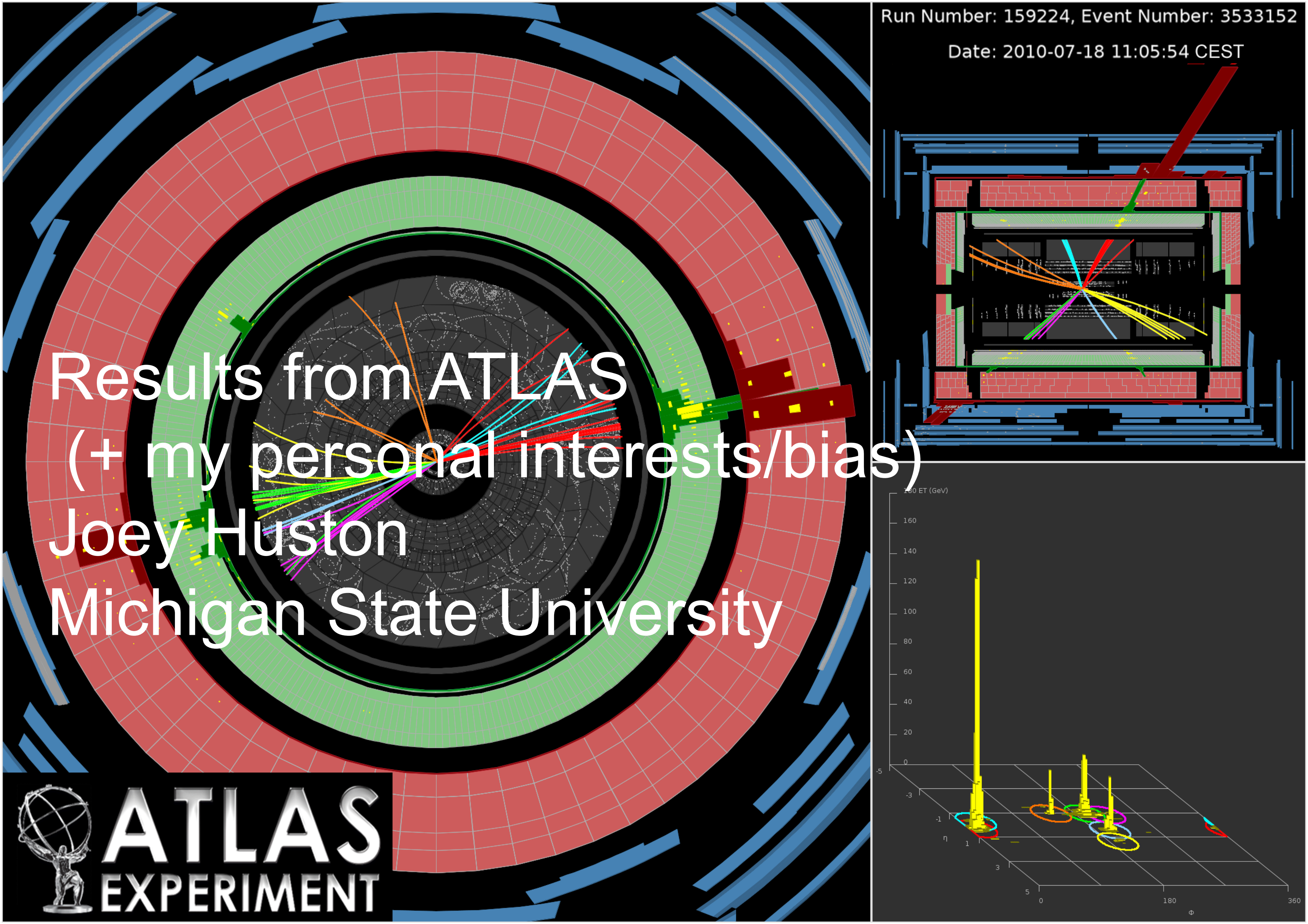
Results from ATLAS
(+ my personal interests/bias)

Joey Huston
Michigan State University

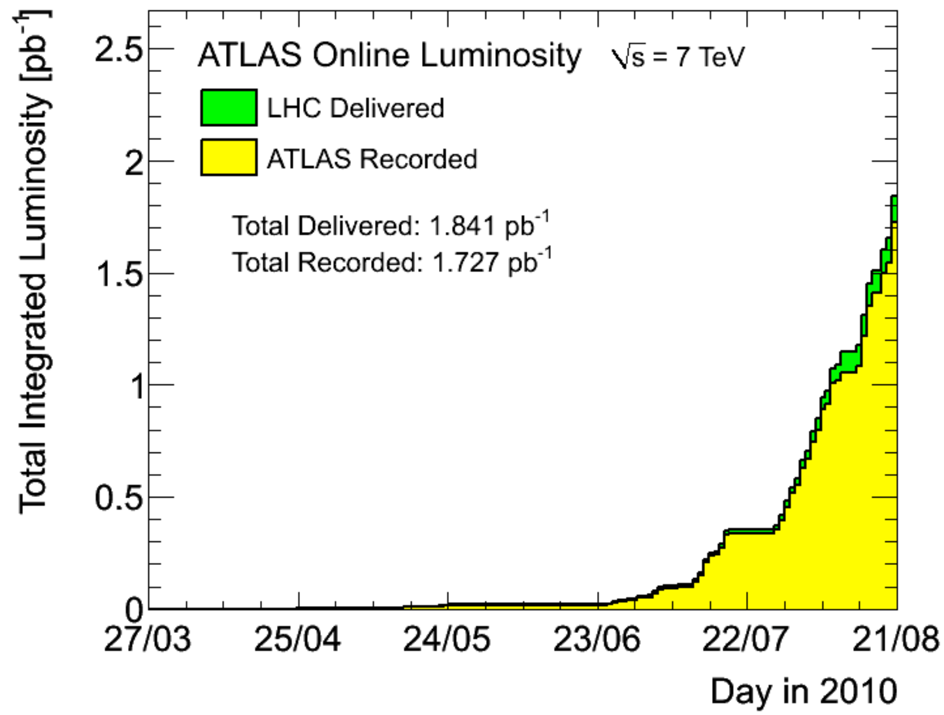


ATLAS physics

- Most results are from ICHEP with some recent blessings for HCP

online luminosity
calibrated with dedicated
van der Meer scans
(see ATLAS-CONF-2010-060)

luminosity uncertainty ~11%



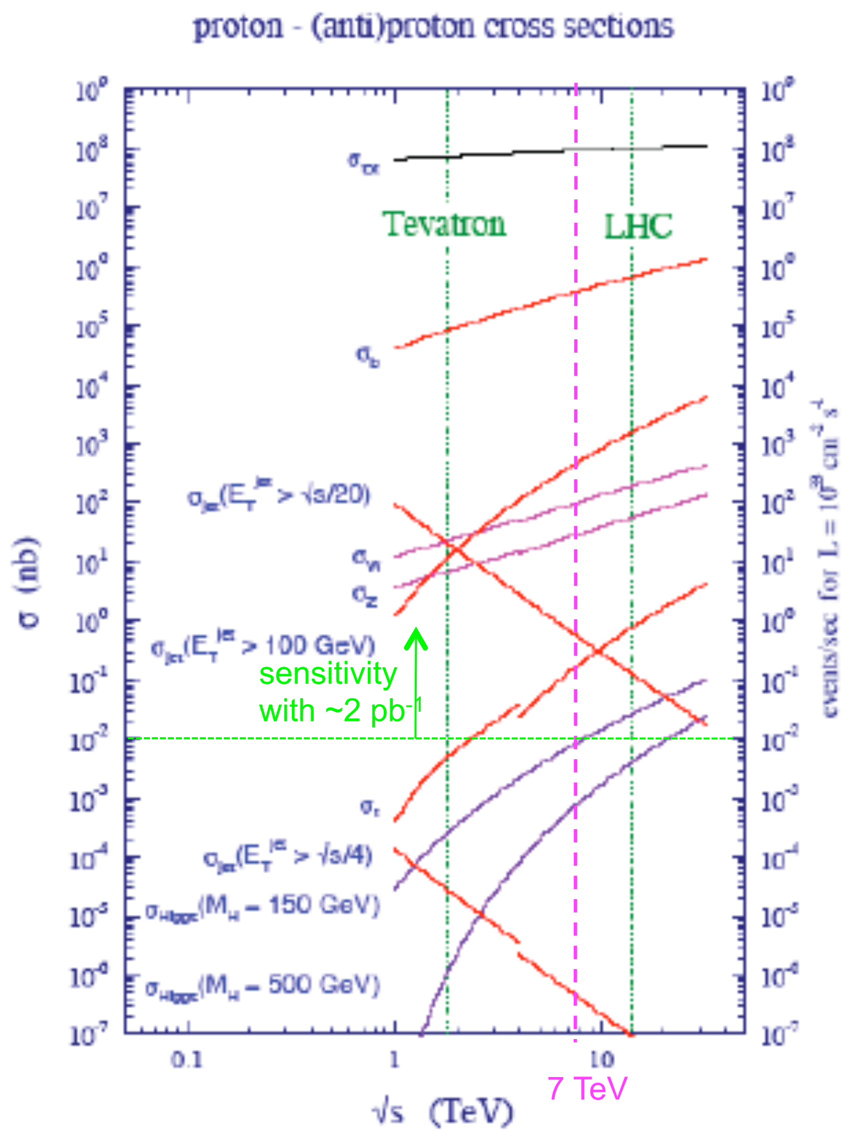
Fraction of "good quality" data collected

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	TGC	CSC
97.1	98.2	100	93.8	98.8	99.1	100	97.9	96.1	98.1	97.4

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams at $\sqrt{s}$=7 TeV between March 30th and July 16th (in %)

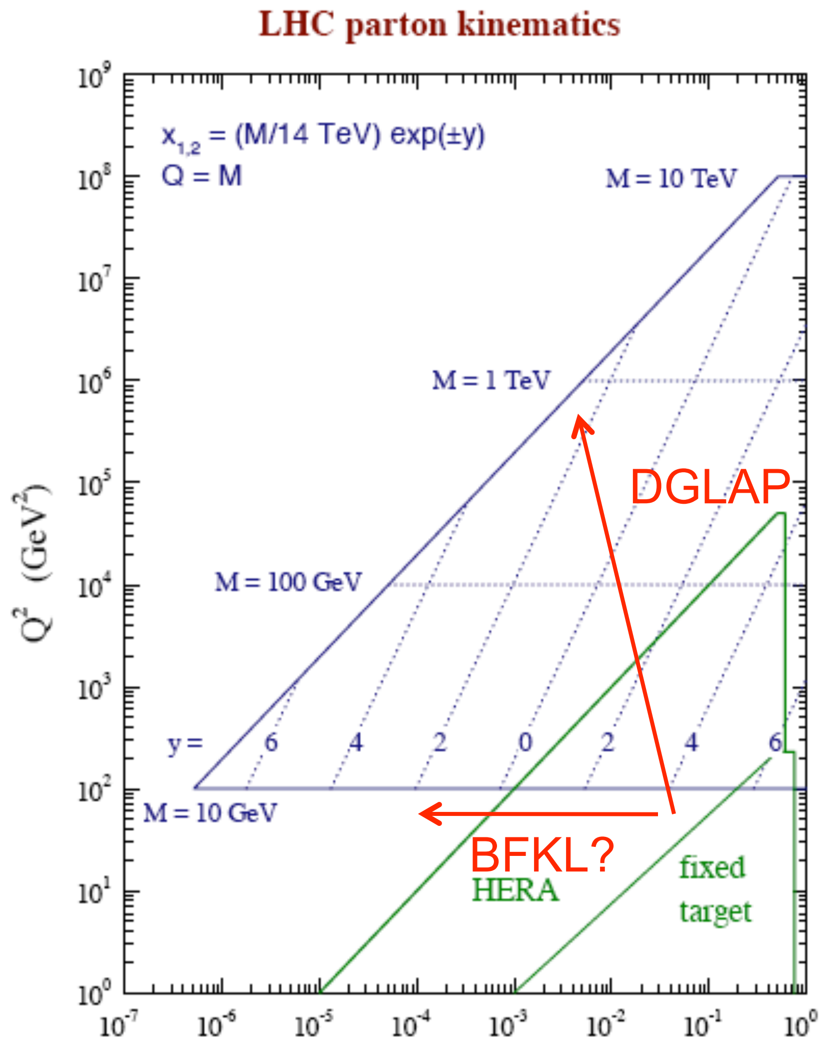
Understanding cross sections at the LHC

- We're all looking for BSM physics at the LHC
- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand SM cross sections
  - detector and reconstruction algorithms operating properly
  - SM backgrounds to BSM physics correctly taken into account
  - and, in particular, that QCD at the LHC is properly understood
  - now at low luminosity is our first chance



Cross sections at the LHC

- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just "rescaled" scattering at the Tevatron
- Small typical momentum fractions x for the quarks and gluons in many key searches
  - dominance of gluon and sea quark scattering
  - large phase space for gluon emission and thus for production of extra jets
  - intensive QCD backgrounds
  - or to summarize,…lots of Standard Model to wade through to find the BSM pony



…and we don't yet know whether BFKL dynamics will be important

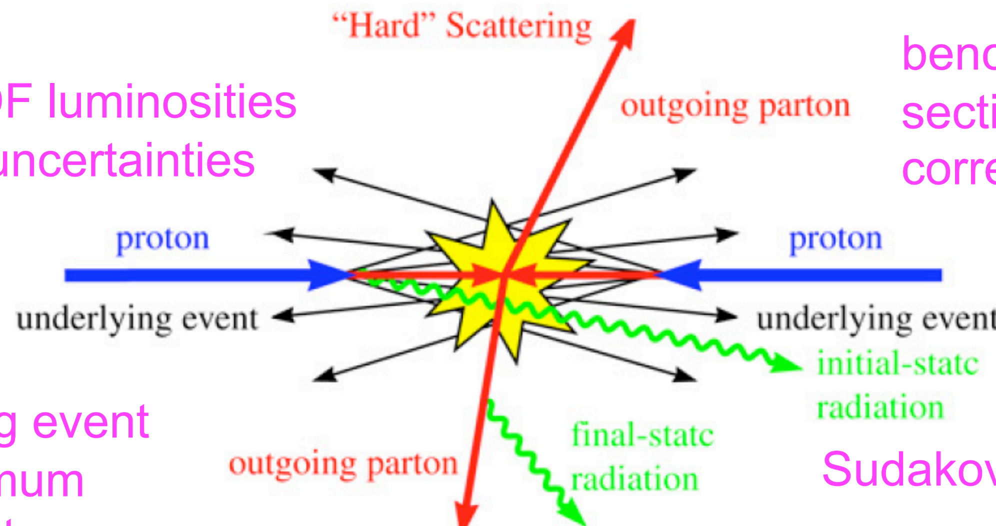
Rediscovering the Standard Model

(my phrase by the way)

LO, NLO and NNLO calculations
K-factors

PDF's, PDF luminosities
and PDF uncertainties

benchmark cross
sections and pdf
correlations



underlying event
and minimum
bias events

Sudakov form factors

jet algorithms and jet reconstruction

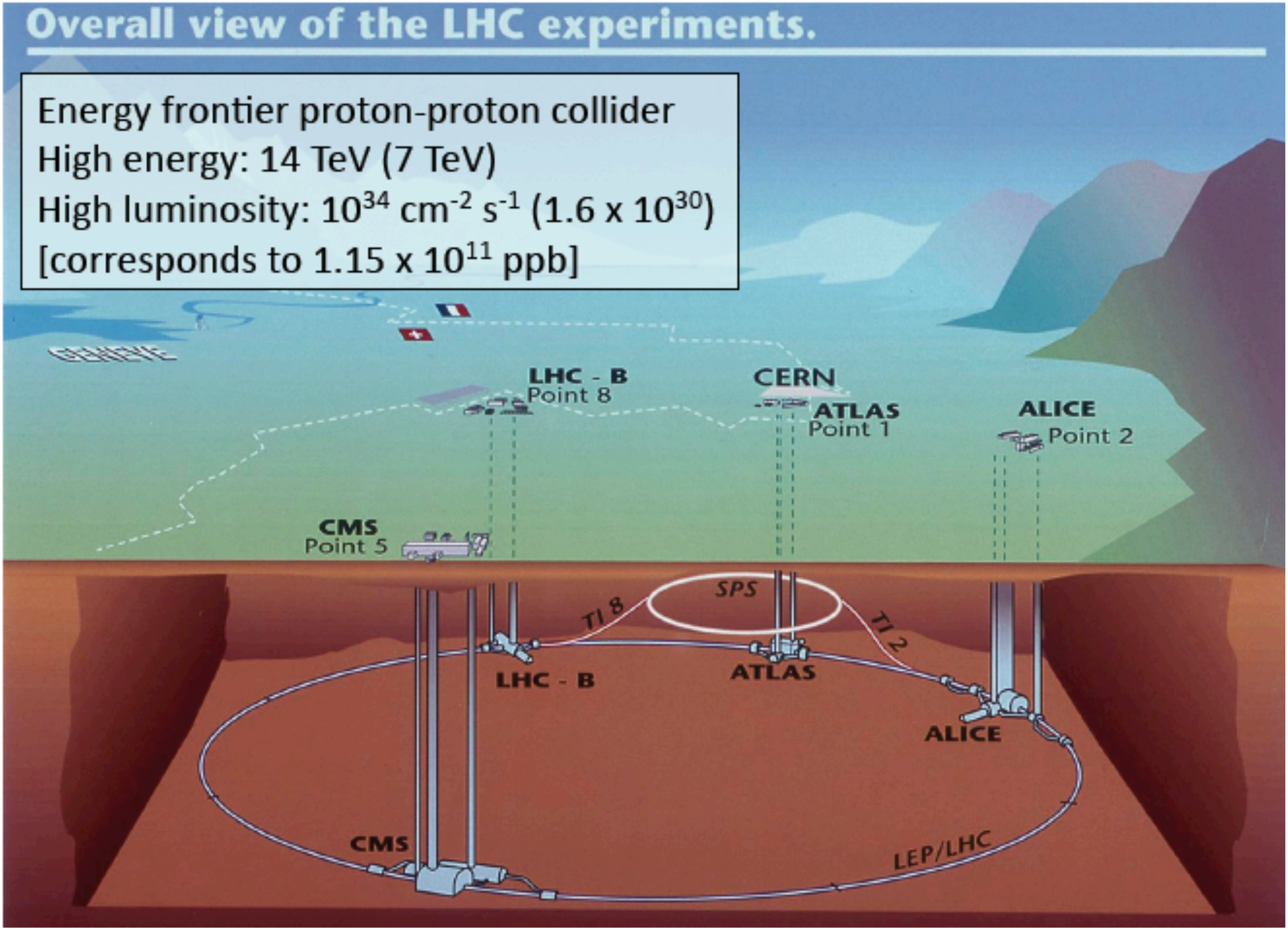
First results for underlying event, minimum bias, photons, leptons, jets, missing E_T, benchmark cross sections (W/Z, W/Z + jets, top)

Energy frontier proton-proton collider

High energy: 14 TeV (7 TeV)

High luminosity: 10^{34} cm^{-2} s^{-1} (1.6×10^{30})

[corresponds to 1.15×10^{11} ppb]



ATLAS detector

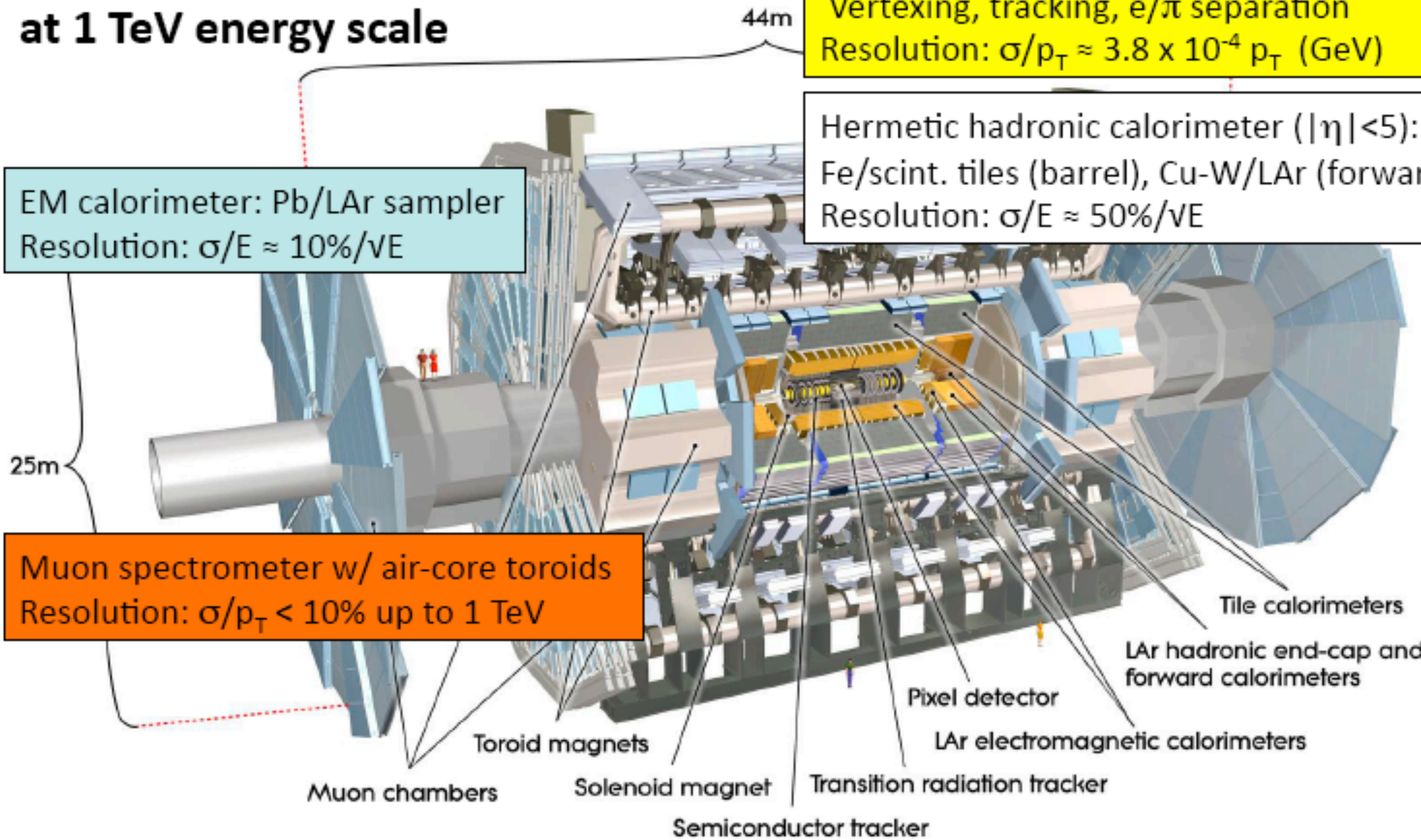
Designed for discovery at 1 TeV energy scale

Inner detector: Si strips/pixels;TRT straws)
Vertexing, tracking, e/π separation
Resolution: $\sigma/p_T \approx 3.8 \times 10^{-4}\ p_T$ (GeV)

Hermetic hadronic calorimeter ($|\eta|<5$):
Fe/scint. tiles (barrel), Cu-W/LAr (forward)
Resolution: $\sigma/E \approx 50\%/\sqrt{E}$

EM calorimeter: Pb/LAr sampler
Resolution: $\sigma/E \approx 10\%/\sqrt{E}$

Muon spectrometer w/ air-core toroids
Resolution: $\sigma/p_T < 10\%$ up to 1 TeV



ATLAS detector

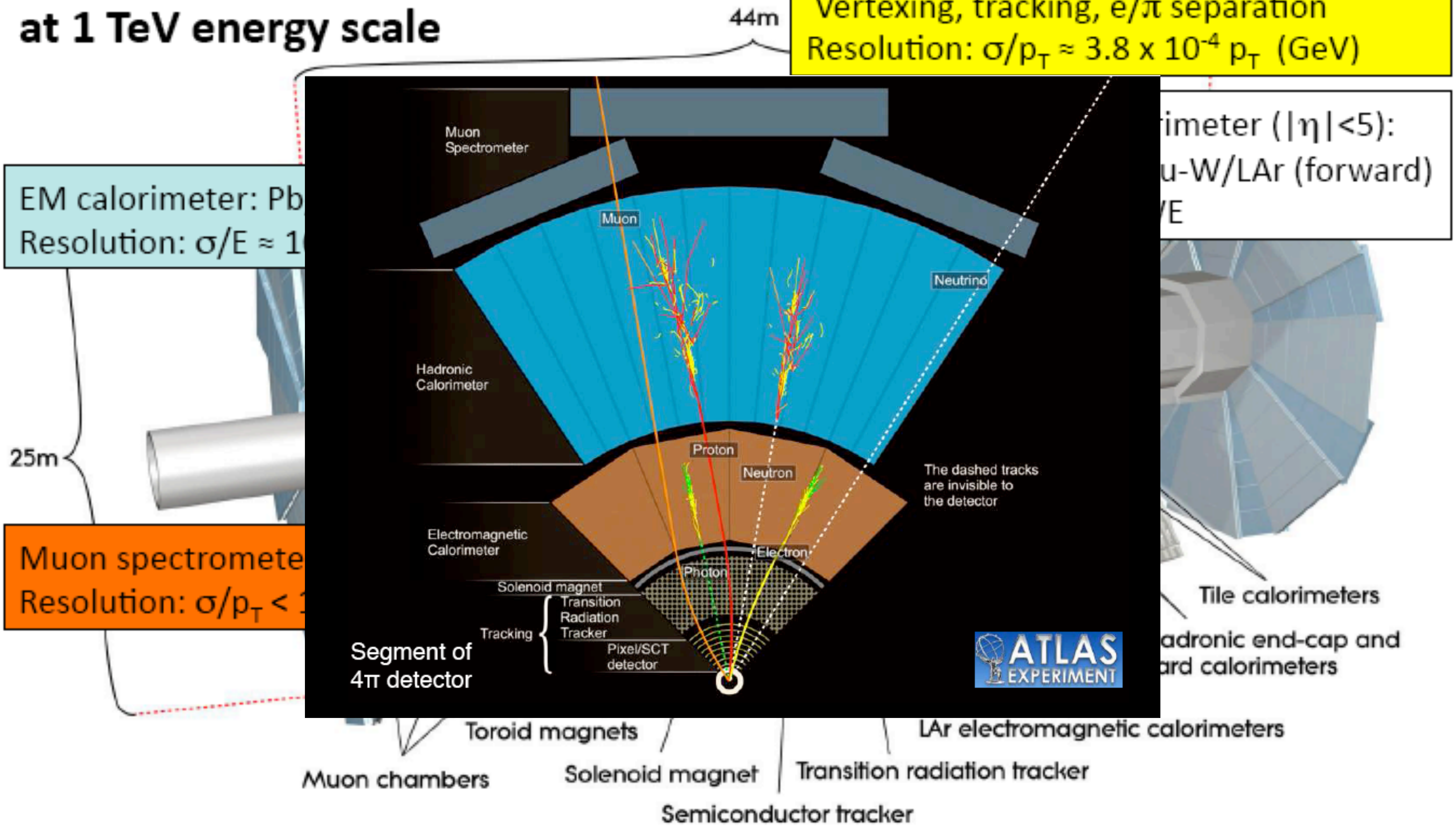
Designed for discovery at 1 TeV energy scale

Inner detector: Si strips/pixels;TRT straws)
Vertexing, tracking, e/π separation
Resolution: $\sigma/p_T \approx 3.8 \times 10^{-4}\ p_T$ (GeV)

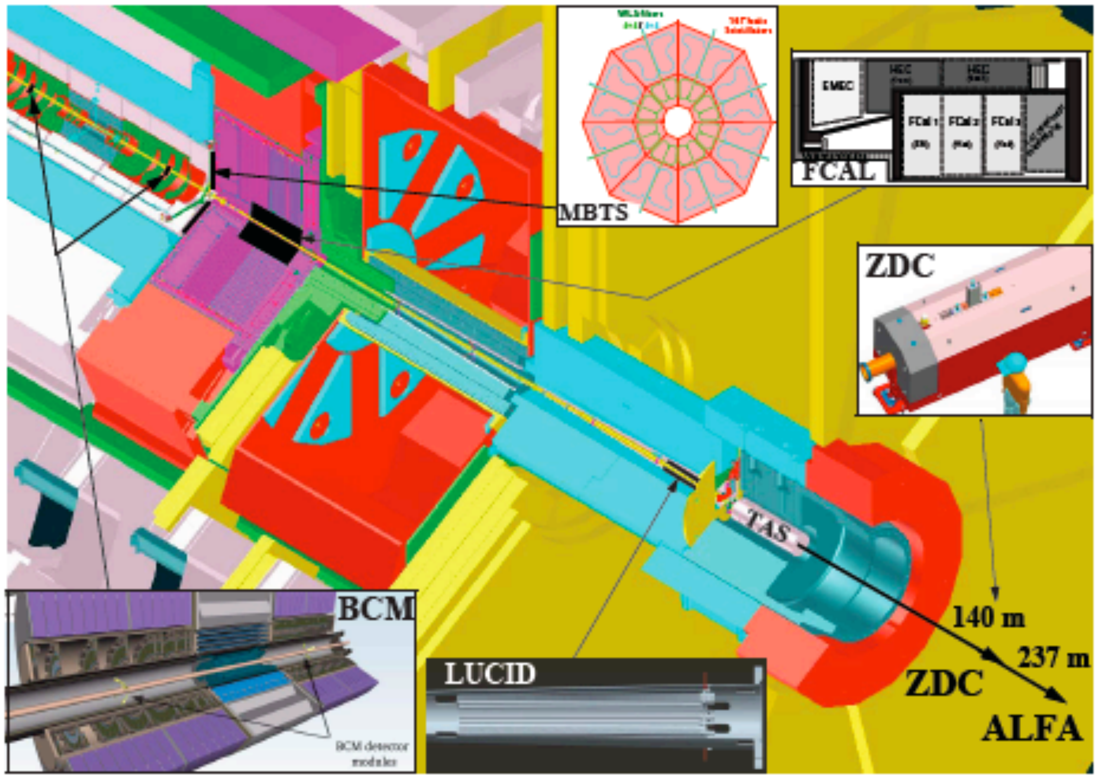
EM calorimeter: Pb
Resolution: σ/E ≈ 1

…rimeter (|η|<5):
…u-W/LAr (forward)
…/E

Muon spectromete
Resolution: σ/p_T < 1



ATLAS luminosity subdetectors



<u>Online and offline:</u>

-BCM (Beam Condition Monitor)

-$|\eta| \sim 4$

-MBTS (Minimum Bias Trigger Scintillators)

-2.09 < $|\eta|$ < 3.84

-FCAL (Forward CALorimeter)

-3,2< $|\eta|$ <4,9

-LUCID (Cherenkov Integrating Detector)

-5.6 < $|\eta|$ < 6

-ZDC (Zero Degree Calorimeter)

-8,3 > $|\eta|$

-Vertexing (High Level Trigger)

-$|\eta|$ < 2,5

-Liquid Argon Calorimeter Endcaps

-2,5< $|\eta|$ <4,9

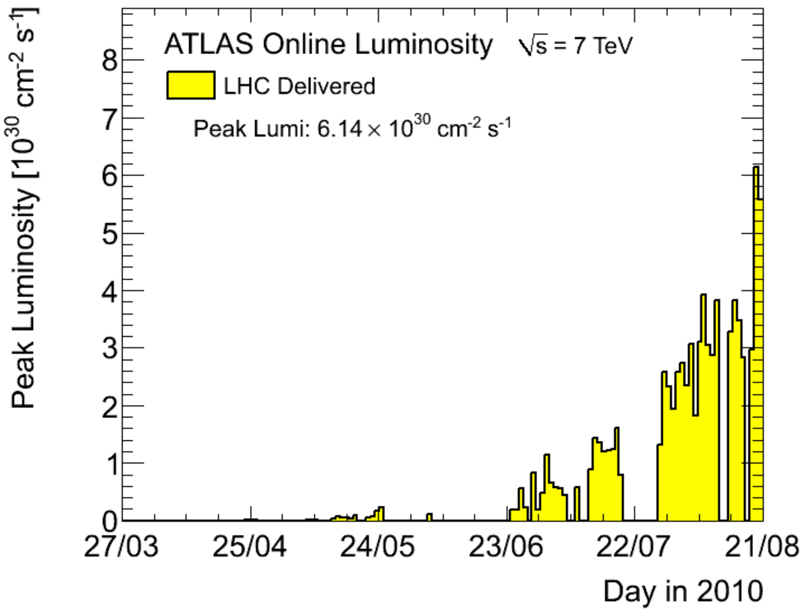
Measure the luminosity in as many ways as possible:

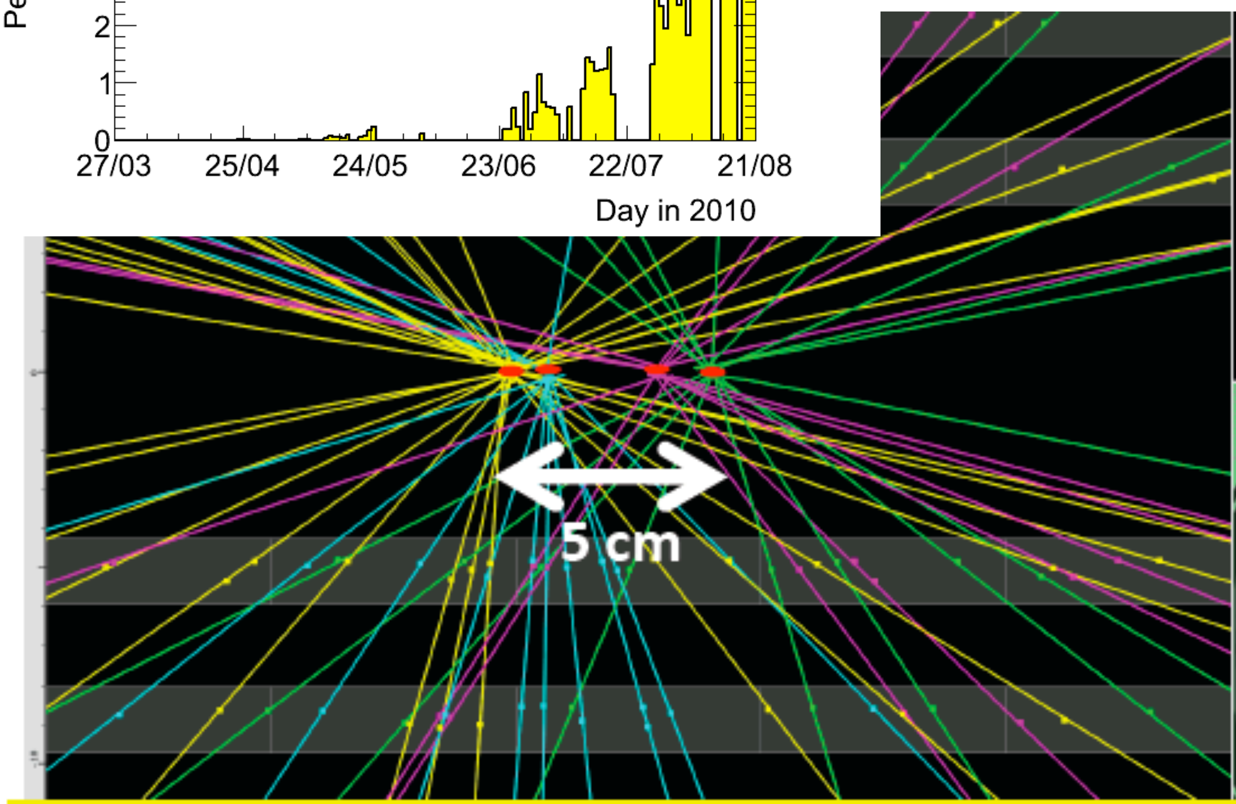
-Different systematics and sensitivity to background

