Top physics and the top mass

Lecture 1/3

2013 CERN-Fermilab HCP Summer School

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(and this year also: LHC Physics Centre, Fermilab)

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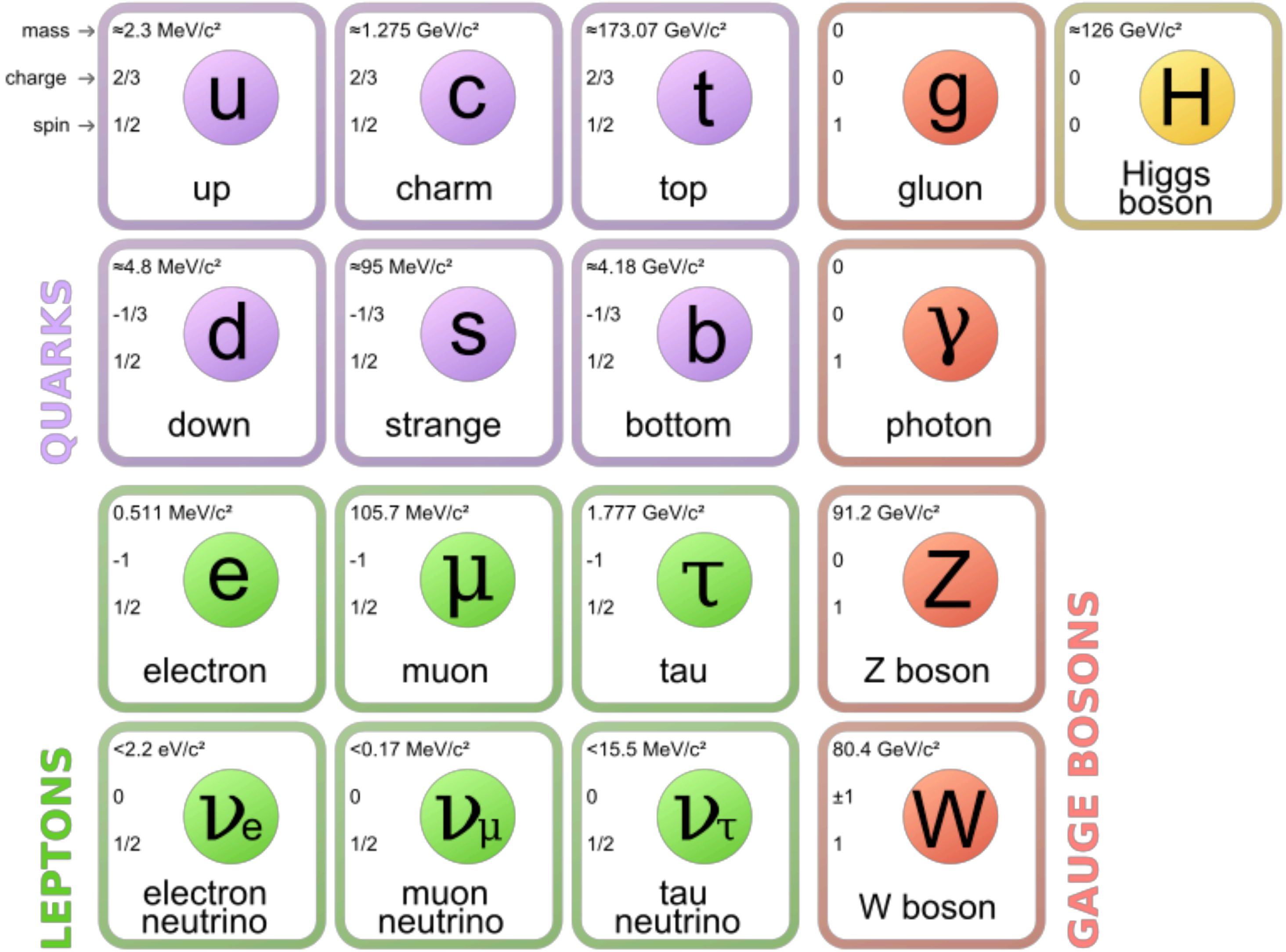
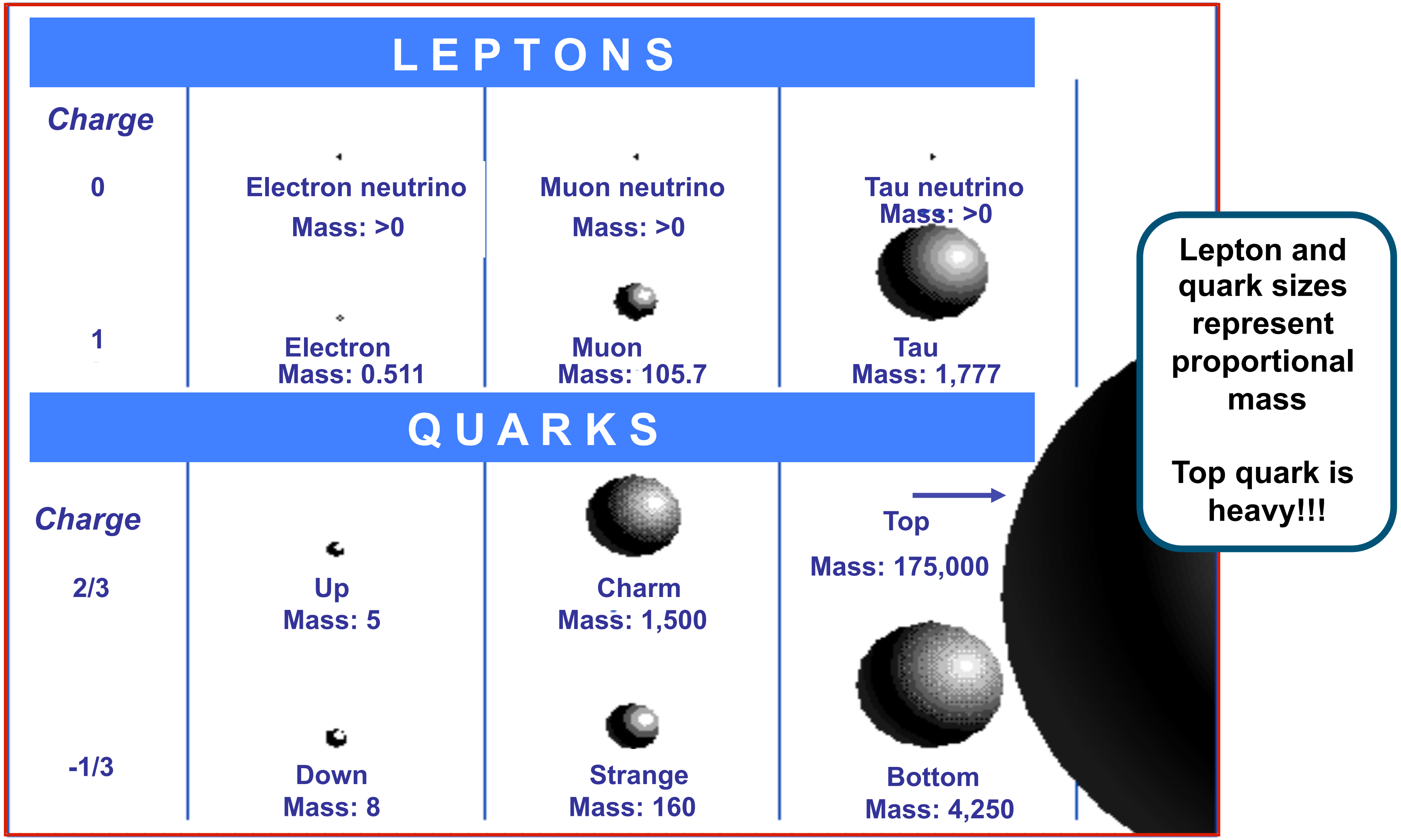
Outline

- Wednesday:
  - Lecture 1: Intro to top physics and its jargon.
    - Historic perspective
    - Experimental aspects
- Thursday:
  - Lecture 2: SM top physics and the top mass
- Friday:
  - Lecture 3: SM and top physics, the portal to physics searches

The building blocks of matter



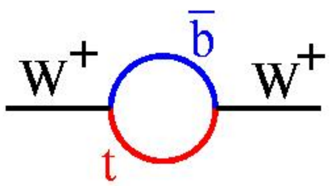
The building blocks of matter

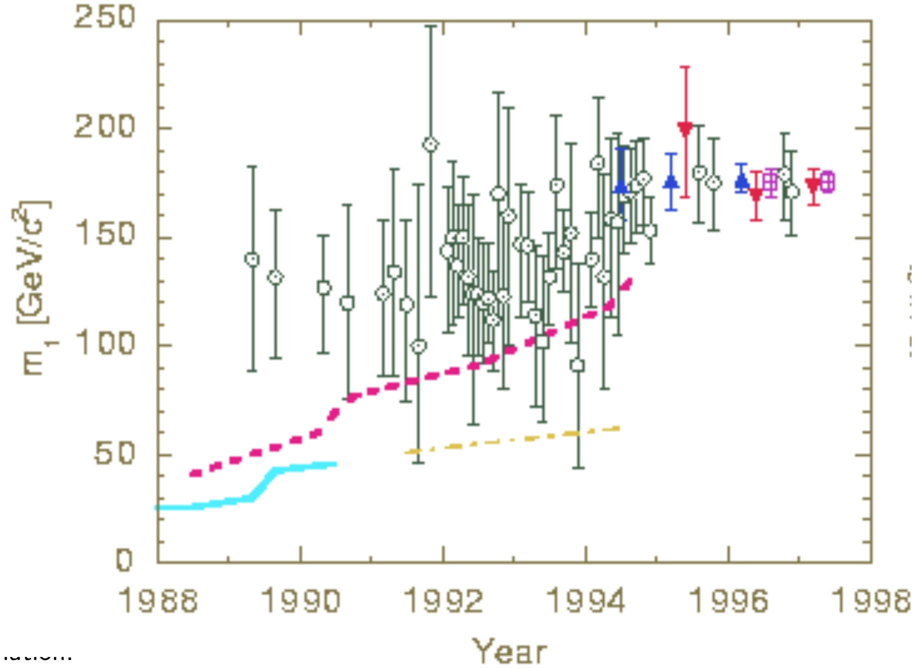


Masses are in millions of Electron Volts [MeV/c^2]

History of the top quark

- 1989: Indirect constraints on top from precision measurements at LEP





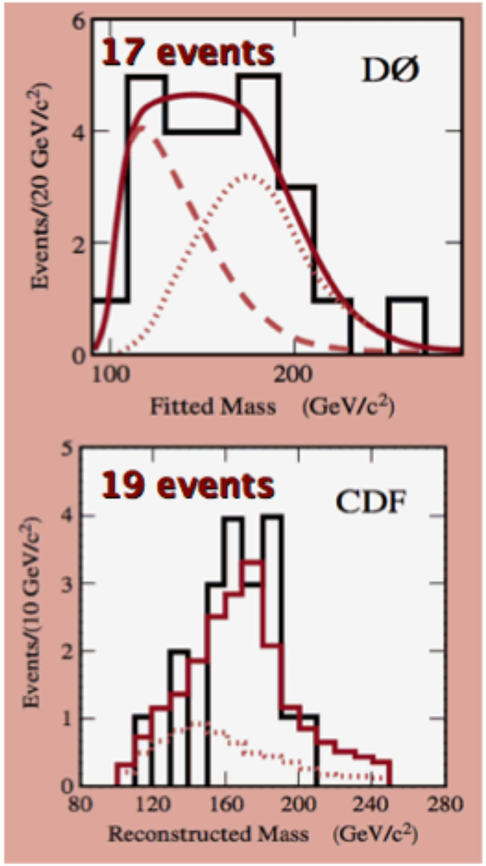
- 1995: Observation of Top-quark at the TeVatron collider at Fermilab
- Historic perspective indirect -> direct measurements -> precision

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
173.07± 0.52± 0.72 OUR EVALUATION				See comments in the header above.
174.5 ± 0.6 ± 2.3	[1] AAD	12I	ATLS	$\ell+\not\!\!E_T+\geq 4$ jets (≥ 1 b), MT
172.85± 0.71± 0.85	[2] AALTONEN	12AI	CDF	$\ell+\not\!\!E_T+\geq 4$j (0,1,2b) template
172.7 ± 9.3 ± 3.7	[3] AALTONEN	12AL	CDF	$\tau_h+\not\!\!E_T$ +4j ($\geq 1b$)
172.5 ± 1.4 ± 1.5	[4] AALTONEN	12G	CDF	6–8 jets with ≥ 1 b
173.9 ± 1.9 ± 1.6	[5] ABAZOV	12AB	D0	$\ell\ell+\not\!\!E_T+\geq 2$j ($\nu$WT+MWT)
172.5 ± 0.4 ± 1.5	[6] CHATRCHYAN	12BA	CMS	$\ell\ell+\not\!\!E_T+\geq 2$j ($\geq 1b$), AMWT
173.49± 0.43± 0.98	[7] CHATRCHYAN	12BP	CMS	$\ell+\not\!\!E_T+\geq 4$j ($\geq 2b$)
172.3 ± 2.4 ± 1.0	[8] AALTONEN	11AK	CDF	$\not\!\!E_T+\geq 4$ jets (≥ 1 b-tag)
172.1 ± 1.1 ± 0.9	[9] AALTONEN	11E	CDF	ℓ + jets and dilepton
174.94± 0.83± 1.24	[10] ABAZOV	11P	D0	$\ell+\not\!\!E_T+4$ jets (≥ 1 b-tag)
173.0 ± 1.2	[11] AALTONEN	10AE	CDF	$\ell+\not\!\!E_T+4$ jets (≥ 1 b-tag), ME method
170.7 ± 6.3 ± 2.6	[12] AALTONEN	10D	CDF	$\ell+\not\!\!E_T+4$ jets (b-tag)

History of the top quark

discovery

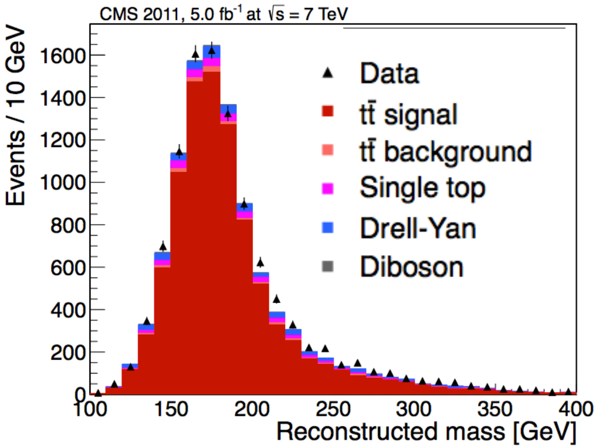
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

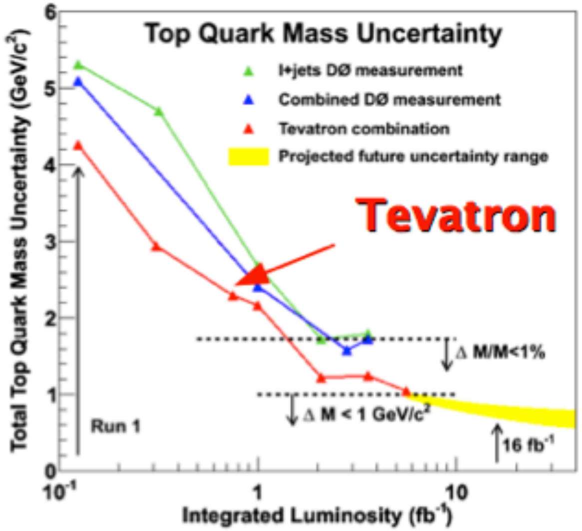
today

10000s of events



LHC: top quark factory

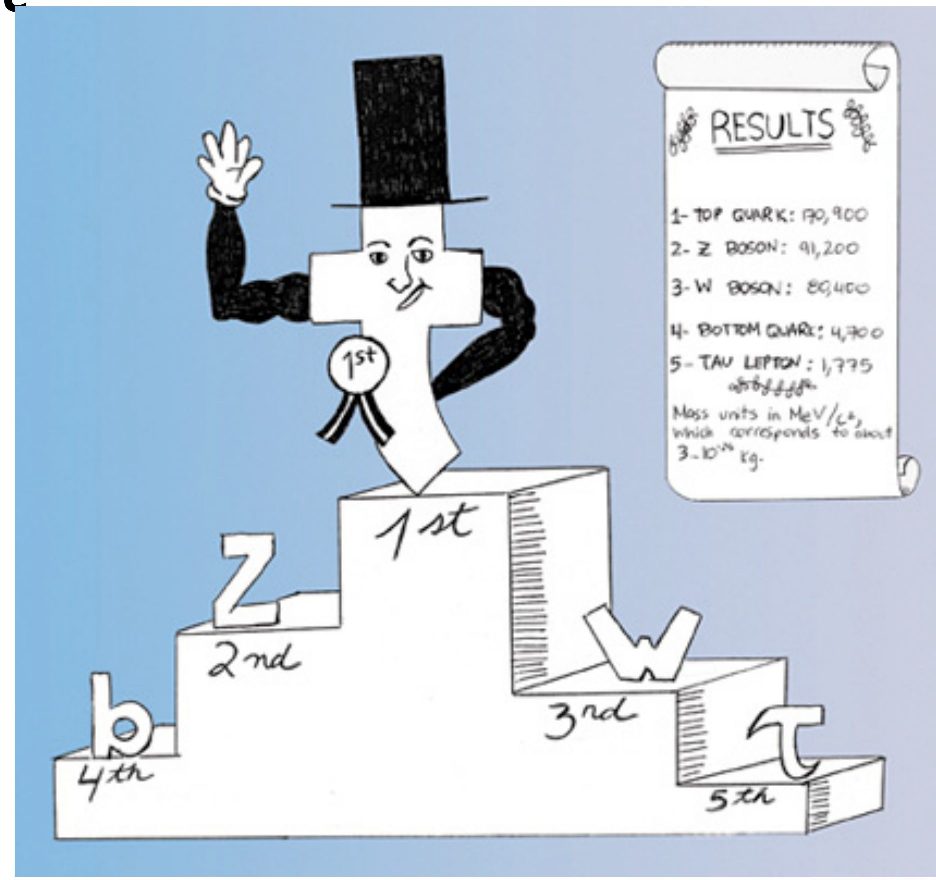
precision



searches

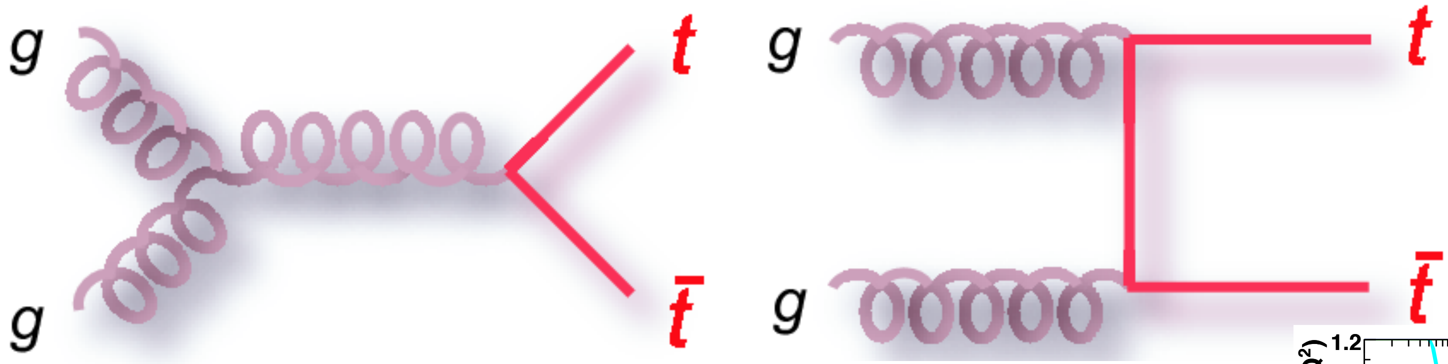
Top quark – special?

