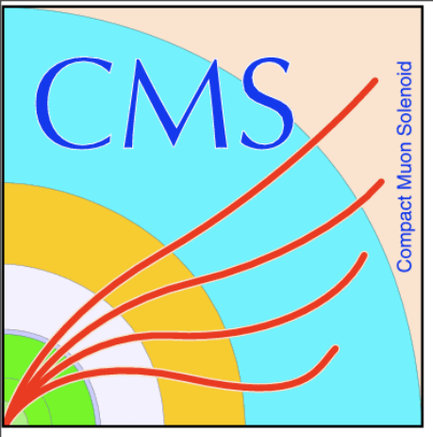


Top Quarks at CMS

First results with data and outlook of what's coming up

Slava Krutelyov (UCSB)
on behalf of CMS Collaboration

Workshop on Heavy Particles at the LHC
Pauli center, ETH Zürich

Jan 7, 2011

Outline

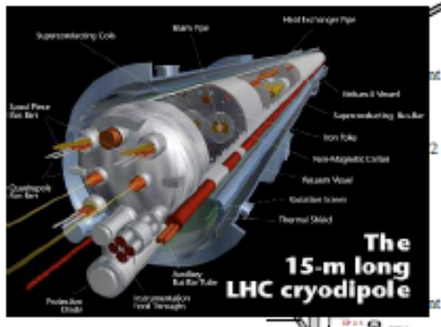
- LHC and production of top quarks
- CMS detector
- Top quarks
  - ➡ First excitements
  - ➡ First measurement of top pair production cross section in dileptons
  - ➡ Early $t\bar{t}$ studies in single-lepton+jets channel
- Summary

Acknowledgements go to my CMS collaborators from whom I took a number of slides
K. Lannon "Top physics with CMS" in LHC First Data, Ann Arbor MI, U.S.A. Dec 2010
F.-P.Schilling "Prospects for Top physics at CMS" in HCP2010, Toronto Canada, Aug 2010

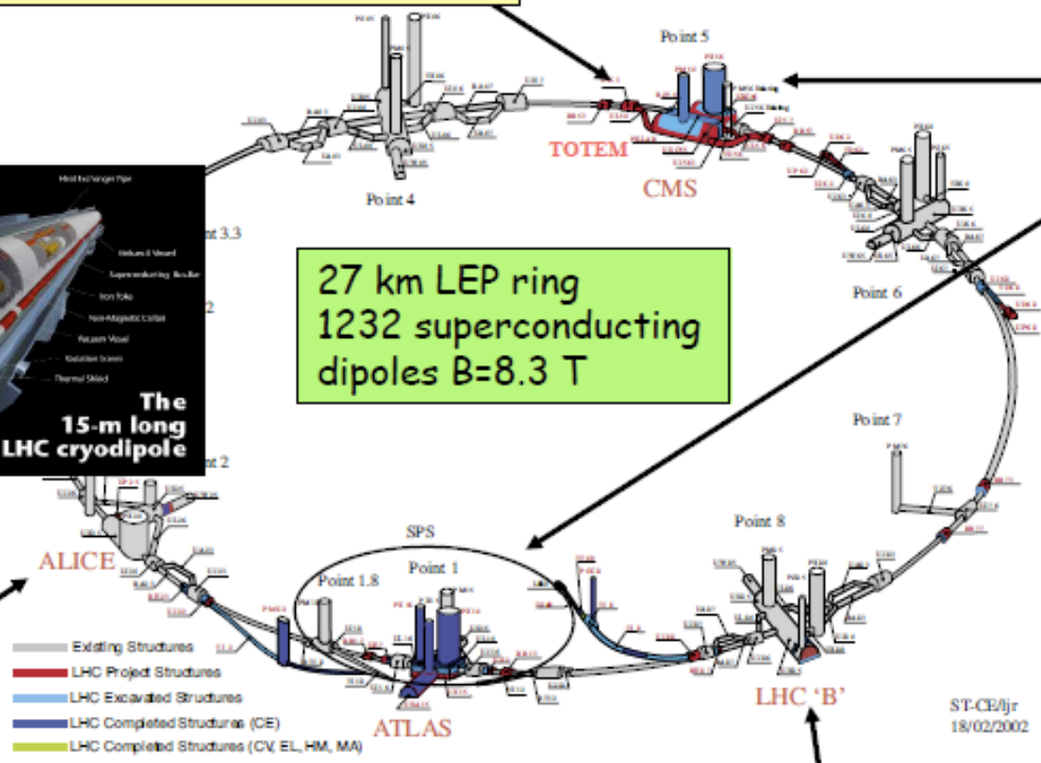
LHC and production of top

TOTEM (integrated with CMS):
pp, cross-section, diffractive physics

ATLAS and CMS :
general purpose

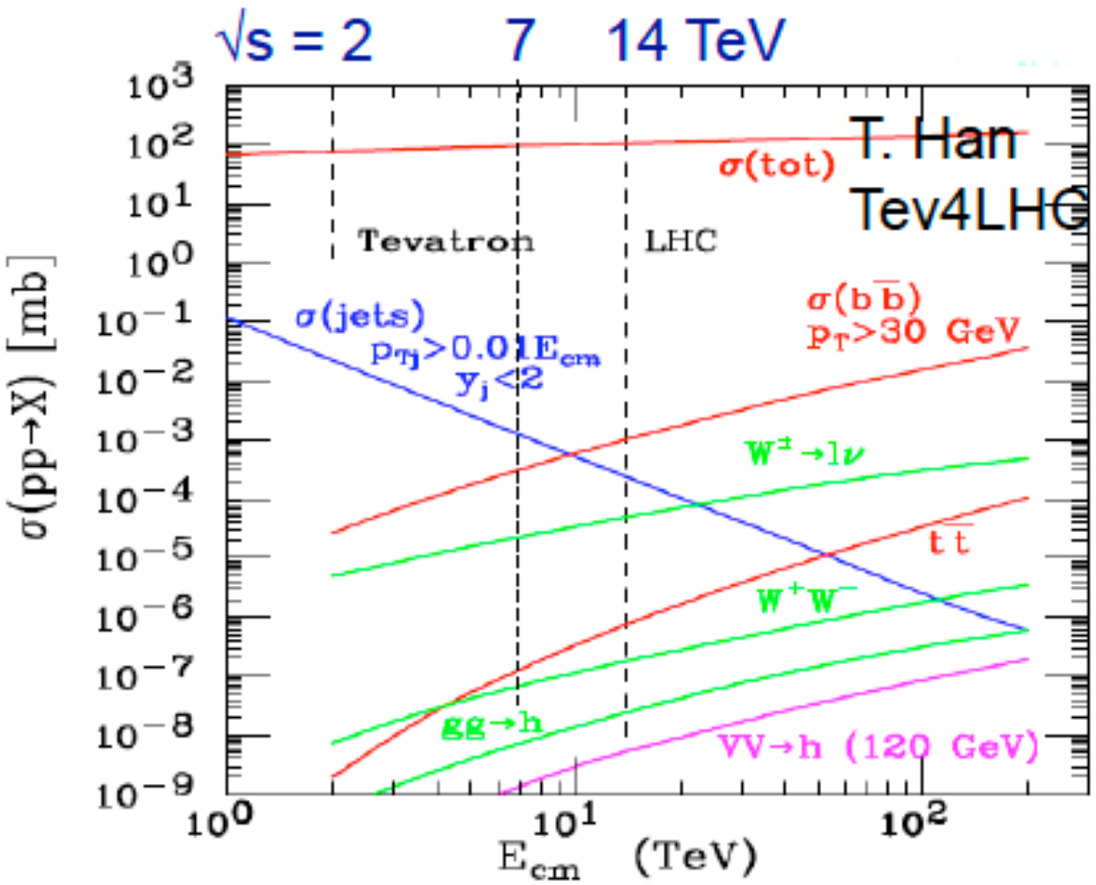


27 km LEP ring
1232 superconducting
dipoles B=8.3 T



ALICE :
ion-ion,
p-ion

LHCb :
pp, B-physics, CP-violation



Design parameters:

pp collisions at $\sqrt{s}$ = 14 TeV

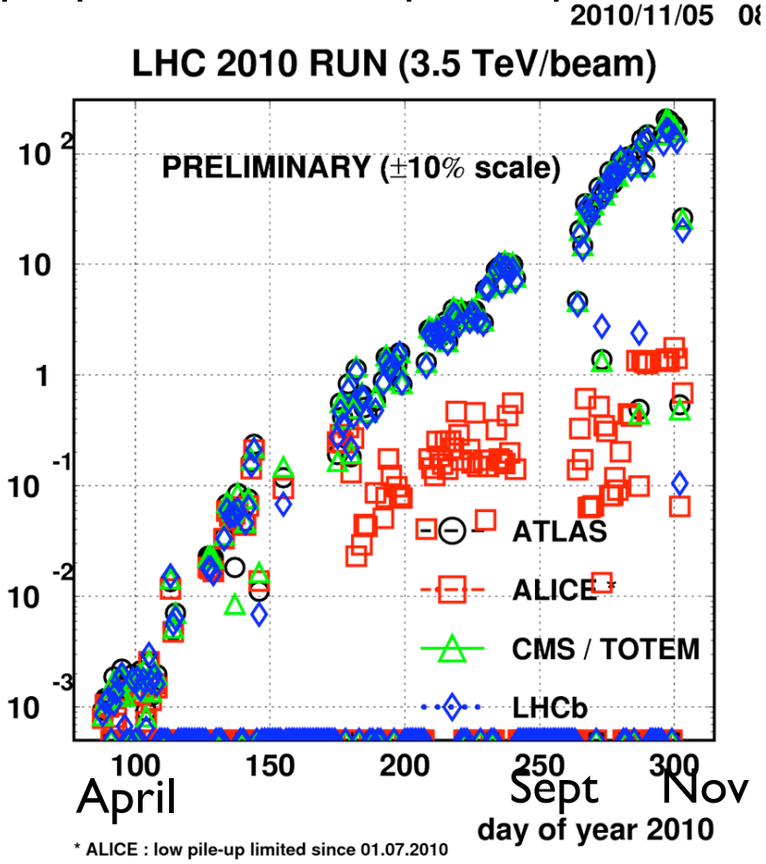
$L = 10^{34}\ cm^{-2}s^{-1} \approx 100\ fb^{-1}$/year

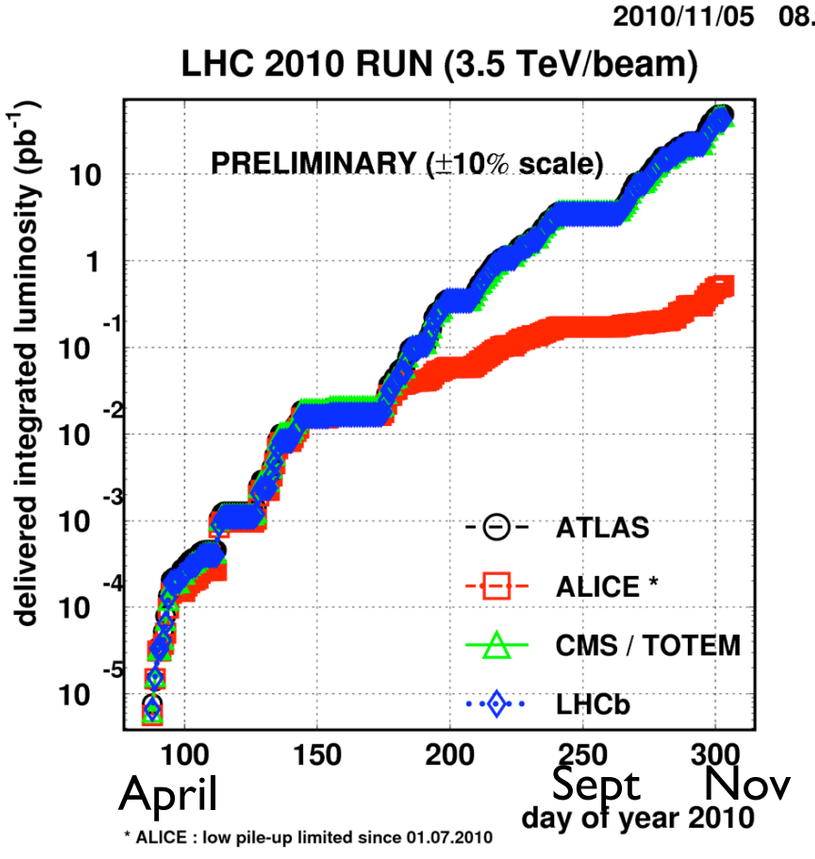
- $t\bar{t}$ — 0.8 nb or 10 Hz at design
- Design parameters yet to be reached

  ➡ 2010 and expectations in 2011 are a step to it …

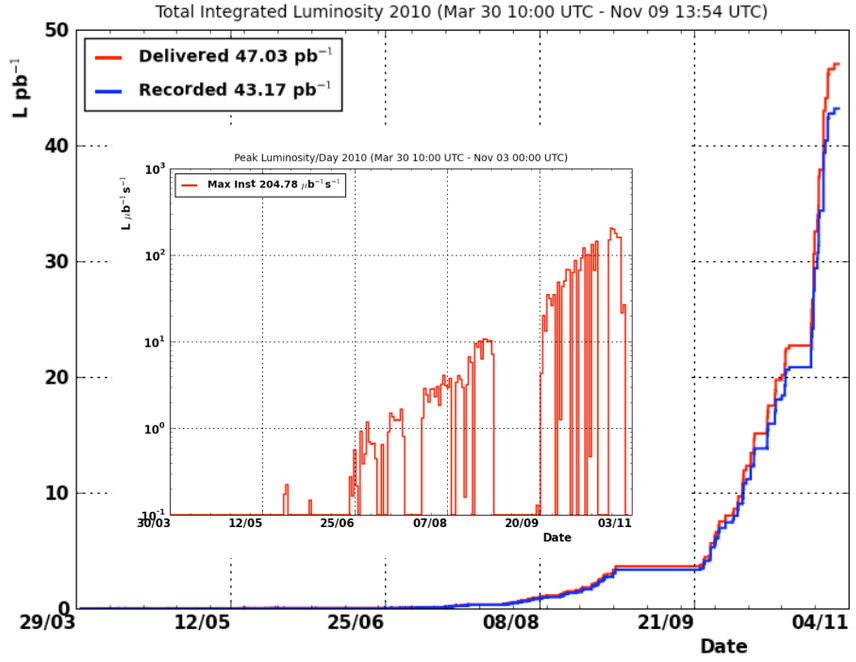
LHC 2010 data

http://lpc.web.cern.ch/lpc/lumiplots.htm

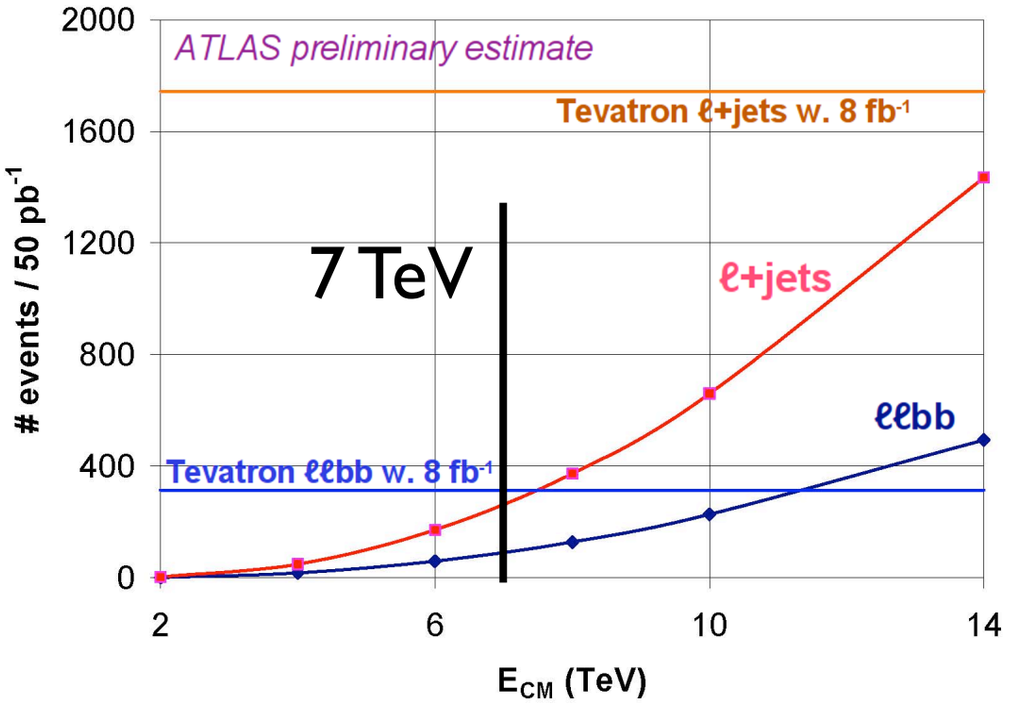




Delivered/recorded by CMS



- LHC ran at 7 TeV in 2010
  - ✓ delivered almost 50 pb^{-1}
  - ✓ peak luminosity 2×10^{32} $cm^{-2}s^{-1}$ (200 $\mu b^{-1}s^{-1}$)
- "Standard candle" measurements: (di)jets, B, $c\bar{c}$- and $b\bar{b}$-onia, W, Z, $t\bar{t}$
  - ✓ Some are already published with up to 3pb^{-1}
  - ✓ Most new results expected by Moriond



LHC Plans in 2011

104th LHCC Nov 17-18, 2010
http://indico.cern.ch/event/112439

Possible running scenarios to be finalized later this month

"Reasonable"

Peak luminosity	6.4 x 10^{32}
Integrated per day	11 pb^{-1}
200 days	2.2 fb^{-1}

"Ultimate"

