First Results from the LHC

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LHC and approved experiments

LHC schedule

Milestones:

- 10 Sep. 2008: First proton beam
- 20 Nov. 2009: Restart after accident
- 23 Nov. 2009: First proton collisions at 900 GeV
- 30 Nov. 2009: World record energy 2.36 TeV
- 30 March 2010: New world record energy 7 TeV
- 8 Nov. 2010: First collisions of lead ions at 2.76 TeV per nucleon pair
- 6 Dec. 2010: Last day of LHC running in 2010
- March 2011: Restart with protons at 7 TeV … then maybe go to 8 TeV
- 2012: Shutdown for magnet interconnection reinforcement … OR keep running!
- 2013: Restart at 13 or 14 TeV
- 2015 or 2016: Shutdown for luminosity upgrade

LHC achievements and prospects with protons

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

Integrated proton luminosities

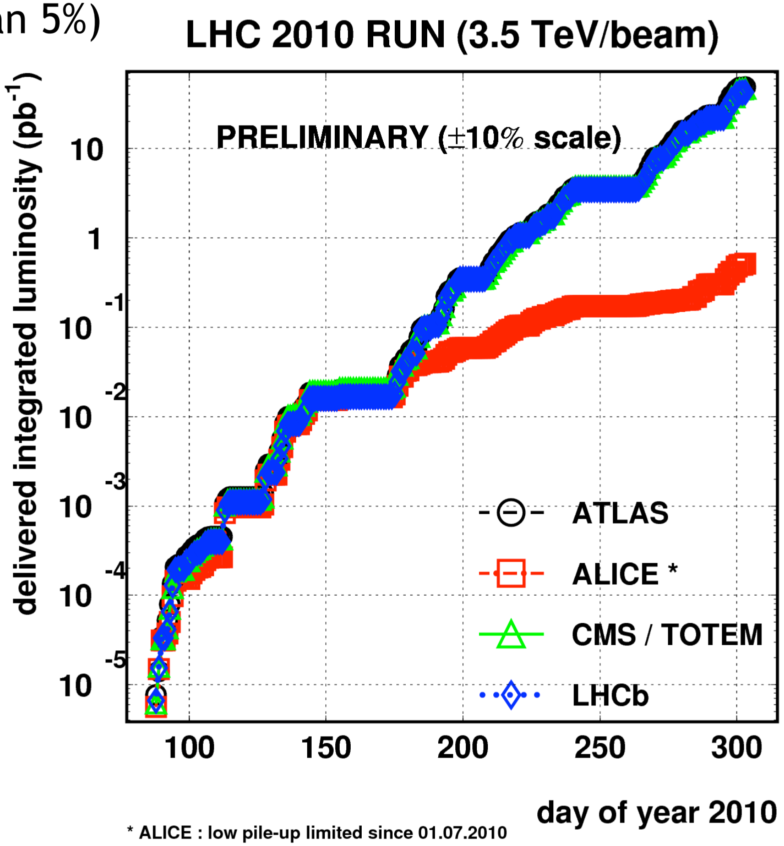
- Almost 50 pb^{-1} delivered per experiment
  (except ALICE: to keep pile-up in the TPC at less than 5%)
- > 1 fb^{-1} till end of 2011,
  maybe 5 – 10 fb^{-1} if running in 2012
- 250 to 300 fb^{-1} till end of 7 TeV Phase

Peak luminosity: 2 x 10^{32} $cm^{-2}s^{-1}$

Number of bunches: 368 per beam

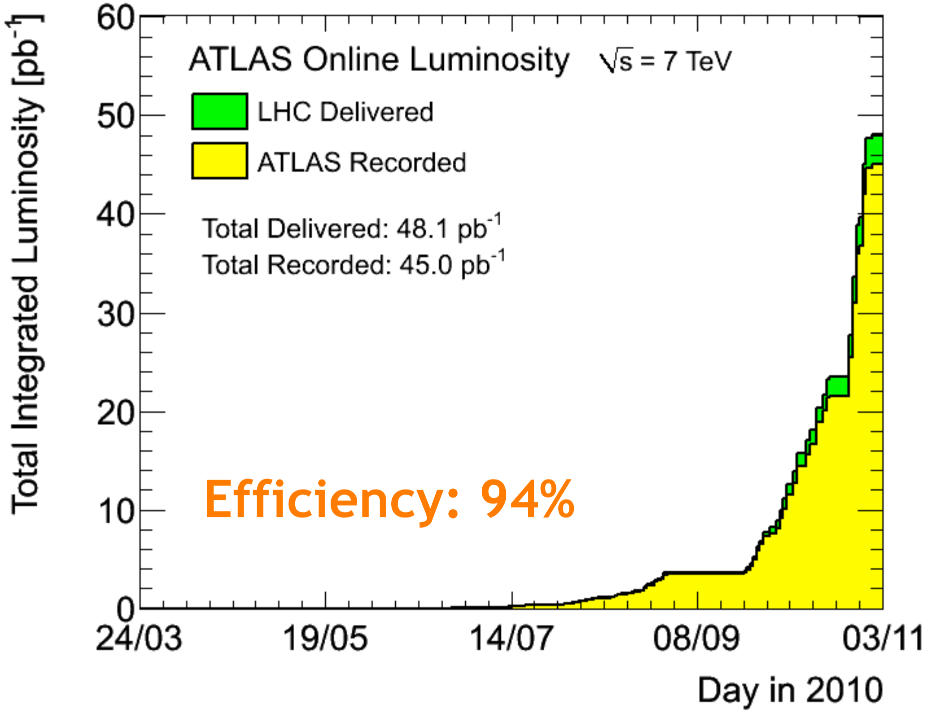
Stored beam energy: 25 MJ

Bunch spacing: 150 ns, 75 ns and 50 ns

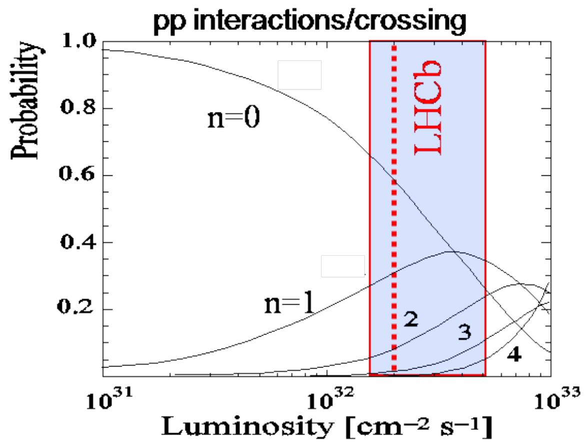


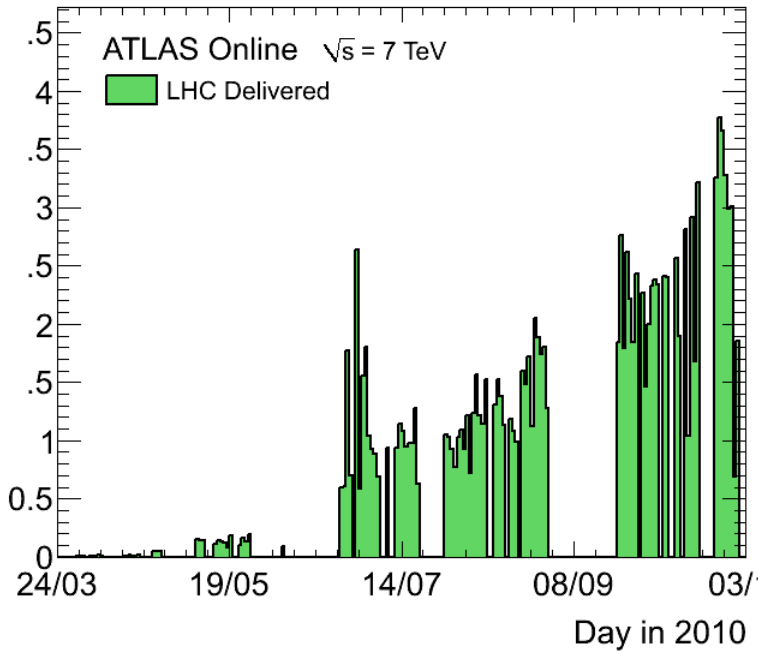
Luminosities, multiple interactions

Delivered and recorded total integrated proton luminosities

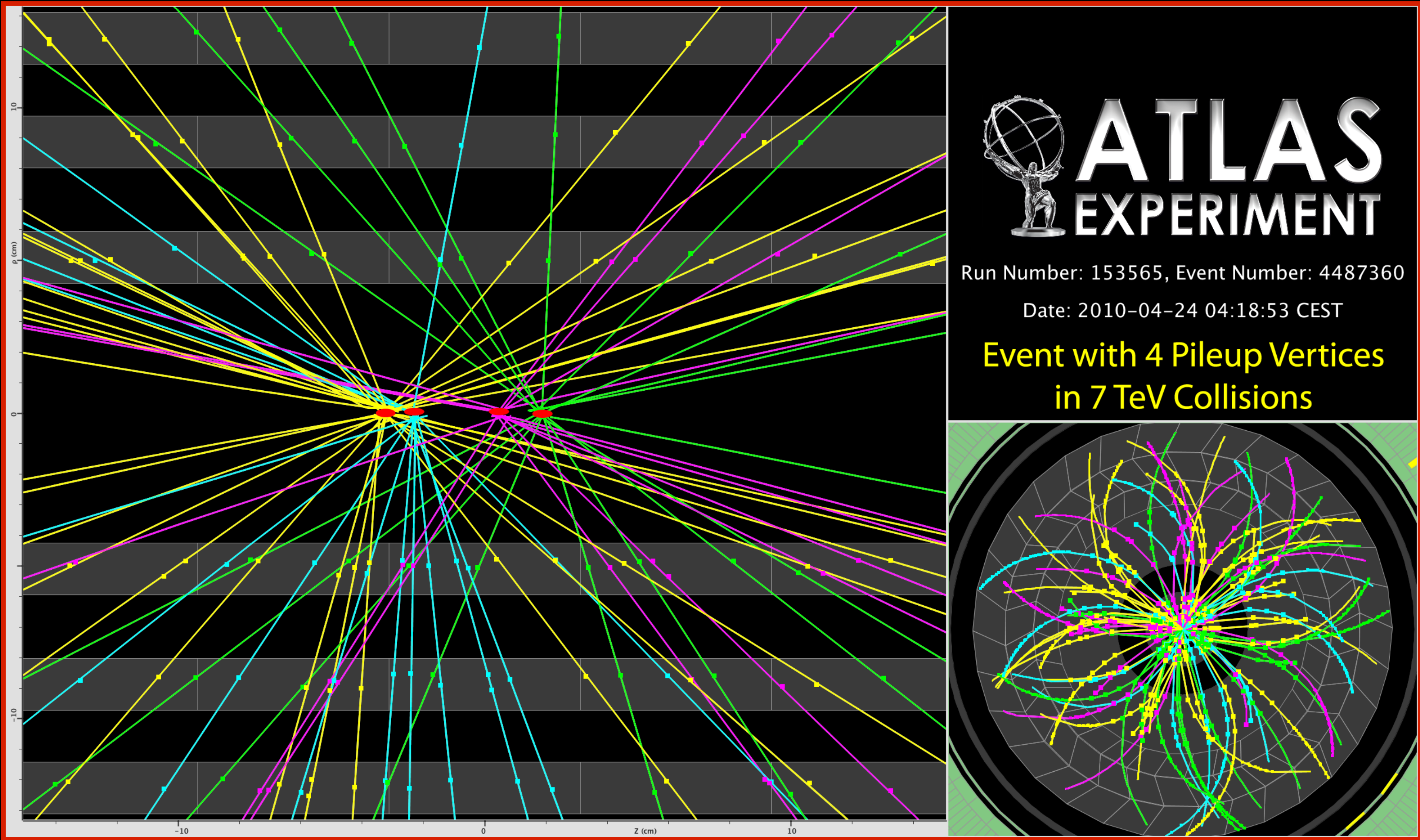


Superimposed interactions





Multiple vertices



~ 10-45 tracks with p_T > 150 MeV per vertex
z-positions of vertices : −3.2, −2.3, 0.5, 1.9 cm (vertex resolution better than ~200 µm)

Physics goals of the multi-purpose experiments ATLAS and CMS

Standard Model physics

- confirmation and search for the Standard Model Higgs boson

Discovery physics beyond the Standard Model (examples)

- Search for any deviations from the Standard Model
- Supersymmetry, Dark Matter
- Compositeness, Leptoquarks
- Extra dimensions, Black Holes
- W', Z'

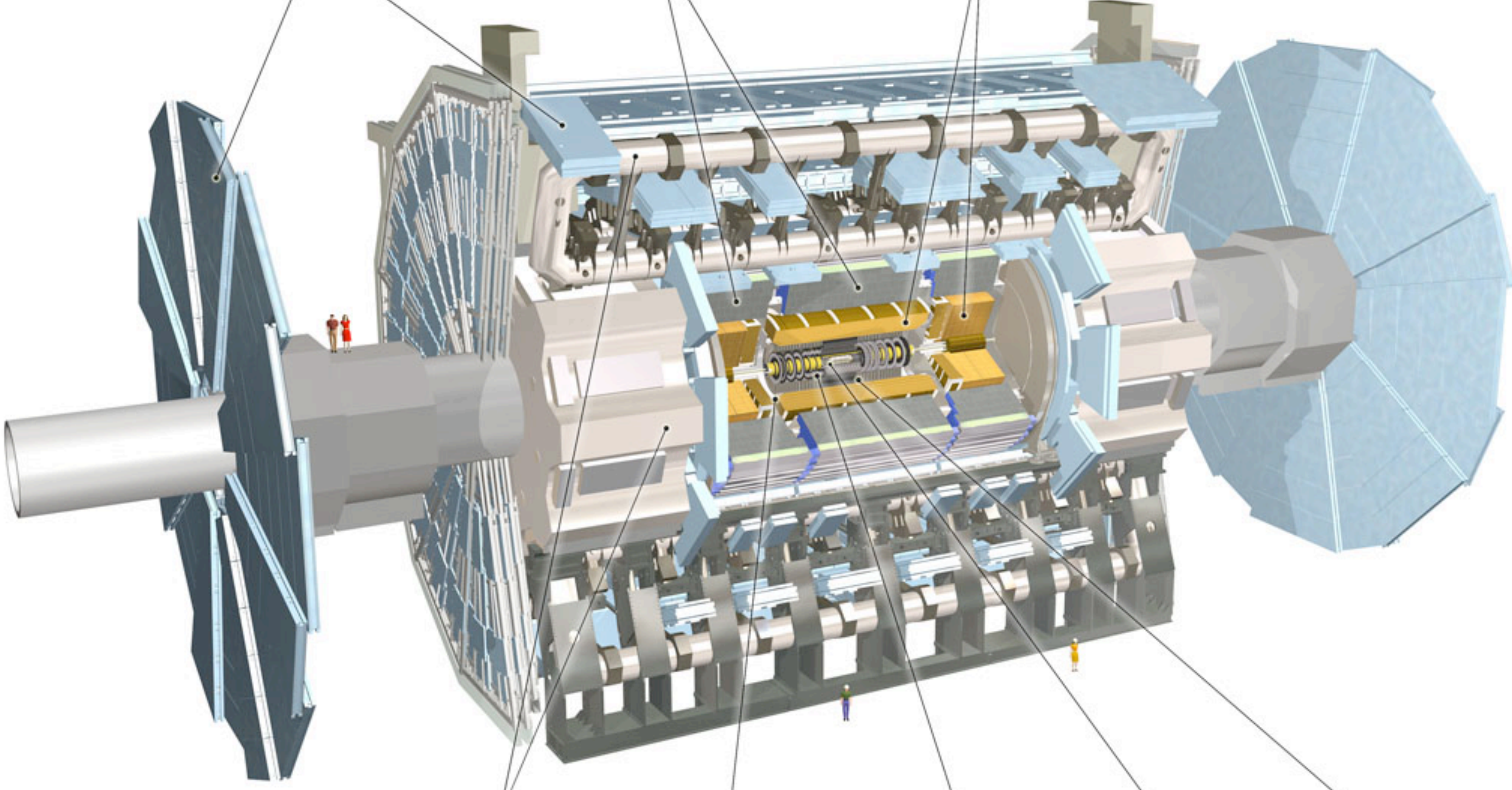
Precision measurements (examples)

- W mass
- Top mass and couplings
- Higgs parameters (masses, spins, couplings)
- QCD: cross sections, α_s
- B physics: CP violation, rare decays of B hadrons, B^0-$\bar{B}^0$ oscillations

