9 pb^{-1}	3.1 pb^{-1}
Combination: Lepton+Jets – Dilepton	Dilepton channel only



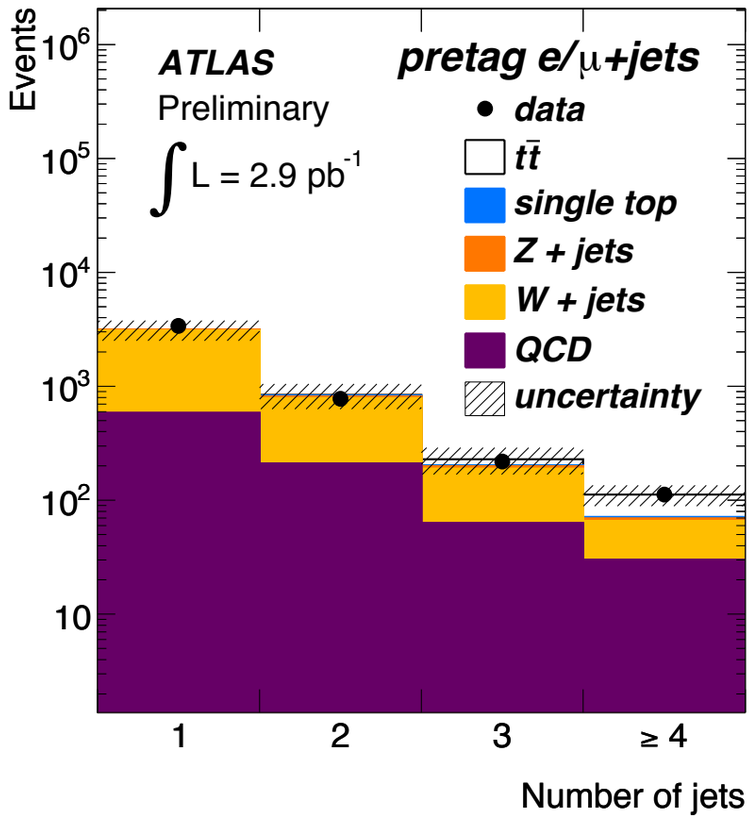
ATLAS: Lepton + Jets Channel

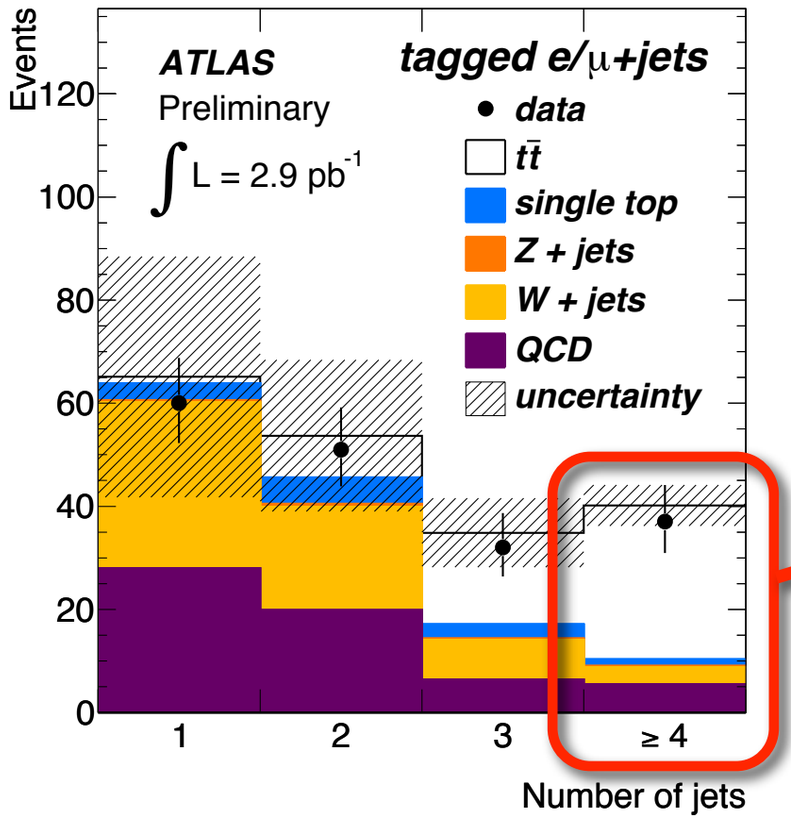


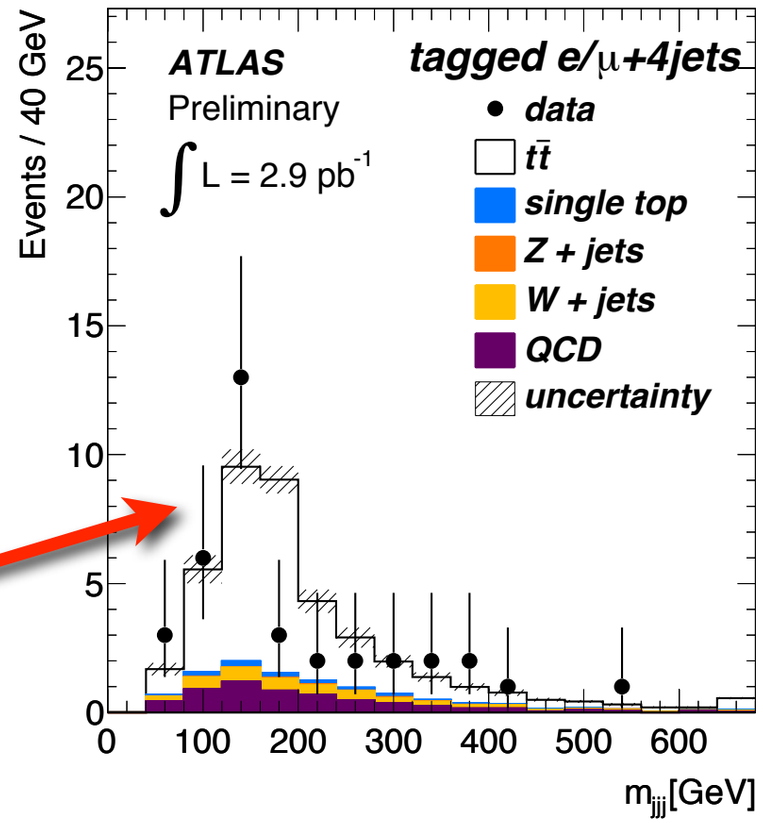


- Signal region: ≥4 jets, ≥ 1 b-tag → very clean
- Kinematics compatible with top production, e.g. invariant mass of three highest p_T jets (mostly from hadronic top decay)
- Background determination for W+jets and QCD → data-driven

ATLAS: Lepton + Jets Channel







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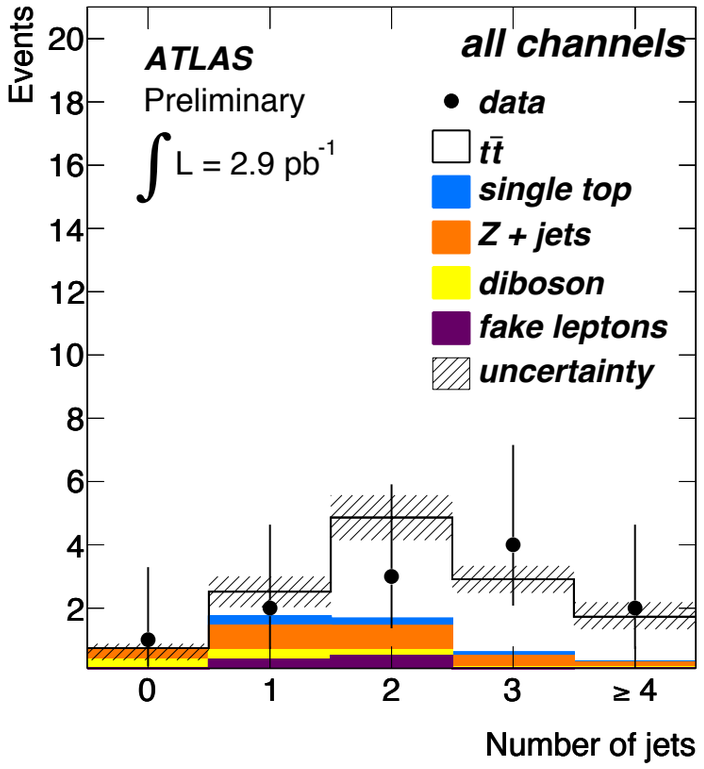
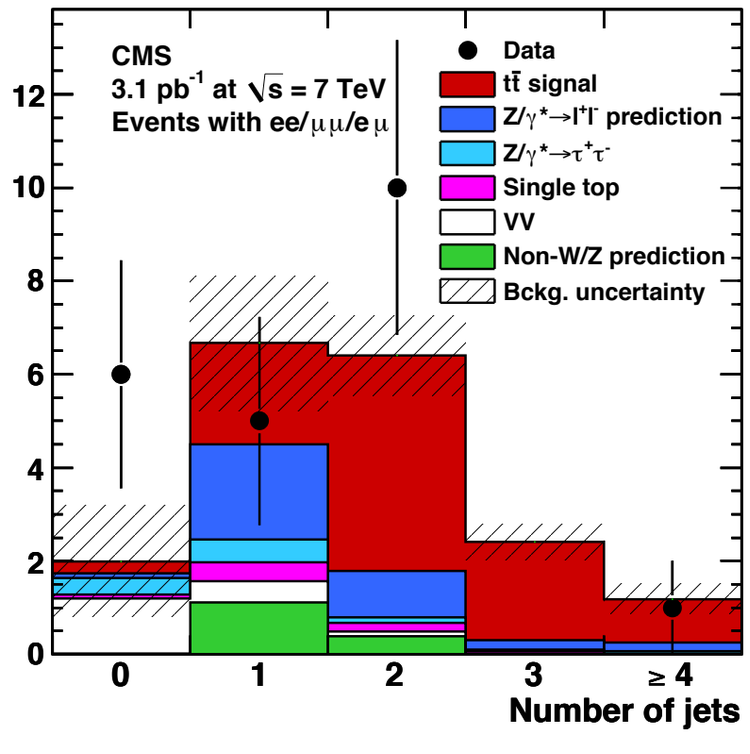
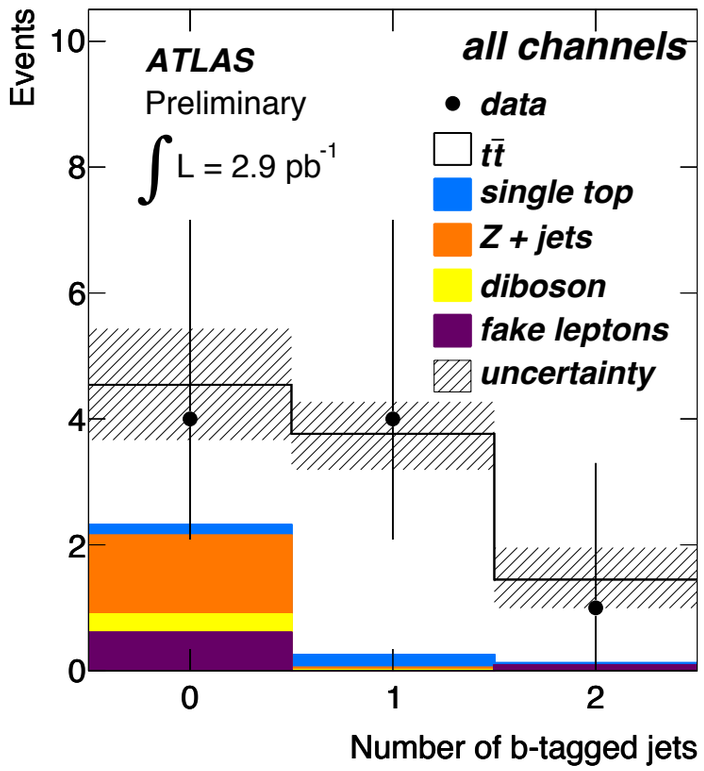
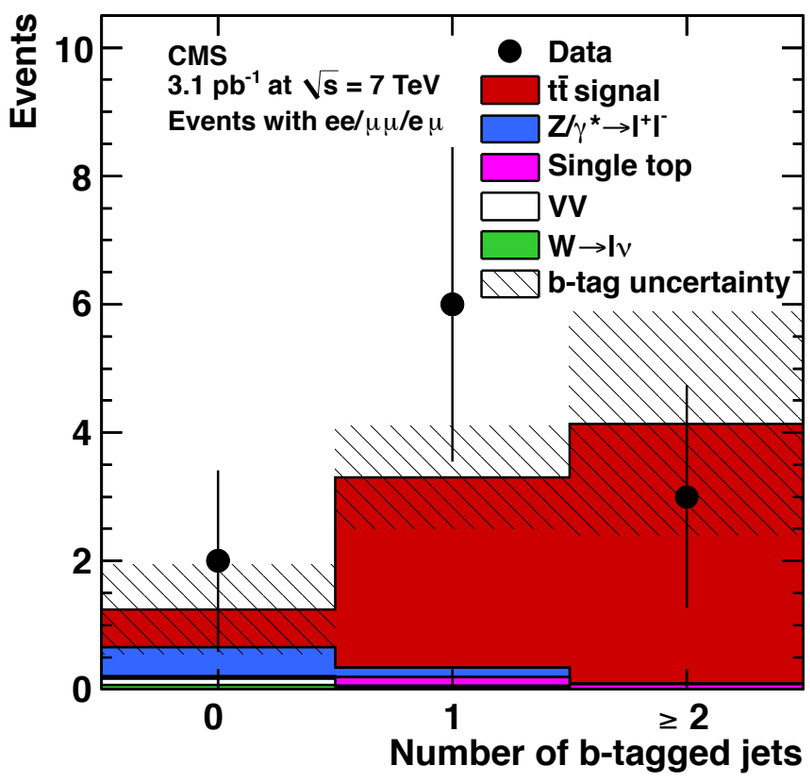
Dilepton Channel





- Signal extraction:
  - 2 opposite sign leptons (ee, μμ, eμ)
  - ≥2 jets
  - No b-tag requirement
- Mostly data-driven backgrounds
- Around 10 candidate events per experiment





arXiv:1010.5994 [hep-ex]

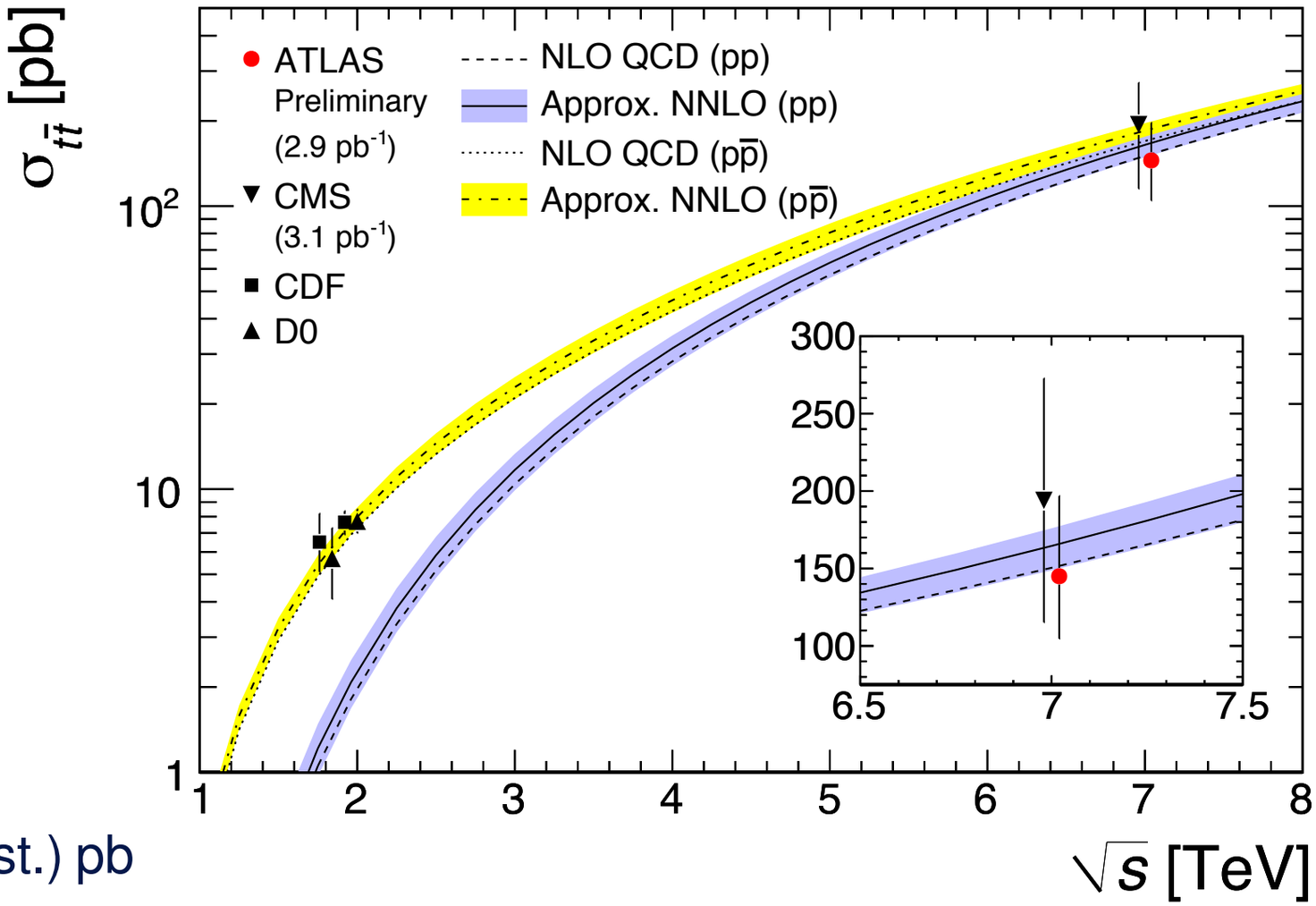
Top Cross Section Summary

- Theory predictions:
  - Hathor, m_t = 172.5 GeV CTEQ66 PDFs
  - QCD at approx. NNLO (Moch/Uwer, Beneke et al.)