Peak luminosity	2.2 x 10^{33}
Integrated per day	38 pb^{-1}
200 days	7.6 fb^{-1}

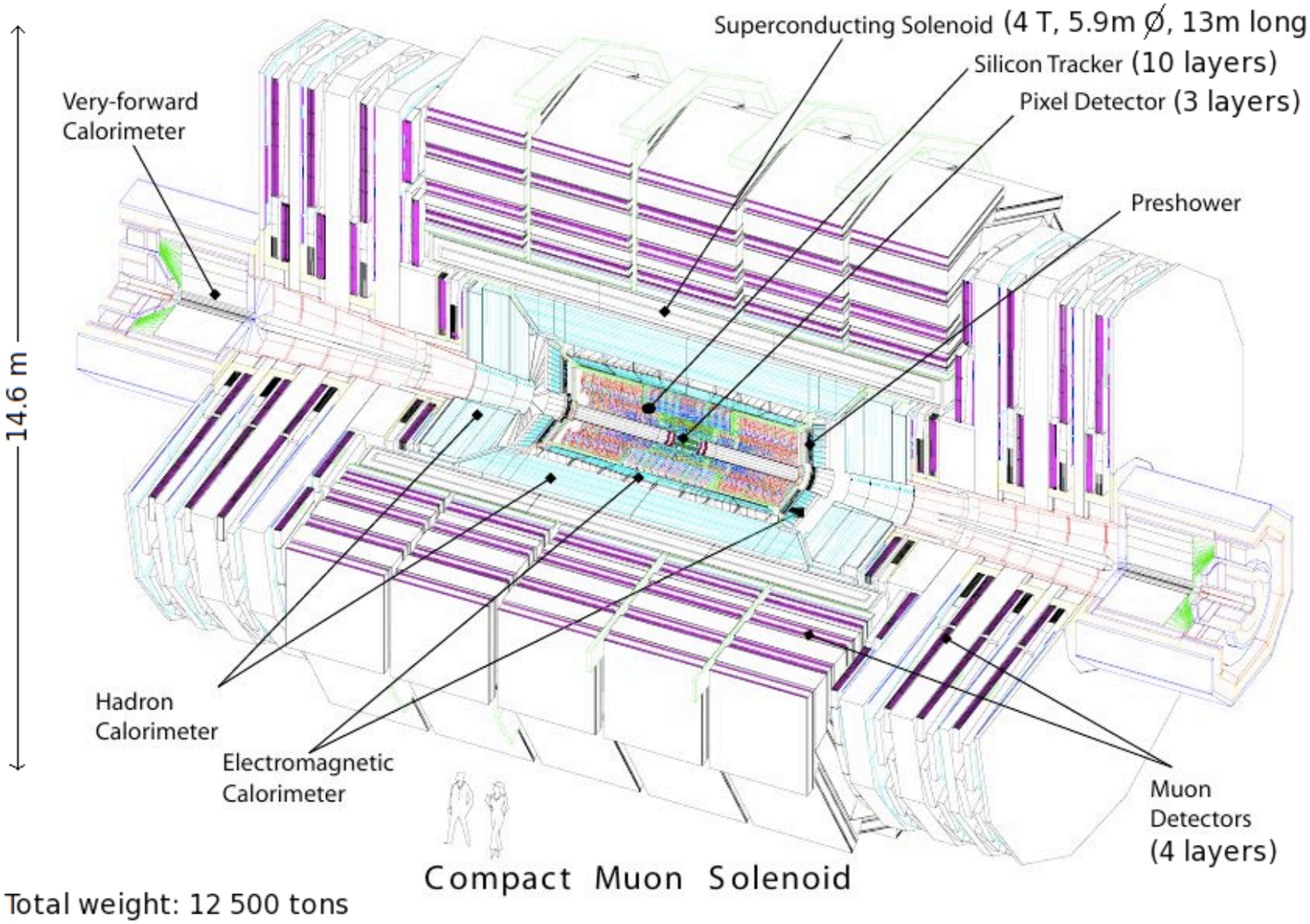
- Beam back late February
- pp collisions for ~200 days until mid-Nov
- Collide at $\sqrt{s}$ = 8 TeV

- Either option will give many more top events than ever to be delivered at the Tevatron
- Exciting times are up ahead

CMS Detector: 2008 JINST 3 S08004

CMS Detector

Excellent performance from first days of collisions



Tracker: $\sigma/p_T \simeq 1.5 \times 10^{-5} \times p_T \oplus 0.005$

Muon standalone @ 1 TeV: $\sigma/p_T \simeq 0.10$

Electromagnetic energy resolution

$$\frac{\sigma(E)}{E} = \frac{3\%}{\sqrt{E}} + 0.3\%$$

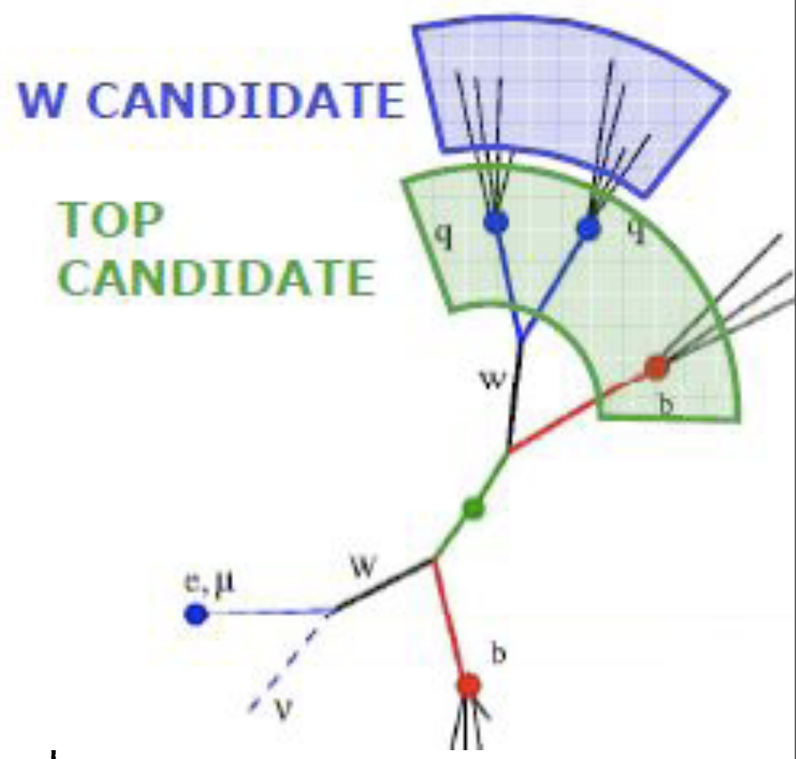
Hadronic energy resolution

$$\frac{\sigma(E)}{E} = \frac{100\%}{\sqrt{E}} + 5\%$$

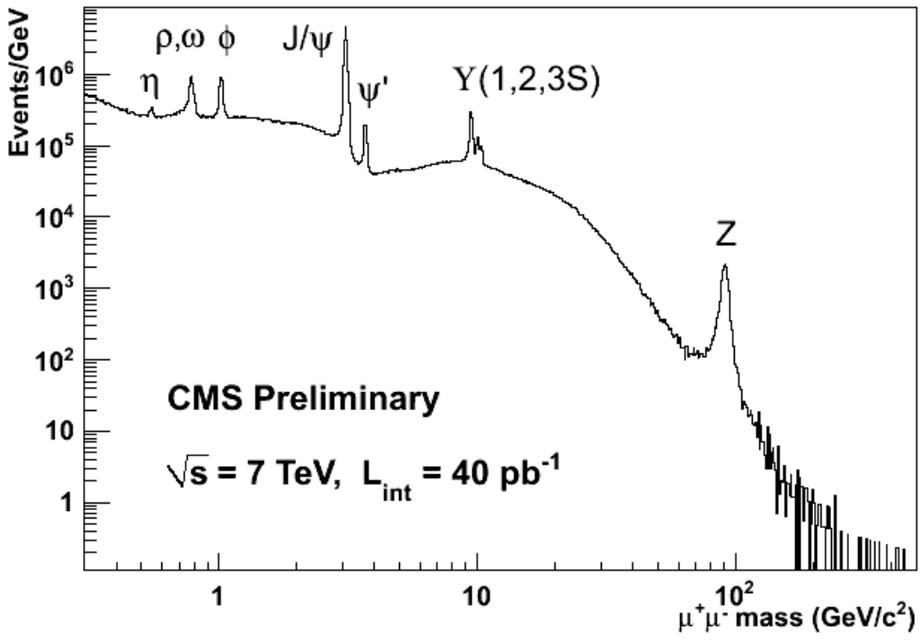
- Trigger system setup to reduce input rate of 40MHz down to 100-200 Hz
  - ✓ Hardware level-1 40MHz → 100 kHz followed by PC farm with near-final reconstruction resolution
  - ➡ No triggering on inner tracks at L1 (available only later)
  - ➡ Final trigger stage can select muons, electrons, photons, jets, MET, displaced vertices

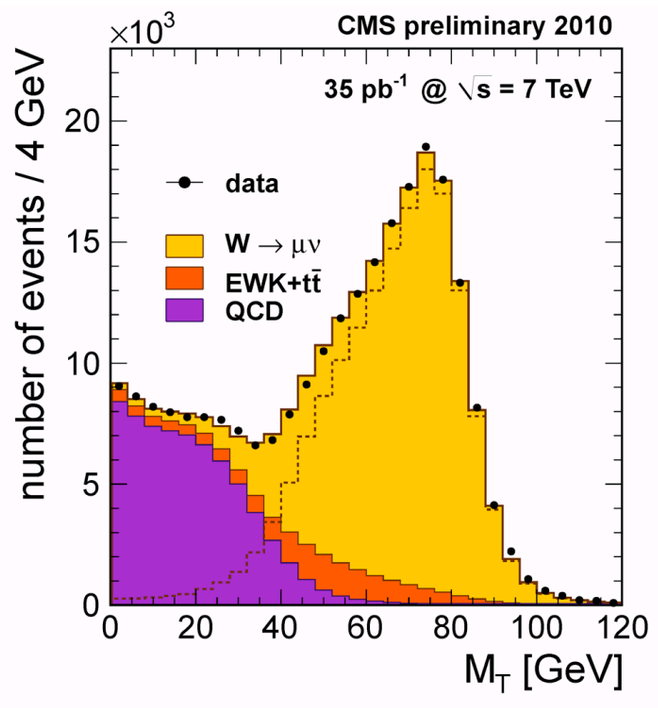
Ingredients for top physics

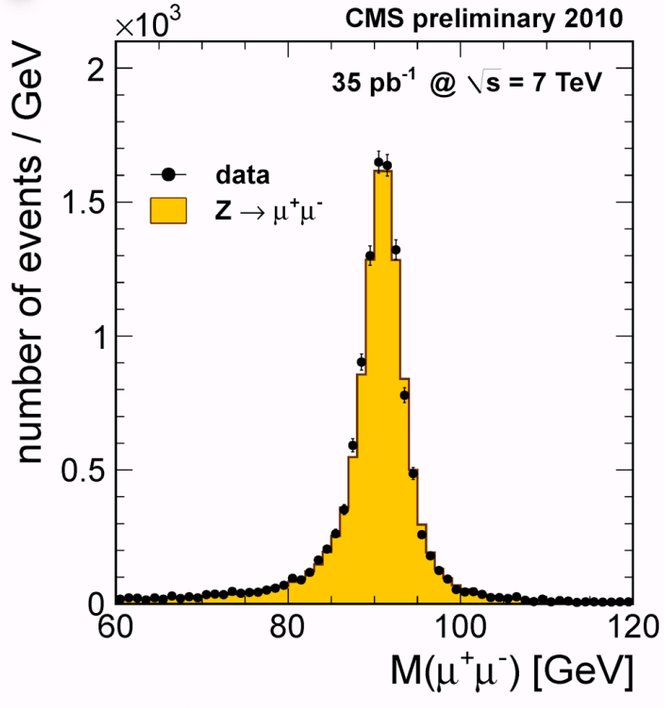
- Includes almost all objects
- Important to understand from data early
  - ➡ Lepton isolation, identification and mis-identification rate
    - ✓ electrons and muons
    - ✓ taus (not well covered here)
  - ➡ Jet resolution and response
  - ➡ Missing transverse energy (MET) resolution and response
  - ➡ b-jet tagging efficiency and mis-identification rate
- All ingredients can be confirmed in situ
  - ➡ Focus on data-driven methods to predict backgrounds, estimate efficiencies
- Combined understanding needed for top-quark physics
  → milestone in physics commissioning

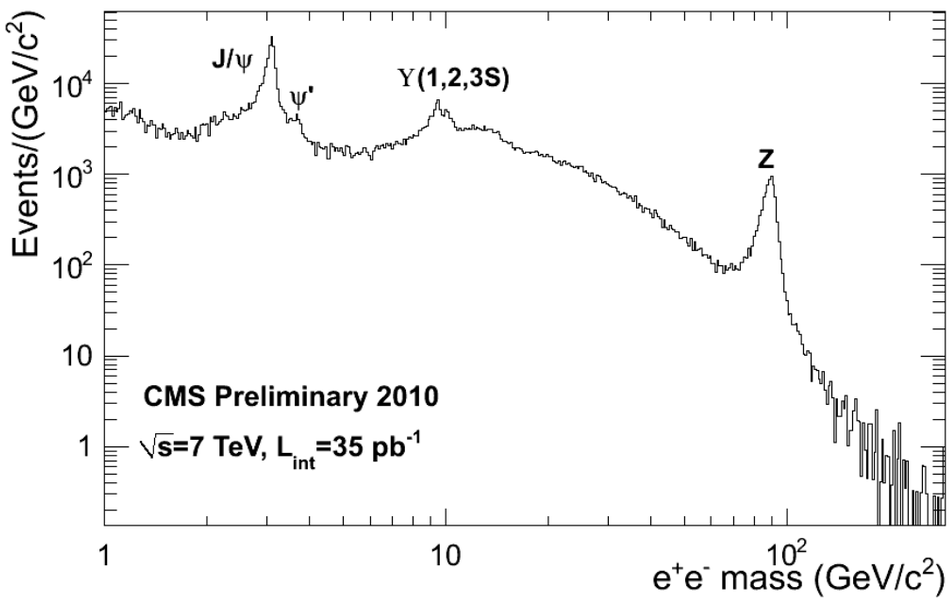


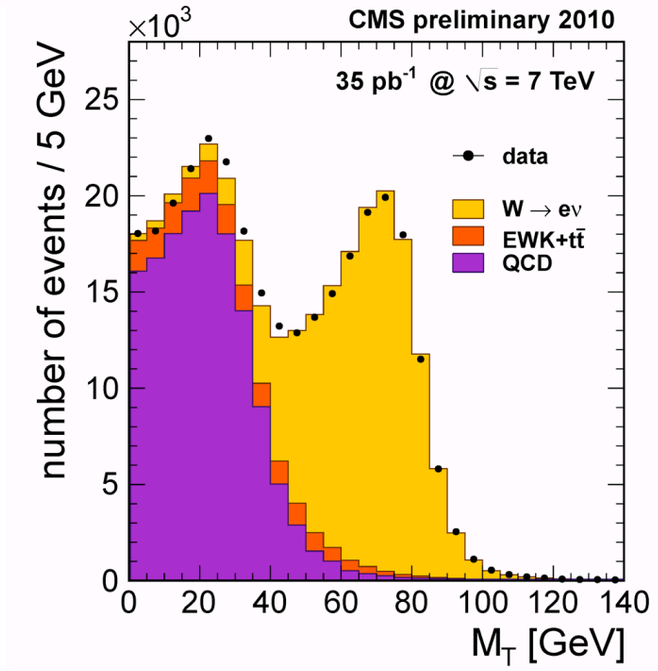
CMS performance: leptons

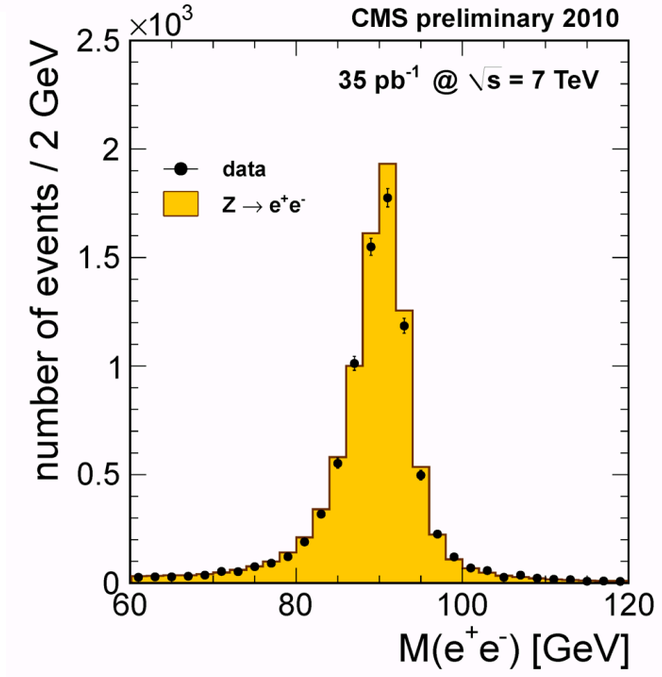








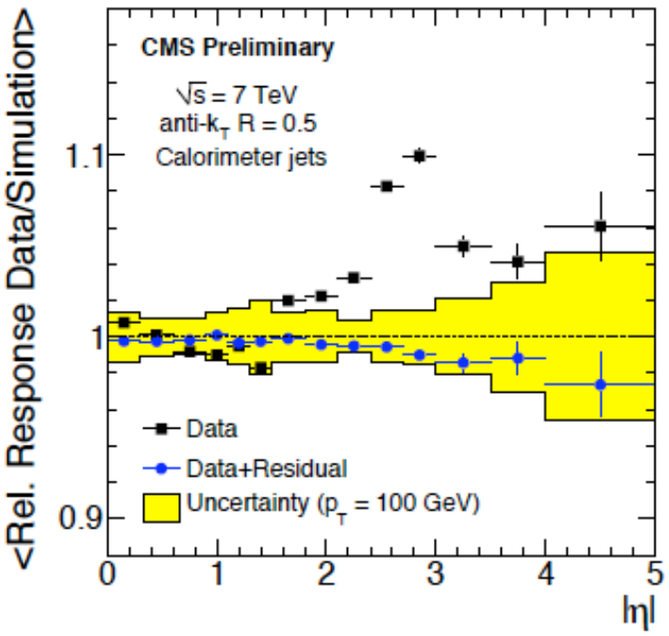


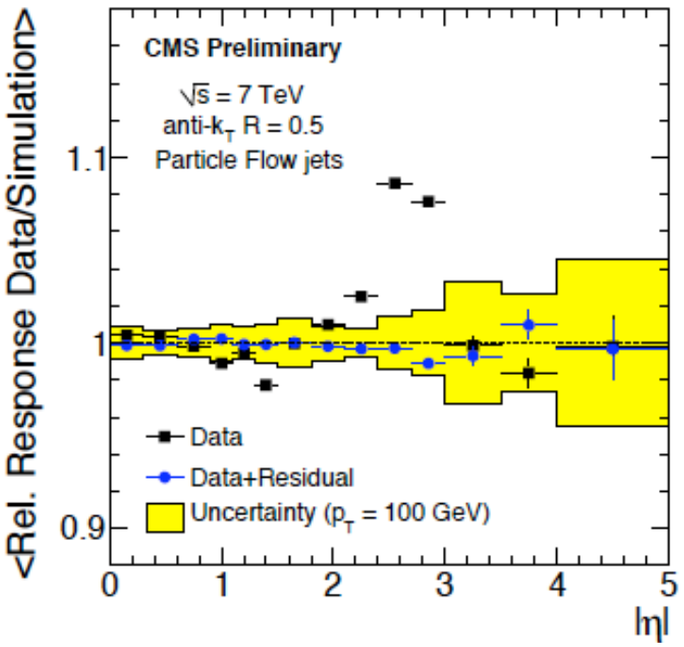


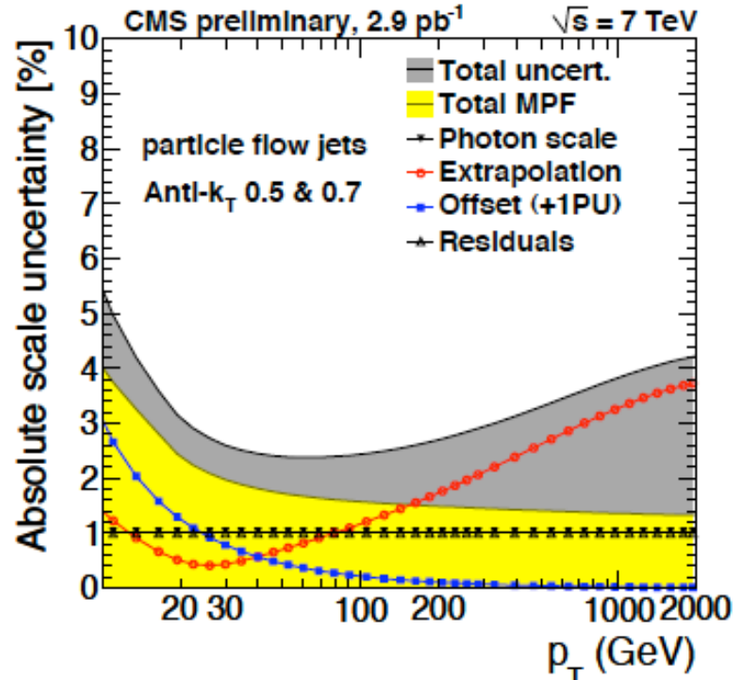
- Electron and muon performance matches expectations from simulation

