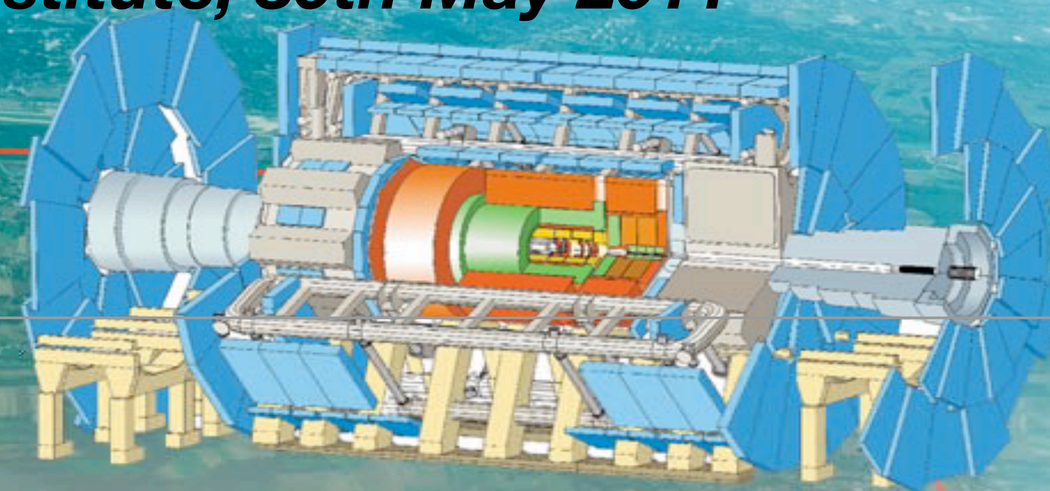
ATLAS EXPERIMENT
http://atlas.ch

Royal Holloway University of London

Towards new physics with Top quark with ATLAS @ LHC

Top MIni Workshop, Weizmann Institute, 30th May 2011



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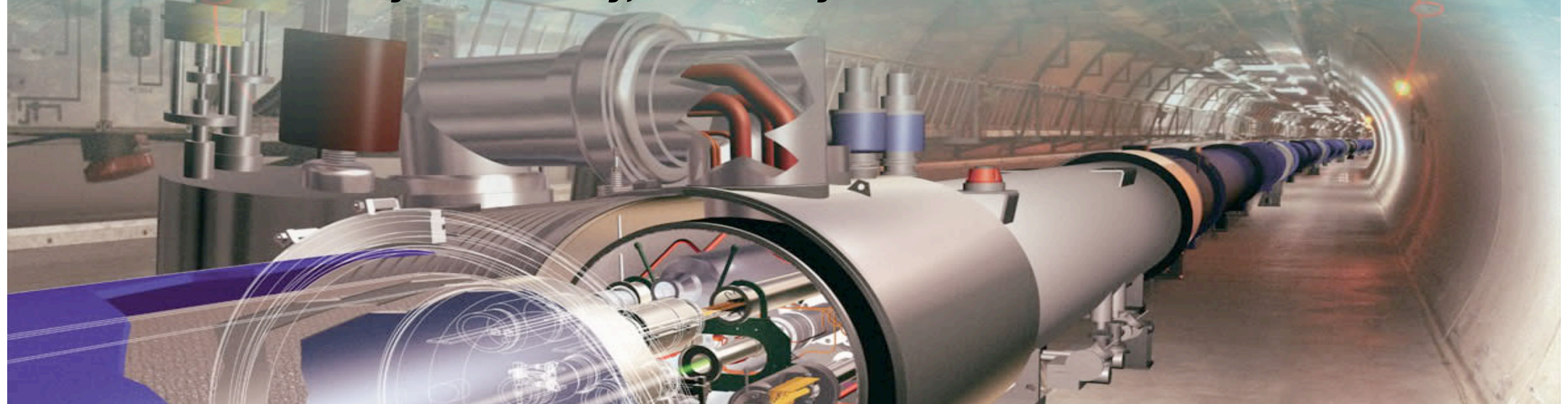

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Outline

- **Why top quark?**
- **The LHC & ATLAS: top factory & observer**

- First ATLAS tops: SM @ 7 TeV
  - cross section
    - mass

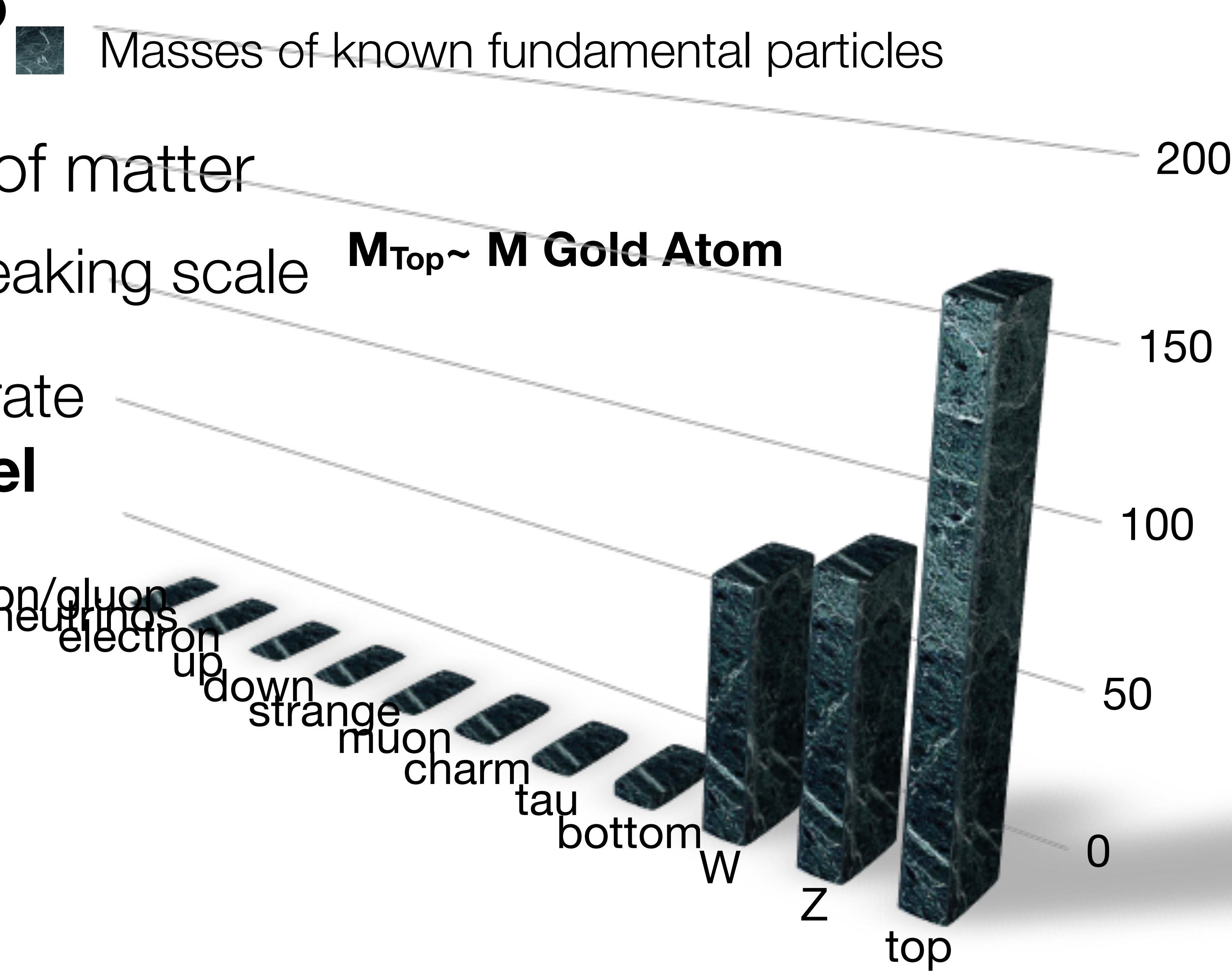
Most recent public results

- Searches for new high mass **top quark phenomena** and their prospects

- Conclusions

Disclaimer: wide field, concentrate on selected topics

Why Top (quark)?

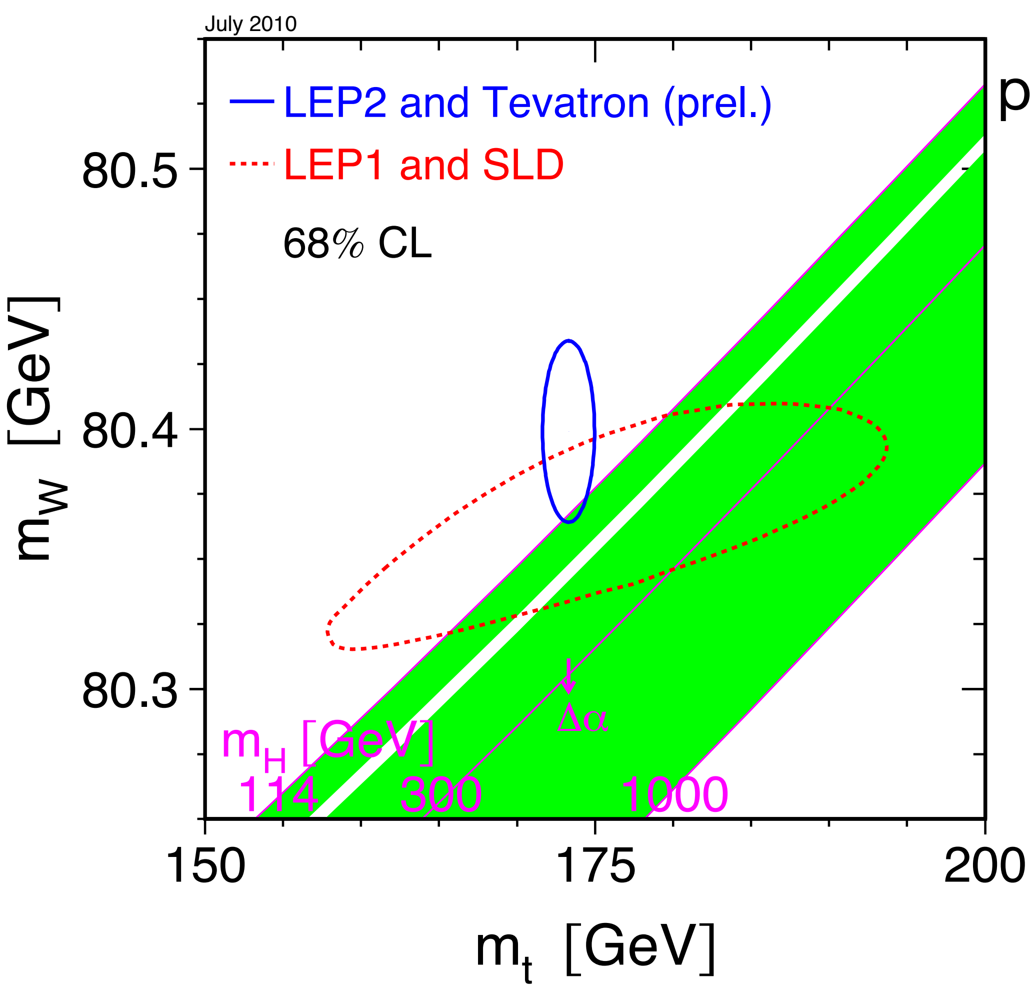


Most massive constituent of matter

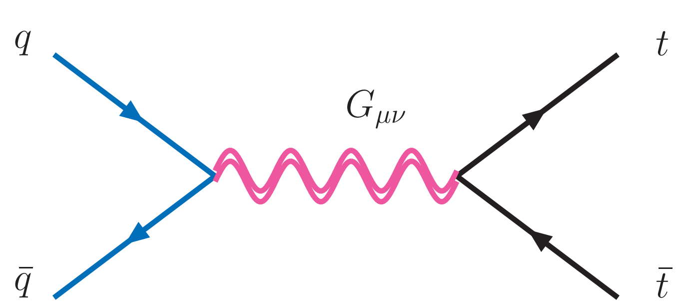
M_{top}~ electroweak symmetry breaking scale

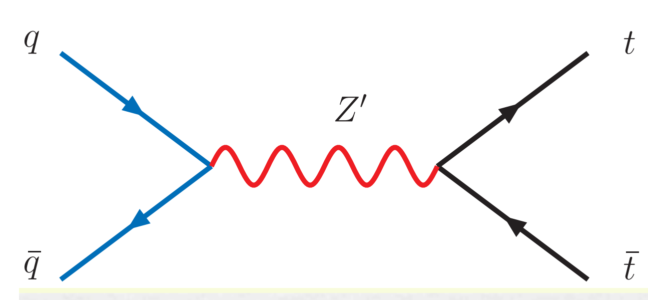
M_{Top}~ M Gold Atom

Decay and strong production rate are **tests of standard model**



Various scenarios with **direct/indirect coupling to new physics:** from extra dimensions to new strong forces





Background to possible **new physics** (Higgs, SUSY)

LHC : a *Top* producer

counter-rotating high intensity proton bunches colliding at center of mass energy (E_{cm}) = 7 TeV in 27 Km tunnel

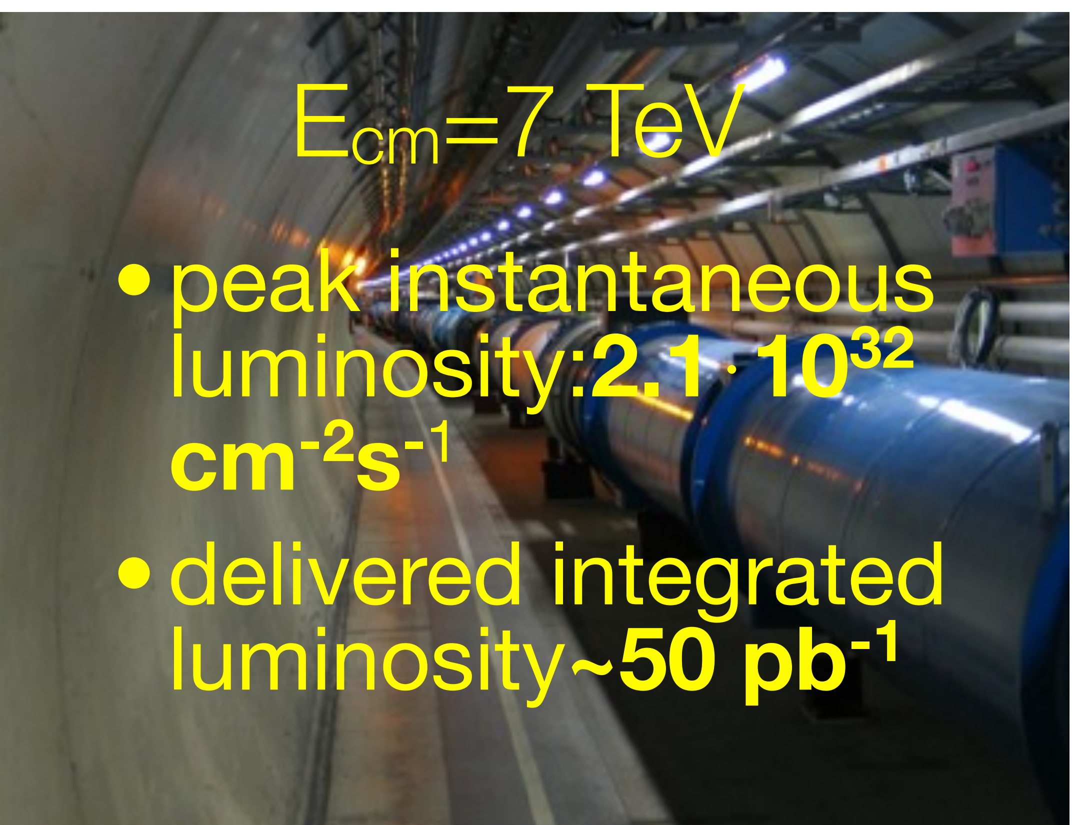
eventually: E_{CM}=14TeV (7 TeV per beam, design value)

Key parameters:
- N_i = bunch intensity
- n_b = number of bunches
- σ = colliding beam size

$$\mathcal{L} \propto \frac{N_1 N_2 n_b}{\sigma^2}$$

Ad maiora..

2010



E_{cm}=7 TeV

- peak instantaneous luminosity:**$2.1 \cdot 10^{32}$ $cm^{-2}s^{-1}$**
- delivered integrated luminosity~**50 pb^{-1}**

E_{cm}(Tevatron)= 1.96 TeV

2011

E_{cm}=7 TeV

23rd May : *$1.1 \cdot 10^{33} cm^{-2} s^{-1}$!!!*

World record for peak lumi @ hadron collider

Plans:

✔ ***peak lumi:~0.5 to $1 \cdot 10^{33} cm^{-2} s^{-1}$***

➡ ***$\int Ldt$ between 1 and 3 fb^{-1}***

2012: run , parameters depend on 2011 perf.

design lumi ***$10^{34} cm^{-2} s^{-1}$***

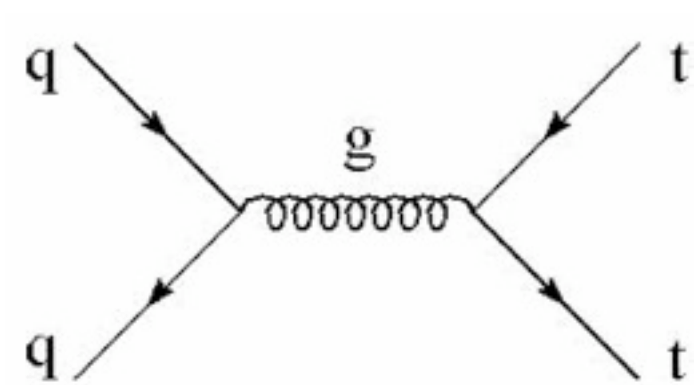
(30 times Tevatron $p\bar{p}$ collider)

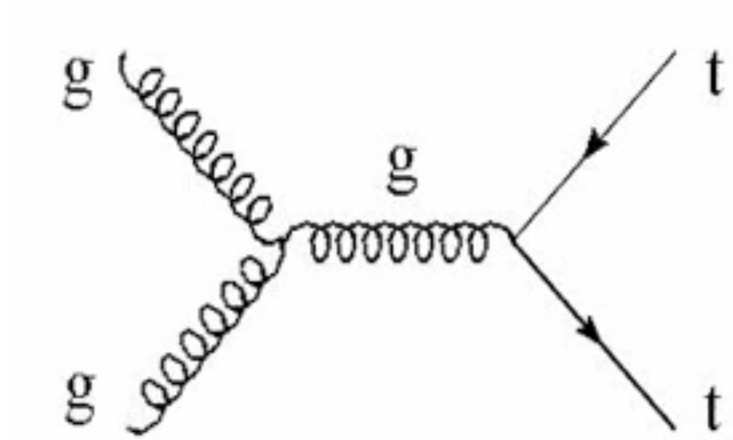
Top quark (pair) production @ E_{CM} = 7 TeV LHC

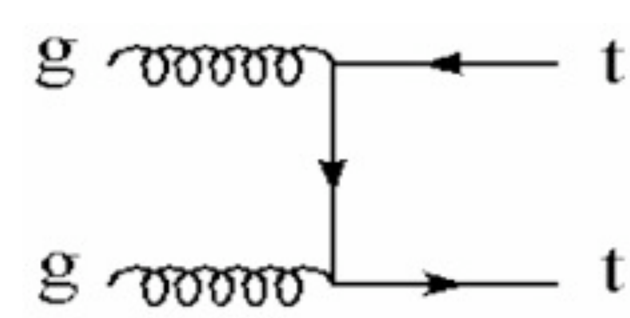
proton-proton collisions

qq annihilation

gluon fusion







~30%

~70%

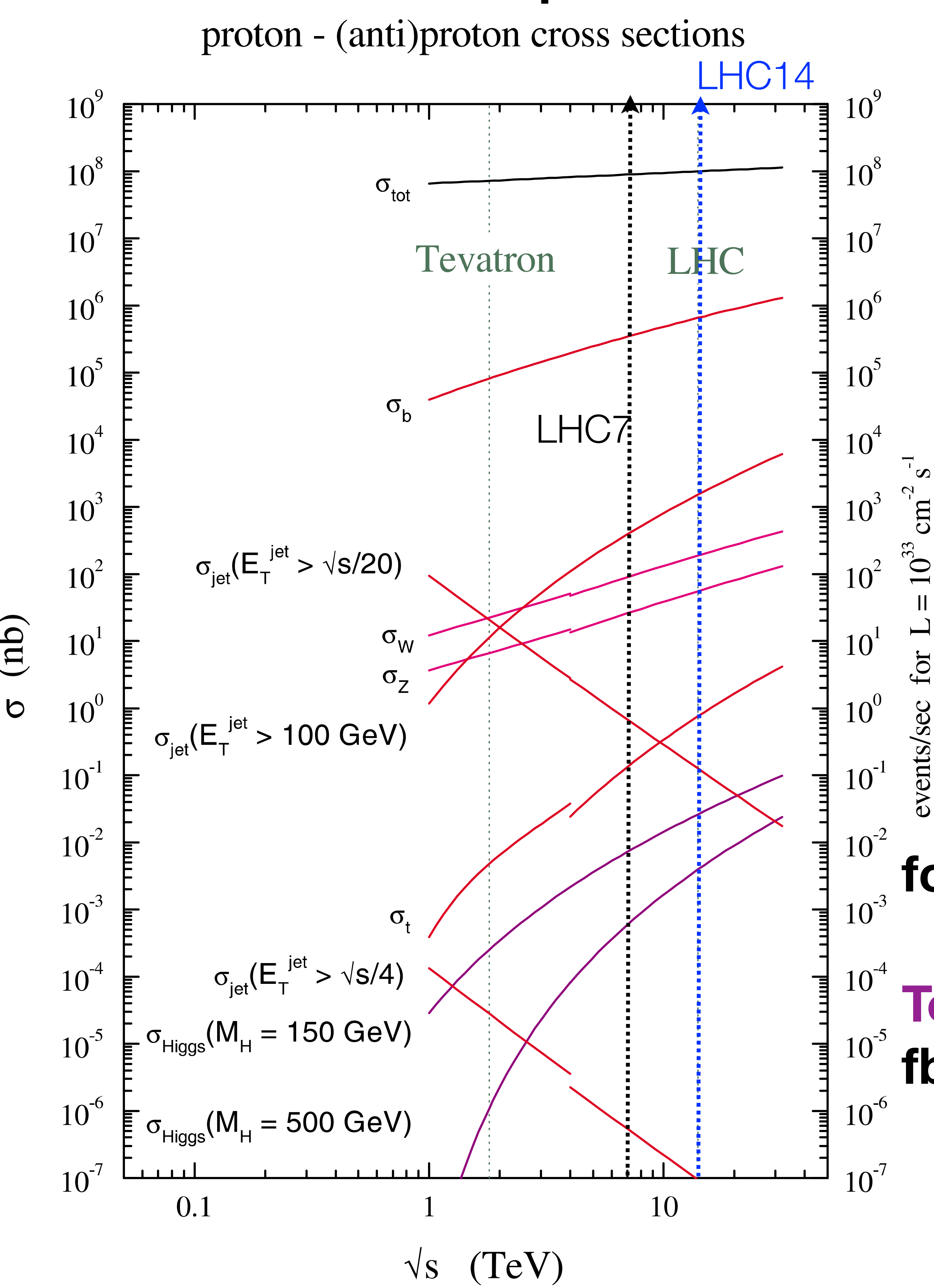
total cross section =165^{+11}_{-11} pb

Aliev et al 2011
Beneke et al 2010
Langefeld Moch Uwer 2009
Moch,Uwer 2008

@ 14 TeV : qq~10%, gg ~90%

top is also singly produced, but ***focus on dominant pair production***

Top @ LHC: in the context



$t\bar{t}$ cross section

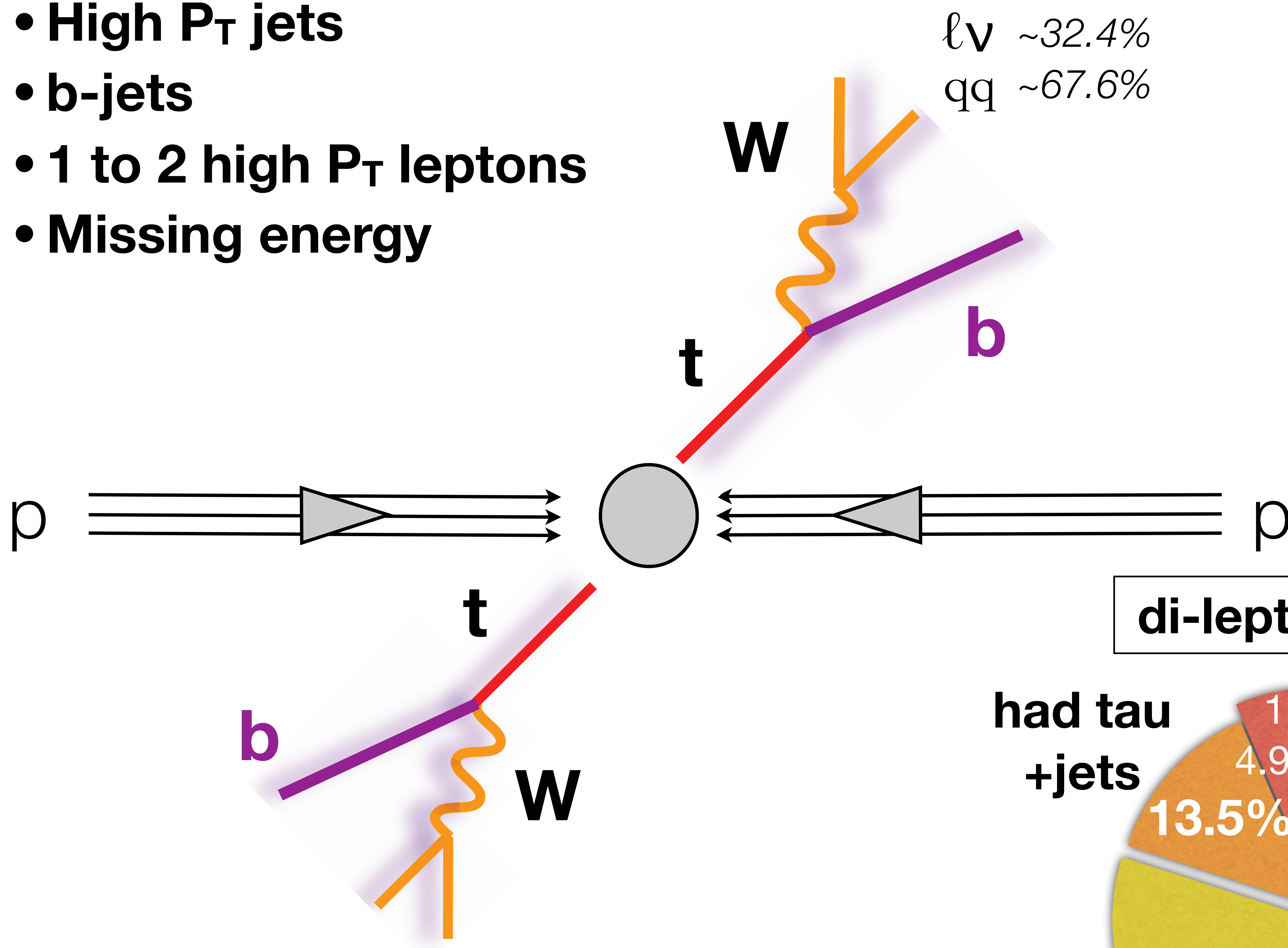
√s(TeV)	xsec (pb)	Rate at L= $10^{33}cm^{-2}\ s^{-1}$
1.96 ($p\bar{p}$)	~7	
7 (pp)	~165	0.2Hz
14 (pp)	~900	0.9Hz

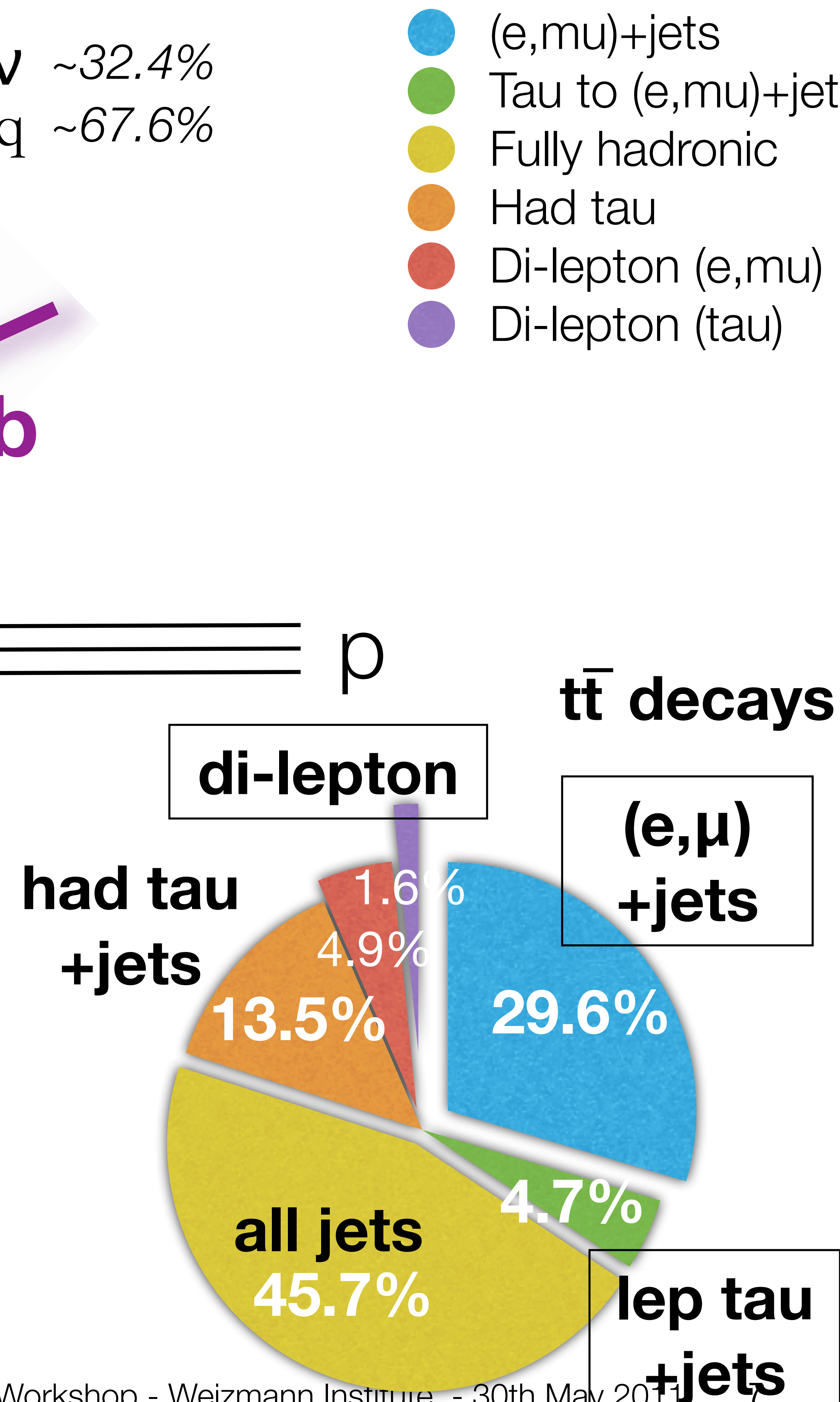
for $\int Ldt$ =1 fb^{-1} @ 7TeV, expect $16 \cdot 10^4$ events

Tevatron (lower energy collider): $\int Ldt$ =9.4 fb^{-1} on tape, expect ~ $6.6 \cdot 10^4$ events

Top signatures

- **High P_T jets**
- **b-jets**
- **1 to 2 high P_T leptons**
- **Missing energy**

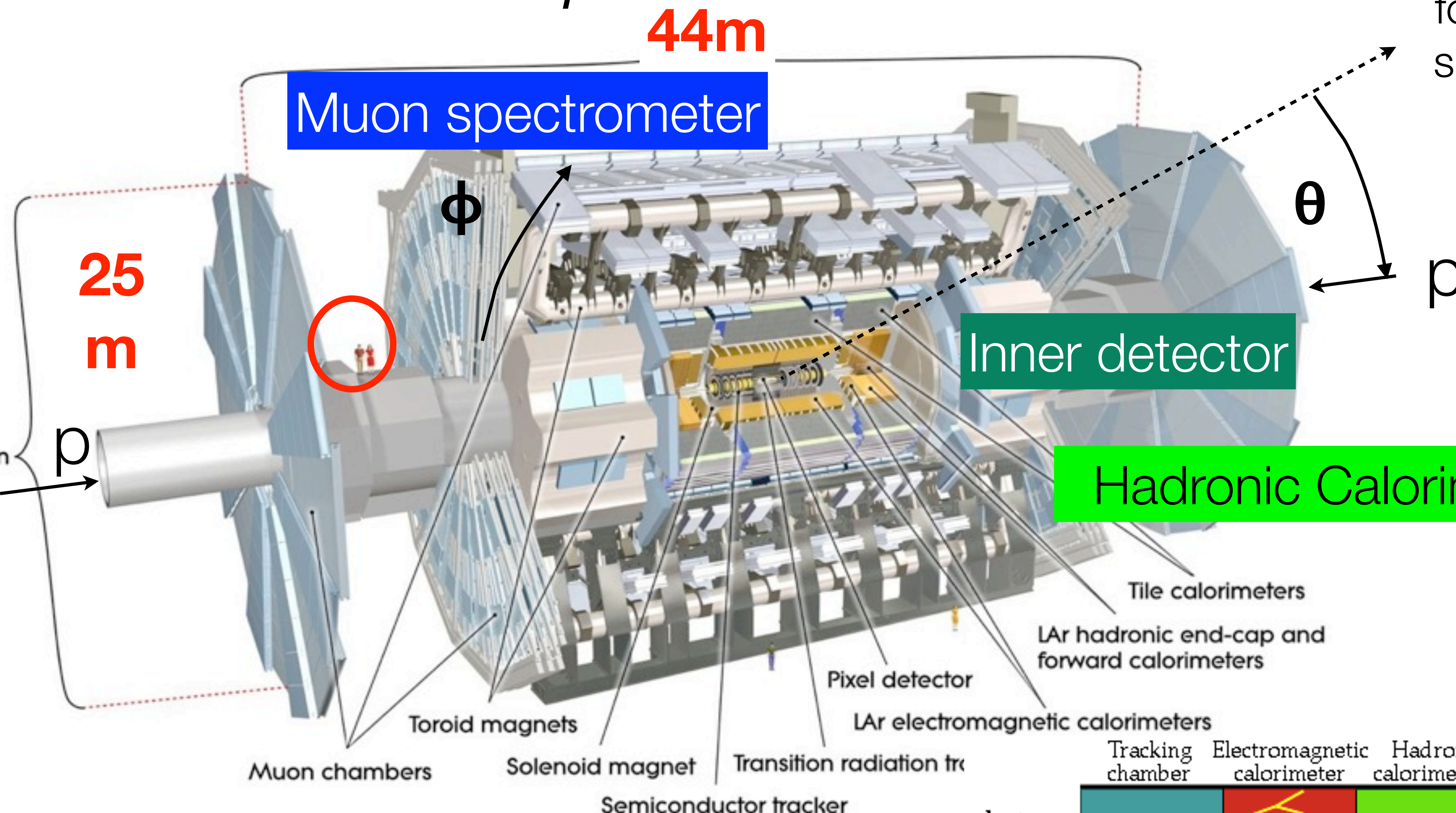




bkgs_tt̄: W/Z(+jets), single top, QCD, Di-bosons

ATLAS : a *Top* observer

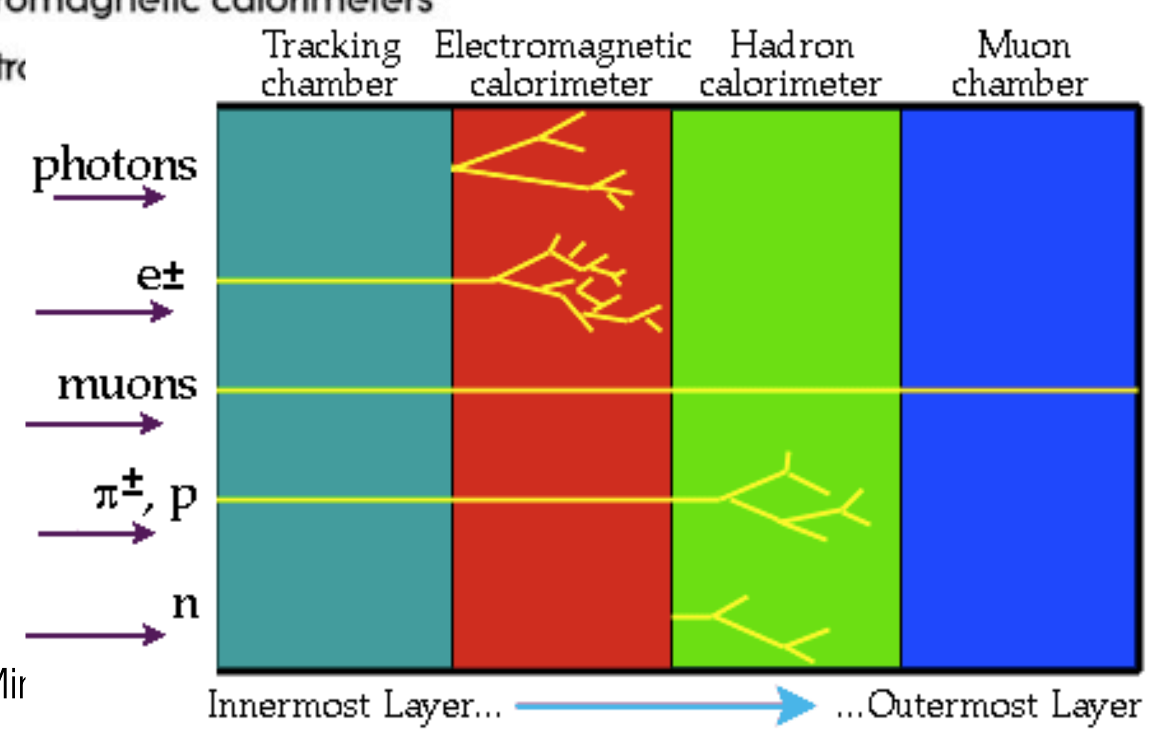
3 trigger levels
for event
selection



EM Calorimeters

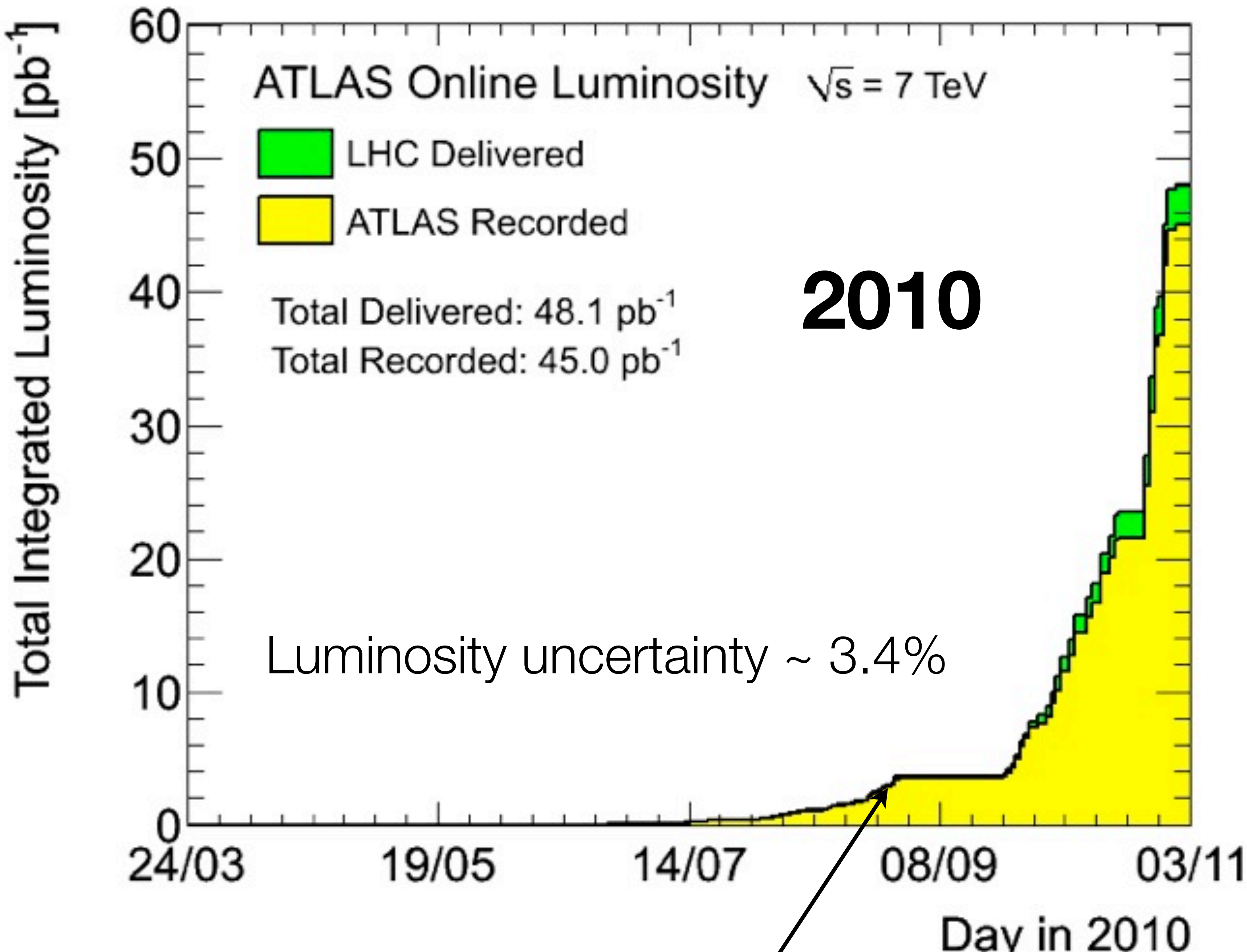
size matters

η = pseudorapidity =-ln (tan(θ/2))



...with excellent data taking performance

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.0	99.9	100	90.5	96.6	97.8	94.3	99.9	99.8	96.2	99.8