    $\sigma_{t\bar{t}} = 164.6\,^{+11.4}_{-15.7}$ pb
- Experimental results:
  - ATLAS preliminary (lepton+jets & dilepton):

    $\sigma_{t\bar{t}} = 145 \pm 31(\text{stat.})\,^{+42}_{-27}\,(\text{syst.})$ pb
  - CMS (dilepton):

    $\sigma_{t\bar{t}} = 194 \pm 72\,(\text{stat.}) \pm 24\,(\text{syst.}) \pm 21\,(\text{lumi})$ pb
  - Good agreement with QCD predictions



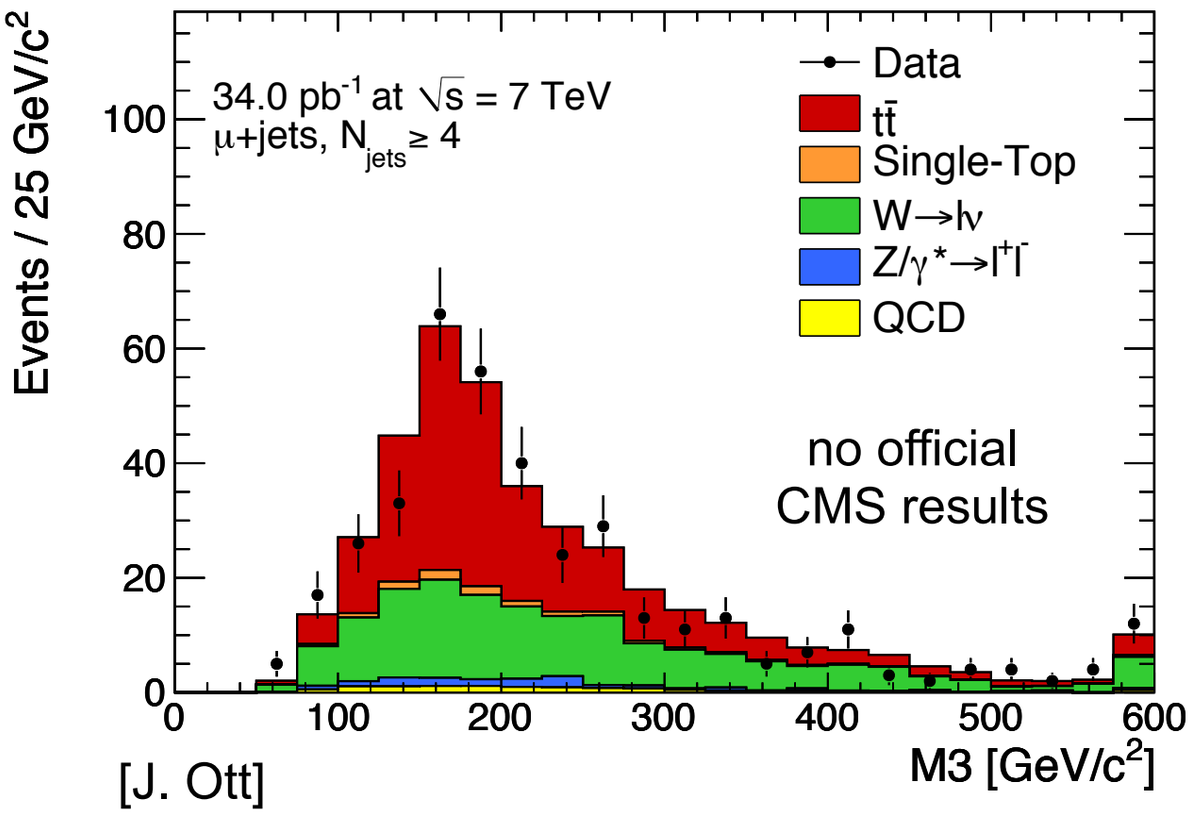
Hathor
(Aliev et al., arXiv: 1007.1327 [hep-ph])
New tool to extract inclusive $t\bar{t}$ cross section at fixed order NLO and approx. NNLO

Top Cross Section: The Next Round

- Next round of top cross section measurements:
  full 2010 LHC proton-proton dataset, integrated luminosity approx. 35 pb^{-1}
- Larger datasets allow to go beyond cut & count

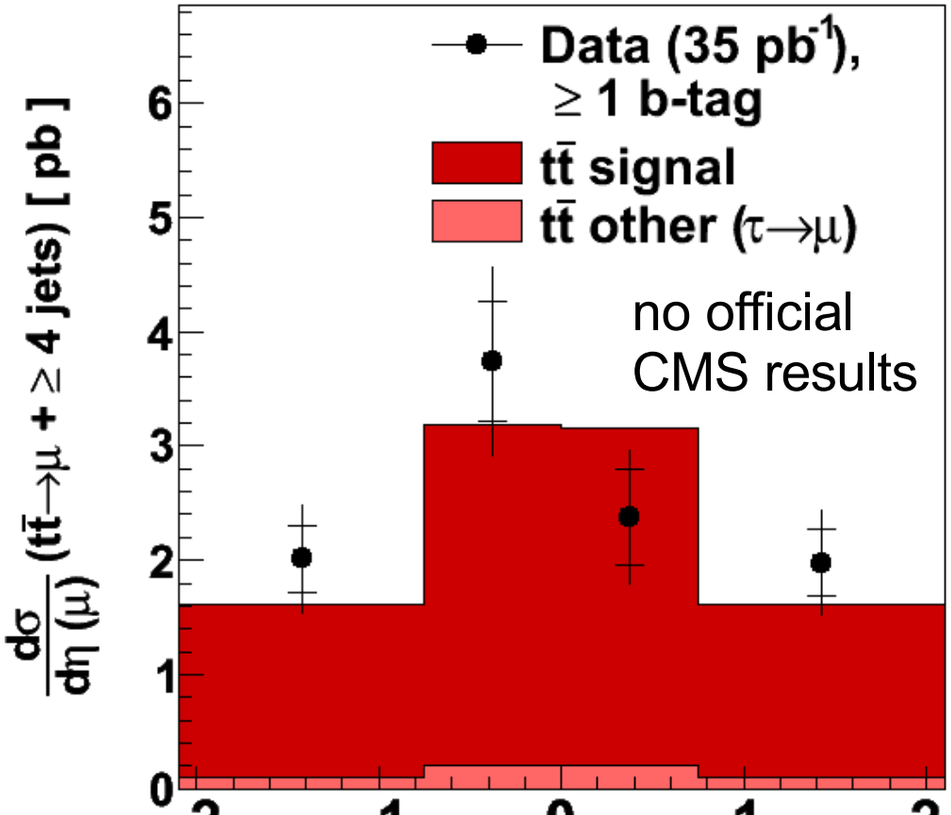
More Data & Differential Cross Section

μ+Jets with Full 2010 Dataset



[J. Ott]

Differential in μ Pseudorapidity

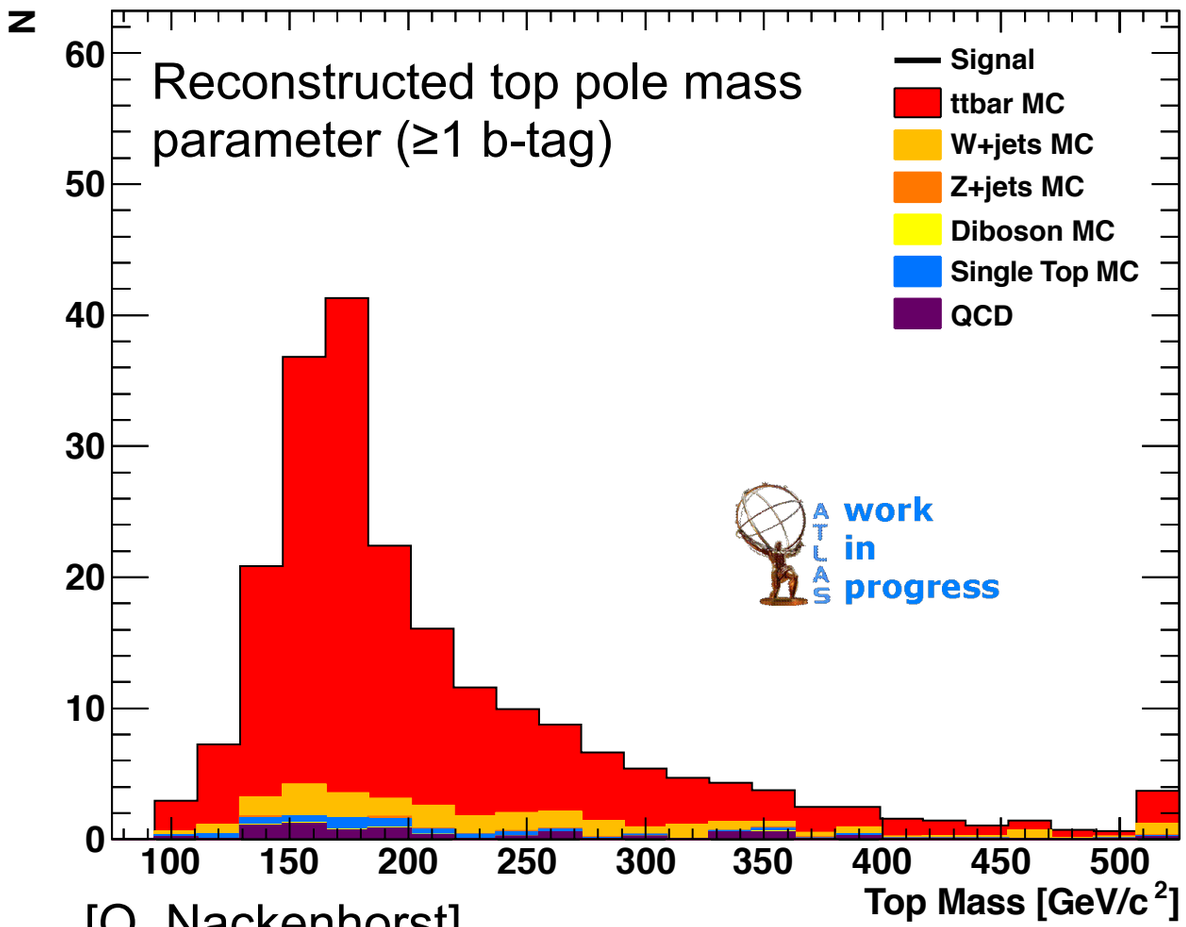


[M. Görner]

Top Cross Section: The Next Round

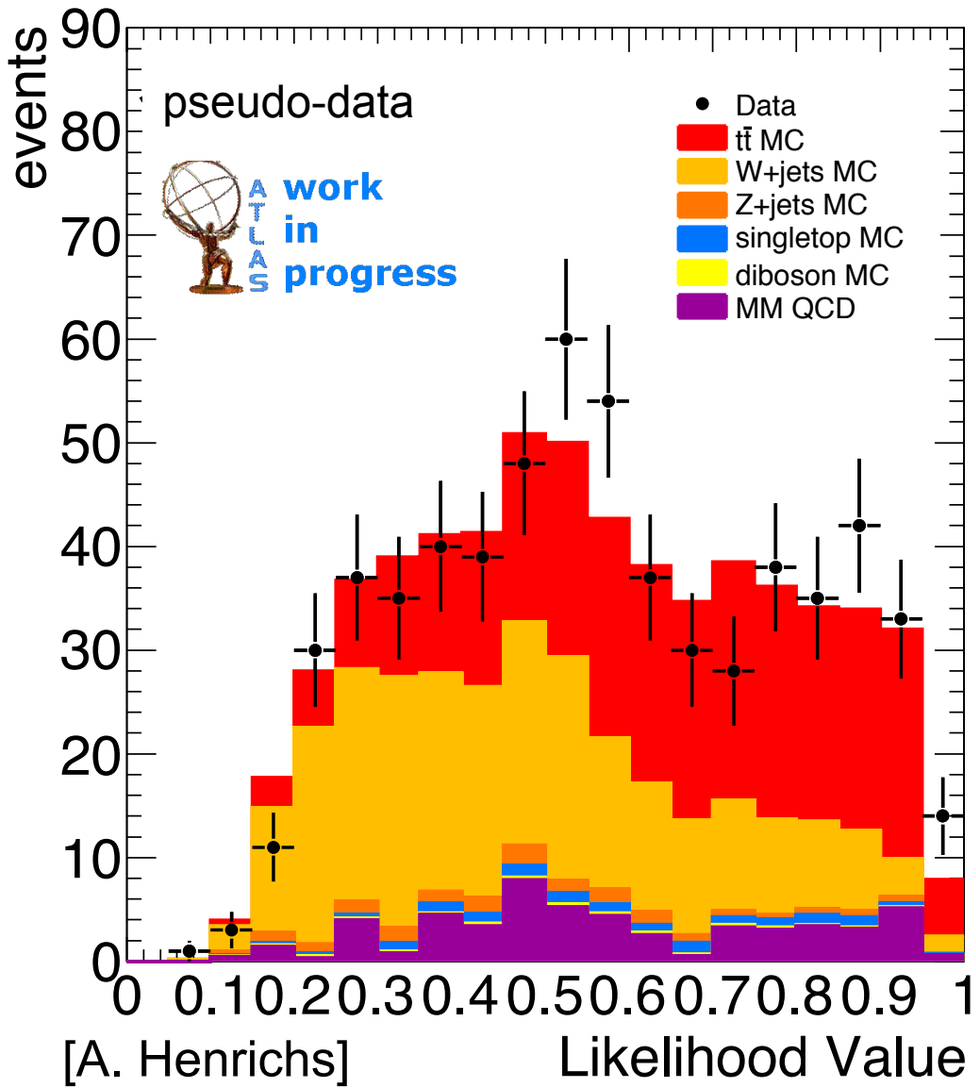
More Sophisticated Analysis Techniques

Top Reconstruction: Kinematic Fitters



[O. Nackenhorst]

Multivariate Likelihood

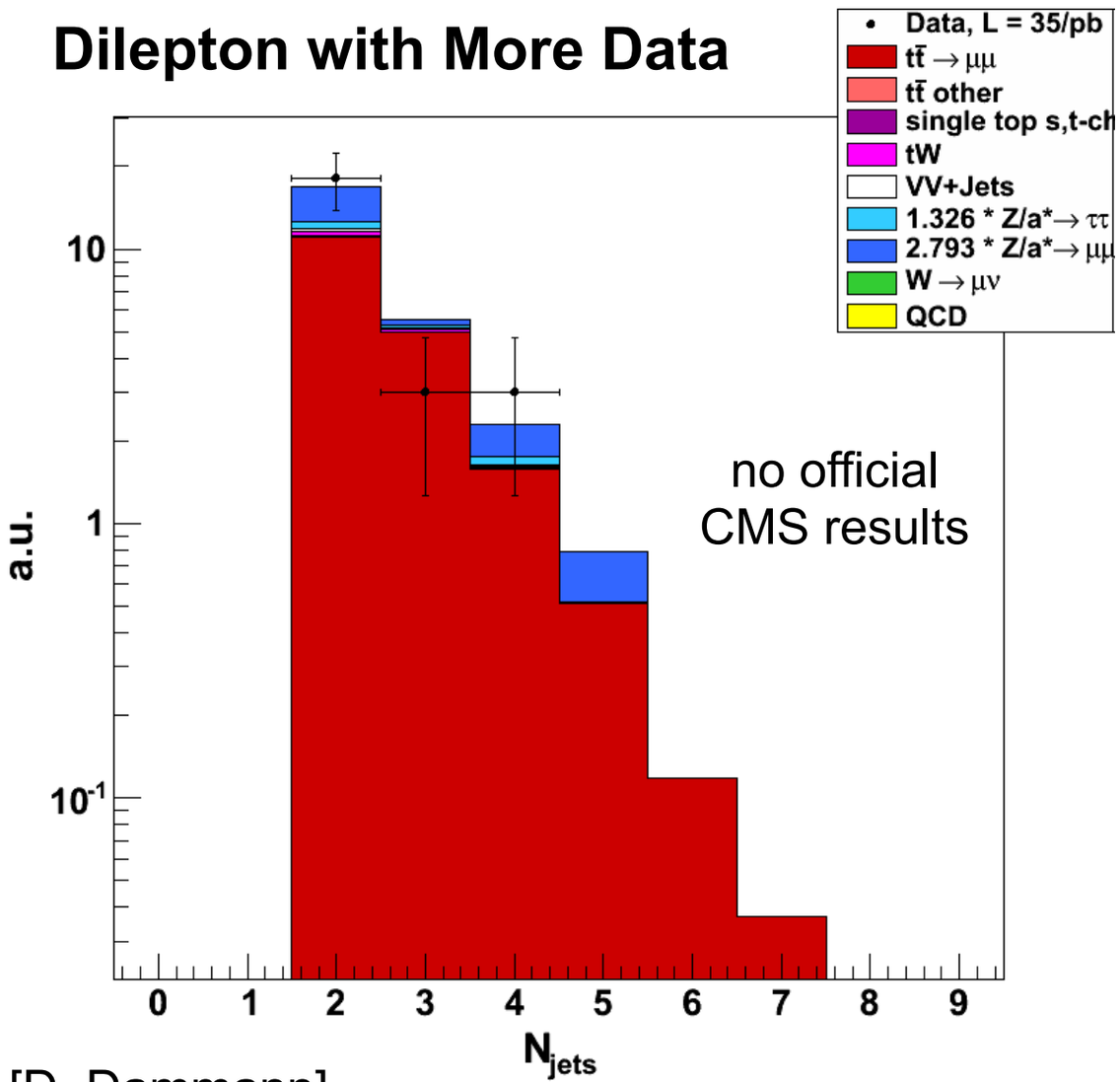


[A. Henrichs]

Top Cross Section: The Next Round

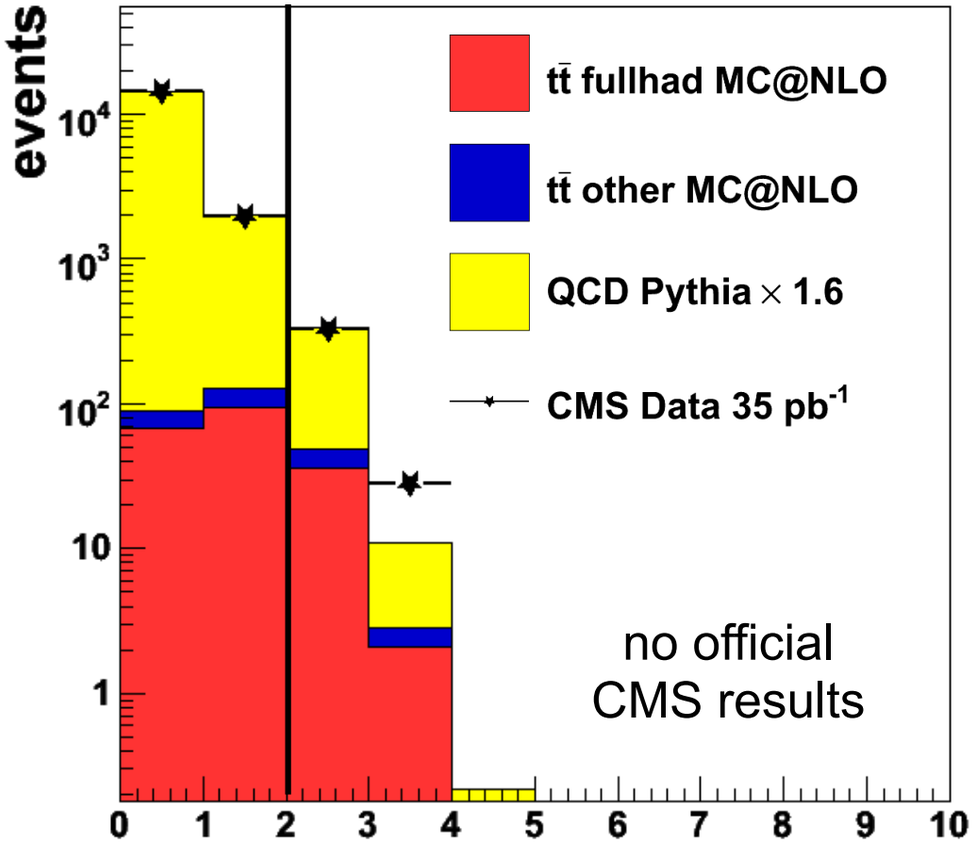
More Channels

Dilepton with More Data



[D. Dammann]