- Many models predict that top is special in order to explain large mass
- Or top quark has special role because of its large mass
  - some more in lecture 3

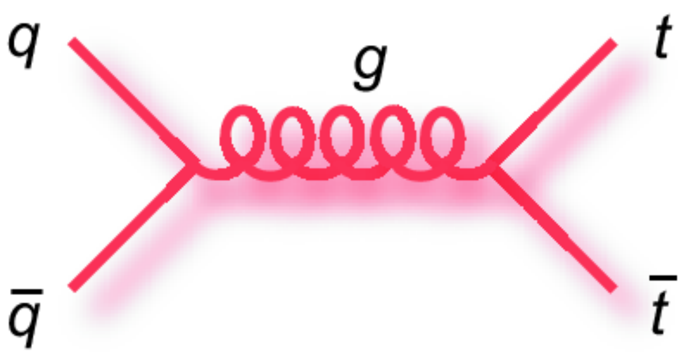


Top pair production at hadron colliders

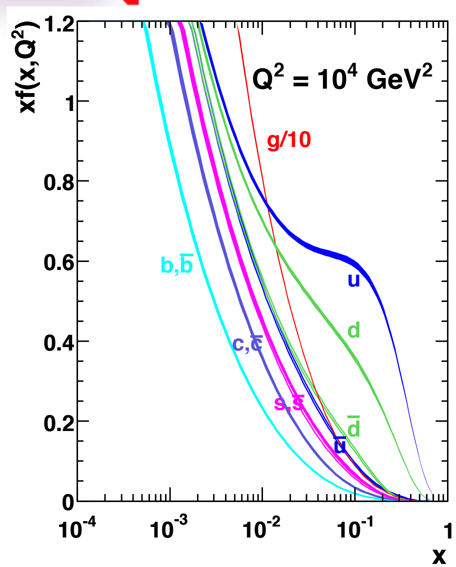
- Pair production in 8 TeV pp collisions:



~90%

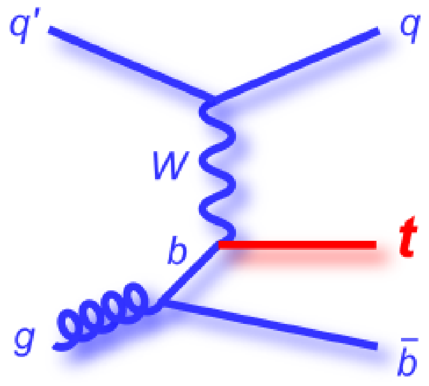


~10%

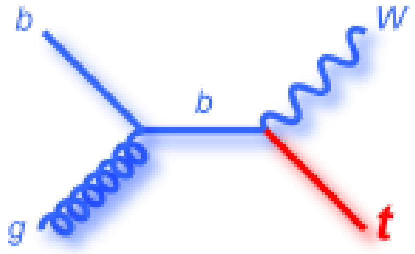


MSTW08:Eur.Phys.J.C63:189-285

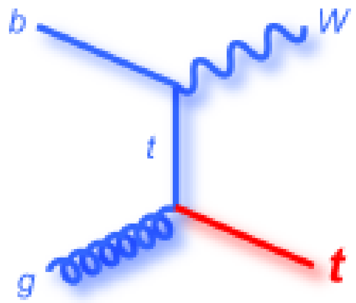
Single Top production

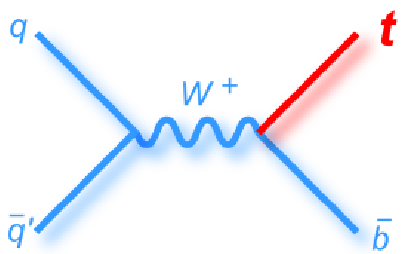


t-channel



tW-channel

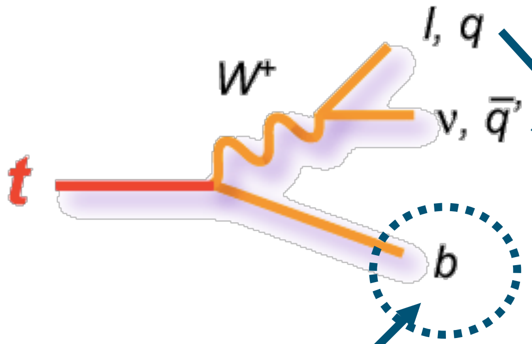




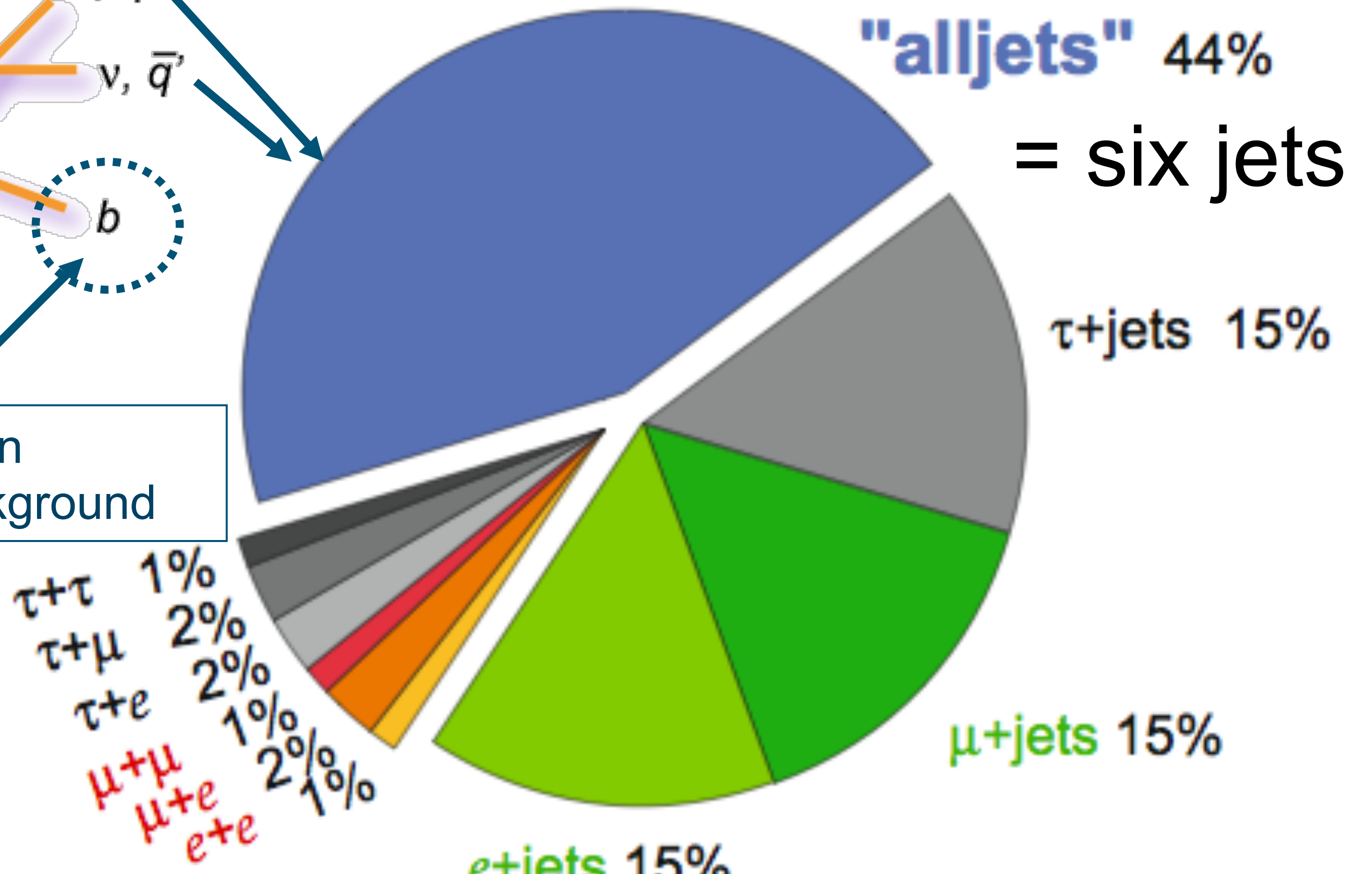
s-channel

- Electroweak production of top quarks
- Dominant channels at LHC @ 8 TeV:
  - t-channel: 87 pb
  - tW channel: 22 pb
  - s-channel: 5.6 pb

Top pair branching fractions



B-quark identification
used to reduce background



= six jets

"dileptons"
= two jets, two leptons, MET

"lepton+jets"
= four jets, lepton, MET

Top physics: decay channel choice

– selection of top quark events inversely proportional to the complexity of the mass reconstruction

	Isolation signal	Reconstruction
Di-lepton	Relatively easy	Two neutrinos, ambiguities
Lepton+jets	Reasonable	One neutrino, use missing transverse energy
All-hadronic	Very difficult	Possibility to observe top as 'peak' in invariant mass spectrum, no energetic neutrinos

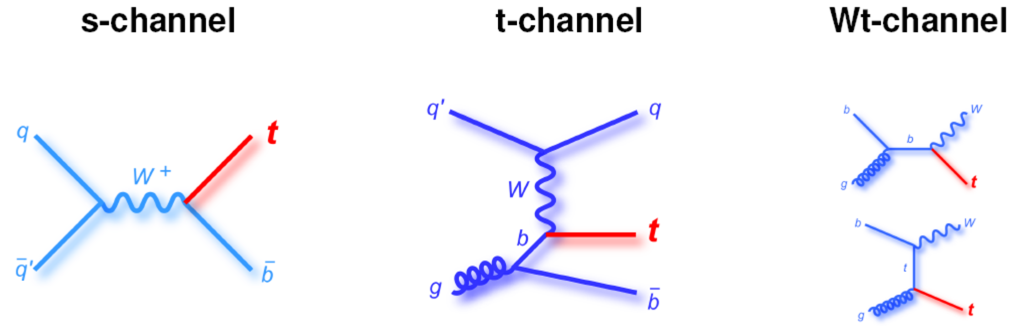
SINGLE TOP PRODUCTION

Observation of single top production:

- cross section $\propto V_{tb}^2$
- study top-polarization and EWK top interaction

Test of non-SM phenomena:

- 4th generation
- FCNC couplings
- W' , $H^{\pm}$
- anomalous W_{tb} couplings



Main backgrounds:

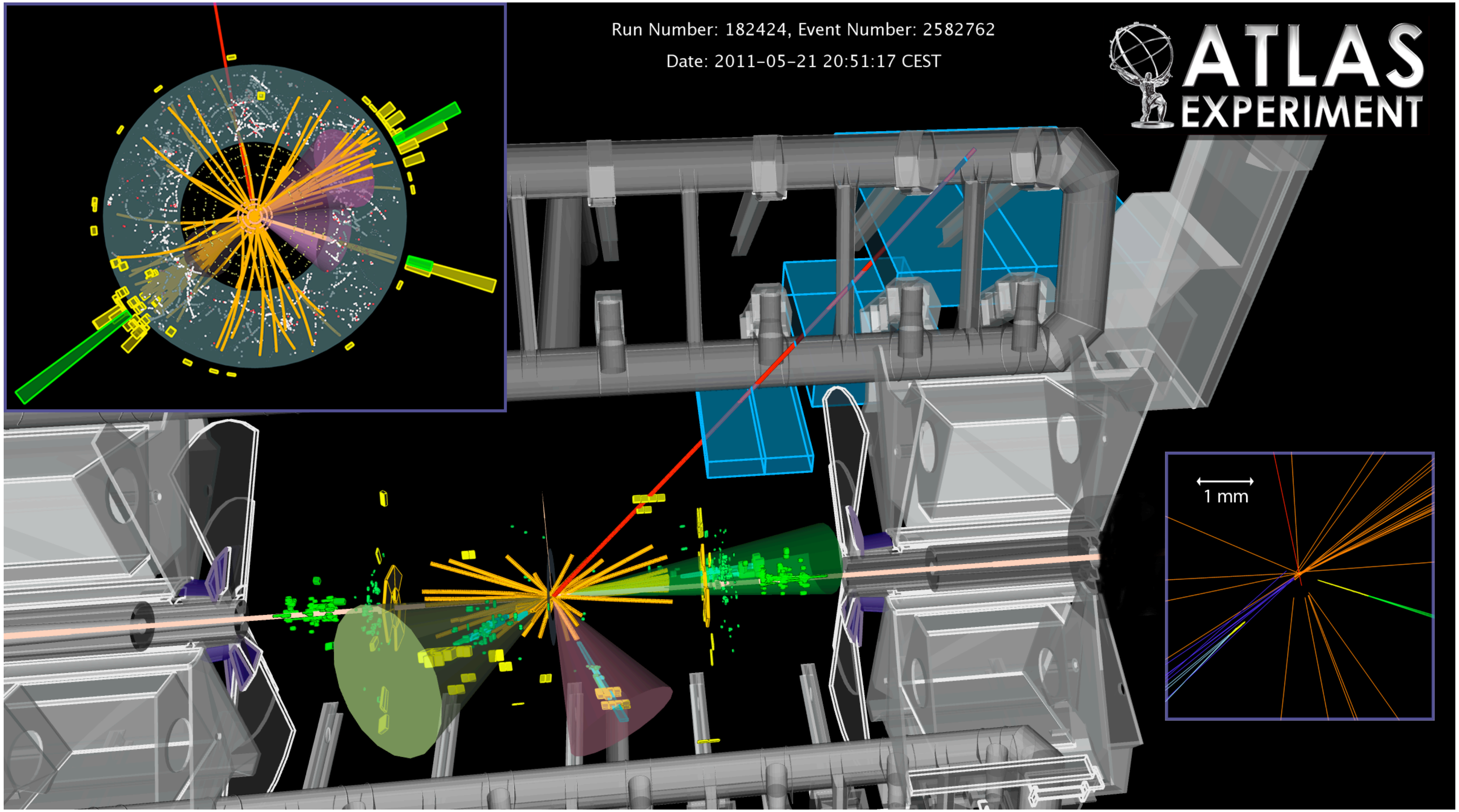
- s-channel: Top pair, W + (HF) jets, QCD
- t-channel: Top pair, W + (HF) jets, QCD
- Wt-channel: Top pair, Z + (HF) jets, QCD

Signal – background discrimination:

- Tevatron: multivariate methods (neural networks, boosted decision trees, matrix element method)
- LHC: cut-based or multivariate method

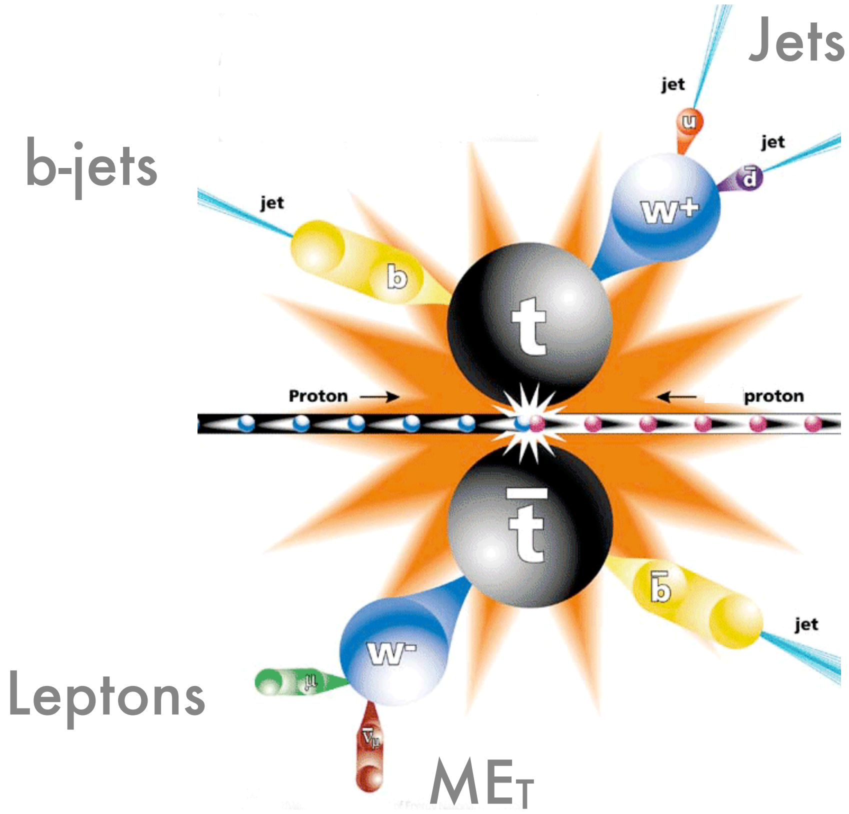
Collider	s-channel: σ_{tb}	t-channel: σ_{tqb}	Wt-channel: σ_{tW}
Tevatron: $p\bar{p}$ (1.96 TeV)	1.05 pb	2.08 pb	0.22 pb
LHC: pp (7 TeV)	4.6 pb	66 pb	15.7 pb

How to find top quarks?

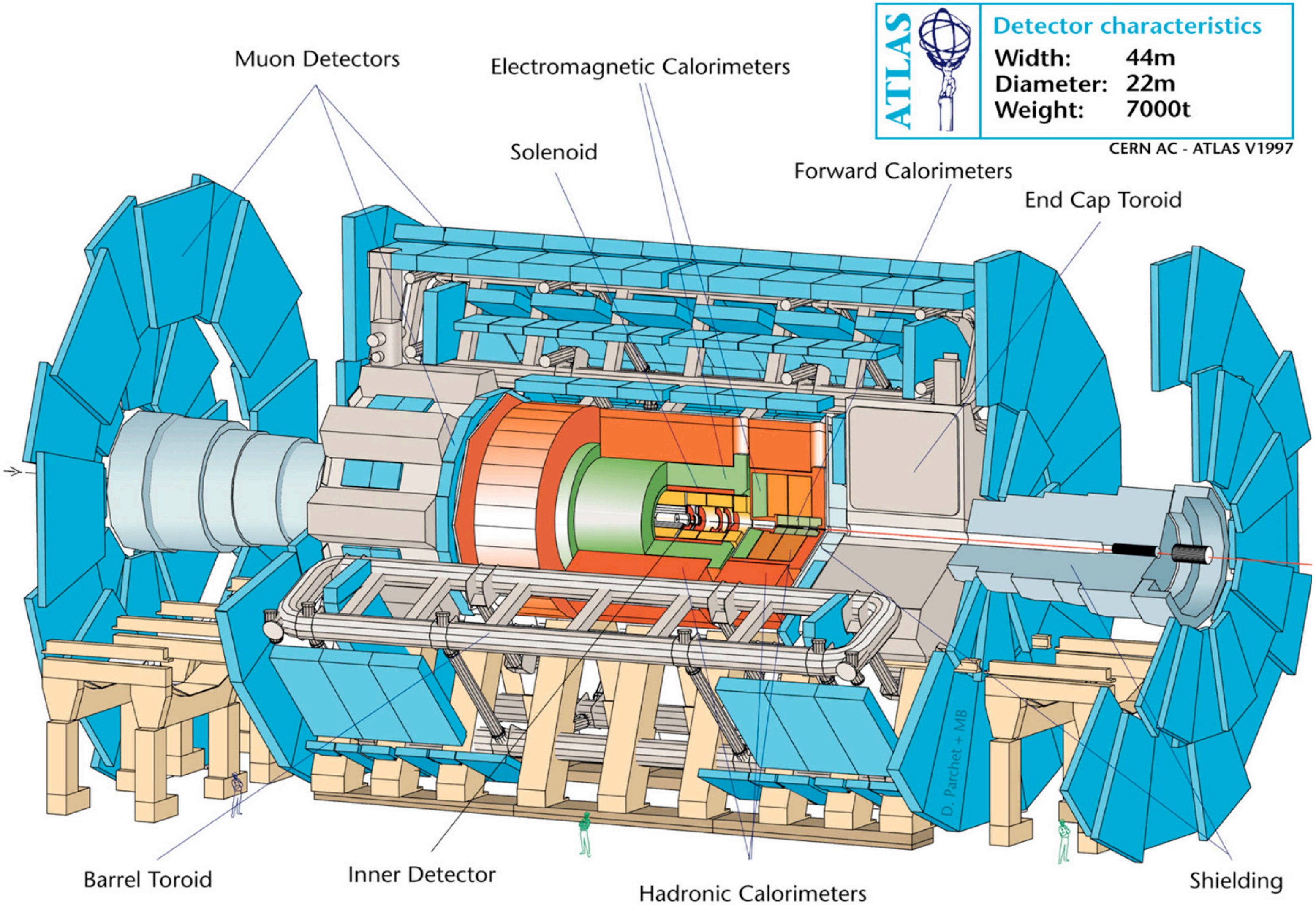


Top quark physics – benchmark physics

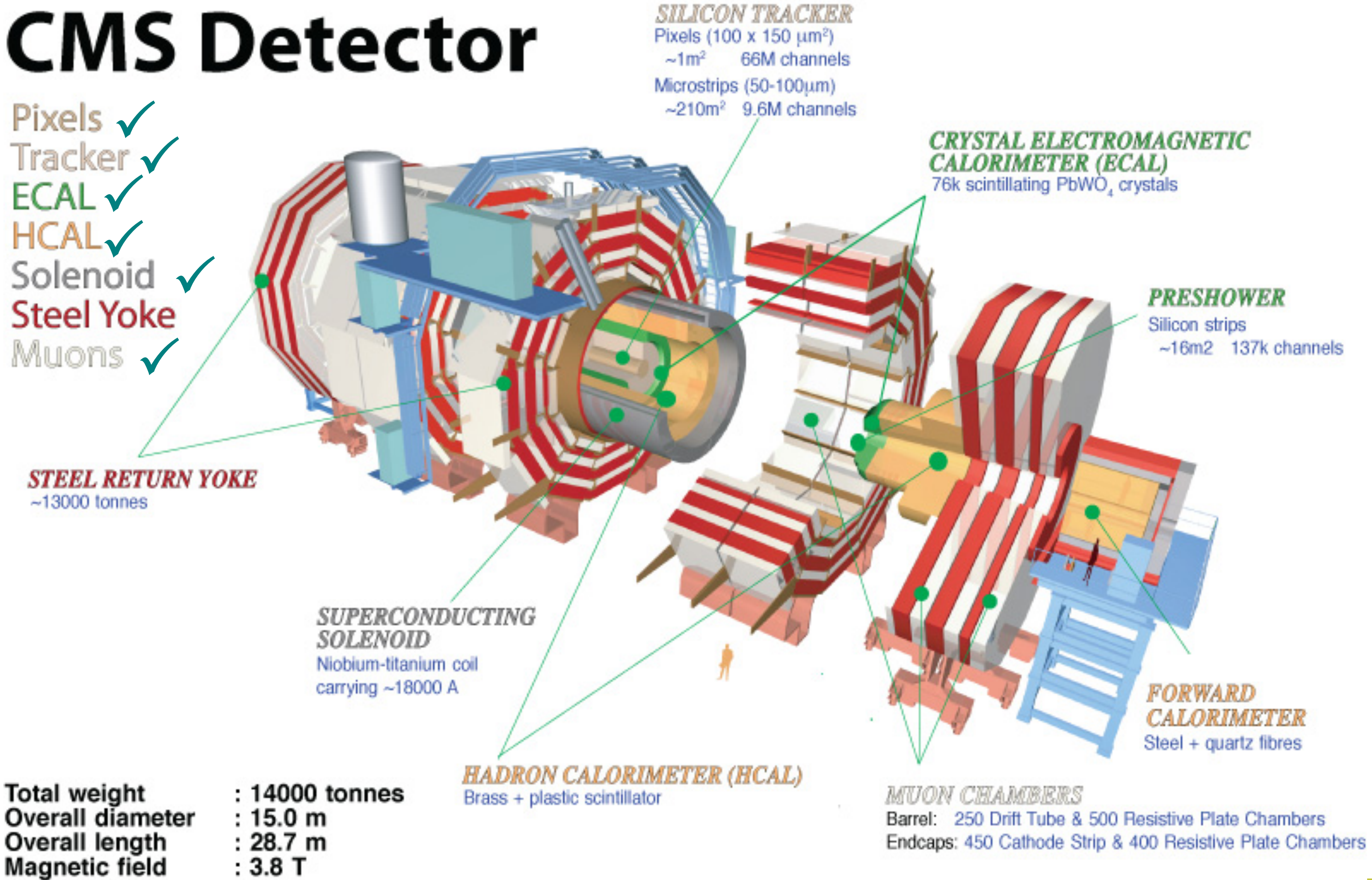
- To find and reconstruct top quarks, a fully operational and hermetic General Purpose Detector is needed
- This is why top quarks were used to confirm and check calibrations and detector performance at the start of the LHC runs at 7 and 8 TeV