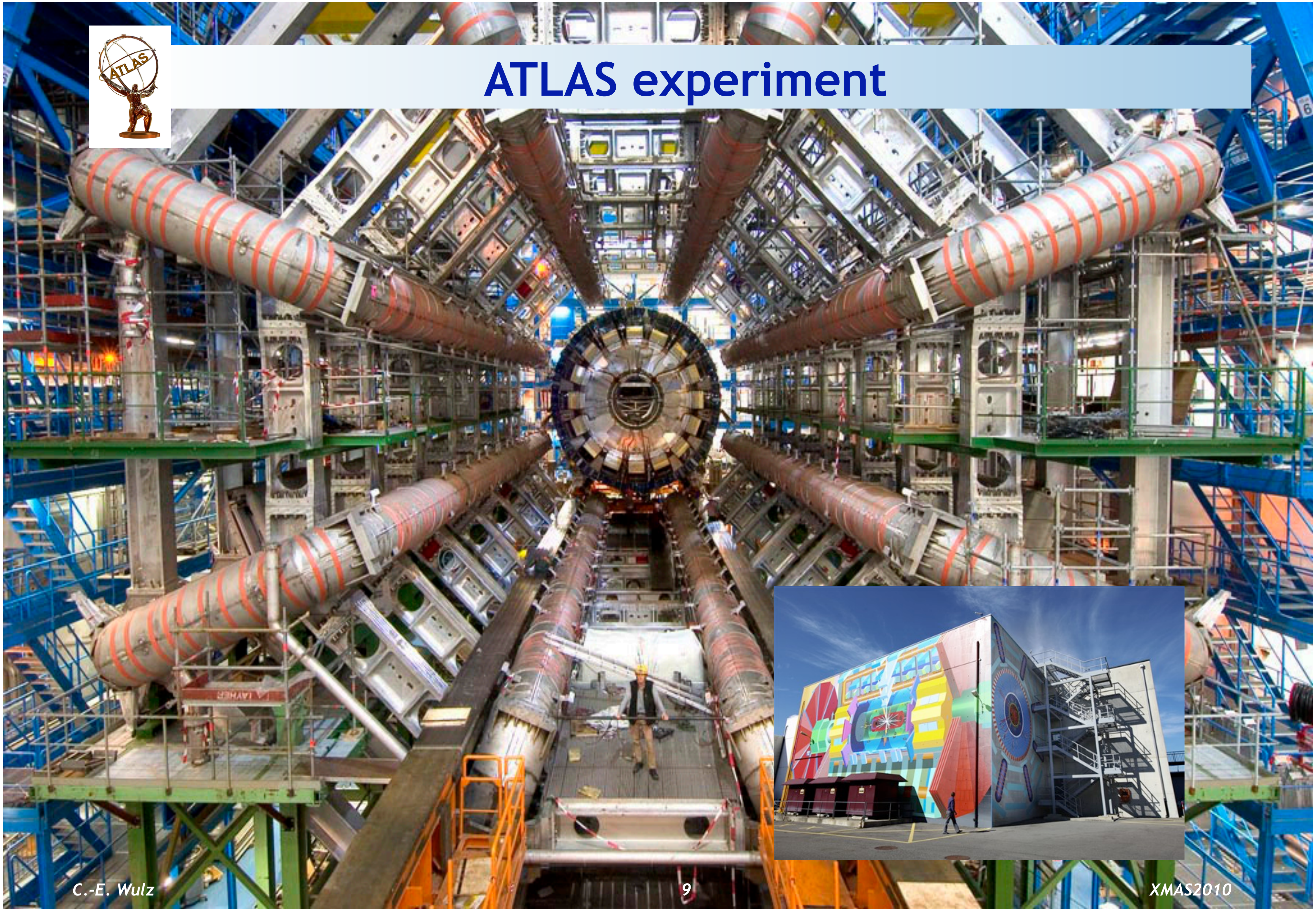
Heavy Ion Physics

- Quark-gluon plasma

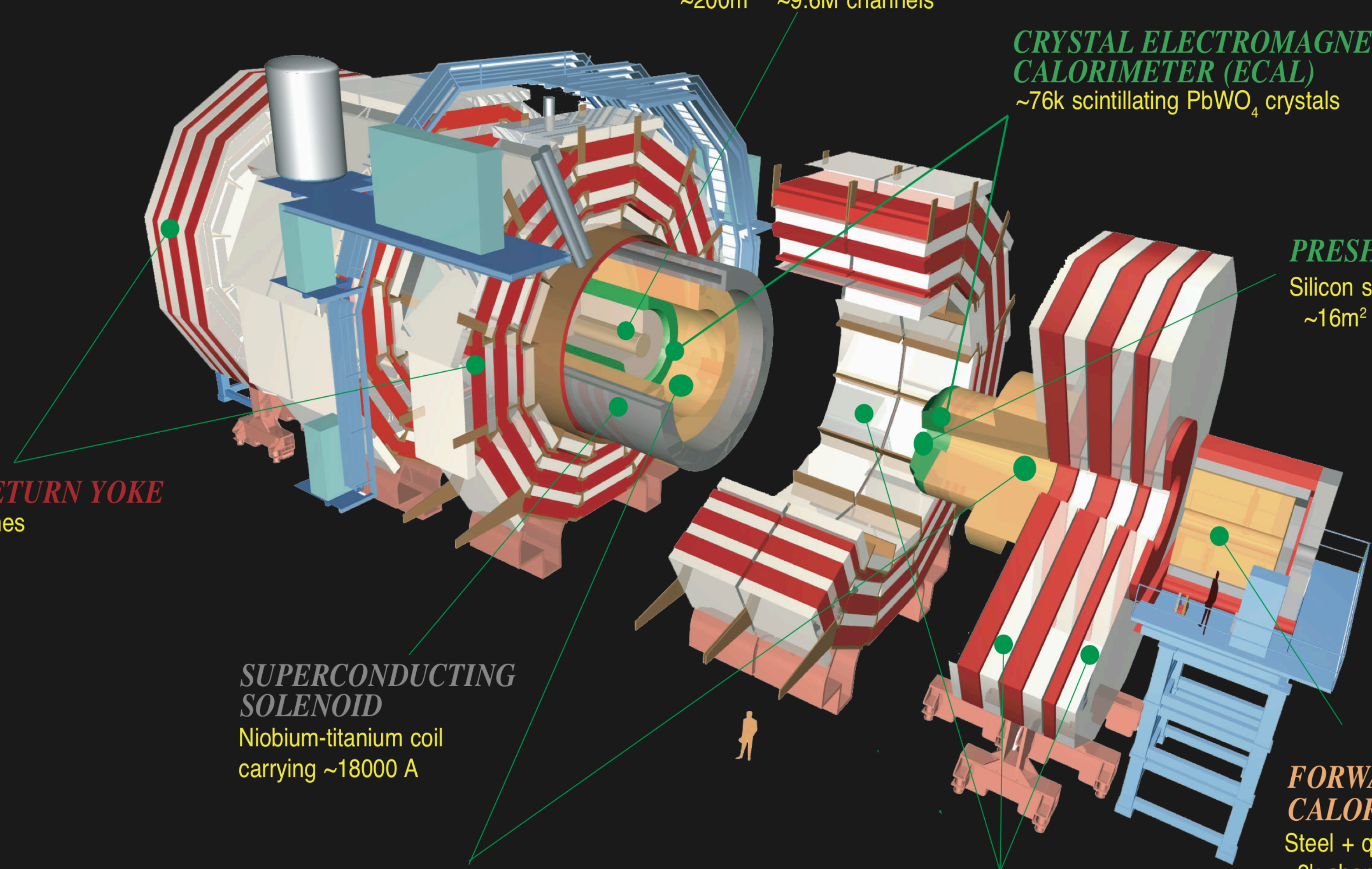
ATLAS experiment



ATLAS experiment

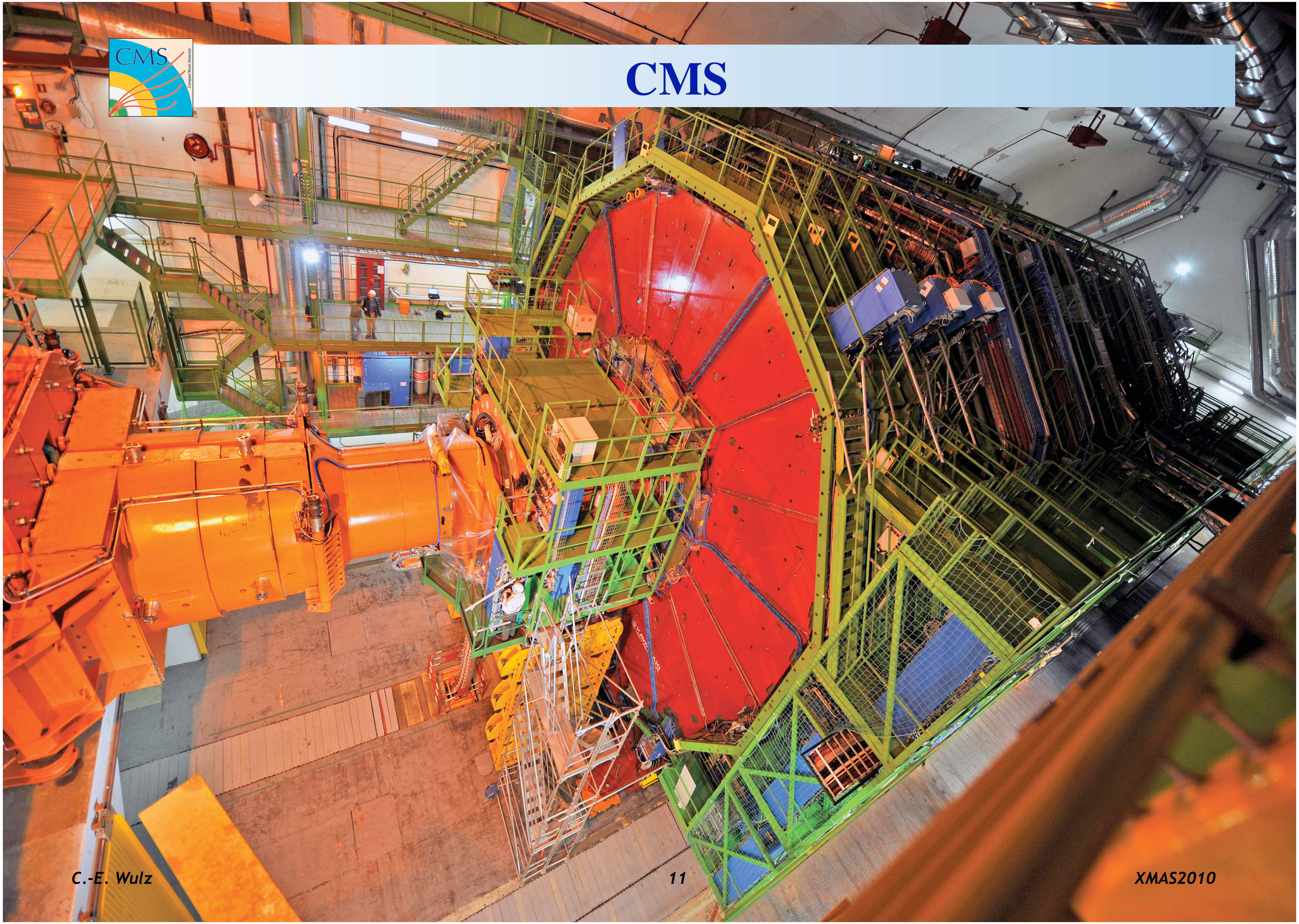


CMS Detector



Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

CMS



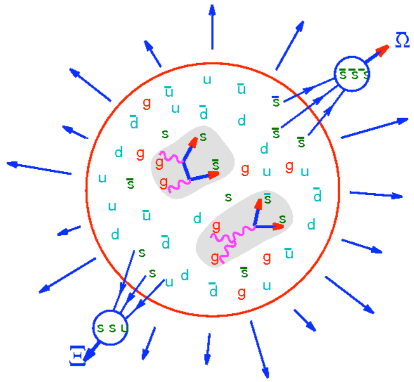
Physics goals of ALICE

Heavy ion physics (about 1 month per year, 28 x RHIC energies)

- Study of matter at high density and temperature (QGP)

  - Strangeness enhancement:

s, heavier than u and d, can only be produced by gluon fusion at high energies



  - Suppression of J/ψ, Y

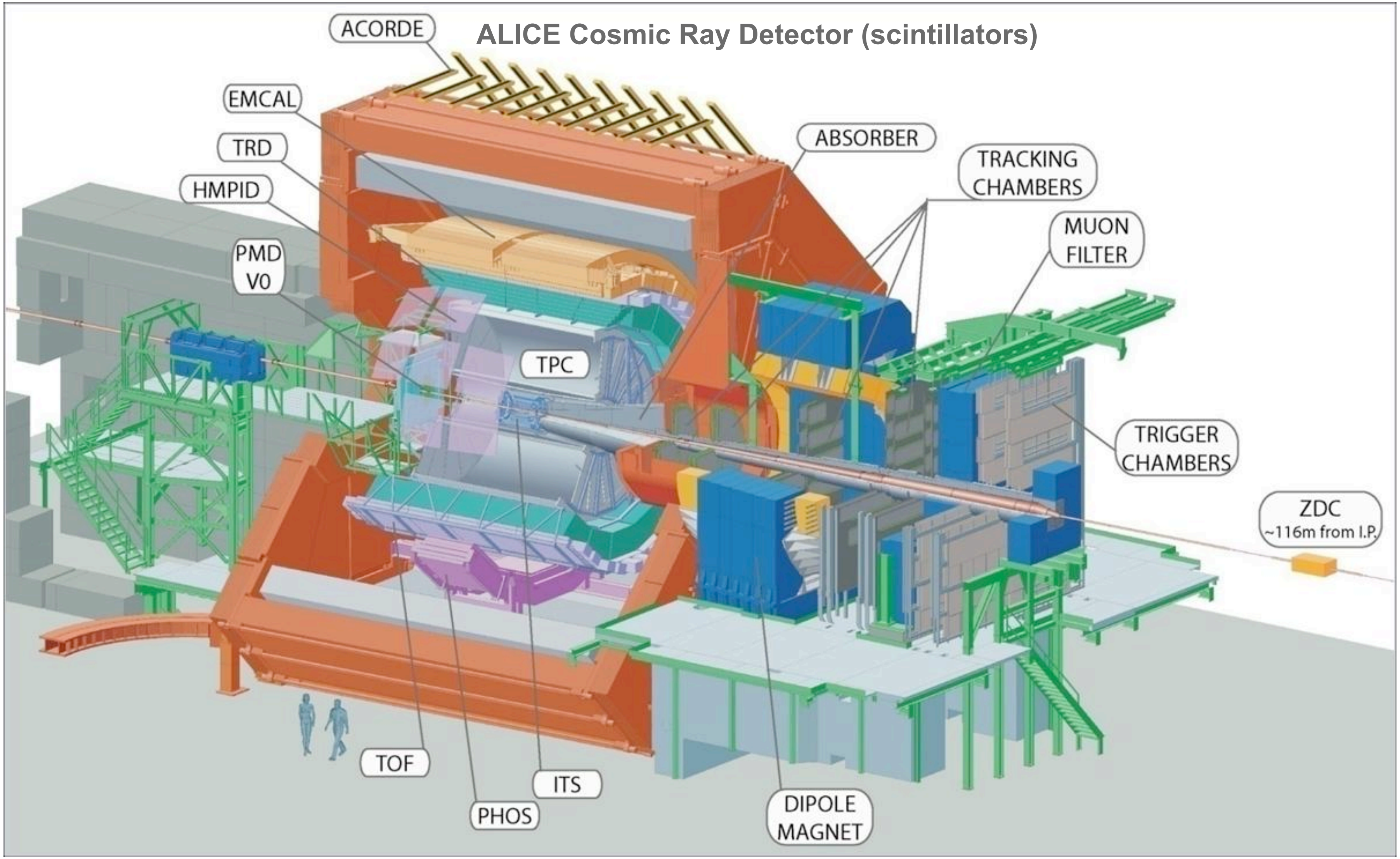
  - Jet Quenching

  - Color glass condensate (CGC): cold and dense (high gluon density)

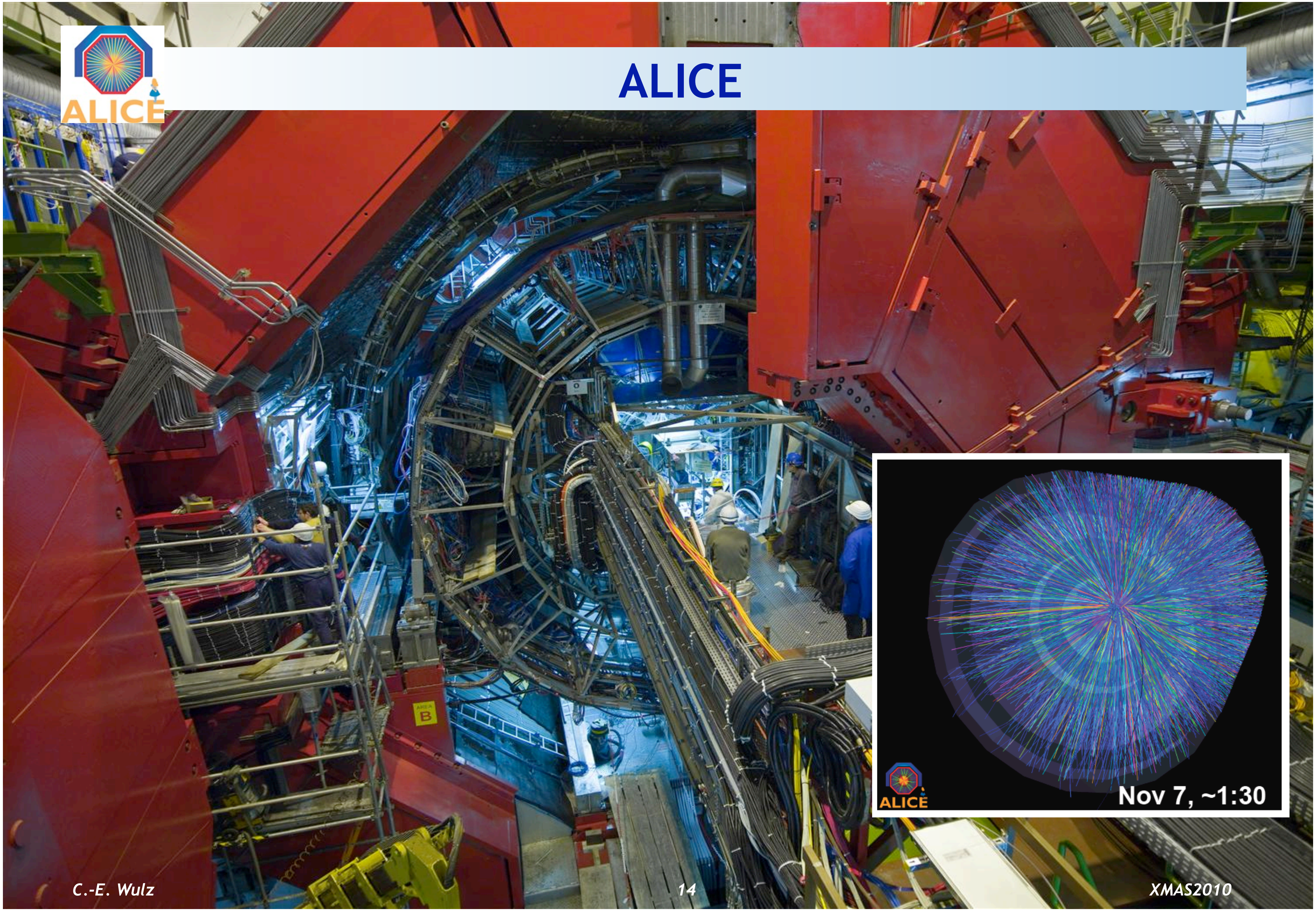
Proton physics

- mainly QCD

ALICE dector



ALICE



Physics goals of LHCb

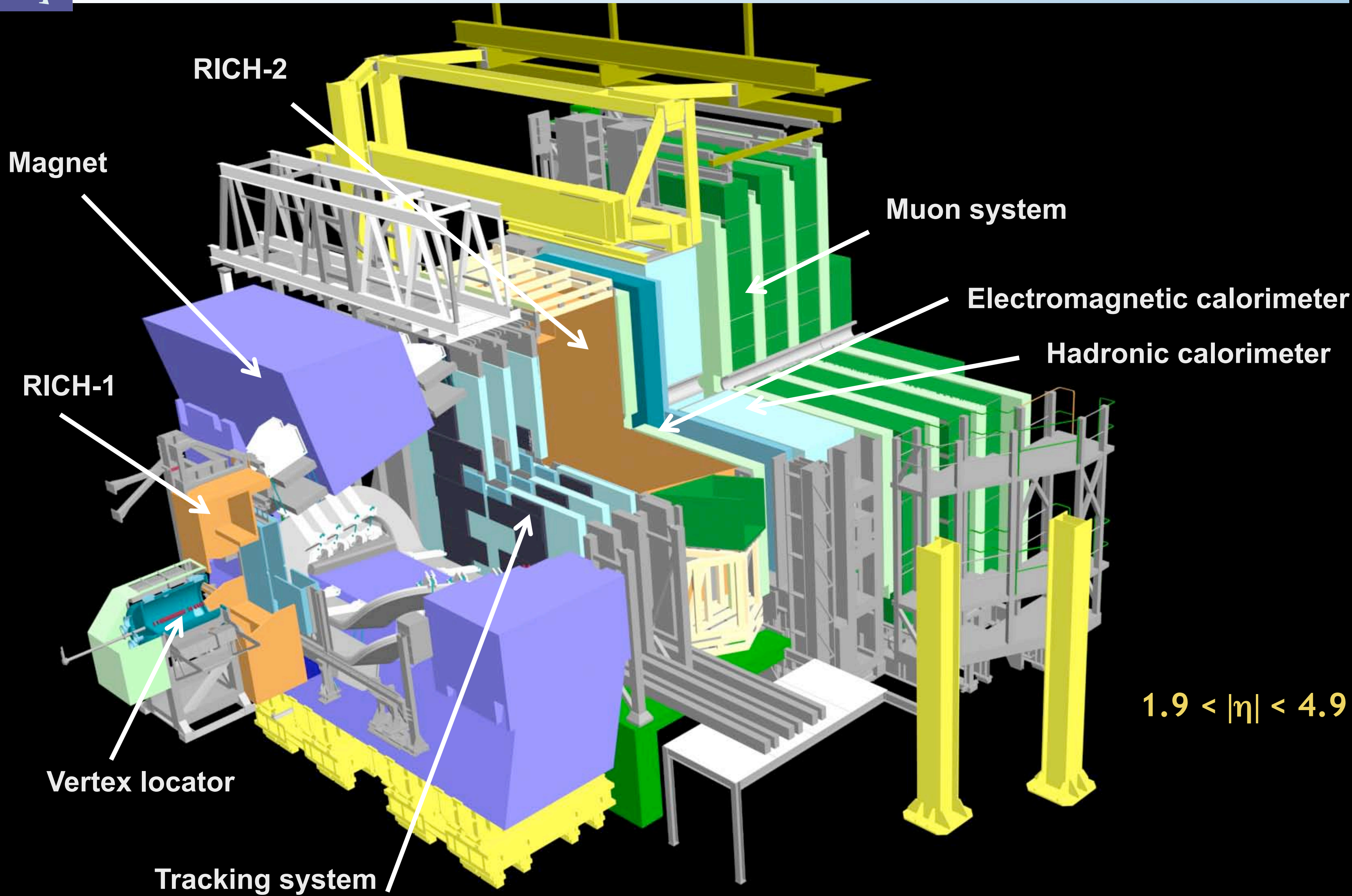
Search for New Physics

- CP violation
  In the B system many decay modes are available
- Determination of CKM parameters
- Rare decays of B hadrons
  e.g. $B^0_s \to \mu\mu$, SM BR: $4x10^{-9}$
- Quarkonia
  J/ψ, Y and excited states (studies of production and polarisation)
- b and c physics
- but also electroweak physics, exotica etc.

Advantages of LHCb compared to B-factories:

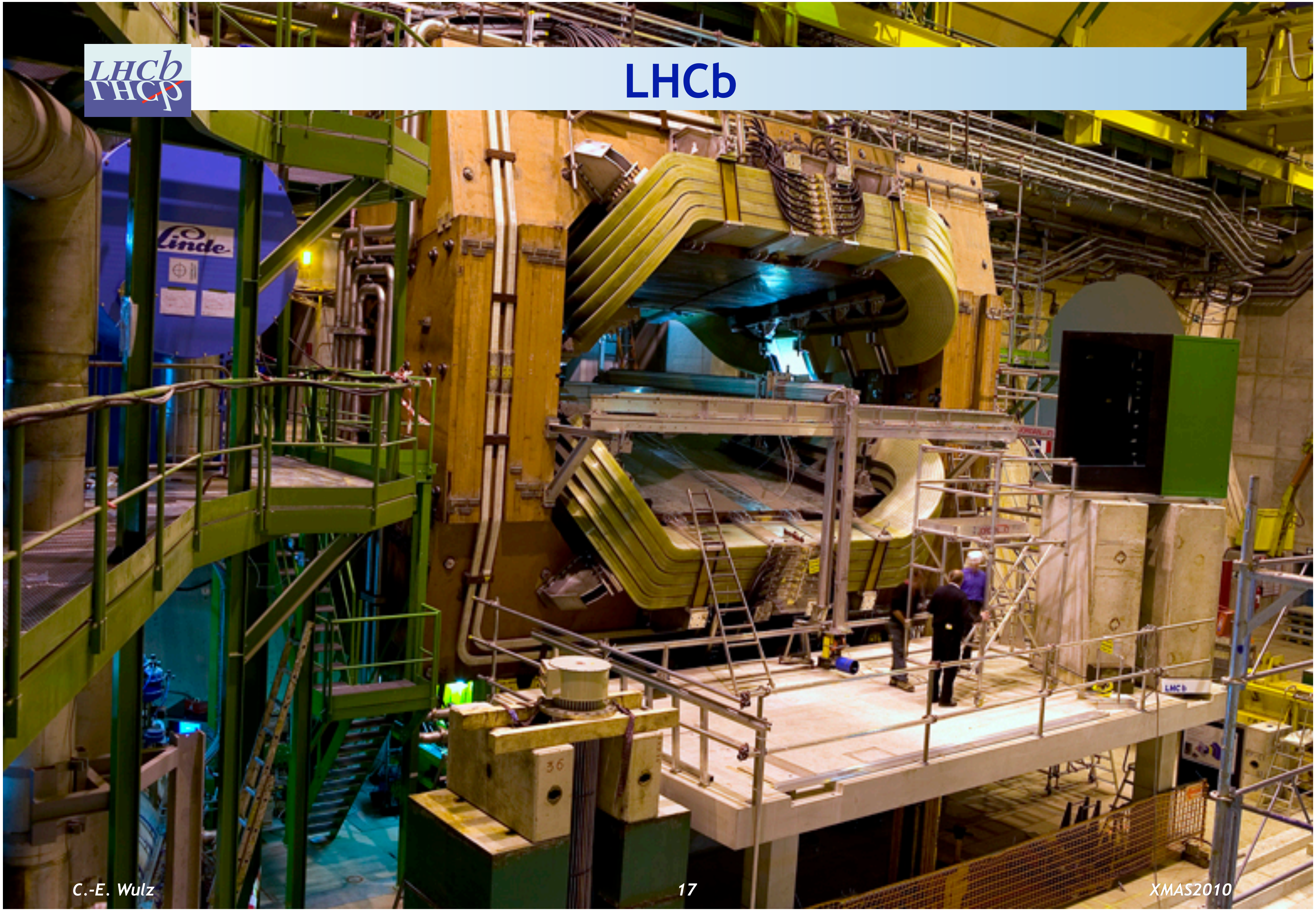
- $\sigma_{b\bar{b}}$ ~ 300 μb at 7 TeV, 500 μb at 14 TeV;
  2 fb^{-1} per year, 10^{12} $b\bar{b}$ pairs per year; $\sigma_{c\bar{c}}$ ~ 3.6 mb.
- All B hadrons are accessible:
  $B^{\pm}(u\bar{b}, \bar{u}b)$, $B^0(d\bar{b}, \bar{d}b)$, $B^0_s(s\bar{b}, \bar{s}b)$, $B_c^{\pm}(c\bar{b}, \bar{c}b)$, b baryons
  The B_s system can be studied in particular.