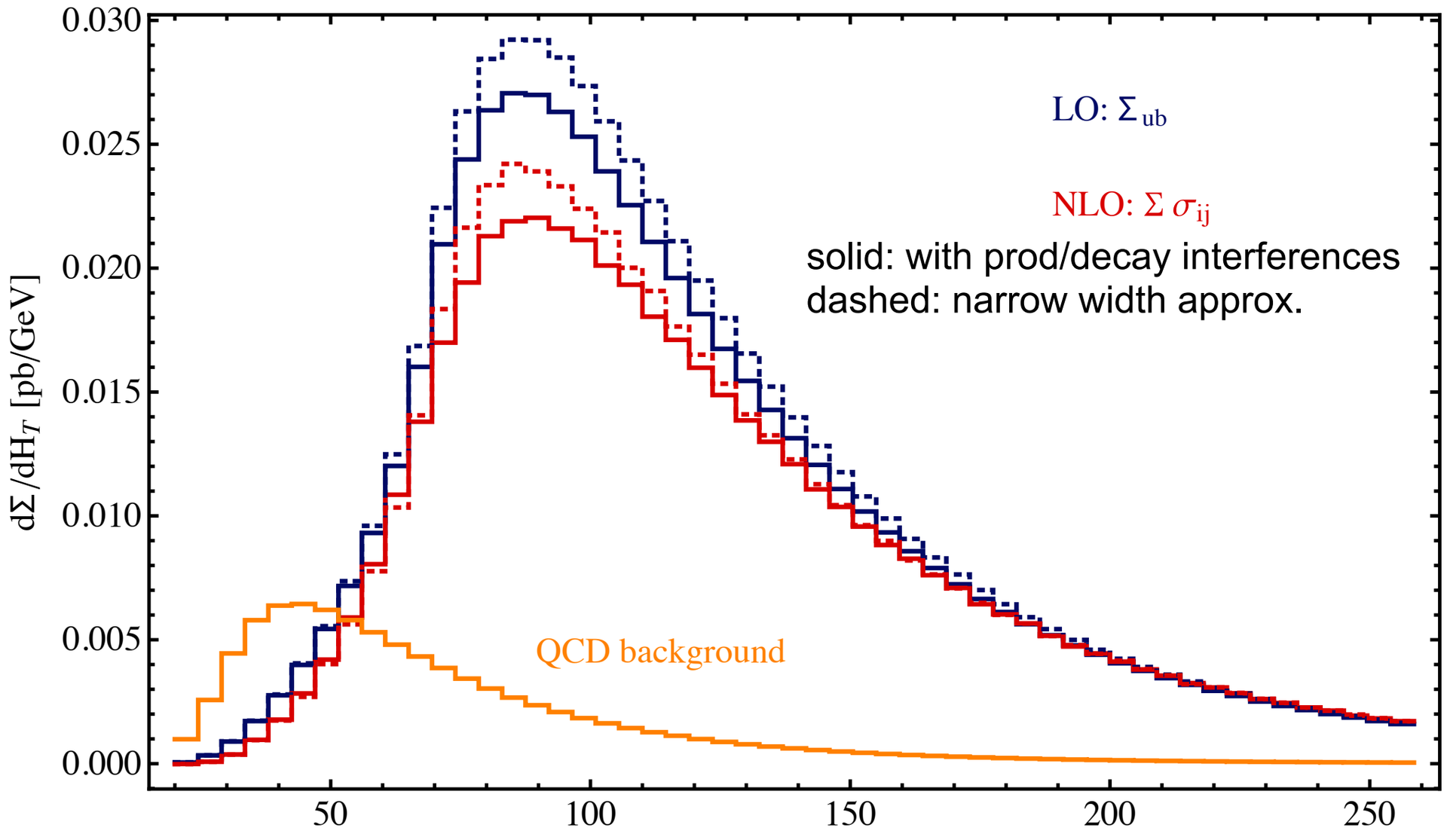
All-Hadronic Top Cross Section



[E. Schlieckau]

Single Top Production

- Single top t-channel at NLO beyond narrow width approximation
  - Goal: NLO calculation of qb → anything → q' Wb
  - Now included: leading non-factorizable production/decay interferences

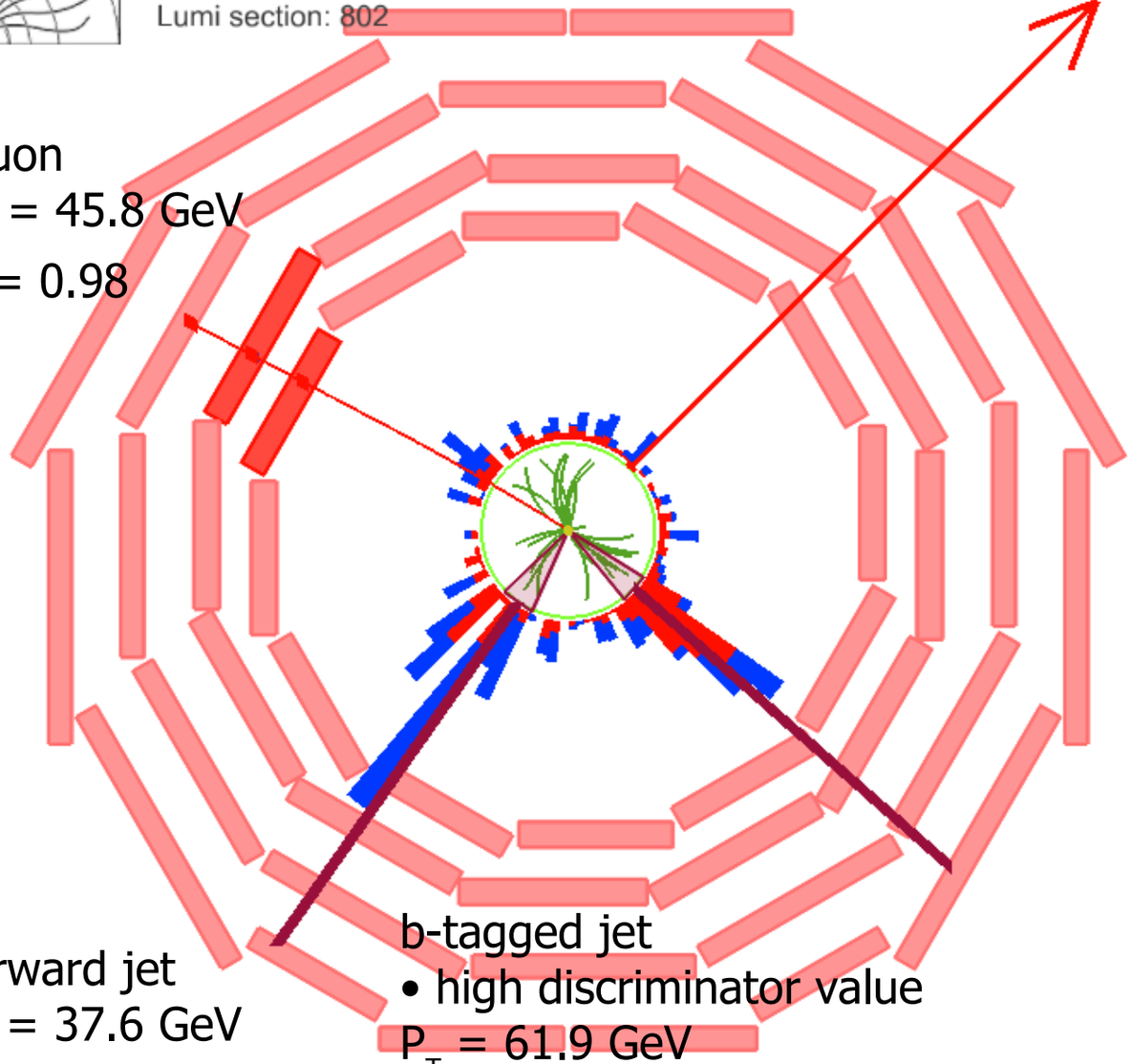


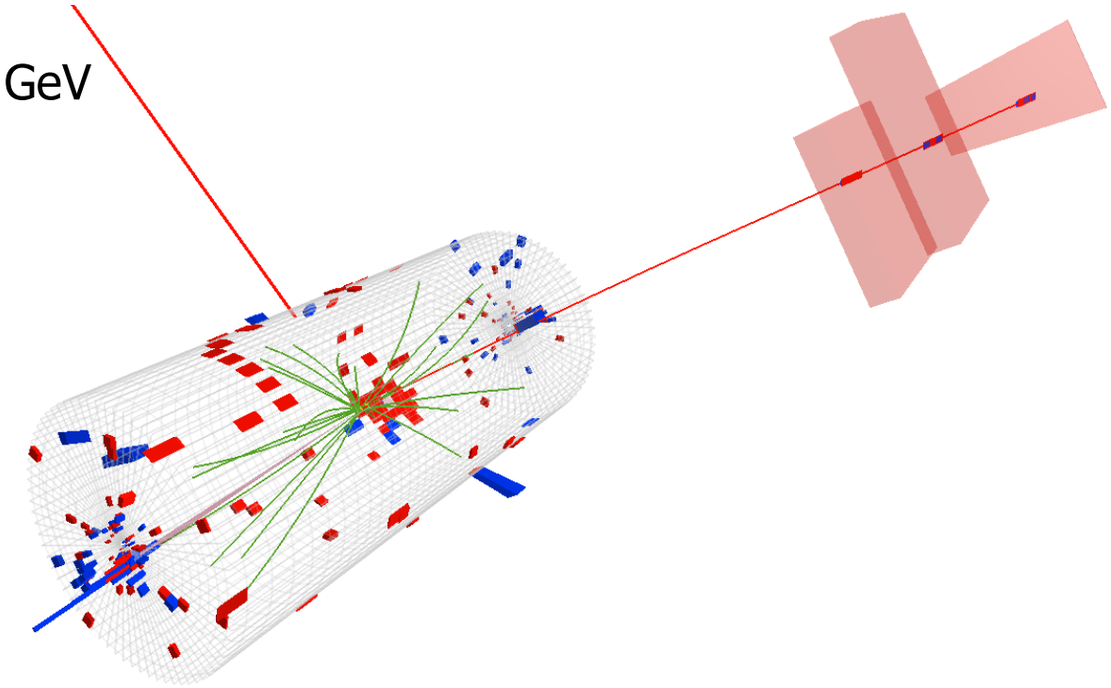
CMS Event Display: Single Top Candidate

CMS Experiment at LHC, CERN
Data recorded: Thu Oct 28 04:29:38 2010 CEST
Run/Event: 149181 / 776938639
Lumi section: 802

MET = 63.9 GeV

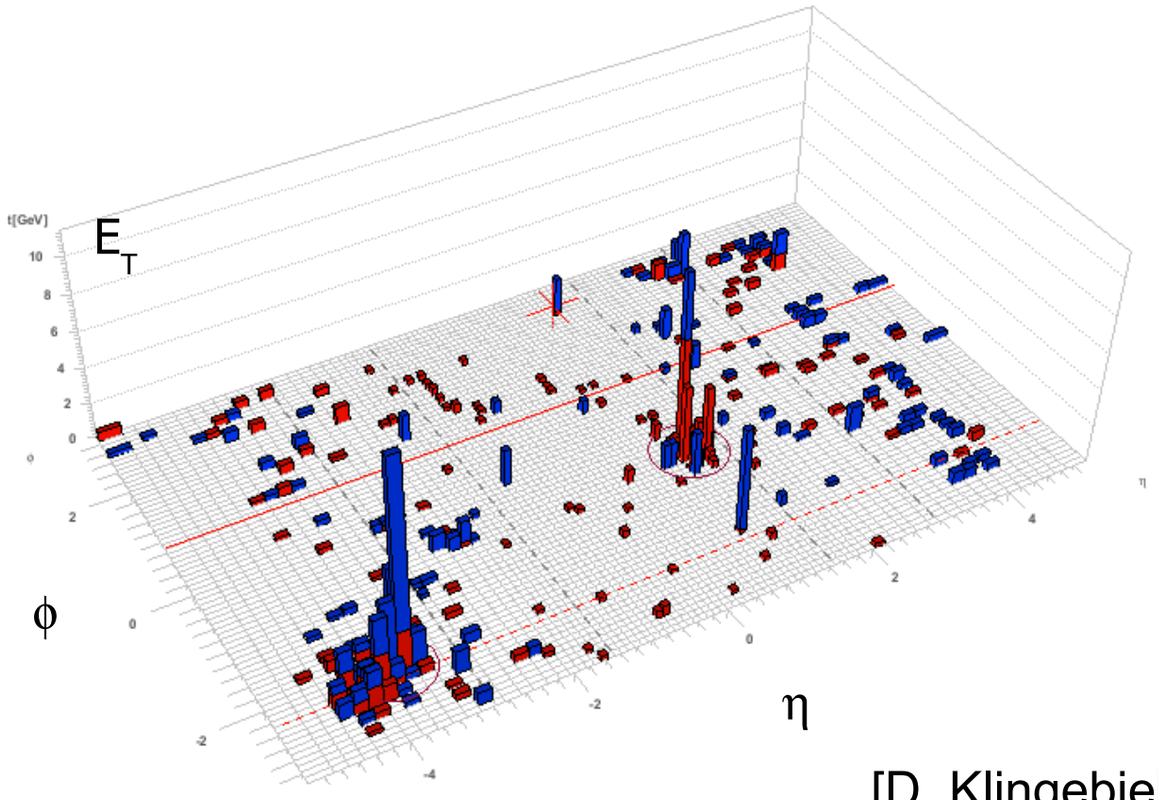
Muon
P_T = 45.8 GeV
η = 0.98





forward jet
P_T = 37.6 GeV
η = -3.76

b-tagged jet
• high discriminator value
P_T = 61.9 GeV
η = 0.99



Transverse W boson mass: 66.9 GeV
Reconstructed top quark mass: 157.7 GeV

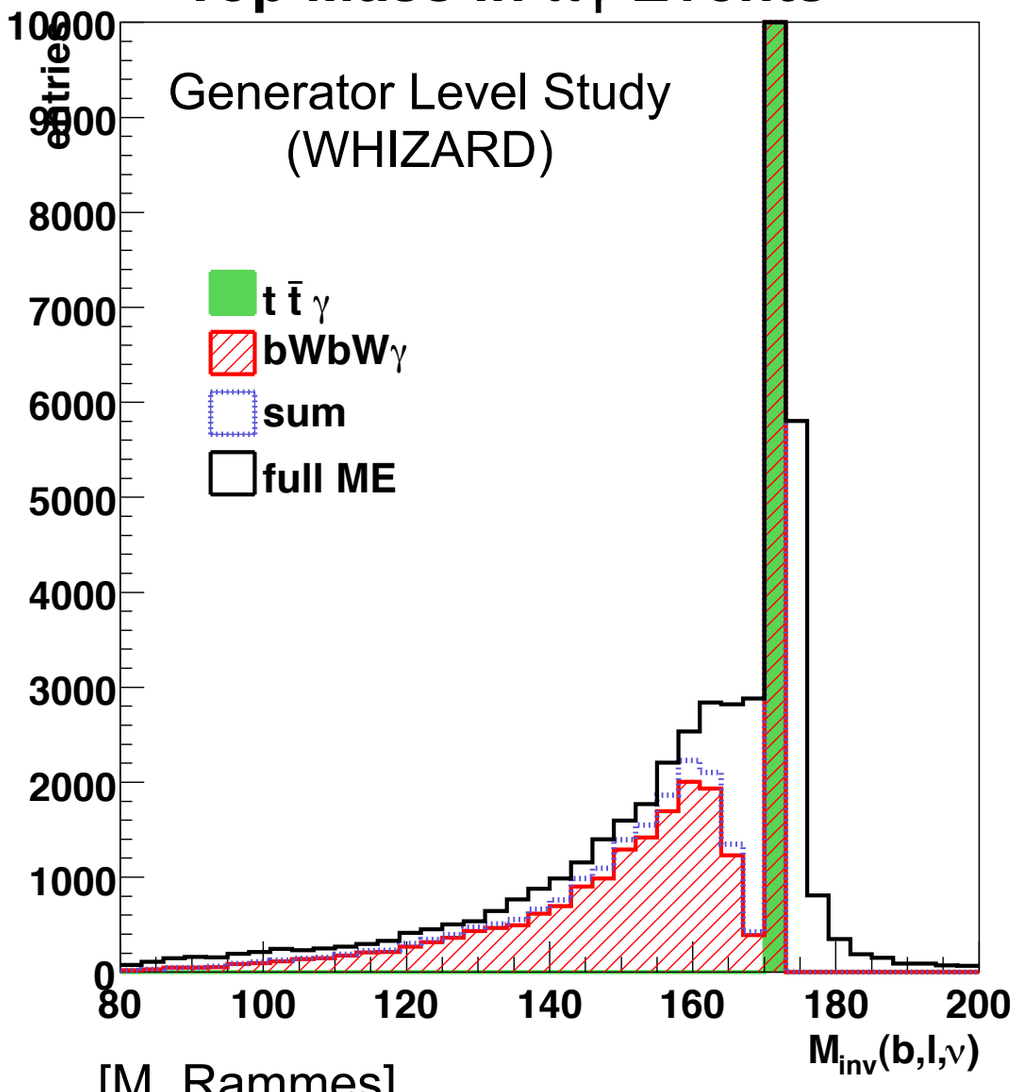
[D. Klingebiel]

Search for New Physics with Top

Top-Photon Coupling
→ sensitive to new physics

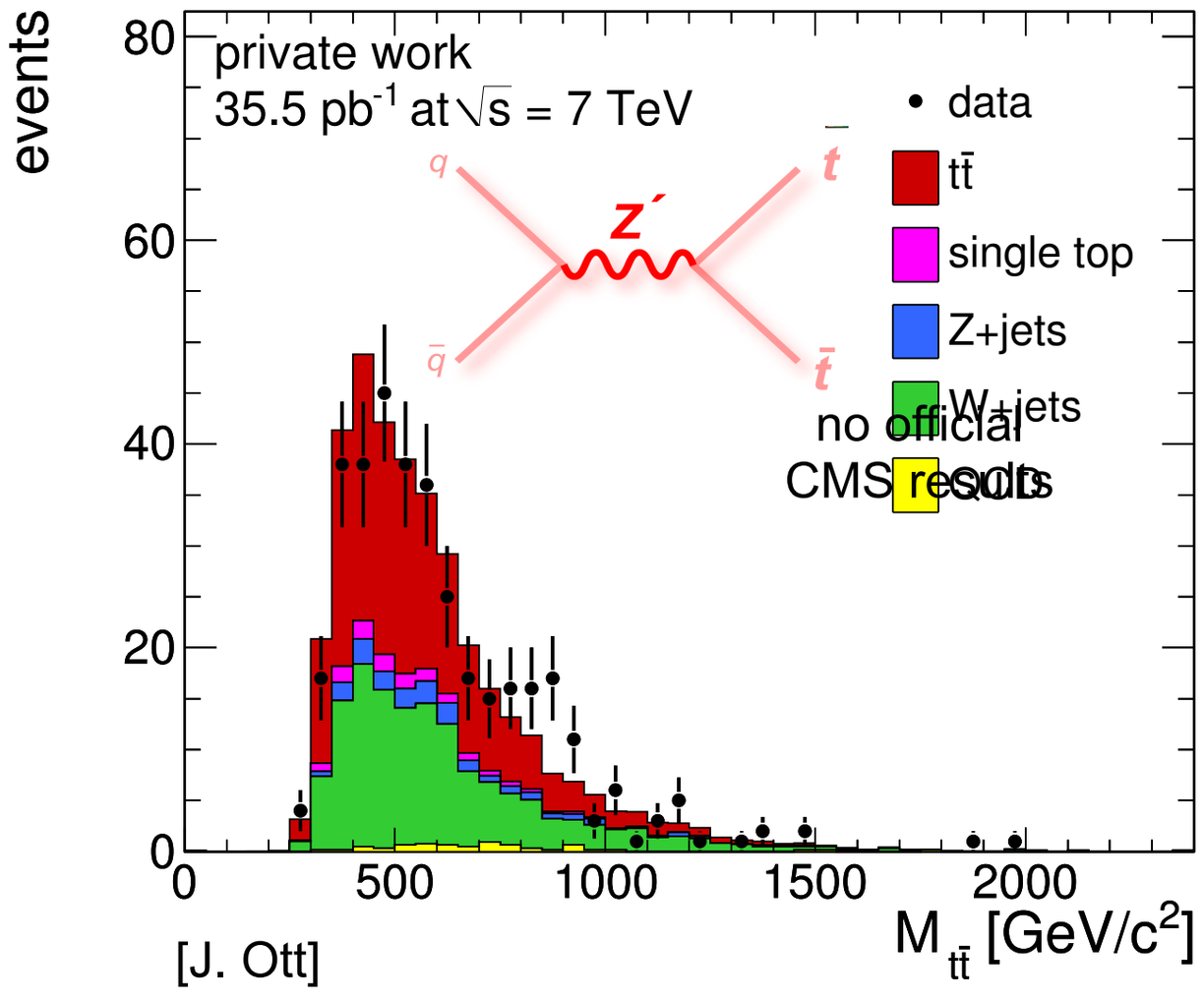
Heavy Resonances
Decaying into Top Pairs