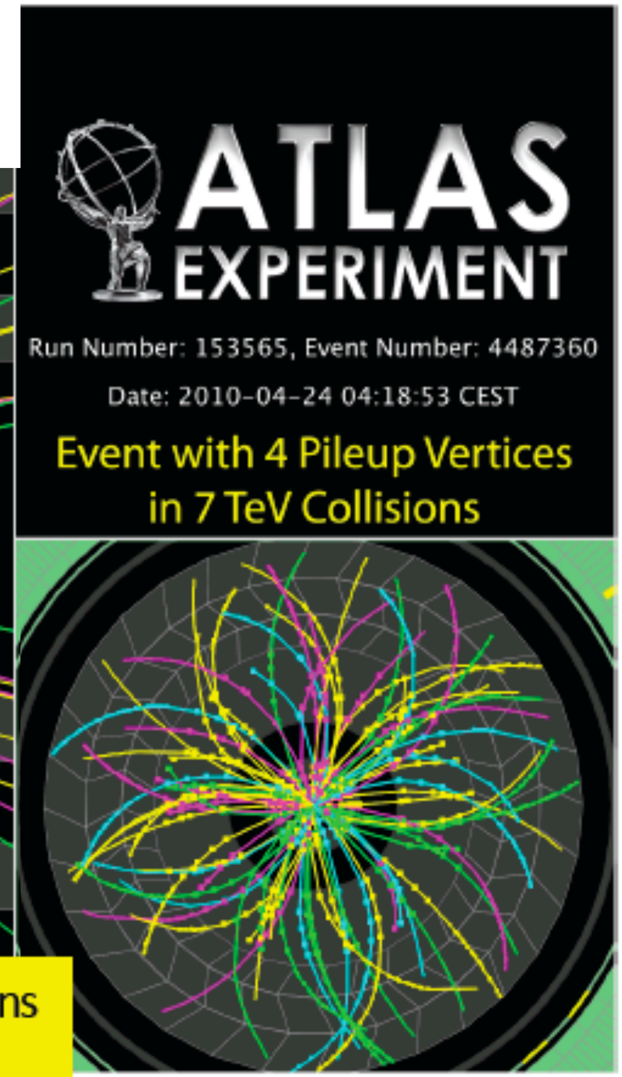
-Redundancy and cross-checks

One of first 7 TeV collisions

Peak Luminosity





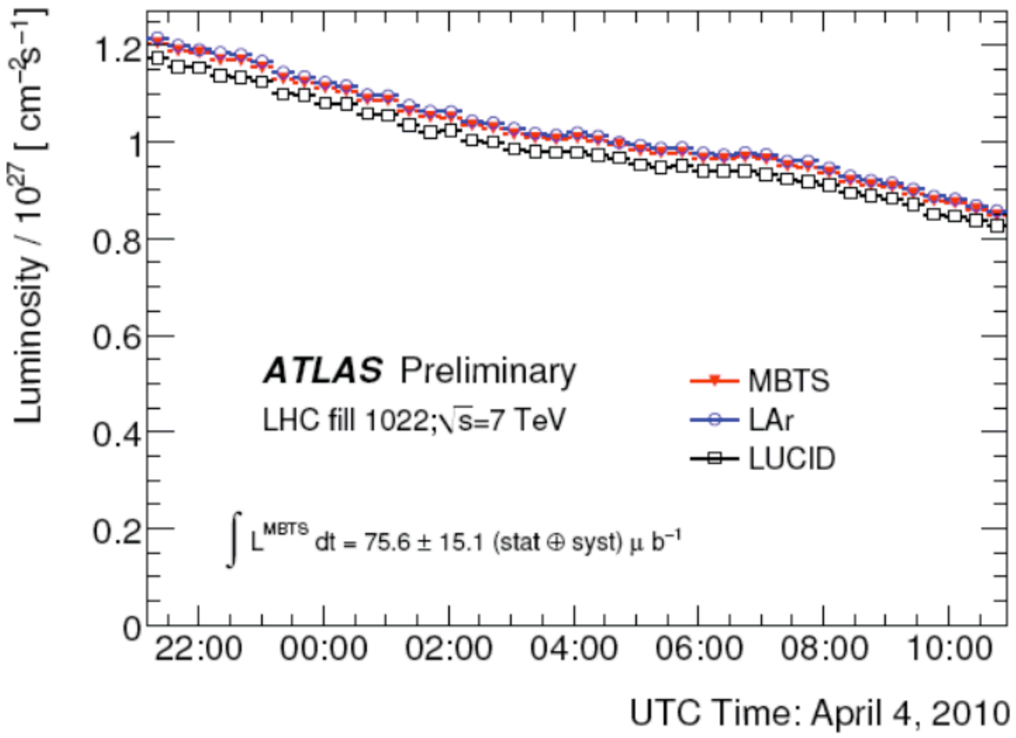


Inner detector performance crucial to separating collisions

Identify vertices with ≥3 tracks having p_T>150 MeV/

Instantaneous luminosity

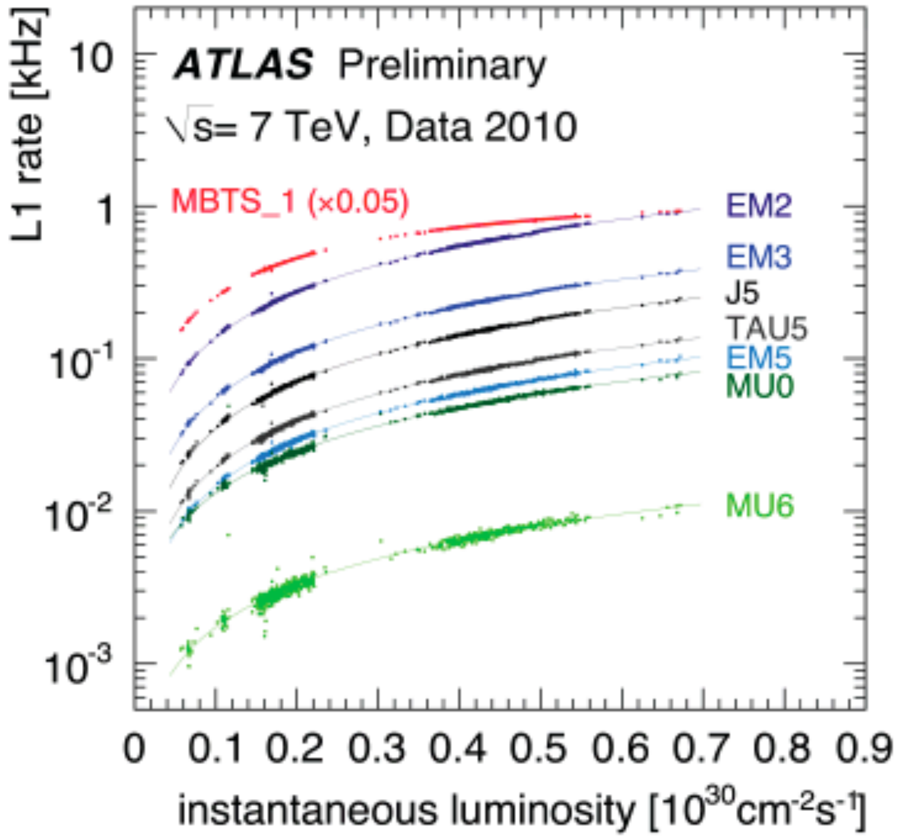
- All luminosity measurements track each other well
- At 7 TeV, MC calibrated luminosities from three systems agree within 3%
- See ATLAS-CONF-2010-060



ATLAS trigger/DAQ

ATLAS operates a 3-level trigger: L1 (hardware), L2 (software), Event Filter (farm)
Software-based levels (L2 & EF) form the High-Level Trigger (HLT)

Linear rise in rates, as expected
Min bias trigger (MBTS) saturates



For $L>10^{27}$ cm^{-2} s^{-1}:
MBTS prescaled (accept predefined fraction of suitable events)
For $L>10^{29}$ cm^{-2} s^{-1}:
HLT activated for e/γ/τ/μ triggers,
Jet triggers prescaled to cope with rate

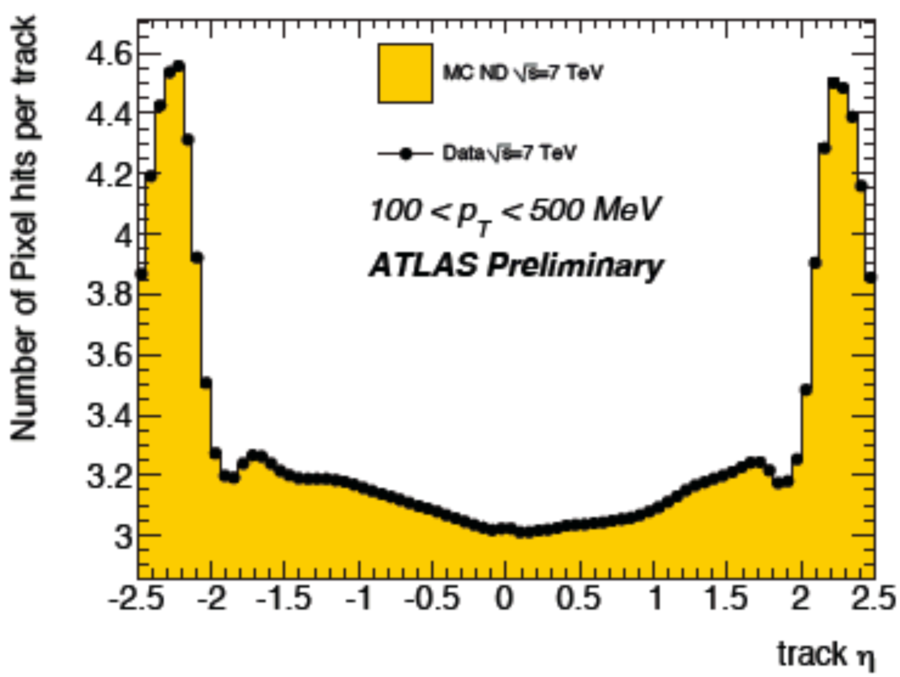
Will need further prescales for low-ET, no prescale for 20 GeV e/γ/μ triggers

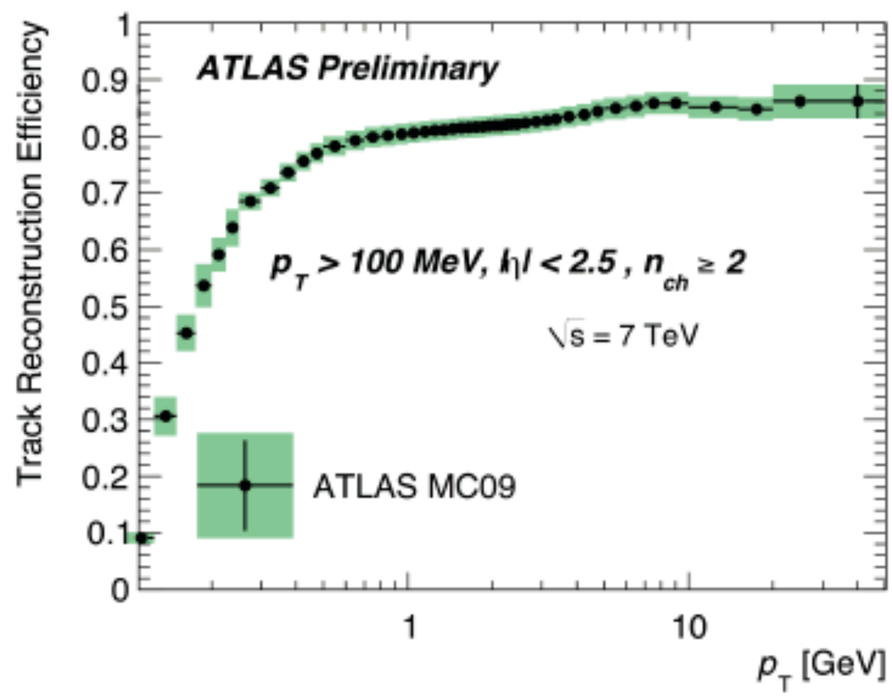
Trigger output rate to tape after EF typically 300 Hz; now reduced to 200 Hz (design)
Average ATLAS event size written to tape: 1.5 MB

Low p_T tracking

Pixel-seeded Kalman filter with extended p_T threshold 100 MeV
Momentum scale checked with light hadronic resonances (K_S^0, Ξ, J/ψ)
Identified electron tracks can be refit for curvature change due to bremsstrahlung
Requires precise knowledge of material location in inner detector

Tracking efficiency measured in simulation; working on data-driven methods

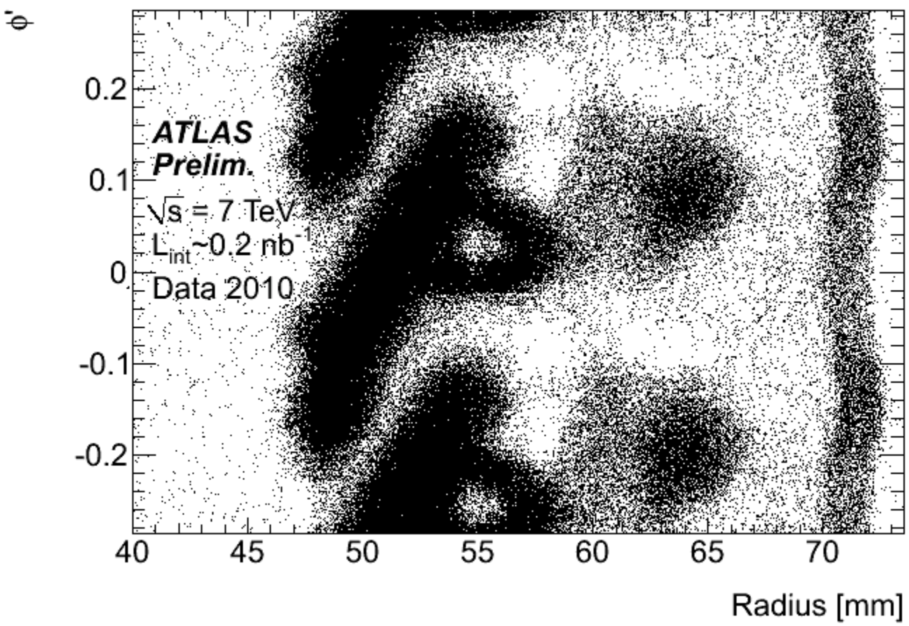




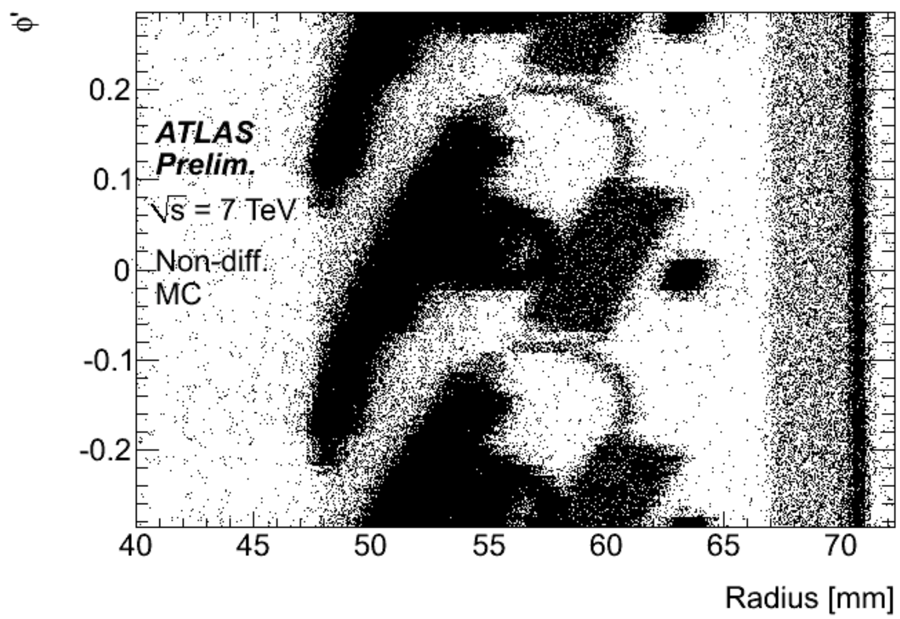
Mapping the material

Phi within a module vs radius for the first pixel layer, after K_s^0, gamma and Lambda vetoes, and |Z|<300 mm cut

Data



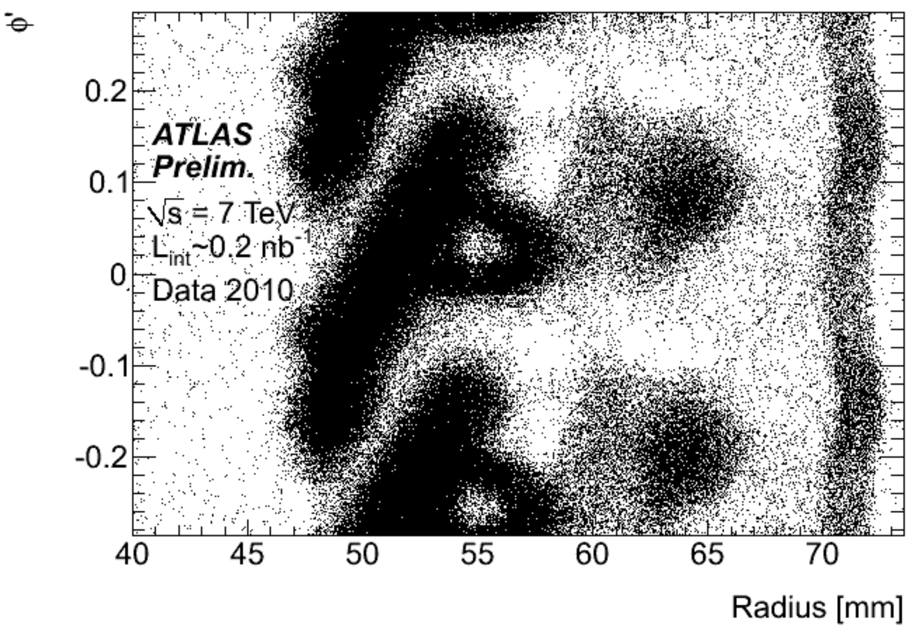
MC



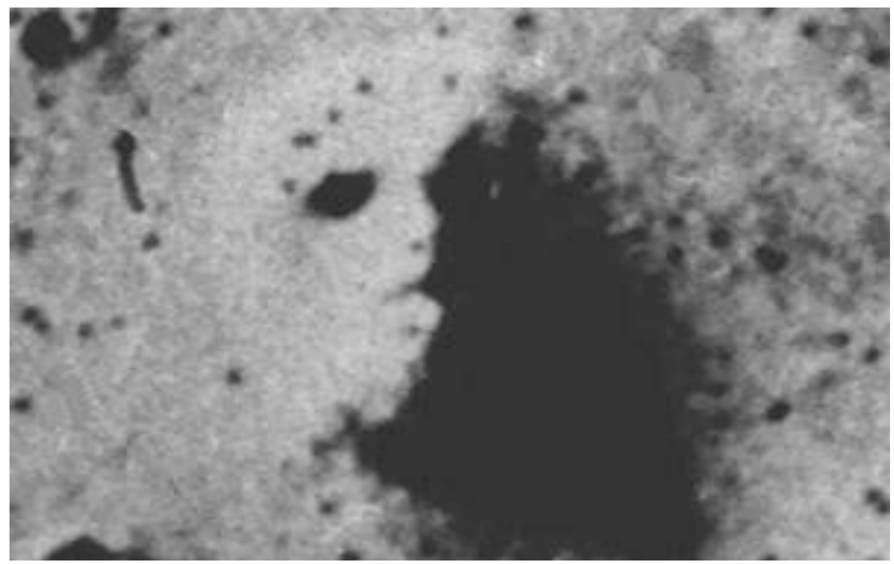
Not to be confused with…

Phi within a module vs radius for the first pixel layer, after K_s^0, gamma and Lambda vetoes, and |Z|<300 mm cut

Data



Face on Mars



…no coverup here!

Underlying event at the LHC

- Range of predictions for level of UE before turn-on; very dependent on small x physics/multi-parton interactions

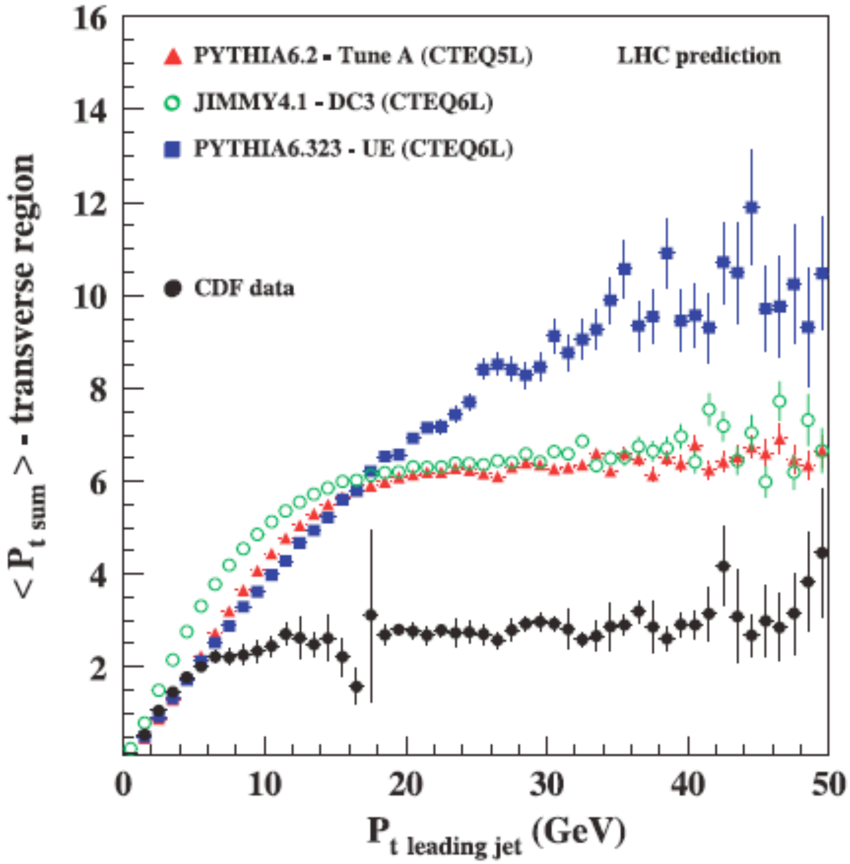
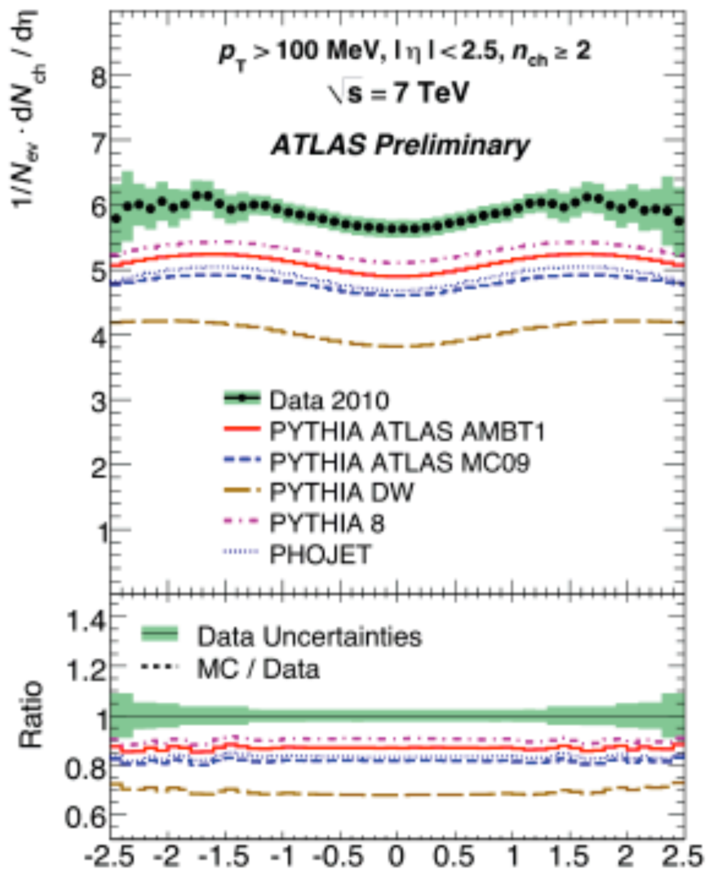


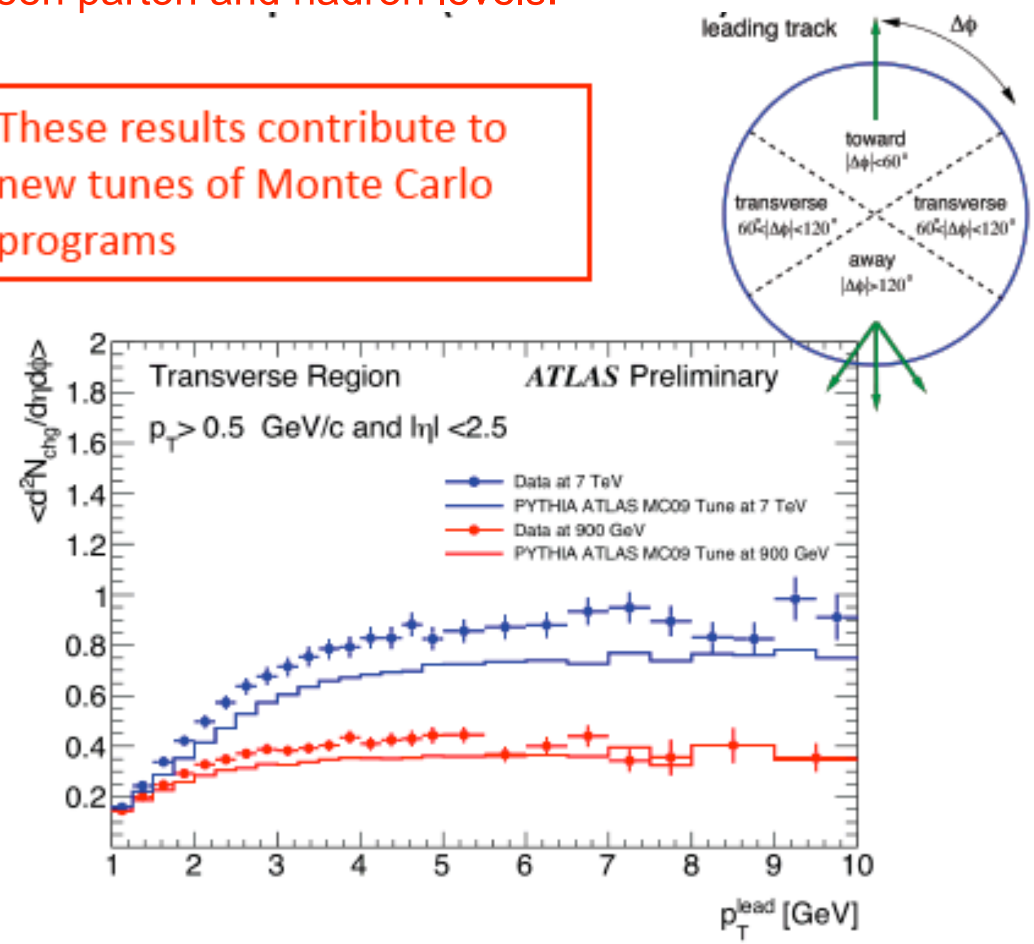
Figure 84. PYTHIA6.2 - Tune A, Jimmy4.1 - UE and PYTHIA6.323 - UE predictions for the average sum of the transverse momenta of charged particles in the transverse region in the underlying event for LHC *pp* collisions.

Underlying event measurements

- The UE affects almost every measurement at the LHC.
- Has to be determined by measurements within the kinematic acceptance of ATLAS and UE tunes for Monte Carlos adjusted to provide (as much as possible) a universal description of the UE at 7 TeV (as done at the Tevatron).
- Tunes used to provide an interface between parton and hadron levels.

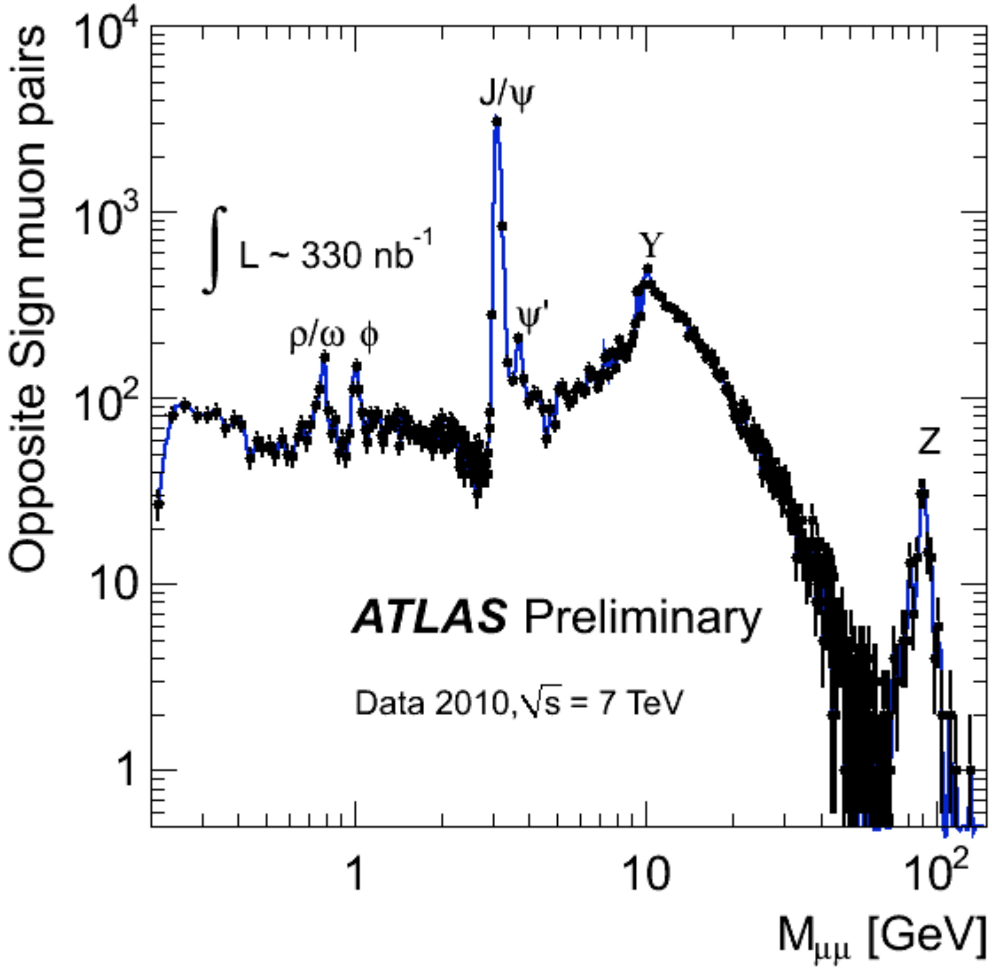


These results contribute to new tunes of Monte Carlo programs



Leptons: dimuon mass spectrum

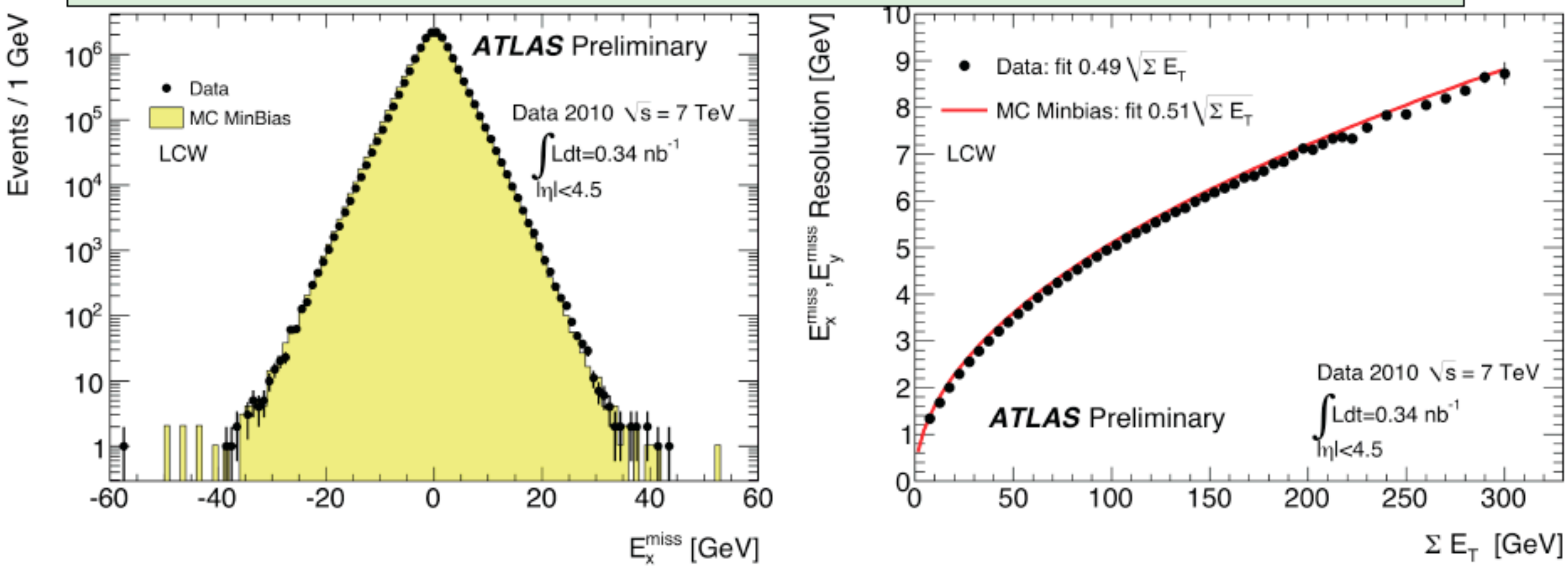
- Opposite sign muons reconstructed in both inner detector and muon spectrometer, using 6 GeV/c muon trigger
- Dimuon mass spectrum mapped across 3 orders of magnitude from ~100 MeV to ~200 GeV



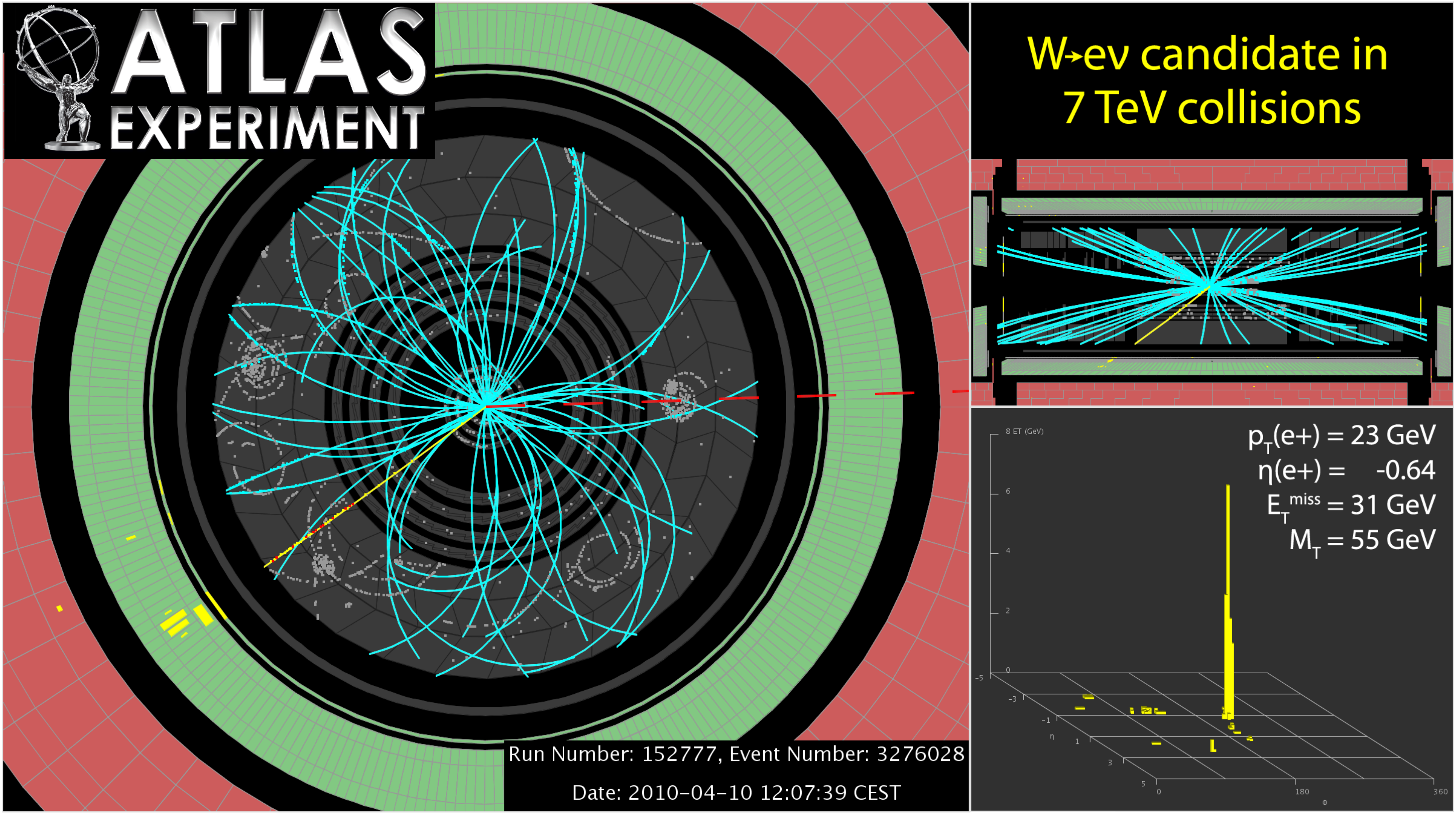
Missing E_T resolution

- Best resolution needed to detect presence of neutrinos/non-interacting particles from new physics
- Using topological clusters of calorimeter cells, with calibration determined for each component based on estimate of hadronic component