Data sample for first top paper~3 pb^{-1}

For top analyses **using 33 pb^{-1}**

expect~5700 $t\bar{t}$ events

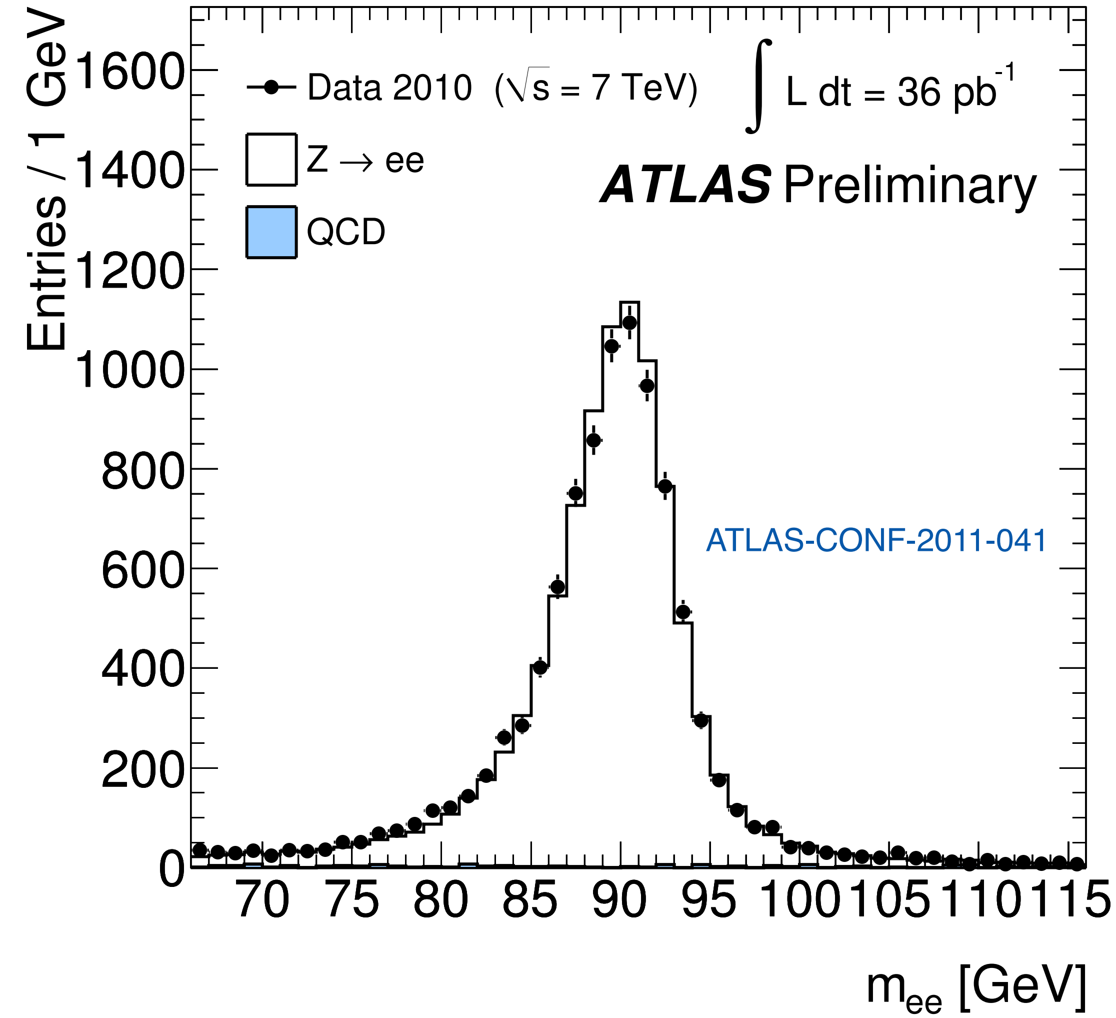
2011

Already collected ~ ~O(0.5) fb^{-1}

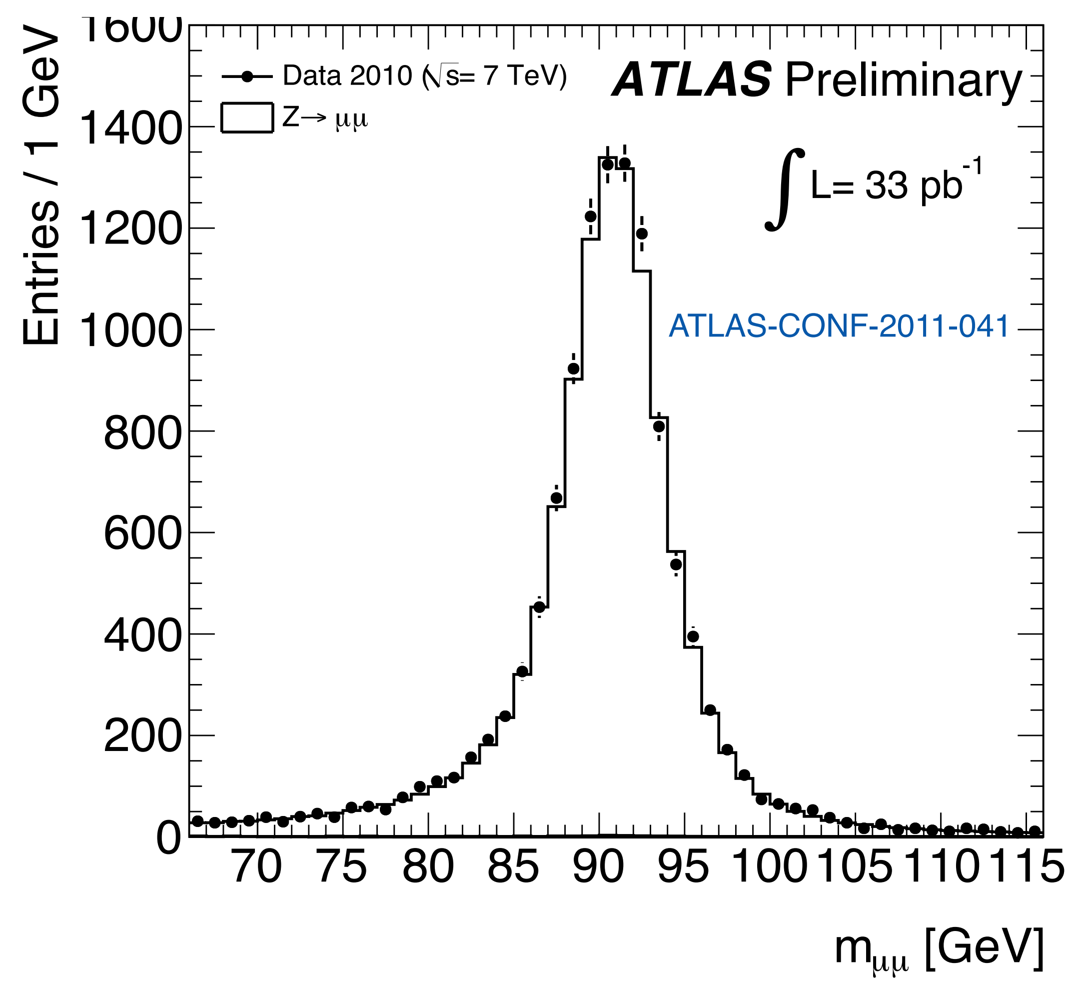
Ingredients I : leptons

* $|\eta_{cluster}| \notin$ [1.37,1,52]

- Electrons
  - **defined** using shower shape variables, track quality, track-cluster matching, E/p, hits in innermost pixel layer
  - **isolated**
  - **central***: $|\eta_{cluster}|<2.4$, $p_T>20$ GeV
  - remove close-by duplicate jets



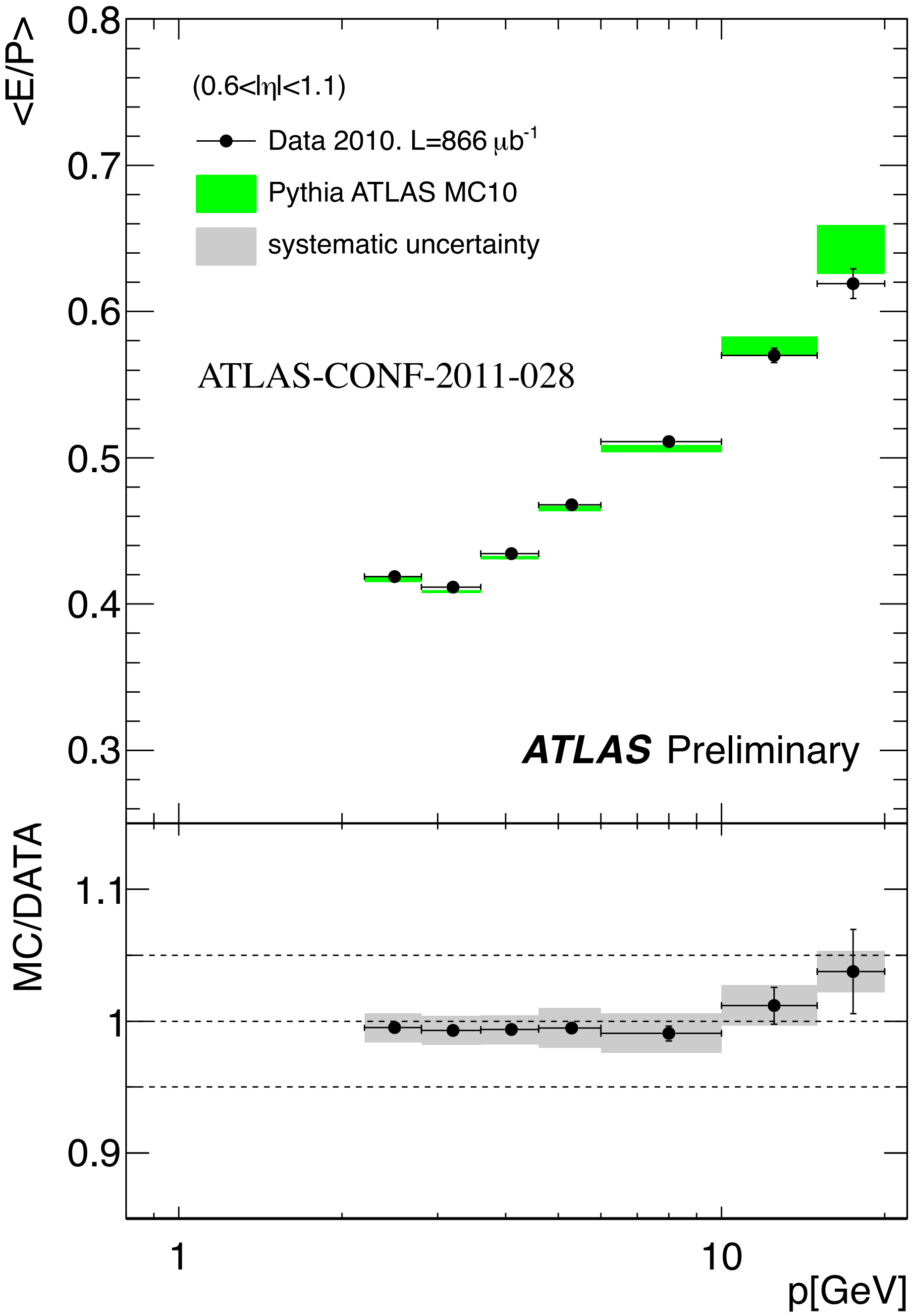
- Muons
  - **combined** fitted **track**
  - **isolated**
  - **central** $|\eta_{track}|<2.5$, $p_T>20$ GeV
  - **suppress heavy flavour decays**: no muon within DR< 0.4 of a jet



scale factors to correct small data/MC mismatch

Ingredients II : jets (making and calibrating)

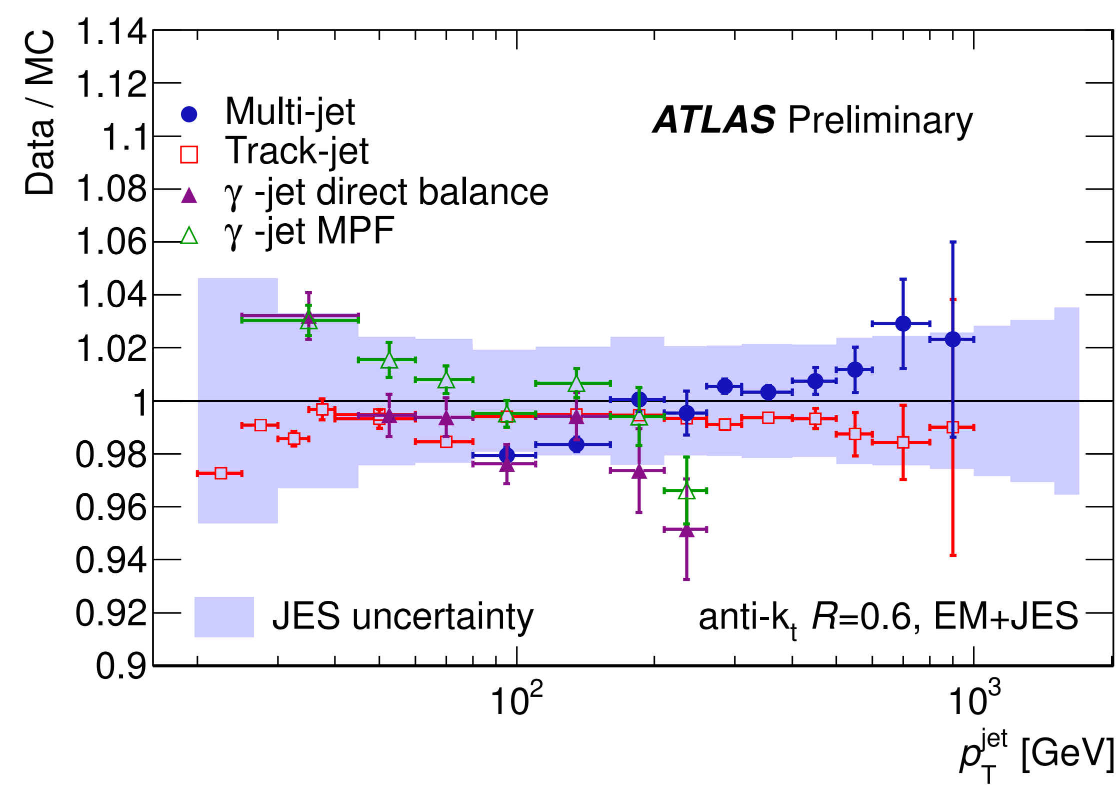
Extensive **validation of simulation in test-beam** data → **good collision data description**



Data/MC within 2% for p<10 GeV

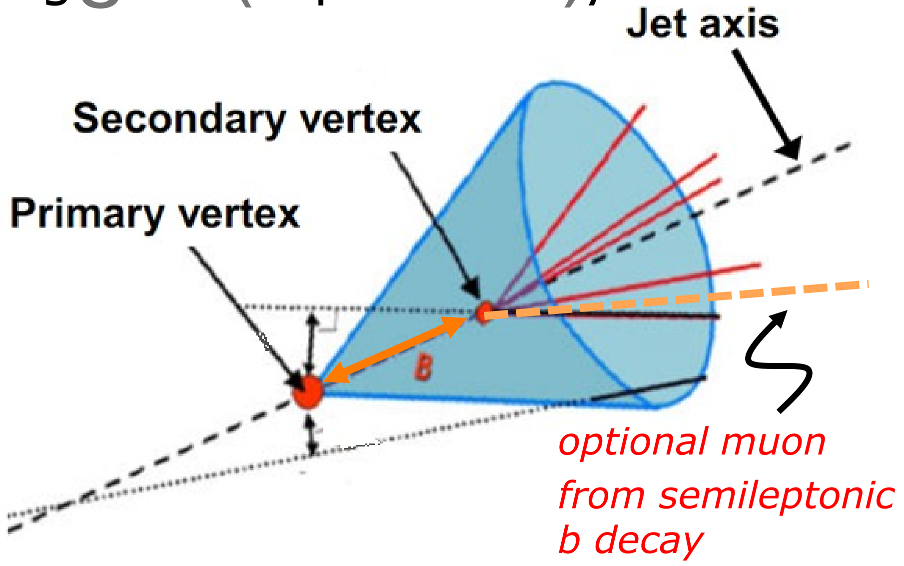
charged hadron response vs track momentum

- **Calibrate jet energy scale** with (η,p_T) dependent weight ***from simulated "true" jet kinematics***
- **Scale uncertainty:** range between 2% to 8% in $\mathbf{p_T}$ and η
  - *Contributions from physics modelling, calo response, det simulation*
- Validation in control samples



Ingredients III : enter b-jets

- B-hadrons have long lifetime ~observable flight (few mm)



Tagging

secondary displaced vertex with decay length significance (L/σ(L))

Performance in data

- **Efficiency:** fit fraction of b-jets in sample with muons in jets, *count how many are b-tagged*
- **Mis-tag rate**: from secondary vertex properties (*invariant mass of tracks, rate of negative decay length significance)*

⇓

p_T dependent scale factors to correct MC

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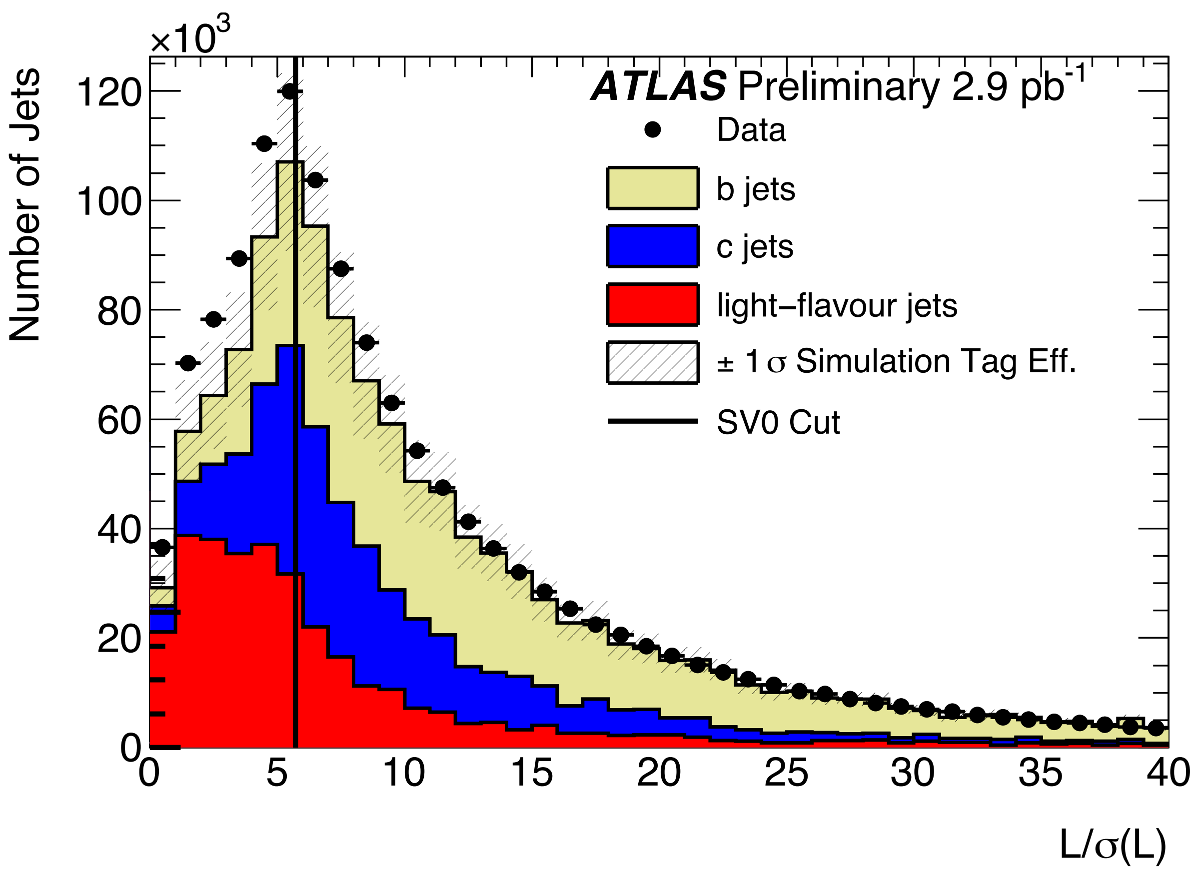
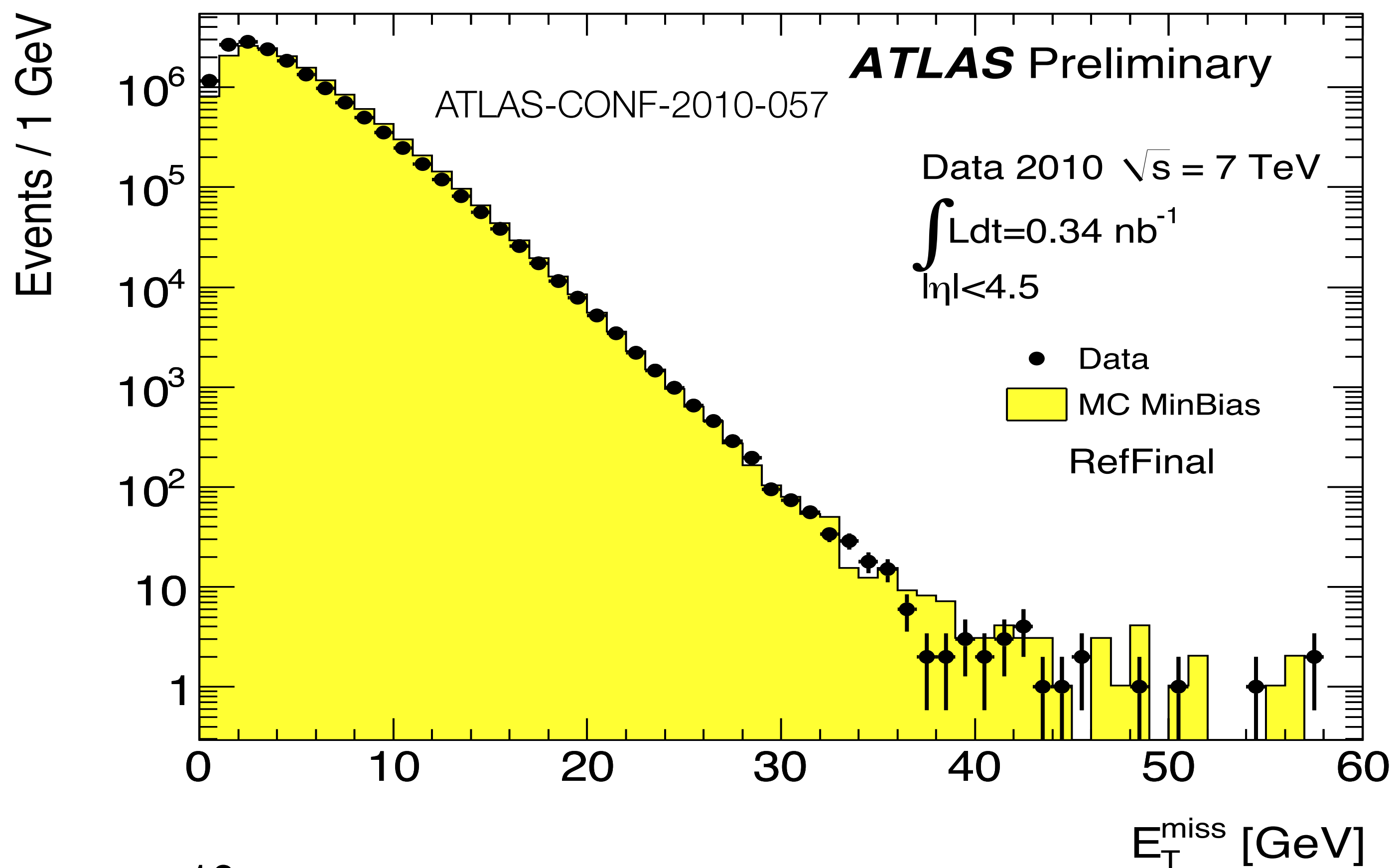


Ingredients IV: missing transverse energy (E_T^{miss})

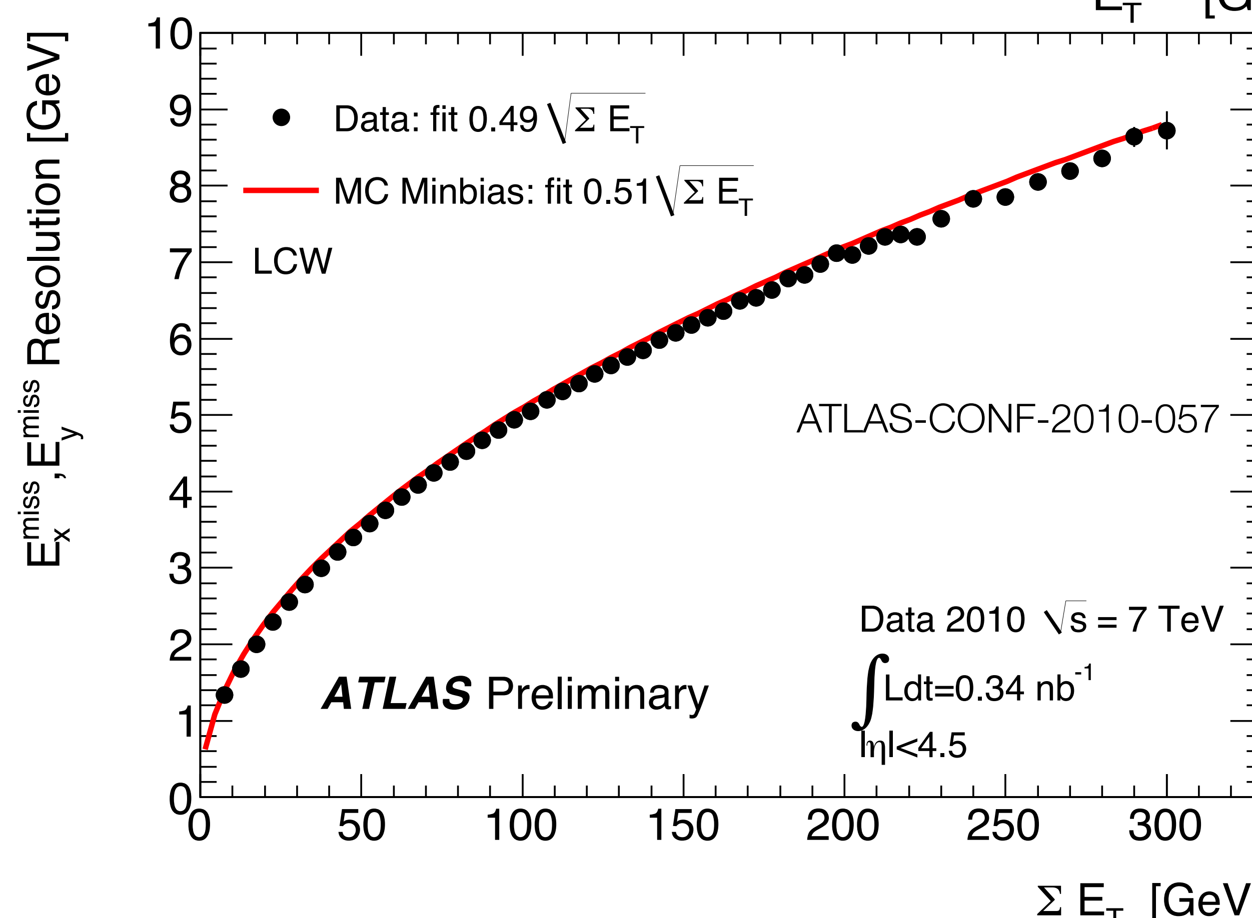
- **Negative vector sum** of
  - **energy in calorimeter cells** in topological or electron-related clusters
  - **muon** momentum
  - ***dead material loss***

  projected in transverse plane



- Cells are **calibrated according to association** to high p_T object (electron, jet, muon). Non-associated cells are at the EM scale

- **Calo cells** with overlapping association **are counted once**



Top quarks visit Europe: ATLAS first tops

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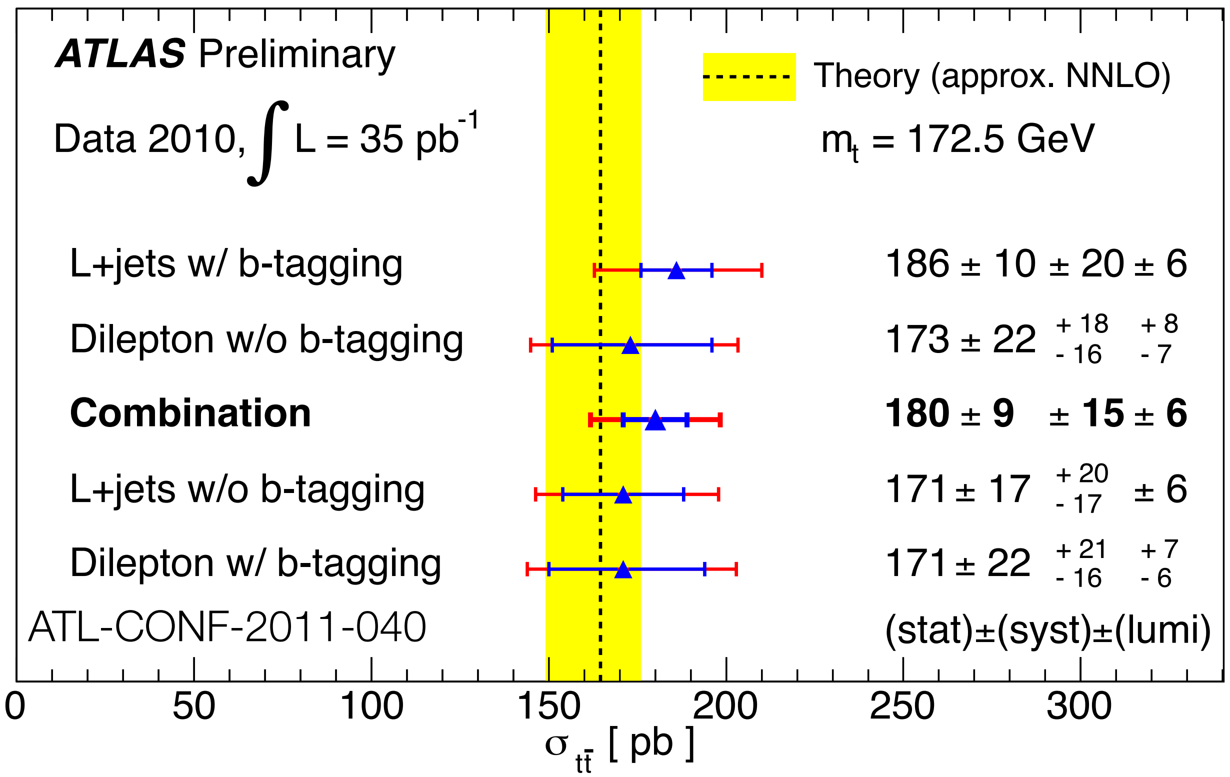

- **Top** pair **cross section** known at **10%: comparable to theory**
  - **ATLAS: 180 ±18 pb (stat+syst)**
  - CMS: 158±19 pb (12%)
- ATLAS **Top mass** is **169.3±4.0(stat)±4.9(syst)** GeV
- **Systematics~stat; dominant in xsec *(jet properties,b-content)***

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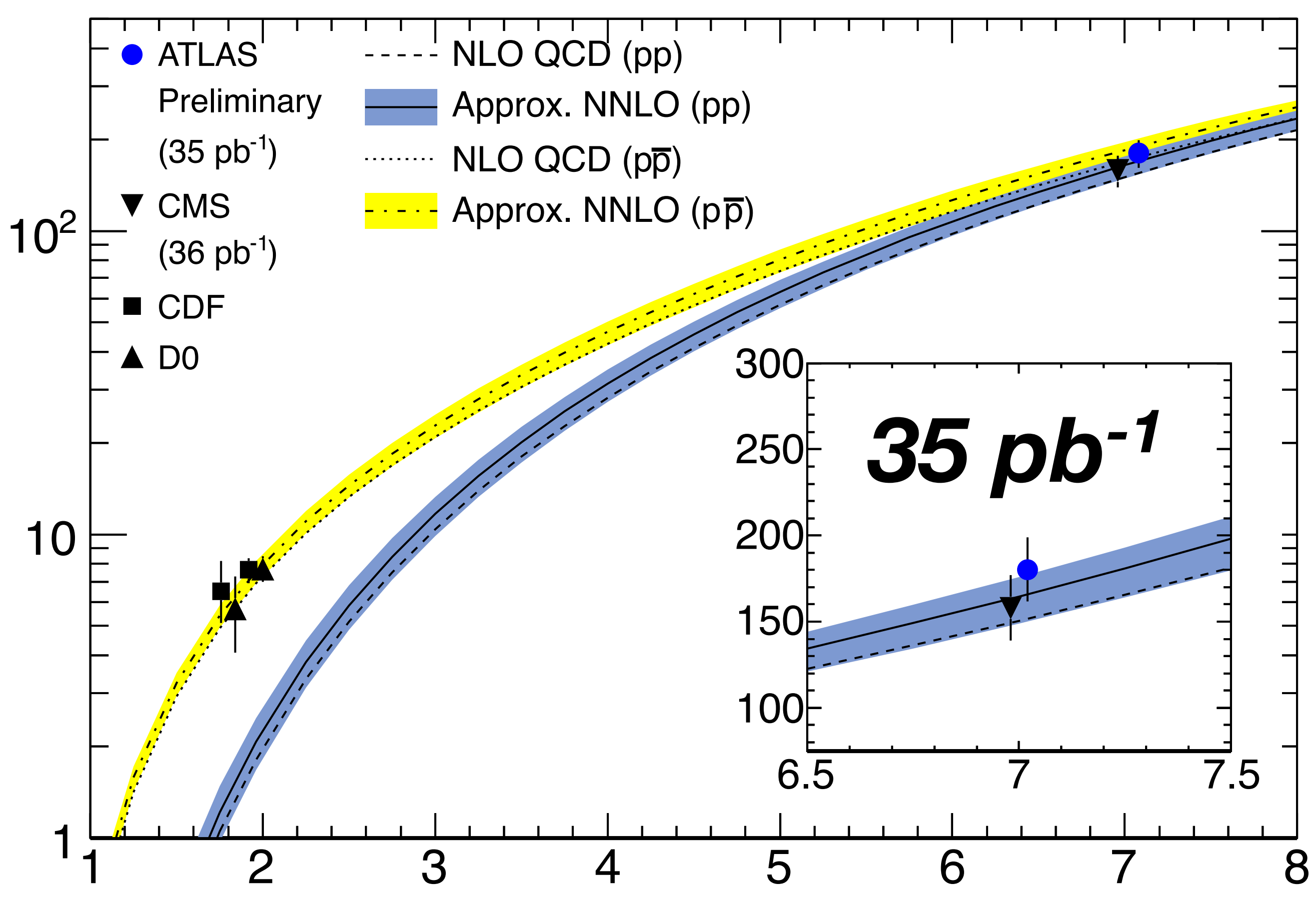
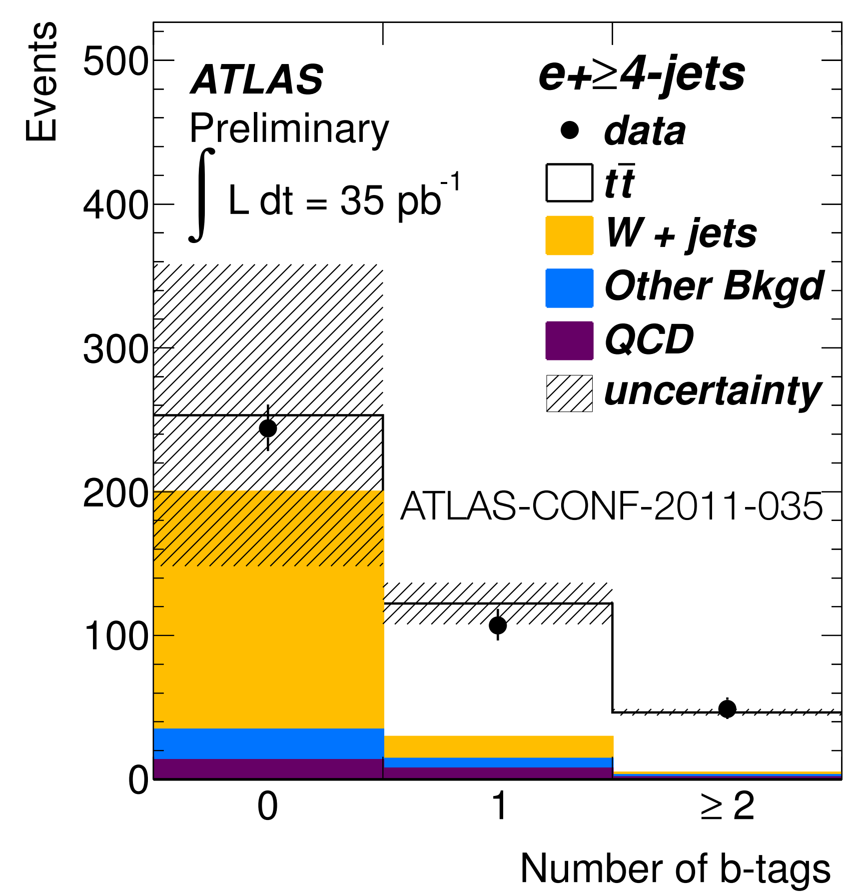




Searches for new high mass phenomena producing top quarks

i.e.

- Heavy particles→tt pairs : **bump** over SM tt continuum

- Anomalous t+X production : **enhanced** high tt mass tail

↓

TopColour Z'

ATL-CONF-2011-070

↓

Quantum Black Hole

$\Gamma_{Z'} = 1.2\% \ M_{Z'}$

EWK symmetry breaking from top condensate

strong scattering from extra dimensions

t+X larger than tt,t/anti t

Search for new high mass phenomena with top: selection

- Use the lepton+jets channel (lepton=electron, muon) reconstructing t+X spectrum with 4 jets+ lepton + neutrino

Selection

- **Trigger on** high p_T **single lepton**
- Good collision and no jet from noise/out-of-time activity
- **only one** high p_T central **lepton** *matching the trigger object*
- **high** E_T^{miss} *> 20 GeV*
- **Large transverse leptonic W mass (M_T^W)*** *> 60GeV - E_T^{miss} for e (μ) channel*
- **≥ 4 central** high p_T **jet** *p_T> 25 GeV*
- **≥1 b-tagged jet** *p_T> 25 GeV*

data-driven ATL-CONF-2011-070

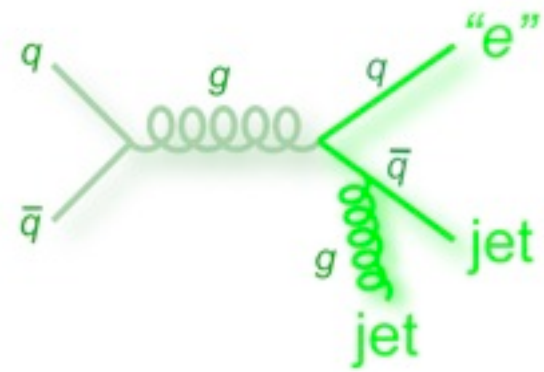
	e	μ
tt	**175**	**187**
QCD	***39***	***12***
W+jets	**18**	**22**
Z+jets	2	1
Single t	9	9
WW,WZ,ZZ	0.1	0.1
Total Exp	**244**	**232**
Data	**240**	**235**

$$* = \sqrt{2 p_T^{\ell} p_T^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

Searches for new phenomena with top:backgrounds (I)

- ***QCD***

- “Fake” leptons: mis-id jets,γ→e^+e^-, non-prompt leptons (b/c-decays)



- **Derive shape template**←control region
  - *jet triggered events with exac. 1 high-em content jet (bef b-tag)*
  - *electron-triggered events with e failing hadronic leakage cut (only used for e-chan)*
  - *reject events with good electrons*

- **Normalize by fitting low E_T^{miss} shape** *(QCD template + simulated samples for tt,single top, W/Z+jets)* **to data→extrapolate to** standard region

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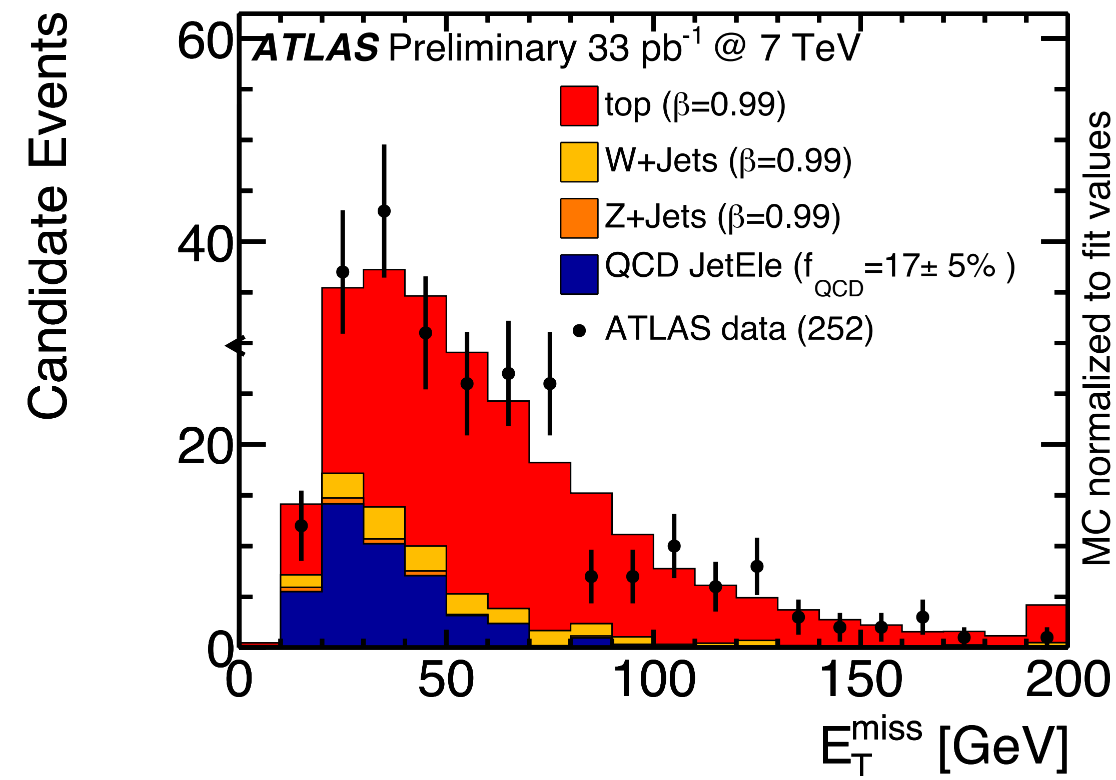

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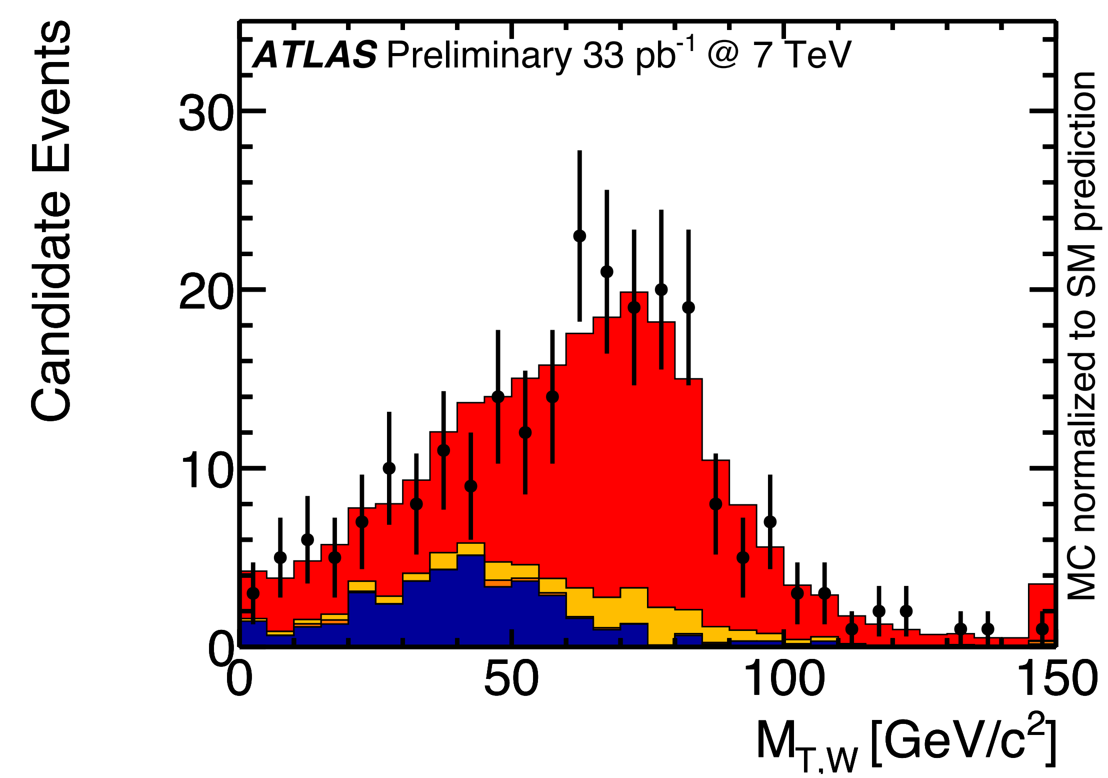
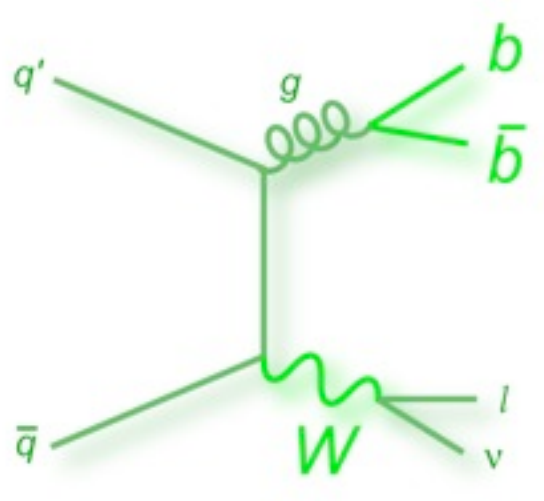


