# Measurement of the top quark mass and the $t\bar{t}$ invariant mass in pp collisions at $\sqrt{s}$ = 7 TeV in CMS


**Martijn Mulders (CERN-PH)**

***for the CMS Collaboration***

***EPS High Energy Physics Conference 2011, July 21-27 Grenoble, France***

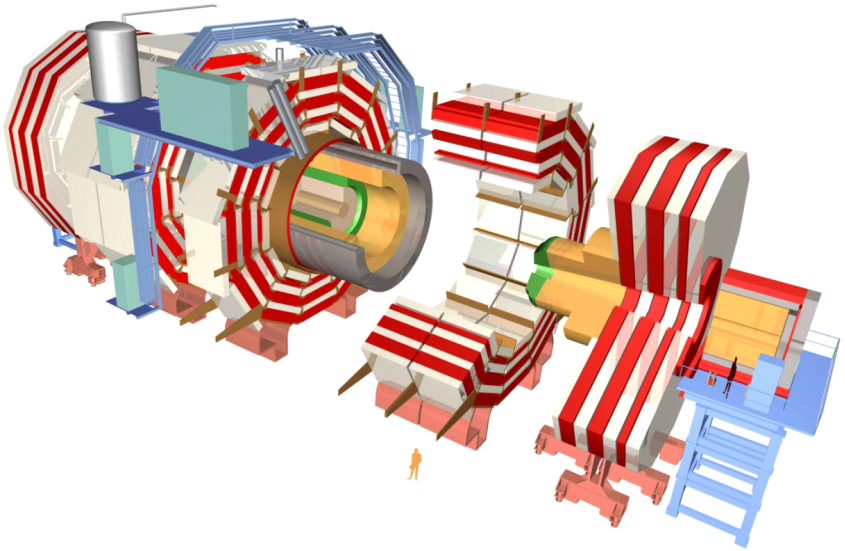
# Compact Muon Solenoid

LHC data recorded and of 'top' quality:

- 2010: 36 $pb^{-1}$
- 2011: >1.0 $fb^{-1}$

CMS, excellent for top physics:

- Powerful lepton (e, μ, tau) trigger, reconstruction and ID
- Hermetic calorimetry, with fine lateral granularity
- All-silicon tracker, in 3.8T field



Superb tracking:

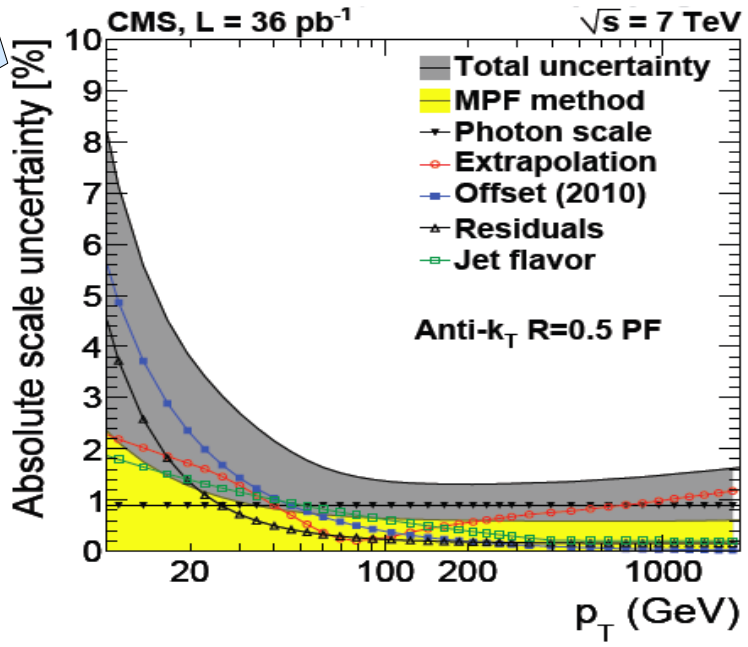
- Employed in Jet and MET reconstruction ("Particle Flow")
- b-tagging: powerful and well described in simulation

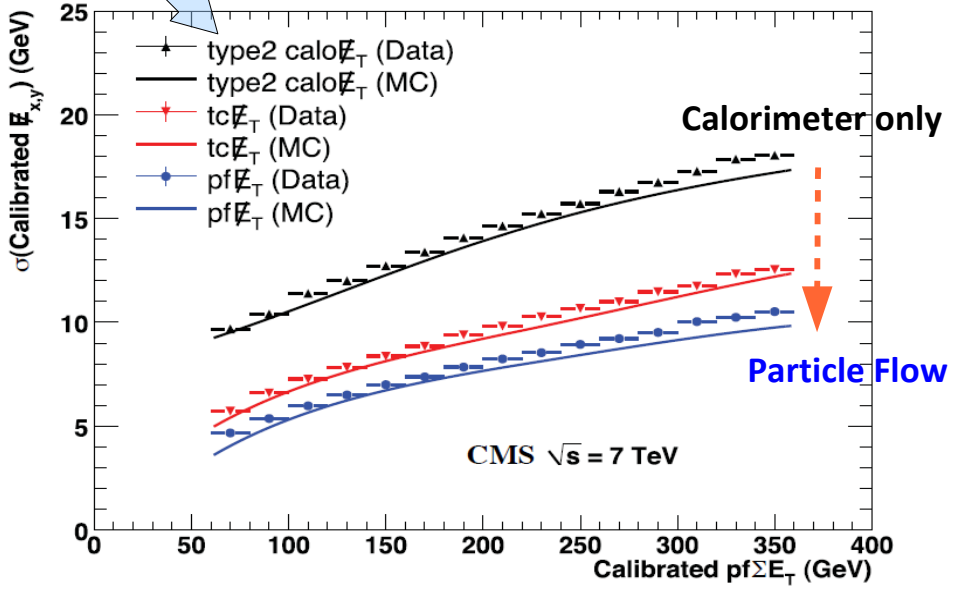
  CMS-PAS-BTV-11-001
- "top"-tagging (more later)

# Jets and Missing $E_T$

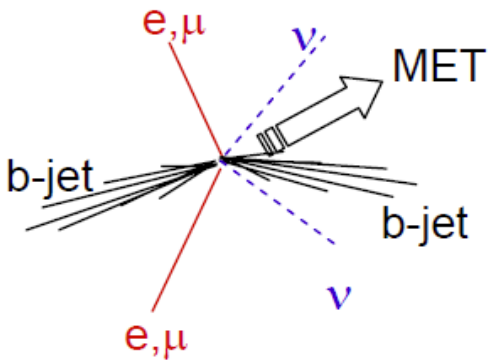
(MET) arXiv:1106.5048 and (Jets) CERN-PH-EP-2011-102 (on arXiv soon) *submitted to JINST*

- Particle Flow (PF) identifies individual particles, combining tracker, calorimetry and muon system information
- Jets clustered from PF particles with anti-kT algorithm (dR=0.5)
- Jet resolution 10-15%
- Jet energy scale uncertainty <2% for jet pT>40 GeV , |η|<1.3
- PF significantly improves MET resolution

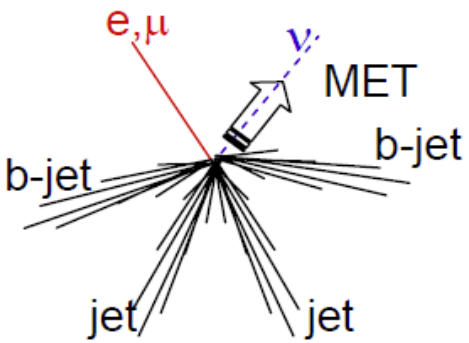


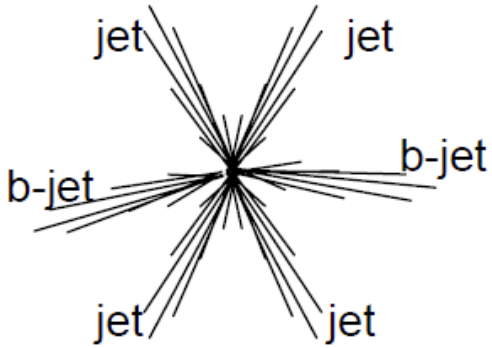
# Mass measurements




***dileptons***




***lepton + jets***




***all hadronic***

**1** top mass 36 $pb^{-1}$

**2** top mass 36 $pb^{-1}$

**3** $t\bar{t}$ pair mass 36 $pb^{-1}$

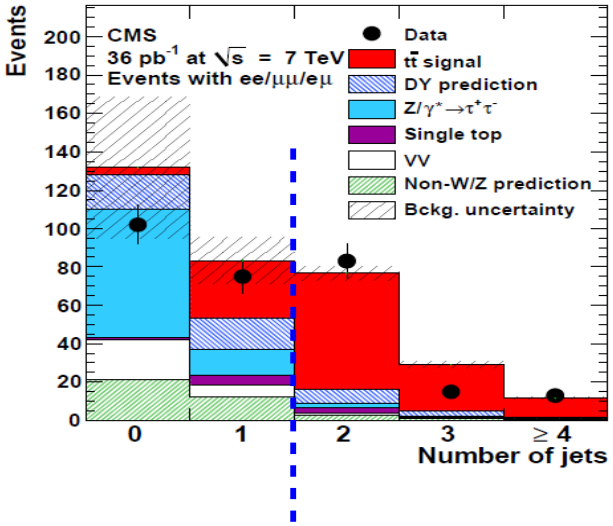
**4** $t\bar{t}$ pair mass

**New: 886 $pb^{-1}$**

# Top Mass di-lepton channel

arXiv:1105.5661

- Selection similar to cross-section analysis: 2 leptons (ee/μμ/eμ), 2 jets, MET → **No** b-tagging requirement
- Priority to b-tagged jets improves correct choice of b-jets by 16% compared to $p_T$-based selection