A Toroidal Lhc ApparatuS



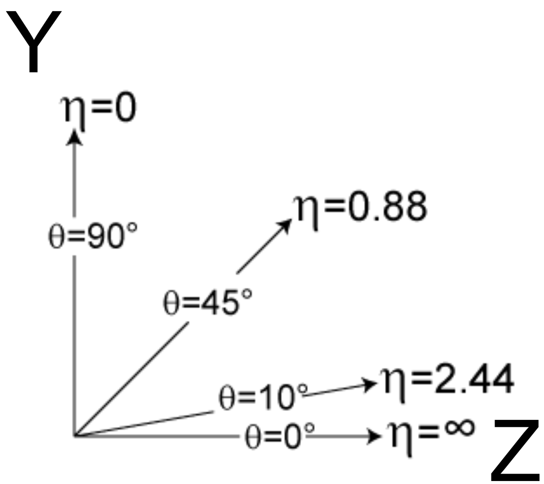
Compact Muon Solenoid

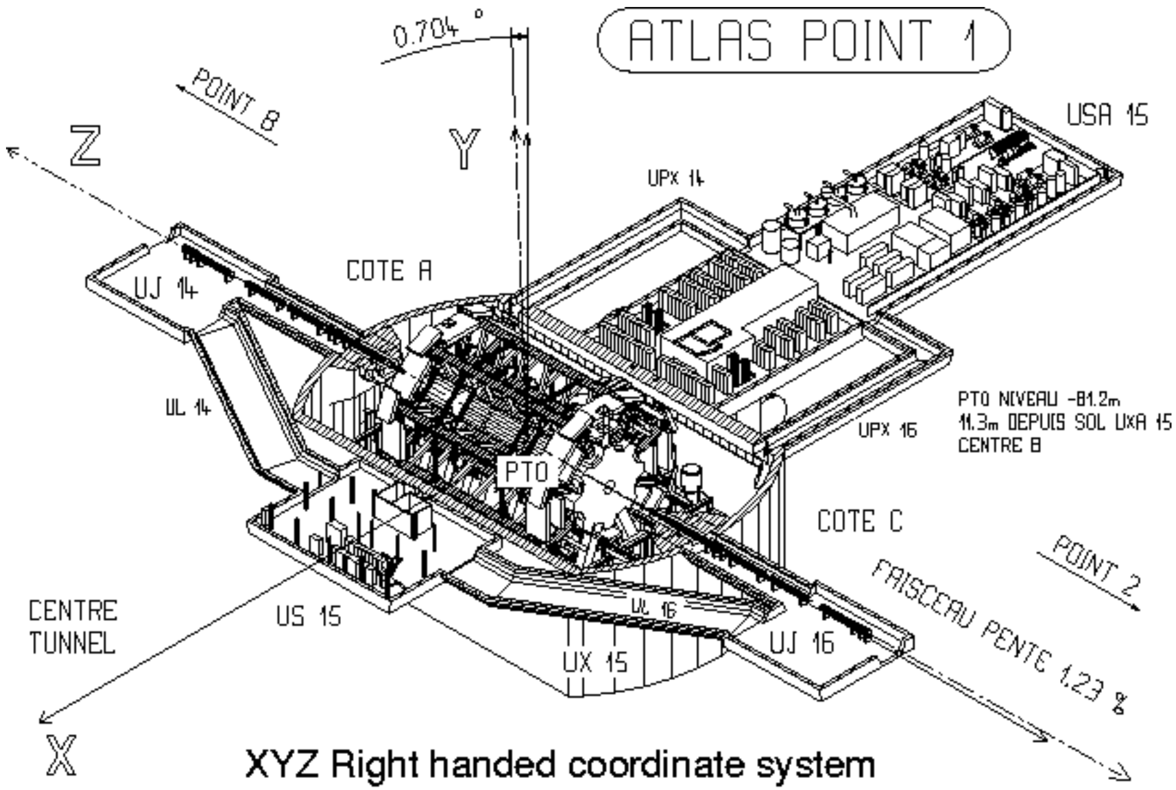


Typical GPD coordinate system

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$



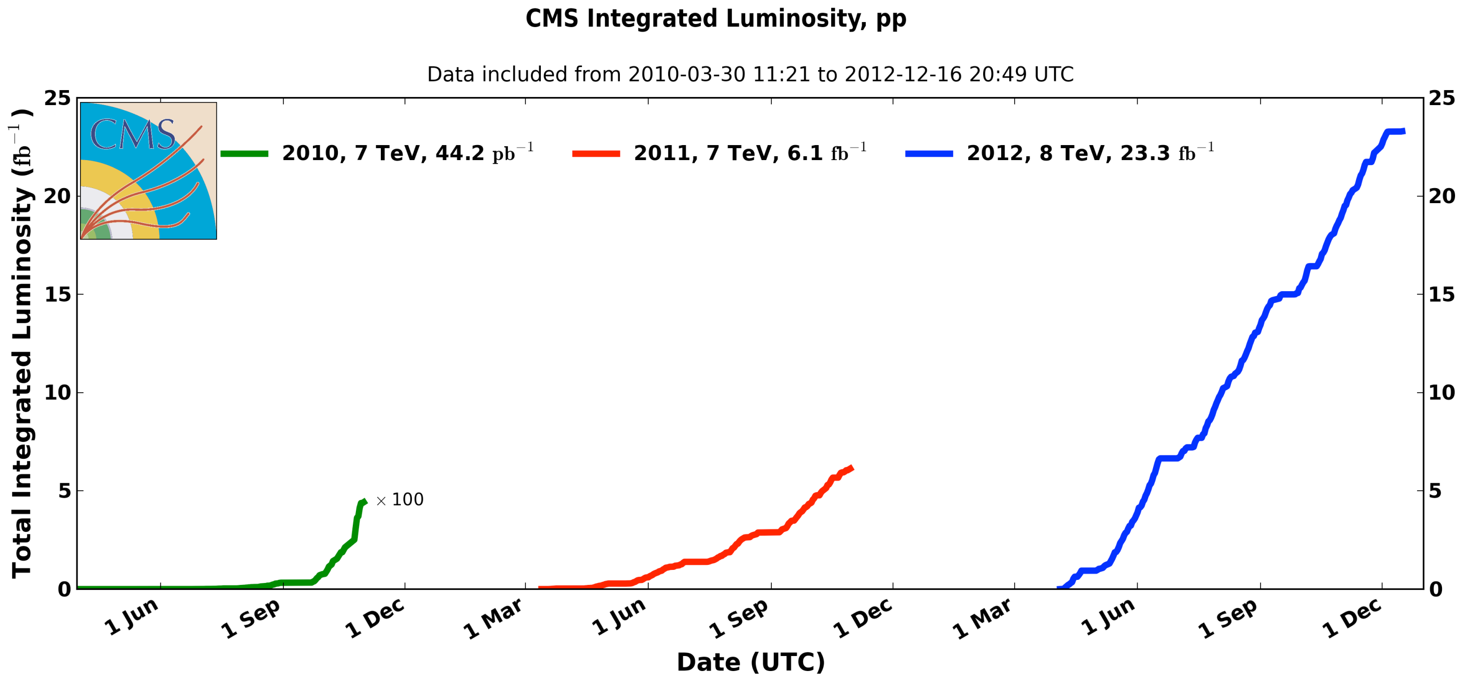


XYZ Right handed coordinate system
with z in beam direction

+ cylindrical coordinates around Z axis

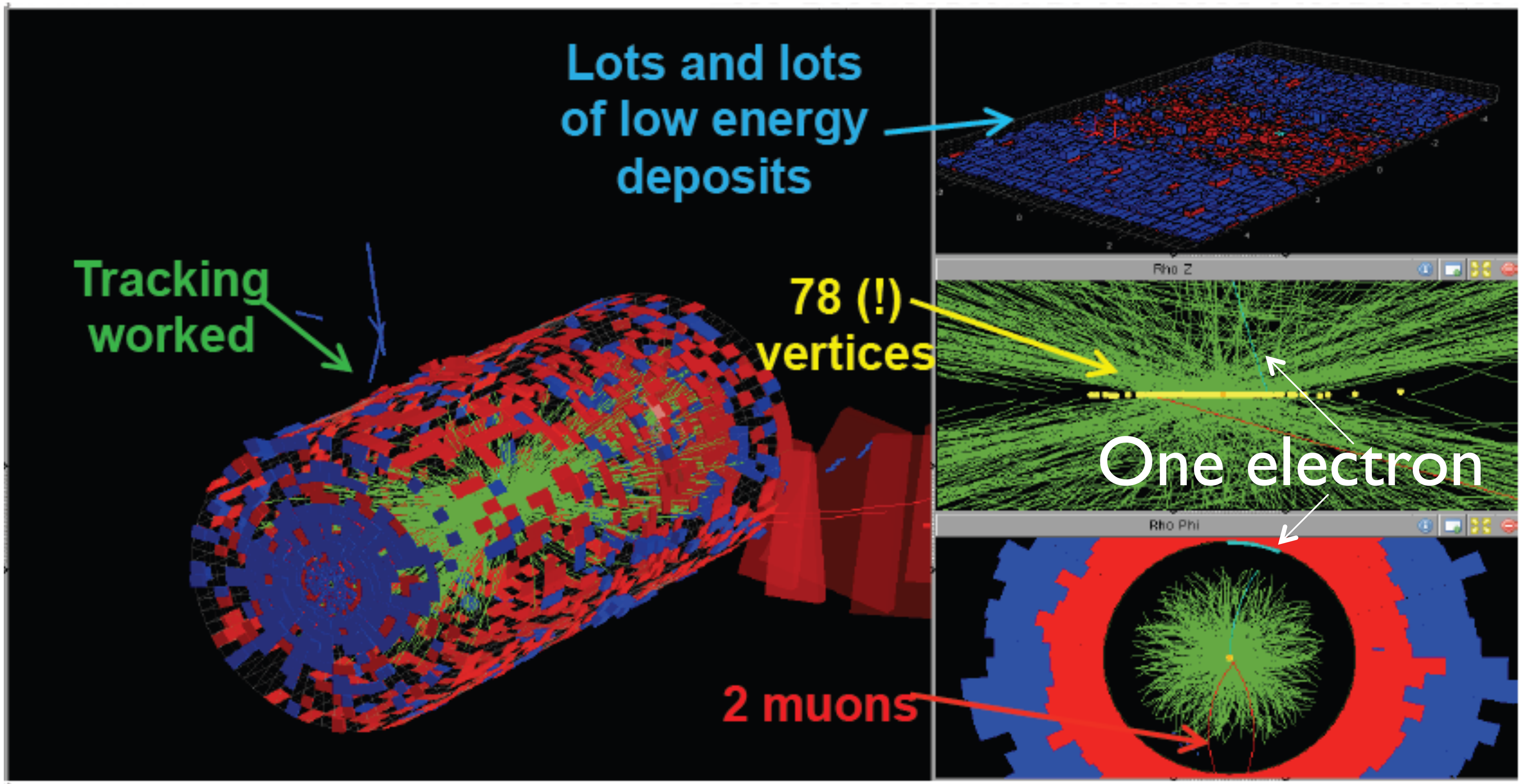
Typical inputs of 4-vector:
pT, phi, eta, E

LHC performance

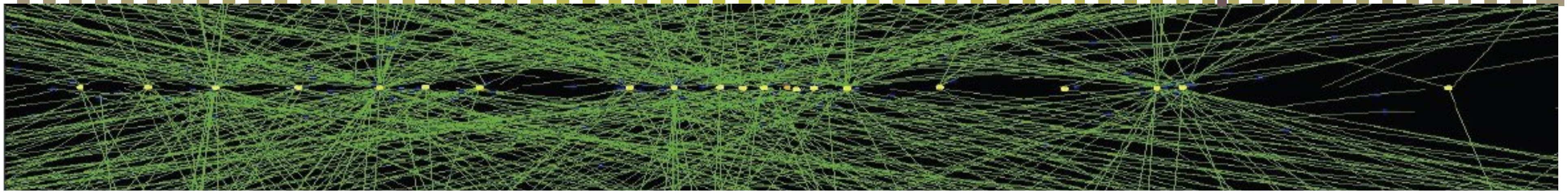


- ATLAS and CMS: outstanding performance during LHC Run 1
- Detector performance consistent during full run, sometimes even improved from between-fill repairs

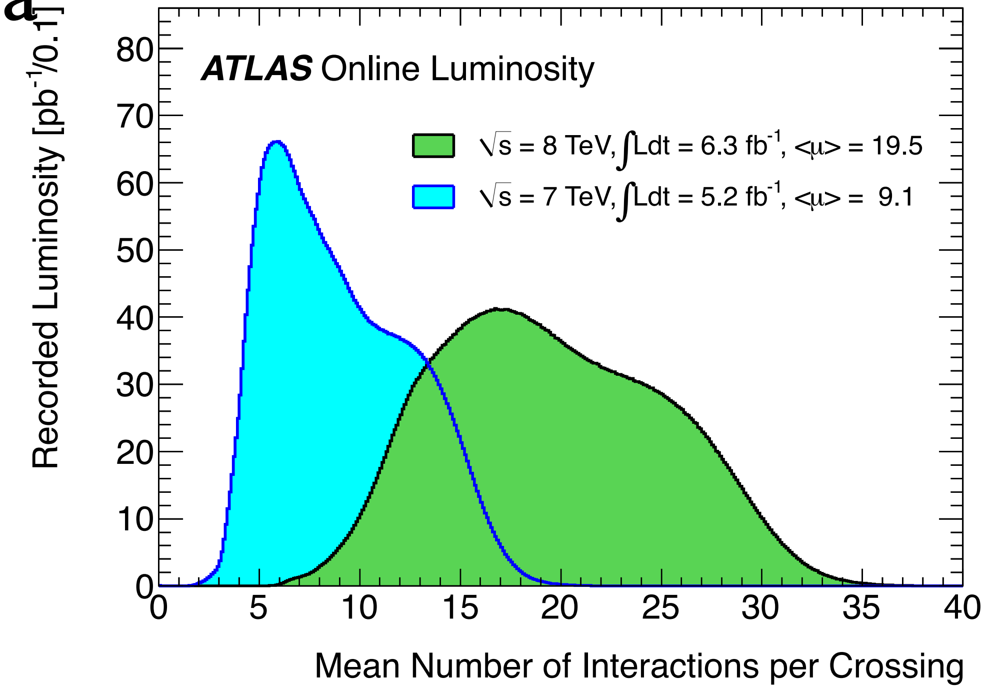
Luminosity comes at a price:Pileup



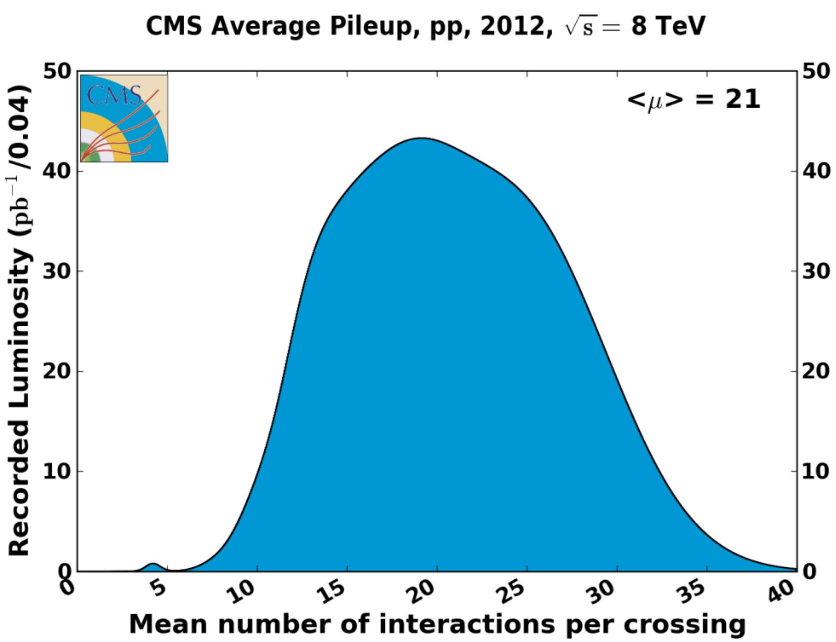
LHC 2012 run: Pile-Up



- Outstanding LHC performance comes at a price:
- 2011:
  - Run A: 5 PU
  - Run B: 8 PU
- 2012:
  - Average: 21 PU

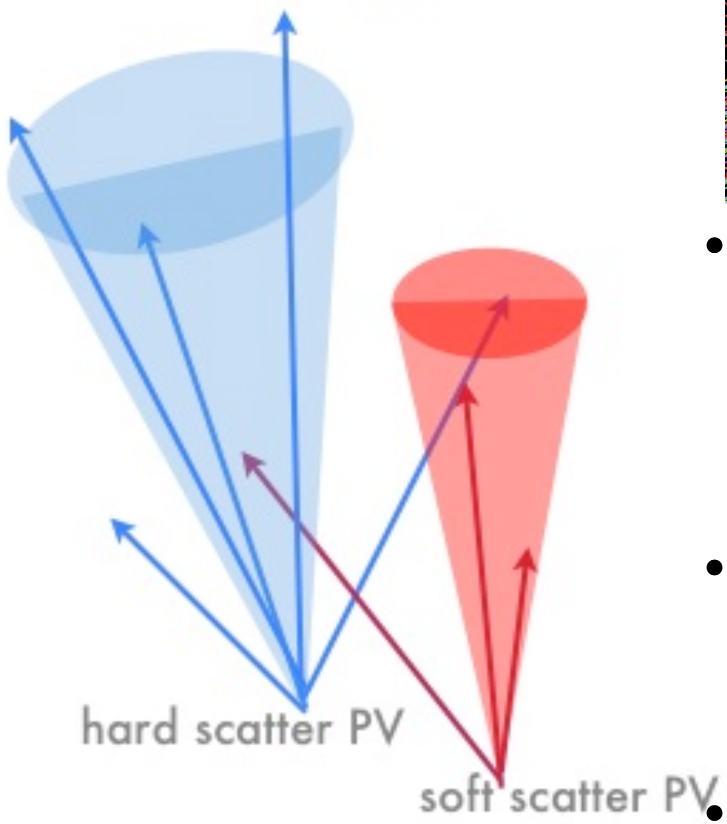


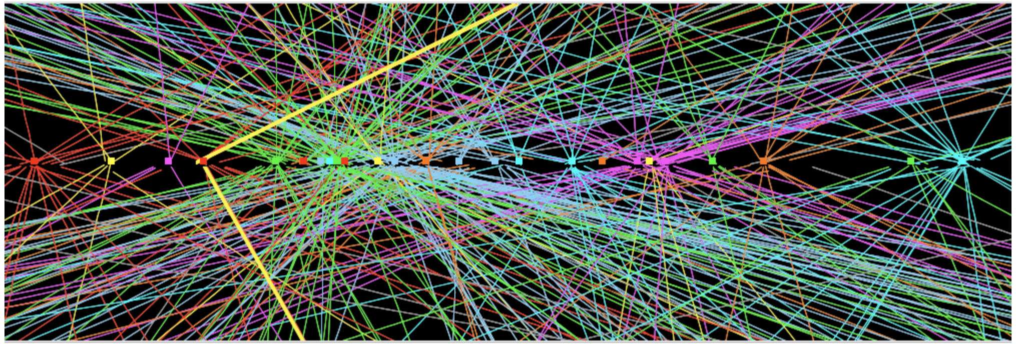
Two kinds of pile-up



- In-time pile-up:
  - Multiple interactions from a single LHC bunch crossing
- Out-of-time pile-up:
  - Particles from previous bunch – 50 ns bunch spacing
  - But detectors can have much longer response time so there might still be some 'remaining' signal from previous collision