Same model for electron and muon channel

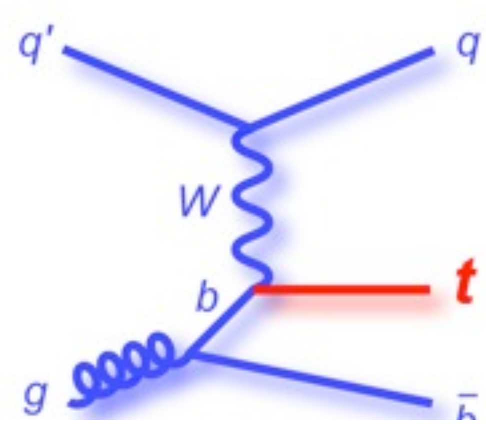
Searches for new phenomena with top: backgrounds (II)

W+jets

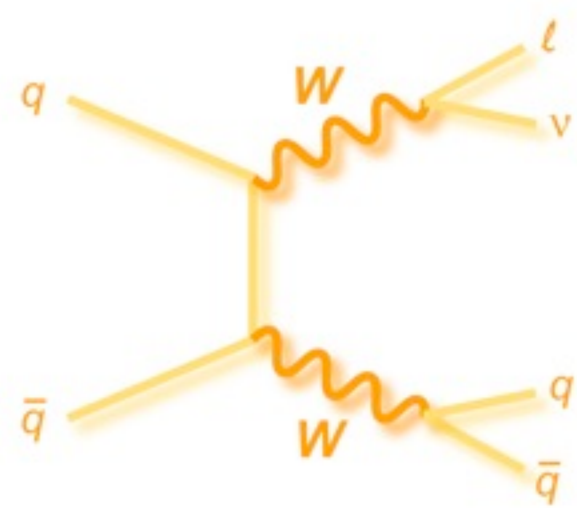


- *simulated shape*
- ***data-driven relative normalization for different light parton multiplicity*** ←*fit jet multiplicity in W+jets enhanced* control region
  - *(b-tag veto,1 hard lepton, E_T^{miss} and M_T^W window ~95% W+jets)*
- ***overall normalization*** *for high jet multiplicity bins (>=4) ←extrapolate content of 2 jet bins (after tagging)*

Single top

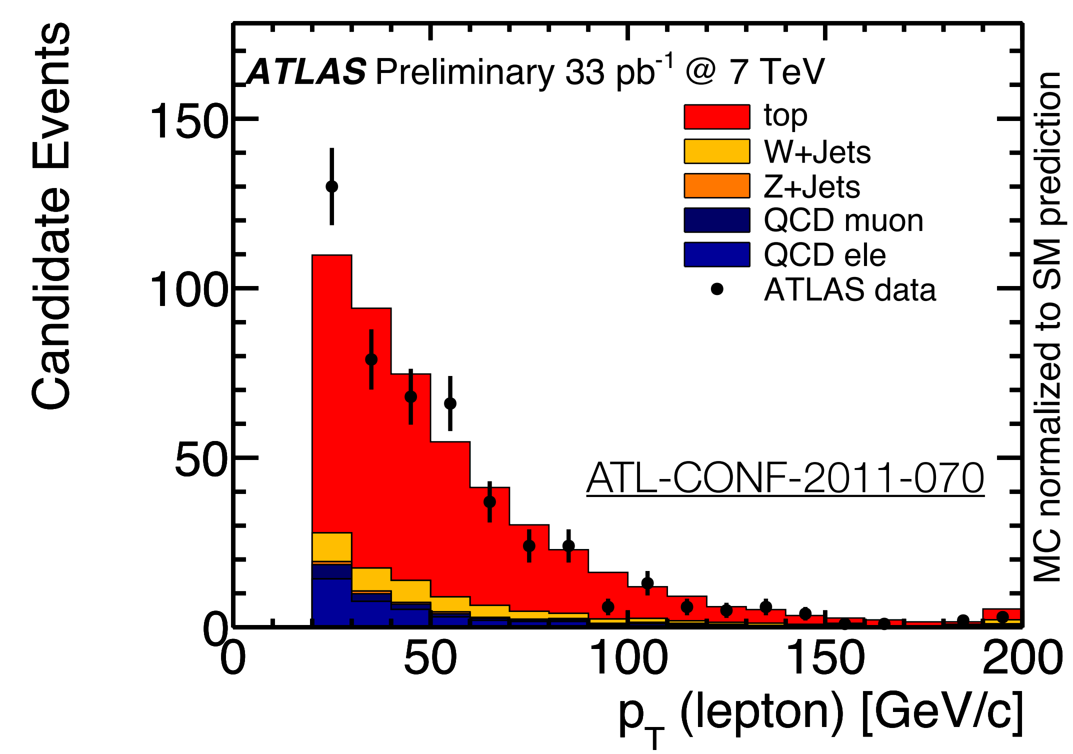


Di-bosons (WW,WZ,ZZ)



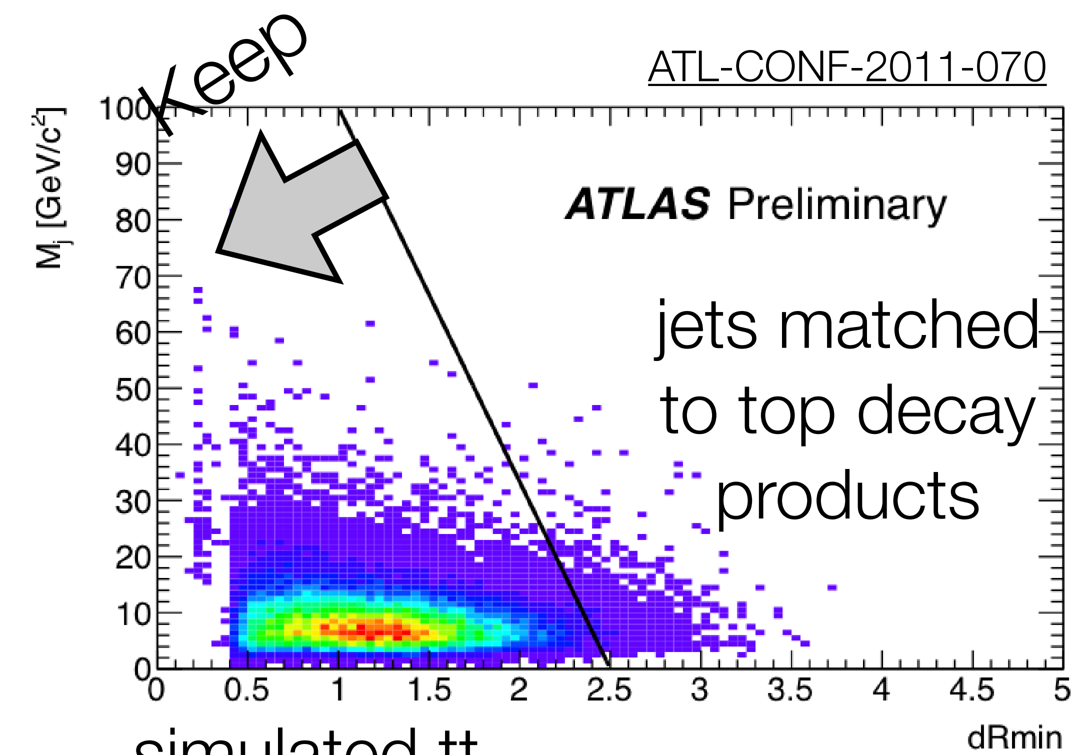
Simulated+ rate set to SM prediction

After all cuts

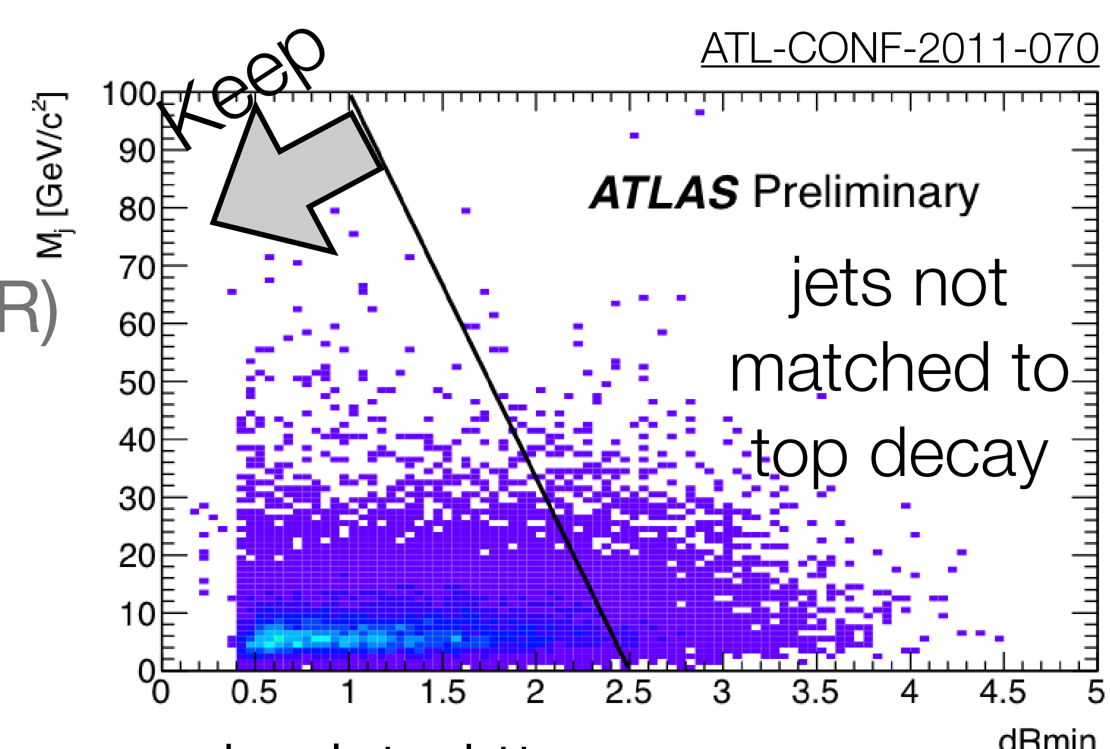


Searches for new phenomena with top: Mass reconstruction (I)

- Sum four momenta of
  - **lepton**
  - **E_T^{miss}**, p_Z from W mass constraint with E_T^{miss} rescaling in case of negative discriminant
  - **jets**
    - **Consider 4 leading p_T jets with p_T >20 GeV . Exclude the jet** for which
      - ❖min(DR (jet,closest jet), DR(jet,lepton)) > 2.5 -0.015 m_{jet}
        - ❖ if >1 jet, take jet with largest (min DR)
          - ❖ (max p_T)
    - **Continue until four or three highest p_T jets remain**
      - ❖reduce far away ISR/FSR jets i.e long non-gaussian tails



simulated tt



simulated tt

Searches for new phenomena with top: Mass reconstruction (II)

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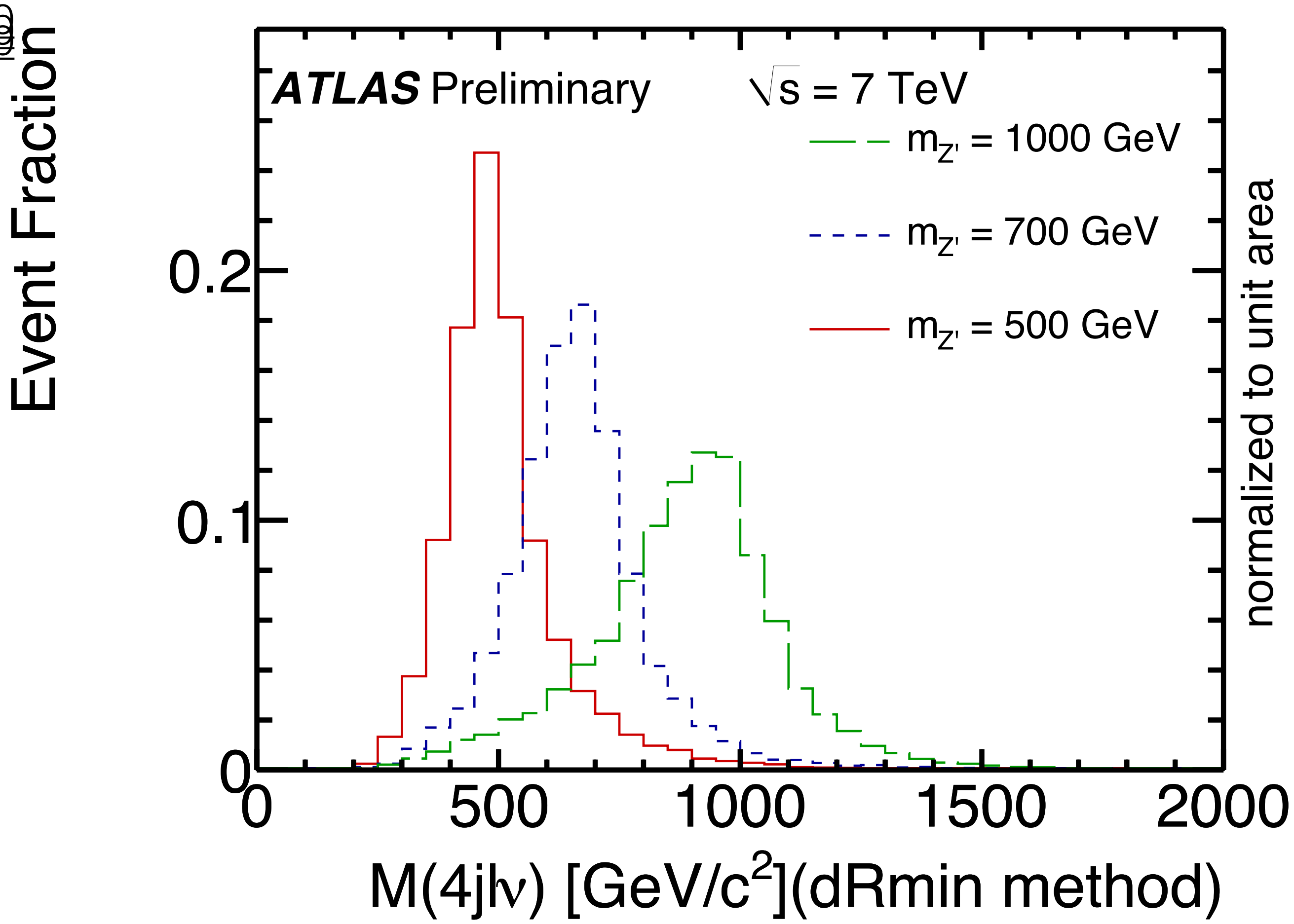

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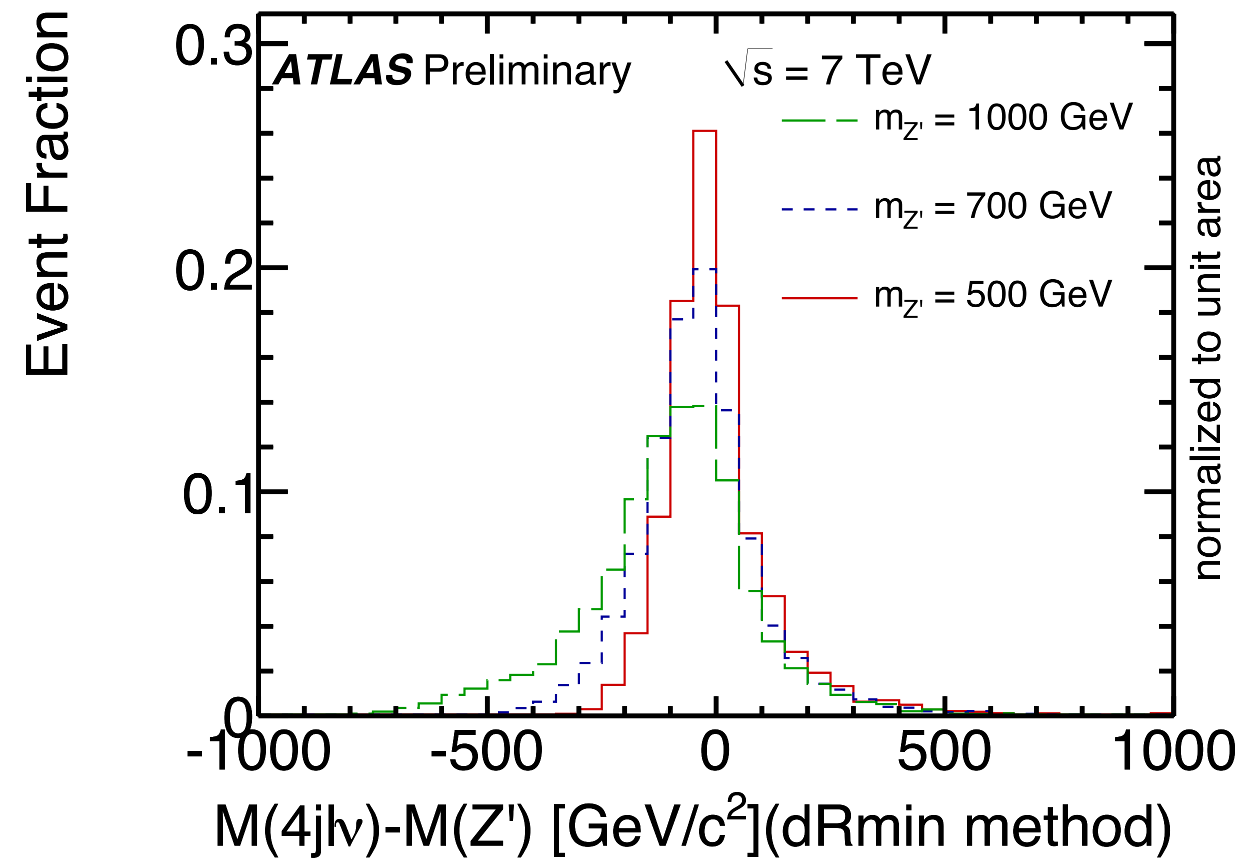

resolution

mass

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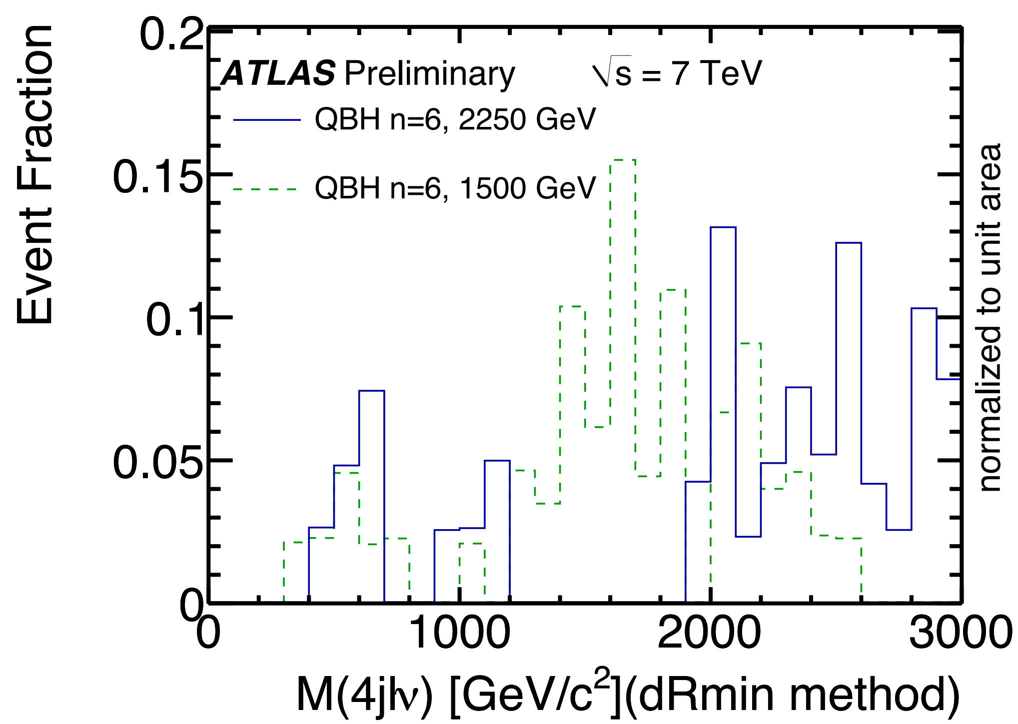

Searches for new phenomena with top: Mass reconstruction (II)

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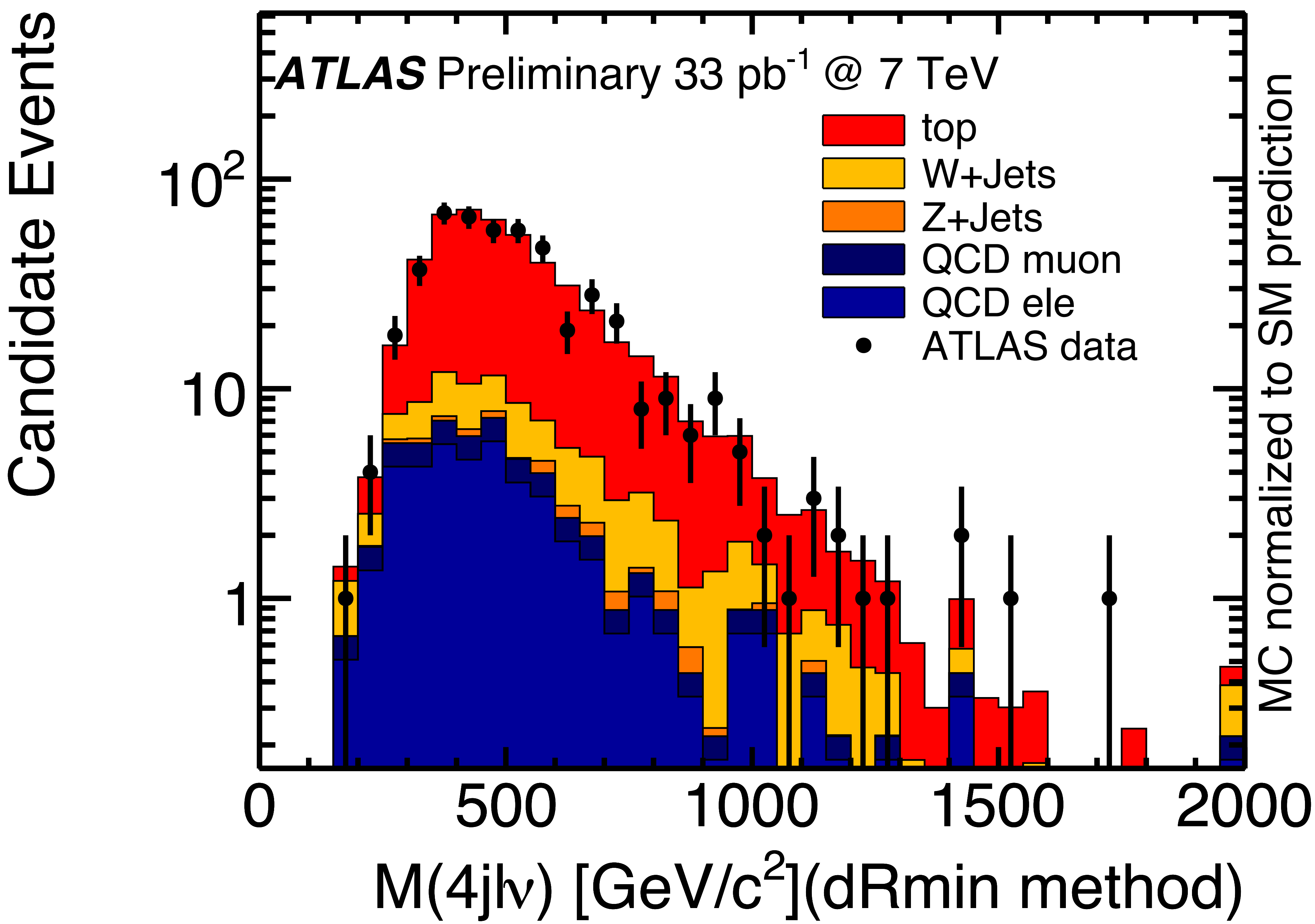

el and μ channel combined

Searches for new phenomena with top: systematic uncertainties

Shape % effects on yields

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Source	Top	W+jets	Other	Z', $m_{Z'}$ = 500 GeV
Jet energy scale	+13% -7.5%	+26% -18%	+15% -8.7%	+14% -8.1%
Jet energy resolution	+12%	+20%	+36%	+14%
Jet reconstruction efficiency	-3.9%	-6.4%	-9.2%	-3.9%
b-tagging efficiency [37] (incl. mistag rate)	+20% -18%	+46% -41%	+34% -34%	+21% -19%
Top quark mass (170 and 175 GeV)	+3.3% -5.0%	- -	- -	- -
$m_{t\bar{t}}$ Shape	±4.0%	-	-	-
Parton shower & Fragmentation	±5.8%	-	-	-
Final-state radiation (FSR)	+7.2% -7.6%	- -	- -	+6.3% -3.2%
Initial-state radiation (ISR)	+4.3% -8.2%	- -	- -	+3.6% -1.2%
ISR+FSR	- -4.1%	- -	- -	+2.5% -4.2%

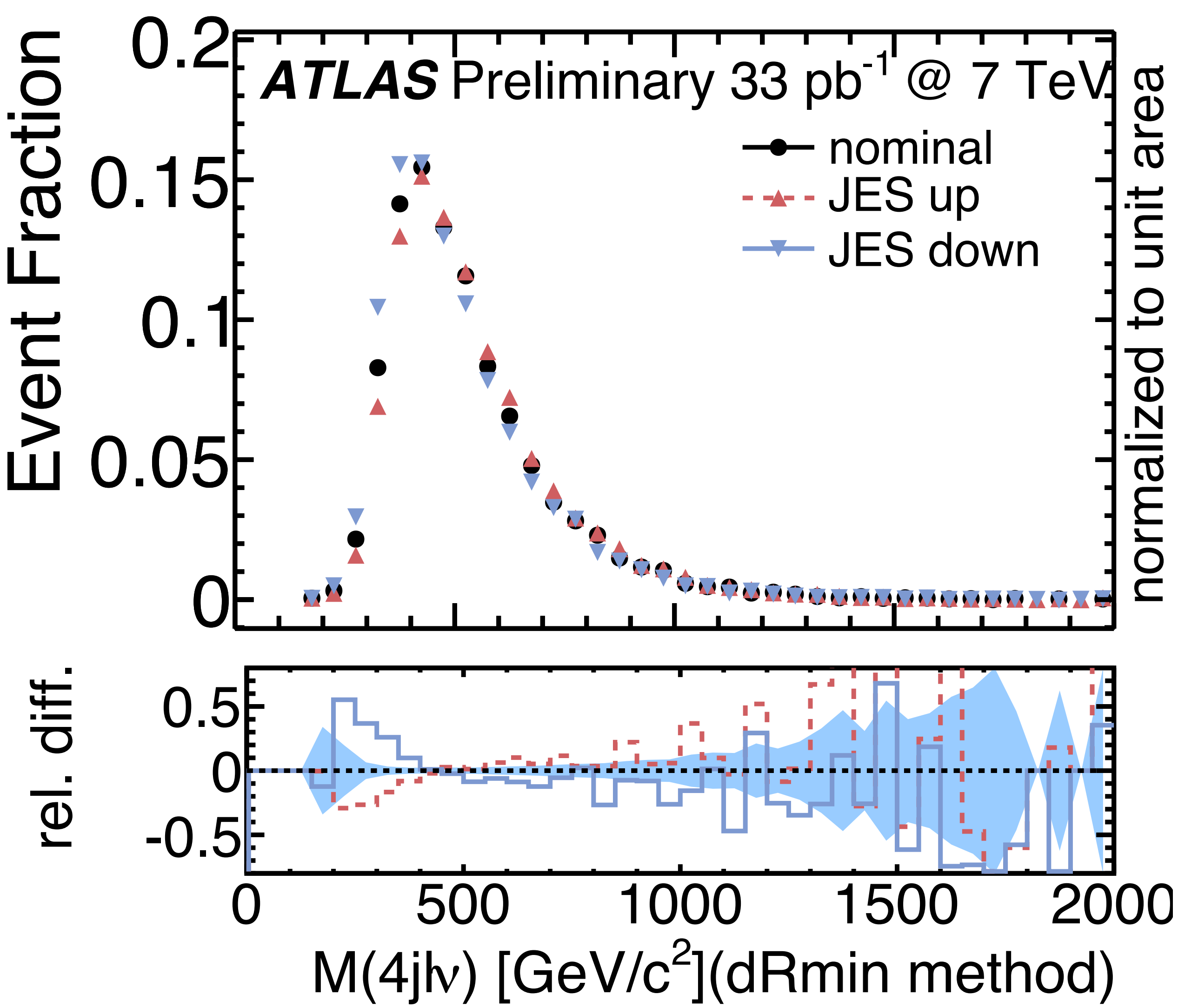
- B-tagging and jet properties (scale, resol, reco eff) are dominant
- ISR/FSR are important for top

Normalization

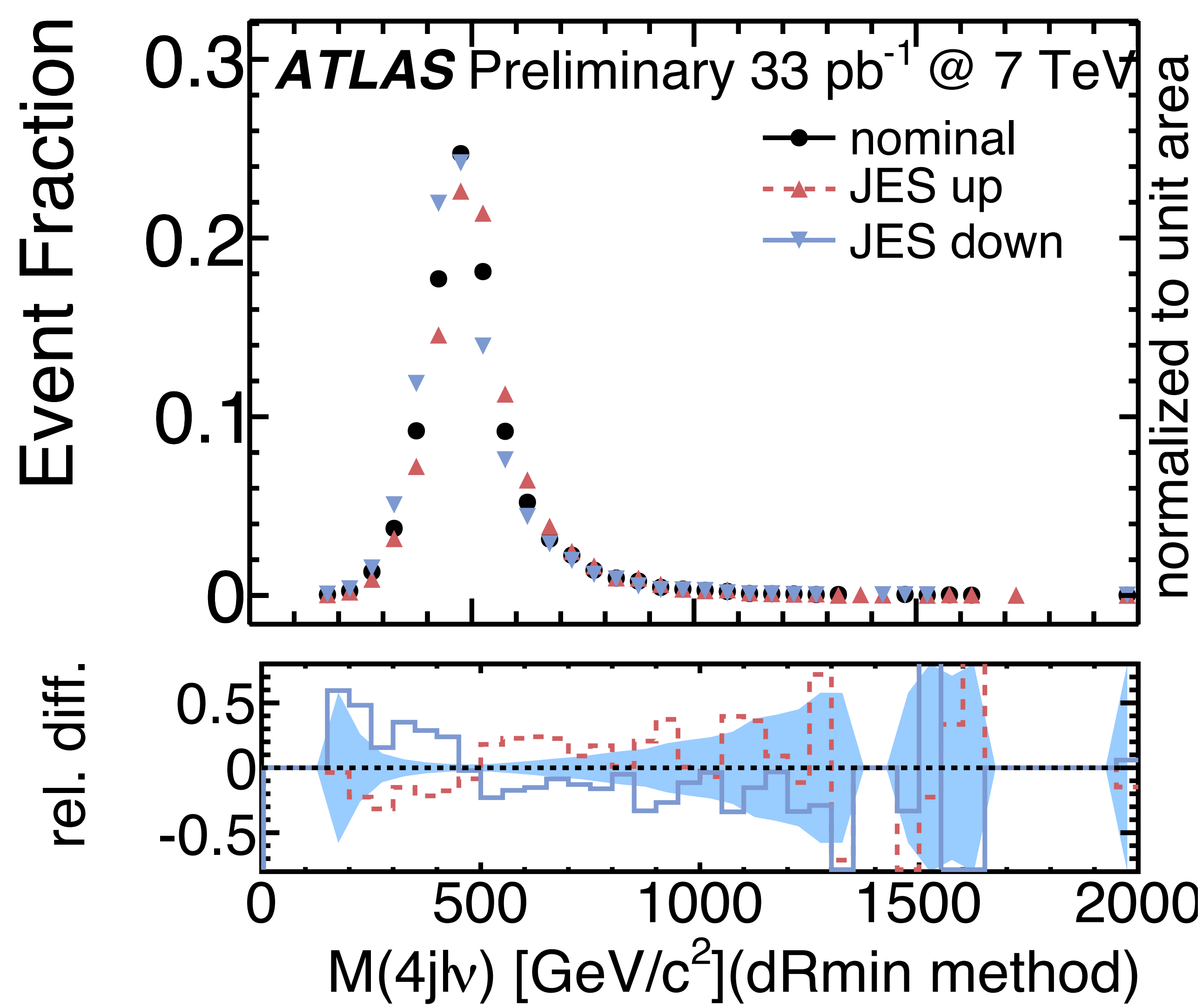
- Lumi~3.4%
- Bkg Norm : tt (6%), W+jets (35%), single top (10%), diboson (5%), QCD (30% el, 50% for μ)
- Lepton reco efficiencies <3.5%, lept id. and pile-up<1%

Systematics example on shape: JES

statistical uncertainty on nominal



simulated $t\bar{t}$



Z' with $m_{Z'}$ =500 GeV

Searches for new phenomena with top: Results

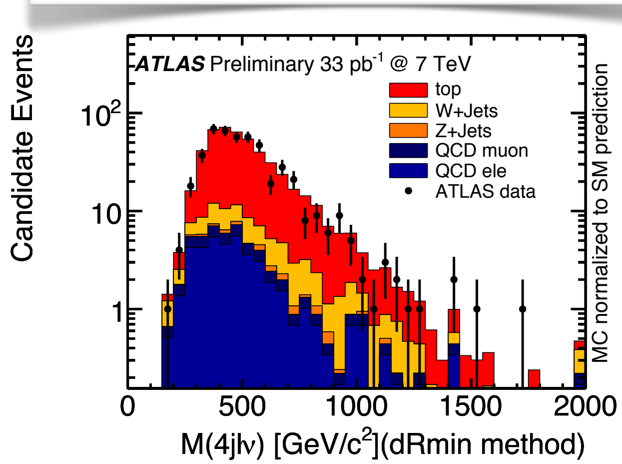
- Compare data to Standard Model prediction. **No excess found.**

Set limit

one spectrum

$$P(\sigma, \mathcal{L}, \epsilon, b|k, I) \propto \frac{e^{-(b+\mathcal{L}\epsilon\sigma)}(b+\mathcal{L}\epsilon\sigma)^k}{k!} P(\sigma|I)P(\mathcal{L}, \epsilon, b|I) ,$$

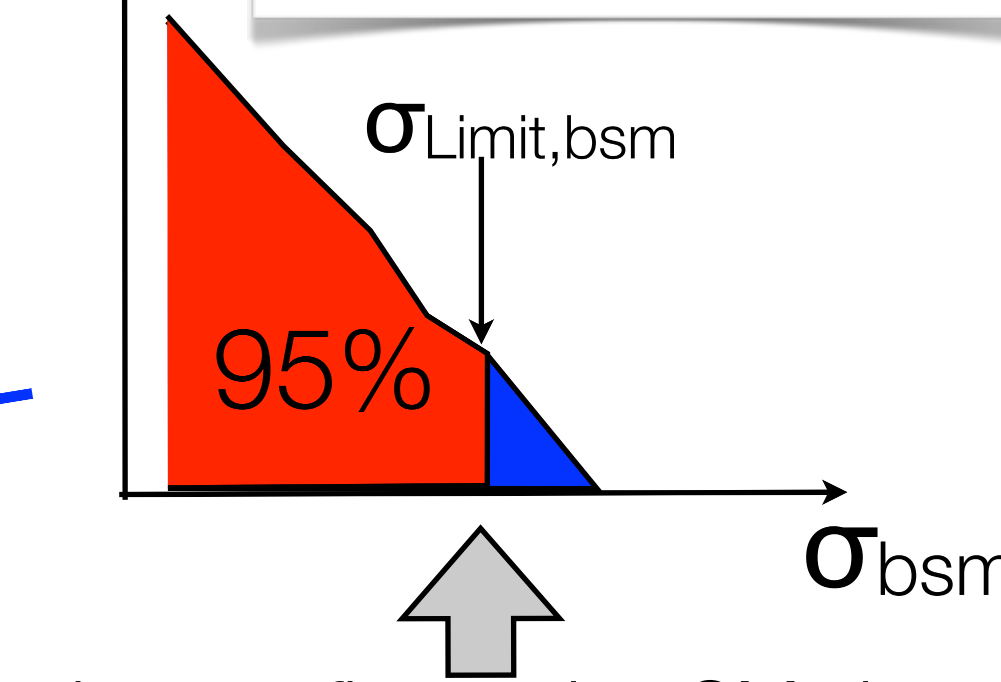
one likelihood value (LKL)



$\sigma = \sigma_{BSM}$

FLAT PRIOR

One limit:95% of $\int Lkl(\sigma_{bsm})\, d\sigma_{bsm}$



BSM=Z' or QBH

Data: do it once

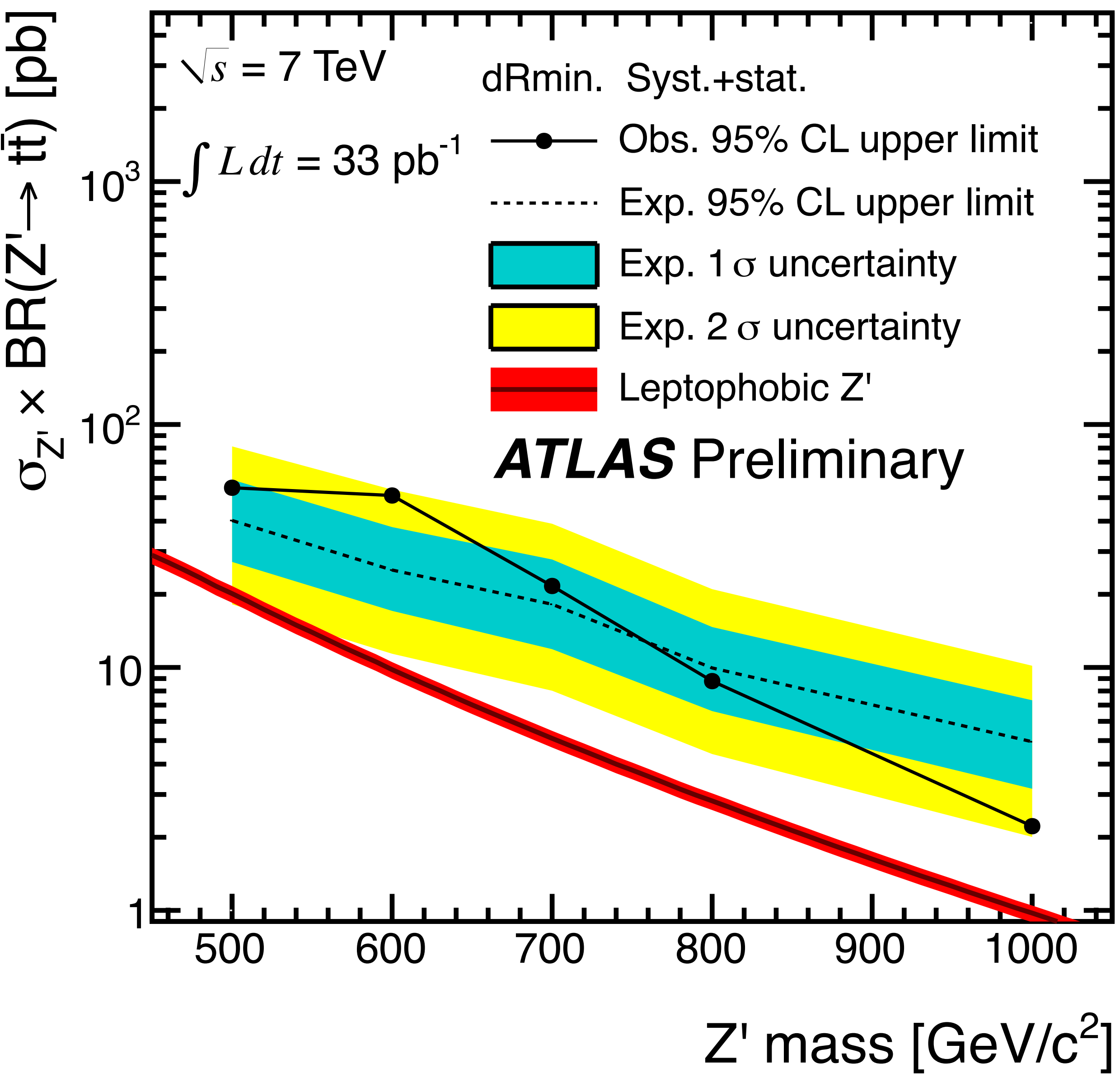
Monte Carlo: take SM only, fluctuate bins content for 5000 exp i.e. 5000 limits

Expected limit = Median of limits,
Error bands = Spread of limits

Include syst: fluctuating SM shape with Gaussian/Log-Normal for each syst then average to get one LKL

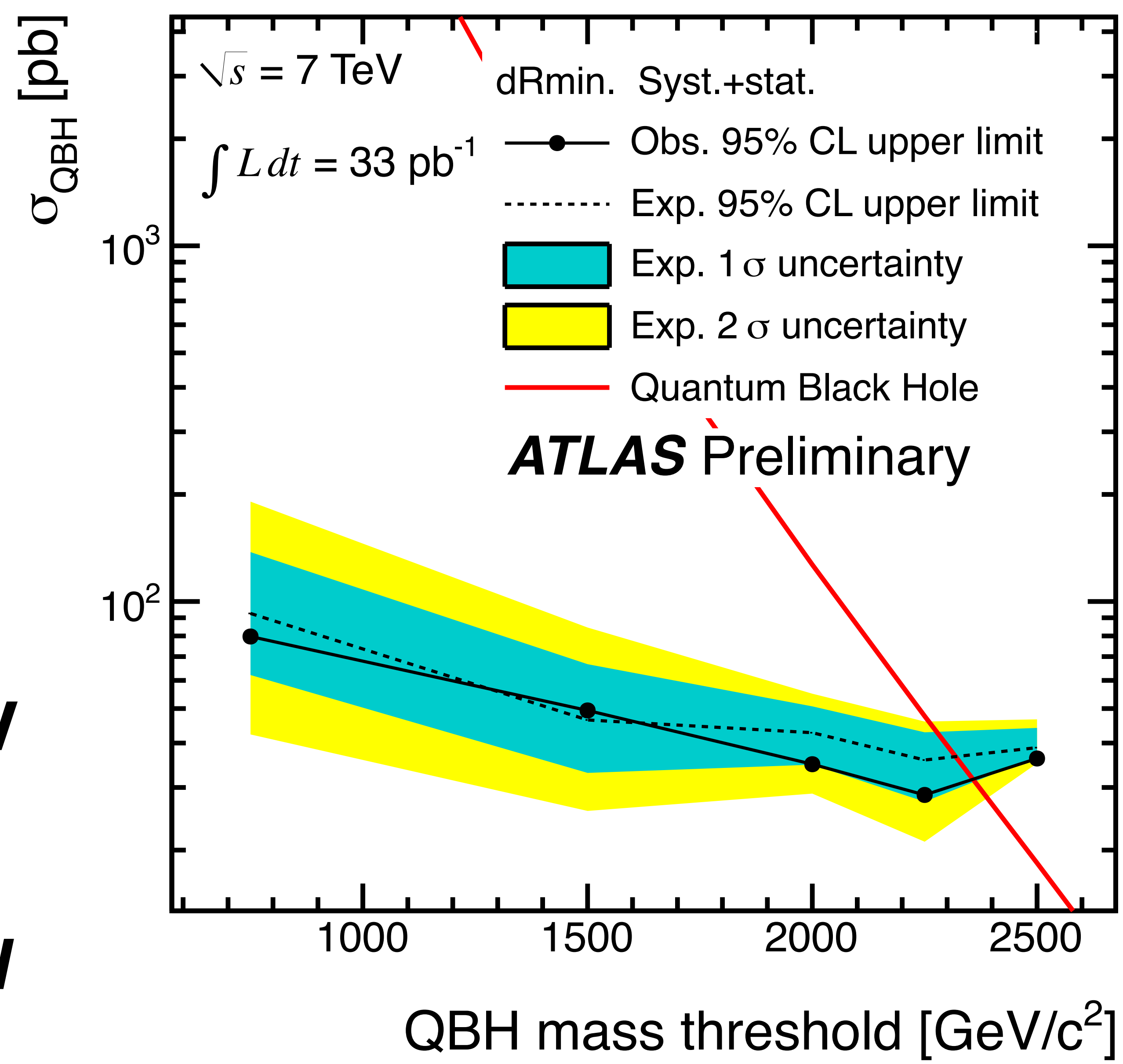
Searches for new phenomena with top: Results

ATL-CONF-2011-070



95%CL observed (expected) u**pper limit on Z' xsec**
from **55** (40) pb $m_{Z'}$=500 GeV
to **2.2**(5) pb $m_{Z'}$=1 TeV

ATL-CONF-2011-070

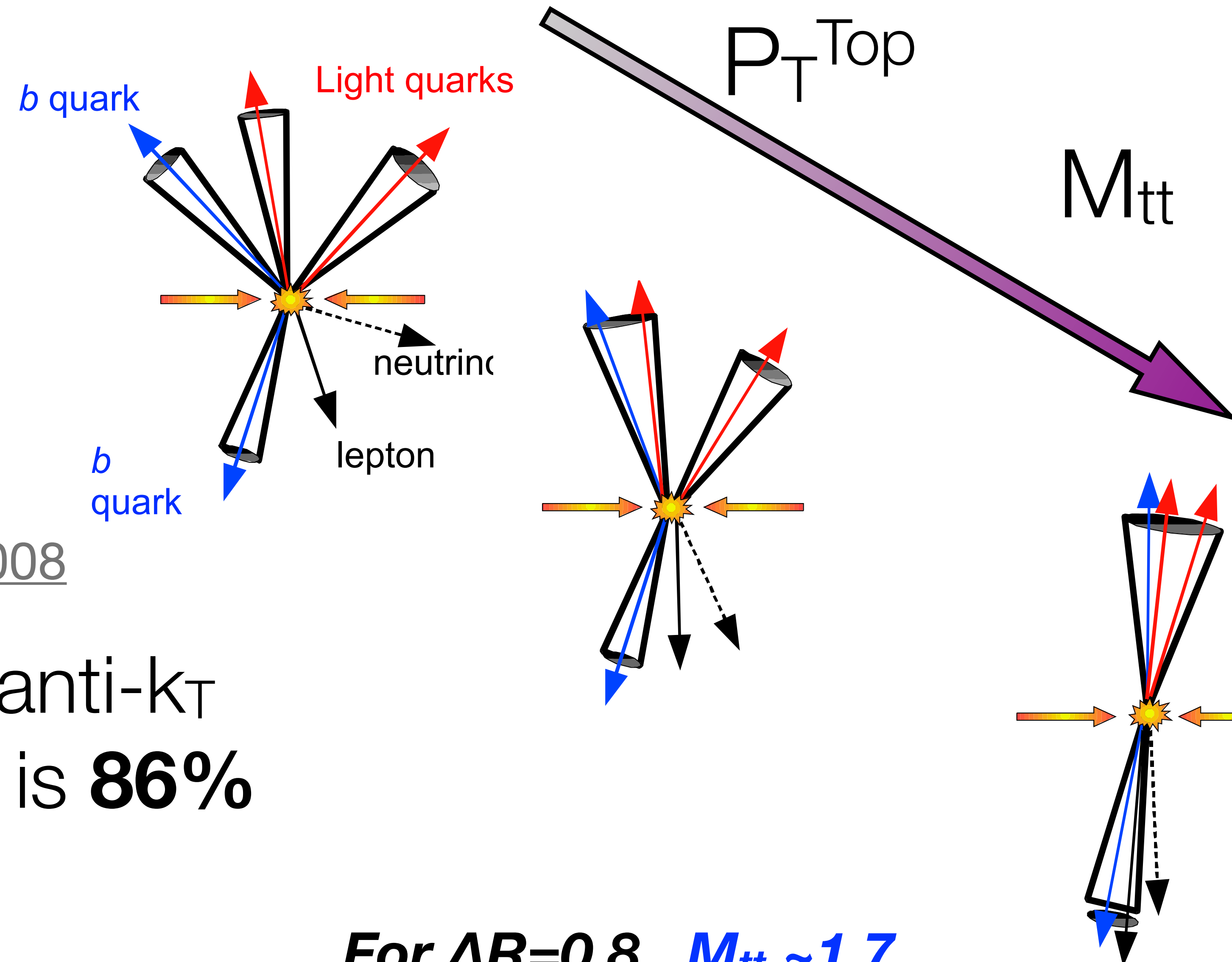


t+X production with Quantum Black Hole **mass threshold below 2.35 TeV is excluded @95%CL**

Analysis with ~200 pb^{-1}: advanced

Where to from here? Towards new territory...