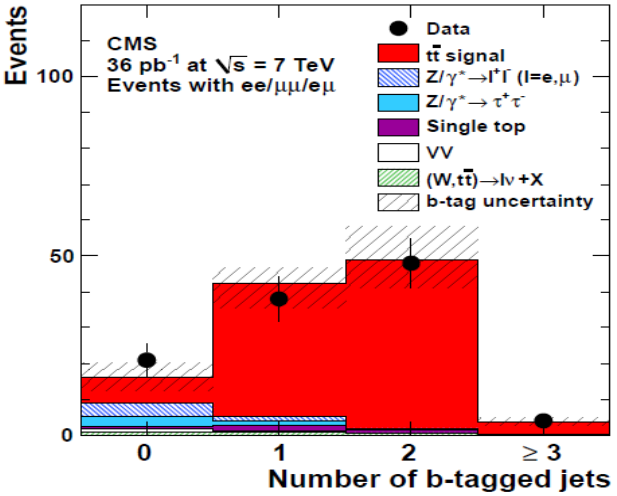

- Two methods to solve under-constrained system:

1) Analytical Matrix Weighting Technique

Based on MWT method from D0
PRL 80 (1998) 2063

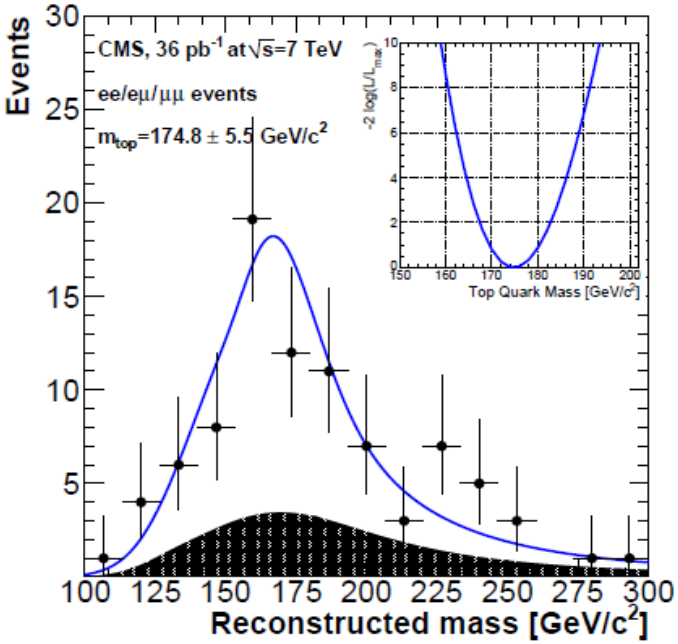
2) KINb method

Based on KIN method from CDF
PRD 73 (2006) 112006

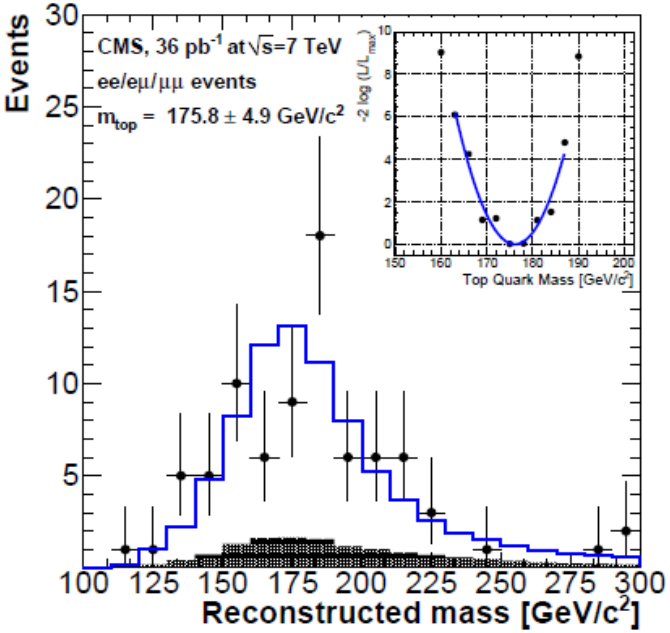


# Top Mass di-lepton channel

KINb




AMWT




- Both methods yield one mass per event
- Likelihood fit of mass distributions to templates of signal and background
- Combination using BLUE method (statistical correlation is 0.57)
- Calibrate linearity and uncertainties with pseudo-experiments

# Top Mass di-lepton channel

- Main systematic uncertainties:
  - JES uncertainties for light-quark and b-jets were still based on first 3 $pb^{-1}$
  - Effects of underlying event tune and pile-up events quoted separately from JES calibration

| Source | KINb | AMWT |
|---|---|---|
| Overall jet energy scale | +3.1/−3.7 | 3.0 |
| b-jet energy scale | +2.2/−2.5 | 2.5 |
| Lepton energy scale | 0.3 | 0.3 |
| Underlying event | 1.2 | 1.5 |
| Pileup | 0.9 | 1.1 |
| Jet-parton matching | 0.7 | 0.7 |
| Factorisation scale | 0.7 | 0.6 |
| Fit calibration | 0.5 | 0.1 |
| MC generator | 0.9 | 0.2 |
| Parton density functions | 0.4 | 0.6 |
| b-tagging | 0.3 | 0.5 |

| Method | Measured $m_{top}$ (in GeV/$c^2$) |
|---|---|
| AMWT | $175.8 \pm 4.9\,(\text{stat.}) \pm 4.5\,(\text{syst.})$ |
| KINb | $174.8 \pm 5.5\,(\text{stat.})^{+4.5}_{-5.0}\,(\text{syst.})$ |
| Combined | $175.5 \pm 4.6\,(\text{stat.}) \pm 4.6\,(\text{syst.})$ |

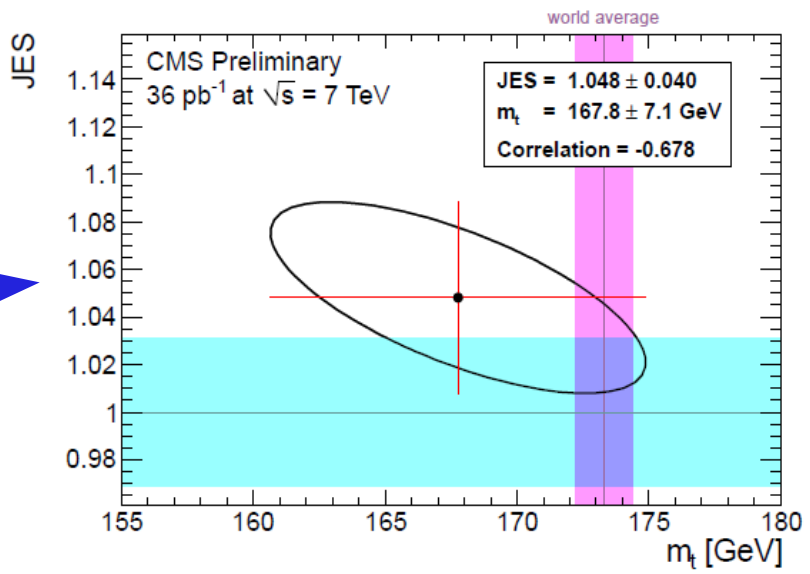
***First measurement of the top mass at the LHC***

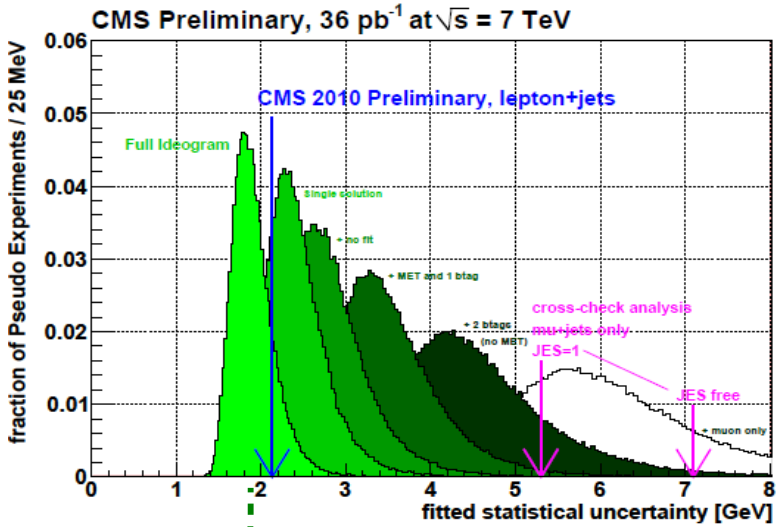
***ArXiv:1105.5661, accepted by JHEP***

# Top Mass lepton+jets channel

CMS-PAS-TOP-10-009

- Same selection as lepton+jets cross-section analysis
- Template fit of $m_t$ and jet energy scale (JES) using highest-pT 3-jet and included 'W candidate' 2-jet reconstructed mass, requiring 2 b-tagged jets, μ+jets only
- Ideogram analysis, optimized for best sensitivity at 36 pb$^{-1}$:
  - No *in-situ* JES fit ~1.3
  - Addition of e+jets ~√2
  - 0, 1 and ≥ 2 b-jets ~1.4
  - Kinematic Fit ~1.3
  - Ideogram likelihood ~1.3