Top Mass in $t\bar{t}\gamma$ Events



[M. Rammes]

Bump Hunt in $M_{t\bar{t}}$ Spectrum



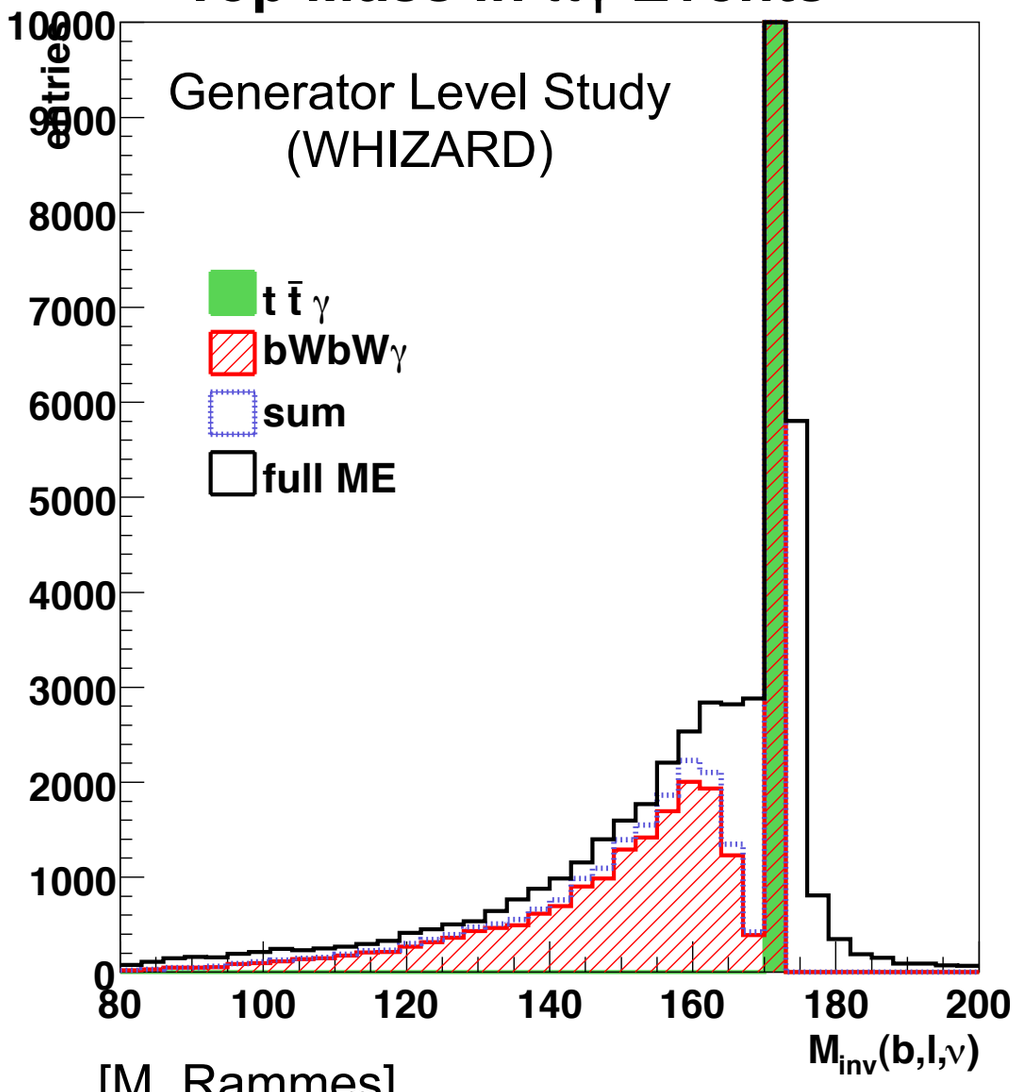
[J. Ott]

Search for New Physics with Top

Top-Photon Coupling
→ sensitive to new physics

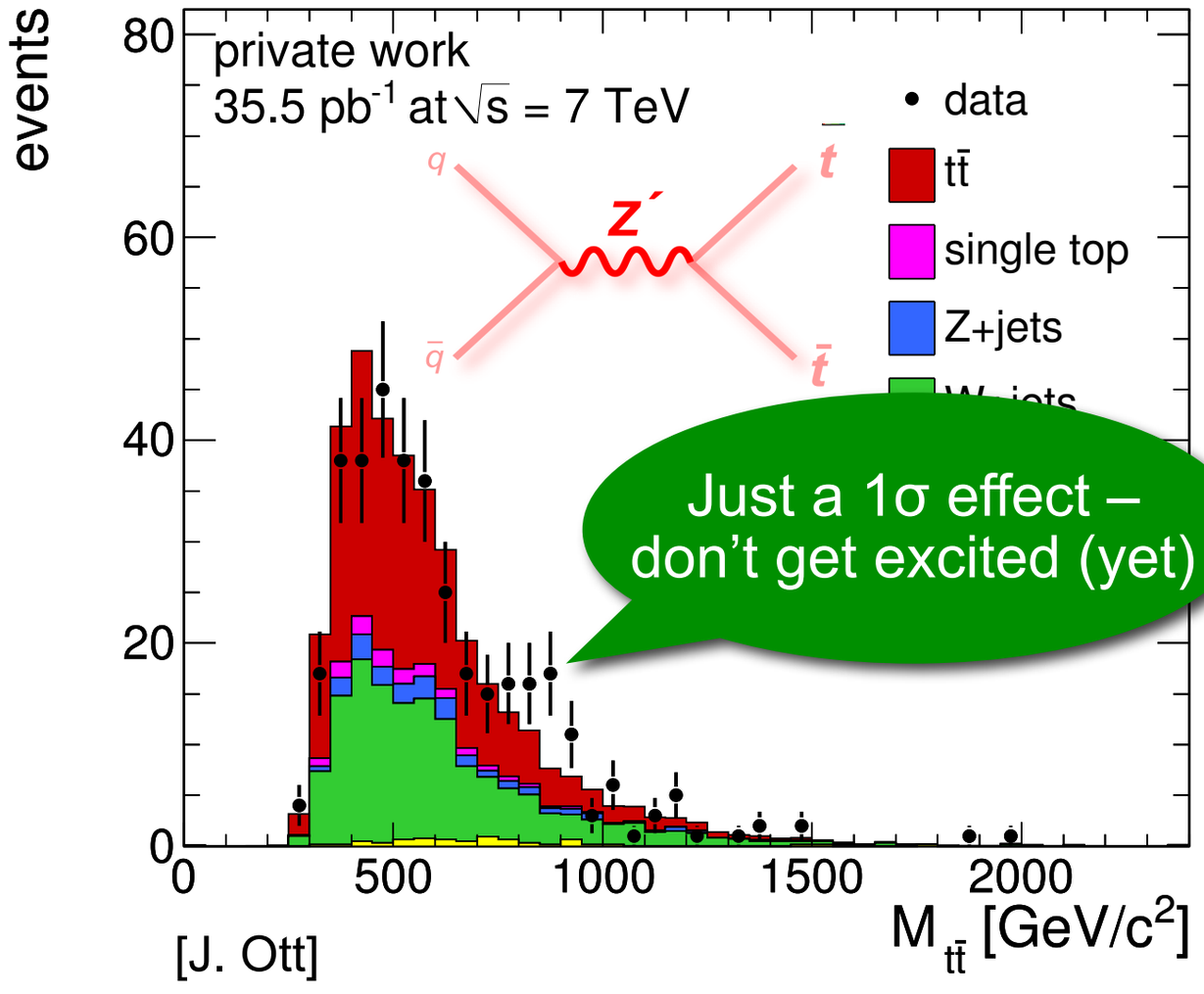
Heavy Resonances
Decaying into Top Pairs

Top Mass in $t\bar{t}\gamma$ Events



[M. Rammes]

Bump Hunt in $M_{t\bar{t}}$ Spectrum



[J. Ott]

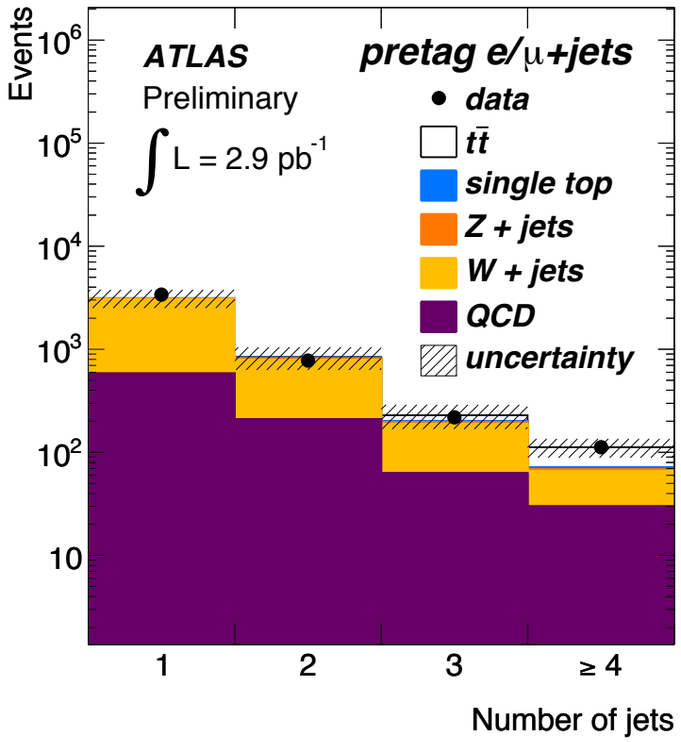
Summary & Outlook

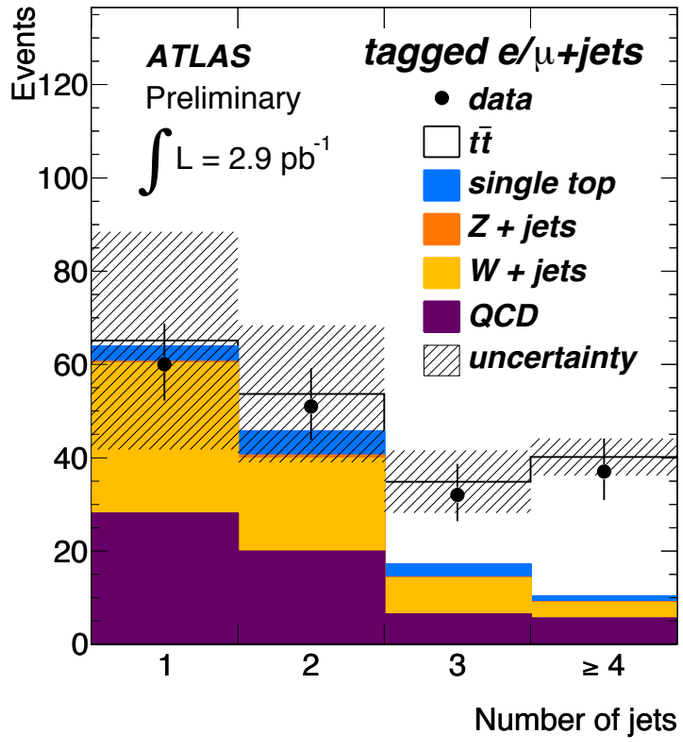
- First LHC top physics results on limited dataset: 3 pb^{-1}
  - ATLAS and CMS can extract involved top signature after only 1/2 year
  - Cross section for top pair production compatible with QCD predictions
- Prospects with full 2010 dataset (around 35 pb^{-1})
  - Refined $t\bar{t}$ cross section 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, …

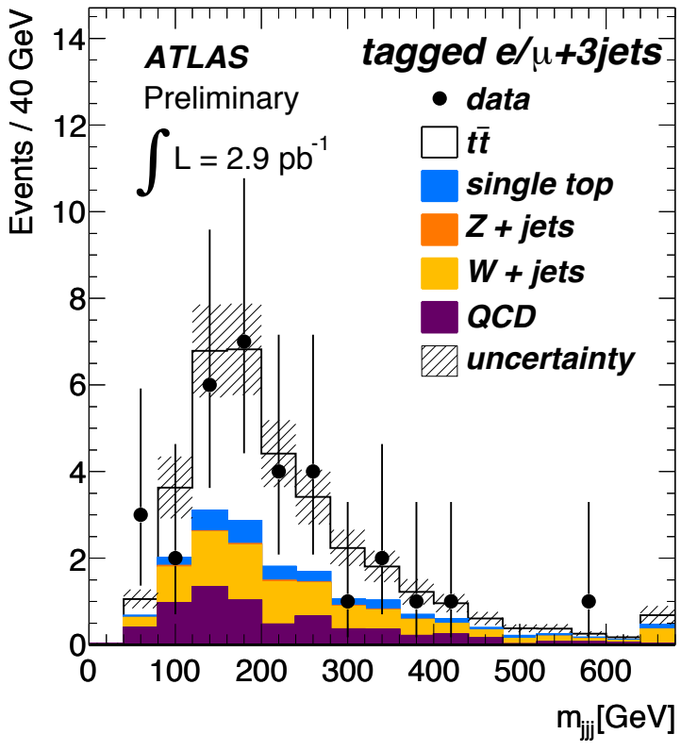
Much more to come in 2011 – Stay tuned!