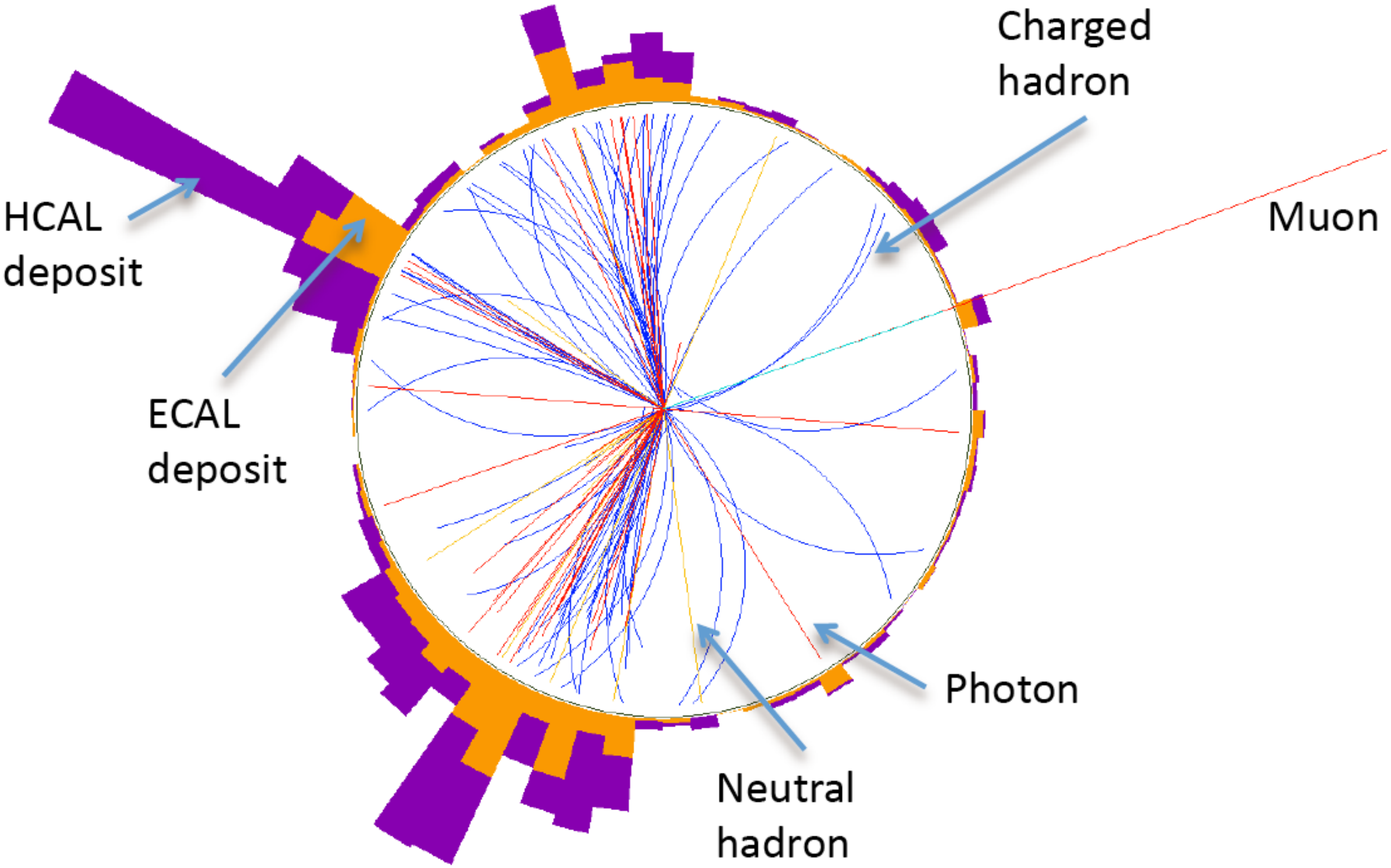
Identify pile-up



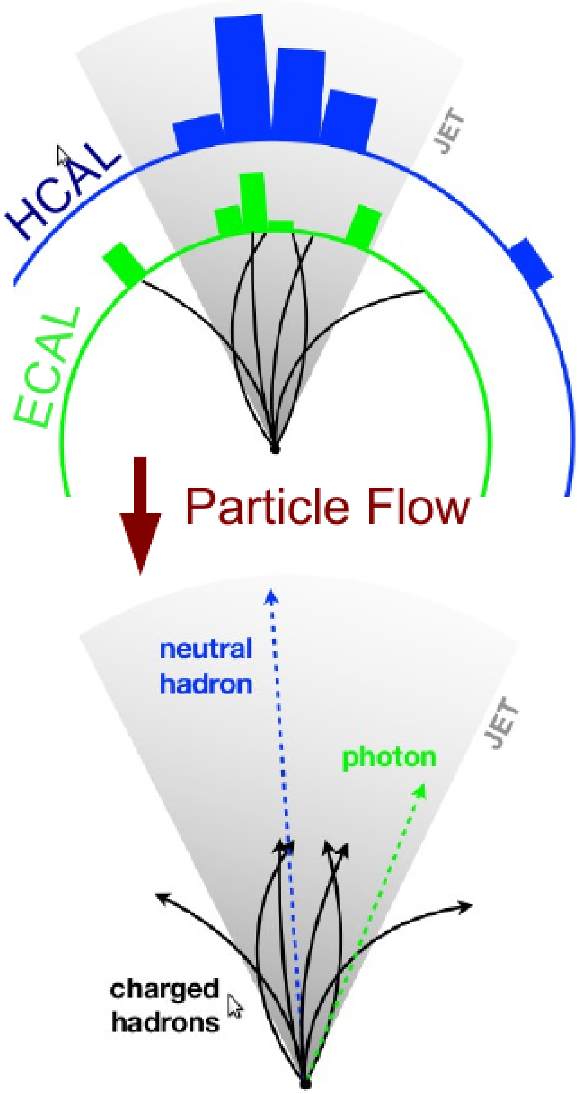


- Tracking and identification of primary vertices used to identify which particle belongs to which collision
- Evident for charged particles but more difficult for neutral hadrons…
- ATLAS uses fraction of tracks in jet associated with hard scatter interaction

Particle flow



Particle flow in practice



- PF combines information from all subdetectors in a global event description
  - reconstruct ‘particles’ such as charged/neutral hadrons, photons, muons, electrons
- These particles are used to construct composite objects such as jets, taus, missing transverse energy
  - Reject tracks from non-leading collisions before creating composite objects
  - And make assumptions for background from neutral particles
- Widely used in CMS, LHCb
  - CMS: big improvements in energy resolution jets, MET, tau identification,

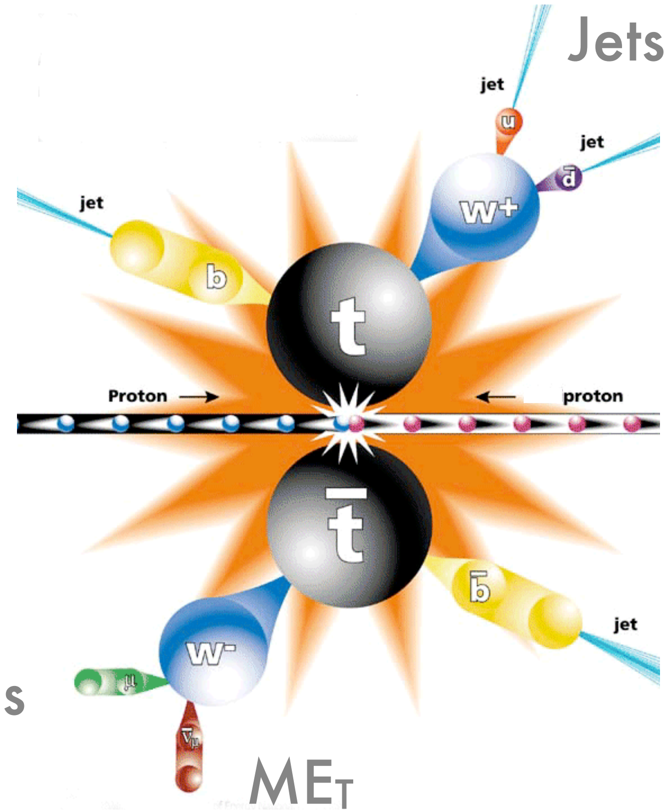
Object reconstruction

Background from long lived non-b jets?
Increased track multiplicity from pile-up degrades performance?

b-jets

Good enough resolution to see W mass peak?

Jets



Pile-up affects reconstruction?
Jets where only lepton seen?
Actual fakes?

Leptons

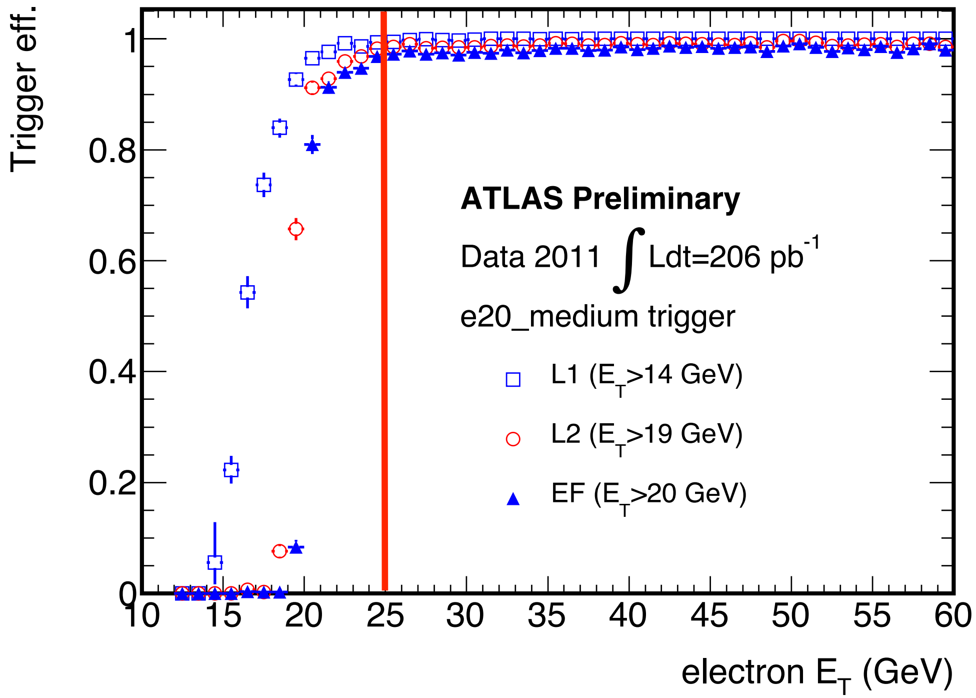
From pile-up?
Electronics/ detector noise?

ME_T

Affected by pile-up?
Electronics/detector noise?

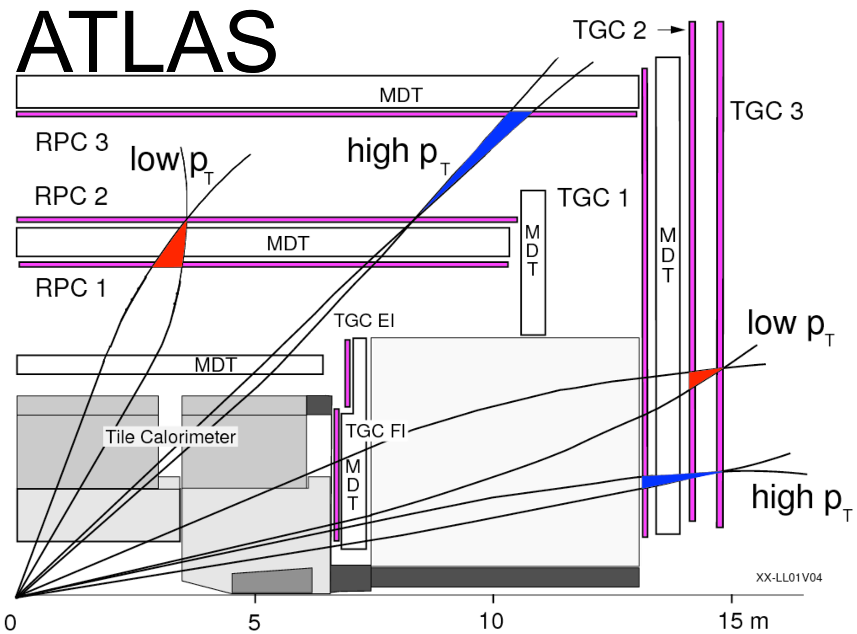
Leptons – trigger

- Most important: **trigger** and get the events on tape

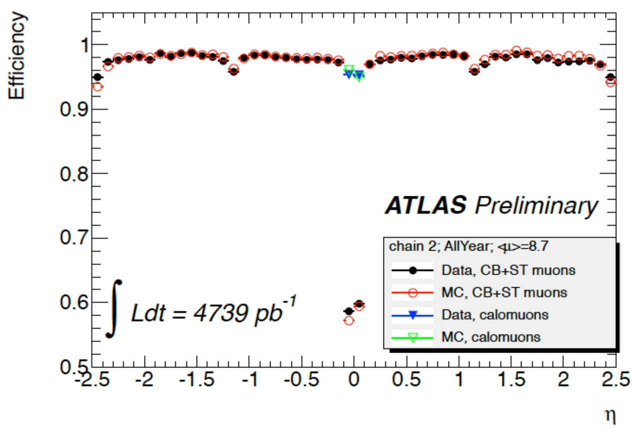


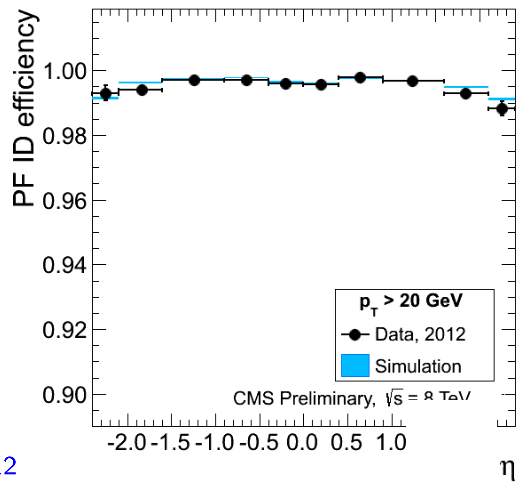
- Different triggers used for different channels
  - ATLAS: extremely good one-lepton triggers
    - pT thresholds of 20 GeV or lower
  - CMS: strong at lepton+jets triggers
    - pT thresholds of 24-27 GeV for single leptons
    - Lower lepton pT thresholds using lepton+jets requirements
  - Di-lepton triggers have low thresholds and high priority
  - Multijet triggers need very stringent requirements and tuning to keep rate low

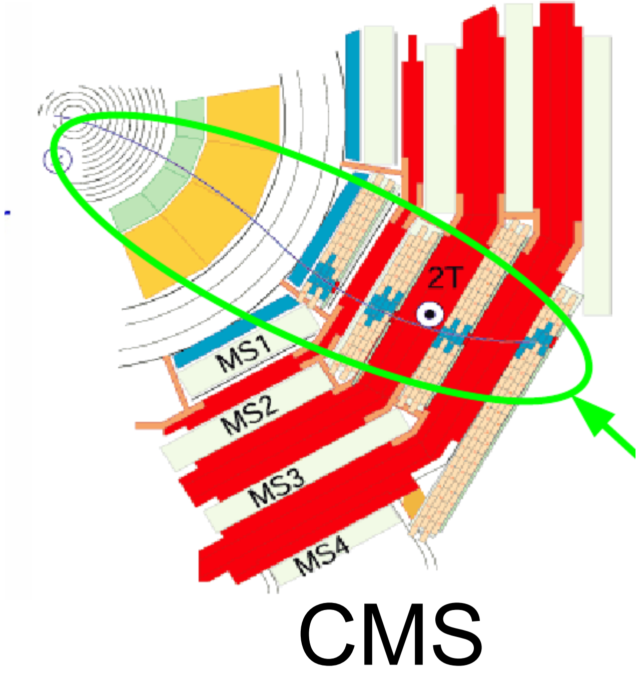
muons



- Muons combine inner tracking and outer muon system information in track fit

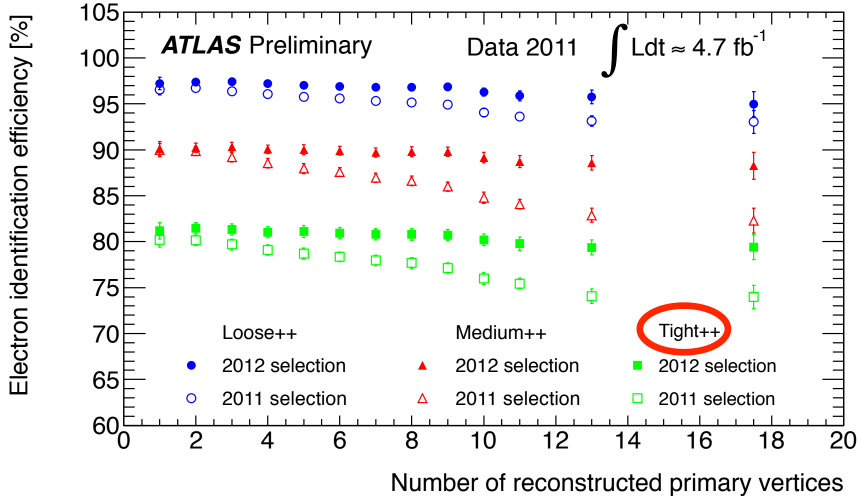


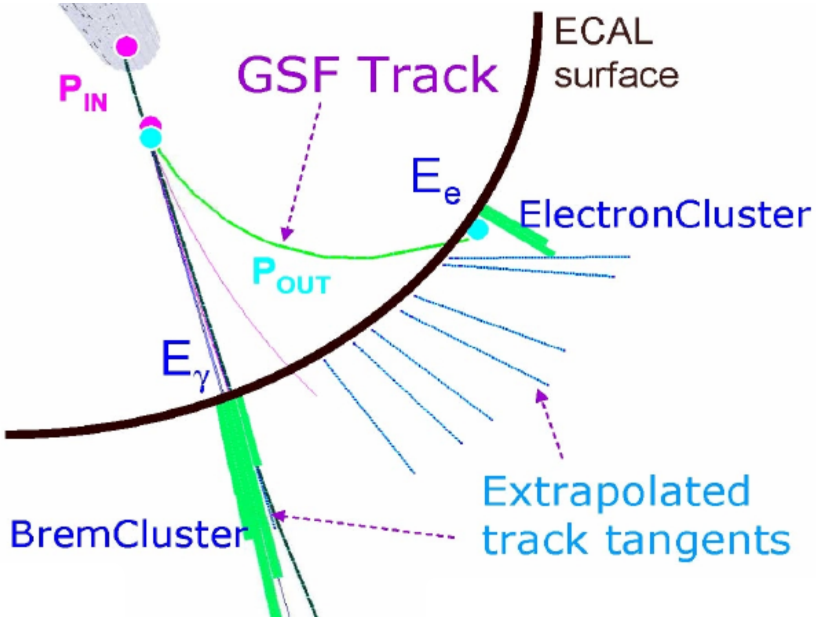


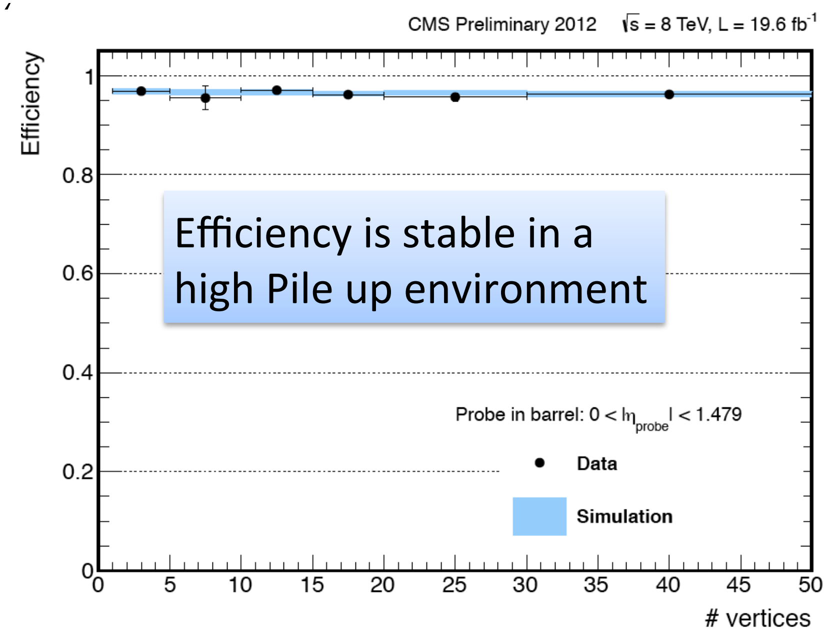


electrons

- Both ATLAS and CMS combine info from tracking and (em) shower shape calorimeter in multivariate technique