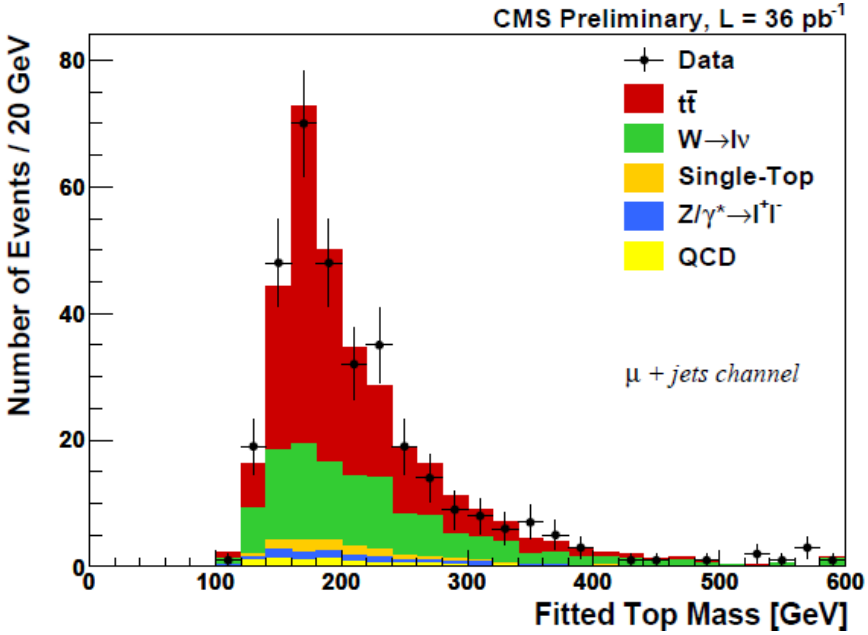



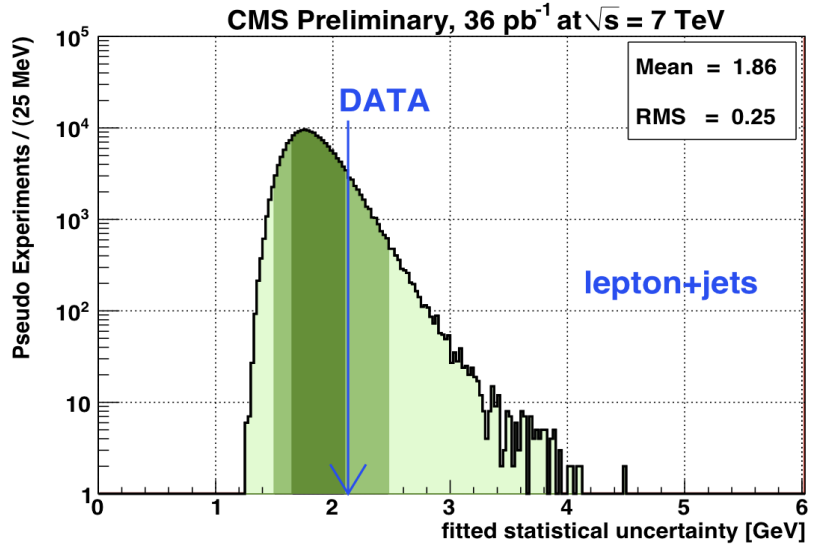

factors improvement in expected stat. uncertainty

~3x

# Top Mass lepton+jets channel

- Ideogram technique used before in DELPHI, D0, CDF
- Event-by-event likelihood takes into account all 24 jet+neutrino combinations (signal), and probability that event is background
- Kinematic fit constrains W masses, equal top mass, $p_T$ balance
- Sample likelihood is product of event likelihoods
- Calibrate method using MC pseudo experiments




Stat. uncertainty from pseudo-experiments

# Top Mass lepton+jets channel

*36 pb$^{-1}$ CMS preliminary*

- lepton+jets result: $m_t = 173.1 \pm 2.1(\text{stat})^{+2.4}_{-2.1}(\text{JES}) \pm 1.4(\text{other syst})$ GeV

Main systematic uncertainties:

- JES uncertainties for light-quark and b-jets, without use of *in-situ* JES fit
- Signal modeling: $Q^2$ scale, ISR, FSR, ME-PS matching
- Background: especially modeling of QCD multi-jet background shape

| Source | Ideogram analysis $\delta m_t$ (GeV) |
|---|---|
| JES (overall data/MC) | +2.4-2.1 |
| JES $p_T$ and $\eta$ dependence | - |
| light vs b-jet scale | - |
| JER (10% effect) | 0.07 |
| MET (10% effect) | 0.4 |
| Factorization scale | 1.1 |
| ME-PS matching threshold | 0.4 |
| ISR/FSR | 0.2 |
| Underlying event | 0.2 |
| Pile-up effect | 0.1 |
| PDF | 0.1 |
| Background | 0.5 |
| B-tagging | 0.05 |
| Fit calibration statistics | 0.1 |
| Total systematic uncertainty | +2.8- 2.5 |

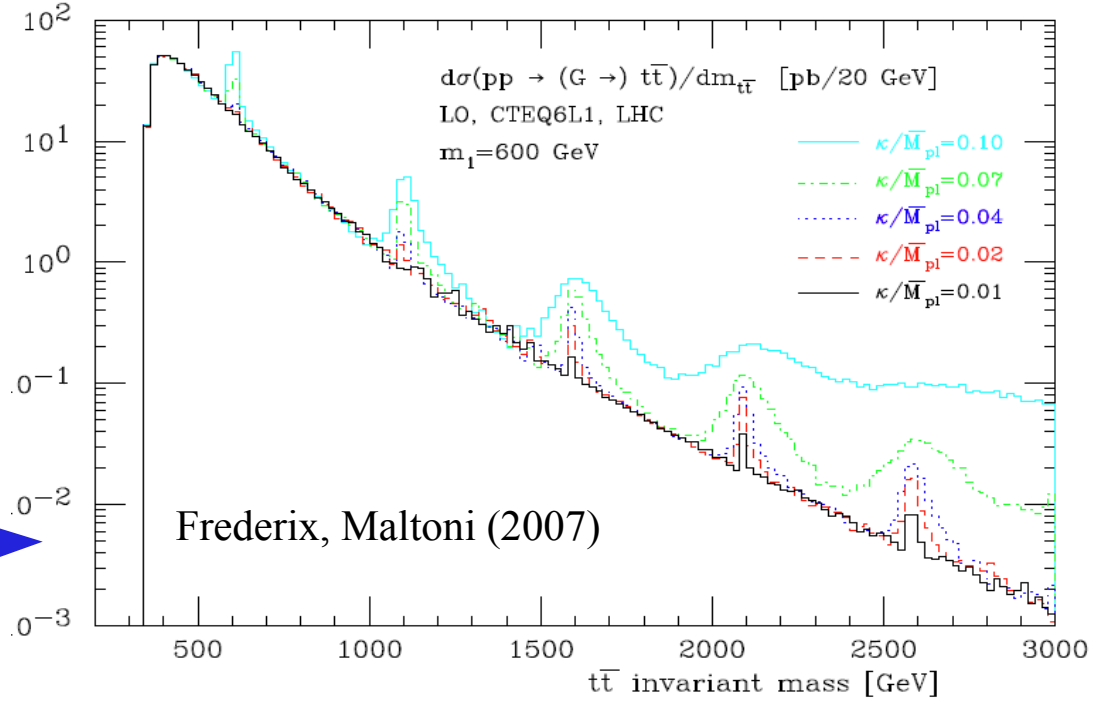
*36 pb$^{-1}$ CMS preliminary*

Combined with dilepton: $m_t = 173.4 \pm 1.9(\text{stat}) \pm 2.7(\text{syst})$ GeV

< 2 % precision on the top mass !

# $t\bar{t}$ invariant mass

- Various extensions to the SM predict new particles that decay (preferentially) to top pairs
  - Spin 0 (eg MSSM Higgs)
  - Spin 1 (eg Technicolor, Topcolor Z' )
  - Spin 2 (KK graviton excitations)
- Other models also predict distortions in m(tt) shape

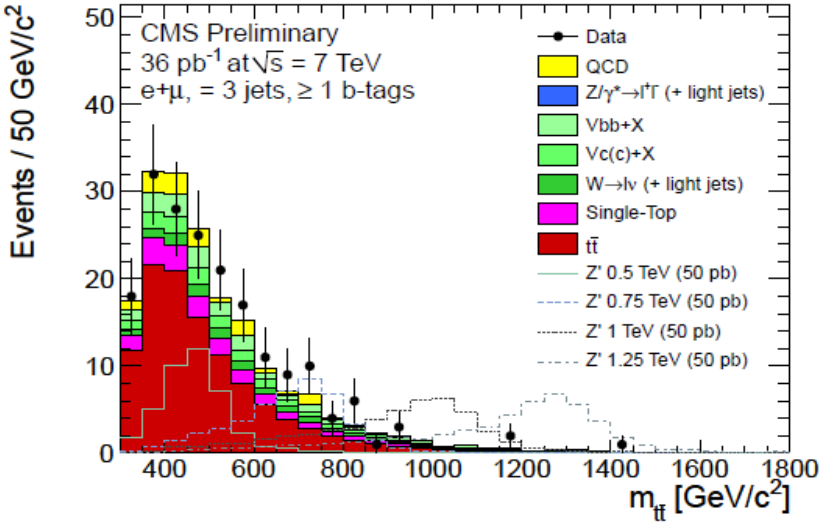


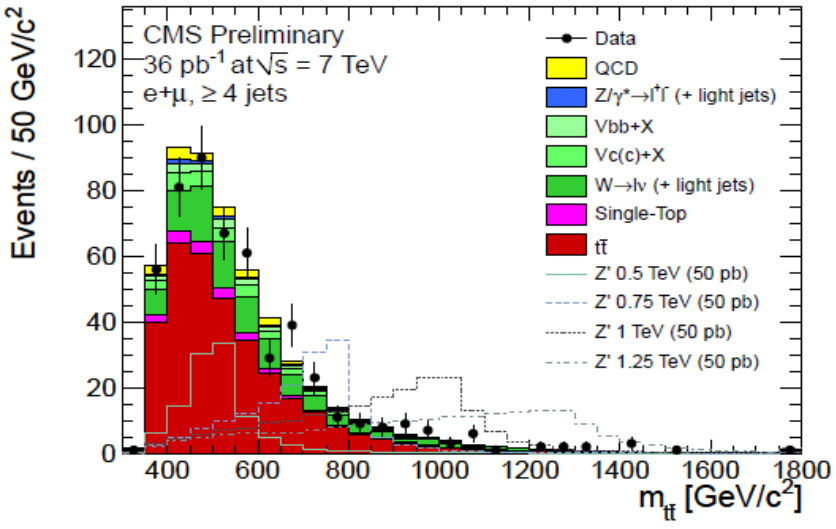

Generic search for narrow resonances in m(tt) spectrum

- At 'low' mass, standard reconstruction is used
- At high mass, the top quarks are boosted and jets and leptons start to merge → use “top tagging” techniques