CMS performance: jets and MET

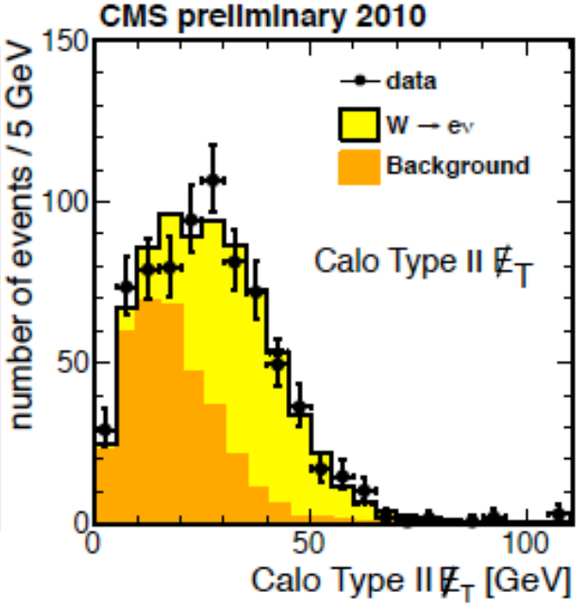
PAS JME-10-010

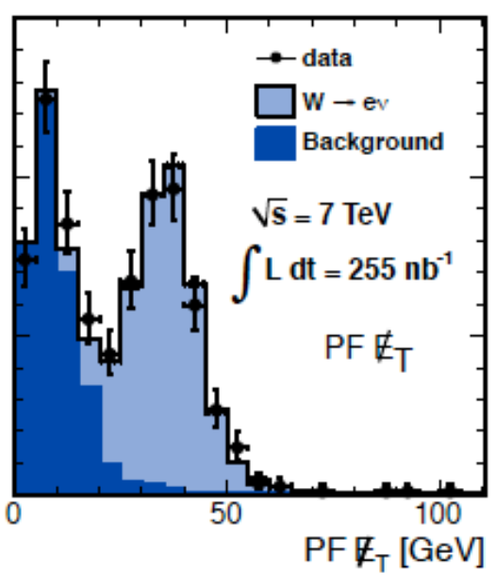


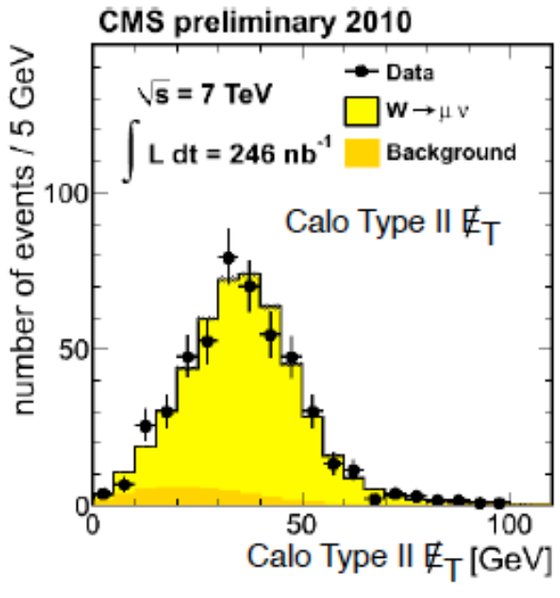


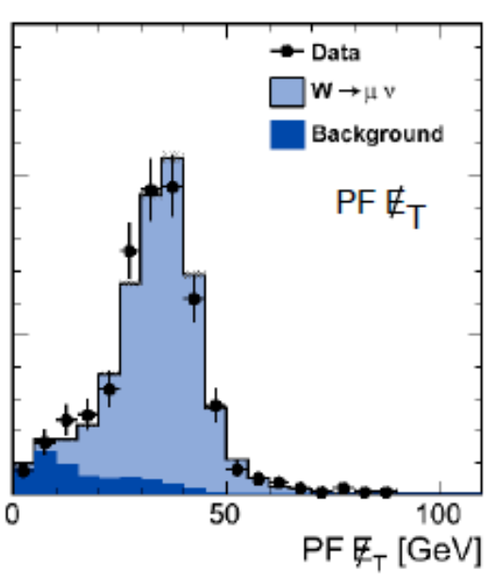


PAS JME-10-005





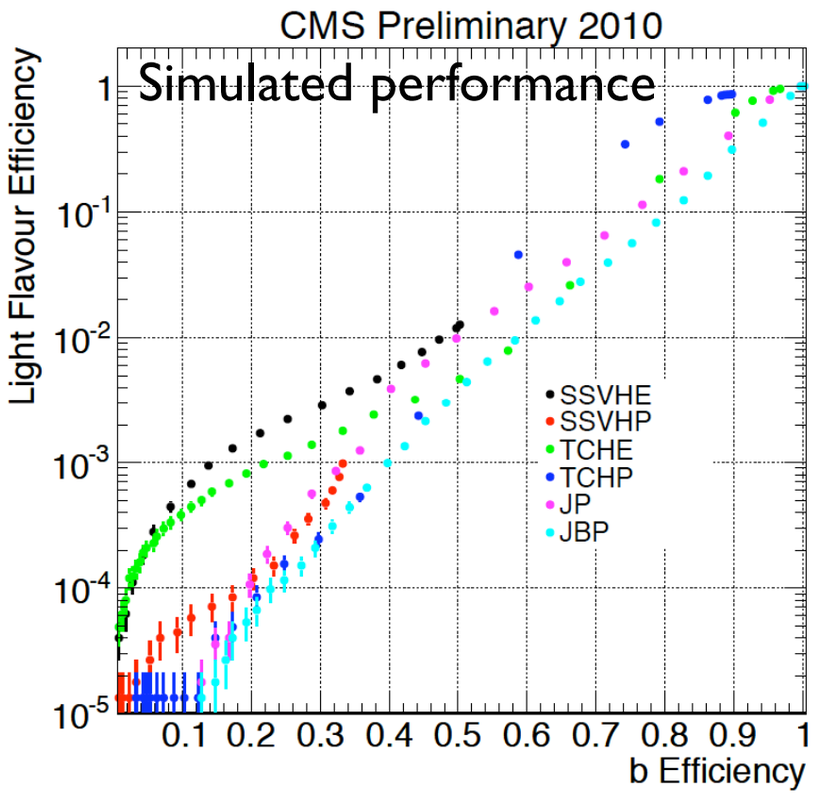


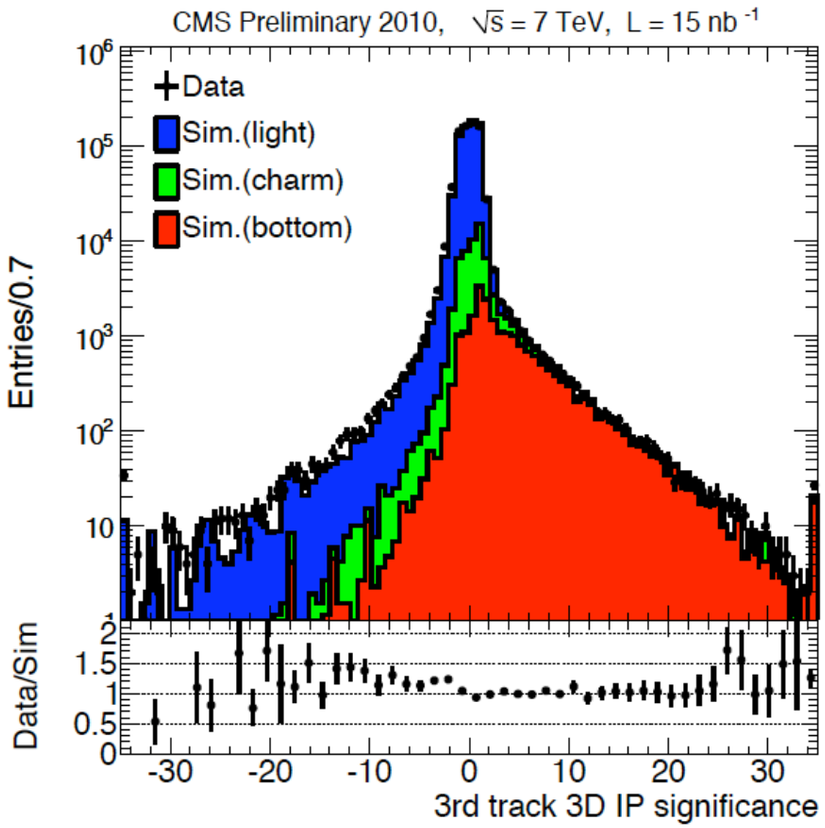


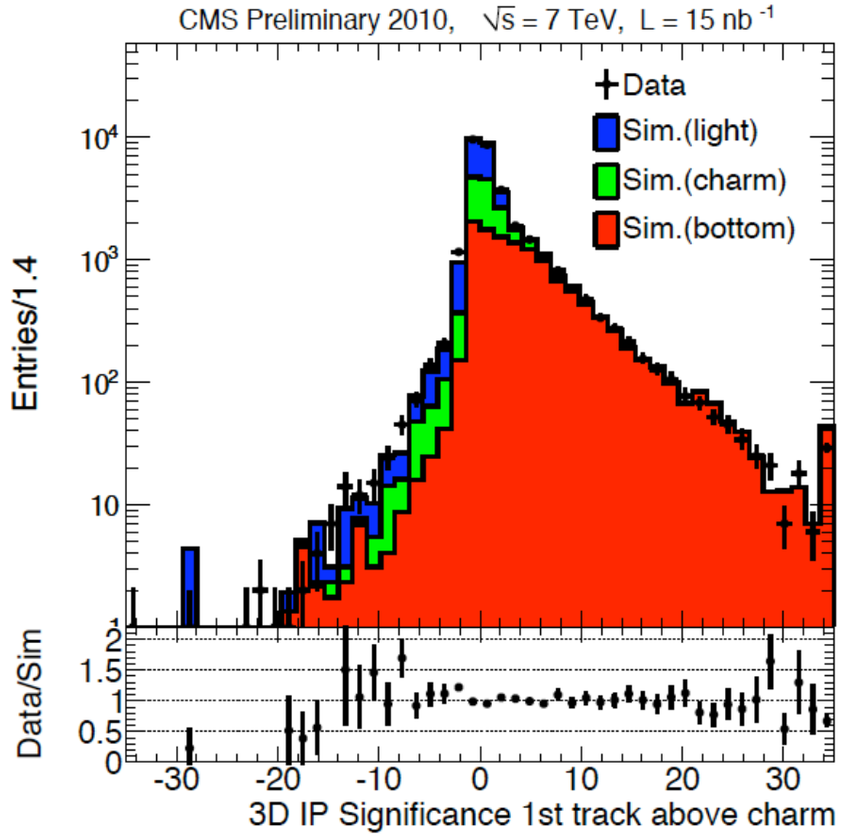
- Three algorithms: calorimeter only; corrected by tracks; particle flow
  - ✓ Best performance is from the particle flow algorithm
- Jet performance matches simulation very well
- Missing transverse energy (MET) has visible effects from extra pp collisions (pileup).

CMS performance: b-tagging

PAS BTV-10-001





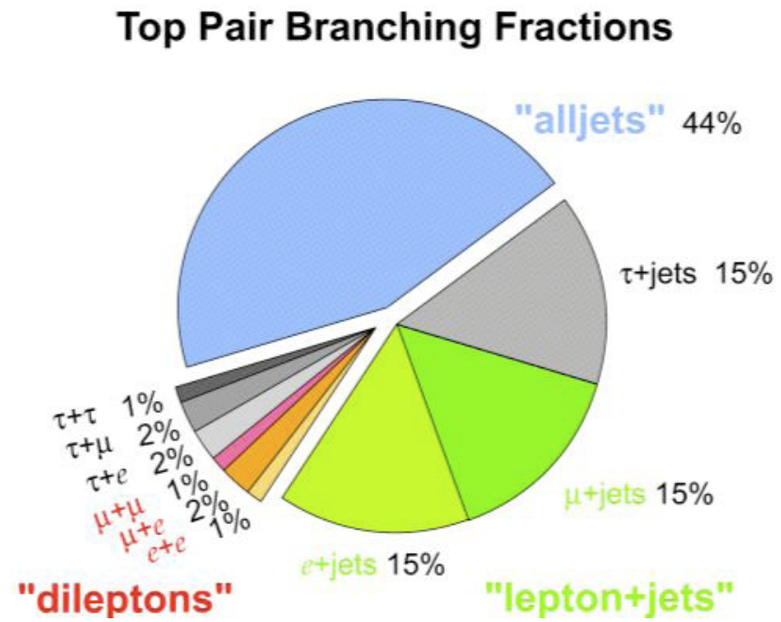


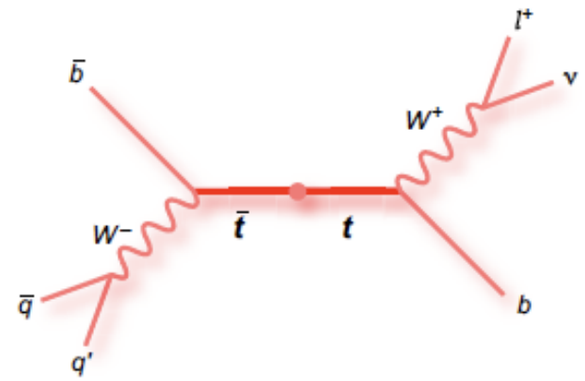
- Good performance from the start
- Taggers available in a range of efficiency:rejection performance points
  - ✓ Simple displaced track counting (TC***) — loose working point: $eff_b \approx 80\%$ at mistag 10%
  - ✓ Secondary vertex (SSV***)
  - ✓ jet-probability (JP***)

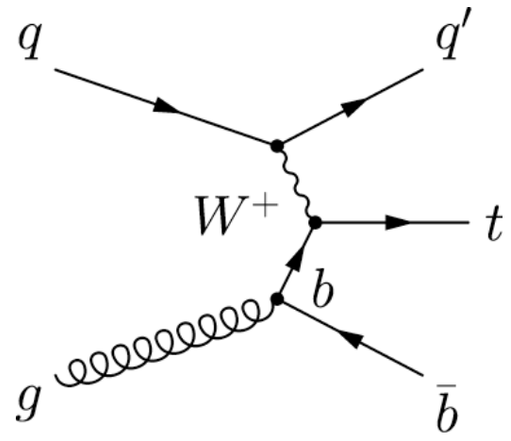
Top physics program (most for 2011)

- High cross section → LHC is a top factory
  - ✓ $\sigma_{t\bar{t}} \sim$ 0.8 nb (x100 of Tevatron) at 14TeV; 0.15 nb at 7TeV
- Top production is main background in many BSM searches
- Rediscovery of $t\bar{t}$ events
  - ✓ in di-lepton and one-lepton final states
- Inclusive and differential cross section
- Top quark resonances
- Top properties
  - ➡ mass, spin correlations in $t\bar{t}$
  - ➡ Rare decays
- Source of calibration measurements
  - ➡ Jet energy scale, b-tagging
- Single top production
  - ➡ s-channel, t-chanel, tW, V_{tb}

Only highlighted topics are covered in this talk







Top physics results

While CMS is preparing to release public results on a number of top quark related measurements with full dataset of 2010...

only top pair cross section in dileptons with 3 pb^{-1} (10% of 2010 data) is available now.

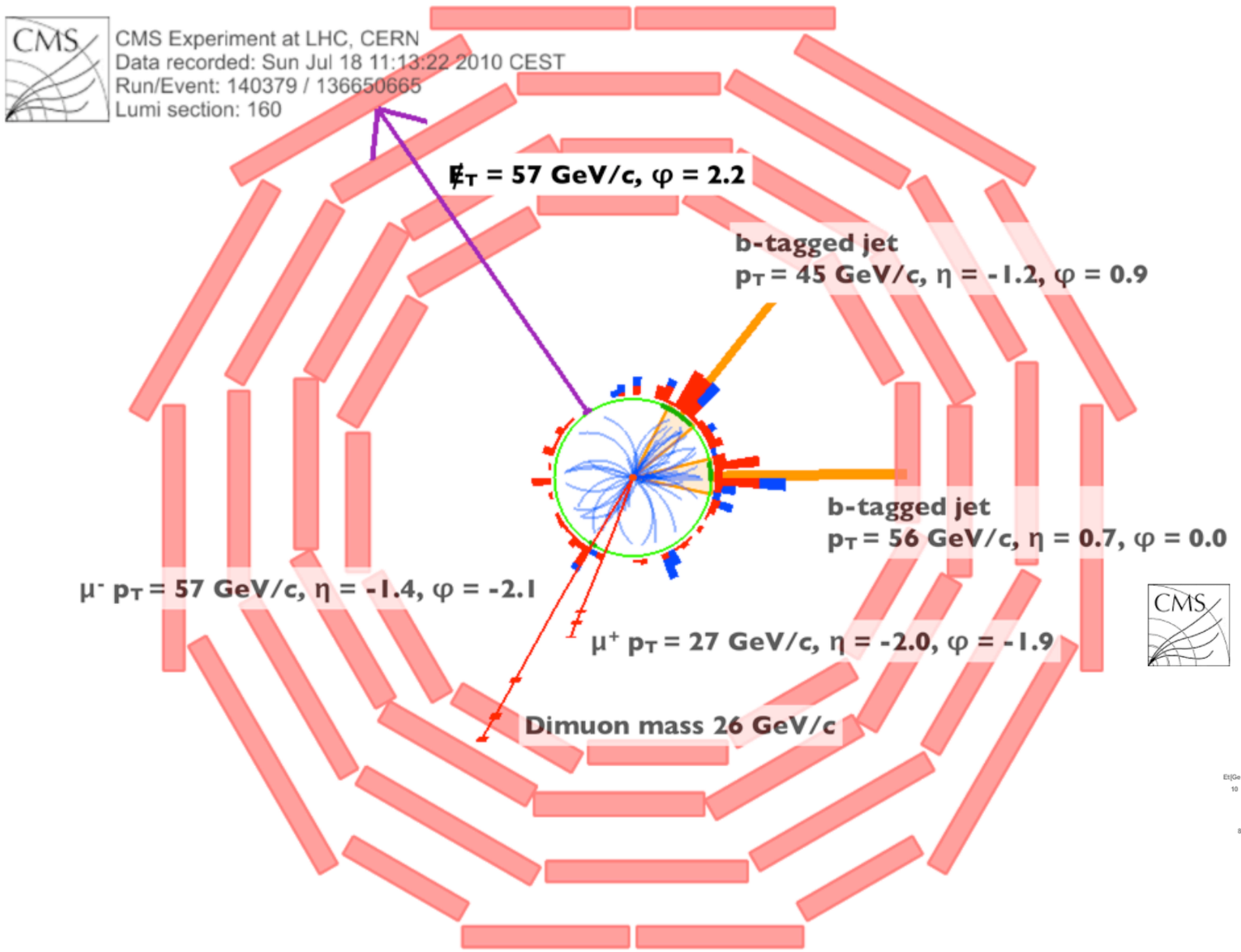
Performance plots will be shown in the following slides