LHCb forward arm spectrometer



$1.9 < |\eta| < 4.9$

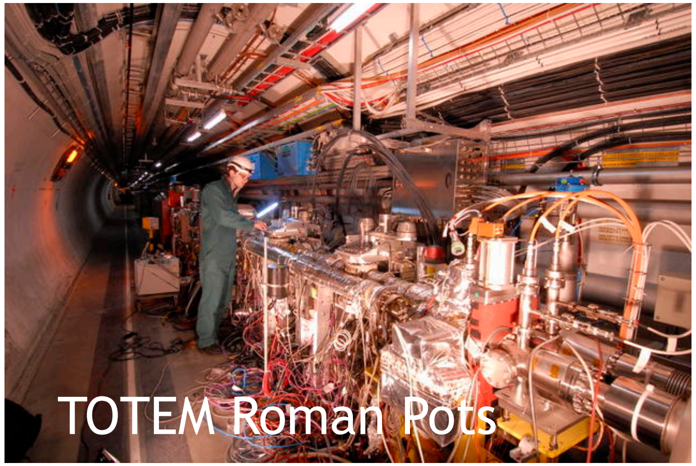
LHCb



TOTEM and LHCf

TOTEM

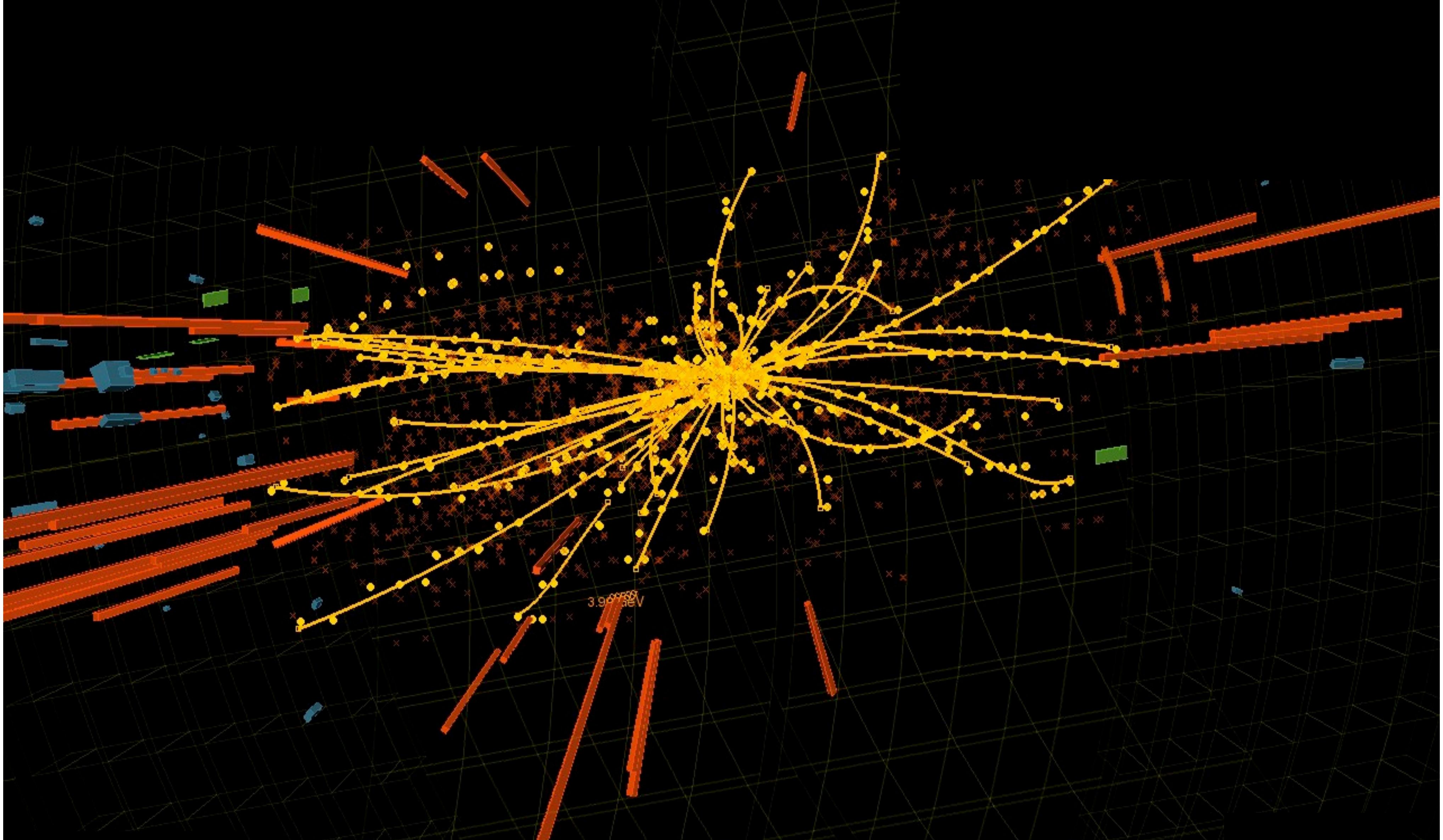
- Measurement of total and elastic pp cross sections
- Study of diffraction, double pomeron exchange
- Calibration of the luminosity monitors of the other experiments
- Measurement of charged particles, 10, 13, 147 and 220 m from CMS



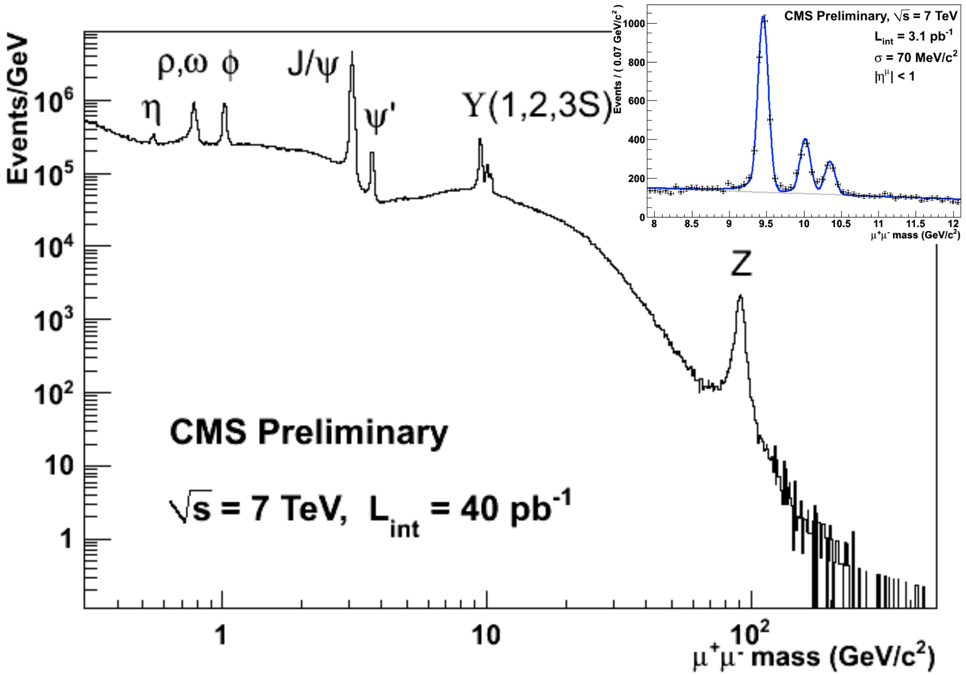
LHCf

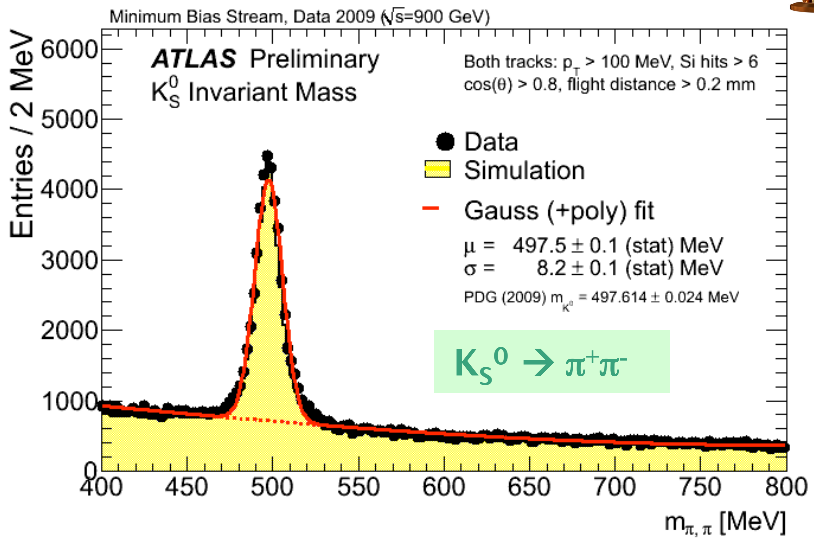
- Simulation and calibration of detectors for cosmic rays, study of the particle showers and comparison with current shower models to estimate the primary energy of ultra highly energetic cosmic rays
- 2 tungsten/scintillator calorimeters, 140 m from ATLAS

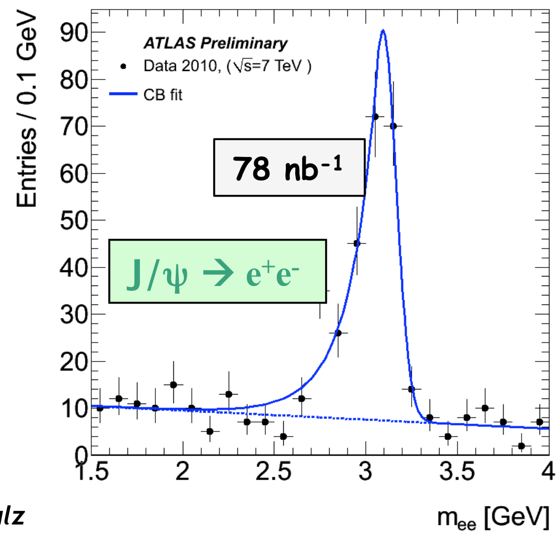
Proton results

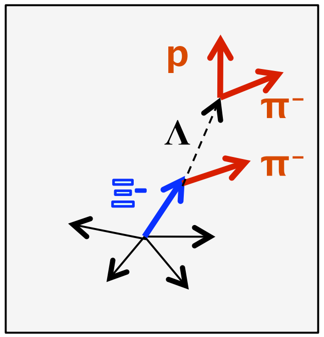


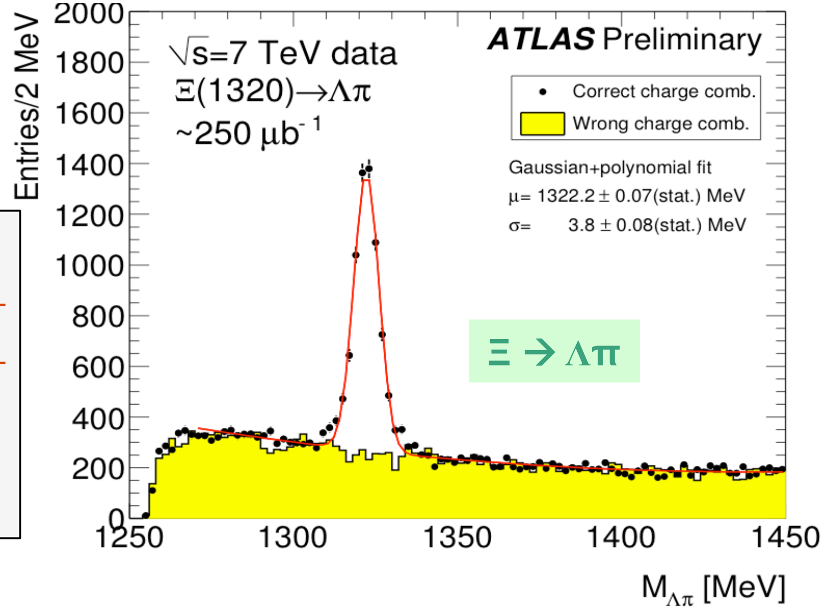
Standard model particle resonances







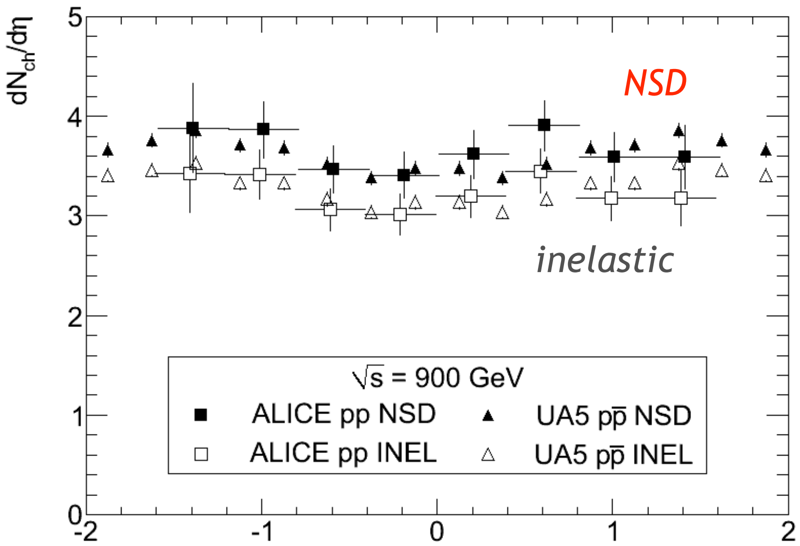




Charged particle distributions

First LHC physics paper by ALICE:

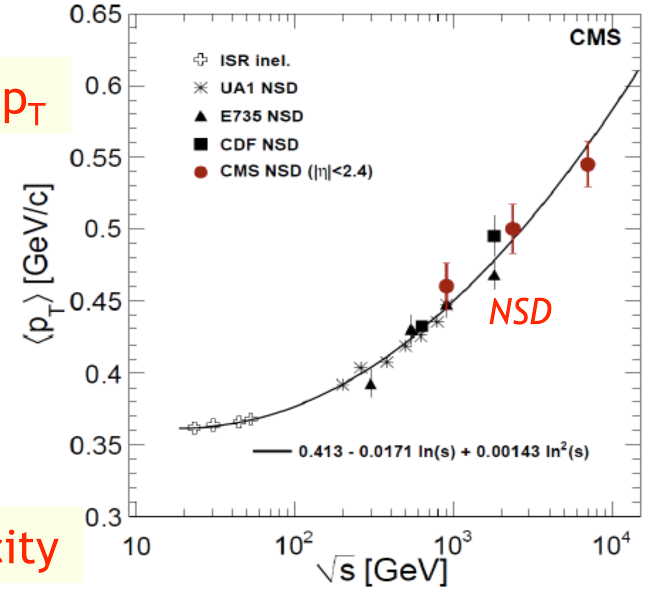
EPJC 65 (2010) 111-125



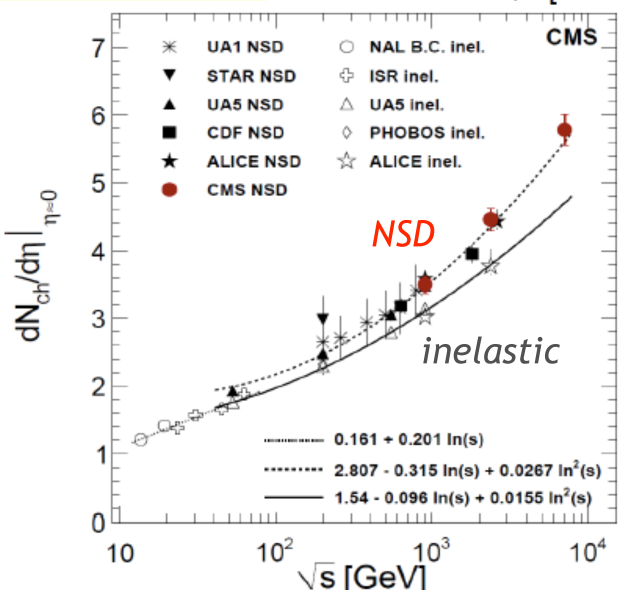
η dependence of charged particle rapidity density

Phys. Rev. Lett. 105, 2010

Average p_T



Multiplicity



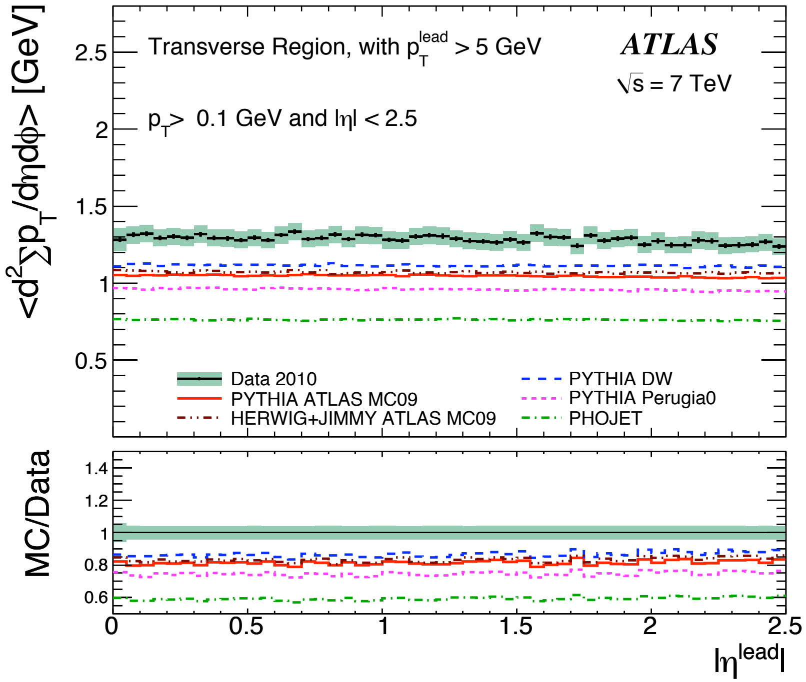
7 TeV data from 1st day!

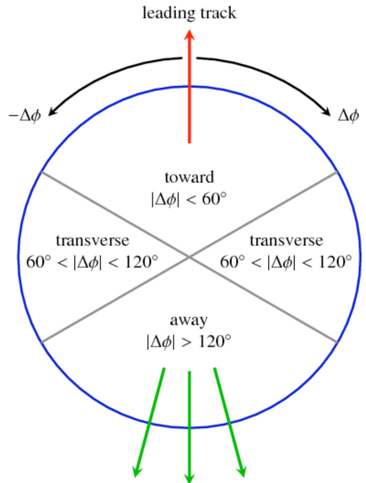
Results are higher than for common Monte Carlo models.

Underlying event characteristics

Study charged particle multiplicity, p_T density, $<p_T>$ in the transverse regions, which are most sensitive to the underlying event -> tune Monte Carlo models.

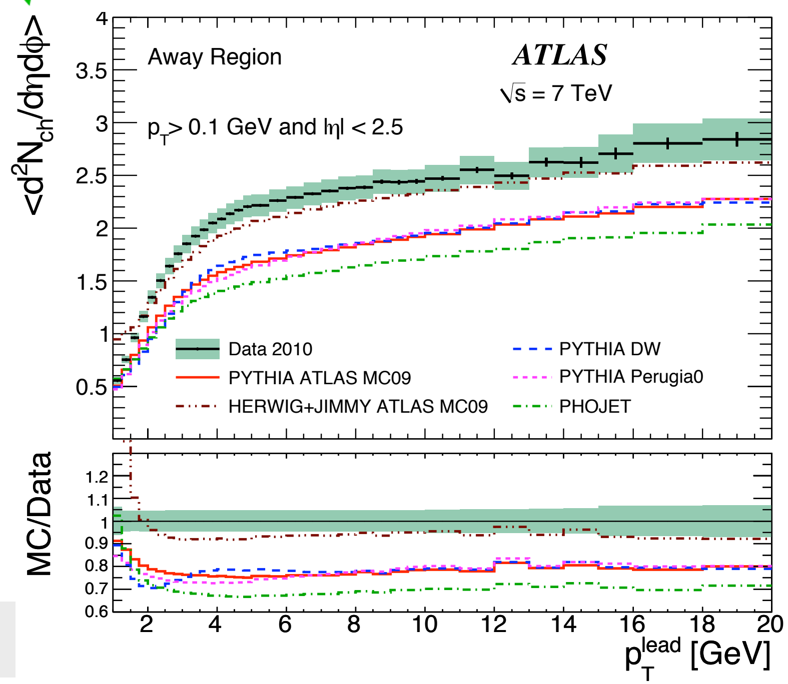
Scalar Σp_T density





Data show higher underlying event activity than Monte Carlo data!