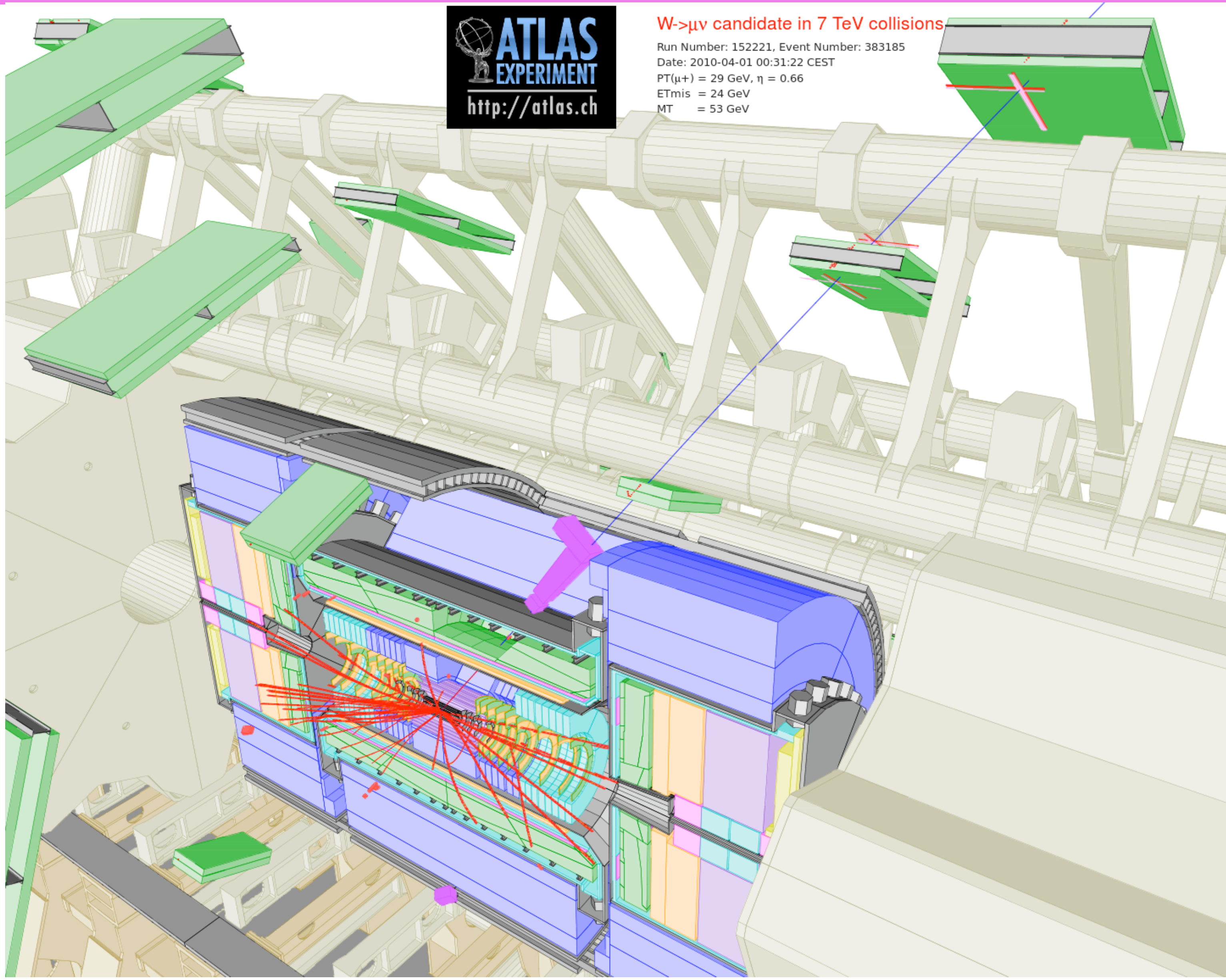
Resolutions measured on 15 million selected minimum bias events at 7 TeV



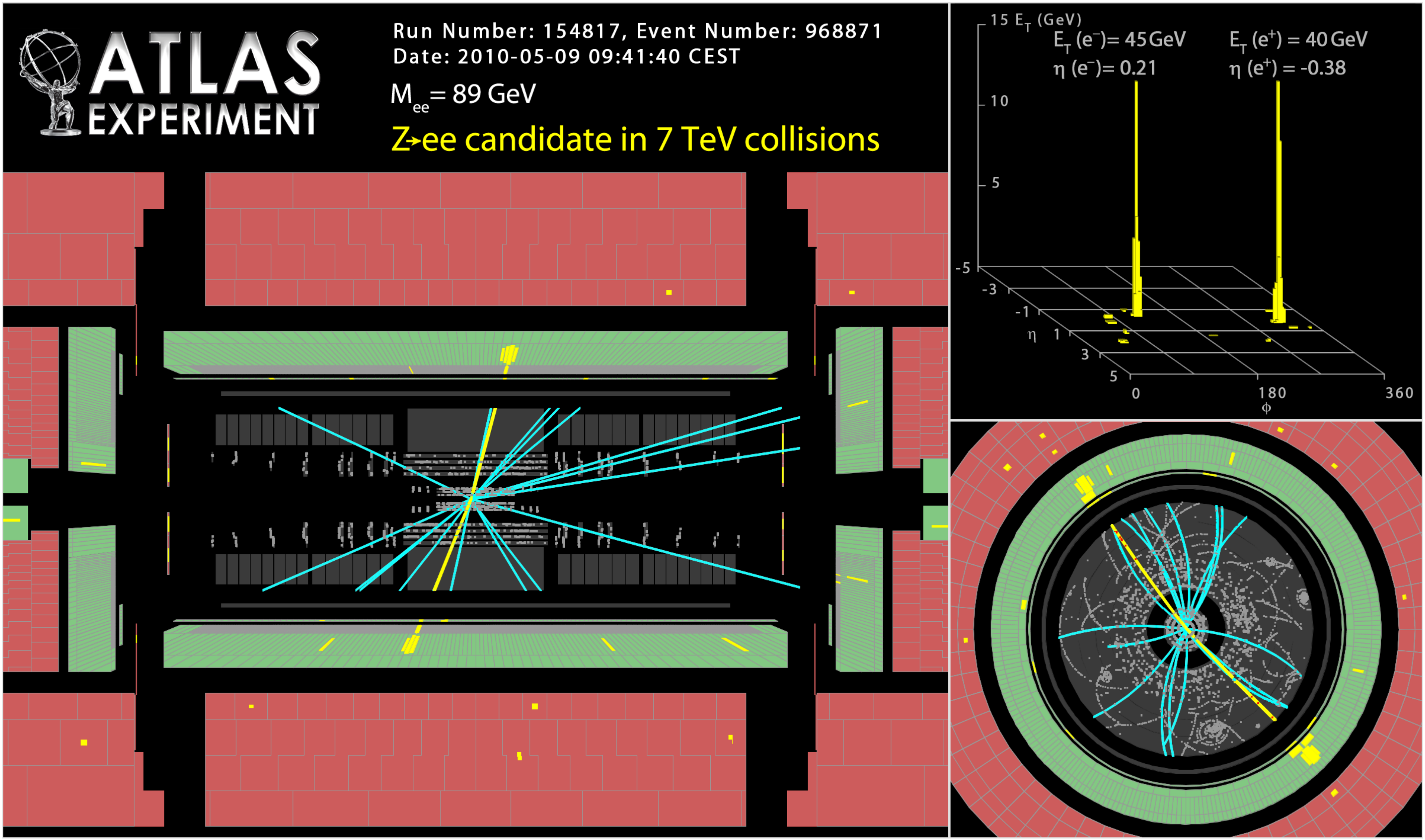
Leptons + missing E_T: W/Z production



Leptons + missing E_T: W/Z production



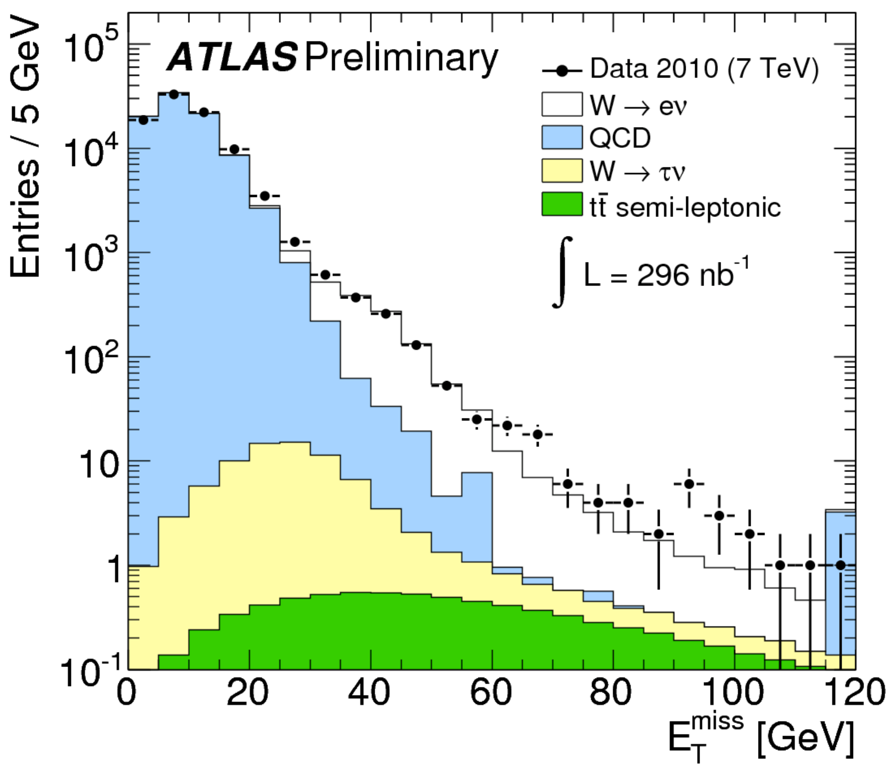
Z->e$^+$e$^-$



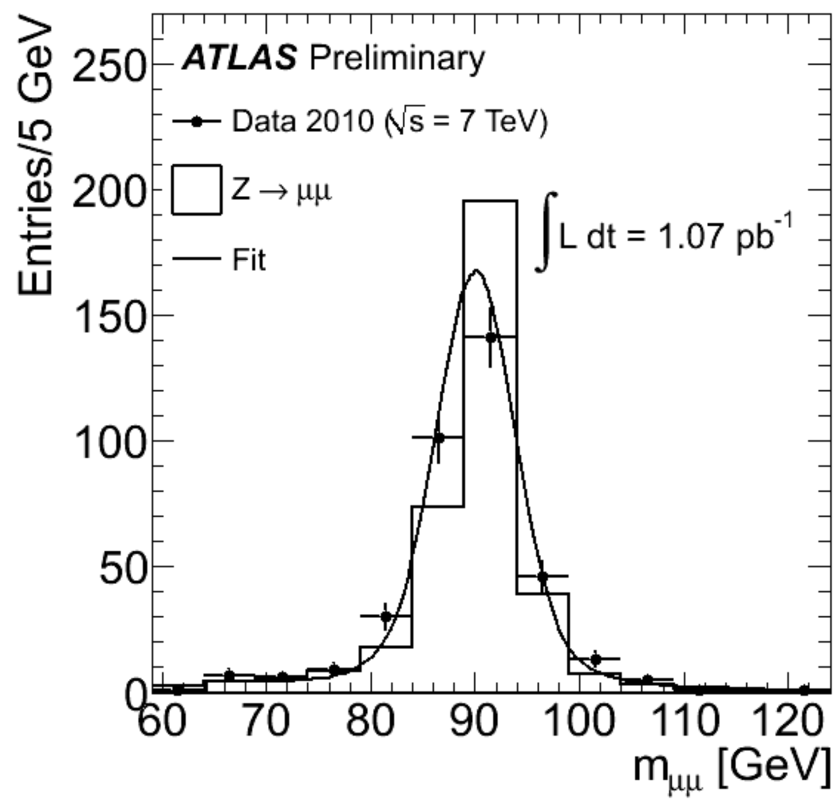
ATLAS EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
M$_{ee}$ = 89 GeV
Z→ee candidate in 7 TeV collisions
E$_T$ (e$^-$)= 45GeV
η (e$^-$)= 0.21
E$_T$ (e$^+$) = 40GeV
η (e$^+$) = -0.38
15 E$_T$ (GeV)
10
5
-5
-3
-1
η
1
3
5
0
180
360
φ

W and Z rediscovery: these are the primary benchmark cross sections

- W
  - e(μ) E_T>20 GeV; |η|<2.5 (2.4)
  - missing E_T > 25 GeV
  - transverse mass > 40 GeV



- Z
  - e(μ) E_T>20 GeV; |η|<2.5 (2.4)
  - 66 < m_{ll} < 116 GeV



W/Z p_T distributions

- BFKL effects may broaden the p_T distributions for W and Z production (at least in some kinematics regions)
- But, expect broader p_T distributions at LHC than at Tevatron from DGLAP alone (lower x partons, more phase space for gluon emission)

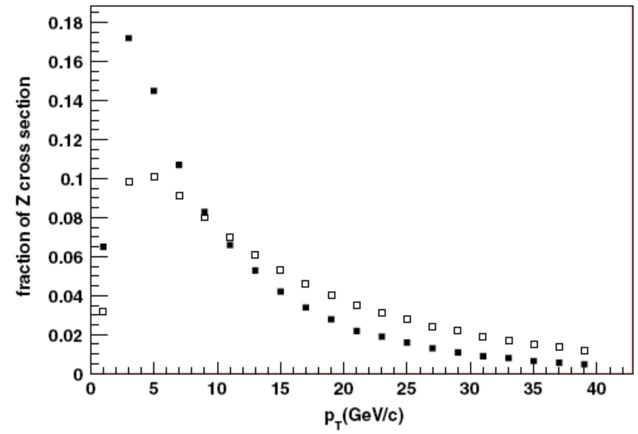
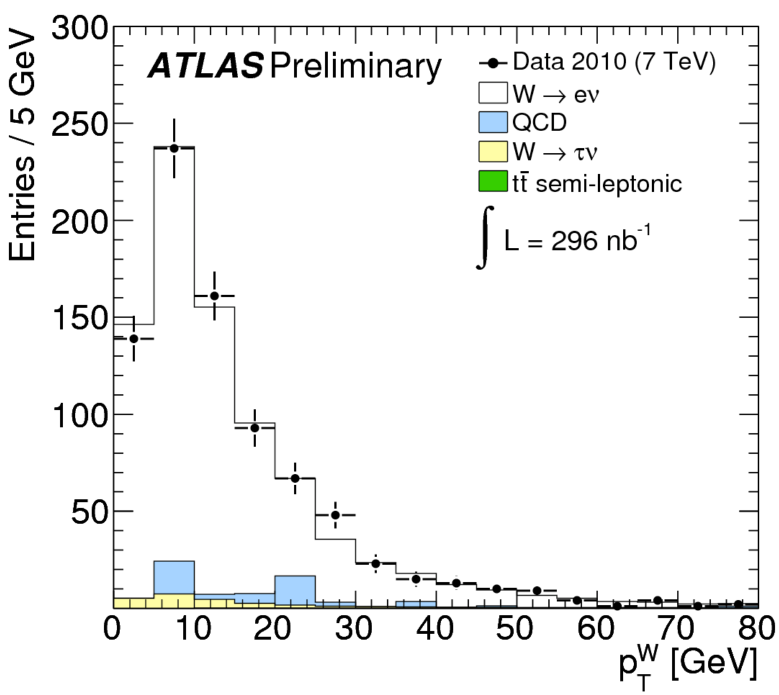
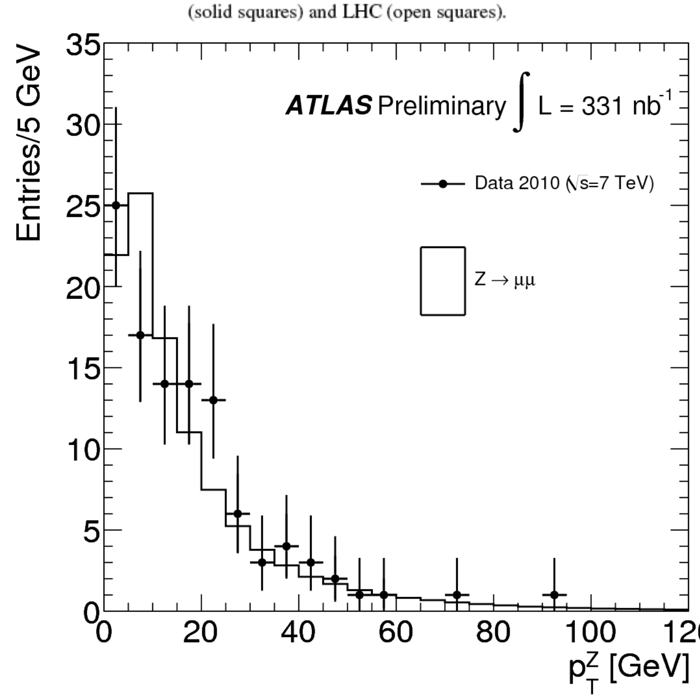


Figure 89. Predictions for the transverse momentum distributions for Z production at the Tevatron (solid squares) and LHC (open squares).



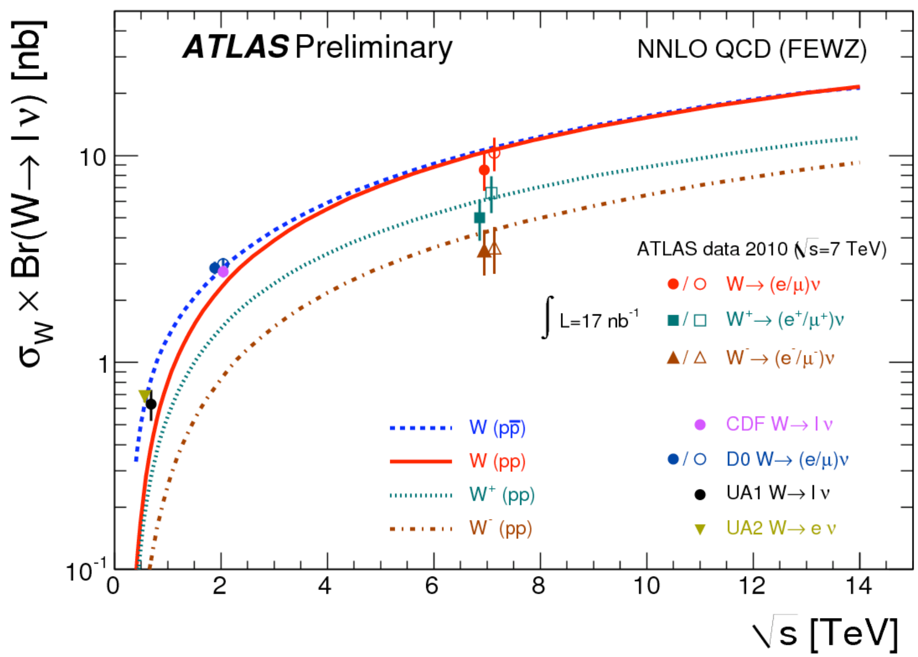


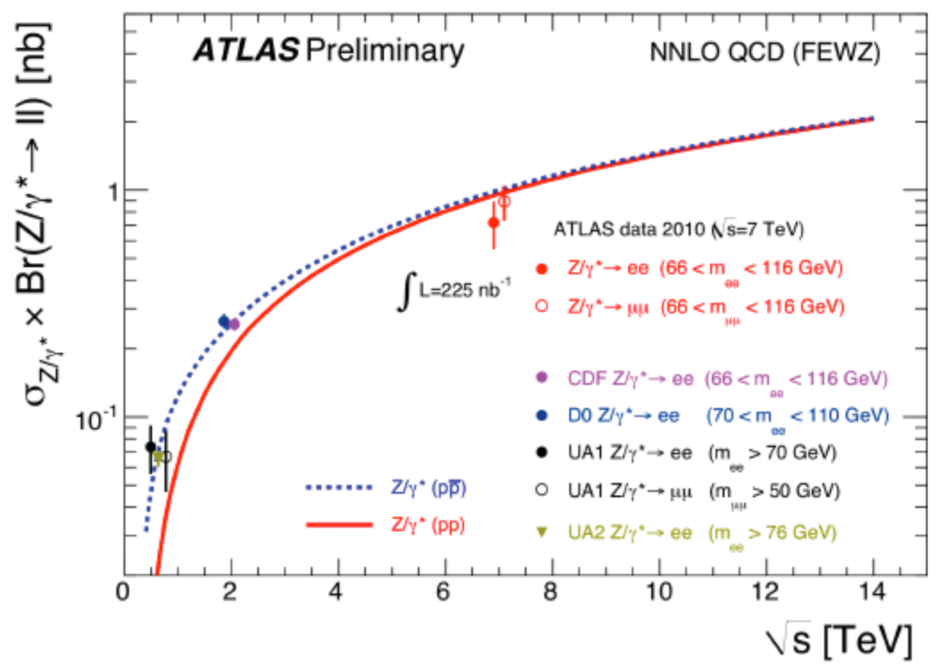
W/Z cross sections

- In reasonable agreement with NNLO predictions for 7 TeV, but still statistics and systematics limited
  - plus the current 11% luminosity uncertainty
- Both will improve with more data: W and Z will be one of SM benchmark cross sections (see ATLAS-CONF-051)

$$\sigma\left(W^+ \to l^+\nu\right) = 5.7 \pm 0.7(stat) \pm 0.4(syst) \pm 0.6(lumi)nb$$

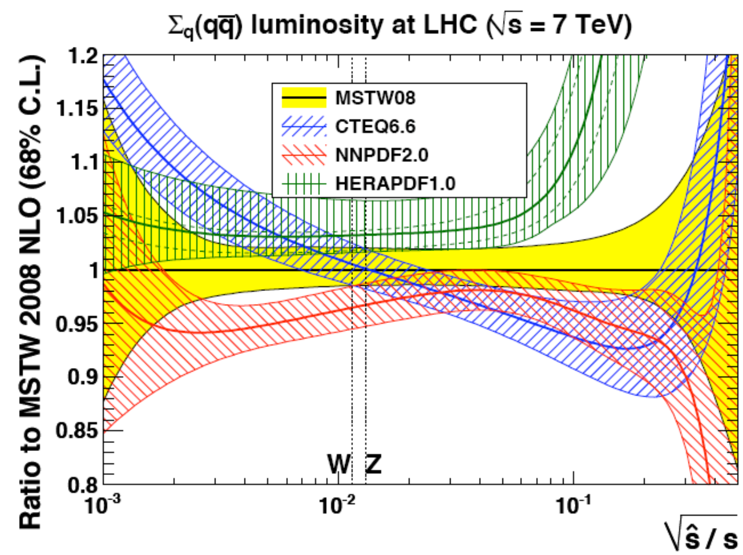
$$\sigma\left(W^- \to l^-\nu\right) = 3.5 \pm 0.5(stat) \pm 0.2(syst) \pm 0.4(lumi)nb \quad \sigma\left(Z \to l^+l^-\right) = 0.83 \pm 0.07(stat) \pm 0.06(syst) \pm 0.10(lumi)nb$$

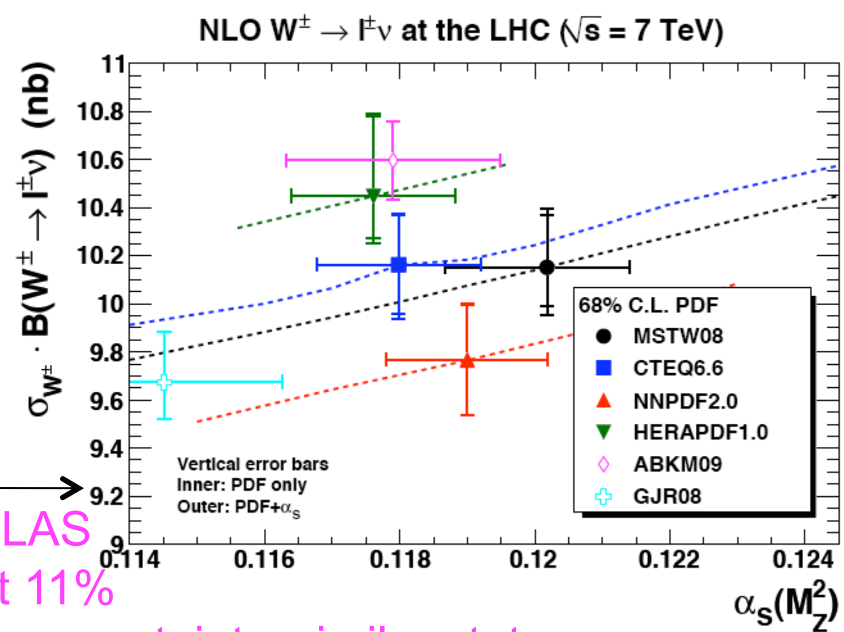




Aside: PDF4LHC benchmarking

- See https://wiki.terascale.de/index.php?title=PDF4LHC_WIKI
- Look at PDF luminosities from different groups and predictions/ratios for cross sections (from G. Watt)
- CTEQ/MSTW predictions for W cross section/uncertainty in very good agreement
  - small impact from different α_s value
  - similar uncertainty bands
- NNPDF prediction low because of use of ZM-VFNS
- HERAPDF1.0 a bit high because of use of combined HERA dataset

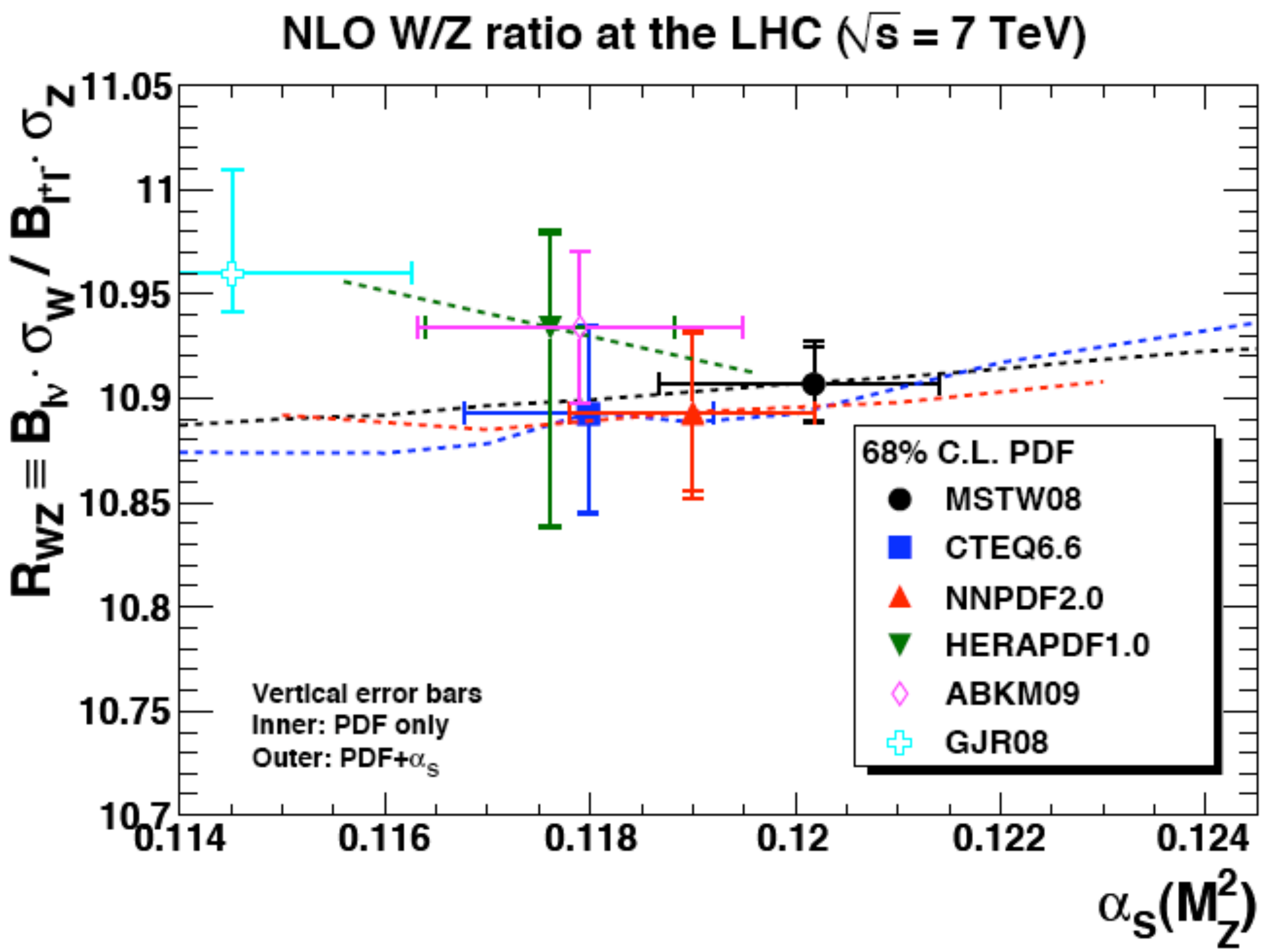




ATLAS but 11% lum uncertainty, similar stat errors

W/Z ratio

- Good agreement among the PDF groups
- Be a good test for ATLAS with higher statistics



The LHC ~~will be~~ is a very *jetty* place

- Total cross sections for tT and Higgs production saturated by tT (Higgs) + jet production for jet p_T values of order 10-20 GeV/c
- $\sigma_{W+3\ jets} > \sigma_{W+2\ jets}$

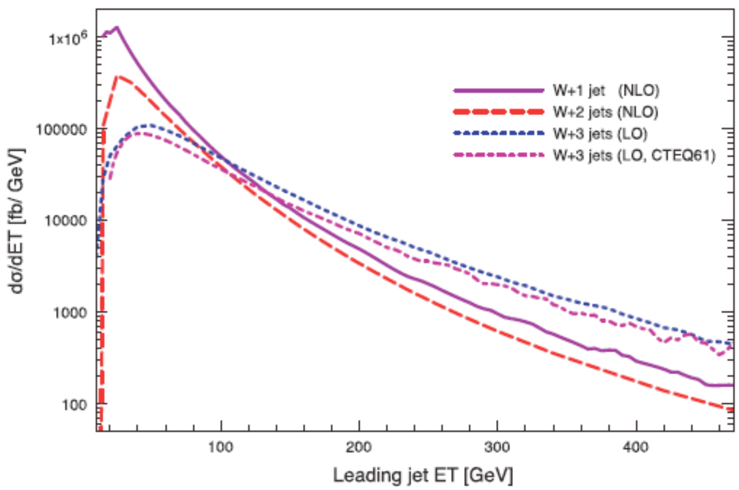


Figure 91. Predictions for the production of $W+\geqslant 1, 2, 3$ jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

- indication that can expect interesting events at LHC to contain many jets(especially from gg initial states)

14 TeV

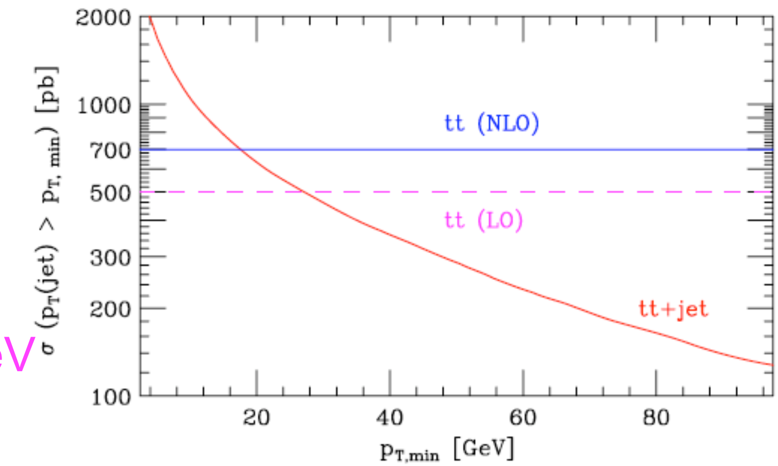


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

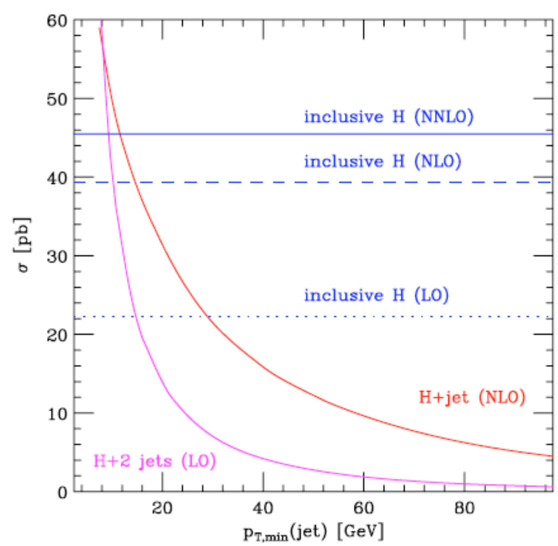
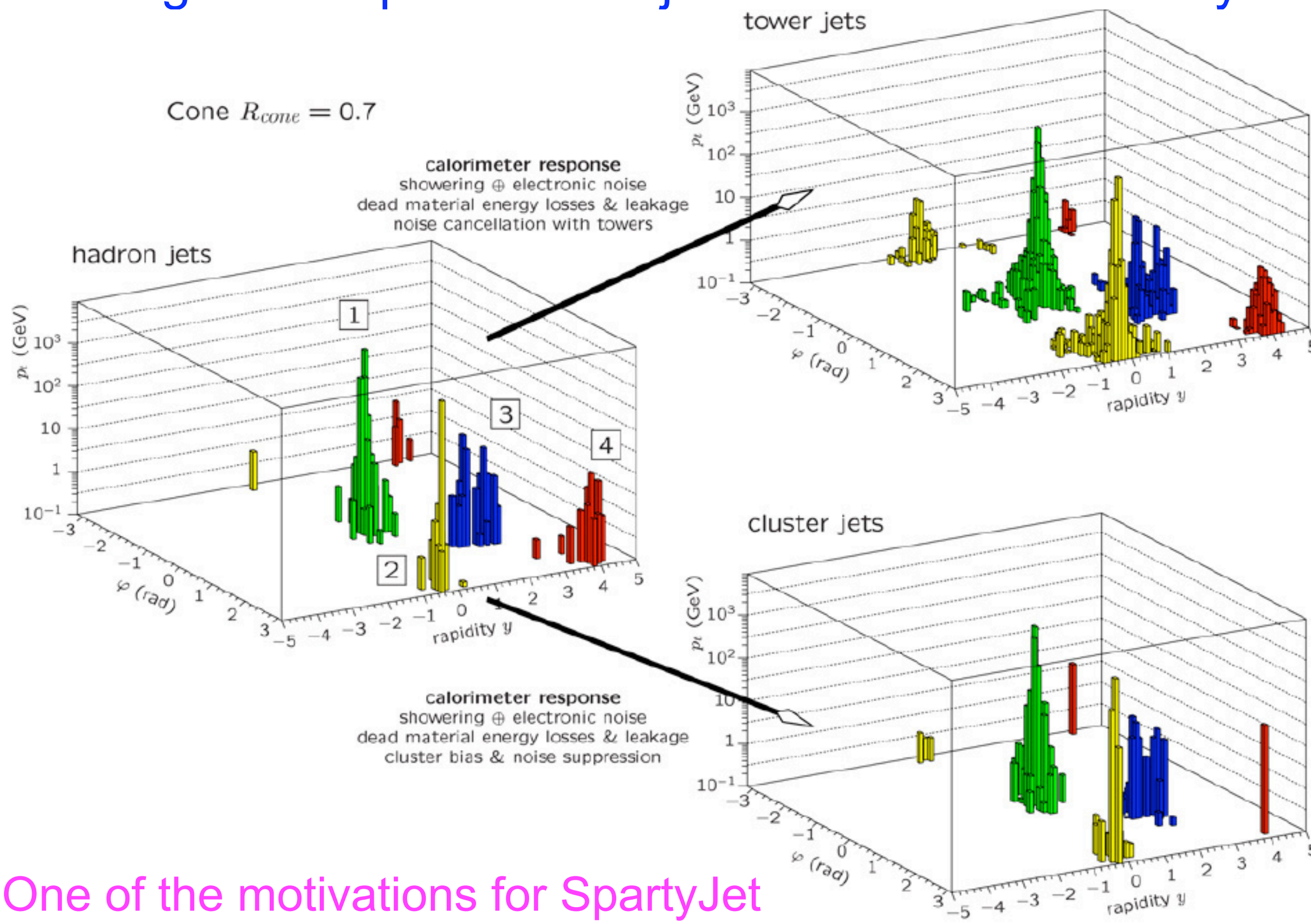