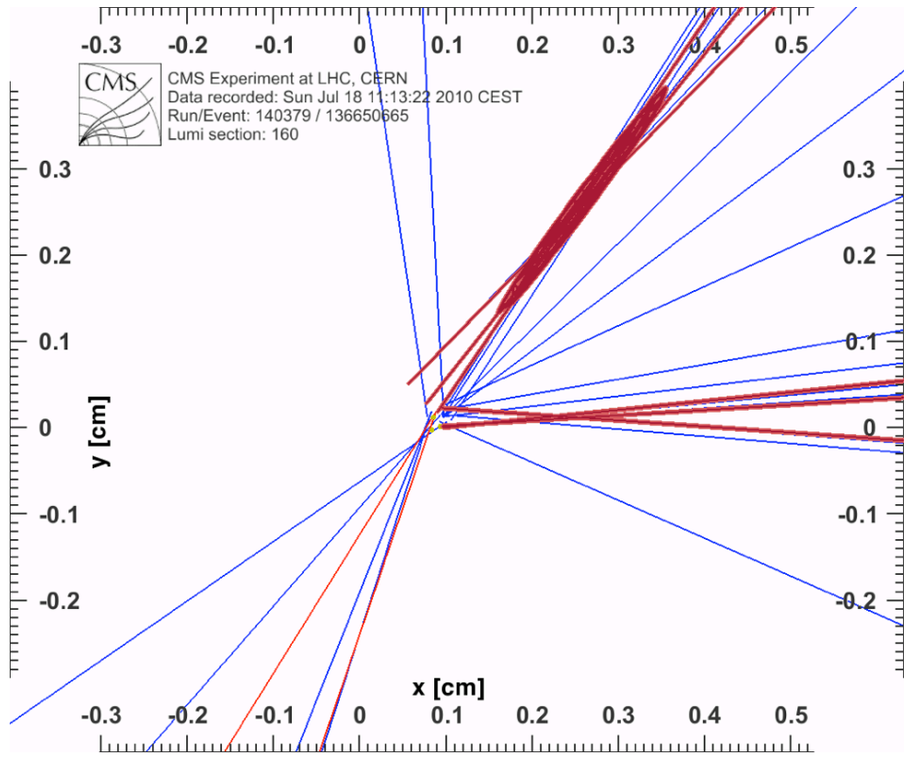
— ***based on early data***

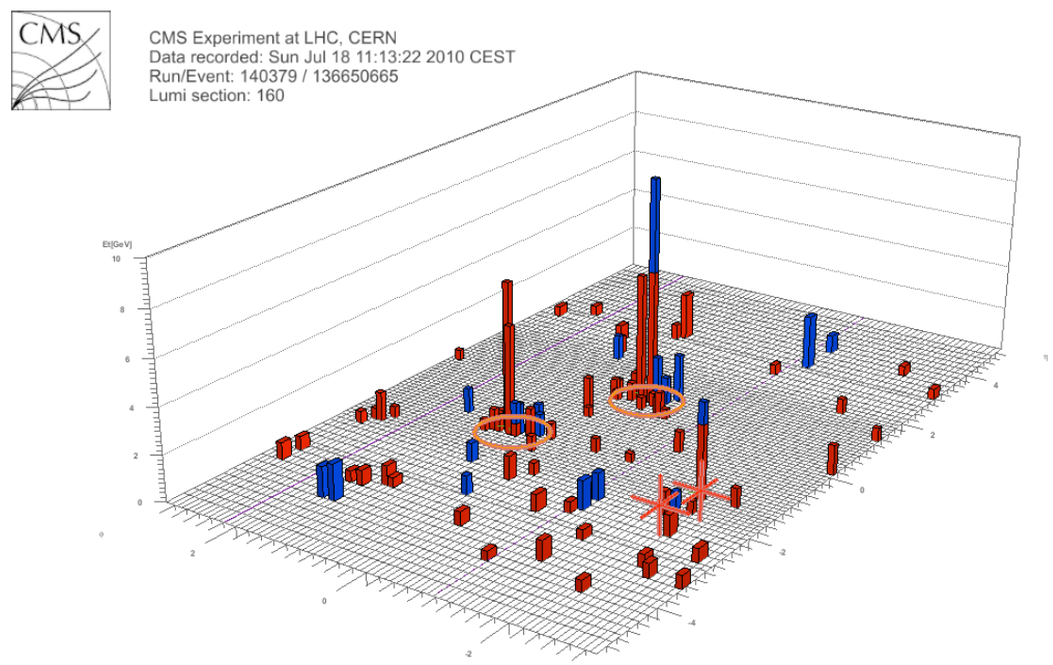
— ***based on earlier estimates in simulation***

note here that there are no new simulation-only results since 2009

First excitements: first events

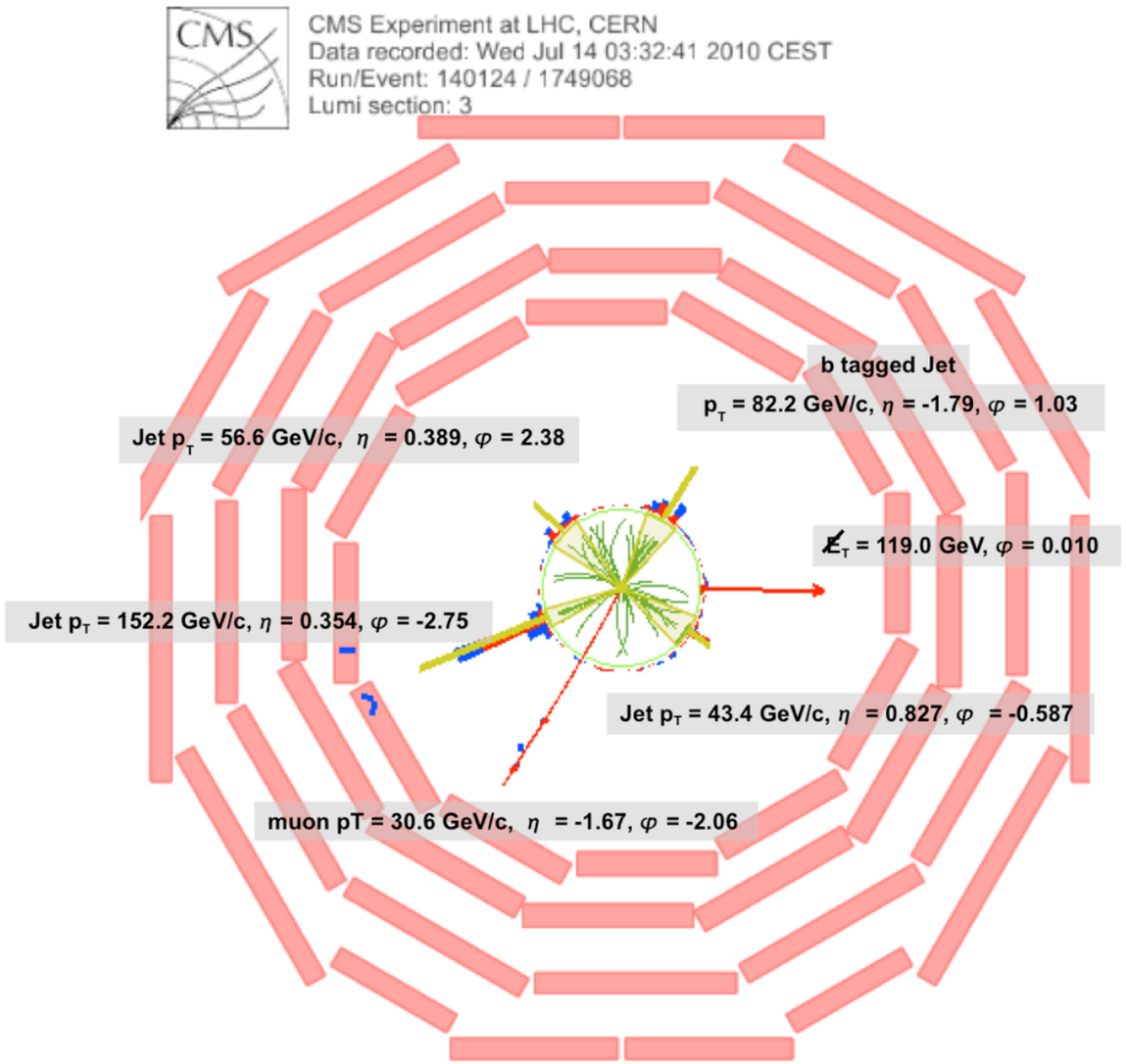


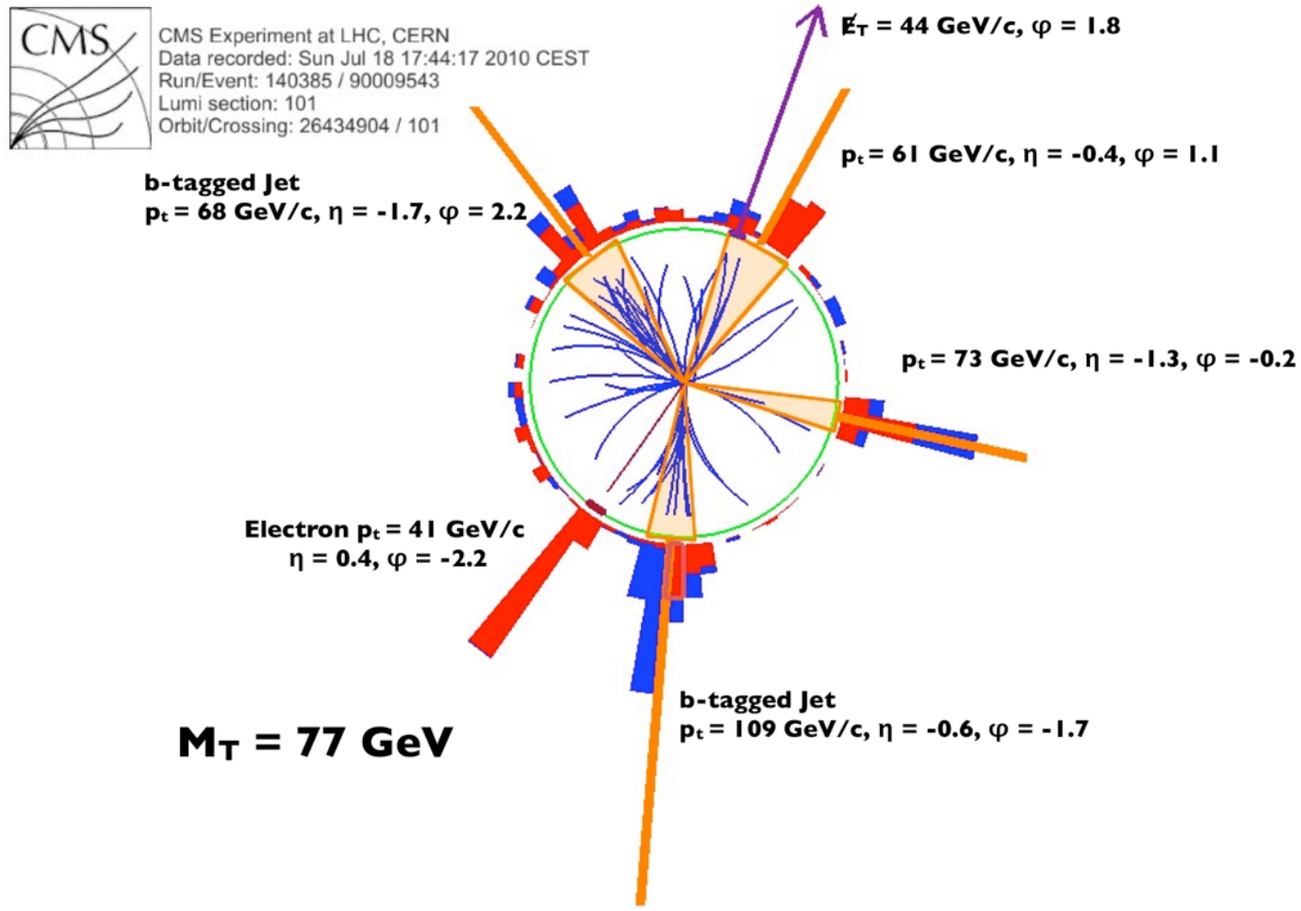




- Candidate dimuon event
- Also featured on BBC and other places

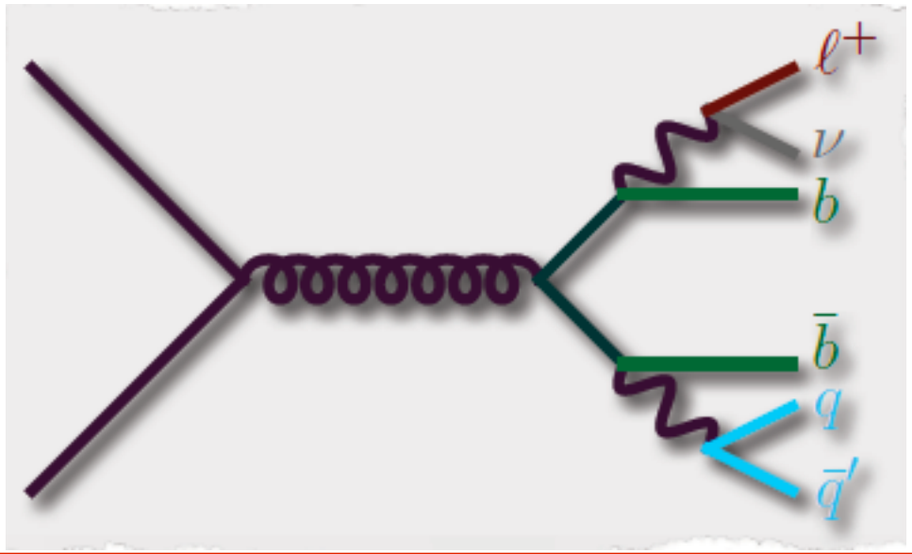
First excitements: first events





- Candidate mu+jets and e+jets events

Top pairs in lepton+jets



While CMS is preparing to release public results on a number of top quark related measurements with full dataset of 2010...

Performance plots will be shown in the following slides

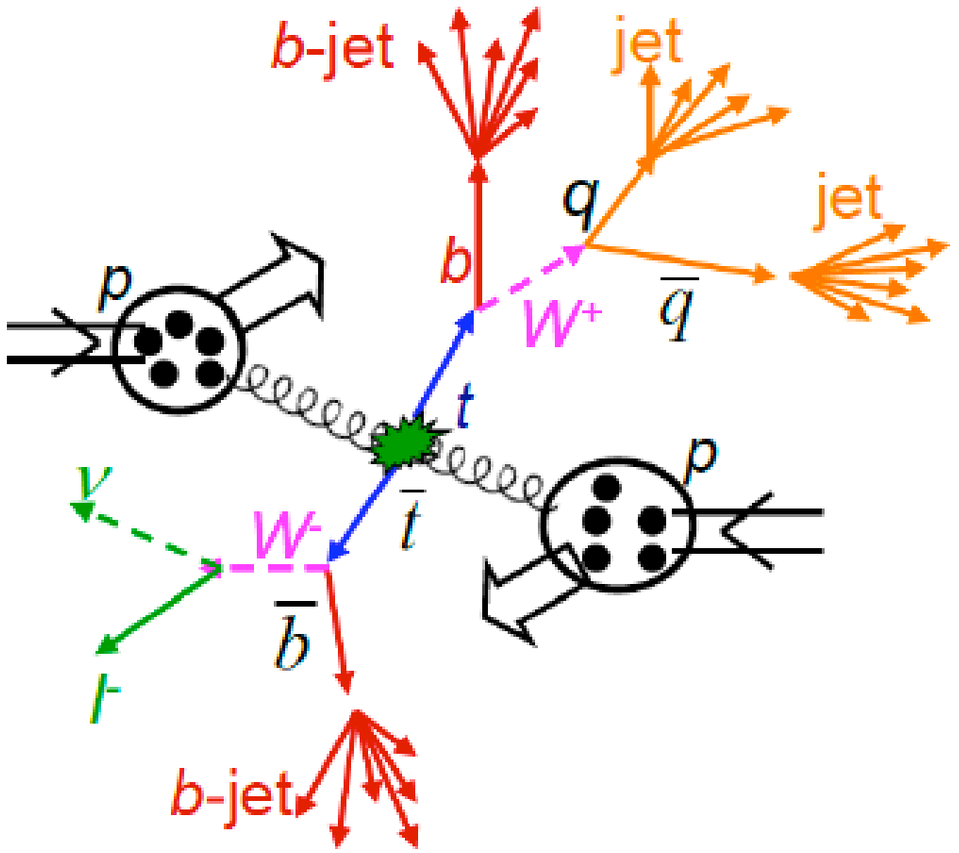
— ***based on early data PAS TOP-10-004 and update to it shown at HCP2010***

— ***see expected performance from simulation alone in these public documents***
PAS TOP-09-004 PAS TOP-09-003 PAS TOP-09-010