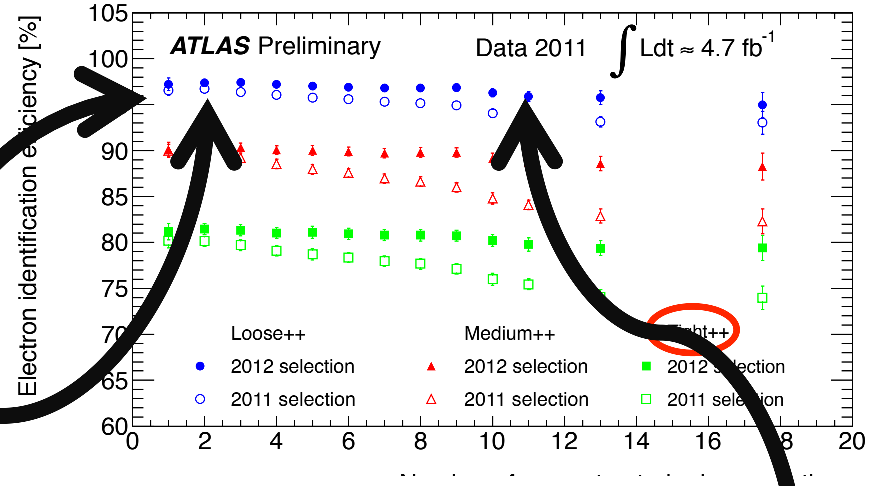


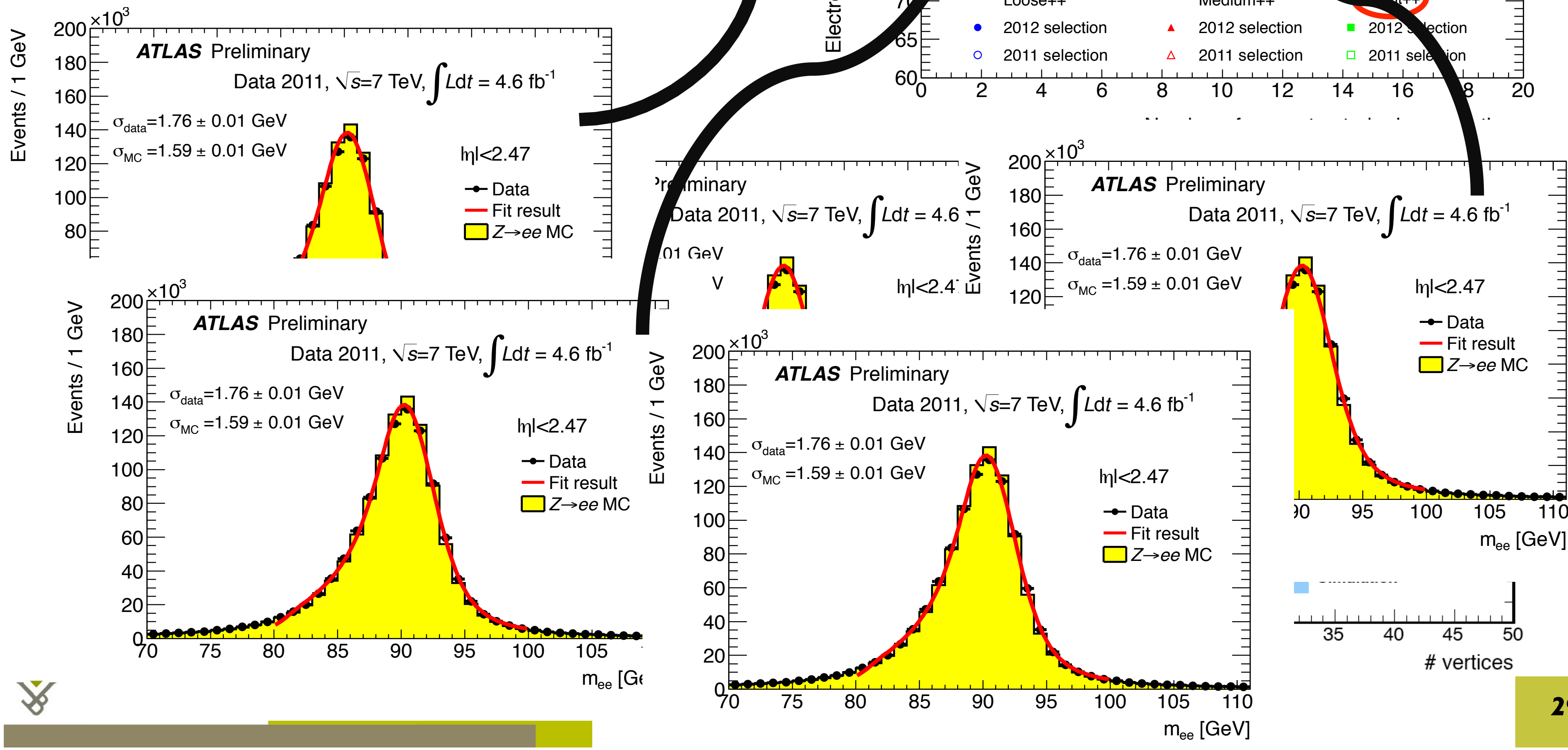




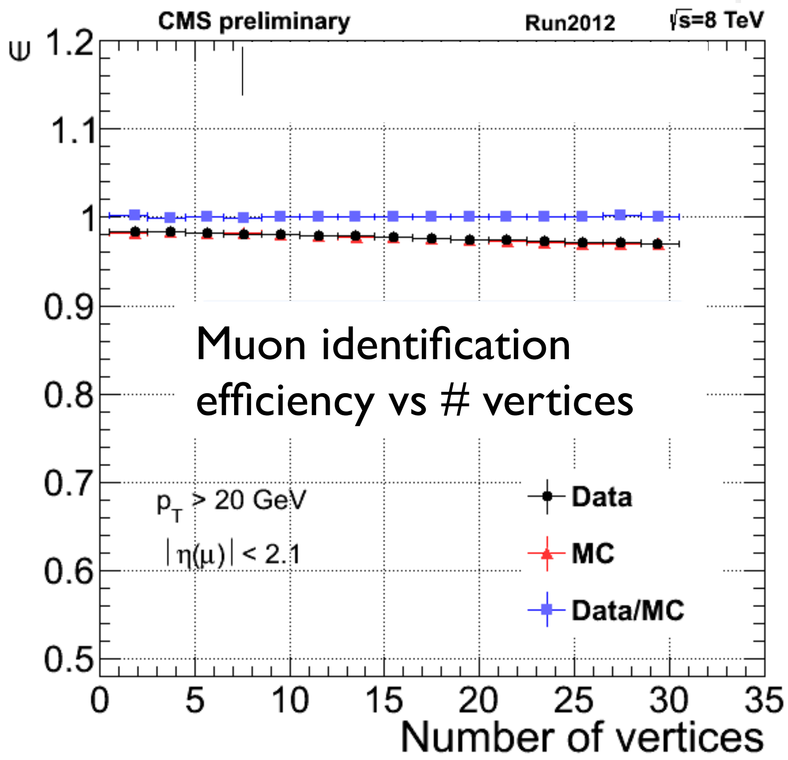
electrons

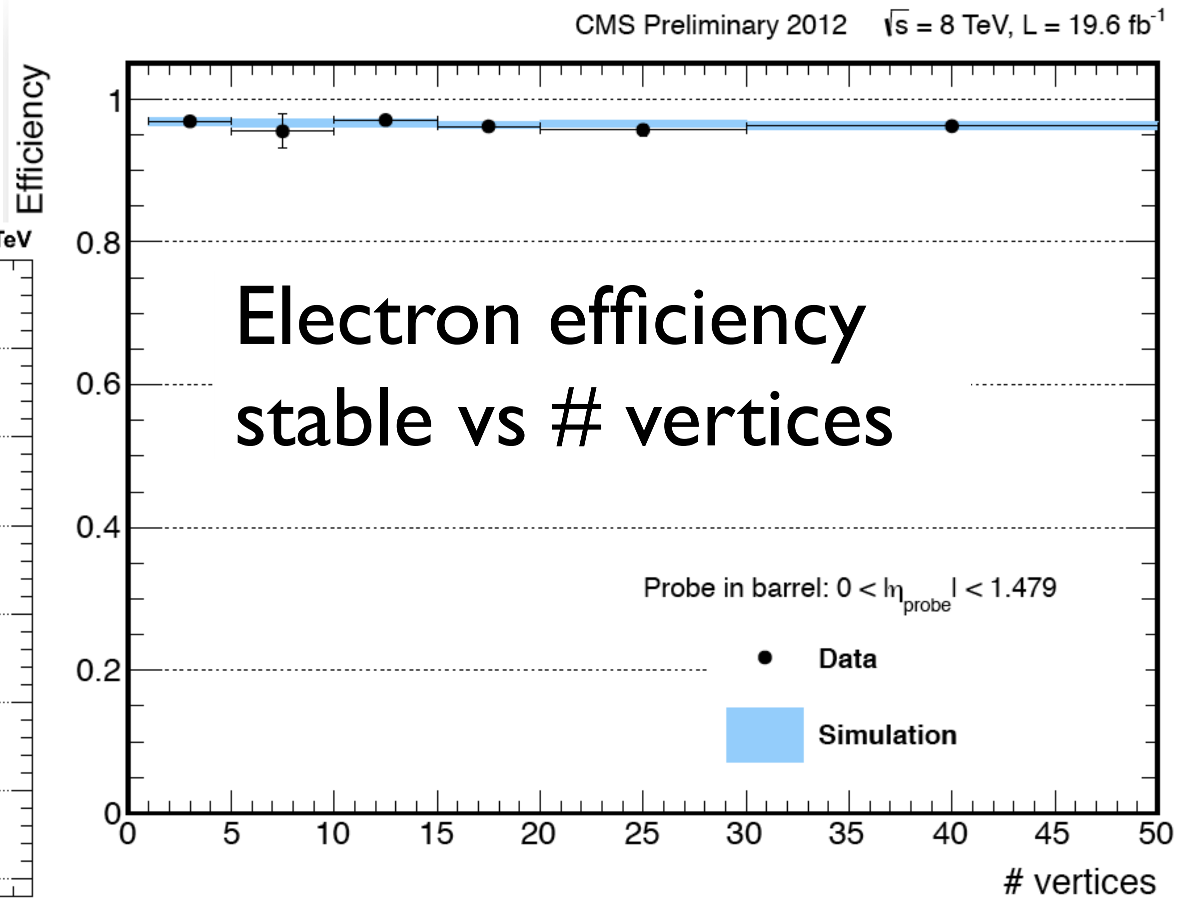
- Both ATLAS and CMS use Z bosons to check performance for muons and electrons





Leptons and pileup

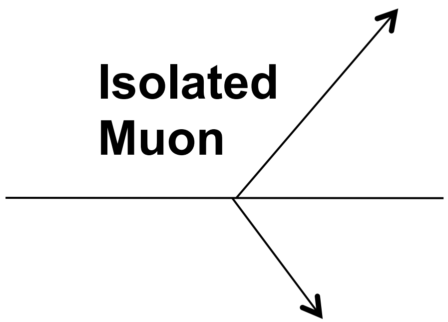


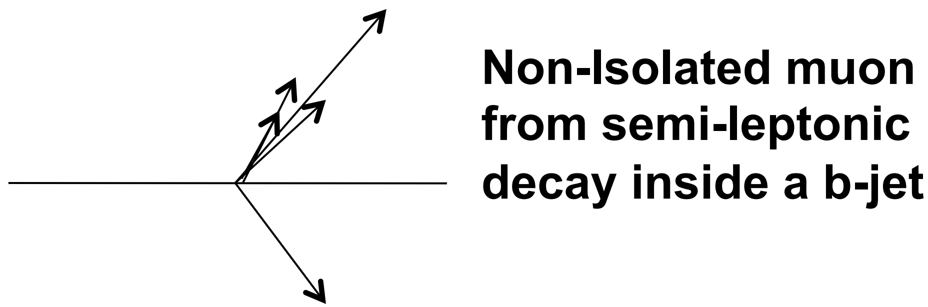


- Substantial effort necessary to achieve this stability

Isolation

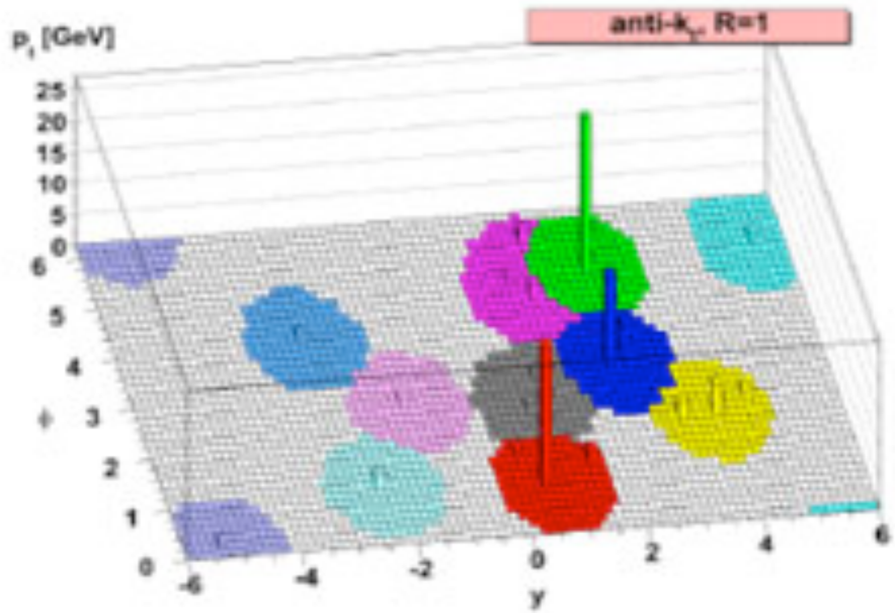
- Since hard processes produce large angles between the final state partons and the beam remnant jets stay close to the beam line, the objects we are interested in for our studies are usually well separated or "isolated" from other objects in the event
- Isolation is applied by drawing a cone around the object of interest in η-ϕ space; adding up the extra E_T in the cone (exclusive of the E_T of the candidate); and rejecting the object if the "extra E_T" is more than a certain fraction of the E_T of the candidate
- Example of isolation: discriminating an isolated muon from a W from a muon coming from the semileptonic decay inside a b-jet

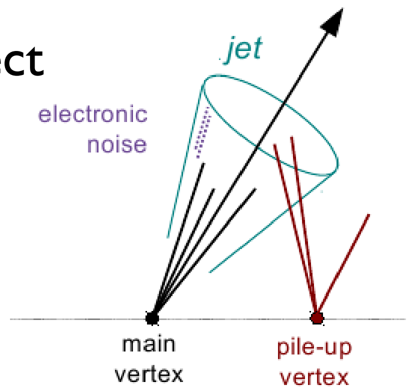


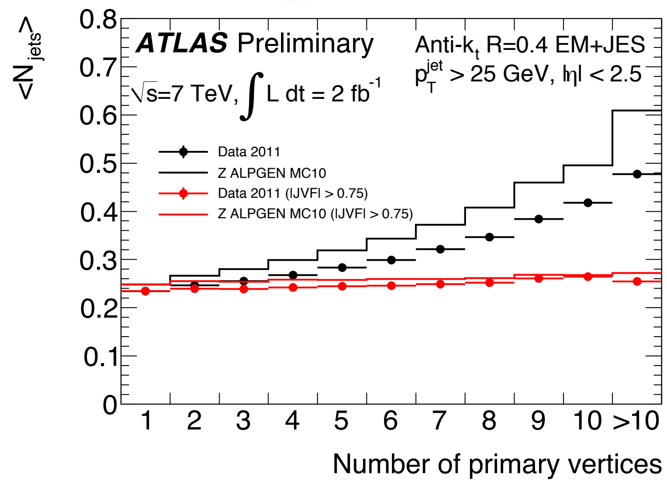


Jets

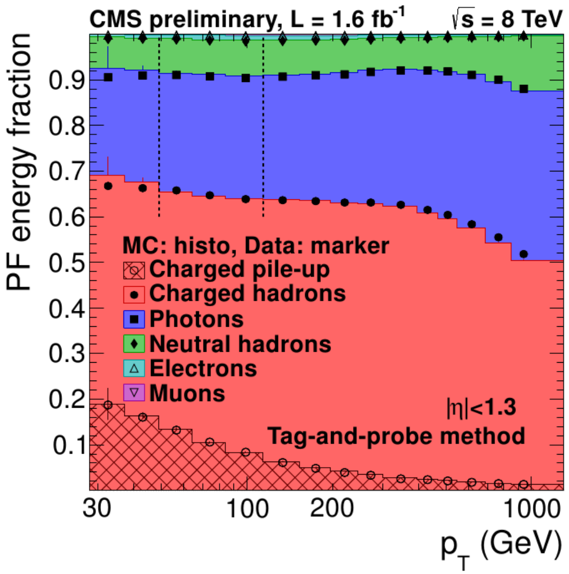
- For most analyses, CMS and ATLAS use anti-k_T jets with a distance parameter d
  - ATLAS : d=0.4
  - CMS: d=0.5
- ATLAS relies on outstanding quality of calorimeter to get good jet performances
- CMS Particle flow algorithm allows very good agreement between data and MC with small uncertainties and good resolution
- Both experiments carefully correct for pile-up vertices





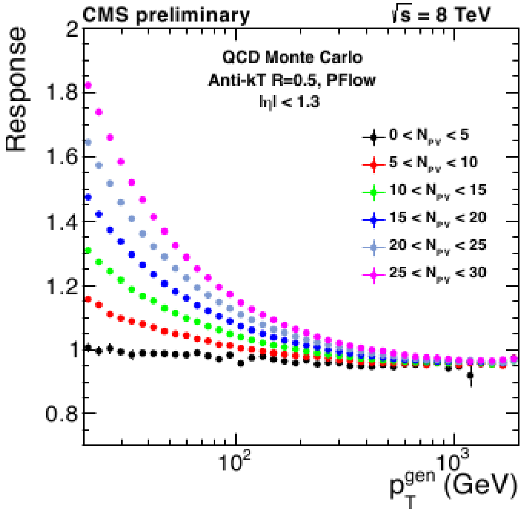


Jets - CMS

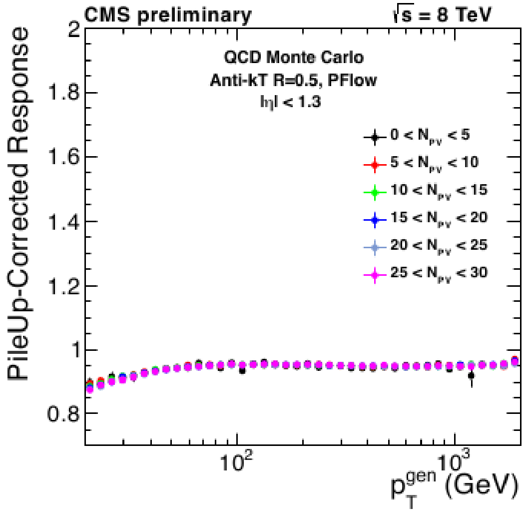


- CMS has need for very detailed understanding of fraction of different particles per jet and fraction of pile-up particles in jet as these are subtracted by the particle flow algorithm

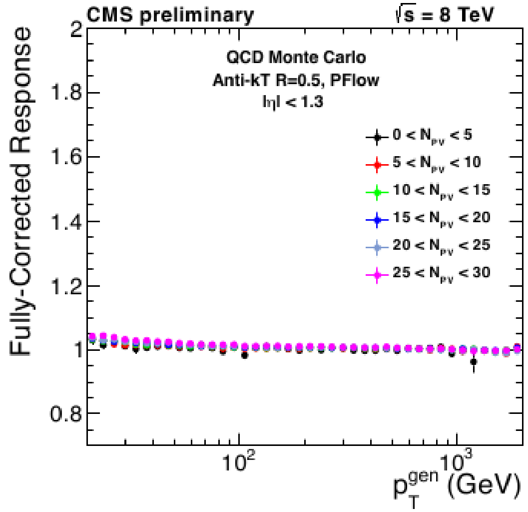
Before corrections



PU corrections



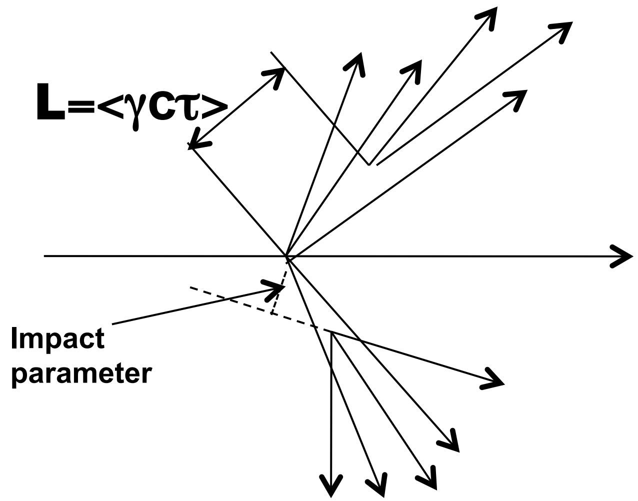
PU+MC truth



b-quark jets

Discriminants of b jets from light quark or gluon jets based on

- Long lifetime of b-hadrons in them
  - τ= 1.512 x 10^{-12} s, $c\tau$ = 455.4 μm
- High masses
- High fraction of semi-leptonic decays
  - ~10% e, μ (and from charm)
- Hard fragmentation