Resolved



ATLAS-PHYS-PUB-2010-008

M_{tt} =1 TeV mass and anti-k_T (R=0.4): **resolved** case is **86%** of events

M_{tt} =with 2 TeV mass and antikt (R=0.8): **60%** events are **boosted**

For ΔR=0.8, M_{tt} ~1.7 TeV, P_T ~600 GeV

Boosted

..for which we see the ***first "boosted-like" signs (I)***

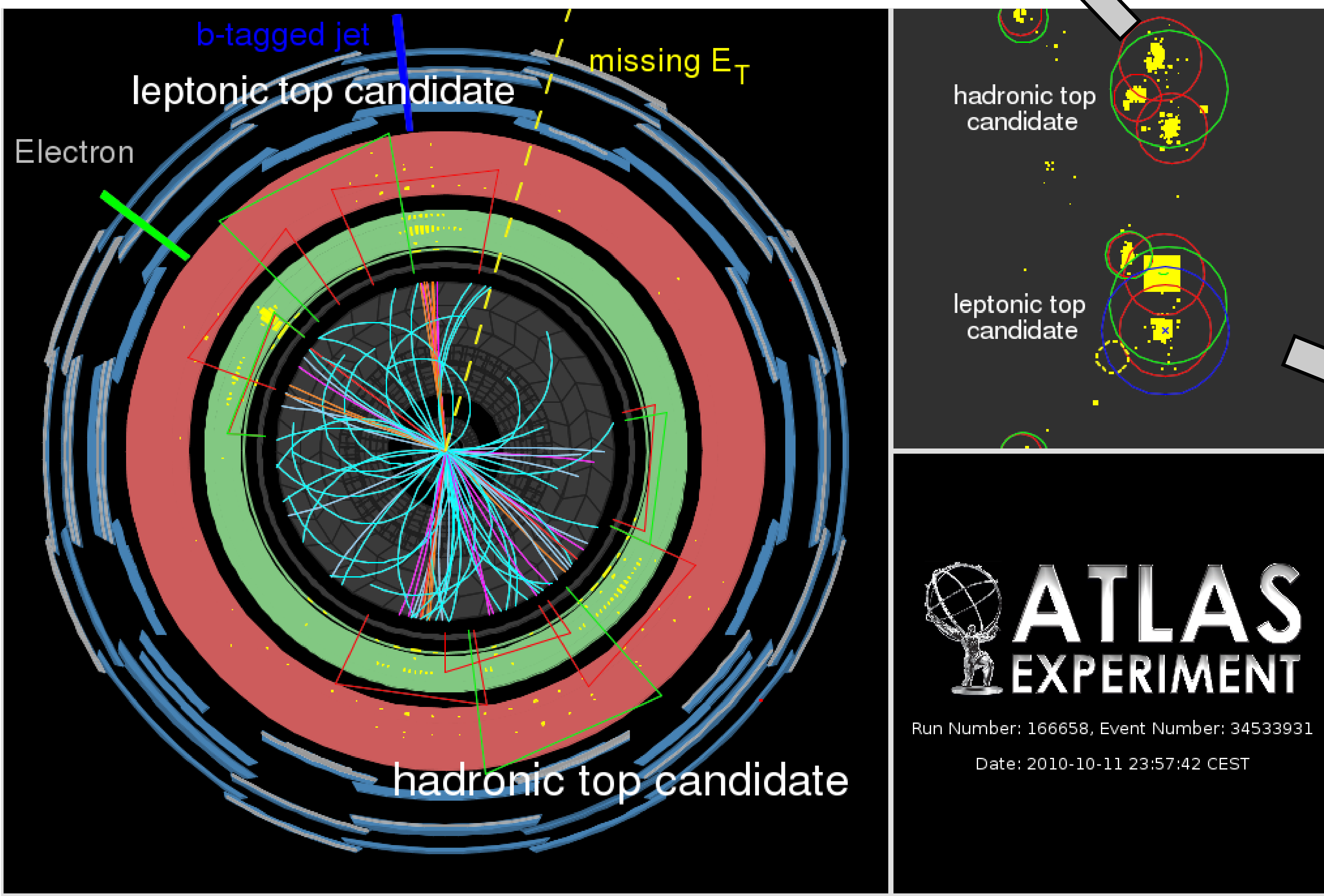
R=0.4

Jet1: m=22 GeV, E_T =155 GeV
Jet2: m=14 GeV, E_T =113 GeV
Jet3: m= 8 GeV, E_T = 54 GeV

→ R=1.0

1 jet, m=197 GeV
E_T= 356 GeV
d_{12}=110

r-ϕ view



η-ϕview

lepton, E_T^{miss}, Jet

m_{tt}^{reco} = 714 GeV

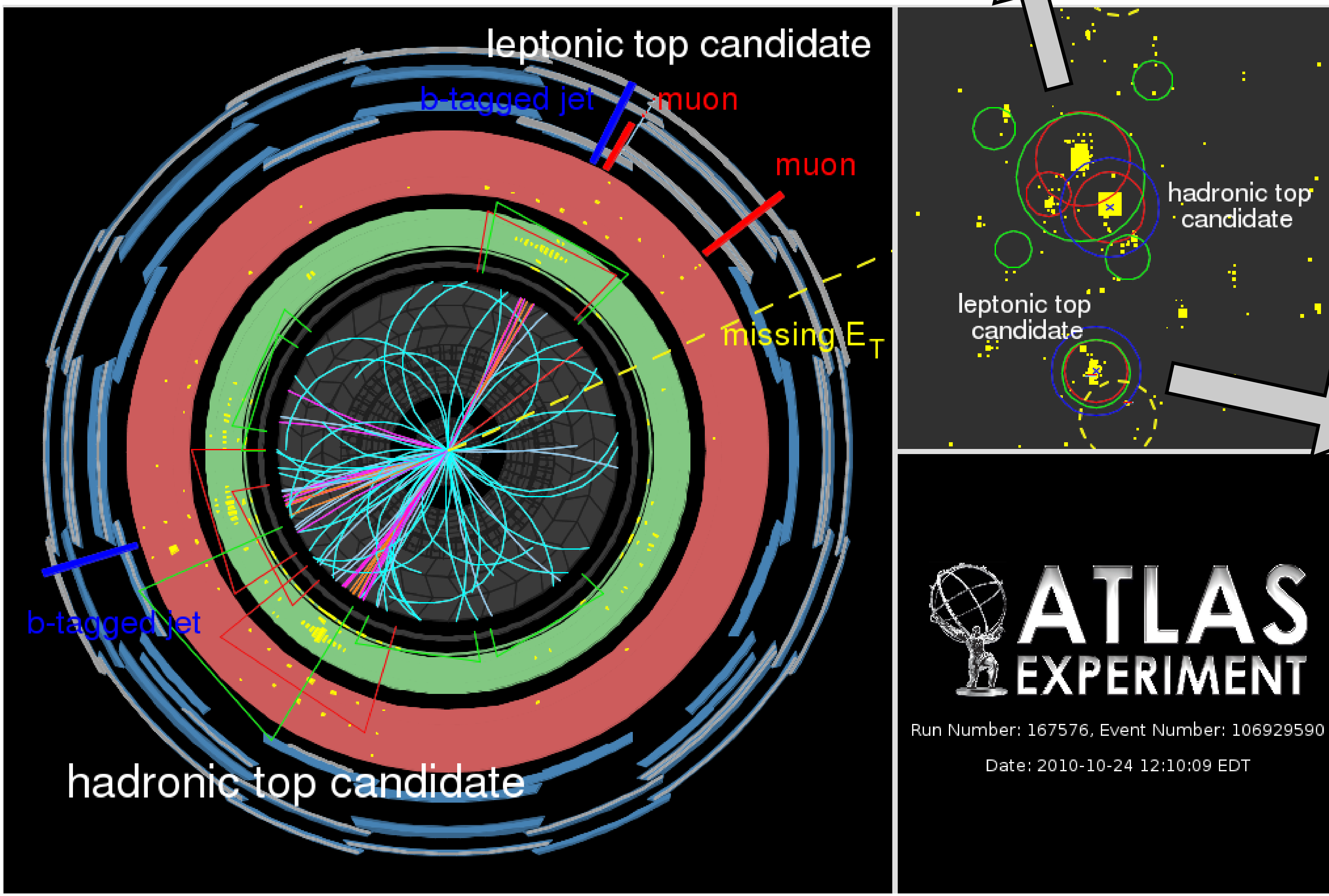
ATL-CONF-2011-073

..for which we see the ***first "boosted-like" signs (II)***

R=0.4
Jet1: m=18 GeV, E_T =205 GeV
Jet2: m=10 GeV, E_T =115 GeV → R=1.0
Jet3: m=11 GeV, E_T = 49 GeV

1 jet, m=225 GeV
E_T=418
d_{12}=105

r-ϕ view



η-ϕview

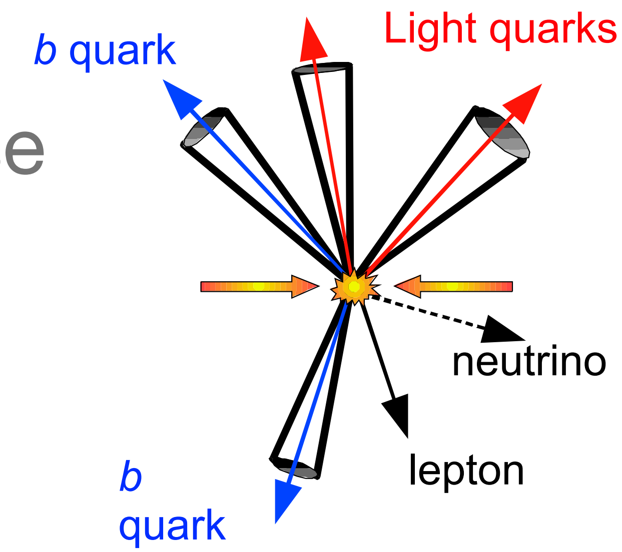
lepton,
E_T^{miss},
Jet

ATL-CONF-2011-073

Prospects: improving resolved reconstruction

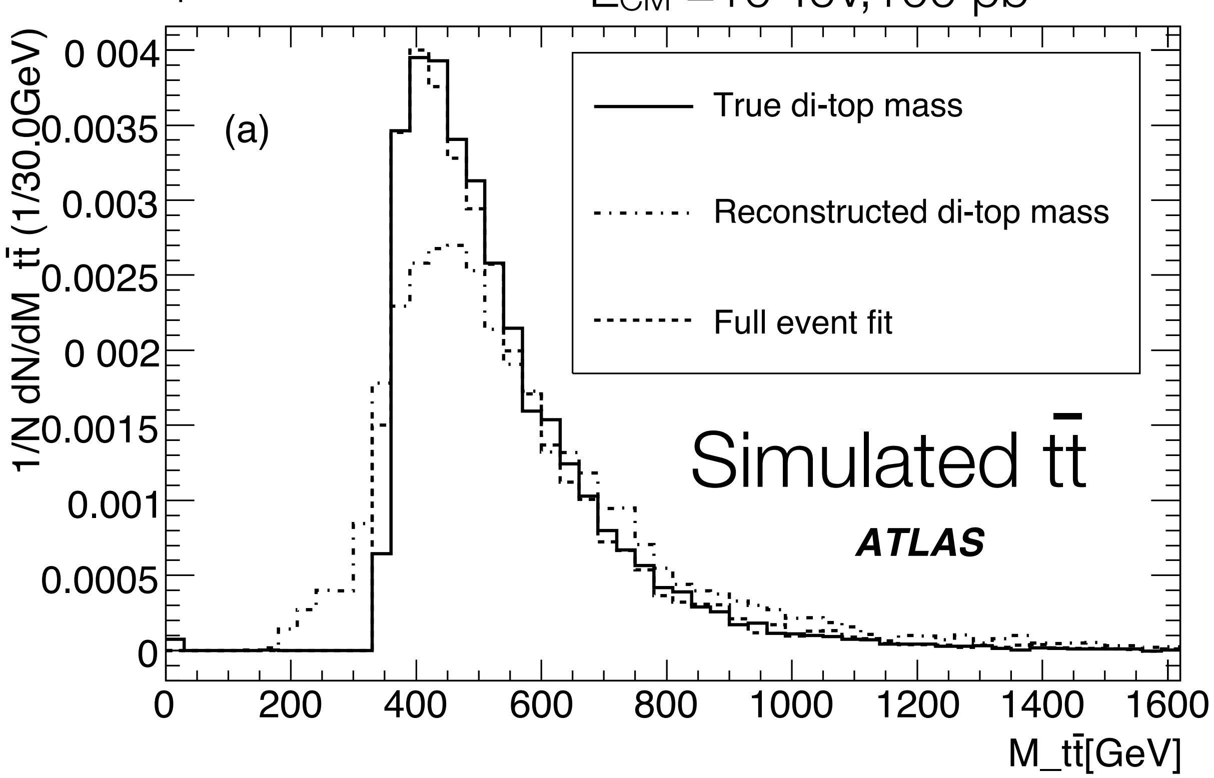
Resolved

- **At "low" M_{tt}**
  - **add final state objects** with χ^2 -based algo to choose jets
  - **perform kinematic fit** using M_W, M_{top}

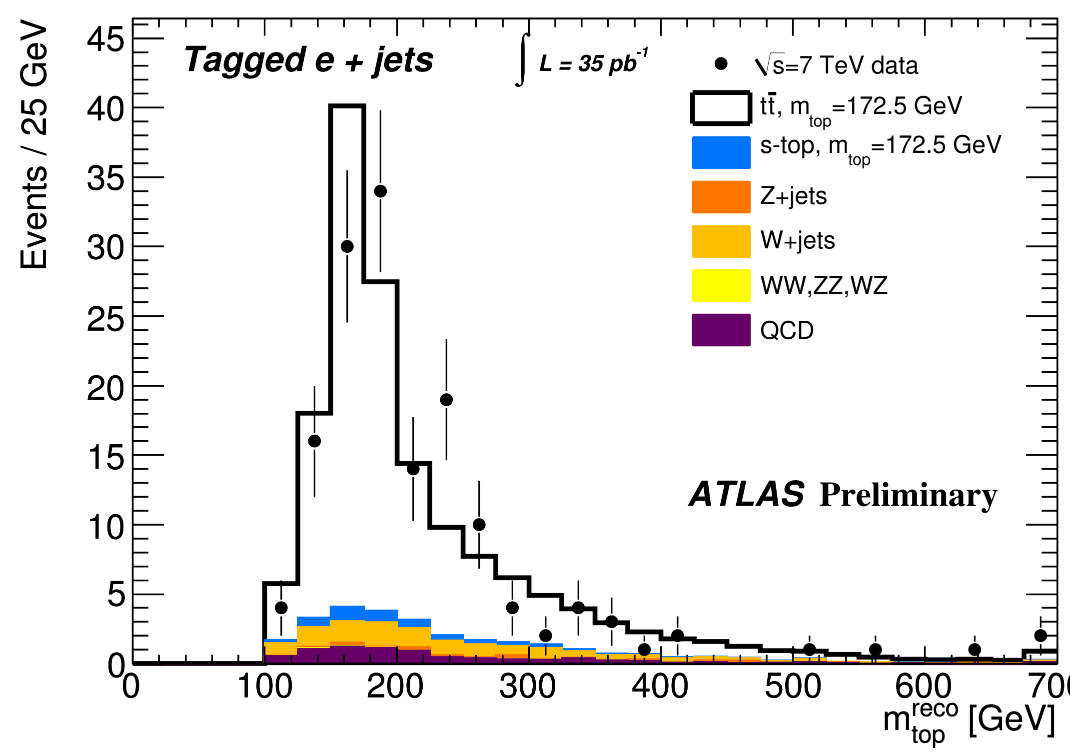


anti-k_T R=0.4

hep-ex:0901.0512 E_{CM} =10 TeV,100 pb^{-1}



ATLAS-CONF-2011-033

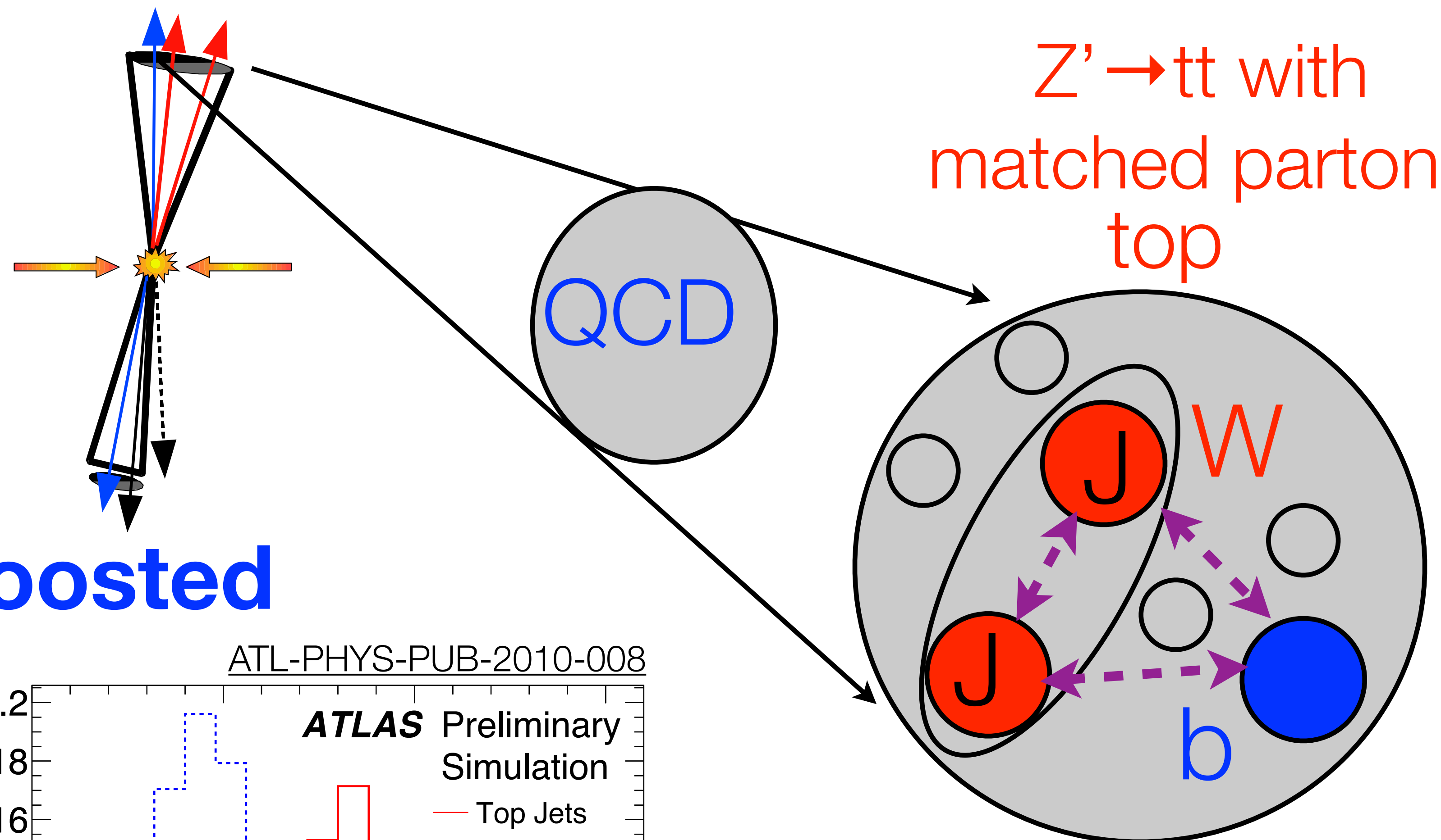


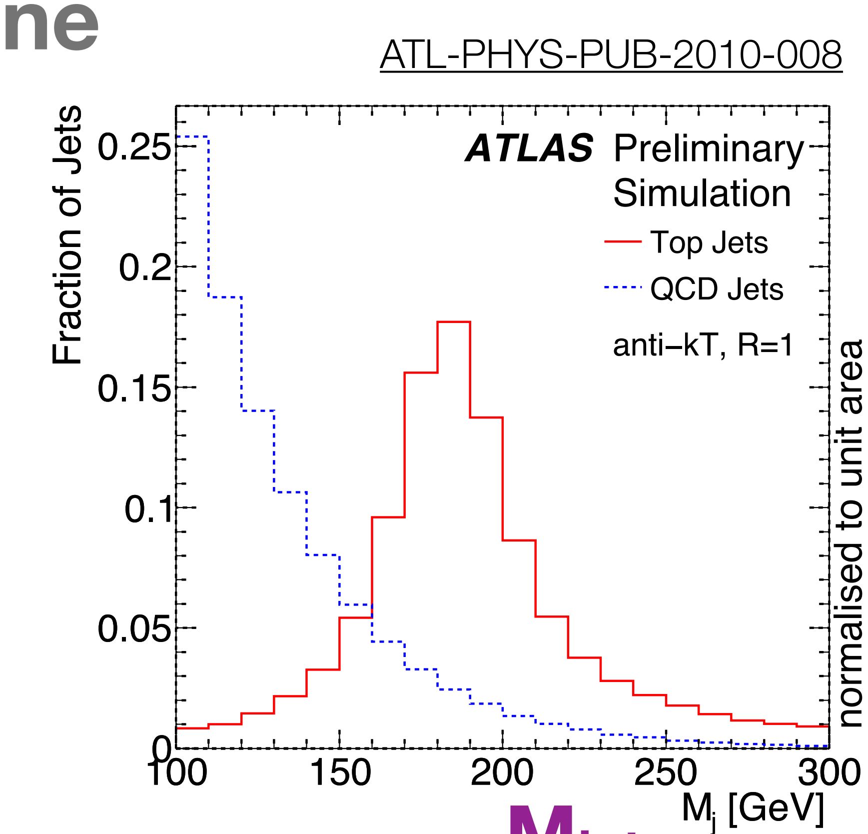
top shape from kine fitter

Prospects:reconstructing **had** boosted top jets

At higher p_T^{top} (M_{tt}) → "top jet" uses large cone

anti-k_T R=1.0, *$p_{T,jet}$ >200 GeV, M_{jet} >100 GeV*

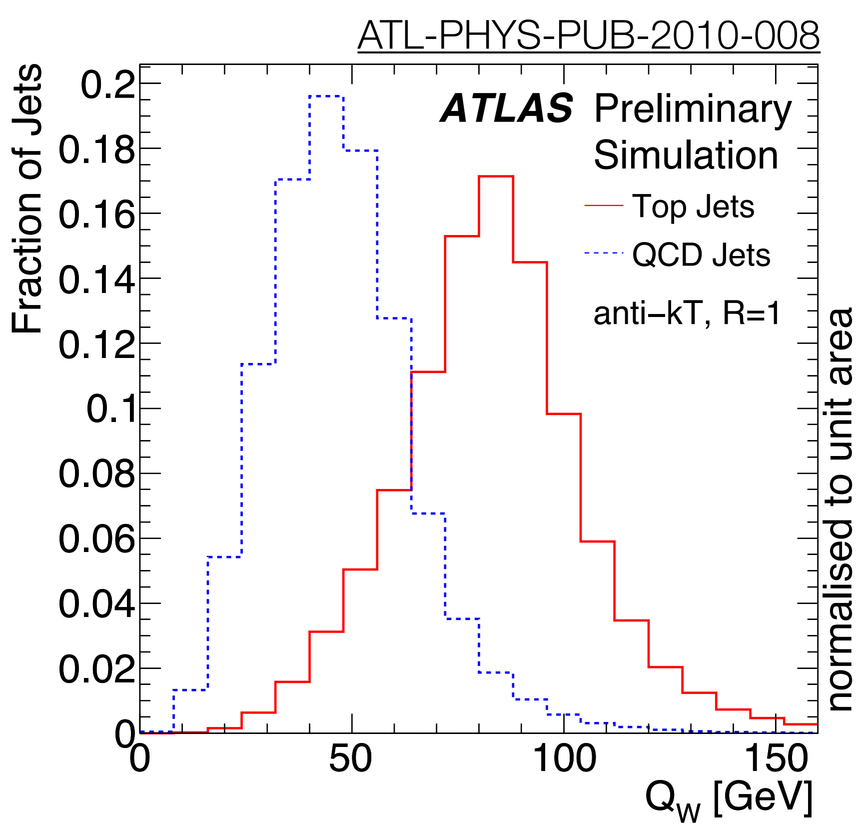




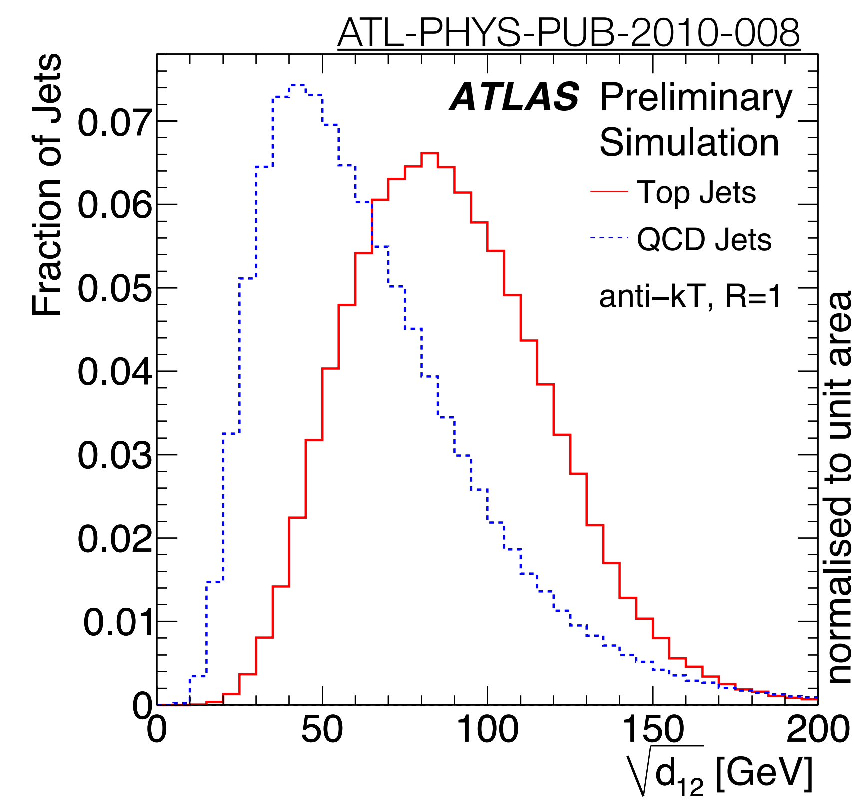
M_{jet}

Boosted

hadronic leg



mass of sub-jet pair
with lowest mass
force 1→3 split

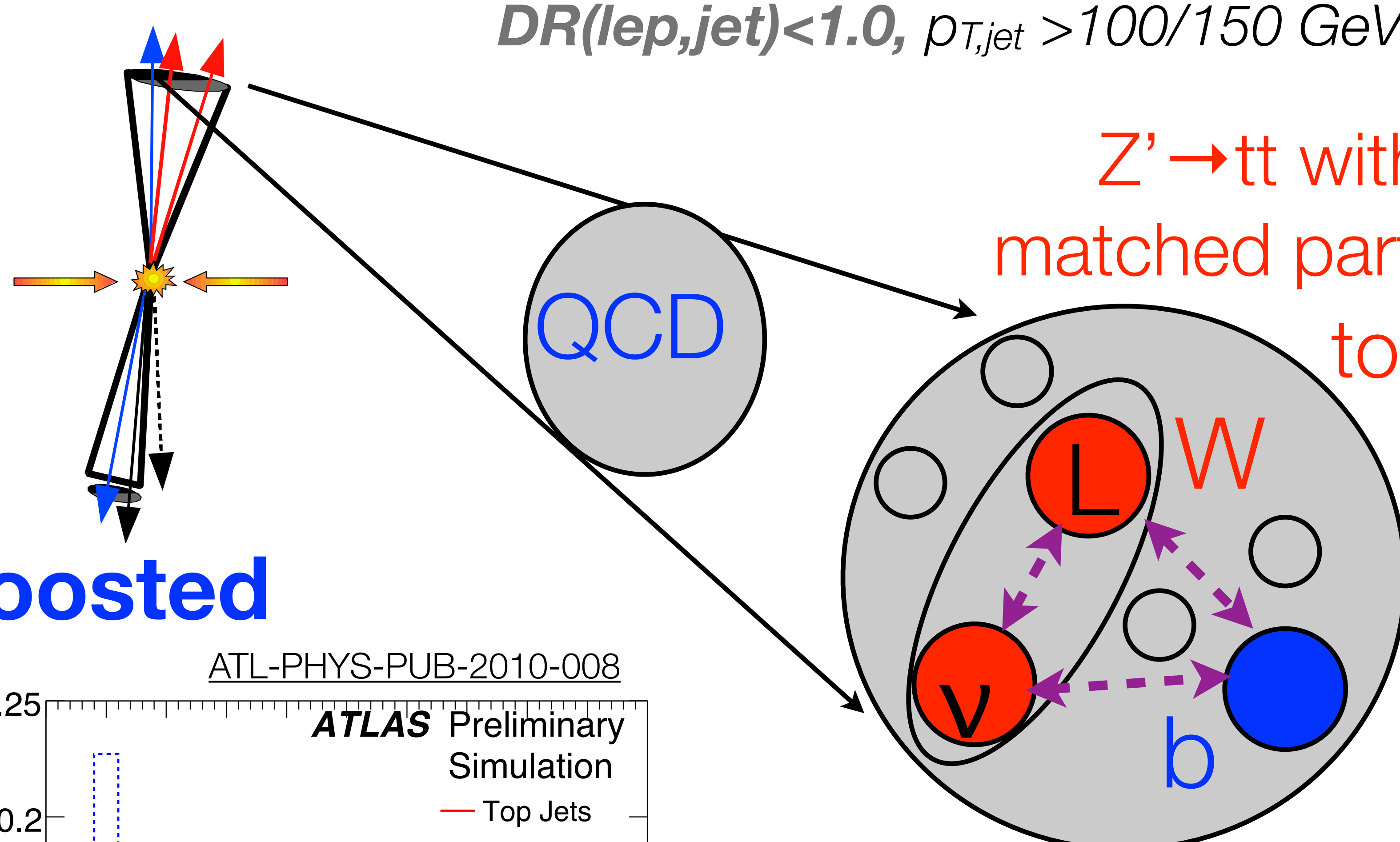


k_T distance of 1→2 splitting

Prospects: reconstructing **leptonic** boosted top jets

At higher p_T^{top} (M_{tt}) → lep **"top jet"** small b-lep distance: **non iso lepton → important b/c jets bkg**

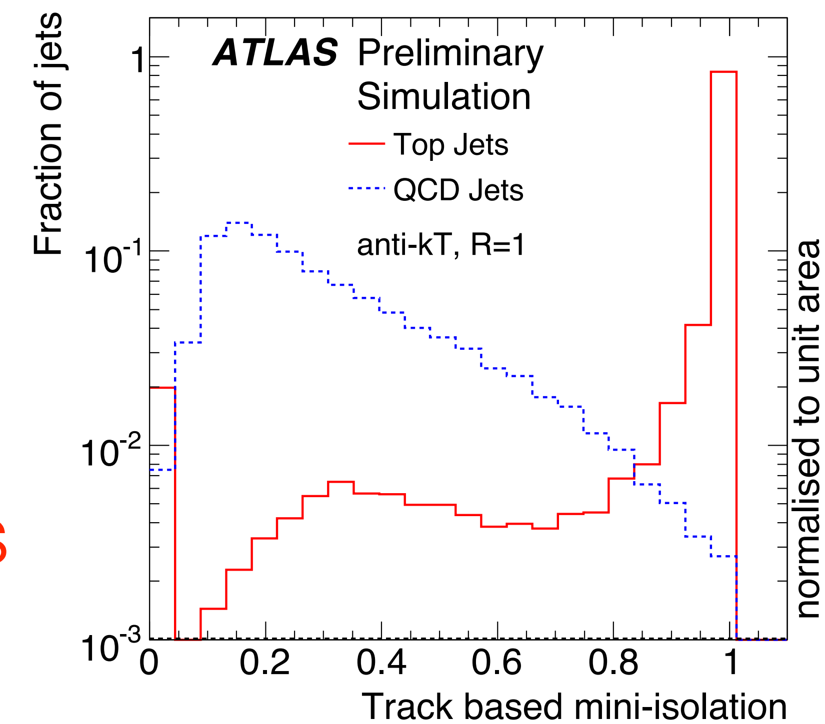
DR(lep,jet)<1.0, *$p_{T,jet}$ >100/150 GeV*



Boosted

leptonic leg

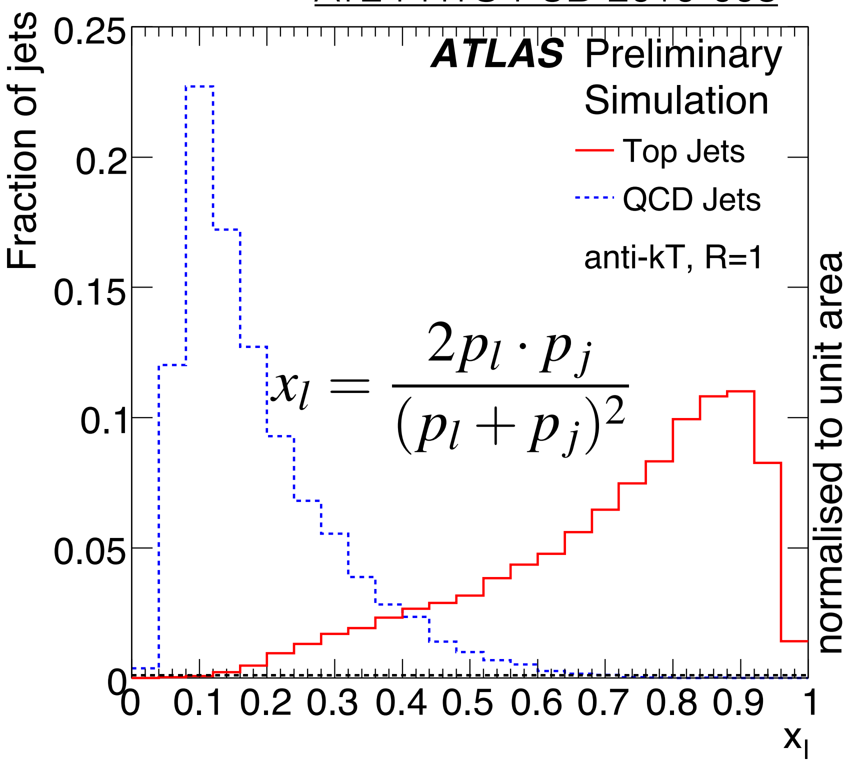
ATL-PHYS-PUB-2010-008



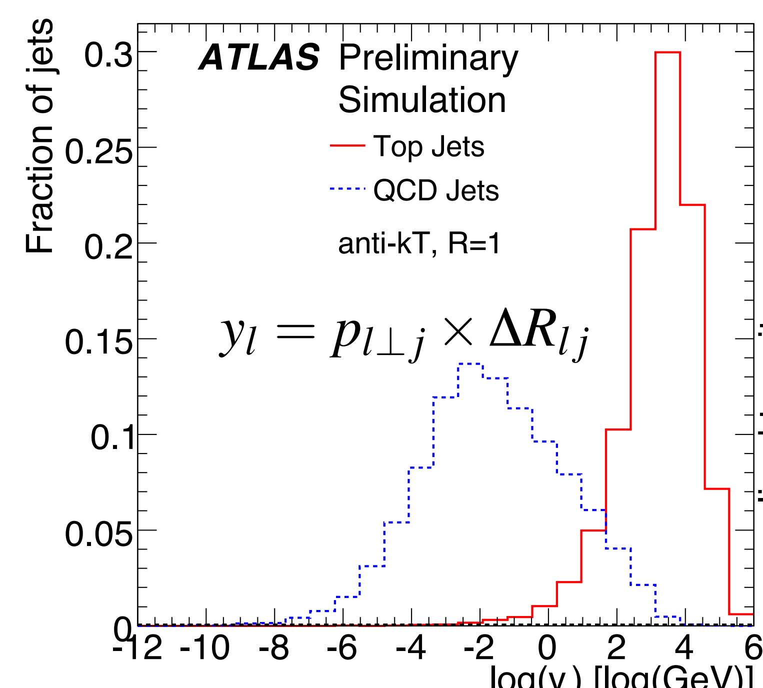
total energy in cone with p_T dependent-size

$\Delta R < 15 \text{ GeV } / p_T^l$

ATL-PHYS-PUB-2010-008



Fraction of jet mass carried by lepton

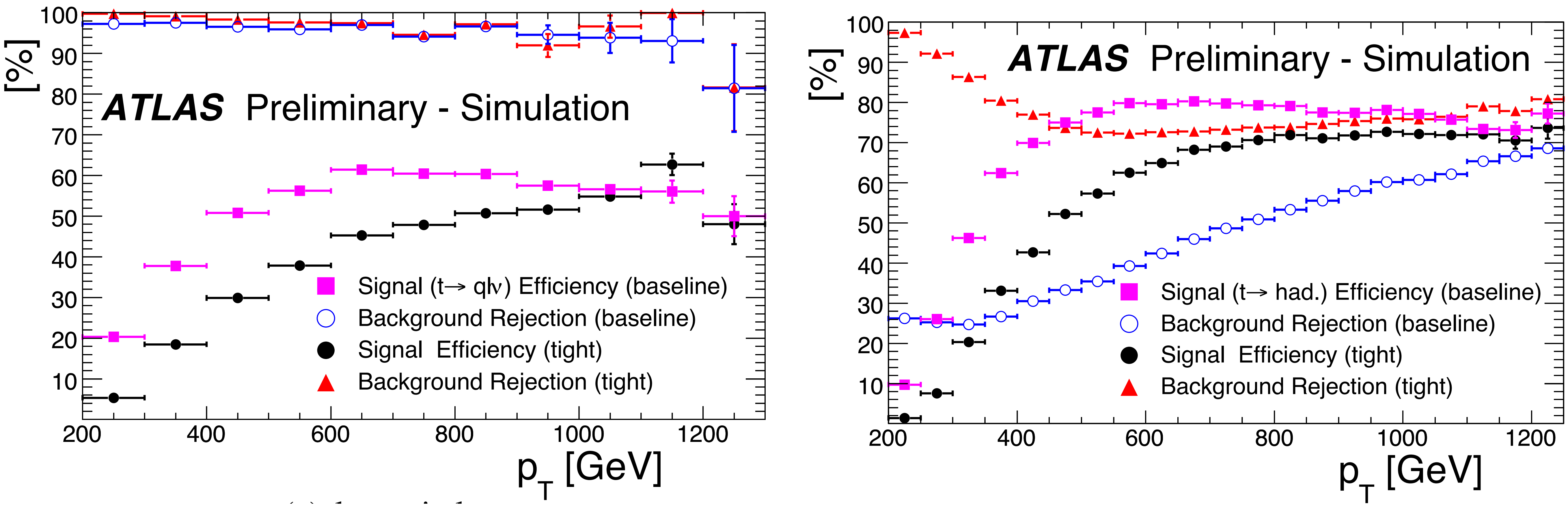


jet-lep k_T-like distance

Prospects: tagging top-jets

ATL-PHYS-PUB-2010-008

leptonic top *anti-k_T R=1.0,leading jet E_T>250 GeV* hadronic top

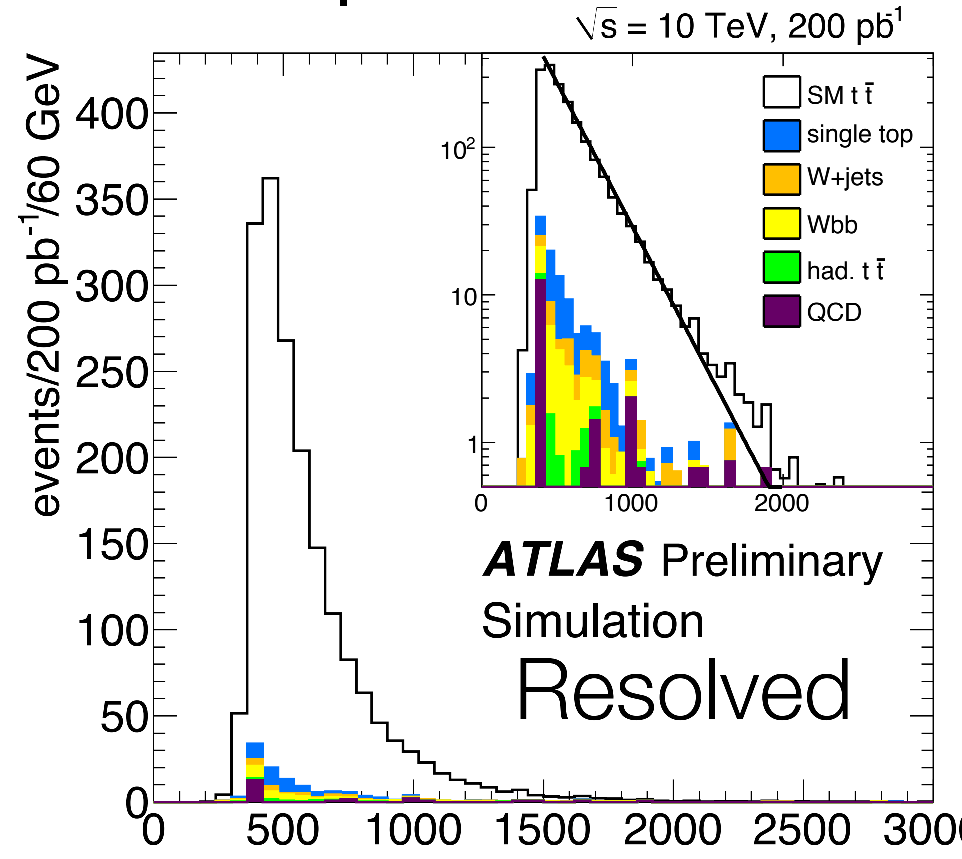


- Signal:tt, Bkg: Pythia QCD
- Pre-selection: standard semi-leptonic object definition
- Selection for early searches
  - **Leptonic**: cuts on alternative isolation variables
  - **Hadronic selection**: “mild” cuts on hadronic substructure to balance signal efficiency and bkg rejection
- No b-tagging (to start with)