Note here that there are no new simulation-only results since 2009

Event selections

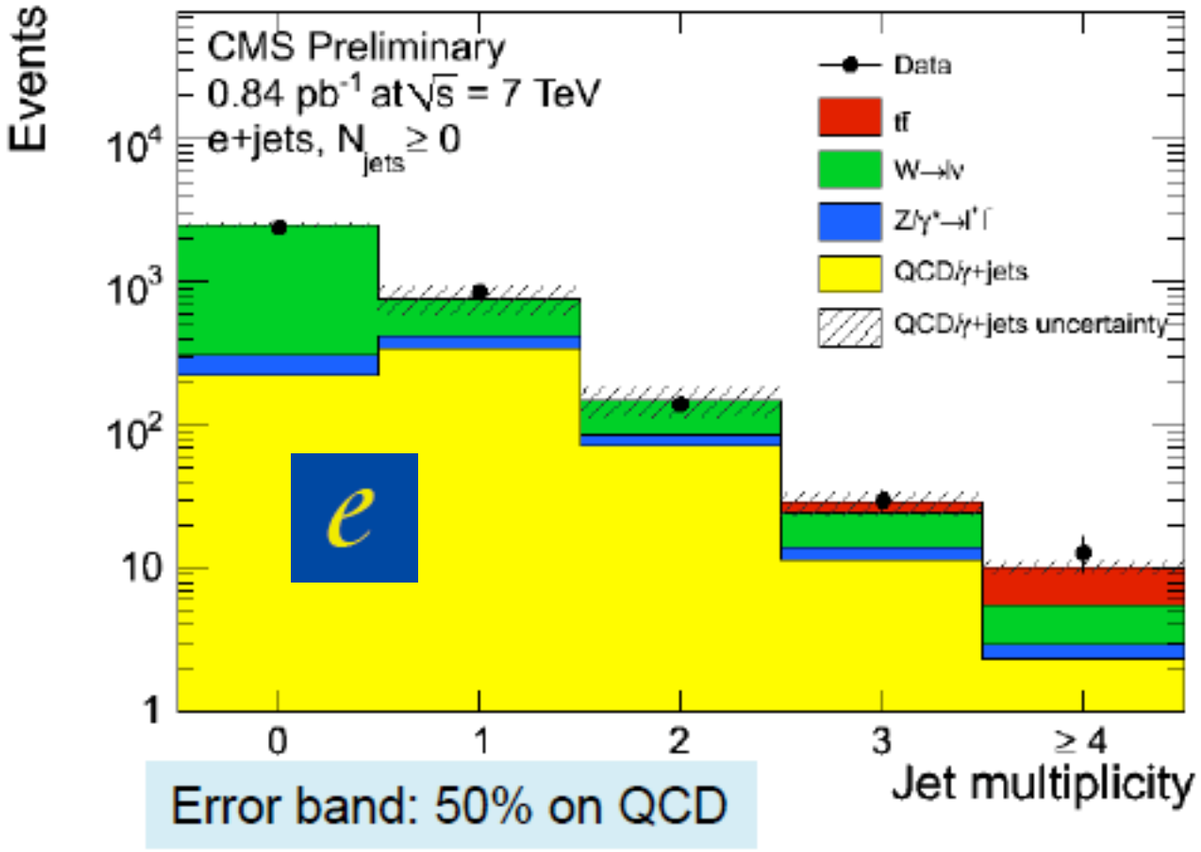
- Consider e+jets and μ+jets modes
- Selection
  - ➡ Online: use single lepton triggers
  - ➡ Offline:
    - ✓ **Exactly one isolated and identified lepton**
      - Muon pt> 20 GeV
      - Electron pt>30 GeV
    - ✓ **Jets (anti-kT 0.5) pt>30 GeV letal<2.4**
      - $t\bar{t}$ becomes significant with ≥ 3 jets
    - ✓ **Missing energy is not used directly**
      - Use to reconstruct transverse mass or other quantities used to choose the event or a correct jet combination



Electron+jets in 0.84 pb^{-1}

No b-tagging

Jet multiplicity	ttbar	single top	W+jets	Z+jets	QCD	Sum MC	Data
$N_{jets} \geq 0$	12 ± 2	3.4 ± 0.4	2619 ± 317	180 ± 21	658 ± 73	3472 ± 326	3434
$N_{jets} \geq 1$	12 ± 2	3.1 ± 0.4	419 ± 77	92 ± 11	436 ± 62	962 ± 99	1022
$N_{jets} \geq 2$	11 ± 2	1.9 ± 0.3	74 ± 18	19 ± 5	85 ± 22	191 ± 29	183
$N_{jets} \geq 3$	8.9 ± 1.8	0.70 ± 0.14	13 ± 4	3.3 ± 1.0	14 ± 5	40 ± 7	43
$N_{jets} \geq 4$	4.8 ± 1.2	0.21 ± 0.06	2.6 ± 1.1	0.60 ± 0.23	2.3 ± 1.1	11 ± 2	13



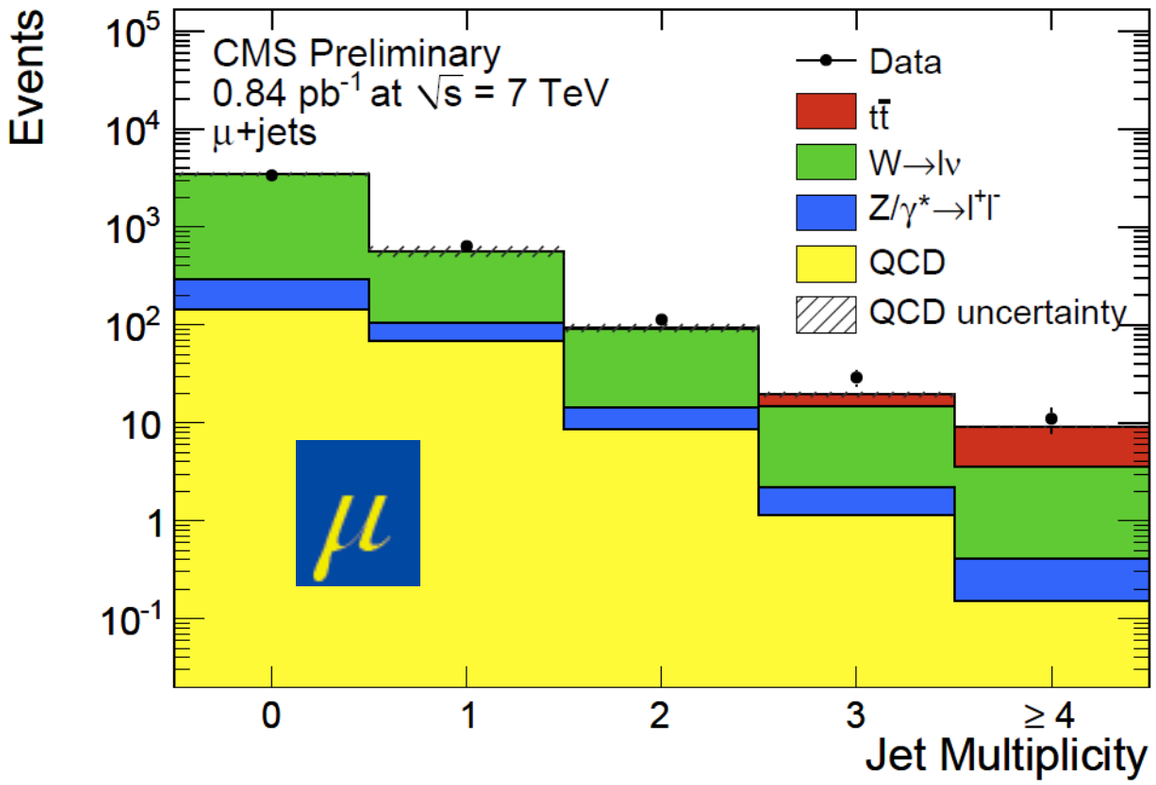
- MC Uncertainties (table):
  - ✓ Jet energy scale (10% uncertainty)
  - ✓ Luminosity (known to 11%)
  - ✓ Cross section unc. (scale,PDF)

- … result presented at HCP 2010 in Toronto

Muon+jets in 0.84 pb^{-1}

No b-tagging

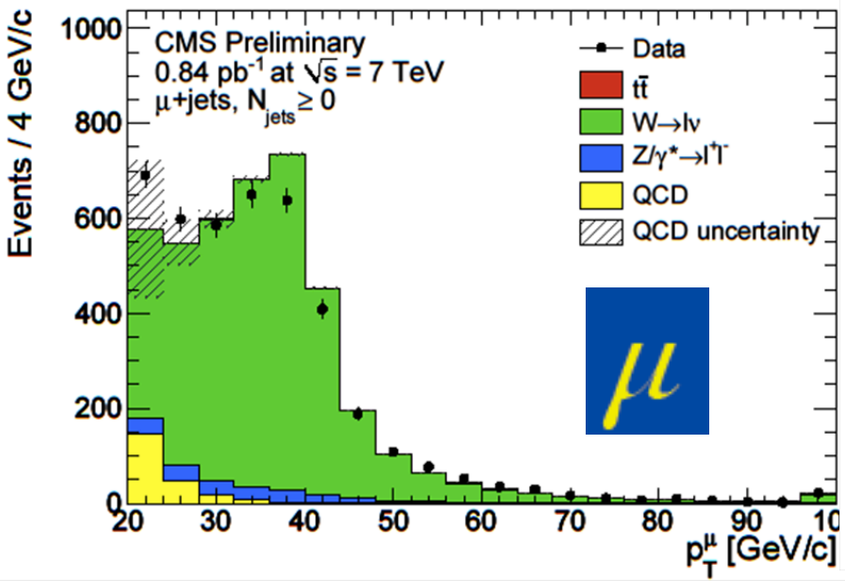
Jet multiplicity	ttbar	single top	W+jets	Z+jets	QCD	Sum MC	Data
$N_{jets} \geq 0$	13 ± 3	4.2 ± 0.4	3708 ± 448	192 ± 29	223 ± 25	4140 ± 450	4142
$N_{jets} \geq 1$	13 ± 3	3.9 ± 0.4	552 ± 106	42 ± 12	79 ± 17	690 ± 108	789
$N_{jets} \geq 2$	13 ± 2	2.3 ± 0.3	92 ± 24	7.1 ± 4.4	10 ± 3	124 ± 25	153
$N_{jets} \geq 3$	10 ± 2	0.82 ± 0.15	16 ± 5	1.3 ± 0.9	1.3 ± 0.5	29 ± 5	40
$N_{jets} \geq 4$	5.6 ± 1.4	0.24 ± 0.06	3.1 ± 1.2	0.25 ± 0.18	0.15 ± 0.07	9.3 ±1.9	11

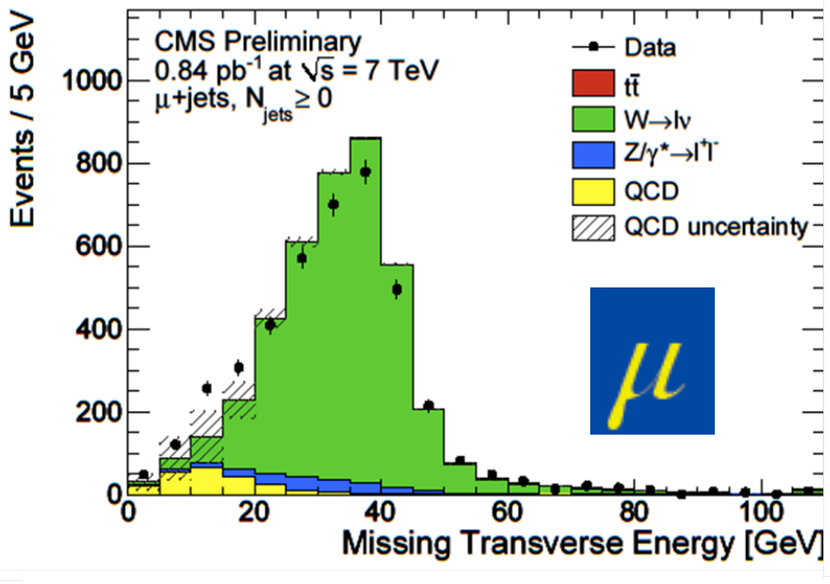


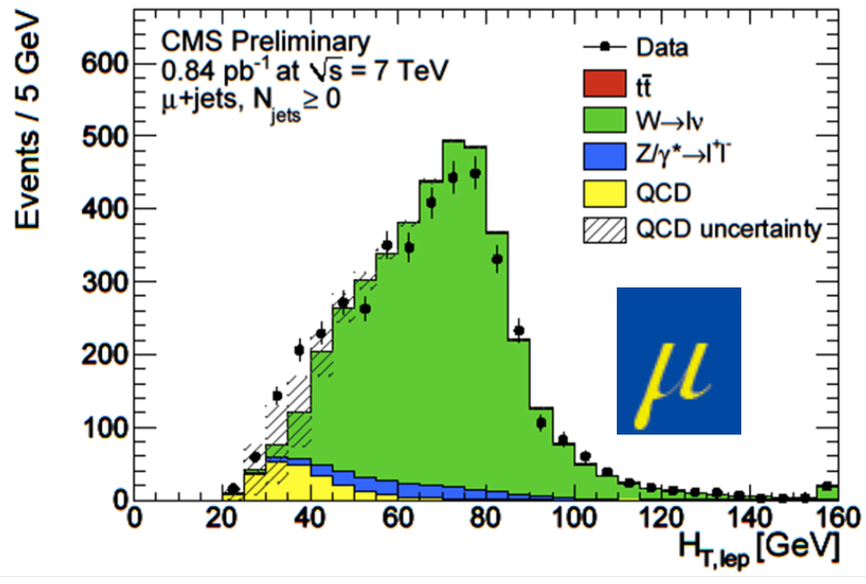
- MC Uncertainties (table):
  - ✓ Jet energy scale (10% uncertainty)
  - ✓ Luminosity (known to 11%)
  - ✓ Cross section unc. (scale,PDF)

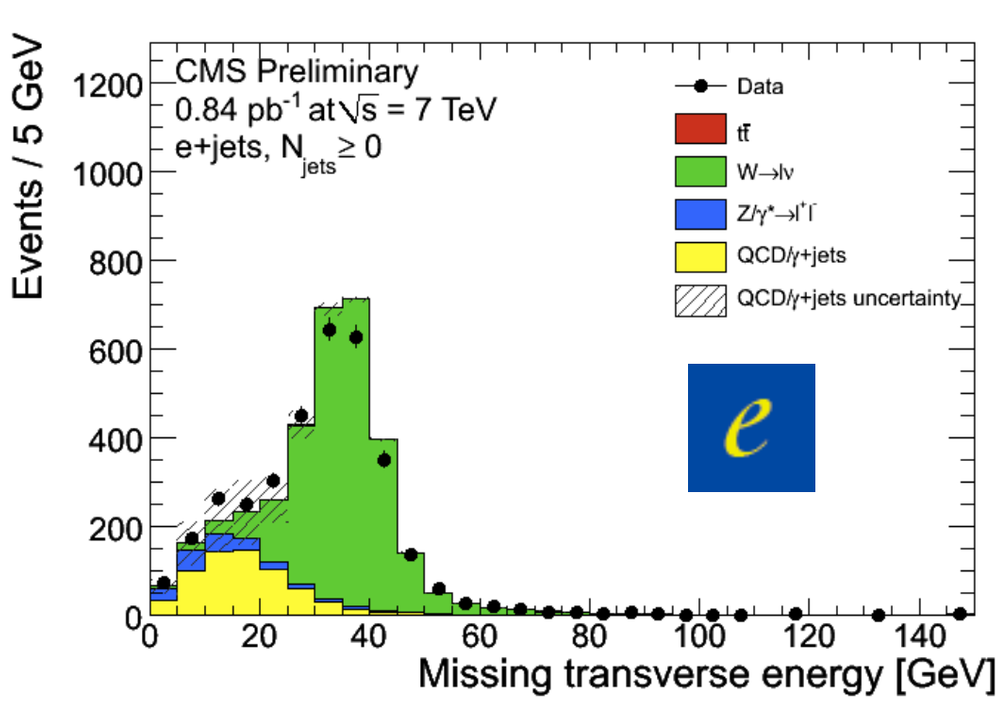
- … result presented at HCP 2010 in Toronto