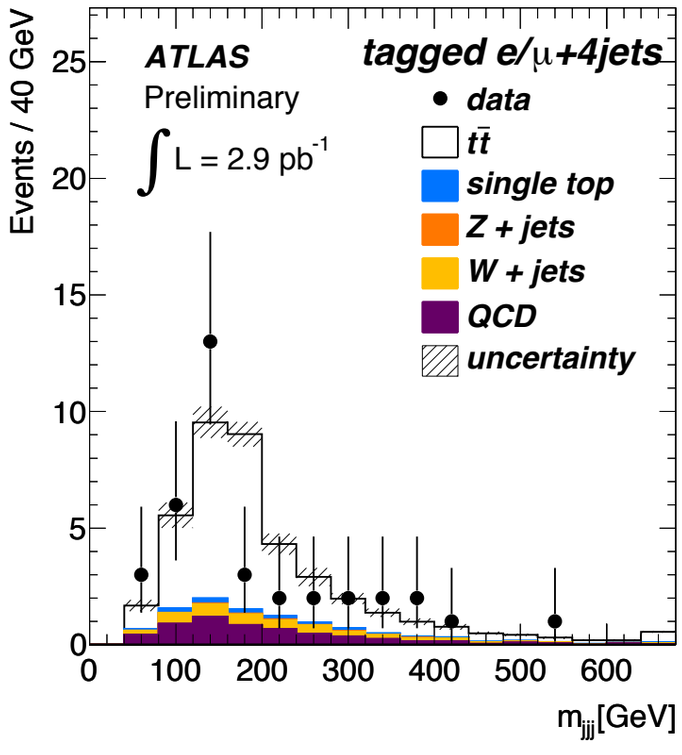
Backup

ATLAS Preliminary: Lepton + Jets

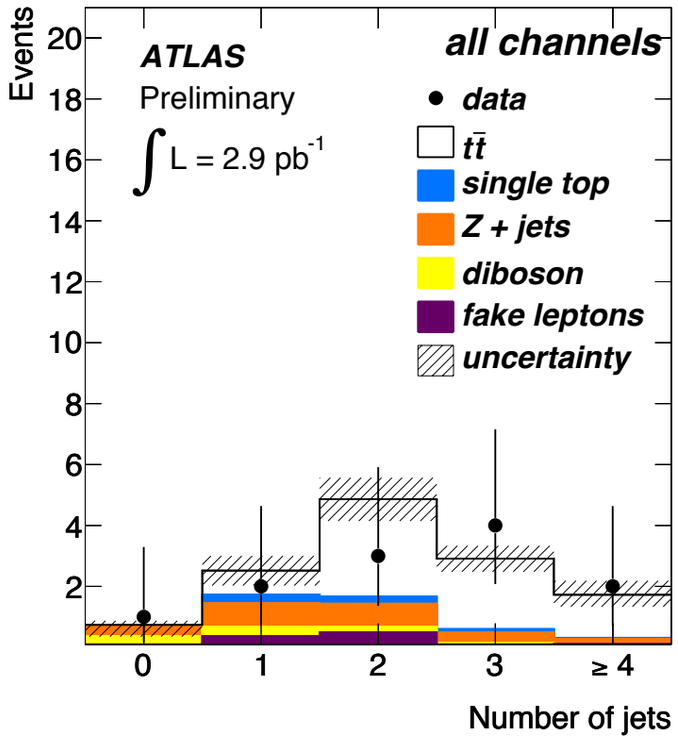


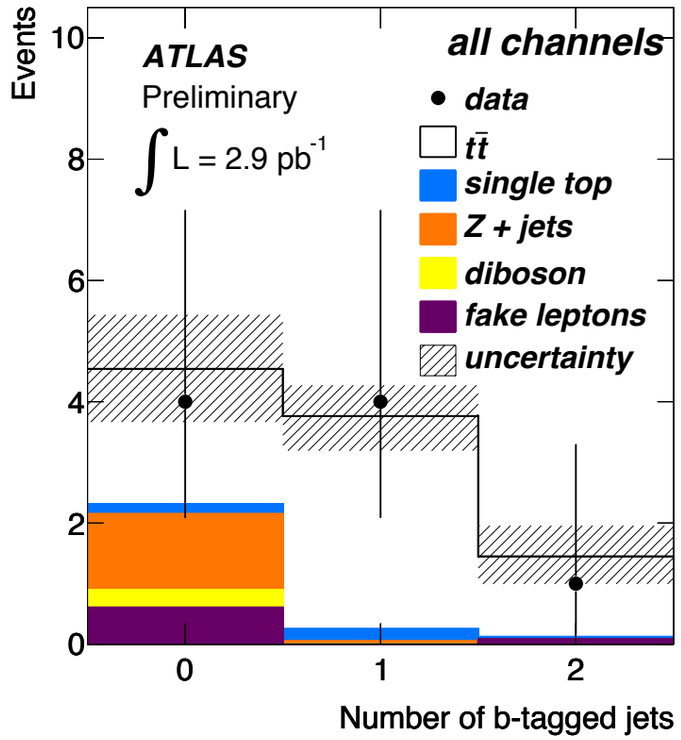


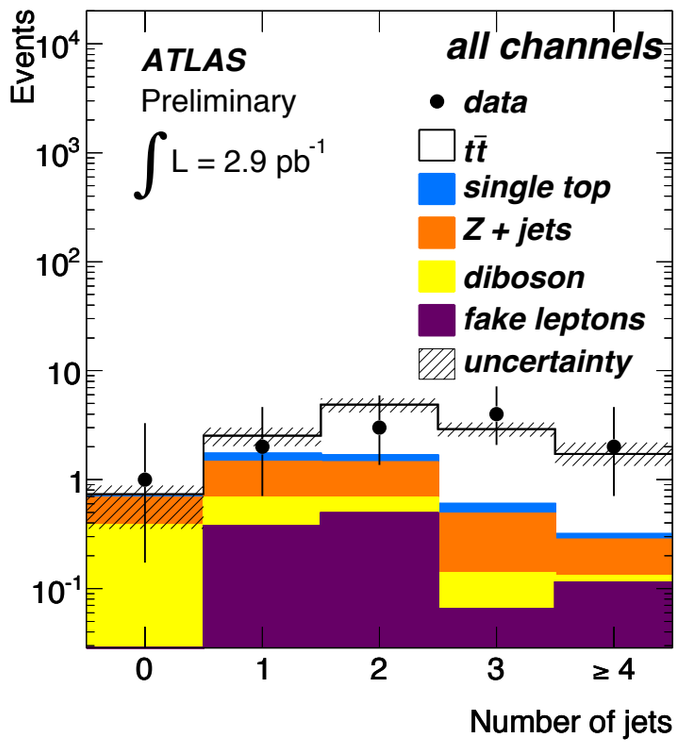


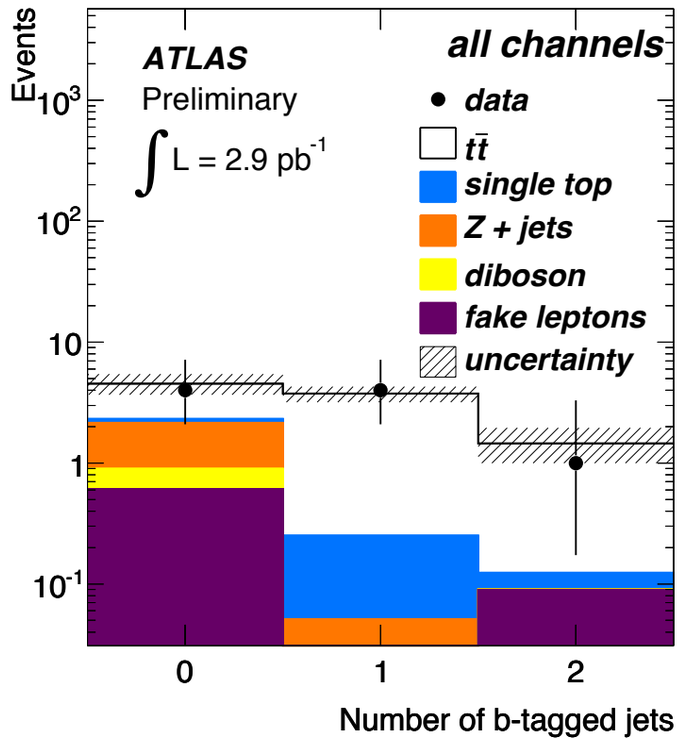


ATLAS Preliminary: Dilepton

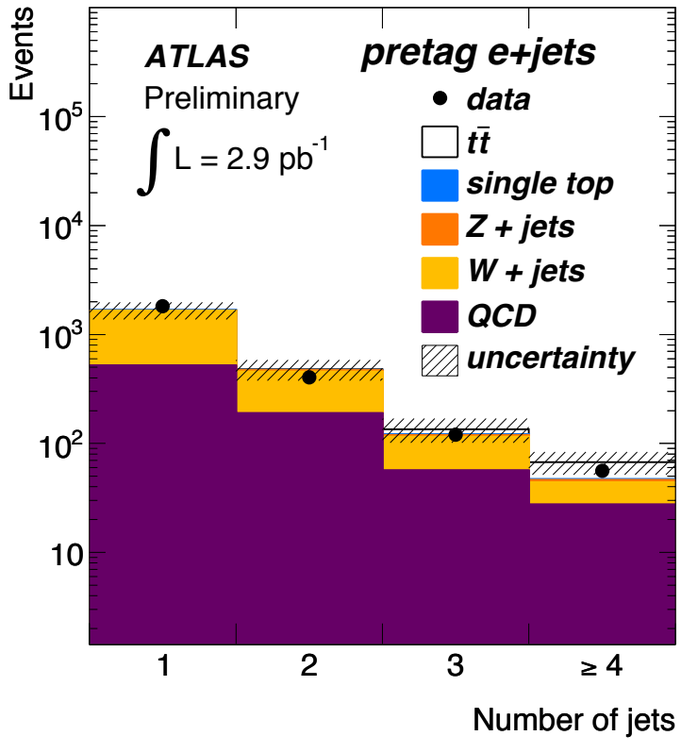


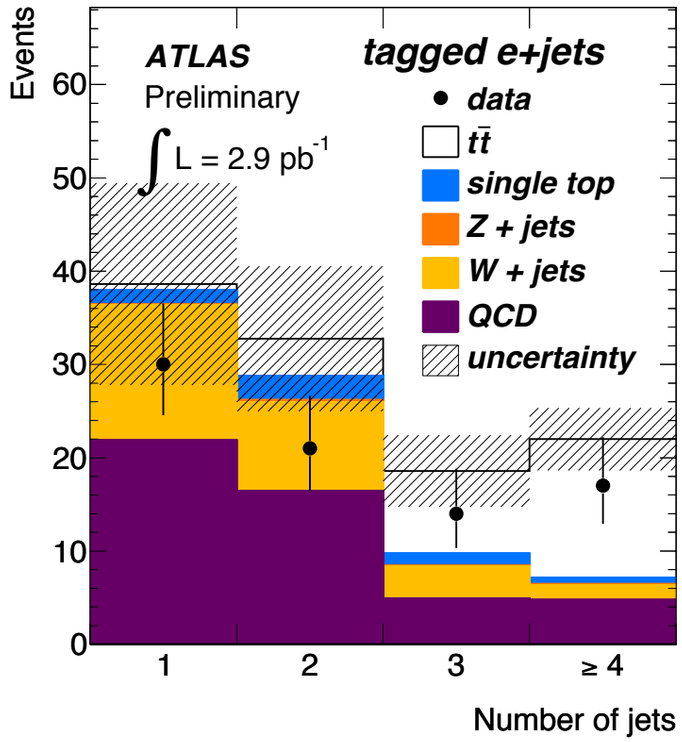


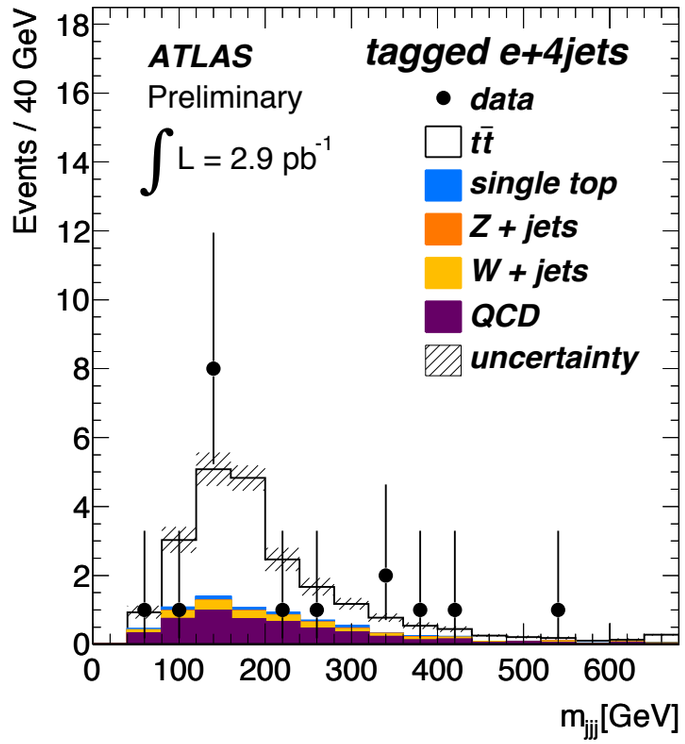


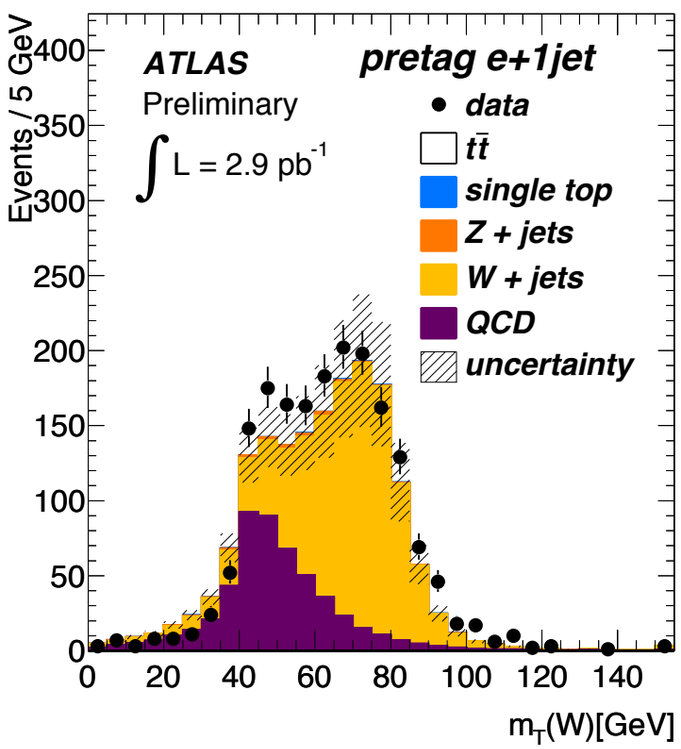


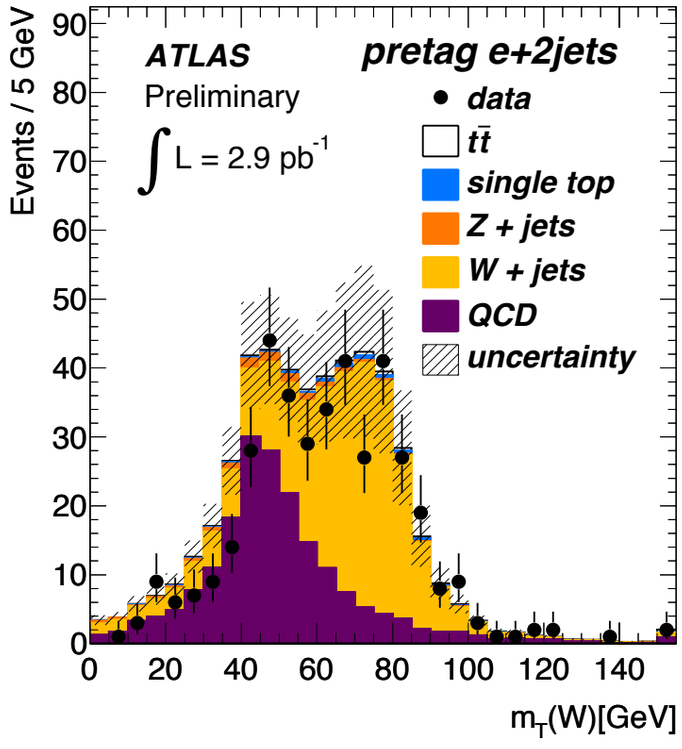
ATLAS Preliminary: e + Jets

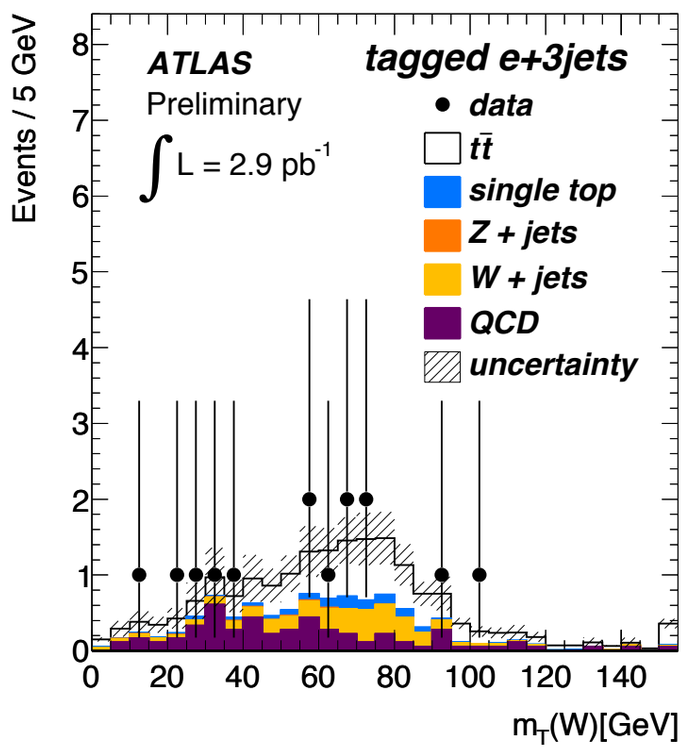




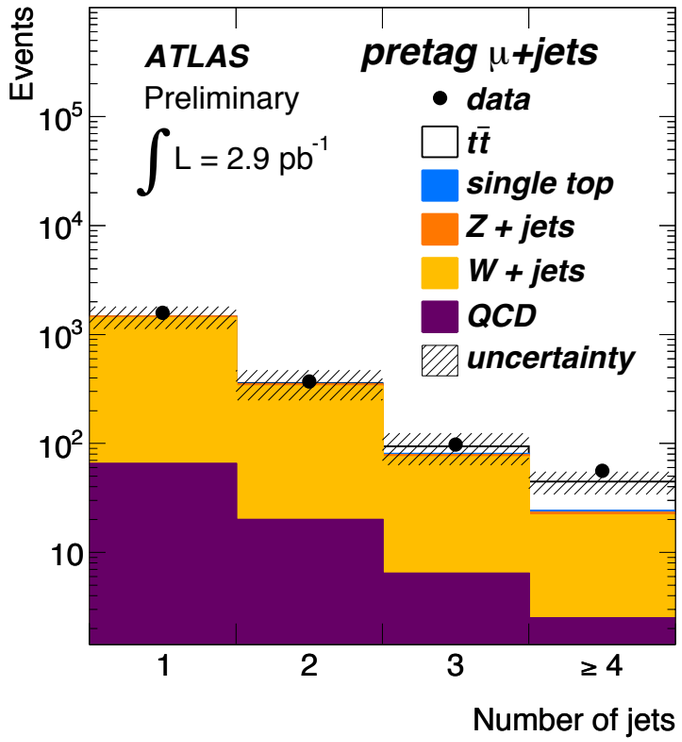


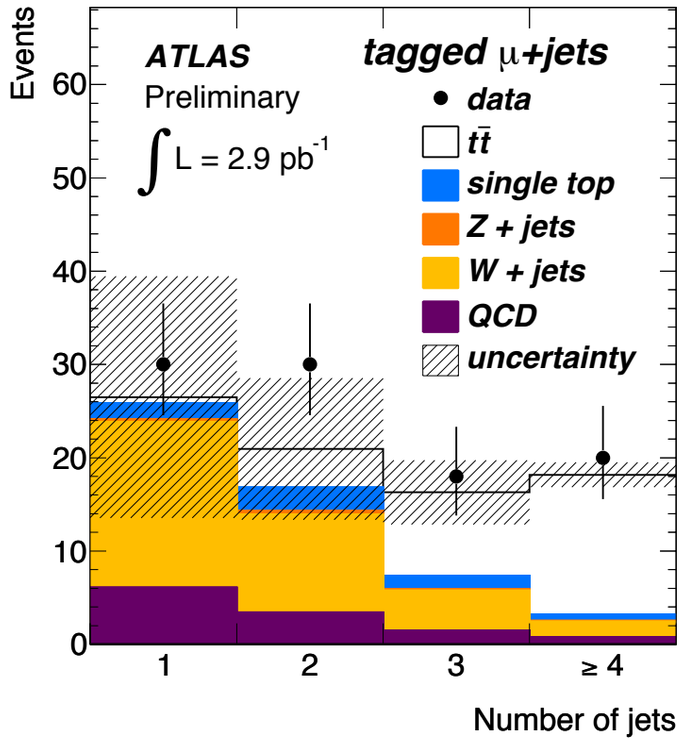