Figure 100. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

ATLAS jet reconstruction

- Using locally calibrated topoclusters, ATLAS has a chance to use jets in a dynamic manner not possible in any previous hadron-hadron calorimeter, i.e. to examine the impact of multiple jet algorithms/parameters/jet substructure on every event



blobs of energy in the calorimeter correspond to 1/few particles (photons, electrons, hadrons); can be corrected back to hadron level

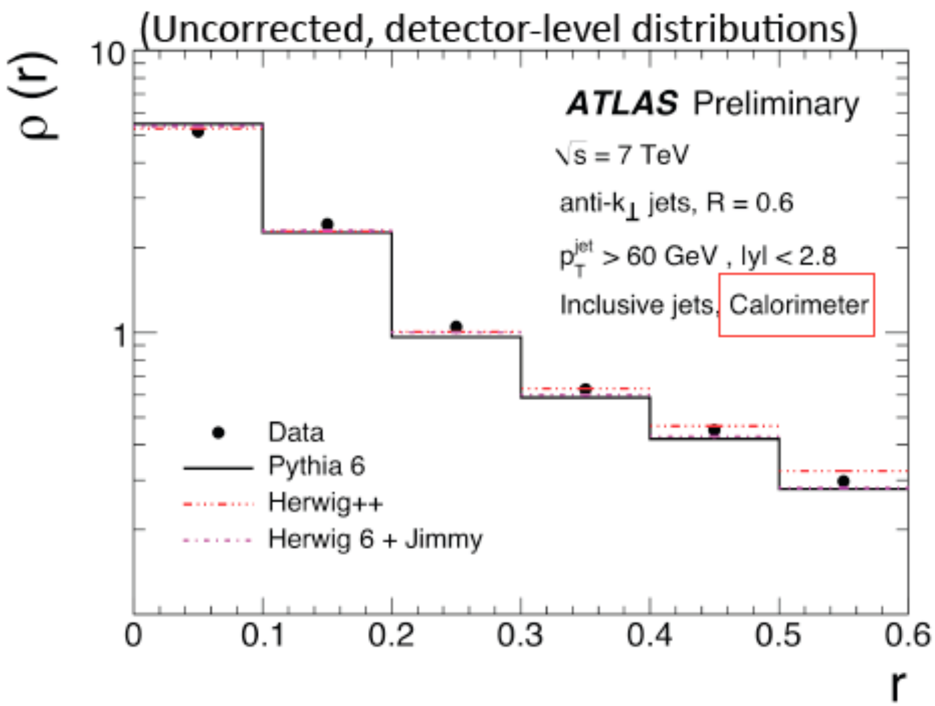
rather than jet itself being corrected

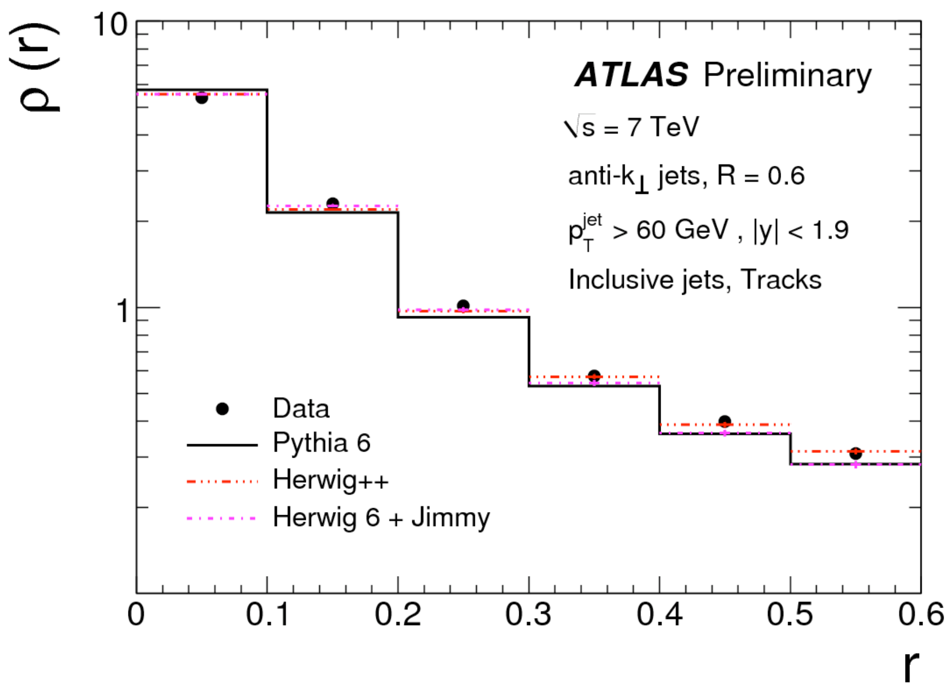
similar to running at hadron level in Monte Carlos

One of the motivations for SpartyJet

QCD engineering: jet shapes

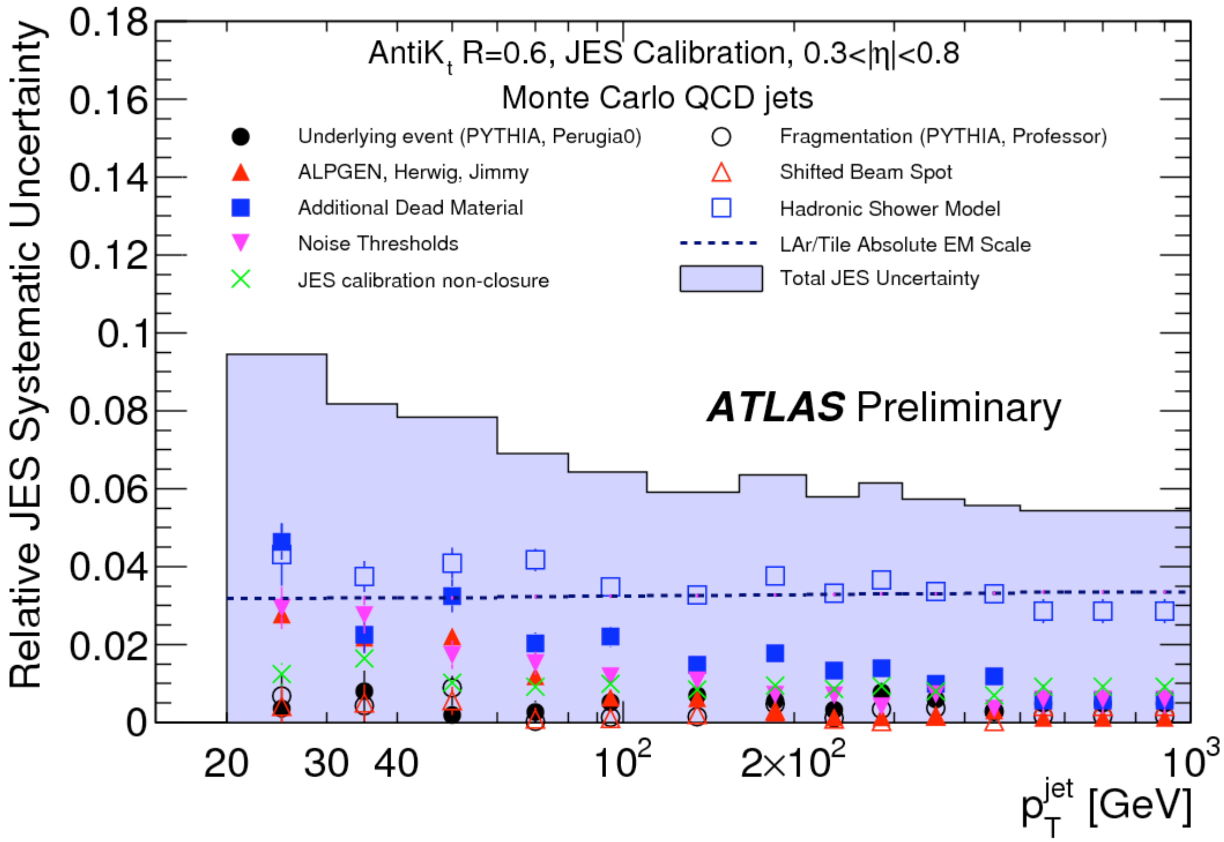
- Validates energy scale corrections and parton shower modelling
- Key input to future jet cross section corrections
- Jet shape (at least at low p_T) depends on correct tune to underlying event, soft radiation and hadronization, in addition to good description of perturbative physics





Jet Energy Scale (JES) uncertainty

- Dominant uncertainty in jet cross section measurements
- Right now are using a very conservative estimate
- Will improve as we get more data/more understanding
- See ATLAS-CONF-2010-056

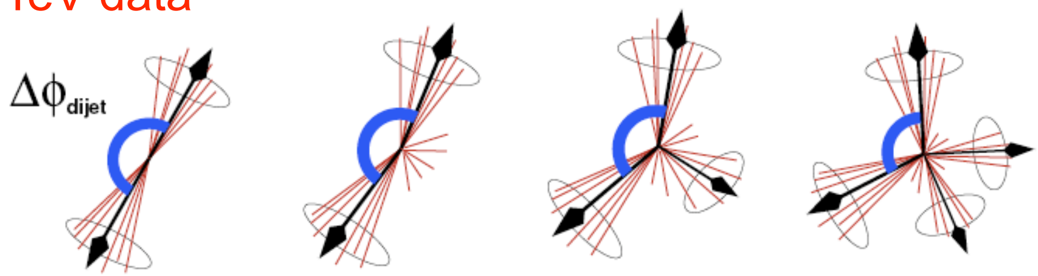


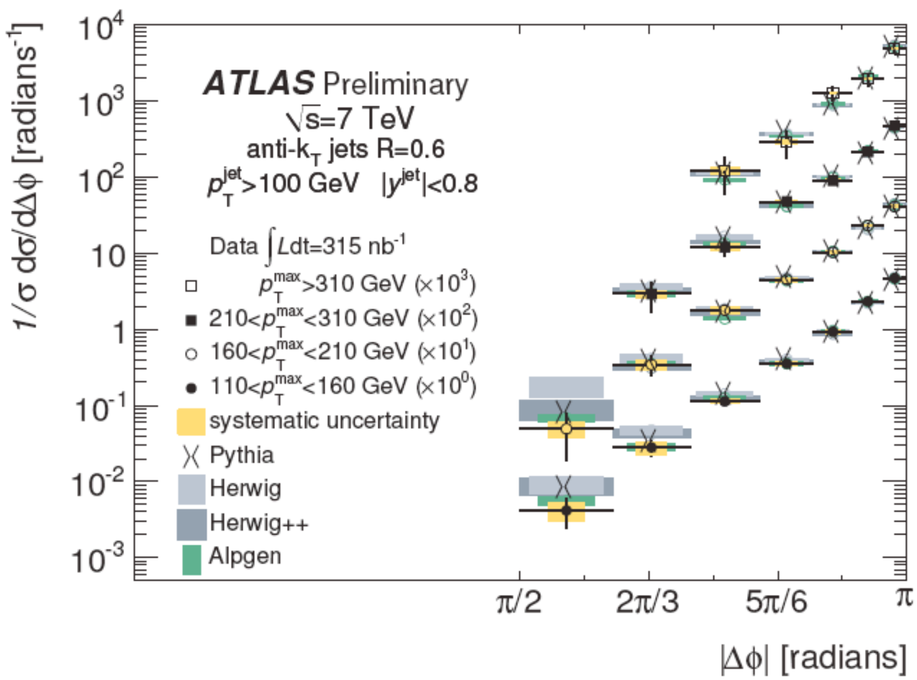
7-10% energy uncertainty in ATLAS results (6-9% for R=0.4)

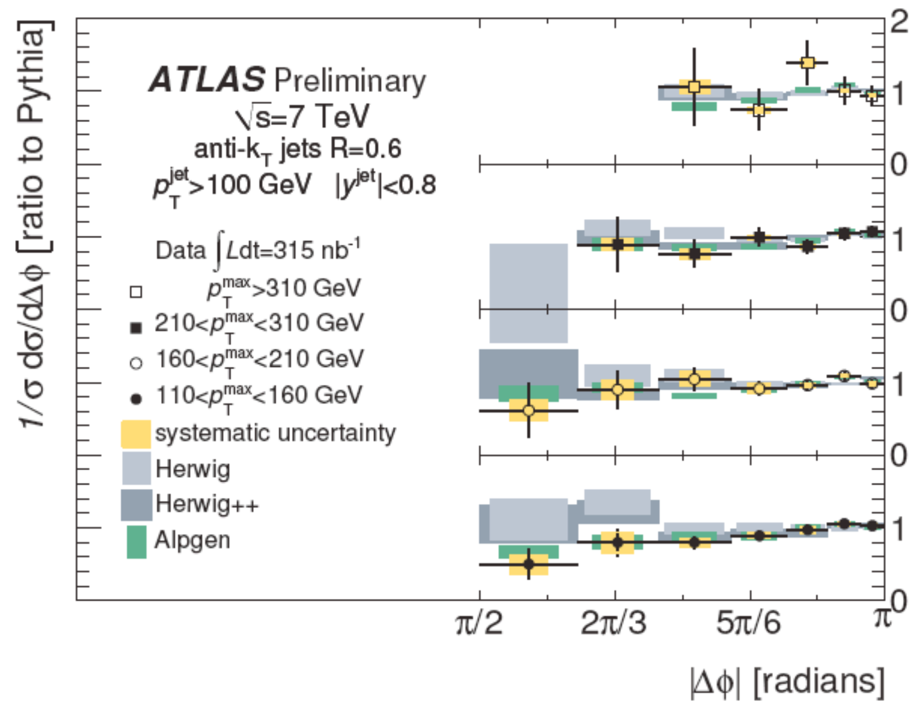
(Not corrected for pileup contributions)

Dijet decorrelation

Dijet decorrelation resulting from both hard and soft gluon radiation: tests level of agreement of matrix element + parton shower calculations with 7 TeV data

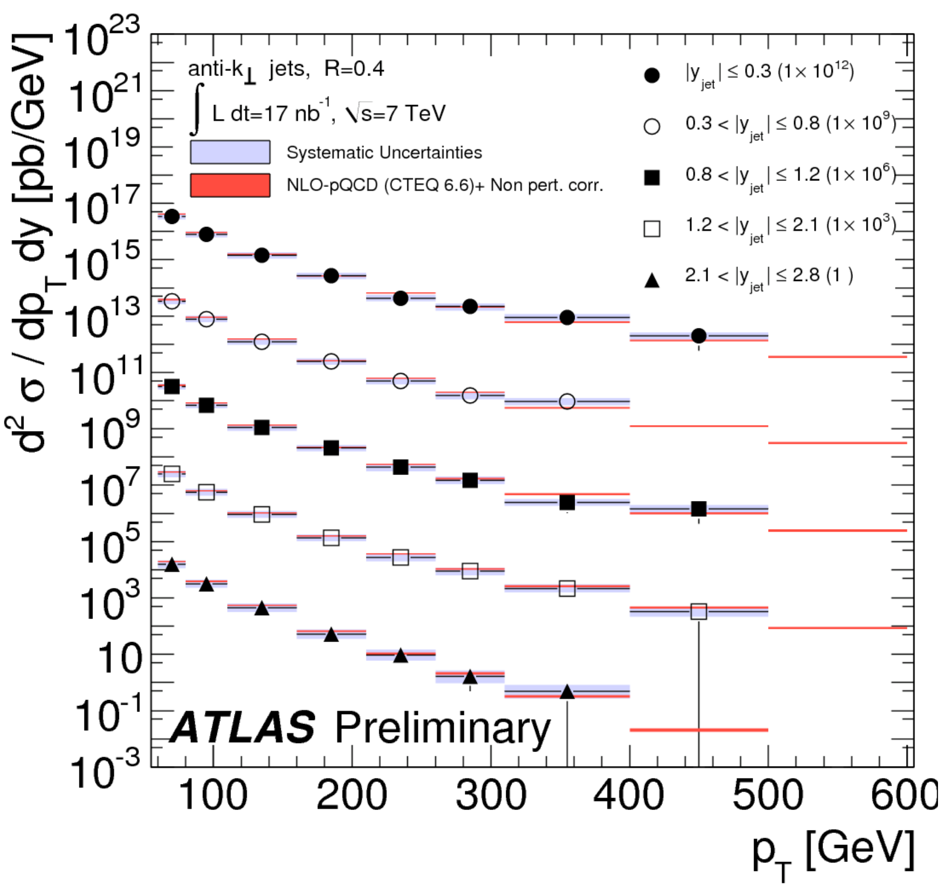


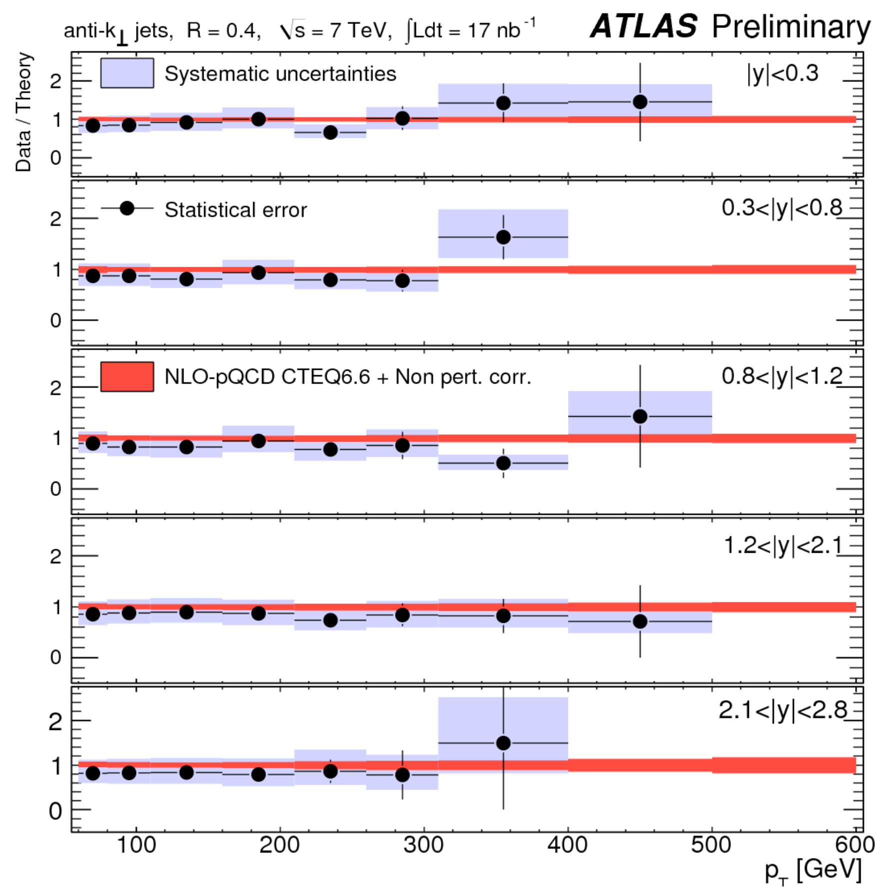




Inclusive jet production R=0.4

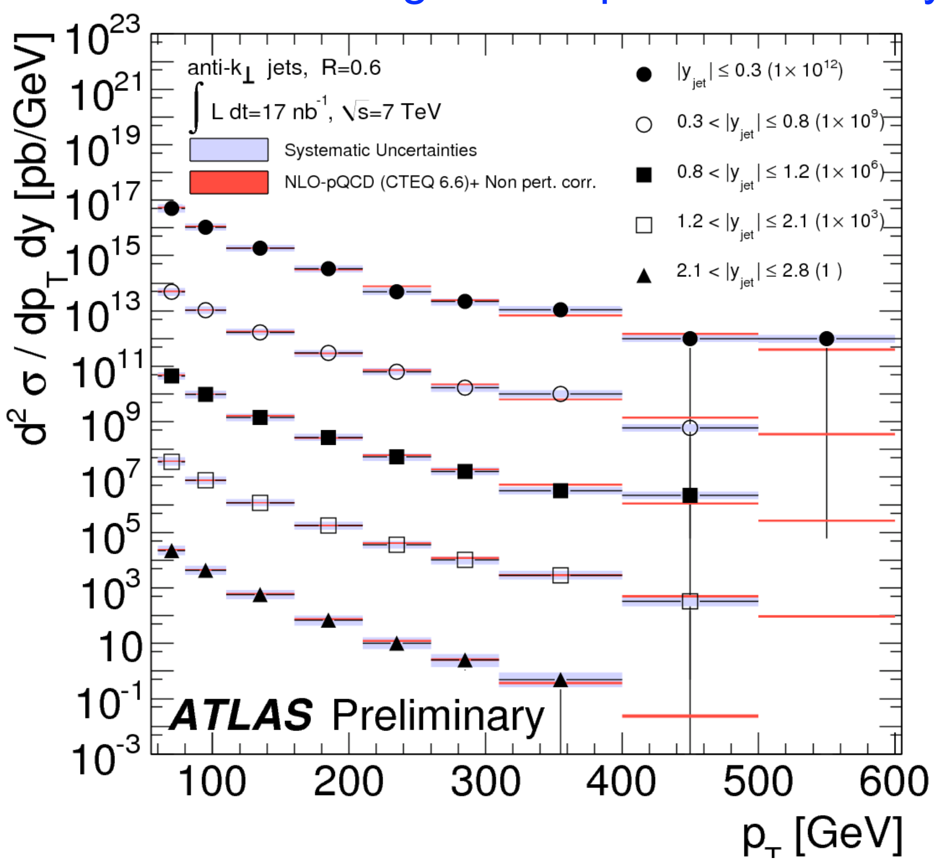
- Antikt jet algorithm used: correct jet cross sections to particle level
- Non-perturbative corrections applied to NLO predictions (NLOJET++)
- Good agreement with NLO predictions using CTEQ6.6 PDFs (see ATLAS-CONF-2010-050)
- Good practice: use the name of the program and the scale choice

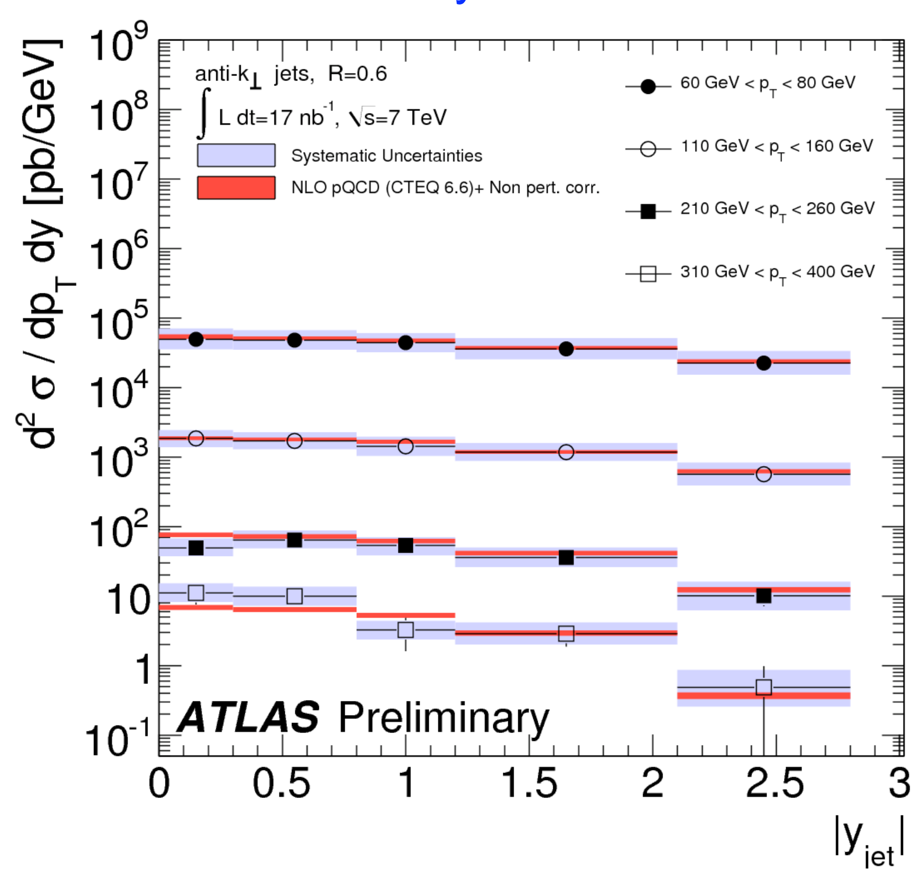




Inclusive jet production R=0.6

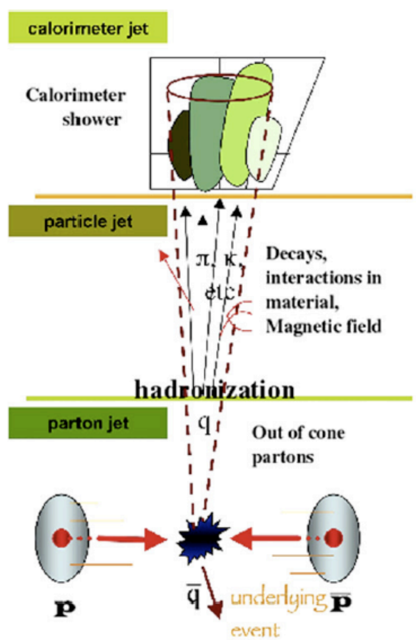
- Important to be able to measure jets with different parameters/algorithms
  - ATLAS uses primarily antikT4 and antikT6
- Not really done in the past in hadron-hadron colliders, but is a crucial part of the LHC physics program
- Different algorithms/parameters may illuminate different dynamics of events





Choosing jet size

- Experimentally
  - in complex final states, such as W + n jets, it is useful to have jet sizes smaller so as to be able to resolve the n jet structure
  - this can also reduce the impact of pileup/ underlying event

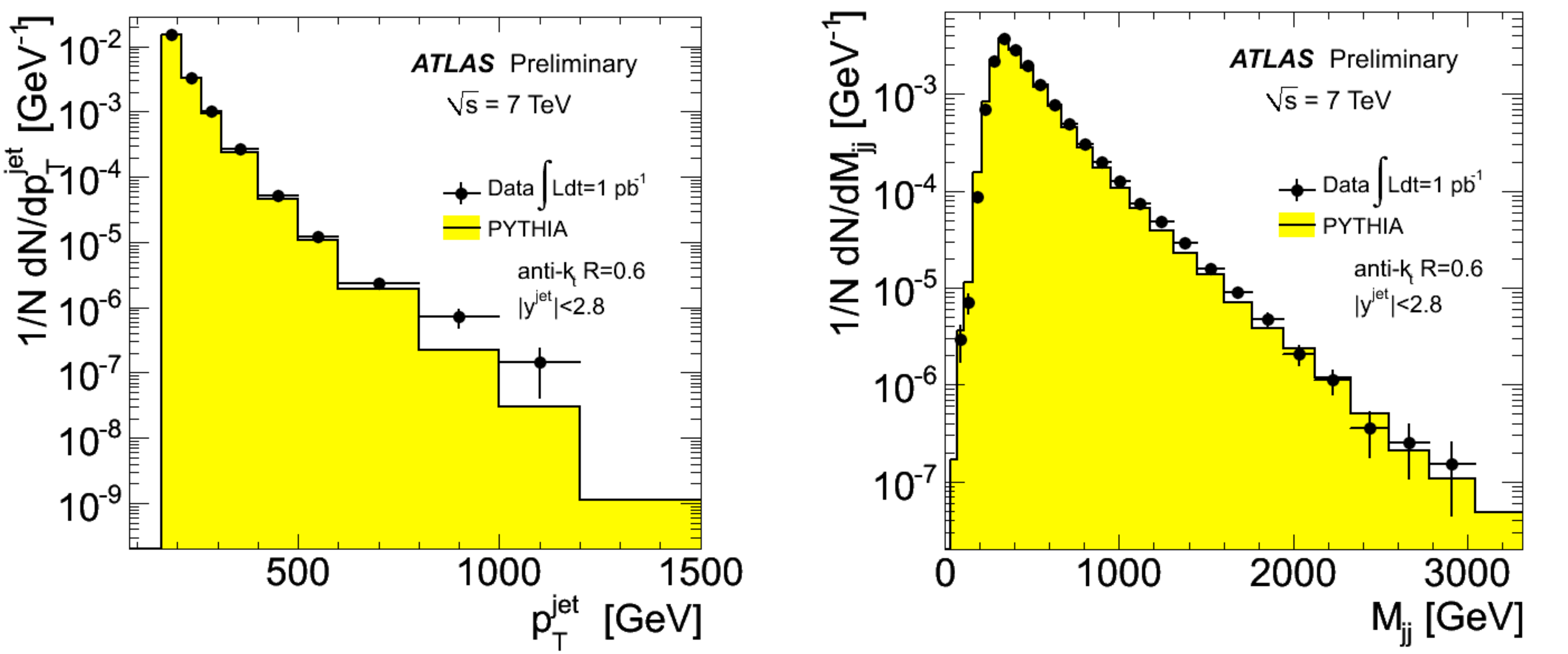


- Theoretically
  - hadronization effects become larger as R decreases
    - more gluons near edge of jet that hadronize to (some) pions outside of jet cone
  - for small R, ln R perturbative terms can become noticeable
  - this restriction in the gluon phase space can affect the scale dependence, i.e. the scale uncertainty for an n-jet final state can depend on the jet size,

Another motivation for the use of multiple jet algorithms/parameters in LHC analyses.

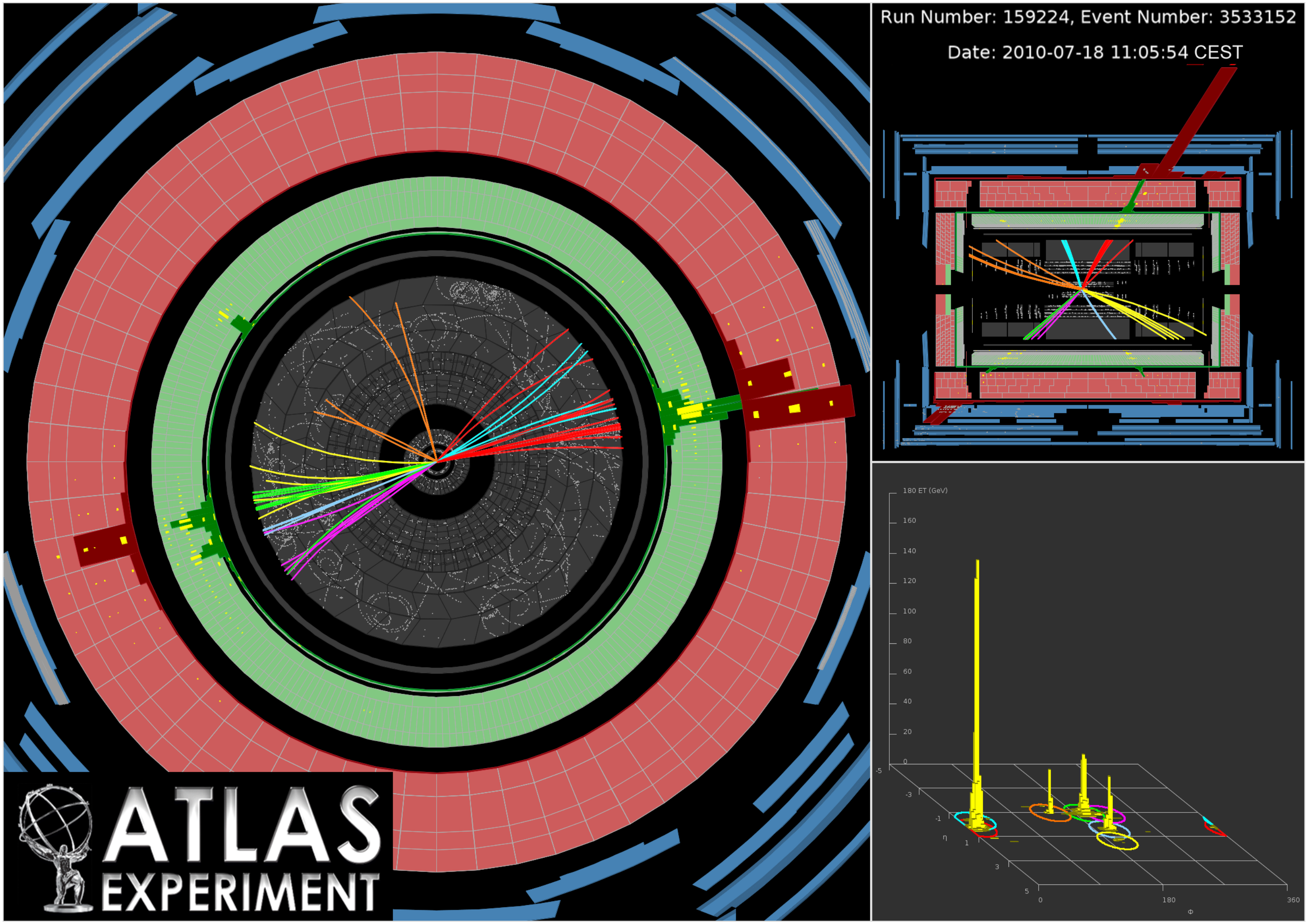
Some higher statistics results

- Now have far exceeded kinematic reach of Tevatron
- Still relatively low x values though, compared to Tevatron's high p_T region
  - not so sensitive to high x gluon for example



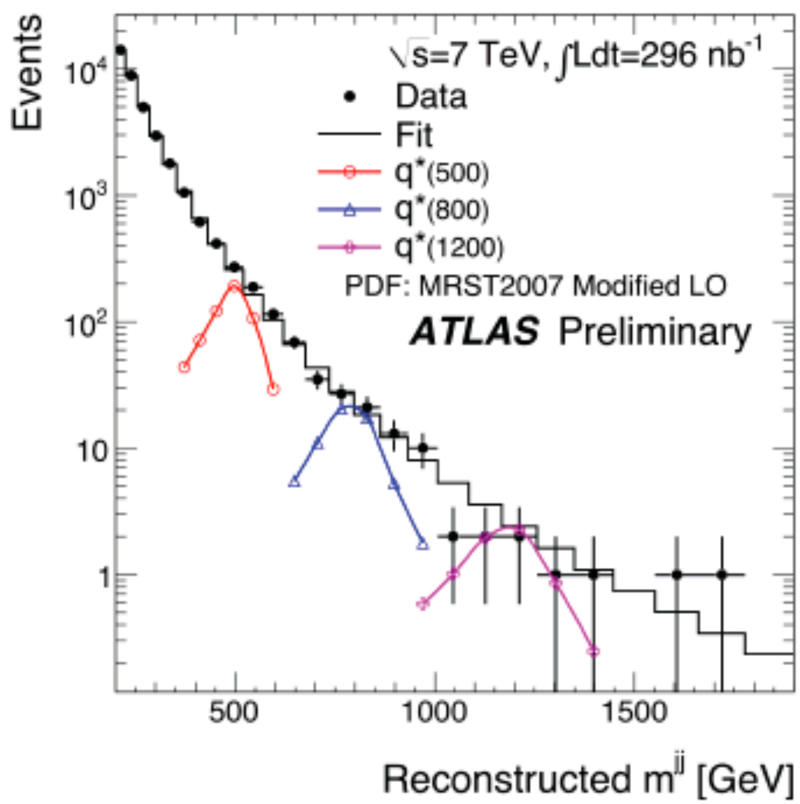
High p_T jet event

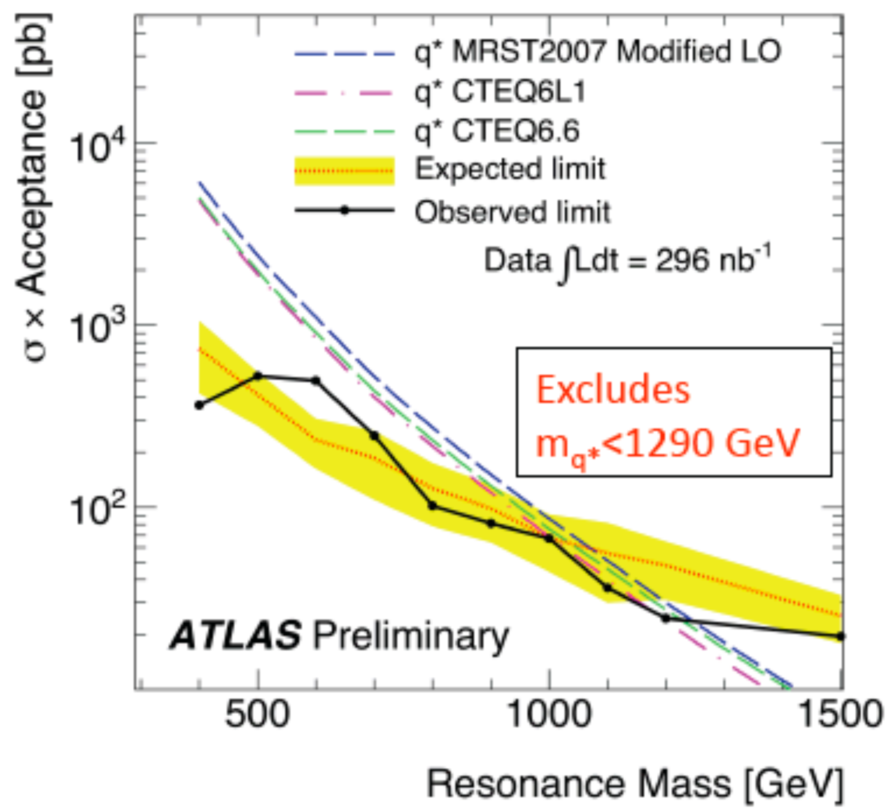
Lead jet has p_T of 1.12 TeV/c; 3 other high p_T jets in event; such multijet structure not uncommon in this high p_T (but still not high x) range



Dijets: TeV-scale resonances

- Searching for TeV-scale resonances with strong-couplings such as excited composite quarks, Randall-Sundrum gravitons, high mass gauge bosons, etc->fit to a smooth curve, look for bumps
- Assume conservative jet energy resolution uncertainty (σ/p_T~14%)
- Didn't find them (so far)   arXiv:1008.2461





Aside: jet masses

- Very useful if looking for resonance in boosted jet (*top jet*)
- Naturally produced by QCD radiation
- Depends on jet algorithm/size

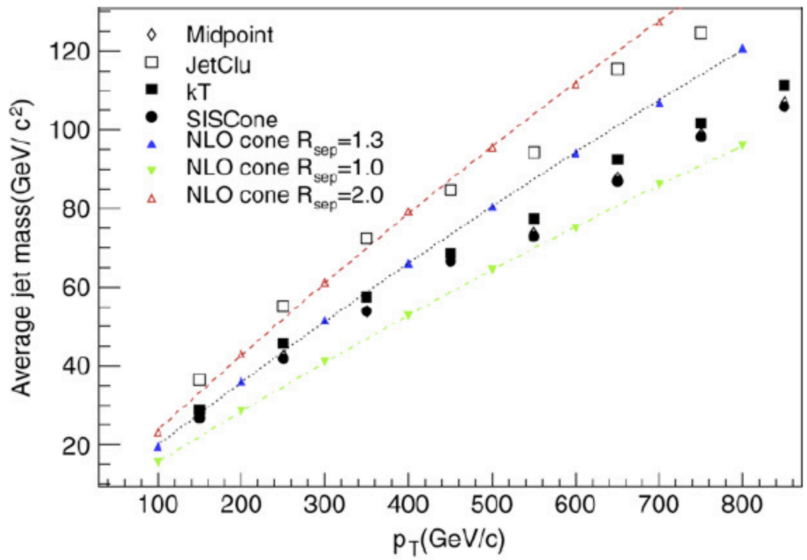


Fig. 53. The average jet mass is plotted versus the transverse momentum of the jet using several different jet algorithms with a distance scale ($D = R_{\rm cone}$) of 0.7.