Charged particle density



hep-ex 1012.0791, submitted to Phys. Rev. D

Bose-Einstein Correlations

Phys. Rev. D82 (2010) 52001

Bose-Einstein correlations stem from constructive interference of boson wave functions, leading to a rise in the number of boson pairs (e.g. $\pi^{\pm}$) with the same charges and small momentum difference.

$$q_{inv} = |\vec{p}_2 - \vec{p}_1|$$

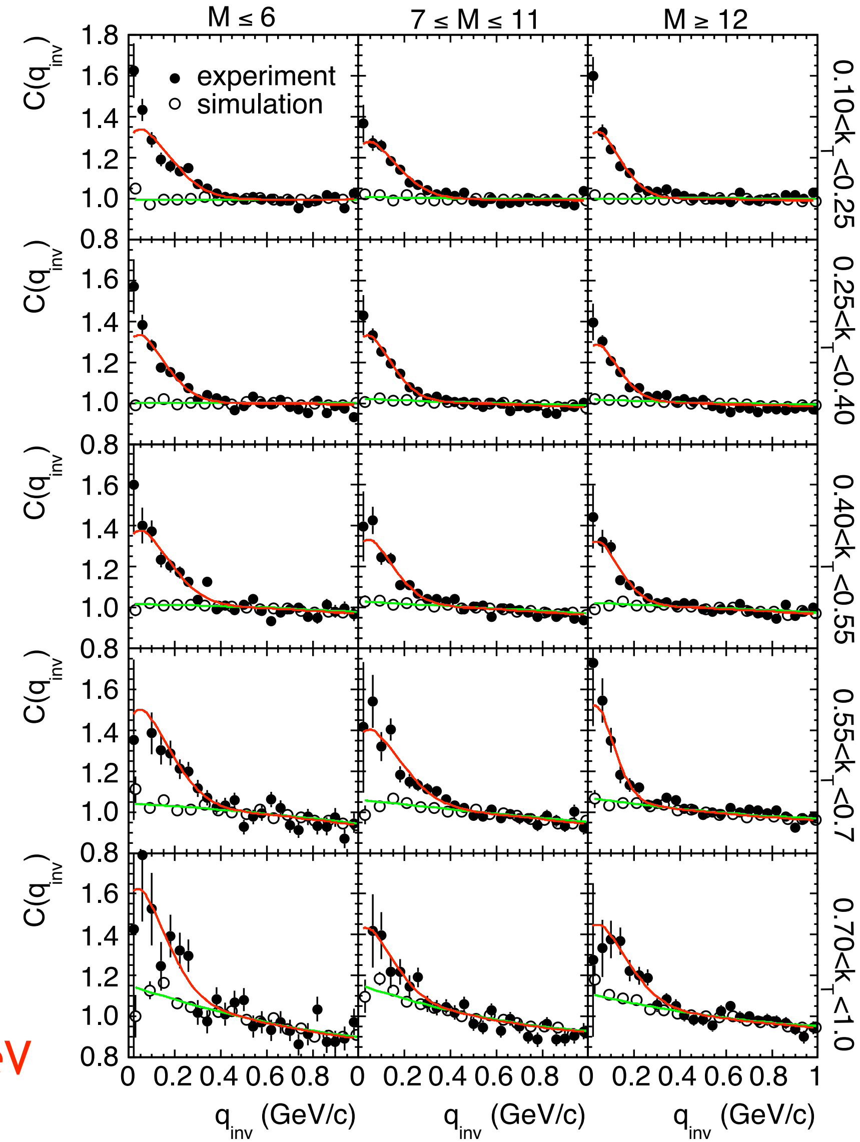
C: 1-dimensional 2-π correlation function

$$C(q_{inv}) = A(q_{inv})/B(q_{inv})$$

A … Momentum difference of pions in the same event
B … Momentum difference of pions in different events
M … Multiplicity

$$k_T = |\vec{p}_{T1} + \vec{p}_{T2}|/2$$

√s = 900 GeV

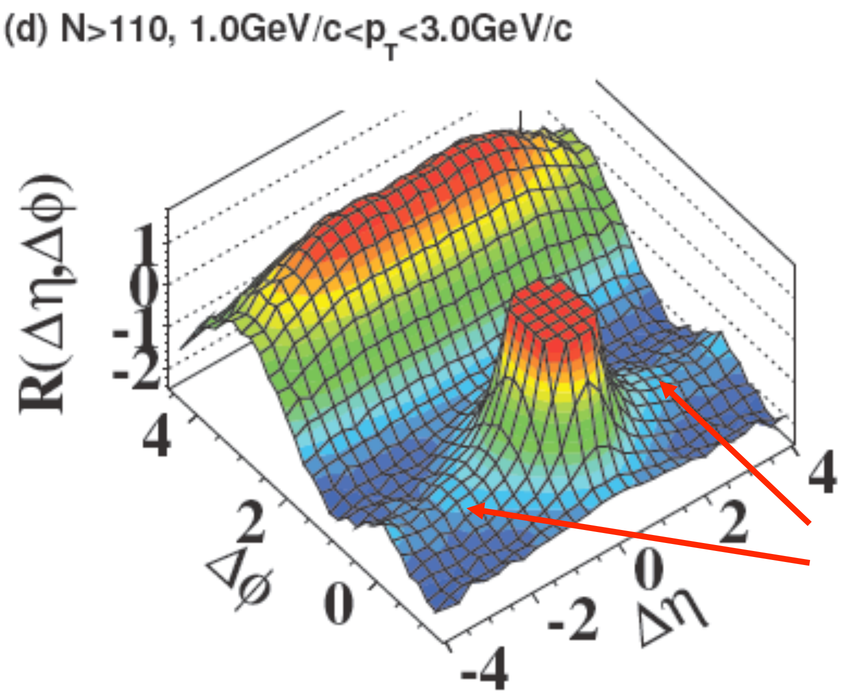


Near-side long-range correlations

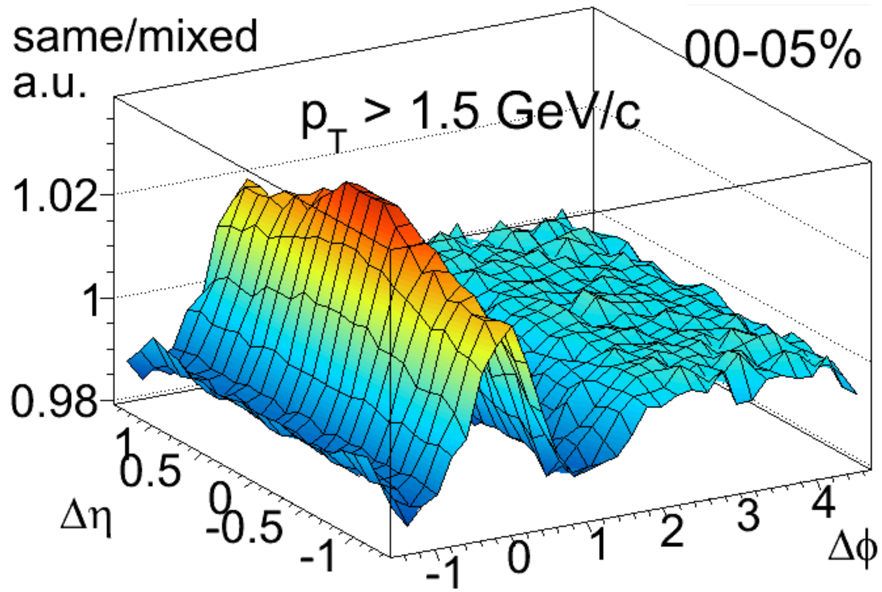
J. High Energy Phys. 09 (2010) 091

First surprise in LHC data!

CMS pp 7 TeV

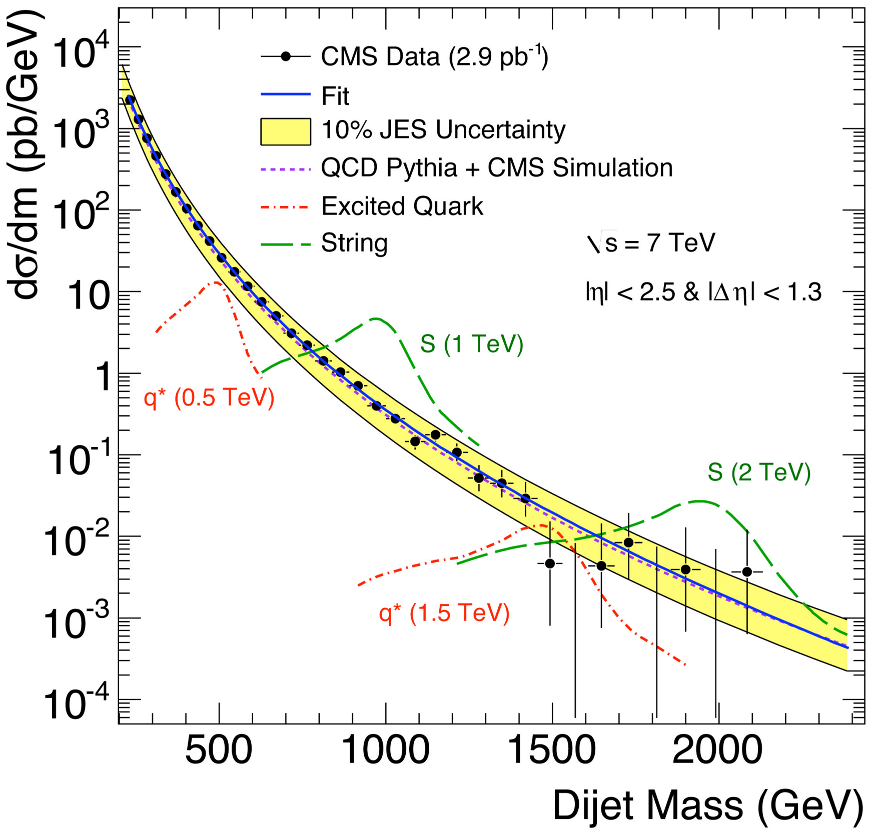


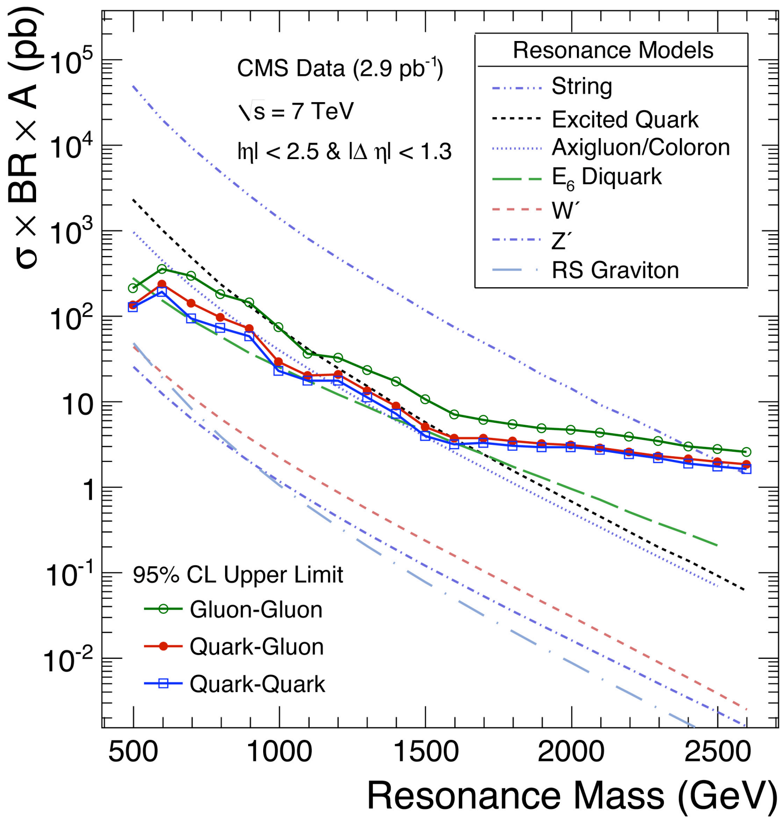
ALICE 2.76 TeV/nn
Central Pb-Pb collisions



Pronounced structure (ridge) in high-multiplicity events for $2.0 < |\Delta\eta| < 4.8$ and $\Delta\phi \approx 0$

Search for dijet resonances



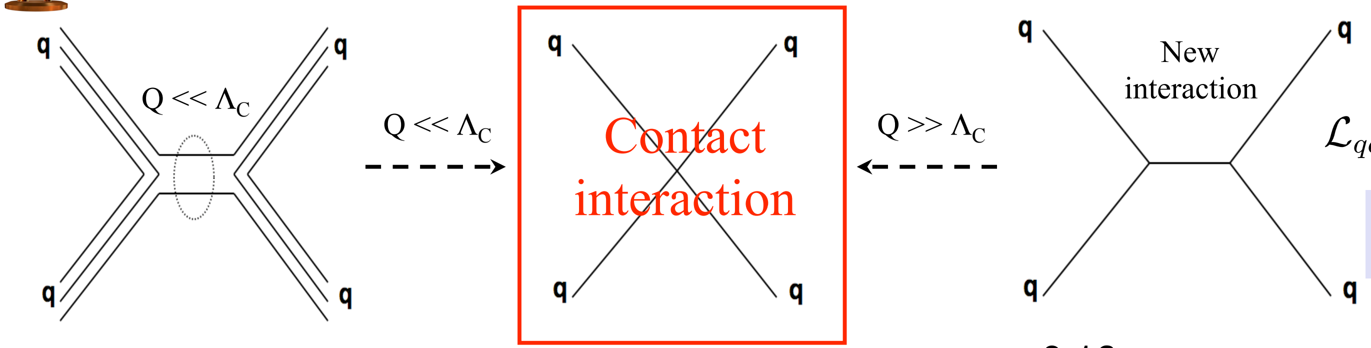


Highest JJ mass event:
m_{JJ} = 2.13 TeV

Exclusion limits:
String: 2.50 TeV
Excited quarks: 1.58 TeV

Phys. Rev. Lett. 105, 211801 (2010)

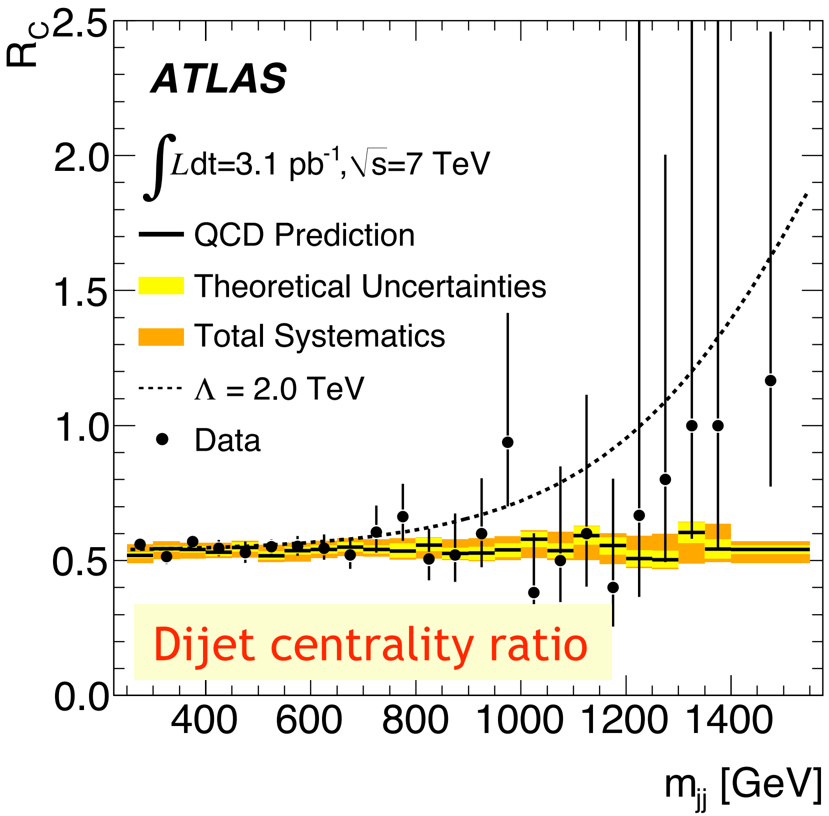
Compositeness, quark contact interactions

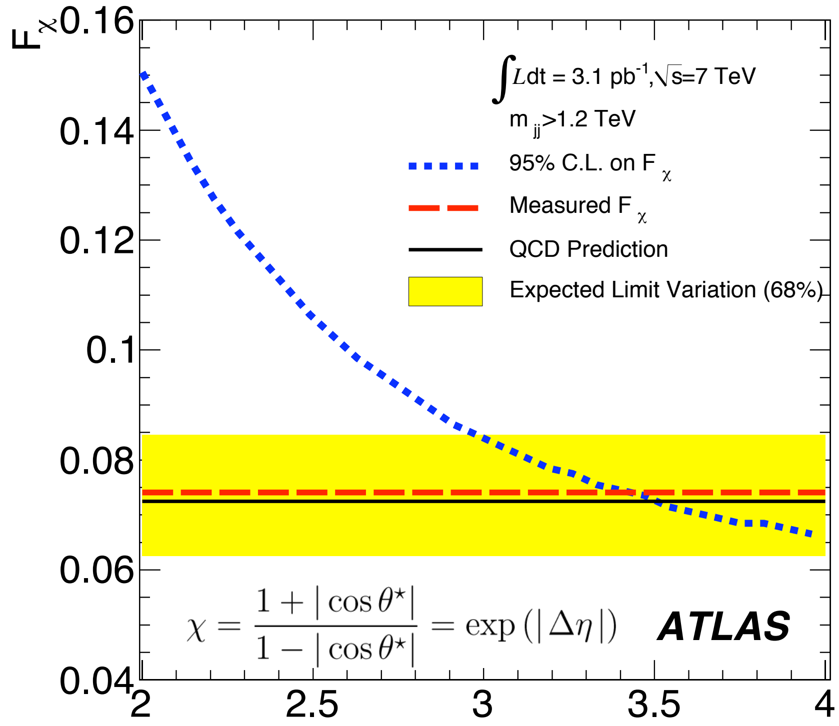


$$\mathcal{L} = \mathcal{L}_{QCD} + \mathcal{L}_{qqqq}$$

$$\mathcal{L}_{qqqq} = \frac{\eta g^2}{2\Lambda_C^2} \overline{\Psi_q^L}\gamma_\mu \Psi_q^L \overline{\Psi_q^L}\gamma^\mu \Psi_q^L$$

Λ_C > 3.4 TeV (95% CL)





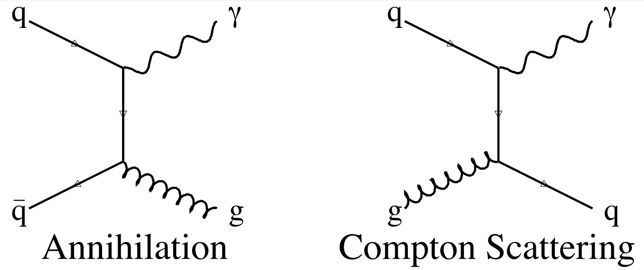
hep-ex 1009.5069, acc. by PLB

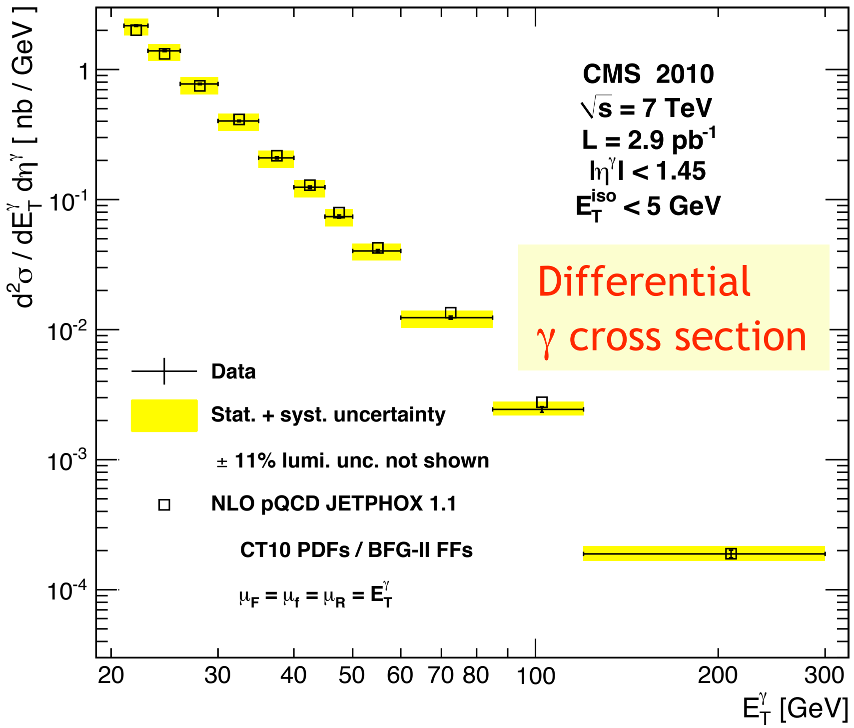
Direct photon production

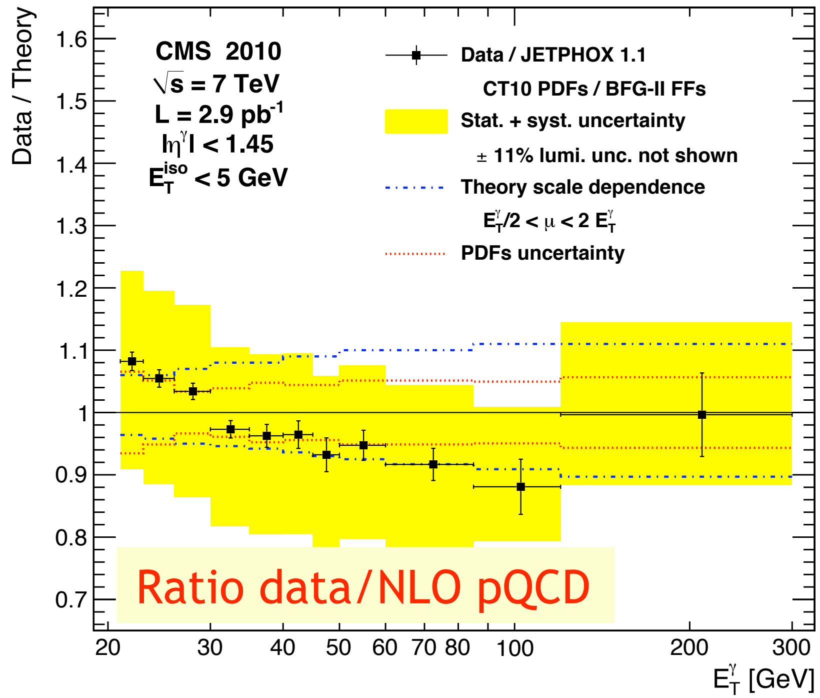
Study of production of isolated photons (γ in jets mostly come from π and η decays) is important:

hep-ex 1012.0799 (Dec. 2010)