$\theta \sim 1/\gamma$

$\sigma_L \sim 1/$

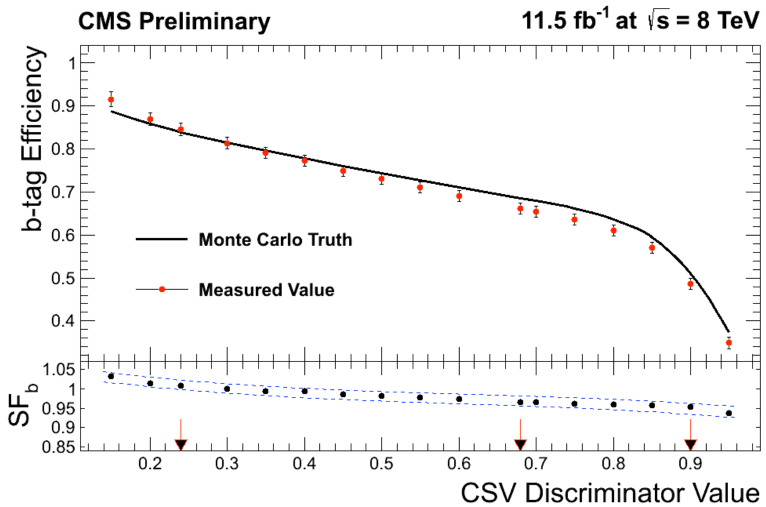
$\theta \sim \gamma$

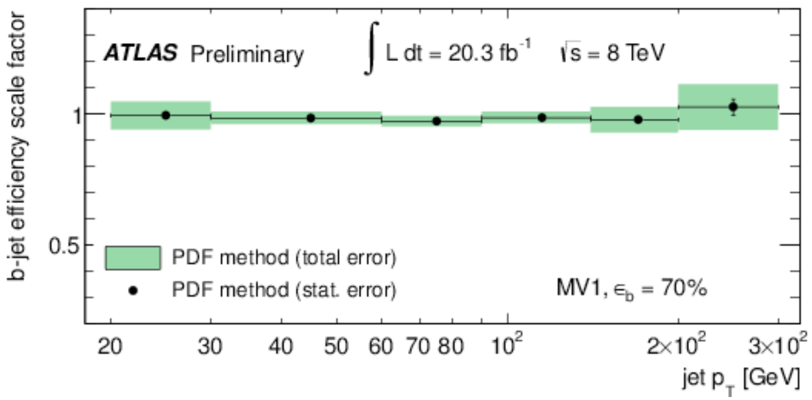
L/σ_L ~ independent of p of B

Impact parameter ~$1/2\pi c\tau$ independent of p

- Methods for discrimination
  - Impact parameter based
    - Track counting high efficiency
    - Track counting high purity
    - Jet probability
    - Jet B probability
  - Secondary vertices
    - Simple secondary vertex
    - Combined secondary vertex
  - Lepton based algorithms
    - Soft muon by PTrel
    - Soft muon by IP signficance
    - Soft electron
  - Combined algorithm
    - Combined MVA

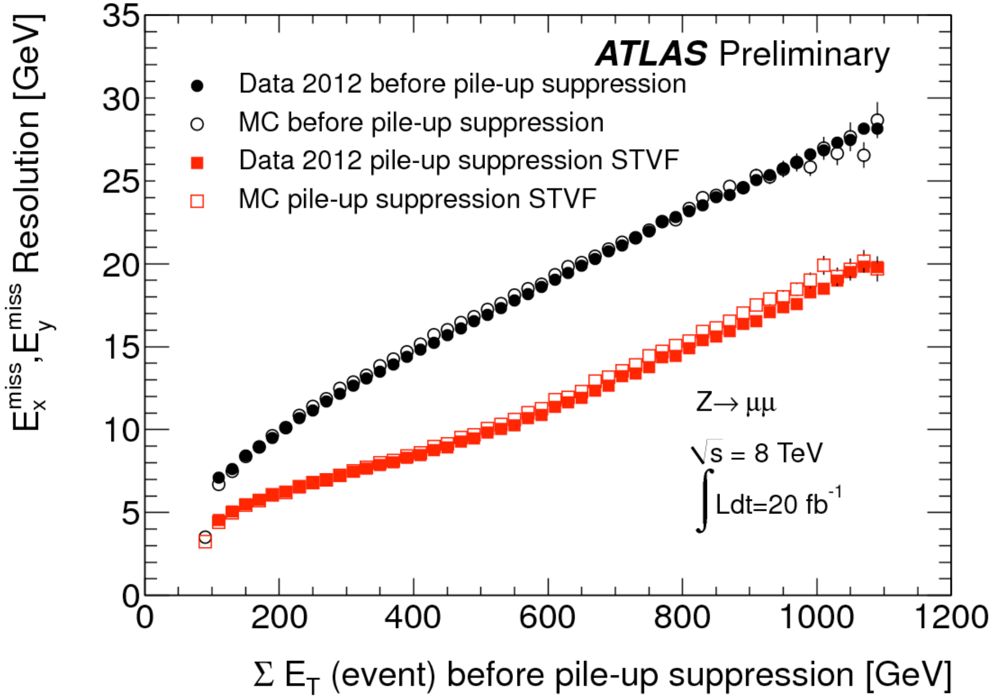
Jets with b-tagging





- Long lifetime of b-hadrons in b-jets
  - $\tau = 1.512 \times 10^{-12}$ s
  - $c\tau = 455.4\ \mu m$
- Combination of lifetime information in MVA
- Efficiency measured in top and QCD events (data) using multiple methods

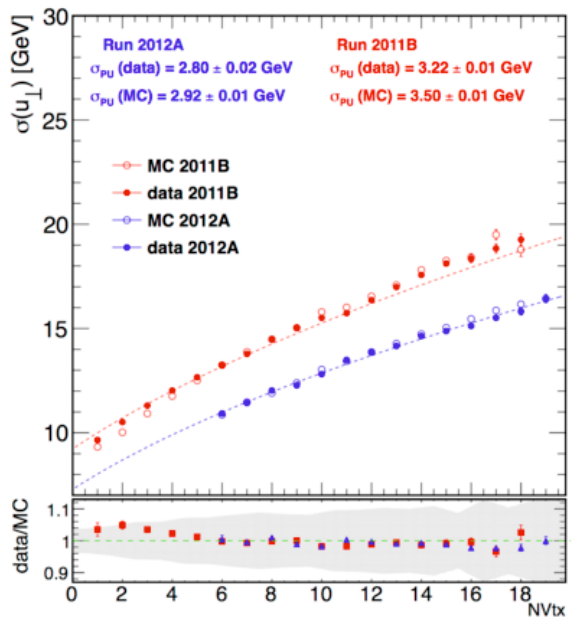
Missing ET



Particle flow extremely powerful approach for missing ET reconstruction

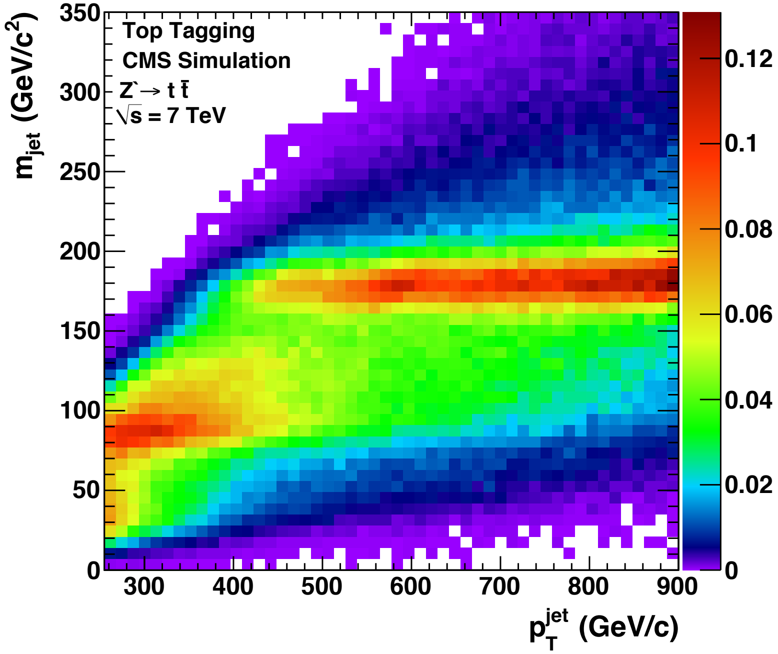
Missing ET sensitivity to PU irreducible

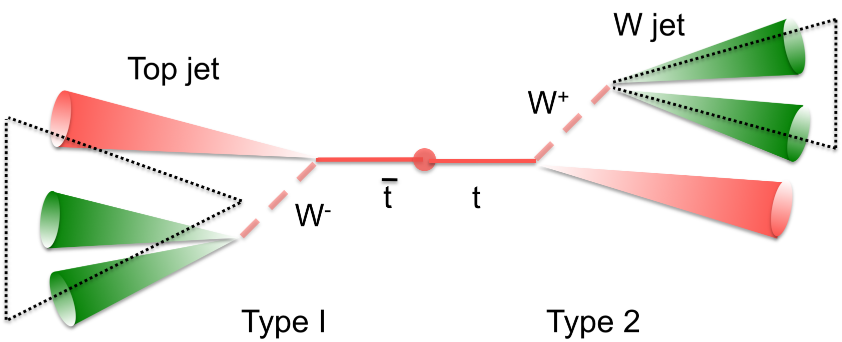
– But well reproduced in MC



On the momentum of top quarks

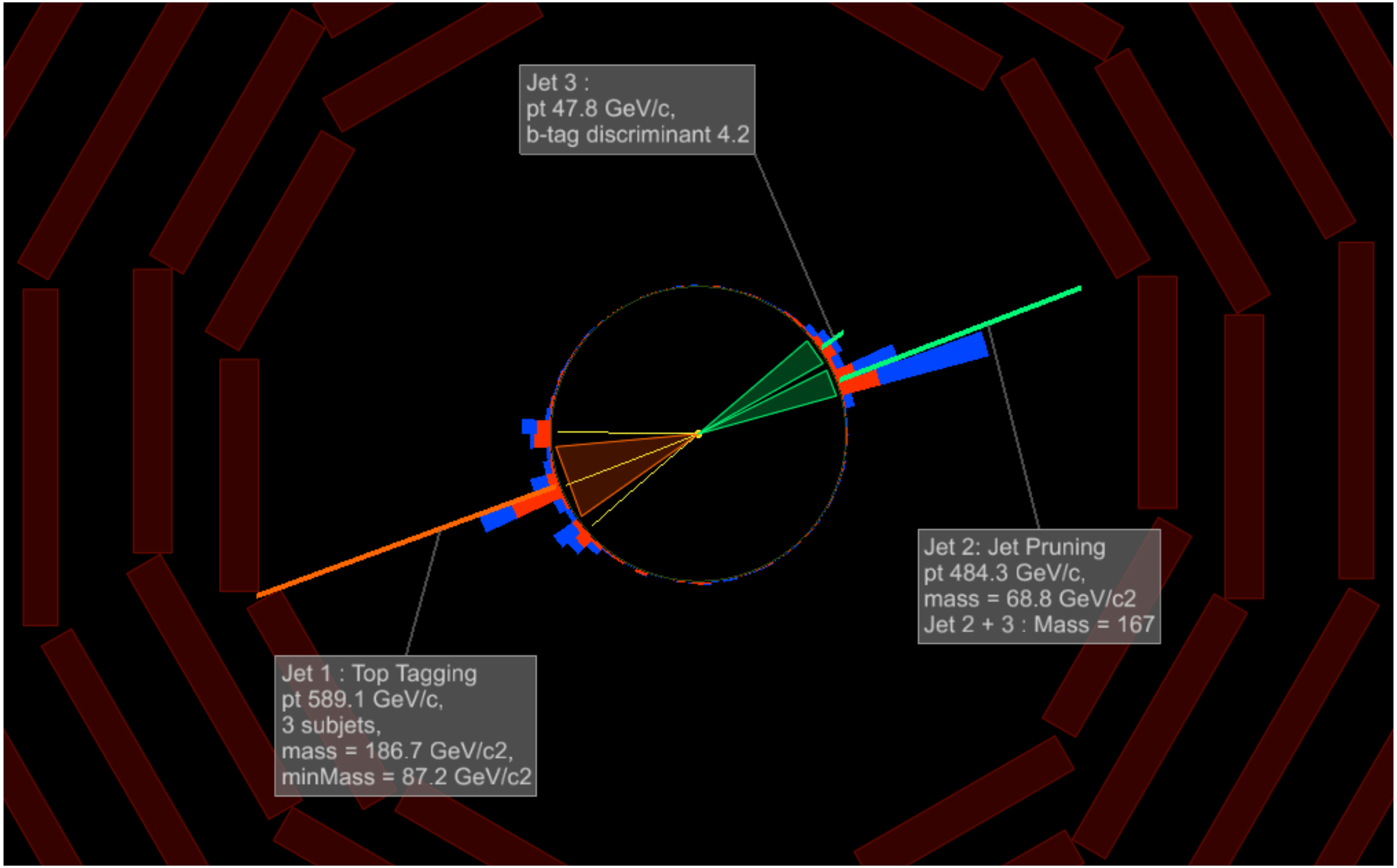
PAS JME-10-013



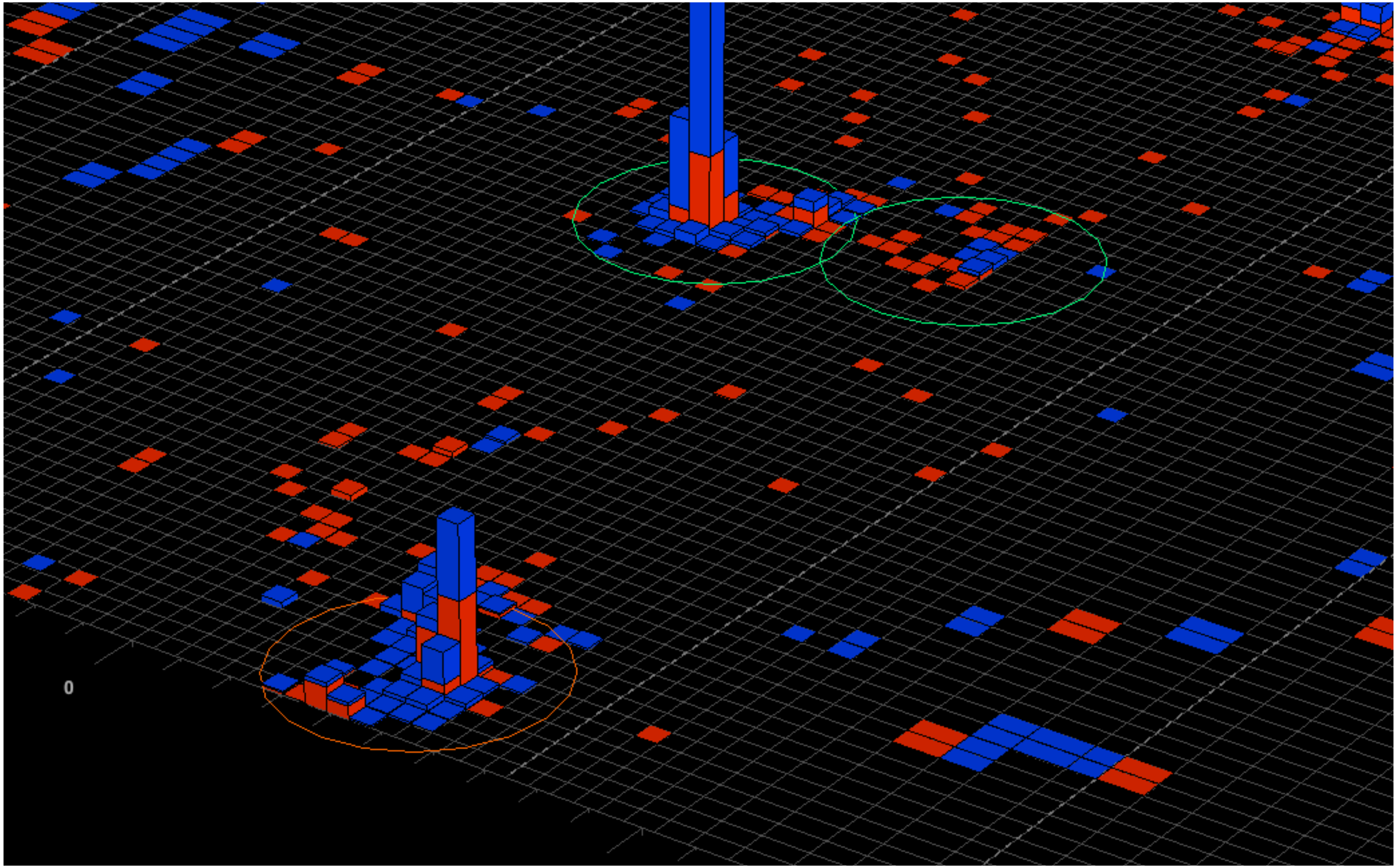


- Once boost of top quarks high enough
- Decay products become collimated
  - W->qq in one jet
  - Or t->bqq in one jet
- Special reconstruction algorithms needed

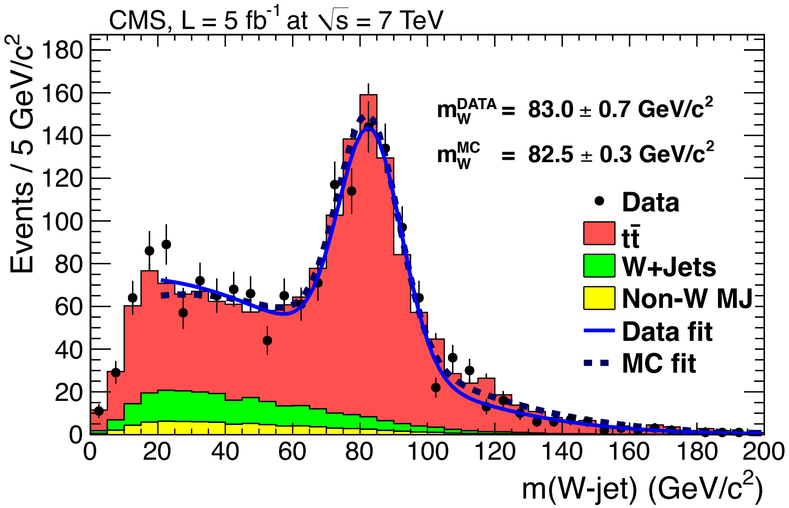
Jets with substructure

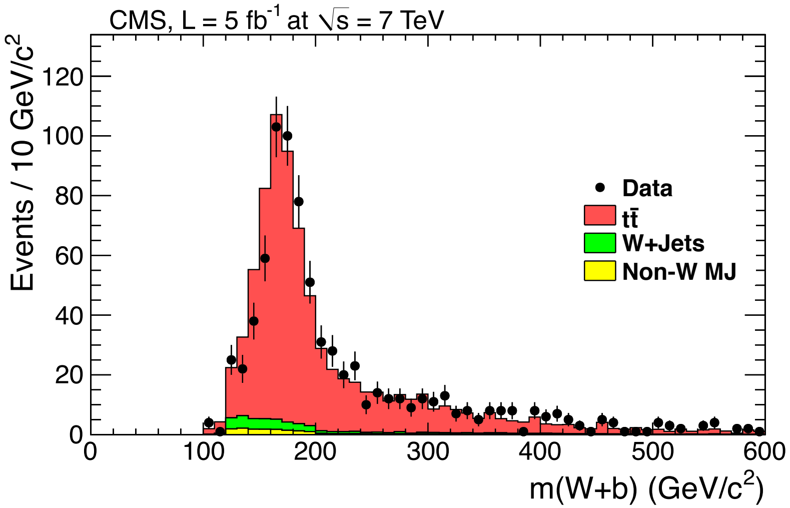


Jets with substructure

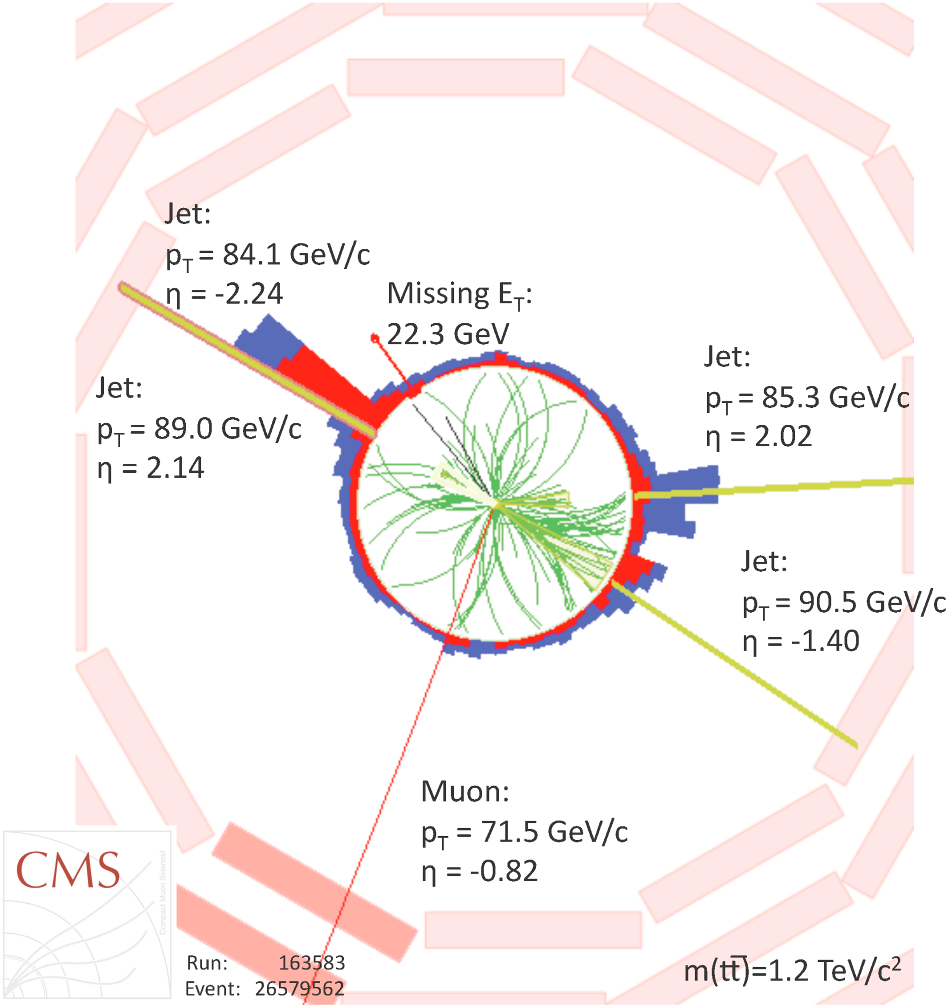


Validation in lepton+jets events



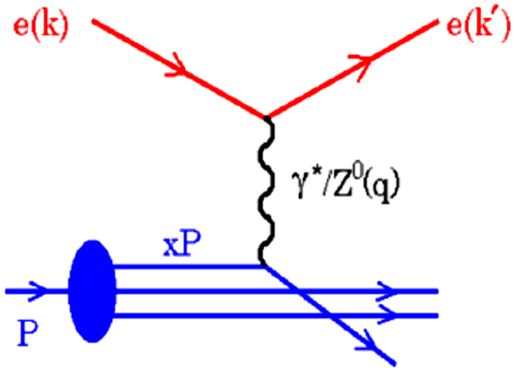


- Algorithm validated using muon+jets selection
- Data shows that W boson and top quark (using di-jet events) can be reconstructed this way and is reasonably well modeled