In NLO pert theory

phase space from pdf's

$$\sqrt{p_{J,\mu}p_J^\mu} = \sqrt{\langle M^2 \rangle_{NLO}} = f\left(\frac{p_J}{\sqrt{s}}\right)\sqrt{\alpha_s(p_J)}\,(p_J R)$$

dimension

jet size

Rule-of-thumb

$$\sqrt{\langle M^2 \rangle_{NLO}} \sim 0.2\, p_J R$$

…from Ellis et al review paper

Distribution of jet masses

- Sudakov suppression for low jet masses
- fall-off as $1/m^2$ due to hard gluon emission
- algorithm suppression at high masses
  - jet algorithms tend to split high mass jets in two

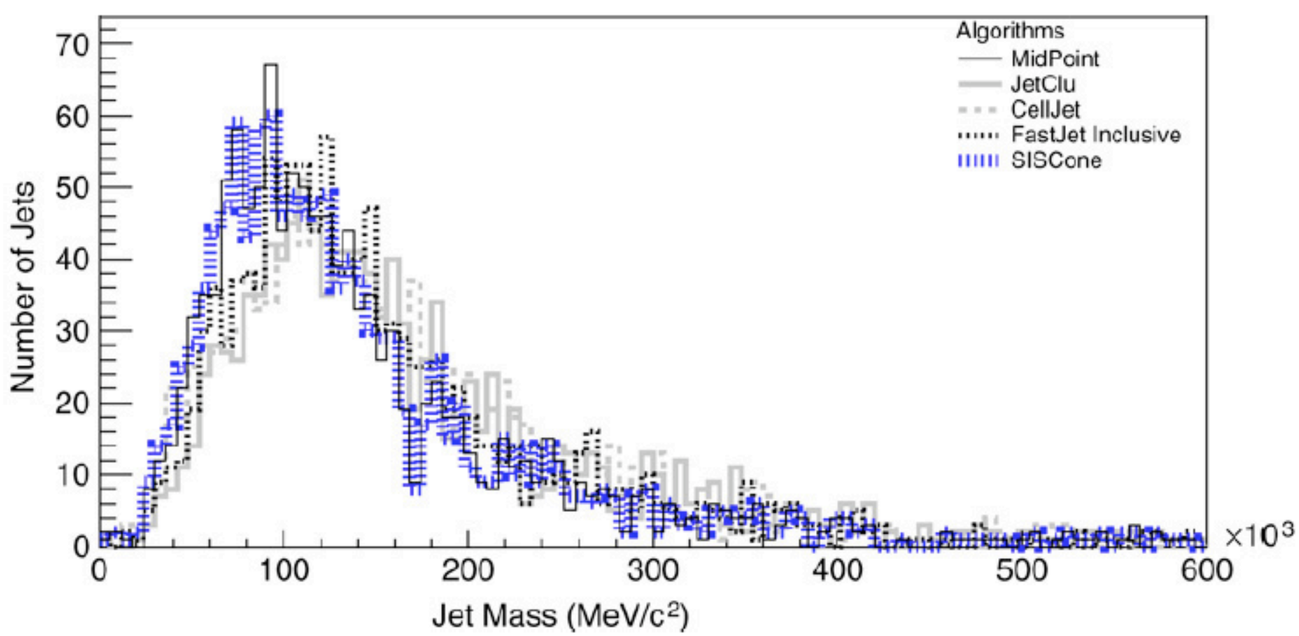
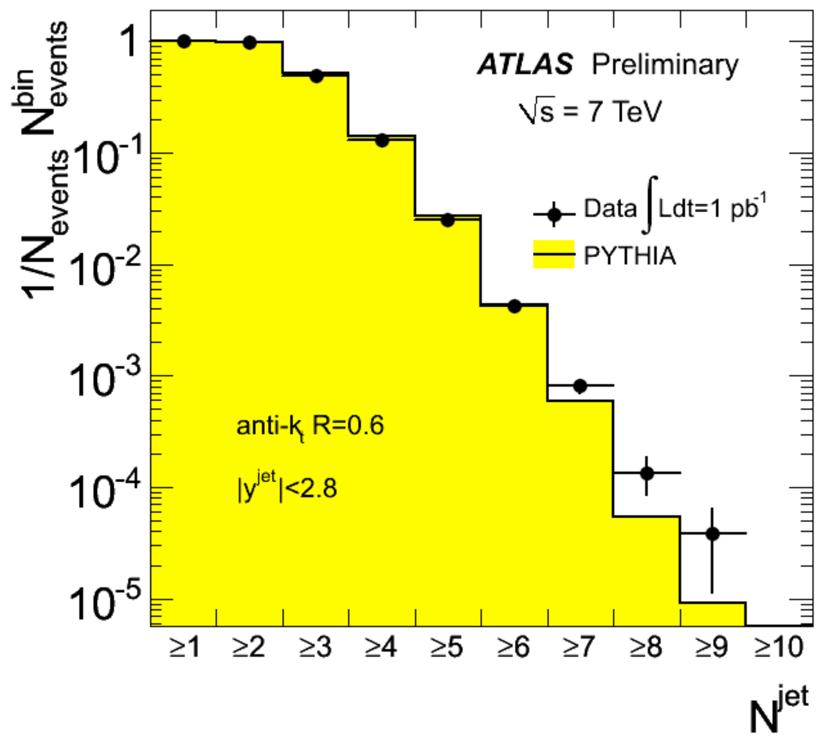


Fig. 51. The jet mass distributions for an inclusive jet sample generated for the LHC with a $p_{T,\min}$ value for the hard scattering of approximately 2 TeV/c, using several different jet algorithms with a distance scale ($D = R_{\text{cone}}$) of 0.7.

Multijets

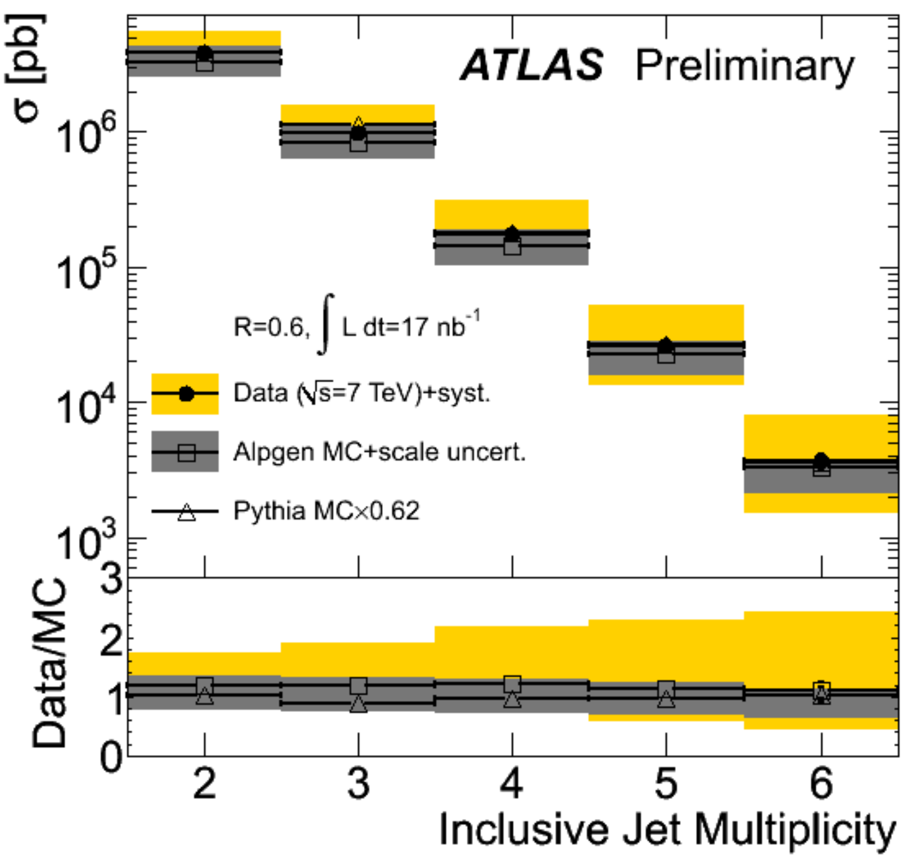
- Larger center-of-mass energy means that are able to routinely produce higher jet multiplicity events than at the Tevatron
  - p_T>30 GeV/c

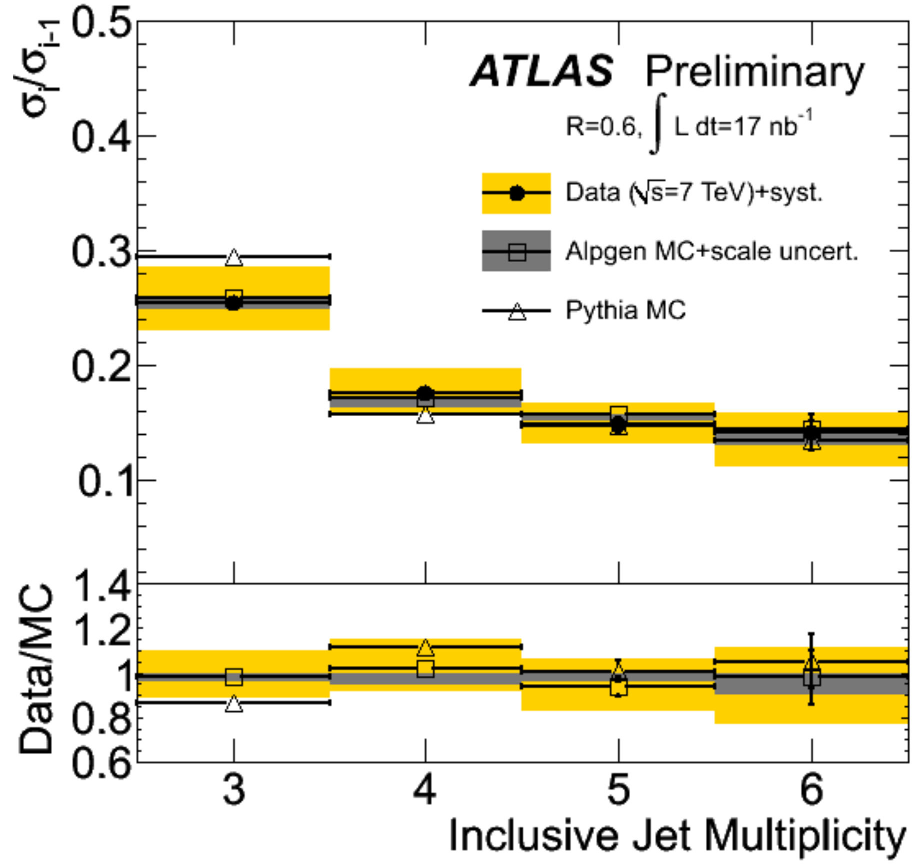


Multijets

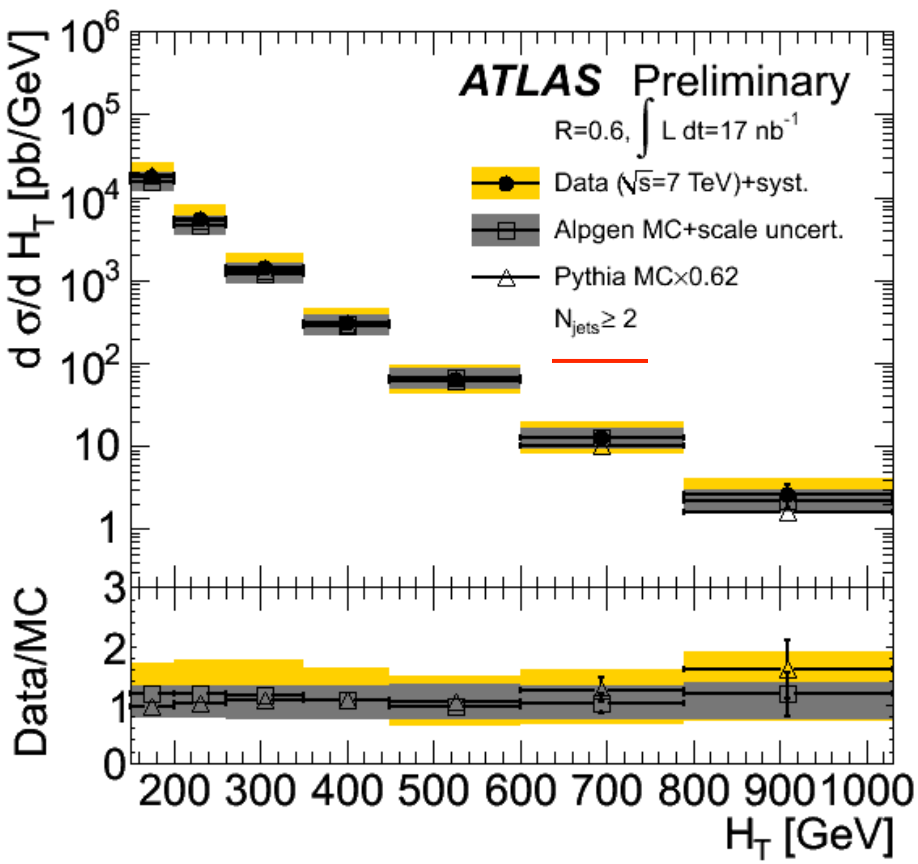
- Inclusive jet multiplicity distribution corrected to particle level compared to Alpgen and to Pythia
    - p_T>30 GeV/c

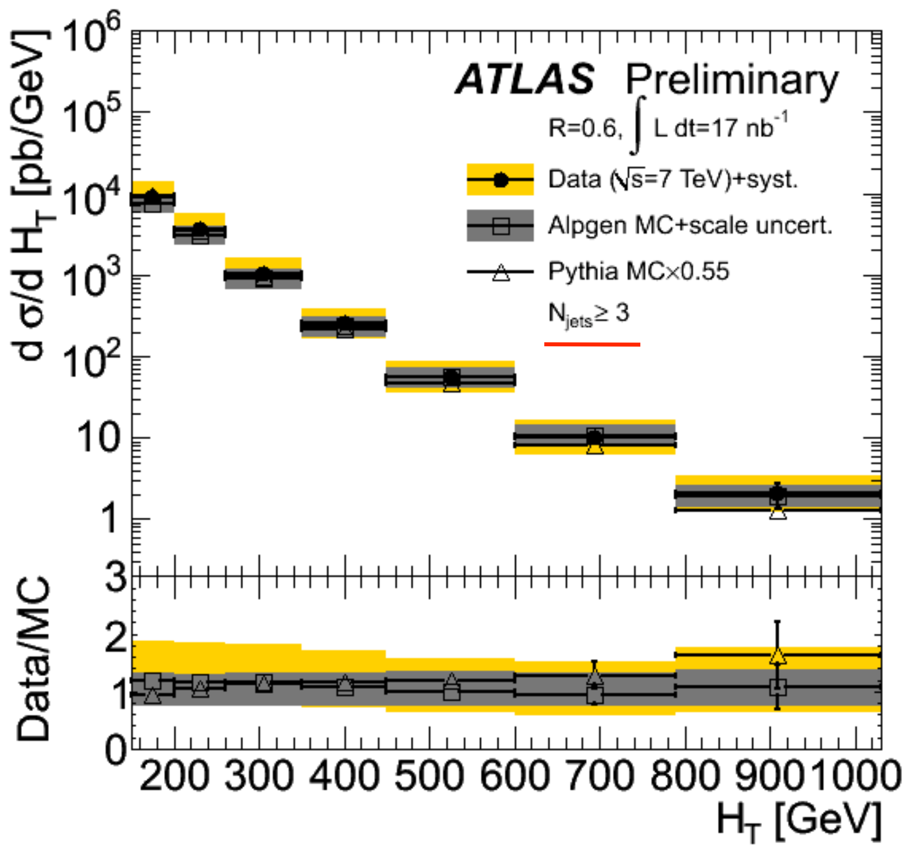
•Ratio of n jet to n-1 jet cross section, corrected to particle level, and compared to Alpgen and to Pythia





H_T distributions

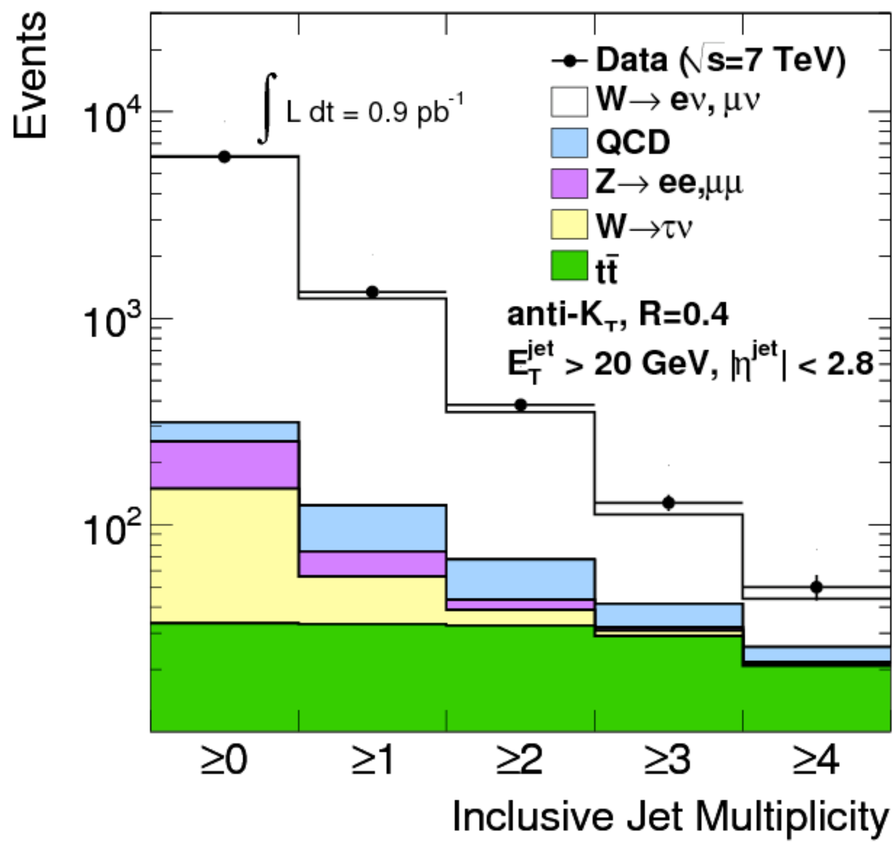


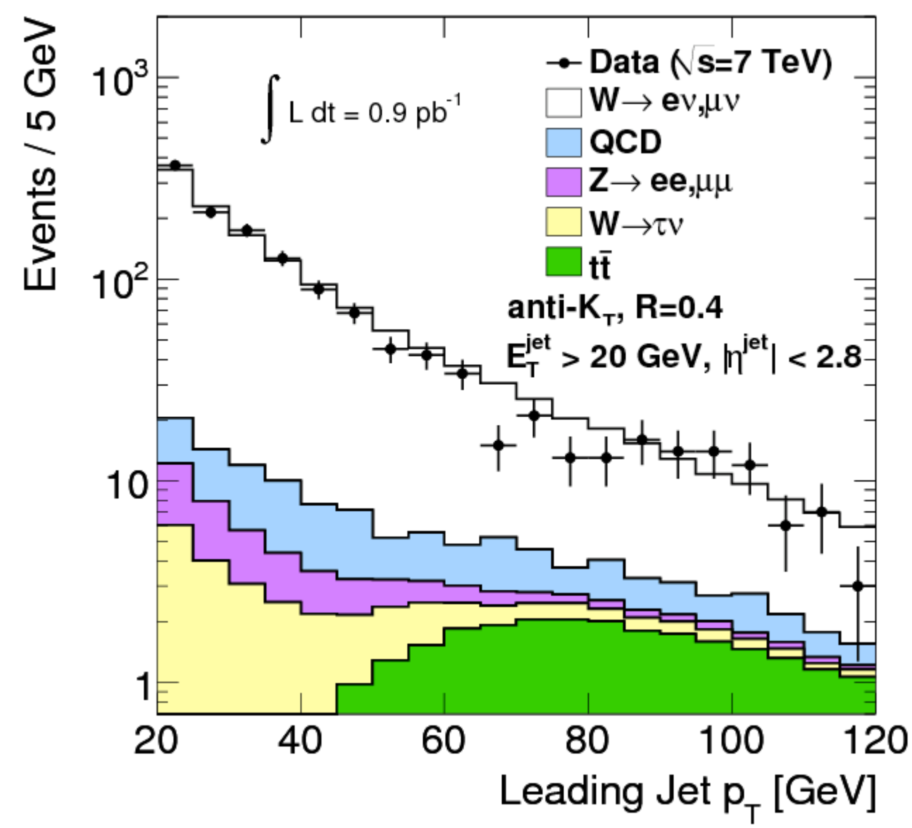


H_T: sum of E_T of all objects in event

Leptons, missing E_T and jets: W + jets

- One of building blocks for SM (top, Higgs) and BSM (SUSY) physics
- Kinematic reach will be far beyond Tevatron

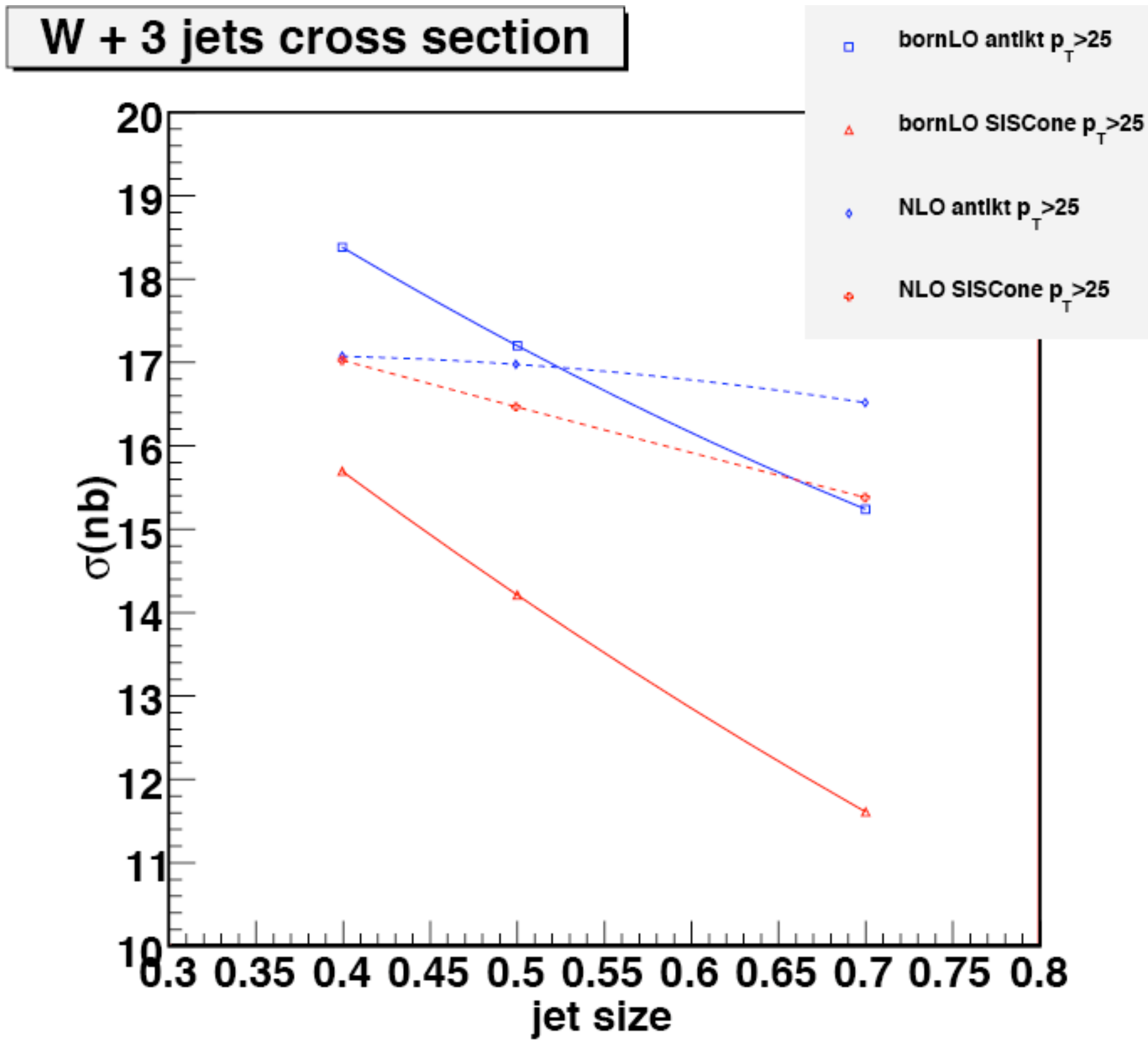




Don't believe (fixed) LO predictions for jet cross sections

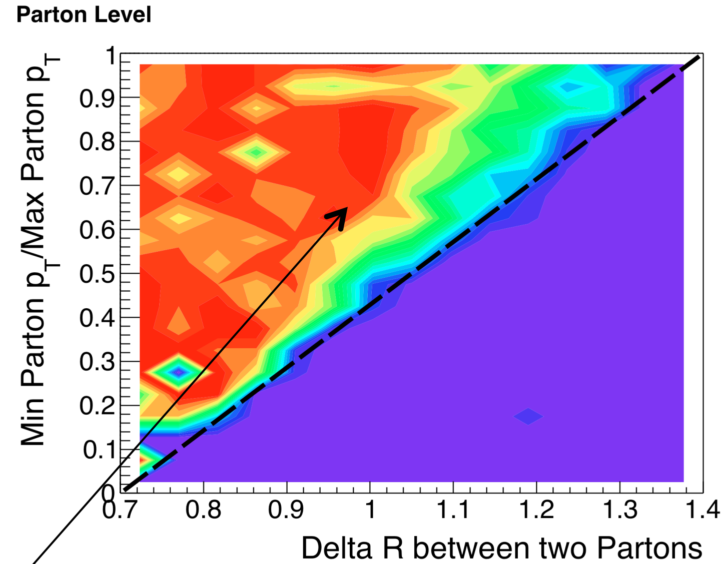
- Often conclusions are made about similarities/differences between jet algorithms based on their behavior for (fixed) LO calculations (where each jet = 1 parton)
- For example, from the LO curves on the right, one would conclude that
  - antikT cross sections are substantially larger than SISCone cross sections
  - cross sections have a large jet size dependence
- This often has little to do with their behavior at NLO (where there can be two partons) or in data/Monte Carlo where there are many partons/hadrons
- The data/MC behavior basically tracks the NLO level, with some differences

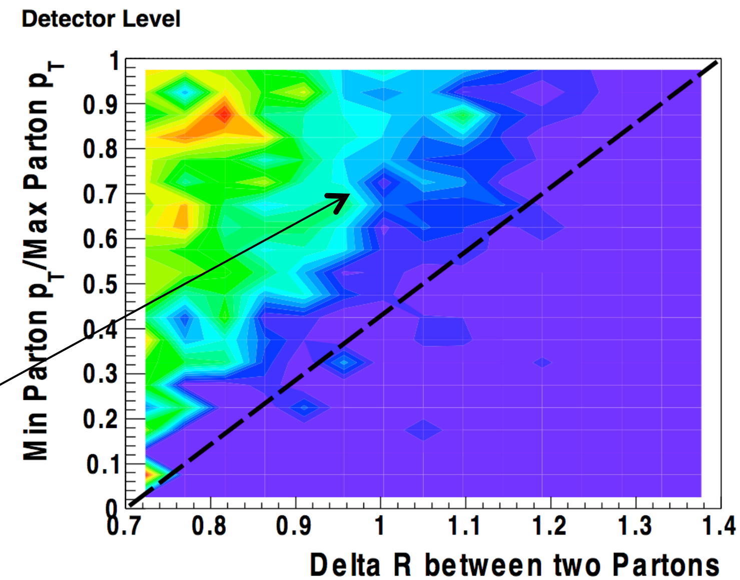
…using ROOT ntuples provided by Blackhat+Sherpa



One of those differences

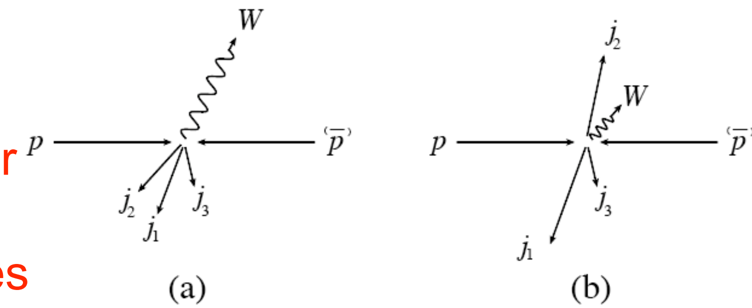
- Take W + 2 parton events (ALPGEN +PYTHIA), run SISCone 0.7 algorithm on parton level, hadron level (not shown) and topocluster level
- Plot the probability for the two sub-jets to merge as a function of the separation of the original two partons in ΔR
- Color code:
  - red: high probability for merging
  - blue: low probability for merging
  - everything for $\Delta R<0.7$ is merged for SISCone (and antikT)
- Parton level reconstruction agrees with naïve expectation
  - everything above the diagonal should be reconstructed as one jet
- Topocluster level reconstruction shows that widely separated sub-jets will not be reconstructed into the same jet





Scale choices: what worked at the Tevatron for W + jets (m_W, E_T^W, $p^2_T{}^W+m_W^2$) won't at the LHC

If configuration (a) dominated, then as jet E_T increased, E_T^W would increase along with it. But configuration (b) is kinematically favored for high jet E_T's (smaller partonic center-of-mass energy); E_T^W remains small, and that scale does not describe the process very well



Note that now split/merge can become important as the partonic jets can overlap and share partons

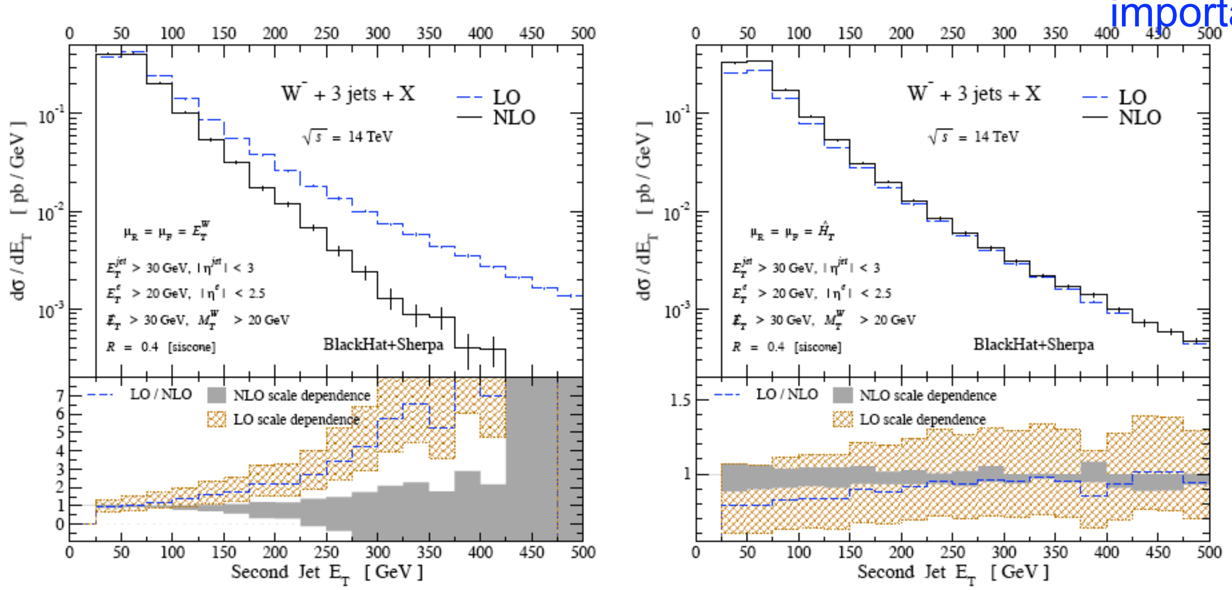


FIG. 9: The E_T distribution of the second jet at LO and NLO, for two dynamical scale choices, $\mu = E_T^W$ (left plot) and $\mu = \hat{H}_T$ (right plot). The histograms and bands have the same meaning as in previous figures. The NLO distribution for $\mu = E_T^W$ turns negative beyond $E_T = 475$ GeV.