# $t\bar{t}$ invariant mass, lepton+jets

CMS-PAS-TOP-10-007

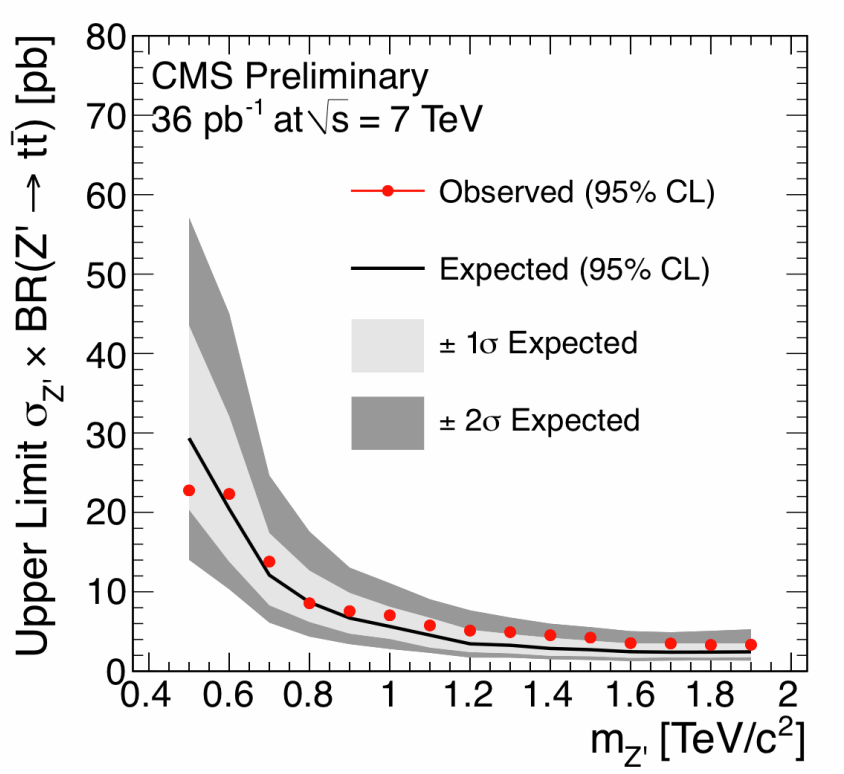



- Similar to μ+jets and e+jets selection for cross-section analysis
- Kinematic fit, consider all jet combinations compatible with b-tags, pick solution with lowest $\chi^2$ (no fit applied in 3-jet event category)
- Use events with 3 jets of which at least one b-tag, or 4 jets with 0, 1 or 2 b-tags, e/μ → 8 categories fitted separately in combined fit of data to templates for SM background and narrow Z' resonances

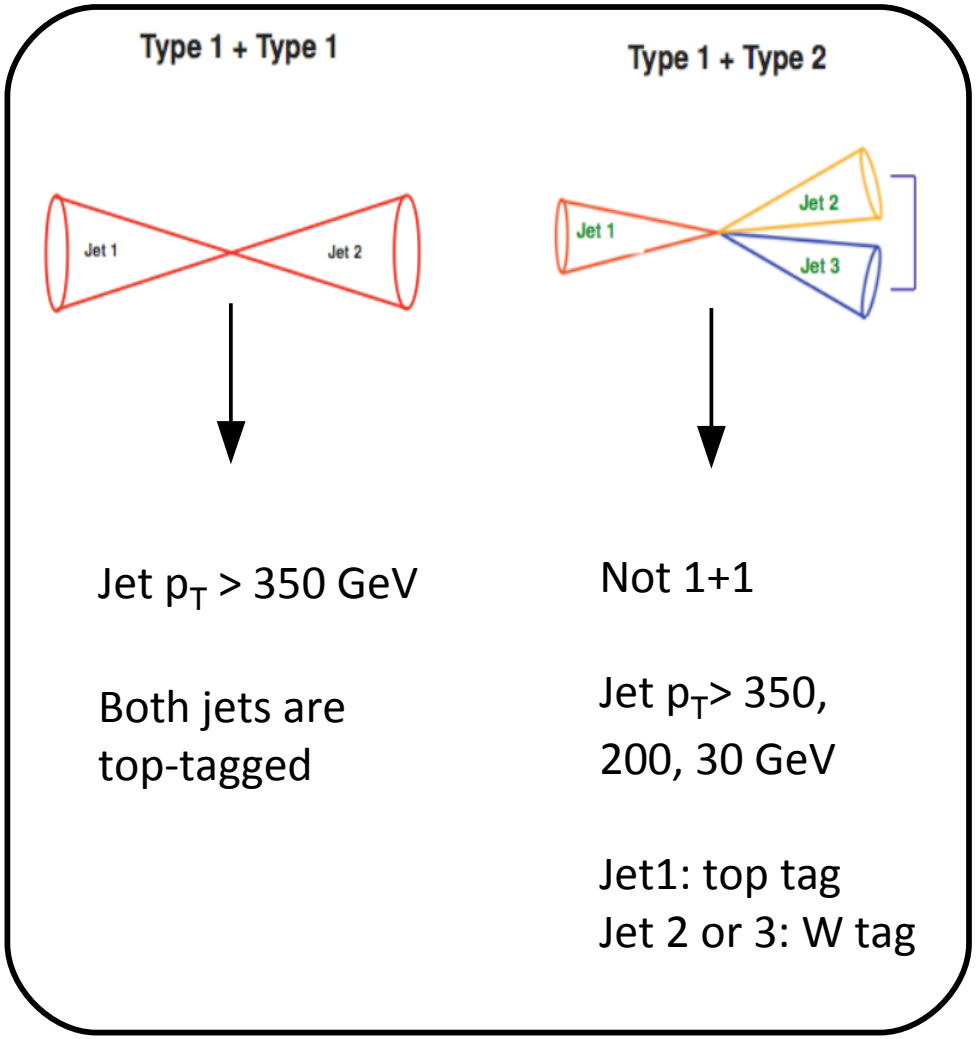
# $t\bar{t}$ invariant mass, lepton+jets

- No significant deviations from SM expectation
- Set non-model-specific 95% CL upper limit on σ(narrow Z' resonance) x BR
  - ~7 pb at 1.0 TeV and
  - ~4 pb at 1.5 TeV



# $t\bar{t}$ mass in all-hadronic channel

CMS-PAS-EXO-11-006 **New!** **886 pb$^{-1}$**

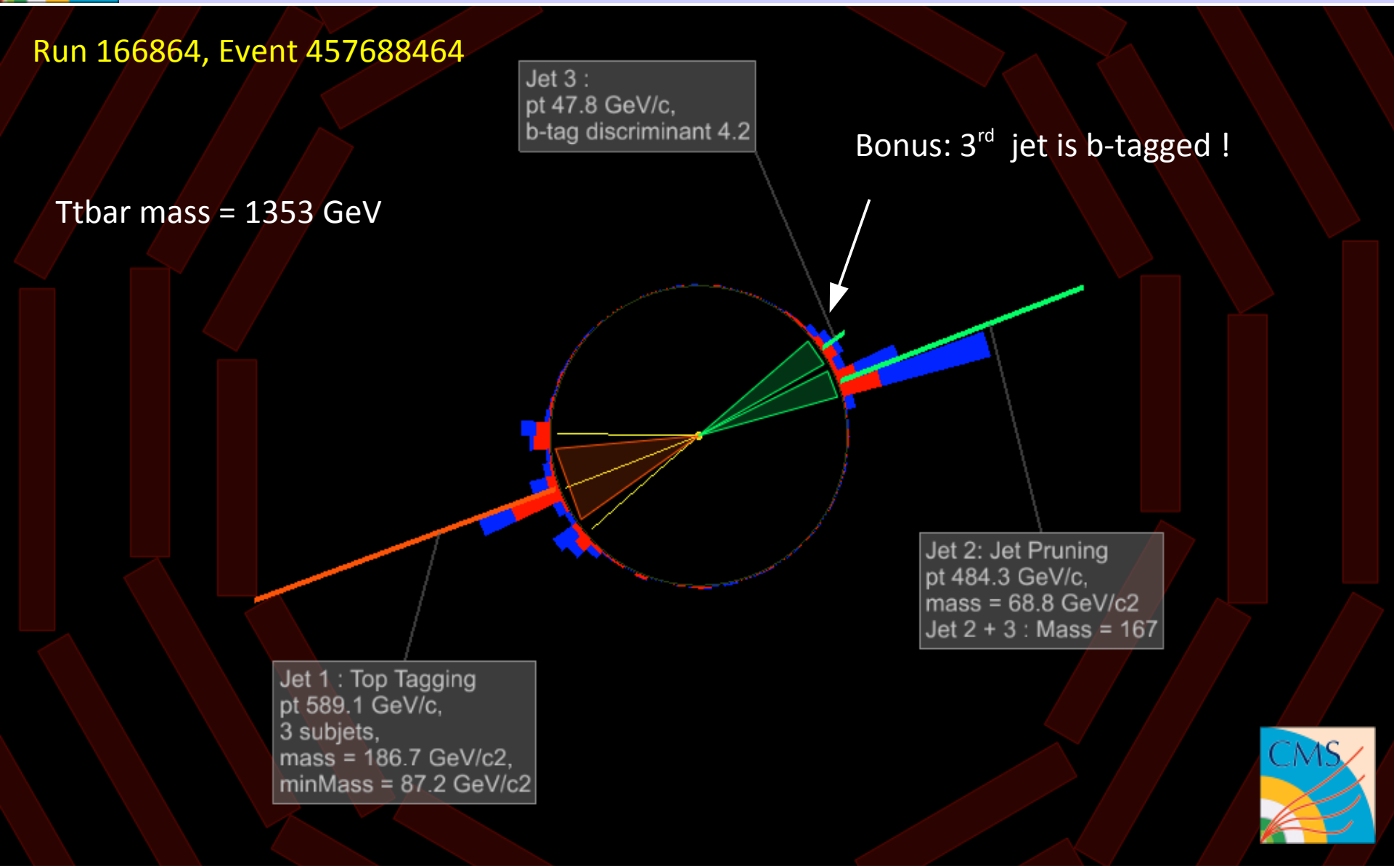



**Aim: high-mass top pairs in highly-boosted back-to-back topology (1+1 and 1+2)**

- "Classic" techniques tend to fail due to jet merging → *Use new jet substructure techniques*
- Start from Cambridge Aachen R=0.8 PF jets
- Use "Top tagging" and "jet pruning" to find Top and W tags, see CMS-PAS-JME-10-013 and references
- "Top Tagging" requirements
  - no. of sub-jets >= 3
  - 100 < jet mass < 250 GeV
  - min. pair-wise mass > 50 GeV