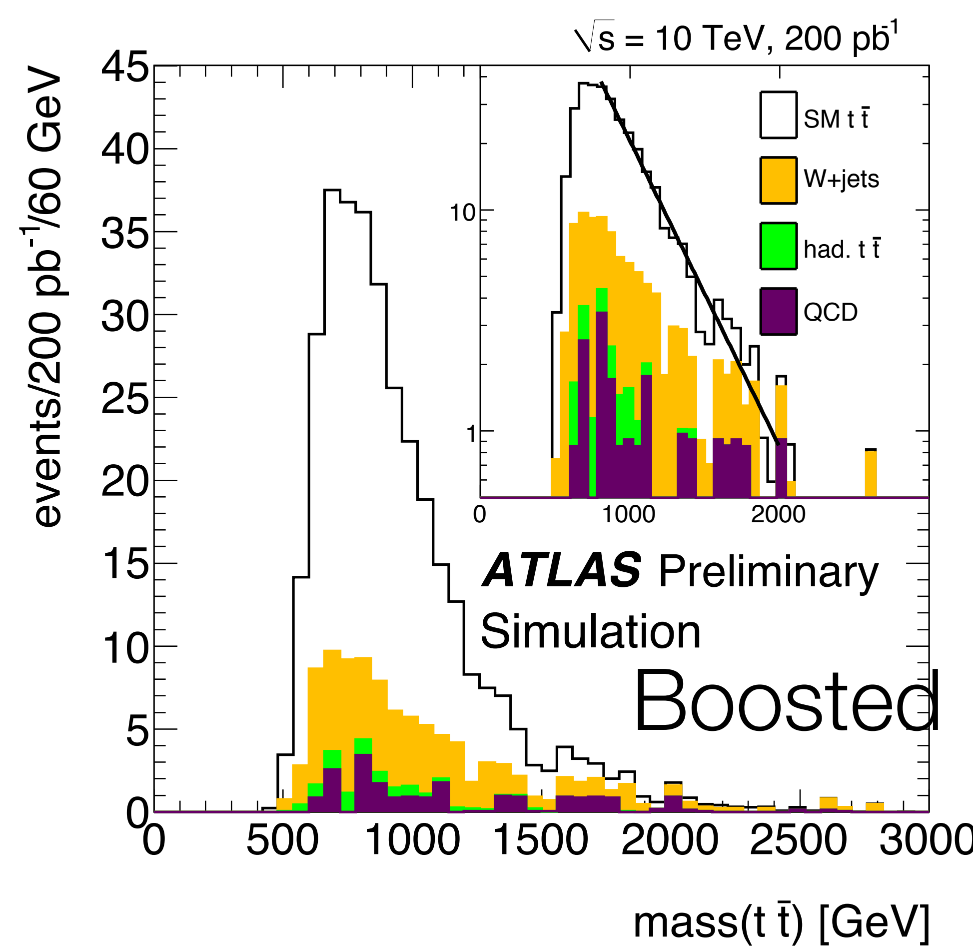
Mass reconstruction and Performance: expectations

ATL-PHYS-PUB-2010-008

- Trigger and Preselection overall efficiency
  - over 55% for Z' from 1 to 2 TeV
- Mass Reconstruction
  - Resolved: classified with leading p_T jet, W mass constraint, simple jet pairing with angles
  - Boosted: single large cone jet
  - similar **resolution**: RMS (M_{true} -M_{reco})~ 14 to 20% in both full reco and mono-jet
- Reconstruction efficiency overlap
  - Resolved:~5% at 2TeV
  - Mono-jet~15% (10% around 1 TeV)

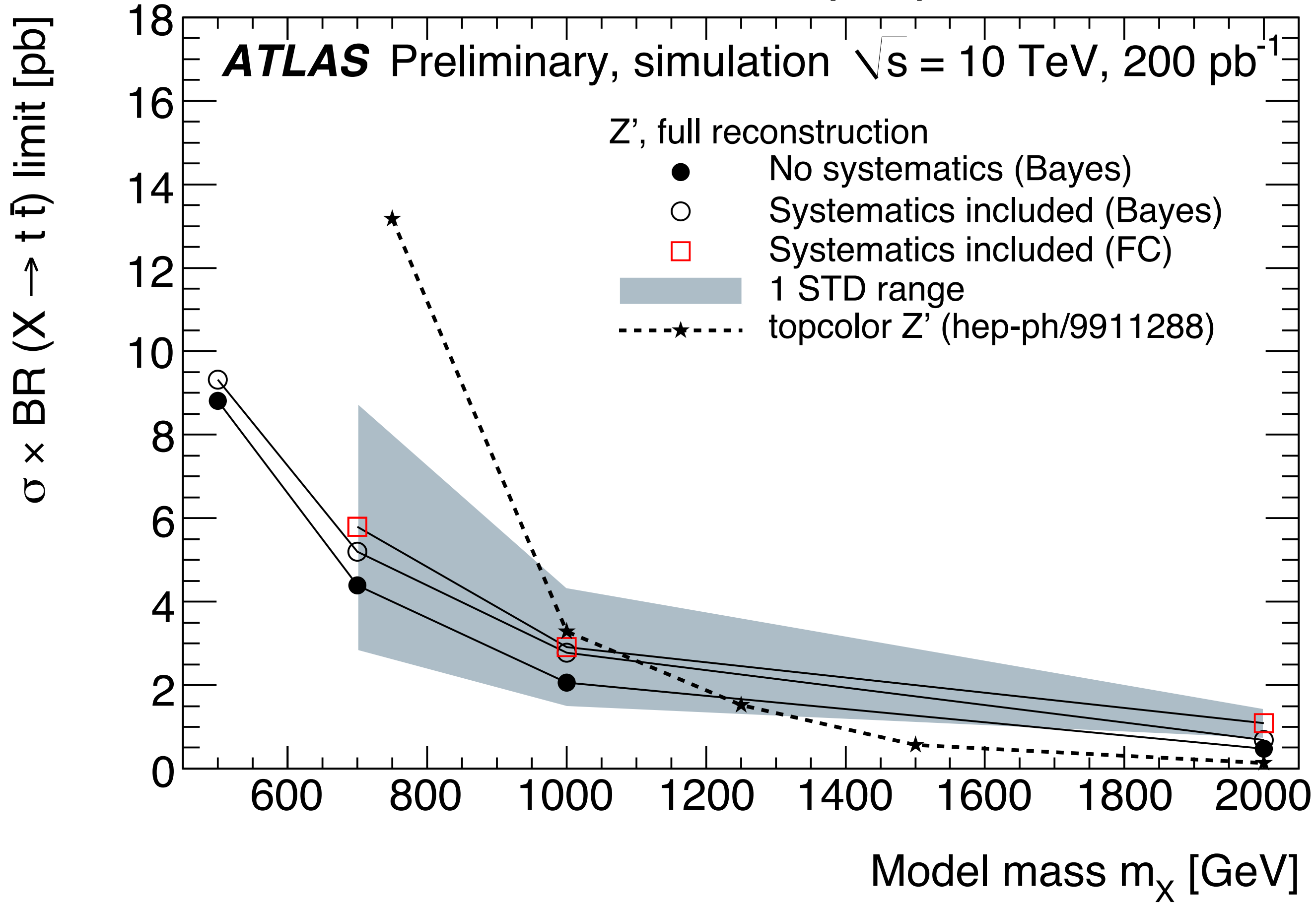


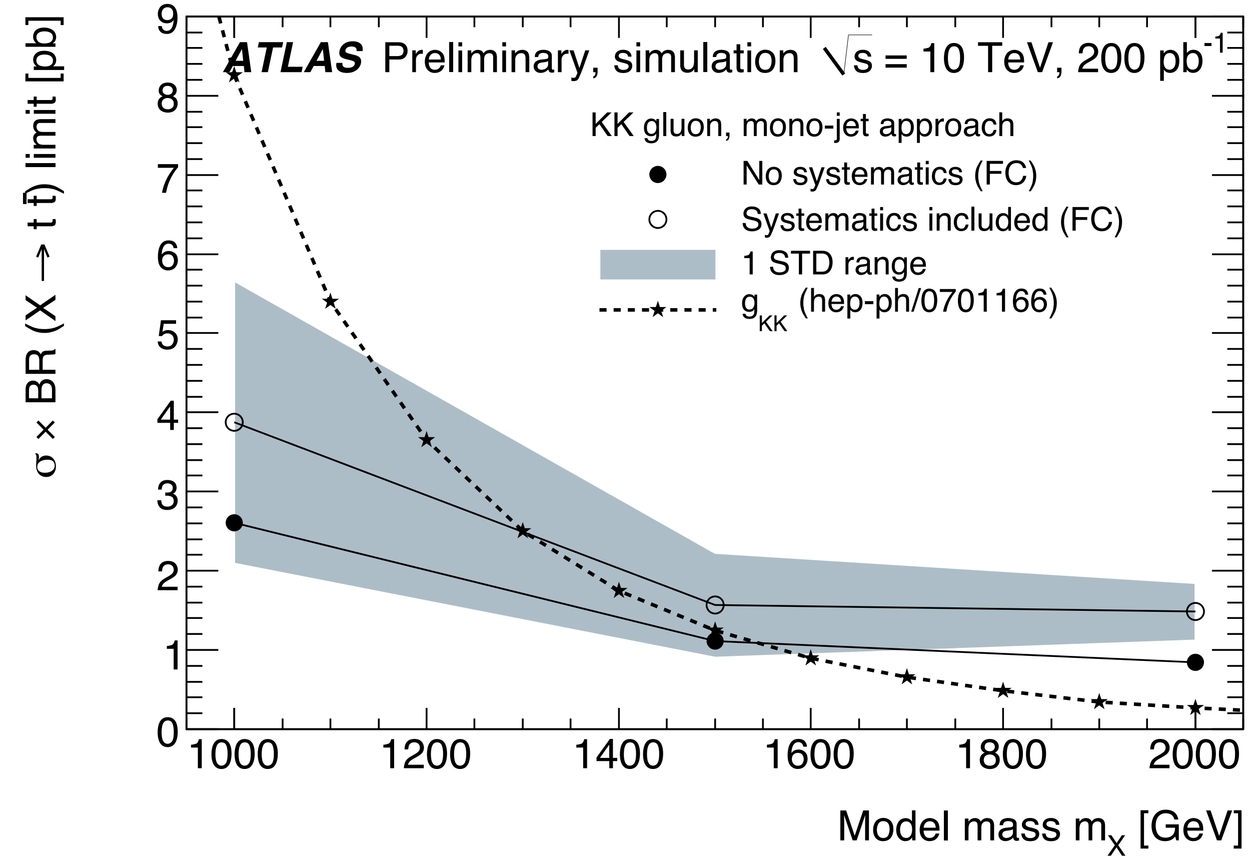
simulated tt



Sensitivity expectations: example

Narrow res(Z') — ATL-PHYS-PUB-2010-008 — Broad res (KKGluon)

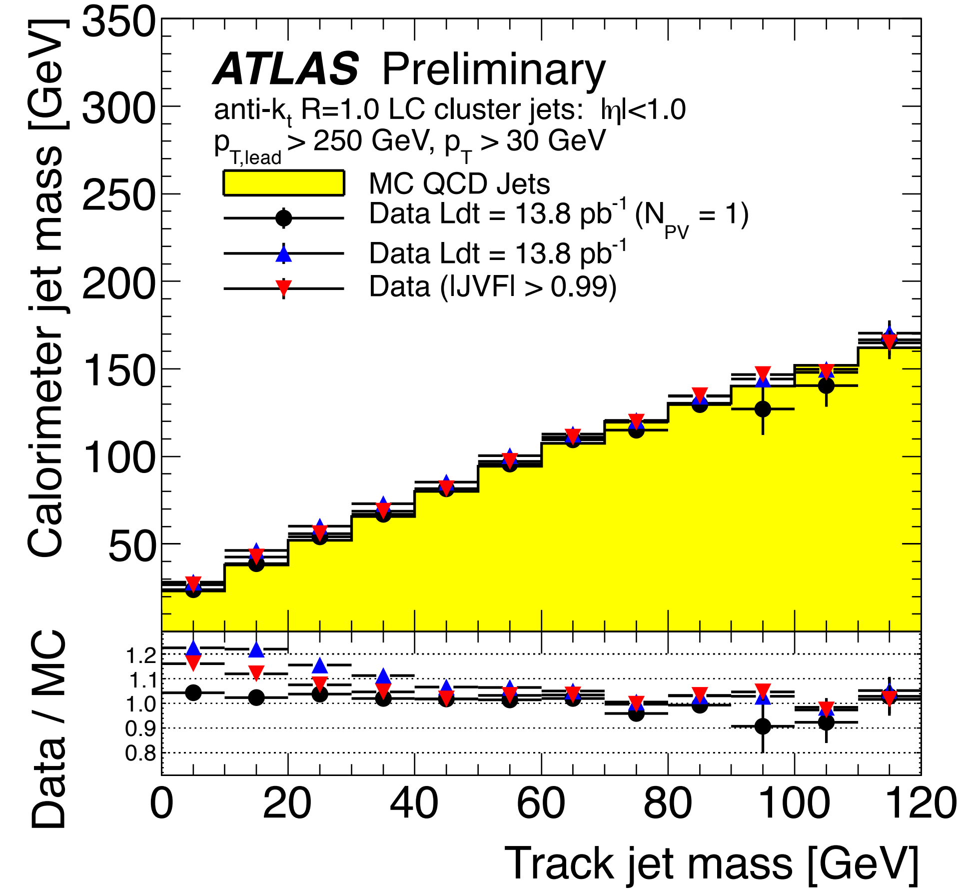




- 200 pb^{-1} at 10 TeV ~ 480 pb^{-1} at 7 TeV if acceptance is similar
- With **O(1) fb^{-1} @ 7 TeV, ATLAS sensitivity** is expected to reach **resonance masses beyond 1 TeV** (ATL_PHYS_PUB_2010_008)

To fulfill/test expectations: start from foundations!

- Start measuring **basic properties**
  - **jet mass** for large cones,
  - k_T **splitting scales** in jet making.



Listen to Trisha Farooque's talk!

Conclusions

- **Top quarks have finally visited Europe!**
  - ATLAS is collecting **a large data sample.** Top pair production **cross section** measurements **is in good agreement with SM**, **systematics limited, close to theory precision**
    - ❖ATLAS **Top mass is 169 ±4(stat)±4.9 (syst) GeV**

- **ATLAS first search for ttbar resonances** with $\int Ldt=33\ pb^{-1}$
  - **sets upper limits on Z' production from 55 to 2 pb^{-1}**
  - excludes high enhancement in the tail due to QBH with M<2.35 TeV
  - Analysis with 200 pb^{-1} is very advanced.

- Interest also directed to
  - **$d\sigma/dm_{tt}$, $d\sigma/dp_t$, tt+jets**
  - variables sensitive to top asymmetry

- **Boosted region is getting closer**: **start understanding basic** variables **for top-jet tagging**. Stay on for Trisha's update!

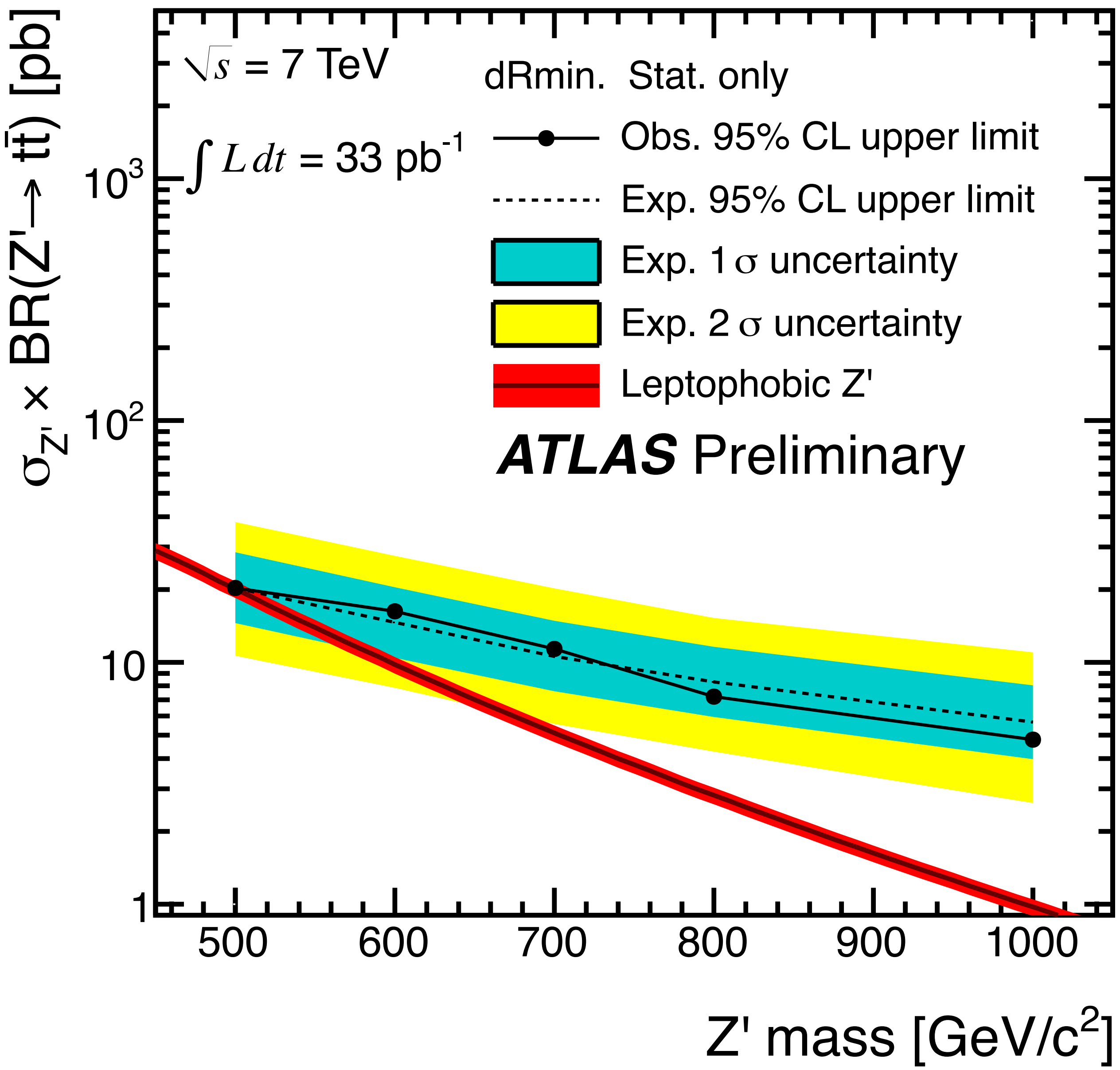
BACK-UP

Full reco in ATL-PHYS-PUB-2010-008

- Pre-selection
  - 1 high pt isolated lepton
  - jets with pt>20 GeV
- Leptonic top: W mass constraint
- Hadronic top
  - No jet with m> 65
    - ❖Require >=4 jets, 2 b-tagged.
    - ❖Hadronic WAmongst Non b-tagged jets get closest pair in DR
    - ❖Hadronic top: add closest jet to W boson
  - If jet with largest m has m in [65 GeV,130 GeV]
    - ❖require at least 3 jets, 1 b-tagge
    - ❖had top = large mass jet + 1 jet
  - if jet with m>130 GeV is found, it is the hadronic top

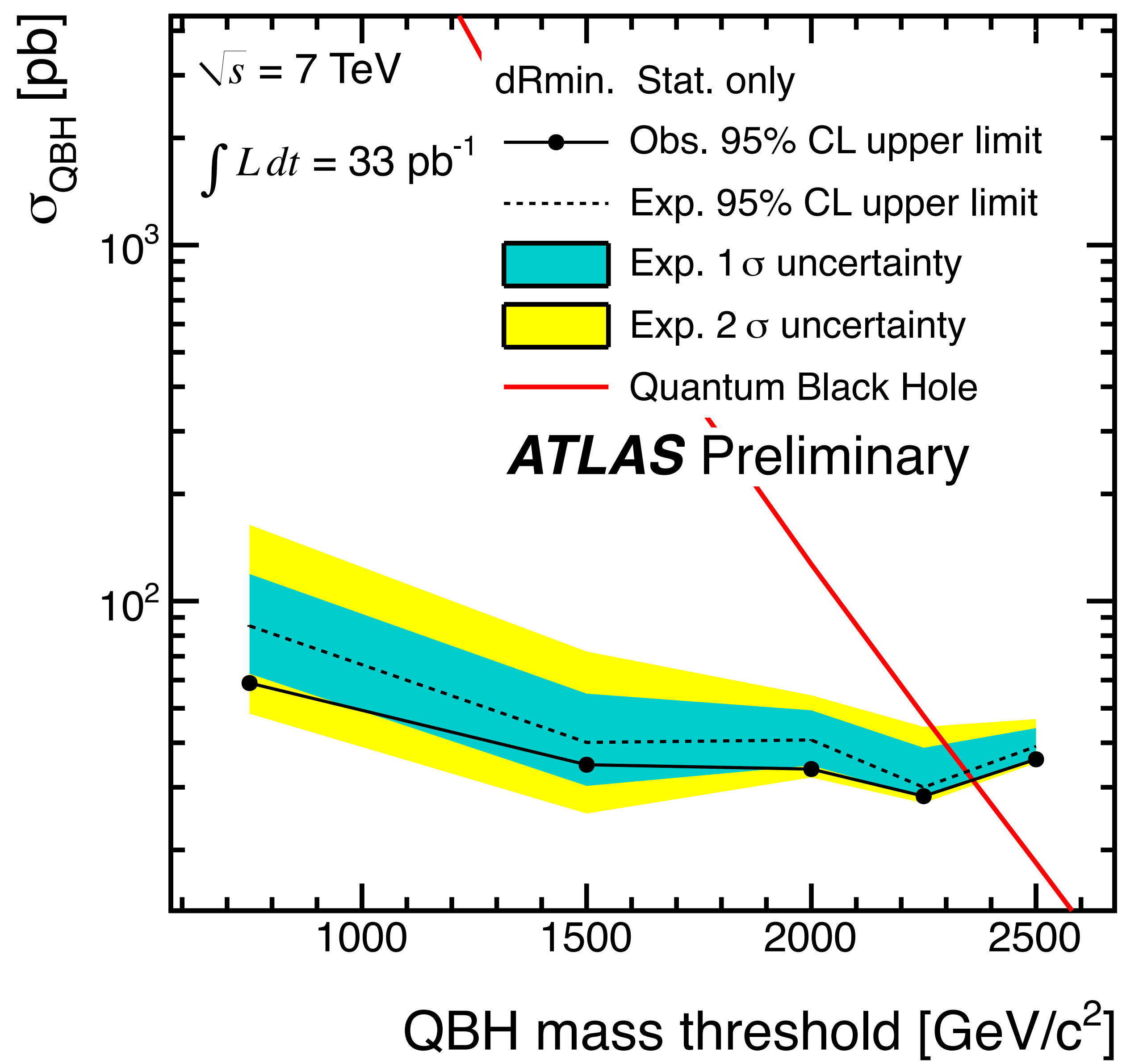
Searches for new phenomena with top: Results

ATL-CONF-2011-070



No systematics

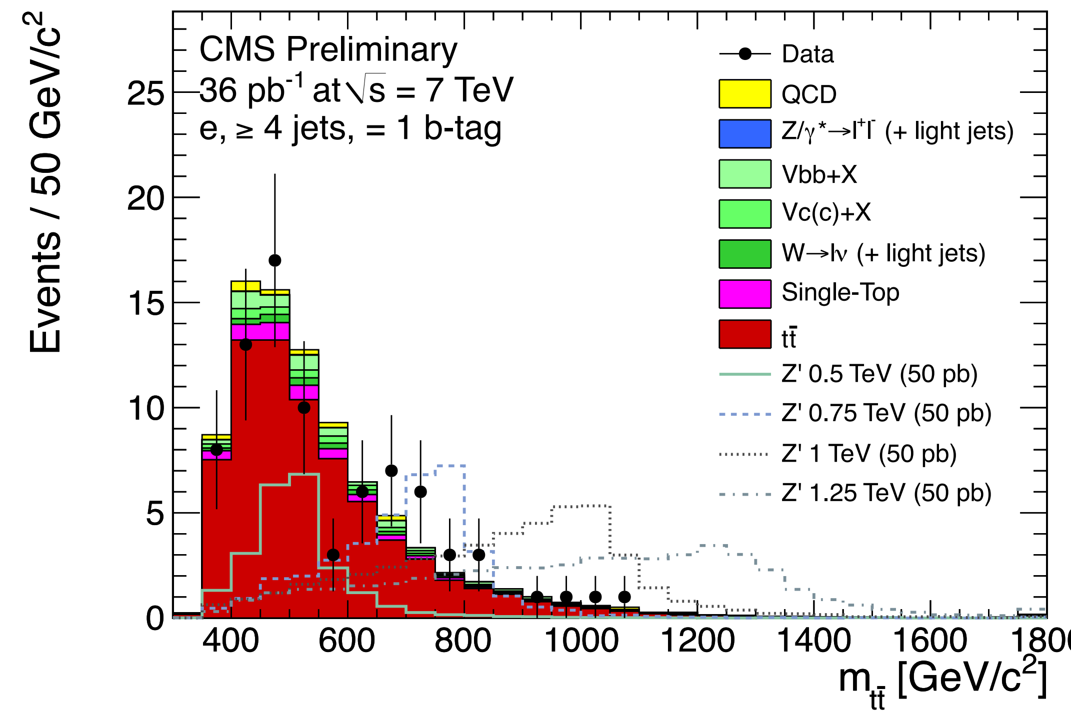
ATL-CONF-2011-070

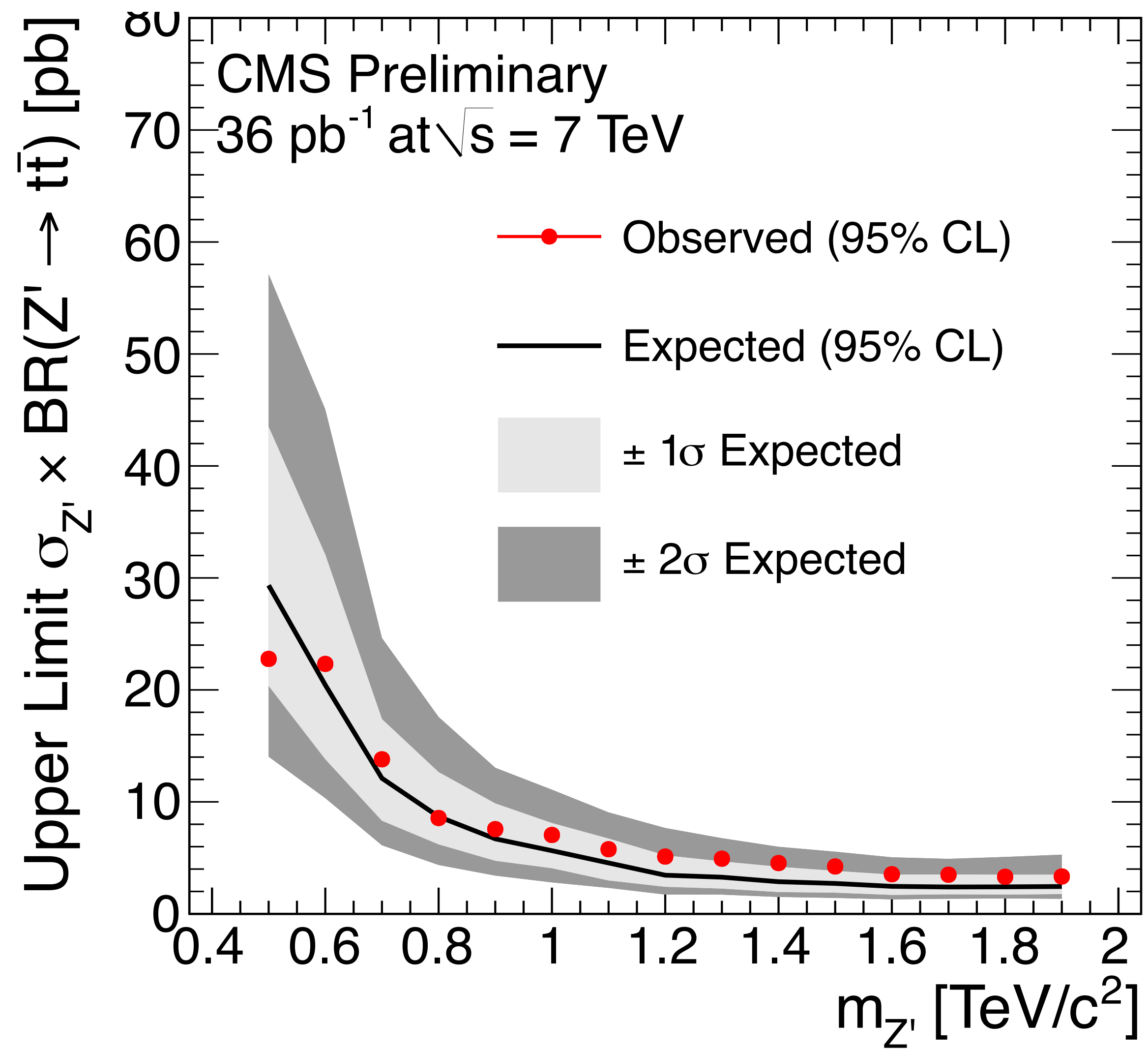


CMS top/anti-top resonance search

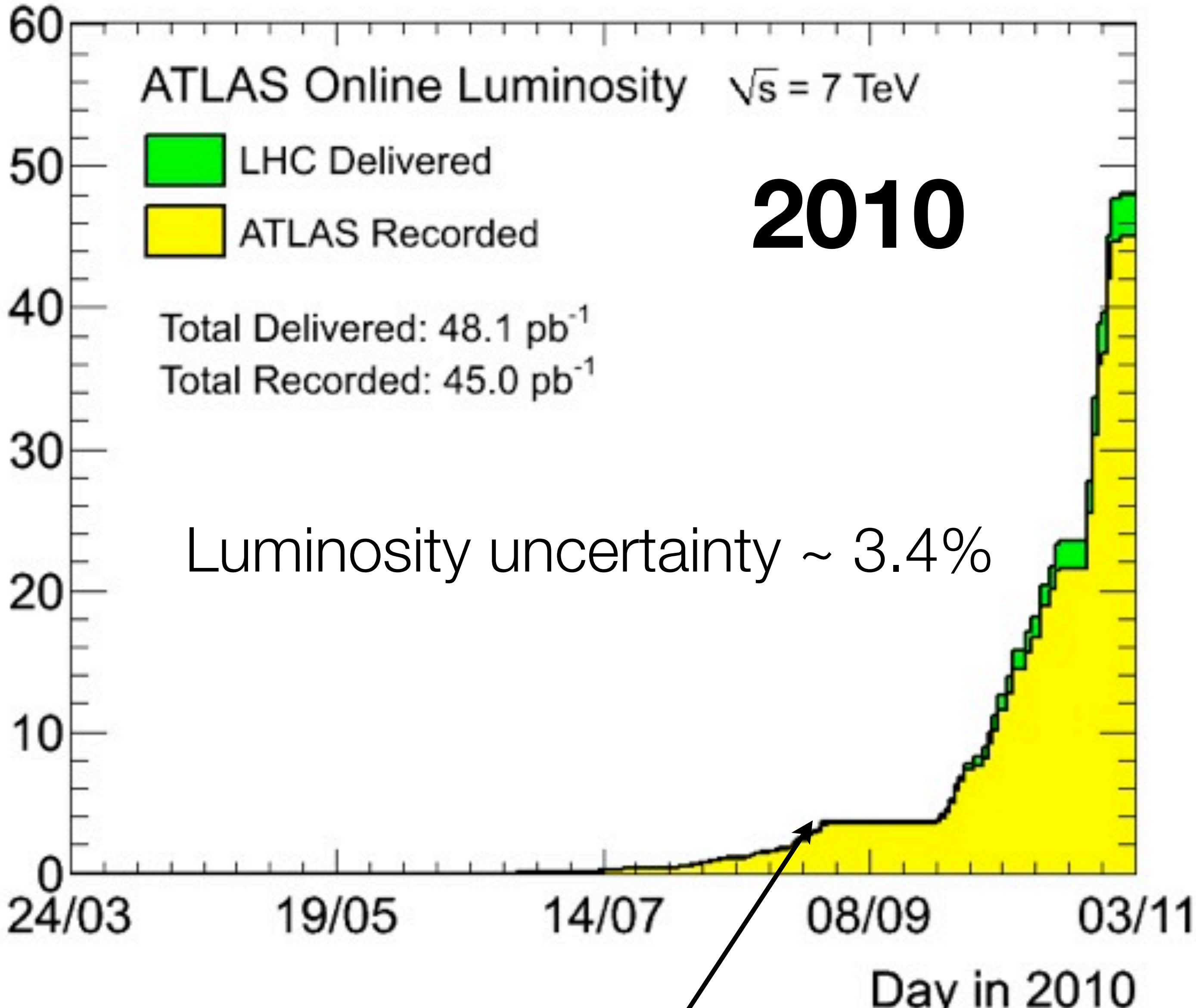
TOP-10-007-PAS

- Use b-tagged and non-b tagged events
- Least squares to choose the jets
- Kinematic fit for mass reconstruction
  - Res is about 6% at 500 GeV , 7% at 1 TeV
- No exclusion statement, upper limit on narrow topcolor Z' xsec
  - 25 pb at $m_{Z'}$=500 GeV
  - 4 pb at $m_{Z'}$>1.4 TeV





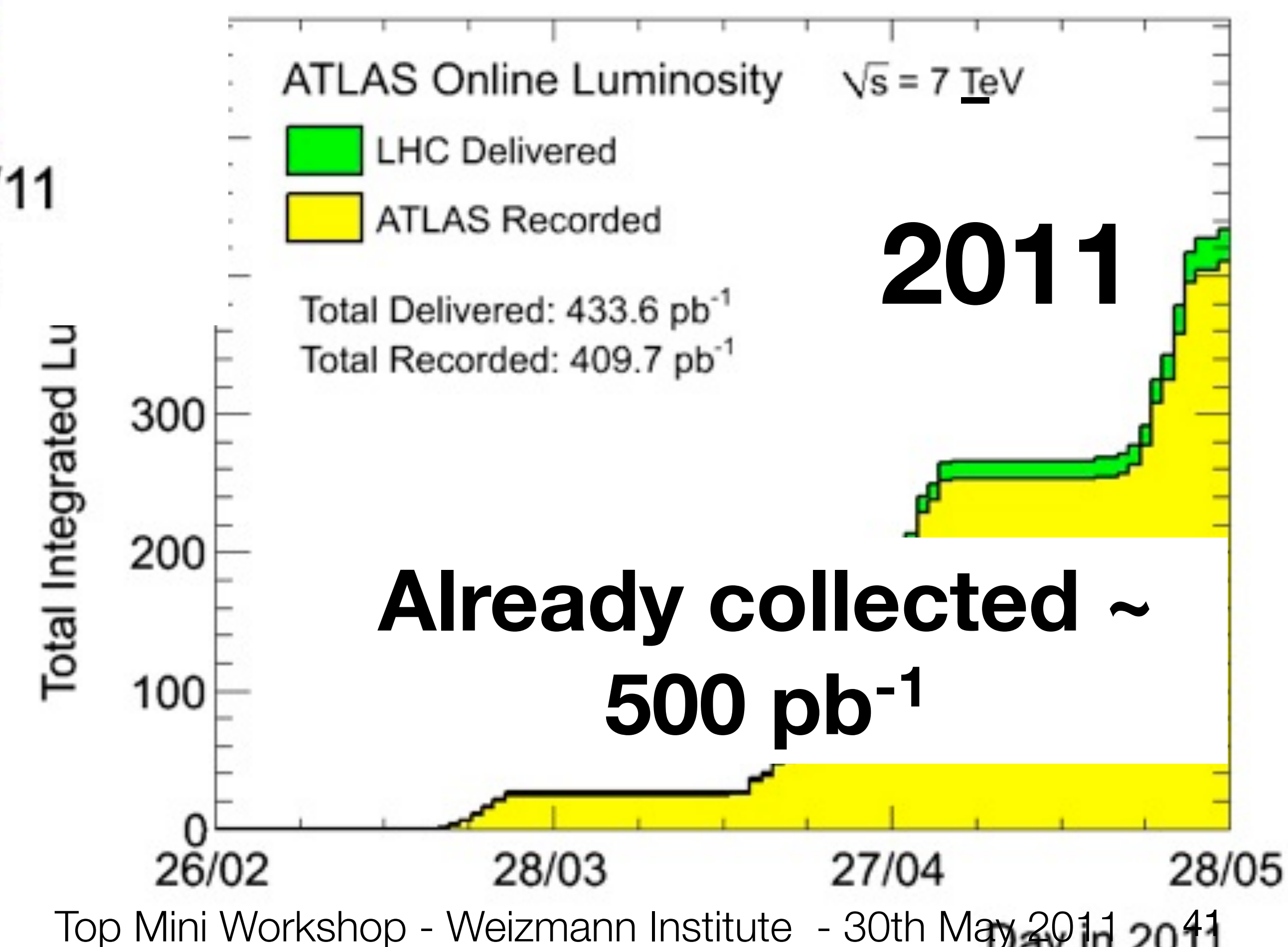
...with excellent data taking performance



Data sample for first top paper~3 pb^{-1}

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.0	99.9	100	90.5	96.6	97.8	94.3	99.9	99.8	96.2	99.8

For top analyses
using 33 pb^{-1}
expect~5700 tt events



Already collected ~ 500 pb^{-1}

The k_t algorithms form one of several "families" of sequential recombination jet algorithm

Others differ in:

1. the choice distance measure between pairs of particles
   [i.e. the relative priority given to soft and collinear divergences]

2. using $3 \to 2$ clustering rather than $2 \to 1$
   [ARCLUS; not used at hadron colliders, so won't discuss it more]

k_t alg. at hadron colliders

3rd attempt: **inclusive k_t algorithm**

- Introduce angular radius R (NB: dimensionless!)

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}\,, \qquad d_{iB} = p_{ti}^2$$

- 1. Find smallest of d_{ij}, d_{iB}
  2. if ij, recombine them
  3. if iB, call i a jet and remove from list of particles
  4. repeat from step 1 until no particles left.

Two parameters to remember

- **R**: sets $y-\phi$ reach of the jet; minimal interjet separation
- **p_t cut** on the jets

These parameters are common to all widely used hadron-collider jet algorithms.

S.D. Ellis & Soper, '93; the simplest to use

Jets all separated by at least R on y, ϕ cylinder.

NB: number of jets not IR safe (soft jets near beam); number of jets above p_t cut **is** IR safe.