Configuration b also tends to dominate in the tails of multi-jet distibutions (such as H_T or M_{ij}); for high jet E_T, W behaves like a massless boson, and so there's a kinematic enhancement when it's soft

arXiv:0907.1984

Scale choices

scales related to H_T work at both LO and NLO; CKKW also seems to agree well with NLO predictions in shape

Les Houches NLM proceedings

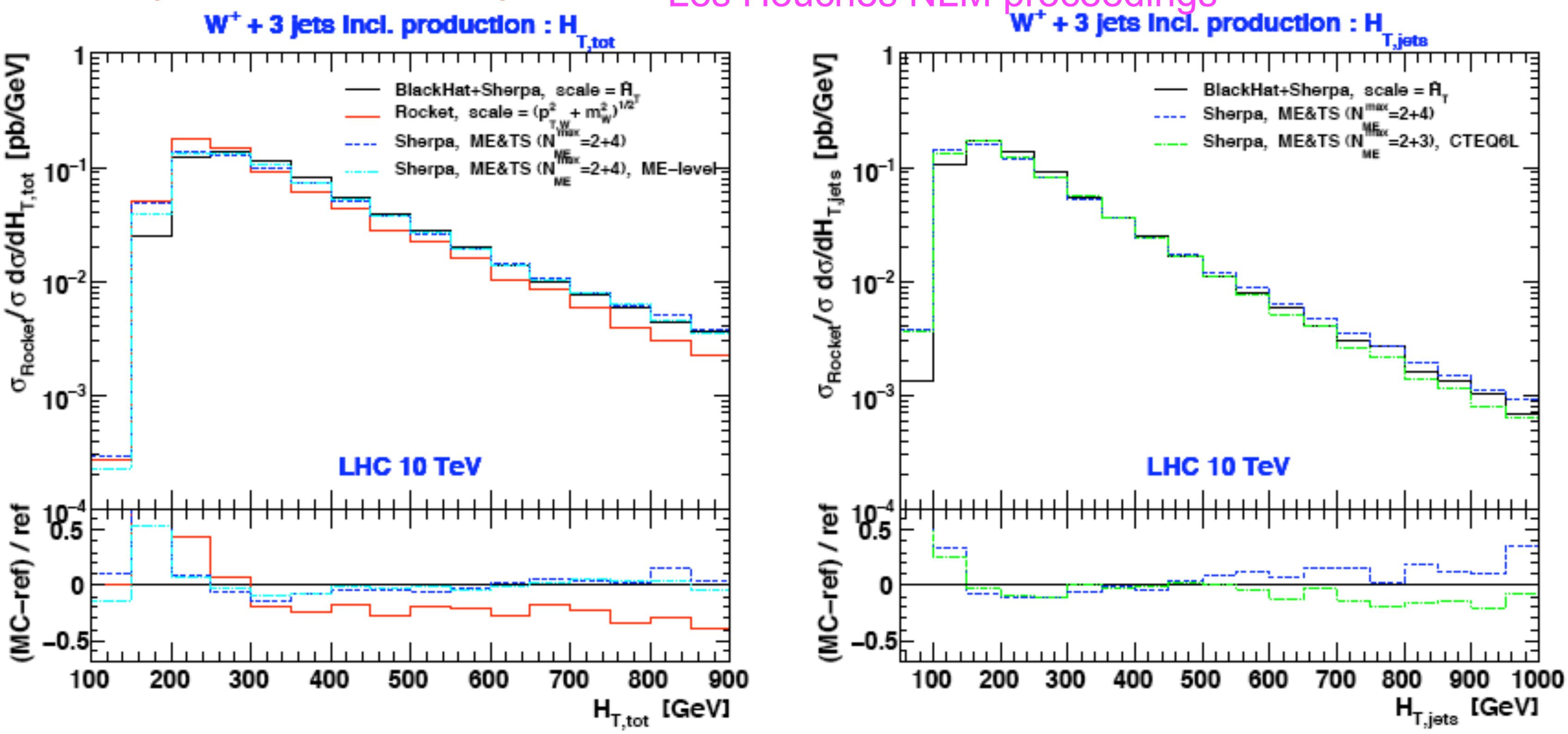


Fig. 19: H_T and $H_{T,\text{jets}}$ distributions in inclusive $W^+ + 3$ jet production at the LHC. NLO predictions obtained from BLACKHAT+SHERPA (black line) and ROCKET (red line) are compared to LO results from SHERPA using the ME&TS merging. All curves have been rescaled to the ROCKET NLO cross section of Table 5; the BLACKHAT+SHERPA prediction is used as the reference; cuts and parameters are detailed in Section 12.2

Aside: realistic NLO wishlist

- Was developed at Les Houches in 2005, and expanded in 2007 and 2009
- Calculations that are important for the LHC AND do-able in finite time
- In 2009, we added tttt, Wbbj, Z+3j, W +4j plus an extra column for each process indicating the level of precision required by the experiments
  - to see for example if EW corrections may need to be calculated
- In order to be most useful, decays for final state particles (t,W,H) need to be provided in the codes as well
- Since the publication of Les Houches 2009 in March, processes 6 and 7 have been completed
- V + 4 jets (process 10) is on the horizon

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [4, 5]; Campbell/Ellis/Zanderighi [6]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [8]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [9, 10]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14, 15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
7. $pp \to VV\,b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
8. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [20–22]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration [23]
NLO calculations added to list in 2009	
10. $pp \to V$+4 jets	top pair production, various new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \to W^*W^*$ $\mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
14. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
15. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
16. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

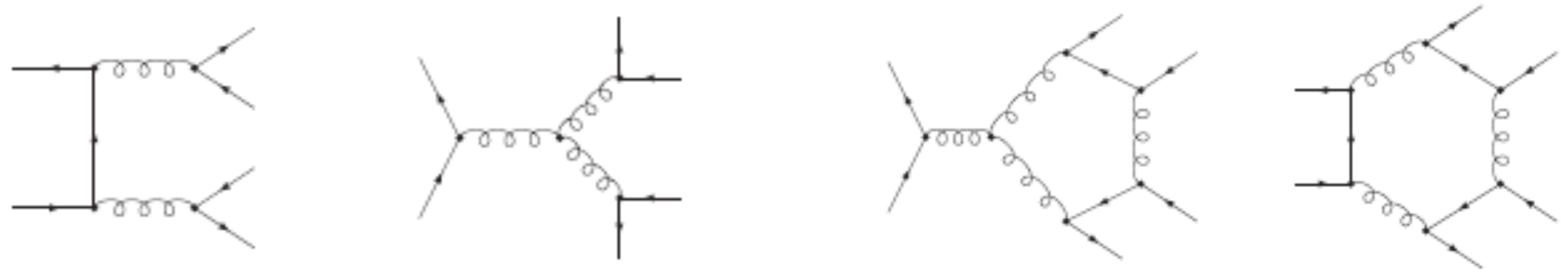
Table 1: The updated experimenter's wishlist for LHC processes

Some issues/questions

- Once we have the calculations, how do we (experimentalists) use them?
- Too often (unfortunately) we don't use them
- Best is to have NLO partonic level calculation interfaced to parton shower/hadronization
  - but that has been done only for relatively simple processes and is very (theorist) labor intensive
    - still waiting for inclusive jets in MC@NLO, for example
- Even with partonic level calculations, need public code and/or ability to write out ROOT ntuples of parton level events
  - so that can generate once with loose cuts and distributions can be re-made without the need for the lengthy re-running of the predictions
  - what is done for example with MCFM
  - it's what Blackhat+Sherpa has provided me for W + 3 jets at NLO; hopefully W + 4 jets soon
    - 10's of Gbytes for file size, but hey we're experimentalists
  - new format has both PDF and scale uncertainties stored in ntuples

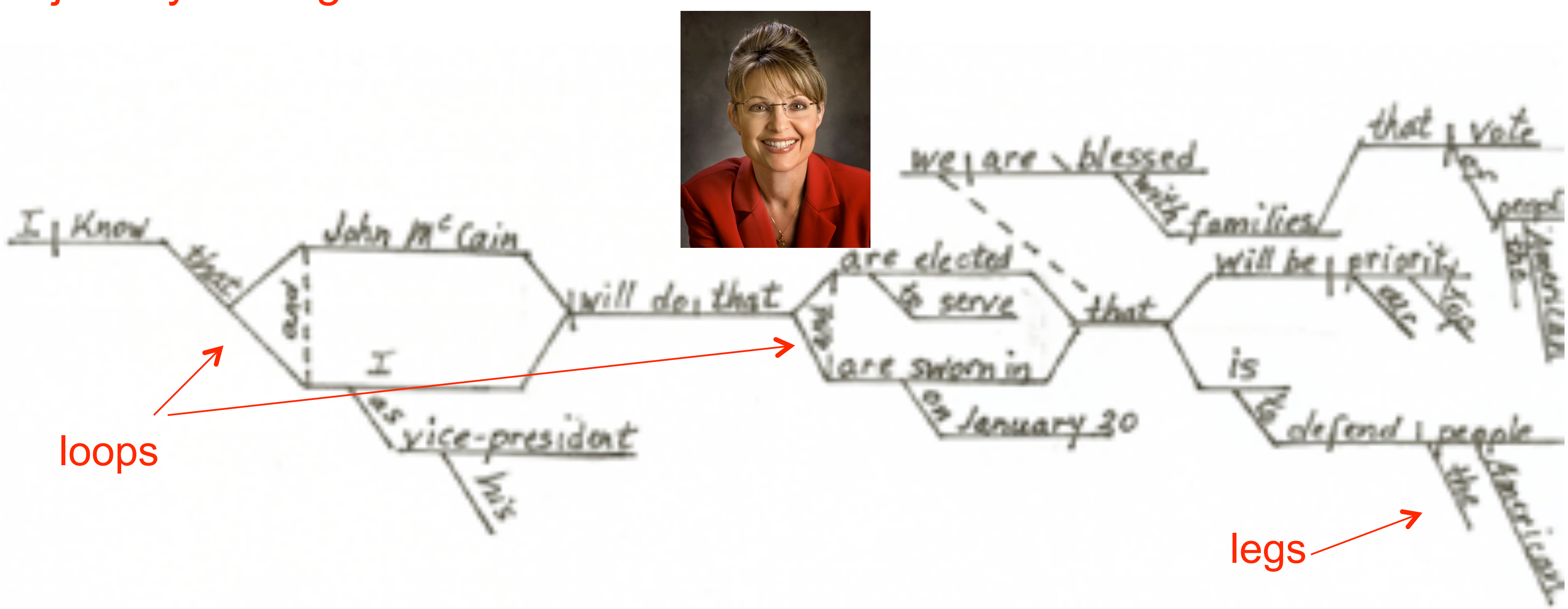
Loops and legs

2->4 is very impressive



but just try to diagram the sentences that Sarah Palin uses

.



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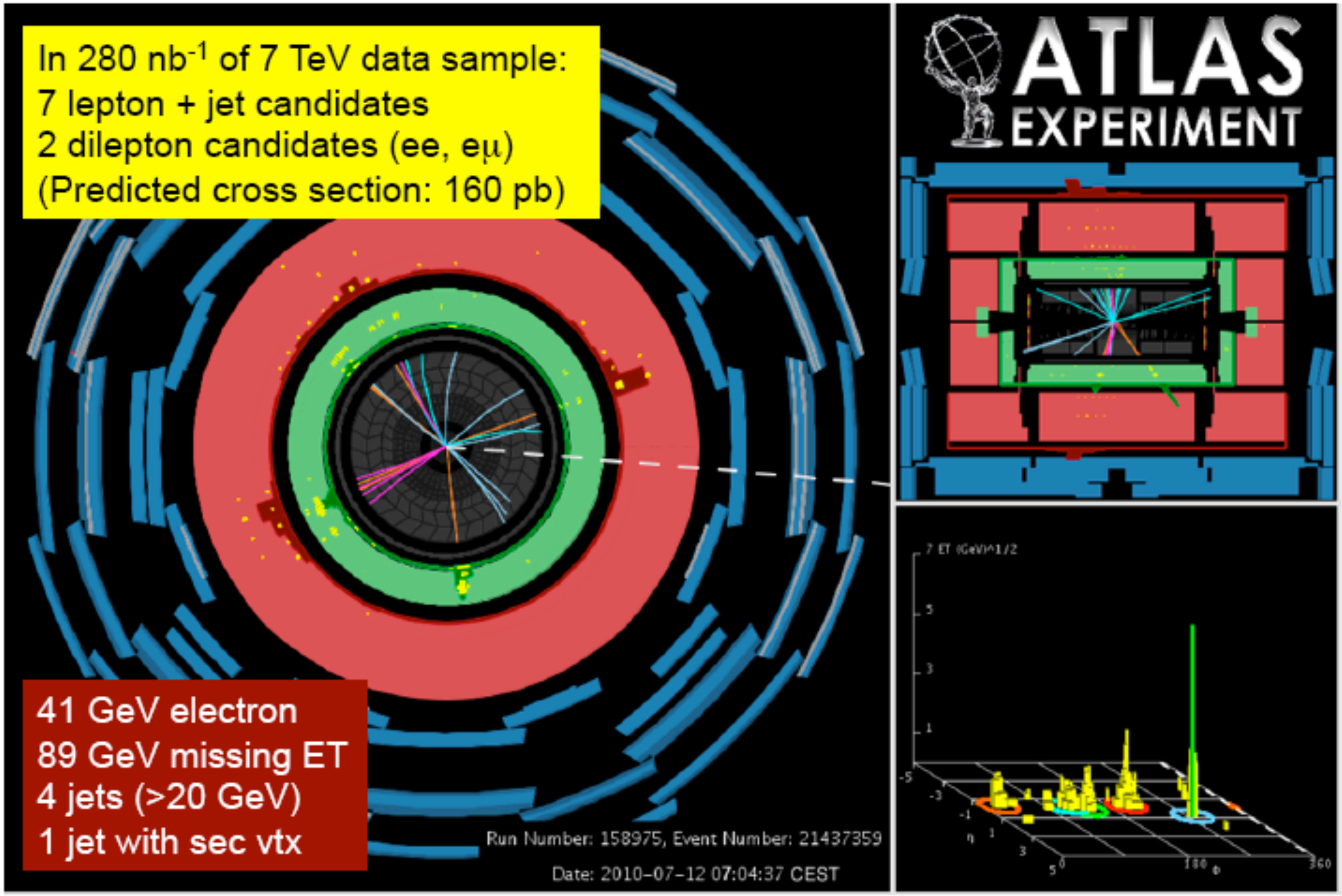
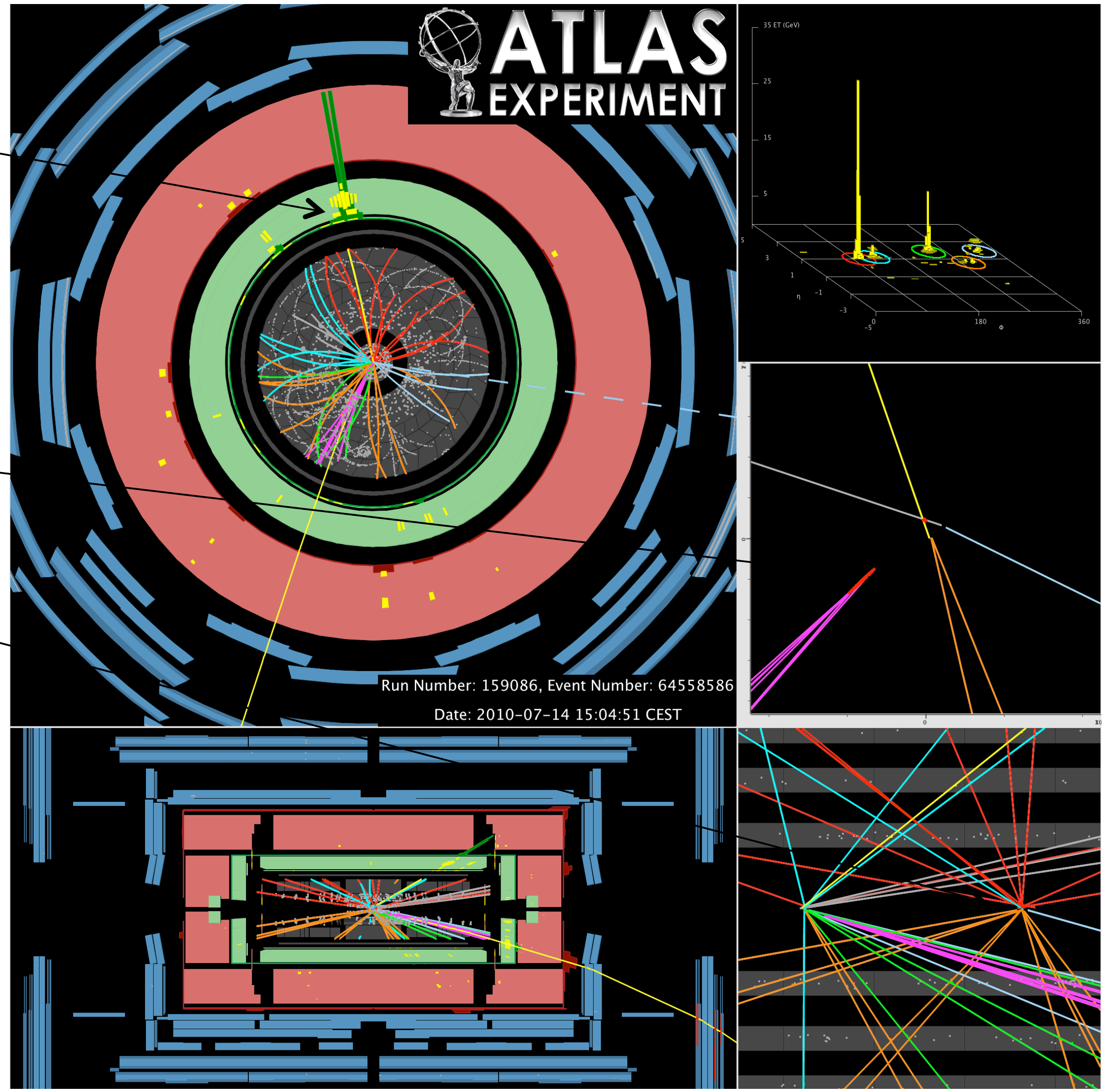
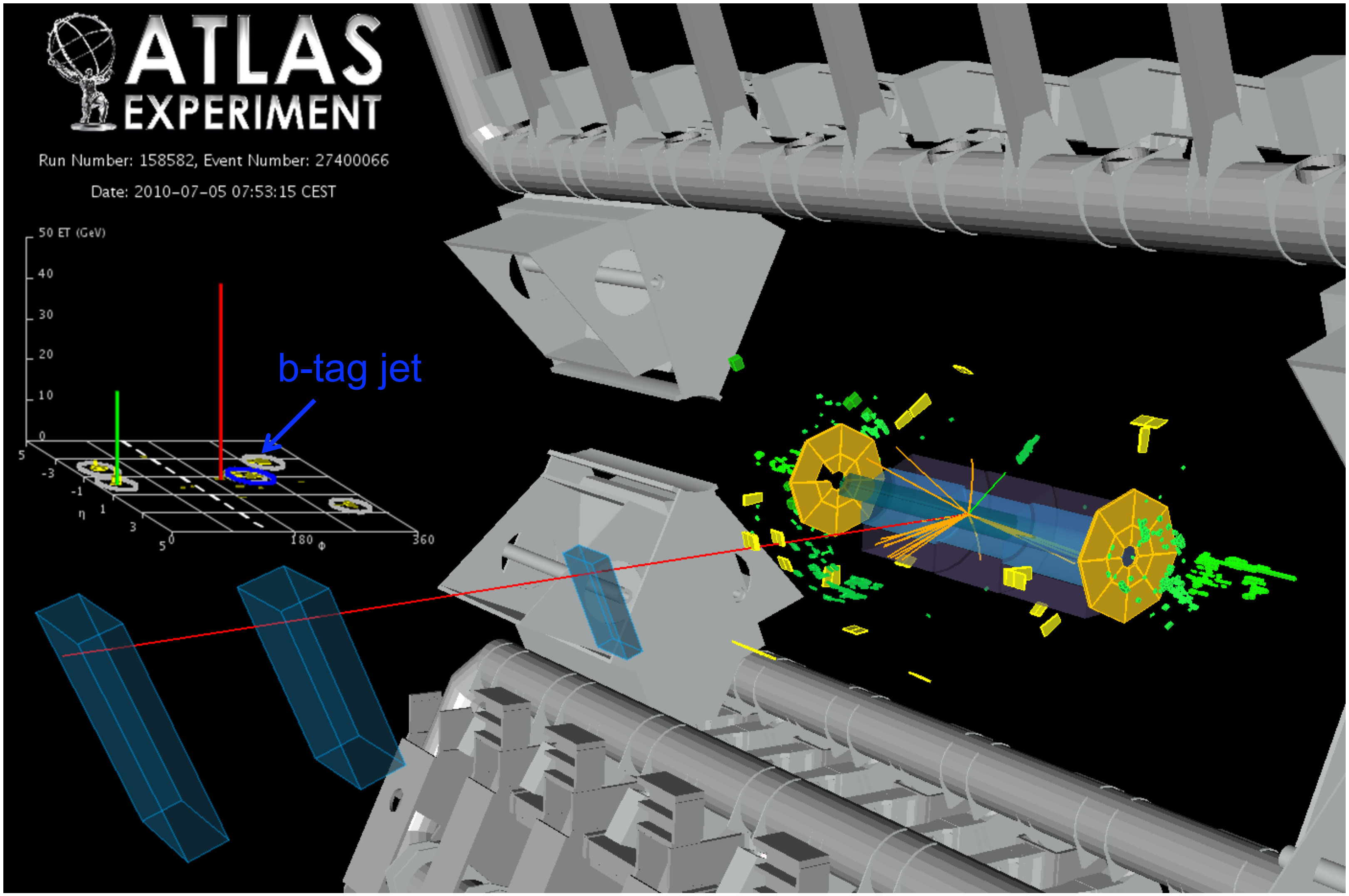


Electron + jets event

- Electron + jets event
- Secondary vertex tagged jet
- Extra pileup interaction

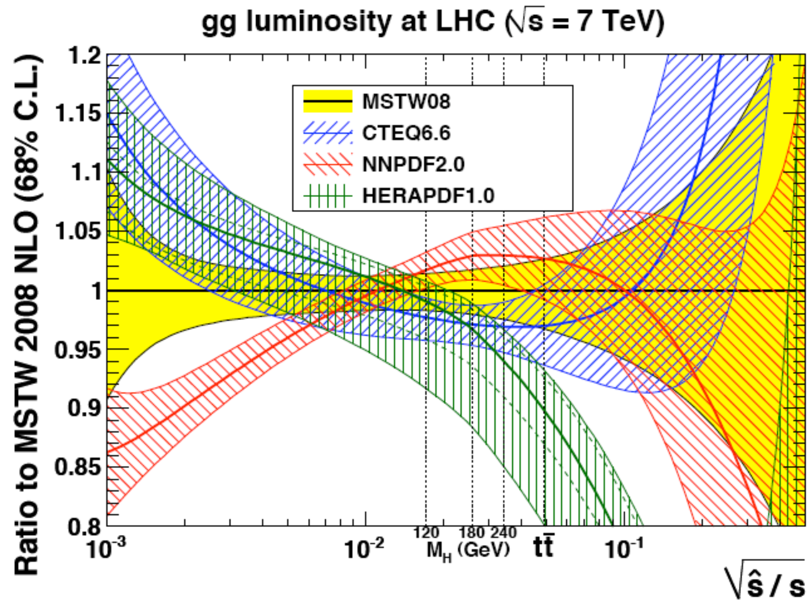


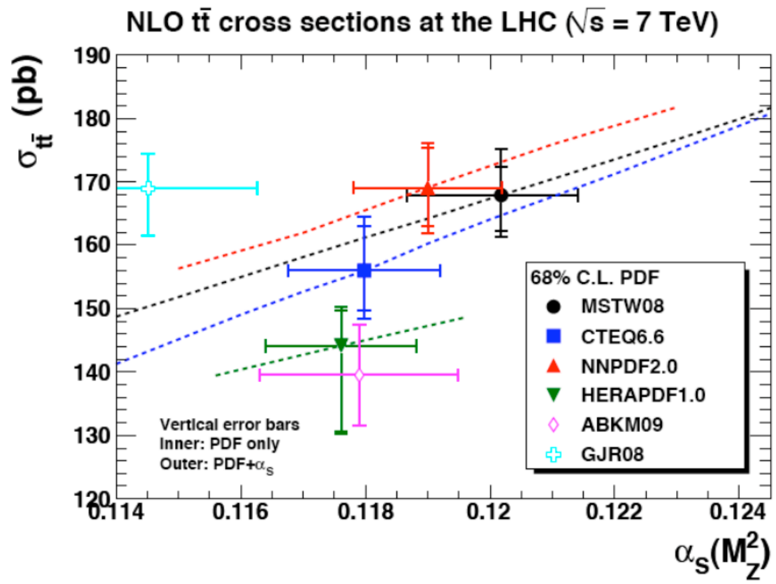
e-μ event


ATLAS
EXPERIMENT
Run Number: 158582, Event Number: 27400066
Date: 2010-07-05 07:53:15 CEST
50 ET (GeV)
40
30
20
10
0
5
-3
-1
η
1
3
5
0
180
Φ
360
b-tag jet

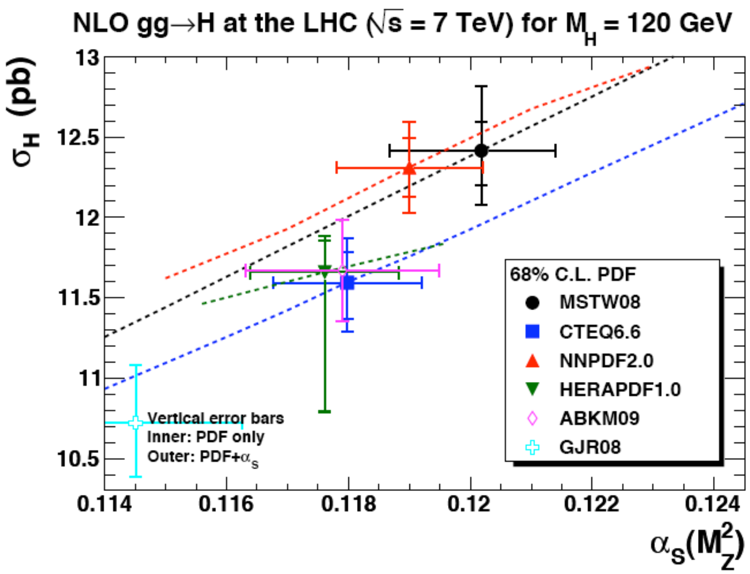
Aside: Some more results from the benchmarking

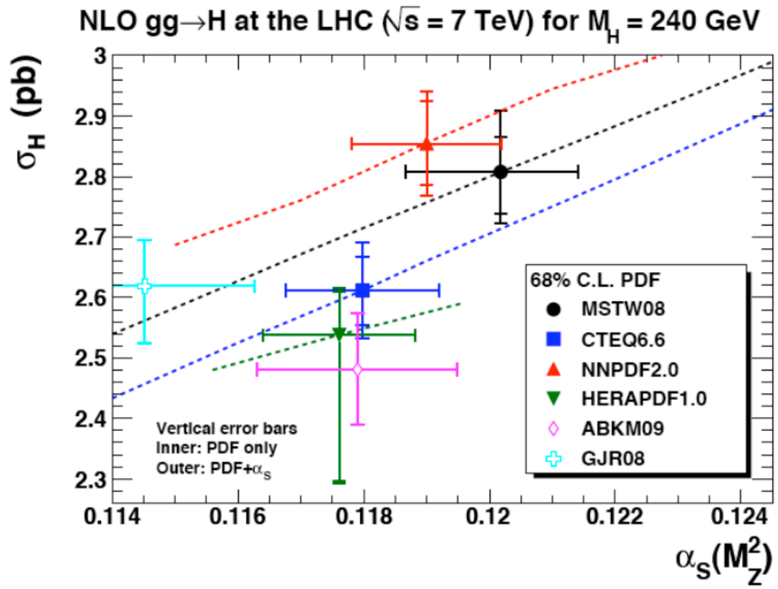
- …from G. Watt's presentation at PDF4LHC meeting on March 26
- Similar gluon-gluon luminosity uncertainty bands, as noted before
- Cross sections fall into two groups, outside 68% CL error bands
- But, slide everyone's prediction along the α_s curve to 0.119 (for example) and predictions agree reasonably well
  - within 68% CL PDF errors

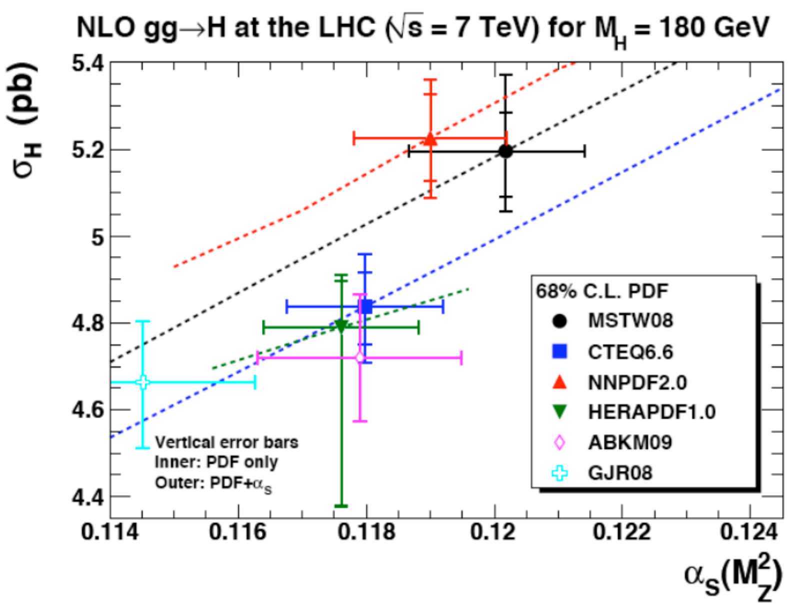




More benchmarking







Correlations with Z, tT

Define a correlation cosine between two quantities

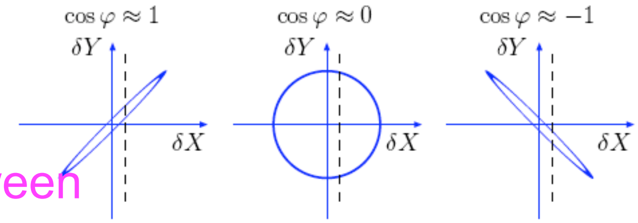
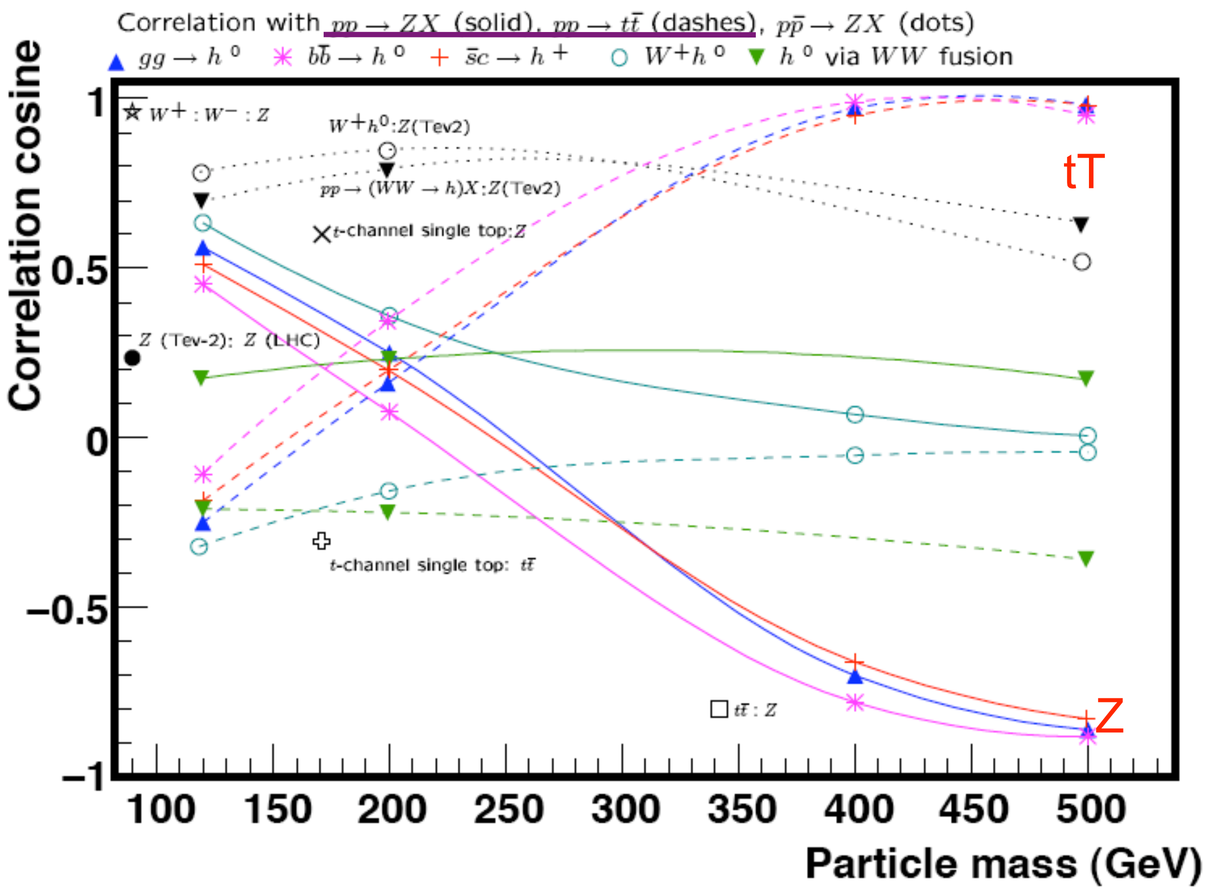


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

- If two cross sections are very correlated, then cosϕ~1
- …uncorrelated, then cosϕ~0
- …anti-correlated, then cosϕ~-1



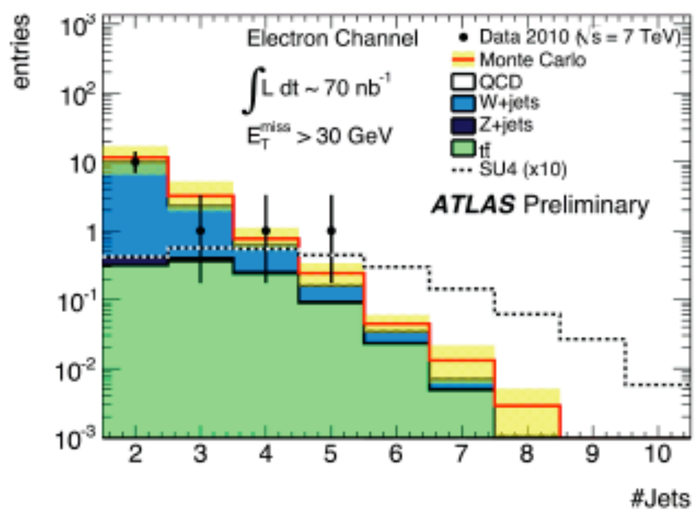
- W and Z will be heavily used for cross section normalization
- Note that correlation curves to Z and to tT are mirror images of each other
- By knowing the pdf correlations, can reduce the uncertainty for a given cross section in ratio to a benchmark cross section **iff** cos ϕ > 0;e.g. $\Delta(\sigma_{W}+/\sigma_{Z})$~1%
- If cos ϕ < 0, pdf uncertainty for one cross section normalized to a benchmark cross section is larger
- So, for gg->H(500 GeV); pdf uncertainty is 4%; $\Delta(\sigma_H/\sigma_Z)$~8%