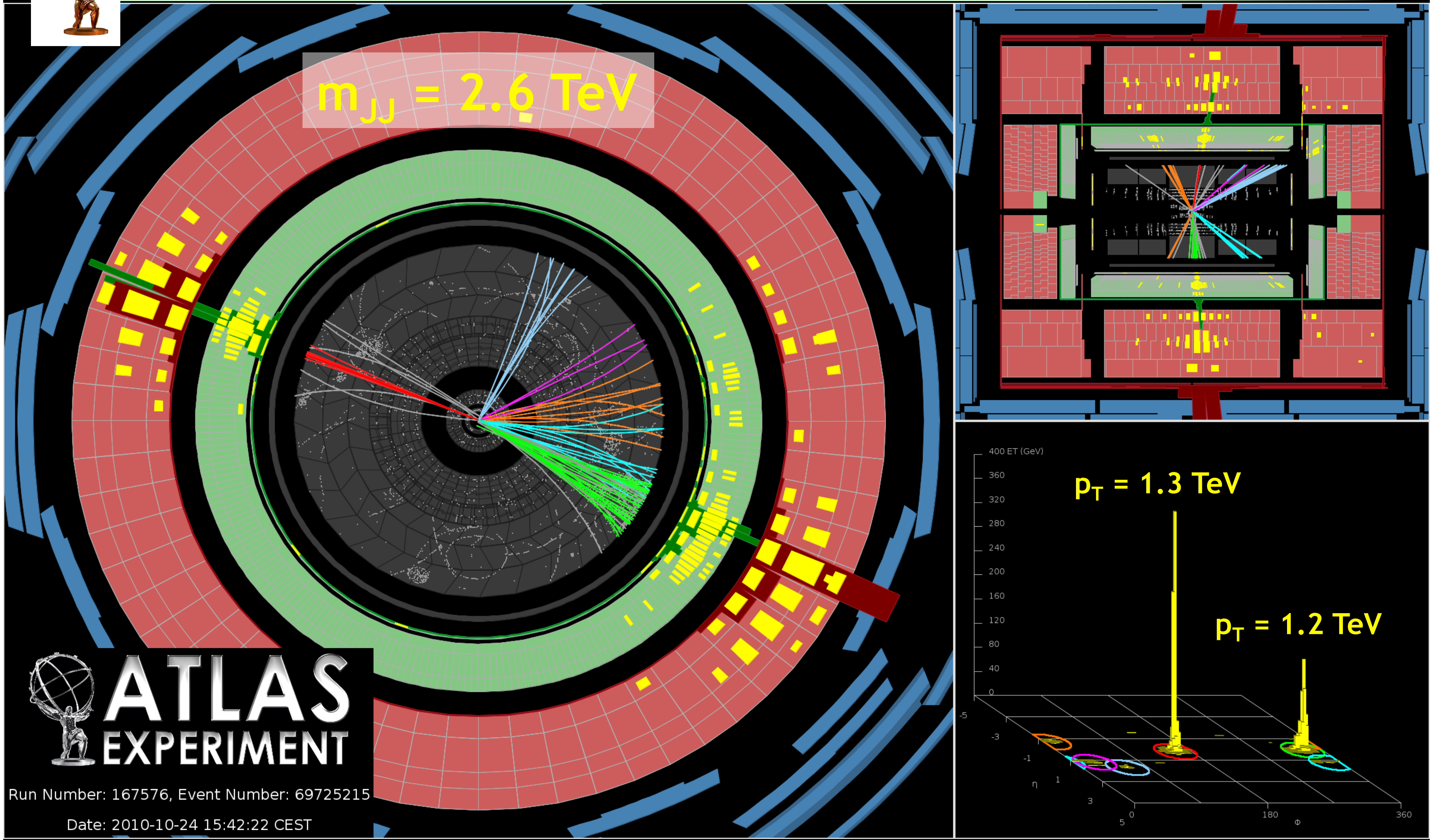
- Precision tests for perturbative QCD
- Constrain PDF in the proton
- Calibration of the jet energy scale
- Background for e.g. $H \to \gamma\gamma$, $G \to \gamma\gamma$, $f^* \to f\gamma$



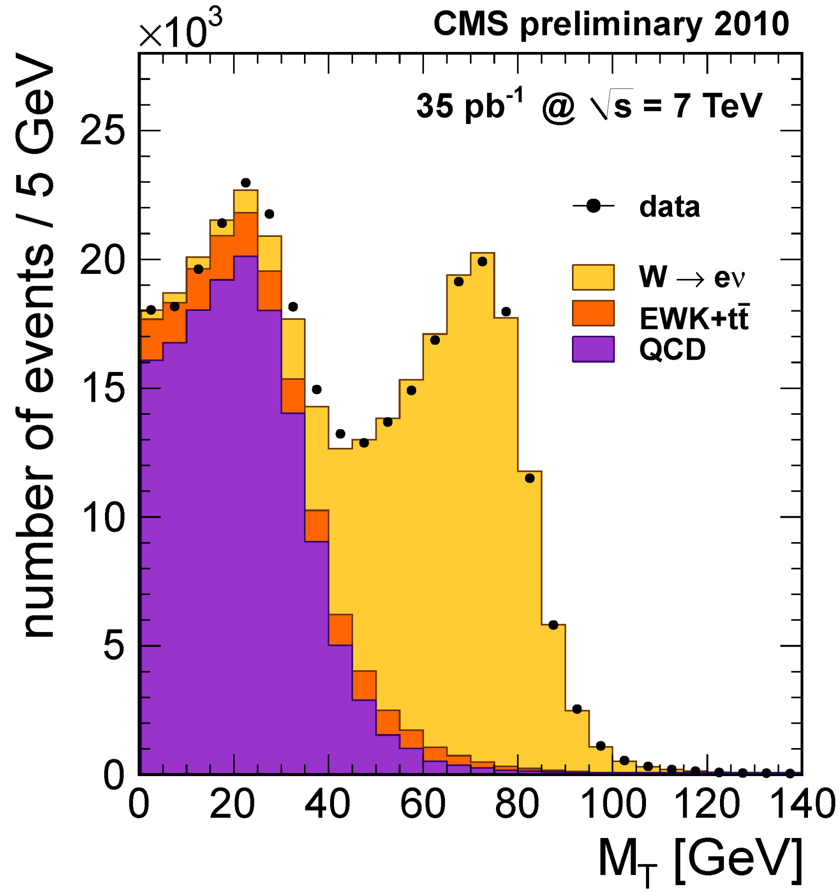


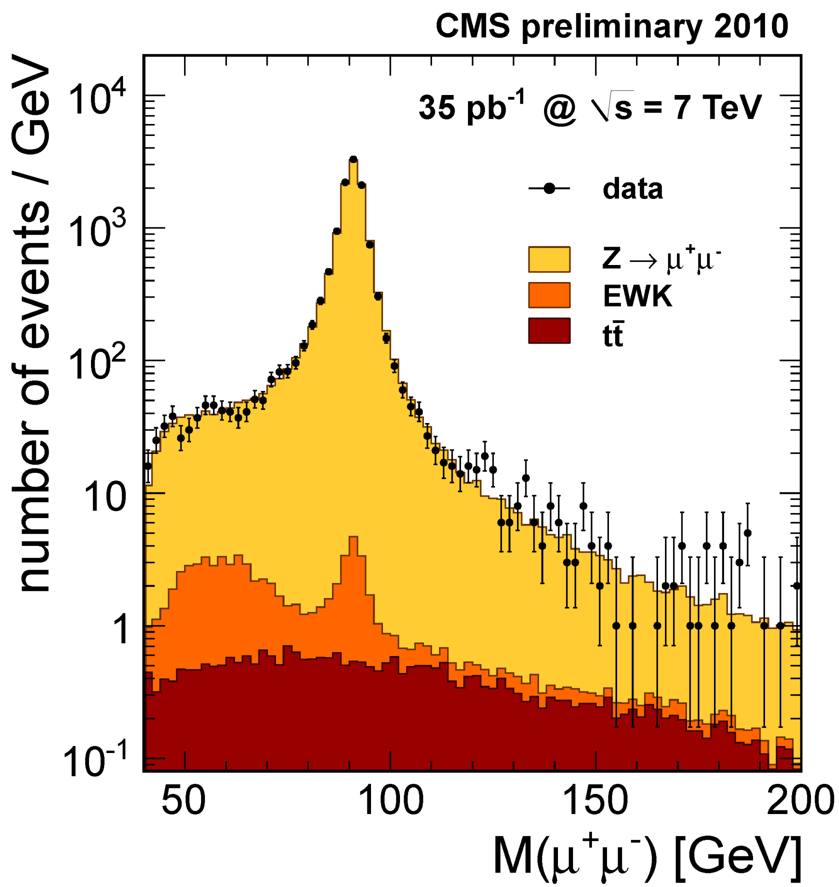


ATLAS high-mass dijet event



W and Z

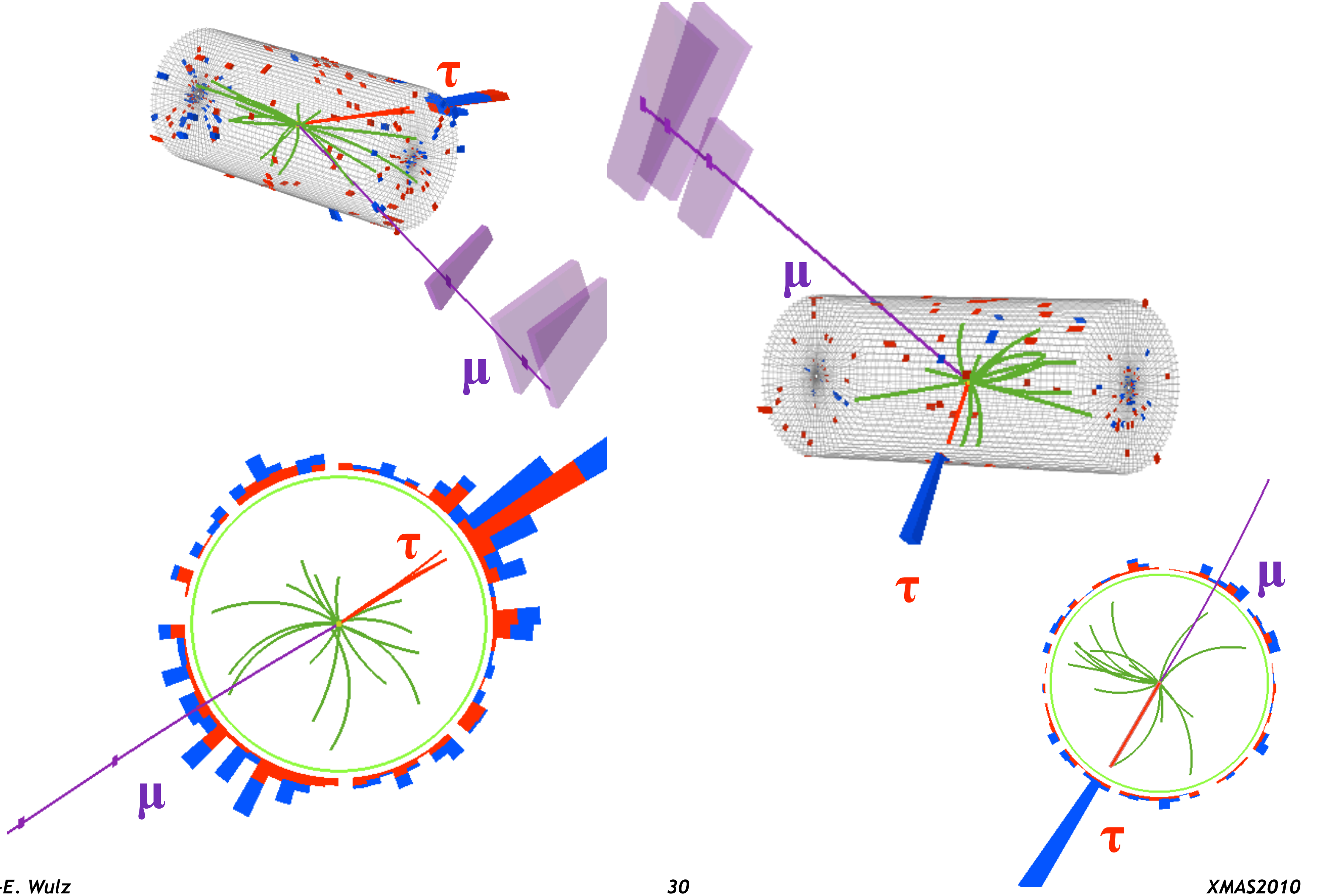




$$M_T = \sqrt{2p_T(\mu)\not{E}_T(1 - cos\Delta\phi_{\mu,\not{E}_T})}$$

$$p_T(\nu) \approx \not{E}_T$$

$Z \to \tau\tau \to \mu + \tau_{had}$ (1- and 3-prong) + X

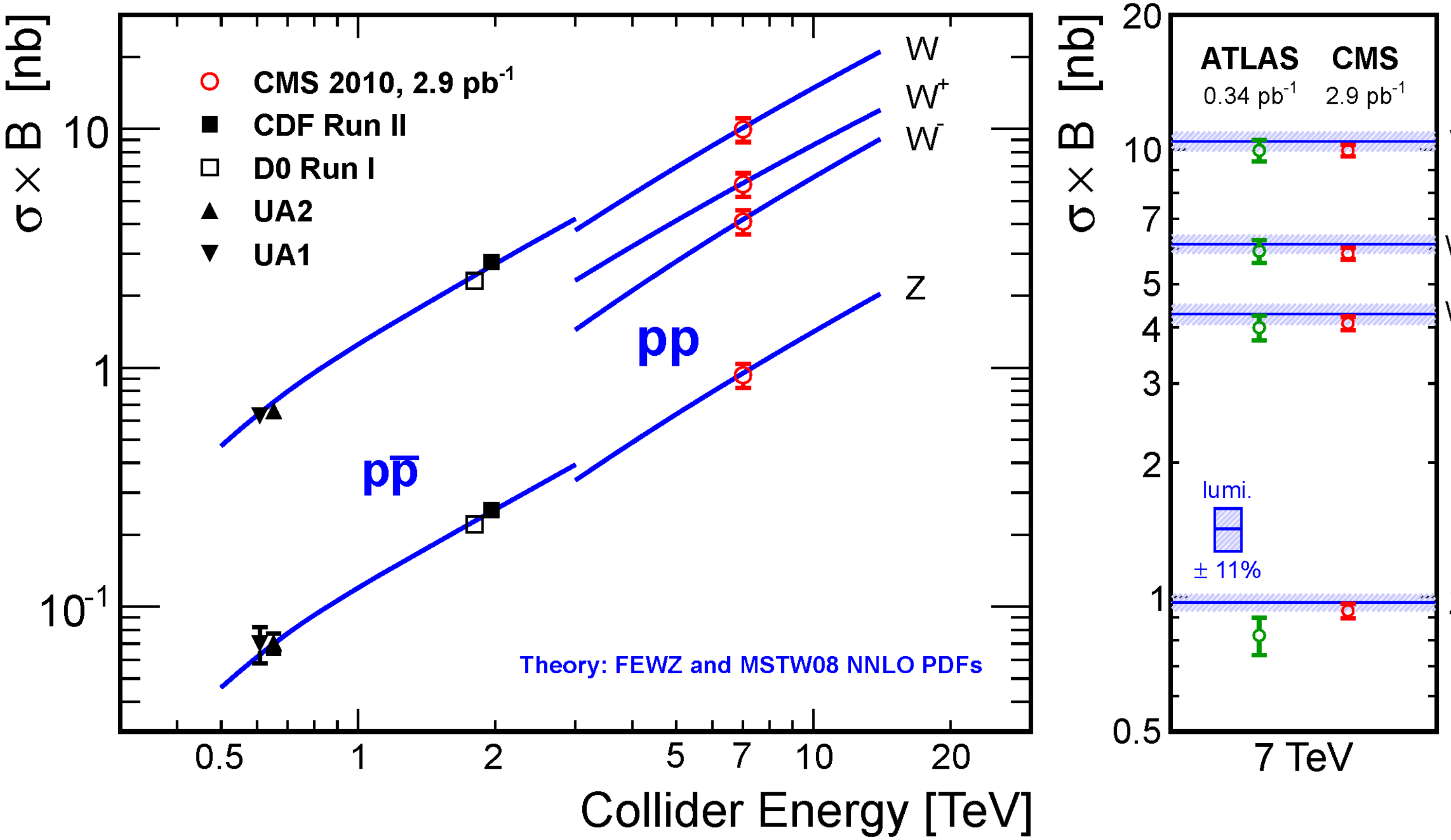


W and Z cross sections

- W and Z (e and μ channels) are the first electroweak processes measured at LHC
- Tests for perturbative QCD and PDF's (W charge asymmetry)
- Detector calibration with Z
- Luminosity measurement
- Background for new physics

hep-ex 1012.2466 (Dec. 2010)

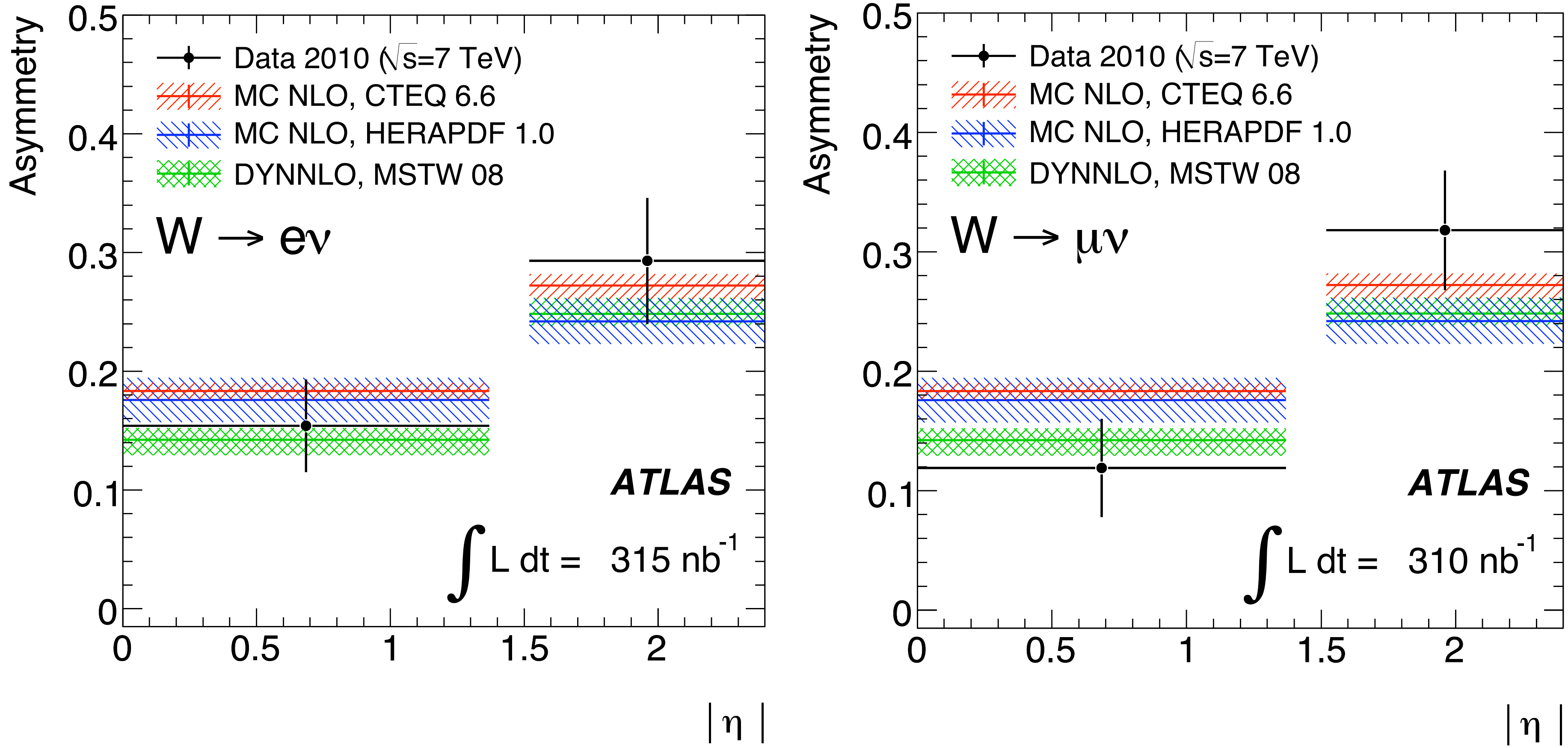
submitted to JHEP



W^+/W^- charge asymmetry

$$A(\eta) = \frac{d\sigma^+/d\eta_\ell - d\sigma^-/d\eta_\ell}{d\sigma^+/d\eta_\ell + d\sigma^-/d\eta_\ell}$$