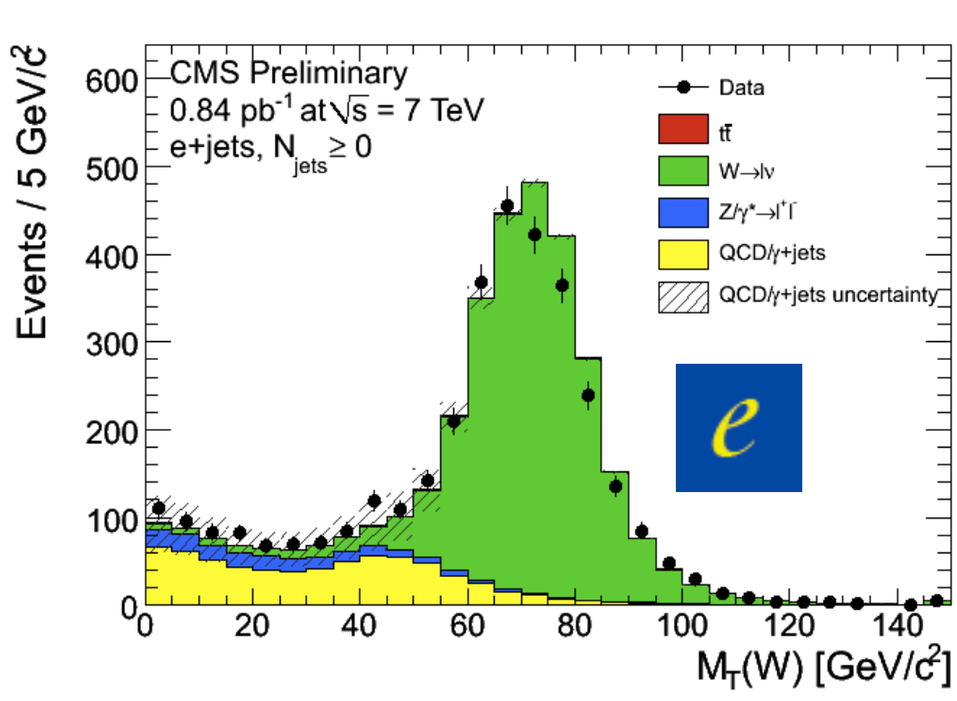
Differential distributions: ≥0 jets





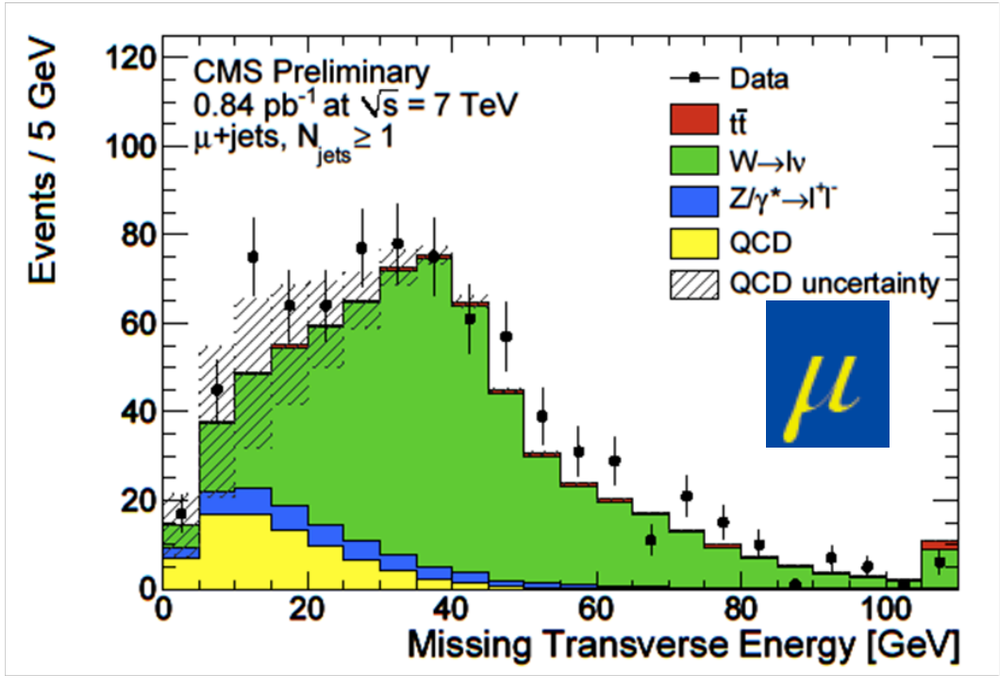


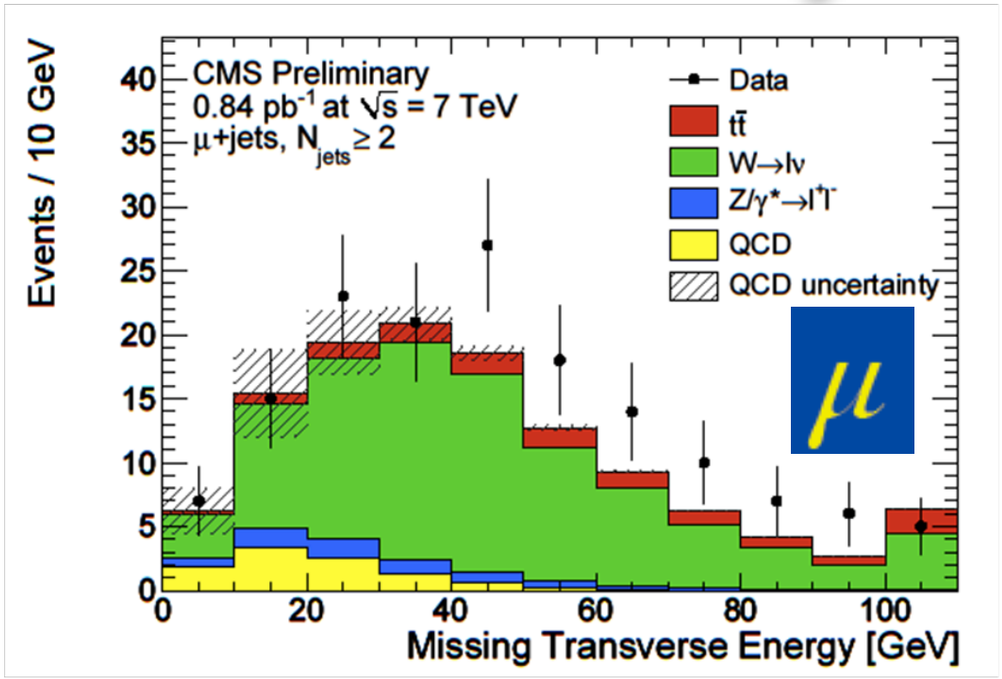


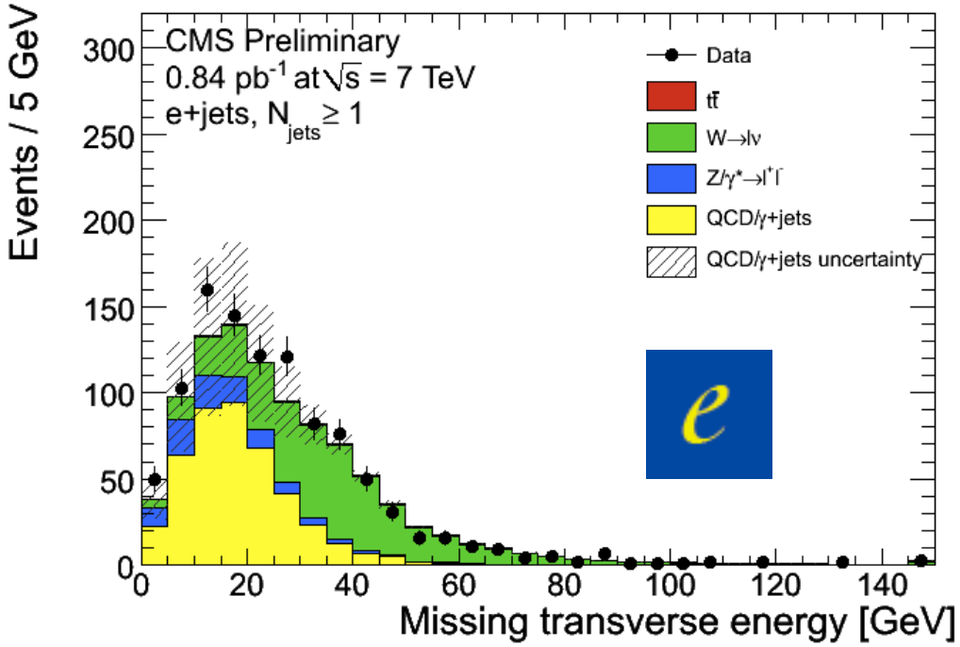


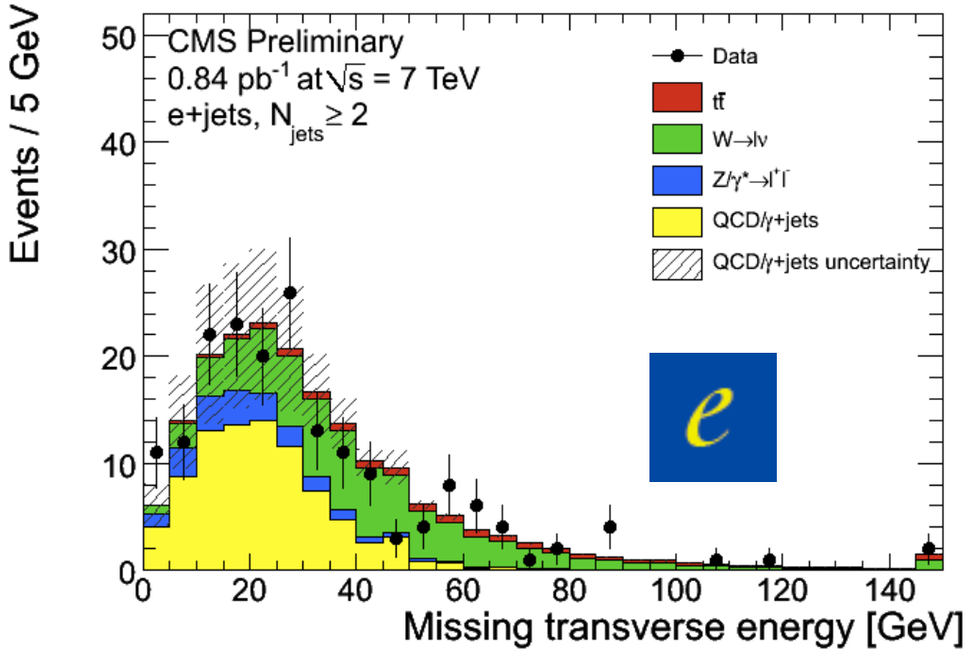
- Muons: excess at low values consistent with QCD x2 low in simulation
- Electrons: simulation predicts observed values well

Differential distributions: ≥ 1 jets





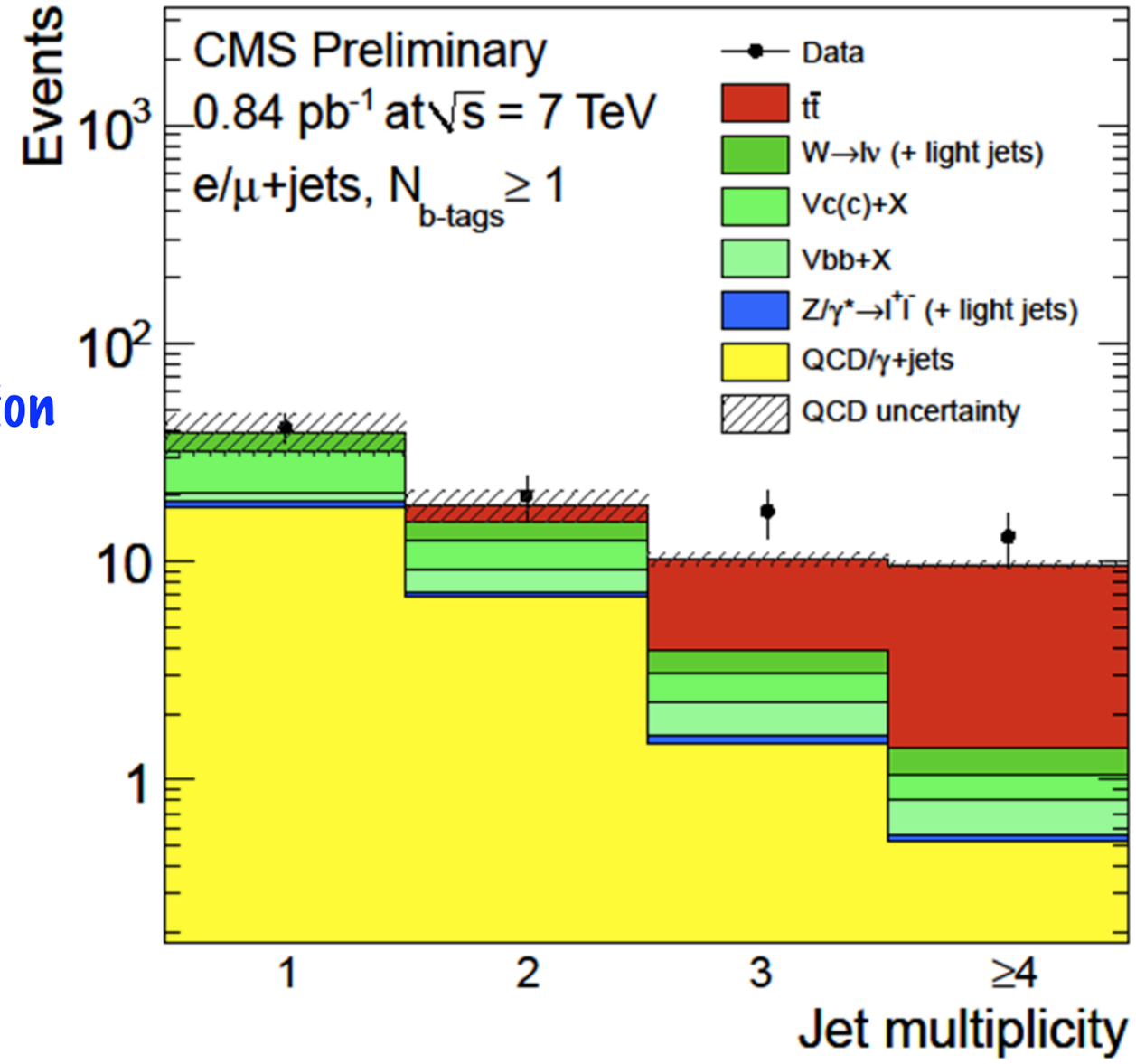




- Muons: excess at low values consistent with QCD x2 low in simulation
- Electrons: simulation predicts observed values well

Events with a b-tagged jet

- Combine e/μ+jets
- Apply secondary vertex tagger
  - ✓ Only 1% mis-tagging rate
- In events with ≥3 jets
  - ✓ Observe 30 events in data
  - ✓ Expect 5.3 events backgrounds (simulation only!)
  - ✓ Expected 15 events from signal
- $t\bar{t}$ events appear at a rate roughly consistent with NLO cross section
  - ✓ experimental (JES,b-tagging) and theoretical (scale, PDF, HF modelling, ...) uncertainties are not included
    - Observed counts are only 1.5 σ above expectations



Physics Letters B 695 (2011) 424–443

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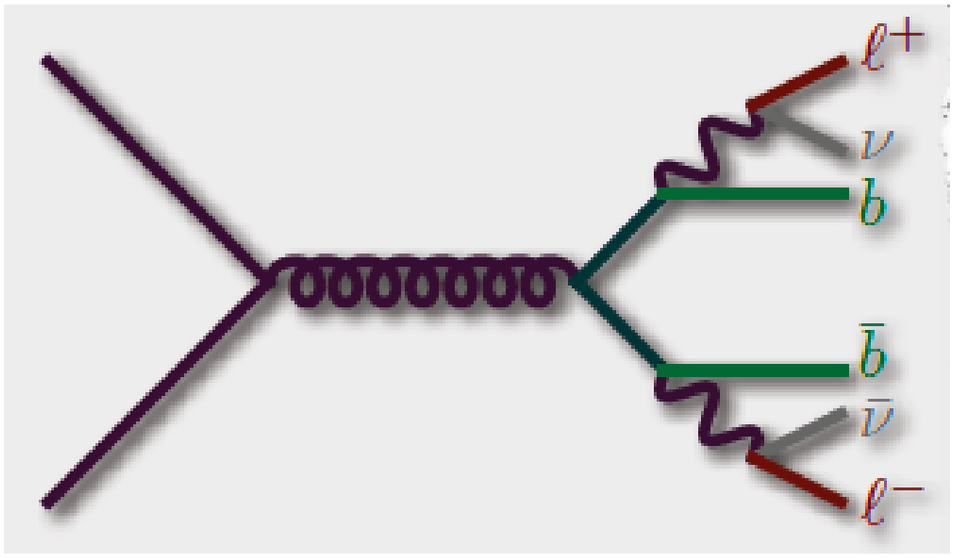
Phys. Lett. B 695 (2011) 424-443

First measurement of the cross section for top-quark pair production in proton–proton collisions at $\sqrt{s} = 7$ TeV ☆



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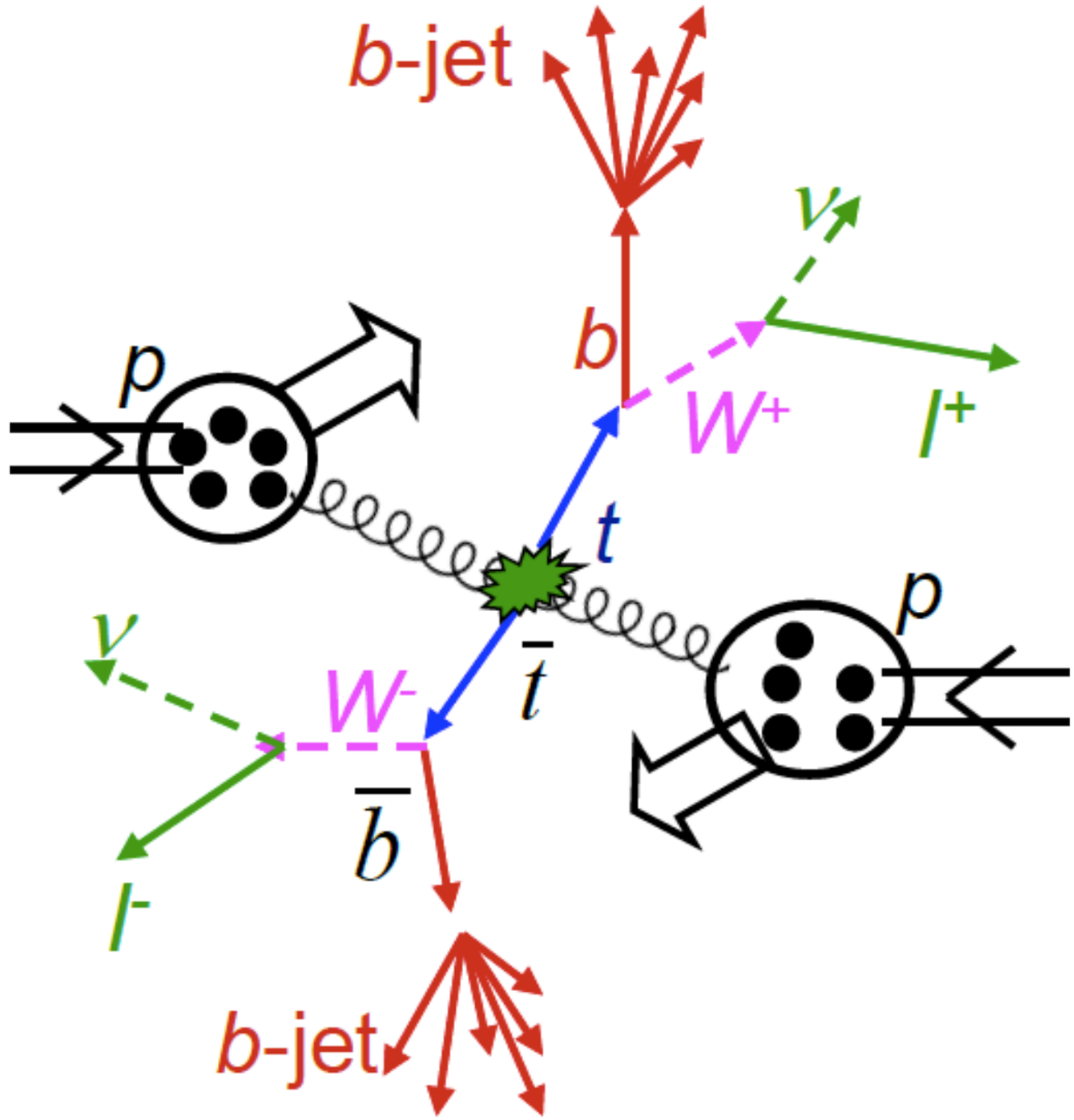
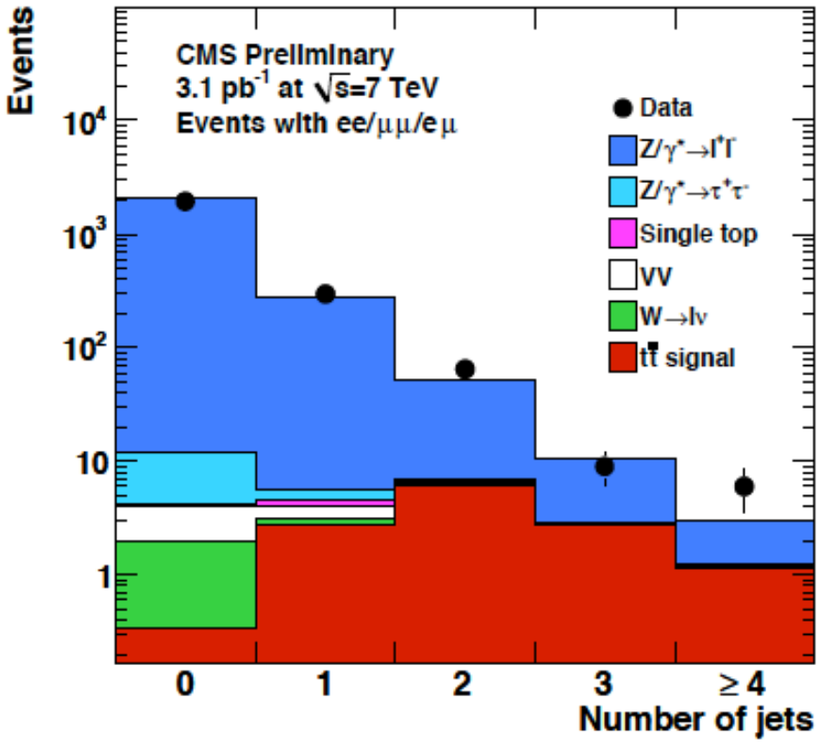
Analysis features and selections