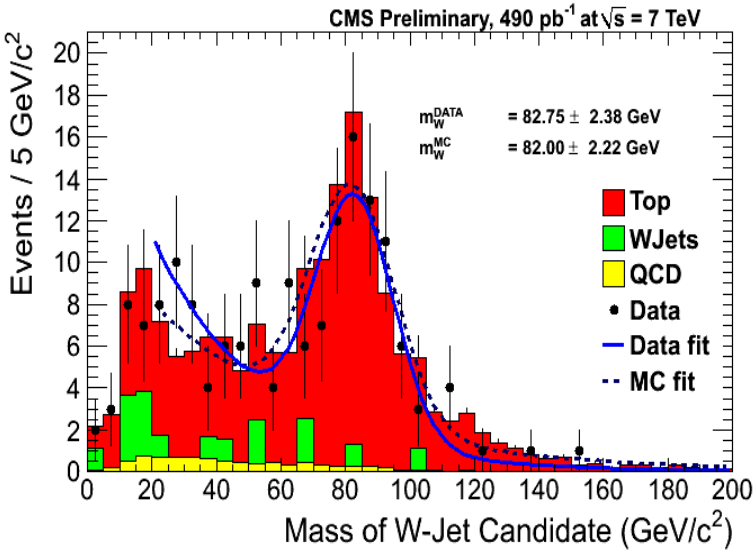
# Golden (1+2) $t\bar{t}$ candidate event

Run 166864, Event 457688464

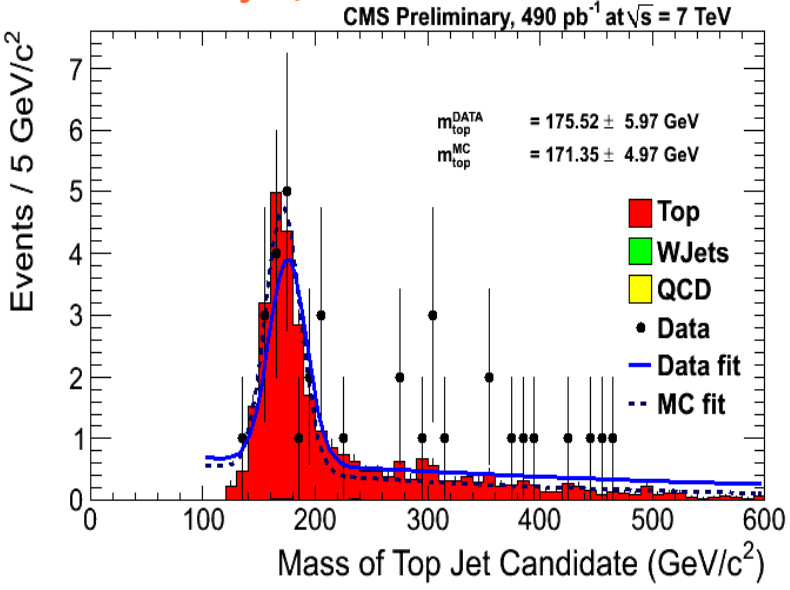


# $t\bar{t}$ mass in all-hadronic channel

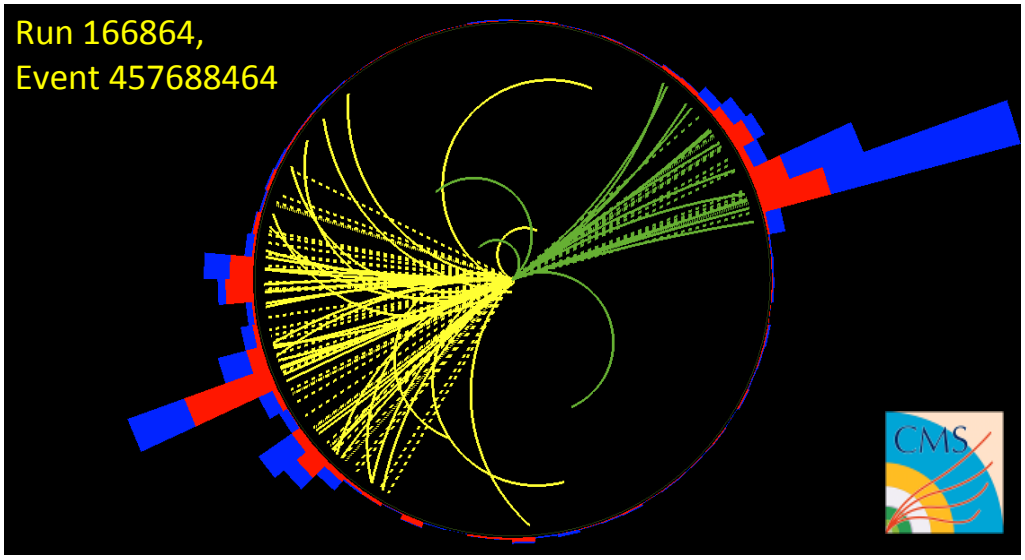
## Test Subjet JES with boosted μ+jets events:

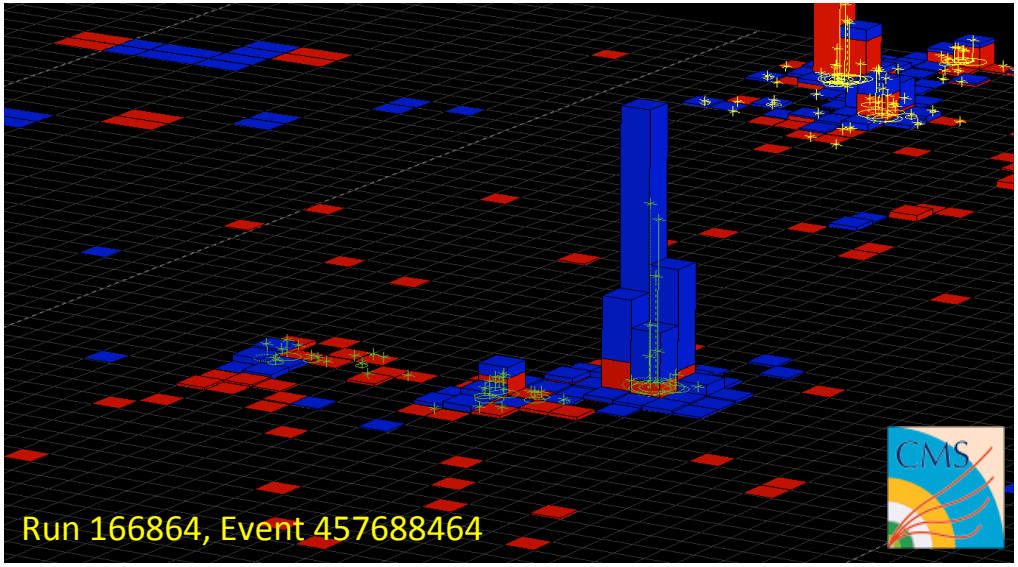



## Add closest jet, W in window 60-100 GeV:

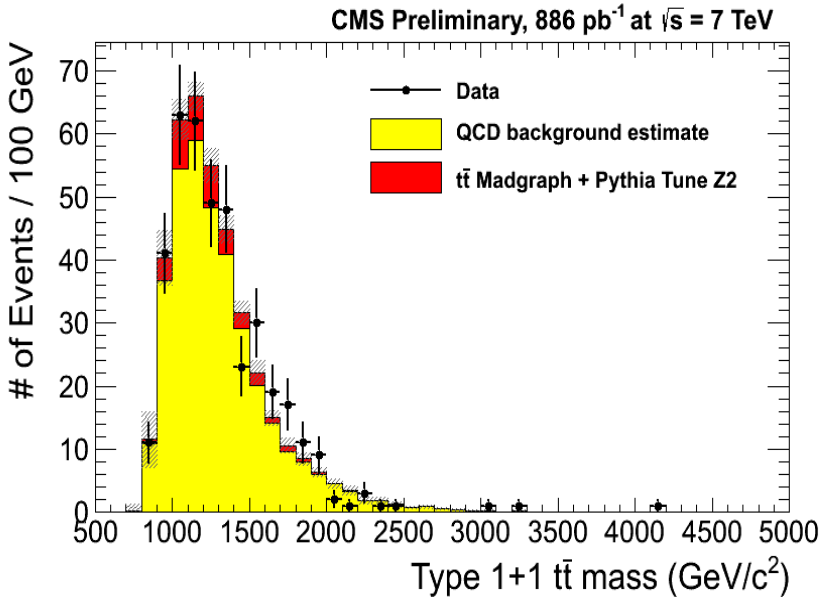



## Particle Flow helps to resolve substructure:

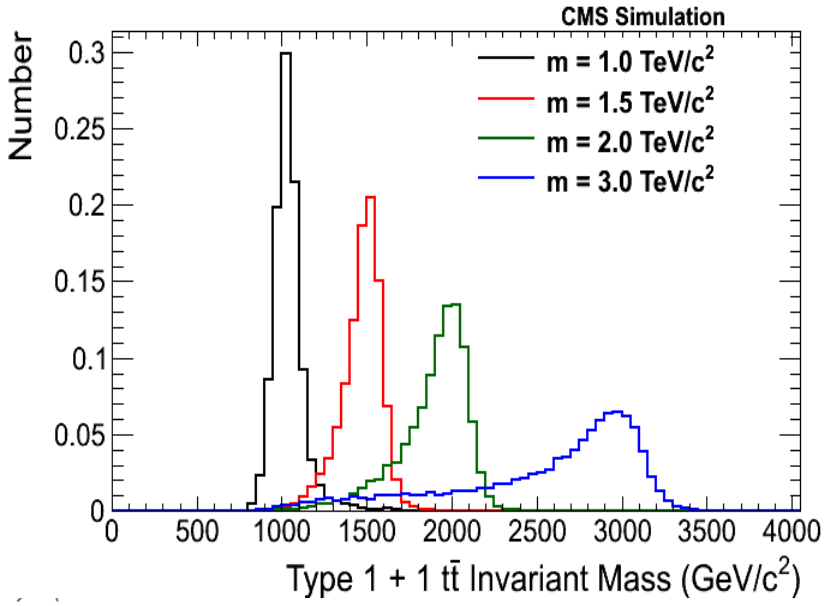


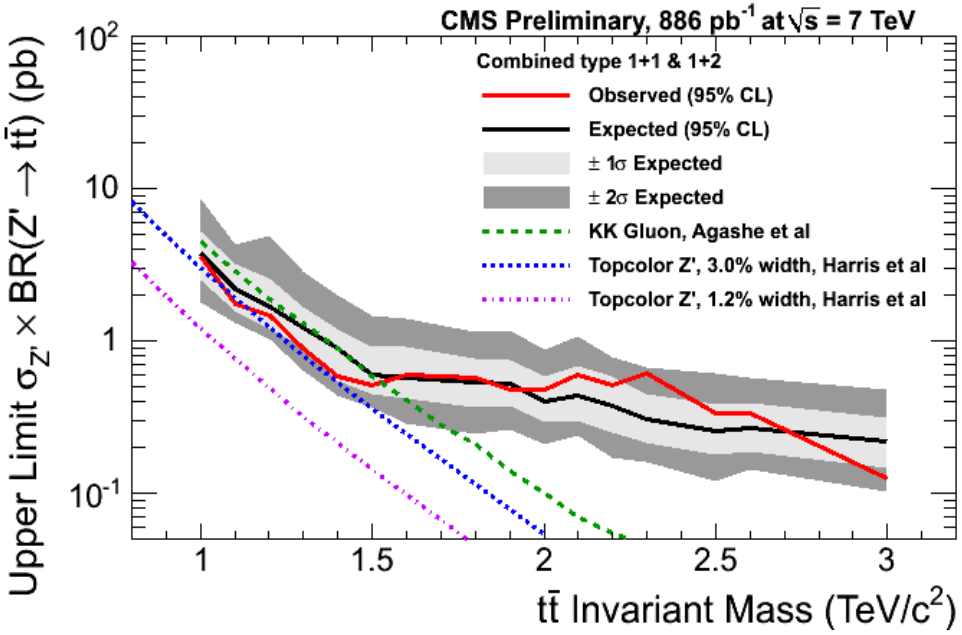



# $t\bar{t}$ mass in all-hadronic channel




- "Mass modified" mis-tag method to estimate QCD background from data
- No excess seen in (1+1) or (1+2)
- Set 95% CL upper limits on σ(Z' )x BR, excluding KK gluon < 1.5 TeV



# Summary

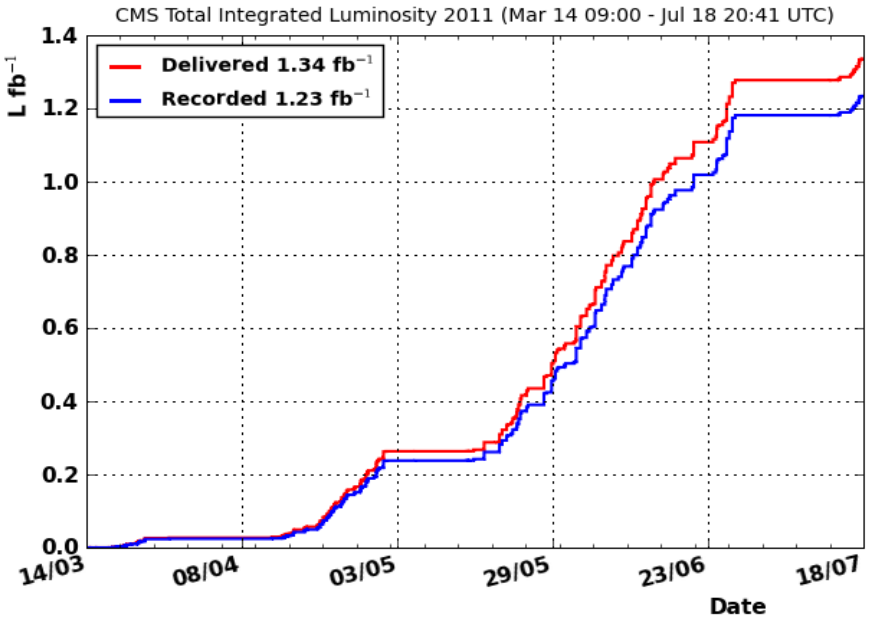
- CMS excellent detector for top measurements and searches
- Jet energy calibration to < 2%
- Top mass measurement to < 2%

  in agreement with world average

} ***With the first 36 pb$^{-1}$ of data !***

- Top pair invariant mass spectrum (so far) in agreement with Standard Model expectations
- Novel methods in search for tt resonances work brilliantly, but no signal seen... yet.
- More than 1 fb$^{-1}$ of data ready for analysis

***More data arriving !***



# References

- General CMS physics results, Overview: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
- All CMS publications: http://cdsweb.cern.ch/collection/CMS%20Papers?ln=en
- CMS preliminary results (Physics Analysis Summaries): http://cdsweb.cern.ch/collection/CMS%20Physics%20Analysis%20Summaries?ln=en
- Results presented in this talk:
  - Di-lepton top mass: arXiv:1105.5661
  - lepton+jets top mass: CMS-PAS-TOP-10-009
  - Ttbar invariant mass (lepton+jets): CMS-PAS-TOP-10-007
  - Ttbar invariant mass (all-hadronic): CMS-PAS-EXO-11-006
  - Jets: CMS-PAS-JME-10-011
  - MET: arXiv:1106.5048
  - B-tagging: CMS-PAS-BTV-11-001

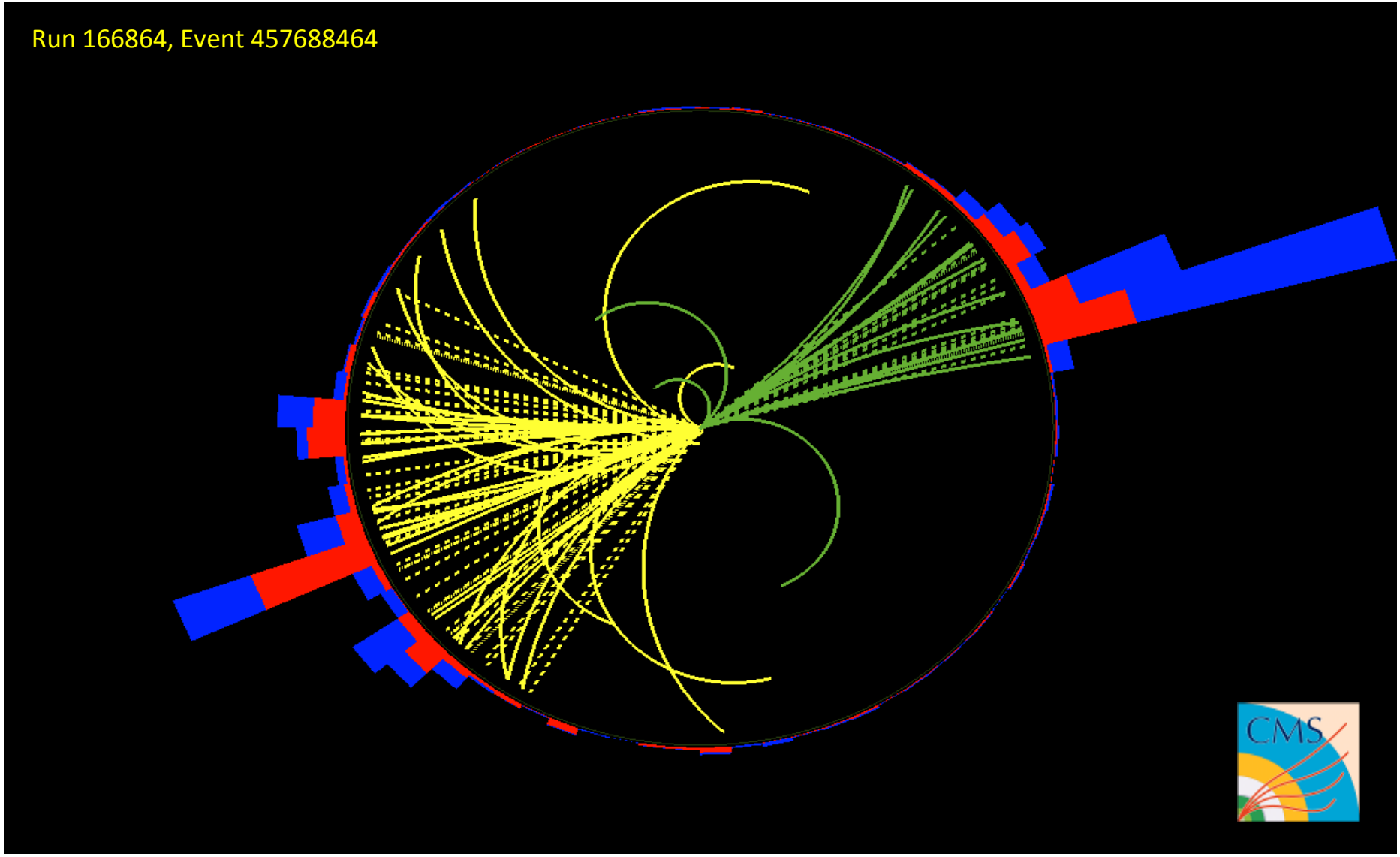
# A few more references

References on Jet Substructure:

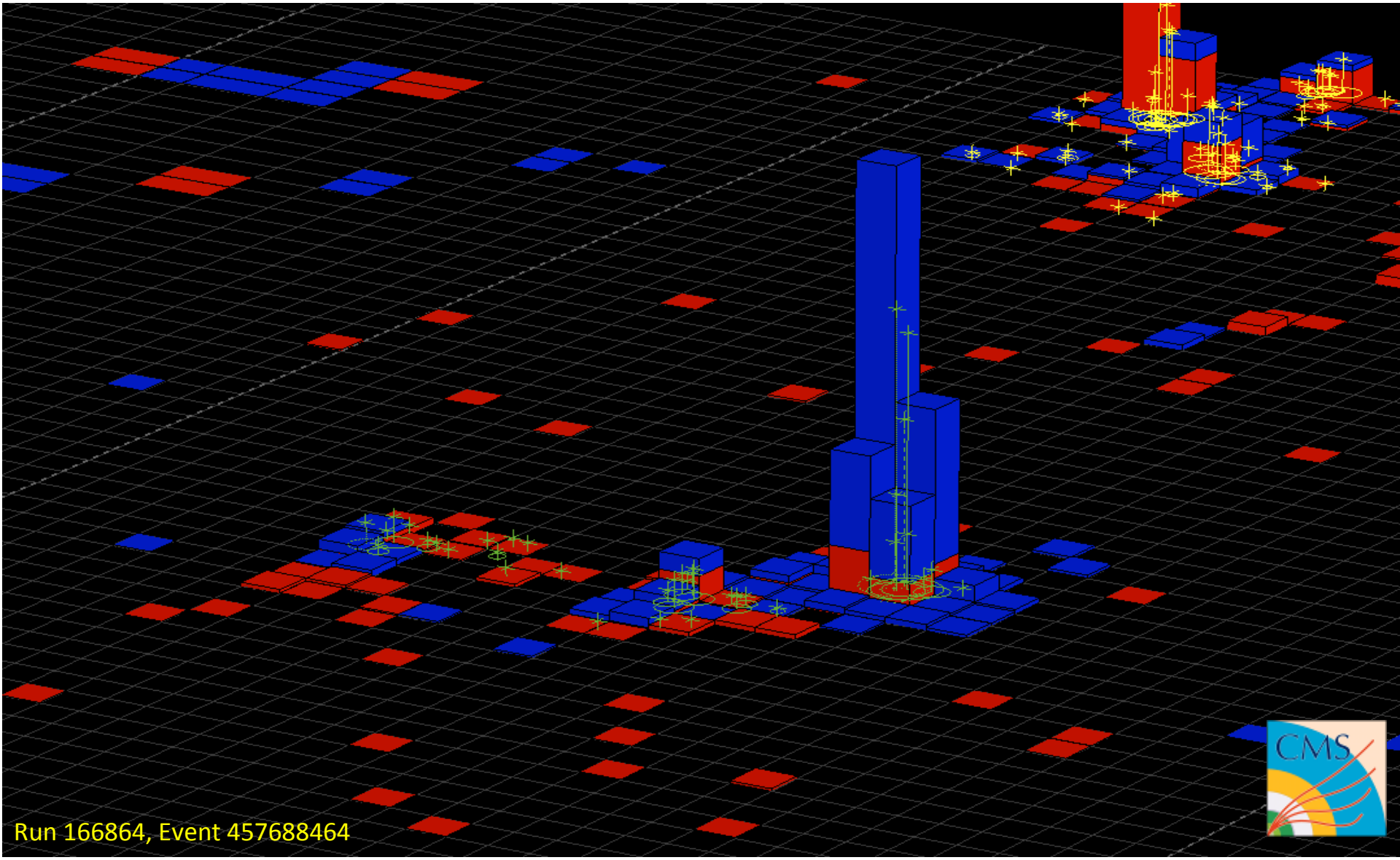

- D. E. Kaplan, K. Rehermann, M. D. Schwartz et al., *"Top Tagging: A Method for Identifying Boosted Hadronically Decaying Top Quarks"*, Phys. Rev. Lett. 101 (2008) 142001, arXiv:0806.0848.
- S. D. Ellis, C. K. Vermilion, and J. R. Walsh, *"Techniques for improved heavy particle searches with jet substructure"*, Phys.Rev. D80 (2009) 051501, arXiv:0903.5081.
- S. D. Ellis, C. K. Vermilion, and J. R. Walsh, *"Recombination Algorithms and Jet Substructure: Pruning as a Tool for Heavy Particle Searches"*, Phys.Rev. D81 (2010) 094023, arXiv:0912.0033.
- J. M. Butterworth, A. R. Davison, M. Rubin et al., *"Jet substructure as a new Higgs search channel at the LHC"*, Phys. Rev. Lett. 100 (2008) 242001, arXiv:0802.2470.

# Additional Material

# Zoom of 'triply' tagged event



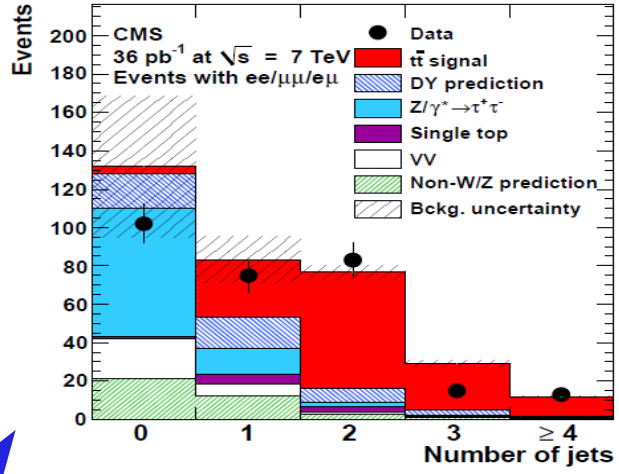
# Zooming in on Top-tagged Jet

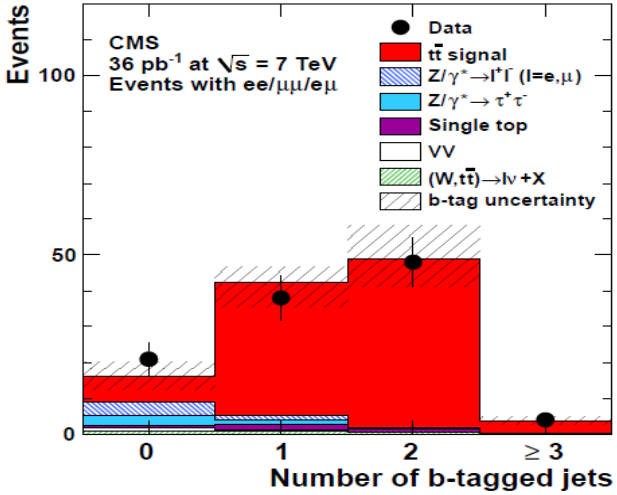


# Selection di-lepton channel

arXiv:1105.5661 http://arxiv.org/abs/1105.5661

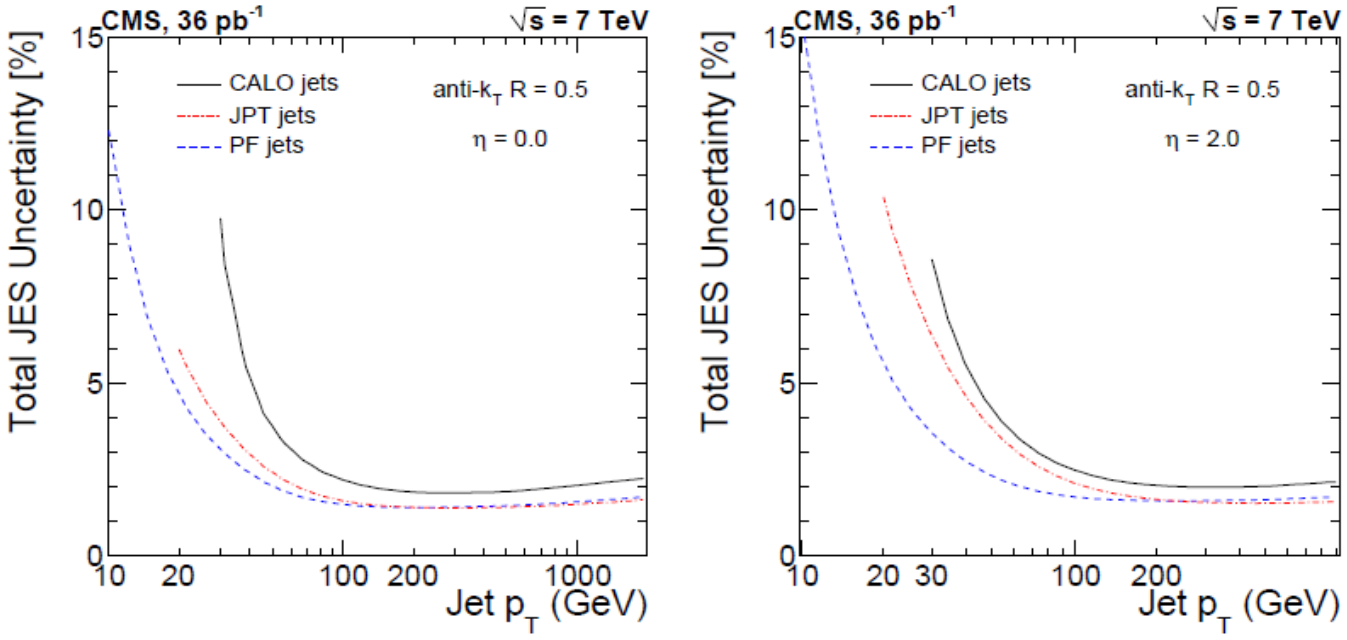
- Trigger: μ $p_T$>15 GeV (μμ/ee) or electron with $E_T$>17 GeV (eμ)
- Two isolated leptons of opposite sign (ee, μμ or eμ)
  - $P_T$> 20 GeV and |η|<2.5 (2.4) for e (μ)
  - dilepton mass M>12 GeV and Z veto: |M – Mz| > 15 GeV
- MET > 30 GeV (ee, μμ) or > 20 GeV (eμ)
- ≥ 2 jets with $p_T$ > 30 GeV, |η|<2.5
- **No** selection on b-tagged jets