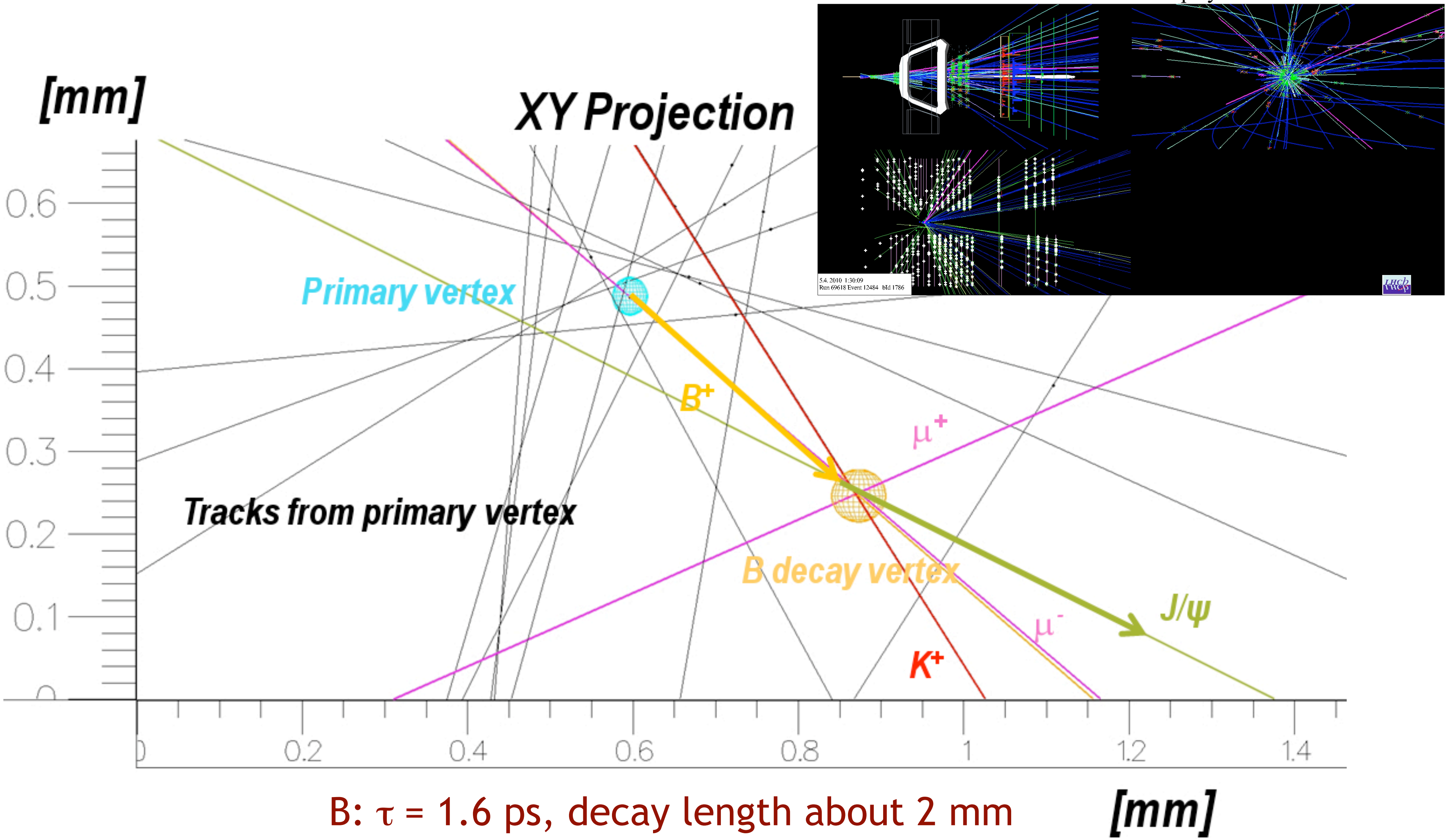
Asymmetry is sensitive to valence quark PDF's.



hep-ex 1010.2130, submitted to JHEP

First Beauty event: B^+ ($\bar{b}u$) -> K^+ + J/ψ

LHCb Event Display

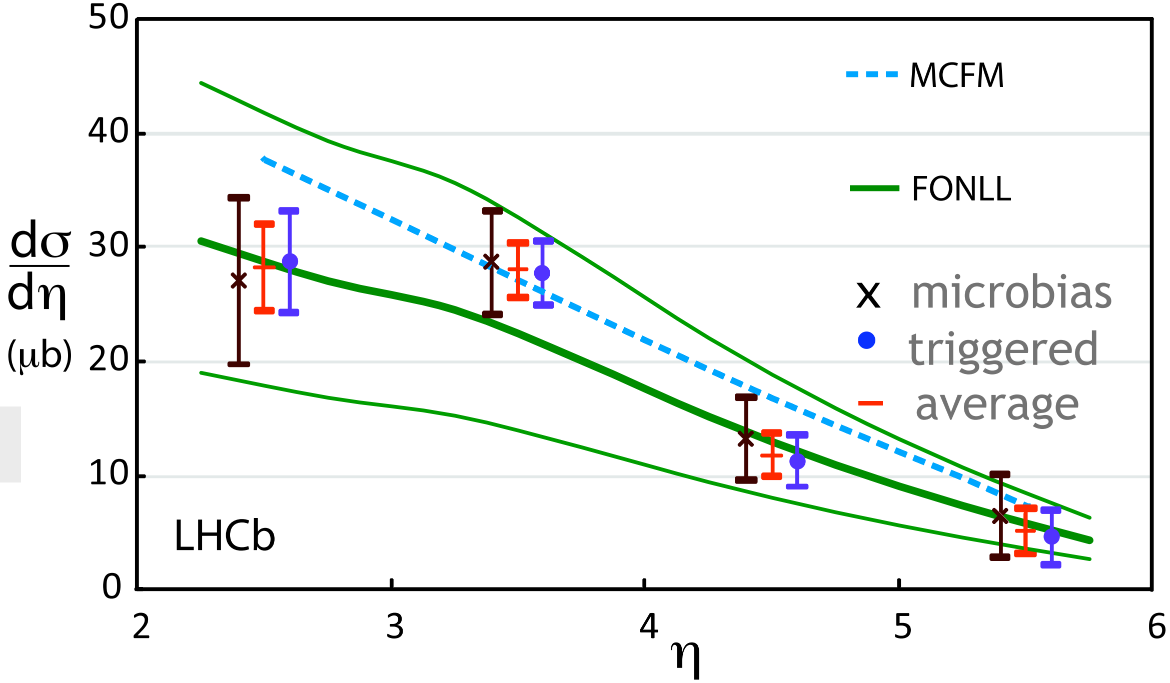


B: τ = 1.6 ps, decay length about 2 mm

B cross sections

b -> $D^0 X \mu \nu$,
D^0 -> $K\pi$

hep-ex 1009.2731



$$\sigma(pp \rightarrow H_b X) = [75.3 \pm 5.4 \text{ (stat.) } \pm 13.0 \text{ (sys.)}] \ \mu\text{b} \qquad 2 < \eta < 6$$

Extrapolation to entire η range with PYTHIA 6.4 (factor 3.77) and using LEP fragmentation fractions gives:

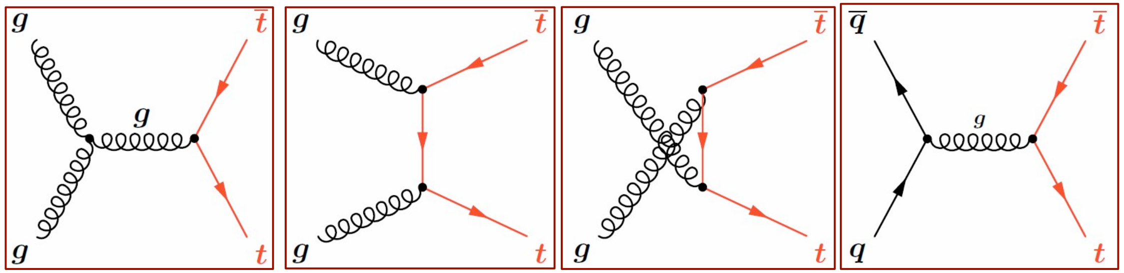
$$\sigma(pp \rightarrow b\bar{b}X) = [284 \pm 20 \text{ (stat.) } \pm 39 \text{ (sys.)}] \ \mu\text{b}$$

Consistent with theoretical predictions in normalization and shape.

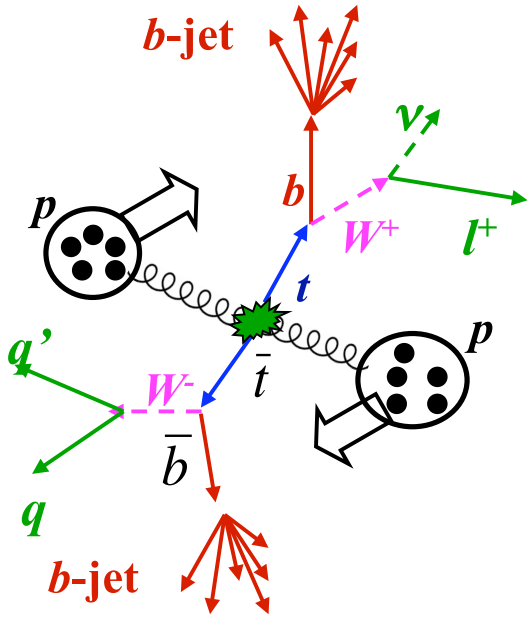
Top

"When top is measured, the experiment is ready for discovery phase"
P. Jenni, XMAS2009

tt production at LHC stems from 87% gluon fusion, 13% qq annihilation
- Interesting in itself since t decays before hadronizing
- Decay products of new particles
- Background to new particle searches

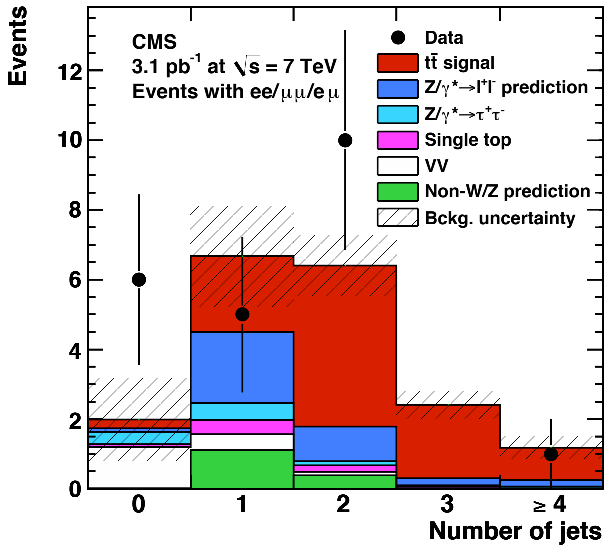


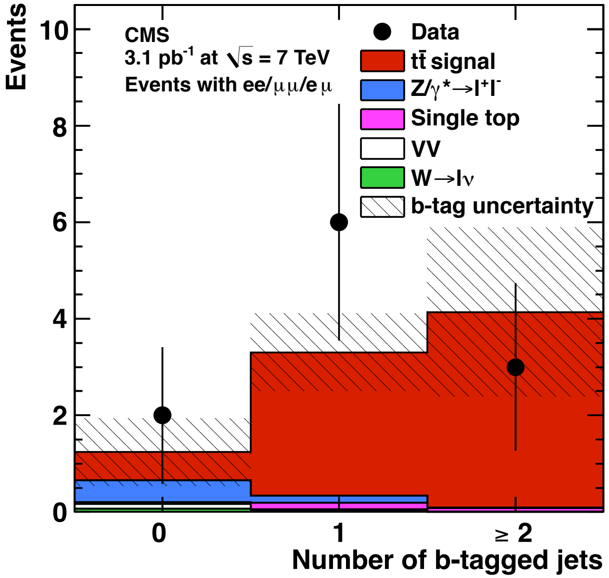
Top decays weakly as t -> Wb almost exclusively.
Event classes according to decay of W:
- All-hadronic
- lepton + jets
- dilepton (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$)

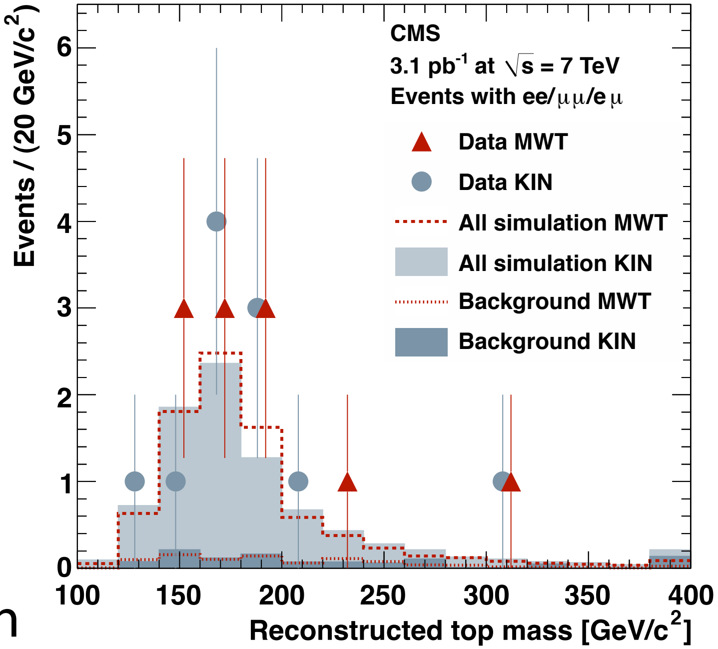


$t\bar{t}$ cross section

hep-ex 1010.5994, submitted to Phys. Lett. B (Oct. 2010)







Backgrounds from Drell-Yan and events with isolated leptons from non-W/Z production are estimated from data.

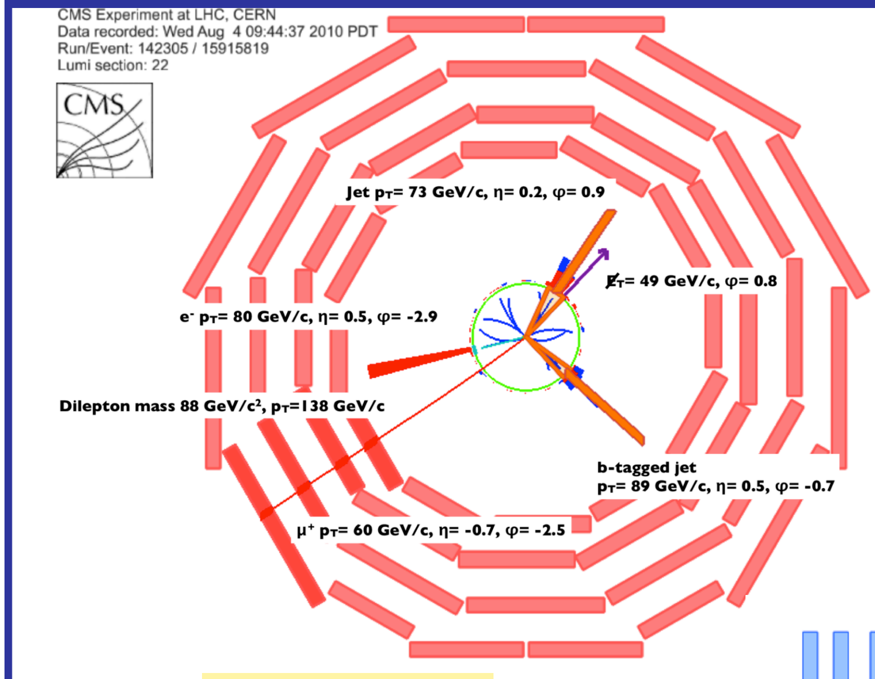
b-tag efficiency: 80%, false positives: 10%

Compatible with prediction of m_t = 172.5 GeV

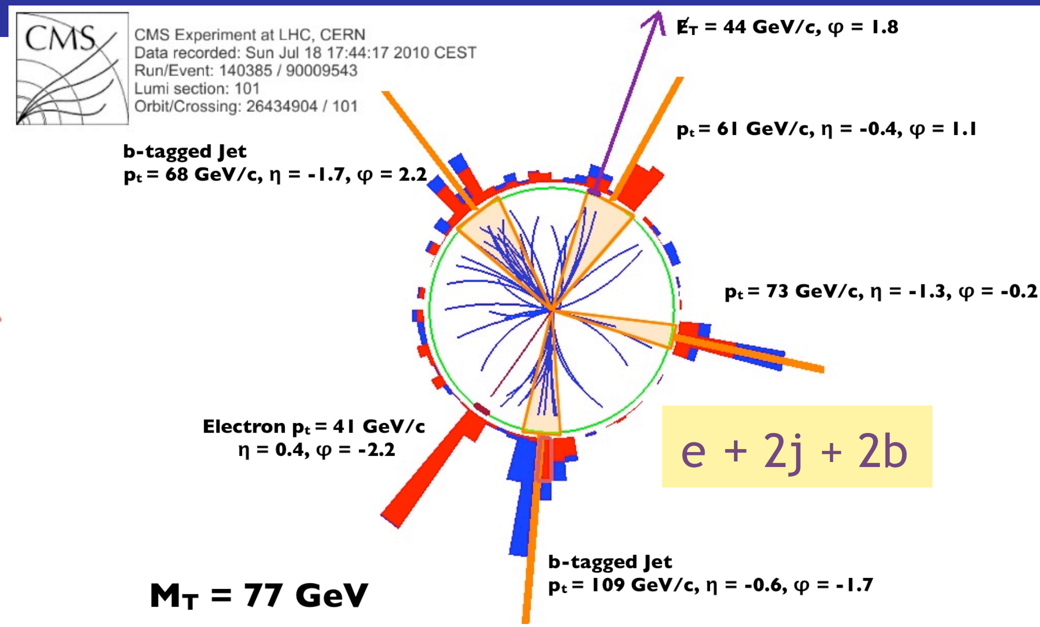
$$\sigma(pp \to t\bar{t}) = [194 \pm 72\ (\text{stat.})\ \pm 24\ (\text{sys.})\ \pm 21\ (\text{lum.})]\ \text{pb}$$

Consistent with NLO prediction: $\sigma(pp \to t\bar{t}) = (157.5^{+23.3}_{-24.4})$ pb

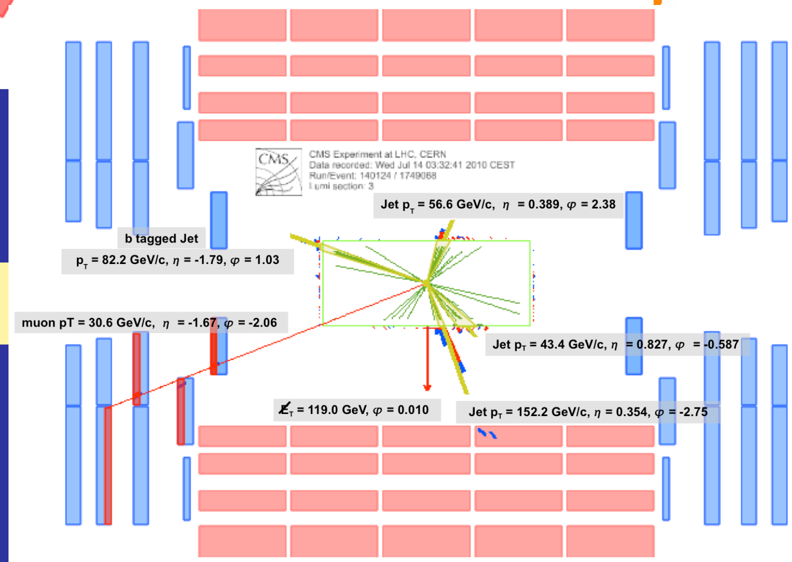
Top events in the dilepton channels



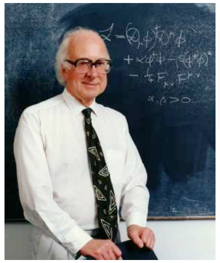
e + μ + jets



e + 2j + 2b



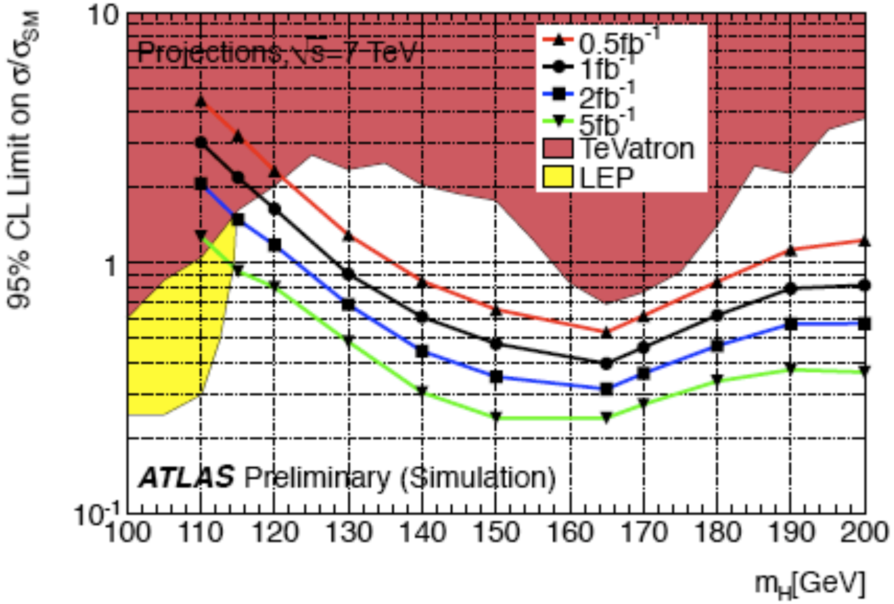
μ + 4 jets

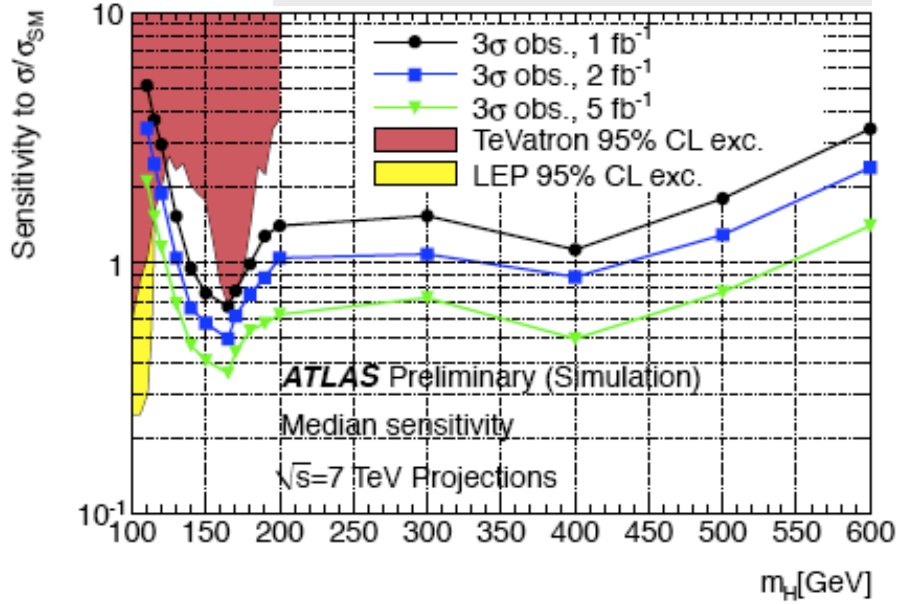


Prospects for Higgs search

LHC starts to be competitive with Tevatron!