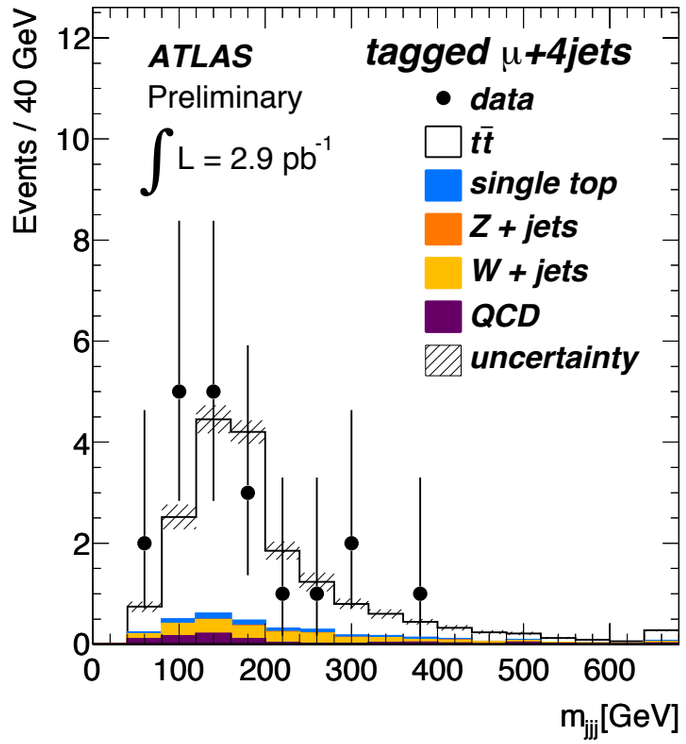


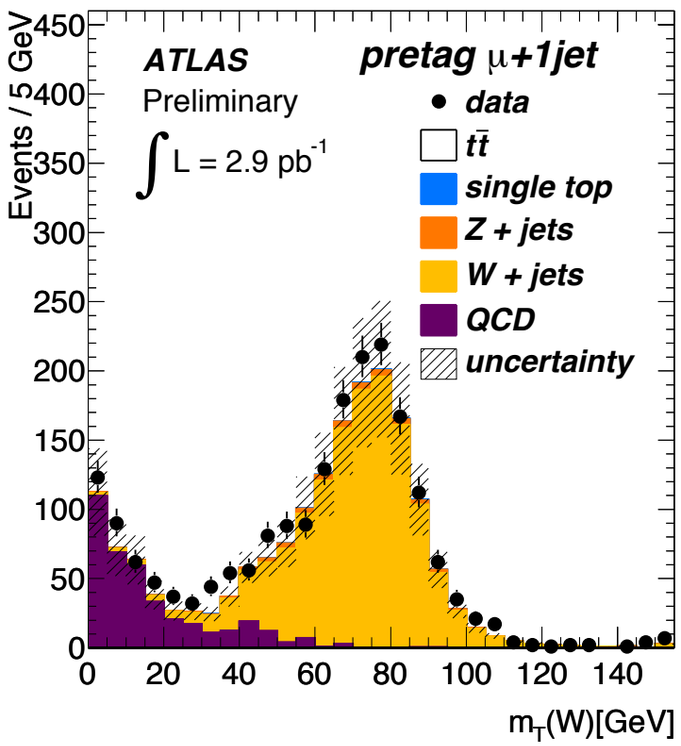


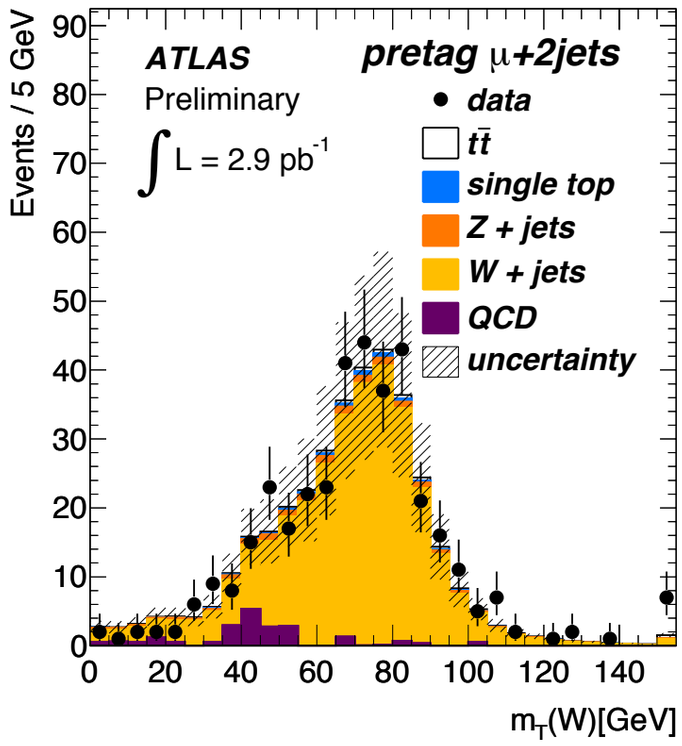
ATLAS Preliminary: μ + Jets

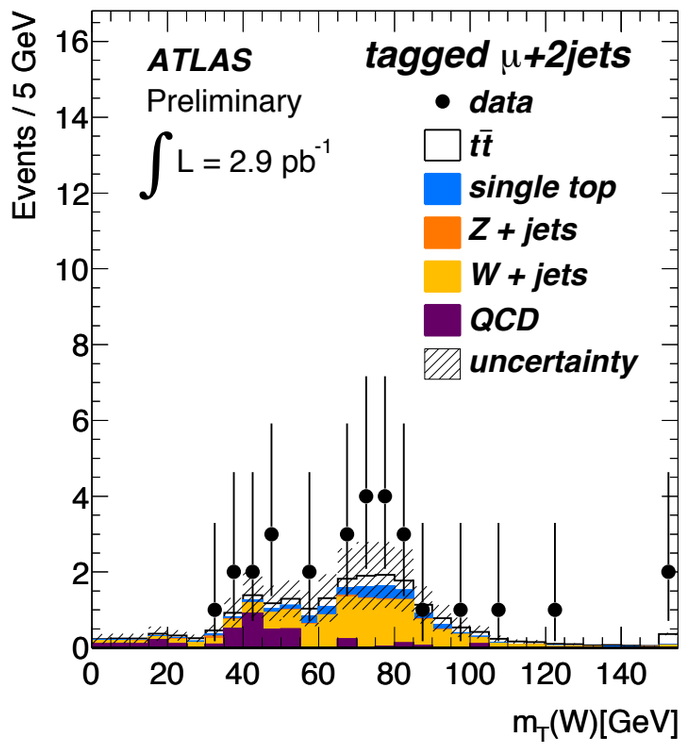




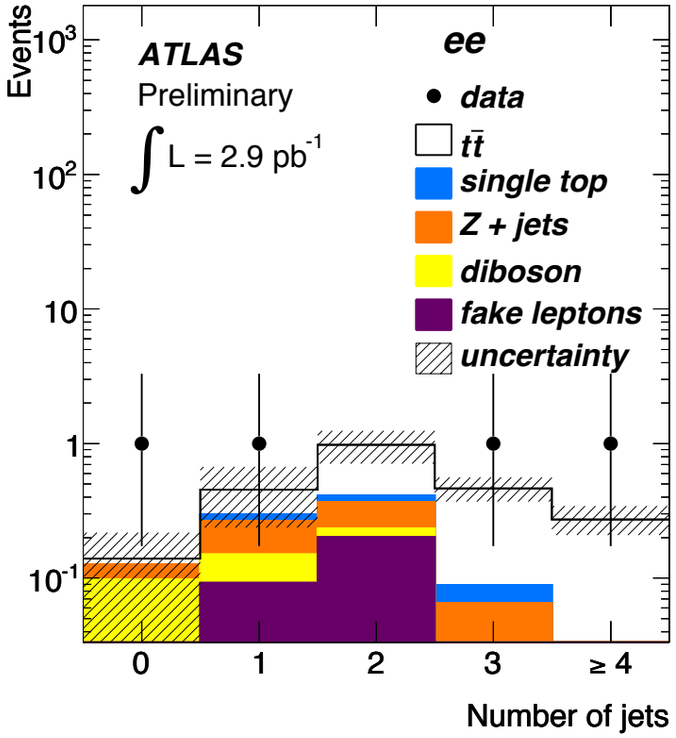


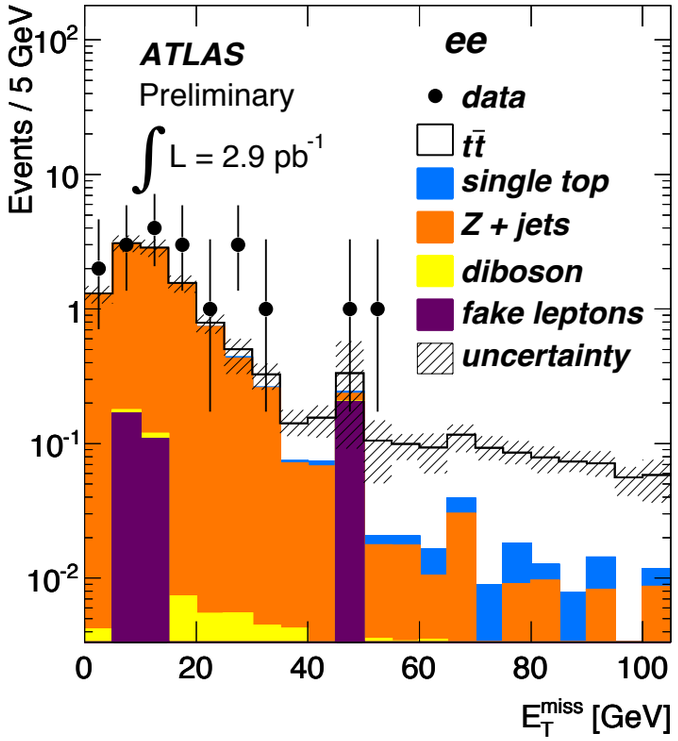


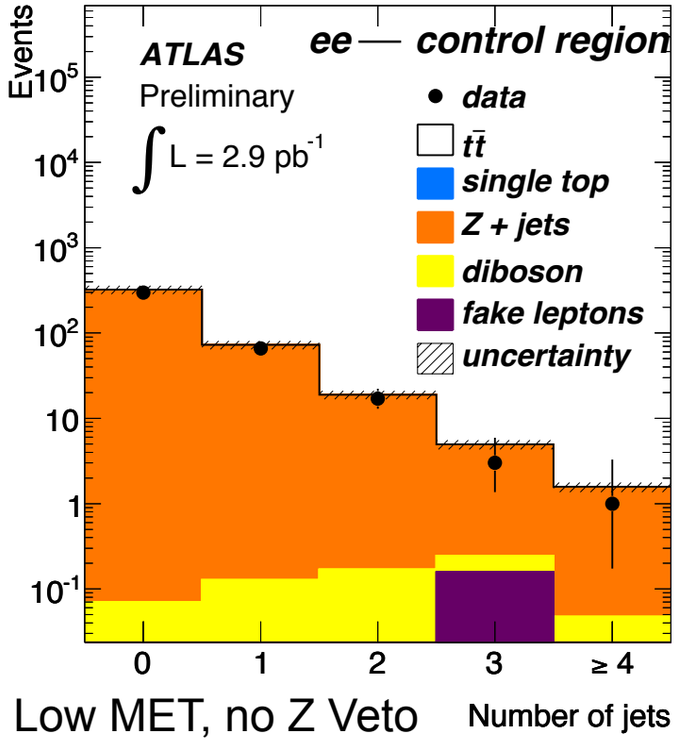


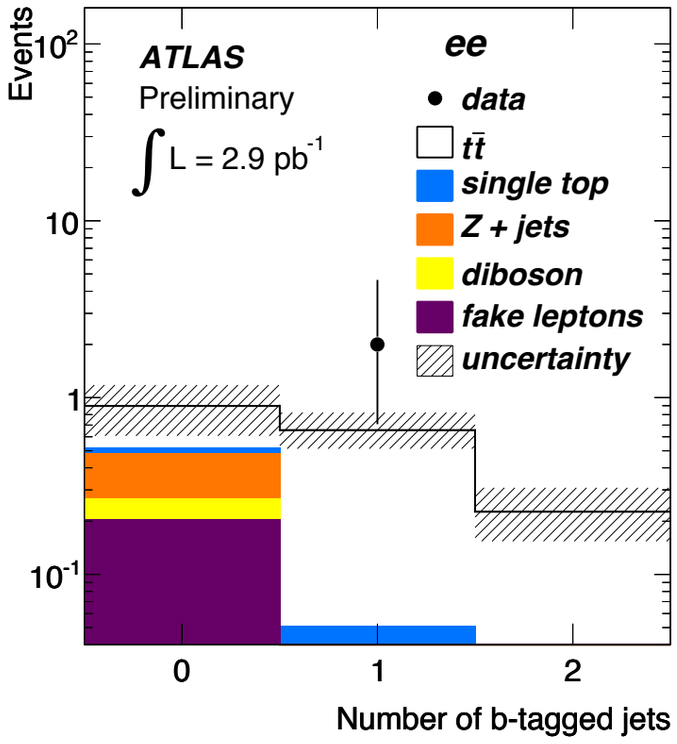


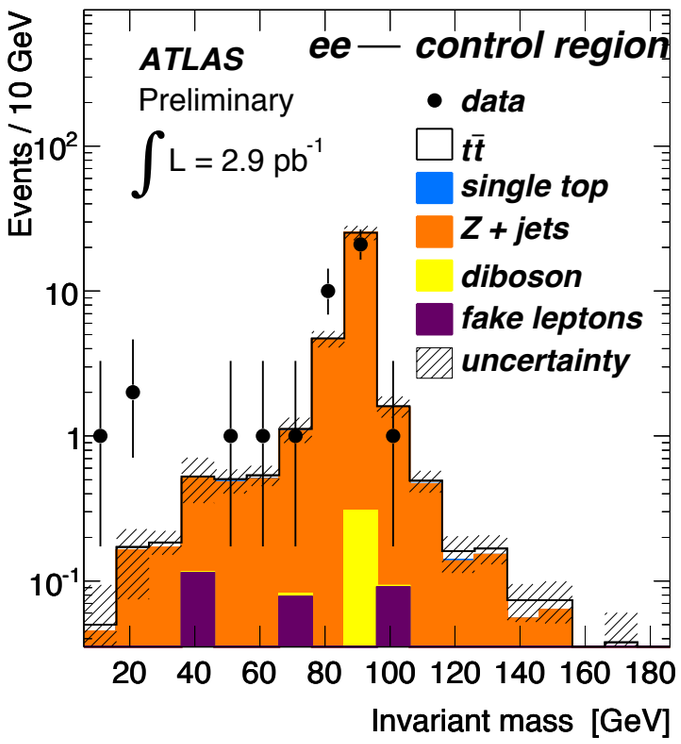
ATLAS Preliminary: Dilepton ee



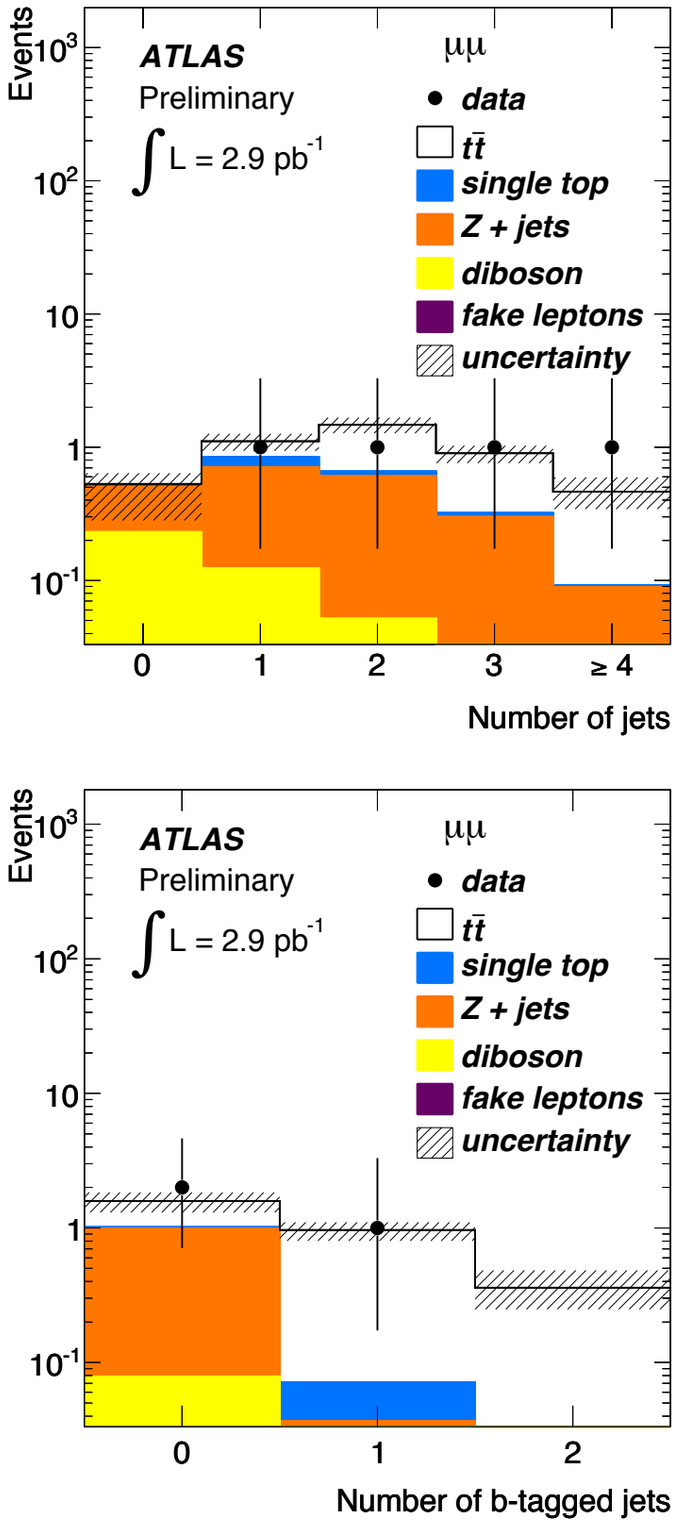


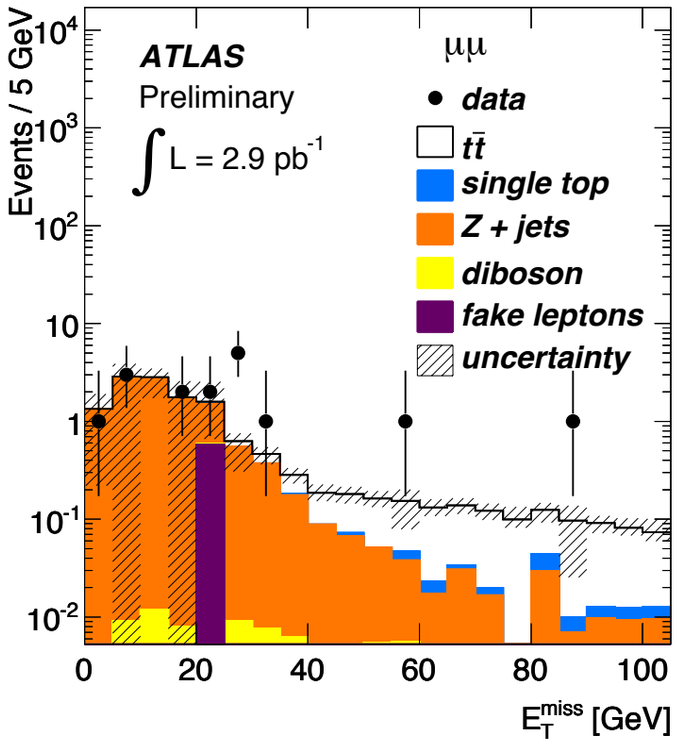


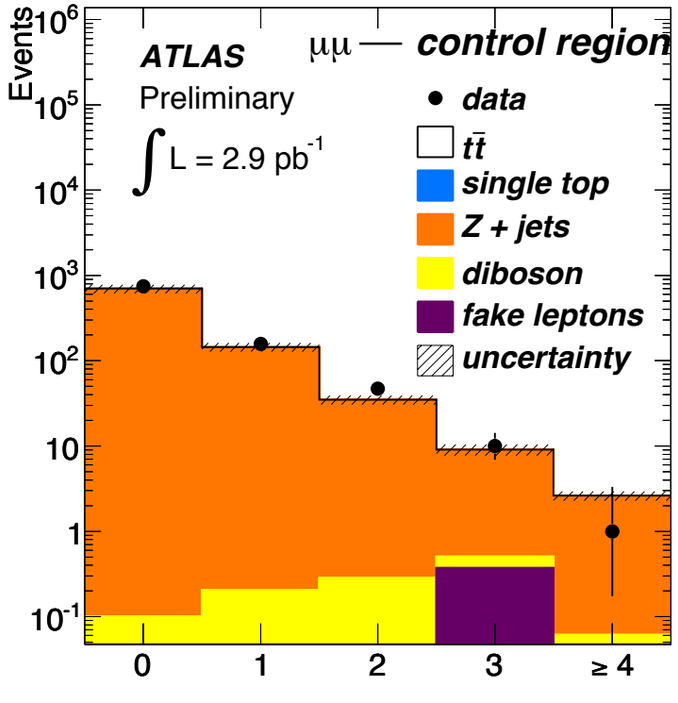




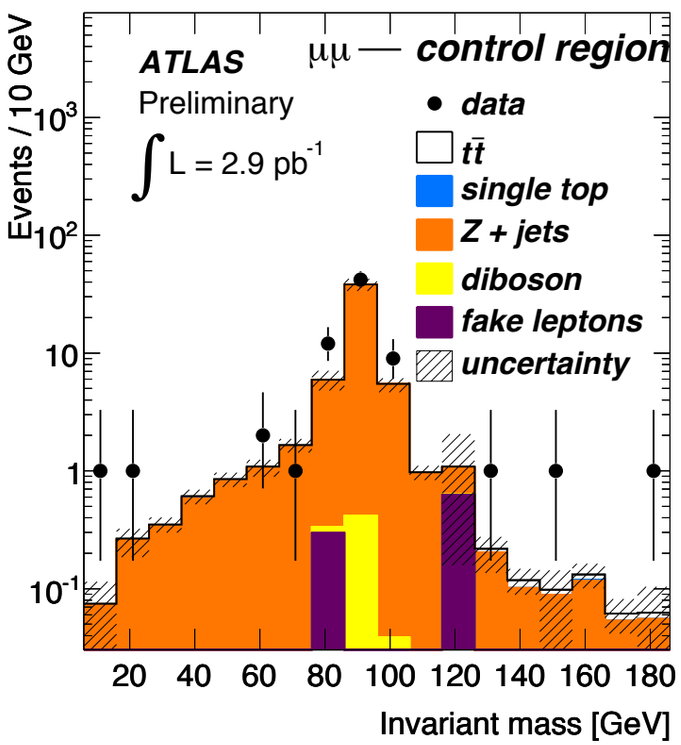
ATLAS Preliminary: Dilepton μμ