# JES, total uncertainty

from CERN-PH-EP-2011-102 (submitted to JINST & arXiv, 20/7/2011)

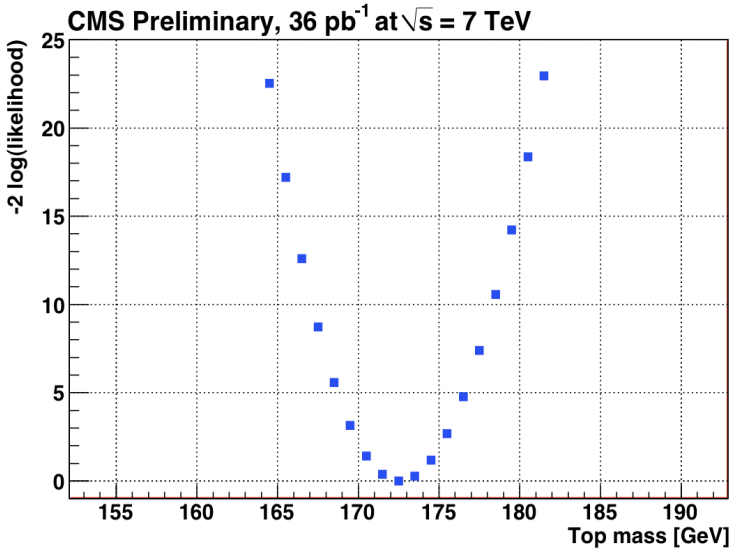


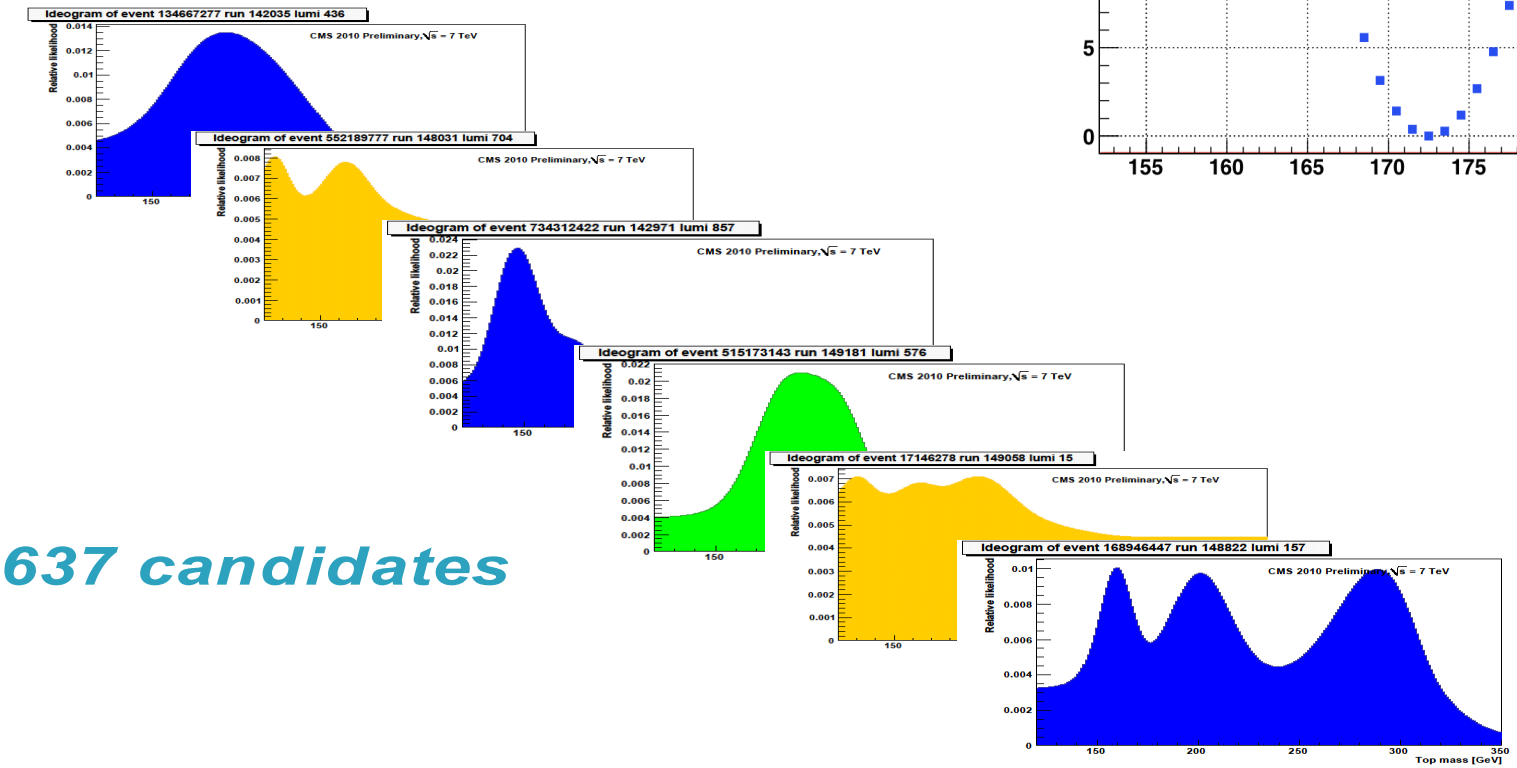

$$C = C_{\text{offset}}(p_T^{raw}) \cdot C_{\text{MC}}(p_T', \eta) \cdot C_{\text{rel}}(\eta) \cdot C_{\text{abs}}(p_T'')$$

- The overall JES uncertainty on the combined correction C includes the uncertainties on the absolute JES scale for |η|<1.3 (shown in slide 3), the offset correction, the MC-based correction, and the relative scale (dependence vs η using di-jet balancing).

# Ideogram Likelihood

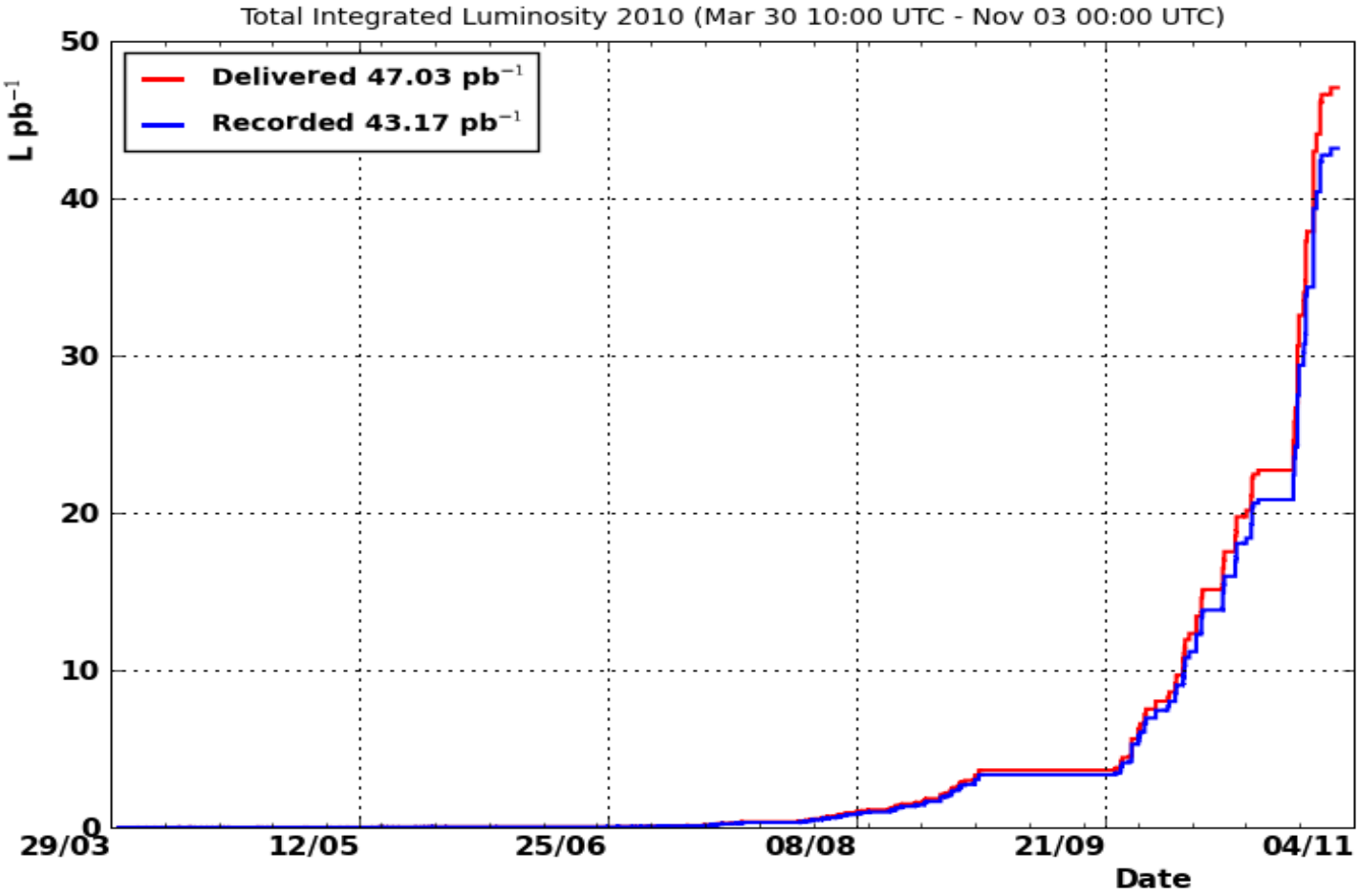
- Sample likelihood is product of event likelihoods:




**637 candidates**

# Luminosity in 2010



# Luminosity in 2011