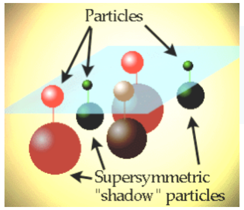
ATLAS-PHYS-PUB-2010-015

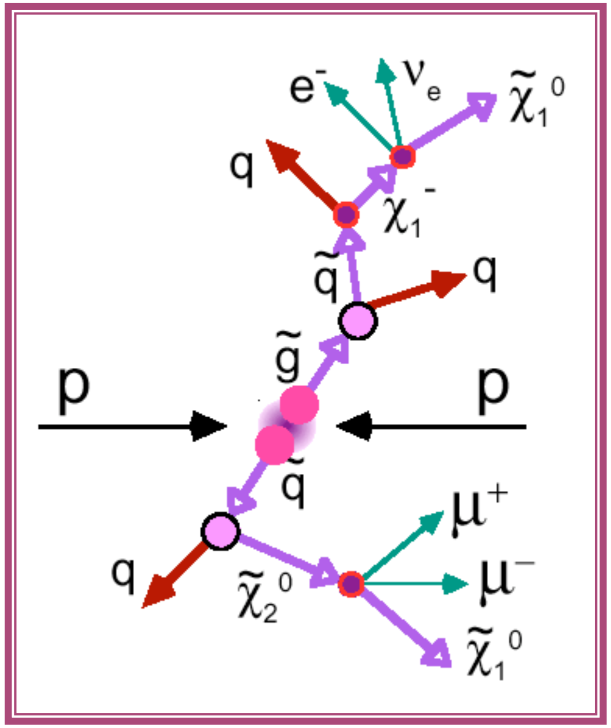




New analyses of H -> ZZ -> ll$\nu\nu$ and H -> ZZ -> llbb are included. ATLAS alone could exclude a SM Higgs boson from 135 to 188 GeV with 0.5 fb^{-1}. With 5 fb^{-1} could go from LEP limit to several hundred GeV! Going from 7 to 8 TeV would save 25% of data taking for same sensitivity, but one would need about 2 months to set up the LHC. From 131 (139) to 180 GeV could have evidence with 2 fb^{-1} (1 fb^{-1}). For comparison: Tevatron would have sensitivity of at least 2.4 σ up to about 180 GeV in 2011, with 10 fb^{-1} per experiment.

Prospects for SUSY





Example of Squark-Gluino cascade event

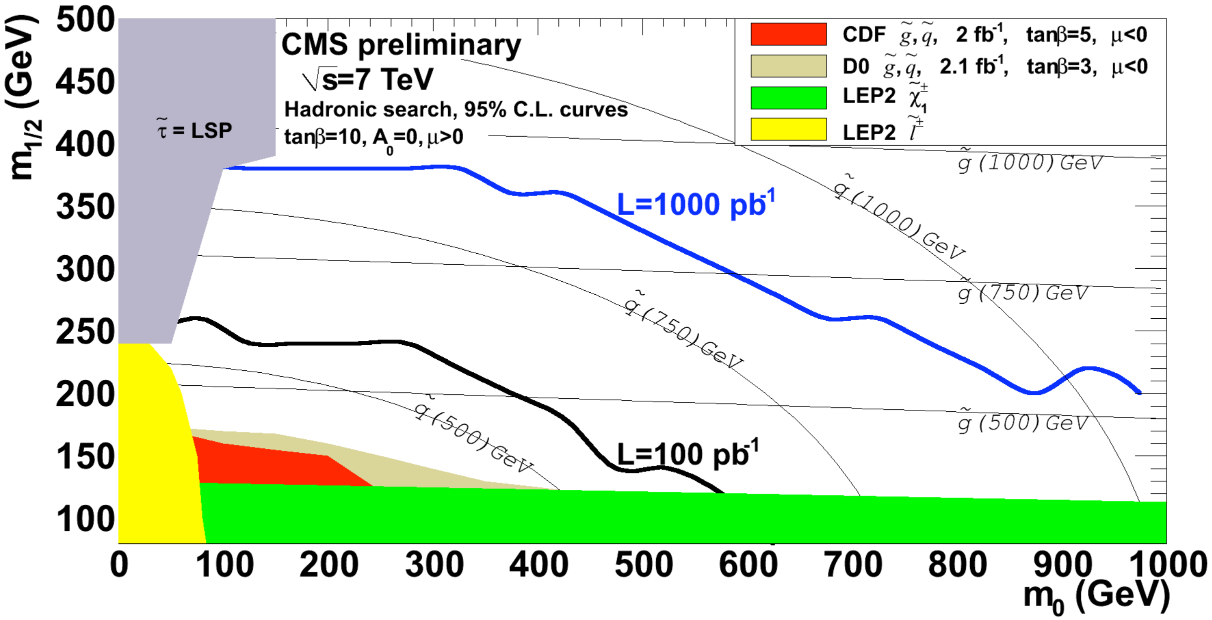
Initial searches are performed with a number of inclusive final states. Signatures can contain jets, missing transverse energy, leptons or photons.

Data-driven background estimations are important, for example to control QCD tails. For isolated lepton signatures, understanding of misidentified hadrons, photon conversions, leptons from decays etc. is also important.

Particle flow techniques, which imply reconstruction of all charged and neutral particles, are more and more widely used.

mSUGRA discovery prospects

95% C.L. exclusion limits for mSUGRA searches in all-hadronic channels

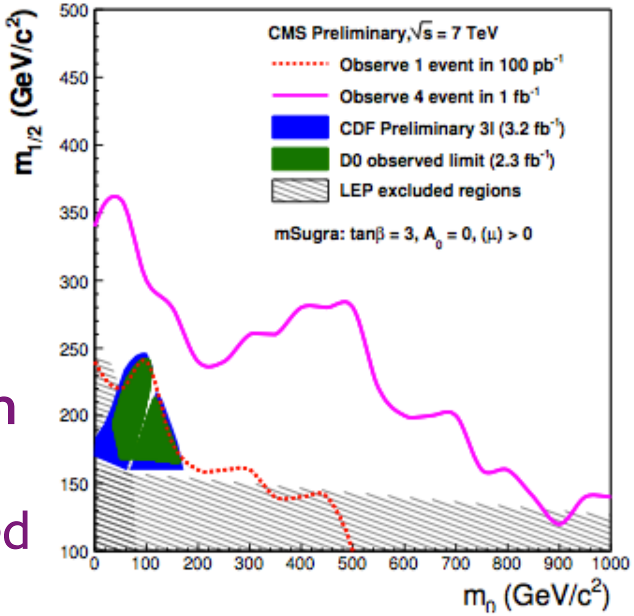


CMS Note 2010/008

Good efficiency, but also much background (QCD, Z+jets, W+jets). Depends only weakly on *tanβ*.

mSUGRA exlusion limits in the like-sign dilepton channels

Background relatively small ($t\bar{t}$, wrongly identified charges from W etc.)

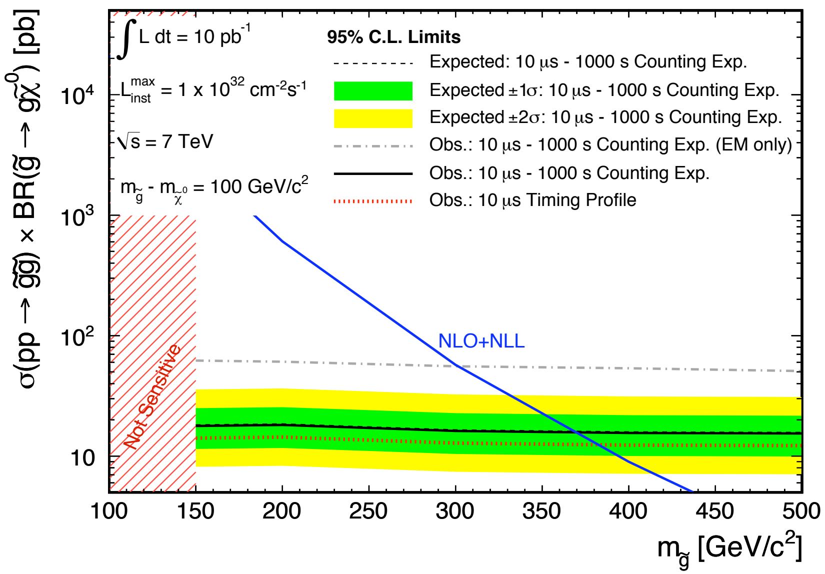


Long-lived, stopped Gluinos

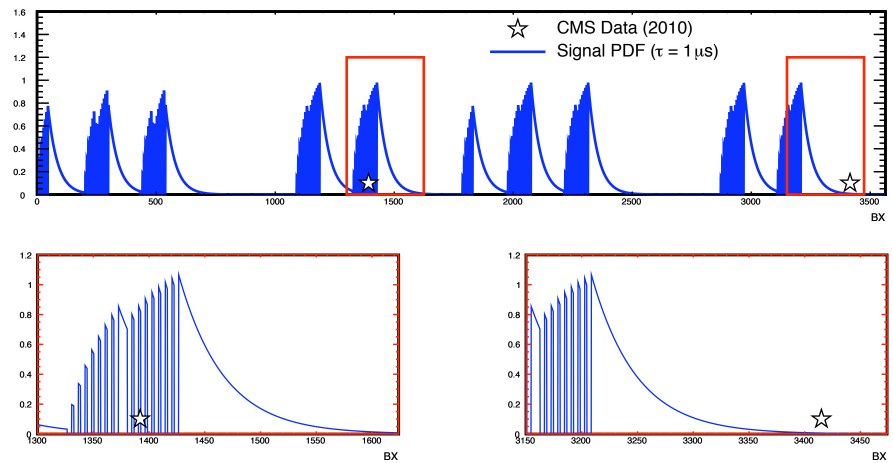
hep-ex 1011.5861, submitted to Phys. Rev. Lett. (Nov. 2010)

Look for decays in time intervals with no pp collisions, using calorimeter triggers.

Assumption: $\mathrm{BR}(\tilde{g} \rightarrow g\tilde{\chi}_1^0) = 100\%$



In-orbit positions of 2 events, with exponential decay profile for 1 μs lifetime hypothesis overlaid



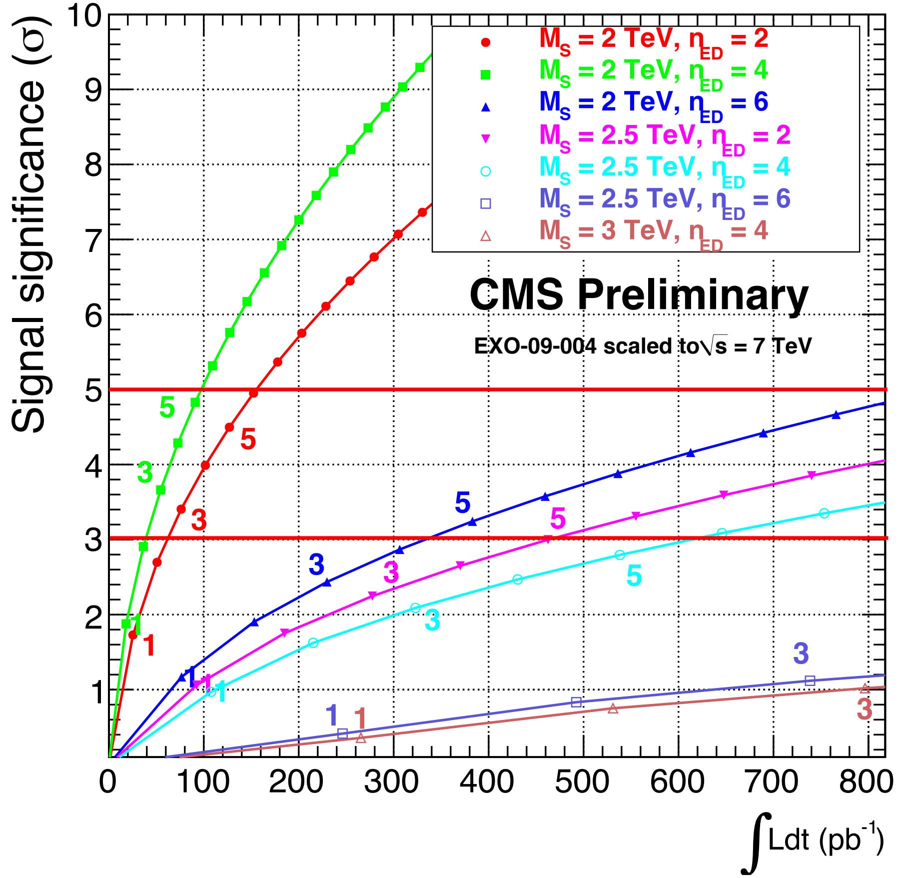
Gluino mass limit:

$$m(\tilde{g}) > 370\ \mathrm{GeV}$$

for lifetimes between 10 μs to 1000 s

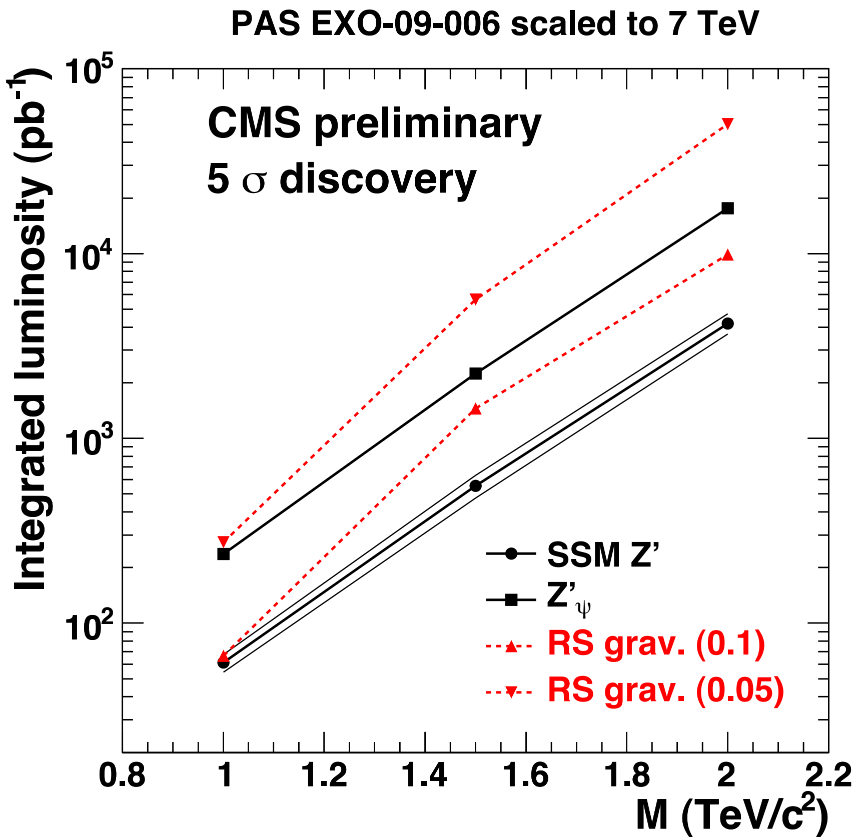
Prospects for extra dimensions

CMS Note 2010/008

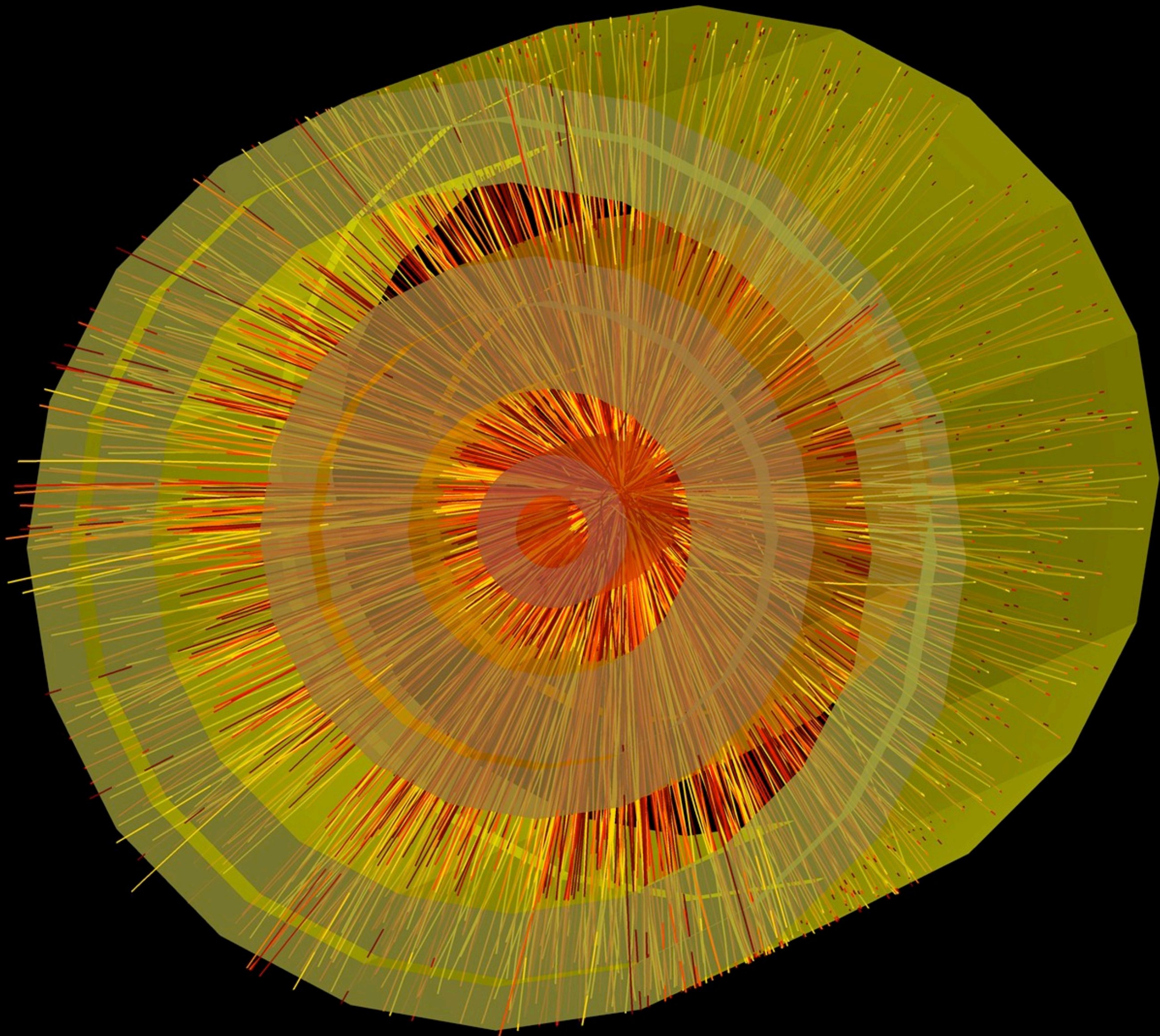


Large extra dimensions in $\gamma\gamma$ channel

Randall-Sundrum gravitons and Z' in *ee* channel



Heavy Ion Results



Summary of Heavy Ion Running

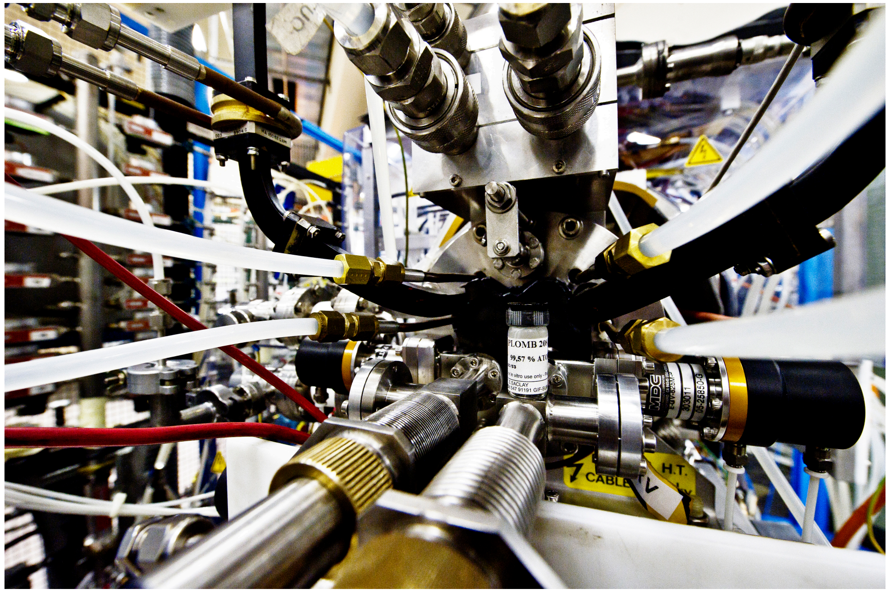
Integrated ion luminosities (http://lpc.web.cern.ch/lpc/lumiplots_ions.htm)