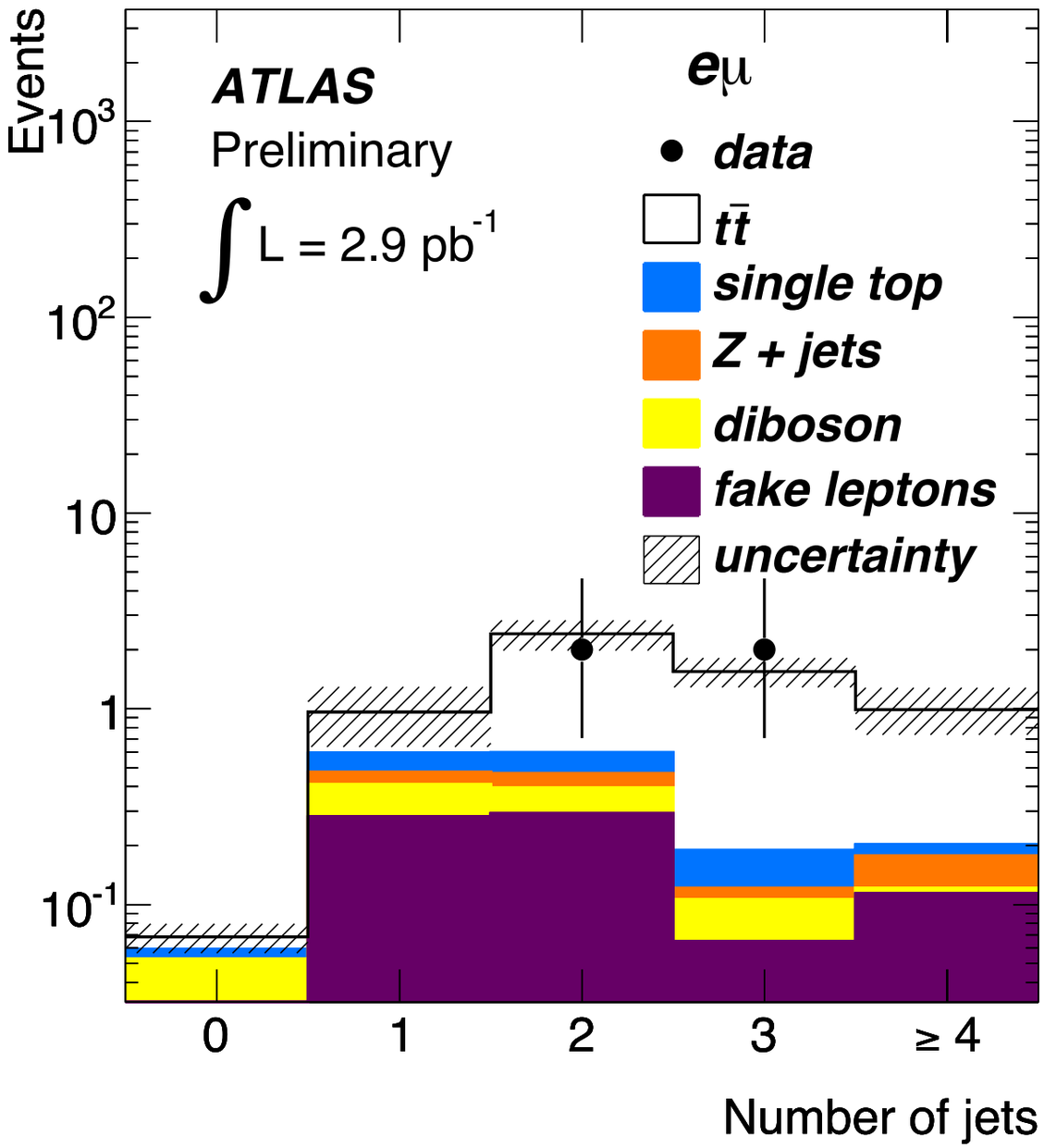


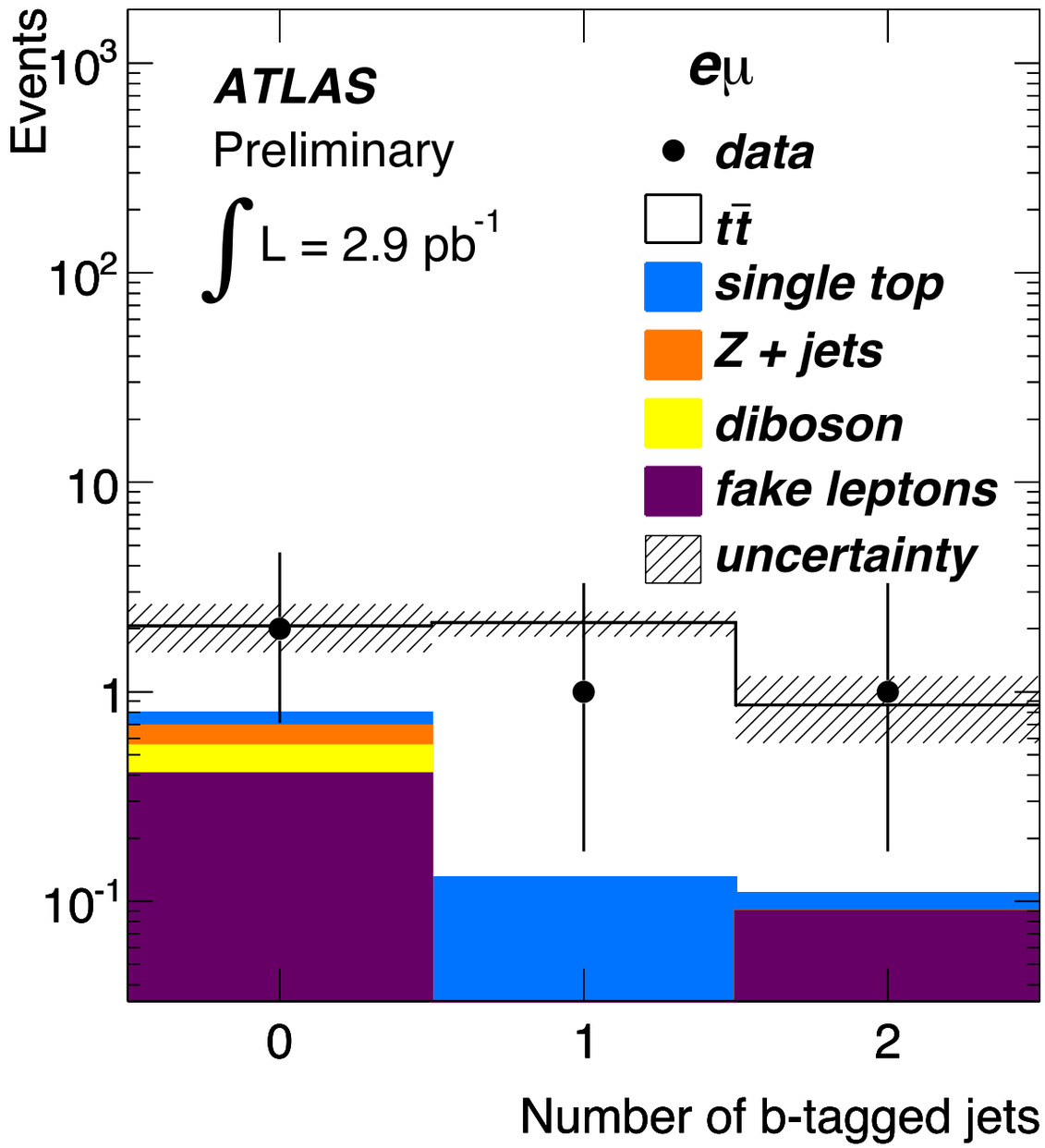


Low MET, no Z Veto

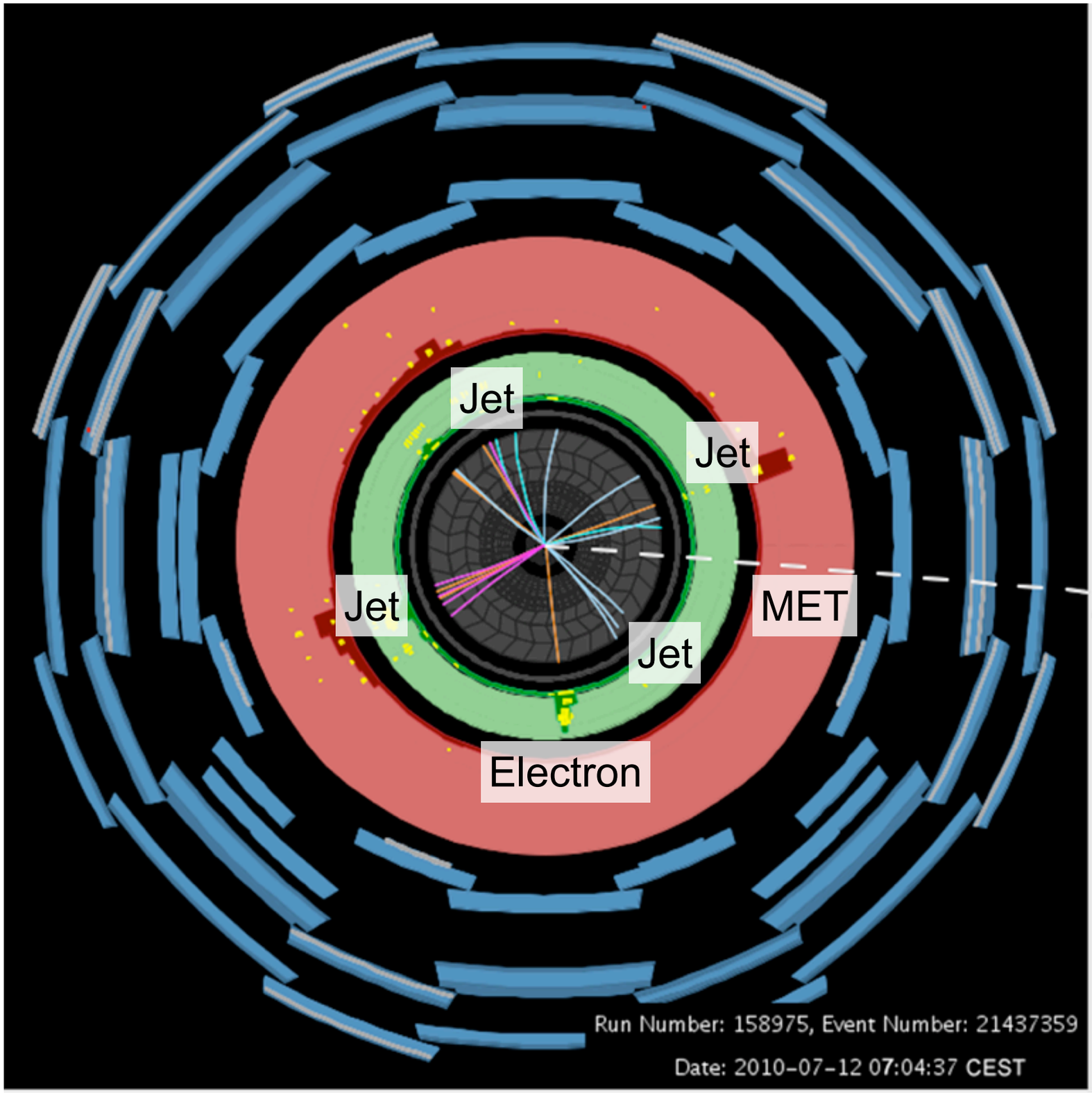


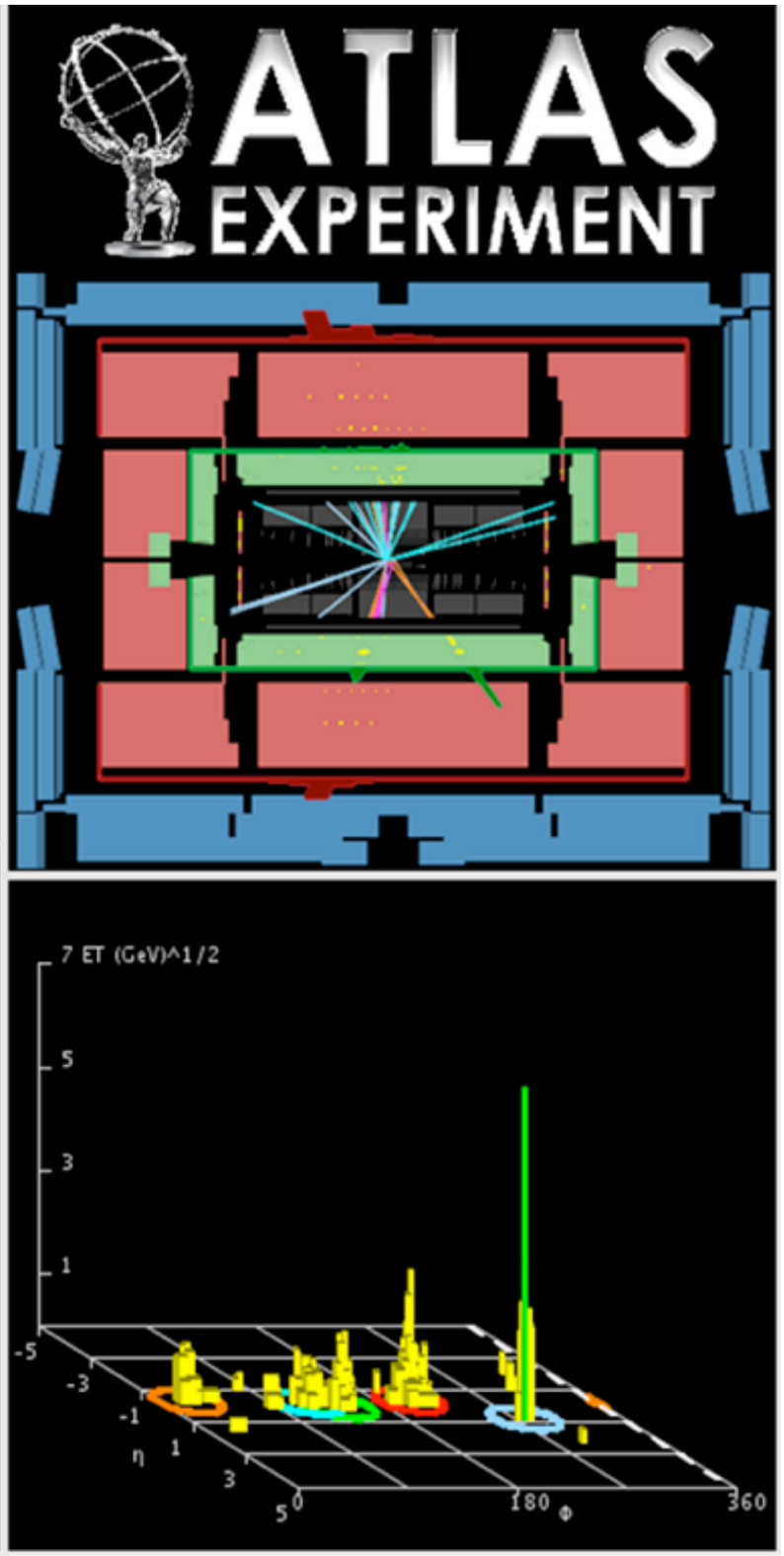
ATLAS Preliminary: Dilepton eμ



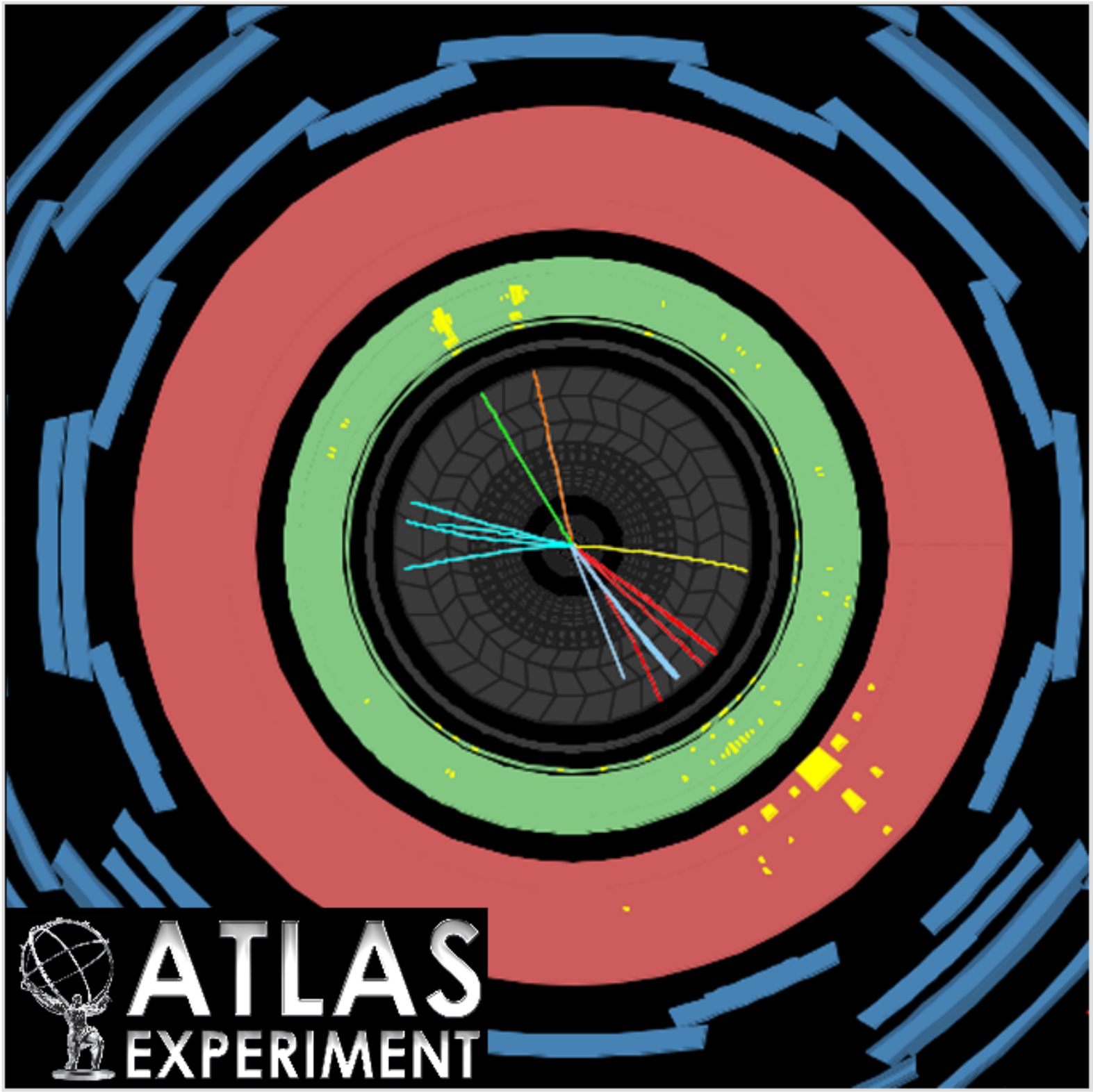


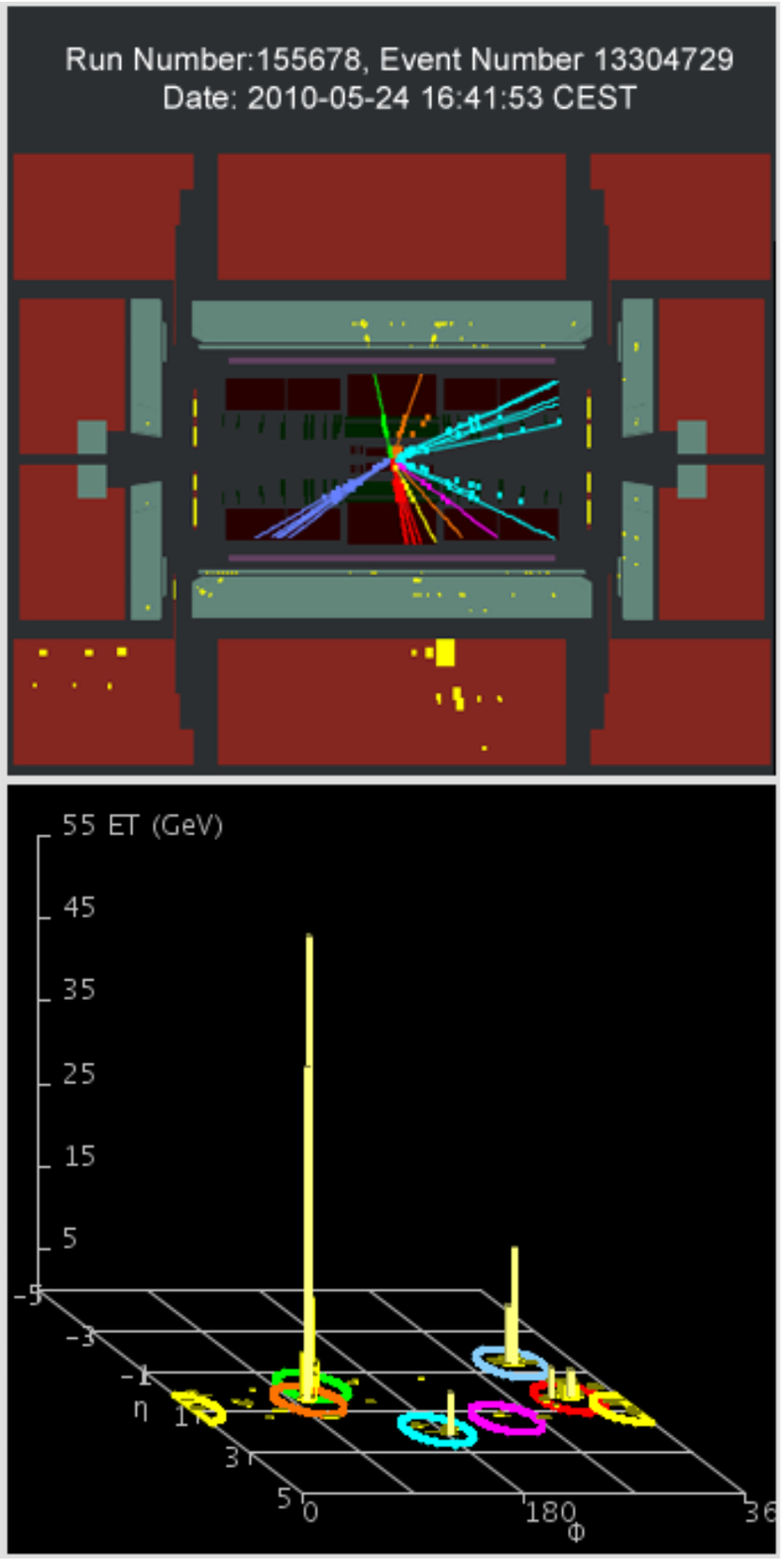
ATLAS Event Display: e + Jets + MET





ATLAS Event Display: ee + Jets + MET

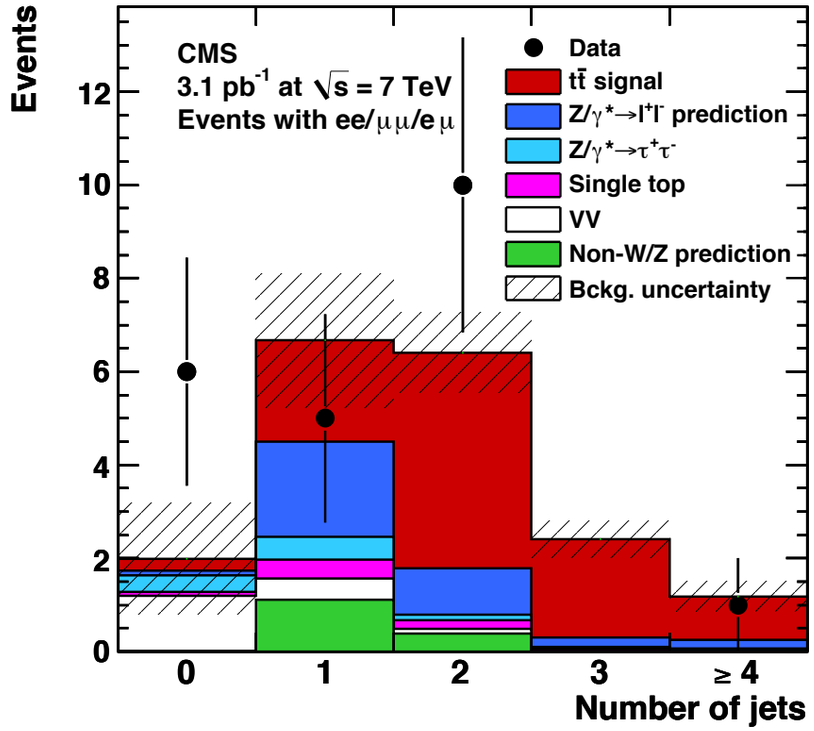


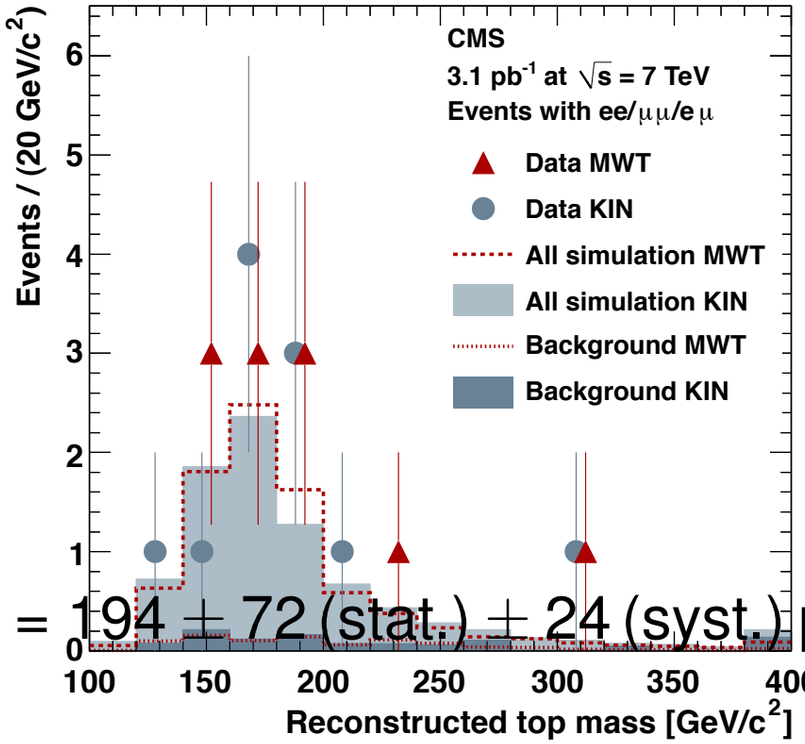


Plots from CMS Paper

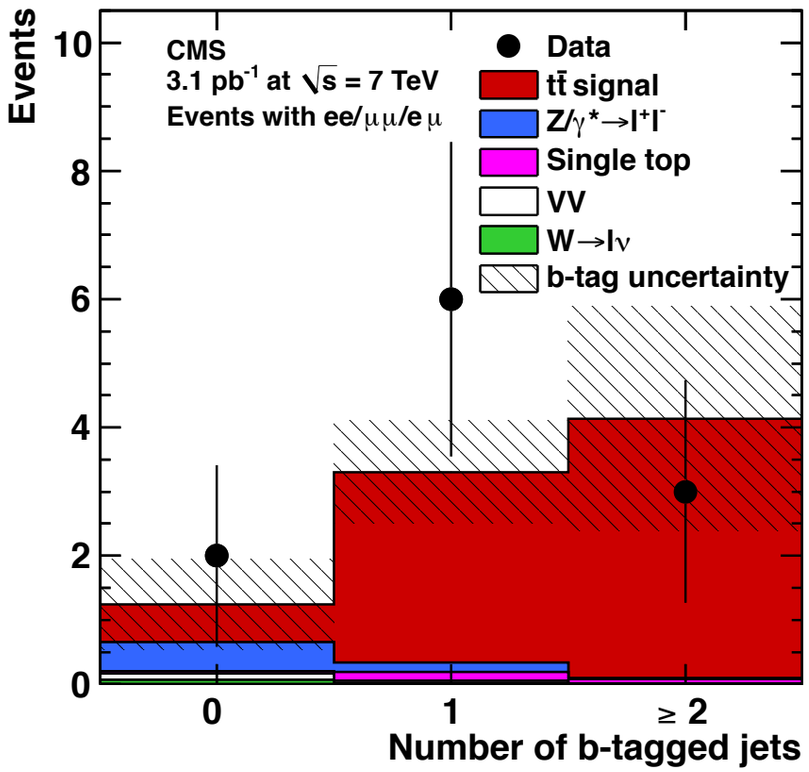
- Dilepton channel only: ee/eμ/μμ
- 11 events observed, 2.1 ± 1.0 background events expected
- Top pair production cross section:

$$\sigma_{t\bar{t}} = 194 \pm 72\,(\text{stat.}) \pm 24\,(\text{syst.})\ \text{pb}$$





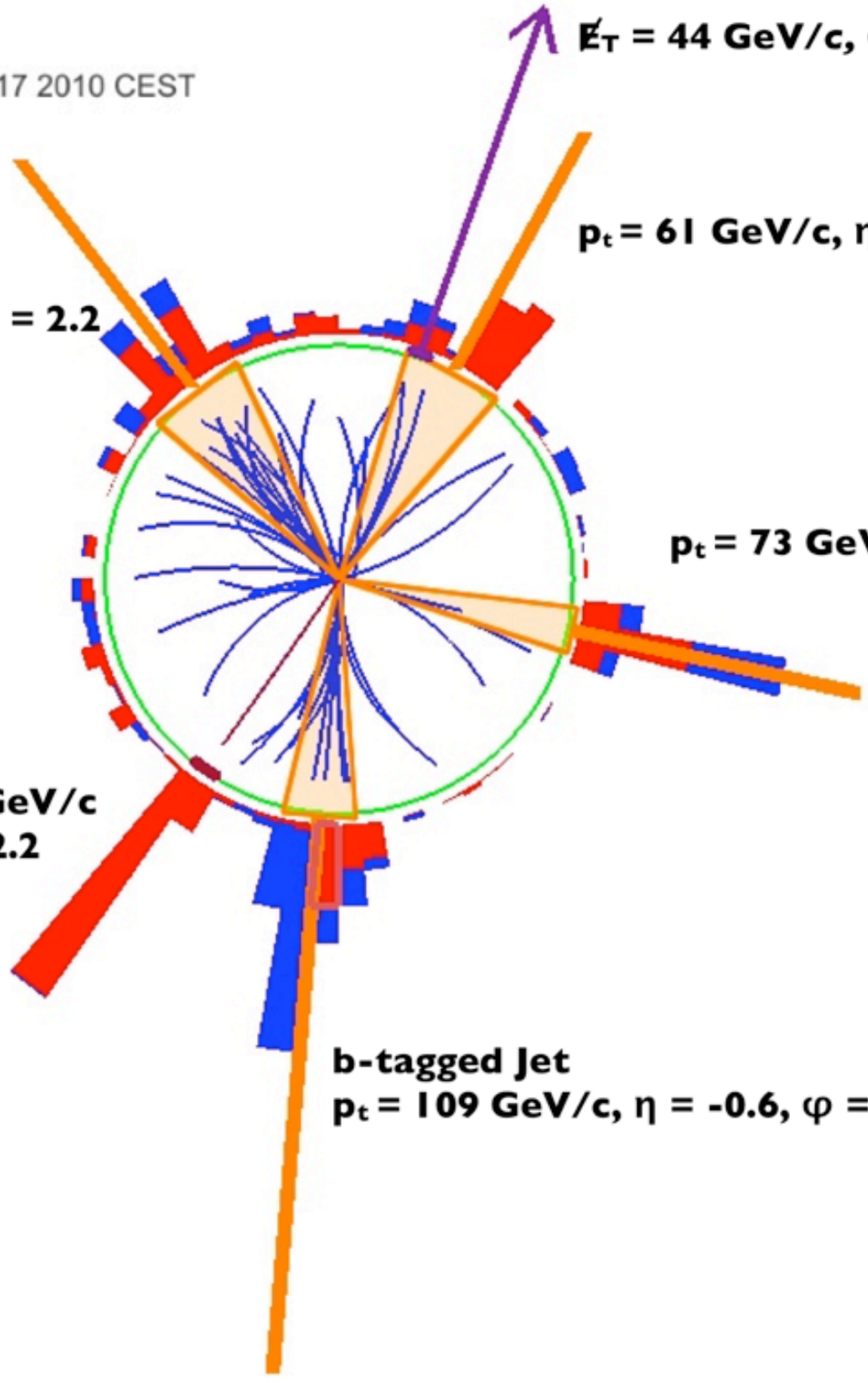
$\sigma_{t\bar{t}} = 194 \pm 72\,(\text{stat.}) \pm 24\,(\text{syst.})\ \text{pb}$



[CMS, arXiv:1010.5994 [hep-ex], submitted to Phys. Lett. B]

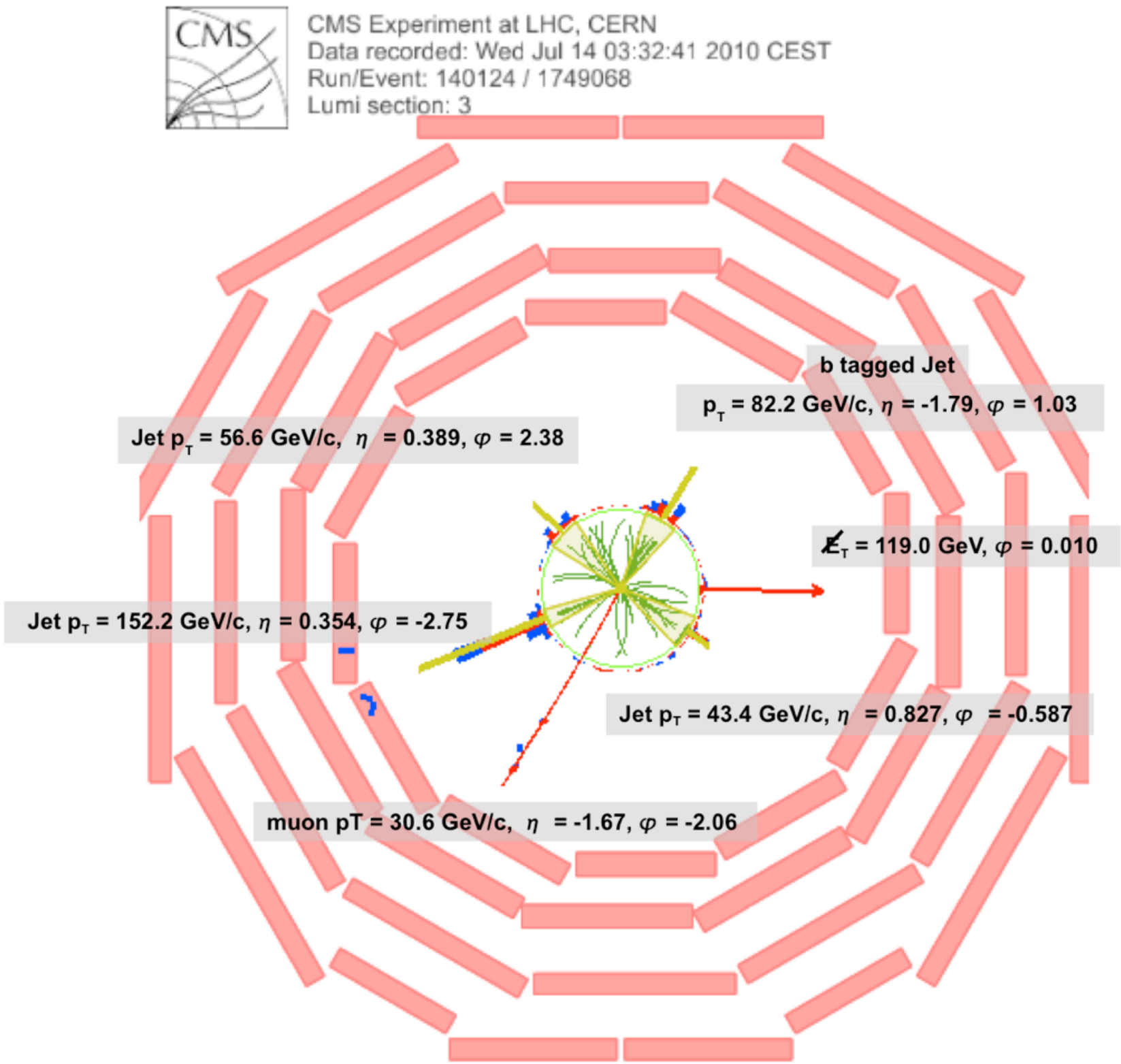
CMS Event Display: e + 4 Jets + MET

CMS Experiment at LHC, CERN
Data recorded: Sun Jul 18 17:44:17 2010 CEST
Run/Event: 140385 / 90009543
Lumi section: 101
Orbit/Crossing: 26434904 / 101

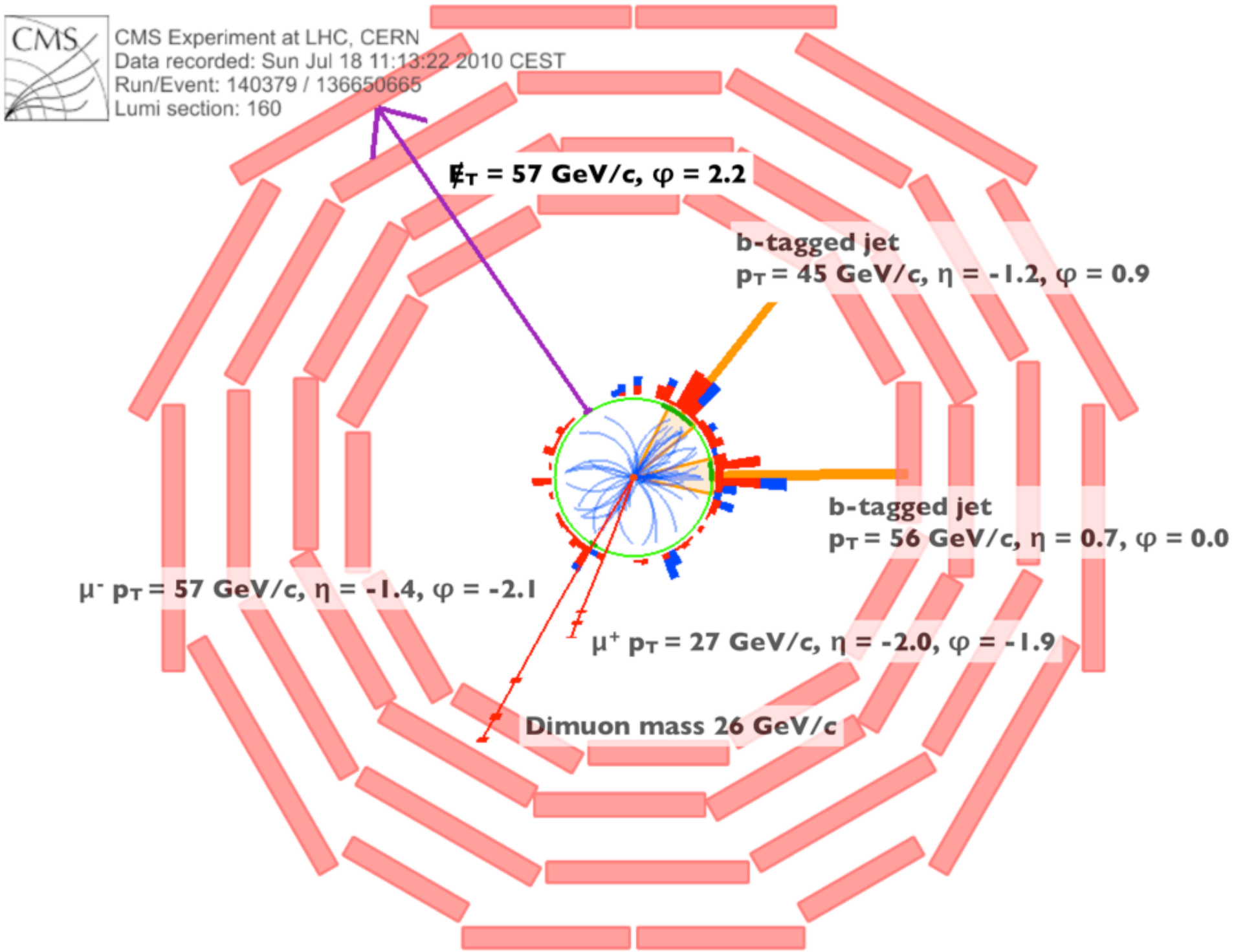


M_T = 77 GeV

CMS Event Display: μ + 4 Jets + MET



CMS Event Display: μμ + 2 Jets + MET



CMS Event Display: eμ + 3 Jets + MET