Jet:
p_T = 84.1 GeV/c
η = -2.24
Missing E_T:
22.3 GeV
Jet:
p_T = 89.0 GeV/c
η = 2.14
Jet:
p_T = 85.3 GeV/c
η = 2.02
Jet:
p_T = 90.5 GeV/c
η = -1.40
Muon:
p_T = 71.5 GeV/c
η = -0.82
CMS
Run: 163583
Event: 26579562
m($t\bar{t}$)=1.2 TeV/c^2

Important: parton density functions determine all LHC cross sections!

Proton structure probe



Neutral current Deep Inelastic Scattering (DIS) cross section:

$$\frac{d^2\sigma^\pm}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x}\sigma_r^\pm =$$

$$= \frac{2\pi\alpha^2 Y_+}{Q^4 x}\left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3\right]$$

where factors $Y_\pm = 1 \pm (1-y)^2$ and y^2 define polarisation of the exchanged boson and $y = Q^2/(S\ x)$.

Kinematics is determined by Q^2 and Bjorken x.
At leading order:

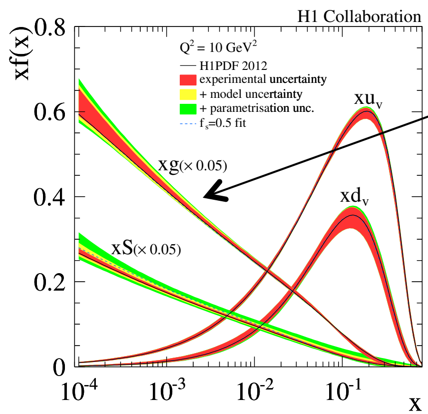
$$F_2 = x\sum e_q^2(q(x) + q(x))$$

$$xF_3 = x\sum 2e_q a_q(q(x) - q(x))$$

$$\sigma_{CC}^+ \sim x(u+c) + x(1-y)^2(d+s)$$

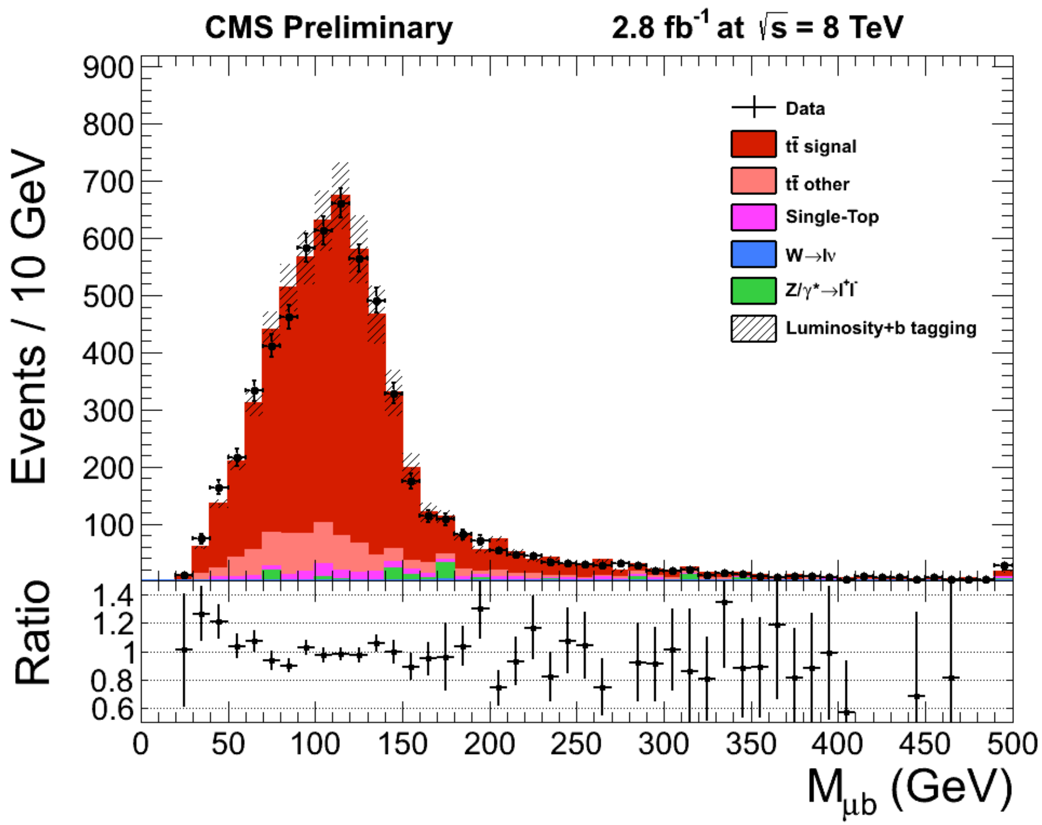
$$\sigma_{CC}^- \sim x(u+c) + x(1-y)^2(d+s)$$

$xg(x)$ — from F_2 scaling violation, jets and F_L



For most processes, LHC essentially is a gg collider

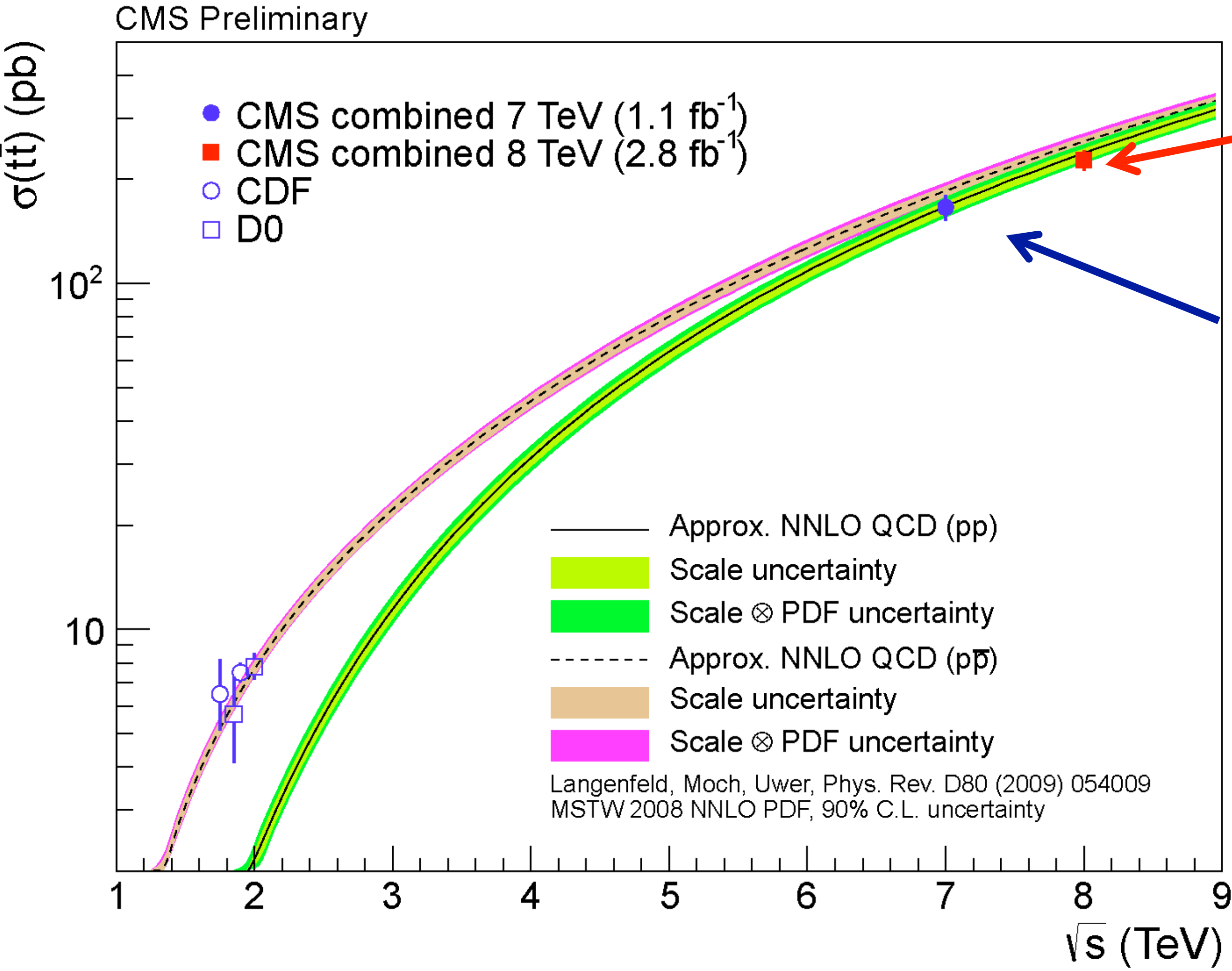
LHC: Top quark pair factory



- Cross sections ~225 pb
- In combination with 20 /fb datasets:
  - LHC is a top factory
  - Very productive program of Standard Model precision top physics

Top pair production

Production cross section overview



228 ±9 ±11 ±10 pb
(ICHEP'12 prelim)

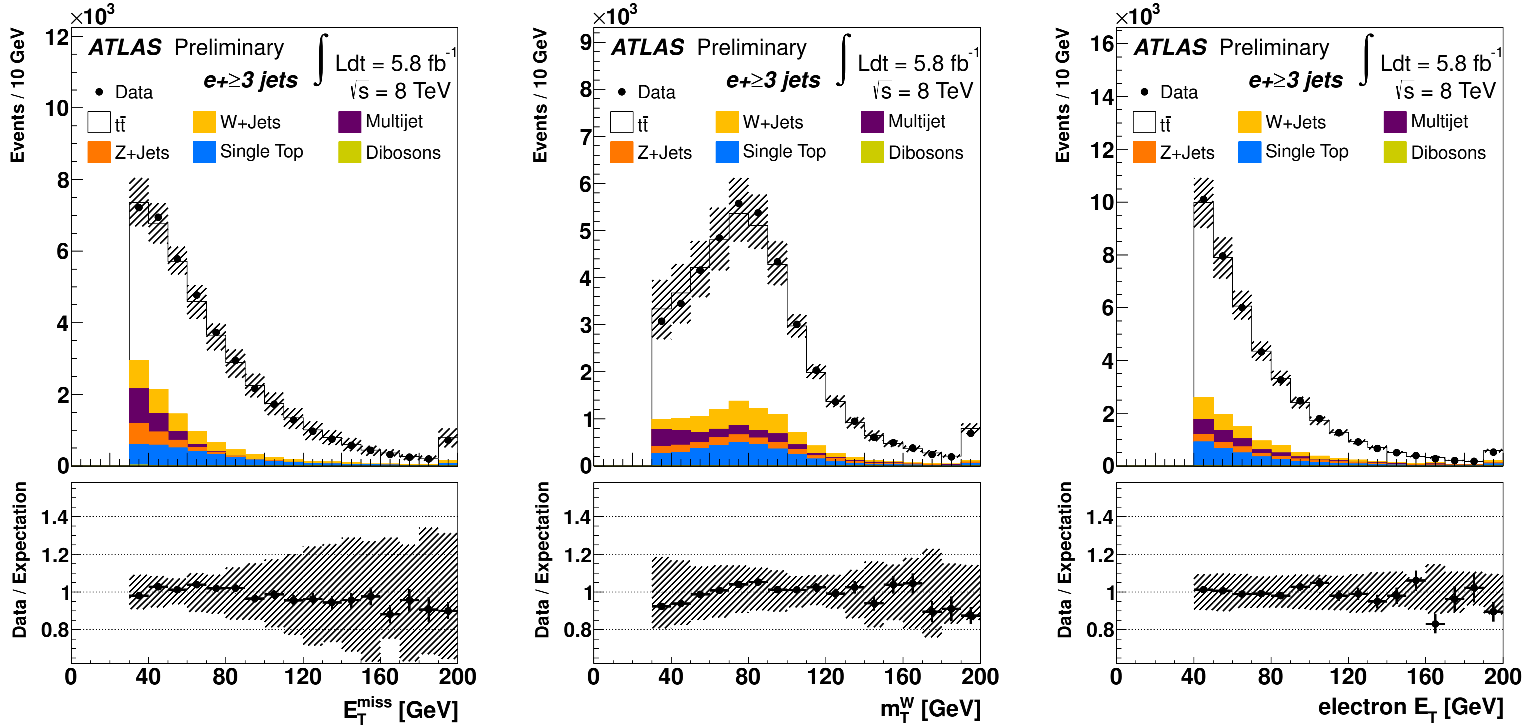
7 TeV dominated by
162 ±2 ±5 ±4 pb
(JHEP 11 (2012) 067)

Top cross sections

- Good benchmark to explain basic strategies in top physics and see main backgrounds
- Chosen result: ATLAS CONF-2012-149

- This is an analysis that uses the kinematical quantities of events with one lepton and (at least) 3 jets, including one b-tagged jet, to derive the total number of top quark events in the sample
  - And from that the production cross section

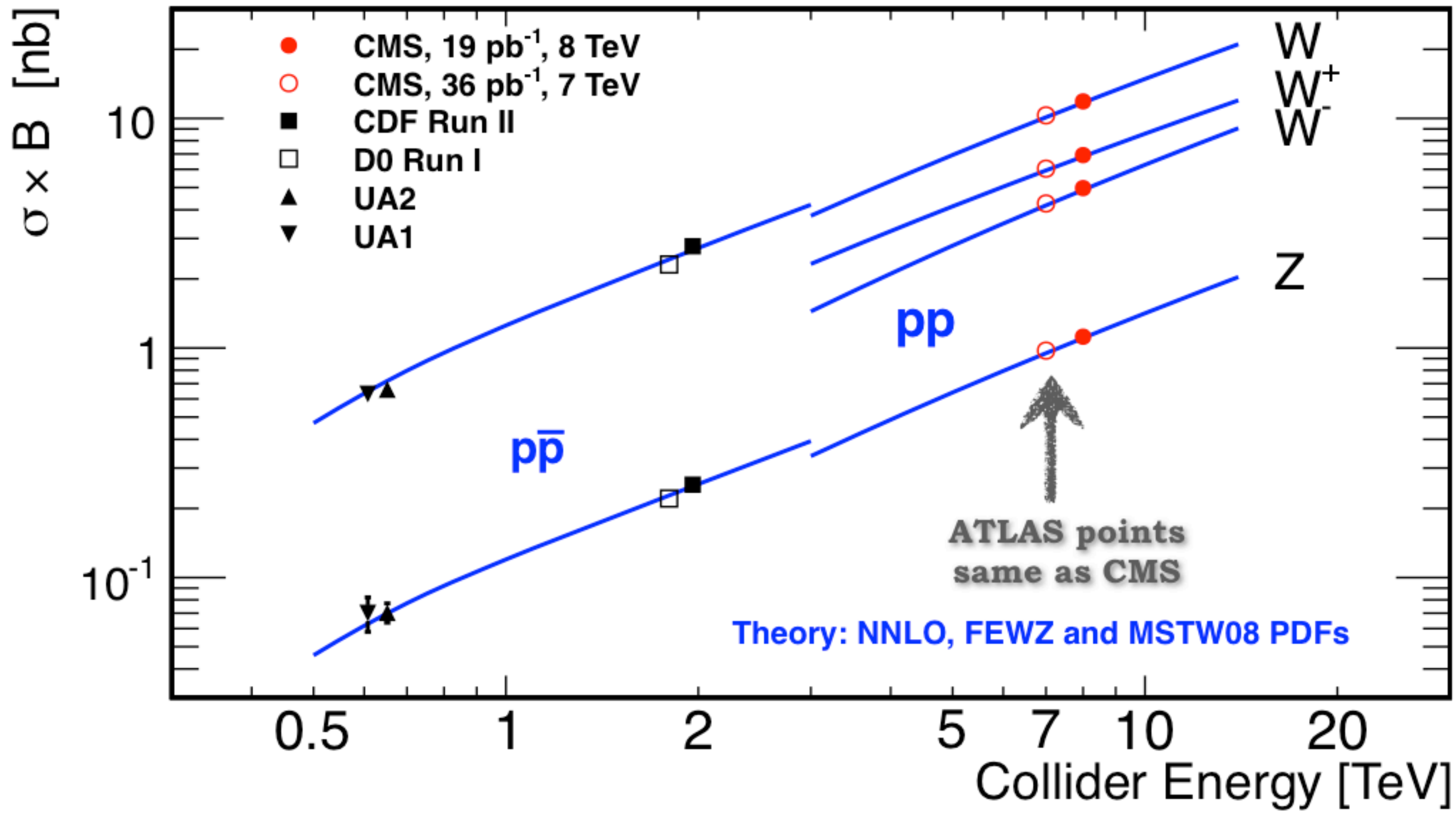
Event quantities



	$e+\geq3$ jets	$\mu+\geq3$ jets
$t\bar{t}$	31000^{+2900}_{-3100}	44000±4000
W+jets	5700±2400	9000±4000
Multijet	1900± 900	1100± 500
Z+jets	1400± 600	1200± 500
Single top	3260± 160	4610± 230
Dibosons	115± 6	158± 8
Total Expected	43000±4000	61000±6000
Data	40794	58872

Expected from detailed MC simulation using full detector response (GEANT)
Events generated with full Standard Model matrix element at Next-to-leading order, and full modeling of hadronization of quarks/gluons
Simulation takes much time (typical: few min/event at least)
Events scaled to NNLO theory cross section predictions

EWK cross section overview



Question: why at LHC W^+ different than W^-?