- 10 μb^{-1} delivered to experiments

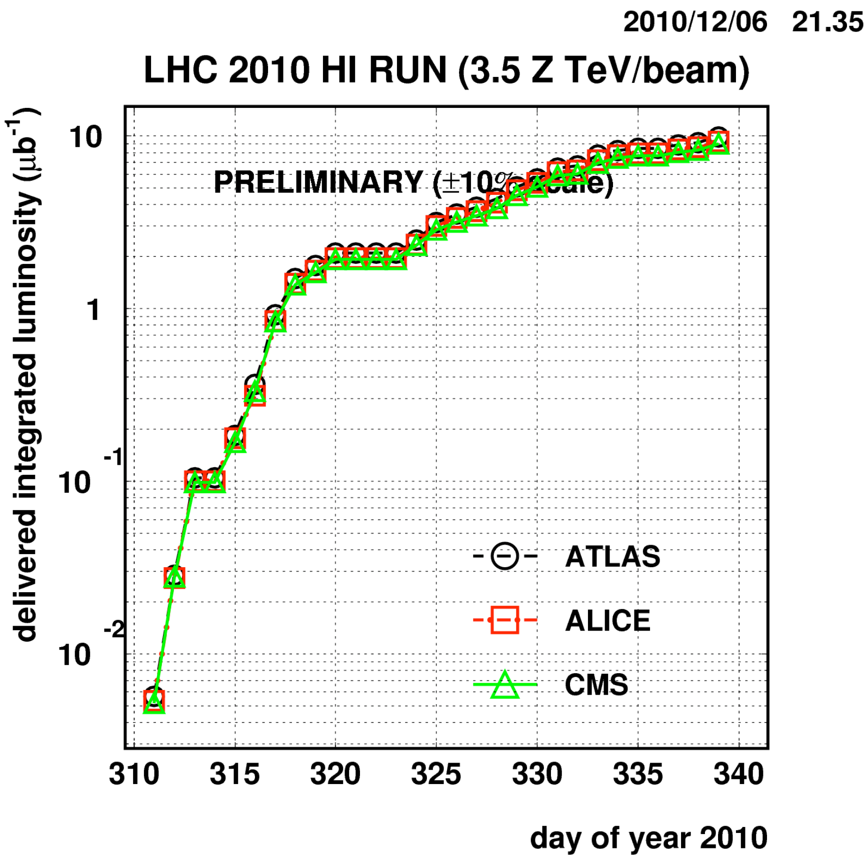
Number of bunches: 137 per beam

Peak luminosity: 3 x 10^{25} $cm^{-2}s^{-1}$

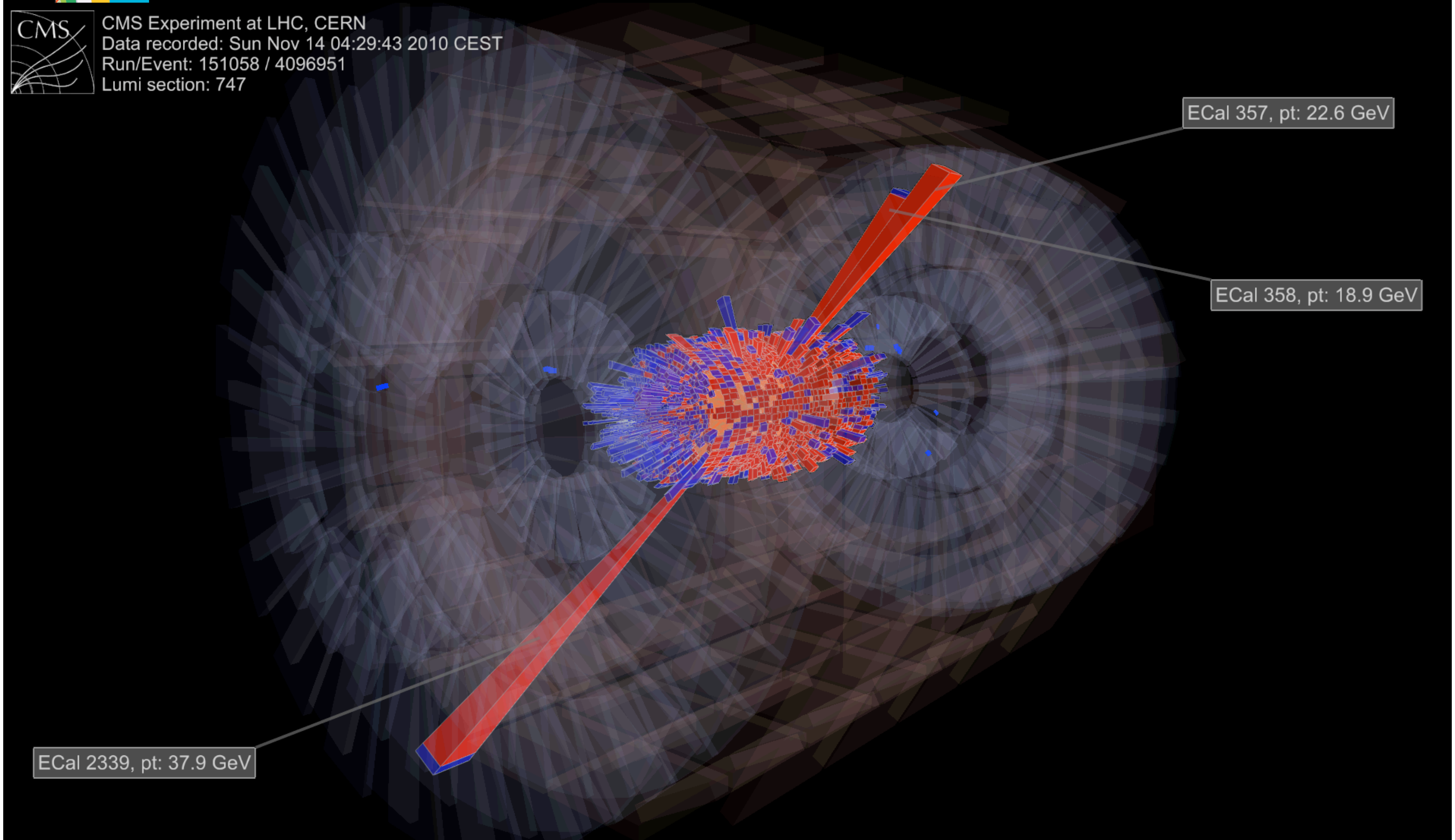
Bunch spacing: 75 ns and 50 ns



Lead ion source



Z in heavy ion collisions

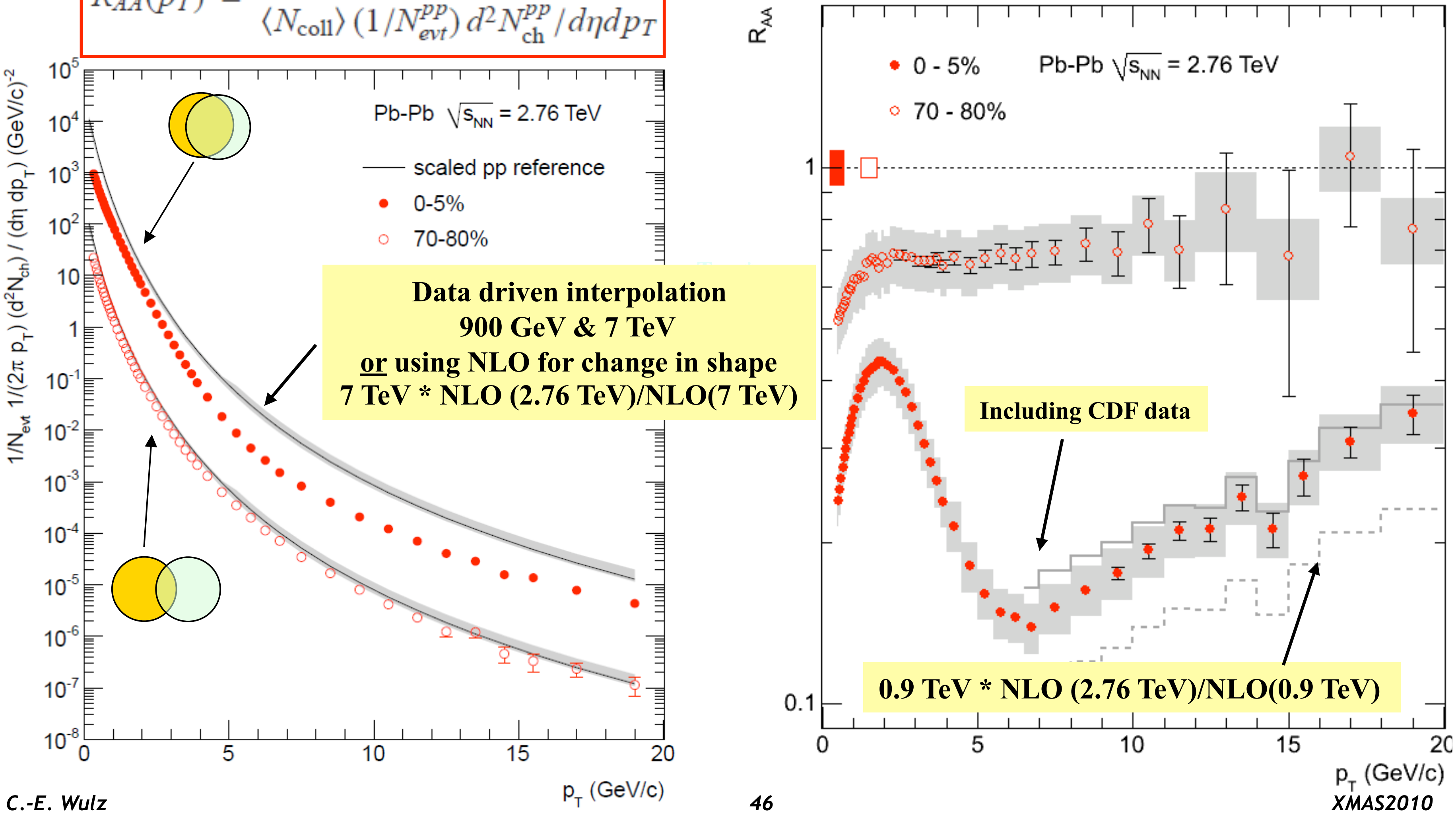


Transverse momentum spectra vs centrality

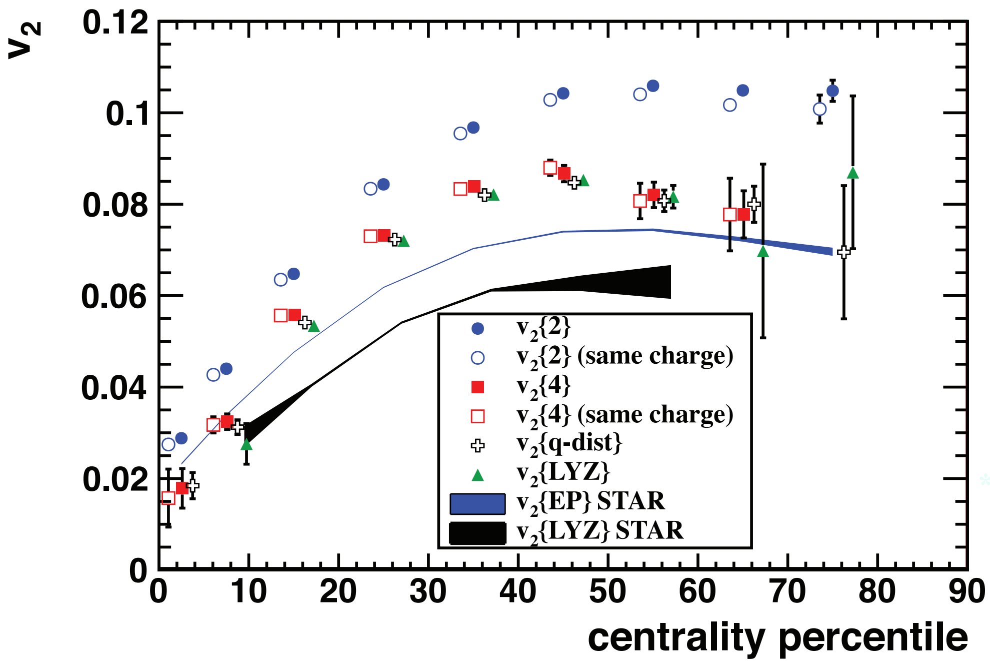
Hadron production in central collisions is suppressed compared to superimposed independent nucleon-nucleon collisions.

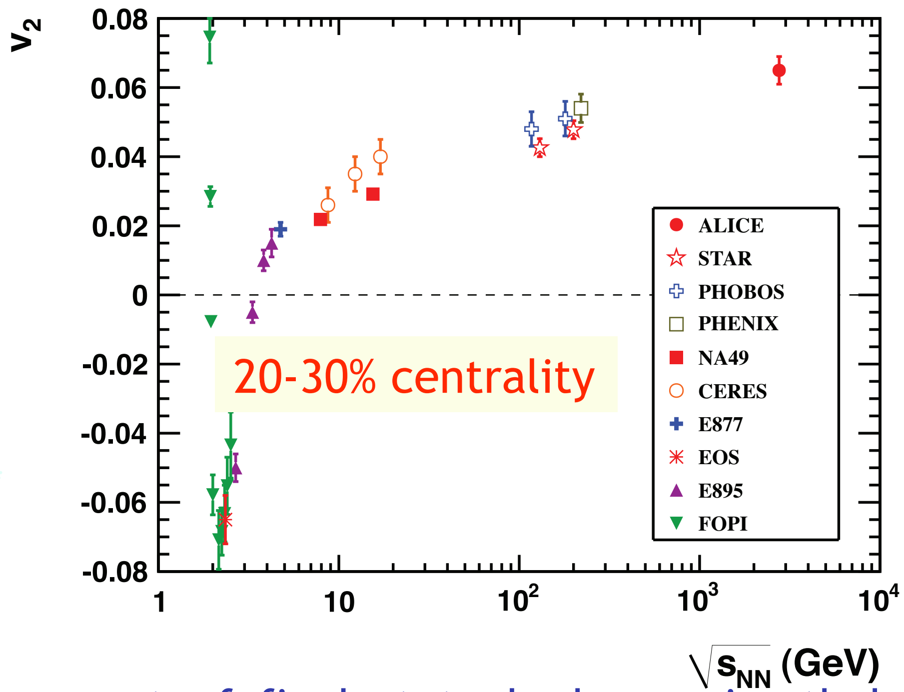
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\,(1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

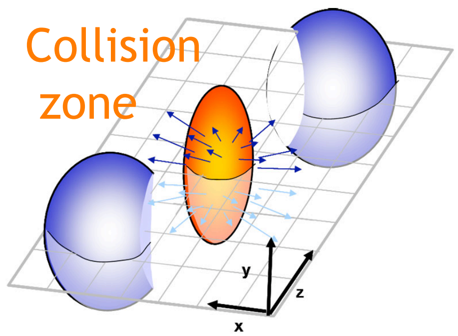
Nuclear modification factor



Elliptic flow







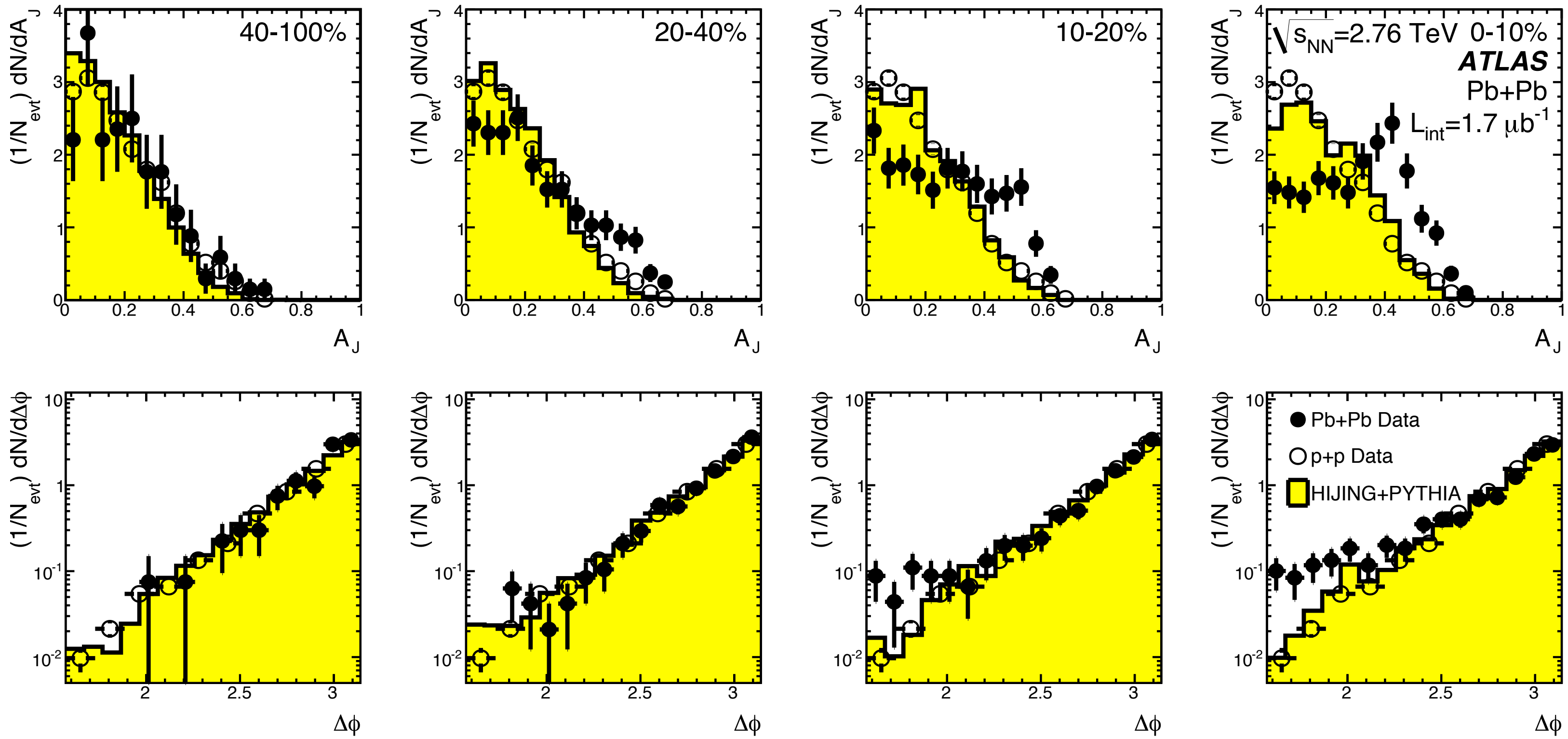
hep-ex 1011.3914 (Nov. 21010)

v2: Second moment of final state hadron azimuthal distribution. There is a continuous increase of the integrated elliptic flow in the 20-30% centrality class. It is about 30% higher than in Au-Au collisions at RHIC, due to the increase in mean p_T. Increase is higher than predictions from ideal hydrodynamic models, but models which incorporate viscous corrections allow for such an increase.

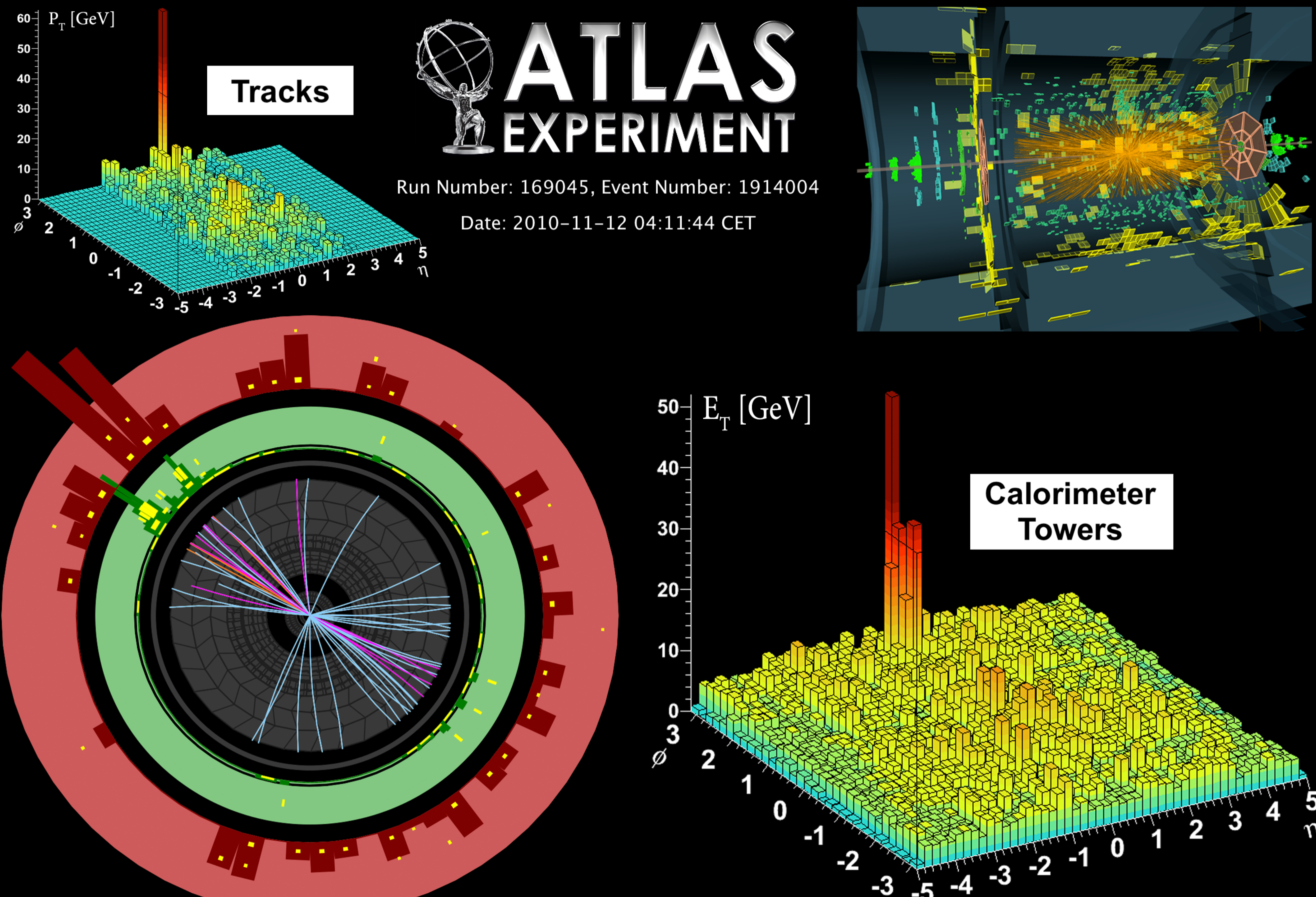
Centrality-dependent dijet asymmetry

$$A_J = \frac{E_{T_1} - E_{T_2}}{E_{T_1} + E_{T_2}}$$

Centrality: Total transverse energy deposited in the forward calorimeters.
Histograms from left to right: from peripheral to central collisions.



hep-ex 1011.6182 (accepted by Phys. Rev. Lett.)



P_T [GeV]
Tracks
ATLAS
EXPERIMENT
Run Number: 169045, Event Number: 1914004
Date: 2010-11-12 04:11:44 CET
E_T [GeV]
Calorimeter Towers

Conclusions and outlook

- Both the proton and the heavy-ion runs of LHC have been very successful.
- The Collaborations have produced the first data analyses remarkably fast.
- The LHC has already begun to be a discovery machine, but will also become a precision machine in the near future.

The LHC experiments have measured and published in the space of around eight months just about all the physics of the last half-century. That alone is a remarkable achievement, but on top of that they have also published new physics. Things are looking very promising for 2011.

S. Bertolucci, CERN Director of Research, 7 Dec. 2010

Thank you for the invitation to this Workshop!