Back to ATLAS: new physics searches

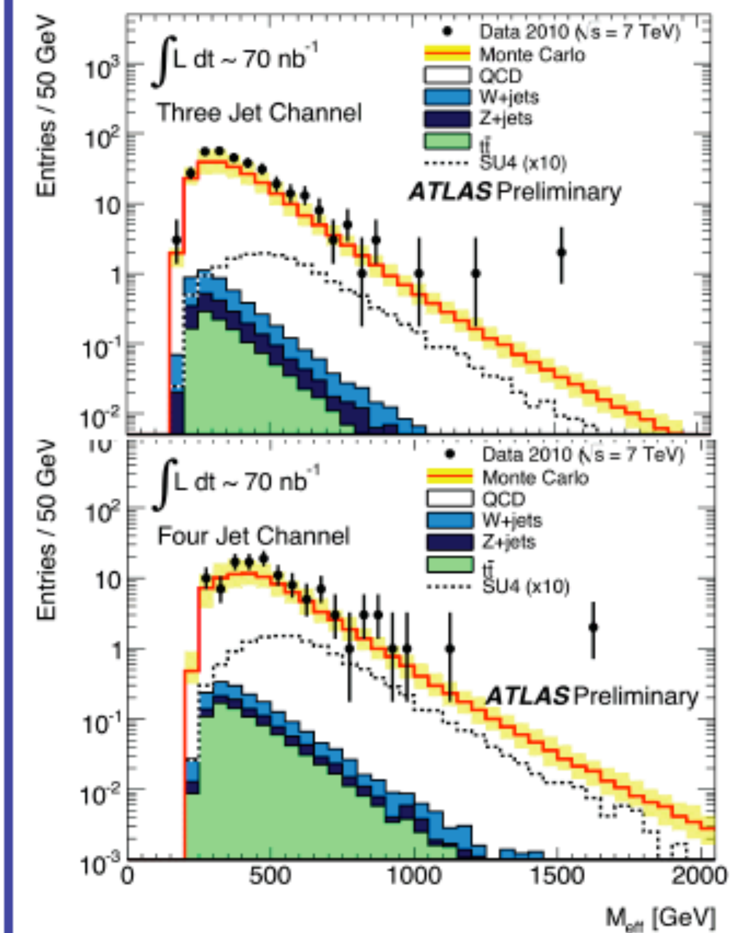
General search strategy for heavy squark/ gluino production and decay to invisible Lightest Supersymmetric Particles (LSPs)

Require jets and significant missing E_T; measure "effective mass" as estimate of supersymmetry mass scale

$$M_{\mathrm{eff}} \equiv \sum_{i=1}^{n} |\mathbf{p}_{\mathrm{T}}^{(i)}| + E_{\mathrm{T}}^{\mathrm{miss}}$$



"0-lepton searches" after missing E_T cut



Didn't find any: so far

…but

Exciting candidate…

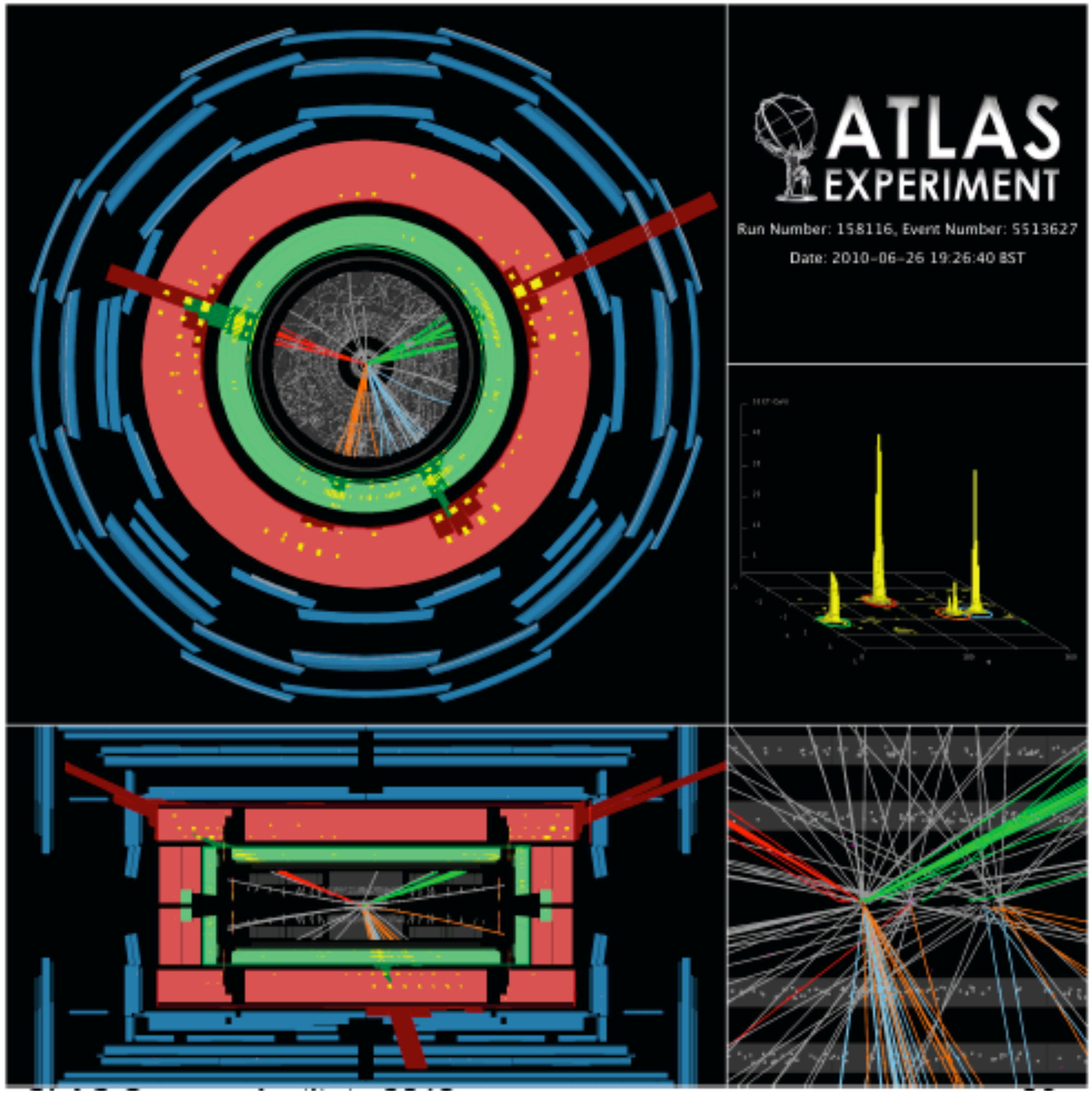
Jet + missing ET selection
4 high-energy jets
(same primary vertex)

Effective mass of 1.65 TeV
(incl. 4 jets)

…with a few problems

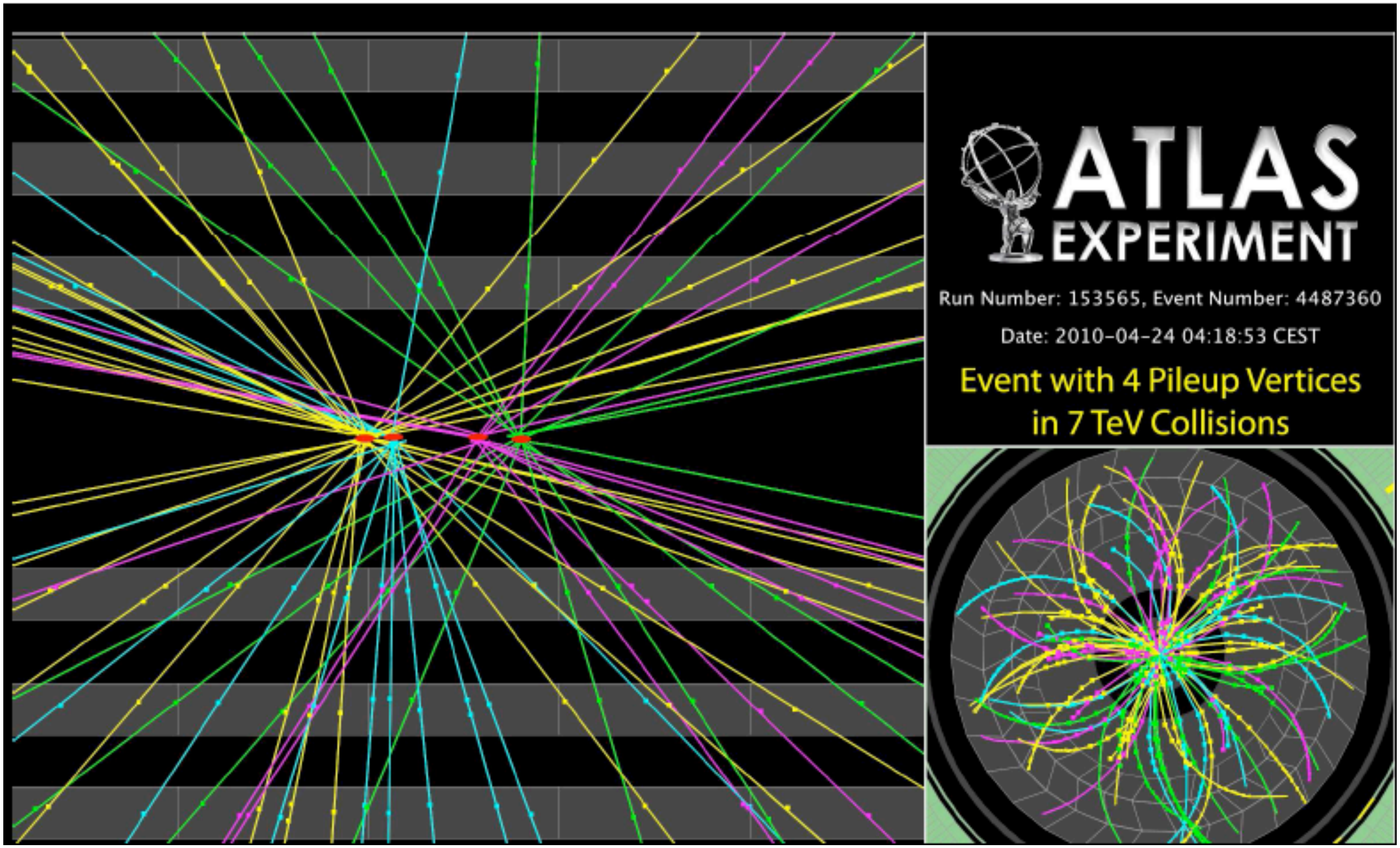
Missing ET ≈ 100 GeV, but lies in direction of vertex-tagged jet (semilep decay?)

Event does not pass selection criteria for $\Delta\phi$(jet, ptmiss) nor ratio of missing ET to effective mass



Higher luminosity is coming

…and with it precision comparisons of data to theory

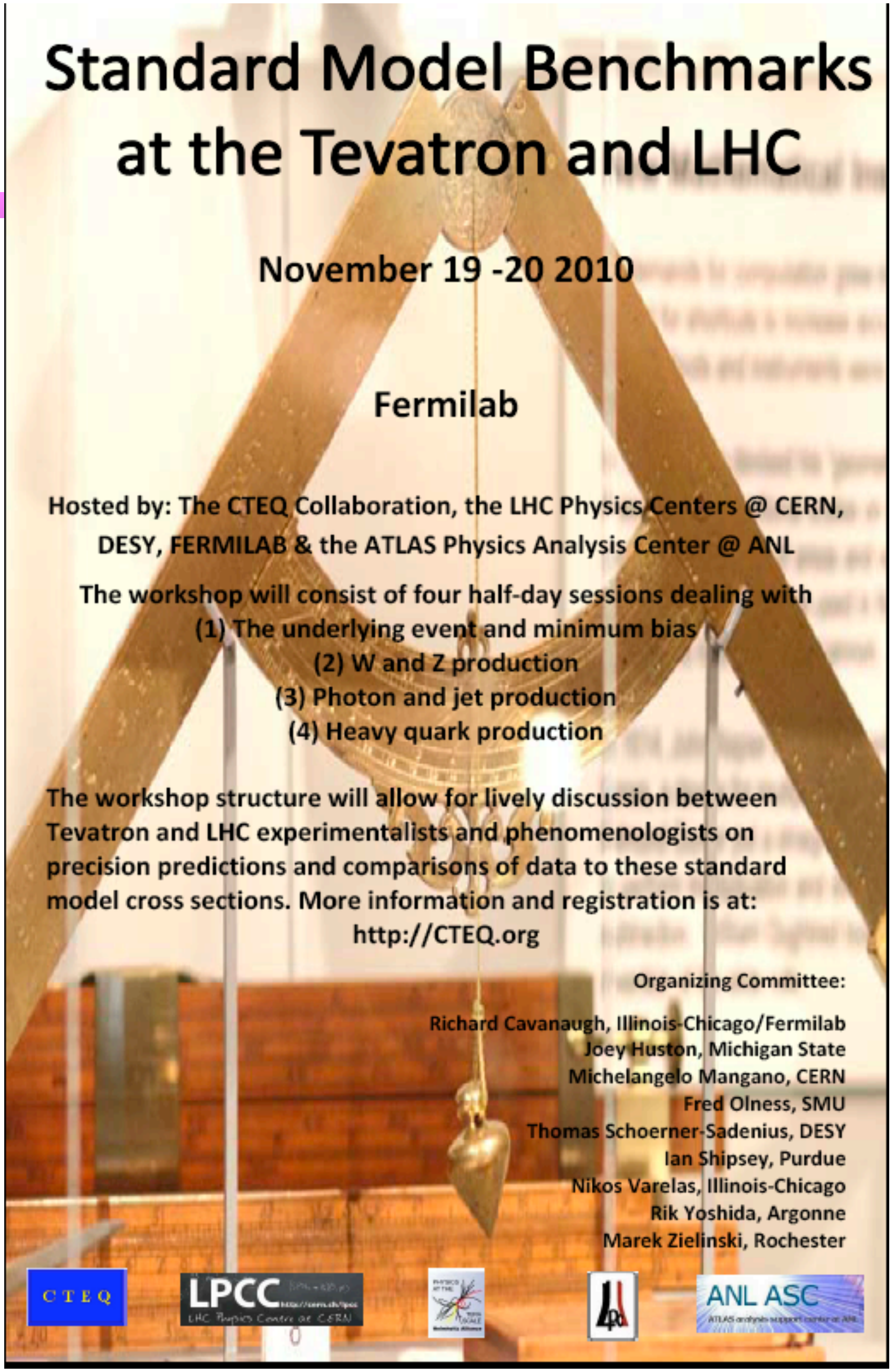


Summary

- We have an opportunity (forced on us) to understand the QCD environment at the LHC before we reach discover-potential integrated luminosities
- We have the ability (with the ATLAS detector) to make more detailed measurements of final states including jets than any previous collider detector
- ATLAS/LHC are working well, taking and analyzing data, putting together the SM benchmarks needed for robust physics at 7 TeV
- Due to lack of time, have not discussed b-tagging or tau ID in detail
  - see ATLAS-CONF-2010- for more details
- …thanks to ATLAS colleagues whose transparencies I've borrowed, especially Jason Nielsen, and who have provided comments, especially Eric Feng and Brian Martin

Advertisement

- This will be the first workshop sponsored by all 3 LHC LPCs, as well as CTEQ and the ANL ASC
- Evo will be available



Some references

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Rep. Prog. Phys. **70** (2007) 89–193 — doi:10.1088/0034-4885/70/1/R02

Hard interactions of quarks and gluons: a primer for LHC physics

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CHS

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over 1500 downloads so far

Abstract

In this paper, we will develop the perturbative framework for the calculation of hard-scattering processes. We will undertake to provide both a reasonably rigorous development of the formalism of hard-scattering of quarks and gluons as well as an intuitive understanding of the physics behind the scattering. We will emphasize the role of logarithmic corrections as well as power counting in α_S in order to understand the behaviour of hard-scattering processes. We will include 'rules of thumb' as well as 'official recommendations', and where possible will seek to dispel some myths. We will also discuss the impact of soft processes on the measurements of hard-scattering processes. Experiences that have been gained at the Fermilab Tevatron will be recounted and, where appropriate, extrapolated to the LHC.

(Some figures in this article are in colour only in the electronic version)

goal is to provide a reasonably global picture of LHC calculations

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Progress in Particle and Nuclear Physics

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Review

Jets in hadron–hadron collisions

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arXiv:07122447 Dec 14, 2007

Abstract

In this article, we review some of the complexities of jet algorithms and of the resultant comparisons of data to theory. We review the extensive experience with jet measurements at the Tevatron, the extrapolation of this acquired wisdom to the LHC and the differences between the Tevatron and LHC environments. We also describe a framework (SpartyJet) for the convenient comparison of results using different jet algorithms.

Keywords: Jet; Jet algorithm; LHC; Tevatron; Perturbative QCD; SpartyJet

Contents

More references

Towards Jetography

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Abstract

As the LHC prepares to start taking data, this review is intended to provide a QCD theorist's understanding and views on jet finding at hadron colliders, including recent developments. My hope is that it will serve both as a primer for the newcomer to jets and as a quick reference for those with some experience of the subject. It is devoted to the questions of how one defines jets, how jets relate to partons, and to the emerging subject of how best to use jets at the LHC.

THE SM AND NLO MULTILEG WORKING GROUP: Summary Report

Convenors: T. Binoth[1], G. Dissertori[2], J. Huston[3], R. Pittau[4]
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SpartyJet

Sparty

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C. Vermillion, Washington

http://projects.hepforge.org/spartyjet/

If interested for ATLAS, please contact
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Proposed common ntuple output

- A generalization of the FROOT format used in MCFM
- Writeup in NLM proceedings

Table 4: Variables stored in the proposed common ROOT ntuple output.

ROOT Tree Branch	Description
Npart/I	number of partons (incoming and outgoing)
Px[Npart]/D	Px of partons
Py[Npart]/D	Py of partons
Pz[Npart]/D	Pz of partons
E[Npart]/D	E of partons
x1/D	Bjorken-x of incoming parton 1
x2/D	Bjorken-x of incoming parton 2
id1/I	PDG particle ID of incoming parton 1
id2/I	PDF particle ID of incoming parton 2
fac_scale/D	factorization scale
ren_scale/D	renormalization scale
weight/D	global event weight
Nuwgt/I	number of user weights
user_wgts[Nuwgt]/D	user event weights
evt_no/L	unique event number (identifier)
Nptr/I	number of event pointers
evt_pointers[Nptr]/L	event pointers (identifiers of related events)
Npdfs/I	number of PDF weights
pdf_wgts[Npdfs]/D	PDF weights

```
LhaNLOEvent* evt = new LhaNLOEvent();
evt->addParticle(px1,py1,pz1,E1);
evt->setProcInfo(x1,id1,x2,id2);
evt->setRenScale(scale);
...
```

Another class **LhaNLOTreeIO** is responsible for writing the events into the ROOT tree and outputting the tree to disk. In addition to the event-wise information global data such as comments, cross sections etc can be written as well. An example is shown below:

```
LhaNLOTreeIO* writer = new LhaNLOTreeIO(); // create tree writer
writer->initWrite(''test.root'');
...
writer->writeComment(''W+4 jets at NNLO''); // write global comments
writer->writeComment(''total cross section: XYZ+/-IJK fb'');
...
writer->writeEvent(*evt); // write event to tree (in event loop)
...
writer->writeTree(); // write tree to disk
```

Similarly, a tree can be read back from disk:

```
LhaNLOTreeIO* reader = new LhaNLOTreeIO(); // init reader
ierr=reader->initRead("test.root");
if (!ierr) {
  for (int i=0; i< reader->getNumberofEvents();i++) {
    event->reset();
    ierr=reader->readEvent(i,*event);
    ...
  }
}
```

K-factors

- Often we work at LO by necessity (parton shower Monte Carlos), but would like to know the impact of NLO corrections
- K-factors (NLO/LO) can be a useful short-hand for this information
- But caveat emptor; the value of the K-factor depends on a number of things
  - PDFs used at LO and NLO
  - scale(s) at which the cross sections are evaluated
- And often the NLO corrections result in a shape change, so that one K-factor is not sufficient to modify the LO cross sections

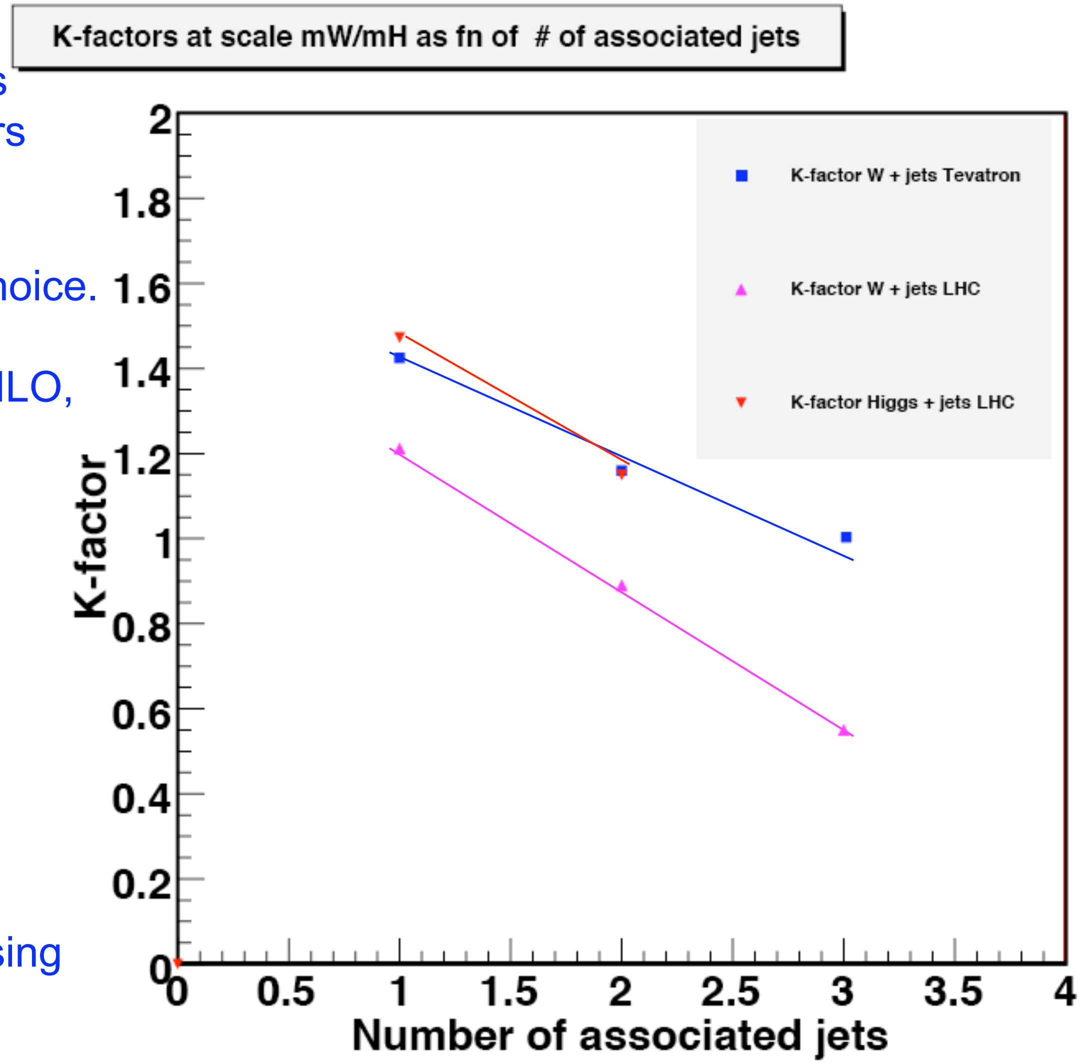
Is the K-factor (at m_W) at the LHC surprising?

The K-factors for W + jets (p_T>30 GeV/c) fall near a straight line, as do the K-factors for the Tevatron. By definition, the K-factors for Higgs + jets fall on a straight line.

Nothing special about m_W; just a typical choice.

The only way to know a cross section to NLO, say for W + 4 jets or Higgs + 3 jets, is to calculate it, but in lieu of the calculations, especially for observables that we have deemed important at Les Houches, can we understand the behavior with the associated number of jets?

Related to this is:
- understanding the reduced scale dependences/pdf uncertainties for cross section ratios we have been discussing
-scale choices at LO for cross sections uncalculated at NLO



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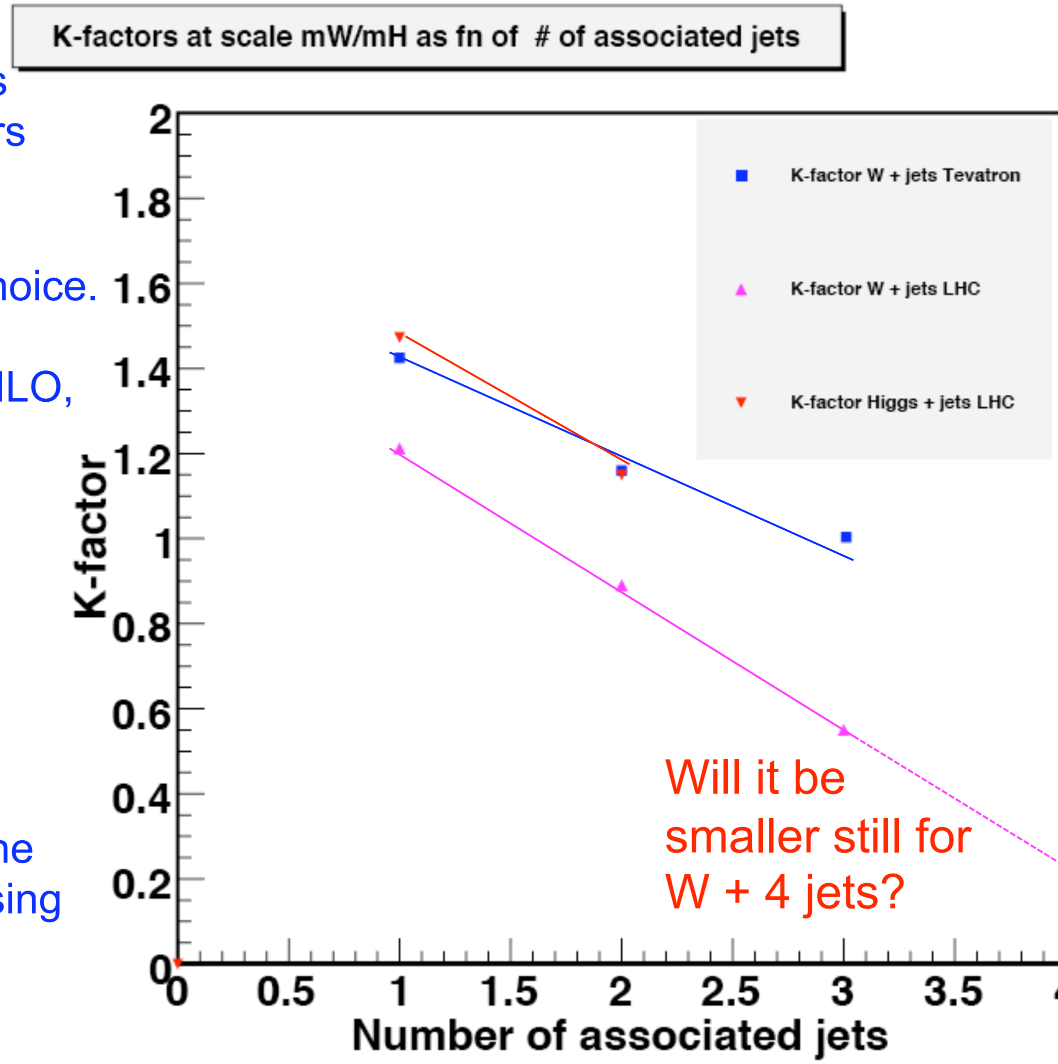
Nothing special about m_W; just a typical choice.

The only way to know a cross section to NLO, say for W + 4 jets or Higgs + 3 jets, is to calculate it, but in lieu of the calculations, especially for observables that we have deemed important at Les Houches, can we make rules of thumb?

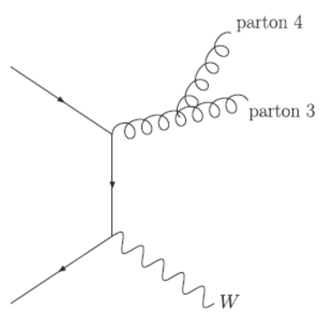
Related to this is:
- understanding the reduced scale dependences/pdf uncertainties for the cross section ratios we have been discussing
-scale choices at LO for cross sections calculated at NLO
-scale choices at LO for cross sections uncalculated at NLO



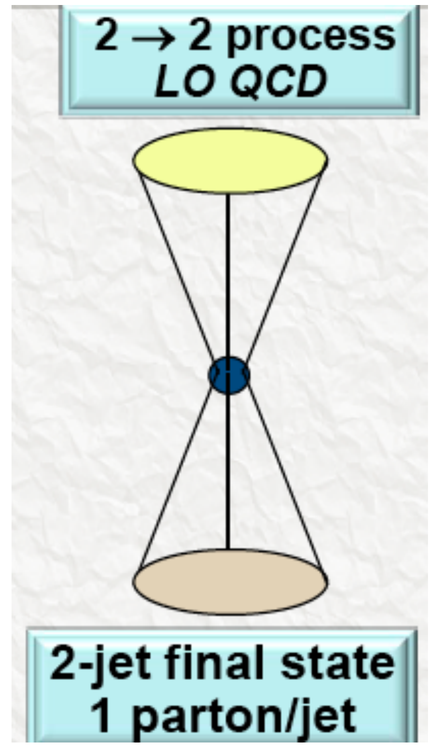
To understand this further, we have to discuss jet algorithms

Jet algorithms at LO

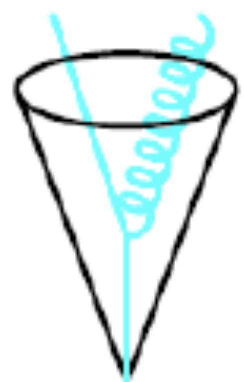
- At (fixed) LO, 1 parton = 1 jet
  - why not more than 1? I have to put a ΔR cut on the separation between two partons; otherwise, there's a collinear divergence. LO parton shower programs effectively put in such a cutoff
  - Remember the collinear singularity



$$\log\left(\frac{1}{\Delta R_{34}}\right)$$



- But at NLO, I have to deal with more than 1 parton in a jet, and so now I have to talk about how to cluster those partons
  - i.e. jet algorithms



Jet algorithms at NLO

- At NLO, there can be two partons in a jet, life becomes more interesting and we have to start talking about jet algorithms to define jets
  - the addition of the real and virtual terms at NLO cancels the divergences in each

$$d_{ij} = \min\left(p_{T,i}^{2p}, p_{T,j}^{2p}\right)\frac{\Delta R_{ij}^2}{D^2}$$

$$d_{ii} = p_{T,i}^{2p}$$

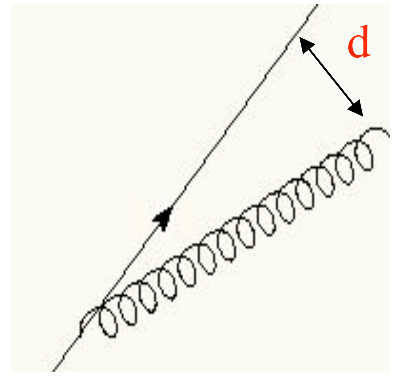
p=0; C-A
p=1: k_T
p=-1 anti-k_T

Pierre-Antoine Delsart's *reverse k_T*

- A jet algorithm is based on some measure of localization of the expected collinear spray of particles
- Start with an inclusive list of particles/partons/calorimeter towers/topoclusters
- End with lists of same for each jet
- …and a list of particles… not in any jet; for example, remnants of the initial hadrons
- Two broad classes of jet algorithms
  - cluster according to proximity in space: cone algorithms
  - ATLAS uses SISCone
  - cluster according to proximity in momenta: k_T algorithms
  - ATLAS uses k_T,antik_T

Jet algorithms at LO/NLO

- Remember at LO, 1 parton = 1 jet
- By choosing a jet algorithm with size parameter D, we are requiring any two partons to be > D apart
- The matrix elements have $1/\Delta R$ poles, so larger D means smaller cross sections
  - it's because of the poles that we have to make a ΔR cut
- At NLO, there can be two (or more) partons in a jet and jets for the first time can have some structure
  - we don't need a ΔR cut, since the virtual corrections cancel the collinear singularity from the gluon emission
  - **but there are residual logs that can become important if D is too small**
- Also, increasing the size parameter D increases the phase space for including an extra gluon in the jet, and thus increases the cross section at NLO (in most cases)



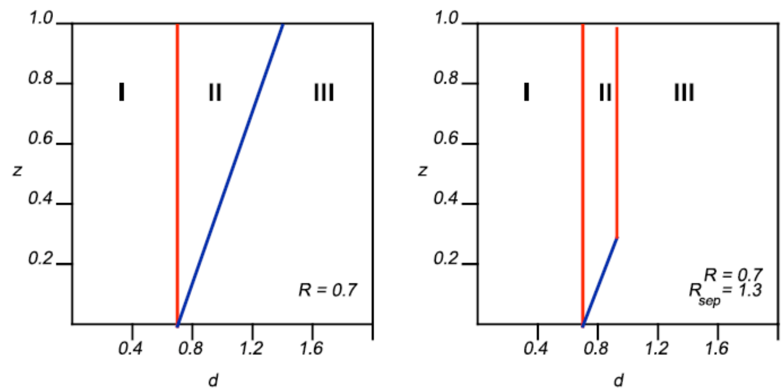
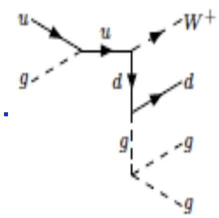


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

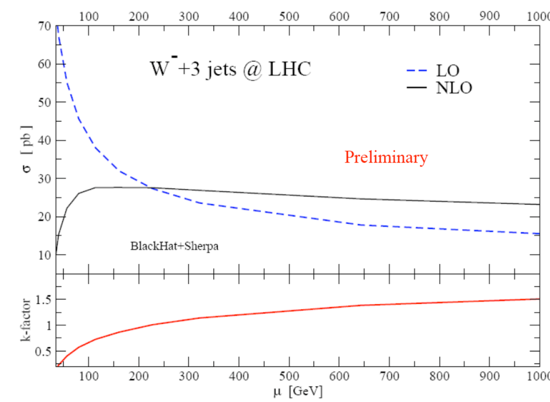
For D=R_{cone}, Region I = k_T jets, Region II (nominally) = cone jets; I say nominally because in data not all of Region II is included for cone jets

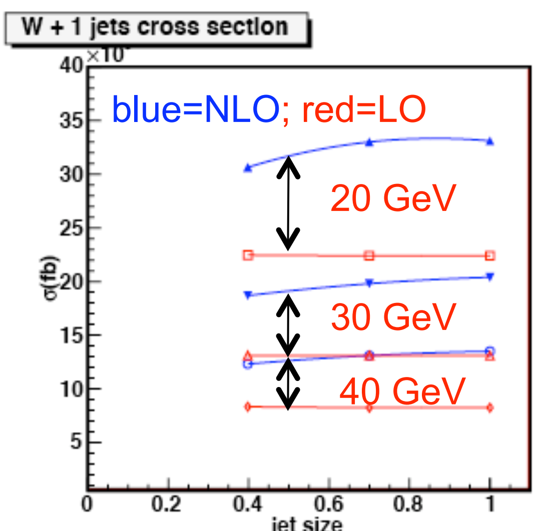
Is the K-factor (at m_W) at the LHC surprising?

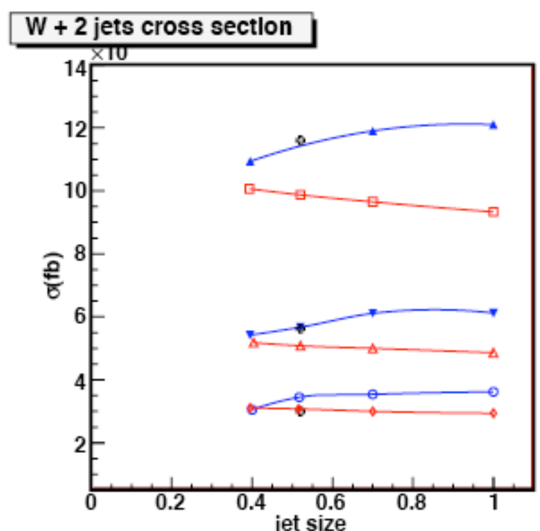
The problem is not the NLO cross section; that is well-behaved.
The problem is that the LO cross section sits 'too-high'. The reason (one of them) for this is that we are 'too-close' to the collinear pole (R=0.4) leading to an enhancement of the LO cross section (double-enhancement if the gluon is soft (~20 GeV/c)). Note that at LO, the cross section increases with decreasing R; at NLO it decreases.
The collinear dependence gets stronger as n_{jet} increases.
The K-factors for W + 3 jets would be more *normal* (>1) if a larger cone size and/or a larger jet p_T cutoff were used. But that's a LO problem; the best approach is to use the appropriate jet sizes/jet p_T's for the analysis and understand the best scales to use at LO (matrix element + parton shower) to approximate the NLO calculation (as well as comparing directly to the NLO calculation).