Anti-k_t

Anti-k_t: *formulated similarly to k_t, but with*

$$d_{ij} = \min\left(\frac{1}{k_{ti}^2}, \frac{1}{k_{tj}^2}\right)\frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = \frac{1}{k_{ti}^2}$$

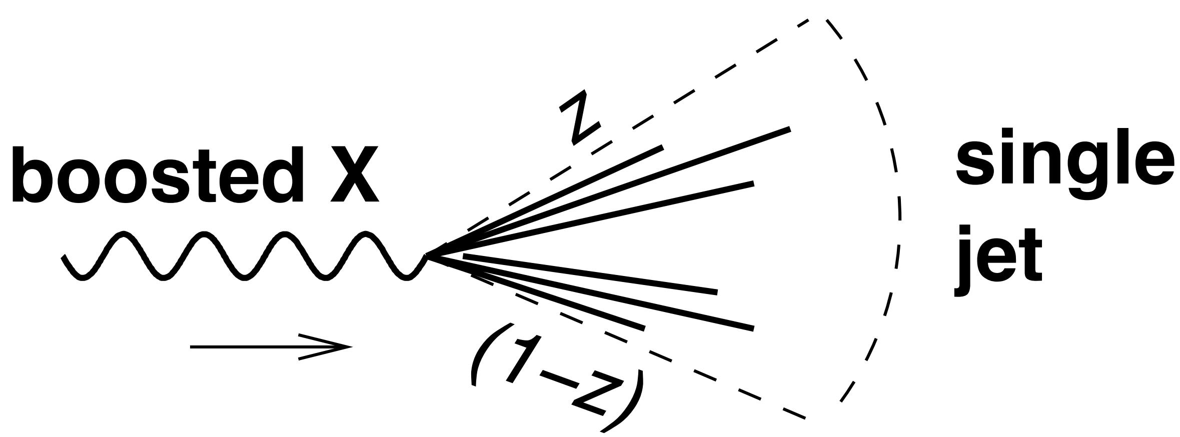
Cacciari, GPS & Soyez, '08 [+ Delsart unpublished]

Anti-k_t privileges the collinear divergence of QCD and disfavours clustering between pairs of soft particles

Most pairwise clusterings involve at least one hard particle

Boosted massive particles, e.g.: EW bosons

Hadronically decaying EW boson at high $p_t \neq$ two jets



$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

Rules of thumb:

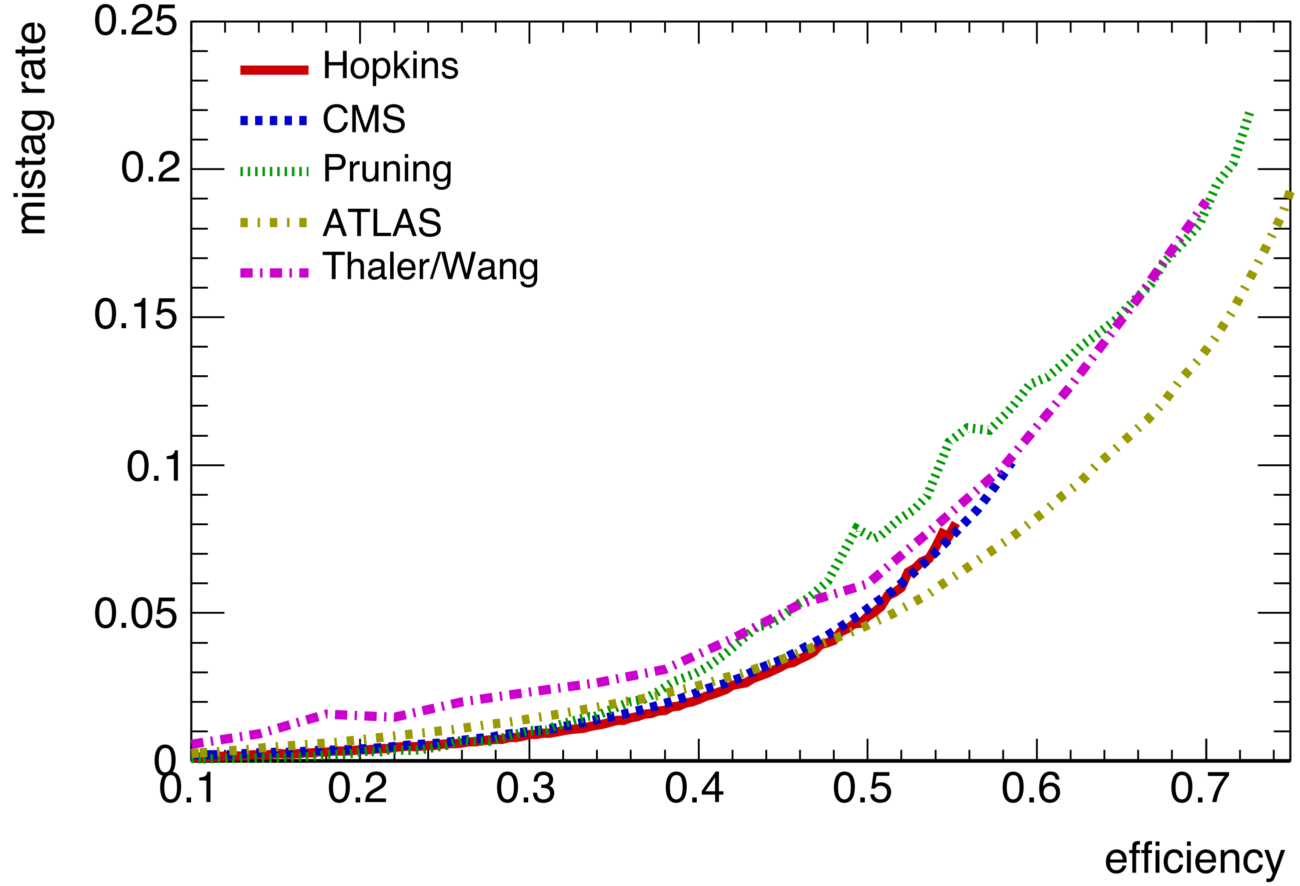
$m = 100$ GeV, $p_t = 500$ GeV

- $R < \dfrac{2m}{p_t}$: always resolve **two** jets — $R < 0.4$
- $R \gtrsim \dfrac{3m}{p_t}$: resolve **one** jet in $\sim$75% of cases $(\frac{1}{8} < z < \frac{7}{8})$ — $R \gtrsim 0.6$

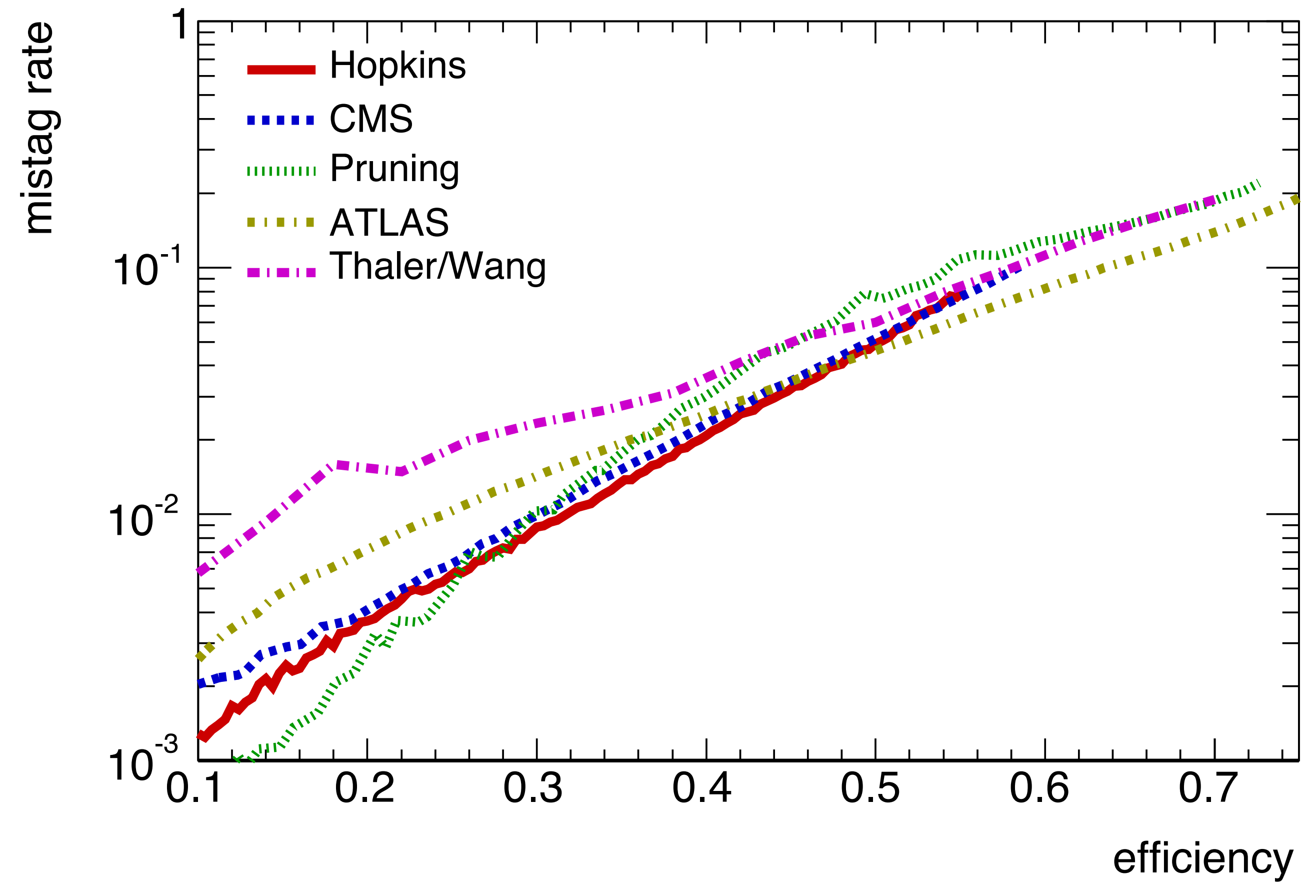
Top taggers comparison

http://arxiv.org/pdf/1012.5412

linear scale



log scale



- Signal: tt , Bkg:di-jet (QCD) (HERWIG)
- anti-k_T Jet with R=1

Tagging boosted tops in ATLAS

ATL-PHYS-PUB-2010-008

Pre-selection

- central combined muon candidate with pt>20 GeV and |eta|<2.5
- medium electron candidates with pt>25 GeV and |eta|<2.47 (not in crack)
- E_T^{miss}> 20 GeV
- Electron energy deposit kept in jet clustering: remove jet-electron overlap
- remove muons within DR=0.3 from jet

Mono-jet-selection

$$z_{ij} = d_{ij}/(d_{ij} + m_j^2)$$

energy sharing, isolation-like, masss-like vars, distance-like

Table 2: The baseline and tight mono-jet selection. The tight selection does not include the baseline cuts.

selection	leptonic	hadronic
baseline, leading jet $E_T > 250$ GeV	$\Delta R_{lj} < 1$, $x_l < 1.2$, $z_l < 0.8$ muon: $I_\mu^{rel} < 0.5$, $Q_{vis}^\mu > 53$ GeV, $\Delta R_{\mu j} > 0.15$, $x_\mu > 0.35$, $z_\mu > 0.15$, electron: $I_e^{rel} < 0.1$, $Q_{vis}^e > 50$ GeV, $\Delta R_{ej} > 0.25$, $x_e > 0.4$	$z_{12} > 0.08$, $Q_W > 30$ GeV, $m_j > 100$ GeV
tight, leading jet $E_T > 250$ GeV	$\Delta R_{lj} < 1$, $\log y_l > 0$, $x_l > 0.3$, $I_{trk}^{mini} > 0.9$, $I_{calo}^{mini} > 0.8$	$z_{12} > 0.06$, $z_{23} > 0.042$, $z_{34} > 0.007$, $Q_W > 50$ GeV, $m_j > 140$ GeV

Selection and reconstruction efficiency

selection	Z' (m = 1 TeV)	SM $t\bar{t}$	W+jets	QCD
muon in acceptance	84.8 %	79.0 %	47.0 %	-
single muon trigger	71.5 % (81.5 %)	65.7 % (81.4 %)	50.4 % (82.2 %)	0.9 (41.1 %)
reconstructed muon	67.6 %	62.8 %	42.0 %	10^{-4}
total pre-selection	63.5 %	56.8 %	38.5 %	10^{-5}
electron in acceptance	81.5 %	74.0 %	44.8 %	-
single electron trigger	78.8 % (98.9 %)	77.7 % (99.3 %)	50.0 % (99.4 %)	0.75 % (95.1 %)
reconstructed electron	60.0 %	59.0 %	63.5 %	10^{-3}
total pre-selection	56.4 %	48.3 %	31.0 %	6×10^{-4}

- Looking at leptonic W decays
- Signal efficiency presented for
- total preselection = lepton+E_T^{miss} 25 GeV

Reco Efficiency

	minimal reconstruction					full	mono-jet	
	3-jet low m_j	3-jet high m_j	4-jet	≥ 5 jets	all	reco.	approach baseline	approach tight
Z' , $m = 1$ TeV , $\Gamma/m \sim 3.3$ %, $\sigma \times BR(X \to t\bar{t}) = 0.634$ pb								
$t\bar{t}$	322.8	41.3	442.4	215.5	1022	214.3	88.8	29.2
reducible bkg.	858	28	272	59	1217	9.9	22.5	2.8
Z'	4.13	2.26	4.18	1.92	12.5	3.36	6.4	2.9
signal eff.	6.0 %	3.3 %	6.1 %	2.8 %	18.2 %	4.9 %	9.3 %	4.3 %
S/B	0.003	0.033	0.006	0.007	0.006	0.015	0.049	0.091
Z' , $m = 2$ TeV , $\Gamma/m \sim 3.3$ %, $\sigma \times BR(X \to t\bar{t}) = 0.0214$ pb								
$t\bar{t}$	51.2	6.11	38.3	25.3	121	15.6	9.7	4.4
reducible bkg.	278	16.7	66	22.2	394	3.0	14.2	1.6
Z'	0.046	0.14	0.13	0.0825	0.40	0.12	0.36	0.29
signal eff.	2.0 %	6.0 %	5.6 %	3.6 %	17.2 %	5.2 %	15.5 %	12.5 %
S/B	1.4×10^{-4}	0.006	0.001	0.002	8×10^{-4}	0.006	0.015	0.04

200 pb^{-1} @ 10 TeV

Noise removal

UE adds $\Lambda \simeq 10 - 15$ GeV of noise per unit rapidity. For a jet of size R, effect on jet mass goes as

$$\langle \delta m^2 \rangle \simeq \Lambda p_t \frac{R^4}{4} \sim 4\Lambda \frac{m^4}{p_t^3}$$

Dasgupta, Magnea & GPS '07

Filtering, Pruning & Trimming are all intended to reduce this noise. Viewing the jet on some smaller scale R_{sub}, throw out softest subjets:

- **Filtering**: break jet into subjets on angular scale R_{filt}, take n_{filt} hardest subjets — Butterworth, Davison, Rubin & GPS '08
- **Trimming**: break jet into subjets on angular scale R_{trim}, take all subjets with $p_{t,sub} > \epsilon_{trim} p_{t,jet}$ — Krohn, Thaler & Wang '09
- **Pruning**: as you build up the jet, if the two subjets about to be recombined have $\Delta R > R_{prune}$ and $\min(p_{t1}, p_{t2}) < \epsilon_{prune}(p_{t1} + p_{t2})$, discard the softer one. — Ellis, Vermilion & Walsh '09

Trimming

D. Krohn,

Jets & Jet Substructure Workshop, University Of Washington, 1/14/10

arxiv:0912.1342

Implementation

1. Cluster all calorimeter data using any algorithm
2. Take the constituents of each jet and recluster them using another, possibly different, algorithm (we advocate k_T) with smaller radius R_{sub} ($R_{sub} = 0.2$ seems to work well).
3. Discard the subjet *i* if

$$p_{Ti} < f_{\rm cut} \cdot \Lambda_{\rm hard}$$

4. Reassemble the remaining subjets into the trimmed jet

Pruning

D. Krohn,

Jets & Jet Substructure Workshop, University Of Washington, 1/14/10

- *Pruning* tries to clean jets by vetoing spurious recombinations in the jet clustering:
  - A jet's constituents are reclustered using k_T or C/A, and wide angle recombinations ($R>R_{cut}$) with a large relative p_T hierarchy ($z<z_{cut}$) are vetoed.

‣S. D. Ellis, C. K. Vermilion, and J. R. Walsh, *Techniques for improved heavy particle searches with jet substructure*, Phys. Rev. D80 (2009) 051501, [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*, 0912.0033.

Math Appendix : Mass, P_T and DR

As we know that for any 4-momentum

$$E = m_T \cosh y \ , \ p_x \ , \ p_y \ , \ p_z = m_T \sinh y$$

where $m_T^2 = m^2 + p_x^2 + p_y^2$. and

$$y = \frac{1}{2} \ln\left(\frac{E+p_z}{E-p_z}\right) = \ln\left(\frac{E+p_z}{m_T}\right) = \tanh^{-1}\left(\frac{p_z}{E}\right) .$$

The invariant mass M of the two-particle system

$$M^2 = m_1^2 + m_2^2 + 2[E_T(1)E_T(2)\cosh\Delta y - \boldsymbol{p}_T(1)\cdot\boldsymbol{p}_T(2)] \ ,$$

where $E_T(i) = \sqrt{|\boldsymbol{p}_T(i)|^2 + m_i^2}$,

This can be re-written as

$M^2 = m_1^2 + m_1^2 + 2[E_T(1) E_T(2) \cosh(Dy) - p_T(1) p_T(2) \cos(DPhi)$

where DPhi =Phi(2)-Phi(1)is the angle between the two momenta in the transverse plane

Now if 1) the masses of the particles are small w.r.t. their momenta and 2) the splitting is quasi collinear i.e. cosDPhi ~1 - $(DPhi)^2/2$ and cosh(Dy)~1+$Dy^2/2$, so $E_T(I)\sim p_T(i)$

http://en.wikipedia.org/wiki/Hyperbolic_function

$M^2 \sim 2[p_T(1) p_T(2) (1+Dy^2/2 - 1+ (DPhi)^2/2)]= p_T(1) p_T(2) (Dy^2/2 + (DPhi)^2)= p_T(1) p_T(2)DR(1,2)^2$

So

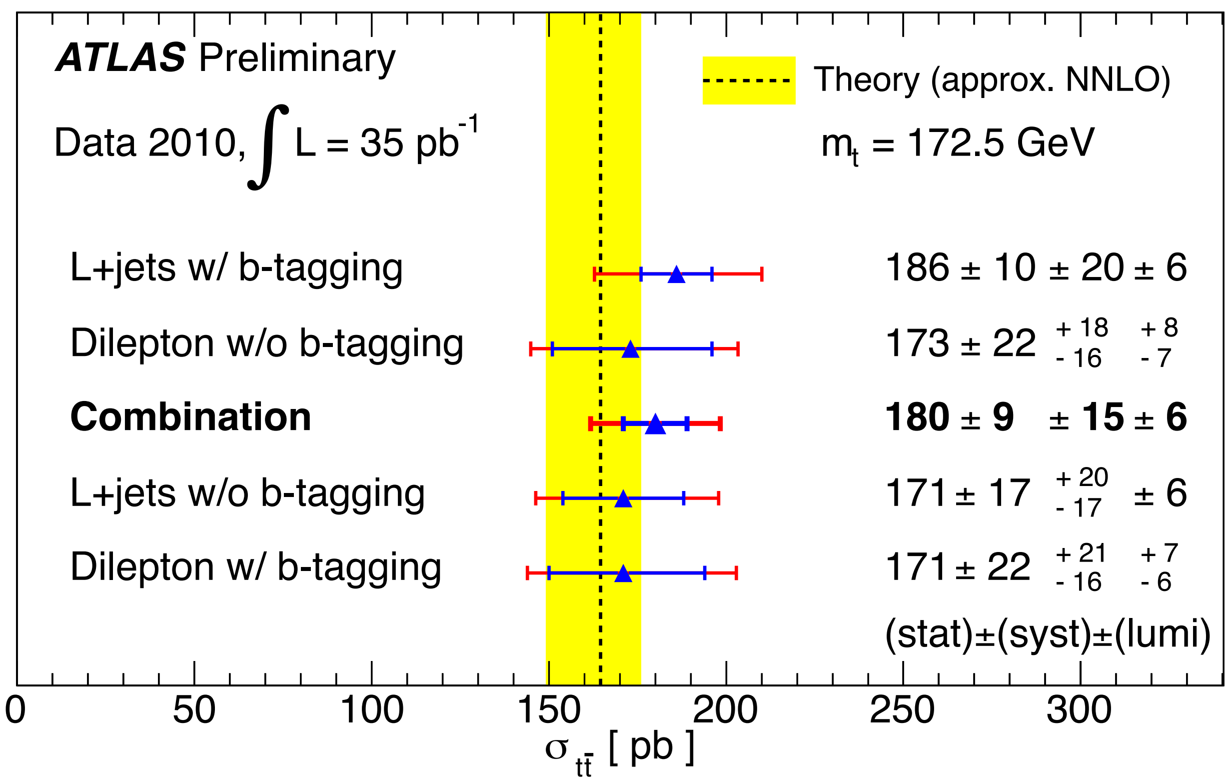
Labelling i and j such that $p_{tj} < p_{ti}$ and defining $z = p_{tj}/p_t$ $(p_t = p_{ti} + p_{tj})$,

$$m^2 \simeq z(1-z)p_t^2 \Delta R_{ij}^2 \ ,$$

$$d_{ij} = z^2 p_t^2 \Delta R_{ij}^2 \simeq \frac{z}{(1-z)} m^2 \ .$$

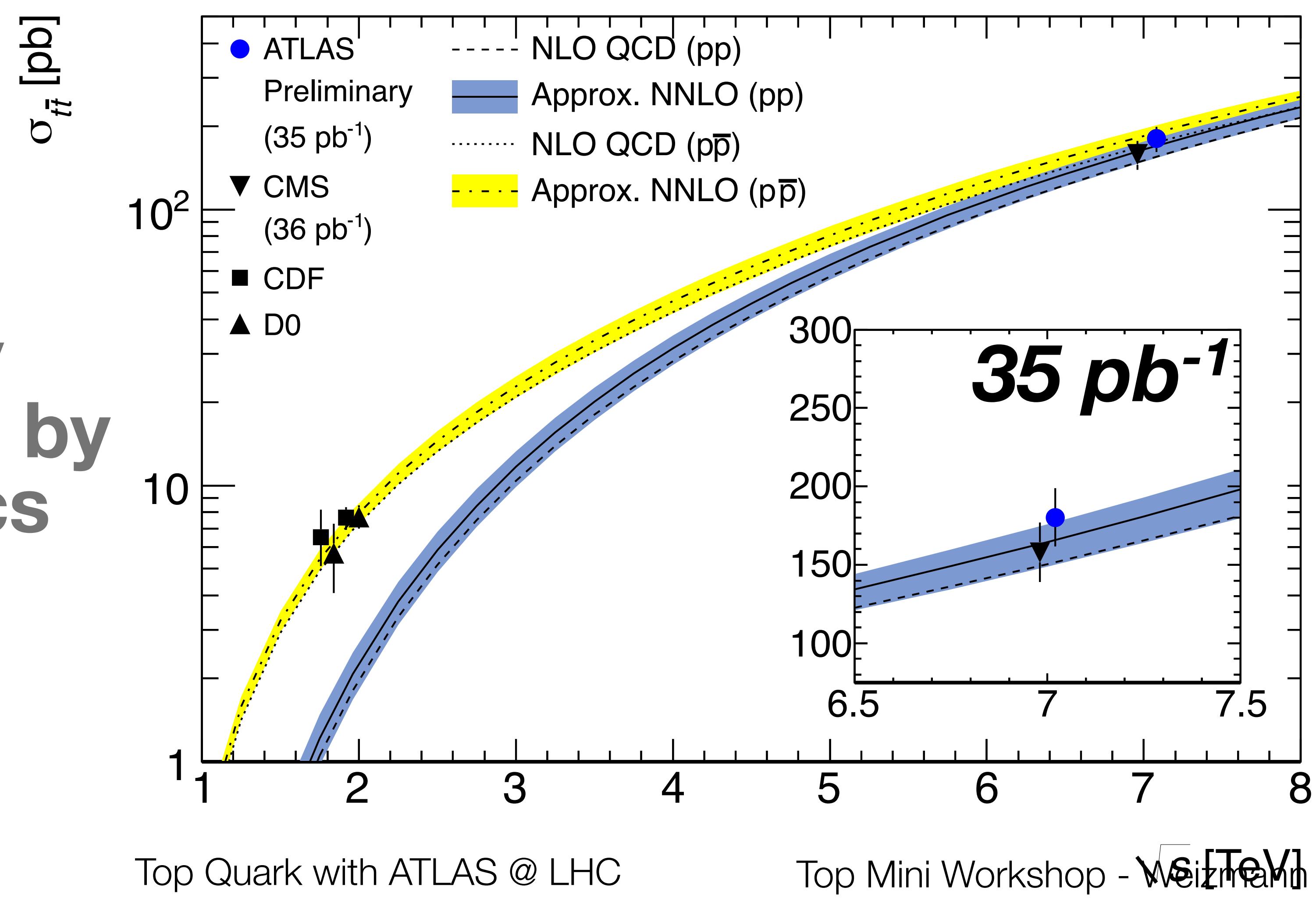
Top cross section

ATL-CONF-2011-040



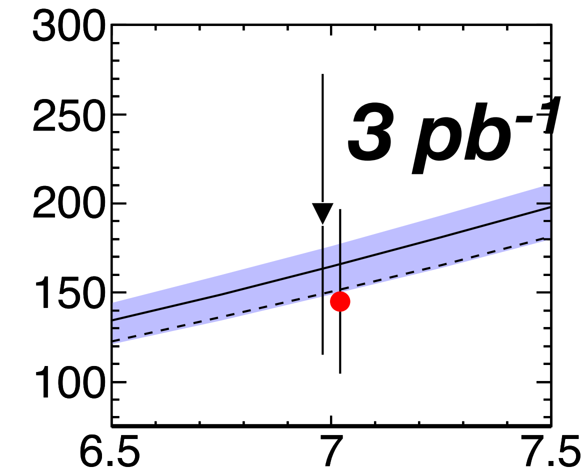
- Combined result uncertainty is **10%: comparable to theory**
  - **ATLAS:** 180 ±18 pb
  - CMS: 158±19 pb (12%)

ATL-CONF-2011-040



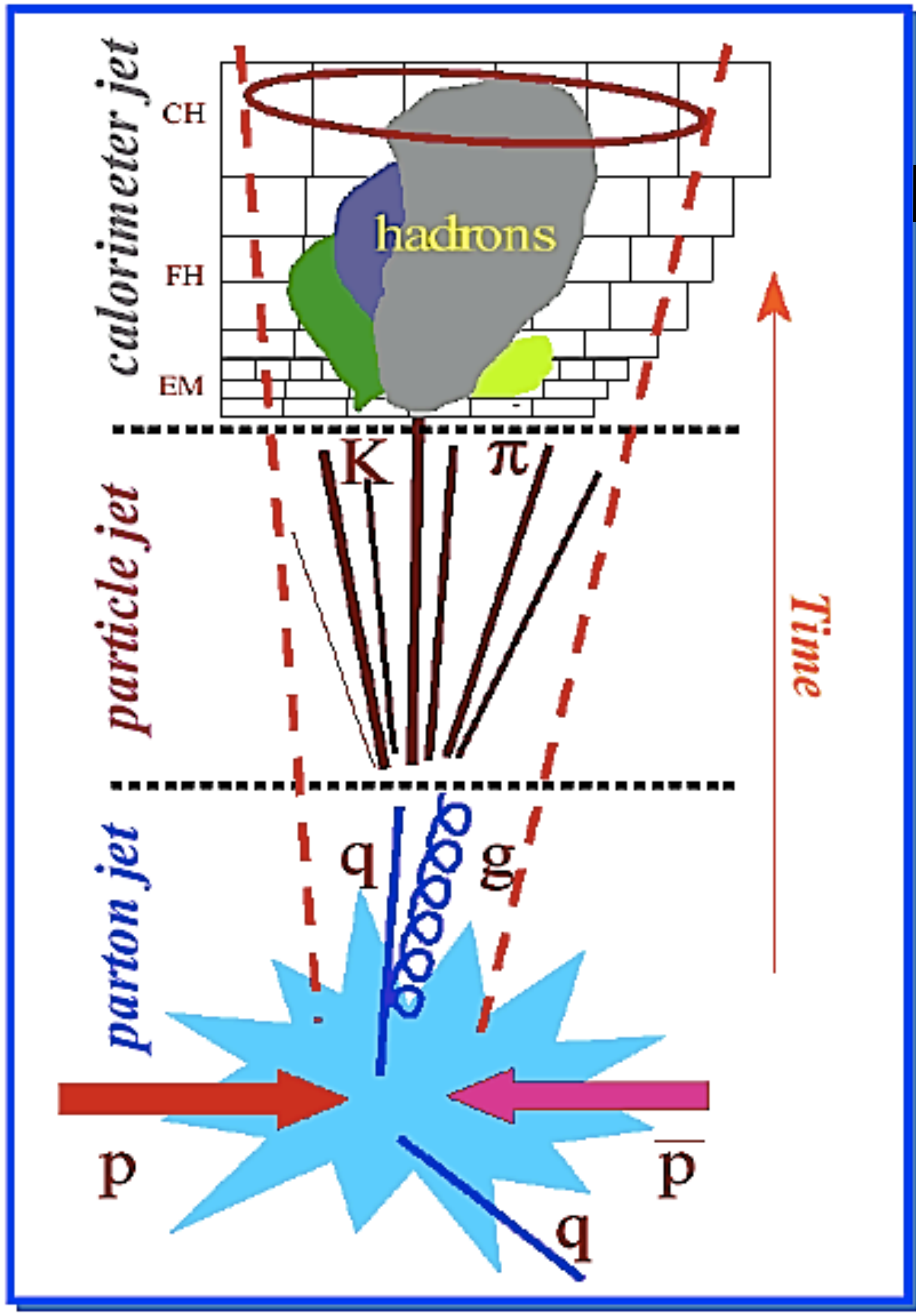
- Uncertainty **dominated by systematics**

http://arxiv.org/abs/1012.1792



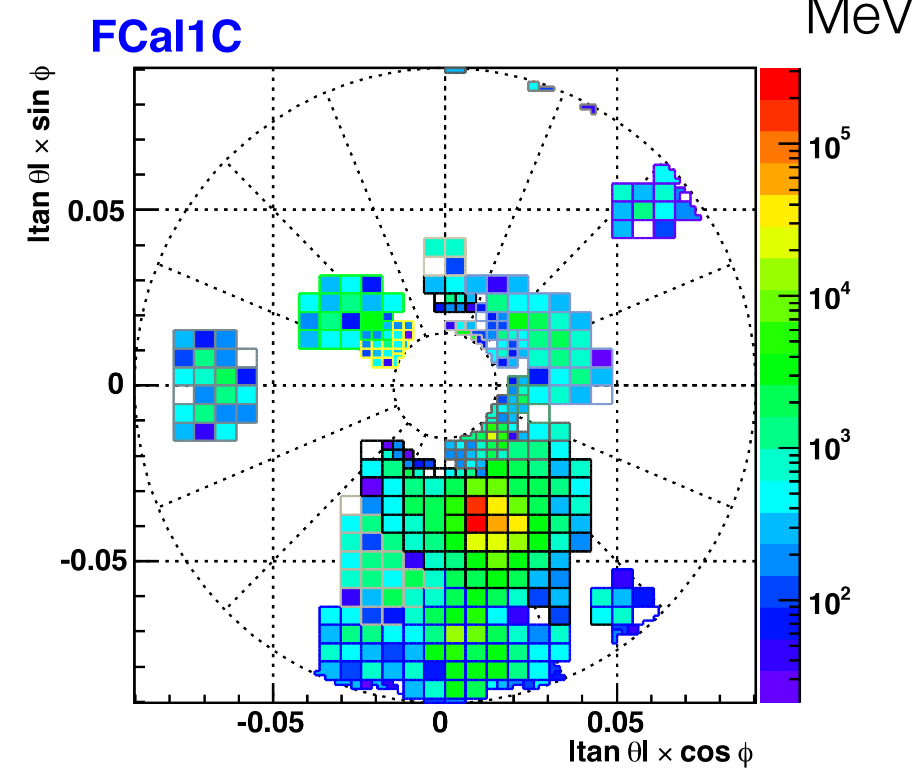
Ingredient: jets

- set of colour-less particles "remembering" momentum/colour flow from parton interaction



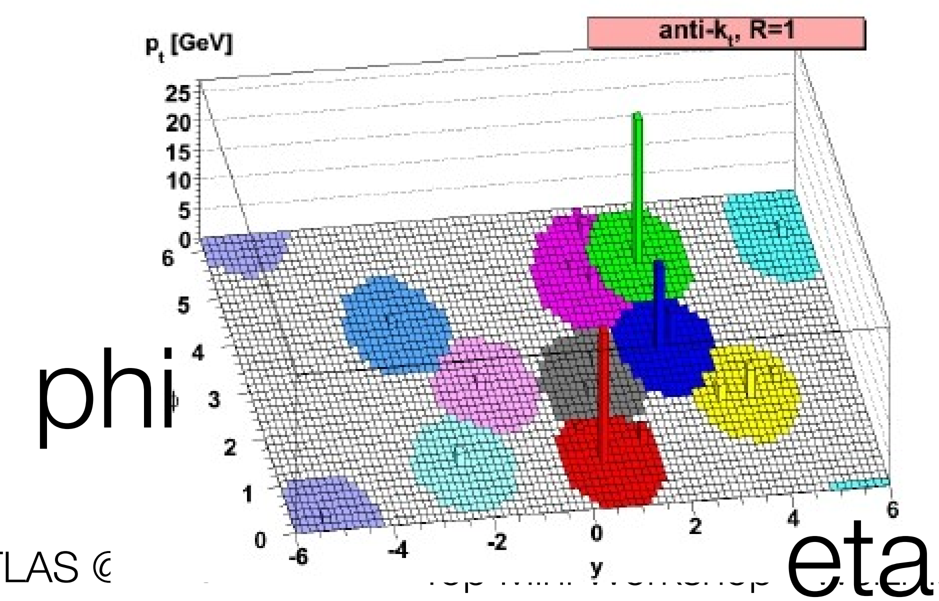
Cluster significant (E_{cell} / exp_noise_{cell}) energy deposits in calorimeters

Simulated QCD di-jet



clusters → jet

with **anti-k$_T$ algorithm**(R=0.4) *(Cacciari,Salam, Soyez,2008)*

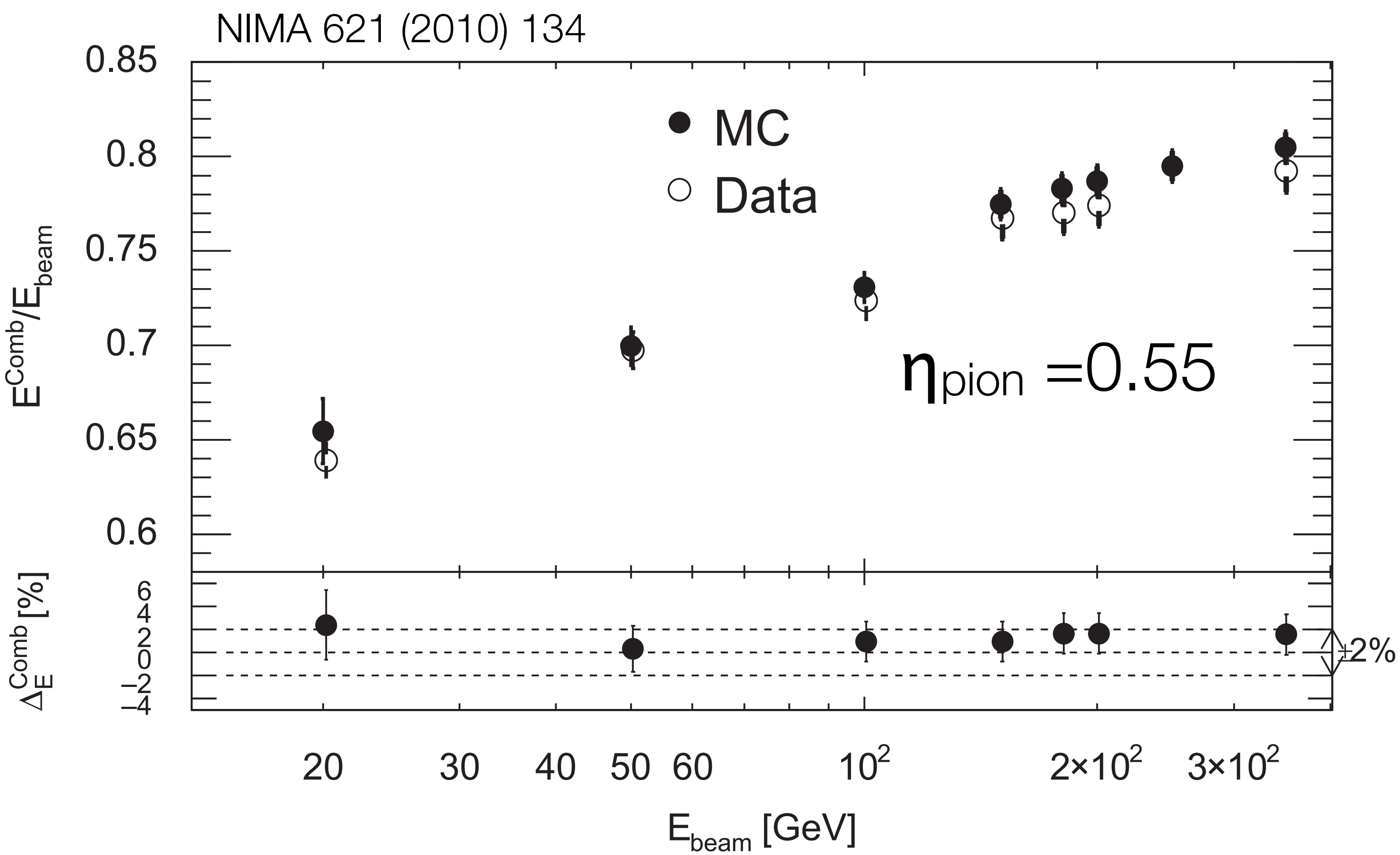


"hard stuff clusters with nearest neighbour"

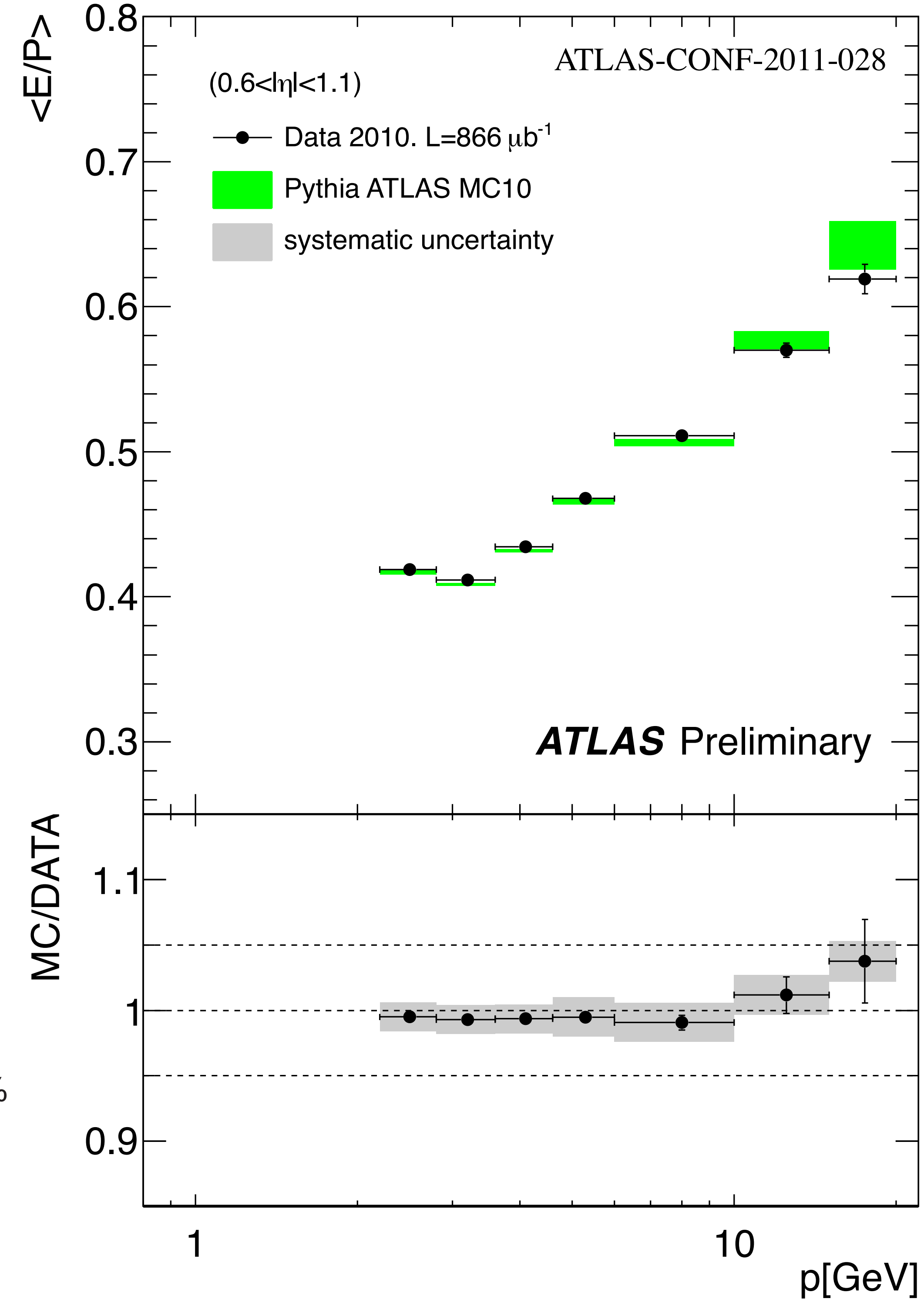
Ingredients II : jets (in the making)

Extensive validation of simulation in test-beam data →good collision data description

ATLAS test beam 2004



ATLAS colllisions 2010



Linearity within ~2%

single pion response for known beam energy

Data/MC within 2% for p<10 GeV

single isolated charged hadron response vs track momentum

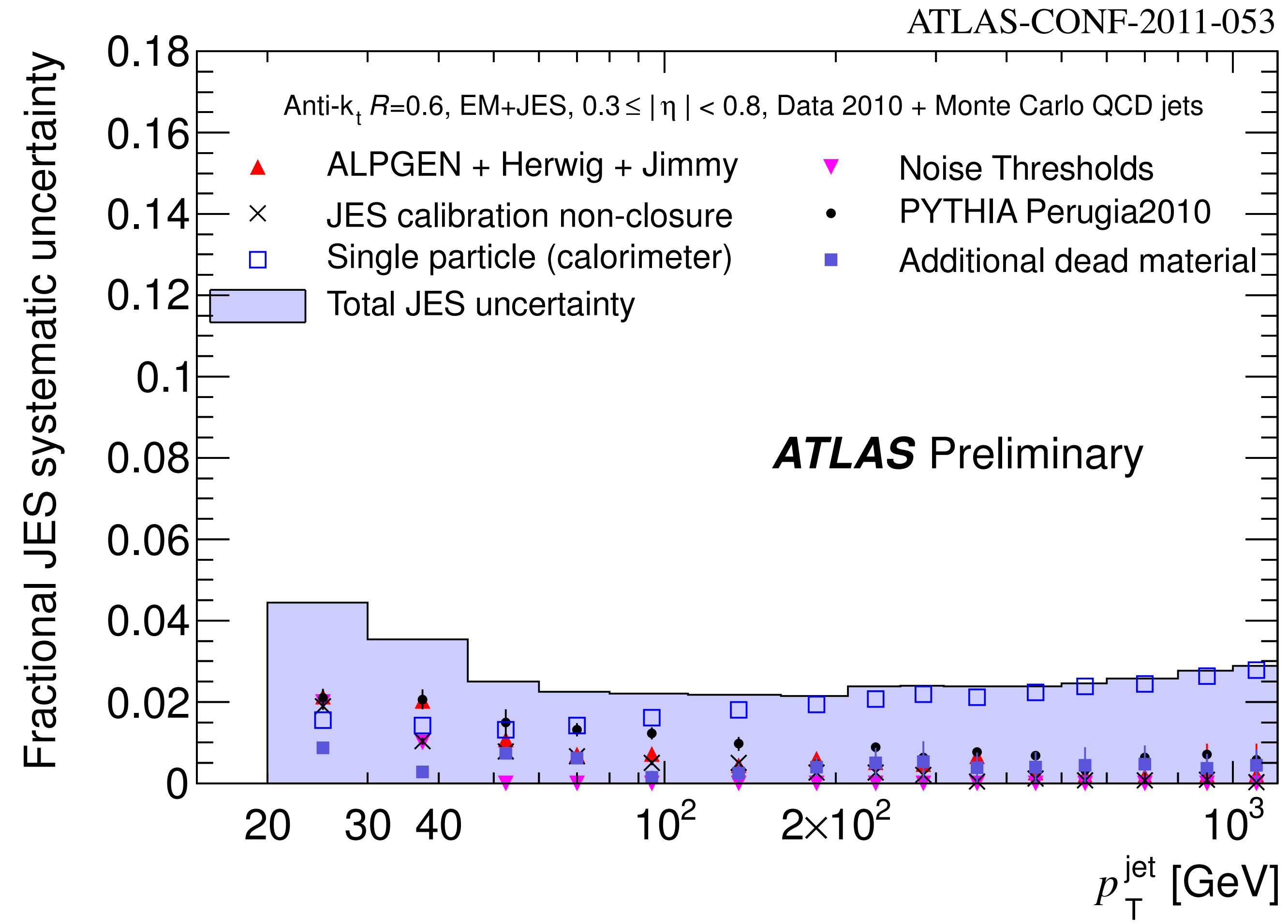
Ingredients II : jets (scale)