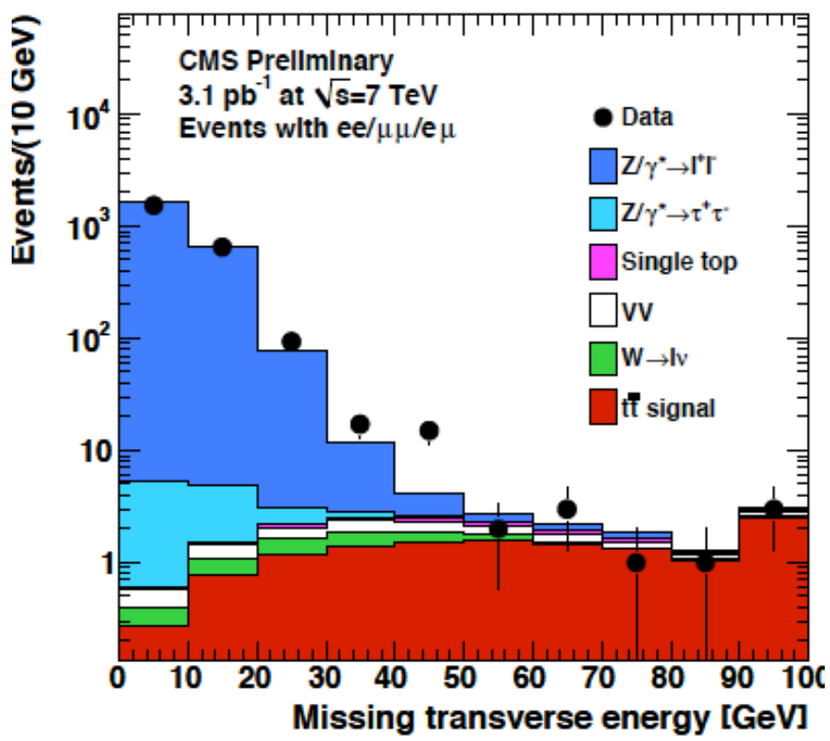
- Using 3 pb^{-1} data sample
  - ✓ Expect ~10 events signal
- Dilepton features:
  - ✓ less frequent but easy to see
  - ✓ Clean final states, eμ the cleanest
- Cut and count method
- Selection
  - ➡ Online: Single e OR μ trigger
  - ➡ Offline
    - ✓ Two opposite-charge leptons p_T>20 GeV
    - ✓ Lepton isolation
    - ✓ Two or more jets (anti-Kt 0.5) with p_T>30 GeV
    - ✓ MET > 30(20) GeV ee,μμ (eμ)
    - ✓ Veto $M_{dilepton}$ near Z in ee,μμ: |Mass-91| > 15GeV
- Backgrounds
  - ➡ Non-W/Z e/μ from j→ l rate in QCD dijets
    - ✓ "jet→ e/μ": Includes fakes and b/c->e/μ
  - ➡ DY in ee/μμ normalized to events near Z
  - ➡ MC for the rest: dibosons, tW, DY→ ττ

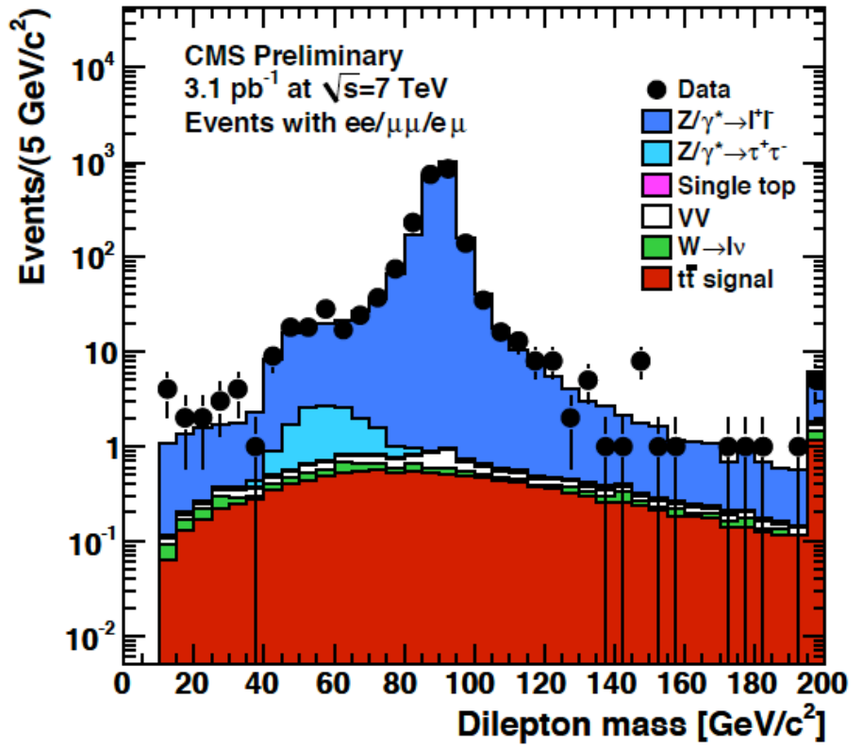


Background check: loose selection

Require only two opp-sign leptons passing ID and Isolation



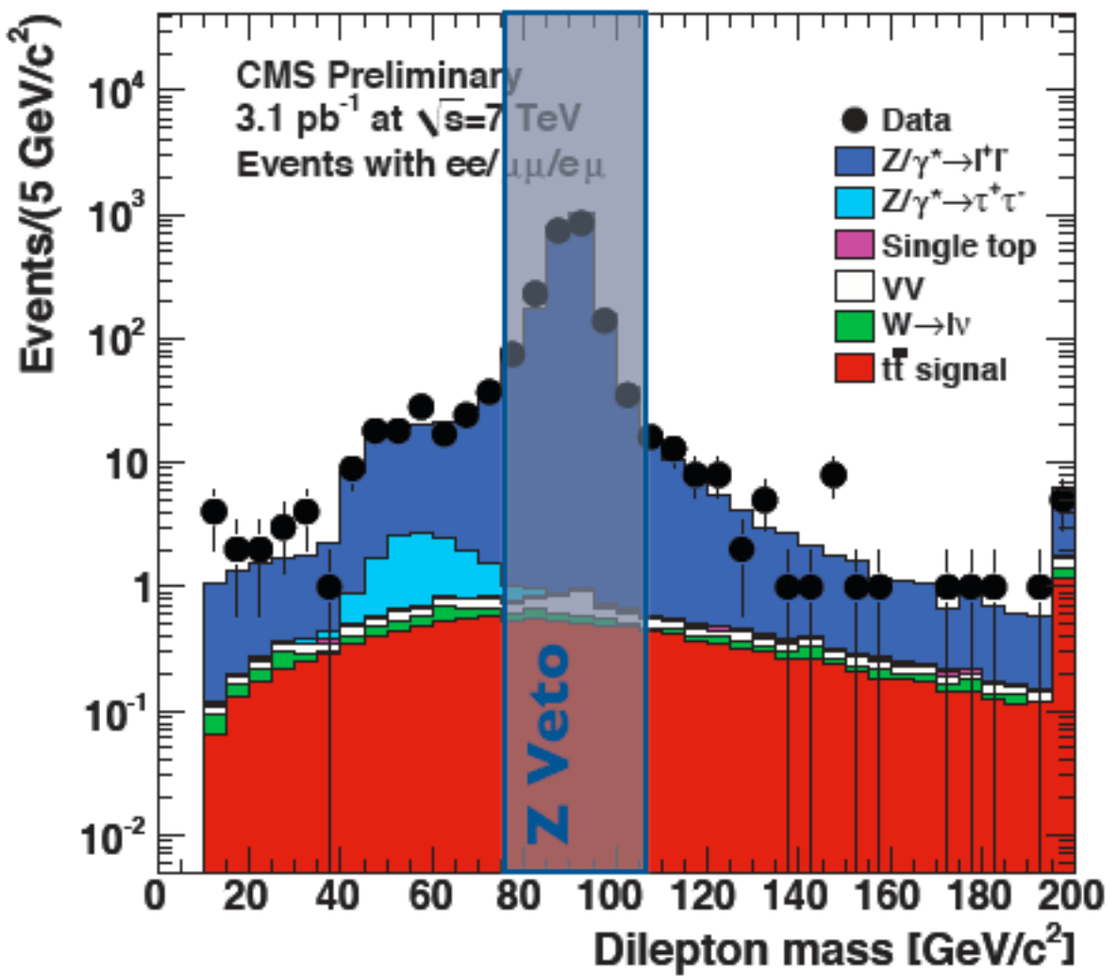




- Good agreement overall
- Some excess in missing energy due to extra pp collisions and not-so-perfect modeling. Not a problem: we rely on normalization to Z in data.

Drell-Yan estimate from data

- Z-boson veto removes most DY background
  - ✓ Close to a factor of 10 suppression
- Residual background estimated from data in Z veto region
  - ✓ Use events with |mass - 91| < 15 GeV/c^2
- Data corrected for non-DY contribution
  - ✓ Mostly WW (from $t\bar{t}$ too) here: use eμ events passing same selections near Z mass
- Amount outside veto normalized to amount inside using MC



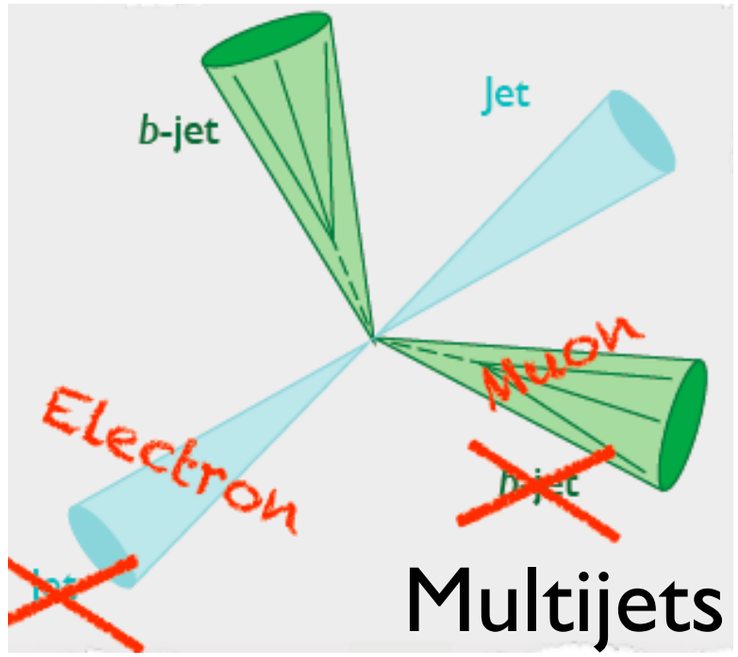
- Note DY to taus estimated separately from simulation

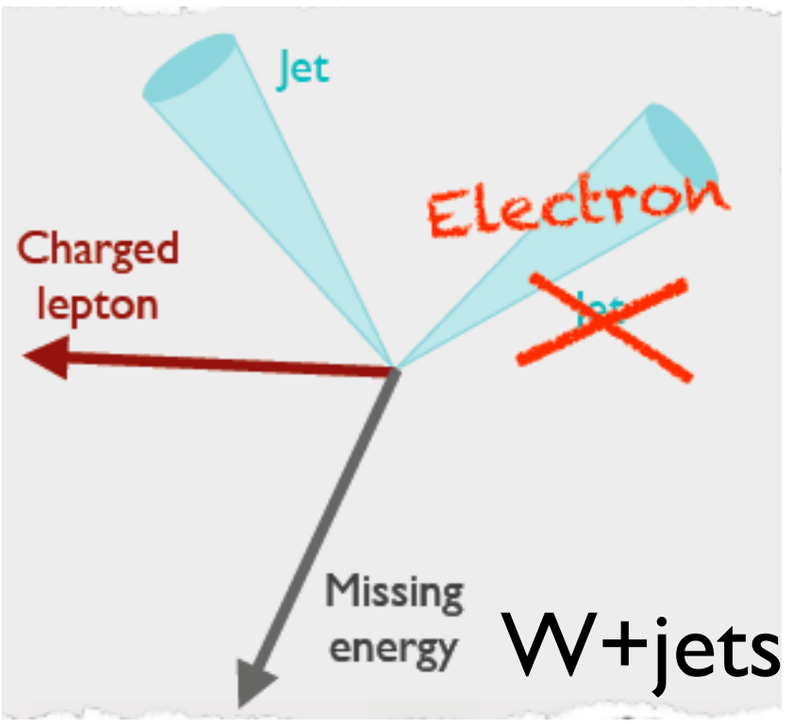
Non-W/Z (jet->e/μ) leptons

- Backgrounds arising from jets faking one or both leptons
  - ✓ Multijet: 2 fake leptons
  - ✓ W+jets: one fake and one real

- Rate of jets faking leptons extracted from jet sample with relaxed selection criteria
  - ✓ R=(pass lepton ID&Isolation)/(pass loose cuts)
  - ✓ Use lepton-like objects (not any jet) in denominator to be more similar to signal

- Fake rate applied to data control sample to predict background
  - ✓ The control samples are dilepton events passing all other selections and failing (one or both) lepton ID&Isolation requirements

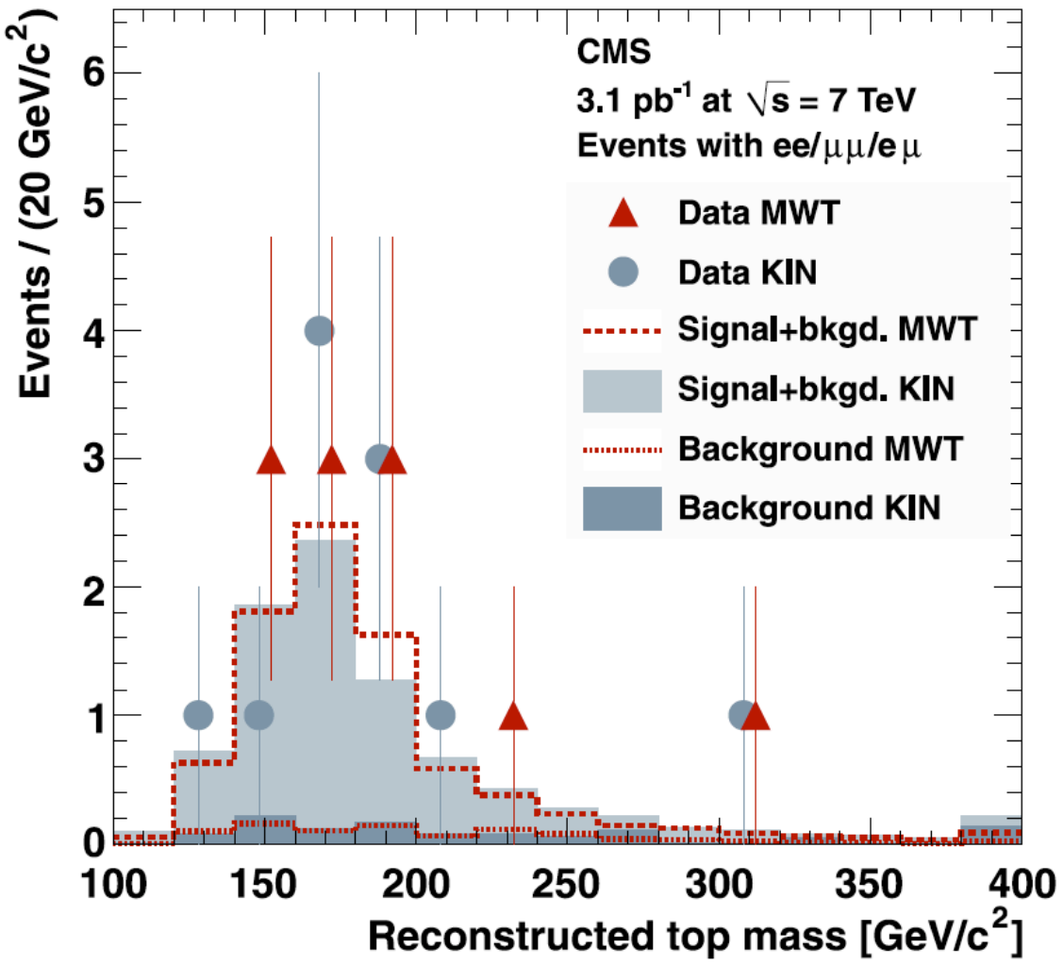


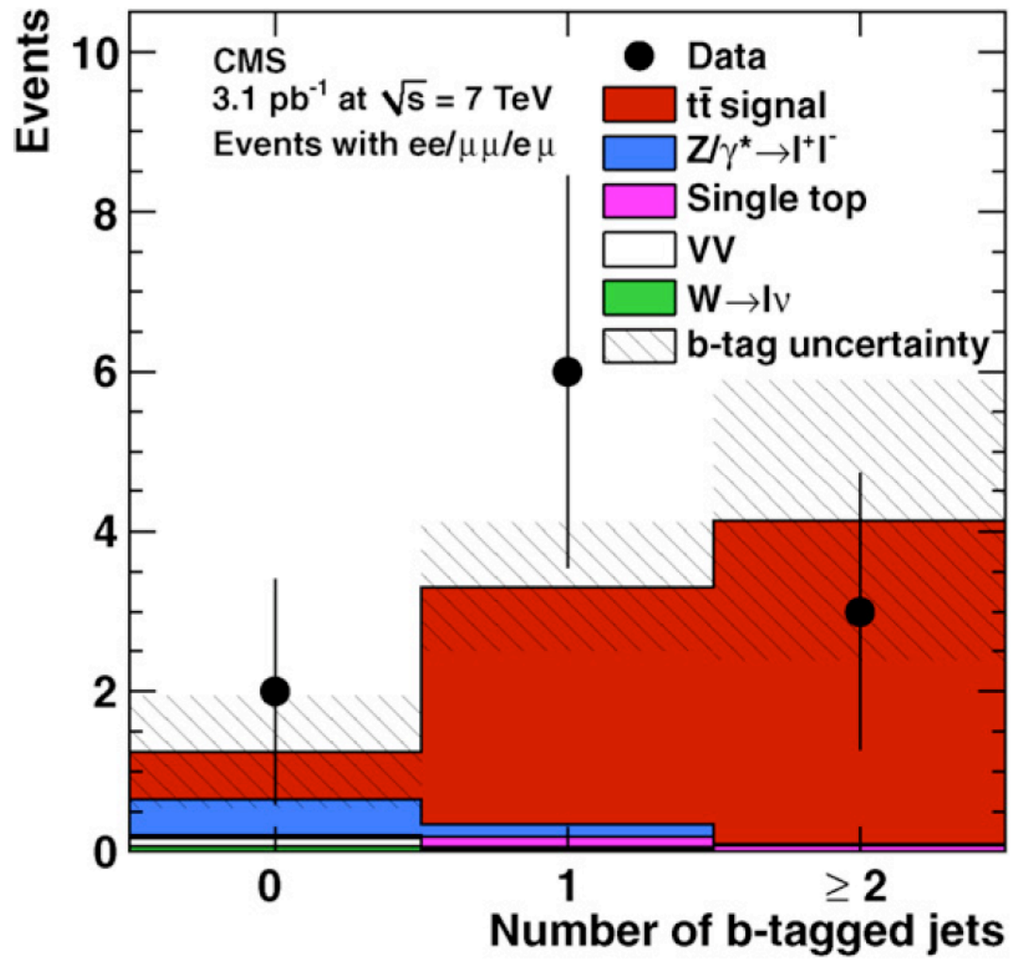


Top-like properties of selected events

11 events pass full selection: 3 e^+e^-, 3 $\mu^+\mu^-$, 5 $e^\pm\mu^\mp$

2.1±1.0 backgrounds





- Reconstructed top mass: includes all event information, gives a global view of consistency. Two methods of reconstruction (different type of constraints) applied to find the solution.
- Multiplicity of b-tagged jets: confirms high rate of b-tags as expected from top