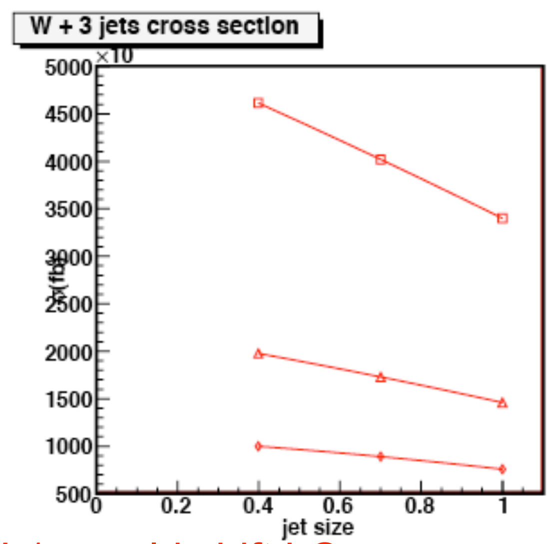


LHC total cross section







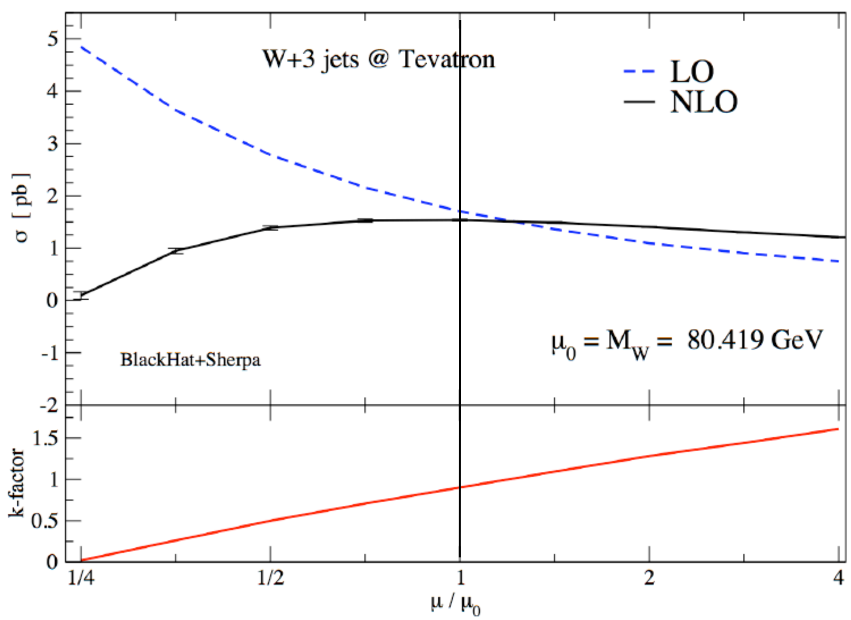


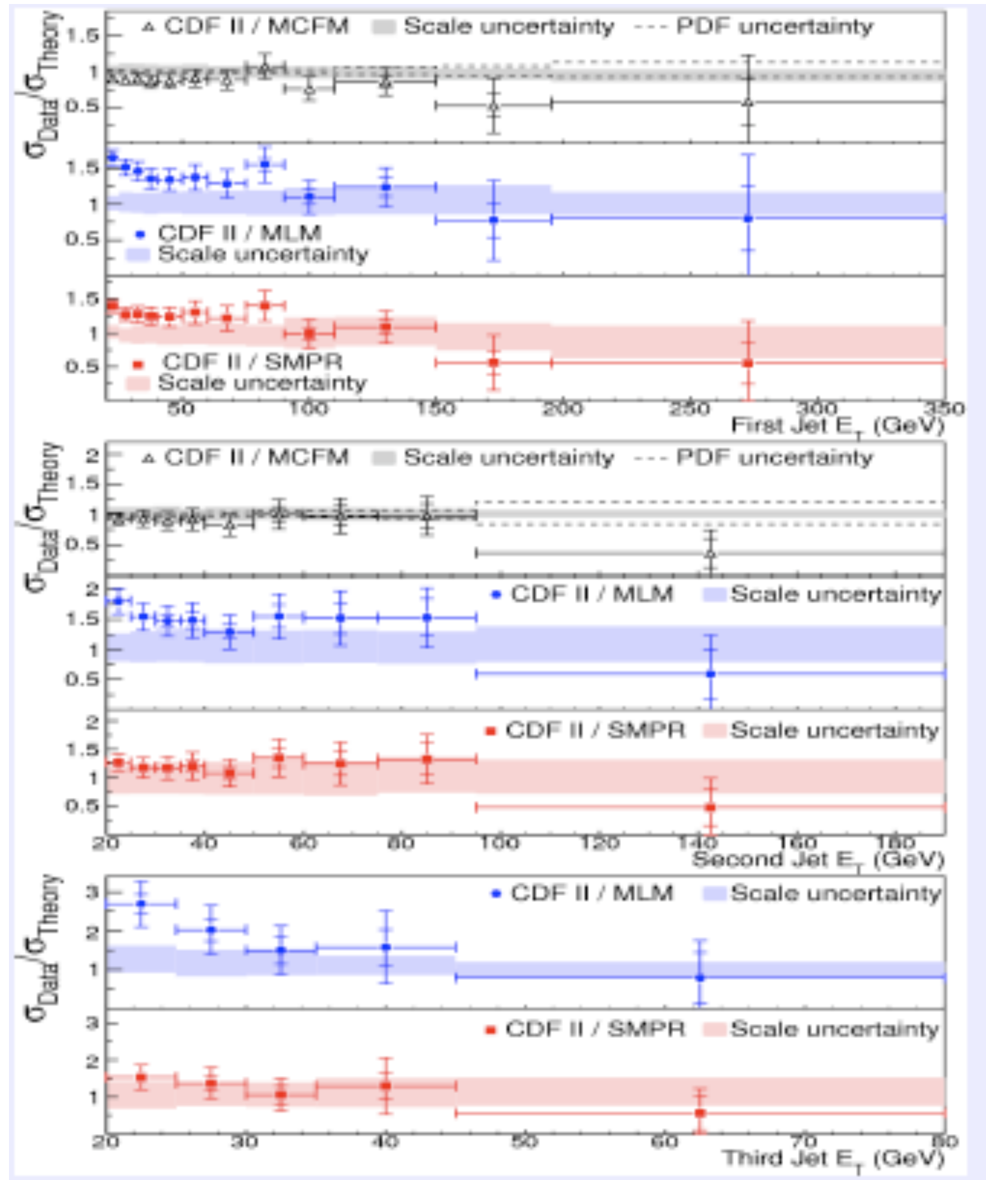
For 3 jets, the LO collinear singularity effects are even more pronounced.

NB: here I have used CTEQ6.6 for both LO and NLO; CTEQ6L1 would shift LO curves up

Scale choices at the Tevatron: W + jets

- At the Tevatron, m_W is a reasonable scale (in terms of K-factor~1)



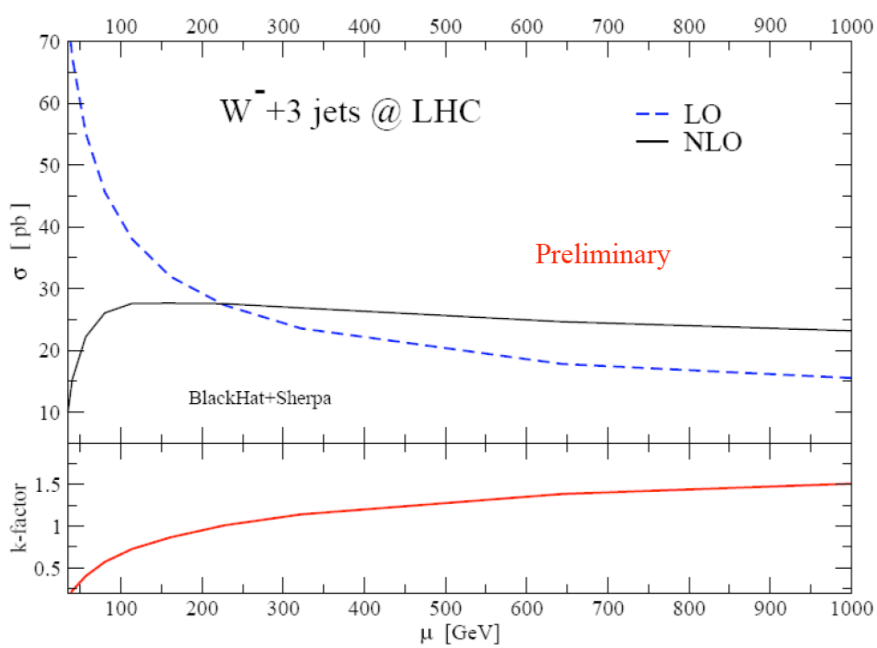


W + 3 jets at the LHC

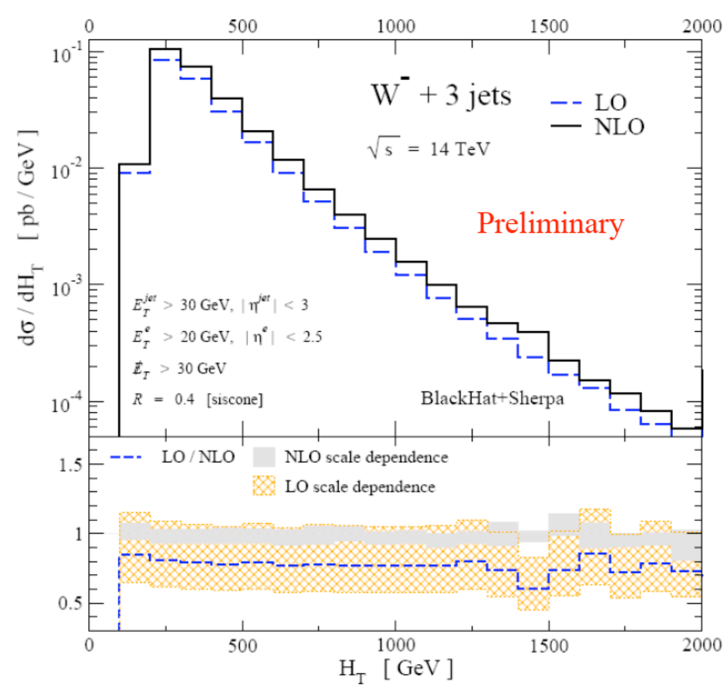
A scale choice of m_W would be in a region where LO >> NLO. In addition, such a scale choice (or related scale choice), leads to sizeable shape differences in the kinematic distributions. The Blackhat+Sherpa people found that a scale choice of H_T worked best to get a constant K-factor for all distributions that they looked at.

Note that from the point-of-view of only NLO, all cross sections with scales above ~100 GeV seem reasonably stable

LHC total cross section



$H_T = \sum_j E_{T,j}^{\rm jet} + E_T^e + \not{E}_T$ distribution



mu = H_T

Jet sizes and scale uncertainties: the Goldilocks theorm

- Take inclusive jet production at the LHC for transverse momenta of the order of 50 GeV
- Look at the theory uncertainty due to scale dependence as a function of jet size
- It appears to be a minimum for cone sizes of the order of 0.7
  - i.e. if you use a cone size of 0.4, there are residual un-cancelled virtual effects
  - if you use a cone size of 1.0, you are adding too much tree level information with its intrinsically larger scale uncertainty
- This effect becomes smaller for jet p_T values on the order of 100 GeV/c
  - how does it translate for multi-parton final states?
  - currently under investigation

Jets at NLO: more complications

- Construct what is called a Snowmass potential

shown in Figure 50, where the towers unclustered into any jet are shaded black. A simple way of understanding these dark towers begins by defining a "Snowmass potential" in terms of the 2-dimensional vector $\vec{r} = (y, \phi)$ via

$$V(\vec{r}) = -\frac{1}{2}\sum_j p_{T,j}\left(R_{cone}^2 - (\vec{r_j} - \vec{r})^2\right)\Theta\left(R_{cone}^2 - (\vec{r_j} - \vec{r})^2\right). \quad (39)$$

The flow is then driven by the "force" $\vec{F}(\vec{r}) = -\vec{\nabla}V(\vec{r})$ which is thus given by,

$$\vec{F}(\vec{r}) = \sum_j p_{T,j}(\vec{r_j} - \vec{r})\Theta\left(R_{cone}^2 - (\vec{r_j} - \vec{r})^2\right) = \left(\vec{r}_{C(\vec{r})} - \vec{r}\right)\sum_{j \subset C(r)} p_{T,j}, \quad (40)$$

where $\vec{r}_{C(\vec{r})} = \left(\overline{y}_{C(\vec{r})}, \overline{\phi}_{C(\vec{r})}\right)$ and the sum runs over $j \subset C(\vec{r})$ such that $\sqrt{(y_j - y)^2 + (\phi_j - \phi)^2} \leq R_{cone}$. As desired, this force pushes the cone to the stable cone position.

- The minima of the potential function indicates the positions of the stable cone solutions
  - the derivative of the potential function is the force that shows the direction of flow of the iterated cone
- The midpoint solution contains both partons

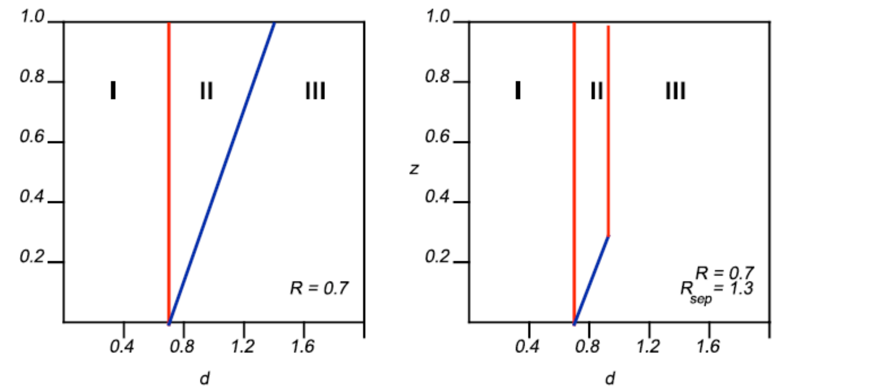


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

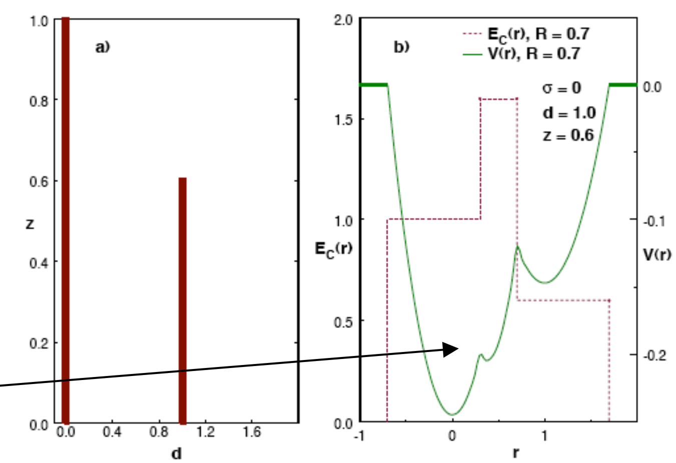


Figure 51. A schematic depiction of a specific parton configuration and the results of applying the midpoint cone jet clustering algorithm. The potential discussed in the text and the resulting energy in the jet are plotted.

Jets in real life

- Jets don't consist of 1 fermi partons but have a spatial distribution
- Can approximate jet shape as a Gaussian smearing of the spatial distribution of the parton energy
  - the effective sigma ranges between around 0.1 and 0.3 depending on the parton type (quark or gluon) and on the parton p_T
- Note that because of the effects of smearing that
  - the midpoint solution is (**almost always**) lost
    - thus region II is effectively truncated to the area shown on the right
  - the solution corresponding to the lower energy parton can also be lost
    - resulting in dark towers

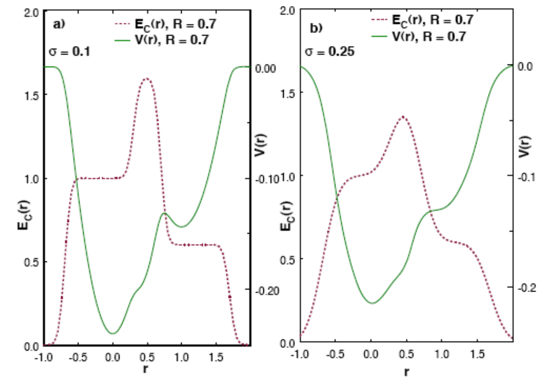


Figure 52. A schematic depiction of the effects of smearing on the midpoint cone jet clustering algorithm

remember the Snowmass potentials

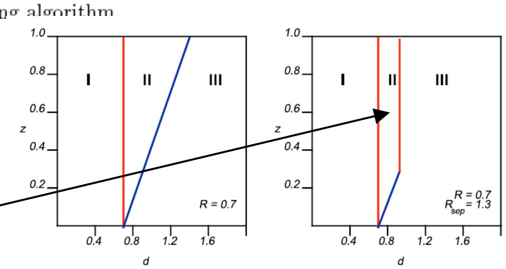


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

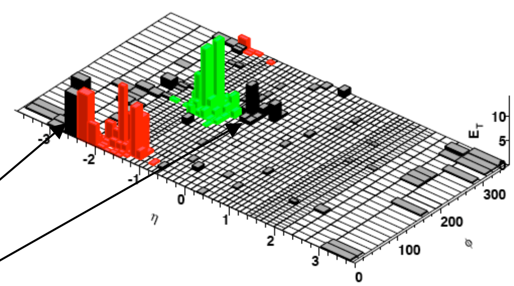


Figure 50. An example of a Monte Carlo inclusive jet event where the midpoint algorithm has left substantial energy unclustered.

Jets in real life

- In NLO theory, can mimic the impact of the truncation of Region II by including a parameter called R_{sep}
  - only merge two partons if they are within R_{sep}*R_{cone} of each other
    - R_{sep}~1.3
  - ~4-5% effect on the theory cross section; effect is smaller with the use of p_T rather than E_T
  - really upsets the theorists (but there are also disadvantages)
- Dark tower effect is also on order of few (<5)% effect on the (experimental) cross section
- Dark towers affect every cone algorithm

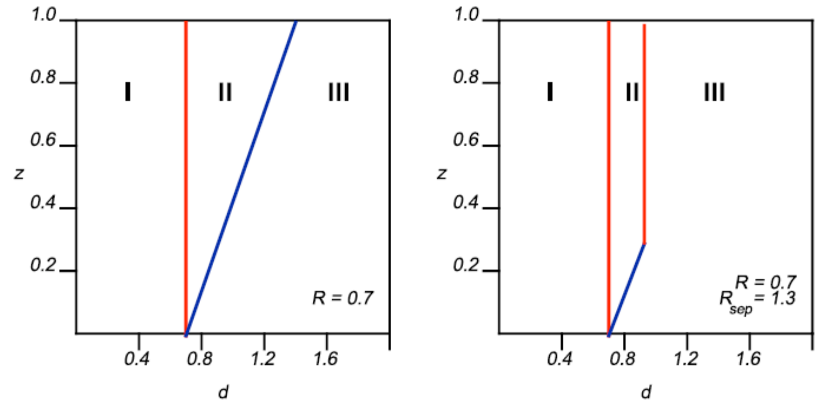
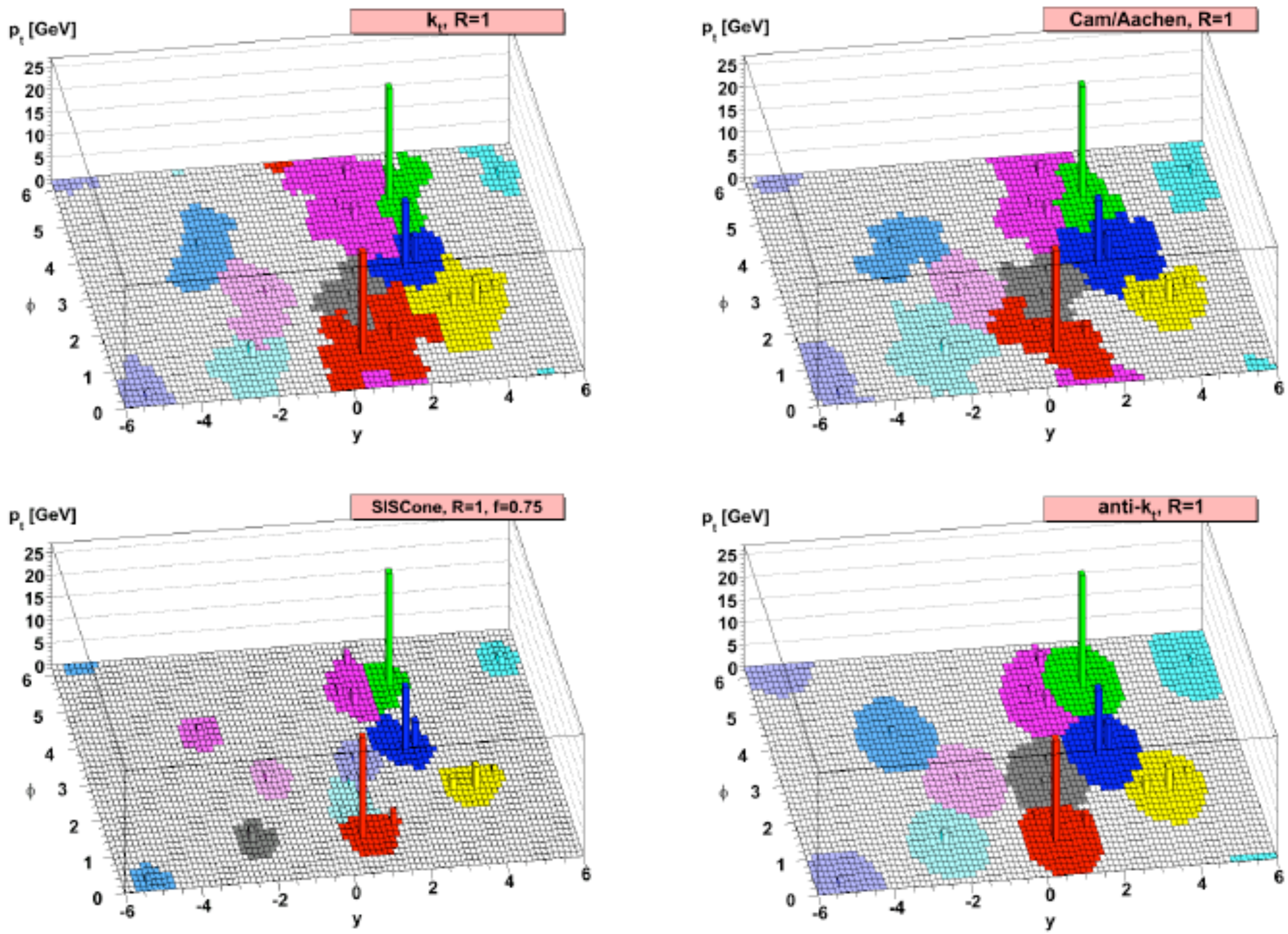


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

UE/pileup corrections: Jet areas



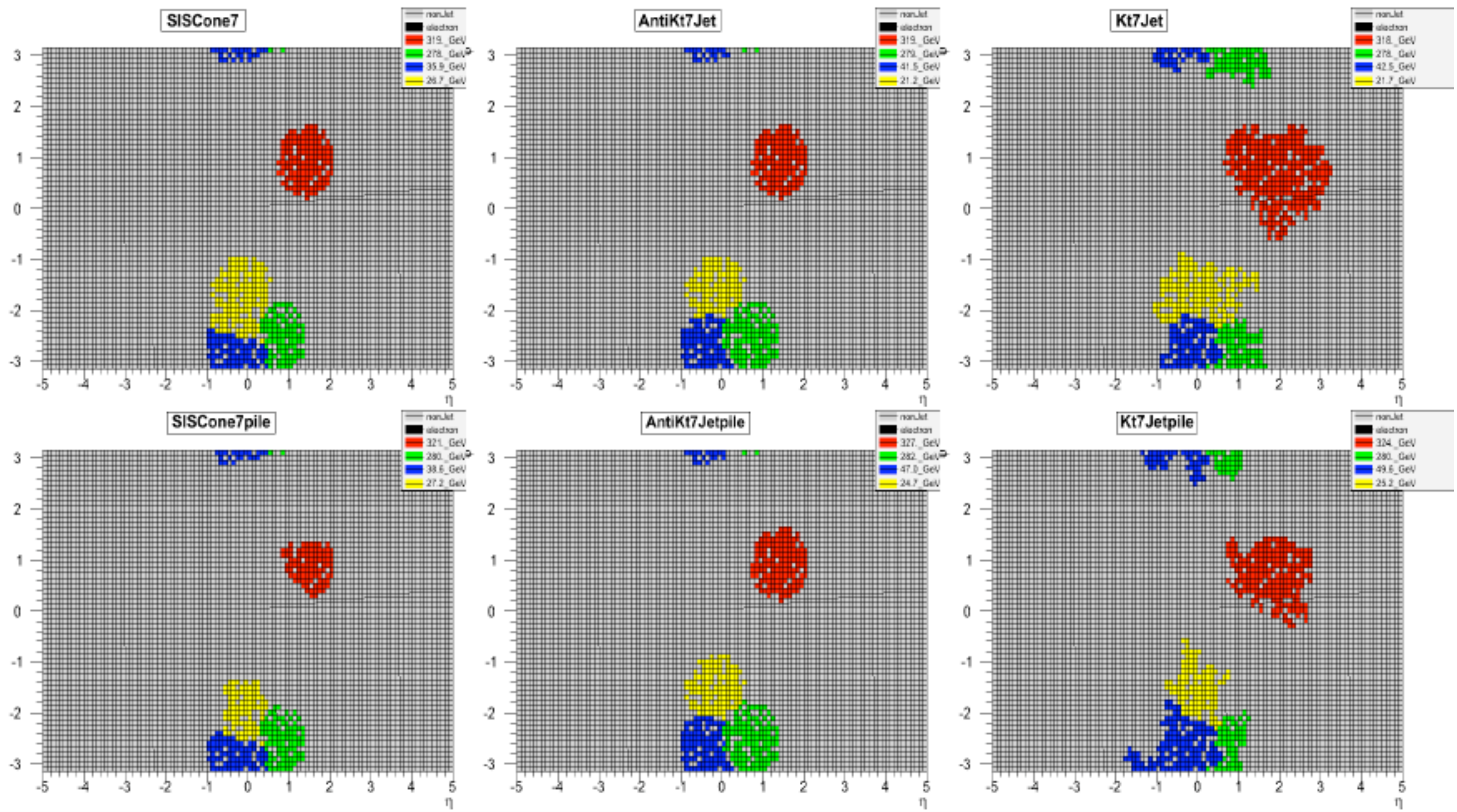
determined by clustering ghost particles of vanishing energy; see jet references

note that the k_T algorithm has the largest jet areas, SISCone the smallest and anti-k_T the most regular; one of the reasons we like the antikt

Jet areas in presence of pileup

- Single W+4jets event, all matched to partons.
- SISCone and kT show decreased area in presence of pileup

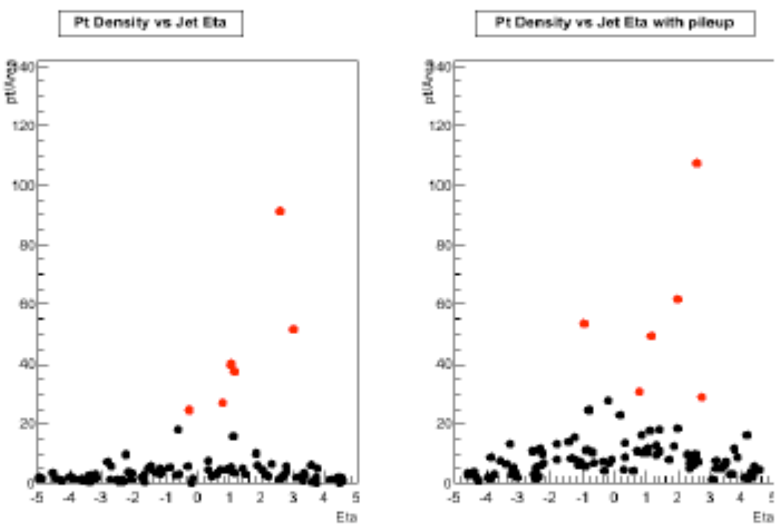
pileup nibbles away at perimeter of jet



Area-based correction: Cacciari/Salam/Soyez

1) Find low p_T jets in event. (< 10GeV) We use kT5jet.
2) From these, find average/median pT density of event ρ
3) Determine area A of signal jets
4) Subtract "pileup/UE"estimate

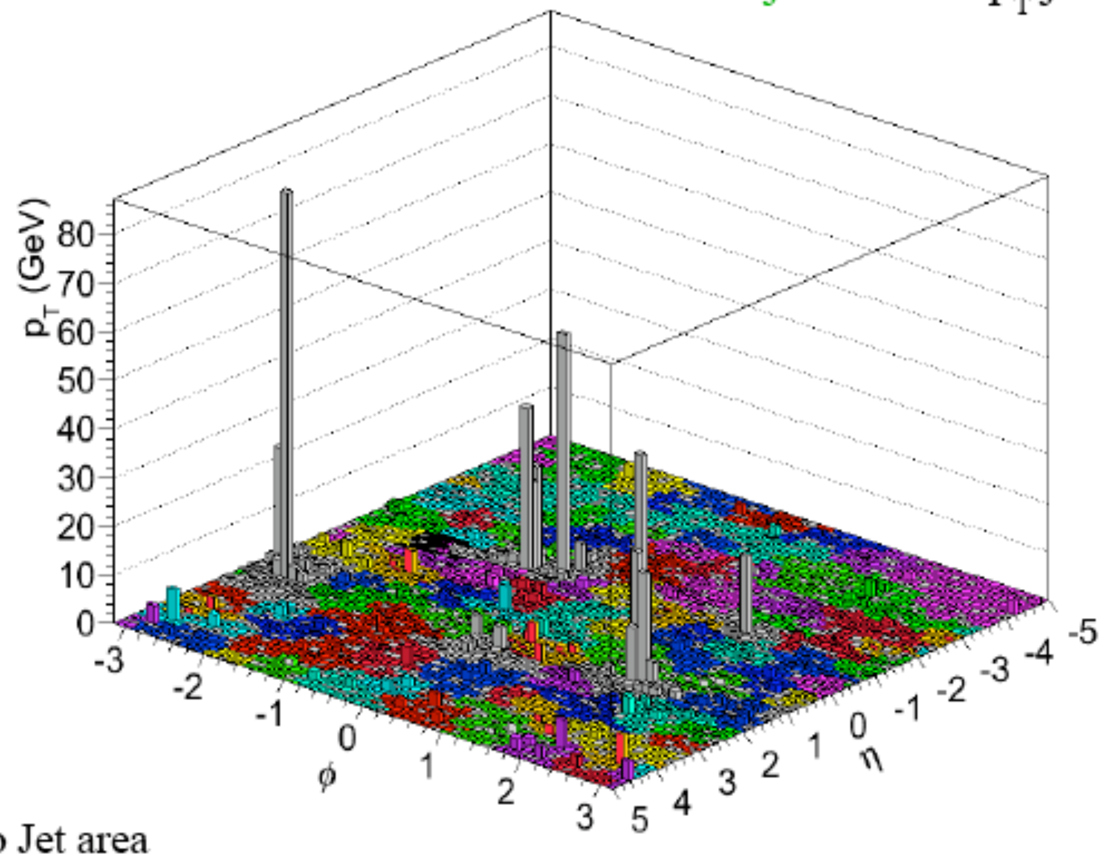
$$p_{Tcorr} = p_T - \rho A$$



W+5j event with kT5Jets

Gray jets = Signal Jets

Colored jets = Low p_T jets

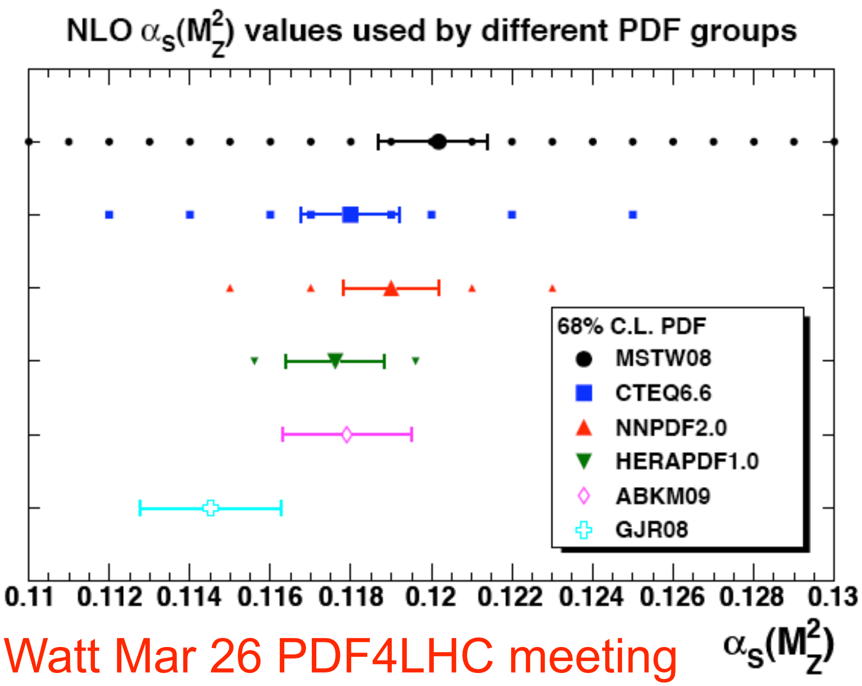


- Black points used to find pT density
- Red points are then corrected according to Jet area

See presentations of Brian Martin in ATLAS jet meetings. Used in SpartyJet.

$\alpha_s(m_Z)$ and uncertainty: a complication

- Different values of α_s and of its uncertainty are used
- CTEQ and NNPDF use the world average (actually 0.118 for CTEQ and 0.119 for NNPDF), where MSTW2008 uses 0.120, as determined from their best fit



G. Watt Mar 26 PDF4LHC meeting

- Latest world average (from Siggi Bethke->PDG)
  - α_s (m_Z) = 0.1184 +/- 0.0007
- What does the error represent?
  - Siggi said that only one of the results included in his world average was outside this range
  - suppose we say that +/-0.002 is a reasonable estimate of the uncertainty

$\alpha_s(m_Z)$ and uncertainty

- Could it be possible for all global PDF groups to use the world average value of α_s in their fits, plus a prescribed 90% range for its uncertainty (if not 0.002, then perhaps another acceptable value)?
- After that, world peace
- For the moment, we try determining uncertainties from α_s over a range of +/- 0.002 from the central value for each PDF group; we also calculate cross sections with a common value of α_s=0.119 for comparison purposes

My recommendation to PDF4LHC/Higgs working group

- Cross sections should be calculated with MSTW2008, CTEQ6.6 and NNPDF
- Upper range of prediction should be given by upper limit of error prediction using prescription for combining α_s uncertainty with error PDFs
  - in quadrature for CTEQ6.6 and NNPDF
  - using eigenvector sets for different values of α_s for MSTW2008
  - note that this effectively creates a larger α_s uncertainty range
- Ditto for lower limit
- So for a Higgs mass of 120 GeV at 14 TeV,it turns out that the gg cross section lower limit would be defined by the CTEQ6.6 lower limit (PDF+α_s error) and the upper limit defined by the MSTW2008 upper limit (PDF+α_s error)
  - with the difference between the central values primarily due to α_s
  - I'll come back to using the Higgs as an example in the last lecture
- To fully understand similarities/differences of cross sections/uncertainties conduct a benchmarking exercise, to which all groups are invited to participate