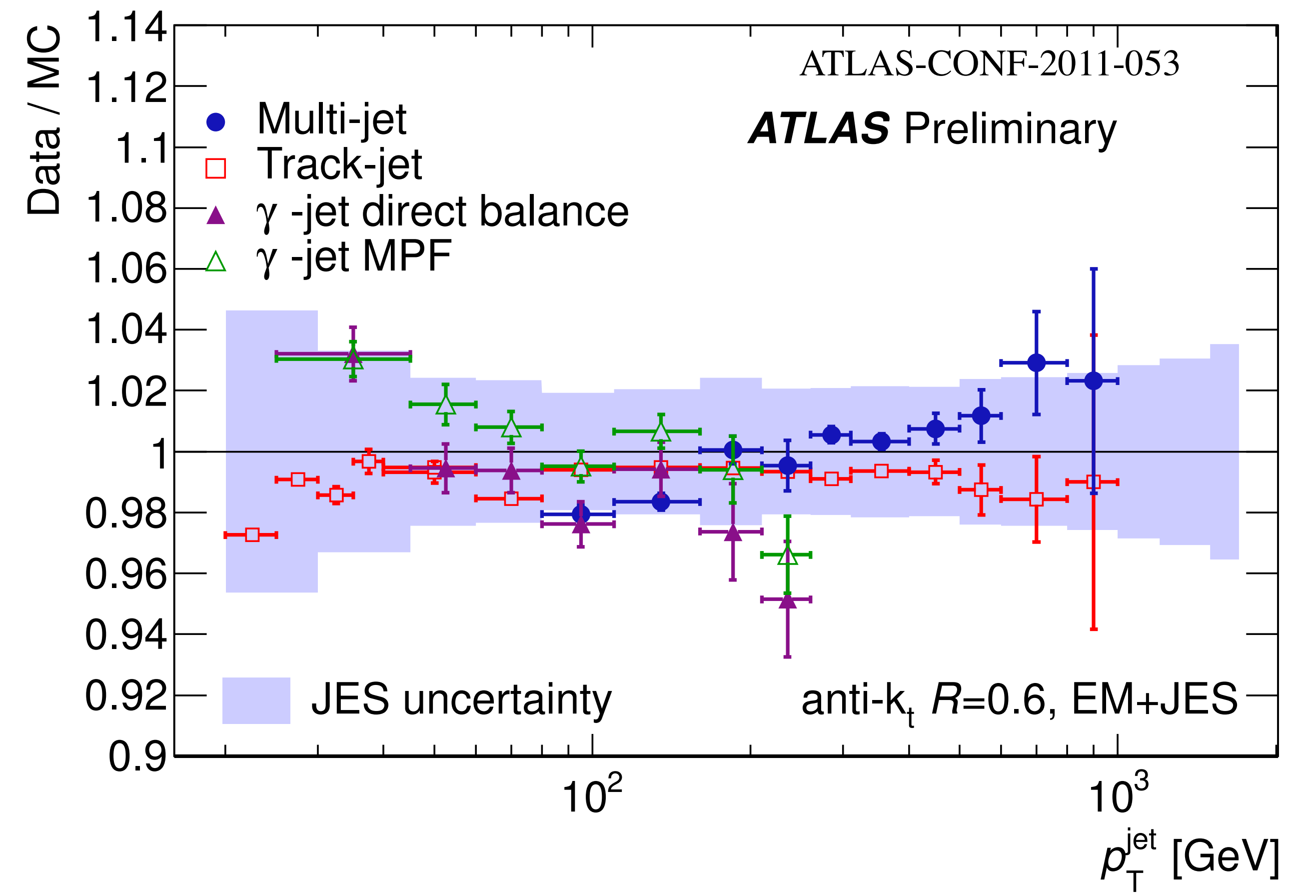
- **Calibrate jet energy scale** with (η,p_T) dependent weight ***from simulated "true" jet kinematics***

- **Scale uncertainty:** range between 2% to 8% in p_T and η

- Contributions from
  - **Physics models** for generation and hadronization
  - **Calorimeter response**: collision single particle data, test beam
  - **Detector simulation**

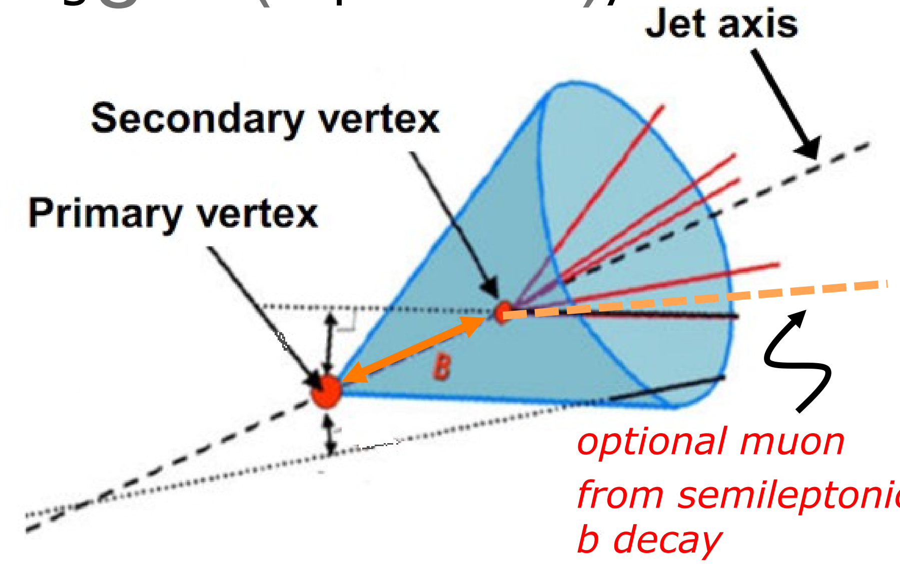
- Validation in control samples





Ingredients IV : enter b-jets

- B-hadrons have long lifetime ~observable flight (few mm)



Tagging

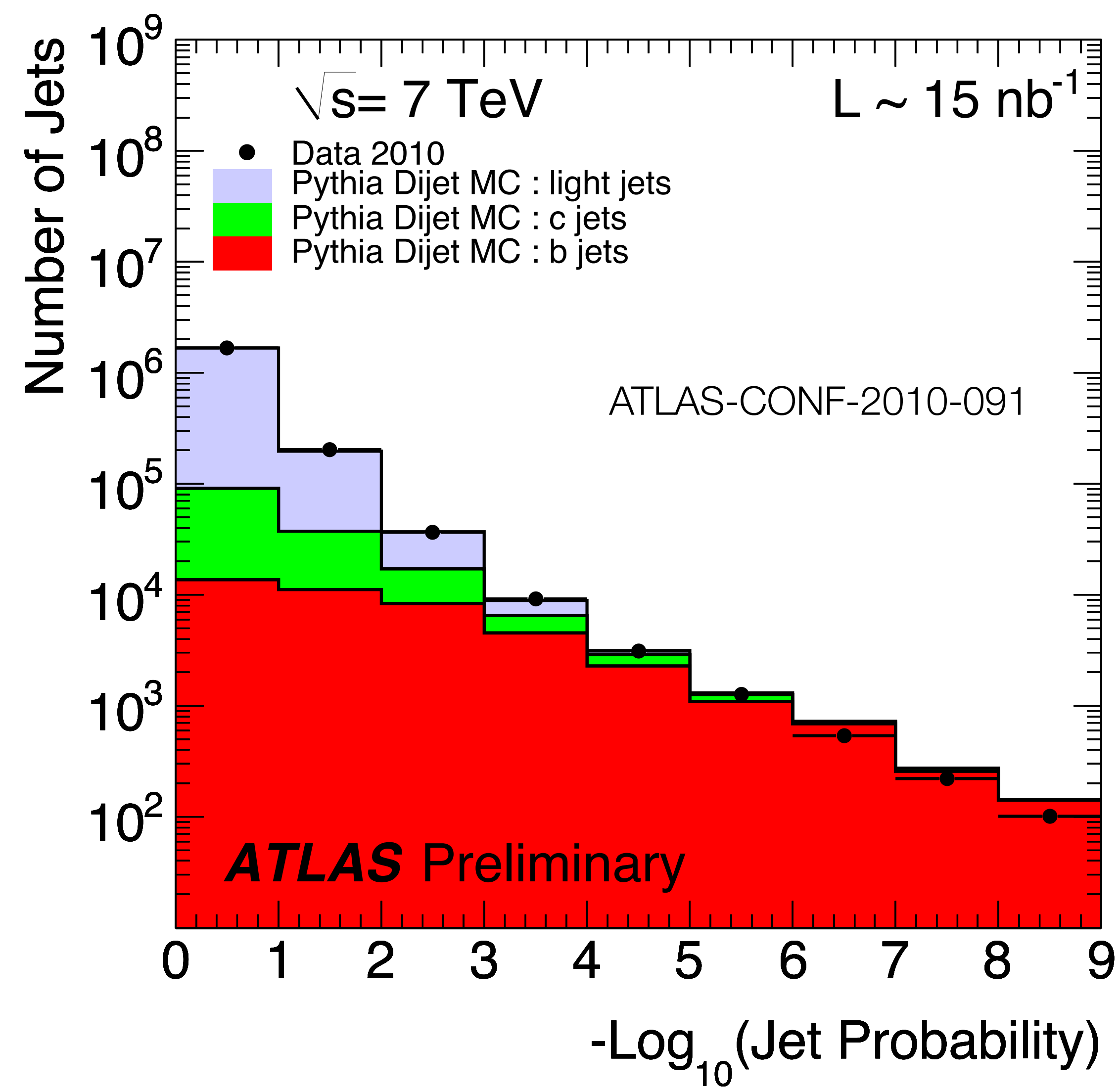
d_0/σ_{d_0}

- track impact parameter resolution d0/ σ_{d0} → **different probability for jet origin** for b-jets

Performance in data

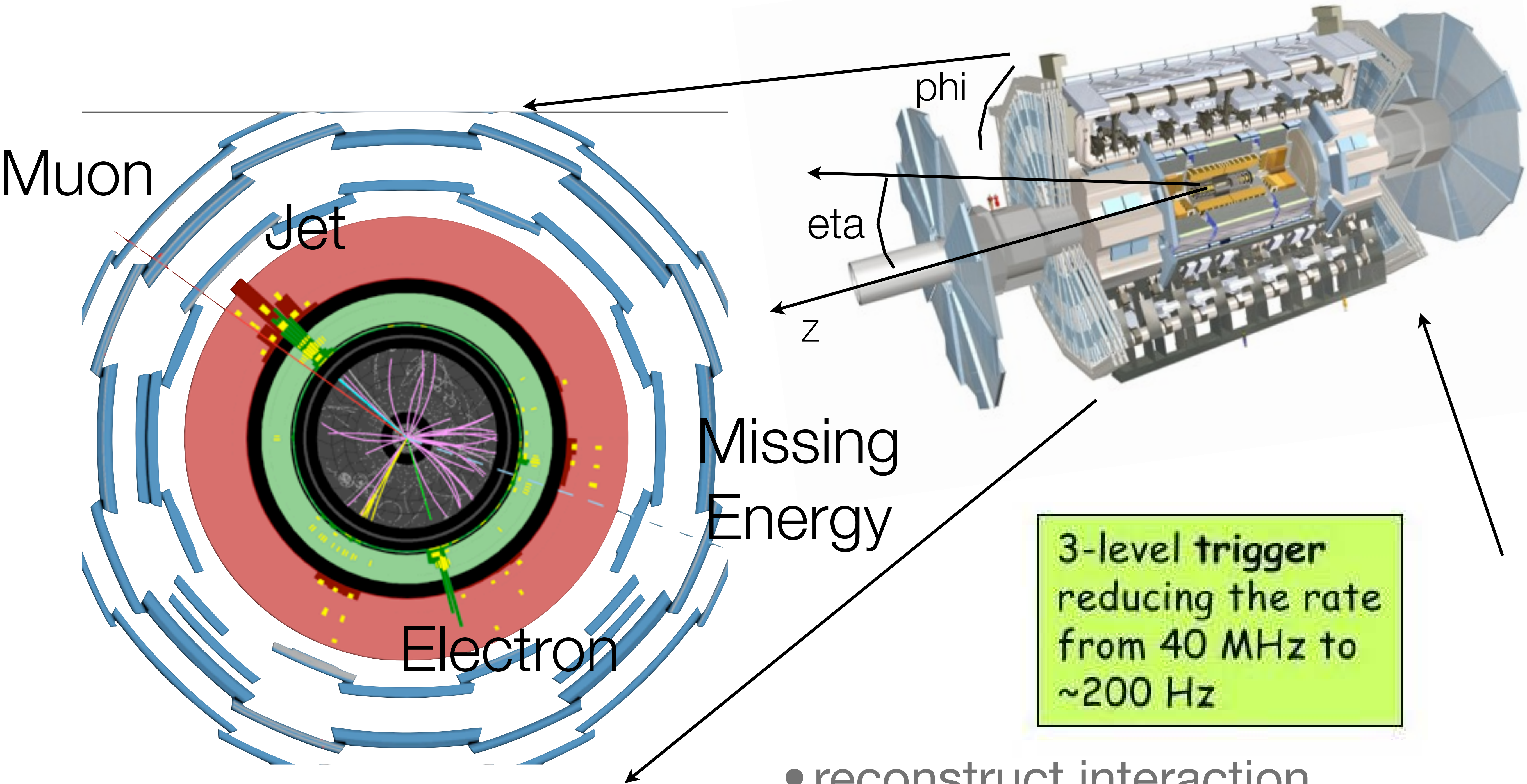
- **Efficiency:** fit fraction of b-jets in sample with muons in jets, *count how many are b-tagged*
- **Mis-tag rate**: from secondary vertex properties (*invariant mass of tracks, rate of negative decay length significance)*

p_T dependent scale factors to correct MC



ATLAS **:** a *Top* observer

Top is a real commissiong tool: full detector at play

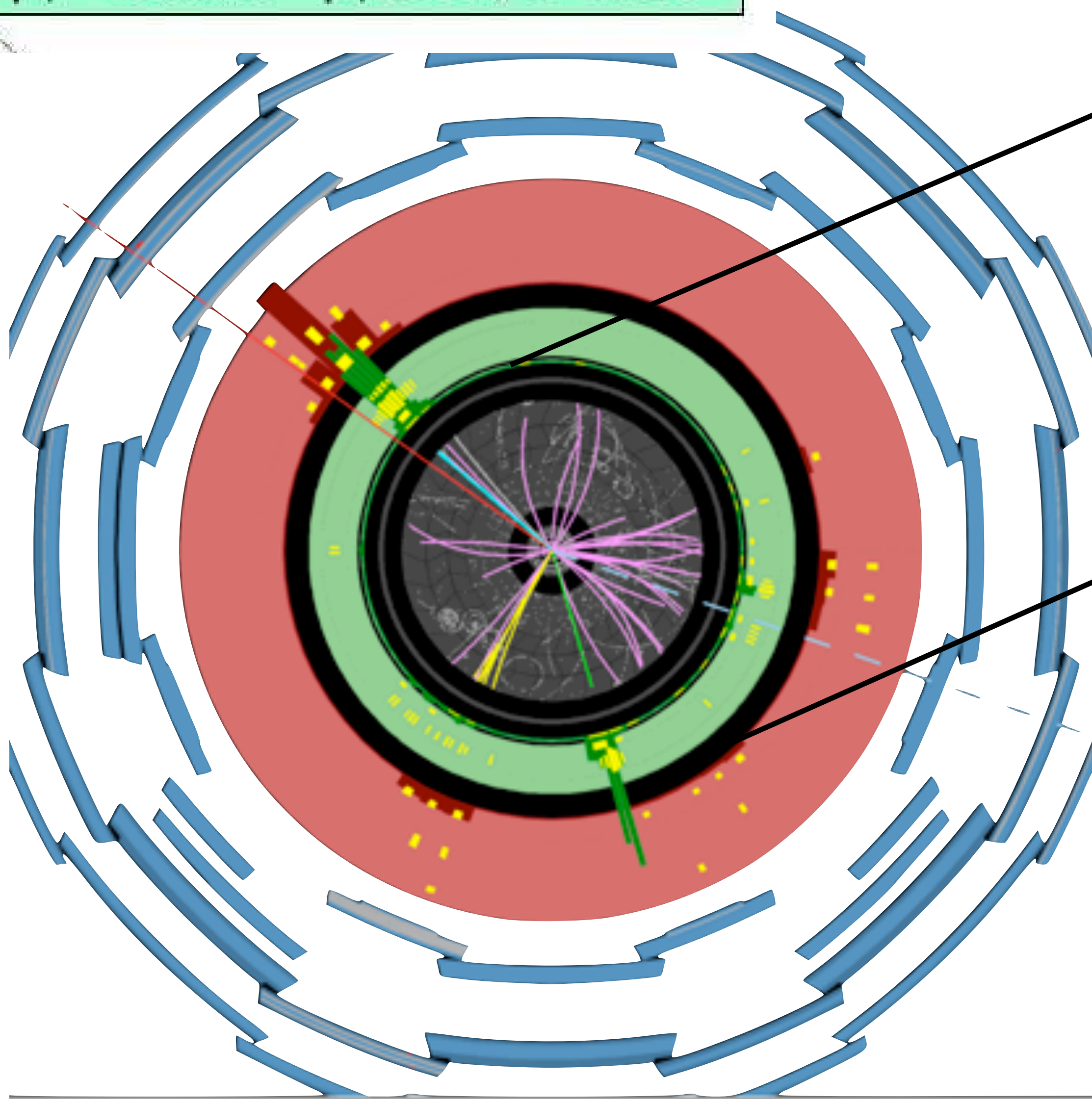


3-level trigger reducing the rate from 40 MHz to ~200 Hz

- reconstruct interaction vertex, electrons, muons, jets and missing energy

ATLAS : a *Top* observer

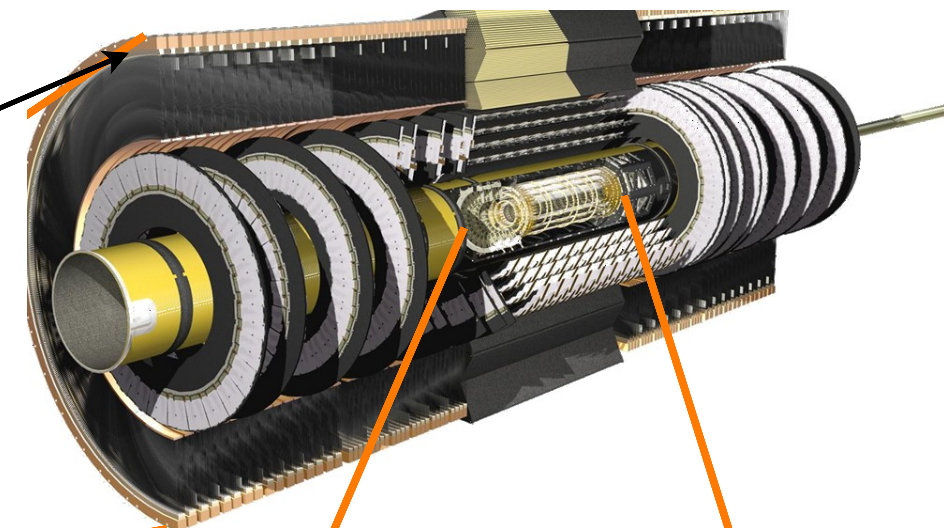
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition
Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$



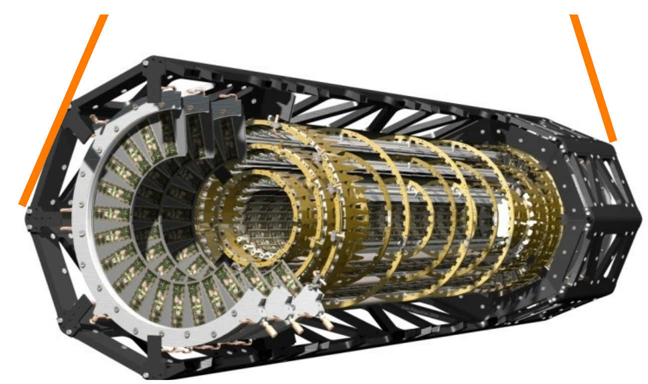
Inner detector

Transition radiation tracker

Semi conductor tracker



track, particle identifcation,
pt measurement



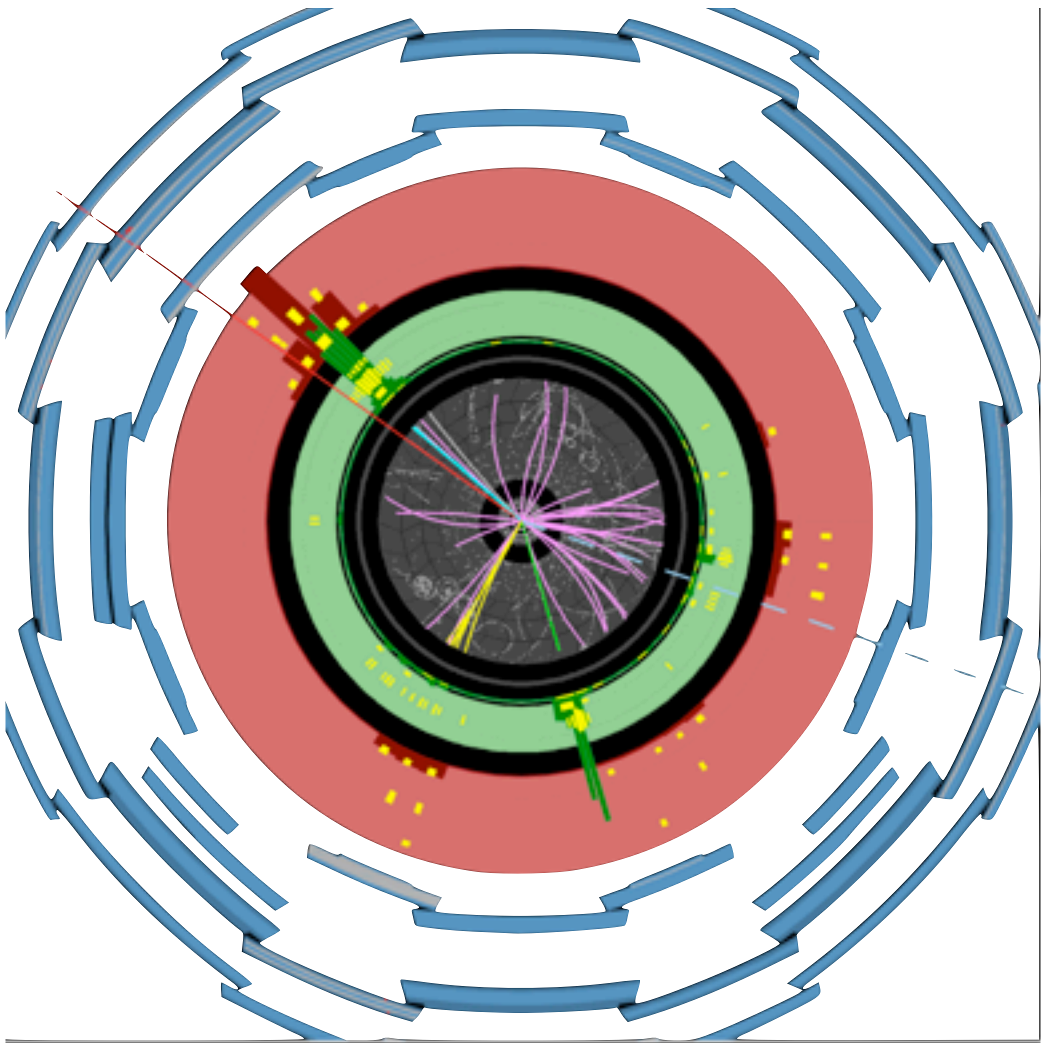
Pixel
detec
tor

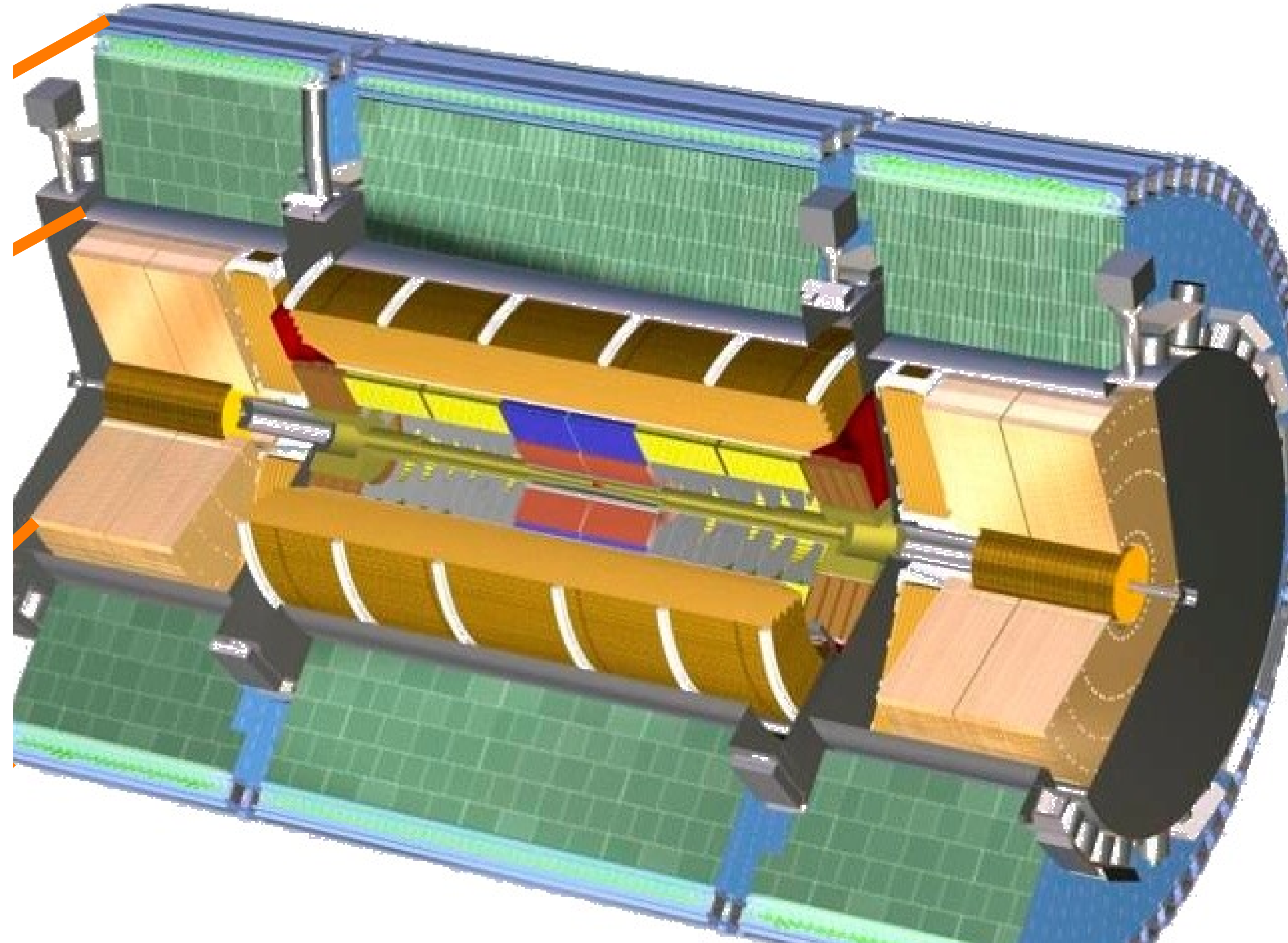
b-tagging

ATLAS **:** a *Top* observer

Calorimeters

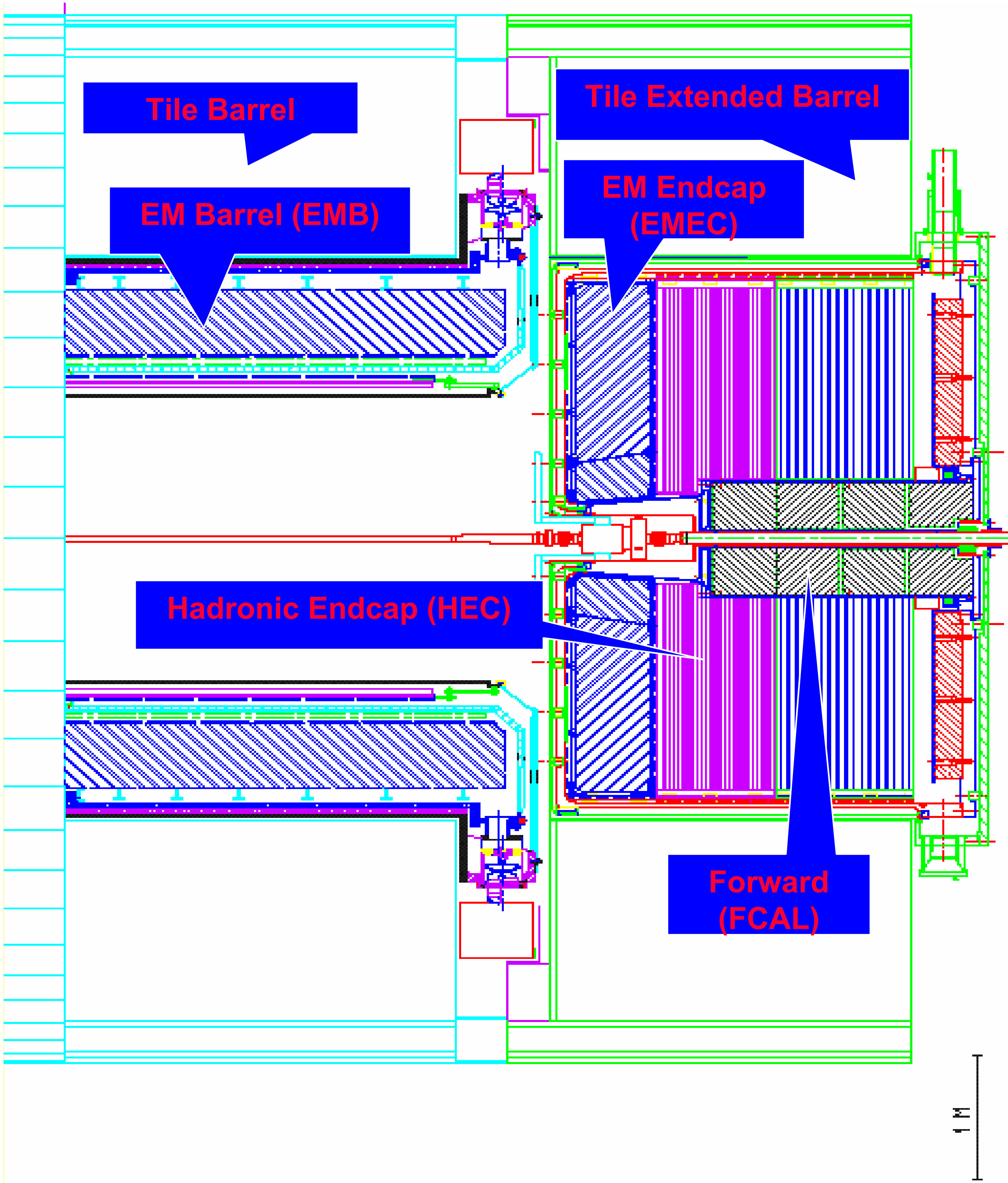
electron and jets reconstruction
Missing transverse energy





EM calorimeter: Pb-LAr Accordion
e/γ trigger, ID and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$



ATLAS Calorimetry

2

- EM LAr-Pb :
  - Barrel (EMB): |η| < 1.5
  - EndCap (EMEC): 1.4<|η|<3.2
- Hadron Calorimeters
  - Barrel (Tile) Scintil.-Steel: |η|<1.7
  - End-Cap (HEC): LAr-Cu 1.5<|η|<3.2
- Forward Calorimeter 3.2 <|η|< 5.0
  - Fcal1: LAr-Cu
  - Fcal2&3: LAr-W

Variety of materials, techniques, granularity, different performances

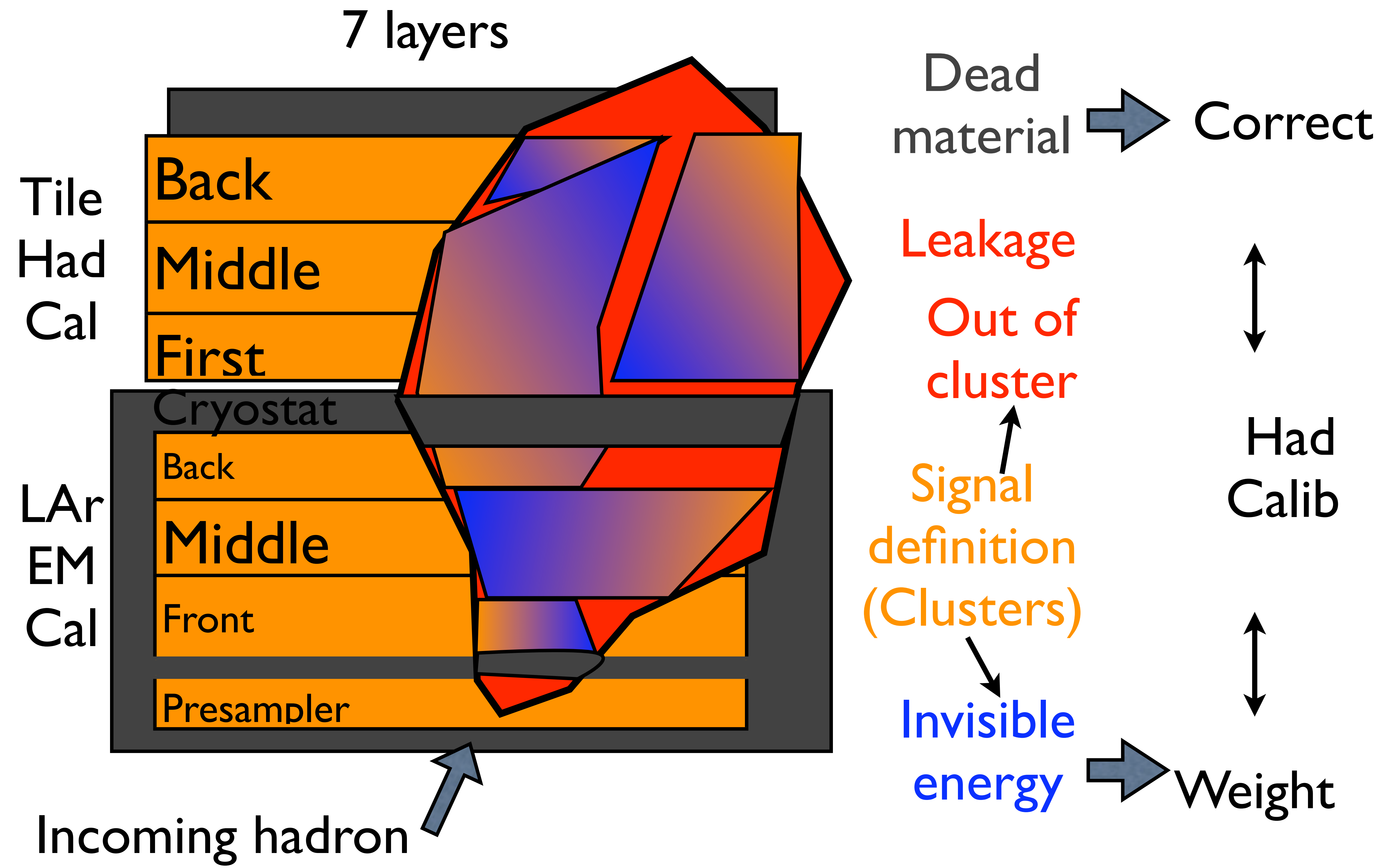
↓

Need coherent view!

Physics Workshop - Roma - 8th June 2005

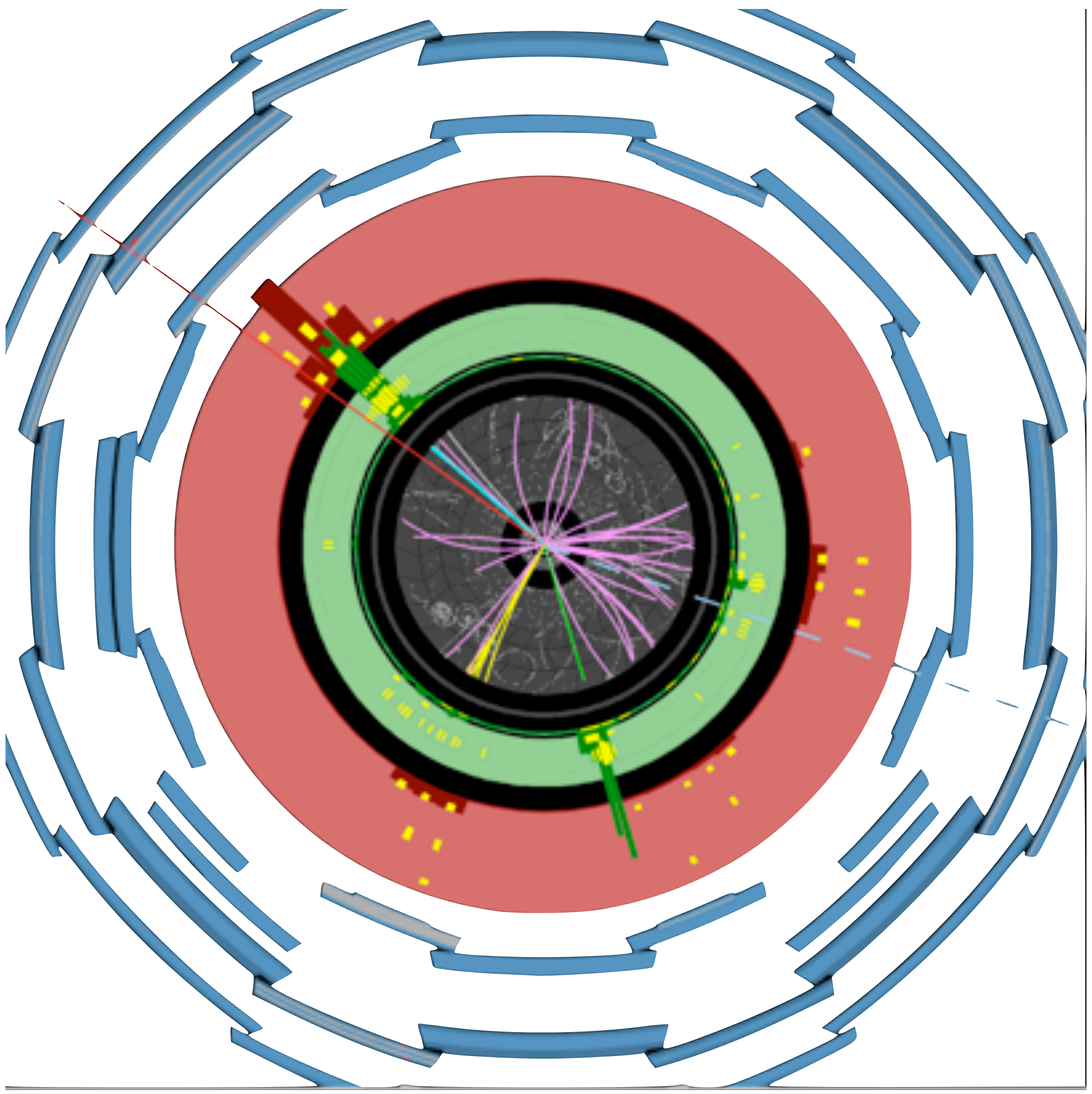
F Spanò, Local Hadron calibration, Atlas Physics Workshop Rome 2005

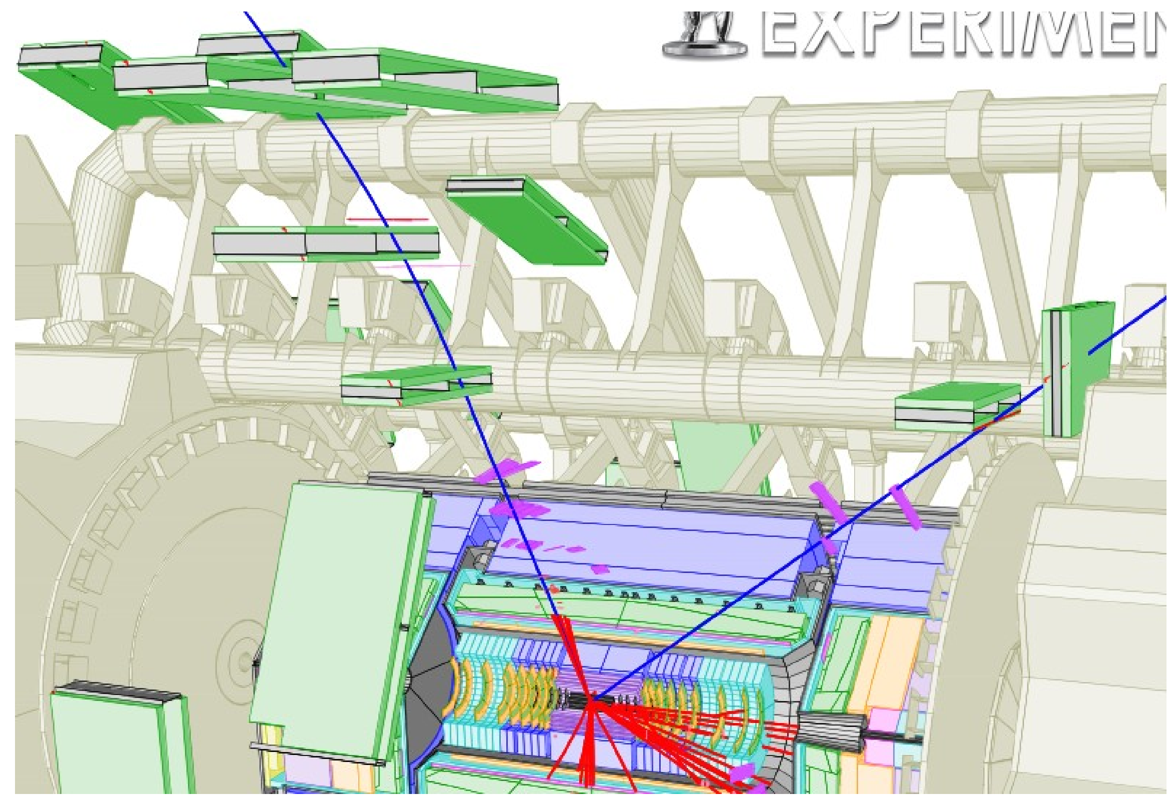
Pion in ATLAS Calo



ATLAS **:** a *Top* observer

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV





Muon spectrometer

particle identification

pt measurement

Monte Carlo used in top analyses

Generation

- **Top quark : MC@NLO**
  - xsec is normalized to NNLO effects
- **Single top : MC@NLO**
  - t, Wt and s channels
  - normalized to MC@NLO, remove Wt overlaps with $t\bar{t}$ final state
- **Z/gamma+jets** : **PYTHIA** for Z_tautau, **ALPGEN** (MLM matching for) Z to ee and Z to mumu NLO factor of 1.25
- **Di-boson** : WW, ZZ: ALPGEN normalized to NLO from MCFM
- **W+jets**: ALPGEN
  - W+n light partons
  - W+bb
  - W+cc
  - W+c

Hadronization

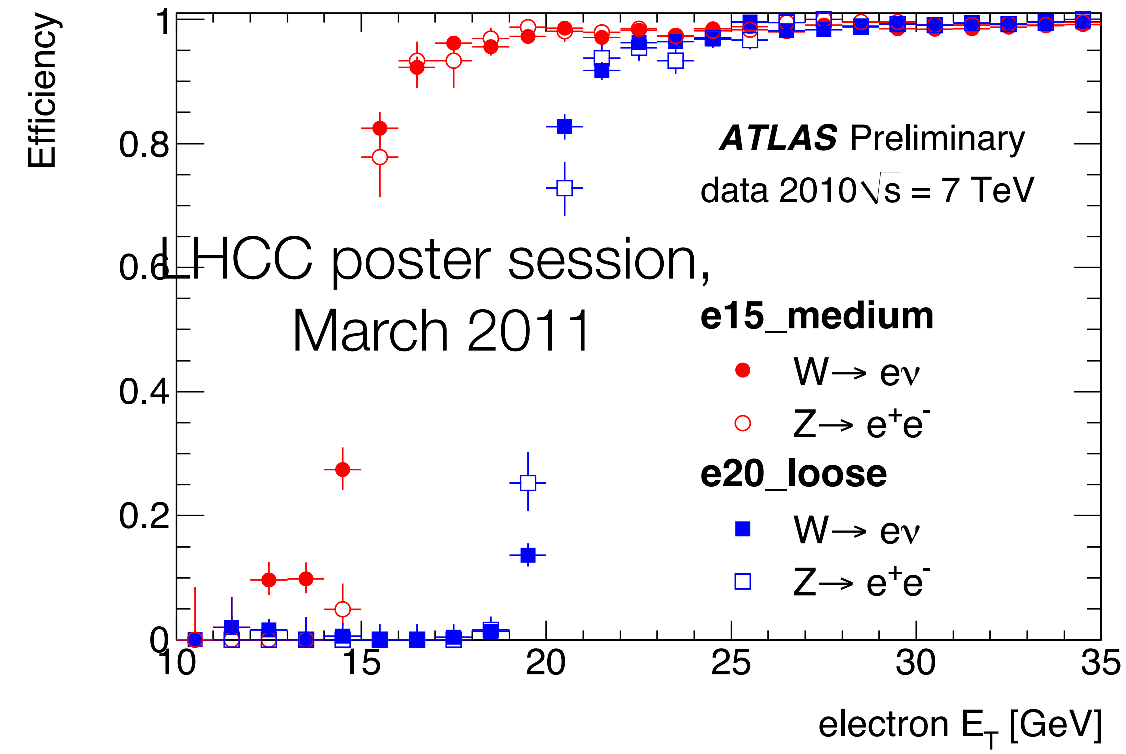
- **HERWIG + JIMMY for underlying event modelling**