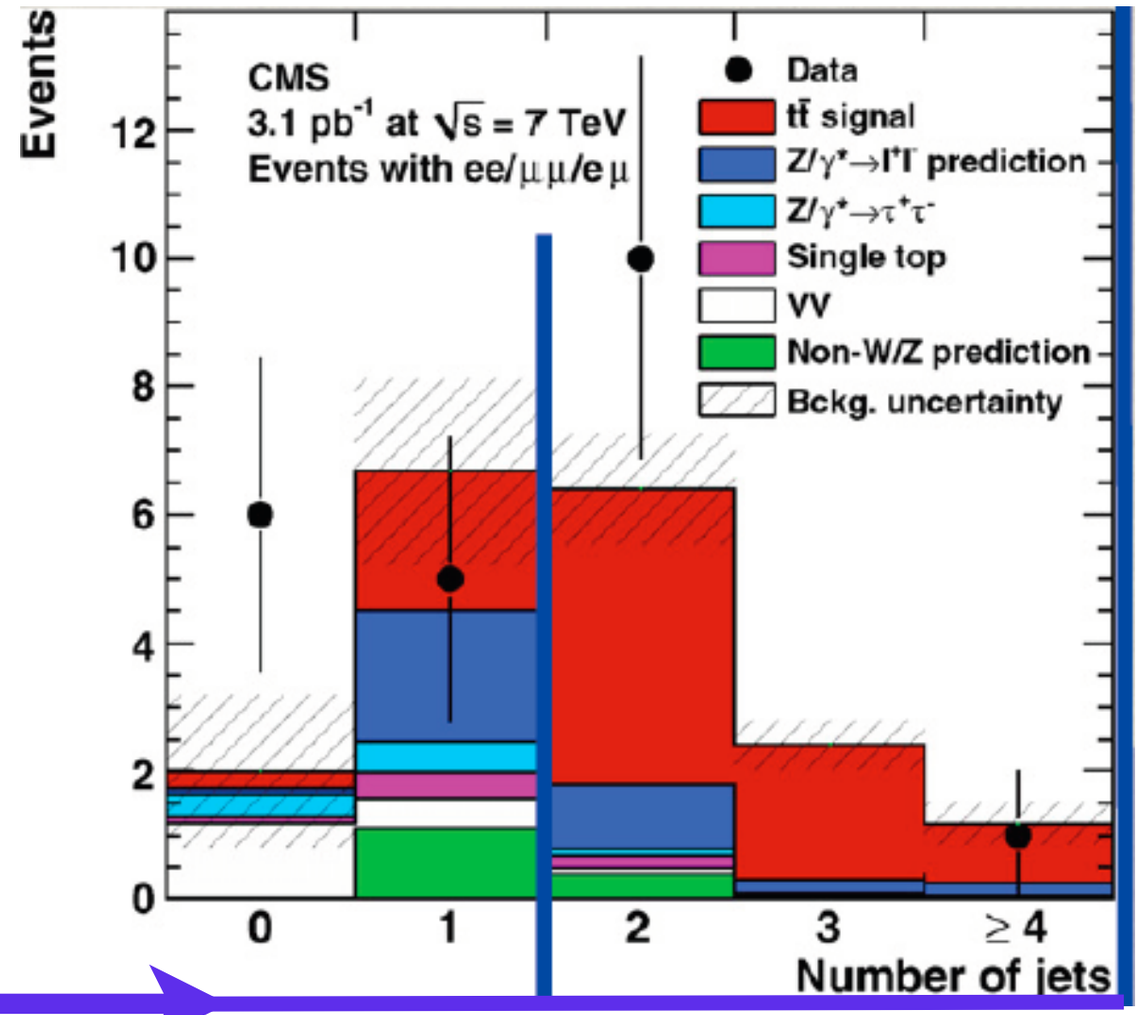
Systematic uncertainty

Source	Relative Uncertainty
Lepton Selection	4.4%
Energy Scale	3.7%
ISR/FSR	1%
Decay Model	2%
Branching Ratio	1.7%
Subtotal (above)	6.4%
Backgrounds	15%
Luminosity	11%

- Background uncertainties are in part driven by statistical uncertainties and will go down somewhat with more data

Results

Source	Events
Expected tt	7.7 ± 1.5
Dibosons	0.13 ± 0.07
Single Top	0.25 ± 0.13
DY (τ)	0.18 ± 0.09
DY (e,μ)	1.4 ± 0.5 ± 0.5
Non-W/Z	0.1 ± 0.5 ± 0.3
Total Bkg	2.1 ± 1.0
Total (incl. top)	9.8 ± 1.8
Data	11

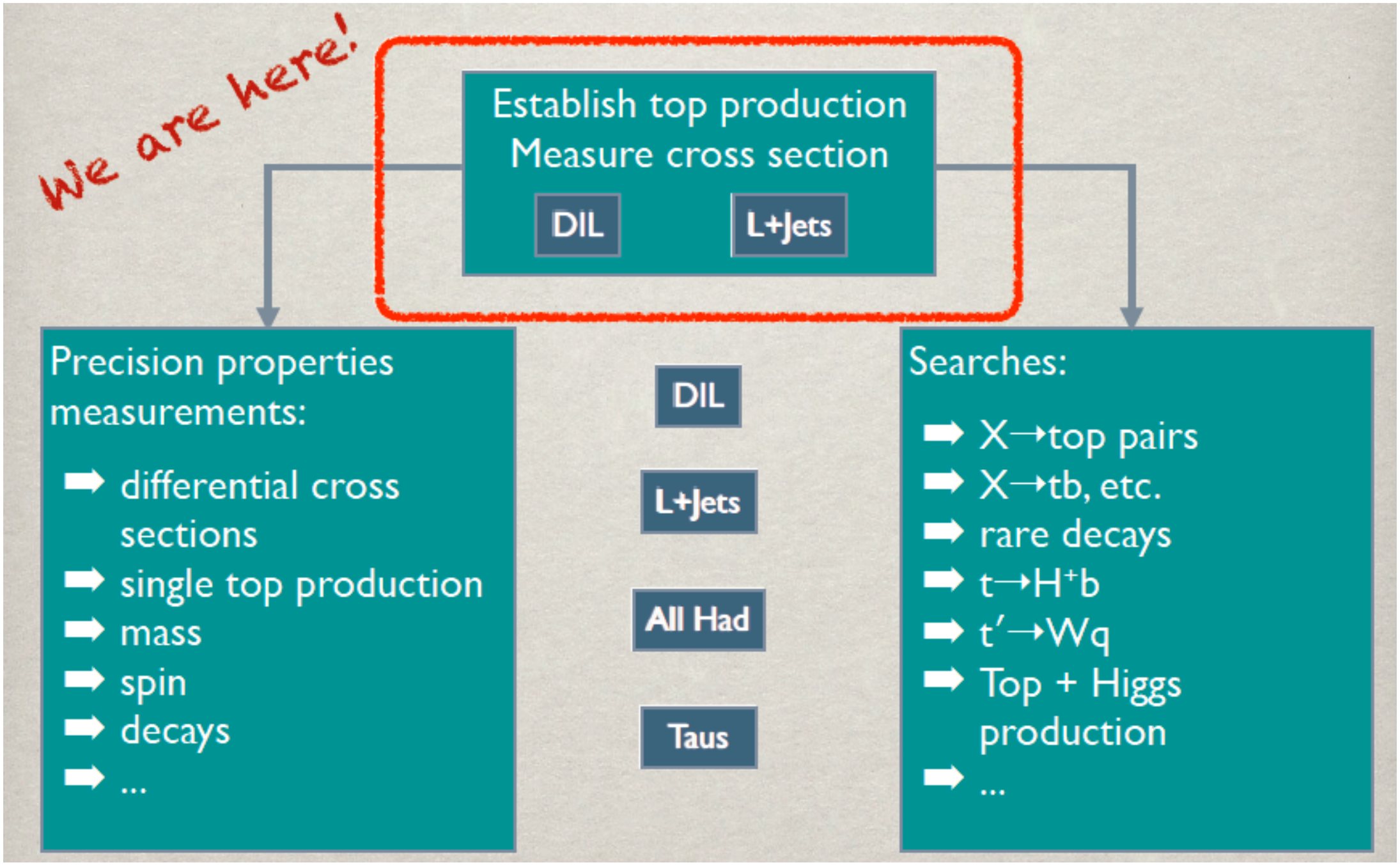


$$\sigma(pp \to t\bar{t} + X) = 194 \pm 72(stat.) \pm 24(syst.) \pm 21(lumi.)\ pb.$$

- The measurement is dominated by statistical uncertainty
- x10 more data available now ==> x2-3 more precision expected

A few words on other topics

Rich top physics program is up ahead
Results from 2010 data analyses are expected in about two months



Summary

- CMS is stepping forward confidently with analysis of data
- Excellent detector performance is established in all ingredients necessary to perform top physics analyses
- LHC run in 2010 brought almost 40 pb^{-1} of integrated luminosity ready for analysis
- LHC run in 2011 is expected to bring as much as two orders of magnitude more data and deliver more top events for analysis then ever available at the Tevatron

- First result from the CMS top physics program using only a fraction of 2010 data has been published (PLB)

- Expect a slew of analyses of full 2010 data set to appear soon
  - ✓ Top pair cross section measurement in dileptons and lepton+jets
  - ✓ Top mass measurements
  - ✓ Establishing single top production (5 σ possible in e/μ combined)
  - ✓ Search for physics beyond the standard model in mass($t\bar{t}$)

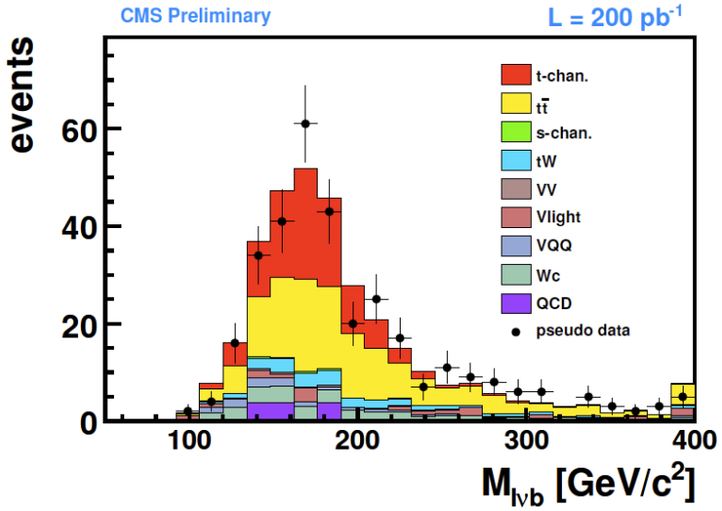
BACKUP SLIDES

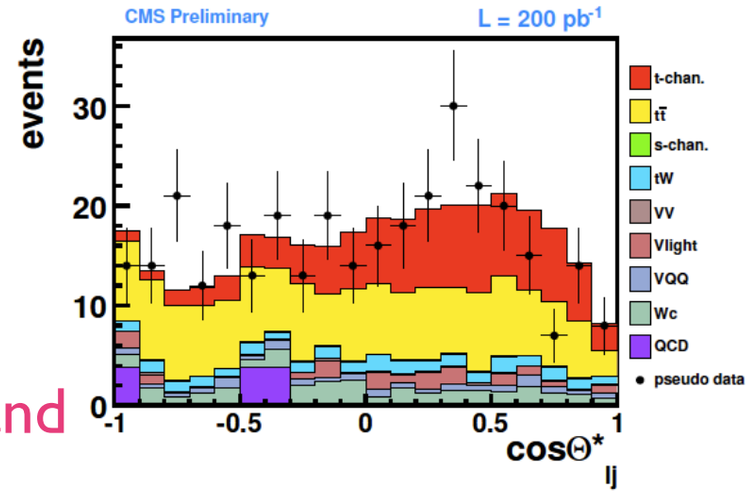
CMS PAS TOP-09-005

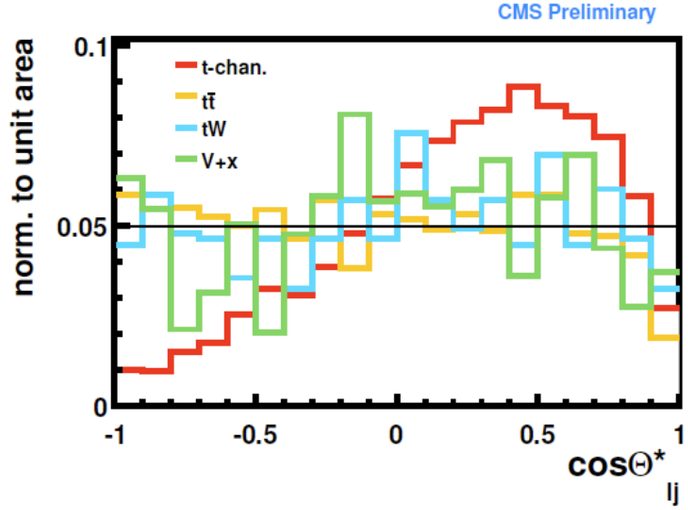
Early t-channel single top @CMS

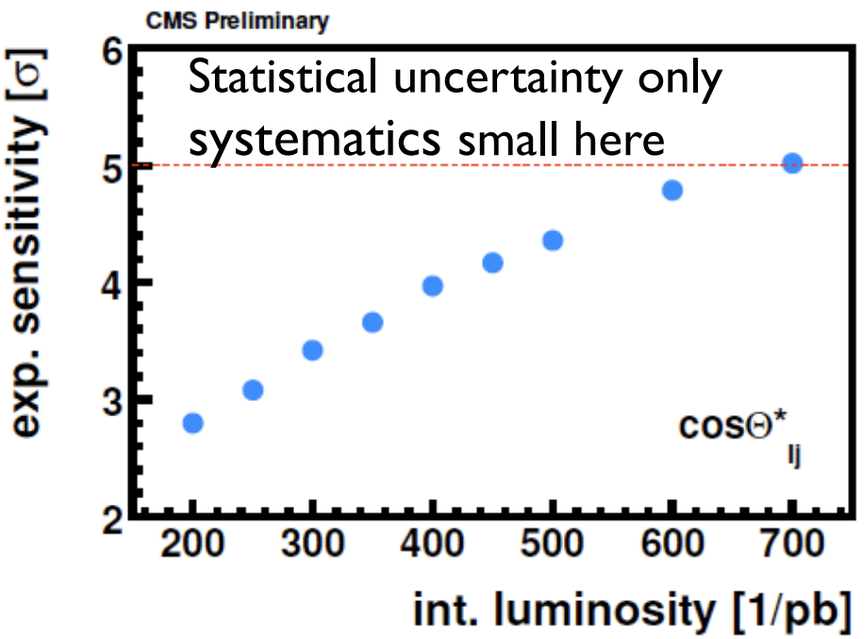
✓ 10 TeV with 200 pb^{-1}

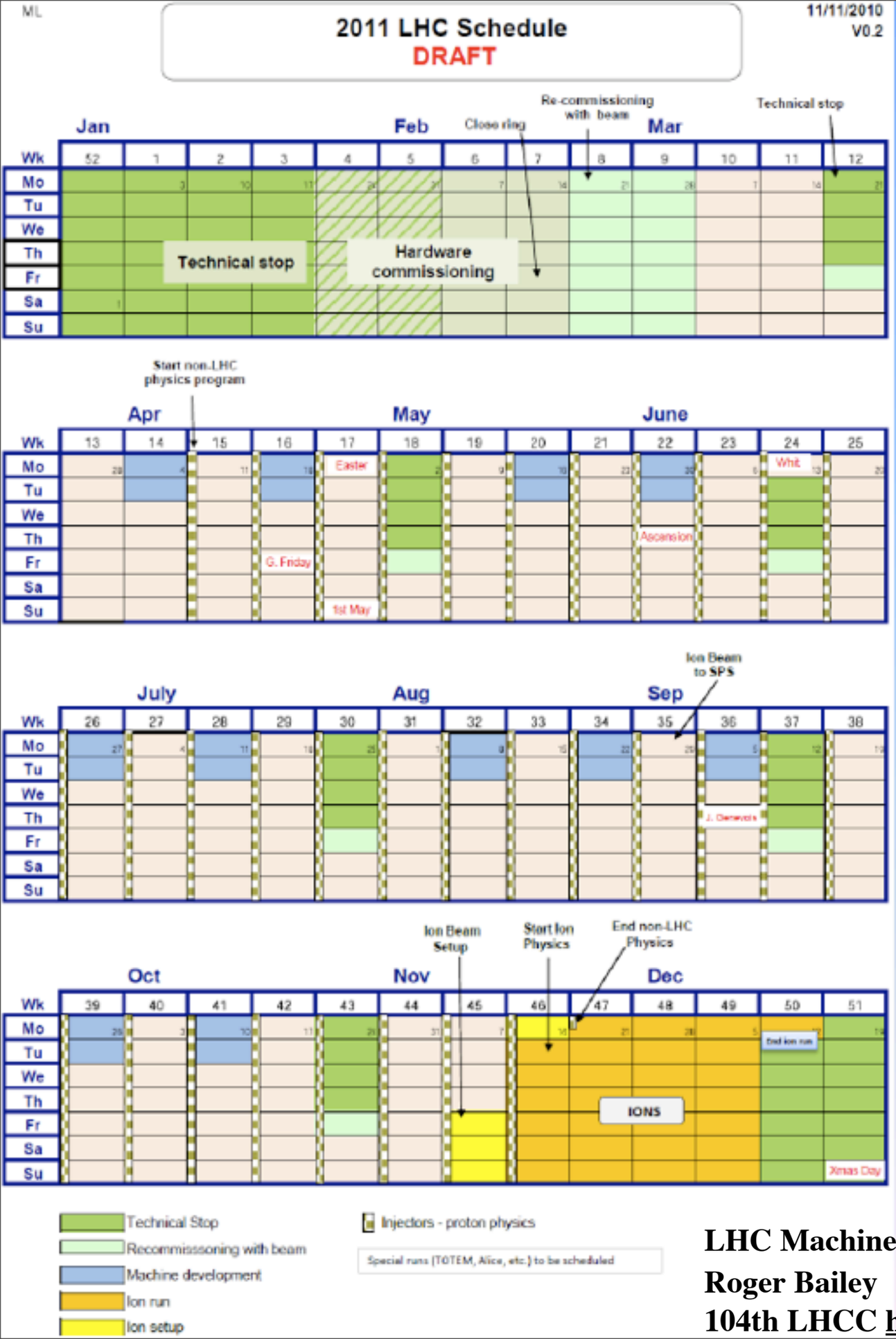
- Motivation
  - ✓ Highest single-top x-section
  - ✓ Most uncertain σ of single top channels
- Selection (after single mu trigger)
  - ✓ muon p_T>20 GeV,
  - ✓ ≡2 jets p_T> 30 GeV, ≡1 b-jet
  - ✓ W-like muon+neutrino: M_T >50GeV
- Reconstruct top mass and fit template shapes to extract signal
- Reconstruct top polarization angle and fit template shapes to extract signal
  - ➡ V-A says $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*_{lj}} = \frac{1}{2}(1 + A\cos\theta^*_{lj})$
- Fit in θ^* has the smallest systematics
  - ➡ use it for early data
- expect ≈3σ evidence with 200 pb^{-1}











2011

- Beam back around 21st February
- 2 weeks re-commissioning with beam (at least)
- 4 day technical stop every 6 weeks
- Count 1 day to recover from TS (optimistic)
- 2 days machine development every 2 weeks or so
- 4 days ions set-up
- 4 weeks ion run
- End of run – 12th December

~200 days proton physics

LHC Machine Status Report
Roger Bailey
104th LHCC http://indico.cern.ch/event/112439