Multijet background, aka ‘QCD’

‘Electron’s that are ‘QCD’

- Overlap track w/ photon
- Photon conversions
- b-quarks and c-quarks that decay to leptons
  - Rest of decay missed? Real leptons
- Jets with fluctuations in hadronization
  - Very few charged tracks
  - Very small hadronic energy fraction

‘Muons’ that are ‘QCD’

- Pions, kaons that decay in flight in tracking region
- b-quarks and c-quarks decaying to leptons
  - rest of decay missed? Real leptons
- Hadrons that did not shower in calorimeter?
- Punch-through hadrons

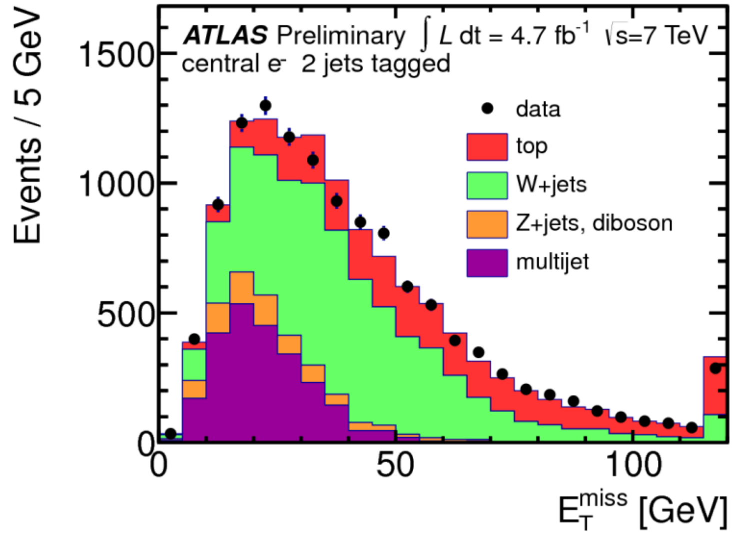
Simulation of fake electrons and muons using simulated QCD events is both **unreliable** and **impractical**

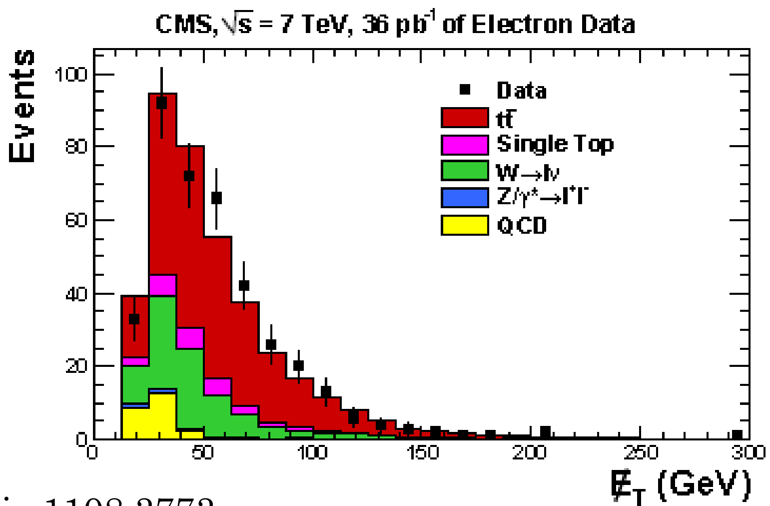
Data-driven methods

Many methods, all rely on isolating a control region enriched in fake leptons

- Select a sample of known lepton-like jets (looser version of your sample) and determine how often you see a muon or electron
  - Derive shapes from this and normalise to sideband (low Missing ET for example)
  - Good at modeling bad hadronization
- Or determine a sample of 'anti' electrons/ muons by inverting one of the selection cuts (typically the isolation requirement)
  - Very good at modeling complex variables
  - Good at modeling HF jets that fake isolated leptons

ATLAS CONF-2012-056





arXiv:1108.3773

Data-driven methods

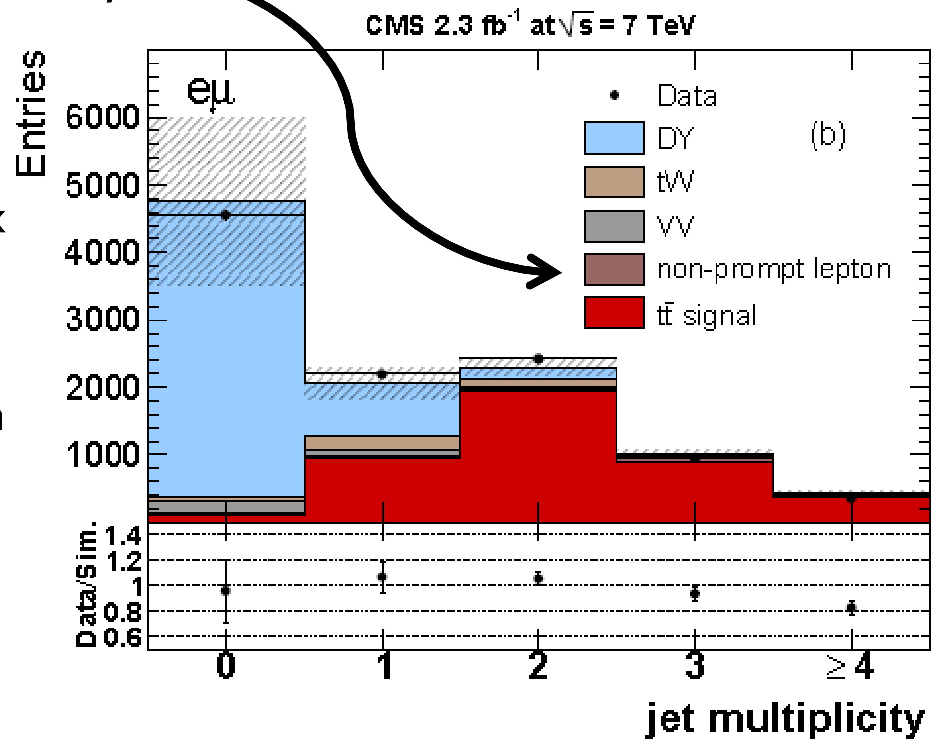
Matrix method:

Use two control regions with different, known, real/fake fraction and compare them to derive both fake rate and efficiency or vice versa

- Involves matrix inversion of 2x2 matrix
- needs well-understood sample composition of loose and tight sample
- Or needs known efficiency and known fake rate derived from other samples such as multijet and Z->ll resonance

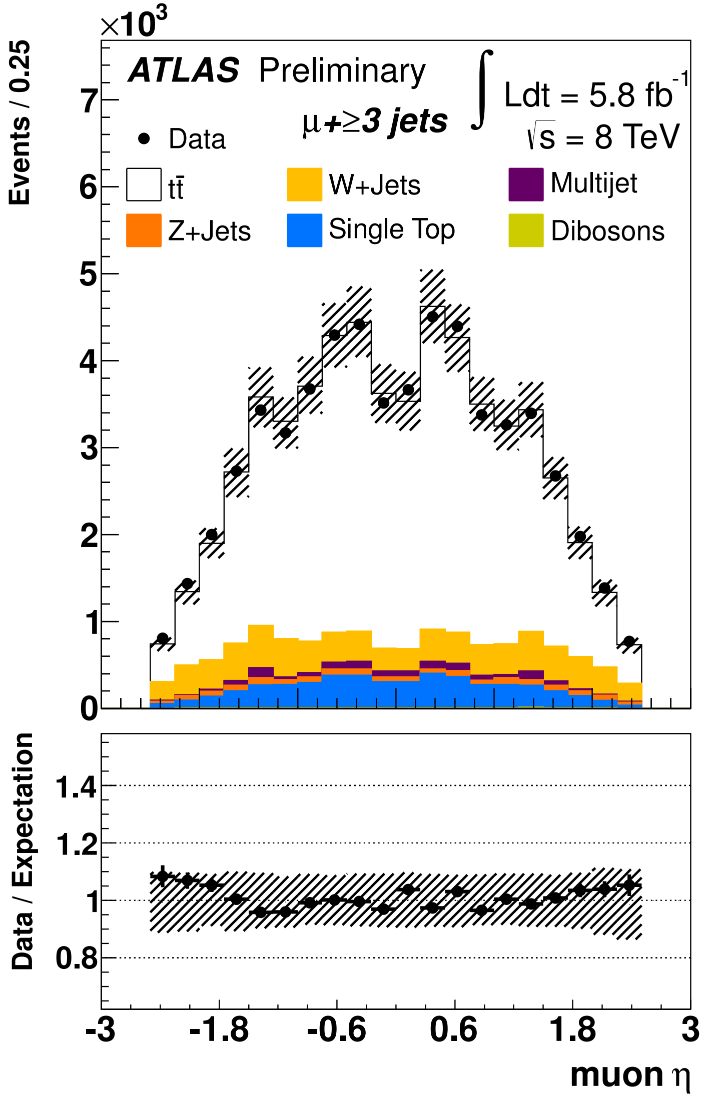
• Advantage: can completely determine composition of samples and with small uncertainties
  - But is complicated and involves many cross checks

Non-prompt background in CMS 7 TeV dilepton cross section analysis derived this way



Also commonly used in determination b-tag efficiency and fake rate from b-bbar events

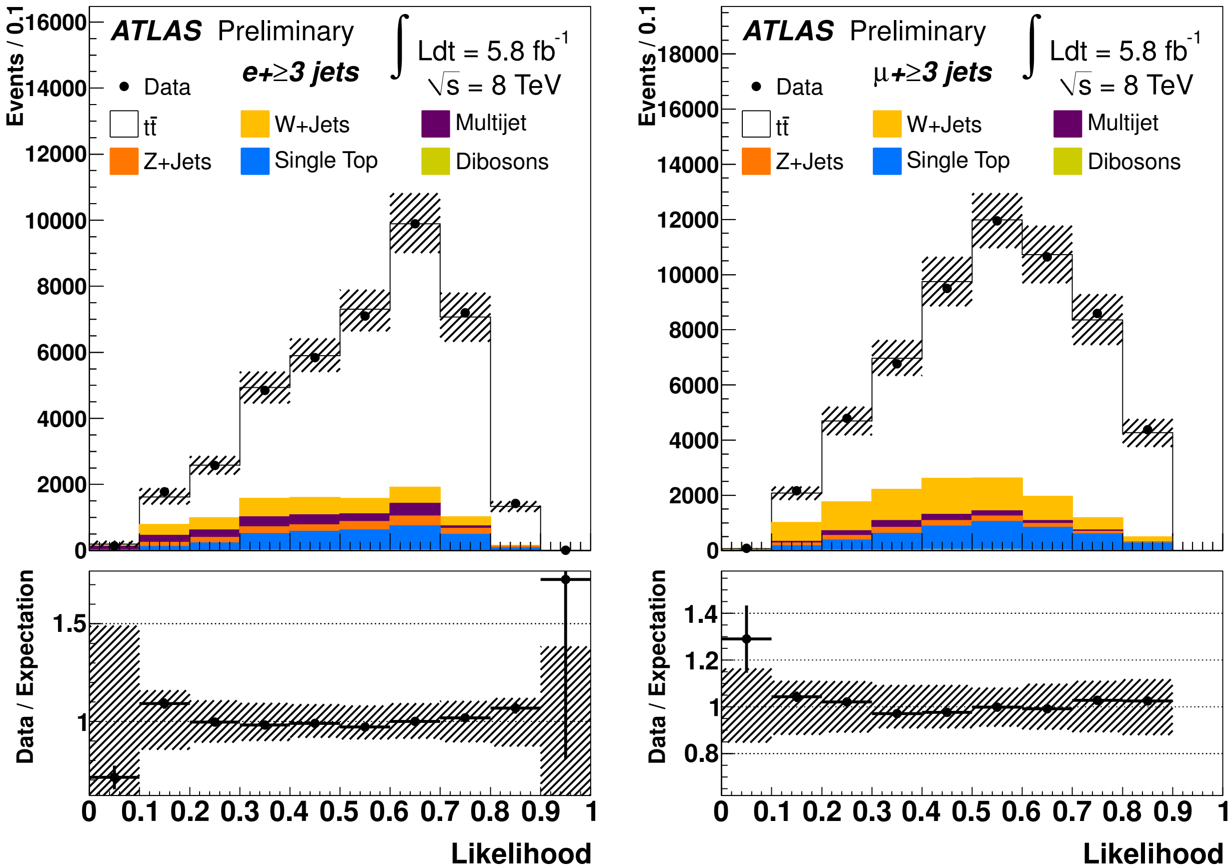
Back to ATLAS' cross section measurement



- Muon multijet contribution derived with matrix method
  - Used high MET (>100) region (few fakes) and low MET (<20) region to determine fake rate.
  - Low MET region of course contained W and Z bosons so those were subtracted using simulated contributions
- Electron multijet contribution derived from jet-enriched sample

Combined in likelyhood

- Likelihood in this case means single number per event quantifying how top-like the event is



- Statistical fit that varies backgrounds within their uncertainties used to determine remaining number of ttbar events, which is then used:

$$\sigma_{t\bar{t}} = \frac{N_{t\bar{t}}}{\mathcal{L} \times BR \times \varepsilon_{\text{sig}}}$$

- Efficiencies: determined from simulation with corrections from data

Systematic uncertainties

Source	$e+\geq 3$ jets	$\mu+\geq 3\,jets$	combined
Jet/MET reconstruction, calibration	6.7, -6.3	5.4, -4.6	5.9, -5.2
Lepton trigger, identification and reconstruction	2.4, -2.7	4.7, -4.2	2.7, -2.8
Background normalization and composition	1.9, -2.2	1.6, -1.5	1.8, -1.9
b-tagging efficiency	1.7, -1.3	1.9, -1.1	1.8, -1.2
MC modelling of the signal	± 12	± 11	± 11
Total	± 14	± 13	± 13

- Each of these numbers involves rerunning the analysis taking into account known uncertainties on the lepton reconstruction, etc.
- Some, like the 'MC modelling' uncertainty, contain many effects such as ISR/FSR model uncertainty, parton density functions, parton shower models, uncertainties of the event generator used for the simulation
- More examples of systematic studies/uncertainties in next lectures

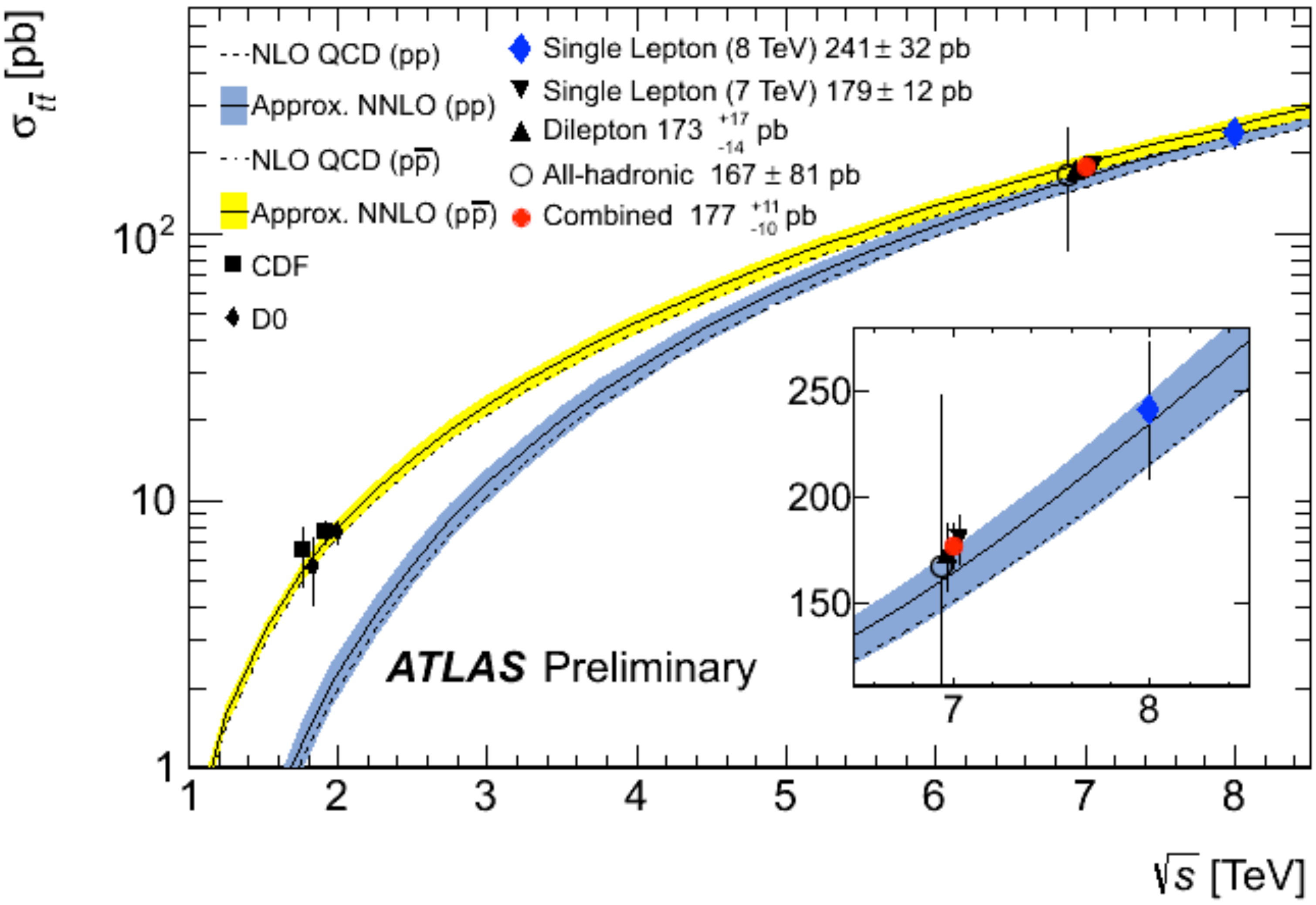
Final cross section

- Final cross sections traditionally (in top physics) have several uncertainties:

$$\sigma_{t\bar{t}} = 241 \pm 2\ (\text{stat.}) \pm 31\ (\text{syst.}) \pm 9\ (\text{lumi.})\ \text{pb.}$$

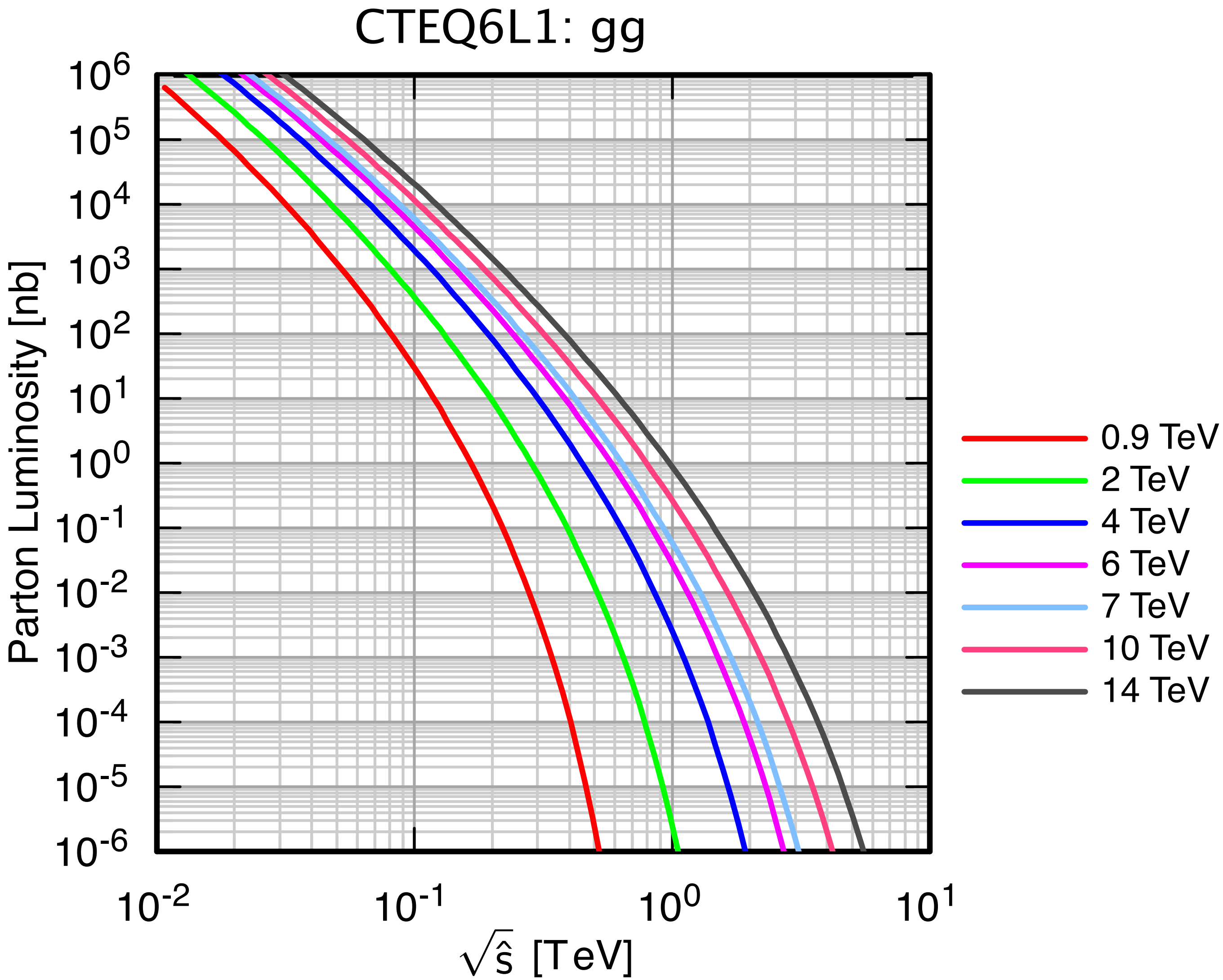
- The analysis determined the cross section at 8 TeV, which of course also has theory predictions. Some examples:
  - (approximate) Next-to-next-to-leading order assuming QCD production of generic heavy quarks: 238±10% pb (HATHOR, arXiv:1007:1327)
  - Full next-to-next-to-leading order: 246±3%±2.6 pb (arXiv:1303.6254)

And in the end…



End of lecture one – questions?

Use to predict cross sections



http://lutece.fnal.gov/PartonLum/