Trigger Details

Efficiency for offline object is at plateau for p_T 20 GeV

Electron

- EM calo energy deposit with E_T between 10 and 15 GeV *at level1*
- More refined selection *at level 2*
- ***Match EM calorimeter cluster and Inner Dret track** at level3*

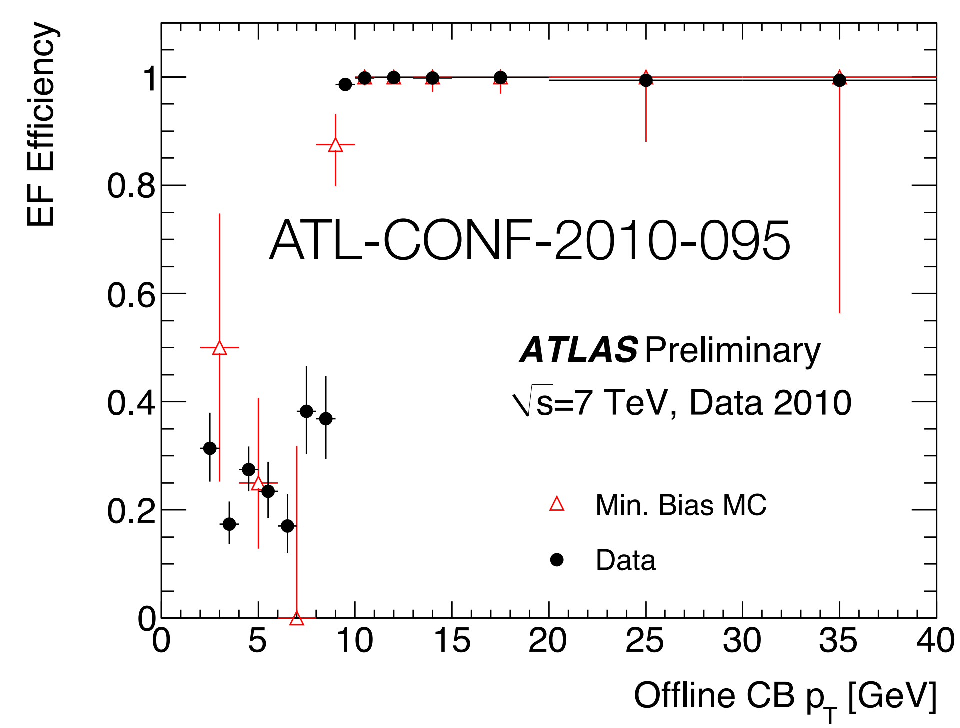


3rd level efficiency with tag and probe method for Z (in Z window), missing ET triggers for W (MET>25 GeV, isolated form Jet, MTw.40 GeV)

Muon

- Level1 track in muon chambers with p_T >10 GeV *at level 1*
- Confirm at level 2
- Match to track in inner detector . P_T threshold between 10 and 13 GeV with p_T >13 GeV muon, use precision chambers *at level 3*

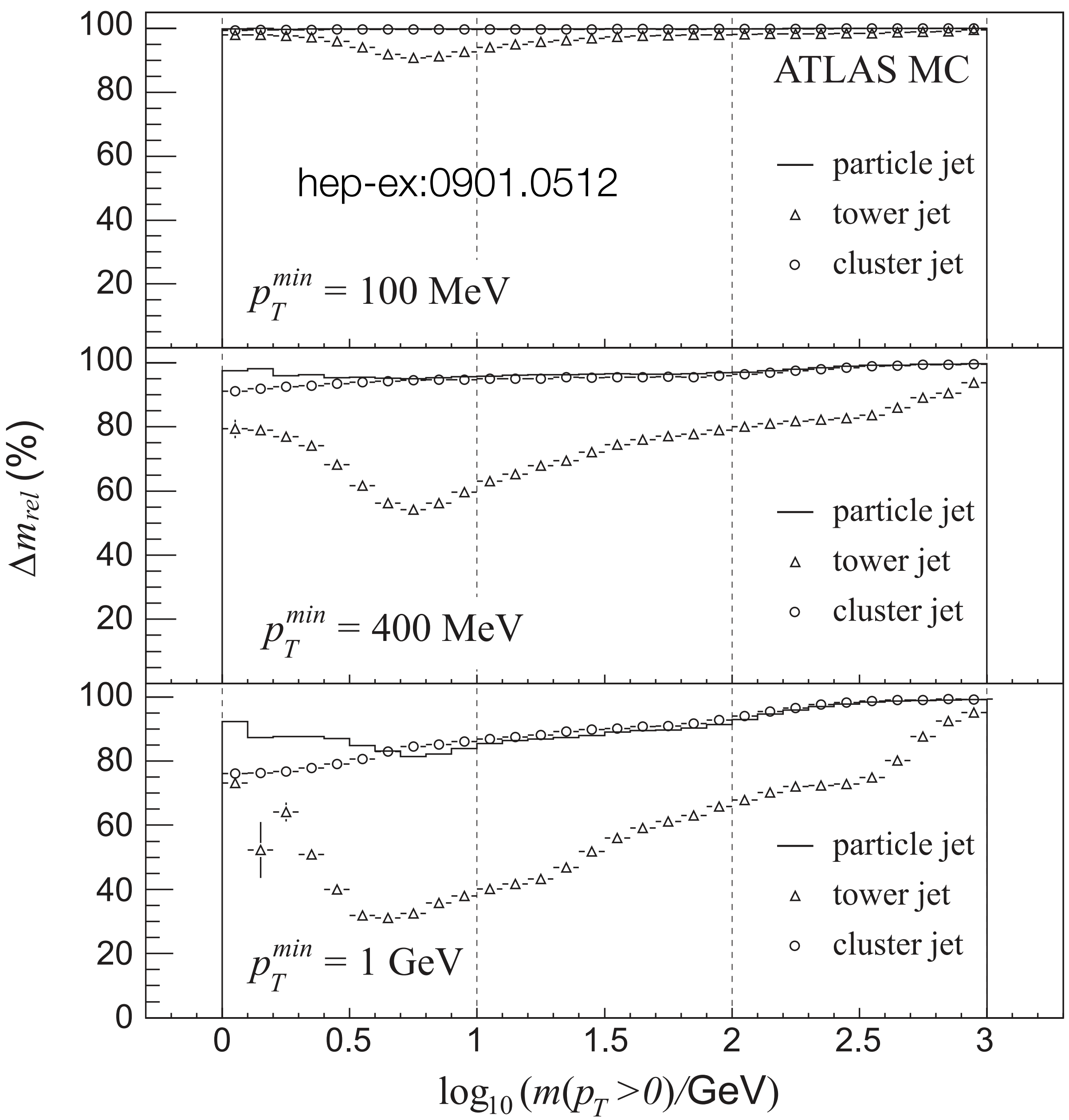
$$\varepsilon_{trigger}(Z\ T\&P) = \frac{N_{matched}}{N_{probes}}$$



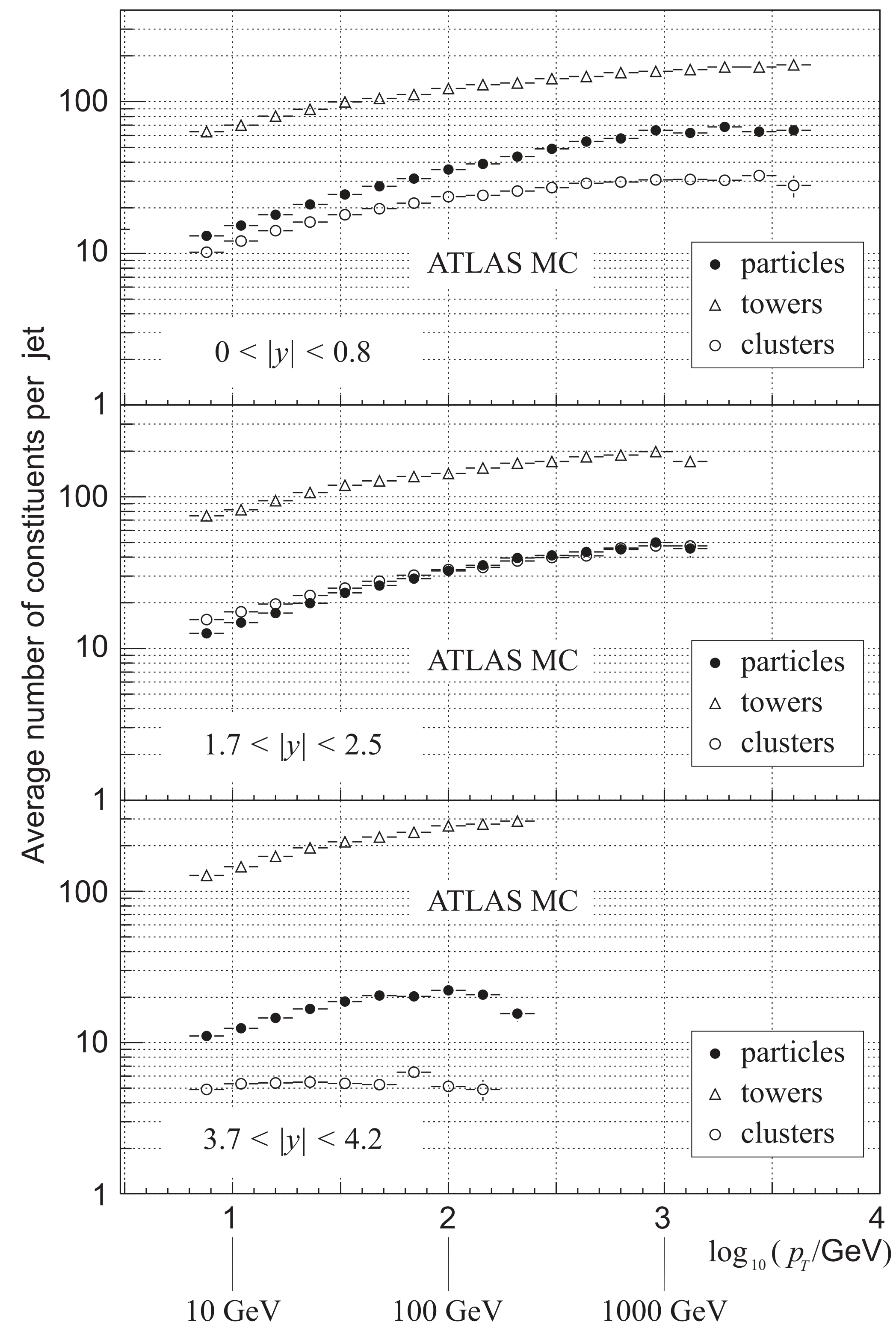
3rd level muon efficiency with respect to offline muon matched to level 1 and level2 di-jet simulated events, anti-k_T R=0.6

Calorimeter Clustering

- Keep particle picture, capture shower, suppress noise
- Number of constituents per jet and jet mass closest to "true" stable particle jets



hep-ex:0901.0512



Jet calibration steps

- **Average pile-up is subtracted** by correction constants derived in-situ
- **jet position is corrected** for the jet to point to primary vertex of interaction (rather than centre of ATLAS detector)
- **jet energy and position are corrected** to corresponding truth jets
  - *truth jets are formed by running jet algorithm on stable interacting particles*, i.e. lifetime>10 ps, muons and neutrinos are excluded)

Jet uncertainty contributions

Estimated by Simulated samples

Estimated by single particle response

Estimated by in situ measurements

- **JES calib method**
- **JES in calorimeter response**
  - in simulation, link true calo deposits to particles from collision
  - uncertainties on single particles constrained from in-situ, derive jet uncertainty. It Includes
    - uncertainties on charged hadrons, calo acceptance,large p particles
    - EM scale for hadronic and EM calo for particles not measured in situ
    - uncertainties for neutral hadrons
- **JES in det simulation**
  - uncertainty in calo noise thresholds
  - detector material description (cryostat, presampler, transition barrel endcap)
- **JES in physics model (hadronization) and parameters in generation**
- JES in relative calib for eta>0.8
- Pile-up

JES in situ methods

- **Photon balance**
  - transverse photon momentum balanced against fullhadronic response by projecting E_T^{miss} on photon direction; no explicit jet algo involved

- **High pt jet balance by one or more lower pt jets**
  - if low p_T jets are well calibrated, check high p_T jets against them.
  - High reach in p_T , $|eta| < 2.8$

- **Compare calo jet to associated tracks**
  - Calculate mean transverse momentum sum of tracks in a cone

Jet calibration : top Specific effects

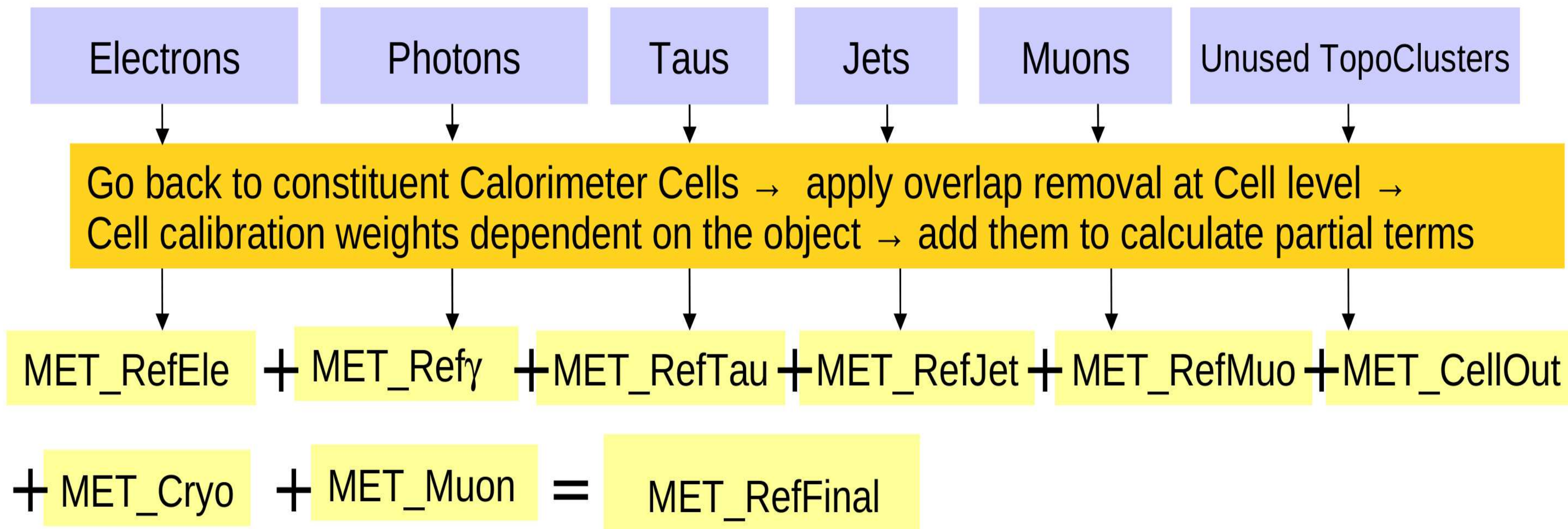
- **Close by jet**
  - jet splitting can bias scale
  - recover by monte carlo baed correction as a function of isolation

- **Gluon vs quark jets**
  - different response in gluon initiated and quark initiated jets
  - validation in di-jet (gluon) and gamma-jet (quark) samples

- **B-jet**
  - tag and probe method in data-MC in di-jet
  - comparison to track jets (data/MC)

MIssing transverse energy (I)

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss,calo}} + E_{x(y)}^{\text{miss,cryo}} + E_{x(y)}^{\text{miss,muon}}$$



- overlap removal order is
  - electron, photon, hadronic taus, jets, muons

MIssing transverse energy (II)

- The three terms are, muons

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss,calo}} + E_{x(y)}^{\text{miss,cryo}} + E_{x(y)}^{\text{miss,muon}}$$

$$E_{x(y)}^{\text{miss,calo,calib}} = E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,calo},\mu} + \boxed{E_{x(y)}^{\text{miss,CellOut}}}$$

$$E_{x(y)}^{\text{miss},\mu} = - \sum_{\text{selected muons}} E_{x(y)}^{\mu}$$

isolated muons

non-isolated muons

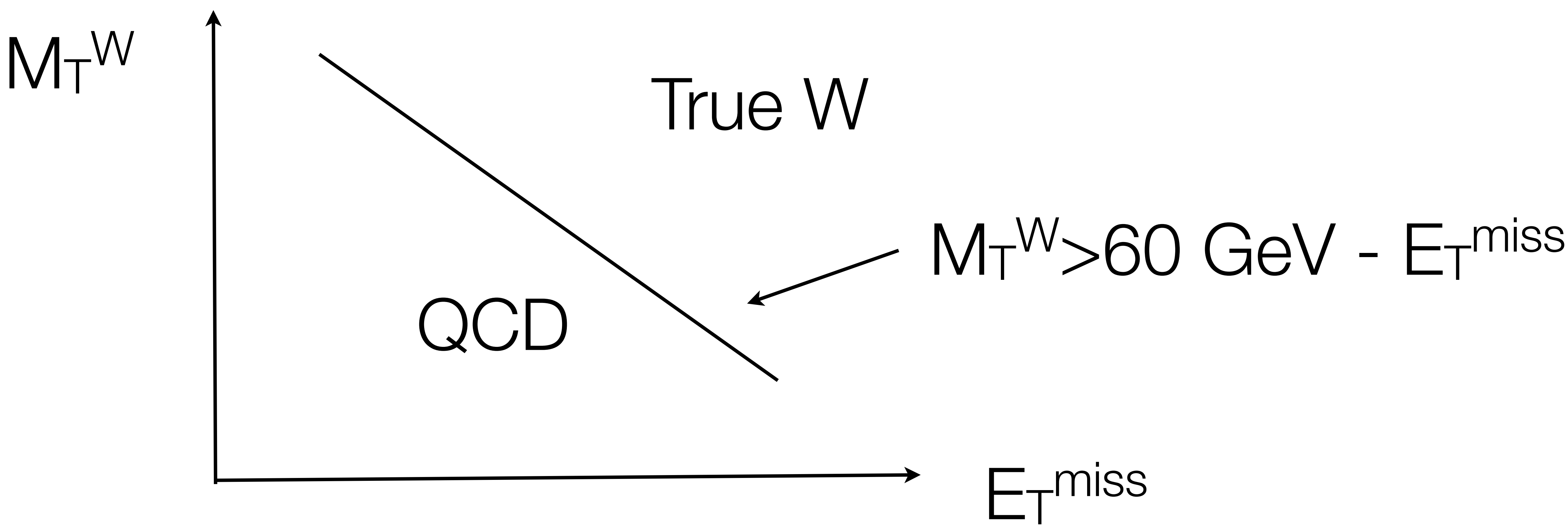
$$E_{x(y)}^{\text{miss,cryo}} = - \sum_{\text{jets}} E_{x(y)}^{\text{jet,cryo}}$$

$$E_x^{\text{jet,cryo}} = w^{\text{cryo}} \sqrt{E_{\text{EM3}}^{\text{jet}} \times E_{\text{HAD1}}^{\text{jet}}} \frac{\cos \phi_{\text{jet}}}{\cosh \eta_{\text{jet}}}$$

$$E_y^{\text{jet,cryo}} = w^{\text{cryo}} \sqrt{E_{\text{EM3}}^{\text{jet}} \times E_{\text{HAD1}}^{\text{jet}}} \frac{\sin \phi_{\text{jet}}}{\cosh \eta_{\text{jet}}}$$

Triangular cut

- True W leptonic decay with large missing transverse energy E_T^{miss} also have large W transverse mass M_T^W
- Mis-measured jets in QCD may have large missing transverse energy E_T^{miss}, but small transverse mass M_T^W
- Requirement on transverse missing energy and transverse mass helps discriminate the two

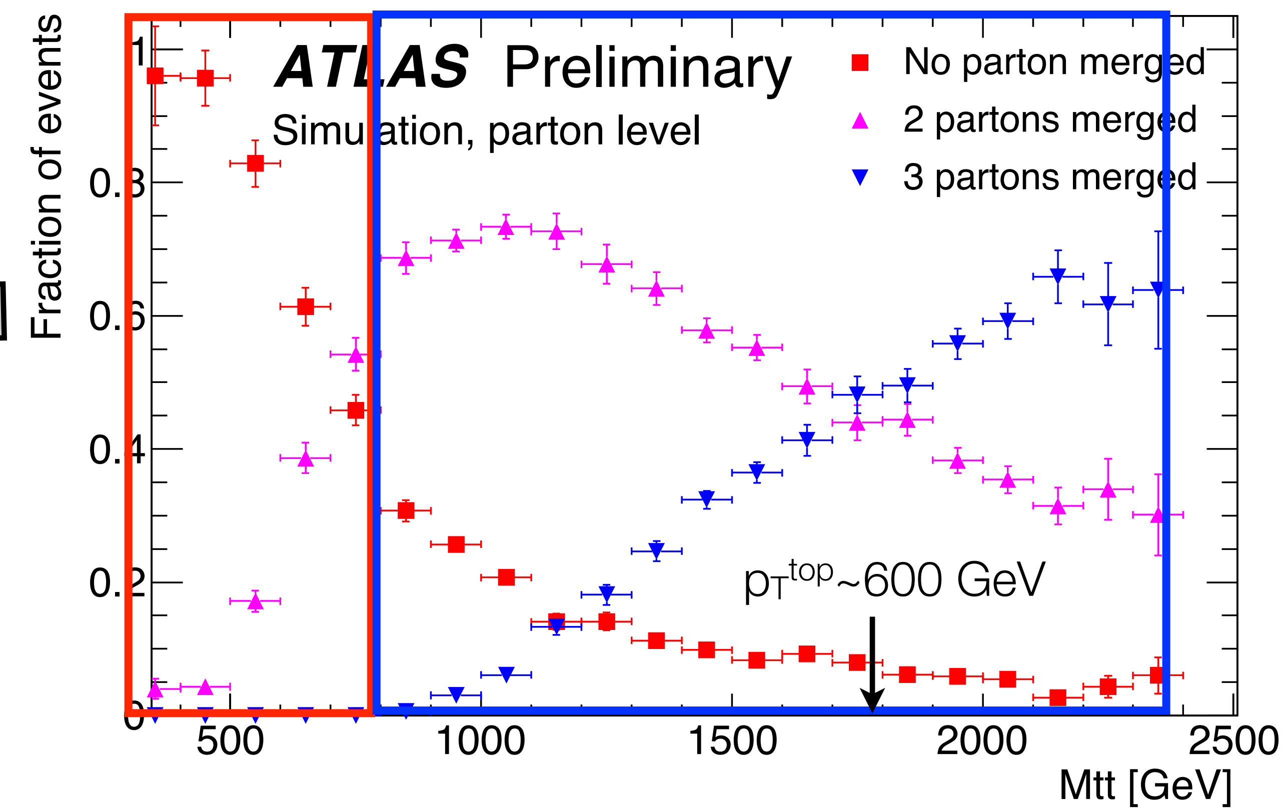


Top/anti-top resonances : ATLAS expectations

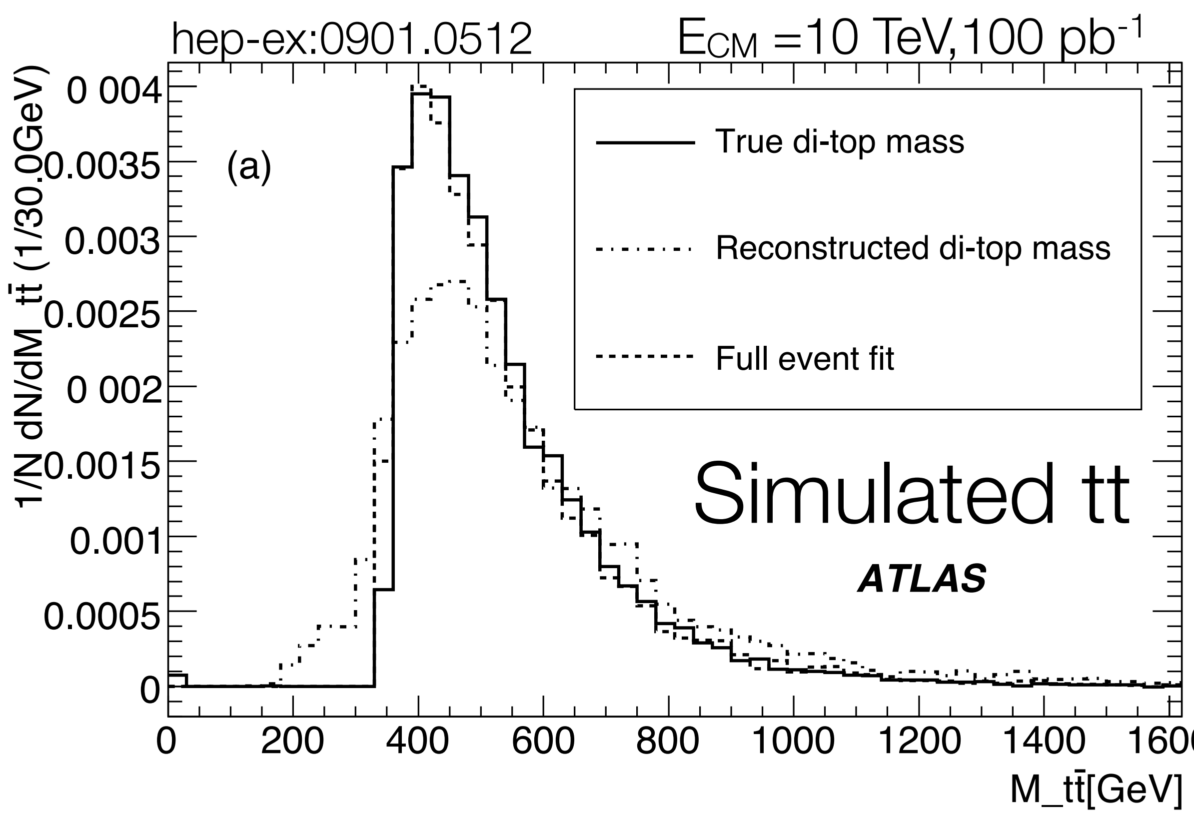
- Search for peaks in M_{tt} → **mass resolution is crucial**

ATLAS-PHYS-PUB-2010-008

- **At "low" M_{tt}**
  - **add final state objects** + algo to choose jets (p_T order,χ^2)
  - **perform kinematic fit** using M_W, M_{top}



Probability to find partons within DR=0.8



- **Higher p_T^{top} (or M_{tt})** → boosted "top jet" → new reco to separate QCD, tt, possible new physics.

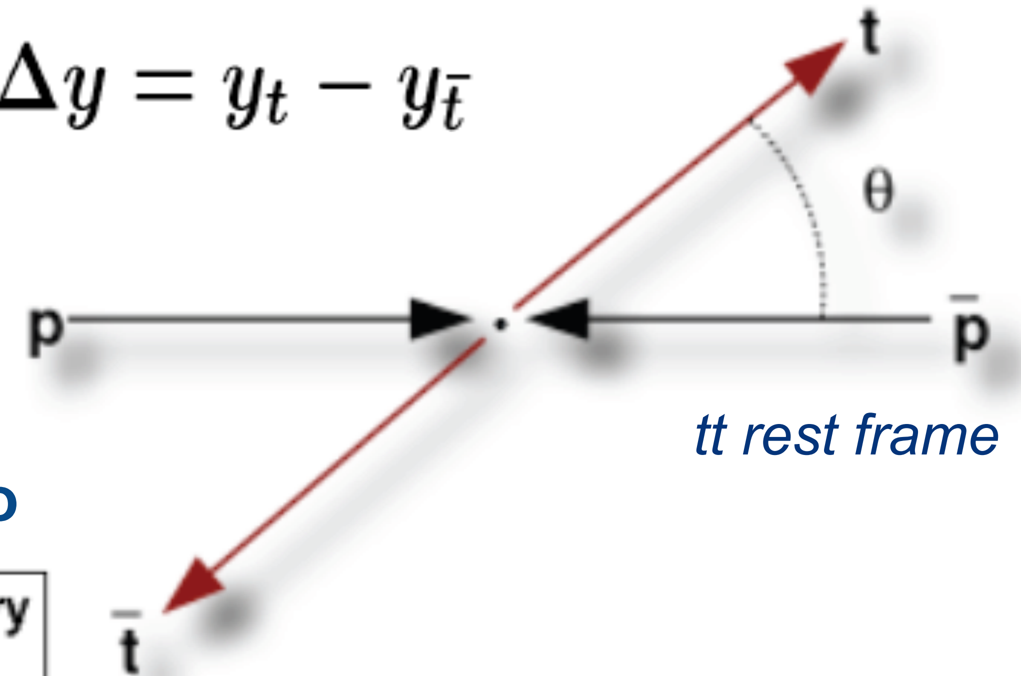
- **ATLAS analysis with 35 pb^{-1} in advanced state**. Expect results soon.

Colour Charge Asymmetry (A_{FB})

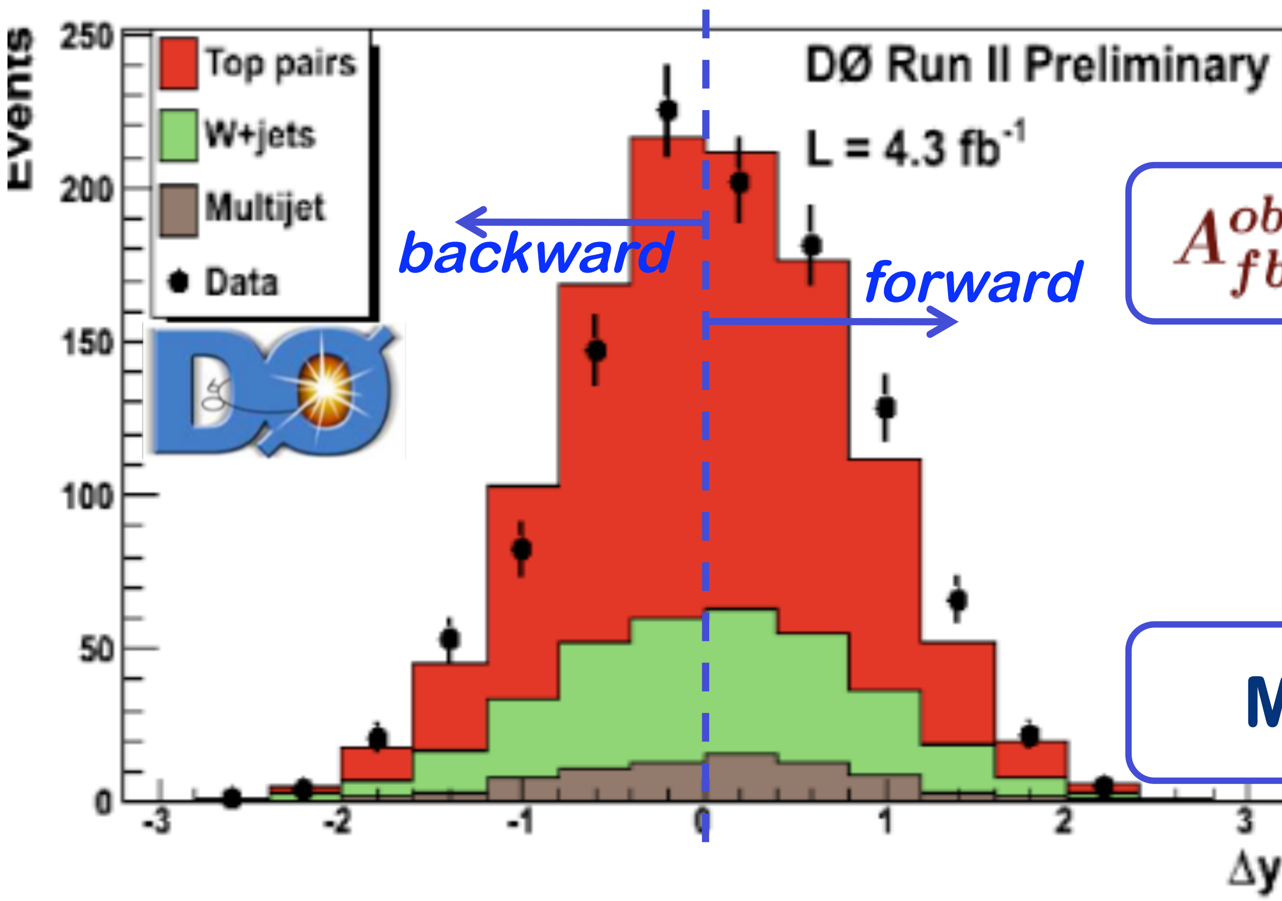
- **Form observable:**

$$\Delta y = y_t - y_{\bar{t}}$$

$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$



  - Use b-tagged events
  - Use kinematic fitter for reco



$$A_{fb}^{obs} = 8 \pm 4(stat) \pm 1(syst)\%$$

Raw result (not unfolded)
+ description of acceptance
& detector effects allowing
comparison to any model

MC@NLO prediction: $1^{+2}_{-1}\%$

[D0 note 6062]

$\sim 2\sigma$

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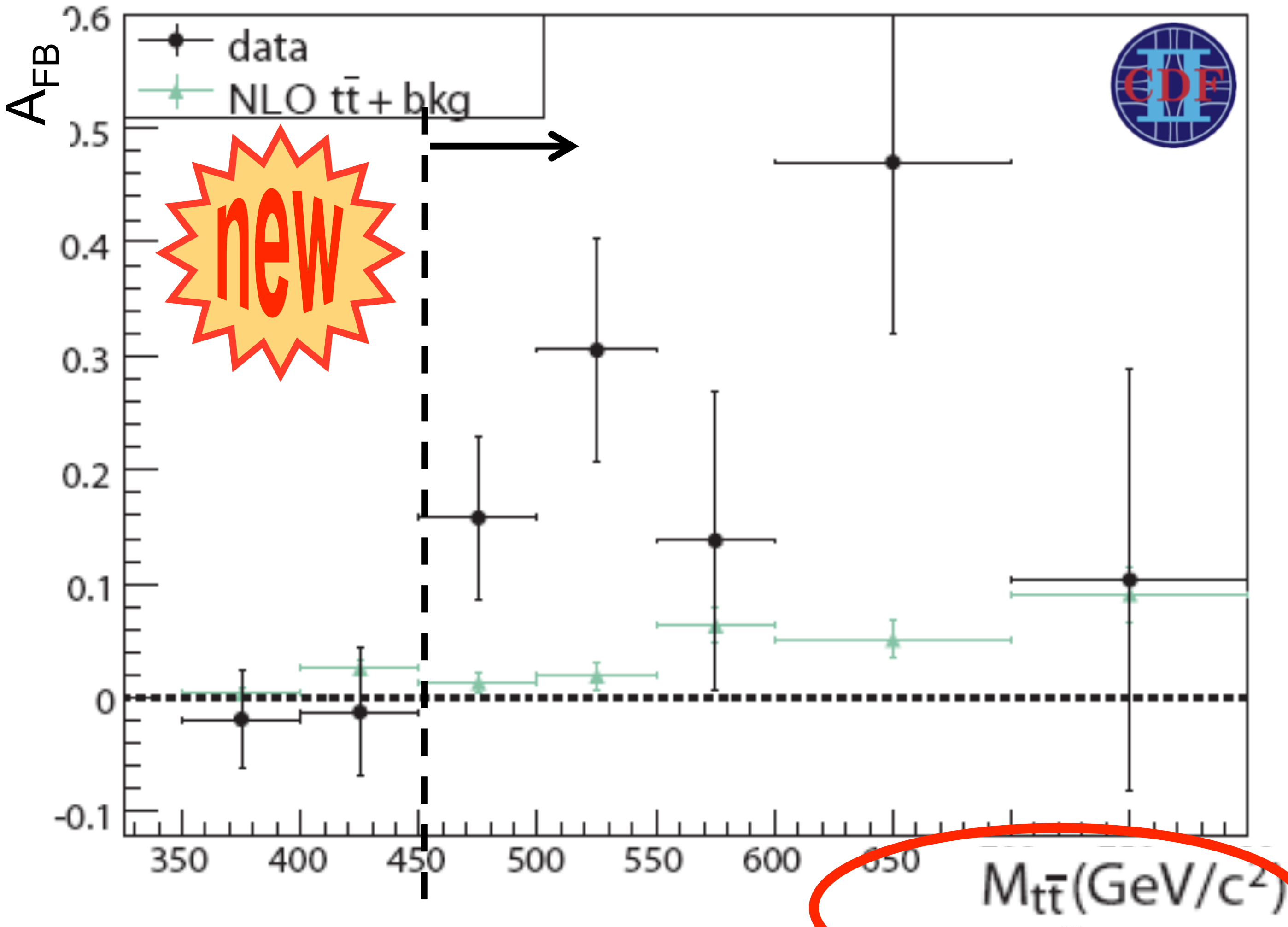
Colour Charge Asymmetry (A_{FB})

- Look at A_{FB} as a function of M_{tt}



Pronounced dependence of A_{FB} on M_{tt}!!!

New physics?

SM prediction at α_s^4? α_s^∞?

Soft QCD effects?

Unfolding

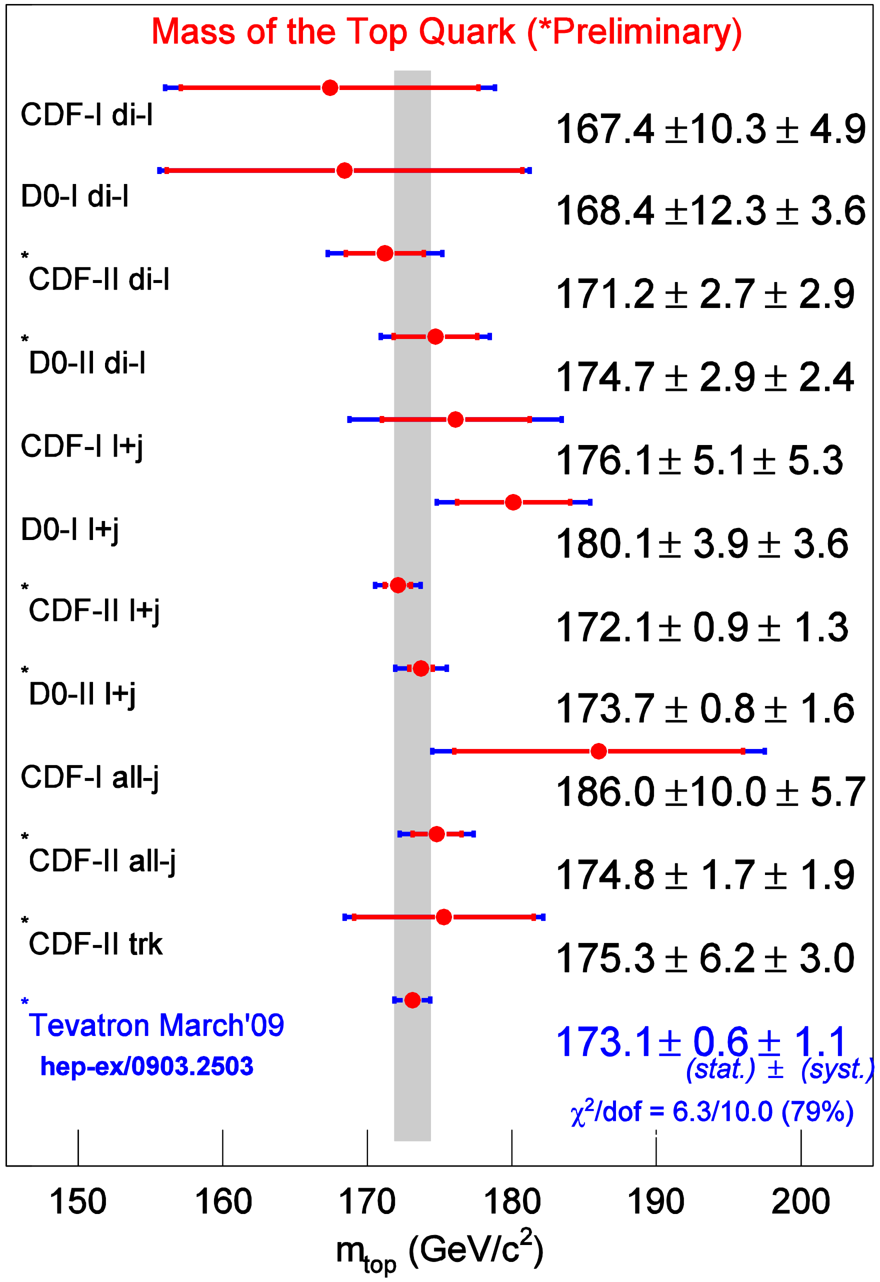
>3σ

selection	$M_{t\bar{t}} < 450$ GeV/c^2	$M_{t\bar{t}} \geq 450$ GeV/c^2
data parton	$-0.116 \pm 0.146 \pm 0.047$	$0.475 \pm 0.101 \pm 0.049$
MCFM	$+0.040 \pm 0.006$	0.088 ± 0.013

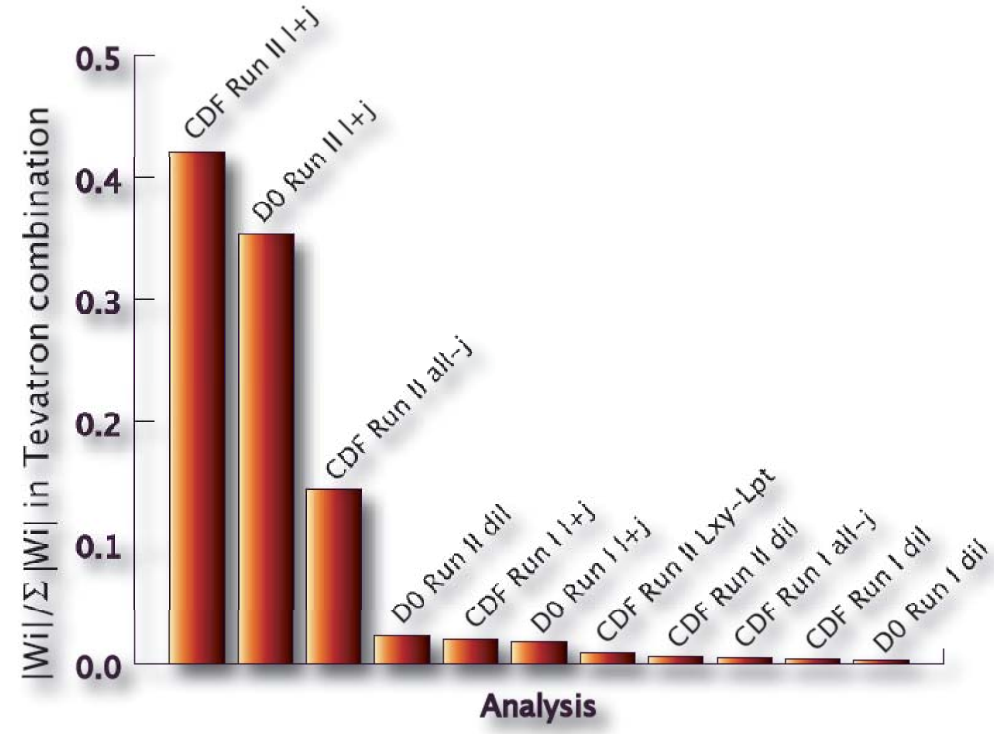
Oleg Brandt - Moriond QCD 2011

H.Lee, Moriond QCD
March 2011

Combination



$$m_{top} = 173.1 \pm 1.3 \text{ GeV}/c^2$$



New measurements

CDF LJ (ME) = 172.8 ± 1.3 GeV/c^2

CDF LJ (TM) = 172.1 ± 1.5 GeV/c^2

CDF DIL(TM) = 170.6 ± 3.8 GeV/c^2

Moriond QCD 2010, Hyunsu Lee, The University of Chicago 14